# Introduction to the phenomenology of extra dimensions

# recent results from CMS some prospects at ILC

Marc Besançon

**ILC physics case**
**SPP may 23rd**

# Extra dimensions phenomenology

## outline

- motivations, models
- ADD approach (and black holes)
- $TeV^{-1}$ extra dimension(s)
- Universal Extra Dimensions (UED)
- Randall Sundrum approach (RS) and bulk RS
- string states, intersecting branes (at angles)
- extra-dimensions, GUT, supersymmetry

# Motivations for extra dimensions

**top-down**

**unification**

**superstring theories (branes, duality, M-theory)**

**bottom-up**

**address hierarchy problem of SM**

**can address :**

**- symmetry breaking (EW, SUSY)** $\longrightarrow$ boundary conditions

**- SM fermions masses and mixing**

EW observables precision measurements
K and B physics (CP violation), rare decays, ...

**model building is challenging !**

# Models for extra dimensions

many possible approaches

with different impact on phenomenology depending on

**how many extra dimensions ? 1 or more ?**

**which geometry ? which type of compactification ?**

**how large and which consequences?**

**which fields where ?**

# How many and which "geometry" ?

**- factorizable or 'flat'** (3 space + 1 time + D - 4 extra space dimensions)

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu \qquad \mu, \nu = 0, 1, 2, 3, \ldots D$$

**- non factorizable or warped** (3 space + 1 time + 1 extra space dimension **y**)

$$ds^2 = a(y)(\eta_{\mu\nu} dx^\mu dx^\nu) + dy^2 \qquad \mu, \nu = 0, 1, 2, 3$$

warp factor

6D multiple warping ? arXiv:1001.2666

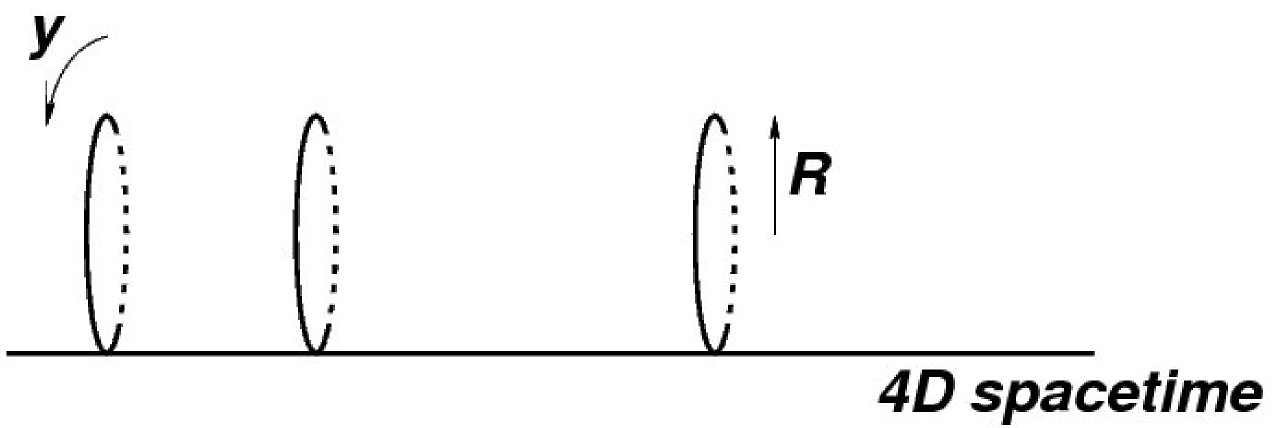
$$ds^2 = b(z)[a(y)\eta_{\mu\nu} dx^\mu dx^\nu + r_y^2 dy^2] + r_z^2 dz^2$$

see also Davoudiasl, Rizzo JHEP11(2008)013

# which type of compactifications ?

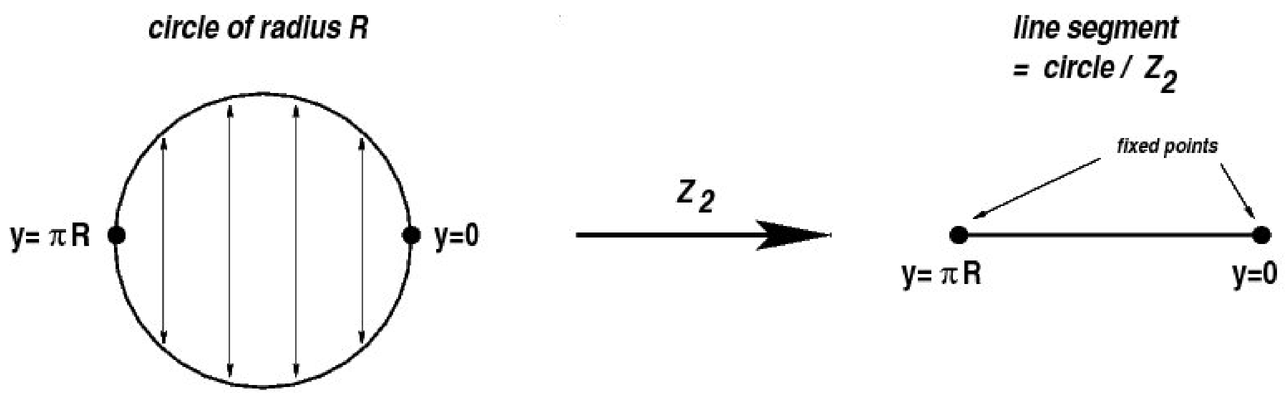
**extra dimensions not (yet) seen → must be small and 'compact'**

## - on circle(s) or torus




## - on orbifolds (coset space M/H where H is a group of discrete symmetries of a manifold M,

**→ space singular at some fixed points)** **e.g. one of the simplest case $S^1/Z_2$ :**



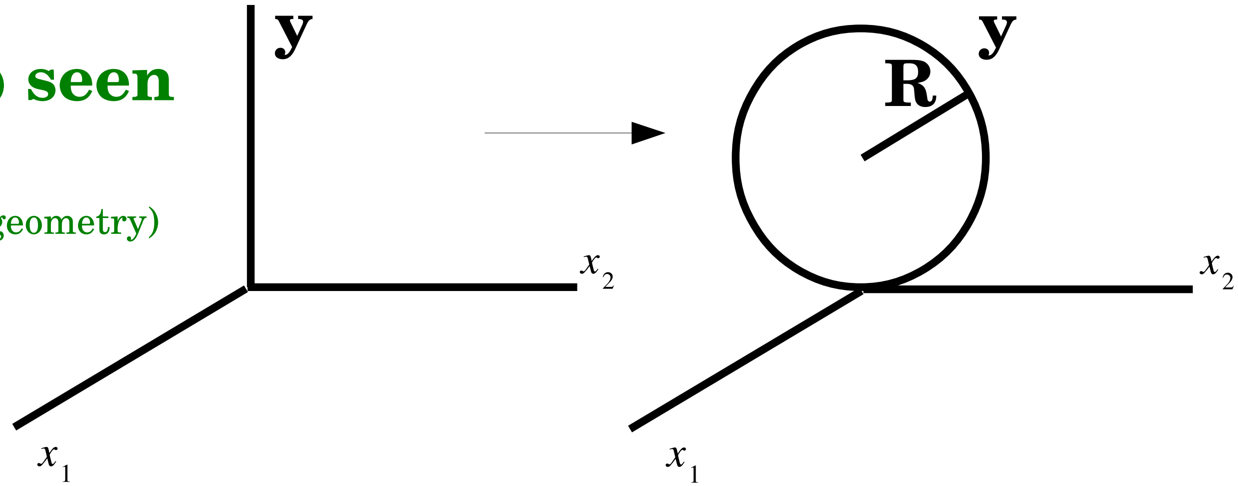

'fixed points ' with respect to the $Z_2$ discrete symmetry $\Gamma : y \to -y$

# How Large and which consequence?

**Extra dimensions not (yet) seen**

→ must be 'small' (for 'flat' geometry)

→ **compact**




**compactified dimensions leads to periodicity conditions**

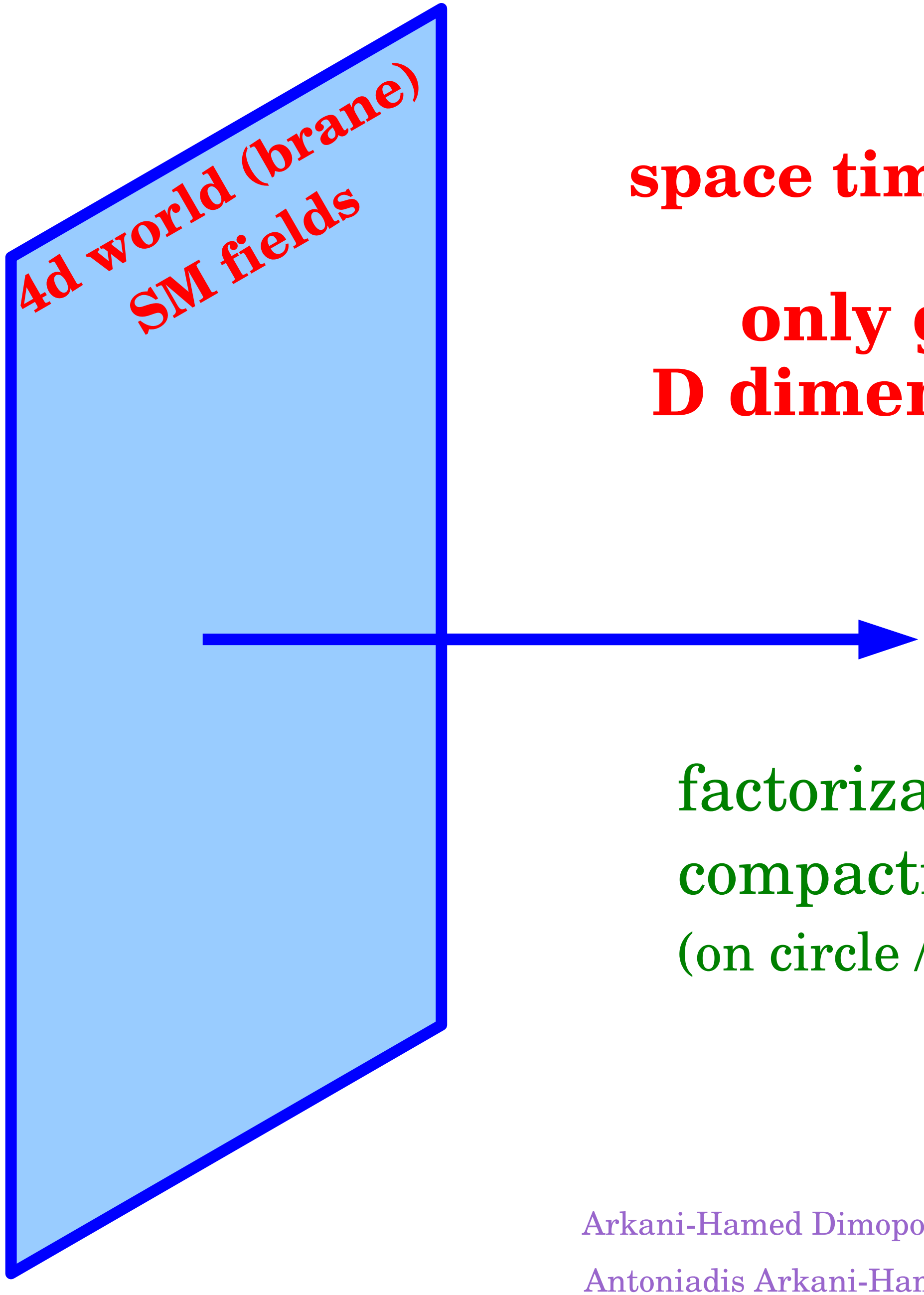
Fourier mode expansion of fields

$$\boxed{\Phi(x,y)=\sum_k \phi^{(k)}(x)\,e^{\frac{iky}{R}}}$$

infinite number of **Kaluza-Klein (KK)** modes/states/excitations

**k^th mode mass** $$\boxed{m_k^2 = m_0^2 + \frac{k^2}{R^2}}$$ → **tower of KK states**

# which fields/particles and where ?




**space time of D = 4 + n dimensions**

**only gravity propagates in D dimensional *(bulk)* full space**

factorizable geometry

compactified **n** extra-dimensions

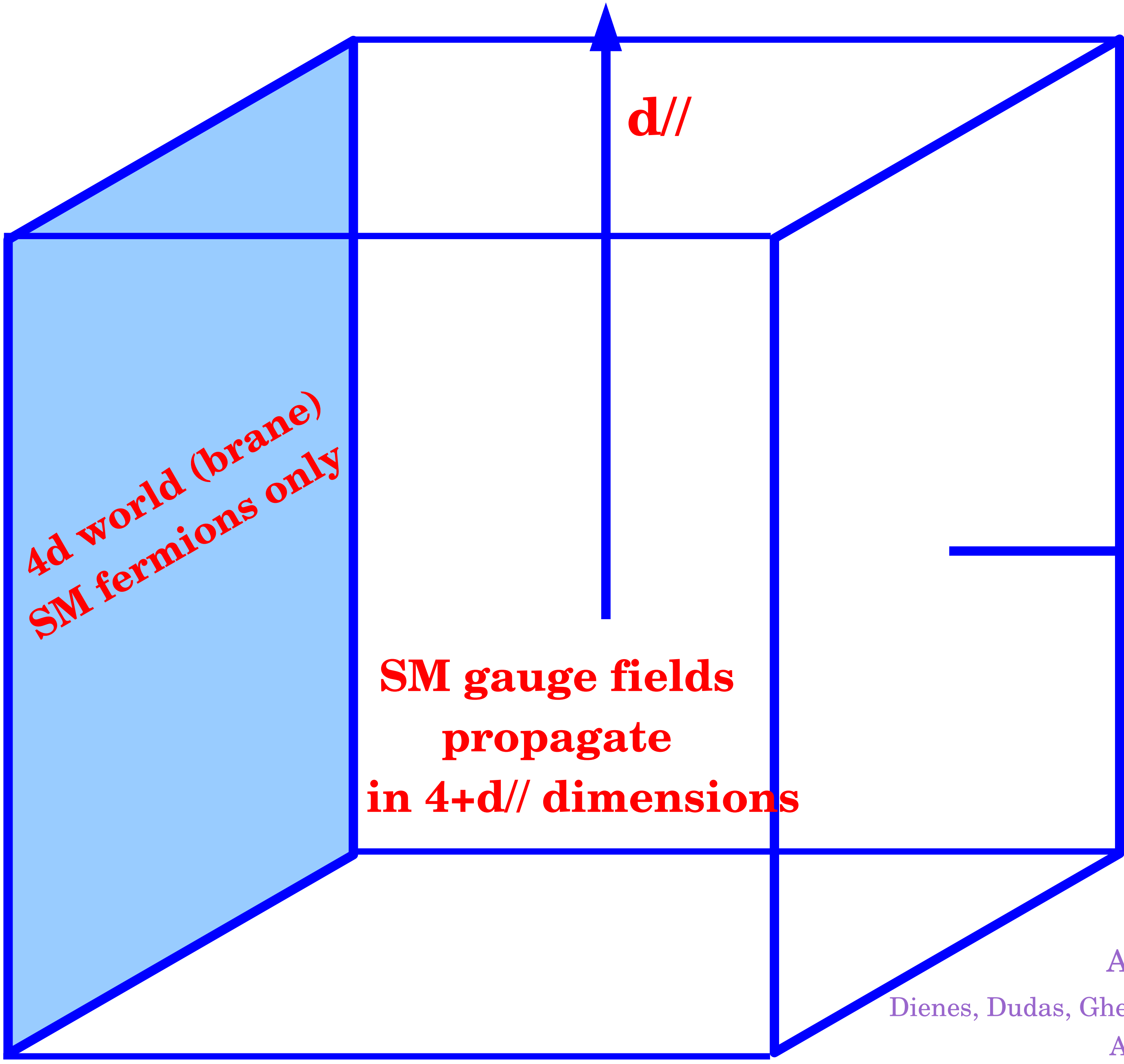
(on circle / torus) as small as ~ mm ?

**ADD model**

Arkani-Hamed Dimopoulos Dvali, PLB 429 (1998) 263, PRD59 (1999) 086004

Antoniadis Arkani-Hamed Dimopoulos Dvali, PLB 436 (1998) 257

## which fields/particles and where ?




# $\mathbf{TeV^{-1}}$ models

~ ADD extension

gravity propagates in
$D = 4 + d_{//} + d_{\perp}$ bulk

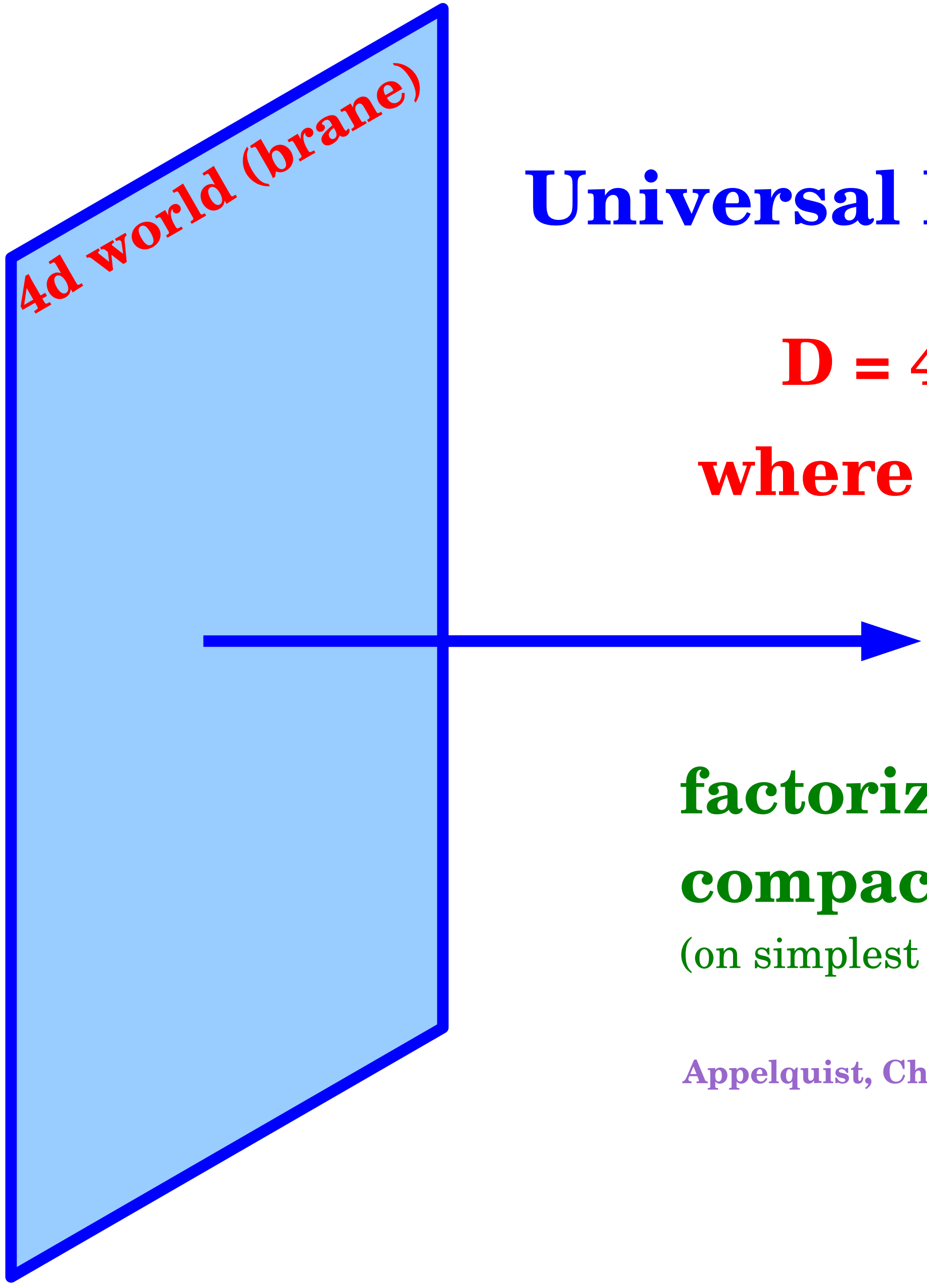
$d_{\perp}$

**factorizable geometry**
**compactified Xtradim**
(on circle/torus)

d// size: $R^{-1} \approx TeV \approx 10^{-19}\, m$


Antoniadis PLB246 (1990) 377
Antoniadis, Benakli, Quiros, PLB 331 (1994) 313
Dienes, Dudas, Gherghetta, PLB 436 (1998) 55, NPB 537 (1999) 47
Antoniadis, Benakli, Quiros, PLB 460 (1999) 176
Rizzo, Wells, PRD61, 016007
Cheung, Landsberg, PRD65, 076003

# which fields/particles and where ?




## Universal Extra-Dimensions (UED)

**D = 4 + n bulk (n=1 mostly)**

**where SM gauge AND fermion fields propagate**

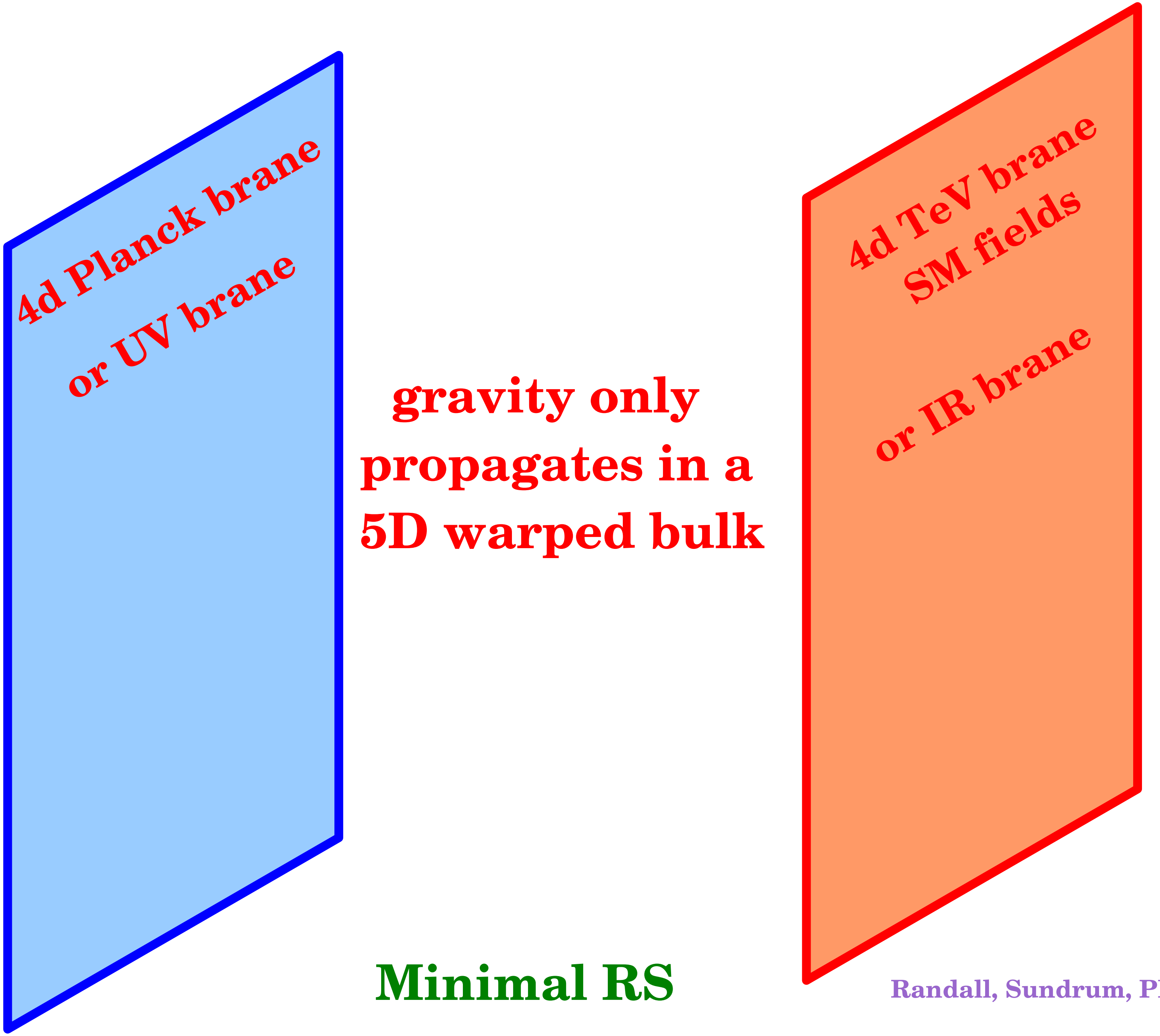
**factorizable geometry**

**compactified extra-dimensions**

(on simplest orbifold)

**Appelquist, Cheng, Dobrescu, PRD64, 035002**

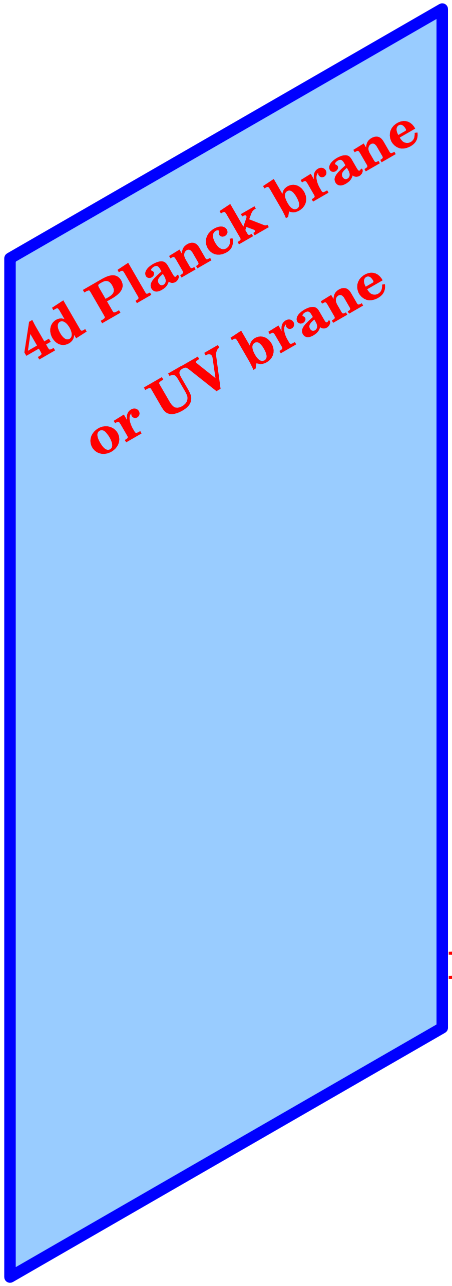
# which fields/particles and where ?




**Minimal RS**

Randall, Sundrum, PRL 83 (1999) 3370

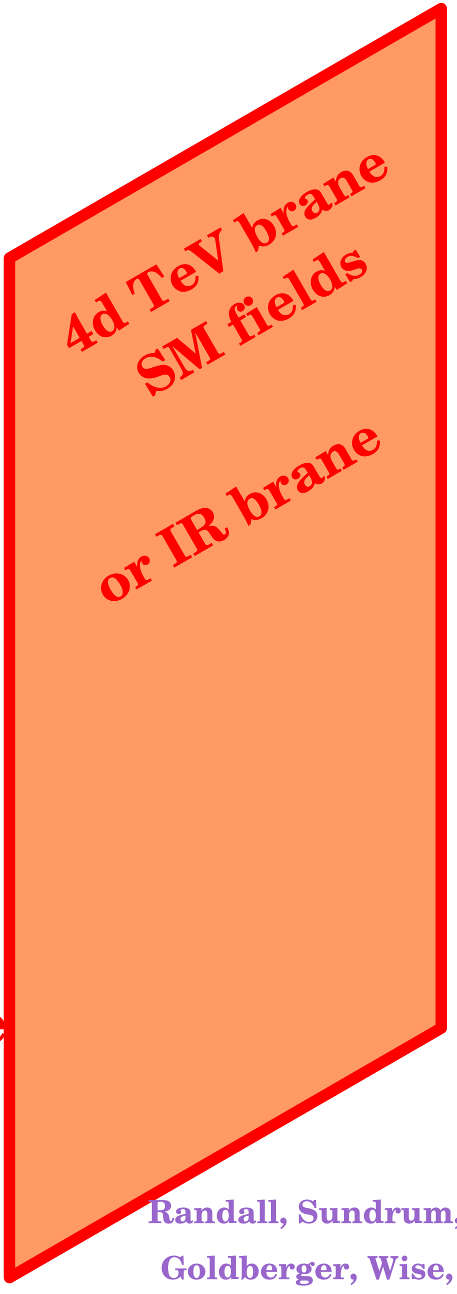
# which fields/particles and where ?




gravity
propagates in a
5D warped bulk

+

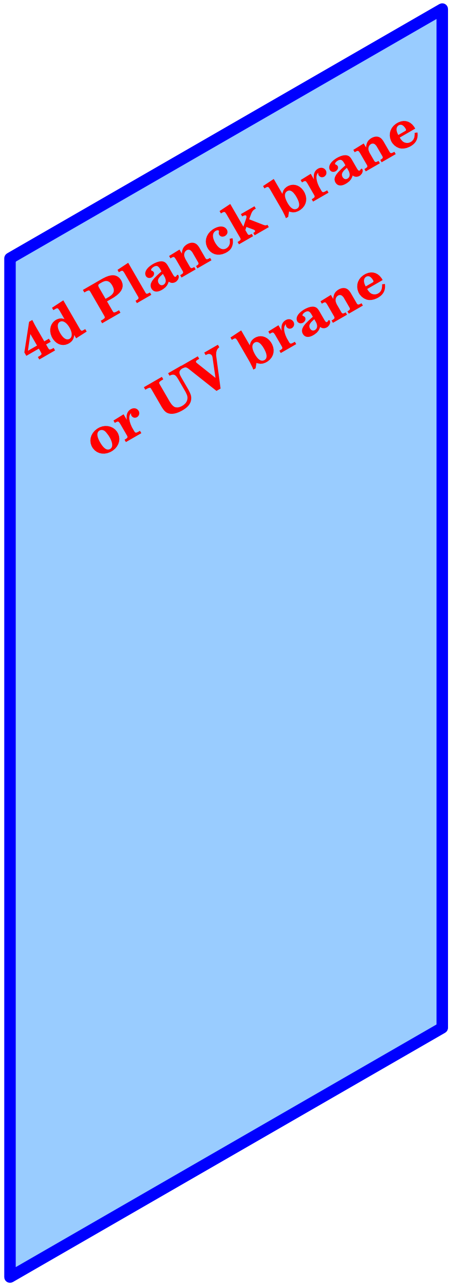
scalar for
interbrane distance
stabilization




stabilized RS

Randall, Sundrum, PRL 83 (1999) 3370
Goldberger, Wise, PRL 83 (1999) 4922,
PRD 60, 107505,
PBL 474 (2000) 275

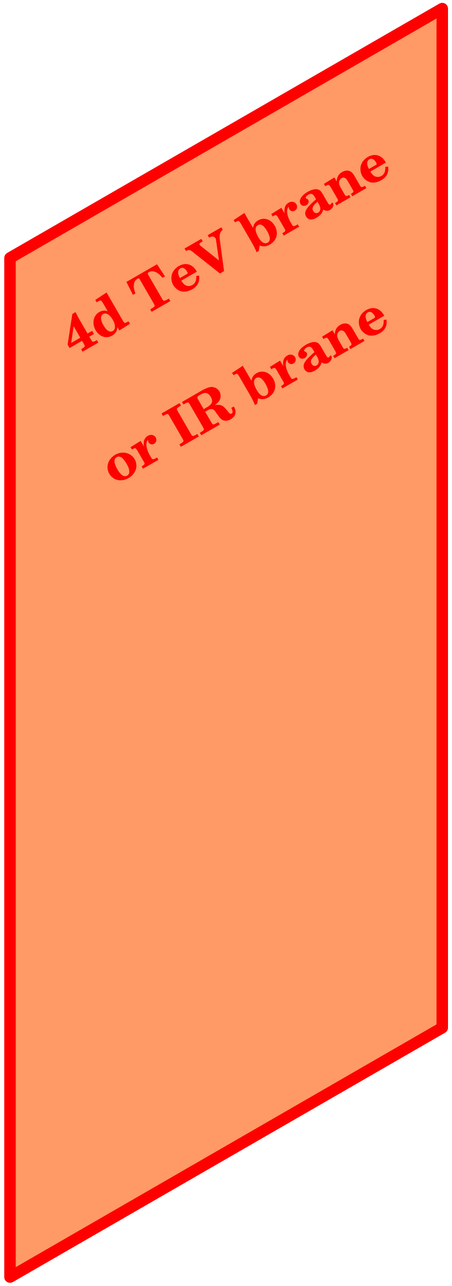
# which fields/particles and where ?




not only gravity
propagates in a
5D warped bulk

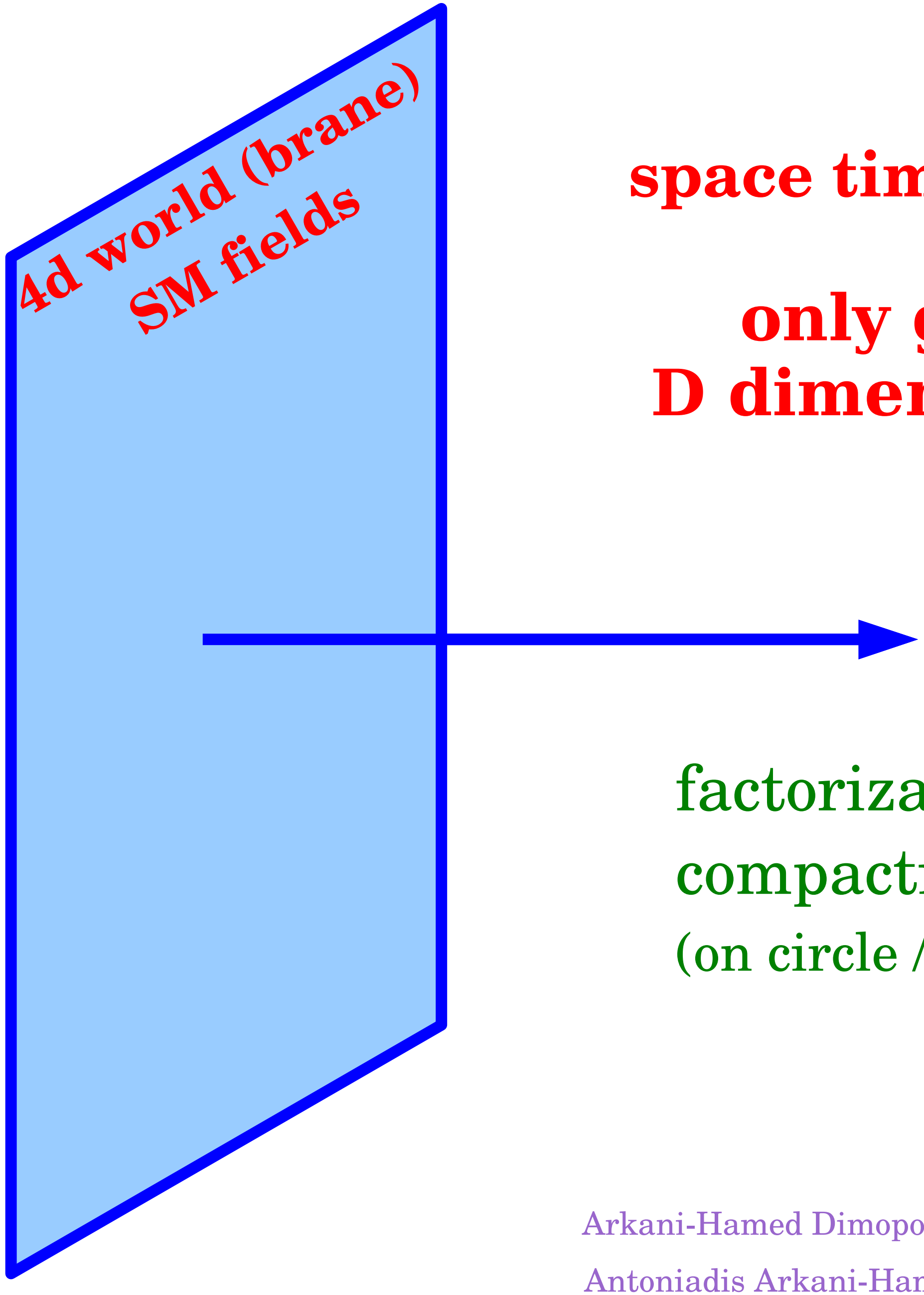
but also
fermion and
gauge fields

Higgs localized
close to TeV brane




**Bulk RS**

# which fields/particles and where ?

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Antoniadis Arkani-Hamed Dimopoulos Dvali, PLB 436 (1998) 257

# ADD approach

Arkani-Hamed Dimopoulos Dvali,
PLB 429 (1998) 263, PRD59 (1999) 086004
Antoniadis Arkani-Hamed Dimopoulos Dvali,
PLB 436 (1998) 257

**gravity at TeV scale in a bulk of 4 + n compactified dimensions**

**SM fields confined in 4D brane**

one of 1st approach of the KK idea renewal after the string duality and brane revolution

**address the hierarchy problem**

$$M^2_{Pl(4)} \sim M^{n+2}_{Pl(4+n)} R^n$$

$$for\ M_D \equiv M_{Pl(4+n)} = 1\ TeV$$

| N | 1 | 2 | 3 ... |
|---|---|---|---|
| R | $10^{10}$ km | 1 mm | 1 nm |

O(solar system)

**'large' ED**

**phenomenology and constraints from various areas:**

- short distance gravity measurement (backup)
- astrophysics and cosmology (backup)
- **collider physics**

Han, Lykken, Zhang, PRD5 9, 105006
Hewett, PRL 82 (1999) 4760
Giudice, Rattazzi, Wells, NPB 544 (1999) 3
Mirabelli, Perelstein, Peskin, PRL 82 (1999) 2236

# ADD approach

the graviton Kaluza-Klein modes have masses equal to $|k|/R$ and therefore the different excitations have mass splittings

$$\Delta m \sim \frac{1}{R} = M_D \left( \frac{M_D}{\bar{M}_{Pl}} \right)^{\frac{2}{n}} = \left( \frac{M_D}{\mathrm{TeV}} \right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}}$$

using $\bar{M}_{Pl} \equiv \sqrt{V_n}\, \bar{M}_D^{\frac{n}{2}+1} = (2\pi R)^{\frac{n}{2}}\, \bar{M}_D^{\frac{n}{2}+1} \equiv R^{\frac{n}{2}}\, M^{\frac{n}{2}+1}$

for $M_D \equiv \sqrt{V_n}\, \bar{M}_D^{\frac{n}{2}+1} = (2\pi R)^{\frac{n}{2}}\, \bar{M}_D^{\frac{n}{2}+1} \equiv R^{\frac{n}{2}}\, M^{\frac{n}{2}+1}$

| n | 4 | 6 | 8 |
|---|---|---|---|
| $\Delta m$ | 20 keV | 7 MeV | 0.1 GeV |

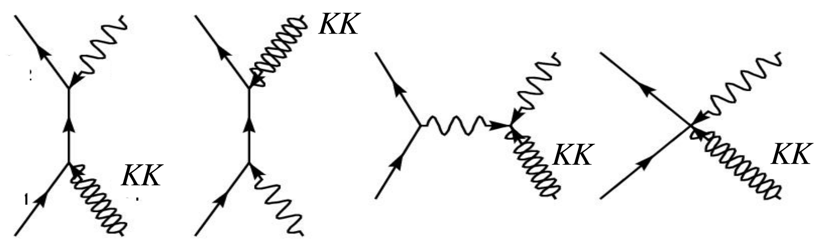
# ADD signatures at colliders in a nutshell

**- direct searches $\longrightarrow$ KK graviton in final states**

**states close to each other in mass O(fraction of eV) quasi-continuum**

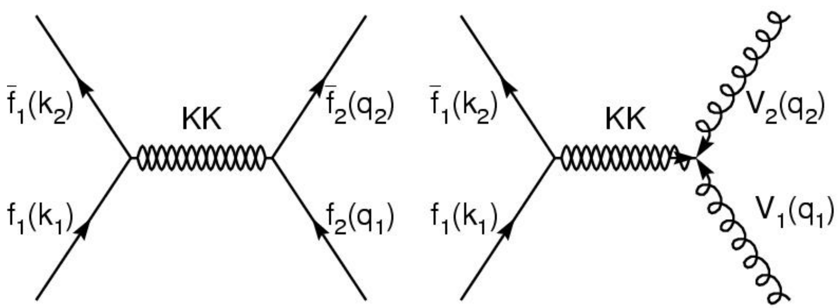
**compensating ~O(1/Mpl) coupling of each KK state to SM fields**

**look for jet + missing energy**
**photon + missing energy**
**Z + missing energy**




**sizeable Xsection directly related to n and scale $M_D$** $\sigma \approx E^n / M_D^{n+2}$

**- indirect searches $\longrightarrow$ no KK states in final states**




**look for deviation in fermion or boson pairs production (diff.) Xsections measurements**

**Xsection divergent for n > 1 $\longrightarrow$ need a cutoff**

**cut-off $M_S$ not related to scale $M_D$ $\longrightarrow$ assume** $M_S \approx M_D$

(possible regularization in string theories context)

**PreLHC collider constraints on scales ~O(1.6 – 2.1 TeV) for n = 2**

# ADD Formalism issues

## - Hewett

interference (sign and n dependence undetermined)

$$\pm\lambda / M_S^4 \text{ with } \lambda \text{ conventionally } \quad \lambda = \pm 1$$

## - Giudice Rattazzi Wells

interference (sign fixed and n dependence undetermined) $\sim 1/\Lambda_T^4$

## - Han Lykken Zhang

interference (sign fixed) $F / M_{HLZ}^4$

$$F = \log \frac{M_{HLZ}^2}{s} \qquad n=2$$

$$F = \frac{2}{n-2} \qquad n>2$$

## - conversion rules

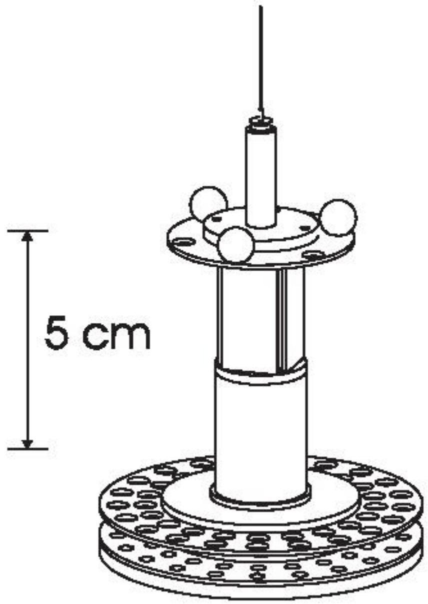
$$M_s[Hewett\ \lambda=+1] = [\frac{2}{\pi}]^{\frac{1}{4}} \Lambda_T(GRW)$$

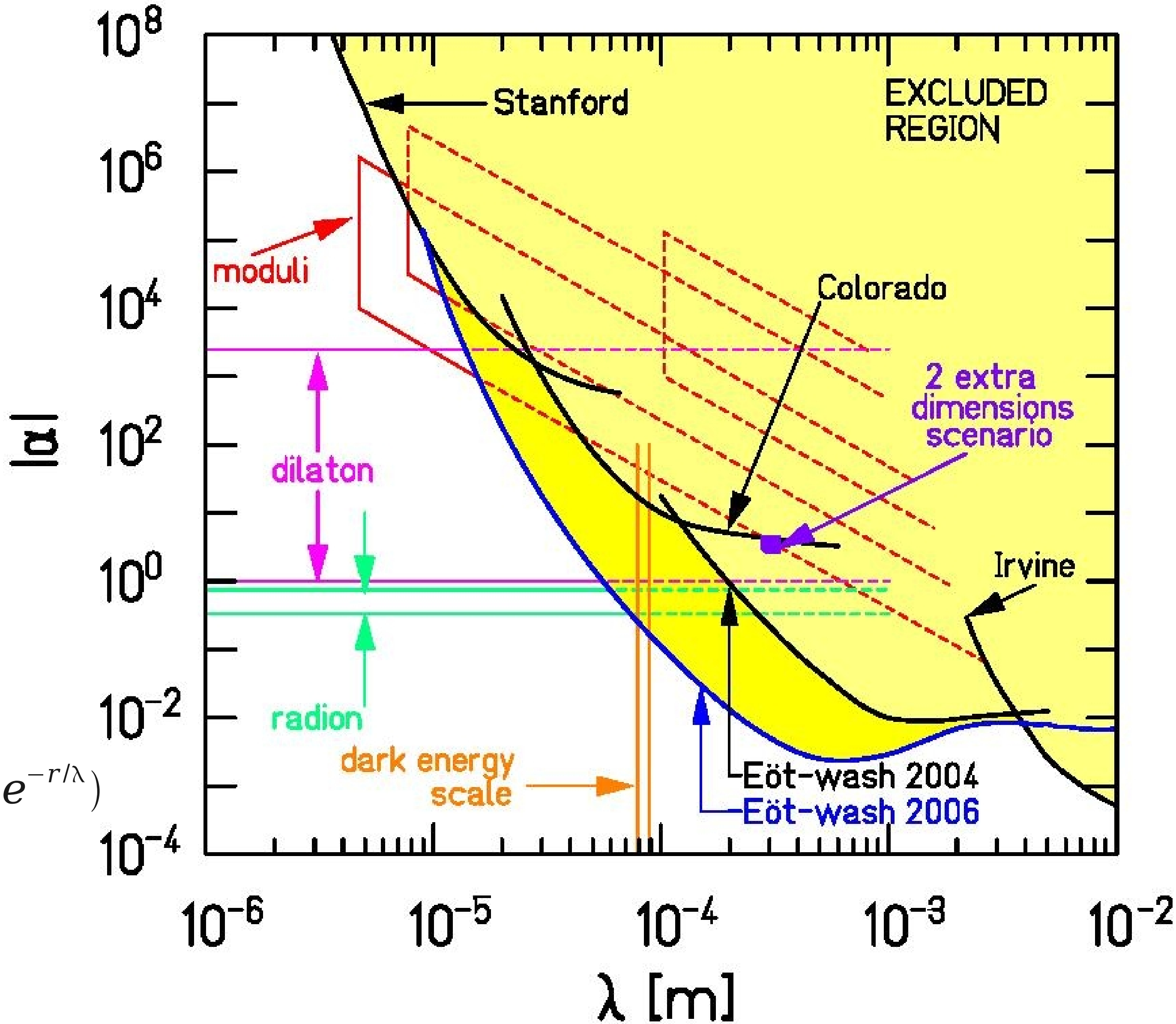
$$\frac{\lambda}{M_S^4(Hewett)} = \frac{\pi}{2} \frac{F}{M_{HLZ}^4}$$

$$\frac{1}{\Lambda^4(GRW)} = \frac{F}{M_{HLZ}^4}$$

Han, Lykken, Zhang, PRD5 9, 105006
Hewett, PRL 82 (1999) 4760
Giudice, Rattazzi, Wells, NPB 544 (1999) 3

# From torsion balance test of gravitational Inverse square law




$$V(r) = -G_{Newton}\frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$

R $\lesssim$ 50 microns

Kapner, Cook, Adelberger, Gundlach, Heckel, Hoyle, Swanson, PRL 98 (2007) 021101

# Branon

- in ('flat') extra-dimensions models with low brane tension $f$ ( lower than $M_D$ ) fluctuations of the brane position along the extra-dimensions are the only relevant low energy modes

- the particles associated to the fluctuations of the brane in the extra dimensions are scalar particles called branons $\pi^\alpha$

- branons can be massive (with mass $M$ )

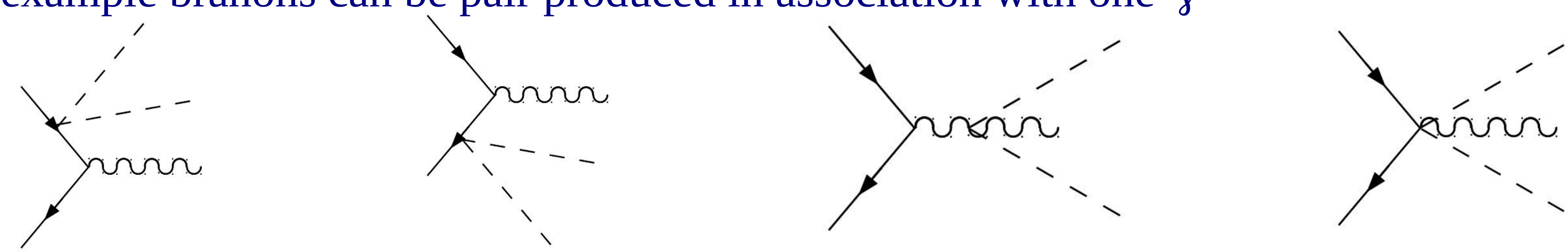
- branons interact by pairs with the SM energy momentum tensor via a mass term and derivative term with $f^4$ suppressed couplings

$$L_{\text{branon}} = \frac{1}{2} g^{\mu\nu} \partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - \frac{1}{2} M^2 \pi^\alpha \pi^\alpha + \frac{1}{8 f^4} \left( 4 \partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - M^2 \pi^\alpha \pi^\alpha g_{\mu\nu} \right) T^{\mu\nu}$$

- branons are stable, weakly interacting and invisible $\rightarrow$ DM candidate

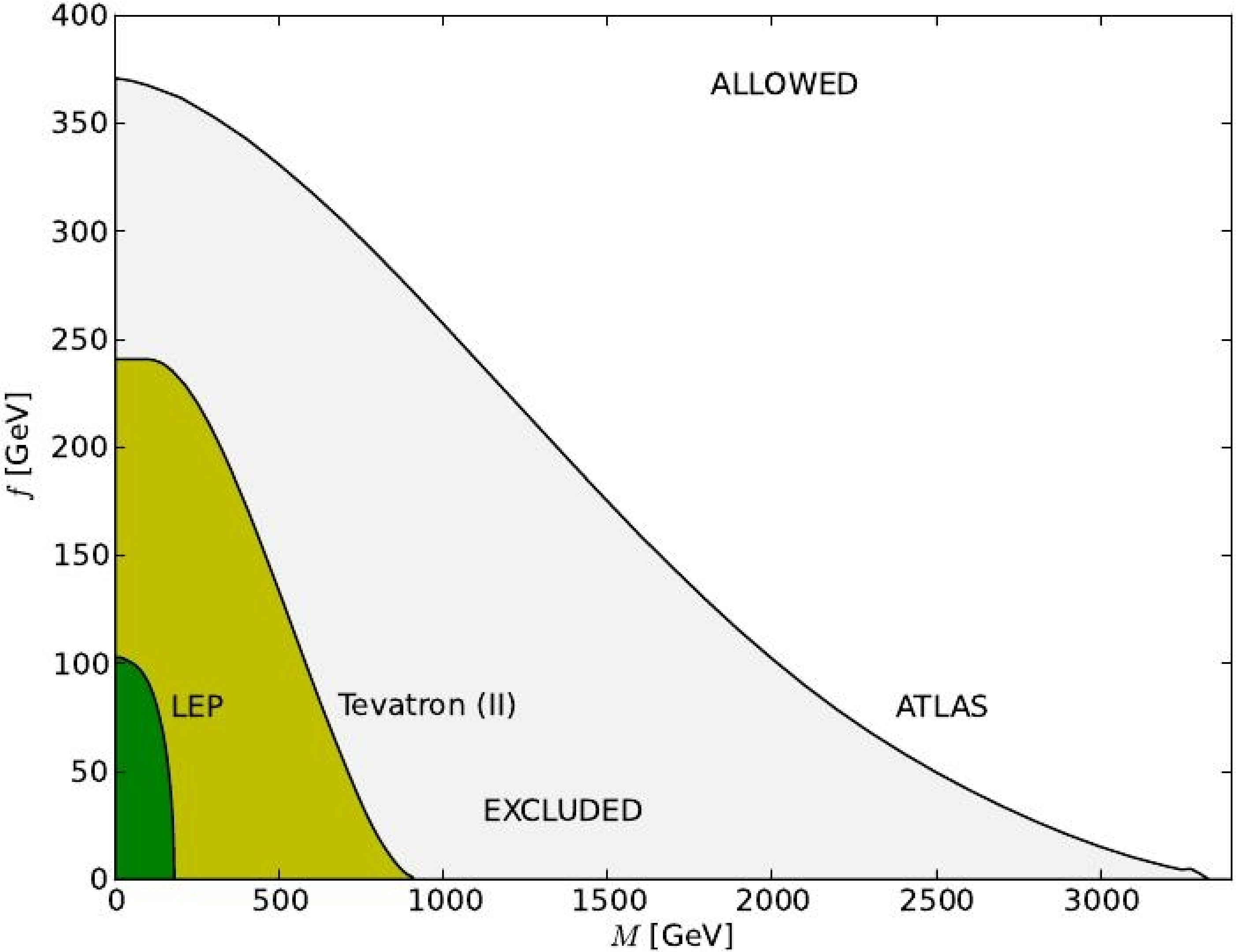
- despite their coupling suppression, branons can be abundantly pair produced in association SM particles at the LHC (and to some extent also at ILC and CLIC, ...)

- for example branons can be pair produced in association with one $\gamma$



e.g. J.A.R. Cembranos, A. Dobado, A.L. Maroto PRD 70 (2004) 096001

# Branons




e.g. J.A.R. Cembranos, A. Dobado, A.L. Maroto PRD 88 (2013) 075021

# Black Holes

Myers, Perry, Annals, Phys. 172 (1986) 304
Argyres, Dimopoulos, March-Russel, PLB 441 (1998) 96
Banks, Fischler, hep-th/9906038
Emparan, Horowitz, PRL 85 (2000) 499
Giddings, Thomas, PRD65, 056010
Dimopoulos, Landsberg, PRL 87 (2001) 161602
Anchordoqui, Goldberg, Shapere, PRD 66, 024033
Dimopoulos, Emparan, PLB 526 (2002) 393
Kanti, Int.J.Mod.Phys. A19 (2004) 4899
Lect.Notes.Phys.769(2009)387

Schwarzschild radius ('flat' ED ~ ADD)

**4D** $R_s \approx \frac{2}{M_{Pl}^2}\frac{M_{BH}}{c^2}$ $\quad R_s \ll 10^{-35}\ m$

**(4+n)D** $R_s \approx \frac{1}{M_d}\left(\frac{M_{BH}}{M_D}\right)^{\frac{1}{n+1}}$ $\quad R_s \approx 10^{-19}\ m$

if **colliding parton impact parameter $< R_S$**
and **$E_{CM} \sim M_{BH} > M_D$**

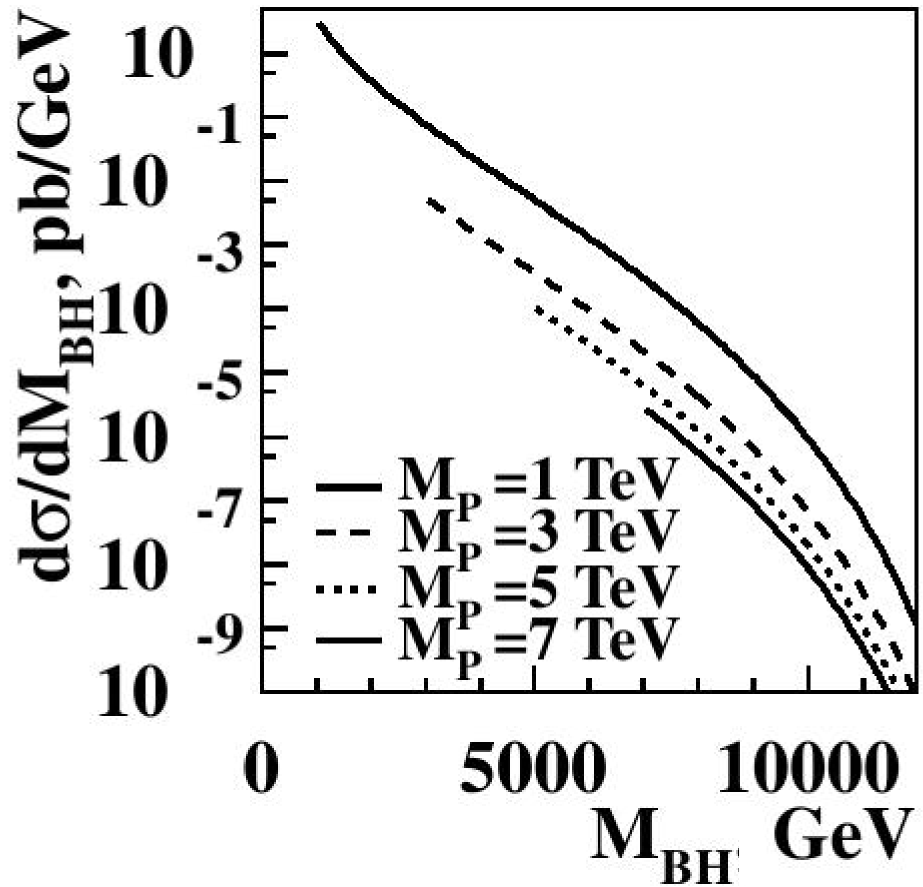
**a black hole can form**

**Cross sections are large**

$\sigma(parton_i\ parton_j \rightarrow BH) \approx \pi R_S^2$

semi-classical approach

$$\sigma(pp \rightarrow BH) \approx 1\text{nb} - 1\,fb$$




Dimopoulos, Landsberg, PRL 87 (2001) 161602

# Black Holes decay

a highly asymetric rotating created Black Hole goes through

## Balding phase

shedding of quantum numbers except a few i.e. M, Q ...

invisible energy (15% of total energy ?)

## Spin-down phase

loss of angular momentum by Hawking radiation

visible energy (25% of total energy ?)

## Schwarzschild phase $M_{BH} >> M_D$

Hawking radiation at $T_H \approx M_D \left(\frac{M_D}{M_{BH}}\right)^{\frac{1}{n+1}} (n+1)$

thermal evaporation black body spectrum + grey-body factors from strong. Grav. field)

visible energy (60% of total energy ?) $\rightarrow$ **mostly in SM particles on our brane**

## Planck phase $M_{BH} \approx M_D$ **(regime of quantum gravity)**

quanta emission ?

string ball formation and evaporation at Hagedorn temperature ?

# Black Holes

BH evaporate/decay democratically into SM particles (or SM+SUSY)

mainly on the brane through Hawking radiation

decay is fast $\sim 10^{-26}$ s $\longrightarrow$ Black Holes do not escape the detector

**spectacular signatures with large jet/lepton multiplicities and small MET**

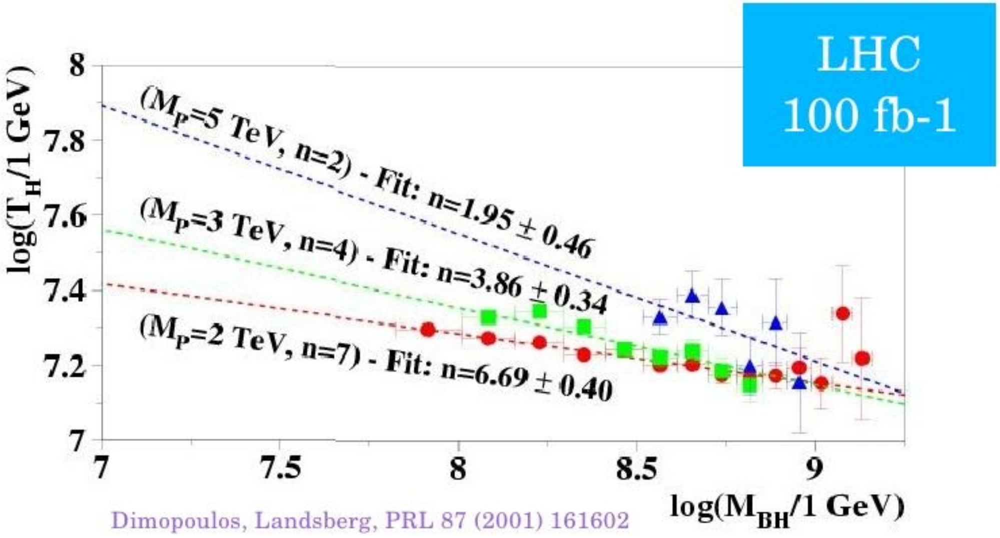
possible to carry dedicated studies → dimensionality of space-time

measure Hawking temperature of black hole $T_{BH}$

(e.g. from energy spectrum of some decay product)

as a function of its mass $M_{BH}$

(e.g. from total energy of all of its decay product)

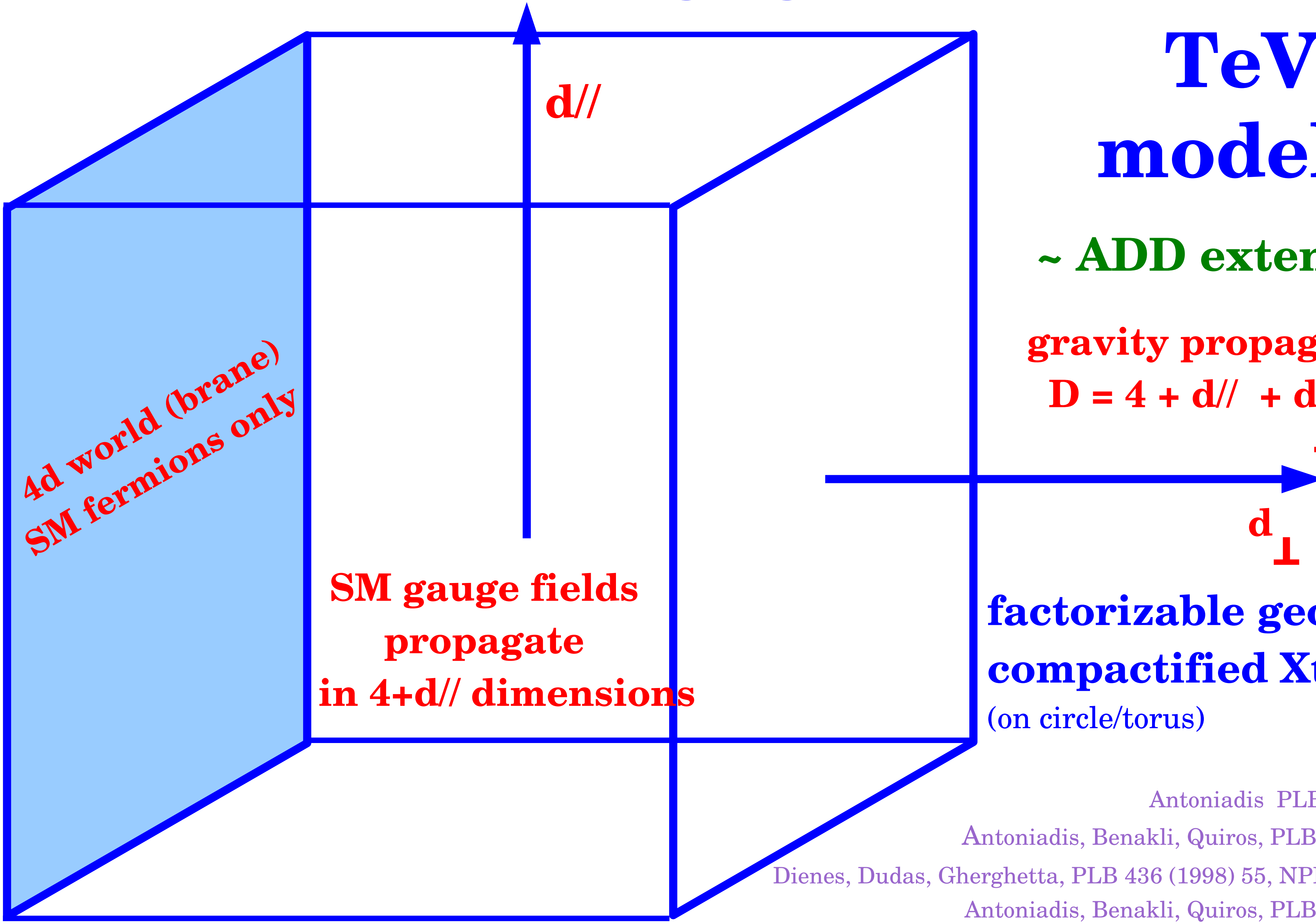



and check that $\log\left(T_{BH}\right) = -\dfrac{1}{n+1}\log\left(M_{BH}\right) + \text{const}$ (extra-dimension equivalent of the Wien law)

# Astrophysical Constraints

| | $M_D$ | $M_D$ |
|---|---|---|
| $\gamma$ ray from galactic bulge (from EGRET) | 450 TeV (n=2)<br>$3.8\ 10^{-10}$ m | 1.9 TeV (n=3)<br>$4.2\ 10^{-12}$ m |
| neutron star halo (KK decay) (from EGRET) | 454 TeV (n=2) | 27 TeV (n=3) |
| neutron star excess heat (from HST) | 1680 TeV (n=2) | 60 TeV (n=3) |

# $TEV^{-1}$ (KK gauge bosons)




# $TeV^{-1}$ models

**~ ADD extension**

**gravity propagates in**
**D = 4 + d// + d⊥ bulk**

**factorizable geometry**
**compactified Xtradim**
(on circle/torus)

d// size: $R^{-1} \approx TeV \approx 10^{-19}\,m$

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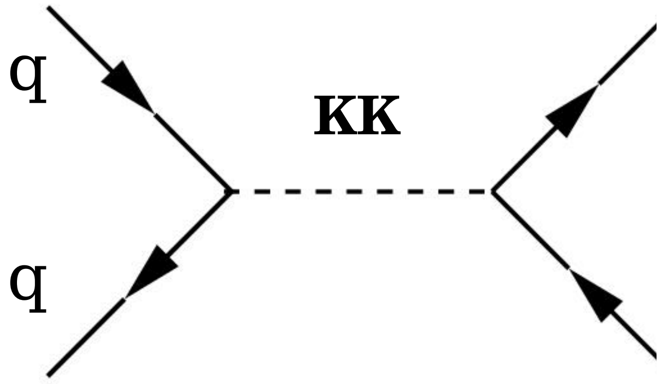
- gauge bosons in 'flat' 5D bulk with R = O (TEV$^{-1}$) extra dimension

- KK 0th mode identified with SM gauge bosons (can mix with non-zero modes)

- combined constraints from LEP, HERA, TEVATRON: $\mathbf{M_{KK} = R^{-1} > 6.8}$ **TeV**
  Cheung, Landsberg, PRD65, 076003

**direct searches (before LHC): $\mathbf{M_{KK} > O}$ (1 TeV)**

- **resonant production if** $M_{KK} < E_{CM}$
  search for dilepton or dijet invariant mass peak
  (or transverse mass jacobian peak from single lepton)
  **to look for the 1$^{st}$ mode at least**
  2$^{nd}$ , 3$^{rd}$ modes for KK pattern would be desirable




Coupling: finite at 5D, divergent for > 5D
but can regularized in specific approaches

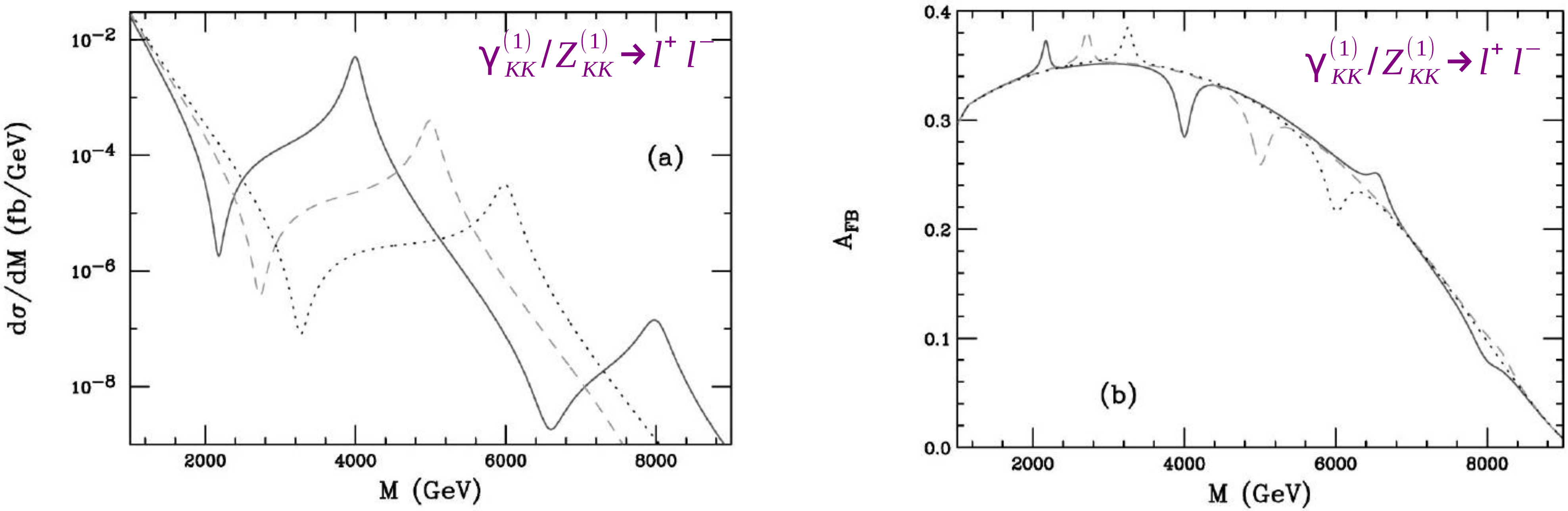
- **virtual effects (?) if** $M_{KK} > E_{CM}$

  Xsection deviations, asymmetries

# TEV$^{-1}$ (KK gauge bosons)

naively, from normalization of gauge fields kinetic energy term → KK gauge bosons couple to SM fermions with a strength larger than the 0-mode by a universal factor of $\sqrt{2}$

example of 4, 5 and 6 TeV $\gamma_{KK}^{(1)}$ and $Z_{KK}^{(1)}$ (which are nearly degenerate in mass as well as with $W_{KK}^{(1)}$) production at the 14 TeV LHC (fermions in one 4D brane)




Rizzo,PRD61 (2000) 055005

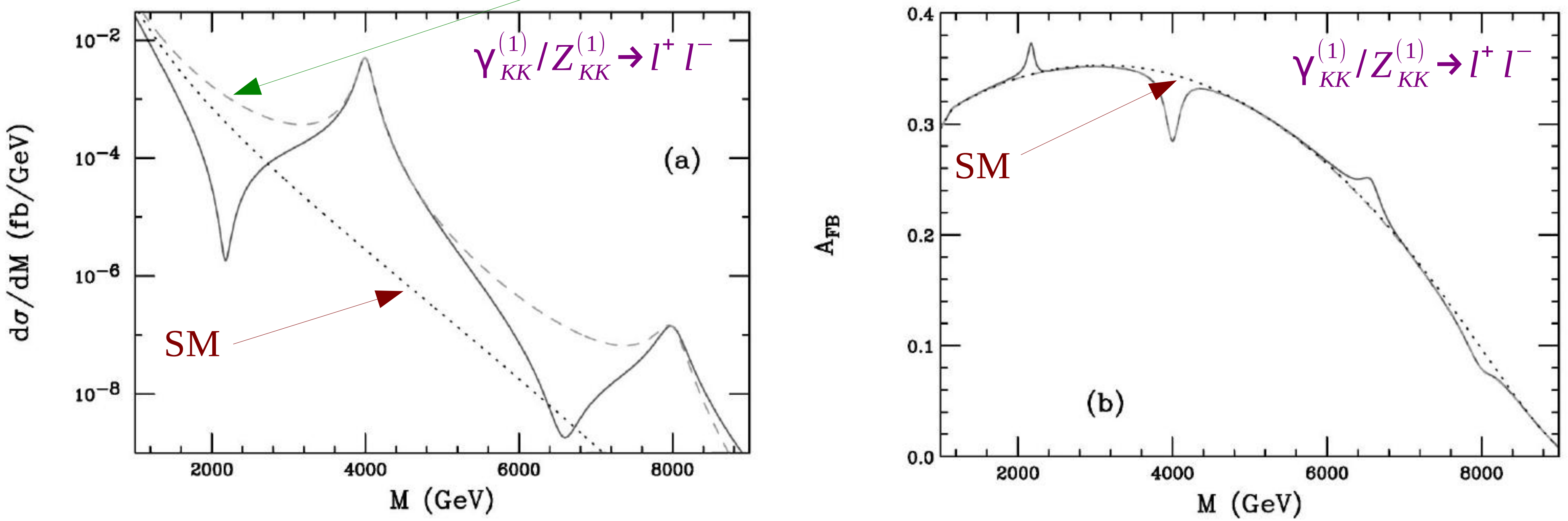
angular distributions to demonstrate that states are spin-1 (if enough statistics)

dips in the distributions → signal for KK scenarios ?

# TEV$^{-1}$ (KK gauge bosons)

dips in the distributions → signal for KK scenarios ?

may depend on fermion location → dips can disappear with different fermions assignments




Rizzo,PRD61 (2000) 055005

if access to second KK level kinematically difficult at LHC →

difficult to distinguish an ordinary Z' and degenerate $\gamma_{KK}^{()1}/Z_{KK}^{(1)}$

difficult to demonstrate the KK nature of the resonance at the LHC ?

way out with lepton collider even below the resonance (see later on) ?

# TEV$^{-1}$ (KK gauge bosons)

what if more than one $\mathrm{TeV}^{-1}$ extra dimension ?

⇒ details of compactifying manifold may become important

- KK excitation spacings more intricate
- many levels degenerate in mass
- strength of couplings to fermions may become level dependent

⇒ constraints from precision measurement more tricky to derive

- assume that the couplings of at least the first few levels to fermions are not vastly different than the naive one (see few slides above)
- in the limit where the effects KK states exchanges viewed as a set as a set of contact interaction (effective approach)

→ new dimension-6 operators with coefficient proportional to a dimensionless quantity V

$$V = \left( M_W R \right) \sum_{\boldsymbol{n}=1}^{\infty} \frac{g_{\boldsymbol{n}}^2}{g_0^2} \frac{1}{\boldsymbol{n} \cdot \boldsymbol{n}}$$

$g_{\boldsymbol{n}}$ is the coupling of the $\boldsymbol{n}$ th level and assuming a simple compactification where 1st KK excitation(s) have mass $\propto \frac{1}{R}$

**the sum in V does not converge with more than one extra dimension**

Rizzo,PRD61 (2000) 055005

# TEV$^{-1}$ (KK gauge bosons)

1st way out : truncation (T)

⇒ sum over a finite number of terms $n_{\max}$ i.e only those states whose mass is below $M_s$ which now acts simply as cutoff

2nd way out : exponential (E)

⇒ exponential damping of contribution from higher terms in the sum (from considerations of the flexibility of the brane or in string context)

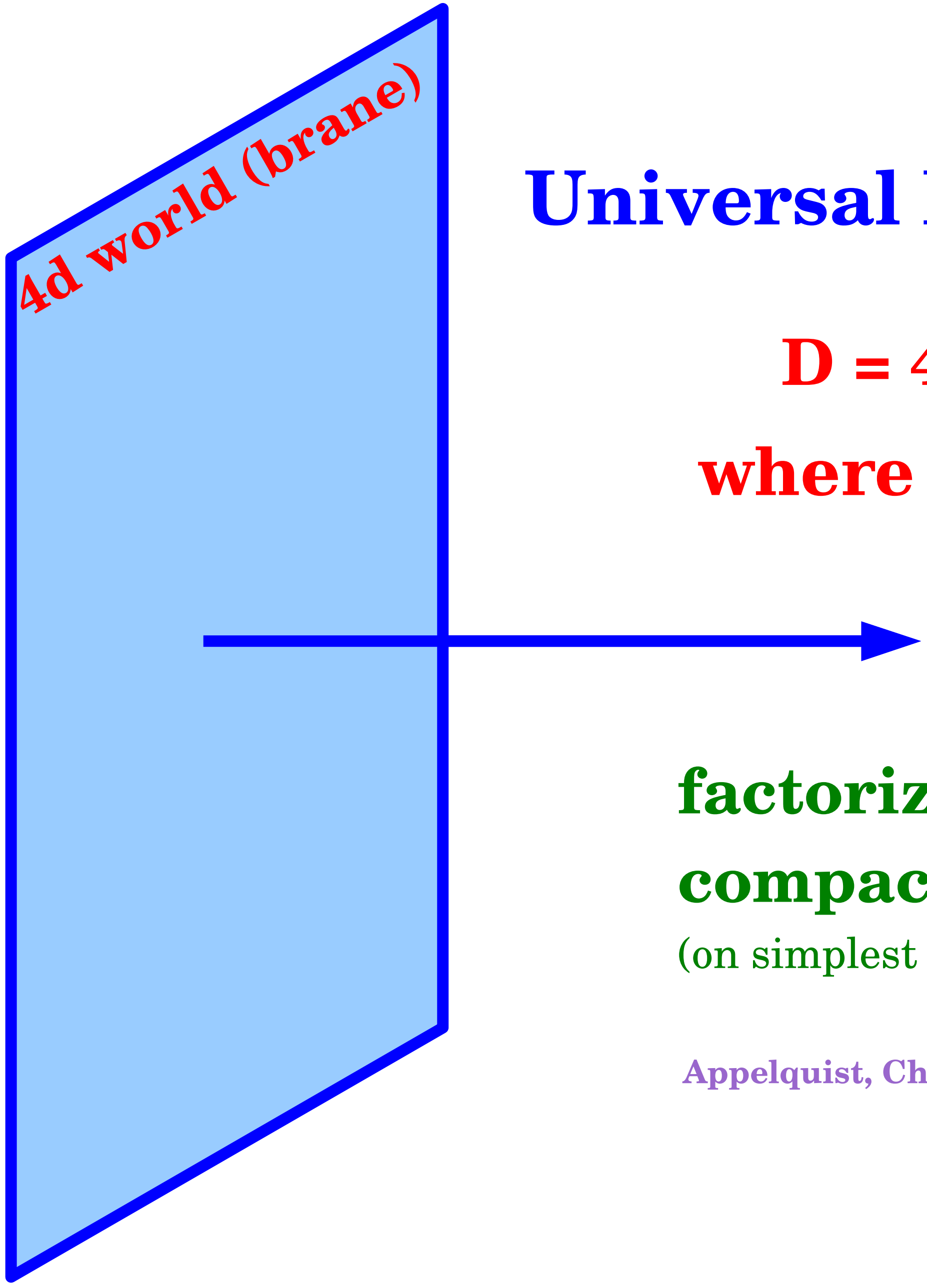
$$V = \left(M_W R\right) \sum_{\boldsymbol{n}=1}^{\infty} \frac{g_{\boldsymbol{n}}^2}{g_0^2} \frac{1}{\boldsymbol{n}\cdot\boldsymbol{n}} e^{-\frac{\boldsymbol{n}\cdot\boldsymbol{n}}{n_{\max}}}$$

Rizzo,PRD61 (2000) 055005

lower bound on the mass of the 1st KK state (TeV) for different compactifications i.e. $Z_2 \times Z_2$, $Z_{3,6}$ and $Z_2 \times Z_2 \times Z_2$

| | $Z_2 \times Z_2$ | | $Z_{3,6}$ | | $Z_2 \times Z_2 \times Z_2$ | |
|---|---|---|---|---|---|---|
| $n_{max}$ | T | E | T | E | T | E |
| 2 | 5.69* | 4.23* | 6.63* | 4.77* | 8.65 | 8.01 |
| 3 | 6.64 | 4.87* | 7.41 | 5.43* | 11.7 | 10.8 |
| 4 | 7.20 | 5.28* | 7.95 | 5.85* | 13.7 | 13.0 |
| 5 | 7.69 | 5.58* | 8.36 | 6.17* | 15.7 | 14.9 |
| 10 | 8.89 | 6.42 | 9.61 | 7.05 | 23.2 | 22.0 |
| 20 | 9.95 | 7.16 | 10.2 | 7.83 | 33.5 | 31.8 |
| 50 | 11.2 | 8.04 | 12.1 | 8.75 | 53.5 | 50.9 |

# which fields/particles and where ?




## Universal Extra-Dimensions (UED)

**D = 4 + n bulk (n=1 mostly)**

**where SM gauge AND fermion fields propagate**

**factorizable geometry**

**compactified extra-dimensions**

(on simplest orbifold)

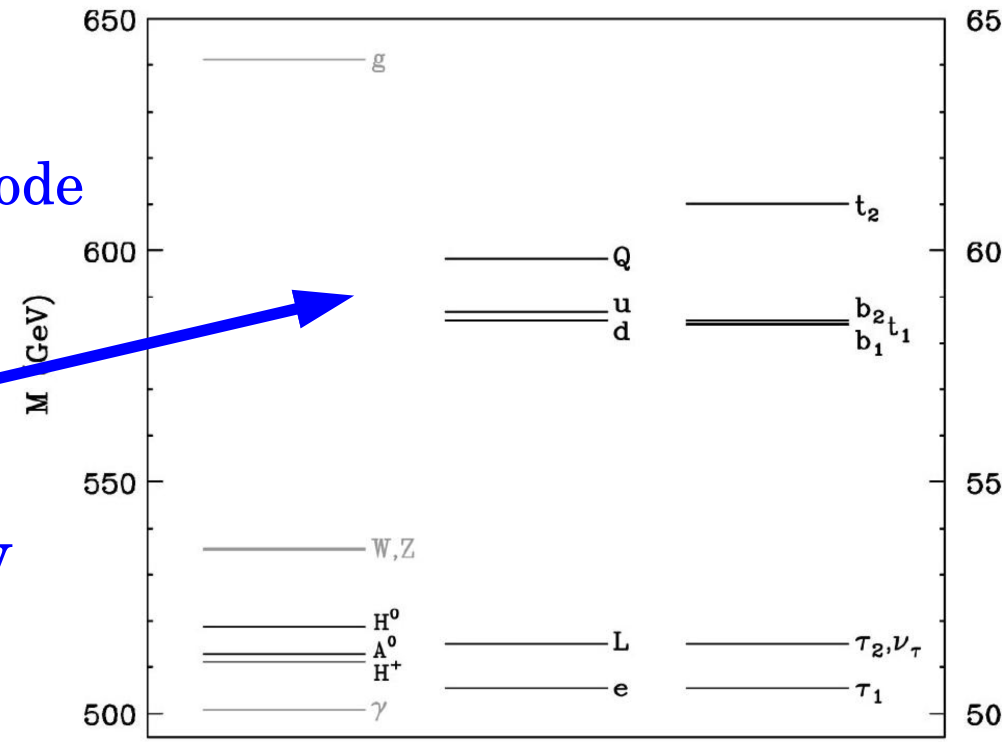
**Appelquist, Cheng, Dobrescu, PRD64, 035002**

# Minimal Universal Extra Dimensions (mUED)

- all SM fields in a 5D bulk
  further extension of TeV$^{-1}$

- 4D SM particles identified to 0th KK mode

- 1st (and beyond) KK modes are massive
  loop corrections involving bulk fields
  lead to non degenerate mass spectrum




Cheng, Matchev, Schmaltz PRD66, 056006

- EW constraints → M > 300 – 600 GeV

- momentum conservation in bulk
  → KK-parity conservation
  → pheno. similar to SUSY with conserved R-parity

**- KK states produced in pairs**

**- 1 KK + 1 SM in a KK state decay**
possible cascade decays

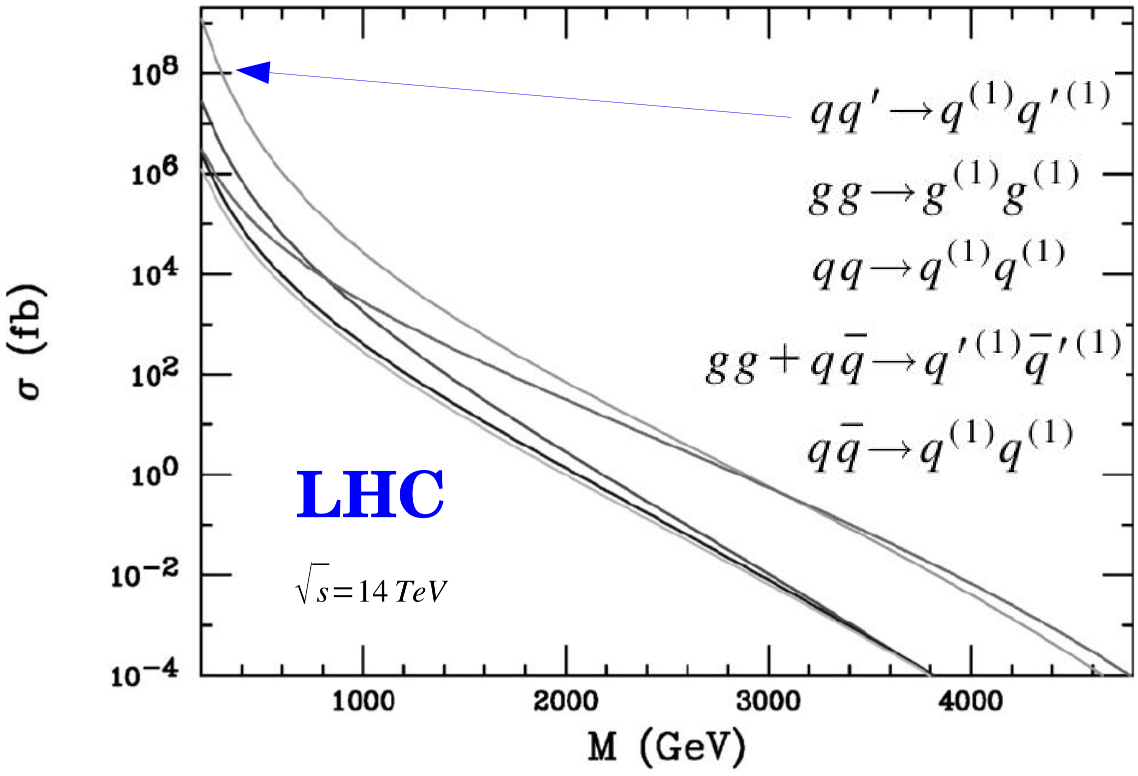
**- stable LKP (DM candidate)**
source of MET

# Minimal UED

- pair production of lightest coloured KK states
  $\rightarrow$ largest Xsection

- possible signatures:

  4 leptons + MET
  3 (or 2 leptons ...) + jets + MET
  2 (or more) jets + MET




Rizzo, PRD 64, 095010

# Minimal UED

*example of decay flow*

$Br(g_1 \rightarrow Q_1 Q_1) \approx 0.5$

$Br(g_1 \rightarrow q_1 q_1) \approx 0.5$

$Br(q_1 \rightarrow q \gamma_1) \approx 1$

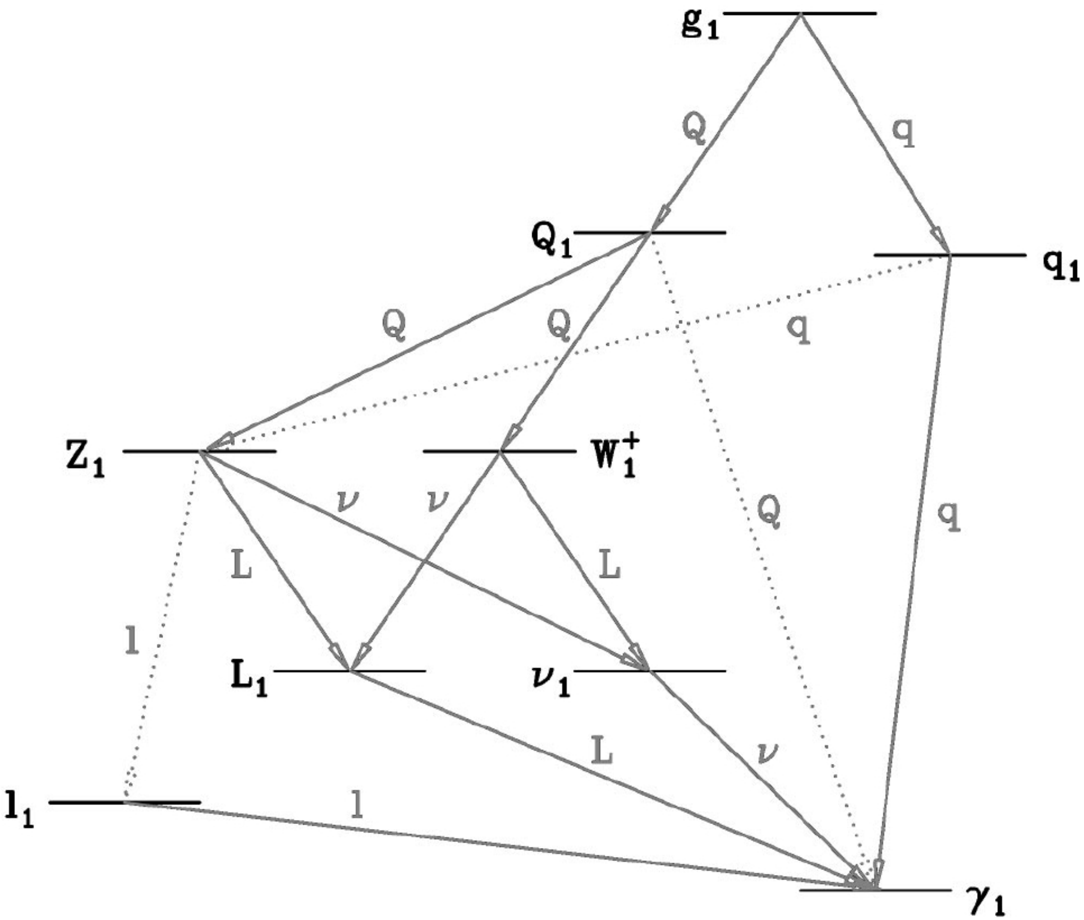
$Br(Q_1 \rightarrow Q Z_1 : W1 : \gamma_1) \approx 0.33 : 0.65 : 0.02$

$Br(W_1 \rightarrow \nu L_1 : \nu_1 L) \approx 1/6 : 1/6$

$Br(Z_1 \rightarrow \nu \nu_1 : L L_1) \approx 1/6 : 1/6$

$Br(L_1 \rightarrow \gamma_1 L) \approx 1$

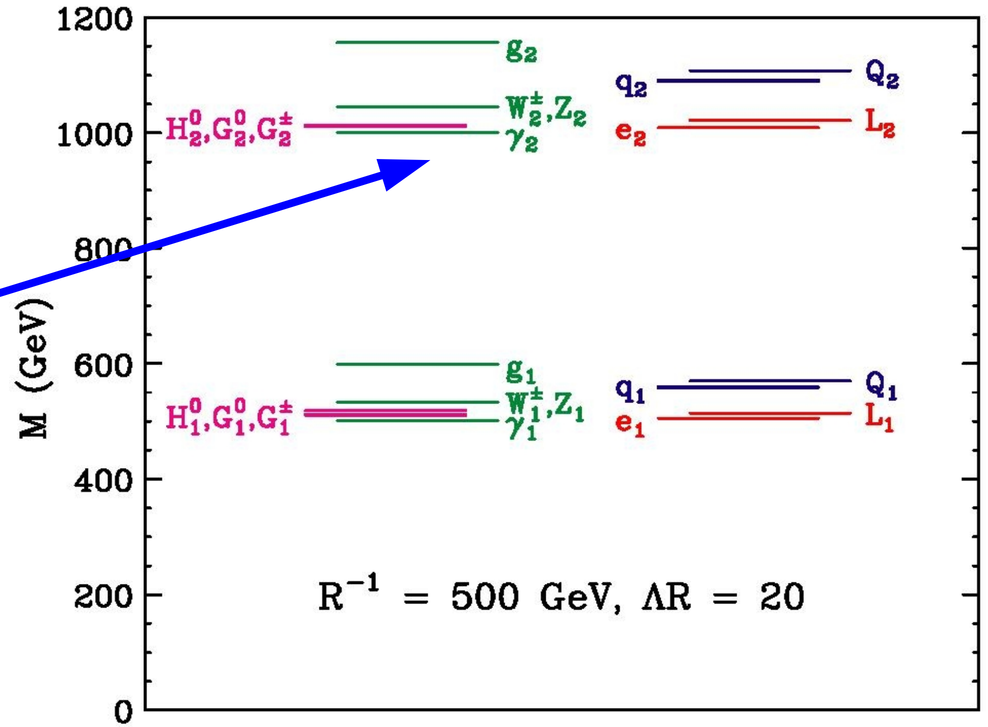
$Br(\nu_1 \rightarrow \gamma_1 \nu) \approx 1$




Cheng Matchev Schmaltz PRD66, 056006

# discriminating mUED w.r.t SUSY ?

Datta, Kong, Matchev, PRD75 (2005) 096006




**search for level 2 KK modes**

i.e. search for KK tower structure

at similar masses

Xsection(UED) > Xsection(SUSY)

e.g. for s-channel production :

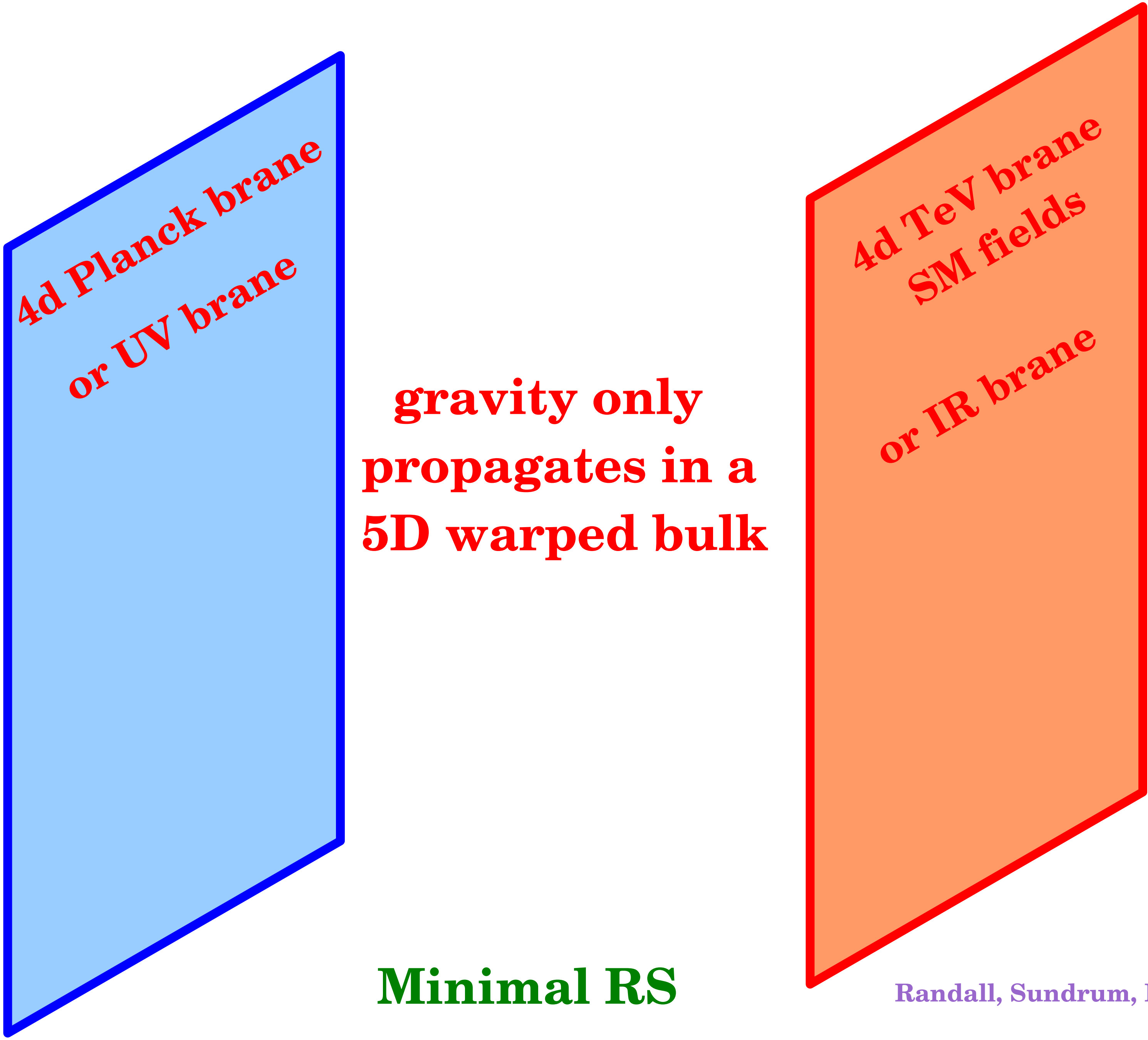
- both L and R handed SU(2) doublet KK fermions in UED (in susy only L handed SU(2) doublet squarks)
- integrating different angular distributions for fermions $(1+\cos^2\theta)$ vs scalars $(1-\cos^2\theta)$
- for production close to threshold (heavy particles)
  different Xsection threshold suppression for fermions ( $\beta$ ) vs scalars ( $\beta^3$ )

**Level 2 KK-quarks (pairs or associated with KK gluons) can be produced directly**

**BUT** **Br (Nleptons + MET) • Xsection still challengingly small**

& challenging small statistics to distinguish from level 1 modes

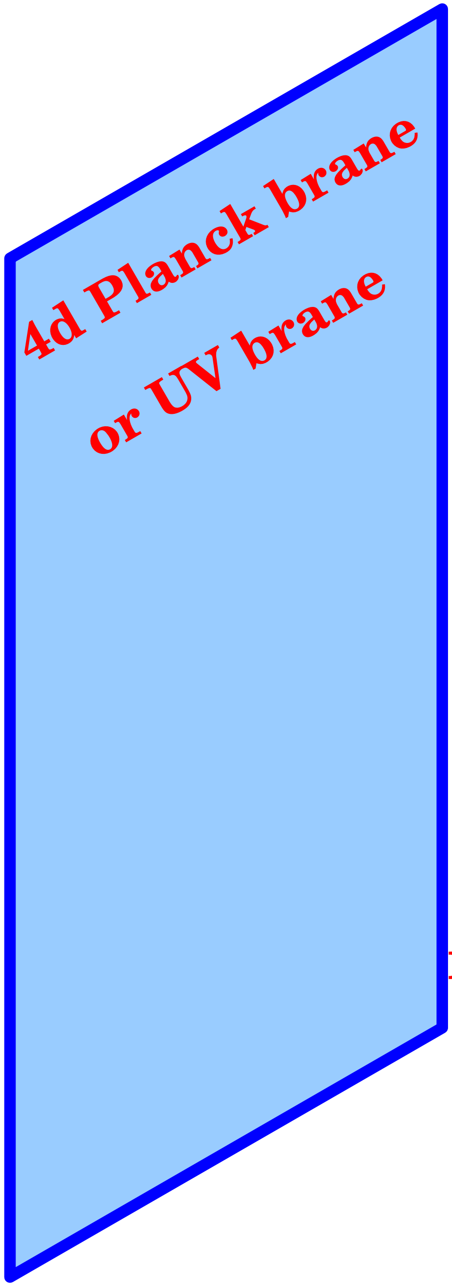
# which fields/particles and where ?




**Minimal RS**

Randall, Sundrum, PRL 83 (1999) 3370

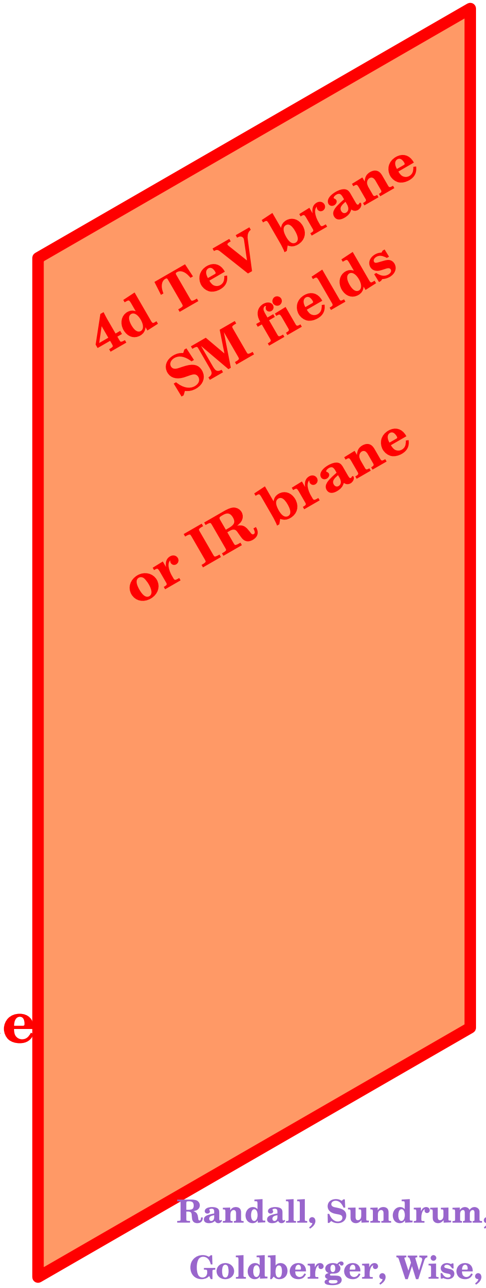
# which fields/particles and where ?




gravity
propagates in a
5D warped bulk

+

scalar for
interbrane distance
stabilization




Randall, Sundrum, PRL 83 (1999) 3370

Goldberger, Wise, PRL 83 (1999) 4922,
PRD 60, 107505,
PBL 474 (2000) 275

**stabilized RS**

# Minimal RS

Randall, Sundrum, PRL 83 (1999) 3370

- **gravity only** in a 5D warped bulk (with 1 compact ED) and 2 4D branes

$$ds^2 = e^{\boxed{-2kr_c\phi}}(\eta_{\mu\nu}dx^\mu dx^\nu) + r_c d\phi^2 \qquad \phi \in [0,\pi] \qquad k \sim M_{Pl(4)}$$

- **warp factor** allows to generate TeV scale on one brane **(TeV Brane)** from Planck scale on the other brane **(Planck Brane)**

$$\Lambda_\pi = M_{Pl(4)} e^{-\pi k r_c} \rightarrow \Lambda_\pi \sim 1\ \mathrm{TeV} \quad \text{for} \quad k r_c \sim 12 \quad r_c = 10^{-32}\ \mathrm{cm}$$

- **KK graviton** with O(TeV) spacing $m_n = k\, x_n e^{-k r_c \pi}$ $x_n$ roots of Bessel function $J_1$

- **SM fields on TeV brane coupling to massive KK graviton** $\sim 1/\Lambda_\pi$

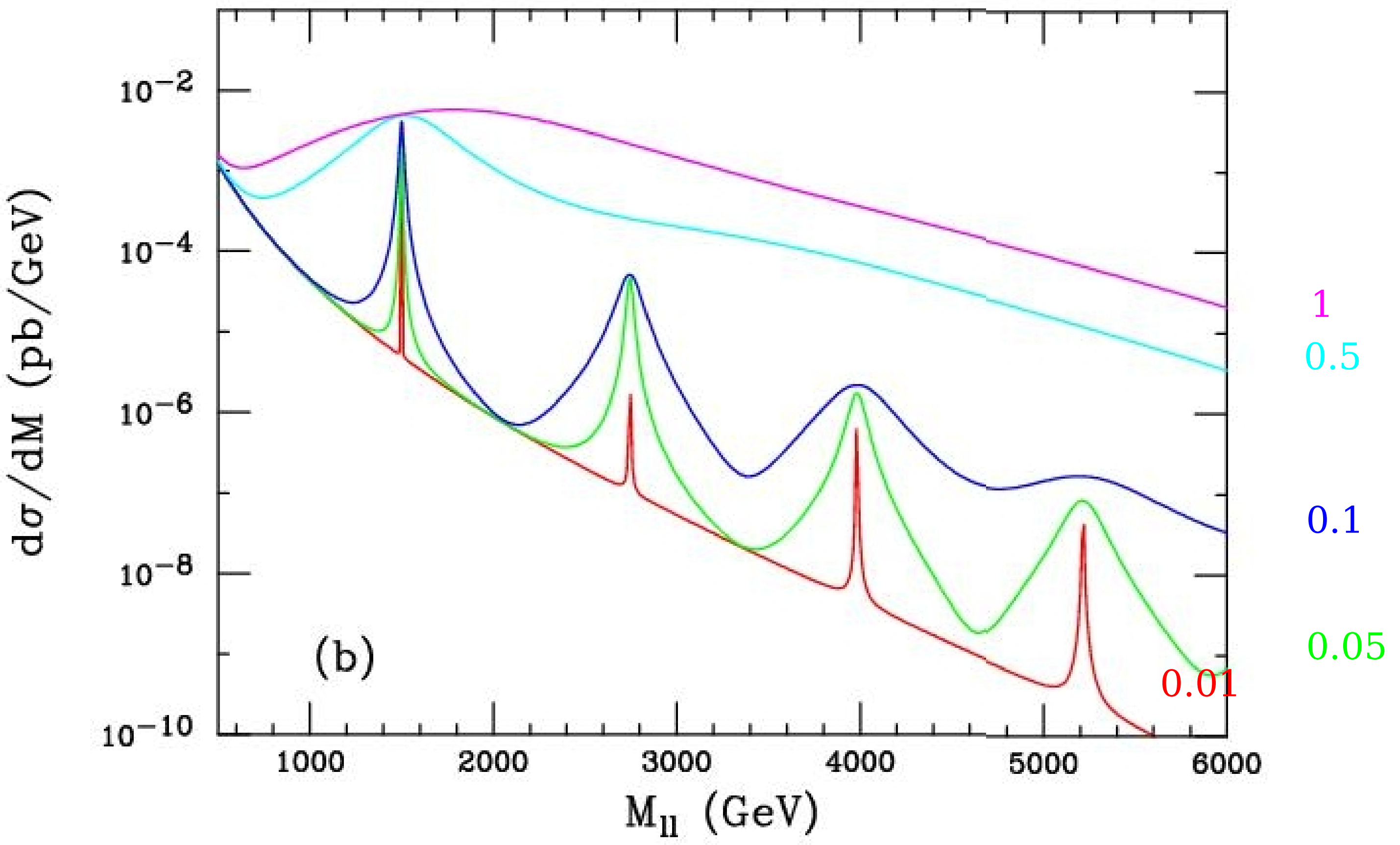
- phenomenology described by 2 parameters

$m_1$ mass of 1st mode, and $c = \dfrac{m_1}{x_1 \Lambda_\pi}$ $\qquad 0.01 < c < 0.1$ theoretically reasonable range

**search for narrow resonances** $pp \rightarrow G_{KK} \rightarrow e^+e^-, \mu^+\mu^-, \gamma\gamma, ZZ$

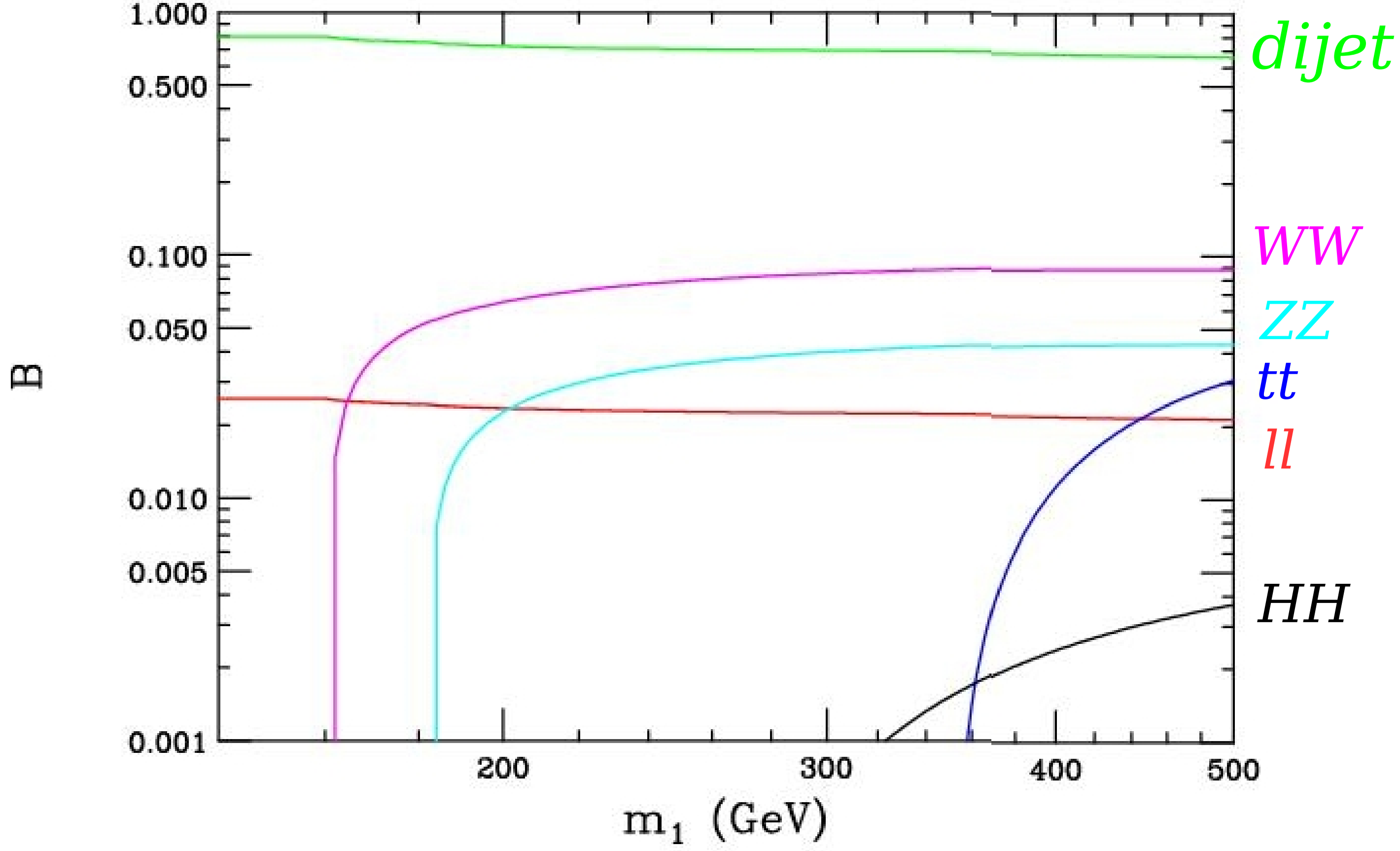
# minimal RS

## $G_{KK}$ production at LHC for various c parameter




Davoudiasl, Hewett, Rizzo, PRD 63, 075004

# Minimal RS: $G_{KK}$ decays




Davoudiasl, Hewett, Rizzo, PRD 63, 075004

# Stabilized RS

gravitational fluctuations around RS metric $ds^2 = e^{-2kr_c\phi}(\eta_{\mu\nu} dx^\mu dx^\nu) + r_c d\phi^2$

→ contain massless scalar mode (modulus) $r_c \to T(x)$ : **the radion**

→ v.e.v stabilizing the interbrane distance $<T(x)> = r_c$

**(Goldberger Wise mechanism)**
bulk scalar generating potential
can stabilize the modulus
at minimum of potential

radion must be massive to recover ordinary 4D Einstein gravity

in order to have $k r_c \approx 12$ **radion should be lighter than O(TeV) KK graviton**

**radion likely the lightest state from RS models**

**radion couples directly to gluon and photon**

**possible Higgs-radion mixing** (also in type I string)

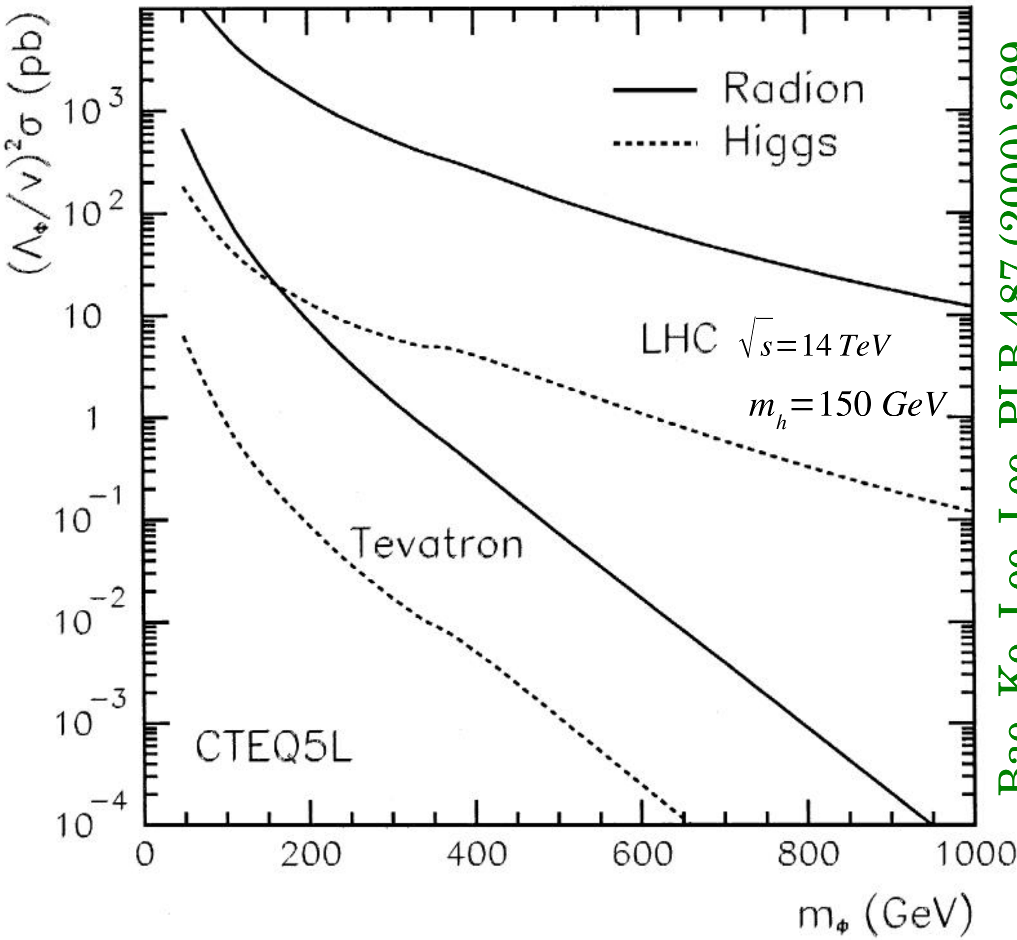
parameterized by $\xi$ with $|\xi| \approx O(1)$


**Goldberger, Wise, PRL 83 (1999) 4922**
**Goldberger, Wise, PRD 60, 107505**
**Goldberger, Wise, PBL 474 (2000) 275**
**Csaki, Graesser, Randall, Terning, PRD 62 (2000) 045015**
**Charmousis, Gregory, Rubakov, PRD 62 (2000) 067505**

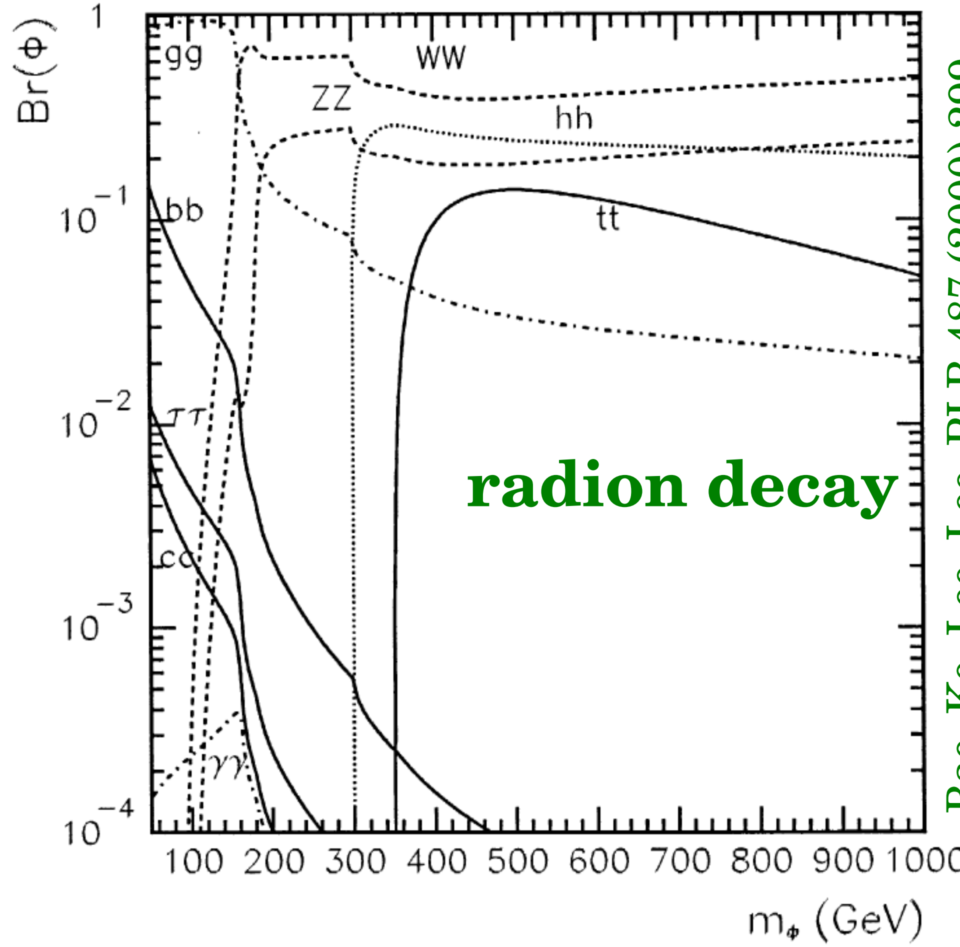
**stabilized RS**


Mahanta, Rakshit, PLB 480 (2000) 176
Mahanta, Datta, PLB 483 (2000) 196
Bae, Ko, Lee, Lee, PLB 487 (2000) 299
Mahanta, PRD 63, 076006
Cheung, PRD 63, 056007
Giudice, Rattazzi, Wells, NPB 595 (2001) 250
Rizzo, JHEP 06 (2002) 056
Bae, Lee, PLB 506 (2001) 147
Chaichian, Datta, Huitu, Yu, PLB 524 (2002) 161
Das, Mahanta, PLB 529 (2002) 253
Azuelos, Cavalli, Przysiezniak, Vacavant, Eur. Phys. J. Direct C4 (2002) 16
Csaki, Graesser, Kribs, PRD63, 065002
Han, Kribs, McElrath, PRD 64, 076003
Antoniadis, Sturani, NPB 631 (2002) 66
Gupta, Mahajan, PRD 65, 056003
Hewett, Rizzo, JHEP, 08 (2003) 028
Battaglia, De Curtis, De Roeck, Dominici, Gunion, PLB 568 (2003), 92
Das, Mahanta, Mod. Phys. Lett. A19 (2004) 1855
Gunion, Toharia, Wells, PLB 585 (2004) 295
Cheung, Kim, Song, PRD69, 075011
Das, PRD 72,055009
Csaki, Hubisz, Lee, PRD 76,125005


**radion production**




Bae, Ko, Lee, Lee, PLB 487 (2000) 299




**radion decay**

Bae, Ko, Lee, Lee, PLB 487 (2000) 299

# stabilized RS

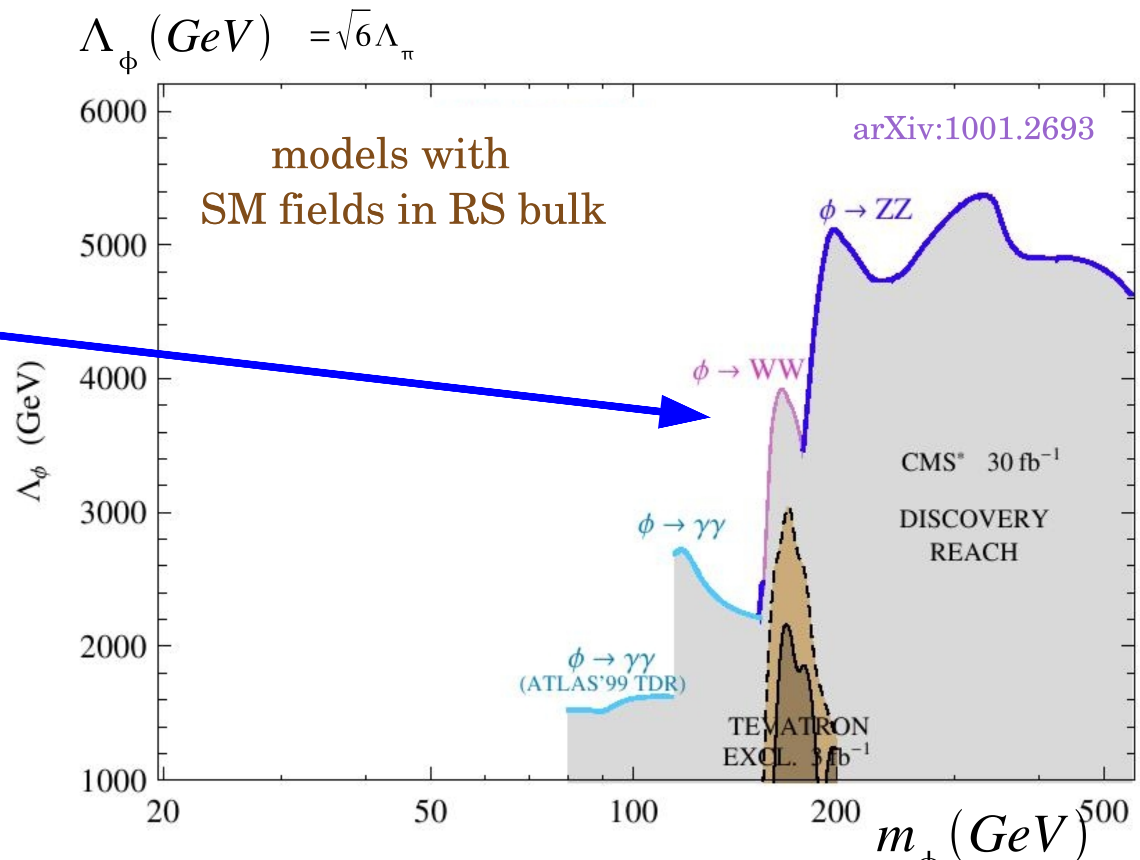
- pure radion effects on precision EW data are small

Gunion, Toharia, Wells, PLB 585 (2004) 295

- radion searches using SM Higgs searches

$\phi \to h\, h$ also possible

key difference w.r.t SM Higgs → direct couplings to gluons




Radion and bulk RS

Rizzo, JHEP 06 (2002) 056
Csaki, Hubisz, Lee, PRD76, 125015
Azatov, Toharia, Zhu, PRD80, 031701

# Bulk RS models

**- to solve hierarchy problem**

→ **only SM Higgs has to be localized on/near TeV Brane**

**- fermion and gauge fields allowed to propagate in the Xtra dim**

**- SM particles correspond to KK zero modes of 5D fields**

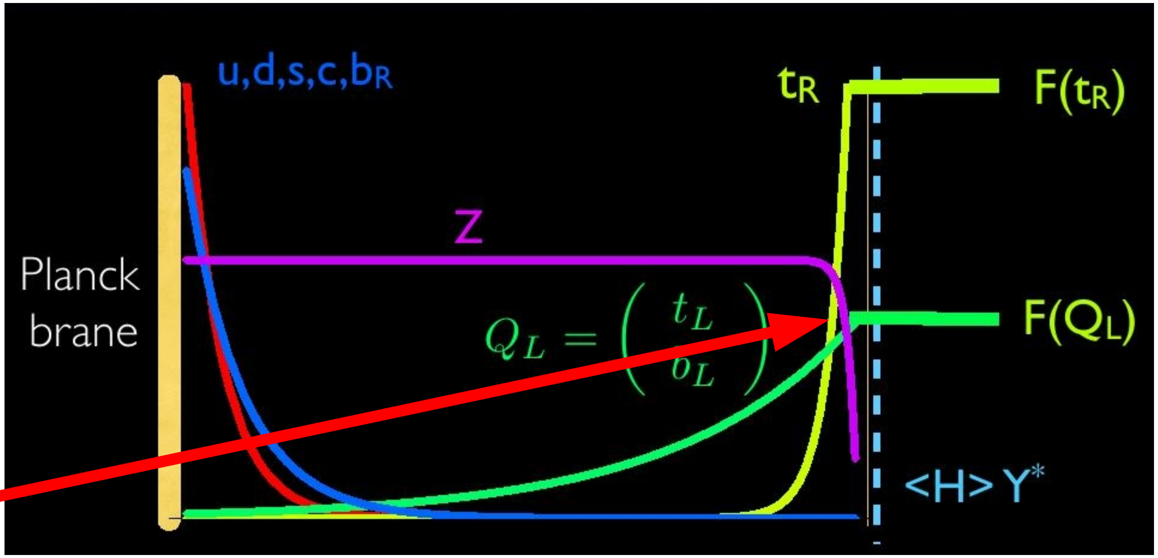
bulk profile of SM fermion depends on its 5D mass parameter

**- choose to localize 1$^{st}$ and 2$^{nd}$ generation fermions near Planck brane**

→ **FCNC from higher dim operator suppressed by scales >> TeV**

→ **SM Yukawa coupling hierarchies**

1$^{st}$ and 2$^{nd}$ generation small Yuk. coup. with Higgs localized near TeV brane




**top quark can be localized near TeV brane to account for its large Yukawa coupling**

from Weiler's talk at GDR Terascale(http://terascale.in2p3.fr)
http://indico.in2p3.fr/conferenceDisplay.py?confId=1617

# constraints on Bulk RS models

**from:**

- **EW precision data** via Oblique parameters S T U
- **FCNC (K physics, CPV, B physics, rare decays)**
- $Z \to b_L b_L$ i.e. $(t_L, b_L)$ not too close to TeV brane

**and with various symmetries in the bulk**

- larger bulk gauge symmetry i.e. $SU(2)_L \times SU(2)_R \times U(1)_X$, $SO(5) \times U(1)$, ....
- flavor symmetries

→ **KK gauge mass > 3 TeV**

→ **KK graviton mass > 2 - 4 TeV** dependent on specific models

w/o fermions in bulk and bulk symmetry > 23 TeV

→ **Fermionic excitations > 1 – 2 TeV**

Additional SU(2) doublet **states with exotic charge** (5/3) **0.5 – 0.8 TeV**

# constraints on Bulk RS models

**from:**

- **EW precision data** via Oblique parameters S T U
- **FCN** ... **cays)**
- $(=\sqrt{6}$ ...

Delgado, Pomarol, Quiros, JHEP (2000) 030
Huber, NPB 666 (2003) 269
Burdman, PLB 590 (2004) 86
Agashe, Perez, Soni PRL 93 (2004) 201804, PRD71, 016002
Moreau, Silva-Marcos, JHEP 03 (2006) 090
Agashe, Contino, NPB 742 (2006) 59
Cacciapaglia,Csaki, Galloway, Marandella, Terning, Weiler, JHEP 04 (2008) 006
Casagrande, Goertz, Haisch, Neubert, Pfoh, JHEP 10 (2008) 094
Santiago, JHEP 12 (2008) 046
Csaki, Falkowski, Weiler, JHEP 09 (2008)008
Fitzpatrick, Perez, Randall, PRL 100 (2008) 171604
Bouchart, Moreau, NPB 810 (2009) 66
Blanke, Buras, Duling, Gori, Weiler, JHEP03 (2009) 001
Blanke, Buras, Duling, Gemmler, Gori, JHEP 03 (2009) 108
Csaki, Perez, Surujon, Weiler, arXiv:0907.0474
Bauer, Casagrande, Grunder, Haisch, Neubert, PRD79, 076001
Csaki, Falkowski, Weiler, PRD 80, 016001
..........................................................................

**and w**

- large
- flavo

Flavour physics constraints striking hard $\rightarrow$ **huge activity in RS flavor models development**

pendent on specific models

Additional SU(2) doublet **states with exotic charge** (5/3) **0.5 – 0.8 TeV**

# Bulk RS models signatures

## - KK graviton

$$g\,g \to G \to t\,\bar{t}$$

$$g\,g \to G \to W_L W_L \to l\,\nu\,j\,j$$

$$g\,g \to G \to W_L W_L \to e^{\pm}\mu^{\mp}\,2\nu$$

$$g\,g \to G \to Z_L Z_L \to 4\,l$$

## - KK Gluon

$$pp \to g^{(1)} \to t\,\bar{t}$$

## - KK EW neutral gauge boson

$$p\,p \to Z' \to W\,W \to 2\,l\,2\,\nu$$

$$\to l\,\nu\,j\,j$$

## - KK EW charged gauge boson

$$pp \to W' \to t\,\bar{b} \to W\,\bar{b}\,b \to l\,\nu\,\bar{b}\,b$$

$$pp \to W'^{+} \to W^{+}\,h$$

## - KK fermions (e.g.)

$$pp \to g + g^{(1)} \to t^{(1)}\bar{t}^{(1)} \to W^{+}\,b\,W^{-}\,\bar{b} \to l^{-}\,\nu\,b\,\bar{b}\,jj\,(l = e\,,\mu)$$


Davoudiasl, Hewett, Rizzo, PLB 473 (2000) 43
Grossman, Neubert, PLB474 (2000) 361
Pomarol, PLB 486 (2000) 153
Chang, Hisano, Okada, Yamaguchi, PRD62, 084025
Randall, Schwartz, JHEP 11 (2001) 003
Huber, Shafi PRD 63, 045010, PLB 498 (2001) 256
Randall, Schwartz, PRL 88 (2002) 081801
Csaki, Erlich, Terning, PRD66 (2002) 064021
Hewett, Petriello, Rizzo, JHEP 09 (2002) 030
Agashe, Delgado, May, Sundrum, JHEP08 (2003) 050
Carena, Delgado, Ponton, Tait, Wagner, PRD68, 035010, PRD71, 015010
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202, PRD76, 035006
Skiba, Tucker-Smith, PRD75, 115010
Aguilar-Saavedra, PLB 625 (2005) 234, PLB 633 (2006) 792
Agashe, Contino, Darold, Pomarol, PLB 641 (2006) 62
Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013
Agashe, Davoudiasl, Perez, Soni, PRD76, 036006
Holdom, JHEP 03 (2007) 063
Antipin, Atwood, Soni, PLB 666 (2008) 155
Antipin, Soni, JHEP10 (2008) 018
Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350
Baur, Orr, PRD 77, 114001
Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347
Lillie, Shu, Tait, PRD 76, 115016
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, PRD76, 115015
Djouadi, Moreau, Singh, NPB 797 (2008) 1
Contino Servant, JHEP 06 (2008) 026
Antipin, Tuominen, PRD 79, 075011
Aguilar, Aguilar-Saavedra, Moretti, Piccinini, Pittau, Treccani, arXiv:0912.3799

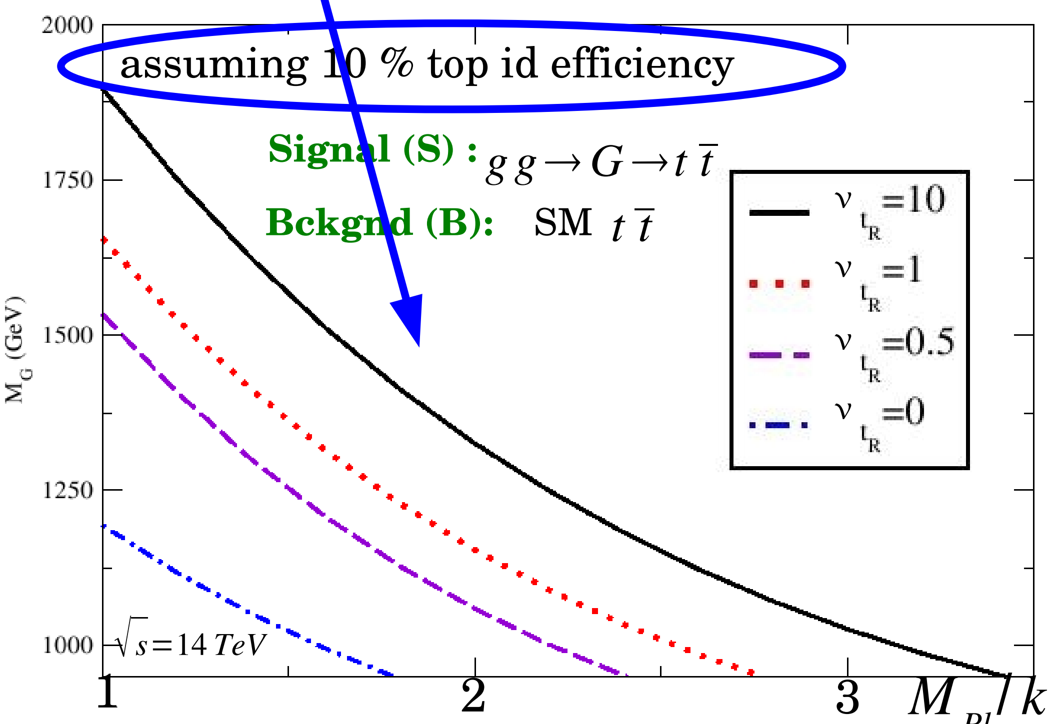
# Bulk RS models

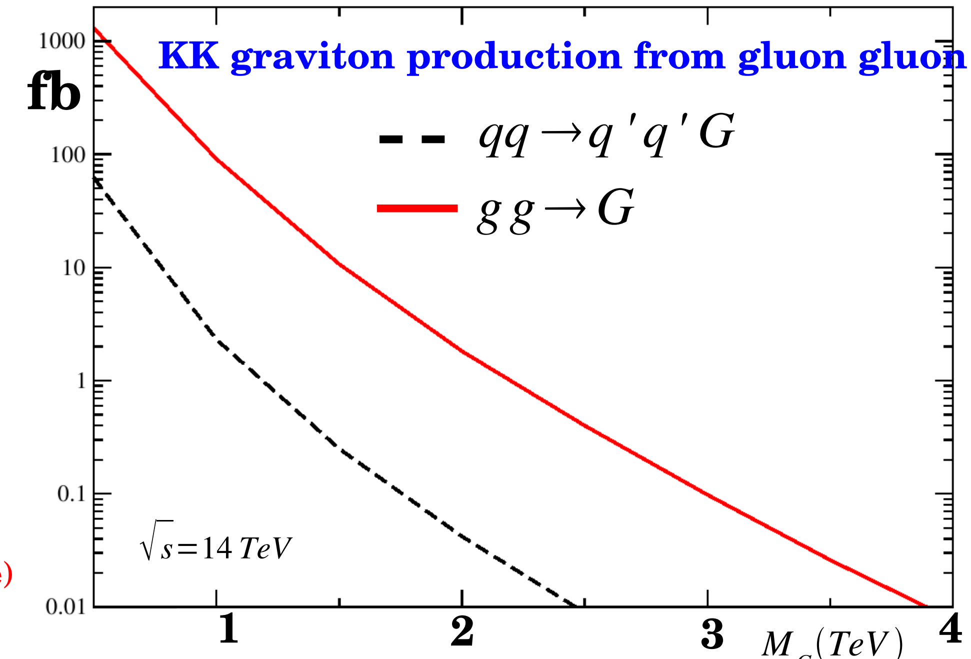
## KK Graviton search

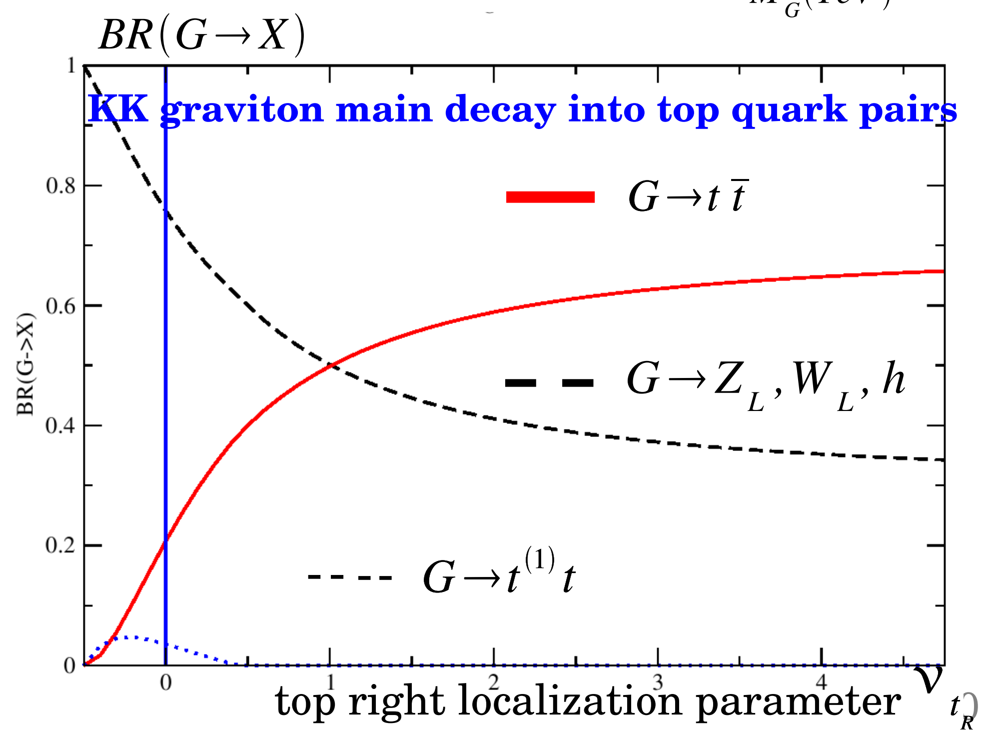
Fitzpatrick, Kaplan, Randall, Wang, JHEP 09 (2007) 013
Agashe, Davoudiasl, Perez, Soni, PRD76, 036006
Antipin, Atwood, Soni, PLB 666 (2008) 155
Antipin, Soni, JHEP10 (2008) 018

- **KK Graviton close to TeV Brane**
- **1$^{st}$** (and 2$^{nd}$) generation fermion near Planck brane
  i.e. small coupling with 1$^{st}$ and 2$^{nd}$ quark generation
- **gluon profile is flat**
- **t and b quark close to TeV brane**

$\frac{S}{\sqrt{B}}=5$ **reach for various t quark IR localization** $\nu_{tR}$ (the bigger the closer to IR brane)



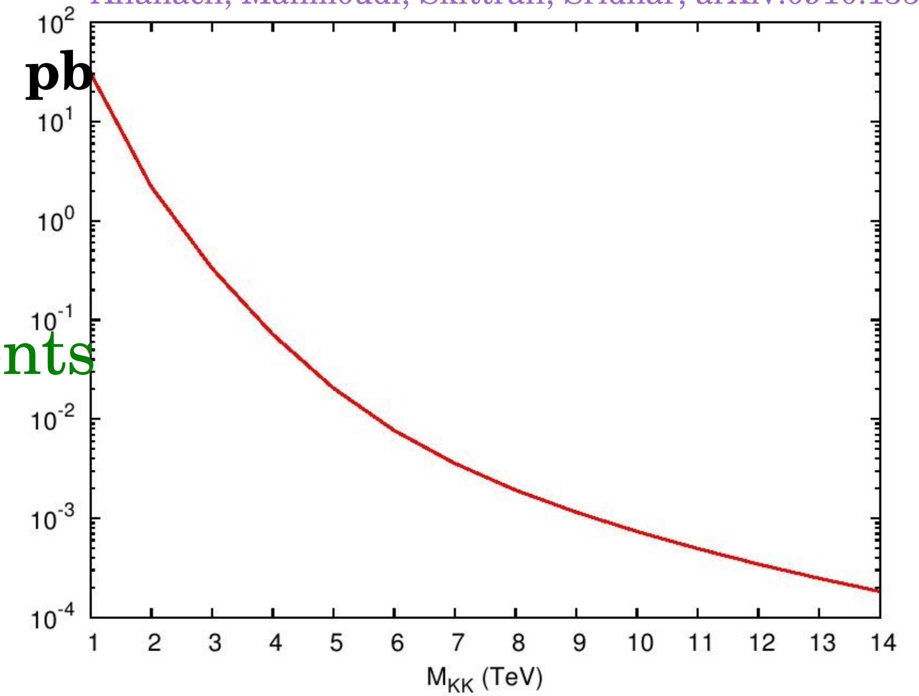



# Bulk RS models

## KK gluon

Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347
Lillie, Shu, Tait, PRD 76, 115016
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Baur, Orr, PRD 77, 114001
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

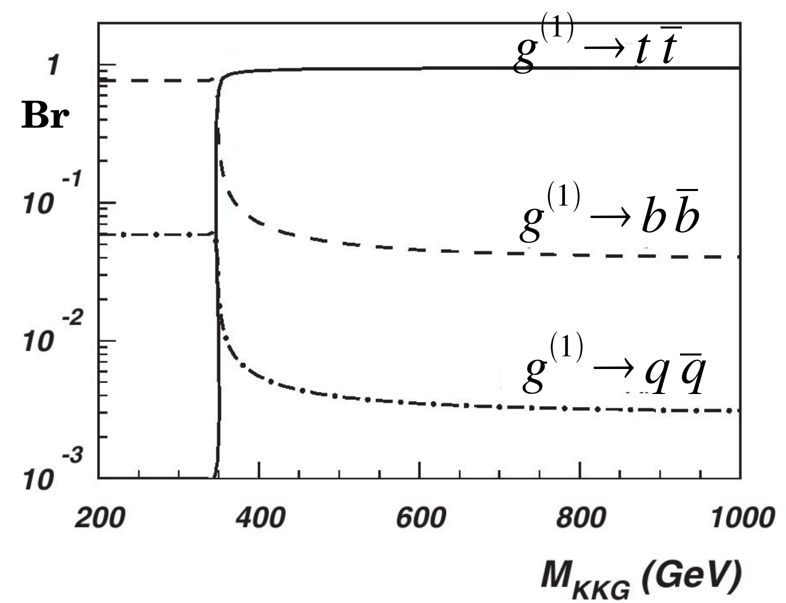



$g^{(1)}$ production suppressed

→ small coupling to proton constituents

fermionic decay dominated by top quark

bias towards RH top




a heavy KK gluon is broad

above 1 TeV width ~ $M_{KK}$ / 6

# States with exotic charge (bulk RS)

**MCHM$_5$ example :** $SO(5)\times U(1)_X\times SU(3)_C$ **as gauge symmetry in the RS bulk**

$SO(5)\times U(1)_X\times SU(3)_C$ broken down to $SO(4)\times U(1)_X\times SU(3)_C$ near IR brane with 4 pseudo Goldstone bosons identified with the Higgs doublet

$SO(4)\approx SU(2)_L\times SU(2)_R$ enlarged to $O(4)$ seen as the custodial symmetry

$G_{SM}=SU(2)_L\times U(1)_Y\times SU(3)_C$ near UV brane and with $Y=X+T_3^R$

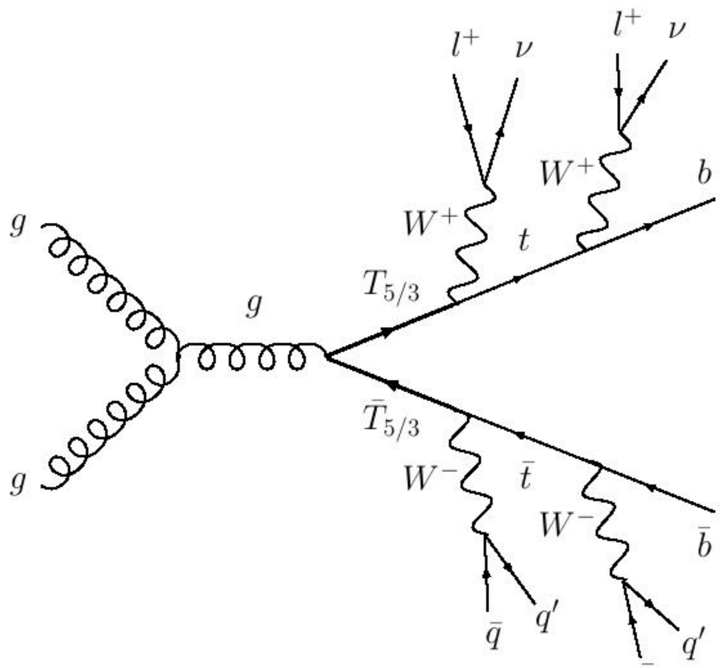
heaviness of top quark $\Rightarrow$ lowest $t_{\mathrm{KK}}$ and lightest O(4) custodial partners (i.e. custodians) are significantly lighter than the other KK resonances

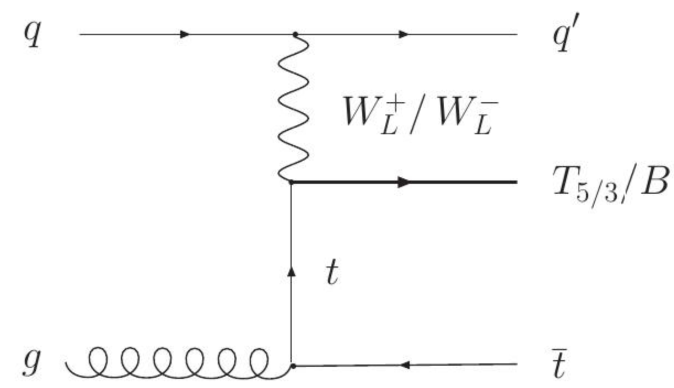
**light custodians have e.m charges $5/3,\ 2/3,\ -1/3$**

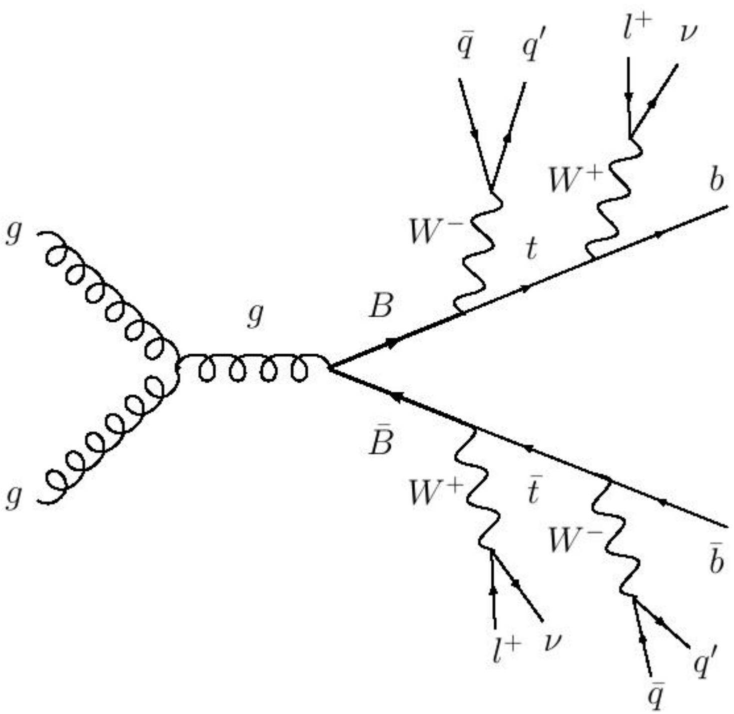
**they have mass roughly in the $500-1500$ GeV range**

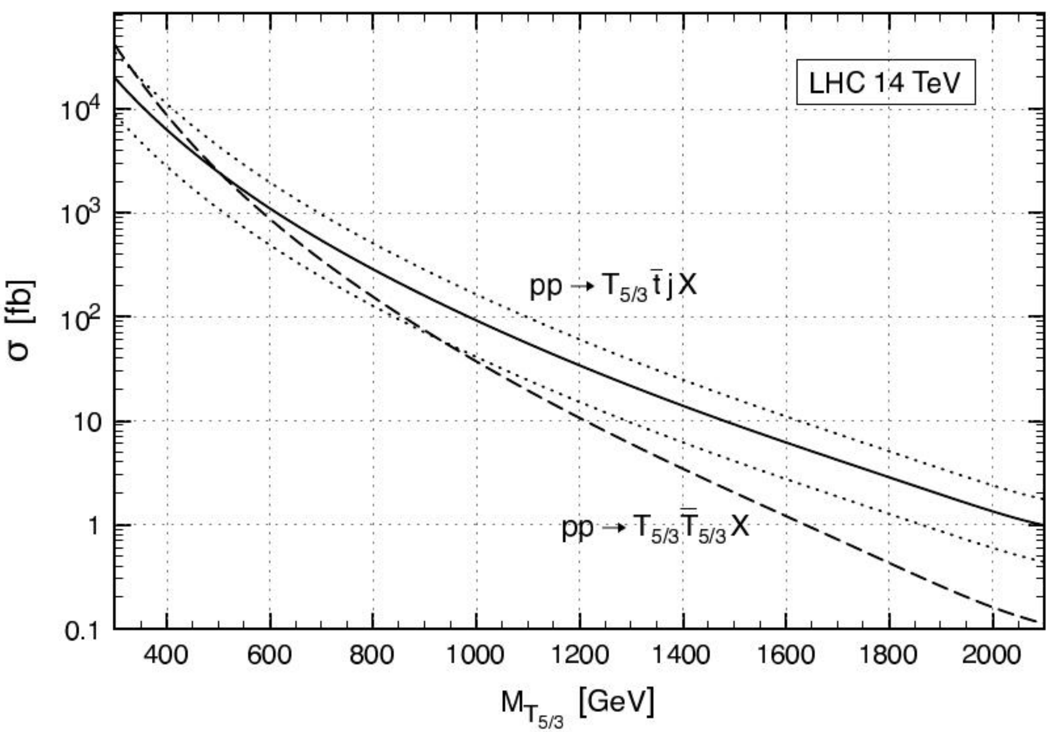
Agashe, Delgado, May, Sundrum, JHEP08 (2003) 050
Agashe, Contino, Pomarol,, NPB 719 2005 165
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202, PRD76, 035006
Contino, Darold, Pomarol,, PRD 75 2007 055014
Contino, Servant, JHEP 06 2008 026

# States with exotic charge (bulk RS)




Contino, Servant, JHEP 06 2008 026

# String states

**assume fundamental scale is low (TeV) and fundamental theory is string theories**

**→ strings scale Ms is low (TeV)**

**spectrum of string states made of 'zero' mass states and massive states**

**'zero' mass states → graviton, anti-sym tensor field, dilaton (scalar)**

**+ others identified with SM fields**

**massive states → (infinite number of) massive Regge excitations of various spin**

**with masses of order of string scale → then here low (TeV) !**

'correction' from Regge excitations : $\dfrac{s^2}{M_s^4}, \quad \dfrac{t^2}{M_s^4}, \quad \dfrac{u^2}{M_s^4}$ (back to pointlike particle limit when $s^2/M_s^4 \to 0$)

4-point amplitudes with Regge excitation : $O(g_s) \sim \dfrac{1}{25}$ i.e. bigger than the one from QFT with KK graviton exchange which is $O(g_s^2)$

**also present in spectrum : KK AND winding excitations of the SM fields**

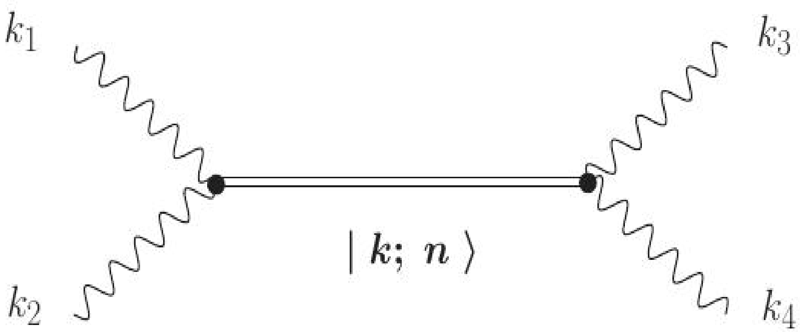
**with masses near string scale, AND moduli**

# String states

Cullen, Perelstein, Peskin , PRD 62 (2000) 055012
Dudas, Mourad, NPB 575 (2000) 3
Anchordoqui, Goldberg, Nawata, Taylor, PRL 100 (2008) 171603
Anchordoqui, Goldberg, Nawata, Taylor, arXiv:0804.2013
Anchordoqui, Goldberg, Lust, Nawata, Stieberger, Taylor, PRL 101 (2008) 241803
Lust, Stieberger, Taylor, NPB 808 (2009) 1
Anchordoqui, Goldberg, Lust, Nawata, Stieberger, Taylor, NPB 821 (2009) 181
Lust, Schlotterer Stieberger, Taylor, NPB 828 (2010) 139
Lust Int. J. Mod. Phys A26 (2011) 4686

dijets production via Regge excitations

$$M_n^2 = n M_{\text{string}}^2 = \frac{n}{\alpha'}$$




many possible combinations

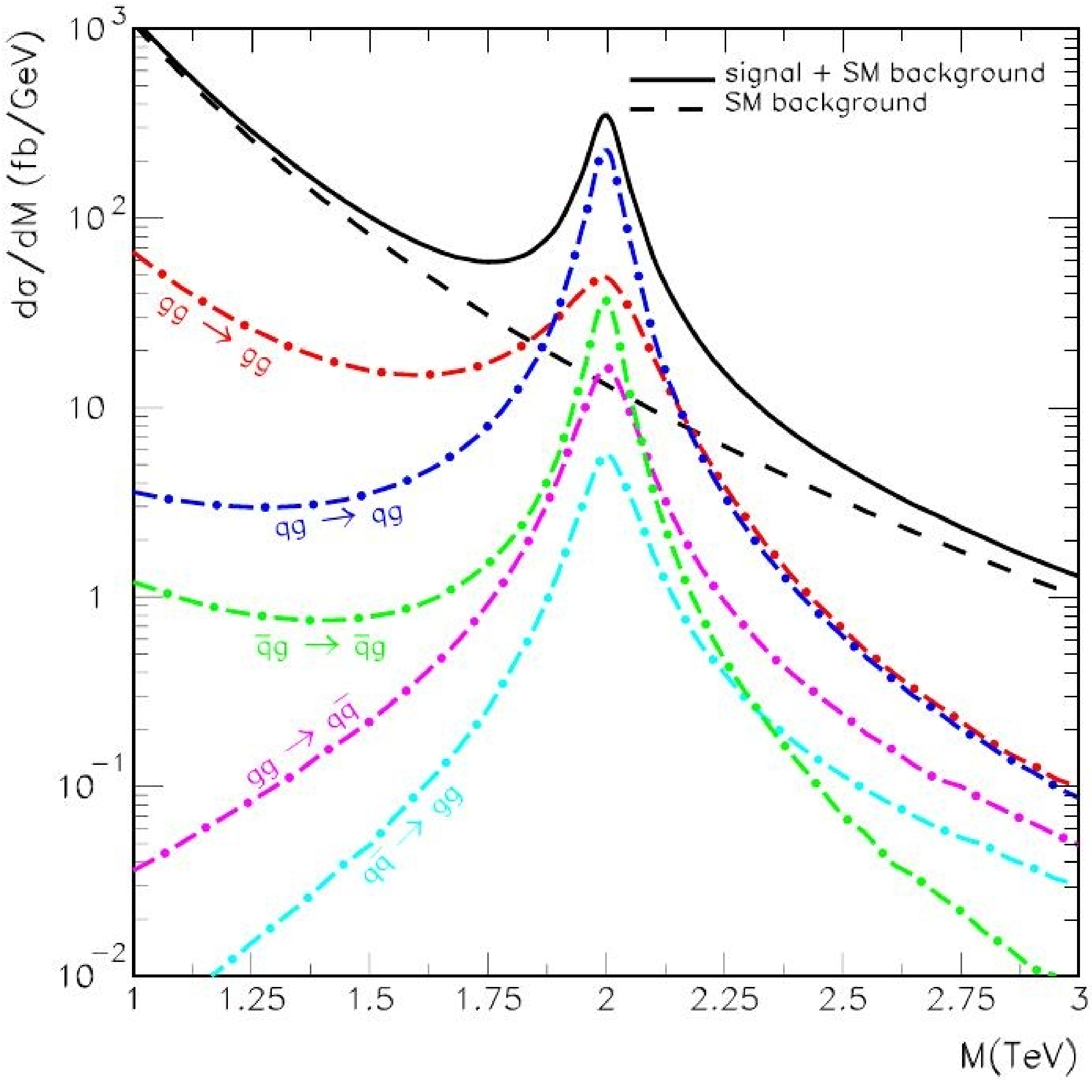
$g\ g \to g\ g$

$q\ g \to q\ g$

$\bar{q}\ g \to \bar{q}\ g$

$g\ g \to q\ \bar{q}$

$q\ \bar{q} \to g\ g$

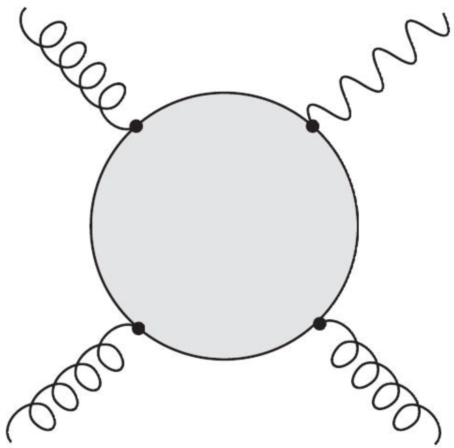


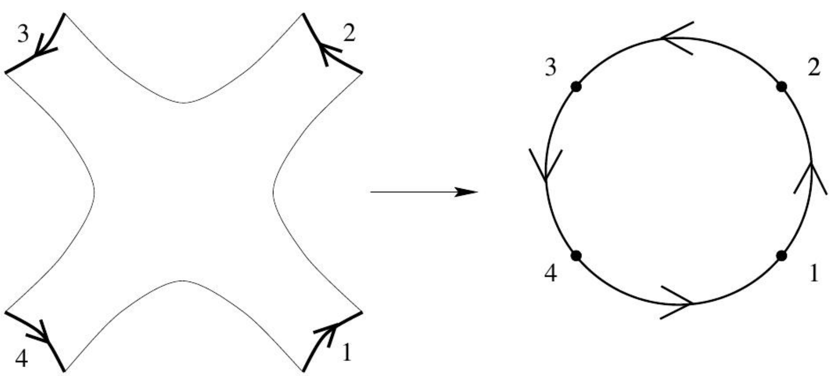

tri-jets production or more via Regge excitations also possible

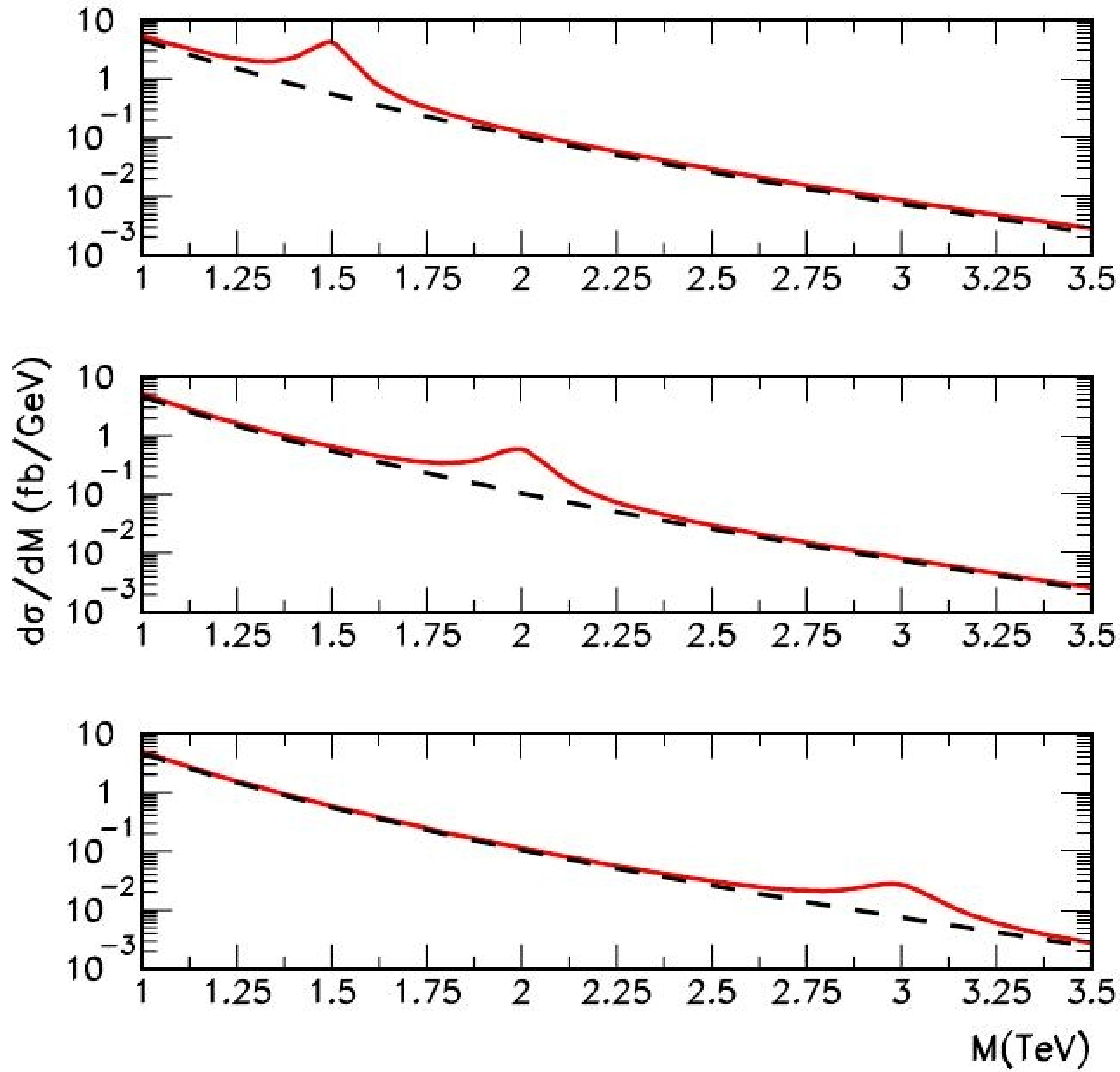
# String states

direct photon via string states

$$g\ g \rightarrow \gamma + g$$





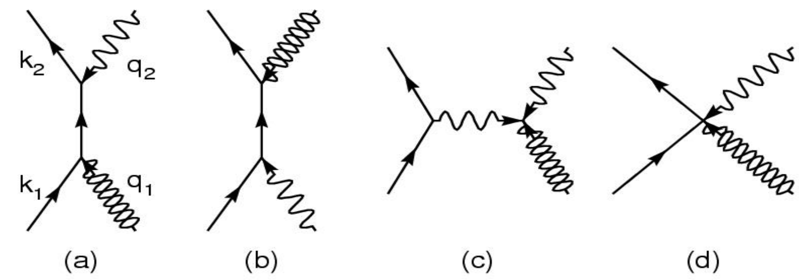



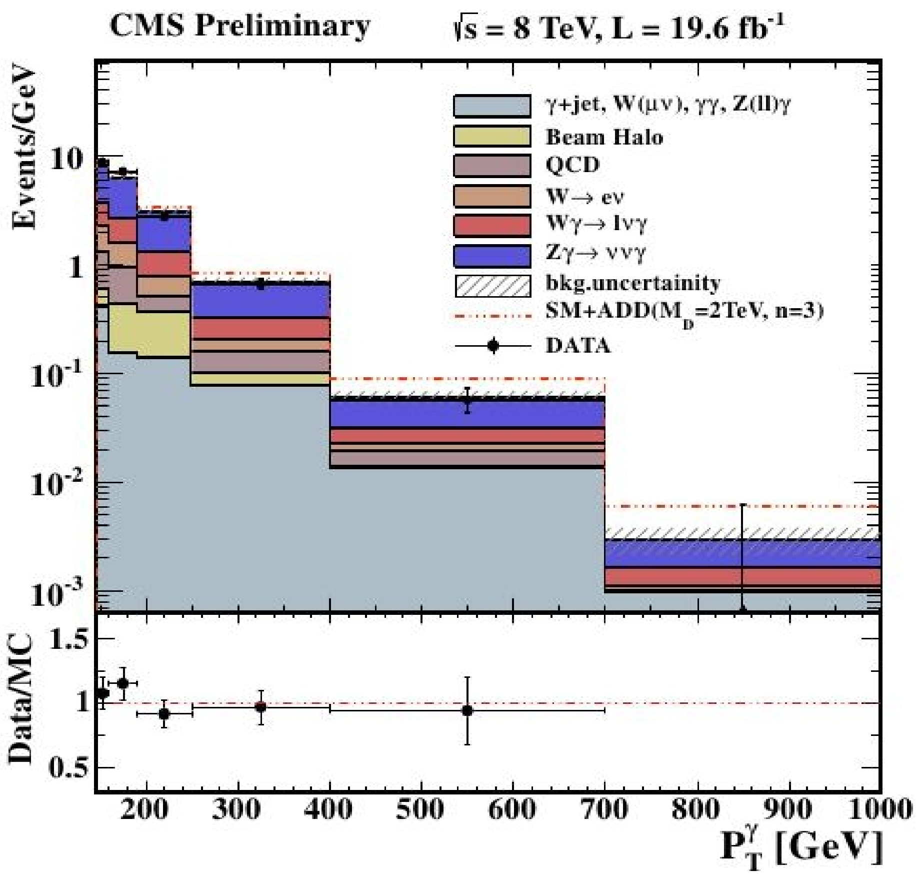
# Recent Results at CMS

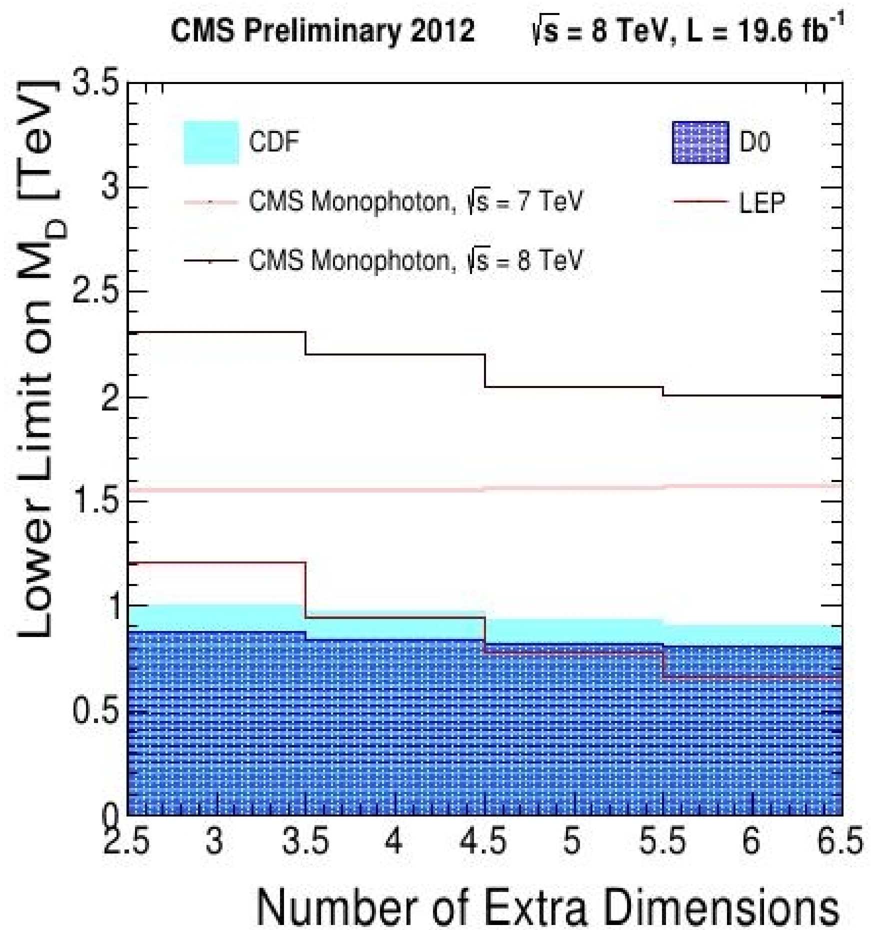
- mono- photon, mono jet
- non resonant and resonant dilepton
- resonant dijet
- lepton + MET
- resonant diboson (W&Z)
- resonant bt and tt
- resonant HH
- exotic fermions
- black holes

# mono-photon ("direct" ADD)

CMS-EXO-12-047

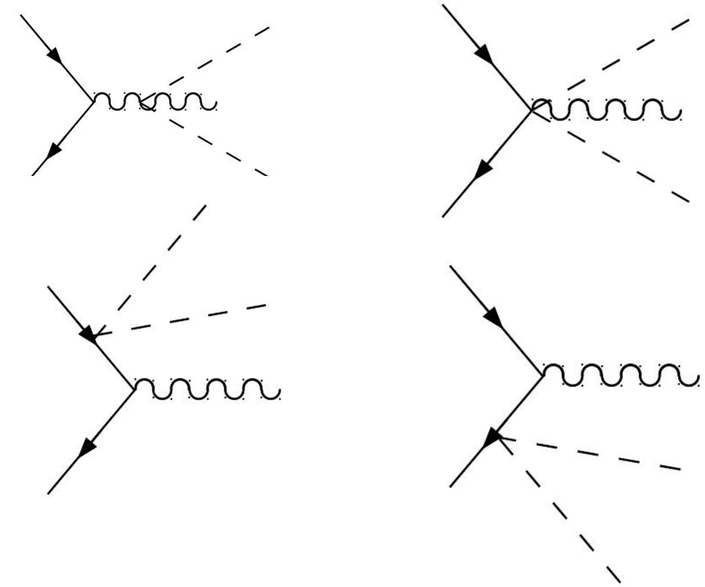


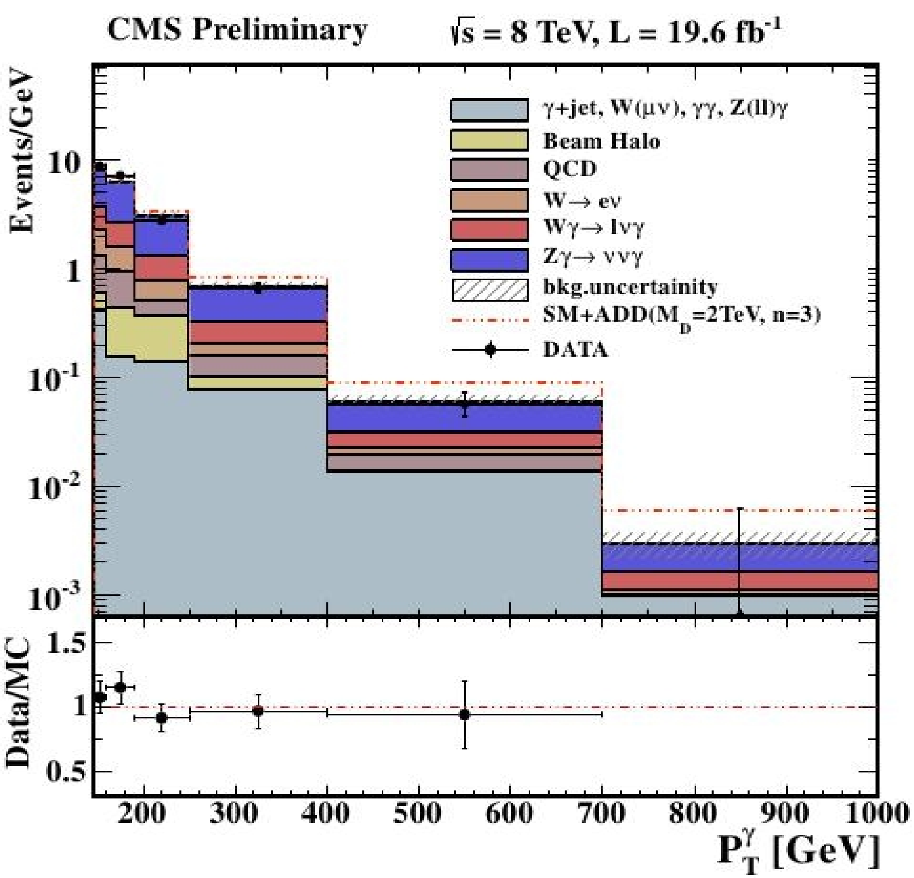



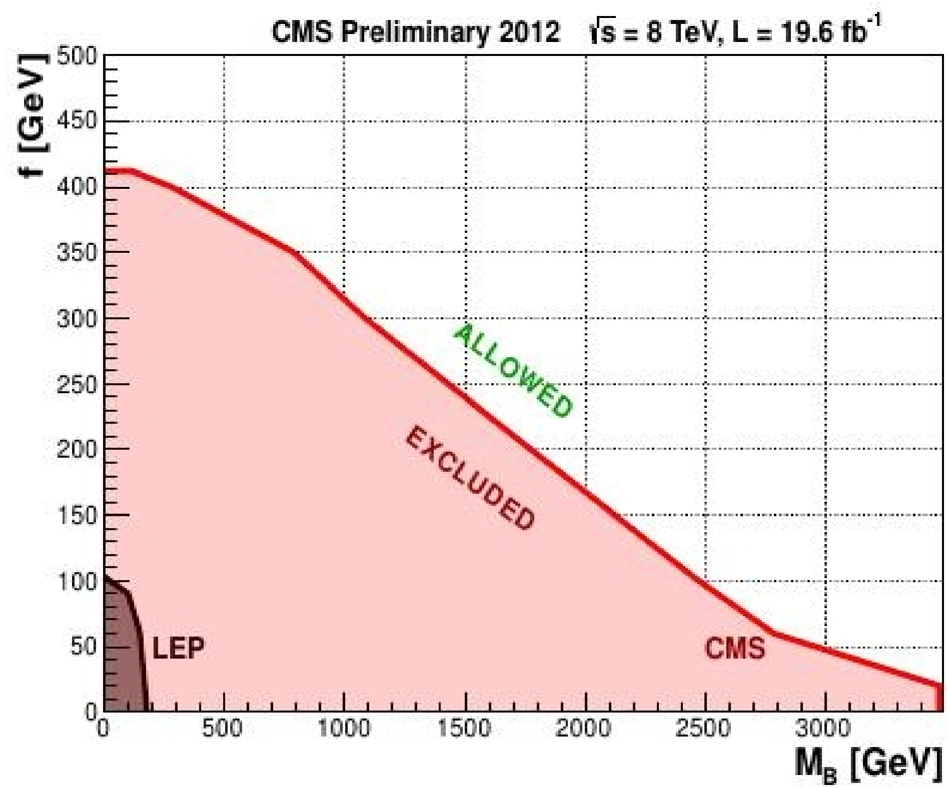



# mono-photon (branons)

CMS-EXO-12-047

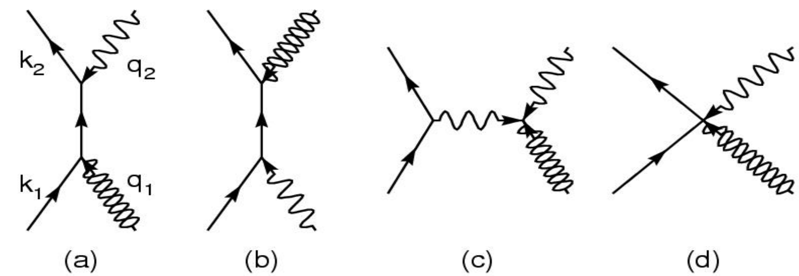


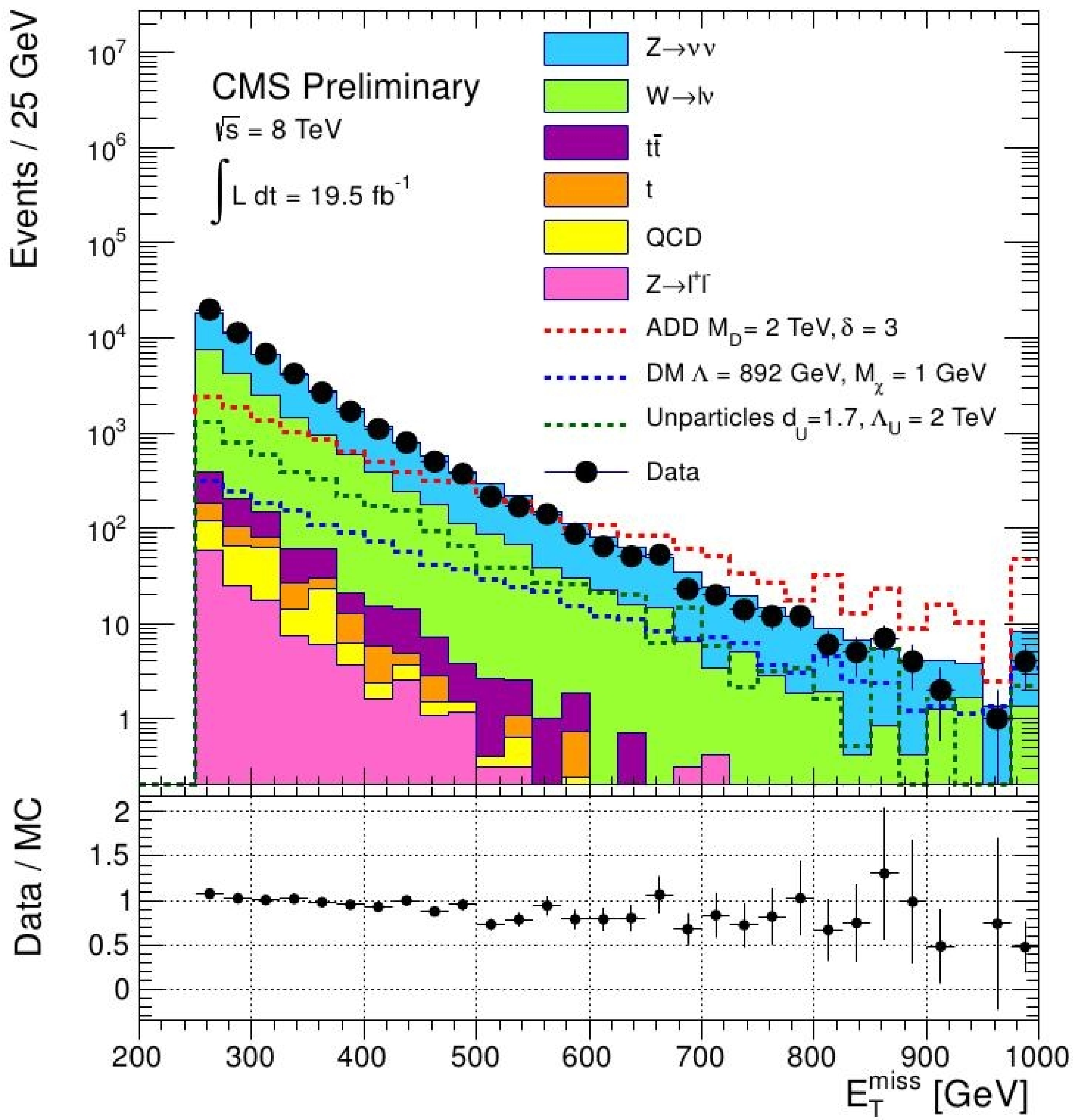


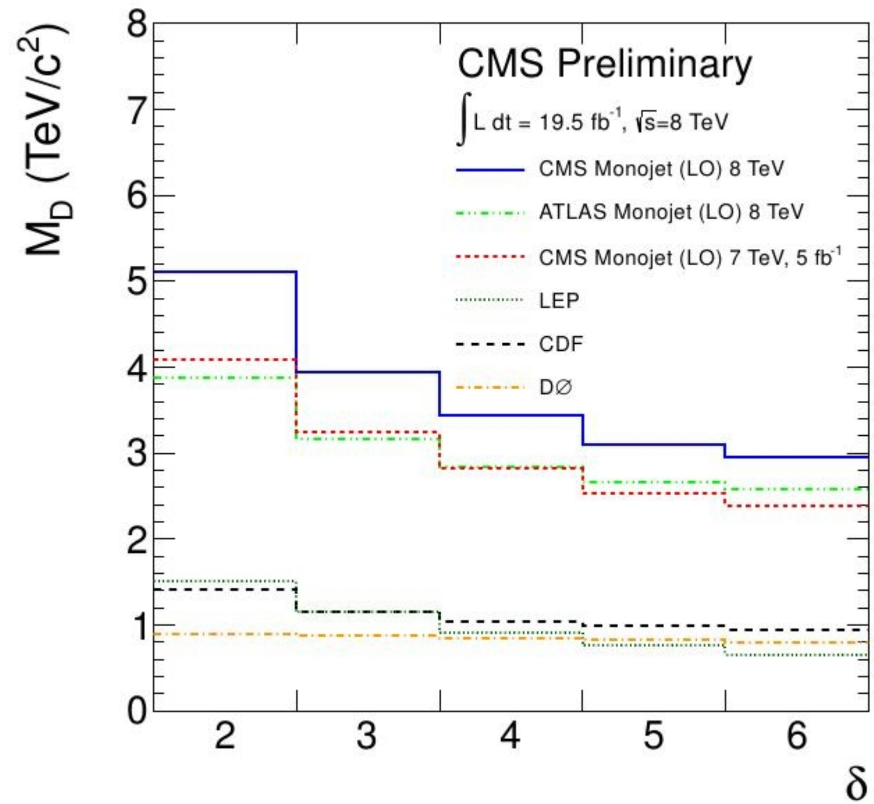



# mono-jet ("direct" ADD)

CMS-EXO-12-048



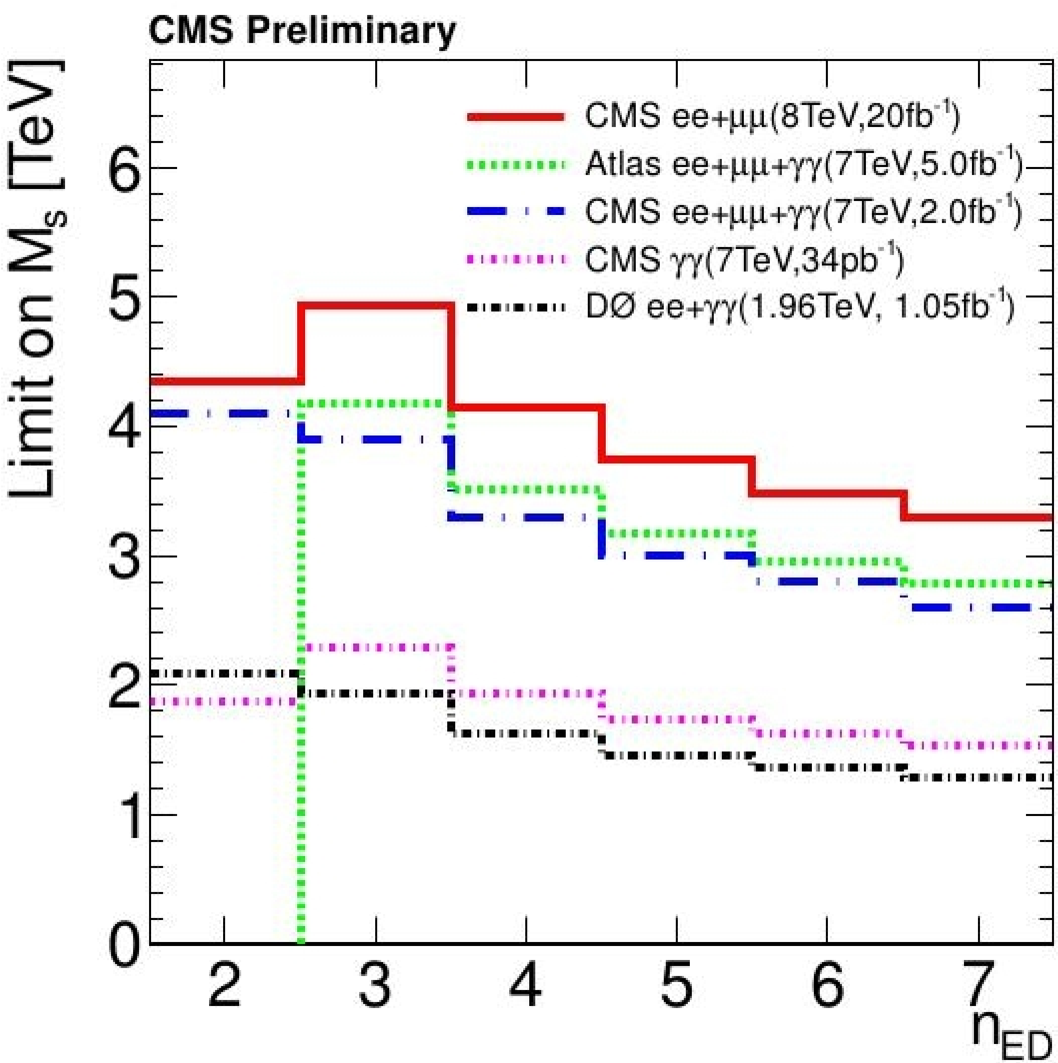



# non resonant dilepton

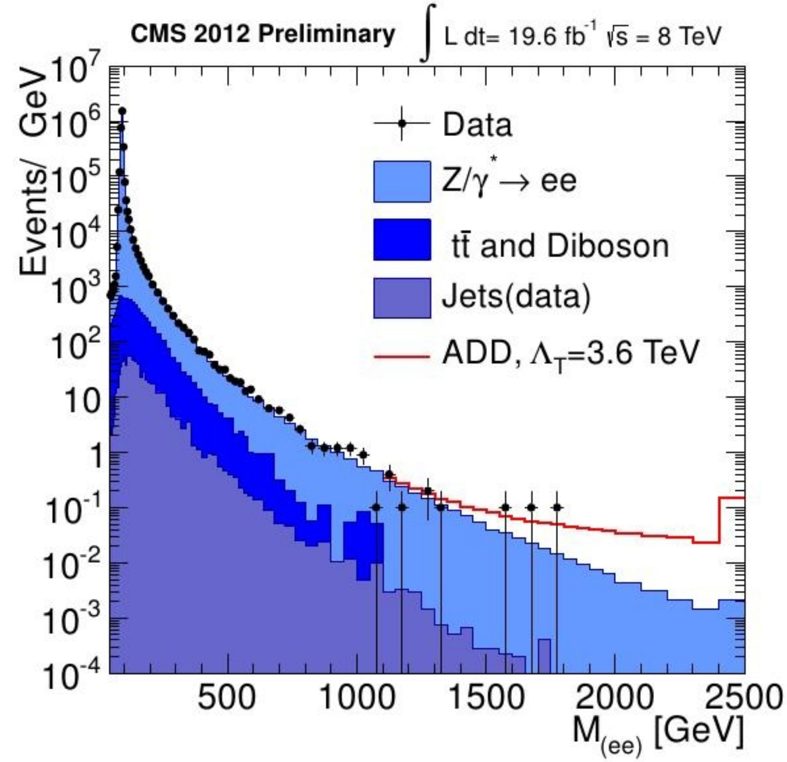
CMS-EXO-12-027

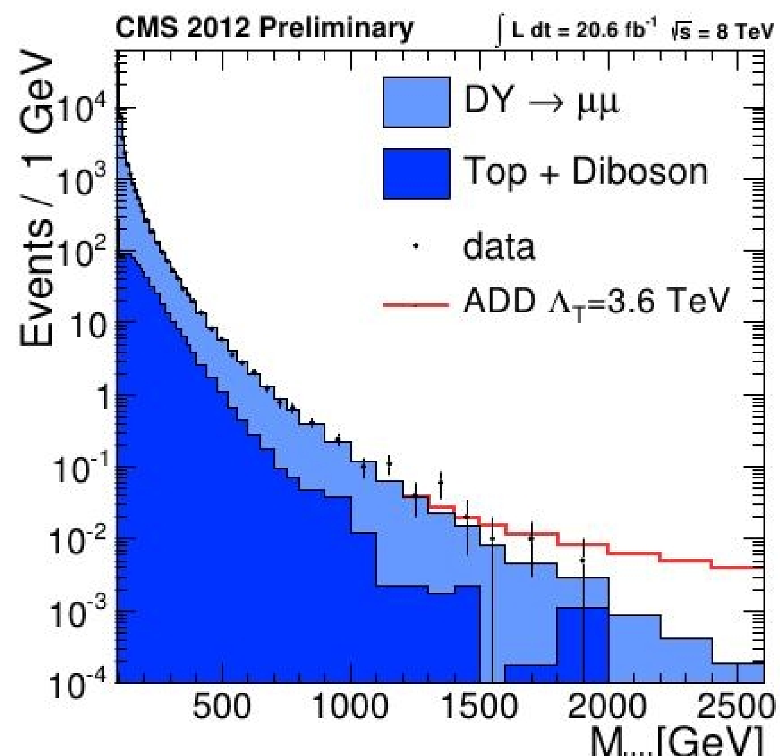
CMS-EXO-12-031

("indirect" ADD)




HLZ convention



# non resonant dilepton

CMS-EXO-12-027

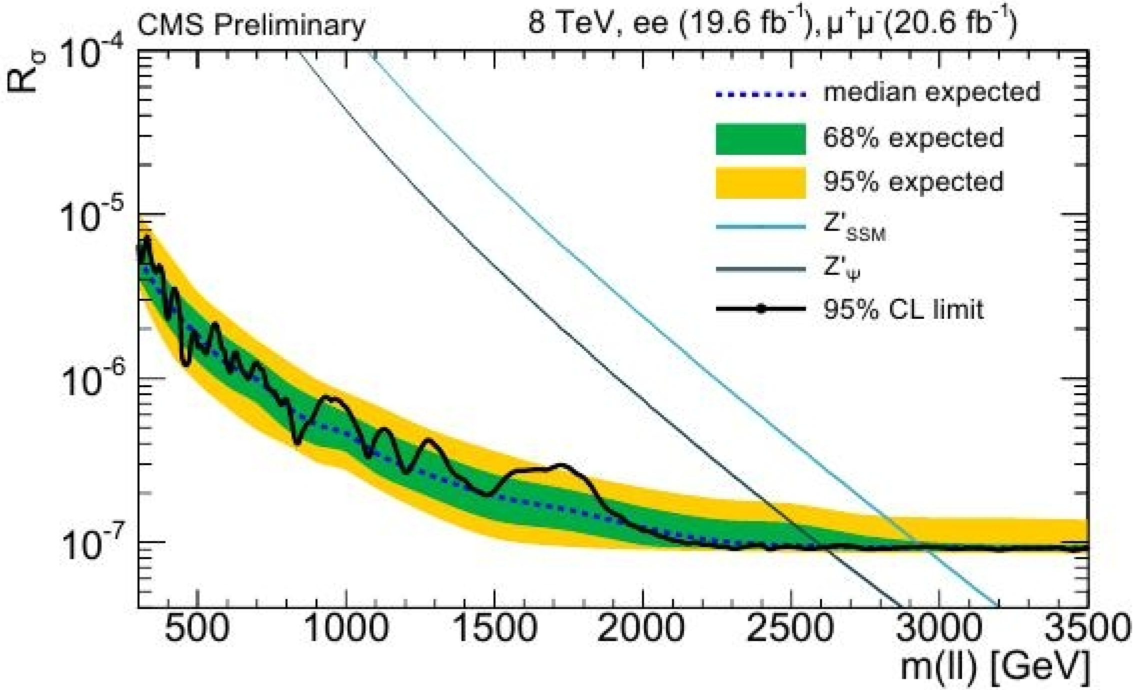
CMS-EXO-12-031

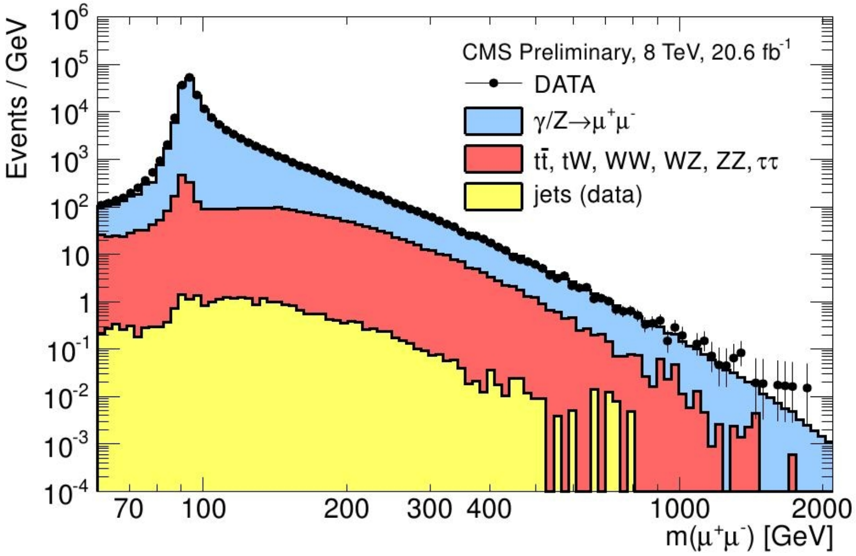
("indirect" ADD)

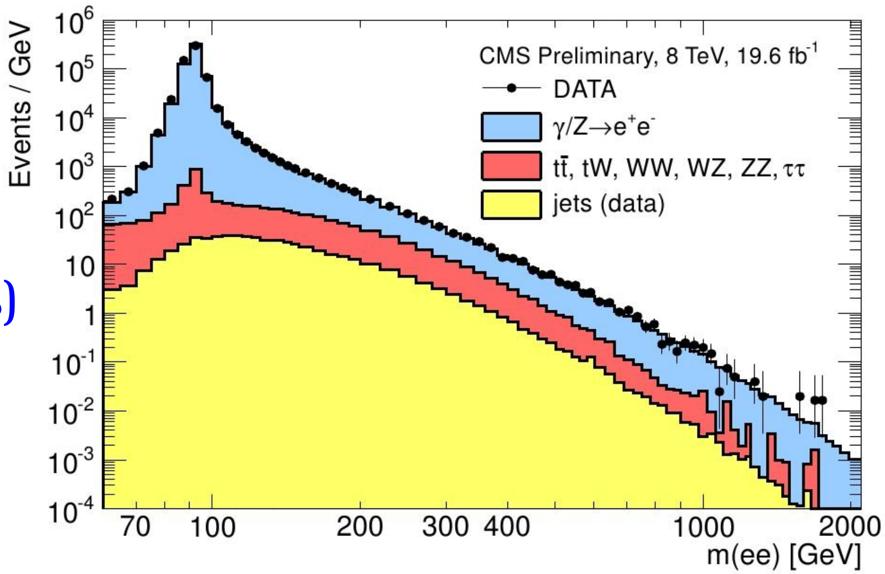
| ADD k-factor | $\Lambda_T$ [TeV] (GRW) | $M_s$ [TeV] (HLZ) $n=2$ | $n=3$ | $n=4$ | $n=5$ | $n=6$ | $n=7$ |
|---|---|---|---|---|---|---|---|
| $\mu\mu$, $\sigma_{s,\mu\mu} < 0.25$ fb (0.25 fb expected) at 95% CL | | | | | | | |
| 1.0 (observed) | 3.64 | 3.48 | 4.33 | 3.64 | 3.29 | 3.06 | 2.89 |
| 1.0 (expected) | 3.65 | 3.50 | 4.34 | 3.65 | 3.30 | 3.07 | 2.90 |
| 1.3 (observed) | 3.77 | 3.69 | 4.49 | 3.77 | 3.41 | 3.17 | 3.00 |
| 1.3 (expected) | 3.78 | 3.70 | 4.50 | 3.78 | 3.42 | 3.18 | 3.01 |
| ee, $\sigma_{s,ee} < 0.19$ fb (0.19 fb expected) at 95% CL | | | | | | | |
| 1.0 (observed) | 3.90 | 3.72 | 4.64 | 3.90 | 3.52 | 3.28 | 3.10 |
| 1.0 (expected) | 3.89 | 3.70 | 4.62 | 3.89 | 3.51 | 3.27 | 3.09 |
| 1.3 (observed) | 4.01 | 3.99 | 4.77 | 4.01 | 3.63 | 3.37 | 3.19 |
| 1.3 (expected) | 4.00 | 3.95 | 4.76 | 4.00 | 3.61 | 3.36 | 3.18 |
| $\mu\mu$ and ee, per channel $\sigma_s < 0.12$ fb (0.12 fb expected) at 95% CL | | | | | | | |
| 1.0 (observed) | 4.01 | 4.14 | 4.77 | 4.01 | 3.63 | 3.37 | 3.19 |
| 1.0 (expected) | 4.00 | 4.13 | 4.76 | 4.00 | 3.62 | 3.37 | 3.18 |
| 1.3 (observed) | 4.15 | 4.35 | 4.94 | 4.15 | 3.75 | 3.49 | 3.30 |
| 1.3 (expected) | 4.14 | 4.37 | 4.93 | 4.14 | 3.74 | 3.48 | 3.30 |

# resonant dileptons

CMS-EXO-12-061



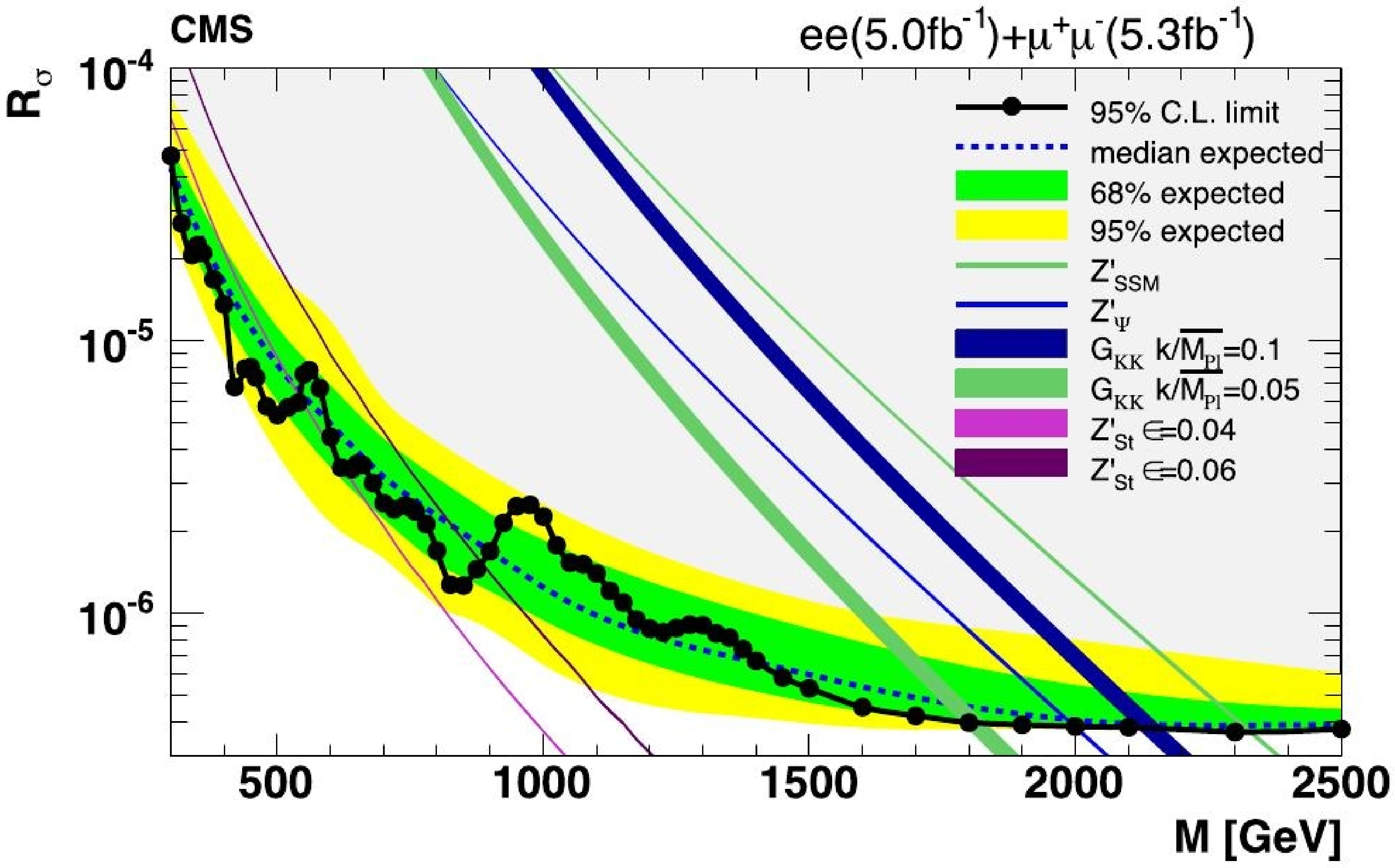




(final state also suited for search for TeV-1, RS, Bulk RS)

# resonant dilepton

PLB 714 (2012) 158

(**RS**, final state also suited to search for, TeV-1, Bulk RS)



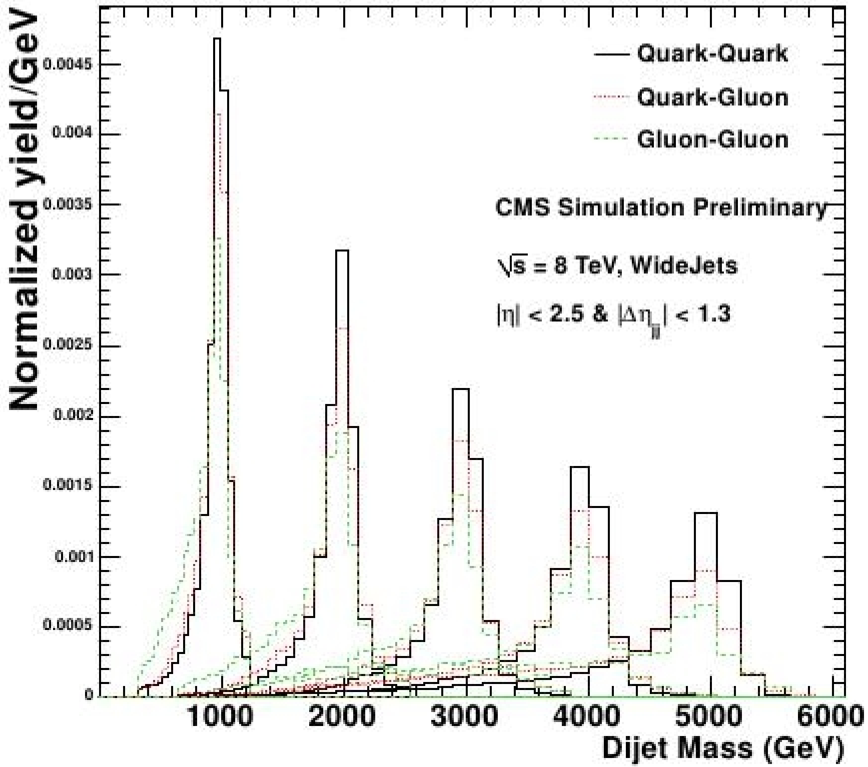

$$m_{G_{KK}^{(1)}} > 2.14 \text{ TeV} \quad (\ \tilde{k}=0.1\ )$$

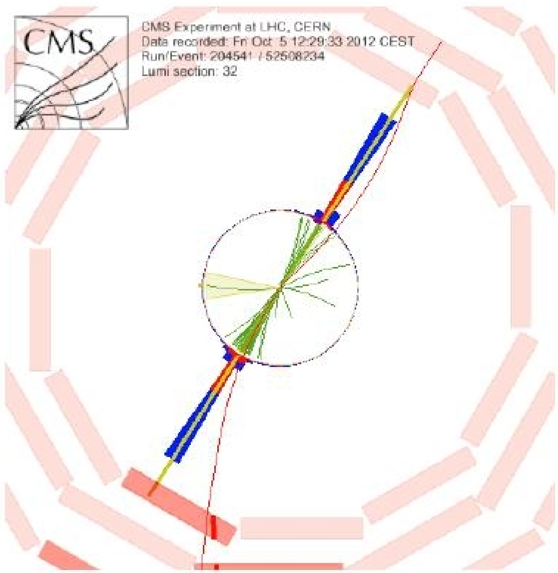
$$m_{G_{KK}^{(1)}} > 1.81 \text{ TeV} \quad (\ \tilde{k}=0.05\ )$$

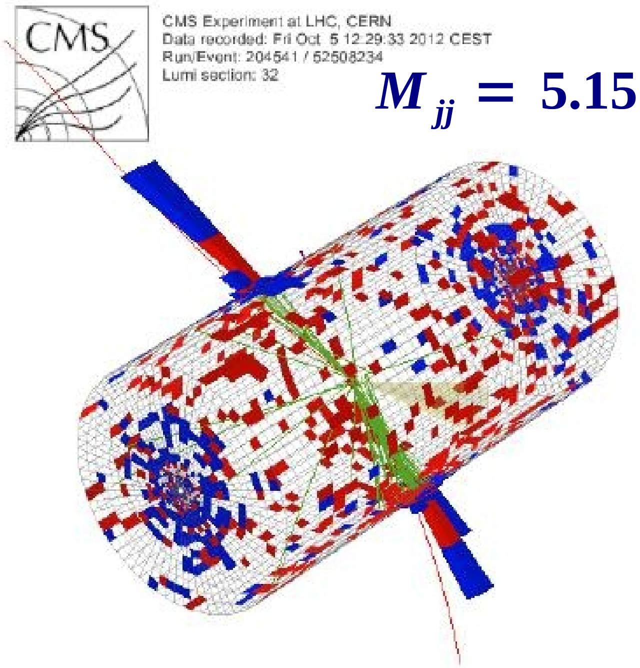
# resonant dijets

CMS-EXO-12-059

(**RS**, **string states,** final state also suited for search for TeV-1, Bulk RS)




$M_{jj}$ = 5.15 TeV

$q\bar{q} \rightarrow G_{KK} \rightarrow q\bar{q}$

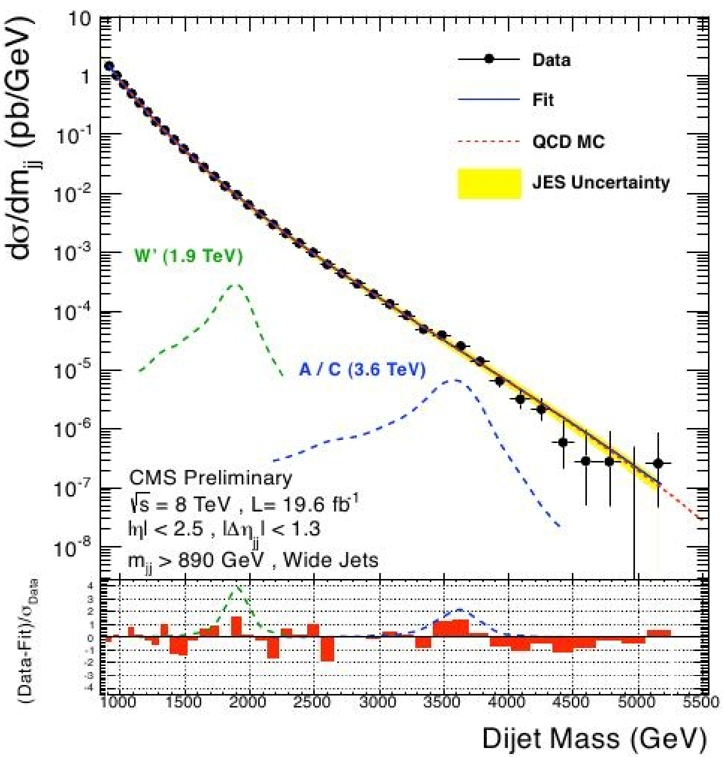
$q g \rightarrow q^{*} \rightarrow q g$

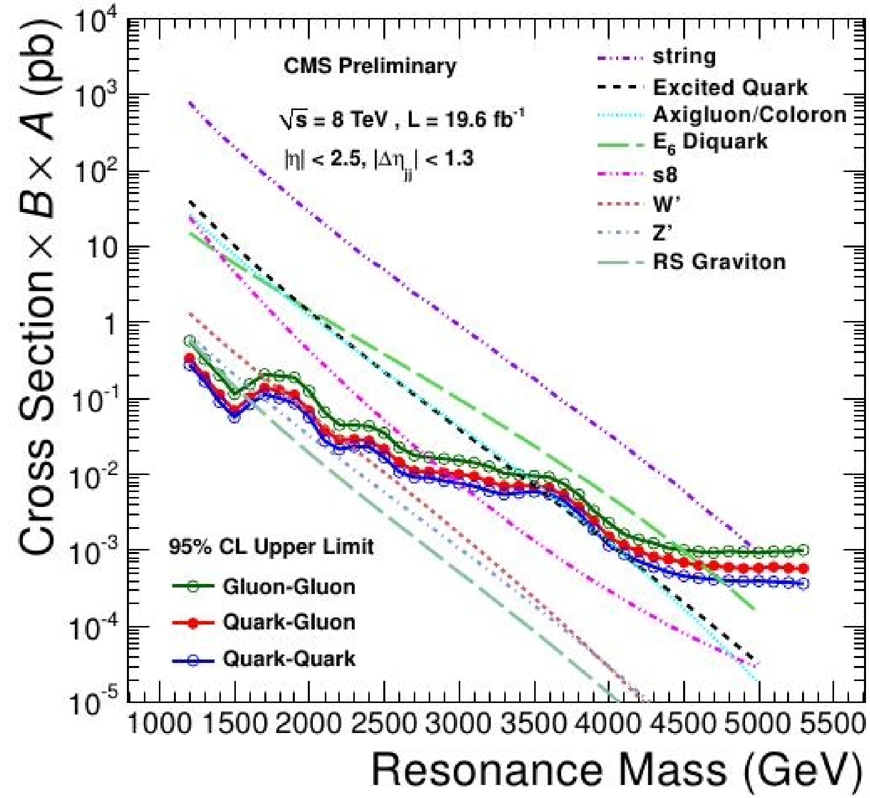
$g g \rightarrow G_{KK} \rightarrow g g$

# resonant dijets

CMS-EXO-12-059

(**RS**, **string states,** final state also suited for search for TeV-1, Bulk RS)



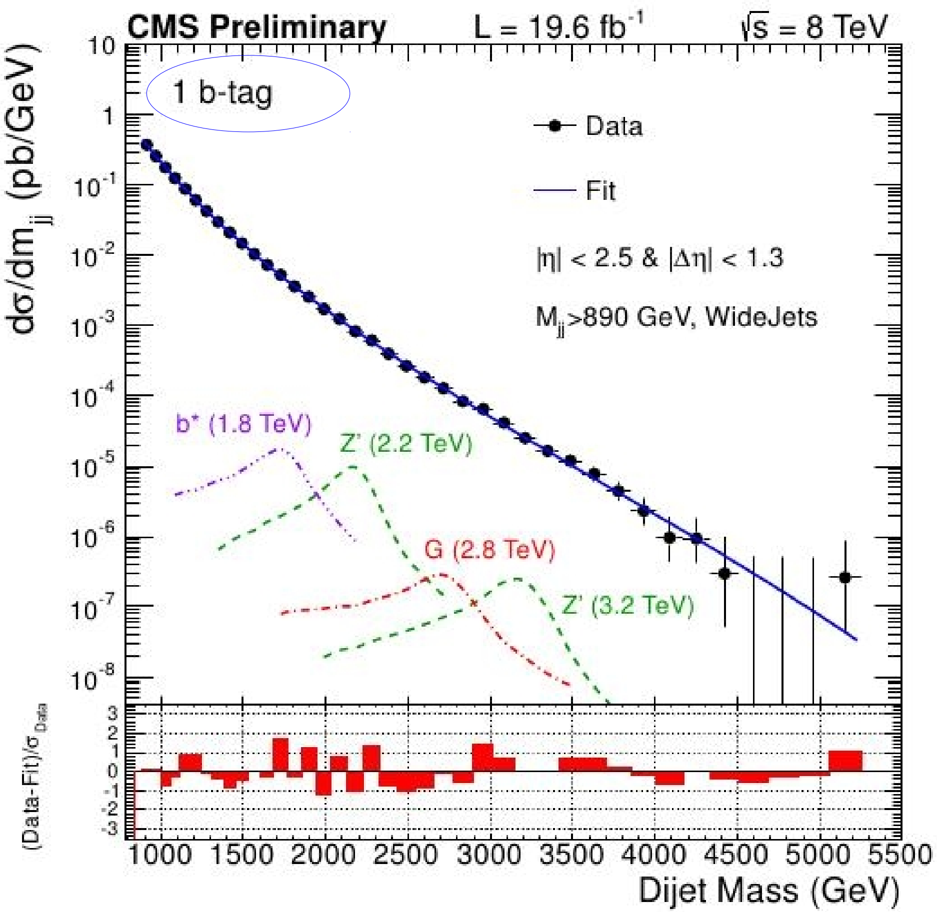

| Model | Final State | Obs. Mass Excl. [TeV] | Exp. Mass Excl. [TeV] |
|---|---|---|---|
| String Resonance (S) | qg | [1.20,5.08] | [1.20,5.00] |
| Excited Quark ($q^*$) | qg | [1.20,3.50] | [1.20,3.75] |
| $E_6$ Diquark (D) | qq | [1.20,4.75] | [1.20,4.50] |
| Axigluon (A)/Coloron (C) | $q\bar{q}$ | [1.20,3.60] + [3.90,4.08] | [1.20,3.87] |
| Color Octet Scalar (s8) | gg | [1.20,2.79] | [1.20,2.74] |
| W′ Boson (W′) | $q\bar{q}$ | [1.20,2.29] | [1.20,2.28] |
| Z′ Boson (Z′) | $q\bar{q}$ | [1.20,1.68] | [1.20,1.87] |
| RS Graviton (G) | $q\bar{q}$+gg | [1.20,1.58] | [1.20,1.43] |

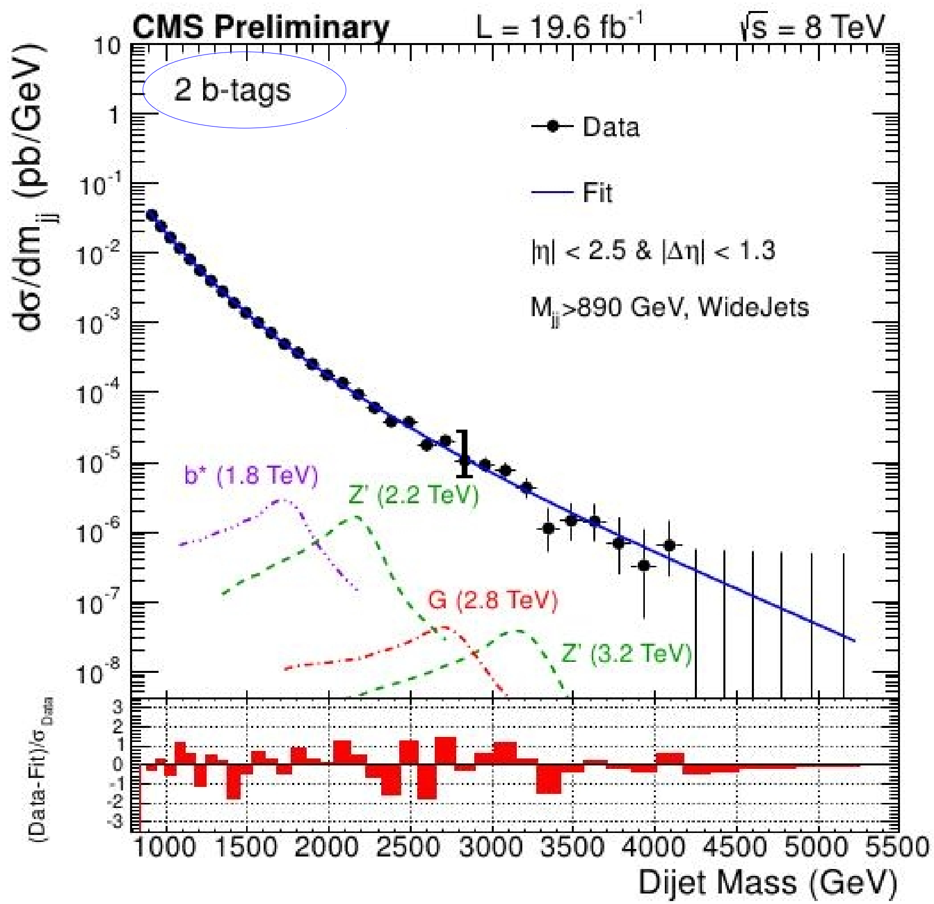
# resonant dijets (with b-jet)

CMS-EXO-12-023

(**RS**, bb final state also suited for search for TeV-1, Bulk RS)

- anti $k_t$ 0.5 jets, $\eta < 2.5$, $|\Delta\eta| < 1.3$
- 3 channels : 0, 1, 2 b-tags

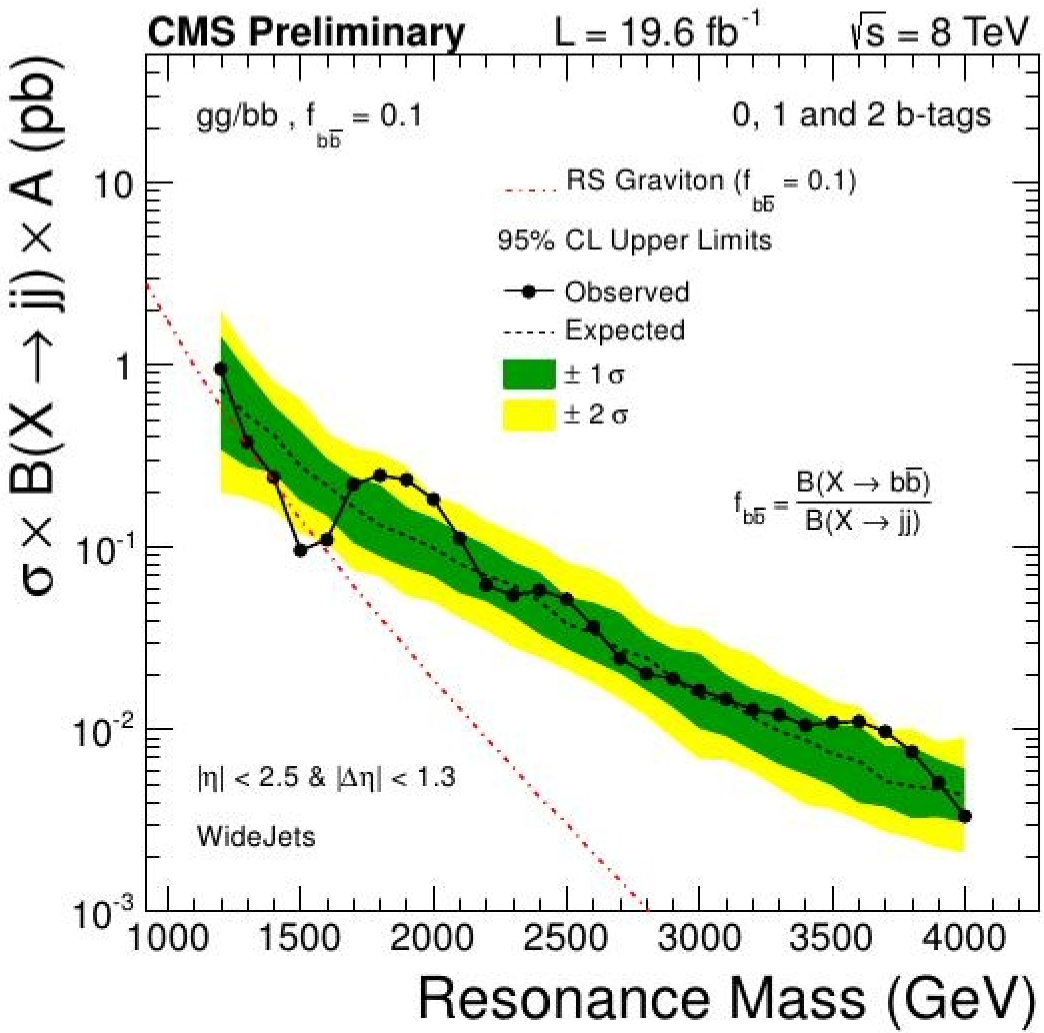


# resonant dijets (with b-jet)

CMS-EXO-12-023

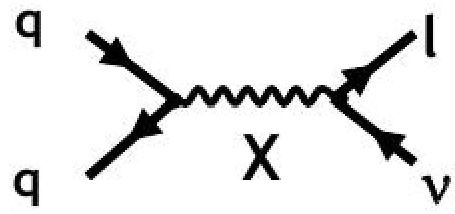
(**RS**, bb final state also suited for search for TeV-1, Bulk RS)




$m_{G_{KK}^{(1)}}$ **in the 1.42 - 1.57 TeV range is excluded**

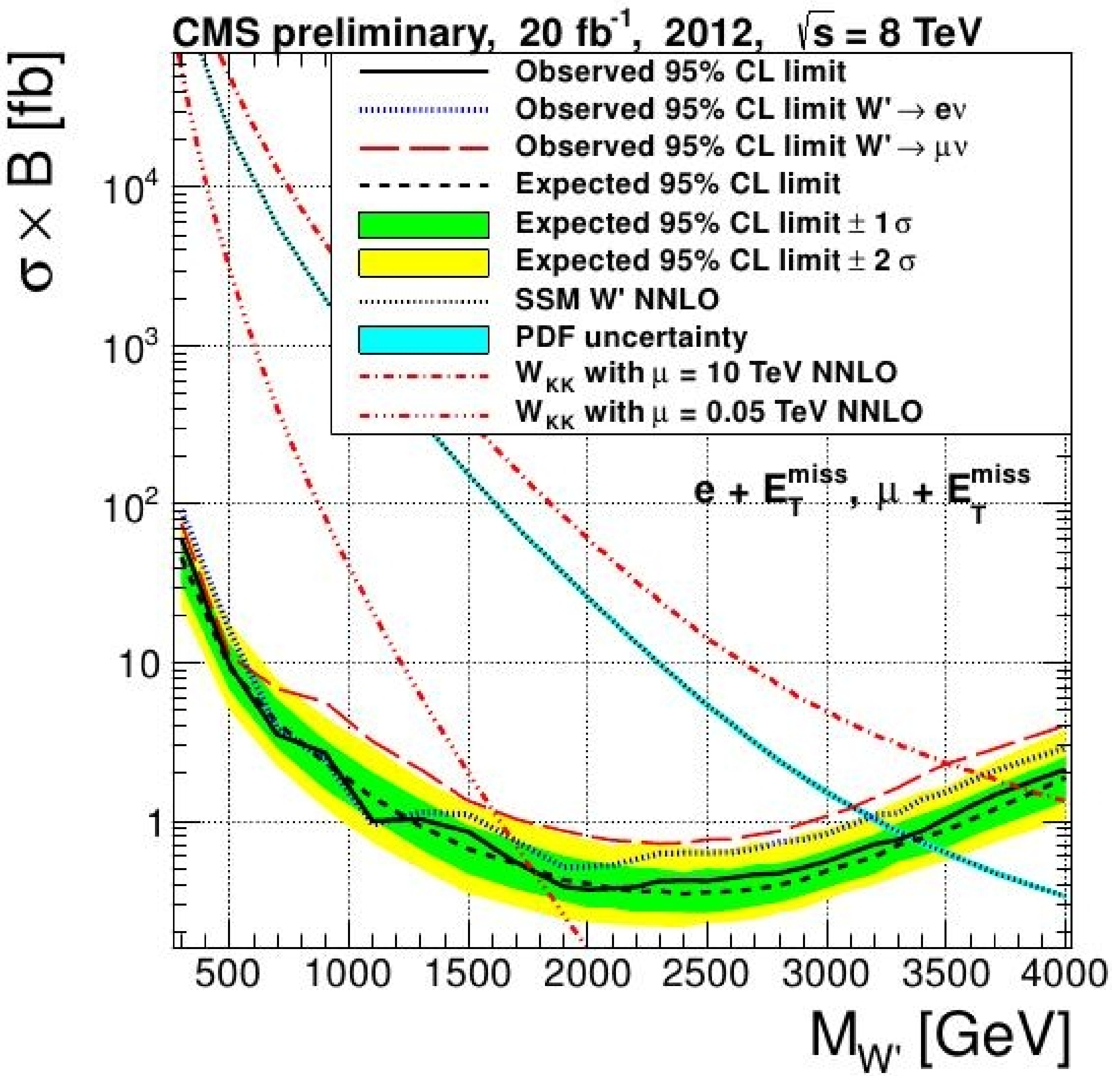
# Lepton + MET

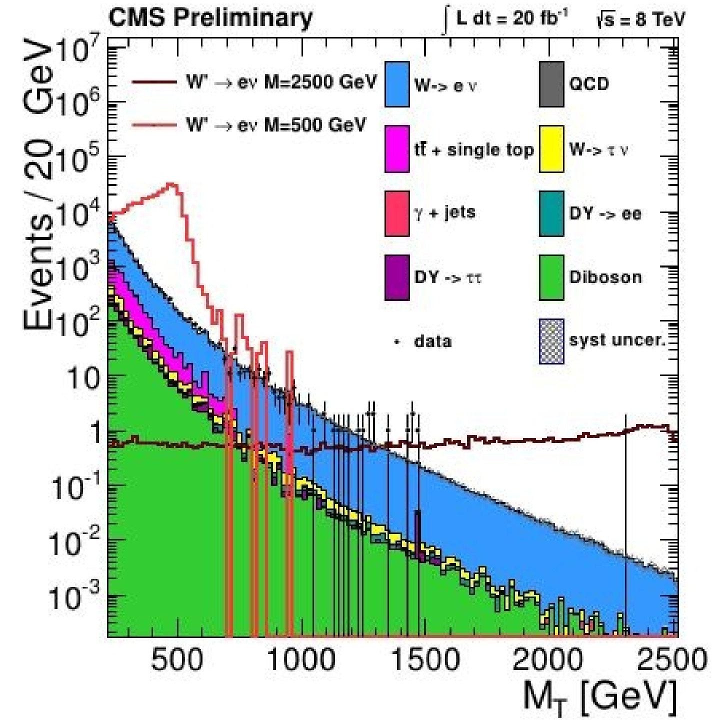
CMS-EXO-12-060

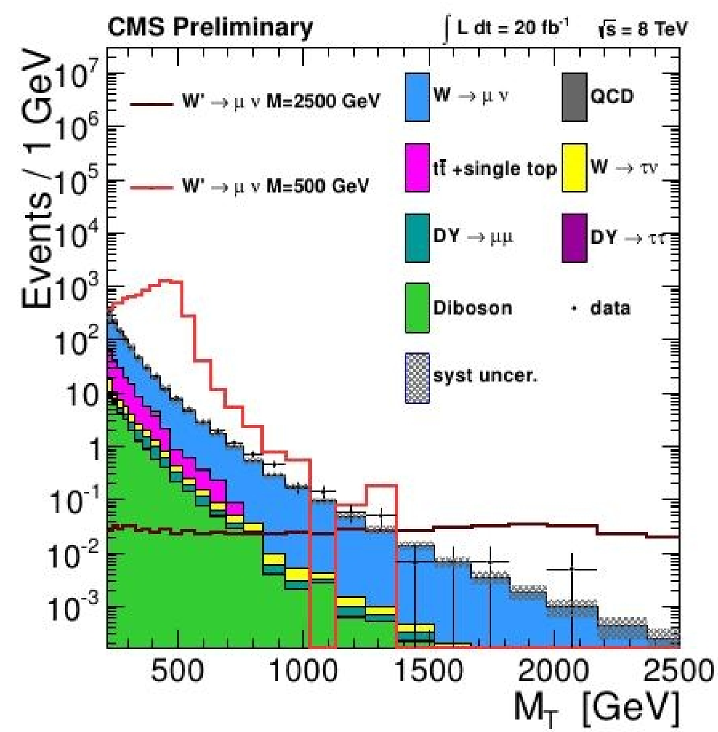



$$m_T = \sqrt{2\, p_T\, E_T^{miss}\left(1 - \cos\theta_{l\nu}\right)}$$

(TeV-1, UED, Bulk RS)

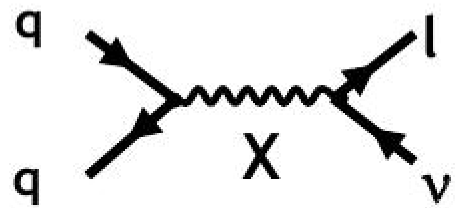


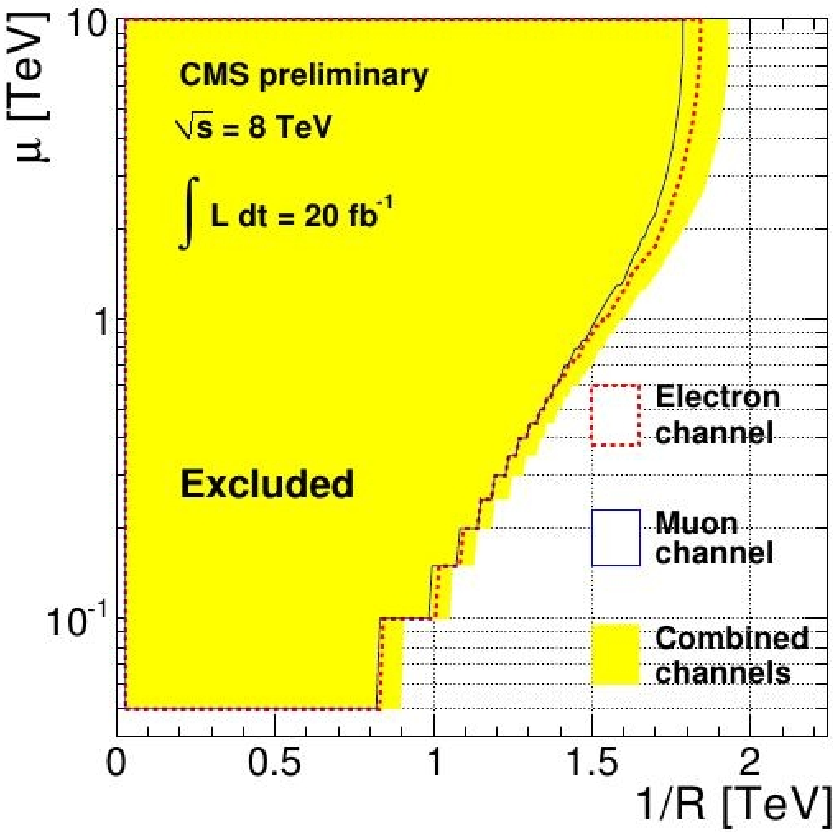
# Lepton + MET

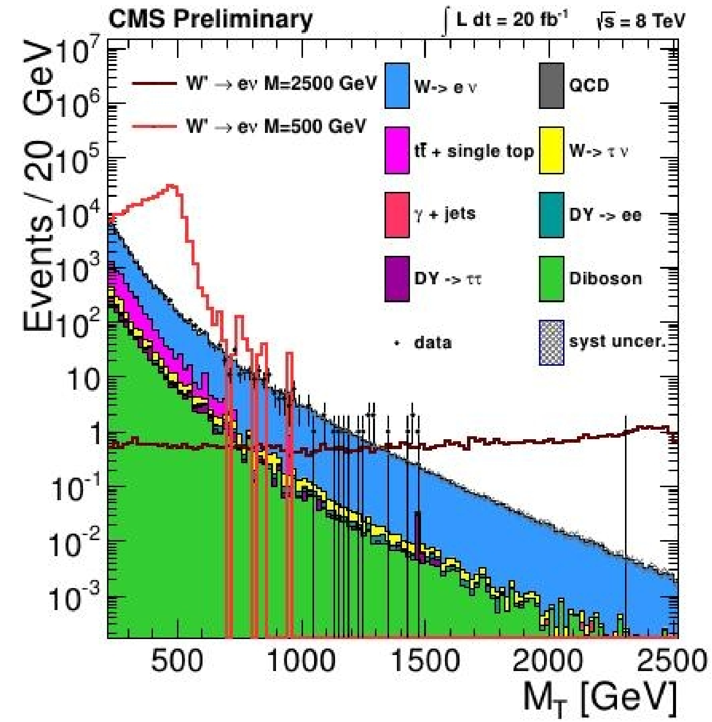
CMS-EXO-12-060

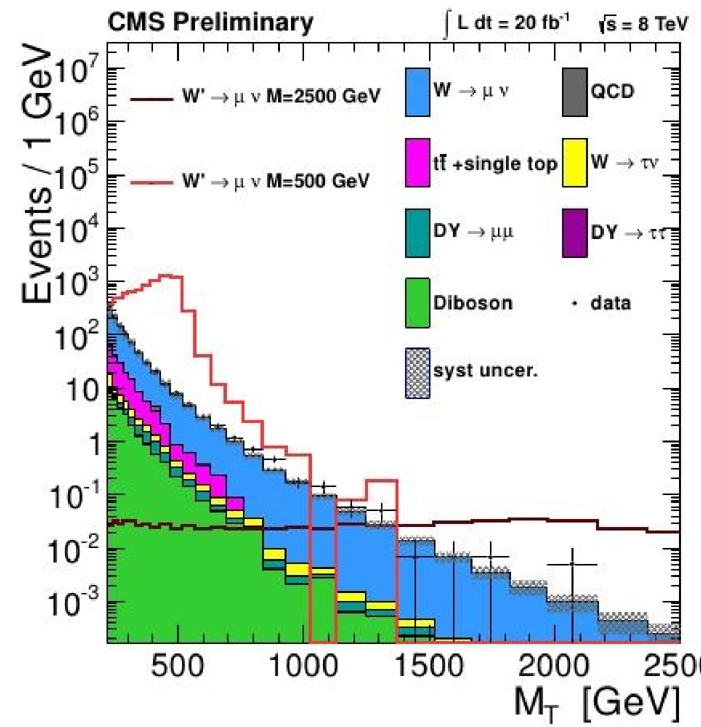



$$m_T = \sqrt{2\, p_T\, E_T^{miss}\left(1 - \cos\theta_{l\nu}\right)}$$

(TeV-1, UED, Bulk RS)



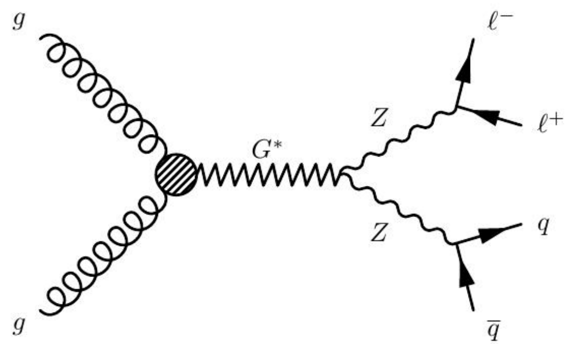

$m_{W_{KK}^{(1)}} > 1.7$ TeV ( $\mu = 0.05$ TeV )

$m_{W_{KK}^{(1)}} > 3.7$ TeV ( $\mu = 10$ TeV )

# semi leptonic resonant diboson (ZZ)

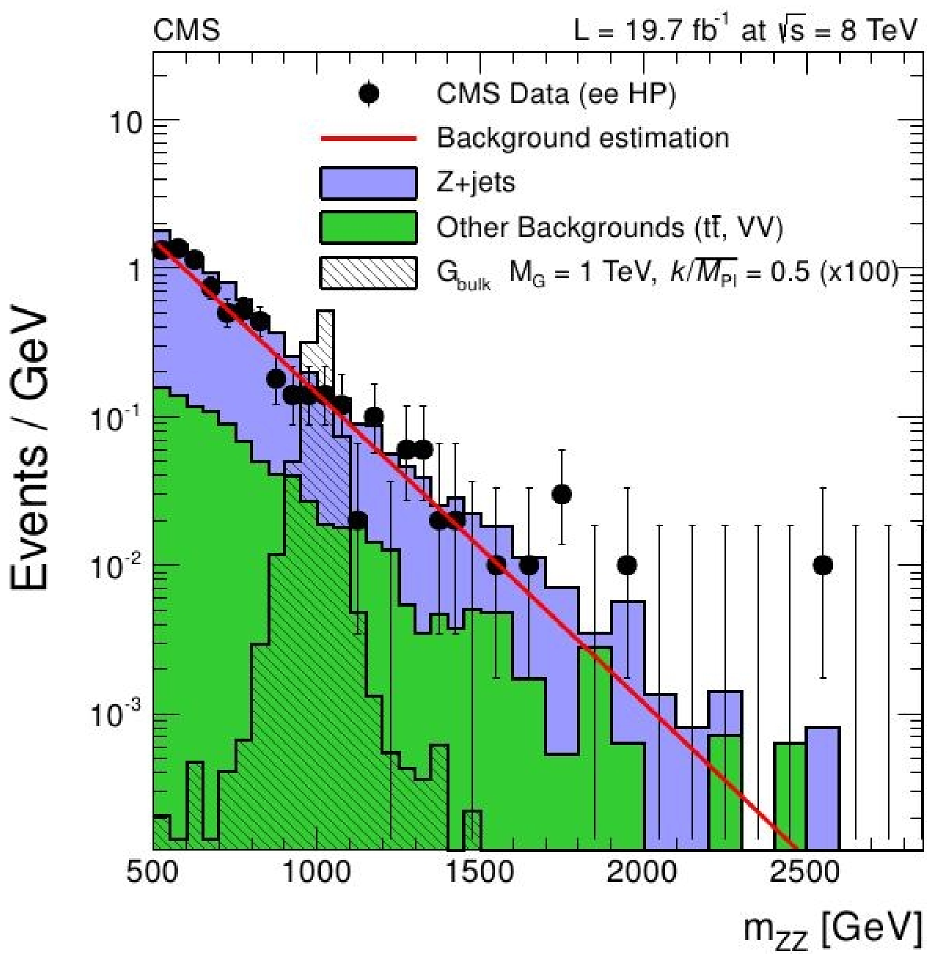
CMS-EXO-13-009, arXiv:1405.3447

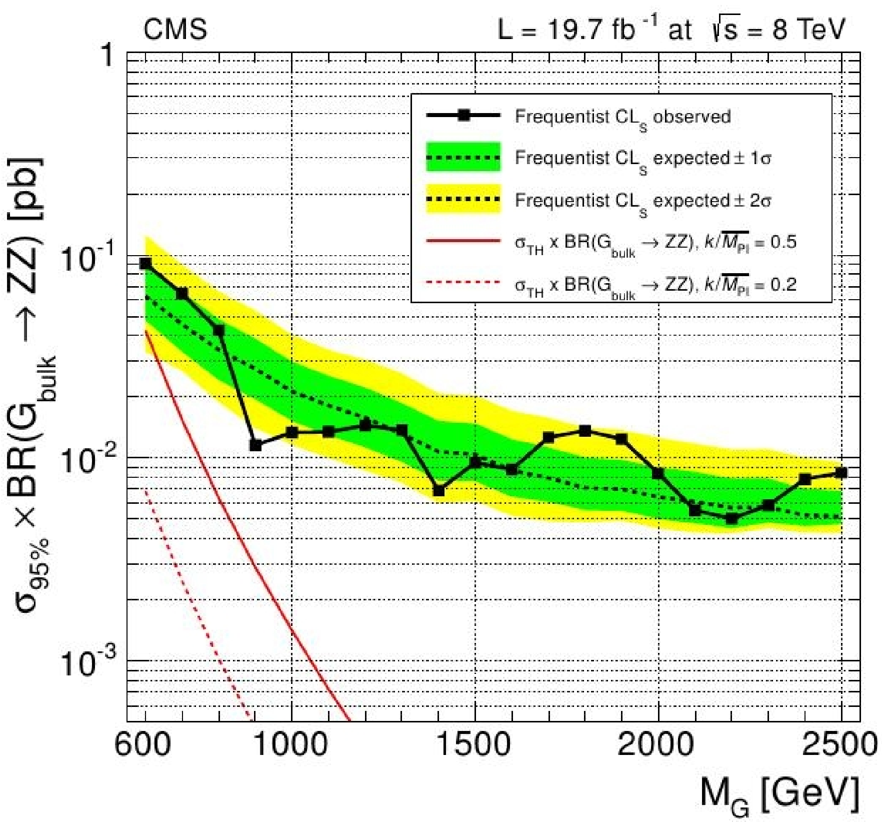
**aiming at $G_{KK}^{RS} \rightarrow ZZ$**




categorize into *ee* and μμ

and low (LP) and high (HP) purity



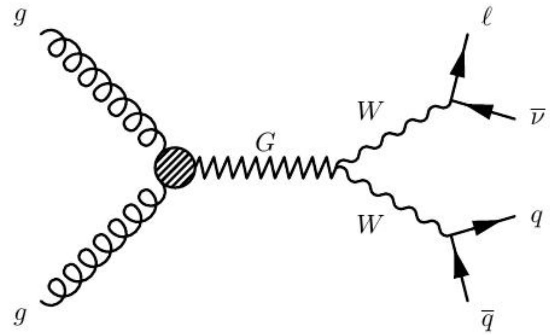

**$\sigma \cdot BR < 90$ fb $-$ 5 fb**

**for $m_{G_{KK}^{(1)}}$ in the 0.6$-$2.5 TeV range**

# semi-leptonic resonant diboson (WW)

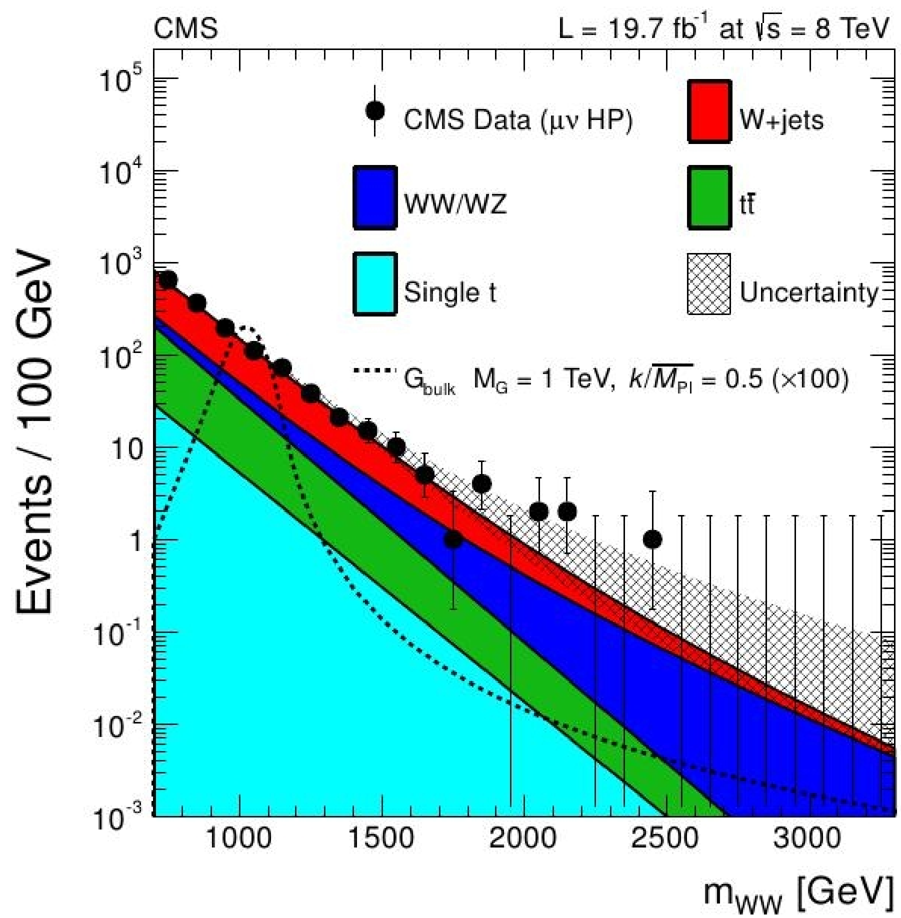
CMS-EXO-13-009, arXiv:1405.3447

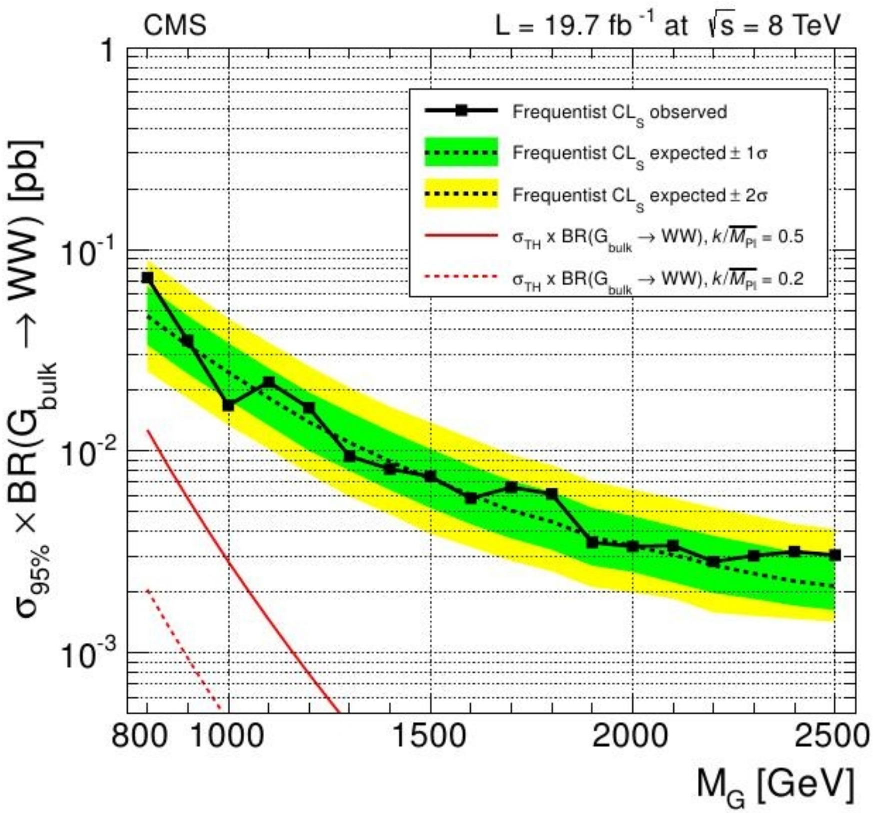
**aiming at $G_{KK}^{RS} \rightarrow WW$**




categorize into $e\,\nu$ and $\mu\,\nu$

and low (LP) and high (HP) purity



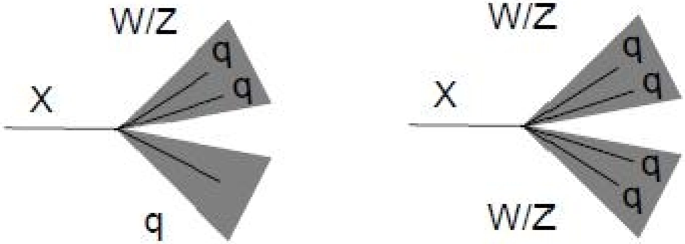

**$\sigma \cdot BR < 70$ fb $-$ 3 fb**

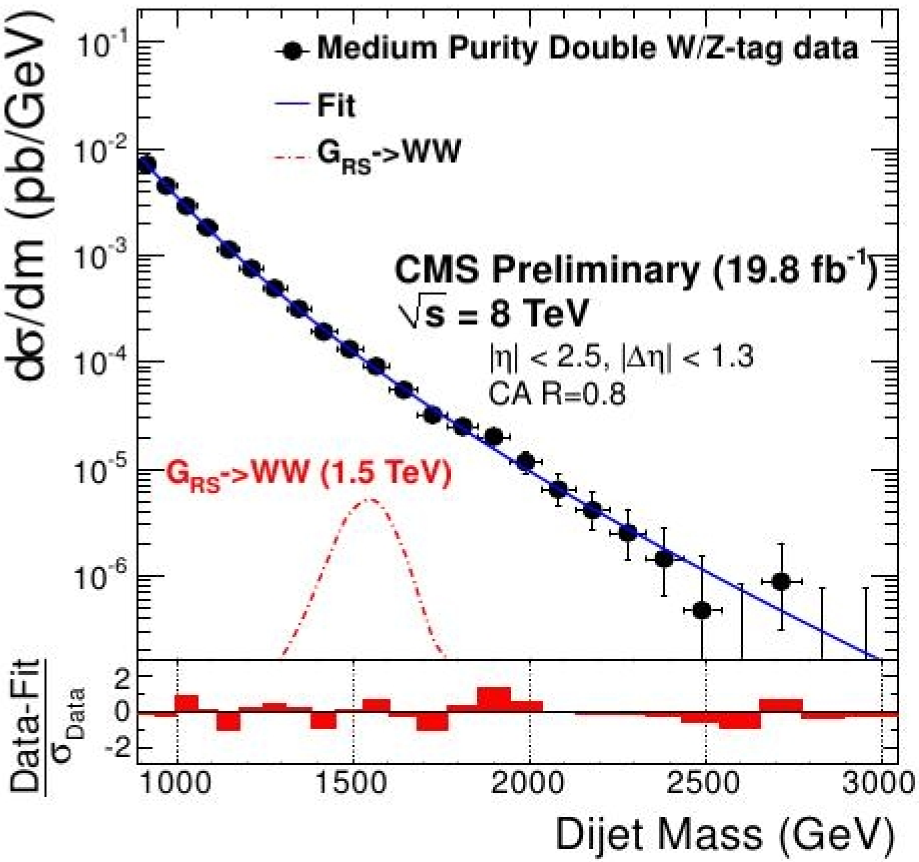
**for $m_{G_{KK}^{(1)}}$ in the $0.8 - 2.5$ TeV range**

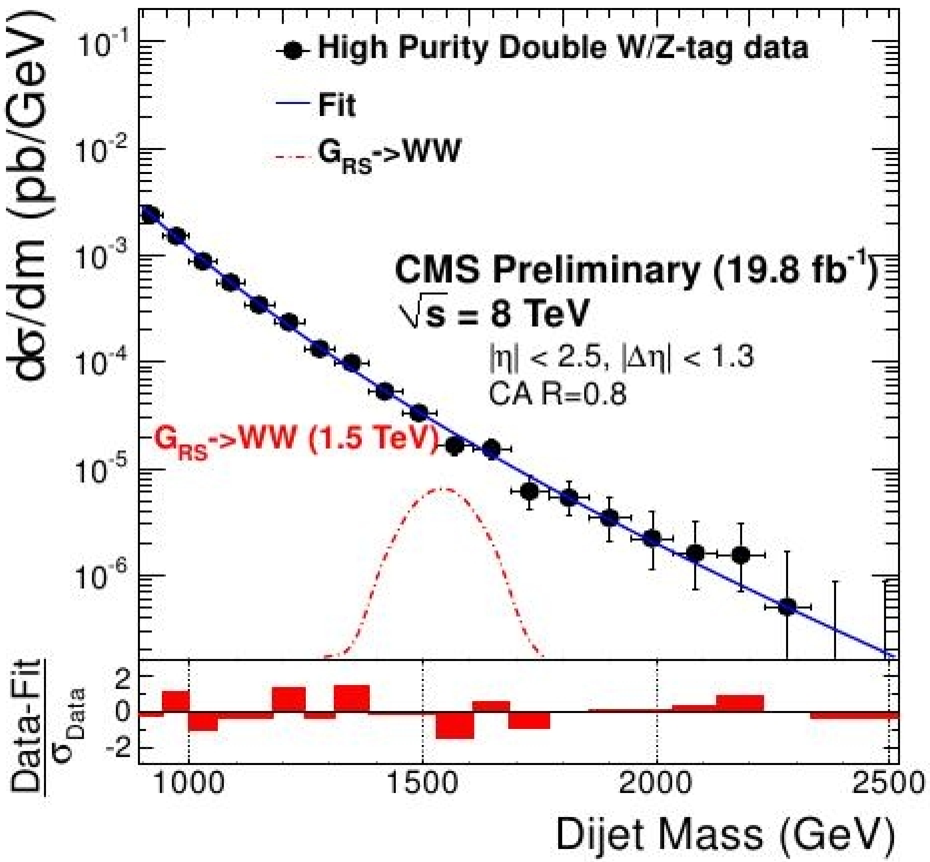
# resonant diboson (jets channel)

CMS-EXO-12-024, arXiv:1405.1994

- 1 or 2 leading jet, **W/Z tagged**

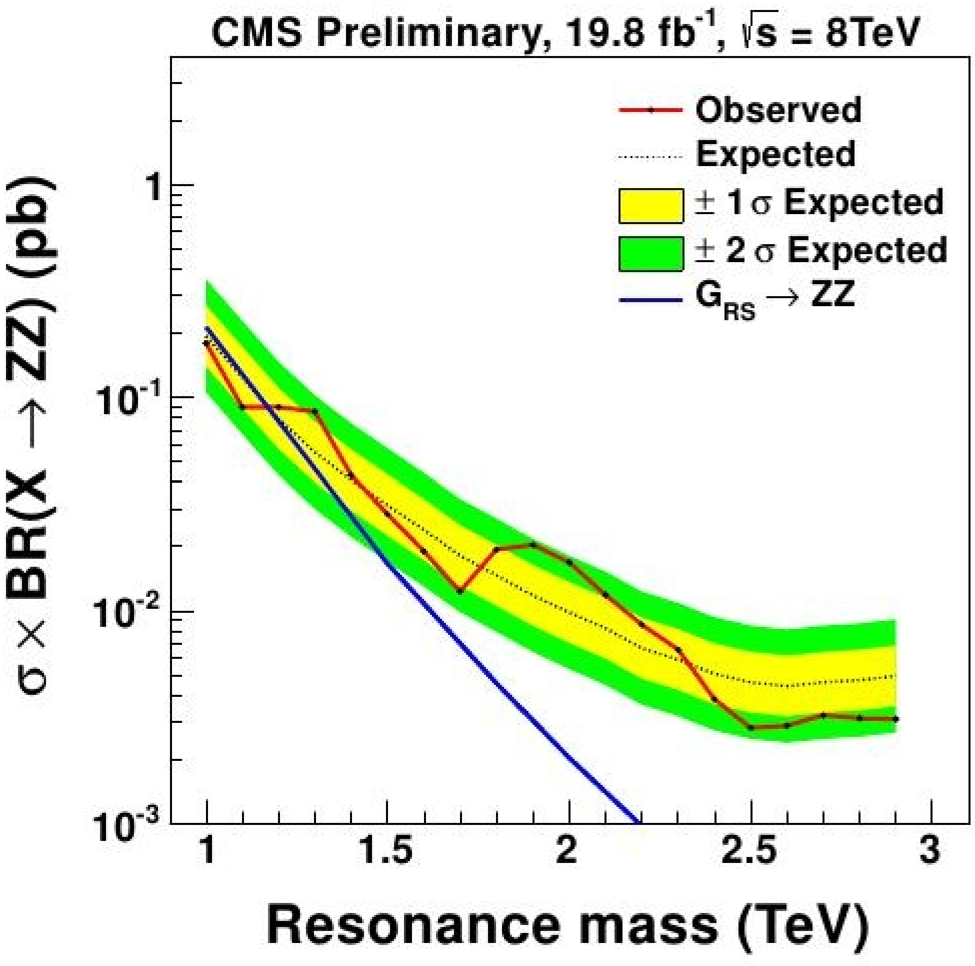


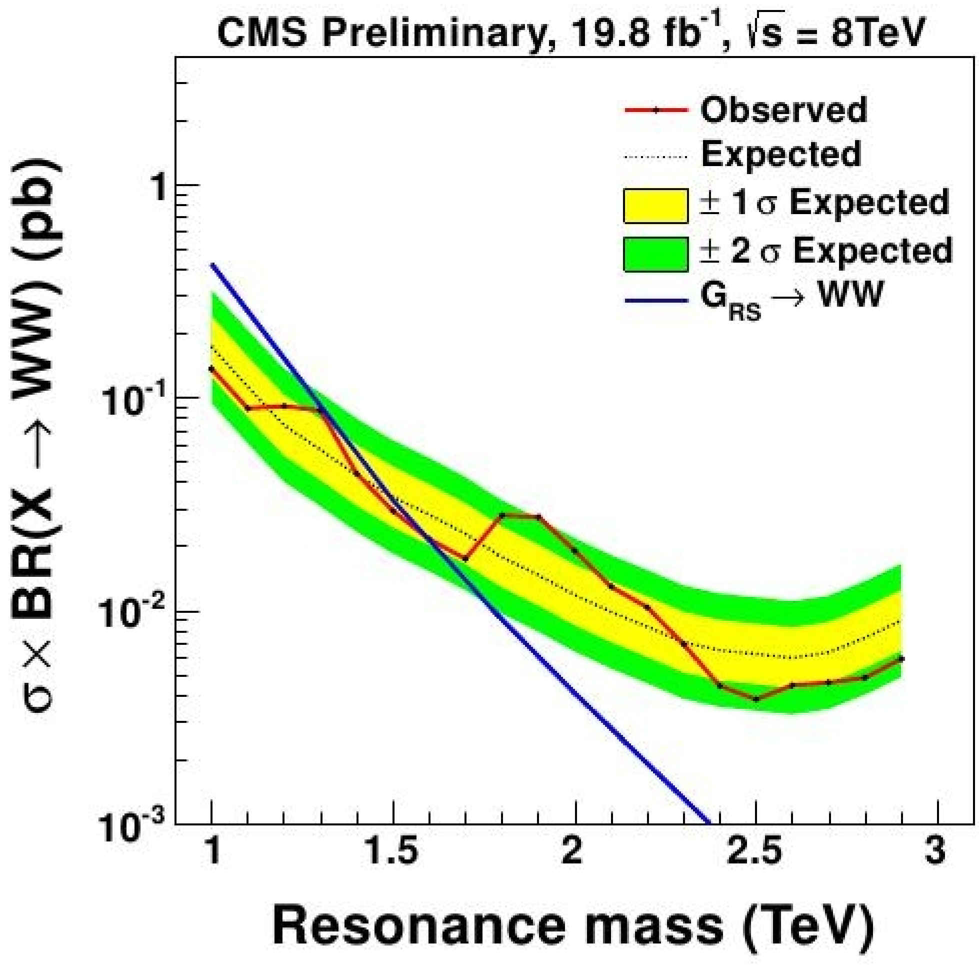



# resonant diboson (jets channel)

CMS-EXO-12-024, arXiv:1405.1994



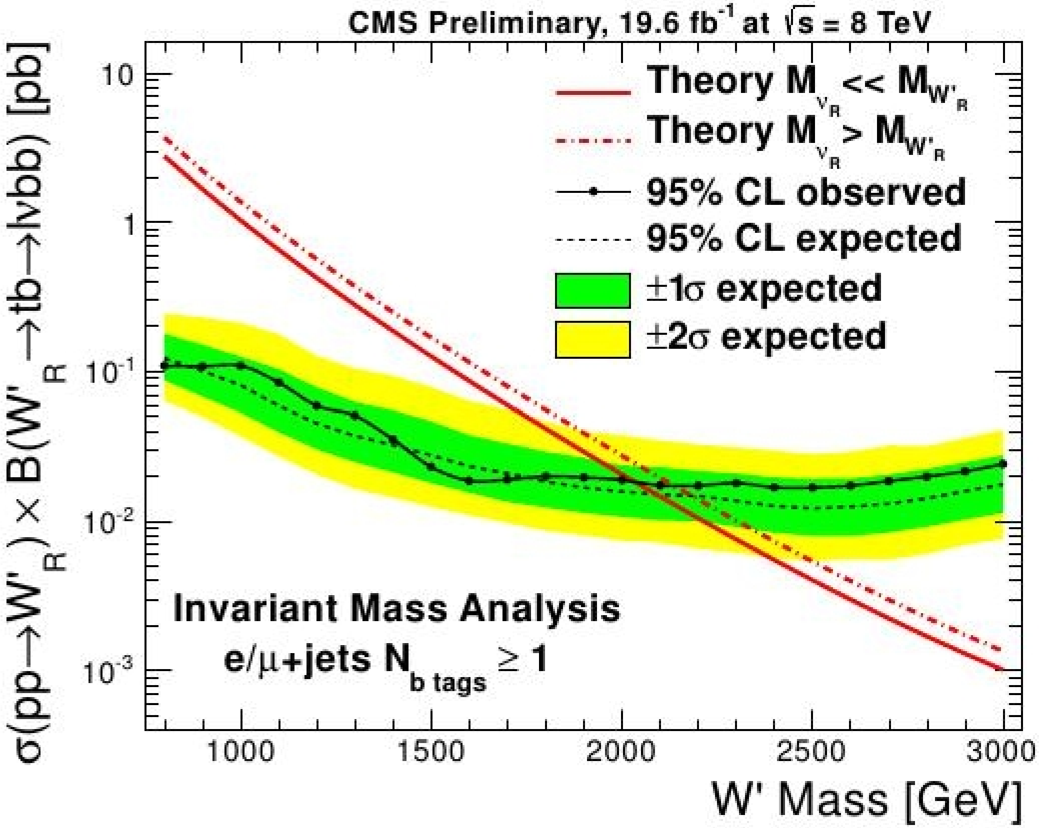

$m_{G_{KK}^{(1)}}$ **> 1.17 TeV** $(\tilde{k} = 0.5)$

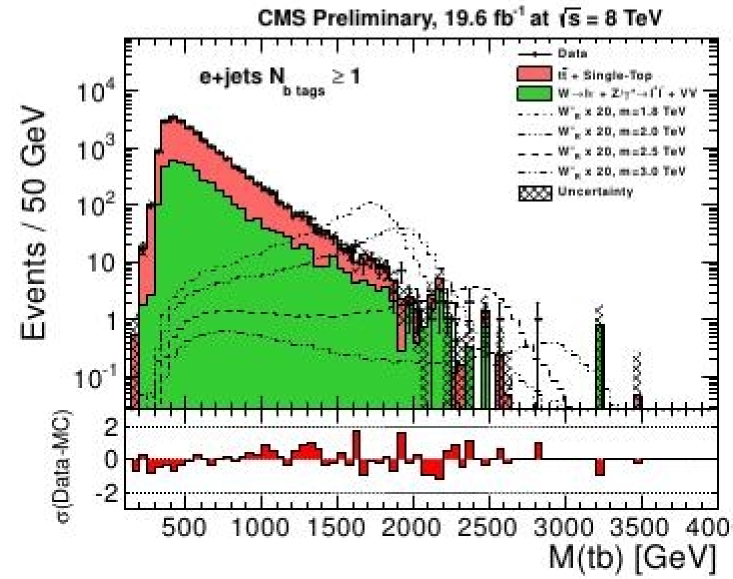
$m_{G_{KK}^{(1)}}$ **> 1.59 TeV** $(\tilde{k} = 0.5)$

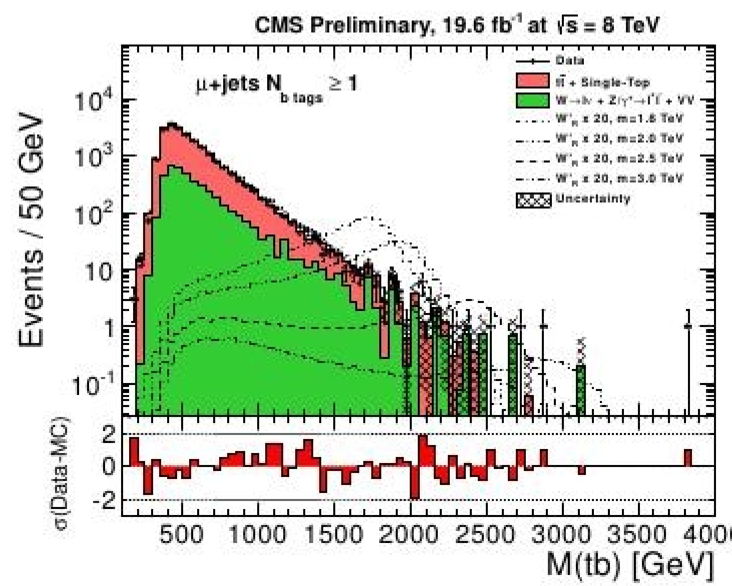
# resonant bt

CMS-B2G-12-010

(final state suited for search for TeV-1, Bulk RS)



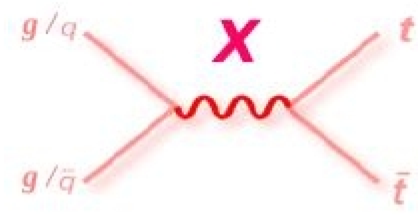

$m_{W'}$ **> 2.03 TeV (obs)**

$m_{W'}$ > 2.09 TeV (exp)

# semileptonic $t\bar{t}$

CMS-B2G-12-006

(**bulk RS**, also suited for search for TeV-1, RS)




- 2 analyses

  low/high mass coverage

  i.e. threshold/boosted

  transition at ~ 1 TeV

- for boosted analysis

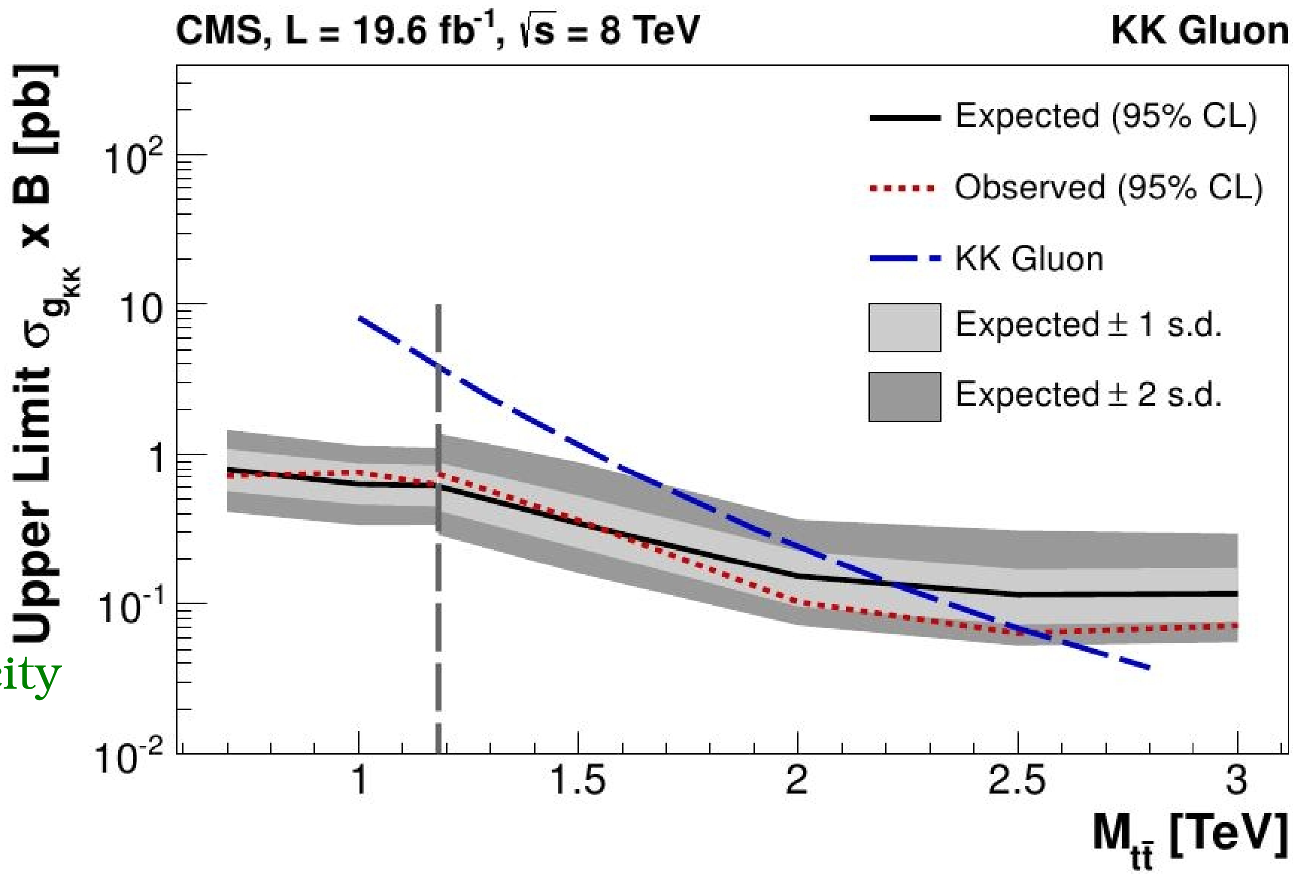
  less isolation

  smaller b-tagged jet multiplicity

  higher 'wide' jet multiplicity

  jet substructure

- limits from the combination of the 2 analyses




$m_{g_{KK}^{(1)}} > 2.54$ TeV

$\sigma . Br(pp \rightarrow g_{KK}^{(1)} \rightarrow t\bar{t}) < 0.101$ pb $(0.150^{+0.072}_{-0.055}$ pb expected$)$

for $m_{g_{KK}^{(1)}} = 2$ TeV

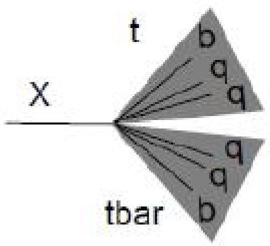
# hadronic $t\bar{t}$

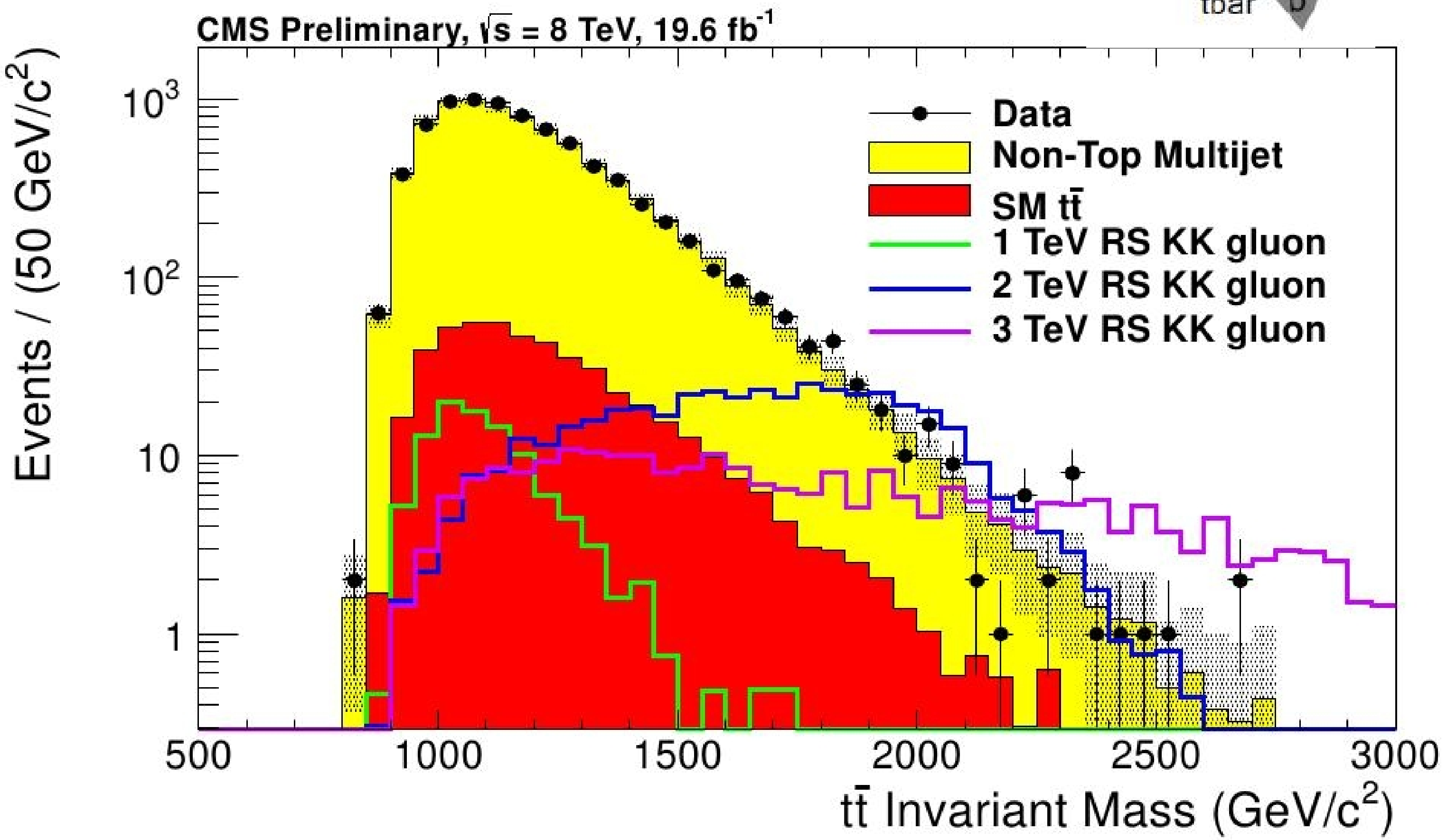
CMS-B2G-12-005

(**Bulk RS**, final state also suited for search for TeV-1, RS)

- look at hadronically decaying boosted top quarks

- use a (boosted) top tagging algorithm

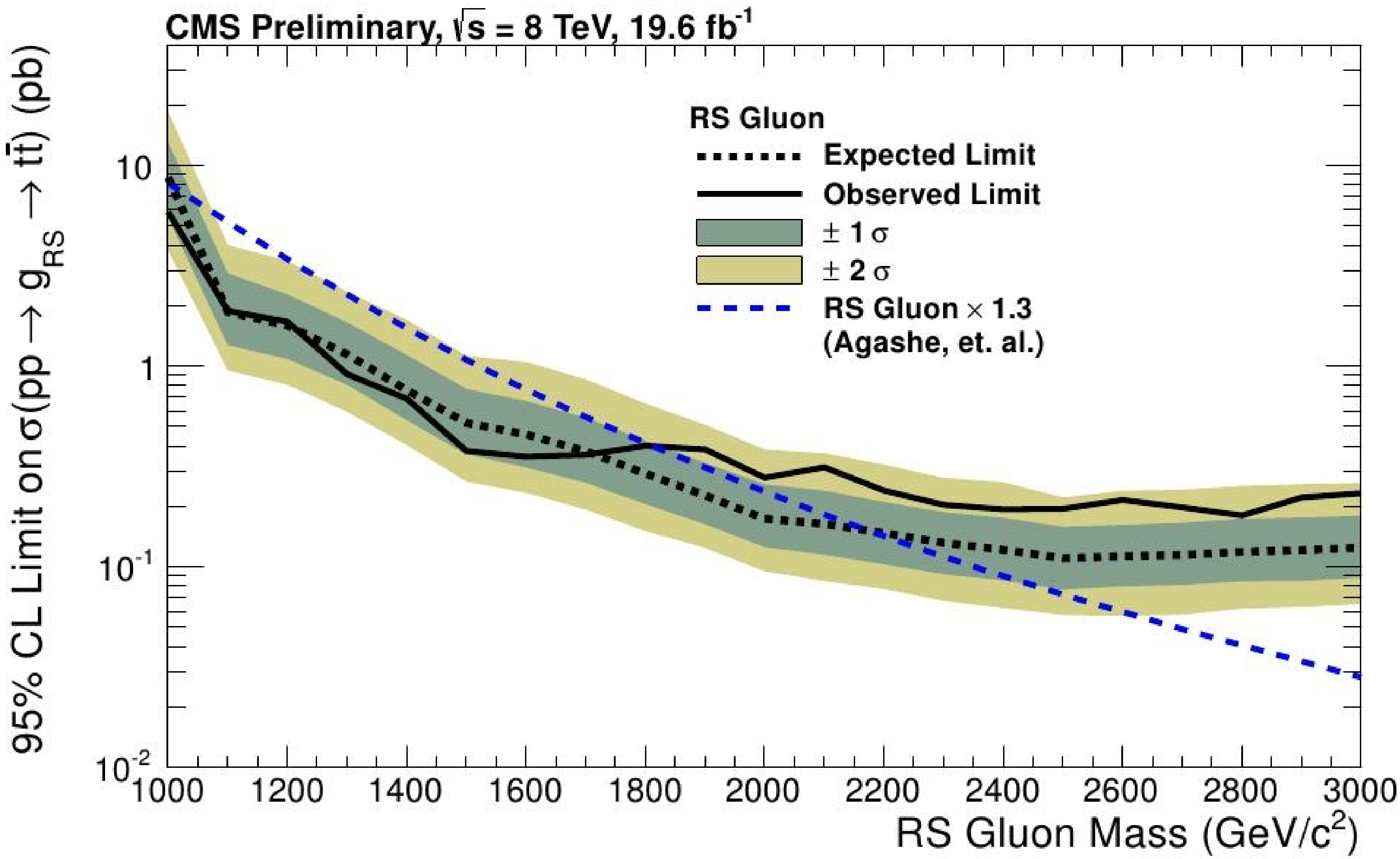


# hadronic $t\bar{t}$

CMS-B2G-12-005

(**Bulk RS**, final state also suited for search for TeV-1, RS)



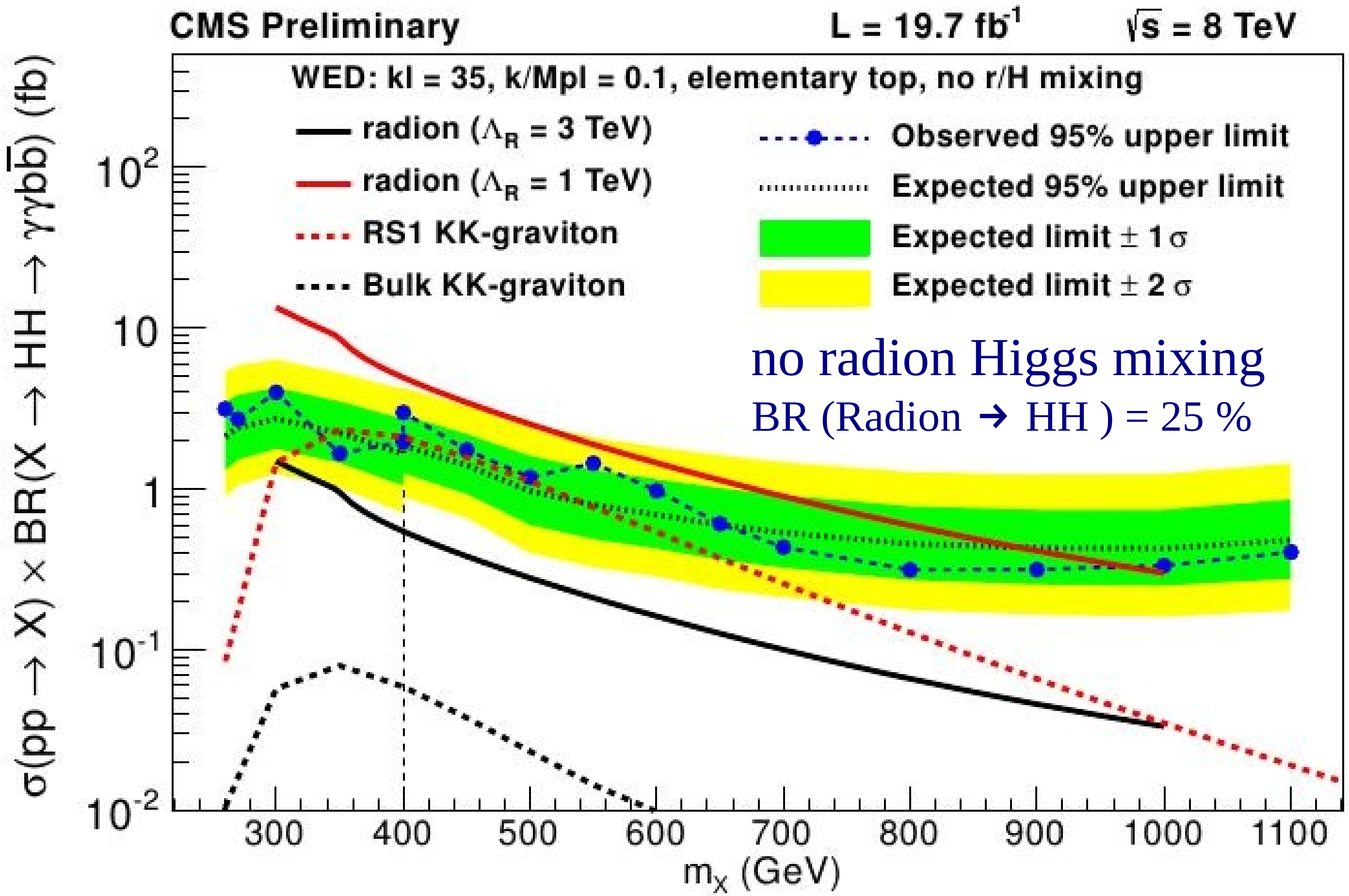

**obtain constraint on KK gluon mass** $m_{g_{KK}^{(1)}} > 1.8$ **TeV**

# resonant HH

HIG-PAS-12-032

## (stabilized RS, Bulk RS, RS)

$X \rightarrow HH \rightarrow \gamma\gamma b\bar{b}$



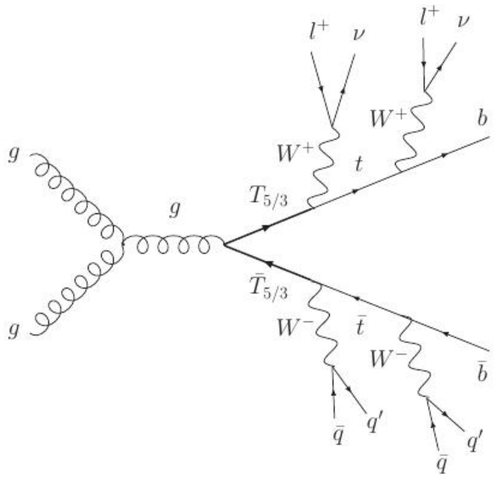

**$M_{\text{radion}}$ < 0.97 TeV excluded at 95% C.L. for $\Lambda_R = 1$ TeV**

RS KK graviton excluded [340, 400] GeV at 95 % C.L.

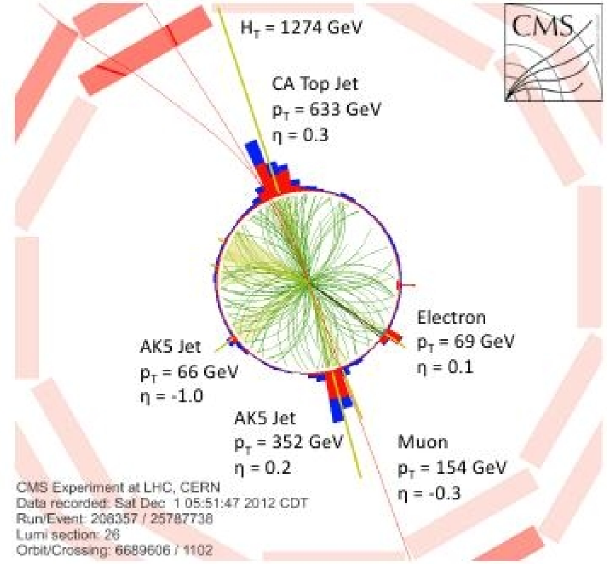
# Exotic fermions (5 e/3)

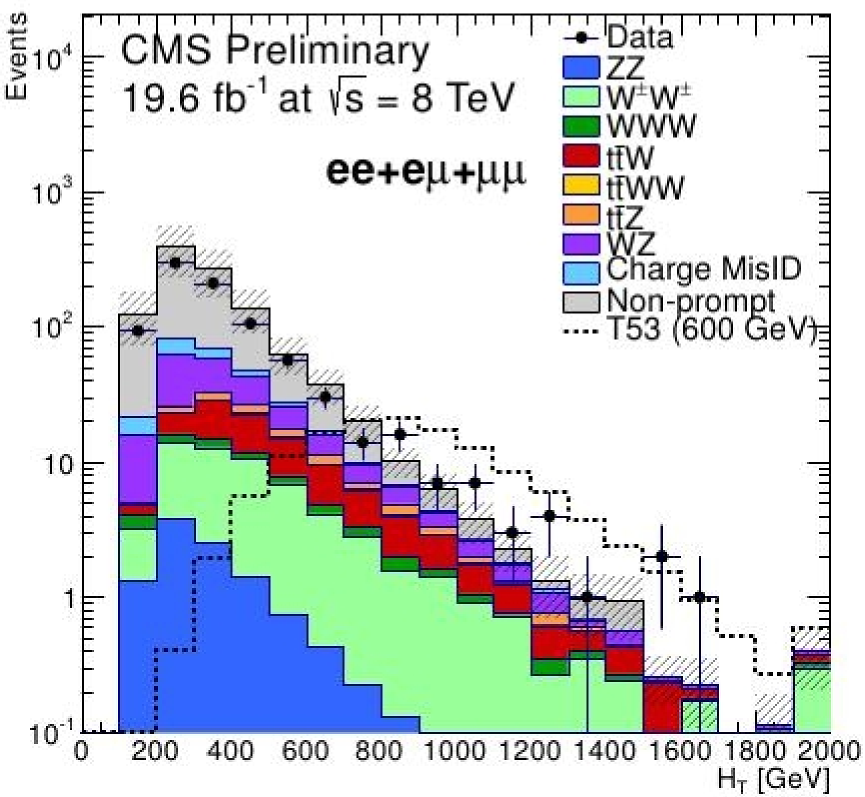
CMS-B2G-12-012

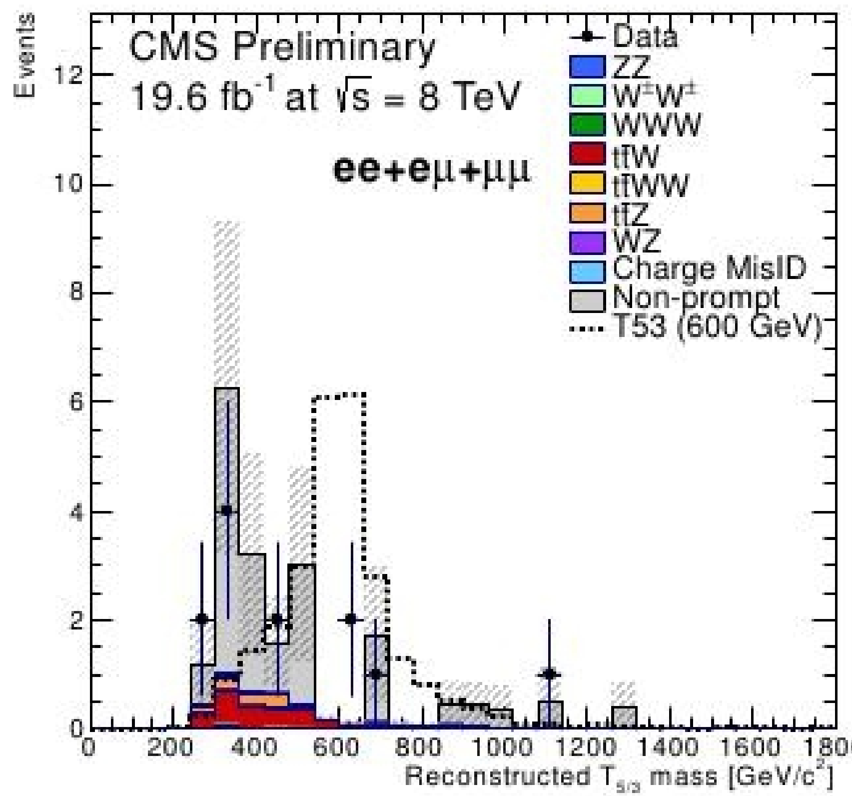
(suited for bulk RS)




same sign dilepton



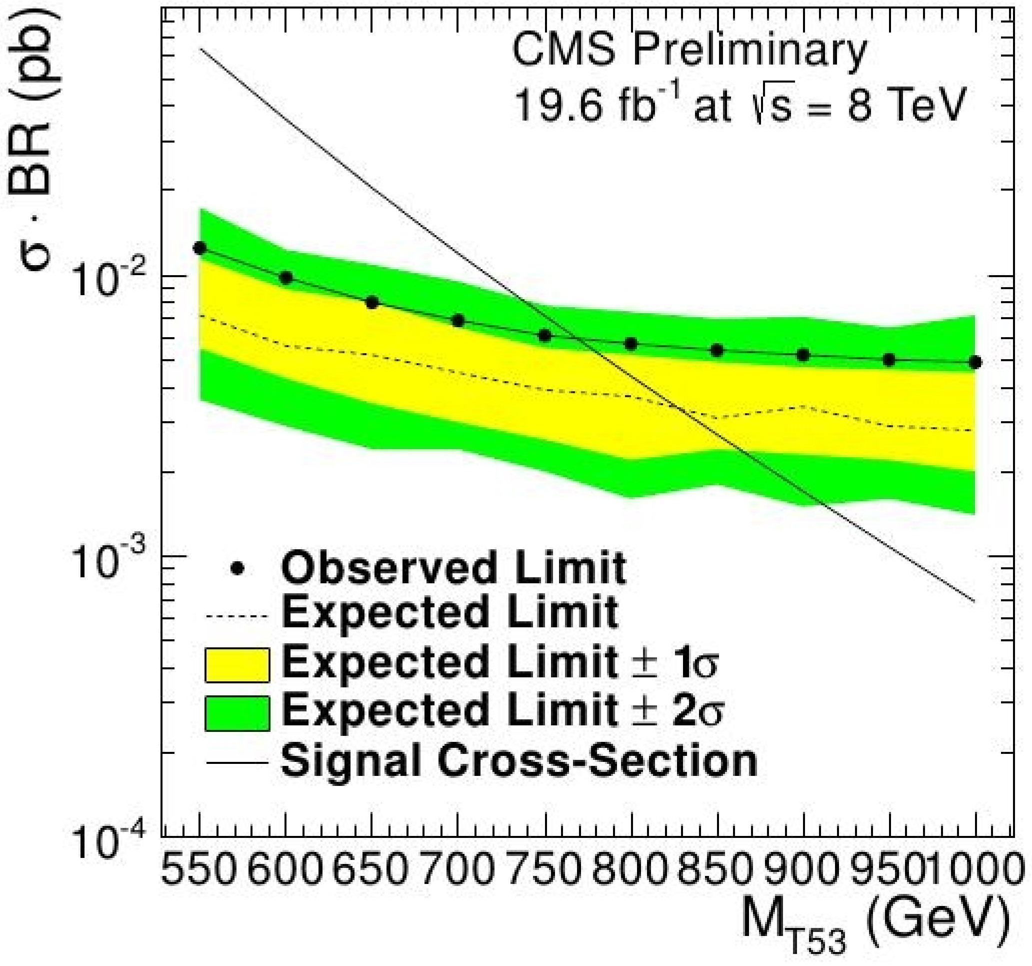




***$H_T$* = scalar sum of all jets and all leptons**

# Exotic fermions (5 e/3)

CMS-B2G-12-012

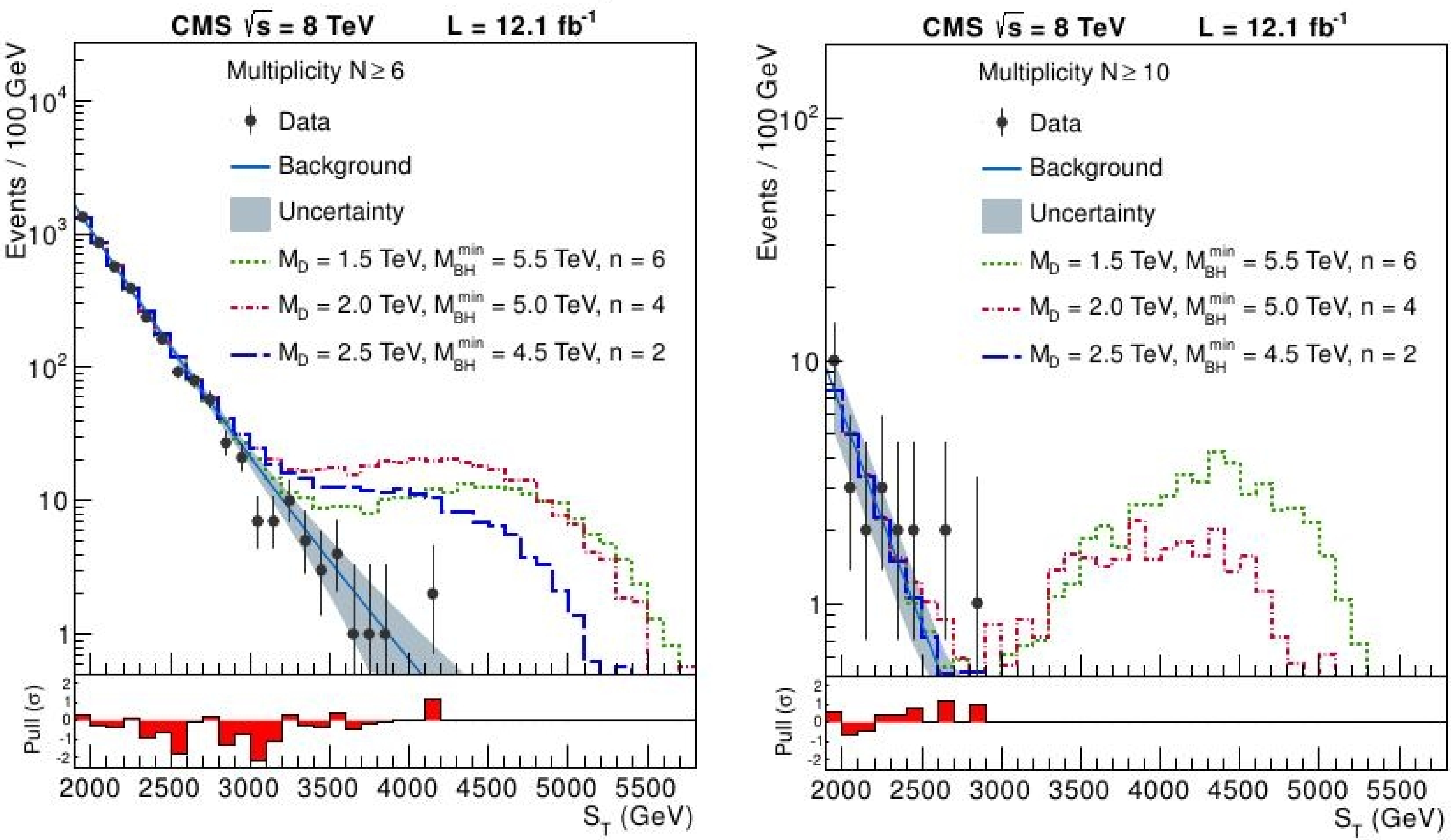
**(bulk RS)**




$M_{T_{5/3}} > 770$ GeV

# black holes

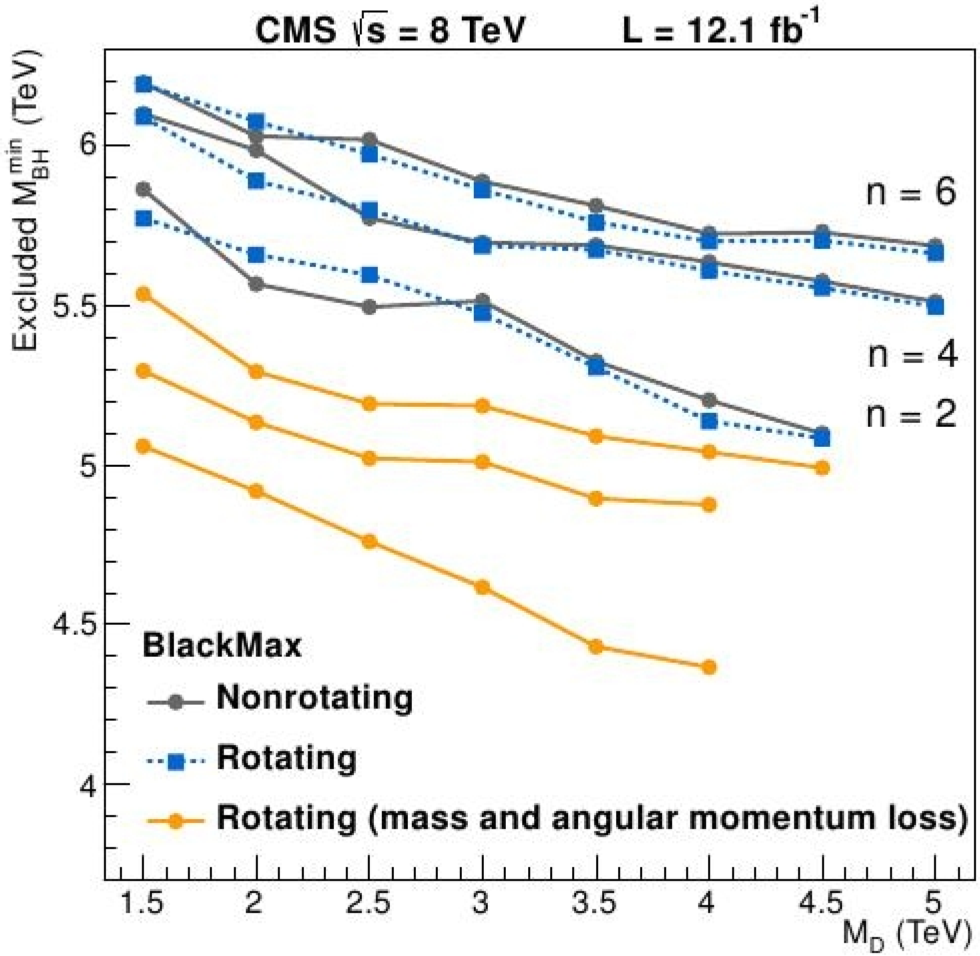
CMS-EXO-12-009, arXiv:1303.5338, jhep 07 (2013) 158

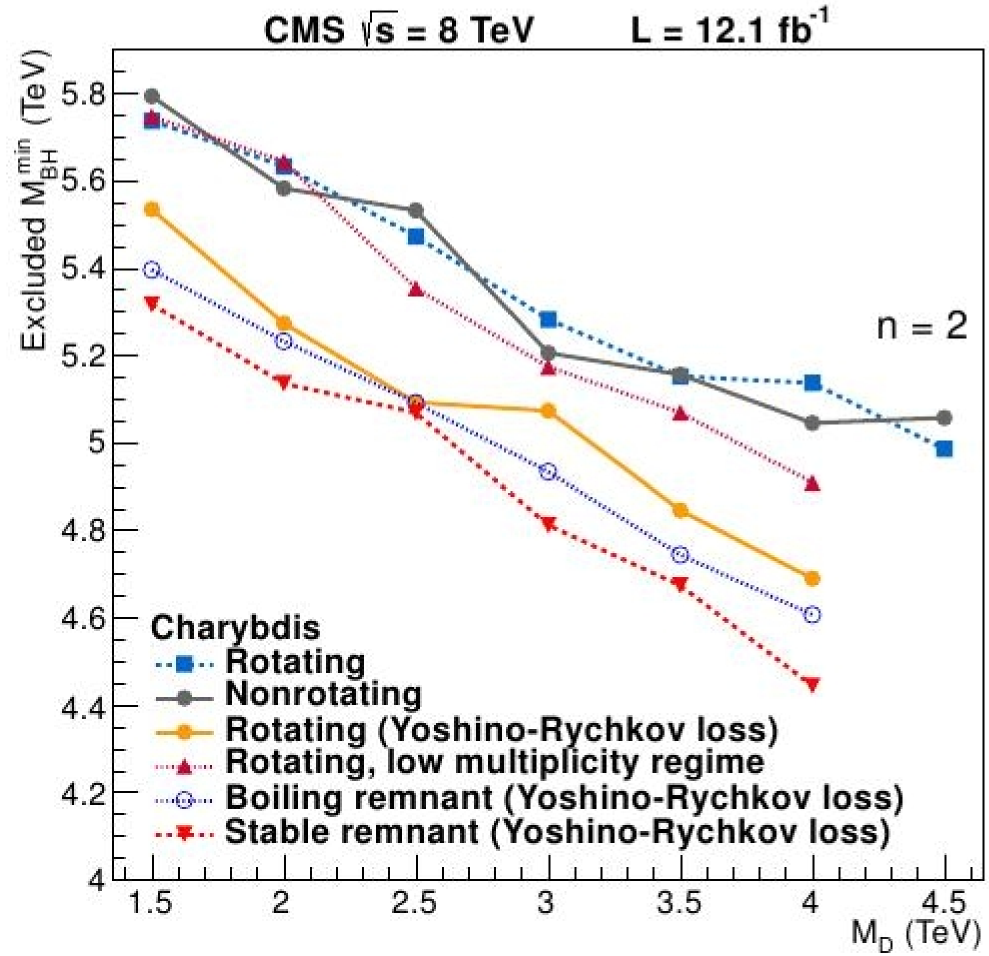



$S_T$ = scalar sum of transverse energies of all final-state objects in the event (i.e. jets, leptons and photons)

# black holes

CMS-EXO-12-009, arXiv:1303.5338, jhep 07 (2013) 158



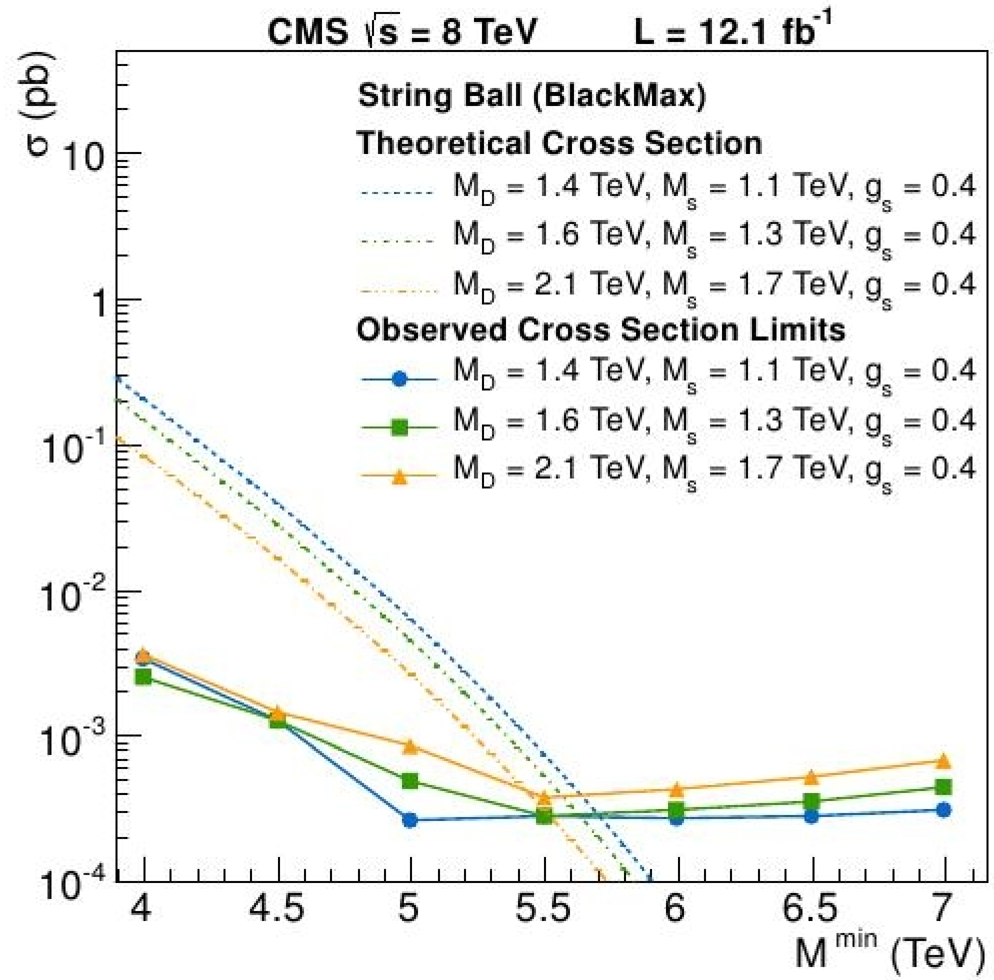



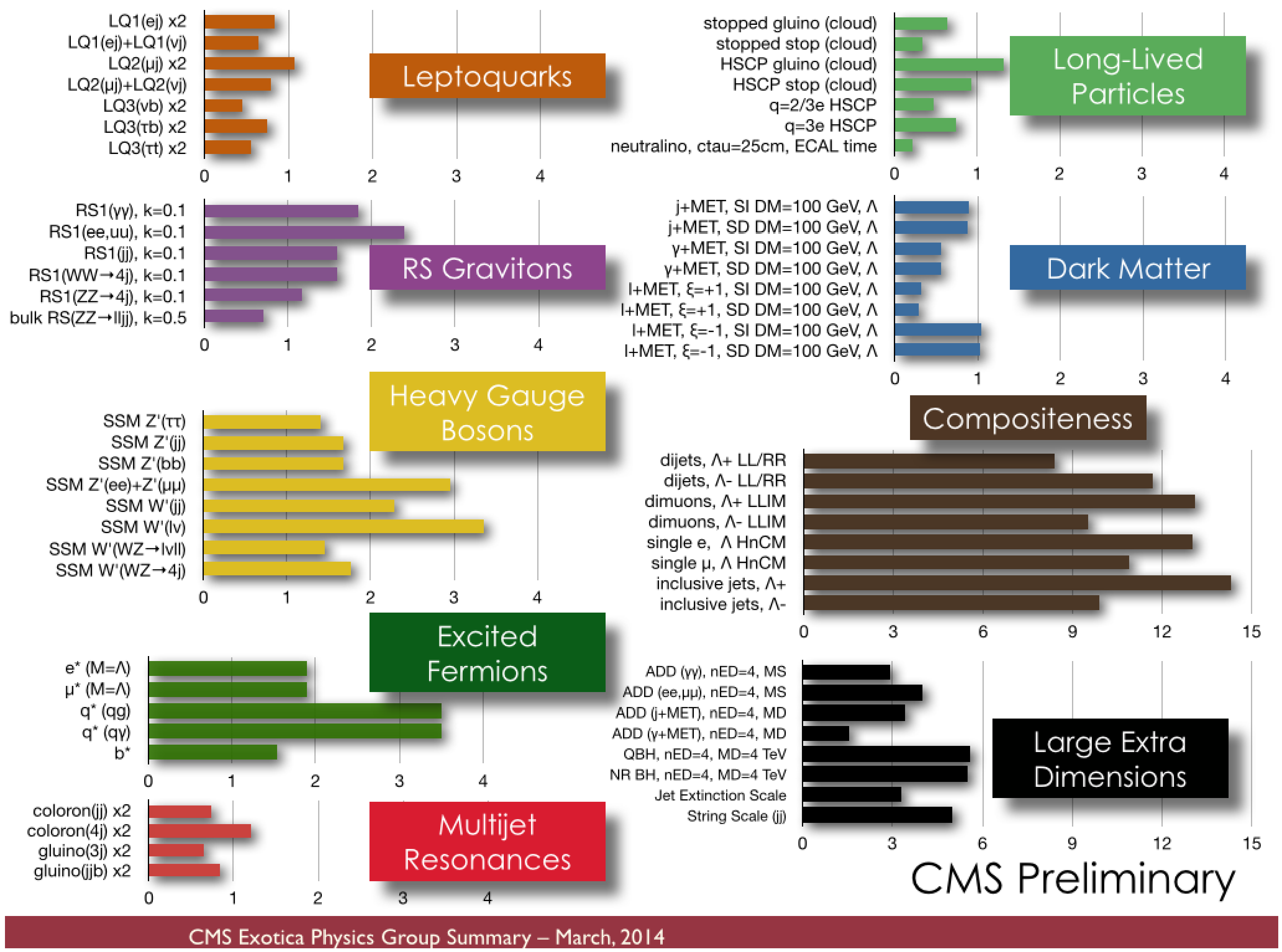

95 % CL lower limits on BH mass as a function of $M_D$

area below the curves are excluded

# black holes

CMS-EXO-12-009, arXiv:1303.5338, jhep 07 (2013) 158






https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults

# Some propects at ILC

## ADD direct

# mono photon production

most sensitive

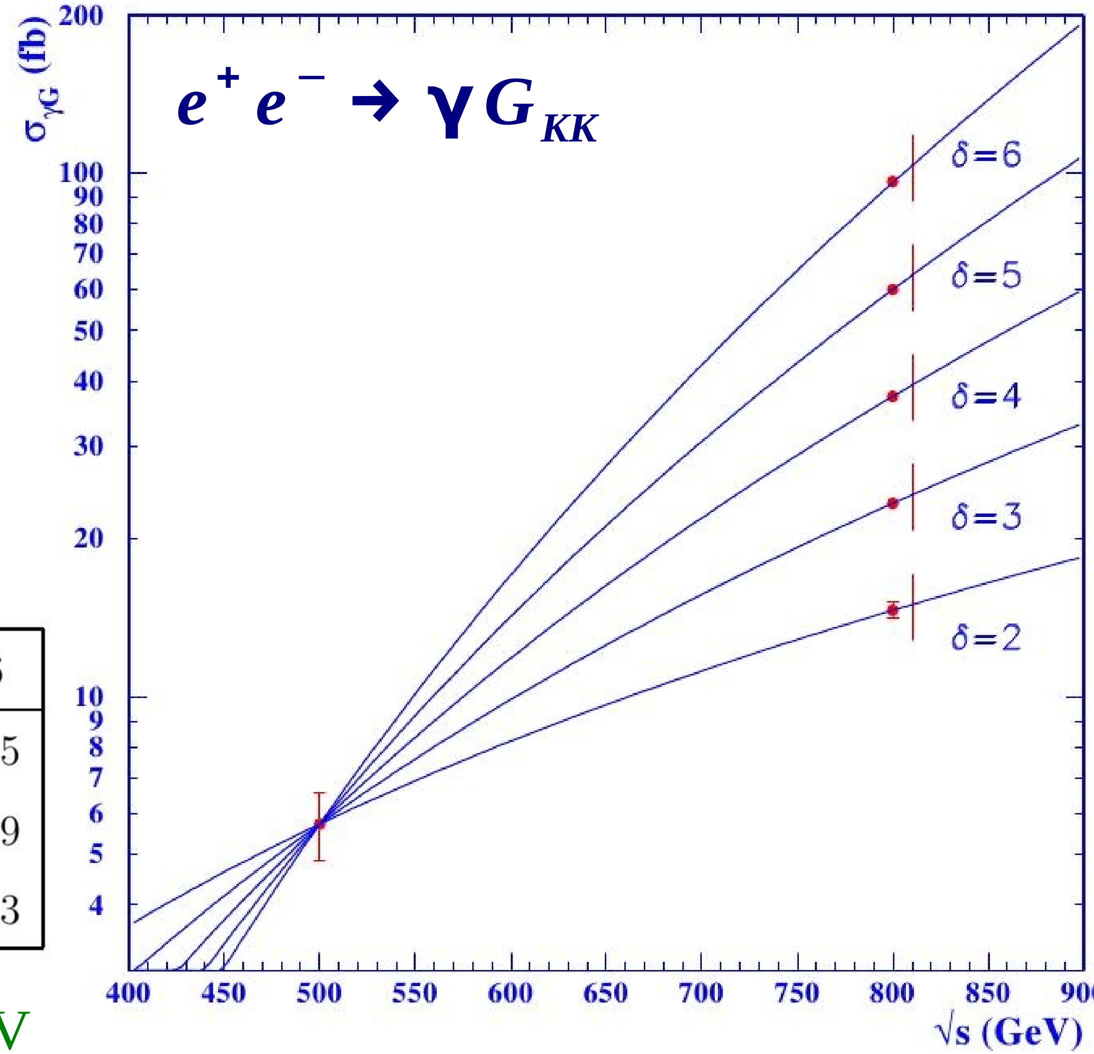
background from $e^+e^- \to \nu\bar{\nu}\gamma$

(with dominant $W^+W^-$ intermediate state)

measured directly by modifying beam polarization

| $\delta$ | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|
| $M_D(P_{-,+}=0)$ | 5.9 | 4.4 | 3.5 | 2.9 | 2.5 |
| $M_D(P_-=0.8)$ | 8.3 | 5.8 | 4.4 | 3.5 | 2.9 |
| $M_D(P_-=0.8, P_+=0.6)$ | 10.4 | 6.9 | 5.1 | 4.0 | 3.3 |

sensitivity on $M_D$(TeV) at $\sqrt{s}=800$ GeV




signal cross section normalized to a common value at $\sqrt{s}=500$ GeV

Aguilar Saavedra et al. ,hep-ph/0106315

Rizzo,arXiv:1003.1698

# ADD indirect

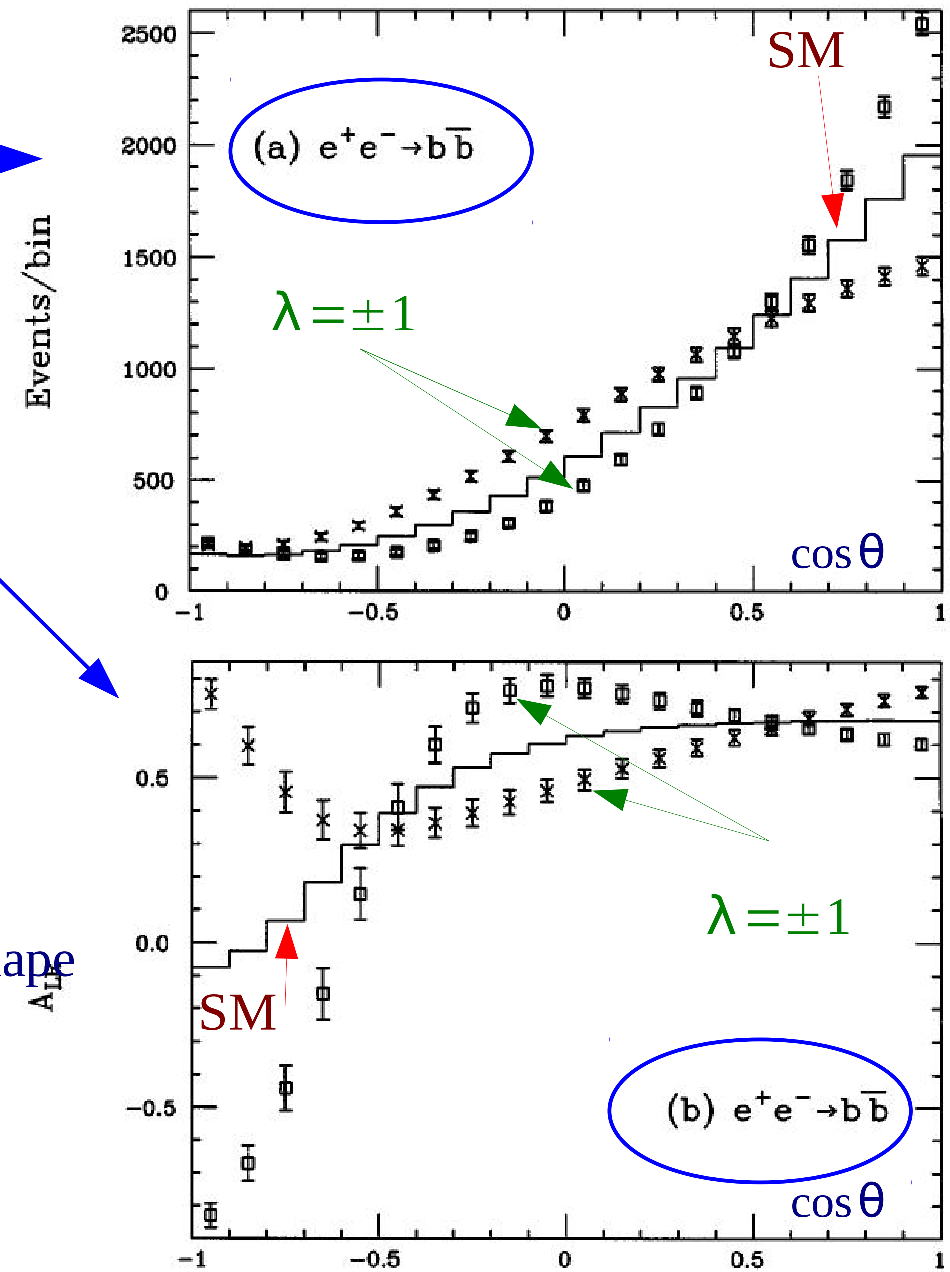
$e^+ e^- \rightarrow f \bar{f}$

angular distribution

$\cos\theta$ dependent left-right asymmetry
(if polarized beams are available)

assuming : 60 % b-tagging efficiency
90 % electron beam polarization
75 $\text{fb}^{-1}$ of integrated luminosity

KK graviton exchanges do not have the $1 + \cos^2\theta$ shape
that is typical of the SM or any spin-1 exchange




Hewett, PRL 82 (1999) 4765

# ADD indirect

summing over
$e, \mu, \tau, c, b, t$ final states
including $\tau$ polarization asymmetry

**reaches in TeV on $M_s$**

| | $\sqrt{s}$ (TeV) | $\mathcal{L}$ (fb$^{-1}$) | $\lambda = \pm 1$ |
|---|---|---|---|
| LEP II | 0.195 | 2.5 | 1.1 |
| Linear collider | 0.5 | 75 | 3.4 |
| | 0.5 | 500 | 4.1 |
| | 1.0 | 200 | 6.6 |
| Tevatron | 1.8 | 0.11 | 0.99 |
| | 2.0 | 2 | 1.3 |
| | 2.0 | 30 | 1.7 |
| LHC | 14 | 10 | 5.2 |
| | 14 | 100 | 6.0 |

Hewett, PRL 82 (1999) 4765

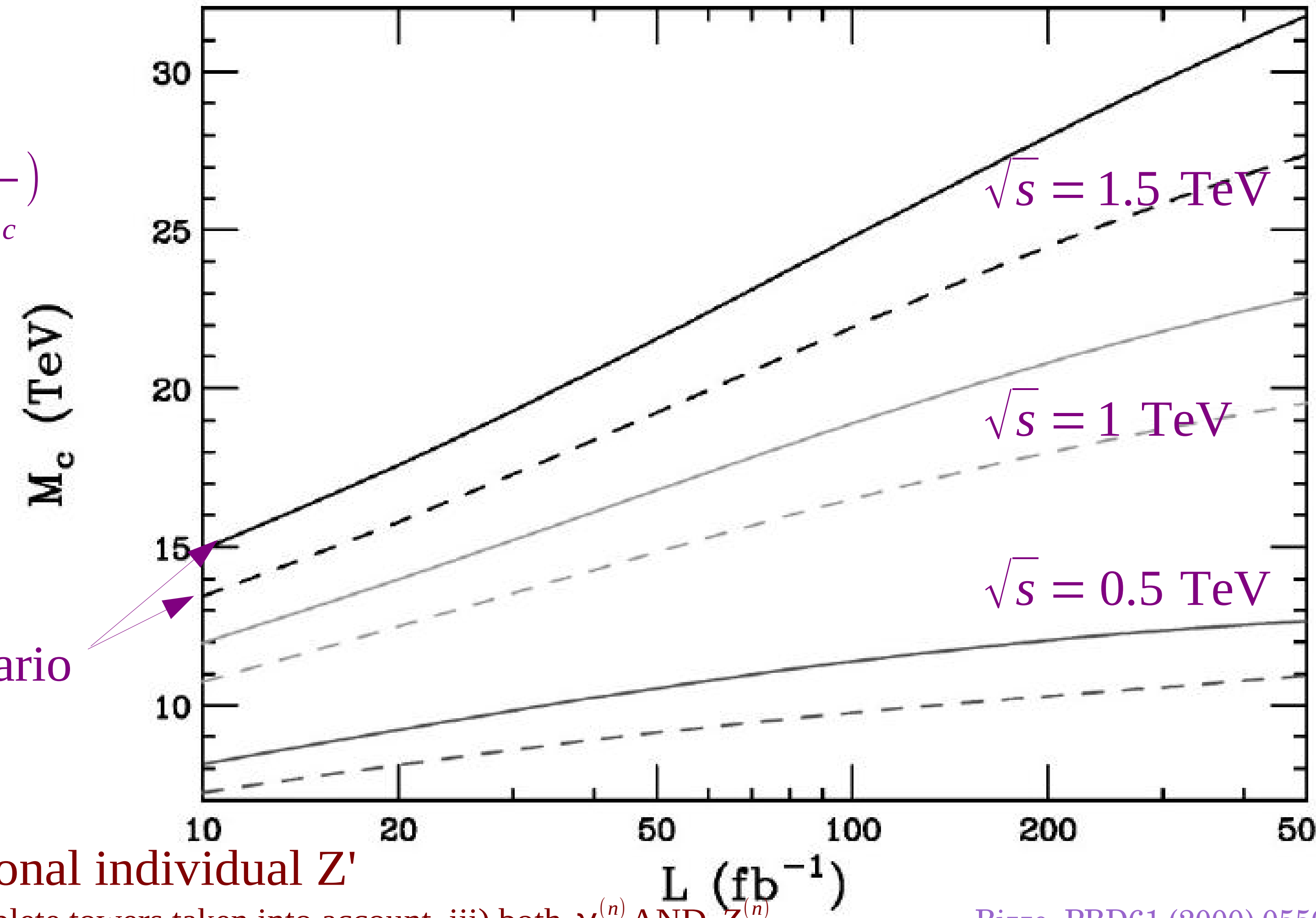
# TeV-1 extra dimensions

most likely below resonance → indirect effect

combining angular distributions and $A^f_{LR}$ measurements
using $f=e,\mu,\tau,b,c,t$ and assuming 90% beam polarization

reach in $M_c$ (TeV) $\left(\propto \frac{1}{R_c}\right)$

with various coupling scenario




reach greater than conventional individual Z'

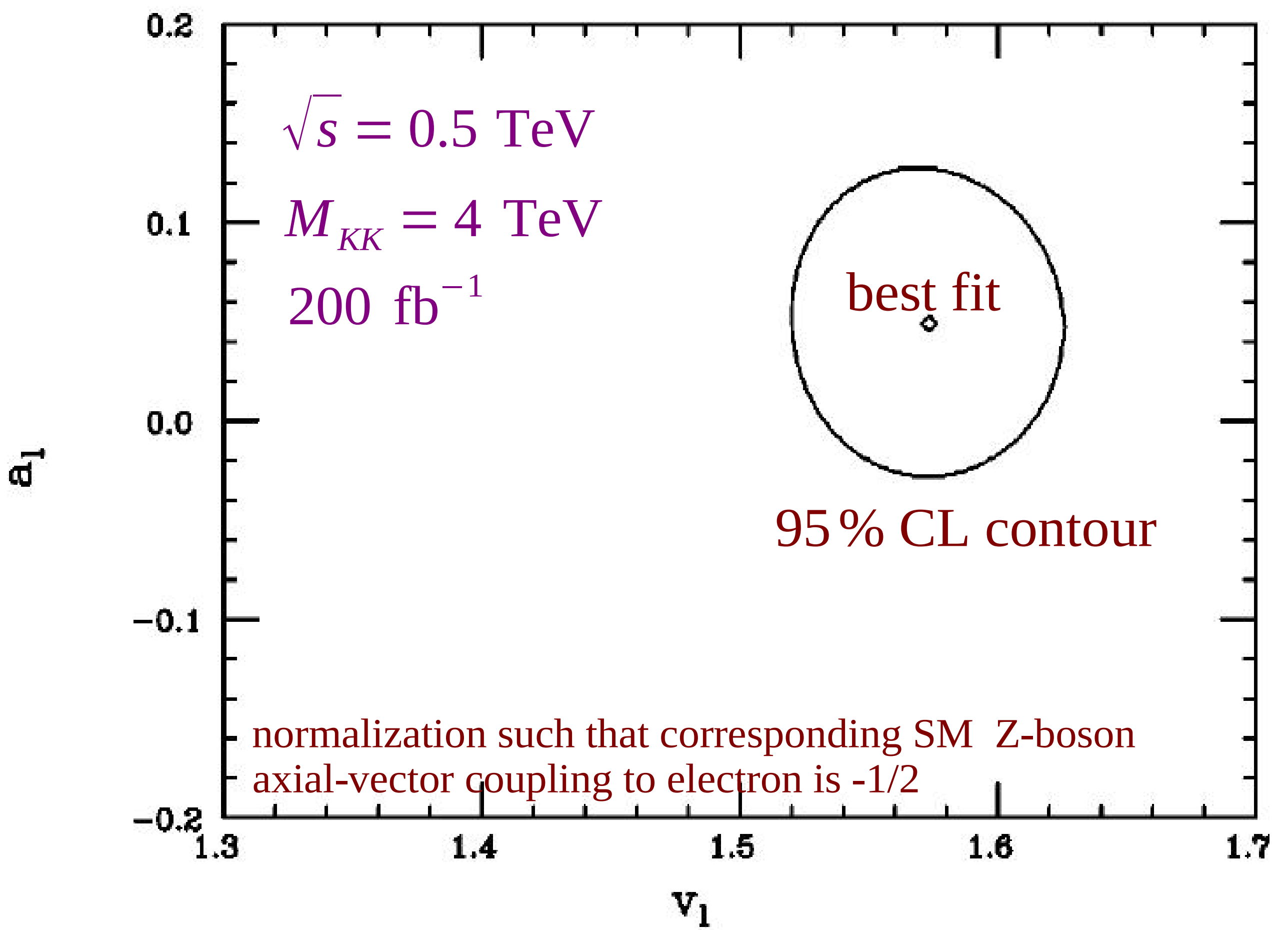
⇒ i) $\sqrt{2}$ coupling enhancement, ii) complete towers taken into account, iii) both $\gamma^{(n)}$ AND $Z^{(n)}$

Rizzo, PRD61 (2000) 055005

# TeV-1 extra dimensions

if resonance mass is known from elsewhere (e.g. LHC)

⇒ couplings to fermions can be 'precisely' measured
for example using $A_{LR}^{f=e,\mu\tau}$




Rizzo, PRD61 (2000) 055005

# string states influences

## influence on KK states production $e^+ e^- \to \gamma G_{KK}$

stringy correction → enhancement of rate for graviton emission processes (by a common factor)

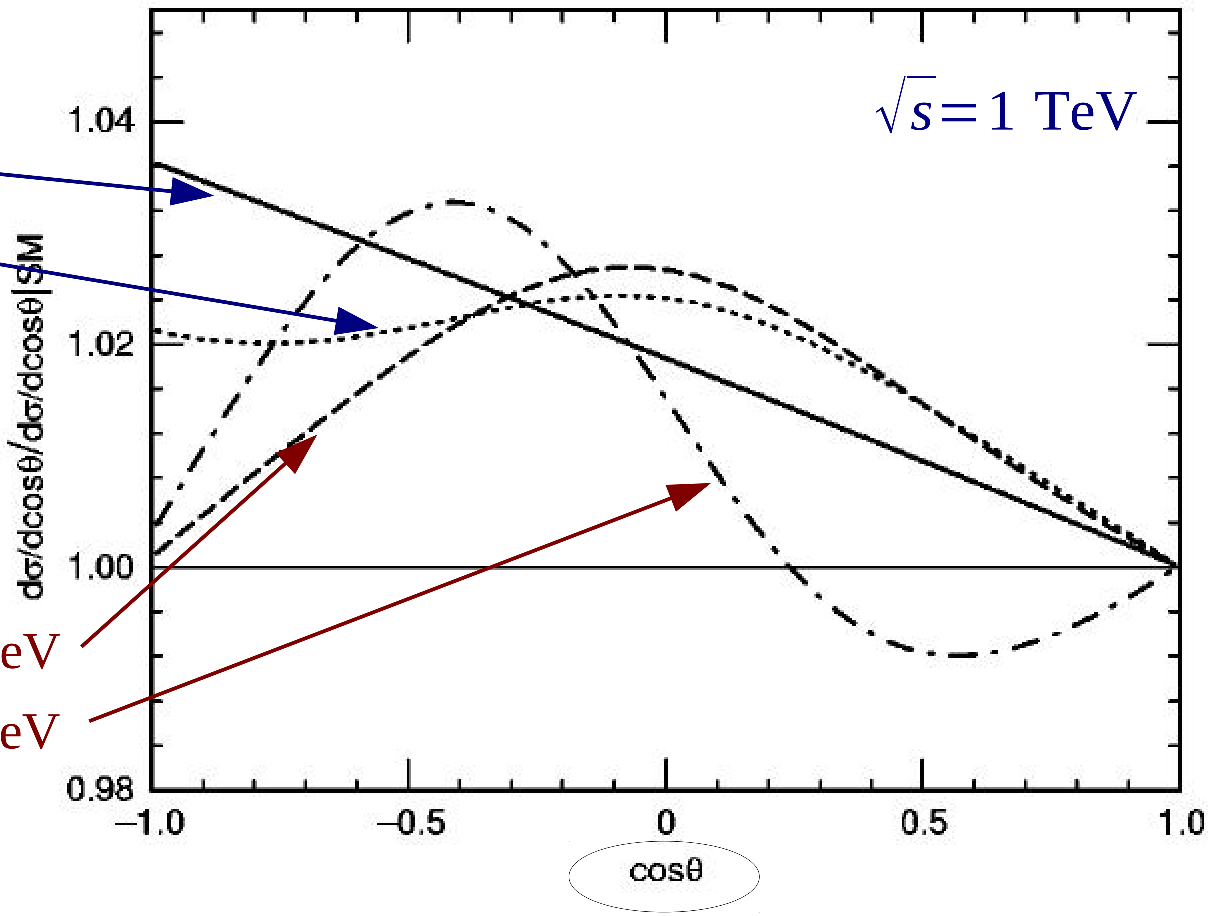
## influence on Bhabha scattering $e^+ e^- \to e^+ e^-$

string states with $M_s = 3.1$ TeV

KK exchange with $M_{\text{Hewett}} = 6.2$ TeV

VV contact interactions with $\Lambda = 88$ TeV

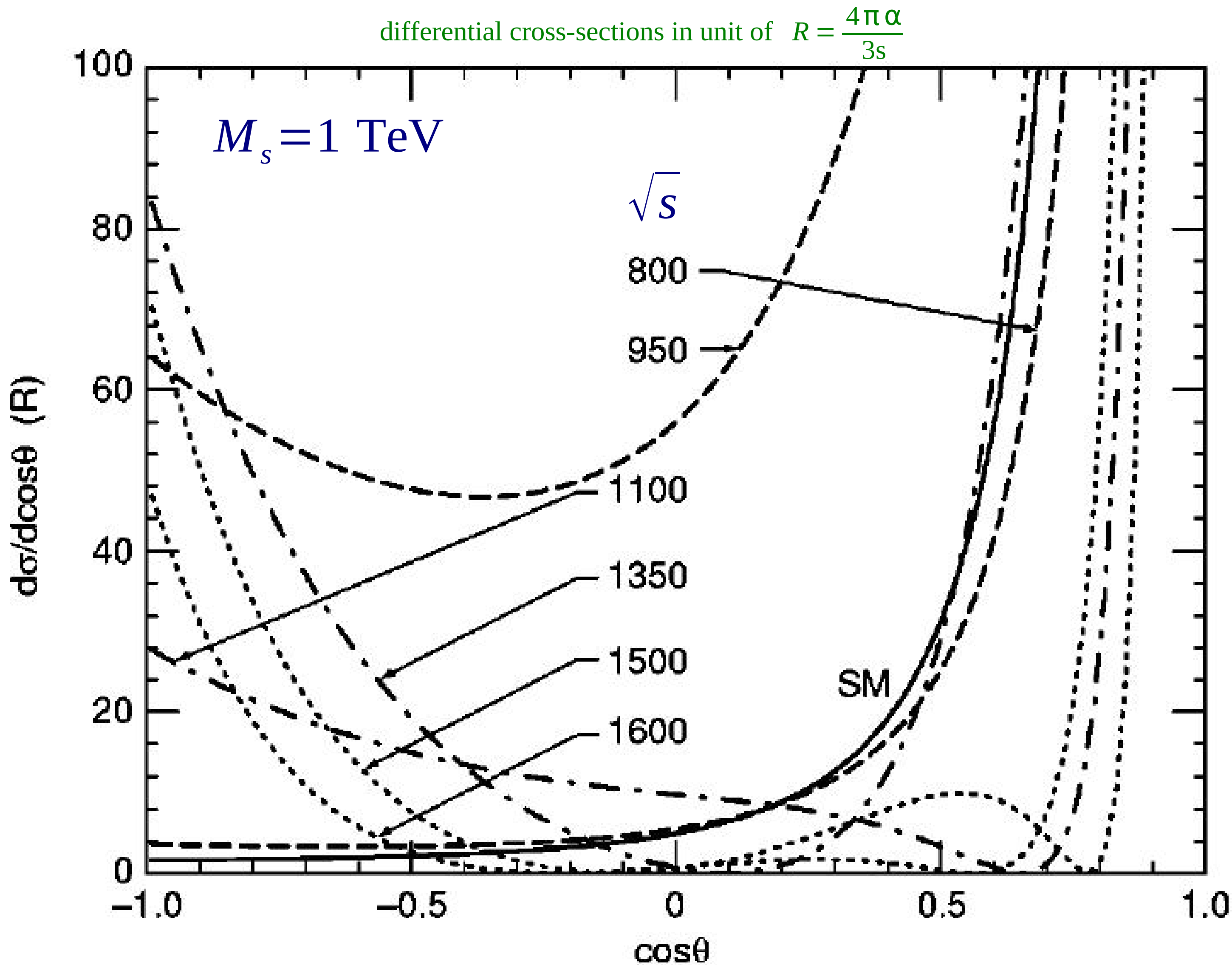
AA contact interactions with $\Lambda = 62$ TeV




Cullen, Perelstein, Peskin, PRD 62 (2000) 055012

# string states

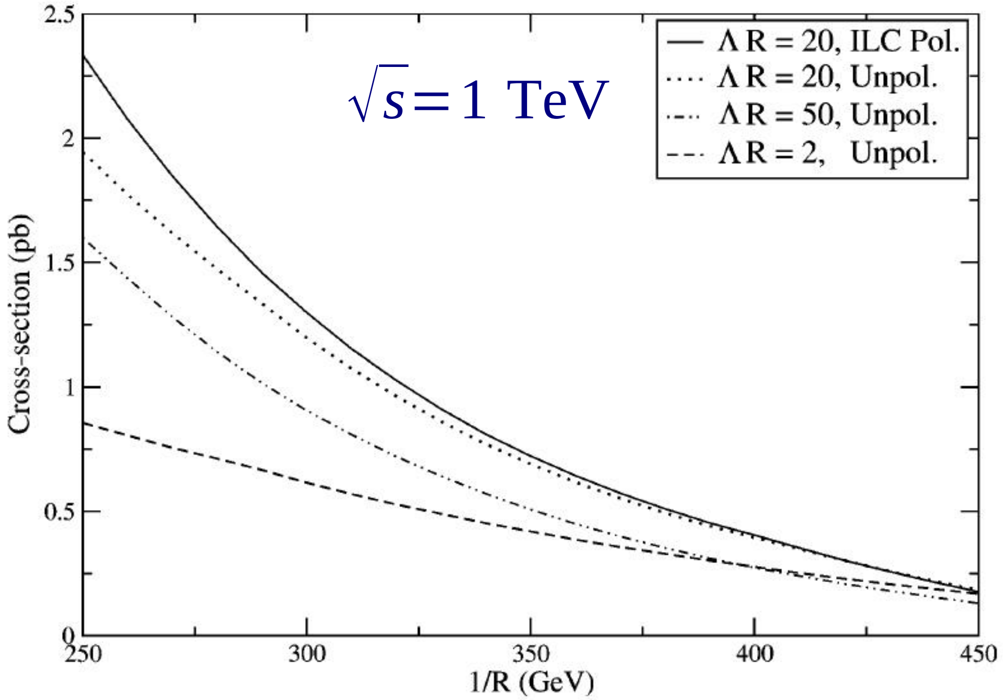
## string states influence on Bhabha scattering $e^+ e^- \to e^+ e^-$



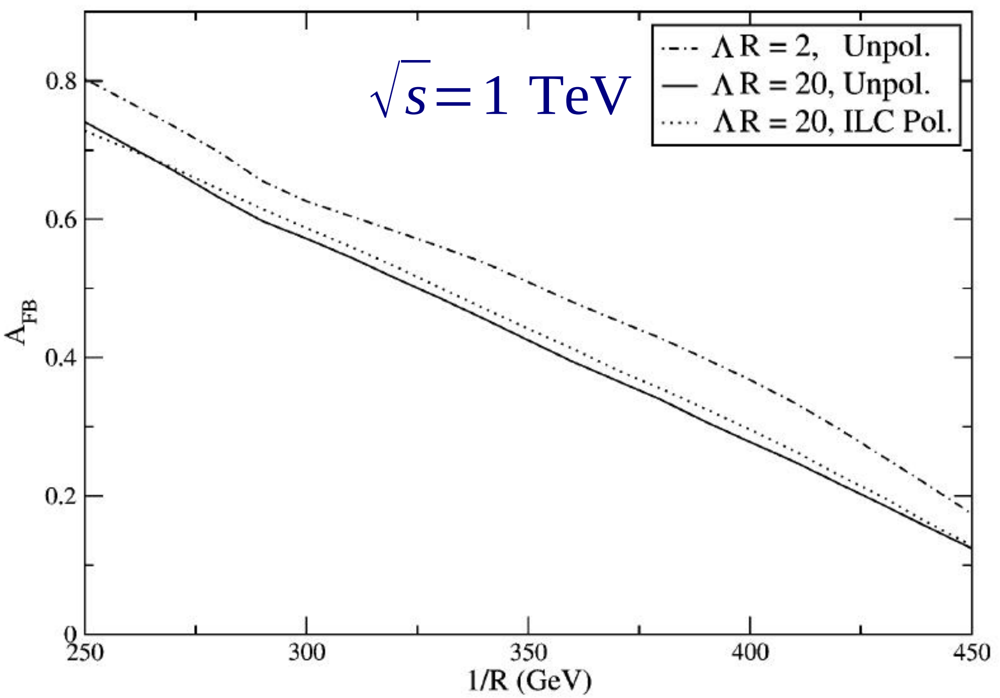

Cullen, Perelstein, Peskin, PRD 62 (2000) 055012

# UED

$e^+e^- \rightarrow e_{KK}^{(1)+} e_{KK}^{(1)-} \rightarrow \gamma_{KK}^{(1)}\ e^+\ \gamma_{KK}^{(1)}\ e^-$ i.e. $e^+e^- + \text{MET}$ final state




cross section as a function of $\frac{1}{R}$

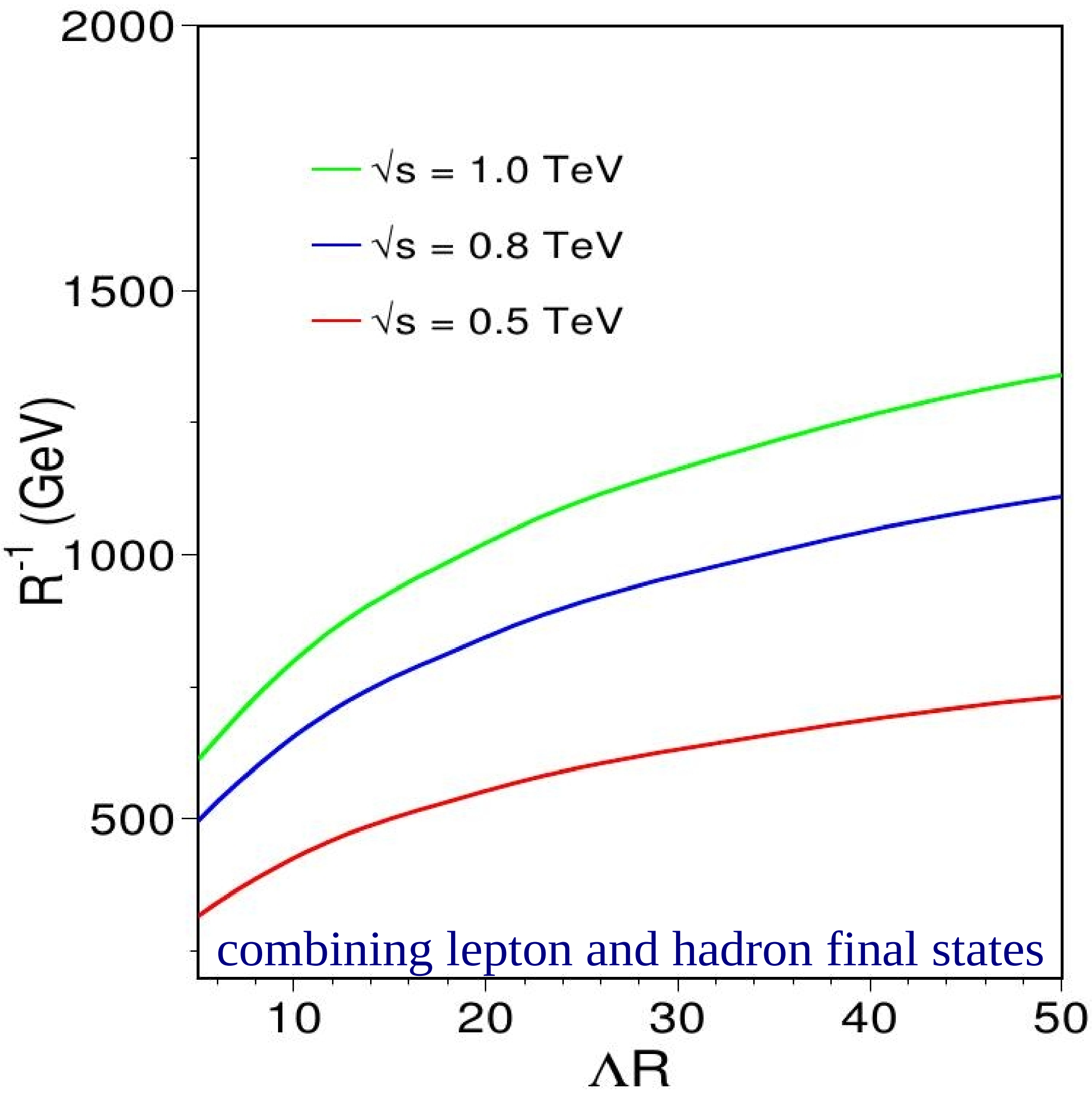



$A_{FB}$ as a function of $\frac{1}{R}$

Bhattacharyya, Dey, Kundu, Raychaudhuri, PLB 628 (2005) 141

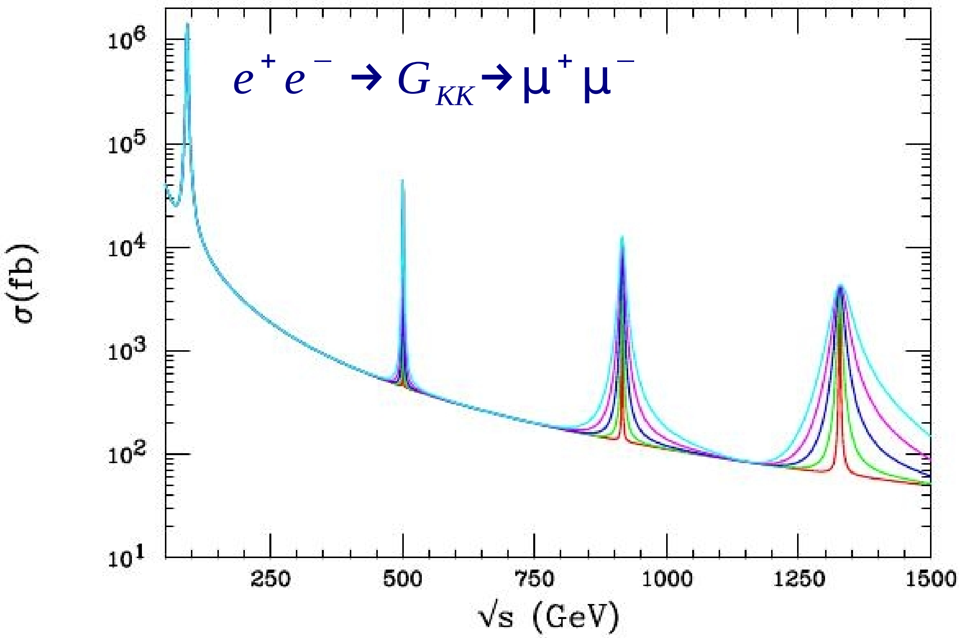
# UED

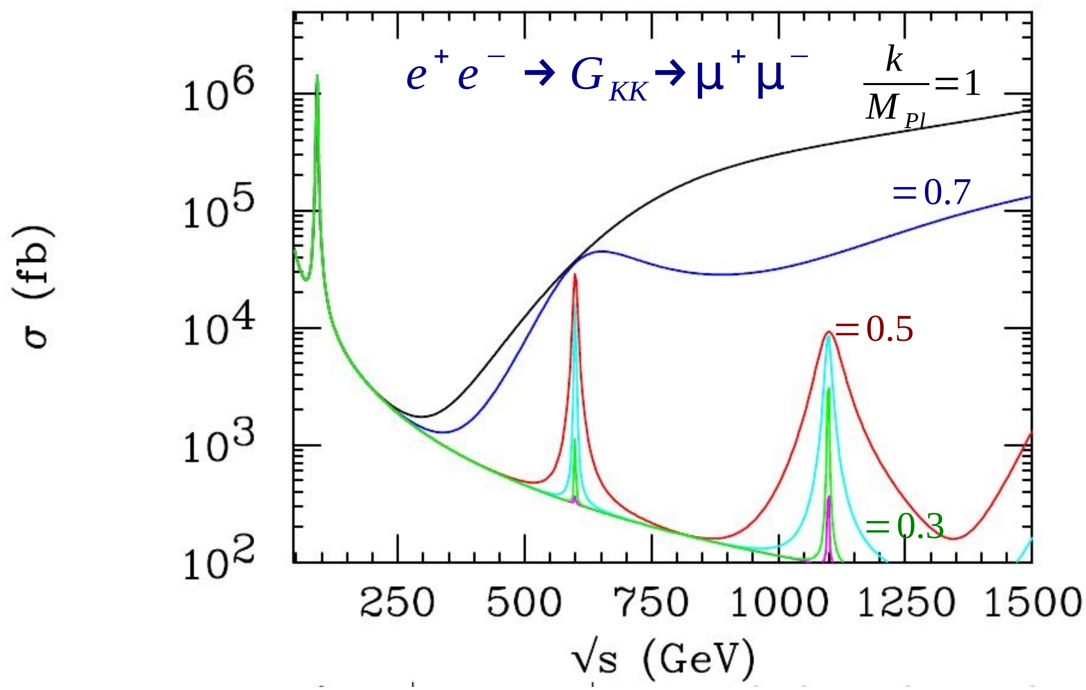
KK level 2 gauge boson exchange in $e^+e^- \rightarrow f\bar{f}$ with KK-number violating coupling




Riemann, eConf C 050318 (2005)0303, hep-ph/0508136

# RS approaches




indirect effect if below resonance

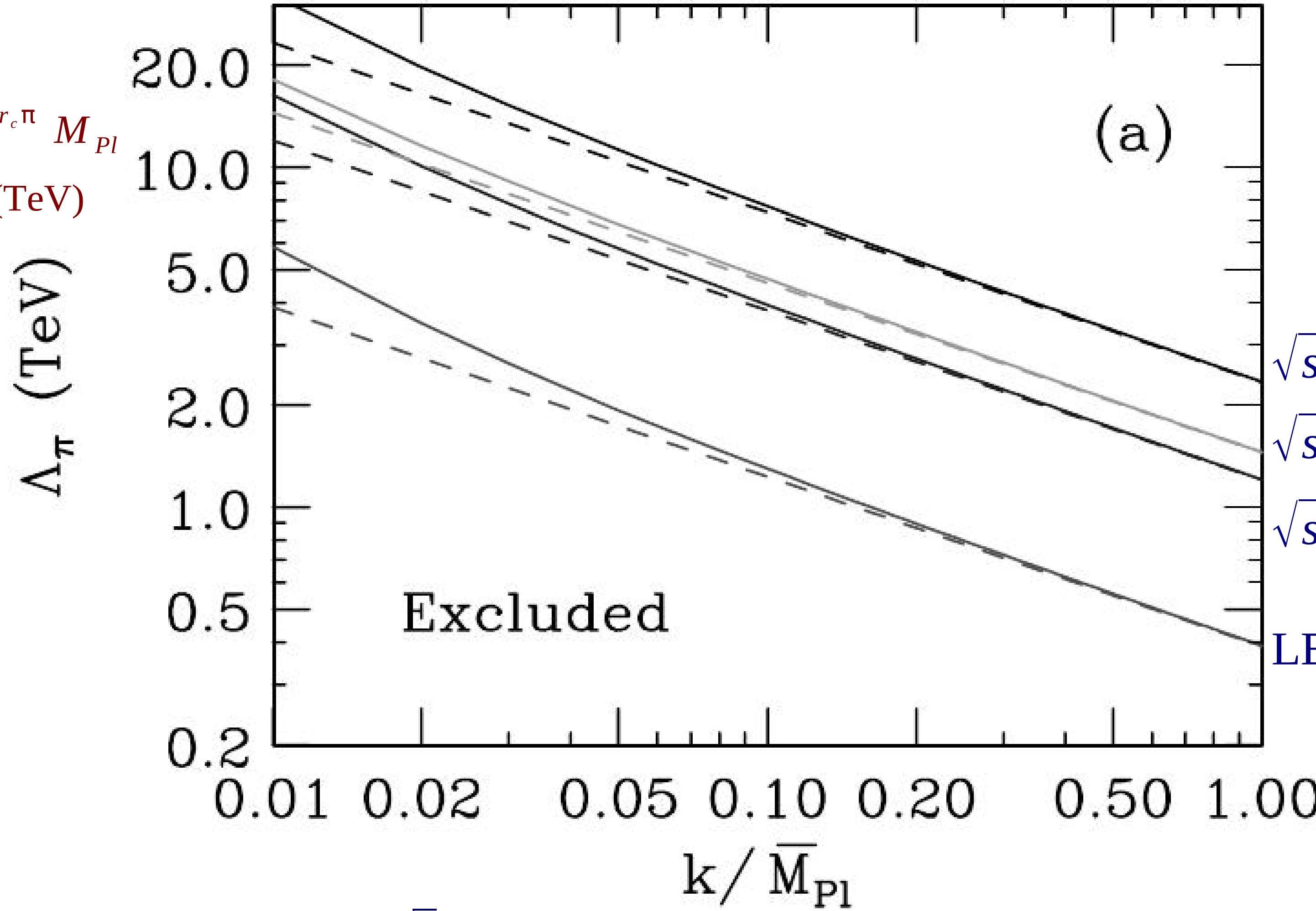
Aguilar Saavedra et al. ,hep-ph/0106315

# RS approaches

## sensitivity via virtual effects

from angular distributions, using (when applicable)
$e$, $\mu$, $\tau$, $c$, $b$, $t$ and 90% beam polarization

$\Lambda_\pi = e^{-kr_c\pi} M_{Pl}$
$\sim$ O(TeV)




$\sqrt{s} = 1\,\text{TeV},\ 200\,\text{fb}^{-1}$

$\sqrt{s} = 0.5\,\text{TeV},\ 500\,\text{fb}^{-1}$

$\sqrt{s} = 0.5\,\text{TeV},\ 75\,\text{fb}^{-1}$

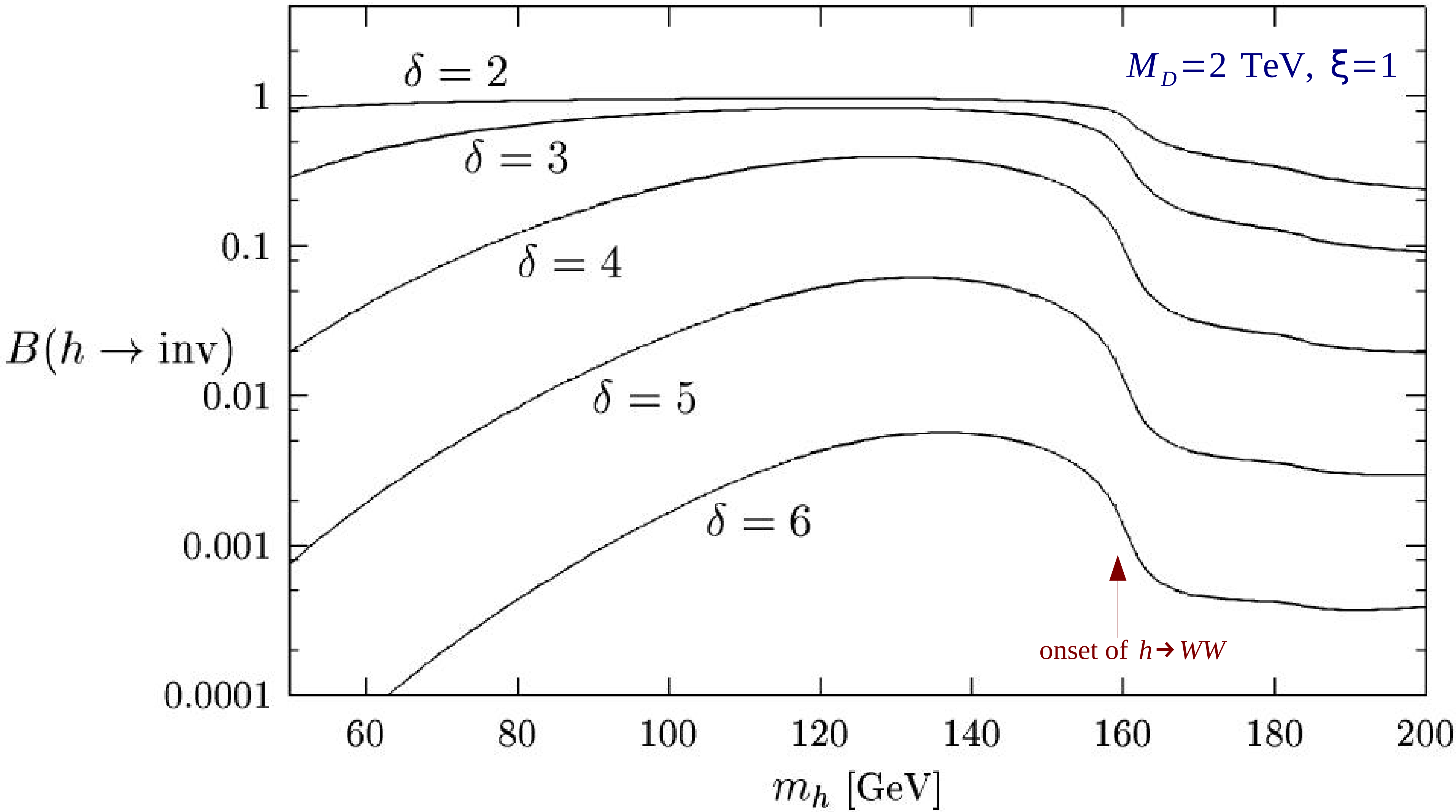
LEP II exclusion

dashed curves : $M_{G_{KK}} >> \sqrt{s}$
solid curves : 2 first excitations close to $\sqrt{s}$

Davoudiasl, Hewett, Rizzo PRL 83 (2000) 2080

# Higgs-graviscalars mixing

Higgs-graviscalars (only 1 in RS i.e. the radion) mixing and invisible Higgs decay




Giudice, Rattazzi, Wells, NPB 595 (2001) 250

see also Kubota, Nojiri, arXiv:1404.3013

# summary

- present constraints from LHC8 and future contraints (discovery ?) from LHC13 have (will have) profound impact on the searches for for extra dimension at ILC

- few room left for direct searches at ILC polarization is very important in the few applicable cases

- ILC with polarization is good at measurements of indirect effects (ADD, TEV-1, RS)

- precision measurements of Higgs invisible width very important per se to explore some extra dimensions scenarii

# BACKUP

# Extra dimensions phenomenology

K .R. Dienes, TASI lectures 2002

C. Csaki, TASI lectures 2002, hep-ph/0404096

A. Muck, diplomarbeit, 2001

Pioneering articles of (see specific references later on) :
I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G. Dvali
R.K. Dienes, E. Dudas, T. Ghergetta
I. Antoniadis, K. Benakli, M. Quiros
L. Randall, R. Sundrum
W.D. Goldberger, M.B. Wise
T. Appelquist H.S. Cheng, B.A. Dobrescu

G.F. Giudice, R. Rattazzi, J.D. Wells NPB 544 (1999)

M.B. arXiv1005.2755, Acta Phys. Polon. B36 (2005) 3487 and CR phys. 4 (2003) 319

and references therein !

# Some historical milestones

- 1914 G. Nordström : Maxwell equations in 5D recovering 4D EM + gravity
- 1915 A. Einstein, D. Hilbert : general relativity (GR) in 4D
- 1918 H. Weyl : attempt to use its geometrical formulation to unify EM and gravity leading to the gauge invariance concept
- 1919-1921 T. Kaluza : Einstein-Hilbert theory in 5D leading to Maxwell-Einstein theory
- 1926 O. Klein : Schrödinger equation in a 5D framework
- 1938 P. Bergmann, A. Einstein : emphasize the link between compactification and (abelian) gauge symmetry
- 1938 O. Klein : Einstein-Hilbert theory in more than 5D leading to the notion of non abelian gauge symmetry (Yang Mills 1954)

extra dimensions linked to the concept of unification of forces (gravity and EM) from the beginning

even more so in the context of supersymmetry, supergravity and superstrings

# Some historical milestones

- 1971-1974 P. Ramond (2D), A. Neveu, J. Gervais, B. Sakita, L. Susskind and Y. Golfand, E. Likhtman, D. Volkov, A. Akulov and then J. Wess, B Zumino, P. Fayet, **beginning of supersymmetry**
  (see also W. Heisenberg, L. Okun, R.M. Weiner in the 60's)

- 1974 J. Scherk, J. Schwarz, **beginning of string theories** for the description of the gravitational interaction
  (see also G. Veneziano 1968)

- 1976 V. A. Soroka, S. Deser, D.Z. Freedman, S. Ferrara, P. Van Nieuwenhuizen, B Zumino, **beginning of supergravity**

- 1978 E. Cremmer, B. Julia, J. Scherk, **11D supergravity**

- 1974-1984 26D **strings** and 10D **superstrings** developments
  (type I and type Iia and IIb)

-1984 10D **heterotic superstrings** (SO(32) and E8xE8)

$\longrightarrow$ 5 known 10D superstrings theories in total

# Some historical milestones

- 1990 I. Antoniadis : possible **extra dimensions at TeV scales**

  from consideratioins on superstrings in the non perturbative regime and supersymmetry breaking)

- 1995 C.M. Hull, P.K. Townsend M. J. Duff, E. Witten, J. Dai, R.G. Leigh, J. Polchinski C. Bachas,

  **dualities** (T-Duality het SO(32)/het E8xE8, S-Duality type I/het SO(32)) and

  **branes** (D-brane for type I and type II)

- 1996 E. Witten from duality arguments string scale not fixed at the Planck mass anymore but arbitrary (1 order of magnitude lower)

- 1996 P. Horava and E. Witten, Horava-Witten theory

  (11D bulk and 2 10D branes addressing susy breaking issues i.e. susy broken in one brane and transmitted to the other brane via bulk)

- 1996 J. Lykken : if string (fundamental) scale is arbitrary why not push it down to TeV values10D

- 1998 renewal of the idea of extra dimensions at TeV scale for low energy phenomenological purposes then for more

# ADD direct searches

G.F. Giudice et al. / Nuclear Physics B 544 (1999) 3–38

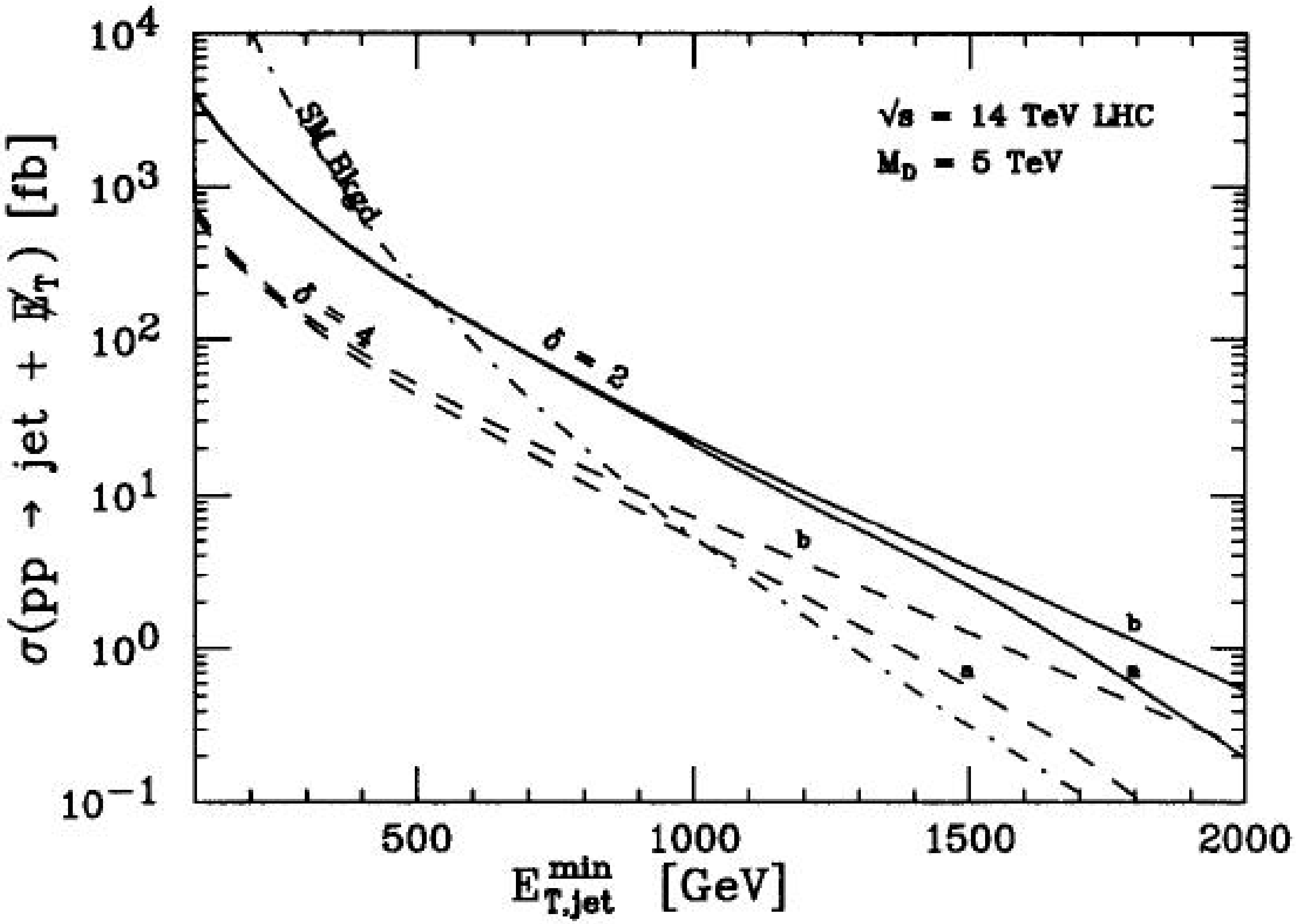



Fig. 3. The total jet + nothing cross section at the LHC integrated for all $E_{T,\mathrm{jet}} > E^{\mathrm{min}}_{T,\mathrm{jet}}$ with the requirement that $|\eta_{\mathrm{jet}}| < 3.0$. The Standard Model background is the dash-dotted line, and the signal is plotted as solid and dashed lines for fixed $M_D = 5\,\mathrm{TeV}$ with $\delta = 2$ and 4 extra dimensions. The **a** (**b**) lines are constructed by integrating the cross section over $\hat{s} < M_D^2$ (all $\hat{s}$).

# ADD direct searches

G.F. Giudice et al. / Nuclear Physics B 544 (1999) 3–38

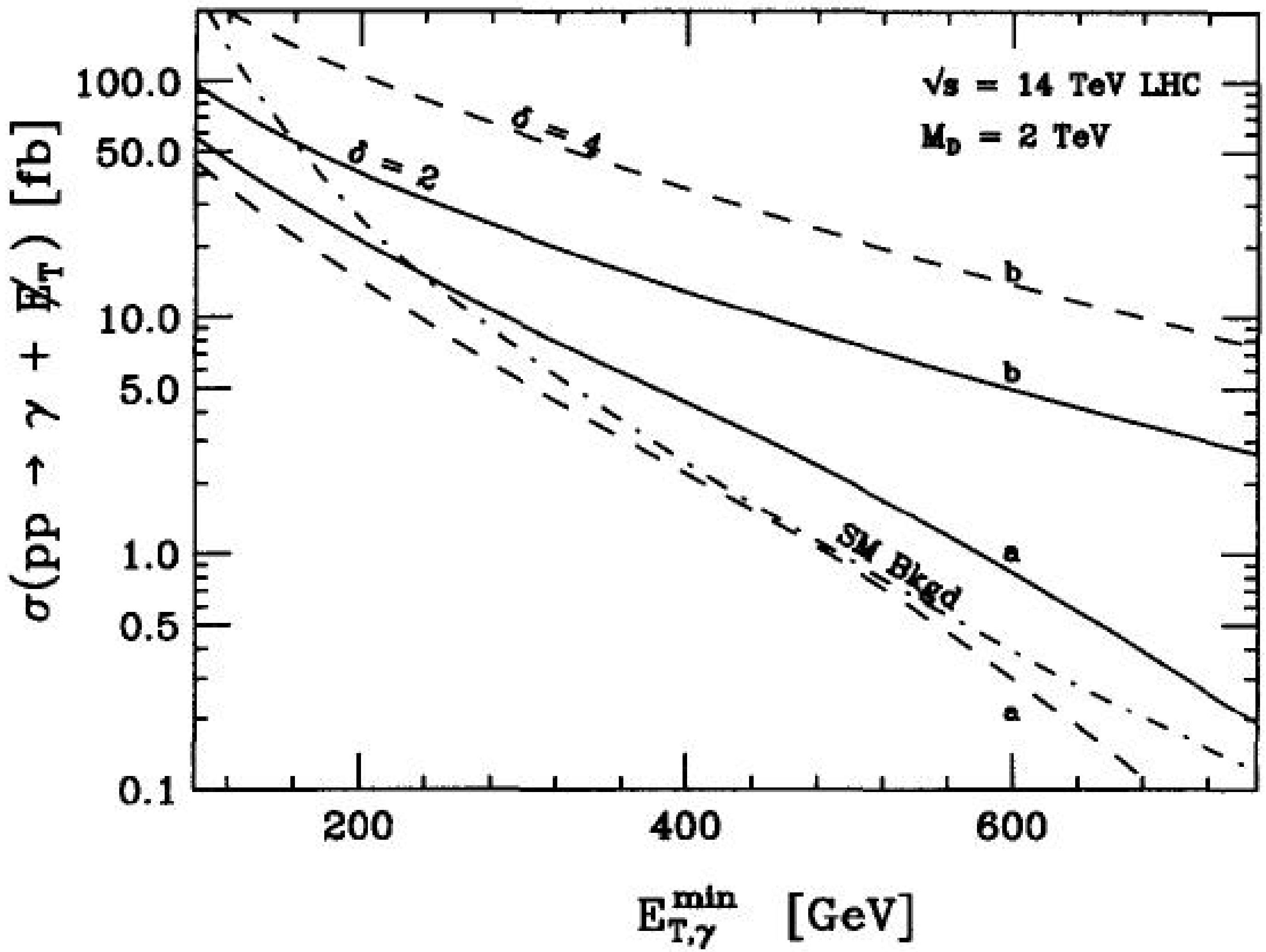



Fig. 5. The total $\gamma +$ nothing cross section at the LHC integrated for all $E_{T,\gamma} > E_{T,\gamma}^{\min}$ with the requirement that $|\eta_\gamma| < 2.5$. The Standard Model background is the dash-dotted line, and the signal is plotted as solid and dashed lines for fixed $M_D = 2\,\mathrm{TeV}$ with $\delta = 2$ and 4 extra dimensions. The **a** (**b**) lines are constructed by integrating the cross section over $\hat{s} < M_D^2$ (all $\hat{s}$).

# ADD direct searches

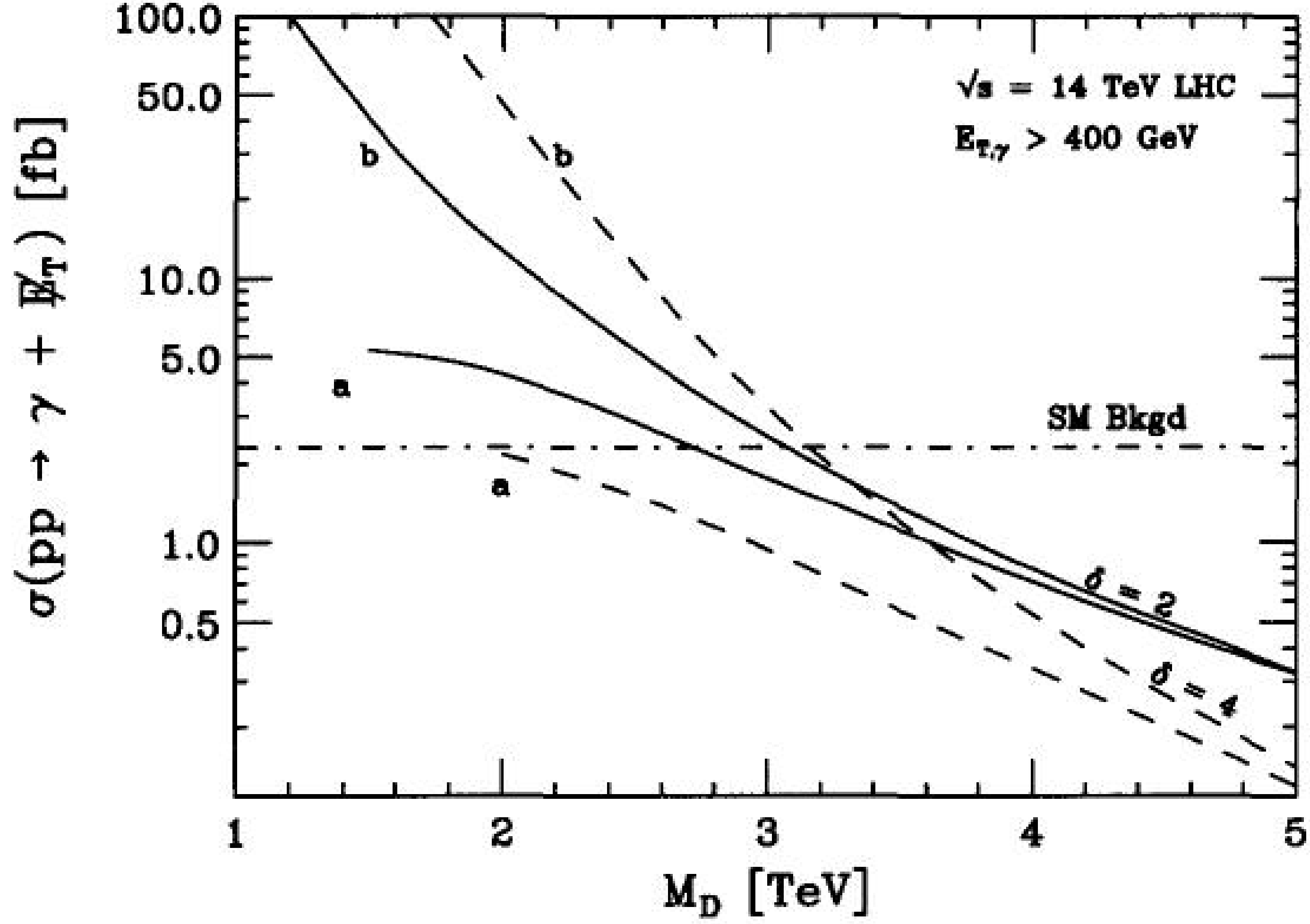



Fig. 6. The total $\gamma +$ nothing cross section versus $M_D$ at the LHC integrated for all $E_{T,\gamma} > 400\,\mathrm{GeV}$ with the requirement that $|\eta_\gamma| < 2.5$. The Standard Model background is the dash-dotted line, and the signal is plotted as solid lines for $\delta = 2$ and 4 extra dimensions. The **a** (**b**) lines are constructed by integrating the cross section over $\hat{s} < M_D^2$ (all $\hat{s}$).

# ADD indirect searches

G.F. Giudice et al. / Nuclear Physics B 544 (1999) 3–38

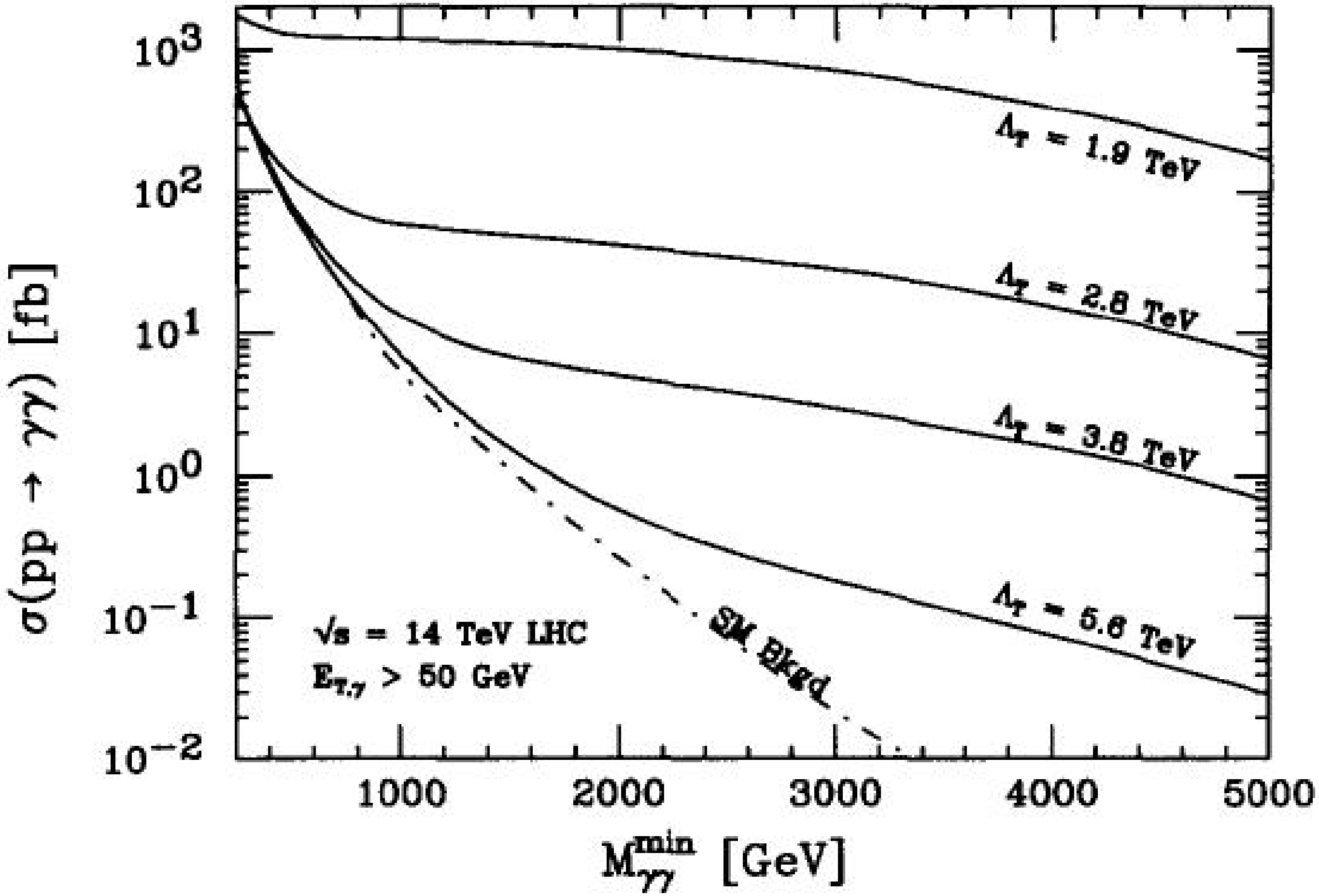
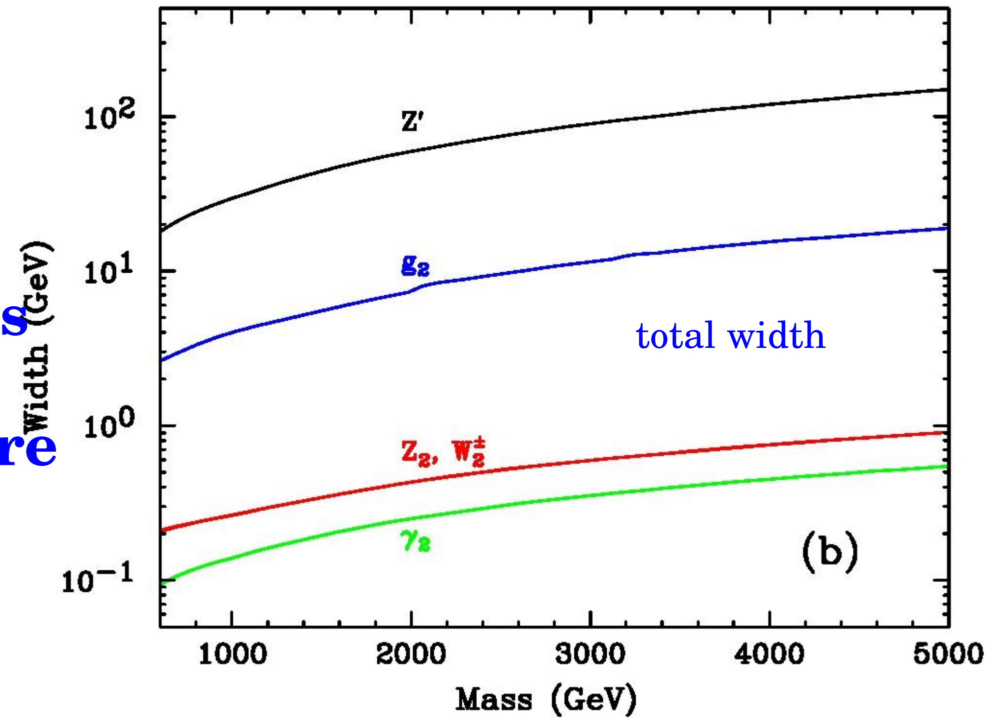



Fig. 10. The total cross section for $pp \to \gamma\gamma$ integrated for $\sqrt{\hat{s}} > M_{\gamma\gamma}^{min}$ with the requirement that $E_{T,\gamma} > 50\,\mathrm{GeV}$ and $|\eta_\gamma| < 2.5$ for each photon. The dashed line is the Standard Model background and the solid lines are the total cross sections for various values of $\Lambda_T$.

# discriminating mUED w.r.t SUSY ?



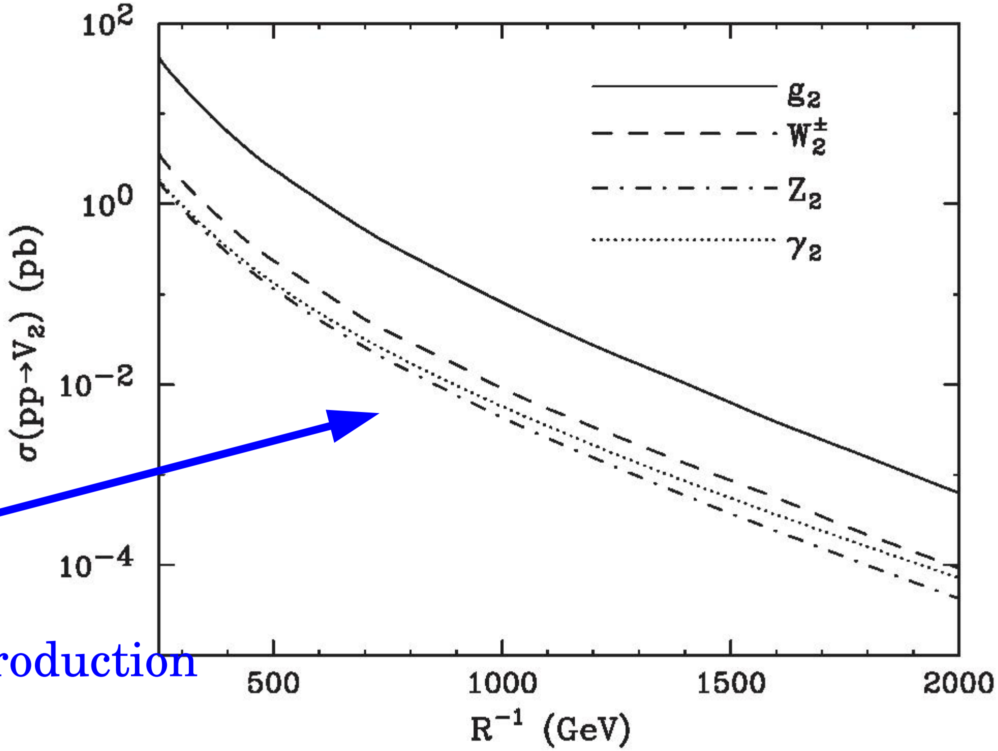

**KK gauge bosons offer good prospects**

**prospects to discover level 2 structure**

KK number conserving interactions (and KK-parity conserved) allows for

$$V_2 \rightarrow f_1 \bar{f}_1 \quad \text{or} \quad V_2 \rightarrow f_2 \bar{f}_0 = f_2 \bar{f}_{SM}$$

**level 2 KK gauge bosons have also KK number violating interaction allowing for** $V_2 \rightarrow f_0 \bar{f}_0 = f_{SM} \bar{f}_{SM}$




**i.e. single production**

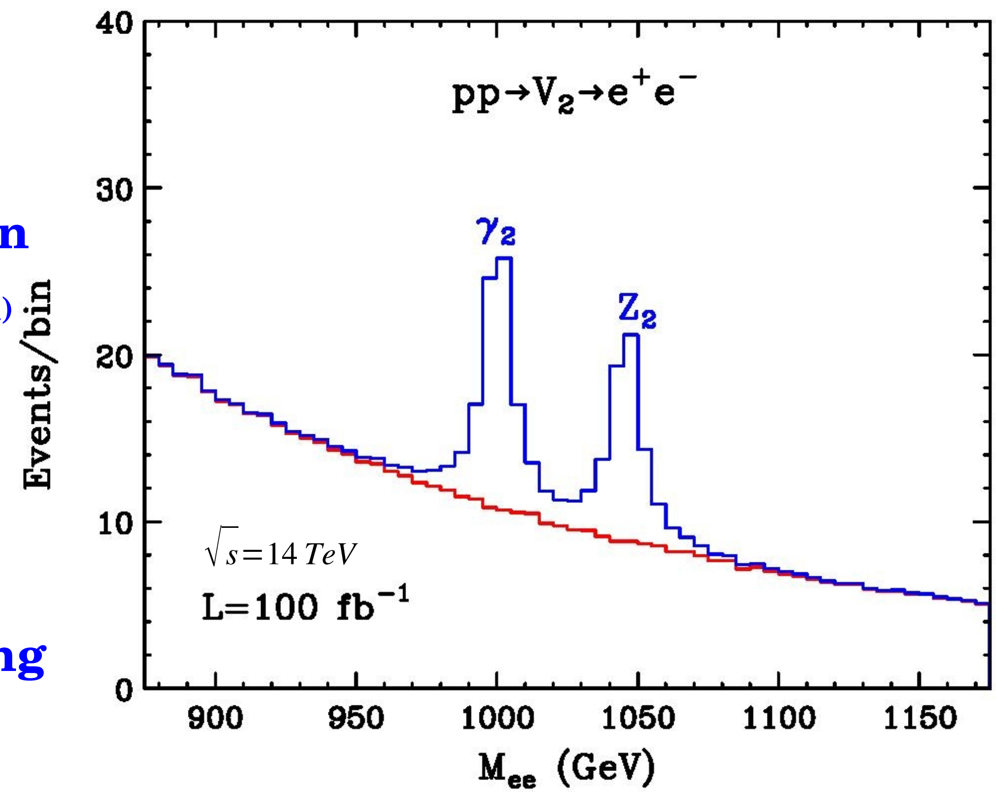
kinematically not suppressed w.r.t pair production

# mUED w.r.t SUSY ?

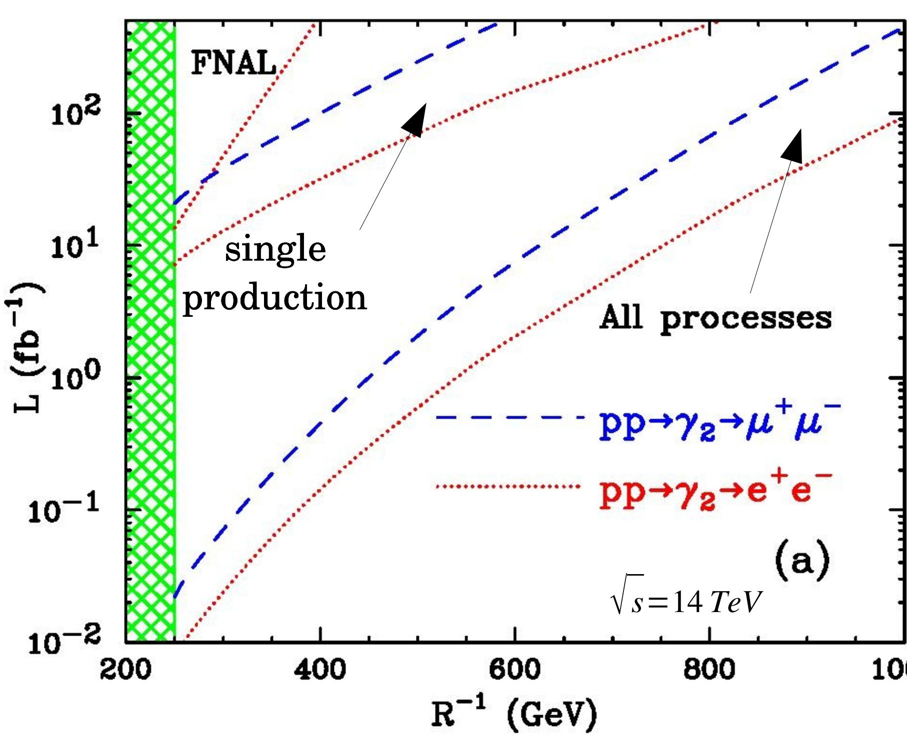
- **look for level 2 KK gauge bosons production including single production** (KK number violation)

$$pp \to V_2 \to f_0 \bar{f}_0 = f_{SM} \bar{f}_{SM}$$

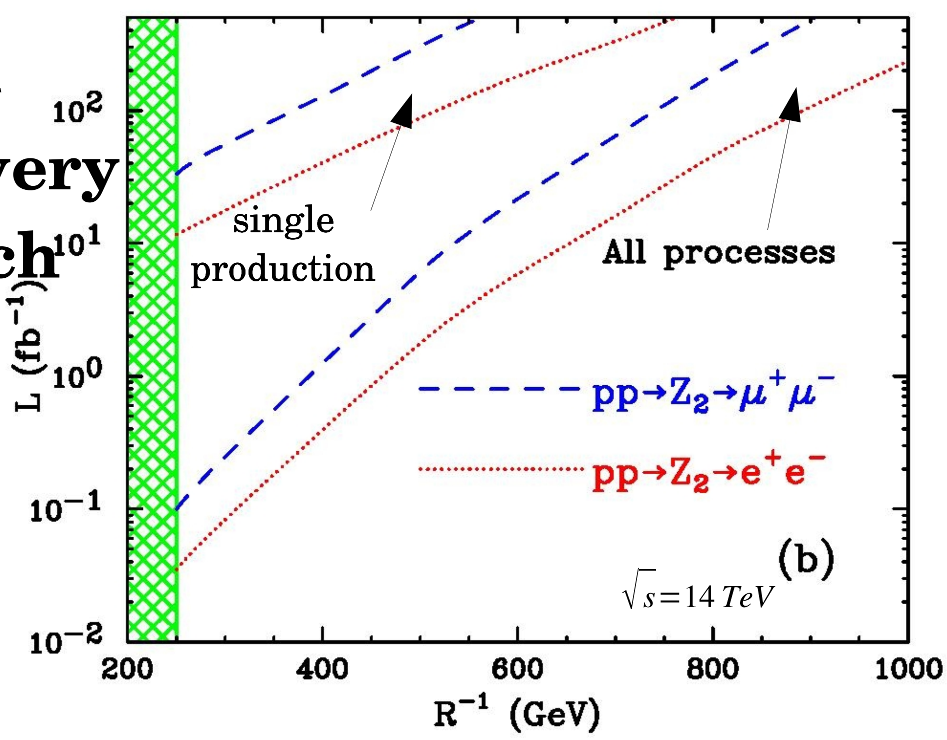
- **double peak structure in dilepton mass**
- **near mass-degeneracy further corroborating UED interpretation** w.r.t susy or Z'




Datta, Kong, Matchev, PRD75 (2005) 096006




**5σ discovery reach**

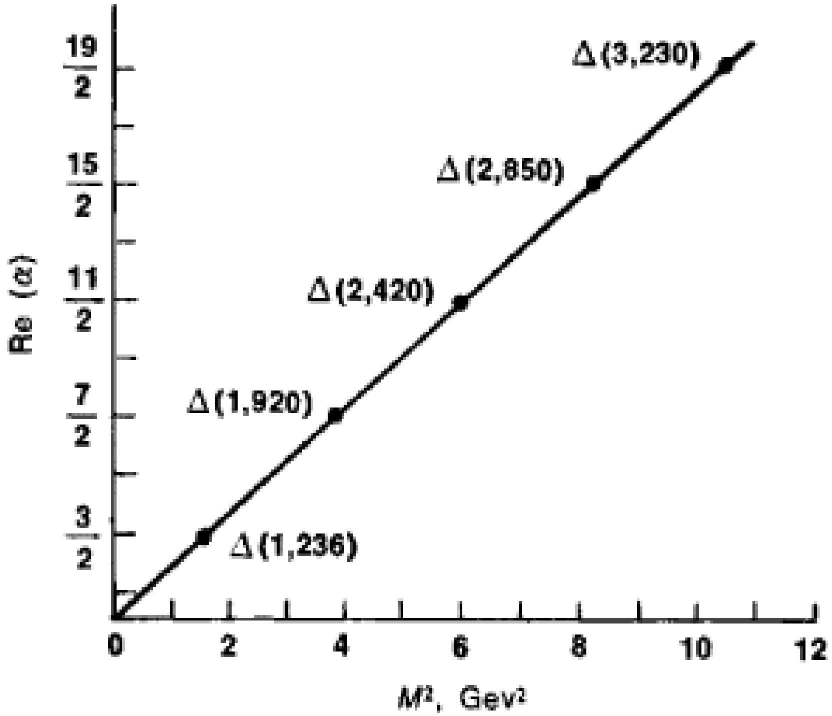


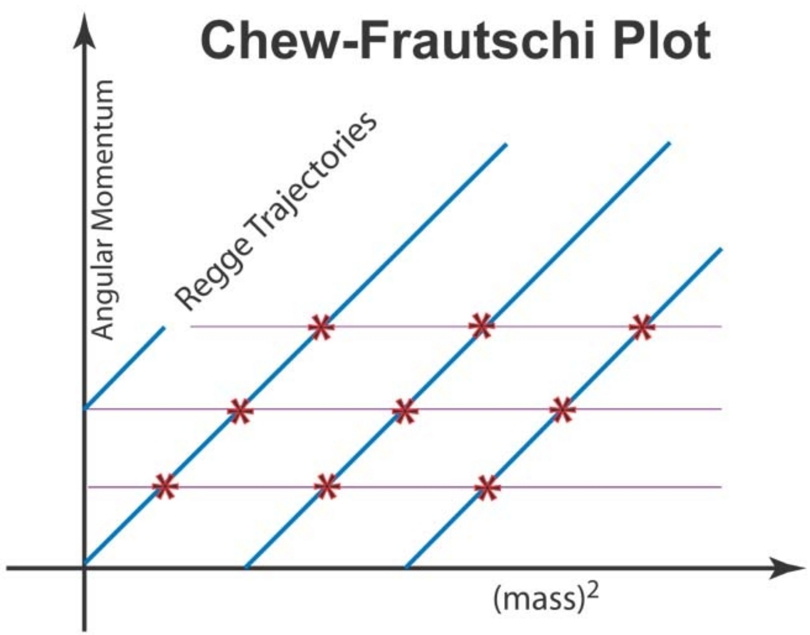
# String states

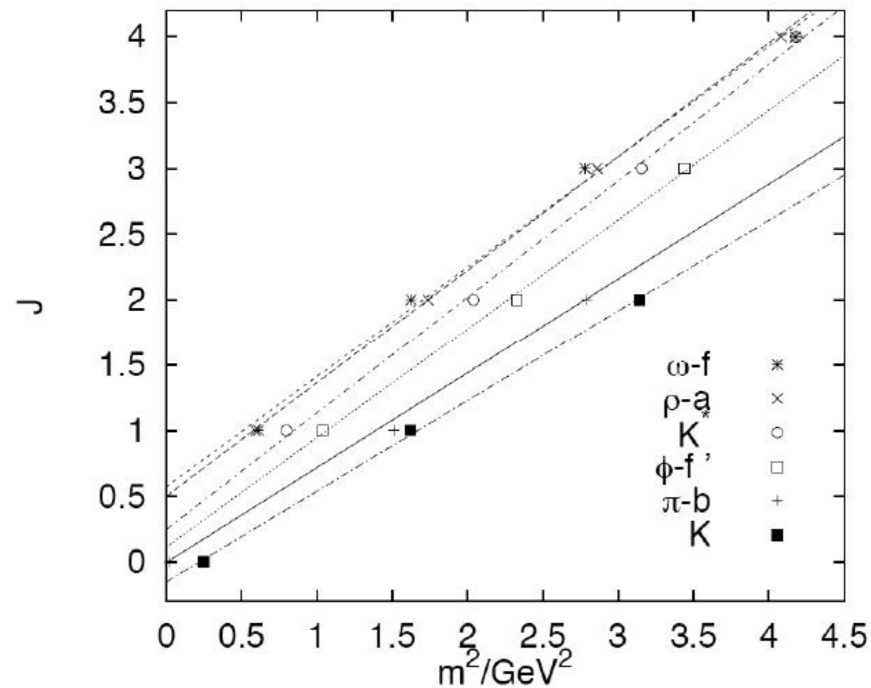
## Regge trajectories

$$\frac{J}{M^2} = \frac{1}{2\pi T} = \alpha'$$

more generally : $\alpha(s) = \alpha(0) - n + \alpha' s$

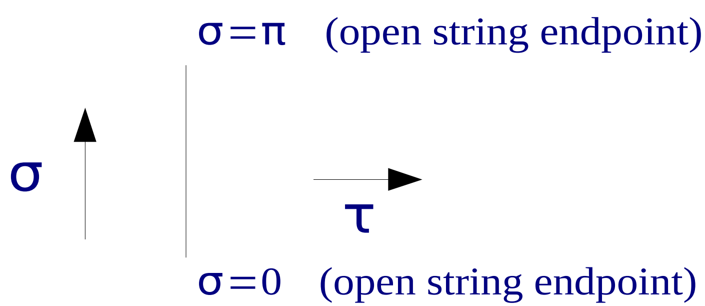


# String states

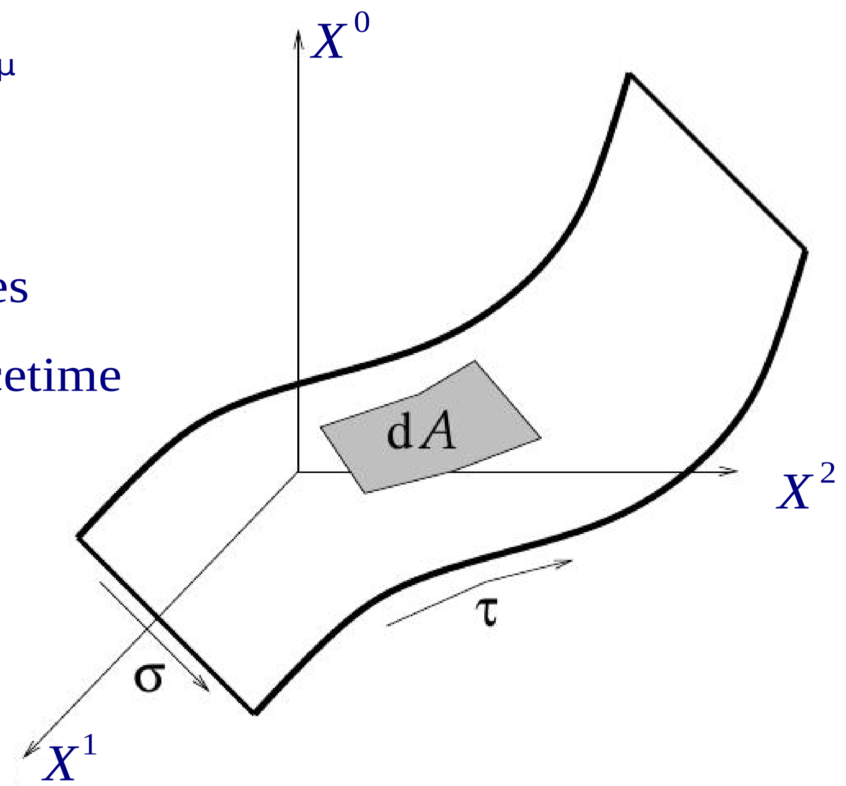
open string sweeping out a 2d worldsheet (as $\tau$ increases) parameterized by $\sigma$ and $\tau$





embedded in a D dimensional spacetime $X^\mu$

$\mu=0,1,2\ldots D-1$




string action whose variational law minimizes

the total area of the string worldsheet in spacetime

$$S=-T\int dA$$

with the string tension $T=\dfrac{1}{2\pi\alpha'}$

and string length $l_s=\sqrt{\alpha'}$

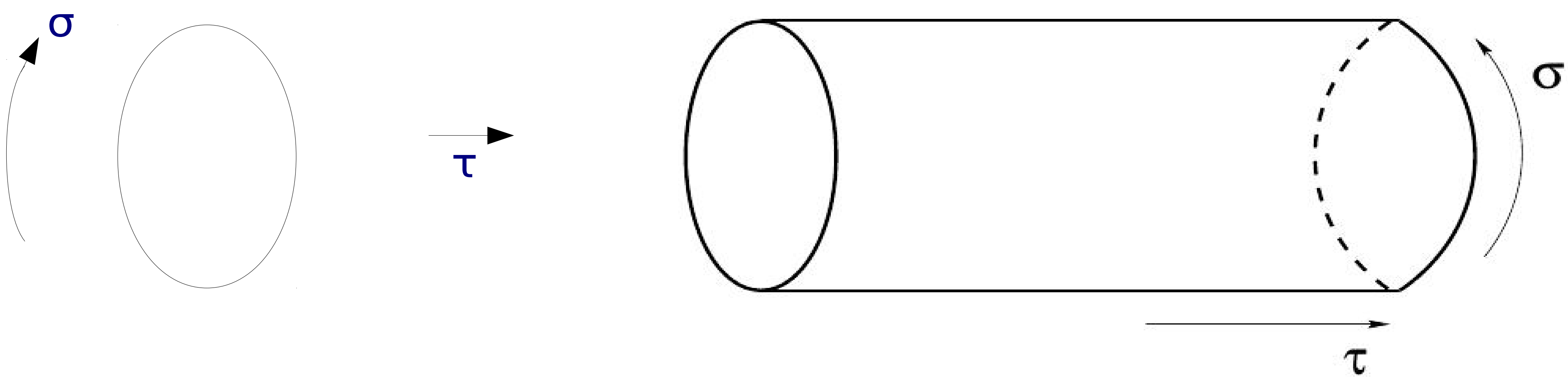
# String states

closed string → the 2 endpoints of the open string tied together i.e. periodic conditions imposed

$$X^{\mu}(\tau, 0) = X^{\mu}(\tau, \pi)$$

$$\frac{\partial X^{\mu}(\tau, 0)}{\partial \sigma} = \frac{\partial X^{\mu}(\tau, \pi)}{\partial \sigma}$$

closed string sweeping out a 2d worldsheet (as $\tau$ increases) parameterized by $\sigma$ and $\tau$




also embedded in a D dimensional spacetime $X^{\mu}$ $(\mu = 0,1,2 \ldots D-1)$

# String states

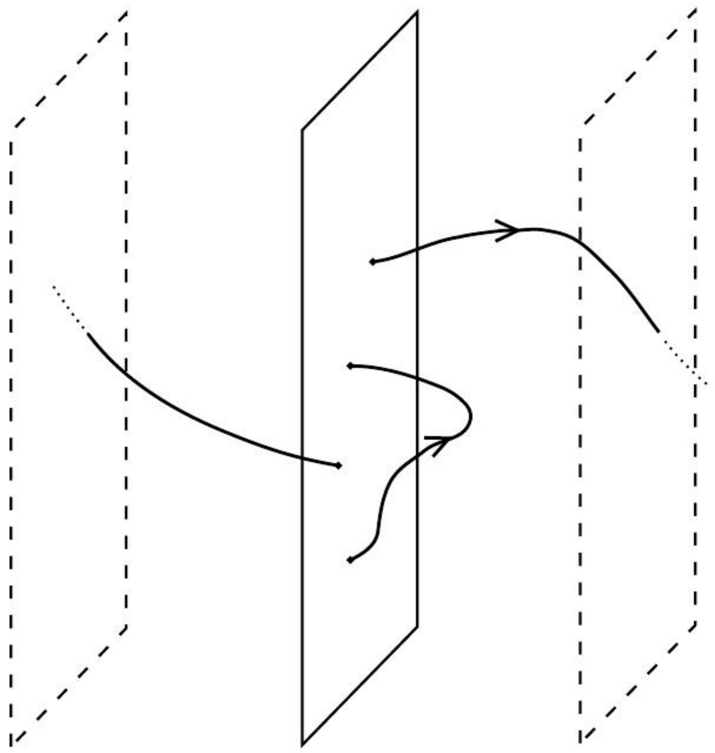
| | # of $Q$'s | # of $\psi_\mu$'s | bosonic spectrum | | |
|---|---|---|---|---|---|
| IIA | 32 | 2 | NS-NS | $g_{\mu\nu}$, $b_{\mu\nu}$, $D$ | closed strings |
| | | | R-R | $A_\mu$, $C_{\mu\nu\rho}$ | |
| IIB | 32 | 2 | NS-NS | $g_{\mu\nu}$, $b_{\mu\nu}$, $D$ | closed strings |
| | | | R-R | $c^*_{\mu\nu\rho\sigma}$, $b'_{\mu\nu}$, $D'$ | |
| heterotic $E_8 \times E_8$ | 16 | 1 | $g_{\mu\nu}$, $b_{\mu\nu}$, $D$ <br> $A^a_\mu$ in adjoint of $E_8 \times E_8$ | | closed strings |
| heterotic $SO(32)$ | 16 | 1 | $g_{\mu\nu}$, $b_{\mu\nu}$, $D$ <br> $A^a_\mu$ in adjoint of $SO(32)$ | | closed strings |
| type I $SO(32)$ | 16 | 1 | NS-NS | $g_{\mu\nu}$, $D$ | closed and open strings |
| | | | open string | $A^a_\mu$ in adjoint of $SO(32)$ | |
| | | | R-R | $b_{\mu\nu}$ | |

5 consistent fundamental string theories in 10 D

# String states

$D_p$ brane (or Dirichlet brane or D-brane) as a p-dimensional extended object on which open strings end (one or both) can be attached

string endpoints coordinates $X^{\mu}(\tau,\sigma)$ satisfy boundary conditions :



**- Dirichlet boundary conditions** $\left.\frac{\partial X^{\mu}}{\partial \tau}\right|_{\sigma=0,\pi} = 0$

integrating over $\tau$ specifies a spacetime location on which the string ends

Dirichlet boudary conditions are equivalent to fixing the endpoints of the string hence the name Dirichlet Brane

**- Neumann boundary conditions** $\left.\frac{\partial X^{\mu}}{\partial \sigma}\right|_{\sigma=0,\pi} = 0$

in this case the ends of the string can sit anywhere in space

# String states

**example of string duality**

take type II closed string theories (D=10, N=2) and compactify one dimension on a circle of radius R ➔ this results into the appearance of :

- $m$ massive winding modes with mass : $M^2 = \dfrac{m^2 R^4}{4}$
- $k$ massive Kaluza-Klein (KK) modes with mass : $M^2 = \dfrac{k^2}{R^2}$

**spectrum of modes invariant under** $\boldsymbol{R \rightarrow \frac{2}{R}}$

**this T-duality of type IIA and type IIB closed string theories**

for $R \rightarrow \infty$ winding modes are 'out' $\Rightarrow$ quasi continuum of KK modes
for $R \rightarrow 0$ infinitely massive KK modes decouple 'out' $\Rightarrow$ quasi continuum of winding modes

T-duality exchanges the Neumann and Dirichlet boundary conditions

# String states

D-brane with one attached open string and one closed string moving in the bulk

- physics away from the D-brane can be described by a type II string theory

- everything happen as if the closed string 'feels' the hypersurface via
  closed-open string interactions

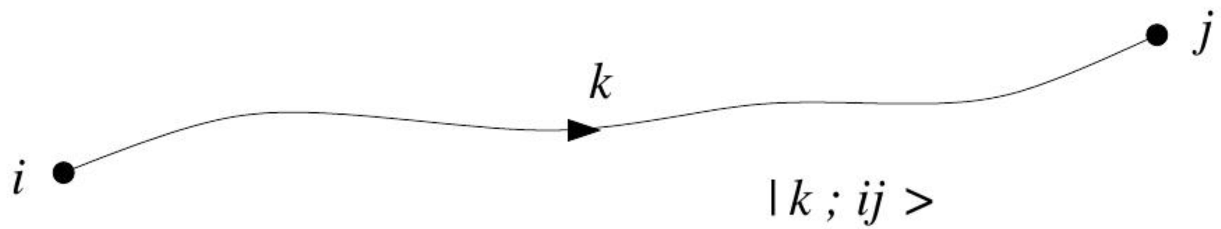
# String states

it is possible to assume that open string carries 'charges' at its enpoints

⇒ assume non-dynamical degrees of freedom at the endpoints in a way which preserves Poincare invariance and invariance of the worldsheet

in addition to the usual fock space labels of string state

- demand that each end of the string be in a state $i$ or $j$
- demand that Hamiltonian of the states $i=1,\ldots n$ is 0 so that they stay in the state that we originally put them in for all time




decompose open string wavefunction $|k;ij>$ in a basis of $\lambda_{ij}^{a}$ of $n\times n$ matrices as

$$|k;a>=\sum_{i,j=1}^{n}|k;ij>\lambda_{ij}^{a}$$

these matrices are called **Chan-Paton factors**

# String states

open string scattering amplitudes contain traces of products of Chan Paton factors

amplitudes are invariant under a global U(n) worldsheet symmetry
under which the endpoint $i$ transforms in the fundamental representation of U(n)

**global U(n) symmetry on the worldsheet can be promoted**
**to a local U(n) gauge symmetry in spacetime**

$\Rightarrow$ **endpoints of open string carry gauge charges and describe gauge symmetries**

# String states

consider an open string with endpoints moving on p-dimensional hypersurface
i.e. a $D_p$ - brane or D-brane

under which the endpoint $i$ transforms in the fundamental representation of U(n)

'zero' mass state of the open string are :

- 1 vector (see the table few slides above the bosonic content of the open string zero mass states of the type I string theory)
- 1 spinor

forming a supermultipet of a supersymmetric gauge theory with gauge group U(1)

**- the zero mass boson moves as a U(1) gauge boson in the p-dimensional D-brane**

- the 10-p remaining components appear as scalars in the 'bulk'

**stack of N coincident D-branes corresponds to an unbroken U(N) gauge symmetry**

**whose effective action is a 10D U(N) SYM theory reduced to p dimensions**

**D-branes brake half of the supersymmetries**

Polchinski, hep-th/9407031,,Witten hep-th/9510135

# String states

**some examples with two D-branes**

➔ open string with both endpoints on the D-brane gives a $U(1)\times U(1)$ theory

➔ open string stretching between two D-branes with one endpoint on one D-brane and the other one on another D-brane **parallel** to the first one with a distance given by the string length also gives a $U(1)\times U(1)$ theory

➔ if the two branes coincide (string length going to zero giving rise to new massless states) the gauge group becomes U(2)

- a 2 coincident branes separation viewed as a symmetry breaking $U(2) \rightarrow U(1)\times U(1)$

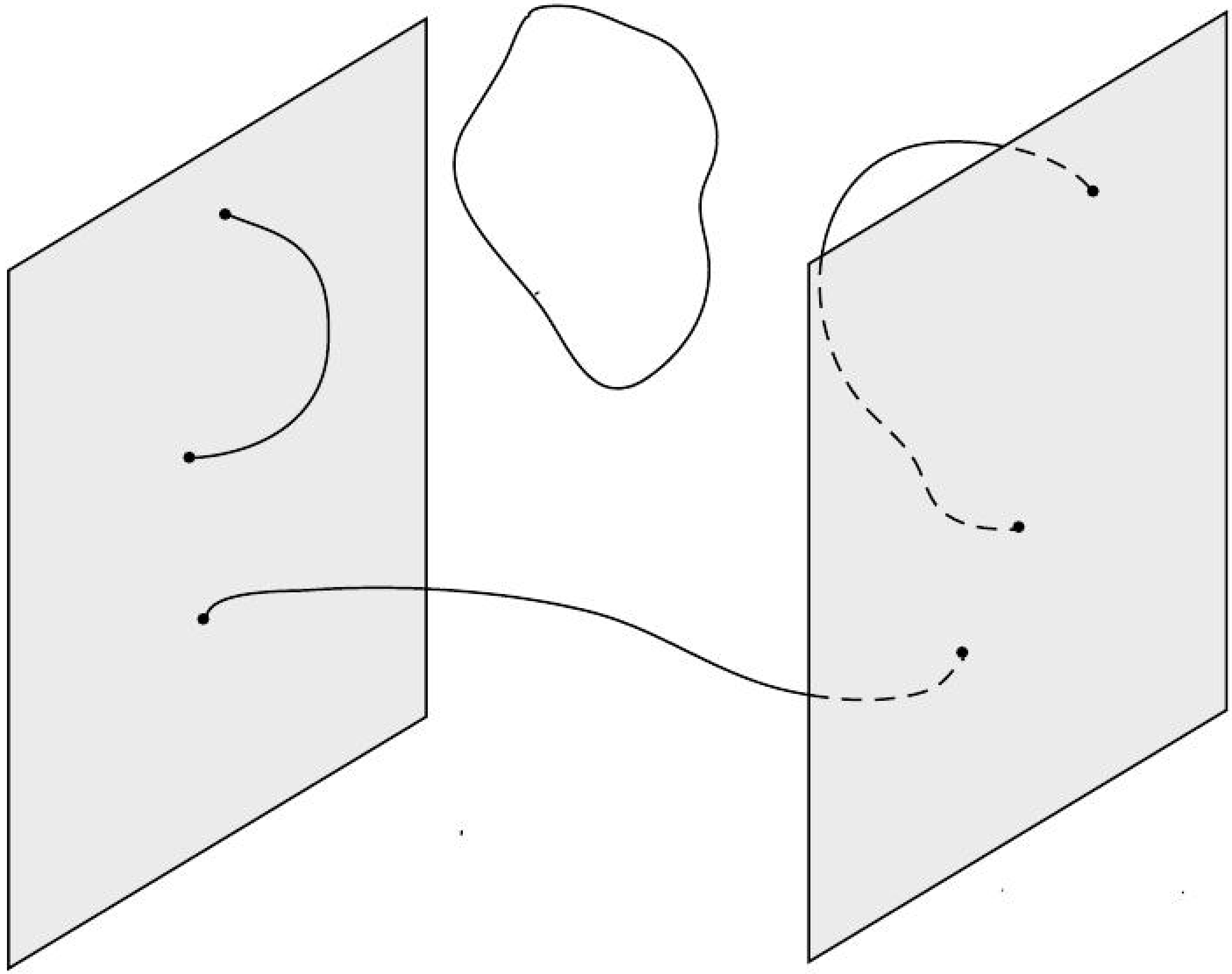
- $U(2)$ symmetry restauration when the 2 parallel branes become coincident

➔ interesting configurations:

- 5 coincident D-branes or **stack** of 5 D-branes giving $U(5)$
- stack of 3 D-branes + stack of 2 D-branes + 1 D-brane give $U(3)\times U(2)\times (U1)$

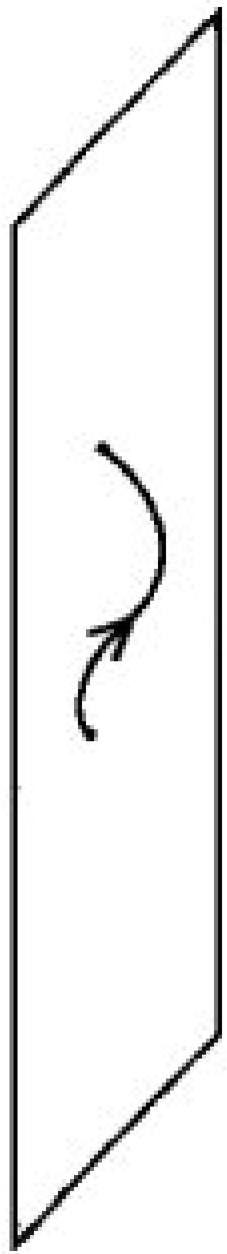
Polchinski, hep-th/9407031,,Witten hep-th/9510135

# String states



# String states

**D-branes brake half of the supersymmetries**

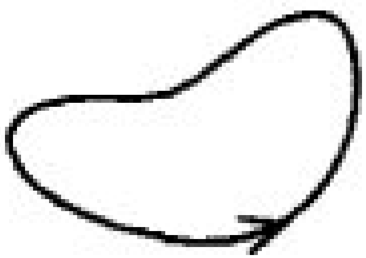


'far' from the D-brane (bulk)

- physics can be described by a type II closed string theory
- D-brane 'sees' only the type II (B) string spectrum
- in particular it 'sees' its 2 gravitinos **(recall we have N=2 in 10 D for type II**

'closer' to the brane 'sees' only a linear combination of the 2 gravitinos

- which is the gravitino of the type I theory **(recall we have N=1 in 10 D for type I**
- this defines one the duality 'symmetry' between string theories (called $\Omega$ projection) here between type IIB and type I



**D-brane responsible for:** $\boldsymbol{N = 2 \rightarrow N = 1}$

**i.e. half of the supersymmetry breaking**

vacuum without D-brane is invariant under 10D N=2 susy

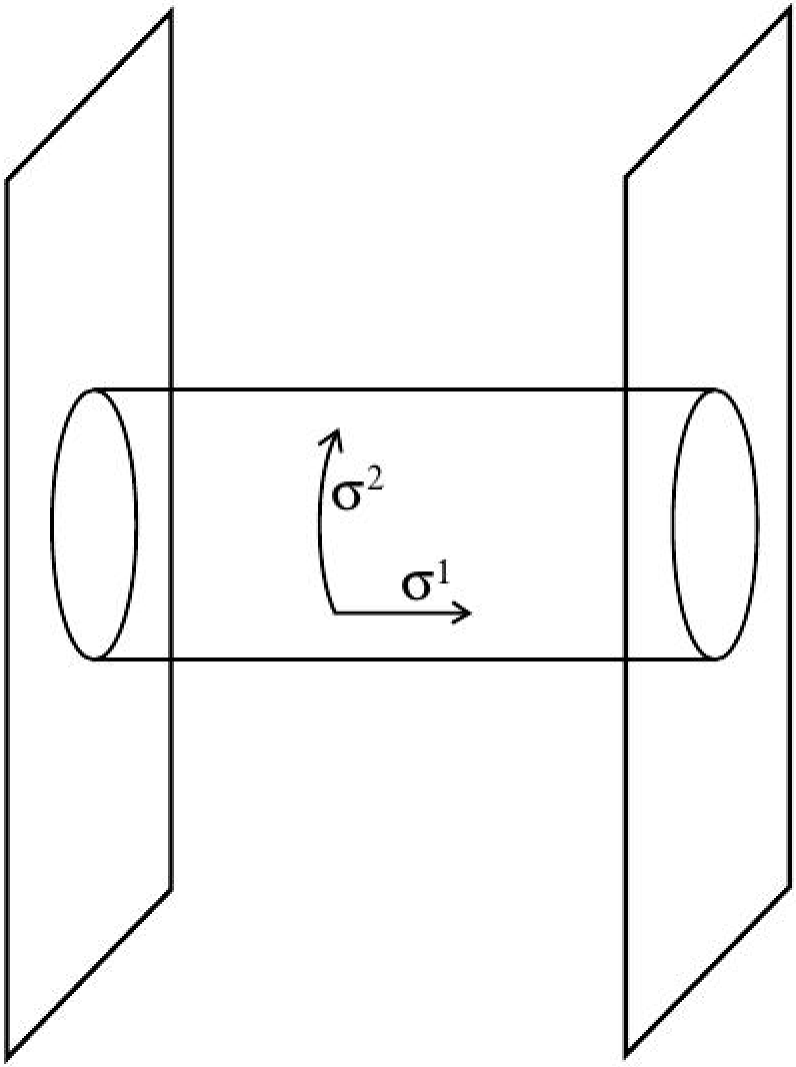
state with D-brane invariant under 10D N=1 susy only

this is a called a BPS state (Polchinski hep-th/9510017, hep-th/9611050)

**stack of D-branes can break supersymmetry further**

Polchinski, hep-th/9407031,,Witten hep-th/9510135

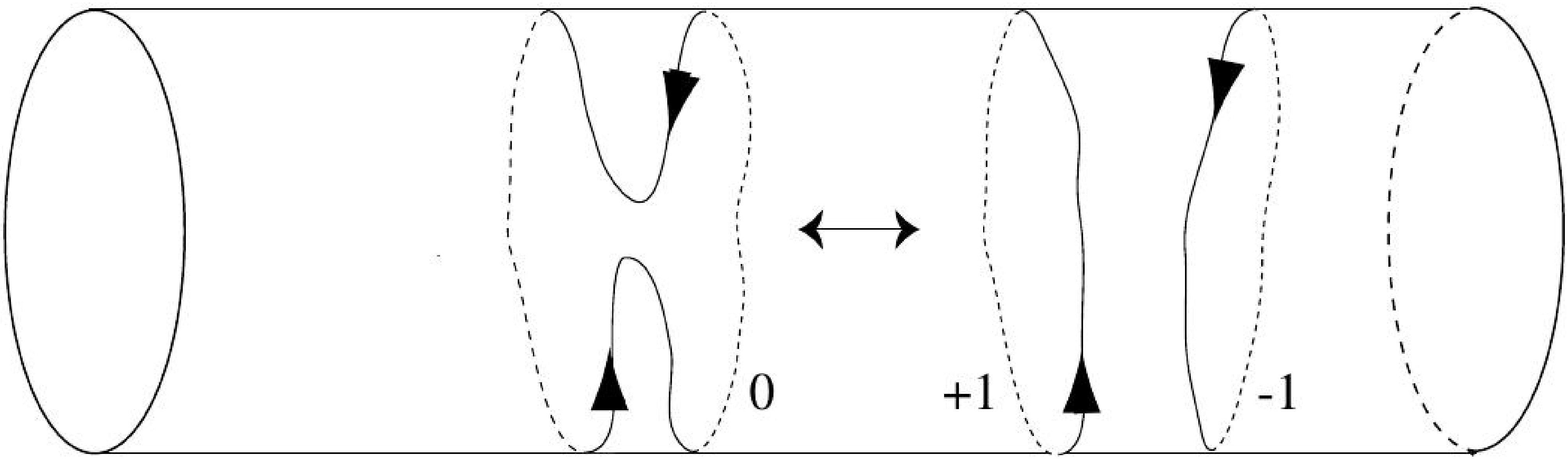
# String states




exchange of a closed string between two D-branes

equivalently a vacuum loop of an open string with one end on each D-brane

# String states



# String states

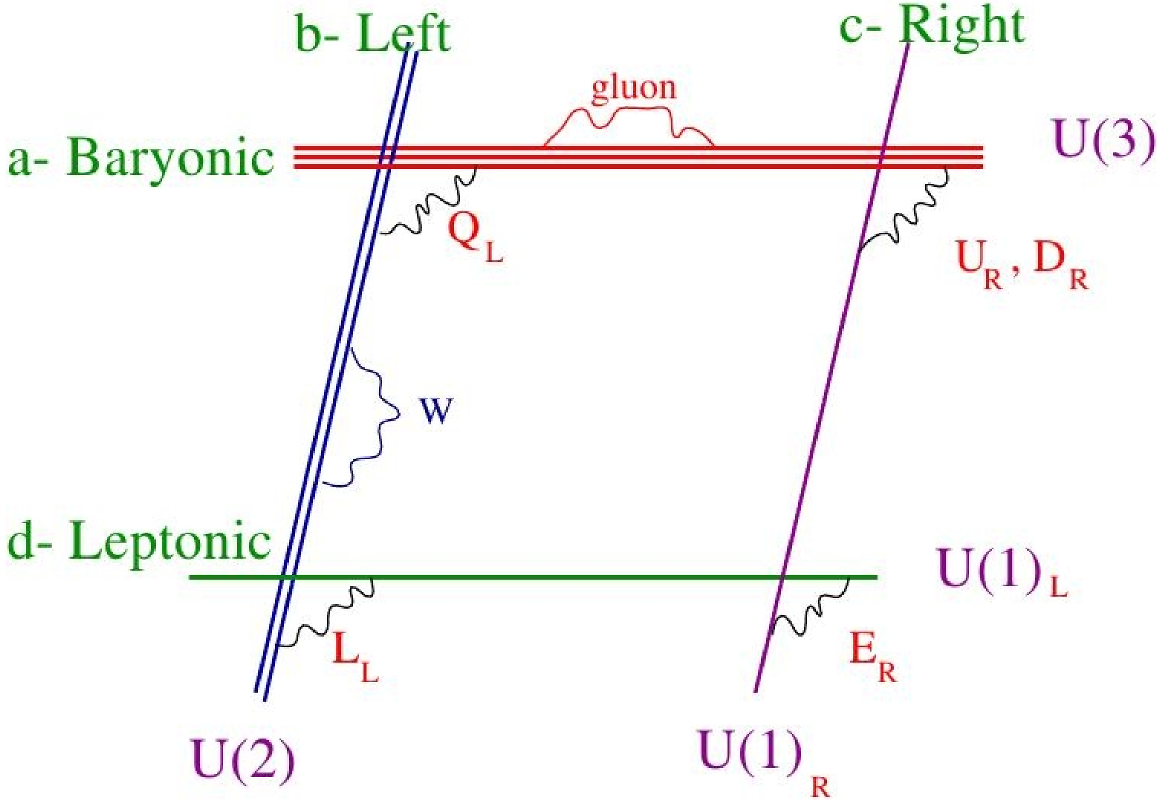
**D-branes or stack of D-branes can intersect at right angles or at (any) angles**

→ can preserve a supersymmetry

→ scalars and **chiral** fermions **localized at branes intersections**

→ SM-like susy or non-susy model building

often with extra U(1) i.e. Z' , extra exotic chiral matter (large literature on this)




Bachas, hep-th/9503030,,Berkooz, Douglas, Leigh, hep-th/9606139

# String states

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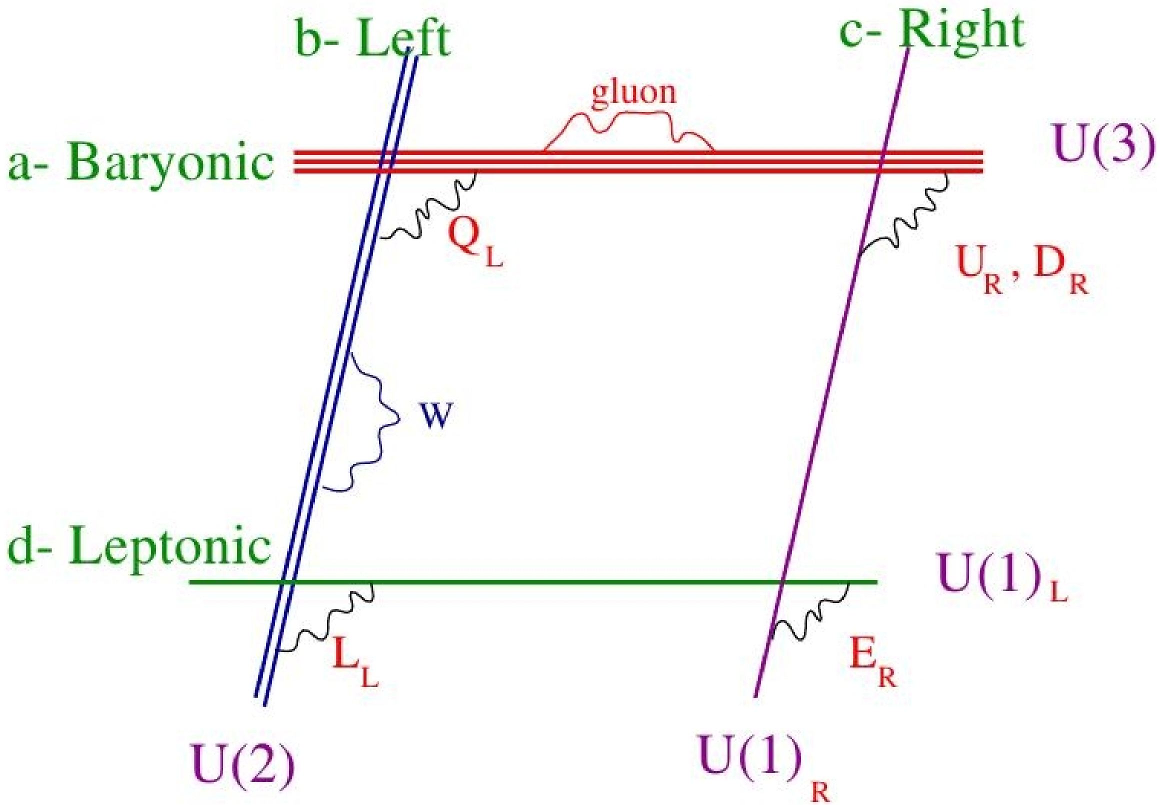
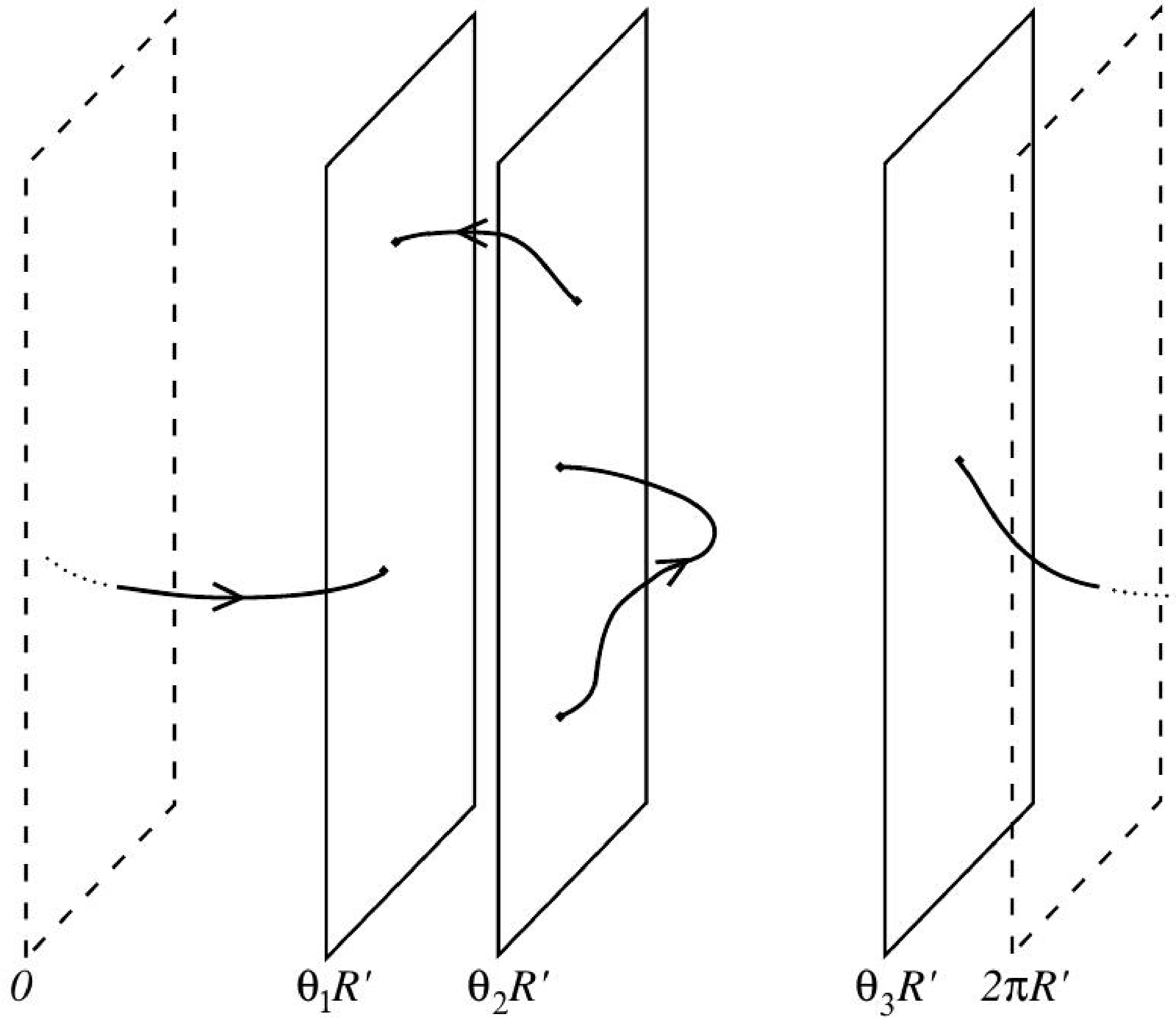
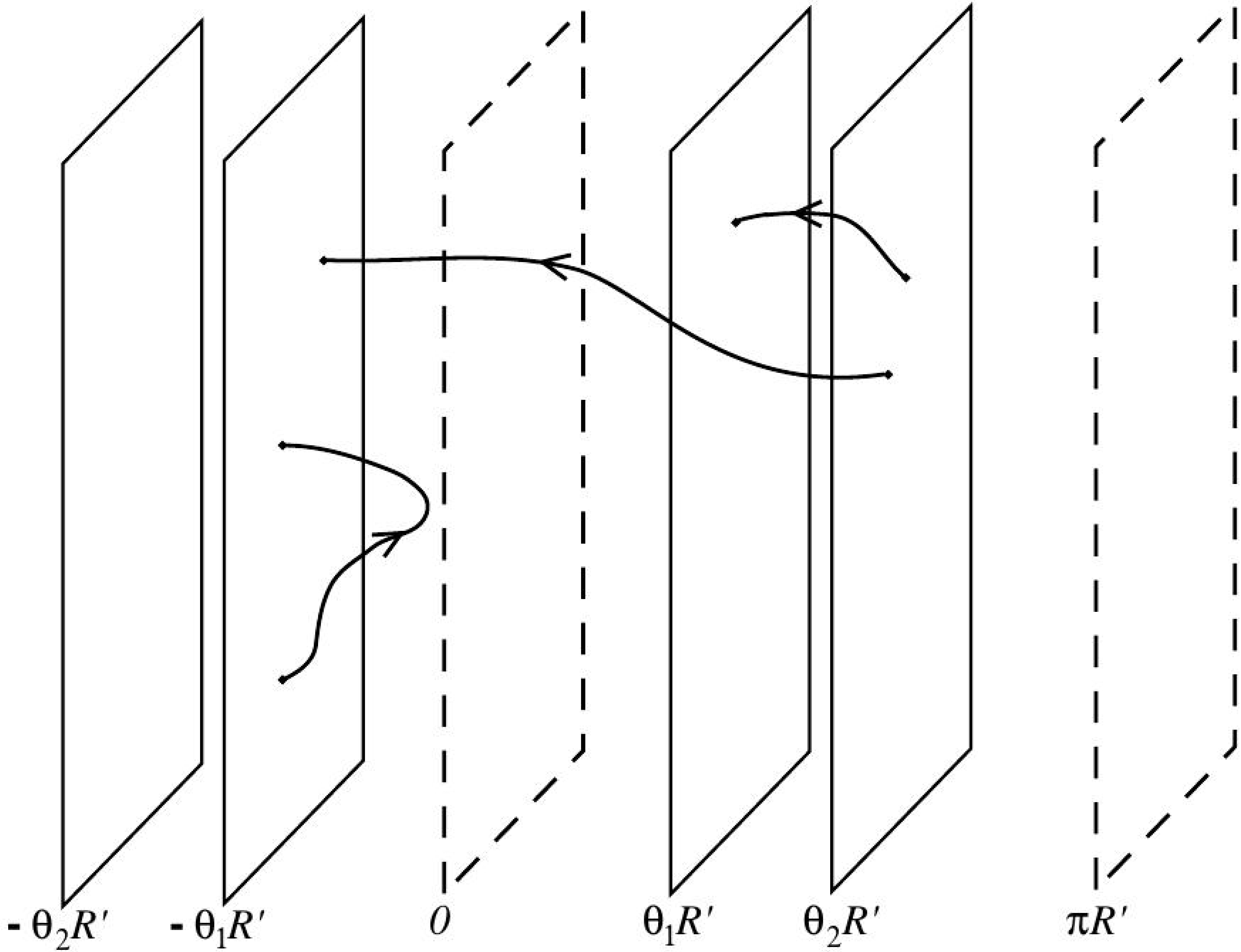



Bachas, hep-th/9503030,,Berkooz, Douglas, Leigh, hep-th/9606139

# String states



# String states



# Higgs radion mixing

all SM invariances and Poincare invariance on the TeV brane

are still fulfilled if one add the following term to the SM lagrangian :

$$S_\xi = \xi \int dx^4 \sqrt{g_{\text{induced}}}\; R\left(g_{\text{induced}}\right) \Phi^\dagger \Phi$$

mixing the Ricci scalar from the 4D induced metric on the TeV brane

and the Higgs field $\Phi$

➔ gives additional effective contribution to the SM $T^{\mu\nu}$
(which is a total divergence)

➔ $T^{\mu\nu}$ still conserved (invariances are unchanged)

➔ contribution ressembling to the one generically coming from dilatation invariance
(4d conformal invariance)

⇒ **mixing term between Higgs and curvature**

- Higgs-graviscalar mixing (ADD)
- Higgs-radion mixing (stabilized RS)

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs radion mixing

example of the dilatation invariance from the current $j_{\nu}^{(D)} = x^{\mu} T_{\mu\nu}$

which is conserved **classically** i.e. $\partial^{\mu} j_{\mu}^{(D)} = T_{\mu}^{\mu} = 0$ (trace of $T_{\mu\nu}$ is zero)

$\phi^4$ theory $\rightarrow$ $\xi = \frac{1}{6}$ (see P. Ramond : Field theory a modern primer p30-33

Gursey : Ann. of Phys. 24 (1963) 211

Coleman Jackiw: Ann. of Phys. 67 (1971) 552

QCD (with $m=0$) is **classically** invariant

but with quantum corrections $T_{\mathrm{QCD}}^{\mu\nu}$ is not traceless anymore

$T_{\mu}^{\mu}$ given by the trace anomaly

(see for example M. Shifman Phys. Rep. 209 (1991) 341)

# Higgs-radion mixing

more convenient to express radion field in terms of a field $\phi$ with : $\phi \equiv \Lambda_\phi \, e^{-k\pi(T-r_c)}$

with $\Lambda_\phi = \langle\phi\rangle = \sqrt{\frac{24 M_5^3}{k}} e^{-k\pi r_c}$

integrating over the 5th dimension one gets a canonically normalized effective action

$$S_\phi = \int d^4x \sqrt{-g} \left[ \frac{2M_5^3}{k} \left( 1 - \frac{\phi^2}{\Lambda_\phi^2} e^{-2k\pi r_c} \right) R + \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) + \left( 1 - \frac{\phi}{\Lambda_\phi} \right) T_\mu^\mu \right]$$

$$T_\mu^{(1)\mu} = 6\xi v \, \Box h$$

$$T_\mu^{(2)\mu} = (6\xi - 1)\partial_\mu h \partial^\mu h + 6\xi h \, \Box h + 2 m_h^2 h^2 + m_{ij} \bar{\psi}_i \psi_j - M_V^2 V_{A\mu} V_A^\mu$$

$T_\mu^{(1)\mu}$ induces a kinetic mixing between $\phi$ and $h$

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs-radion mixing

fields re-defined by :

$$\phi = \left(\sin\theta - \sin\rho\cos\theta\right)\, h' + \left(\cos\theta + \sin\rho\sin\theta\right)\, \phi'$$

$$h = \cos\rho\cos\theta\;\, h' - \cos\rho\sin\theta\;\, \phi'$$

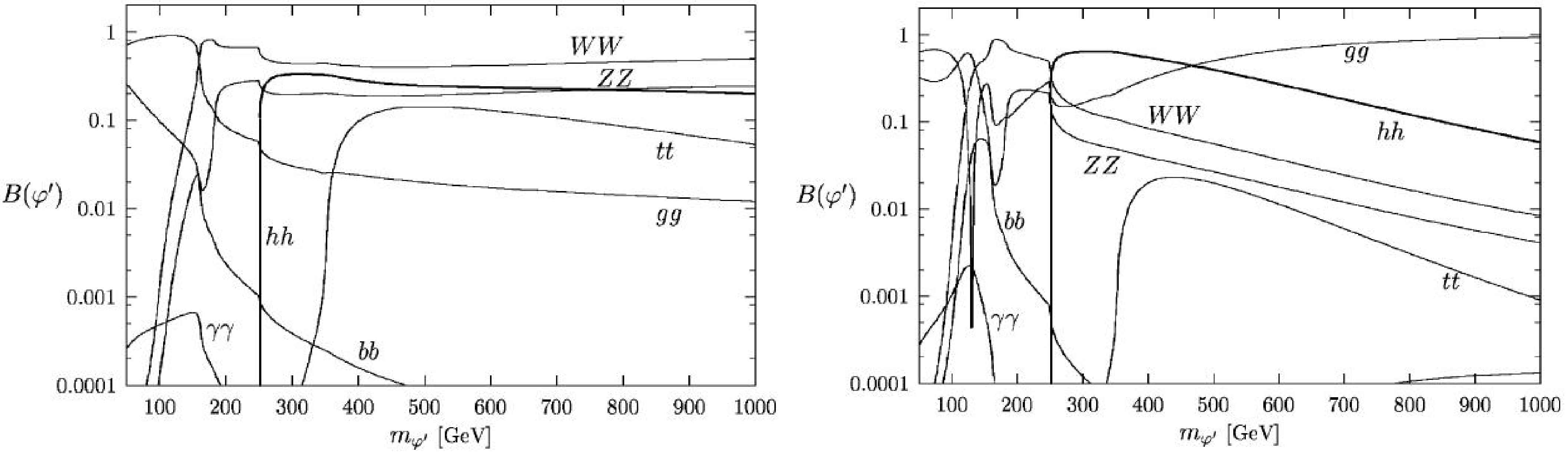
with $\tan\rho \equiv \dfrac{6\xi v}{\Lambda_\phi}$ and $\tan 2\theta \equiv \dfrac{2\sin\rho\, m_\phi^2}{\cos^2\rho\left(m_\phi^2 - m_h^2\right)}$

new fields $\phi'$ and $h'$ are mass eigenstates with eigenvalues :

$$m^2_{\phi',h'} = \frac{1}{2}\left[\,\left(1+\sin^2\rho\right)\, m_\phi^2 + \cos^2\phi\;\, m_h^2 \;\pm \sqrt{\cos^4\rho\left(m_\phi^2 - m_h^2\right)^2 + 4\sin^2\rho\, m_\phi^4}\;\right]$$

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs-radion mixing

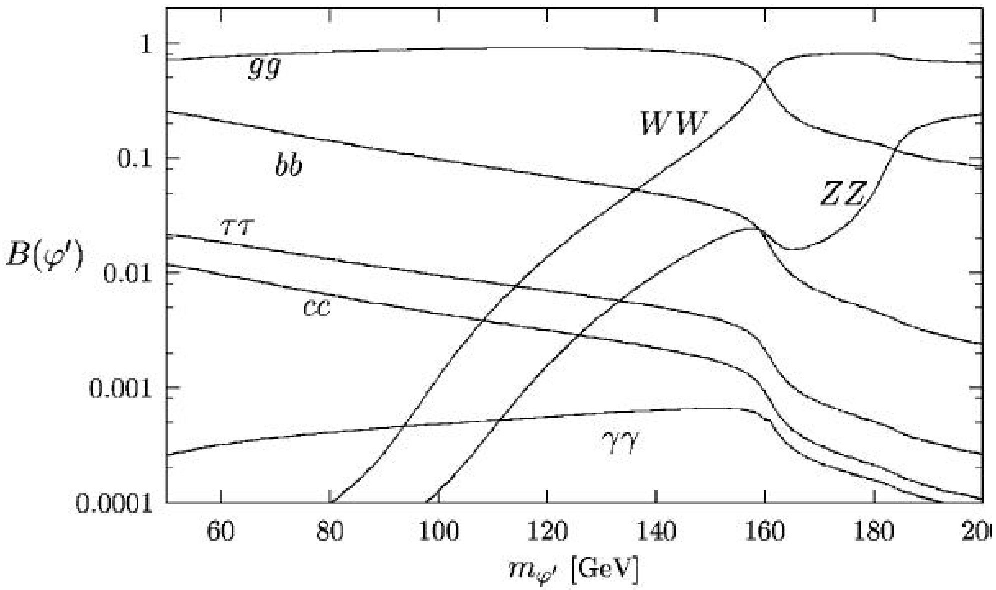


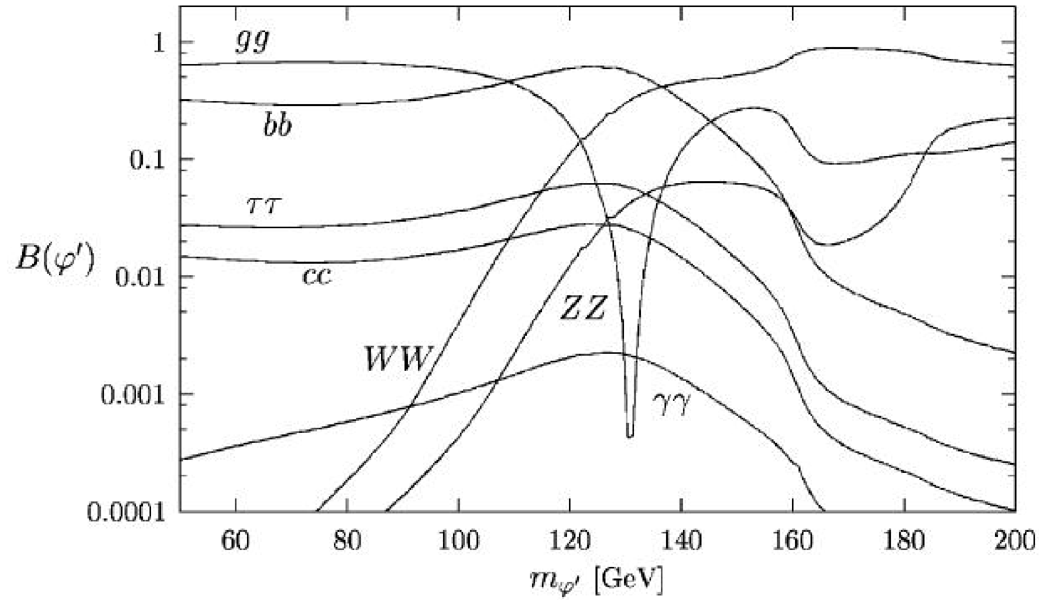

$m_h = 125$ GeV, $\Lambda_\phi = 10$ TeV, $\xi = 0$

$m_h = 125$ GeV, $\Lambda_\phi = 10$ TeV, $\xi = 1/6$

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs-radion mixing

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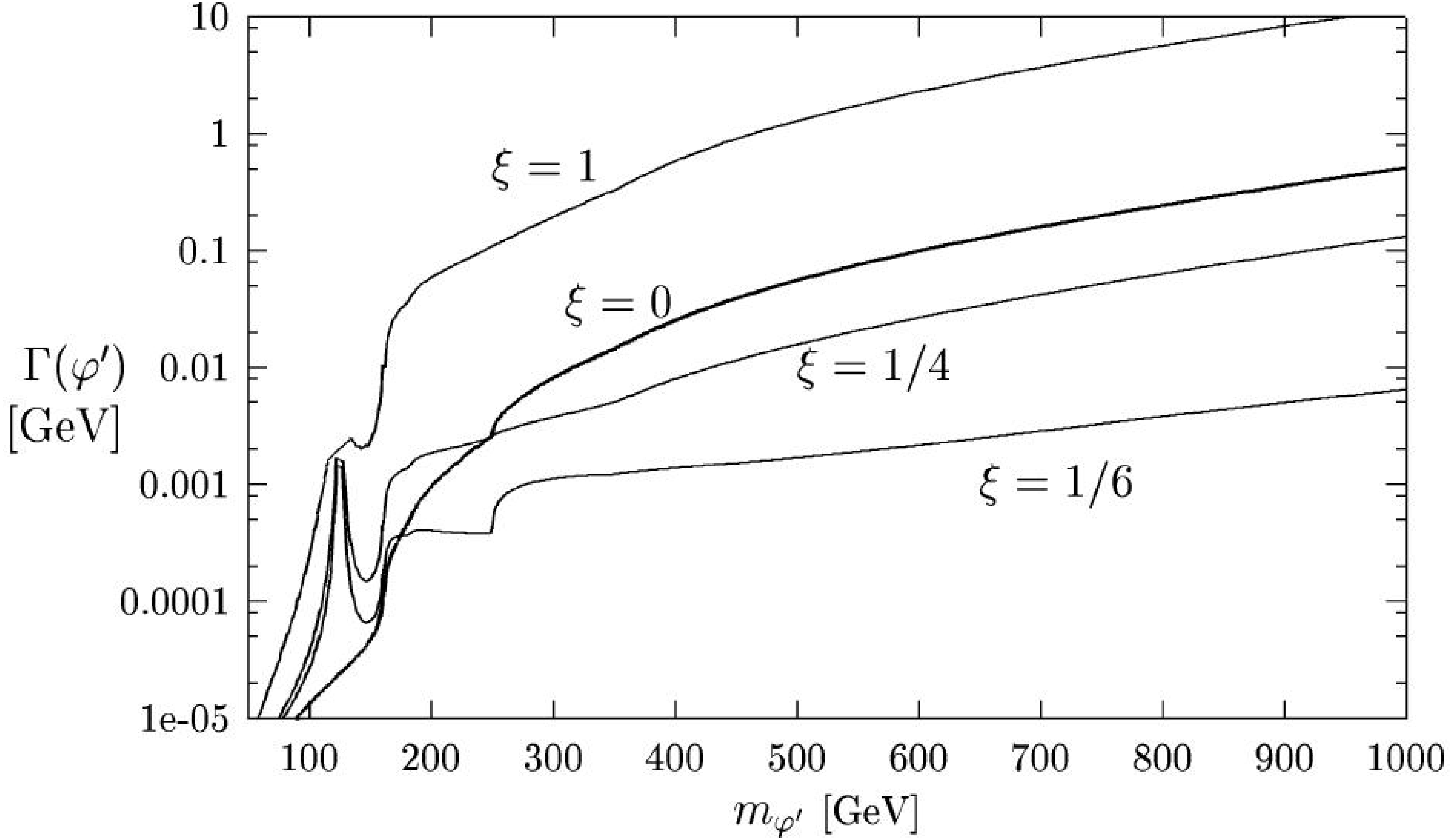
Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs-radion mixing

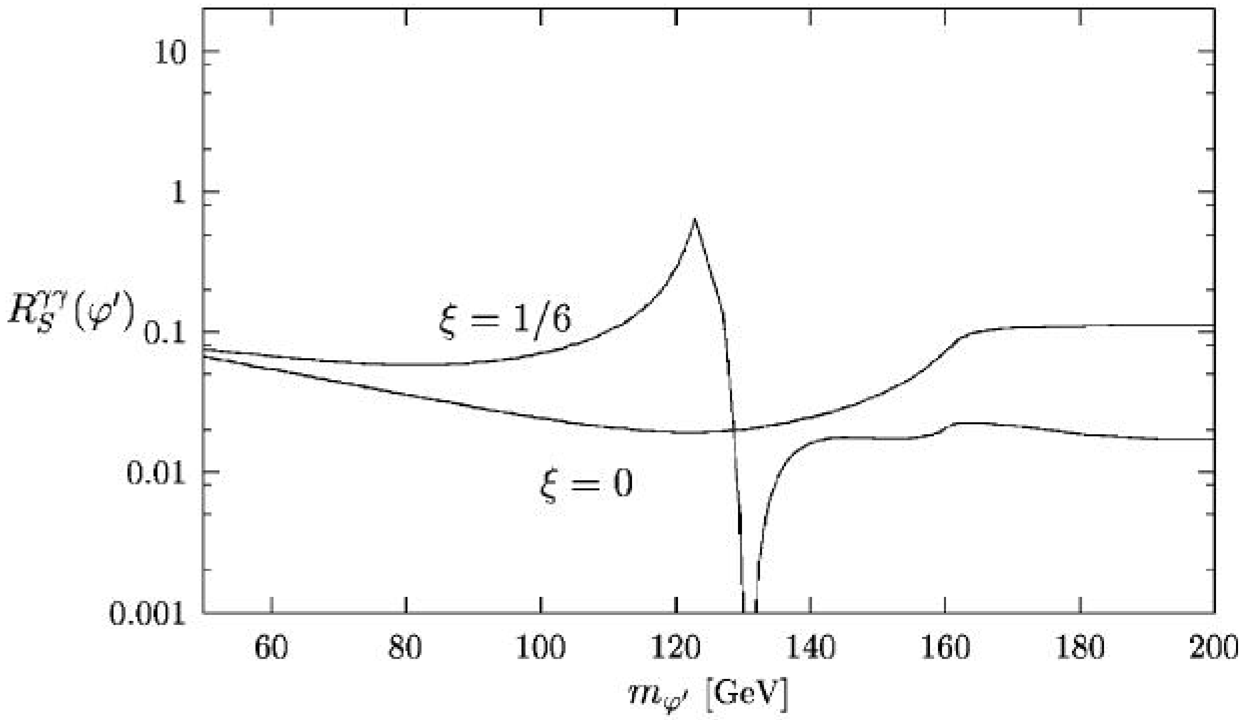



$m_h = 125$ GeV, $\Lambda_\phi = 10$ TeV

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs-radion mixing

$$R_S^{\gamma\gamma}(\phi') = \frac{\Gamma(\phi' \to g g)}{\Gamma(h_{SM} \to g g)} \frac{B(\phi' \to \gamma\gamma)}{B(h_{SM} \to \gamma\gamma)} \sqrt{\frac{\max(\Gamma_{tot}(h_{SM}), \Delta M_{\gamma\gamma})}{\max(\Gamma_{tot}(\phi'), \Delta M_{\gamma\gamma})}}$$

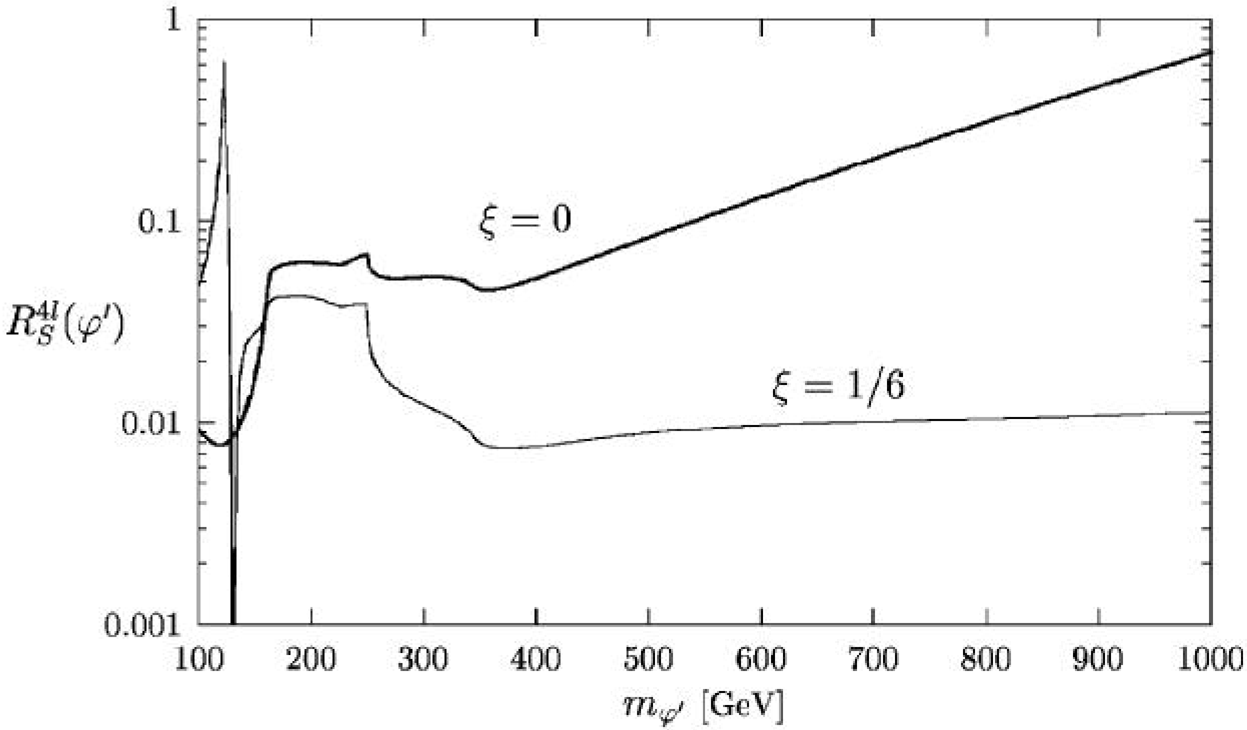



$$m_h = 125 \text{ GeV}, \quad \Lambda_\phi = 10 \text{ TeV}$$

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs-radion mixing

$$R_S^{4l}(\phi') = \frac{\Gamma(\phi' \to g\,g)}{\Gamma(h_{SM} \to g\,g)} \frac{B(\phi' \to Z\,Z)}{B(h_{SM} \to Z\,Z)} \sqrt{\frac{\max(\Gamma_{tot}(h_{SM}), \Delta M_{4l})}{\max(\Gamma_{tot}(\phi'), \Delta M_{4l})}}$$




$$m_h = 125\ \text{GeV},\quad \Lambda_\phi = 10\ \text{TeV}$$

Giudice, Rattazzi, Wells, NPB 595 (2001) 250

# Higgs radion mixing

Higgs radion mixing term also in the context of type I strings theory and D-branes

mixing between brane fluctuations (branons) and closed string excitations modes of the type I theory (containing gravitons, graviphoton, dilaton, graviscalar) described in terms of mixing of open and closed strings excitations modes

several possible configurations

- Higgs identified to excitations of open string with both ends attached to same stack of D-branes
  - → Higgs-graviscalar mixing (but also Higgs-graviphoton)
  - → effective conformal coupling
  - → 4D effective theory as a N=4 SYM conformal theory
- Higgs identified to excitations of open string with one end attached to one brane and the other end to another brane
  - → Higgs-graviscalar mixing disappears but Higgs-graviphoton mixing stays
- Higgs localized at the (orthogonal) intersection of 2 branes
  - → Higgs-graviphoton mixing disappears

effective conformal coupling $$\xi = \sqrt{\frac{\delta+5}{6\delta(\delta-1)}}$$

| | |
|---|---|
| $\delta=2$ | $\xi \sim 0.76$ |
| $\delta=3$ | $\xi \sim 0.47$ |
| $\delta=6$ | $\xi \sim 1/4$ |

Antoniadis, Sturani, NPB 631 (2002) 66

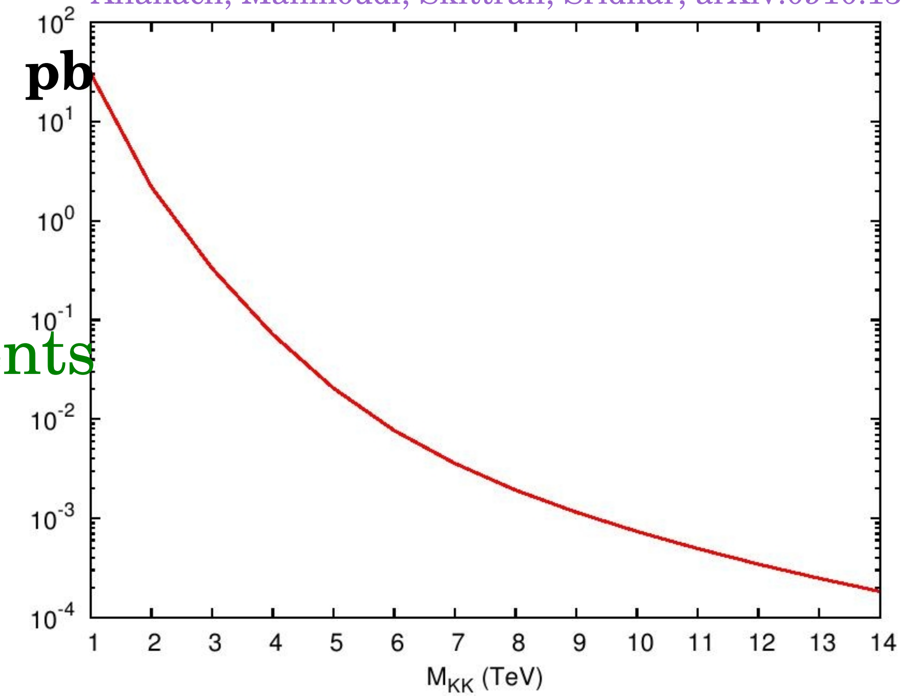
Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347
Lillie, Shu, Tait, PRD 76, 115016
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Baur, Orr, PRD 77, 114001
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

# Bulk RS models

## KK gluon

$g^{(1)}$ production suppressed

→ small coupling to proton constituents

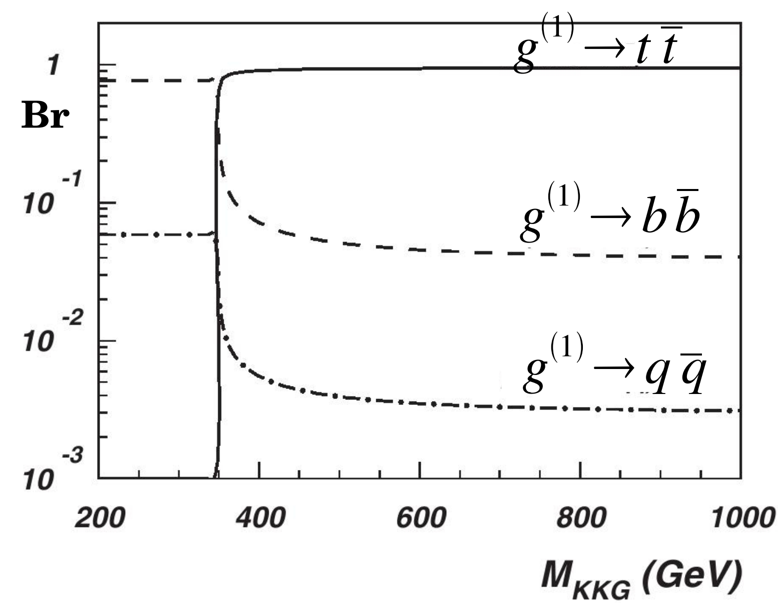



fermionic decay dominated by top quark

bias towards RH top

a heavy KK gluon is broad

above 1 TeV    width ~ $M_{KK}$ / 6



# Bulk RS models: KK gluon in all hadronic mode

$p\,p \rightarrow g^{(1)} \rightarrow t\,\bar{t} \rightarrow b\,\bar{b}\,j\,j\,j\,j$ **need**

**boosted top-quark jets algorithm**

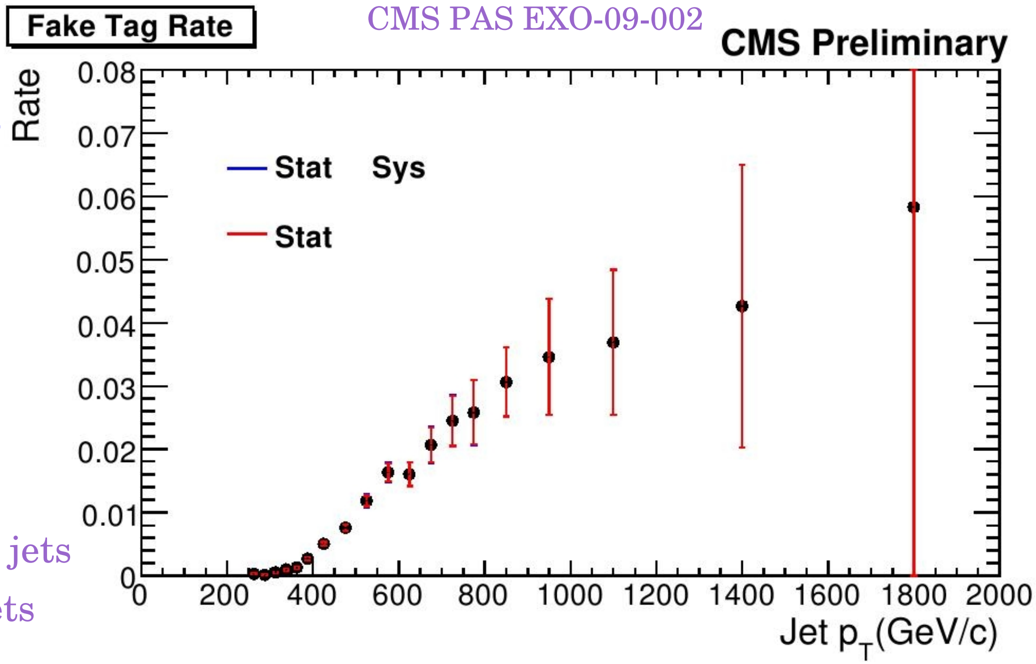
using Dokshitzer, Leder, Moretti, Webber, JHEP 08 (1997) 001, i.e. CA algorithm and Kaplan, Rehermann, Schwatz, Tweedie, PRL 101 (2008) 142001

similar to: Butterworth, Davison Rubin Salam, PRL 100 (2008) 242001, for Higgs jets

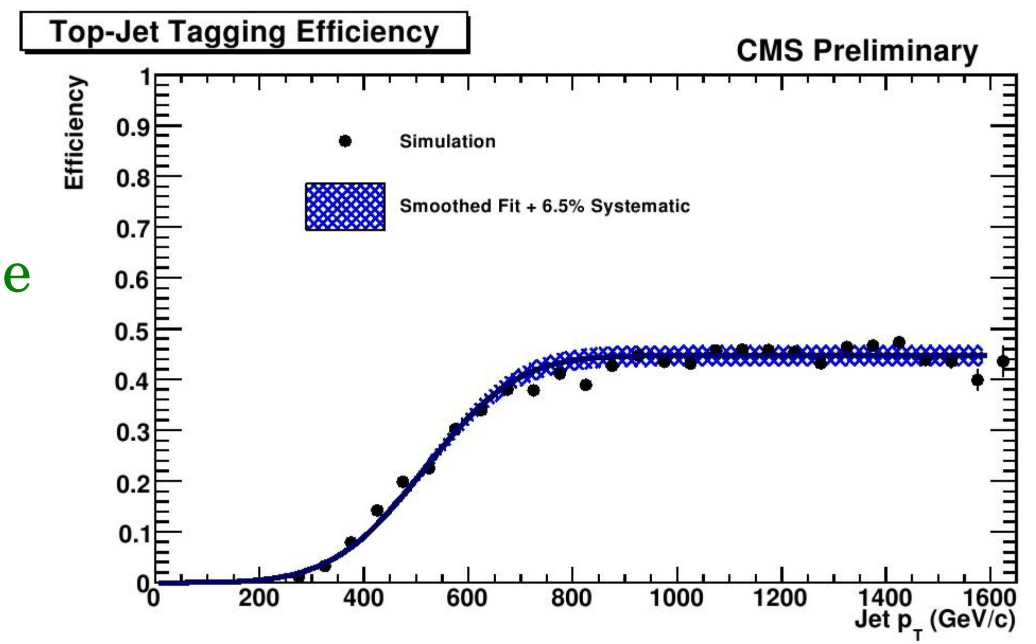
Butterworth, Cox, Fowshaw PRD65 (2002) 096014, for W jets

Butterworth, Ellis, Raklev, JHEP 05 (2007) 033, for W jets

CMS PAS EXO-09-002




cluster using a large jet radius
then iteratively decluster each jet
to search for jet structure and impose kinematic constraints



# Bulk RS models : KK gluon in all hadronic mode

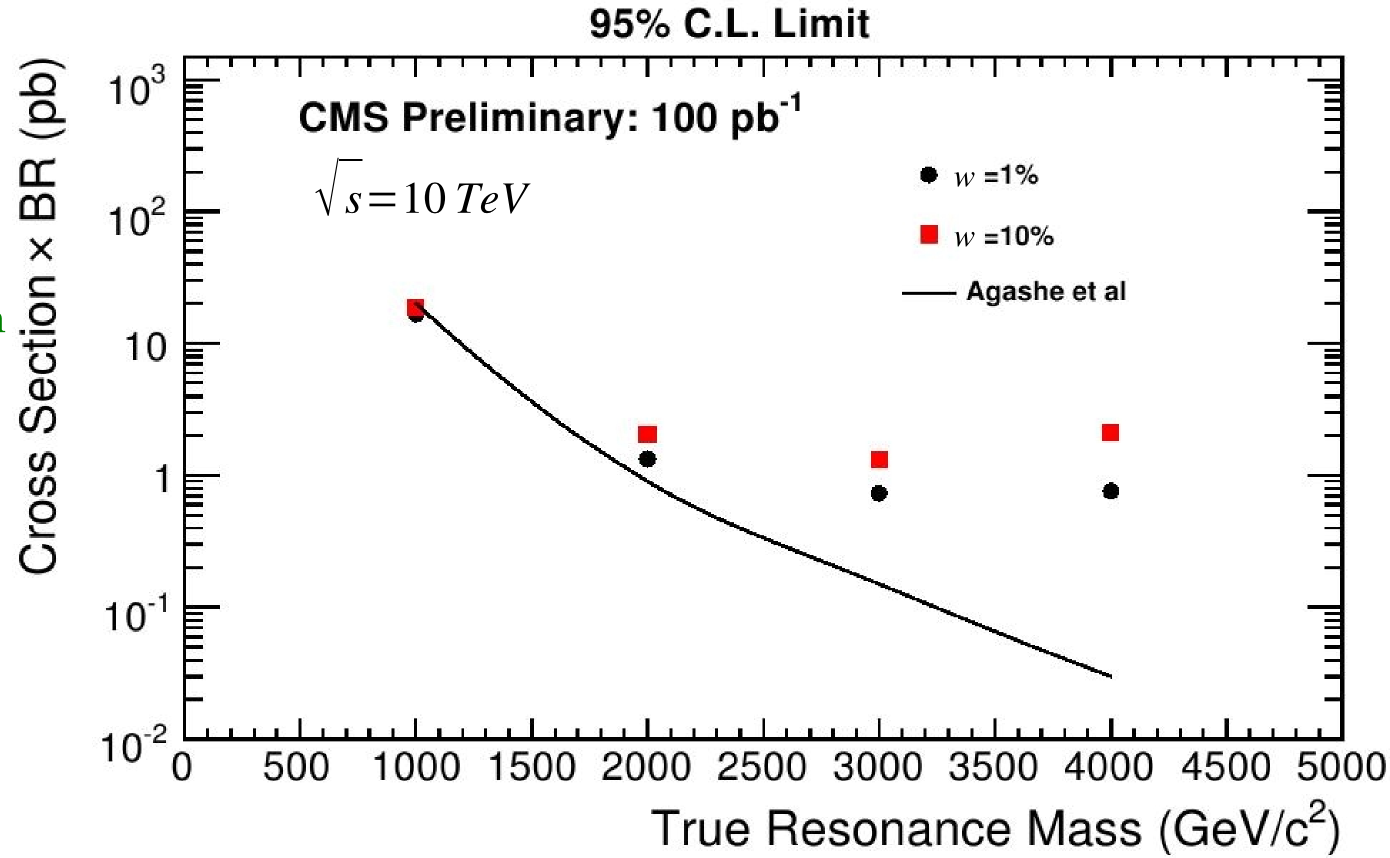
$$p\,p \rightarrow g^{(1)} \rightarrow t\,\bar{t} \rightarrow b\,\bar{b}\,j\,j\,j\,j$$

$w = 1\%$
for the case where resonance is narrower than detector resolution

$w = 10\%$
for the case where resonance is wide

$\epsilon$ : top jet tagging efficiency

A: kinematic acceptance




| Mass and Width ($GeV/c^2$) | Background (events) | $\epsilon \cdot A \cdot BR$ (%) | 95% C.L. limit (pb) | $3\sigma$ Evidence (pb) | $5\sigma$ Discovery (pb) |
|---|---|---|---|---|---|
| $M = 1000, w = 10$ | $2.18 \pm 0.90$ | $0.34 \pm 0.05$ | 17.2 | 23.0 | 43.6 |
| $M = 2000, w = 20$ | $5.81 \pm 2.18$ | $6.06 \pm 0.85$ | 1.45 | 2.18 | 3.99 |
| $M = 3000, w = 30$ | $0.95 \pm 0.41$ | $6.21 \pm 0.88$ | 0.74 | 0.97 | 1.62 |
| $M = 4000, w = 40$ | $0.11 \pm 0.12$ | $4.62 \pm 0.66$ | 0.75 | 0.62 | 1.27 |
| $M = 1000, w = 100$ | $2.18 \pm 0.90$ | $0.30 \pm 0.05$ | 19.3 | 25.7 | 48.6 |
| $M = 2000, w = 200$ | $9.04 \pm 3.31$ | $4.90 \pm 0.69$ | 2.30 | 3.46 | 6.32 |
| $M = 3000, w = 300$ | $2.04 \pm 0.79$ | $4.25 \pm 0.61$ | 1.34 | 1.87 | 3.28 |
| $M = 4000, w = 400$ | $0.98 \pm 0.41$ | $2.21 \pm 0.34$ | 2.13 | 2.73 | 5.00 |

at least 3 events

at least 5 events

# Bulk RS models

Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Guchait, Mahmoudi, Sridhar, JHEP05 (2007) 103, PLB 666 (2008) 347
Lillie, Shu, Tait, PRD 76, 115016
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Baur, Orr, PRD 77, 114001
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

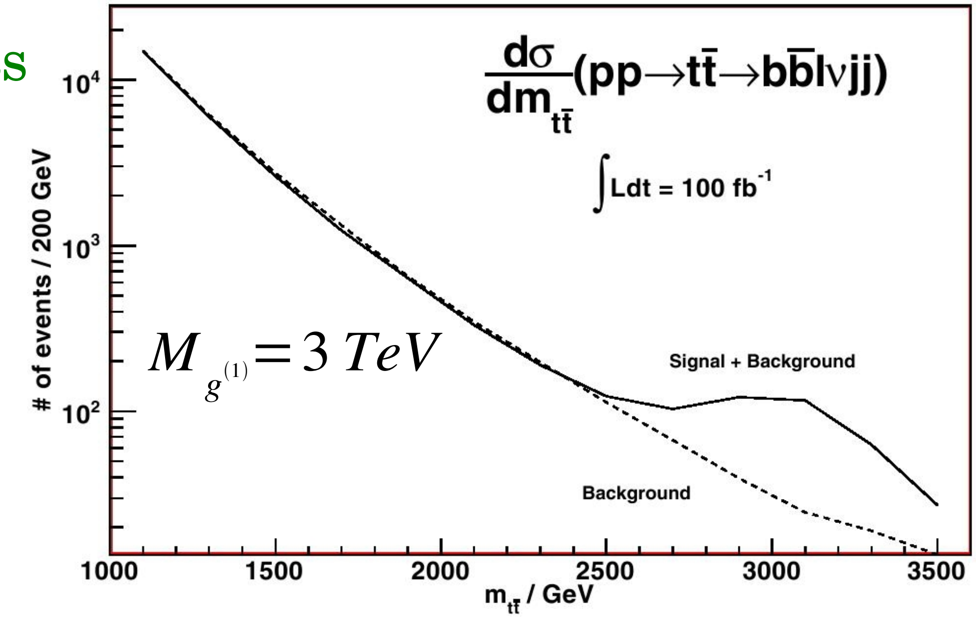
**KK gluon** $p\,p \to g^{(1)} \to t\,\bar{t} \to b\,\bar{b}\,j\,j\,l\,\nu$

background: SM $t\,\bar{t}$, single top, W+jets

**for 100 pb$^{-1}$** $M_{g^{(1)}} = 3\ TeV \quad S/\sqrt{B} \approx 11$

$M_{g^{(1)}} = 4\ TeV \quad S/\sqrt{B} \approx 4.2$

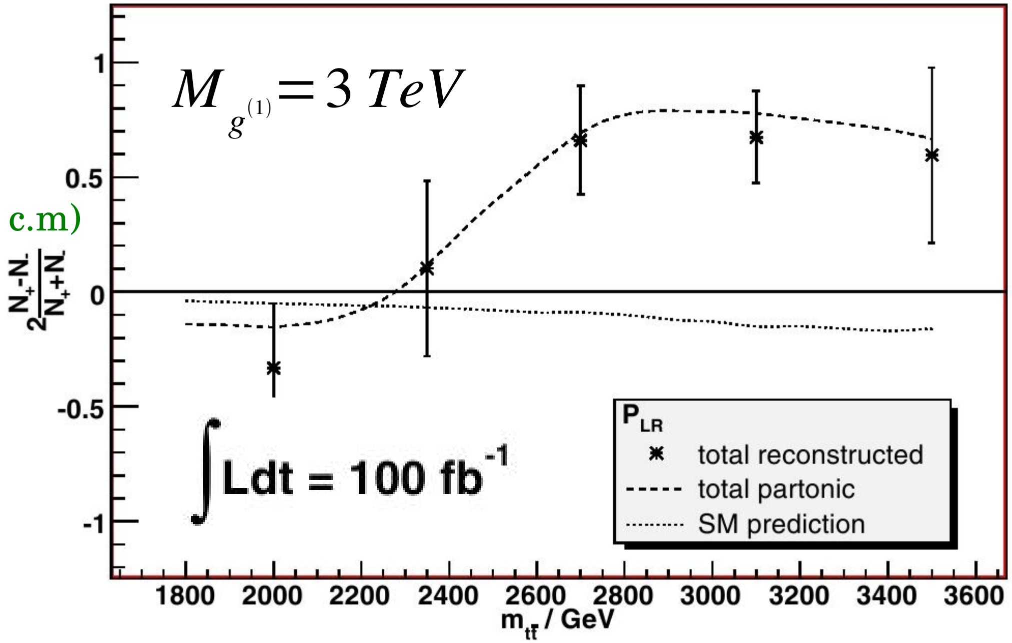
**reach < 4 TeV**




**asymmetry** $2 \times \frac{N_+ - N_-}{N_+ + N_-}$

$N_-$ number of positron
along direction of top-quark boost (in top pair c.m)

**expect strong bias towards RH top from KK gluon decay**



# Bulk RS models

Lillie, Randall, Wang, JHEP 09 (2007) 074
Agashe, Belyaev, Krupovnickas, Perez, Virzi, PRD 77, 015003
Allanach, Mahmoudi, Skittrall, Sridhar, arXiv:0910.1350

## KK gluon $\quad p\,p \to g^{(1)} \to t\,\bar{t} \to b\,\bar{b}\,j\,j\,l\,\nu$

| Selection | Variables | Cuts |
|---|---|---|
| Kinematic and acceptance | Lepton | $p_T > 10$ GeV, $\lvert\eta\rvert < 2.5$ |
| | $\geq 2$ jets | $p_T > 30$ GeV, $\lvert\eta\rvert < 2.5$ |
| | Tagged $b$-jets | $\geq 1$ |
| | Missing energy ($\nu$) | $p_T^{\mathrm{miss}} > 20$ GeV |
| | Lepton isolation | $\Delta R \geq 0.4$ (non-$b$ jets) |
| | $b$-jet lepton isolation | $\Delta R \geq 0.4$ *or* $m_{bl} \geq 40$ GeV |
| Reconstruction quality | $\lvert M_W^{\mathrm{had}} - M_W\rvert$ | <50 GeV |
| for #jets > 2, | $\lvert M_t^{\mathrm{had}} - M_t\rvert$ | <50 GeV |
| 2 $b$-jets required | $\lvert M_t^{\mathrm{lep}} - M_t\rvert$ | <50 GeV |
| Reconstruction quality | $\lvert M_t^{\mathrm{lep}} - M_t\rvert$ | <50 GeV |
| a $b$-jet + $t$-jet | "Top jet" | $p_{T^t} > 800$ GeV |

**one could use in addition the fowardness of the SM** $t\,\bar{t}$

i.e. dominant production via gluon fusion more forward

**KK gluons produced by quark annihilation**

# Bulk RS models

Agashe, Davoudiasl, Gopalakrishna, Han, Huang, Perez, PRD76, 115015

Djouadi, Moreau, Singh, NPB 797 (2008) 1

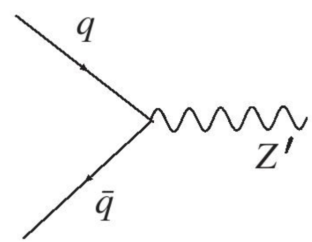
## Warped EW neutral gauge bosons

**from underlying $SU(2)_L$ x $SU(2)_R$ x $(U1)_X$ in the bulk**

**3 neutral KK gauge bosons tower from $U(1)_{L,R,X}$** → $A_{1,}\ Z_{1,}\ Z_{X1}$ (after mixing)

→ **generically Z'**

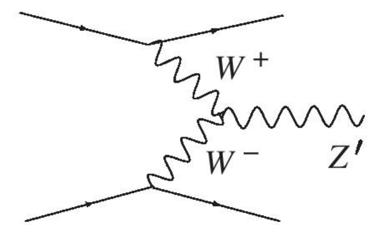
**Z' coupling** to light quarks and leptons are suppressed




**process still dominant !**

**Z' coupling to top and bottom are enhanced**

**Z' coupling to longitudinal W, Z and Higgs enhanced**




**Z' signatures into top and bottom overwhelmed by KK gluon decay into b and t**

$Z' \to WW \to 2l2\nu$ or $\to l\nu jj$ **sensitivity up to 2 TeV (3 TeV) with 100 $fb^{-1}$(1 $ab^{-1}$)**

**luminosity upgrade crucial**

luminosity upgrade also crucial for associate production with heavy quarks

# Bulk RS models

Agashe, Gopalakrishna, Han, Huang, Soni, PRD 80, 075007

## Warped EW charged gauge bosons

**2 charged KK gauge bosons tower (mixing) → generically W'**

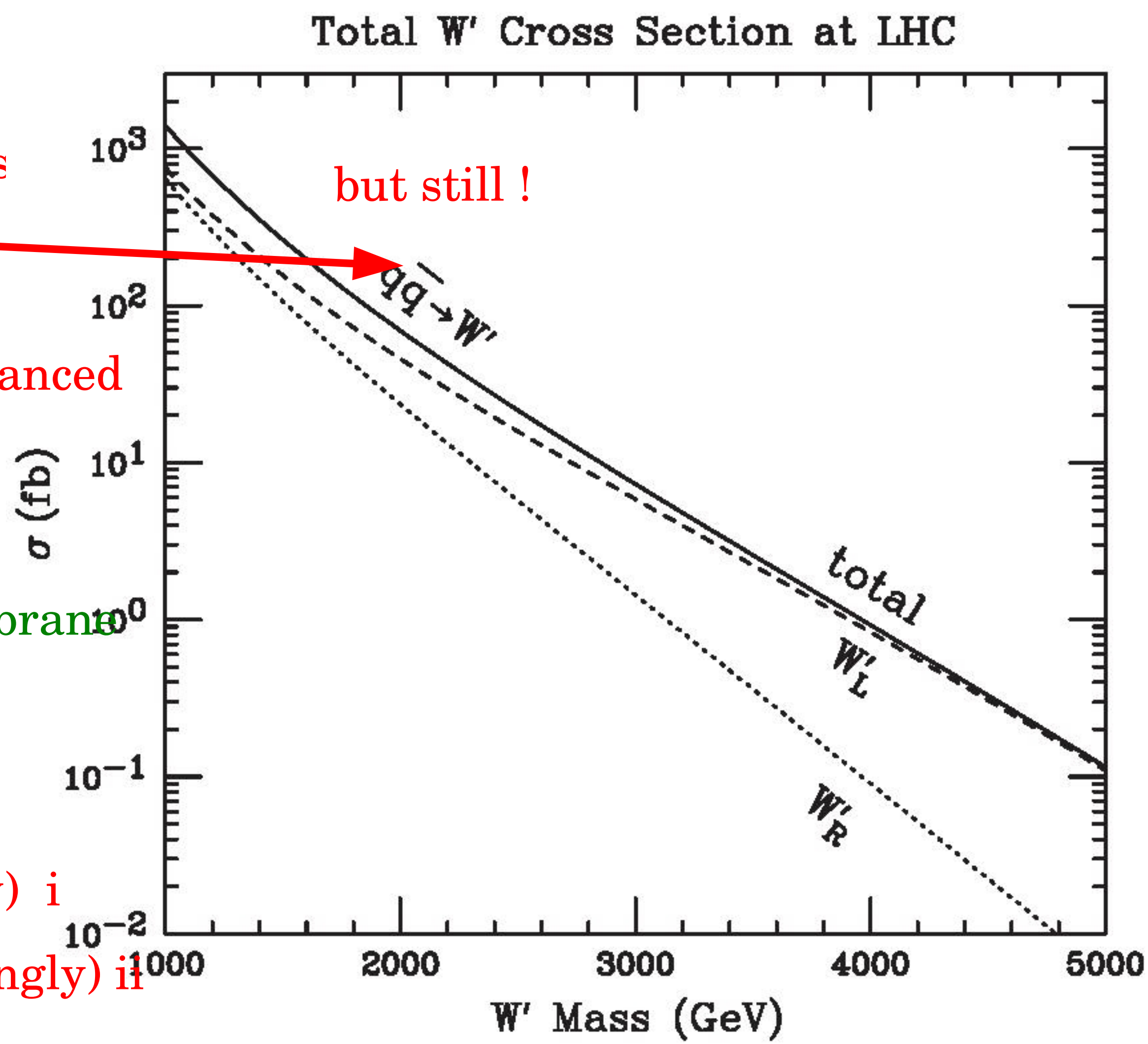
W' coupling to light quarks and leptons are suppressed

W' coupling to top and bottom are enhanced

→ two cases :

case i) $t_R$ close-to-flat profile in bulk
and $(t,b)_L$ profile close to TeV brane

case ii) vice-versa



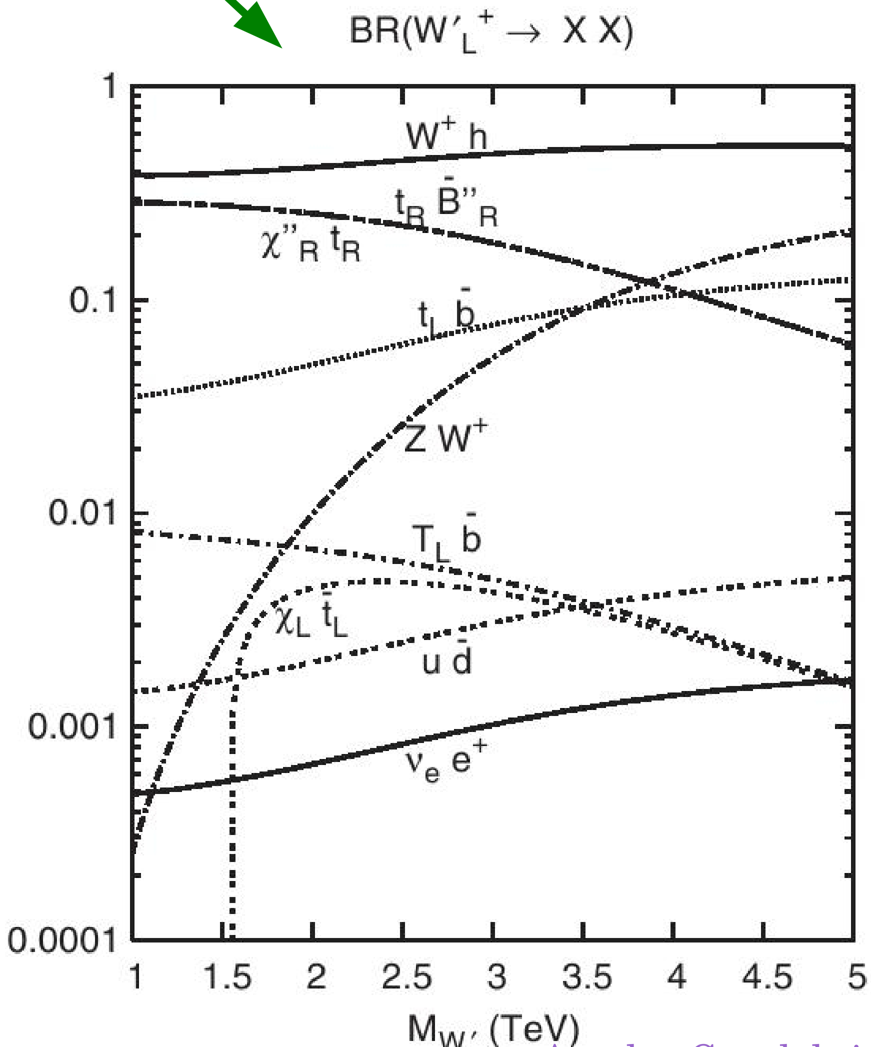

EW precision tests tend to prefer (mildly) i

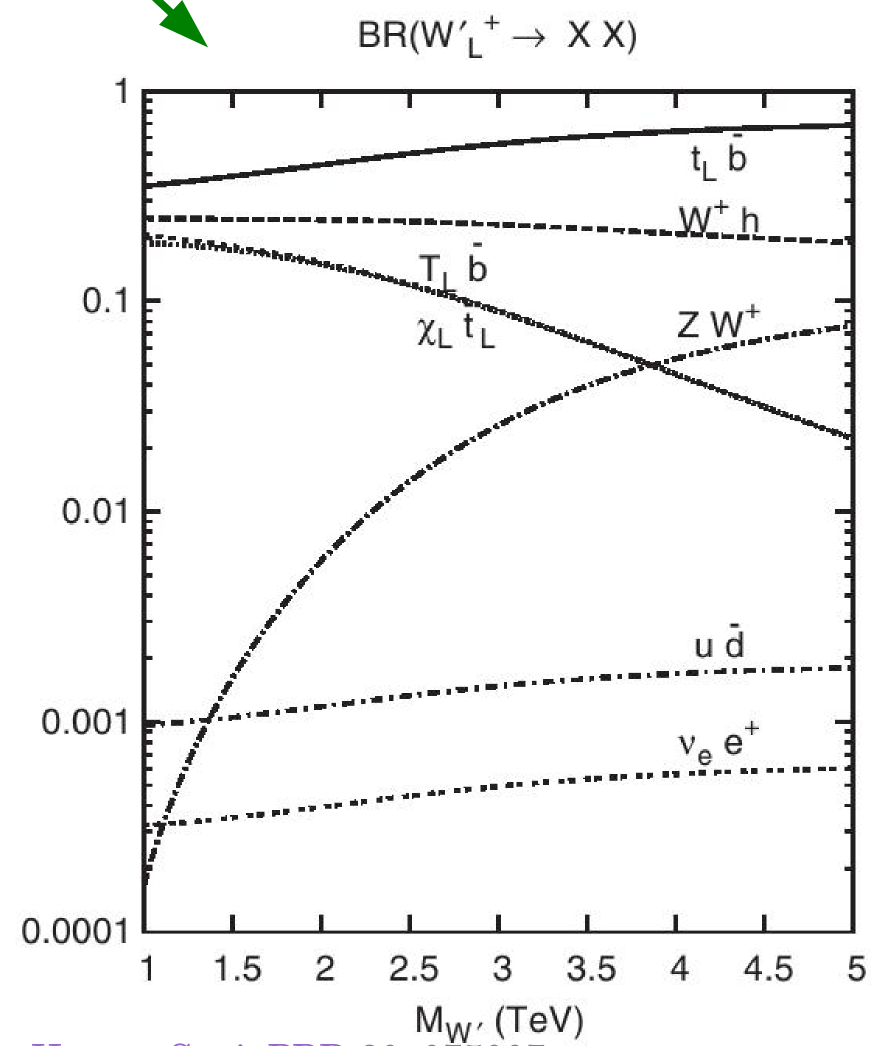
flavor precision tests tend to prefer (strongly) ii

**Bulk RS models** **Warped EW charged gauge boson decay**

i) $t_R$ close-to-flat profile in bulk and $(t,b)_L$ profile close to TeV brane

ii) vice versa



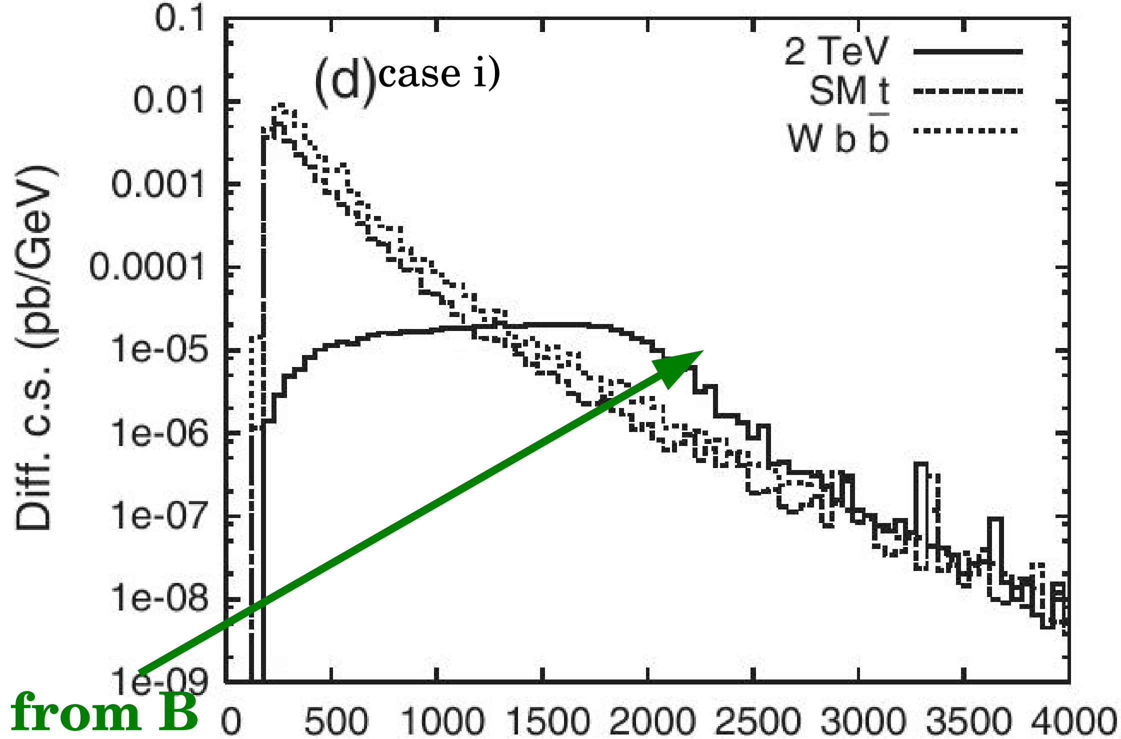

Agashe, Gopalakrishna, Han, Huang, Soni, PRD 80, 075007

# Bulk RS models

Agashe, Gopalakrishna, Han, Huang, Soni, PRD 80, 075007

## Warped EW charged gauge bosons

## tb channel




$$pp \rightarrow W' \rightarrow t\,\bar{b} \rightarrow W\,\bar{b}\,b \rightarrow l\,\nu\,\bar{b}\,b$$

$(l = e, \mu)$

**main SM Backgrounds (B)**

→ **single top and Wbb**

**possible separation of Signal (S) from B**

Wb angle cut, jet-mass cut, 2 btags,

$$M_{TWb\bar{b}} = p_{Tb} + p_{T\bar{b}} + \sqrt{p_{TW}^2 + m_W^2}$$

$M_{TWb} = (\sqrt{p_{TW}^2 + m_W^2} + p_{Tb})^2 - |P_{TW} + P_{Tb}|^2$ and $M_{TWb\bar{b}}$ mass window

| | | | | | |
|---|---|---|---|---|---|
| **case i)** | $M_{W'} = 2\,TeV$ | $L = 100\,fb^{-1}$ | (20 events) | $S/B = 2.5$ | $S/\sqrt{B} = 7$ |
| | $M_{W'} = 3\,TeV$ | $L = 300\,fb^{-1}$ | (7 events) | $S/B = 5.8$ | $S/\sqrt{B} = 4.5$ |
| **case ii)** | $M_{W'} = 2\,TeV$ | $L = 1000\,fb^{-1}$ | (30 events) | $S/B = 0.38$ | $S/\sqrt{B} = 3.4$ |

# Bulk RS models

Aguilar-Saavedra, PLB 625 (2005) 234, PLB 633 (2006) 792
Carena, Ponton, Santiago, Wagner, NPB 759 (2006) 202
Holdom, JHEP 03 (2007) 063
Skiba, Tucker-Smith, PRD75, 115010
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003
Contino Servant, JHEP 06 (2008) 026

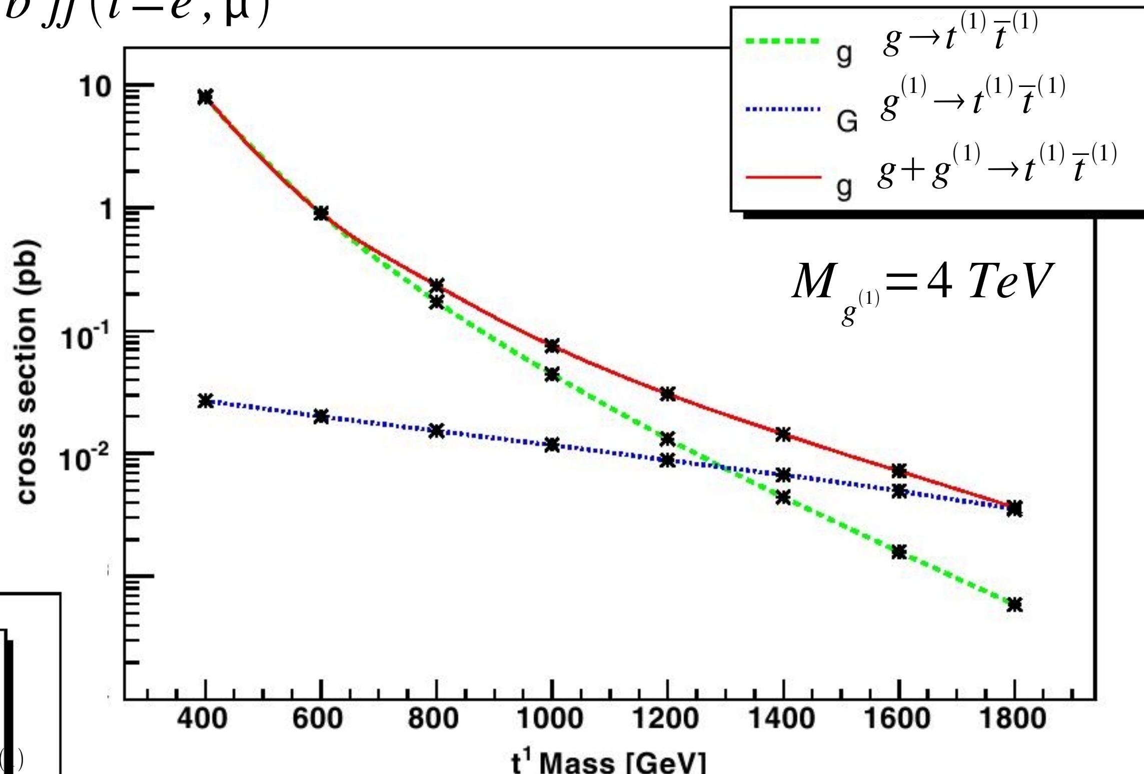
## 1 example of KK fermions search

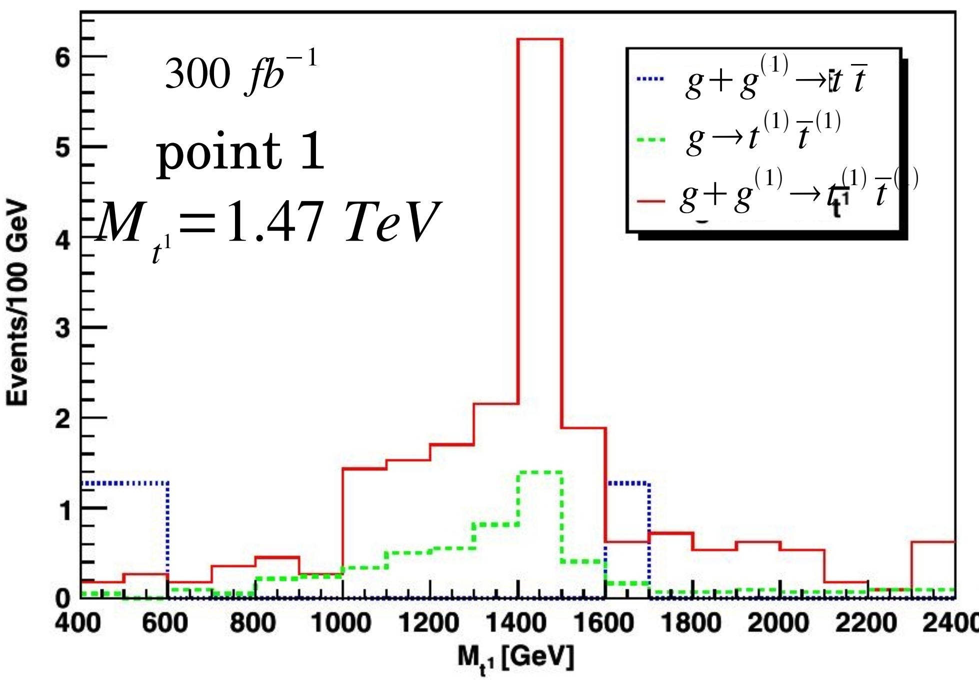
$$pp \to g + g^{(1)} \to t^{(1)} \bar{t}^{(1)} \to W^+ b W^- \bar{b} \to l^- \nu b \bar{b} jj \, (l = e, \mu)$$

**Backgrounds :**

SM model top pair prod. and W/Z + jets
top pair prod. from KK gluon decay (!)

high pT lepton, high pT jets, MET, Ht, 2b-tags, single jet from boosted W and Wb system requirement i.e. bottom having biggest $\Delta R$ w.r.t W




$5\sigma$ significance $S/\sqrt{S+B}$ at $300\ fb^{-1}$

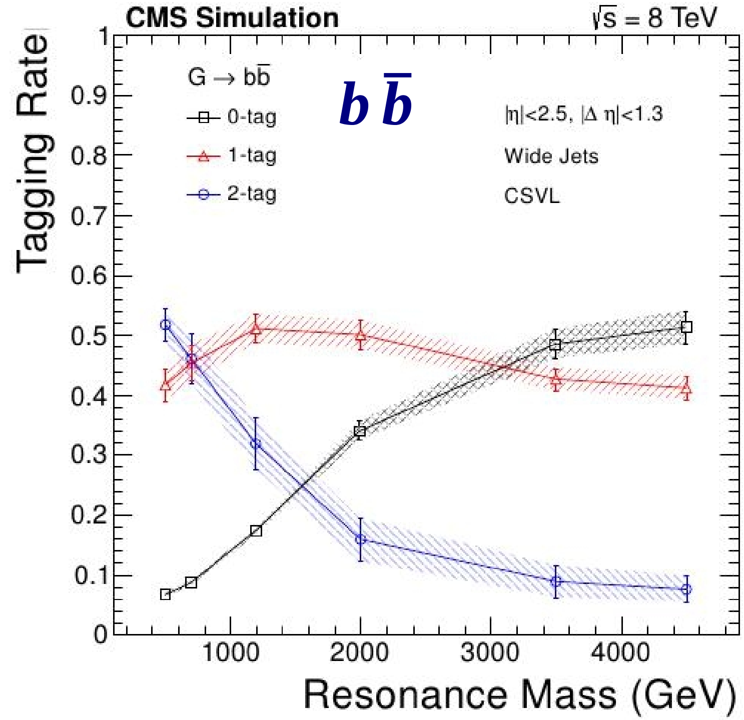
with K-factor = 1.5

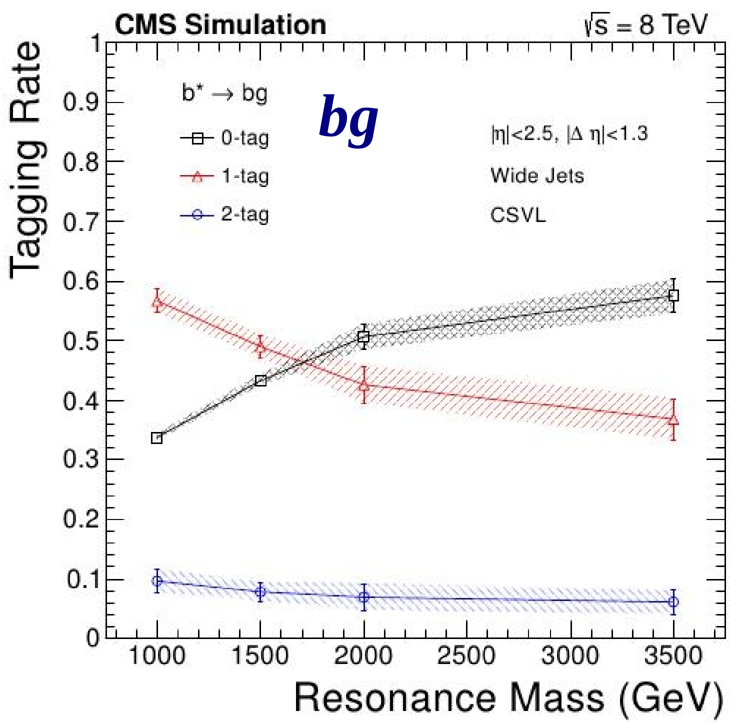
Carena, Medina, Panes, Shah, Wagner, PRD 77, 076003

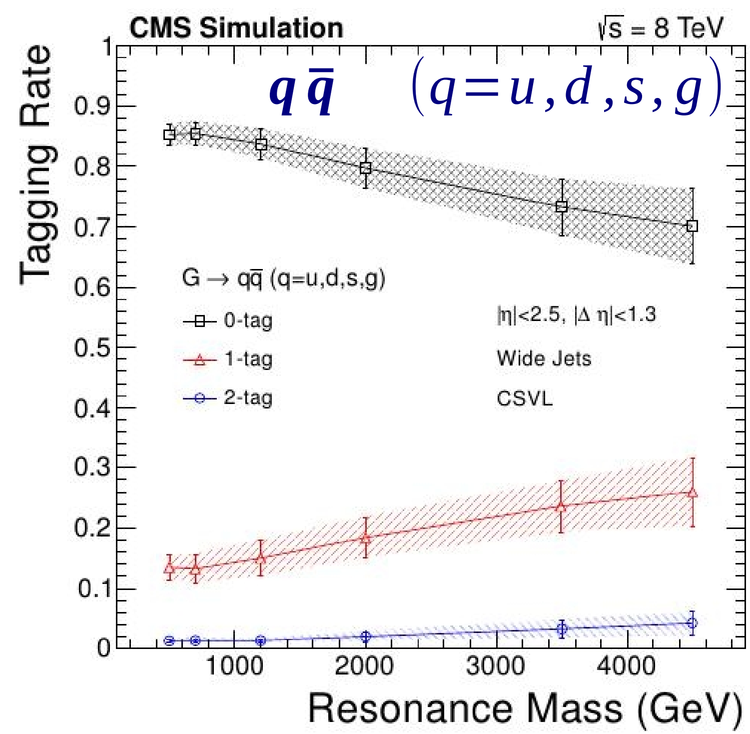
# resonant dijets (with b-jet)

CMS-EXO-12-023

## tagging rates



# Bulk RS models: KK gluon in all hadronic mode

$p\,p \rightarrow g^{(1)} \rightarrow t\,\bar{t} \rightarrow b\,\bar{b}\,j\,j\,j\,j$ **need**

**boosted top-quark jets algorithm**

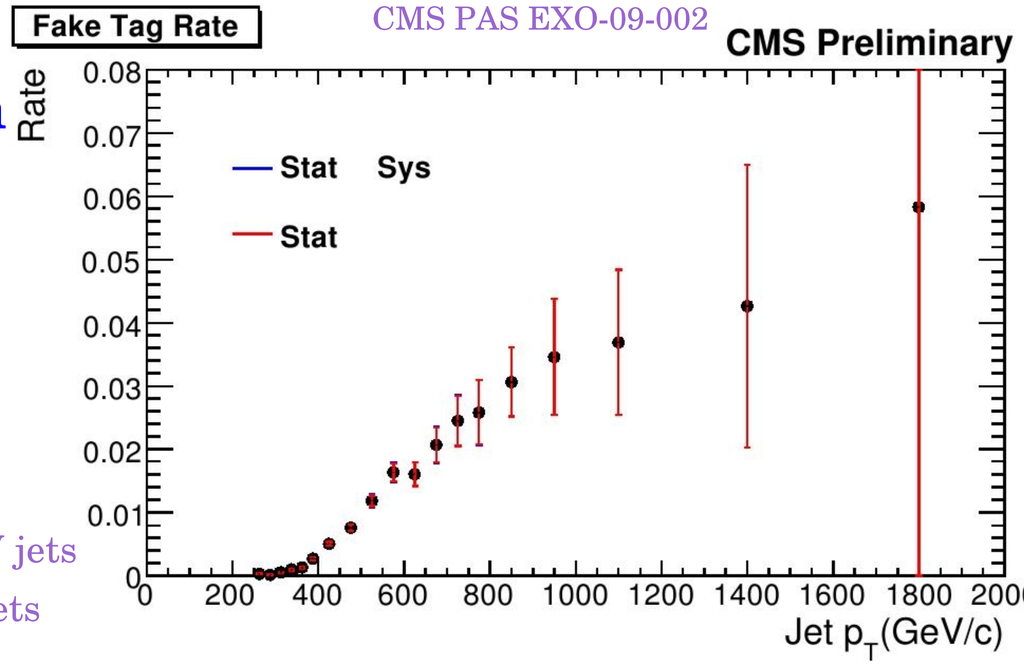
using Dokshitzer, Leder, Moretti, Webber, JHEP 08 (1997) 001, i.e. CA algorithm and Kaplan, Rehermann, Schwartz, Tweedie, PRL 101 (2008) 142001

similar to: Butterworth, Davison Rubin Salam, PRL 100 (2008) 242001, for Higgs jets

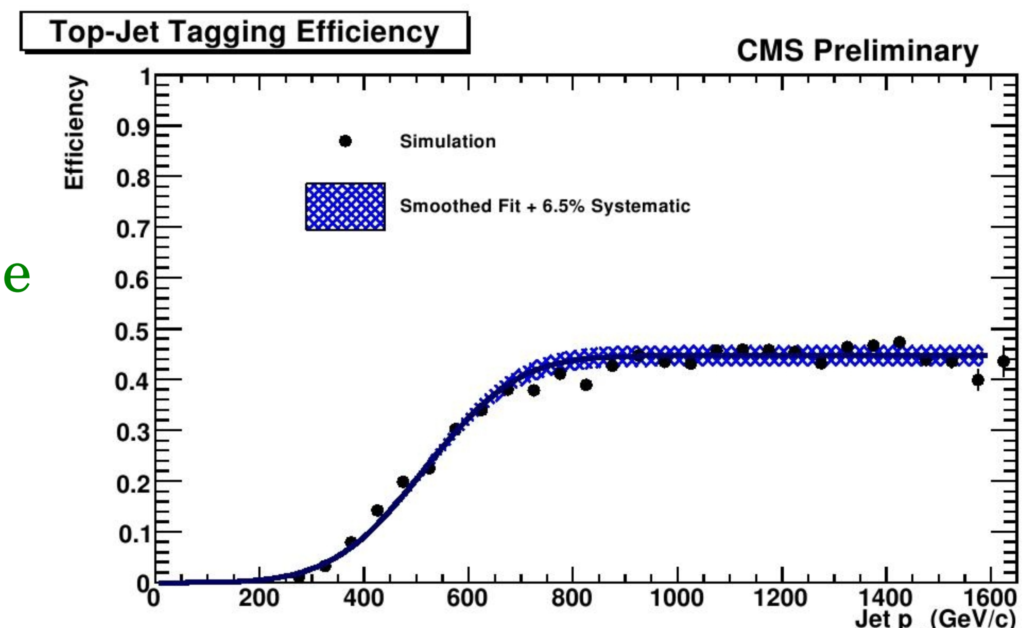
Butterworth, Cox, Fowshaw PRD65 (2002) 096014, for W jets

Butterworth, Ellis, Raklev, JHEP 05 (2007) 033, for W jets

CMS PAS EXO-09-002




cluster using a large jet radius
then iteratively decluster each jet
to search for jet structure and impose kinematic constraints



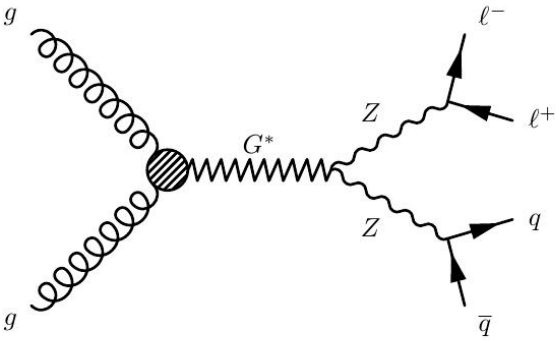


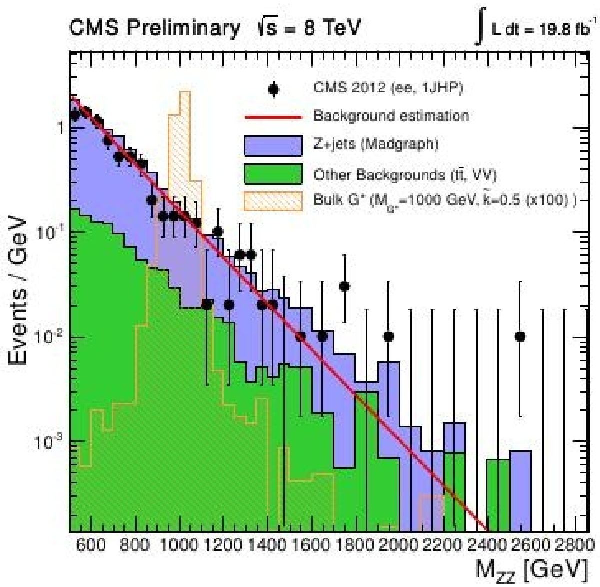
Moriond EW March 2010

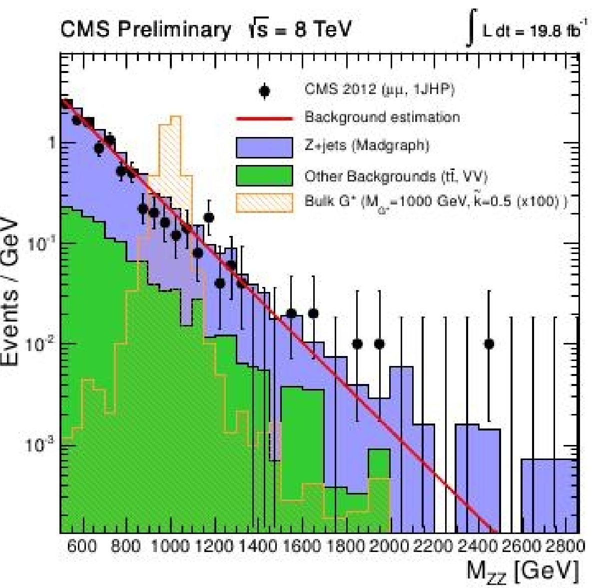
# semi leptonic resonant diboson (ZZ)

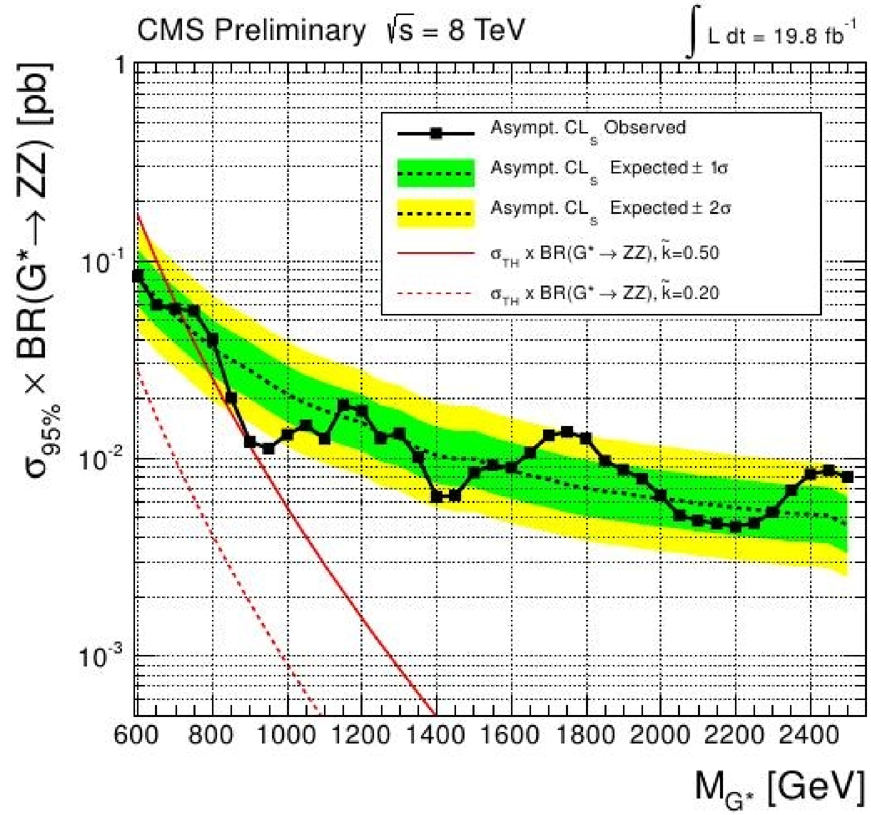
CMS-EXO-12-021

**aiming at $G_{KK}^{RS} \rightarrow ZZ$**



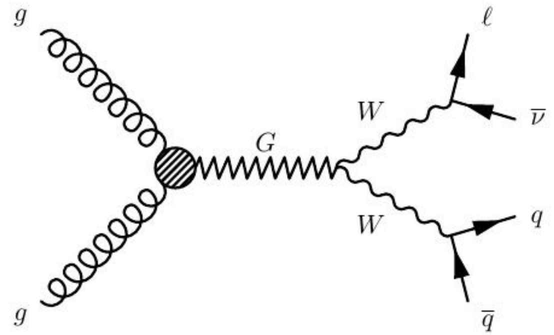

$m_{G_{KK}^{(1)}} > 710$ GeV

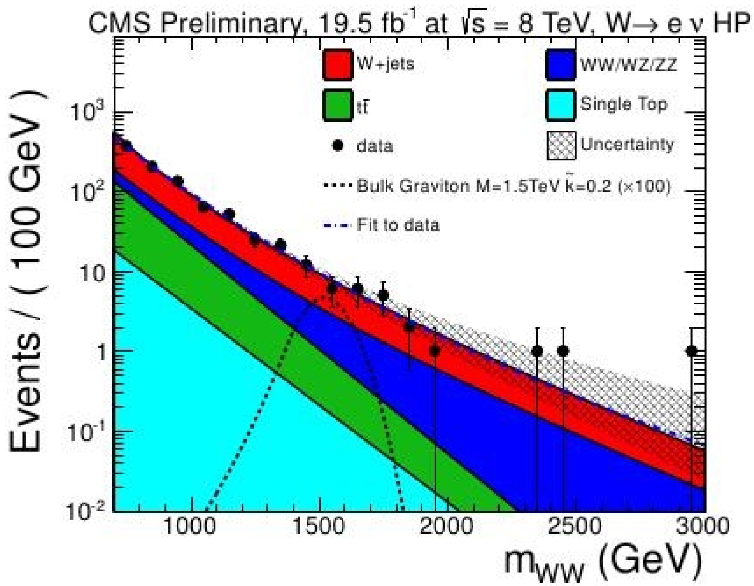
categorize into *ee* and μμ
and low (LP) and high (HP) purity

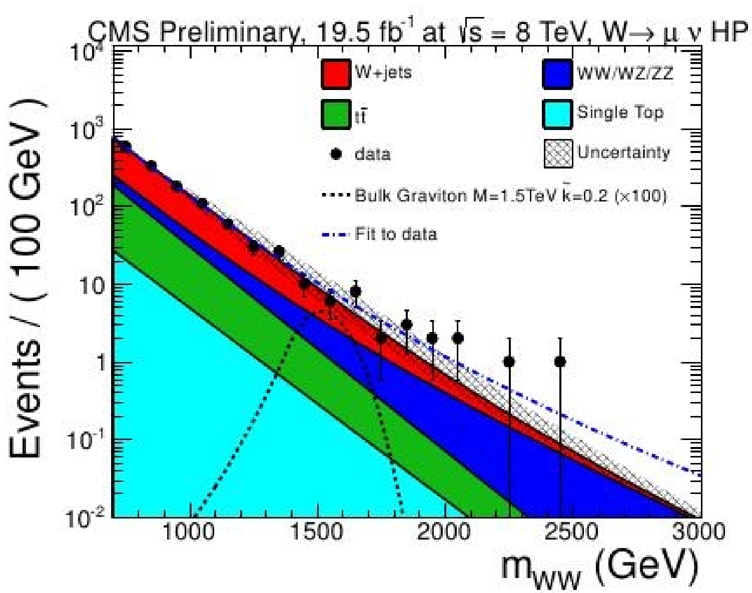
# semi-leptonic resonant diboson (WW)

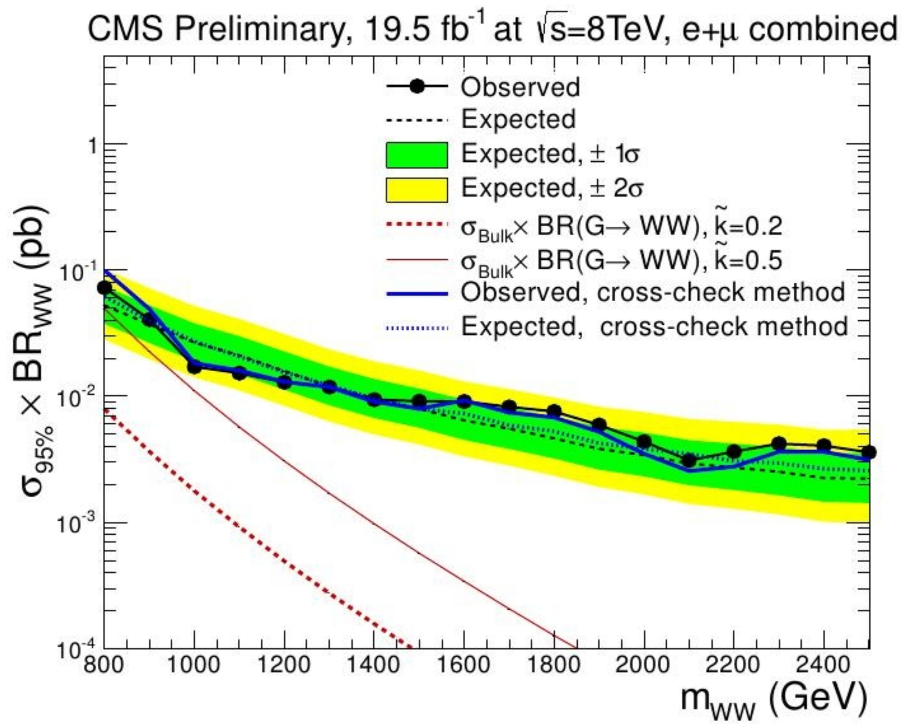
CMS-EXO-12-021

**aiming at $G_{KK}^{RS} \rightarrow WW$**



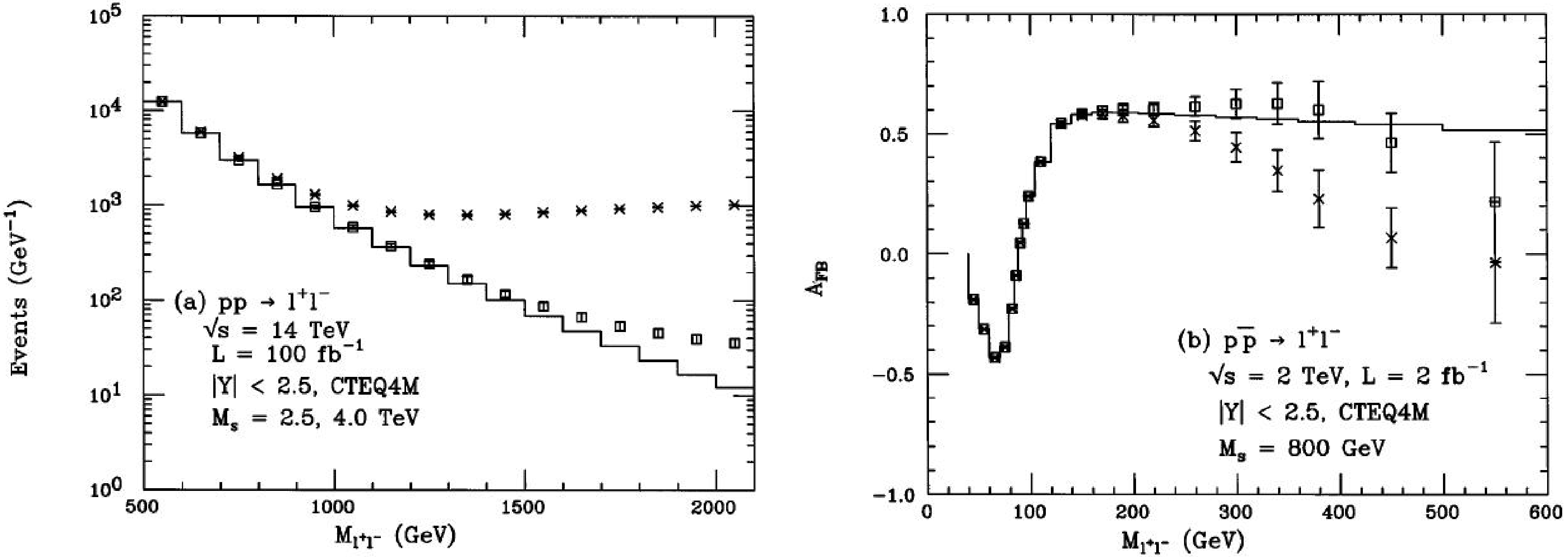




categorize into $e\nu$ and $\mu\nu$
and low (LP) and high (HP) purity

$$\sigma \cdot BR < 70 \;\; fb \; - \; 3 \;\; fb$$

**for $m_{G_{KK}^{(1)}}$ in the $0.8 - 2.5$ TeV range**

# ADD indirect

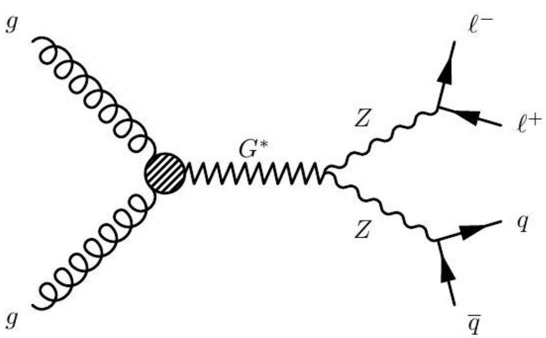


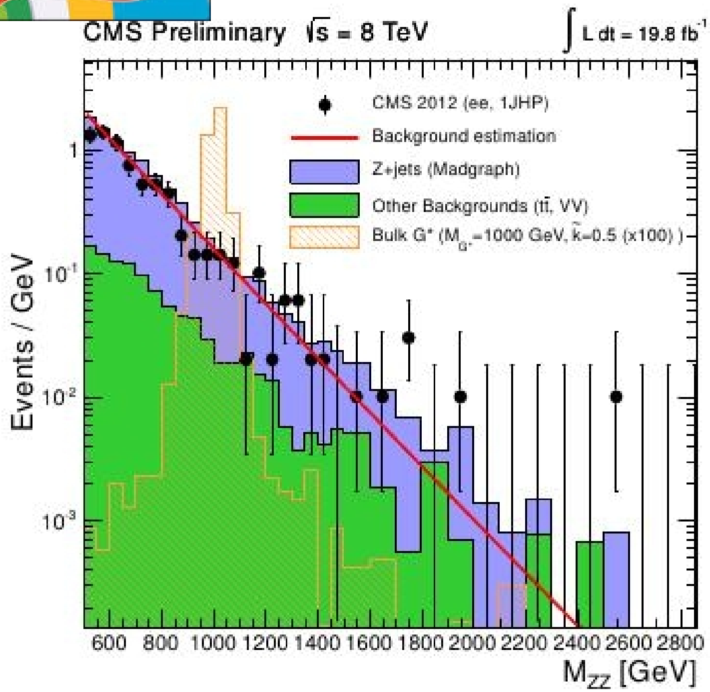

Hewett, PRL 82 (1999) 4765

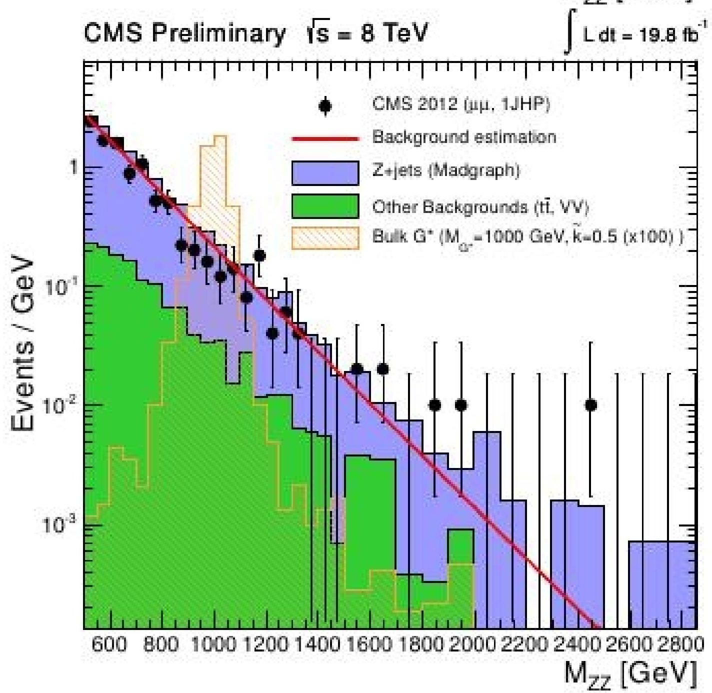
# resonant diboson (Z)

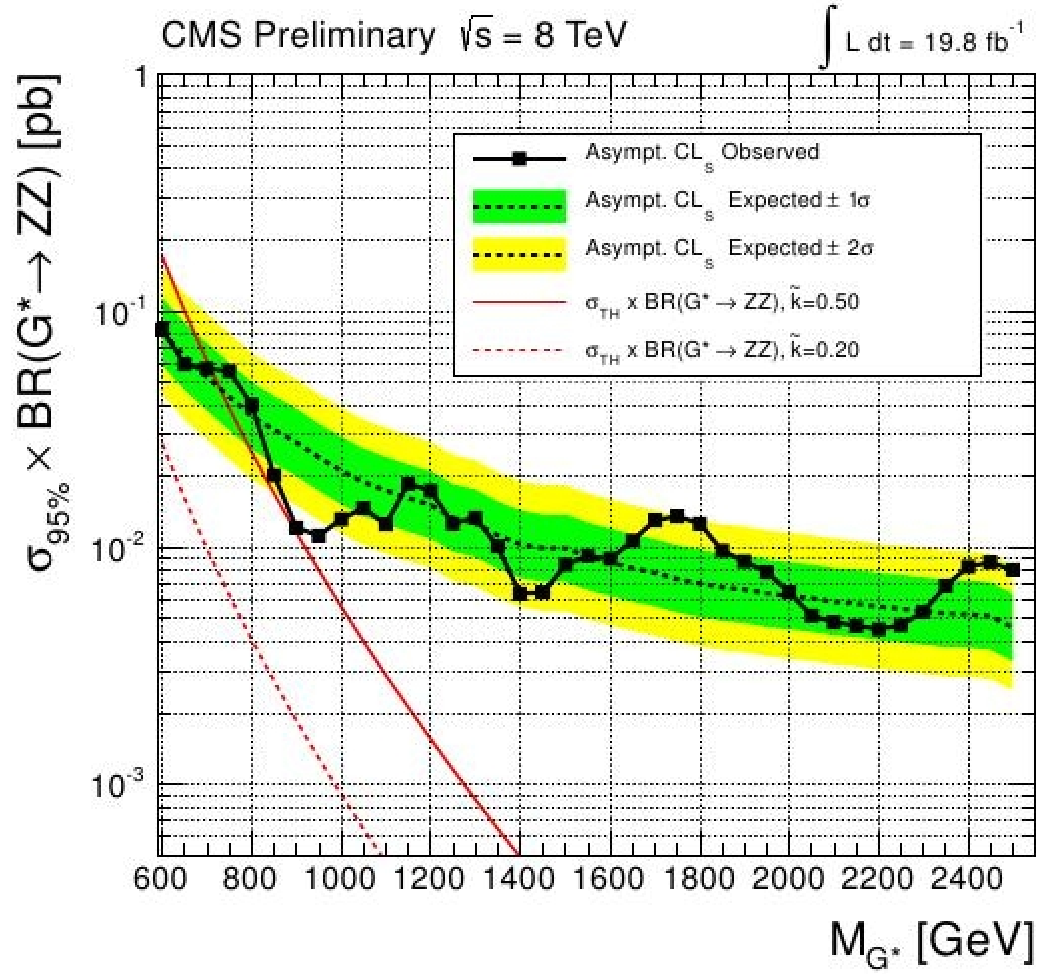
CMS-EXO-12-022

**aiming at $G_{KK}^{RS} \rightarrow ZZ$**



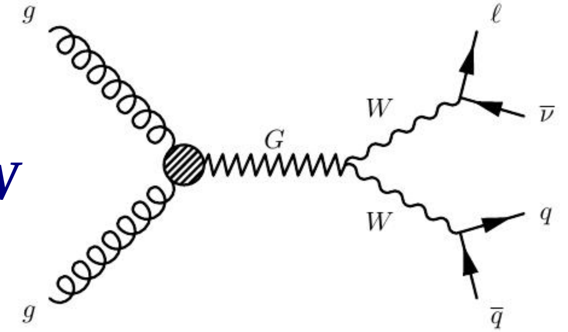



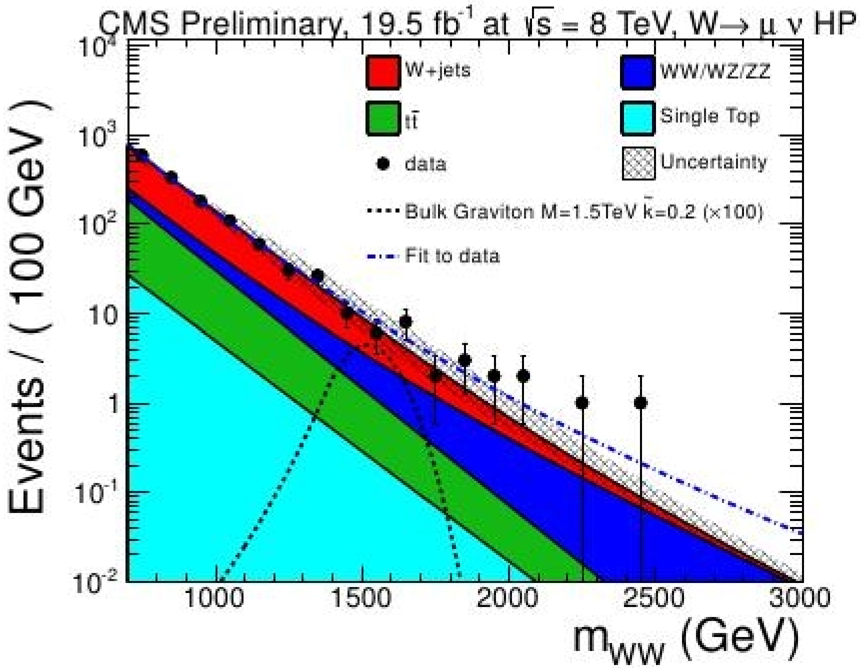

$m_{G_{KK}^{(1)}}$ **> 710 GeV** $(\ \tilde{k} = 0.5\ )$

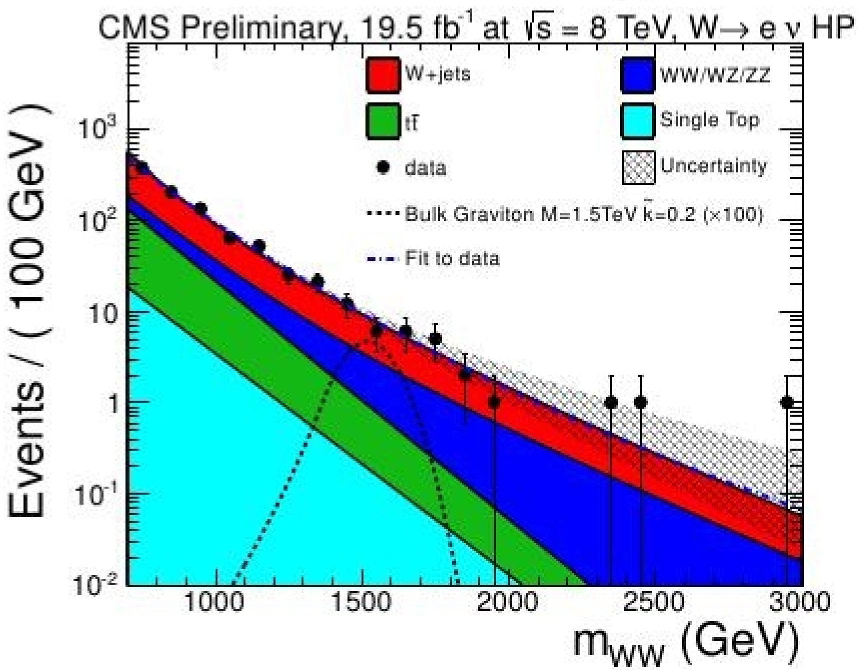
# resonant diboson (W)

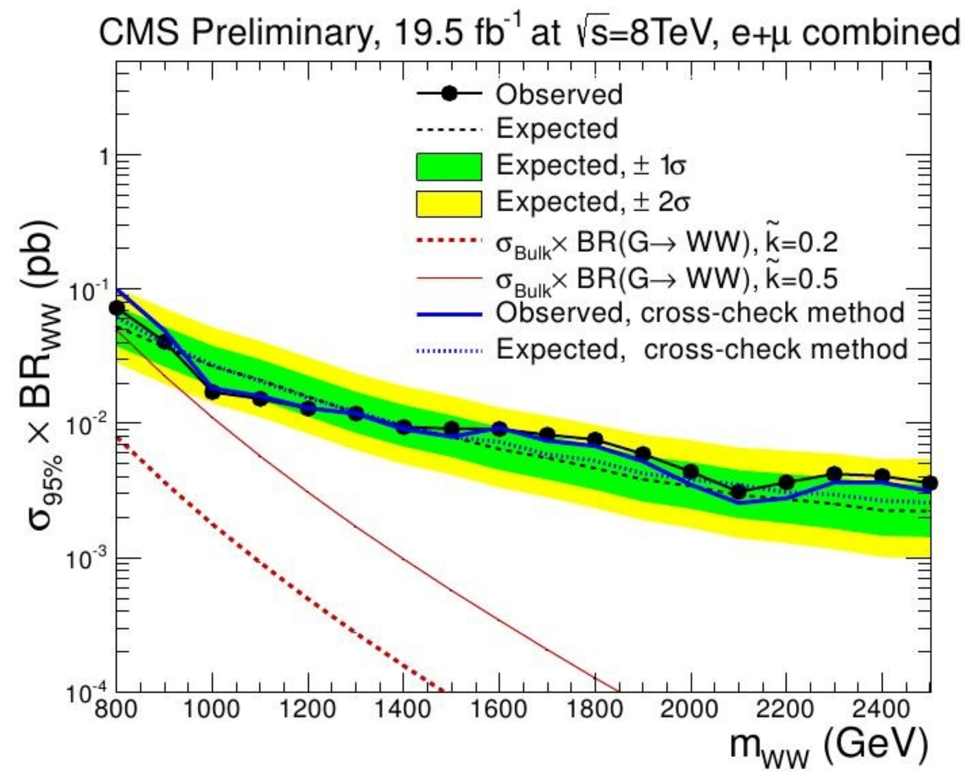
CMS-EXO-12-021

aiming at $G_{KK}^{RS} \to WW$




$\sigma \cdot BR < 70 \text{ fb} - 3 \text{ fb}$

for $m_{G_{KK}^{(1)}}$ in the $0.8 - 2.5$ TeV range