Composite Higgs dynamics with a better chance at CLIC than at LHC

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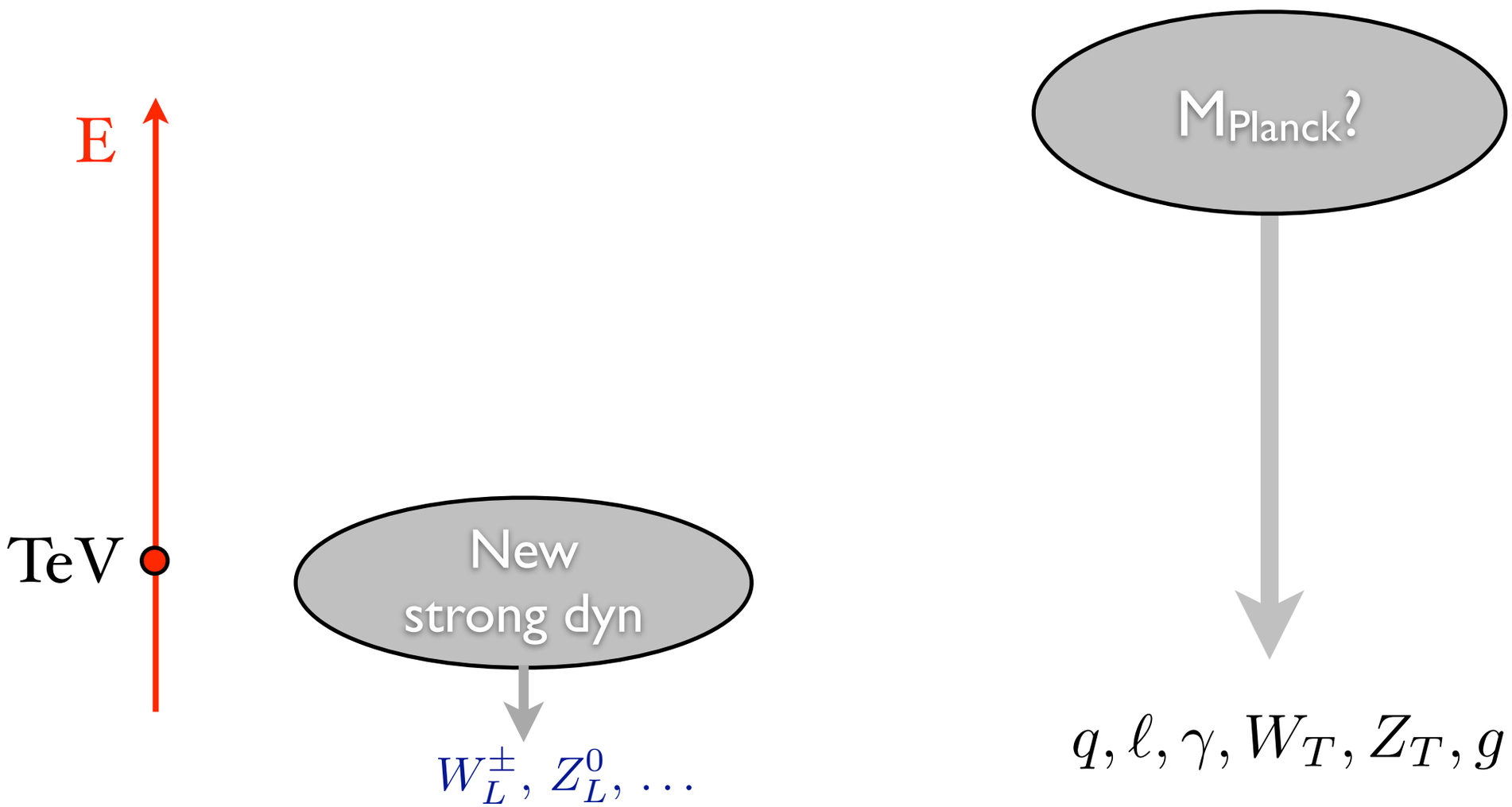
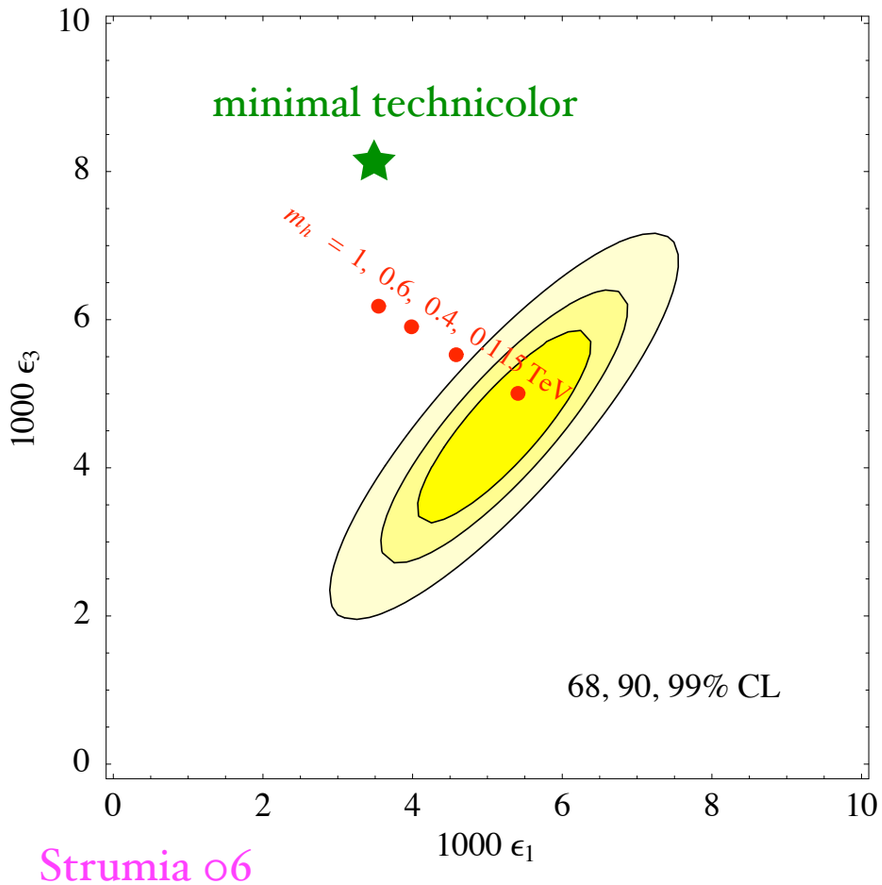
A composite electroweak symmetry breaking sector would be a logical solution to the hierarchy problem

Collider data display no signal of compositeness for quarks, leptons and ***transversely polarized*** vector bosons

Plausible scenario



Technicolor: not even a narrow light Higgs resonance



Strumia 06

$$\Delta\epsilon_3 \equiv \widehat{S} = \widehat{S}_{IR} + \widehat{S}_{UV}$$

$$\widehat{S}_{IR} = \frac{g^2}{96\pi^2}\ln(m_h/m_Z) > 0$$

$$\widehat{S}_{UV} \sim \frac{m_W^2}{m_\rho^2} \sim \frac{g^2}{96\pi^2}N_{TF}N_{TC} > 0$$

Peskin, Takeuchi '89

Absence of light Higgs necessarily implies new states, normally vectors, to 'unitarize' WW scattering below 2 TeV → embarassing $\widehat{S}_{UV} > 0$

Situation unchanged in 5D Higgsless models

Csaki,Grojean,Murayama,Pilo,Terning 03

Barbieri,Pomarol,Rattazzi 03

Pseudo-Goldstone Higgs

Georgi, Kaplan '84
Banks '84
Arkani-Hamed, Cohen, Katz, Nelson '02
Agashe, Contino, Pomarol '04

strong dynamics

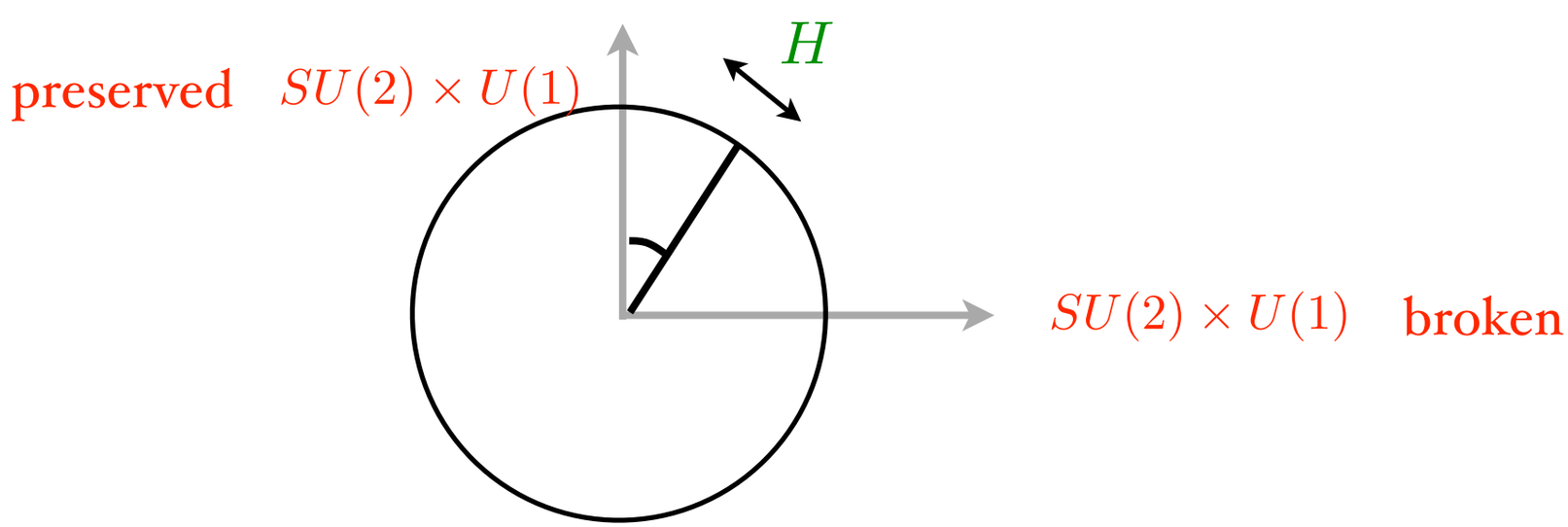
$$H = \begin{pmatrix} w^+ \\ h + iz^0 \end{pmatrix} \subseteq \mathcal{G}/\mathcal{H}$$

- minimal example

$H = SO(5)/SO(4)$

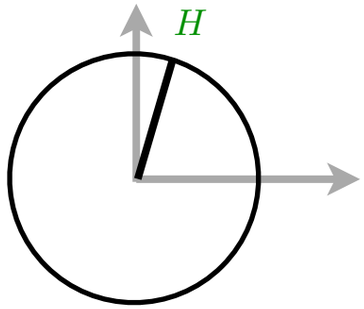
$\langle H \rangle \equiv v$

from vacuum alignment in coset space
controlled by small explicit breaking of $\mathcal{G}$



Conceivable to have v a bit smaller than Goldstone decay const. f

either by mild tuning or by Little Higgs mech



unwanted corrections to S,T,..etc suppressed with respect to technicolor

- resonances become heavier than 2 TeV

$$m_\rho > 2.5\,\mathrm{TeV} \qquad \widehat{S}_{UV} \sim \frac{m_W^2}{m_\rho^2} < 10^{-3}$$

- *h* behaves *approximately* like SM Higgs → $\widehat{S}_{IR}$ under control

- In practice $\frac{v^2}{f^2} \equiv \xi \sim 0.3$ sufficient to control EWPT in some explicit models

PseudoGoldstone Higgs models are not so exotic

- technicolor $SU(2)_{TC}$ with 4 fermion doublets sits in this class
  $H \subset SU(4)/Sp(4)$

  Evans, Galloway, Luty, Altair Tacchi '10

- there exists several *calculable* realizations in 5D

  Agashe, Contino, Pomarol '04

- can think of extended cosets $SU(4)/Sp(4) = H \oplus \text{singlet}$

  $SO(6)/SO(4) \times SO(2) = H_1 \oplus H_2$

  Gripaios,Pomarol,Riva,Serra, 09
  Mrazek,Pomarol,RR,Redi,Serra,Wulzer '10

Flavor remains a generic difficulty like in TC.
But interesting solution is provided in 5D by allowing for small mixing between elementary and composite fermions (Kaplan mechanism)

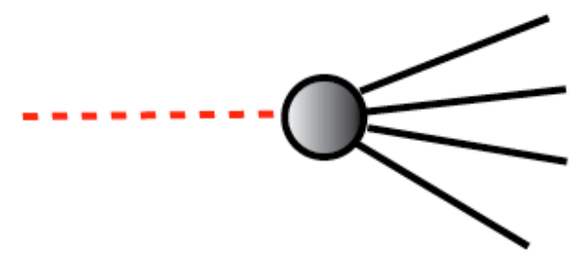
In order to produce the mass of the top, the best option is probably to allow for a fully composite t_R

All models are broadly described by to parameters
(up to O(1) coefficients)

the mass of the resonances m_ρ

$\mathcal{G}/\mathcal{H}$ decay constant f

f controls Higgs interactions $\frac{H}{f}$



$g_\rho \equiv \frac{m_\rho}{f}$ defines the coupling of the composites

Naive dimensional analysis: $g_\rho \lesssim 4\pi =$ maximally strong

Higgs potential and tuning

$$V(H) = \frac{\alpha_{SM}}{4\pi} F(H/f)$$

leading effects
normally from top
$\alpha_{SM} \rightarrow \alpha_t$

✦ generically expect $v \equiv \langle H \rangle \sim f$

✦ $v < f$ requires $O(\frac{v^2}{f^2})$ tuning of the potential

$$\xi \equiv \frac{v^2}{f^2}$$

measures the plausibility of the scenario

Phenomenology

- production of resonances (vectors, top partners,...)

- anomalous Higgs (top) couplings → Effective Lagrangian

Effective Lagrangian for composite Higgs

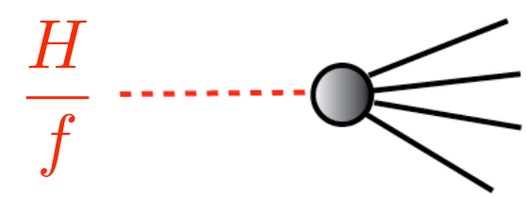
Giudice, Grojean, Pomarol, Rattazzi 07

Principles

- ✦ Goldstone symmetry and selection rules
- ✦ Naive counting of powers of g_ρ and m_ρ

Two types of effects

I. non-linear Higgs self coupligs controlled by $\frac{1}{f}$



II. Form factors: higher derivatives controlled by $\frac{1}{m_\rho}$ $\left(\frac{\partial_\mu}{m_\rho}, \frac{F_{\mu\nu}}{m_\rho^2}, \ldots\right)$

grossly $m_\rho >> f$

Effective Lagrangian for composite Higgs

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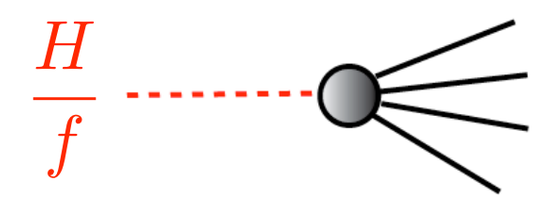

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subdominant

grossly $m_\rho >> f$

General parametrization of *Higgslike scalar h*

Contino, Grojean, Moretti, Piccinini, RR '10

$$
\begin{aligned}
\mathcal{L} \;=\;& \frac{1}{2}(\partial_\mu h)^2 + \frac{M_V^2}{2}\mathrm{Tr}\left(V_\mu V^\mu\right)\left[1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \ldots\right] - m_i\bar{\psi}_{Li}\left(1 + c\frac{h}{v}\right)\psi_{Ri} + \text{h.c.} \\
+\;& \frac{1}{2}m_h^2 h^2 + d_3\,\frac{1}{6}\left(\frac{3m_h^2}{v}\right)h^3 + d_4\,\frac{1}{24}\left(\frac{3m_h^2}{v^2}\right)h^4 + \ldots \\
+\;& c_g\frac{\alpha_s}{4\pi}\frac{h}{v}G_{\mu\nu}G^{\mu\nu} + c_\gamma\frac{\alpha}{4\pi}\frac{h}{v}F_{\mu\nu}F^{\mu\nu}
\end{aligned}
$$

c flavor universal in minimal flavor violating set up

✦ Standard Model: $a = b = c = d_3 = 1$ $\qquad c_g = c_\gamma = 0$

✦ h = pseudo-Goldstone implies additional constraints

$SO(5)/SO(4)$ Pseudo-Goldstone Higgs

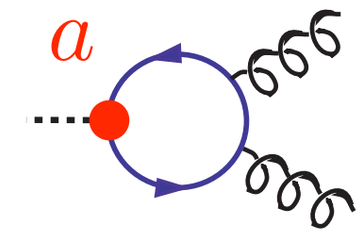
Agashe, Contino, Pomarol '04

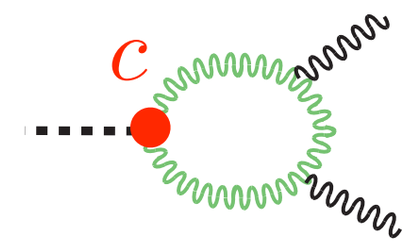
3 parameters

$a = \sqrt{1 - v^2/f^2}$ $\quad b = 1 - 2v^2/f^2$ model independent

$c,\ d_3 \ = \ 1 + O(v^2/f^2)$ model dependent

$c_g,\ c_\gamma \ \sim \ \dfrac{\alpha_t}{4\pi}$ controlled by small explicit SO(5) breaking NEGLIGIBLE!





✦ Leading order in v^2/f^2 → 3 independent effective operators

$$\mathcal{L}_{eff} \ = \frac{1}{2f^2}\partial^\mu \left(H^\dagger H\right) \partial_\mu \left(H^\dagger H\right) \ + \ y \left(\frac{c_y}{f^2} H^\dagger H \, \bar{\psi}_L H \psi_R + \text{h.c.}\right) - \ \frac{c_6 \lambda}{f^2} \left(H^\dagger H\right)^3$$

$$a = 1 - \frac{1}{2}\frac{v^2}{f^2} \qquad b = 1 - 2c_H \frac{v^2}{f^2} \qquad c = 1 - \left(\frac{c_H}{2} + c_y\right)\frac{v^2}{f^2}$$

Deviations in Higgs production and decay controlled by a and c

$$\frac{\Gamma(h \to gg)}{\Gamma(h \to gg)|_{SM}} = \frac{\Gamma(h \to f\bar{f})}{\Gamma(h \to f\bar{f})|_{SM}} = c^2$$

$$\frac{\Gamma(h \to VV)}{\Gamma(h \to VV)|_{SM}} = a^2$$

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)|_{SM}} = a^2 \left[1 + R(1 - c/a)\right]^2 \sim a^2$$

$$R \sim 0.22 \div 0.28$$

- LHC with 300 fb^{-1} sensitive to $\xi \equiv \frac{v^2}{f^2} \sim 0.1 - 0.4$
- In principle pseudo-Goldstone hypothesis can be tested by suitable ratios of rates

Composite h fails to fully unitarize VV scattering

$$\mathcal{A}(VV \to VV) = \frac{s}{v^2}(1-a^2) \overset{\text{Goldstone}}{=} \frac{s}{f^2}$$

$$\mathcal{A}(VV \to hh) = \frac{s}{v^2}(a^2-b) = \frac{s}{f^2}$$

I. strong VV scattering direct signal of Higgs compositeness

$$\sigma\left(pp \to V_L V_L' X\right) = \left(\frac{v^2}{f^2}\right)^2 \sigma\left(pp \to V_L V_L' X\right)_{\not{H}}$$

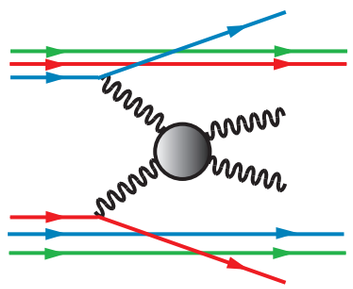
sensitivity with 300 fb^{-1}

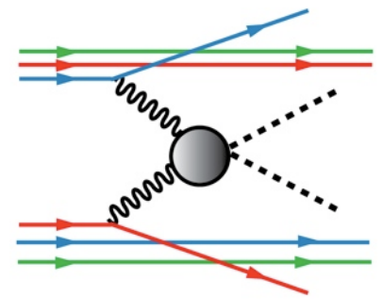
$$\frac{v^2}{f^2} = 0.5 - 0.7$$

Bagger et al., '95

II. Strong double Higgs production related to strong VV scattering by custodial O(4) symmetry

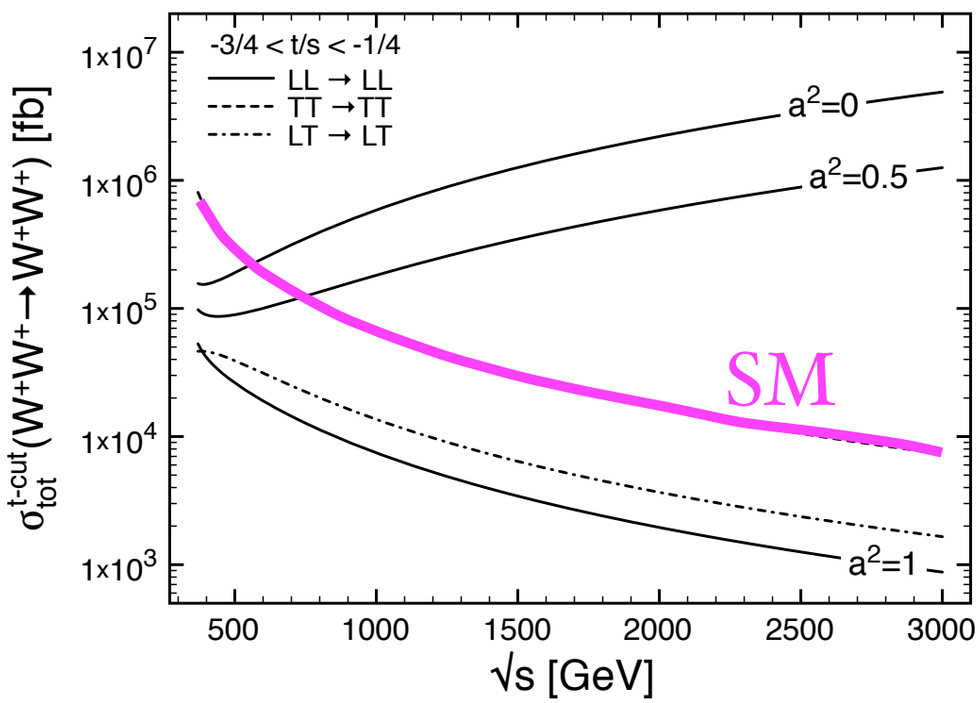
VV → VV versus VV → hh

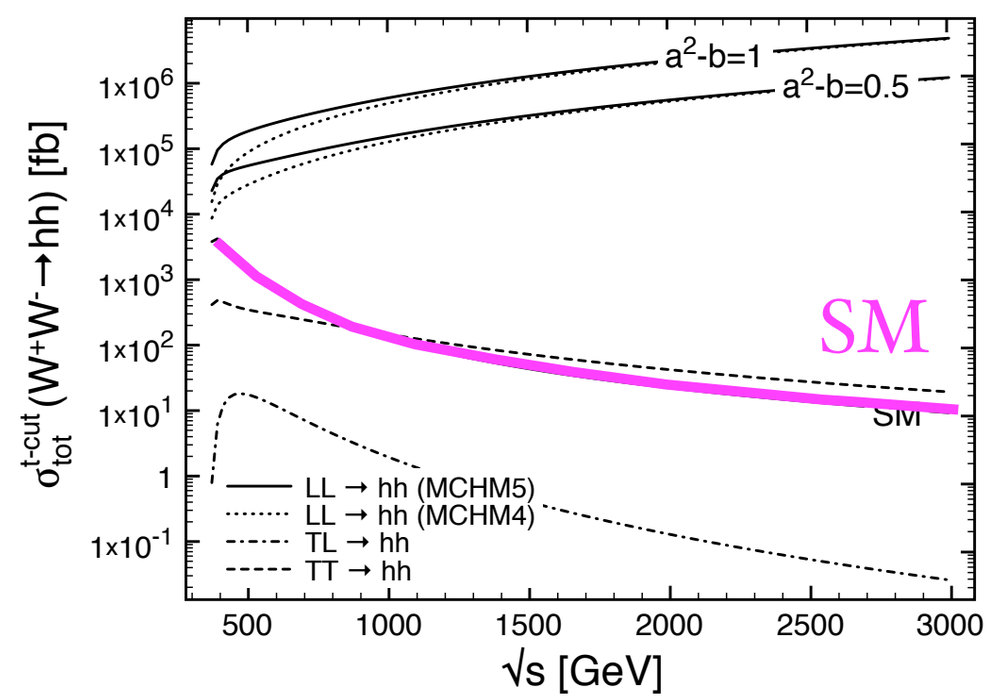




$$\mathcal{A}(VV \to VV) \simeq \frac{s}{v^2}(1 - a^2)$$

$$\mathcal{A}(VV \to hh) \simeq \frac{s}{v^2}(b - a^2)$$





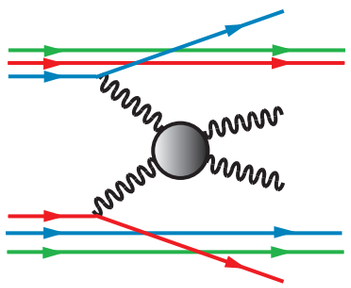
$\sigma(V_T V_T \to V_T V_T)$

large in SM by
'numerical accident'

$\sigma(VV \to hh)$

beats SM as expected
but final state
more difficult to detect

VV → VV versus VV → hh



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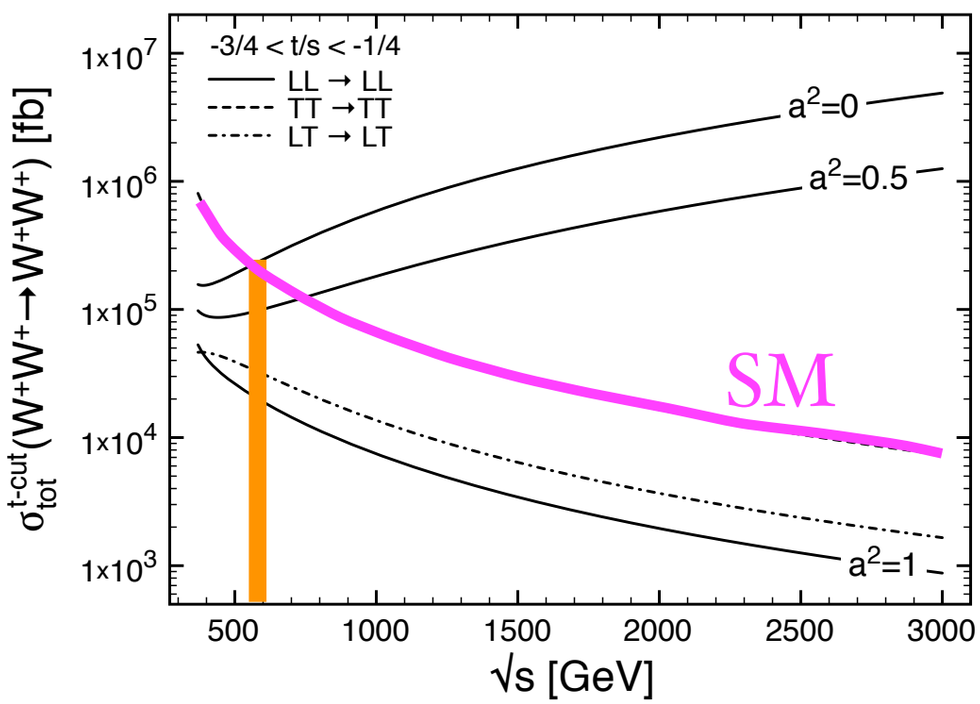

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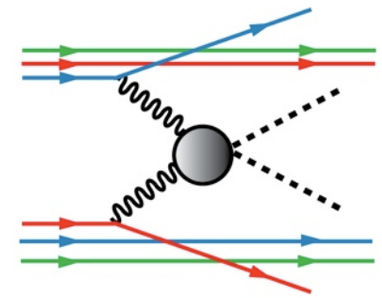

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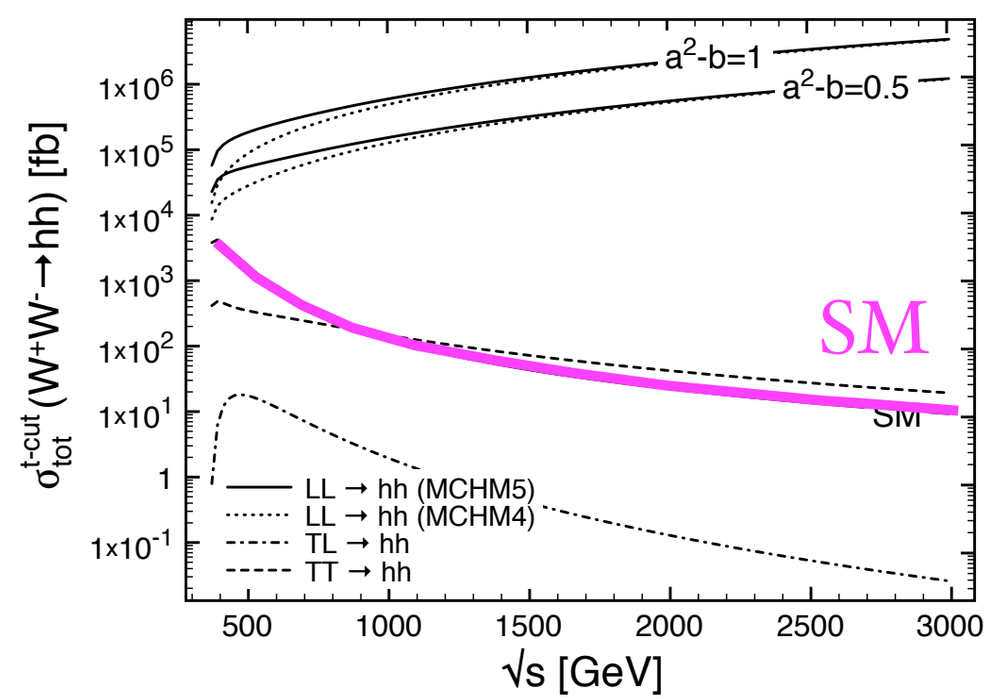

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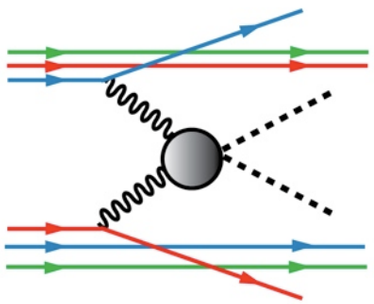
VV➔ hh at the LHC



Contino, Grojean, Moretti, Piccinini, RR
arXiv:1002.1011

- $hh \longrightarrow bbbb$ QCD background too big
- $hh \longrightarrow 4W \longrightarrow \text{leptons} + \text{jets} + \not{E}_T$ doable...

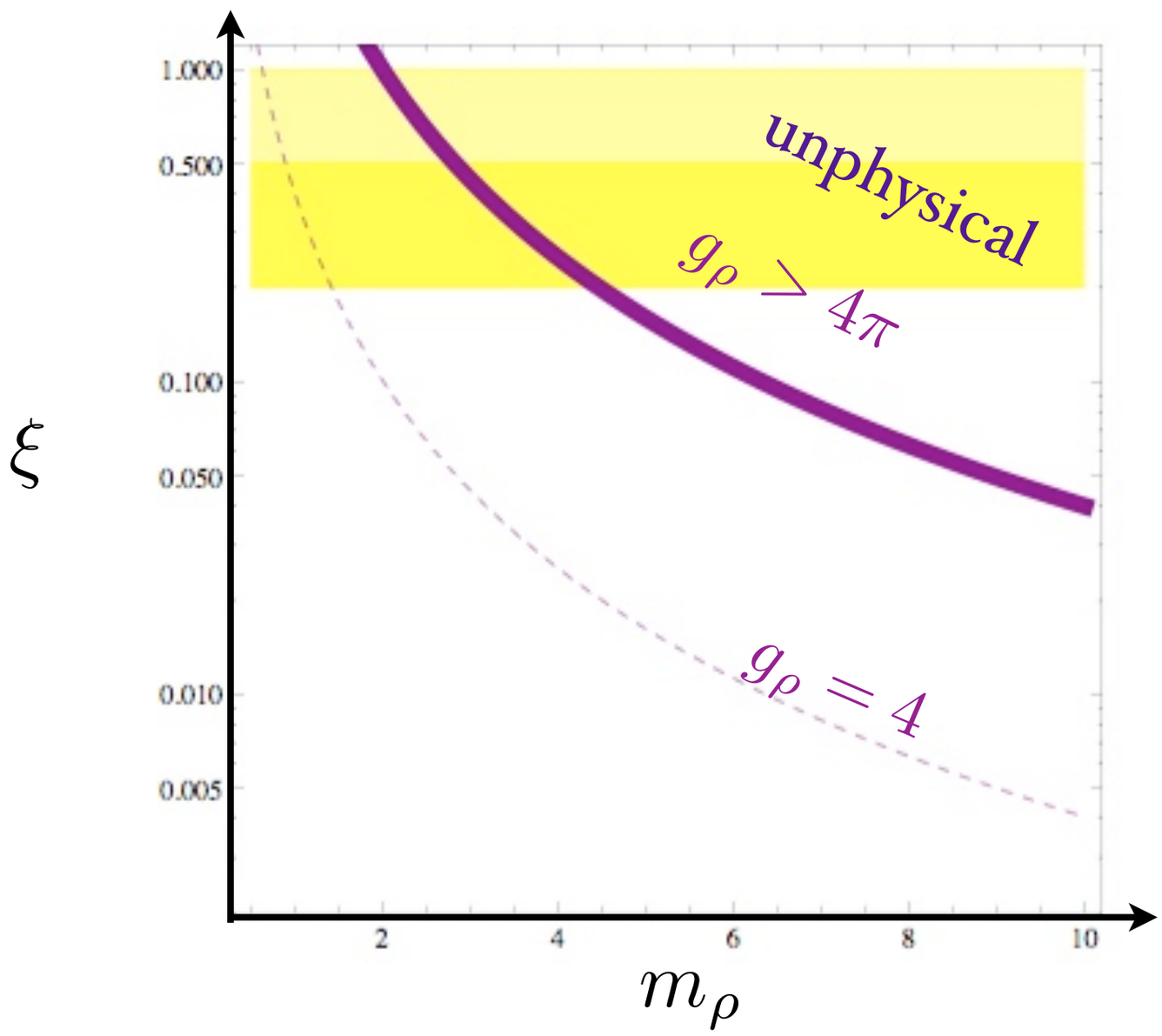
Visible signal for $\dfrac{v^2}{f^2} = 0.5$ at luminosity upgrade (not too encouraging)

Significance		3 leptons	2 leptons
MCHM4	$\xi = 1$	3.1 (10.3)	3.2 (10.3)
	$\xi = 0.8$	2.1 (7.2)	2.1 (6.9)
	$\xi = 0.5$	0.9 (3.4)	1.0 (3.2)
MCHM5	$\xi = 0.8$	2.5 (8.2)	2.5 (8.2)
	$\xi = 0.5$	1.5 (5.3)	1.6 (5.2)

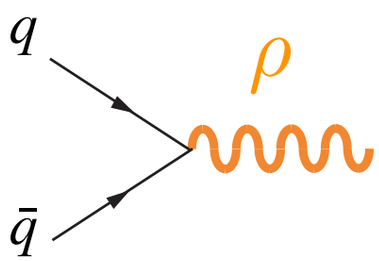
$3\ ab^{-1}$

Cartoon of parameter space

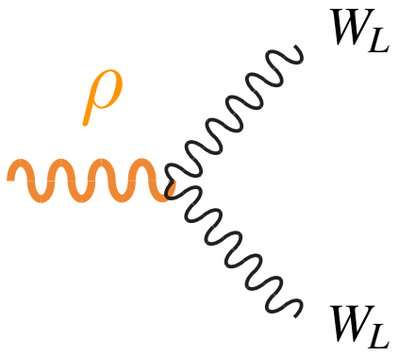
$$\sqrt{\xi}\, m_\rho \;=\; g_\rho v < 2\,\mathrm{TeV}$$



★ vector resonances (example)

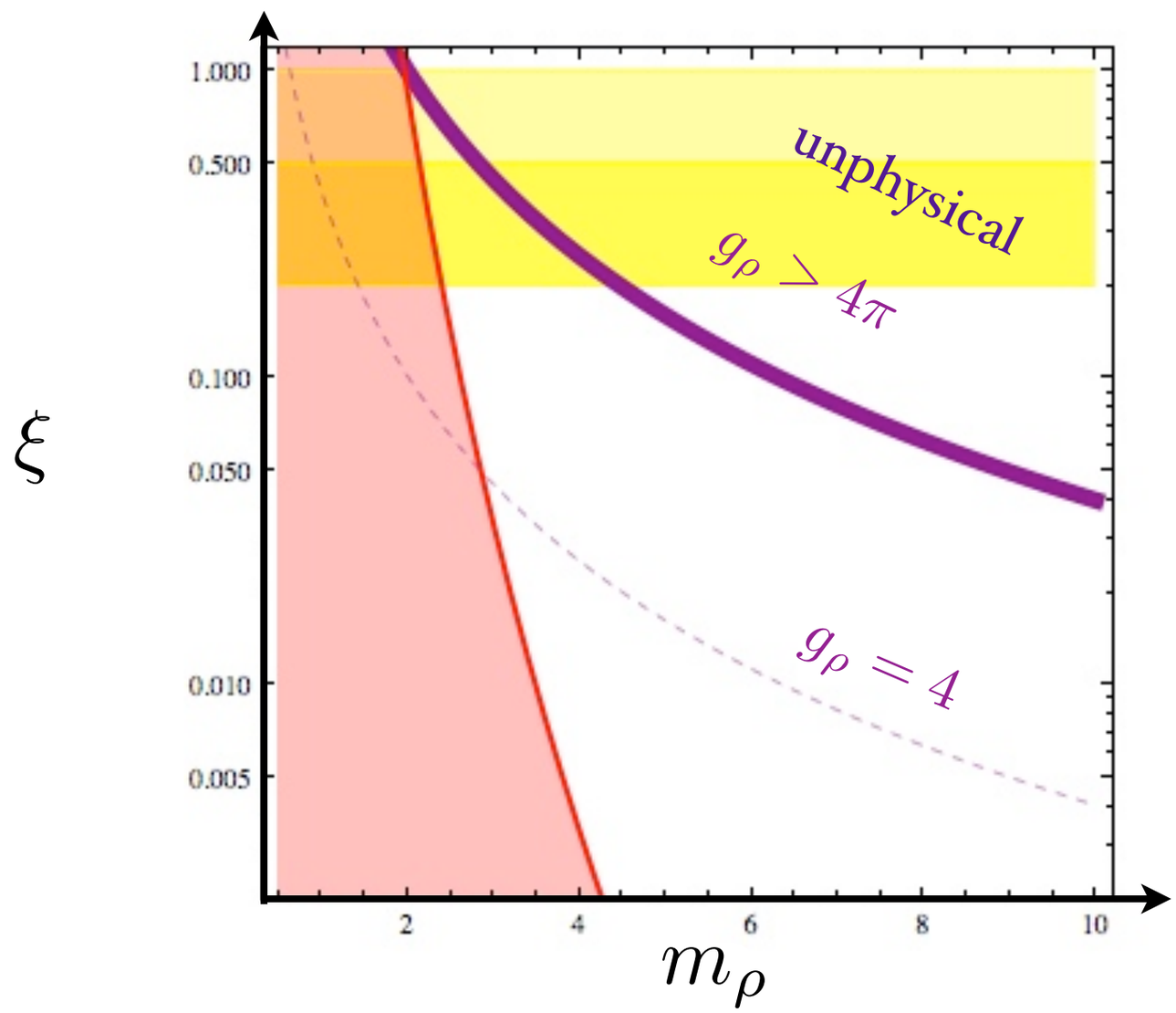


$$= \frac{g_W^2}{g_\rho} \ll g_W$$



$$= g_\rho$$

resonances couple 'superweakly' to light fermions



1 ab^{-1} LHC reach from Agashe et al. arXiv:0709.0007

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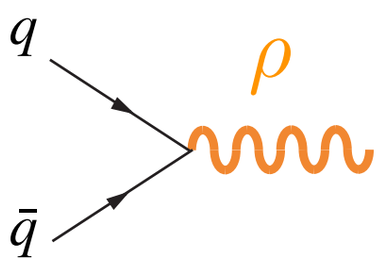

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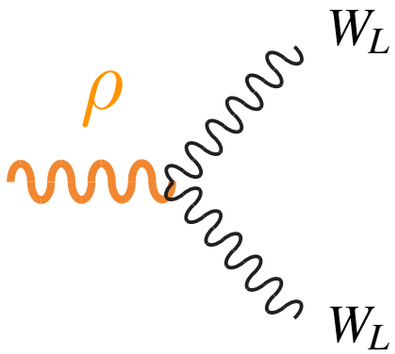

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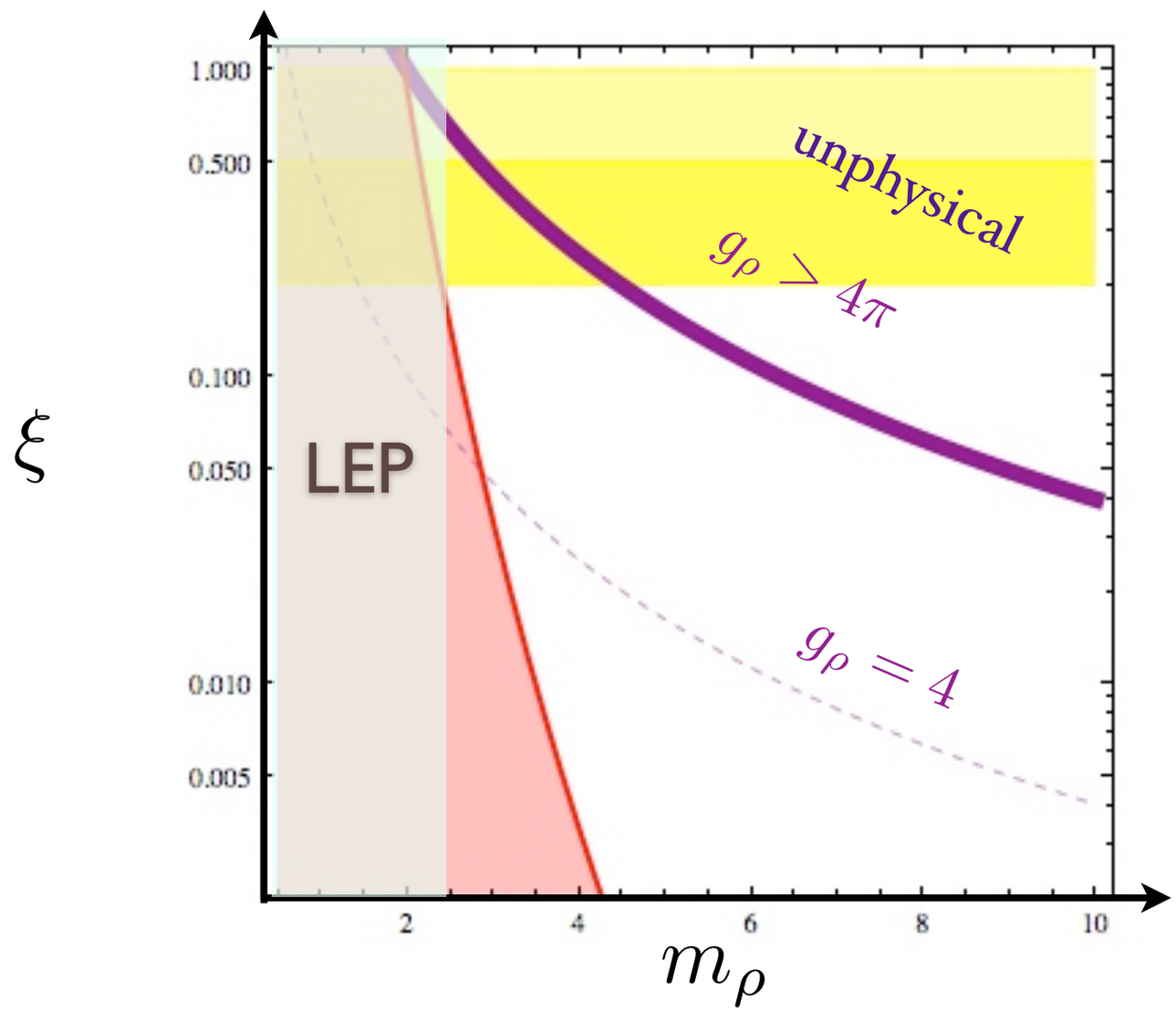

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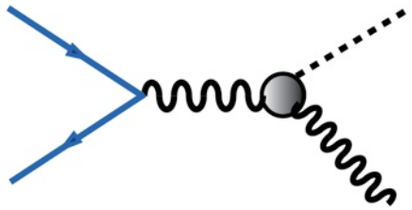
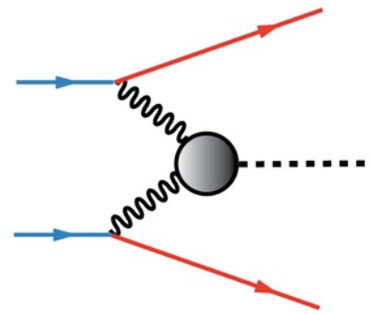
Single Higgs production at ILC/CLIC $\left(\sqrt{s} < 1\,\mathrm{TeV} \right)$





$$h \to b\bar{b},\ c\bar{c},\ \tau\bar{\tau},\ WW$$

Coupling	$M_H = 120$ GeV	140 GeV
g_{HWW}	$\pm$ 0.012	$\pm$ 0.020
g_{HZZ}	$\pm$ 0.012	$\pm$ 0.013
g_{HWW}/g_{HZZ}	$\pm$ 0.017	$\pm$ 0.024
g_{Htt}/g_{HWW}	$\pm$ 0.029	$\pm$ 0.052
g_{Hbb}/g_{HWW}	$\pm$ 0.012	$\pm$ 0.022
$g_{H\tau\tau}/g_{HWW}$	$\pm$ 0.033	$\pm$ 0.041
g_{Htt}/g_{Hbb}	$\pm$ 0.026	$\pm$ 0.057
g_{Hcc}/g_{Hbb}	$\pm$ 0.041	$\pm$ 0.100
$g_{H\tau\tau}/g_{Hbb}$	$\pm$ 0.027	$\pm$ 0.042

J.A. Aguilar Saavedra et al.
[ECFA/DESY LC Physics WG]

0.5 ab^{-1} at 500 GeV
1ab^{-1} at 800 GeV for top coupling

sensitivity $\frac{v^2}{f^2} \sim 0.01$ (**σ**−model)

$c_b \frac{v^2}{f^2} \sim 0.01$ (bottom & top yukawa) learn about flavor

At CLIC with 3 TeV and 1ab^{-1}: sensitivity $\frac{v^2}{f^2} \sim 0.002$

Barger, Han,Langacker, McElrath,Zerwas 03

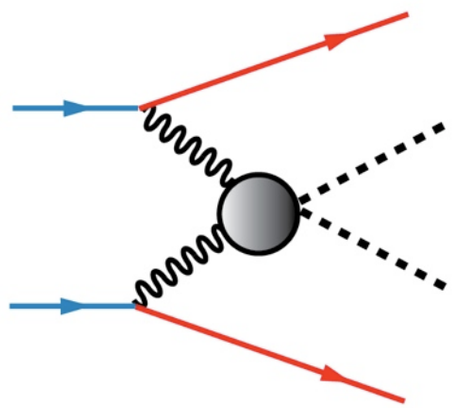
If a deviation is discovered, how can we attribute it to *h* compositeness ?

Possible alternative explanation: *h* couplings depleted by mixing to heavy states

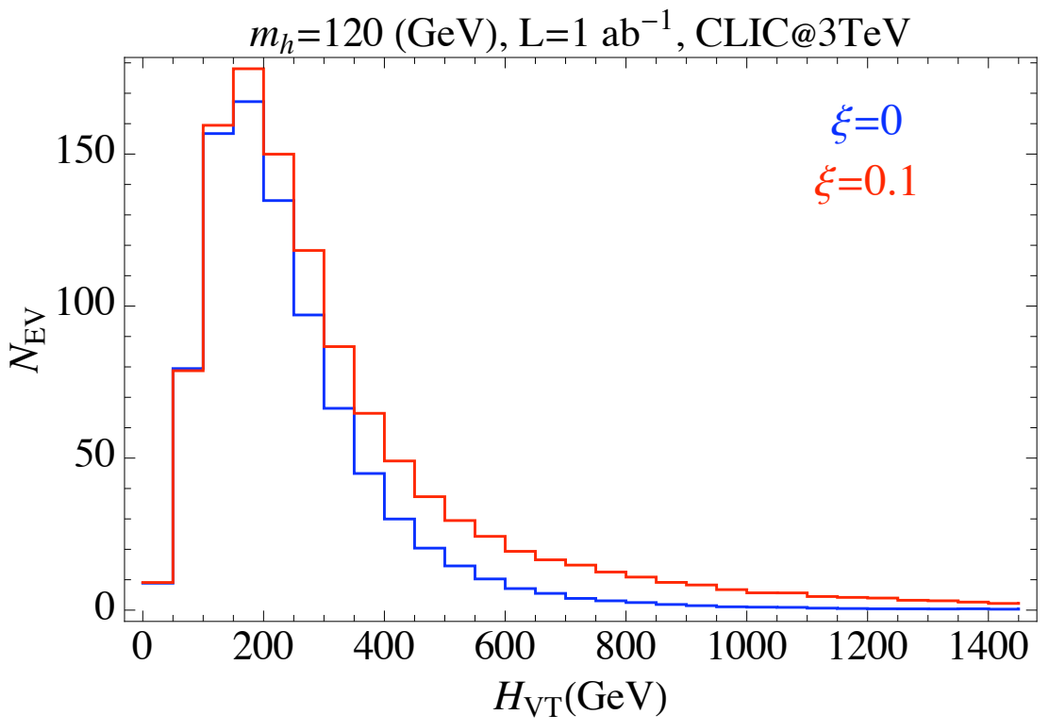
$$\frac{\delta g}{g_{SM}} \sim \frac{m_h^2}{m_{heavy}^2}$$

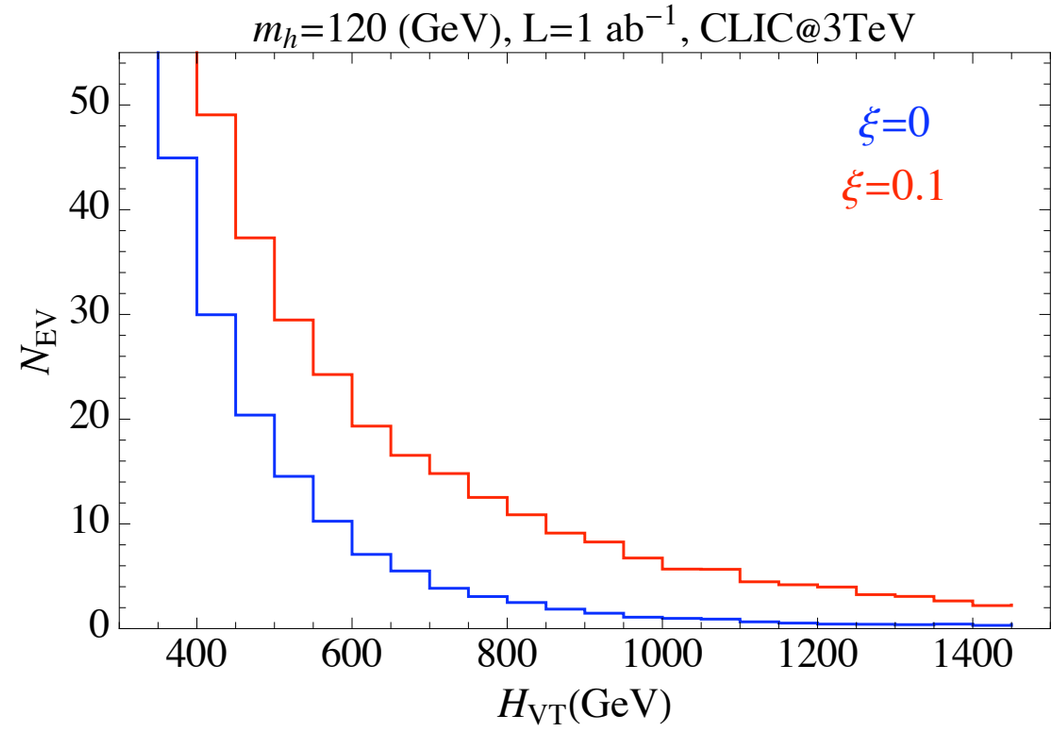
Ex: if 10% deviation discovered with no new states below 1 TeV
that would be, indirect, but strong, evidence of *h* compositeness

Direct evidence of Higgs compositeness: strong WW ➔ hh



way above threshold growing s-wave $\sigma \sim \frac{s}{f^4}$





Contino, Grojean, Pappadopulo, RR, Thamm in progress

direct sensitivity to **σ**−model growing s-wave better than $\frac{v^2}{f^2} \sim 0.05$

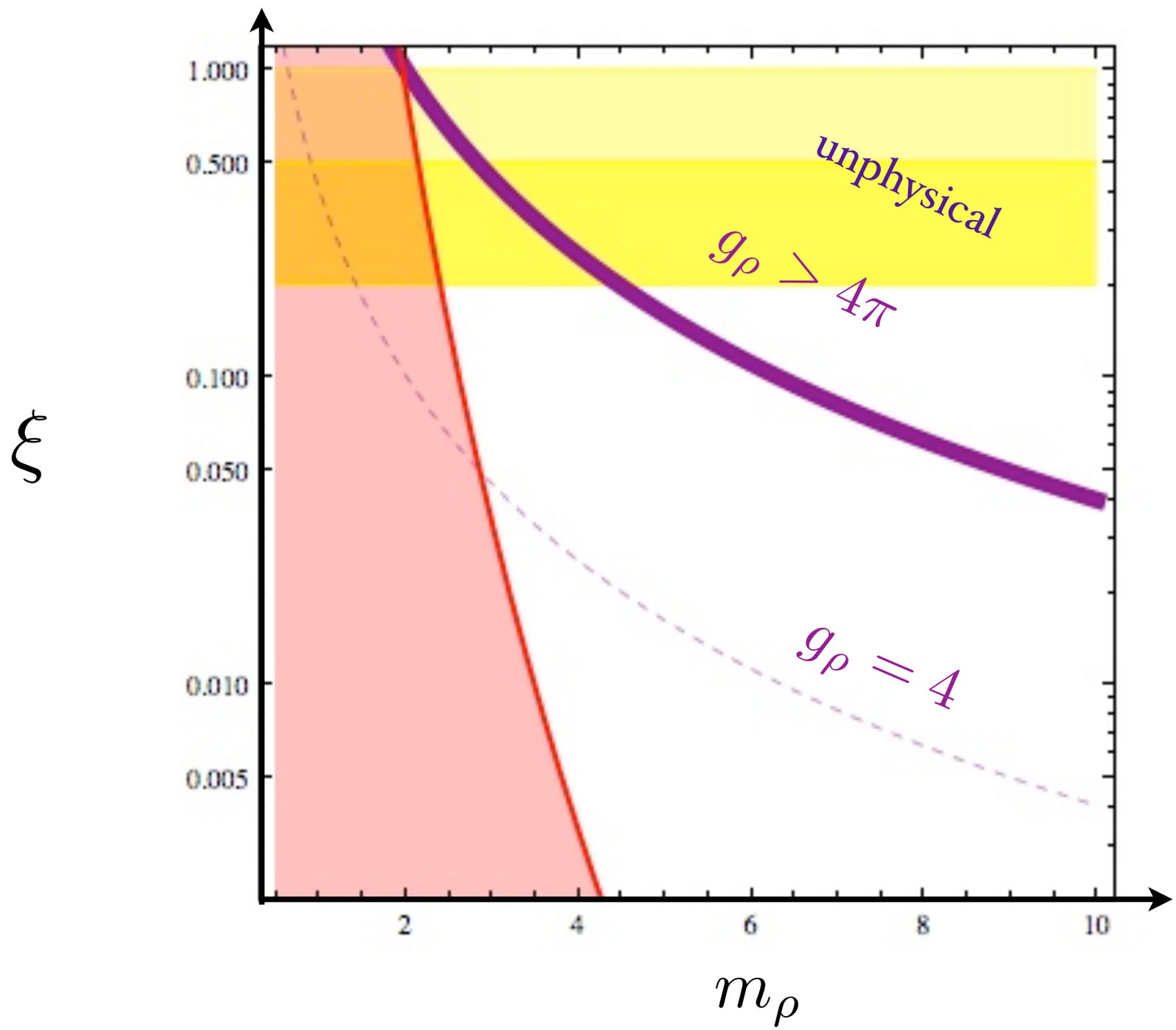
Fit to hh energy distribution allows to also extract correction to h cubic d_3

$$d_3 - 1 \sim 0.1$$

interesting but not crucial to assess Higgs compositeness

Would be interesting to compare relevance of WW WW
with respect to WW hh at CLIC

work in progress


1.000
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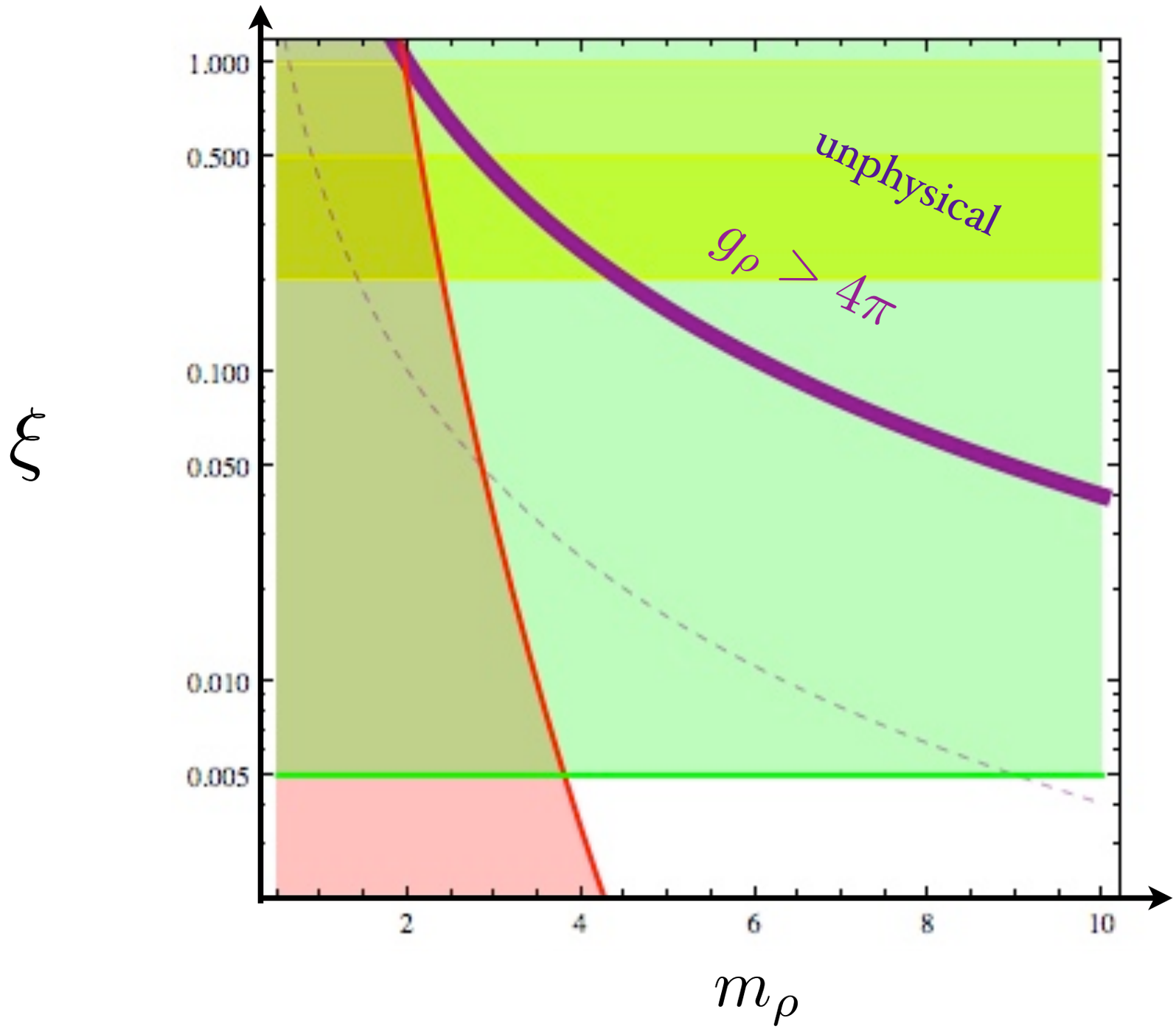
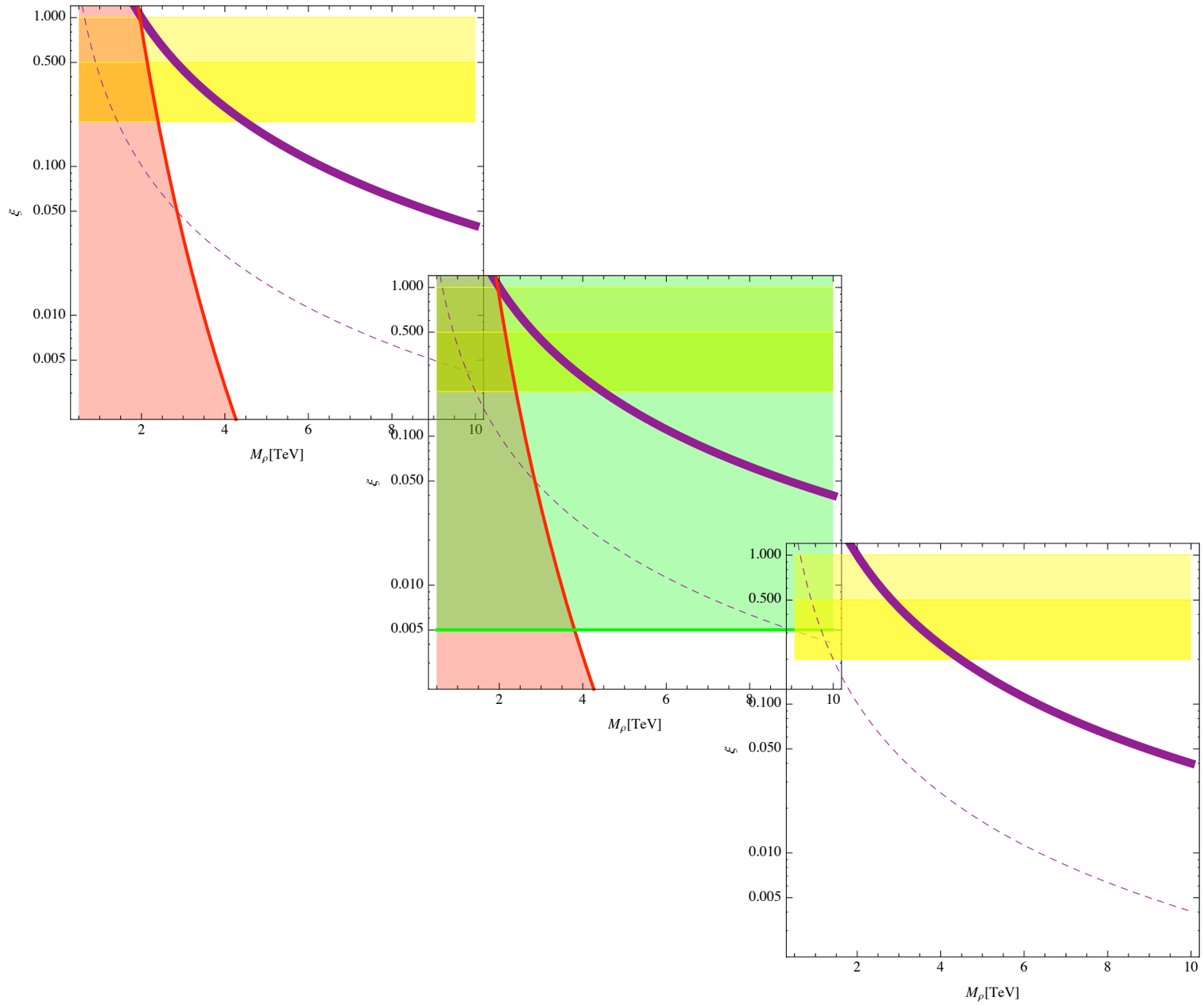
0.010
0.005
2
4
6
8
10
unphysical
$g_\rho > 4\pi$
$g_\rho = 4$
ξ
m_ρ



CLIC will fully test the relevance of compositeness to electroweak symmetry breaking


1.000
0.500
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0.010
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ξ
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M_ρ[TeV]

Trilinear vector boson couplings

$$\mathcal{L}_V = -ig\cos\theta_W g_1^Z Z^\mu \left(W^{+\nu}W^-_{\mu\nu} - W^{-\nu}W^+_{\mu\nu}\right) - ig\left(\cos\theta_W \kappa_Z Z^{\mu\nu} + \sin\theta_W \kappa_\gamma A^{\mu\nu}\right) W^+_\mu W^-_\nu$$

$$g_1^Z = \frac{m_Z^2}{m_\rho^2}\left[c_W + (\frac{g_\rho}{4\pi})^2 c_{HW}\right]$$

$$\kappa_\gamma = \frac{m_W^2}{m_\rho^2}\left(\frac{g_\rho}{4\pi}\right)^2 (c_{HW} + c_{HB}), \qquad \kappa_Z = g_1^Z - \tan^2\theta_W \kappa_\gamma$$

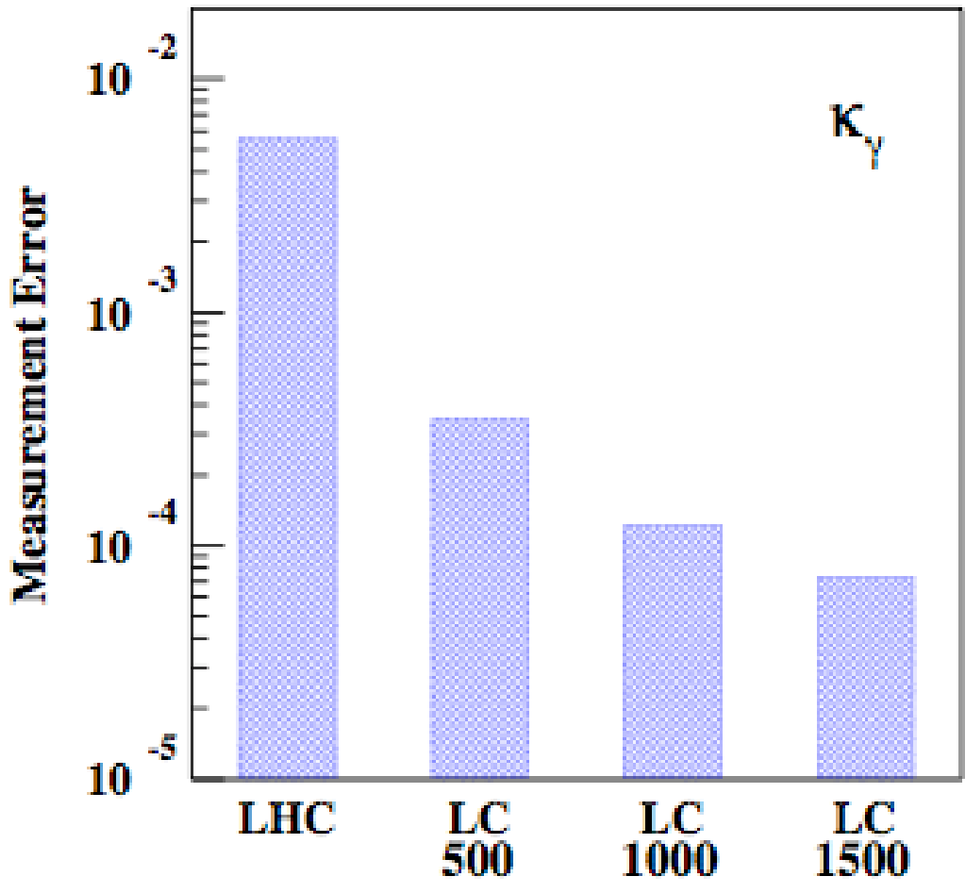
other trilinears $\lambda_{Z,\gamma} \sim \frac{\alpha_W}{4\pi} k_{Z,\gamma}$ $\longrightarrow$ negligible

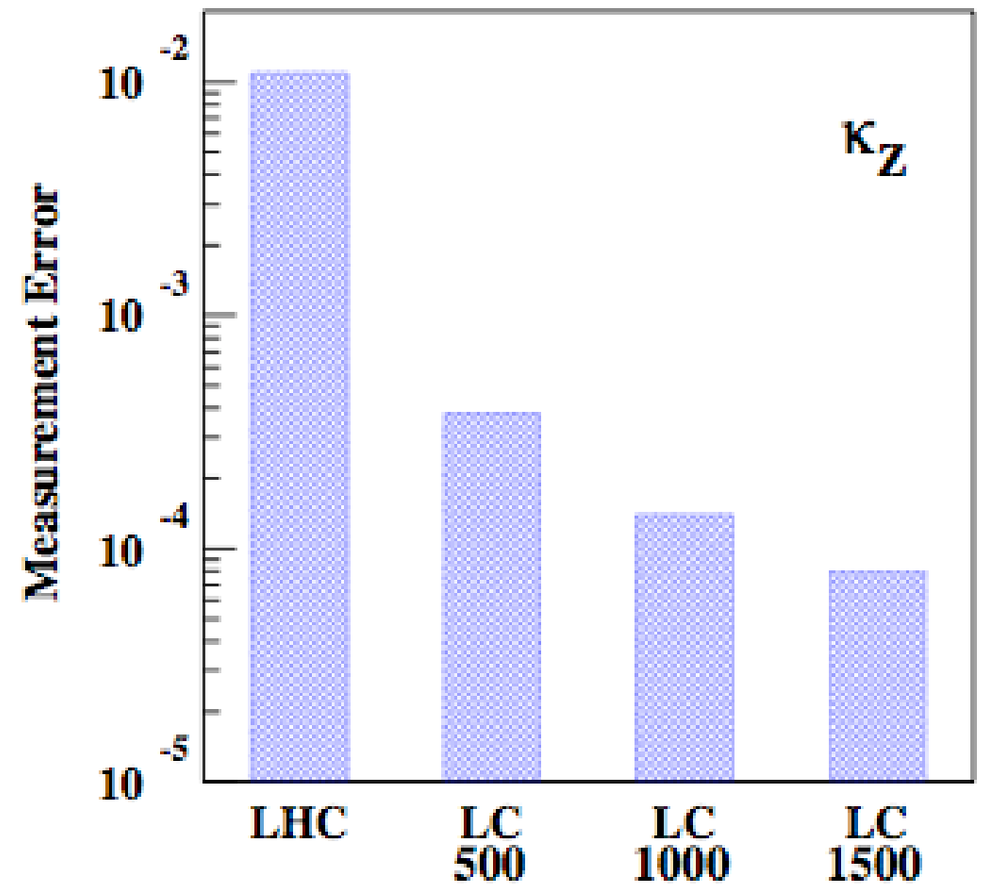
LHC with 100 fb^{-1} can test down to $g_1^Z = 1\%$, $k_{Z,\gamma} = 5\%$

weaker sensitivity on m_ρ than from direct production of heavy states

or than LEP bound $\widehat{S} < 2 \times 10^{-3}$

Trilinears at ILC

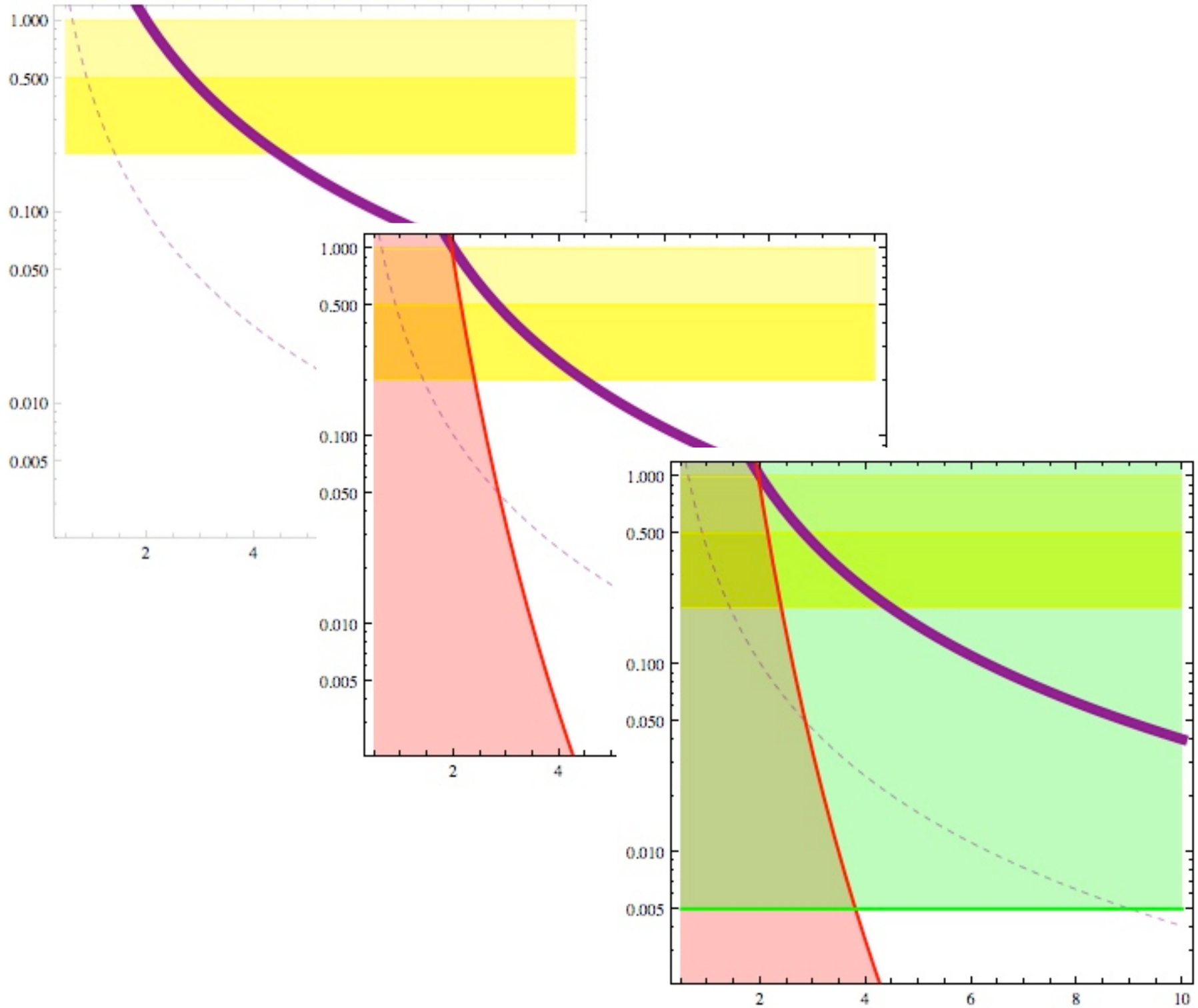




T.Abe et al., [American Linear Collider Working Group]
Snowmass 2001.

indirect reach $$m_\rho = 6 - 8\,\mathrm{TeV}$$

in NDA limit $$g_\rho = 4\pi$$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