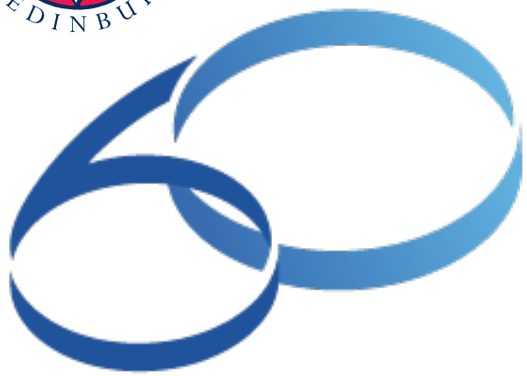
LHC physics prospects for the forth-coming period at full energy & goals for the high-luminosity runs

Victoria Martin, University *of* Edinburgh
On behalf of the ATLAS and CMS collaborations



LHC Run 1

IN

proton-proton collisions at ATLAS and CMS

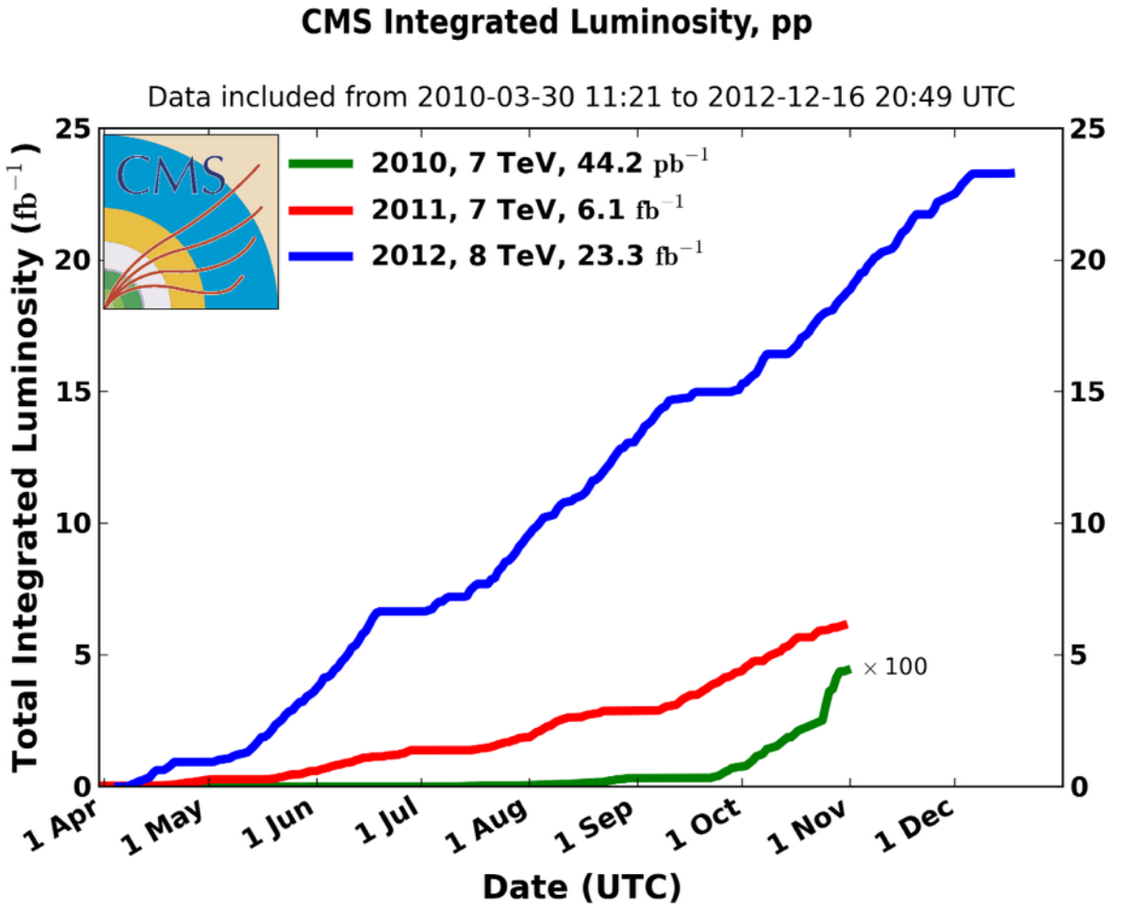
- 2010 $\sqrt{s}$=7 TeV, 44 pb^{-1}
- 2011 $\sqrt{s}$=7 TeV, 6 fb^{-1}
- 2012 $\sqrt{s}$=8 TeV, 23 fb^{-1}

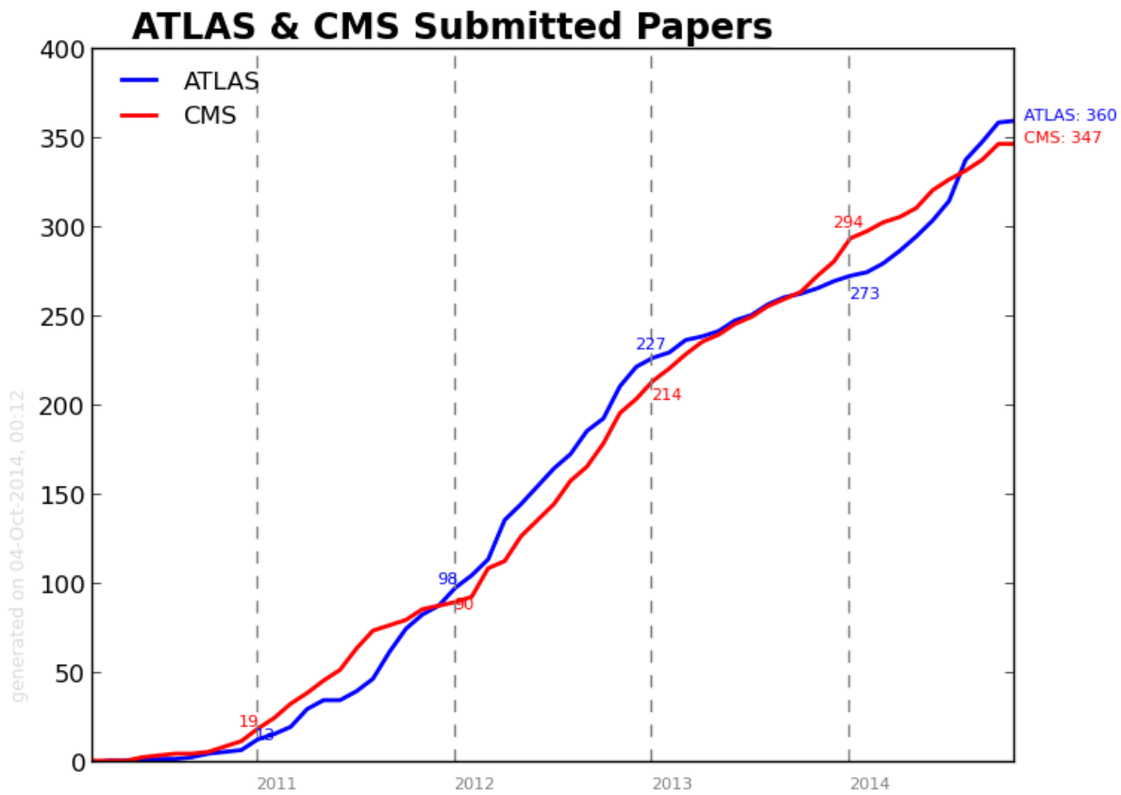
Total ~30 fb^{-1}

OUT

Physics results!

- Over 700 submitted papers on collision data





MIDDLE

Over 6,000 ATLAS and CMS physicists operating the detectors; collecting and analysing the data.

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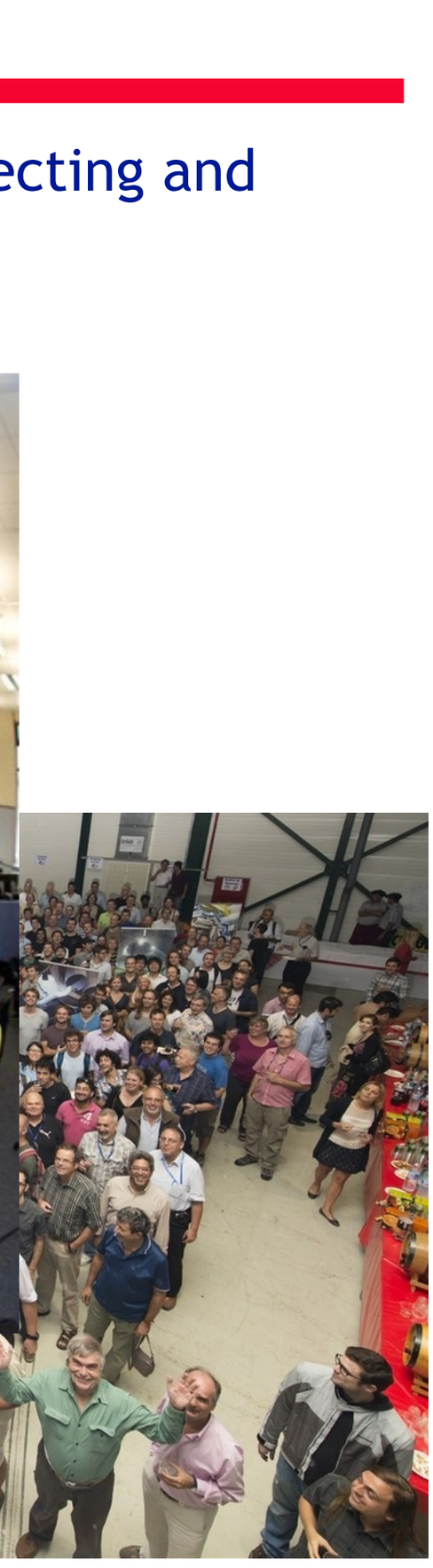

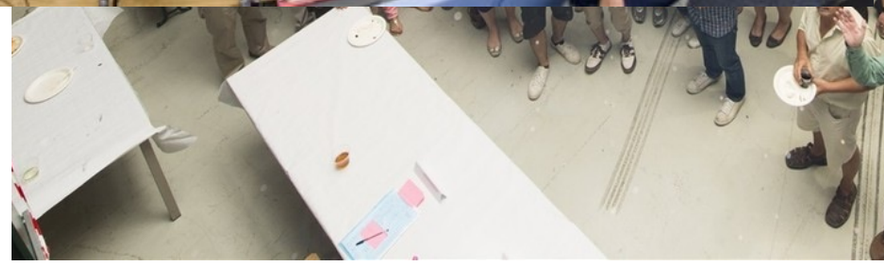

The Nobel Prize in Physics 2013
François Englert and Peter W. Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Higgs Boson Results

All observations from the LHC consistent with a Standard Model Higgs boson with $m_H \sim 125\ \mathrm{GeV}$.

Phys. Rev. D. 90, 052004 (2014)

CMS-PAS-HIG-14-009

arXiv:1407.0558

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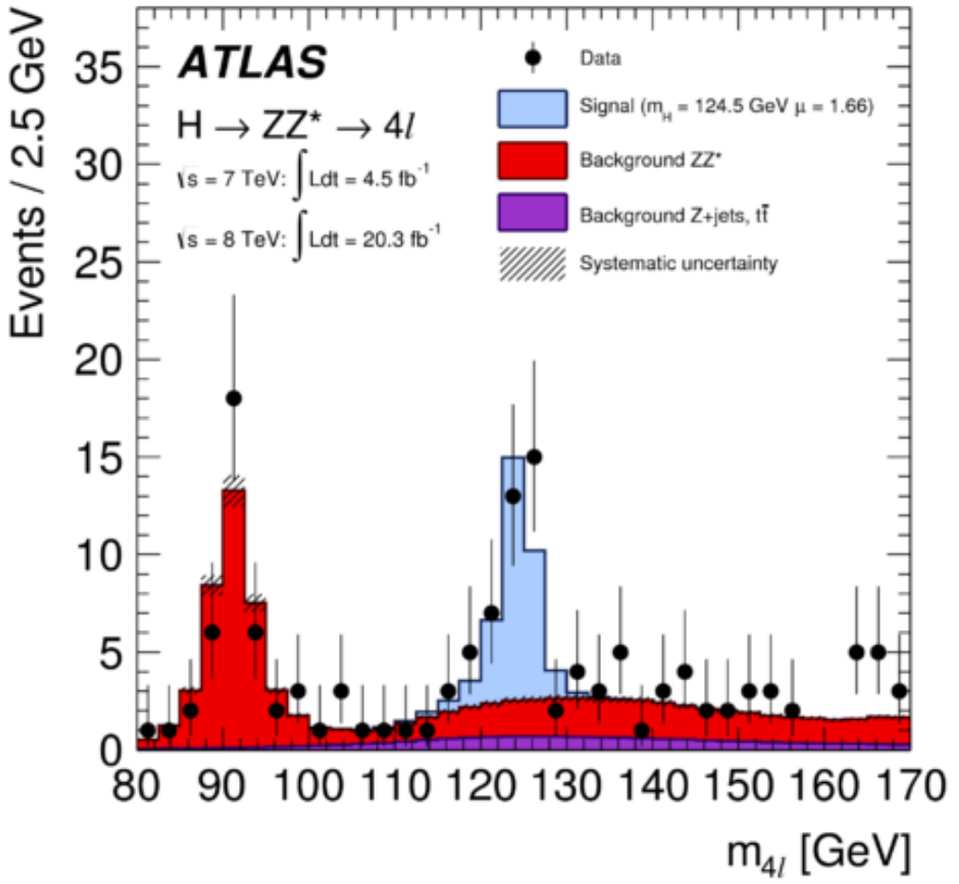

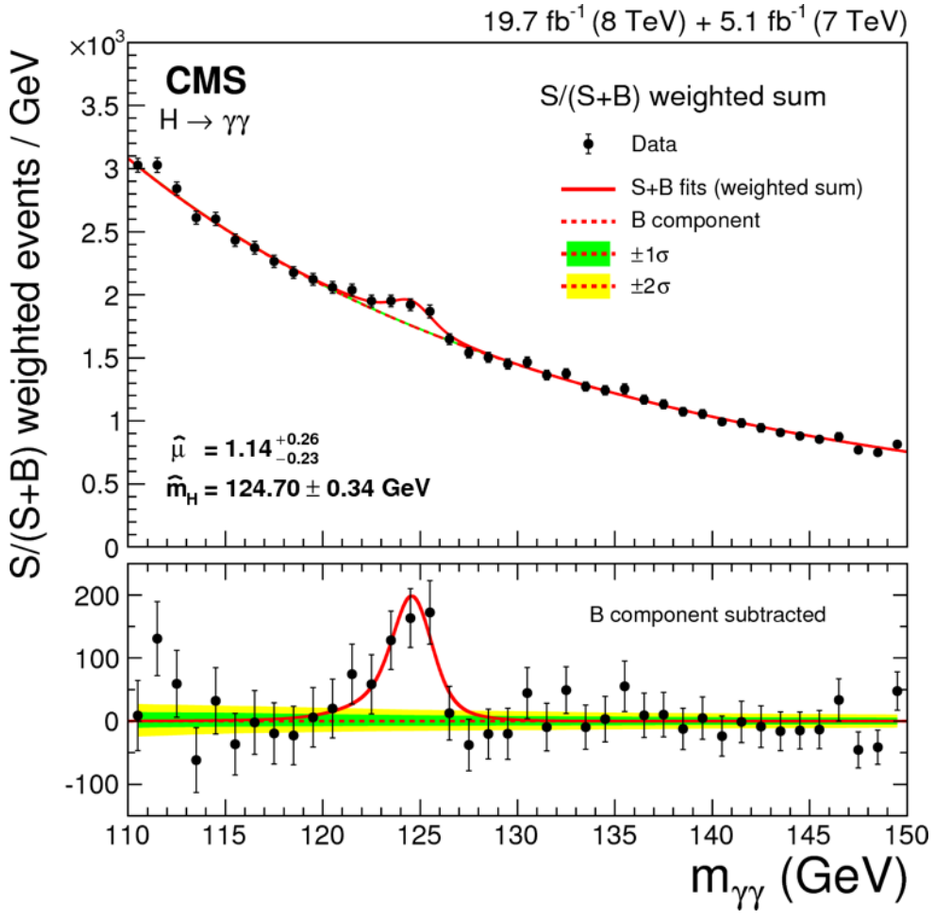

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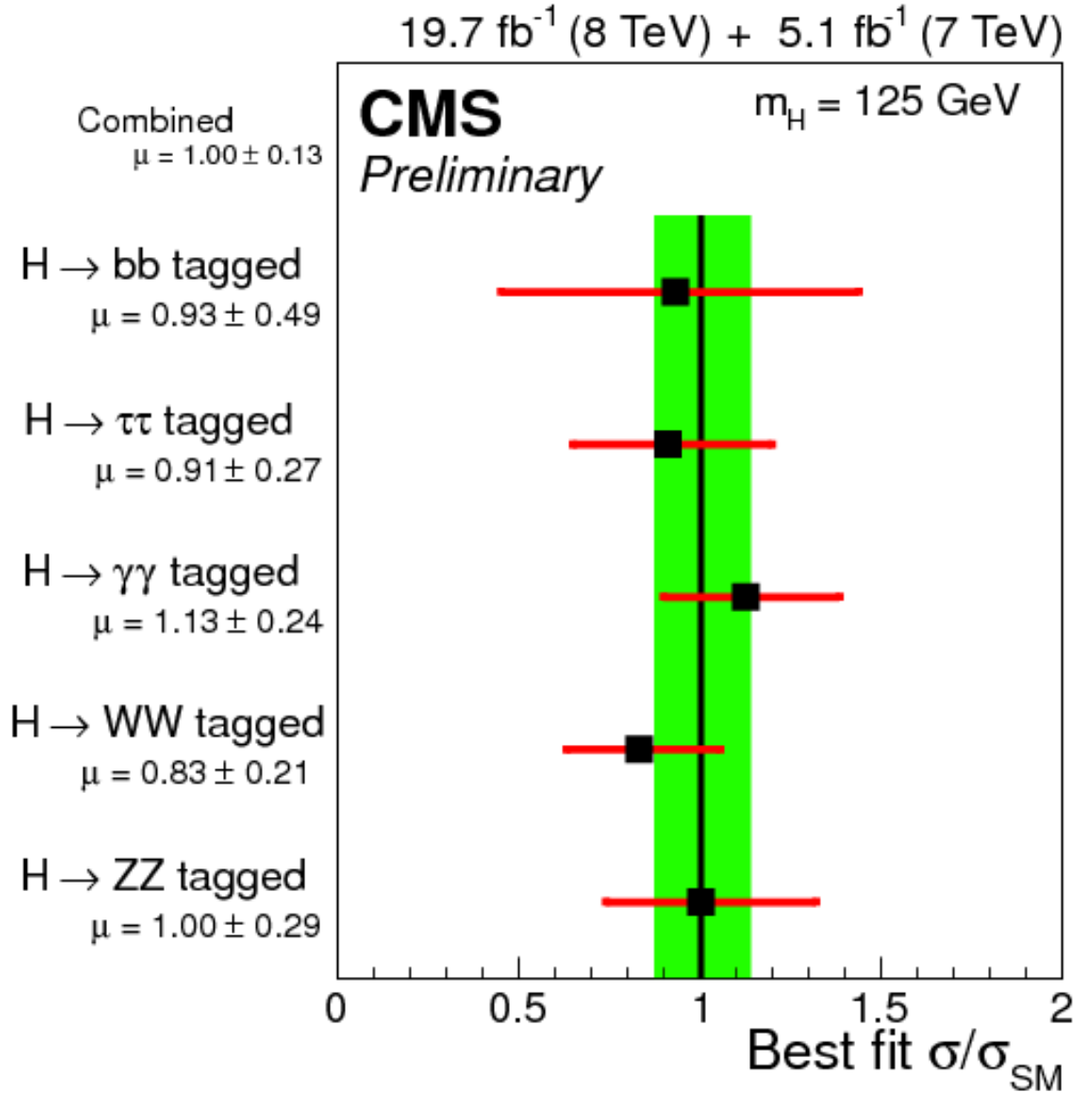

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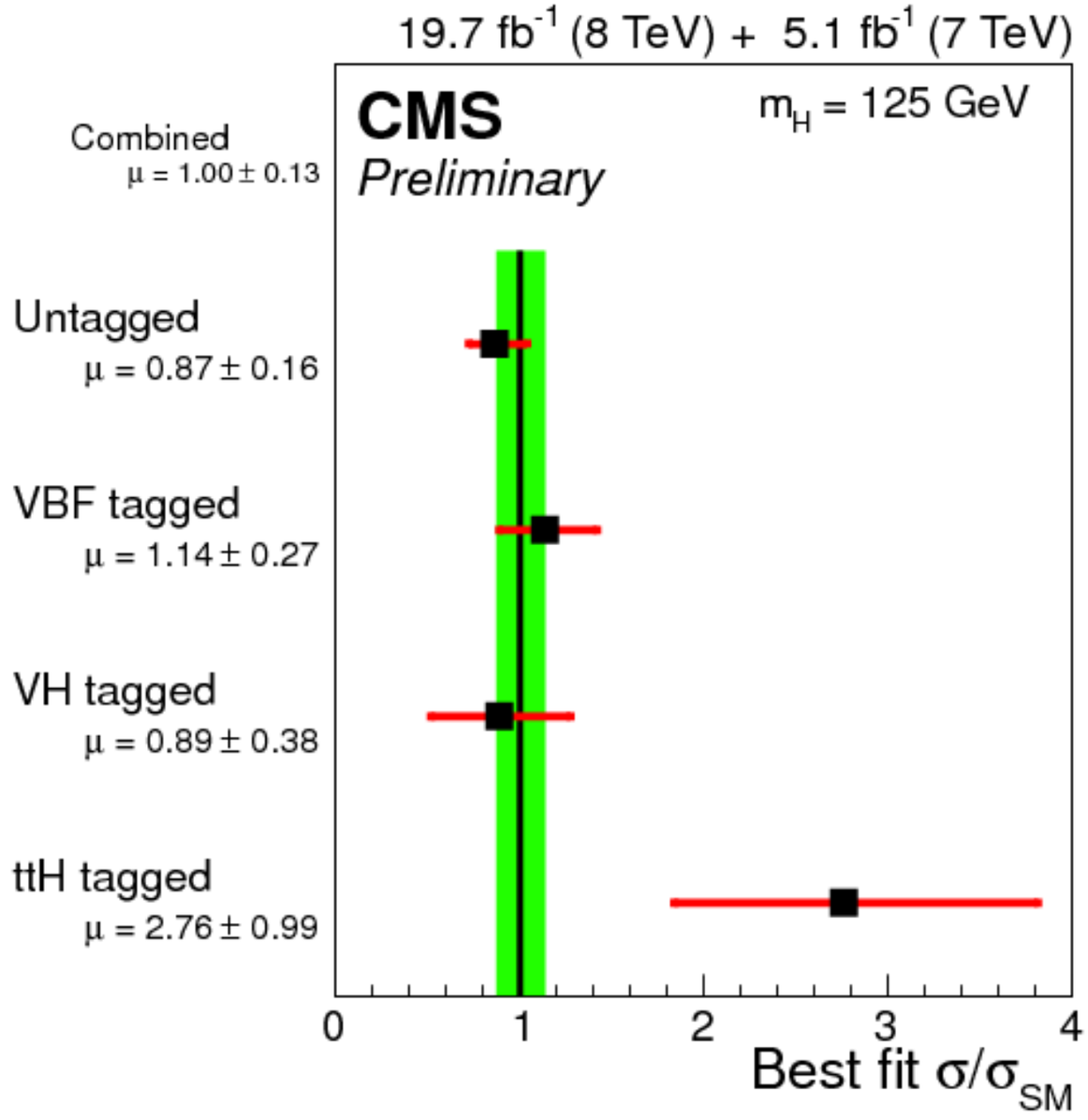

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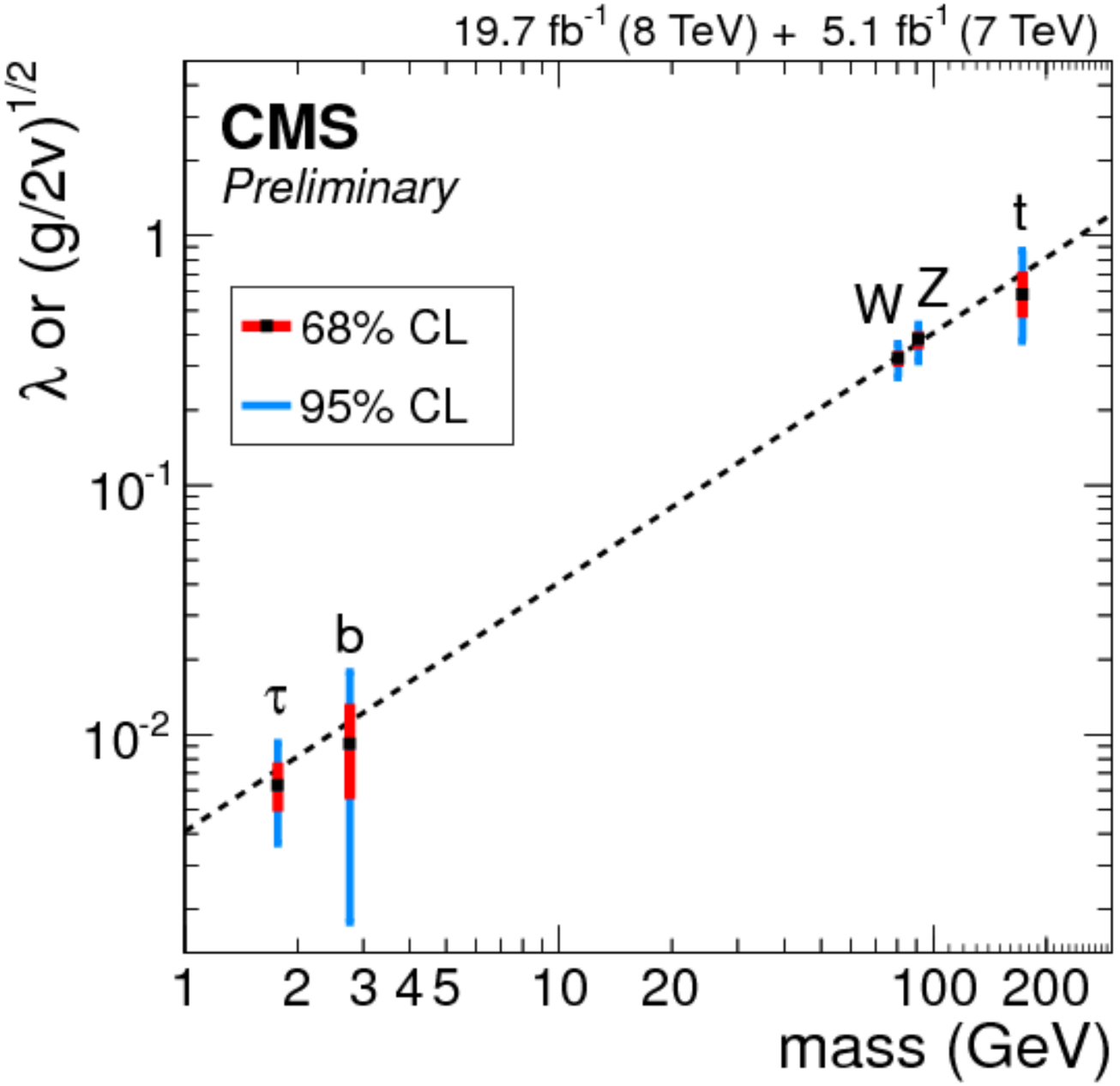

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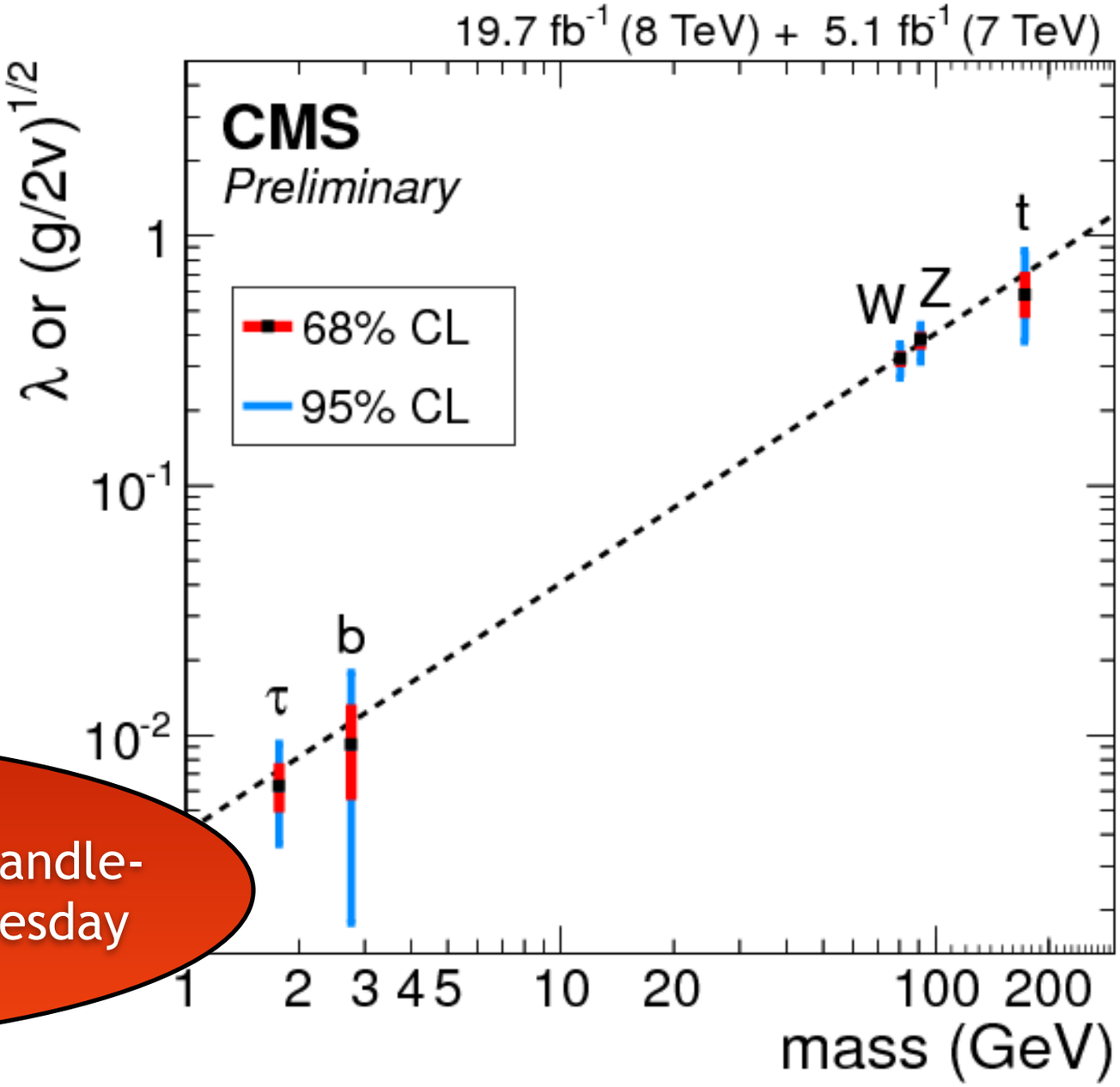
➡It's pre

More information from Aidan Randle-Condein in Higgs session on Tuesday



Phys. Rev. D [illegible]004 (2014)

CMS-PAS-HIG-14-009

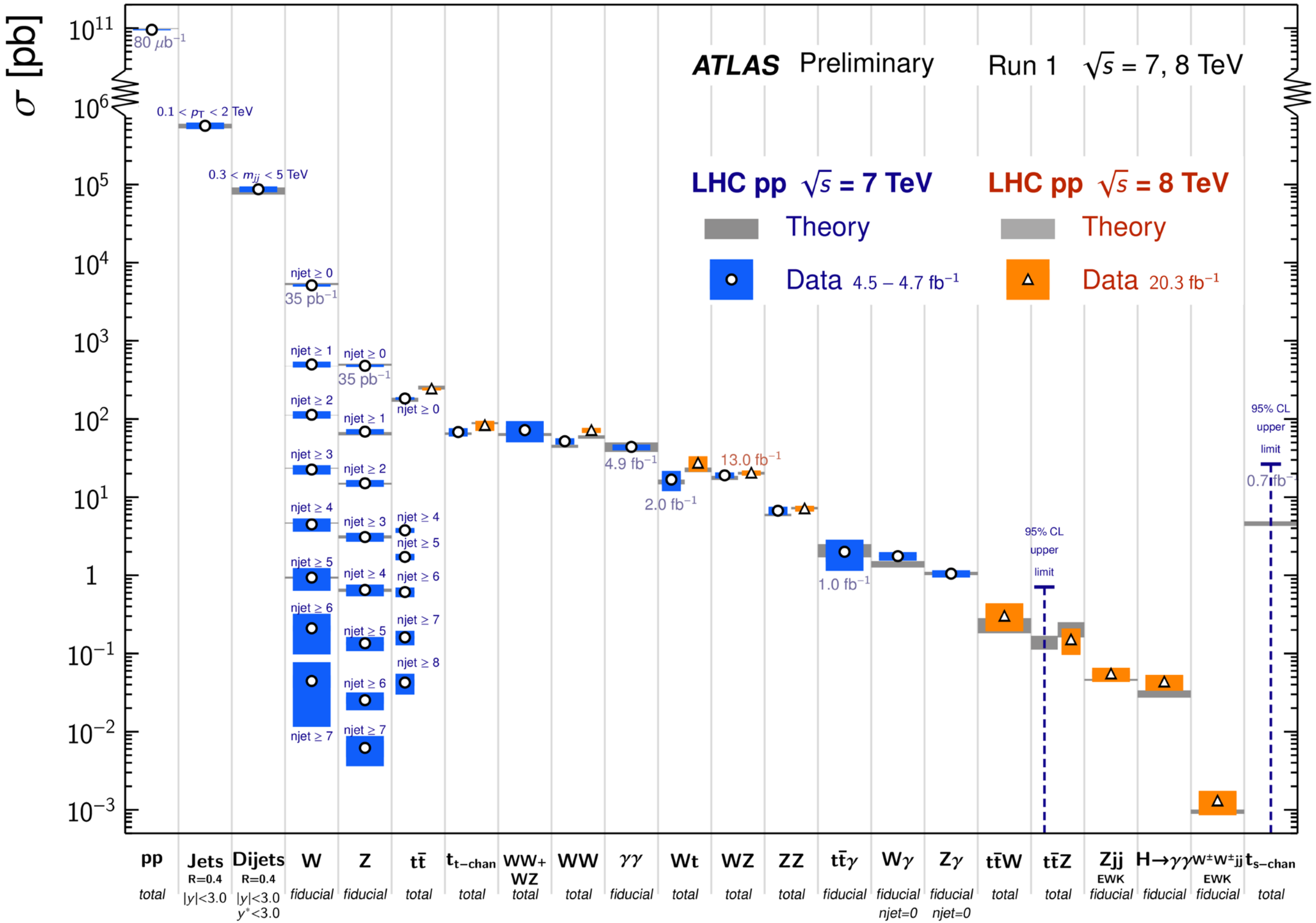
arXiv:1407.0558

Run 1 was not *all* about the Higgs boson

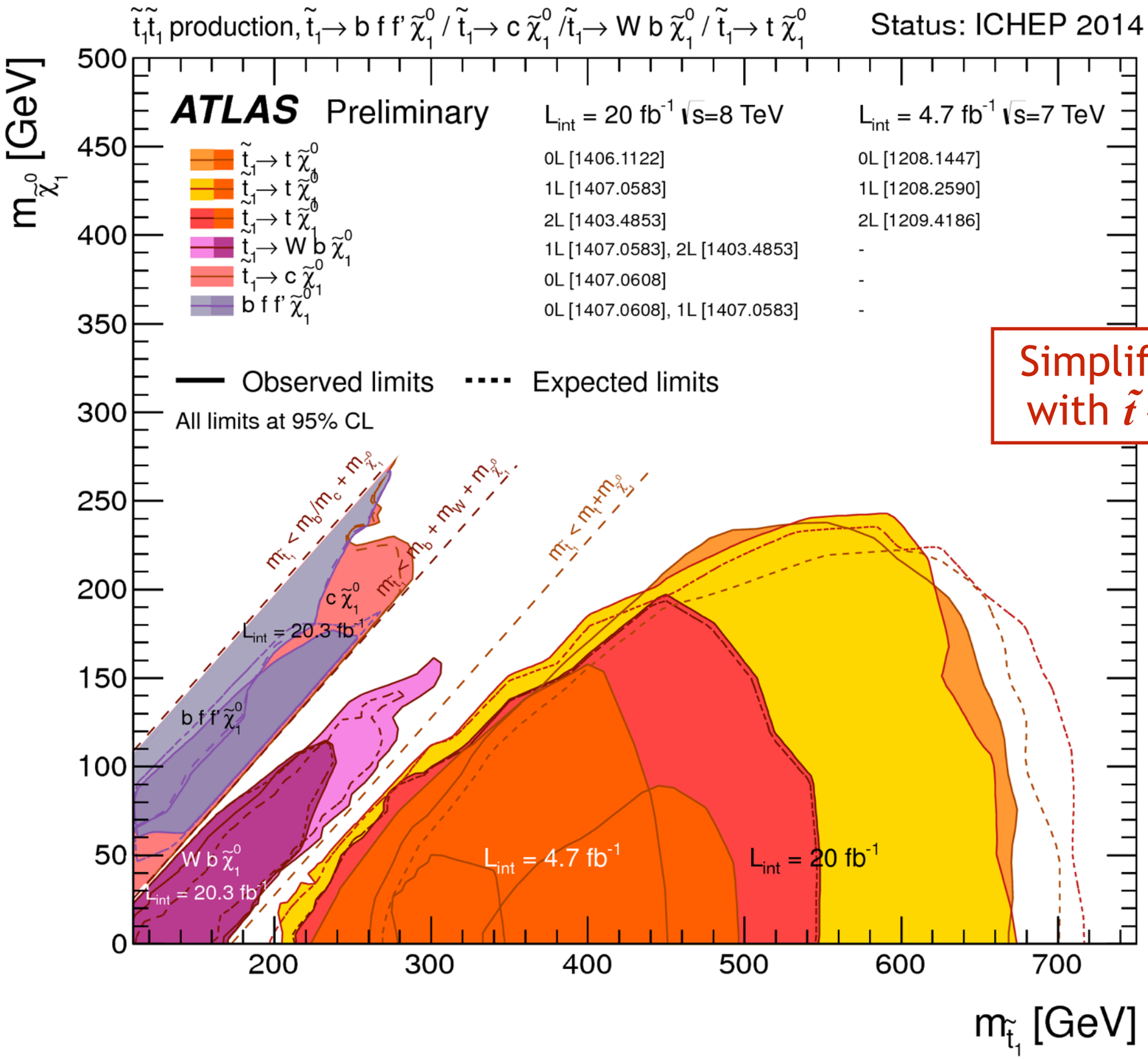
- We didn't find supersymmetry…
- We didn't find any other new physics…
- We *did* confirm the Standard Model and learn more about top quarks

Standard Model Production Cross Section Measurements

Status: July 2014



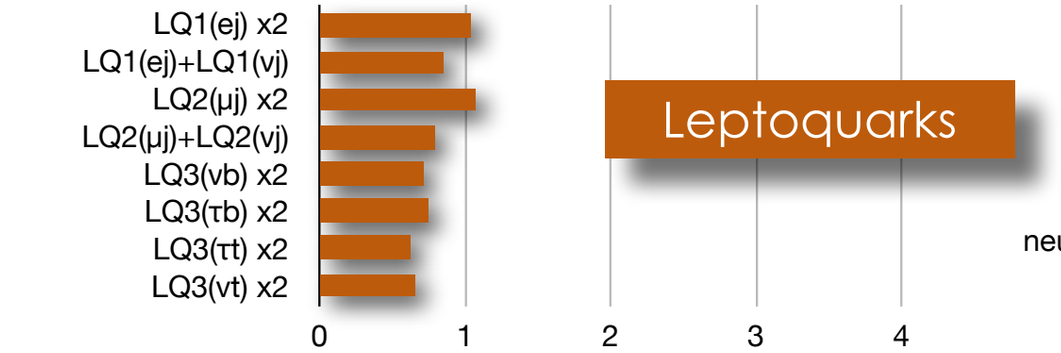
e.g. Observed limits on stop and LSP mass



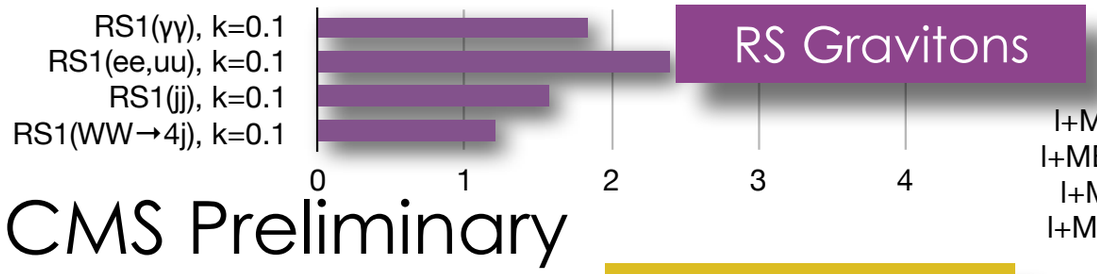
arxiv:1208.1447
arxiv:1208.2590
arxiv:1209.4186
arxiv:1407.0583
arxiv:1406.1122
arxiv:1403.4853
arxiv:1407.0608

Simplified models with $\tilde{t} \to \mathbf{LSP} + X$

95% CL Limits on Masses of Exotic Phenomena in TeV

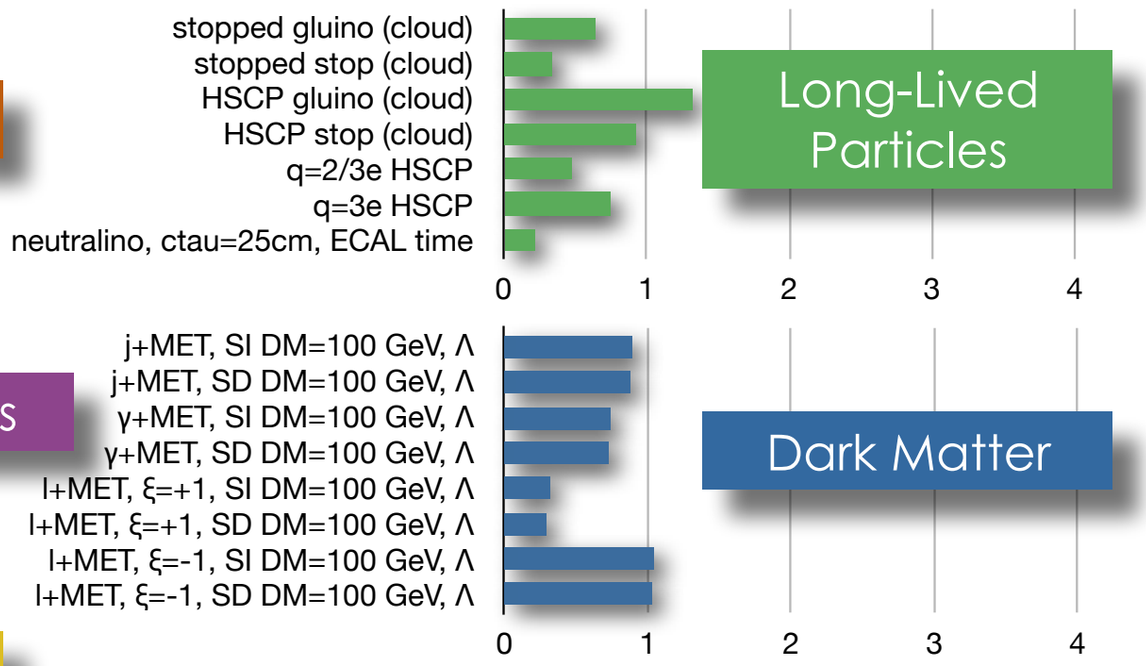


Leptoquarks



RS Gravitons

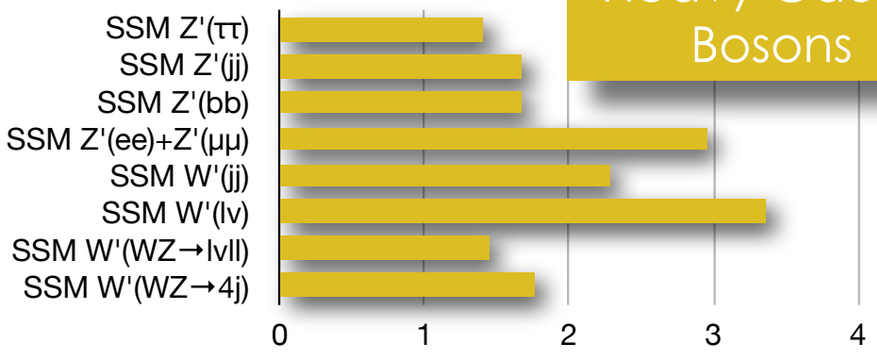
CMS Preliminary

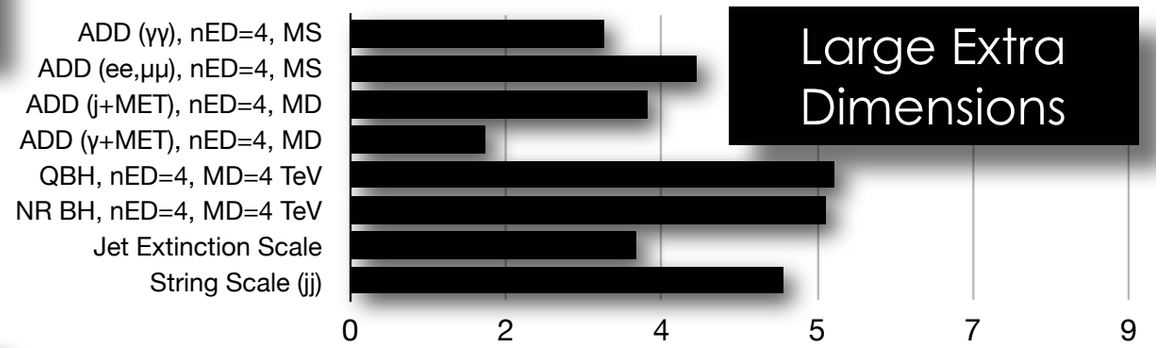


Long-Lived Particles

Dark Matter

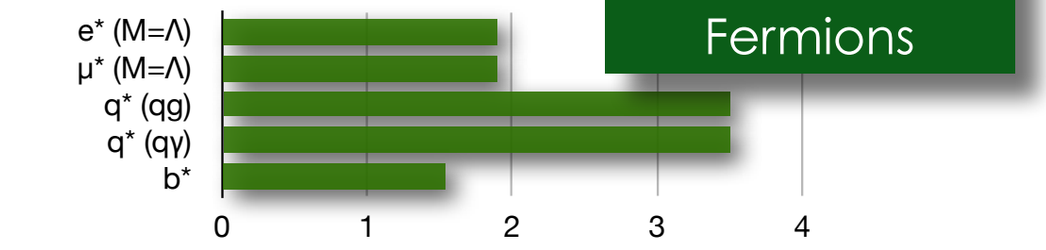
Heavy Gauge Bosons



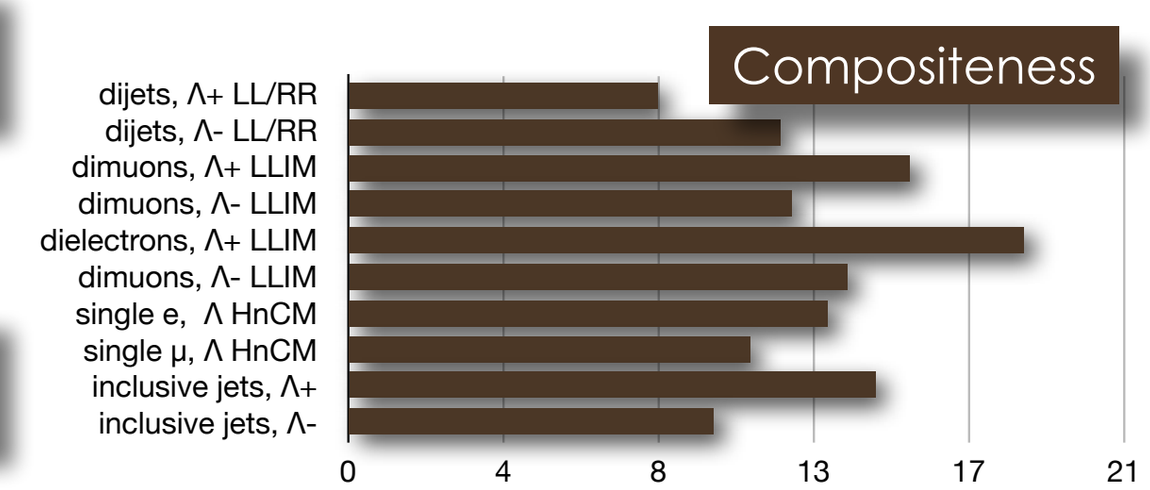


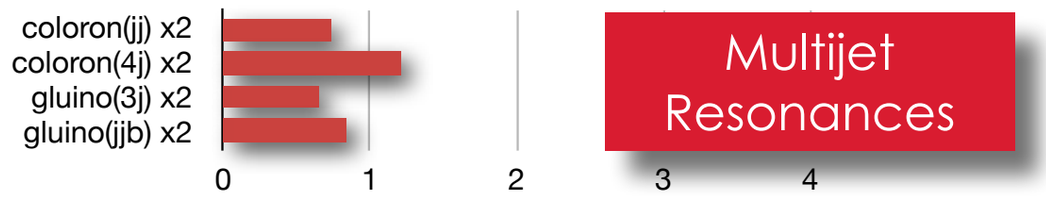
Large Extra Dimensions

Excited Fermions



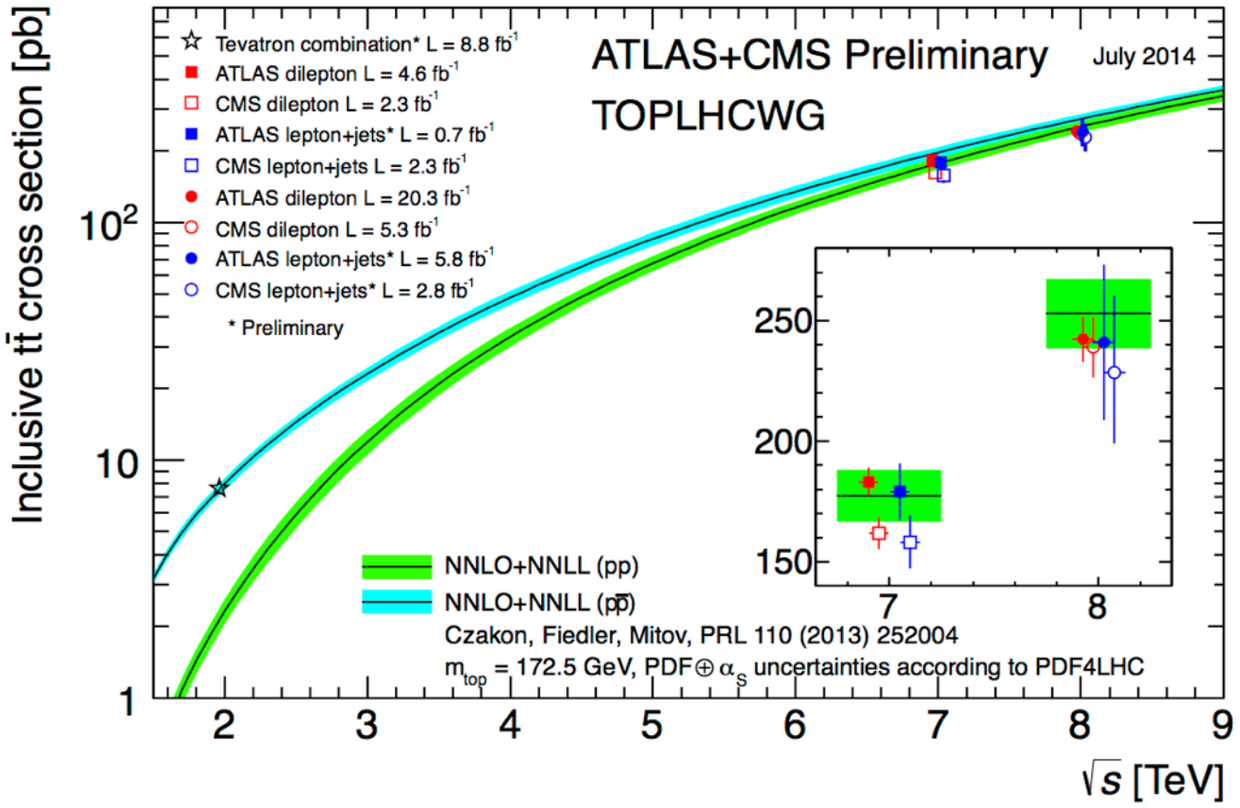
Compositeness





Multijet Resonances

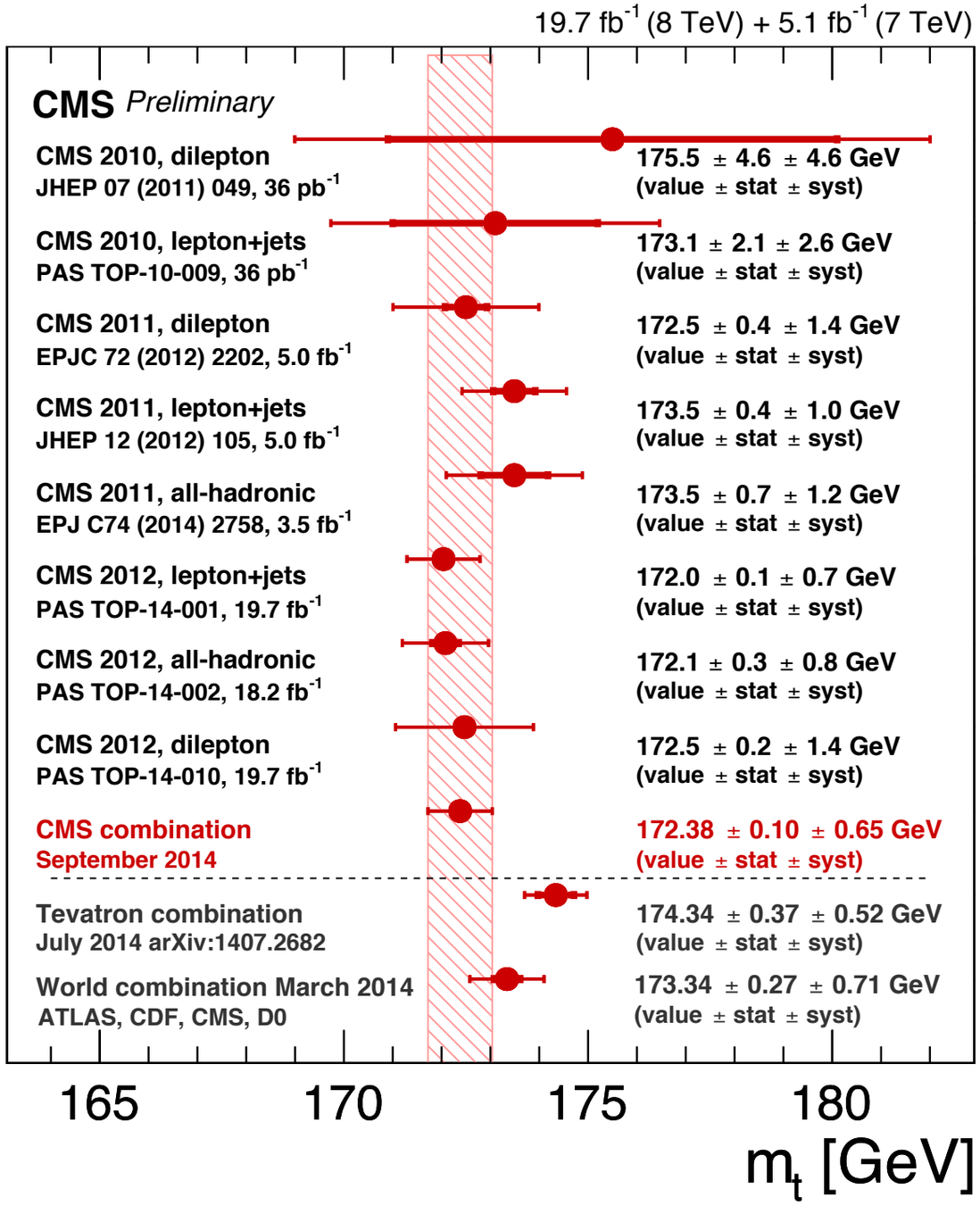
Run 1 Top Quark Properties



Much more on top quarks at the LHC from Andrey Loginov in top session on Tuesday

arXiv:1403.4427

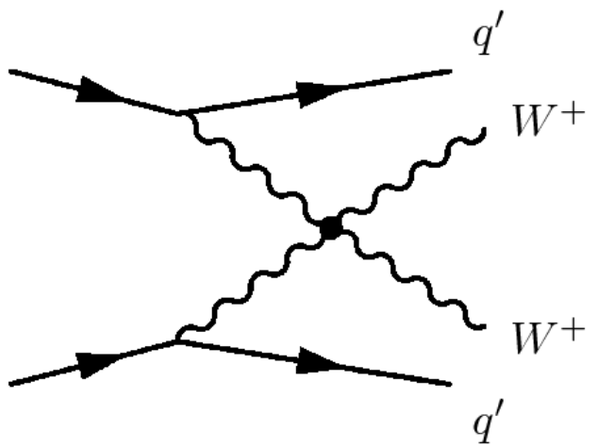
CMS-PAS-TOP-14-015

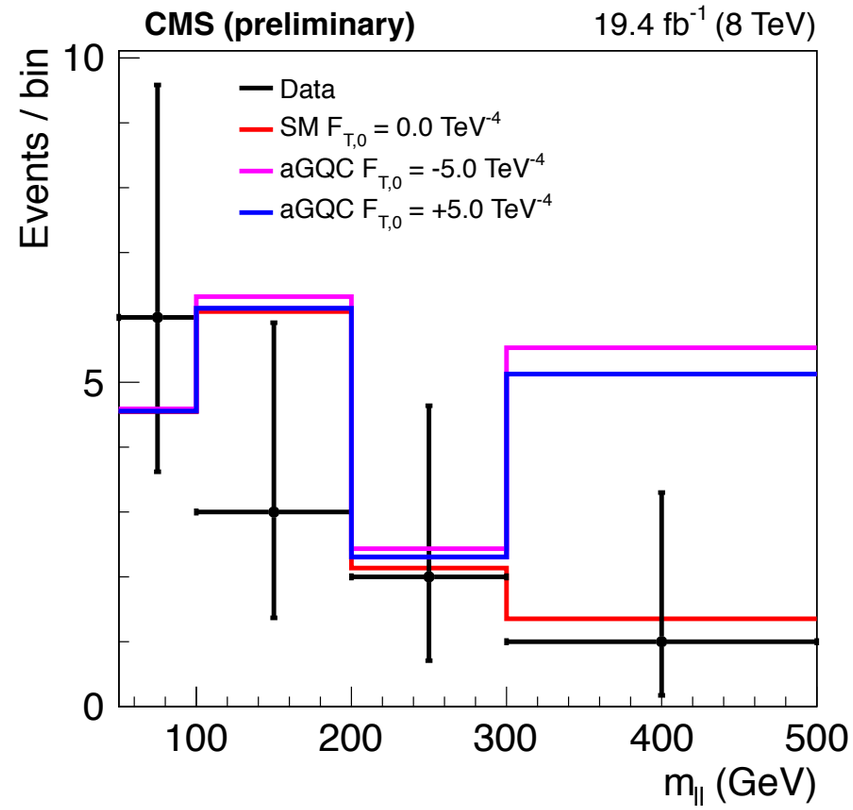


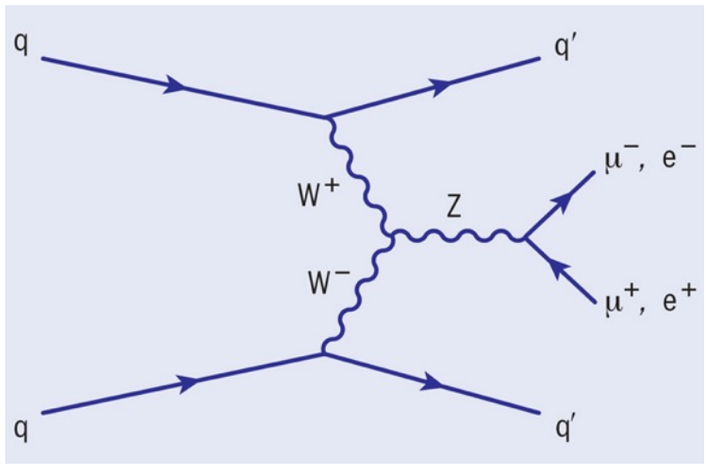
First Evidence for Weak Boson Scattering

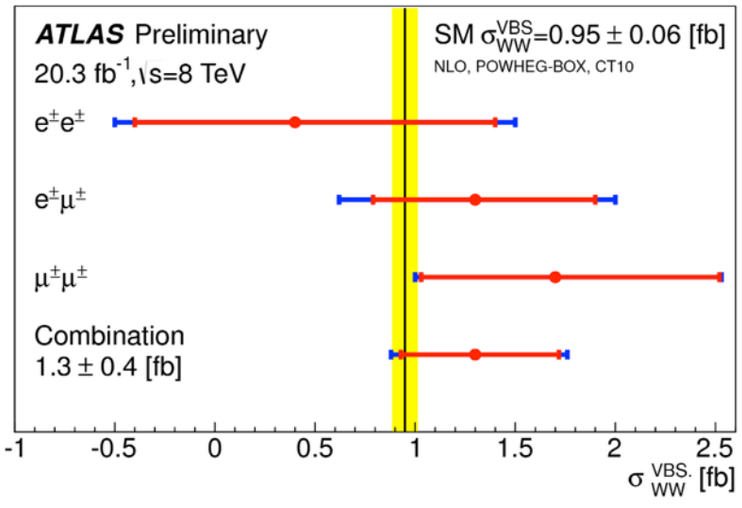
arXi:1401.7610 arXiv:1405.6241
CMS-PAS-FSQ-12-035 CMS-PAS-SMP-13-015

- Same sign ***ee, eμ, μμ*** signature
  - ATLAS (CMS) observe **4.5σ** (**2.0σ**) evidence for $W^{\pm}W^{\pm}jj$ production





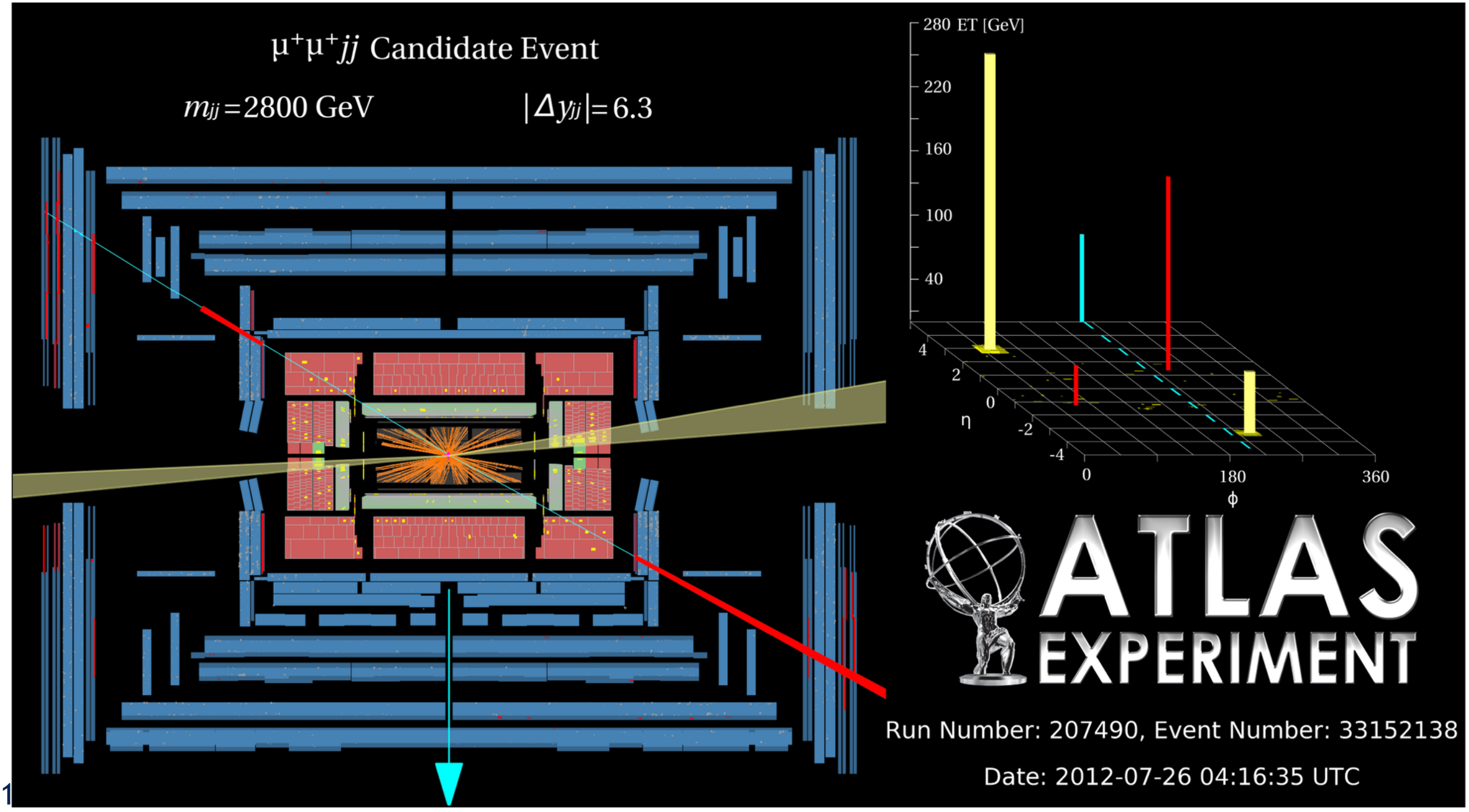




- ATLAS and CMS have also observed ***Zjj*** production consistent with $W^+W^-jj \rightarrow Zjj$

First Evidence for Weak Boson Scattering

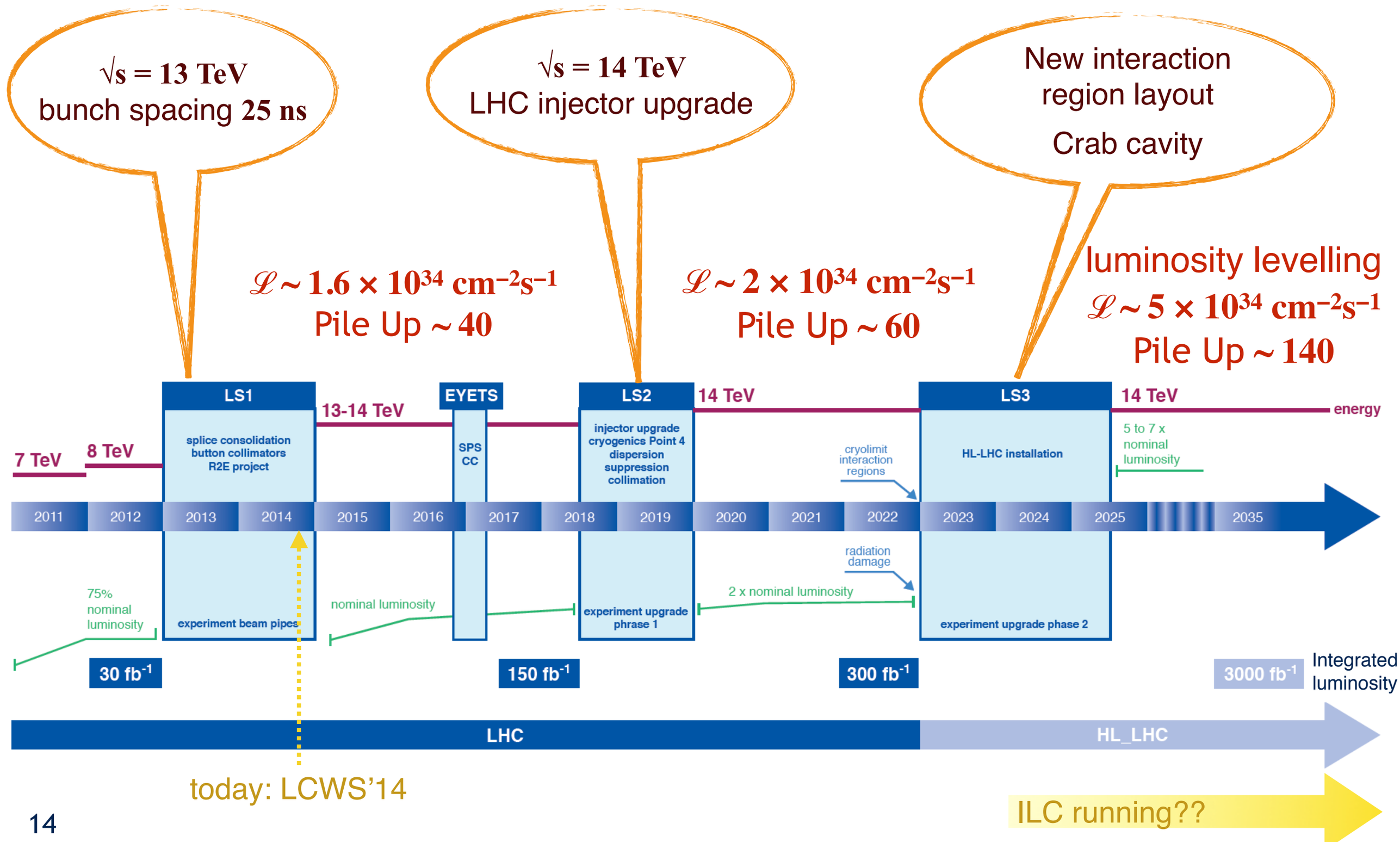
arXiv:1405.6241



Beyond Run 1

LHC → HL-LHC

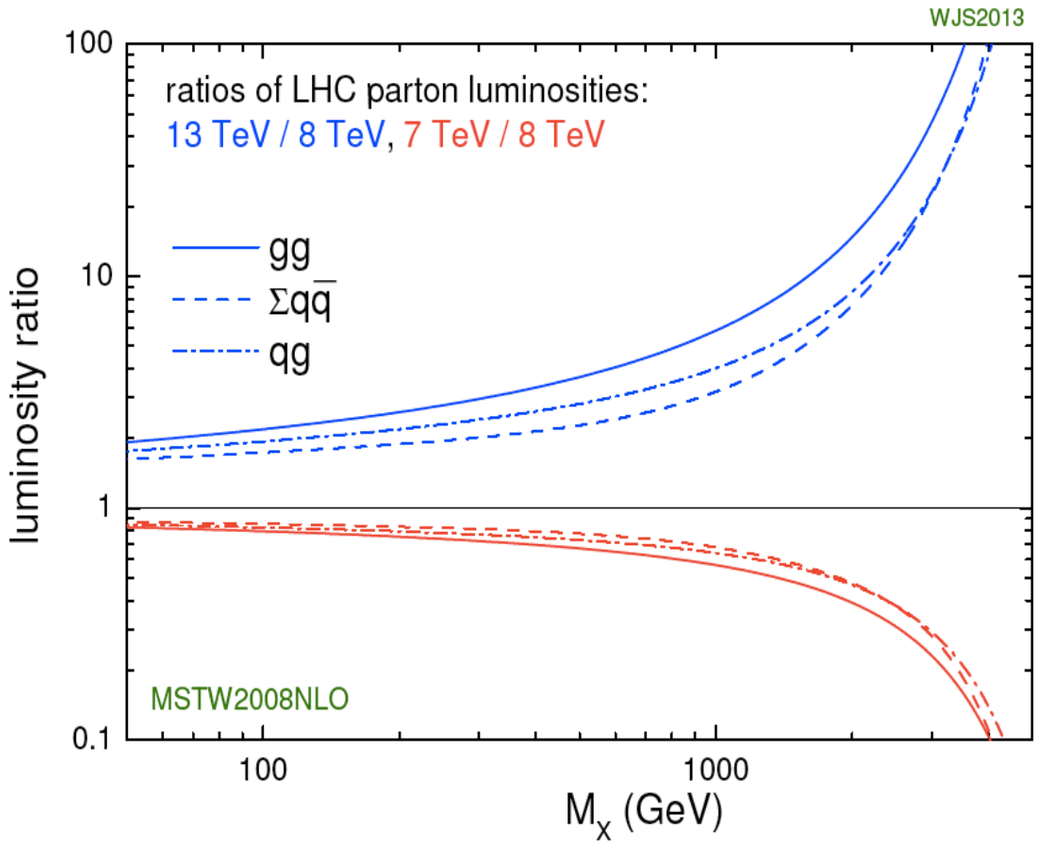
http://hilumilhc.web.cern.ch/about/hl-lhc-project

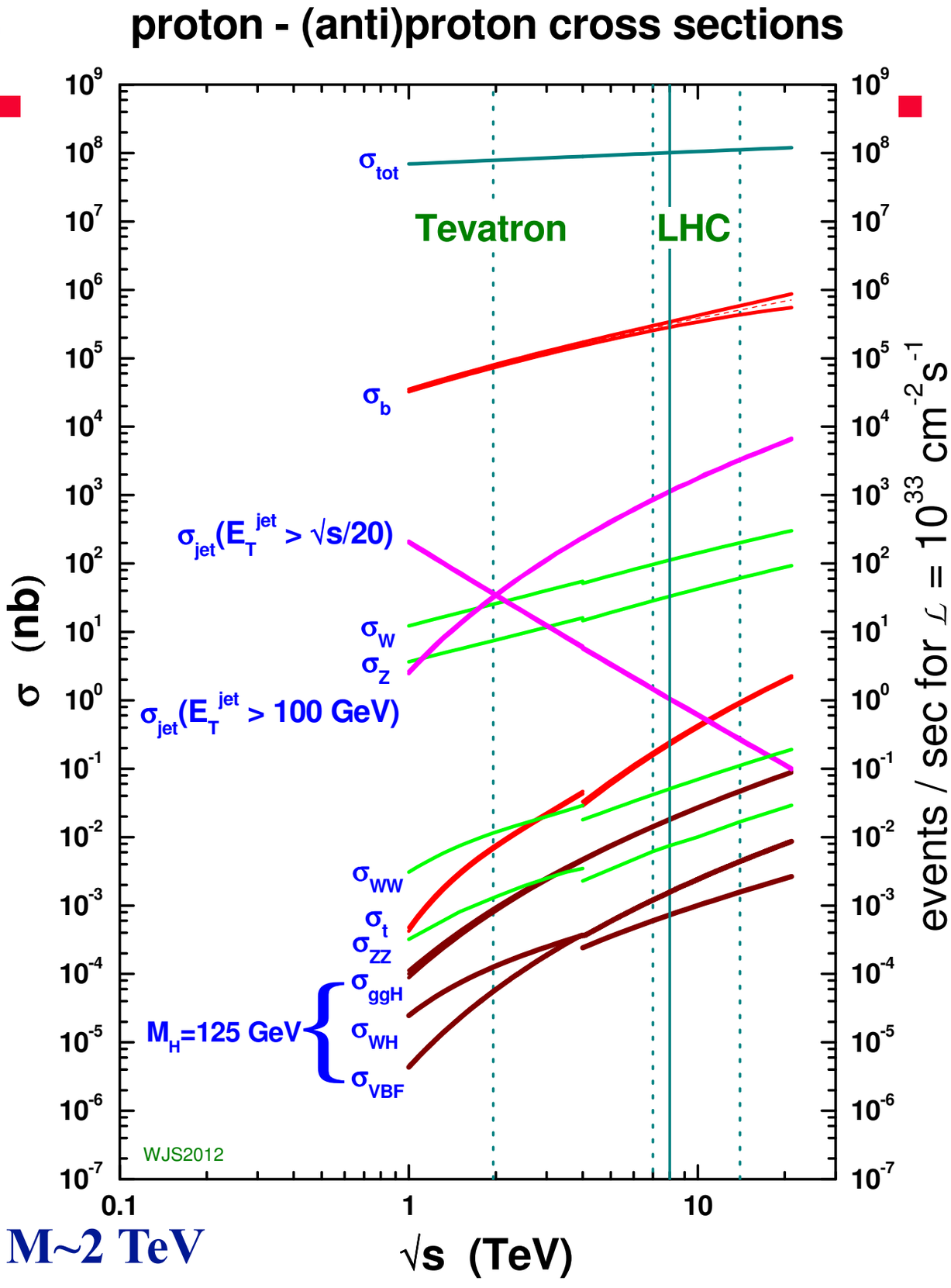


Physics Prospects for Run 2

Huge increase in cross section for many interesting processes

- but life is harder for states lighter than $t\bar{t}$





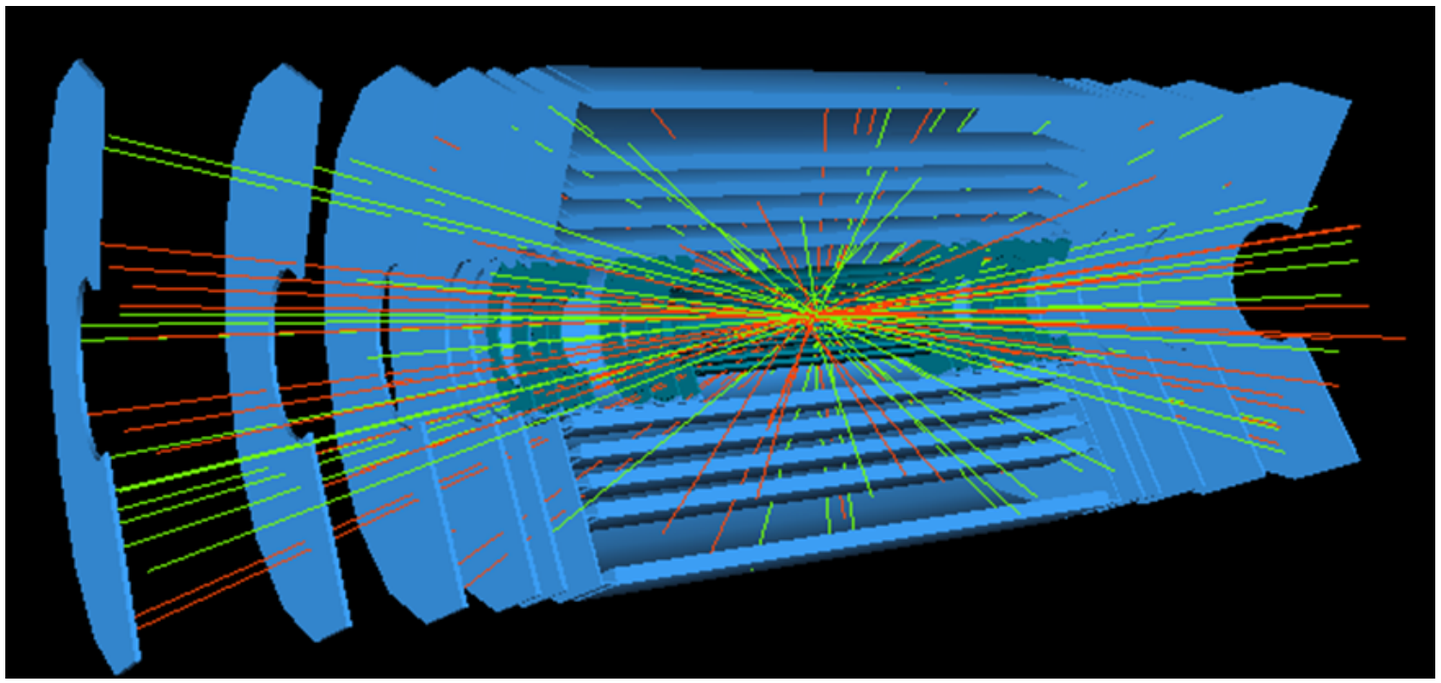
- Increase in cross section by factor ~10 for **M~2 TeV**

➡ Discovery of TeV-scale particles possible with a few **fb^{-1}** !!

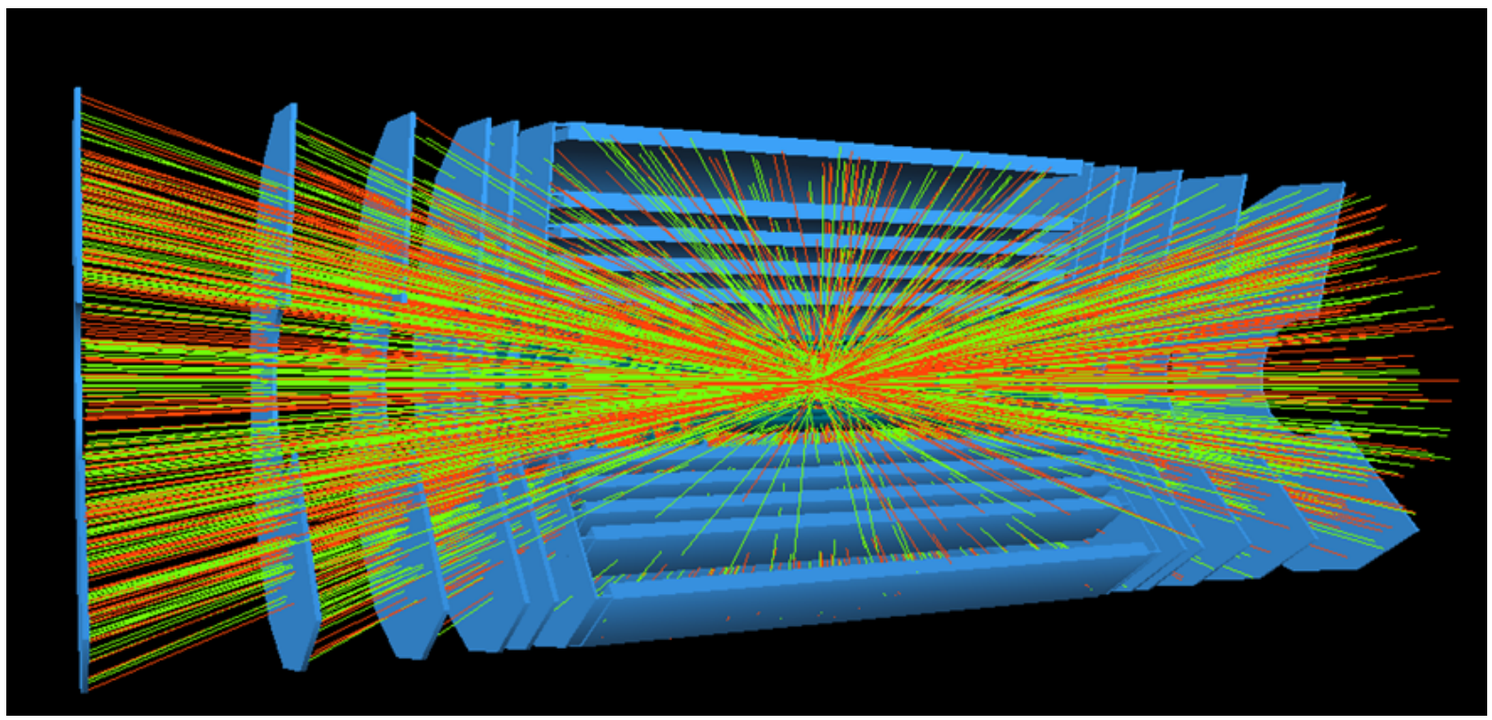
The Challenge of Pileup

- Pileup = number of proton-proton collision per bunch crossing

Simulated pileup in ATLAS tracker



Run 1
Pile up of **23**

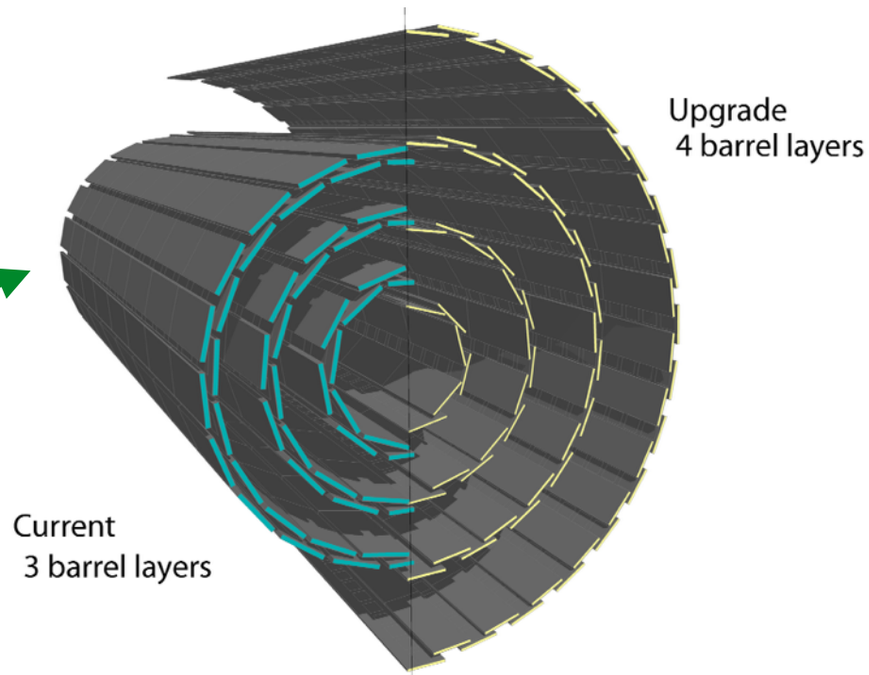


HL-HLC
Pile up of **230**

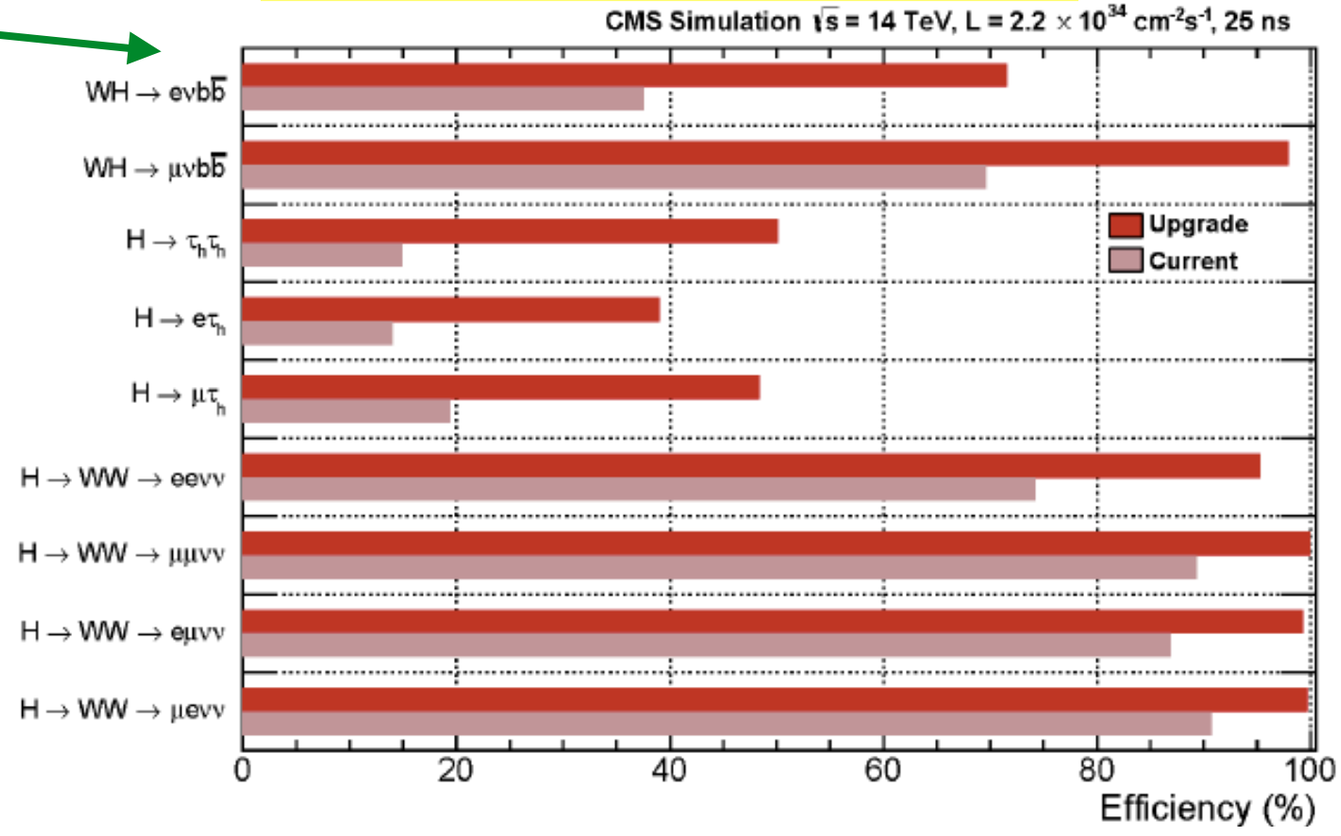
CMS Upgrade

CMS PAS FTR-13-003

- Long Shutdown 1:
  - Complete Muon coverage
  - New HCAL photo-detectors
- Long Shutdown 2:
  - New Pixel detector (2017)
  - New HCAL electronics
  - L1-Trigger upgrade
- For HL-LHC:
  - Tracker replacement, L1 Track-Trigger
  - New forward calorimetry, muons and tracking
  - High precision timing for pileup mitigation

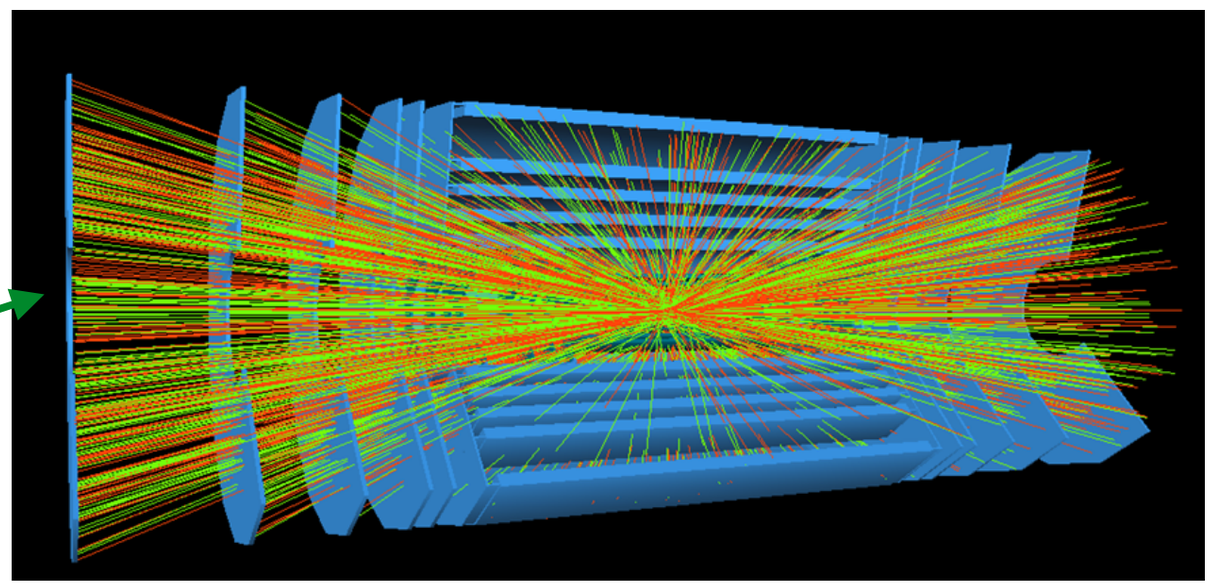


Greater trigger efficiency



ATLAS Upgrades

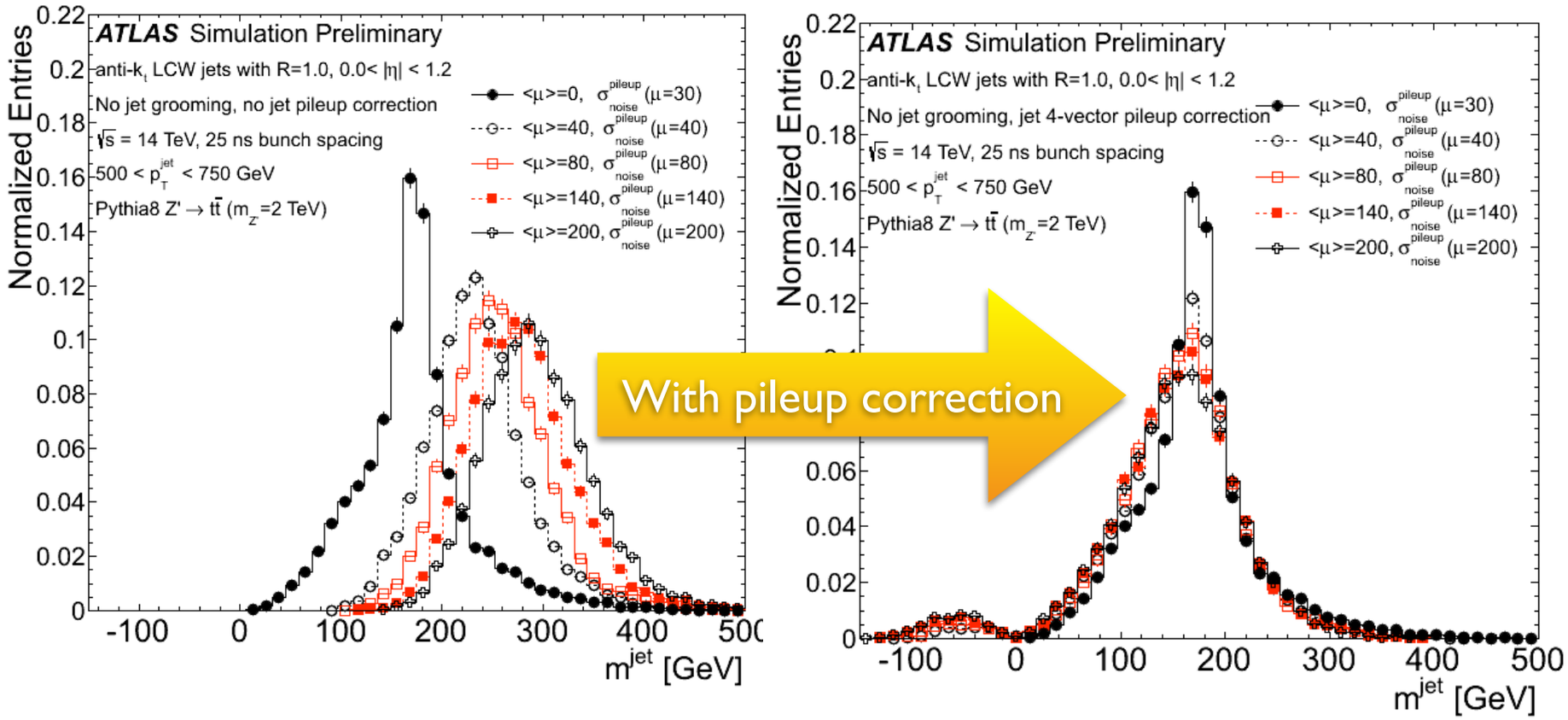
- Long Shutdown 1
  - New beam pipe at **r=25mm**
  - New insertable ***b***-layer at **31 < r/mm < 40**
  - Refurbished pixel readout
  - More complete muon coverage: extended endcap installation complete
- Fast Tracking for L2-trigger will come online during run 2
- Long Shutdown 2
  - New muon small wheel forward spectrometer
  - Topological L1-trigger processors
  - New forward detectors
- For HL-LHC
  - Completely new trigger architecture with new hardware at L0/L1
  - Completely new tracking detector
  - Calorimeter electronics upgrades



Run 2 and HL-LHC Analysis Techniques

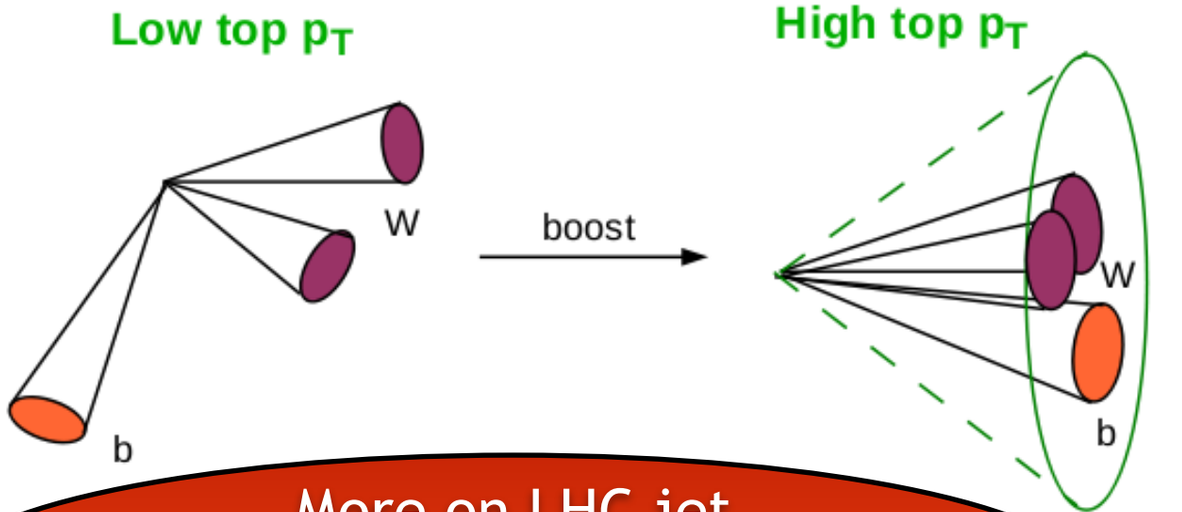
High Pileup

High pileup requires improved algorithms e.g. primary vertex reconstruction, ***b***-tagging, pileup jet rejection.



Jet Substructure

- High mass final states and high collision energy lead to highly boosted and close objects e.g. ***W→jj, Z→jj, t→Wb→jjb***
- Jet substructure techniques will be key to reconstruct some of these signals; may be crucial for new high-mass objects.

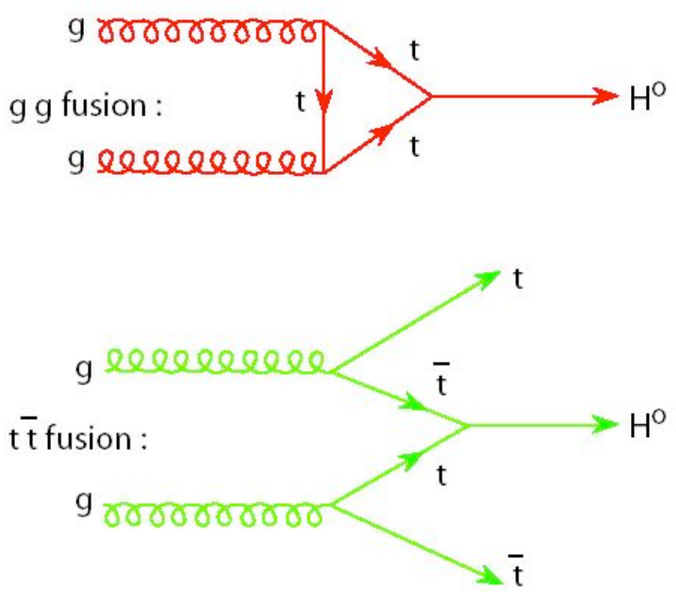


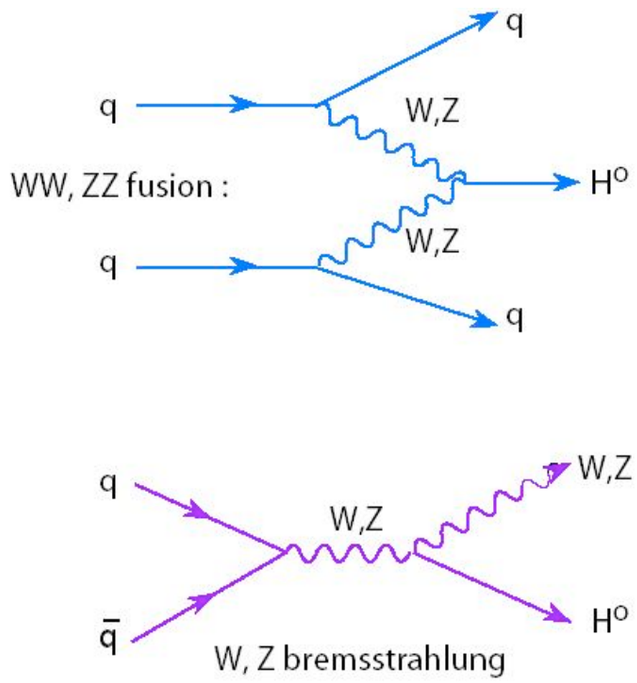
More on LHC jet reconstruction in Djamel Boumediene's talk

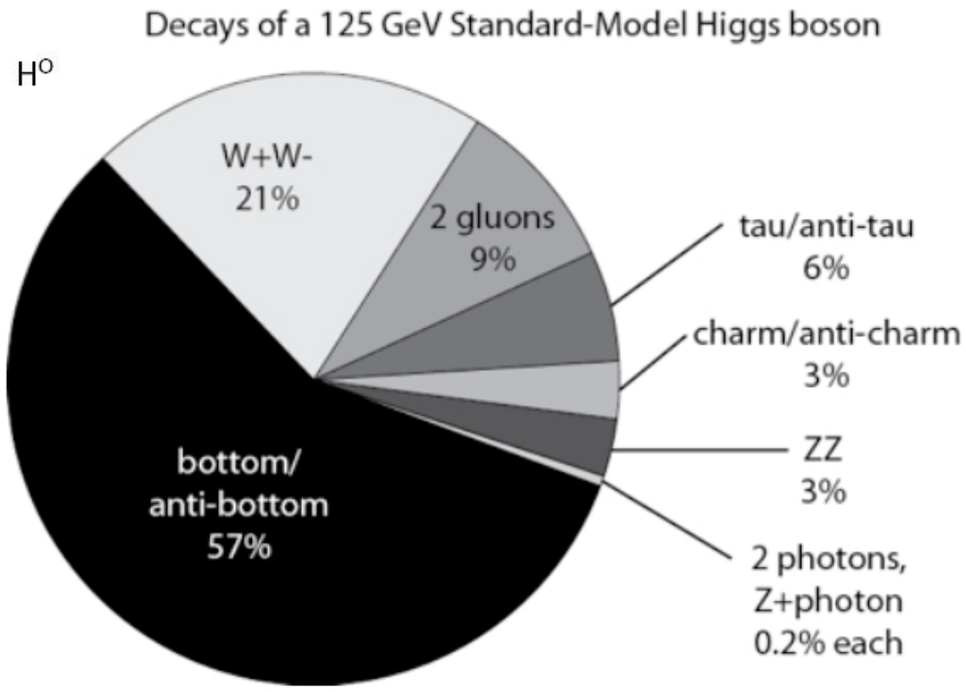
Projection for Run 2 and HL-LHC

- Projections from refining current analyses or designing new ones
- Different systematic uncertainty scenarios often considered, in particular the different theoretical uncertainties on the signal cross section.
- Results are presented for $\mathbf{300\ fb^{-1}}$ (2022) and/or $\mathbf{3000\ fb^{-1}}$ (2035?)
- Many results are presented in the context of specific models.

Higgs Boson Prospects



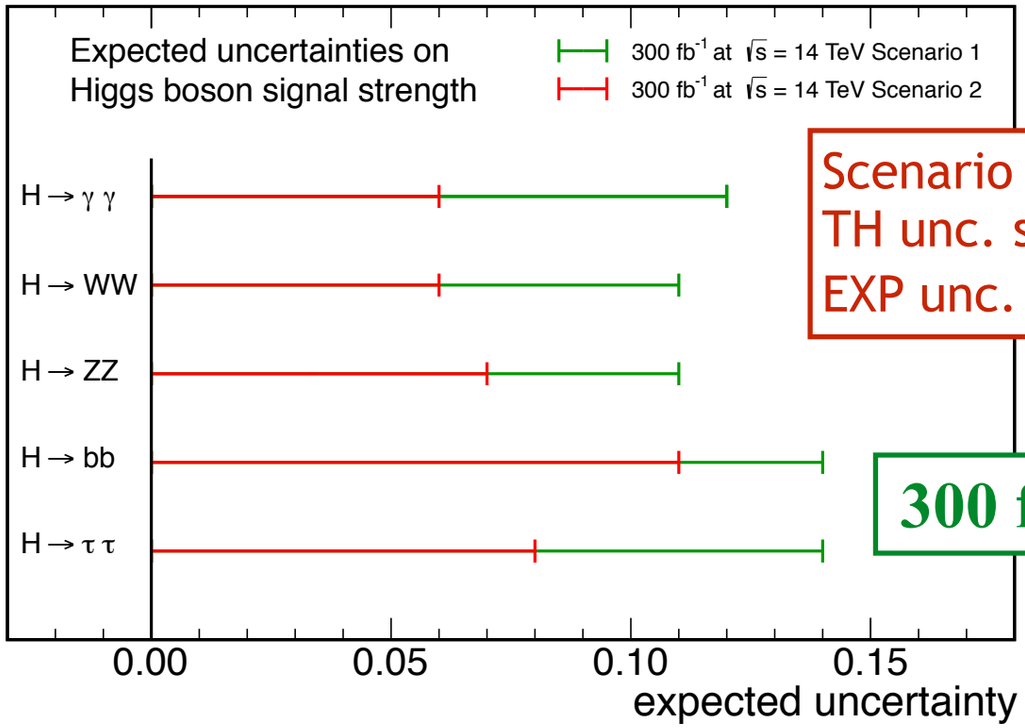




Higgs Boson Decay Sensitivity

arXiv:1307.7135
ATL-PHYS-PUB-2013-014

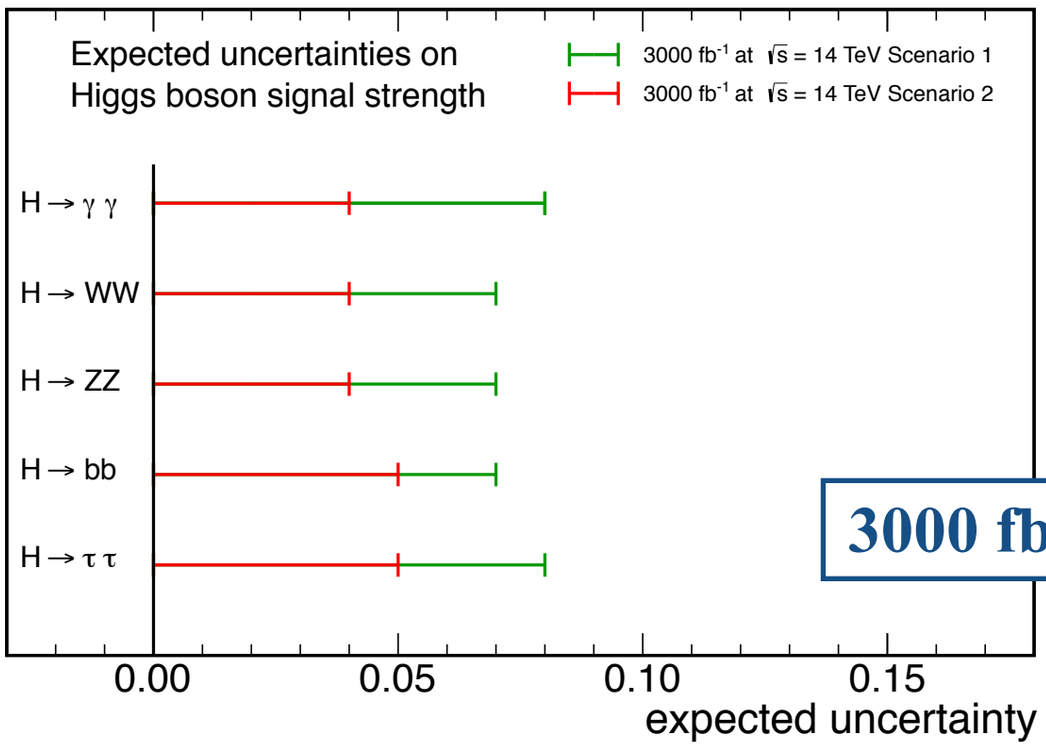
CMS Projection



Scenario 2:
TH unc. scaled by **1/2**
EXP unc. scaled by $\sqrt{\mathscr{L}}$

300 fb^{-1}

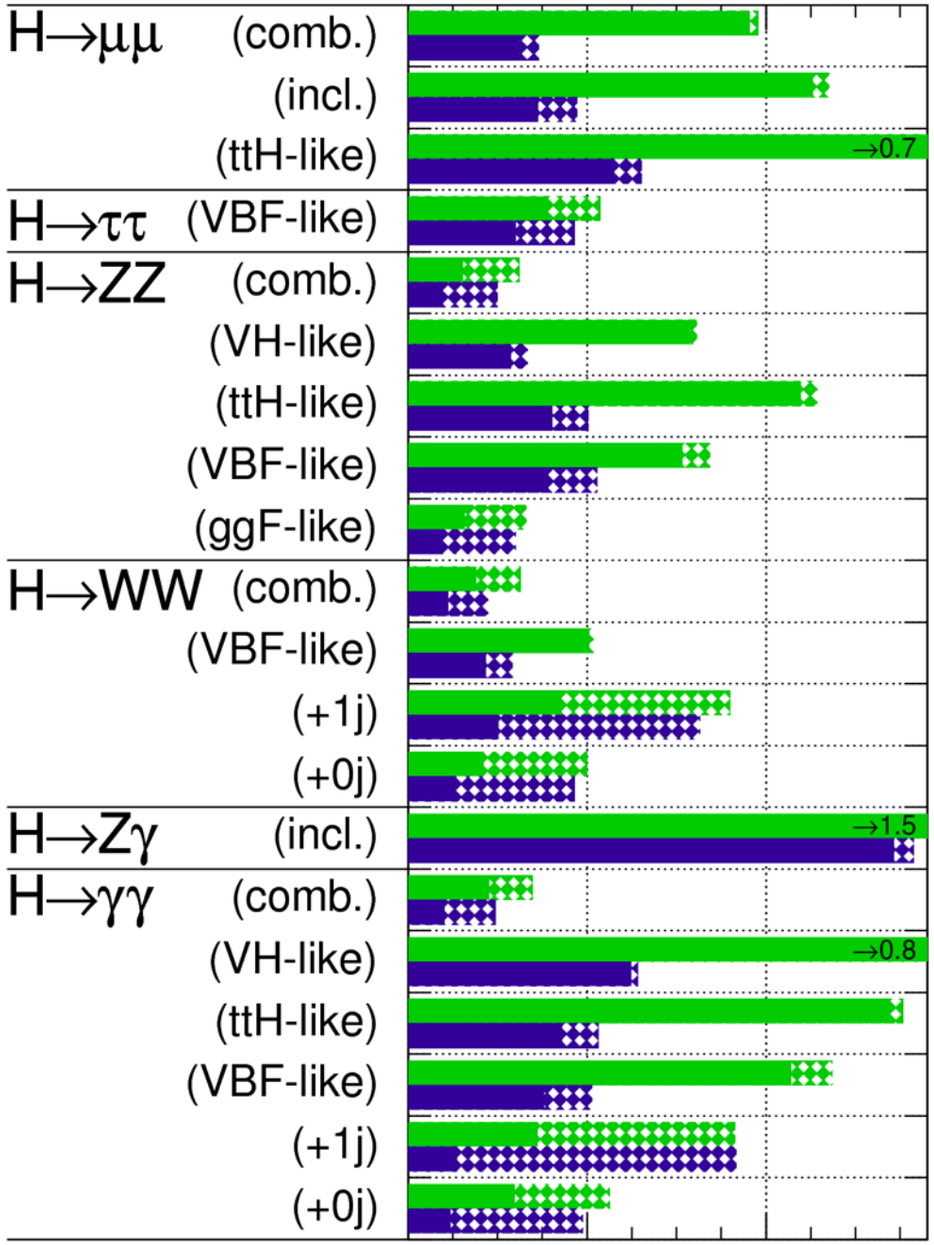
CMS Projection



3000 fb^{-1}

ATLAS Simulation Preliminary

$\sqrt{s}$ = 14 TeV: $\int Ldt$=300 fb^{-1} ; $\int Ldt$=3000 fb^{-1}



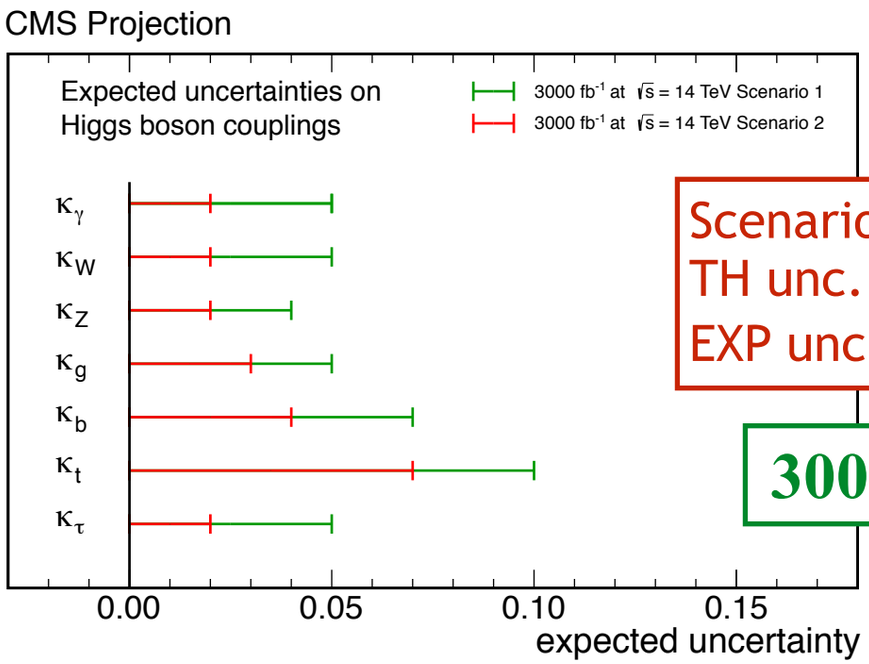
Dashed band includes current TH unc.

Higgs Boson Couplings Fit

arXiv:1307.7135
ATL-PHYS-PUB-2013-014

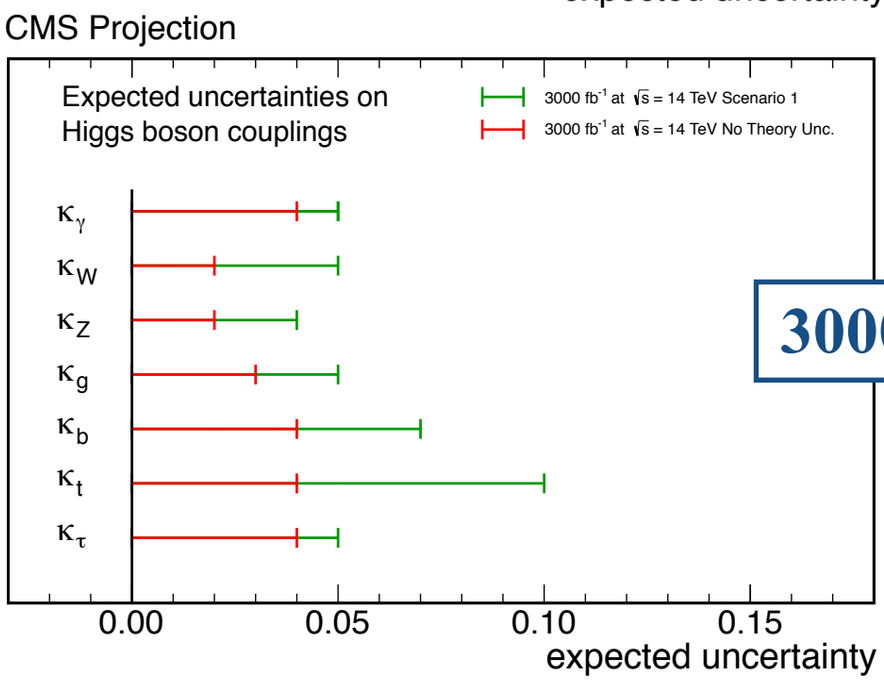
- Assuming Γ_H is sum of SM widths, calculate uncertainties on Higgs boson couplings.
- Deviations from the SM are quantified using κ multiplier, in SM $\kappa_i = 1$, *e.g.*:

$$(\sigma \cdot \mathrm{BR})(gg \to H \to \gamma\gamma) = \sigma_{\mathrm{SM}}(gg \to H) \cdot \mathrm{BR}_{\mathrm{SM}}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

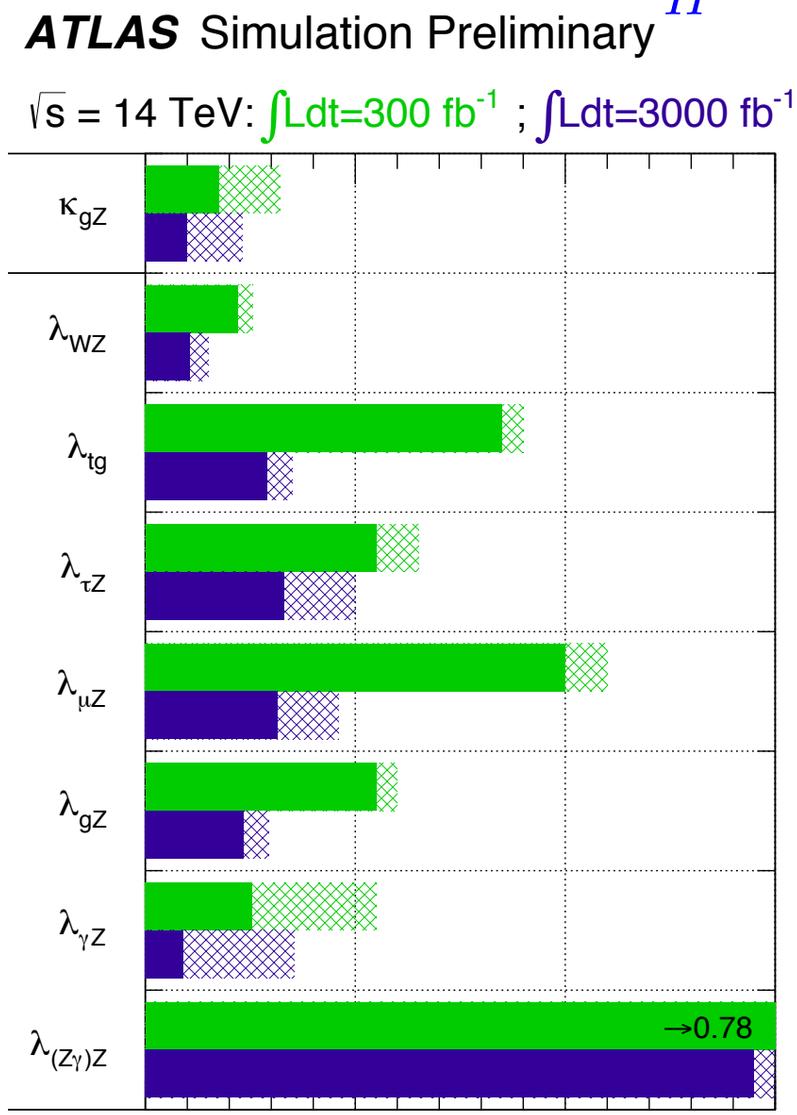


Scenario 2:
TH unc. scaled by **1/2**
EXP unc. scaled by $\sqrt{\mathscr{L}}$

300 fb^{-1}



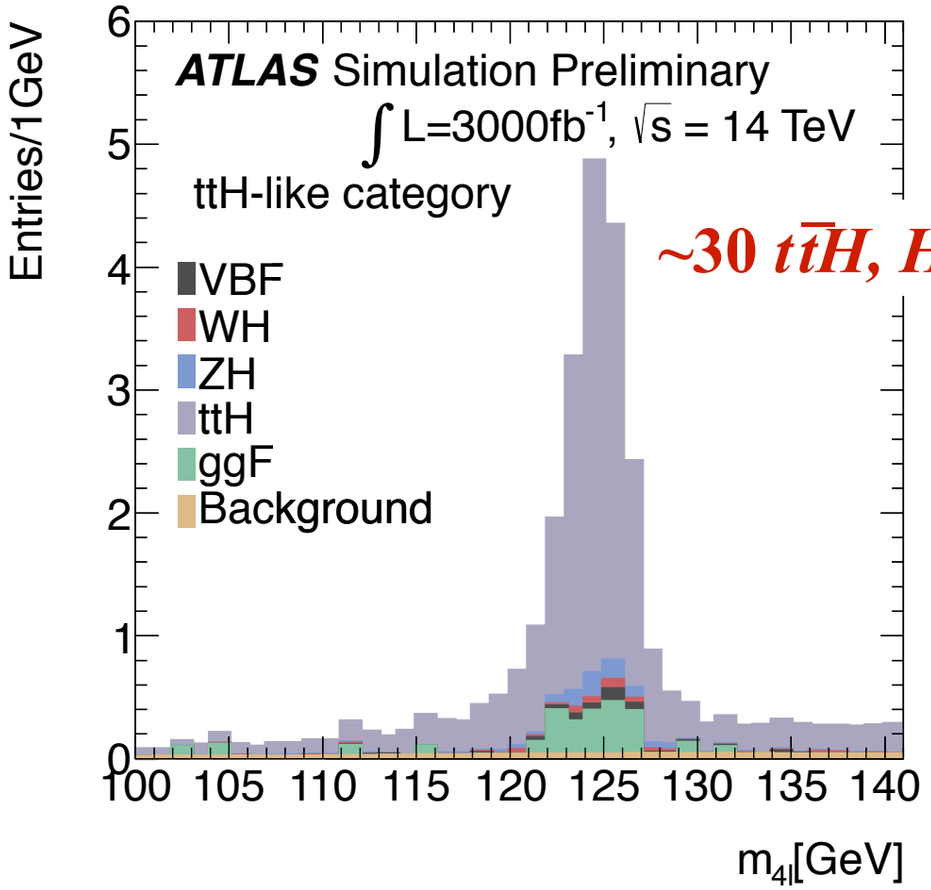
3000 fb^{-1}



ATLAS combined results do not include new information for **Zγ, VH(γγ), ttH(γγ) & VH(bb)**

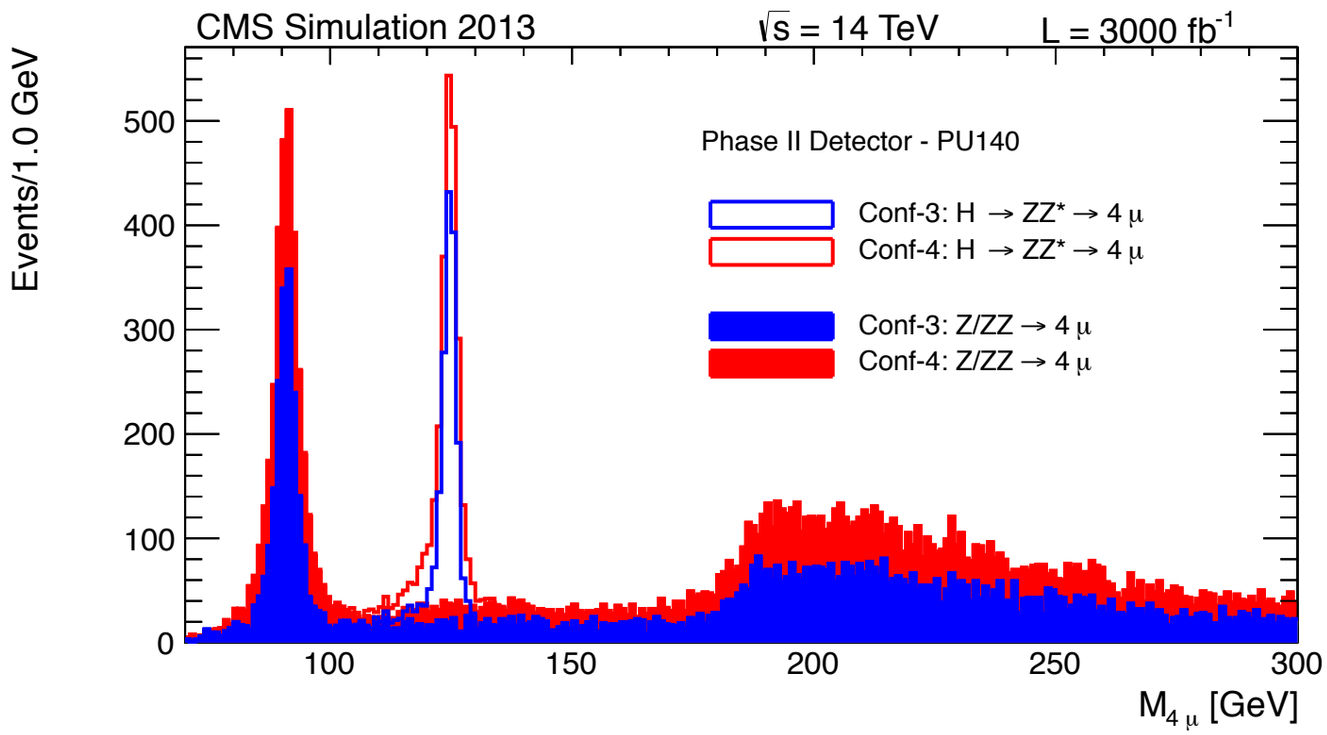
Still the Golden Channel: $H \to ZZ^* \to 4\ell$

- $H \to ZZ^* \to 4\ell$: very clean signature and small backgrounds.
- Large statistics will allow a probe of all main production modes.
- Higgs boson production cross-section uncertainty constrained to $O(10\%)$
- Allows measurement of **CP** properties of the Higgs boson.



~30 $t\bar{t}H$, $H \to 4\ell$ events

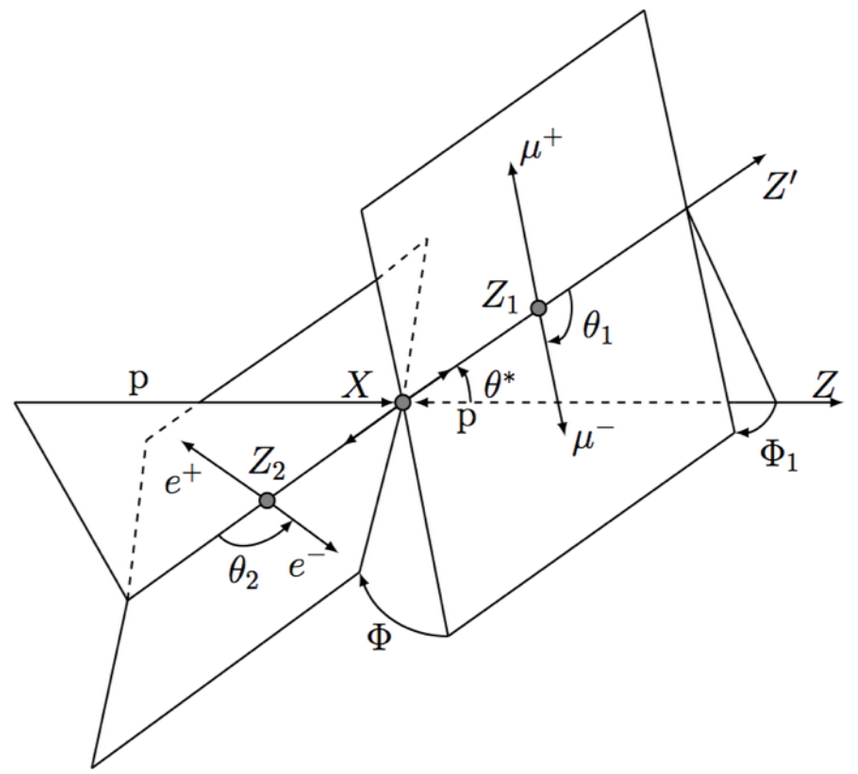
$O(3000)$ $gg \to H \to 4\mu$ events



ATL-PHYS-PUB-2013-014

CMS-PAS-FTR-13-003

Higgs CP Studies



- $H \to ZZ \to 4\ell$ used to reconstruct the full angular decay structure.

- Very sensitive to non-SM ($\mathbf{CP = 0^+}$) contributions.

$$A(H \to ZZ) = v^{-1}\left(a_1 m_Z^2 \epsilon_1^\star \epsilon_2^\star + a_2 f_{\mu\nu}^{\star(1)} f^{\star(2),\mu\nu} + a_3 f_{\mu\nu}^{\star(1)} \tilde{f}^{\star(2),\mu\nu}\right)$$

SM tree processes | loop CP-even contributions | CP-odd contributions (BSM)

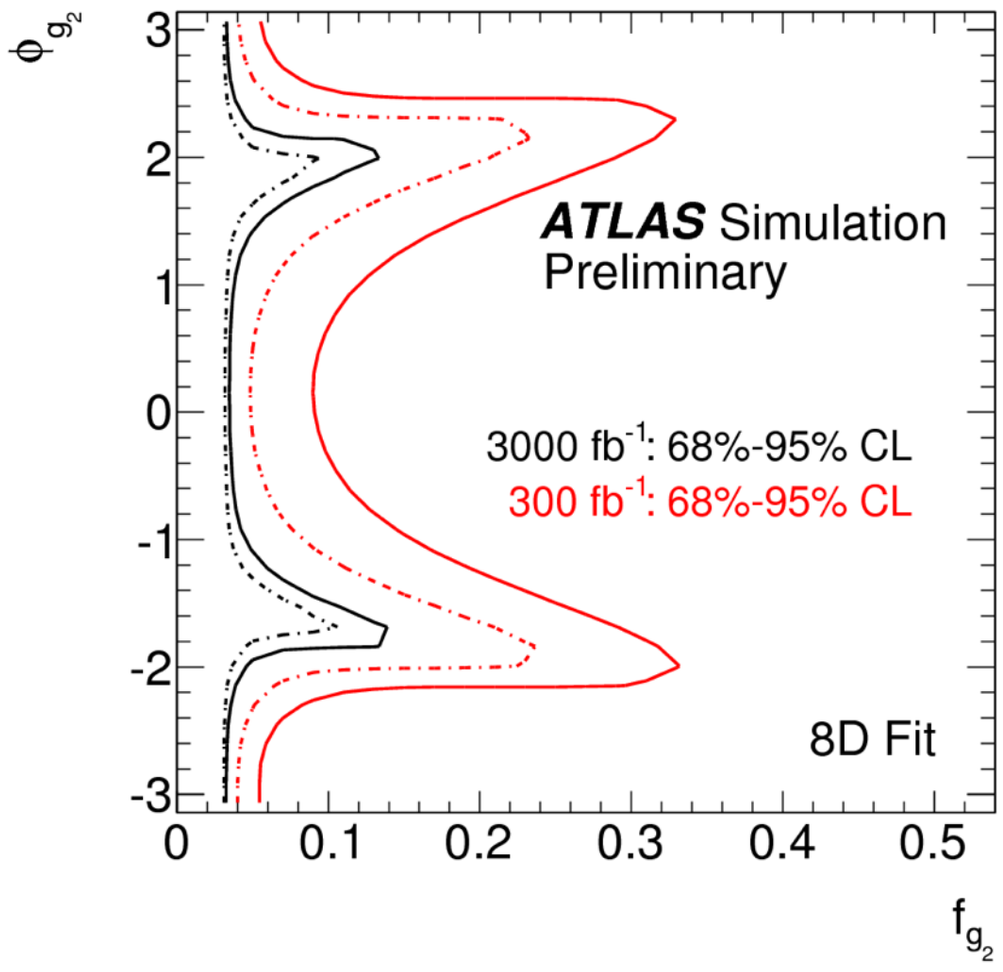
- Fit fraction of event (f_{ai}) and phases (ϕ_i) to observed decay:

$$\phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right) \qquad f_{a_i} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_i|^2 \sigma_i}$$

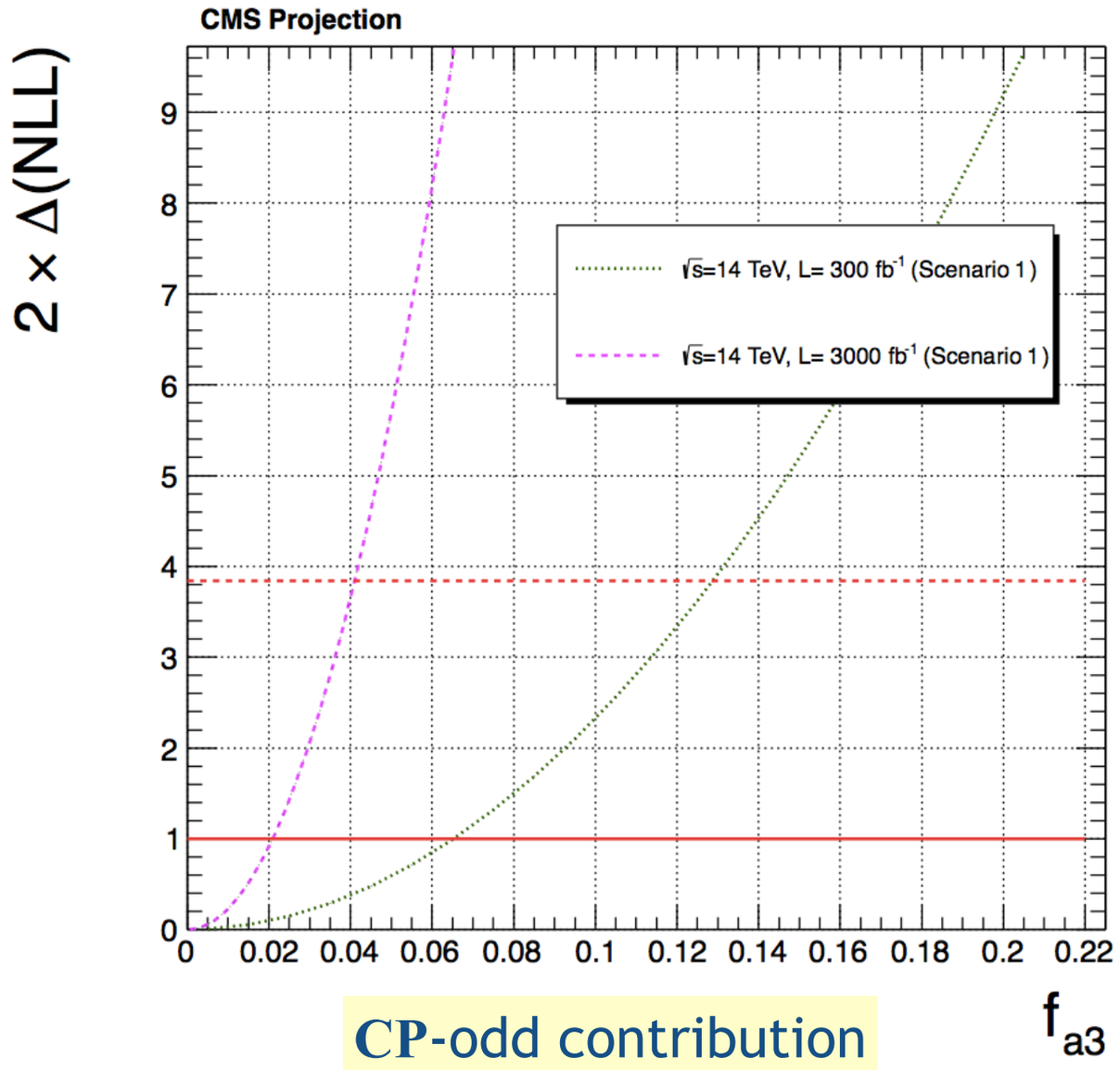
Higgs CP Studies

arXiv:1307.7135

ATL-PHYS-PUB-2013-013



Loop-induced CP-even contribution

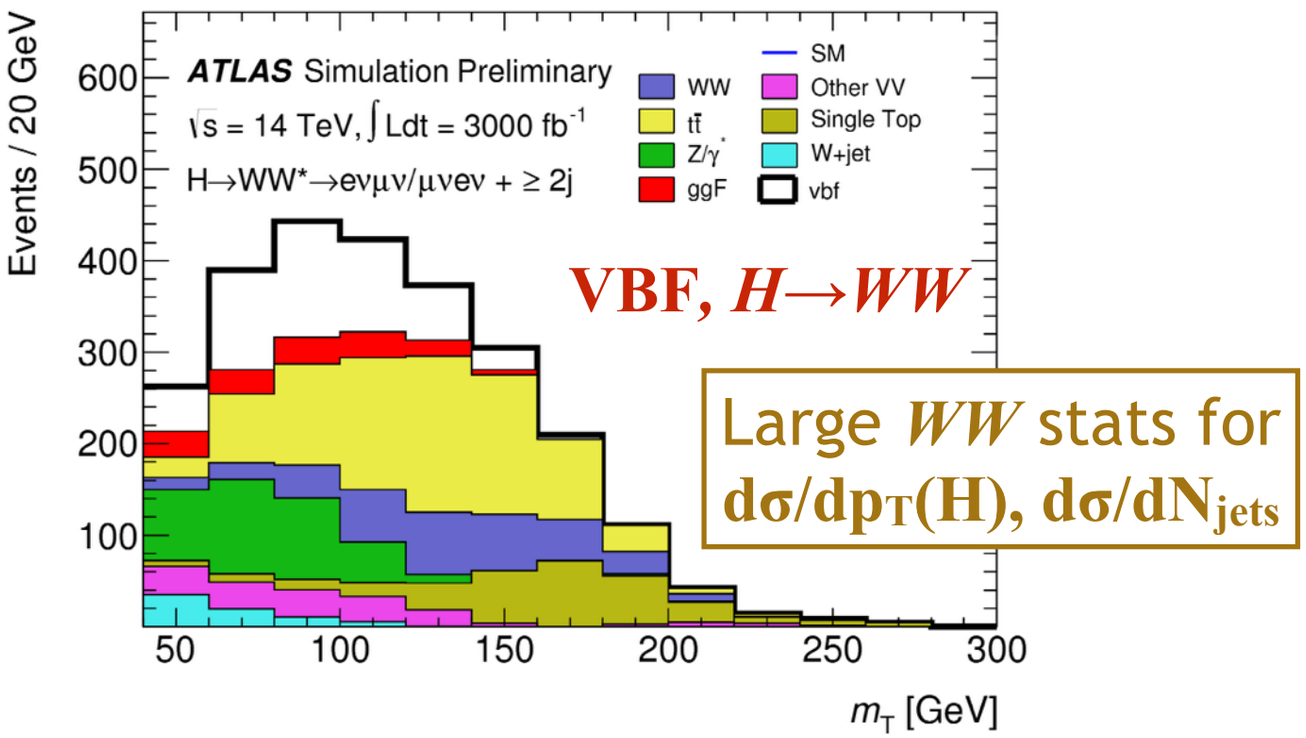


CP-odd contribution

- Extra contributions constrained to $|f| \sim 10$ % with 3000 fb^{-1}.

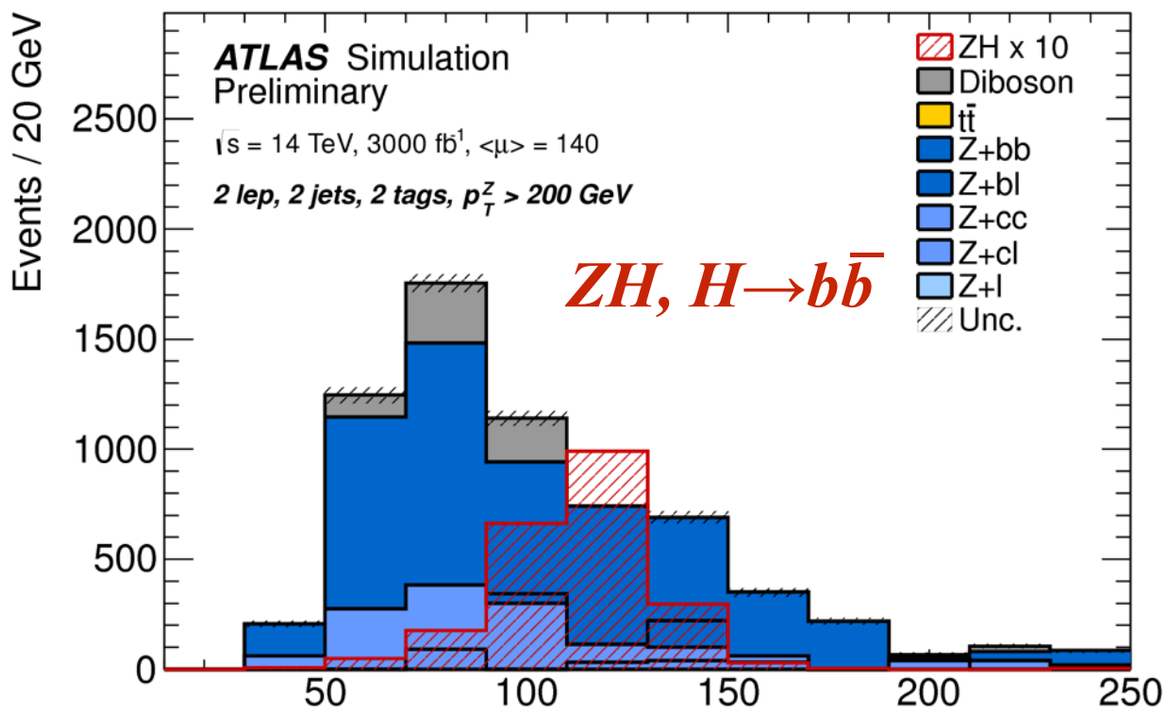
$\gamma\gamma$, WW, $b\bar{b}$

ATL-PHYS-PUB-2014-012
ATL-PHYS-PUB-2014-011
ATL-PHYS-PUB-2013-014



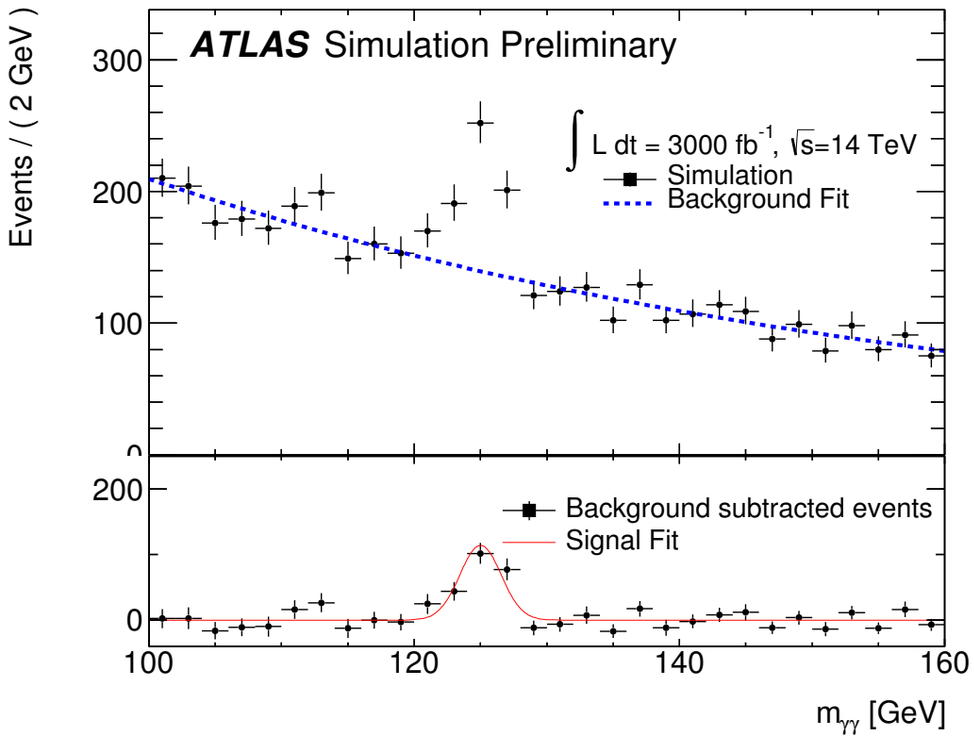
VBF, $H\rightarrow WW$

Large WW stats for $d\sigma/dp_T(H)$, $d\sigma/dN_{jets}$



ZH, $H\rightarrow b\bar{b}$

$t\bar{t}H$, $H\rightarrow\gamma\gamma$; 1 lepton



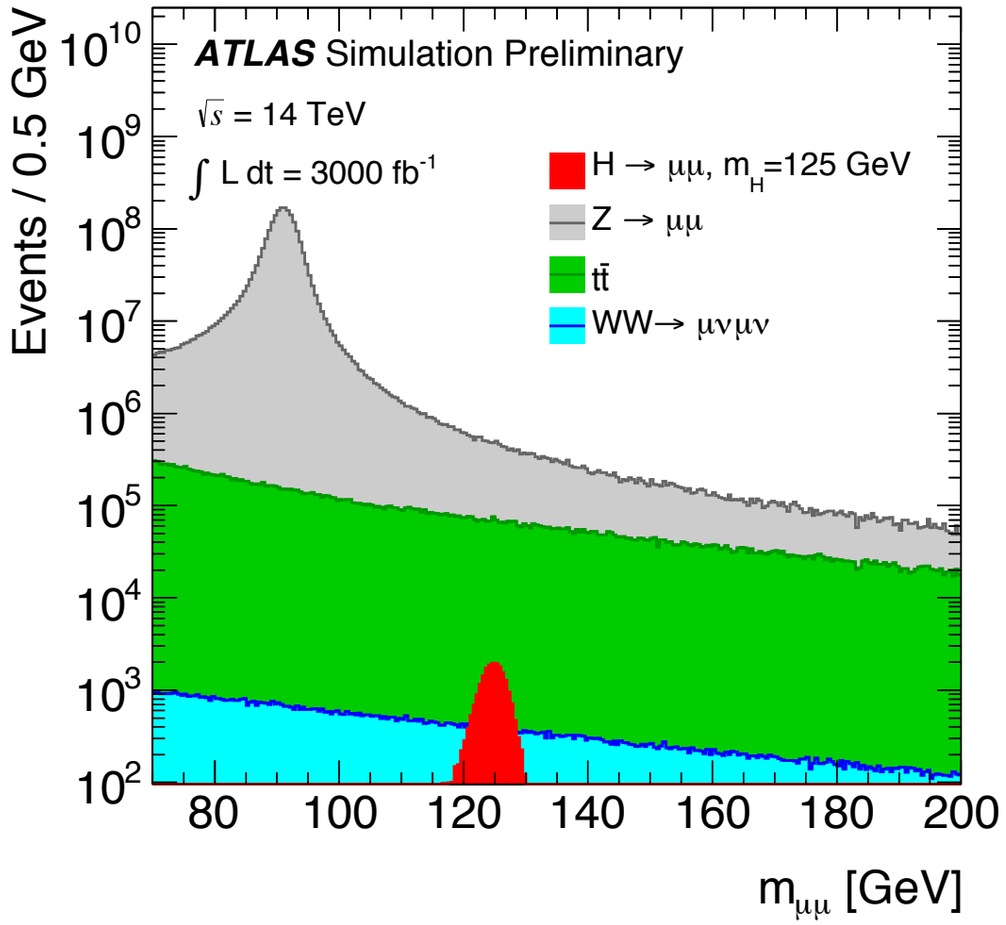
VH, $H\rightarrow b\bar{b}$ expected significance in **3000 fb^{-1}**

		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{\text{Stats}}$ error	+0.07 −0.06	+0.09 −0.09	+0.05 −0.05
Theory-only	$\hat{\mu}_{\text{Theory}}$ error	+0.09 −0.07	+0.07 −0.08	+0.07 −007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{\text{w/Theory}}$ error	+0.37 −0.36	+0.15 −0.15	+0.14 −0.14
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.36 −0.36	+0.14 −0.12	+0.12 −0.12
Scenario II	Significance	4.7	-	9.6
	$\hat{\mu}_{\text{w/Theory}}$ error	+0.23 −0.22	-	+0.13 −0.13
	$\hat{\mu}_{\text{wo/Theory}}$ error	+0.21 −0.21	-	+0.11 −0.11

Higgs Boson Rare Decays

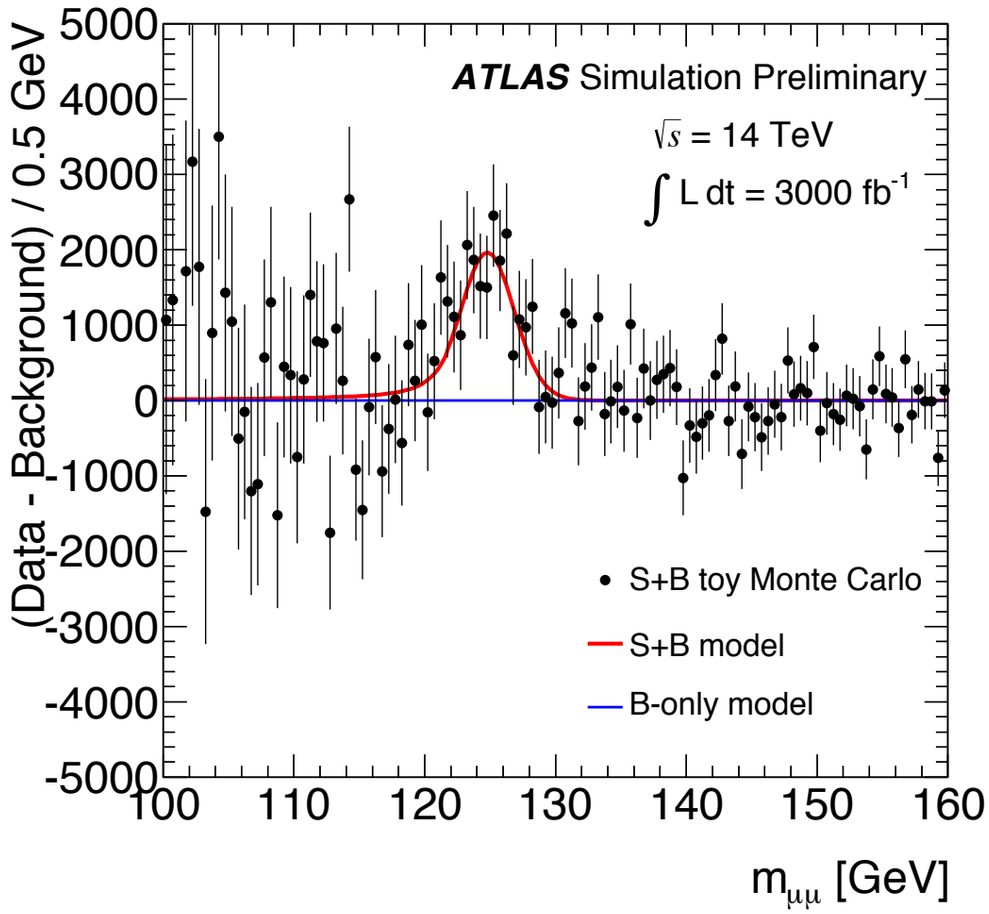
$H \to \mu\mu$

- SM prediction is $\mathbf{BR}(H \to \mu\mu) = \mathbf{2.19 \times 10^{-4}}$
- Observation of $H \to \mu\mu$ gives access to Higgs coupling to 2nd generation of fermions.
- Run 1 limit is 7 × SM
- With $\mathbf{3000\ fb^{-1}}$:
  - Observation at ~7σ
  - uncertainty of 20-25 % on signal strength (~8% on κ_μ)



***ATLAS* Simulation Preliminary**

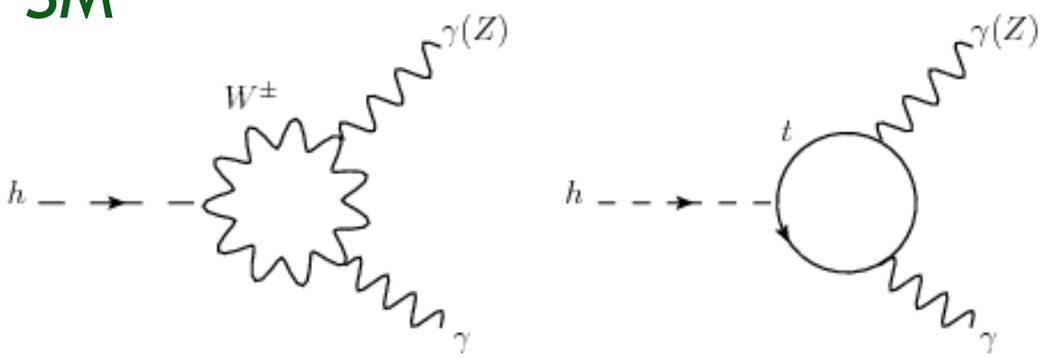
$\mathcal{L}$ [fb^{-1}]	300	3000
N_{ggH}	1510	15100
N_{VBF}	125	1250
N_{WH}	45	450
N_{ZH}	27	270
N_{ttH}	18	180
N_{Bkg}	564000	5640000
Δ^{sys}_{Bkg} (model)	68	110
Δ^{sys}_{Bkg} (fit)	190	620
Δ^{stat}_{S+B}	750	2380
Signal significance	2.3σ	7.0σ
$\Delta\mu/\mu$	46%	21%



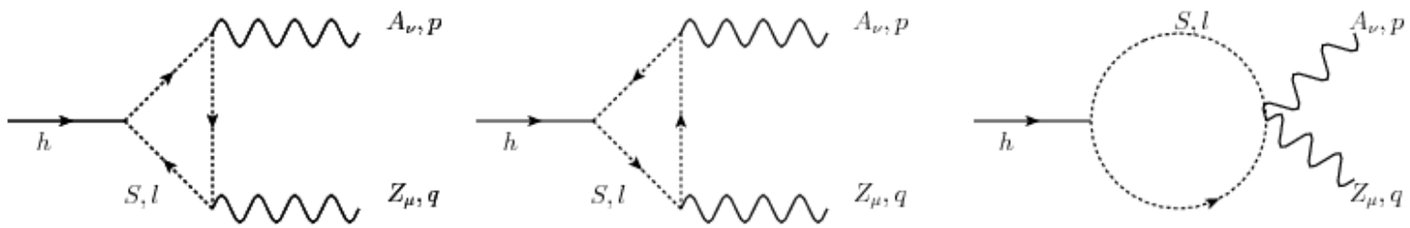
$H \rightarrow Z\gamma$

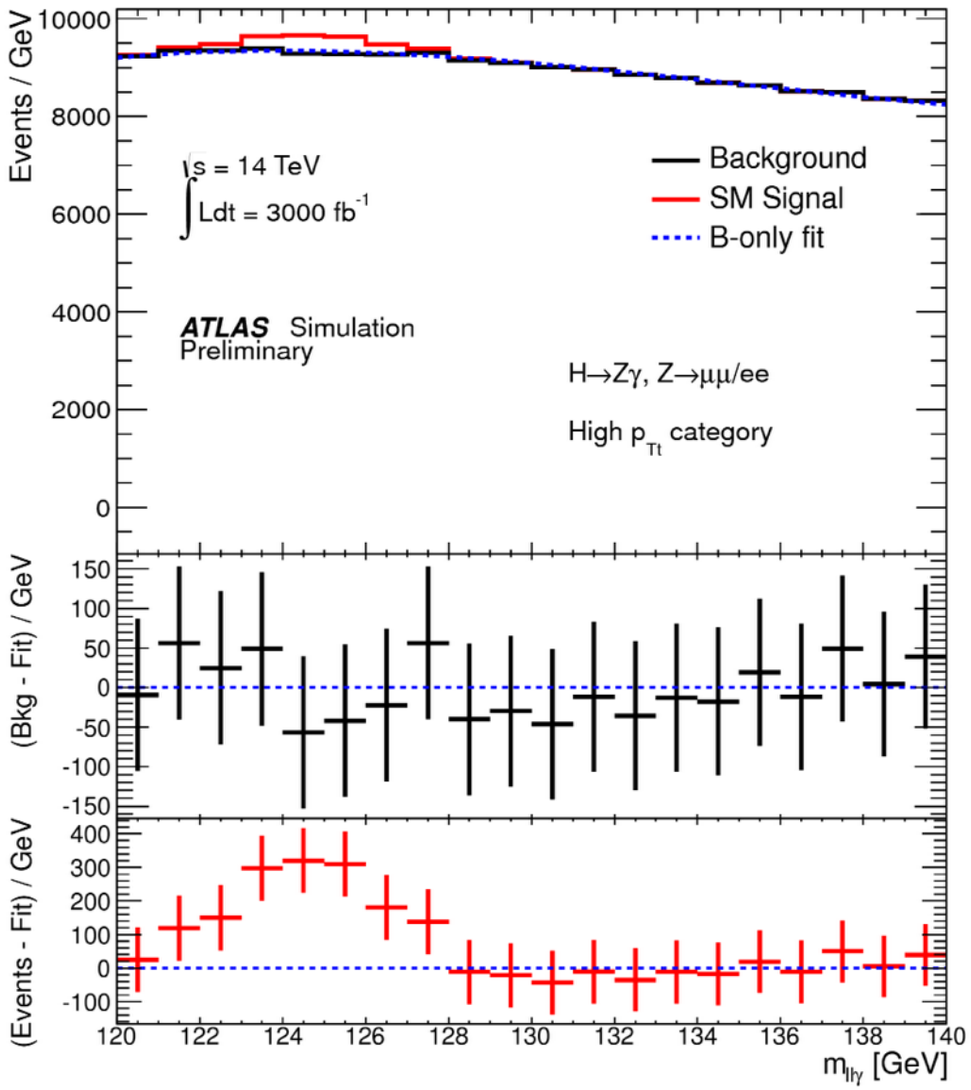
- SM prediction is $\mathbf{BR}(H \rightarrow Z\gamma) = \mathbf{1.54 \times 10^{-3}}$
- $H \rightarrow Z\gamma$ sensitive to potential new particles in loop

SM



e.g. new scalar contribution

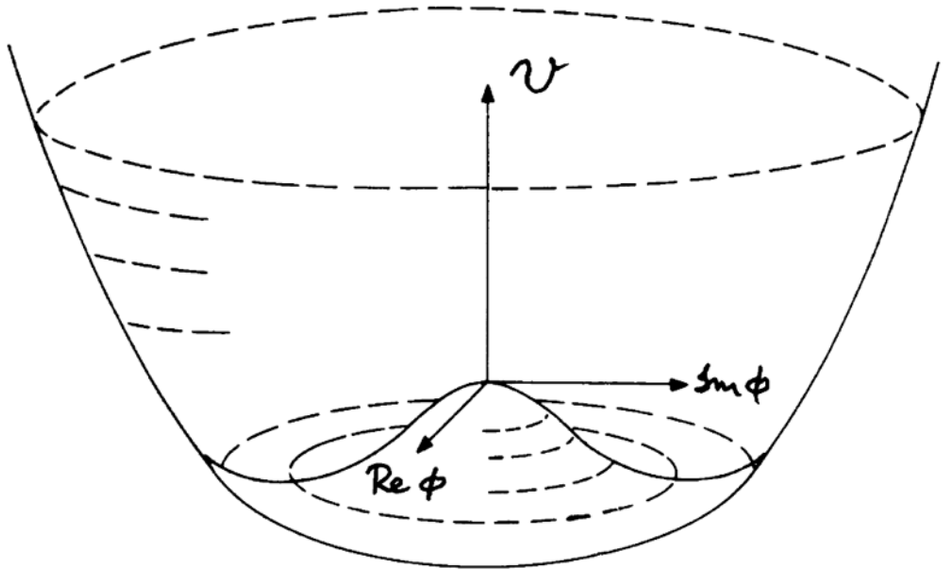


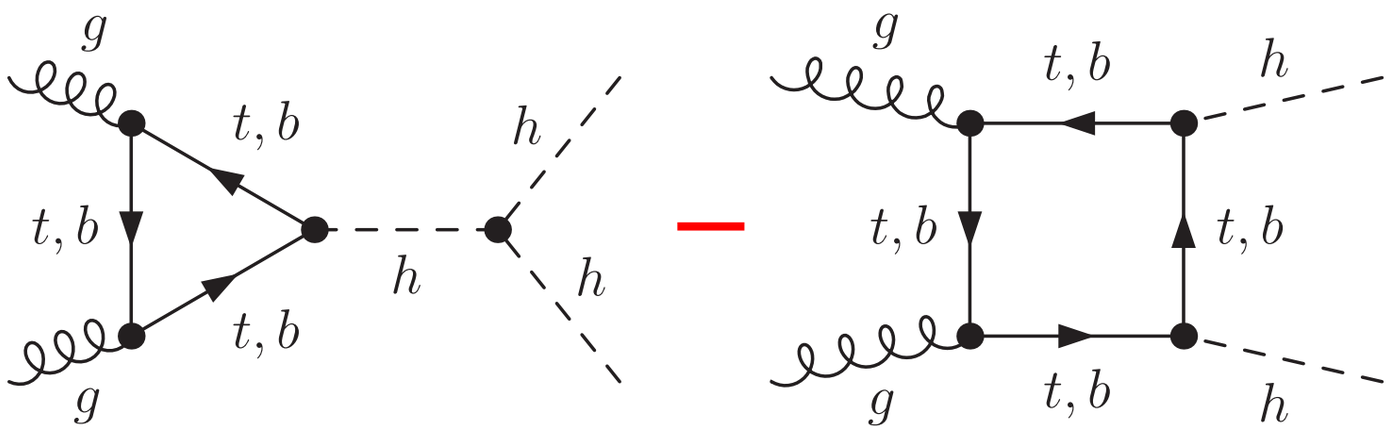


- Run 1 limits are 10 × SM
- At $\mathbf{3000\ fb^{-1}}$ a precision of 20-30% on the signal strength (~10% on $\kappa_{Z\gamma}$)

Di-Higgs Boson Production

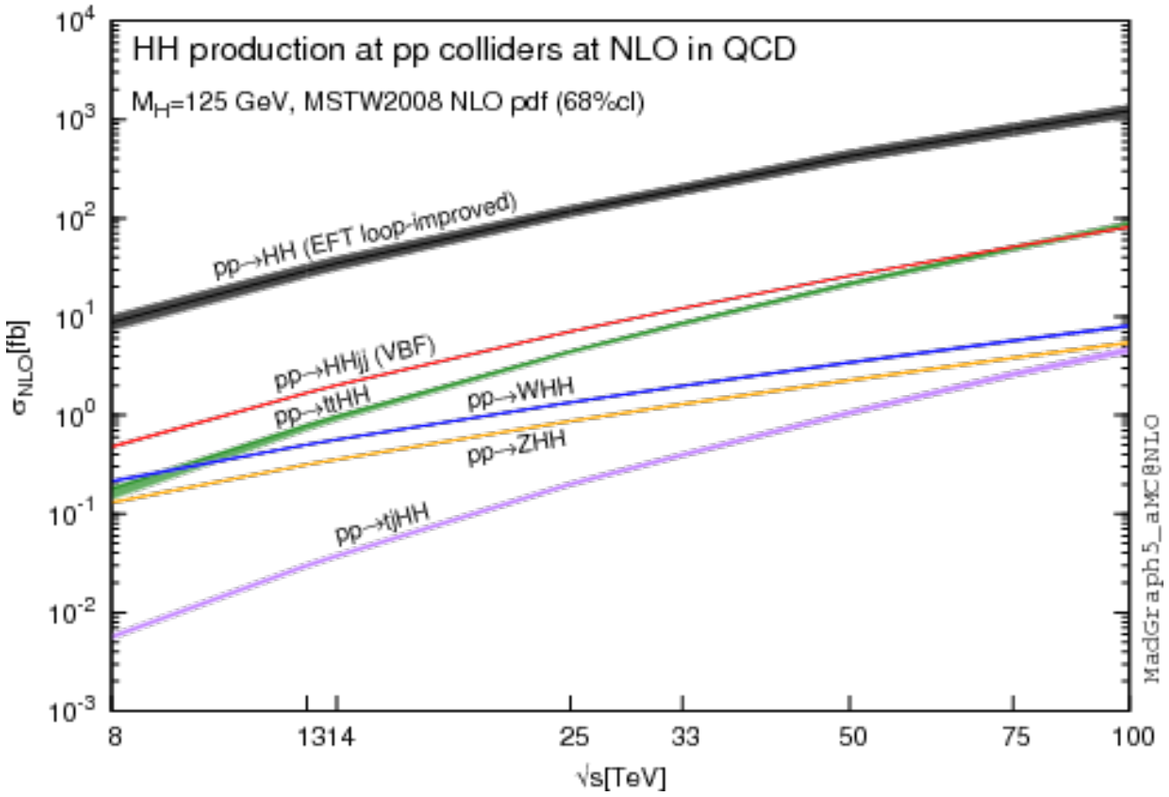
- We want to probe the shape of the Higgs potential
- Observation of di-Higgs production is a first step… but very challenging





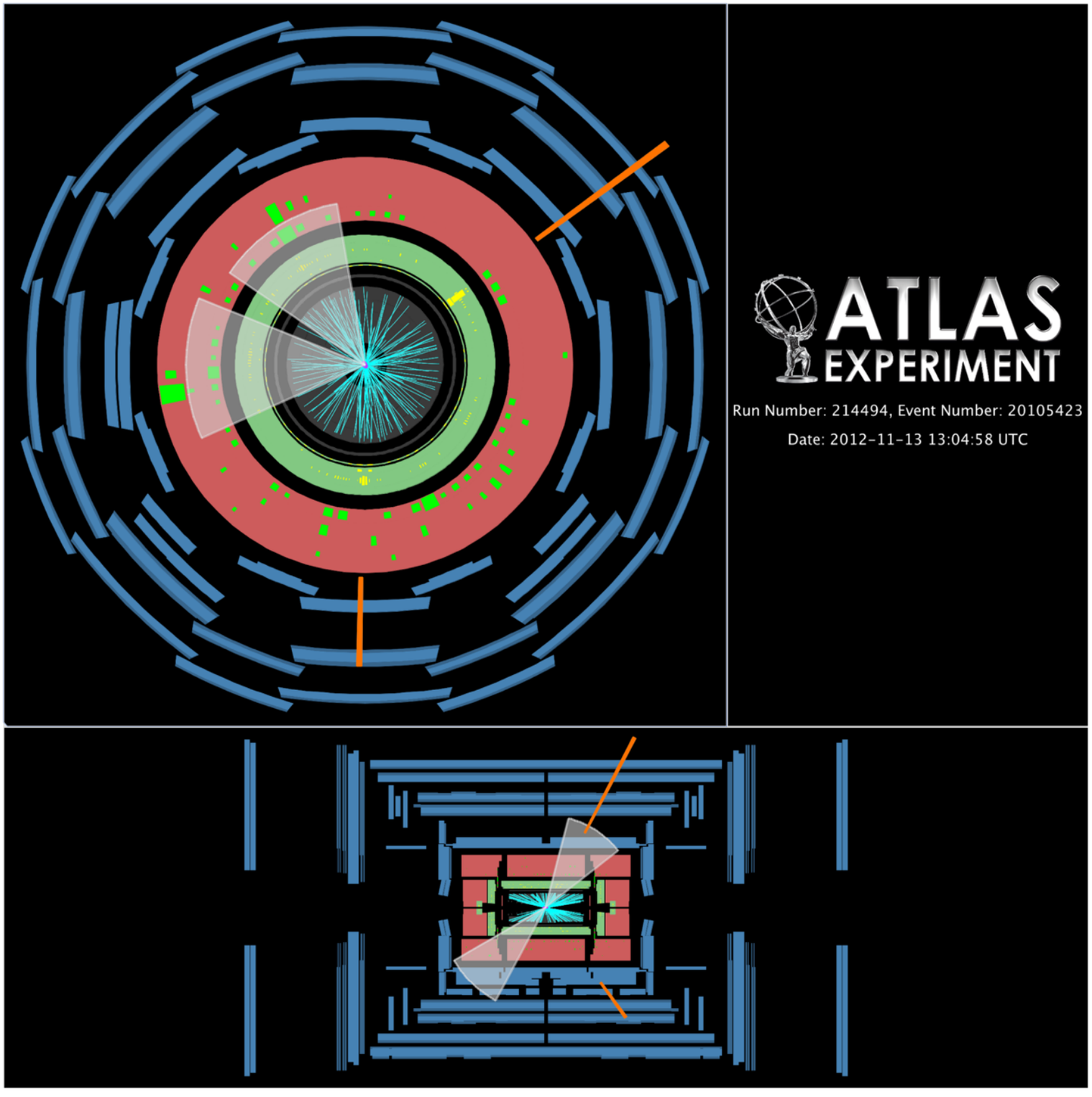
- Production dominated by box diagram, negative interference with self-coupling diagrams

arXiv:1401.7340



$H\to\gamma\gamma$, $H\to b\bar{b}$ candidate event at $\sqrt{s}$=8 TeV

arXiv:1406.5053



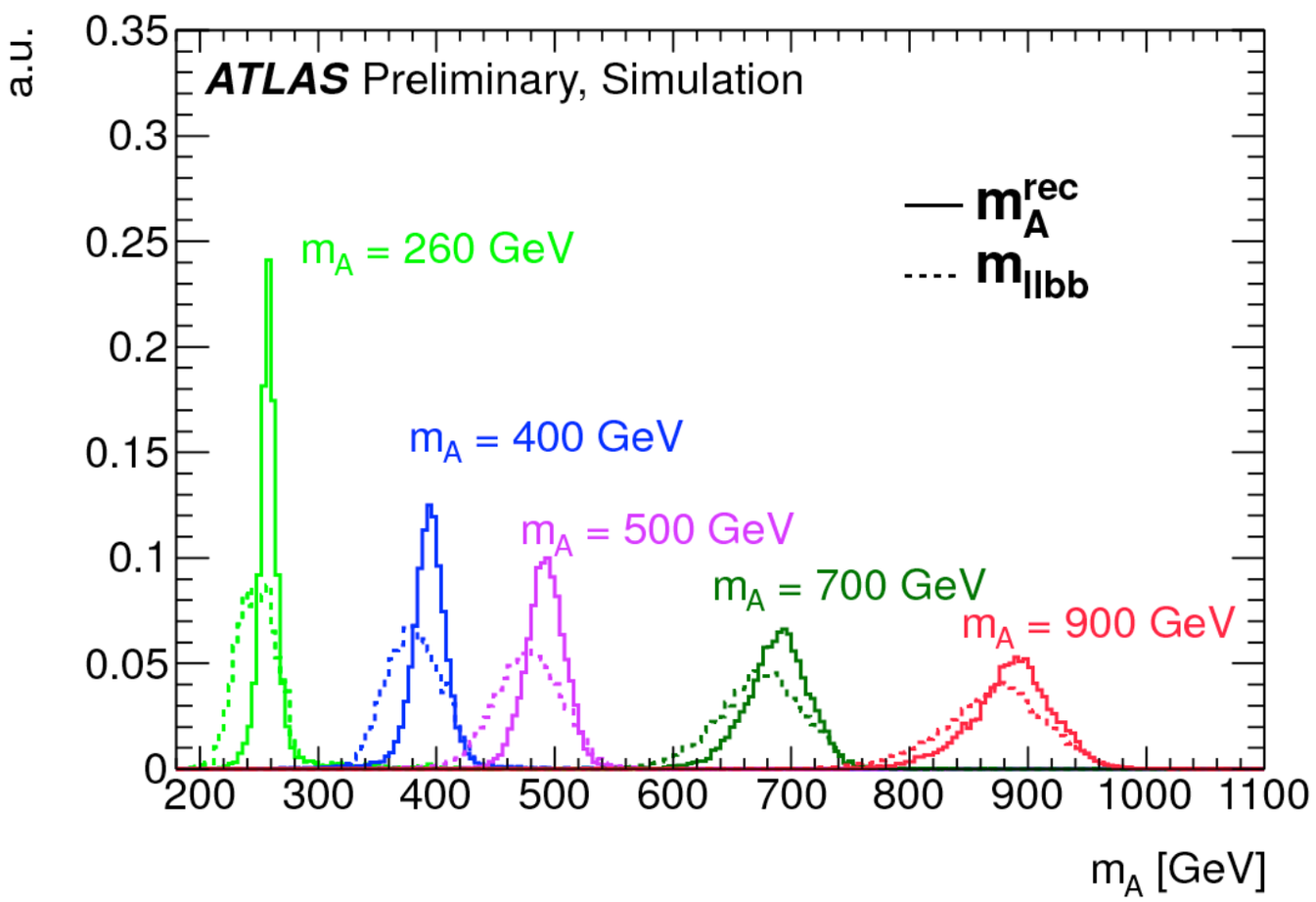
Higgs beyond the Standard Model

Additional Heavy Higgs bosons

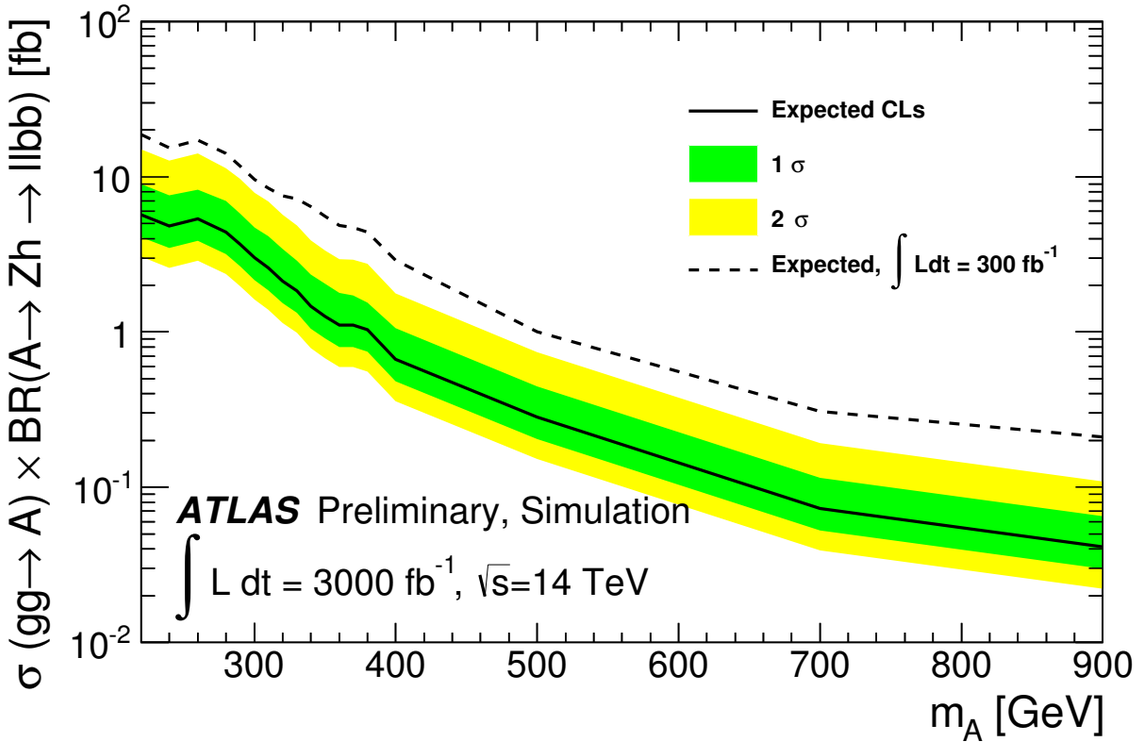
- Additional Higgs doublets predicted in many models, including Supersymmetry.
- e.g. A two-Higgs doublet (2HDM) model includes four new Higgs boson:

- **tanβ** is the ratio between the vev of the Higgs doublets

$A \to Zh \to \ell\ell bb$ reconstruction (2HDM)



ATL-PHYS-PUB-2013-016

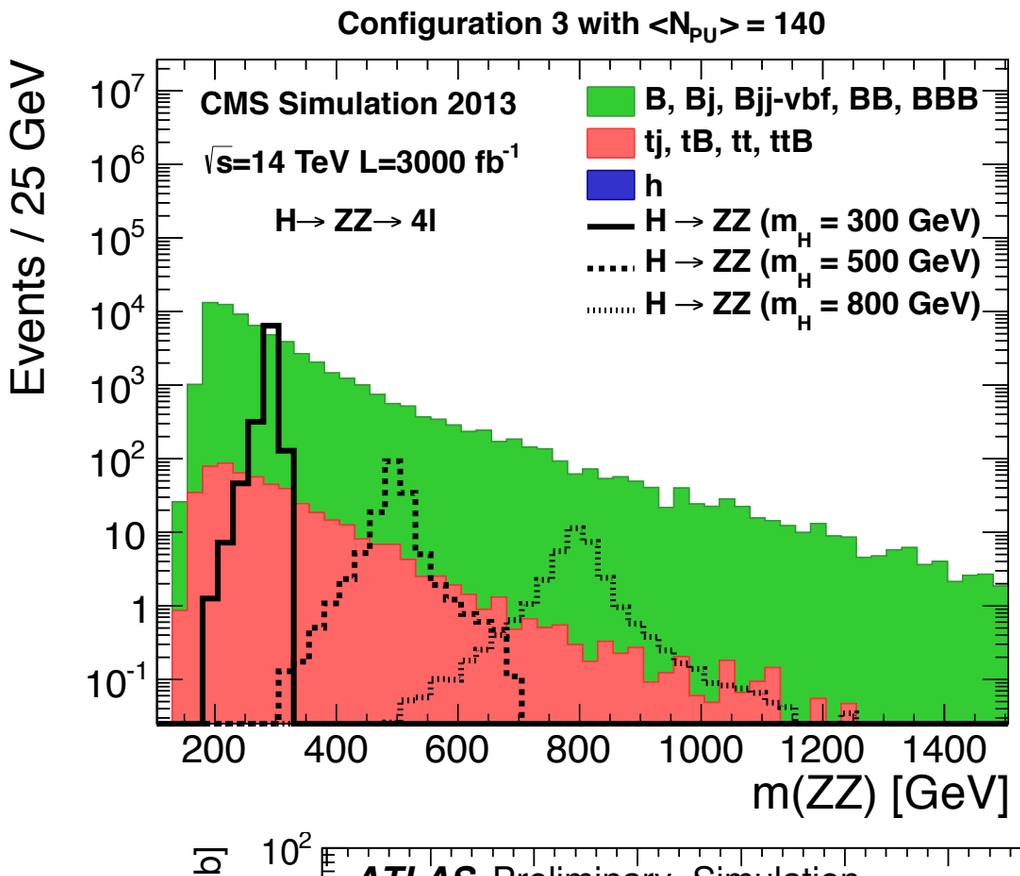


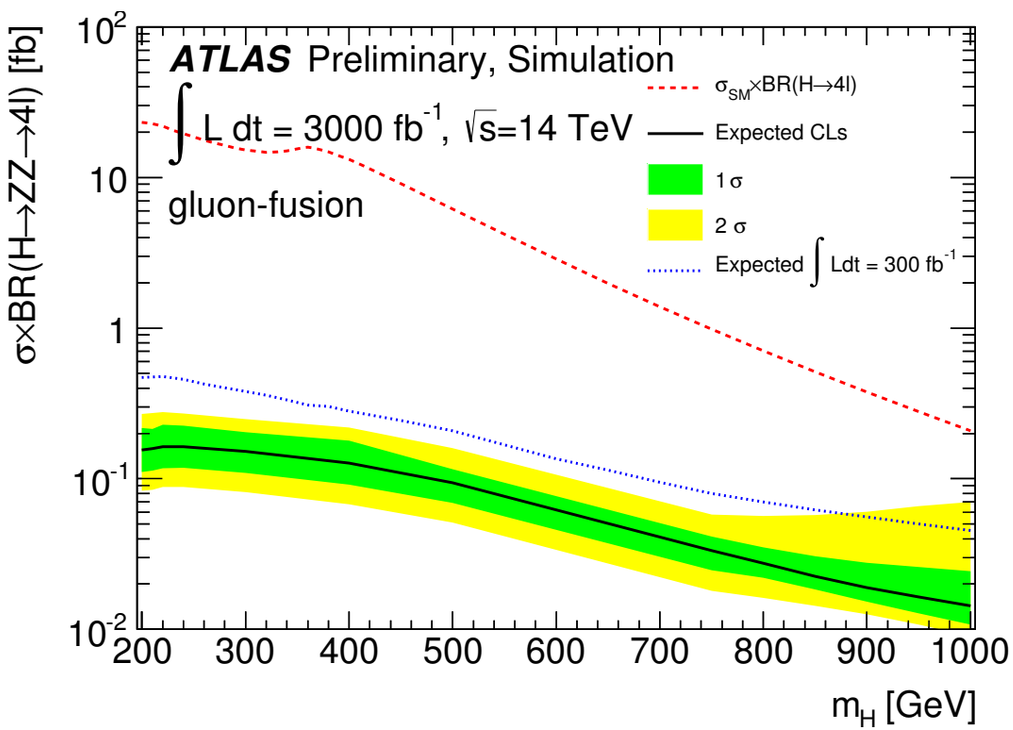
Additional Heavy Higgs bosons

Prospects for $H' \to ZZ \to 4\ell$ production

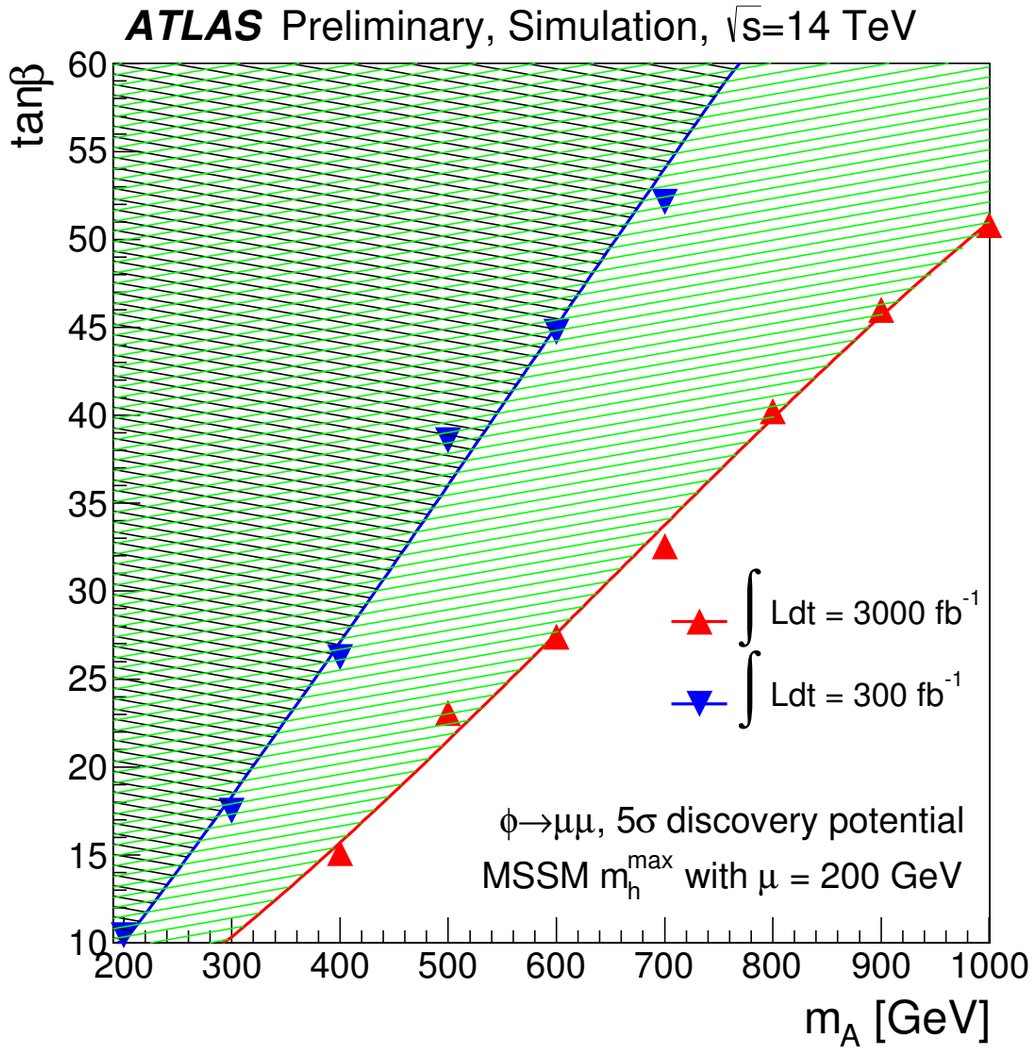
ATL-PHYS-PUB-2013-016

CMS-PAS-FTR-13-024



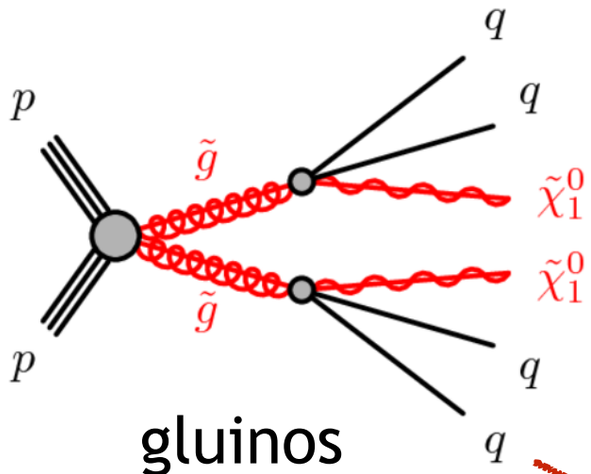


Prospects for $\phi \to \mu\mu$ production

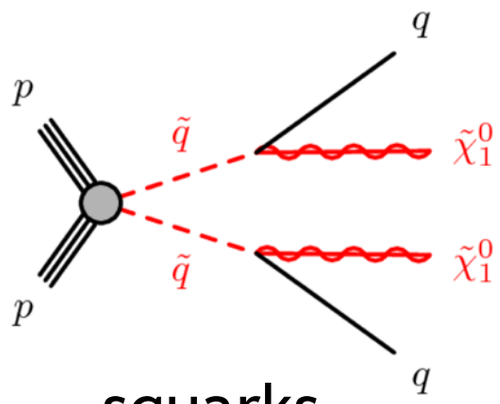


Supersymmetry Searches

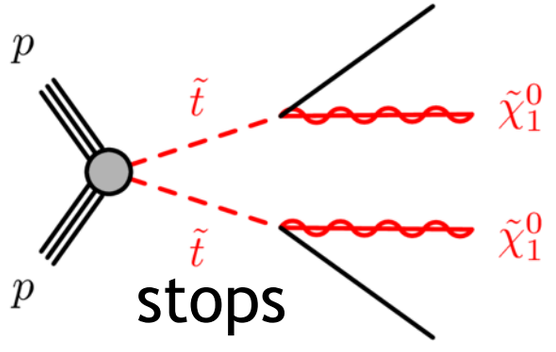
SUSY production at the LHC



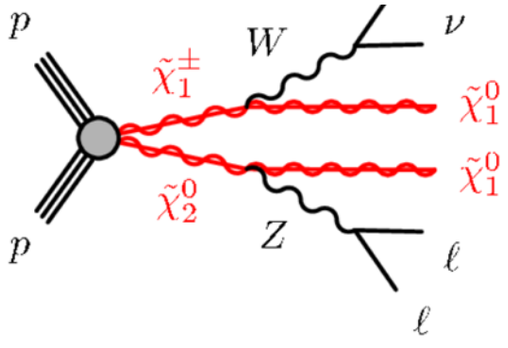
gluinos

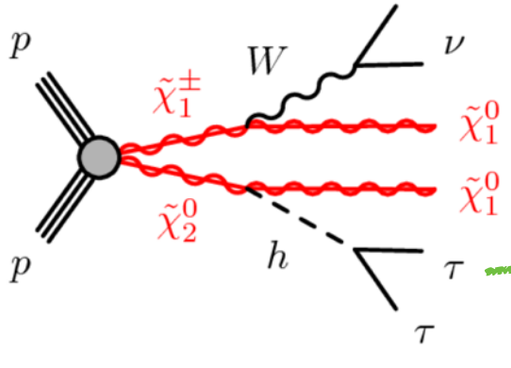


squarks

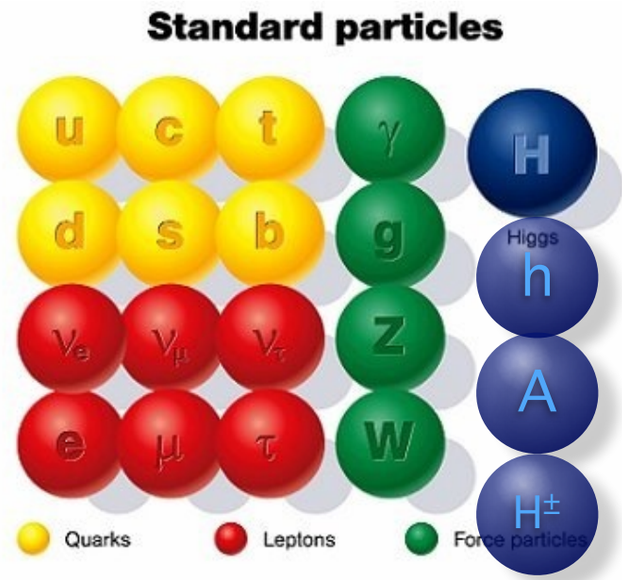


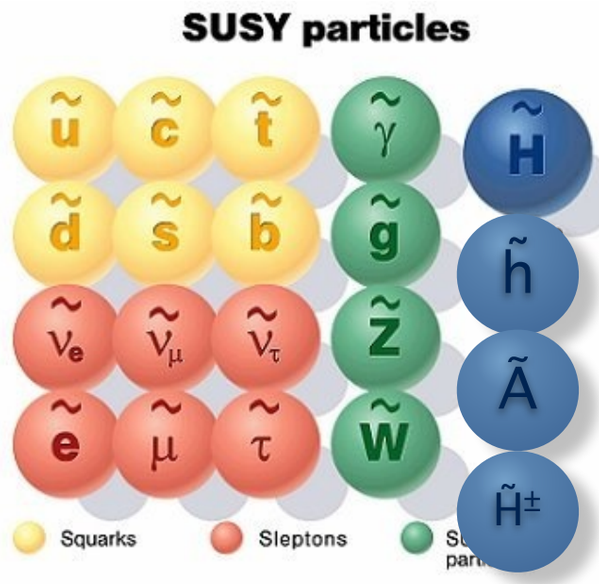
stops





neutralinos ($\tilde{\chi}^0$) & charginos ($\tilde{\chi}^\pm$):
superpositions of Higgsinos, Wino, Bino



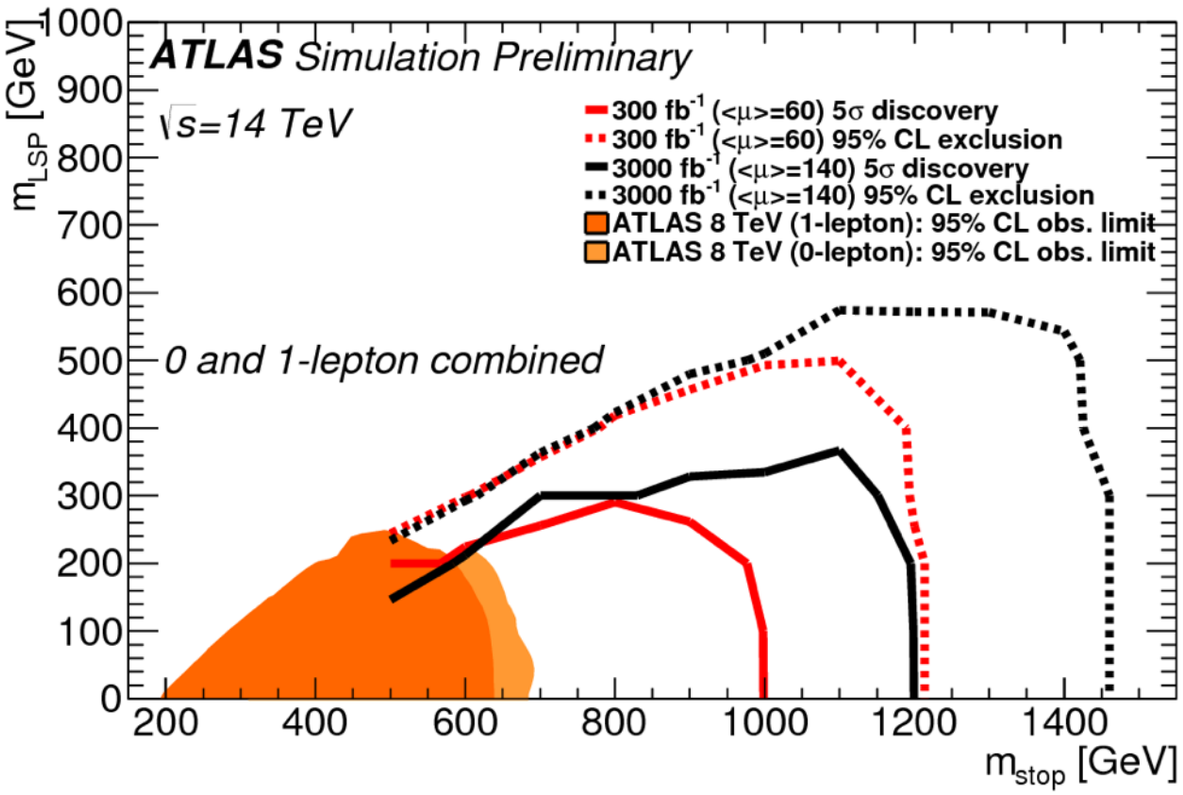


The lightest neutralino (LSP) is candidate to explain dark matter.

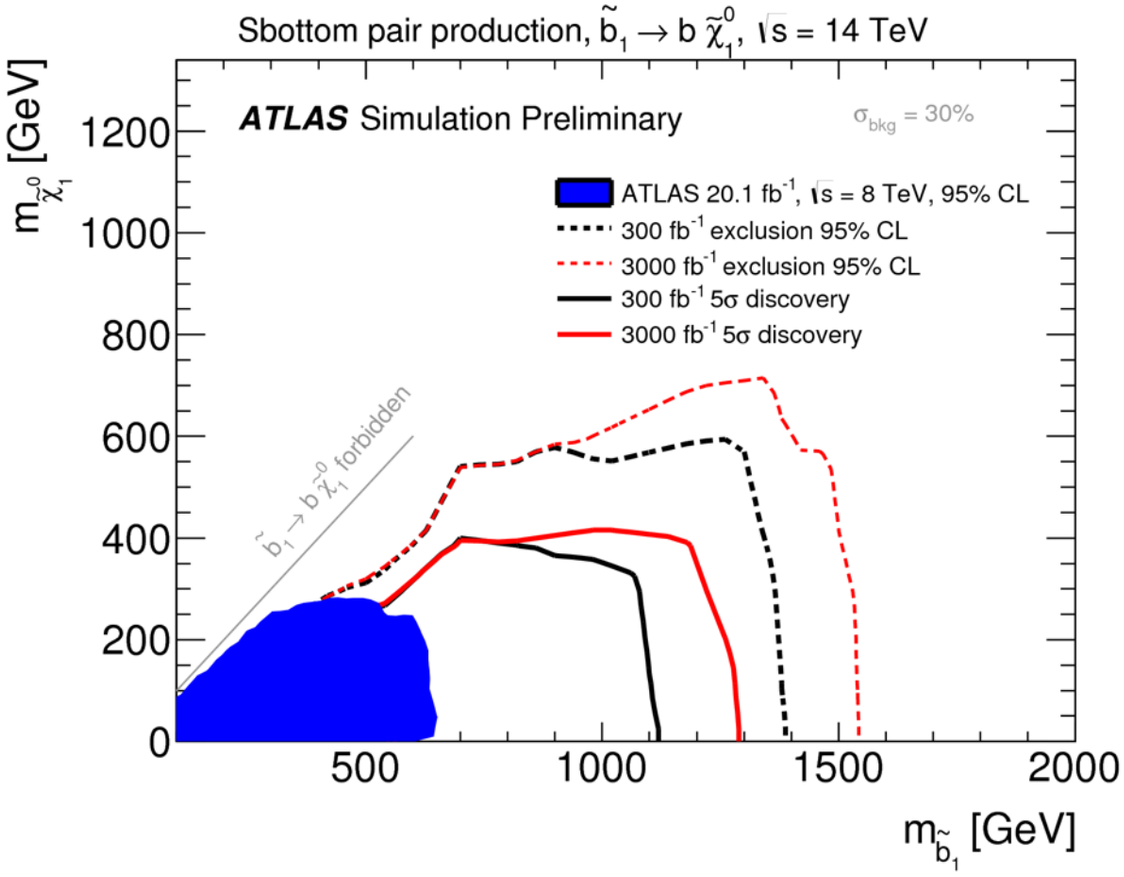
Stop and Sbottom Searches

CMS-PAS-FTR-13-014
ATL-PHYS-PUB-2013-011
ATL-PHYS-PUB-2014-010

Stop pair production; $\tilde{t} \rightarrow t\tilde{\chi}_1^0$



Sbottom pair production; $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$



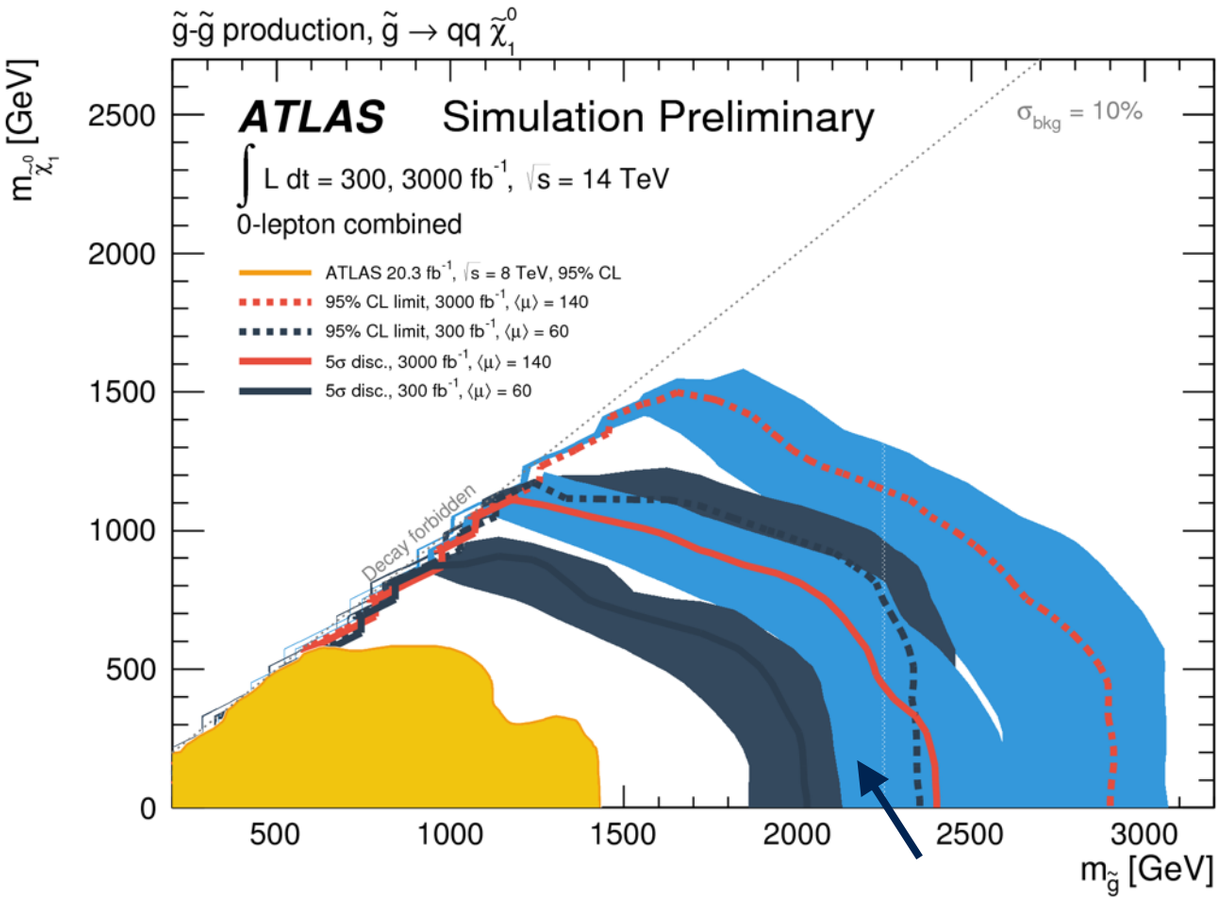
Simplified SUSY model

Strong and Weak SUSY Production Limits

CMS-PAS-FTR-13-014

ATL-PHYS-PUB-2014-010

Strong SUSY:
Gluino pair production

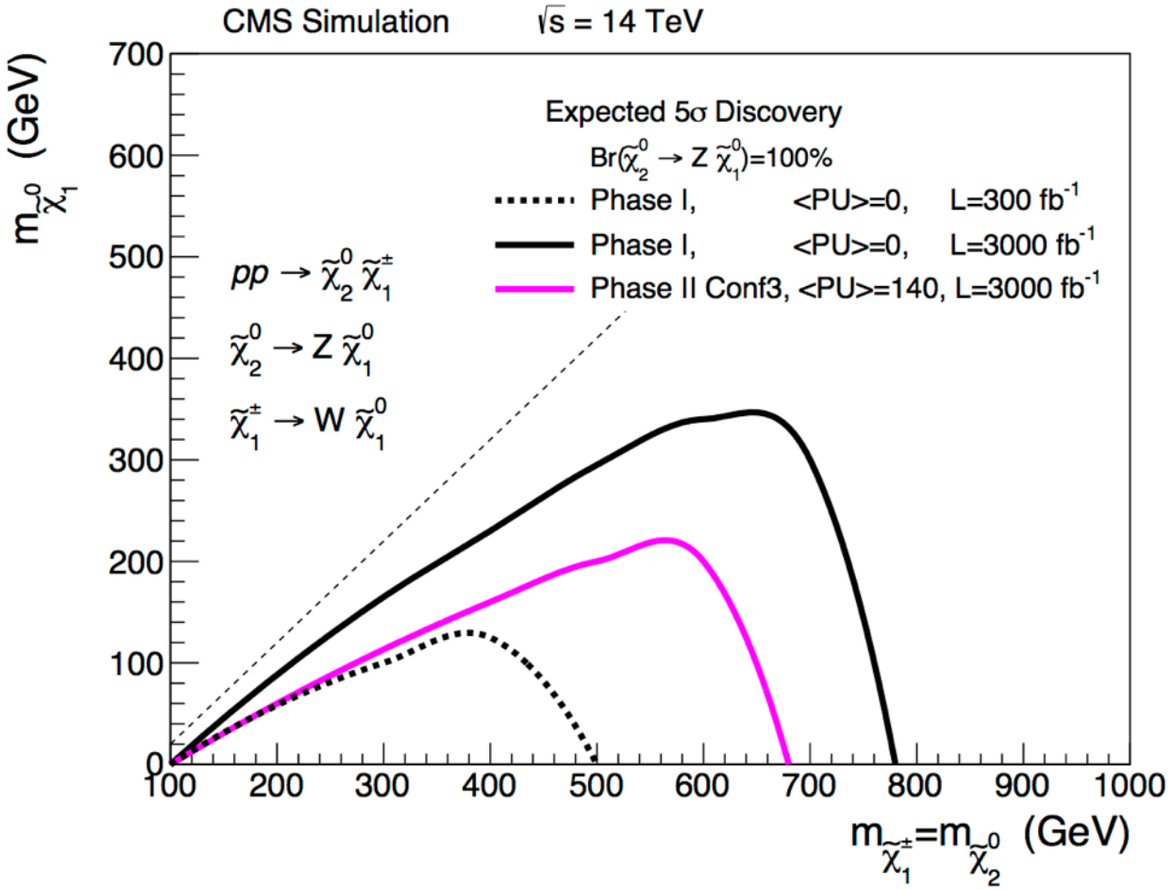


Large uncertainties on σ from knowledge of PDFs

Weak SUSY: Chargino and neutralino decaying via ***WZ***

$$\chi_1^{\pm} \rightarrow W^{\pm}\chi_1^0,$$

$$\chi_2^0 \rightarrow Z\chi_1^0$$



Simplified SUSY model

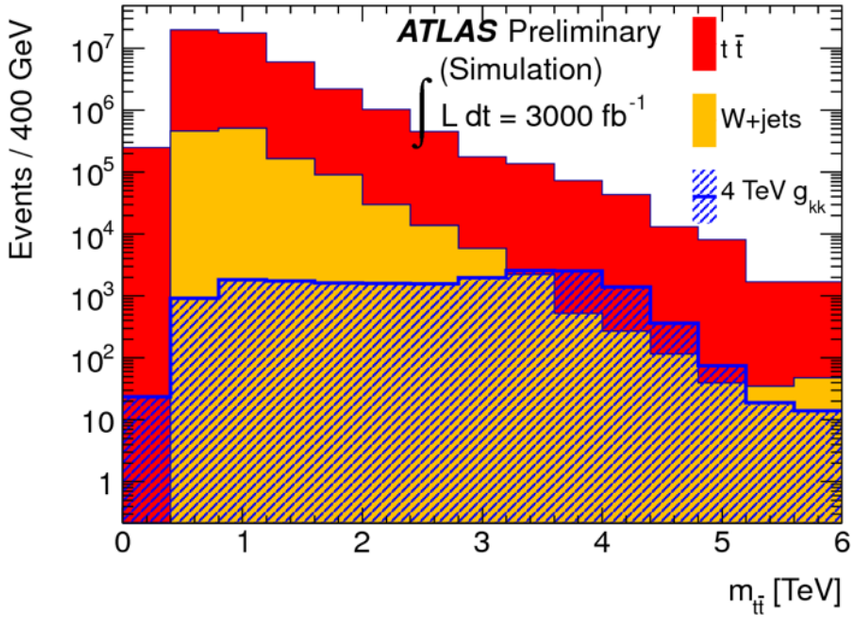
And More…

Resonance Searches

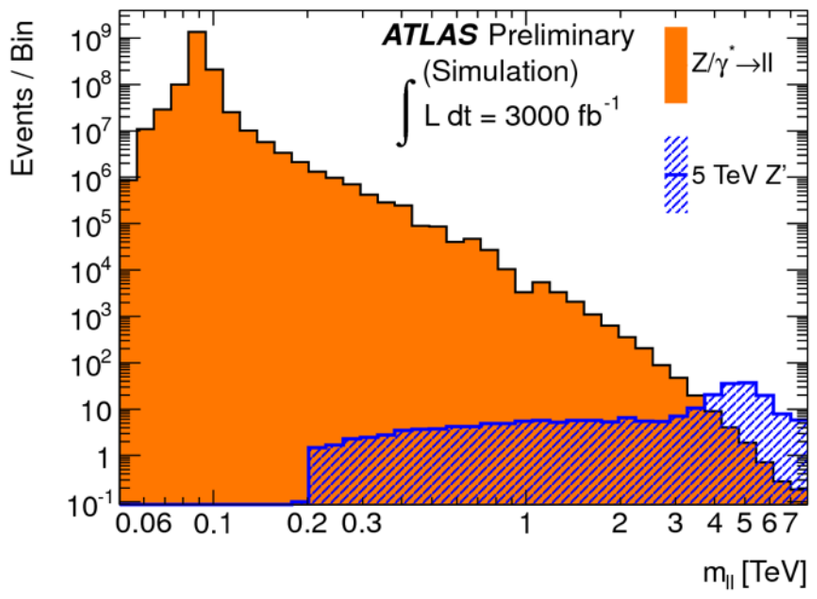
arXiv:1307.7135
ATL-PHYS-PUB-2014-007
ATL-PHYS-PUB-2013-003

- New physics could appear anywhere!
  - Look for resonances in di-leptons, $\gamma\gamma$, $t\bar{t}$, di-bosons (WW, WZ, ZZ) and extra missing transverse momentum.
- With **3000 fb^{-1}** probe $t\bar{t}$ resonances up to **6.7 TeV** and di-lepton resonances up to **7.8 TeV.**

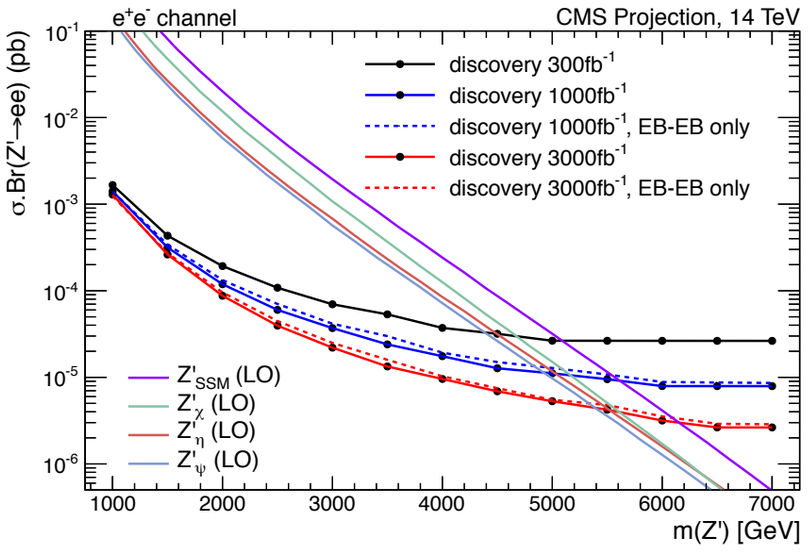
4 TeV Kaluza-Klein gluon, $g_{KK} \rightarrow t\bar{t}$



5 TeV $Z' \rightarrow \mu^+\mu^-$



$Z' \rightarrow e^+e^-$

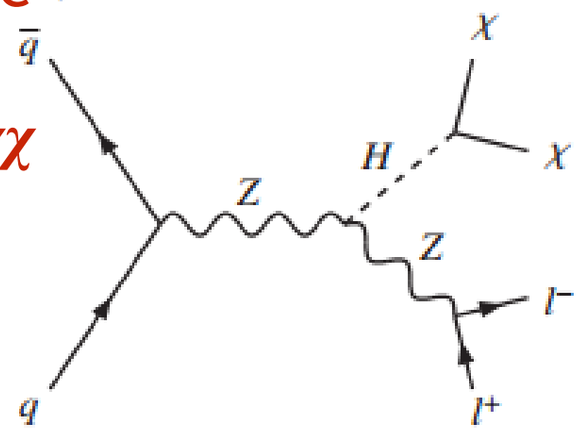


WIMP searches

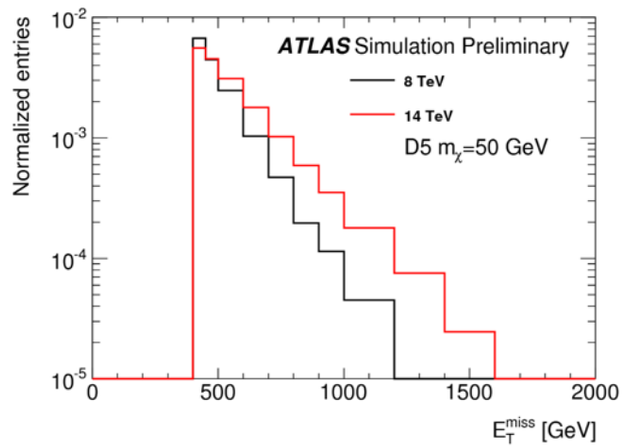
ATL-PHYS-PUB-2014-007

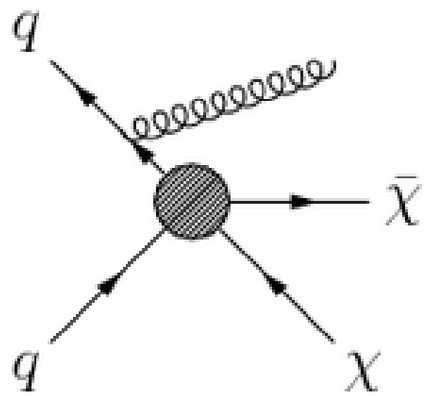
ATL-PHYS-PUB-2013-014

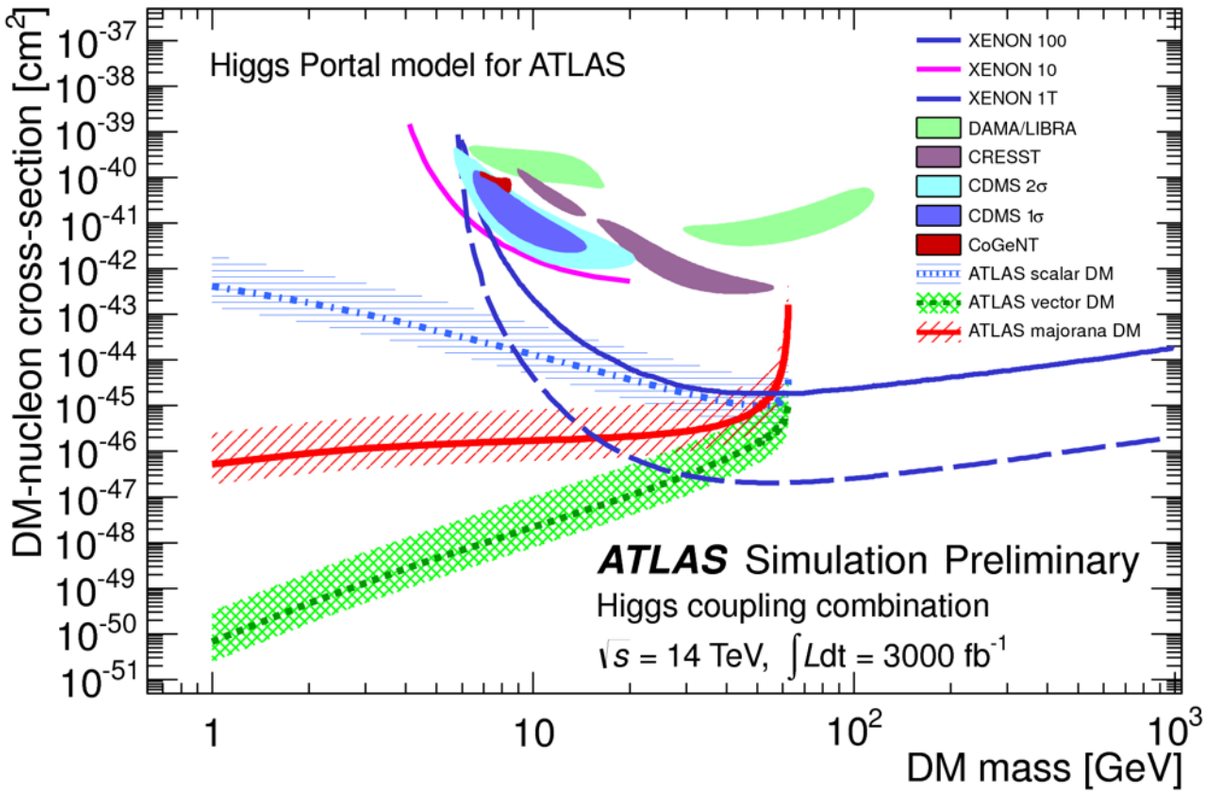
- WIMP = weakly interacting massive particle → look for large missing-E_T signature
  - e.g. from invisible decay of Higgs boson, $ZH \to \ell^+\ell^-\chi\chi$

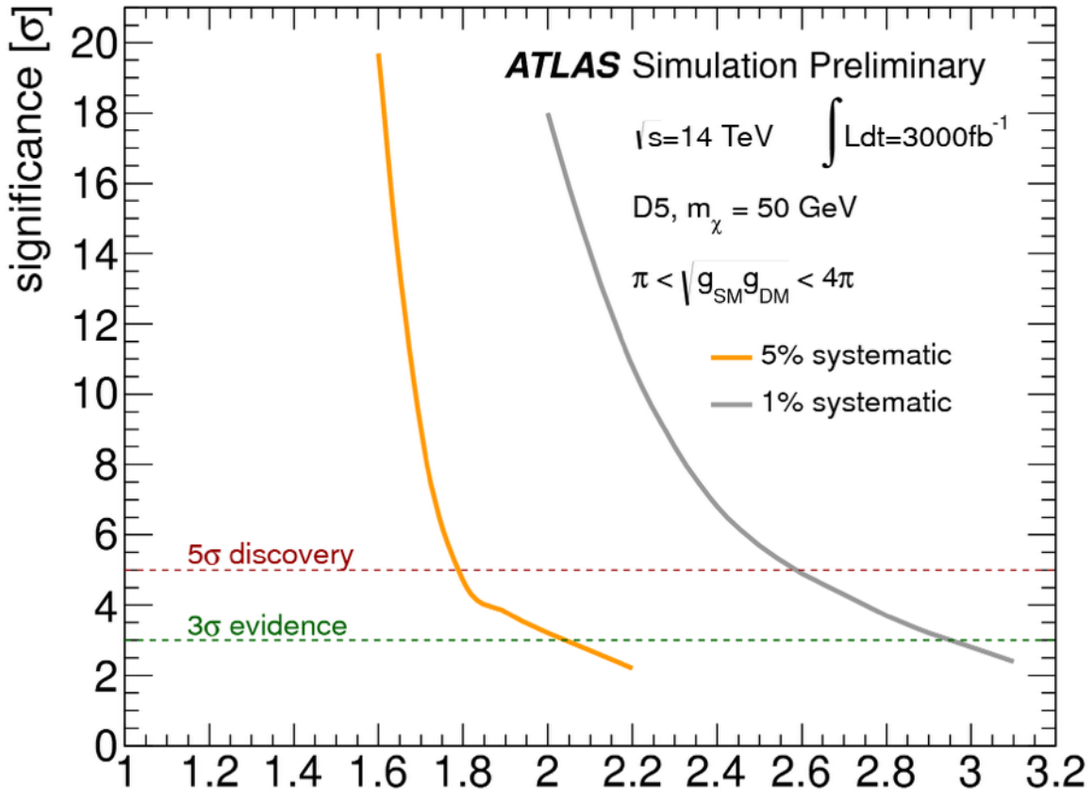


  - e.g. with high-p_T jet in SM-WIMP contact interaction model







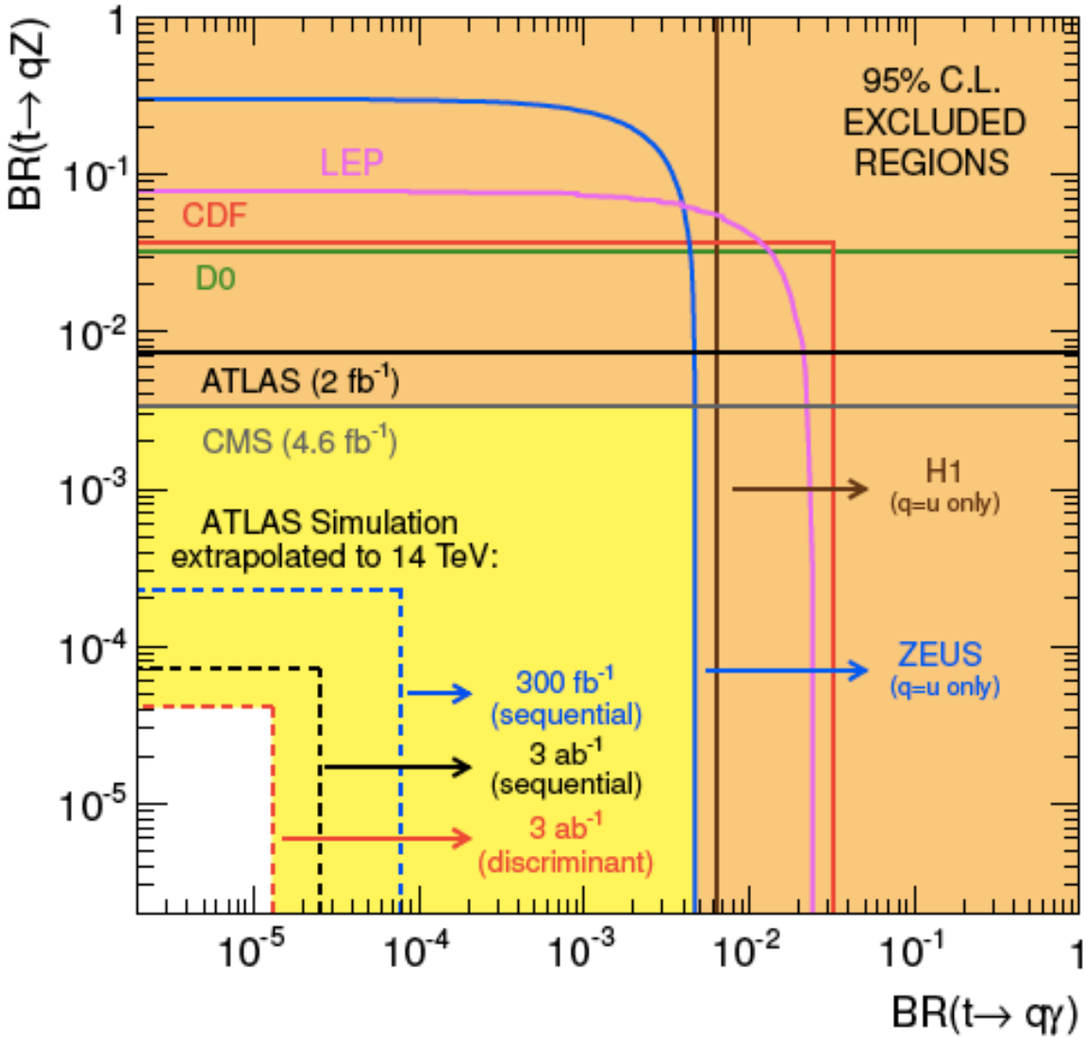


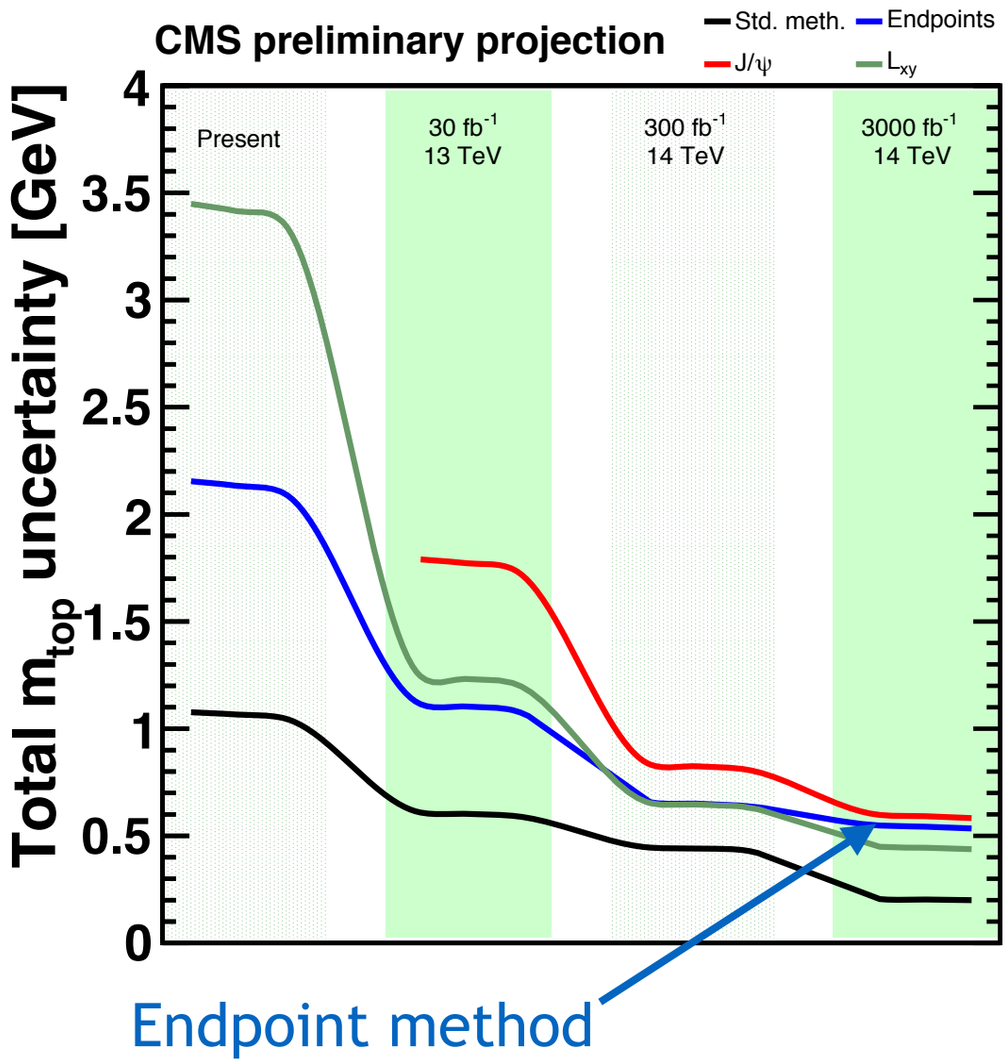
$$M_* = \frac{M_{\text{mediator}}}{\sqrt{g_{\text{SM}}\, g_{\text{DM}}}}\ [\text{TeV}]$$

Top Quark Physics

ATL-PHYS-PUB-2013-012
CMS-PAS-FTR-13-016
CMS-PAS-FTR-13-017

- HL-LHC Measure top quark mass to **200 MeV.**
  - Endpoint method, which probes the pole mass, can measure m_t to **500 MeV**
- In SM **BR($t \to Wb$) ≈ 100%** Many models predict enhancements, interesting range starts at **$\sim 10^{-4}$** ⇒ Observing decays to other modes clear sign of new physics
  - HL-LHC will probe **BR($t \to qZ$), BR($t \to q\gamma$)** at **$\sim 3\times10^{-5}$** at least and **BR($t \to cH$)** at **$\sim 10^{-4}$**





Outlook

- We've come a long way, baby, but there's still far to go…
- With $\mathbf{3000\ fb^{-1}}$ the LHC will offer a comprehensive physics programme:

Precision Higgs physics: measure production rates to a few %

SUSY: Assuming light LSP (<1 TeV) discover squarks up to 1.1 TeV discover gluinos up to 2 TeV

Sensitivity to generic resonances and missing energy up to $O(7\ \mathbf{TeV})$

Observation of $H\to Z\gamma$ and $H\to\mu^+\mu^-$

Measure $\mathbf{m_{top}}$ to 200 MeV Sensitivity to rare top quark decays of $<10^{-4}$

Theory uncertainty dominant for many analyses

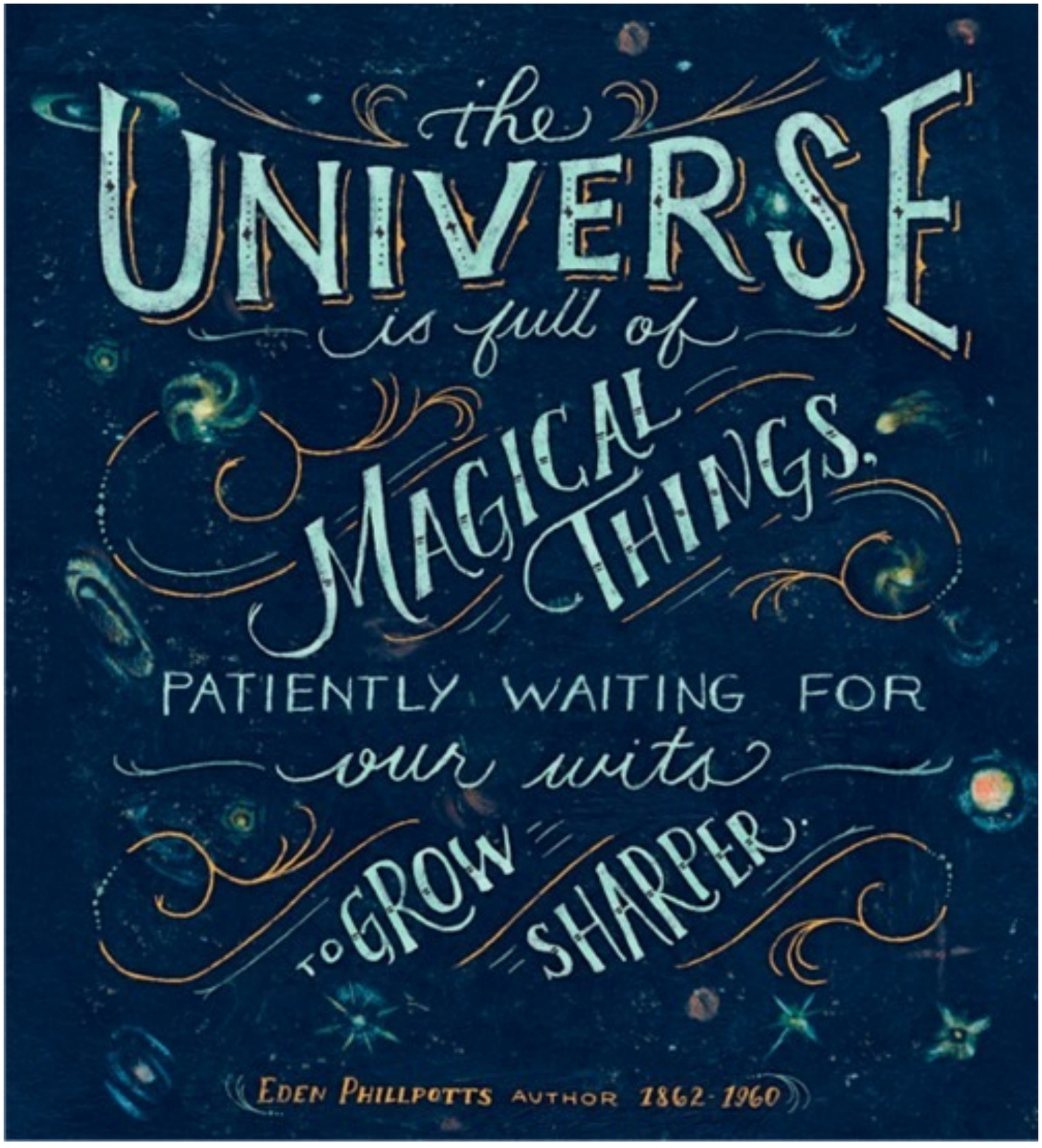
Discovery of additional Higgs bosons up to O (1 TeV)

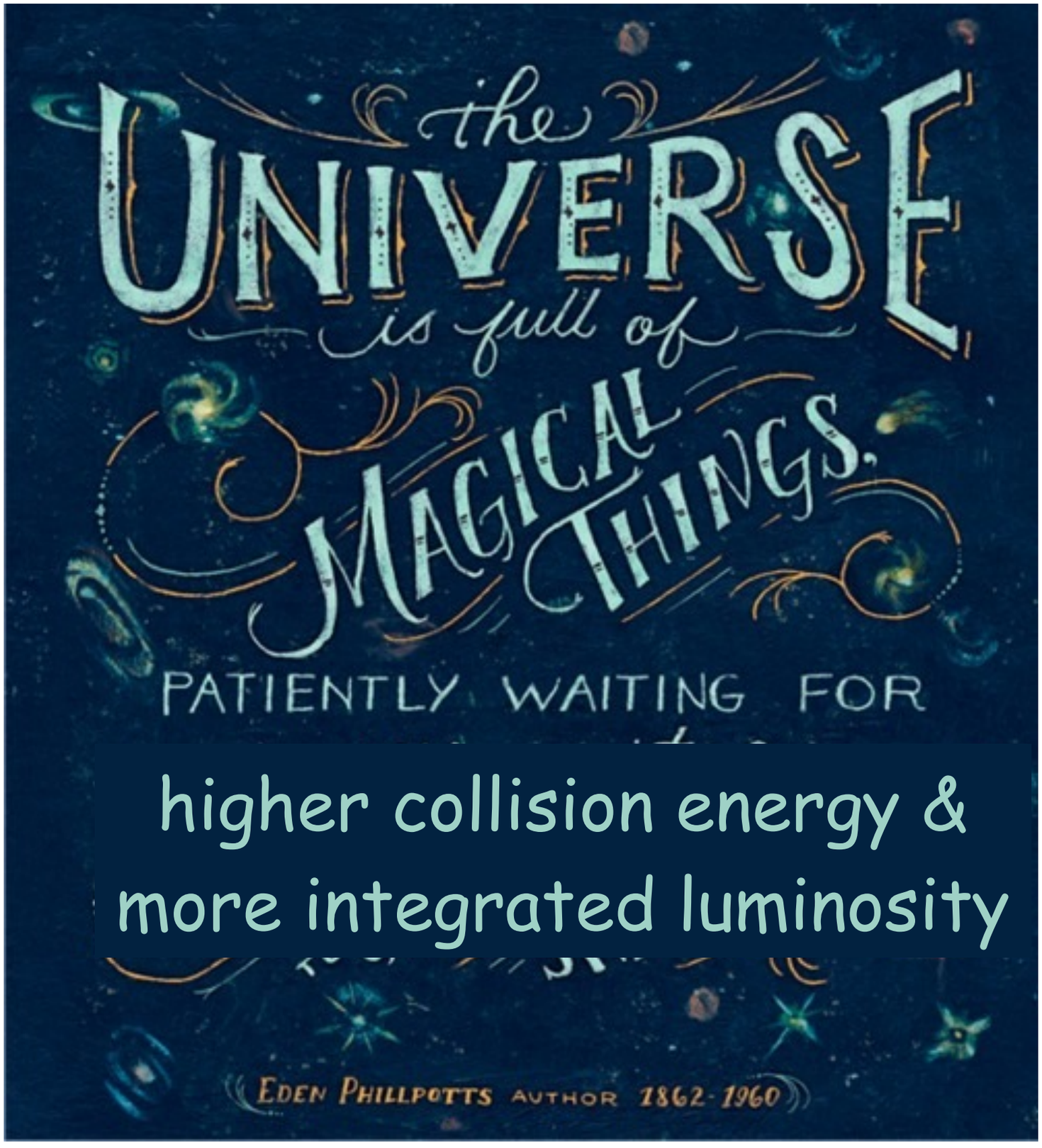
- Some analyses do remain challenging at HL-LHC:

di-Higgs boson

$H\to c\bar{c}$

triple-Higgs boson


the
UNIVERSE
is full of
MAGICAL THINGS.
PATIENTLY WAITING FOR
our wits
TO GROW SHARPER.
EDEN PHILLPOTTS AUTHOR 1862-1960



higher collision energy &
more integrated luminosity