Physics Prospects at the HL-LHC

Victoria Martin, University of Edinburgh
Higgs Maxwell workshop 2016

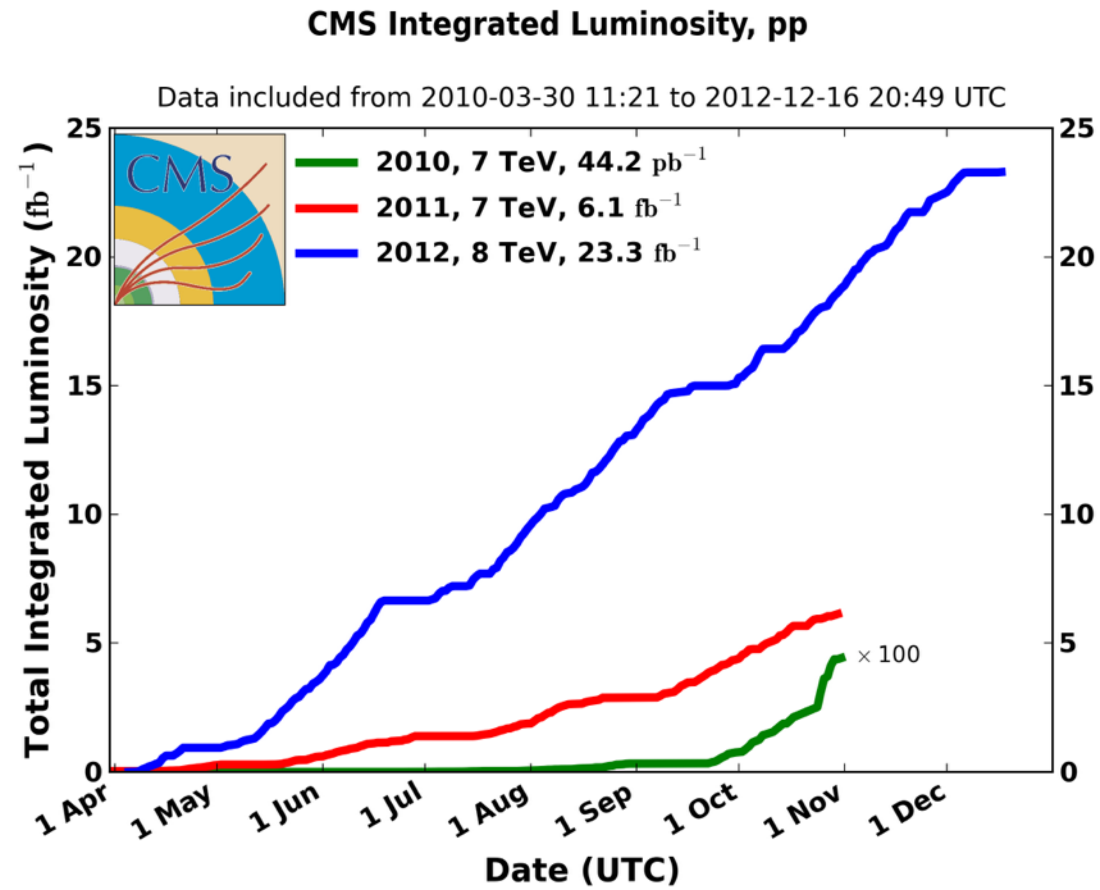
LHC Run 1 (& 2)

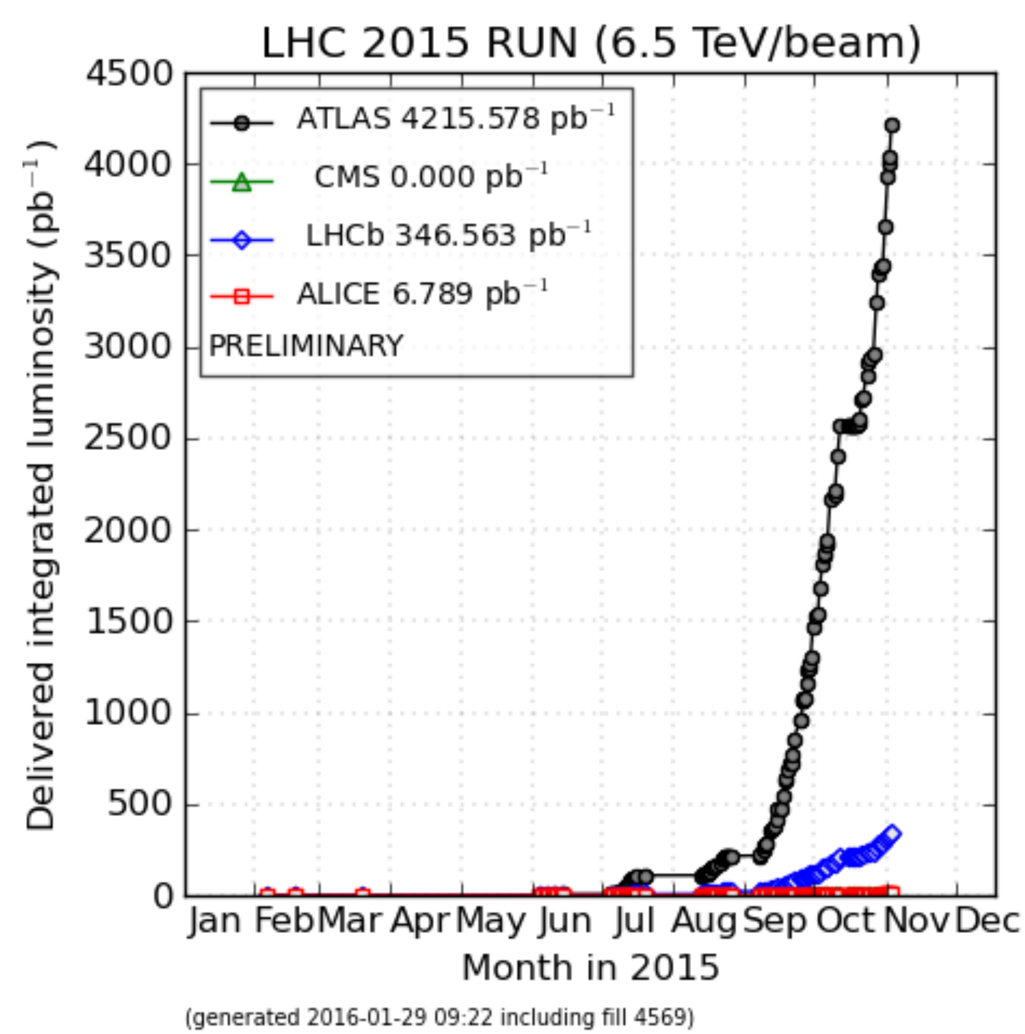
IN

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}

- **Run 2:** 2015 $\sqrt{s}$=13 TeV, 4 fb^{-1}





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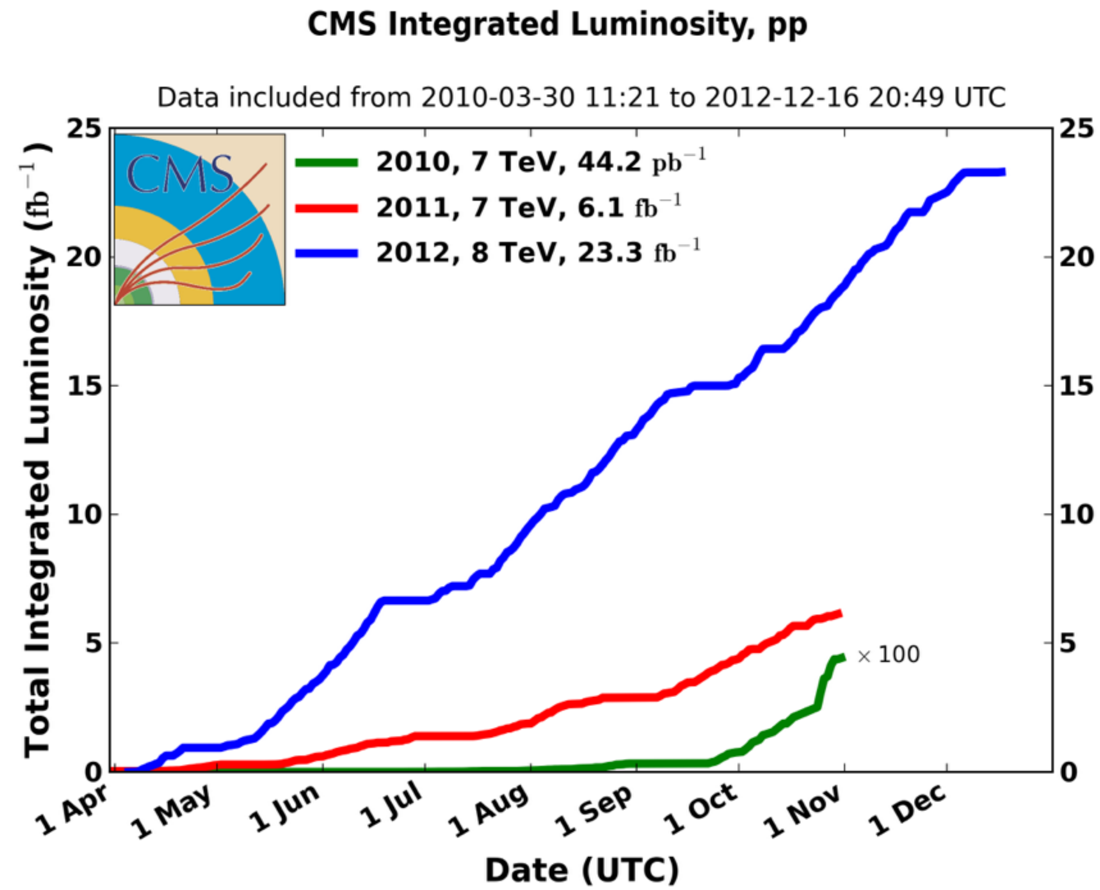
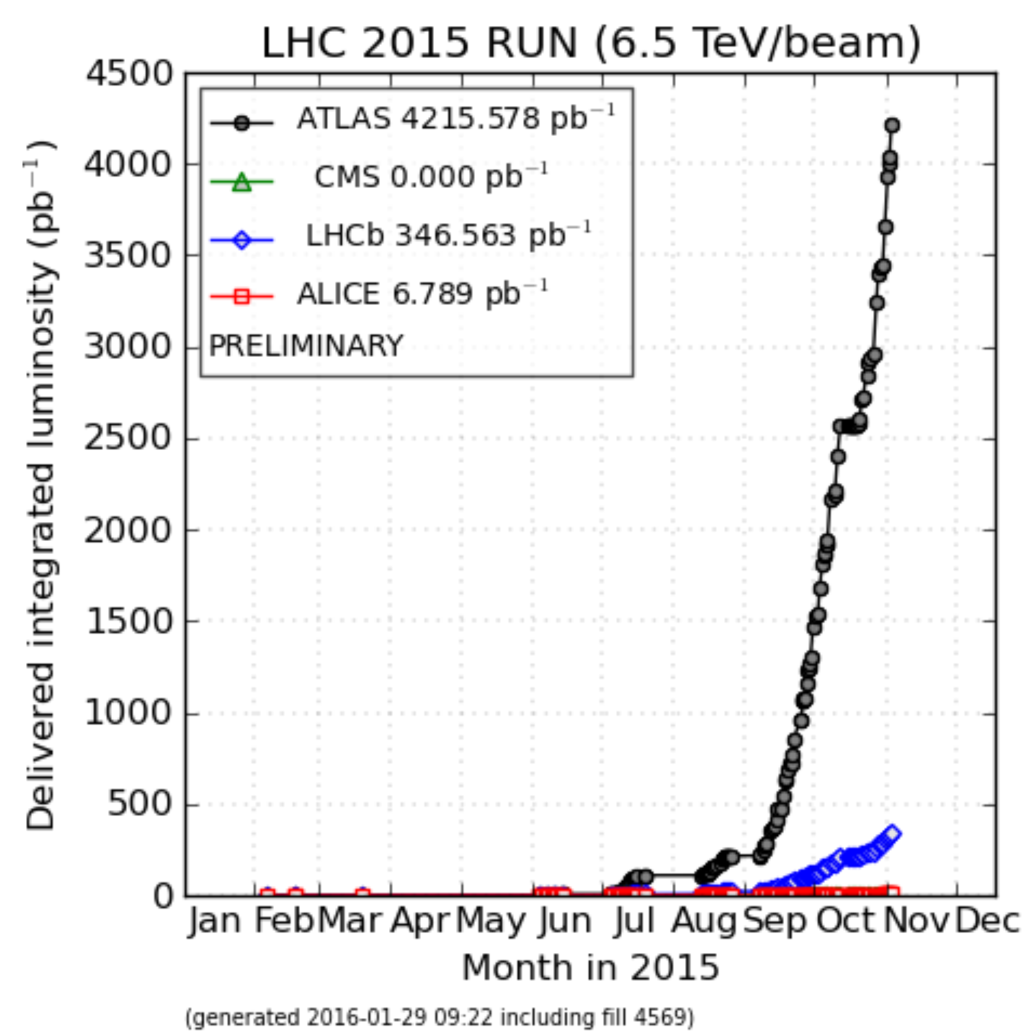
OUT

Physics results!

- Nearly 1000 submitted papers on Run 1 collision data
- 9 papers on Run 2 data





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"

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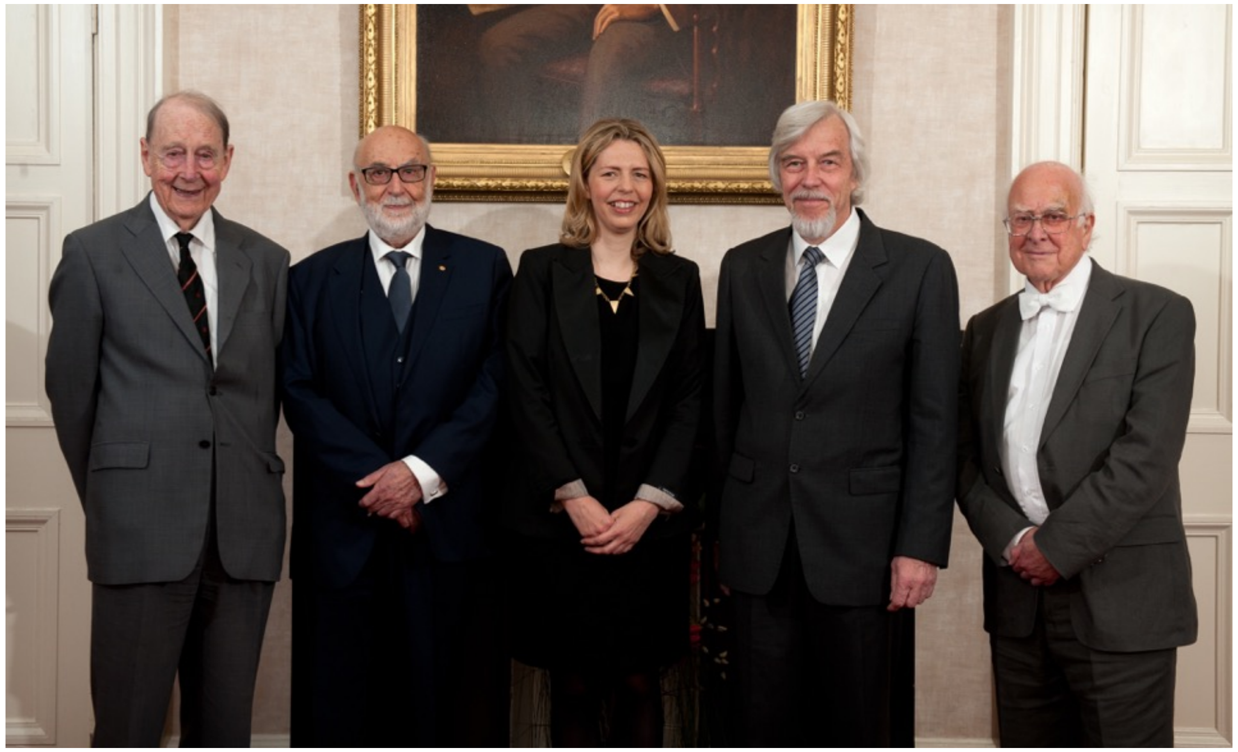

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All observations from the LHC consistent with a Standard Model Higgs boson with $m_H \sim 125$ GeV.

arXiv:1412.8662

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

ATLAS-CONF-044

Eur. Phys. J. C 74 (2014) 3076

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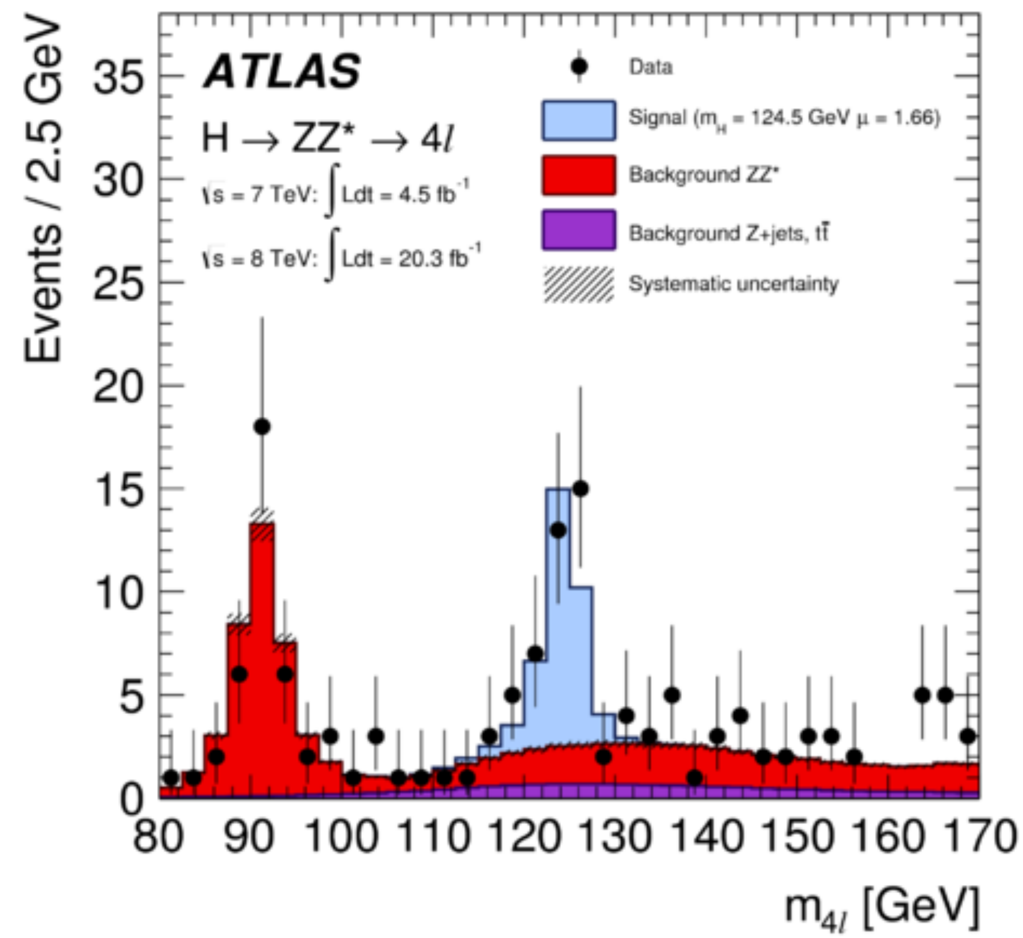

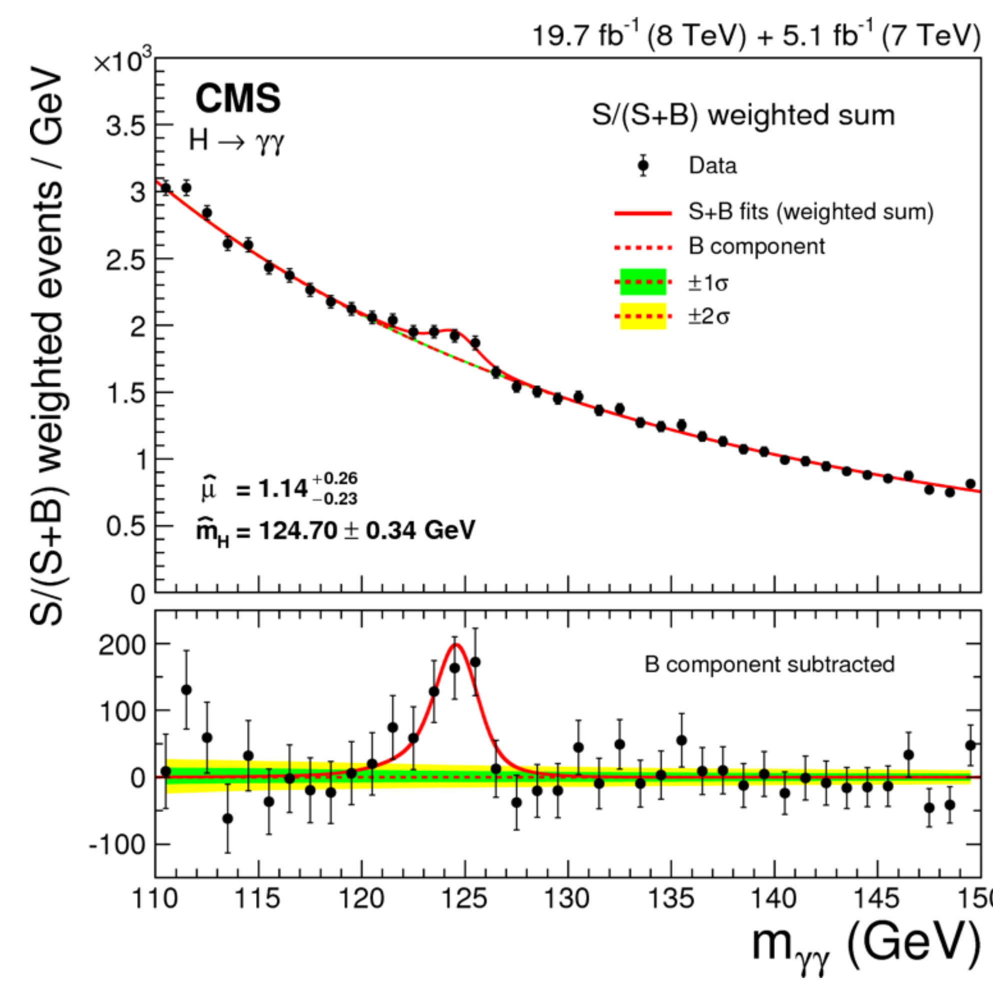

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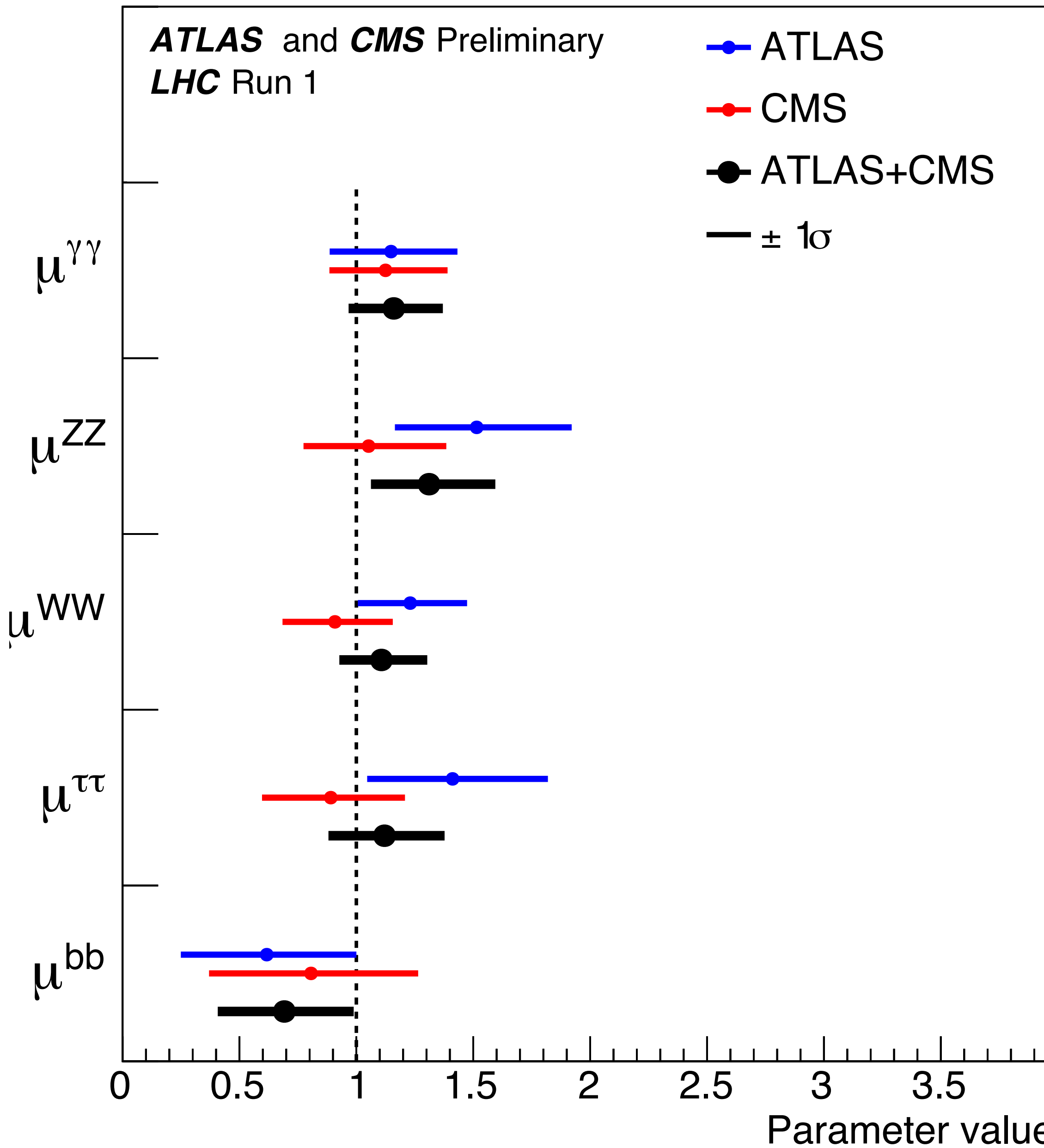

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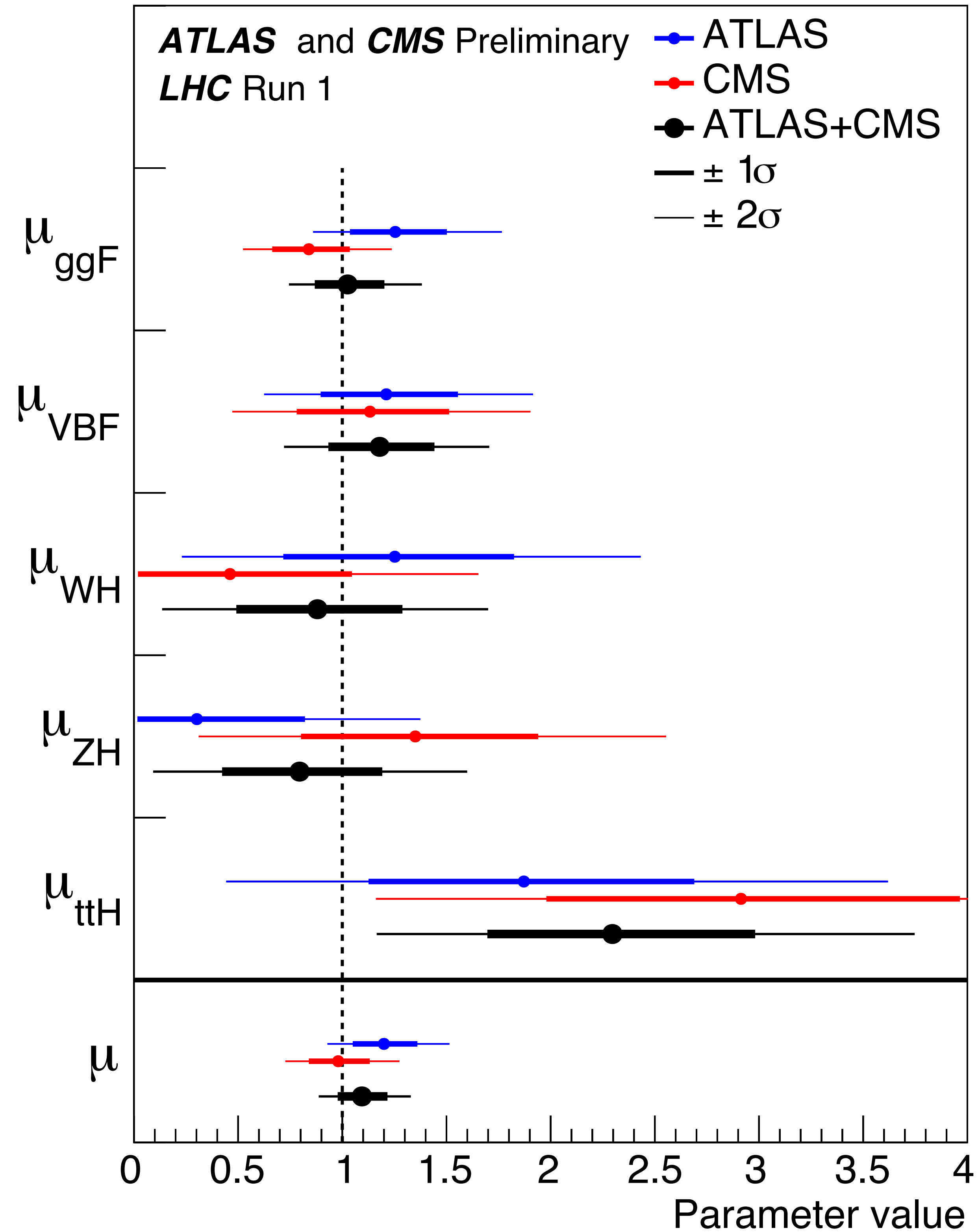

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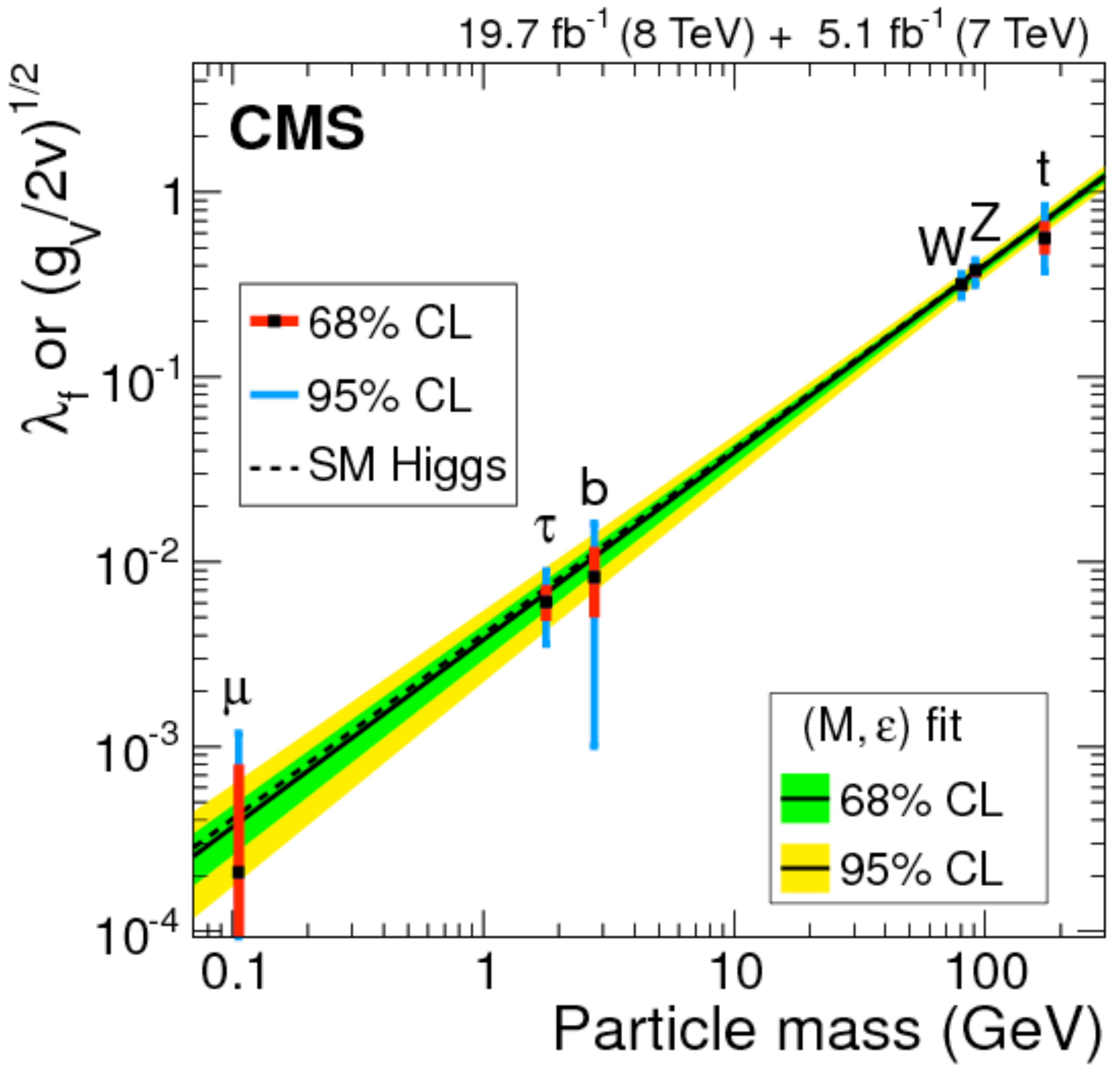

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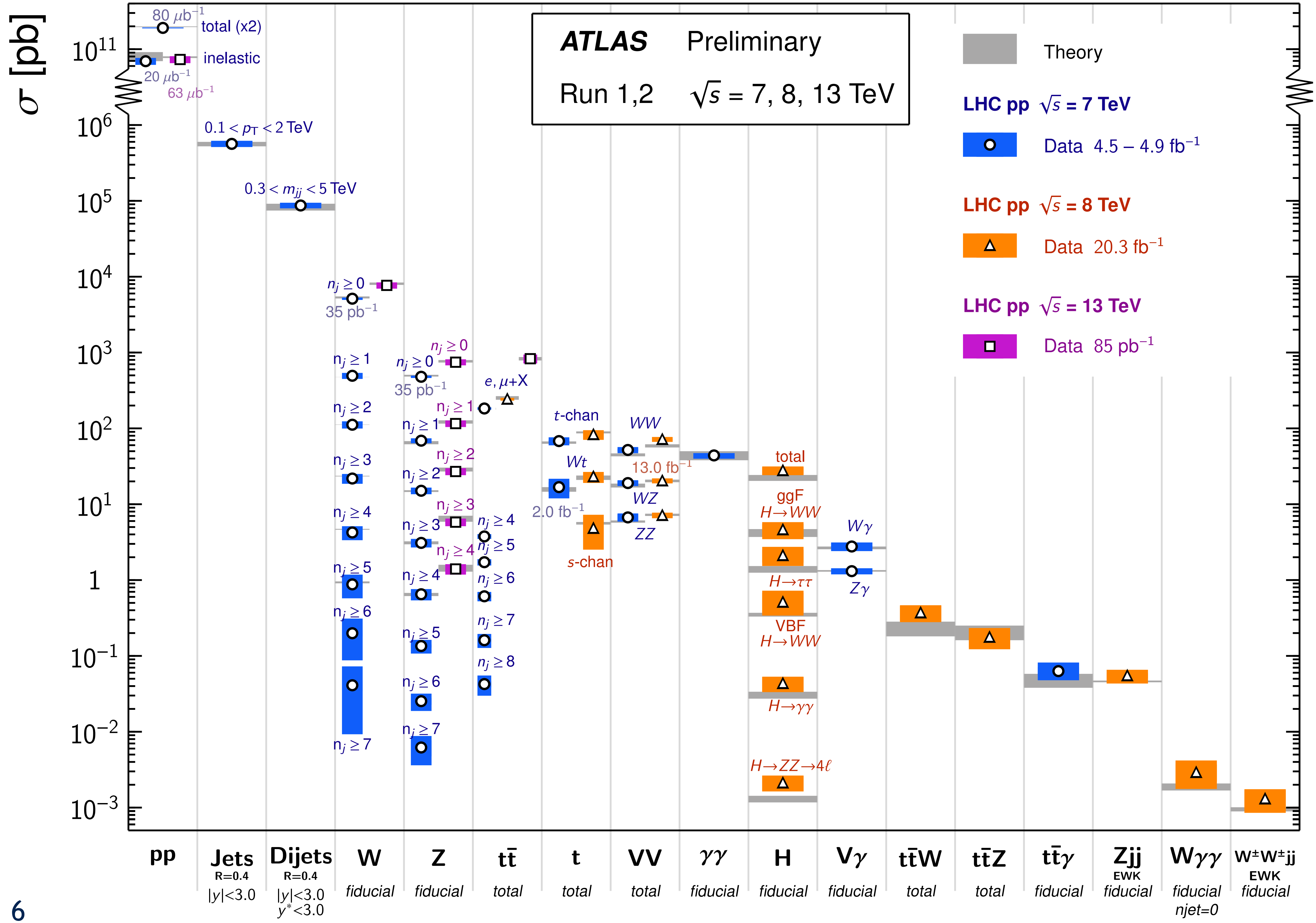
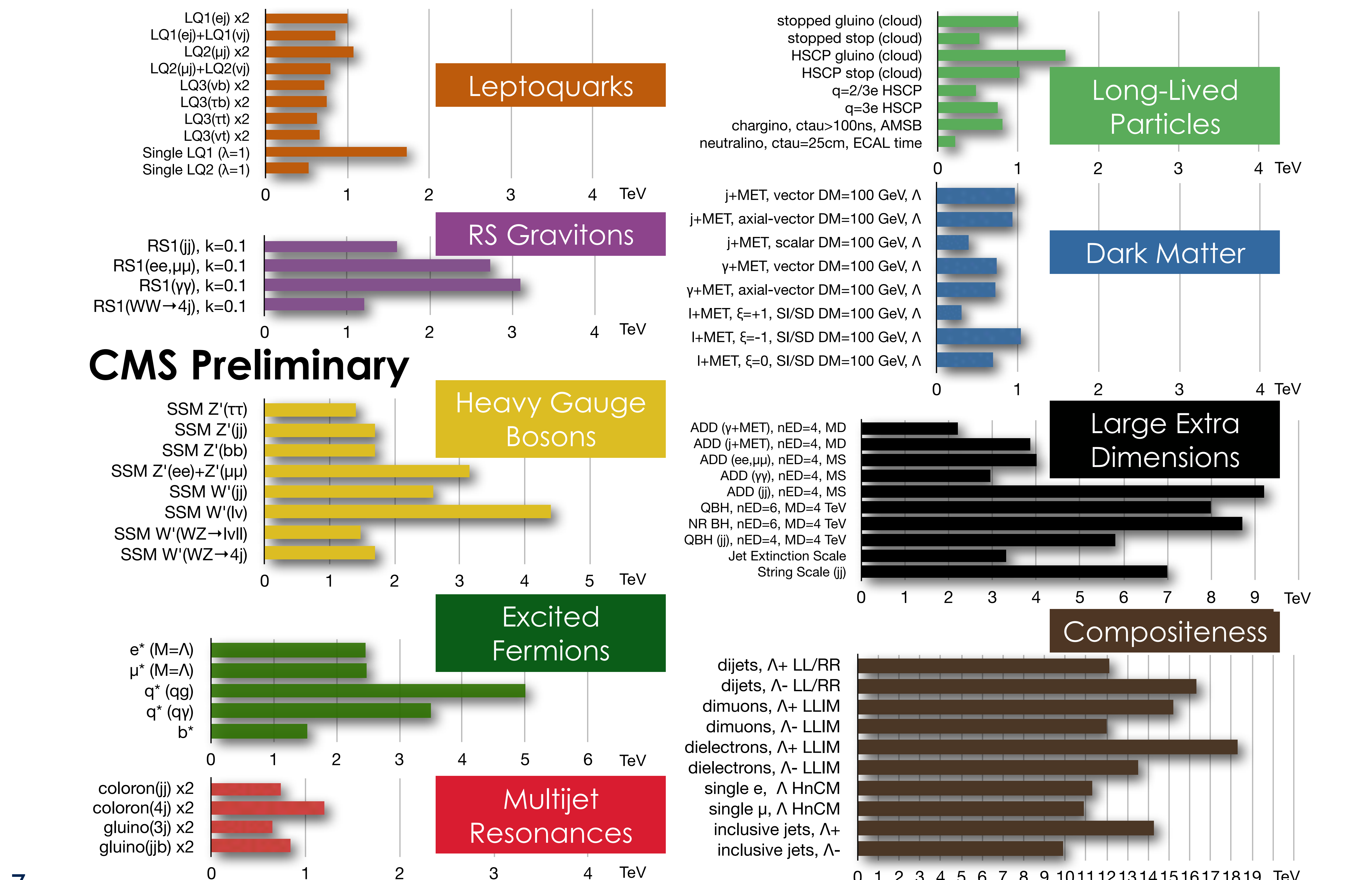
But not only …

Standard Model Production Cross Section Measurements

Status: Nov 2015



95% CL Limits on Masses of Exotic Phenomena in TeV



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: July 2015

ATLAS Preliminary

$\sqrt{s}$ = 7, 8 TeV

$\sqrt{s}$ = 7 TeV | $\sqrt{s}$ = 8 TeV

	Model	e, μ, τ, γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	$\int \mathcal{L}\, dt [\mathrm{fb}^{-1}]$		Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.8 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1$^{\mathrm{st}}$ gen. $\tilde{q}$)=m(2$^{\mathrm{nd}}$ gen. $\tilde{q}$)	1405.7875
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$ (compressed)	mono-jet	1-3 jets	Yes	20.3	$\tilde{q}$	100-440 GeV	m($\tilde{q}$)-m($\tilde{\chi}_1^0$)<10 GeV	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ (off-Z)	2 jets	Yes	20.3	$\tilde{q}$	780 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1503.03290
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	0-1 e,μ	2-6 jets	Yes	20	$\tilde{g}$	1.26 TeV	m($\tilde{\chi}_1^0$)<300 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	1507.05525
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e,μ	0-3 jets	-	20	$\tilde{g}$	1.32 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1501.03555
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.29 TeV	$c\tau$(NLSP)<0.1 mm	1507.05493
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<900 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	20.3	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<850 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	1507.05493
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	$\tilde{g}$	850 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale	865 GeV	m($\tilde{G}$)>1.8 × 10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e,μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{b}_1$	275-440 GeV	m($\tilde{\chi}_1^{\pm}$)=2 m($\tilde{\chi}_1^0$)	1404.2500
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e,μ	1-2 b	Yes	4.7/20.3	$\tilde{t}_1$	110-167 GeV (7 TeV); 230-460 GeV	m($\tilde{\chi}_1^{\pm}$) = 2m($\tilde{\chi}_1^0$), m($\tilde{\chi}_1^0$)=55 GeV	1209.2102, 1407.0583
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$	90-191 GeV; 210-700 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1506.08616
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}$, $\tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e,μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	100-350 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\tau},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1407.0350
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_{\mathrm{L}}\nu\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_{\mathrm{L}}\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e,μ	0-2 jets	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^0$	250 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0\tilde{\chi}_3^0$, $\tilde{\chi}_{2,3}^0\to\tilde{\ell}_{\mathrm{R}}\ell$	4 e,μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell},\tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu+\gamma$	-	Yes	20.3	$\tilde{W}$	124-361 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	1310.3675
	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	dE/dx trk	-	Yes	18.4	$\tilde{\chi}_1^{\pm}$	482 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)~160 MeV, τ($\tilde{\chi}_1^{\pm}$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	19.1	$\tilde{g}$	1.27 TeV		1411.6795
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	$\tilde{\chi}_1^0$	537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	435 GeV	2<τ($\tilde{\chi}_1^0$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to eev/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	7 <$c\tau$($\tilde{\chi}_1^0$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	$\tilde{\chi}_1^0$	1.0 TeV	6 <$c\tau$($\tilde{\chi}_1^0$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu,e\tau,\mu\tau$	-	-	20.3	$\tilde{\nu}_\tau$	1.7 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1503.04430
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{q},\tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e,μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq 0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e,\mu+\tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq 0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	917 GeV	BR(t)=BR(b)=BR(c)=0%	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	870 GeV	m($\tilde{\chi}_1^0$)=600 GeV	1502.05686
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e,μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	20.3	$\tilde{t}_1$	100-308 GeV		ATLAS-CONF-2015-026
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	$\tilde{t}_1$	0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}_1^0$	0	2 c	Yes	20.3	$\tilde{c}$	490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325

10^{-1} | 1 — Mass scale [TeV]

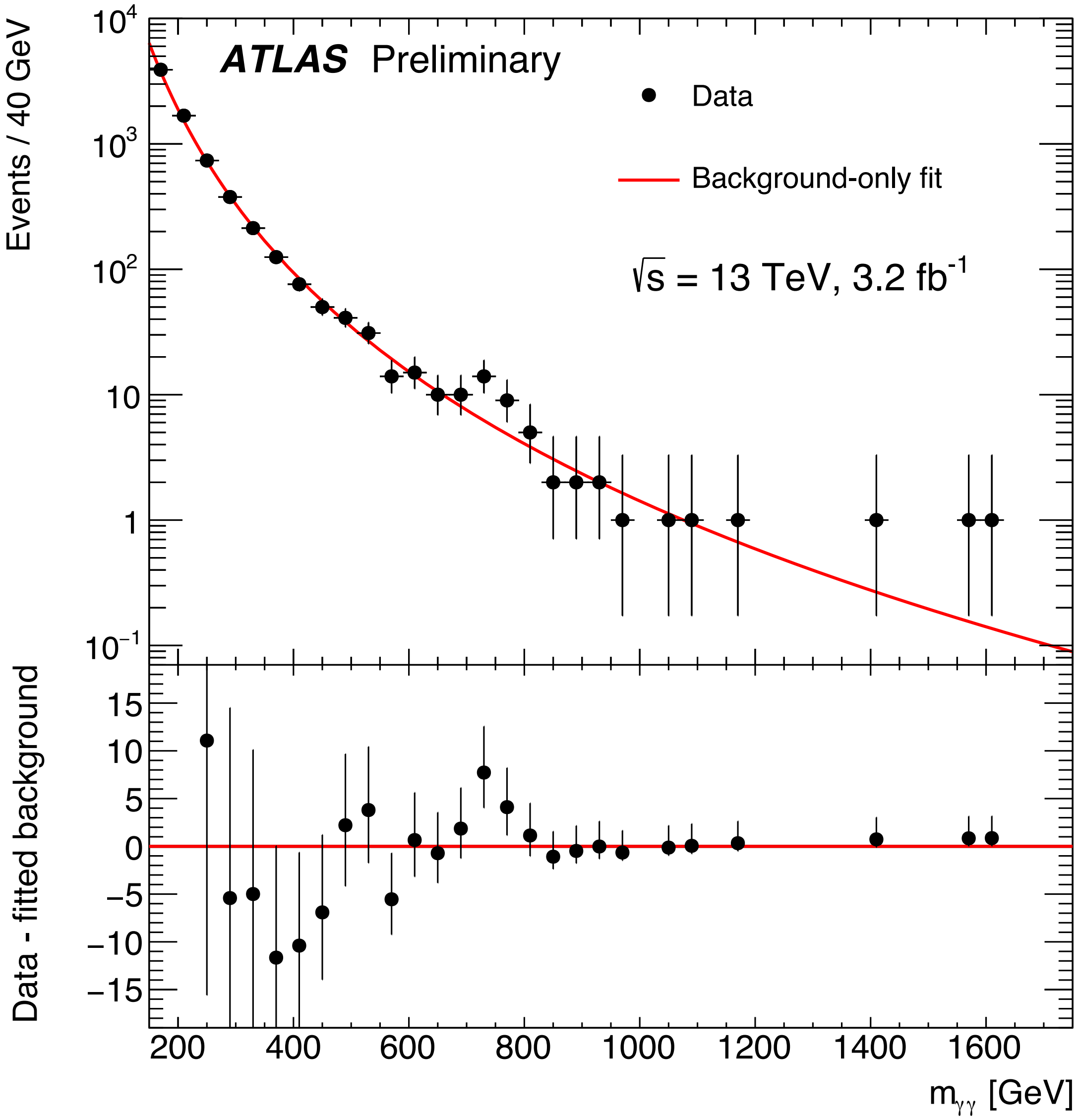
*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.

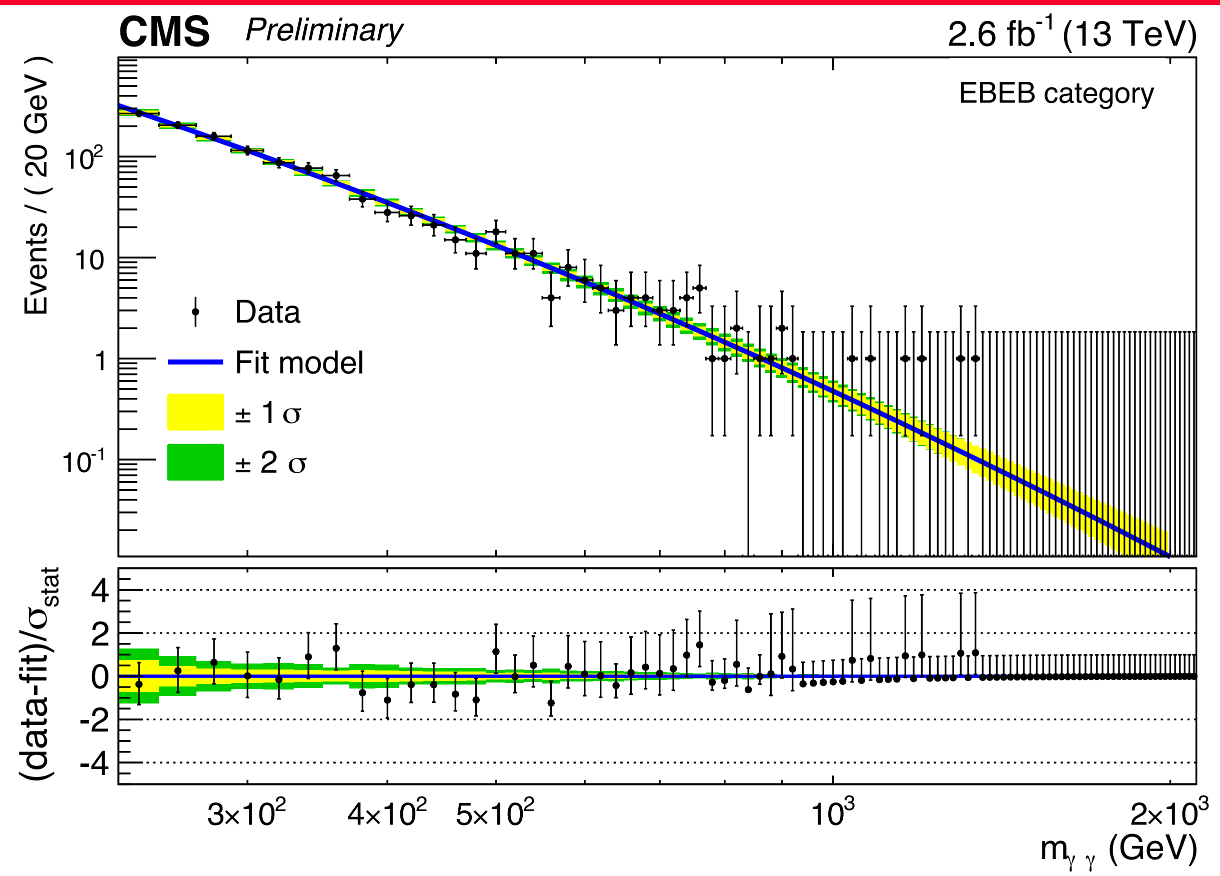
And even …

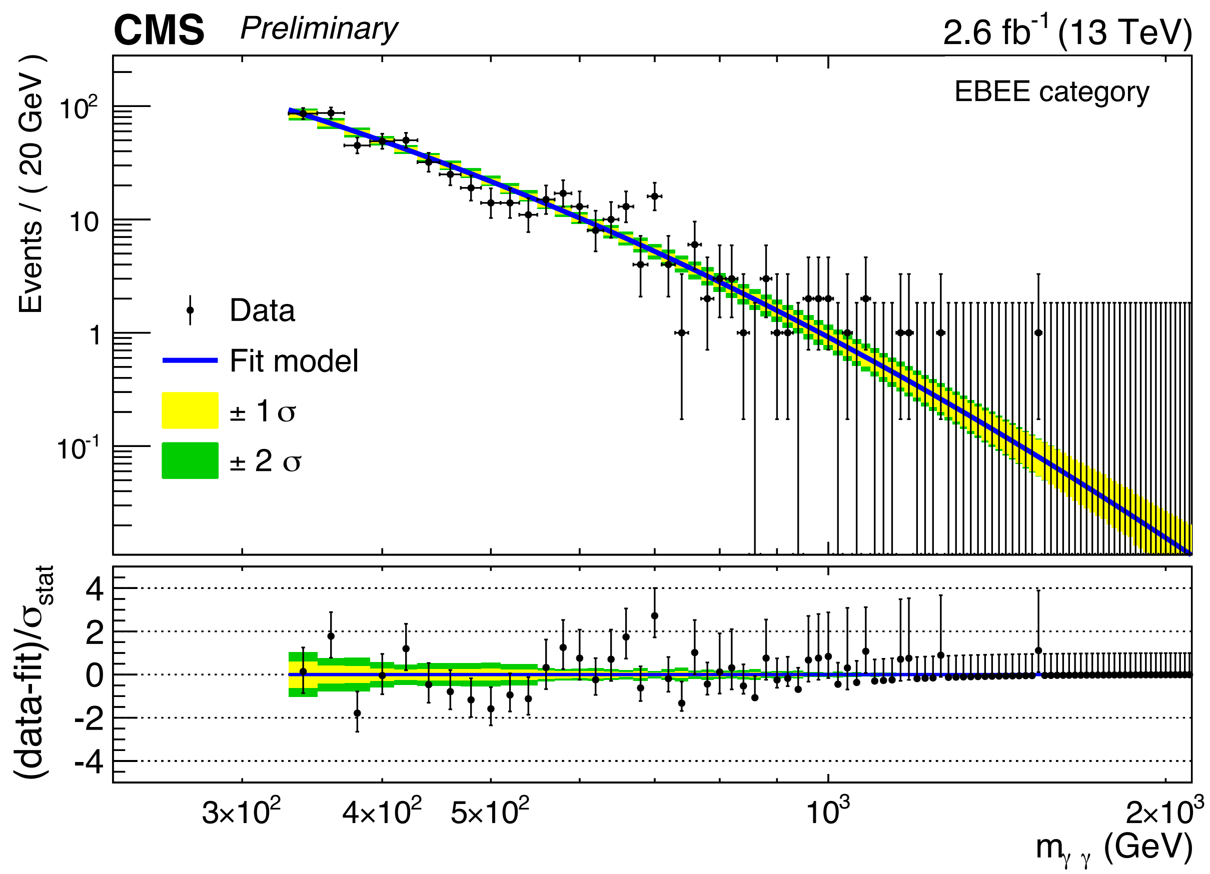
… a little intrigue

CMS-PAS-EXO-15-004

ATLAS-CONF-2015-081







To the Future!

LHC → HL-LHC

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

$\sqrt{s} = 13$ TeV
bunch spacing 25 ns

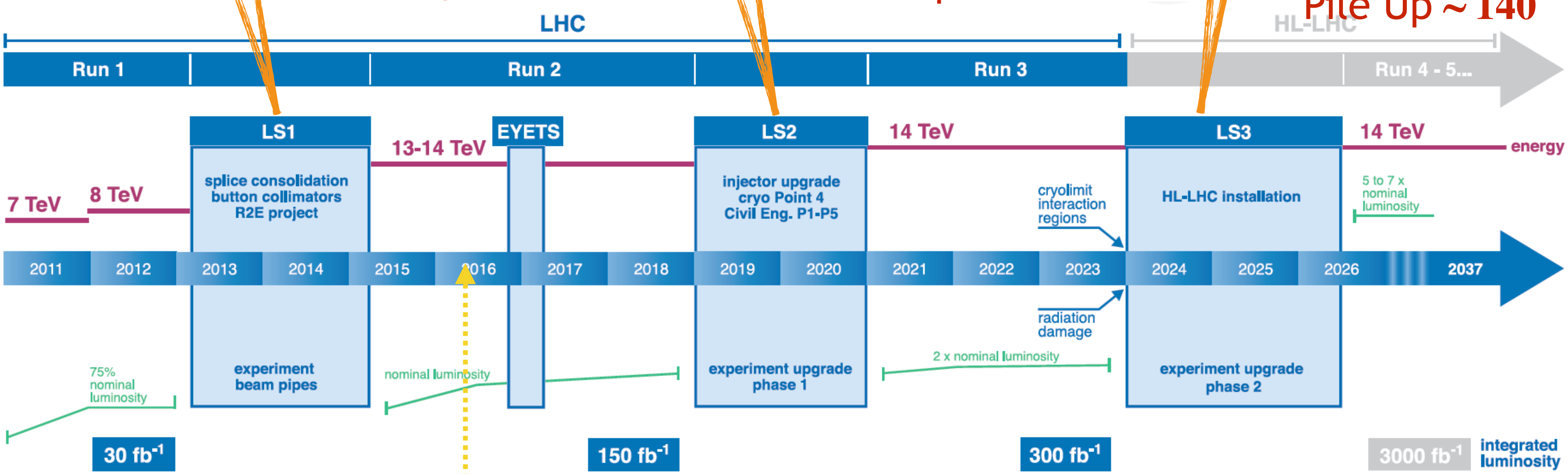
$\sqrt{s} = 14$ TeV
LHC injector upgrade

New interaction
region layout
Crab cavity

$\mathscr{L} \sim 1.6 \times 10^{34}$ cm^{-2}s^{-1}
Pile Up ~ 40

$\mathscr{L} \sim 2 \times 10^{34}$ cm^{-2}s^{-1}
Pile Up ~ 60

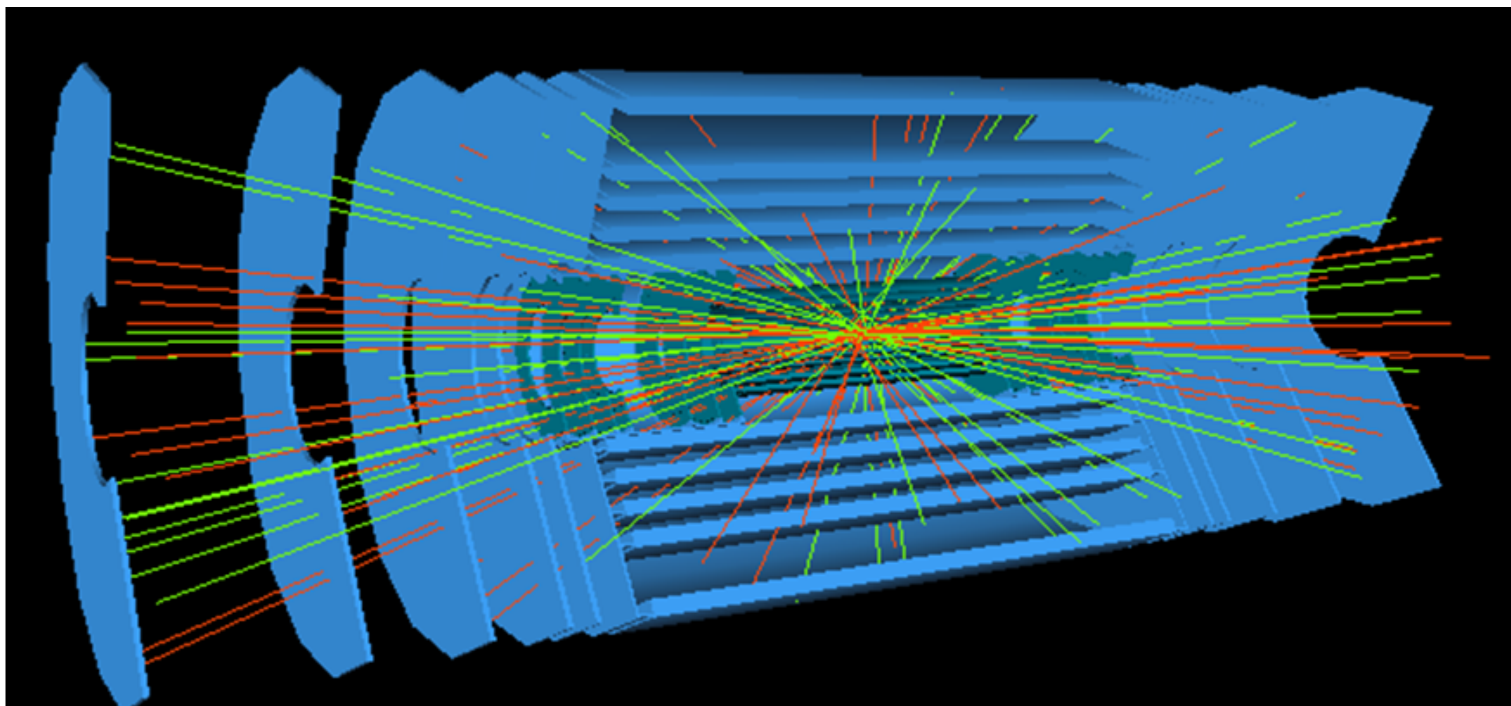
luminosity levelling
$\mathscr{L} \sim 5 \times 10^{34}$ cm^{-2}s^{-1}
Pile Up ~ 140



today: Higgs Maxwell meeting 2016

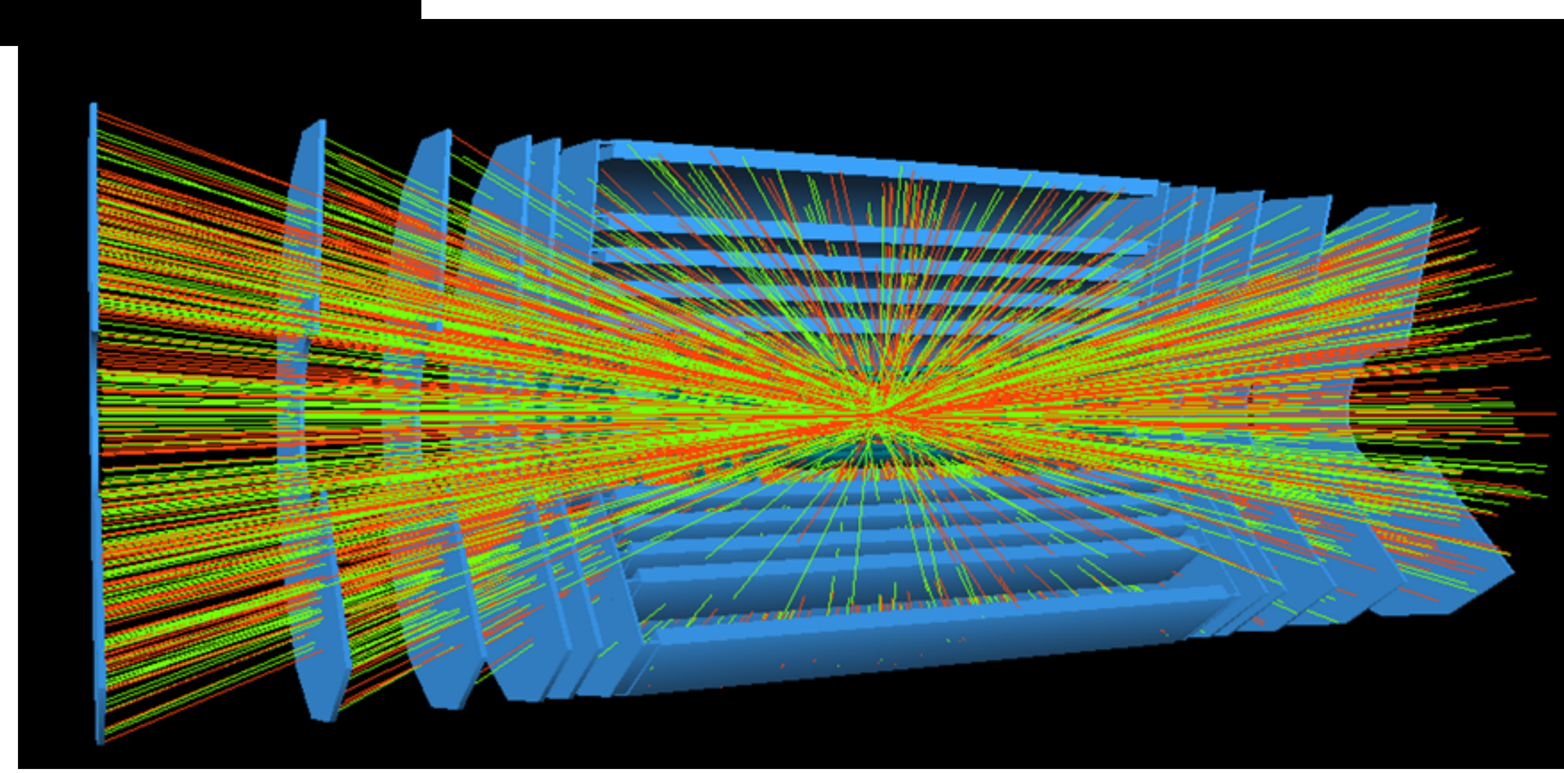
The Challenge of Pileup

- Pileup = number of proton-proton collision per bunch crossing
- Instantaneous luminosity of $5\ (7)\ \times 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponds to an average pileup of $\langle\mu\rangle$ of **140 (200).**



Simulated pileup in ATLAS tracker

Run 1
Pile up of **23**



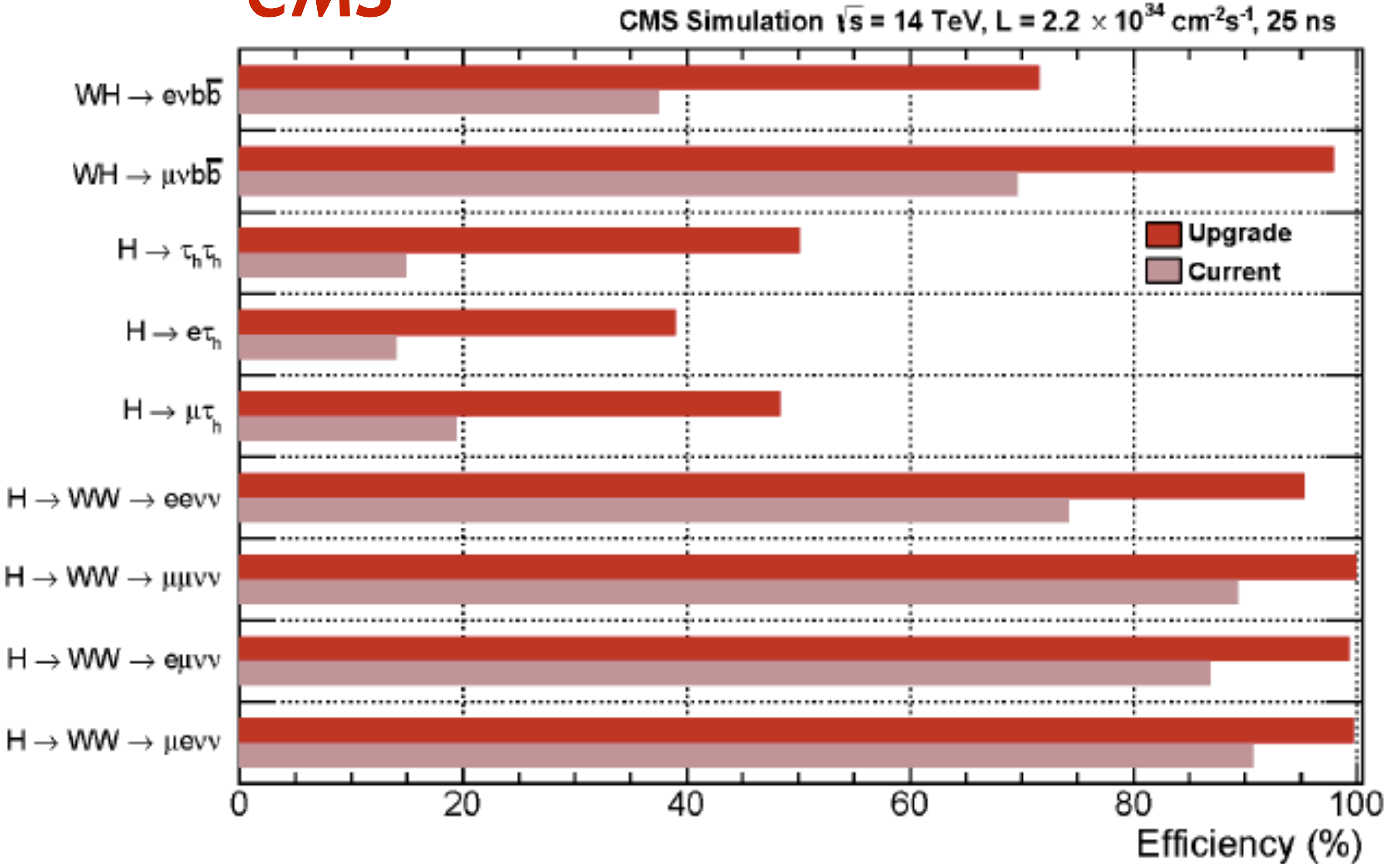
HL-HLC
Pile up of **230**

ATLAS and CMS Upgrades

- ATLAS and CMS will be upgraded to achieve the same or better performance as in Run 1.
  - Pileup mitigation is a critical element of detector designs.
- Recently released detector *Scoping Documents* investigate the impact of different detector cost scenarios on physics performance.
- e.g. for 2022: New tracking detectors, new trigger systems, new timing detectors.

ATLAS

CMS



HL-LHC Analysis Techniques

High Pileup

- Much effort is focussed on understanding how to mitigate pileup in physics analyses
- e.g. New method proposed in the literature *Pileup Per Particle Identification* arXiv:1407.6013

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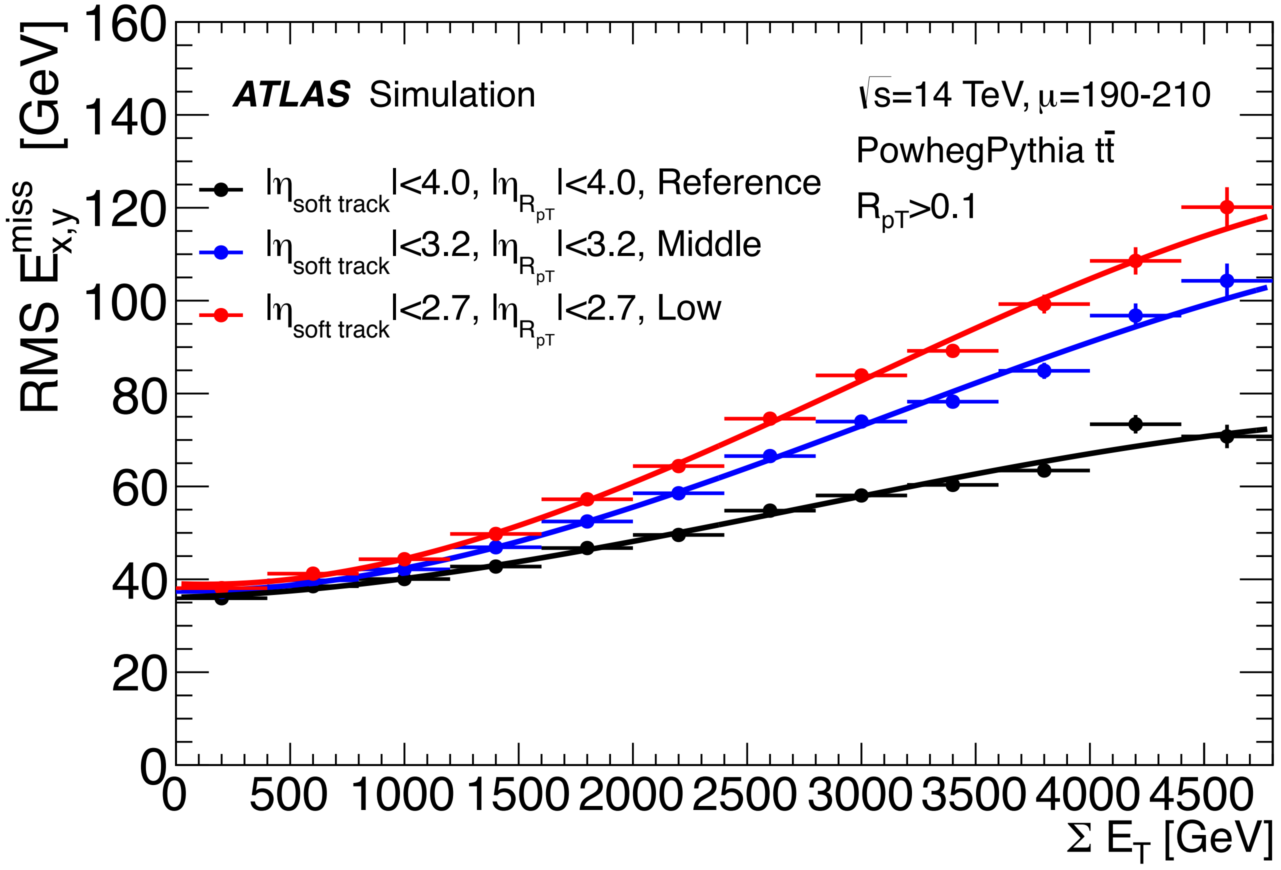
ATLAS:
Resolution as a function of ΣE_T in $t\bar{t}$ events:
use extended tracking to reject pile-up jets



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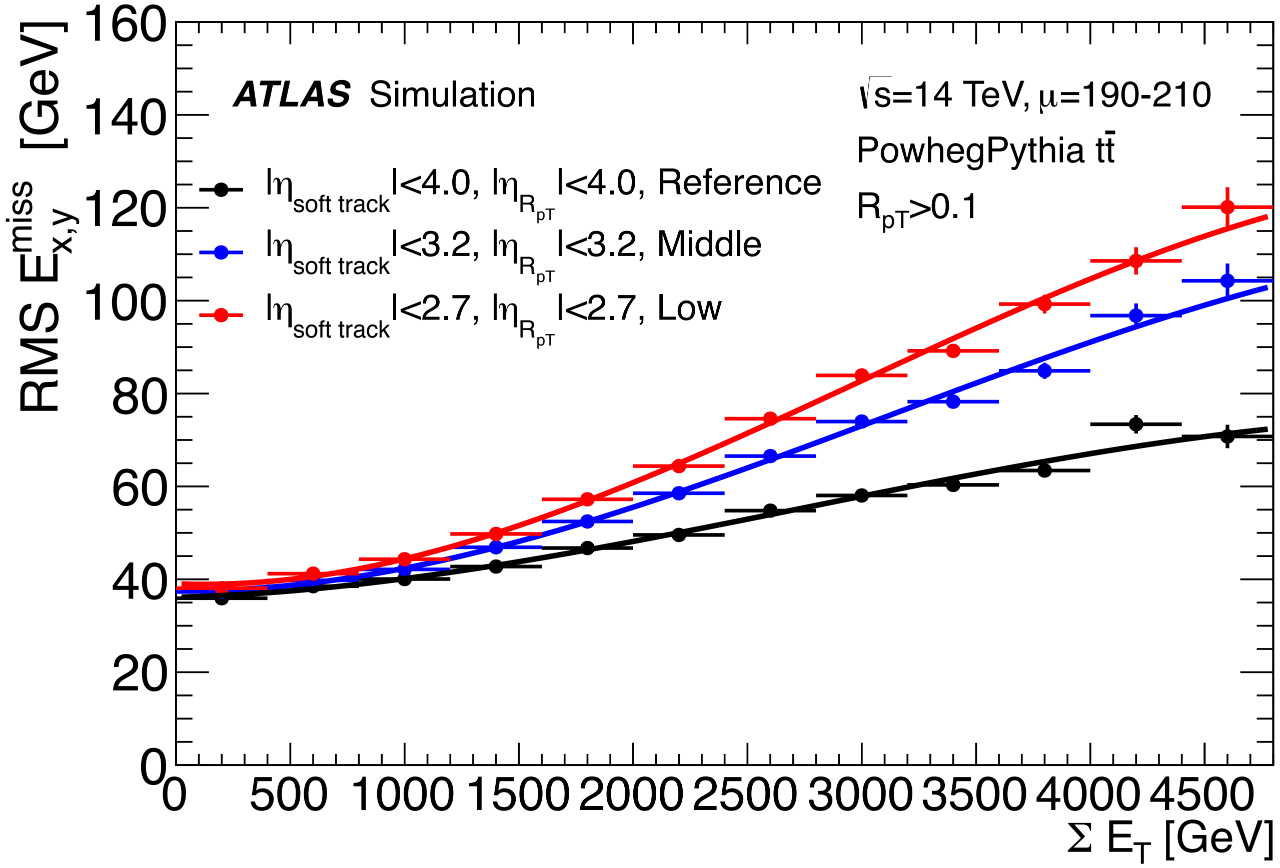
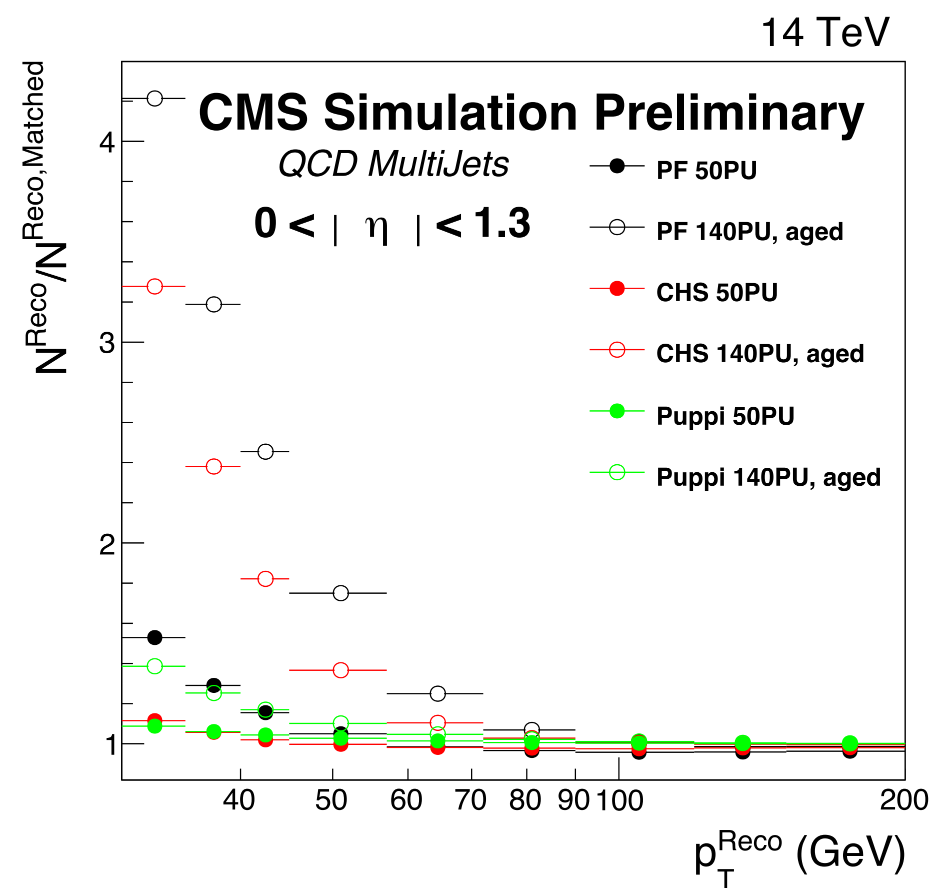


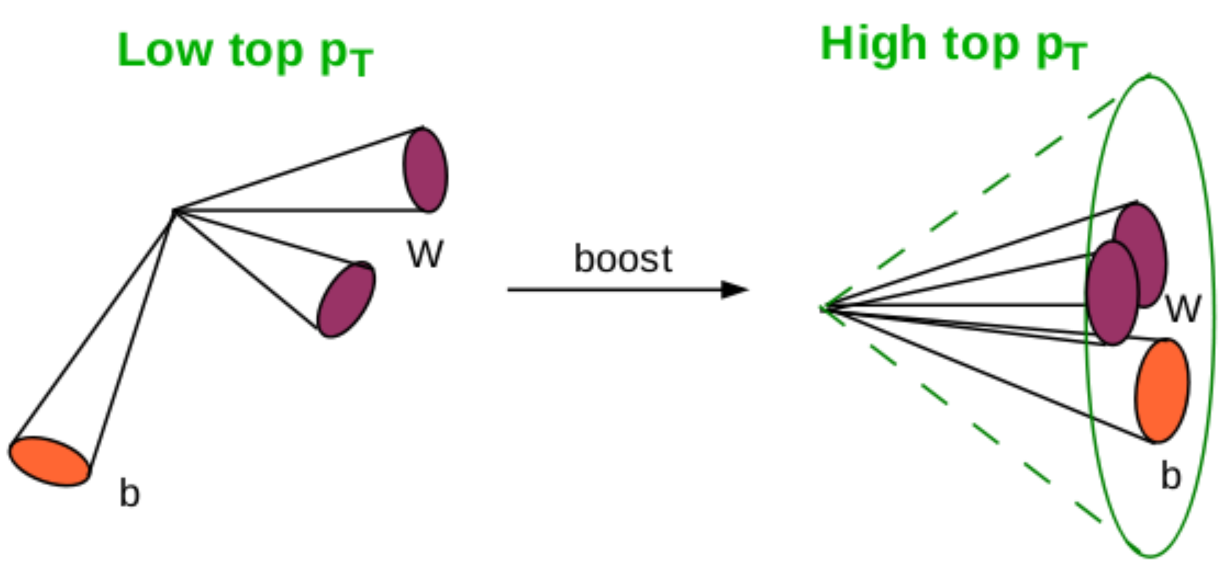
CMS: Rate of pileup jets/true jets for
- Particle Flow algorithm (PF)
- PF + rejecting charged hadrons from pileup
- Using Puppi algorithm



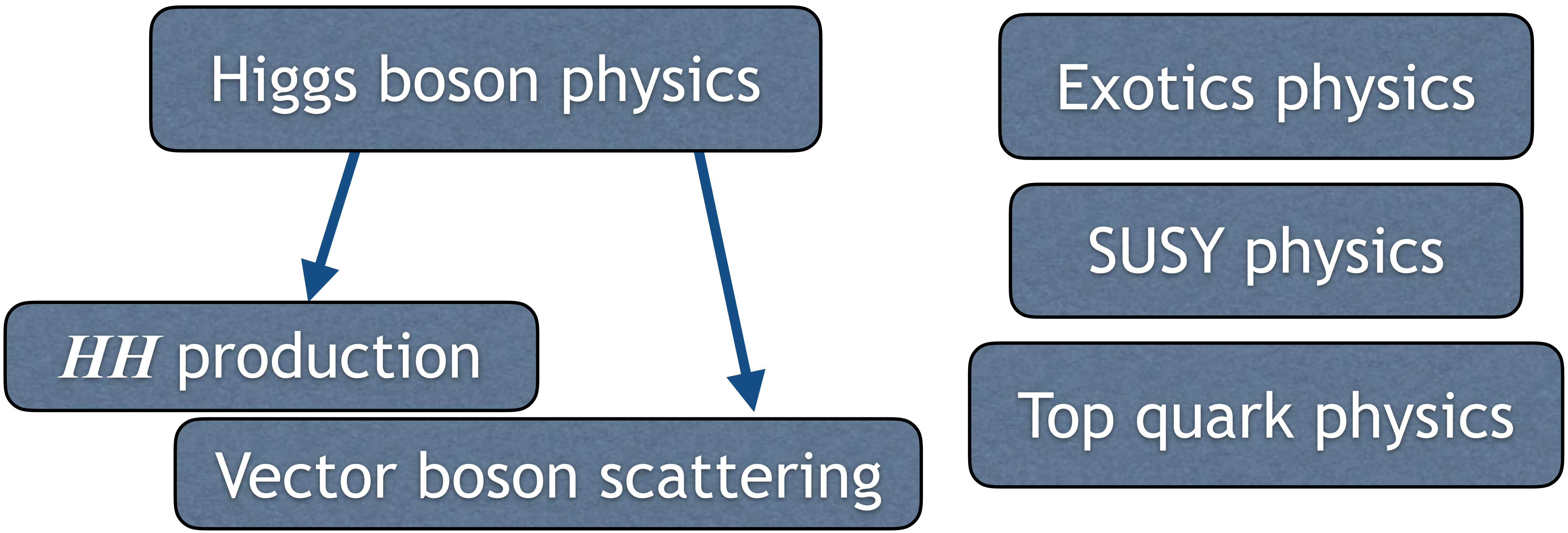
HL-LHC Analysis Techniques

Jet Substructure

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



HL-LHC Physics Prospects



- Results are projections from refining current analyses or designing new ones.
- In some cases, several different systematic uncertainty scenarios are presented.
- Many results are presented in the context of specific models.

Higgs Boson Physics

- **HL-LHC will be a Higgs boson factory** $\Rightarrow$ over 100 million Higgs bosons in $\mathbf{3000\ fb^{-1}}$

Higgs Boson Physics

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➡ Over 1 million for each of the main production mechanisms, spread over many decay modes

  - 400k $H\to\gamma\gamma$
  - 20k $H\to ZZ\to llll$
  - 40k $H\to\mu\mu$
  - 50 leptonic $H\to J/\psi\ \gamma$ (very rare mode)

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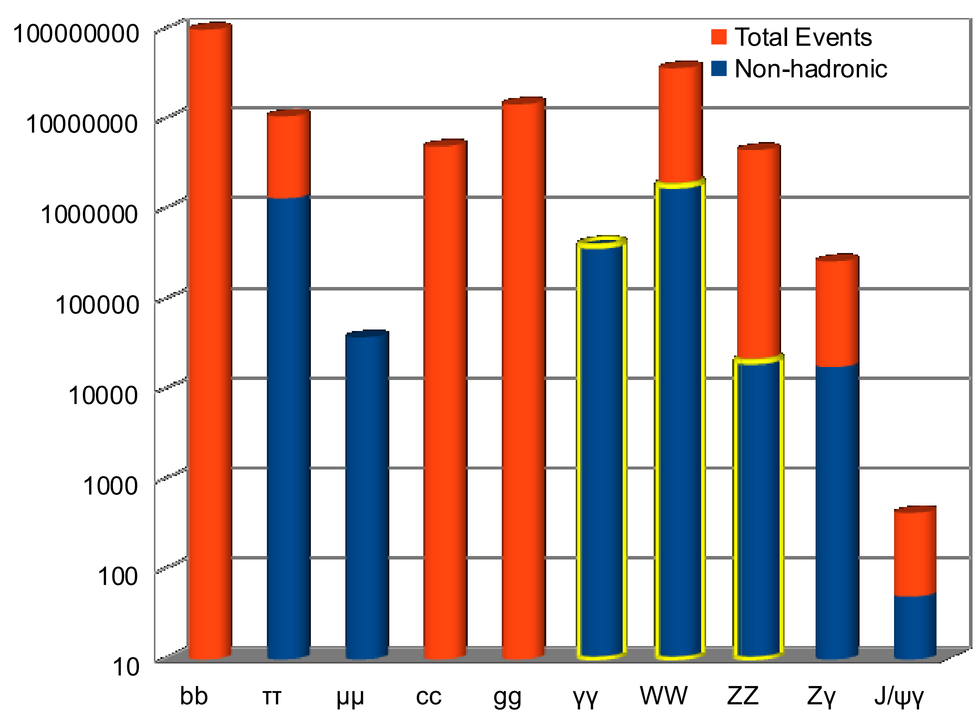

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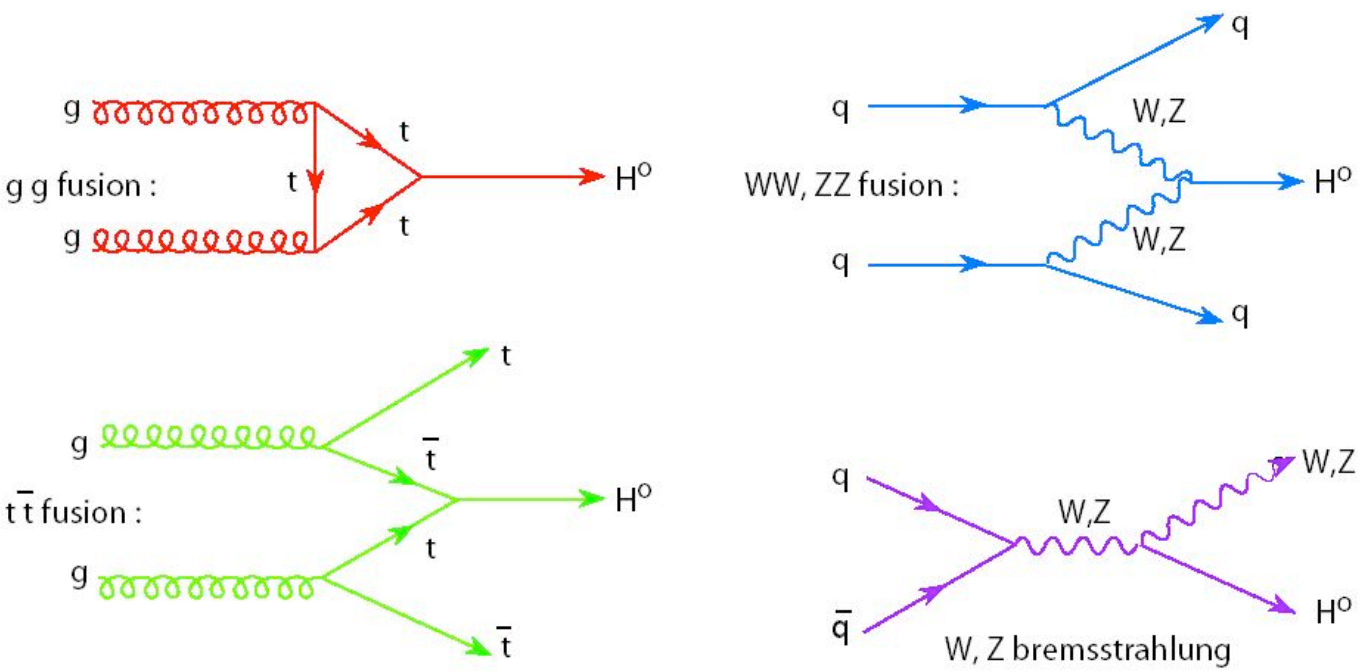

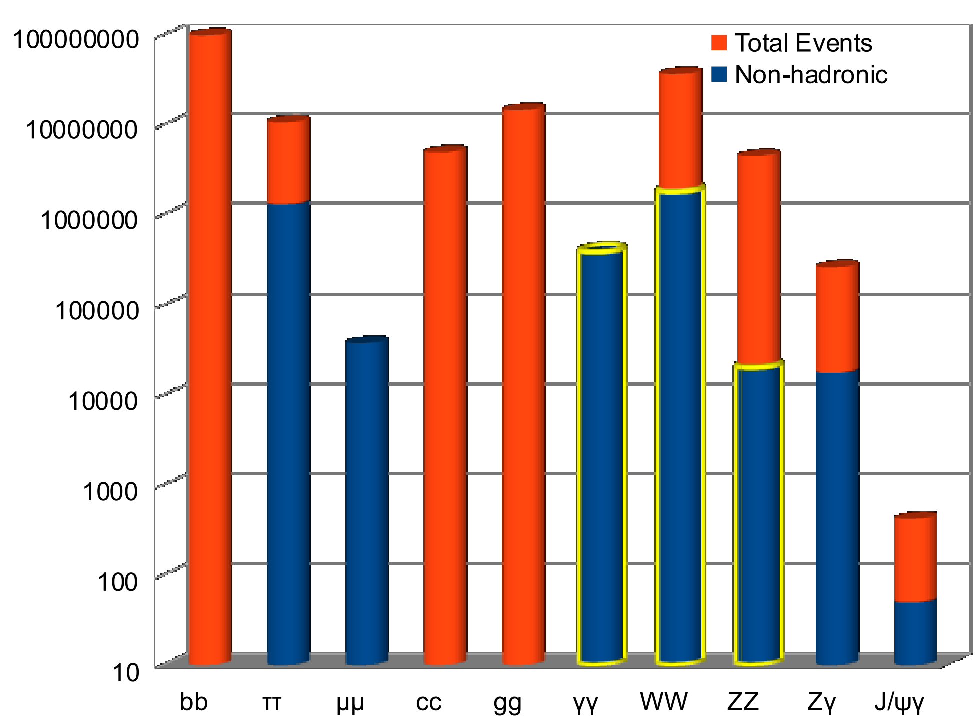

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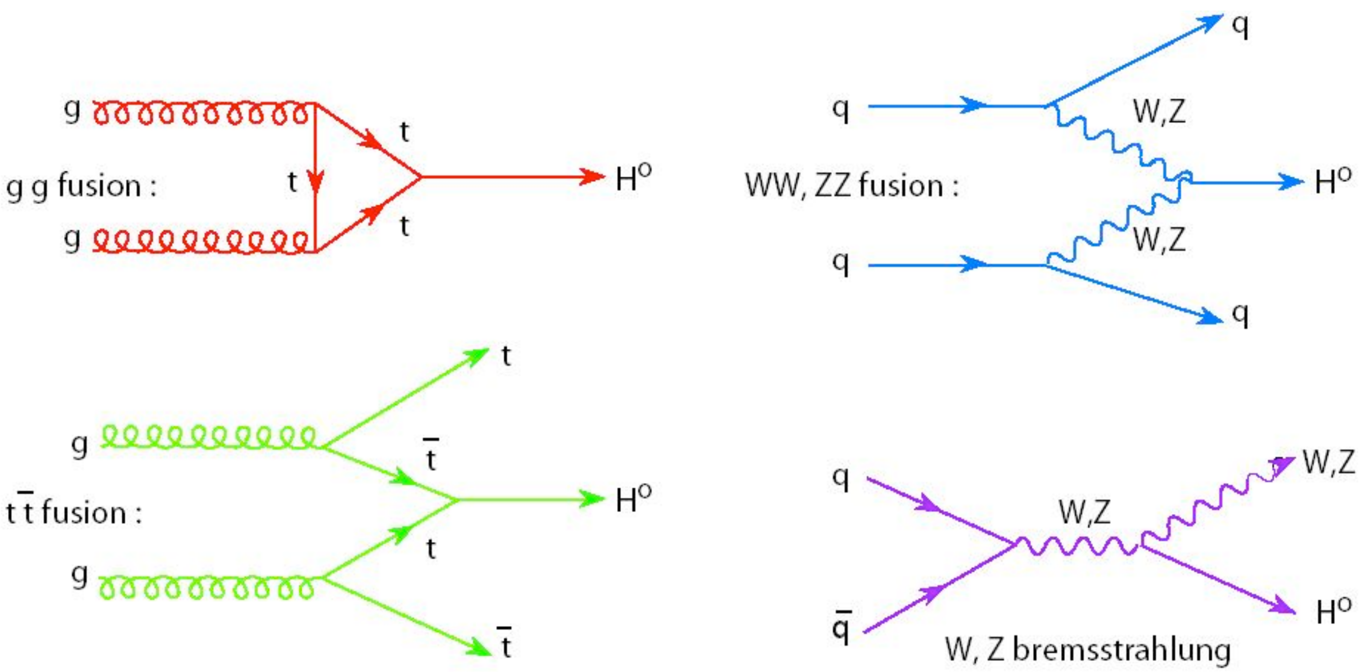
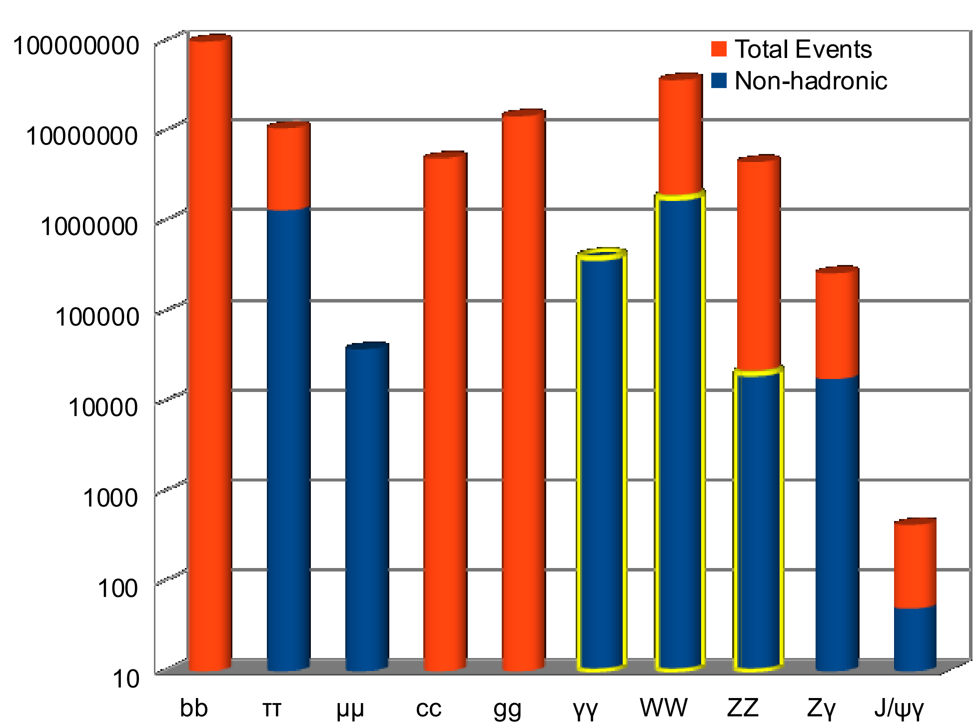
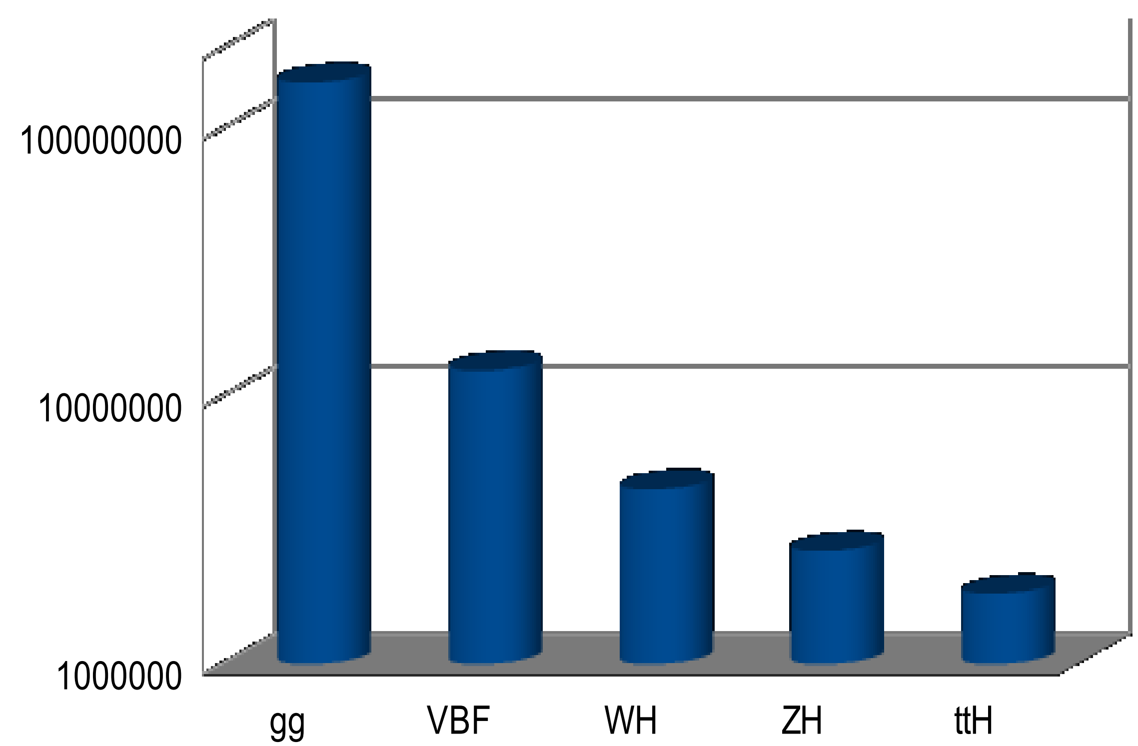


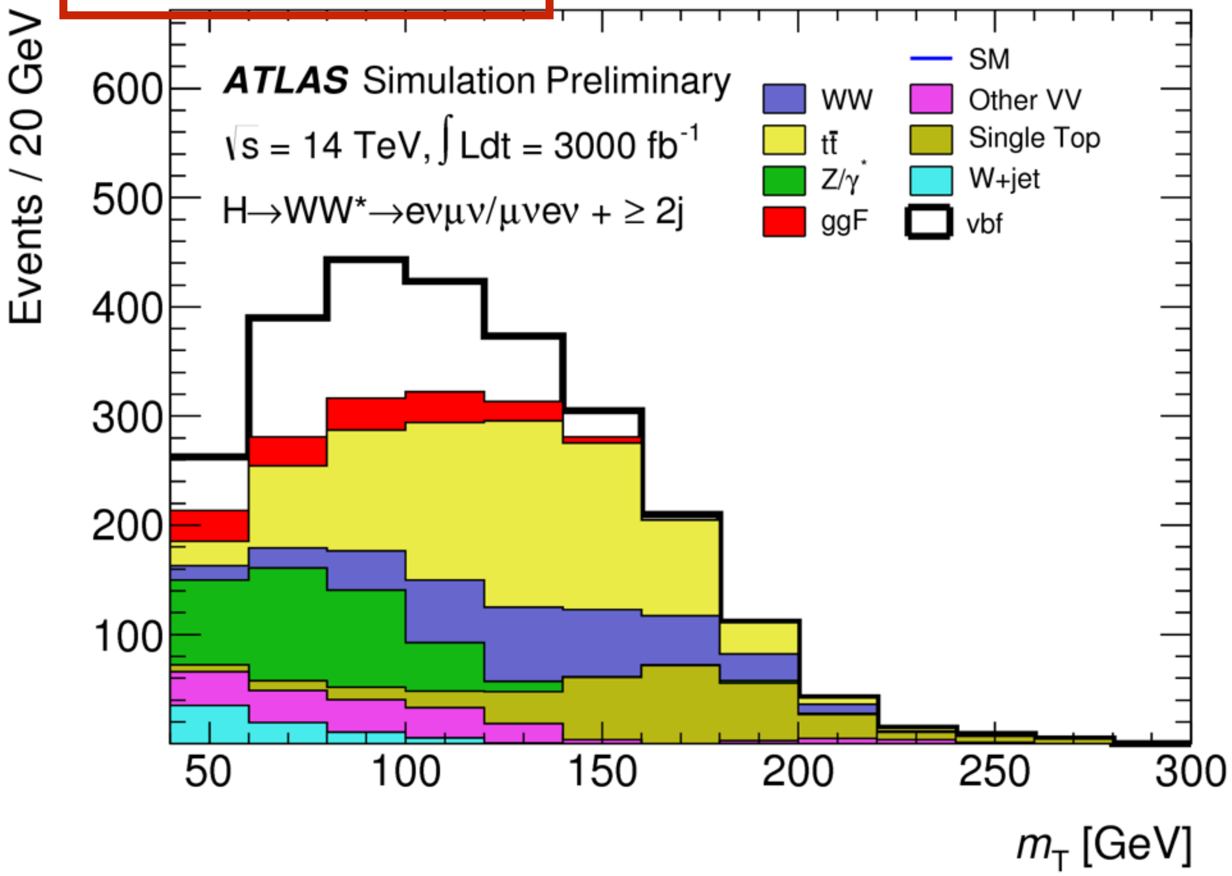




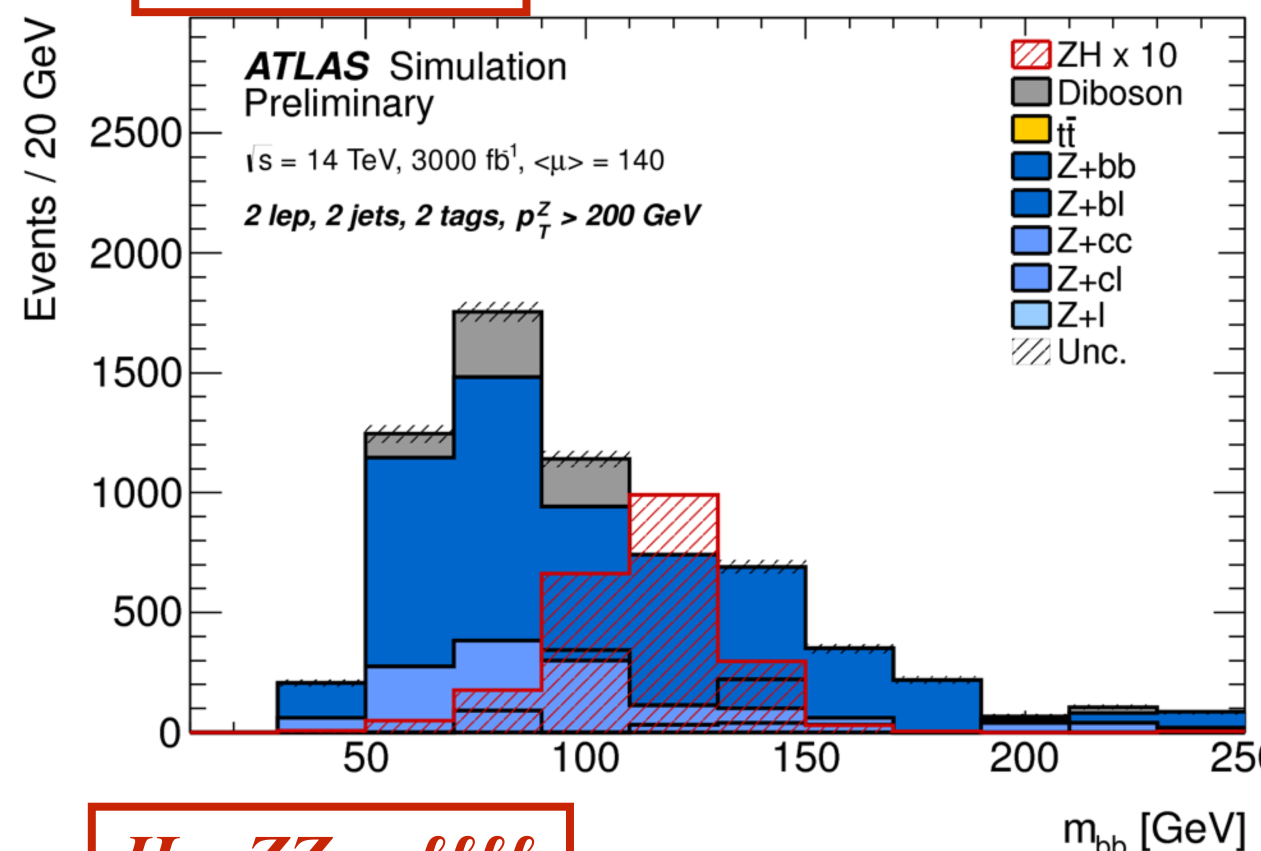
Higgs Boson Peaks with 3000 fb^{-1}

ATL-PHYS-PUB-2013-014
ATL-PHYS-PUB-2014-012
CERN-LHCC-2015-010

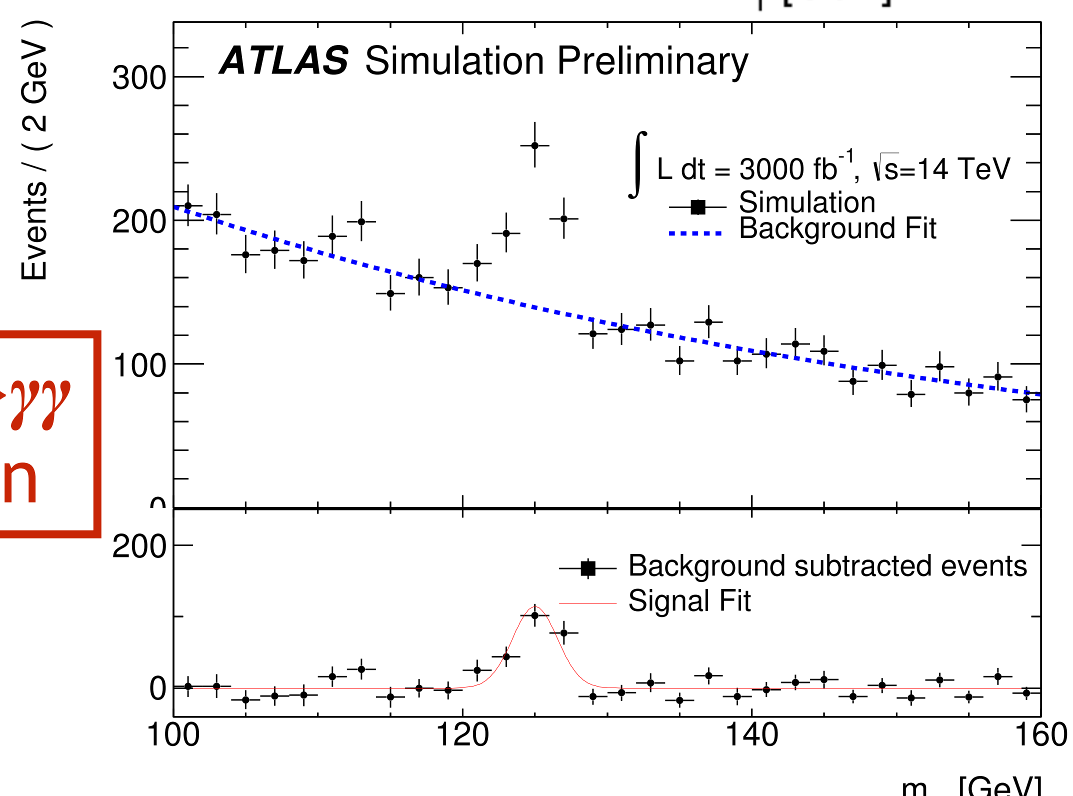
VBF, $H\to WW$



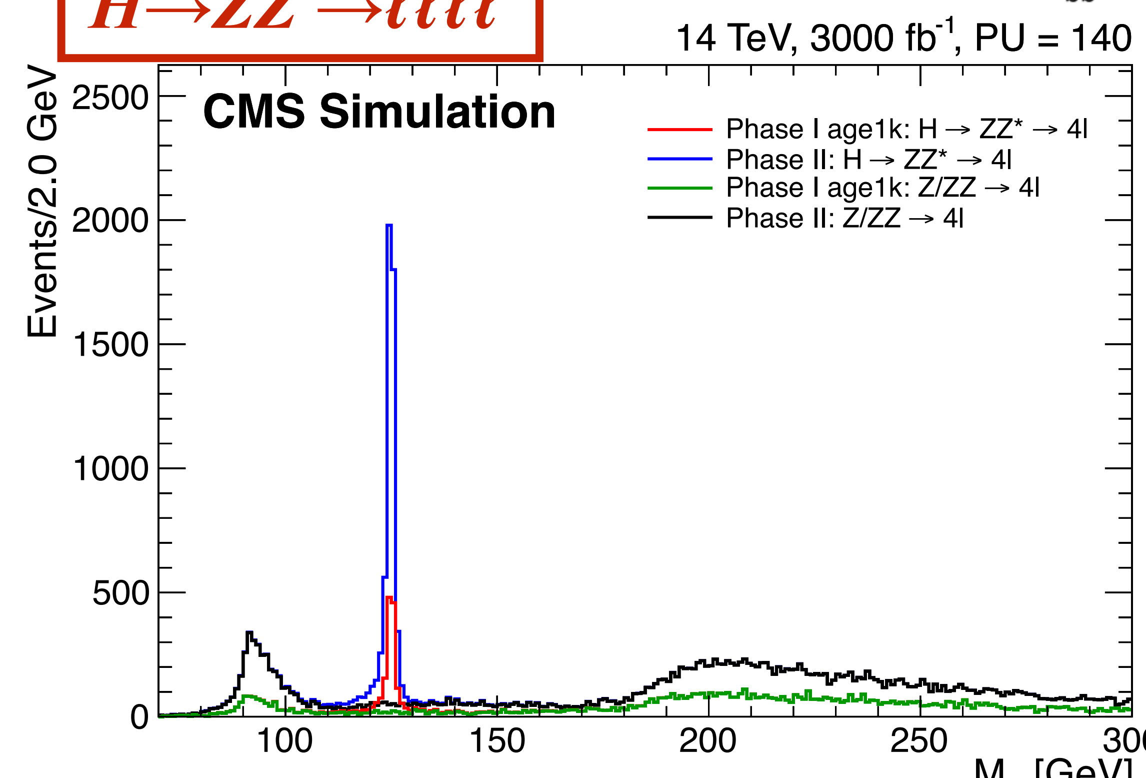
ZH, $H\to b\bar{b}$



$t\bar{t}H$, $H\to\gamma\gamma$
1 lepton



$H\to ZZ\to\ell\ell\ell\ell$

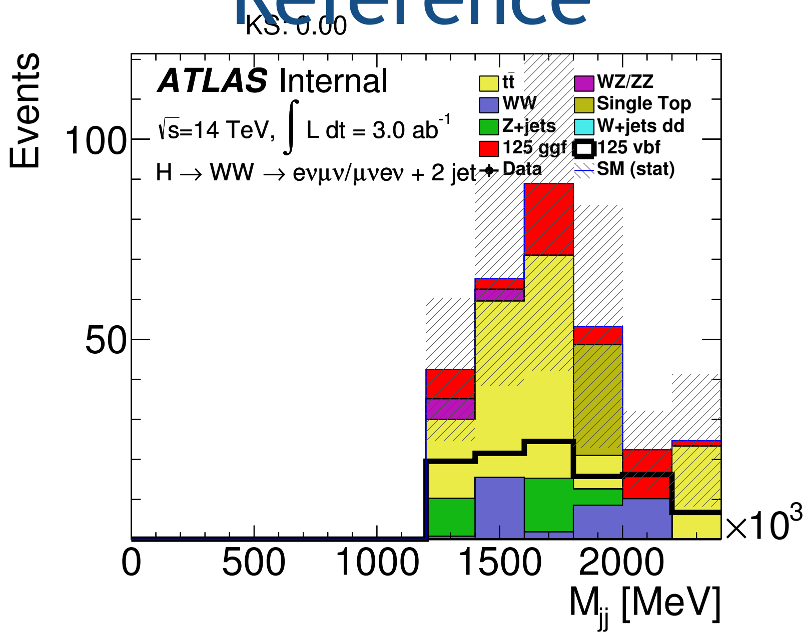


VBF $H \to WW$

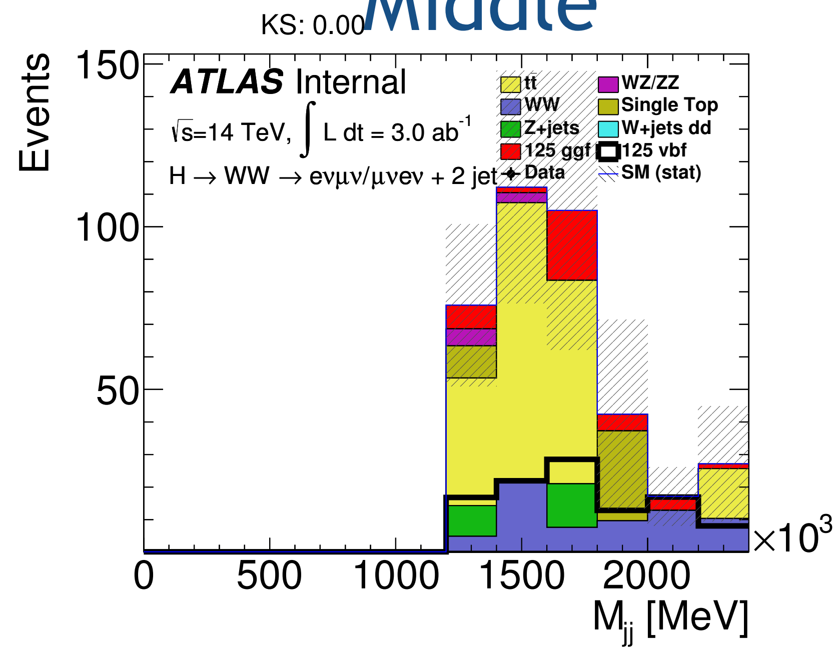
- Used to motivate the ATLAS upgrade detector design in the Scoping Document.
- Two forward jets in the detector

Mass of two forward jets:

Reference



Middle



Low

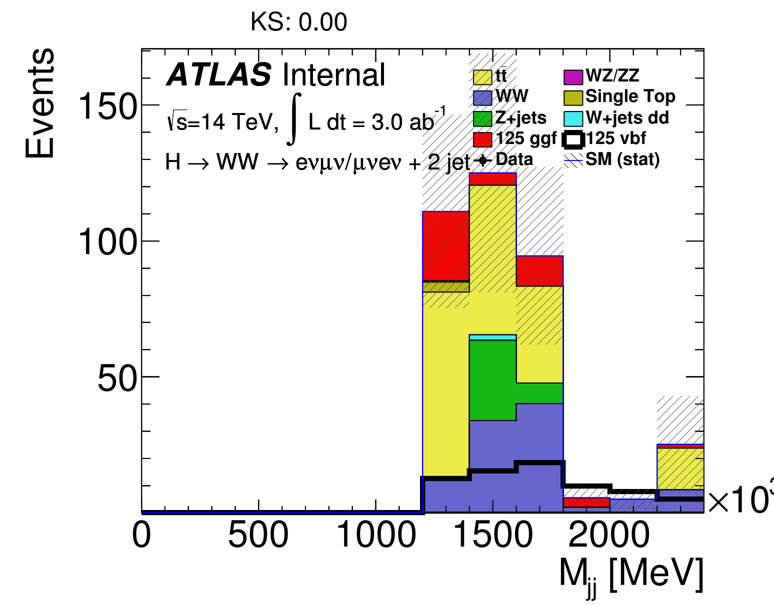


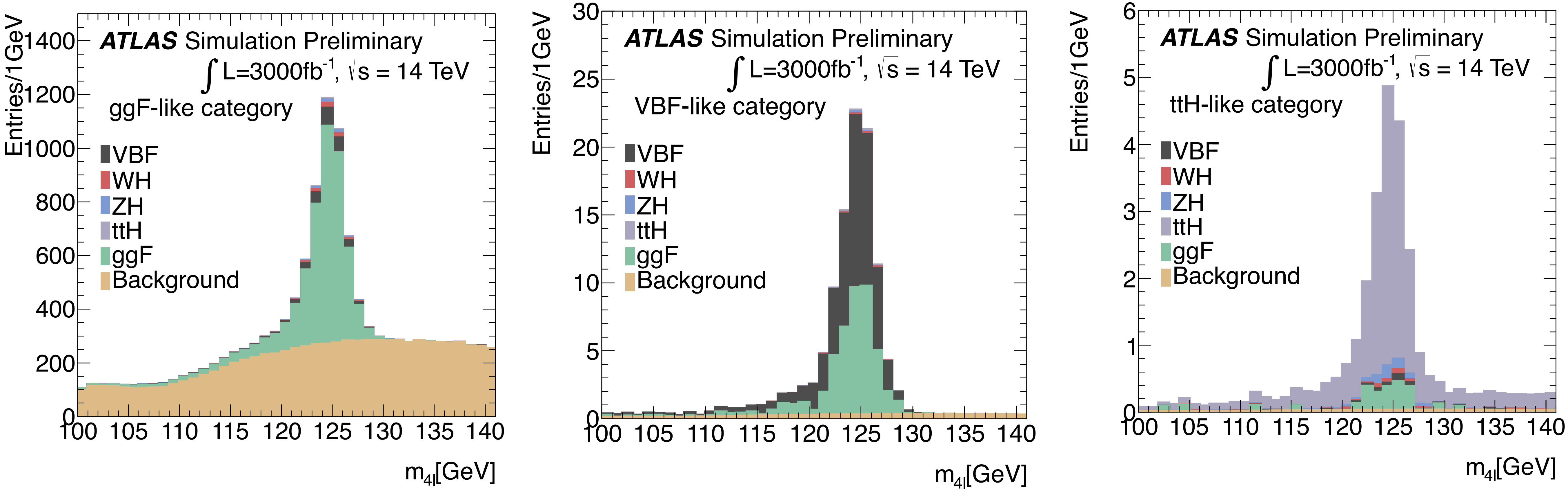
Table 35. The $\Delta\mu/\mu$ and significance for VBF $H \to WW^{(*)}$ are shown for the three scoping scenarios. Results with and without the theoretical uncertainties on the VBF or ggF Higgs boson production are included.

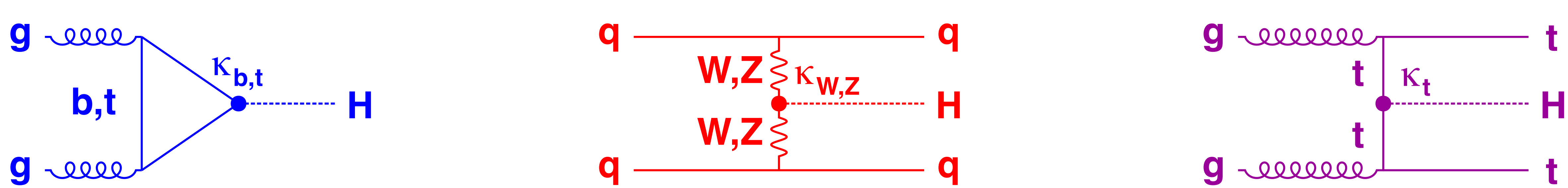
Scoping Scenario	without theo. unc.		with theo. unc.	
	$\Delta\mu/\mu$	Z_0-value (σ)	$\Delta\mu/\mu$	Z_0-value (σ)
Reference	0.14	8.0	0.20	5.7
Middle	0.20	5.4	0.25	4.4
Low	0.30	3.5	0.39	2.7

Still Golden: $H \to ZZ \to \ell\ell\ell\ell$

ATL-PHYS-PUB-2013-014

signal events	ggH	VBF	$t\bar{t}H$	WH	ZH
3000 fb^{-1}	3800	97	35	67	6

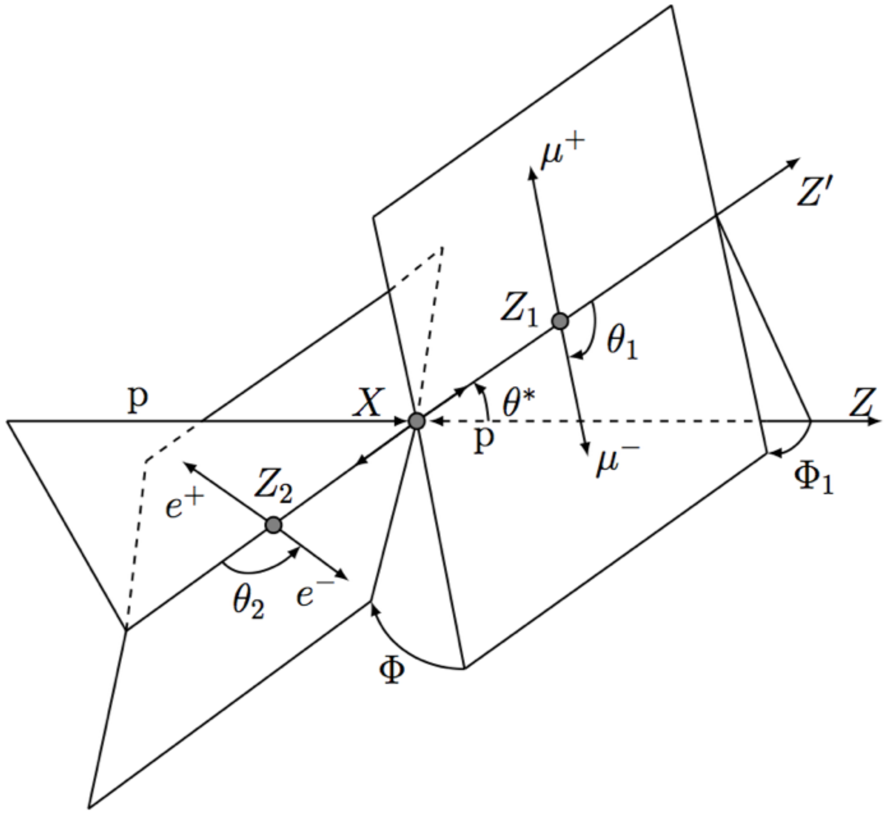




Large statistics will be used for **dσ/dp$_T$(H), dσ/dN$_{jets}$**

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.

$$A(H \to ZZ) = v^{-1}\left(\underbrace{a_1 m_Z^2 \epsilon_1^\star \epsilon_2^\star}_{\text{SM tree processes}} + \underbrace{a_2 f_{\mu\nu}^{\star(1)} f^{\star(2),\mu\nu}}_{\text{loop CP-even contributions}} + \underbrace{a_3 f_{\mu\nu}^{\star(1)} \tilde{f}^{\star(2),\mu\nu}}_{\text{CP-odd contributions (BSM)}}\right)$$

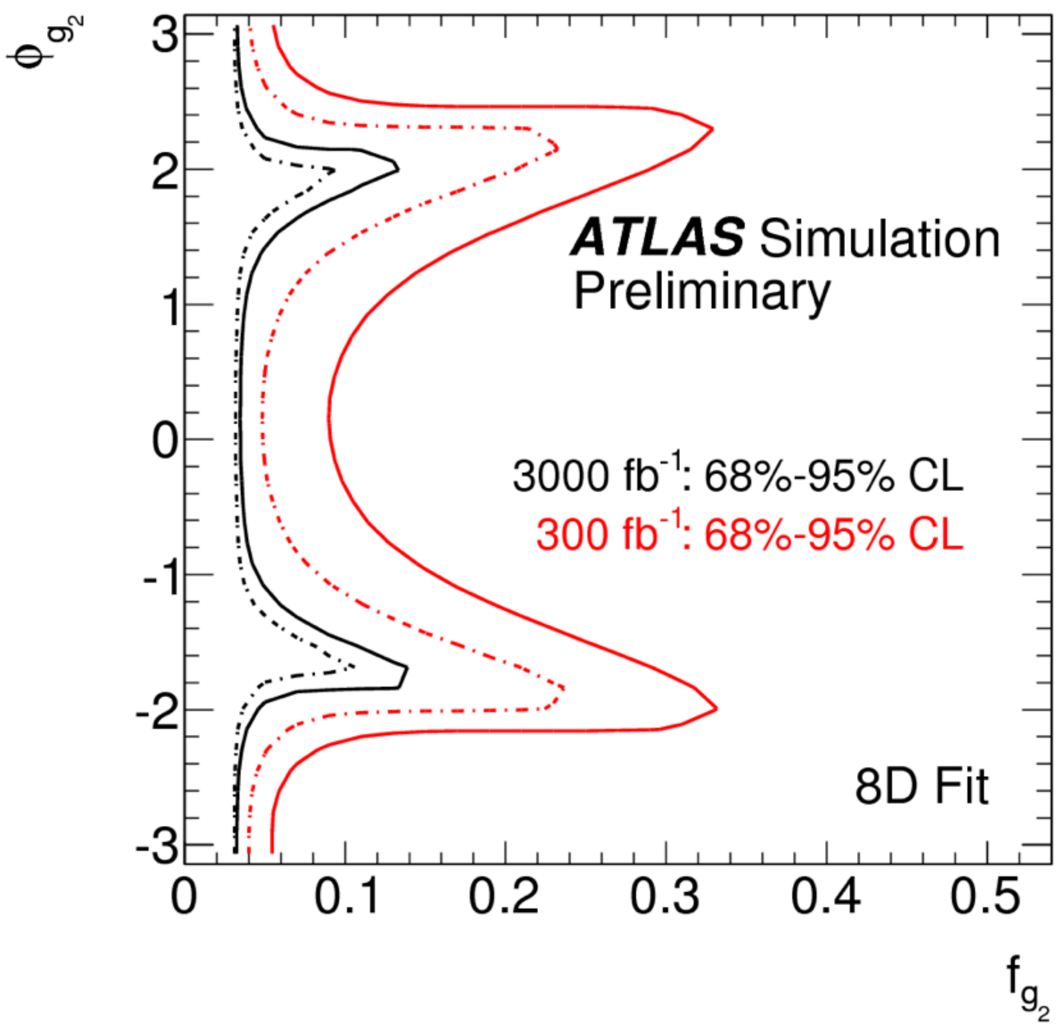
- Fit fraction of event (f_{ai}) and phases (ϕ_i) to observed decay:

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

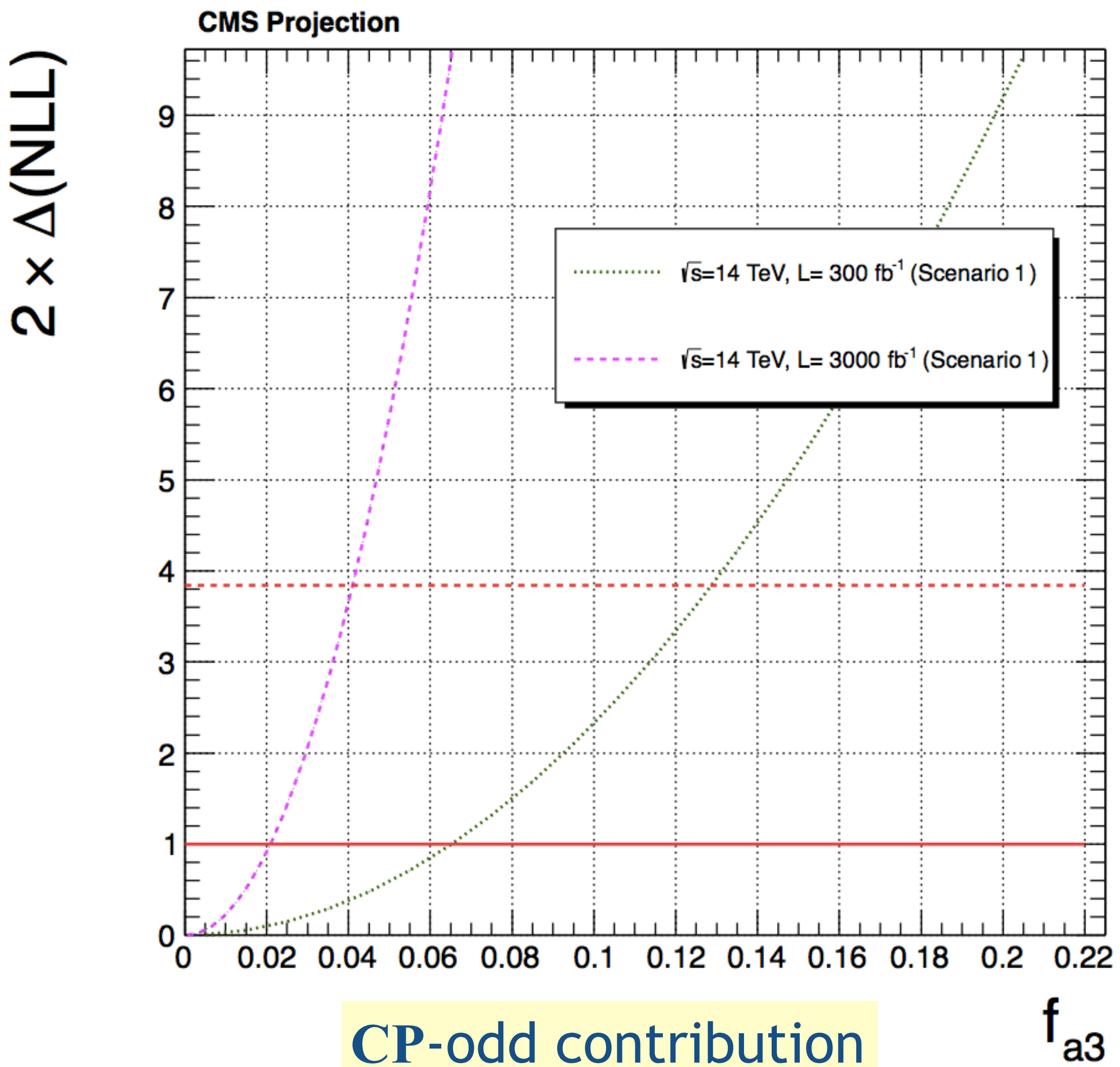
Higgs CP Studies

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}.

Rare Processes

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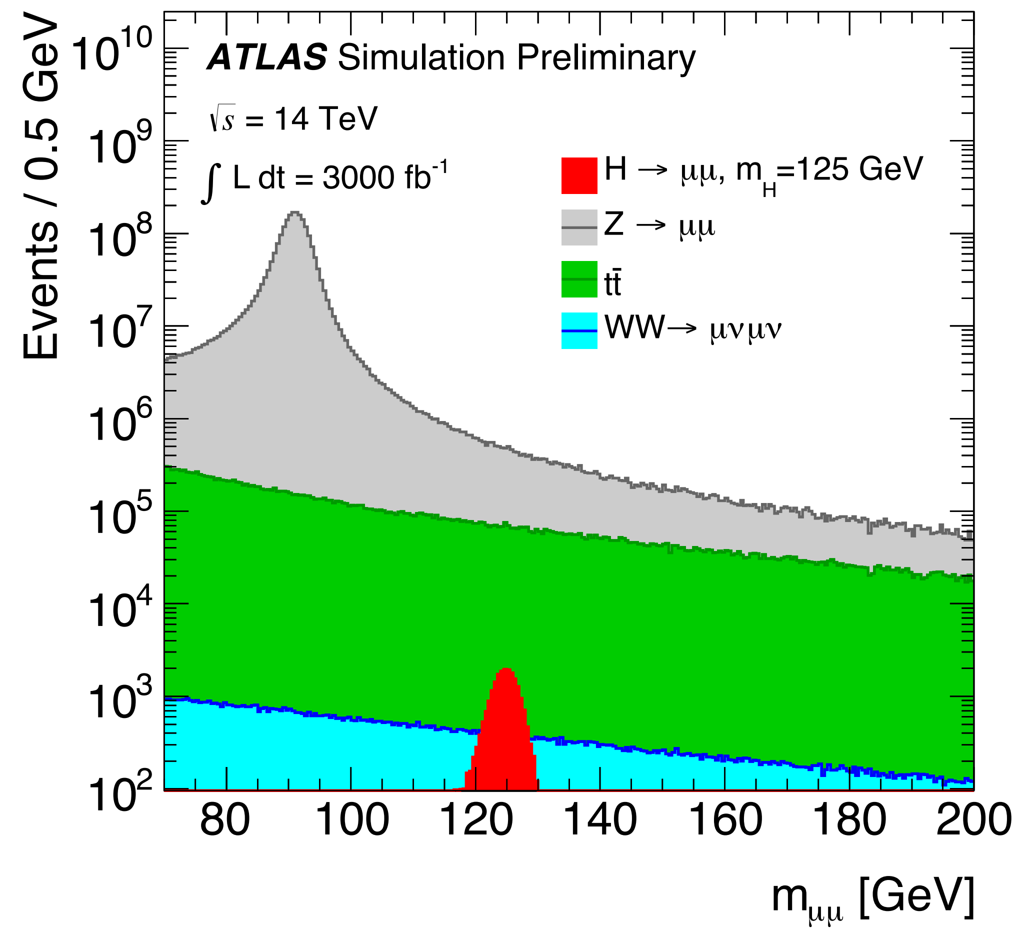
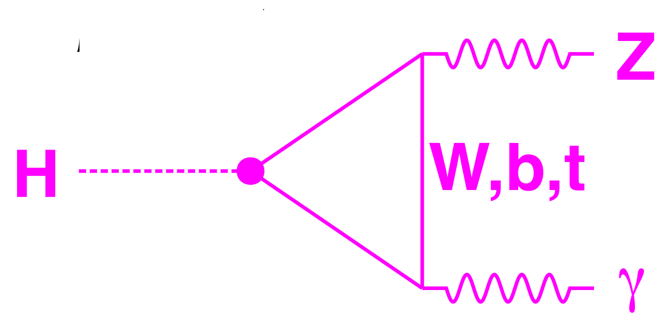
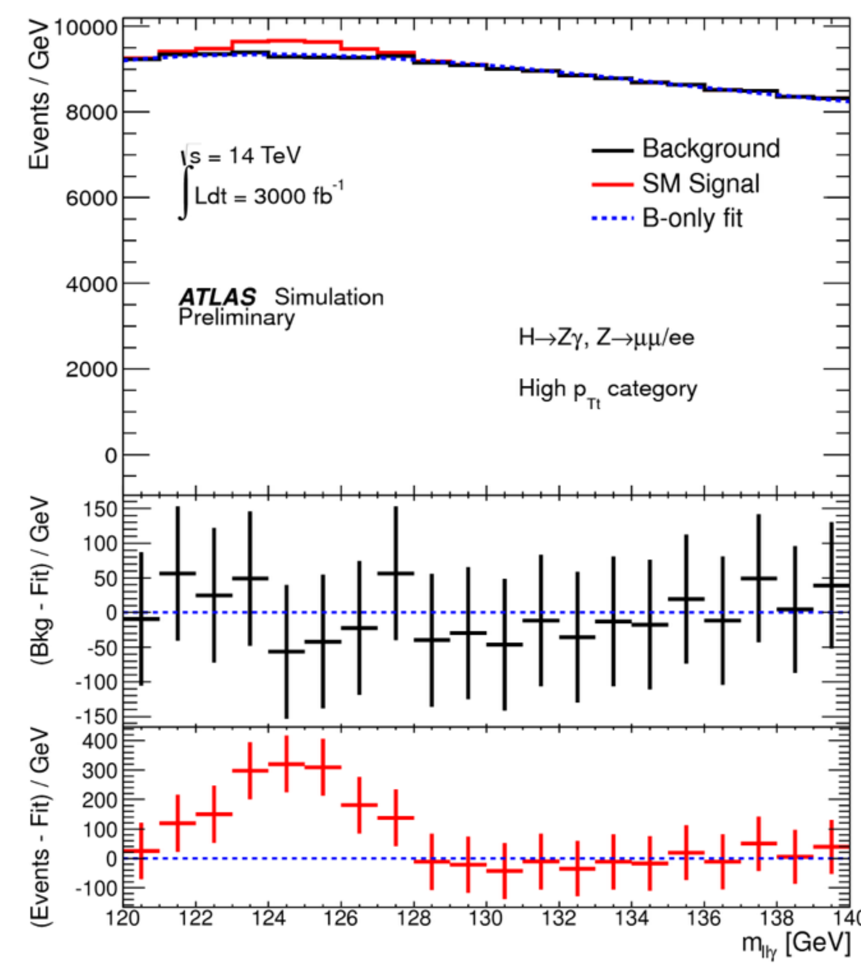


- ***H→μμ*** – measures coupling to second fermion generation
  - ATLAS and CMS expect >7**σ** significance with **3000 fb^{-1}**
  - coupling measured to **5-10%**



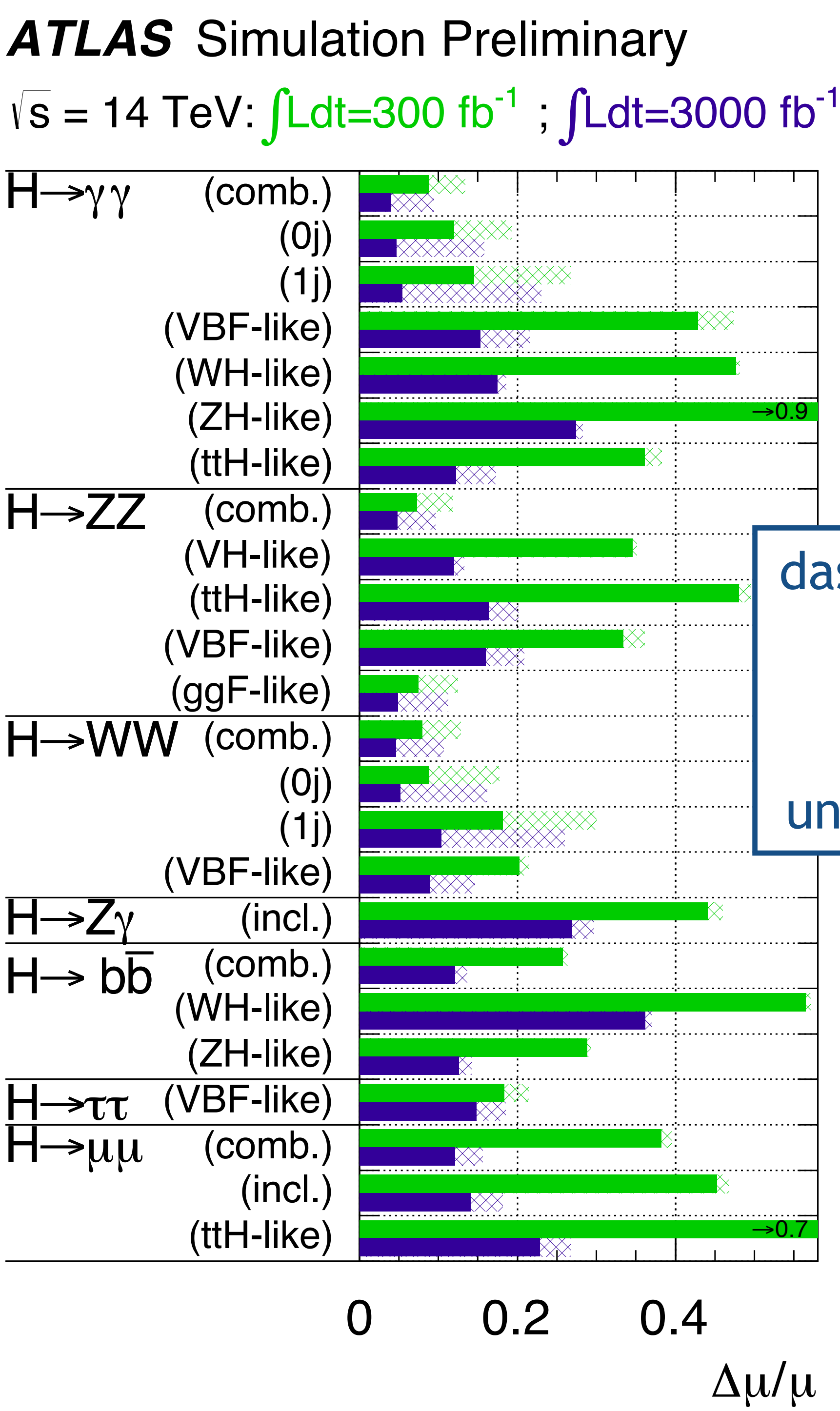


- ***H→Zγ***
  - Tests loop structure of decay, compare with ***H→ZZ H→γγ***
  - **~4σ** significance possible with **3000 fb^{-1}** despite the challenging background

Higgs Boson Signal Strength Sensitivity

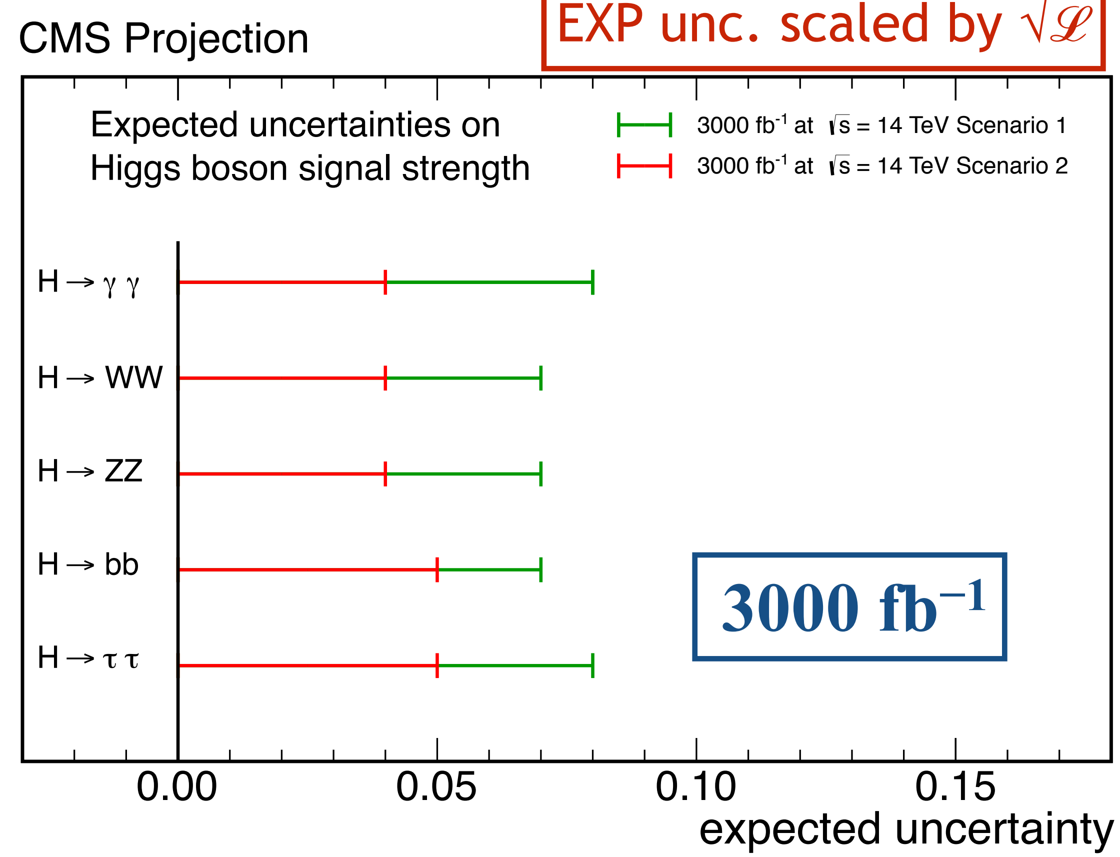
[ATL-PHYS-PUB-2014-016](#)
[arXiv:1307.7135](#)

- All production modes can be observed for ZZ and $\gamma\gamma$ final states
- Combine production modes for best information on branching ratios



dashed bands includes current theory uncertainties

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

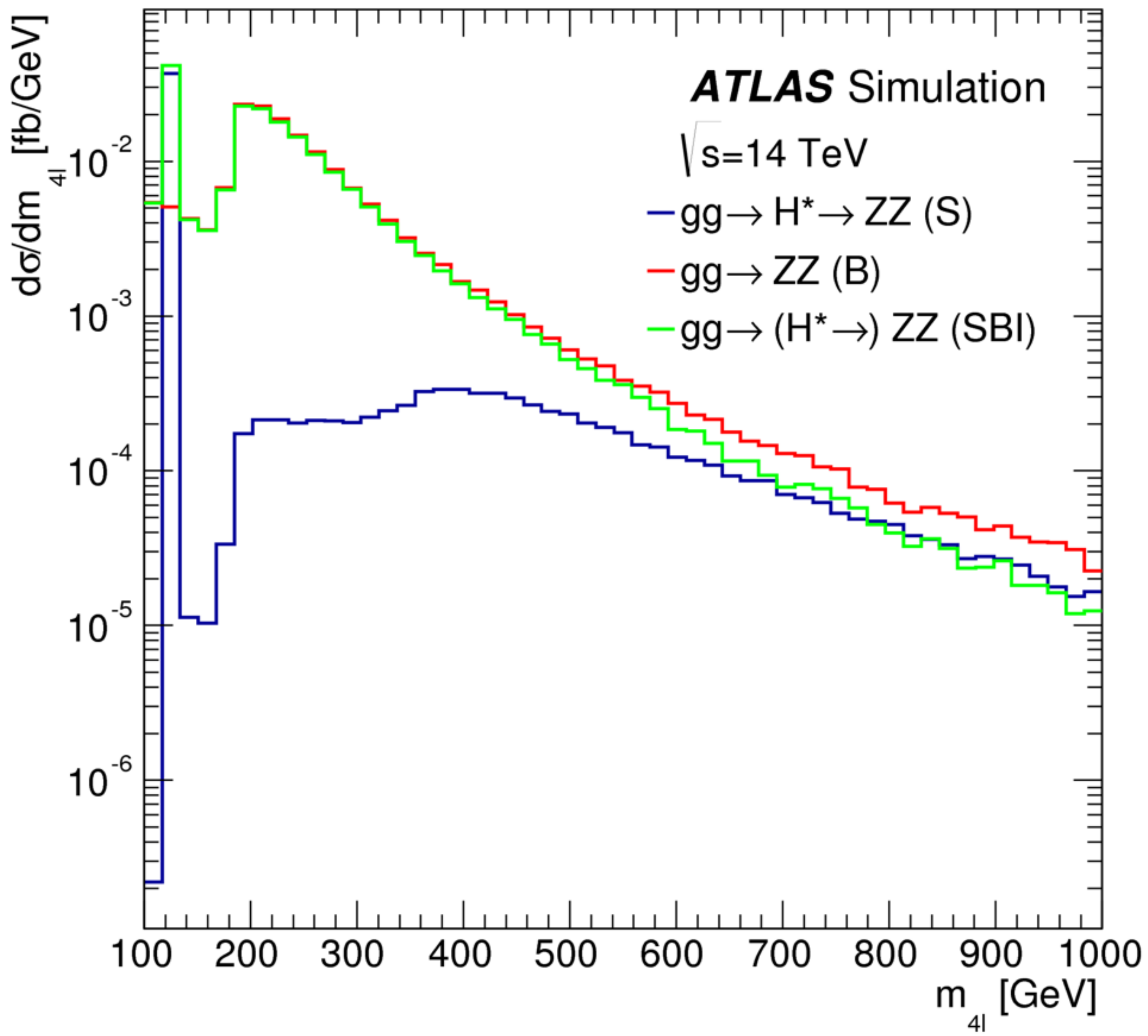


Summary of precision for **3000 fb^{-1}**:
- ~ **4 - 5%** for main channels
- ~ **10 - 20%** on rare modes

Higgs Boson Width

ATL-PHYS-PUB-2015-024

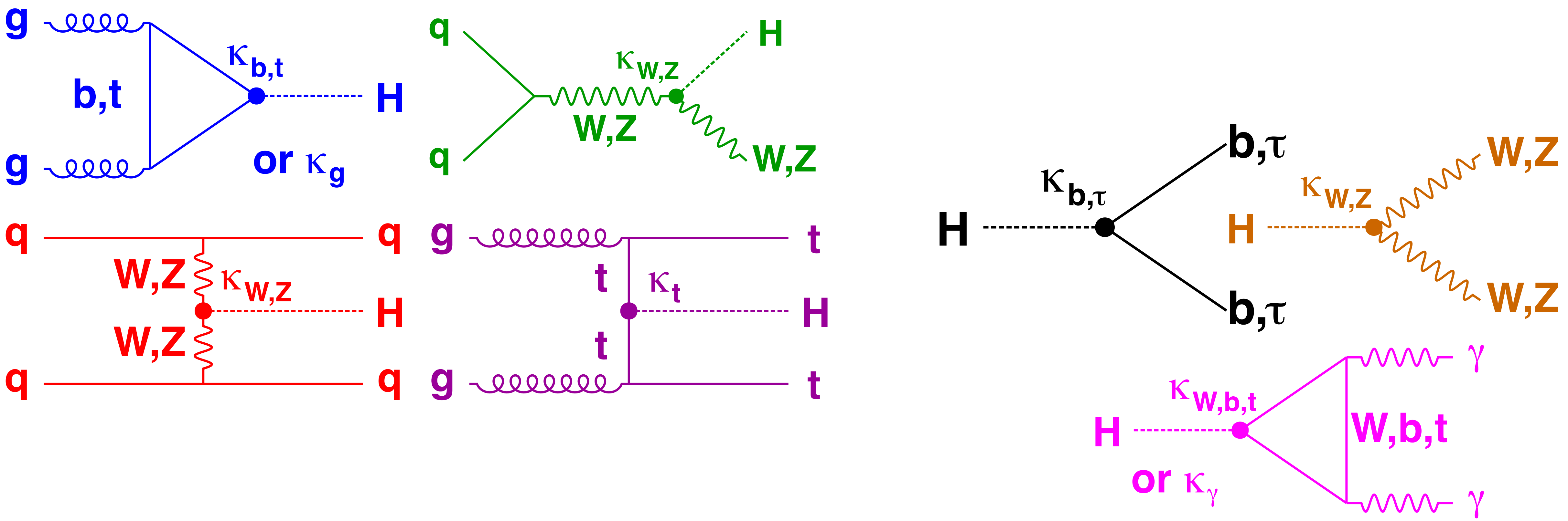
- $H \rightarrow ZZ \rightarrow 4\ell$: Use the interference between off-shell and on-shell production to measure $\Gamma(H)$



- For $\mathbf{3000\ fb^{-1}}$; using uncertainty between background signal of $\sigma(R_{H^*}{}^{B}) = 10\%$;combining on-shell and off-shell measurement; assuming off-shell measurement dominates, for $\Gamma = \Gamma_{SM}$ gives:
$\Gamma_H = 4.2^{+1.5}_{-2.1}$ MeV (stat+sys)

Interpretation as Coupling Scale Factors

- Experiments measure cross section times branching ratio
- Interpretation with coupling scale factors, κ, is model dependent



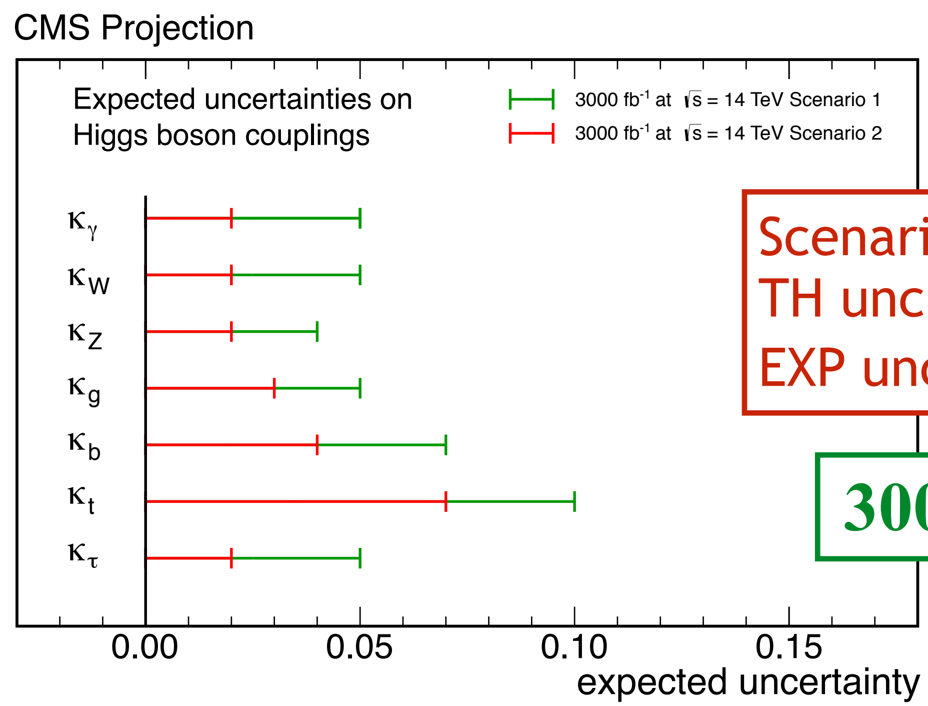
- *e.g.*

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

- Assume Γ_{H} is sum of sum of visible widths - no additional invisible modes

Higgs Boson Couplings Fit

arXiv:1307.7135
ATL-PHYS-PUB-2014-016



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TH unc. scaled by **1/2**
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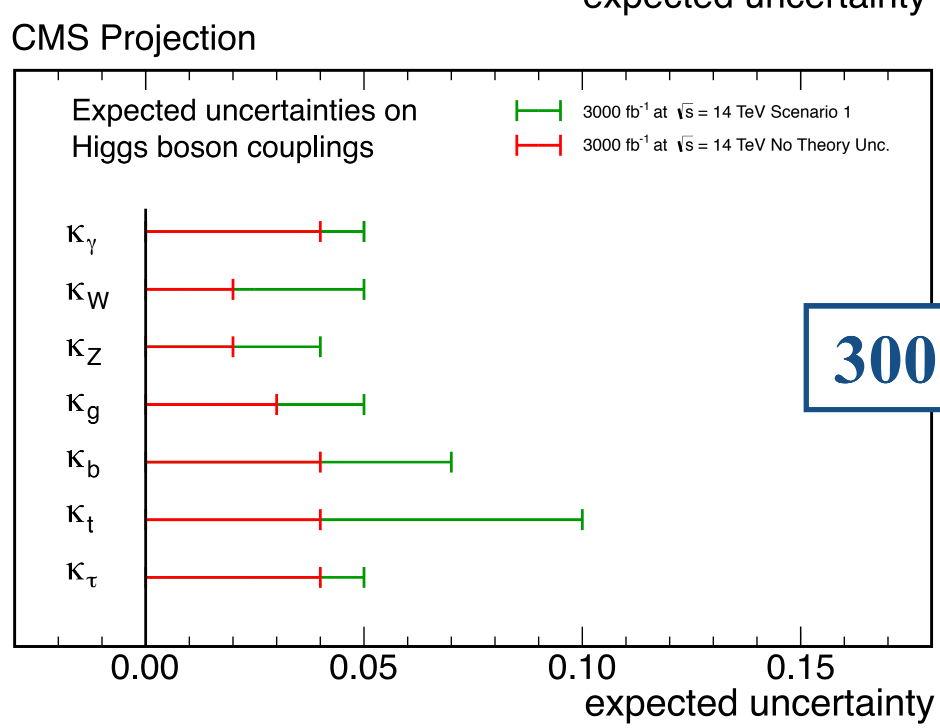
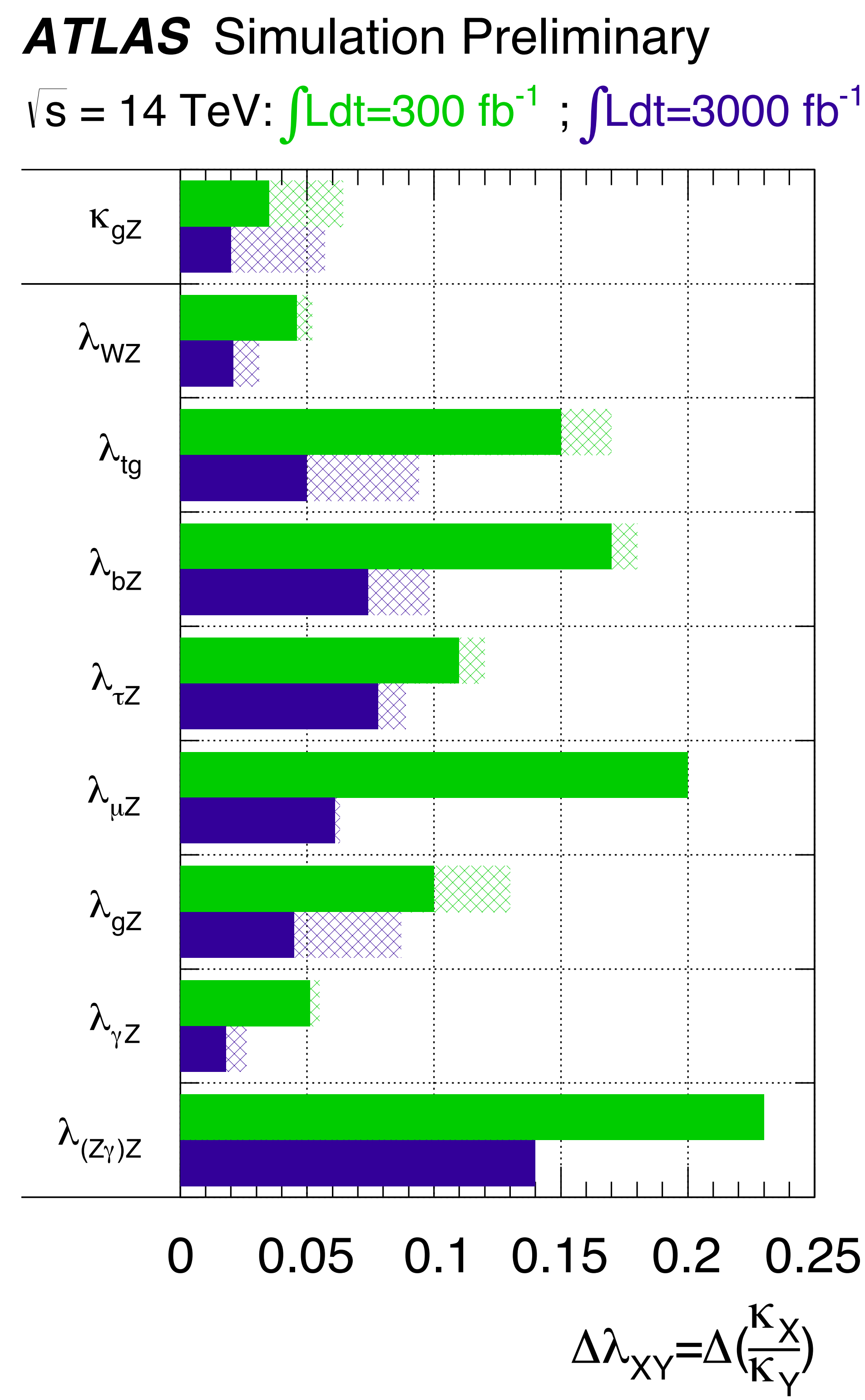
$300\ \mathrm{fb}^{-1}$



$3000\ \mathrm{fb}^{-1}$



Mass scaled couplings

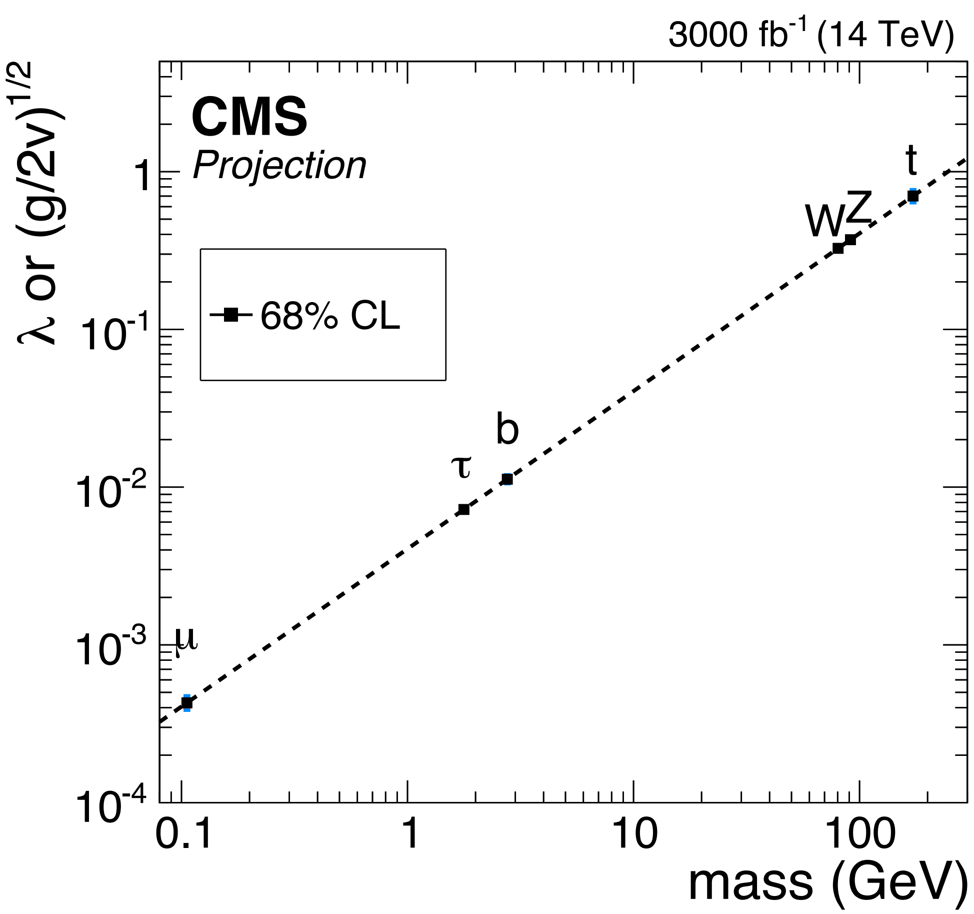
CERN-LHCC-2015-010
ATL-PHYS-PUB-2014-016

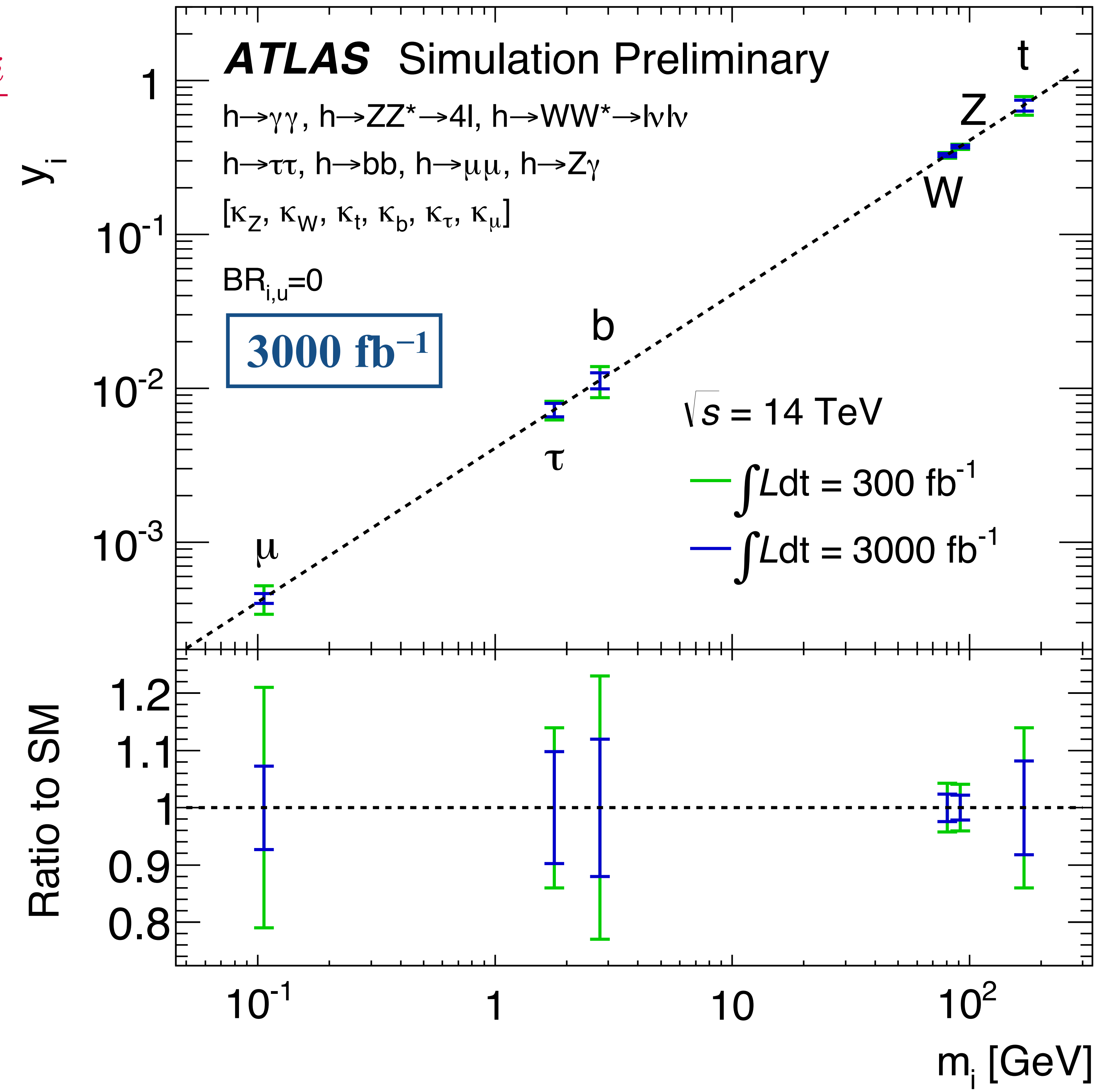
Vector boson coupling

$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

Fermion couplings

$$y_{f,i} = \kappa_{f,i}\frac{g_{f,i}}{\sqrt{2}} = \kappa_{f,i}\frac{m_{f,i}}{v}$$

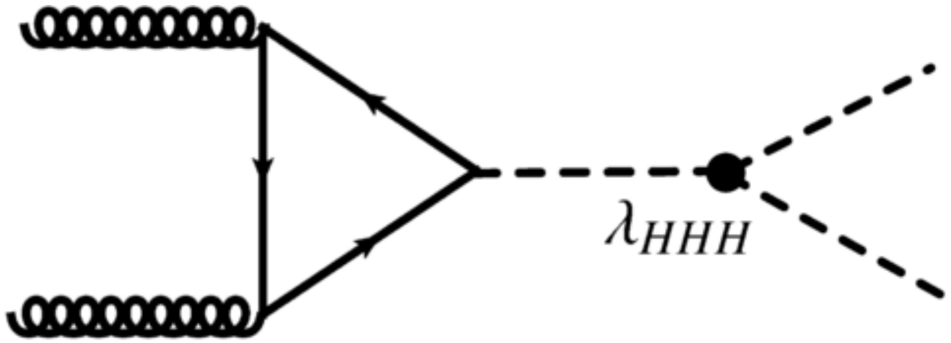


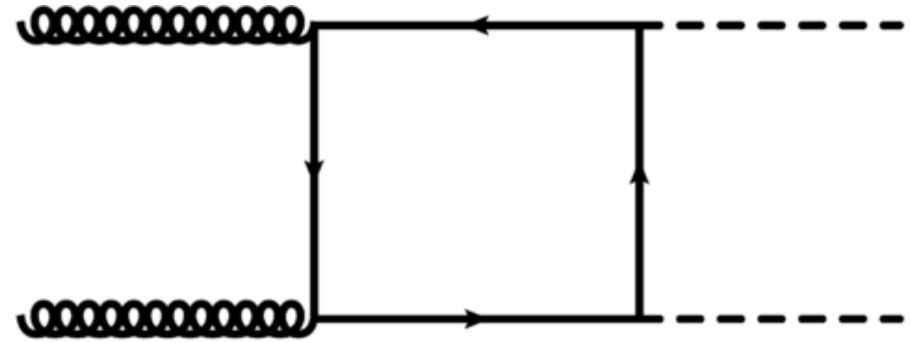


HH

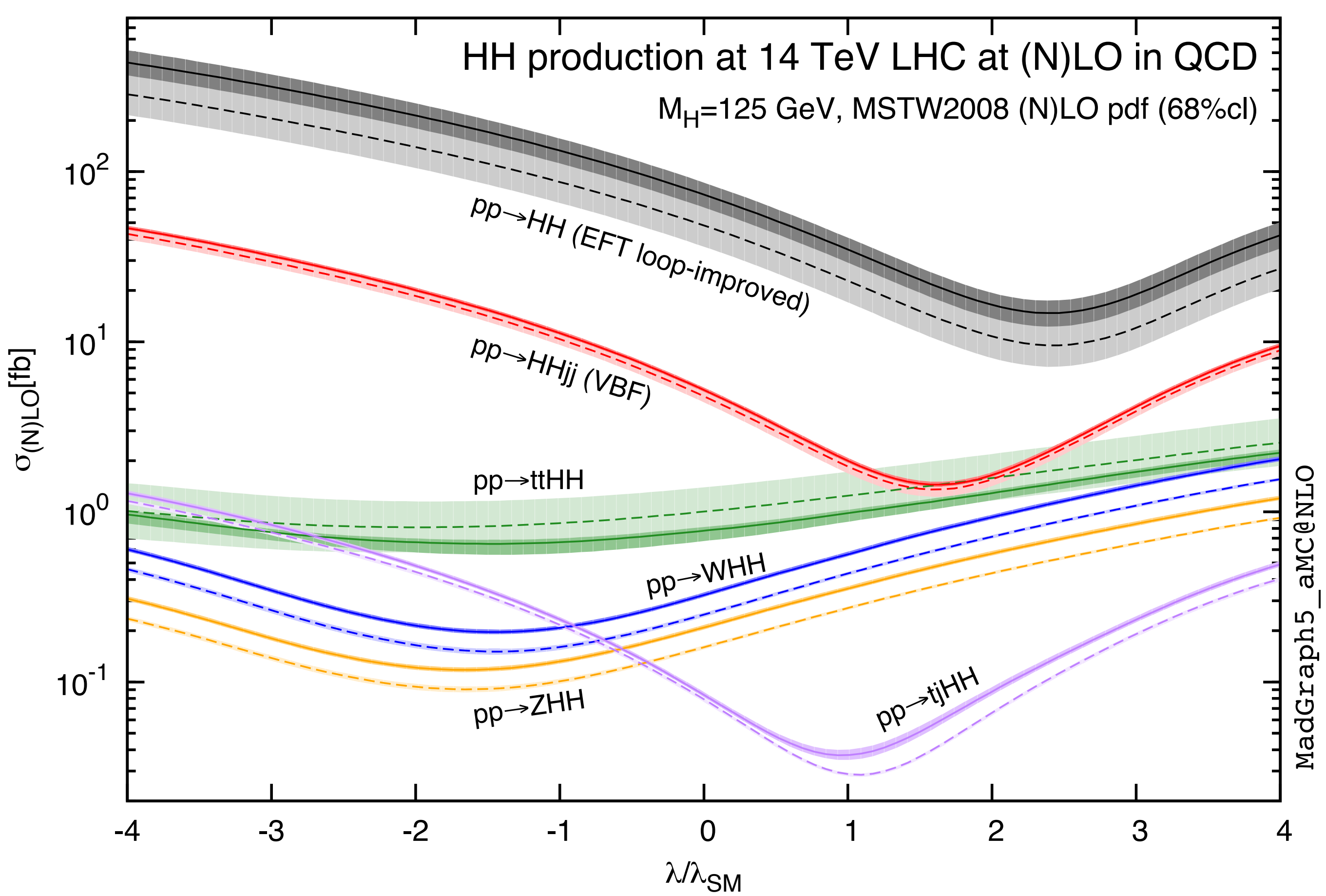
Higgs Boson Pair Production

- Higgs boson pair production includes destructive interference between two types of processes:





arXiv:1401.7340v2



NNLO σ^{SM}=40.8 fb

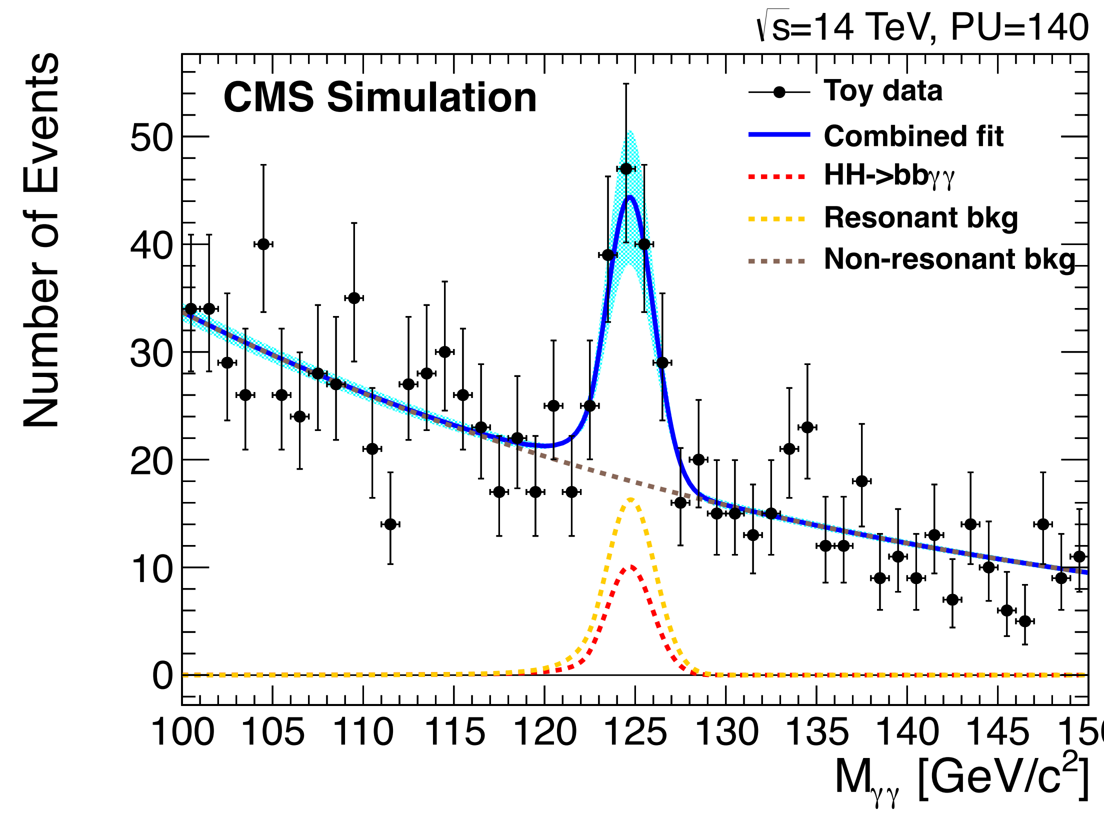
Number of events in 3000 fb^{-1}	
$bbWW$	30000
$bb\tau\tau$	9000
$WWWW$	6000
$\gamma\gamma bb$	320
$\gamma\gamma\gamma\gamma$	1

e.g. $HH \rightarrow bb\gamma\gamma$

CERN-LHCC-2015-010

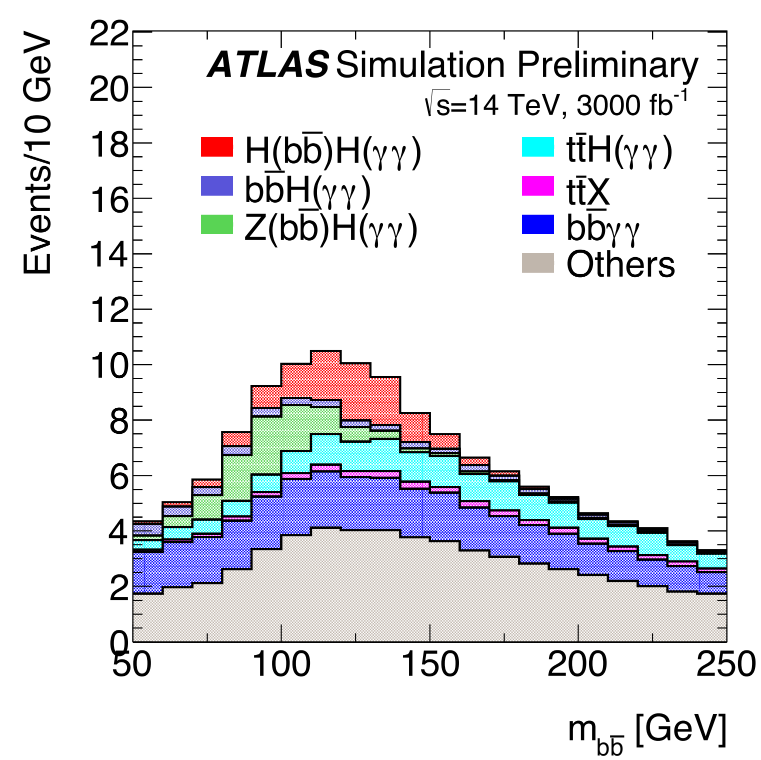
ATL-PHYS-PUB-2014-019

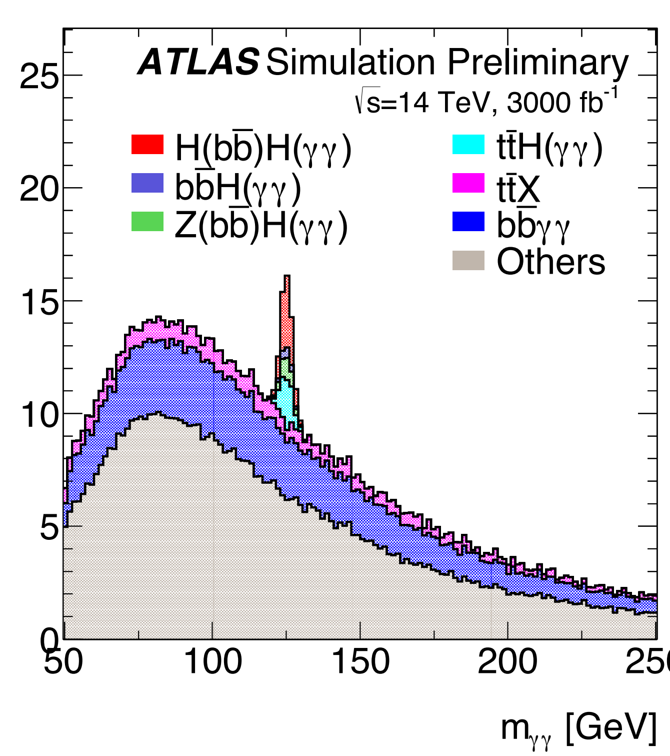
- bb mass peak is broad
- $\gamma\gamma$ shows narrow resonance



- *CMS*: 2d fit of $\mathbf{m}(bb)$ and $\mathbf{m}(\gamma\gamma)$ distributions (control background from data)

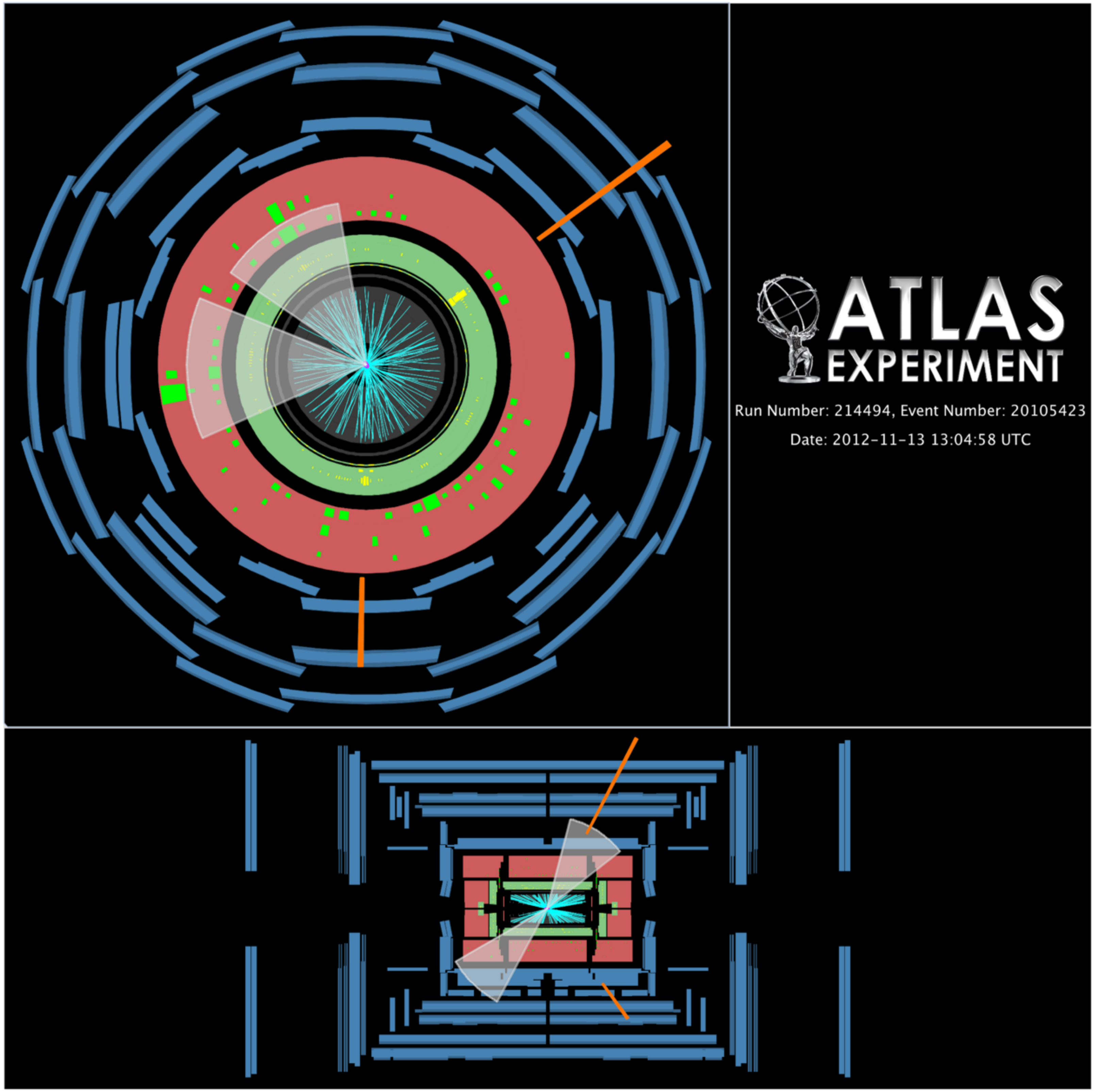
- *ATLAS* cut based analysis





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

arXiv:1406.5053

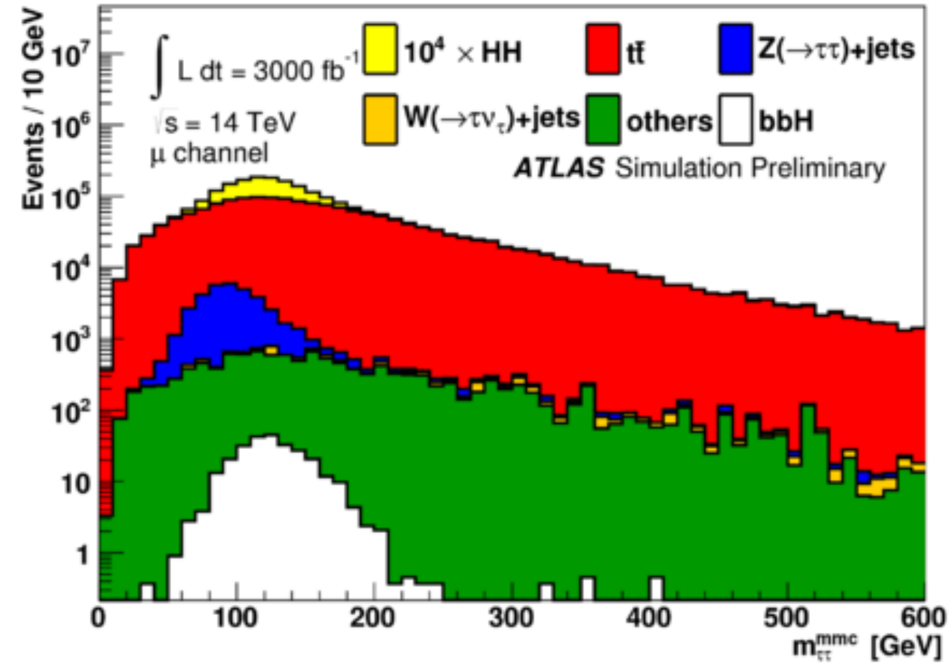


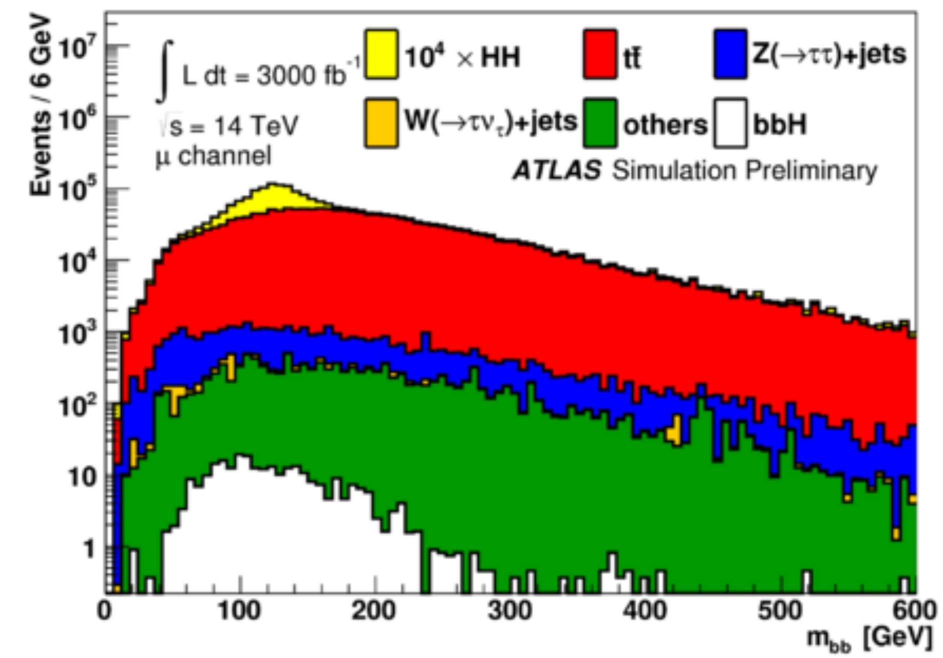
HH→bbττ

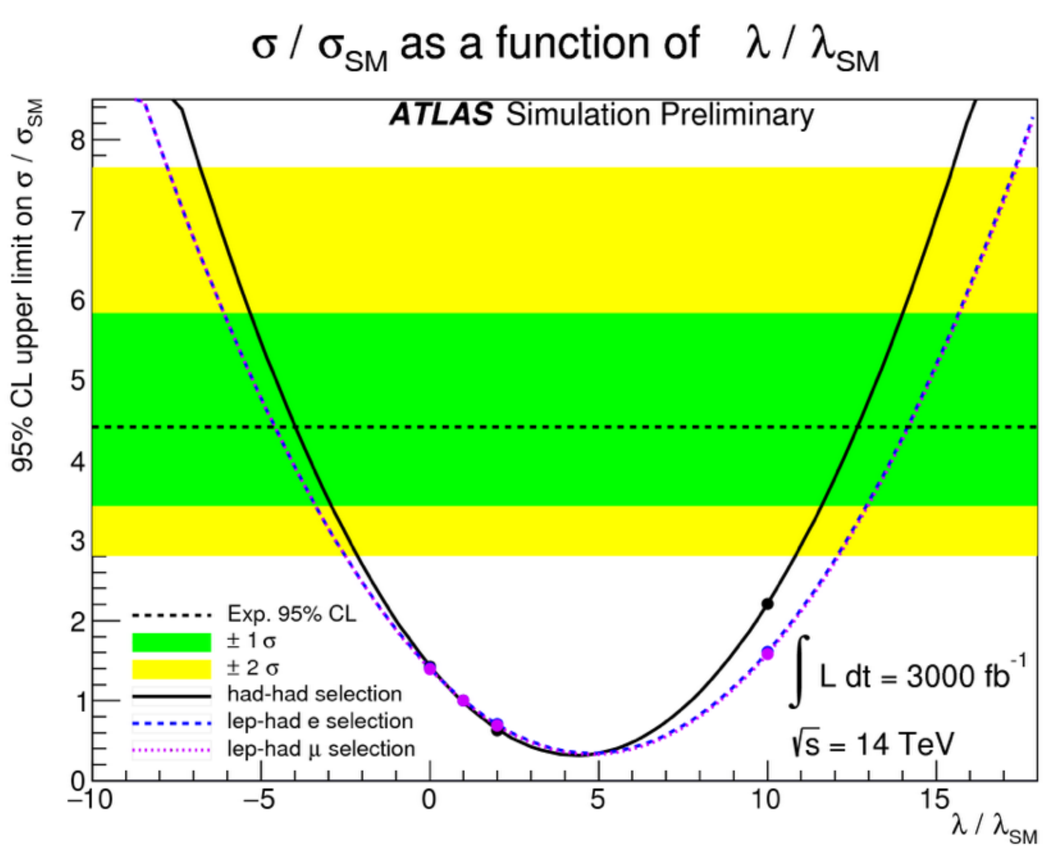
CERN-LHCC-2015-010

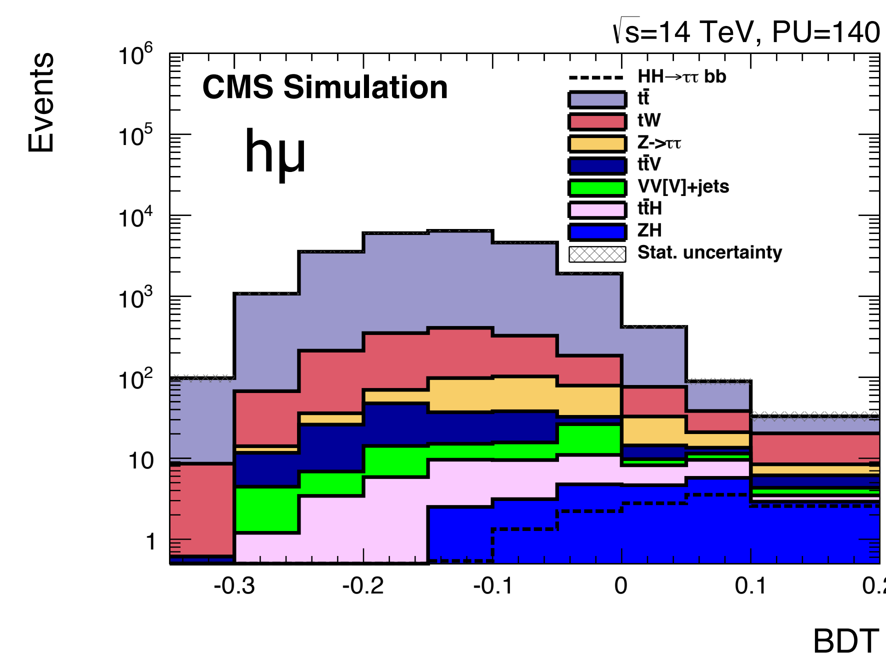
ATL-PHYS-PUB-2015-046

- Major background from $t\bar{t}$, with $t\to\tau\nu b$
- Results for $\mathbf{3000\ fb^{-1}}$ and SM ($\lambda=1$):
  - **ATLAS**: All $\tau\tau$ final states considered
    - ‣ 13 *HH→bbττ* events after full event selection *cf* 803 background events
  - **CMS**: τ(had) τ(had) & $\tau(\mu)$ τ(had) ; kinematic variables to distinguish signal from background
    - ‣ Just **0.9 σ** sensitivity







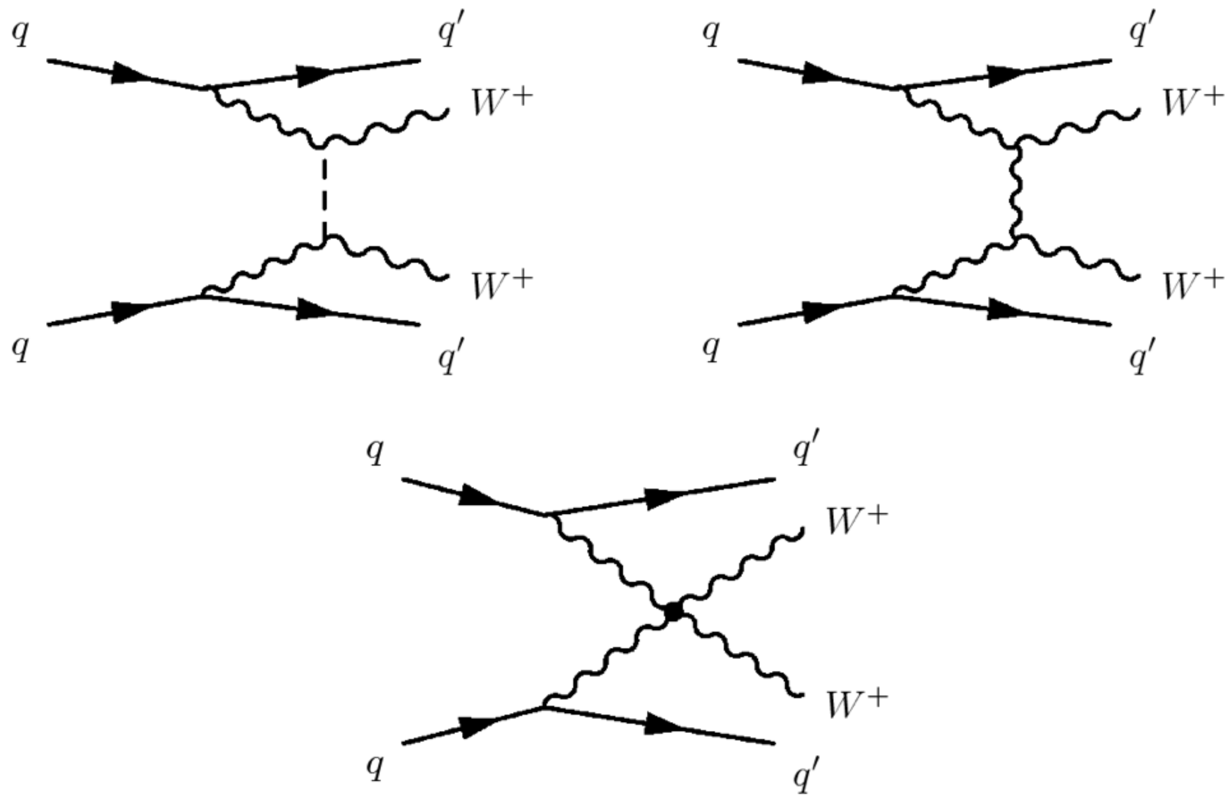


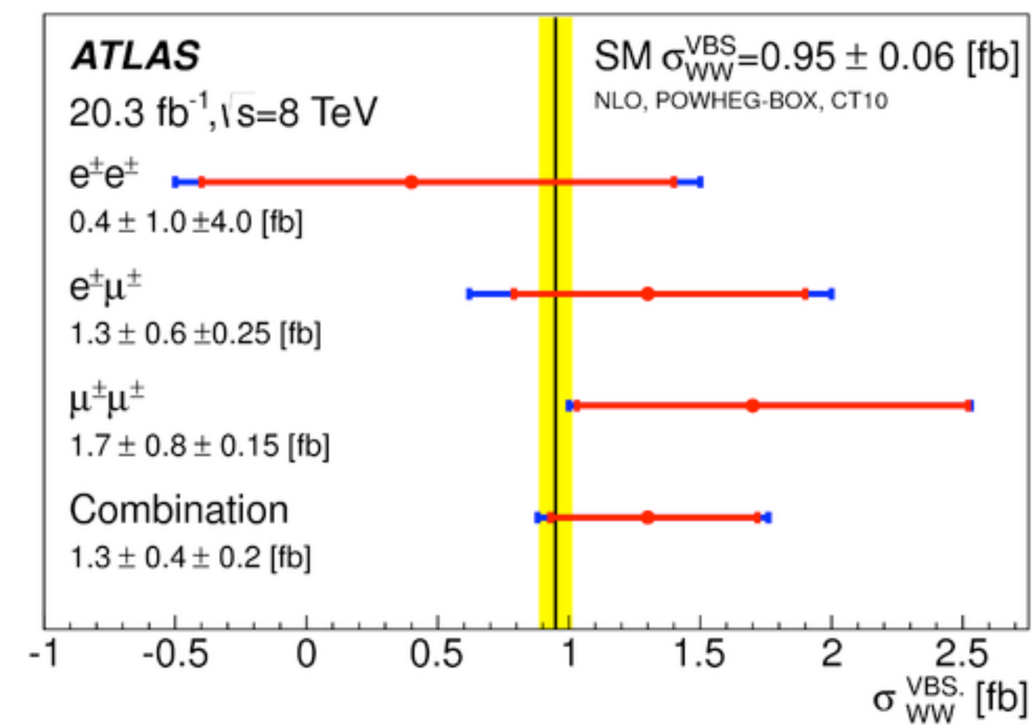
Vector Boson Scattering

Vector Boson Scattering

arXiv:1405.6241
arXiv:1410.6315

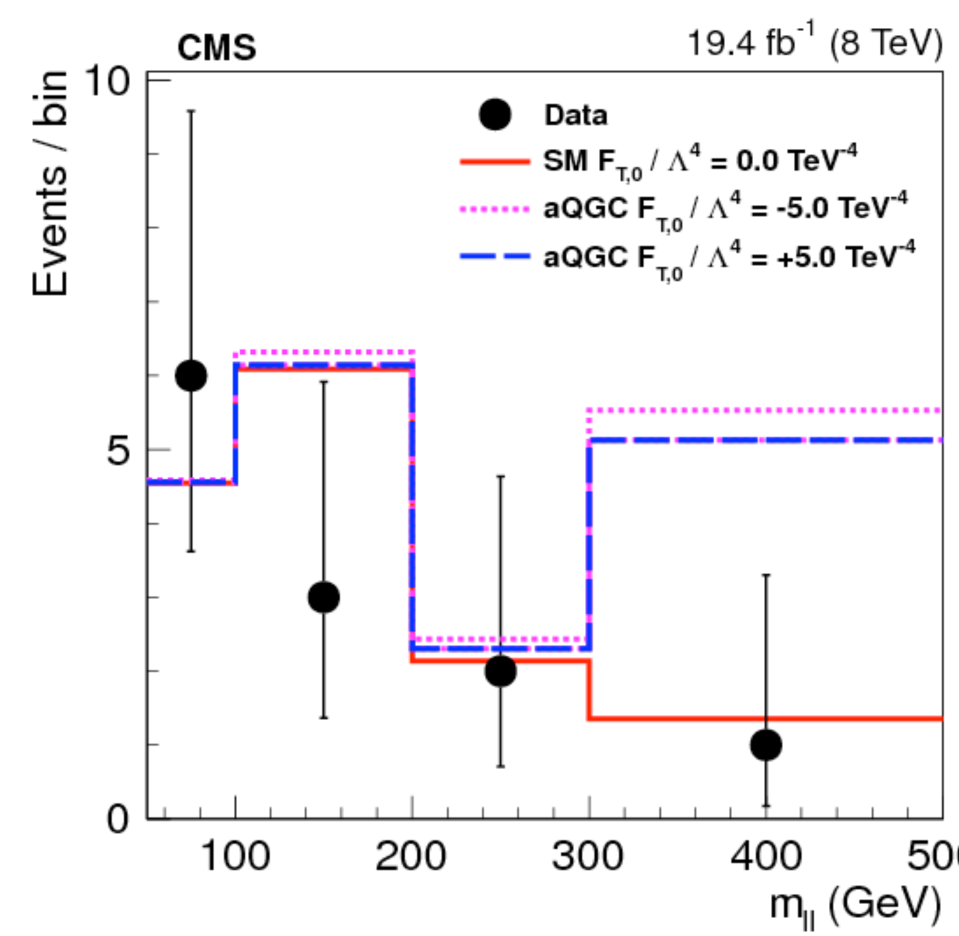
- Explore electroweak symmetry breaking through VBS: e.g. Look for W^+W^+, W^-W^- and WZ final states





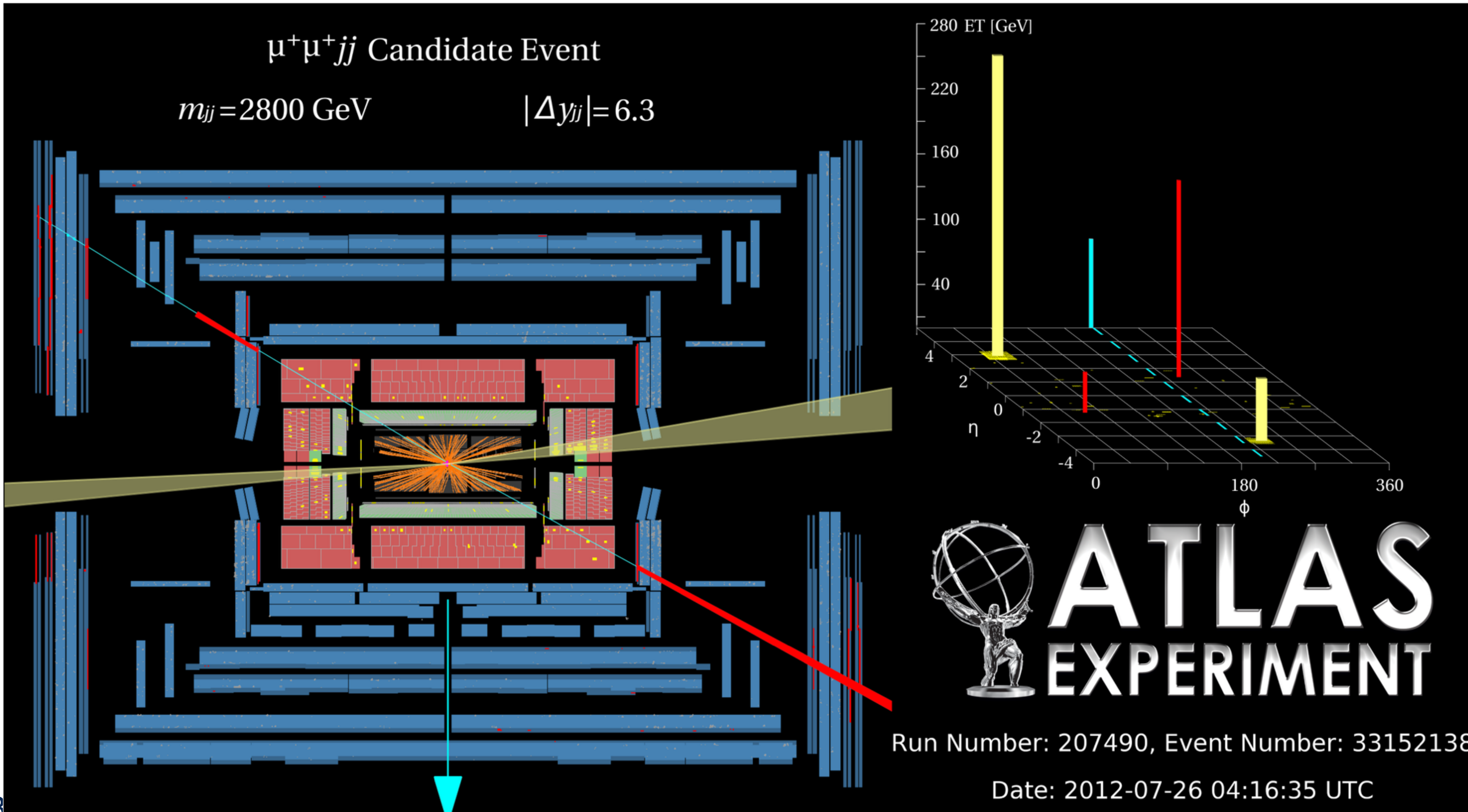
- In Run 1, **ATLAS** (**CMS**) observed $\mathbf{4.5\sigma}$ ($\mathbf{2.0\sigma}$) evidence for $W^{\pm}W^{\pm}jj$ production

- **CMS**: Limits placed on dimension-8 operators, f_X/Λ^4 (à la Eboli, Gonzalez-Garcia, Mizukoshi arXiv:hep-ph/0606118)



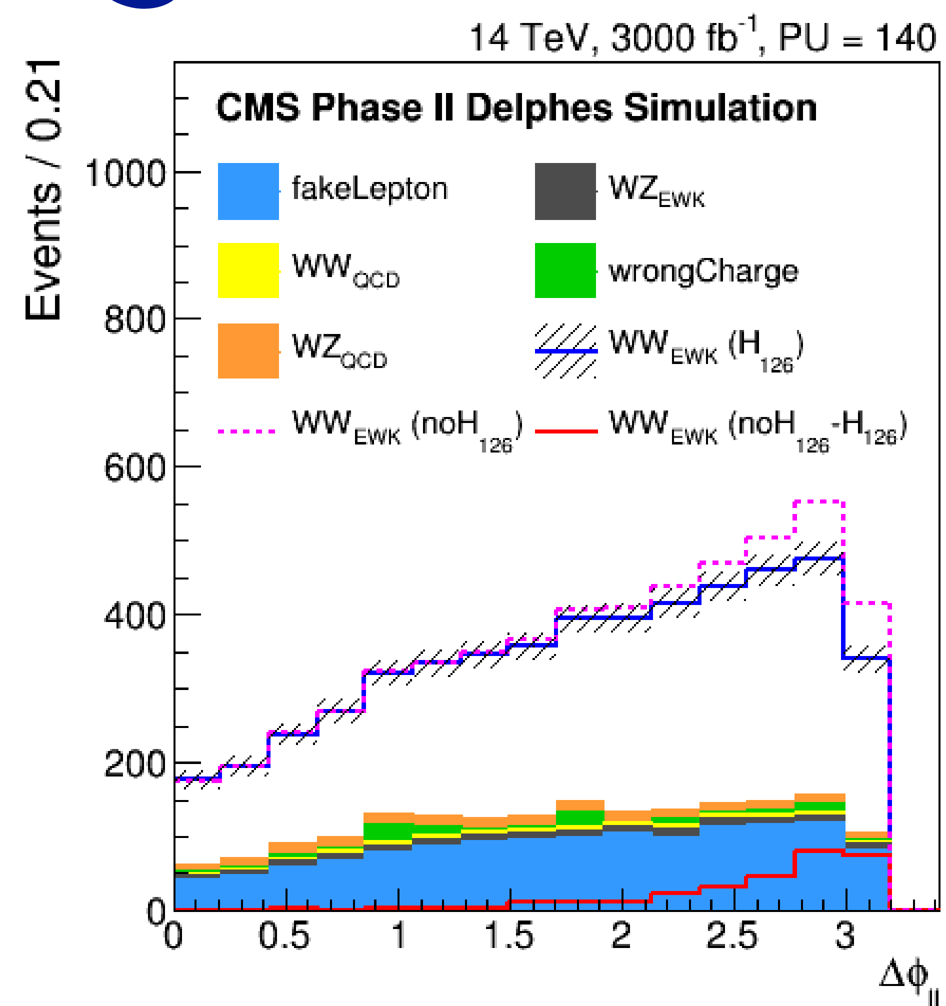
Run 1 Evidence for Weak Boson Scattering

arXiv:1405.6241



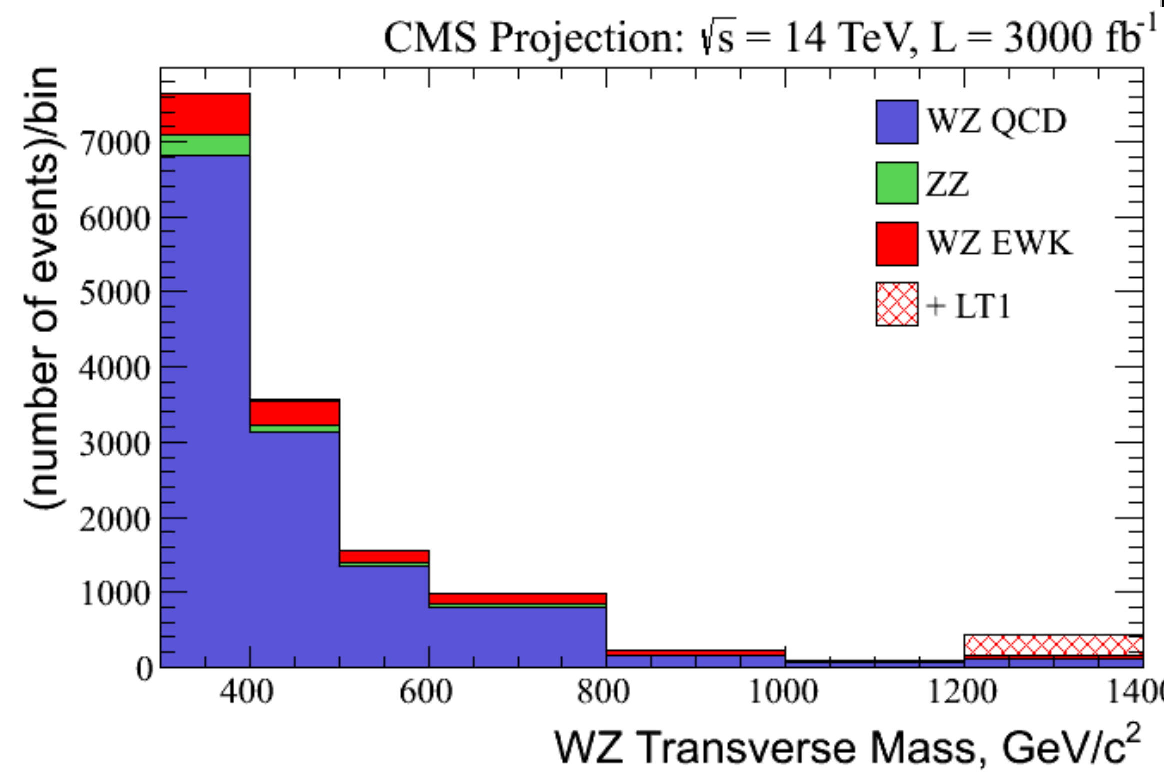
CMS-PAS-FTR-13-006

Weak Boson Scattering Prospects



- ***WW***: Very clear signature expected with sensitivity to 125 GeV Higgs boson propagator

- ***WZ:*** More challenging due to large QCD contribution.

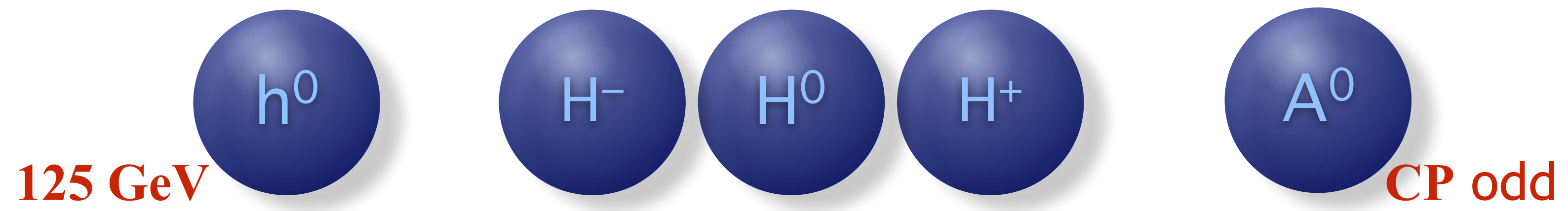


Beyond the Standard Model

ATL-PHYS-PUB-2013-016
CMS-PAS-FTR-13-024

Additional Heavy Higgs bosons

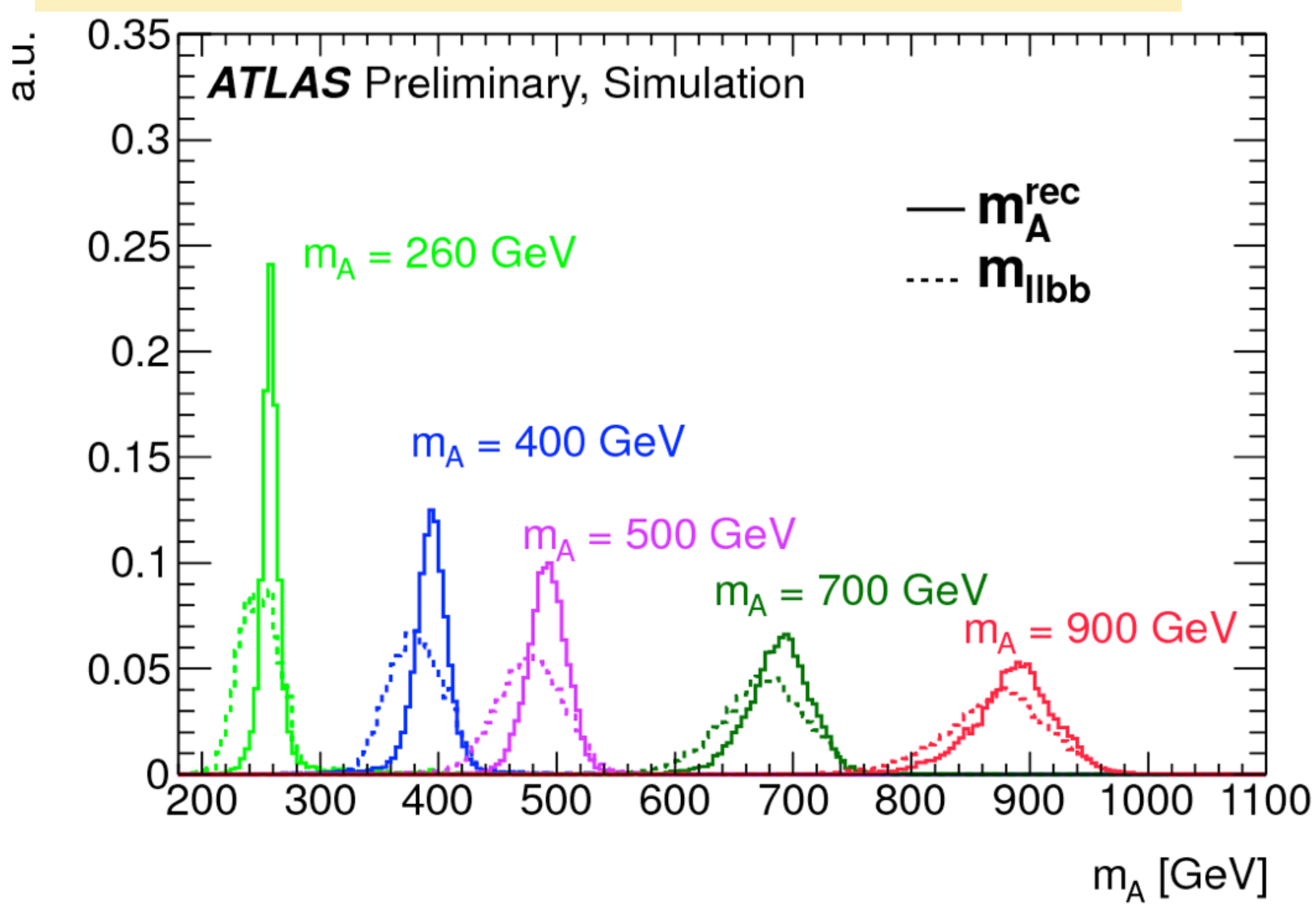
- Additional Higgs doublets predicted in many models, including Supersymmetry.
- e.g. A two-Higgs doublet (2HDM) model includes four new Higgs boson:

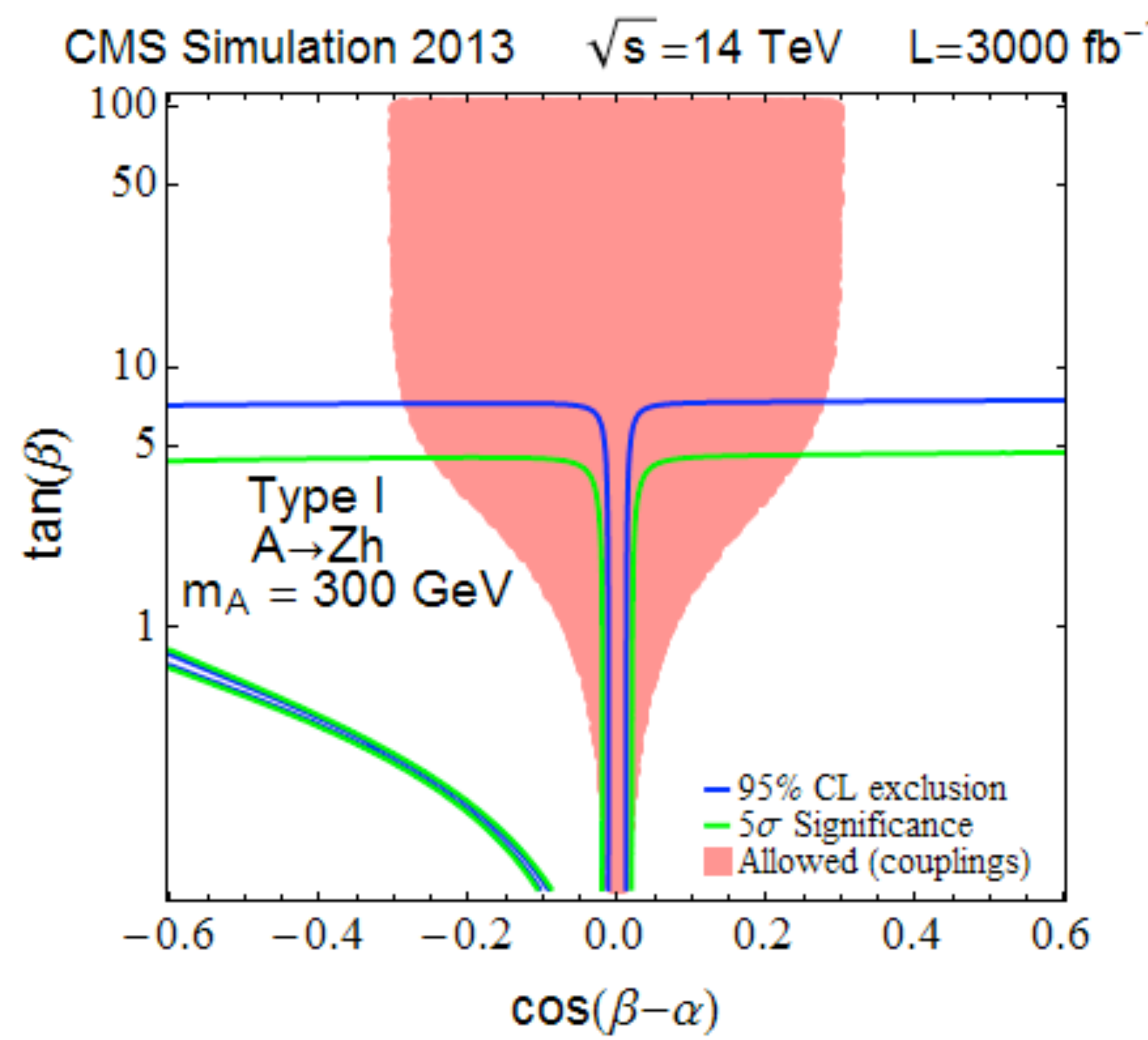


$\cos(\beta-\alpha)\to 0$ if h^0 is SM-like

  - **α** is a mixing angle between the Higgs doublets
  - **$\tan\beta$** is the ratio between the vev the Higgs doublets

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

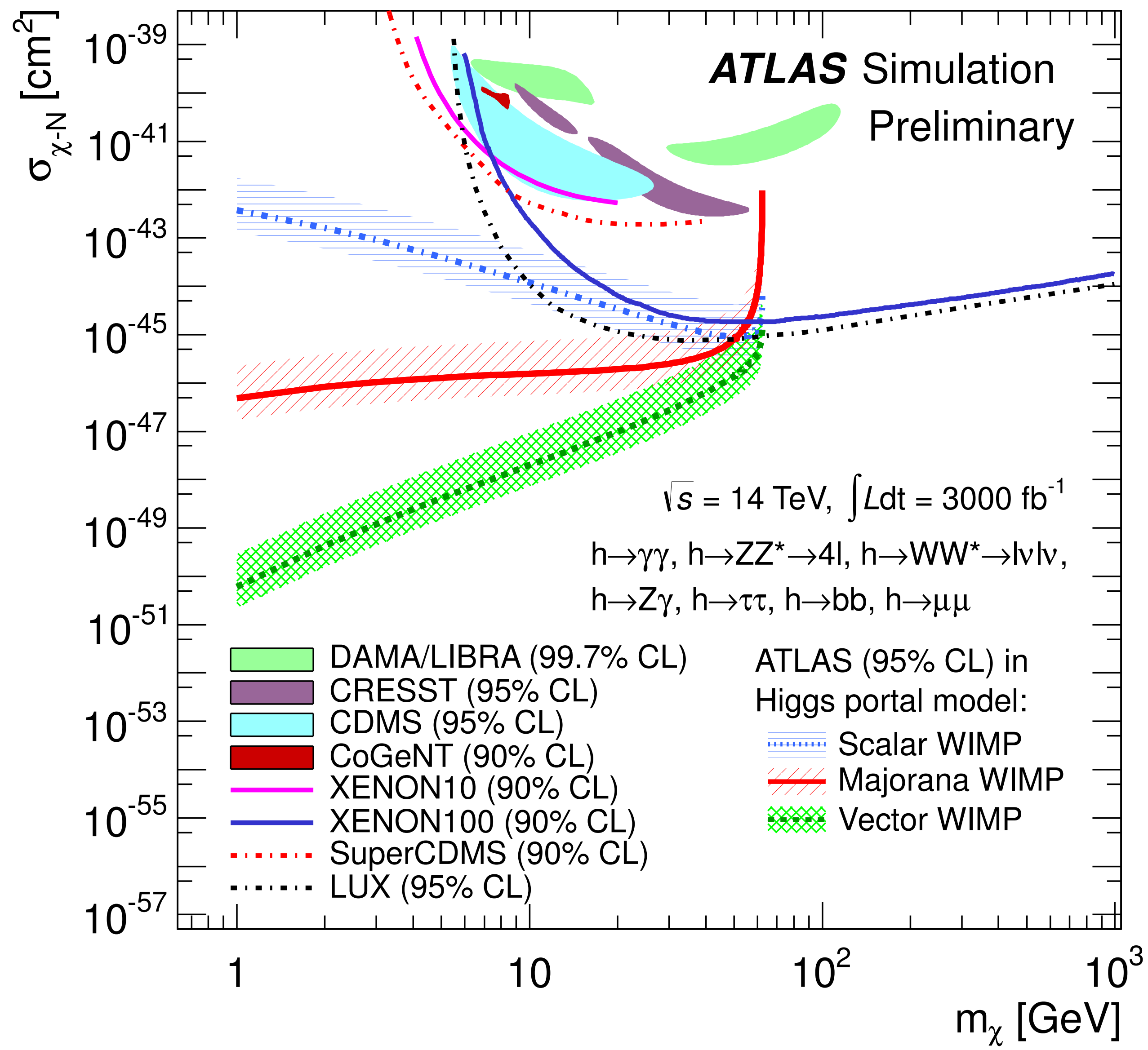




Higgs Portal to Dark Matter

ATL-PHYS-PUB-2014-017

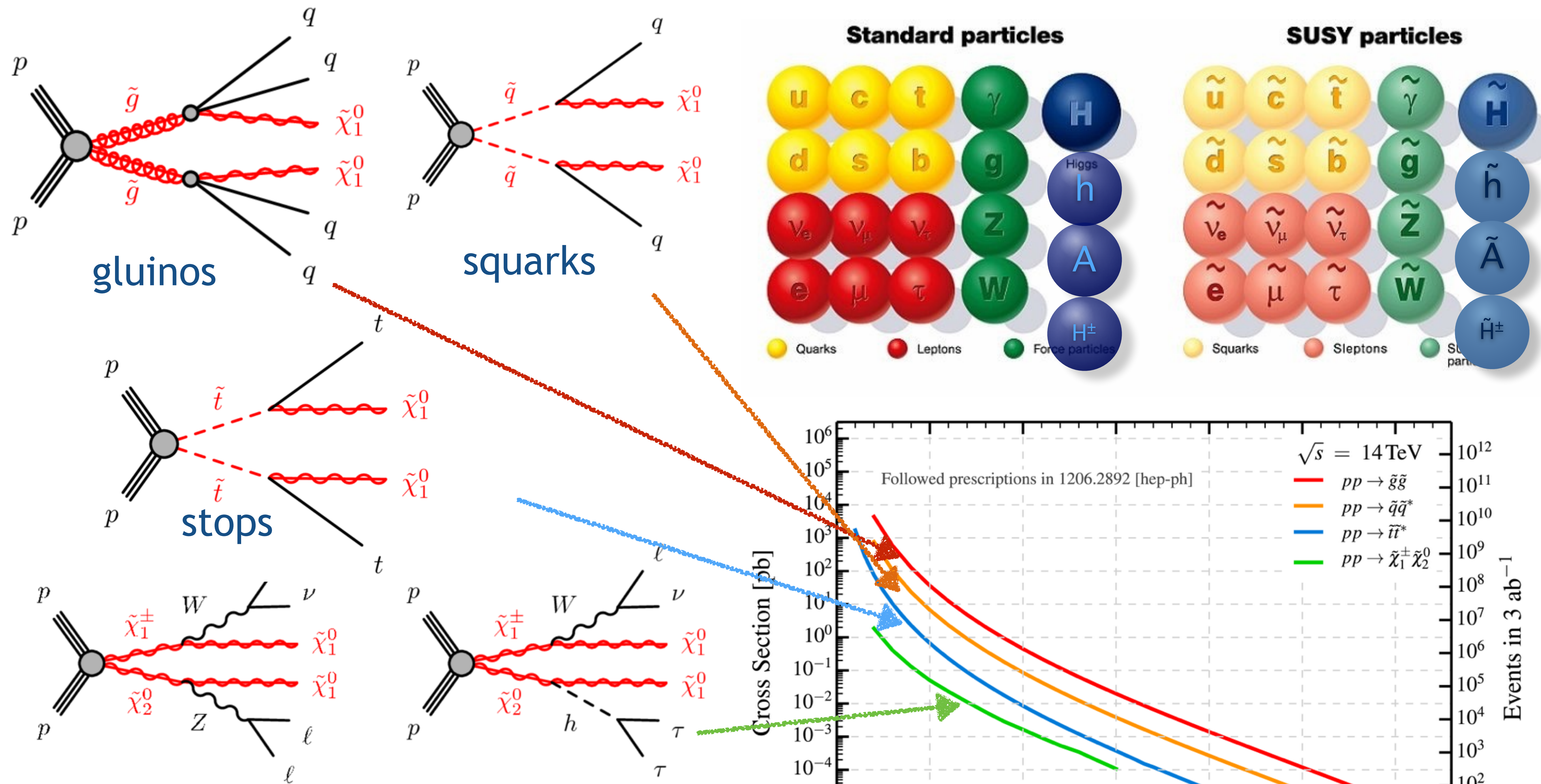
- In the SM Higgs boson couples to all massive particles
  - very likely Higgs boson will also couple to any DM WIMPs, χ
  - look for a branching ratio for Higgs boson to invisible particles
  - Coupling of χ to $\mathbf{H}$ take as free parameter; $\mathbf{BR(inv)}$ sets a limit on the interactions of χ



- In $\mathbf{3000\ fb^{-1}}$
  - ATLAS: $\mathbf{BR(inv) < 0.13}$ ($\mathbf{0.09}$ w/out theory uncertainties)
  - CMS: $\mathbf{BR(inv) < 0.11}$ ($\mathbf{0.07}$ in alt. theory uncertainty)

LHC complements direct DM search experiments in the lower mass range

SUSY production at the LHC



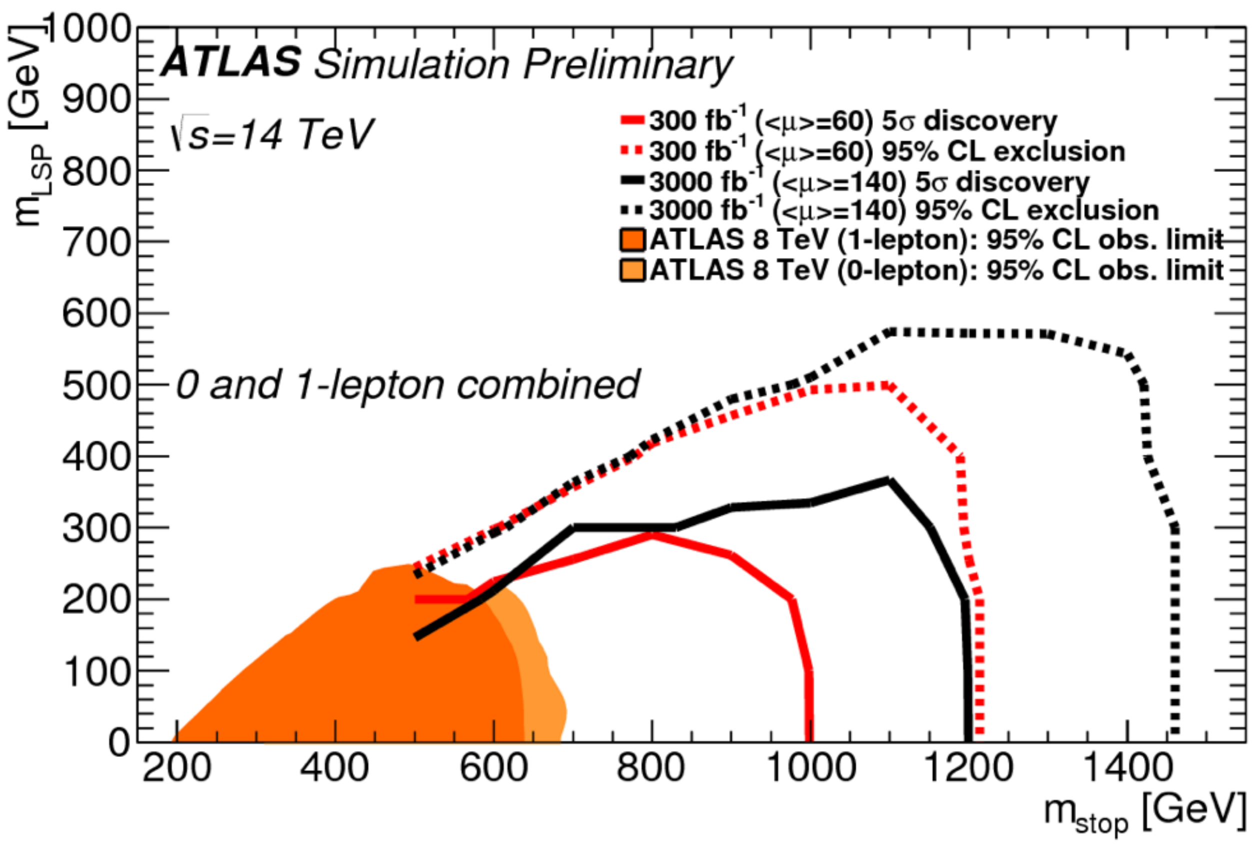
neutralinos ($\tilde{\chi}^0$) & charginos ($\tilde{\chi}^{\pm}$):
superpositions of Higgsinos, Wino, Bino

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

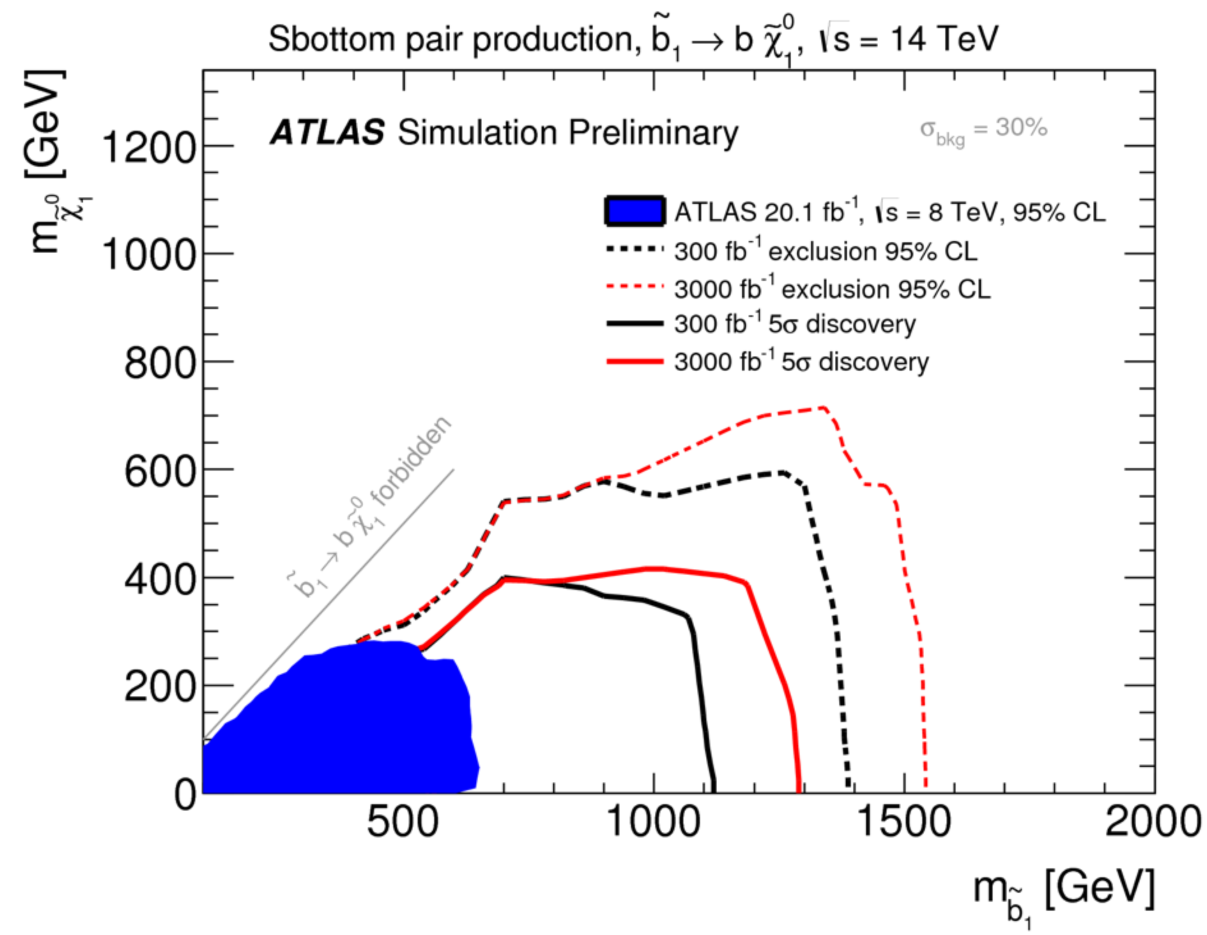
Stop and Sbottom Searches

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

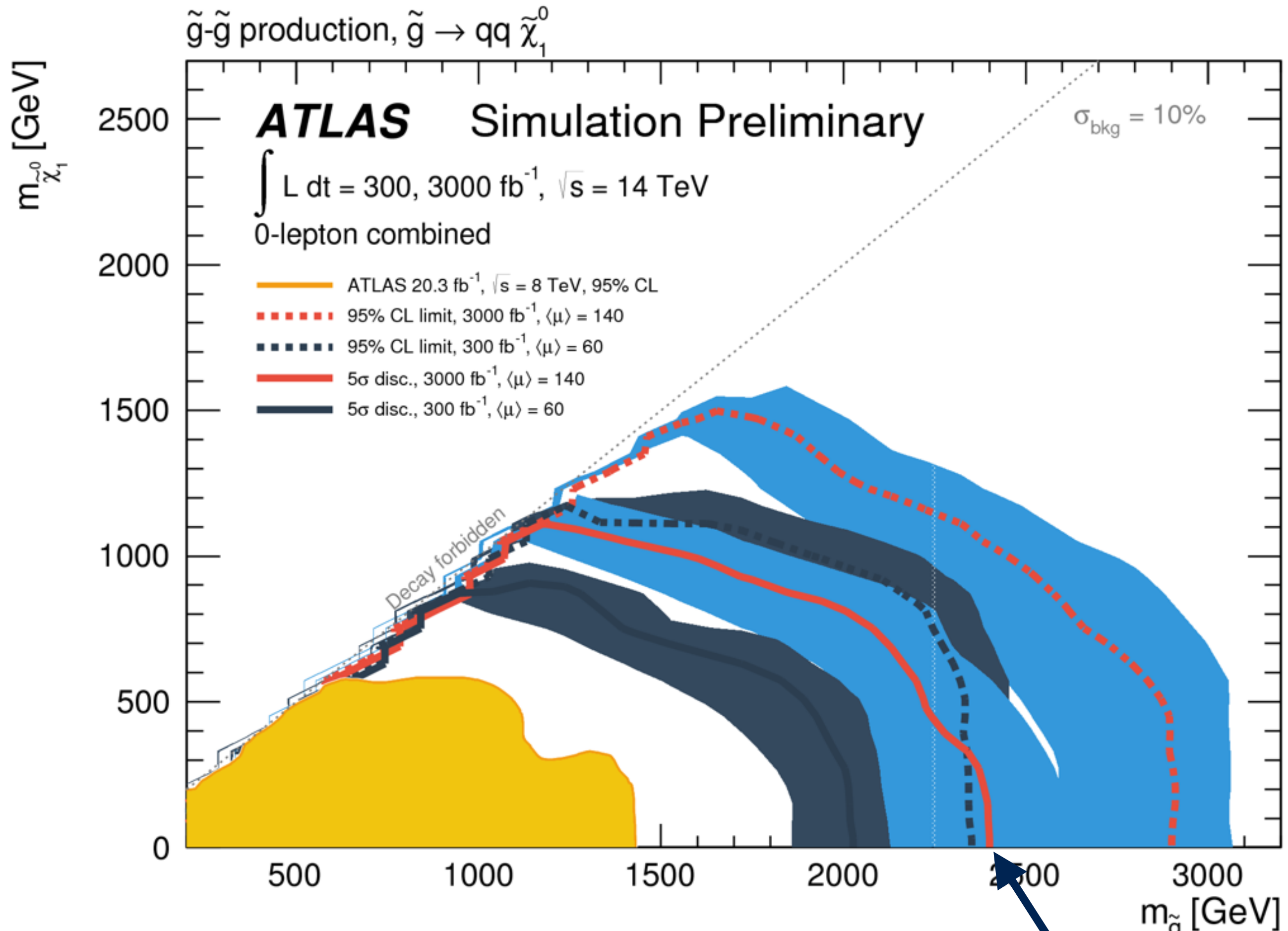


5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
stop mass from direct production [ATLAS]	Up to 1.0 TeV	Up to 1.2 TeV
gluino mass with decay to stop [CMS]	Up to 1.9 TeV	Up to 2.2 TeV
sbottom mass from direct production [ATLAS]	Up to 1.1 TeV	Up to 1.3 TeV

Strong and Weak SUSY Production Limits

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

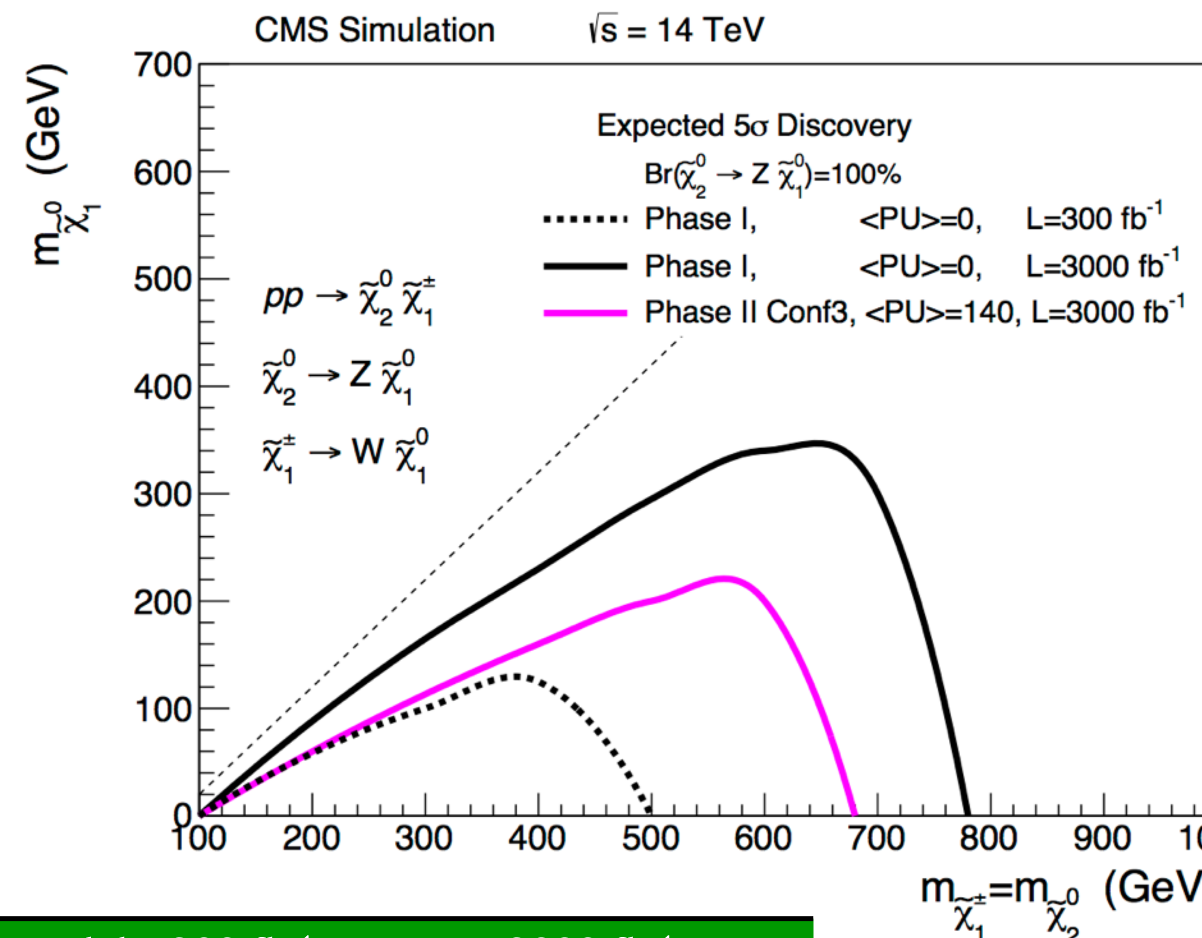
Strong SUSY:
Gluino pair production



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

Chargino mass 5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
WZ (3l analysis) [ATLAS]	Up to 560 GeV	Up to 820 GeV
WZ (3l analysis) [CMS]	Up to 600 GeV	Up to 900 GeV
WH (3l analysis) [ATLAS]	(<5σ reach)	Up to 650 GeV
WH (bb analysis) [ATLAS] (new in 2015)	(<5σ reach)	Up to 800 GeV
WH (bb analysis) [CMS]	350-460 GeV	Up to 950 GeV

Summary of SUSY Simplified Models Reach

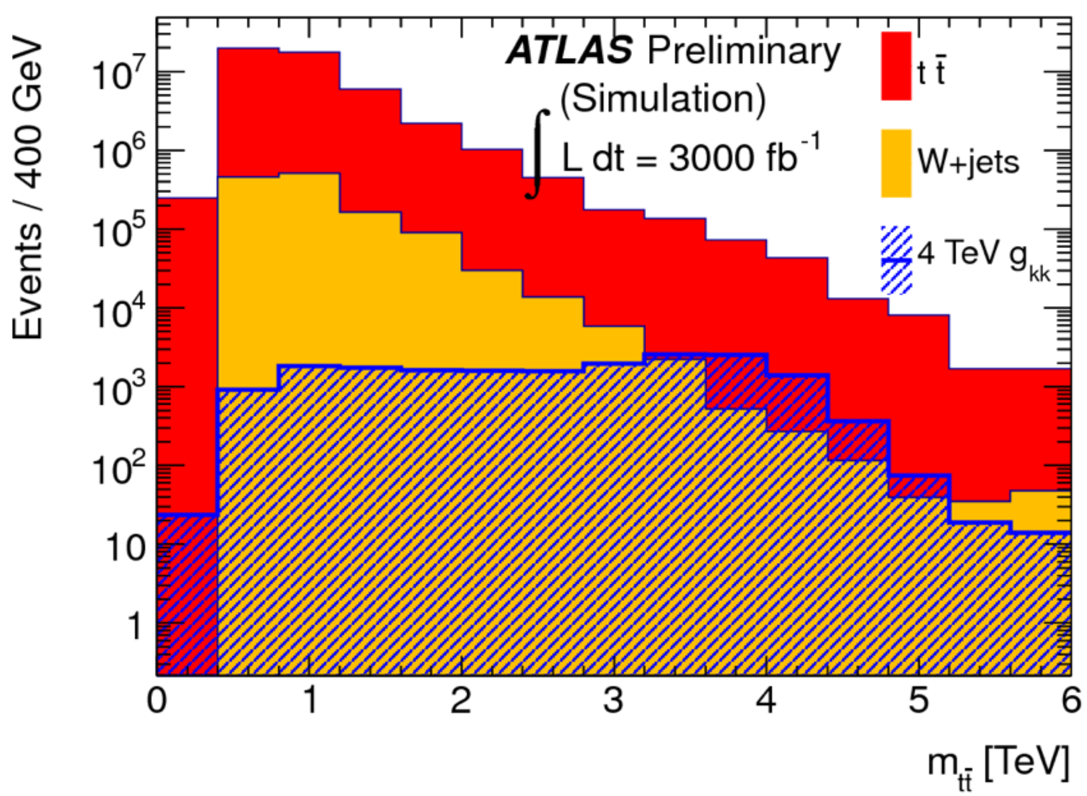
ATLAS projection	gluino mass	squark mass	stop mass	sbottom mass	χ_1^+ mass WZ mode	χ_1^+ mass WH mode
300 fb^{-1}	2.0 TeV	2.6 TeV	1.0 TeV	1.1 TeV	560 GeV	None
3000 fb^{-1}	2.4 TeV	3.1 TeV	1.2 TeV	1.3 TeV	820 GeV	650 GeV

Resonance Searches

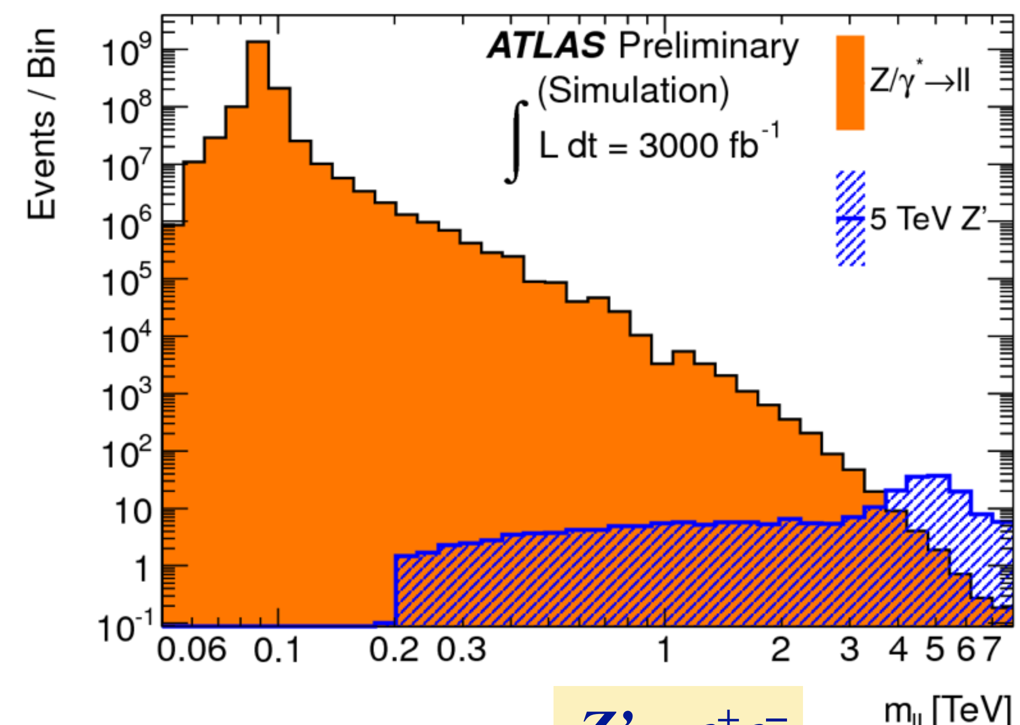
arXiv:1307.7135
ATL-PHYS-PUB-2014-007
ATL-PHYS-PUB-2013-003

- 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.

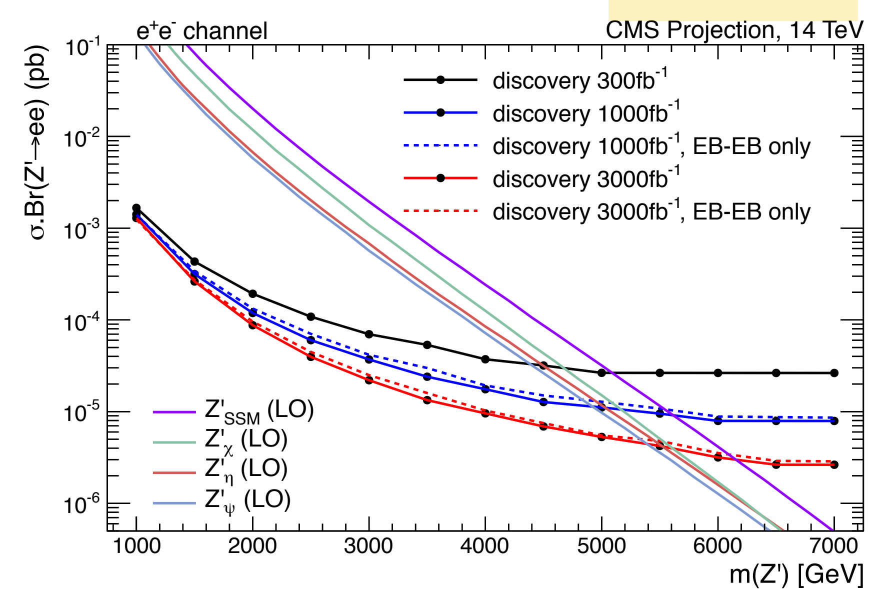
4 TeV Kaluza-Klein gluon, $g_{KK} \rightarrow t\bar{t}$



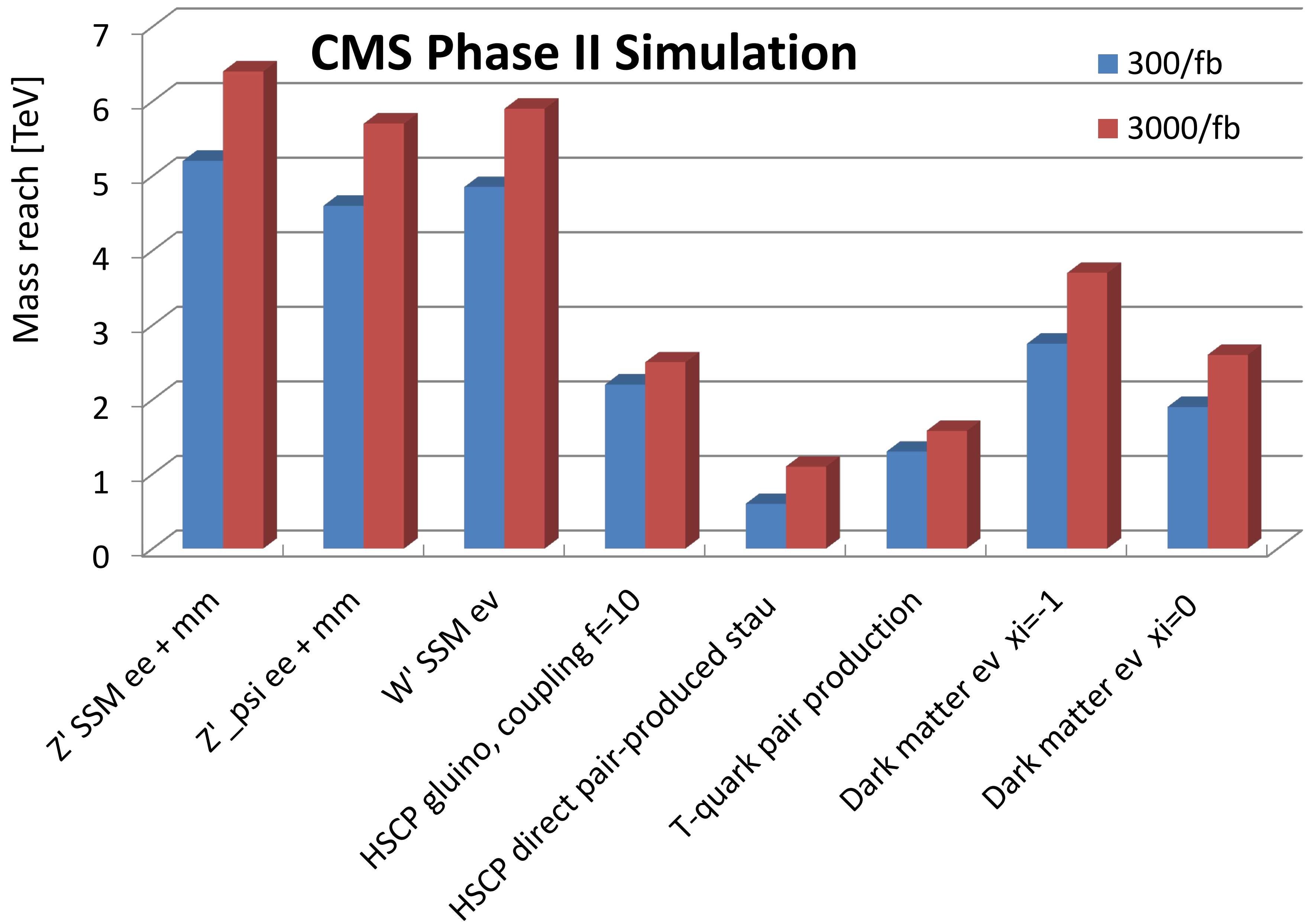
5 TeV $Z' \rightarrow \mu^+\mu^-$



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



Mass Reach for Exotic Signatures



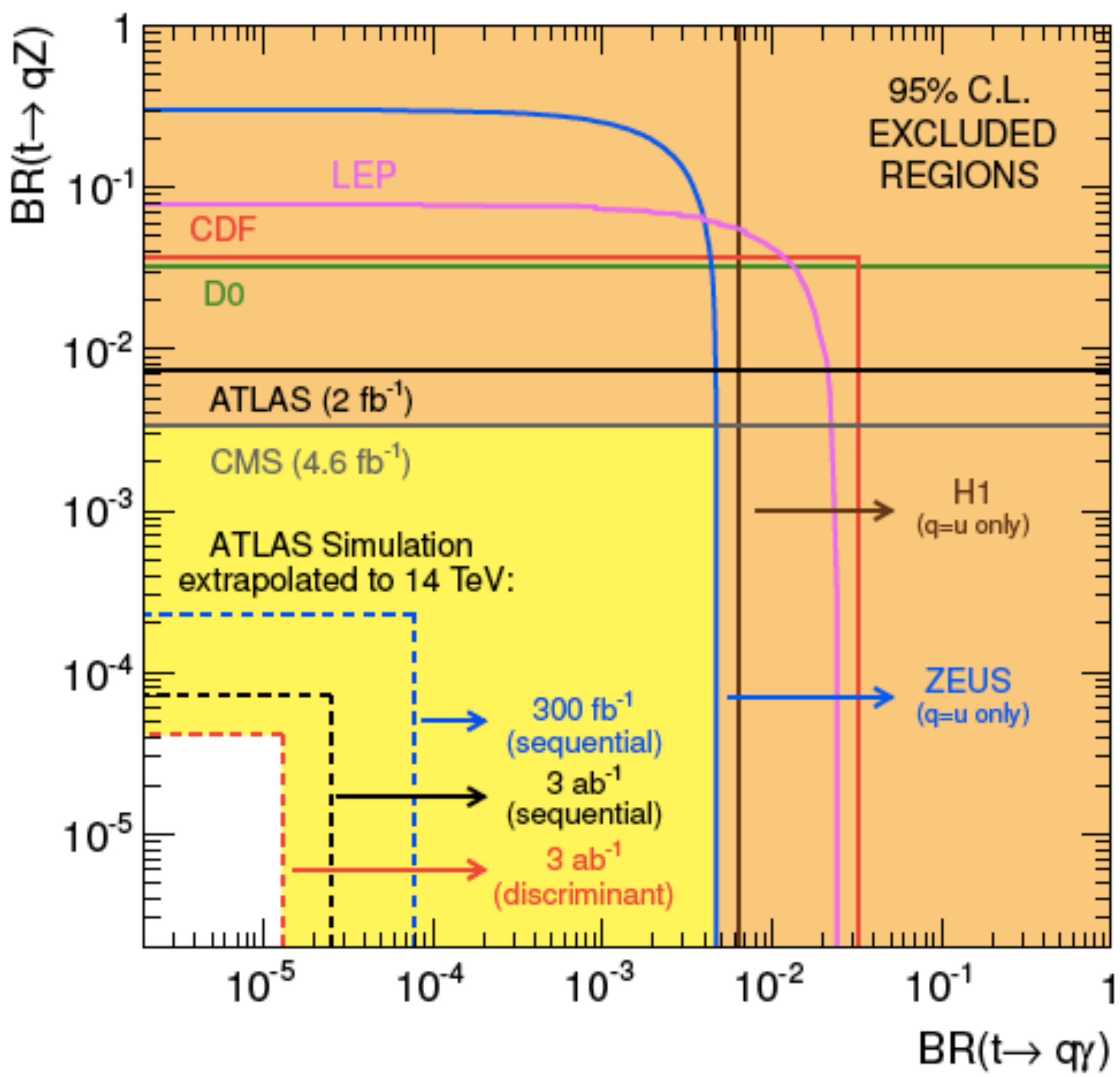
ATLAS @14 TeV	Z' → ee SSM 95% CL limit	g_{KK} → t t RS 95% CL limit	Dark matter M* 5σ discovery
300 fb^{-1}	6.5 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	7.8 TeV	6.7 TeV	2.6 TeV

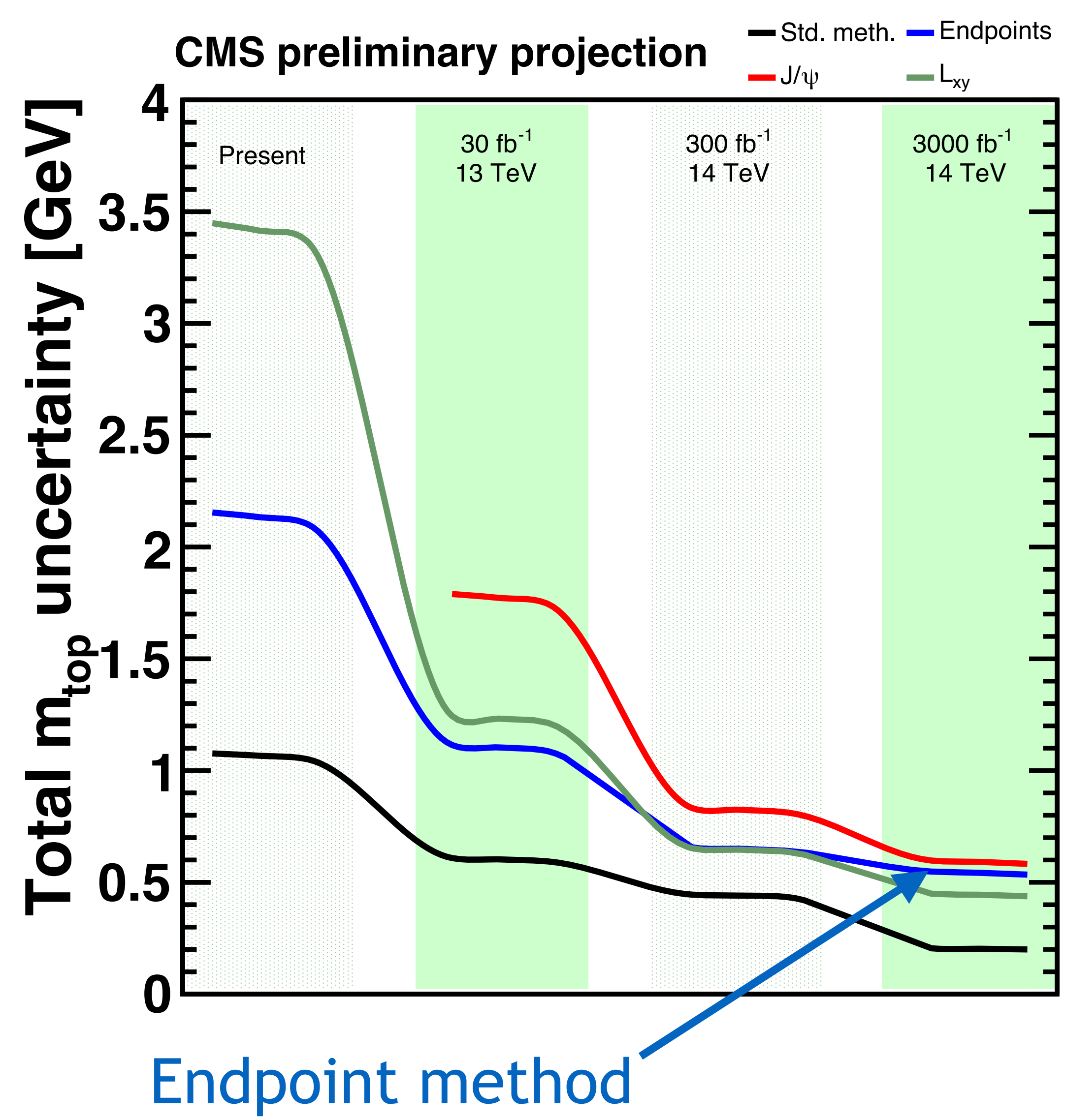
Top Quark Physics

Top Quark Physics

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

- *Top quark mass parameter* can be measured to Λ_{QCD} **~200 MeV** in **3000 fb^{-1}**.
  - Endpoint method, which probes the pole mass, can measure m_t to **500 MeV**
- In SM $\mathbf{BR}(t \to Wb) \simeq 100\%$ Many models predict enhancements, interesting range starts at $\sim 10^{-4} \Rightarrow$ Observing decays to other modes clear sign of new physics
  - HL-LHC will probe $\mathbf{BR}(t \to qZ)$, $\mathbf{BR}(t \to q\gamma)$ at $\sim 3\times10^{-5}$ at least and $\mathbf{BR}(t \to cH)$ at $\sim 10^{-4}$





Outlook

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

Precision Higgs physics: measure production rates to a few % (model dep.)

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 TeV)

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

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

HH observation … might reach 5σ

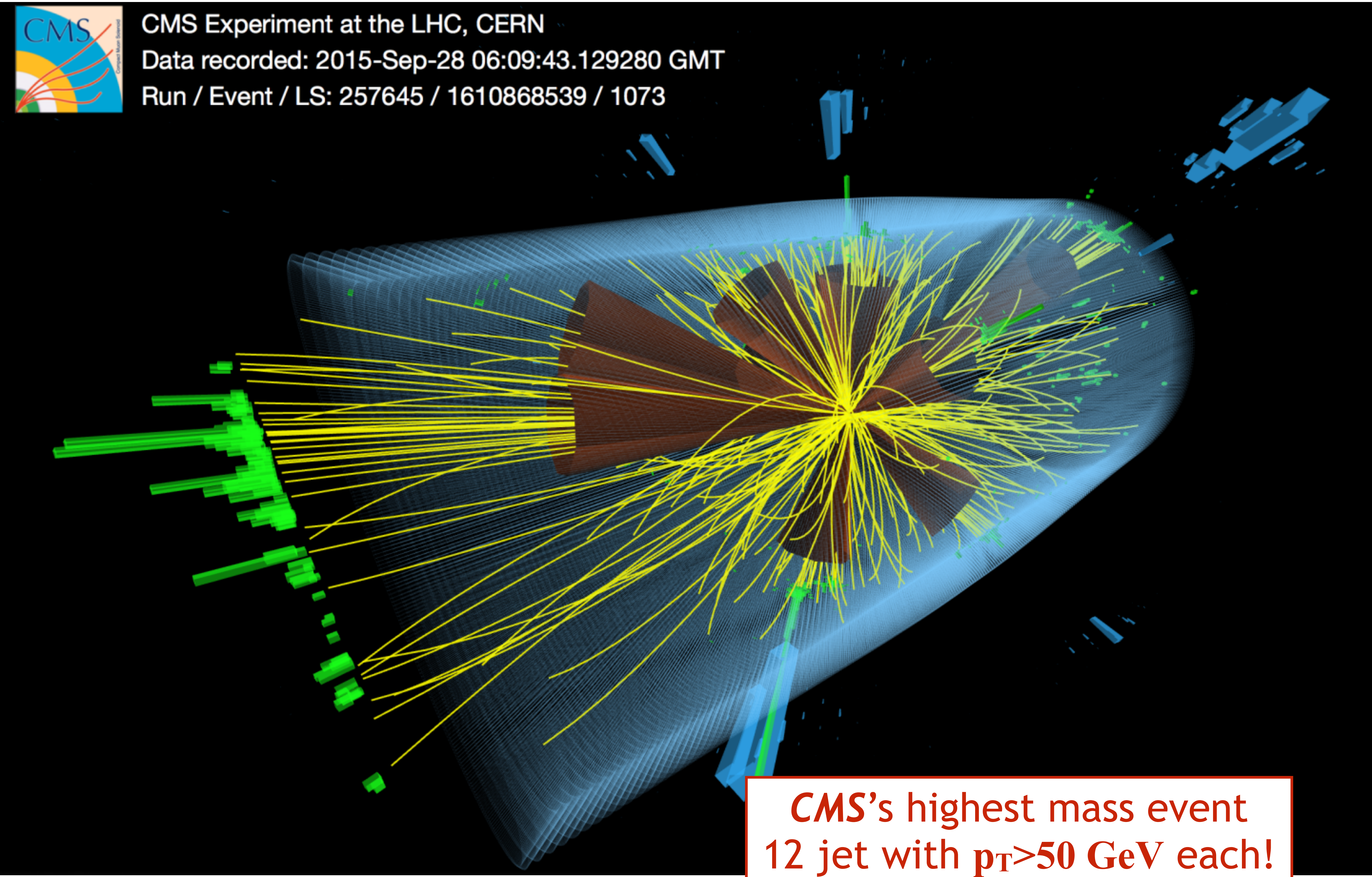
Discovery of additional Higgs bosons up to O (1 TeV)

Theory uncertainty dominant for many analyses

- Some analyses do remain beyond the reach of HL-LHC:

$H\rightarrow c\bar{c}$

triple-Higgs boson

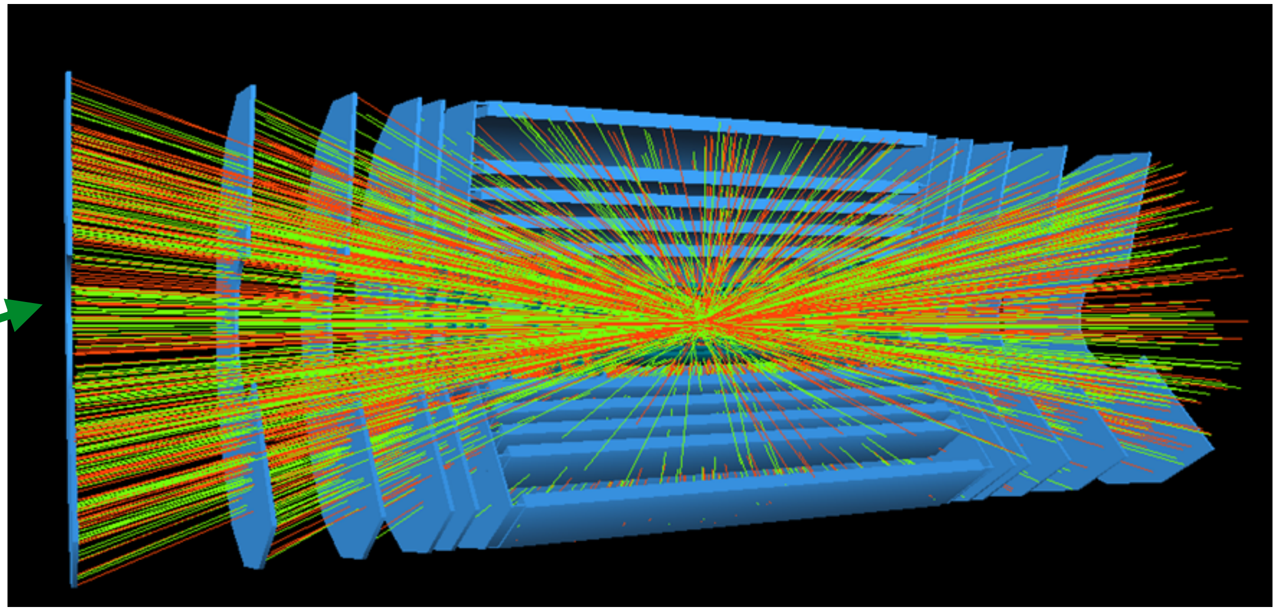


CMS's highest mass event
12 jet with p_T>50 GeV each!
Total mass of system **6.4 TeV**

Backup

ATLAS Upgrades

- Long Shutdown 1
  - New beam pipe at r=25mm
  - New insertable *b*-layer at $31 < r/\mathrm{mm} < 40$
  - 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



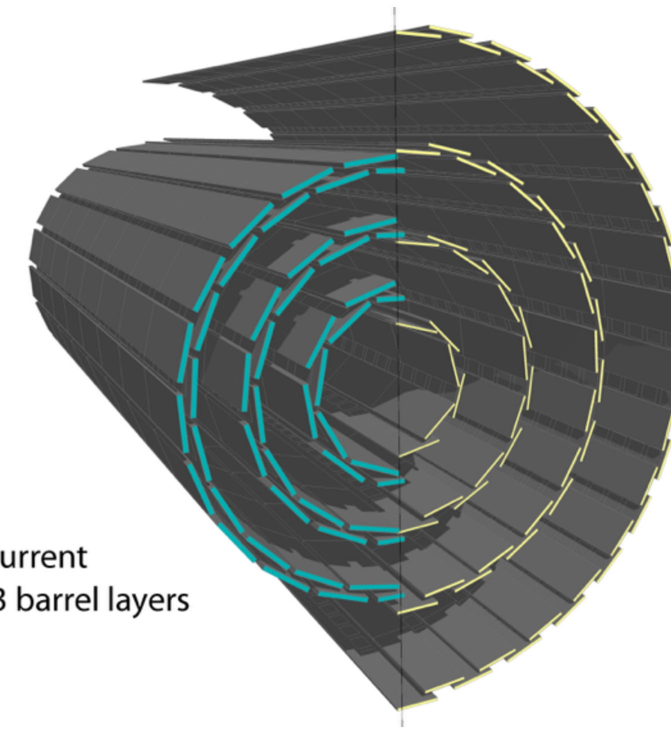
ATLAS & CMS Higgs boson coupling fits

L(fb^{-1})	Exp.	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$
300	ATLAS	[9, 9]	[9, 9]	[8, 8]	[11, 14]	[22, 23]	[20, 22]	[13, 14]	[24, 24]	[21, 21]
	CMS	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]
3000	ATLAS	[4, 5]	[4, 5]	[4, 4]	[5, 9]	[10, 12]	[8, 11]	[9, 10]	[14, 14]	[7, 8]
	CMS	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]

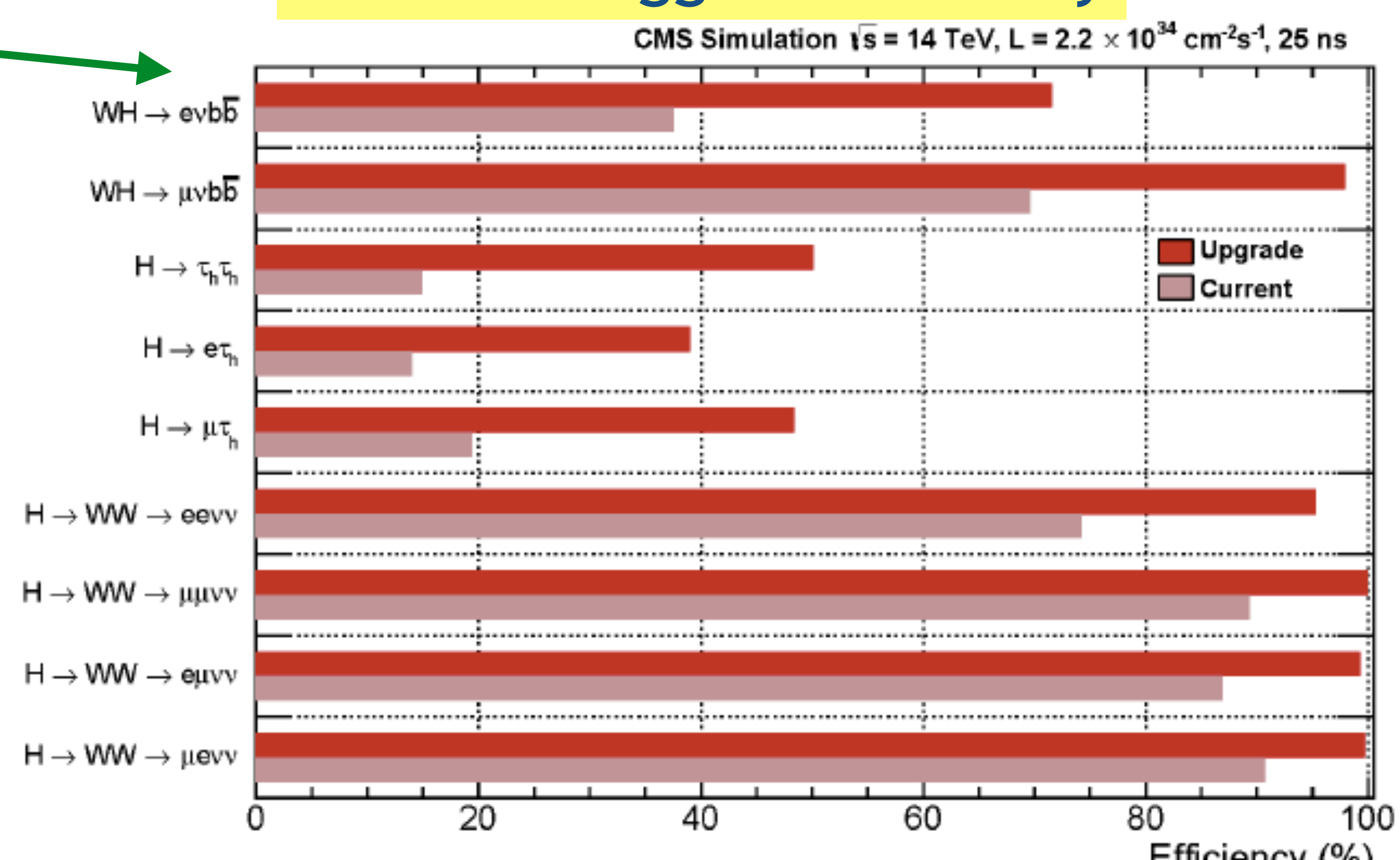
CMS Upgrade

CMS PAS FTR-13-003

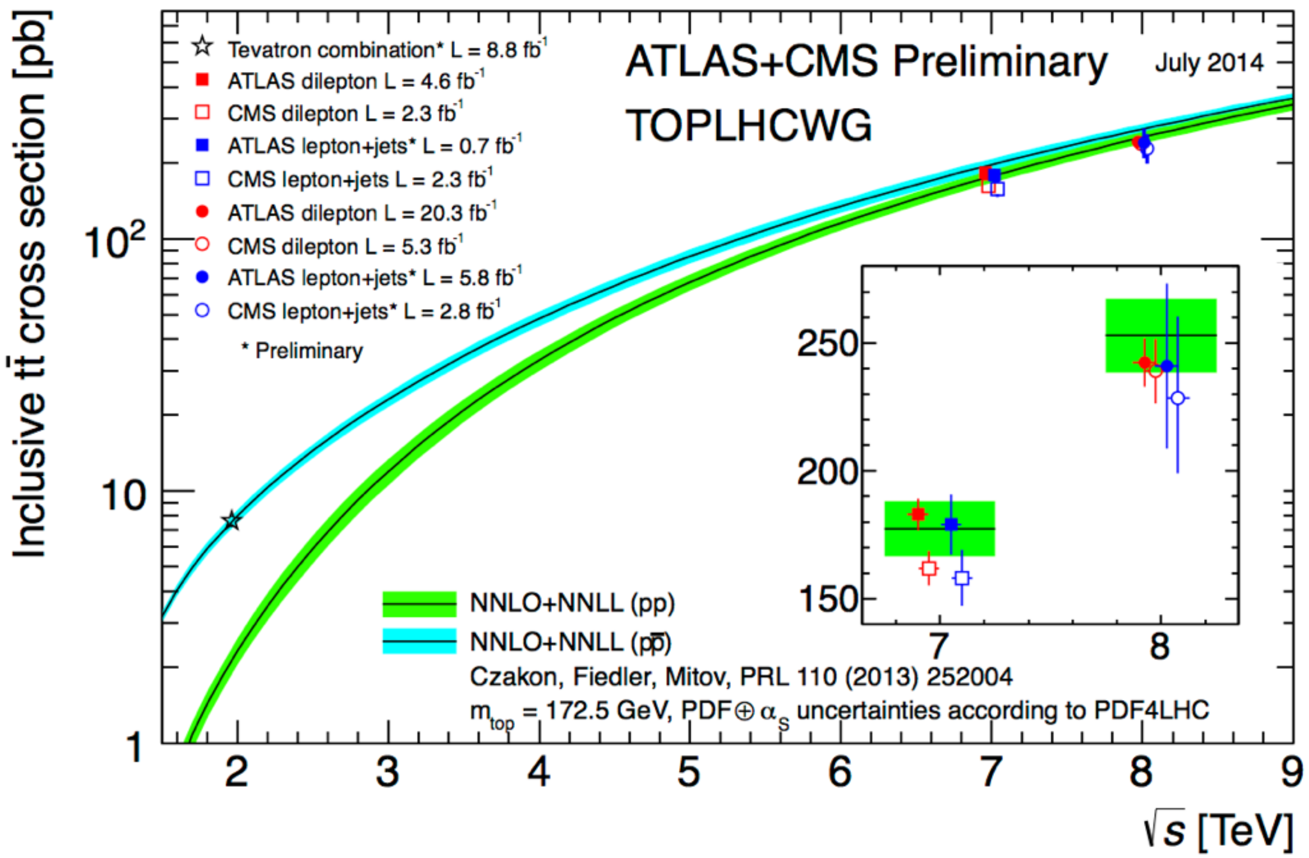
- Long Shutdown 1:
  - Complete Muon coverage
  - New HCAL photo-detectors
- Long Shutdown 2:
  - New Pixel detector (2017)
  - New HCAL electronics
  - L1-Trigger upgrade
- For HL-LHC:
  - Tracker replacement, L1 Track-Trigger
  - New forward calorimetry, muons and tracking
  - High precision timing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



Greater trigger efficiency

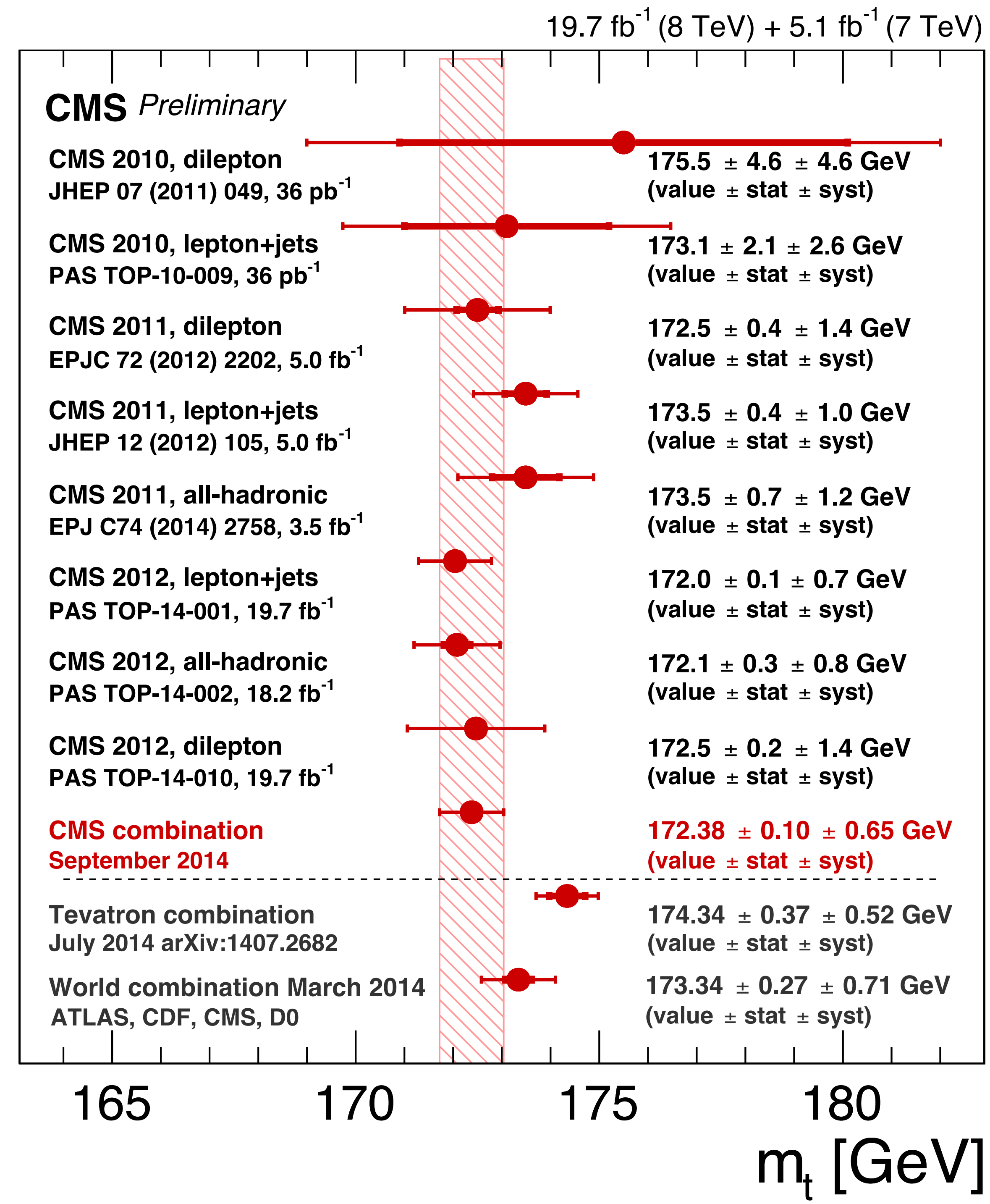


Run 1 Top Quark Properties



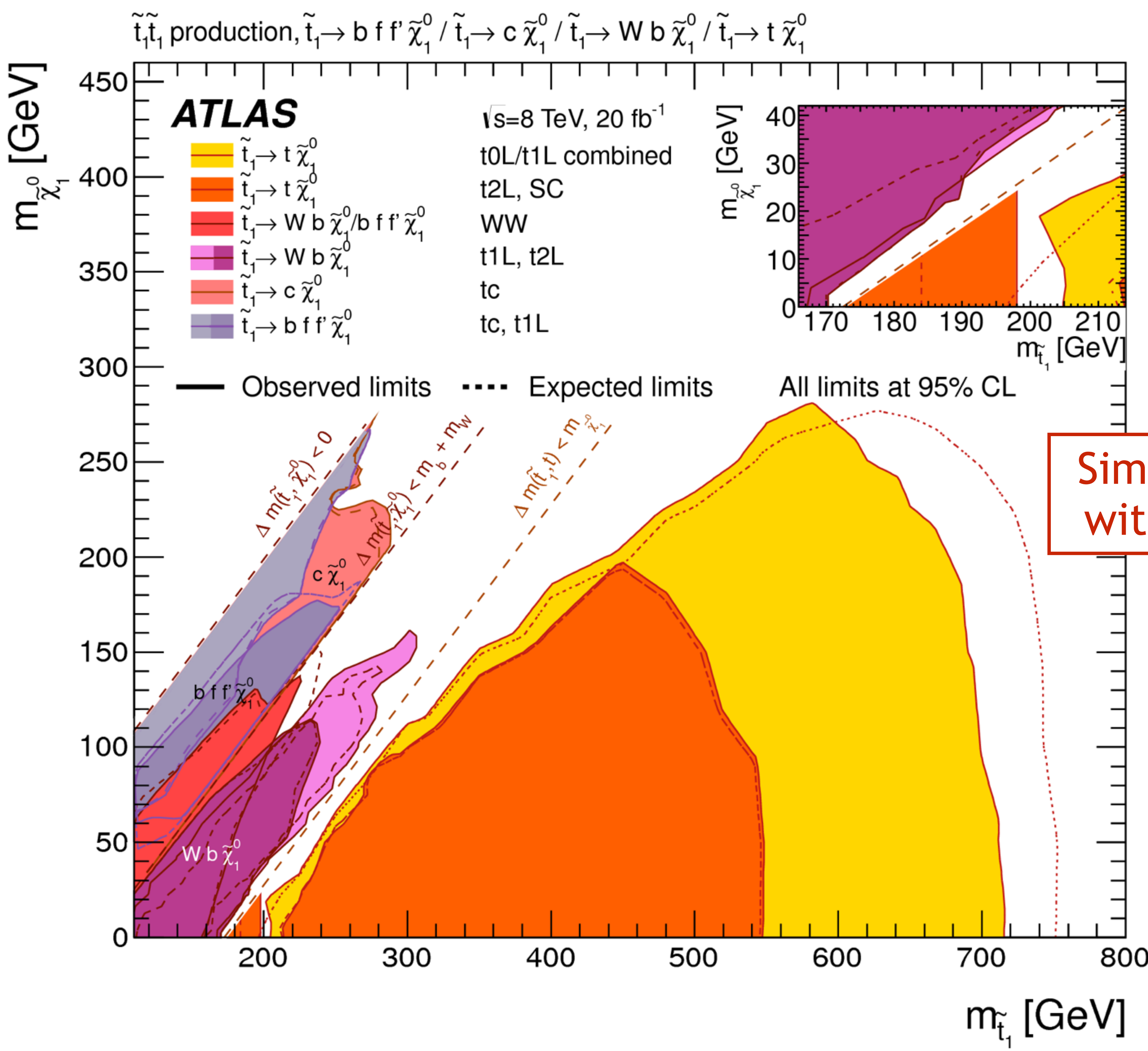
arXiv:1403.4427

CMS-PAS-TOP-14-015



Run 1 observed limits on stop and LSP

arXiv:1506.08616



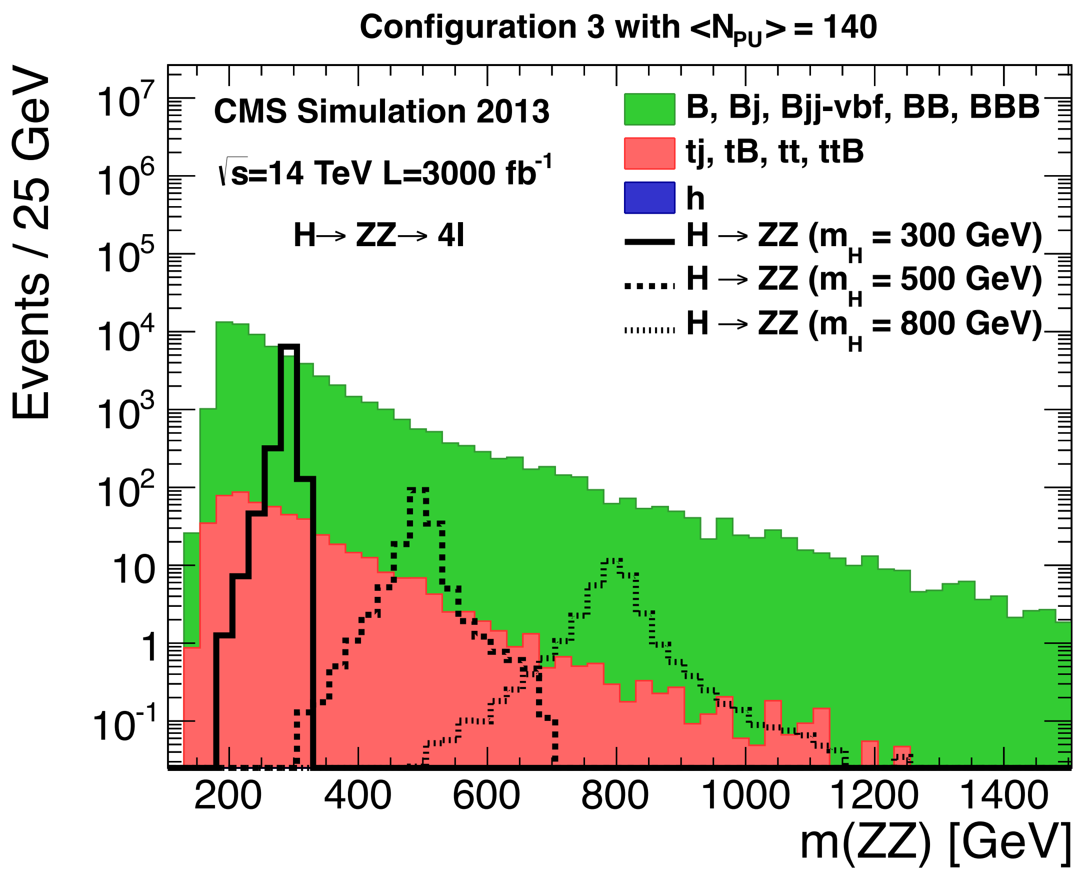
Simplified models with $\tilde{t} \to \mathbf{LSP} + X$

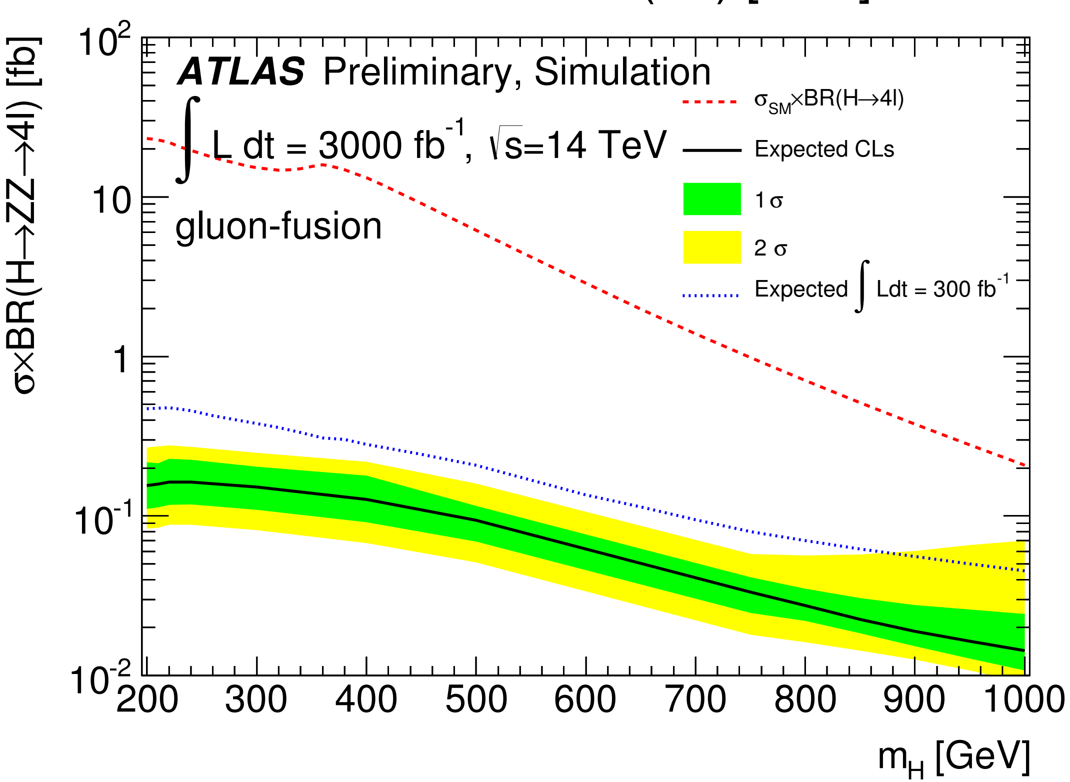
HL-LHC: Additional Heavy Higgs bosons

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

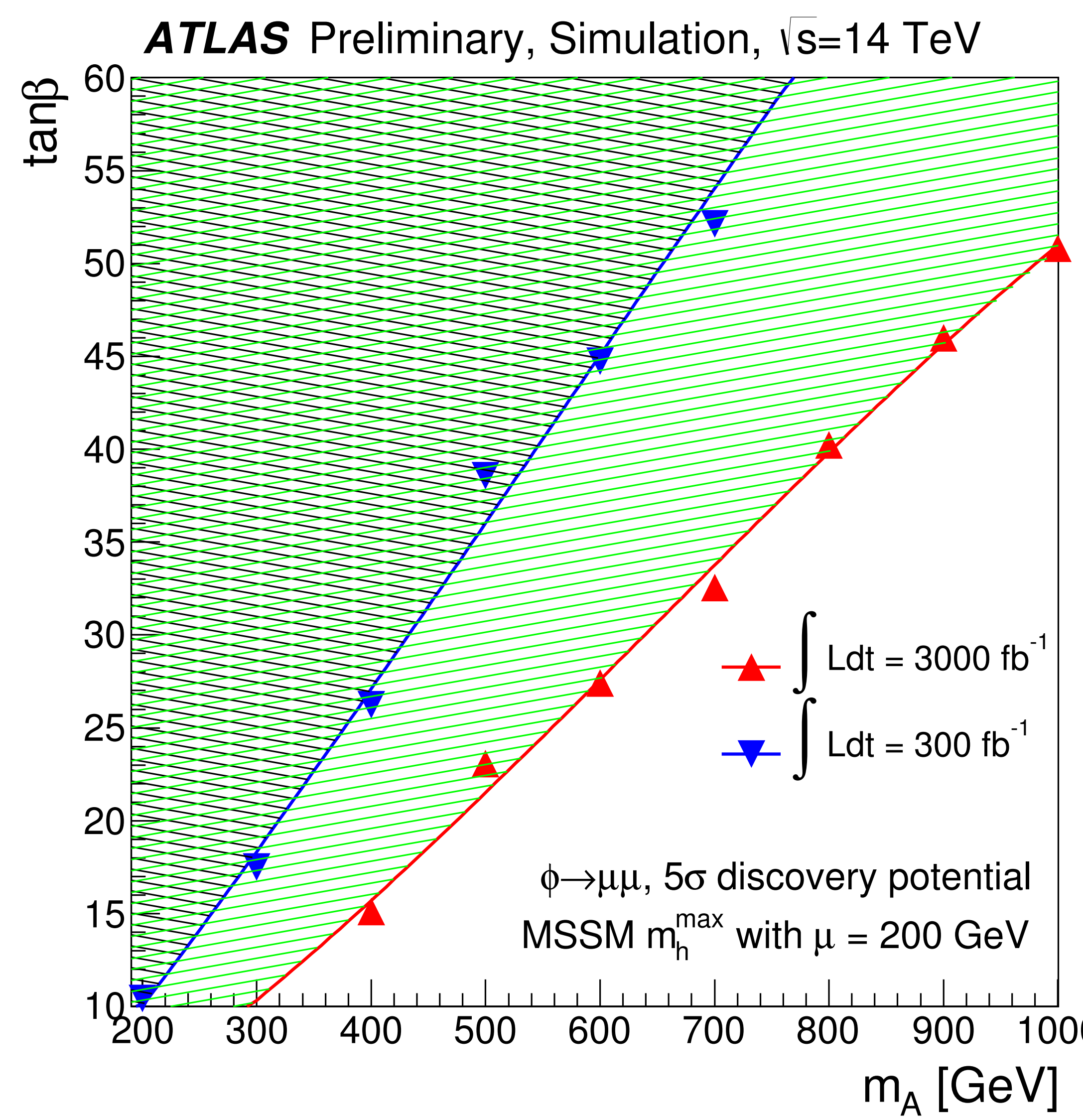
ATL-PHYS-PUB-2013-016

CMS-PAS-FTR-13-024



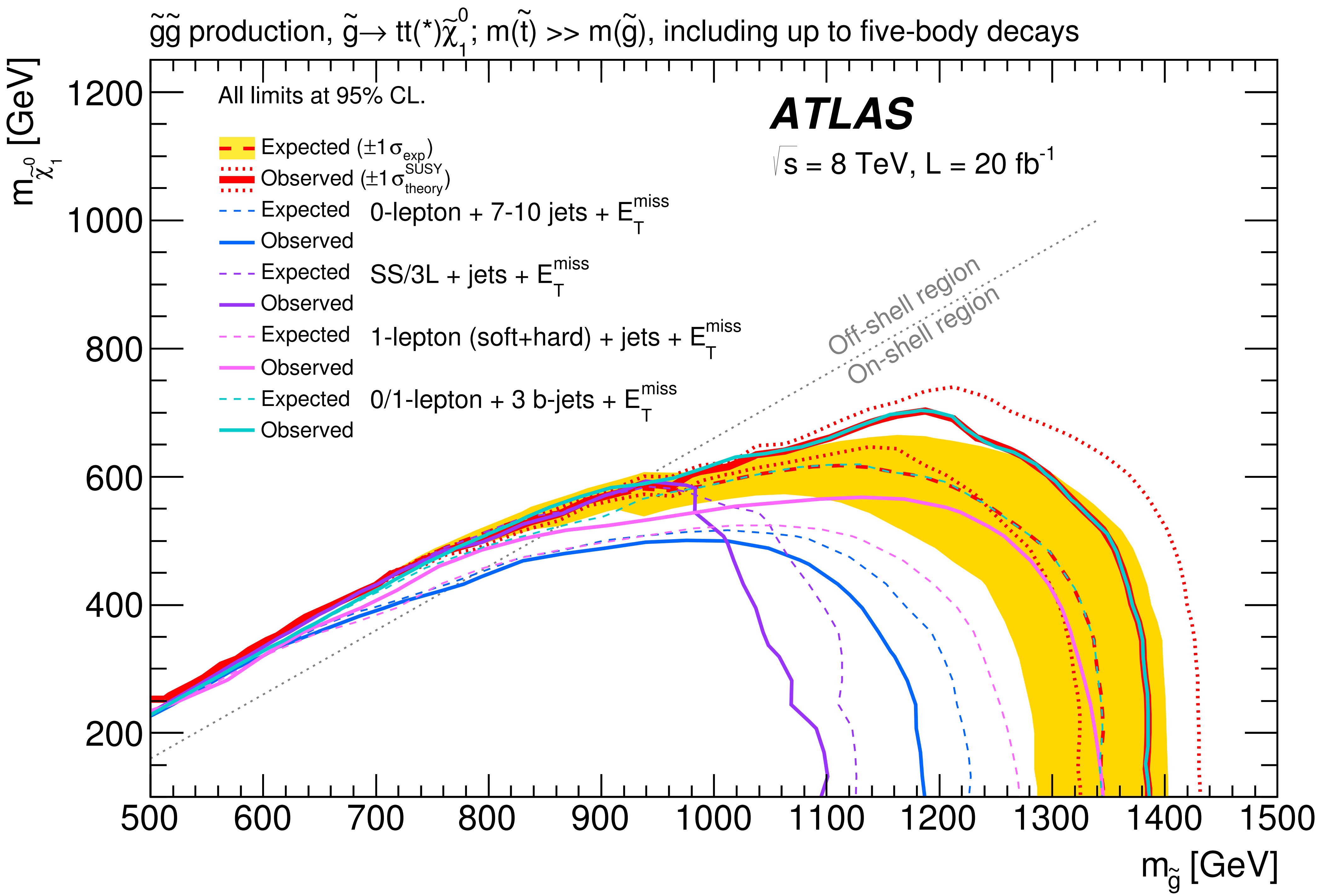


Prospects for $\phi \to \mu\mu$ production



Run 1 SUSY limits

arXiv:1507.05525



HL-LHC Cross Sections