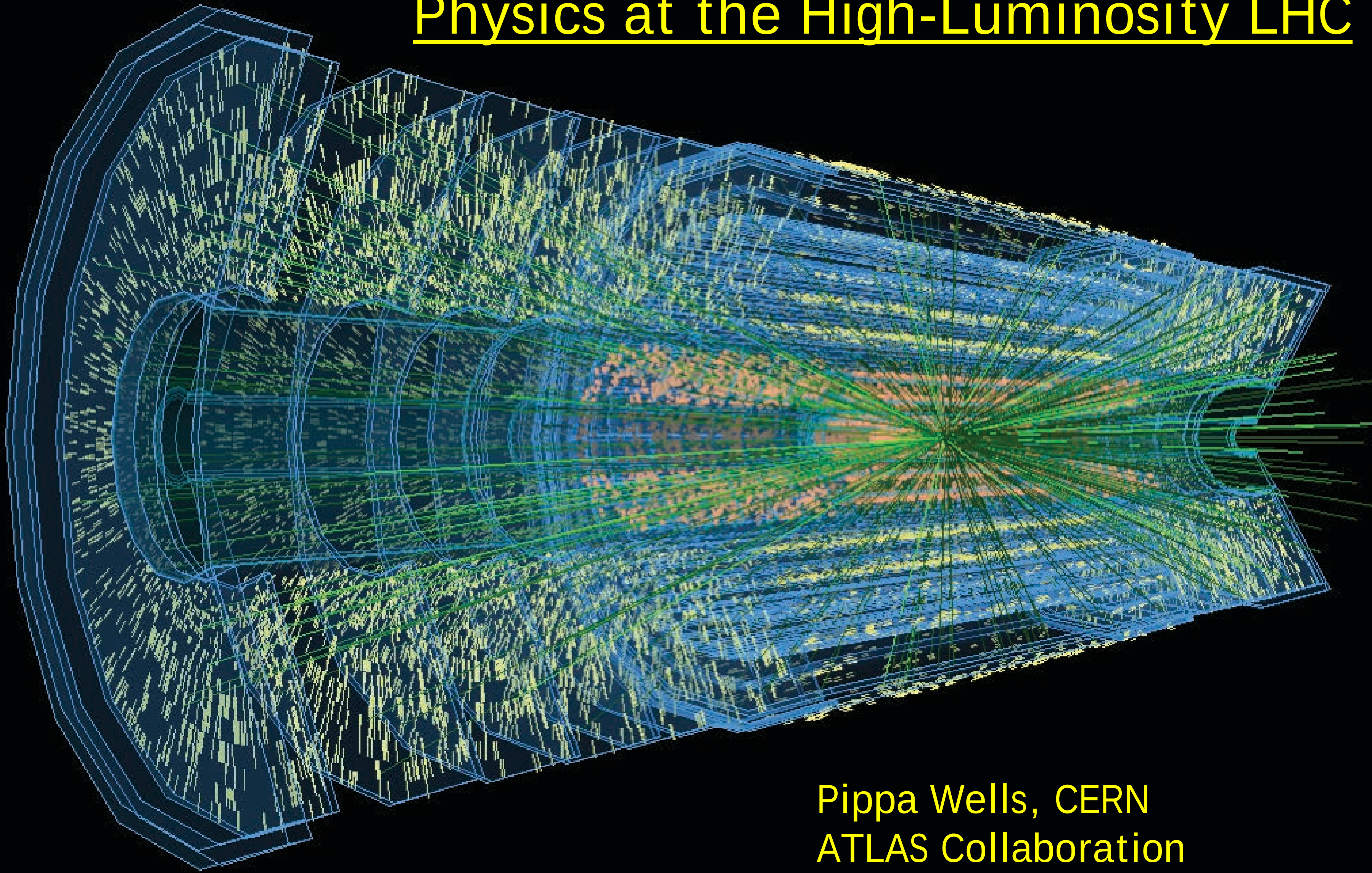
Physics at the High-Luminosity LHC



Pippa Wells, CERN
ATLAS Collaboration

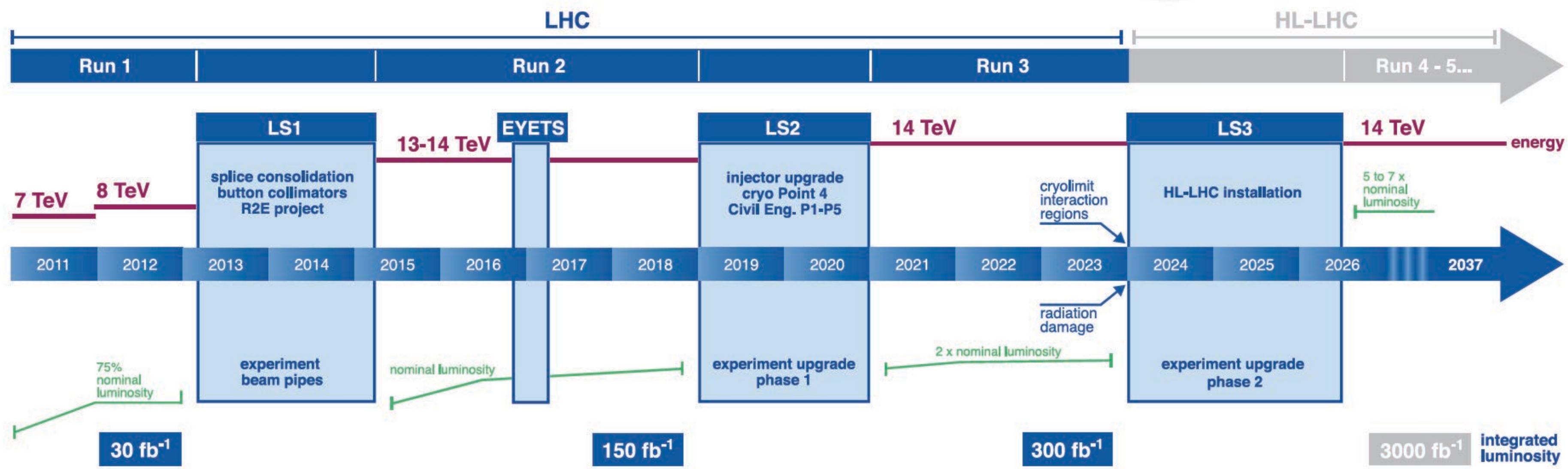
Freiburg seminar

February 2016

HL-LHC Physics

- HL-LHC program
- Detector configurations
  - Pileup mitigation and performance
- Higgs boson measurements
  - Precision coupling measurements
  - Rare processes
  - Higgs boson pair production
- Beyond the Standard Model
  - In the Higgs sector
  - Dark matter
  - SUSY
  - Exotica
- Conclusions

LHC / HL-LHC Plan



Run 1	Magnet splice update	Run 2 at ~full design energy	Phase I upgrades (injectors)	Run 3 → original design lumi	Phase II upgrades (final focus)	HL-LHC: ten times design lumi

Full exploitation of LHC is top priority in Europe & US for high energy physics

Operate HL-LHC with 5 (nominal) to 7.5 (ultimate) x10^{34}cm^{-2}s^{-1} to collect 3000/fb in order ten years.

Detector upgrades

Detector upgrades

- Luminosity of 5 (7.5) $\times 10^{34}$ $cm^{-2}s^{-1}$ corresponds to *average* pileup, μ, of 140 (200) events (interactions in the same bunch crossing)
  - Higher occupancy, larger integrated radiation dose
  - Need to distinguish particles from hard scatter vertex
- ATLAS and CMS will fully replace their inner trackers
  - All silicon trackers, with higher granularity
  - Pixel detectors extended to $|\eta| = 4.0$ (ATLAS), 3.8 (CMS)
- Calorimeter upgrades – including precise timing
  - CMS will fully replace the end cap calorimeter ($1.5 < |\eta| < 3.0$), with precise timing information from each layer, plus improved timing information in the barrel region
  - ATLAS propose a high granularity timing detector between the barrel and endcap LAr calorimeter cryostats ($2.4 < |\eta| < 4.3$)
  - For both experiments, the timing aspects are not yet fully integrated in simulation and/or reconstruction algorithms
  - ATLAS may also replace the forward calorimeter ($3.2 < |\eta| < 4.9$)
- Additional improvements to improve triggers and increase bandwidth

References

- Scoping documents prepared in 2015 to compare detector options:
  ATLAS [CERN-LHCC-2015-020]
  CMS [CERN-LHCC-2015-019]

- ATLAS Phase II Letter of Intent [CERN-LHCC-2012-022],
  CMS Technical Proposal [CERN-LHCC-2015-010]

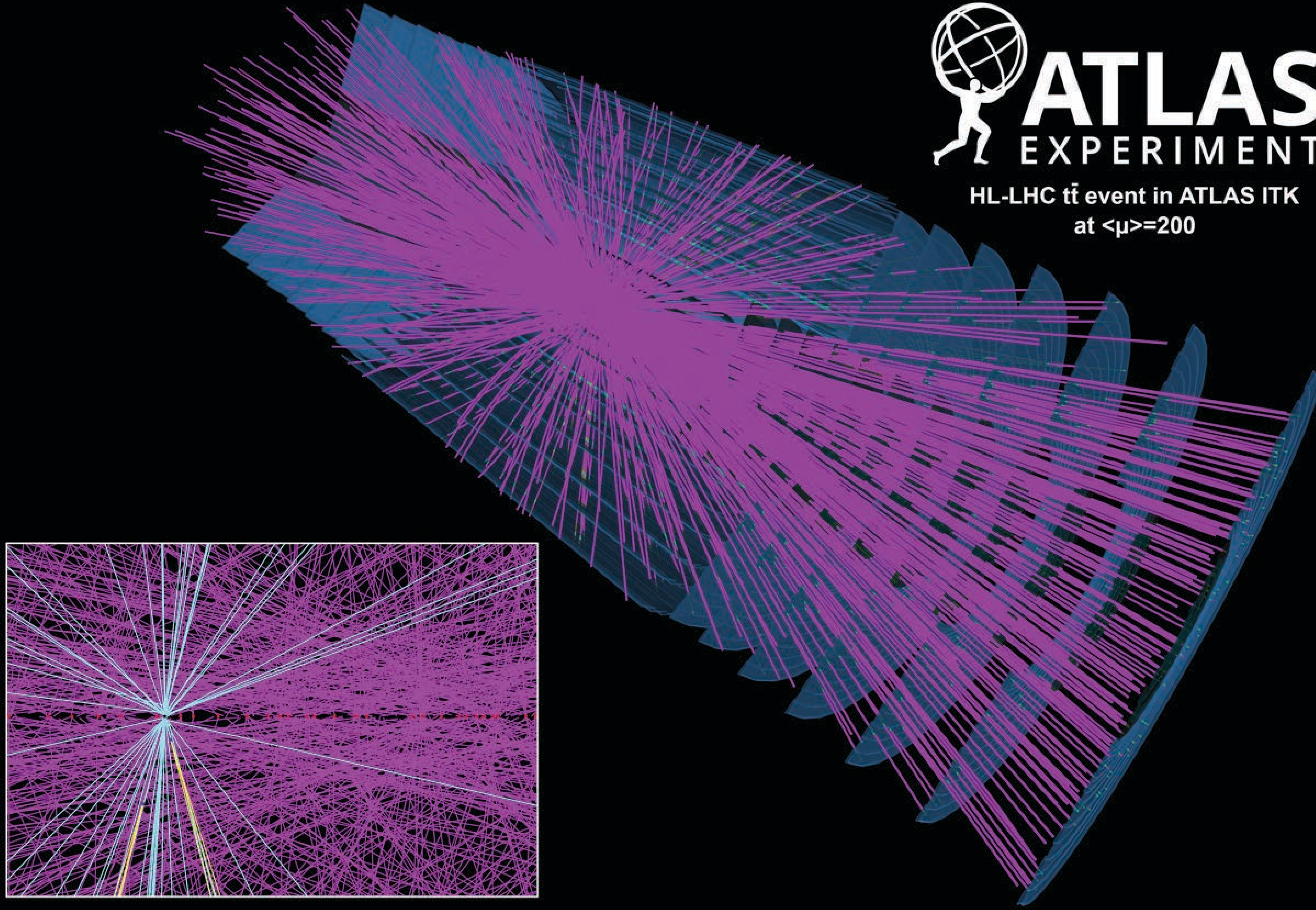
- Collections of public results:

  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

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

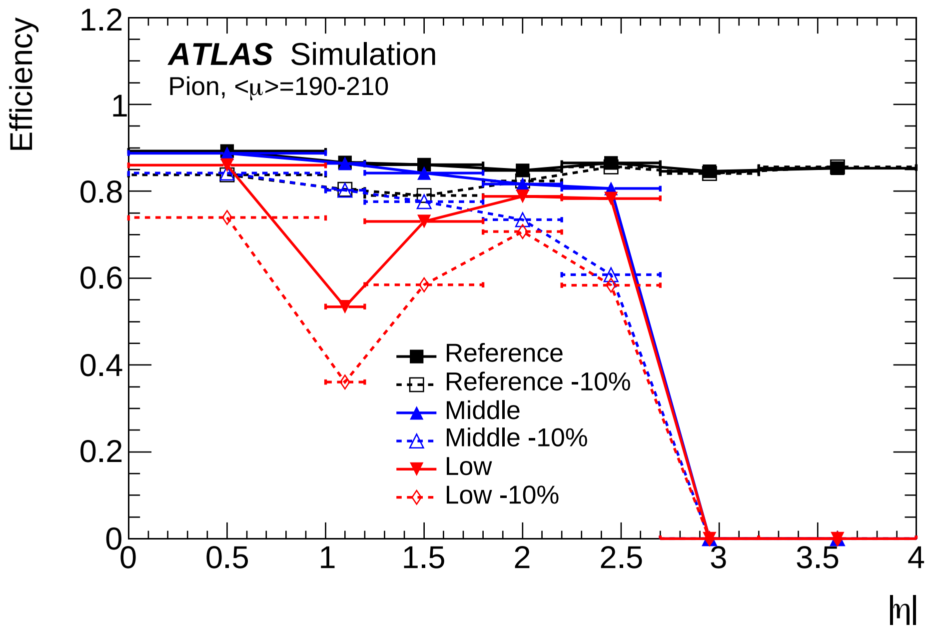
- ECFA HL-LHC workshop 2014: https://indico.cern.ch/event/315626/

- Next steps: Technical Design Reports (TDRs)

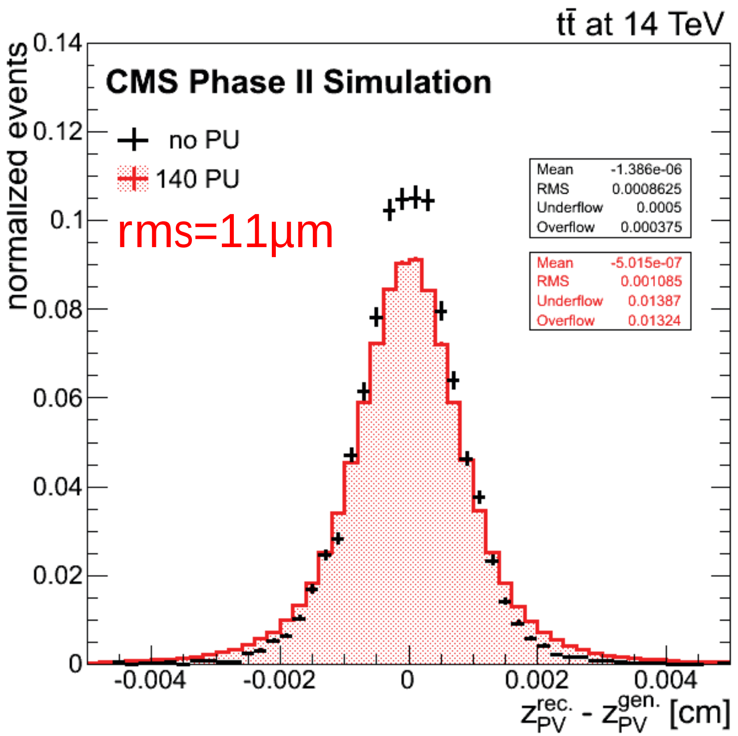

ATLAS
EXPERIMENT
HL-LHC tt̄ event in ATLAS ITK
at <μ>=200

Track and vertex reconstruction

- Pion tracking efficiency in ttbar events for ATLAS full and reduced scenarios, PU of 200



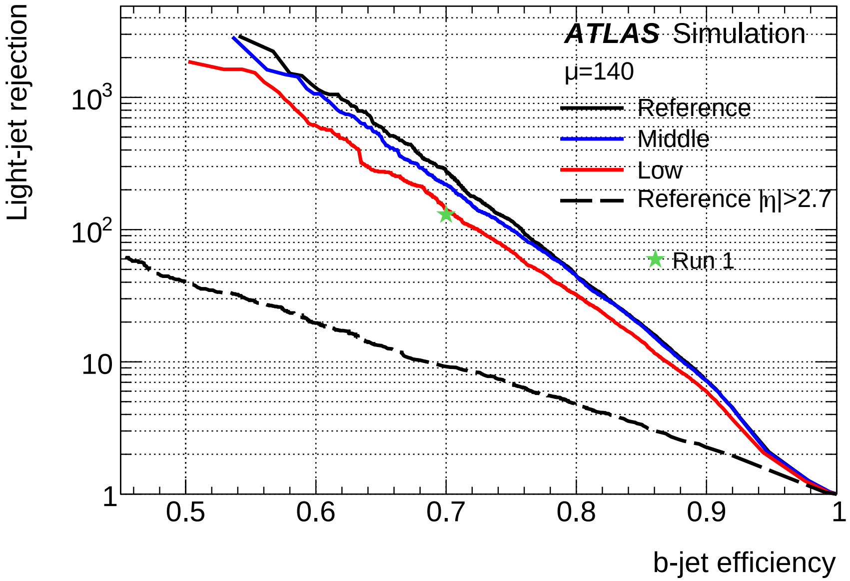
- ttbar events reconstructed with the CMS Phase II detector

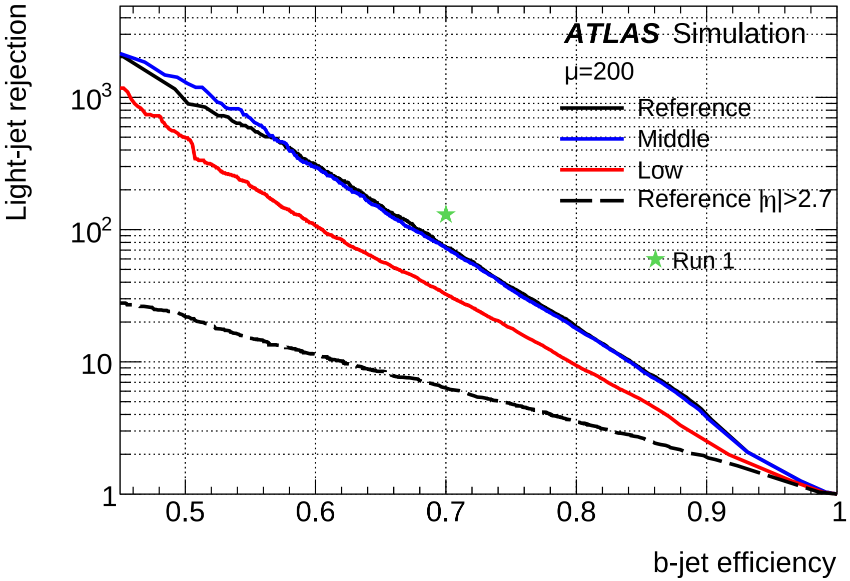


- For both experiments, fake rates are well under control
- Muon tracking efficiency is uniformly high (about 99%)
- Efficiency for picking the right primary vertex depends on process

B-tagging performance

- Example from the ATLAS Scoping Document
  - Use a Run 1 b-tagging algorithm out-of-the box
  - With mu=140, better performance than Run 1
  - With mu=200, similar performance to Run 1 (for Reference scenario)
  - Useful b-tagging capability in large η region in Reference scenario



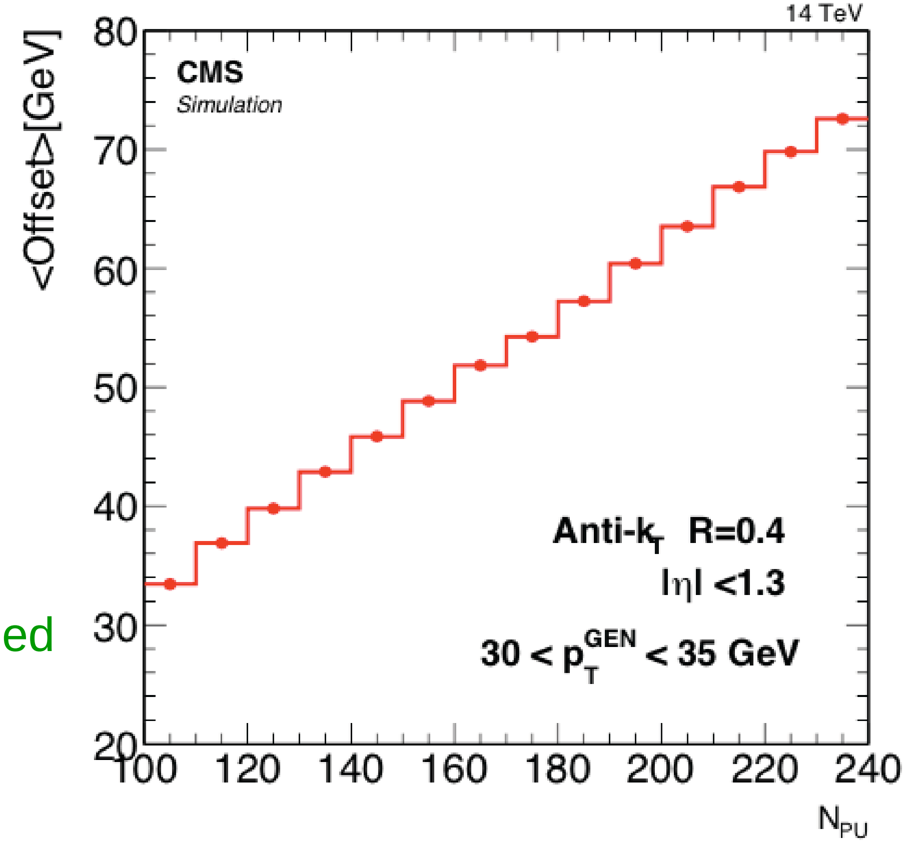


Jets and pileup

- Particles from pileup events make a significant contribution to the jet energy of true low p_T jets
- Pileup events can also produce additional QCD-like jets (usually at low p_T), and jets from random combinations of particles from several pileup events

- Plot shows additional energy from pileup overlaid on low energy QCD jets with radius 0.4 in η-φ space

- Reconstructed jet energy depends on detector specific algorithms which reject/correct pileup
- Jet energy scale correction is applied to estimate true jet energy

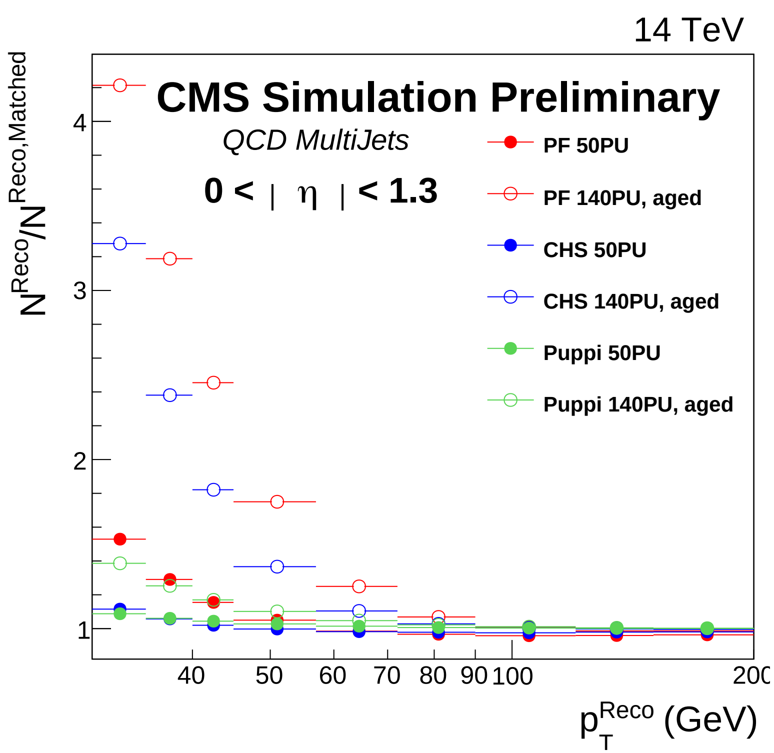


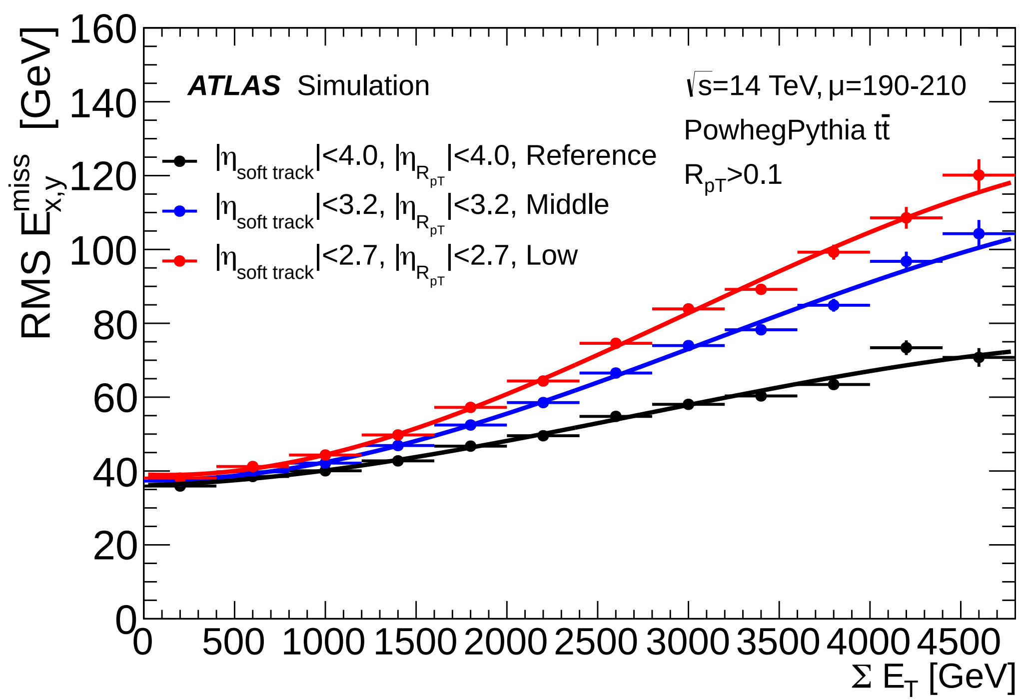
Pile-up jet rejection

Pileup Per Particle Identification
arXiv:1407.6013 [hep-ph]

- Rate of pileup jets/true jets for
  Particle Flow algorithm (PF)
  Plus rejecting charged hadrons from pileup vertices (CHS)
  Using Puppi algorithm

- Impact on E_T^{miss} of using extended tracking information to reject pile-up jets
  - (resolution as a function of ΣE_T in ttbar events)



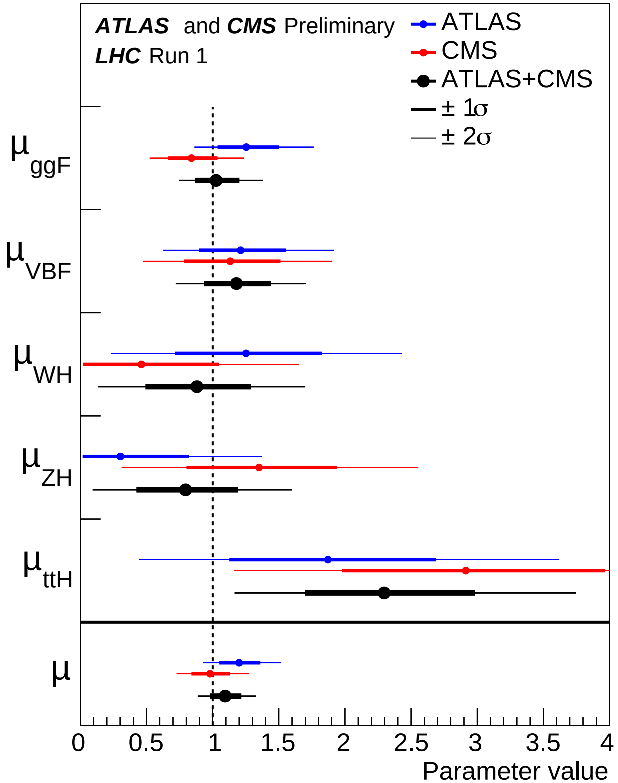


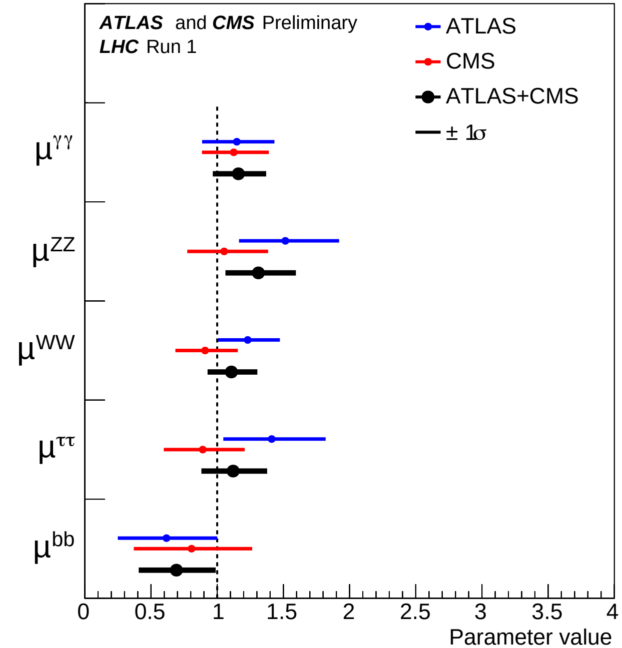
Higgs boson measurements

Combined ATLAS & CMS Run 1 Higgs boson

m_H = 125.09 ± 0.21(stat.) ± 0.11(syst.) GeV

μ = 1.09 ± 0.11



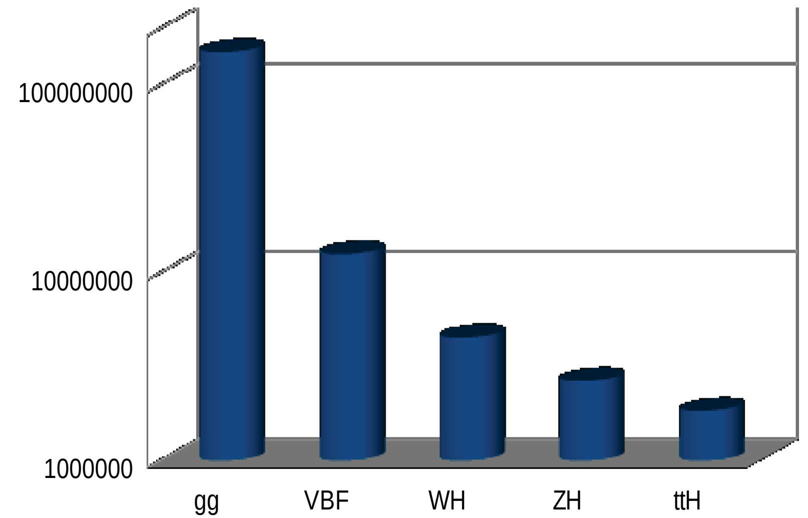


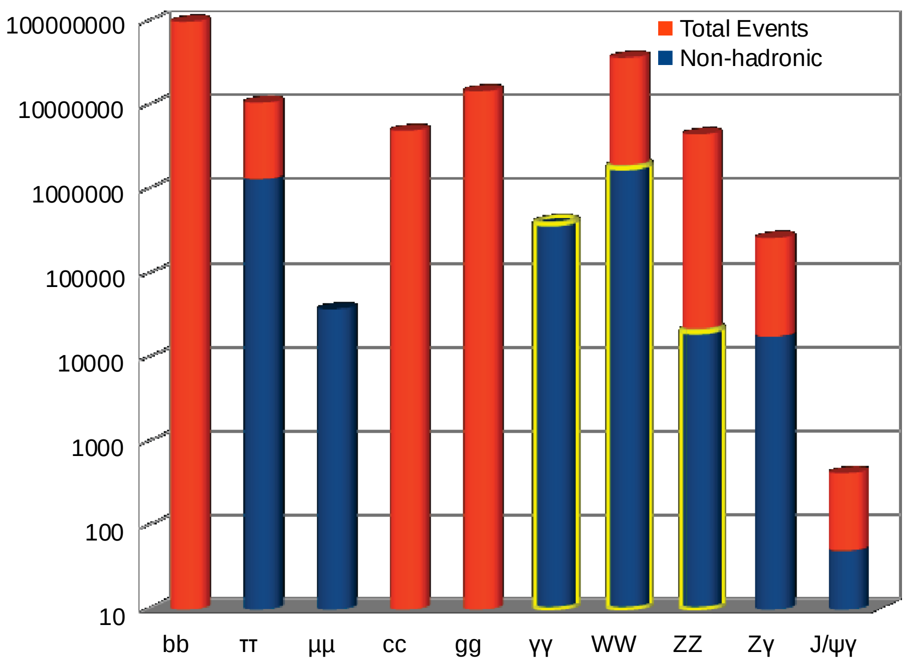
10 to 20% precision for main channels

- J^P consistent with 0^+. Other hypotheses excluded at >99% CL
- Model dependent constraint on width from off-shell H→ZZ: Γ_H<22 MeV

HL-LHC a Higgs boson factory with 3000 fb^{-1}

- Over 100 million SM Higgs bosons in total
  - Over 1 million for each of the main production mechanisms (→ production cross sections)





- Spread over many decay modes (→ branching ratios)
  - 20k H→ZZ→llll
  - 400k H→γγ
  - 40k H→μμ
  - Only 50 leptonic H→J/ψγ (a very rare mode)

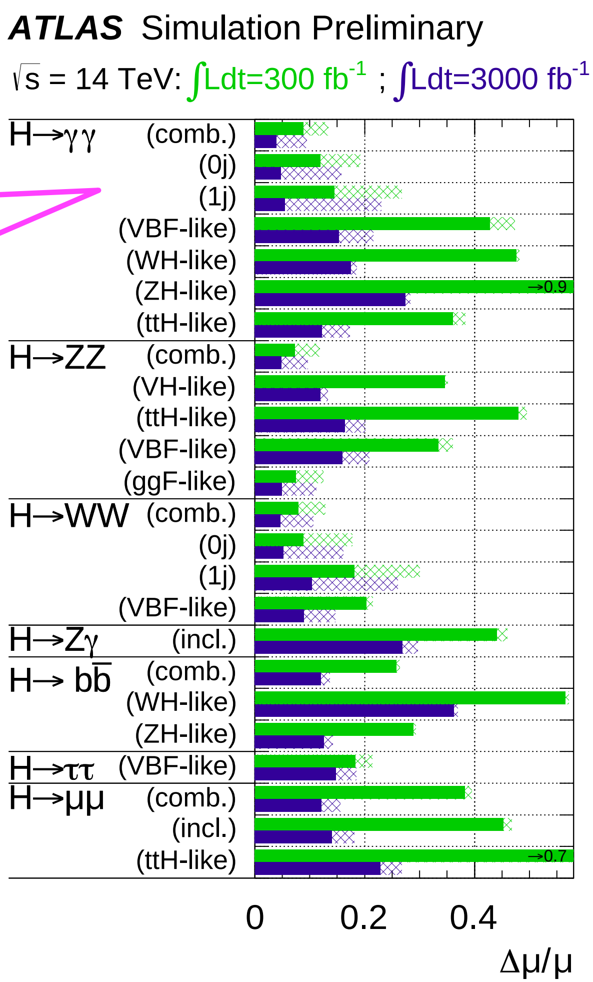
Prospects for the Higgs boson

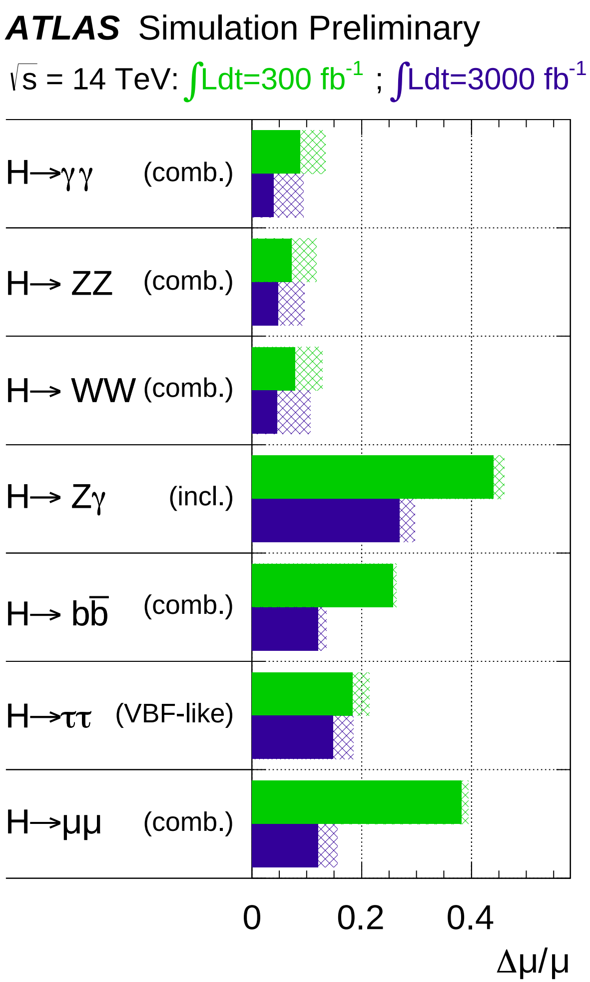
- Compare prospects with “LHC” 300 fb^{-1} and “HL-LHC” 3000 fb^{-1}
  - Results are always given for 1 experiment, not 2 combined
- ATLAS uses detector response functions based on full simulation for
  - Phase I detector with new pixel layer for Run 2, pile-up of 50
  - Phase II detector with pile-up of 140
  - Results are shown with and without theory uncertainty
- CMS extrapolated from the present 7-8 TeV analyses, assuming that the upgrades maintain the detector performance.
  - Scenario 1 – Experimental systematic and theoretical uncertainties unchanged. Statistical uncertainties scale with $1/\sqrt{L}$
  - Scenario 2 - Statistical and experimental systematic uncertainties scale with $1/\sqrt{L}$, theoretical uncertainties reduced by a factor 2.
  - (Newer analyses use other techniques)
- Systematic uncertainties are therefore always included, but with different assumptions on possible detector/algorithm/theoretical improvements.

Signal strength precision

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

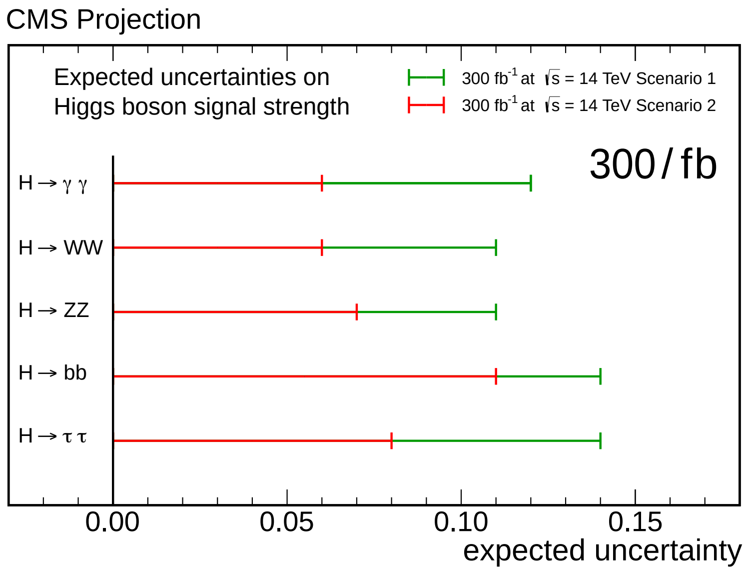
Uncertainties between 0 & 1 jet cancel out in combination

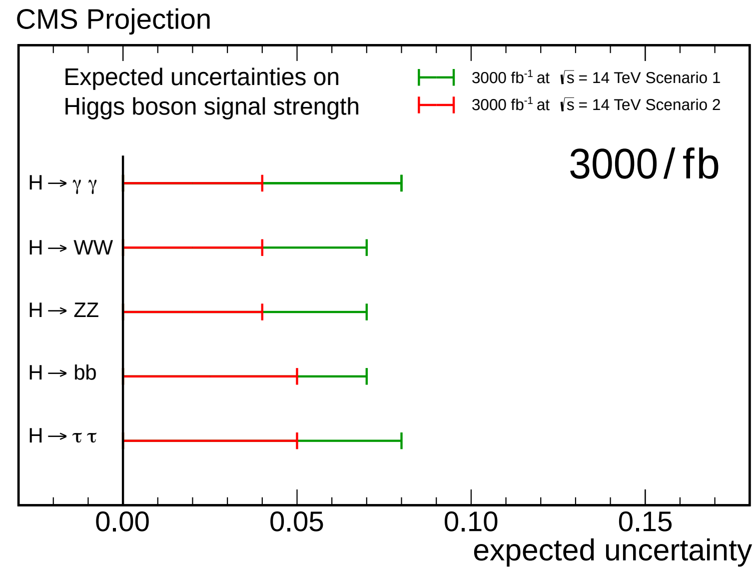




Signal strength precision

Scenario 1 (present errors). Scenario 2 (scaled errors).





Summary of precision (%): 4~5% for main channels, 10~20% on rare modes

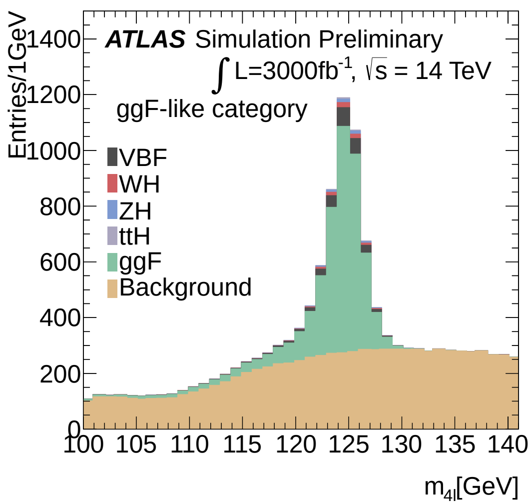
ATLAS without/with theory uncertainty, CMS Scenario 1 and Scenario 2

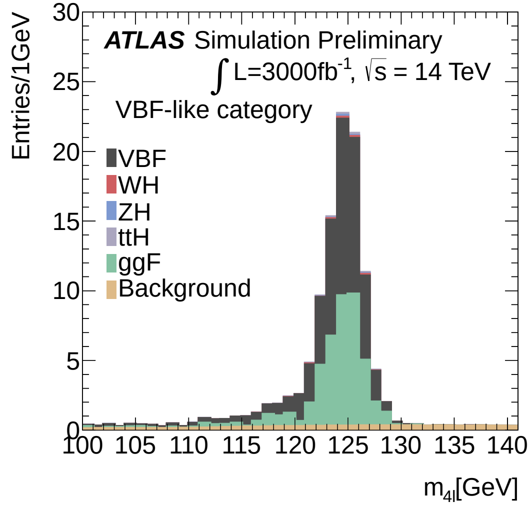
L(fb^{-1})	Exp.	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$
300	ATLAS	[9, 13]	[8, 13]	[7, 11]	[26 , 26]	[18, 21]	[44, 46]	[38,39]
	CMS	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]
3000	ATLAS	[4, 9]	[5, 11]	[4, 9]	[12, 14]	[15, 19]	[27, 30]	[12,16]
	CMS	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[14,20]

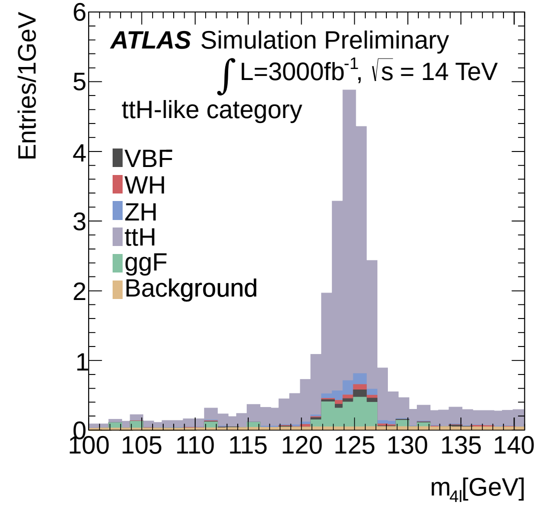
Example – H→ZZ→4 leptons

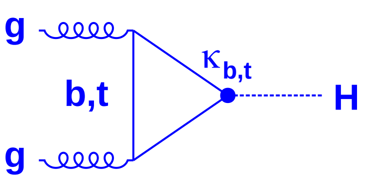
- High purity signal. Measure all 5 main production modes with 3000 fb^{-1}

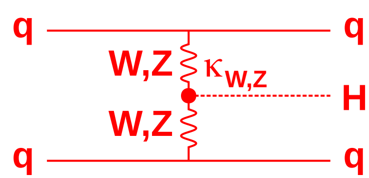
Signal events	ggH	VBF	ttH	WH	ZH
3000 fb^{-1}	3800	97	35	67	5.7

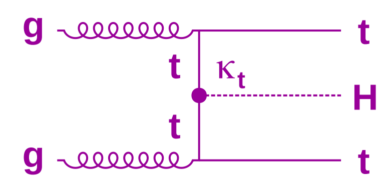




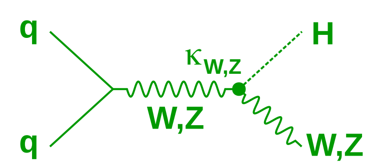






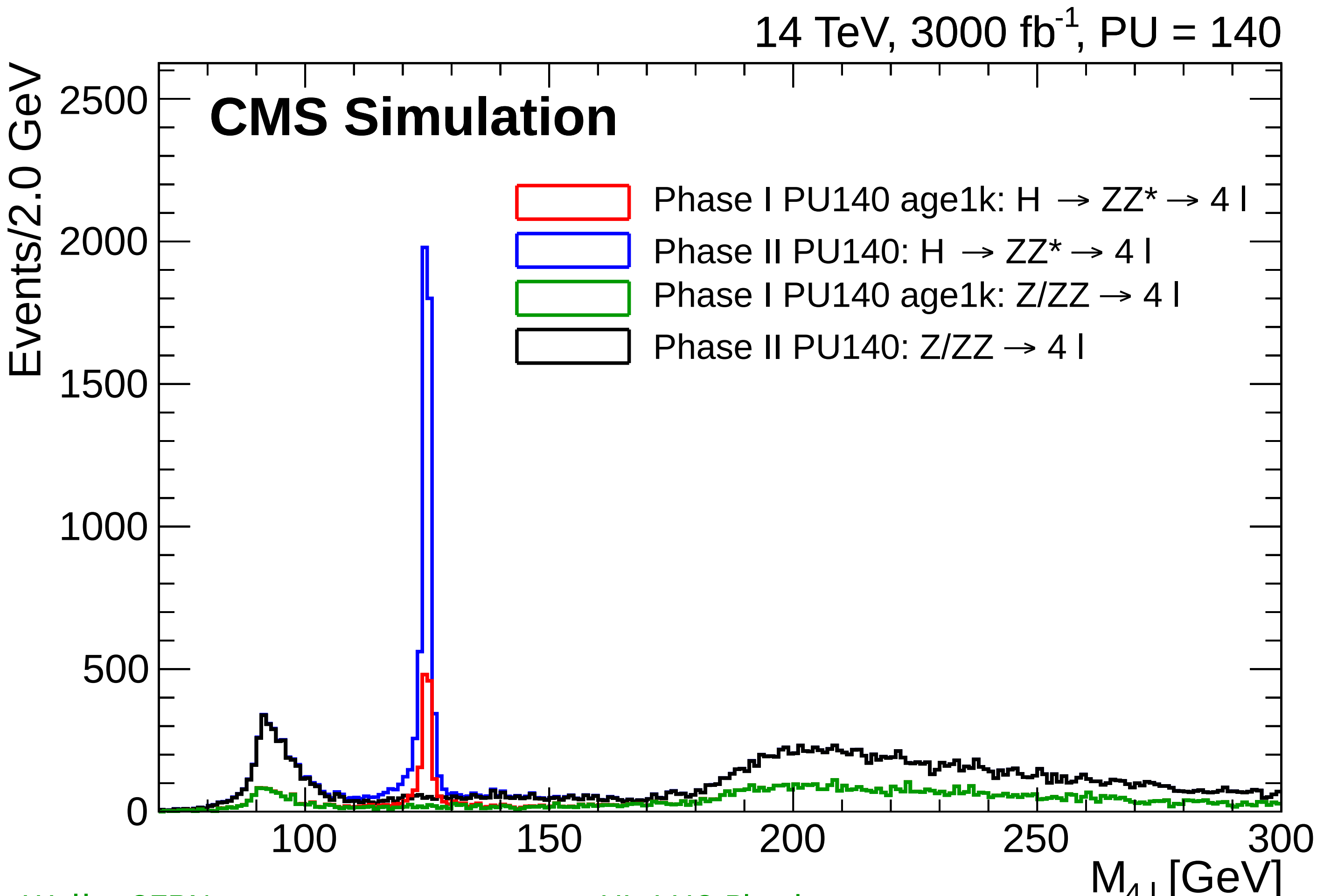


- Vector Boson Fusion and ttH events have extra jets.
- WH, ZH events have extra leptons



CMS H→4l

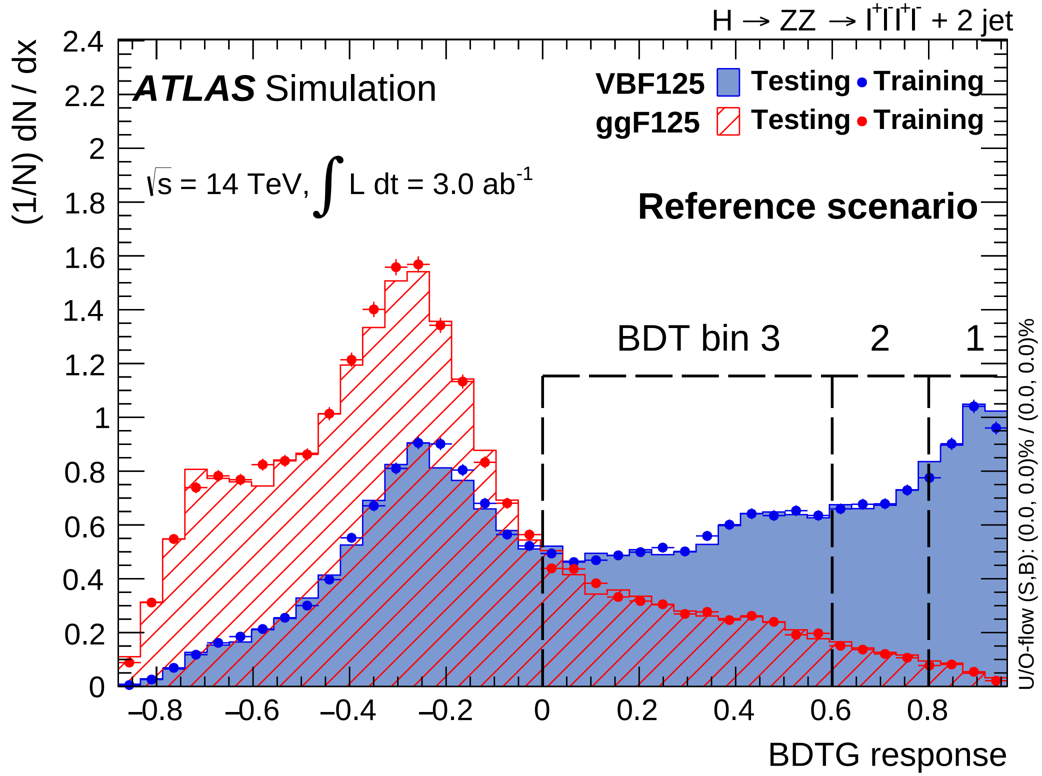
- 20% more 4μ events by extending acceptance to |η|<3.0
  - Important for differential/fiducial measurements
- Improved mass resolution resolution (from e and μ)



ATLAS new result for VBF H→ZZ→4l

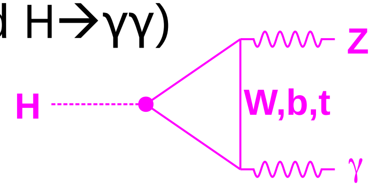
- Old result, PU = 140, cut on m_{jj} > 350 GeV
  - $\Delta\mu/\mu$ (stat + experimental) = 0.293
- New result, PU = 200, use a BDT to distinguish ggF and VBF. Also improved pileup jet rejection from forward tracking.
  - $\Delta\mu/\mu$ (stat + experimental) = 0.134

- Just one example – more sophisticated techniques not yet propagated through HL-LHC projections

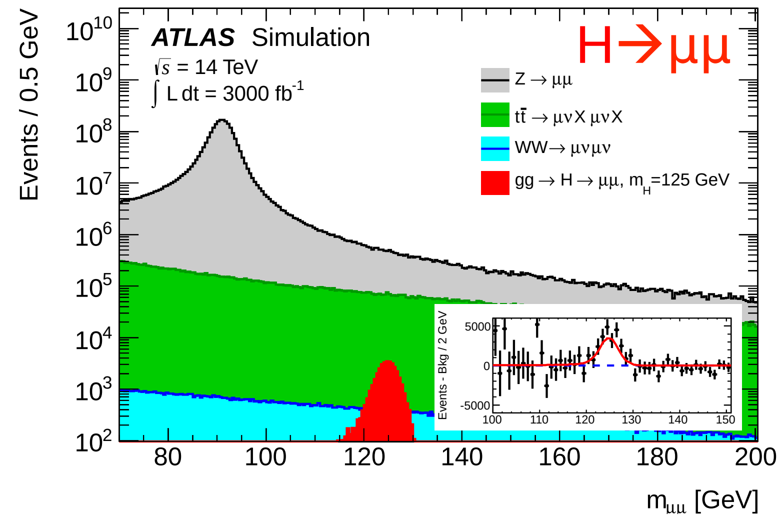


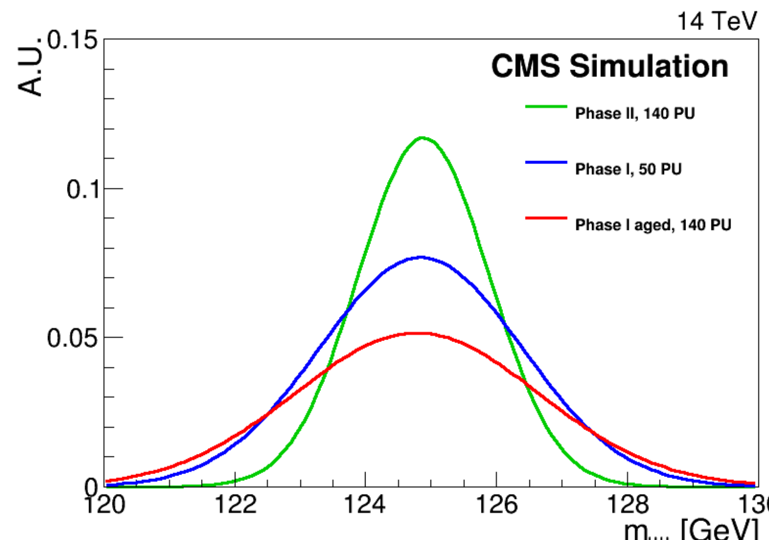
Rare processes

- $H \rightarrow \mu\mu$ – second generation
  - ATLAS and CMS expect >7σ significance with 3000 fb^{-1}
  - → coupling measured to 5-10%
- ttH, $H \rightarrow \mu\mu$ (ATLAS)
  - ~30 signal events in 3000 fb^{-1} but good signal:background
- $H \rightarrow Z\gamma$
  - Tests the loop structure of the decay (compare with $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$)



  - ~4σ significance possible with 3000 fb^{-1} despite the challenging background



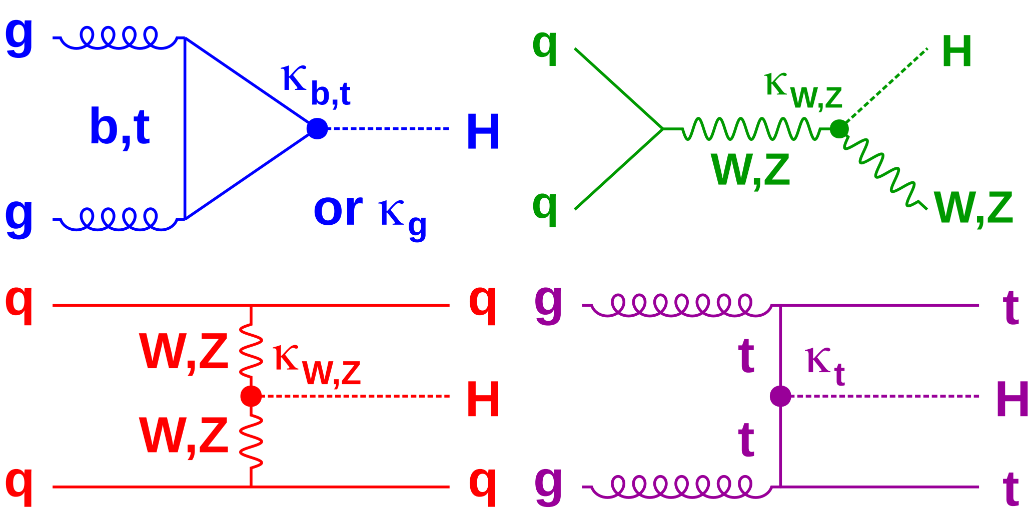


CMS $H \rightarrow \mu\mu$ coupling precision improves from 8% to 5% with Phase II upgrade

Interpretation as coupling scale factors

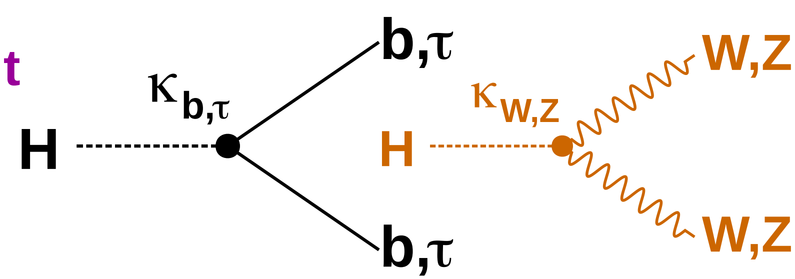
- Experiments measure cross section times branching ratio
- Interpretation with coupling scale factors, κ, is model dependent

gluon-gluon fusion

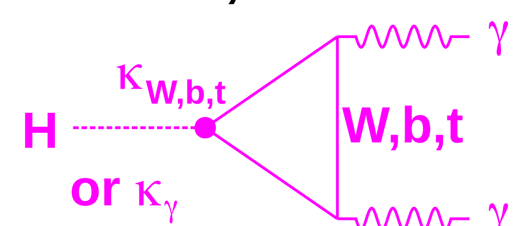


vector boson fusion, VBF

Production → cross section



Decay → branching ratio

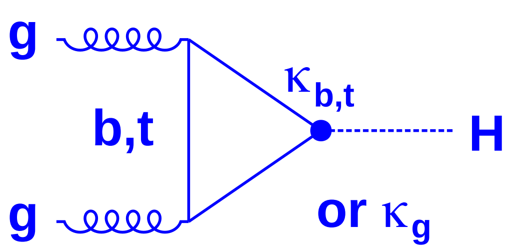


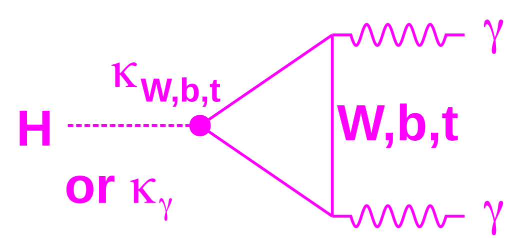
Coupling fits - the small print…

- The cross section times branching ratio for initial state *i* and final state *f* is given by

$$\sigma \cdot Br(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

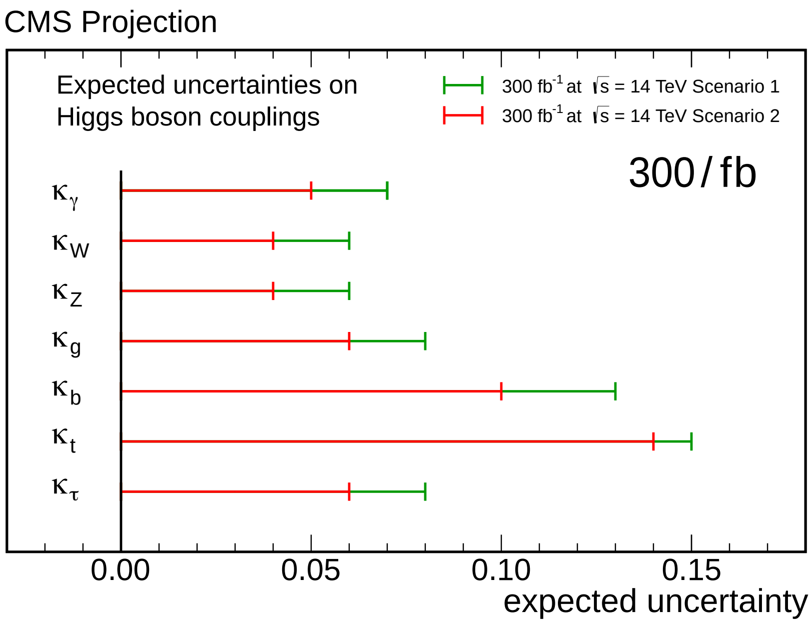
- The total width Γ_H is too narrow to measure directly
  - Assume it is the sum of the visible partial widths – no additional invisible modes
  - (Charm coupling is assumed to scale with top coupling)
- Cross sections and branching ratios scale with κ^2 ($\rightarrow \Delta\kappa \sim 0.5\ \Delta\mu$)
- Gluon and photon couplings can be assumed to depend on other SM couplings, or to be independent to allow for new particles in the loop

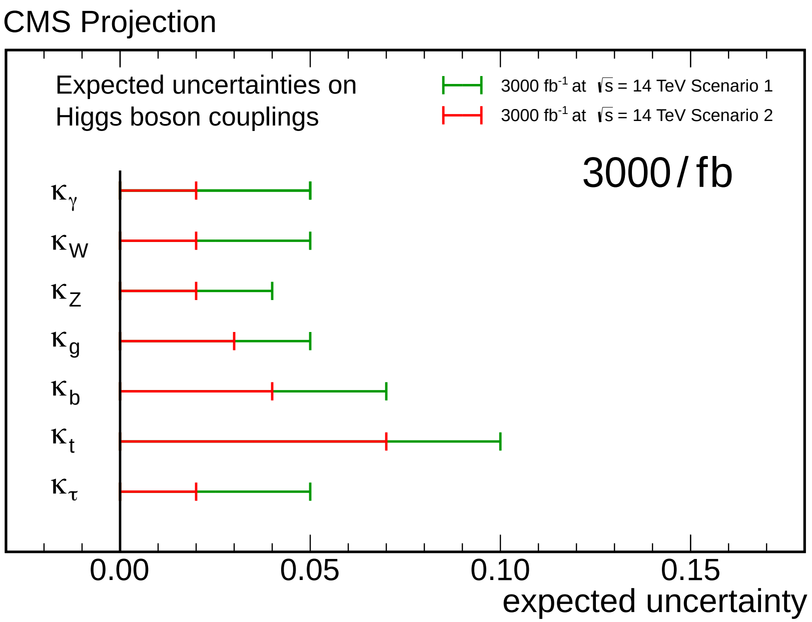




General coupling fit

- Photon, gluon, heavy fermions each have have their own scale factor





- ATLAS and CMS general coupling fits compared (%)

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]

Coupling ratios

- Systematic uncertainties partly cancel
- Ratios are almost model independent

$L(\mathrm{fb}^{-1})$	Exp.	$\frac{\kappa_g \cdot \kappa_Z}{\kappa_H}$	$\frac{\kappa_\gamma}{\kappa_Z}$	$\frac{\kappa_W}{\kappa_Z}$	$\frac{\kappa_b}{\kappa_Z}$	$\frac{\kappa_\tau}{\kappa_Z}$	$\frac{\kappa_Z}{\kappa_g}$	$\frac{\kappa_t}{\kappa_g}$	$\frac{\kappa_\mu}{\kappa_Z}$	$\frac{\kappa_{Z\gamma}}{\kappa_Z}$
300	ATLAS	[4,6]	[5,6]	[5,5]	[17,18]	[11,12]	[10,13]	[15,17]	[20,20]	[23,23]
	CMS	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	ATLAS	[2,6]	[2,3]	[2,3]	[7,10]	[8,9]	[5,9]	[5,9]	[6,6]	[14,14]
	CMS	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]

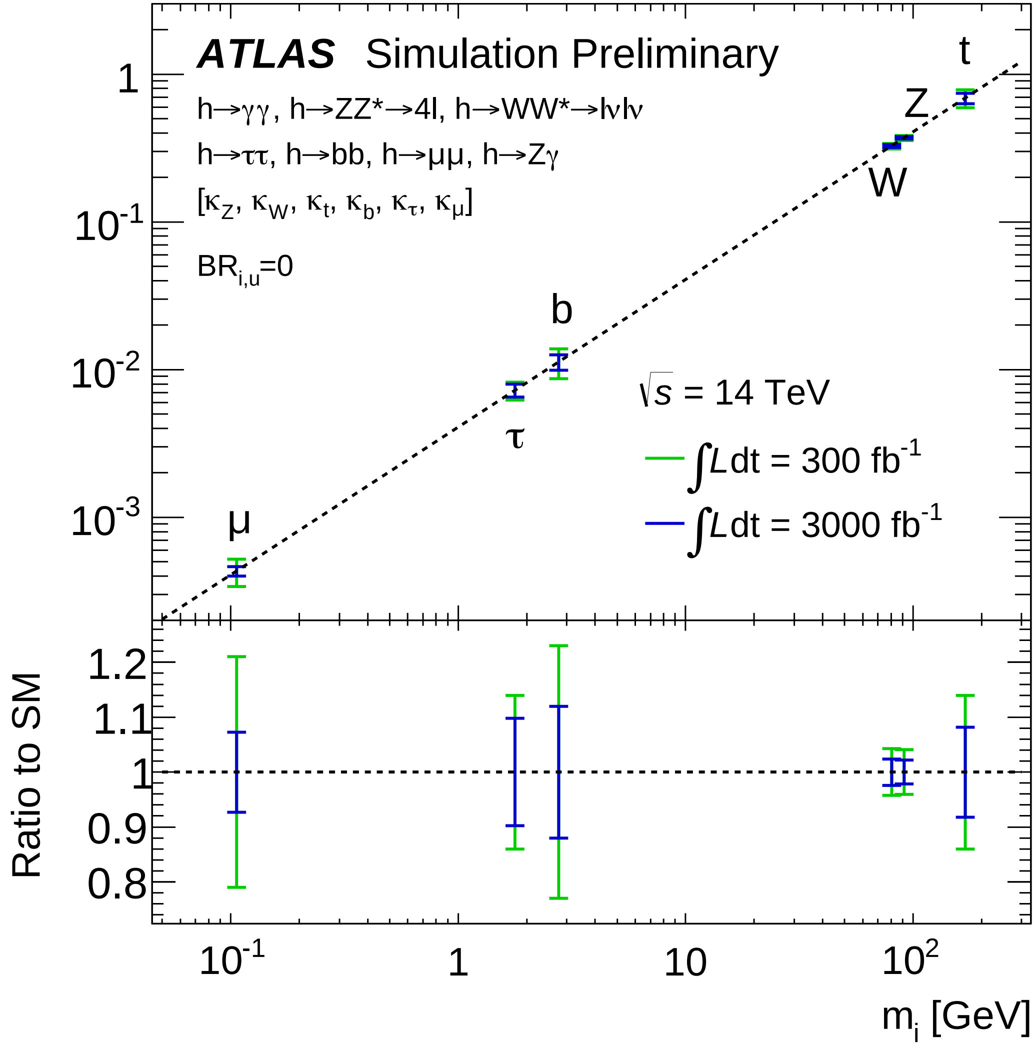
- This results in better agreement between the two experiments
  - Can achieve 2~3% precision in main channels if systematic uncertainties are controlled
- HL-LHC yields a factor 2~3 improvement in coupling ratio determination

Mass scaled couplings

- Coupling factors plotted as a function of particle mass

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

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



Theoretical uncertainties

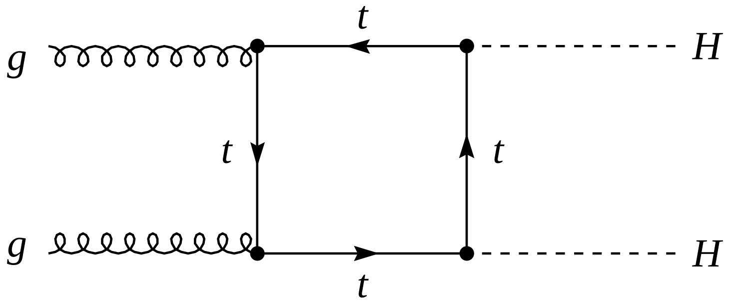
- ATLAS: Deduced size of theory uncertainty to increase total uncertainty by <10% of the experimental uncertainty
  - (MHOU - missing higher order uncertainty)

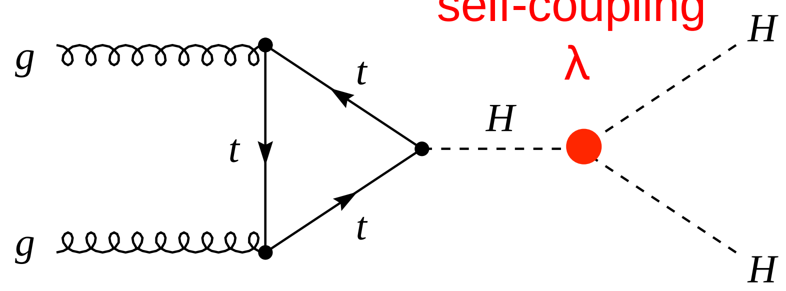
Scenario	Status 2014	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j $\to$ 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j $\to$ 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j $\to$ VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j $\to$ VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

[10-12] LHC Higgs Cross Section Working Group

Higgs boson pair production

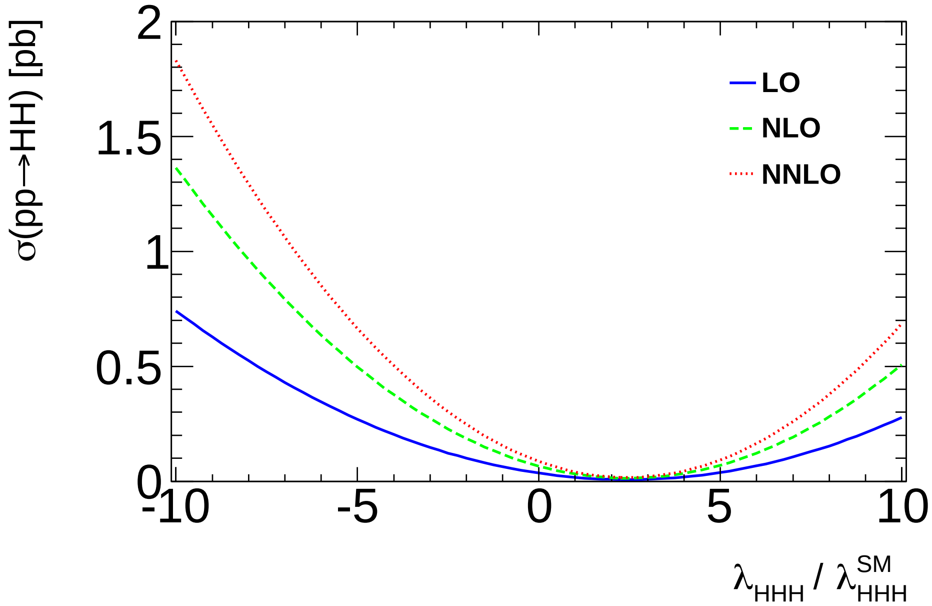
- Higgs boson pair production includes destructive interference between two types of processes:





- ~factor 2 increase in cross section if $\lambda \rightarrow 0$

NNLO σ^{SM}=40.8 fb

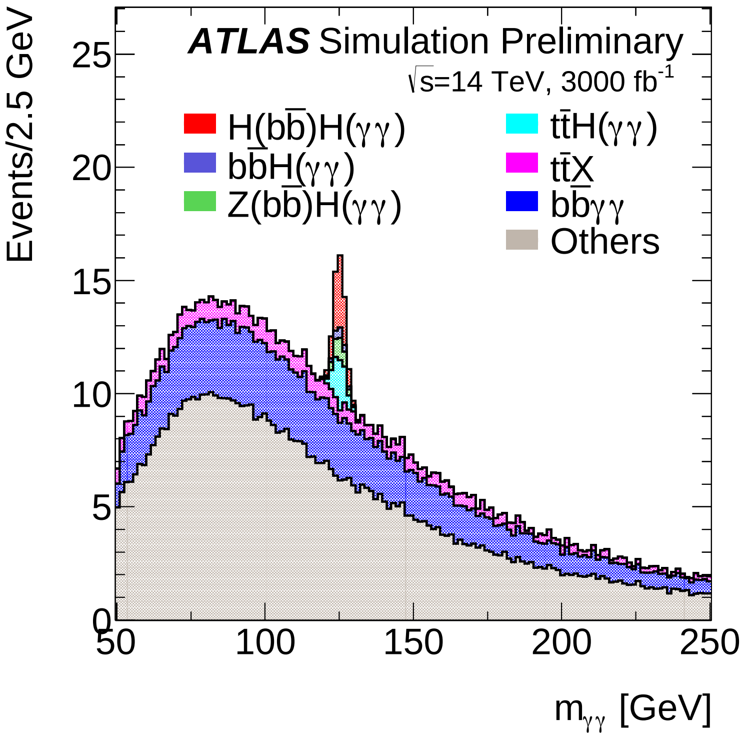


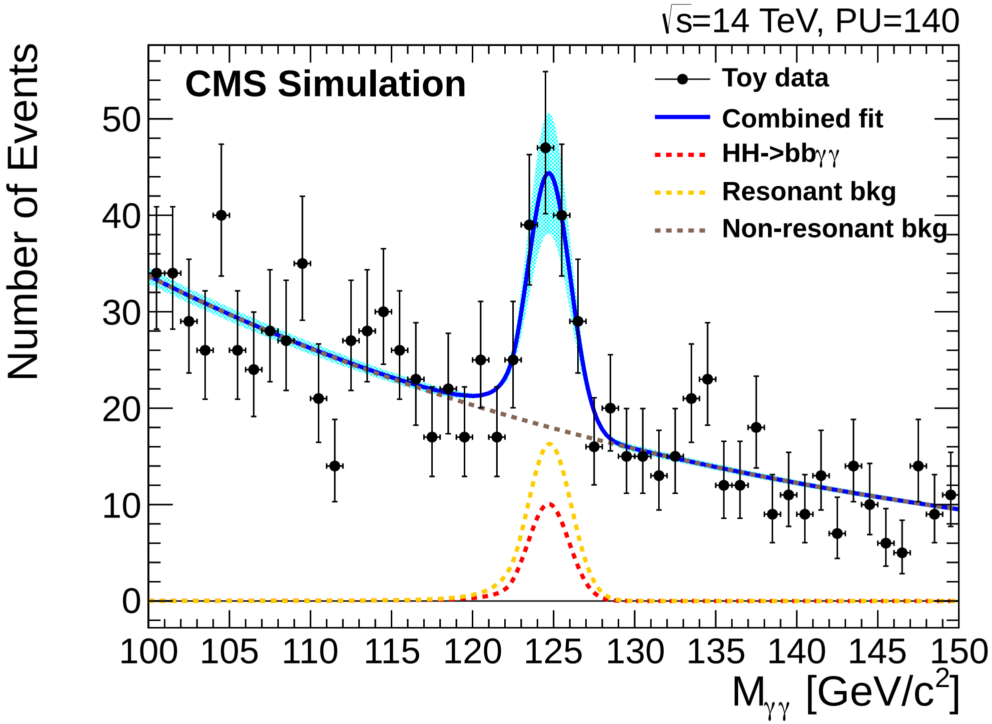
Number of events	
bbWW	30000
$bb\tau\tau$	9000
WWWW	6000
$\gamma\gamma$ bb	320
$\gamma\gamma\gamma\gamma$	1

ATL-PHYS-PUB-2014-019
CMS CERN-LHCC-2015-010

HH→bbγγ

- Parametrised object performances
  - CMS 2d fit of m(bb) and m(γγ) distributions (control background from data)
  - ATLAS cut based analysis
  - bb mass peak is broad. γγ shows narrow resonance





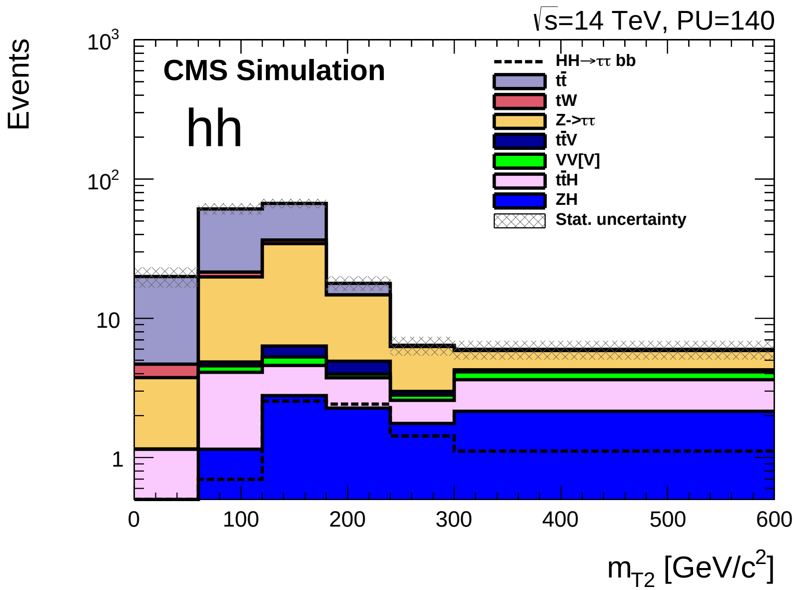
bbγγ results

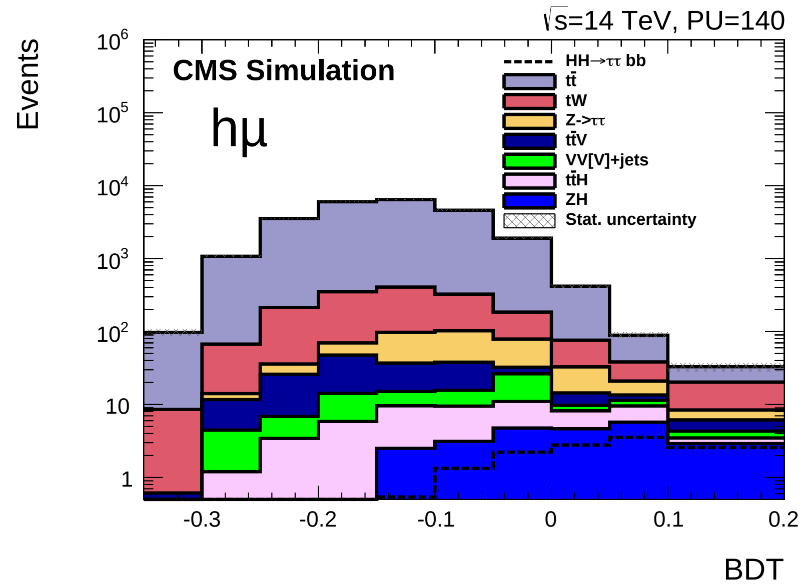
- Numbers of events in 3000 fb^{-1} in signal mass windows
  - CMS preferred result uses a likelihood fit in a larger mass range, which gives 67% relative uncertainty on the signal
  - Differences understood - due to assumptions in b/γ performance

process	ATLAS		CMS
SM HH→bbγγ	8.4± 0.1		9.0
bbγγ	9.7 ± 1.5	γγ+jets	13.0
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2	γ+jets, jets	7.4
top background	3.4 ± 2.2		1.2
ttH(γγ)	6.1 ± 0.5		1.6
Z(bb)H(γγ)	2.7 ± 0.1		3.4
bbH(γγ)	1.2 ± 0.1		0.8
Total background	47.1 ± 3.5		27.4
S/√B (barrel+endcap)	1.2		
S/√B (split barrel and endcap)	1.3		

CMS HH→bbττ

- Major background from ttbar, with t→τνb
  - Kinematic variables to distinguish signal from background





- Combining $\tau_h\tau_h$ and $\tau_h\tau_\mu$ gives 105% signal uncertainty
- Combining bbγγ and bbττ: 1.9σ significance, 54% signal uncertainty

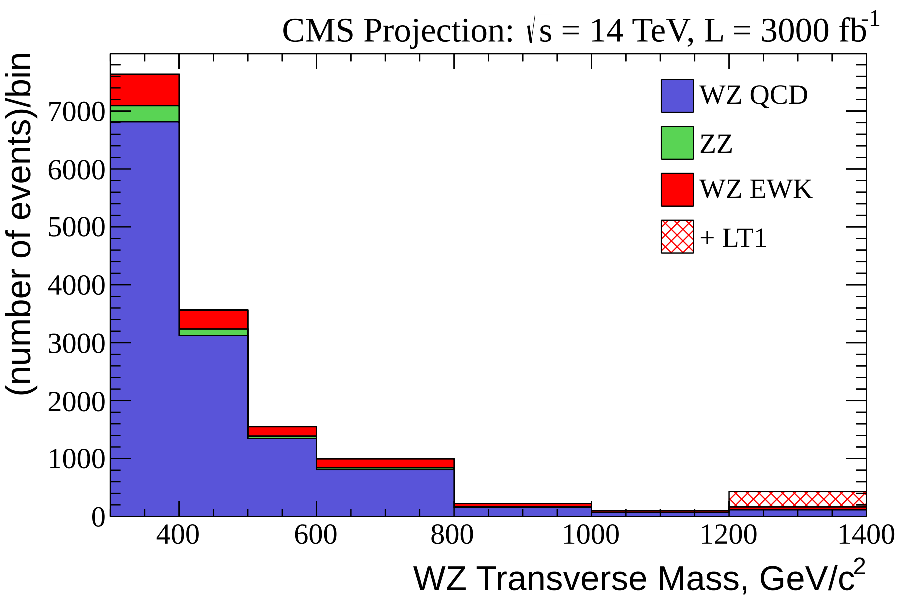
- HH→bbWW, 37.1 signal events with 3875 background (ttbar) → 200% uncertainty on signal strength

Beyond the Standard Model

ATLAS CERN-LHCC-2015-020
CMS-PAS-FTR-13-006
CMS CERN-LHCC-2015-010

Vector Boson Scattering

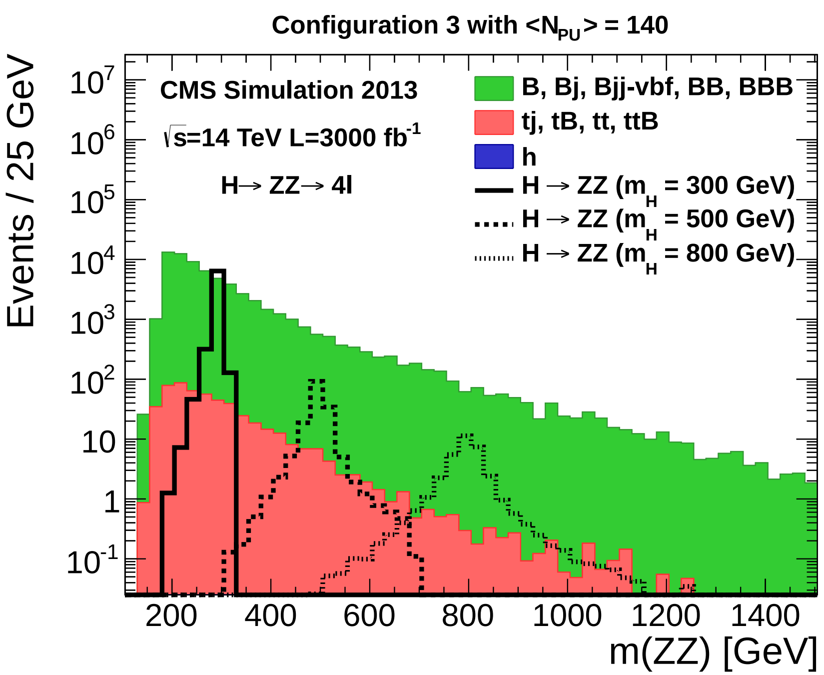
- Explore electroweak symmetry breaking through VBS
  - Distinguish electroweak and QCD induced processes
  - Same sign WW pair production and WZ final states
  - CMS: interpretation as limits on dimension-eight operators f_X/Λ^4 [arXiv:hep-ph/0606118].



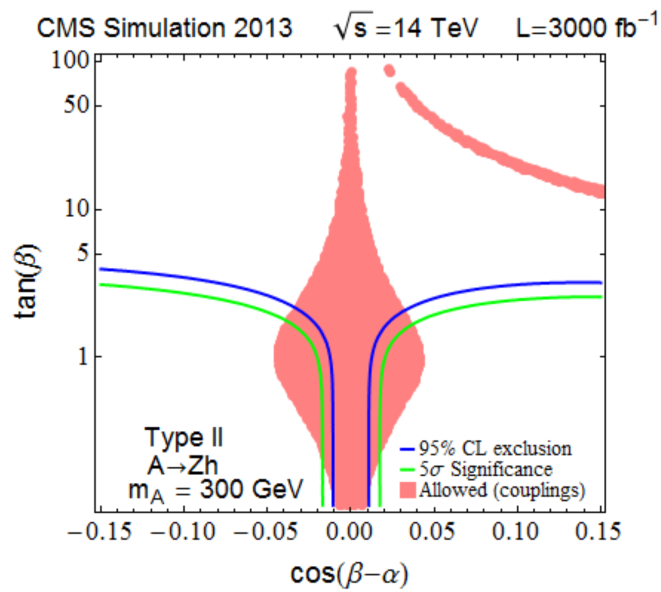
Coeff.	Channel	Limit [TeV^{-4}]
T1	WZ (3σ)	0.45
S0	WW (95% CL)	1.07
S1	WW (95% CL)	3.55
T1	WW (95% CL)	0.033

BSM Higgs direct/indirect searches

- Models such as supersymmetry require more Higgs bosons
  - Neutral: h,H,A ; Charged: H^+, H^- ("2 Higgs doublet model")
- Direct searches complemented by constraints from coupling fits
  - If the 125 GeV Higgs boson (which is "h" in this model) looks very like the SM Higgs, it rules out some other possibilities



Trial heavy H→ZZ signals



Coupling fits constrain angles α and β
Direct search results for A→Zh depend on the mass of the A

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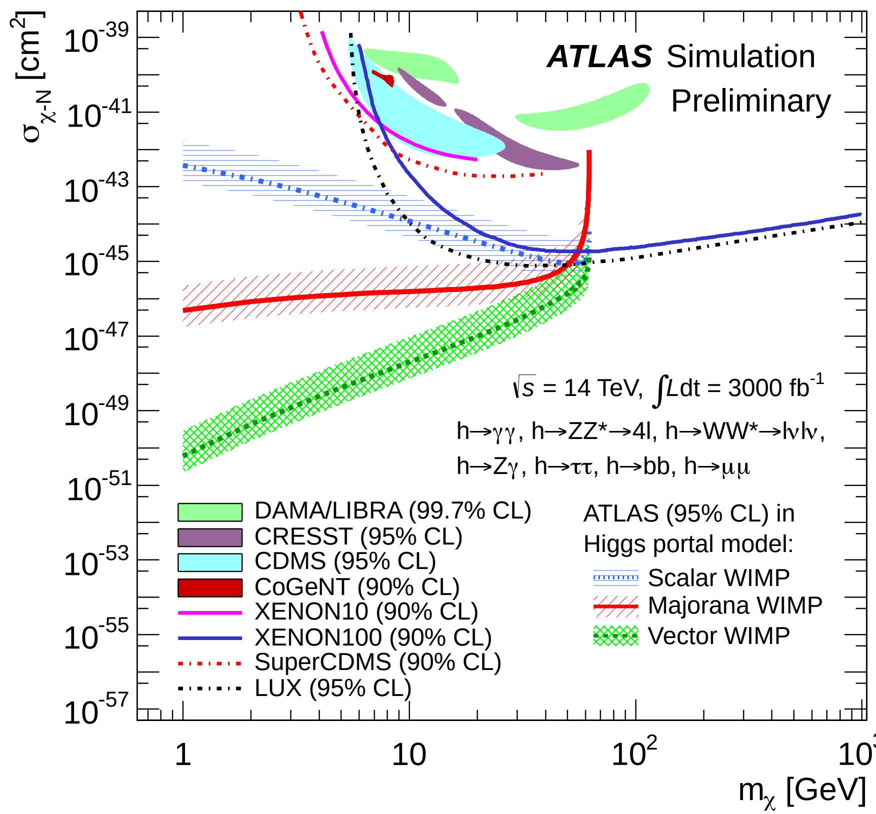
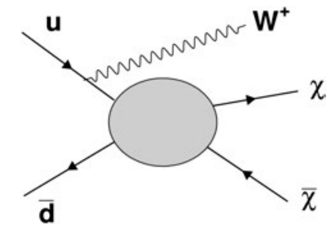
Higgs portal to Dark Matter

- BR of Higgs decays to invisible final states
  - ATLAS: BR_{inv}< 0.13 (0.09 w/out theory uncertainties) at 3000fb^{-1}
  - CMS: BR_{inv}< 0.11 (0.07 in Scenario 2) at 3000fb^{-1}
- The coupling of WIMP to SM Higgs is taken as the free parameter
- Translate limit on BR to the coupling of Higgs to WIMP

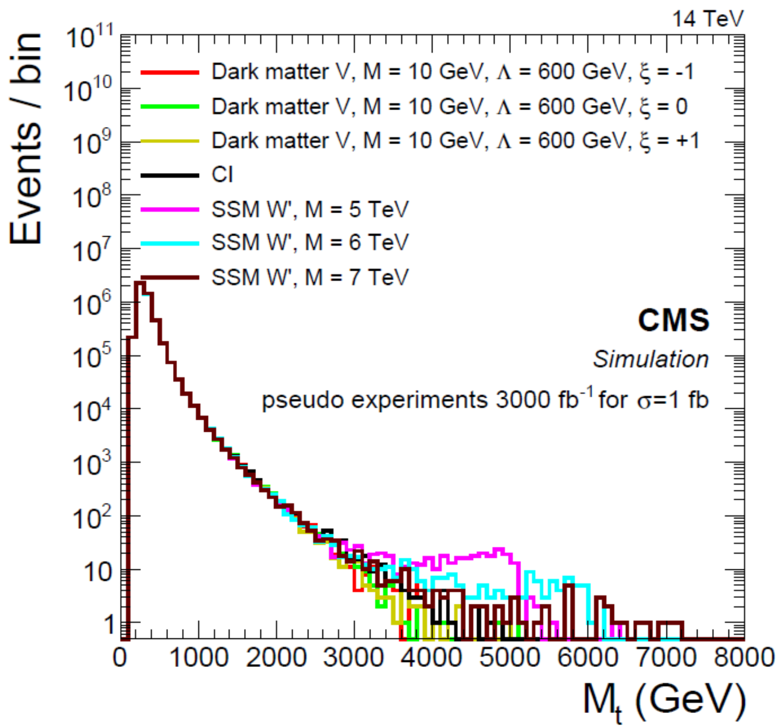


- LHC complements direct DM search experiments in the lower mass range

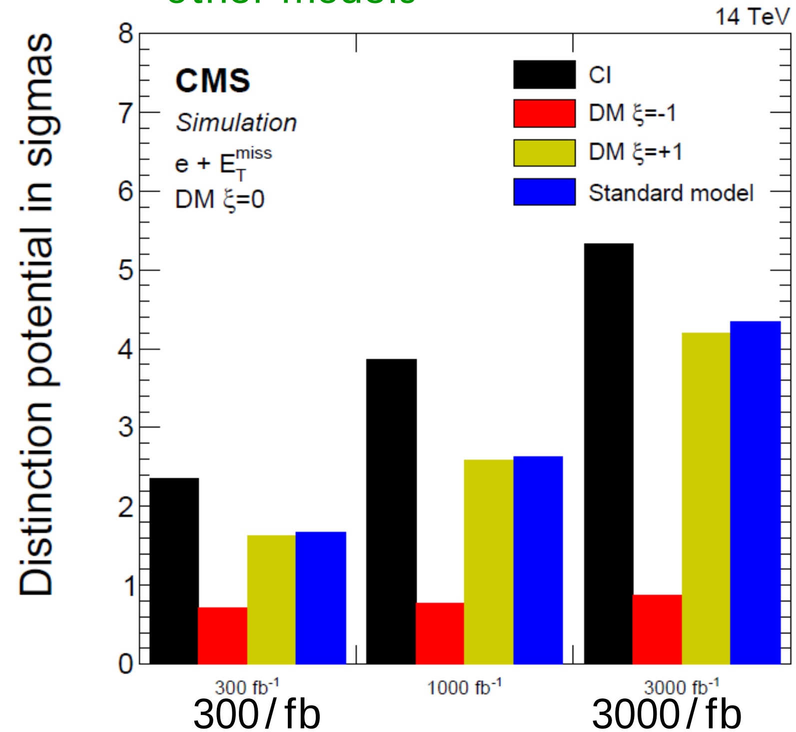
Mono-X searches for dark matter



- DM pair production with eg. initial W→lv
- Shape discrimination in transverse mass distribution
  - Also probes contact interactions in qq→lv and W' production
  - Significant separation between a DM model and Standard Model only achieved at HL-LHC

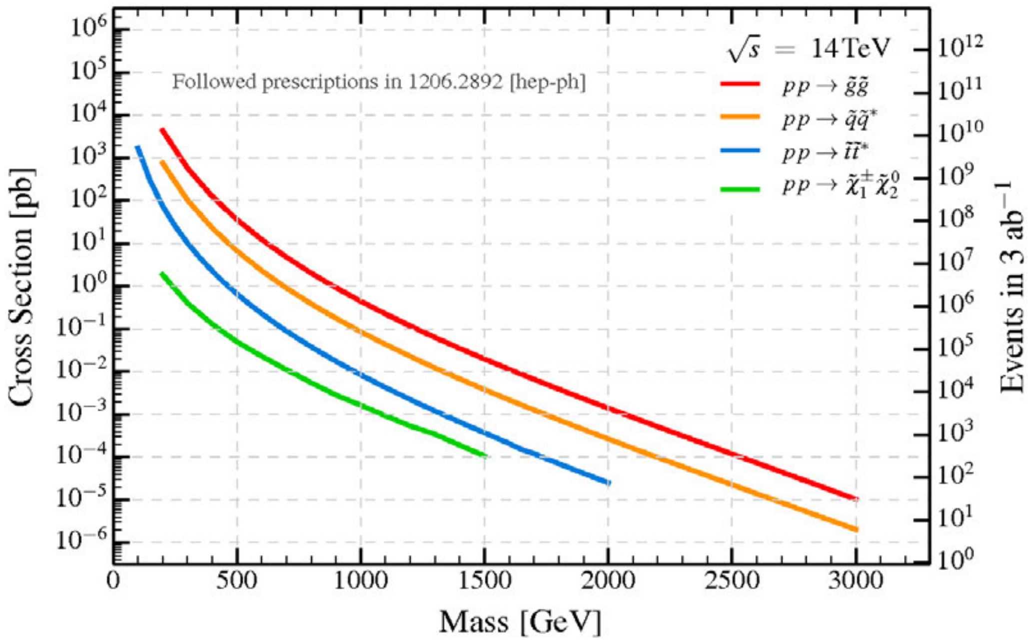


Distinction between DM ξ=0 and other models

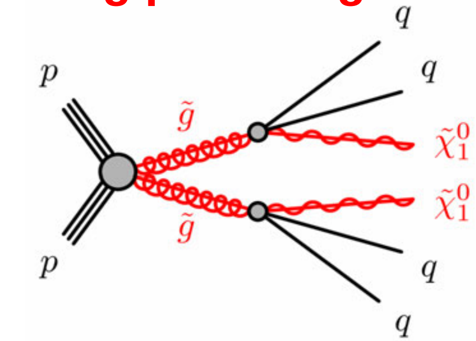


Supersymmetry

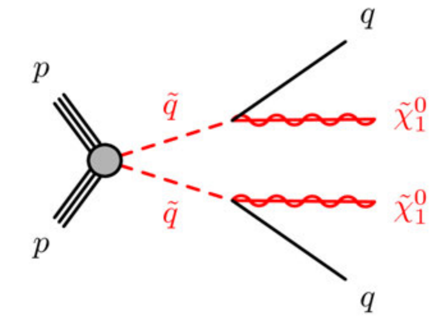
Motivated by naturalness, dark matter…



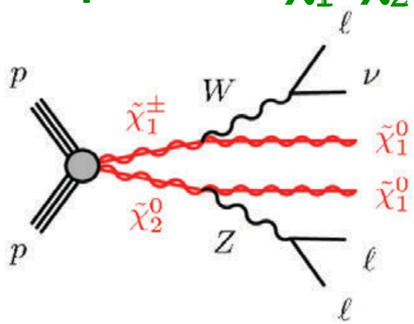
Strong prod. of gluinos



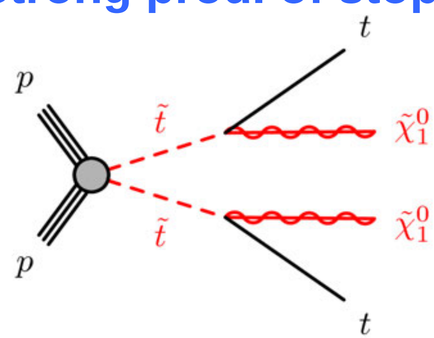
Strong prod. of squarks



EW prod. of $\chi_1^{+}\chi_2^{0}$



Strong prod. of stops



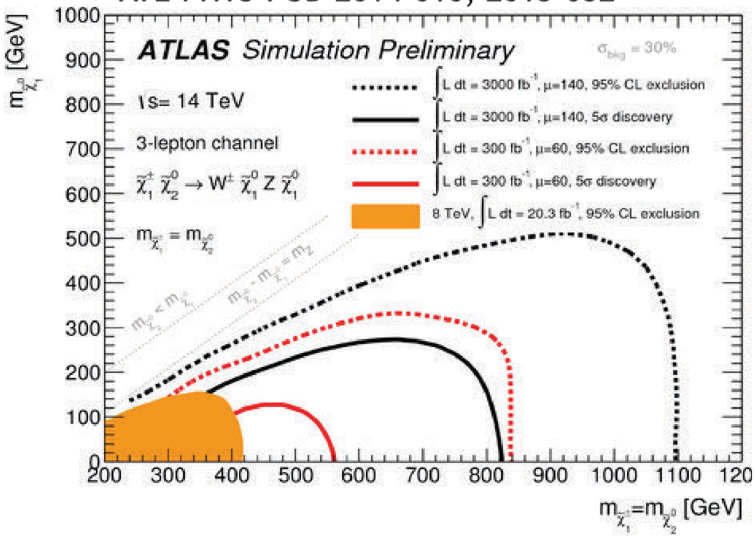
Stop, sbottom, gluino and higgsino tend to be light in natural models.

Consider simplified and full-spectrum models

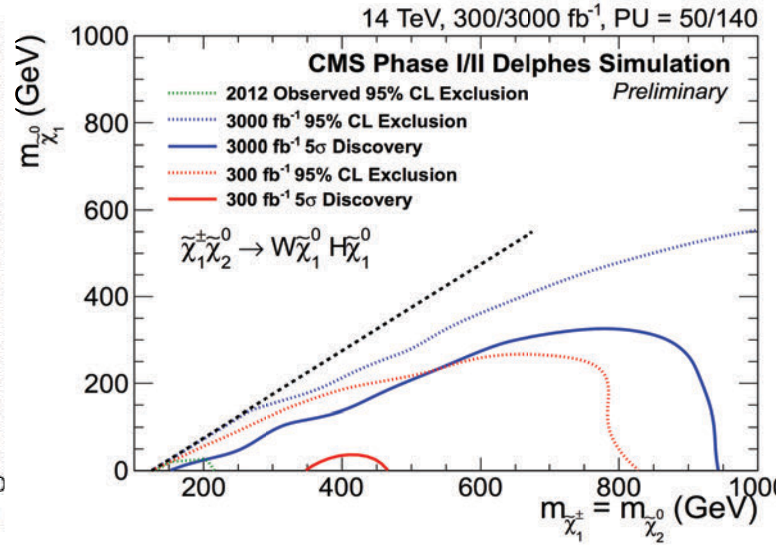
Electroweak processes eg $\chi_1^{\pm}\chi_2^0$ production

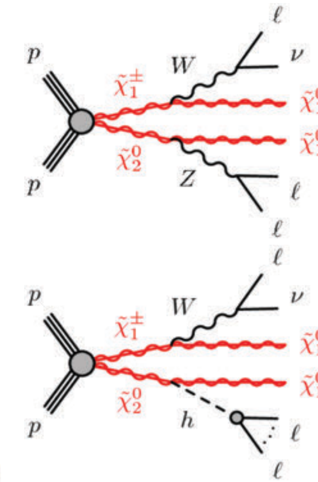
- Weak process – benefit from high luminosity

ATL-PHYS-PUB-2014-010, 2015-032



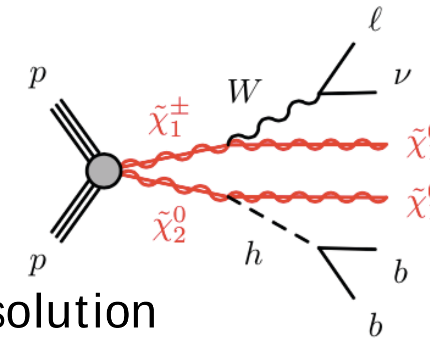
CMS PAS SUS-14-012



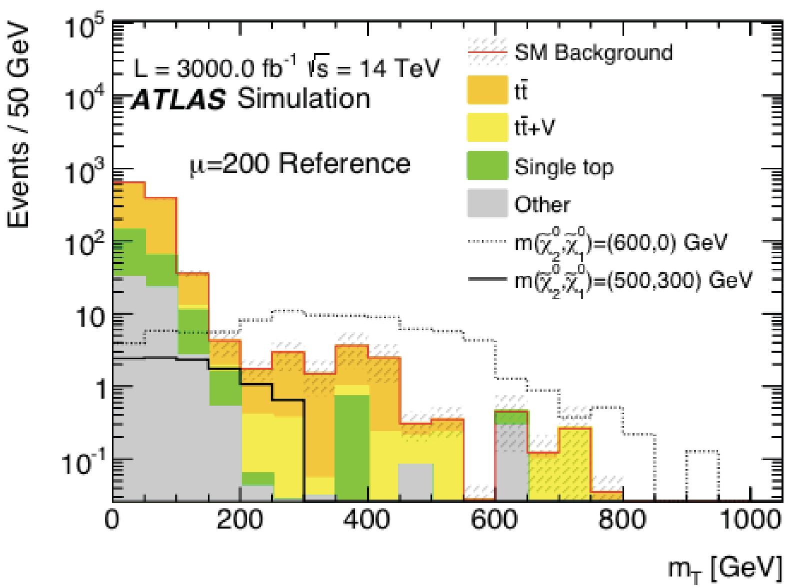


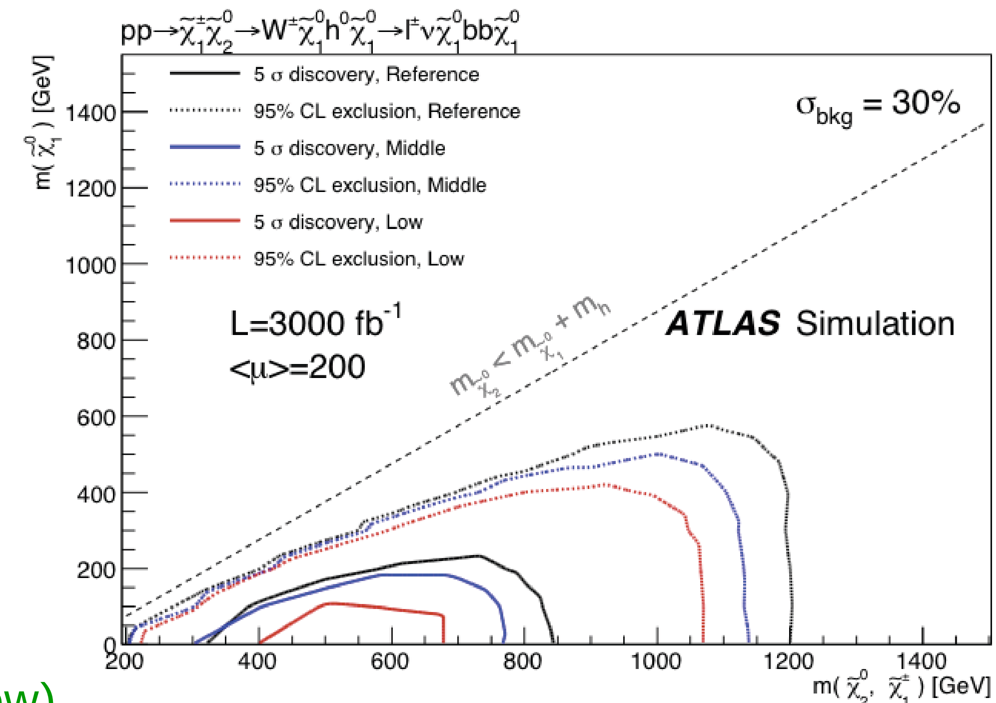
Chargino mass 5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
WZ (3l analysis) [ATLAS]	Up to 560 GeV	Up to 820 GeV
WZ (3l analysis) [CMS]	Up to 600 GeV	Up to 900 GeV
WH (3l analysis) [ATLAS]	(<5σ reach)	Up to 650 GeV
WH (bb analysis) [ATLAS] (new in 2015)	(<5σ reach)	Up to 800 GeV
WH (bb analysis)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

Example of scoping exercise, WH(bb)



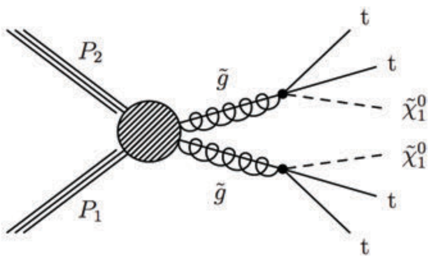
- Lepton and 2 b-jets with E_T^{miss}
- Main backgrounds ttbar, single top, W+jets, ttW, ttZ
  - Sensitive to modelling of leptons, b-tagging, E_T^{miss} resolution
  - Three scenarios, Reference, Middle, Low



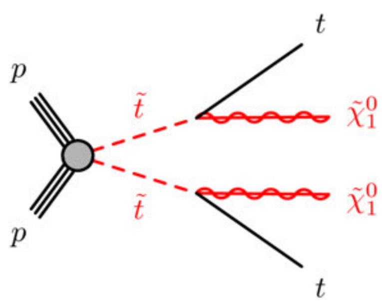


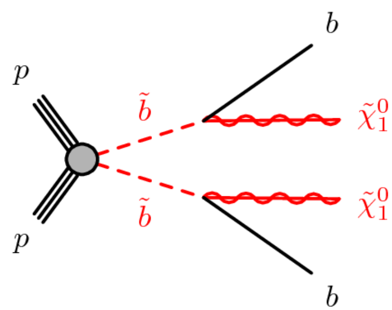
- Mass reach in GeV:
  850 (Ref), 770 (Mid), 675 (Low)
- Need 6000 (12000)/fb in Mid. (Low) to match the reach of Ref.

Stop and sbottom

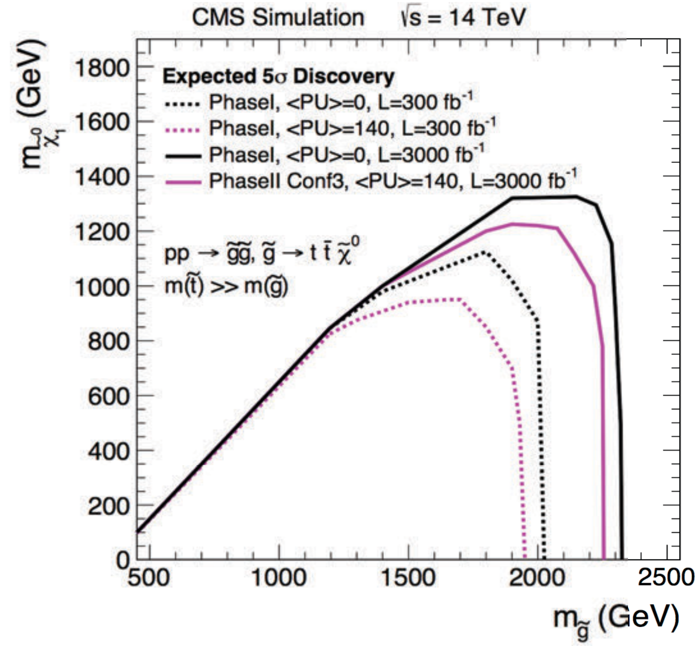


- Naturalness motivates stop/sbottom searches where the third family squarks are lightest
    - ATLAS stop & sbottom pair production





CMS PAS FTR-13-014



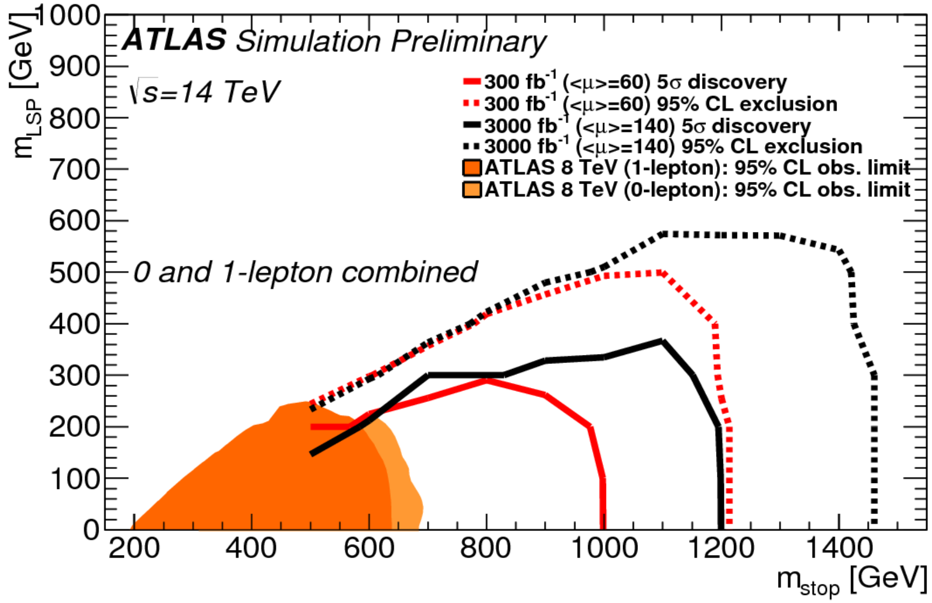
- CMS gluino pair production with decay via stop to ttχ

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

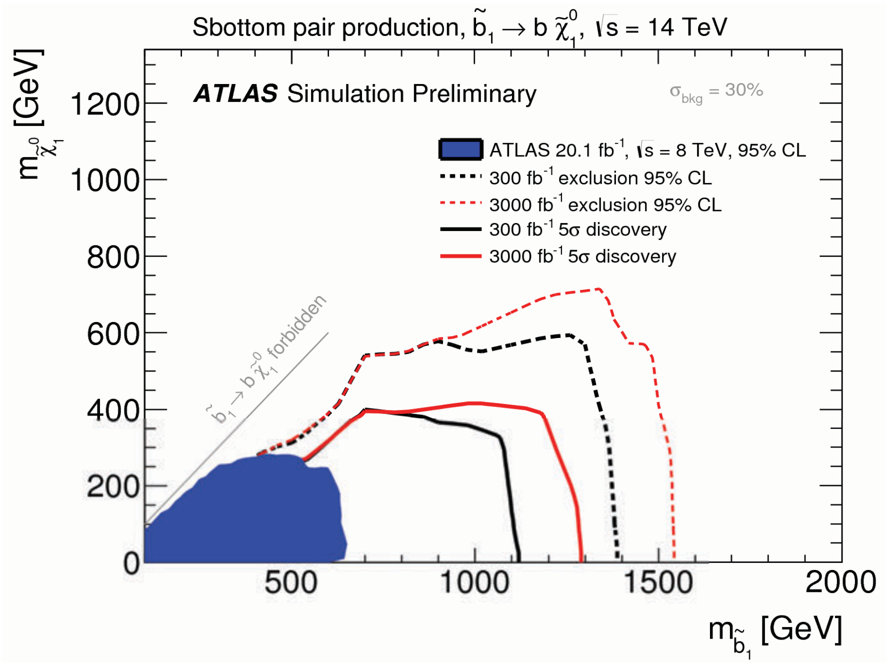
ATLAS stop/sbottom

- Results in m(LSP)-m(squark) plane from simplified models

ATL-PHYS-PUB-2013-011



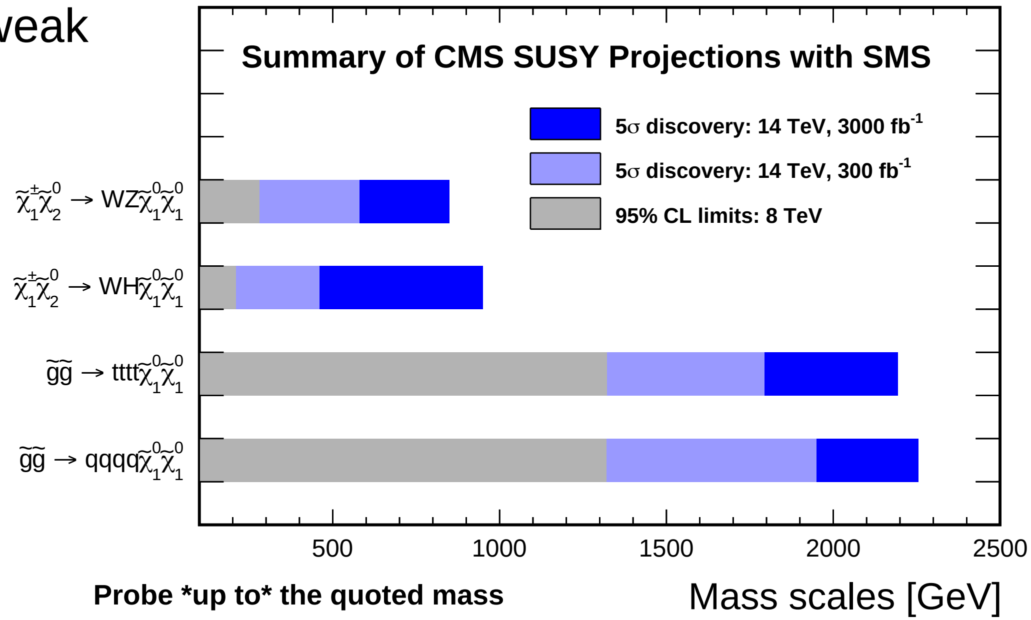
ATL-PHYS-PUB-2014-010



Summary of simplified models

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

- HL-LHC increases discovery reach by
  - ~20% for gluino, squark, stop
  - ~50 to 100% for electroweak production of $\chi_1^+\chi_2^0$



Probe *up to* the quoted mass

CMS PAS SUS-14-012
CMS CERN-LHCC-2015-019

Full spectrum SUSY models

- 5 different full-spectrum SUSY models which respect DM relic density
  - 3 pMSSM models motivated by naturalness, different LSPs: NM1(2): bino-like with low(high) slepton mass; NM3: higgsino-like
  - 2 p(C)MSSM models with χ_1^0 coannihilation with different nearly mass-degenerate particle: STC = stau ; STOC = stop

- Explored 9 different experimental signatures
- Different models lead to different patterns of discoveries in different final states after different amounts of data

Exploring SUSY model space

Exploring experimental signature space

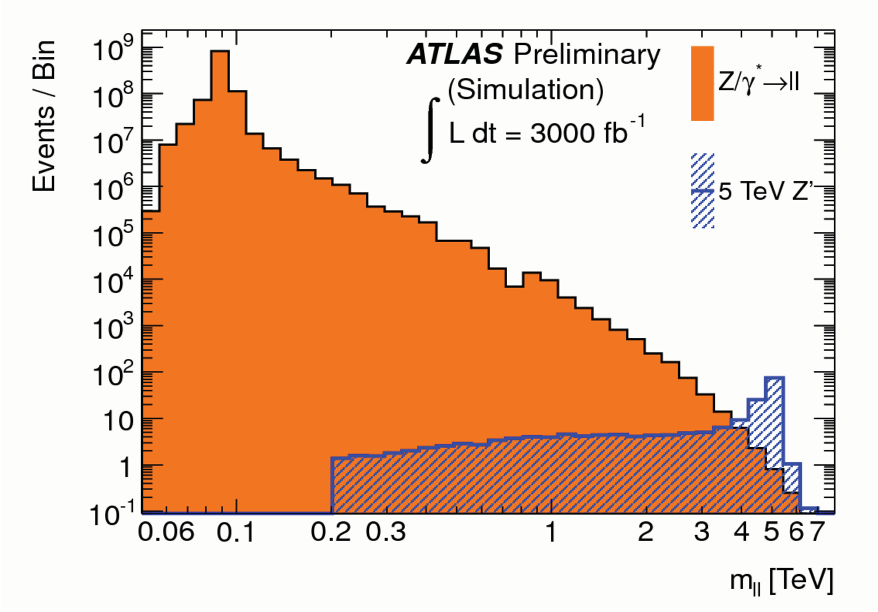
Analysis	Luminosity (fb^{-1})	Model: NM1	NM2	NM3	STC	STOC
all-hadronic (H_T-H_T^{miss}) search	300				$< 3\sigma$	$3-5\sigma$
	3000				$3-5\sigma$	$> 5\sigma$
all-hadronic (M_{T2}) search	300	$3-5\sigma$	$> 5\sigma$	$> 5\sigma$		
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$		
all-hadronic $\tilde{b}_1$ search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$> 5\sigma$	$< 3\sigma$
1-lepton $\tilde{t}_1$ search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	$< 3\sigma$
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$
monojet $\tilde{t}_1$ search	300					$3-5\sigma$
	3000					$3-5\sigma$
$m_{\ell^+\ell^-}$ kinematic edge	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$		
	3000	$> 5\sigma$	$< 3\sigma$	$< 3\sigma$		
multilepton + b-tag search	300	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$3-5\sigma$	
	3000	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	$> 5\sigma$	
multilepton search	300	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	$< 3\sigma$	
	3000	$3-5\sigma$	$3-5\sigma$	$< 3\sigma$	$3-5\sigma$	
ewkino WH search	300		$< 3\sigma$			
	3000		$3-5\sigma$			

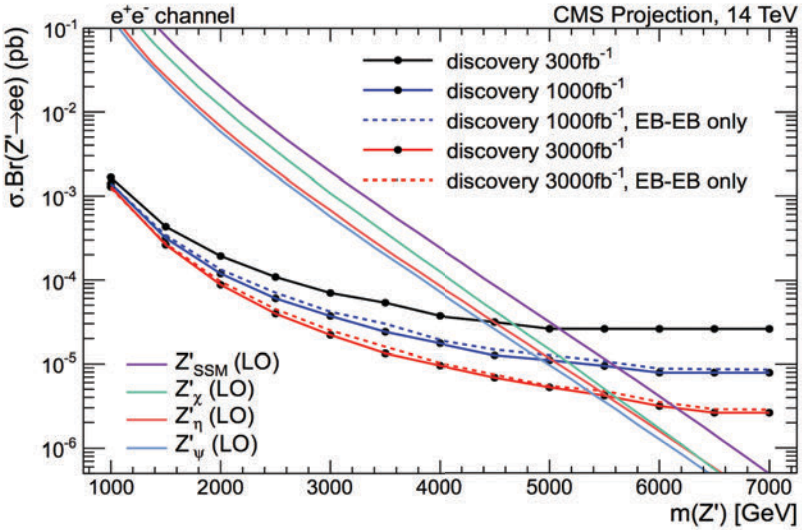
$< 3\sigma$ | $3-5\sigma$ | $> 5\sigma$

Exotica – dilepton resonances

ATL-PHYS-PUB-2013-003
CMS arXiv:1307.7135

- Many extensions of the SM predict new resonances
  - Heavy gauge bosons W' and Z'
  - KK excitations of vector bosons
- Clean decay channels, eg $Z' \rightarrow e^+e^-$ or $\mu^+\mu^-$

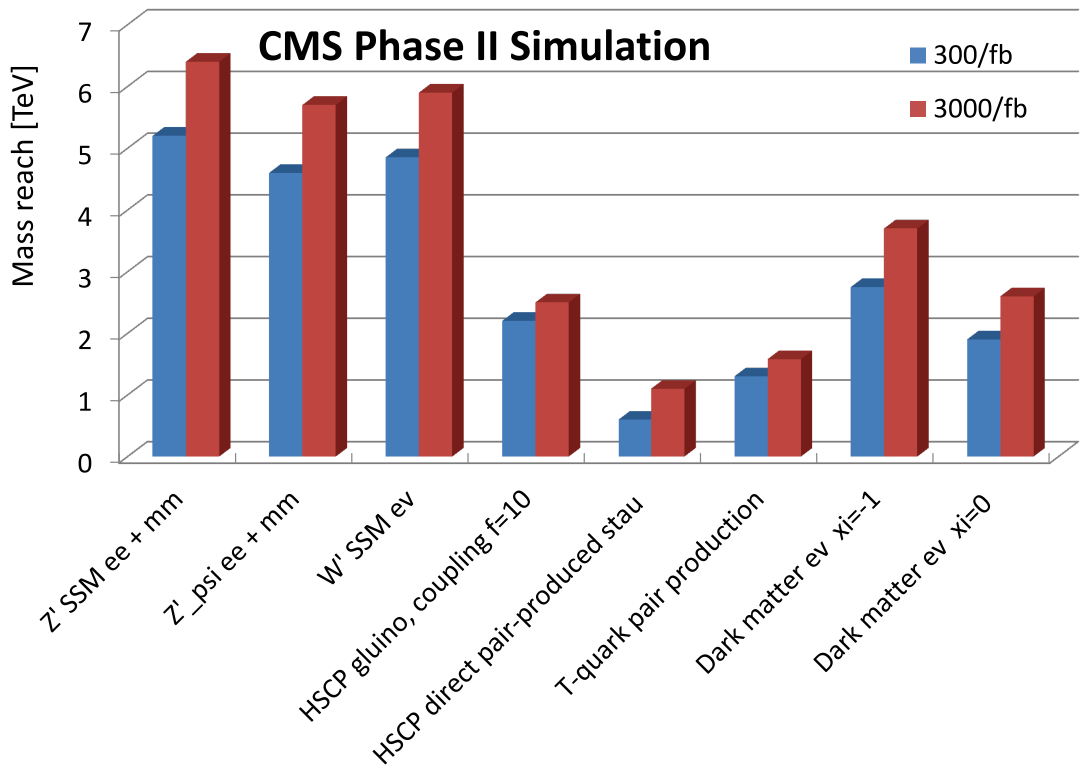




Discovery up to 6.2 TeV (for SSM Z')

Mass reach for exotic signatures

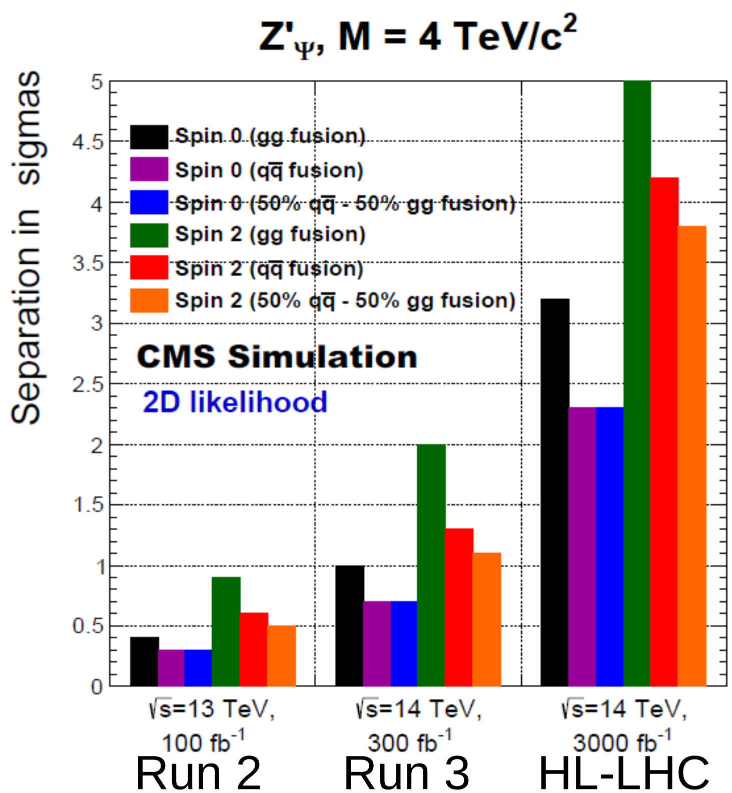
- Sensitivity in multi-TeV range increases by ~20% with HL-LHC

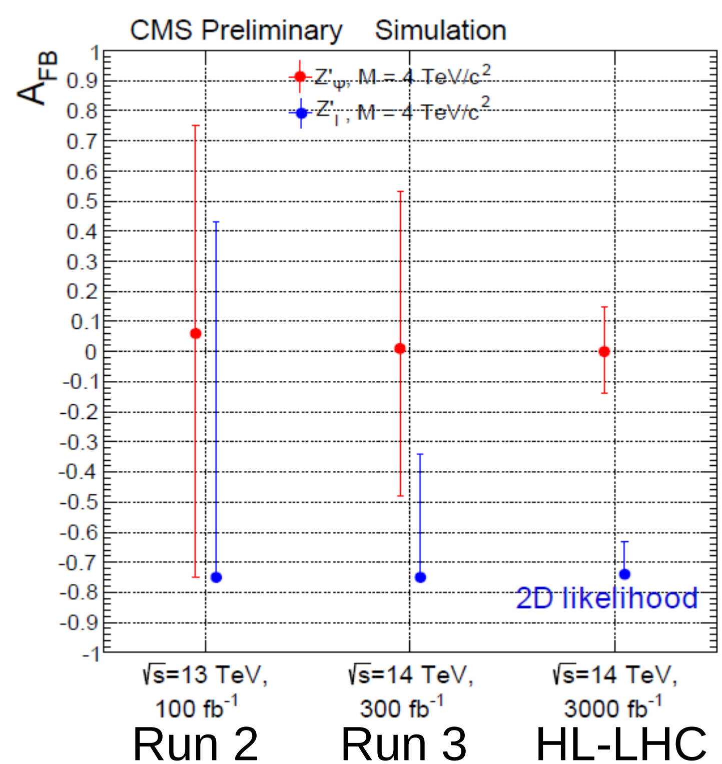


ATLAS @14 TeV	Z' → ee SSM 95% CL limit	$g_{KK} \rightarrow t\,t$ RS 95% CL limit	Dark matter M* 5σ discovery
300 fb^{-1}	6.5 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	7.8 TeV	6.7 TeV	2.6 TeV

Model discrimination after a discovery

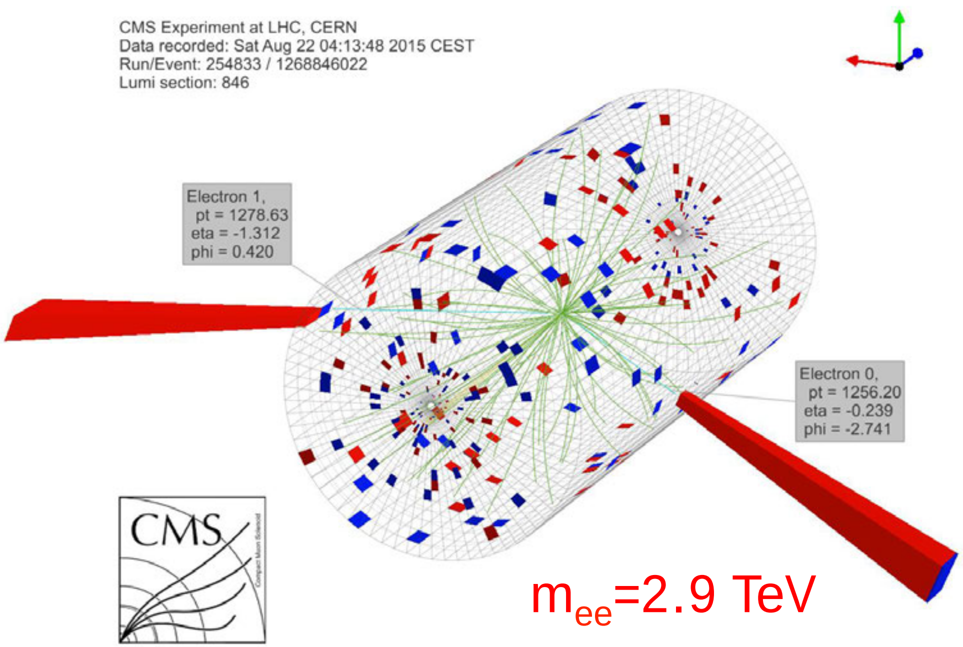
- Ability to discriminate improves dramatically with HL-LHC
  - Separation between spin-1 (Z') and spin-2 (G_{KK}) interpretation or other interpretations ranges from ~2 to 5 σ
  - Use 2d likelihood with dilepton angular and rapidity distributions or forward-backward asymmetry

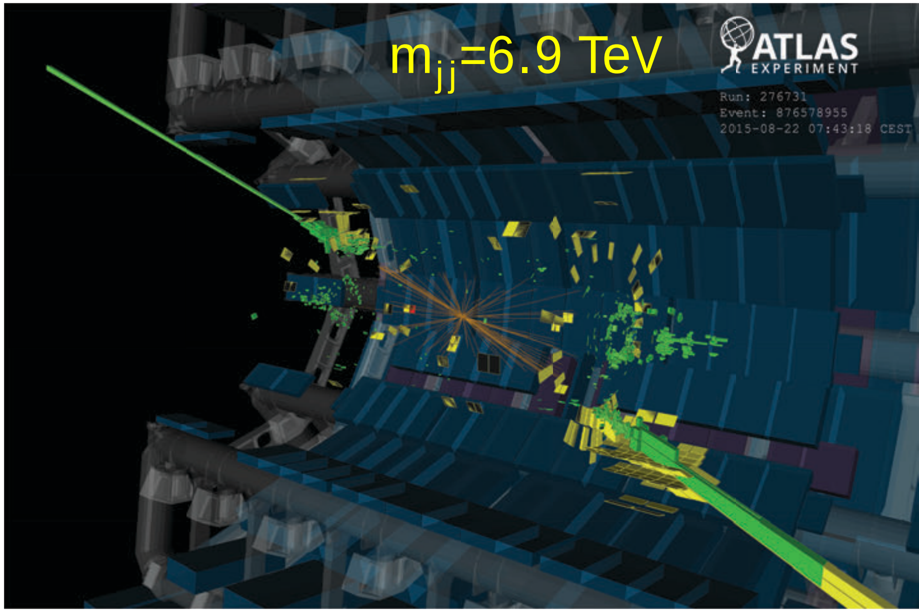




Conclusion and outlook

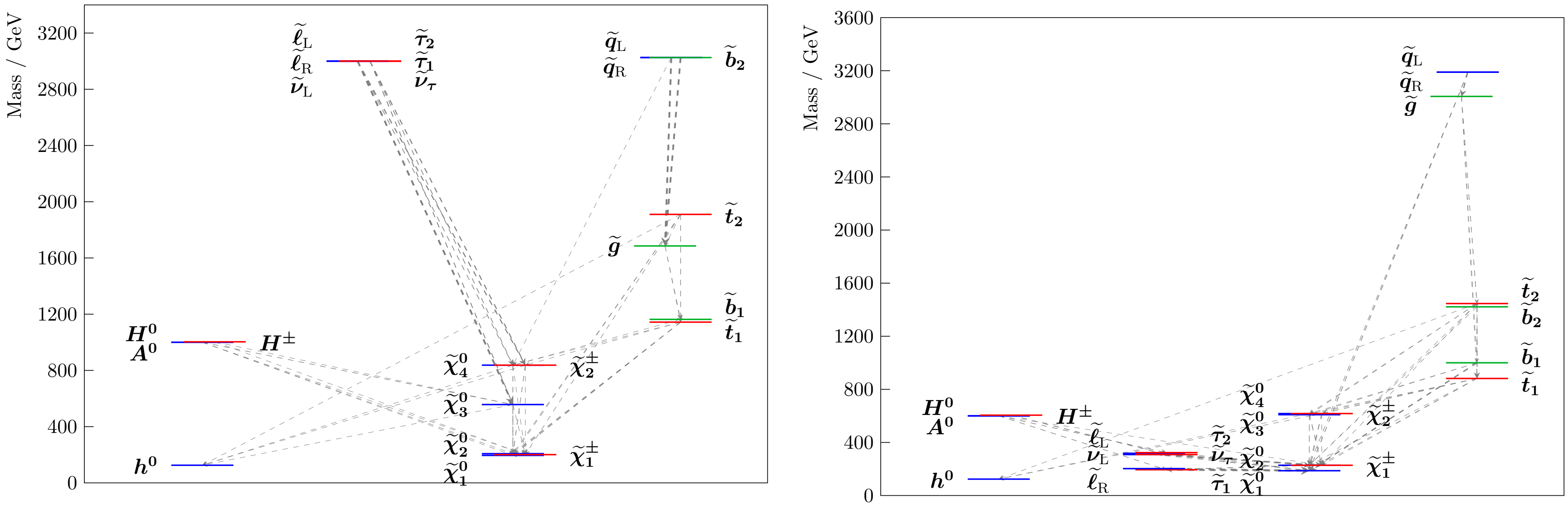
- Excellent progress with evaluating the HL-LHC physics case
- The main Higgs couplings can be measured to a few percent precision
  - Also sensitivity to rare processes
- HL-LHC extends discovery reach in strongly motivated areas
  - If discoveries or hints observed in Runs 2 & 3, HL-LHC will be crucial to unravel what is seen





Additional material

Two examples of full spectrum SUSY models



(a) NM3

(b) STC

Figure 10.19: Examples of SUSY full-spectrum models: (a) the natural SUSY model NM3 and (b) the stau coannihilation model STC, which are among the five full-spectrum scenarios used in the studies presented here. In NM3, the masses of the $\widetilde{\mathrm{g}}$, $\widetilde{\mathrm{t}}_1$, $\widetilde{\mathrm{t}}_2$, and $\widetilde{\mathrm{b}}_1$ are all below 2 TeV. The $\widetilde{\chi}_1^0$ is higgsino-like. In the STC model, the gluino is much heavier than the top squarks, and the slepton sector is light, with the $\widetilde{\tau}$ nearly degenerate with the $\widetilde{\chi}_1^0$. The lines between different states indicate transitions with branching fractions greater than 5%.