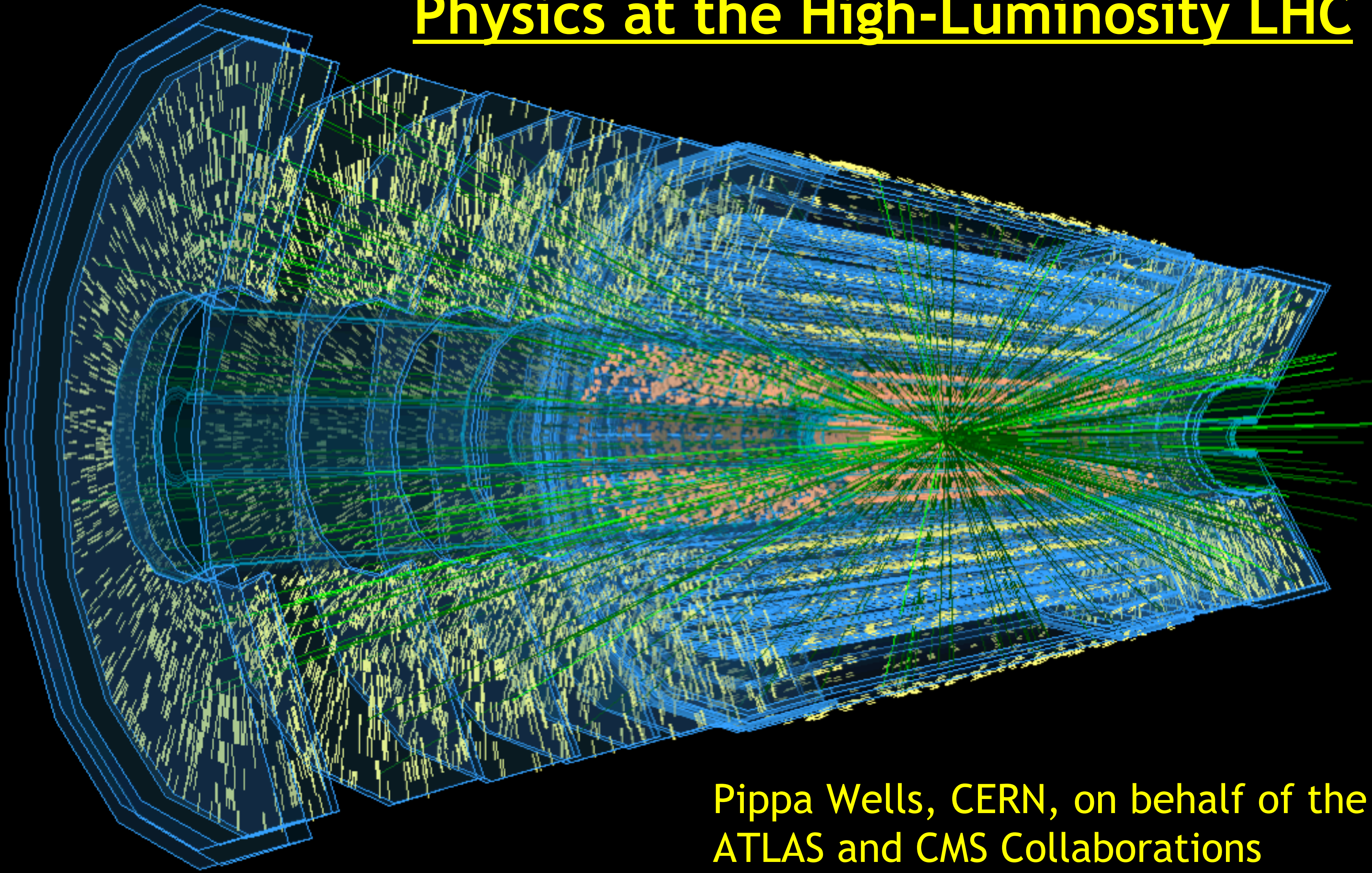
Physics at the High-Luminosity LHC



Pippa Wells, CERN, on behalf of the ATLAS and CMS Collaborations

UK HEP Forum — Cosener's House

Future Colliders, November 2014

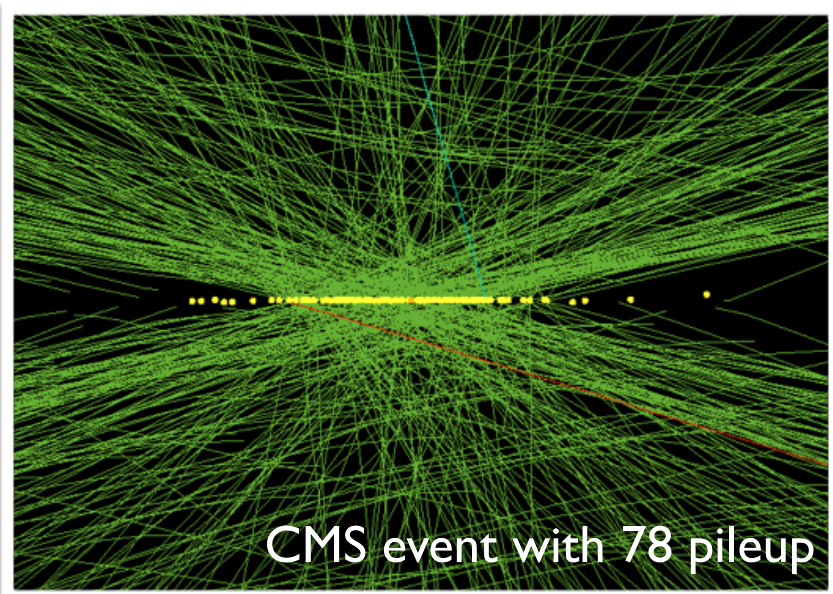
HL-LHC Physics

- Detector performance – underpins any physics measurement
  - Pileup mitigation
  - Extensions and improvements in the forward region
- Higgs boson measurements
  - Precision coupling measurements
  - Rare processes
- Beyond the Standard Model
  - In the Higgs sector
  - Exotica
  - SUSY
- Conclusions

- Links to more information:
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsFP
  ECFA HL-LHC workshop: https://indico.cern.ch/event/315626/

Pileup basics and key questions

- Luminosity of $5x10^{34}cm^{-2}s^{-1}$ corresponds to an *average* pileup of 140 events
  - Upper estimate of average number of pileup events for this lumi – partly accounts for bunch-to-bunch variation
  - Average of a Poisson distribution with a sigma of about 12 events
- Key questions:
  - Can the detectors work with even higher (average) pileup to allow 3000 /fb to be delivered more quickly?
  - Can a longer beam spot help pileup mitigation?
- Need to take into account in-time pileup (same bunch crossing) and out-of-time pileup (previous crossings) – particularly for ATLAS colorimeter and for muon spectrometers

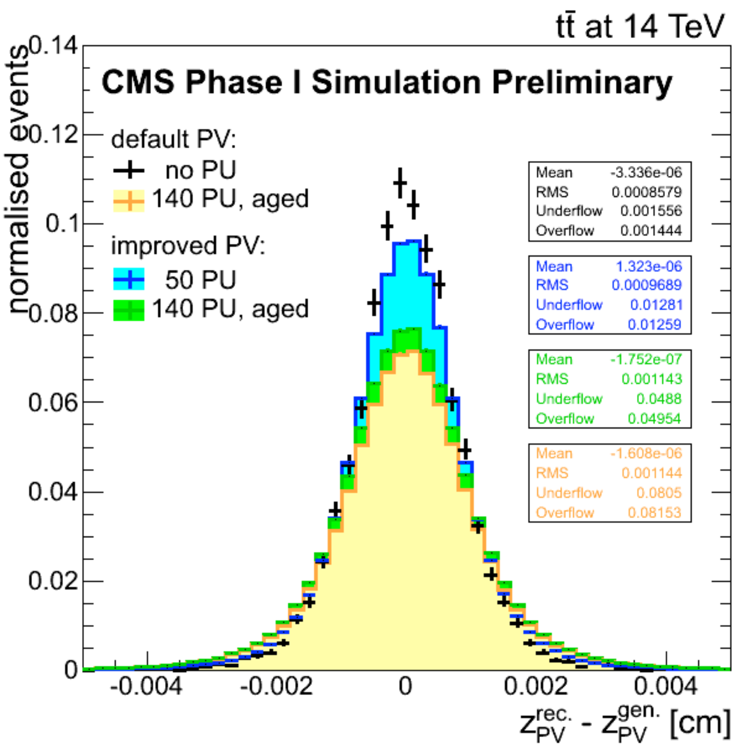


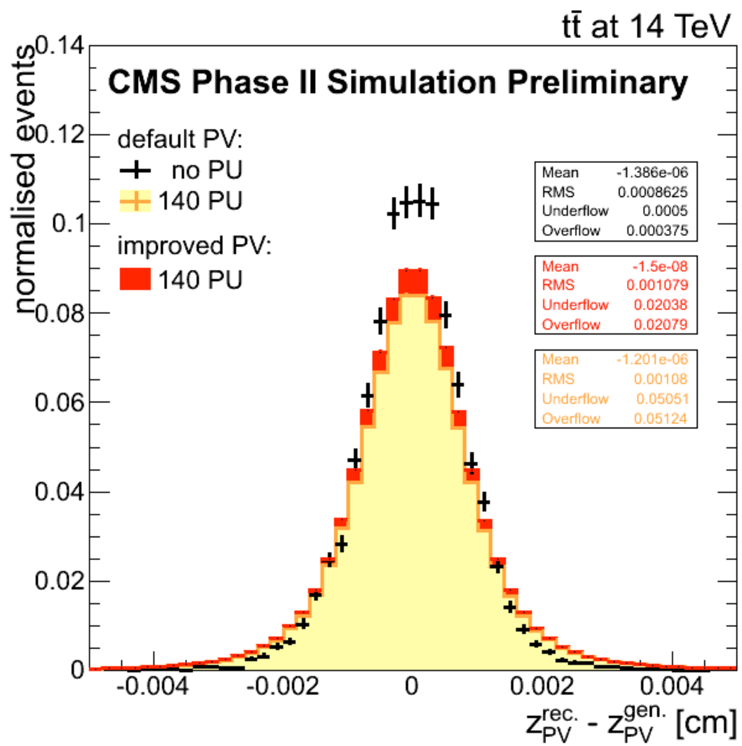
Detector configurations

- ATLAS performance evaluated with full simulation
  - Run 2 detector with μ=50 (for 300/fb studies)
  - Phase II LoI baseline tracker (ITK) in Run 1 calo+muon systems, studied with varying μ and beam spot shapes
  - Parametrised response functions for physics projections
- CMS performance evaluated with
  - 2019 detector with μ=50
    - New pixel detector
  - 2019 detector "aged" after 1000/fb and with μ=140
    - New pixel detector, aged strip detector
    - Aged calorimeter
  - Phase II 2013 detector with
    - 2019 pixel detector, new strips, calorimeter recovered
    - In future - studies with upgraded pixel det, endcap calo..
  - Parametrised responses in Delphes with tracking to $|\eta|< 4$ for some physics studies (not tuned to full simulation)

Primary vertex finding

- ttbar events with the CMS Phase I and Phase II detectors
- (Reconstructed – Generated) vx positions for no PU, 50 PU, 140 PU





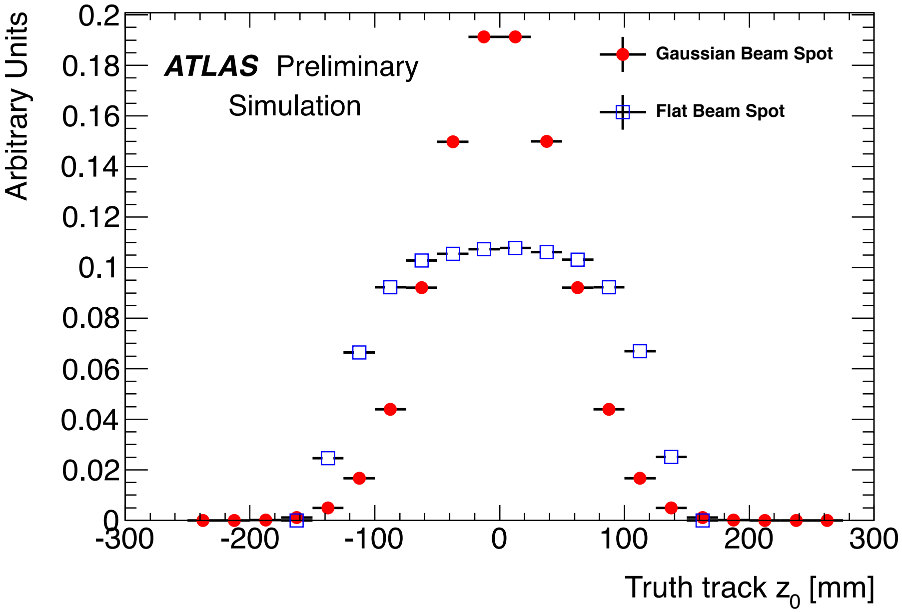
140 PU and aged tracker: vertex finding efficiency increases from 84% to 90% with improved algorithm

140 PU and Phase II strips: vertex finding efficiency increases from 90% to 96% with improved algorithm

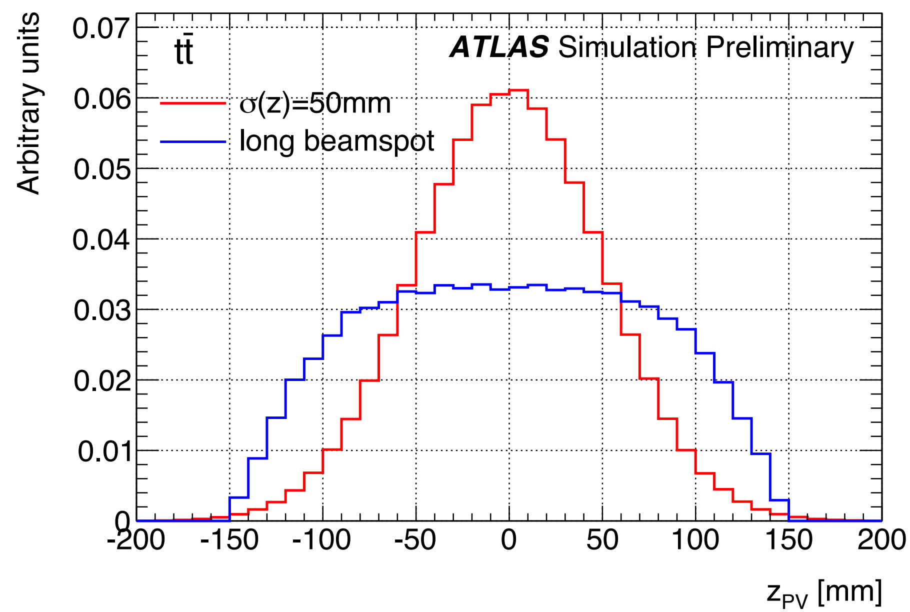
Effect of a longer beam spot

- Generate ttbar events with pileup, ATLAS Phase II tracker, μ=140
  - (ttbar events are high multiplicity – easiest for PV finding)
  - Different longitudinal (z) beam spot profiles: Gaussian with σ=5cm or Long beam spot, ~flat to ±10cm

Generated tracks



Reconstructed vertices



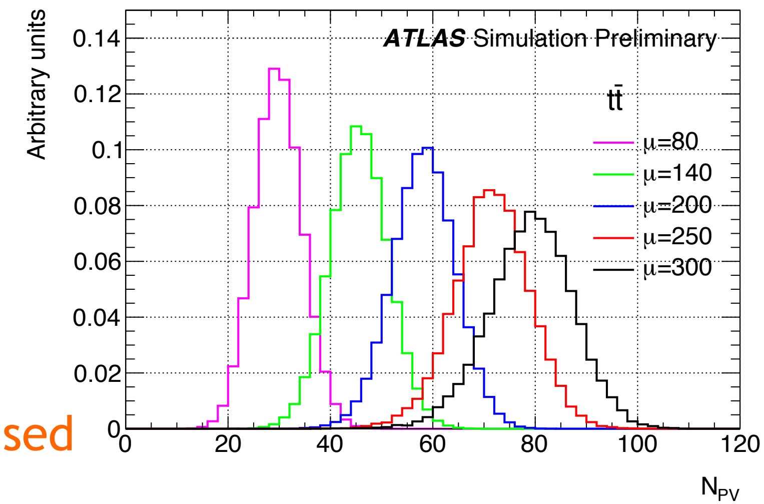
Effect of a longer beam spot - primary vertex

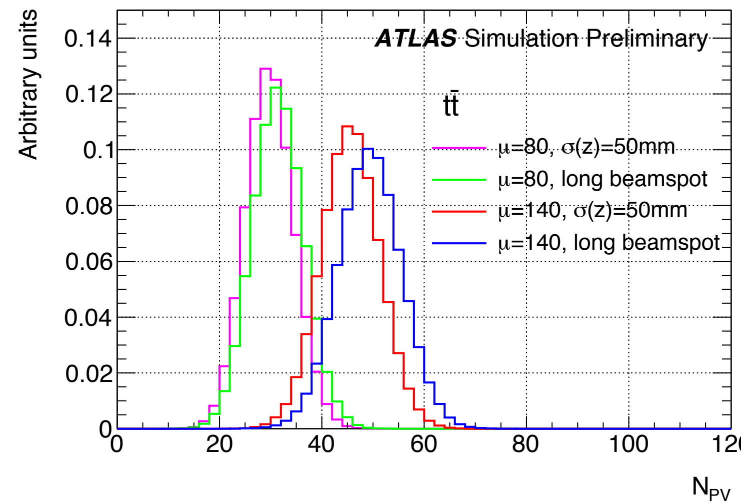
- ttbar events with varying pileup and beam spot z distributions

Gaussian, μ [80,300]

Varying shape, μ=80,140

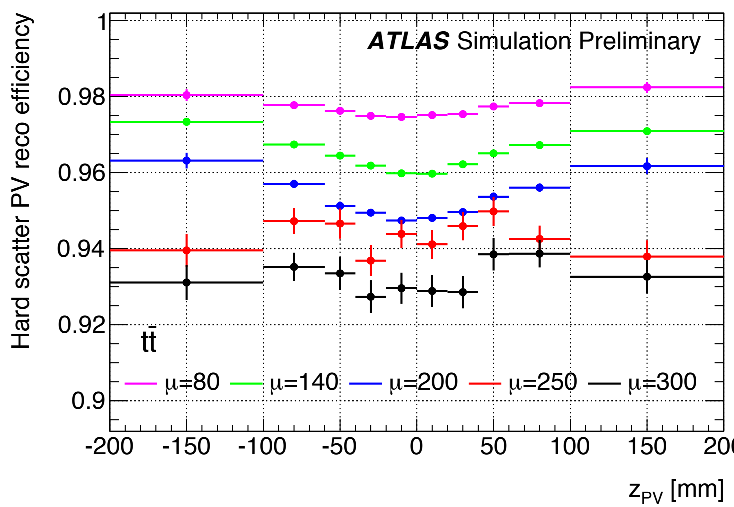
N reco primary vertices

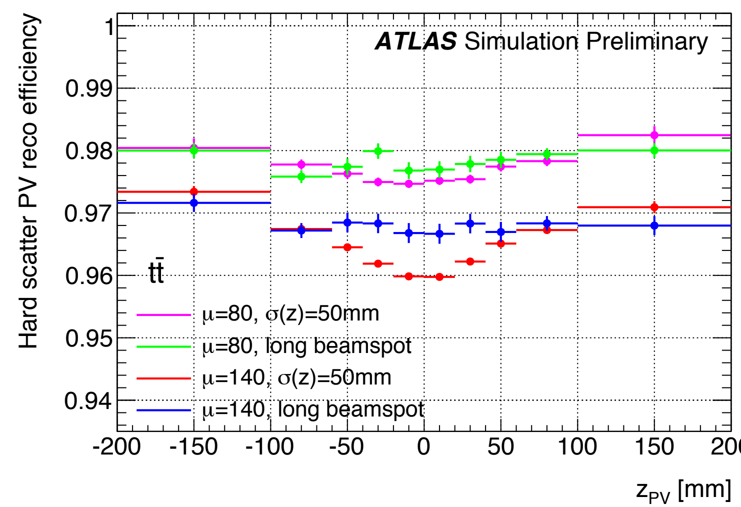




Non-optimised algorithms

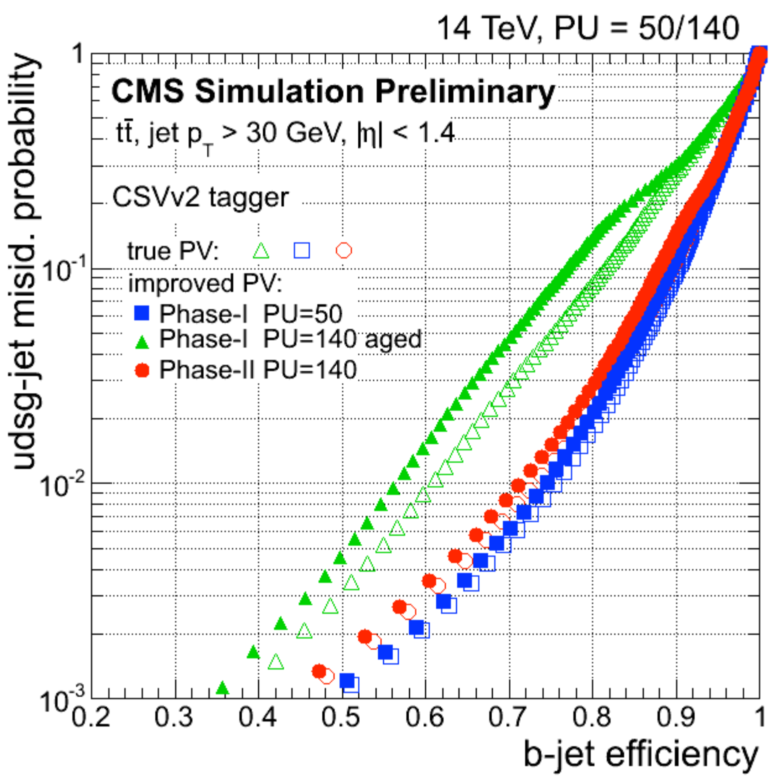
ttbar PV efficiency vs z

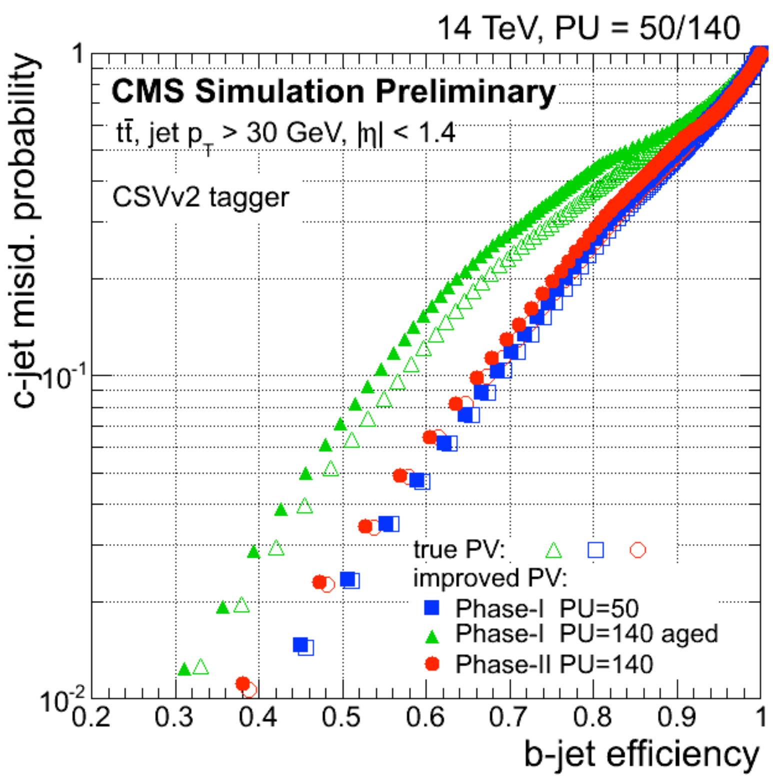




b-tagging – CMS Phase II

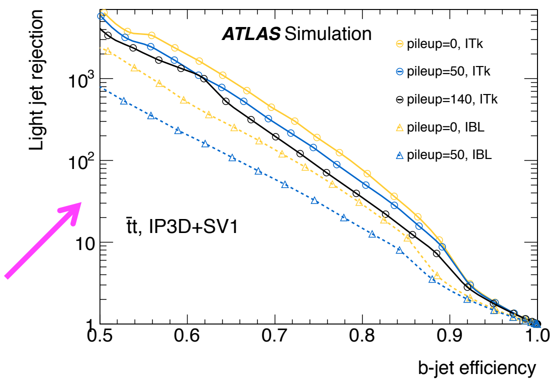
- Increased pileup and detector aging cause misid rate to increase
  - Performance is not recovered even if the true PV is used
- Phase II detector with μ=140 nearly recovers performance to that of the Phase I detector with μ=50
- Performance of aged detector is much worse

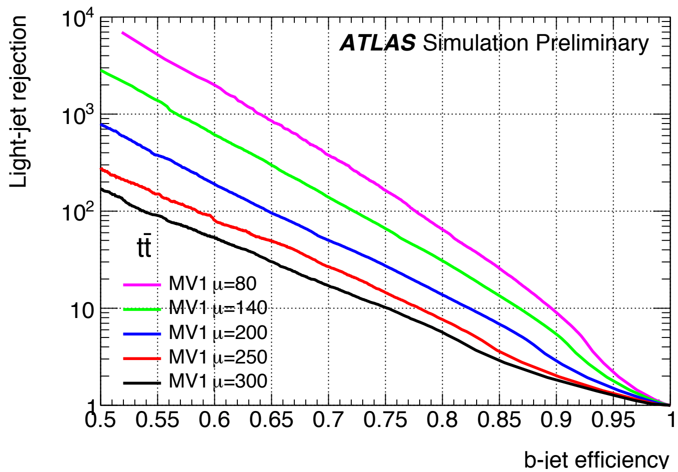


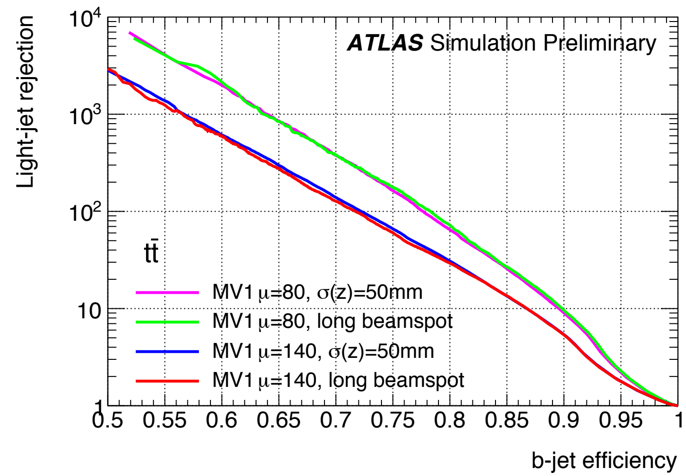


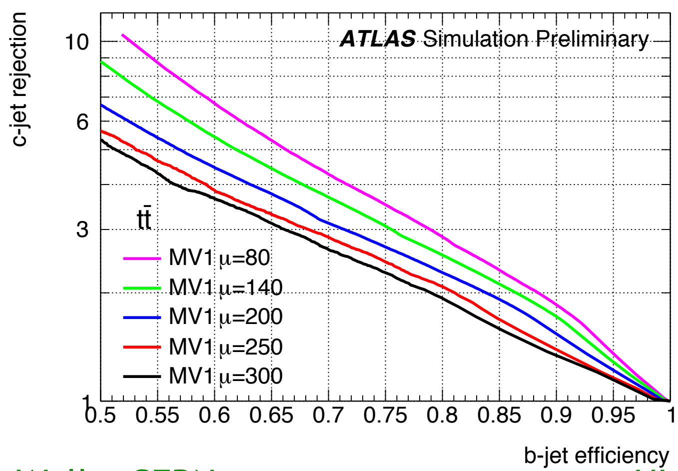
b-tagging - higher pileup

- ATLAS Phase II ITk performance with μ=140 better than Run 2 performance expected with μ=50 [LoI]
  - b-tagging degrades gradually with higher μ





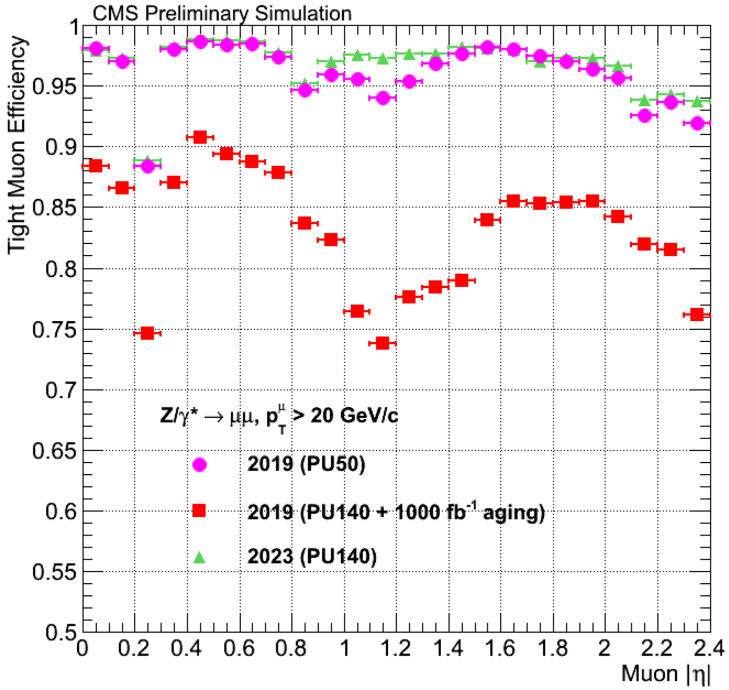




- Only events with the correct primary vertex enter the plots
  - b-tagging is insensitive to beam spot shape IF the correct ttbar primary vertex is found
- NB: rejection = 1/(misid-prob)
- Non-optimised algorithms from Run 1

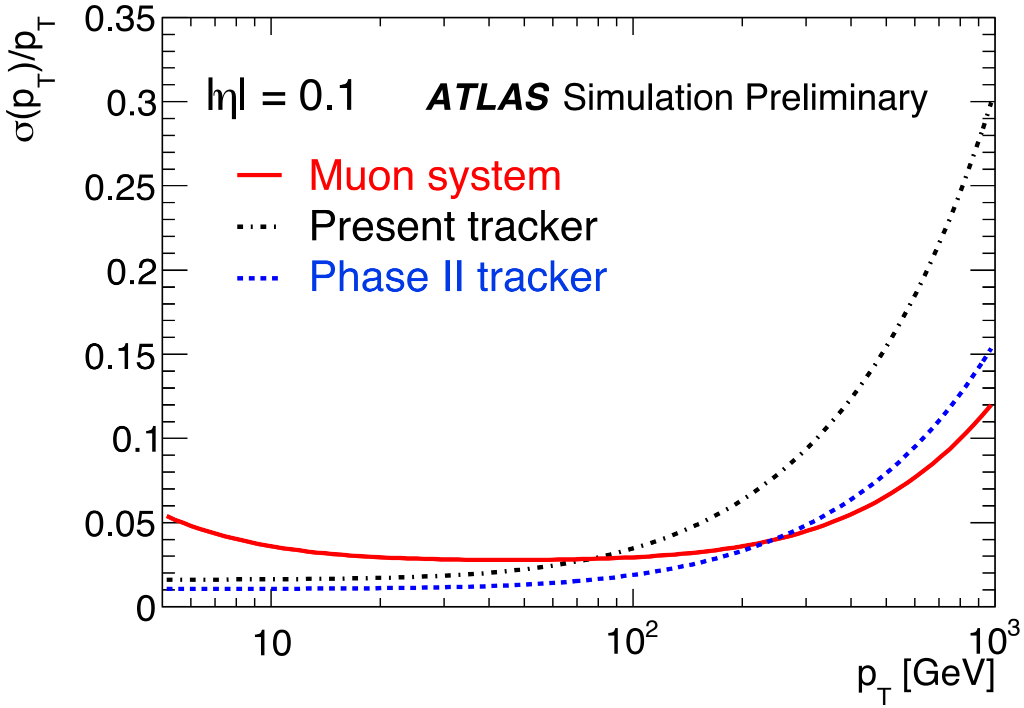
Muon performance

- CMS Muon performance strongly affected by aging
- eg. Efficiency vs η



2019 PU50
2019 aged, PU140
Phase II, PU140

- ATLAS and CMS Phase II trackers will both improve the muon p_T resolution

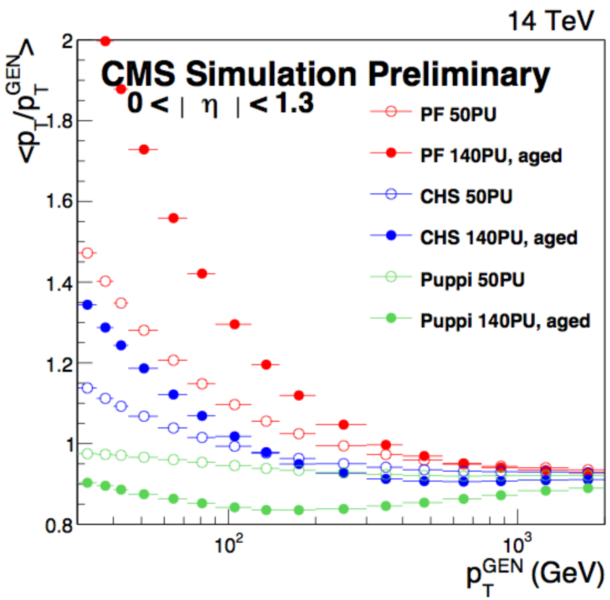


Pileup Per Particle Identification
arXiv:1407.6013 [hep-ph]

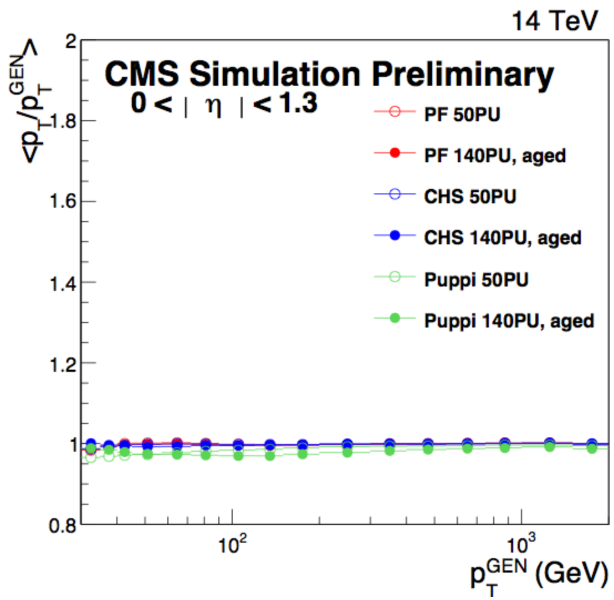
Jet reconstruction in CMS

- Anti-k_t jets with R=0.4 from
  1. All Particle Flow candidates (PF)
  2. Plus rejecting charged hadrons from pileup vertices (CHS)
  3. PF candidates weighted by Puppi algorithm – best resolution

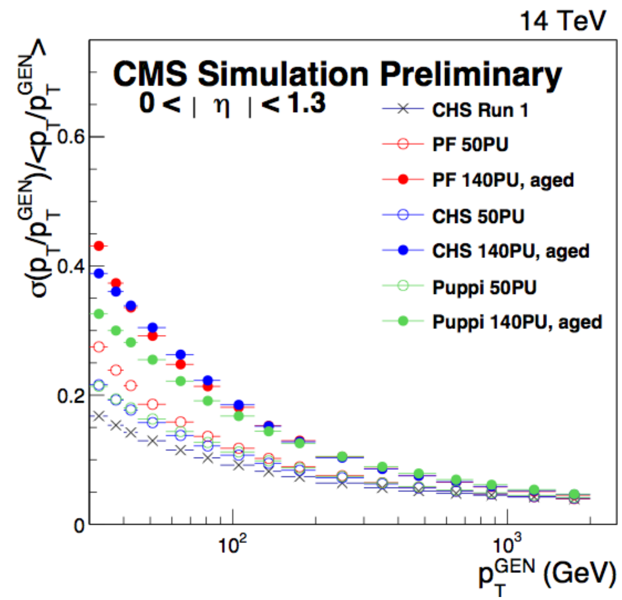
Jet p_T response



Corrected response



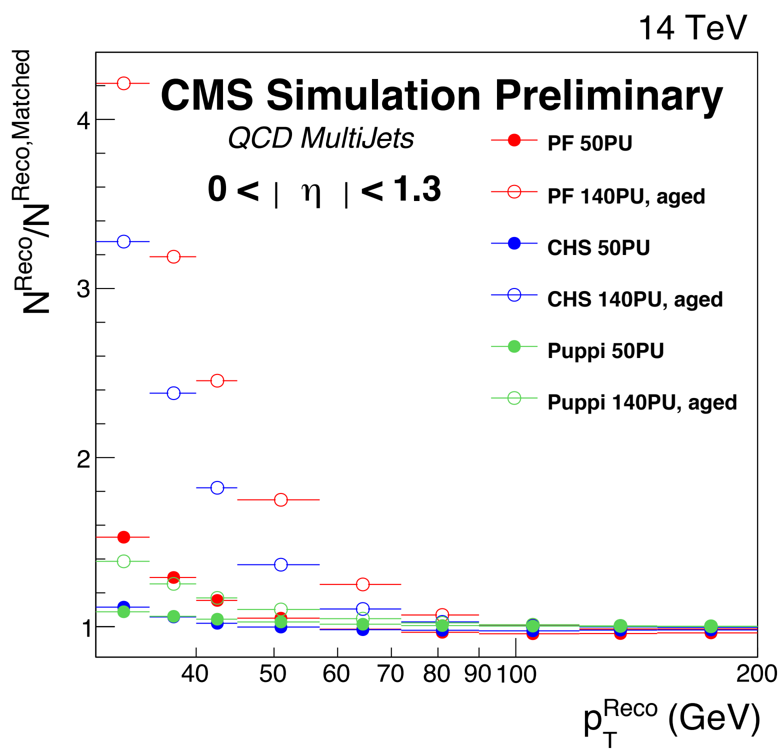
Jet resolution

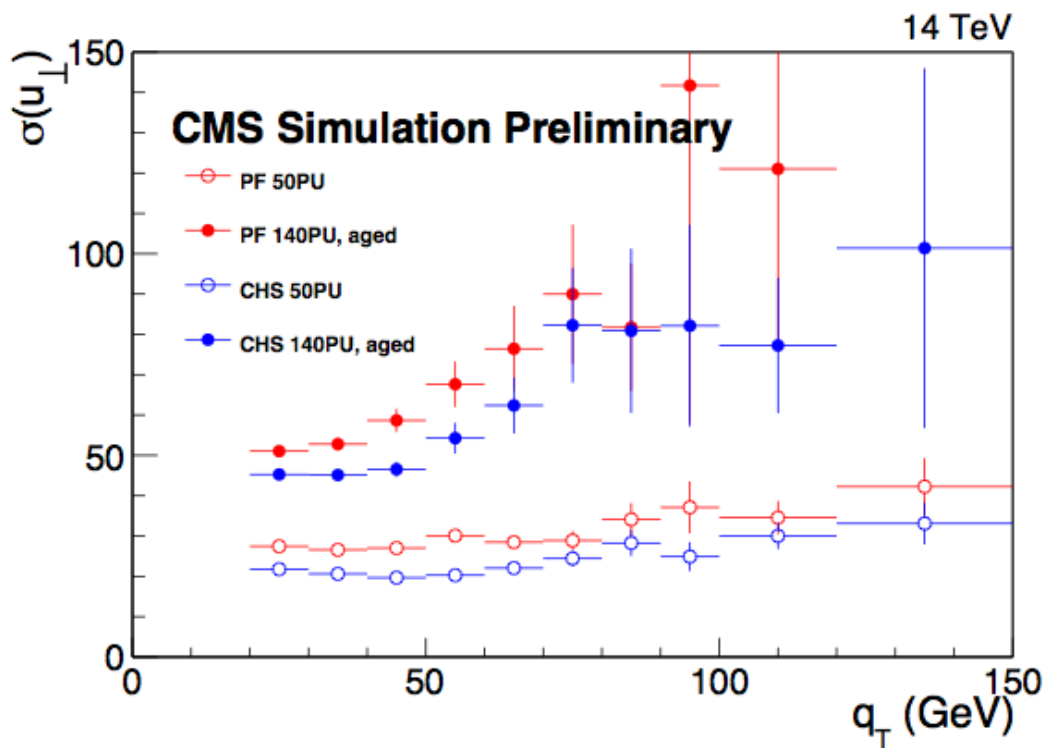


Jets and MET

- Pileup jet rate – Puppi lowest
- Rate defined as ratio between all reco jets and reco jets matched to a generated hard-scatter jet in a multijet sample

- MET resolution degrades with aging
- Plot: the component of the hadronic recoil perpendicular to the Z direction in Z→μμ events

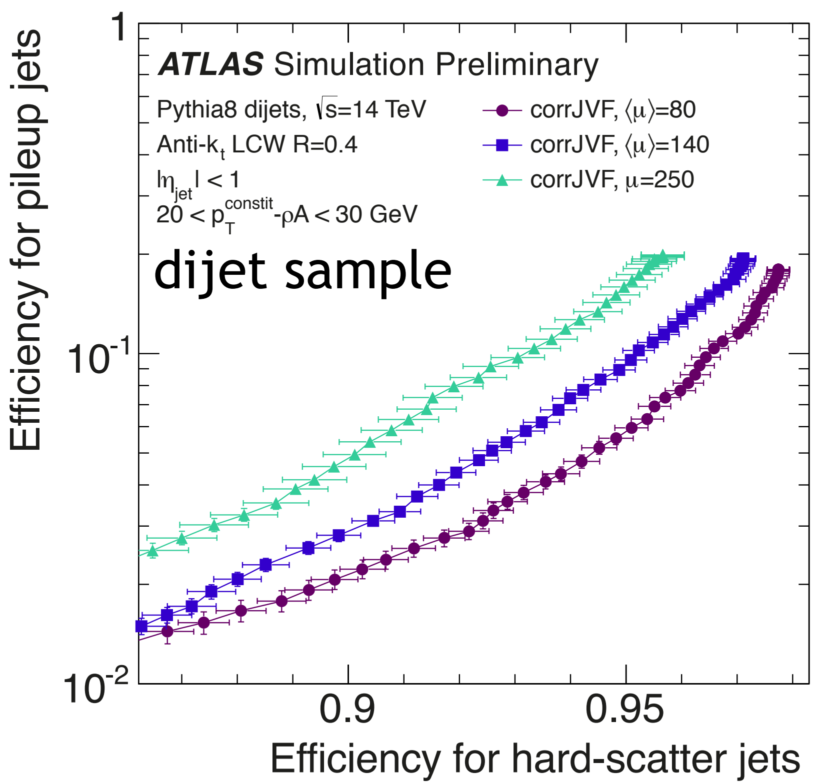


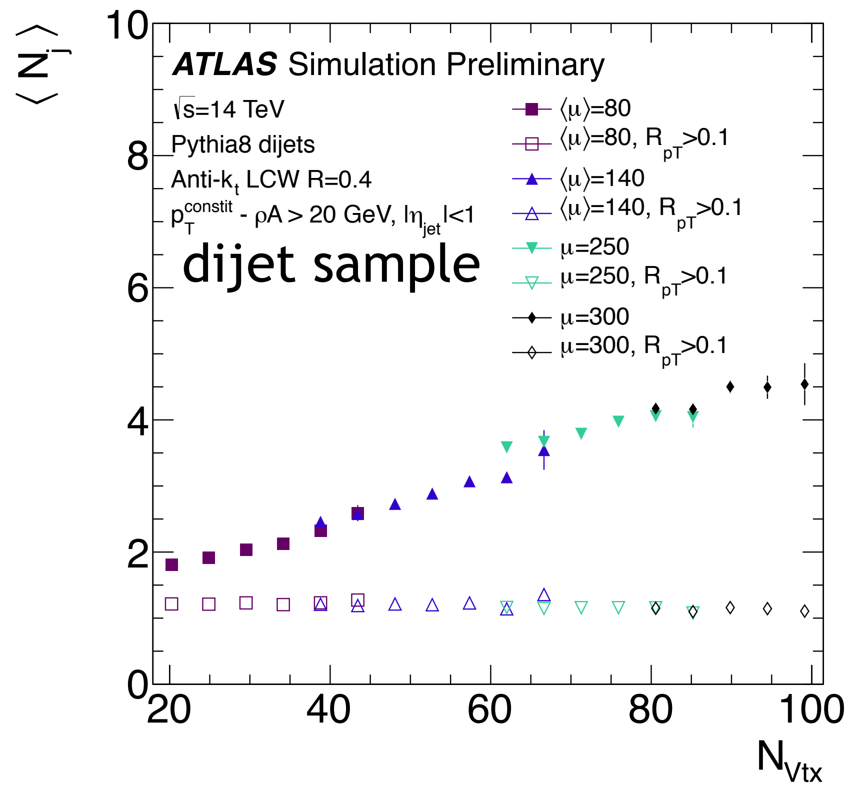


Pileup jet suppression with tracks - ATLAS

- Efficiency for pileup jets vs. hard-scatter jets (20-30 GeV), scanning a track-vertex match variable
- Pileup jets do not match any true jet
- Performance degrades with μ

- Mean number of jets (p_T>20 GeV) vs. number of reconstructed vertices, before/after pileup suppression with a charged fraction variable

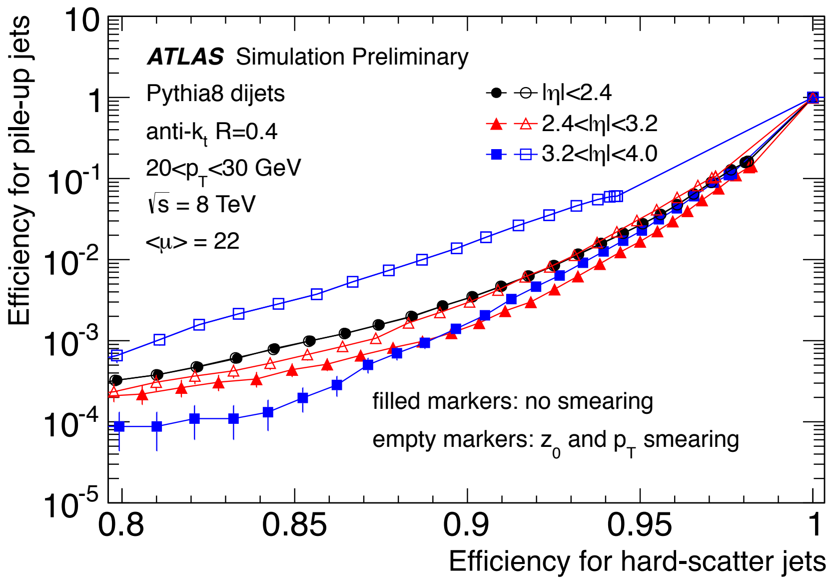


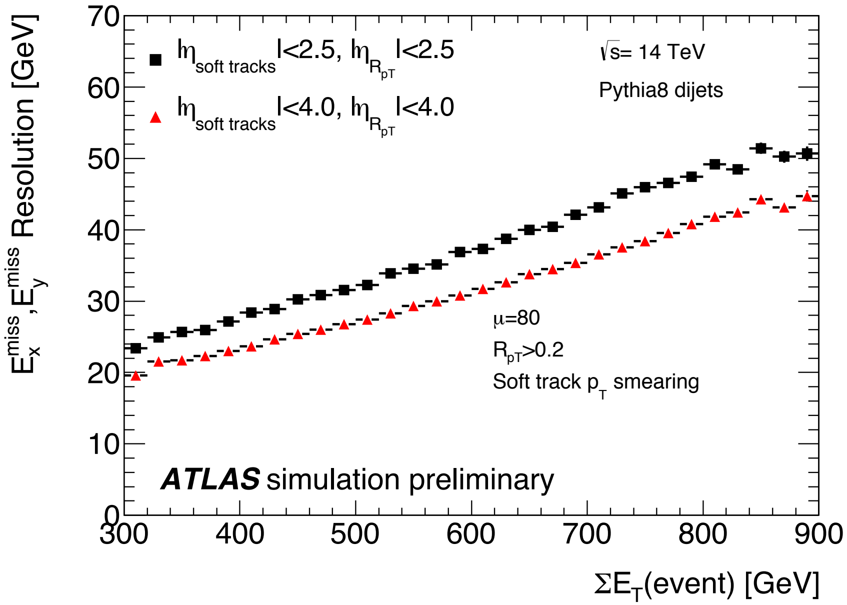


Improvements with tracker to |η|<4

- Possible to reject 90% of low p_T pileup jets even in the forward region while keeping 95% of hard scatter jets

- ETmiss resolution is improved
- Small contribution from adding tracks in the soft term
- Bigger effect from rejecting pileup jets



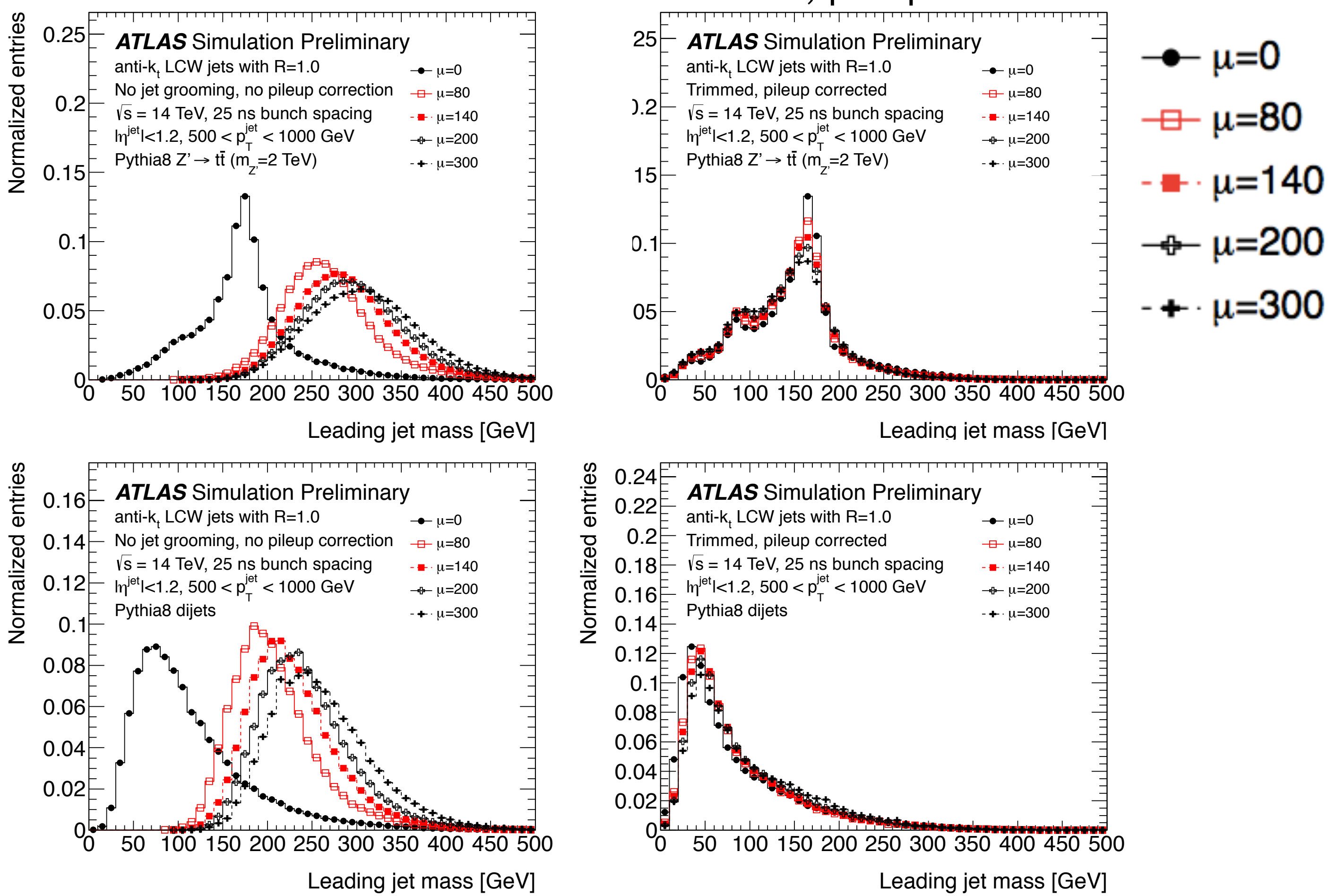


Jet Substructure - leading jet mass

No correction — Trimmed, pileup subtracted

Z'→ttbar: top and W mass peaks emerge

dijet background: low jet mass



Form R=0.3 subjets in R=1.0 jet. Reject low p_T subjets, pileup "area" correction.

Less efficient and worse mass resolution for higher pileup (up to μ=300)

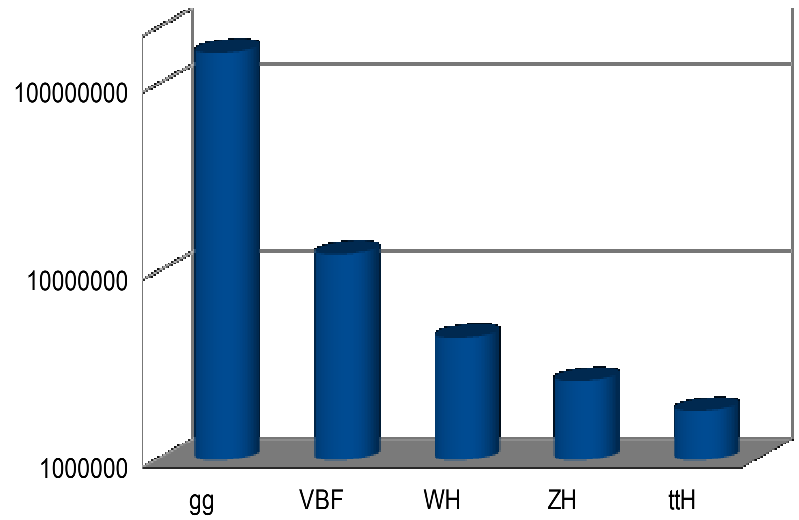
NB: Algorithms "out of the box". No systematic error evaluation.

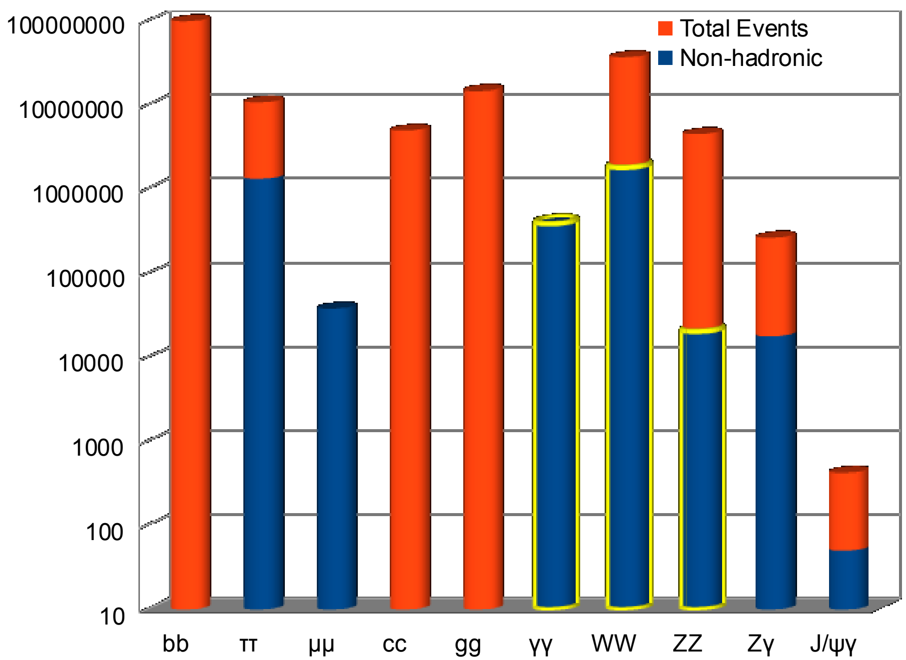
Prospects for the Higgs boson

- Compare prospects with "LHC" 300 fb^{-1} and "HL-LHC" 3000 fb^{-1}
  - Full exploitation of the LHC investment
  - Explore the properties of the new boson
- Focus here on the measuring the rate of all possible production and decay modes. Deviations from the SM indicate new physics
  - Precise measurements of main processes
  - Observation of rare processes
  - Interpretation in terms of Higgs boson couplings
  - Searches for additional Higgs bosons and indirect constraints from the coupling measurements
- Mass & width are hard to improve beyond Run 2
  - Direct measurement of width limited by resolution. Indirect constraints from interference effects or on-shell vs. off-shell measurements
- Dominant spin/parity should already be well established
  - HL-LHC will allow constraints on additional non-standard contributions

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)

Account for detector performance

- ATLAS uses detector response functions based on full simulation for
  - Phase I detector with new pixel layer, pile-up of 50
  - Phase II detector with pile-up of 140
  - Results are shown with and without theory uncertainty

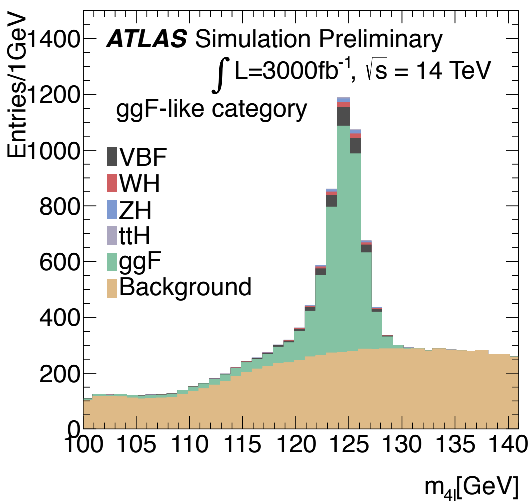
- CMS extrapolate from the present 7-8 TeV analyses, assuming that the upgrades maintain the detector performance.
  - Scenario 1 – Experimental systematic and theoretical uncertainties unchanged. Statistical uncertainties scale with $1/\sqrt{L}$
  - Scenario 2 - Statistical and experimental systematic uncertainties scale with $1/\sqrt{L}$, theoretical uncertainties reduced by a factor 2.

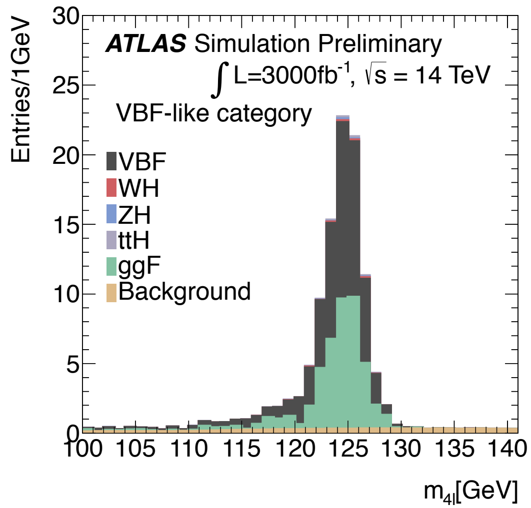
- Systematic uncertainties are therefore always included, but with different assumptions on possible detector/algorithm/theoretical improvements.

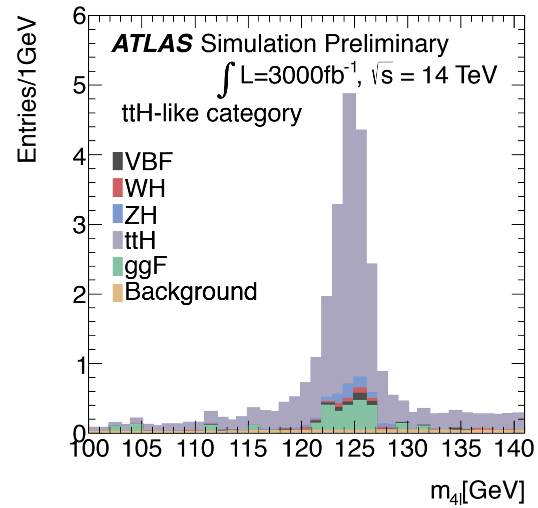
Example - H→ZZ→4 leptons

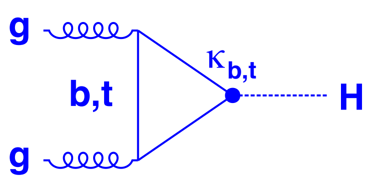
- High purity signal. Measure all 5 main production modes with 3000 fb^{-1}

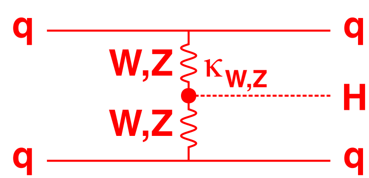
Signal events	ggH	VBF	ttH	WH	ZH
3000 fb^{-1}	3800	97	35	67	5.7

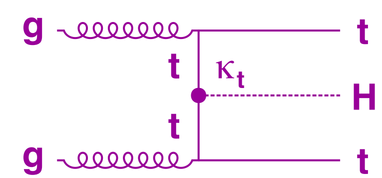




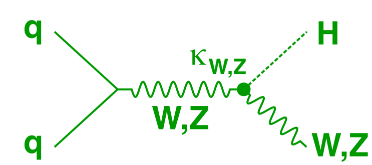






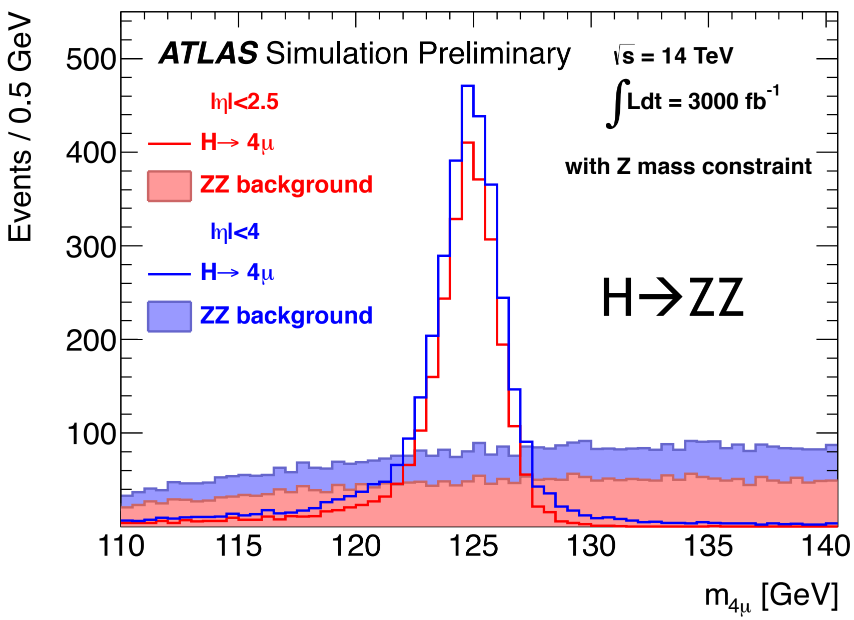


- Vector Boson Fusion and ttH events have extra jets.
- WH, ZH events have extra leptons



Extension of detector coverage

- ATLAS and CMS are both studying increasing/improving forward parts of the detectors
  - Increased acceptance for some channels
  - Improved rejection of pileup jets and ETmiss resolution



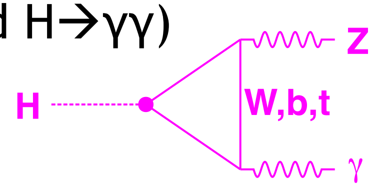
Signal strength precision Δμ for ATLAS VBF H→ττ (lep-had) with assumptions on pileup jet rejection (No loss of hard scatter jets)

Factor 3 improvement in Δμ from 0.24 to 0.08

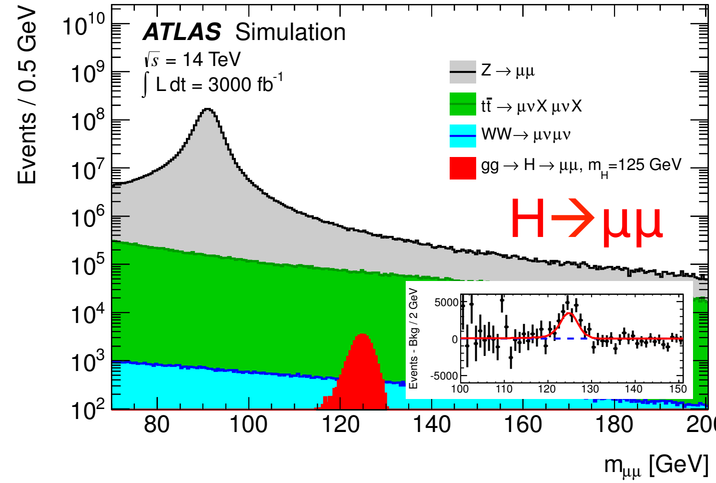
forward pile-up jet rejection	50%	75%	90%
forward tracker coverage		$\Delta\mu$	
Run-I tracking volume		0.24	
$\|\eta\| < 3.0$	0.18	0.15	0.14
$\|\eta\| < 3.5$	0.18	0.13	0.11
$\|\eta\| < 4.0$	0.16	0.12	0.08

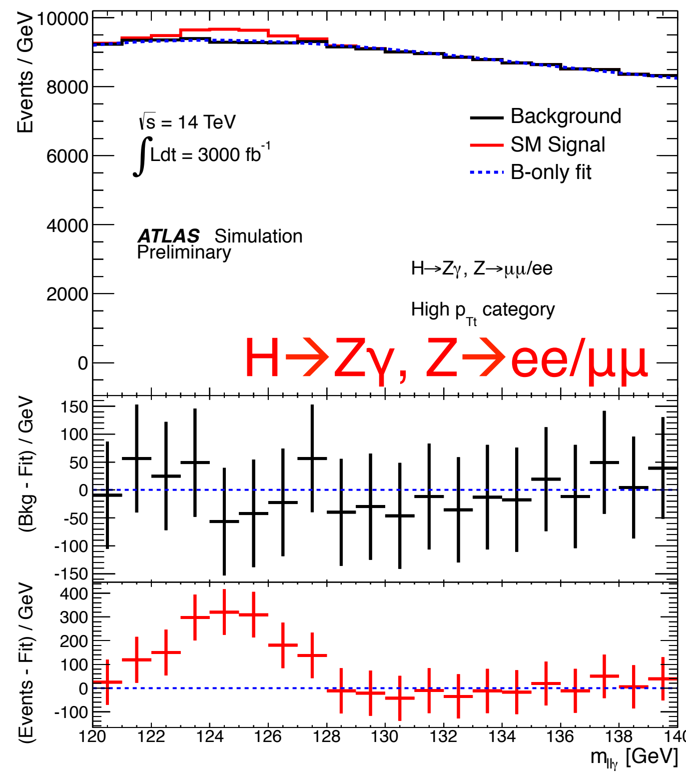
Rare processes

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



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

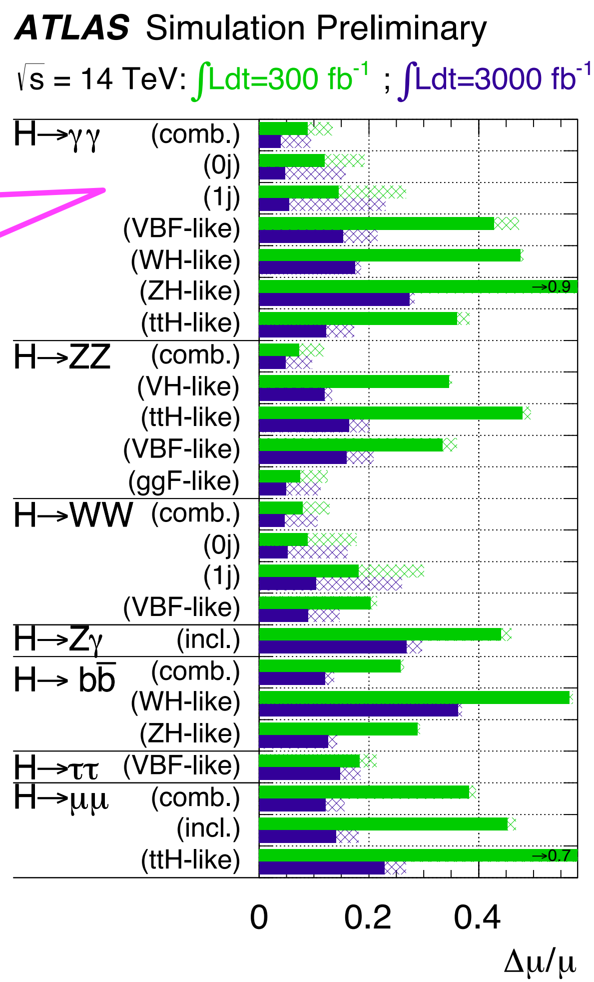


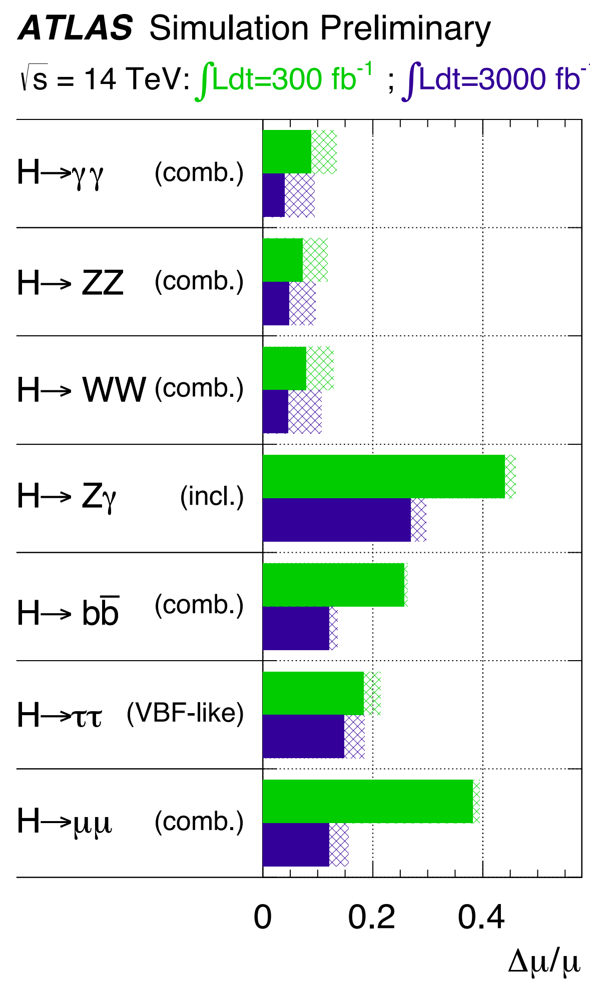


Signal strength precision

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

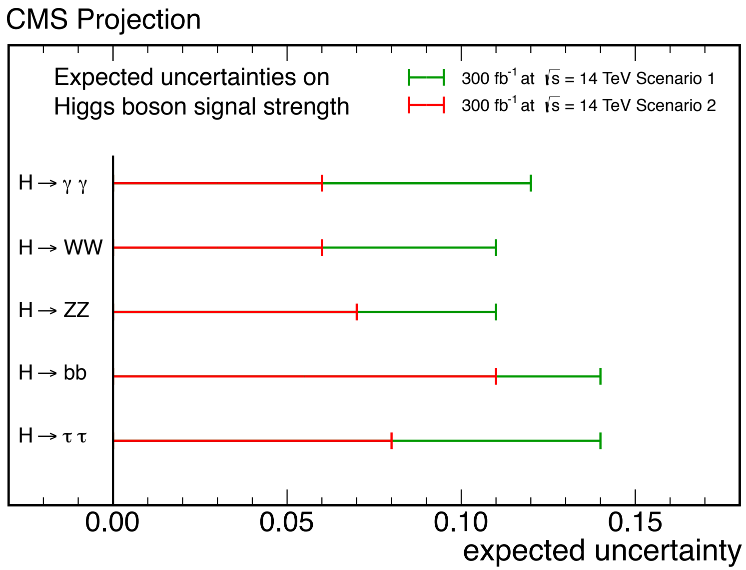
Uncertainties between 0 & 1 jet cancel out in combination

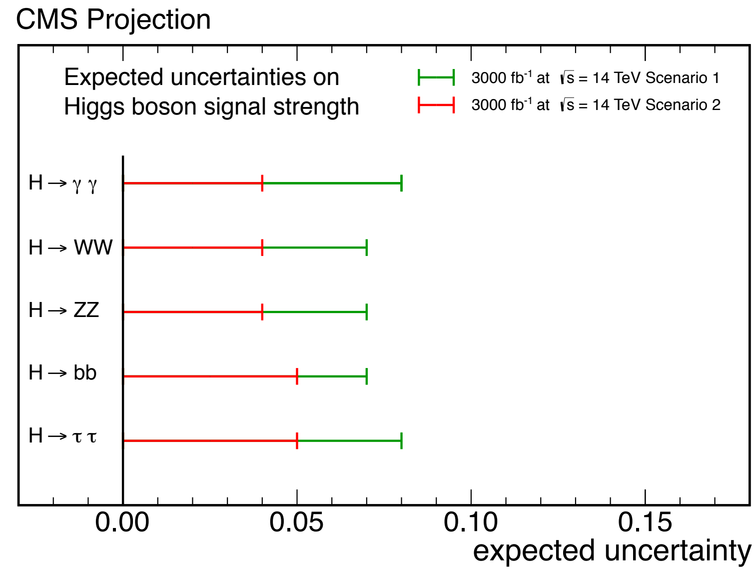




Signal strength precision

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





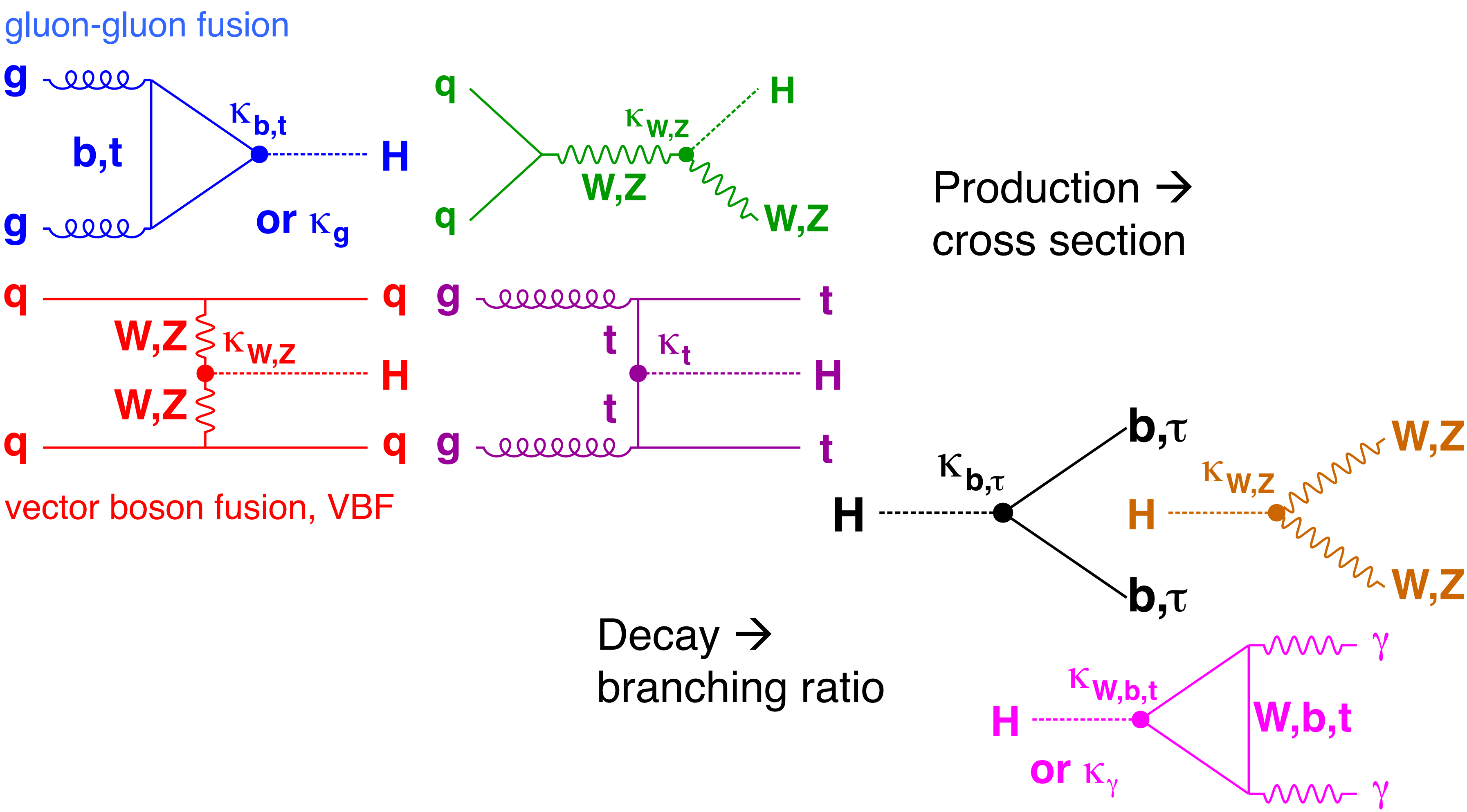
Summary of precision (%): 4~5% for main channels, 10~20% on rare modes

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]

Interpretation as coupling scale factors

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

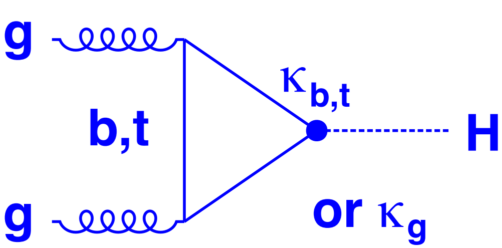


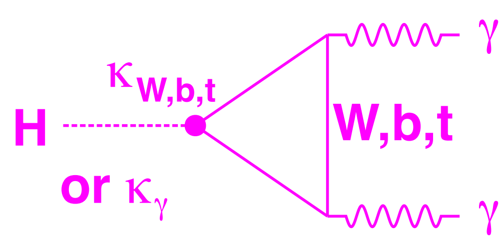
Coupling fits - the small print...

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

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

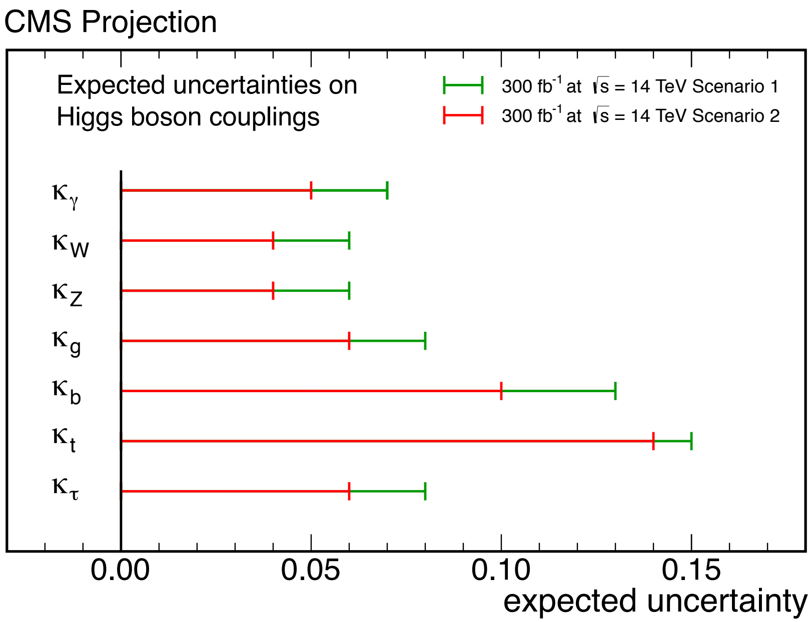
- The total width Γ_H is too narrow to measure
  - Assume it is the sum of the visible partial widths – no additional invisible modes
  - (Charm coupling is assumed to scale with top coupling)
- Cross sections and branching ratios scale with κ^2 ($\rightarrow \Delta\kappa \sim 0.5\ \Delta\mu$)
- Gluon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

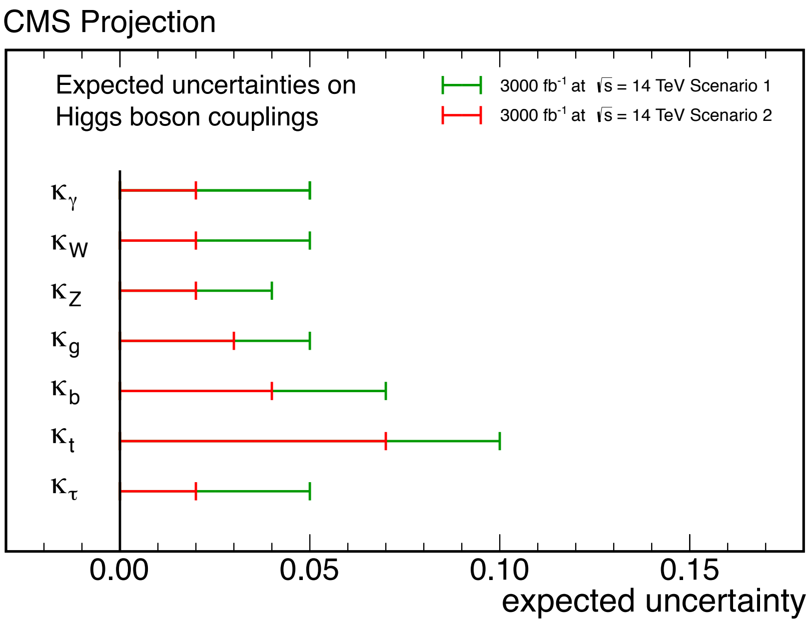




General coupling fit

- 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

$L(fb^{-1})$	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]

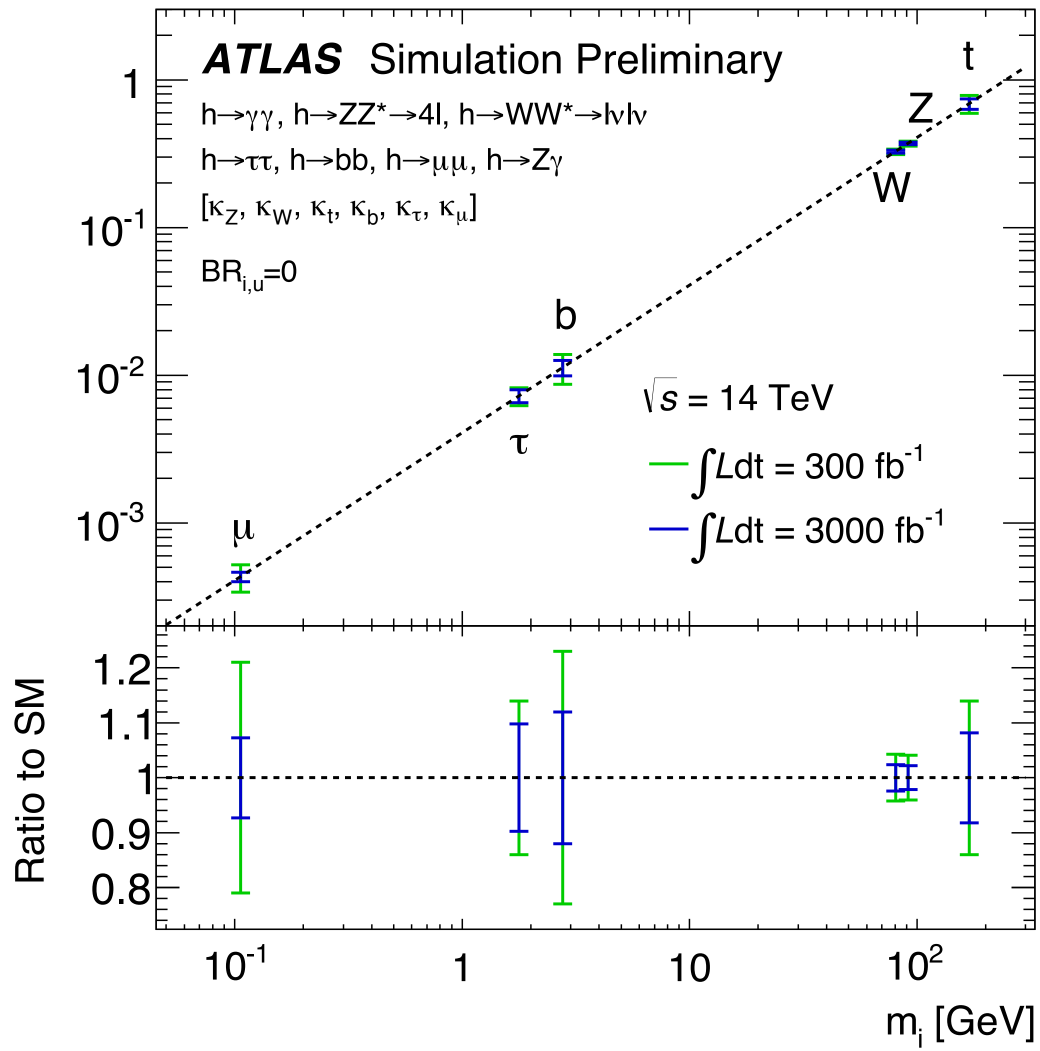
- This results in better agreement between the two experiments
  - Can achieve 2~3% precision in main channels if systematic uncertainties are controlled
- HL-LHC yields a factor 2~3 improvement in coupling ratio determination

Mass scaled couplings

- Coupling factors plotted as a function of particle mass

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

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



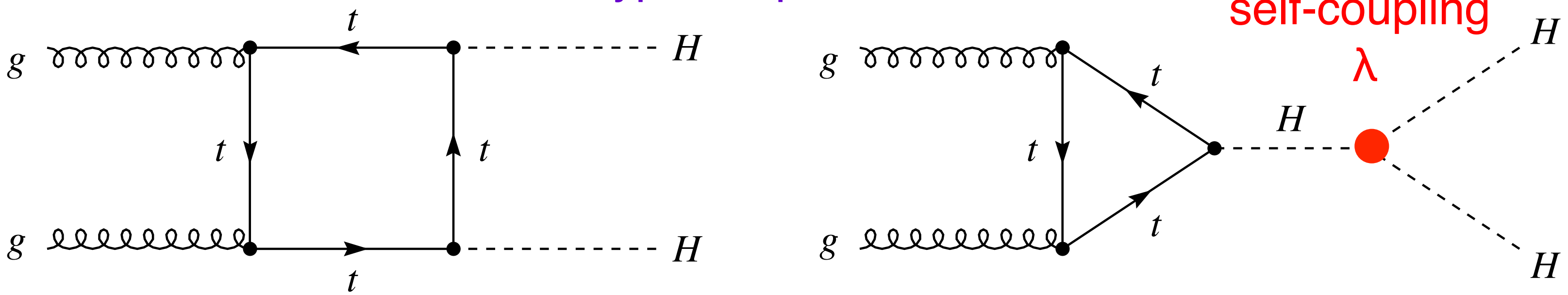
Theoretical uncertainties

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

Scenario	Status	Deduced size of uncertainty to increase total uncertainty							
	2014	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

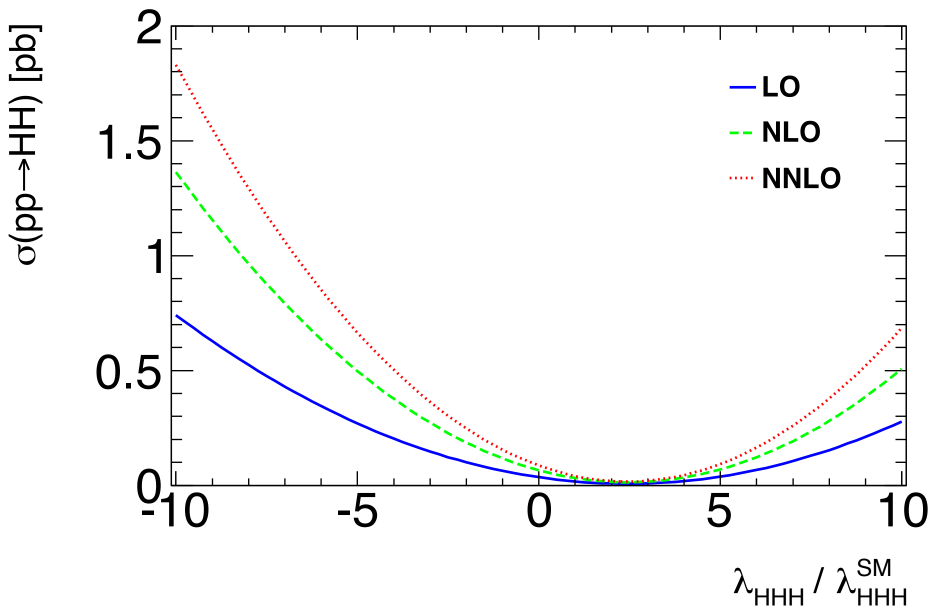
Higgs pair production

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



- ~factor 2 increase in cross section if λ→0

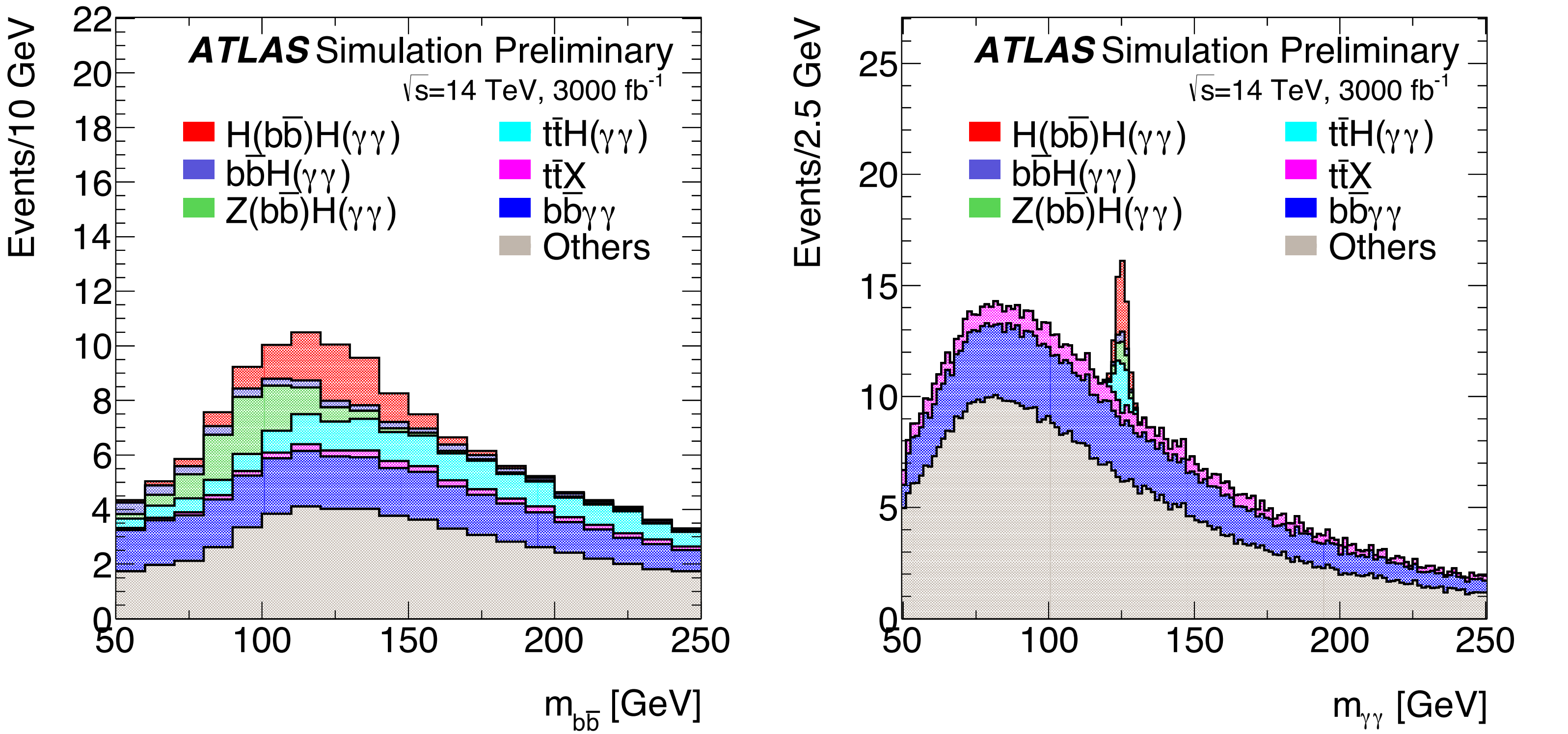
NNLO σ^{SM}=40.8 fb



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

HH→bbγγ

- Parametrised object performances
  - CMS 2d fit of m(bb) and m(γγ) distributions (control background from data)
  - ATLAS cut based analysis (ATL-PHYS-PUB-2014-019)



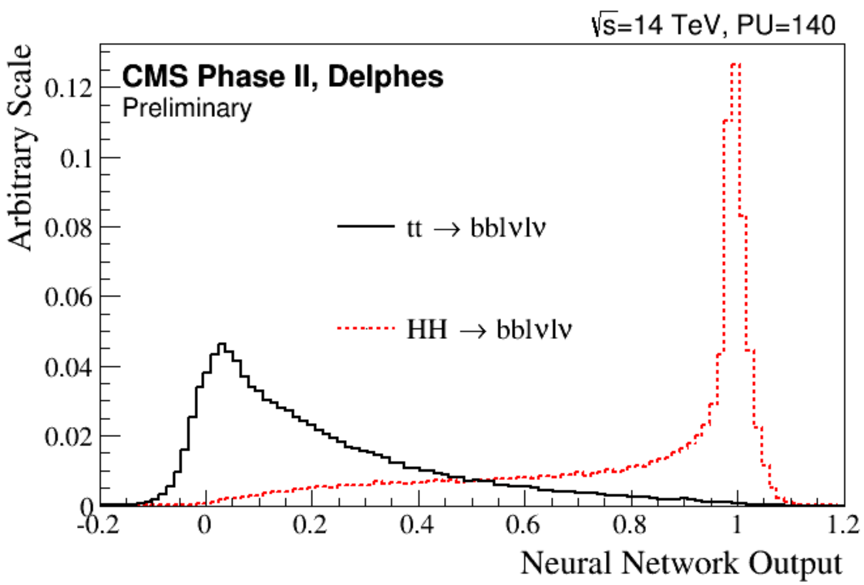
bbγγ results

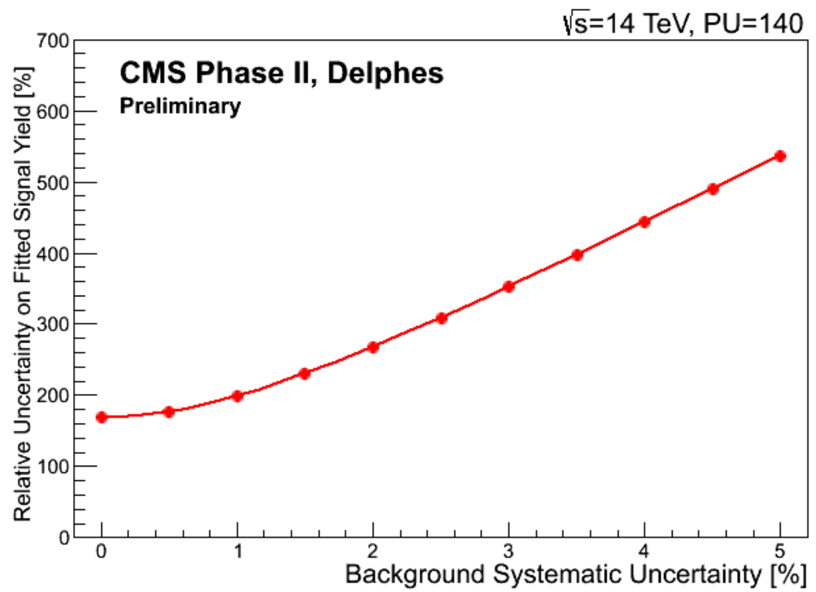
- Numbers of events in 3000 fb^{-1} in signal mass windows
  - CMS preferred result uses a likelihood fit in a larger mass range, which gives 60% relative uncertainty on the signal

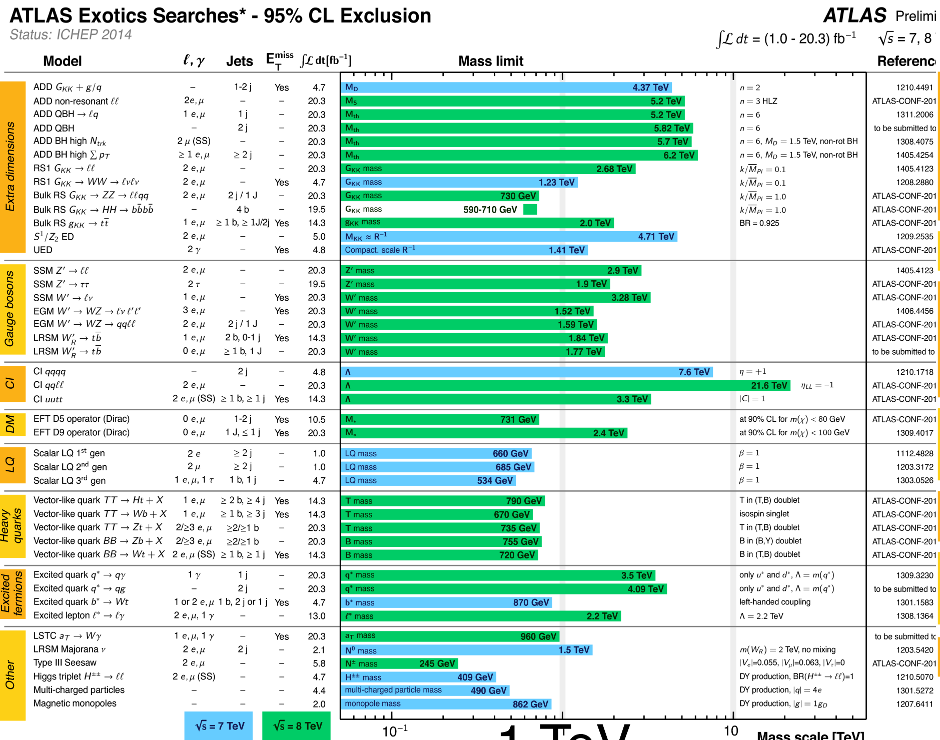
process	ATLAS		CMS
SM HH→bbγγ	8.4± 0.1		9.9
bbγγ	9.7 ± 1.5	γγ+jets	8.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2	γ+jets, jets	7.4
top background	3.4 ± 2.2		1.1
ttH(γγ)	6.1 ± 0.5		1.5
Z(bb)H(γγ)	2.7 ± 0.1		3.3
bbH(γγ)	1.2 ± 0.1		0.8
Total background	47.1 ± 3.5		22.6
S/√B (barrel+endcap)	1.2		
S/√B (split barrel and endcap)	1.3		

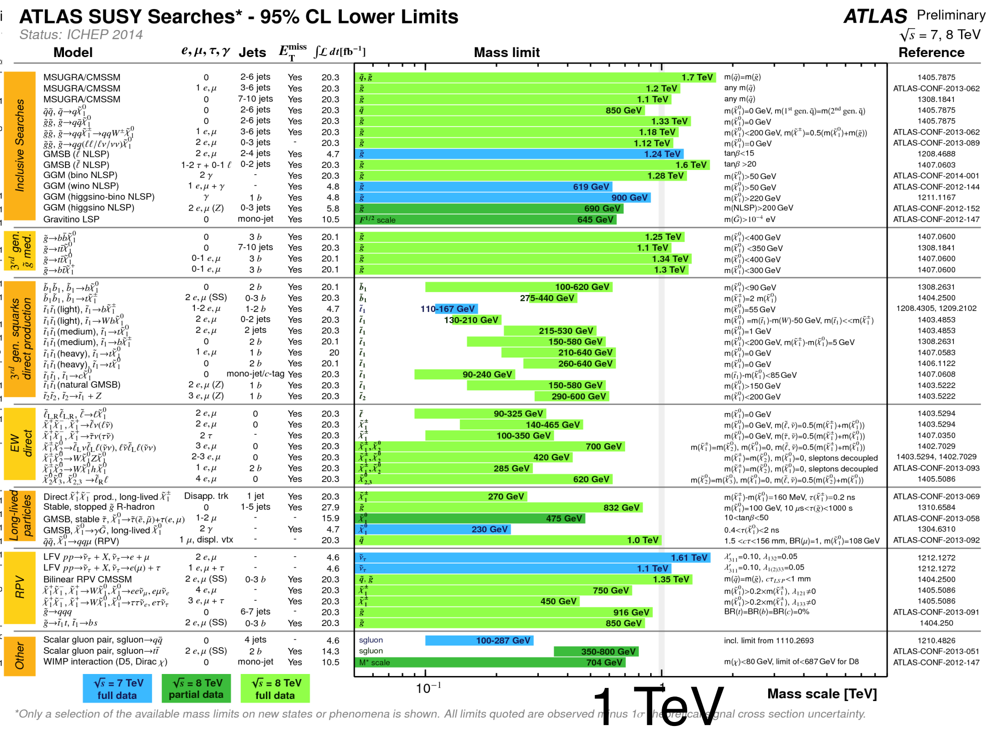
CMS HH→bbWW

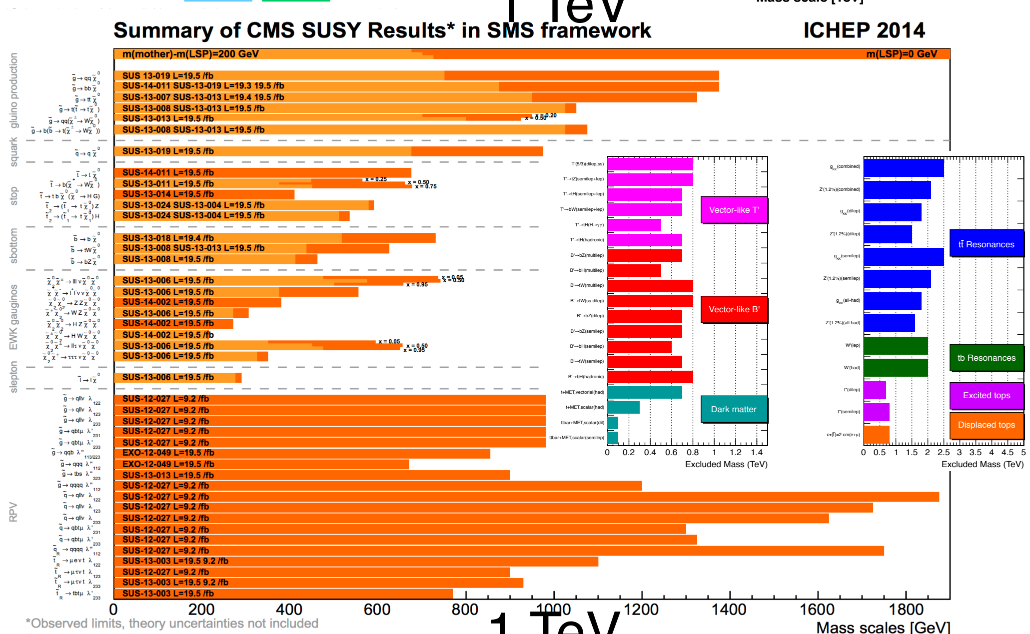
- Only consider dominant ttbar background
  - Other backgrounds negligible
  - Based on Delphes smearing
  - Signal region: Neural Network output > 0.97
- Result quoted as a function of background systematic uncertainty
  - Expect to constrain this to ~1% from data driven methods
- Challenging analysis – would be sensitive to large deviation from SM

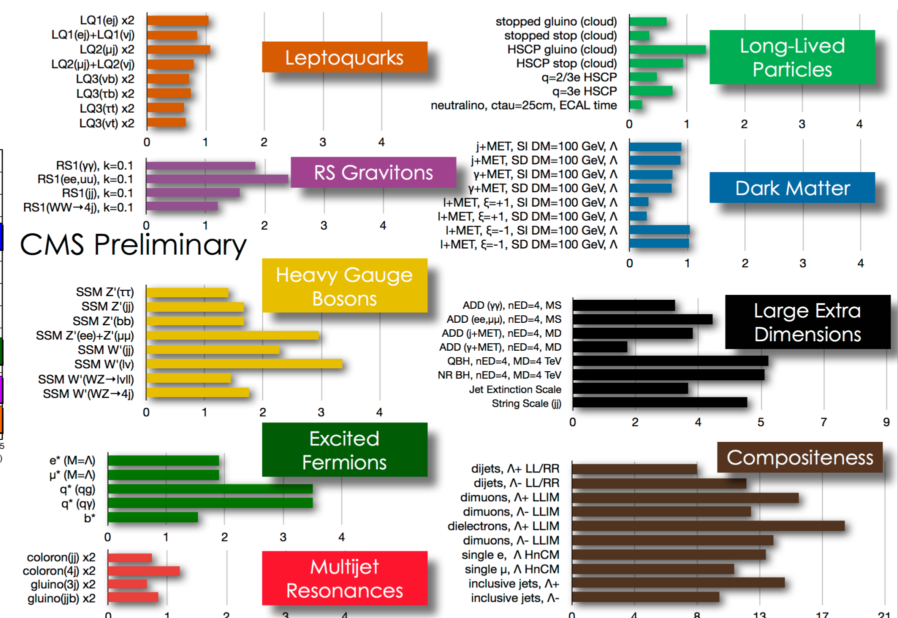




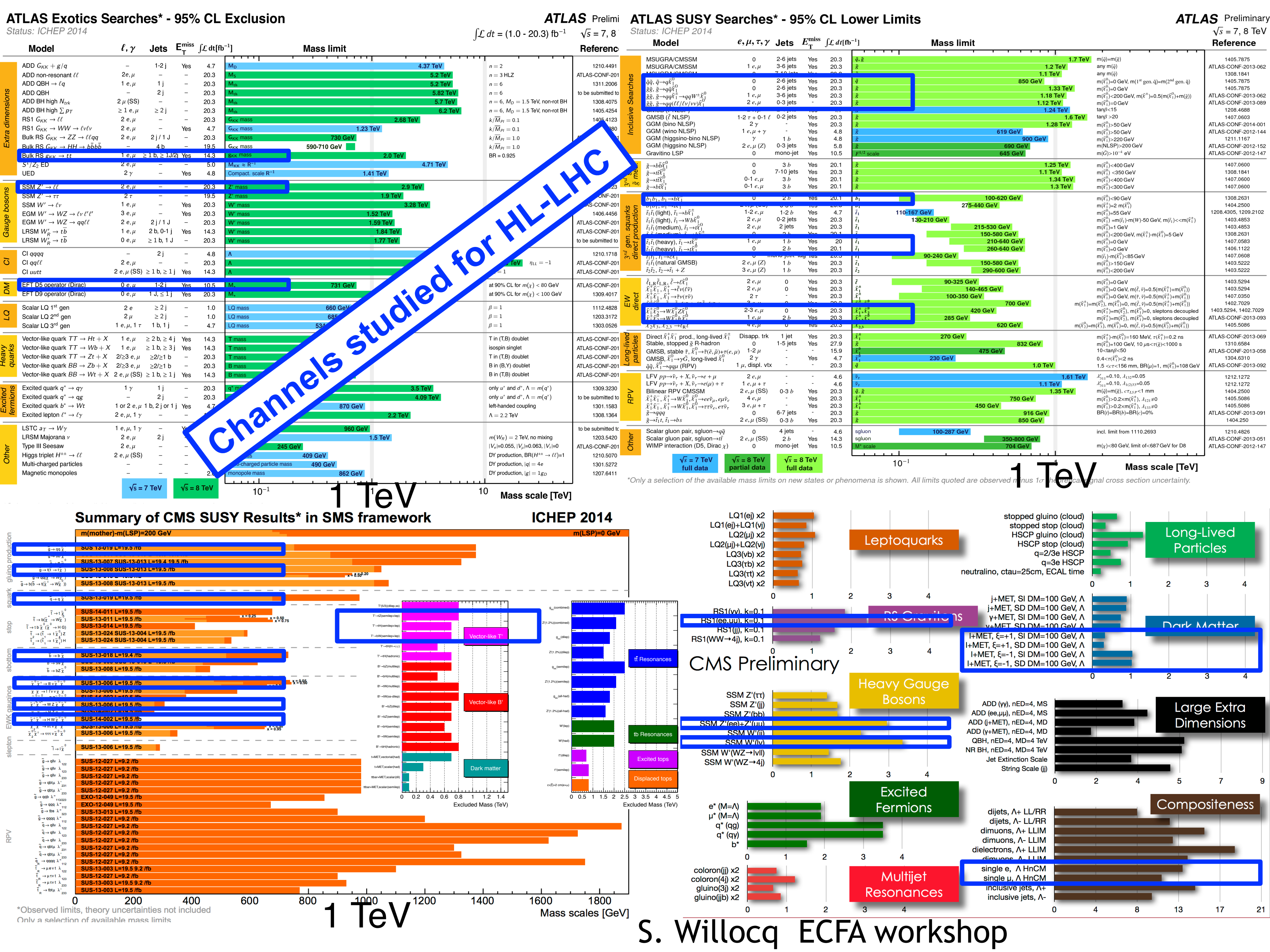






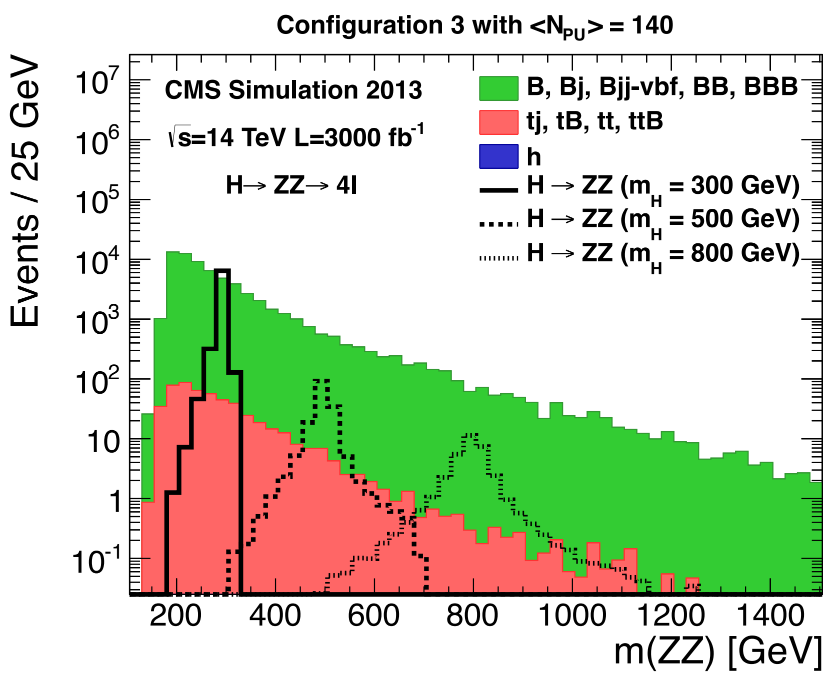


BSM - S. Willocq - ECFA workshop

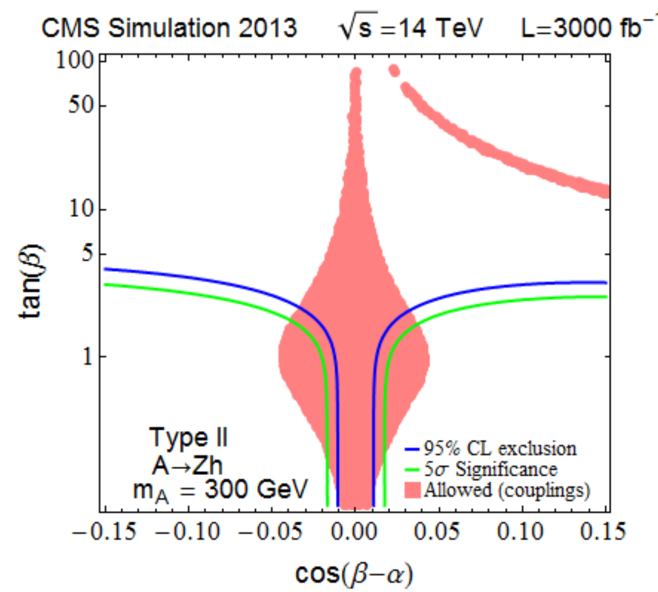

ATLAS Exotics Searches* - 95% CL Exclusion
Status: ICHEP 2014
ATLAS Preliminary
ATLAS SUSY Searches* - 95% CL Lower Limits
Status: ICHEP 2014
Model
Mass limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
Channels studied for HL-LHC
1 TeV
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.
Summary of CMS SUSY Results* in SMS framework
ICHEP 2014
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
squark
stop
sbottom
EWK gauginos
slepton
RPV
Vector-like T
Vector-like B'
Dark matter
tt̄ Resonances
tb Resonances
Excited tops
Displaced tops
Excluded Mass (TeV)
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Leptoquarks
Long-Lived Particles
RS Gravitons
Dark Matter
CMS Preliminary
Heavy Gauge Bosons
Large Extra Dimensions
Excited Fermions
Compositeness
Multijet Resonances
S. Willocq ECFA workshop

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



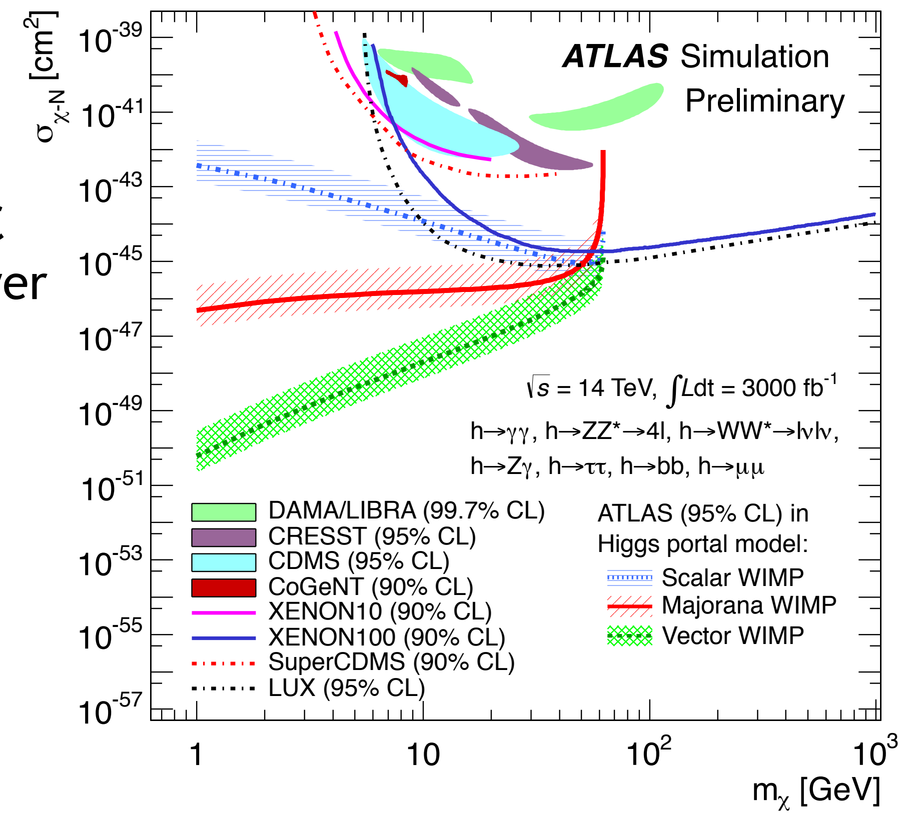
Trial heavy H→ZZ signals



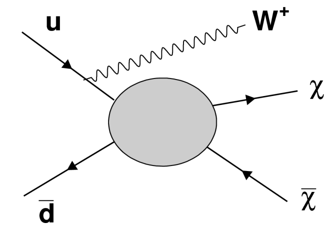
Coupling fits constrain parameters α and β. Direct search results for A→Zh depend on the mass of the A

Higgs portal to Dark Matter

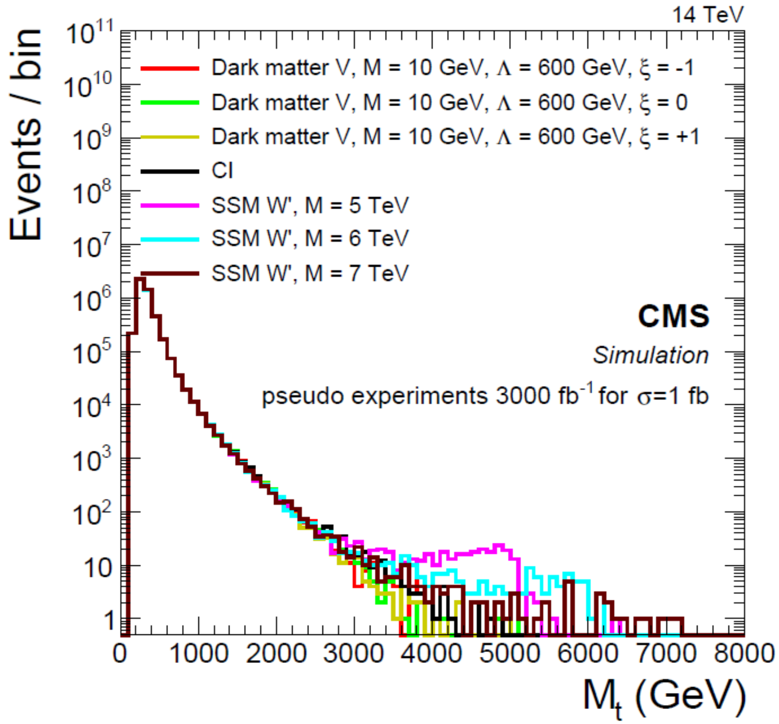
- BR of Higgs decays to invisible final states
  - ATLAS: $BR_{inv} < 0.13$ (0.09 w/out theory uncertainties) at $3000 fb^{-1}$
  - CMS: $BR_{inv} < 0.11$ (0.07 in Scenario 2) at $3000 fb^{-1}$
- The coupling of WIMP to SM Higgs is taken as the free parameter
- Translate limit on BR to the coupling of Higgs to WIMP
- Compare with constraints from direct searches – LHC has more sensitivity in lower mass range



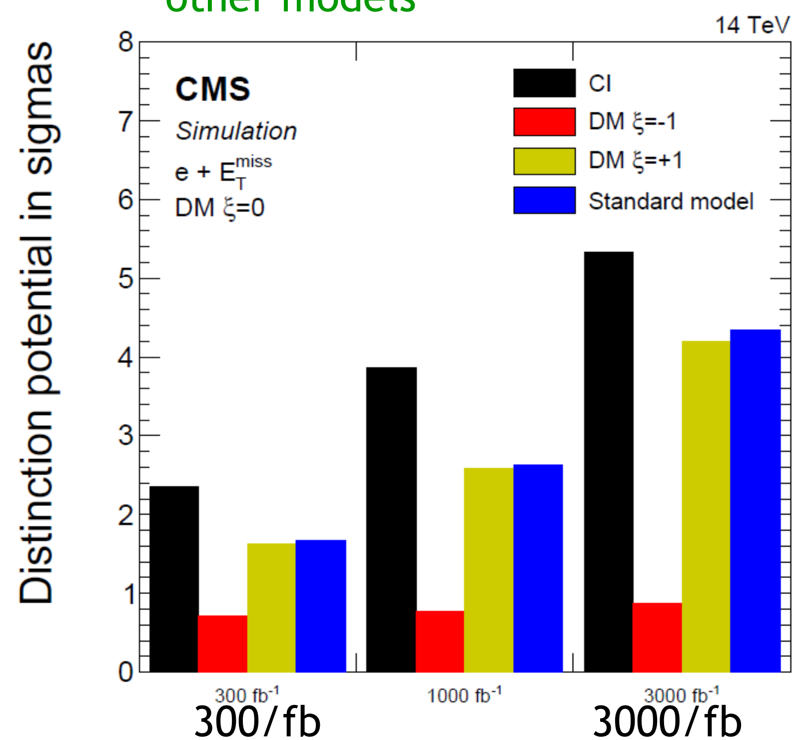
Mono-X searches for dark matter



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



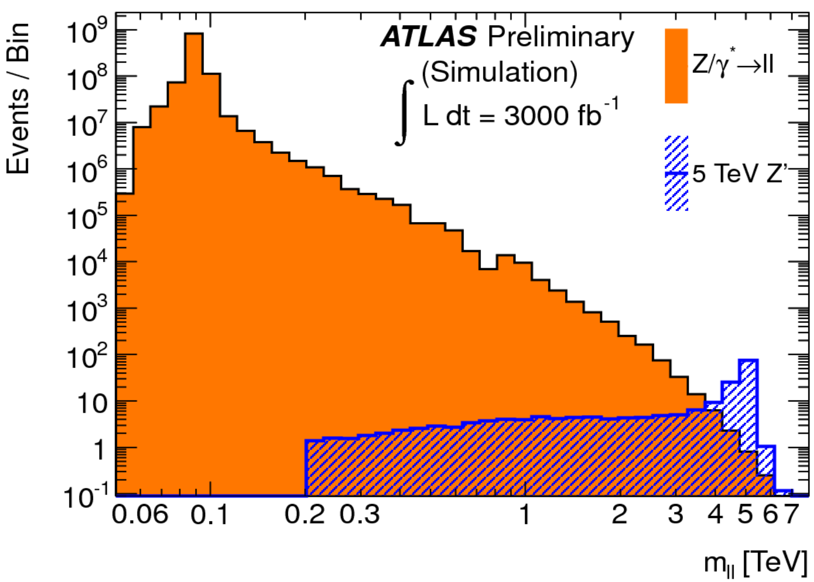
Distinction between DM ξ=0 and other models

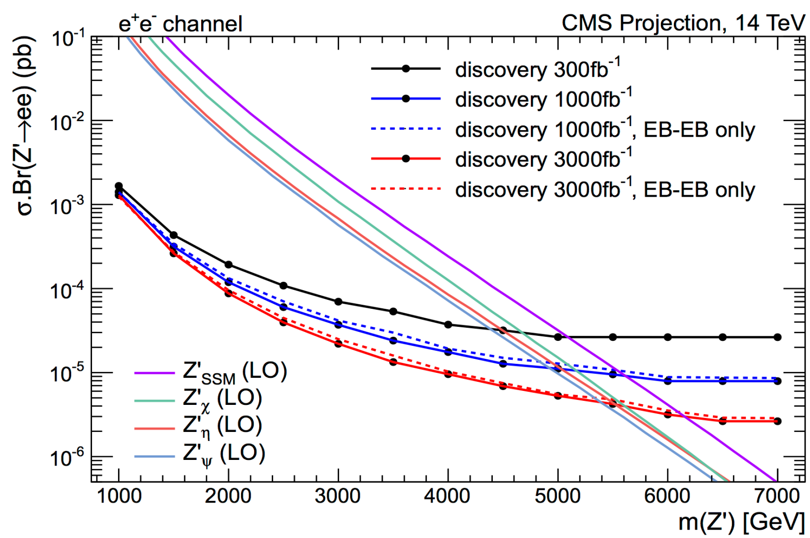


ATL-PHYS-PUB-2013-003
CMS arXiv:1307.7135

Dilepton resonances

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

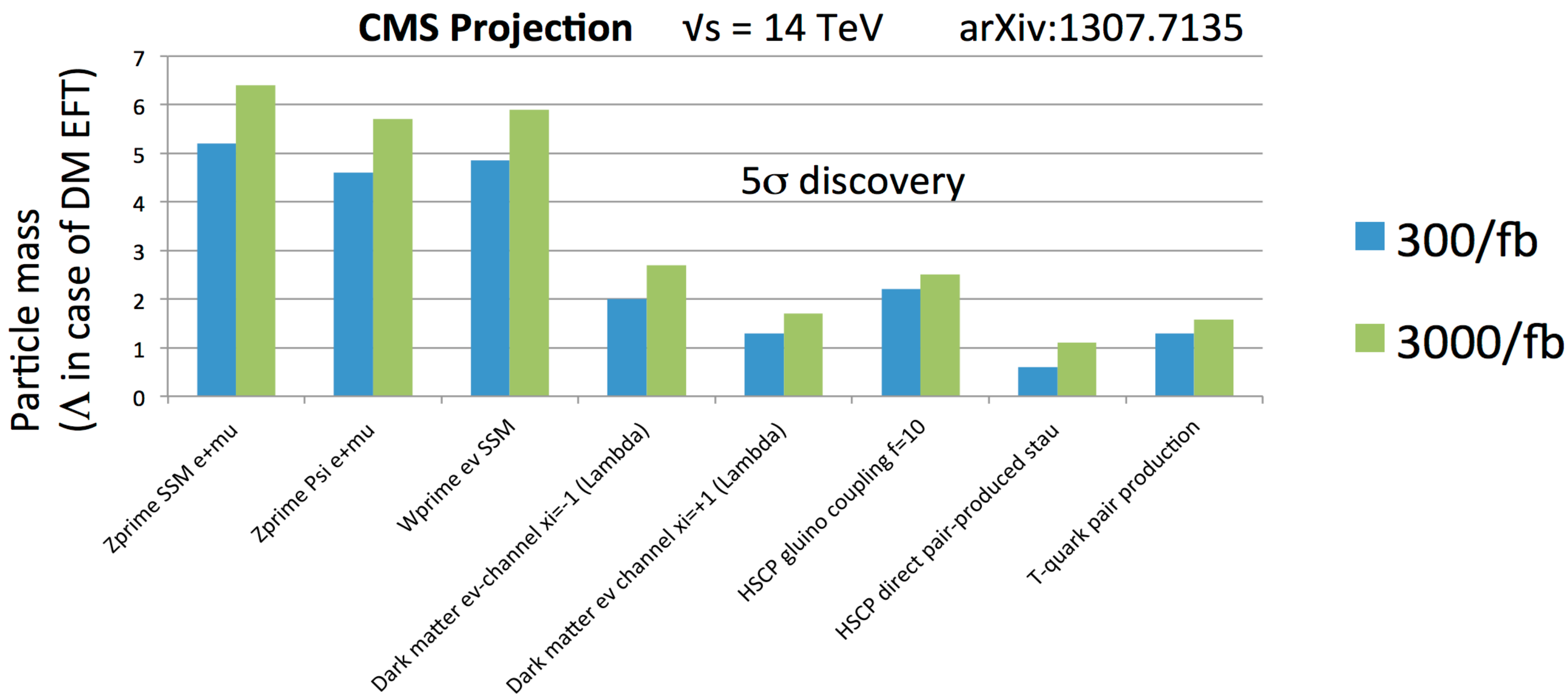




Discovery up to 6.2 TeV (for SSM Z')

Mass reach for exotic signatures

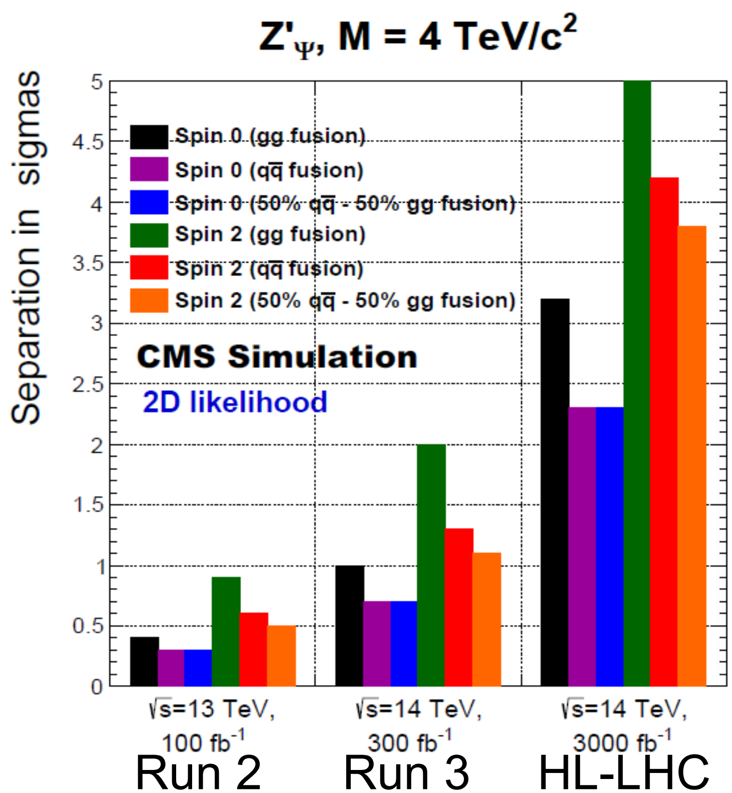
- Sensitivity in multi-TeV range increases by ~20% with HL-LHC

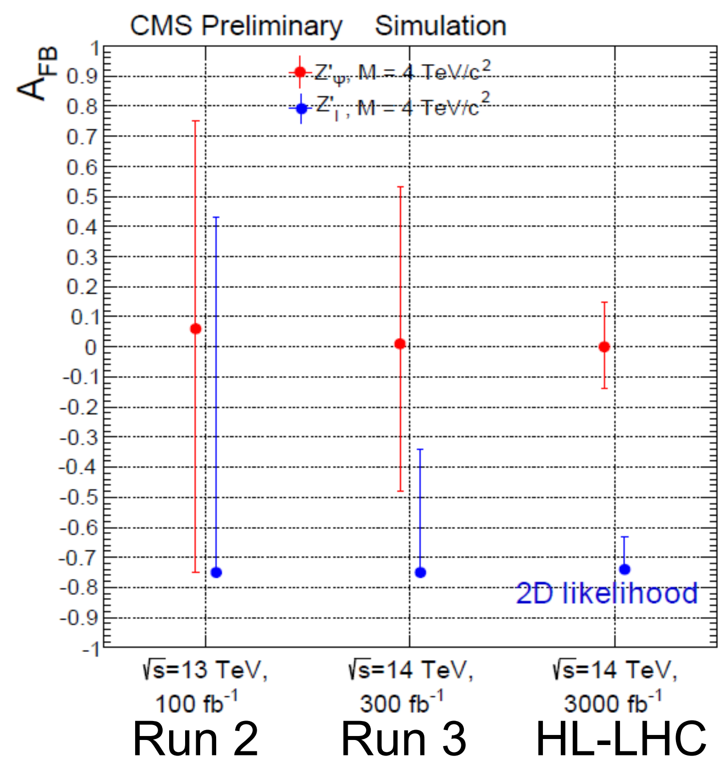


ATLAS @14 TeV	Z' → ee SSM 95% CL limit	g_{KK} → t t RS 95% CL limit	Dark matter M* 5σ discovery
300 fb^{-1}	6.5 TeV	4.3 TeV	2.2 TeV
3000 fb^{-1}	7.8 TeV	6.7 TeV	2.6 TeV

Model discrimination after a discovery

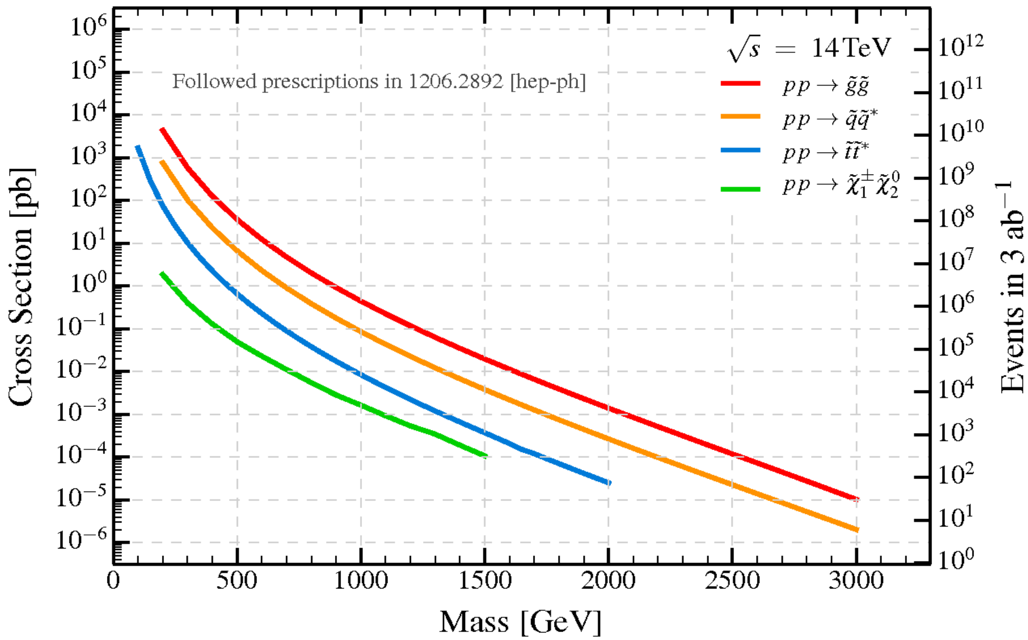
- Ability to discriminate improves dramatically with HL-LHC
  - Separation between spin-1 (Z') or spin-2 (G_{KK}) interpretation and other interpretations ranges from ~2 to 5 σ
  - Use 2d likelihood with dilepton angular and rapidity distributions or forward-backward asymmetry



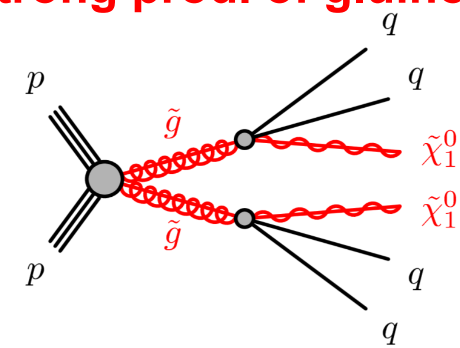


Supersymmetry

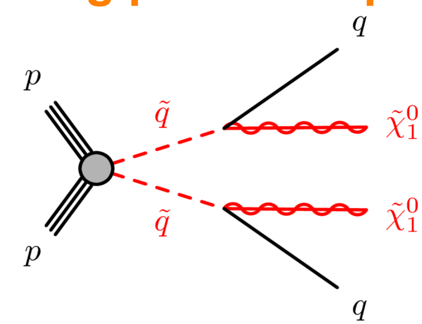
- Motivated by naturalness, dark matter...



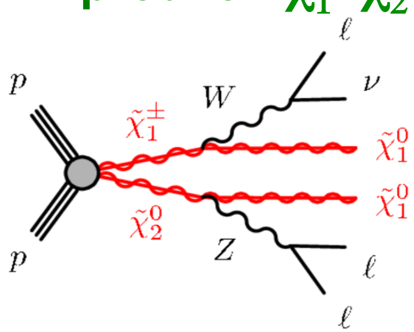
Strong prod. of gluinos



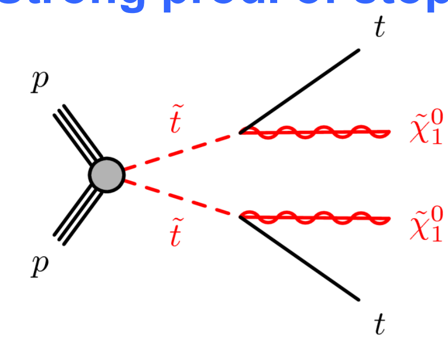
Strong prod. of squarks



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



Strong prod. of stops



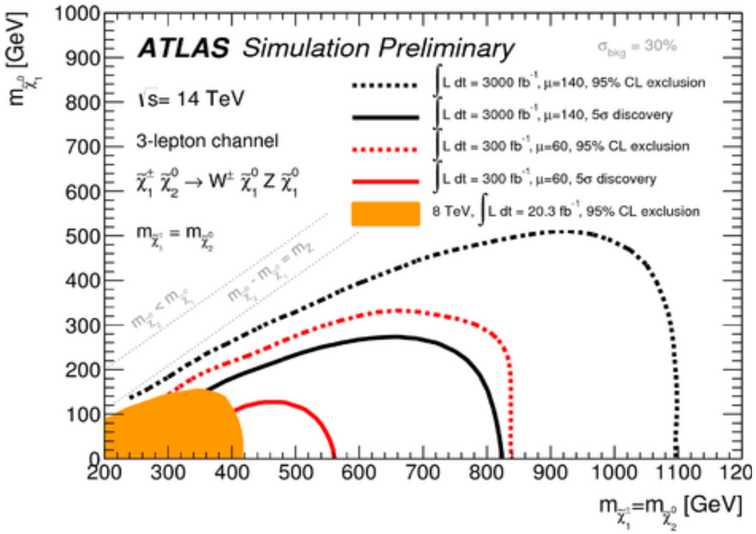
Gluinos not necessarily first to be discovered

(many different mass spectra possible)

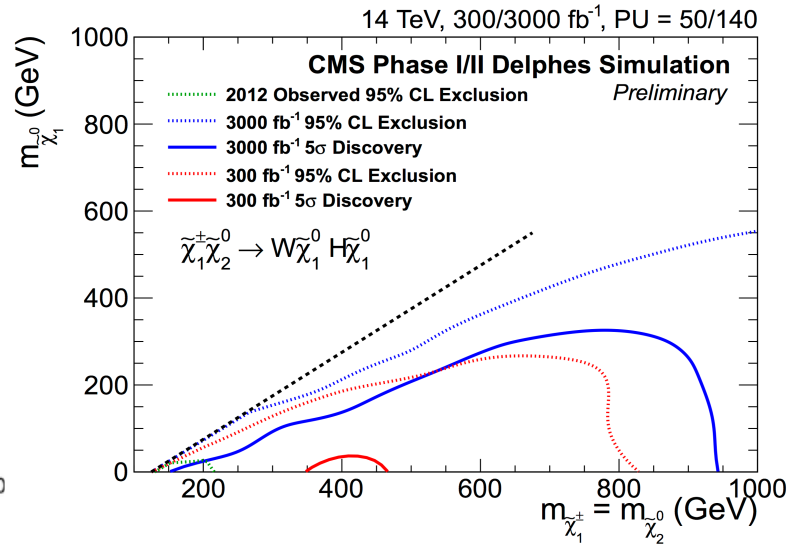
Electroweak processes eg $\chi_1^+\chi_2^0$ production

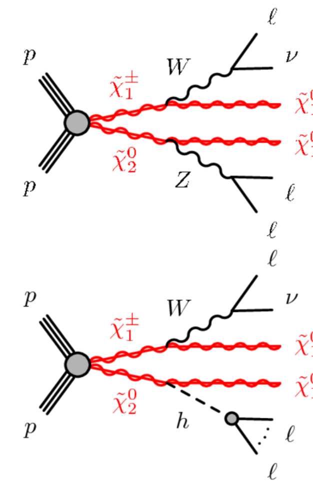
- May be the dominant SUSY processes if squarks/gluinos heavy
  - weak process – benefit from high luminosity

ATL-PHYS-PUB-2014-010



CMS PAS SUS-14-012

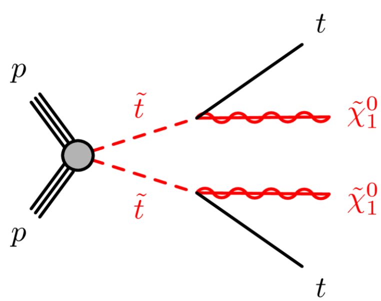


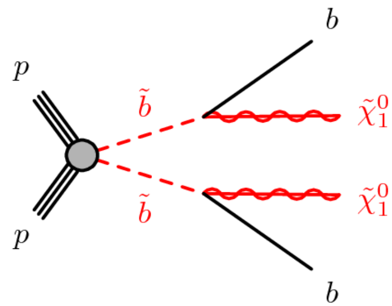


Chargino mass 5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
WZ (3l analysis) [ATLAS]	Up to 560 GeV	Up to 820 GeV
WZ (3l analysis) [CMS]	Up to 600 GeV	Up to 900 GeV
WH (3l analysis) [ATLAS]	(<5σ reach)	Up to 650 GeV
WH (bb analysis) [CMS]	350-460 GeV	Up to 950 GeV

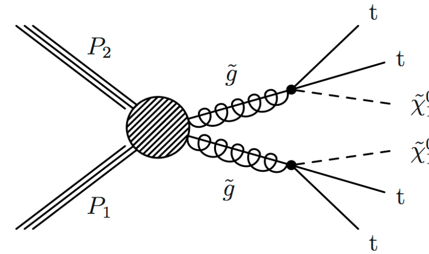
Stop and sbottom

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

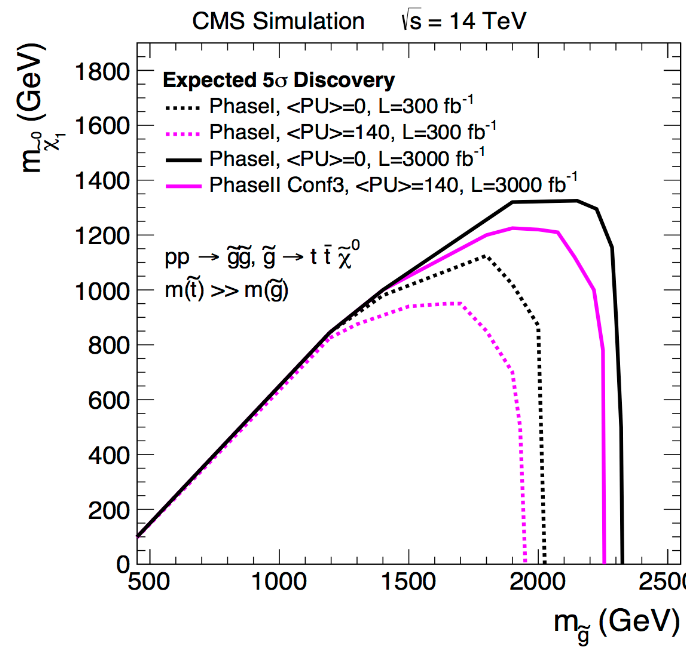




  - CMS gluino pair production with decay via stop to ttχ



CMS PAS FTR-13-014

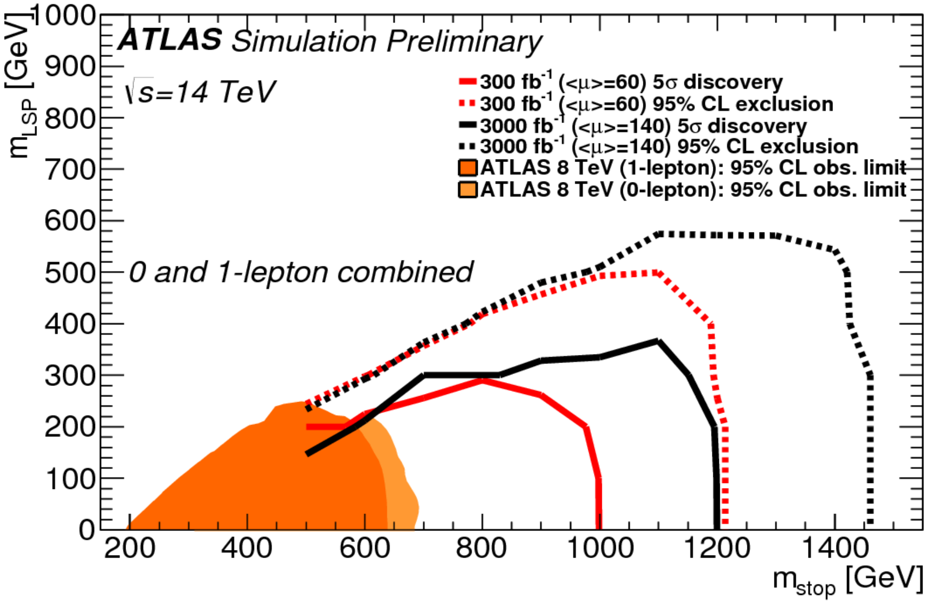


5σ discovery, simplified model	300 fb^{-1}	3000 fb^{-1}
stop mass from direct production [ATLAS]	Up to 1.0 TeV	Up to 1.2 TeV
gluino mass with decay to stop [CMS]	Up to 1.9 TeV	Up to 2.2 TeV
sbottom mass from direct production [ATLAS]	Up to 1.1 TeV	Up to 1.3 TeV

ATLAS stop/sbottom

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

ATL-PHYS-PUB-2013-011



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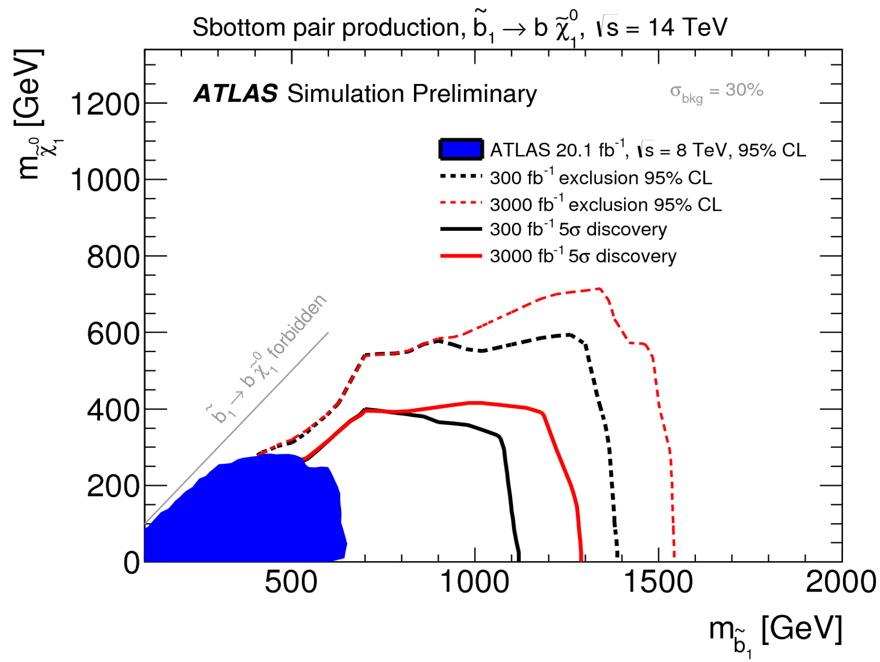
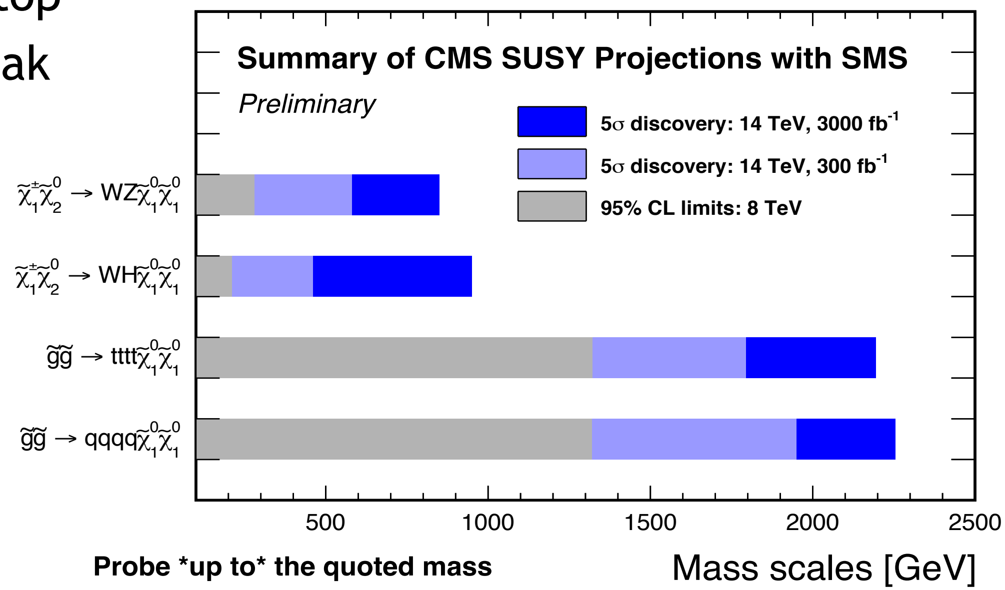


Summary of simplified models

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 $\chi_1^+\chi_2^0$



Full spectrum SUSY models

- 3 pMSSM models motivated by naturalness, different LSP
  - NM1(2): bino-like with low(high) slepton mass; NM3: higgsino-like
- 2 p(C)MSSM models, DM relic density, different coannihilation
  - STC: stau + χ_1^0 coann;
    STOC: stop + χ_1^0 coann.
- Explored:
  - 9 different experimental signatures
  - 5 different types of SUSY models
- 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 (HT-MHT) search	300				$<3\sigma$	$3-5\sigma$
	3000				$3-5\sigma$	$>5\sigma$
all-hadronic (MT2) 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		$3-5\sigma$			

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

The next 6-12 months...

- Optimise the Phase II detector layouts for cost/performance/physics sensitivity
    - Interplay of layout and reconstruction algorithms

http://xkcd.com/1445/

STUDIES TAKE A LONG TIME

Conclusion and outlook

- Very good progress with evaluating the baseline Phase II layouts in ATLAS and CMS
    - A combination of new detector components and improved algorithms provide pileup mitigation
    - Need to continue to quantify how the performance changes with layout and algorithm improvements
- The main Higgs couplings can be measured to a few percent precision with HL-LHC
    - Also sensitivity to rare processes
    - Constraints on physics beyond the Standard Model
- 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
- Full exploitation of the LHC needs the high-luminosity upgrade to address questions of electroweak symmetry breaking, dark matter and gravity