Higgs Measurements

Part 2: Higgs prospects for Run 2/3

Xin Chen

Tsinghua University

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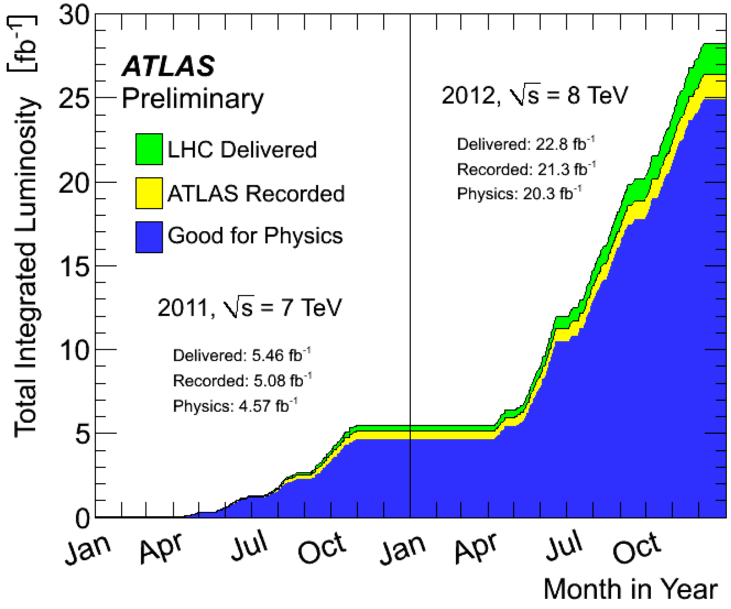
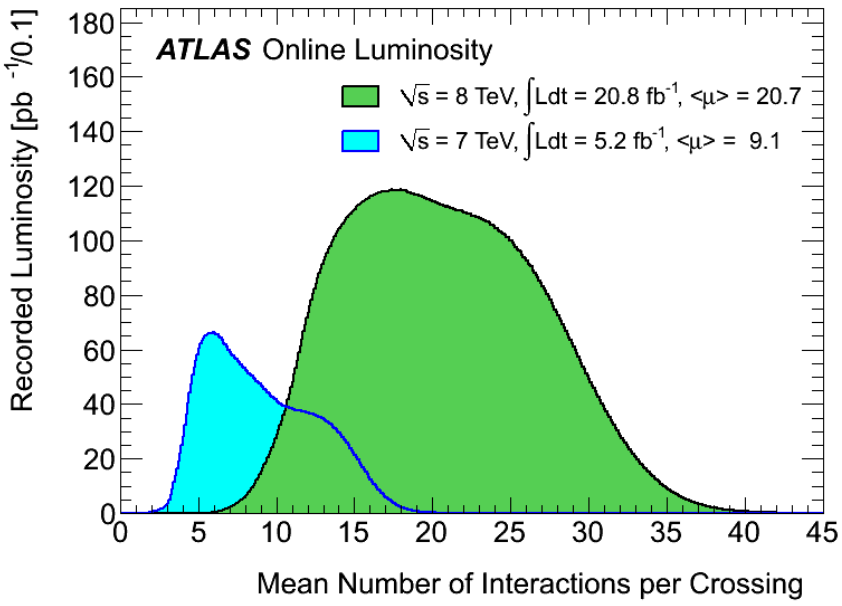
ATLAS Luminosity in Run 1 & 2

Run 1





ATLAS Luminosity in Run 1 & 2

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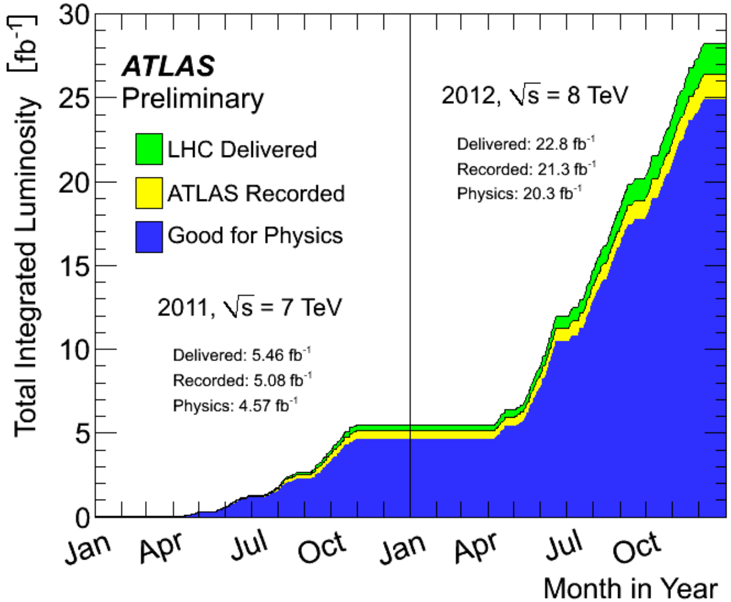
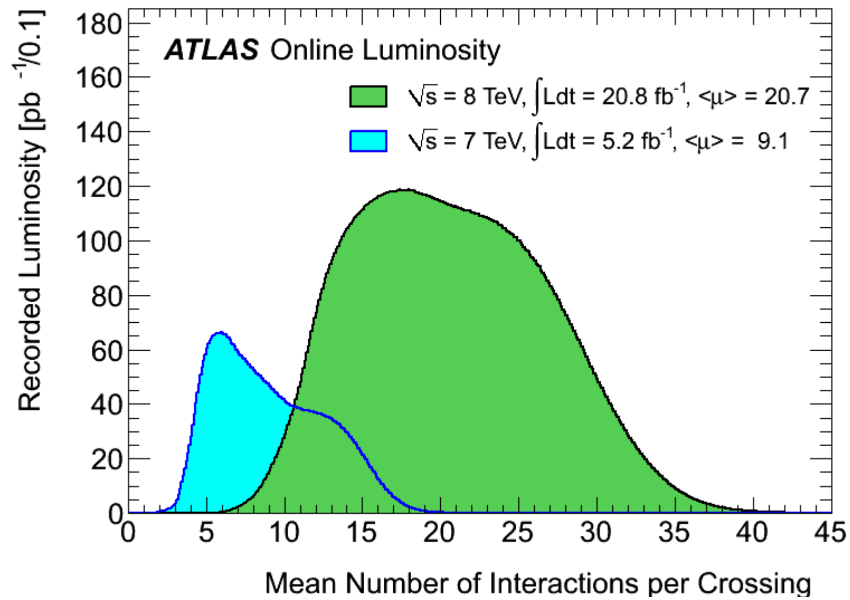
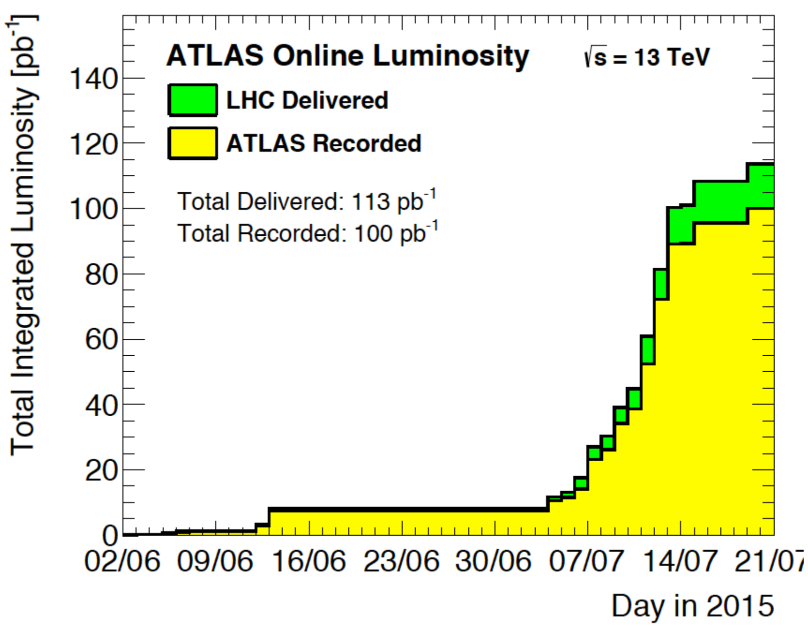
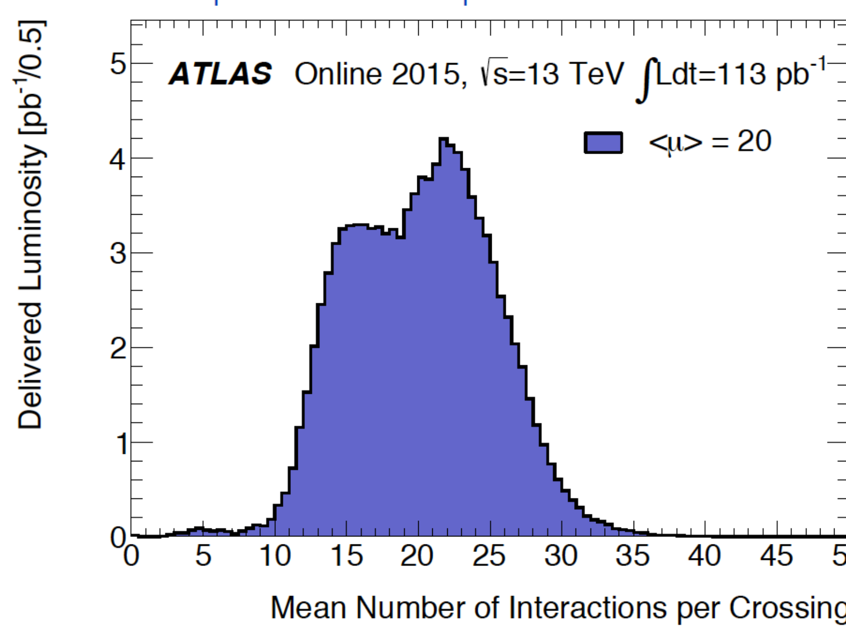




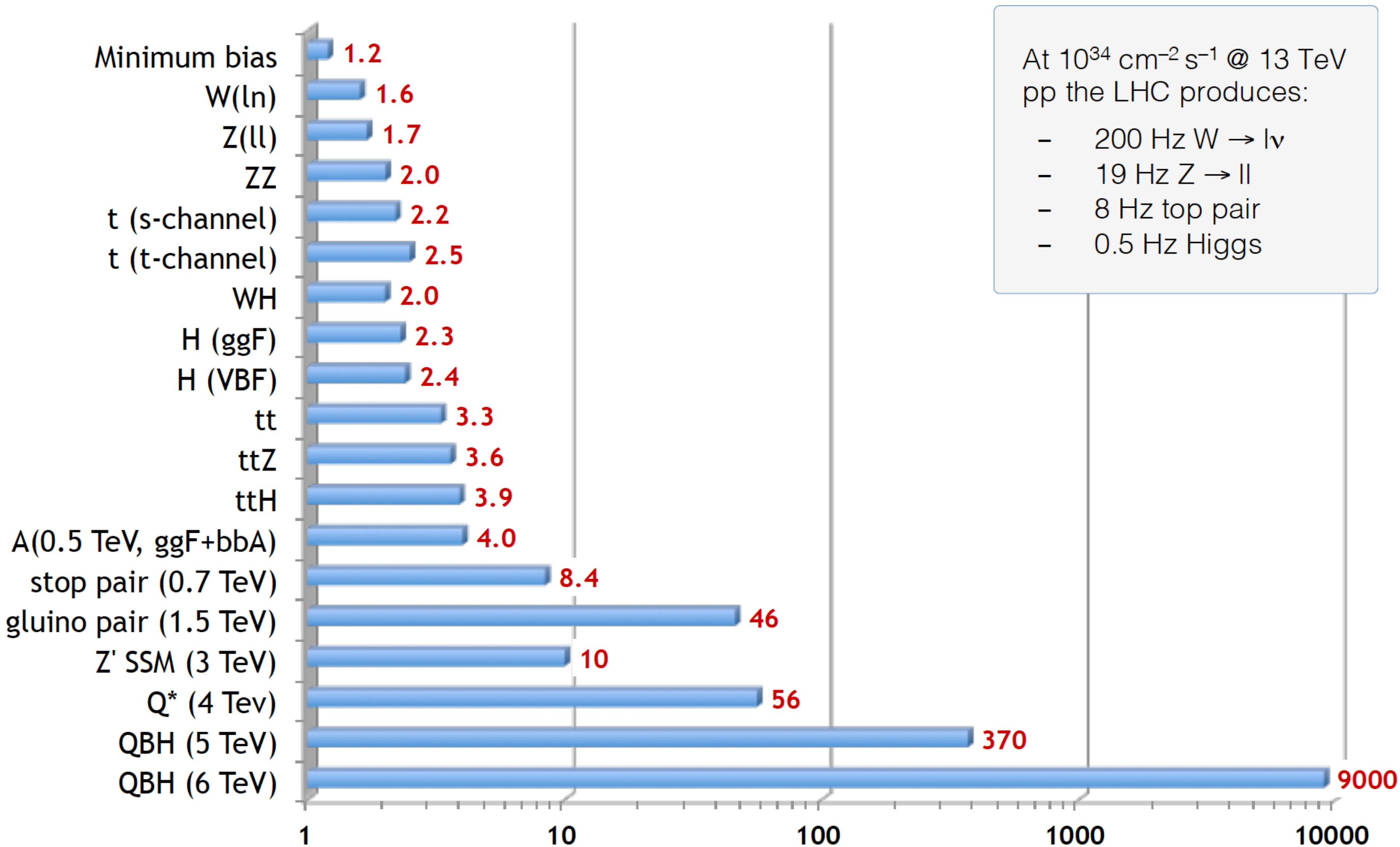
Pileup interactions profile

Run 2

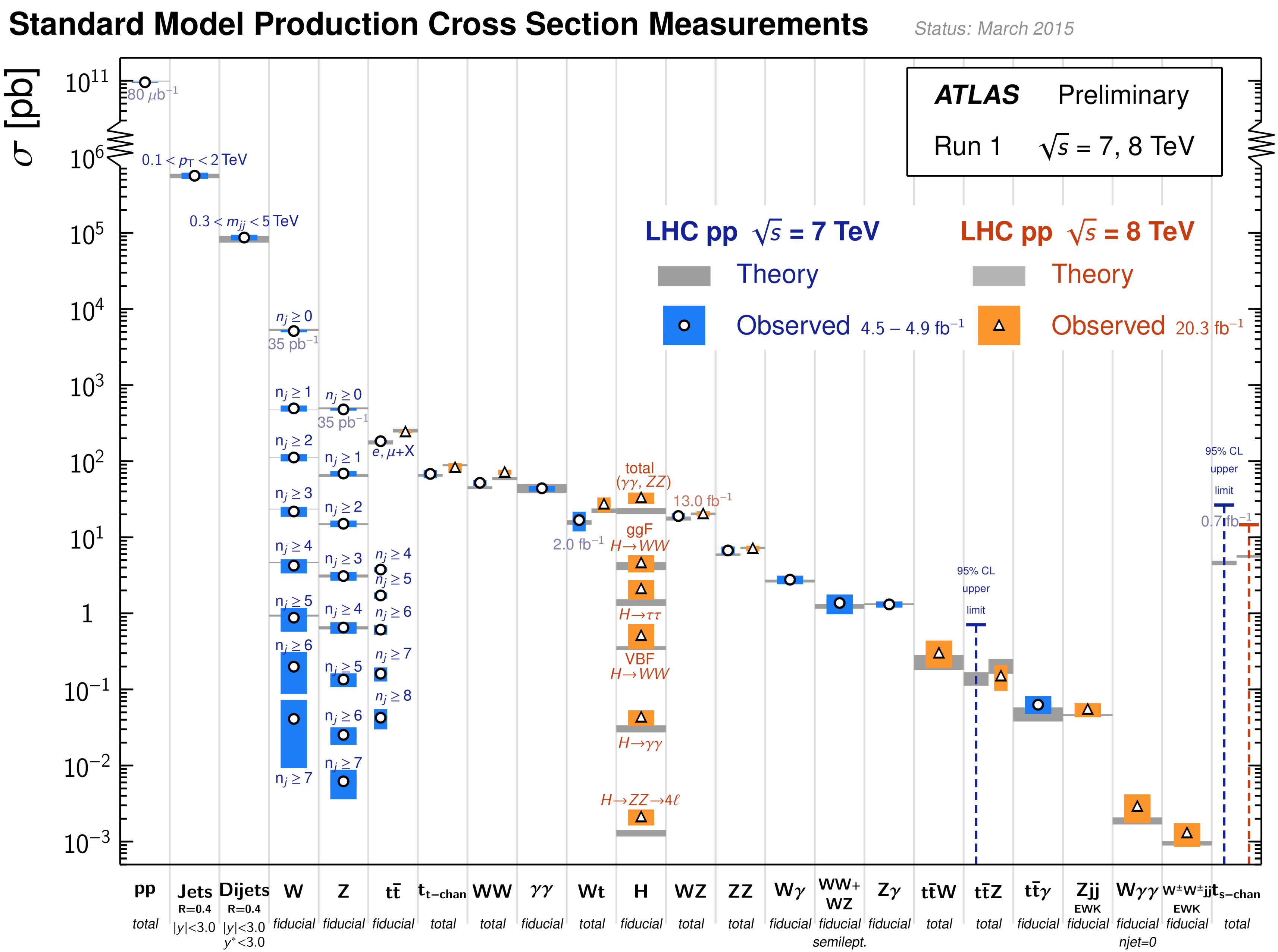




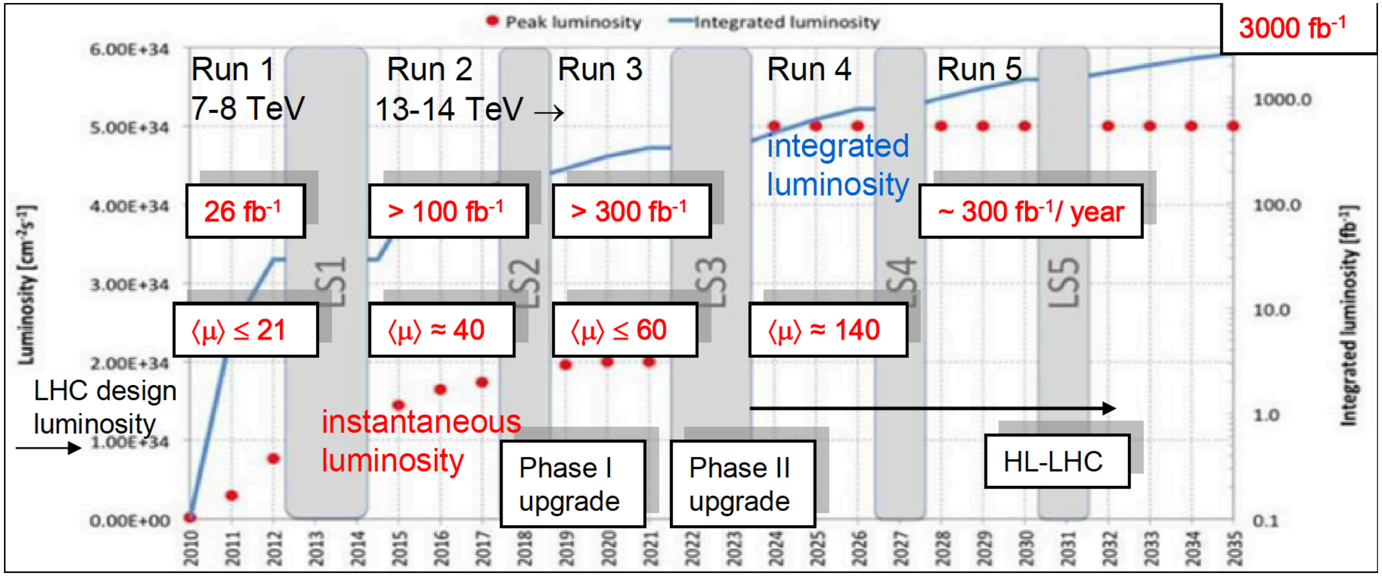
Scaling factors from 8 to 13 TeV

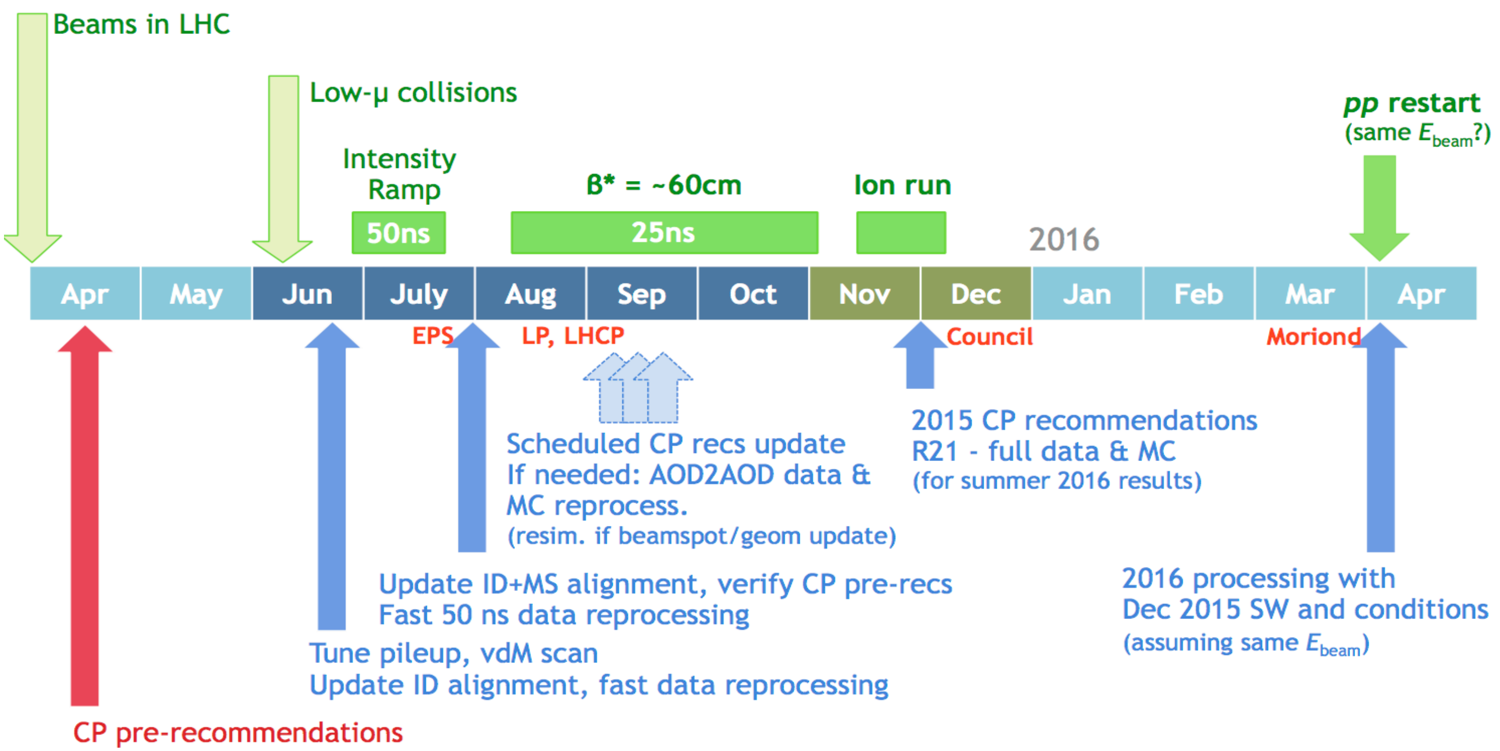


Confirming SM prediction with Run 1



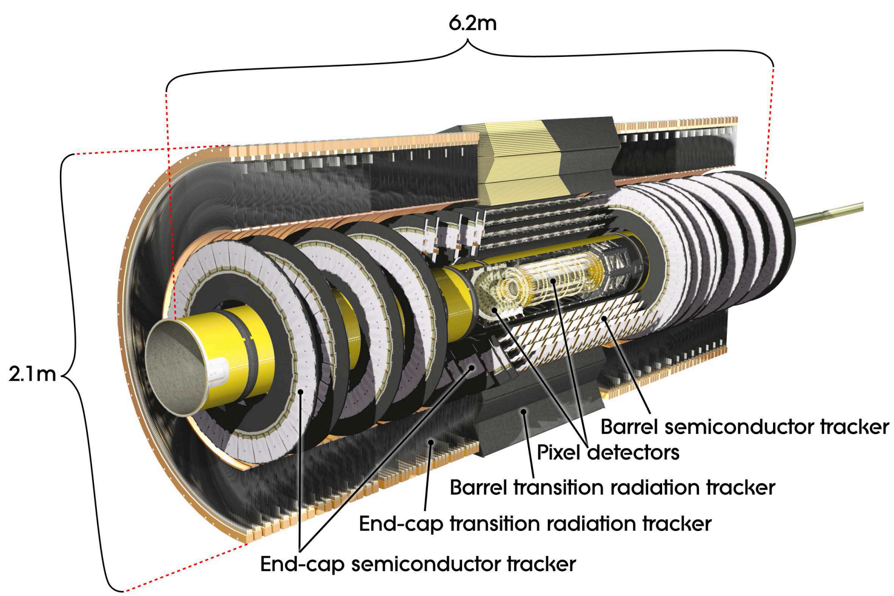
LHC Schedule

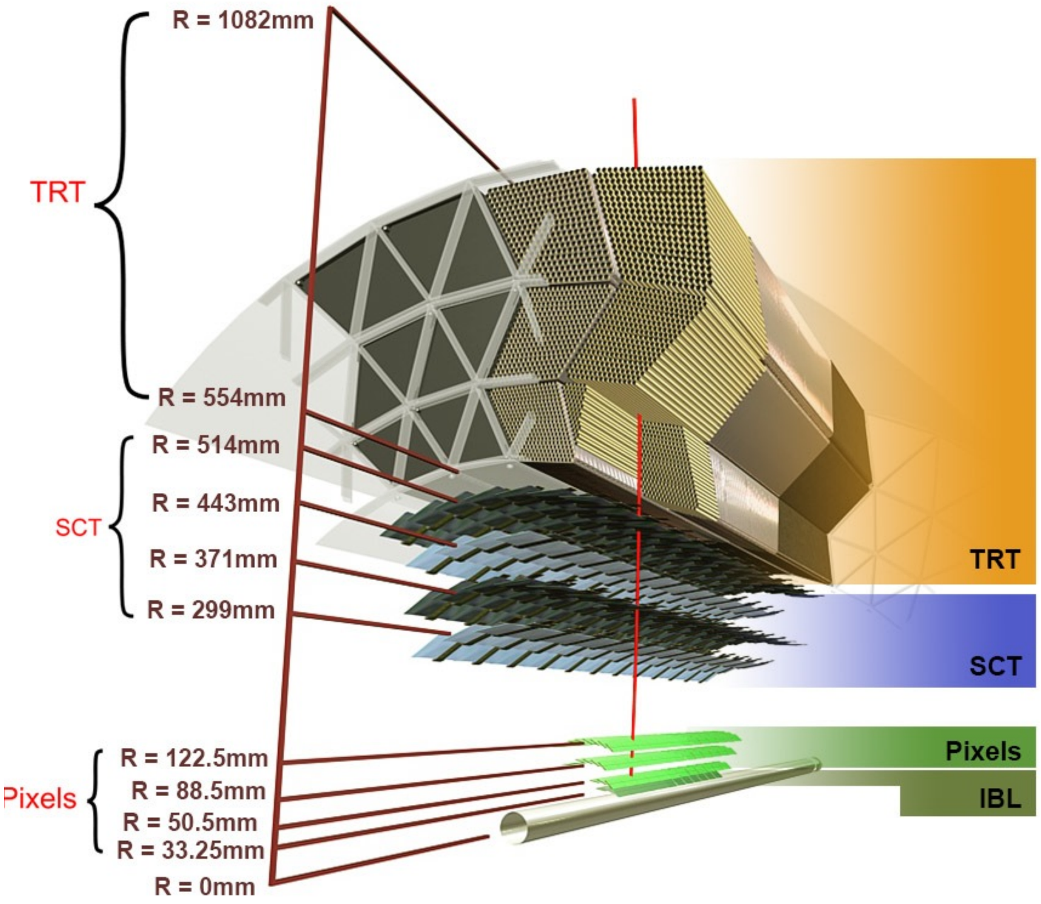




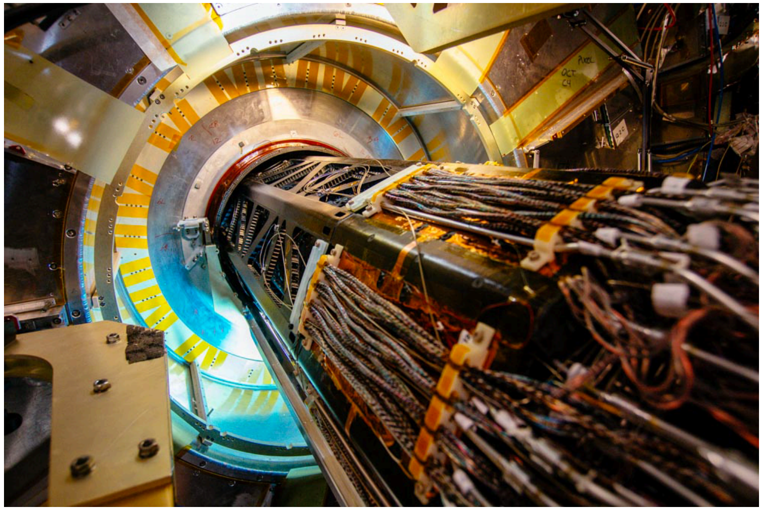
ATLAS Inner Detector for Run 2

- New Isertable-B-Layer (IBL)
- Silicon Pixel detector (Pixels)
- Silicon Tracker (SCT)
- Transition Radiation Tracker (TRT)
- 2T B-field in the tracking volume
- Fiducial coverage |η|<2.5

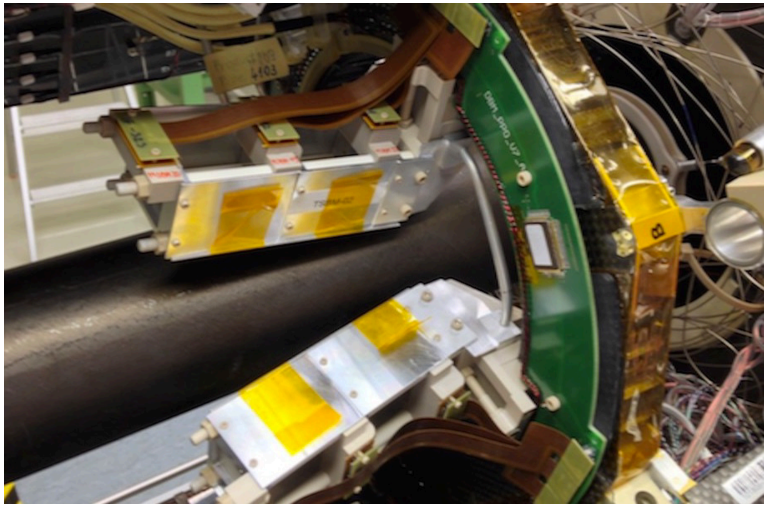




Pixel Upgrade during LS1

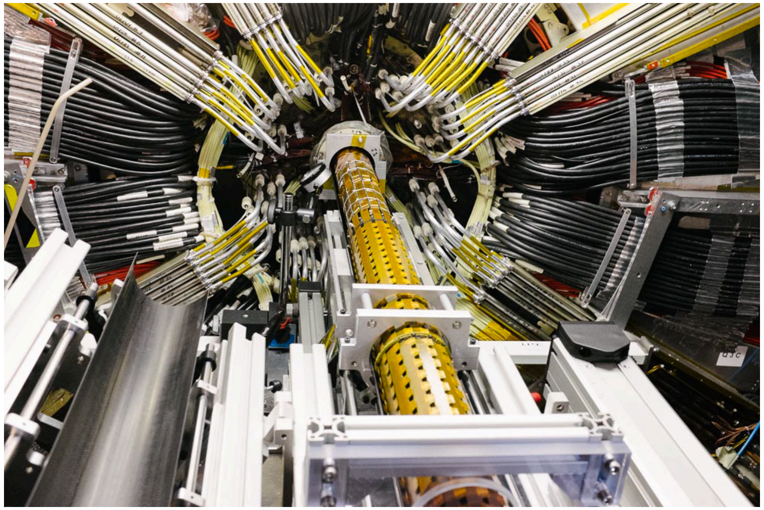


Upgraded Pixel



DBM

- Major upgrade to ATLAS in LS1
- Pixel: new services, new optical links
- New Diamond Beam Monitor (DBM) in the Pixel volume
- New IBL

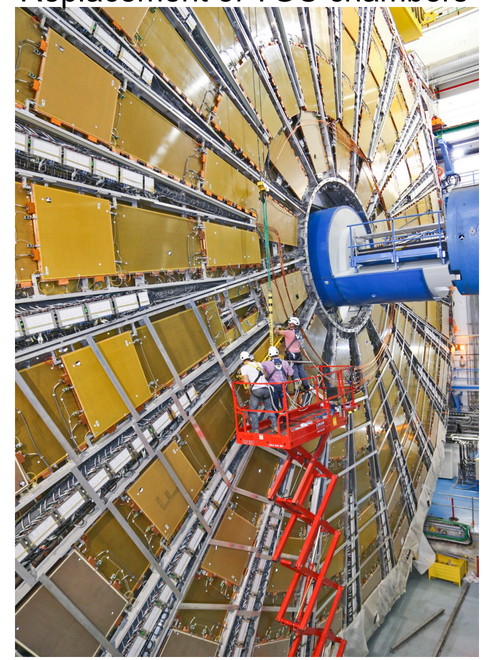


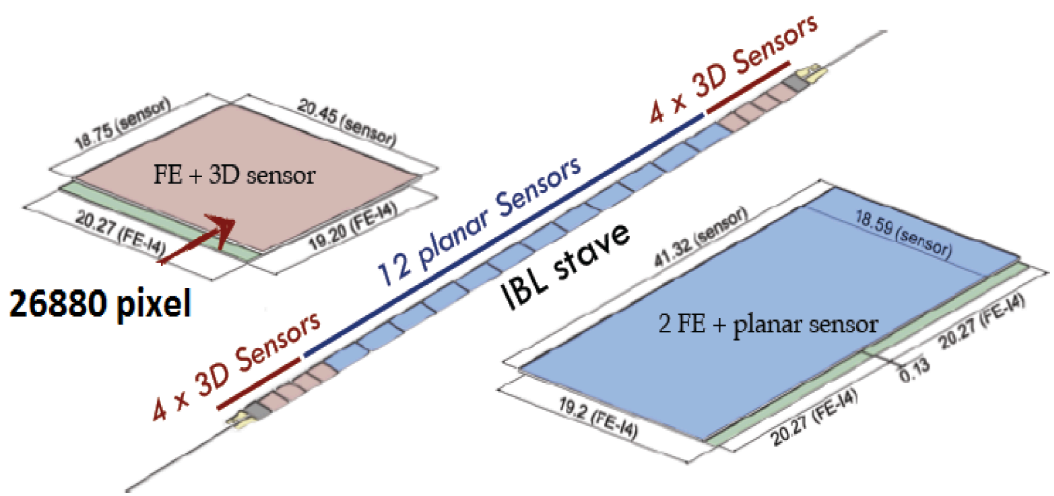
IBL

ATLAS Upgrade during LS1

- Infrastructure: magnet & cryogenic systems, additional muon chamber shielding, new beam pipes
- Detector: muon chamber completion (1.0< |η| <1.3) & replacements, calorimeter electronics repairs, improved inner detector read-out capability to cope with 100 kHz L1 trigger rate, new pixel detector services and module repair
- New IBL, improved ID tracking algorithm in dense environment (TIDE)
- New topological L1 trigger and new central trigger processor, restructured high-level trigger
- New software, new production system, new analysis model (xAOD)

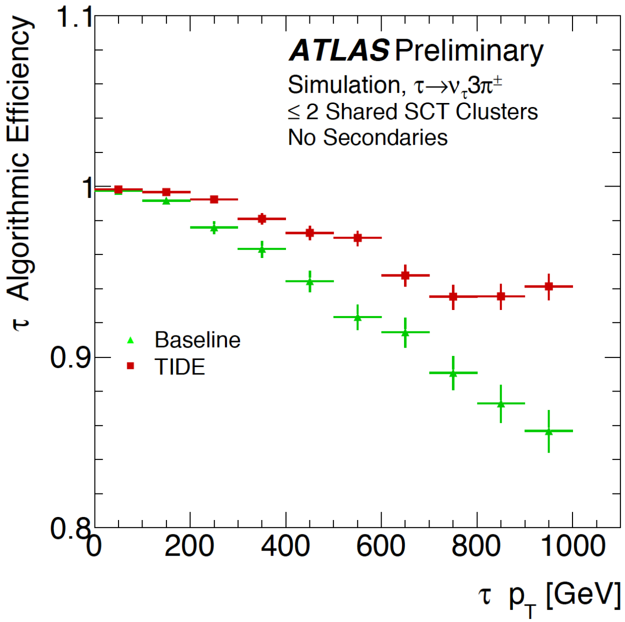
Replacement of TGC chambers

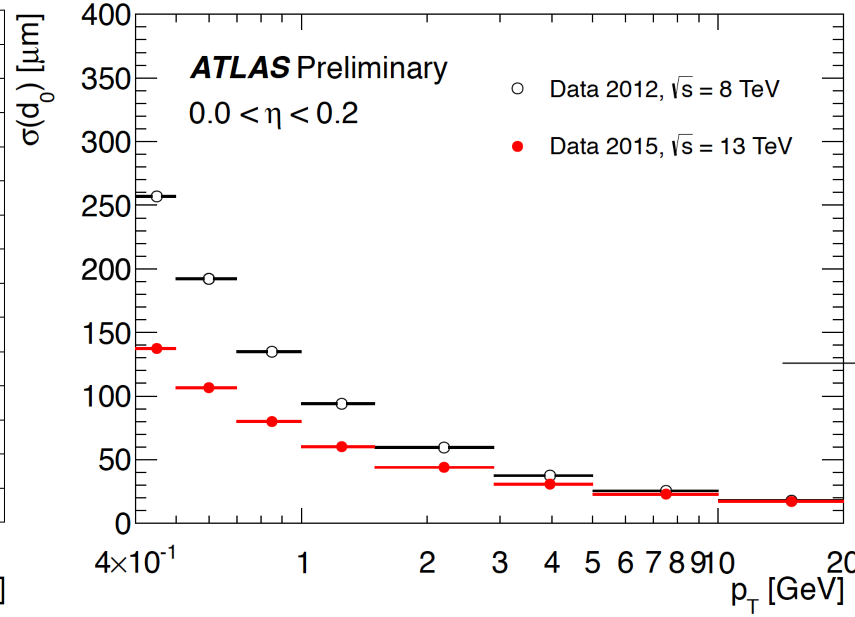


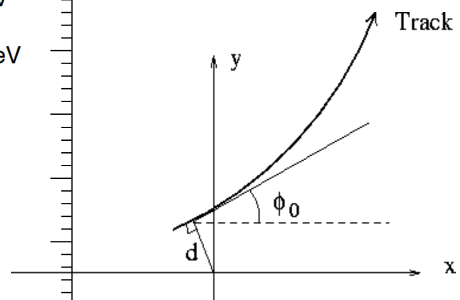


[IDTR-2015-003/IDTR-2015-007]

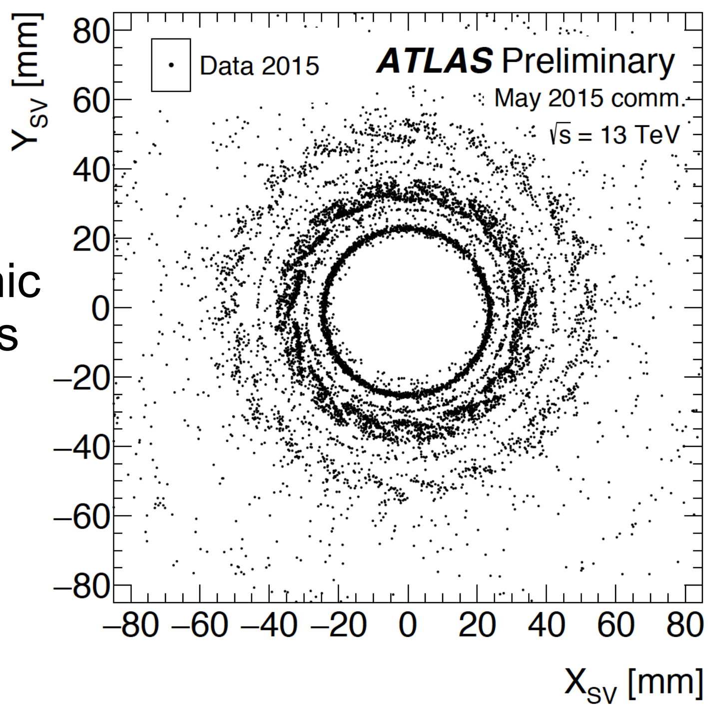
Tracking Improvement

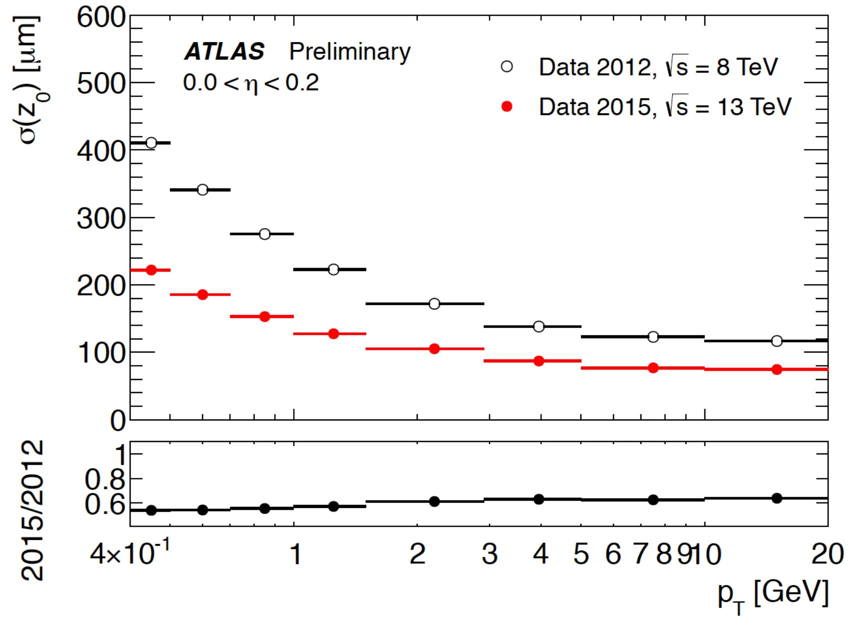




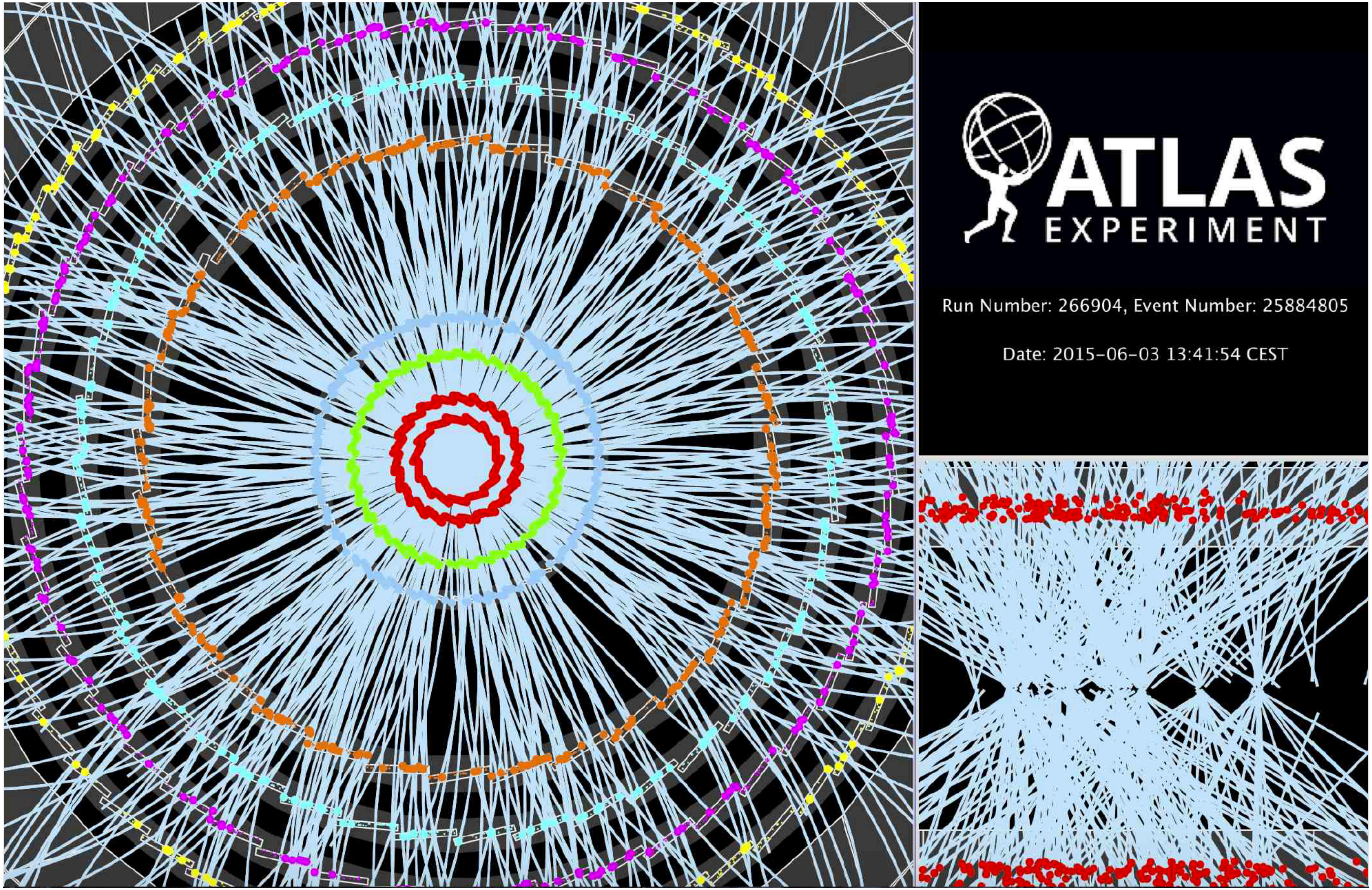


Hadronic Vertices in ID



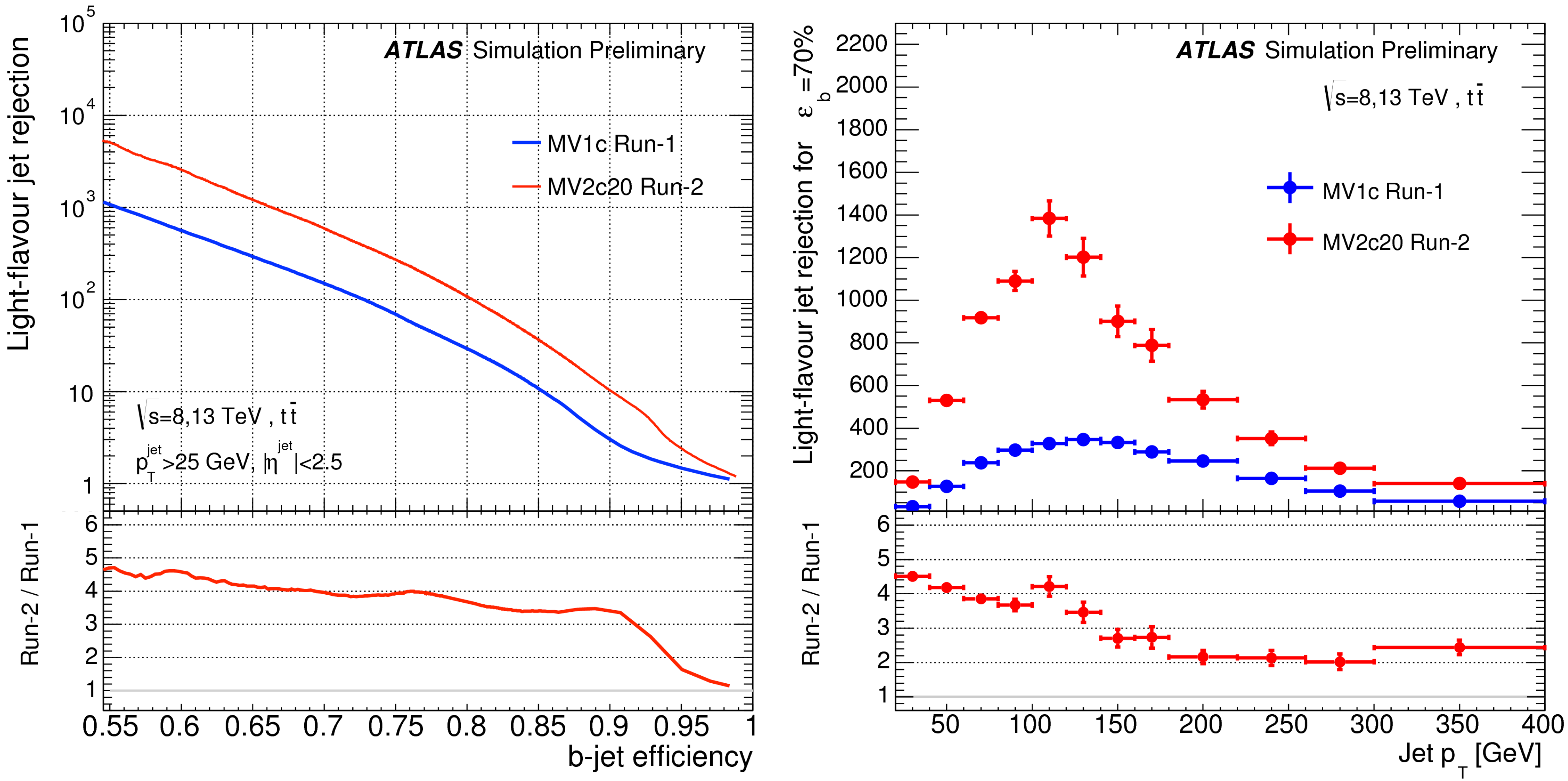


First Run 2 collisions with a 4-layer Pixel



[ATL-PHYS-PUB-2015-022]

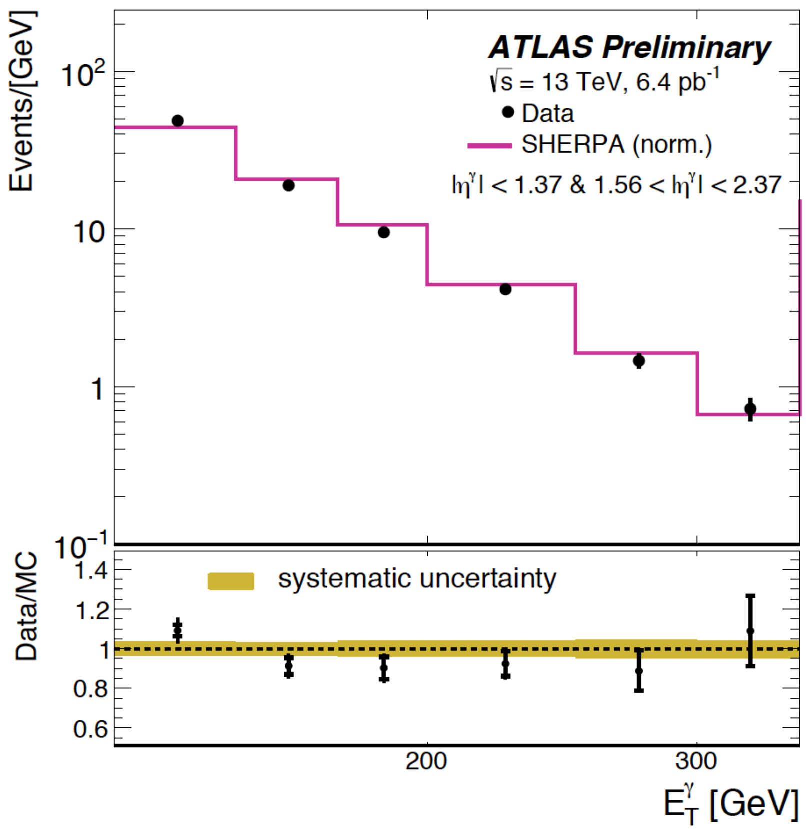
Improvement of b-tagging



- Significant b-tagging improvement for Run 2
- Improved light-avour jet rejection due to IBL and algorithmic improvements

(new multivariate tagger MV2, tracking, esp. TIDE)

Initial data understanding for Run 2



- Single isolated photon production
- Background subtracted
- Detector level E_T
- Sherpa MC normalized to data

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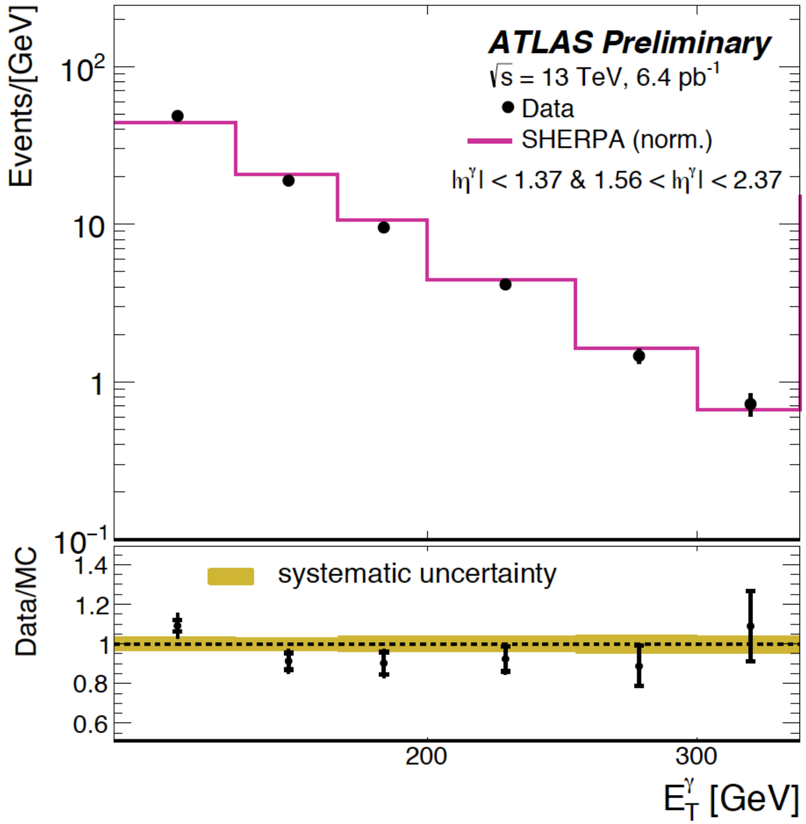
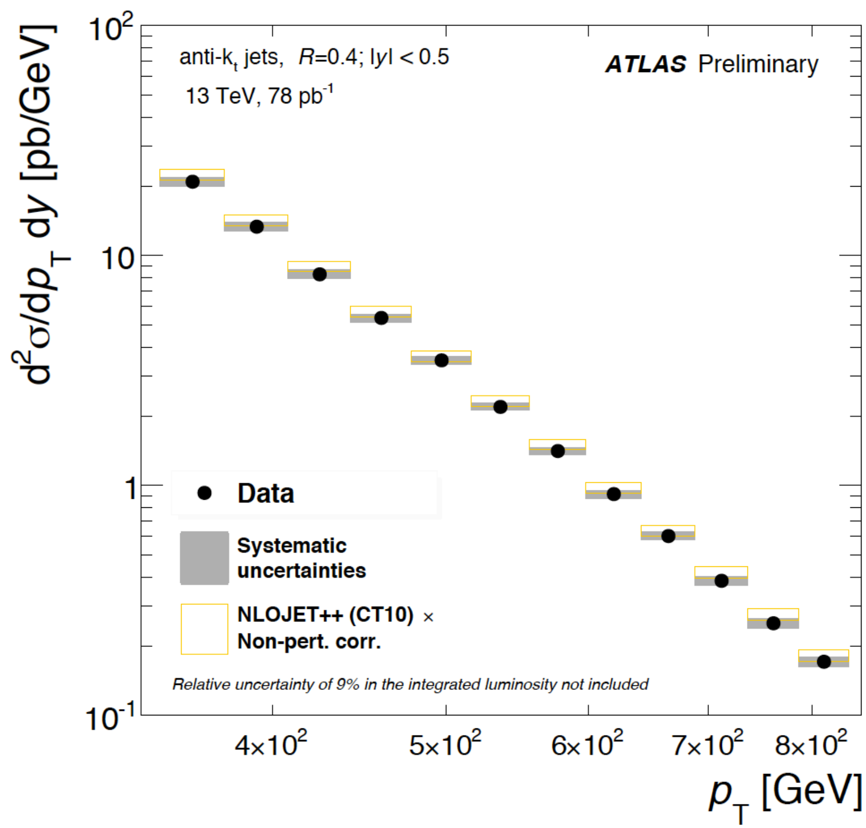
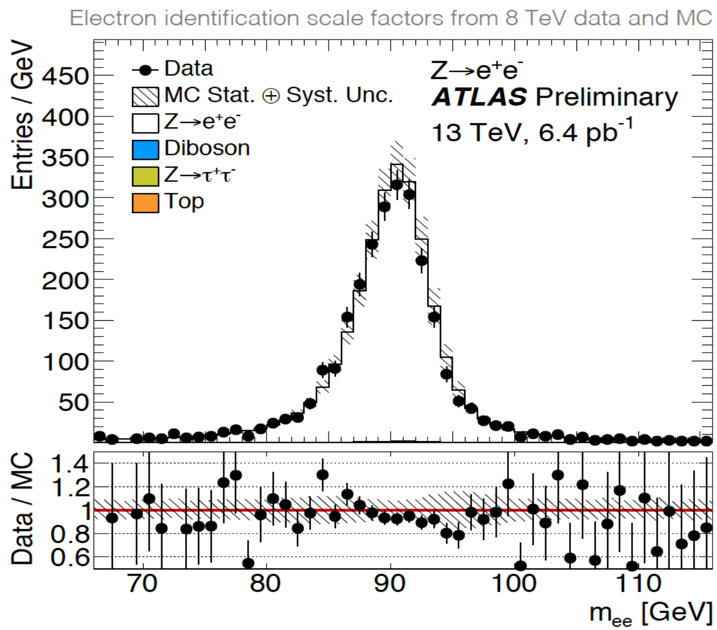


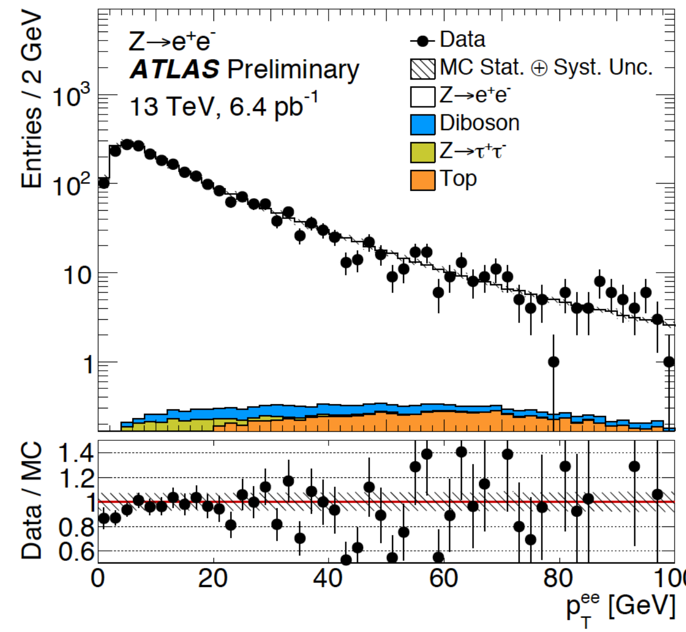
- Single isolated photon production
- Background subtracted
- Detector level E_T
- Sherpa MC normalized to data

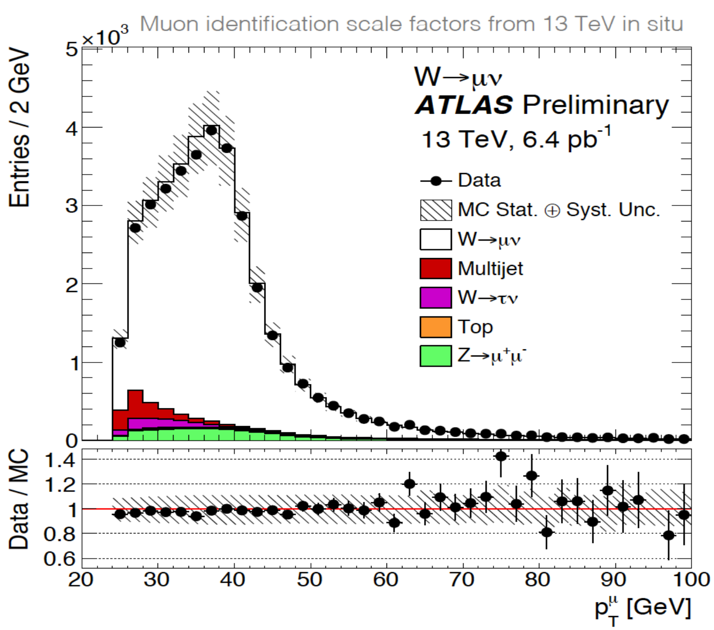
- Single jet trigger, fully efficient above 300 GeV
- Anti-kt R=0.4 jets calibrated with Run 1 and validated with Run 2
- Unfold to particle level

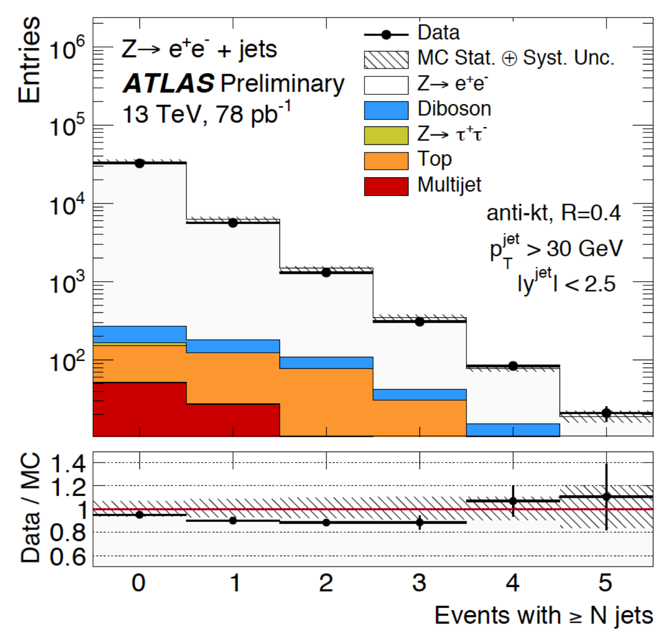


Standard candle – W/Z in 13 TeV









Higgs physics with 100-300 fb^{-1} with Run 2/3

With ~10 x existing data set, 2.4 x inclusive Higgs production cross section

- Precise measurements of Higgs production and decay rates, couplings and mass
- Test of the SM in the Higgs sector and probe for new physics such as MSSM, double Higgs (order of few percent effects on Higgs couplings in most models)
- Search for rare/new/invisible decay modes
- Use EFT for Higgs tensor structure study

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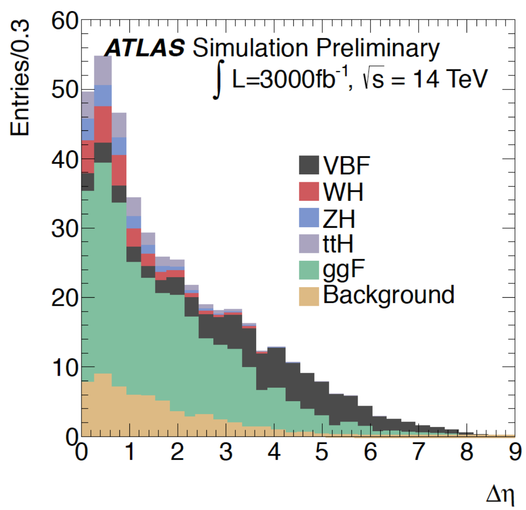
Current theory limit on Higgs cross section and BRs:

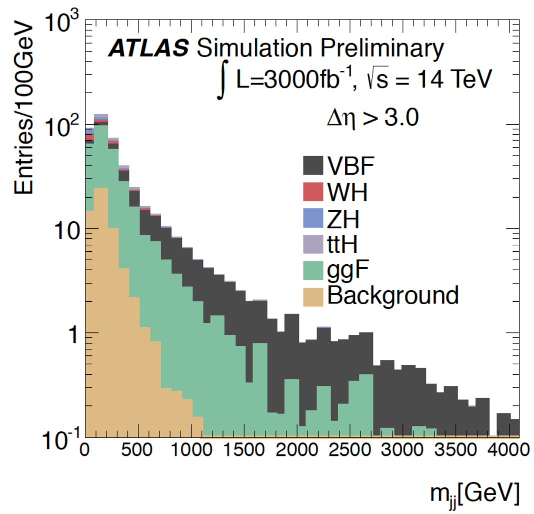
- NNLO/NNLL QCD + NLO EWK calculations of Higgs ggF (VBF) production cross sections with 8% (0.6%) scale and 7% (1.7%) PDF+αs uncertainties
- Branching ratios with typically 3-5% uncertainty

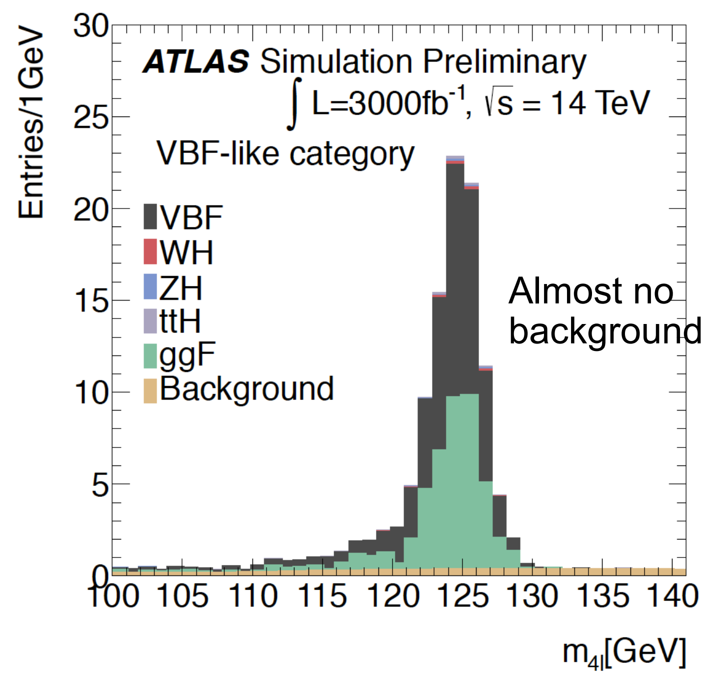
[ATL-PHYS-PUB-2013-014]

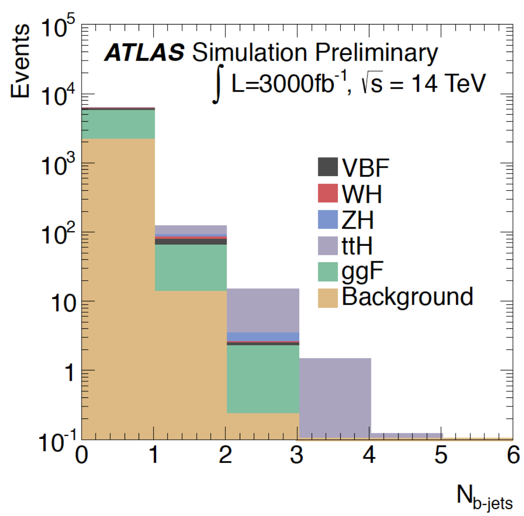
Projections for H->ZZ

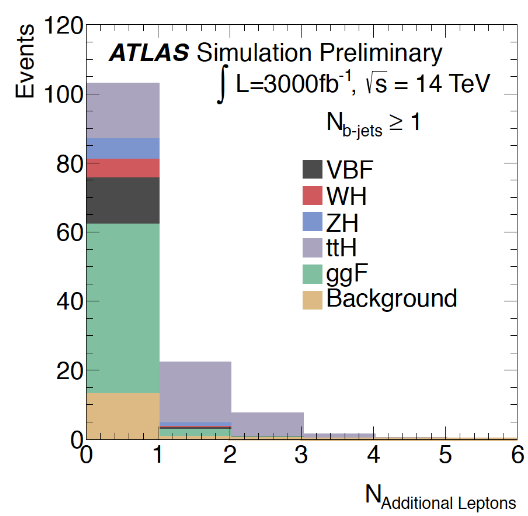
Signal events are very clean. Further divide the signals into VBF, VH, ttH and ggH categories (divide by 30 the numbers in the plots to get 100 fb^{-1})







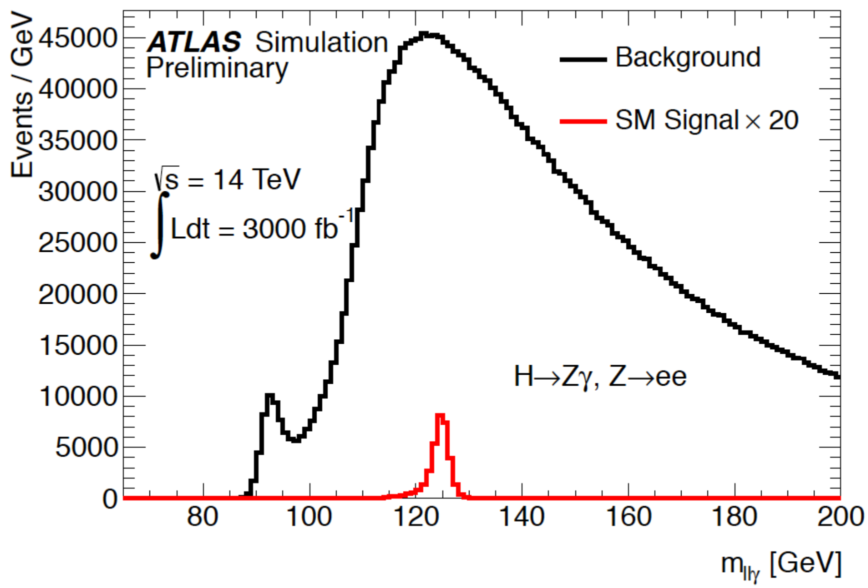


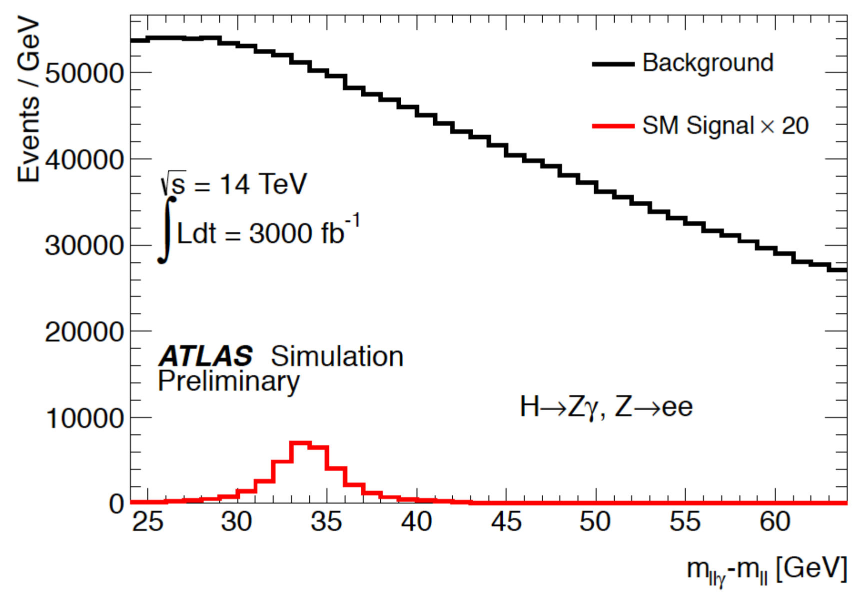


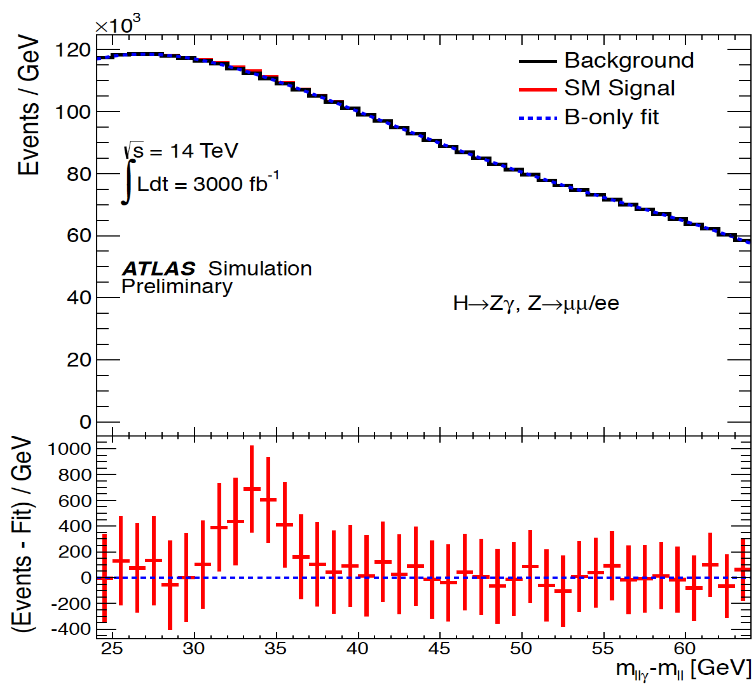
$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
Production mode		300 fb^{-1}		
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
$t\bar{t}$H	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108

[ATL-PHYS-PUB-2013-014]

Projections for H->Zγ







Still a very tough channel, S/B ratio much worse than γγ:

Senario	Inclusive, 300 fb^{-1}
Expected CLs limit (×SM)	2.53
Signal strength (σ)	0.67

However, sensitive to New Physics through the loop

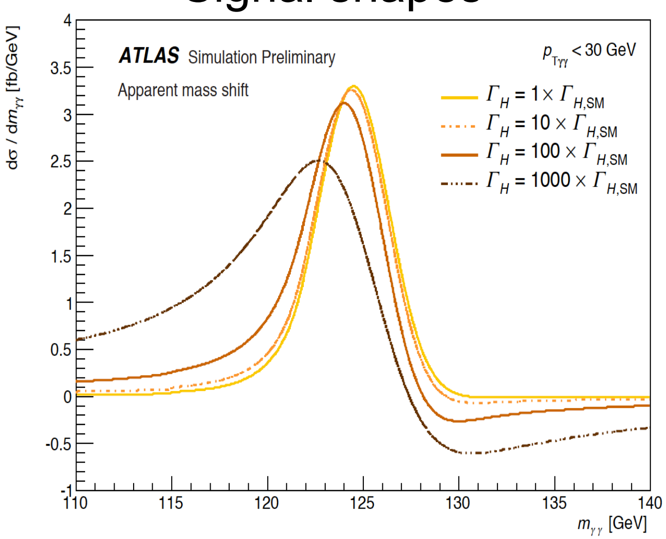
[ATL-PHYS-PUB-2013-014]

Probing the Higgs width

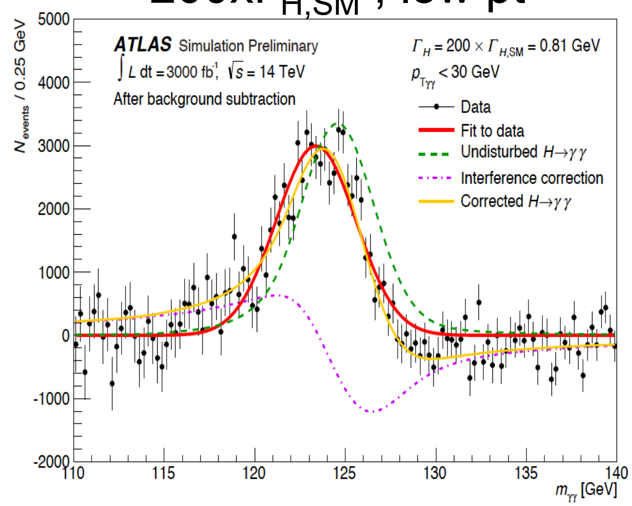
It was proposed that the interference between the H->γγ signal and gg->γγ irreducible background (box diagram) can distort the Higgs mass shape and shift its peak position

- The shift is due to the real component of the interference term, and in the negative direction
- The shift is reduces if the Higgs has a high pt – divide the signal region events at pt=30 GeV, and test for the relative mass shift between the two samples

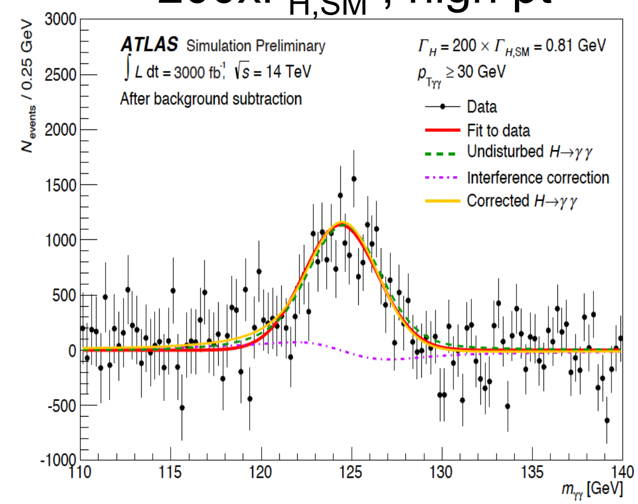
Signal shapes



200x$\Gamma_{H,SM}$, low pt



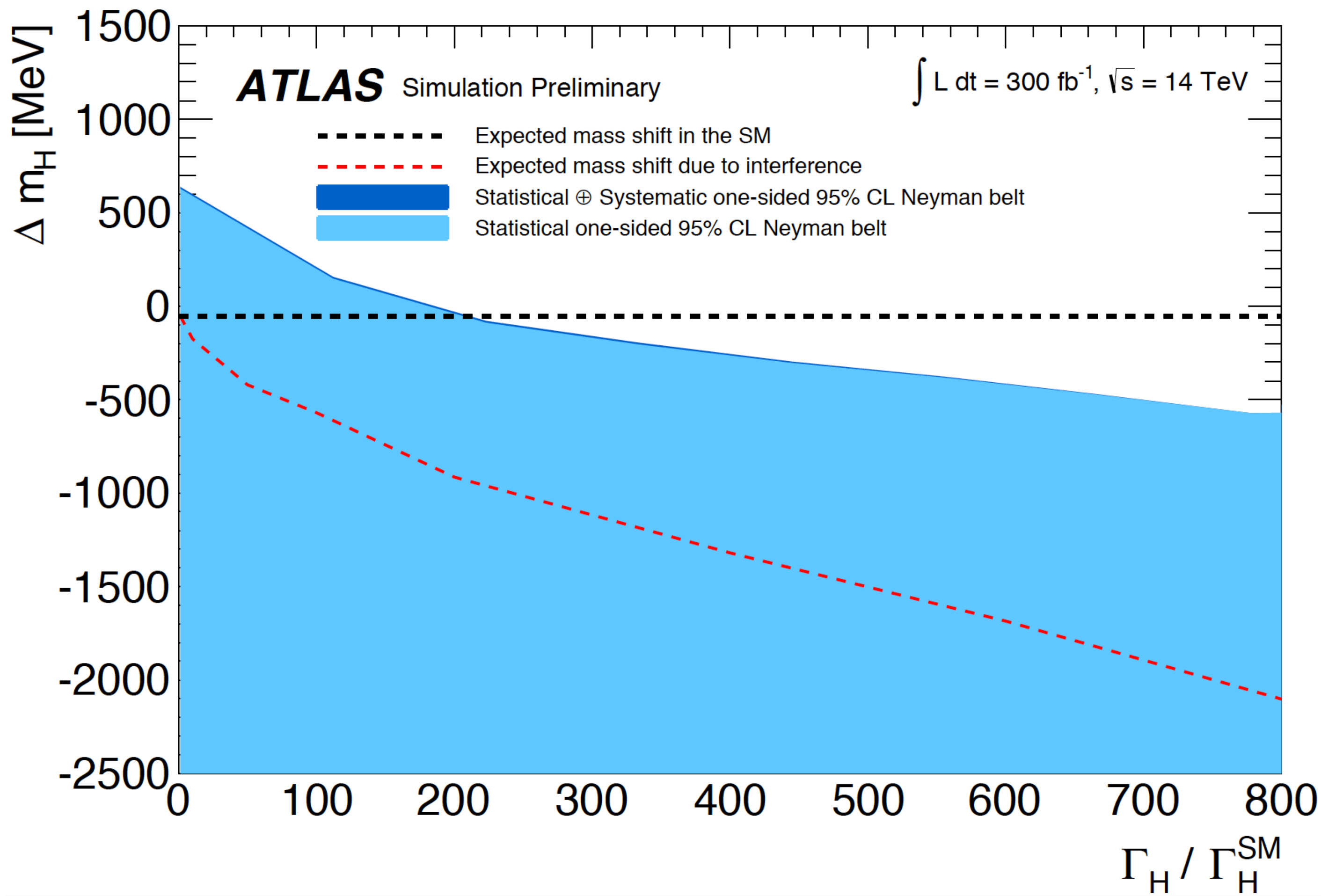
200x$\Gamma_{H,SM}$, high pt



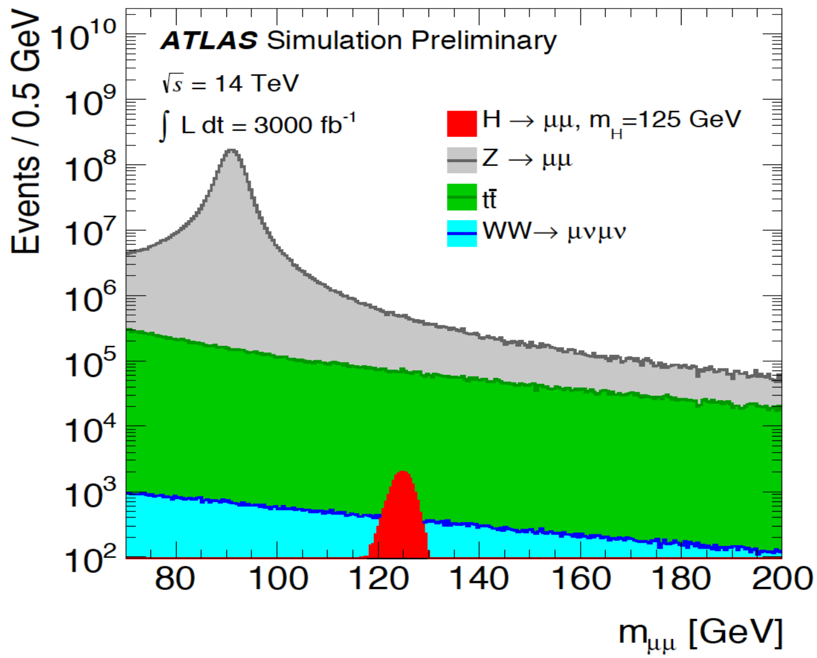
Probing the Higgs width

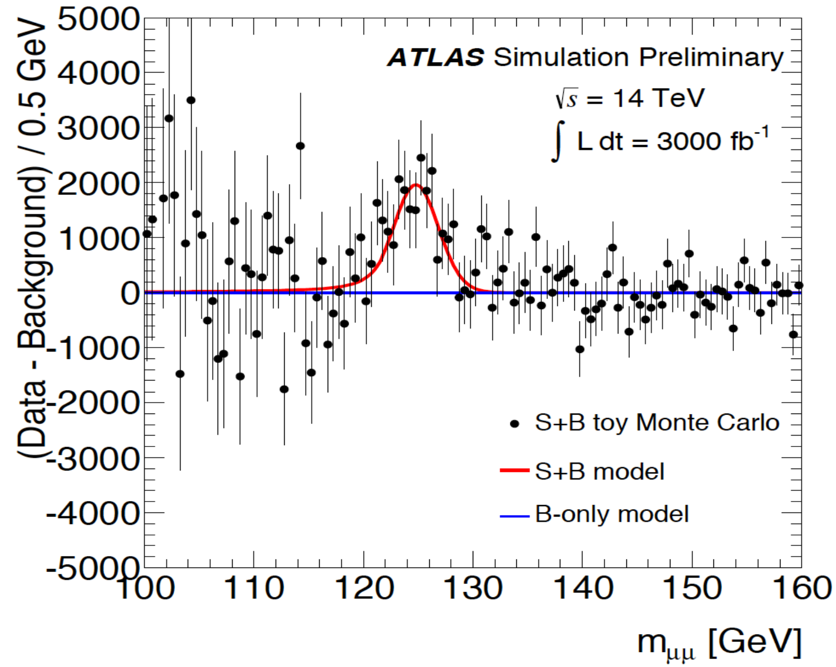
A one-sided 95% CL interval can be set for the mass shift

- For SM, this shift is about -54 MeV
- The analysis is very sensitive to photon energy scale systematics. However, by dividing the data into two subsets, the systematics is cancelled substantially



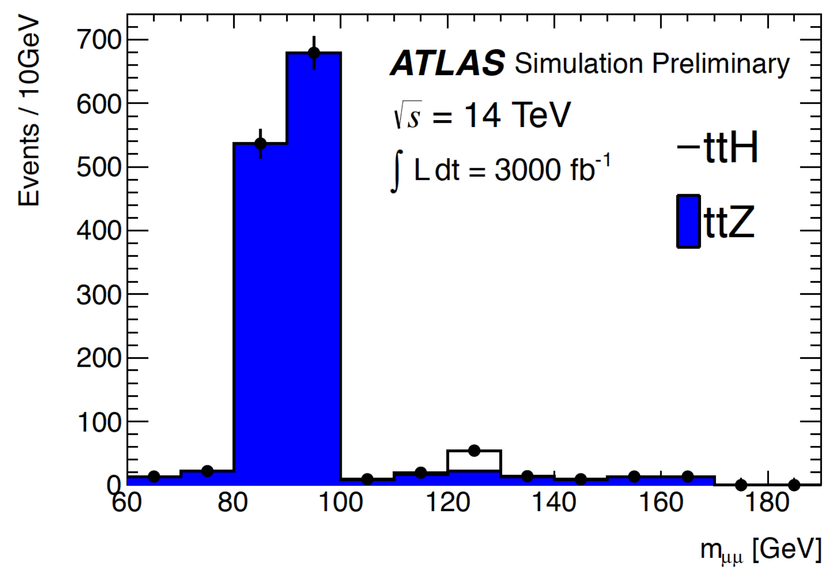
H->μμ



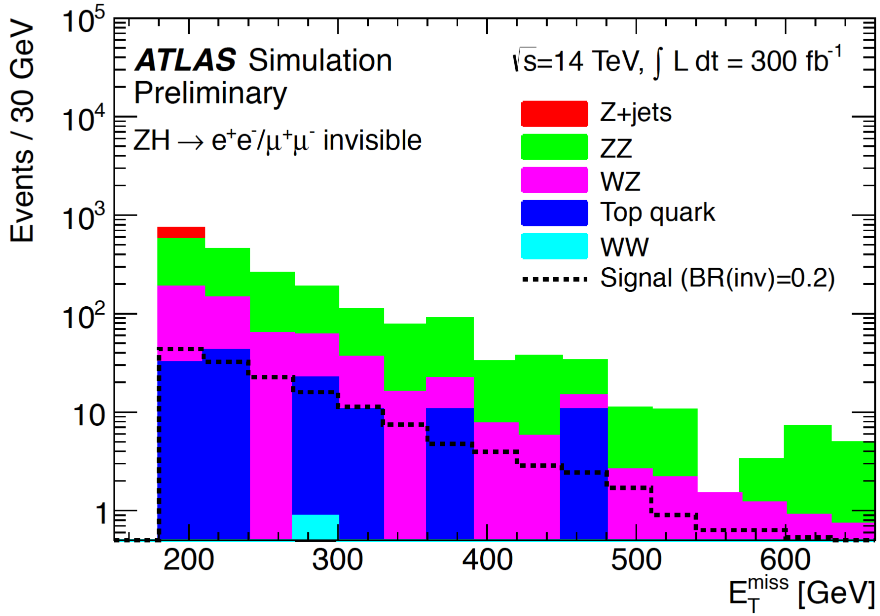


Still very tough even at 3000 fb^{-1}, but can have about 33 signal events (with 22 background events) in the ttH->μμ channel

$\mathcal{L}$ [fb^{-1}]	300
Signal significance	2.3σ
$\Delta\mu/\mu$	46%



ZH with H->invisible



Event yields after all selection:

Expected yields	300 fb^{-1}
ZZ	1321 ± 53
WZ	440 ± 2
WW	0.9 ± 0.9
Top	127 ± 37
Z+jets	172 ± 87
Signal (125 GeV, BR($H \to$ inv.)=20%)	154 ± 2

- Direct search for Higgs coupling to dark matter particles
- The largest background comes from the ZZ->llνν, can be estimated from ZZ->4l events
- Upper limit on Higgs invisible decay BR can be set:

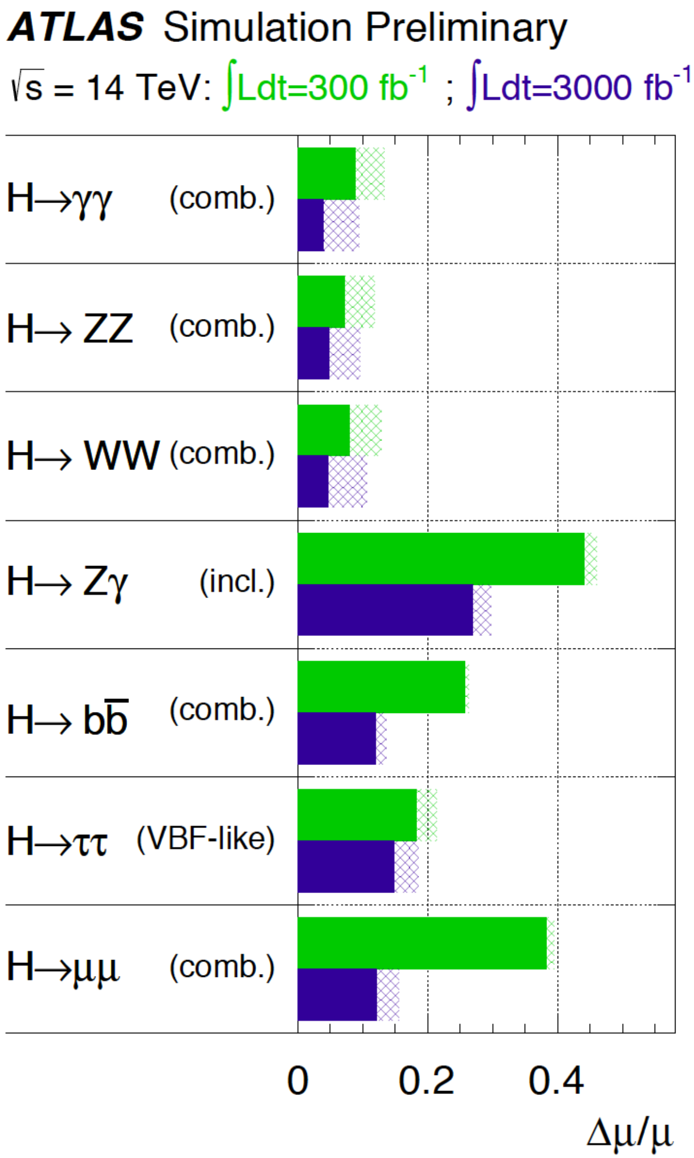
BR($H \to$inv.) limits at 95% (90%) CL	300 fb^{-1}
Realistic scenario	23% (19%)
Conservative scenario	32% (27%)

If search for New Physics is null, what can we learn from Higgs coupling rates measurement?

[ATL-PHYS-PUB-2014-016]

Rates -> Signal Strength

For Higgs decay channels:



For Higgs production modes:

$\Delta\mu/\mu$	300 fb^{-1}	
	All unc.	No theory unc.
$gg \to H$	0.12	0.06
VBF	0.18	0.15
WH	0.41	0.41
$qqZH$	0.80	0.79
$ggZH$	3.71	3.62
ttH	0.32	0.30

- Shown are the ratio of the signal strength error to the strength based on MC projections for 14 TeV
- Have to scale the numbers (green) by $1/\sqrt{3}$ to get a rough estimate of 100 fb^{-1} (Run 1 only)

[ATL-PHYS-PUB-2014-016]

Rates -> coupling scale factors

- Results are derived in the coupling fit framework:

$$\sigma \cdot \mathrm{BR}(i \to H \to f) = \frac{\sigma_i^{\mathrm{SM}} \cdot \Gamma_f^{\mathrm{SM}}}{\Gamma_H^{\mathrm{SM}}} \cdot \frac{\kappa_i^2 \kappa_f^2}{\kappa_{\mathrm{H}}^2}$$

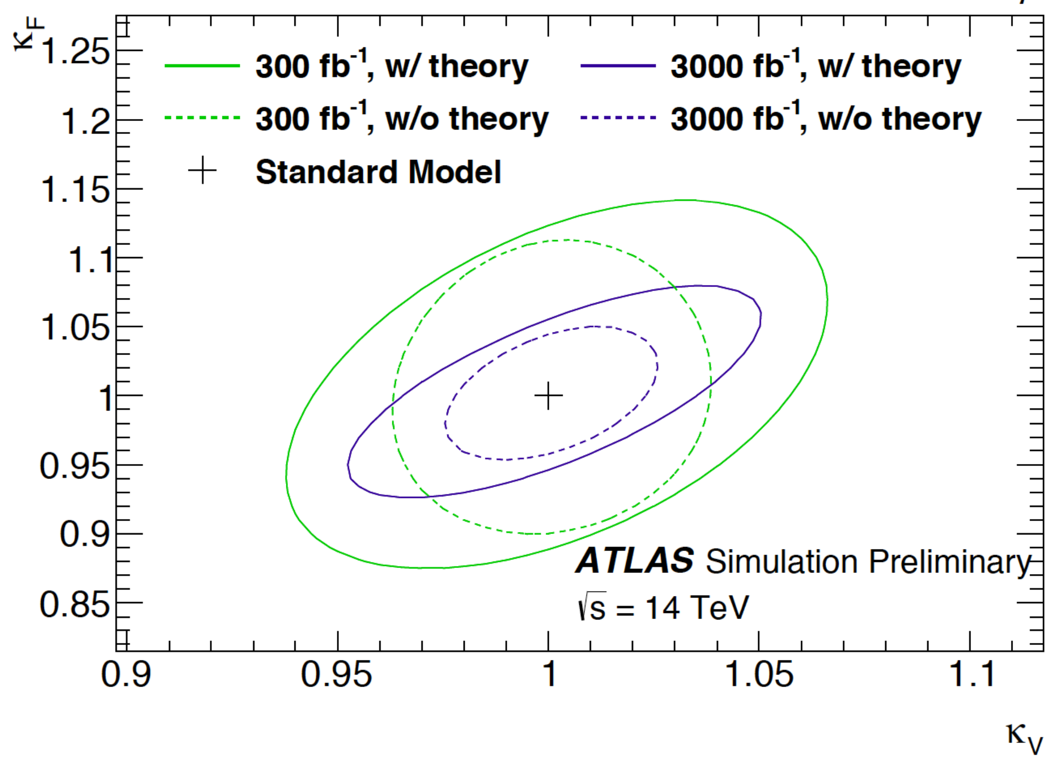
$$\kappa_h^2 = \sum_i \frac{\kappa_i^2 \Gamma_i^{\mathrm{SM}}}{\Gamma_h^{\mathrm{SM}}}, (i = WW, ZZ, b\bar{b}...)$$

$$\kappa_V = \kappa_Z = \kappa_W$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$

Errors on individual factors:

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None
8	κ_Z	8.1%	7.9%	7.9%
	κ_W	9.0%	8.7%	8.6%
	κ_t	22%	21%	20%
	κ_b	23%	22%	22%
	κ_τ	14%	14%	13%
	κ_μ	21%	21%	21%
	κ_g	14%	12%	11%
	κ_γ	9.3%	9.0%	8.9%
	$\kappa_{Z\gamma}$	24%	24%	24%



[ATL-PHYS-PUB-2014-016]

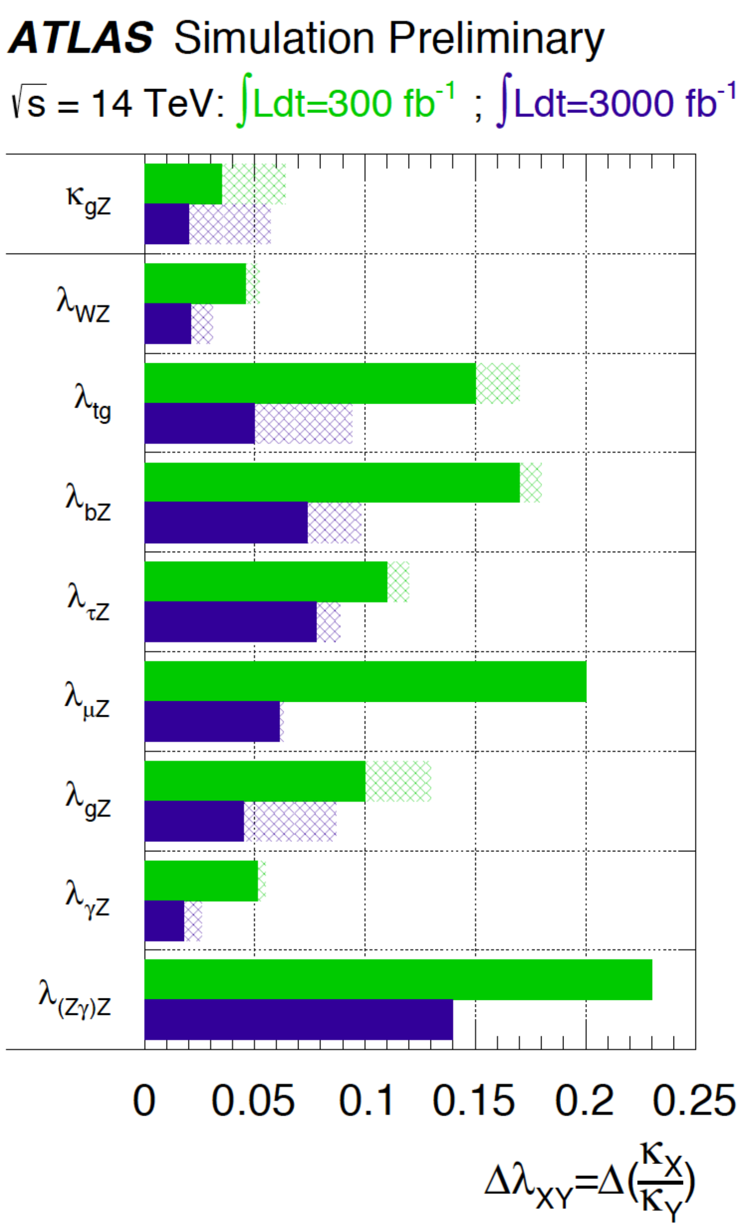
Rates -> coupling scale factors

- If we make no assumptions on the total Higgs decay width, the coupling factor ratios can be estimated:

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

- Many experimental and theoretical systematic uncertainties cancel in the ratios (such as the uncertainty on the integrated luminosity)

- Some ratio, such as $\lambda_{\gamma Z} = \kappa_{\gamma\gamma} / \kappa_{ZZ}$, is very important to look for new particles in the diphoton loop compared with tree-level H->ZZ



[ATL-PHYS-PUB-2014-017]

Higgs mass scaling and VEV

$$\begin{cases} \kappa_{f,i} = \upsilon \dfrac{m_{f,i}^{\varepsilon}}{M^{1+\varepsilon}}, \\ \kappa_{V,i} = \upsilon \dfrac{m_{V,i}^{2\varepsilon}}{M^{1+2\varepsilon}} \end{cases}$$

- κ_f, κ_V are the Higgs coupling scale factors for fermions and vector bosons
- $\upsilon = 246$ GeV is the vacuum expectation value (VEV)
- ε is the mass scaling factor, $\varepsilon = 0$ for the SM case
- M is the new VEV. $M = \upsilon$ for SM

The Higgs production and decay rates can be directly translated into these coupling scale factors:

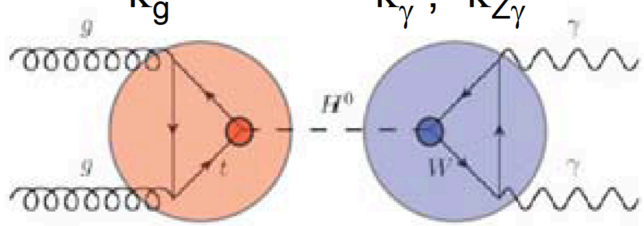
$$\mu = \frac{\sigma \times BR}{(\sigma \times BR)_{SM}} = \frac{\kappa_g^2 \kappa_Z^2}{\kappa_h^2},$$

$$\kappa_h^2 = \sum_i \frac{\kappa_i^2 \Gamma_i^{SM}}{\Gamma_h^{SM}}, (i = WW, ZZ, b\bar{b}...)$$

$$\kappa_g^2(\kappa_b, \kappa_t) = \frac{\kappa_t^2 \sigma_{ggh}^{tt} + \kappa_b^2 \sigma_{ggh}^{bb} + \kappa_t \kappa_b \sigma_{ggh}^{tb}}{\sigma_{ggh}^{tt} + \sigma_{ggh}^{bb} + \sigma_{ggh}^{tb}}$$

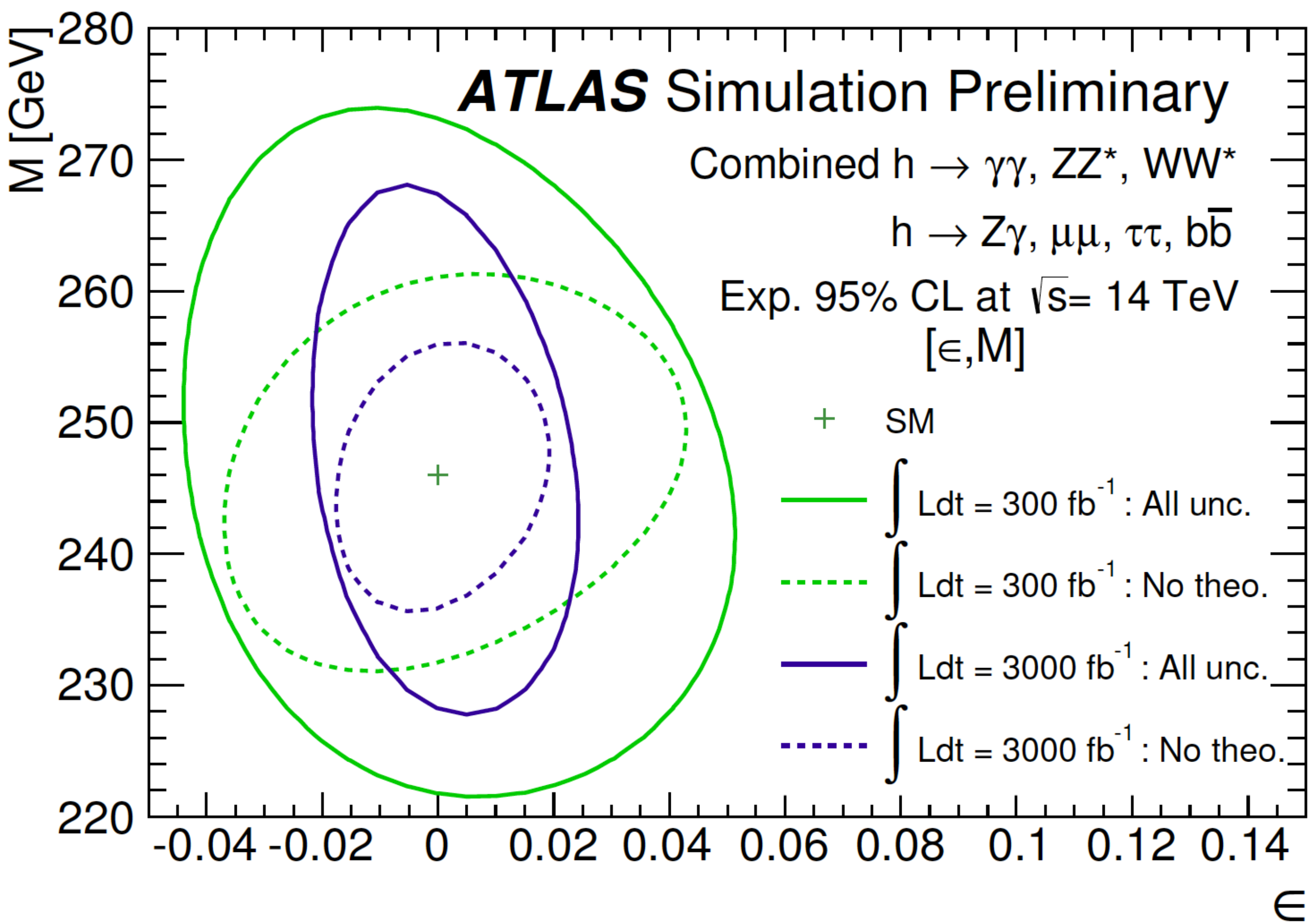
$$\kappa_\gamma^2(\kappa_{f,i}, \kappa_W) = \frac{\sum_{i,j} \kappa_i \kappa_j \Gamma_{\gamma\gamma}^{ij}}{\sum_{i,j} \Gamma_{\gamma\gamma}^{ij}}$$

κ_g κ_γ , $\kappa_{Z\gamma}$



Higgs mass scaling and VEV

- The Higgs mass is assumed to be 125 GeV
- Only SM coupling, modified by κ through ε and M, are considered

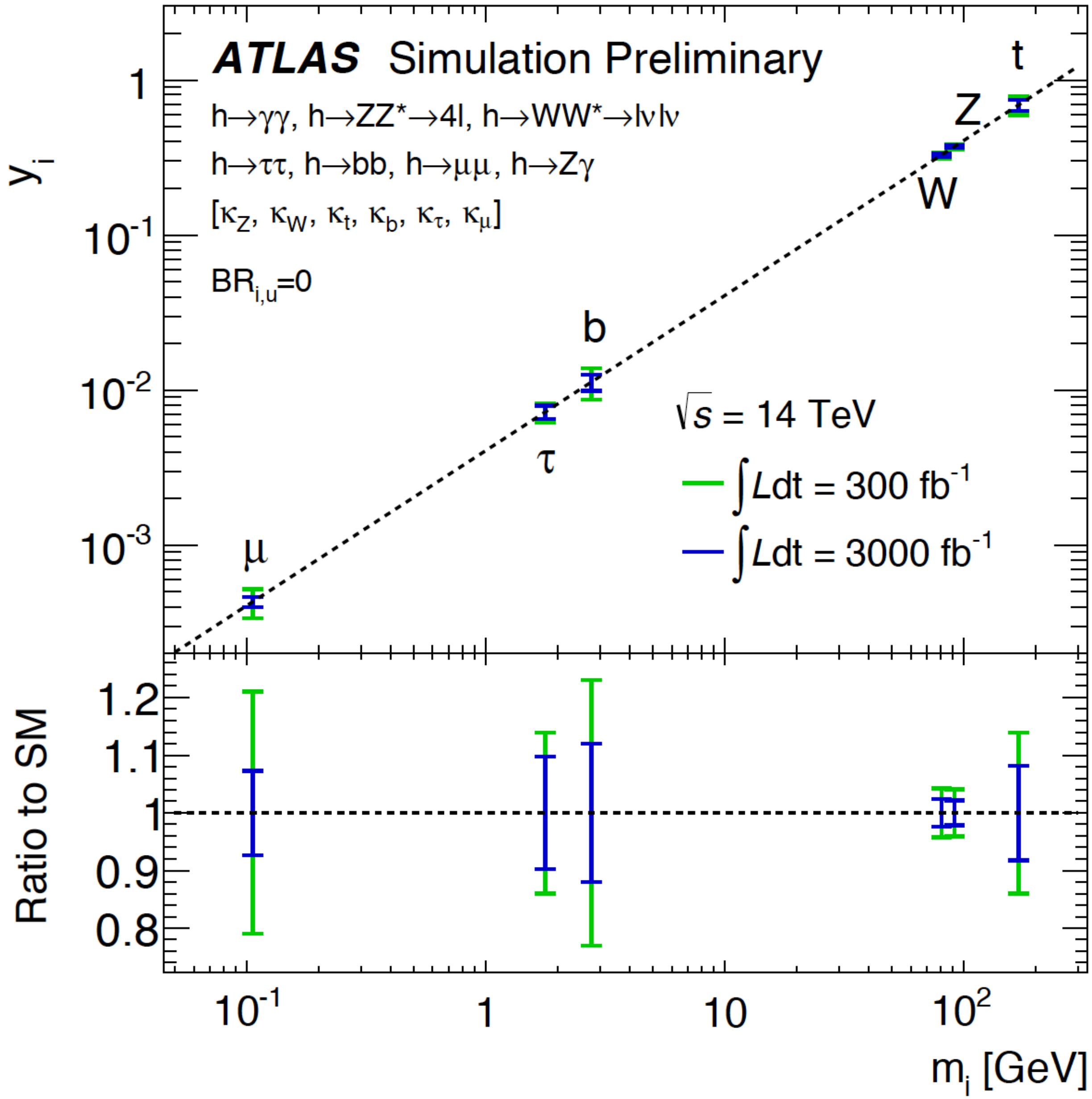


Reduced coupling scale factors

- If reduced coupling scale factors are defined, we can test the Higgs coupling dependence on the mass:

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

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



Minimal Composite Higgs Model

- Mininal Composite Higgs Models (MCHM) represent a possible explanation for the scalar naturalness problem.
- Higgs in MCHM is a composite, pseudo-Nambu-Goldstone boson rather than an elementary particle
- Higgs couplings to SM particles are modified as a function of the Higgs boson compositeness scale f
- In MCHM4:

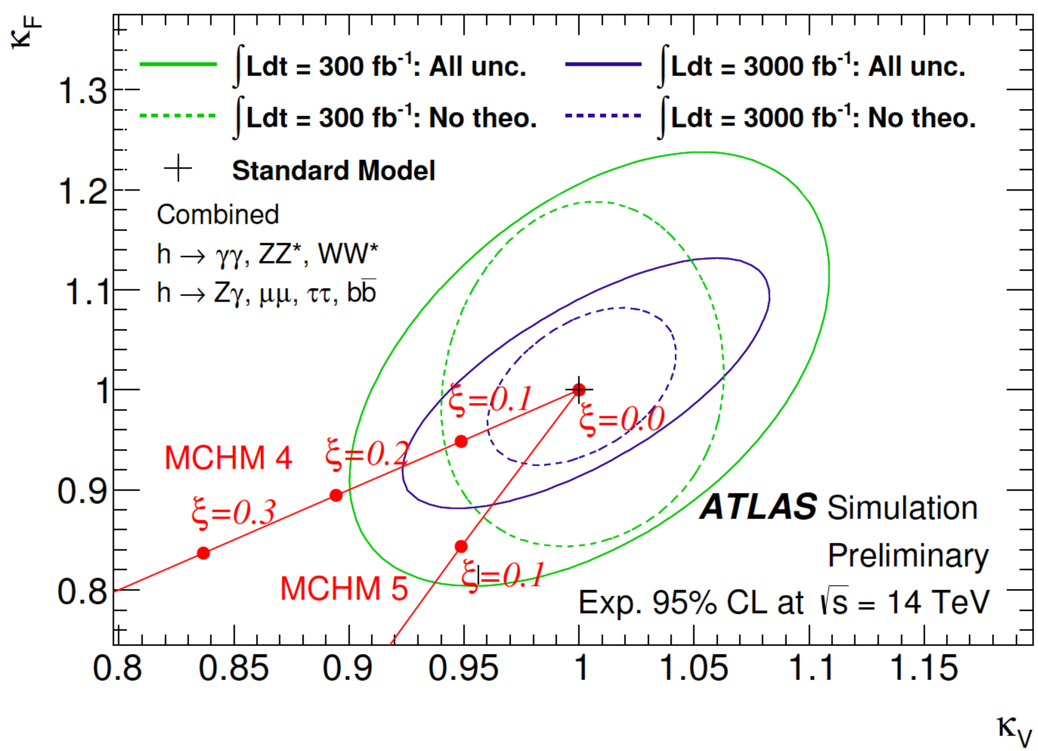
$$\kappa_f = \kappa_V = \sqrt{1-\xi}, \xi = \upsilon^2 / f^2$$

- In MCHM5:

$$\kappa_V = \sqrt{1-\xi}, \kappa_f = \frac{1-2\xi}{\sqrt{1-\xi}}$$

- f=∞ is SM. Lower limits of f:

Model	300 fb^{-1}	
	All unc.	No theory unc.
MCHM4	620 GeV	810 GeV
MCHM5	780 GeV	950 GeV



[ATL-PHYS-PUB-2014-017]

Simple SM extension – an extra EW singlet

- Both the Higgs doublet and the singlet acquire non-zero VEV
- Spontaneous symmetry breaking leads to mixing between the singlet state and the surviving state of the doublet
- Two CP even Higgs scalars are resulted, who couples to other particles in a similar way as the SM Higgs, but each scales by a common factor:

$$\kappa^2 + \kappa'^2 = 1$$

- For the light (125 GeV) h and heavy H, we have

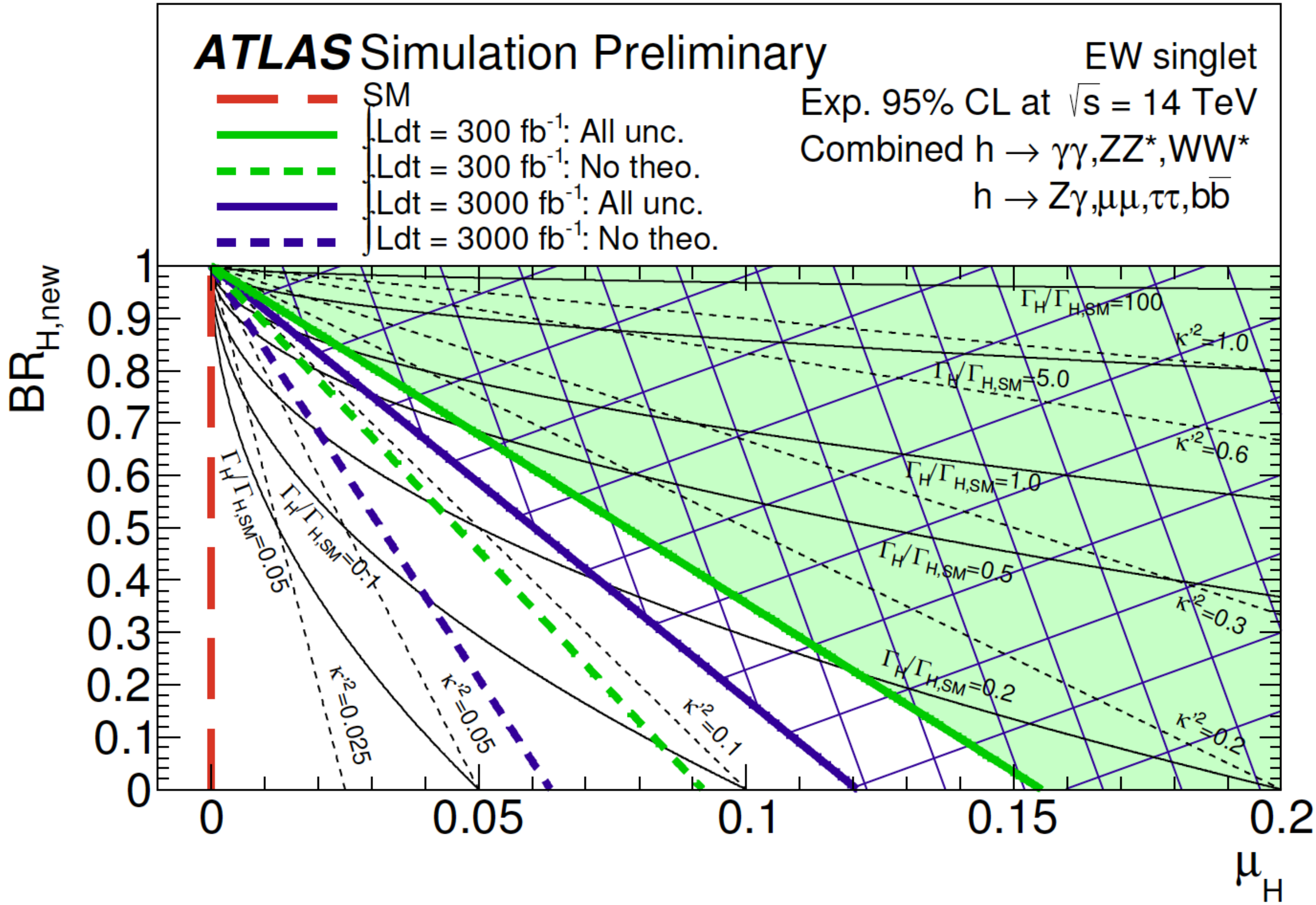
$$\sigma_h = \kappa^2 \sigma_{h,SM},$$
$$\Gamma_h = \kappa^2 \Gamma_{h,SM},$$
$$BR_{h,i} = BR_{h,SM,i},$$
$$\mu_h = \frac{\sigma_h \times BR_h}{(\sigma_h \times BR_h)_{SM}} = \kappa^2$$

$$\sigma_H = \kappa'^2 \sigma_{H,SM},$$
$$\Gamma_H = \frac{\kappa'^2}{1 - BR_{H,new}} \Gamma_{H,SM},$$
$$BR_{H,i} = (1 - BR_{H,new}) \cdot BR_{H,SM,i},$$
$$\mu_H = \frac{\sigma_H \times BR_H}{(\sigma_H \times BR_H)_{SM}} = \kappa'^2 (1 - BR_{H,new})$$

$BR_{H,new}$: new decay modes of H not found in SM, such as H->hh

Simple SM extension – an extra EW singlet

- κ' is constrained through $\kappa'^2 = 1 - \mu_h$, thus μ_H can not be too large and $BR_{H,new}$ not too small. This can be expressed as excluded region in the $BR_{H,new} - \mu_H$ plane



Two Higgs Doublet Model

- In Two Higgs Doublet Model (2HDM), both acquire a VEV and five Higgs bosons are resulted:

$$m_h, m_H, m_A, m_{H^\pm}$$

- Two additional parameters are need to describe the model: the ratios of VEV's ($\tan\beta = \upsilon_2 / \upsilon_1$) and the mixing angle α of the two neutral CP-even Higgs

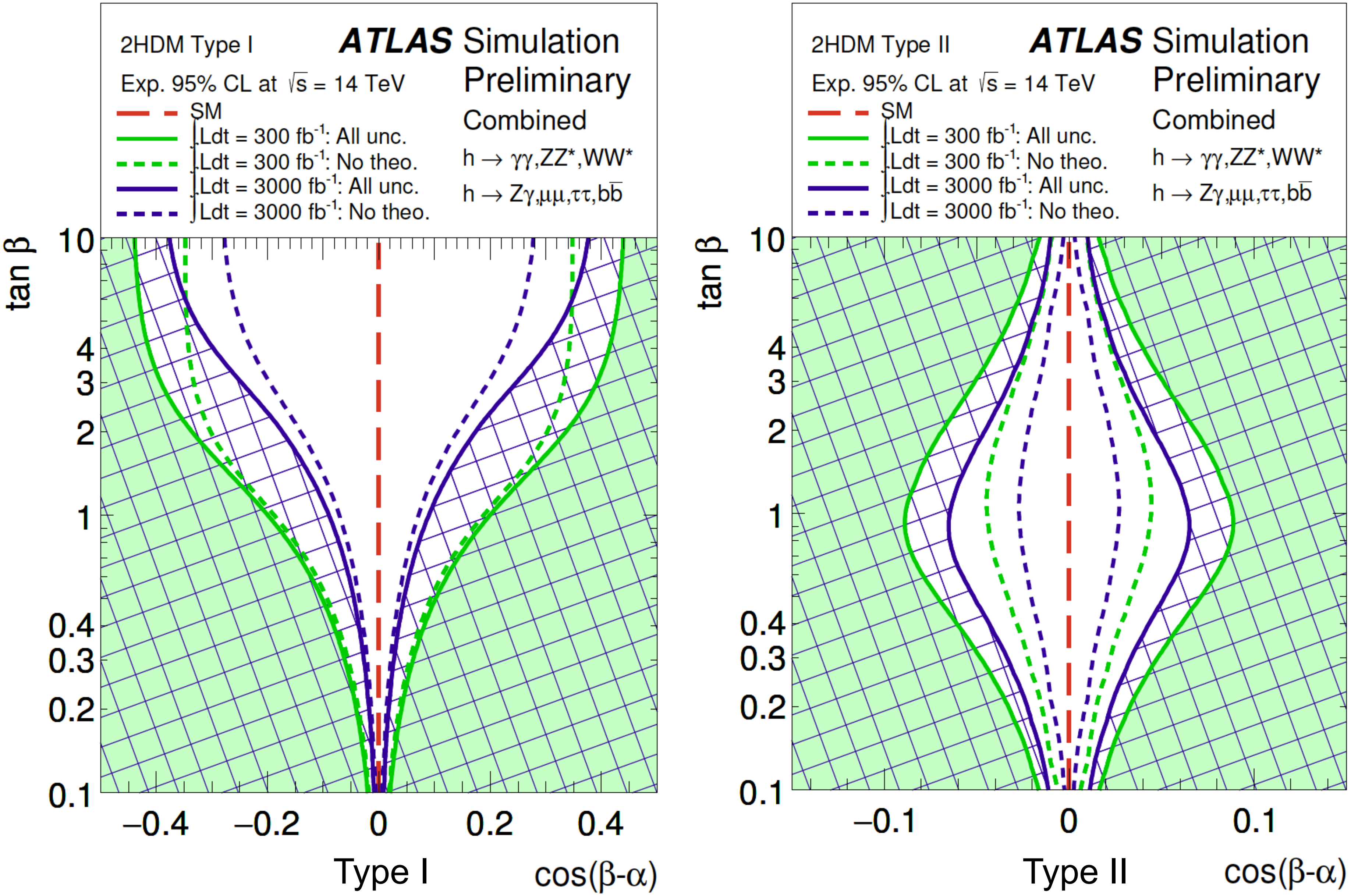
- Assume h is the 125 GeV Higgs, its coupling to vector bosons is complementary with H:

$$g_{hVV}^{2HDM} / g_{hVV}^{SM} = \sin(\beta - \alpha), \quad g_{HVV}^{2HDM} / g_{HVV}^{SM} = \cos(\beta - \alpha)$$

- 4 types of models if CP is conserved and no FCNC:

Coupling scale factor	Type I	Type II	Type III	Type IV
κ_V	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
κ_u	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$	$\cos(\alpha)/\sin(\beta)$
κ_d	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$
κ_l	$\cos(\alpha)/\sin(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$-\sin(\alpha)/\cos(\beta)$	$\cos(\alpha)/\sin(\beta)$

Two Higgs Doublet Model



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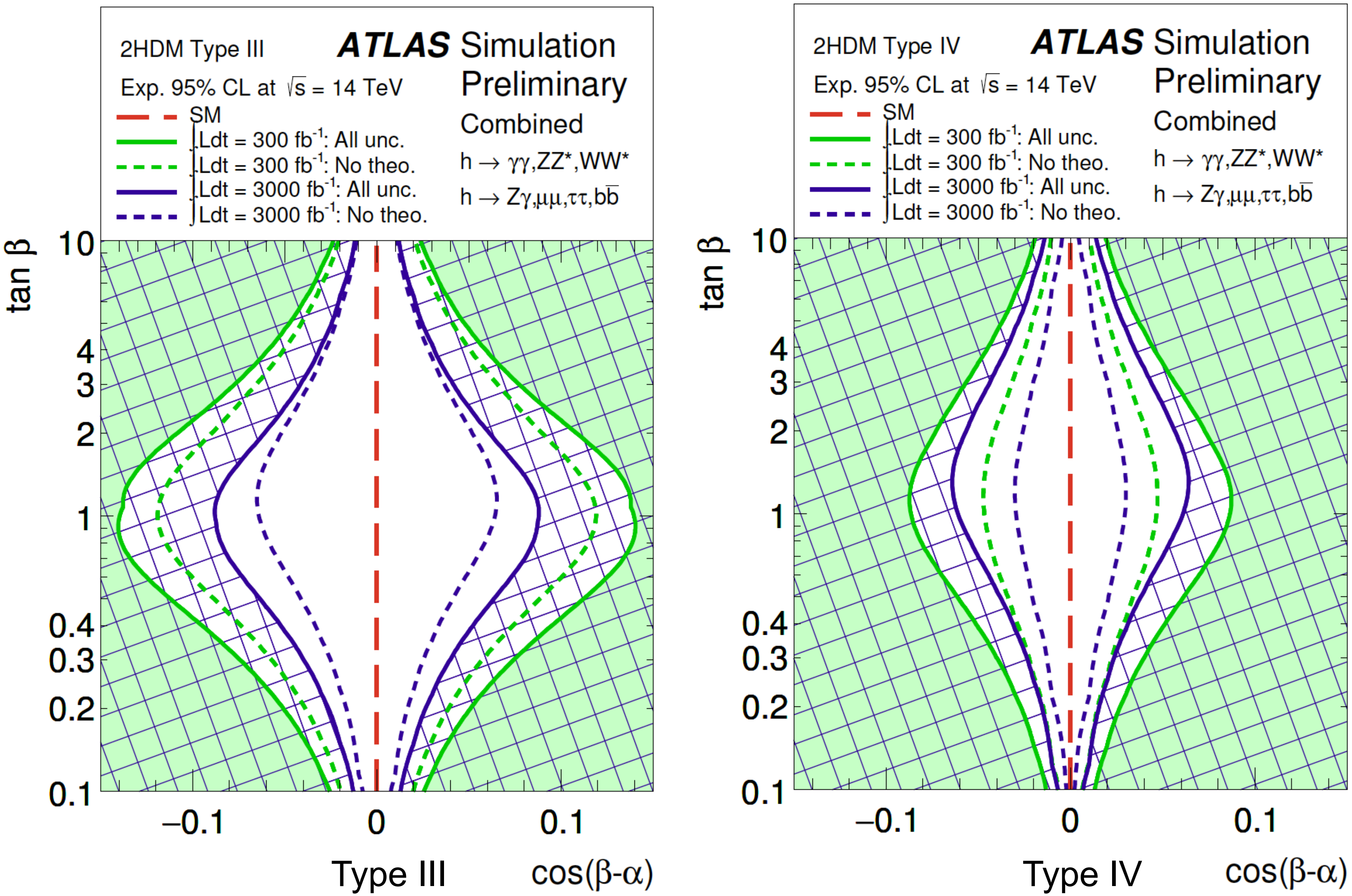


Simplified MSSM model

- In the Minimal Supersymmetric Standard Model (MSSM), the mass mixing matrix for the neutral, CP-even Higgs bosons is

$$\mathcal{M}_S^2 = (m_Z^2+\delta_1)\begin{bmatrix} \cos^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \sin^2(\beta) \end{bmatrix} + m_A^2\begin{bmatrix} \sin^2(\beta) & -\cos(\beta)\sin(\beta) \\ -\cos(\beta)\sin(\beta) & \cos^2(\beta) \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & \frac{\delta}{\sin^2(\beta)} \end{bmatrix}$$

δ_1 and δ represent top and stop radiative corrections

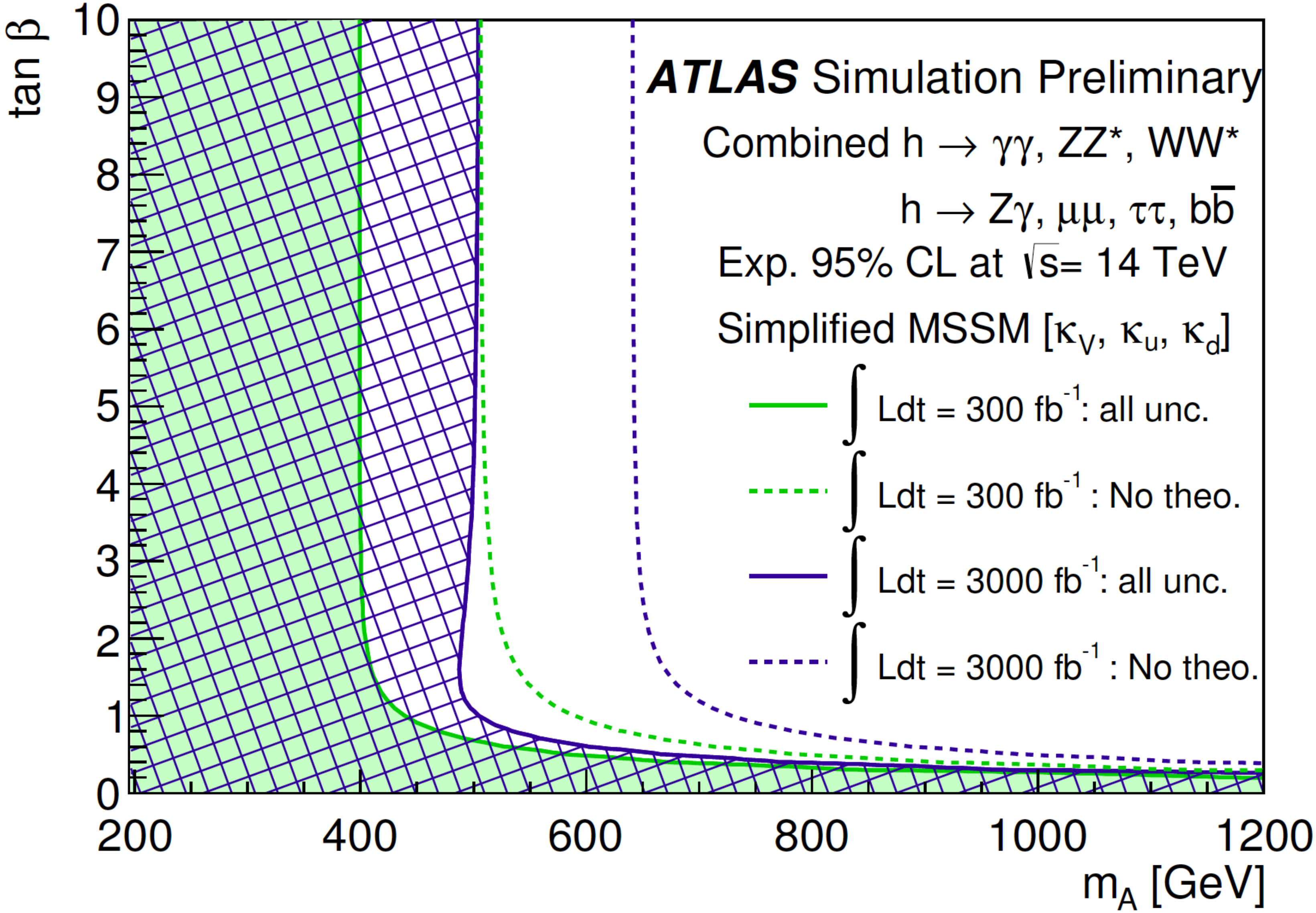
- In the simplified model, subleading correction δ_1 is neglected. After the matrix diagonalization, the light Higgs mass is set to 125 GeV, allowing δ to be expressed as function of m_A and $\tan\beta$
- The eigen vector of the light Higgs (s_u, s_d) from diagonalization determines the coupling to up- and down-type fermions:

$$\kappa_u = s_u(m_A, \tan\beta)\frac{\sqrt{1+\tan^2\beta}}{\tan\beta},$$

$$\kappa_d = s_d(m_A, \tan\beta)\sqrt{1+\tan^2\beta},$$

$$\kappa_V = \frac{s_d + \tan\beta s_u}{\sqrt{1+\tan^2\beta}}$$

Simplified MSSM model



Particles other than SM ones (e.g. SUSY) are not considered in the fit

[ATL-PHYS-PUB-2014-017]

Higgs Decay to Dark Matter

- If Higgs decays to WIMP particles (mass < $m_H/2$), the Higgs decay BR to visible modes will be suppressed. The effect can be parametrized as

$$\kappa_h^2 = \frac{\Gamma_h}{\Gamma_{h,SM}} = \frac{\sum_i \kappa_i^2 BR_i}{1 - BR_{inv}},$$

$$\sum_i \kappa_i^2 BR_i = 0.085\kappa_g^2 + 0.0023\kappa_\gamma^2 + 0.0016\kappa_{Z\gamma}^2 + 0.91$$

BR_{inv} is the 125 GeV Higgs BR to invisible decay products. The scale factors for di-gluon, diphoton and $Z\gamma$ are included based on the consideration that new particles might enter the loop can change the BRs

- With 300 fb^{-1}, it is estimated that the 95% CL upper limit on BR_{inv} is

$$BR_{inv} < 0.22$$

- This limit can be translated into a WIMP mass vs. cross section as usually shown by direct dark matter searches

Higgs Decay to Dark Matter

The Higgs decay width (and WIMP-Nucleon cross section) to WIMP depends on whether the WIMP particle is a scalar, fermion (Majorana), or vector

- Scalar S:

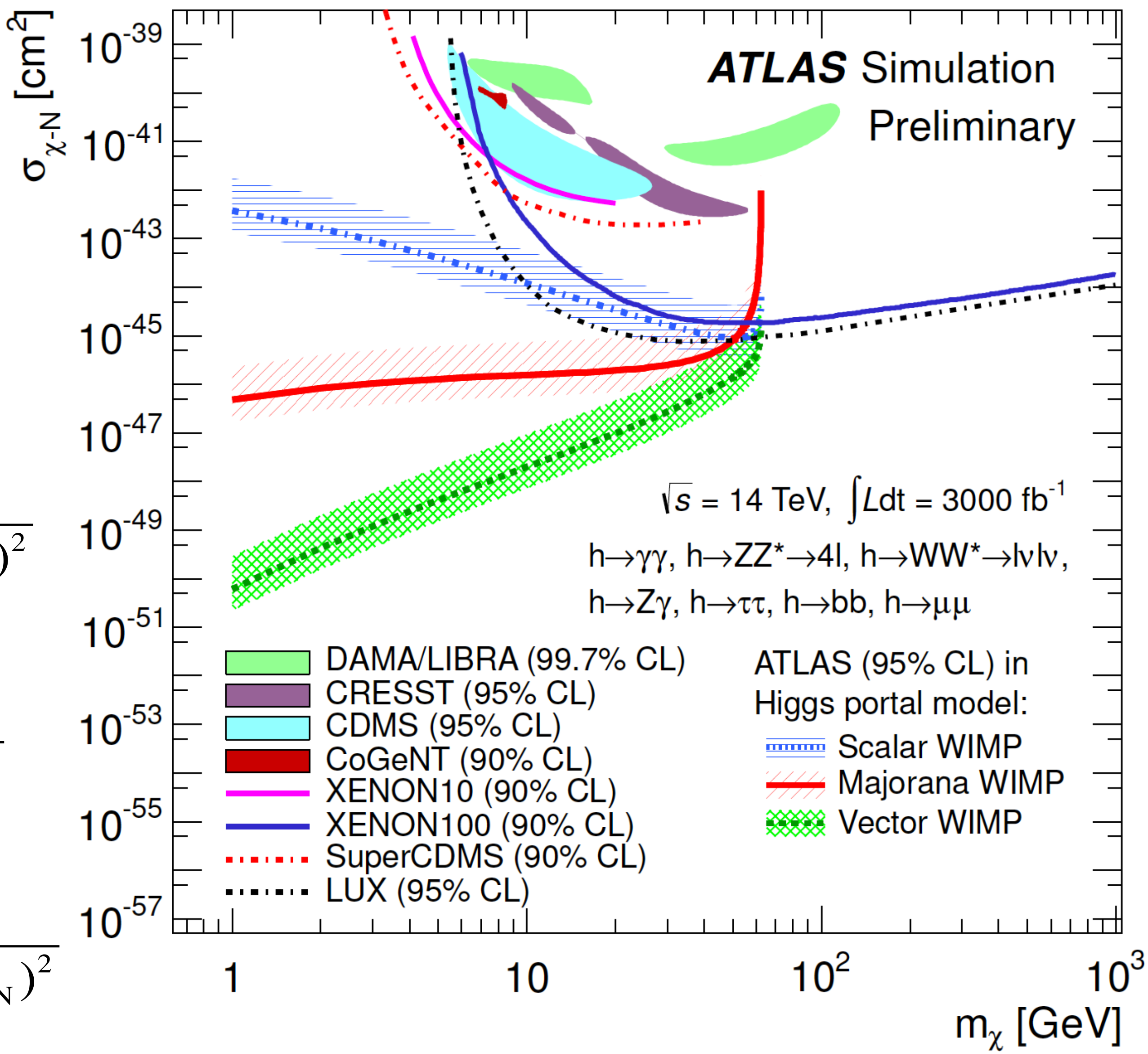
$$\sigma_{S-N} = \lambda_{hSS}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_S + m_N)^2}$$

- Fermion f:

$$\sigma_{f-N} = \frac{\lambda_{hff}^2}{\Lambda^2} \frac{m_N^4 f_N^2 m_f^2}{4\pi m_h^4 (m_f + m_N)^2}$$

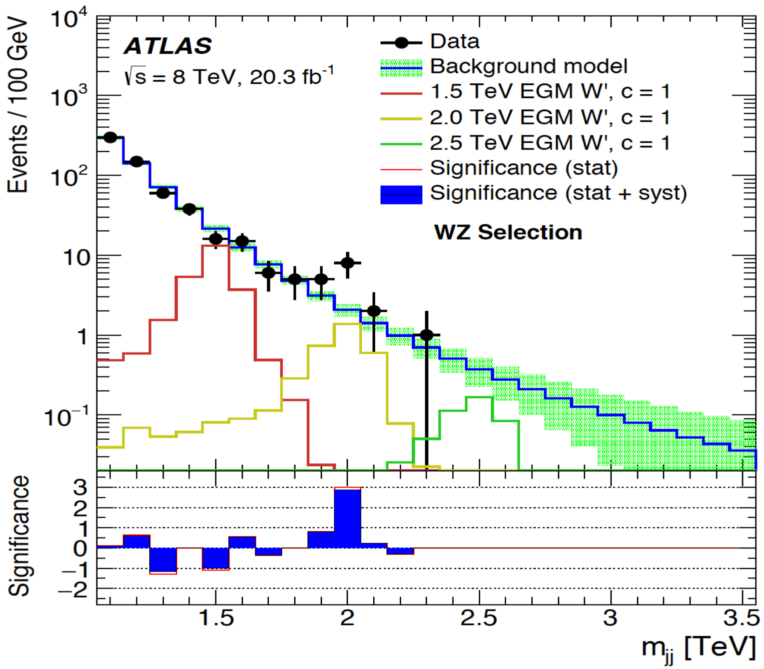
- Vector V:

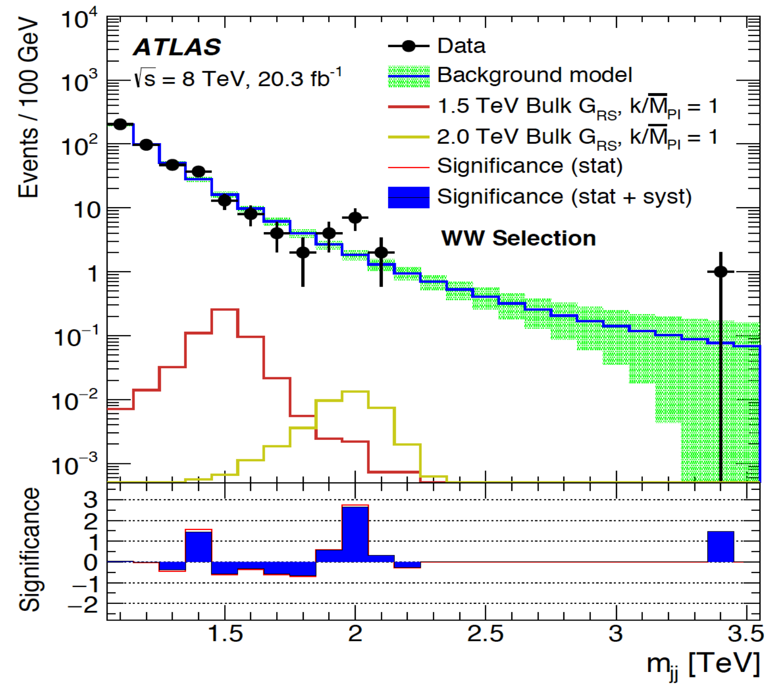
$$\sigma_{V-N} = \lambda_{hVV}^2 \frac{m_N^4 f_N^2}{16\pi m_h^4 (m_V + m_N)^2}$$



[arXiv:1506.00962]

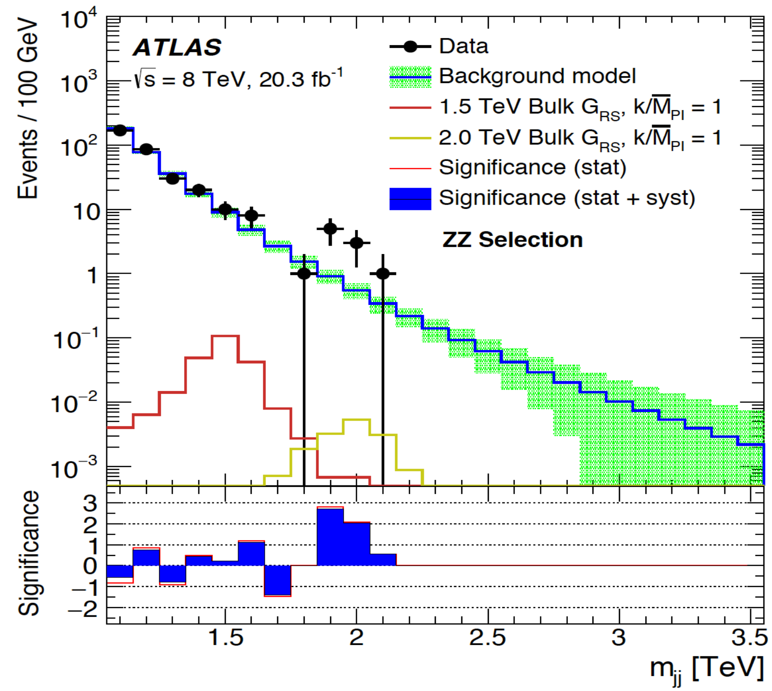
Some Hints for New Physics from Run 1





A new heavy resonance (W' or RS graviton) can decay into W/Z in the form of two boosted jets

A resonance at 2 TeV is observed, most significant in WZ with ~3.4σ

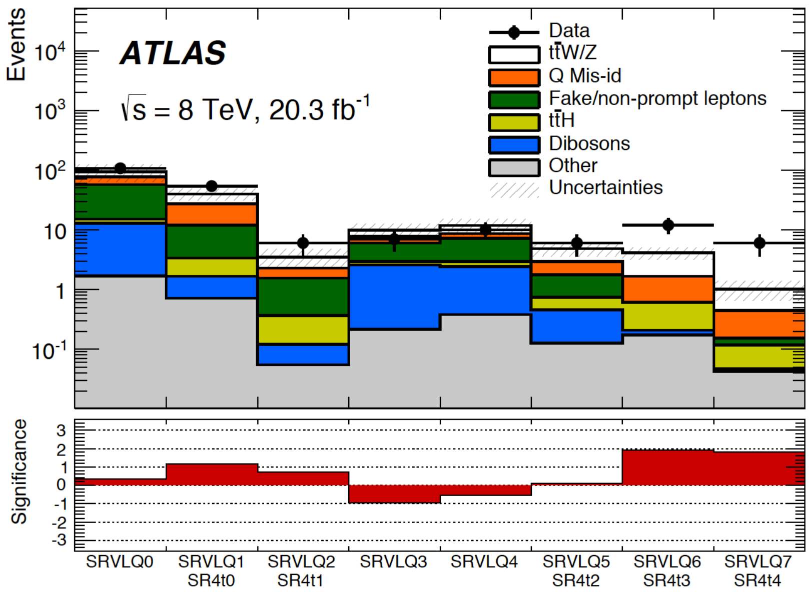


Some Hints for New Physics from Run 1

[arXiv:1504.04605]

2.5σ excess with 2/3 b-jets, large MET and HT, and same-sign leptons

vector-like quarks, chiral b'-quark pair production, two positively charged top quarks, 4-top production …



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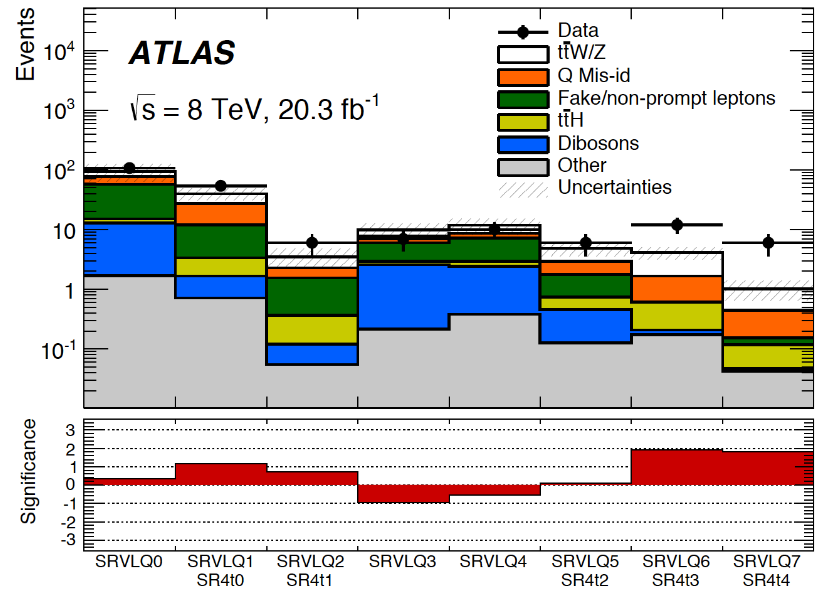
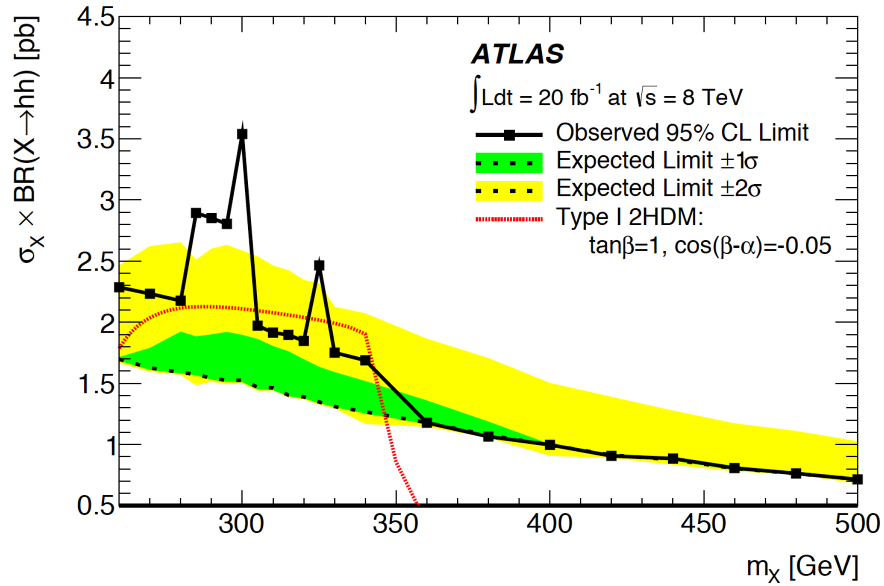


[Phys. Rev. Lett.114 (2015) 081802]

Searches for heavy resonance or non-resonance decaying into double Higgs ($X \rightarrow hh$)

2.1σ at m_X ~300 GeV is observed in bbγγ final state



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We look forward to a very successful and fruitful Run 2 !