Camille Flammarion, Universum, 1888

Prospects for measurements with photons beyond LHC Run2

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- Physics at the HL-LHC
- Pile-up and Detector upgrade
- Object reconstruction; photons
- Production of $H \rightarrow \gamma\gamma$
- $H \rightarrow Z\gamma$ rare decay
- FCNC $t \rightarrow Hq$
- $HH \rightarrow bb\gamma\gamma$
- Summary

Issues for the Future *(Starting now!)*

1. What is the agent of EWSB? *There is a Higgs boson!* Might there be several?
2. Is the Higgs boson elementary or composite? How does it interact with itself? What triggers EWSB?
3. Does the Higgs boson give mass to fermions, or only to the weak bosons? What sets the masses and mixings of the quarks and leptons? *(How) is fermion mass related to the electroweak scale?*
4. Are there new flavor symmetries that give insights into fermion masses and mixings?
5. What stabilizes the Higgs-boson mass below 1 TeV?

C. Quigg, The Future of High Energy Physics conference (Hong-Kong 2015)

Higgs Physics Programme

1. Measurement of couplings to elementary fermions and bosons
2. Precision measurement of the mass and width of this new particle
3. Determination of the quantum numbers: spin and CP properties
4. Measurement of the self-coupling (di-Higgs boson production)
5. Search for possible partners (neutral and/or charged) of this boson
6. Fundamental/composite particle
7. Strongly associate to this: Vector Boson Scattering

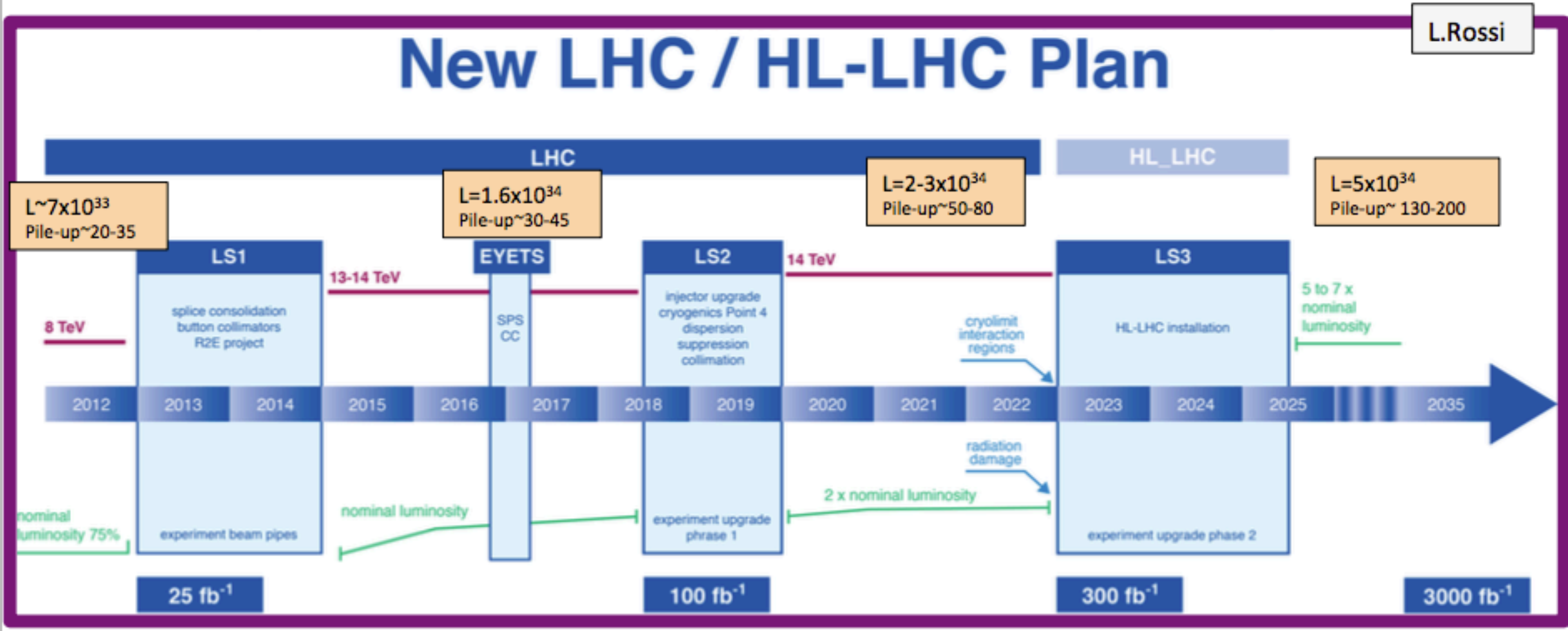
HL-LHC Physics goals

- HL-LHC will be alone, in the near future for sure, exploring multi-TeV
  - There will be a wide physics programme
  - Higgs physics plays a central role

HL-LHC Benchmark scenario

- Approved running to deliver 300 fb^{-1} by ~2021
  - With 20x Higgs boson production so far
- Post LS3 operation at $5 \times 10^{34} cm^{-2} s^{-1}$ (lumi leveling)
  - 25 ns bunch spacing
  - 140 events per bunch crossing
  - 3000 fb^{-1} over 10 years
- Detector upgrades needed
  - to cope with radiation damage and pileup
  - aim to maintain/enhance physics performance
- Trigger is a key component:
  - Thresholds not too dissimilar to today
  - Mandated by need to study the Higgs boson

LHC roadmap beyond LS1

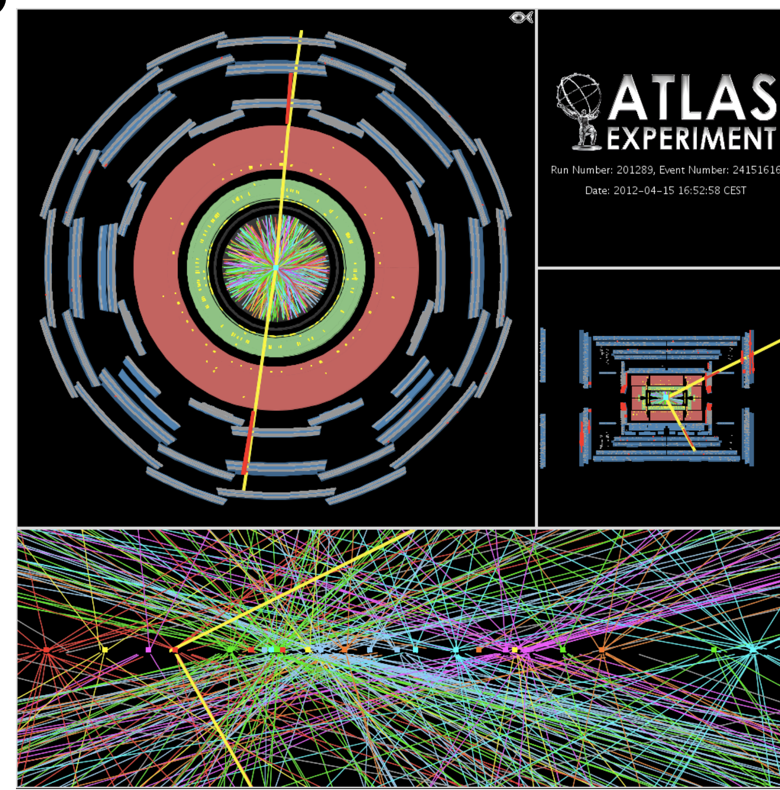


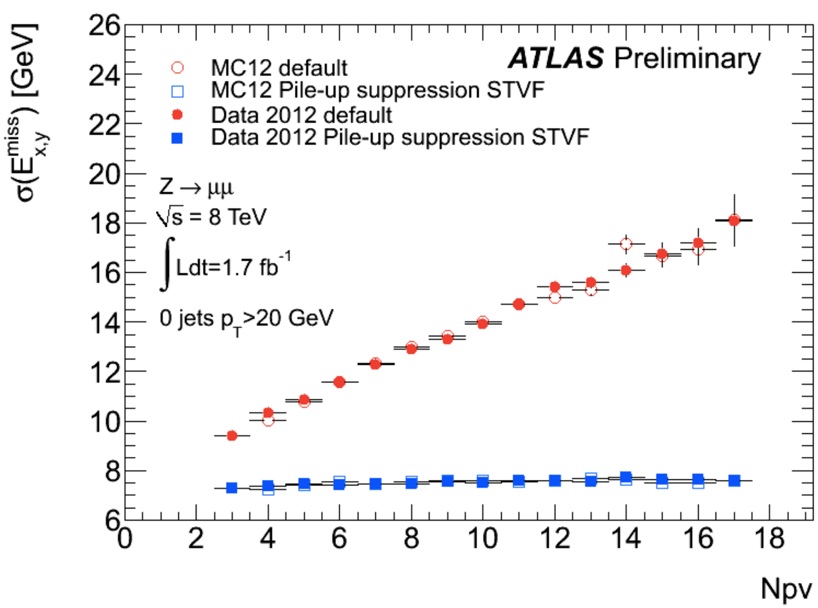
?

Event pileup at the LHC

- Present ATLAS and CMS detectors have been designed for <μ> ~ 23 pp interactions / bunch-crossing
  - And continue to do an excellent job with 35

Z→μμ decay in a large pileup event

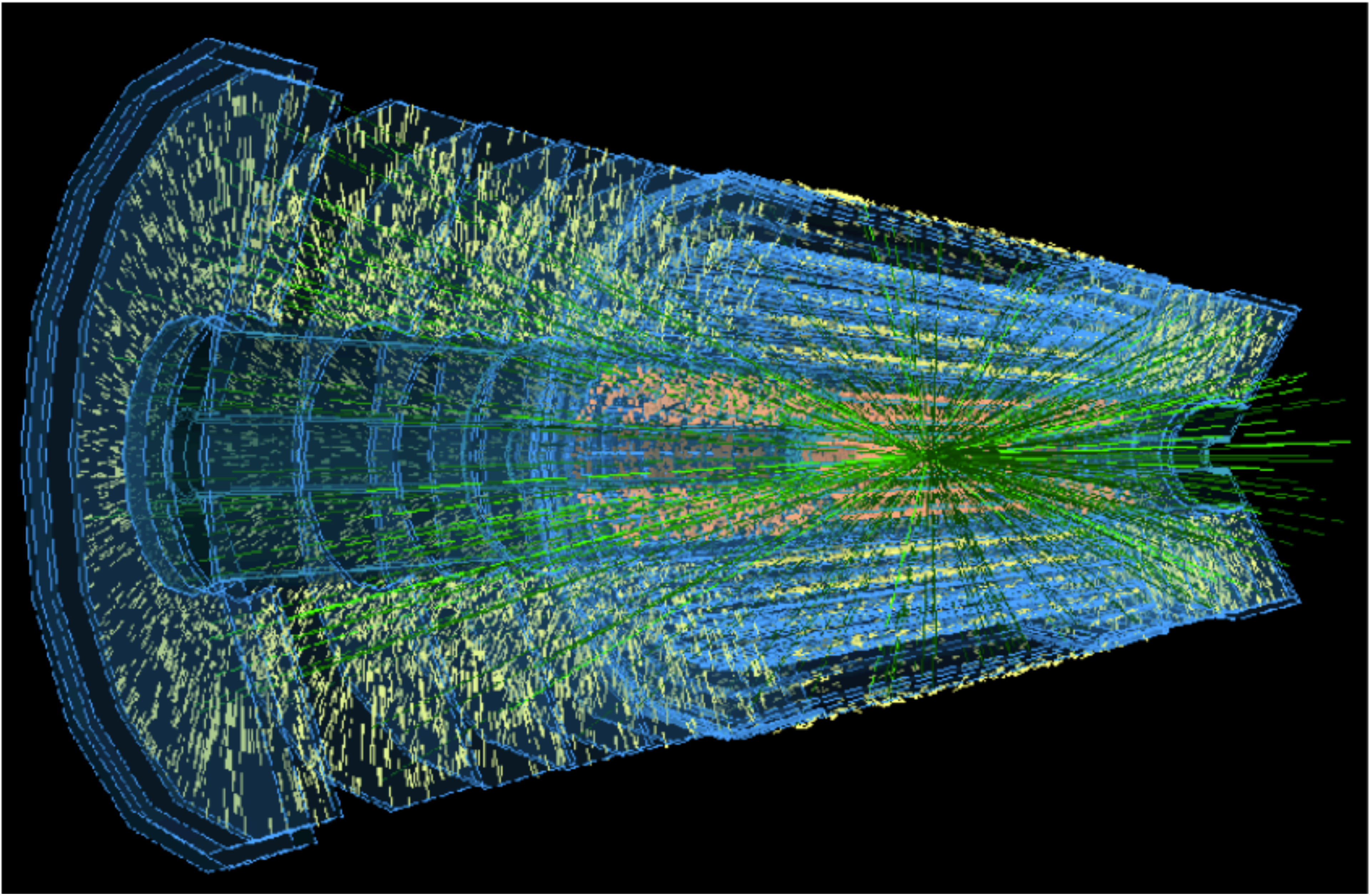




Missing transverse energy resolution as a function of the number of the reconstructed vertices

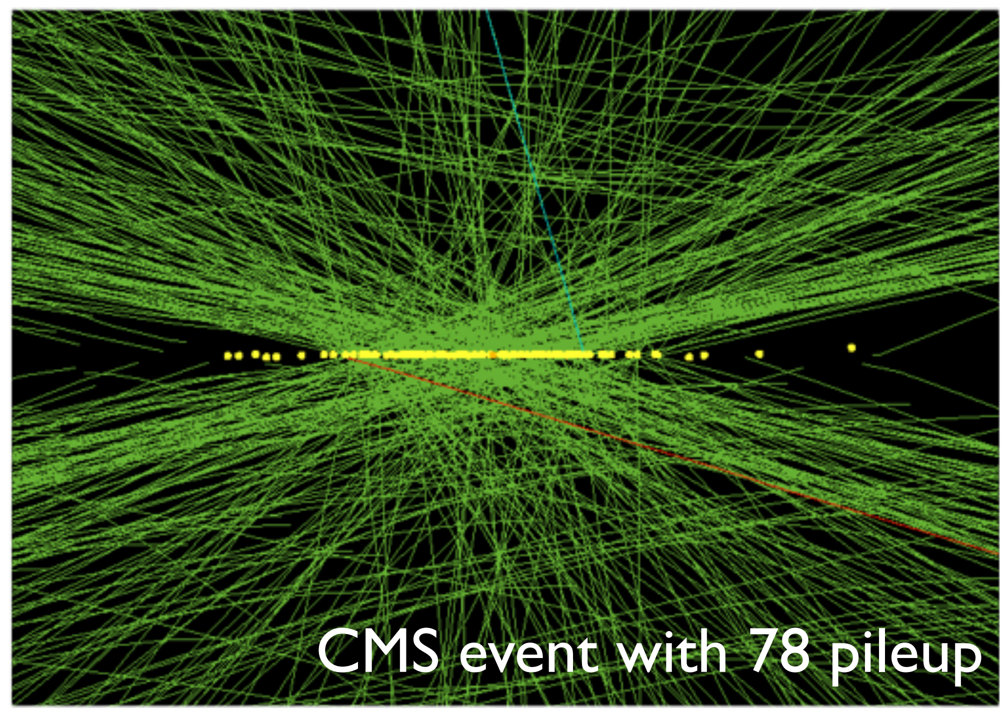
- But cannot handle (an average of) 140 events of pileup

Typical event at HL-LHC <m>=140, reconstructed by ATLAS simulation



Detector Upgrade

- In a nutshell – detector upgrades are planned so as to maintain or improve on the present performance as the instantaneous luminosity increases
- A particular challenge is to refine the hardware (level-1) and software (high level) triggers to maintain sensitivity with many interactions per bunch crossing – "pileup"
- Offline algorithms also need to be developed to maintain performance with pileup
- Focus here on upgrades which change the performance. In addition, there is a continuous huge effort in consolidation, eg. new cooling systems, improved electronics and power supplies, shielding additions...
- Phase 0/I upgrades are better defined than Phase II

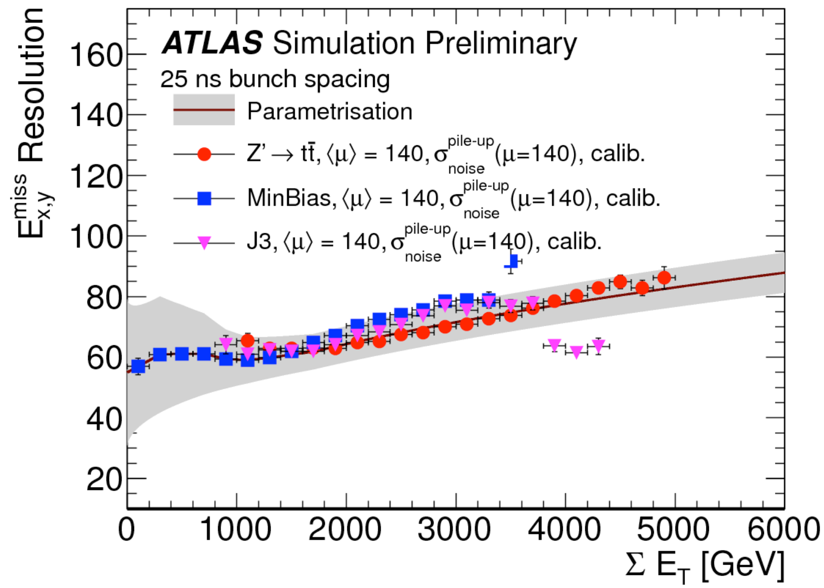


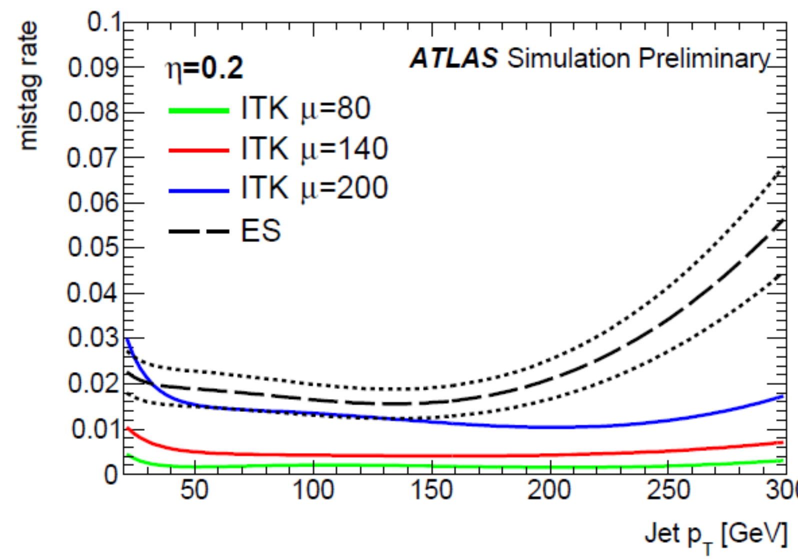
Simulation methods

- ATLAS:
  - Efficiency and resolution functions are applied to physics objects
  - Performance of the new detector will not be worse than the current detector at Run I conditions
- CMS:
  - Scale signal and background yields of current analyses
  - Two scenarios for systematic uncertainties
    - Scenario 1: Systematic uncertainties remain the same
    - Scenario 2: Theoretical uncertainties scaled by ½, other systematic uncertainties scaled by $1/\sqrt{L}$

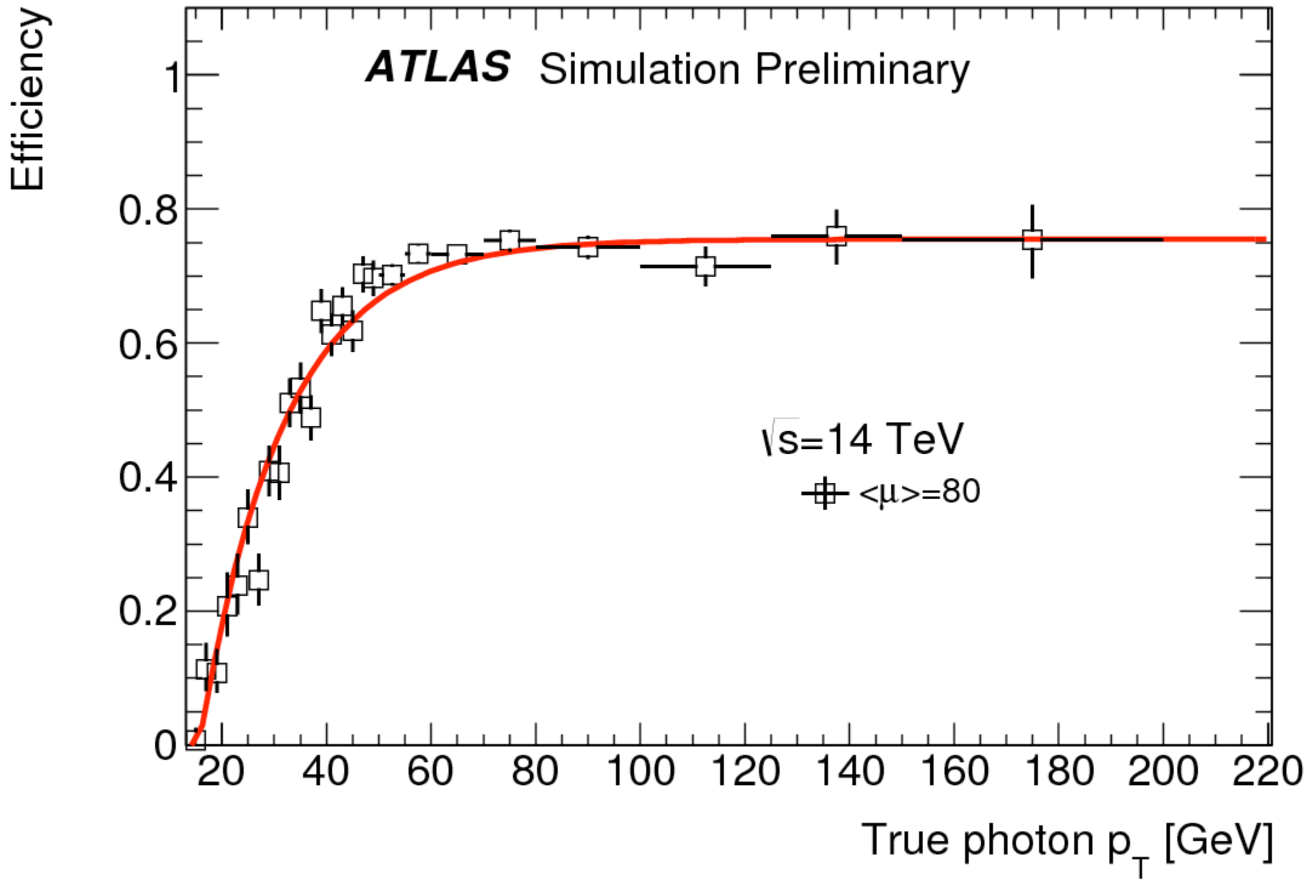
Full simulation object studies

- Parametrization of object performance in the HL-LHC pile-up environment
- Some examples here:
  - ATLAS E_T^{miss} resolution with parametrization overlayed
- ATLAS b-tag fake rate for 70% efficiency compared with rate assumed for ES studies
  - ITK brings enhanced tracking
  - Mistag below 0.5% for <μ>=140 pT=100 GeV





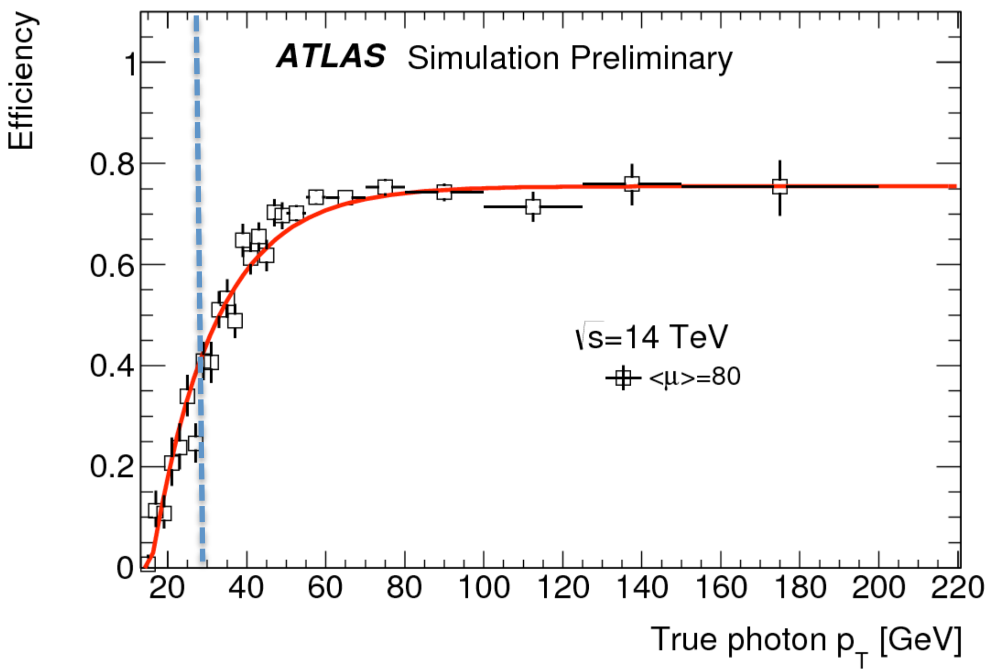
Photon Identification & Reconstruction

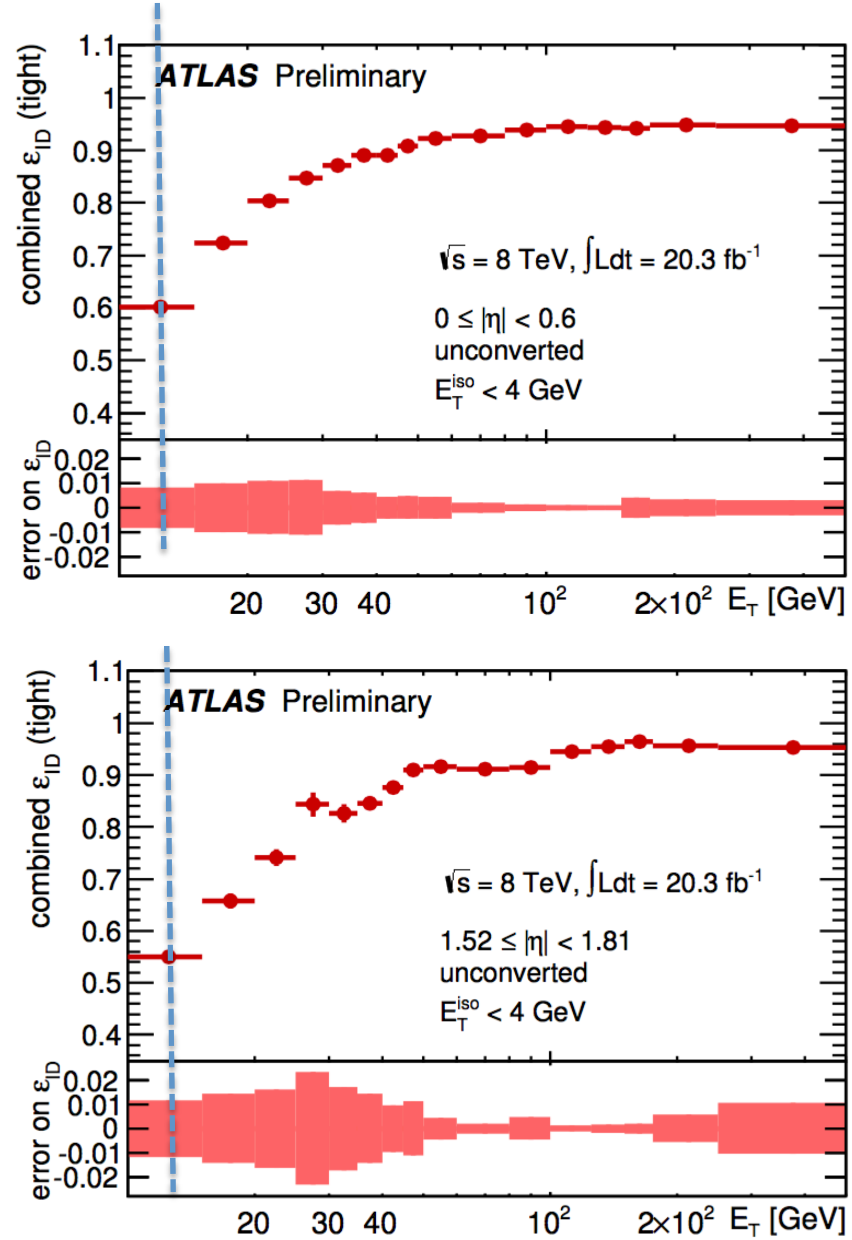


The efficiency of the photon identification and isolation requirements as a function of the true photon p_T. The fitted parametrisation is superimposed.

Photon Identification & Reconstruction

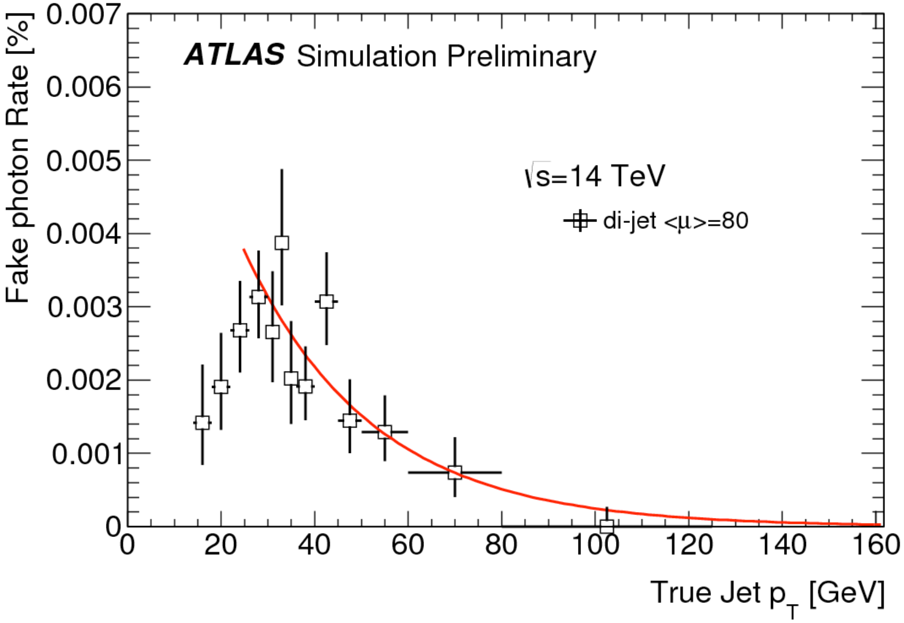
Plateau: 75%
Threshold: 30 GeV

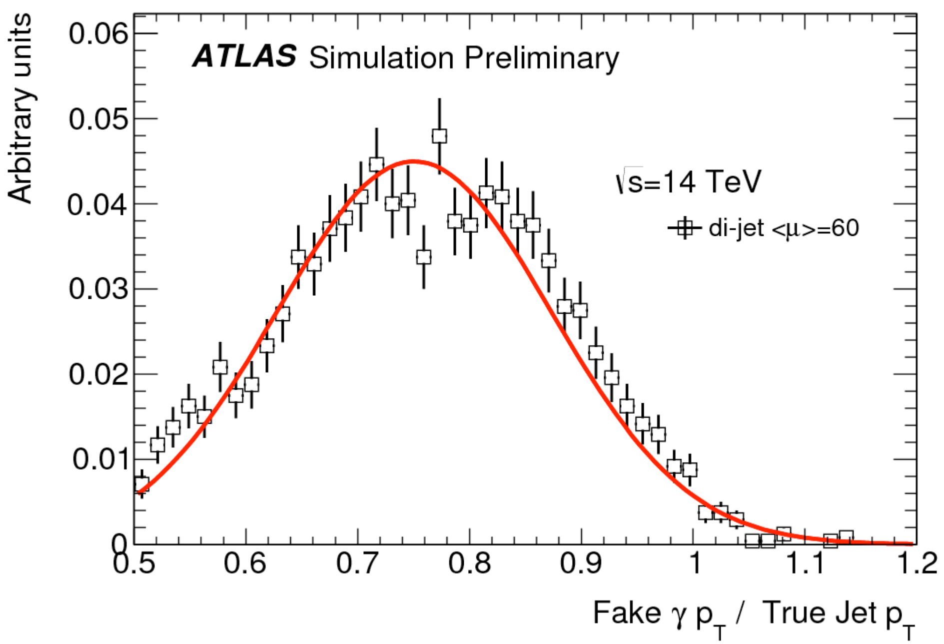




Plateau: 95%
Threshold: <15 GeV

Photon Fakes

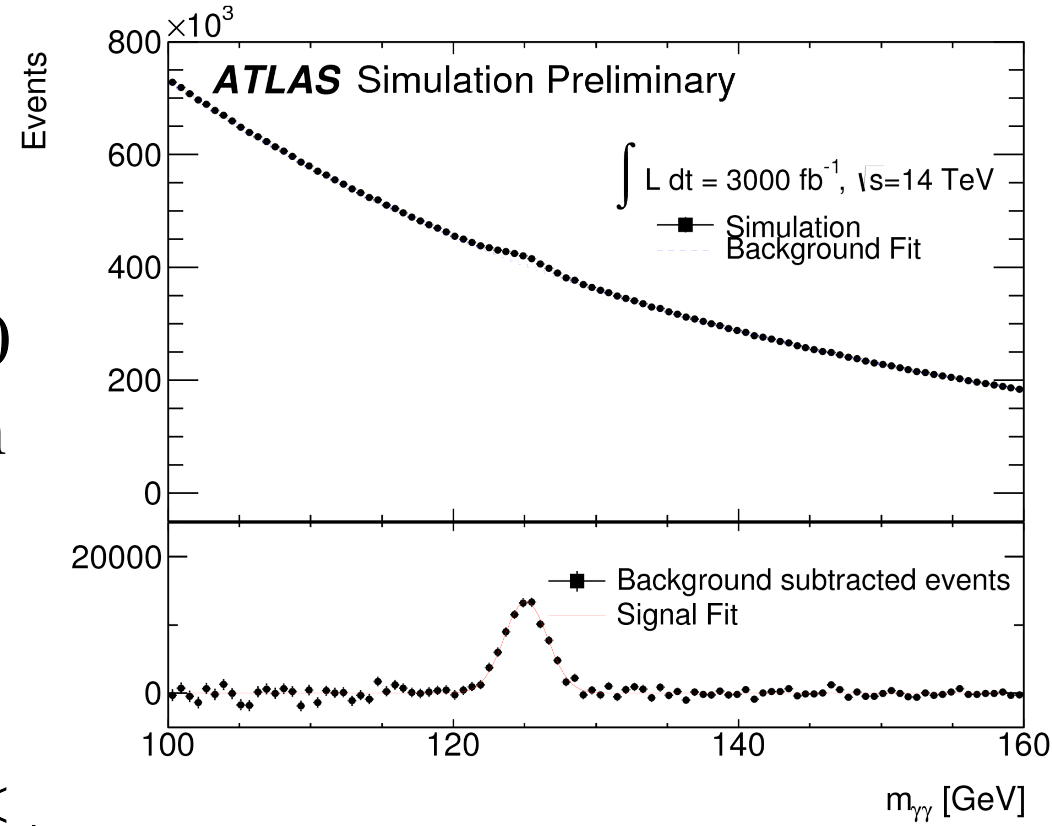




- Left: The fake rate after applying photon identification and isolation requirements as a function of true jet p_T
- Right: the ratio of reconstructed photon p_T to the true jet p_T (b).

H→γγ

- inclusive analysis: very similar to the one of Run1
  - two isolated photons,
  - one photon with pT>40 GeV and the other with pT>30 GeV,
  - both photons within |η| <2.37 and outside the transition region 1.37 < |η| < 1.52.



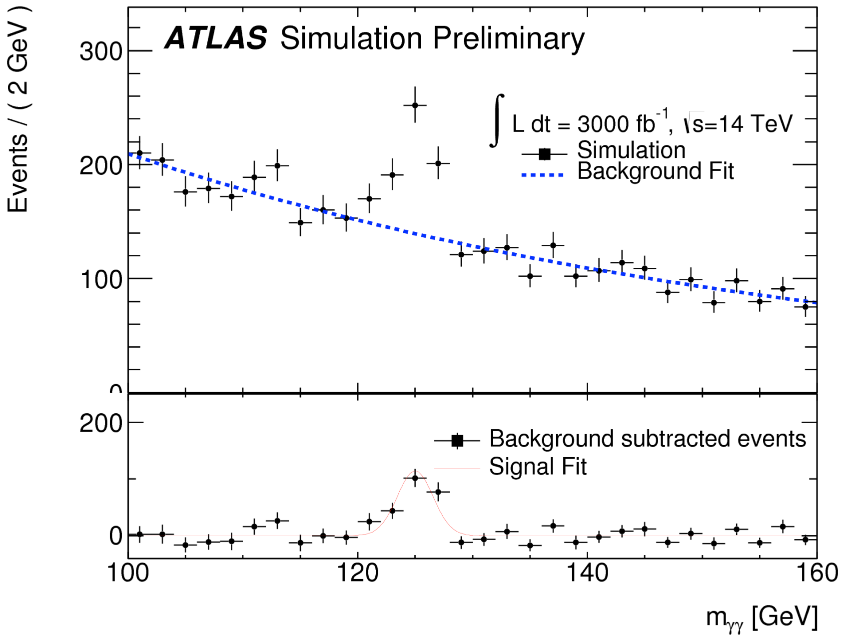
H→γγ

- **Exclusive analyses**
  - The systematic uncertainty on this background modelling is estimated as the difference in the number of background events under the signal peak when fitting the background with an order-4 Bernstein polynomial and a 6-degree polynomial.

Category	Inclusive	0-jet	1-jet	2-jet
$300\ \mathrm{fb}^{-1}$				
S	$8.08 \cdot 10^3$	$4.92 \cdot 10^3$	$1.25 \cdot 10^3$	36.2
B	$4.06 \cdot 10^5$	$3.16 \cdot 10^5$	$3.00 \cdot 10^4$	202.7
S/B (%)	1.99	1.55	4.16	17.8
VBF/(VBF+ggF)	0.07	0.03	0.14	0.60
$3000\ \mathrm{fb}^{-1}$				
S	$8.08 \cdot 10^4$	$4.92 \cdot 10^4$	$1.25 \cdot 10^4$	$2.13 \cdot 10^2$
B	$4.06 \cdot 10^6$	$3.16 \cdot 10^6$	$3.00 \cdot 10^5$	$8.02 \cdot 10^2$
S/B (%)	1.99	1.55	4.16	26.56
VBF/(VBF+ggF)	0.07	0.03	0.14	0.70

Table 3: Summary of number of signal and background events in each category, ratio of signal to background and fractional contribution of VBF events to the signal with $300\ \mathrm{fb}^{-1}$ and $3000\ \mathrm{fb}^{-1}$

ttH, H→γγ



- Sensitive to top in both production and decay
- Yields top Yukawa coupling

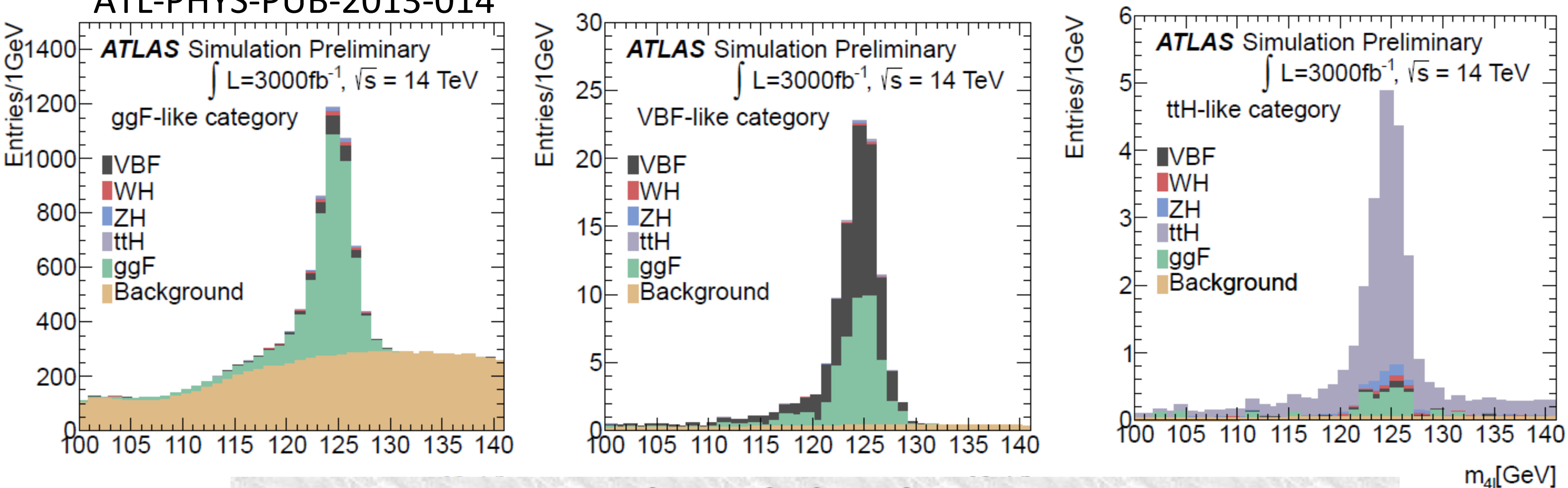
ATL-PHYS-PUB-2014-012

	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
Production mode	Total	Statistical	Experimental	Theoretical
$t\bar{t}H$	$^{+21}_{-17}$	$^{+13}_{-12}$	$^{+5}_{-4}$	$^{+17}_{-11}$
WH	$^{+26}_{-25}$	$^{+21}_{-20}$	$^{+13}_{-12}$	$^{+10}_{-8}$
ZH	$^{+35}_{-31}$	$^{+32}_{-29}$	$^{+7}_{-7}$	$^{+12}_{-8}$
ggF	$^{+19}_{-14}$	$^{+3}_{-3}$	$^{+1}_{-1}$	$^{+19}_{-14}$
VBF	$^{+29}_{-29}$	$^{+18}_{-18}$	$^{+1}_{-1}$	$^{+23}_{-23}$

ttH measured with an accuracy of ~ 15%

H→ZZ*→4l

ATL-PHYS-PUB-2013-014



Selected signal event rates					
	ttH	ZH	WH	VBF	ggH
$3000 fb^{-1}$	35	5.7	67	97	3800

- Very high signal purity
- Separate into all 5 production modes
- WH, ZH use lepton tags

ttH only possible at HL-LHC

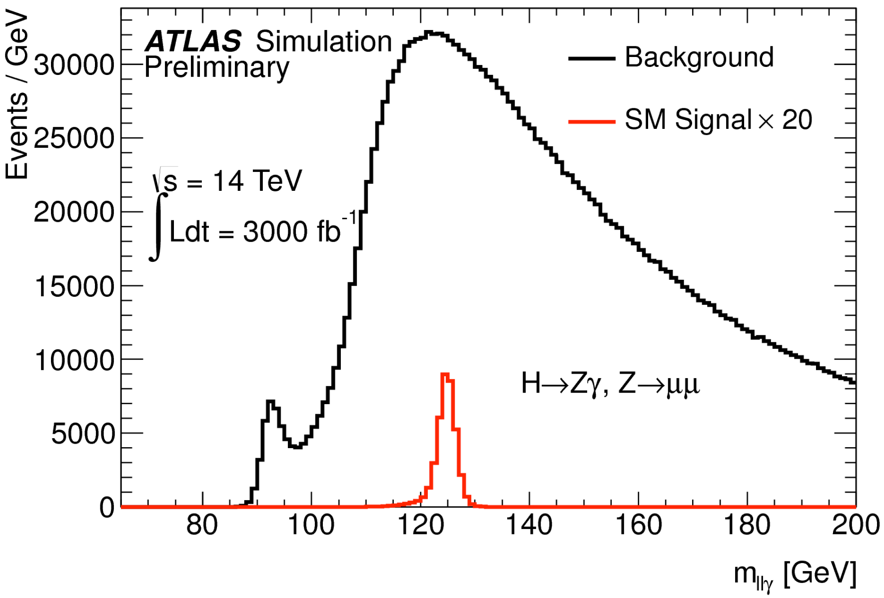
$H \rightarrow ZZ^* \rightarrow 4l$

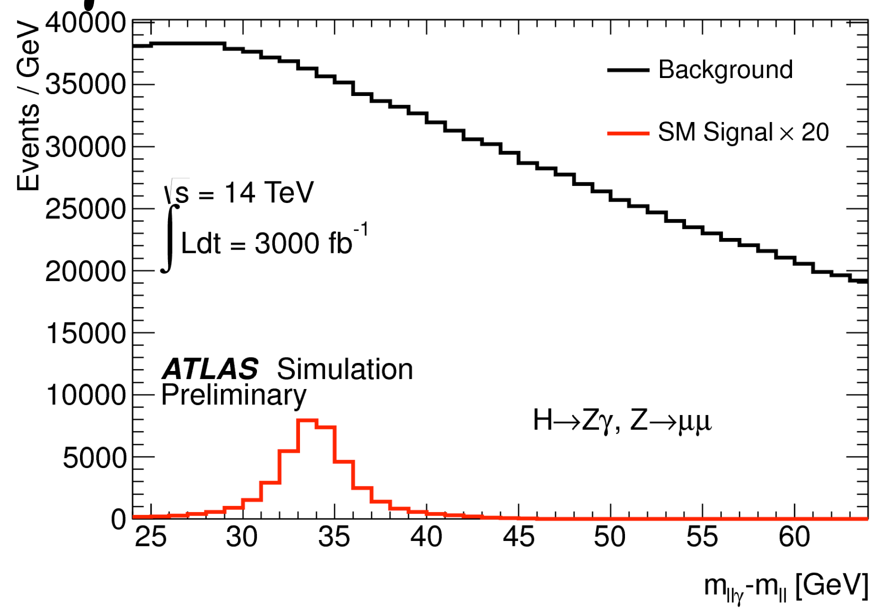
$\Delta\mu/\mu$	Total	Stat.	Expt. syst.	Theory
Production mode		300 fb^{-1}		
ggF	0.152	0.066	0.053	0.124
VBF	0.625	0.545	0.233	0.226
WH	1.074	1.064	0.061	0.085
$t\bar{t}H$	0.535	0.516	0.038	0.120
Combined	0.125	0.042	0.044	0.108
		3000 fb^{-1}		
ggF	0.131	0.025	0.040	0.124
VBF	0.371	0.187	0.225	0.226
WH	0.390	0.375	0.061	0.085
ZH	0.532	0.526	0.038	0.073
$t\bar{t}H$	0.224	0.184	0.034	0.120
Combined	0.100	0.016	0.036	0.093

Table 2: Expected relative uncertainties on the signal strength, for samples of 300 fb^{-1} and 3000 fb^{-1}, for the various Higgs production mechanisms and their combination.

ttH measured with an accuracy of ~ 20% with 4lepton final states

H→Zγ





Category	high p_{Tt}		low p_{Tt} low $\lvert\Delta\eta_{Z\gamma}\rvert$		low p_{Tt} high $\lvert\Delta\eta_{Z\gamma}\rvert$	
Final states	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$	$ee\gamma$	$\mu\mu\gamma$
S	602	721	703	839	138	165
B	$2.56 \cdot 10^4$	$3.05 \cdot 10^4$	$1.09 \cdot 10^5$	$1.30 \cdot 10^5$	$2.56 \cdot 10^4$	$3.06 \cdot 10^4$
S/B (%)	2.4	2.4	0.64	0.64	0.54	0.54
$S/\sqrt{B}$	3.8	4.1	2.1	2.3	0.86	0.94

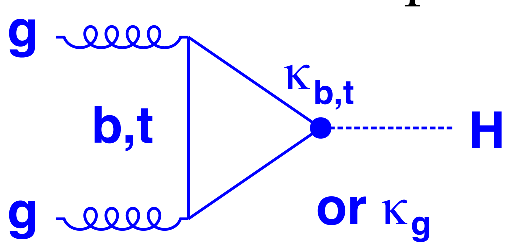
- Tests loop structure
- Small Signal to background ratio
- But a measurement is possible

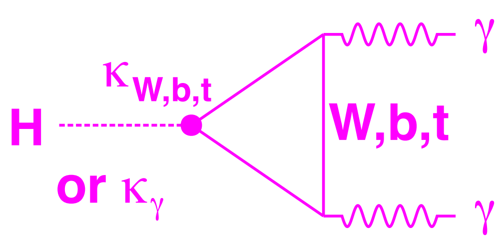
From signal rates to Higgs couplings

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

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

- The total width Γ_H is too narrow to measure
  - Assume it is the sum of the visible partial widths – no additional invisible modes
- 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





Higgs Couplings

- New: VH->bb included in ATLAS, updates for H->Zγ, VH/ttH->γγ (*)
- No BSM Higgs decay modes assumed

–Comparable numbers for κ_W,$\kappa_{Z,}$ $\kappa_{t,}$ and κ_γ between the experiments

–Couplings can be determined with 2-10% precision at 3000fb^{-1} (for CMS Scenario 2)

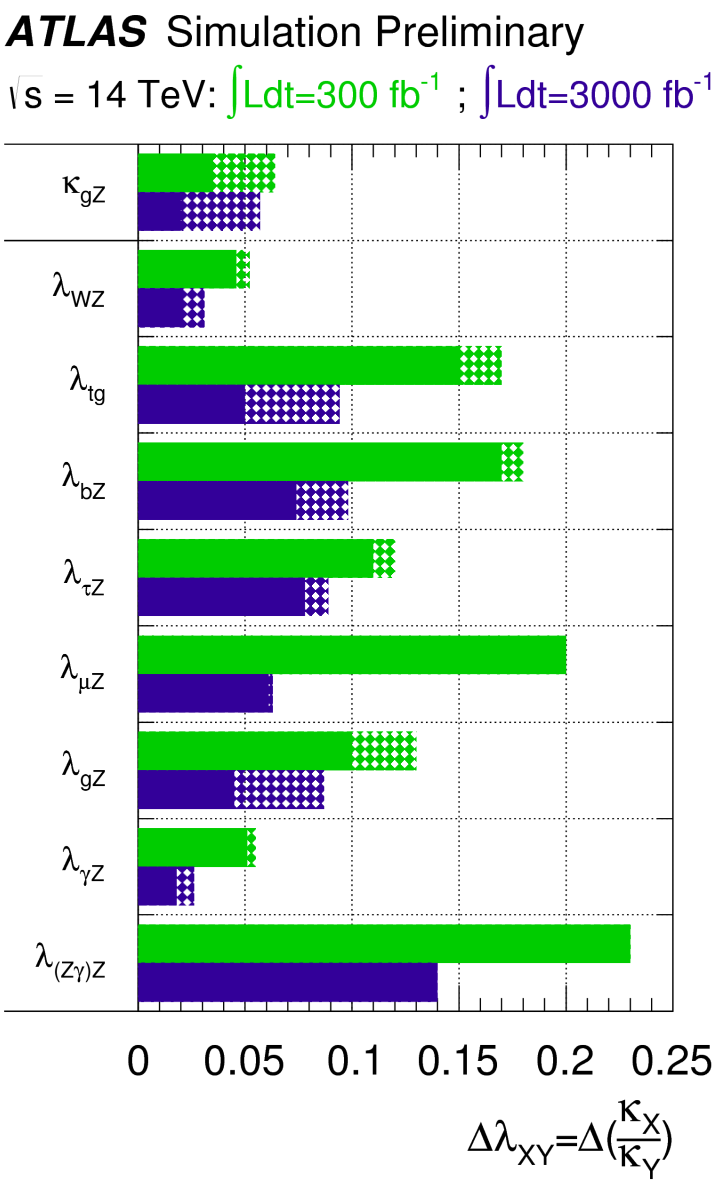
		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[9,9]	[9,9]	[8,8]	[11,14]	[22,23]	[20,22]	[13,14]	[24,24]	[21,21]
300fb^{-1}	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]
3000fb^{-1}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

–ATLAS: [no theory uncert., full theory uncert.]

–CMS: [Scenario 2, Scenario1]

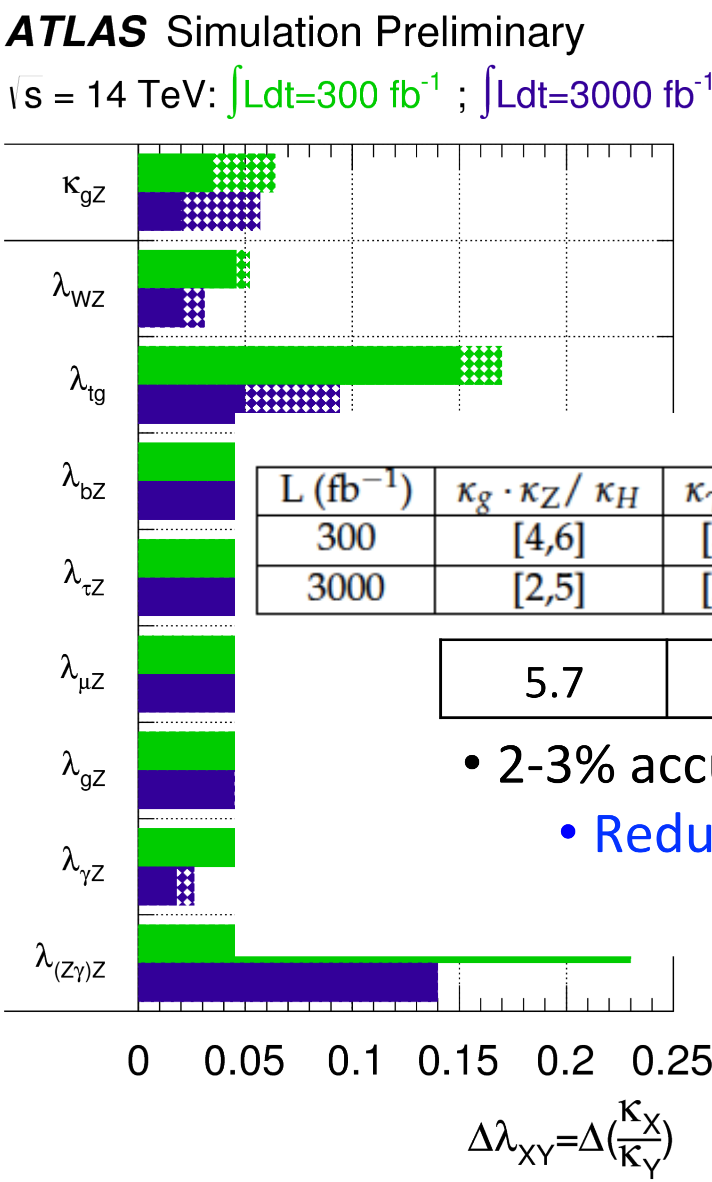
(*)
ATL-PHYS-PUB-2014-011
ATL-PHYS-PUB-2014-006
ATL-PHYS-PUB-2014-012
ATL-PHYS-PUB-2014-016

Higgs Couplings



- Remove the assumption on the total width
  - Only ratios of the coupling scale factors can be determined at LHC
  - Use given process as a reference

Higgs Couplings



CMS [Scenario2,Scenario1]

L (fb^{-1})	$\kappa_g \cdot \kappa_Z / \kappa_H$	κ_γ / κ_Z	κ_W / κ_Z	κ_b / κ_Z	κ_τ / κ_Z	κ_Z / κ_g	κ_t / κ_g	κ_μ / κ_Z	$\kappa_{Z\gamma} / \kappa_Z$
300	[4,6]	[5,8]	[4,7]	[8,11]	[6,9]	[6,9]	[13,14]	[22,23]	[40,42]
3000	[2,5]	[2,5]	[2,3]	[3,5]	[2,4]	[3,5]	[6,8]	[7,8]	[12,12]
	5.7	2.6	3.1	9.8	8.9	8.7	9.4	6.3	14

- 2-3% accuracy on few coupling constants at HL-LHC
  - Reduced theoretical uncertainties needed

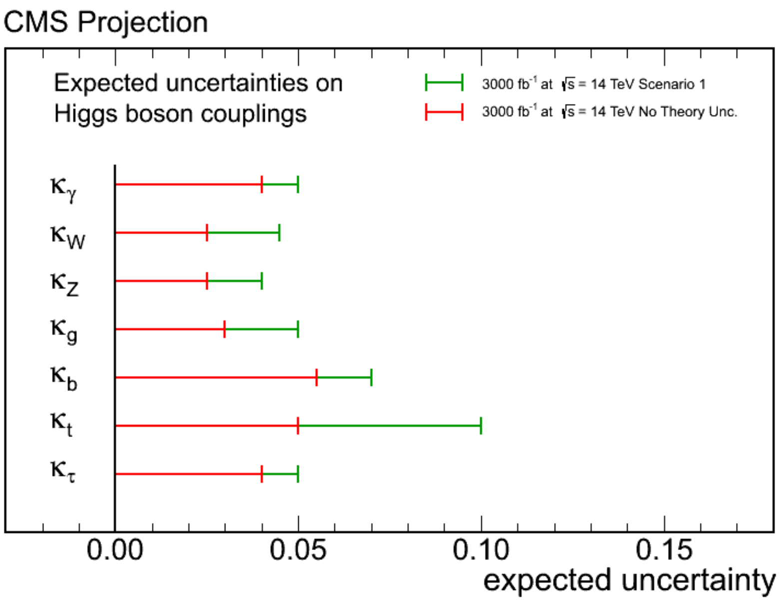
Effects of theory uncertainties

- Theoretical uncertainties limit the achieved precision
- Reducing the theoretical uncertainties is a worthwhile endeavor

CMS:

Scenario 1

No theory uncertainty

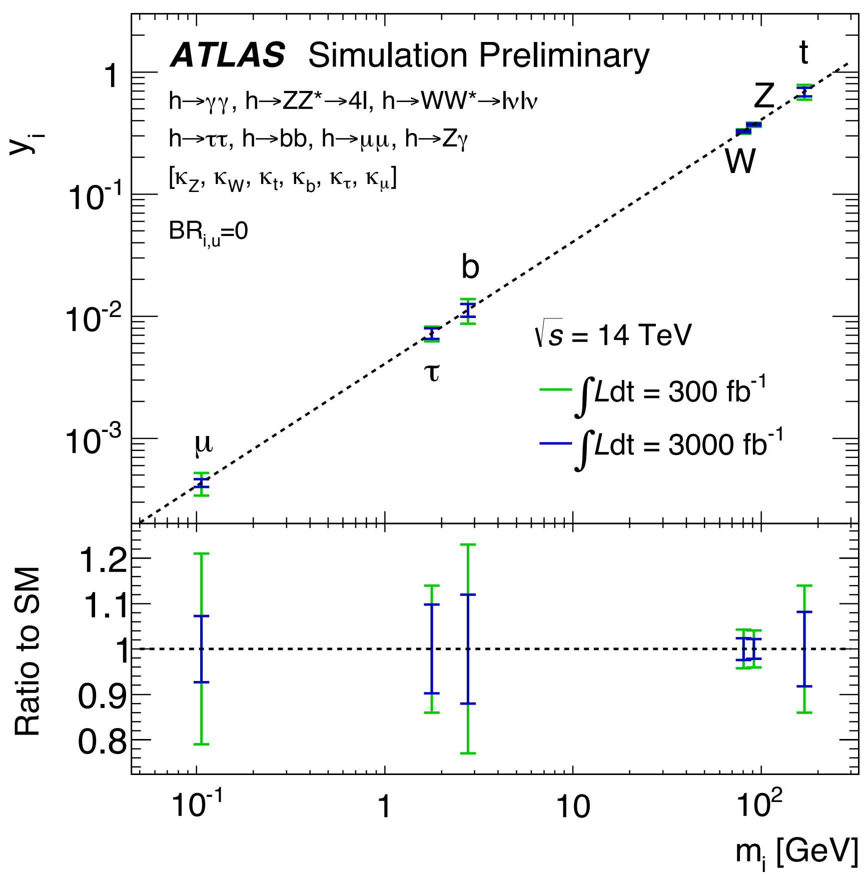


ATLAS: Deduced size of theory uncertainty to increase total uncertainty by <10% for 3000 fb^{-1}

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

Higgs Couplings

- Higgs boson couplings versus the SM particle masses
- Define 'reduced' coupling parameters

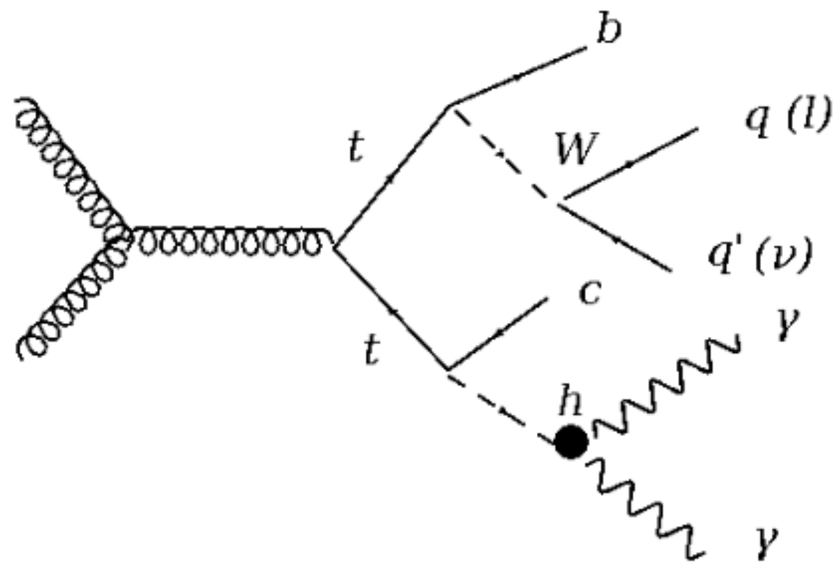


$$y_{V,i} = \sqrt{\kappa_{V,i}\frac{g_{V,i}}{2v}} = \sqrt{\kappa_{V,i}}\frac{m_{V,i}}{v}$$

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

Rare decays involving H→γγ

- FCNC: t->cH
- Higgs-induced flavor changing neutral currents can be probed with rare top decays
- ATLAS has published a search for t->qH in which the Higgs boson decays to a photon pair in **arXiv: 1403.6293**
- The projection study in **ATL-PHYS-PUB-2013-012** follows this analysis



t→Hq→γγj

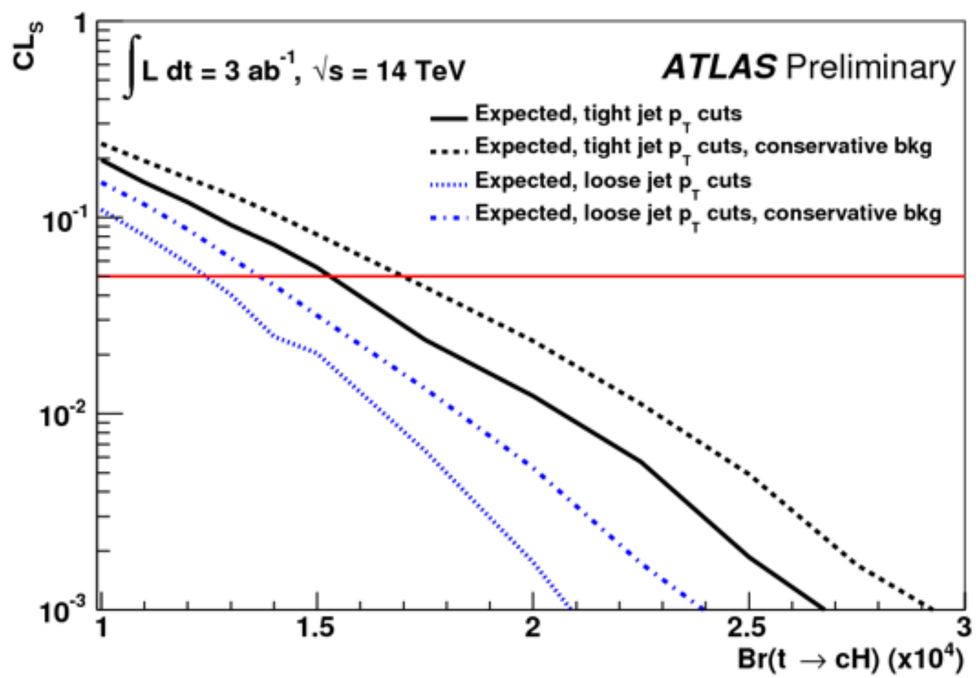
- Expected yields in $100<m_{\gamma\gamma}<160$ GeV and in signal region (SR) $123<m_{\gamma\gamma}<129$ GeV (signal BR=0.01%) after scaling 8 TeV results:

	Lumi factor	xsec factor	hadronic channel			leptonic channel		
			A*ε factor	evts	evts in SR	A*ε factor	evts	evts in SR
tt, t→qH	150	3.9	0.29±0.04	16	13	0.50±0.03	8.4	7
ttH	150	4.7	0.29±0.04	28	24	0.50±0.03	16	14
γγj	150	2.2	0.18±0.03	2320	350	0.57±0.05	163	25

t→Hq→γγj

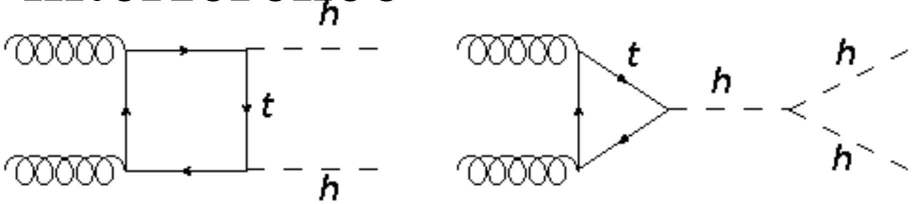
- Expected yields in $100<m_{\gamma\gamma}<160$ GeV and in signal region (SR) $123<m_{\gamma\gamma}<129$ GeV (signal BR=0.01%) after scaling 8 TeV results:

- Expected limit on BR (t→qH) at 95% CL (assuming no signal)
  - 1.5×10^{-4} with nominal background level
  - 1.7×10^{-4} with background increased by 1σ



Di-Higgs production

- One of the exciting prospects of HL-LHC
  - Cross section at $\sqrt{s}$=14 TeV is 40.2 fb [NNLO]
  - Challenging measurement
    - New preliminary results from ATLAS and CMS
- Destructive interference

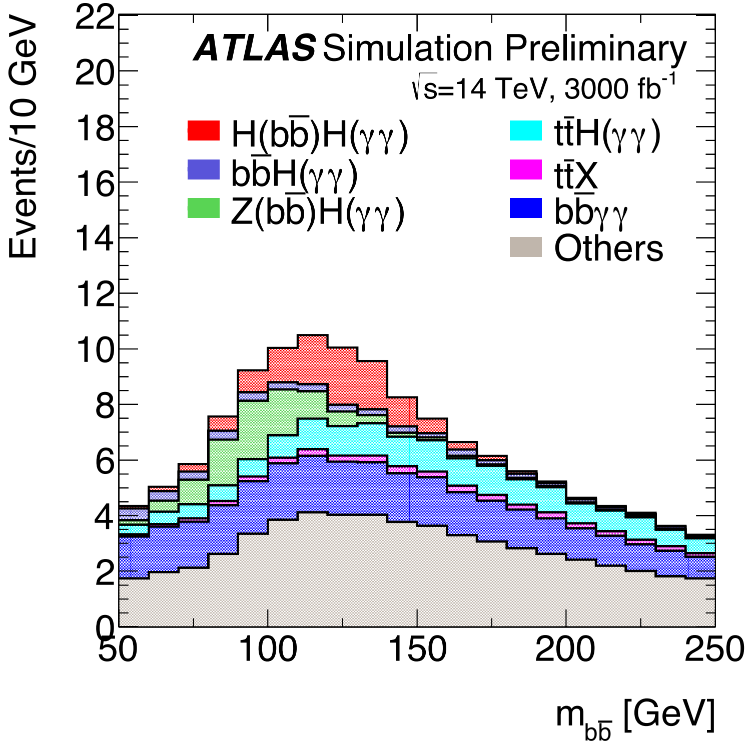


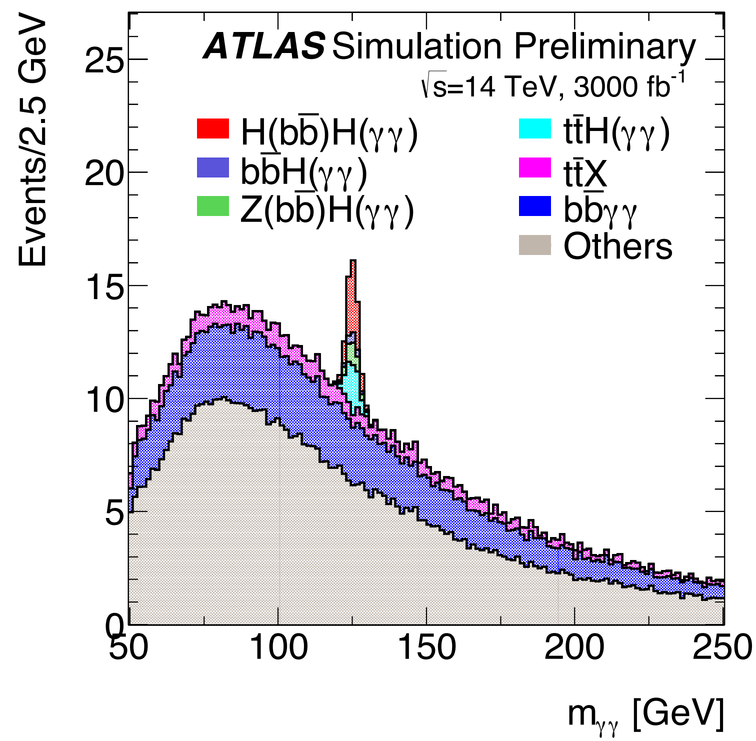
- Final states shown today
  - $bb\gamma\gamma$ [320 expected events at HL-LHC, 3000fb^{-1}]
    - But relatively clean signature
  - bbWW [30000 expected events at HL-LHC, 3000fb^{-1}]
    - But large backgrounds
- bbbb and $bb\tau\tau$ final states under consideration

Di-Higgs production

- CMS:
  - Parameterized object performance tuned to CMS Phase II detector at <PU>=140
  - 2D fit of M_{bb} and $M_{\gamma\gamma}$ distributions
- ATLAS:
  - Parameterized object performance obtained from full simulation
  - Cut based analysis
  - Electron to photon misidentification probability of 2% (5%) in barrel (endcap) is assumed
  - ATL-PHYS-PUB-2014-019

Mass distribution





The distributions of m_{bb} / m_{bb} in 3000 fb^{-1} after applying all the selection criteria except for m_{bb}/ $m_{\gamma\gamma}$. The individual shaped of the contributions are obtained using the events surviving event selection before the mass criteria and angular cuts are applied, but normalized to the number of expected events after the full event selection. The *ttX* contribution includes *tt*(≥ 1 lepton) and *tt*γ, while 'Others' includes *cc*γγ, *bb*γ*j*, *bbjj* and *j j*γγ.

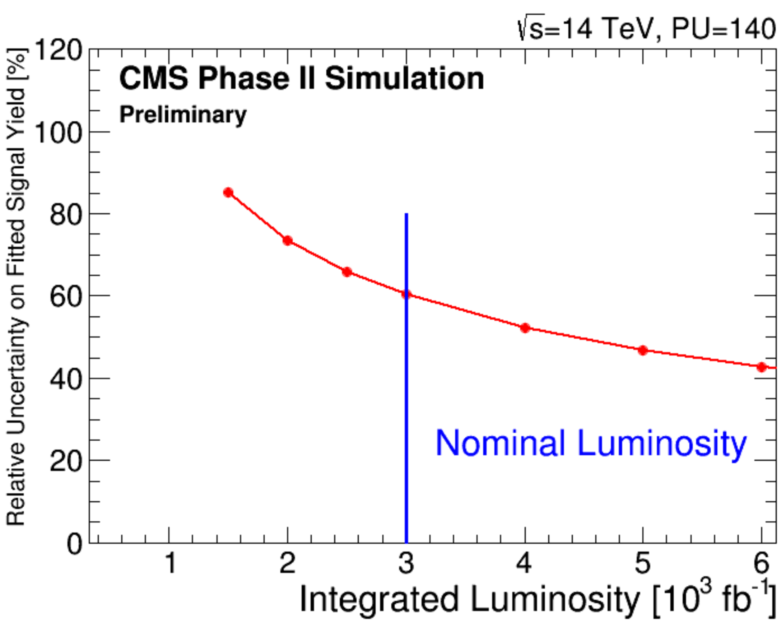
ATLAS prediction

process	Expected events in 3000 fb^{-1}
SM HH→bbγγ	8.4± 0.1
bbγγ	9.7 ± 1.5
ccγγ, bbγj, bbjj, jjγγ	24.1 ± 2.2
top background	3.4 ± 2.2
ttH(γγ)	6.1 ± 0.5
Z(bb)H(γγ)	2.7 ± 0.1
bbH(γγ)	1.2 ± 0.1
Total background	47.1 ± 3.5
S/√B (barrel+endcap)	1.2
S/√B (split barrel and endcap)	1.3

CMS results

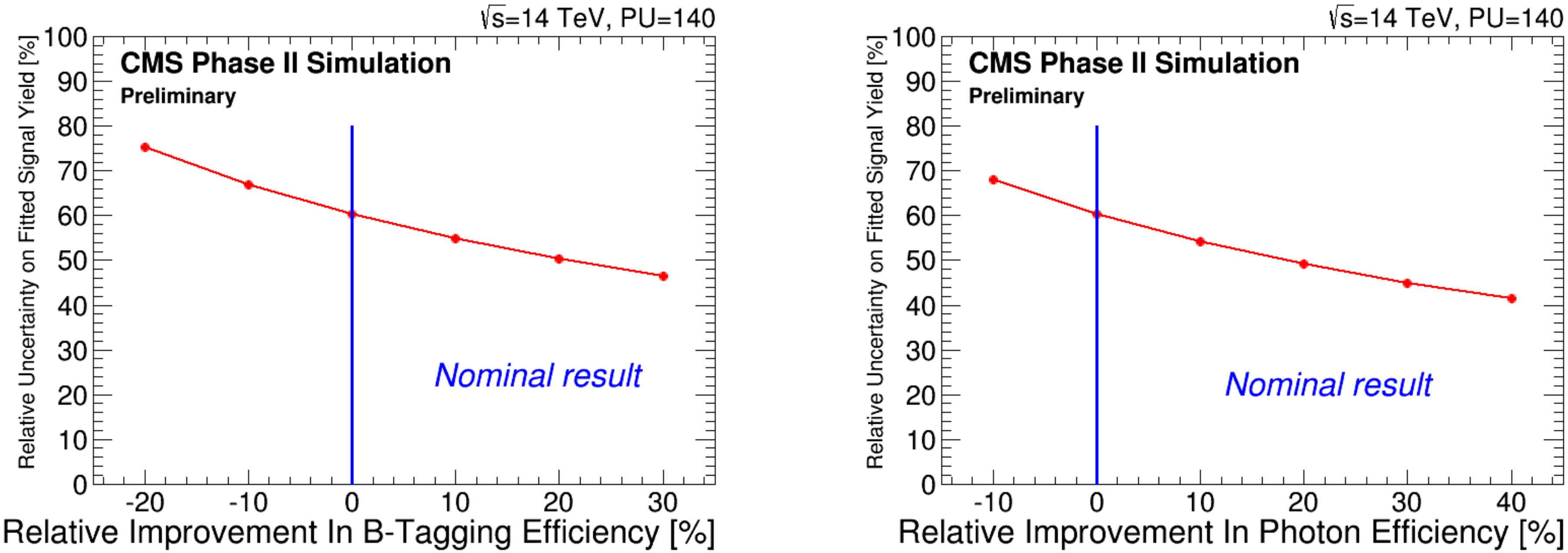
Process / Selection Stage	HH	ZH	$t\bar{t}H$	$b\bar{b}H$	$\gamma\gamma$+jets	γ+jets	jets	$t\bar{t}$
Object Selection & Fit Mass Window	22.8	29.6	178	6.3	2891	1616	292	113
Kinematic Selection	14.6	14.6	3.3	2.0	128	96.9	20	20
Mass Windows	9.9	3.3	1.5	0.8	8.5	6.3	1.1	1.1

Table 3: The expected event yields of the signal and background processes for 3000 fb^{-1} of integrated luminosity are shown at various stages of the cut-based selection for the both photons in the barrel region. Mass window cuts are 120 GeV to 130 GeV for $M_{\gamma\gamma}$ and 105 GeV to 145 GeV for M_{bb}. A large fit mass window, 100 GeV to 150 GeV for $M_{\gamma\gamma}$ and 70 GeV to 200 GeV for M_{bb}, is used for the likelihood fit analysis. The statistical uncertainties on the yields are of the order of percent or smaller.



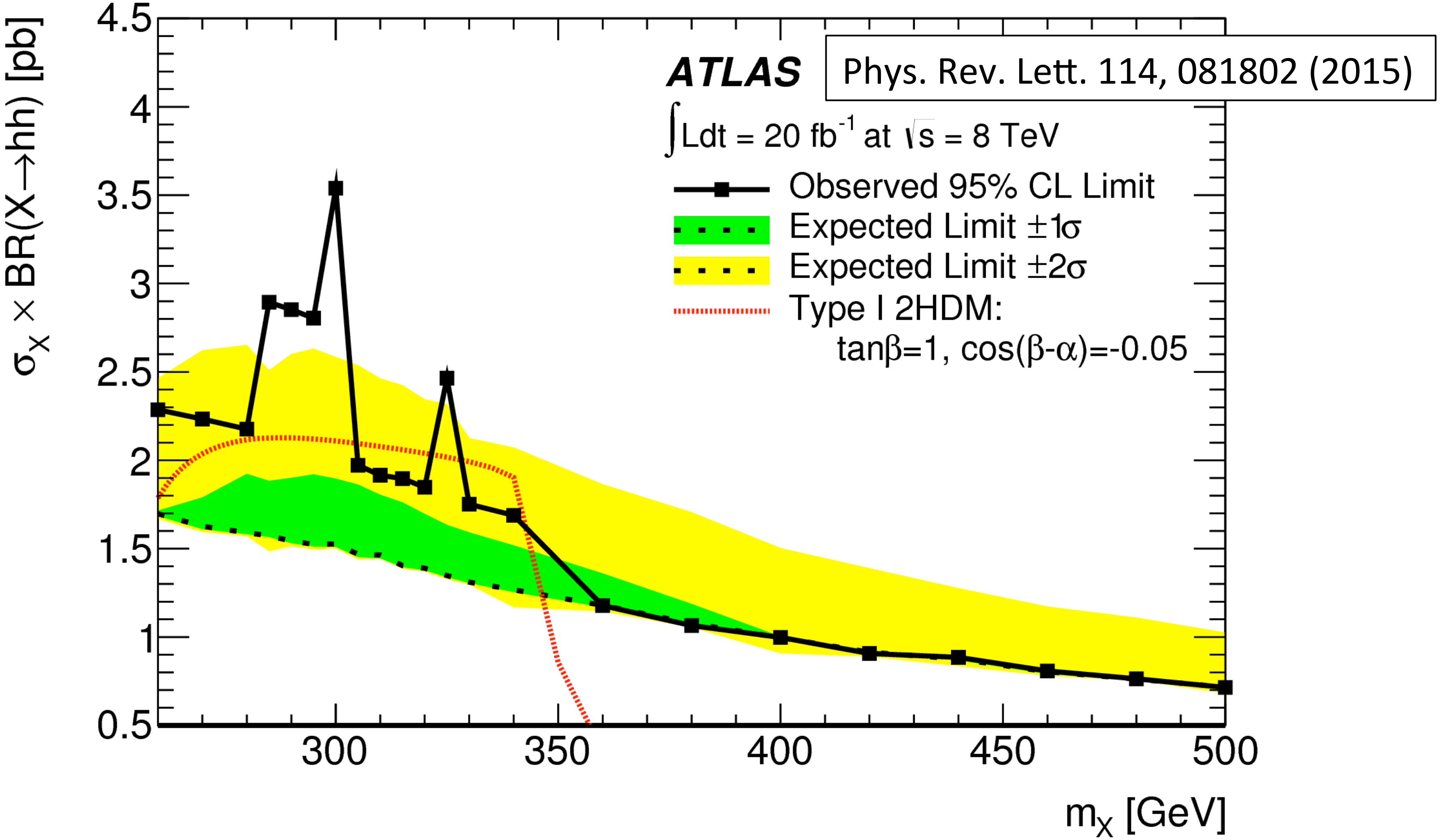
ATLAS and CMS are discussing the analyses to continue to better understand remaining differences and avenues for sensitivity improvement

CMS results



- The average expected relative uncertainty on the di-Higgs cross section measurement is shown as a function of the b-tagging efficiency (left) and the photon efficiency (right).

HH resonant production



- A 95% CL upper limit on the cross section times branching ratio of a narrow resonance decaying to pairs of Higgs bosons as a function of m_X.

Summary

- **30 fb^{-1}** of LHC data at $\sqrt{s}$ = 8 (and 7) TeV has allowed the Higgs discovery
- **300 fb^{-1}** at 14 TeV will allow lots of precision measurements in the Higgs sector, SM and continue NP searches
- **3000 fb^{-1}** will extends/complete the LHC Physics Programme:
  - LHC ultimate precision Higgs couplings to elementary bosons and fermions
  - Search for rare Higgs boson decays
  - Coupling structure
  - Di-Higgs boson production
- The final states with photons are crucial to shade light to the most important points of the physics programme:
  - Top Yukawa coupling
  - Rare Higgs decays
  - HH production

backup

CMS: HH→WWbb

- Results are quoted as a function of the background systematic uncertainty
  - Data driven techniques will likely constraint the uncertainties to the percent level