

SM Higgs boson rare decays and production

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The HL-LHC scenario

- High-luminosity LHC phase with $L=5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (w/ luminosity levelling)

Parameter	HL-LHC	LHC Run1 (2012 values)
bunch spacing	25 ns	50 ns
events per bunch crossing ($\langle \mu \rangle$)	140	20 (23 = ATLAS&CMS design value)
integrated luminosity	3000 fb^{-1}	20 fb^{-1}
\sqrt{s}	14 TeV	8 TeV

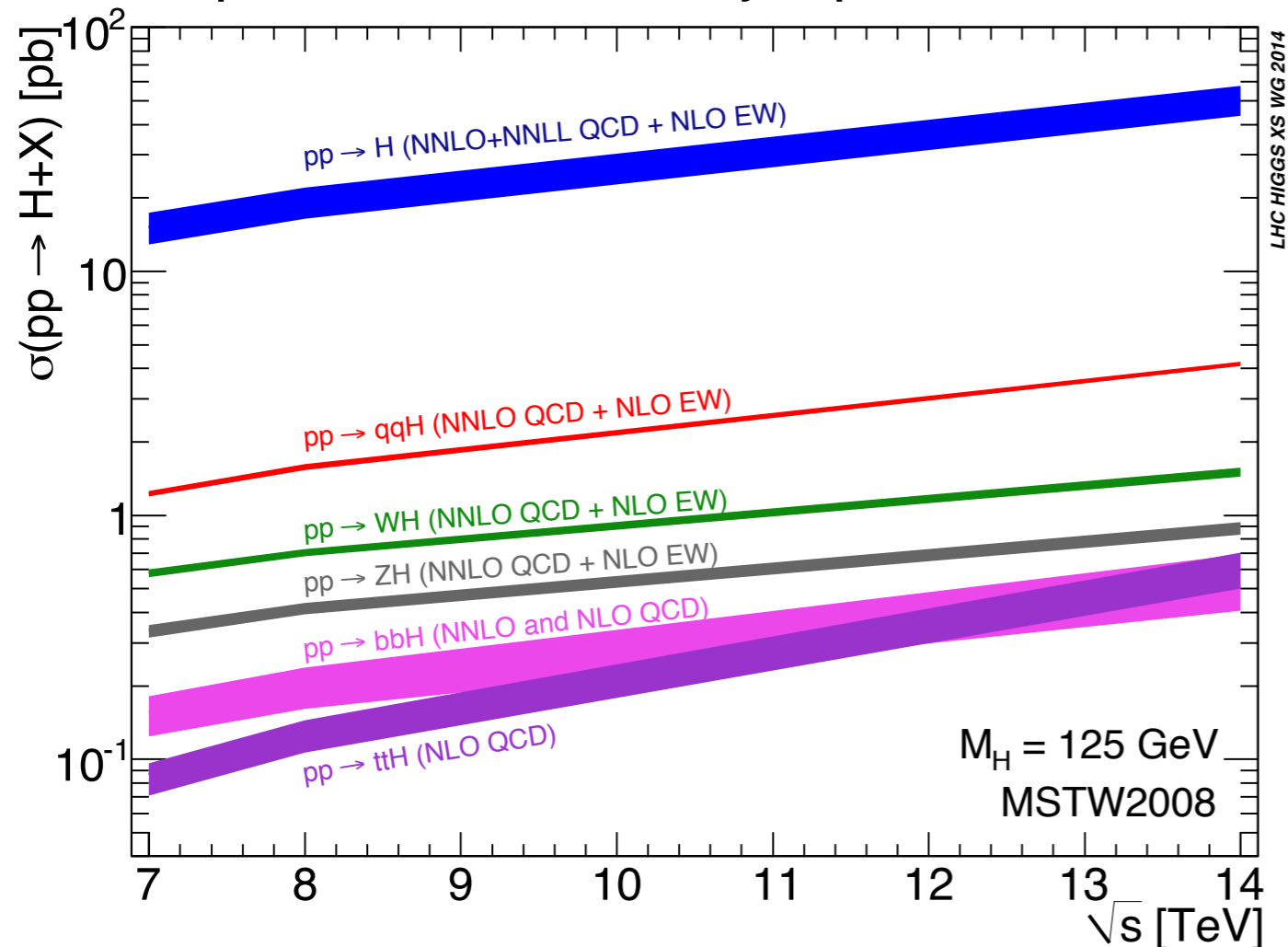
- Detector upgrades foreseen:
 - to cope with radiation damage and pileup
 - aim to maintain or enhance physics performance
 - trigger upgrades (finer granularity, additional levels, track-trigger ...) to keep thresholds similar to today for large acceptance for Higgs boson decays

HL-LHC Higgs boson perspective studies

- CMS: simple rescaling of Run1 yields and errors in 2 scenarios
 - scenario 1: uncertainties as in Run1
 - scenario 2: theory uncertainties * 0.5; experimental syst. $\sim 1/\sqrt{\text{lumi}}$
 - underlying assumption: future upgrade to provide same level of detector and trigger performance as in 2012
- ATLAS: extrapolations of yields and differential shapes using truth-level distributions “smeared” with parametrisations of efficiencies and resolutions vs μ from full simulations based on HL-LHC detector Lol (see talks by R. Polifka & T. Scanlon)
 - basic reoptimisation to cope with the effects induced by event pile-up, room for further improvement
 - usually similar systematic uncertainties (theory and experimental) assumed
 - some results w/o theory uncertainties are also quoted

Higgs boson physics @ HL-LHC

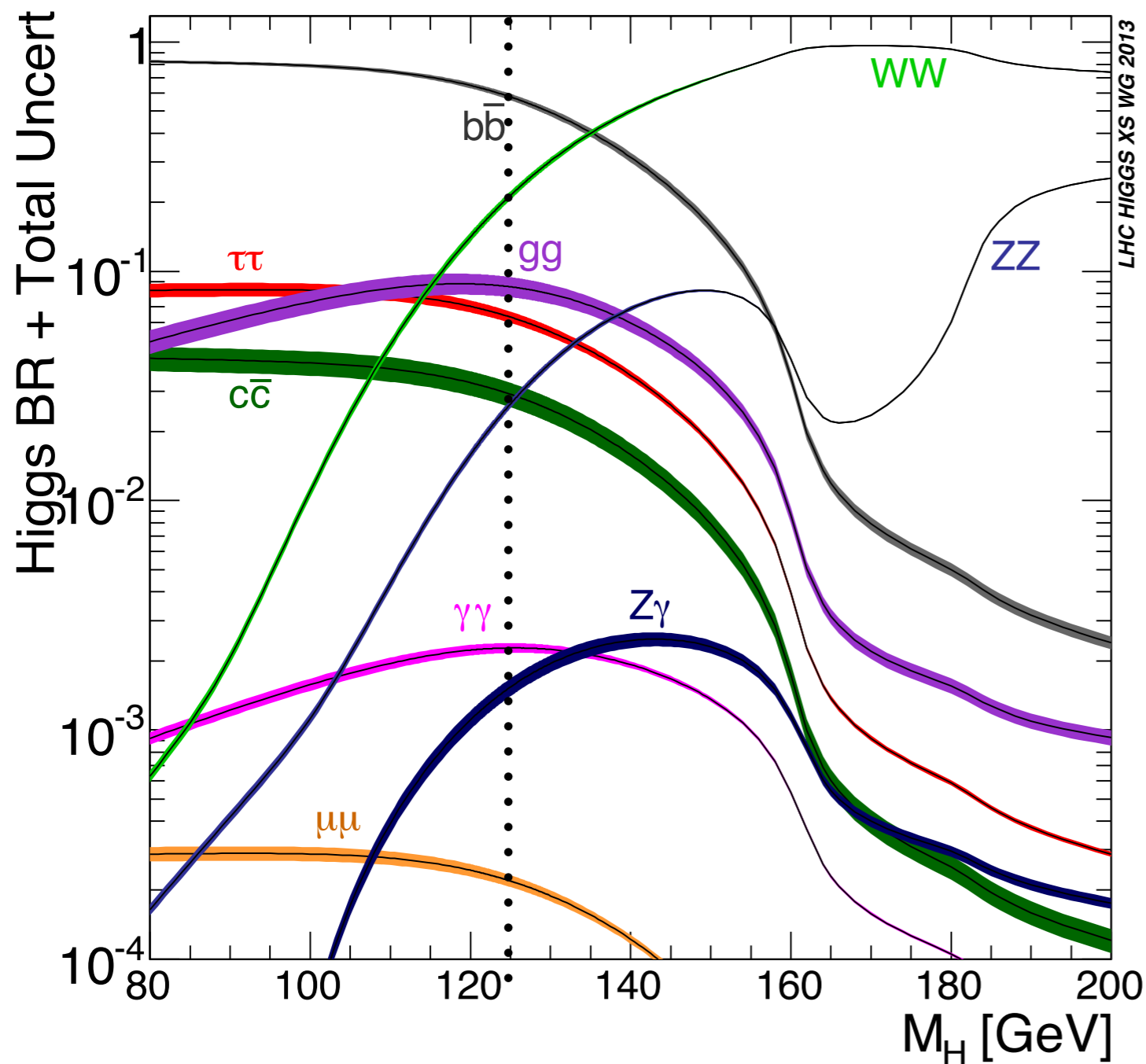
- Increased luminosity (x150) and cross-section (x2.6) wrt 8 TeV lead to 170M (~400x more than 2012) Higgs bosons produced
- >1M produced in all major production modes



	$\sigma(14\text{TeV})/\sigma(8\text{TeV})$
$gg \rightarrow H$	2.6 ($M_X = M_H$)
$qq \rightarrow qqH$	2.6 (probes high M_X)
$qq \rightarrow VH$	2.1 ($M_X = M_V + M_H$)
$gg \rightarrow ttH$	4.7 (phase space + M_X)

- The HL-LHC is a Higgs-boson factory
- Have access to rare(r) Higgs boson decays and production modes

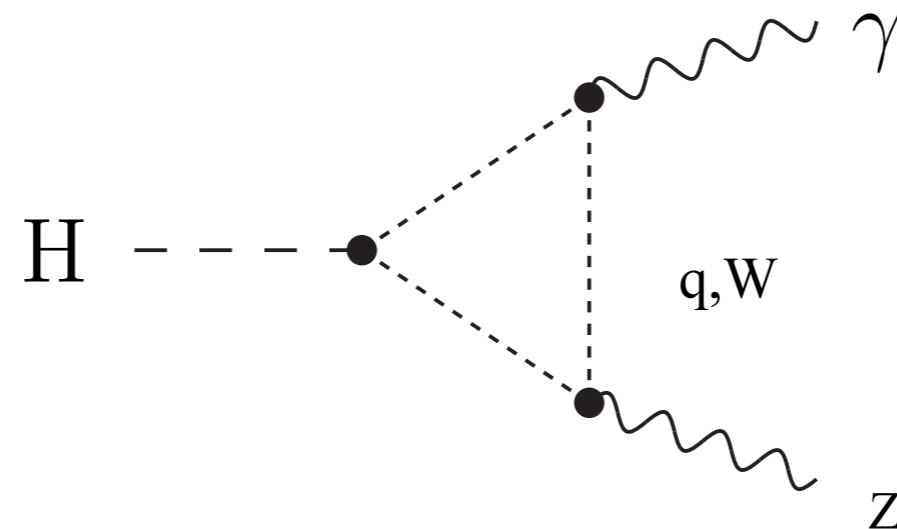
Higgs boson decays - current status



Channel	BR [%]	Results ATLAS & CMS	notes
bb	58	$\sim 2\sigma$	in VH; $\sim 3\sigma$ from Tevatron
WW	22	$\sim 5-6\sigma$	lvlv
gg	8.6	-	requires gluon tagging
$\tau\tau$	6.3	$\sim 4\sigma$	in VBF
cc	2.9	-	requires c-tagging*
ZZ	2.6	$\sim 7-8\sigma$	4l
$\gamma\gamma$	0.23	$\sim 5-6\sigma$	
$Z\gamma$	0.15	$< \sim 10xSM$	
$\mu\mu$	0.022	$< \sim 7xSM$	

- Will present perspectives for $H \rightarrow Z\gamma$, $H \rightarrow \mu\mu$, and how to possibly access to the Hcc coupling (circumventing *), as well as rare production in FCNC $t \rightarrow qH$ decays, for a 125 GeV SM Higgs boson

$H \rightarrow Z\gamma \rightarrow ll\gamma$



- Loop-induced decay \Rightarrow sensitive to BSM particles
- Diagrams for $H \rightarrow \gamma\gamma$ also induce $H \rightarrow Z\gamma$, but opposite not always true
 - could be enhanced wrt SM while $\mu(H \rightarrow \gamma\gamma) \sim 1$ (e.g. composite models)
- Not a “rare” decay by itself ($BR_{Z\gamma} \sim 0.65 \cdot BR_{\gamma\gamma}$), but due to $BR(Z \rightarrow ll) \sim 6.7\%$ ($l=e, \mu$) to enhance S/B (huge γ +jet bkg in hadronic final state)
- Signature: 2 same-flavor, opposite-sign isolated leptons ($m_{ll} \sim m_Z$) + 1 isolated photon ($m_{ll\gamma} \sim m_H$)
- Large bkg from SM $Z+\gamma$ and Z +jets, $S/B \sim 0.3\%$

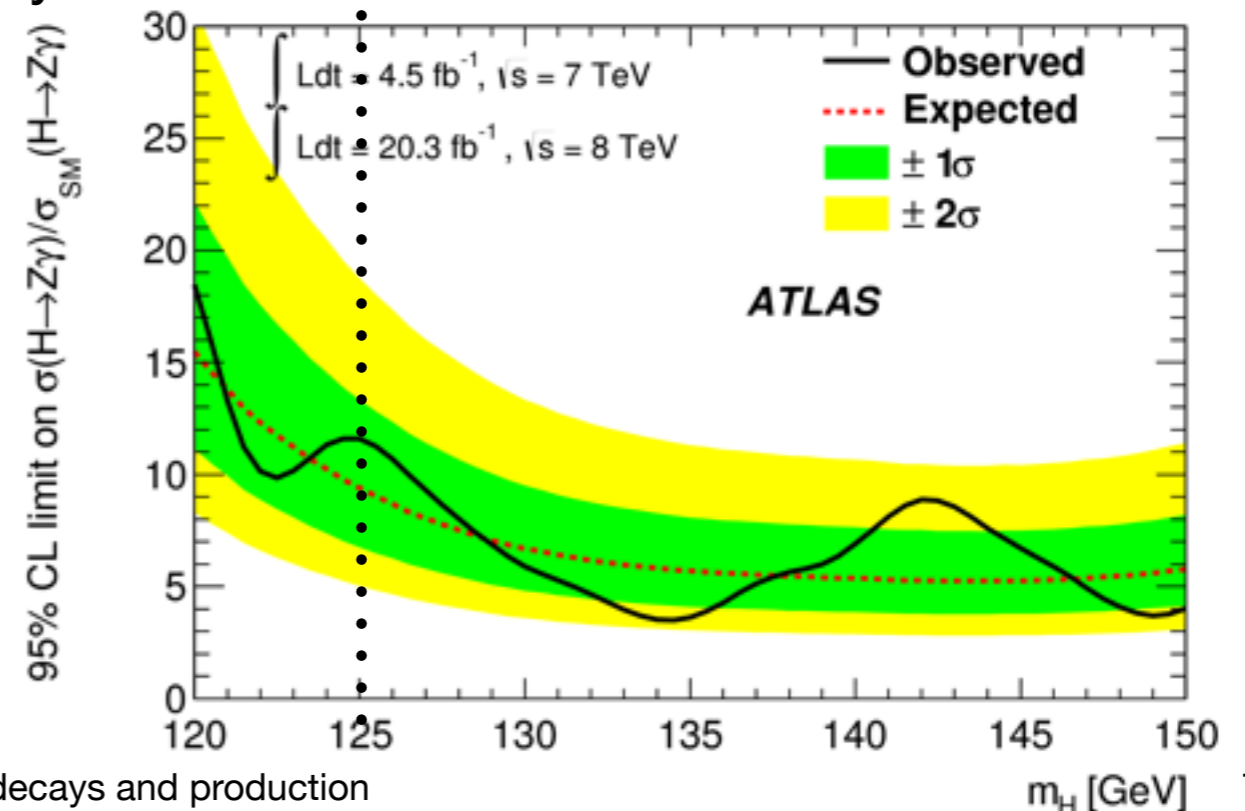
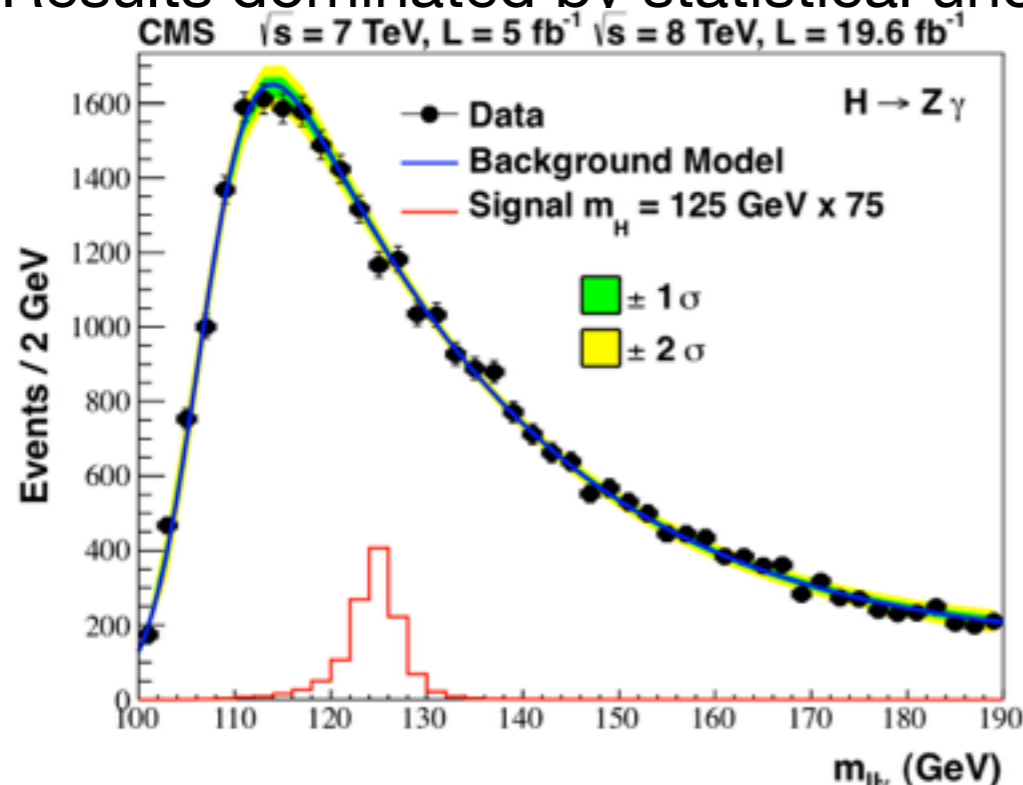
H → Zγ → llγ: Run1 analyses

ATLAS: *PLB 732 (2014) 8-27*

CMS: *PLB 726 (2013) 587-609*

	p_T^ℓ [GeV]	p_T^γ [GeV]	$\Delta R_{l\gamma}$	$m_{ll\gamma}$ [GeV]	m_{ll} [GeV]	categories for each l, \sqrt{s}
ATLAS	>10-15	>15	>0.3	115-170	>81	2 or 3 based on $ \Delta\eta^{Z\gamma} $ and p_{Tt}
CMS	>10-20	>15 >15/110 $m_{ll\gamma}$	>0.4	100-190	>50 >185- $m_{ll\gamma}$	1 dijet-like + 4 based on $ \eta^l $, $ \eta^\gamma $, γ conversion

- $\Delta R_{l\gamma}$, m_{ll} and $m_{ll\gamma}$ cuts suppress FSR and $H \rightarrow \gamma\gamma^* \rightarrow ll\gamma^*$
- MVA e, γ energy regression (CMS), m_Z constraint (ATLAS) yield $\sigma_m/m \sim 1.5\%$
- Category-based analysis improves sensitivity by 20-40%
- $A^*\epsilon \sim 30\%$, expected signal yield ~ 15 per experiment
- S+B fit to $m_{ll\gamma}$ in data. No significant excess $\Rightarrow \mu (= \sigma^*BR/\sigma_{SM}^*BR_{SM}) < \sim 10$ @ 125 GeV
- Results dominated by statistical uncertainty

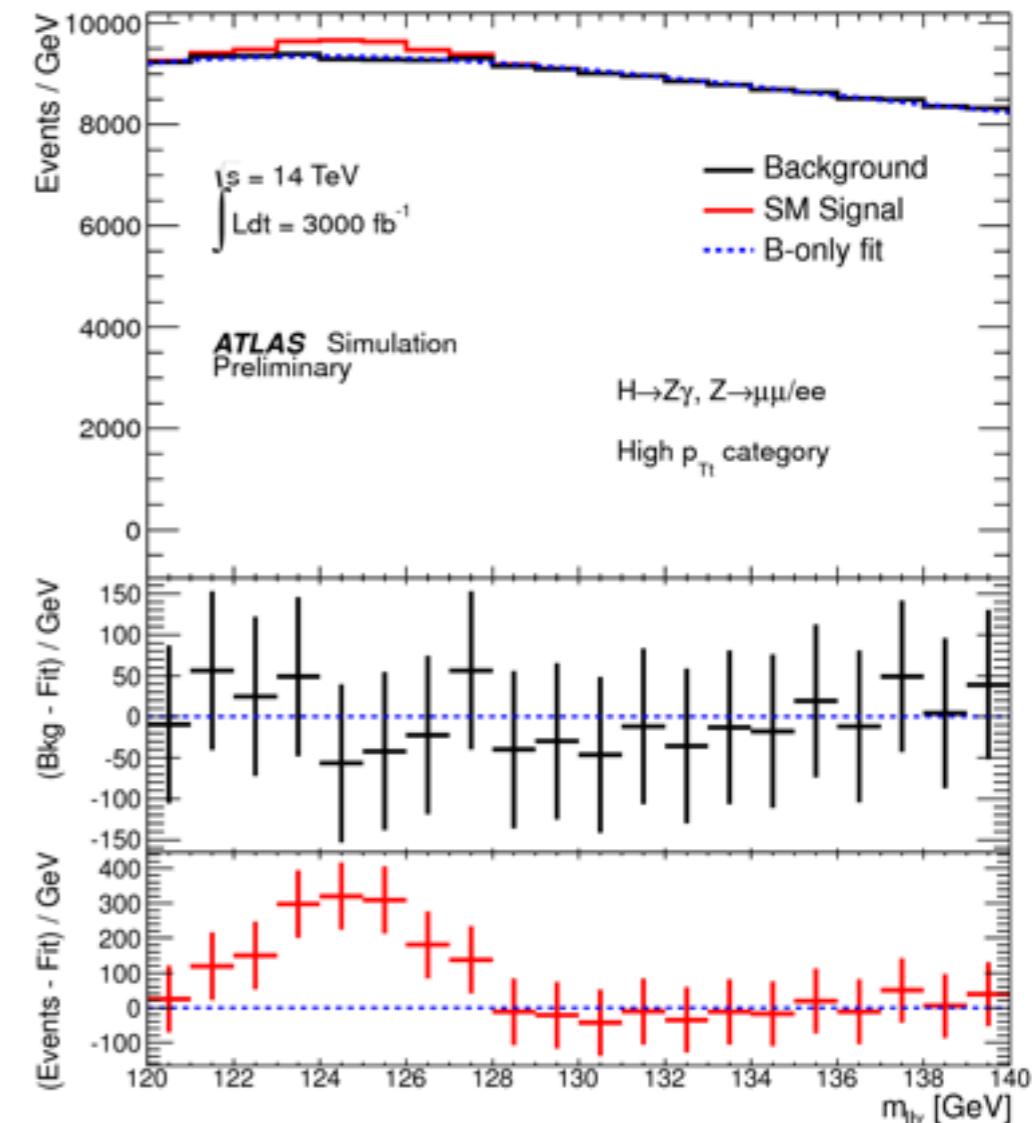


$H \rightarrow Z\gamma \rightarrow ll\gamma$: perspectives

ATL-PHYS-PUB-2014-006

arXiv:1307.7135

- ATLAS:
 - signal: “smeared” ggF & VBF (Powheg, $>250 \text{ ab}^{-1}$), assume similar efficiency for other production modes
 - bkg: smeared $Z+\gamma$ (Sherpa, 4.5 ab^{-1}), assume same shape for $Z+\text{jets}$
 - assume di-lepton (15 GeV) and single-lepton (25 GeV) triggers
 - bkg shape normalised to yield(data, 8TeV) * scale factor(14 TeV/8 TeV)
 - luminosity: 150
 - xsection: 1.82
 - ϵ : 59%, mostly due to not-reoptimised γ -ID
 - signal from fit to $m_{ll\gamma}$ (reoptimised fit range and function), **$\sim 3\text{k events}$**
 - **expected $p_0=3.9\sigma$; $\sigma_\mu=0.30$ (0.25 stat, 0.17 syst); 0.27 w/o theory errors**
- CMS: scaling Run1 yields in 2 scenarios
 - **$\sigma_\mu=0.24$ in scenario 1** (uncertainties as in Run1)
 - **$\sigma_\mu=0.20$ in scenario 2** (theory uncertainties*0.5; experimental syst $\sim 1/\sqrt{\text{lumi}}$)



$H \rightarrow \mu\mu$

- Only channel for measuring Yukawa couplings to 2nd gen. fermions^(*)
- Can be combined with $H \rightarrow \tau\tau$ to test directly if the coupling of the new boson is proportional to the lepton mass
- May be enhanced in some BSM models (MSSM)
- Signature: 2 opposite-sign, isolated muons
 - $m_{\mu\mu} \sim m_H$, good mass resolution ($\sim 1.5\text{-}2.5\%$)
- Huge bkg from Drell-Yan. Some bkg also from $t\bar{t}$ and WW , can be suppressed with requirement on E_T^{miss}

^(*) *but see later slides on Hcc coupling*

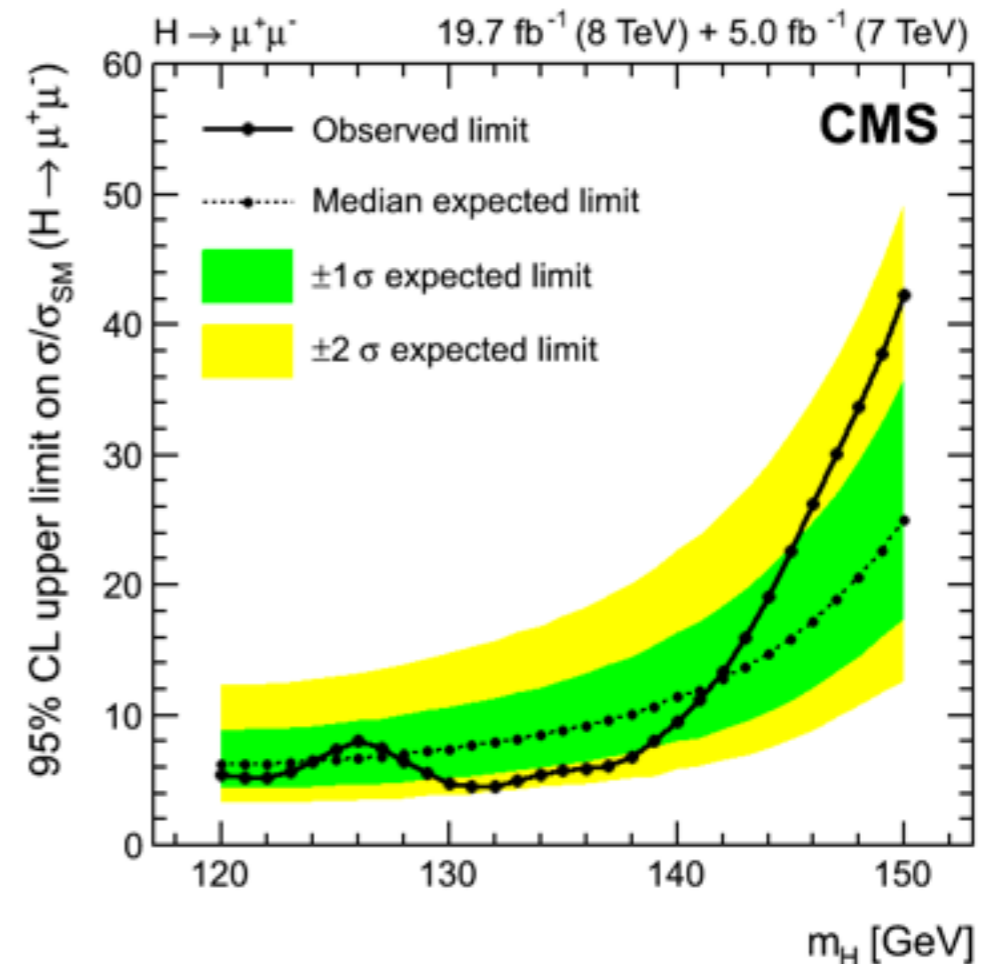
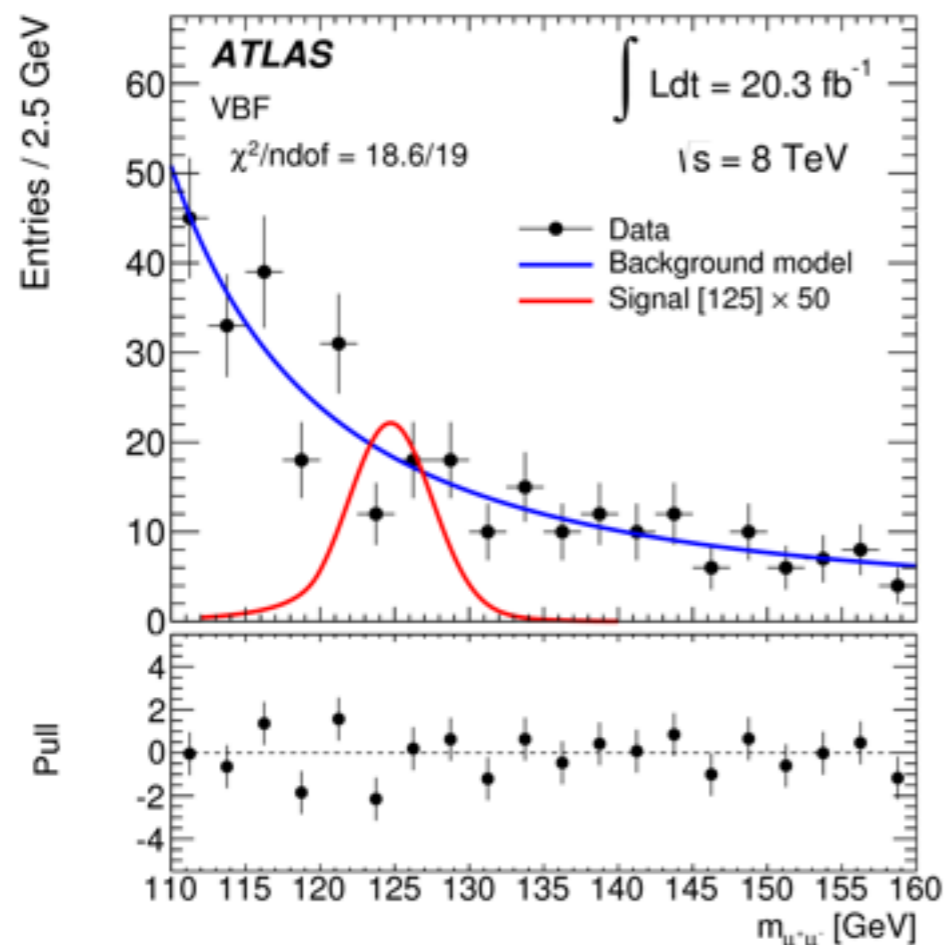
H → μμ: Run1 analyses

ATLAS: *PLB 738 (2014) 68*

CMS: *PLB 744 (2015) 184*

	trigger μ	offline μ	jets	E _T ^{miss}	m _{μμ} [GeV]	categories
ATLAS	p _T >24 GeV, η <2.4	p _T >25,15 GeV η <2.5, iso, from PV	p _T >25(30) GeV η <2.4 (2.4-4.5)	<80 GeV	110-160	1 dijet (VBF-like) + 6 based on p _T ^{μμ} and η ^μ
CMS	p _T >24 GeV, η <2.1	p _T >25,15 GeV η <2.1, iso, from PV	p _T >30 GeV η <4.7	-	110-160	3 dijet + 12 based on p _T ^{μμ} and η ^μ

- A*ε ~ 50-55%, expected S ~ 50 (per experiment), S/B~0.4%
- Signal from S+B fit to m_{μμ} in data. No significant excess ⇒ μ < ~7 @ 125 GeV
- Results dominated by statistical uncertainty

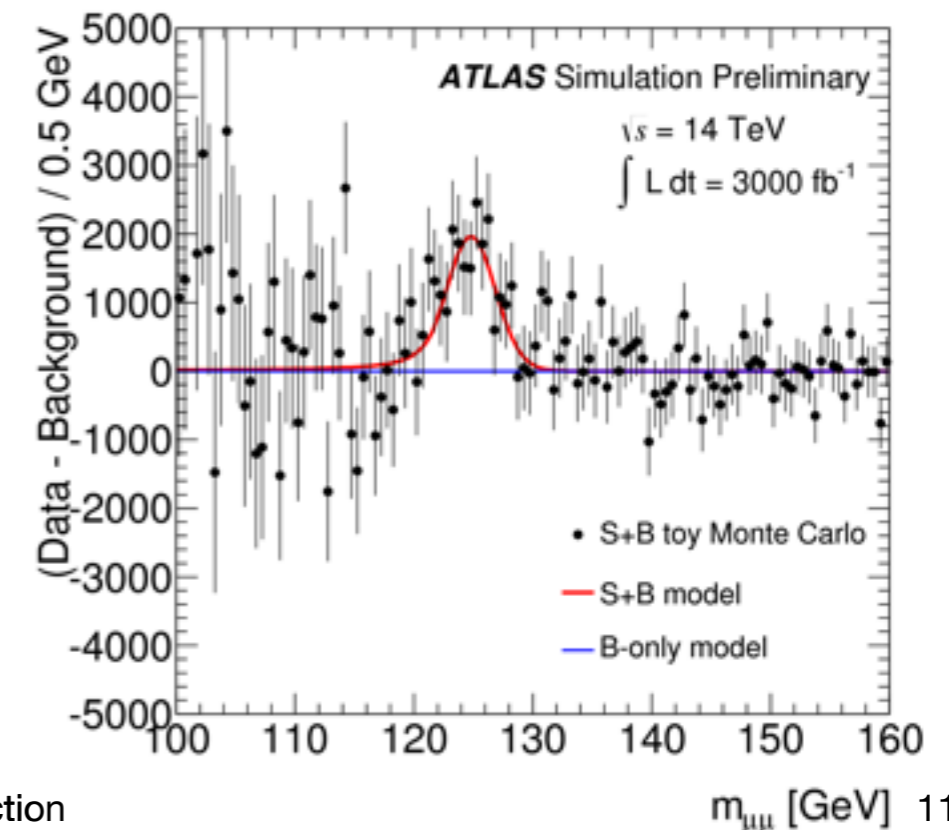
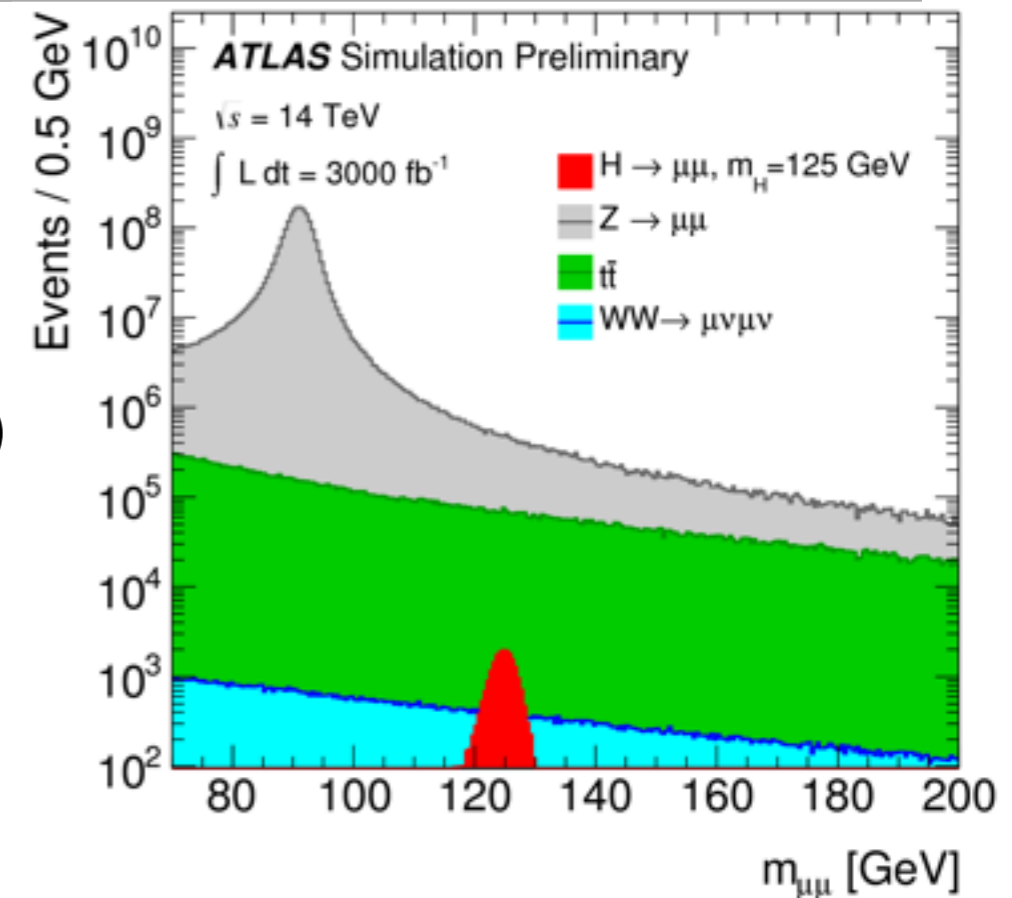


H $\rightarrow\mu\mu$: perspectives

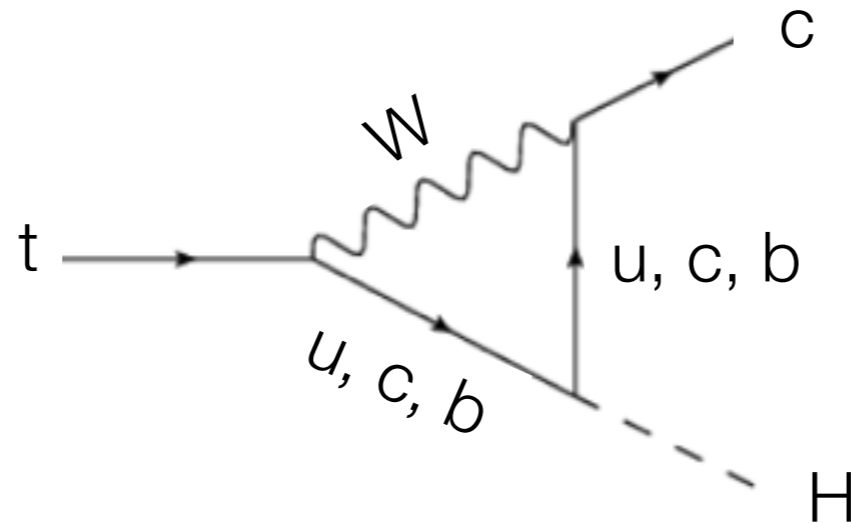
ATLAS: [ATL-PHYS-PUB-2013-014](#)

CMS: [arXiv:1307.7135](#)

- ATLAS:
 - signal: smeared Powheg+Pythia gluon-fusion sample, assume similar efficiency for other production modes
 - bkg: smeared Z+jets (Alpgen), tt, WW (MC@NLO)
 - does not exploit improved resolution from Phase-II inner tracker nor improved sensitivity from event categories used in Run1 publication
 - single muon trigger, $p_T > 25$ GeV, $|\eta| < 2.4$
 - 2 OS muons with $p_T > 25, 20$ GeV, $|\eta| < 2.5$, isolated in the tracker
 - signal from fit to $m_{\mu\mu}$ (BW+exp), **$\sim 17k$ events**
 - **expected $p_0 = 7.0\sigma$, $\sigma_\mu = 0.18$; $\sigma_\mu = 0.14$ w/o theory errors (mostly stat: syst ~ 0.04 from bkg model)**
- CMS: scaling Run1 yields
 - **$\sigma_\mu = 0.20$ in scenario 1**
 - **$\sigma_\mu = 0.14$ in scenario 2**



$t \rightarrow qH$



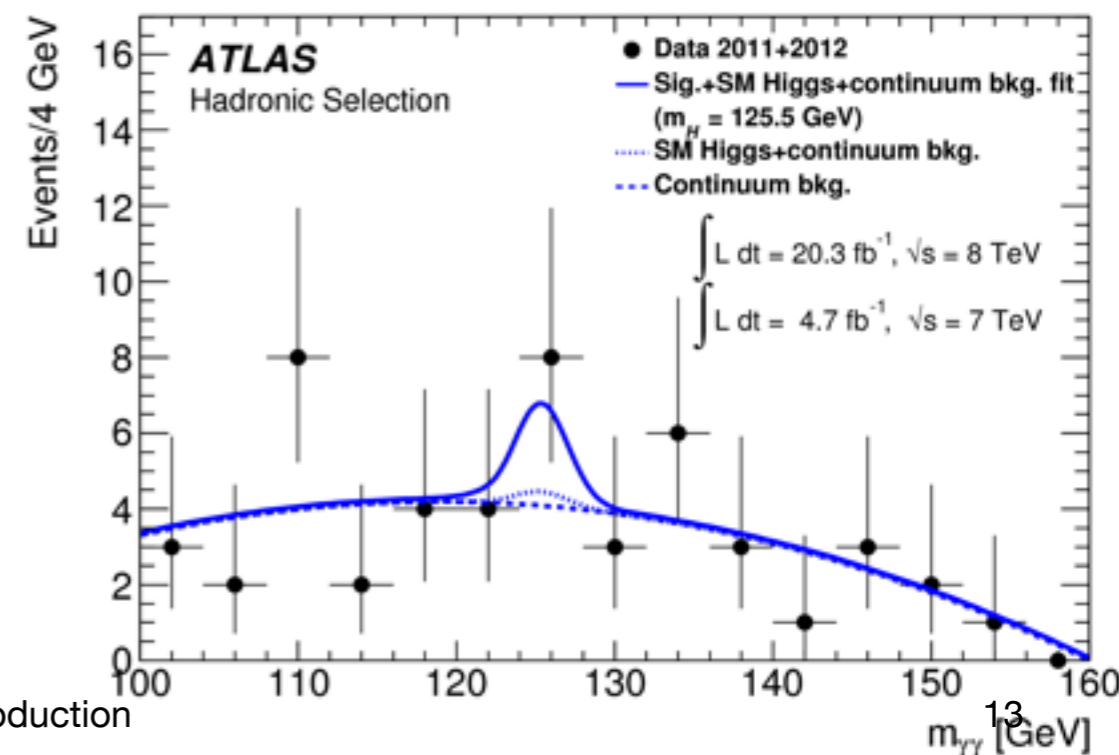
- strong GIM suppression in SM: $BR(t \rightarrow cH) \sim 3 \cdot 10^{-15}$
- BR up to 10^{-5} in various BSM models (and up to $1.5 \cdot 10^{-3}$ in 2HDM type III)
- searches performed both by ATLAS and CMS in Run1
 - ATLAS: $H \rightarrow \gamma\gamma$ [JHEP06\(2014\)008](#) [dedicated analysis]
 - expected limit: $BR < 0.51\%$ @95% CL
 - CMS: $H \rightarrow \gamma\gamma$ and multileptons ($WW^*/ZZ^*/\tau\tau$) [HIG-13-034](#) [reinterpretation of SM and BSM Higgs searches]
 - expected limit: $BR < 0.65\%$ @95% CL (0.81% from $\gamma\gamma$ only)
- HL-LHC studies by ATLAS ([ATLAS-PHYS-PUB-2013-012](#))
 - same final state and analysis as Run1: expected limit $1.5-1.7 \cdot 10^{-4}$
- see also talk by N. Rompotis on BSM Higgs searches

$t \rightarrow qH, H \rightarrow \gamma\gamma$: ATLAS Run1 analysis

JHEP06 (2014) 008

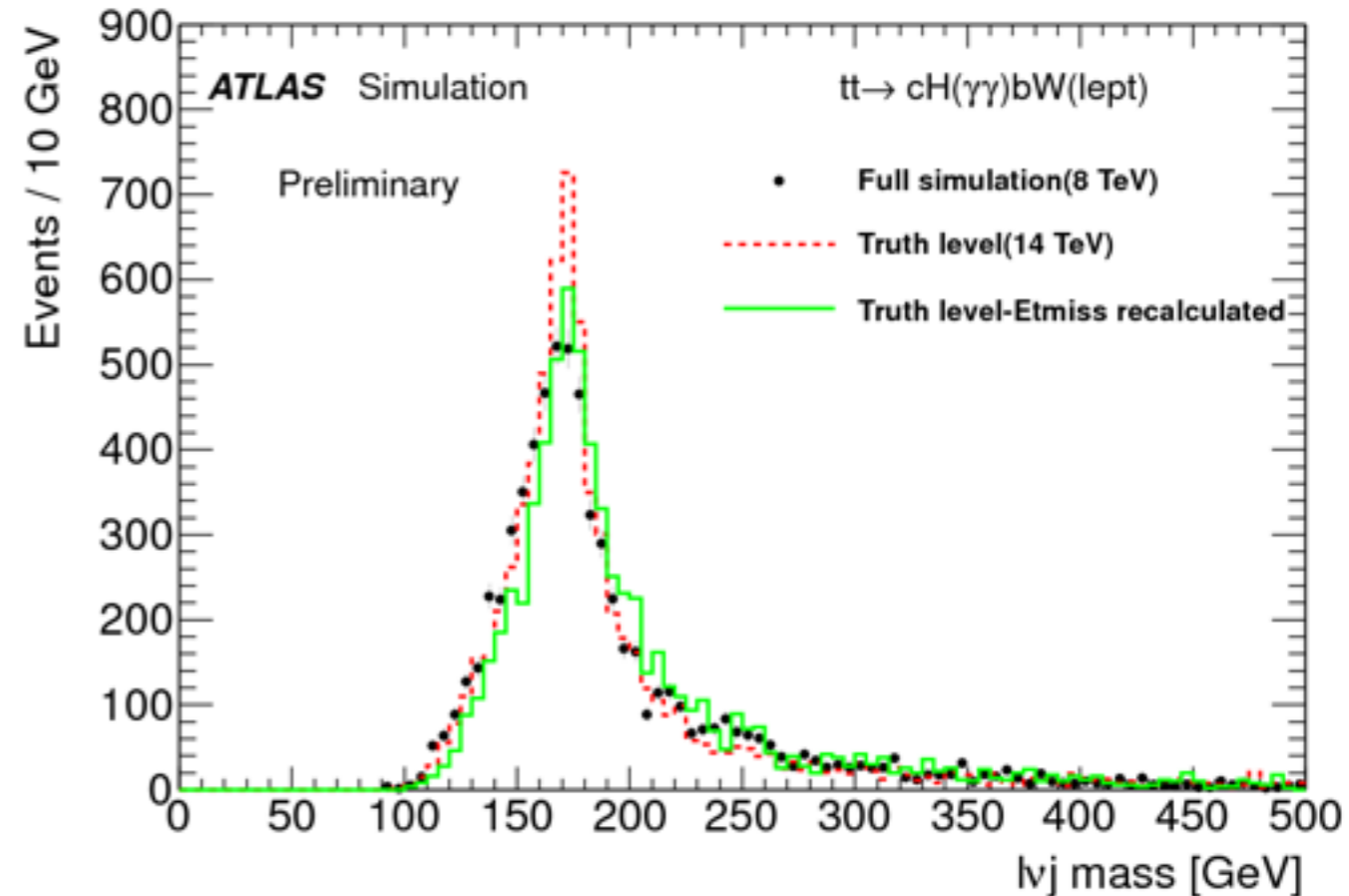
- Signal: $tt, t_1 \rightarrow qH \rightarrow j\gamma\gamma, t_2 \rightarrow Wb \rightarrow jjb$ (had), lvb (lep), $m_{\gamma\gamma} \sim m_t$ and m_{jjj} or $m_{lvj} \sim m_t$
 - Protos+Pythia (LO)
- SM backgrounds:
 - non-Higgs: dominated by $\gamma\gamma$ +jets [Sherpa, data $m_{\gamma\gamma}$ sidebands]
 - Higgs: dominated by ttH [Pythia], small
- Selection:
 - 2 high- p_T , isolated γ , also for trigger (as in baseline $H \rightarrow \gamma\gamma$ analysis)
 - jets: $p_T > 25(30)$ GeV for $|\eta| < (>) 2.4$, not from PU
 - b-tagging: $\epsilon_b = 70\%$, $\epsilon_c = 20\%$, $\epsilon_l < 1\%$
 - leptons: isolated, $p_T^e > 15$ GeV, $p_T^\mu > 10$ GeV
 - MET: all identified objects + clusters of calo cells not associated to any object
- $BR < 0.79\%$ (0.51% expected) @95% CL

	Hadronic	Leptonic
p_{T^γ} [GeV]	>40,30	>40,30
leptons	0	1
jets	≥ 4	≥ 2
b-jet	≥ 1	≥ 1
m_T		>30 GeV
m_1 [GeV]	156-191	156-191
m_2 [GeV]	130-210	135-205
ϵ	4%	1.3%
N_{exp}	39	1
N_{obs}	43	1



- Same analysis as in Run1, except for two pile-up related changes

- minimum jet p_T raised from 25/30 GeV to 35/50 GeV
 - only 0.4 pileup jets/evt above 40 GeV for $\mu=140$ from full-sim
- MET (lepton channel): computed only from lepton, two photons and jets passing the p_T cuts



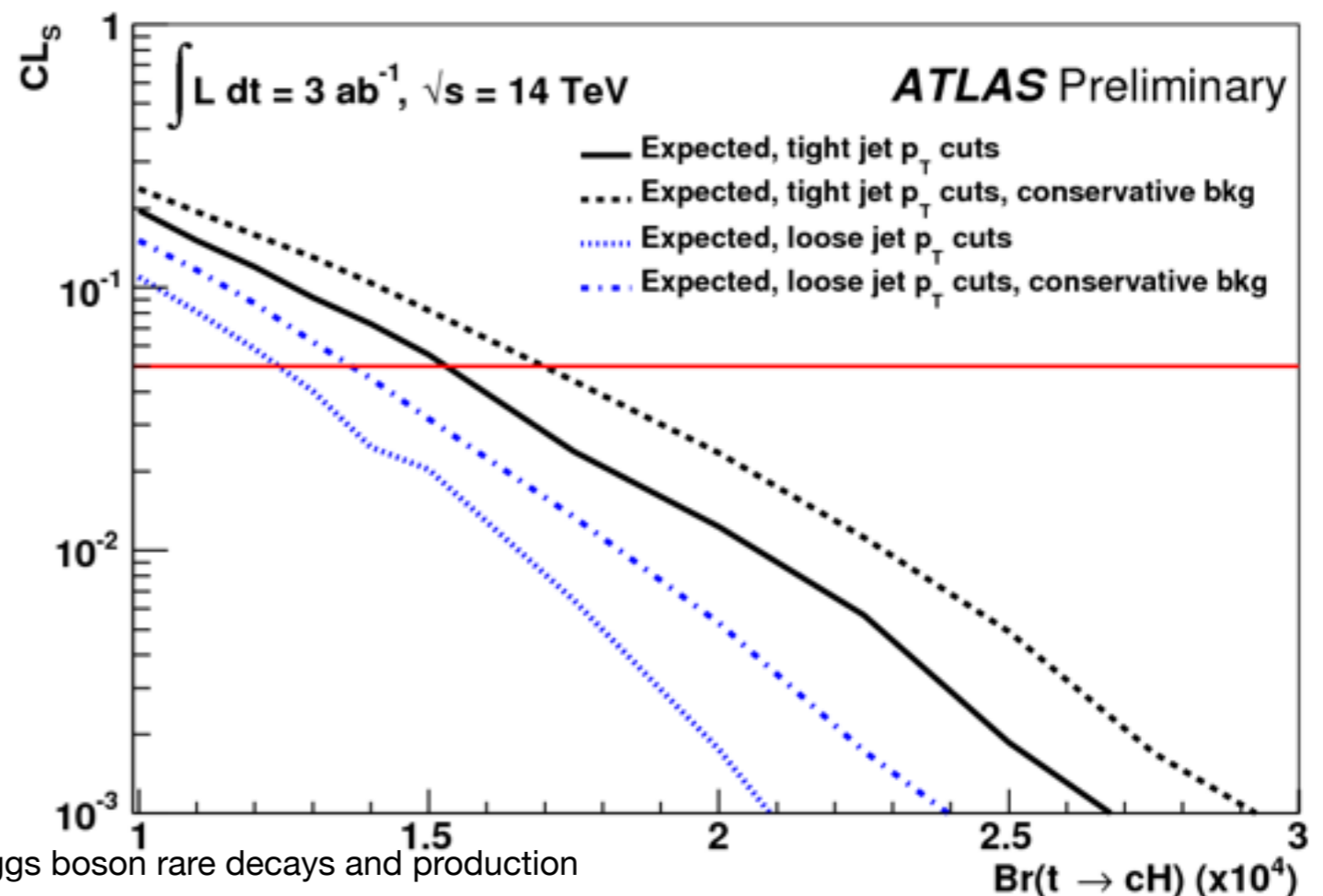
- Scale 8 TeV data (non-Higgs bkg) and full-sim (signal, ttH) yields by luminosity, xsection, acceptance, efficiency ratios (14TeV / 8 TeV)
 - non-Higgs bkg: assume 100% $\gamma\gamma j$ for xsec and $A \cdot \epsilon$ ratios
 - acceptance ratio from truth-particle-level MC. Impact of tighter jet p_T cuts
 - efficiency: -14% from photon isolation. b-tagging performance in full-sim MC similar to Run1 thanks to improved tracker

$t \rightarrow qH$, $H \rightarrow \gamma\gamma$ ATLAS projections: results

- 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		
			$A^*\epsilon$ factor	evts	evts in SR	$A^*\epsilon$ factor	evts	evts in SR
tt, $t \rightarrow qH$	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
$\gamma\gamma j$	150	2.2	0.18 ± 0.03	2320	350	0.57 ± 0.05	163	25

- Expected limit** on BR($t \rightarrow qH$) at 95% CL if no signal:
 - $1.5 \cdot 10^{-4}$ w/ nominal (bkg) yields
 - $1.7 \cdot 10^{-4}$ w/ bkg yields increased by 1σ
- Add more Higgs final states?

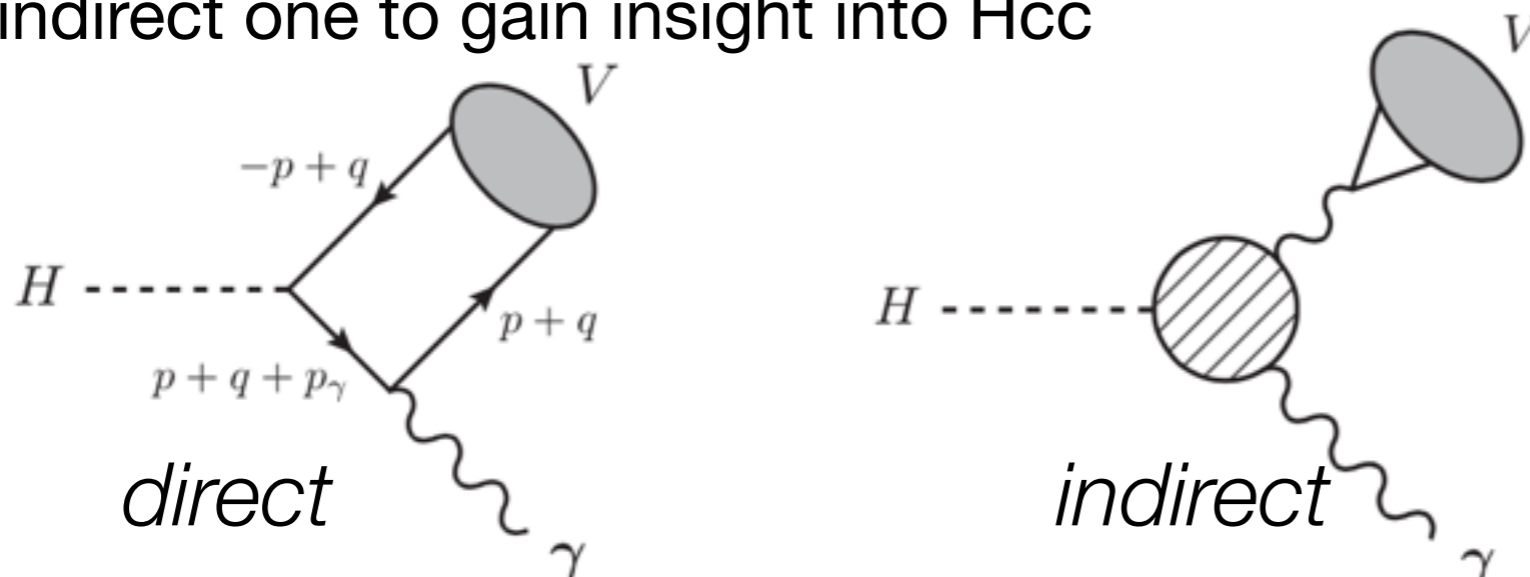


$H \rightarrow J/\psi \gamma$: accessing the Hcc coupling? *PRD 88, 053003 (2013)*

- Hcc another test of the coupling to 2nd generation fermions
- In some models (2HDM..) Hcc alone can be enhanced up to few times wrt SM
- $BR(H \rightarrow cc) \sim 2.9\%$ - sufficient statistics if decent S/B, but huge QCD bkg and poor c-tagging performance
 - ATLAS SUSY search with pair of c-quarks in final state:

$\epsilon(\text{c-jet})$	$1/\epsilon(\text{b-jet})$	$1/\epsilon(\text{light-jet})$
20%	8	200
95%	2.5	~ 1

- $B \rightarrow J/\psi \gamma$: exploit interference between direct (Hcc mediated) amplitude and indirect one to gain insight into Hcc



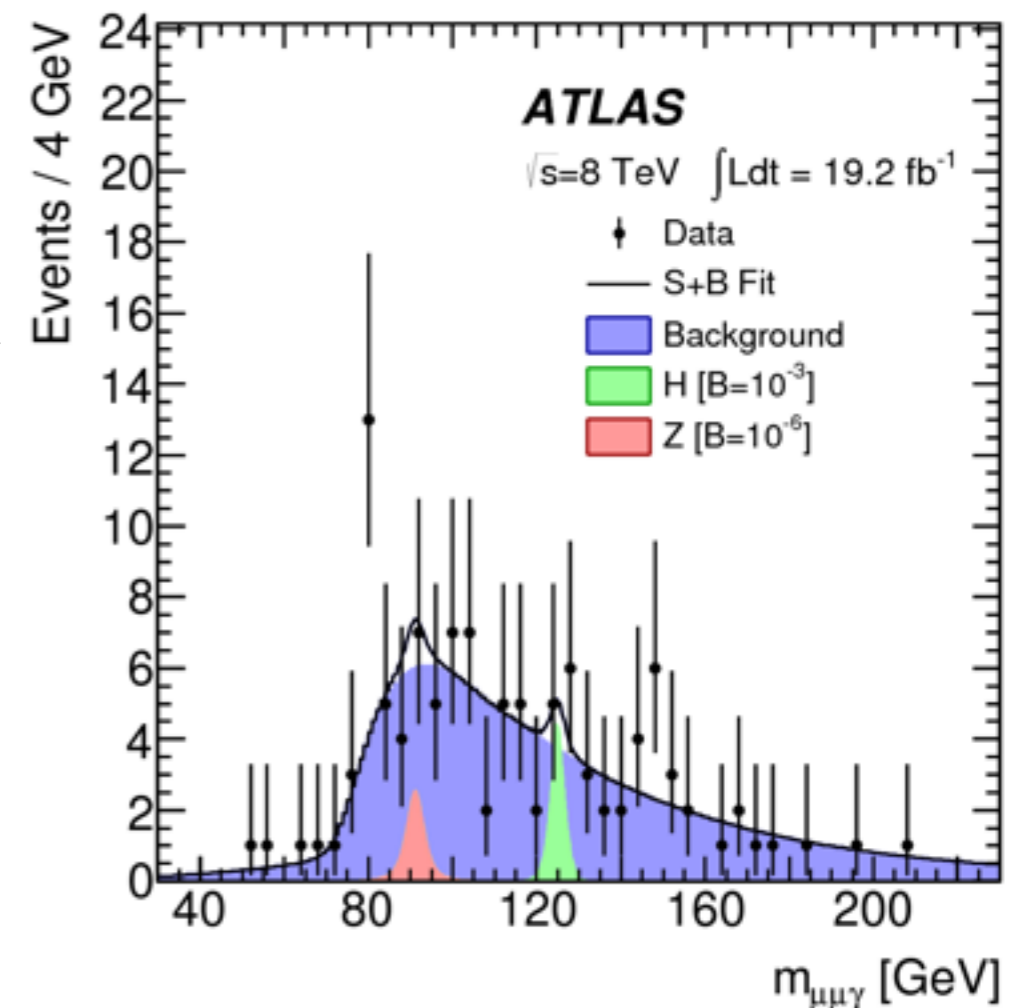
$BR(\text{direct}): 5 \cdot 10^{-8}$
 $BR(\text{indirect only}): 3.3 \cdot 10^{-6}$
 $BR(\text{tot}): 2.5 \cdot 10^{-6}$
 ➔ -30% from interference with Hcc -mediated diagram

- Reduce large QCD bkg selecting $J/\psi \rightarrow ll$ ($l=e,\mu$): BR=5.9% for each flavor
- Signature: one high- p_T lepton pair with $m_{ll} \sim m(J/\psi)$, back-to-back wrt high- $p_T \gamma$
- **About 25 signal events per experiment if $A \cdot \epsilon \sim 50\%$**
- Bkg from $H \rightarrow ll\gamma$ in $m_{ll} = m(J/\psi) \pm 50$ MeV = $1.5 \cdot S$
- At limit of observability (ATLAS+CMS combined) if $B/S < 10$
 - assuming similar sensitivity for $ee+\gamma$ and $\mu\mu+\gamma$ final states
 - optimistic? boosted J/ψ means close-by leptons, $dR \sim 0.15$, and partially overlapping clusters \Rightarrow standard electron reconstruction needs to be revisited, as well as triggers..

H \rightarrow J/ ψ γ : Run1 measurements

ATLAS: *PRL* 114 (2015) 121801

- $\sqrt{s}=8$ TeV, only muon channel exploited
- Trigger: $p_T^\mu > 18$ GeV, $|\eta^\mu| < 2.4$
- Selection:
 - 2 isolated μ , $p_T > 20, 3$ GeV; isolated γ , $p_T > 36$ GeV
 - $|m_{\mu\mu} - m(J/\psi)| < 0.15$ (0.20) GeV for central (non-central) μ 's
 - $p_T^{\mu\mu} > 36$ GeV
 - $L_{xy}/\sigma(L_{xy}) < 3$
 - $\Delta\phi(\mu\mu, \gamma) > 0.5$
 - $A^*\epsilon = 22\%$
- 4 categories based on $|\eta^\mu|$ (B/E) and photon conversion status (U/C)
- Main bkg: inclusive J/ ψ + jet $\rightarrow\gamma$ misID
- In 125 ± 2.5 GeV $m_{\mu\mu\gamma}$ window, B/S \sim 330
- **Observed upper limit: BR $<1.5e-3$ (600xSM)**
- **\rightarrow Very challenging even at HL-LHC!**



Conclusion

- HL-LHC a Higgs boson factory \Rightarrow possible to access rare Higgs boson decays and production modes
- Based on some preliminary studies
 - $\sim 4\sigma$ evidence of $H \rightarrow Z\gamma$ per experiment, possible to test models predicting $Z\gamma$ enhancements (composite Higgs)
 - $> 7\sigma$ observation of $H \rightarrow \mu\mu$, careful test of models with deviations in couplings to 2nd generation
 - can set limit on $t \rightarrow qH \sim 1.5 \cdot 10^{-4}$, constraining part of the phase space of extended Higgs boson sectors
 - few tens of events in $H \rightarrow J/\psi\gamma$, maybe some “direct” constraints on Hcc coupling possible but very challenging
- There’s room for further improvement and more refined studies

More details

Open questions

- What other channels we should try to search for and study in detail?
- What is the sensitivity we should aim for in order to set “interesting” constraints on the SM extensions?
- What are the ultimate theoretical uncertainties we should expect for these channels in ~ 2035 :
 - scale uncertainties: can we keep going to higher orders? is N3LO the end?
 - PDFs (gluon, in particular): How to improve? Photon data in PDF fits? Extract g from photon and jet data: NNLO calculations?
 - PS/UE: better tunes? NNLO generators for ggF and VBF?
 - $H \rightarrow Z\gamma$: uncertainty on non-resonant $H \rightarrow l\bar{l}\gamma$ contribution?
- Some points to be improved in the current studies:
 - further optimisation (for instance, in J/γ) for higher \sqrt{s}
 - $Z\gamma$: implement Run1-like Z-mass constraint
 - $\mu\mu$: use latest performance studies (ATLAS ITK resolution)
- Can we increase the acceptance keeping good S/B with detector extensions?

Performance assumptions (ATLAS)

- From full simulation of L0 baseline new tracker (ITK) for Phase-II, embedded into Run1 calorimeter and muon spectrometer:
 - significant impact on b-tagging, muon p_T resolution
 - detailed studies of jet/ E_T^{miss} performance
- Trigger:
 - rate projections assuming
 - L0+L1 hardware trigger (500 kHz @L0, 200 @L1)
 - full granularity in EM calo trigger
 - topological capabilities
 - track trigger (e, μ .. $\epsilon \sim 95\%$)
 - for signal, assume efficiencies as in Run1 (x track-trigger efficiency if applicable)

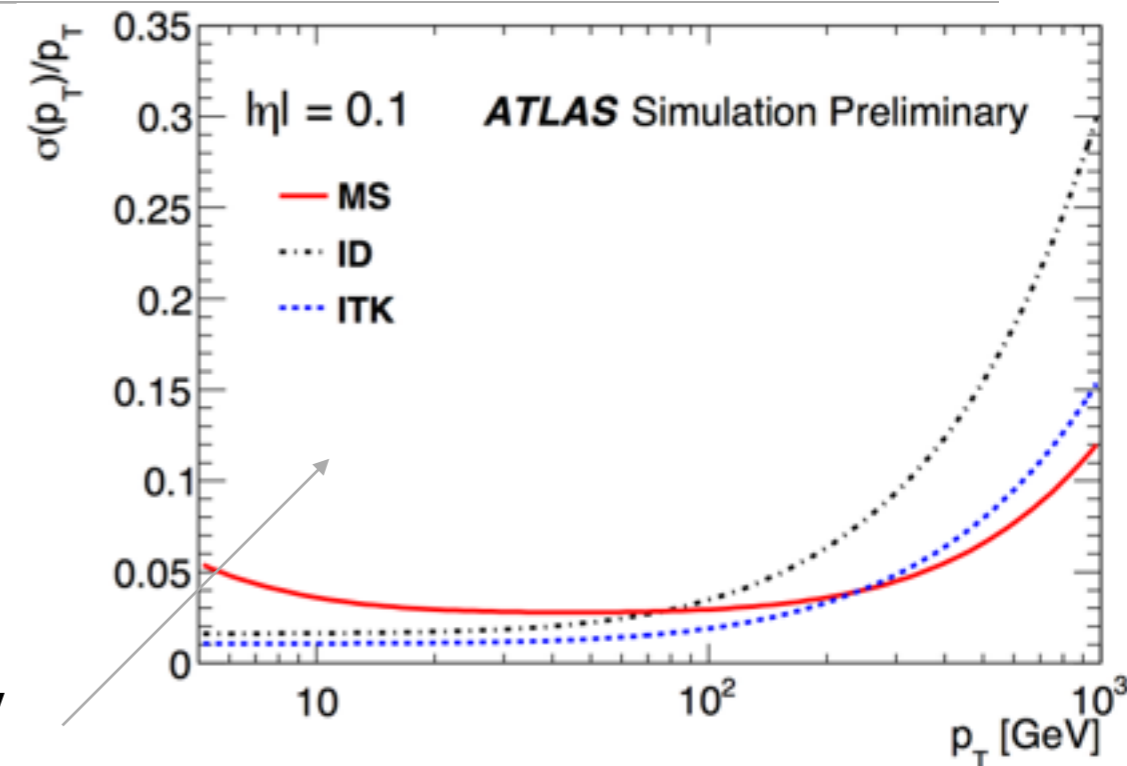
Performance assumptions (ATLAS)

- Photons:
 - triggers: single-photon: $E_T > 60$ GeV, multi-object: $E_T > 15$ GeV; $\epsilon \sim 100\%$
 - ID: assume reoptimised algo to give at $\langle \mu \rangle = 140$ similar efficiency and rejection of 2012 algo at $\langle \mu \rangle = 80$ and $\sqrt{s} = 14$ TeV; use $gg \rightarrow H \rightarrow \gamma\gamma$ and dijet MC
 - efficiency: plateau at $\sim 76\%$ above $p_T \sim 80$ GeV
 - jet mis-ID: $\sim 0.3\% \exp(-p_T/27.5 \text{ GeV})$, $p_T^\gamma/p_T^{\text{jet}} \sim 75\%$
- Electrons:
 - triggers: single-electron: $E_T > 25$ GeV, multi-object: $E_T > 15$ GeV; $\epsilon \sim 88\%$
 - ID: assume reoptimised algo (MVA) to give at $\langle \mu \rangle = 140$ similar efficiency and rejection of 2012 also (cut-based) on 2012 MC; use Zee and dijet MC
 - efficiency: plateau at $\sim 97\%$ (loose) or 85% (tight) at 50-60 GeV
 - jet mis-ID: $11\% e^{-p_T/30 \text{ GeV}}$ (loose), $0.5\% e^{-p_T/30 \text{ GeV}}$ (tight), $p_T^e/p_T^{\text{jet}} \sim 40\%$
 - energy resolution: assume 2012 values (pile-up affects sub-dominant noise term)
 - $30\%/E + 10\%(15\%)/\sqrt{E} + 1\%(1.5\%)$ for $|\eta| < (>) 1.4$

Performance assumptions (ATLAS)

- Muons

- triggers: single- μ : $p_T > 25$ GeV, multi-object: $p_T > 15$ GeV; $\epsilon \sim 70\%$ for $|\eta| < 1.05$, 86% for $1.05 < |\eta| < 2.4$
- reco*selection efficiency:
 - tight selection (high purity): $\epsilon \sim 54\%$ for $|\eta| < 0.1$, 97% for $0.1 < |\eta| < 2.5$
 - $\sigma(p_T)$: from full-sim, improved for $p_T < 100$ GeV



- Jets:

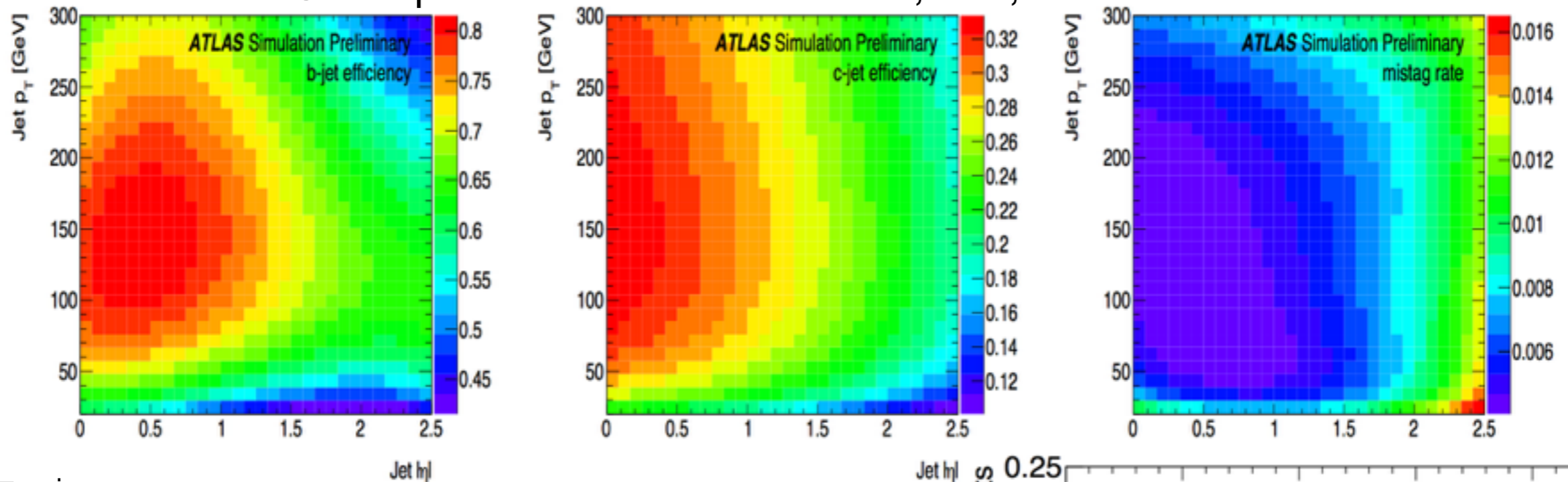
- p_T resolution: $N/p_T \oplus S/\sqrt{p_T} \oplus C$, only N affected by pile-up
 - $C=5\%$, $S=74-83\%$, $N = a(\eta)+b(\eta)*\mu$, $a \sim 3$, $b \sim 0.04$
- p_T threshold (left table): such that less than 1 PU jet in 10% or 1% of events
- reco efficiency (right table): from MC

Eta	10% (GeV)	1% (GeV)
0–2.1	60 (30)	80 (40)
2.1–2.8	50	80
2.8–3.2	50	80
3.2–4.5	30	50

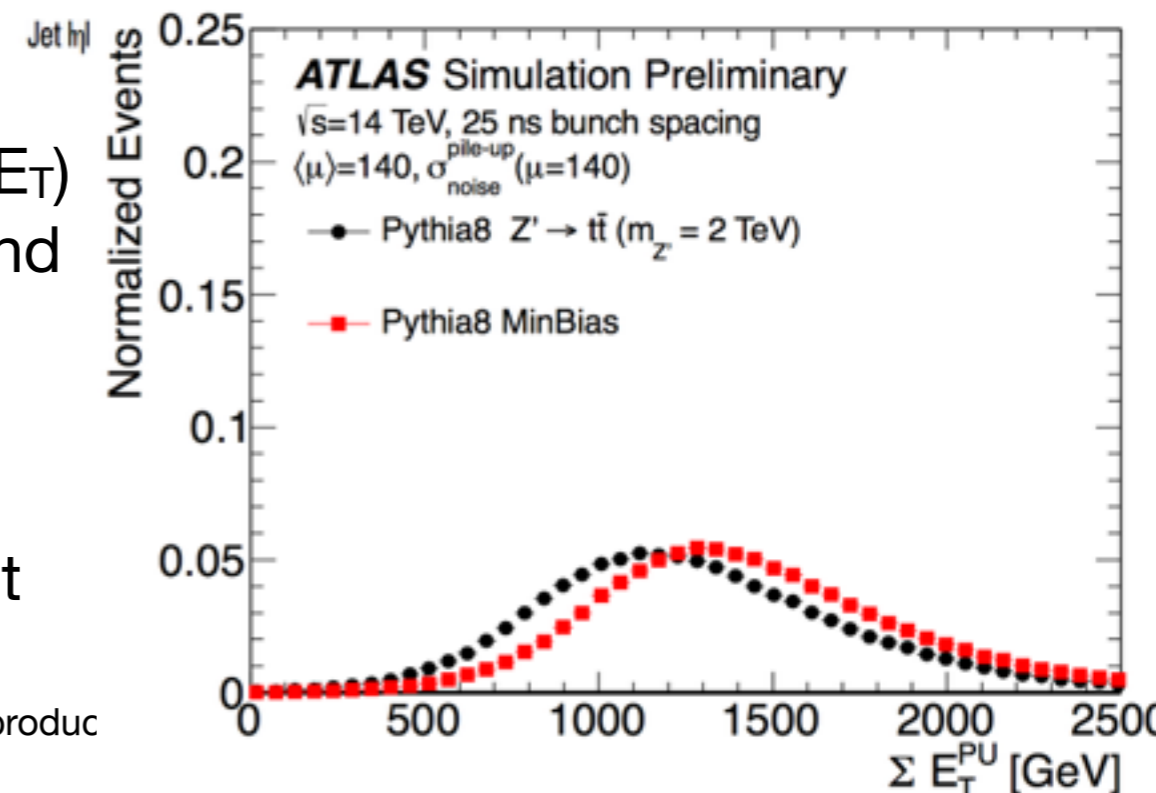
Jet p_T	eff
20-25 GeV	75%
30-35 GeV	80 %
50 GeV	>95%

Performance assumptions (ATLAS)

- b-tagging:
 - same algorithm used in Run1 (no reoptimisation of track selection, no tuning to exploit new tracker)
 - from $t\bar{t}$ MC samples at 14 TeV and $\mu=80, 140, 200$



- E_T^{miss} :
 - resolution vs ΣE_T derived from $Z' \rightarrow t\bar{t}$ (high ΣE_T) and minimum bias (low ΣE_T) MC at 14 TeV and $\mu=60, 80, 140$
 - ΣE_T in each event = true ΣE_T (from hard scattering) + pile-up ΣE_T , latter is generated randomly from distribution observed in $Z' \rightarrow t\bar{t}$ and minimum bias MC samples



$H \rightarrow \mu\mu$ in Run1 (ATLAS)

- Signal and bkg MC samples:
 - Higgs: ggF, VBF: Powheg+Pythia; VH: Pythia
 - Z: Powheg+Pythia
 - tt: MC@NLO
 - WW: Powheg+Pythia (qq) and gg2WW+Herwig (gg)
- Selection: exactly 2 OS muons passing the cuts + trigger-match
- Categories: low/med/hi $p_{T^{\mu\mu}}$ (<15/15-50/>50 GeV), central/rest ($|\eta^\mu| < 1$ or not) + VBF (2 leading jets with $m_{jj} > 500$ GeV, $|\Delta\eta_{jj}| > 3$)
 - $m_{\mu\mu}$ FWHM=5.5-7.2 GeV, $S/\sqrt{B}=0.06-0.15$
- Fit models ($m_{\mu\mu}$):
 - signal (from MC): Gaussian + Crystal Ball
 - bkg (shape from MC studies, parameters fitted to data):
 - VBF: $BW * \exp(m_{\mu\mu})$
 - other categories: $BW \otimes \text{Gaussian} + \exp(m_{\mu\mu})/m_{\mu\mu}^3$
 - BW parameters fixed to PDG values (Z). Gaussian resolution from Z MC
 - choose shape giving bias < 20% of exp. uncertainty in high-stat bkg-only MC (truth + parametrised detector response)
- Systematic uncertainties only change expected limit by 2% for $m_H = 125$ GeV

$H \rightarrow \mu\mu$ in Run1 (CMS)

- Signal and bkg MC samples:
 - Higgs: ggF, VBF: Powheg+Pythia; VH: Powheg+Herwig++
 - Z, tt: Madgraph+Pythia
- Selection: 2 OS muons passing the cuts
- Categories:
 - di-jet: 2 jets with $p_T > 40, 30$ GeV, not from pile-up; $p_T^{\text{miss}} < 40$ GeV
 - tight VBF: $m_{jj} > 650$ GeV, $|\Delta\eta_{jj}| > 3.5$ (80% of signal from VBF)
 - tight ggF: $m_{jj} > 250$ GeV, $p_T^{\mu\mu} > 50$ GeV
 - loose
 - $p_T^{\mu\mu}$ loose/tight: $< 10 / > 10$ GeV; BB/BO/BE/OO/OE/EE (B: $|\eta_\mu| < 0.8$; O: 0.8-1.6; E: > 1.6)
 - $m_{\mu\mu}$ FWHM=3.9-6.4 GeV, $S/\sqrt{B}=0.01-0.30$
- Fit models ($m_{\mu\mu}$):
 - signal (from MC): double gaussian
 - bkg (shape from MC studies, parameters fitted to data):
 - $BW * \exp(m_{\mu\mu}) + \exp(m_{\mu\mu}) / m_{\mu\mu}^2$
 - BW parameters from fits to data near Z peak
 - impact of bkg model uncertainty $< 20\%$ of expected limit (fit S+B model to pseudo-data from various bkg models fitted to data)

$H \rightarrow \mu\mu$ in Run1 (CMS)

Source	GF [%]	VBF [%]
Higher-order corrections [18]	1–25	1–7
PDF [18]	11	5
PS/UE	6–60	2–15
$\mathcal{B}(H \rightarrow \mu^+ \mu^-)$ [18]	6	6
Integrated luminosity [39,40]	2.2–2.6	2.2–2.6
MC statistics	1–8	1–8
Muon efficiency	1.6	1.6
Pileup	<1–5	<1–2
Jet energy resolution	1–3	1–2
Jet energy scale	1–8	2–6
Pileup jet rejection	1–4	1–4

$t \rightarrow qH, H \rightarrow \gamma\gamma$: ATLAS Run1 analysis

- MC samples:
 - signal: Protos+Pythia, 30k had, 30k semi-lep
 - Higgs: gg+VBF: Powheg+Pythia; VH+ttH: Pythia
 - $\gamma\gamma$ +jets: 10M Sherpa $\gamma\gamma$ + ≤ 3 parton events
 - tt (15M): MC@NLO+Herwig; $W\gamma$ (20M): Alpgen+Herwig
- m_2 for lept. channel (m_{lvj}): W-mass constraint + solution with smaller $|m_2 - m_t|$
- Bkg subtraction:
 - hadronic channel: fit to $m_{\gamma\gamma}$ in 100-160 GeV
 - leptonic channel: counting, extrapolate from $m_{\gamma\gamma}$ CR (100-122, 129-160 GeV) to SR (122-129 GeV)
- Signal and SM Higgs: Crystal Ball ($\sigma \sim 1.7$ GeV)+wide Gaussian, 90% in SR
- Bkg (hadronic channel): 2nd-order polynomial, shape chosen after bias studies on pseudo-data generated from smoothed MC
- Bkg (leptonic channel): transfer factor = 0.15 with 2nd-order poly and 0.13 with flat $m_{\gamma\gamma}$ distribution - assume conservative 30% uncertainty

$t \rightarrow qH$, $H \rightarrow \gamma\gamma$: ATLAS Run1 analysis

Selection	Hadronic		Leptonic
Centre of mass energy	7 TeV	8 TeV	
$t\bar{t}$ cross-section (pb)	177^{+10}_{-11}	253^{+13}_{-15}	
$H \rightarrow \gamma\gamma$ Br (%)	0.23 ± 0.01		

5%

4%

Selection	Hadronic		Leptonic
	7 TeV	8 TeV	8 TeV
Trigger efficiency	± 0.2	± 0.5	± 0.5
Photon identification	± 9.3	± 4.6	± 2.4
Photon isolation	± 3.0		± 1.0
Jet Energy Scale	± 5.4	$+7.4$ -4.5	$+3.2$ -2.8
Jet Energy Resolution	± 0.2		± 0.2
Jet Vertex Fraction	± 1.0		± 1.0
b -tagging	± 3.5	± 4.8	± 5.2
Lepton reco./ID/scale	—	—	± 0.6
E_T^{miss} scale	—	—	$+1.4$ -0.4
ISR/FSR	$+7.0$ -3.0		$+8.0$ -2.0
Underlying event	± 3.5		± 1.8
Combined uncertainty	$+14.1$ -12.6	$+13.1$ -9.8	$+10.6$ -7.1

- luminosity: 2.8%
- negligible effect from m_t : cross-section*acceptance \sim constant for shift of 0.6 GeV

$H \rightarrow J/\psi \gamma$ in Run1

- Signal and bkg modeling:
 - Higgs (ggF, VBF): Powheg+Pythia; assume VBF efficiency for VH and ttH
 - Z: Powheg+Pythia
 - QCD bkg: data-driven (relaxed dimuon and photon p_T and isolation cuts)
- Bkg composition (not used for the results):
 - simultaneous fit to $m_{\mu\mu}$ and $|L_{xy}/\sigma(L_{xy})|$ to extract fractions of prompt J/ψ (56%), non-prompt J/ψ (3%), combinatoric (41%)
 - fit to $m_{\mu\mu}$ and $m_{\mu\mu\gamma}$ shows no evidence of $Z \rightarrow \mu\mu\gamma$
- Signal yields: from simultaneous fit to $m_{\mu\mu\gamma}$ and $p_T^{\mu\mu}$
- Systematic uncertainties:
 - expected bkg: 10-20% bkg shape
 - signal efficiency: 1.7% trigger, 0.5% photon, 0.4% muon
 - luminosity: 2.8%
 - $m_{\mu\mu\gamma}$ scale: 0.2% from photon energy scale

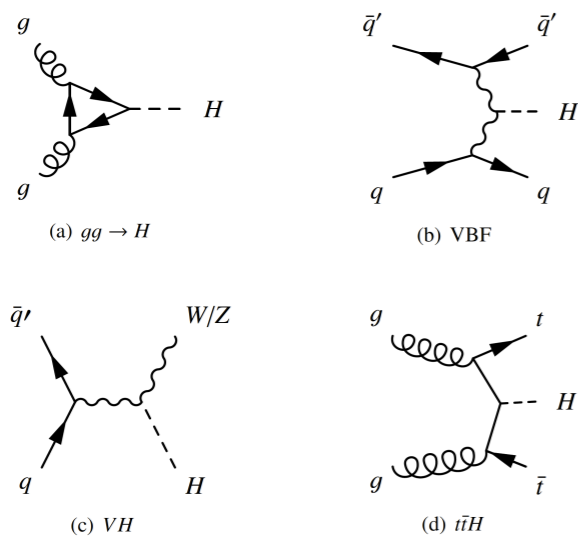
Cross section ratio $\sigma_{14\text{TeV}}/\sigma_{8\text{TeV}}$

Frequently-asked-question:

Q) Why gains in $gg \rightarrow H$ and $qq \rightarrow qqH$ are the same? A) accidental!

Q) Why ttH gain is so large? A) phase space opening + large $M_X = 2M_t + M_H$ in gg

Gains can be estimated via parton luminosity ratio if kinematically fully open.



	$\sigma(14\text{TeV})/\sigma(8\text{TeV})$	
$gg \rightarrow H$	2.6 ($M_X = M_H$)	●
$qq \rightarrow qqH$	2.6 (probes high M_X)	●
$qq \rightarrow VH$	2.1 ($M_X = M_V + M_H$)	●
$gg \rightarrow ttH$	4.7 (phase space + M_X)	●

