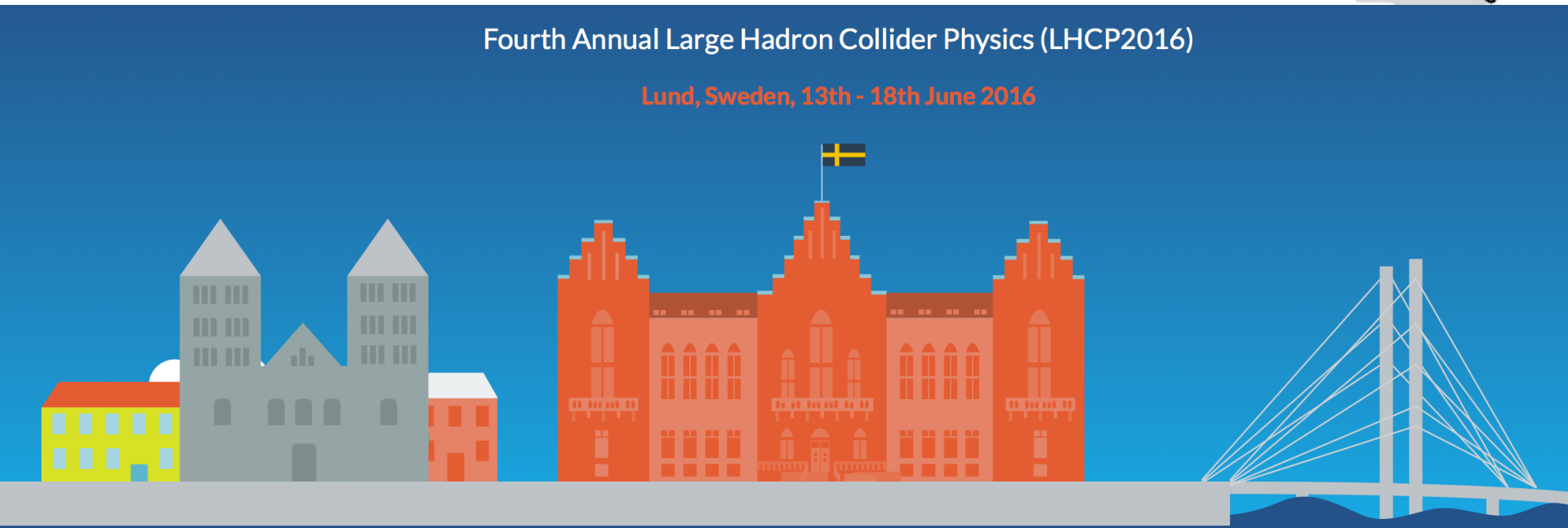
Standard Model and Higgs Physics at the HL-LHC with ATLAS and CMS

P.Krieger, University of Toronto

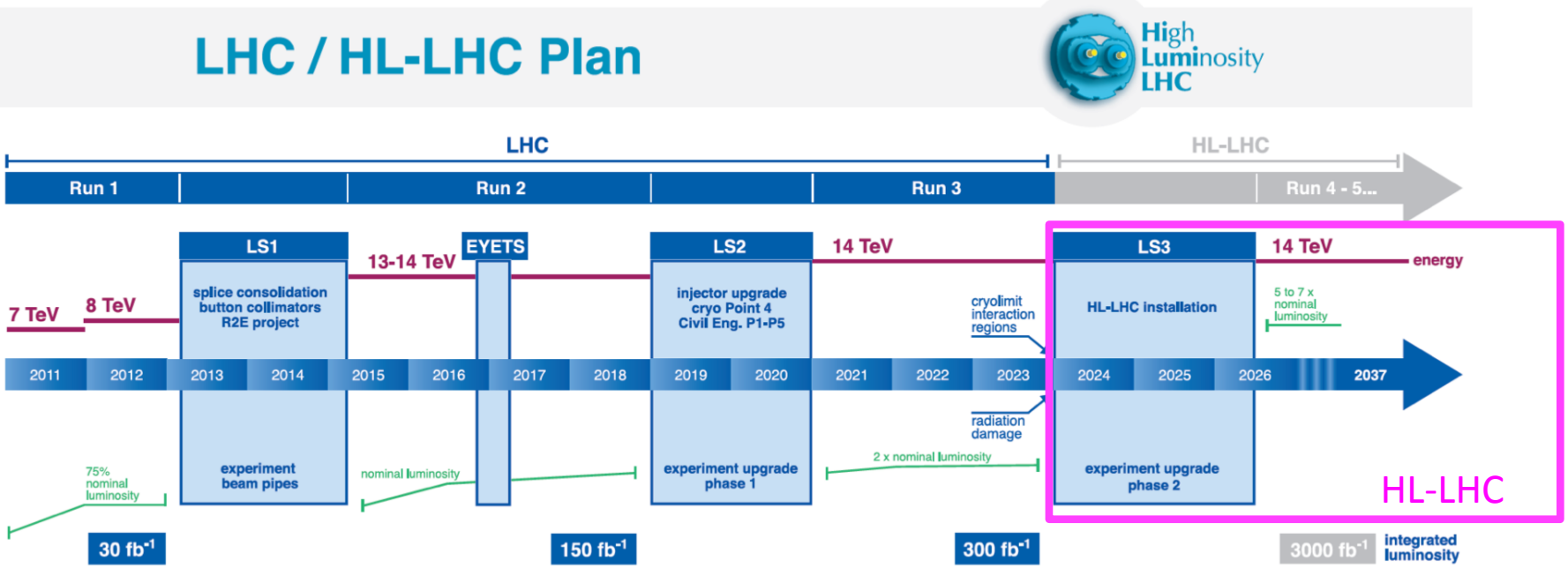
(on behalf of the ATLAS & CMS Collaborations)



The High-Luminosity Large Hadron Collider (HL-LHC)

- Upgrade LHC luminosity to permit accumulation of 3 ab^{-1} data sample over a ~ 10 year run period following LS3 for machine and detector upgrades
- Plan for $\mathcal{L} = 5\times10^{34}\ cm^{-2}s^{-1}$ with ultimate luminosity of $\mathcal{L} = 7.5\times10^{34}\ cm^{-2}s^{-1}$

μ=140 μ=200



High $\mathcal{L}$ results in higher radiation dose and detector occupancy issues

Detector upgrades needed, with focus on pileup mitigation (PU) strategies

Detector Challenges at High Rate

- Existing detectors were designed for 10 years of running at $\mathcal{L} = 10^{34}\ cm^{-2}s^{-1}$
- Harsher HL-LHC conditions dictate what MUST be replaced:
  - Need to maintain current performance for object reconstruction
  - New detectors can be developed with improved coverage / performance
- Tracking critical to PU mitigation strategies. Both ATLAS & CMS planning for new silicon trackers (with options for coverage out to to (as far as) $|\eta| \approx 4$):
  - Increased granularity for reduced occupancy, reduced material budget
  - Inclusion of tracking information for improved PU rejection in L1 trigger
- Trigger upgrades: up to 1MHz L0/L1, 10kHZ recording
- Muon system: some coverage, trigger improvements expected
- Endcap calorimeters:
  - CMS to replace endcap calorimeter with "HGCAL" (with good timing)
  - ATLAS considering new high-granularity forward calorimeter, as well as a dedicated timing detector in the endcap/forward region.

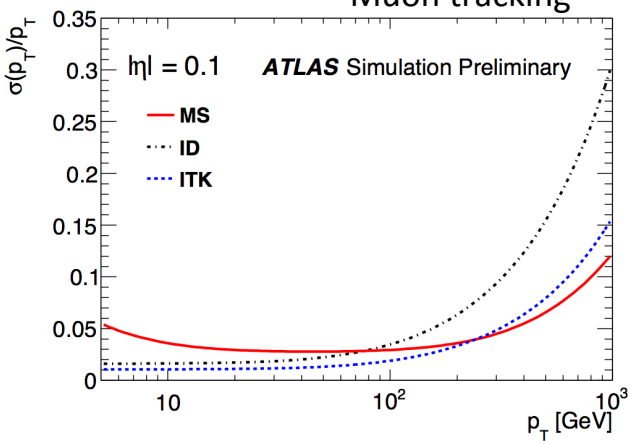
For details see Sat. morning talks by A. Henriques (ATLAS) and A.Belloni (CMS)

HL-LHC Performance & Physics Simulations

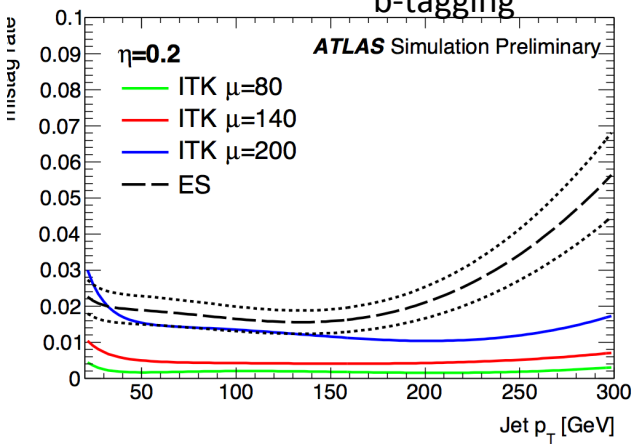
- Full simulations for all channels impractical. Different strategies:
  - Parametrize object-level performance based on full simulations: use parametrizations (efficiencies, fake rates, smearing) for generator-level studies of benchmark channels

Main ATLAS strategy

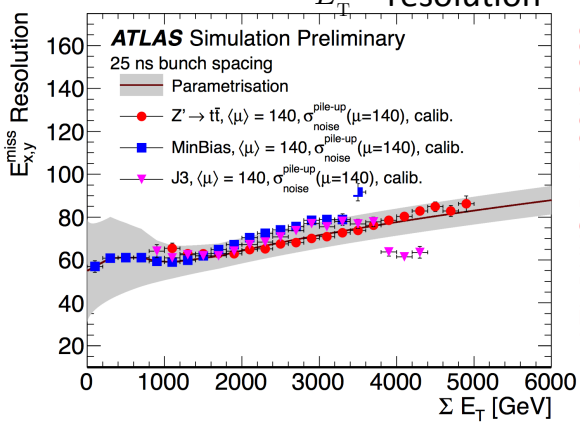
Muon tracking



b-tagging



E_T^{miss} resolution



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  - Extrapolate 8 TeV analyses to higher $\mathcal{L}$ and $\sqrt{s}$ based on assumption that strategies will be developed to allow performance to be maintained at high PU

Main CMS strategy

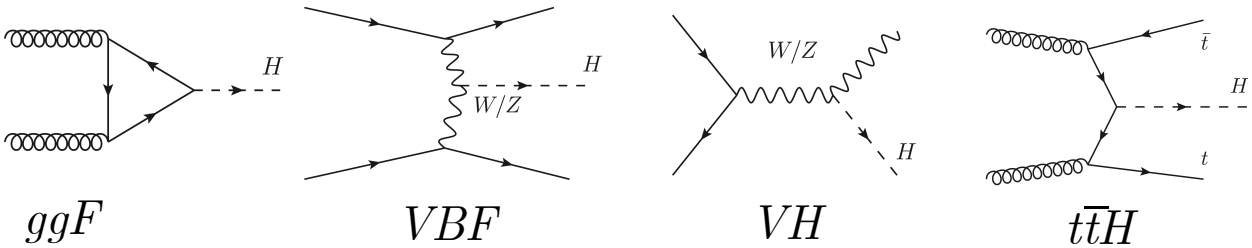
Quoted CMS results from CMS Note-13-002 [arXiv: 1307.7135] except where noted

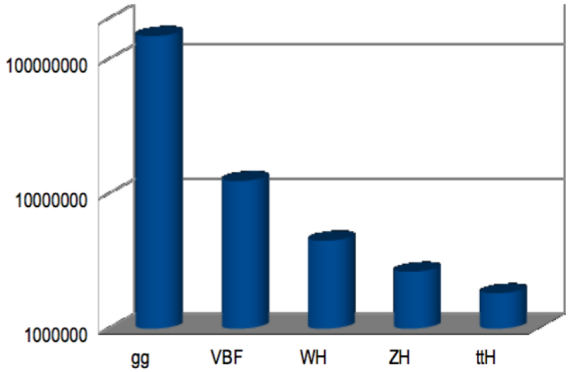
Two scenarios for scaling of systematic uncertainties
- Scenario 1: all systematic uncertainties remain the same
- Scenario 2: Theoretical uncertainties scaled by ½ and all others scaled by $\mathcal{L}^{-1/2}$

Most available results (ATLAS & CMS) from studies done for μ = 140

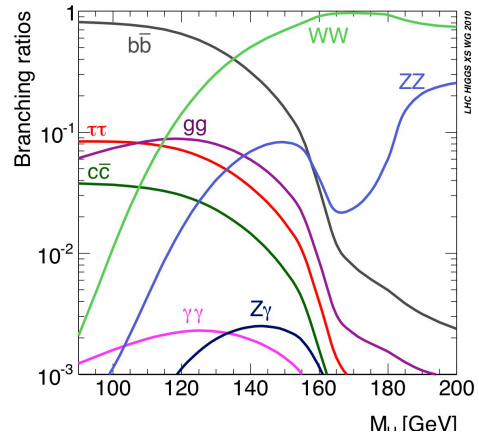
The HL-LHC as a Higgs Factory

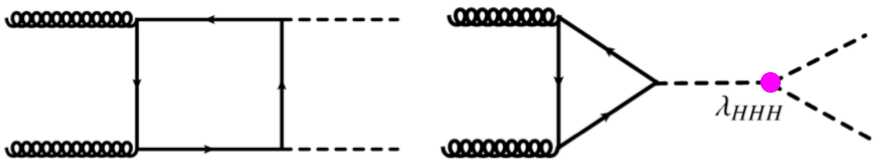
- Large numbers of Higgs bosons expected at the HL-LHC:
  - All production mechanisms can be investigated

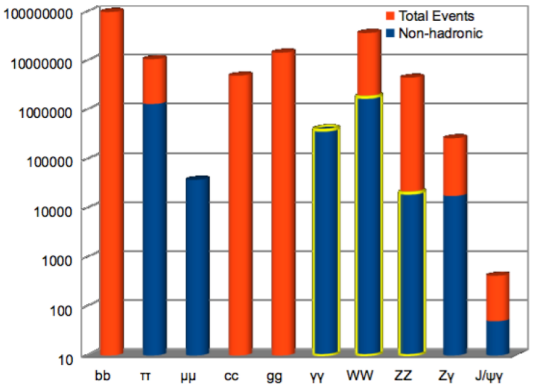




- Expect:
  - Higher precision for quantities measured with 300 fb^{-1}
  - Differential cross-sections for all production modes
  - Access to second-generation fermion couplings: $H \to \mu\mu$
  - Other rare decay modes: e.g. $H \to Z\gamma$
  - Studies of other Higgs properties (width Γ_H, CP) as well as vector boson scattering (VBS)
  - HH production, for study of self coupling



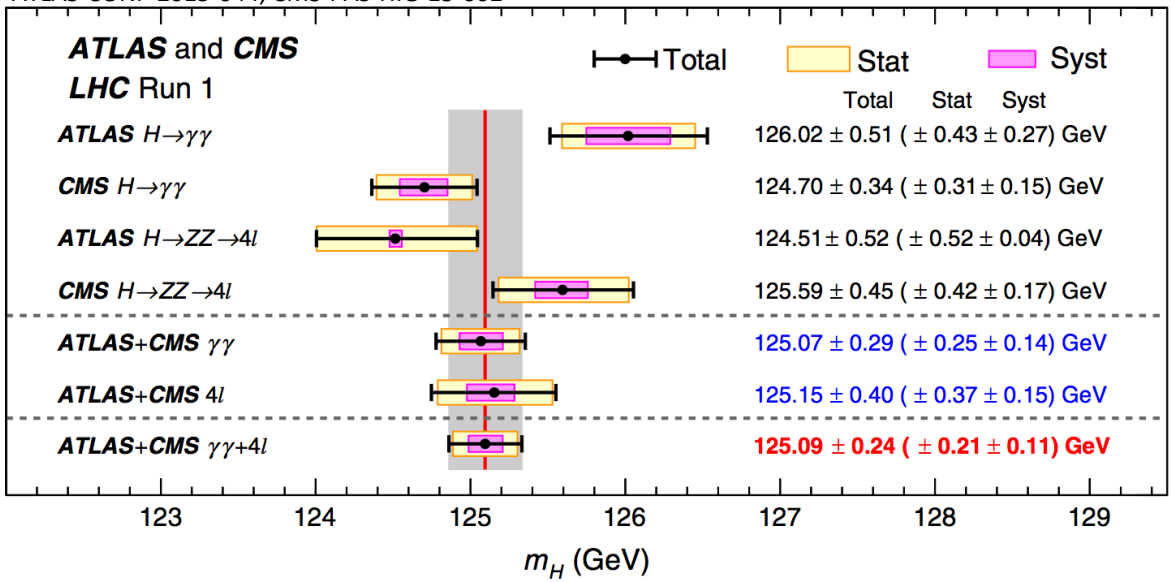


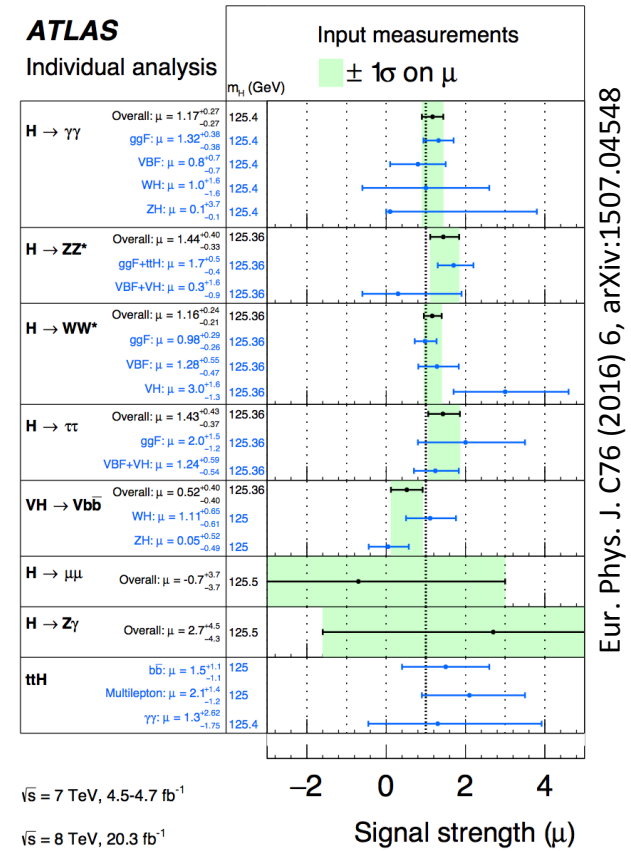


Where Things Stand Now

- See talks from Monday afternoon (J.Strandberg, S.Donato + J.Takana for BSM)

ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002





Eur. Phys. J. C76 (2016) 6, arXiv:1507.04548

- H(125): Spin-parity $J^P=0^+$ strongly favoured
- Couplings to both fermions and bosons observed
  - couplings still not precisely measured
  - ggF and VBF production modes seen
  - Associated production modes $(WH, ZH, t\bar{t}H)$ investigated; statistics not yet sufficient
- Statistics also too low for detailed studies of CP properties, total width Γ_H
- Not yet known if there are other Higgs bosons
- Focus here will be on improvements to SM Higgs measurements

$H \to ZZ^{(*)} \to 4\ell$

- Still "golden": narrow peak over low background: Access to all production modes.

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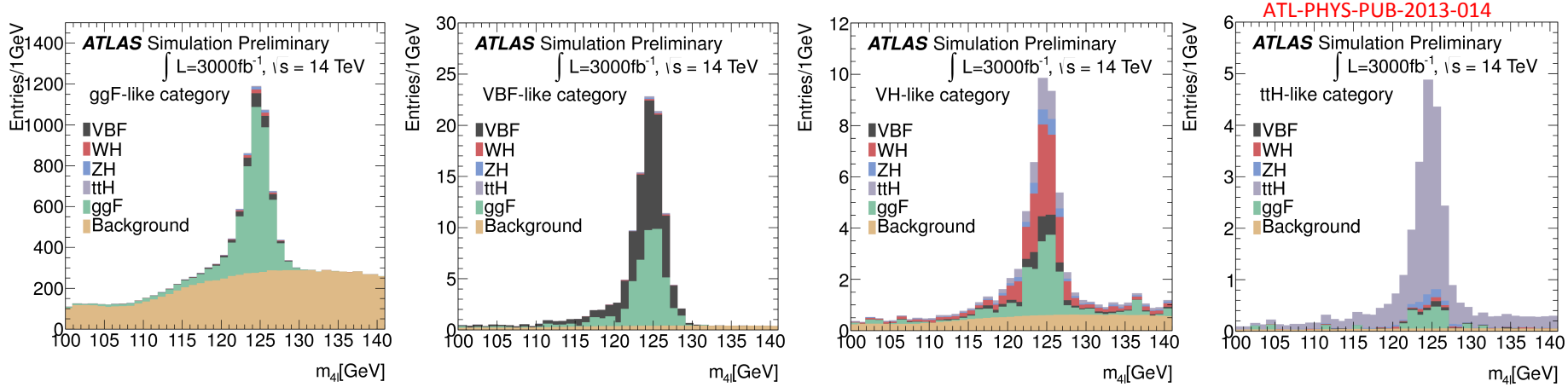
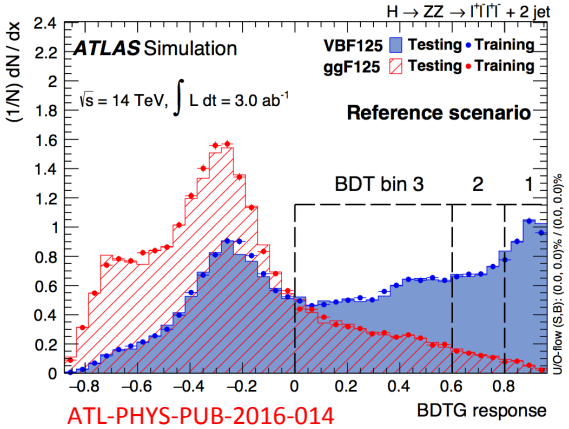


- Performance sensitive to upgrade scenario:
  - Illustrated on next slide for CMS
  - Above ATLAS results do not include improvements from tracker extension (+ 21% acceptance for 4μ)
  - Better than 10% precision expected on ZZ signal strength from both ATLAS and CMS (w. current theory uncertainties)

Category	True Origin					
	ggF	VBF	*WH*	*ZH*	*ttH*	Background
ttH-like	3.1 ±1.0	0.6 ±0.1	0.6 ±0.1	1.1 ±0.2	30 ±6	1.6 ±1.0
ZH-like	0.0	0.0	0.01 ±0.01	4.4 ±0.3	1.3 ±0.3	0.06 ±0.06
WH-like	22 ±7	6.6 ±0.4	25 ±2	4.4 ±0.3	8.8 ±1.8	13 ±0.8
VBF-like	41 ±14	54 ±6	0.7 ±0.1	0.4 ±0.1	1.0 ±0.2	4.2 ±1.5
ggF-like	3380 ±650	274 ±17	77 ±5	53 ±3	25 ±4	2110 ±50

- Updated results for VBF production (BDT analysis)

Scoping Scenario	without theo. unc.			with theo. unc.		
	$\Delta\mu/\mu$	$\Delta\mathcal{I}$ (fb^{-1})	Z_0-value (σ)	$\Delta\mu/\mu$	$\Delta\mathcal{I}$ (fb^{-1})	Z_0-value (σ)
Reference scenario	0.134	–	11.41	0.167	–	7.64
Middle scenario	0.137	125	10.86	0.174	350	7.48
Low scenario	0.142	425	9.84	0.186	1000	6.75



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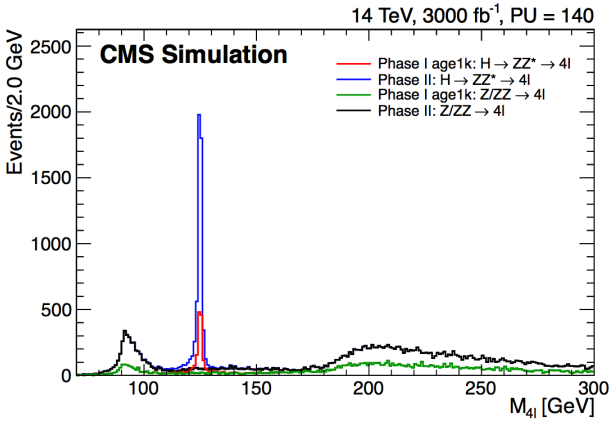
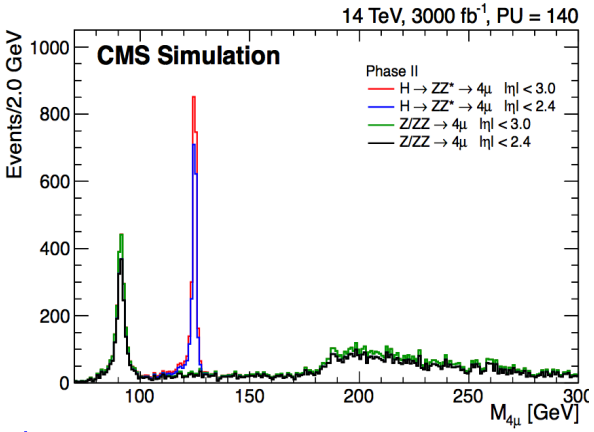
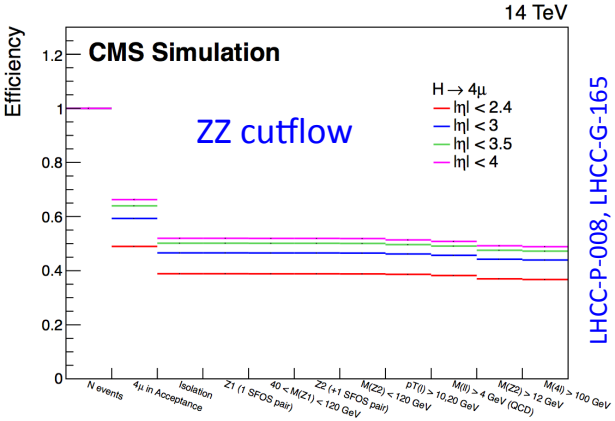
$H \to ZZ^{(*)} \to 4\ell$

- This channel an excellent illustration of the need for detector upgrades:





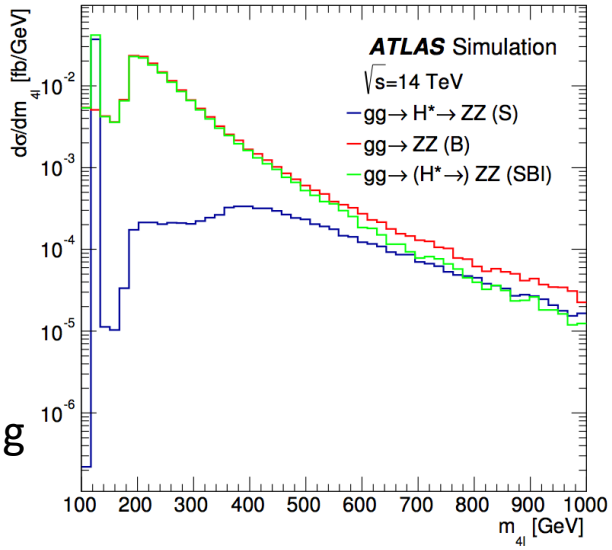


LHCC-P-008, LHCC-G-165

Detector: Phase-I (aged) vs. Phase-II

Effect of tracker extensions in η

- Other physics studies utilizing $H \to ZZ^{(*)} \to 4\ell$
  - Comparison of off-/on-shell couplings sensitive to Γ_H:
    - Interference between signal and ZZ background
    - Run-1 measurements from both ATLAS and CMS
      - arXiv:1503.01060, arXiv:1405.3455
    - For 3000 fb^{-1} ATLAS projects $\Gamma_H = 4.2 \pm {}^{1.5}_{2.1}$ MeV
  - Differential cross-sections for all modes
  - CP studies and tests of tensor structure of HZZ coupling have been investigated for HL-LHC, using this channel



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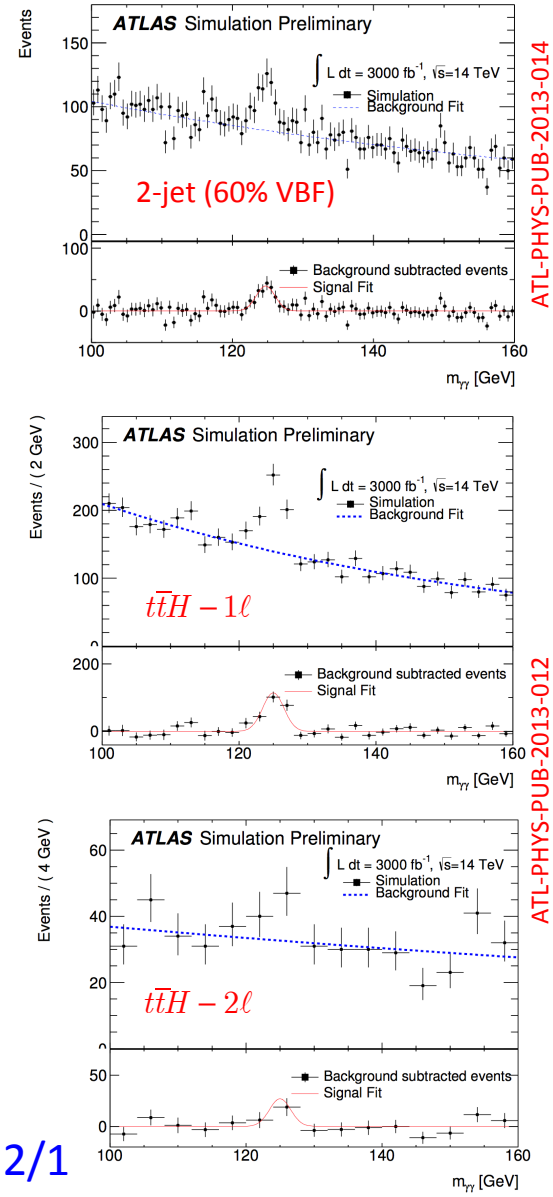
$H \to \gamma\gamma$

- Also provides a narrow peak, so useful for studies of rare modes:
- Also gives access to all production modes.
  - Classify signal into events with exactly 0, 1, 2 jets
    - different sensitivities to ggF, VBF
  - Separate analysis for associated production modes
    - Also classify according to number of leptons, b-tags
    - $\mathcal{O}(100)$ events reconstructed in VH, ttH modes
- Inclusive signal strength precision: 9%
- For non-ggF modes, signal strength uncertainties at level of 17-28% depending on the production mode
- Estimated significances:

	$t\bar{t}H$	WH	ZH	VBF
Significance	8.2	4.2	3.7	3.8

High significance for $t\bar{t}H$



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ATL-PHYS-PUB-2013-012

CMS expects 4/8% (inclusive) signal strength precision for Scenario 2/1

$H \to WW^* \to \ell\nu\ell\nu$

- Study based on 8 TeV samples:
  - Includes emulation of expected performance degradation:
    - $E_{\mathrm{T}}^{\mathrm{miss}}$, b-tagging, jet-energy resolution all an issue
  - Divide events according to number of jets (0,1,2): study ggF and VBF modes (below)
  - Select $e\mu$ / μe only, to reduce backgrounds: final selection on transverse mass m_{T}
  - VBF analysis updated in 2015 for μ=200, three ATLAS scoping scenarios

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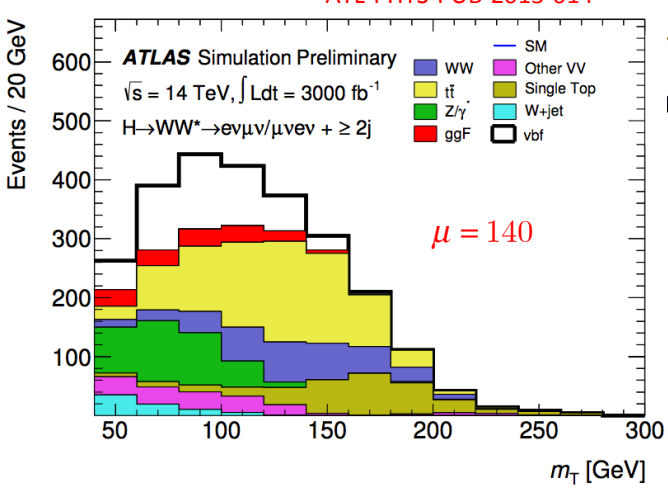

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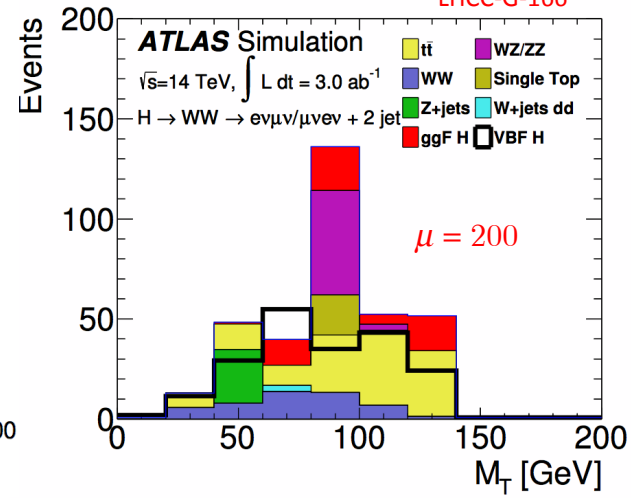


ATLAS	μ_{ggF}	μ_{VBF}	$\mu_{\mathrm{ggF+VBF}}$
300 fb^{-1}	$1^{+0.18}_{-0.15}$	$1^{+0.25}_{-0.22}$	$1^{+0.14}_{-0.13}$
3000 fb^{-1}	$1^{+0.16}_{-0.14}$	$1^{+0.15}_{-0.15}$	$1^{+0.10}_{-0.09}$

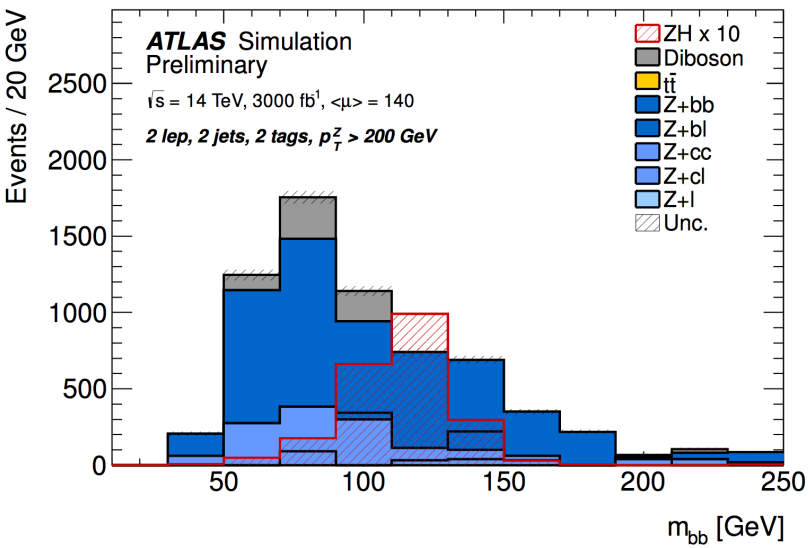
Scoping Scenario	without theo. unc.		with theo. unc.	
	$\Delta\mu/\mu$	Z_0-value (σ)	$\Delta\mu/\mu$	Z_0-value (σ)
Reference	0.14	8.0	0.20	5.7
Middle	0.20	5.4	0.25	4.4
Low	0.30	3.5	0.39	2.7

ATLAS anticipates combined signal strength sensitivity of ~ 10%

CMS projects signal-strength sensitivity of 4/7% in Scenario 2/1

Associated Production: $H \to b\bar{b}$

- (W/Z)H with leptonic final states can be used to investigate $H \to b\bar{b}$
  - Leptons needed for triggering
- ATLAS: 18 signal categories according to p_{T}^{V} , the number jets, b-jets, leptons
- Analysis validated by comparison with 8 TeV data



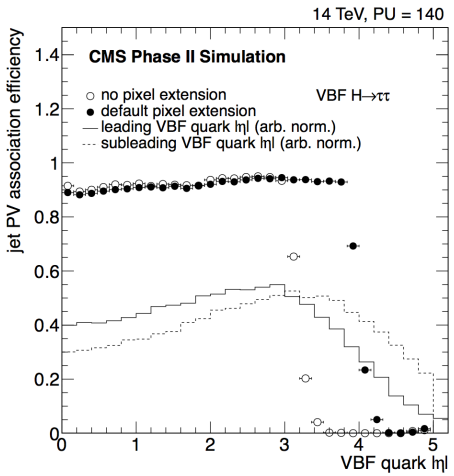
		One-lepton	Two-lepton	One+Two-lepton
Stat-only	Significance	15.4	11.3	19.1
	$\hat{\mu}_{\mathrm{Stats}}$ error	+0.07 − 0.06	+0.09 − 0.09	+0.05 − 0.05
Theory-only	$\hat{\mu}_{\mathrm{Theory}}$ error	+0.09 − 0.07	+0.07 − 0.08	+0.07 − 007
Scenario I	Significance	2.7	8.4	8.8
	$\hat{\mu}_{\mathrm{w/Theory}}$ error	+0.37 − 0.36	+0.15 − 0.15	+0.14 − 0.14
	$\hat{\mu}_{\mathrm{wo/Theory}}$ error	+0.36 − 0.36	+0.14 − 0.12	+0.12 − 0.12
Scenario II	Significance	4.7	-	9.6
	$\hat{\mu}_{\mathrm{w/Theory}}$ error	+0.23 − 0.22	-	+0.13 − 0.13
	$\hat{\mu}_{\mathrm{wo/Theory}}$ error	+0.21 − 0.21	-	+0.11 − 0.11

ATL-PUB-2014-011

- Anticipate combined 8.8σ observation and 14% precision on signal strength
- CMS projects precision of 5/8% on the signal strength in Scenario 2/1

VBF $H \to \tau\tau$

- VBF for background suppression
- Need effective suppression of PU in forward region and good $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution:
  - both are strong motivations for high-|η| tracker extension



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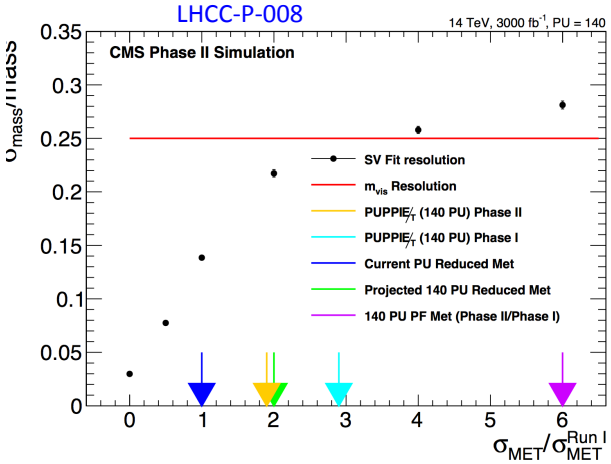
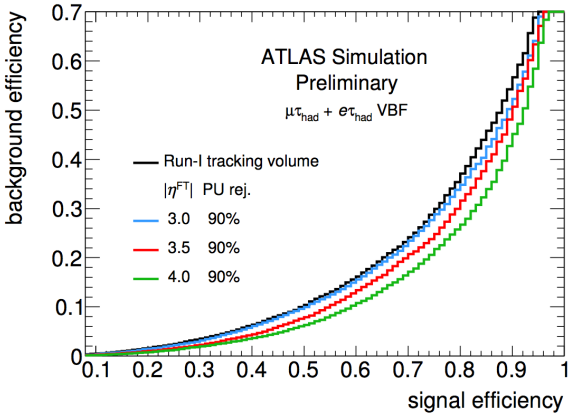
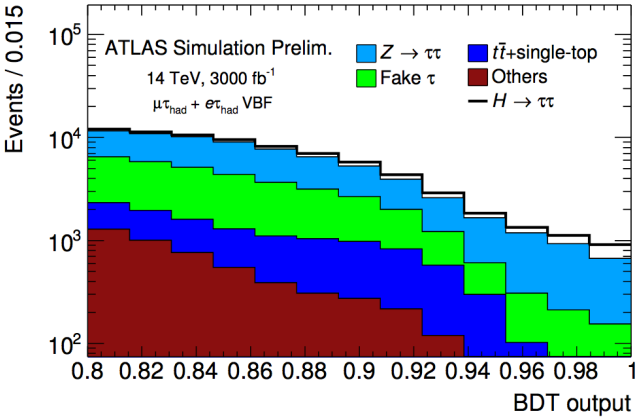


- ATLAS study extrapolates from Run-1 BDT analysis: $\ell\tau_{had}$ final states, μ=140
  - Also investigate performance improvements from increased tracker acceptance
  - Expect uncertainty on signal strength of about 8% for tracker coverage out to |η|=4.0





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

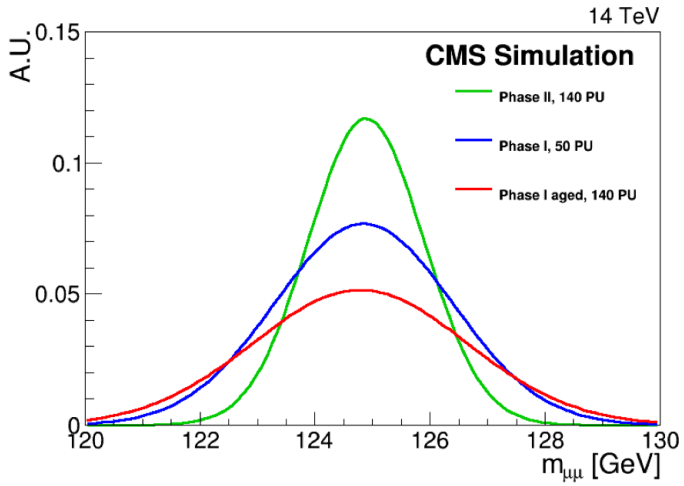
CMS projects 5/8% precision on the signal strength in Scenario 2/1.

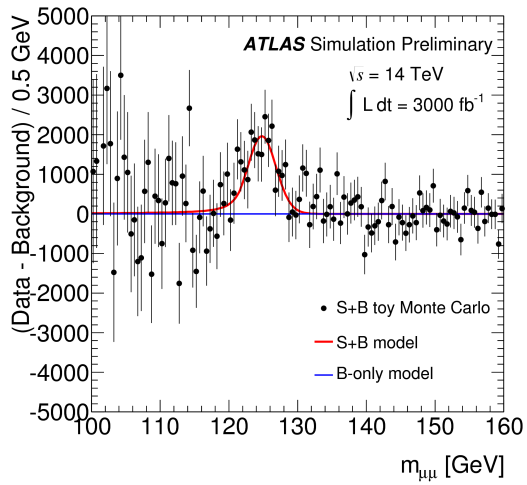
$H \to \mu\mu$

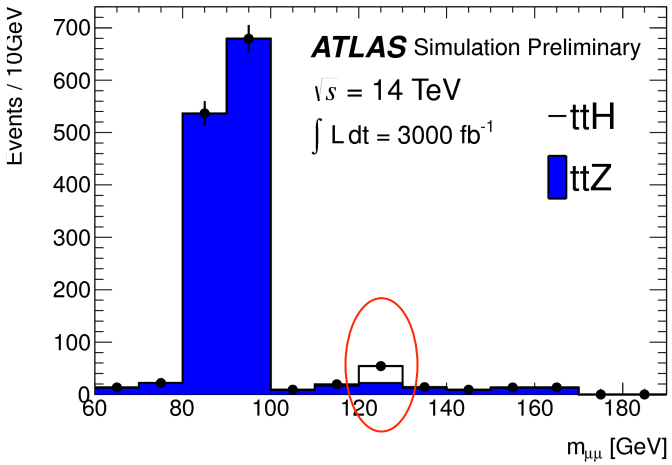
ATL-PHYS-PUB-2013-014

LHCC-P-008 (CMS)

- Access to second generation fermion couplings via $H \to \mu\mu$
- Good mass resolution: can contribute to precision mass measurement
  - Resolution depends on upgrade scenario (as shown here for CMS):
    - Improvements due to better spatial hit resolution and reduced material







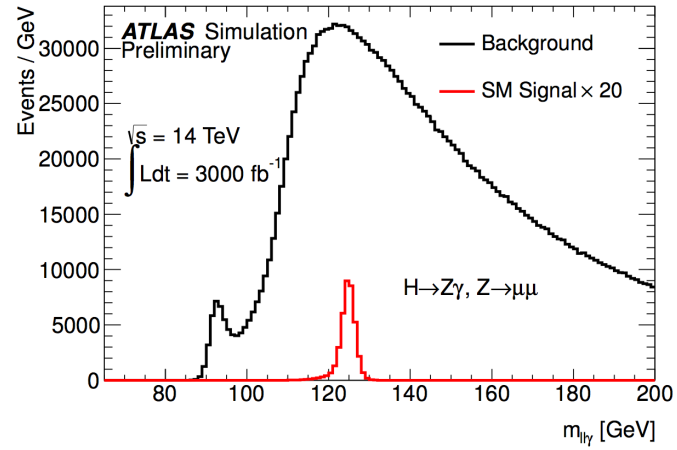
- CMS projection for precision on coupling updated to 5% in 2015
- ATLAS: expect ~20% measurement of signal strength, 7σ significance
  - ATLAS results do not take advantage of tracker extension to higher |η|
  - ATLAS has also investigated $t\bar{t}H, H \to \mu\mu$
    - Gives access to product of top, μ Yukawa couplings
    - Expect 33 signal events over 22 background

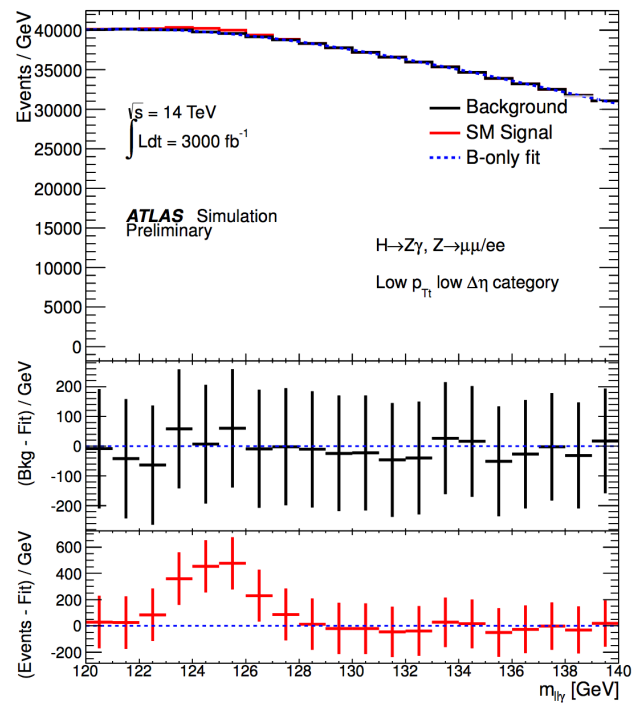
Other rare decays

- Other rare decay modes investigated:
  - $H \to Z\gamma$
    - via loops so sensitive to possible heavy new states

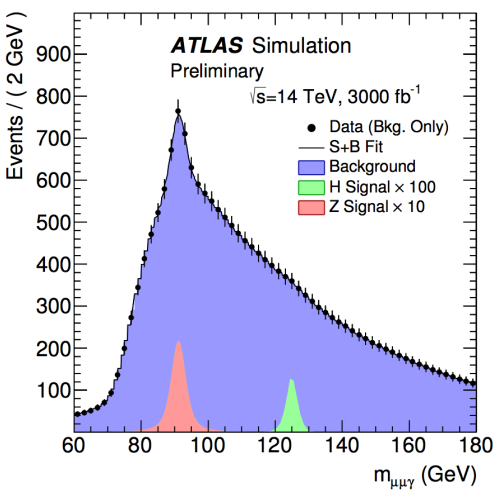
    ATLAS projects:
    - combined (ee/μμ) significance of 3.9σ
    - Signal strength uncertainly of ~30%, dominated by statistics.

    CMS projects:
    - Signal strength uncertainty of 20/24% in Scenario 2/1.





  - $H \to (J/\psi)\gamma$ (would give access to 2nd generation quarks)



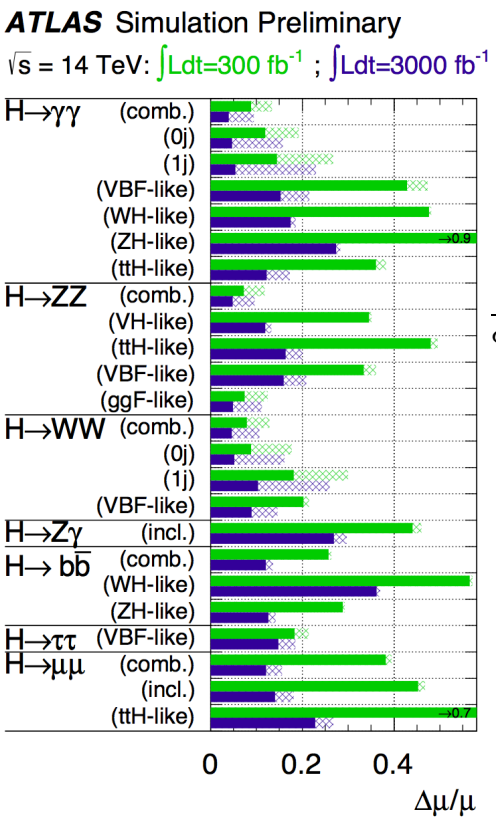
Only limits anticipated

	Expected $\sigma \times \mathcal{B}$ limit at 95% CL $\sigma(pp \to H) \times \mathcal{B}(H \to J/\psi\gamma)$ [fb]	
	Cut Based	Multivariate Analysis
300 fb^{-1}	$10.4^{+2.9}_{-4.5}$	$8.6^{+2.4}_{-3.7}$
3000 fb^{-1}	$3.1^{+0.9}_{-1.3}$	$2.5^{+0.7}_{-1.0}$

ATL-PHYS-PUB-2015-043

Signal Strengths & Couplings

- Couplings extracted from simultaneous fit to signal strength measurements. For coupling ratios:
  - No assumptions about total width
  - Cancellation of some experimental & systematic uncertainties
  - Couplings vs. mass: current uncertainties can be reduced to the few-% level with 3000 fb^{-1}



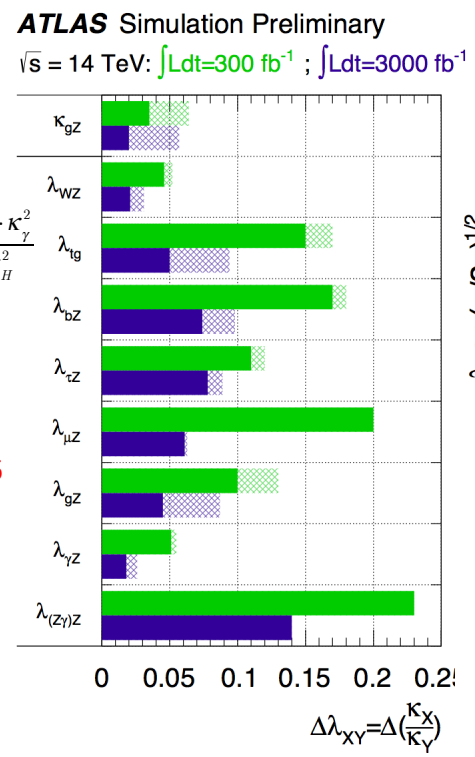
$$\frac{\sigma \cdot B\left(gg \to H \to \gamma\gamma\right)}{\sigma_{SM}\left(gg \to H\right) \cdot B_{SM}\left(H \to \gamma\gamma\right)} = \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Assuming the SM

ATL-PHYS-PUB-2014-016

For CMS see

arXiv:1307.7135



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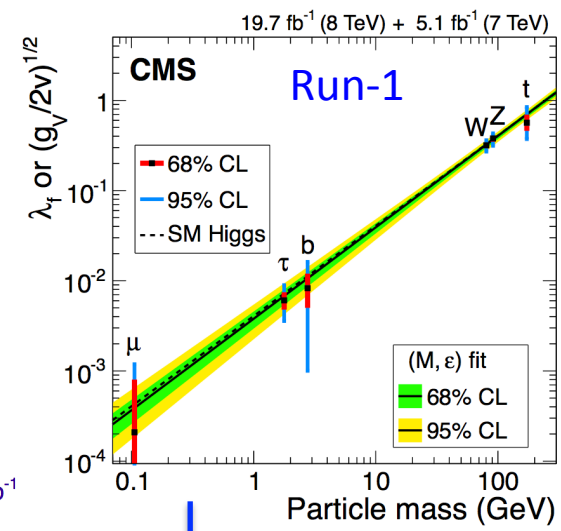
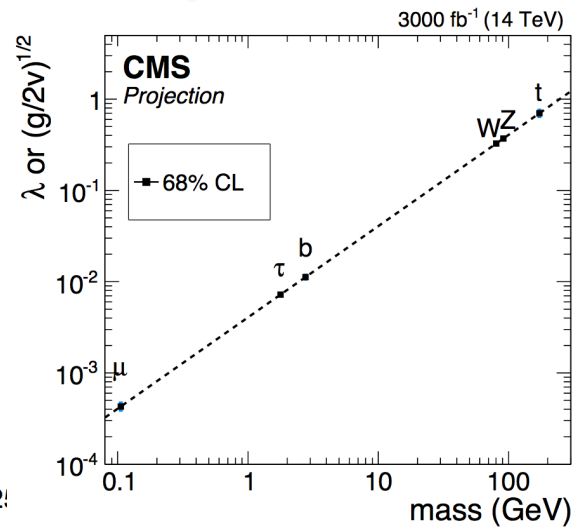
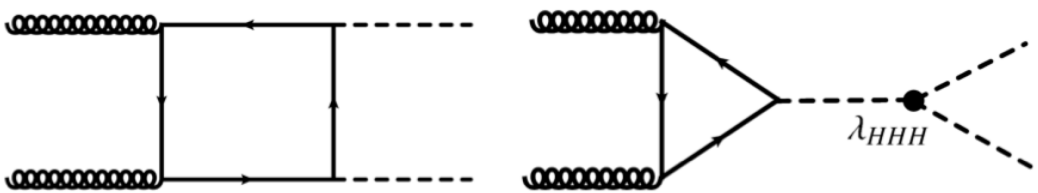


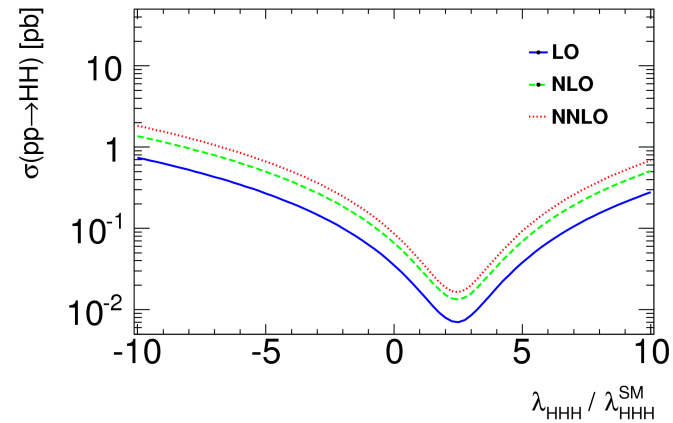


HH Production

- Di-Higgs (HH) production relevant to investigations of Higgs trilinear coupling λ_{HHH}. Dominant production (~90%) via ggF

$$\sigma_{HH}^{NNLO} = 40.8\,\mathrm{fb}$$





- Destructive interference: $\lambda_{HHH} = \lambda_{HHH}^{SM}$ yields near-minimal cross-section
  - minimum is at $\lambda_{HHH} / \lambda_{HHH}^{SM}$ = 2.44
  - $\lambda_{HHH} = 0$ increases cross-section by ~ factor of 2

Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b} + b\bar{b}$	33%	4.1×10^4
$b\bar{b} + W^+W^-$	25%	3.1×10^4
$b\bar{b} + \tau^+\tau^-$	7.4%	9.0×10^3
$W^+W^- + \tau^+\tau^-$	5.4%	6.6×10^3
$ZZ + b\bar{b}$	3.1%	3.8×10^3
$ZZ + W^+W^-$	1.2%	1.4×10^3
$\gamma\gamma + b\bar{b}$	0.3%	3.3×10^2
$\gamma\gamma + \gamma\gamma$	0.0010%	1

Studied in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states by both ATLAS & CMS

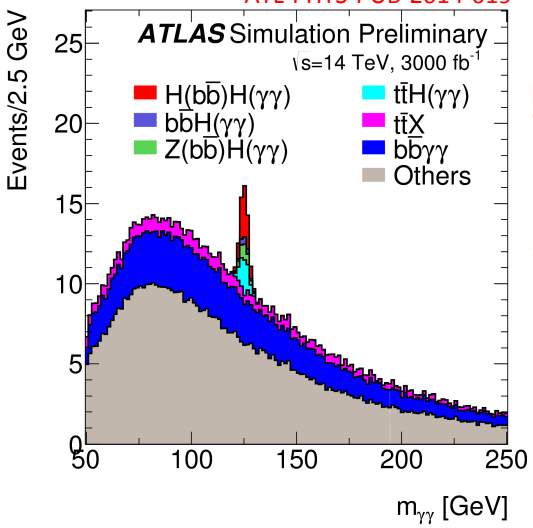
CMS has additionally studied $b\bar{b}(WW \to l\nu l\nu)$

ATLAS has studied RS $G_{KK}^* \to hh$

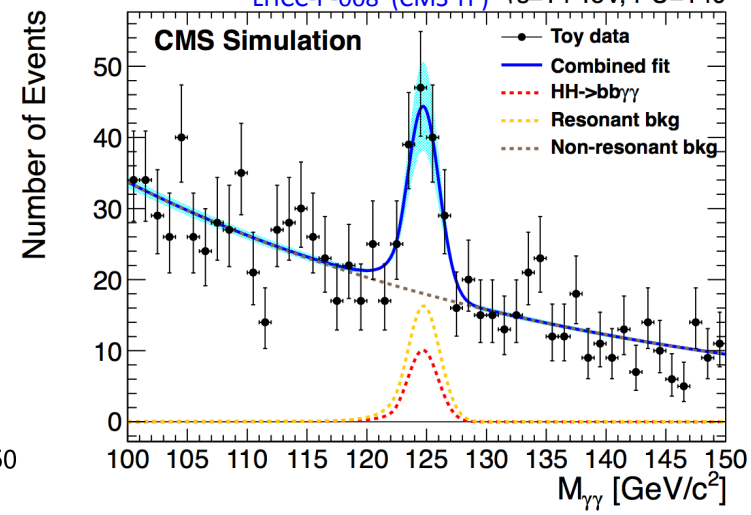
Di-Higgs Production in $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ Final States

- $m_{\gamma\gamma}$ distribution narrow, while m_{bb} *is* broad: 2D fit (CMS) or cut & count (ATLAS)

ATL-PHYS-PUB-2014-019



LHCC-P-008 (CMS TP)



Expected significances:

ATLAS: 1.3σ

CMS: 1.6σ

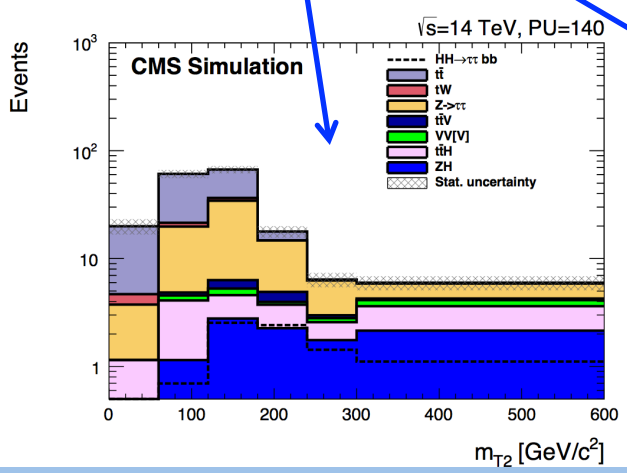
ATLAS projects exclusion regions for non-SM trilinear coupling:

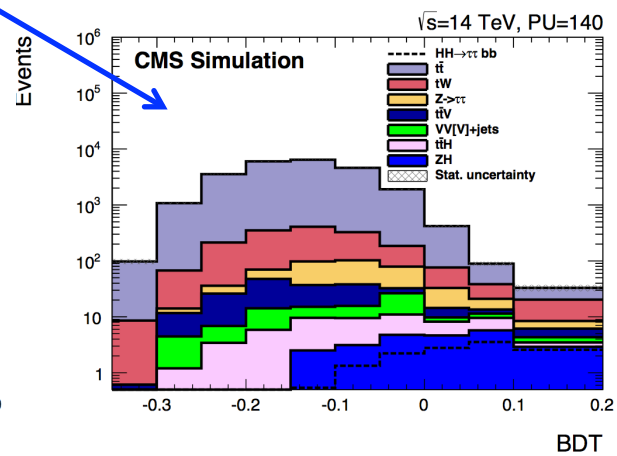
$$\lambda_{HHH} / \lambda_{HHH}^{\mathrm{SM}} \leq -1.3 \text{ or } \geq 8.7$$

- CMS: $\tau_h\tau_h$ and $\tau_h\tau_\mu$; ATLAS: $\tau_h\tau_h$, $\tau_h\tau_\ell$, $\tau_\ell\tau_\ell$ $(\ell = e, \mu)$

ATL-PHYS-PUB-2015-046

CMS-PAS-FTR-15-002





Expected significances:

ATLAS: 0.6σ

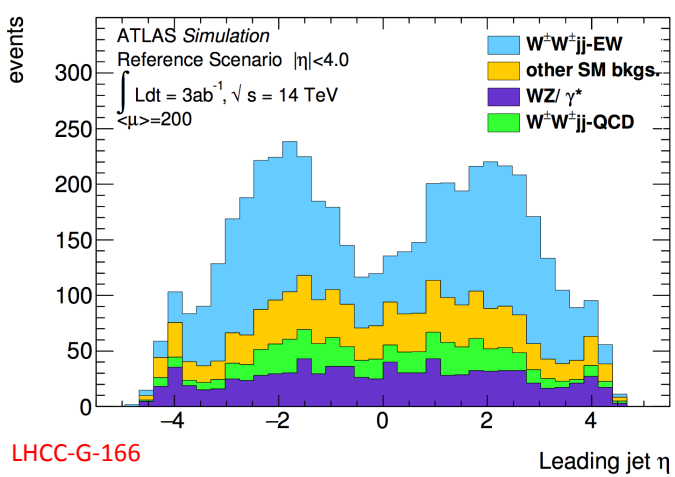
CMS: 0.9σ

ATLAS projects exclusion regions for non-SM trilinear coupling:

$$\lambda_{HHH} / \lambda_{HHH}^{\mathrm{SM}} \leq -1.4 \text{ or } \geq 12$$

Vector Boson Scattering (VBS)

- Sensitive to EWSB mechanism:
  - In SM, $\sigma\left(V_L V_L \to V_L V_L\right)$ unitarized by the Higgs boson
  - Strong and EW-only contributions:
    - Same sign VV best channel: cross-section not dominated by strong component
    - $W^{\pm}W^{\pm}$ + 2jets $\longrightarrow \ell^{\pm}\ell^{\pm} + E_{\mathrm{T}}^{\mathrm{miss}} + jj$: Signal selection based on m_{jj} and $|\Delta\eta_{jj}|$
    - Evidence for EW production from Run-1 (ATLAS: 30% uncertainty on σ_{EW})
- Prospects for HL-LHC: ATLAS (WW), CMS (WW,WZ)
  - Sensitive to performance improvements from increased tracker acceptance:
    - Increased lepton acceptance, PU suppression
    - For WW, expect ~5% measurement of σ_{EW} from each experiment



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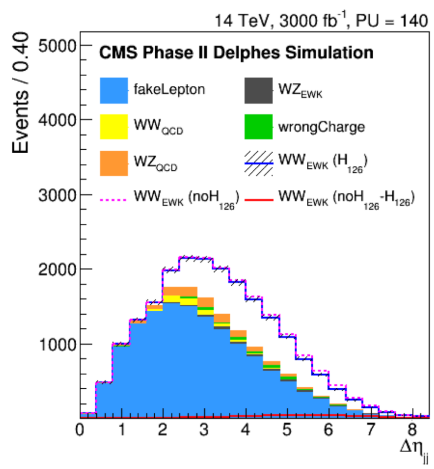
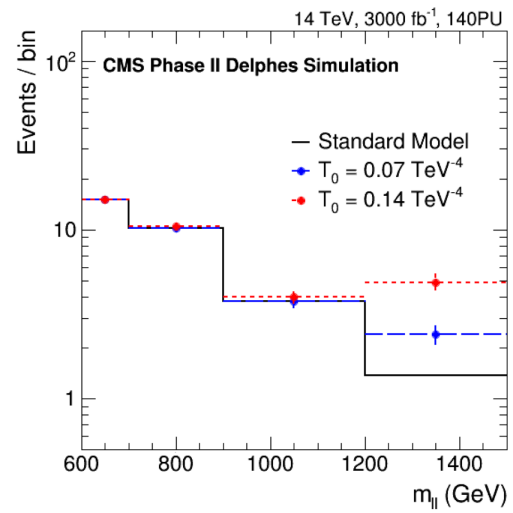




LHCC-P-008

Sensitivity to models in which Higgs only partially responsibly for unitarizing $\sigma\left(V_L V_L \to V_L V_L\right)$

Precision SM Measurements: $B_s^0 \,/\, B^0 \to \mu^+\mu^-$

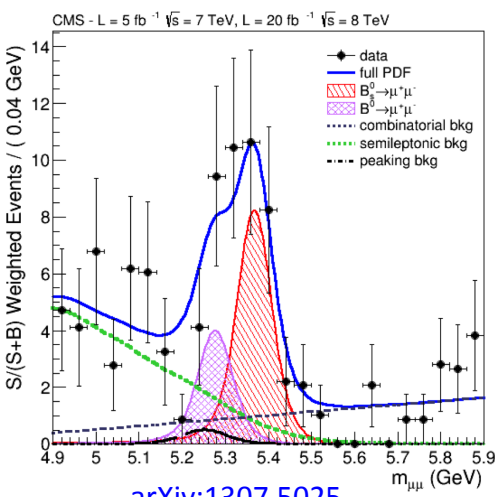
- Decay $B_s^0 \,/\, B^0 \to \mu^+\mu^-$ highly suppressed in SM
  - CMS measured $Br(B_s^0 \to \mu^+\mu^-) = 3.0 \pm^{1.0}_{0.9} \times 10^{-9}$ consistent with SM prediction
  - Branching ratio for $B^0 \to \mu^+\mu^-$ predicted to be lower by a factor of 30
  - CMS+LHCb combined results:

$$Br(B_s^0 \to \mu^+\mu^-) = 2.8 \pm^{0.7}_{0.6} \times 10^{-9} \quad (6.2\sigma)$$

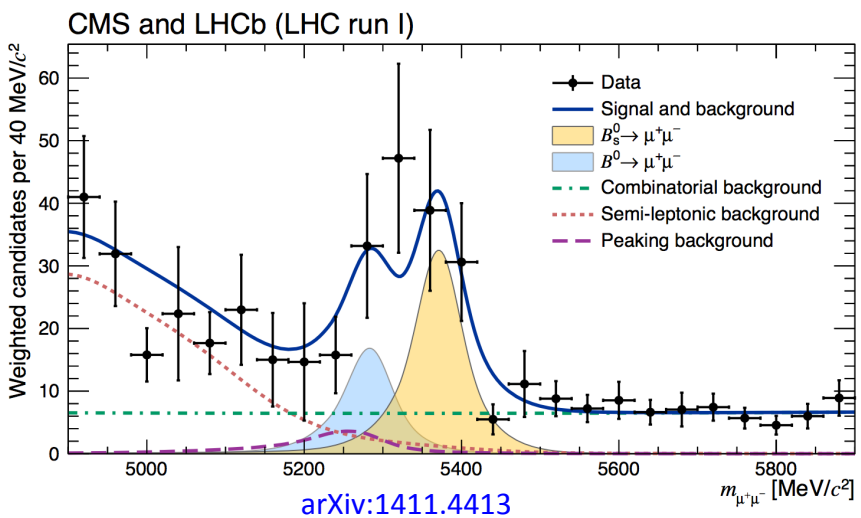
$$Br(B^0 \to \mu^+\mu^-) = 3.9 \pm^{1.6}_{1.4} \times 10^{-10} \quad (3.2\sigma)$$

ATLAS measures lower values:
arXiv:1604.04263

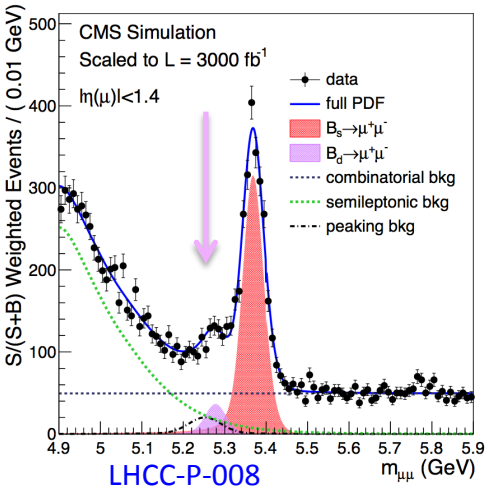
  - $Br(B_s^0 \to \mu^+\mu^-)$ will be precisely measured at the HL-LHC
  - $Br(B^0 \to \mu^+\mu^-)$ should be well measured with expected significance of 6.9σ



arXiv:1307.5025



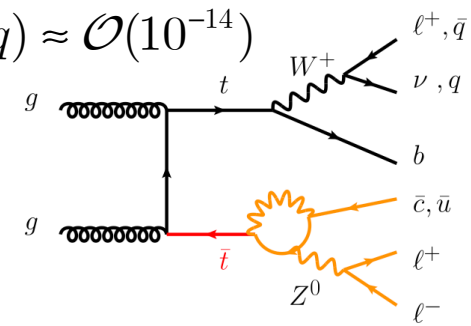
arXiv:1411.4413



LHCC-P-008

Top Quark: Mass, Rare Decays

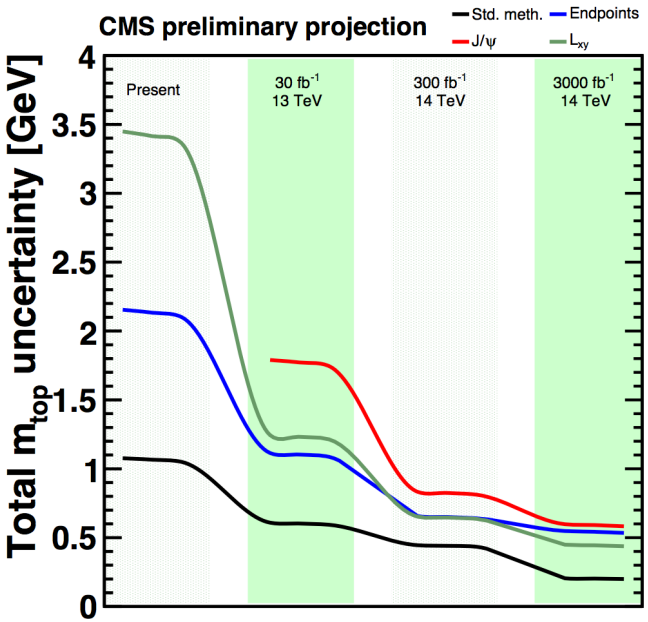
- Searches for FCNC via $t \to Zq$: SM predicts $BR(t \to Zq) \approx \mathcal{O}(10^{-14})$
  - Can be $\mathcal{O}(10^{-4})$ in some BSM models:
    - Current CMS limit 5 x 10^{-4} (9 x 10^{-4} expected)
      - Phys. Rev. Lett. 112 (2014) 171802
    - CMS Projects 95% CL limit for 3000 fb^{-1}: 1 x 10^{-4}



CMS-PAS-FTR-13-016

- Top quark mass determination: CMS has investigated expected precision on the top quark mass for a number of techniques. Expect ~ 200 MeV precision for 3000 fb^{-1} (with standard methods)

	Current	Future			Comment
Center-of-mass energy	7 TeV	13 TeV	14 TeV	14 TeV	
	l+jets				
Integrated luminosity	5 fb^{-1}	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}	
Fit calibration	0.06	0.03	0.03	0.03	MC statistics
b-JES	0.61	0.27	0.09	0.03	3D fit
Residual JES	0.28	0.28	*0.2*	*0.06*	*differential*
Lepton energy scale	0.02	0.02	0.02	0.02	unchanged
Missing transverse momentum	0.06	0.06	0.06	0.06	unchanged
Jet energy resolution	0.23	0.23	*0.2*	*0.06*	*differential*
b tagging	0.12	0.06	0.06	0.06	factor 2 (data)
Pileup	0.07	0.07	0.07	0.07	unchanged
Non-$t\bar{t}$ background	0.13	0.06	0.06	0.06	factor 2 (S/B)
Parton distribution functions	0.07	0.04	0.04	0.04	factor 2 (PDF fits)
Renormalization and factorization scales	0.24	0.12	0.12	*0.06*	full NLO + *differential*
ME-PS matching threshold	0.18	0.09	0.09	*0.06*	full NLO + *differential*
Underlying event	0.15	0.15	0.15	*0.06*	*differential*
Color reconnection effects	0.54	0.27	*0.2*	*0.06*	factor 2 + *differential*
Systematic	0.98	0.60	0.44	0.20	
Statistical	0.43	0.15	0.05	0.01	
Total	1.07	0.62	0.44	0.20	



CMS-PAS-FTR-13-017

Summary

- Detector design, physics & performance studies well advanced and continuing:

- Preparations in progress for ECFA HL-LHC 2016 (3-6 Oct, Aix-Les-Bains):
  - Performance updates planned (reference upgrade detectors + options)
- Many existing performance studies not optimized for higher energy and $\mathcal{L}$
- Most are also not fully optimized to take advantage of detector upgrade features
- Detector design and associated performance studies will continue to evolve