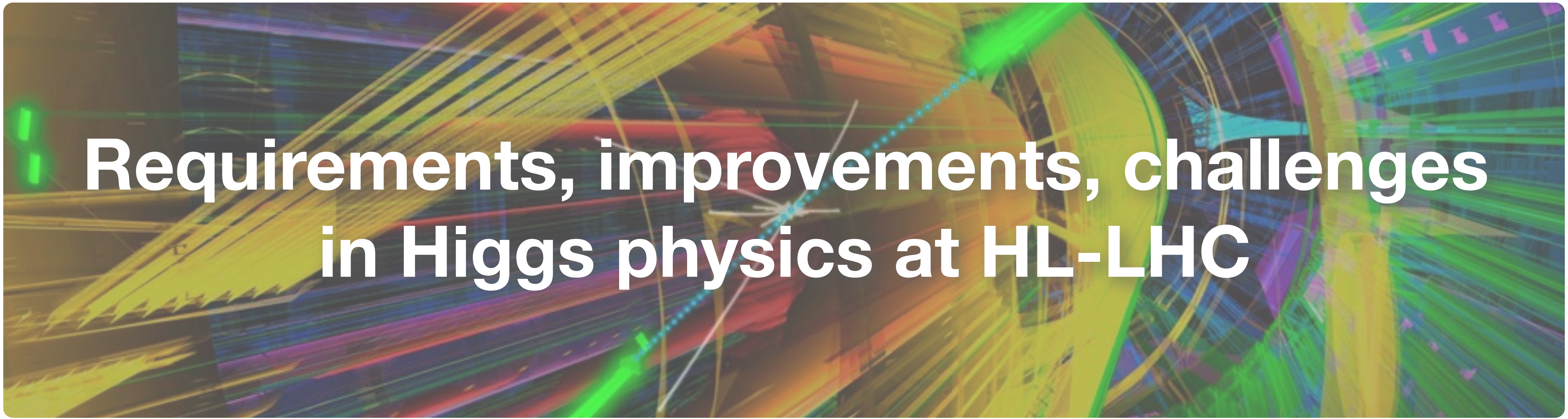


Requirements, improvements, challenges in Higgs physics at HL-LHC

Precision theory
for precise measurements
at the LHC and future colliders
25/9 - 1/10 2016
Quy Nhon, Vietnam

Ioannis Nomidis
on behalf of ATLAS+CMS collaborations

Carleton
UNIVERSITY

Requirements, improvements, challenges in Higgs physics at HL-LHC

- We are required to improve, and that poses a challenge…
    - on the detectors
    - on the analyses
    - on the theory

☞ *To exploit the full potential of the HL-LHC, improvements are mandatory in all aspects*

In this presentation:

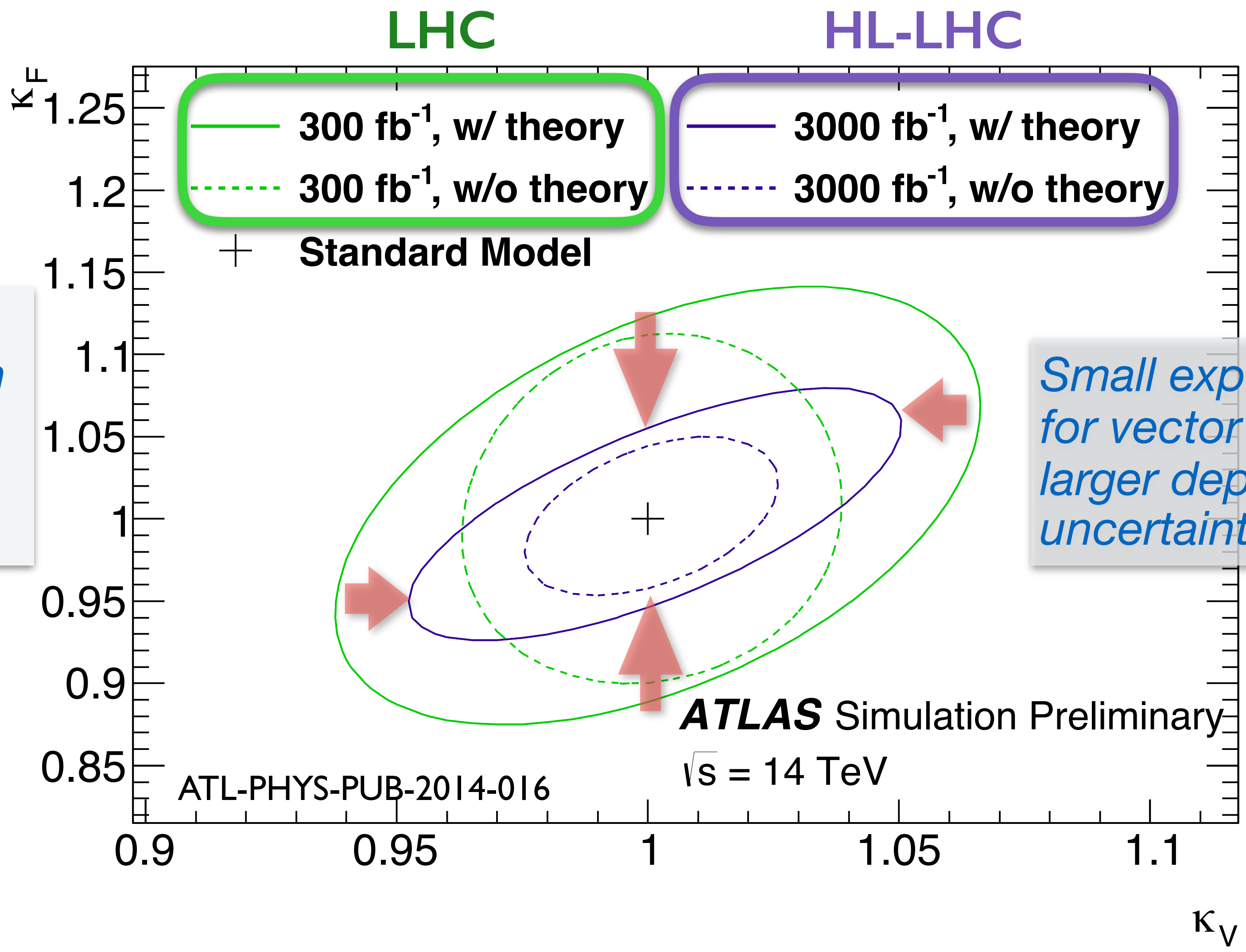
- Plans for detector upgrade
- Projected performance of object reconstruction
- Projected analysis results for interesting channels
- Theory dependence of measurements

For expected results with <3000 fb^{-1}, see talks (29/9) by A. Perieanu (CMS) and O. Boeriu (ATLAS)

Goal for Higgs physics at the HL-LHC

- Measure the couplings of the Higgs boson with few per-cent accuracy

The larger dataset will improve mostly the fermion coupling measurements which generally benefit from higher statistics



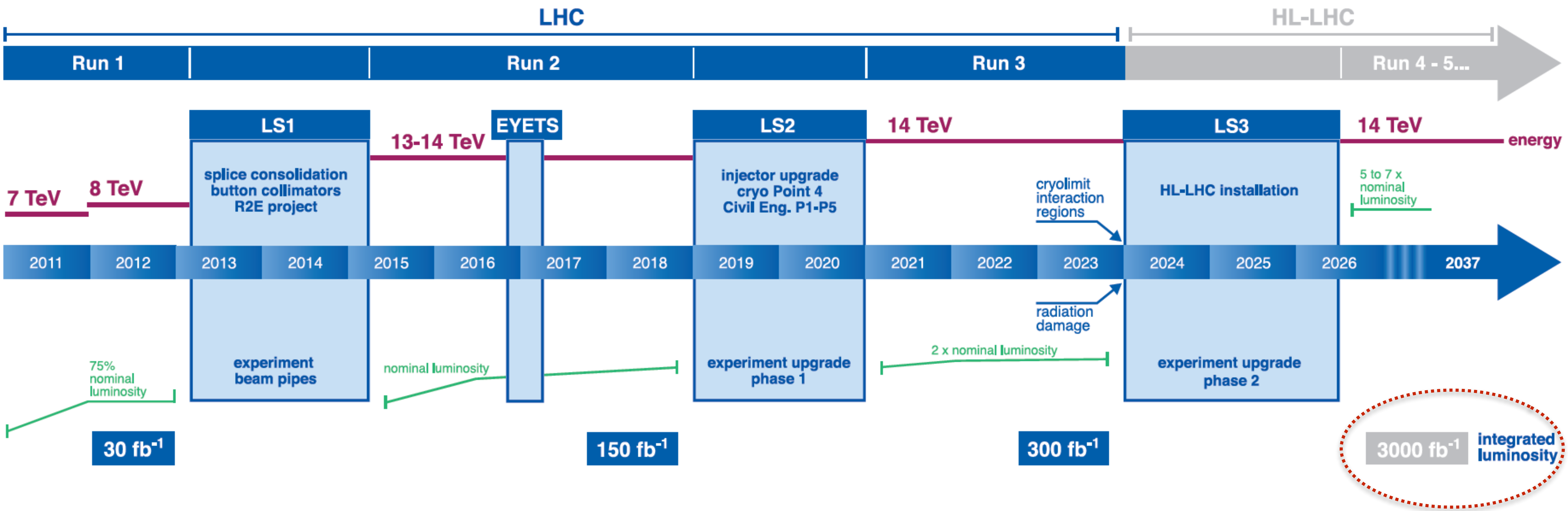
Small experimental uncertainties for vector boson couplings, so larger dependence on theoretical uncertainties

- Access to rare decays and Higgs-pair production

Measurements are extremely important to BSM phenomenology

- Also: direct searches for heavy Higgs partners

LHC / HL-LHC Plan



- Aiming to increase the dataset from 300 fb^{-1} to 3000 fb^{-1} after 10 years of operation (2026-2037)
- Instantaneous luminosity must go up to 5-7.5 × 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, **extreme pile-up conditions** with up to 140-200 interactions per bunch crossing on average ($\langle\mu\rangle$) and **high radiation levels**
- Detector and trigger improvements are mandatory in order to keep the same level of performance and precision physics capability

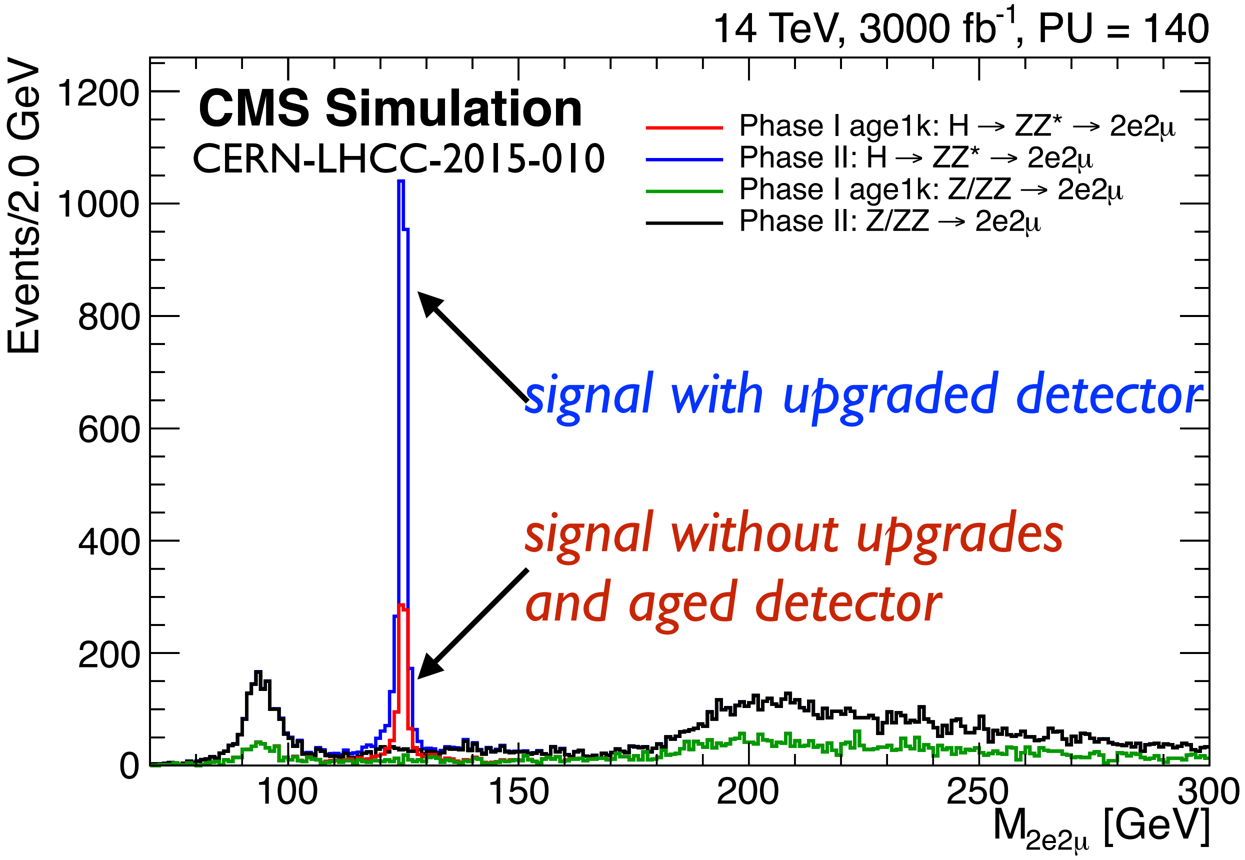
ATLAS and CMS detector upgrade is imperative…

➡ Due to aging that would degrade the performance dramatically

➡ Current detectors simply cannot handle $\langle\mu\rangle$ of 140 or above

Life in 2030 with $\langle\mu\rangle$ ~ 140 without upgrades

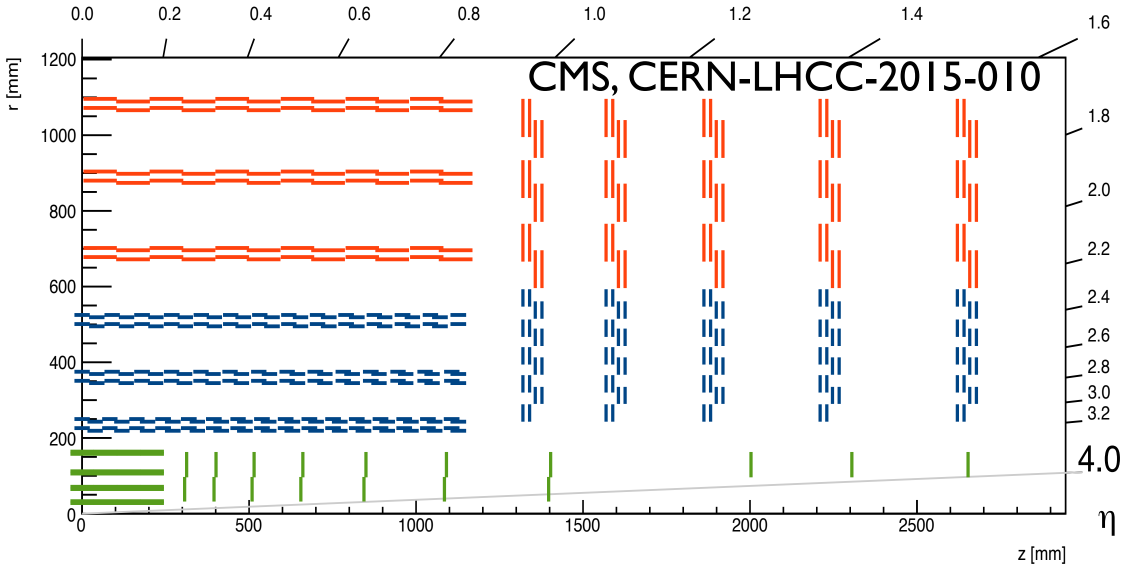
- Trigger: p_T thresholds will rise, will be losing interesting events
- Inner tracker: performance will drop dramatically for efficiency; much higher fake rates
  - Degradation of primary vertex reconstruction and identification will have strong impact on b-tagging performance and pile-up jet suppression
- Calorimeters: swamped with noise
  - Challenge on jet energy resolution and missing E_T
- Physics example: highly reduced yields for one of the ‘golden’ channels, H→ZZ→4ℓ



The upgraded detectors should help to maintain similar levels of performance as today.

ATLAS and CMS detector upgrade

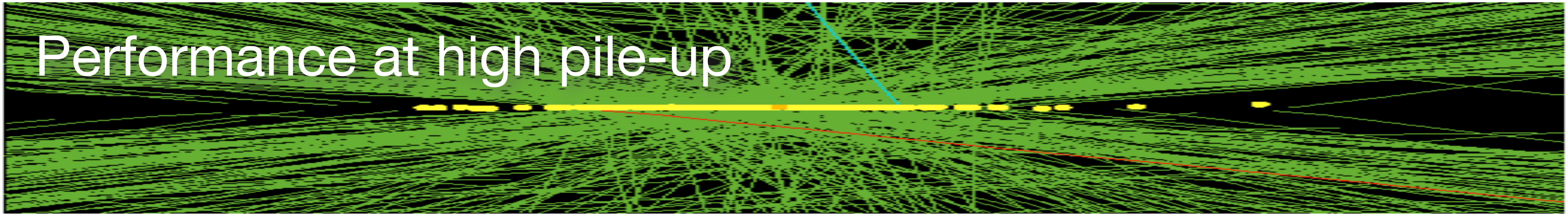
*Very similar planning between the two experiments for the Phase-II upgrade; different scenarios studied but **decision not taken yet***



- Replacement of inner detectors with all-Si trackers
    - Better radiation tolerance, high granularity; maintain efficiency and acceptable fake rate
- Considering extending coverage of tracking detectors up to as far as |η|=4
    - Tracker extension extremely useful for pile-up mitigation in the forward region
- Smarter and faster electronics for trigger at level-1 to keep the p_T thresholds low
    - Increased latency (10-30 μsec) and output rate (400-1000 kHz) for L1 trigger
- Upgrades to muon systems
    - For better performance and triggering at large |η|, already in Phase-I upgrade for ATLAS, later for CMS
- Forward calorimetry
    - CMS to replace endcap calorimeter with "HGCAL" (with good timing)
    - ATLAS considering new high-granularity calorimeter and dedicated timing detector

Scoping documents:
CMS: CERN-LHCC-2015-019
ATLAS: CERN-LHCC-2015-020

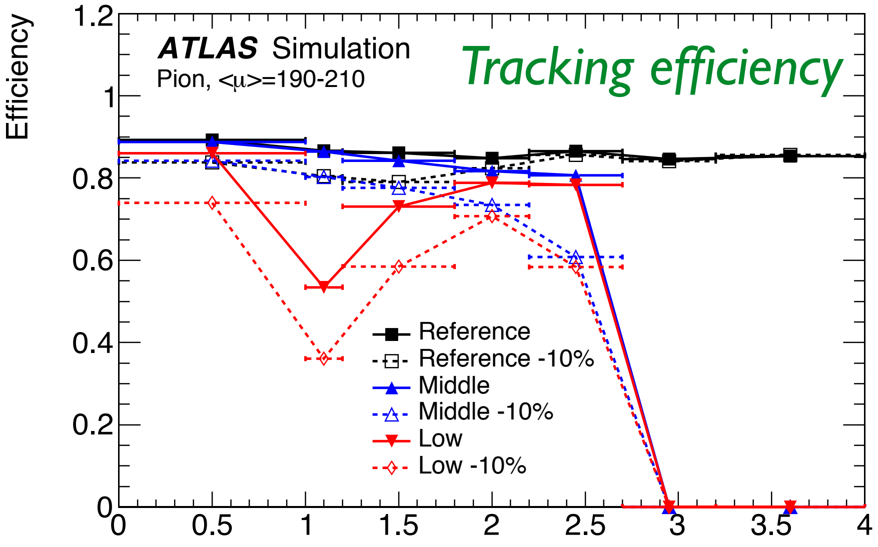
Performance at high pile-up



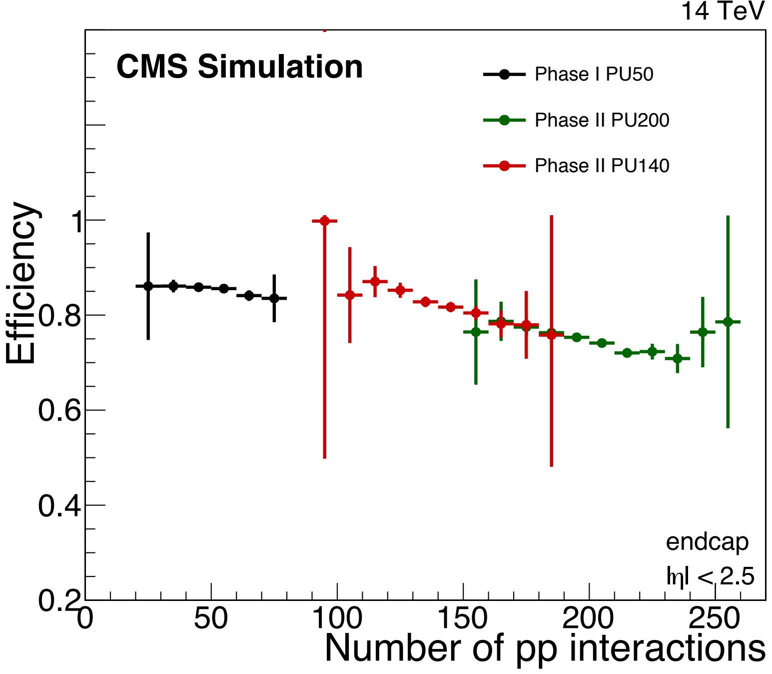
- Detector response modelled with full Geant4 simulation of benchmark processes (e.g. ttbar, $Z \to \ell\ell$)
- Pile-up assumed to be $\langle \mu \rangle$=140/200 and is added by overlaying minimum-bias events in generated processes
- *Note-I*: reconstruction + identification not fully optimized for extreme pile-up conditions
- *Note-II*: simple pile-up mitigation techniques are utilized

Scoping documents:
CMS: CERN-LHCC-2015-019
ATLAS: CERN-LHCC-2015-020

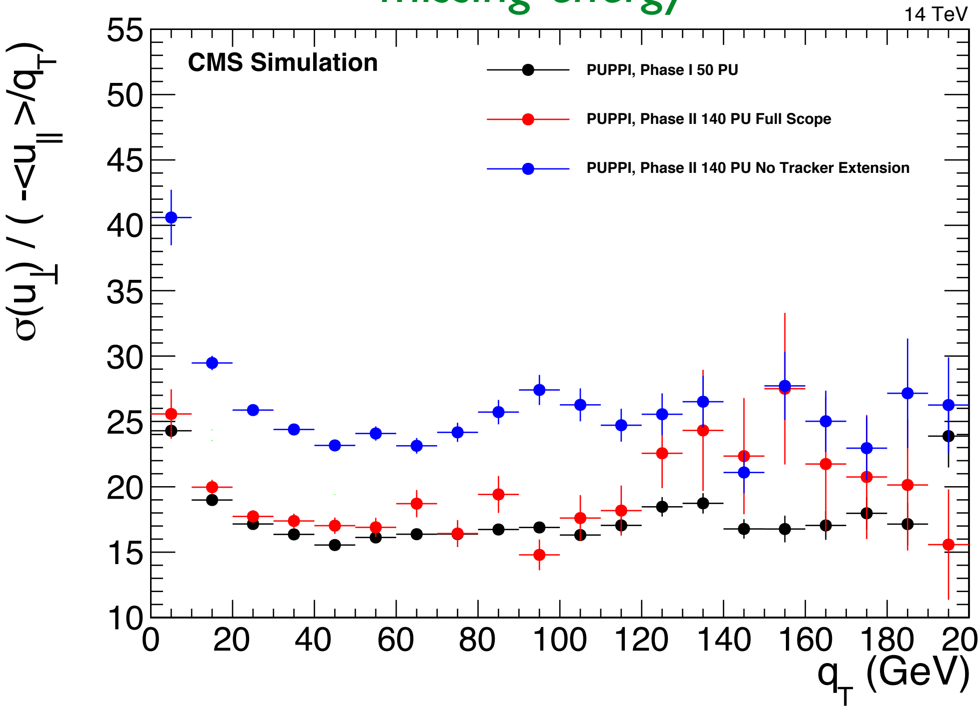
Tracking efficiency

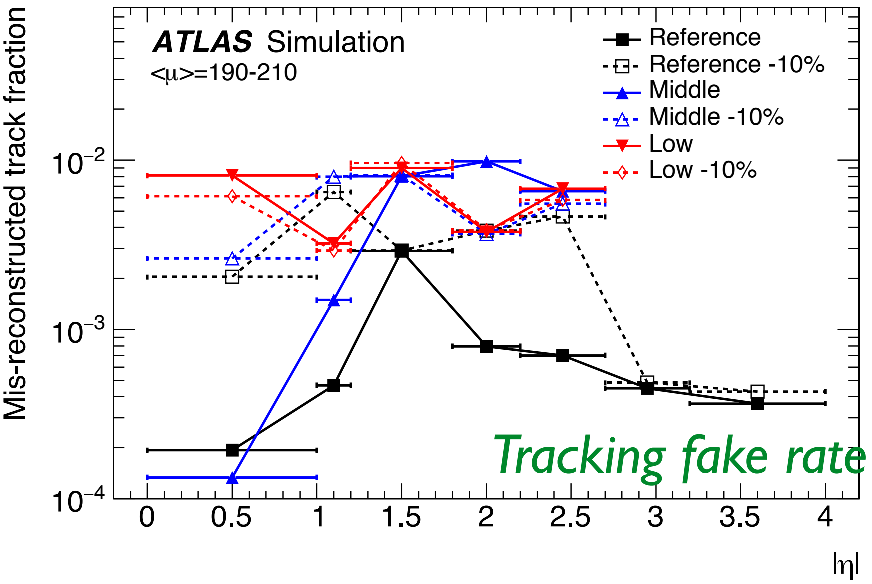


e-reconstruction



missing energy





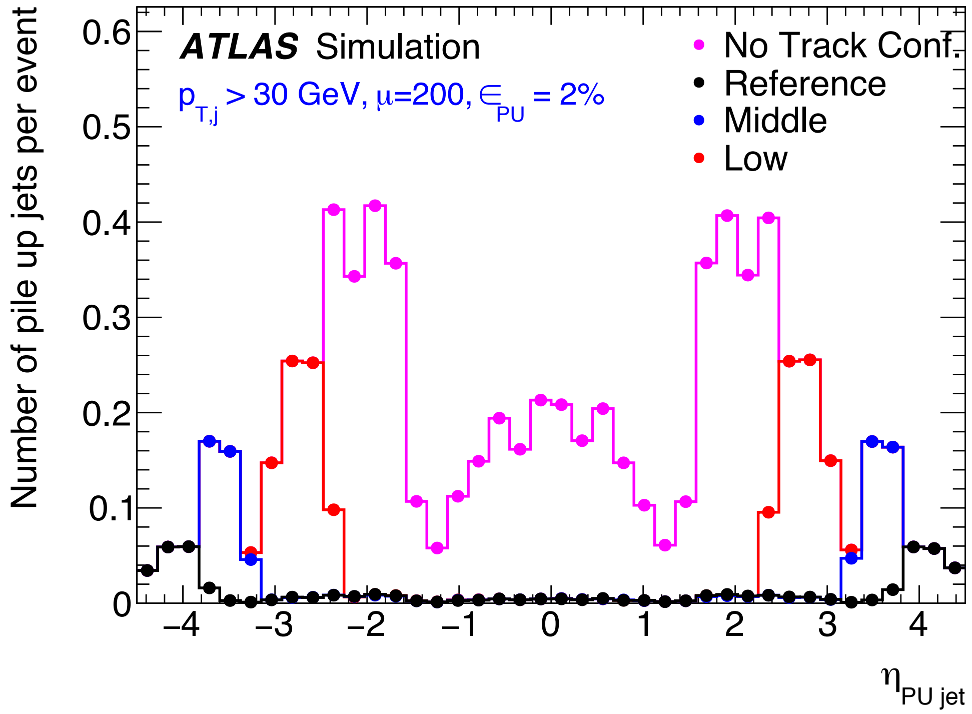
Tracking fake rate

Pile-up mitigation

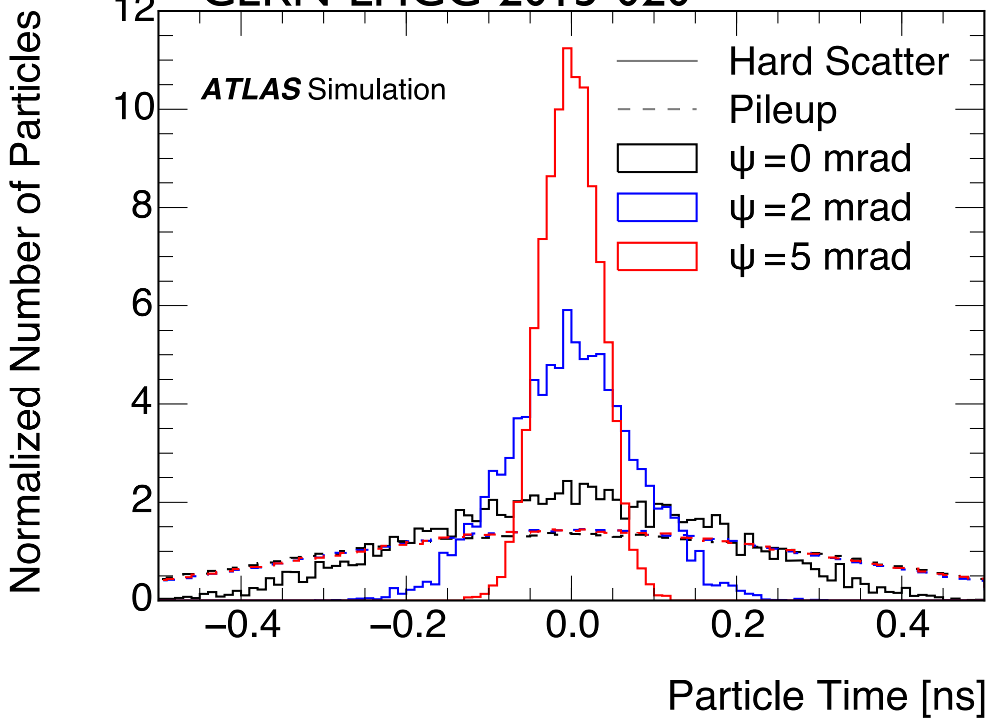
See also talk by N.Tran (29/9)

- Critical aspect for almost all analyses
- Basic approach: associate tracks of jet with the primary vertex
    - Tracker extended in |η| helps
- Other ideas to mitigate pile-up:
    - With timing information from the calorimeters
    - With longer beam spot

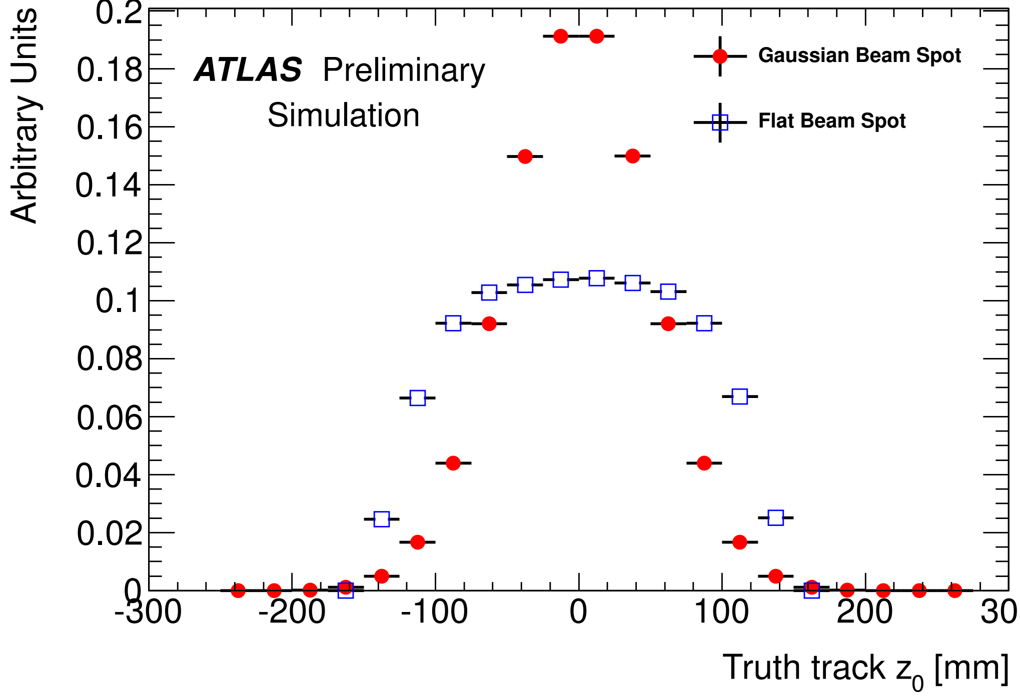
CERN-LHCC-2015-020



CERN-LHCC-2015-020



ECFA 2014



Projection methodology

- *ATLAS*:
  - Resolution and efficiency are extracted from fully-simulated benchmark processes
  - Corrections functions are applied on generator-level objects to emulate detector response
  - Performance of upgraded detector most times is similar as today, so keeping systematics at the same level
  - Quoting results with full theoretical uncertainties (as in Run-I or with best available), also reduced to 50% and 0%
- *CMS*:
  - For combination results: projecting current analyses to 3 ab^{-1}, assuming same performance as today
  - Quoting results with total systematics as in Run-I ('scenario 1') or with theoretical uncertainties reduced by 50% and systematics scaled by $1/\sqrt{L_{int}}$ ('scenario 2')
  - For dedicated analyses (HH): detector response extracted from fully-simulated benchmark processes, using smearing functions on generator-level objects or Delphes fast simulation
  - Full simulation for $H \rightarrow ZZ^* \rightarrow 4\ell$

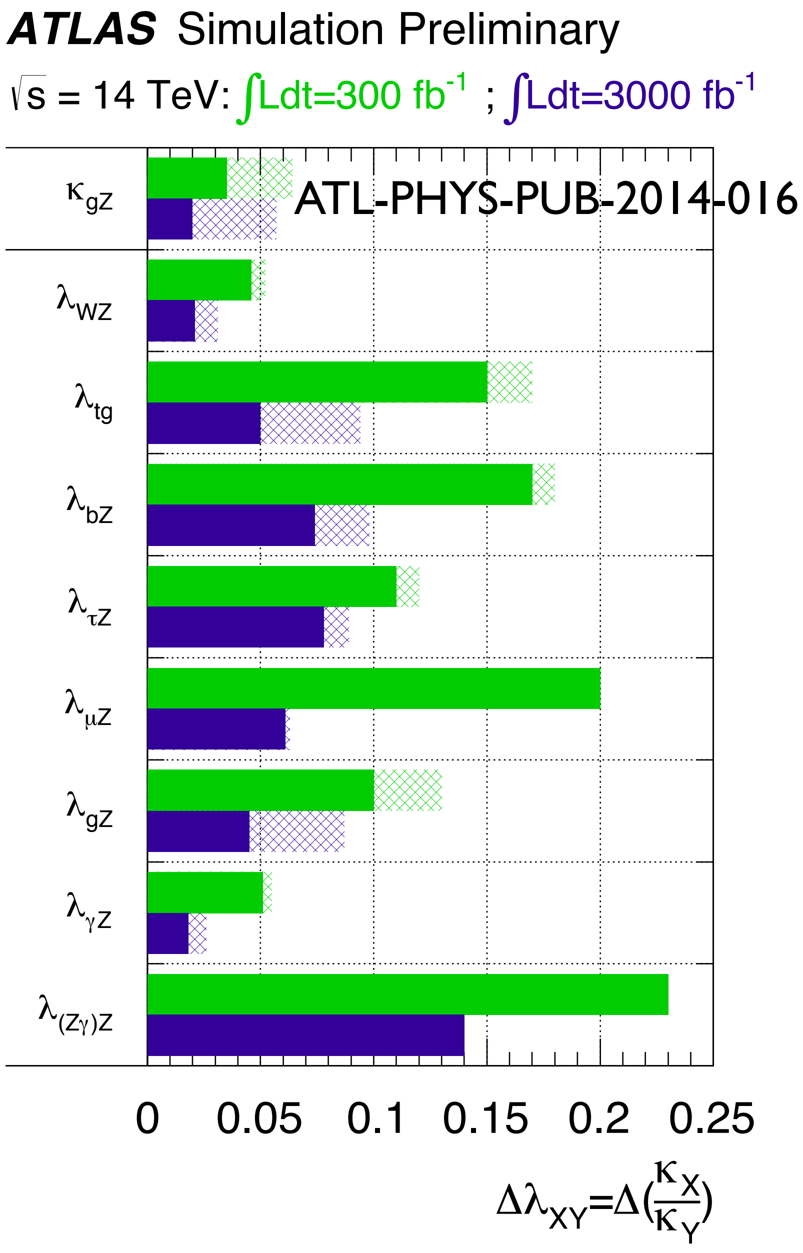
Coupling precisions

- Using narrow-width approximation for Higgs, can relate observed yields to production cross-section (σ_i) and partial +total decay widths (Γ_i, Γ_{tot}):

$$(\sigma \cdot BR)(i \to H \to f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_{\text{tot}}}$$

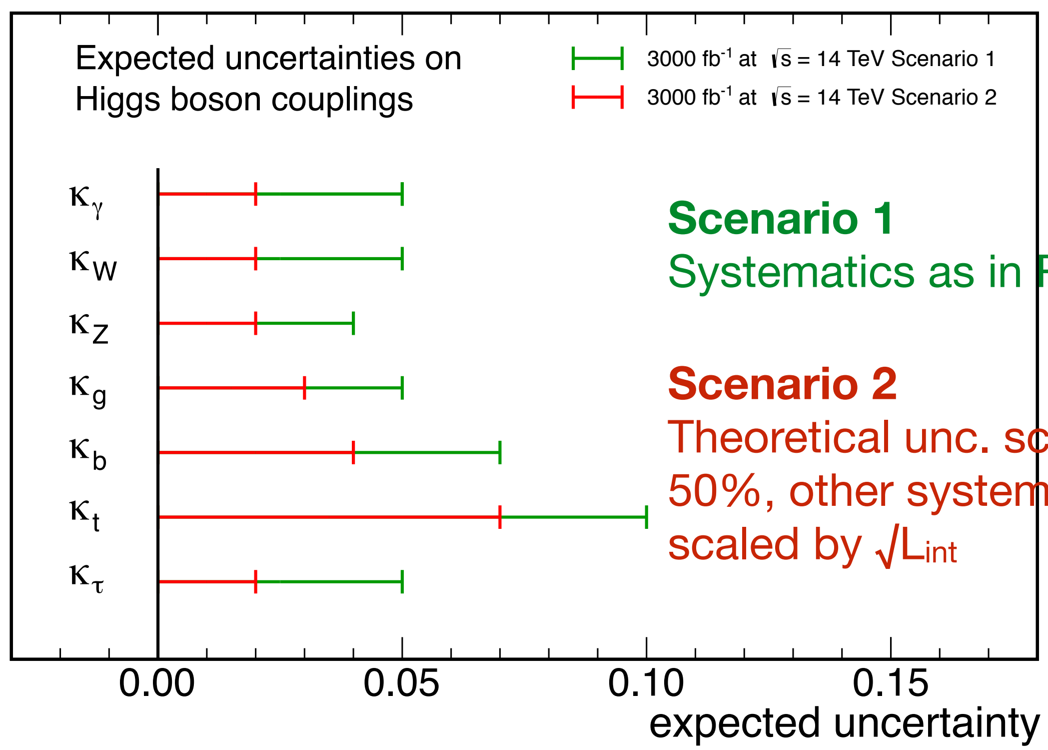
- Expressing compatibility of measurements with respect to SM expectation with the coupling modifiers (κ_x) and their ratios ($\lambda_{xy}=\kappa_x/\kappa_y$)

- Ultimate precision: <5% for κ, λ



ATL-PHYS-PUB-2014-016

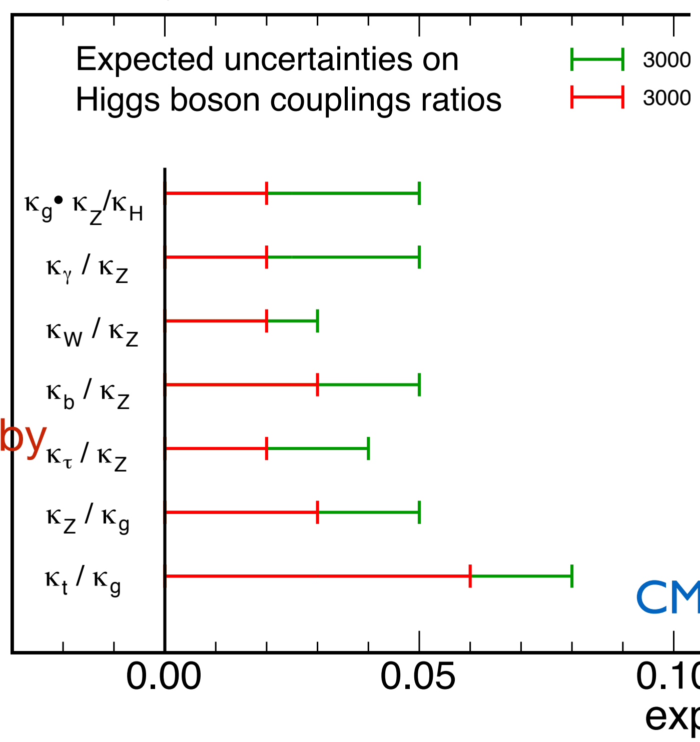
CMS Projection



Scenario 1
Systematics as in Run-1

Scenario 2
Theoretical unc. scaled by 50%, other systematics scaled by $\sqrt{L_{int}}$

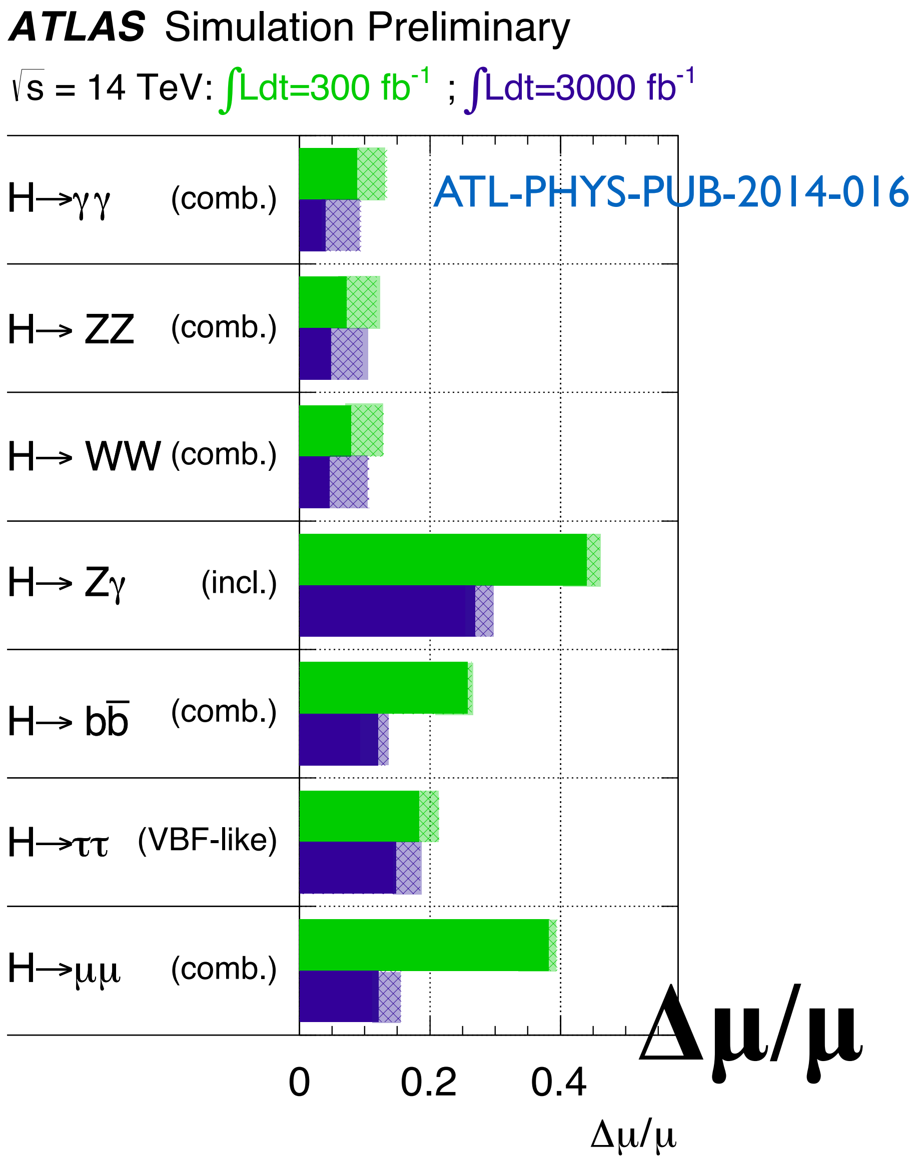
CMS Projection



CMS NOTE-13-002

Signal strength precisions

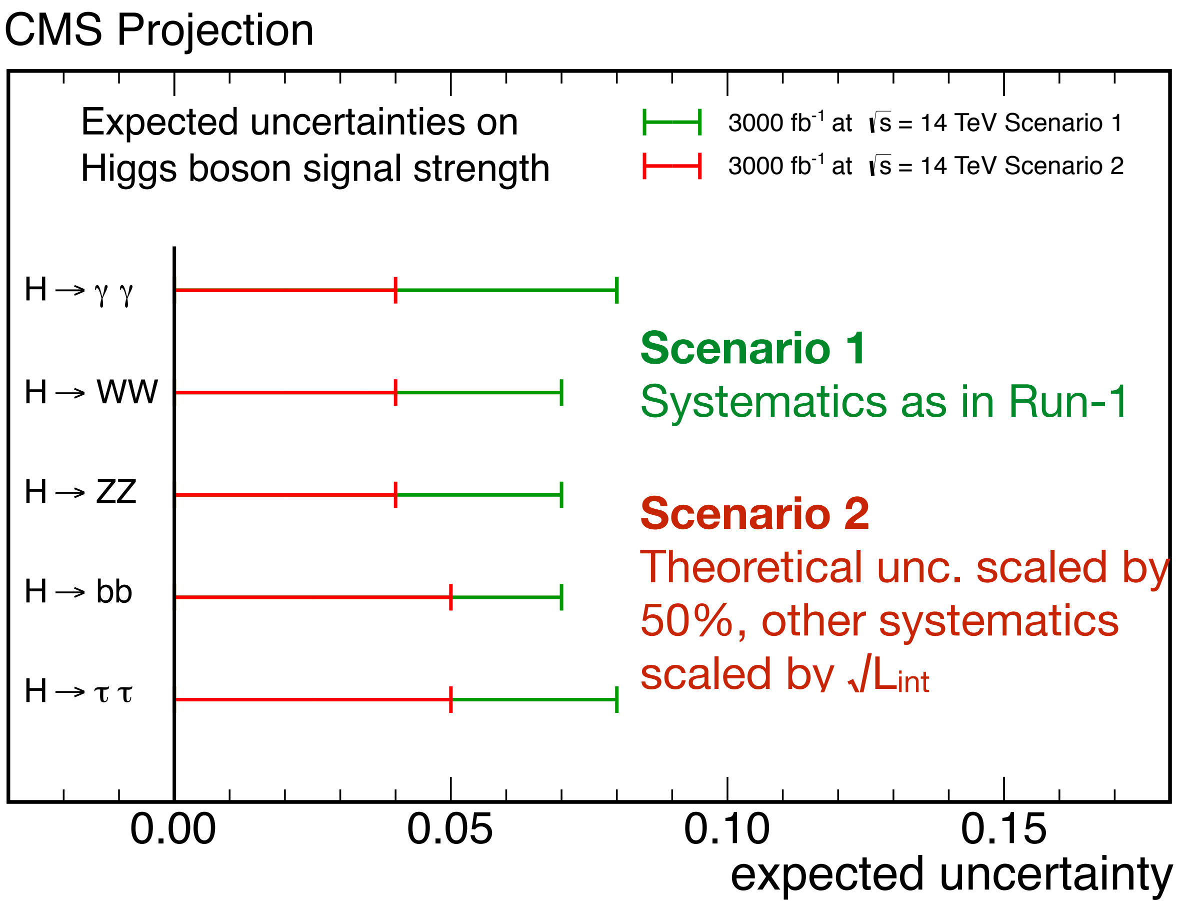
- Signal strength (μ) used to express compatibility of σ×BR measurements with theory
- Goal is to minimize the uncertainty of the measurements (Δμ/μ) — QCD+PDF uncertainties become significant



ATL-PHYS-PUB-2014-016

CMS NOTE-13-002

L (fb^{-1})	$\gamma\gamma$	WW	ZZ	bb	$\tau\tau$	$Z\gamma$	$\mu\mu$	inv.
300	[6, 12]	[6, 11]	[7, 11]	[11, 14]	[8, 14]	[62, 62]	[40,42]	[17, 28]
3000	[4, 8]	[4, 7]	[4, 7]	[5, 7]	[5, 8]	[20, 24]	[20,24]	[6, 17]



Scenario 1
Systematics as in Run-1

Scenario 2
Theoretical unc. scaled by 50%, other systematics scaled by $\sqrt{L_{int}}$

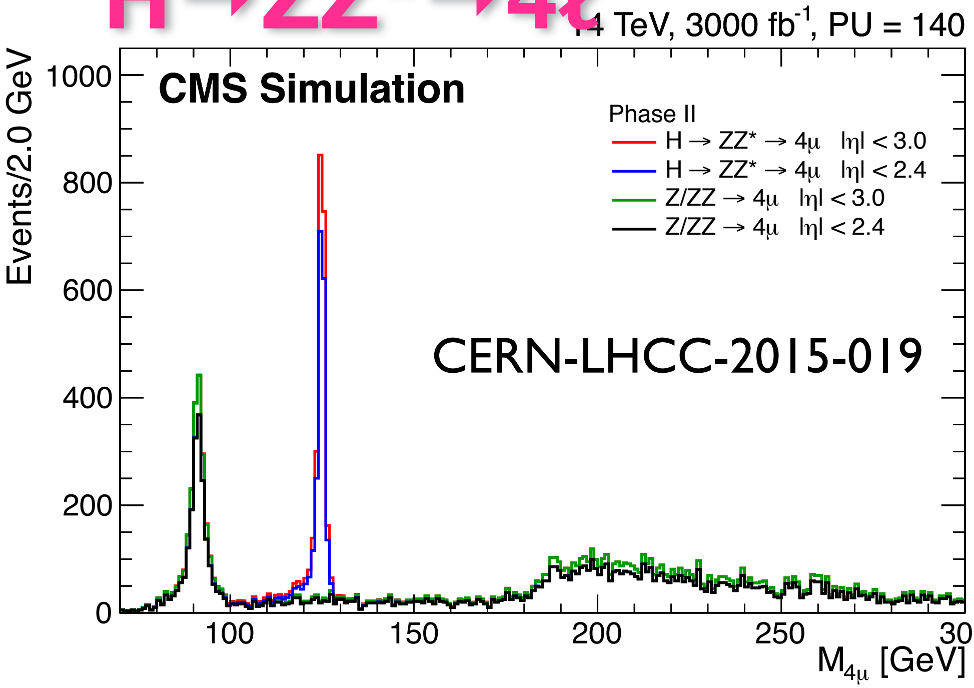
Very similar precisions for ATLAS and CMS projections.

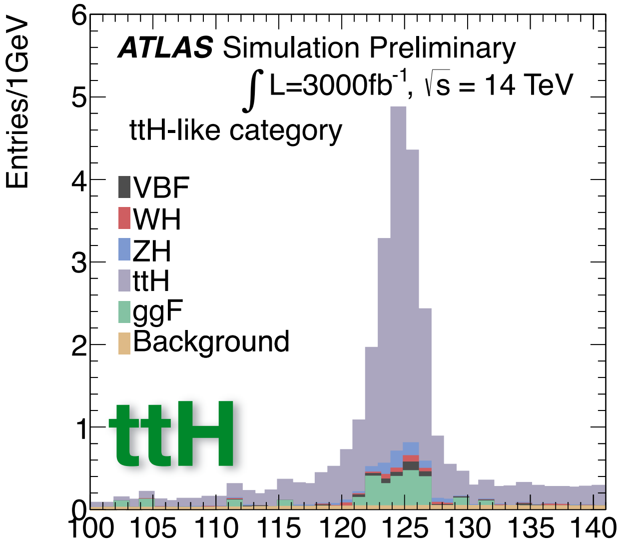
Some large differences (H→ττ, H→bb) due to more channels used in the combination for CMS

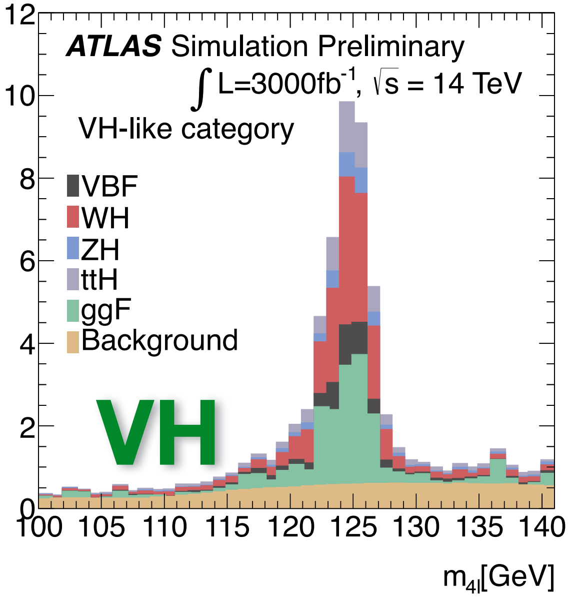
‘Golden’ channels: H→ZZ*→4ℓ (ℓ=e,μ) and H→γγ

- Clean signal peaks on top of smooth background continuum; good performance even in these extreme conditions
- Can provide clean observation of all production modes

H→ZZ*→4ℓ



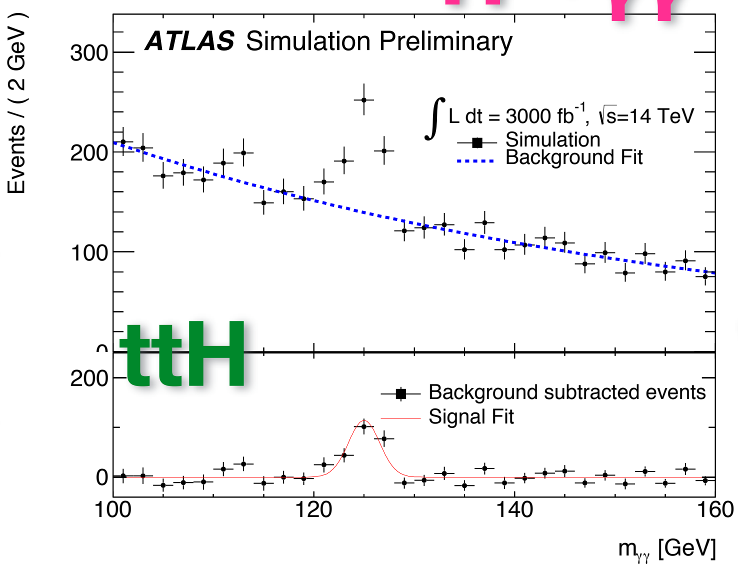


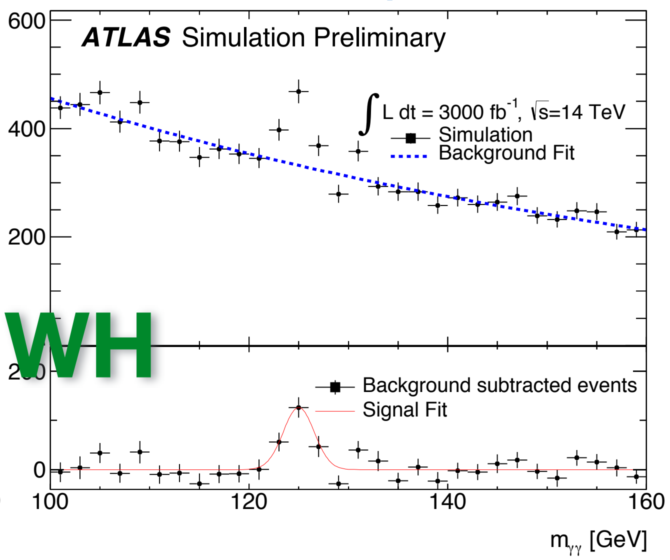


ATL-PHYS-PUB-2013-014

H→γγ

⟨μ⟩=140





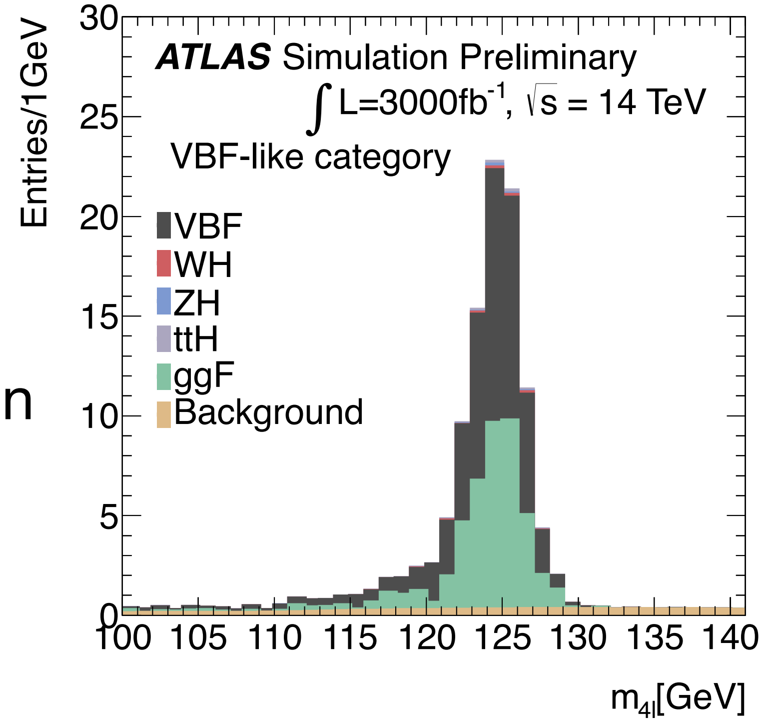
	$t\bar{t}H$	WH	ZH
Significance	8.2	4.2	3.7

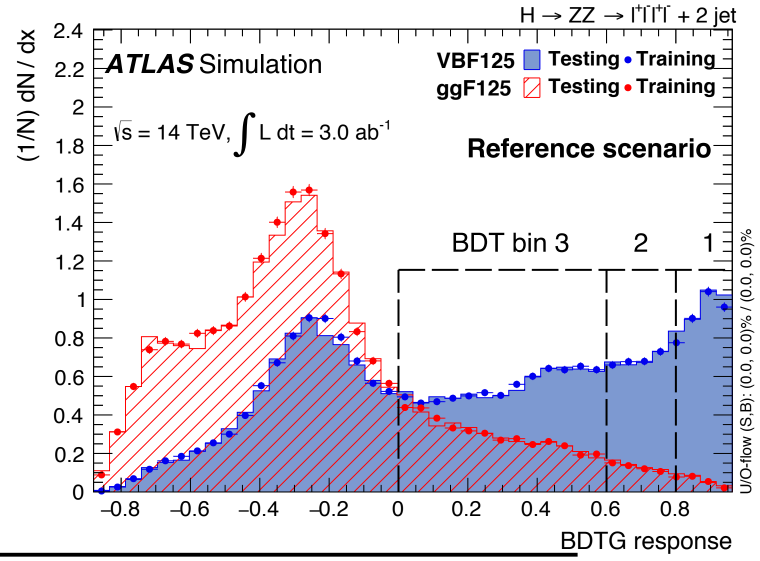
ATL-PHYS-PUB-2014-012

	$\Delta\hat{\mu}/\hat{\mu}$ (%)			
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 H→ZZ*→4ℓ

- Must disentangle ggF/VBF production modes
- Must control the background from pile-up jets in the forward region
- Analysis approach: using BDT method for optimal signal/background separation
- Nice case study to quantify benefit from upgraded detector: extended tracking scenarios (‘reference’, ‘middle’) greatly help in reducing pile-up background, pile-up background doubles in the modest scenario (‘low’)
- Notice vulnerability of measurements to large theoretical uncertainties (QCD scale for ggF+jets with VBF signature)





	Pile-up impurity (%)		
Scoping scenario	Bin 1	Bin 2	Bin 3
VBF Sample			
Reference	2.0	4.6	13.1
Middle	3.0	6.4	23.6
Low	5.2	12.0	38.7
ggF Sample			
Reference	23.2	37.9	52.1
Middle	24.0	43.4	65.0
Low	41.2	59.4	76.2

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)
0.134	–	11.41	0.167	–	7.64
0.137	125	10.86	0.174	350	7.48
0.142	425	9.84	0.186	1000	6.75

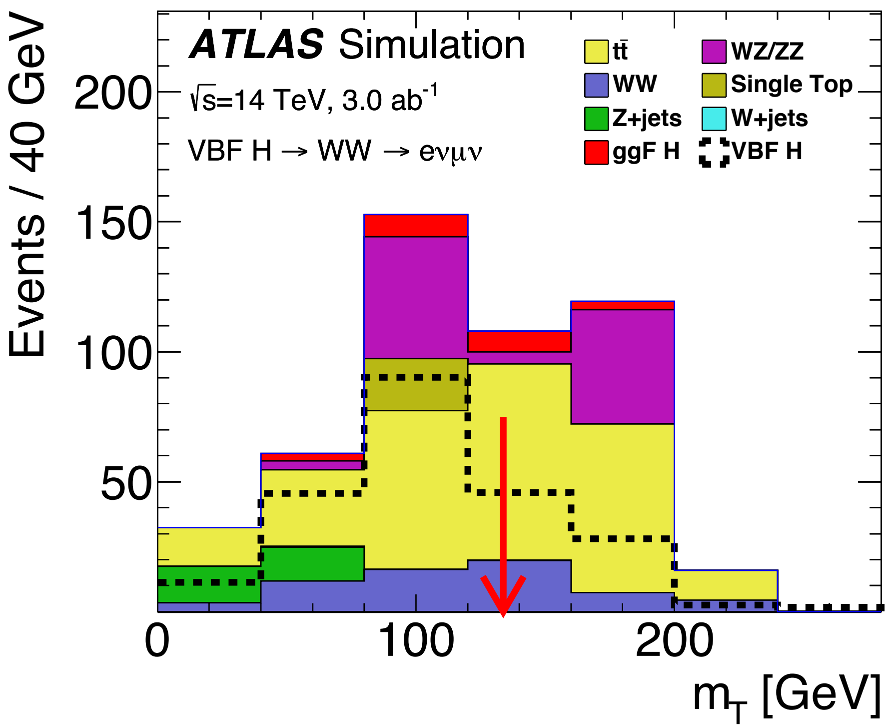
ATL-PHYS-PUB-2016-008

$\langle\mu\rangle$=200

VBF H→WW→ℓνℓν (ℓ=e,μ)

- Particularly challenging due to large backgrounds (dominant systematic uncertainty)
- Good benchmark for performance at HL-LHC conditions: depends on performance of E_T^{miss}, central-jet veto, b-tagging for forward jets (ttbar veto)
- Deficiencies of more modest upgrade scenarios result in larger background contributions that cannot be recovered with larger integrated luminosity
- Careful analysis optimization carried out assuming the predicted performance shows that we can achieve 2.7-7σ significance depending on the upgrade scenario and size of theoretical uncertainties, reaching a precision of 39-16%, respectively

ATL-PHYS-PUB-2016-018



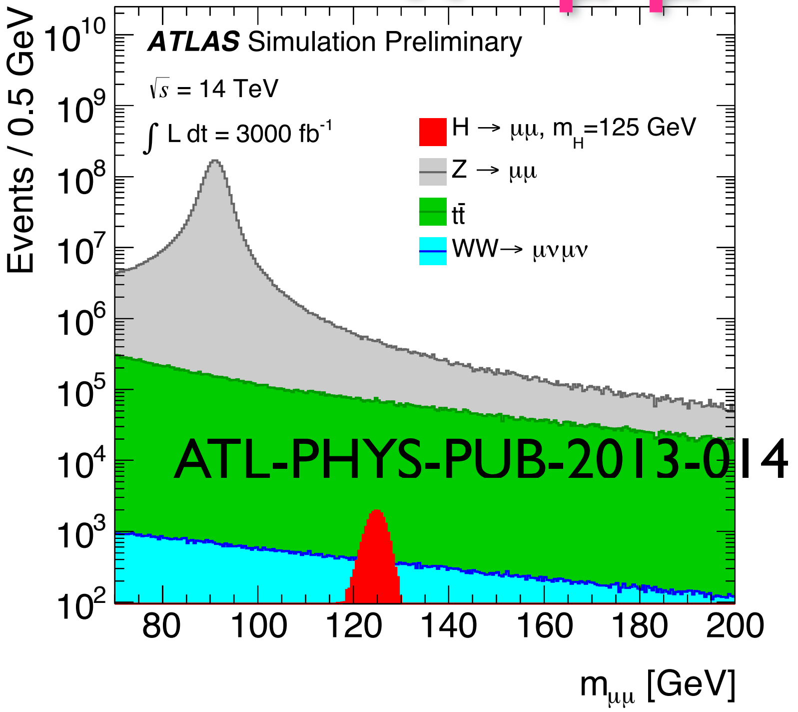
$\langle\mu\rangle$=200

Syst. unc.	ggF (%)	VBF (%)
QCD N_{jet} cross-section	43	1
QCD acceptance	4	4
PDF	8	3
UE/PS	9	3
Total	44	6

Scoping scenario	Δ_μ			**Significance** (σ)		
Signal unc.	Full	1/2	None	Full	1/2	None
Reference	0.20	0.16	0.14	5.7	7.1	8.0
Middle	0.25	0.21	0.20	4.4	5.2	5.4
Low	0.39	0.32	0.30	2.7	3.3	3.5

Rare decays

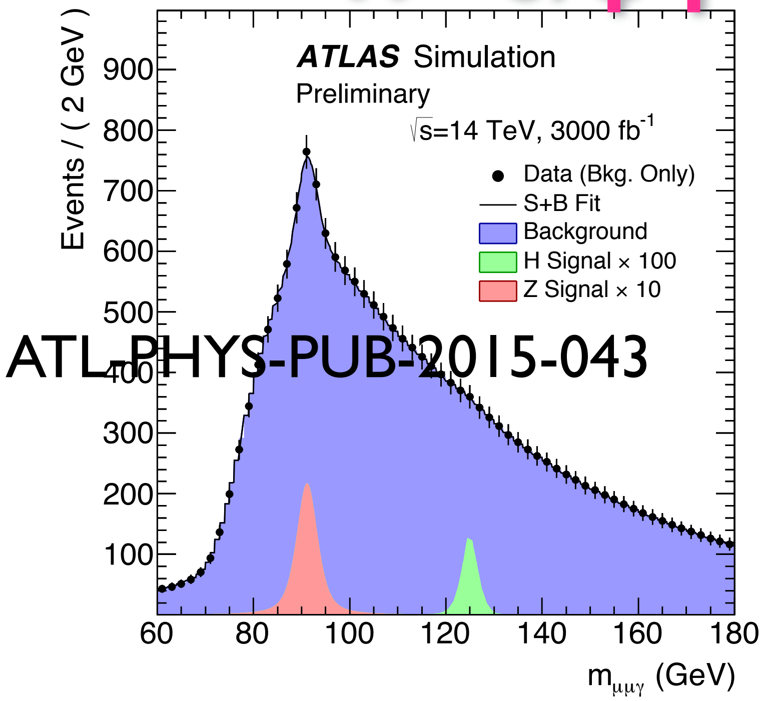
$H \rightarrow \mu^+\mu^-$



ATL-PHYS-PUB-2013-014

- Probe coupling to 2nd generation fermions
- ATLAS: **7σ** observation for ⟨μ⟩ ~140, measurement of 25% (stat.) ⊕ 17% (syst.) precision
- CMS expects 14/20% uncertainty with scenario 2/1 [*]

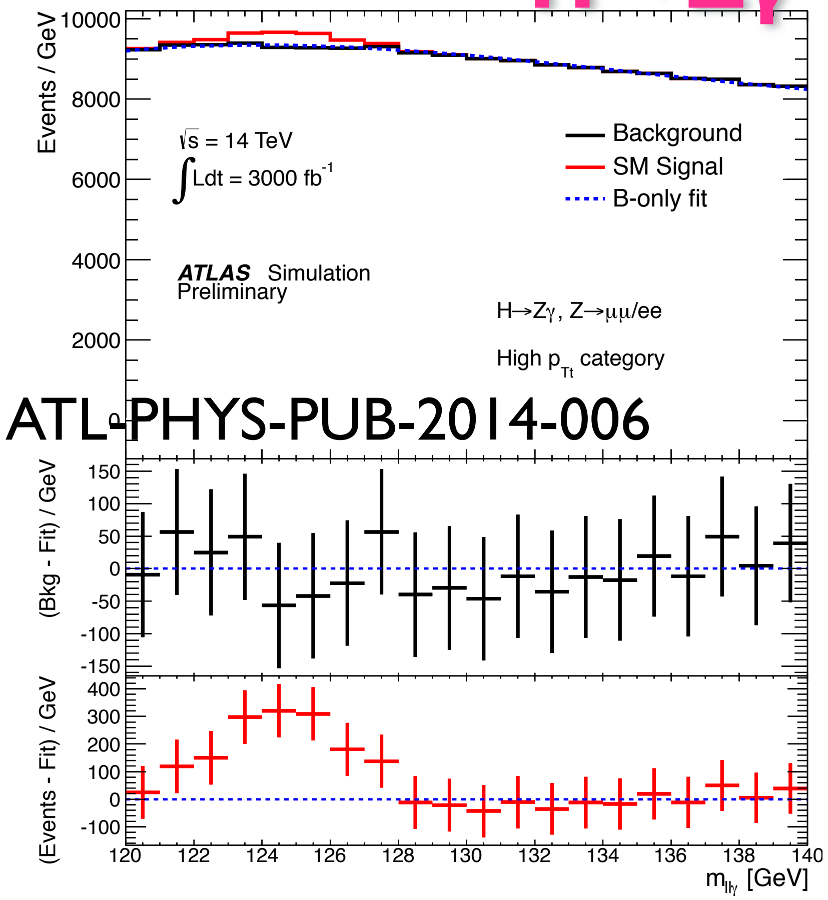
$H \rightarrow J/\psi\ \gamma$



ATL-PHYS-PUB-2015-043

- Probe for Yukawa couplings
- ATLAS anticipates to set the limit of the BR(H→J/ψ γ) at 15×SM expectation
- First limit set from ATLAS at 600×SM (PRL 114 (2015) 121801)

$H \rightarrow Z\gamma$



ATL-PHYS-PUB-2014-006

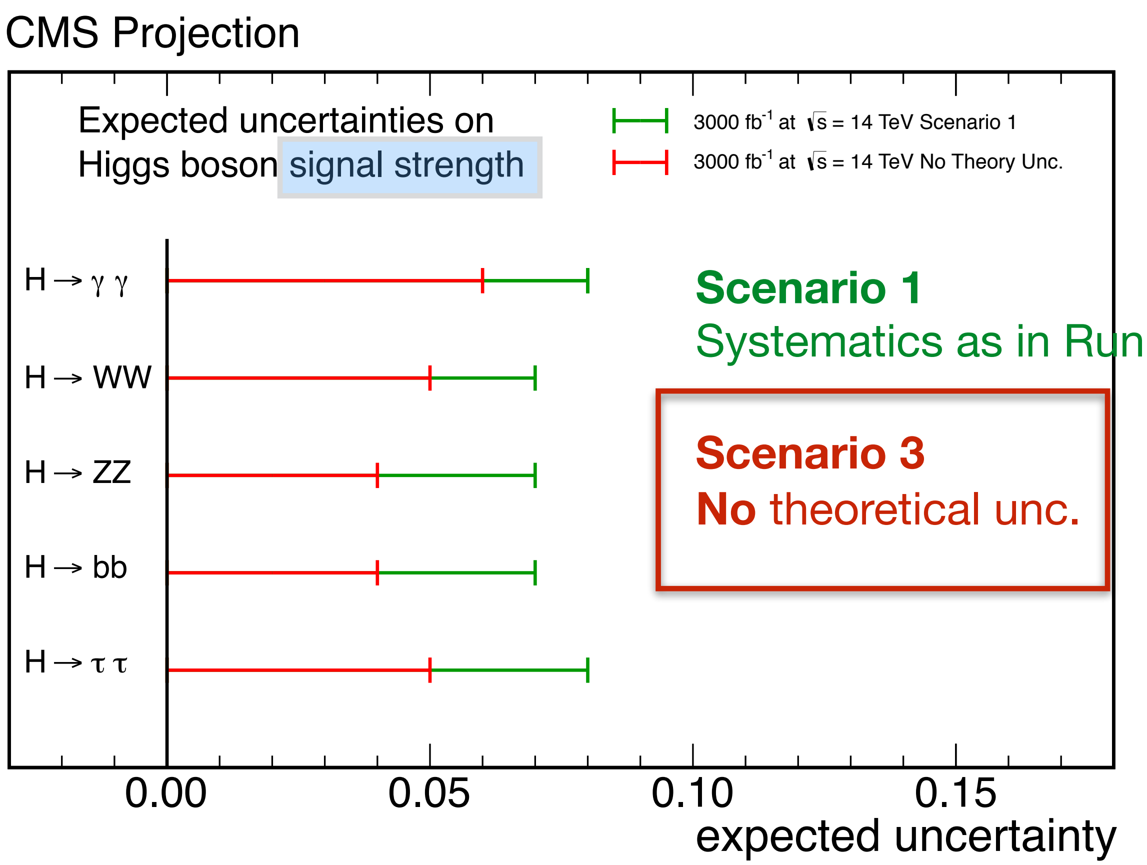
- Probe for new physics in the loop; important for coupling measurement
- ATLAS: **3.9σ** observation for ⟨μ⟩~140, measurement of 25% (stat.) ⊕ 17% (syst.) precision
- CMS expects 20/24% uncertainty with scenario 2/1 [*]

- Rare Higgs decays are sensitive probes for new physics
- Observation at the SM rate for H→μμ, H→Zγ will only be possible with the HL-LHC dataset

[*] CMS NOTE-13-002

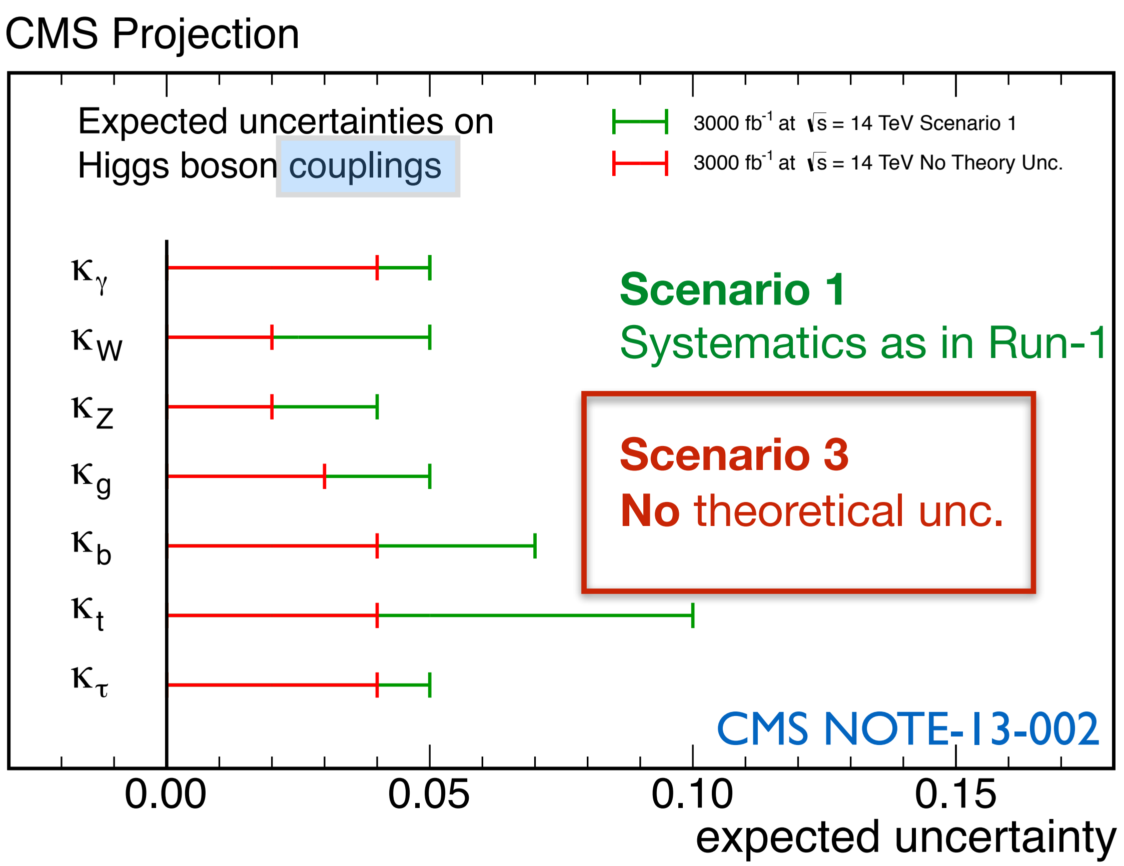
Dependence of measurements on theory input

- Significant contribution from theoretical uncertainties to the total uncertainty, can be up to 50%



Scenario 1
Systematics as in Run-1

Scenario 3
No theoretical unc.



Scenario 1
Systematics as in Run-1

Scenario 3
No theoretical unc.

CMS NOTE-13-002

- To reach the ultimate precision on Higgs measurements, improvements are required also on the theoretical calculations for the signal processes

- Uncertainties for background processes also relevant for specific channels: e.g. electroweak unc. for high mass ZZ (H→4ℓ), V/tt+heavy flavour production for VH/ttH (H→bb)

Theory uncertainties for Higgs signal

- What must be achieved for theory calculations in order to have a smaller than 10% contribution to the total uncertainty

Scenario	Status	Deduced size of uncertainty to increase total uncertainty							
	2014	by $\lesssim$10% for 300 fb^{-1}			by $\lesssim$10% for 3000 fb^{-1}				
Theory uncertainty (%)	[10–12]	κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \rightarrow H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

ATL-PHYS-PUB-2014-016

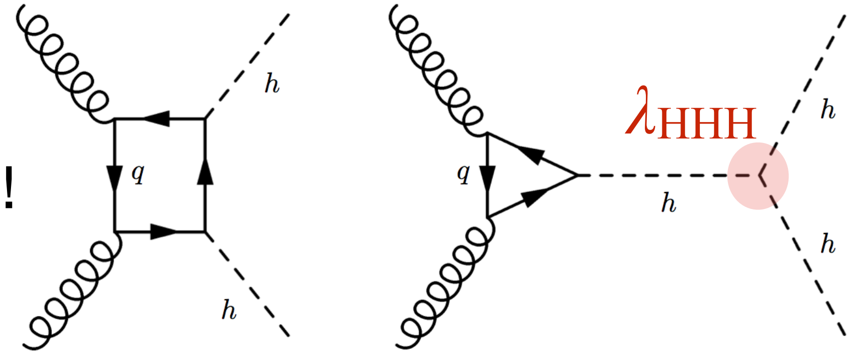
- Need for improved PDFs and QCD calculations

  - ggH: clearly needing higher order calculations for multi-jet final states

The ultimate goal for HL-LHC: HH

- Access to λ_{HHH} is a unique way to fully establish the Higgs field potential, particularly interesting for BSM…

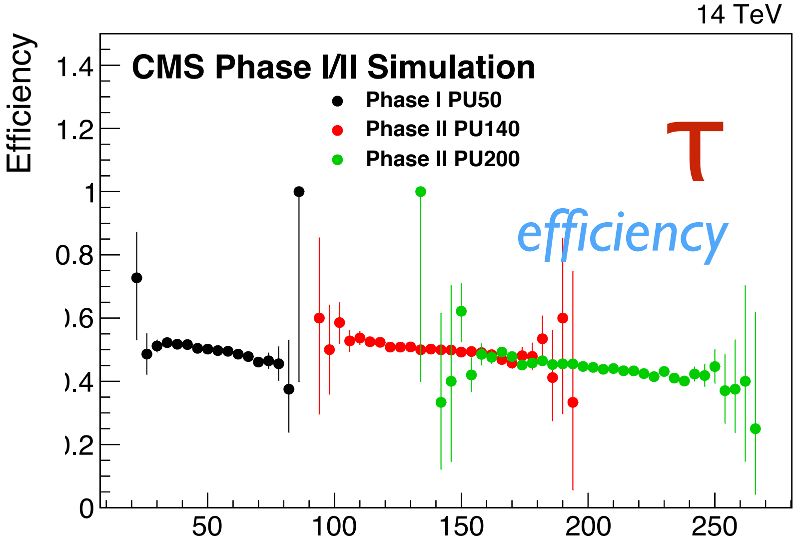
σ(pp→HH)~40 fb @ NNLO!



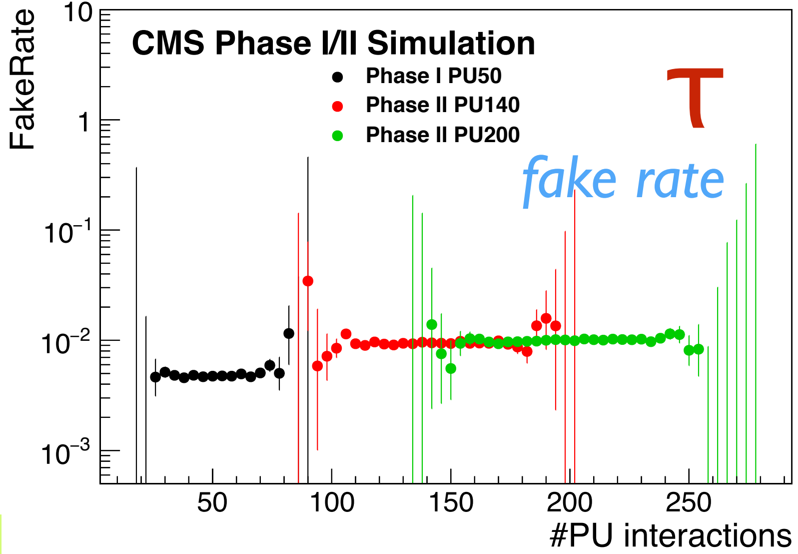
Decay Channel	Branching Ratio	Total Yield (3000 fb^{-1})
$b\bar{b}+b\bar{b}$	33%	4.1×10^4
$b\bar{b}+W^+W^-$	25%	3.1×10^4
$b\bar{b}+\tau^+\tau^-$	7.4%	9.0×10^3
$W^+W^-+\tau^+\tau^-$	5.4%	6.6×10^3
$ZZ+b\bar{b}$	3.1%	3.8×10^3
$ZZ+W^+W^-$	1.2%	1.4×10^3
$\gamma\gamma+b\bar{b}$	0.3%	3.3×10^2
$\gamma\gamma+\gamma\gamma$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

- Considering decays with high BR: **bb+ττ** and **bb+γγ** channels are our best chances to observe a signal

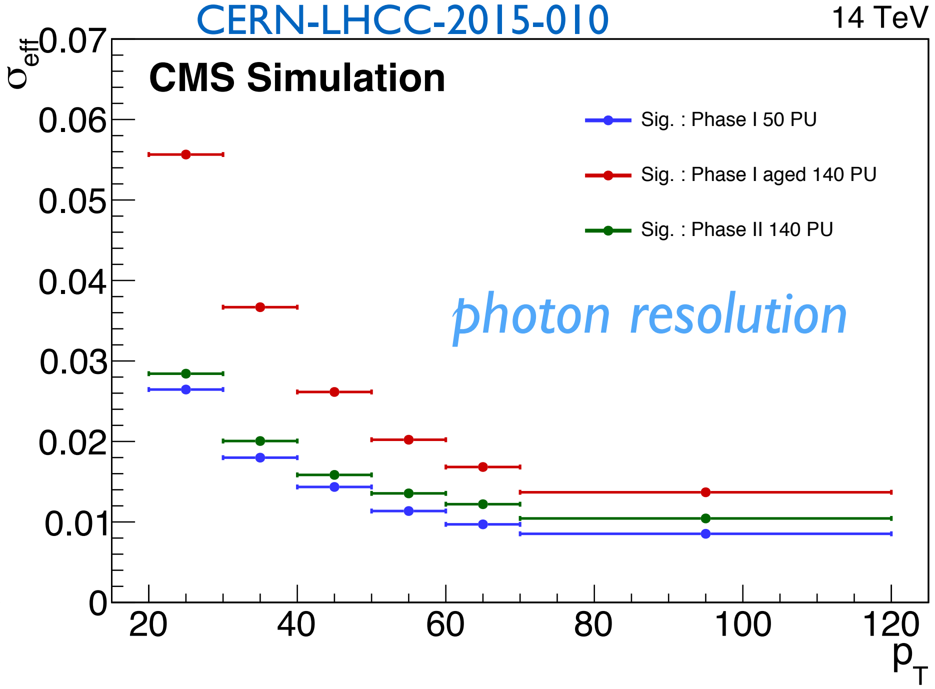
- Must have excellent performance in b-tagging, γ resolution, τ-efficiency and fake rate

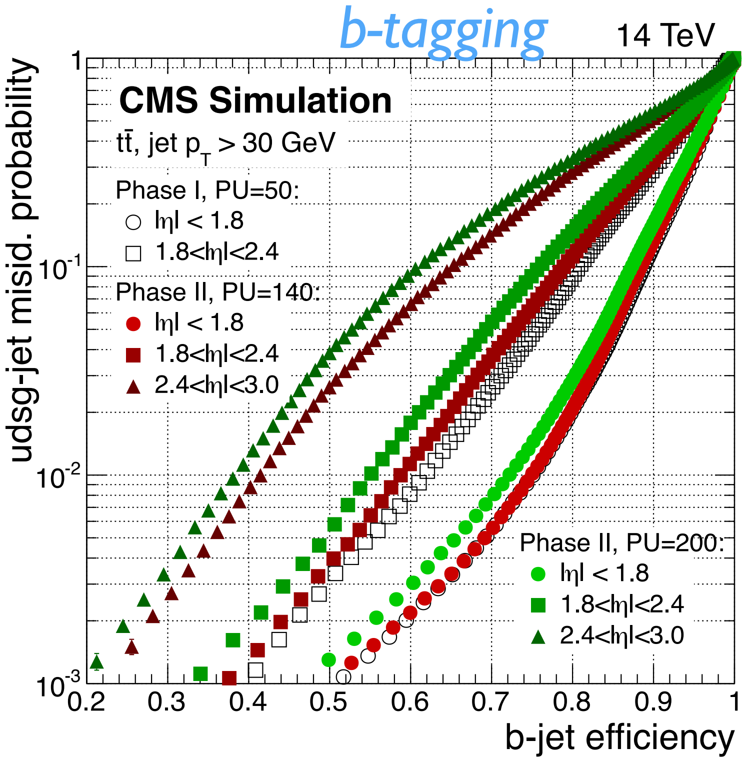


CERN-LHCC-2015-019



CERN-LHCC-2015-010



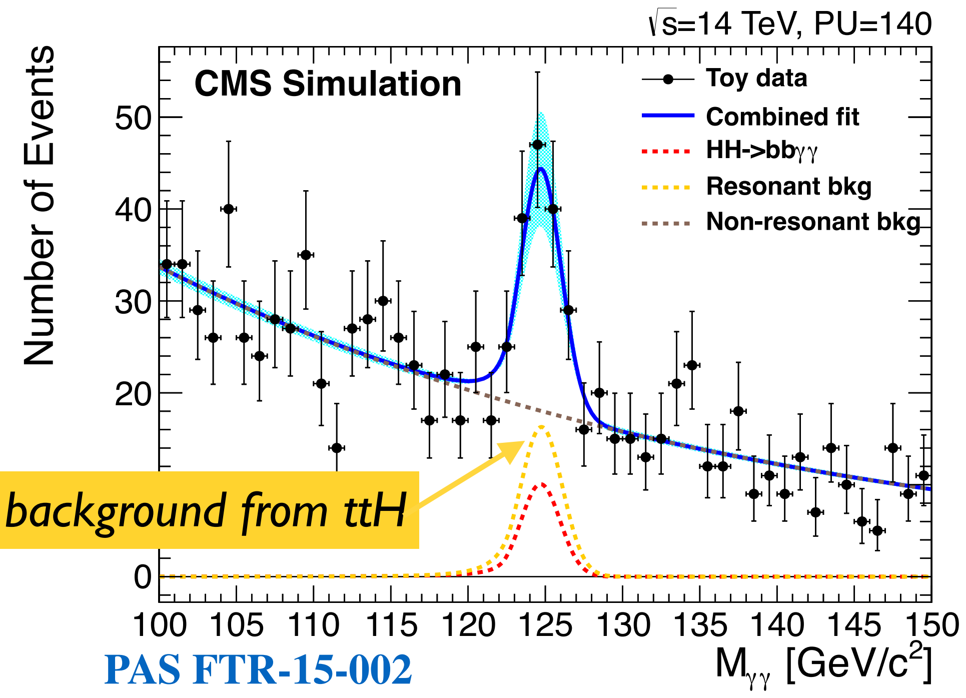


The ultimate goal for HL-LHC: HH

H H→bb γγ

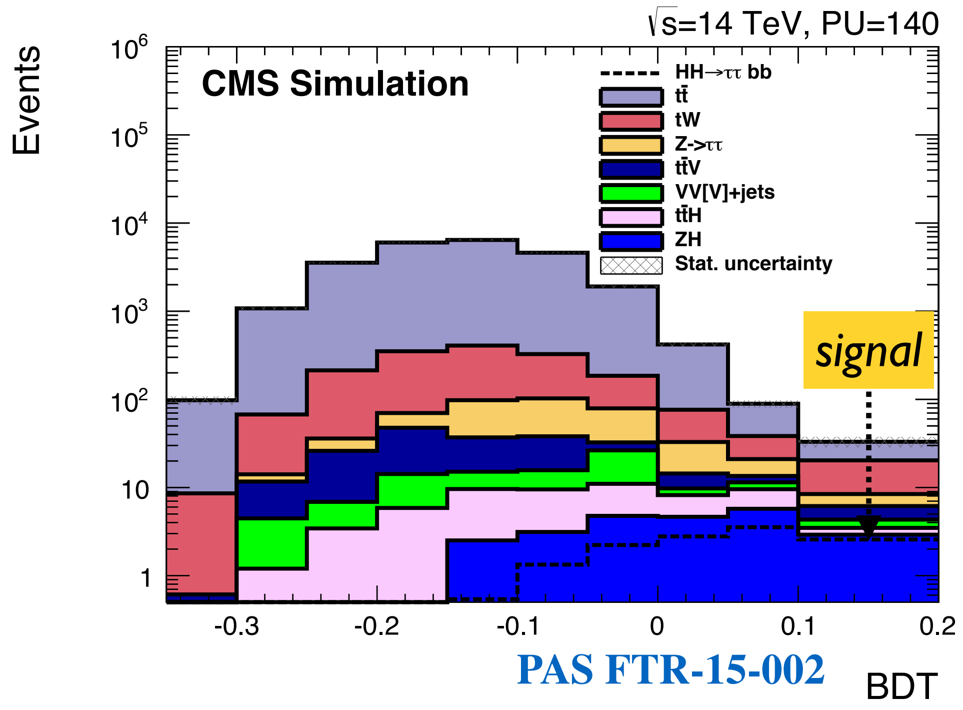
$\langle\mu\rangle=140$

H H→bb ττ



resonant background from ttH

PAS FTR-15-002



signal

PAS FTR-15-002

- Observation at the SM rate possible for ATLAS and CMS with the HL-LHC dataset
  - Expectations: CMS 1.6σ, ATLAS 1.3σ [CMS-PAS-FTR-15-002], [ATL-PHYS-PUB-2014-019]

- Dominated by large backgrounds but important for combination
  - Expectations: CMS 0.9σ, ATLAS 0.6σ [CMS-PAS-FTR-15-002], [ATL-PHYS-PUB-2015-046]

- Combination of both channels provides and expected significance of 1.9σ for CMS
- With better performance than the conservative estimates used in the projections and with more channels in the combination (bb+WW, bb+bb), there is good chance to observe first hints for HH production at the HL-LHC

Summary

- Look to the future of Higgs physics with measurements at the HL-LHC

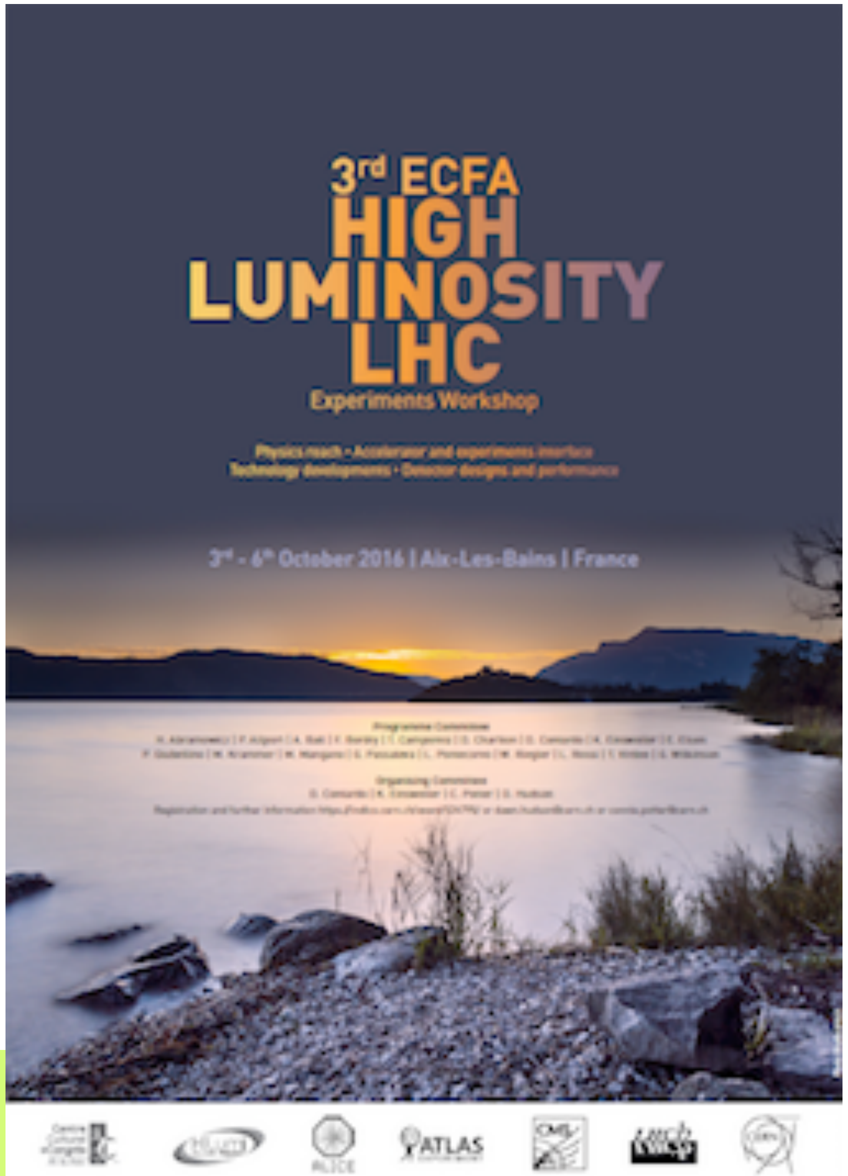
What we aim to achieve:

- Access almost all decays of the Higgs boson and measure couplings with <5% precision
- First measurements of Higgs-pair production for a more complete understanding of the electroweak symmetry breaking mechanism

What we need:

- Detector upgrades and more advanced and pile-up robust algorithms
- Smarter analysis techniques to cope with the extreme background conditions
- Reduced theoretical uncertainties

Disclaimer: New results and updated upgrade plans to be presented at ECFA next week



Additional material

H→bb

- Largest BR but studies limited to **VH** and **ttH** production mode due to large backgrounds
- Important to probe coupling to fermions and constrain BR for BSM
- Not observed yet… Possible at the LHC but multiple analyses must be combined to exceed 5σ
- ATLAS expects >9σ just in VH, V leptonic modes

ATL-PHYS-PUB-2014-011

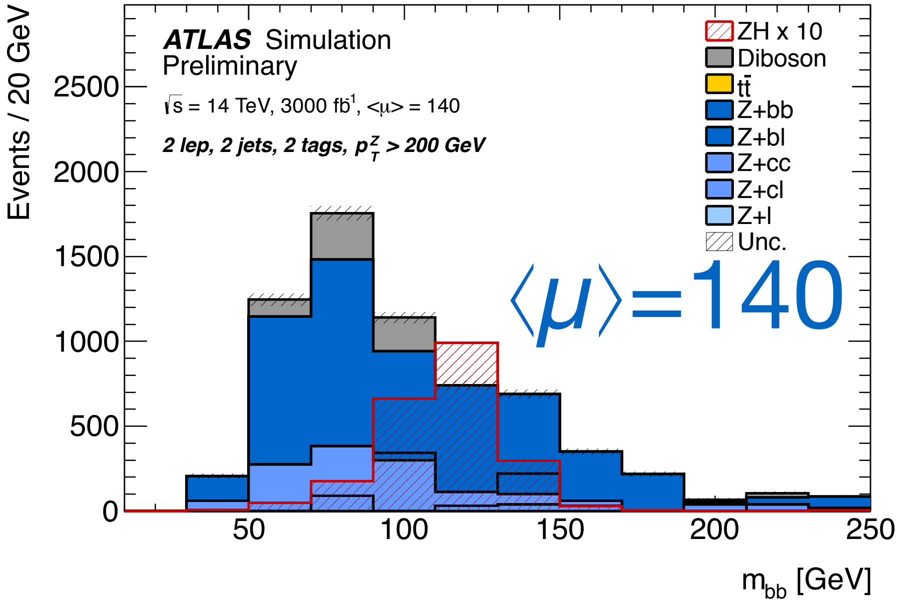
1) Conservative scenario:

Run-1-like analysis projected at much higher pile-up

2) Realistic / optimistic scenario:

MVA techniques, improved b-tagging and jet calibration

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



- CMS demonstrates an ultimate precision of Δμ/μ ~ 5-7% to be achieved with the combination of VH with ttH using multiple decay channels

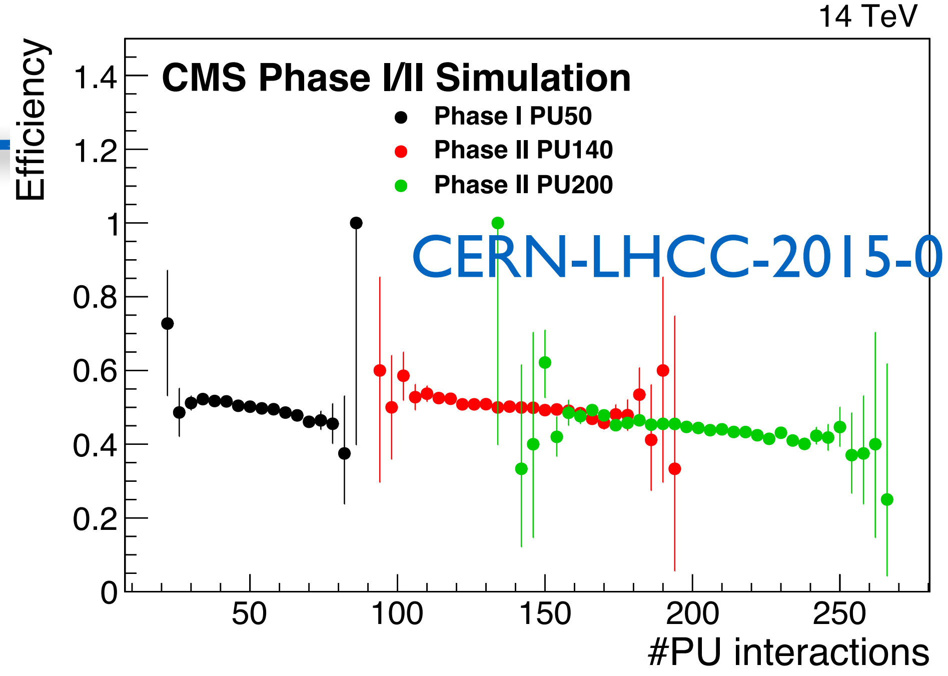
CMS NOTE-13-002

channels combined for H→bb measurements

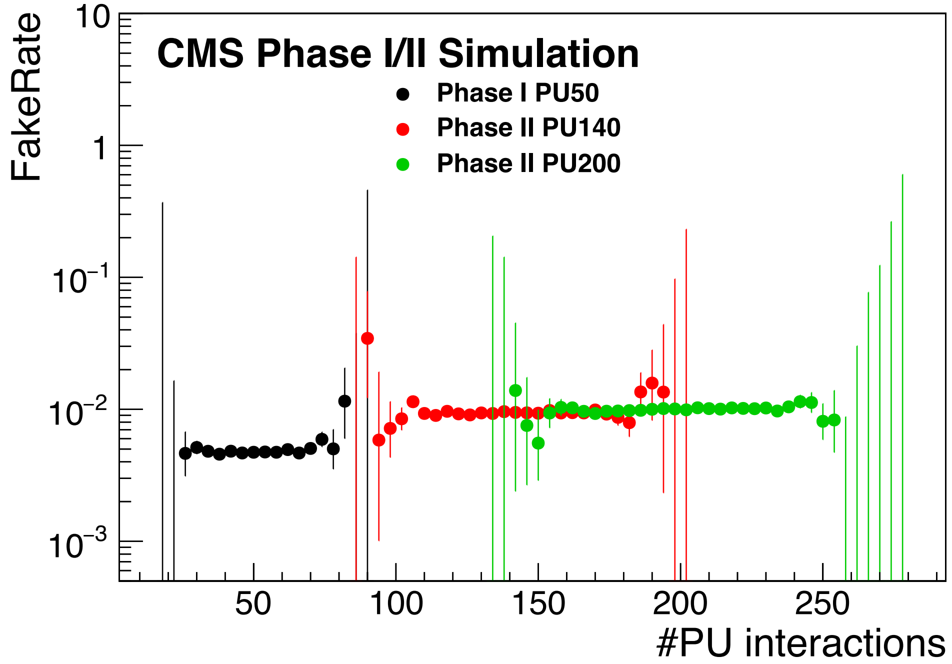
VH-tag	$(\nu\nu$, ee, $\mu\mu$, eν, $\mu\nu$ with 2 b-jets$)\times$x
ttH-tag	(ℓ with 4, 5 or $\geq$6 jets) $\times$ (3 or $\geq$4 b-tags); (ℓ with 6 jets with 2 b-tags); ($\ell\ell$ with 2 or $\geq$3 b-jets)

H→$\tau^+\tau^-$

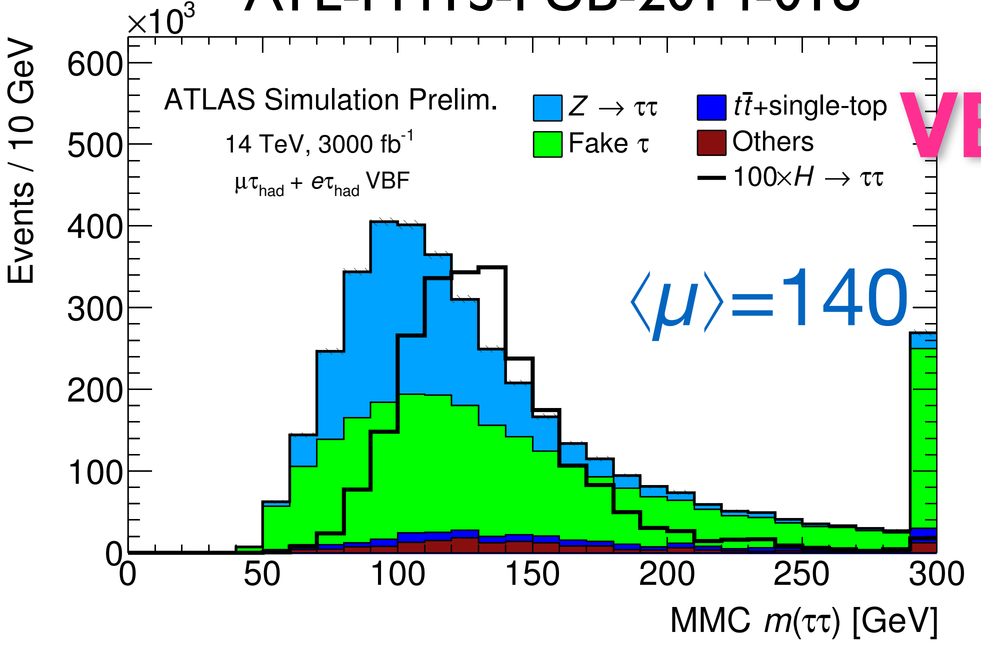
- Important to probe coupling to fermions
- Expecting impact on E_T^{miss} and τ-lepton performance
- CMS detailed performance studies with Z→$\tau^+\tau^-$
  - Upgrades will allow to maintain efficiency at same levels
  - Fake rate will double in the high pile-up conditions, but can keep it relatively stable with increasing ⟨μ⟩



CERN-LHCC-2015-019



ATL-PHYS-PUB-2014-018



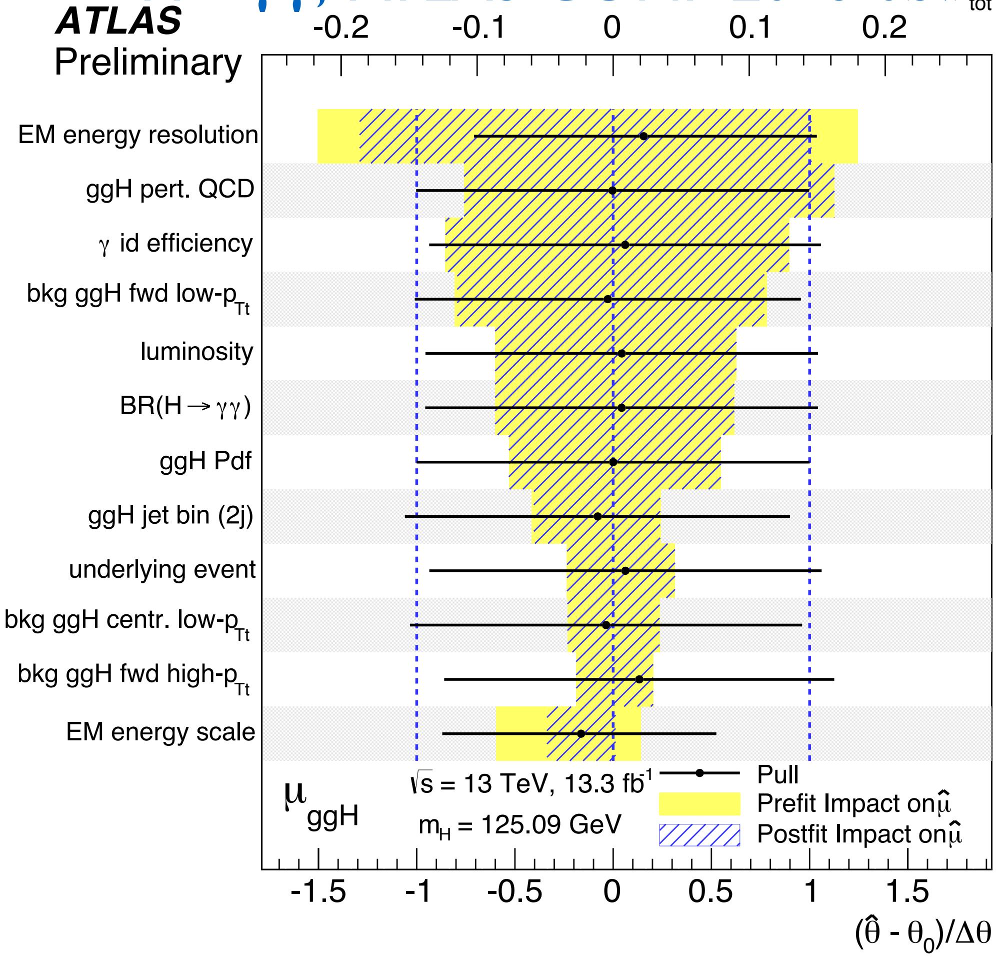
⟨μ⟩=140

VBF H→$\tau_{lep}\,\tau_{had}$

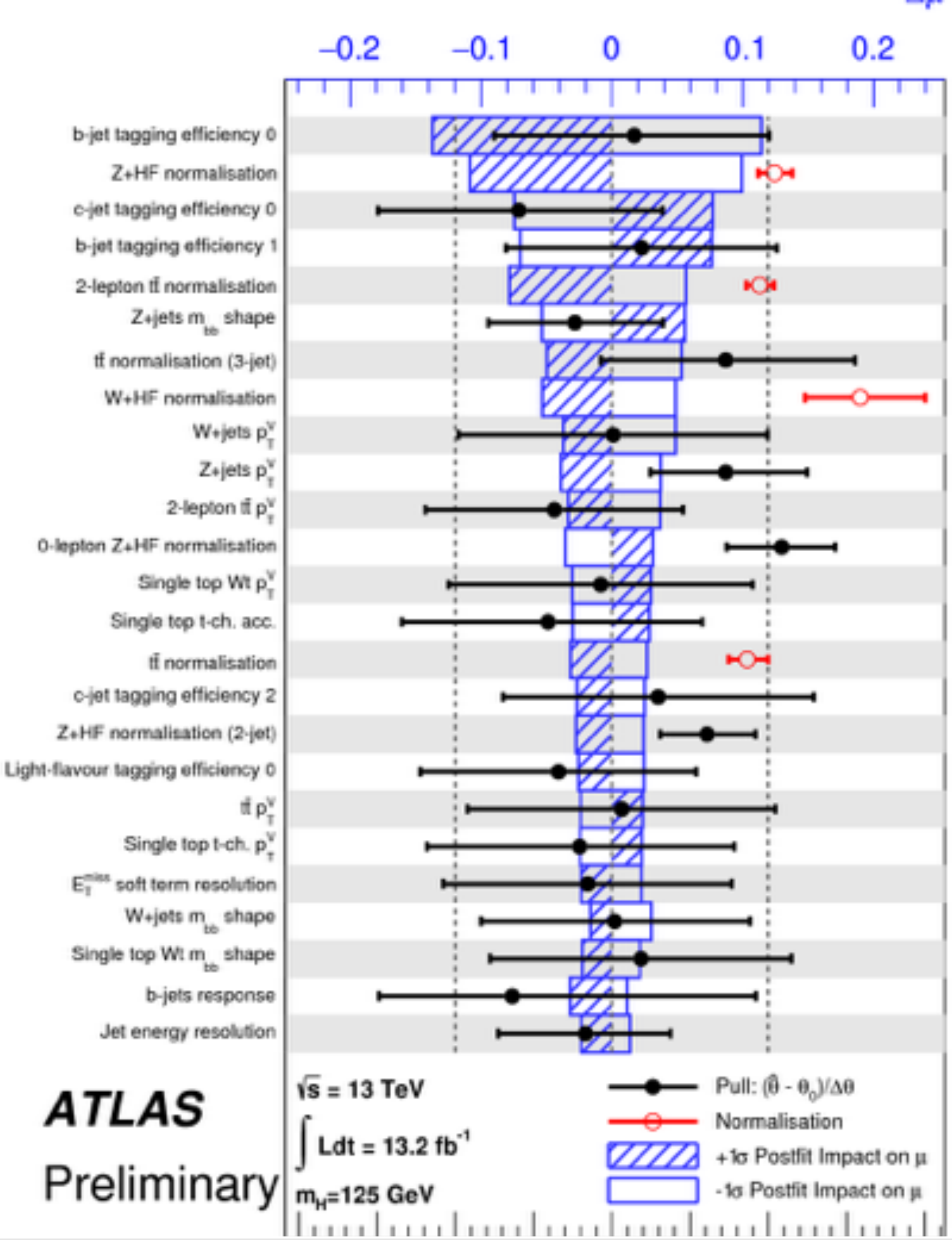
- ATLAS projections with same MVA approach as in Run-1:
  - W/o theory uncertainties: Δμ/μ ~ 24% in the extreme background scenarios… could be reduced to 8%-18%, depending on the forward tracker coverage scenario / pile-up jet rejection

Uncertainties in various channels

H→γγ, ATLAS-CONF-2016-067



Source	Uncertainty on fiducial cross section (%)		
	Baseline	VBF-enhanced	single-lepton
Fit (stat.)	34.5	35.0	52.9
Fit (syst.)	9.0	11.1	9.3
Photon efficiency	4.4	4.4	4.4
Jet energy scale/resolution	-	9.4	-
Lepton selection	-	-	0.8
Pileup	1.1	2.0	1.4
Theoretical modelling	4.3	9.4	8.4
Luminosity	2.9	2.9	2.9



	Signal
Cross section (scale)	0.7% ($q\bar{q}$), 27% (gg)
Cross section (PDF)	1.9% ($q\bar{q}\to WH$), 1.6% ($q\bar{q}\to ZH$), 5% (gg)
Branching ratio	1.7 %
Acceptance (scale)	1.4%–5%
3-jet acceptance (scale)	1.4%–4.7%
p_T^V shape (scale)	S
Acceptance (PDF)	0.3%–0.7%
p_T^V shape (NLO EW correction)	S
Acceptance (parton shower)	4%–7.5%

VH(bb), ATLAS-CONF-2016-0

Uncertainties in various channels

H→WW, Phys. Rev. D 92, 012006 (2015)

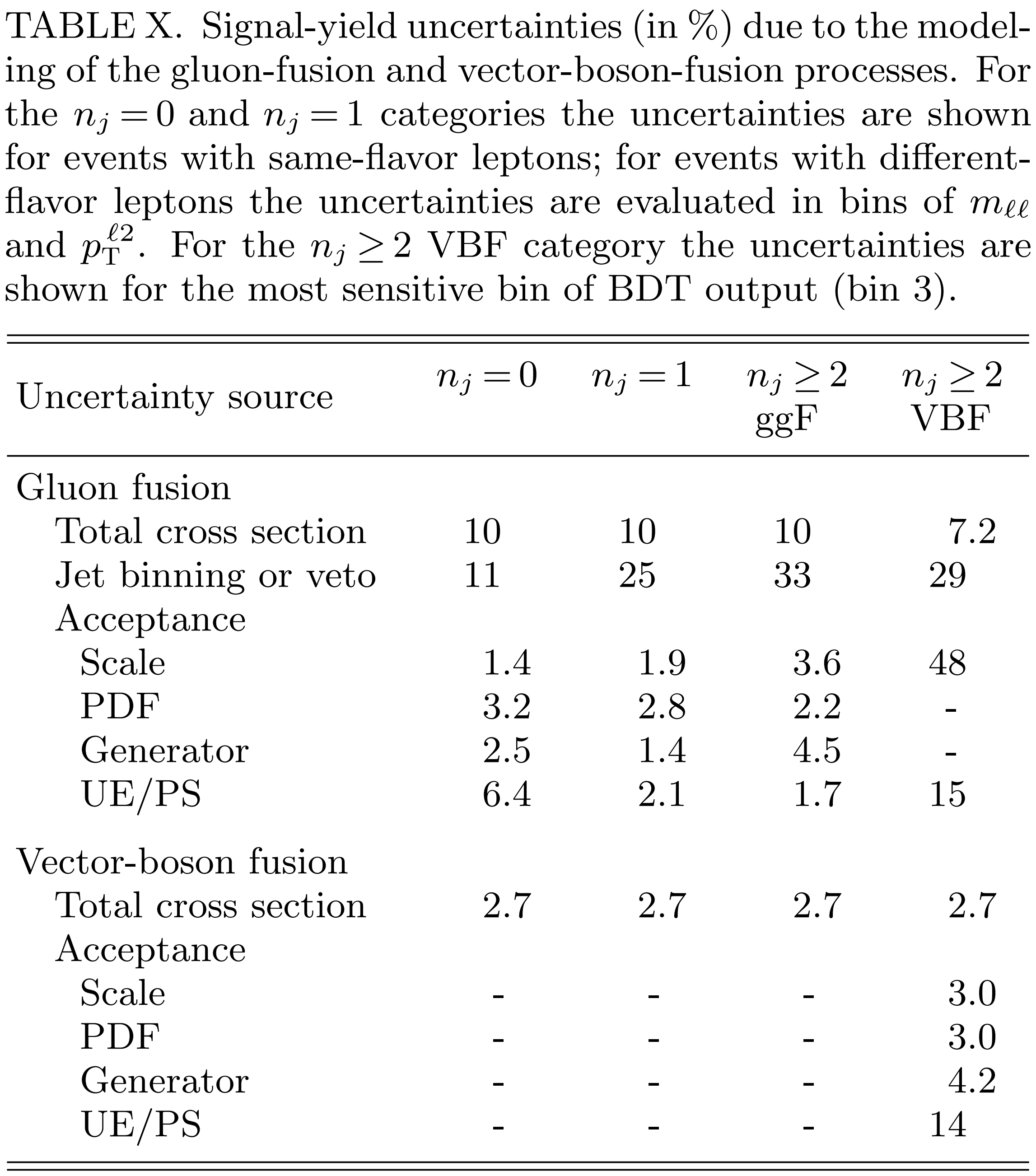
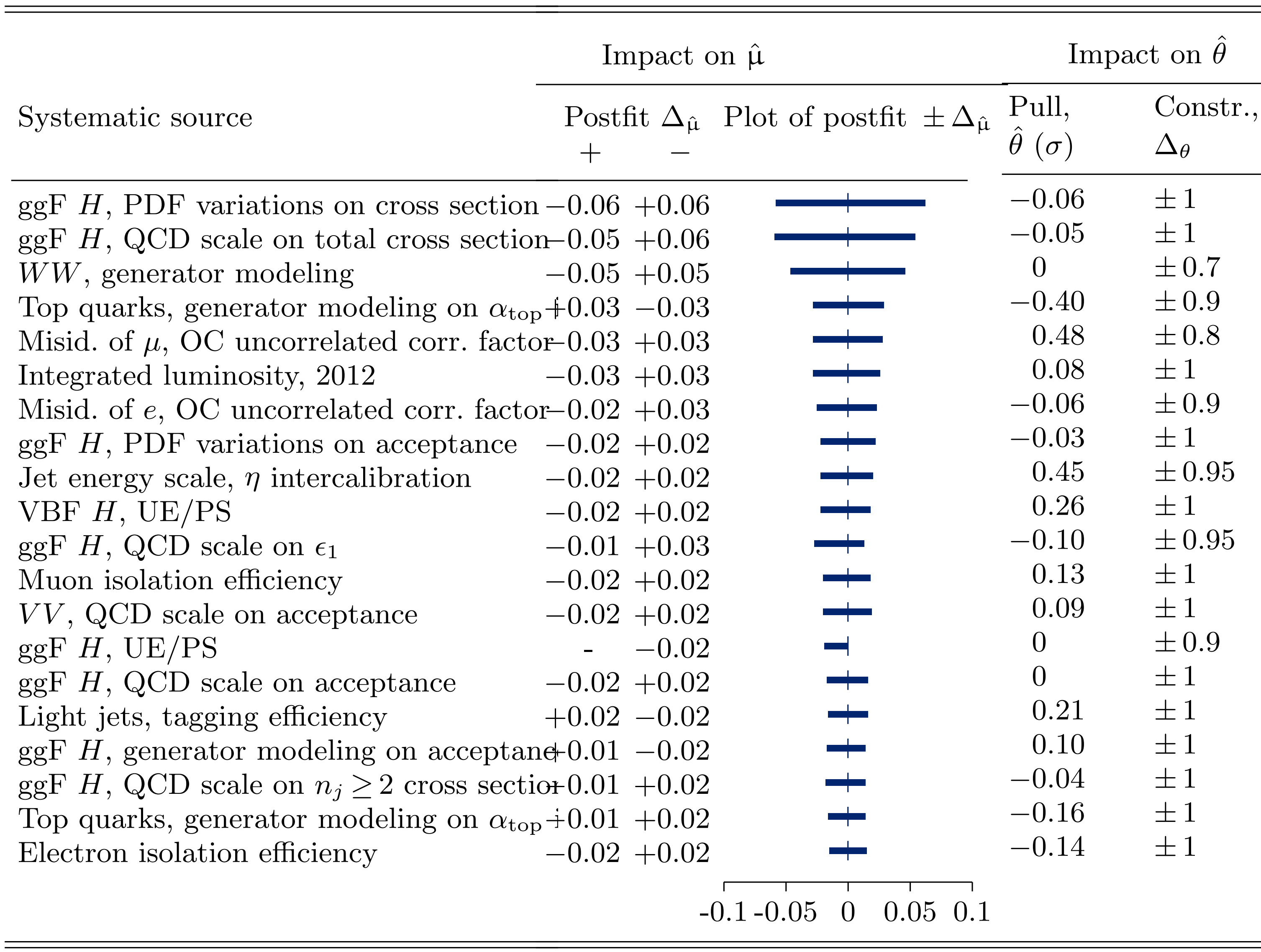


TABLE X. Signal-yield uncertainties (in %) due to the modeling of the gluon-fusion and vector-boson-fusion processes. For the $n_j = 0$ and $n_j = 1$ categories the uncertainties are shown for events with same-flavor leptons; for events with different-flavor leptons the uncertainties are evaluated in bins of $m_{\ell\ell}$ and $p_{\mathrm{T}}^{\ell 2}$. For the $n_j \geq 2$ VBF category the uncertainties are shown for the most sensitive bin of BDT output (bin 3).

Uncertainty source	$n_j = 0$	$n_j = 1$	$n_j \geq 2$ ggF	$n_j \geq 2$ VBF
Gluon fusion				
Total cross section	10	10	10	7.2
Jet binning or veto	11	25	33	29
Acceptance				
Scale	1.4	1.9	3.6	48
PDF	3.2	2.8	2.2	-
Generator	2.5	1.4	4.5	-
UE/PS	6.4	2.1	1.7	15
Vector-boson fusion				
Total cross section	2.7	2.7	2.7	2.7
Acceptance				
Scale	-	-	-	3.0
PDF	-	-	-	3.0
Generator	-	-	-	4.2
UE/PS	-	-	-	14



	Impact on $\hat{\mu}$			Impact on $\hat{\theta}$	
Systematic source	Postfit $\Delta_{\hat{\mu}}$ +	Postfit $\Delta_{\hat{\mu}}$ −	Plot of postfit $\pm\Delta_{\hat{\mu}}$	Pull, $\hat{\theta}$ (σ)	Constr., Δ_θ
ggF H, PDF variations on cross section	−0.06	+0.06		−0.06	±1
ggF H, QCD scale on total cross section	−0.05	+0.06		−0.05	±1
WW, generator modeling	−0.05	+0.05		0	±0.7
Top quarks, generator modeling on α_{top}	+0.03	−0.03		−0.40	±0.9
Misid. of μ, OC uncorrelated corr. factor	−0.03	+0.03		0.48	±0.8
Integrated luminosity, 2012	−0.03	+0.03		0.08	±1
Misid. of e, OC uncorrelated corr. factor	−0.02	+0.03		−0.06	±0.9
ggF H, PDF variations on acceptance	−0.02	+0.02		−0.03	±1
Jet energy scale, η intercalibration	−0.02	+0.02		0.45	±0.95
VBF H, UE/PS	−0.02	+0.02		0.26	±1
ggF H, QCD scale on ϵ_1	−0.01	+0.03		−0.10	±0.95
Muon isolation efficiency	−0.02	+0.02		0.13	±1
VV, QCD scale on acceptance	−0.02	+0.02		0.09	±1
ggF H, UE/PS	-	−0.02		0	±0.9
ggF H, QCD scale on acceptance	−0.02	+0.02		0	±1
Light jets, tagging efficiency	+0.02	−0.02		0.21	±1
ggF H, generator modeling on acceptanc	+0.01	−0.02		0.10	±1
ggF H, QCD scale on $n_j \geq 2$ cross sectio	+0.01	+0.02		−0.04	±1
Top quarks, generator modeling on α_{top}	+0.01	+0.02		−0.16	±1
Electron isolation efficiency	−0.02	+0.02		−0.14	±1