Higgs physics programme at the High-Luminosity LHC with ATLAS

S. Jézéquel
LAPP (CNRS-Université Savoie Mont-Blanc)
On behalf of the ATLAS Collaboration

25th Workshop on Deep Inelastic Scattering 2017 and Related Topics

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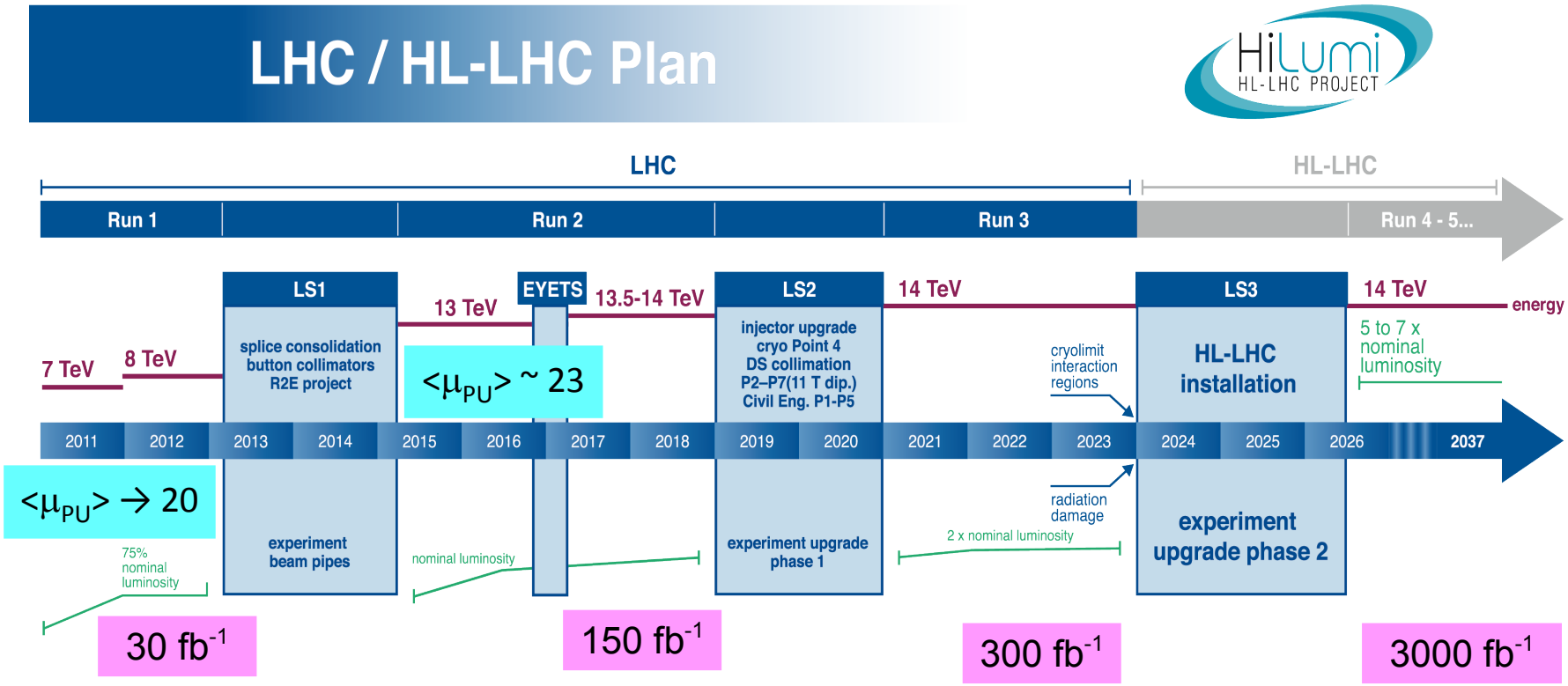
Outline

- High Luminosity LHC (HL-LHC)
- ATLAS detector upgrades and associated performances
- Higgs physics programme
  - Higgs rare decays
  - Higgs production through Vector Boson Fusion (VBF)
  - Higgs boson couplings
  - Higgs boson self-coupling
- Conclusion

High Luminosity LHC (2024-2037)



HL-LHC mode	Peak Luminosity ($cm^{-2}\ s^{-1}$)	Mean number of interactions per bunch-crossing $\langle\mu_{PU}\rangle$	Integrated luminosity (fb^{-1})
Baseline	5×10^{34}	**140**	**3000**
Ultimate	7.5×10^{34}	**200**	4000

Physics targets : precision measurements/rare decays/Beyond SM

ATLAS detector upgrades (2024-2026)

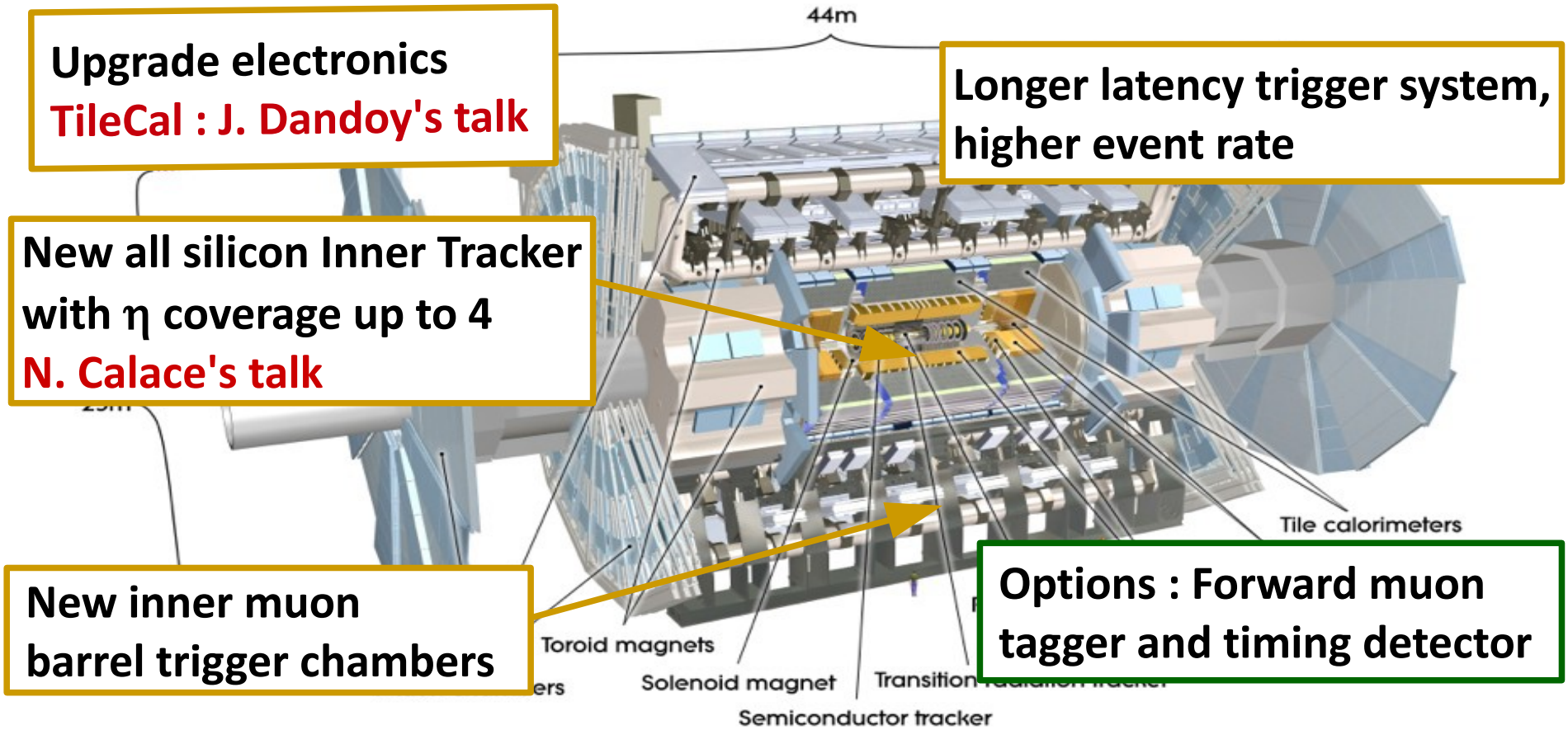
CERN-LHCC-2015-020

ATLAS Phase II Upgrade Scoping Document (SD)

Upgrade electronics
TileCal : J. Dandoy's talk

Longer latency trigger system, higher event rate

New all silicon Inner Tracker with η coverage up to 4
N. Calace's talk



New inner muon barrel trigger chambers

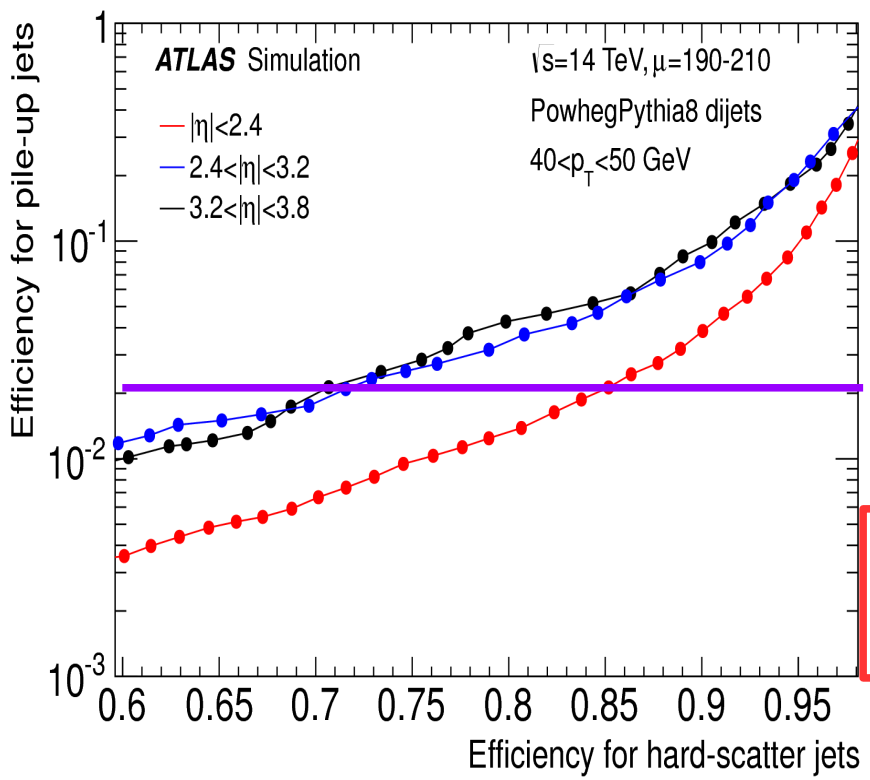
Options : Forward muon tagger and timing detector

2017 : Different design/implementation possibilities being evaluated for each sub-detector Technical Design Report

Expected pile-up jet contamination

CERN-LHCC-2015-020

- $<\mu_{PU}>=200$: 4.8 pile-up jets per event with $p_T>30$ GeV and $|\eta|<3.8$
- Pile-up jet rejection based on vertex reconstruction from tracking information



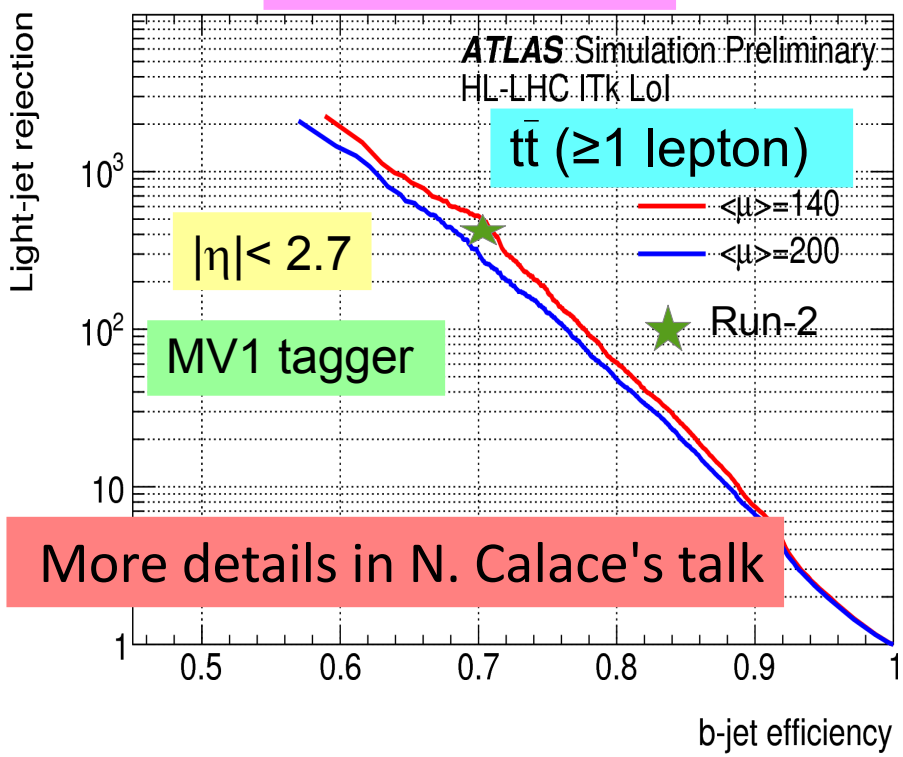
Analyses typically use factor 50 rejection

- ~0.1 pile-up jet per event
- 85-70 % efficiency on hard-scatter jets

Detector performances

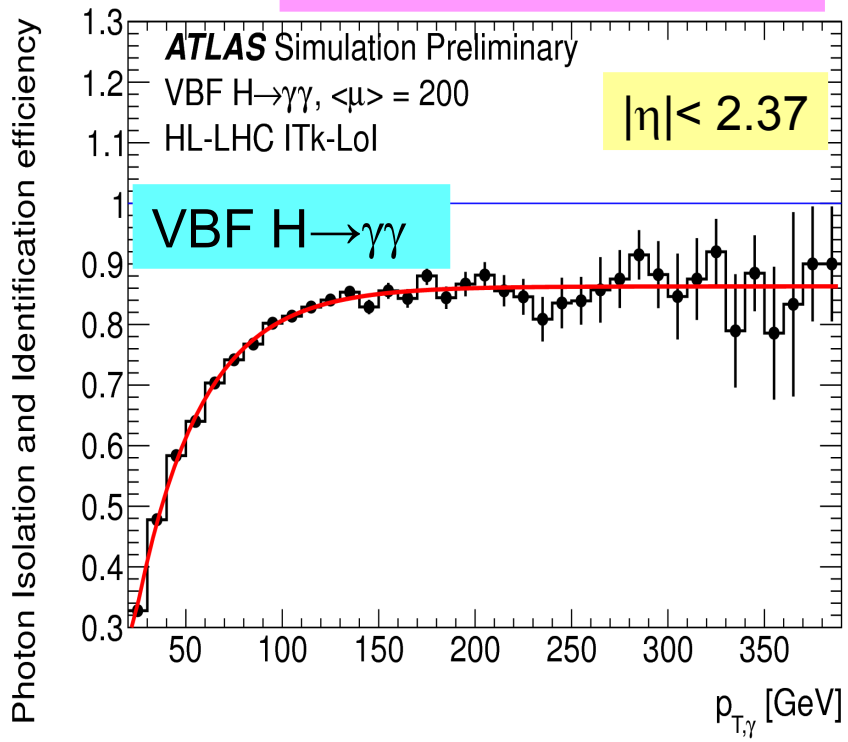
ATL-PHYS-PUB-2016-026

Jet b-tagging



More details in N. Calace's talk

Photon identification



For 70% b-jet efficiency:

Light-jet rejection~300 for $<\mu_{PU}>=200$

(380 at Run-2)

Hard-scatter jet $\rightarrow \gamma$

fake rate : $2.5\ 10^{-4}$

Detector performance implementation and analysis

Not possible to produce enough events fully simulated/reconstructed in the HL-LHC environment → Expected results are computed from :

- **Parametrised performances of upgraded detector layout**
  - Use fully simulated events with pile-up to parametrise efficiency/resolution for particle/object (e, γ, μ, τ, jet, missing-E_T)
  - Particles at event-generator level smeared according to these functions
  - Overlay with pile-up jets

- **Extrapolation from Run-1/Run-2 results**
  - Assume similar detector performances and analysis approach as Run-1/Run-2
  - Scale signal and background level to higher luminosity/CM

Systematics

Large event statistics → systematic uncertainty can become critical

- Theoretical systematics : Implement the ones used for Run-1/Run-2 publications (will have decreased by HL-LHC time)

- Experimental systematics : Scaled to best guess for ATLAS upgraded detector at HL-LHC

Some systematics (background level and shape,...) will be well measured using data-driven methods

Higgs boson physics programme

- LHC : First Higgs factory
  - Many results using Run-1/Run-2 data presented in this conference

- HL-LHC will produce 10 times more Higgs events than end Run-3
  - Reach the precision measurement regime
  - Probe rare phenomena

→ Understanding Electroweak Symmetry Breaking

→ Physics Beyond the Standard Model

Higgs physics : an important benchmark to review ATLAS detector upgrades

Let's go through the recent ATLAS results on Higgs Physics at HL-LHC

Higgs boson rare decays

- $H \rightarrow J/\psi\, \gamma$; $J/\psi \rightarrow \mu^+\mu^-$
- $H \rightarrow \mu^+\mu^-$ ATL-PHYS-PUB-2013-014

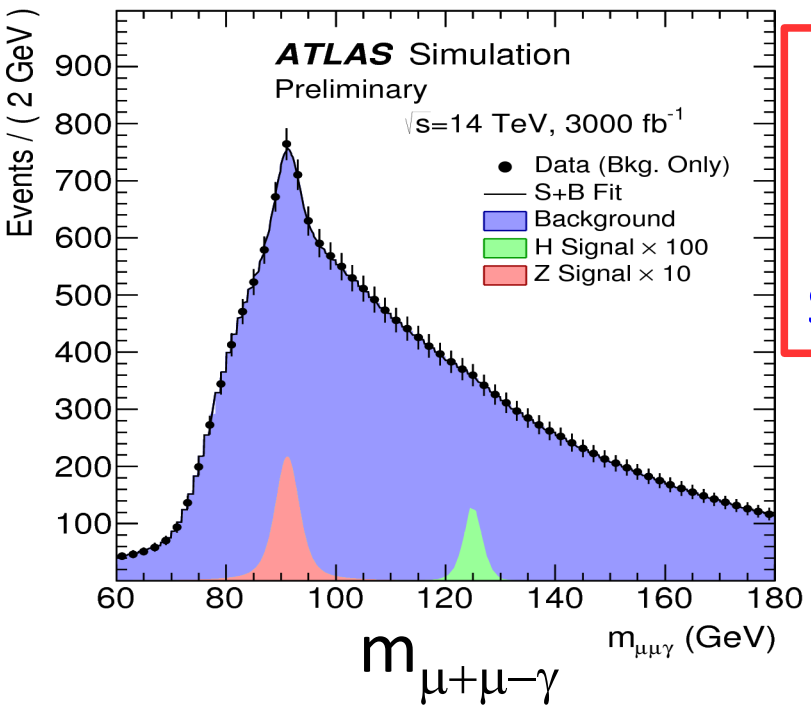
$H \rightarrow J/\psi\ \gamma$ with $J/\psi \rightarrow \mu^+\mu^-$

ATL-PHYS-PUB-2015-043

$\langle\mu_{PU}\rangle=140$

- Assume Run-1 detector performances

- $\mu^+\mu^-$ invariant mass compatible with J/ψ
- Multivariate analysis : $p_T(\gamma)$,$p_T(\mu\mu)$, γ and $\mu\mu$ isolation
  - mass($\mu^+\mu^-\gamma$) : limited to 115-135 GeV window
  - 3 signal events and 1700 background (non resonant $J/\psi\ \gamma$,...)

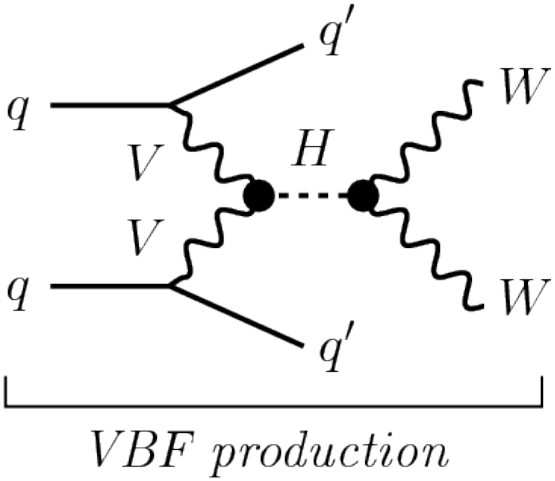


Expected branching ratio limit (no syst.) :

$\mathcal{B}$ ($H \rightarrow J/\Psi\ \gamma$) < $(44^{+19}_{-12})\times10^{-6}$ @ 95% C.L.

Standard Model expectation : $(2.9\pm0.2)\times10^{-6}$

Vector Boson Fusion Higgs production



- VBF H → WW* → eνμν
- VBF H → ZZ* → 4 ℓ

ATL-PHYS-PUB-2016-008

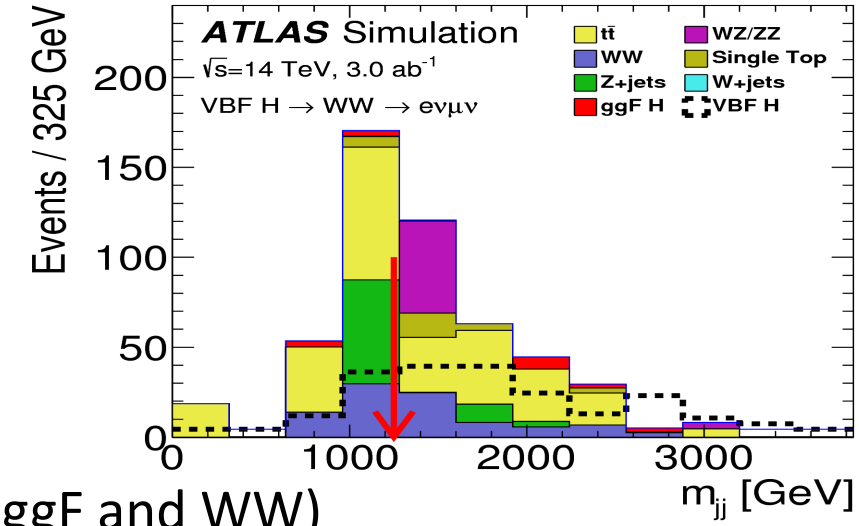
VBF H → WW*→ eνμν

ATL-PHYS-PUB-2016-018

- Detector performances : Run-1 (e/μ) + SD (jets, missing-E_T)

$<\mu_{PU}>=200$

- Cut based analysis :
  - 2 forward jets in opposite hemispheres
  - e + μ / no other jet in between 2 jets
  - Missing-E_T > 20 GeV



- 200 signal events and 410 background ($t\bar{t}$, ggF and WW)
- Main systematics : QCD scale uncertainty impacting ggF+ 2 jets rate
- Tracking coverage extension in η → stat.+ syst. uncertainty reduction by 40%

		WW → eνμν stat.	WW → eνμν stat.+syst.	ZZ → 4ℓ stat.	ZZ → 4ℓ stat.+syst.
Signal strength $\mu=\sigma/\sigma_{SM}$	$\Delta\mu$	0.14	0.20	0.15	0.18
Significance Z_σ	Z_σ	8.0	5.7	10.2	7.2

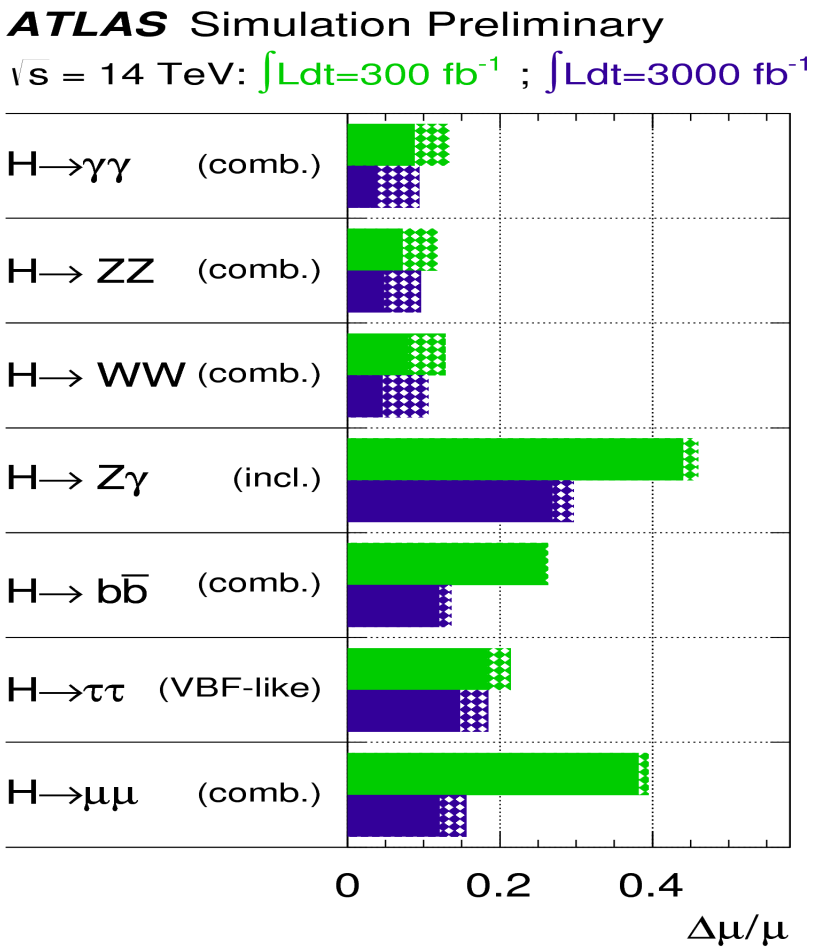
Higgs boson couplings

Higgs couplings

ATL-PHYS-PUB-2014-016

$\langle\mu_{PU}\rangle=140$

- Extrapolation from Run-1 analysis



Coupling precision for 3000 fb^{-1}

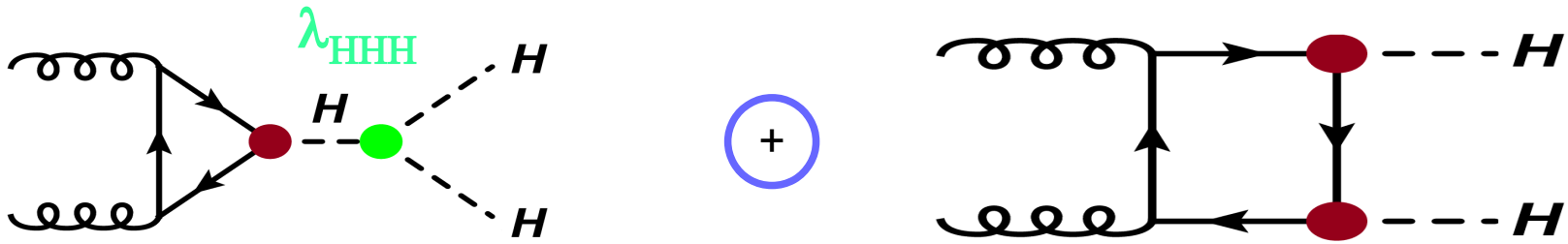
- **W,Z : 3 %**
- **μ :7%**
- **t,b,τ : 8-12 %**

Experimental/theoretical uncertainties

Higgs boson self-coupling

- $HH \rightarrow b\bar{b}\gamma\gamma$
- $HH \rightarrow b\bar{b}b\bar{b}$
- $t\bar{t}HH$; $HH \rightarrow b\bar{b}b\bar{b}$
- ☆ $HH \rightarrow b\bar{b}\tau^{+}\tau^{-}$ ATL-PHYS-PUB-2015-046

Non-resonant double Higgs production



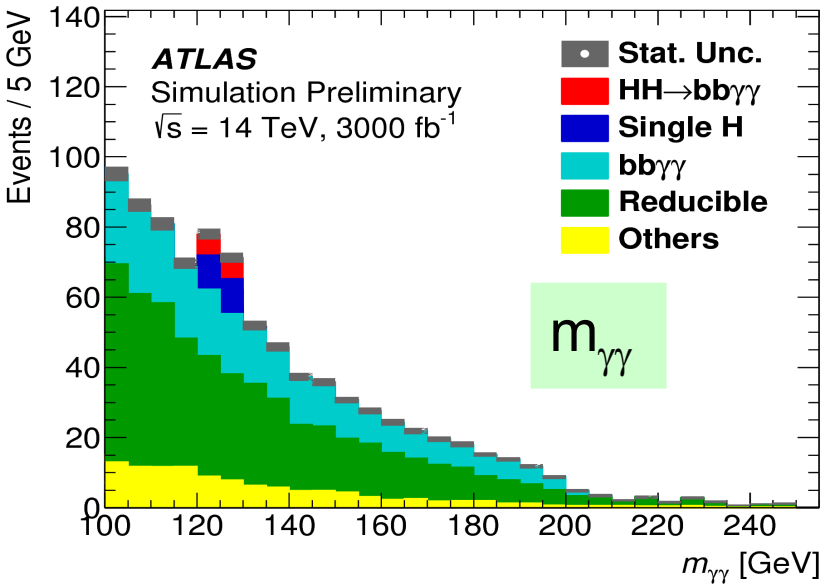
- First opportunity to measure Higgs boson trilinear self coupling (λ_{HHH})
- σ(HH) ~40 fb

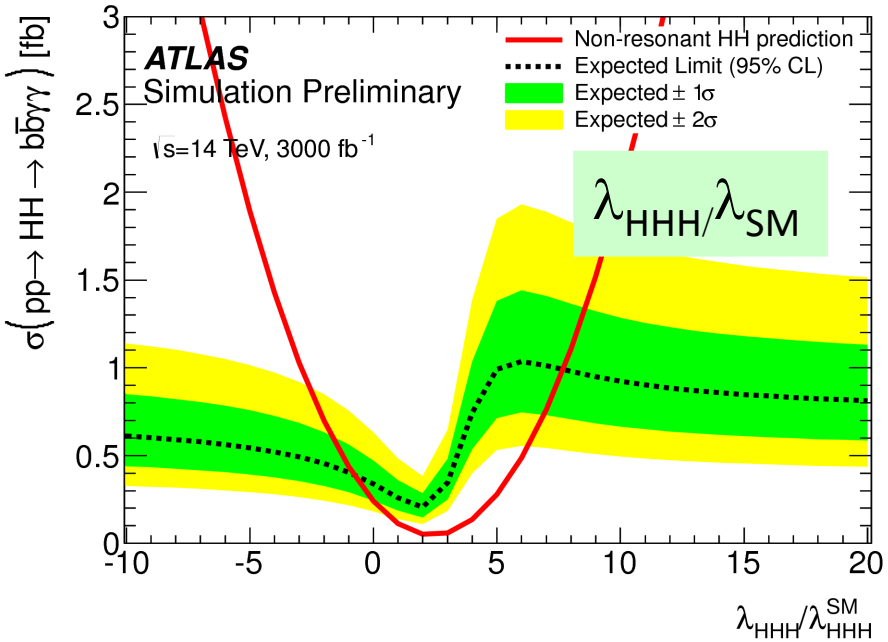
Decay channel	Branching ratio (%)	σ.Br (fb)
$b\bar{b}+b\bar{b}$	33	12.9
$b\bar{b}+W^+W^-$	25	9.9
$b\bar{b}+\tau^+\tau^-$	7.4	2.9
$W^+W^-+\tau^+\tau^-$	5.4	2.1
$ZZ+b\bar{b}$	3.1	1.2
$ZZ+W^+W^-$	1.2	0.48
$b\bar{b}+\gamma\gamma$	0.3	0.12
$\gamma\gamma+\gamma\gamma$	0.001	0.04

HH → $b\bar{b}\gamma\gamma$

$\langle\mu_{PU}\rangle$=200

ATL-PHYS-PUB-2017-001





- Assume SD detector performances for photons and most recent inner tracker layout for b-tagging (N. Calace's talk)

- Cut based analysis : narrow γγ mass peak, m(bb), p_T (γγ/bb)
- After selection : 9.5 signal events for 91 background (bbγγ, bbjγ)

→ significance (no syst. uncertainty) : 1.05 σ

$$-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7 \text{ @ 95\% C.L. (no syst.)}$$

HH → $b\bar{b}b\bar{b}$

ATL-PHYS-PUB-2016-024

- Extrapolation from Run-2 analysis
- Signal : 4 b-tagged jets

- Main background : Multijet QCD
  → main systematic uncertainty
  (estimated from Run-2 data)

95% C.L. limits :

$-0.2 < \lambda_{HHH}/\lambda_{SM} < 7$ (negligible syst.)

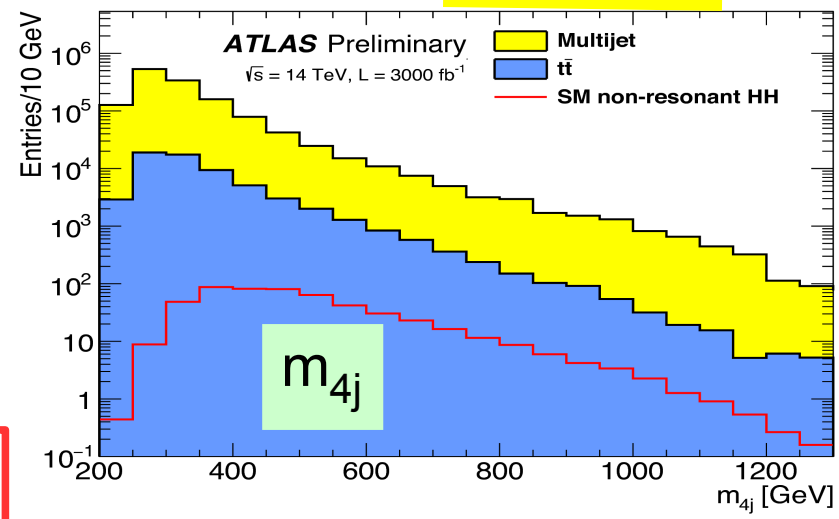
$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11$ (current syst.)

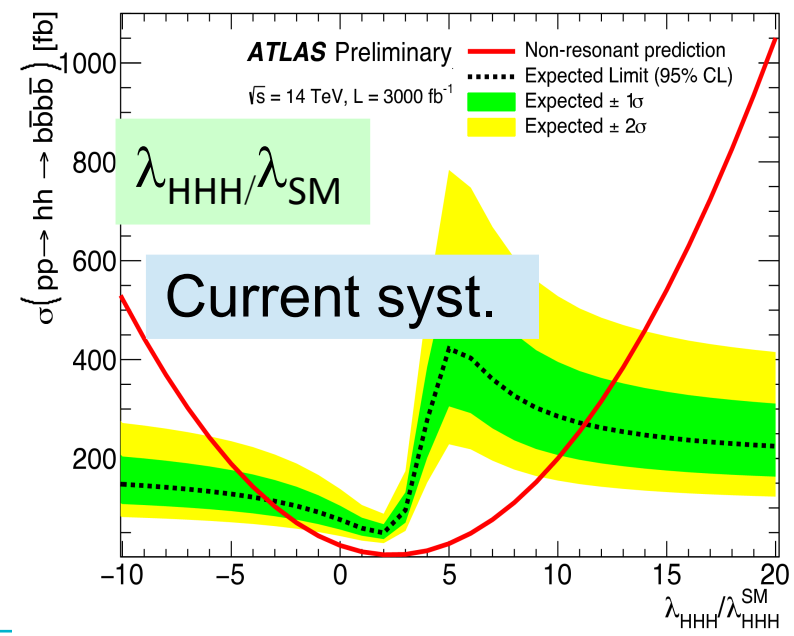
In case trigger p_T threshold 30 → 75 GeV

$-3.4 < \lambda_{HHH}/\lambda_{SM} < 12$ (negligible syst.)

@ 95% C.L.

$<\mu_{PU}>=200$





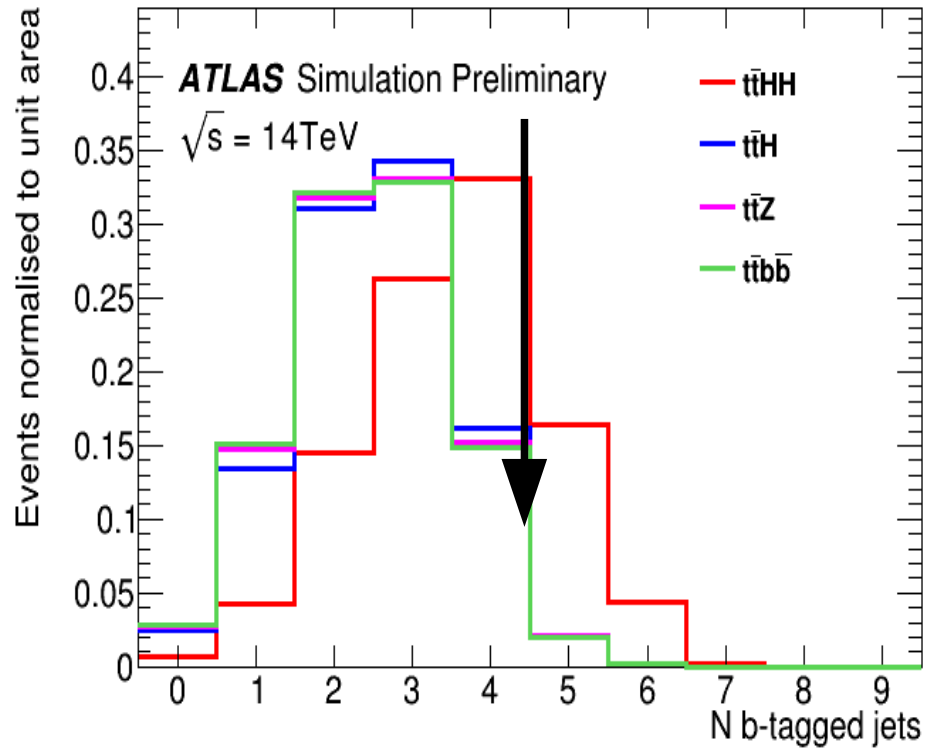
$t\bar{t}HH$, $HH \rightarrow b\bar{b}b\bar{b}$

ATL-PHYS-PUB-2016-023

$<\mu_{PU}>=200$

- $t\bar{t}HH$ cross section ~O(1 fb)
- Semileptonic final state for $t\bar{t}$

- Assume SD detector performances



- Final state :6 b-jets + 2 light jets
  + e or μ + missing-E_T

- Cut based analysis:
  - Main variables : Nb b-tagged jets, angle between jets
  - For ≥5 b-tag jets : 25 signal events and 7100 background (mainly $t\bar{t}b\bar{b}$ + jets)

Significance (no syst. error) : 0.35 σ

Summary of HL-LHC Higgs results

Channel	Result	HH final state	Significance Coupling limit (95 % C.L.)
VBF $H \to WW$	$\Delta\mu/\mu \sim 14$ to 20%	$HH \to b\bar{b}\gamma\gamma$ (stat. uncertainty only)	1.05 σ $-0.8 < \lambda_{HHH}/\lambda_{SM} < 7.7$
VBF $H \to ZZ$	$\Delta\mu/\mu \sim 15$ to 18%		
$t\bar{t}H$, $H \to \gamma\gamma$	$\Delta\mu/\mu \sim 17$ to 20%	$HH \to b\bar{b}\tau^+\tau^-$ (with syst. uncertainties)	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$
VH, $H \to \gamma\gamma$	$\Delta\mu/\mu \sim 25$ to 35%		
$H \to Z\gamma$	$\Delta\mu/\mu \sim 30\%$	$HH \to b\bar{b}b\bar{b}$ (with syst. uncertainties)	$-3.5 < \lambda_{HHH}/\lambda_{SM} < 11.0$
$H \to \mu\mu$	$\Delta\mu/\mu \sim 15\%$		
$H \to J/\psi\,\gamma$	BR < 44 . 10^{-6} @ 95 % C.L.	$t\bar{t}HH$, $HH \to b\bar{b}b\bar{b}$ (stat. uncertainty only)	0.35 σ

Detailed in this presentation

Conclusion

Even in the HL-LHC challenging environnement, Higgs physics programme with ATLAS detector will benefit greatly from HL-LHC data

The current expected ATLAS precisions at HL-LHC are still conservative:

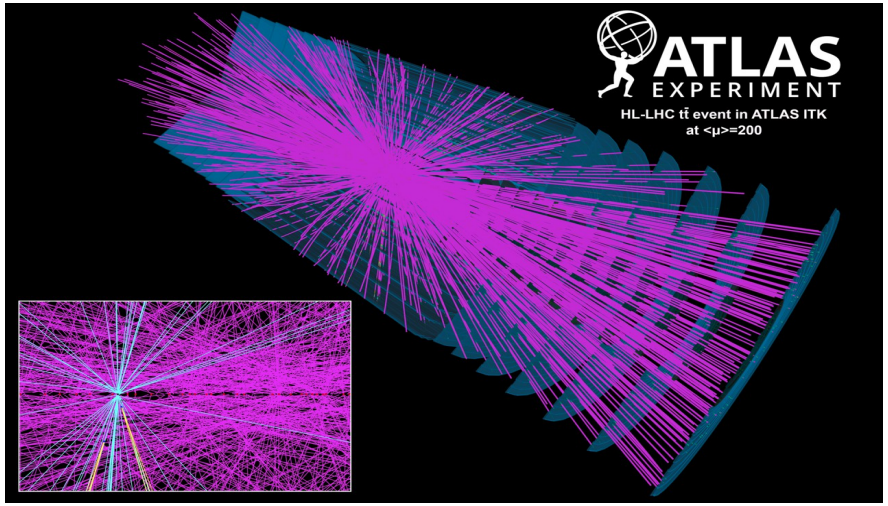
- **Still in detector optimisation phase (TDRs)**
- **More channels will be analysed and analysis techniques will be improved**
- **Better background control with data-driven methods**
- **Theoretical uncertainties expected to decrease with time**

HL-LHC era will be exciting period for Higgs physics studies

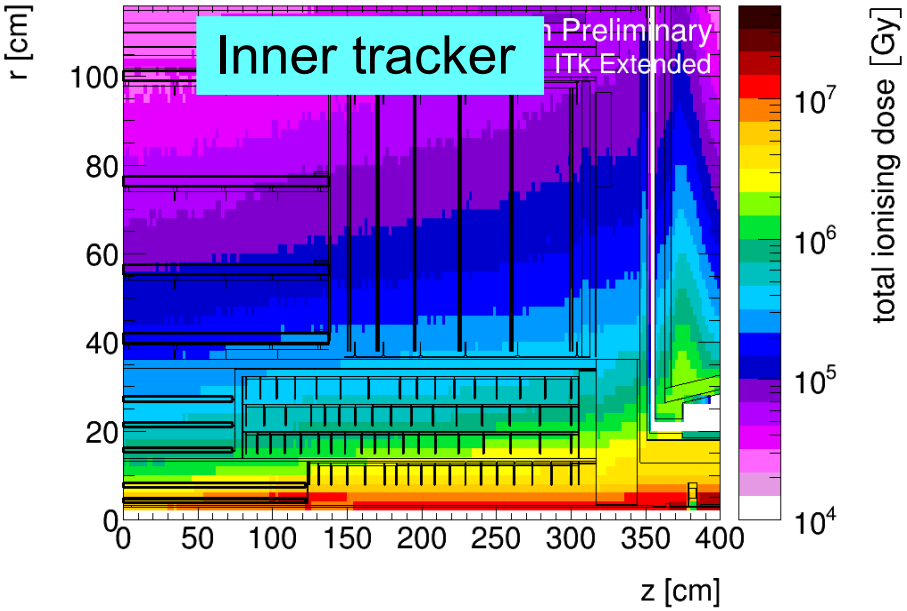
Backup slides

Detector running conditions

High particle density



High integrated radiation dose



Detector requirements to maximize benefits from high int. luminosity:

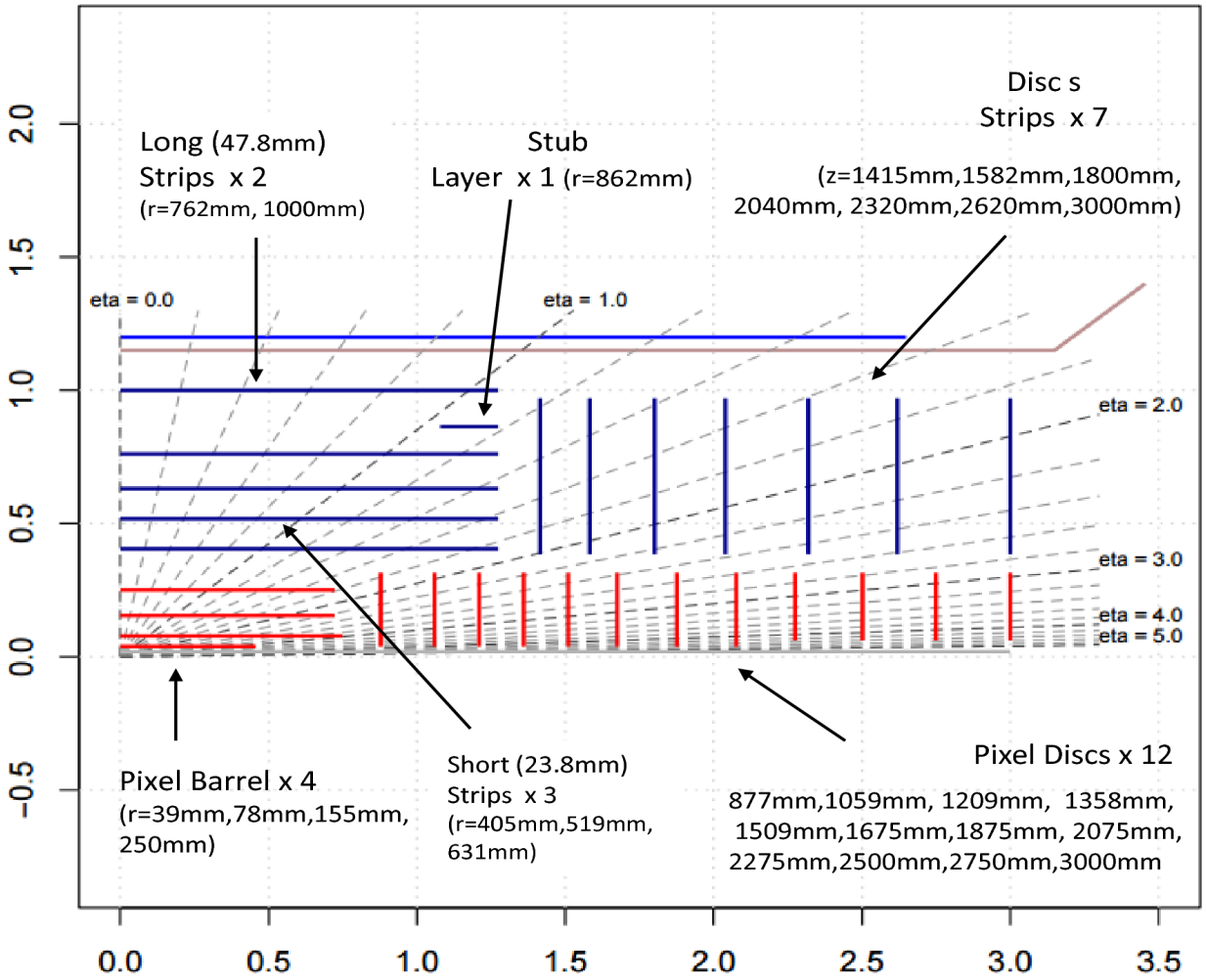
- Replace detector not sustaining integrated radiation dose
- Minimize pile-up effect (high granularity, fast timing)
- Higher trigger acceptance and event rate
- Improve or maintain current detector performances

Trigger menu at HL-LHC

Item	Offline p_T Threshold [GeV]	Offline $\|\|$	L0 Rate [kHz]	L1 Rate [kHz]	EF Rate [kHz]
isolated Single e	22	< 2.5	200	40	2.20
forward e	35	$2.4 - 4.0$	40	8	0.23
single γ	120	< 2.4	66	33	0.27
single μ	20	< 2.4	40	40	2.20
di-γ	25	< 2.4	8	4	0.18
di-e	15	< 2.5	90	10	0.08
di-μ	11	< 2.4	20	20	0.25
$e - \mu$	15	< 2.4	65	10	0.08
single τ	150	< 2.5	20	10	0.13
di-τ	40,30	< 2.5	200	30	0.08
single jet	180	< 3.2	60	30	0.60^*
fat jet	375	< 3.2	35	20	0.35^*
four-jet	75	< 3.2	50	25	0.50^*
H_T	500	< 3.2	60	30	0.60^*
E_T^{miss}	200	< 4.9	50	25	0.50^*
jet + E_T^{miss}	140,125	< 4.9	60	30	0.30^*
forward jet**	180	3.2 - 4.9	30	15	0.30^*
Total			~1000	~400	~10

Scoping Document Inner Tracker

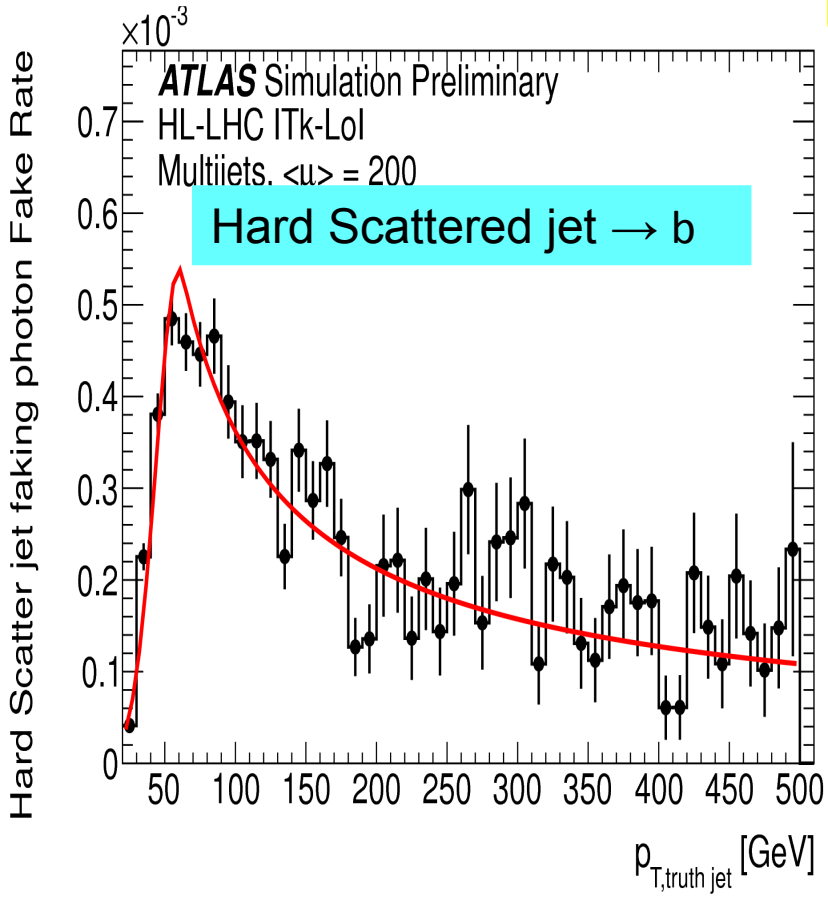
ATL-PHYS-PUB-2015-046

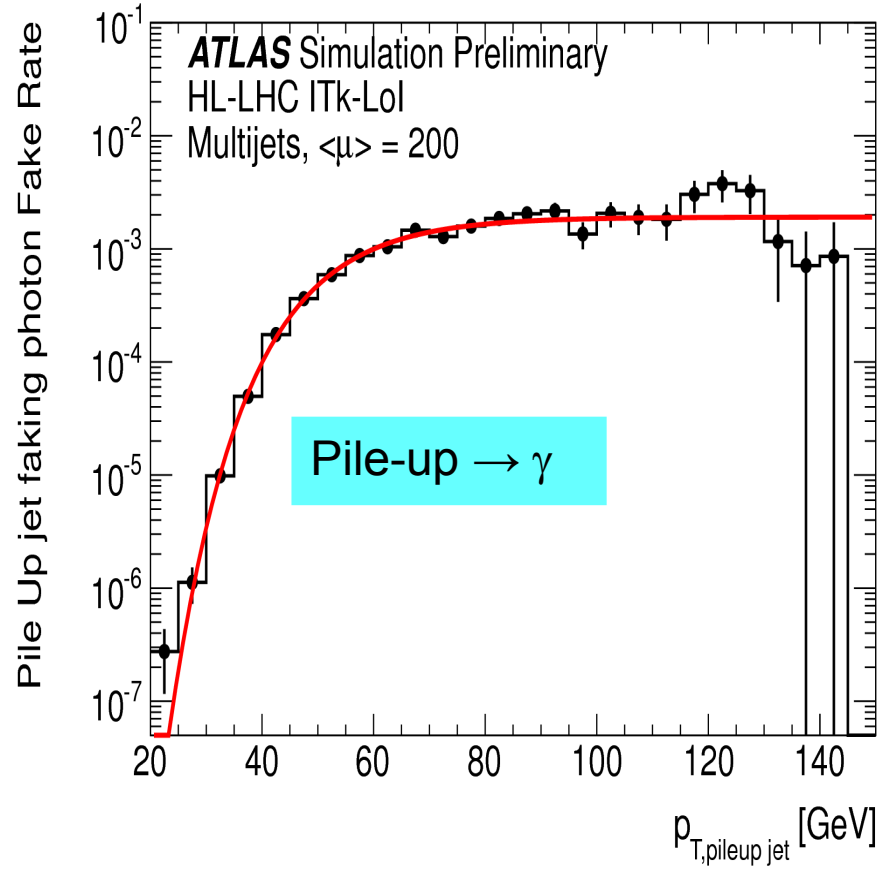


Hard-Scattered/Pile-up jet → γ

ATL-PHYS-PUB-2015-046

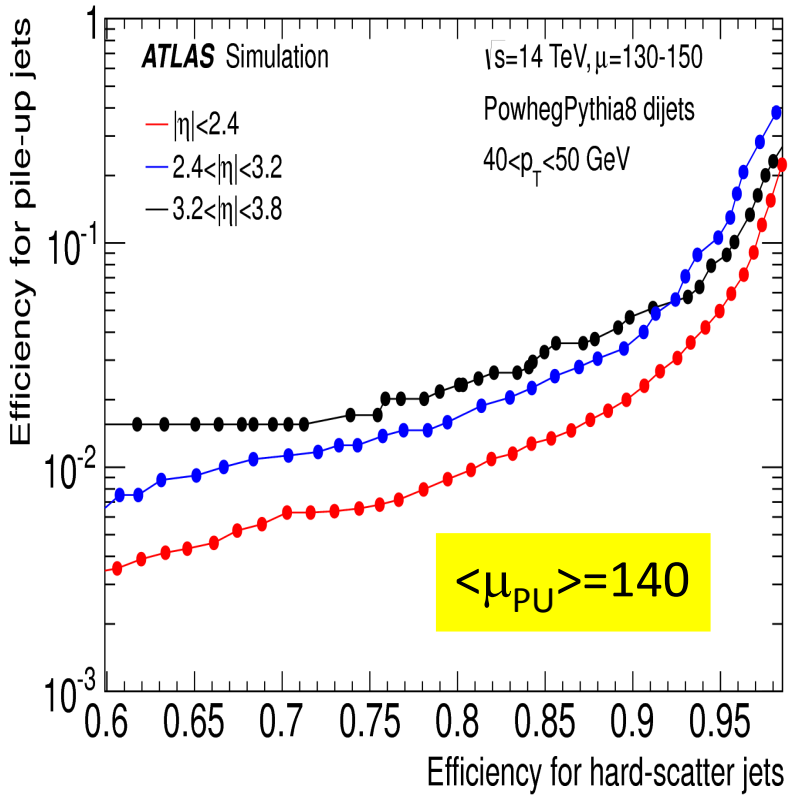
$<\mu_{PU}>=200$





Pile-up jet rejection

CERN-LHCC-2015-020



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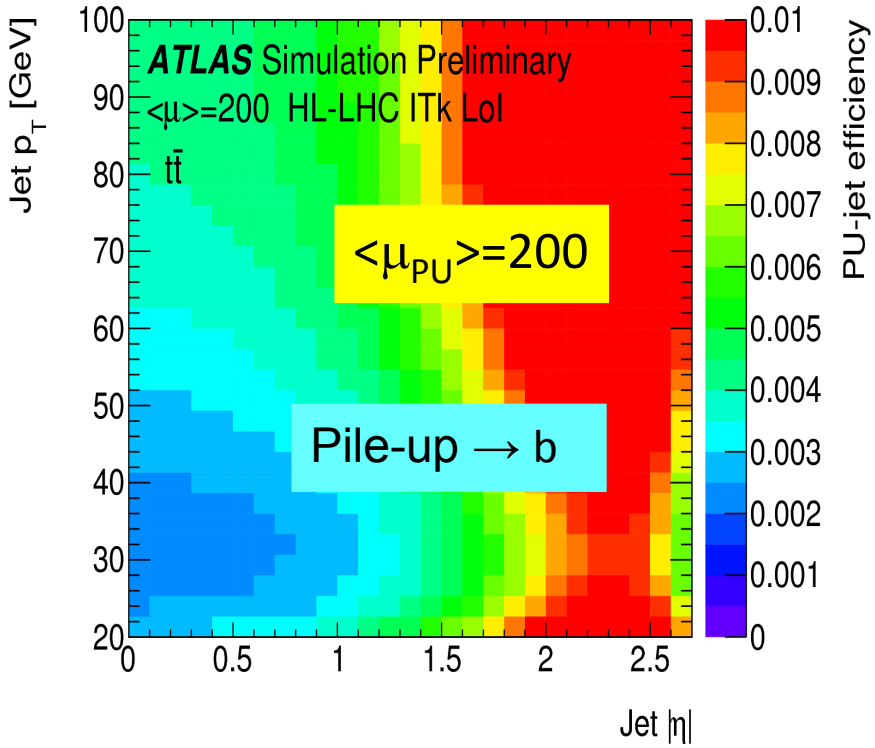
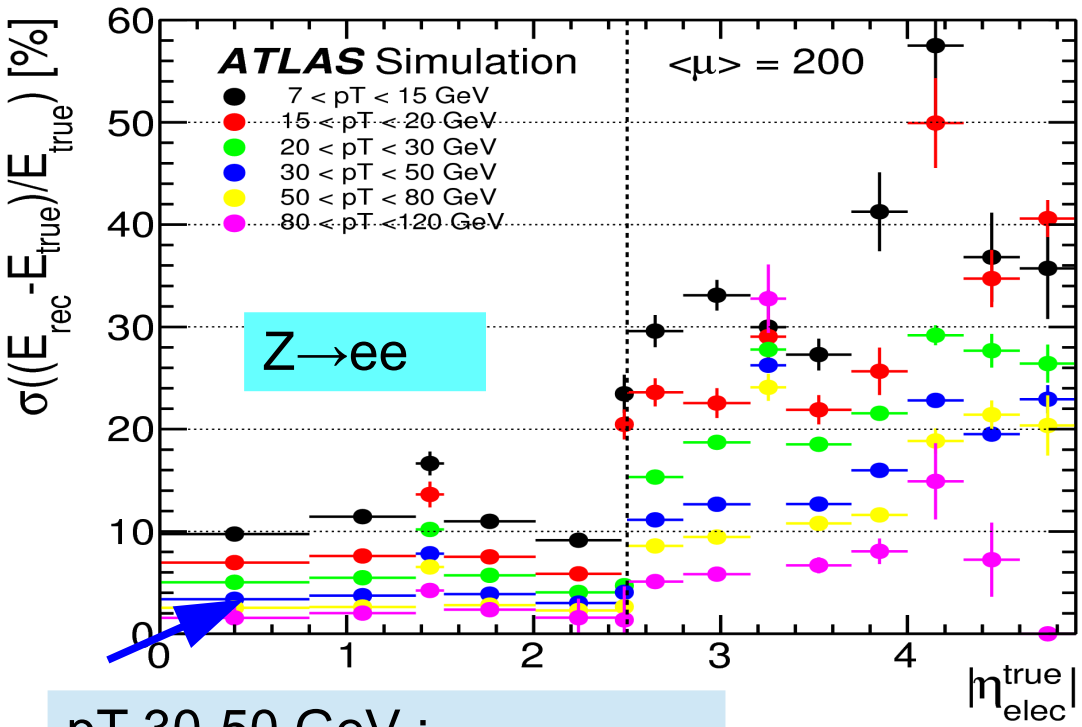


Expected detector performances : electrons

ATL-PHYS-PUB-2016-026



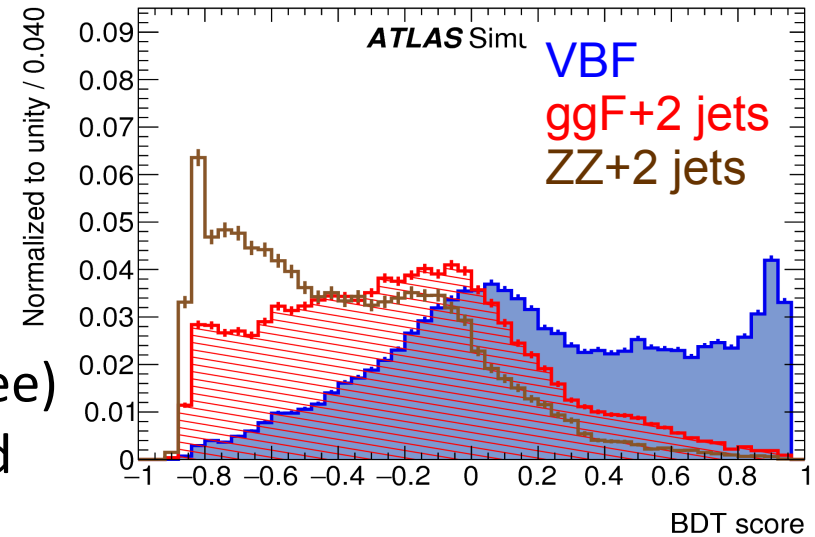
pT 30-50 GeV :
3-4% energy resolution

VBF H → ZZ* → 4ℓ (ℓ=e/μ)

ATL-PHYS-PUB-2016-008

- Detector performances : Run-1 (e/μ) + SD (jets)

- Preselection cuts :
  - 2 jets with m(jj) > 130 GeV
  - 4 leptons consistent with H→ ZZ*



- Multivariate analysis (Boosted Decision Tree)
  → 192 signal events and 326 background

- Main systematics : QCD scale uncertainty impacting ggF+ 2 jets rate

- Tracking coverage extension in η (2.7 → 4.0)
  → stat.+ syst. uncertainty reduction by 14%

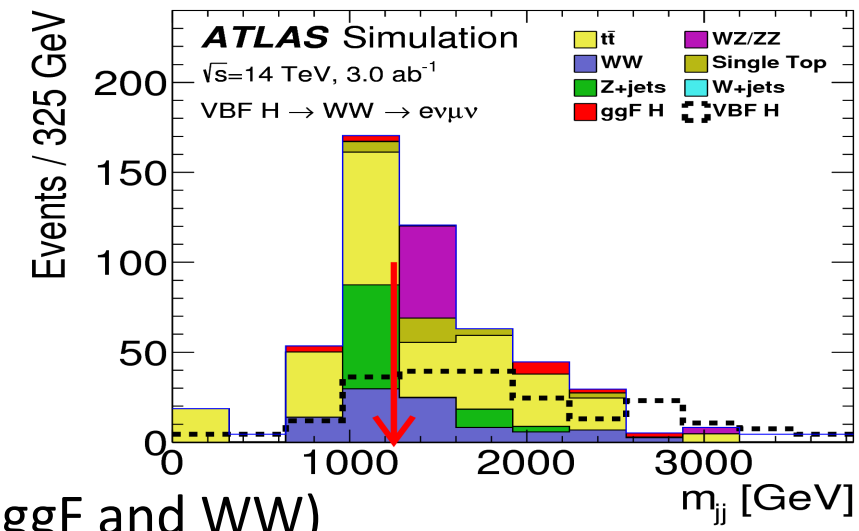
	$<\mu_{PU}>=140$ stat.	$<\mu_{PU}>=140$ stat.+syst.	$<\mu_{PU}>=200$ stat.	$<\mu_{PU}>=200$ stat.+syst.
Signal strength $\mu=\sigma/\sigma_{SM}$ $\Delta\mu$	0.13	0.17	0.15	0.18
Significance Z_σ Z_σ	11.1	7.7	10.2	7.2

VBF H → WW*→ eνμν

ATL-PHYS-PUB-2016-018

- Detector performances : Run-1 (e/μ) + SD (jets, missing-E_T)

- Cut based analysis :
  - 2 forward jets in opposite hemispheres
  - e + μ / no other jet in between 2 jets
  - Missing-E_T > 20 GeV



- 200 signal events and 410 background ($t\bar{t}$, ggF and WW)
- Main systematics : QCD scale uncertainty impacting ggF+ 2 jets rate

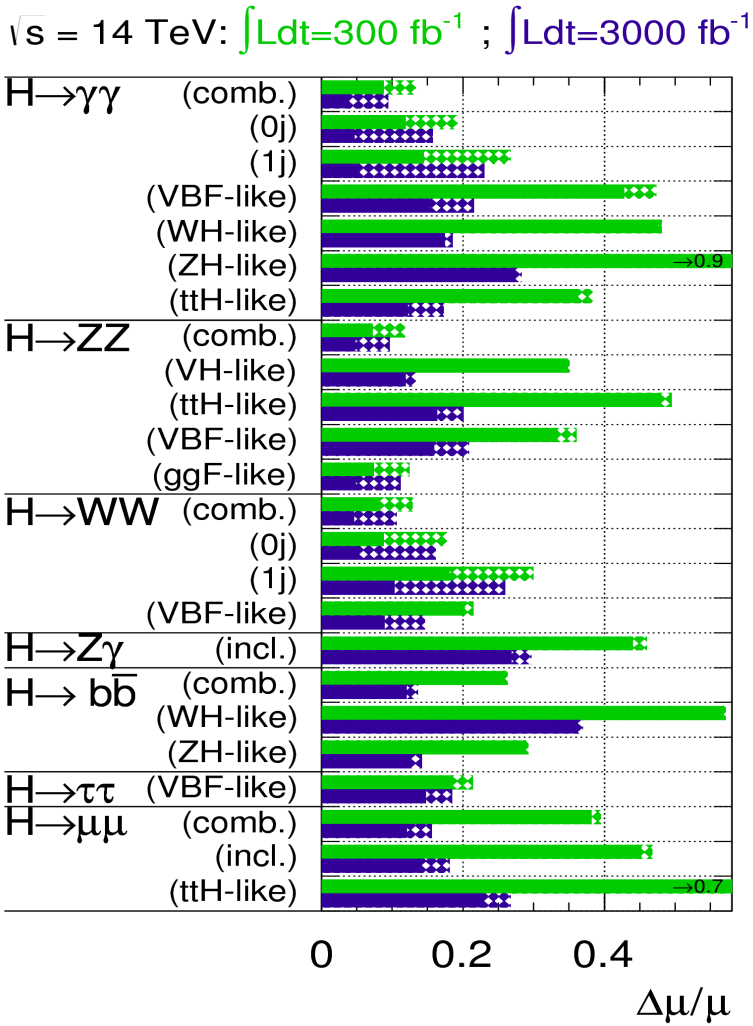
- Tracking coverage extension in η → stat.+ syst. uncertainty reduction by 40%

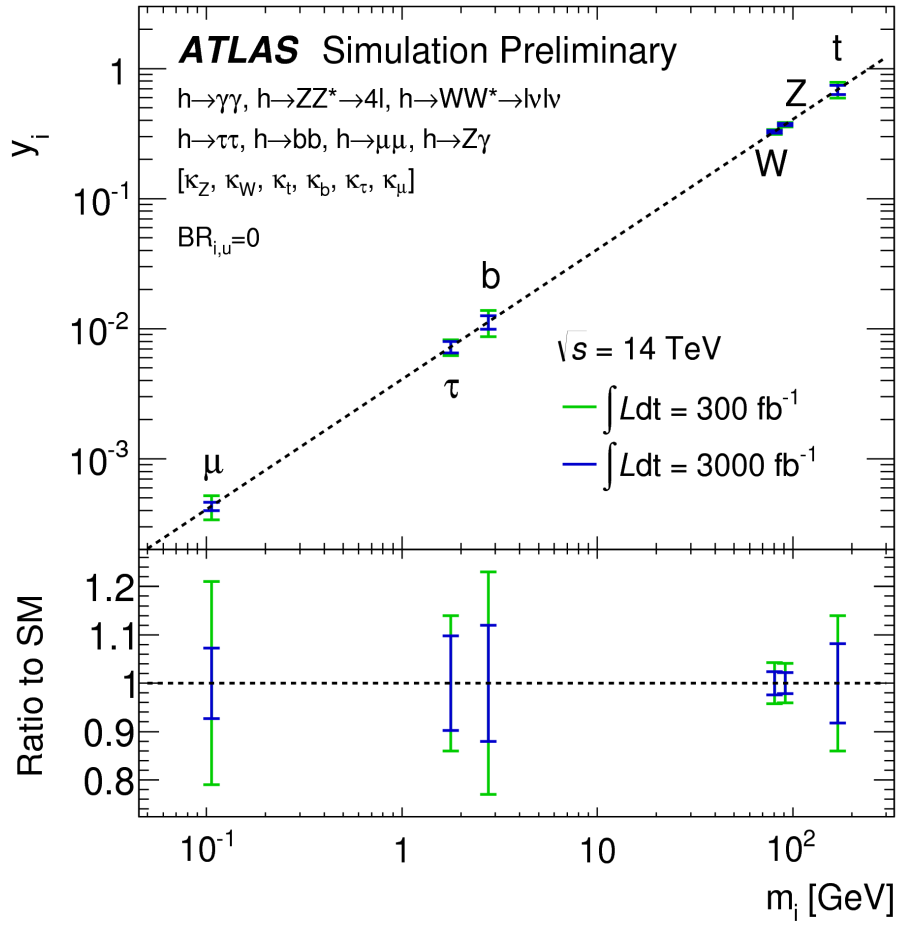
	$<\mu_{PU}>$=200 stat.	$<\mu_{PU}>$=200 stat.+syst.
Δμ	0.14	0.20
Z_σ	8.0	5.7

Higgs couplings (details)

ATL-PHYS-PUB-2014-016

$<\mu_{PU}>=140$

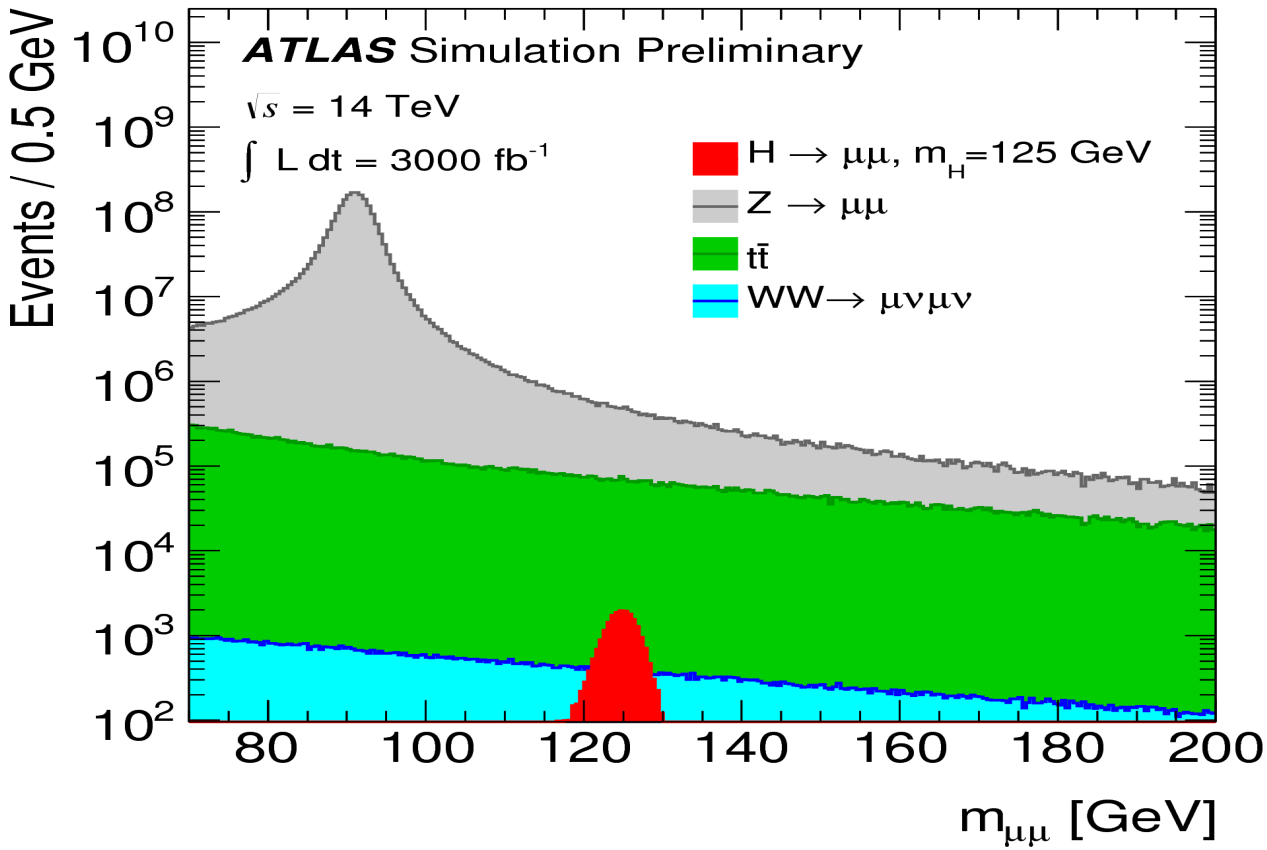




Higgs rare decay : $H \rightarrow \mu^+\mu^-$

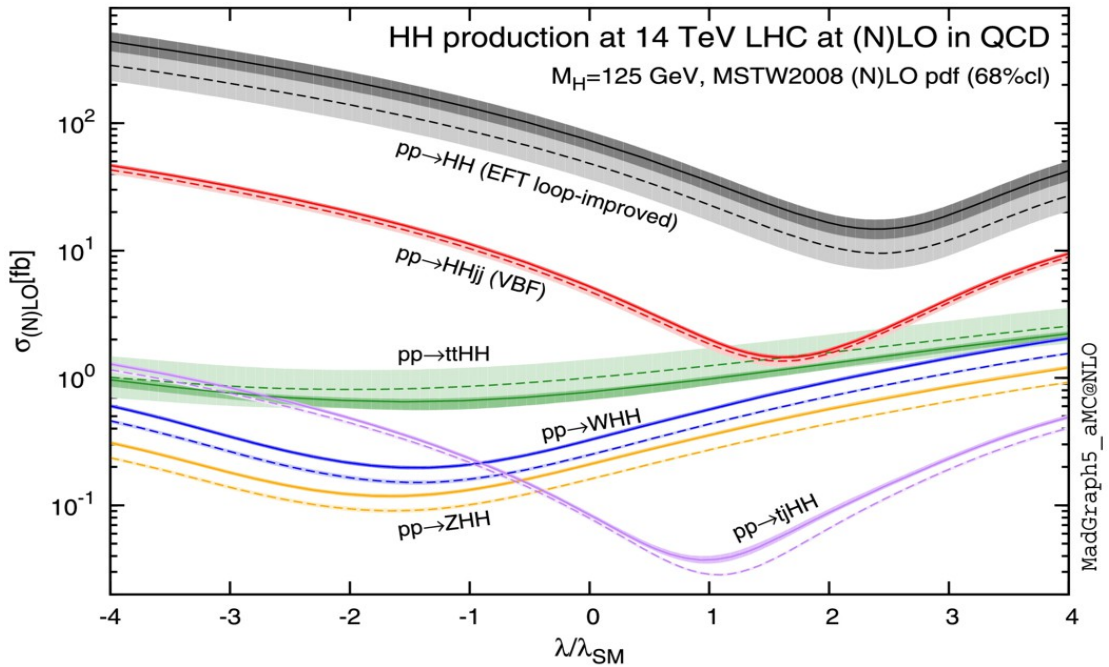
ATL-PHYS-PUB-2013-014

- Signal extraction from high resolution of $\mu^+\mu^-$ invariant mass
- Results assuming same detector performance as Run-1
- 7 σ significance



Non resonant double Higgs production

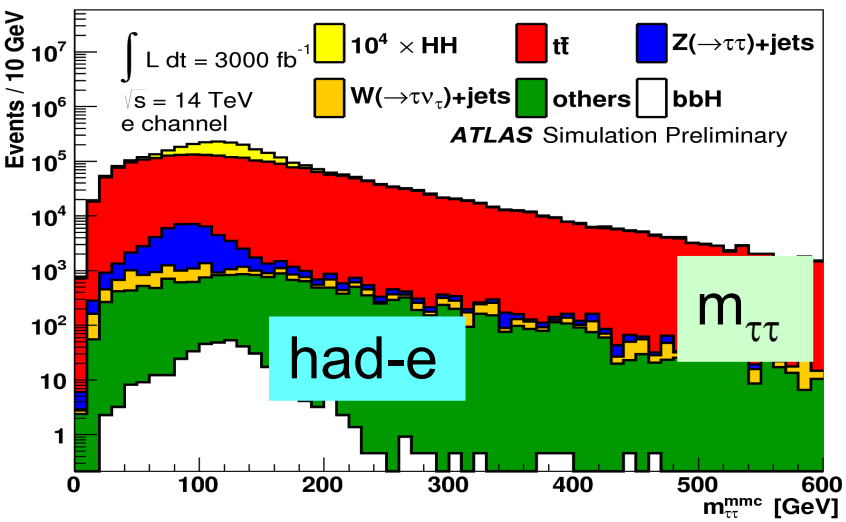
Phys. Lett. B732 (2014) 142-149

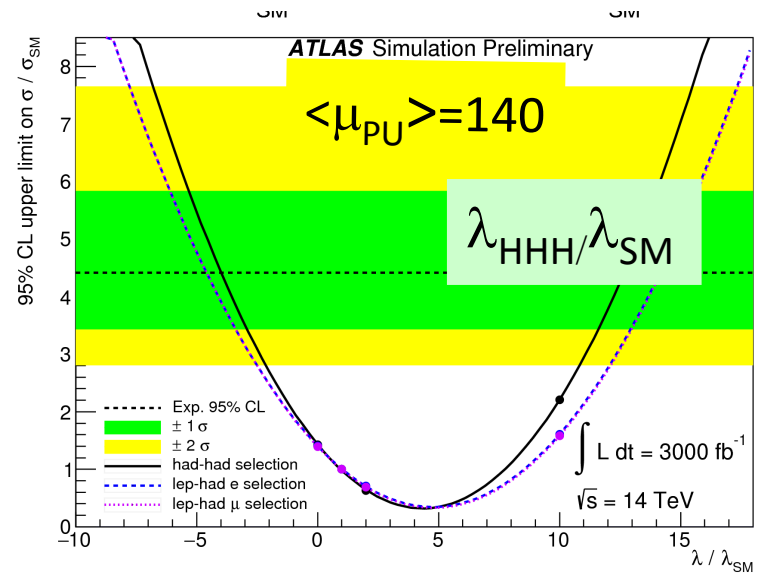


$HH \rightarrow b\bar{b}\tau^+\tau^-$

ATL-PHYS-PUB-2015-046

- Assume Run-1 detector performances
  - Use fully hadronic (had-had) and semileptonic (had-e/μ) final states
  - Main backgrounds : had-e/μ : $t\bar{t}$; had-had : $Z\rightarrow\tau\tau$ + jets, bbjj, $t\bar{t}$
  - Main systematic source: Background modeling uncertainty (Run-1)





Channel	Significance	Combined
e/μ + jets	0.43	0.60
$\tau_{had}\tau_{had}$	0.41	

$-4.0 < \lambda_{HHH}/\lambda_{SM} < 12$ @ 95% C.L. (with syst.)

$HH \rightarrow b\bar{b}b\bar{b}$