Physics at HL-LHC with the upgraded ATLAS detector

Andrea Dell'Acqua, CERN EP-ADE

<andrea.dellacqua@cern.ch>

On behalf of the ATLAS Collaboration

A road to a luminous future

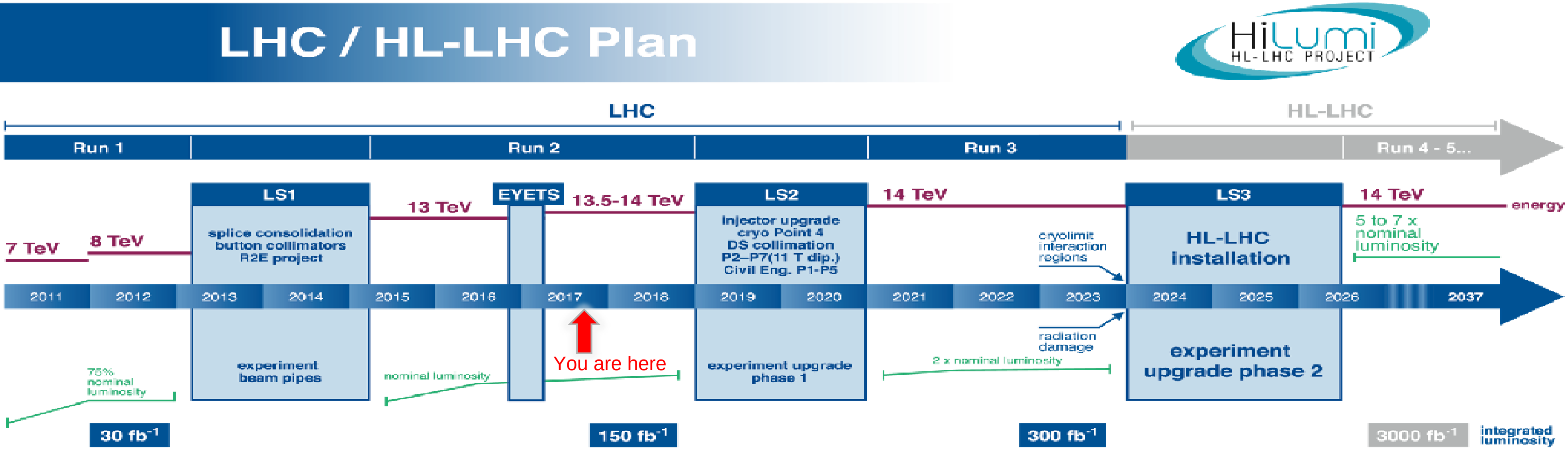
- European Strategy for Particle Physics, 2013

  "Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design by around 2030"

- The HL-LHC project funding was approved in June 2014 and its design study came to a close on Oct. 31st, 2015. The HL-LHC is going to happen!

- In this talk:
  - HL-LHC
  - The ATLAS detector upgrade programme
  - Physics at the HL-LHC with ATLAS
    - SM physics
    - Higgs boson physics
    - BSM

HL-LHC in a nutshell

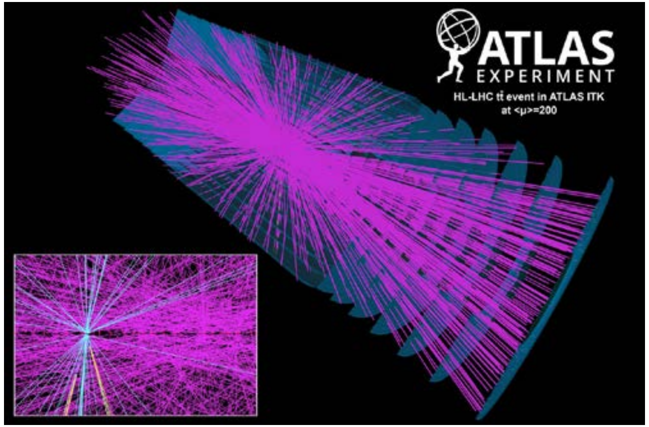


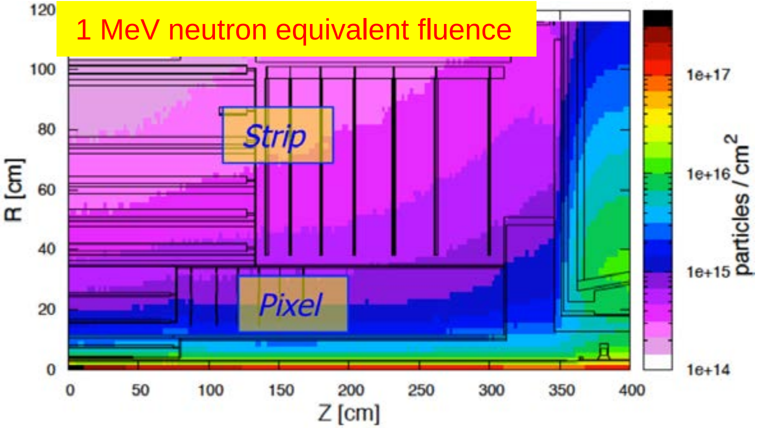
- As we speak, LHC continues to exceed design luminosity while still running at a reduced $\sqrt{s}$=13 TeV.
- Upgrades during Long Shutdown 2 will allow running at the design c.m. energy of $\sqrt{s}$=14 TeV and at $\mathcal{L}$=2-3x10^{34}cm^{-2}s^{-1}. Target is an integrated luminosity of 300 fb^{-1} by ~2025.
- HL-LHC, installed during Long Shutdown 3, will run at luminosities $\mathcal{L}$=5-7.5x10^{34}cm^{-2}s^{-1} with the target of increasing integrated luminosity by a factor 10 (3000 fb^{-1}) by 2037.
- Major strain on the machine, on the experiments and on computing.

The HL-LHC challenges

- High luminosity means a big number of simultaneous events:

  $\langle\mu_{PU}\rangle = 140\text{-}200$
- Requires very granular detectors, very good vertex reconstruction capabilities and bunch crossing identification, fast trigger etc.
- Very high radiation doses
- Detectors aging very quickly and having to be replaced/refurbished
- Accessibility issues in certain regions of the detector





The ATLAS detector upgrade scenario

Phase I
Phase II/ HL-LHC

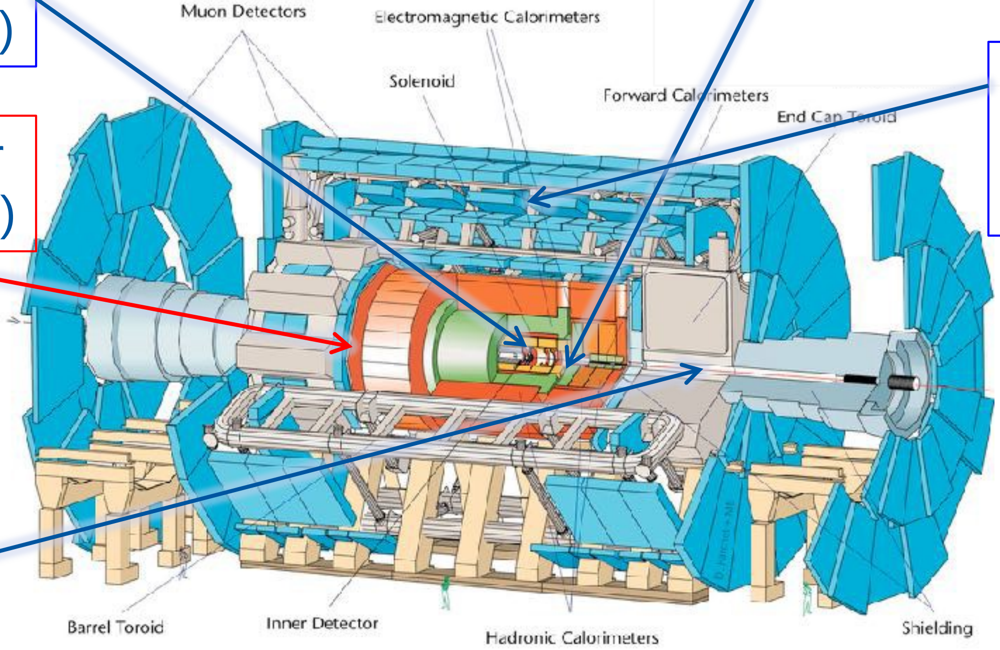
New all-silicon Inner Tracker (ITk)

New end cap inner Muon station (nSW)

Possible high granularity Timing detector

New inner barrel trigger chambers in the muon system

Possible forward muon tagger



And more:
- ✓ New frontend electronics
- ✓ Higher rate, longer latency trigger system

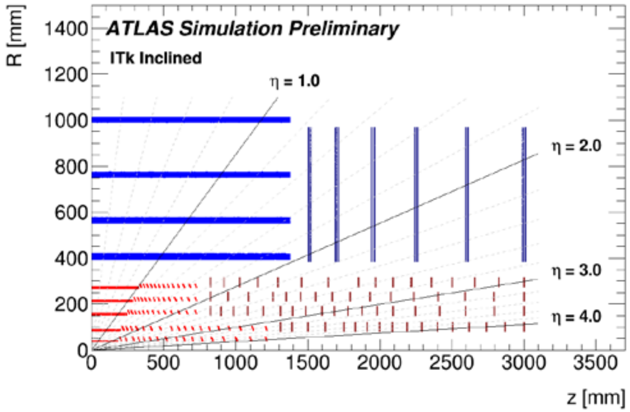
The ATLAS upgrade

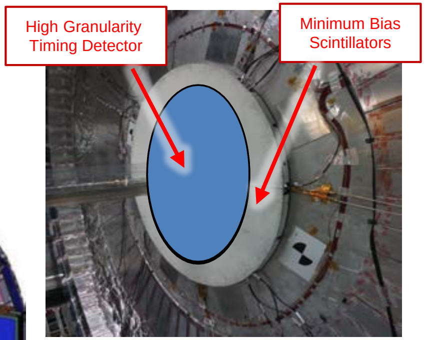
- New all-silicon inner tracker with increased coverage of |η|<4 and increased radiation tolerance (HL-LHC)
  - Pixel: 5 inner barrels and forward disks, occupancy <0.1%
  - Strips: 4 extended barrels and 6 disks, occupancy <1%

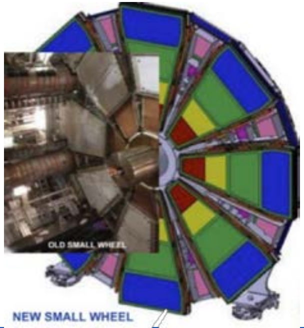
- Replace inner end cap muon stations with a New Small Wheel composed of MicroMeGaS and sTGC for improved tracking and trigger performance (Phase I)
- New RPC layers in the barrel Muon system (|η|<1) for increased trigger coverage and performance (HL-LHC)

- Readout electronics replaced in the Lar and Tile calorimeters
- Proposed High Granularity Timing Detector for improved bunch crossing ID and pile-up suppression, 2.4<|η|<4.3 (HL-LHC)

- Hardware trigger with L0<1 MHz and L1<400 kHz
- High Level Trigger with 10 kHz output (permanently recorded data)
- “Custom hardware” triggers for data streaming at rates 1-40 MHz
- New Inner Tracker, Calorimeter, Muon triggers







ATLAS HL-LHC simulation strategies

- HL-LHC simulation must encompass upgraded ATLAS detector scenarios and trigger systems, a collision energy of $\sqrt{s}$=14 TeV and high pile-up, <μ_{PU}>=140/200.
- For physics analysis, use generator level Monte Carlo samples
  - Overlay with jets from dedicated pile-up library, from fully simulated pile-up jet samples
  - To simulate the detector response, smear p_T and energy of reconstructed physics objects using smearing functions based on fully simulated samples
  - Apply reconstruction efficiencies for electrons, muons, jets…
  - Apply trigger efficiency functions to emulate triggers
- Extrapolation from Run I/II results
  - Signal and background are scaled to higher luminosities and higher collision energy
  - Assume detector performance and analysis techniques remain unchanged
  - Much room for improvements!
- With huge statistics at the HL-LHC, systematics can be the dominant factor in measurement precision
  - Current experimental systematics scaled to best guess for HL-LHC
  - Results provided with current theory systematics and without theory systematics

In the following:
Three ATLAS detector upgrade scenarios
- Reference
- Middle
- Low

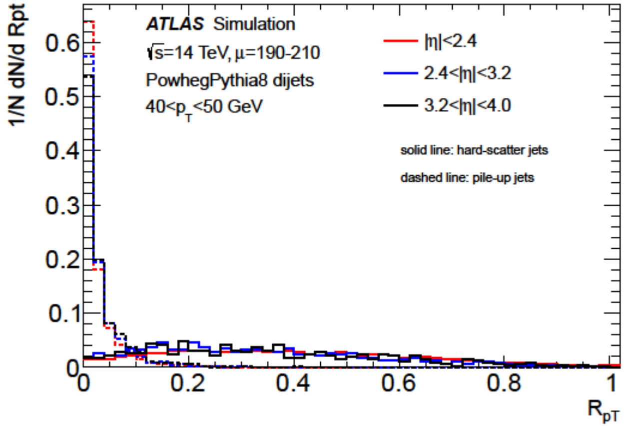
<μ_{PU}>=200 (unless otherwise indicated)

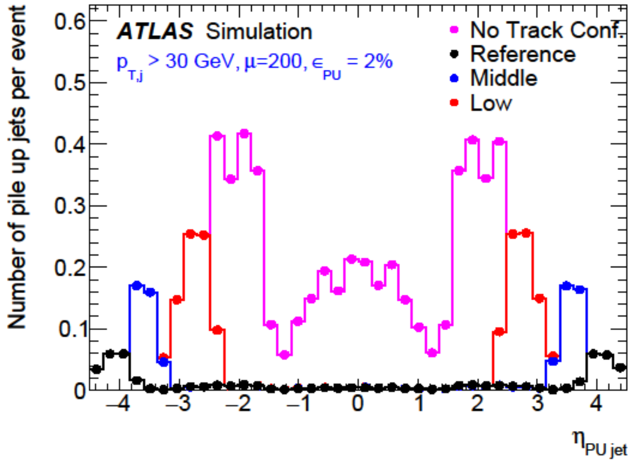
Pile-up mitigation

- Typical jet selections require:

  p_T^{jet}>30 GeV and $|\eta^{jet}|$<3.8
- For $<\mu_{PU}>$ =200 we expect 4.8 pile-up jets per event which satisfy the request
- To reduce jet sensitivity to pile-up a parameterized track confirmation requirement is applied, based on selecting on charged vertex fraction, R_{p_T}

  $$\boldsymbol{R_{p_T}} = {}^{\sum_{tracks} p_T}\big/_{p_T^{jet}}$$
- Applied to all non b-tagged jets with p_T^{jet} <100 GeV and $|\eta^{jet}|$<3.8, the selection reduces pile-up by a factor 50
  - 0.2 selected pile-up jets per event
- More sophisticated pile-up rejection criteria being developed

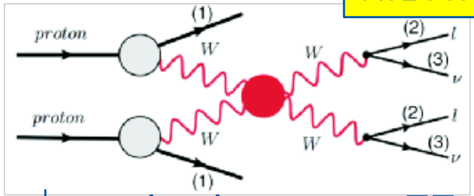




SM physics: Vector boson scattering

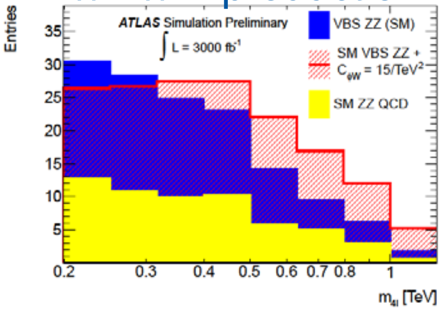
ATL-PHYS-PUB-2013-006

LHCC-G-166

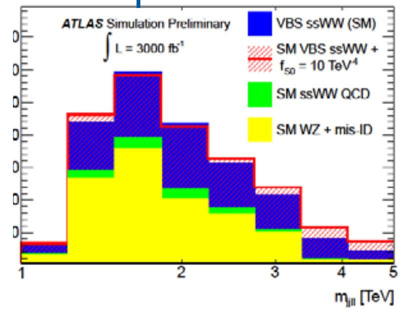


- Sensitive test of the vector boson vertices in the SM
- With 3000 fb^{-1}:
  - Clean observation of W±W±,ZZ and WZ scattering above backgrounds
  - Sensitive to dimension-8 operators at scales ~1 TeV, good case study for BSM

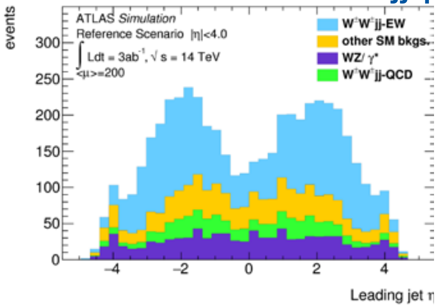
$W^{\pm}W^{\pm}$ production

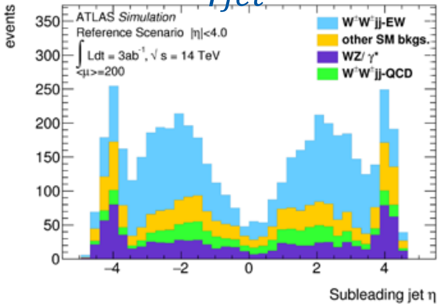


ZZ production



$W^{\pm}W^{\pm}$jj production: η_{jet}





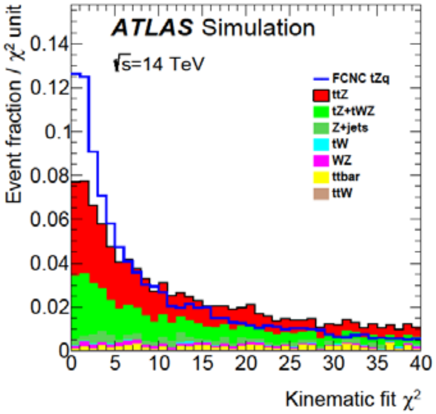
- ➢ Significance of SM $W^{\pm}W^{\pm}$jj production: ~11σ
- ➢ Cross section precision $\Delta\sigma/\sigma$=5.9%

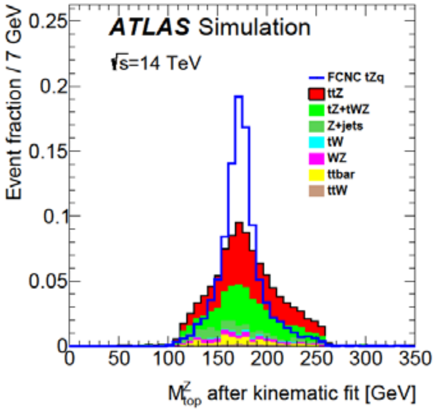
SM physics: Flavour Changing Neutral Currents, $t \to Zq$ and $t \to Hq$

- FCNC not allowed in SM at tree level, only via loops: highly suppressed
- Higher rate predicted in BSM models
- Signature: $t\bar{t}$, one top $t \to Wb$, one top goes FCNC → Strong requirements on event reconstruction

$t \to Zq$: kinematic fit with χ^2

$$\chi^2 = \frac{\left(m_Z - m^{\mathrm{reco}}_{\ell_1\ell_2}\right)^2}{\sigma_Z^2} + \frac{\left(m_W - m^{\mathrm{reco}}_{\ell_3\nu}\right)^2}{\sigma_W^2} + \frac{\left(m_t - m^{\mathrm{reco}}_{\ell_3\nu j_b}\right)^2}{\sigma^2_{t\to Wb}} + \frac{\left(m_t - m^{\mathrm{reco}}_{\ell_1\ell_2 j_u}\right)^2}{\sigma^2_{t\to Zq}}$$





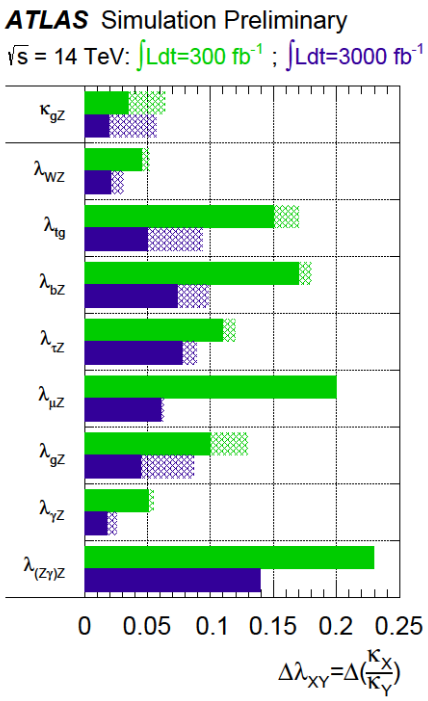
$t \to Hq, H \to b\bar{b}$:
use event categories based on number of (**b**)-jets and discriminant variable, **D**

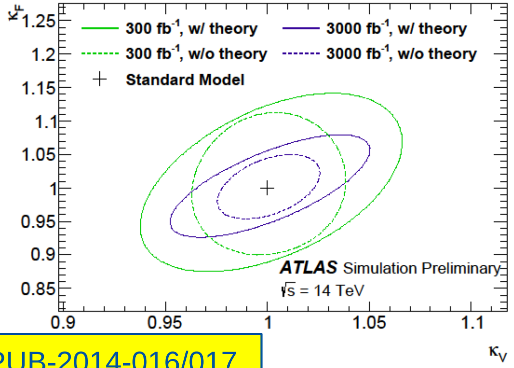
Limits on BR(t→ Zq) ~ 10^{-4}
Limits on BR(t→ Hq) ~ 10^{-4}

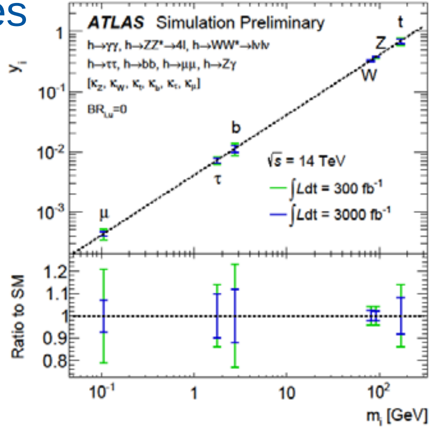
ATL-PHYS-PUB-2016-029

Higgs boson physics: coupling precisions

- Full set of HL-LHC coupling projections are based on Run I analyses ($<\mu_{PU}>=140$)
- with 3000 fb^{-1}:
  - W/Z couplings to 3%
  - μ coupling to 7%
  - t,b,τ couplings to 8-12%
- Projections do not include upgraded detector designs nor improvements in analysis techniques



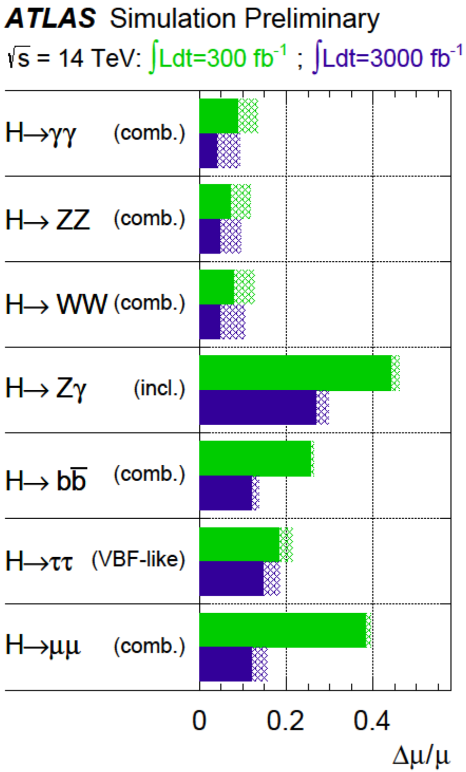


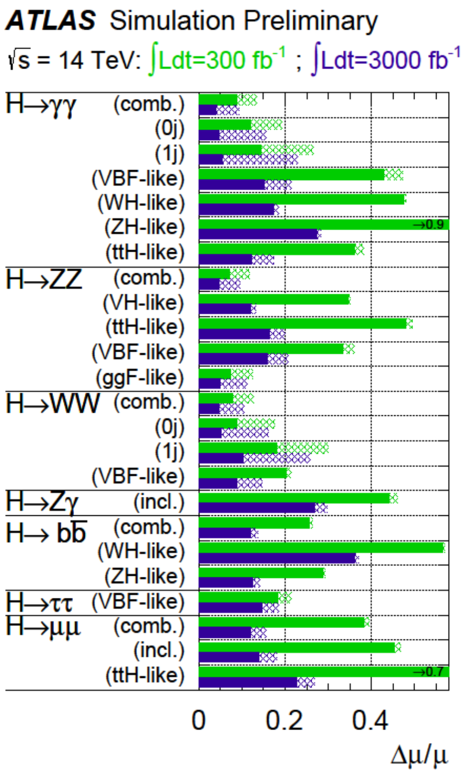


ATL-PHYS-PUB-2014-016/017

Higgs boson physics: Signal strength

- Signal strength $\mu = \sigma / \sigma_{SM}$ used to express compatibility with theory
- Goal is to minimize the uncertainty of the measurements ($\Delta\mu / \mu$)
  - With high statistics QCD and PDF uncertainties become significant



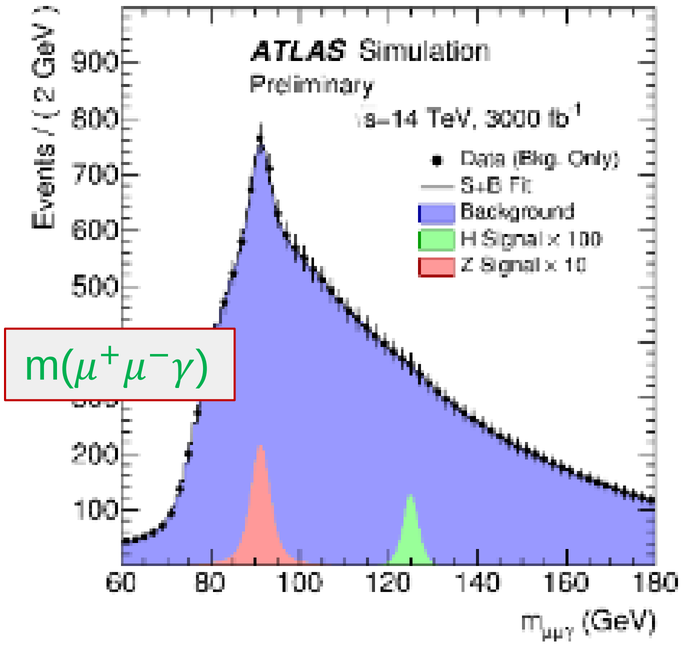


ATL-PHYS-PUB-2014-016/017

Higgs boson physics: a rare decay, H→J/$\psi\gamma$

ATL-PHYS-PUB-2015-043

- Sensitive to the Higgs boson coupling to the charm quark
  - SM expectation: BR(H→J/$\psi\gamma$)=(2.9±0.2)×10^{-6}
  - ATLAS limit from Run I: BR(H→J/$\psi\gamma$)=1.5×10^{-3}
- Using J/$\psi \to \mu^+\mu^-$ decay mode
- Z→J/$\psi\gamma$ as a cross-check
- Using multivariate analysis, ~3 signal events, 1700 background events in m($\mu^+\mu^-\gamma$)∈115-135 GeV



Expected limits at 95% c.l.:

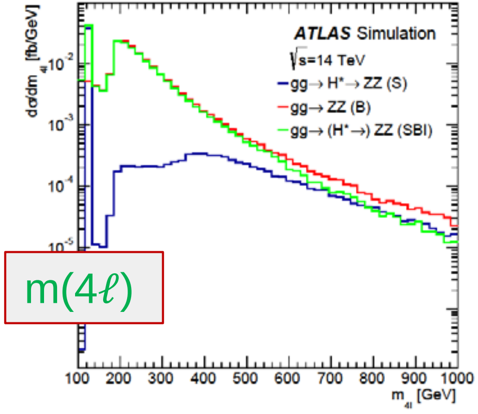
✓ **BR(H→J/$\psi\gamma$)=(44^{+19}_{-12})×10^{-6}**

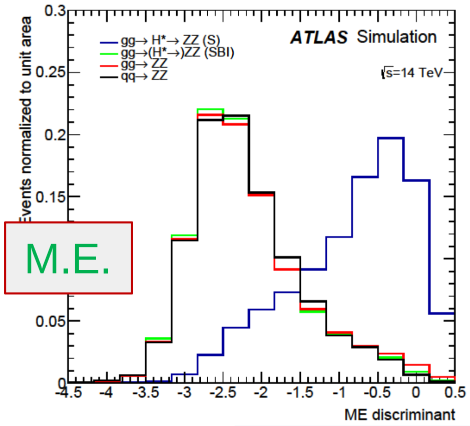
✓ $\sigma(gg \to H) \times$ **BR(H → J/$\psi\gamma$)=($3.1^{+0.9}_{-1.3}$) × 10^{-6}** (no background systematics)

Higgs boson physics: Γ_H from off-shell couplings

- Measure off-shell production of $H\rightarrow ZZ^*\rightarrow 4\ell$ with $m(4\ell)>220$ GeV
- Use $m(4\ell)$ shape and matrix element to discriminate between signal and background
- Off-shell production used to constrain the Higgs boson width Γ_H
- For $\Gamma = \Gamma_{SM}$ combining with on-shell measurement (assuming off-shell measurement dominates):

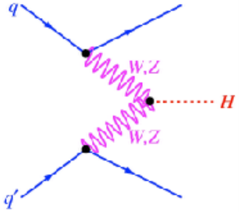
  $\Gamma_H=4.2^{+1.5}_{-2.1}$ MeV (stat.+sys)
- Run I limit: $\Gamma_H<22.7$ MeV at 95% C.L. (WW, ZZ)



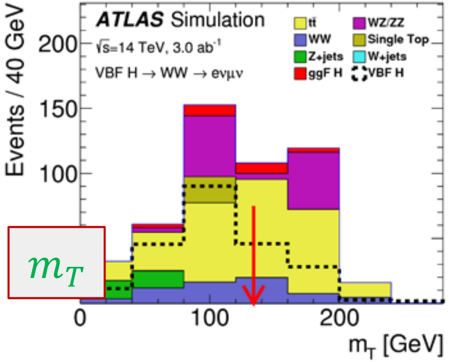


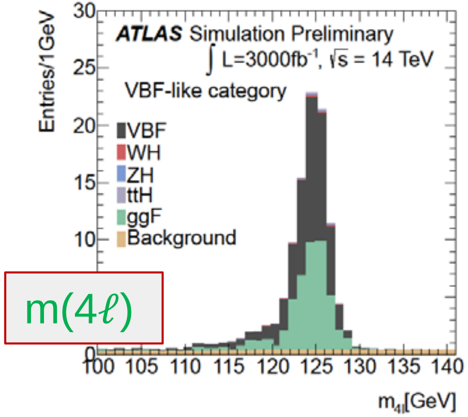
ATL-PHYS-PUB-2015-024

Higgs boson physics:Vector Boson Fusion



- $H \rightarrow WW \rightarrow \ell\nu\ell\nu \ (\ell = e, \mu)$
  - Challenging due to large backgrounds (dominant systematic uncertainty)
  - Good benchmark for performance at HL-LHC: E_T^{miss}, central-jet veto, b-tagging for forward jets
- H→ZZ*→4ℓ
  - Must disentangle ggF/VBF production modes
  - Background from pile-up jets in the forward region
  - Use BDT method for optimal signal/background separation
  - Nice case study to quantify benefit from upgraded detector





Different systematic assumptions:

FULL or NONE

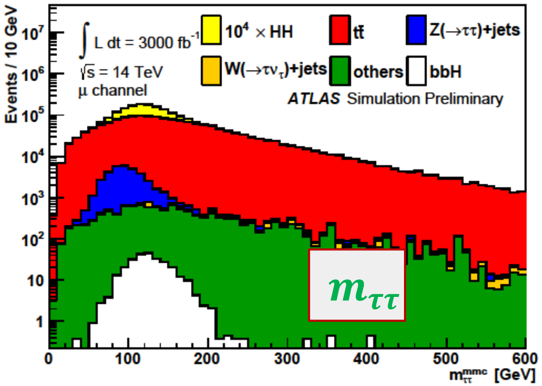
	ZZ $\langle\mu_{PU}\rangle$ = 200 FULL	ZZ $\langle\mu_{PU}\rangle$ = 200 NONE	WW $\langle\mu_{PU}\rangle$=200 FULL	WW $\langle\mu_{PU}\rangle$=200 NONE
$\Delta\mu$	0.18	0.15	0.20	0.14
Significance	7.2σ	10.2σ	5.7σ	8.0σ

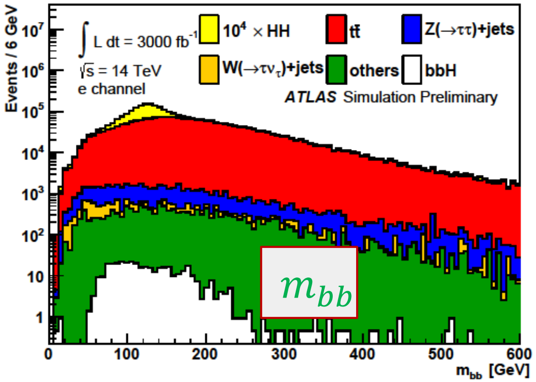
HH production: $HH \to b\bar{b}\ \tau^+\tau^-$

ATL-PHYS-PUB-2015-046

All final states of $\tau\tau$ considered

		trigger	signal events in $3000\ \mathrm{fb}^{-1}$	background in $3000\ \mathrm{fb}^{-1}$
τLEP	τLEP	single e/μ p_T<25GeV	9	6,200
τLEP	τHAD		20	880
τHAD	τHAD	di-τ: $p_T^{\mathrm{vis}}(\tau)$ >40 GeV	19	830



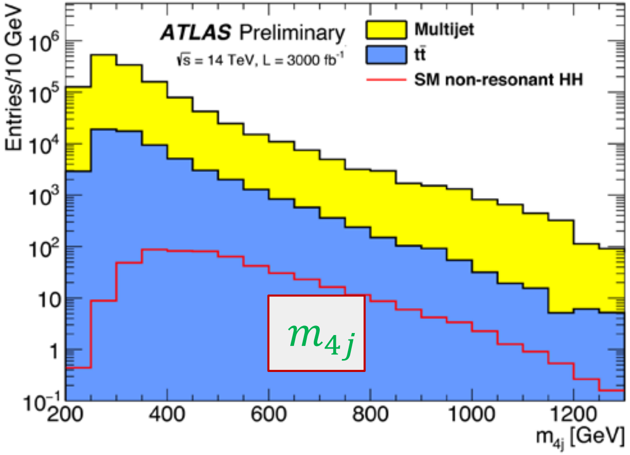


$\tau_{LEP}\tau_{LEP}$ does not add to significance and is not further analysed

Combined significance $HH \to b\bar{b}\ \tau^+\tau^-$ production (no syst. error): 0.6σ

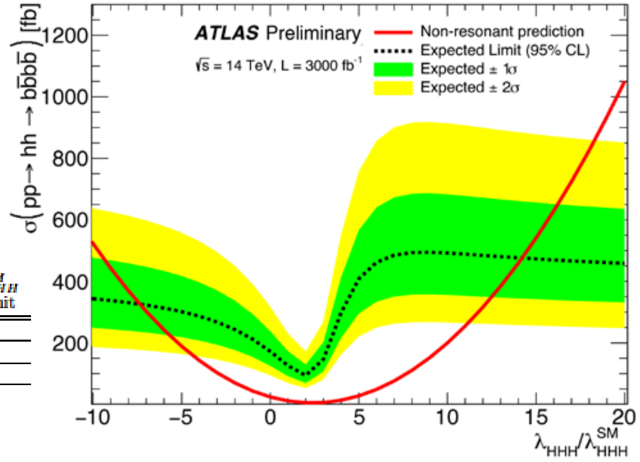
HH production: $HH \rightarrow b\bar{b}b\bar{b}$

- Main background is QCD multi-jet production
- Extrapolation from Run II results
  - Assumes the current detector (i.e. no upgrades), trigger & flavor tagging performance: no consideration of extra pile-up jets
  - Run II trigger threshold p_T^{jet}>30 GeV → HL-LHC p_T^{jet}>75 GeV



$HH \rightarrow b\bar{b}b\bar{b}$ production (no systematic error): combined significance → 0.6σ

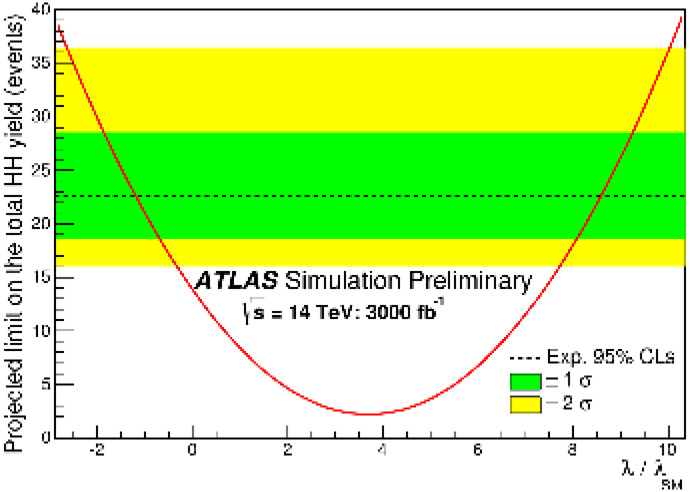
Jet Threshold [GeV]	Background Systematics	σ/σ_{SM} 95% Exclusion	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Lower Limit	$\lambda_{HHH}/\lambda_{HHH}^{SM}$ Upper Limit
30 GeV	Negligible	1.5	0.2	7
30 GeV	Current	5.2	-3.5	11
75 GeV	Negligible	2.0	-3.4	12
75 GeV	Current	11.5	-7.4	14

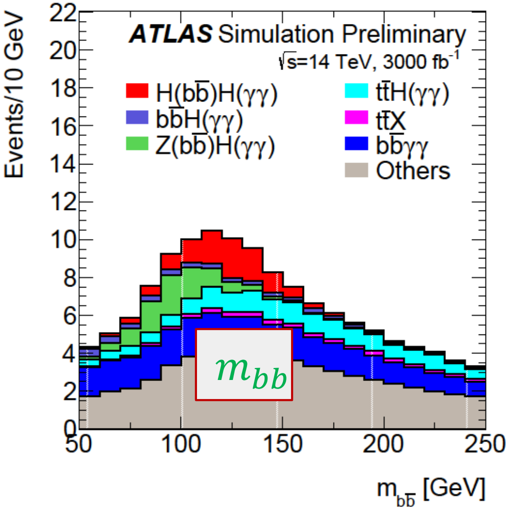


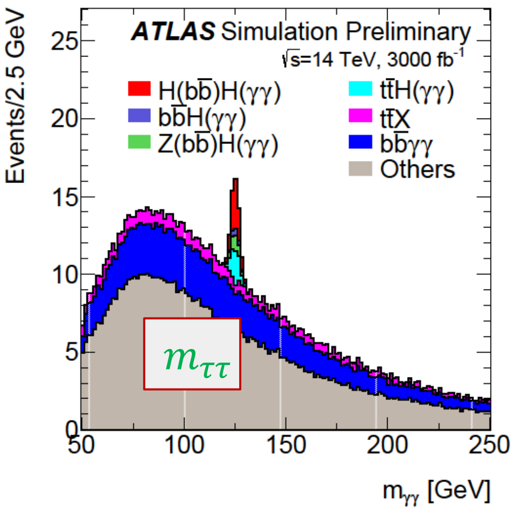
ATL-PHYS-PUB-2016-024

HH production $HH \to b\bar{b}\gamma\gamma$

- After selections: 8.4 signal events, 47 background
- Significance: 1.3σ (no systematic error)







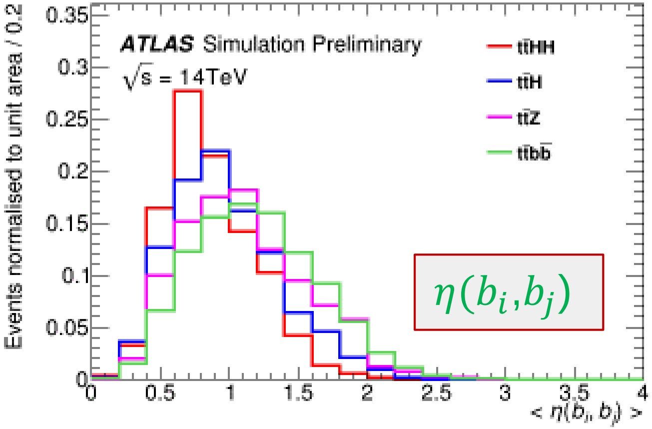
- With no systematic error:

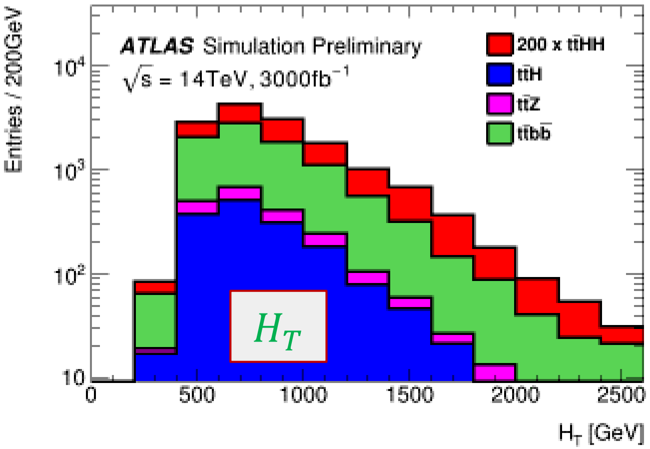
$-1.3 < \lambda_{HHH} / \lambda_{SM} < 8.7$

ATL-PHYS-PUB-2014-019

HH production: $t\bar{t}$HH production

- $\sigma(t\bar{t}\mathrm{HH}) \sim 1$ fb
  - Use $HH \rightarrow b\bar{b}b\bar{b}$ final state and semi-leptonic final state of $t\bar{t}$
  - Single lepton trigger requirement (e, μ)
  - 6 b-jets, 2 light jets, e/μ and E_T^{miss}
- Cut-based analysis: no cut on Higgs candidate mass, too many combinatorics!



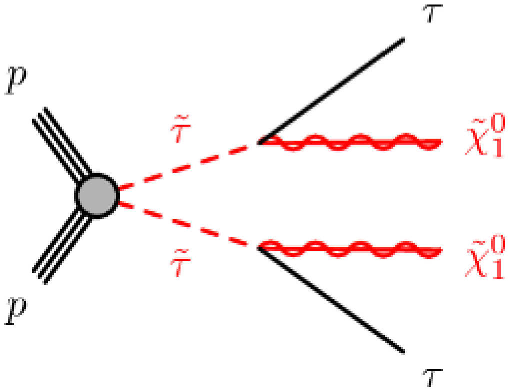


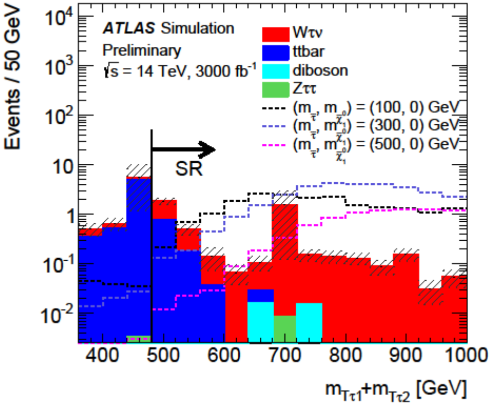
- For ≥5 b-tags: 25 signal events, 7100 background
  - Background is dominated by c-jets mistagged as b-jets from $W \rightarrow cs$
- Significance: 0.35σ (no systematic error)

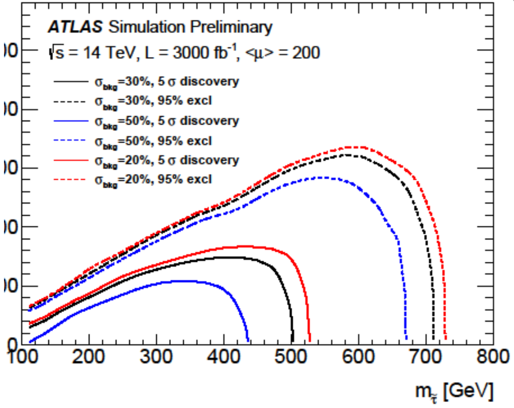
ATL-PHYS-PUB-2016-023

Beyond the SM: Direct production of stau pairs

- Assume 100% branching ratio to τ and LSP, $\tilde{\chi}_1^0$
- Signature:
  - 2 τ-jets
  - Large missing energy
  - Define signal region in $m_T(\tau_1, E_T^{miss}) + m_T(\tau_2, E_T^{miss})$
- Main backgrounds: $W + jets, t\bar{t}$





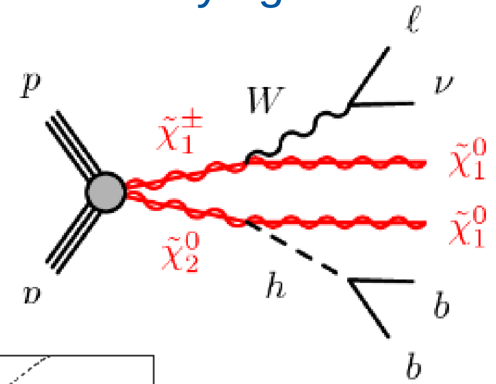


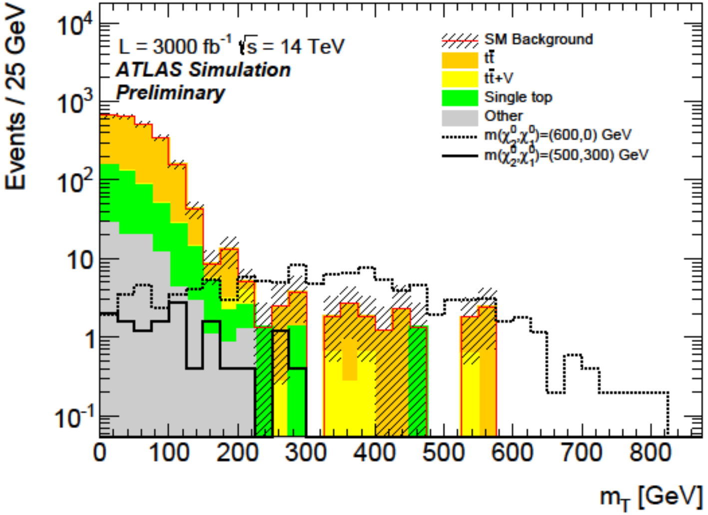
Discovery reach for 3000 fb^{-1} : 430-520 GeV

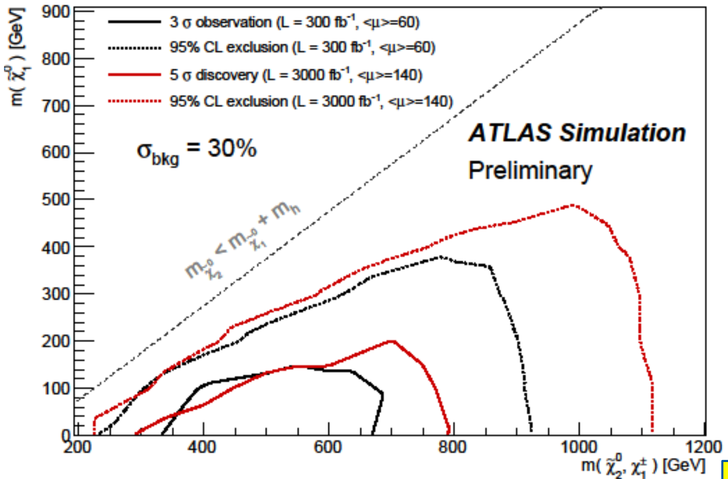
ATL-PHYS-PUB-2016-021

Beyond the SM: Direct production of Charginos and Neutralinos decaying to **Wh**

- Signature:
  - Chargino to leptonic W → clear signature
  - Neutralino to $h \to b\bar{b}$: benefits from detector upgrades
  - Large missing energy
- Background: W+jets, $t\bar{t}$, single top, ttV





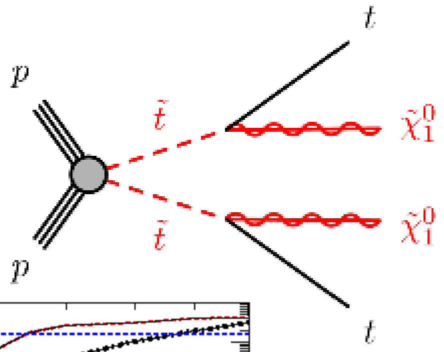


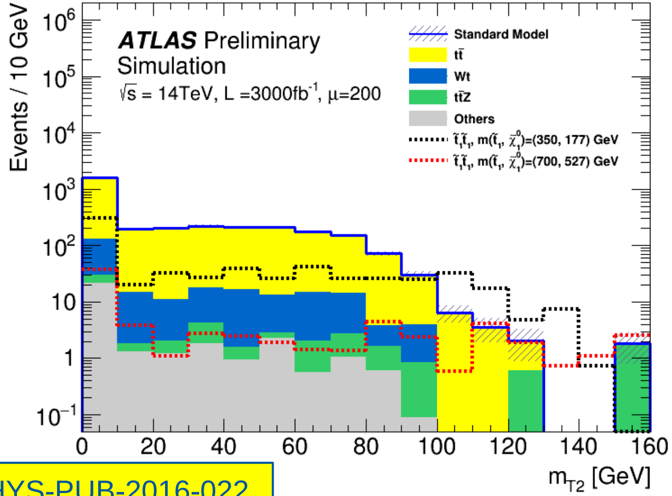
Discovery reach for 3000 fb^{-1} : ~850 GeV

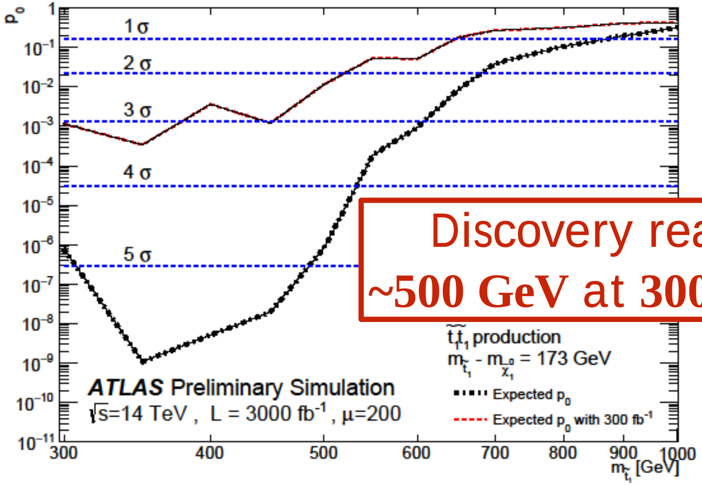
ATL-PHYS-PUB-2015-032

Beyond the SM: Direct stop pair production with compressed mass spectra

- Compressed mass spectra
- Scenario with low stop-neutralino mass difference
  - $m(\tilde{t}) - m(\tilde{\chi}_1^0) \cong m(t)$
- Signature: 2 leptons + 2 b-jets +missing E







Discovery reach ~500 GeV at 3000 fb^{-1}

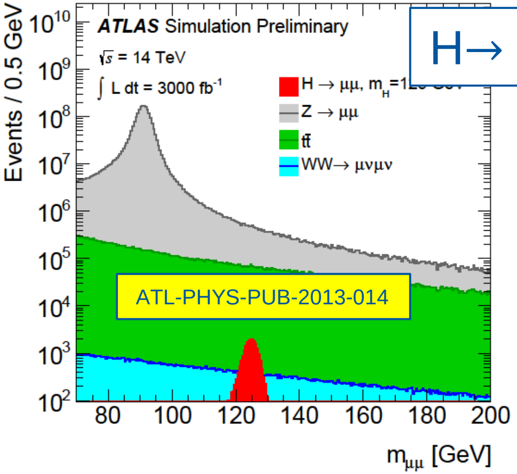
ATL-PHYS-PUB-2016-022

Summary

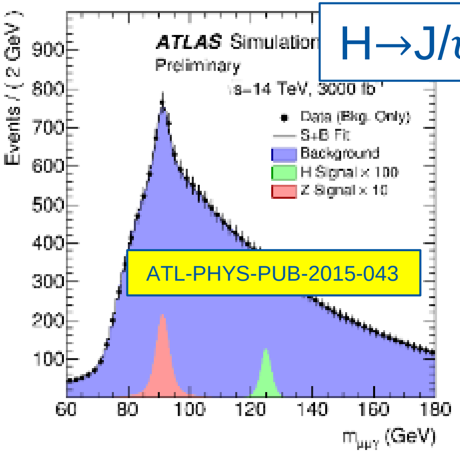
- A clear roadmap to HL-LHC has been set
- The ATLAS Collaboration is proceeding with an upgrade programme aimed at coping with a new, very harsh and challenging environment of increased pile-up and large background
- The HL-LHC will provide very useful insights into the Standard Model and Higgs boson physics
- Measuring the Higgs boson self-coupling is a rather formidable challenge and one of the main targets of the ATLAS experiment at the HL-LHC
- Studies are still ongoing, the rather conservative approach adopted until now suggests that substantial improvements are possible and that we will probably do better than presented here

Backup

Higgs boson physics: rare decays

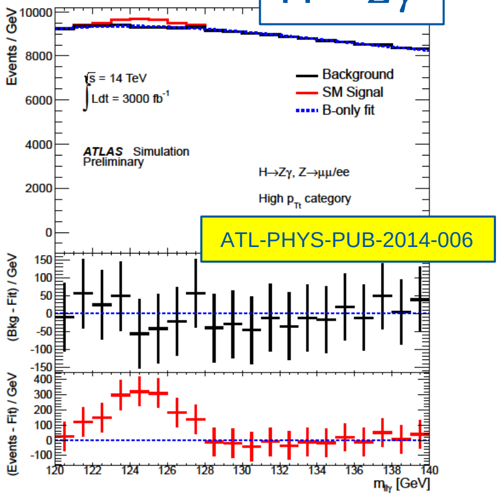


H→ $\mu^+\mu^-$



H→J/$\psi\gamma$

H→ $Z\gamma$



Probe coupling to 2nd generation fermions

7σ observation for $<\mu_{PU}>=140$, 25% (stat)$\oplus$17% (syst.) precision

Probe for Yukawa couplings

Anticipate to set the limit of the BR(H→J/$\psi\gamma$ at 15xSM expectation

First limit set at 600xSM (PRL 114 (2015) 121801)

Probe for new physics in the loop and important for coupling measurement

3.9σ observation for $<\mu_{PU}>=140$, 25% (stat)$\oplus$17% (syst.) precision

- ✓ Rare Higgs decays are sensitive probes for new physics
- ✓ Observation at the SM rate for H→ $\mu\mu$, H →Zγ only possible with the HL-LHC dataset