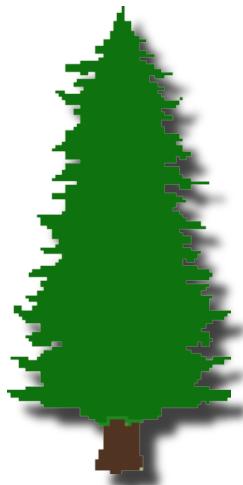


# ATLAS Future

Jason Nielsen (UC Santa Cruz)  
*on behalf of the ATLAS Collaboration*

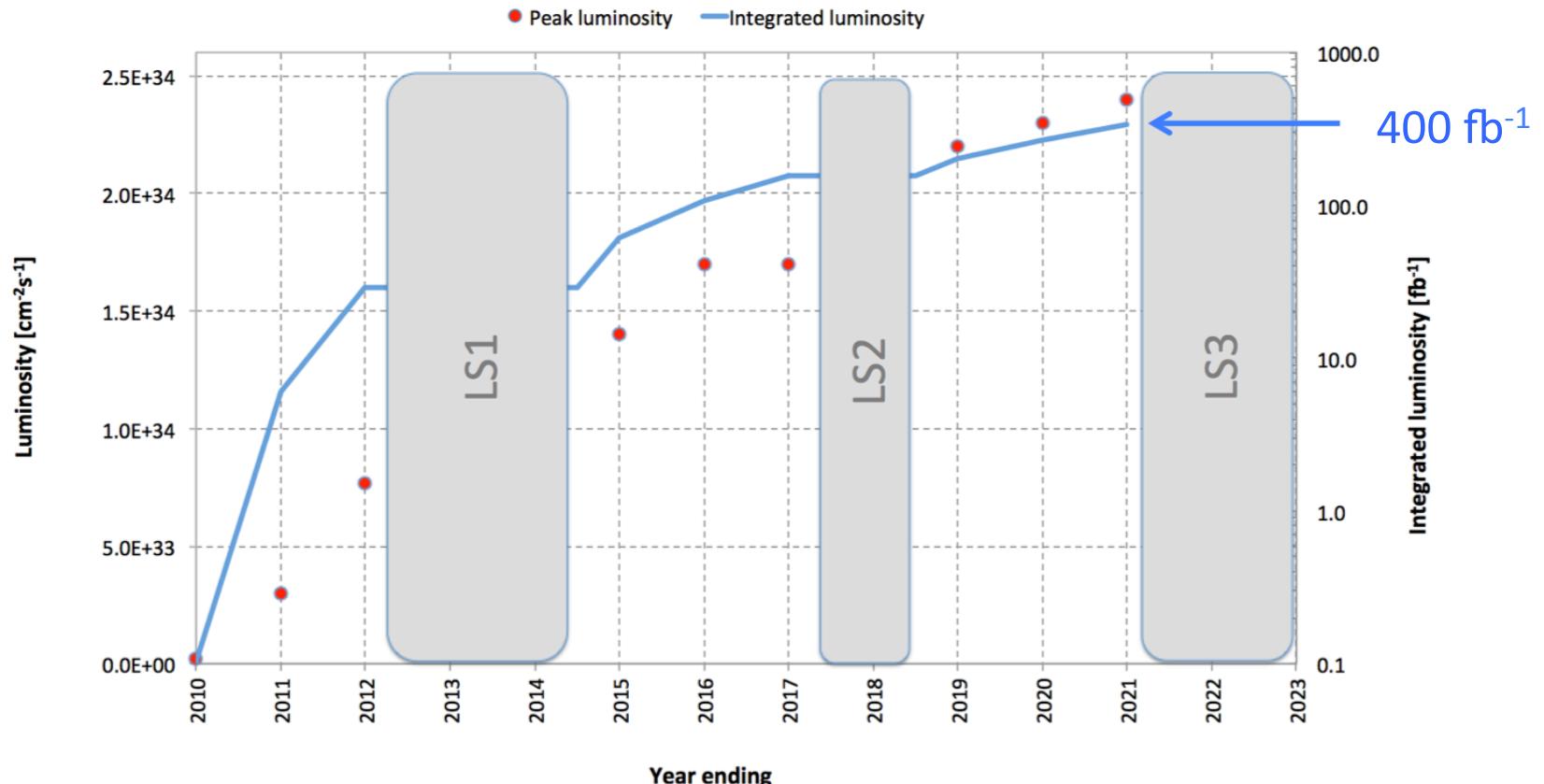


Snowmass Energy Frontier Workshop  
Seattle, Washington  
July 1, 2013

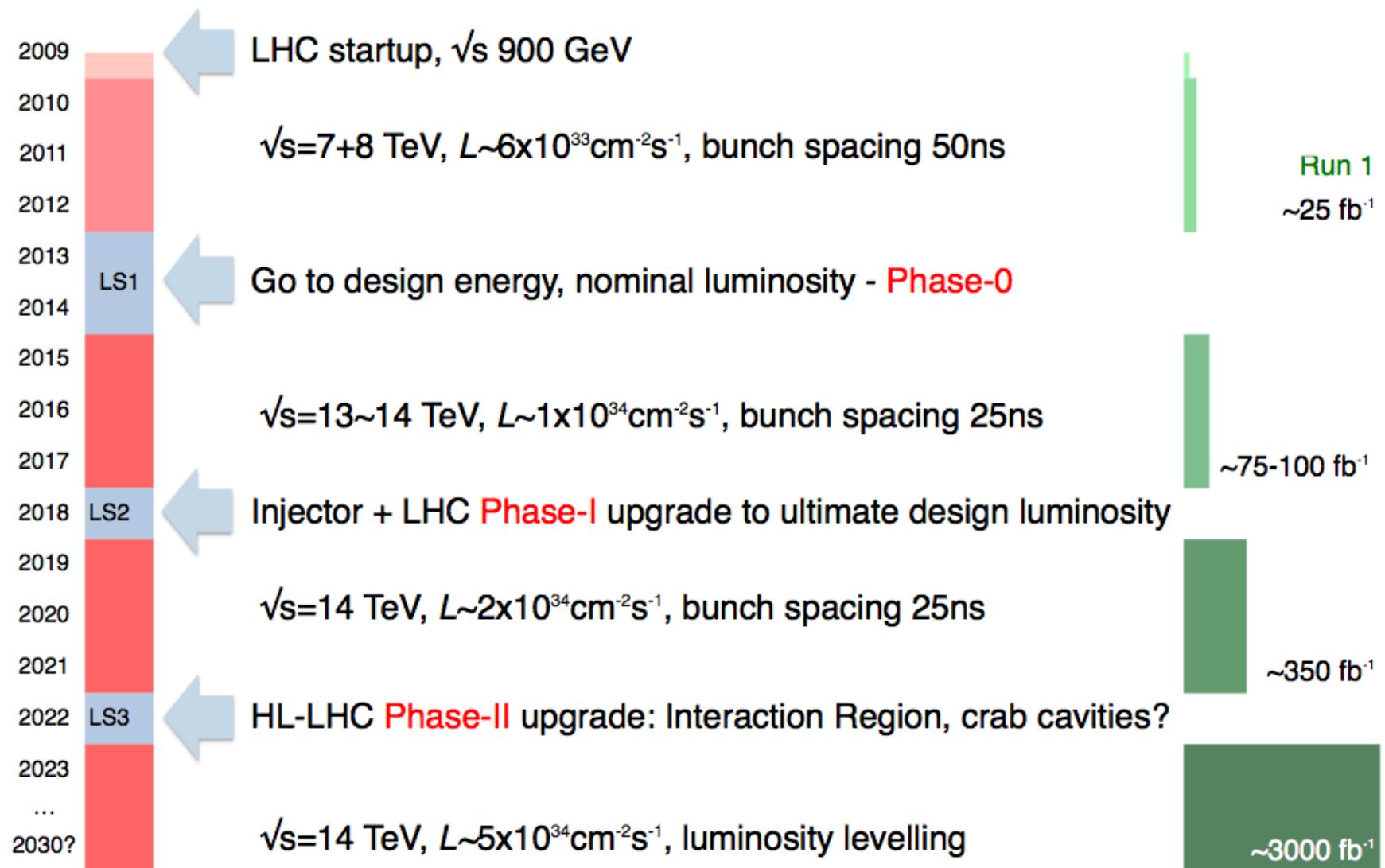


# Approved LHC Program

- Long Shutdown 1 gives 13-14 TeV capability at original design lumi
- LS2 brings new injector systems online for  $2.2 \times 10^{34} \text{ cm}^{-2} \text{s}^{-1}$  lumi
- After  $400 \text{ fb}^{-1}$ , doubling of dataset slows
  - Low- $\beta$  triplet magnets and some detectors will be radiation-damaged

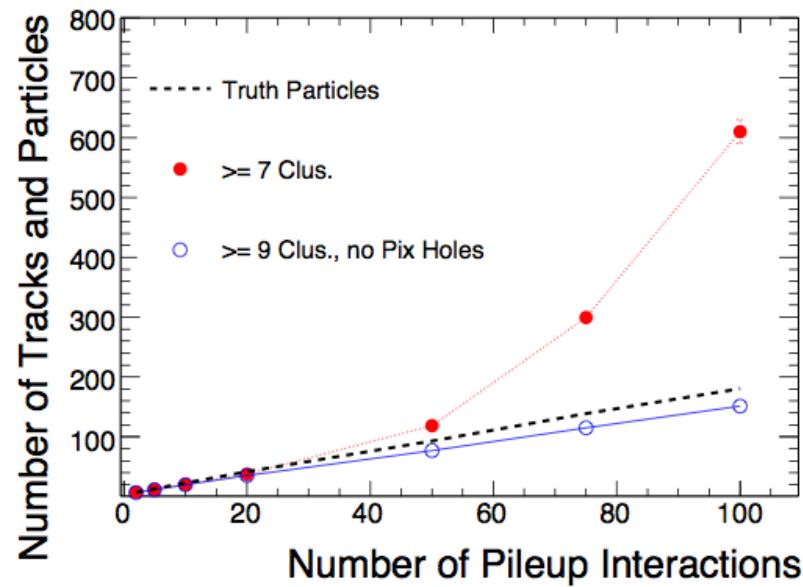
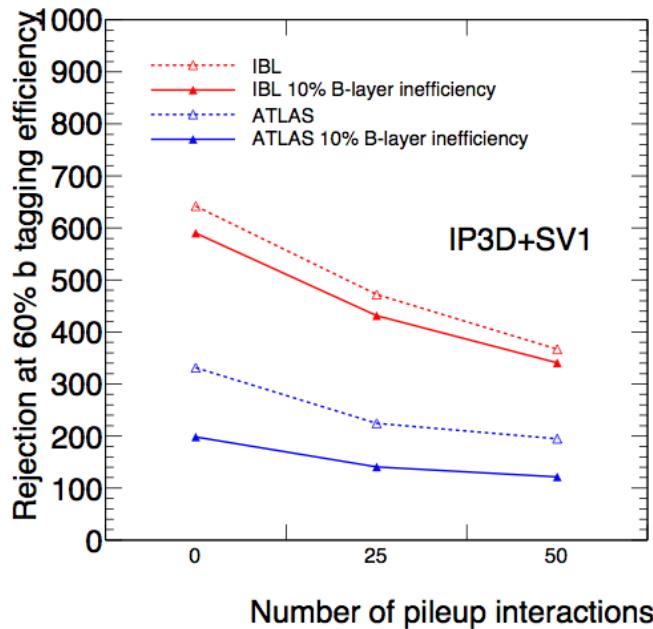


# Evolution of the LHC Program



# ATLAS Upgrades during LS1

- Major Phase 0 upgrade is installation of Insertable B-Layer (IBL) planar silicon pixel detector
  - Improve tracking precision and b-tagging with detector at 35mm radius
  - Recover tracking robustness against pileup occupancy and module failures
  - See [IBL Technical Design Report](#) (CERN-LHCC-2010-013)



- Also installing muon chambers to complete coverage and executing repairs on TRT and Calorimeter systems

# Phase 0 Physics at 13-14 TeV

- With  $75\text{-}100 \text{ fb}^{-1}$  in 2015-2017, reboot ATLAS high-energy physics program with increased energy
  - Extend sensitivity to supersymmetry at high masses
  - Extend discovery reach for high-mass enhancements beyond the SM
  - Pursue observation of Higgs boson decays to fermions
  - Benchmark Z production via vector boson fusion
  - Pursue first measurements of low-mass vector boson scattering
  - Improve measurements of Higgs couplings and spin
  - Measure top quark production and multijet production at high energies
  - Standard Model measurements to constrain PDFs at 14 TeV

Physics program for the next  $100 \text{ fb}^{-1}$  will certainly be as exciting as for the first  $30 \text{ fb}^{-1}$

# ATLAS Upgrades during LS2

- ATLAS Phase-I Upgrade Letter of Intent (CERN-LHCC-2011-012) submitted at end of 2011
  - Eye toward the future: all of the detector upgrades in LS2 are important parts of the detector plans for the HL-LHC project
- Fast Tracker (FTK) uses Associative Memory to find and fit tracks in silicon detectors at rates of 100 kHz and latency < 100  $\mu$ s
- Muon New Small Wheel (NSW) upgrade to maintain tracking performance and trigger rates for single muons in  $1.3 < |\eta| < 2.4$ 
  - Region with high cavern background flux causes high hit occupancy
- Upgrades to calorimeter readout electronics to introduce wider digital path to trigger system
  - Operate in mixed analog/digital trigger mode until overhaul for Phase II
- TDRs for the NSW and FTK projects have been approved by ATLAS

# Phase I Physics at 14 TeV

---

- With  $300 \text{ fb}^{-1}$  in 2019-2021, extend discovery sensitivity
  - Measurements of Higgs couplings to <20% in ZZ,  $\gamma\gamma$ ,  $\tau\tau$
  - Measurements of WW,WZ,ZZ scattering at high invariant mass
  - SUSY searches for high-mass gluinos and squarks up to 2 TeV
  - SUSY searches for charginos up to 350 GeV and neutralinos up to 250 GeV
  - SUSY searches for compressed spectra and light stops
  - Reach above 4 TeV for exotic resonances decaying to top quark pairs
- These depend on maintaining low- $p_T$  thresholds for single lepton and diphoton triggers – a key aspect of the detector upgrades

# ATLAS Phase II (HL-LHC) Program

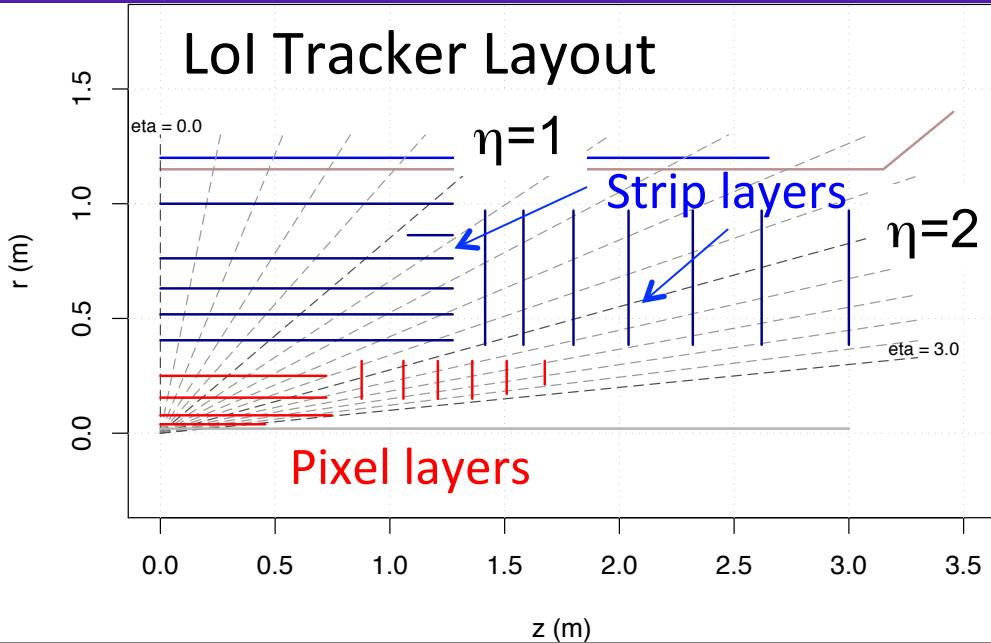
- ATLAS Phase-II Upgrade Letter of Intent (LoI): CERN-LHCC-2012-022, submitted in March 2013
  - “Highest priority should be to exploit full LHC physics potential at highest beyond-design leveled luminosity of  $5 \times 10^{34}$  with a  $3000 \text{ fb}^{-1}$  dataset”
- Aiming for a broad picture of physics at the TeV scale and beyond
  - Precision measurements of the Higgs boson properties, including measurements of some couplings to <10%
  - Measurements of the electroweak sector at TeV scale
  - Expanded sensitivity to new particles in theories of supersymmetry
  - Expanded reach for other high-mass particles beyond the Standard Model
  - Probes of rare decays in the top quark sector
  - ... and other unknown opportunities on the frontier
- Focus today on the most important points of HL-LHC program
- Achieving full physics potential depends on overcoming known experimental (and theoretical) challenges

# Proposed ATLAS Upgrades during LS3

---

- Main challenges: radiation, pileup
  - Detectors must be upgraded just to keep up with the latter challenge
- Extensive redesign of trigger system architecture
  - 2-step first-level hardware trigger: L0 @ 500 kHz + L1 @ 200 kHz
  - Full calorimeter granularity and track trigger capability at L1
- Silicon tracking detectors replace current Inner Detector (Si + TRT)
  - Guarantee 11 hits with 4 pixel layers + 3 short-strip layers + 2 long-strip layers
  - Barrel stave design for pixels and strips to ease construction and installation
- Calorimeter upgrades: electronics and new forward calorimeters
  - New LAr ASIC with full digitization at 40 MHz and 140 Tbps off detector
  - New TileCal readout with fine granularity for detailed trigger algorithms
- Muon spectrometer upgrades
  - Replace readout electronics to reduce trigger latency
- Software and computing redesign to cope with large data volume

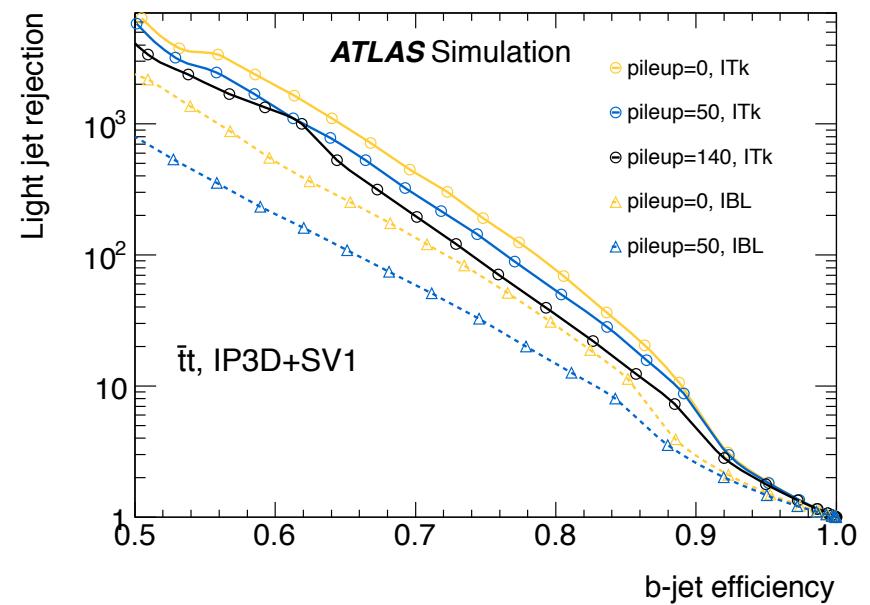
# Silicon Tracker Upgrade



- Provide sufficient hits to minimize fakes from pileup
- R&D in rad-hard sensors, readout electronics, lightweight structure
- Reduced inner pixel size to  $25 \times 150 \mu\text{m}^2$

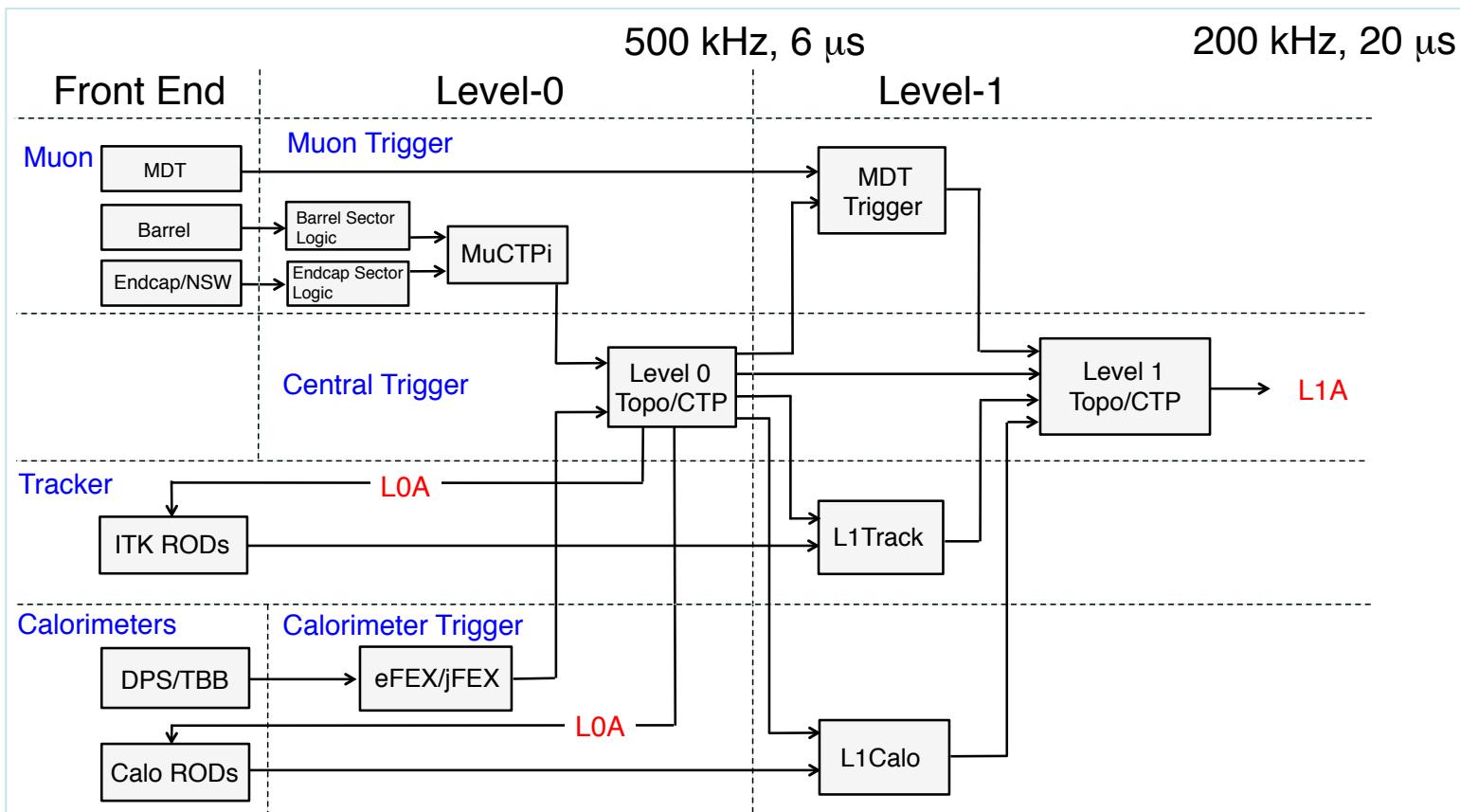
New pixel size and less material offset effects of pileup

- Maintain tracking efficiency in dense boosted jet environment
- 2x reduction in tracker material in central region



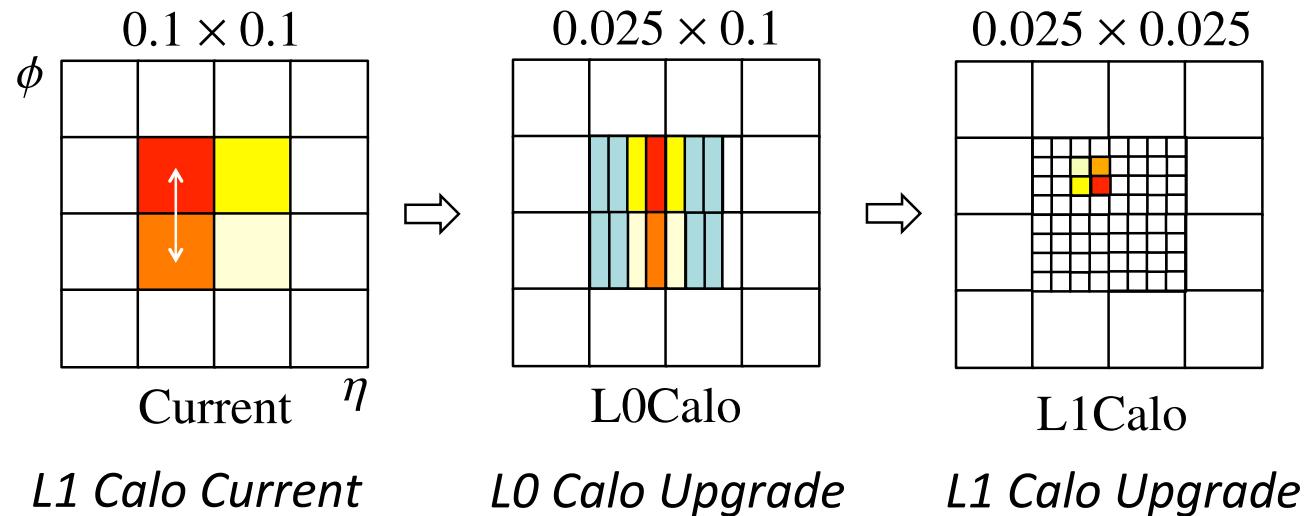
# Trigger System Upgrade

- Maintain efficient 20 GeV isolated lepton triggers at  $7 \times 10^{34}$
- Phase-II L0 trigger has same functionality as Phase-I L1 trigger, but allows for higher event rate (>100 kHz for electrons)
  - Tight constraints on readout capabilities in detector systems



# Calorimeter Electronics Upgrade

- LAr rad-hard front-end electronics upgrade to full digitization of every cell with 16-bit dynamic range at 40 MHz
  - Effectively removes any LAr constraints on trigger system, but requires 140 Tbps optical path to back-end electronics in non-radiation environment
- Allows highly granular pattern extraction in L0/L1 triggers



- TileCal rad-hard front-end upgrade also provides full digitization
  - Allows full jet feature extraction in Regions of Interest defined by L0

# Performance Estimates for HL-LHC Studies

- Detailed studies of potential physics program topics were prepared in 2012 for the European Strategy sessions
- ATLAS philosophy is to extrapolate detector performance from current pileup  $\langle\mu\rangle$  values to future pileup  $\langle\mu\rangle$  values, based on combination of data and full simulation samples
  - Developed a set of smearing functions in [ATL-PHYS-PUB-2013-004](#) to simulate physics object resolutions in upgraded detector with  $\langle\mu\rangle=140$
  - Lepton momenta, b-tagging, missing transverse energy, pileup jets
  - Developed realistic trigger menus to preserve low- $p_T$  lepton and photon triggers, even at  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  [typical threshold 20 GeV]
- **Conservative approach that does not account for future advances**

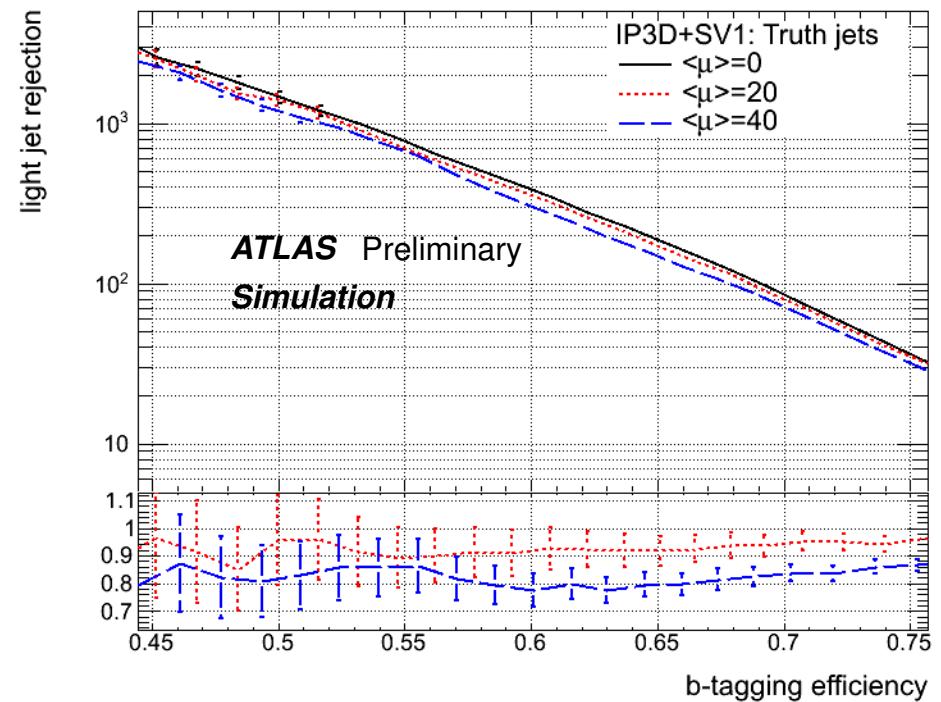
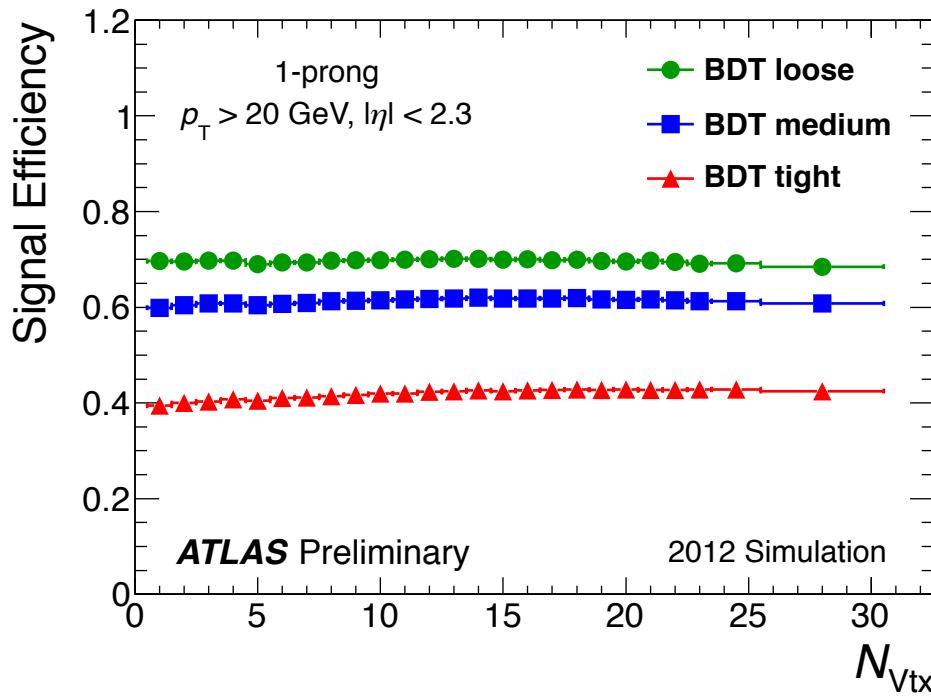
Two examples of parameterized resolutions:

$$\sigma/E_{\text{electron}}[\text{GeV}] = 0.3 \oplus 0.10 \times \sqrt{E[\text{GeV}]} \oplus 0.010 \times E[\text{GeV}]$$

$$\sigma(E_{x,y}^{\text{miss}})[\text{GeV}] = (0.40 + 0.09 \times \sqrt{\mu}) \times \sqrt{\sum E_T[\text{GeV}] + \mu \times 20}$$

# Performance Estimates for HL-LHC Studies

- Estimates of tracking performance: tau identification and b-tagging

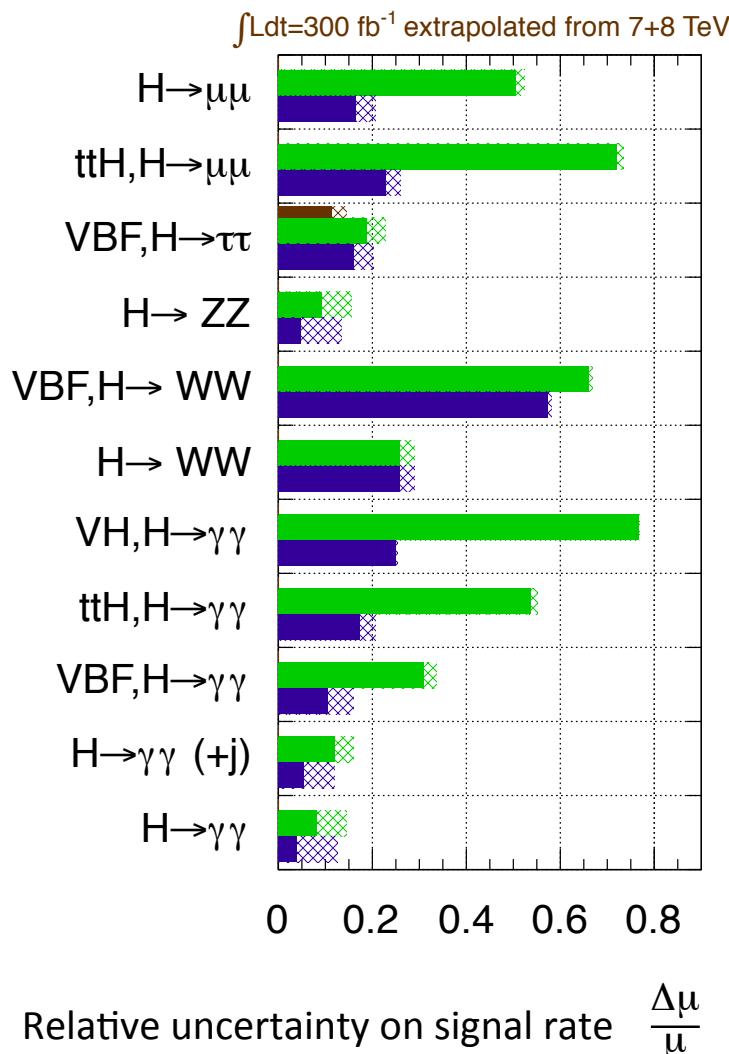


- Note that the assumed b-tagging performance is worse than the new result from full simulation on p. 10
- Based on our excellent understanding of detector in Run-1 data, we believe that other assumptions are also likely fair to pessimistic
  - To be re-evaluated this summer with full simulation up to  $\langle \mu \rangle = 200$

# Higgs Production Measurements

ATLAS Preliminary (Simulation)

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$

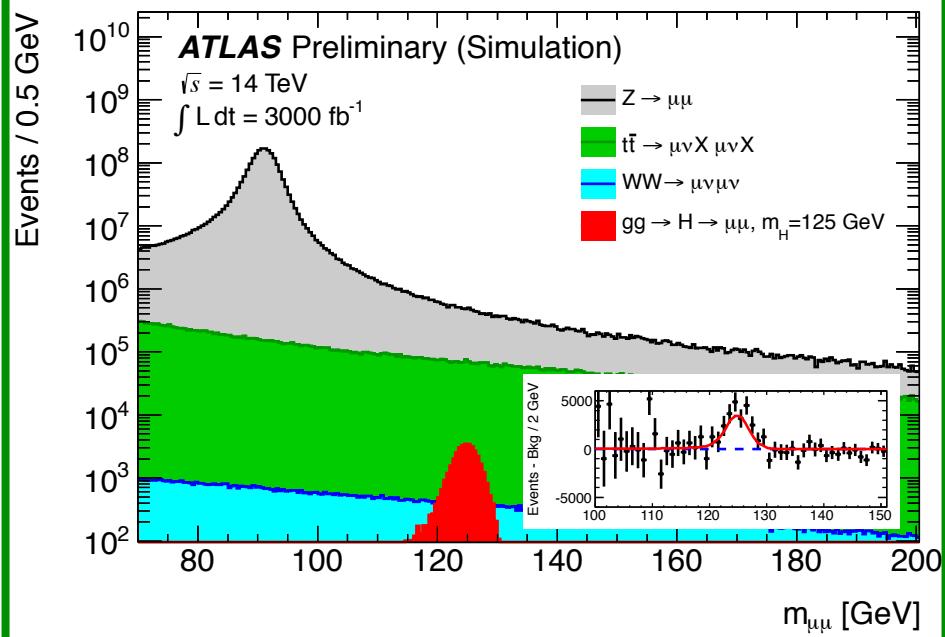


- Relative uncertainty on signal rate
  - Dashed areas show theory uncerts., dominated by scales and PDFs, as discussed in Jianming's Higgs WG talk
- Low-rate signal channels benefit from high luminosity
  - WW dominated by current background syst. uncertainties
  - Likely very pessimistic, as is  $\tau\tau$
- With  $3000 \text{ fb}^{-1}$ :
  - $\mu\mu$  becomes a key fermionic channel
  - $\gamma\gamma$  precision approaches 4% (13% with theory uncertainties)
  - $t\bar{t}H$  precision reaches <20%

# Rare Higgs Decays

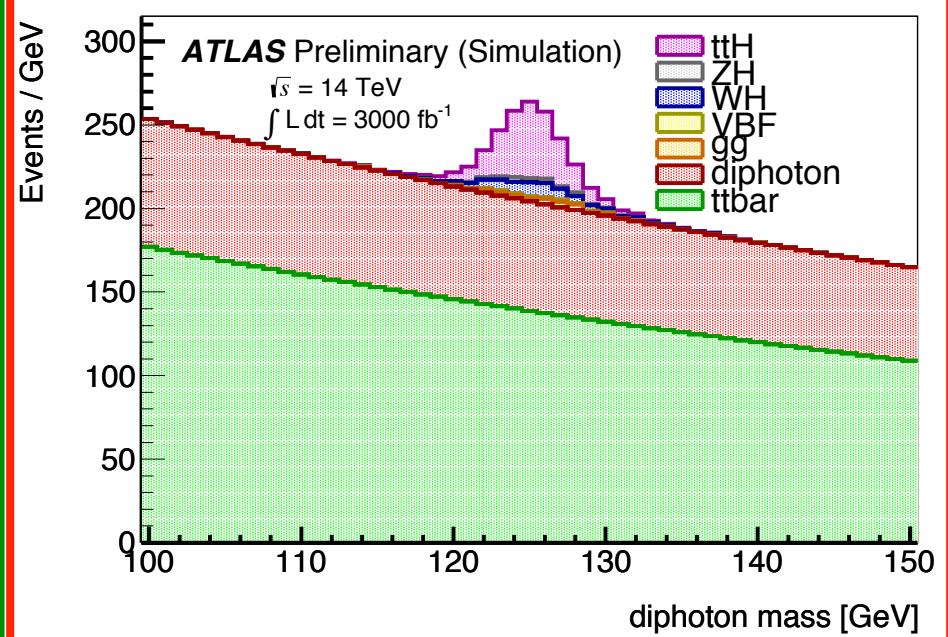
## Higgs decay to $\mu\mu$

- Allows comparison of 2<sup>nd</sup> and 3<sup>rd</sup>-generation Higgs couplings
- Optimized analysis achieves  $>6\sigma$  with  $3000 \text{ fb}^{-1}$ , giving 15-20% precision on relative  $H\mu\mu$  coupling



## $ttH$ in $\gamma\gamma$ decay mode

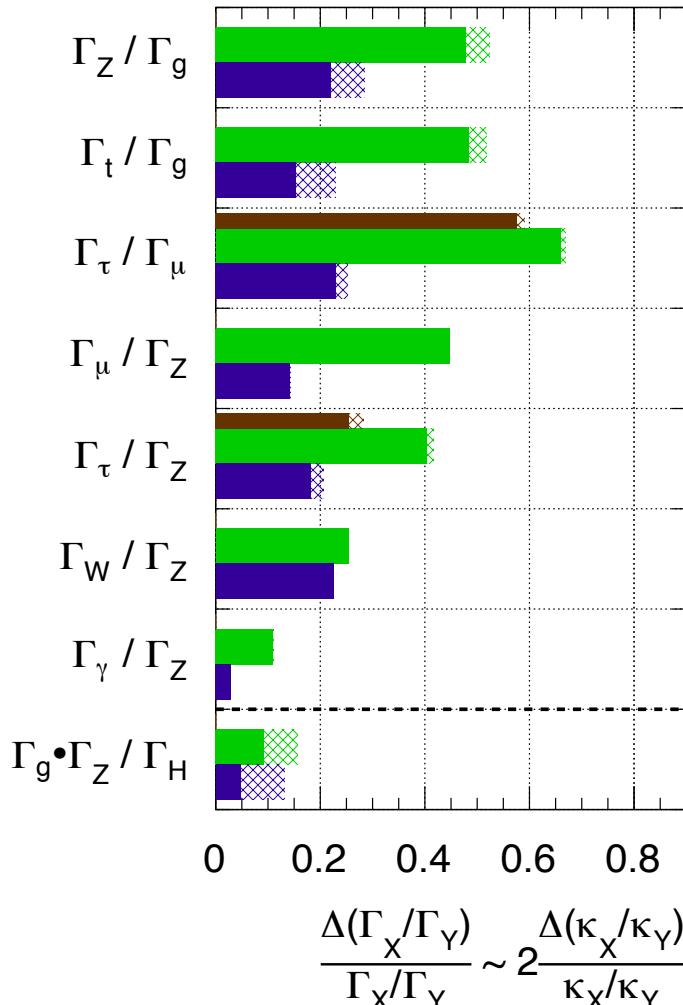
- Allows precise measurement of top Yukawa coupling
- $S/B=0.2 @ 3000 \text{ fb}^{-1}$ , even better than  $ZH(\gamma\gamma)$  channel
- 15-20% precision on relative  $Htt$



# Higgs Couplings

**ATLAS Preliminary (Simulation)**

$\sqrt{s} = 14 \text{ TeV}$ :  $\int L dt = 300 \text{ fb}^{-1}$ ;  $\int L dt = 3000 \text{ fb}^{-1}$   
 $\int L dt = 300 \text{ fb}^{-1}$  extrapolated from 7+8 TeV



- In the general coupling fits, no assumption is made on possible BSM decay modes or total width  $\Gamma_H$ 
  - Only the ratios of coupling parameters can be measured from this fit
- Ratios of partial widths are related to couplings via  $\Gamma_X/\Gamma_Y = \kappa_X^2/\kappa_Y^2$ 
  - Matches LHC Higgs Xsec Working Group
- Experimental precision improves by a factor of 2-3 with  $3000 \text{ fb}^{-1}$  dataset

2-parameter fit with (w/o) theory uncert.

ATLAS	$300 \text{ fb}^{-1}$	$3000 \text{ fb}^{-1}$
$K_V$	3.0 % (5.6 %)	1.9 % (4.5 %)
$K_F$	8.9 % (10 %)	3.6 % (5.9 %)

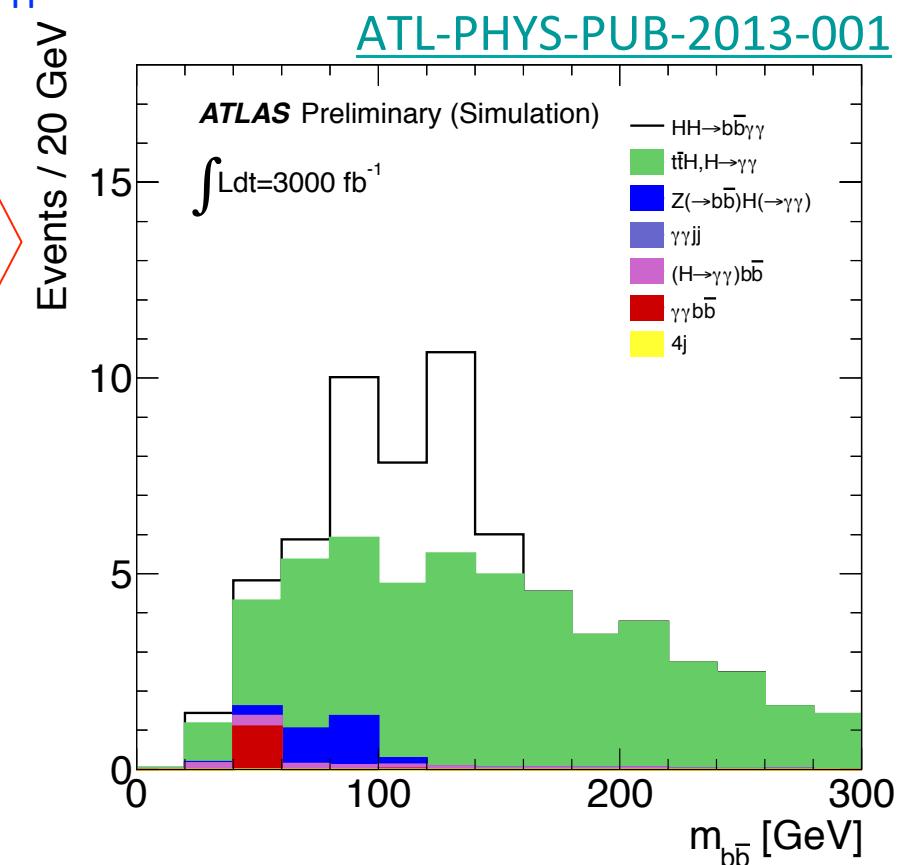
# Higgs Self-Coupling

- Derive trilinear self-coupling  $\lambda_{\text{HHH}}$  from Higgs pair production
  - Destructive interference with HH pair production via top loop
  - HH cross section increases from 34 to 71 fb if  $\lambda_{\text{HHH}}=0$
- Many channels to pursue, since  $m_H=125 \text{ GeV}$

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

Tight  $m_{\gamma\gamma}$  cut and b-tag pT cut  
leave mostly ttH background

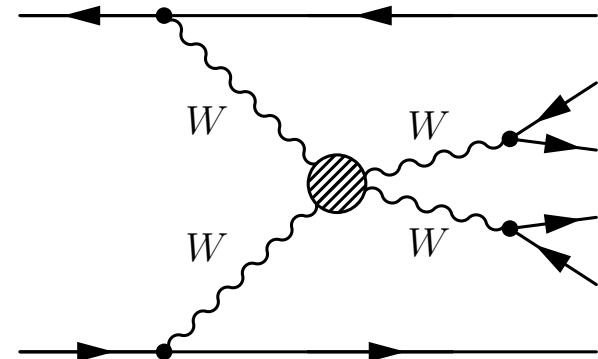
$S/VB \sim 3$  for  $3000 \text{ fb}^{-1}$



- Expect that additional channels ( $b\bar{b}\tau\tau$ ) and 2 experiments combined could lead to 30% measurement of  $\lambda_{\text{HHH}}$  at HL-LHC

# Vector Boson Scattering

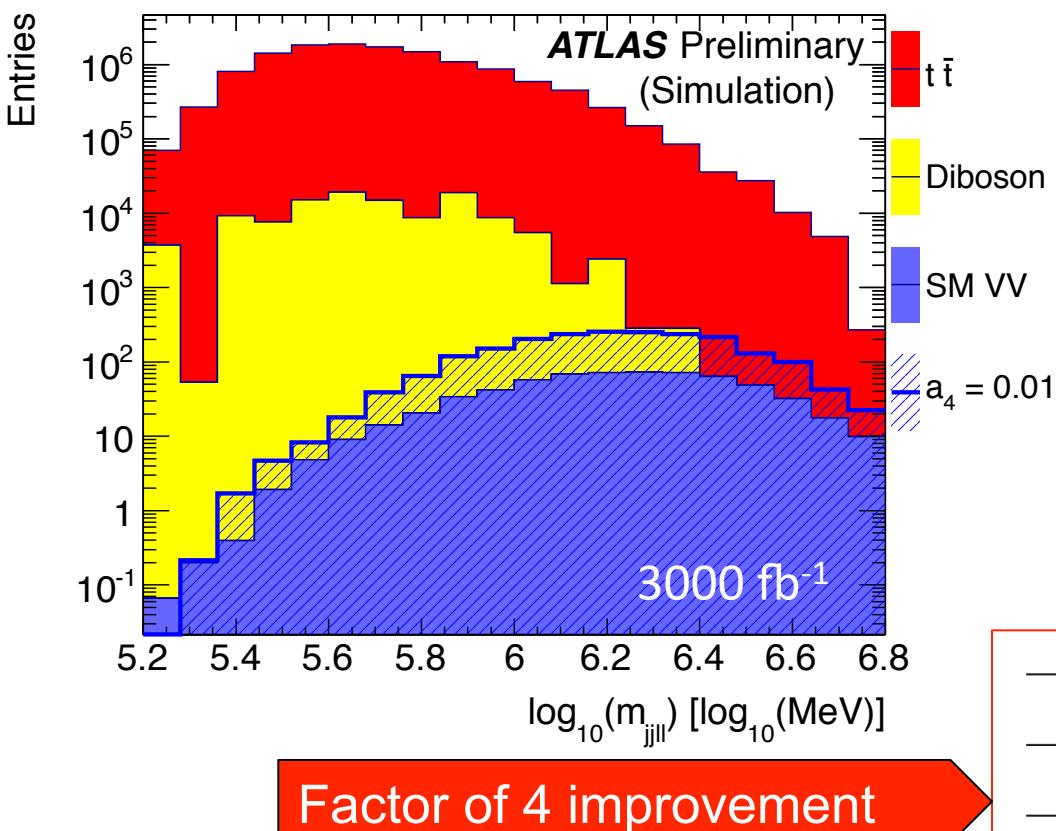
- Given Higgs discovery, focus on its impact in electroweak sector
  - Confirm unitarity of VBS through differential cross section
  - Check for new contributions to VBS from new particles or interactions
  - Includes any strong resonances or 2HDM
- Combination of Higgs couplings, vector boson scattering, and triboson production probes gauge-Higgs sector for new physics
- New ATLAS results in [ATL-PHYS-PUB-2013-006](#) focus on sensitivity to new physics contributions
  - Anomalous quartic couplings calculated with post-Higgs unitarization
  - Higher-dimension operators in effective field theories with mass scale  $\Lambda$



# W<sup>+</sup>W<sup>-</sup> Scattering

- Early results from Electroweak Chiral Lagrangian focused on anomalous quartic couplings that conserve weak isospin
  - Contributions parameterized in terms of couplings  $a_4$  and  $a_5$

[ATL-PHYS-PUB-2012-005](#)



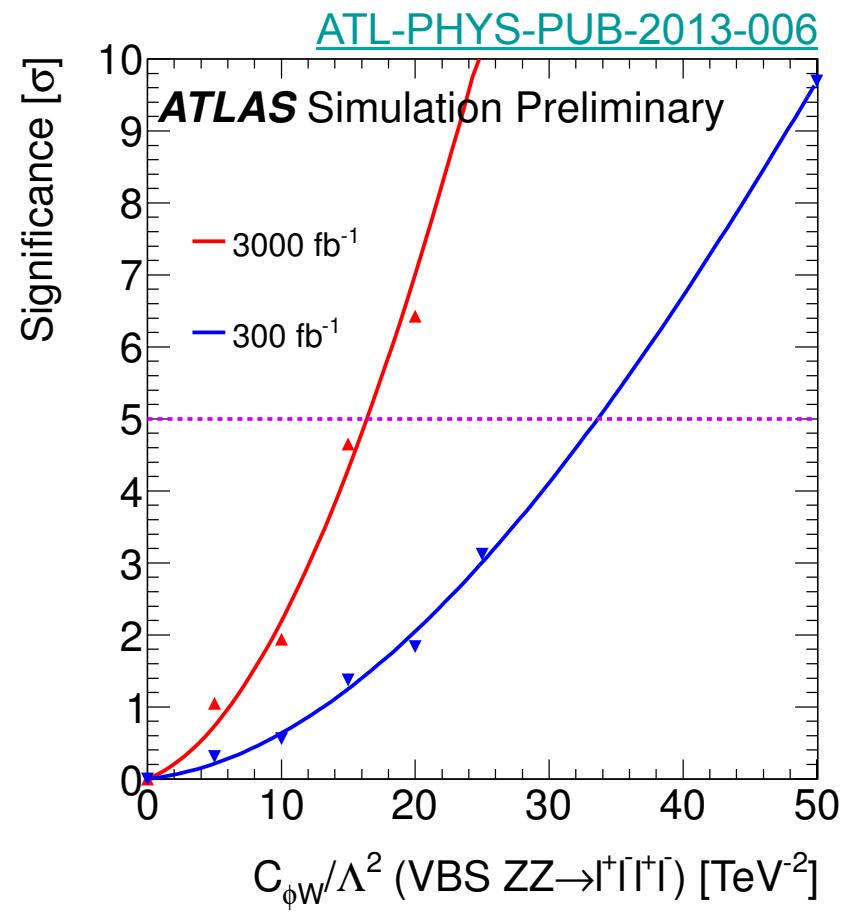
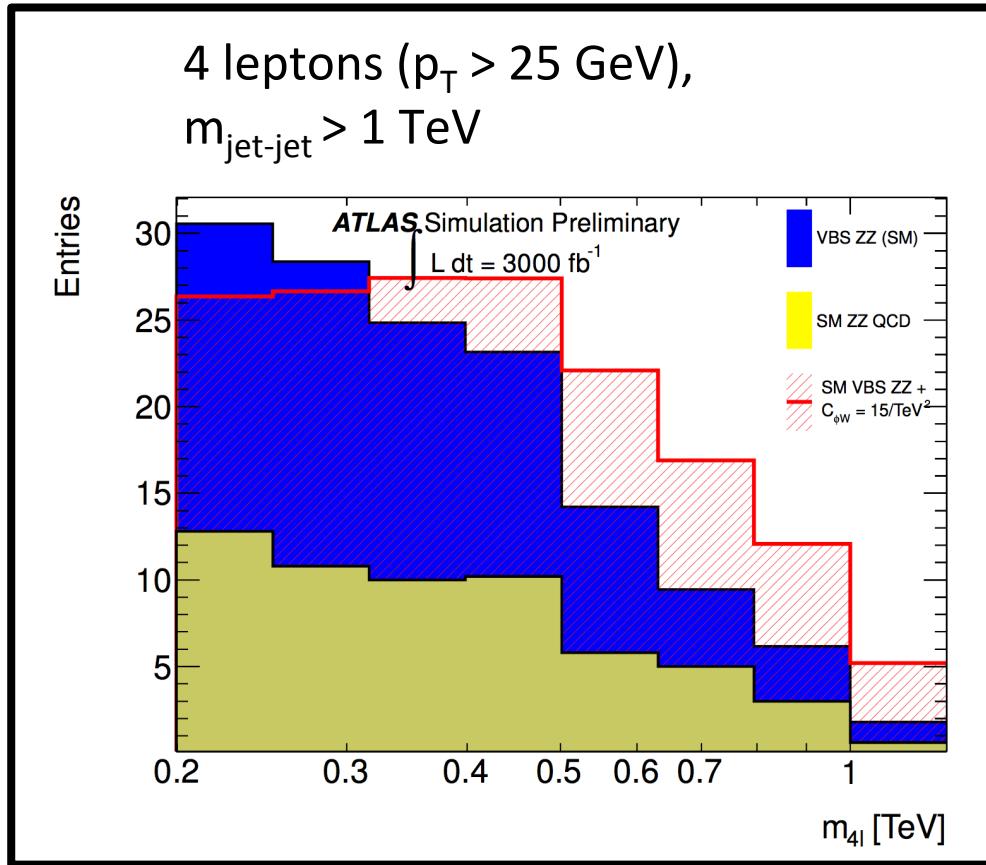
Recover invariant mass information in dilepton channel with 4-body mass

With  $a_5=0$ , what sensitivity do we have to new  $a_4$ ?  
(For these values, the typical resonance mass is  $\sim 1 \text{ TeV}$ )

model	$300 \text{ fb}^{-1}$	$1 \text{ ab}^{-1}$	$3 \text{ ab}^{-1}$
$a_4$	0.066	0.025	0.016

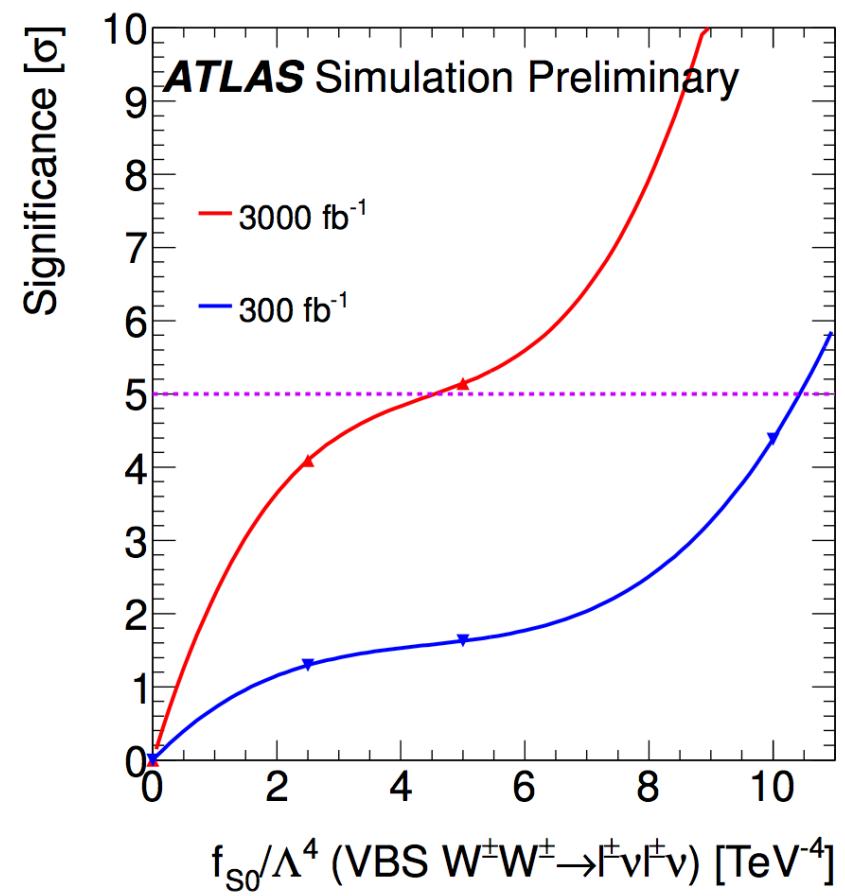
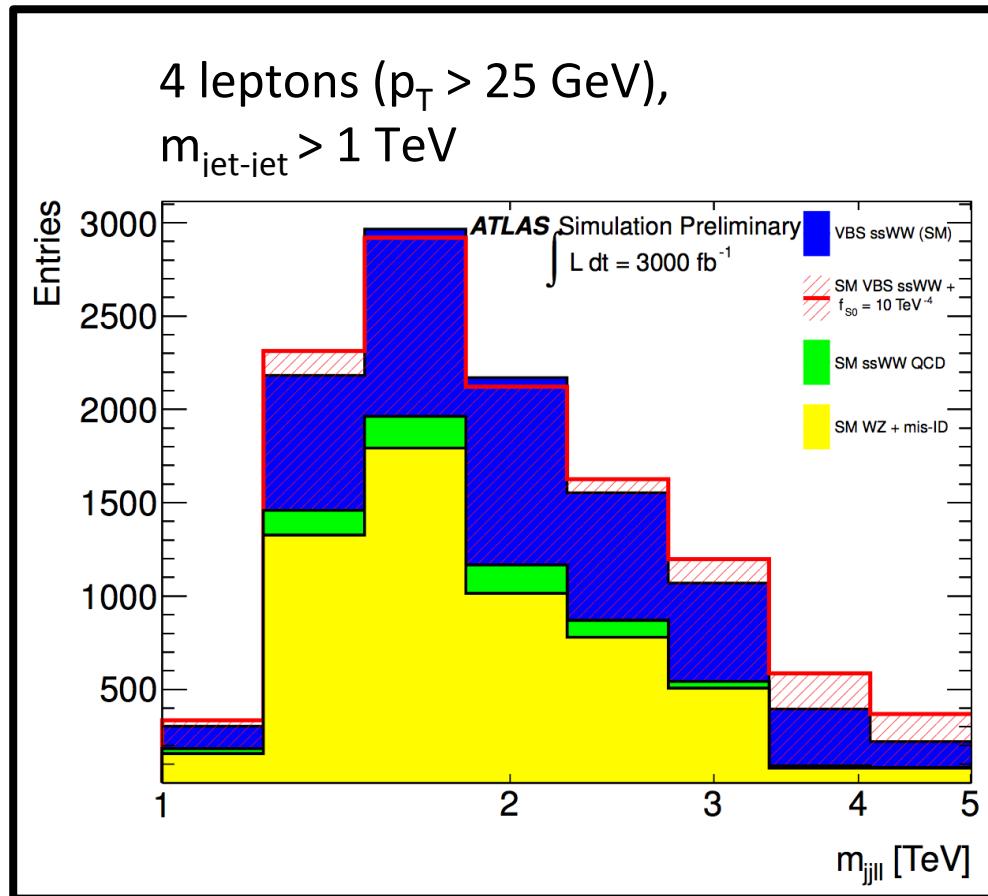
# ZZ Scattering

- Sensitivity to higher-dimension operators in effective field theory
- Example:  $\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \text{Tr}(W^{\mu\nu}W_{\mu\nu})\phi^\dagger\phi$  doesn't affect diboson production but can give rise to non-SM gauge-Higgs couplings

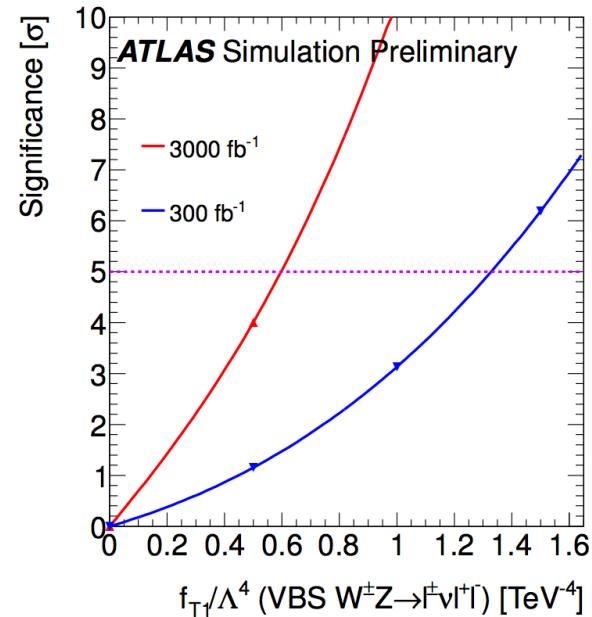
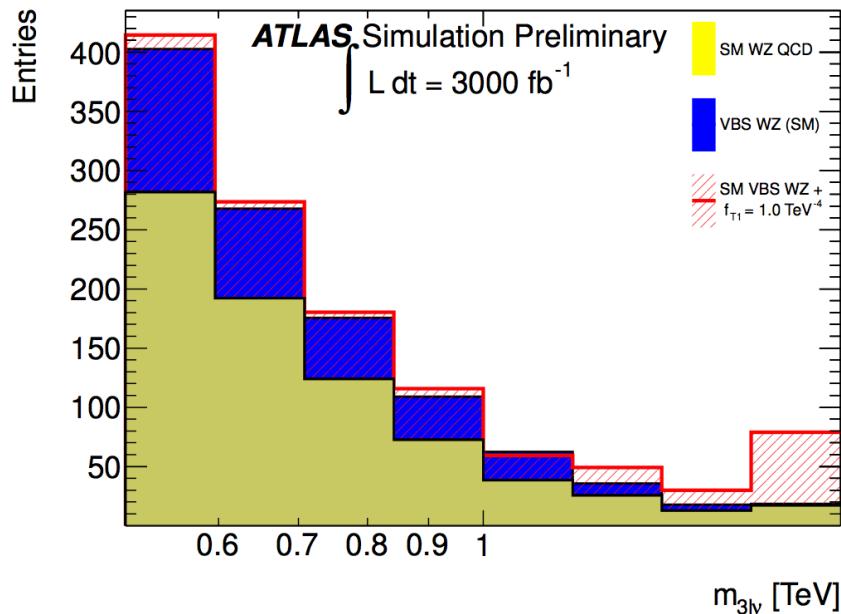


# W $^\pm$ W $^\pm$ Scattering

- Building on experience with similar studies at 8 TeV
  - Detailed knowledge of physics and detector backgrounds (charge flip, fakes)
- New physics via dim-8 operator  $\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu \phi)^\dagger D_\nu \phi] \times [(D^\mu \phi)^\dagger D^\nu \phi]$



# WZ Scattering

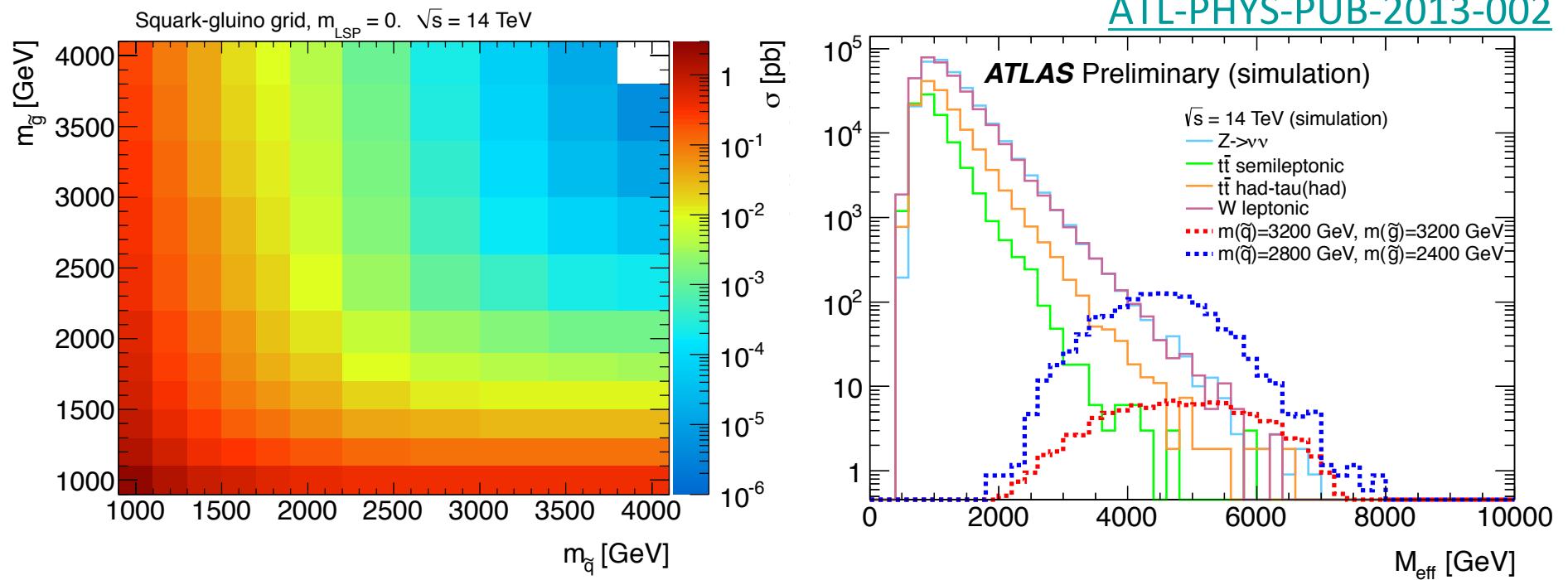


- When contrasted with  $W^\pm W^\pm$ , makes it possible to distinguish between different new physics operators

Parameter	dimension	channel	$\Lambda_{UV}$ [TeV]	300 $\text{fb}^{-1}$		3000 $\text{fb}^{-1}$	
				5 $\sigma$	95% CL	5 $\sigma$	95% CL
$c_\phi W/\Lambda^2$	6	$ZZ$	1.9	$34 \text{ TeV}^{-2}$	$20 \text{ TeV}^{-2}$	$16 \text{ TeV}^{-2}$	$9.3 \text{ TeV}^{-2}$
$f_{S0}/\Lambda^4$	8	$W^\pm W^\pm$	2.0	$10 \text{ TeV}^{-4}$	$6.8 \text{ TeV}^{-4}$	$4.5 \text{ TeV}^{-4}$	$0.8 \text{ TeV}^{-4}$
$f_{T1}/\Lambda^4$	8	$WZ$	3.7	$1.3 \text{ TeV}^{-4}$	$0.7 \text{ TeV}^{-4}$	$0.6 \text{ TeV}^{-4}$	$0.3 \text{ TeV}^{-4}$
$f_{T8}/\Lambda^4$	8	$Z\gamma\gamma$	12	$0.9 \text{ TeV}^{-4}$	$0.5 \text{ TeV}^{-4}$	$0.4 \text{ TeV}^{-4}$	$0.2 \text{ TeV}^{-4}$
$f_{T9}/\Lambda^4$	8	$Z\gamma\gamma$	13	$2.0 \text{ TeV}^{-4}$	$0.9 \text{ TeV}^{-4}$	$0.7 \text{ TeV}^{-4}$	$0.3 \text{ TeV}^{-4}$

# Searches for Supersymmetric Particles

- Benchmark searches for R-parity-conserving signatures
  - Already reaching past TeV scale for strongly-produced SUSY



Even though  $M_{\text{eff}}$ -style searches gain sensitivity with  $3000 \text{ fb}^{-1}$ , expect bigger relative gains in challenging signatures:

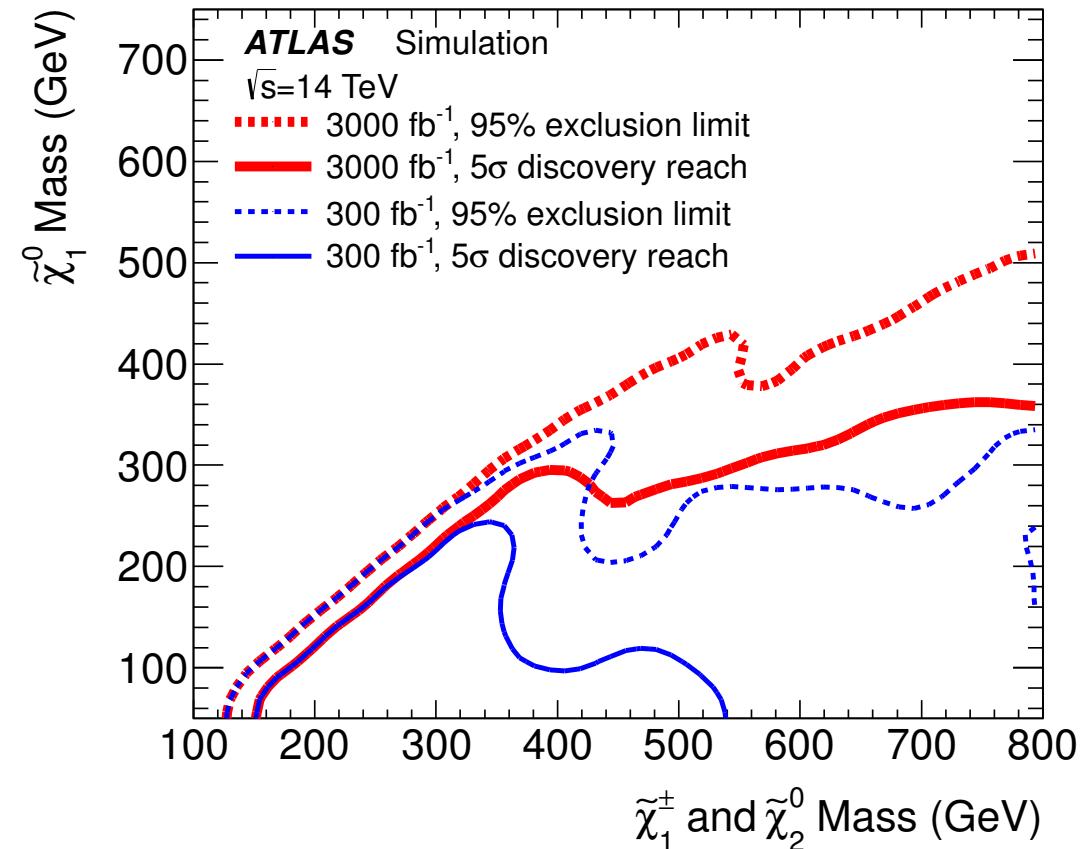
- electroweak production*
- cascade decays through Higgs bosons*

# Direct Production of Weak Gauginos

- Weak gauginos can be produced in cascades from strong interaction or directly from weak interactions
  - If the squarks/gluinos are very heavy, then weak production dominates
- Small weak production cross section means **big gains** at HL-LHC

Tri-lepton analysis:  
dedicated BDTs for  
high/low mass splitting

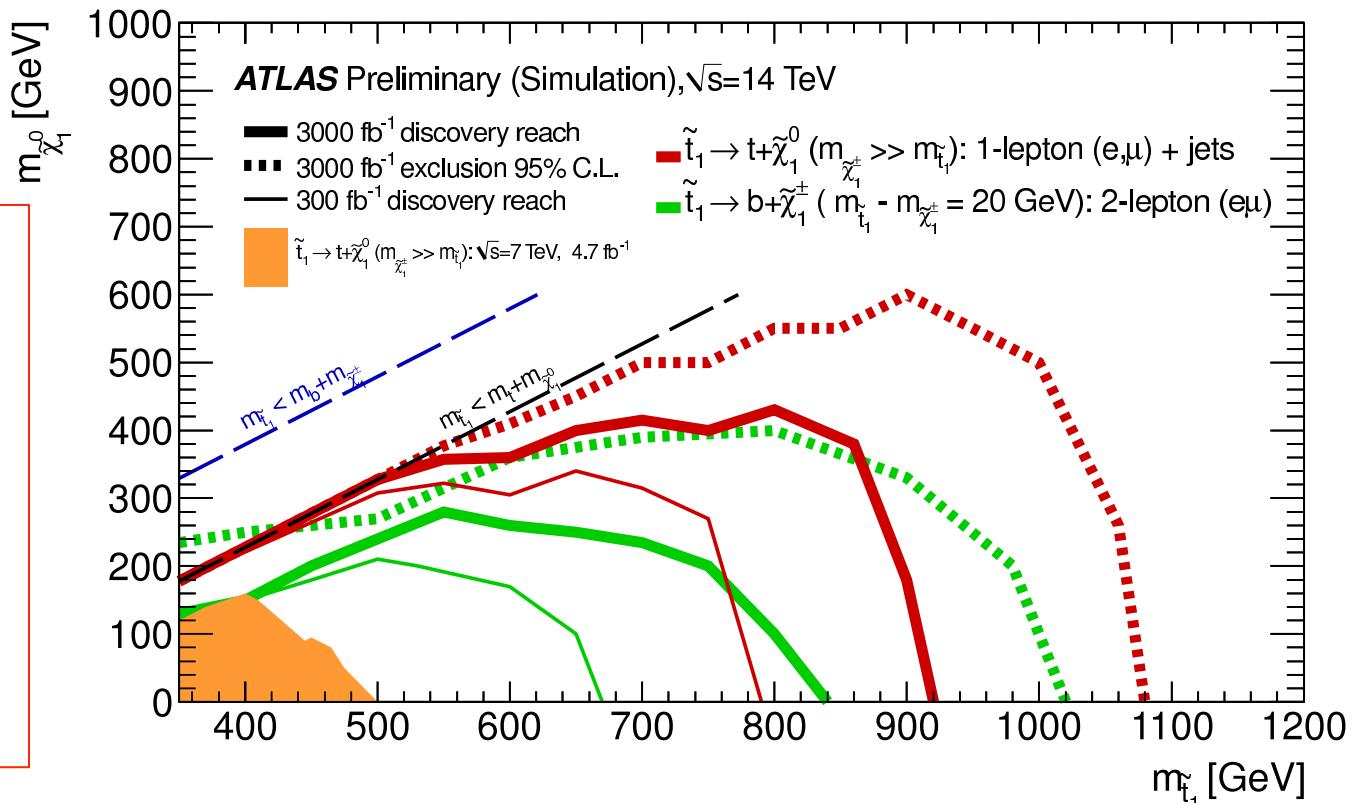
Chargino mass  
reach improves  
**from 250 GeV to**  
**>800 GeV** with  
3000  $\text{fb}^{-1}$  data



# Searches for Scalar Top

- Increasing focus on stops due to naturalness arguments
- Dedicated full analyses for decays to top or bottom quarks
  - Challenging analyses re-optimized for highest luminosity datasets, including requirements on  $m_T$  (1-lepton) and use of  $m_{T2}$  as discriminant (2-lepton)

Stop mass reach improves by up to **150 GeV** with  $3000 \text{ fb}^{-1}$  data, but sensitivity in plane increases even more dramatically

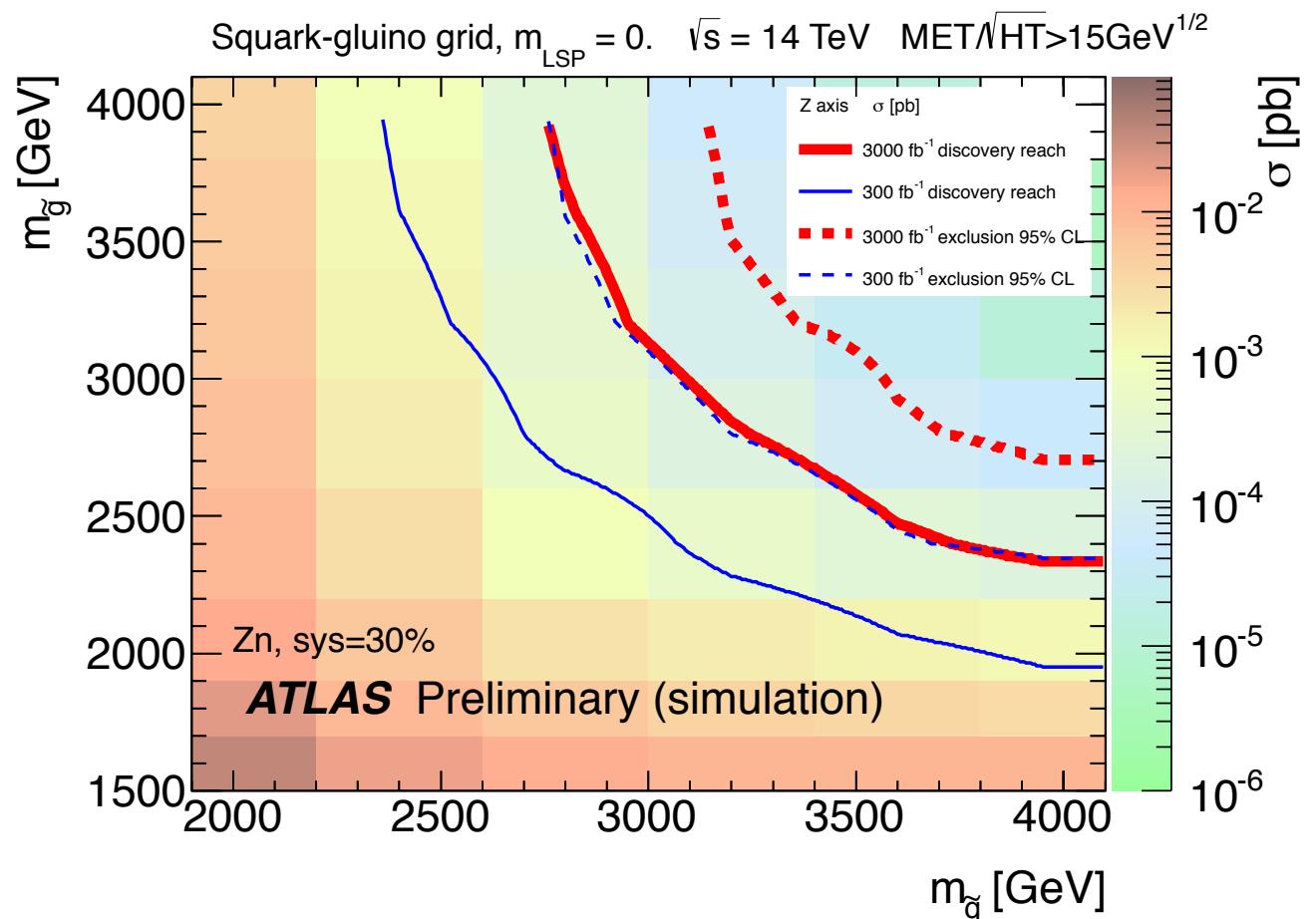


# Searches for Squarks and Gluinos

- Full study to characterize sensitivity to strongly-produced SUSY
  - Dominated by physics backgrounds  $Z(\nu\nu) + \text{jets}$  and top pairs
  - Large missing energy requirement robust against pileup

Reach for 3000  $\text{fb}^{-1}$ :  
 $m_{\text{sq}} = 3.2 \text{ TeV}$ ,  
 $m_{\text{gl}} = 2.7 \text{ TeV}$

Roughly 400-500 GeV sensitivity improvement with 3000  $\text{fb}^{-1}$  dataset, independent of LSP mass



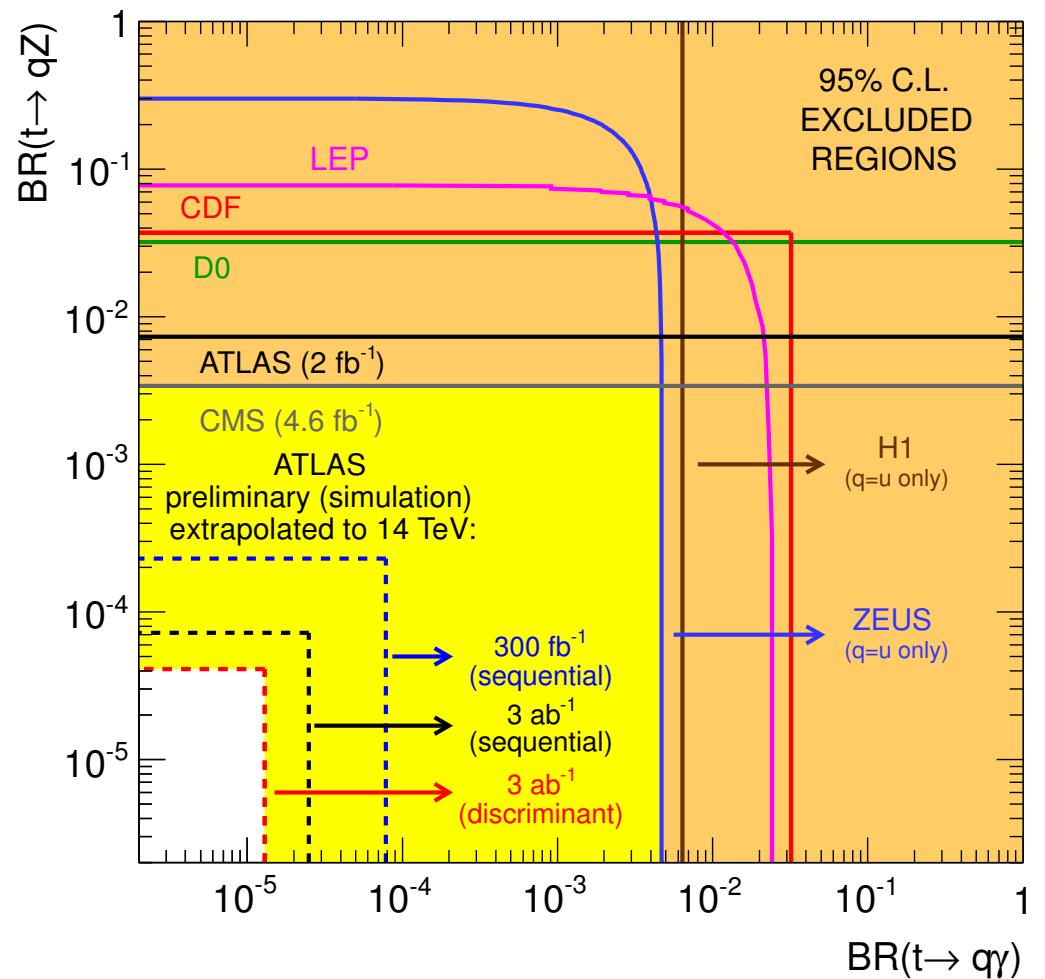
# FCNC with Top Quarks

- HL-LHC would provide large top samples for rare decay studies
- FCNC level in SM is  $10^{-14}$ , but BSM extensions can push this to  $10^{-4}$

## Extrapolation to 14 TeV

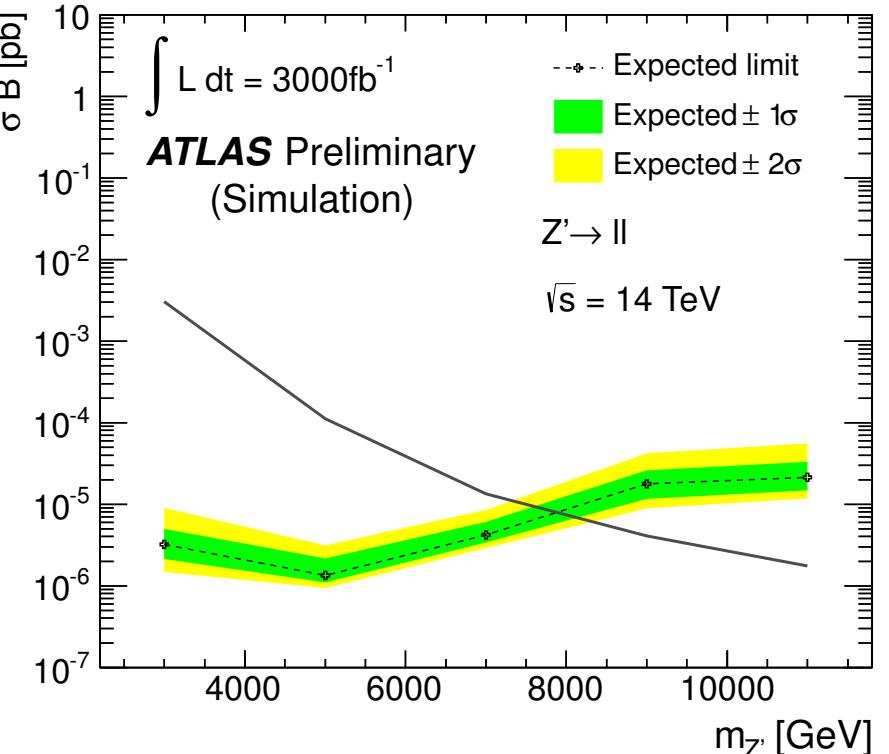
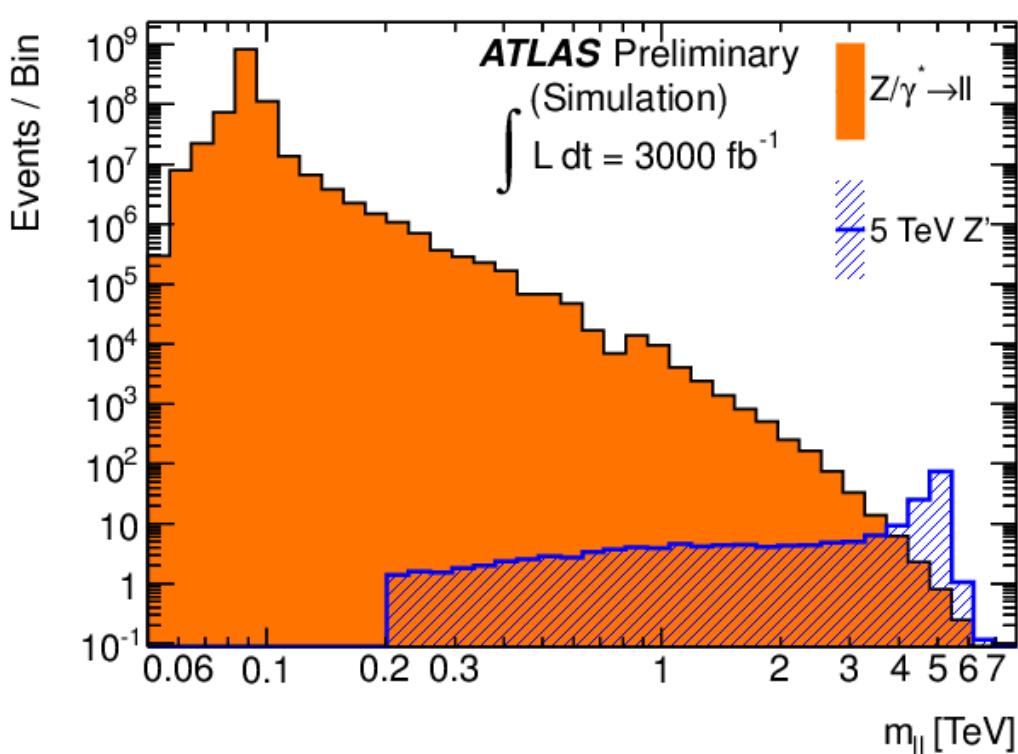
- Based on  $2 \text{ fb}^{-1}$  result, using kinematic fit for top
- Limits on  $t \rightarrow q\gamma$  and  $t \rightarrow qZ$  are entering interesting range
- Dominant SM top background scales to 14 TeV

Improvements of 5x with respect to results at  $300 \text{ fb}^{-1}$



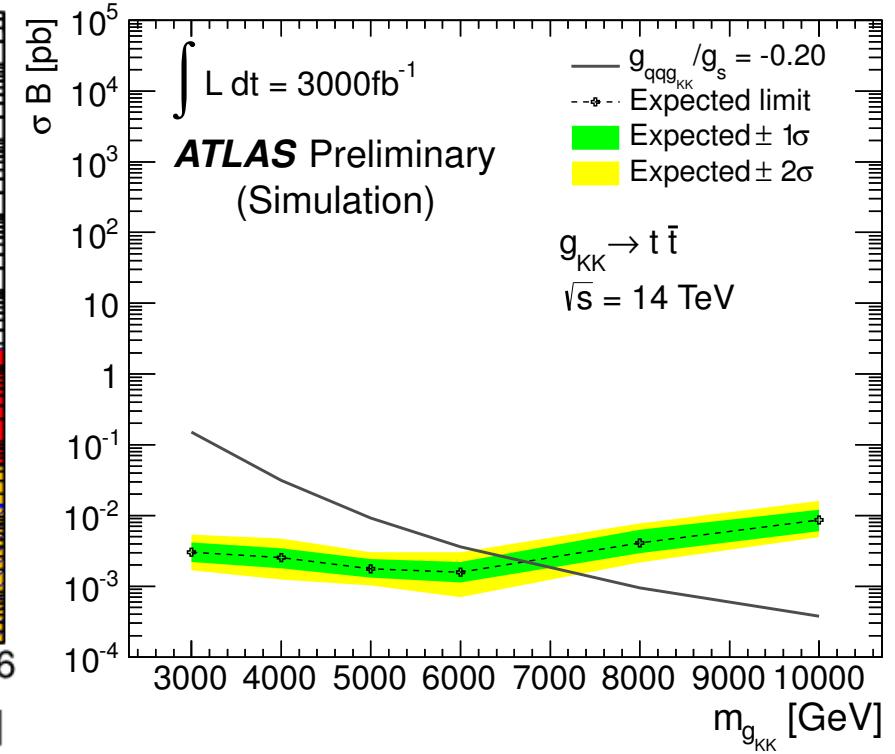
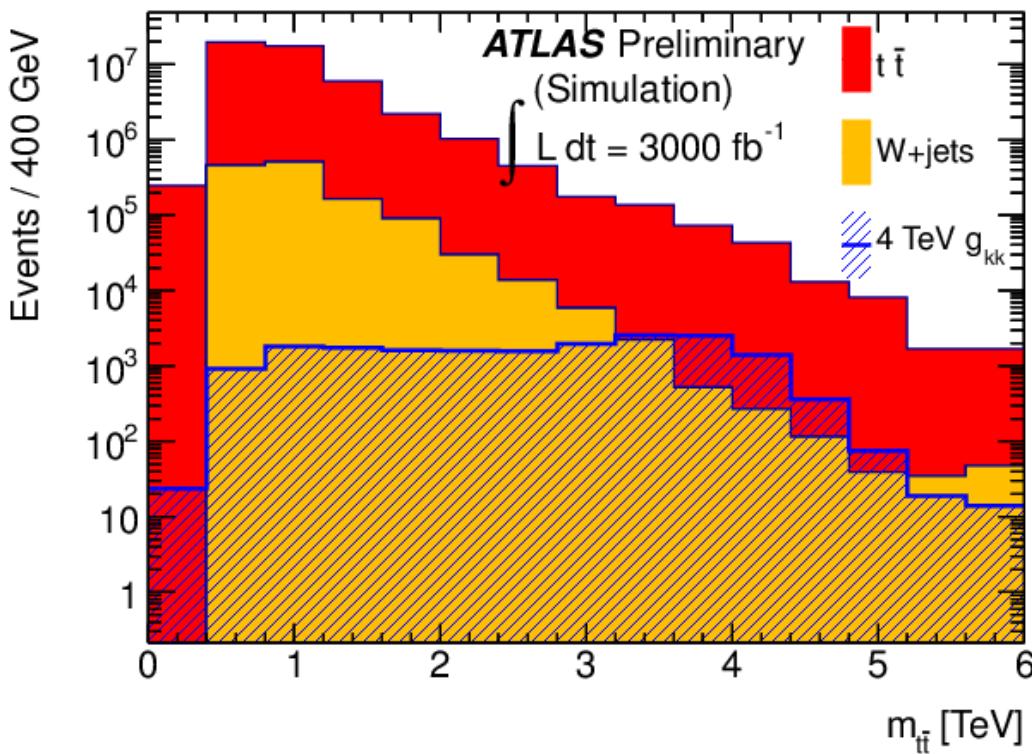
# Exotic Resonances

- Direct discovery probe of new physics at highest mass scales
  - Narrow weak resonances:  $Z'$  bosons in extended electroweak sectors
  - Broad strong resonances: KK gluons in models with extra dimensions
- For concrete comparisons, assume  $Z'$  with SM couplings
- Dielectron reach: 7.8 (6.5) TeV w/ 3000 (300)  $\text{fb}^{-1}$  (muons similar)



# Exotic Top Quark Resonances

- KK gluons (broad) or topcolor Z' (narrow) high-mass resonances
- Top quark signature tagged with anti-kT 1.0 “hadronic top jet”
  - Mass from lepton + jets signature (good for narrow resonance)
- $g_{KK}$  mass reach: 6.7 (4.3) TeV w/ 3000 (300)  $\text{fb}^{-1}$ 
  - Typical observation that more complex signals benefit from larger dataset



# Links to “ATLAS Future” Documentation

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- All documentation collected on ATLAS Public Twiki
  - [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome-Upgrade\\_Projects\\_and\\_Physics\\_Pro](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/WebHome-Upgrade_Projects_and_Physics_Pro)
- Includes the Technical Design Reports and Letters of Intent submitted to CERN Council:
  - IBL TDR: <https://cds.cern.ch/record/1291633/>
  - Phase-I upgrade Lol: <https://cds.cern.ch/record/1402470>
  - Phase-II upgrade Lol: <https://cds.cern.ch/record/1502664>
- And all physics studies approved by ATLAS Upgrade Physics group:
  - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies>
- Other items will be added here as they are approved by ATLAS

# Conclusion and Outlook

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- ATLAS has a rich physics program planned with 14 TeV pp collisions
  - Letter of Intent approved to collect  $300 \text{ fb}^{-1}$  at 14 TeV through 2021
  - Requires selected detector upgrades to preserve performance for physics
- Proposed HL-LHC program exploits full potential of LHC
  - Ultimate luminosity of  $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , integrated dataset of  $3000 \text{ fb}^{-1}$
- Expanded physics reach with  $3000 \text{ fb}^{-1}$  relative to  $300 \text{ fb}^{-1}$ 
  - Improved measurements of Higgs production in various channels (2-3x)
  - Measurements of rare Higgs decay to  $\mu\mu$  and rare process of  $t\bar{t}H(\gamma\gamma)$
  - Improved measurements of Higgs couplings (2x)
  - Measurement of Higgs self-coupling in  $HH$  production
  - Increased sensitivity to BSM contributions to vector boson scattering
  - Increased reach for electroweak production of SUSY particles (2x to 1 TeV) and strong production of SUSY particles ( $\sim 3 \text{ TeV}$ )
- Energy frontier at LHC remains open to discovery and exploration of unexpected physics results at the highest energy scales