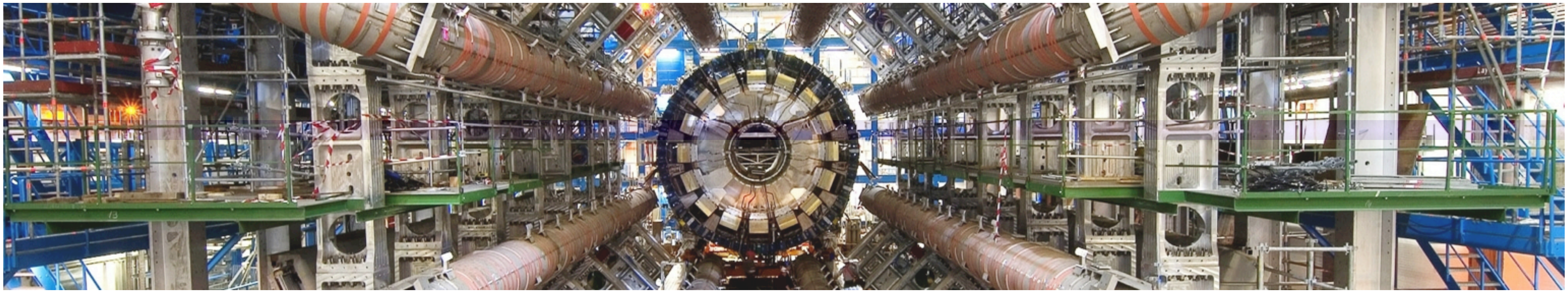

ATLAS Physics Prospects at a High-Luminosity LHC

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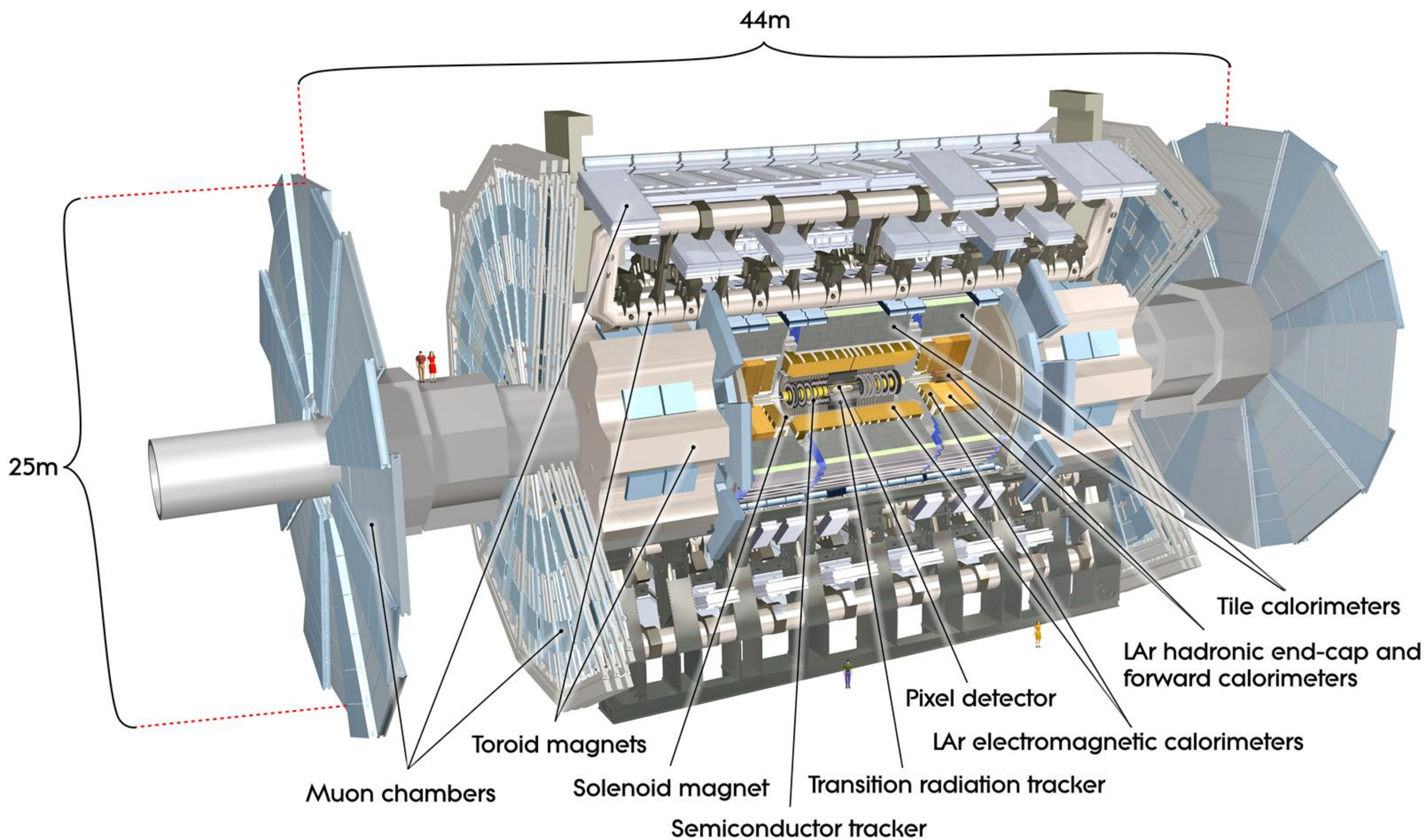
UC Davis HEP Seminar

October 29, 2013

Introduction

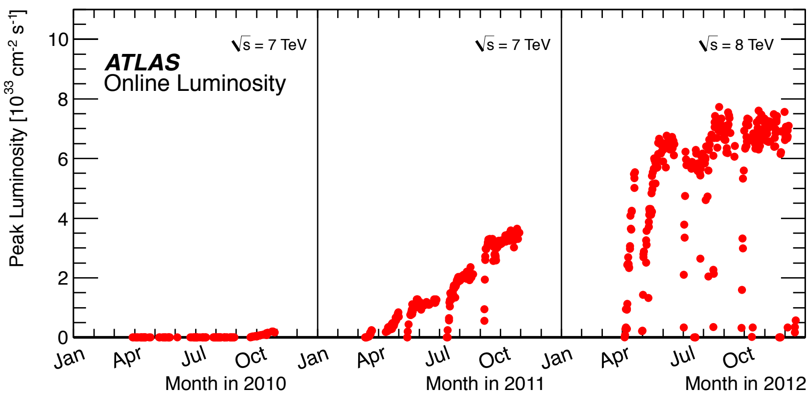
- Large Hadron Collider is a unique facility, utilized by 2 large general-purpose experiments with deep and broad physics reach
  - Measurements of the non-Higgs Standard Model particles and interactions, even at very high Q^2 and very low x
  - Measurements of the Higgs couplings and eventually the Higgs potential
  - Discovery reach for high-mass particles and resonances
- ATLAS and CMS experiments both pursue studies of future physics prospects, based on designed experimental performance
  - Feedback loop with detector R&D community during design phase
- Series of meetings in the past year have formalized these efforts
  - European Strategy for Particle Physics (Sept. 2012)
  - Division of Particles and Fields Snowmass Community Study (2012-2013)
  - ECFA HL-LHC Experiments Workshop (Oct. 2013)
- Many new results on the future prospects for ATLAS

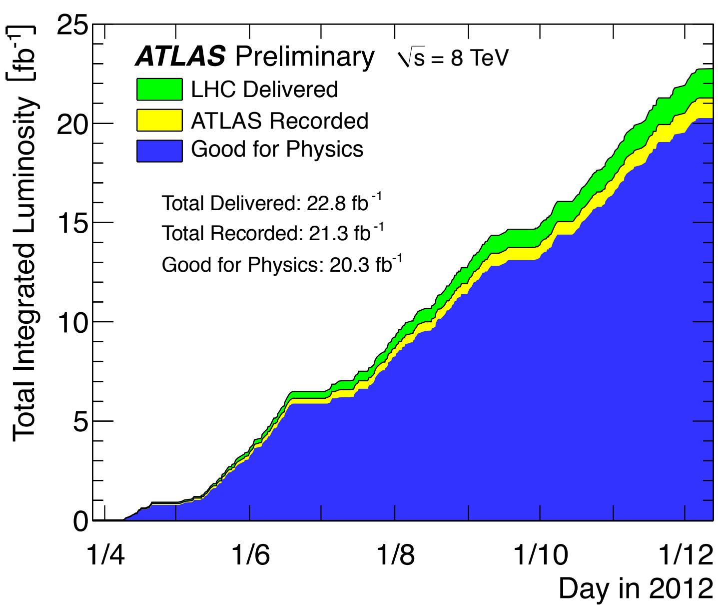
ATLAS Experiment at LHC



Success of LHC Run 1

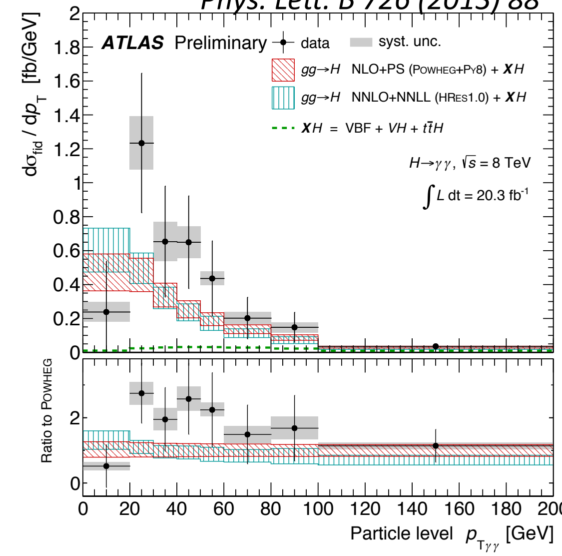
Excellent accelerator and experiment performance



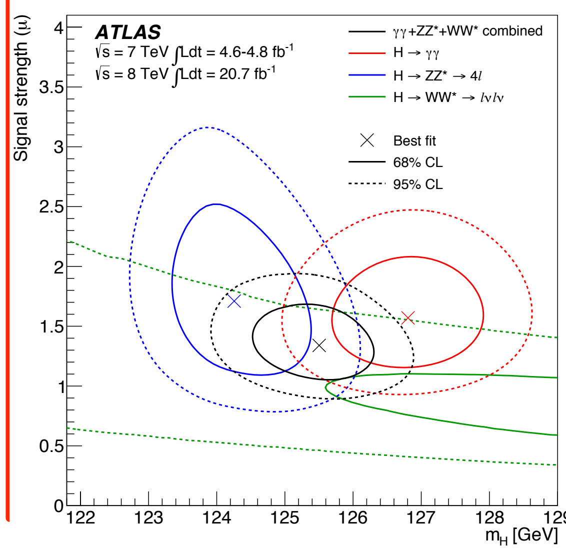


Higgs boson discovery and measurements

Phys. Lett. B 726 (2013) 88

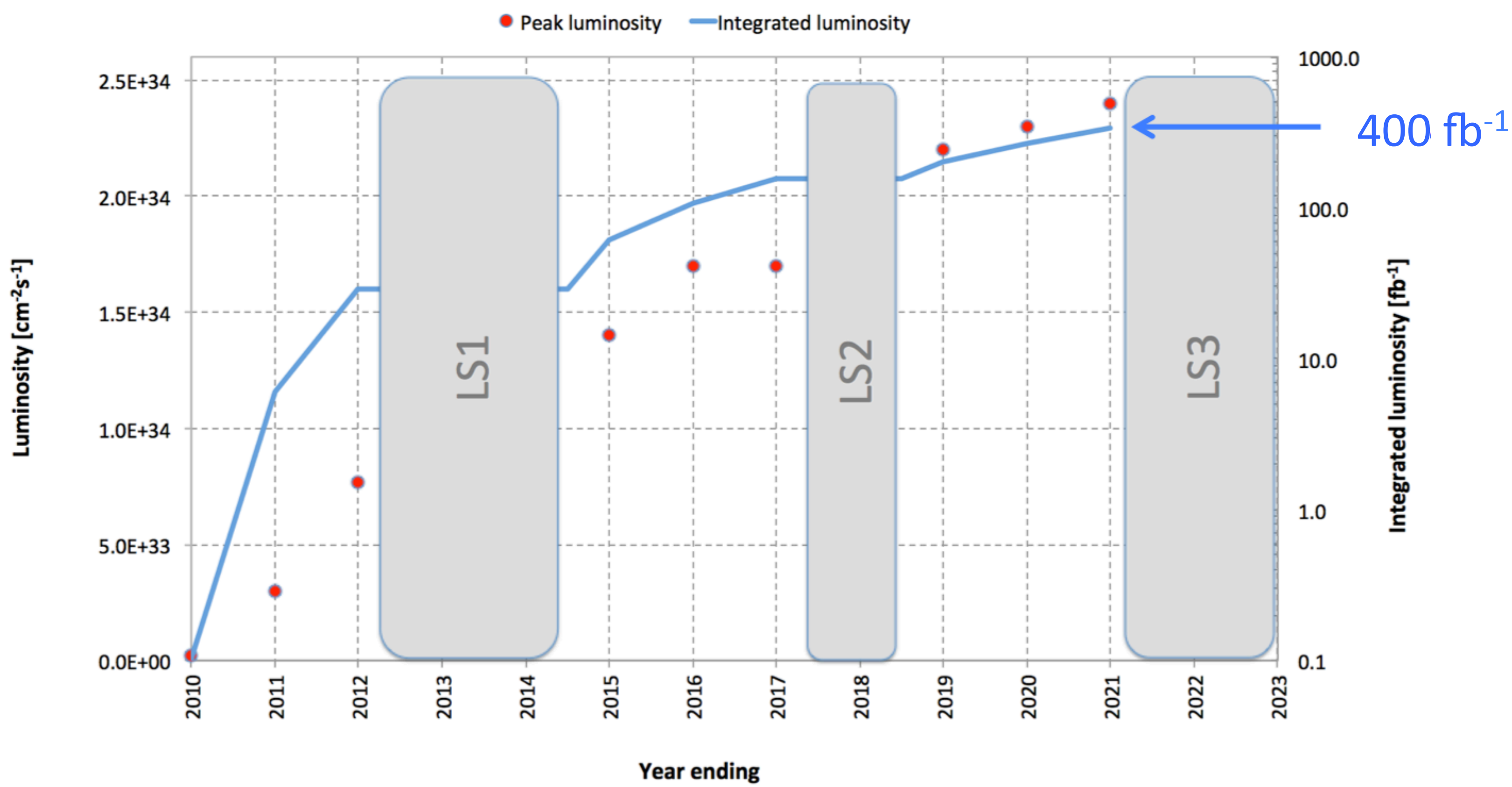


ATLAS-CONF-2013-072

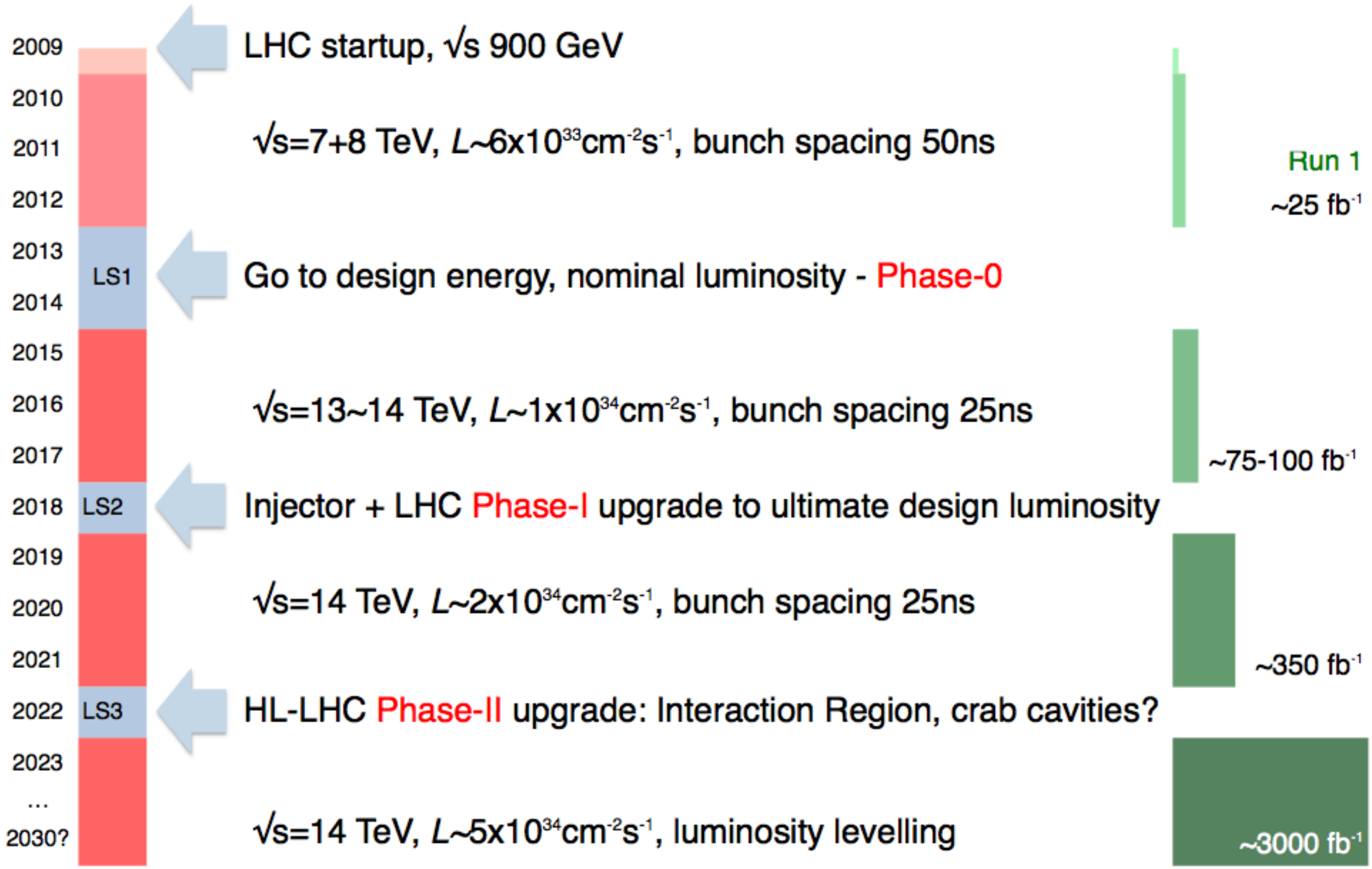


Approved LHC Program

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

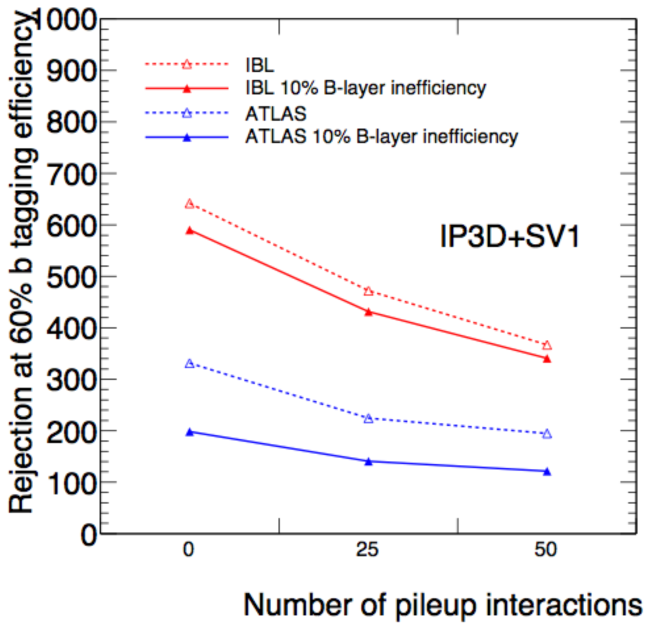


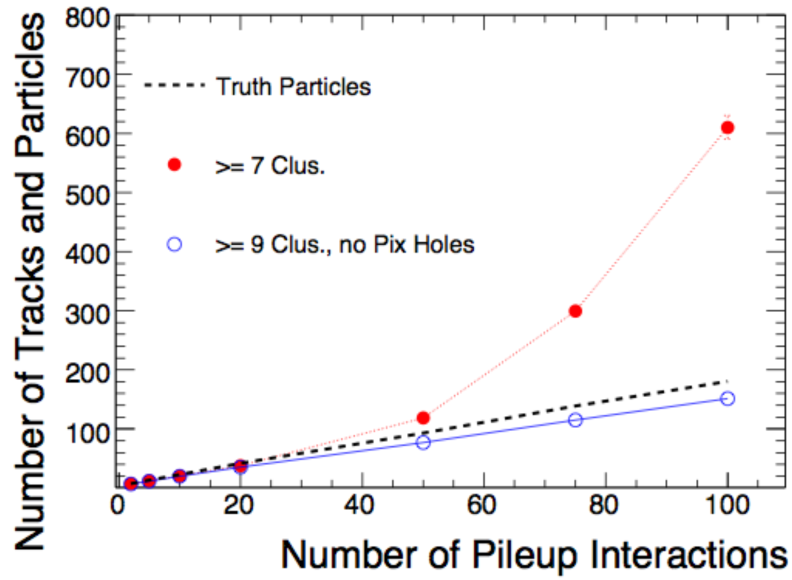
Evolution of the LHC Program



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)





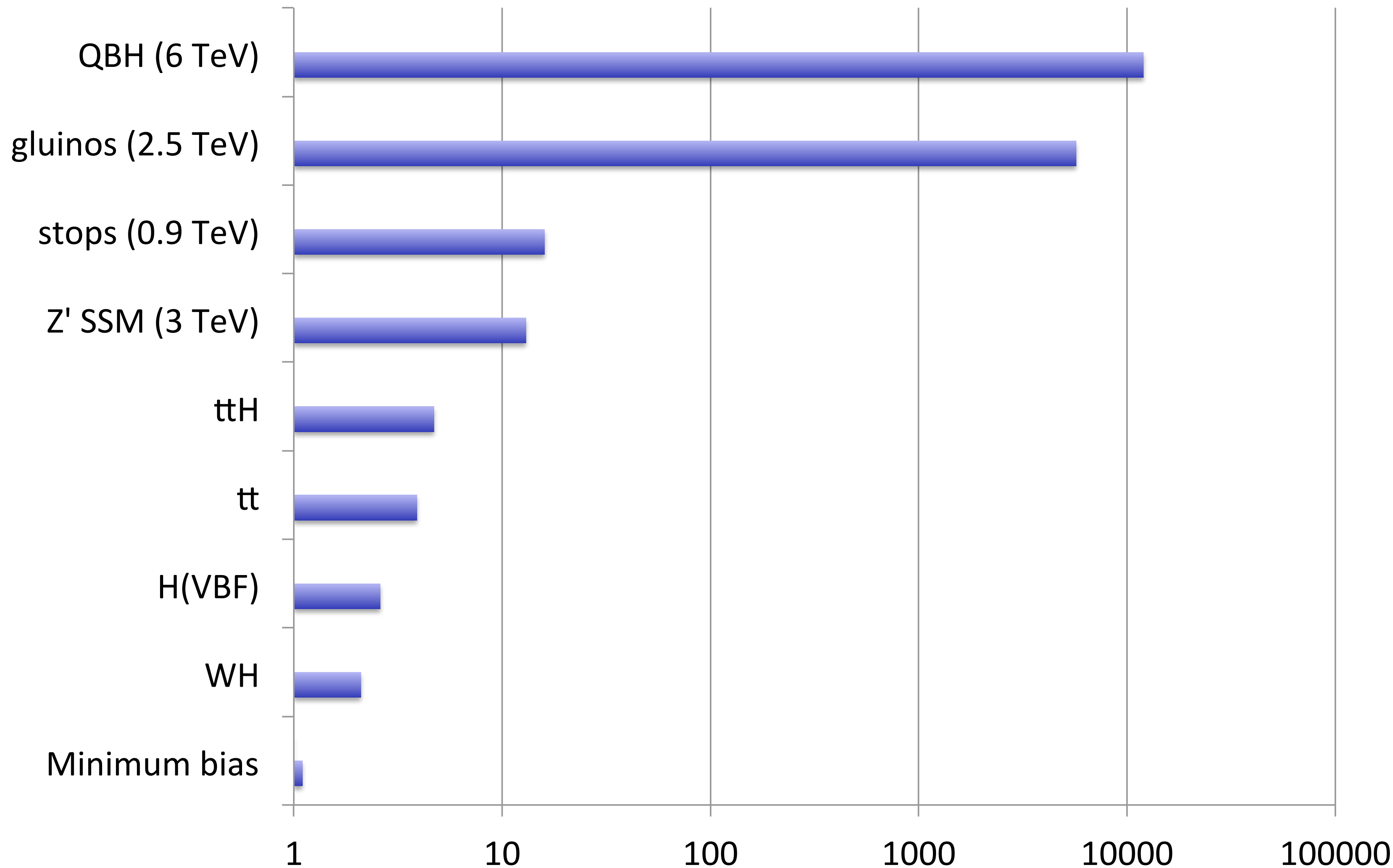
- Also installing muon chambers to complete coverage and executing repairs on TRT and Calorimeter systems

Phase 0 Physics at 13-14 TeV

- With 75-100 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 fb^{-1} will certainly be as exciting as for the first 30 fb^{-1}

Cross Section Comparison: 14 to 8 TeV



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 μs
- 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 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

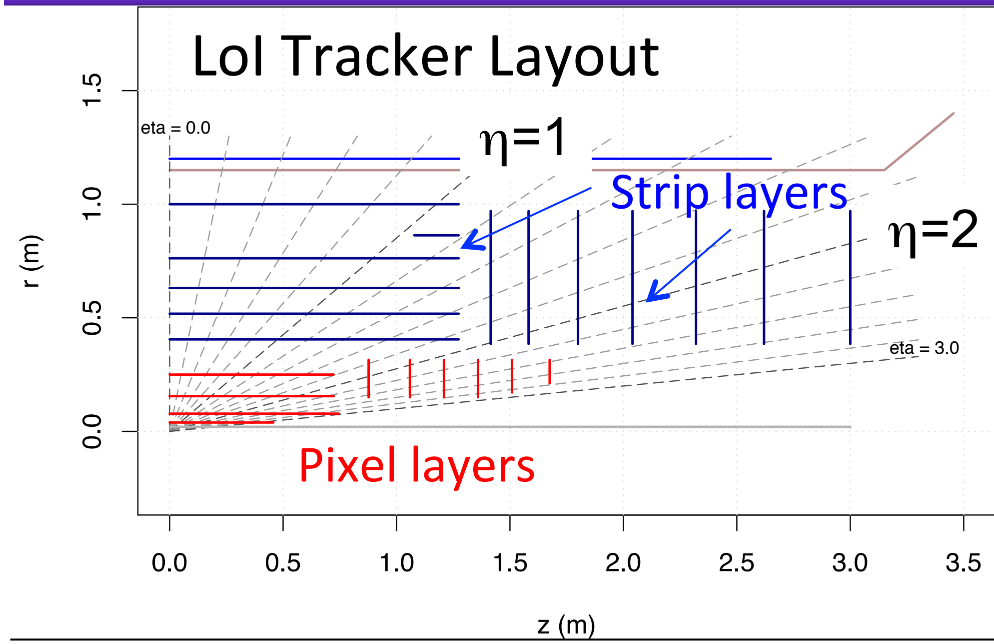
ATLAS Phase II (HL-LHC) Program

- 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 $5x10^{34}$ with a 3000 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 ($<\mu>=140$) *ATL-UPGRADE-PUB-2013-014*
  - 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

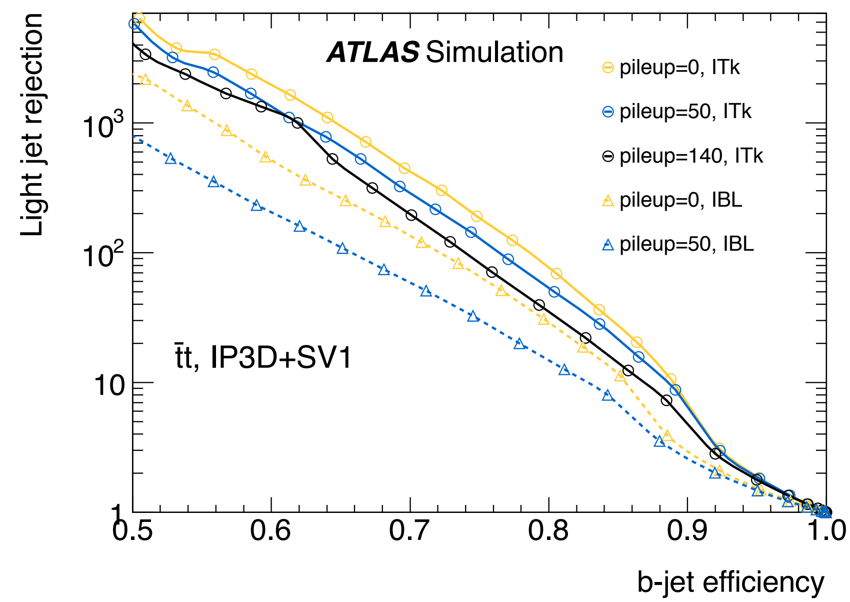
Silicon Tracker Upgrade



- Provide sufficient hits to minimize fakes from pileup
- R&D in rad-hard sensors, readout electronics, lightweight structure
- Reduced inner pixel size to $25\times150\mu m^2$

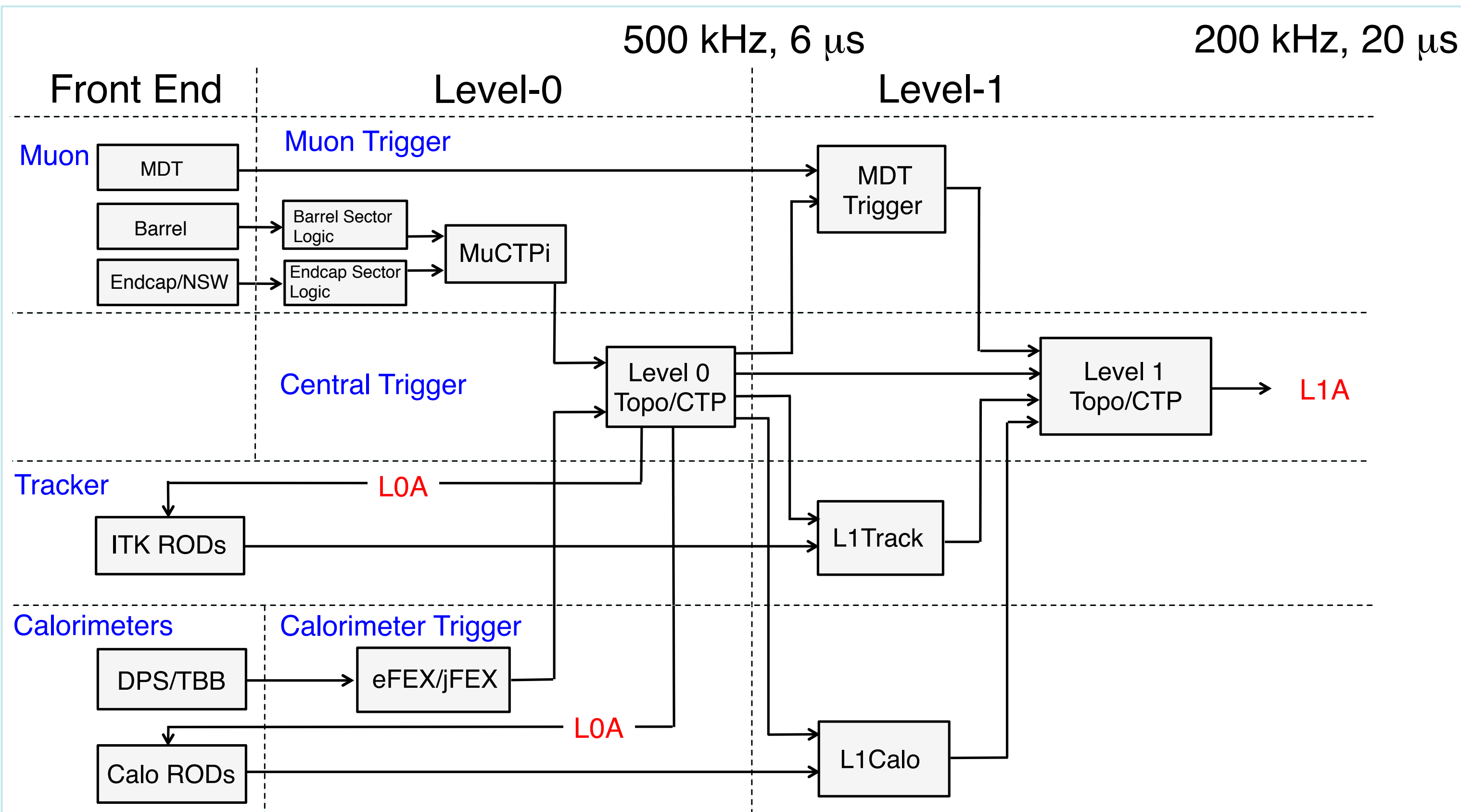
New pixel size and less material offset effects of pileup

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



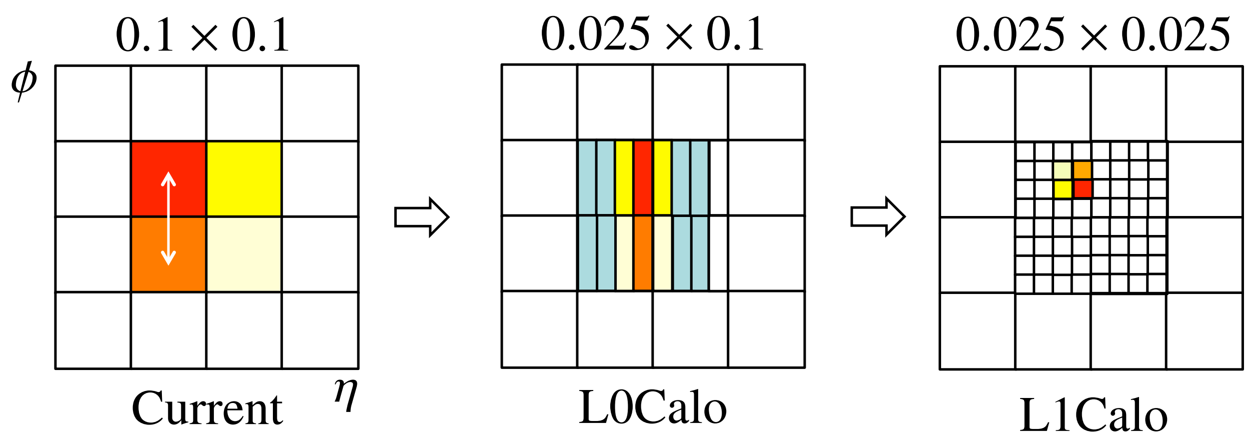
Trigger System Upgrade

- Maintain efficient 20 GeV isolated lepton triggers at 7×10^{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



L1 Calo Current *L0 Calo Upgrade* *L1 Calo Upgrade*

- 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

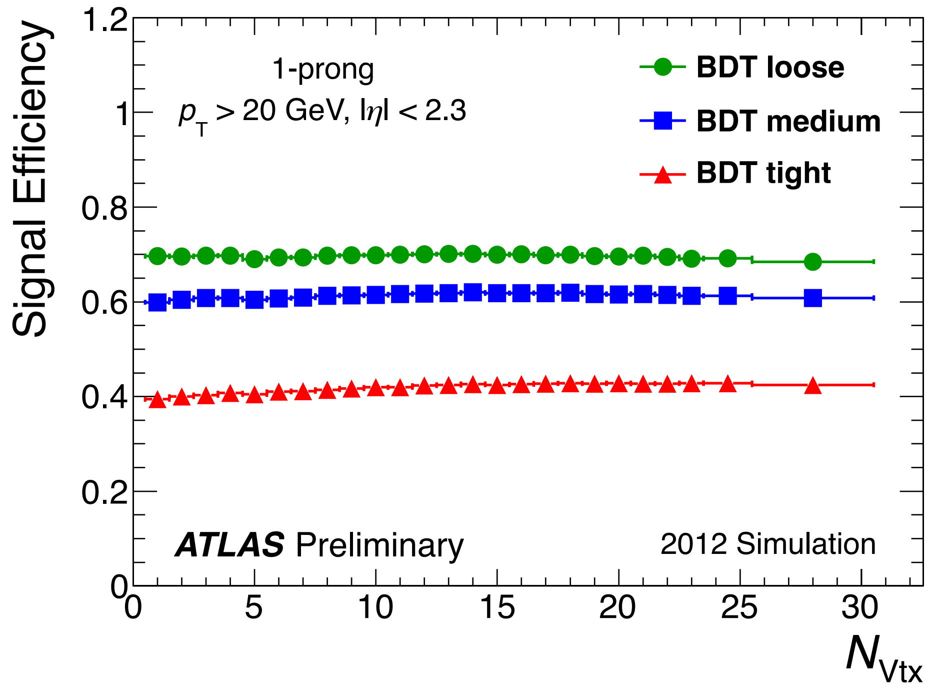
- Detailed studies of potential physics program topics were prepared in European Strategy sessions (2012) and ECFA (2013)
- ATLAS philosophy is to extrapolate detector performance from current pileup $\langle\mu\rangle$ values to future pileup $\langle\mu\rangle$ values, based on combination of data 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. Updated results in ATL-PHYS-PUB-2013-009 use full detector simulation.
  - Lepton momenta, b-tagging, missing transverse energy, pileup jets
  - Developed realistic trigger menus to preserve low-p_T lepton and photon triggers, even at $5\times10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ [typical threshold 20 GeV]
- **Conservative approach that does not account for future advances**

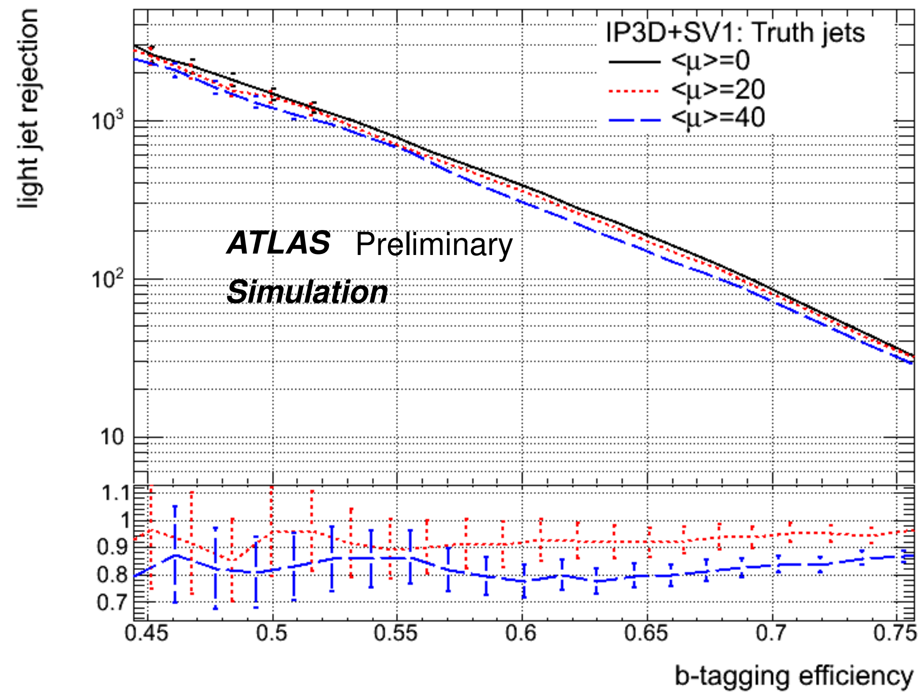
Example of parameterized resolutions:

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

Performance Estimates for HL-LHC Studies

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

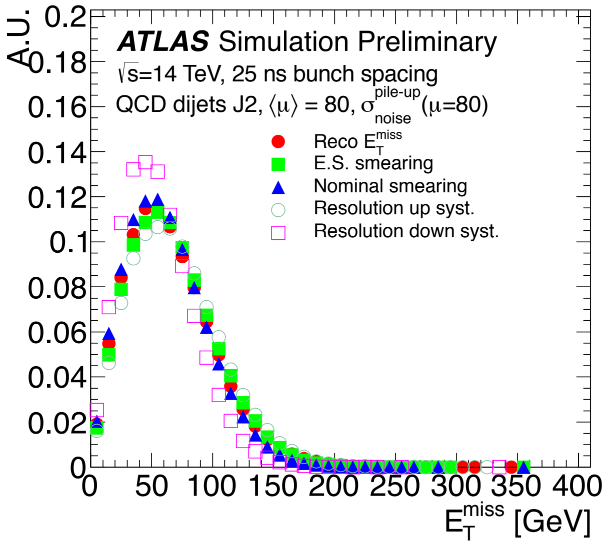


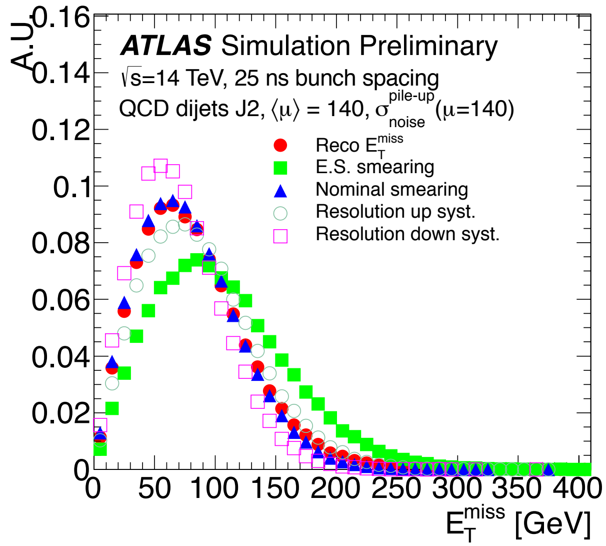


- Note that the assumed b-tagging performance is worse than the new result from full simulation on p. 14
- Based on our excellent understanding of detector in Run-1 data, we believe that other assumptions are also likely fair to pessimistic
  - To be re-evaluated this summer with full simulation up to <μ>=200

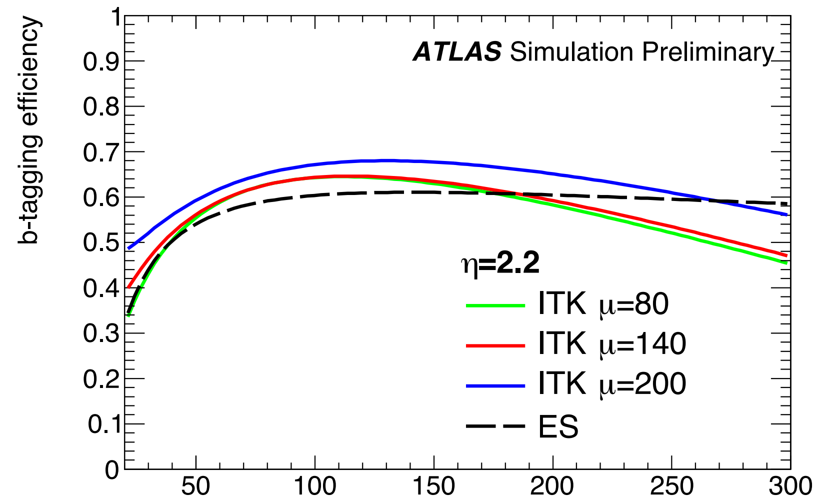
Comparison of Parameterizations

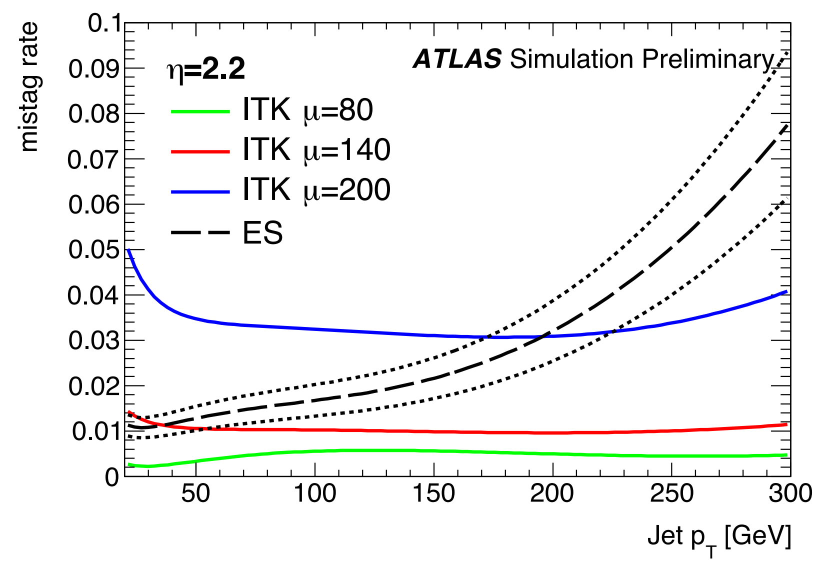
Missing ET reconstruction



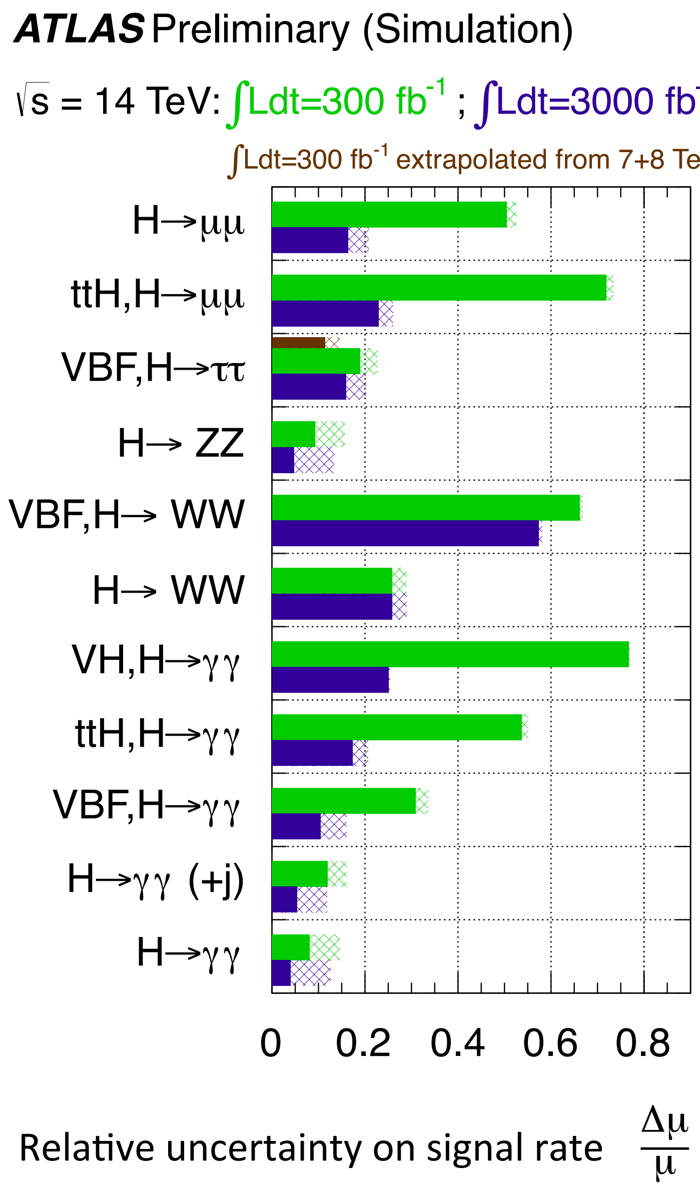


B-tagging performance





Higgs Production Measurements



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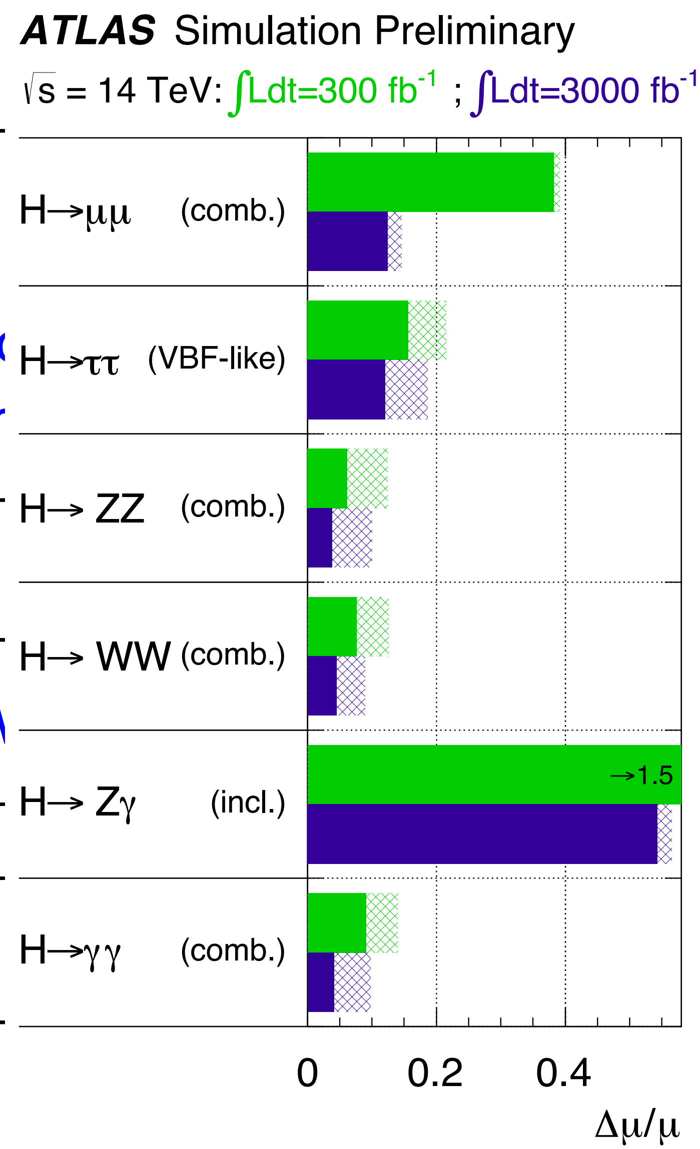
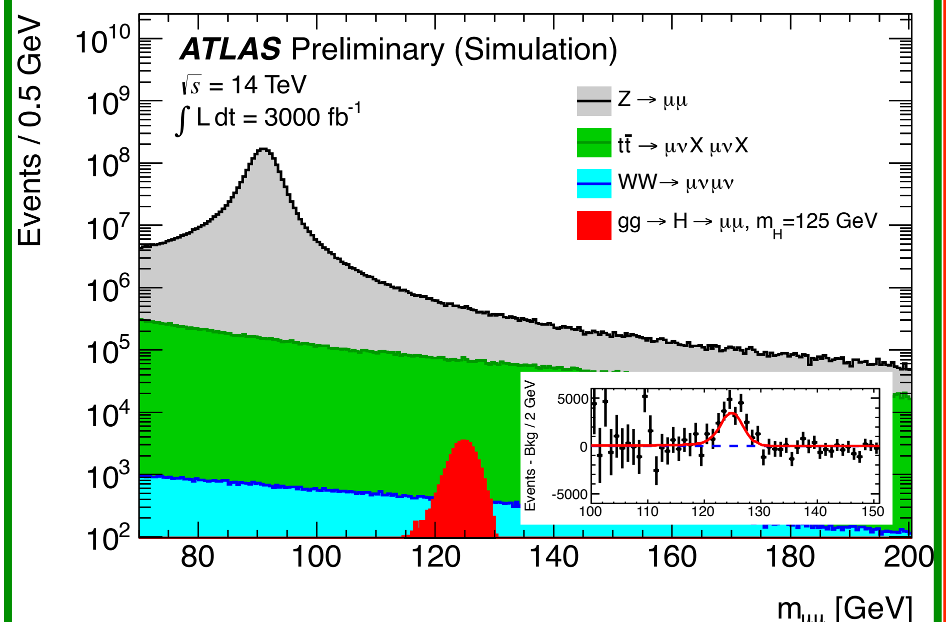


Rare Higgs Decays

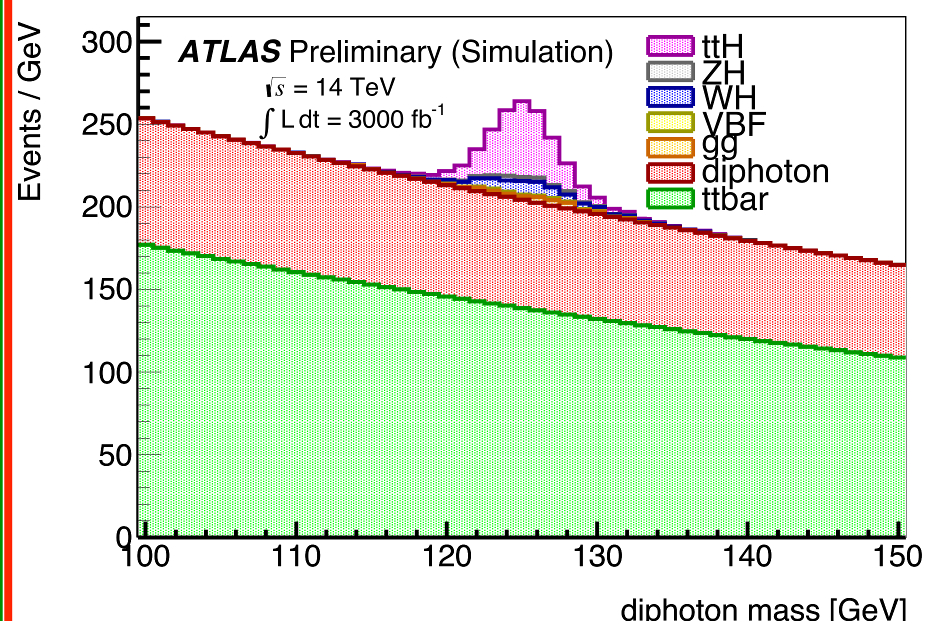
Higgs decay to μμ

- Allows comparison of 2nd and 3rd-generation Higgs couplings
- Optimized analysis achieves >6σ with 3000 fb^{-1}, giving 15-20% precision on relative Hμμ coupling

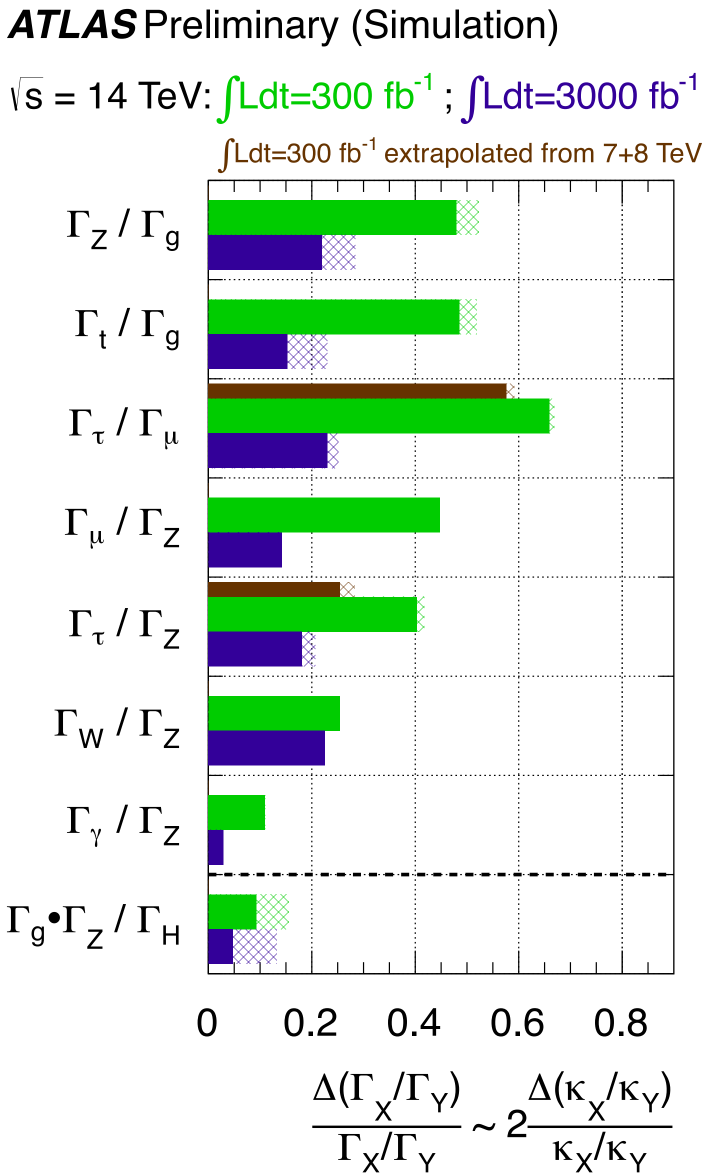


ttH in γγ decay mode

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



Higgs Couplings

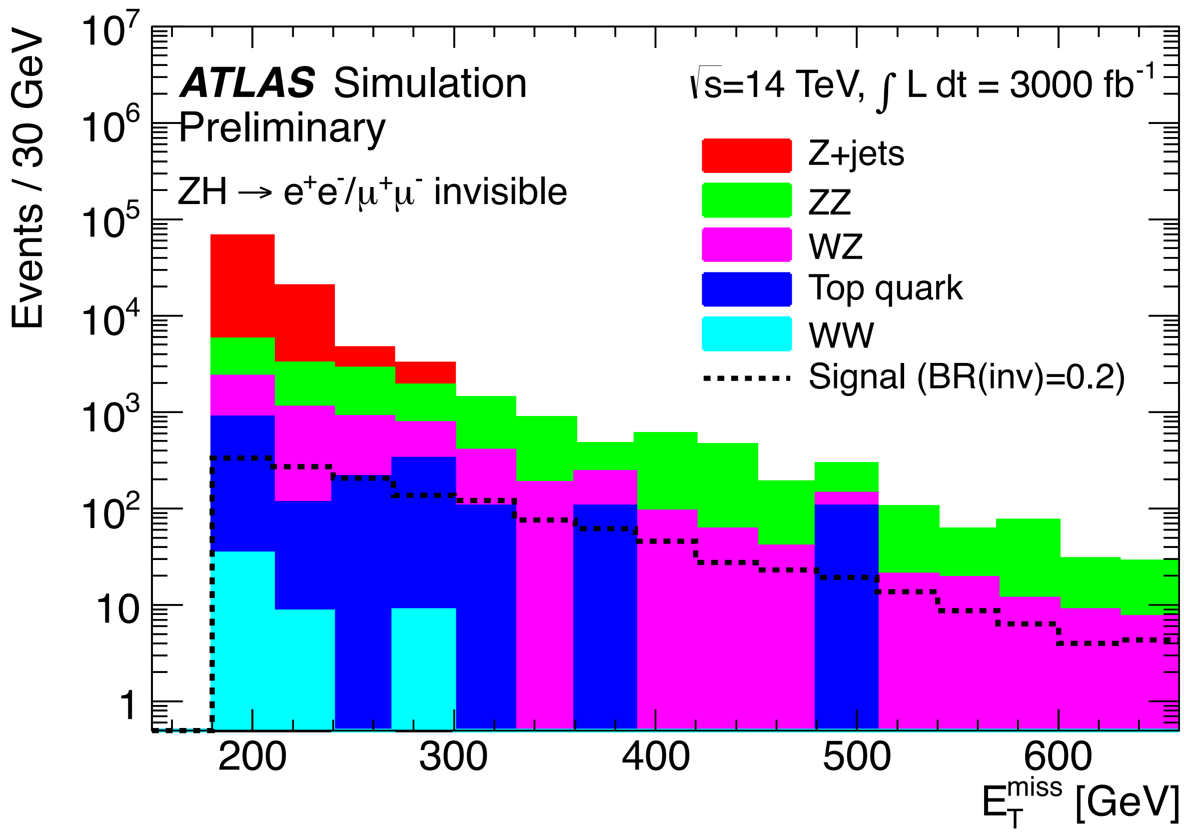


- In the general coupling fits, no assumption is made on possible BSM decay modes or total width Γ_H
  - Only the ratios of coupling parameters can be measured from this fit
- Ratios of partial widths are related to couplings via $\Gamma_X/\Gamma_Y = \kappa_X^2/\kappa_Y^2$
  - Matches LHC Higgs Xsec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

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

ATLAS	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0 % (5.6 %)	1.9 % (4.5 %)
κ_F	8.9 % (10 %)	3.6 % (5.9 %)

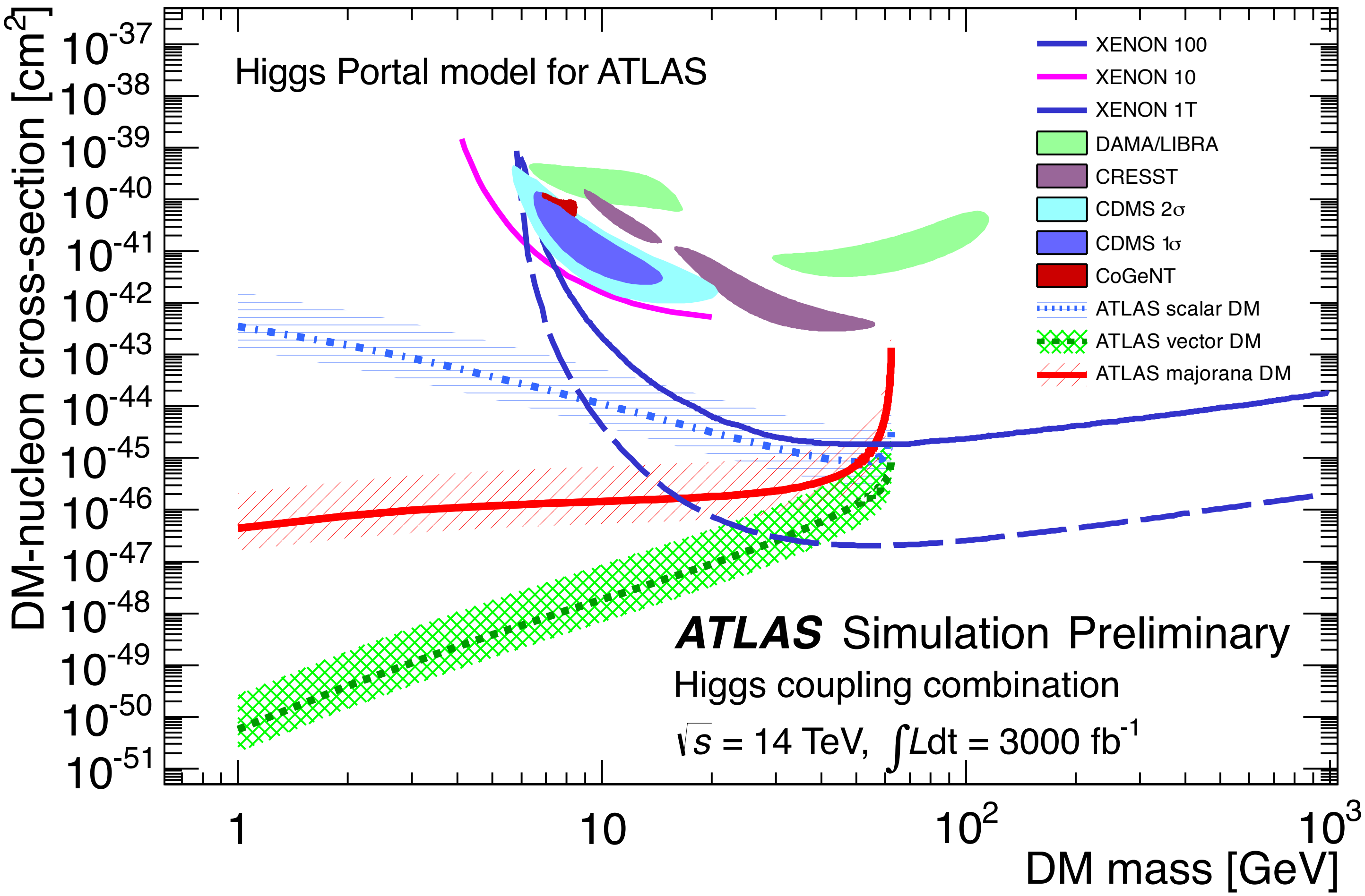
Invisible Higgs Branching Fraction



BR($H \rightarrow$inv.) limits at 95% (90%) CL	300 fb^{-1}	3000 fb^{-1}
Realistic scenario	23% (19%)	8.0% (6.7%)
Conservative scenario	32% (27%)	16% (13%)

Dark Matter Interpretation

- Translate bounds on invisible couplings to constraints on WIMP coupling to Higgs bosons (assuming $2m_{WIMP} < m_{Higgs}$)
  - Note dependence on WIMP spin hypothesis



Higgs Coupling Measurement Comparison

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

- Snowmass study to compare prospects for future colliders
- Higgs coupling results based mostly on CMS studies
  - Significant improvements (2x) with 3 ab^{-1} data at HL-LHC
  - Lepton colliders offer further significant improvement in vector boson and fermion couplings

Higgs Self-Coupling

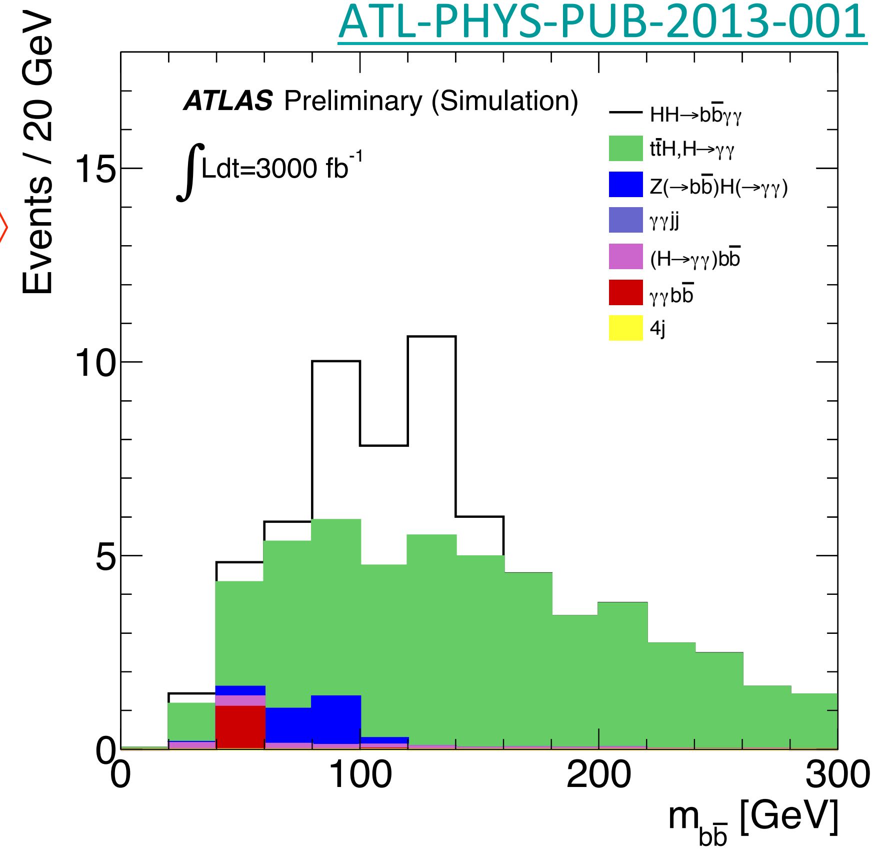
- Derive trilinear self-coupling λ_{HHH} from Higgs pair production
  - Destructive interference with HH pair production via top loop
  - HH cross section increases from 34 to 71 fb if λ_{HHH}=0
- Many channels to pursue, since m_H=125 GeV

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

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

S/√B~3 for 3000 fb⁻¹

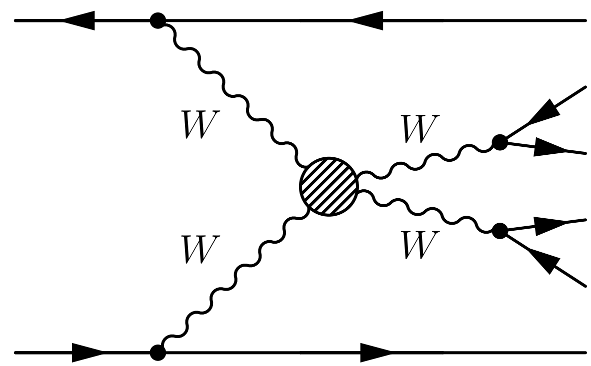
ATL-PHYS-PUB-2013-001



- Expect that additional channels (bbττ) and 2 experiments combined could lead to 30% measurement of λ_{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

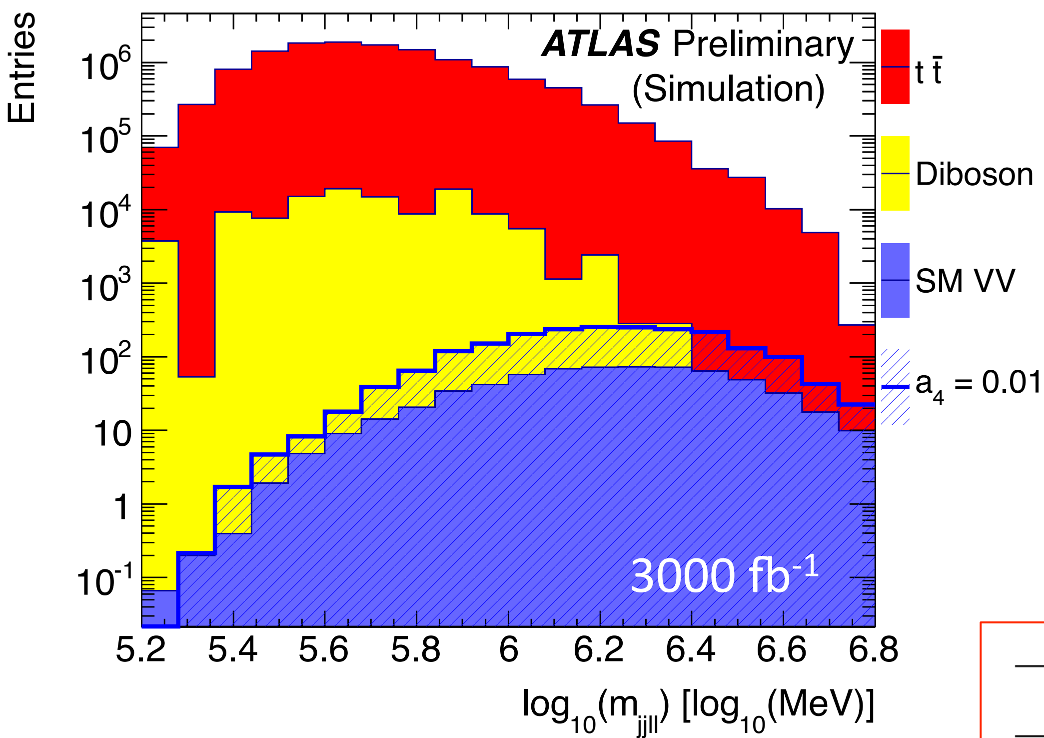


- Combination of Higgs couplings, vector boson scattering, and triboson production probes gauge-Higgs sector for new physics
- New ATLAS results in ATL-PHYS-PUB-2013-006 focus on sensitivity to new physics contributions
  - Anomalous quartic couplings calculated with post-Higgs unitarization
  - Higher-dimension operators in effective field theories with mass scale Λ

W^+W^- 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 ~1 TeV)

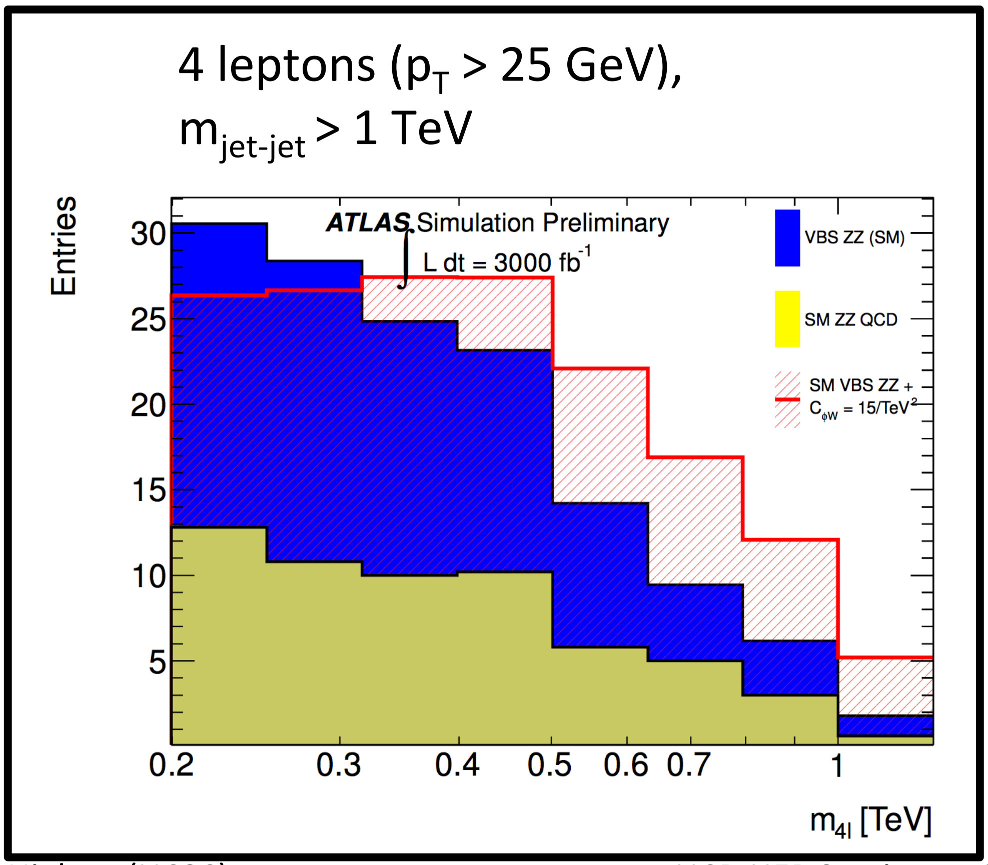
Factor of 4 improvement

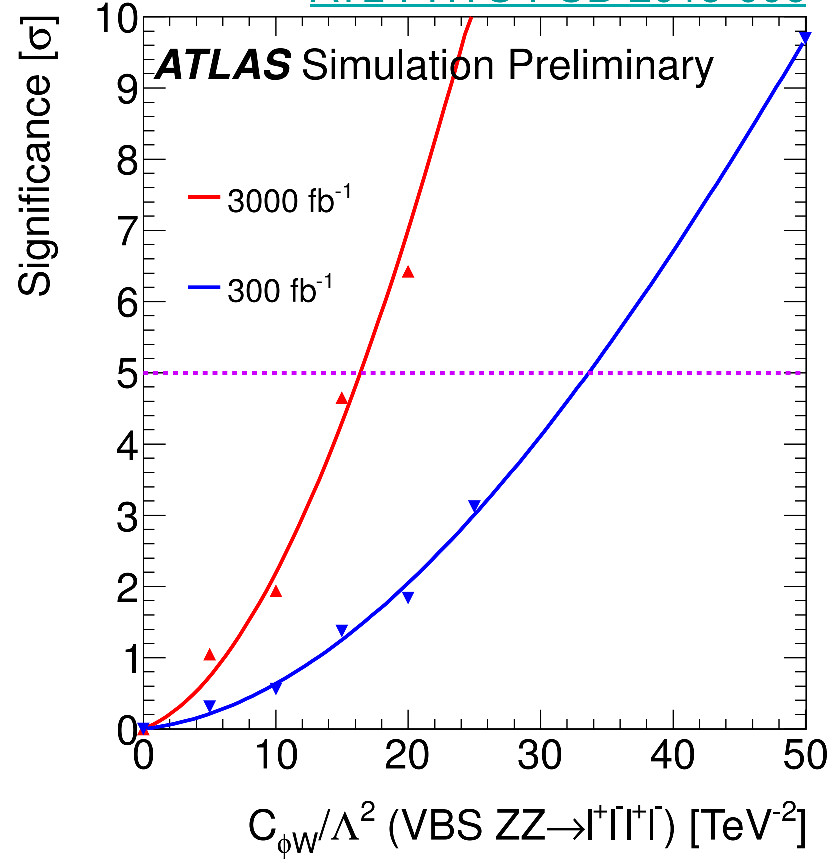
model	300 fb^{-1}	1 ab^{-1}	3 ab^{-1}
a_4	0.066	0.025	0.016

ZZ Scattering

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

ATL-PHYS-PUB-2013-006

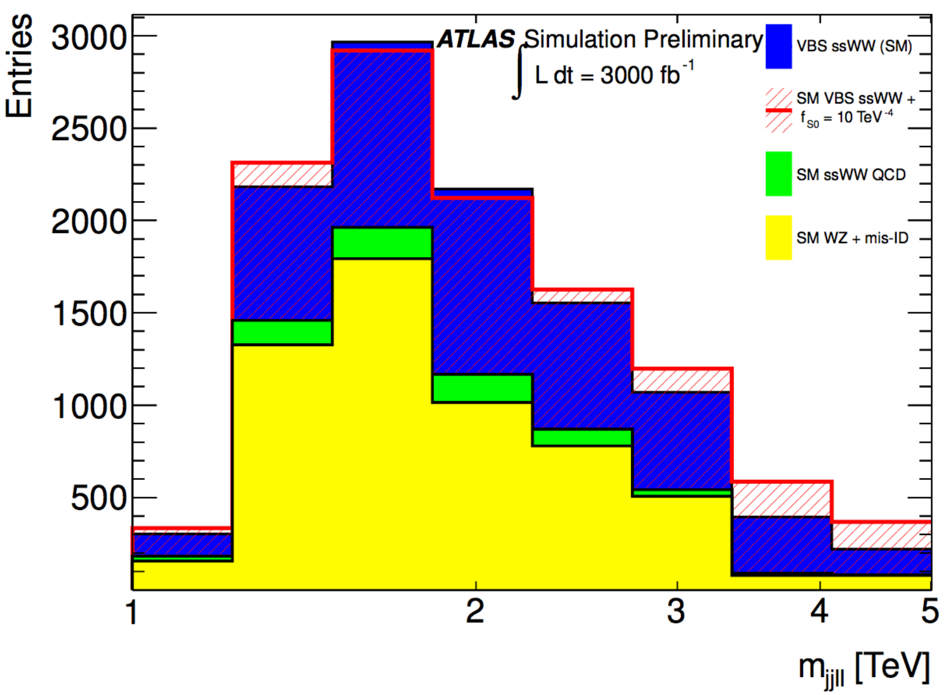


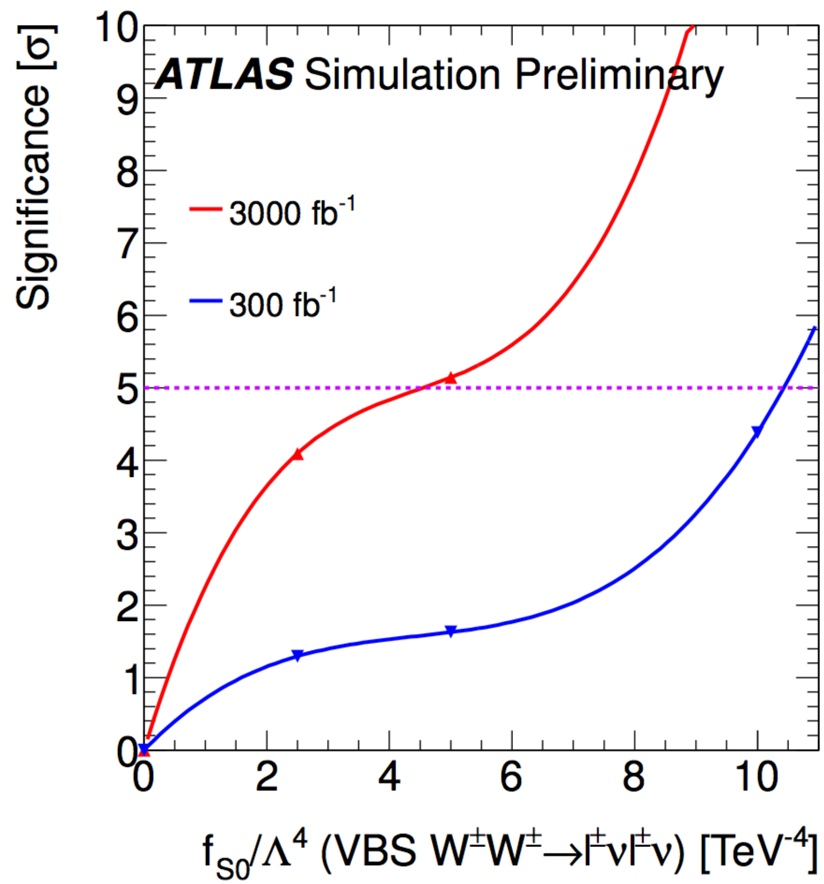


$W^{\pm}W^{\pm}$ Scattering

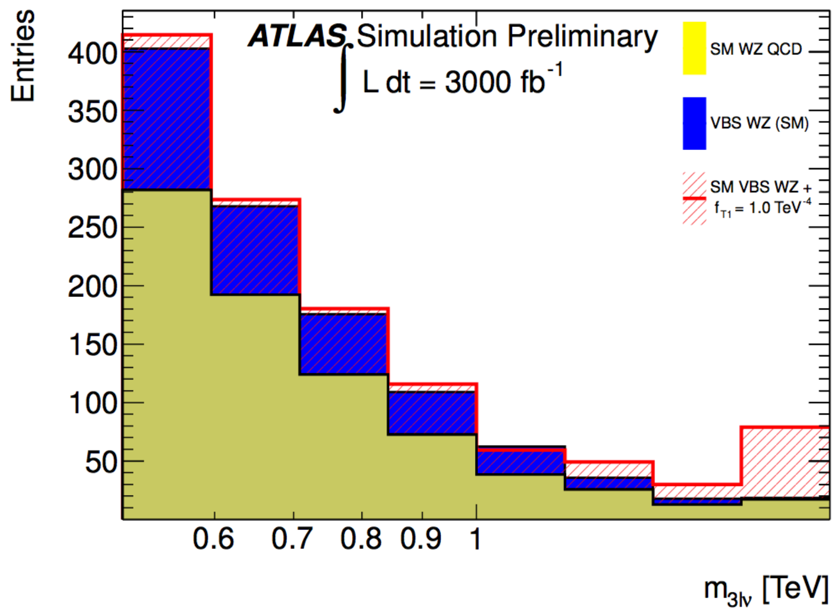
- Building on experience with similar studies at 8 TeV
  - Detailed knowledge of physics and detector backgrounds (charge flip, fakes)
- New physics via dim-8 operator $\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4}[(D_\mu\phi)^\dagger D_\nu\phi] \times [(D^\mu\phi)^\dagger D^\nu\phi]$

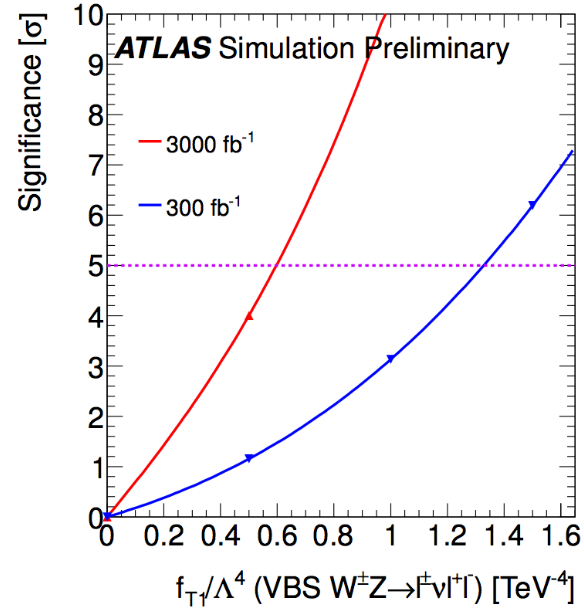
4 leptons (p_T > 25 GeV),
$m_{jet\text{-}jet}$ > 1 TeV





WZ Scattering





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

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

Searches for Supersymmetric Particles

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

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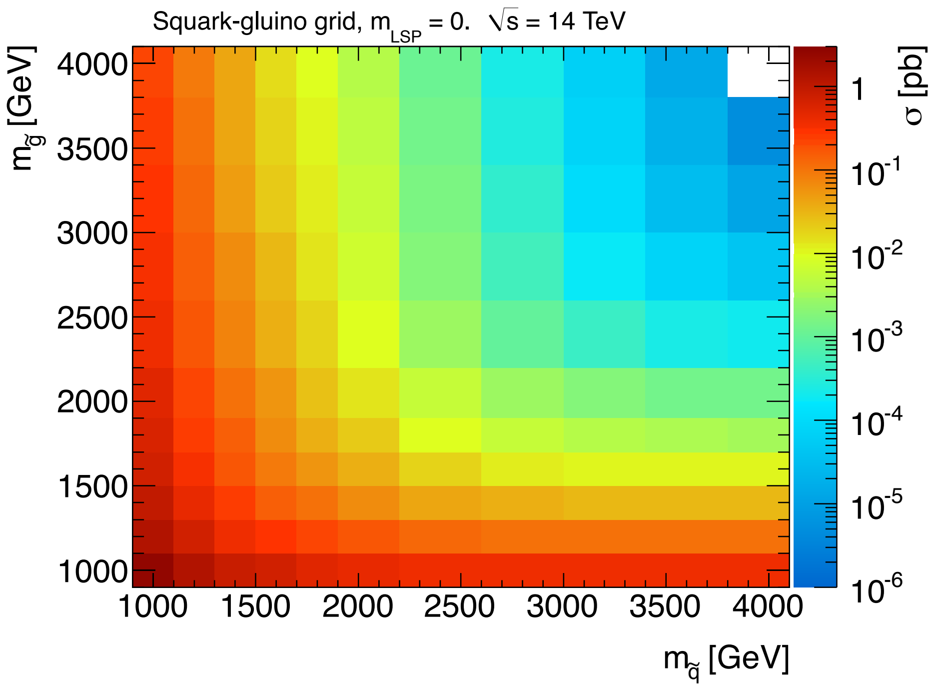

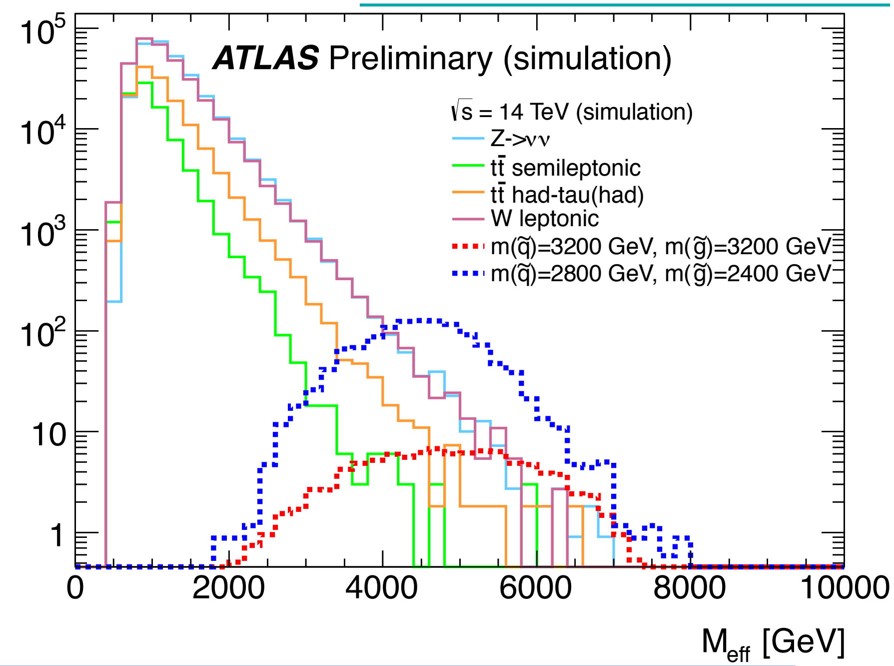

Even though M_{eff}-style searches gain sensitivity with 3000 fb^{-1}, expect bigger relative gains in challenging signatures:

- *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 750 GeV to >1100 GeV** with 3000 fb^{-1} data

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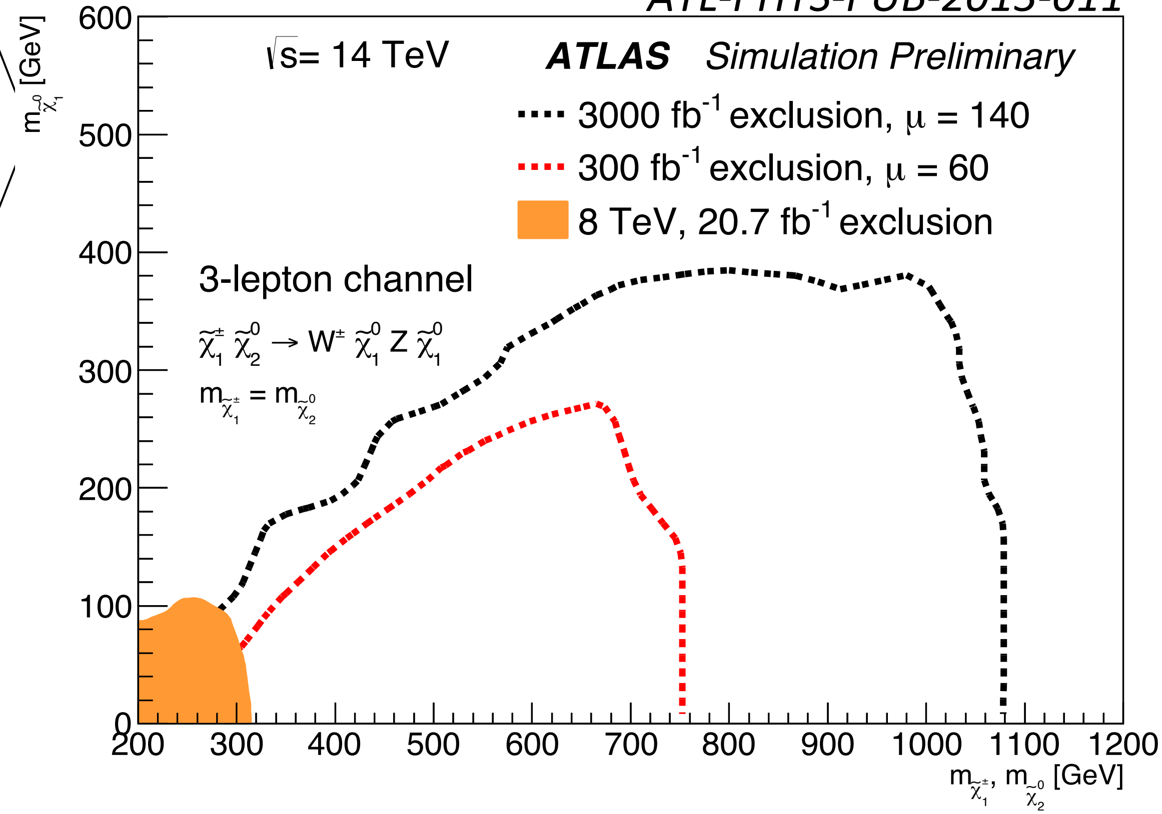
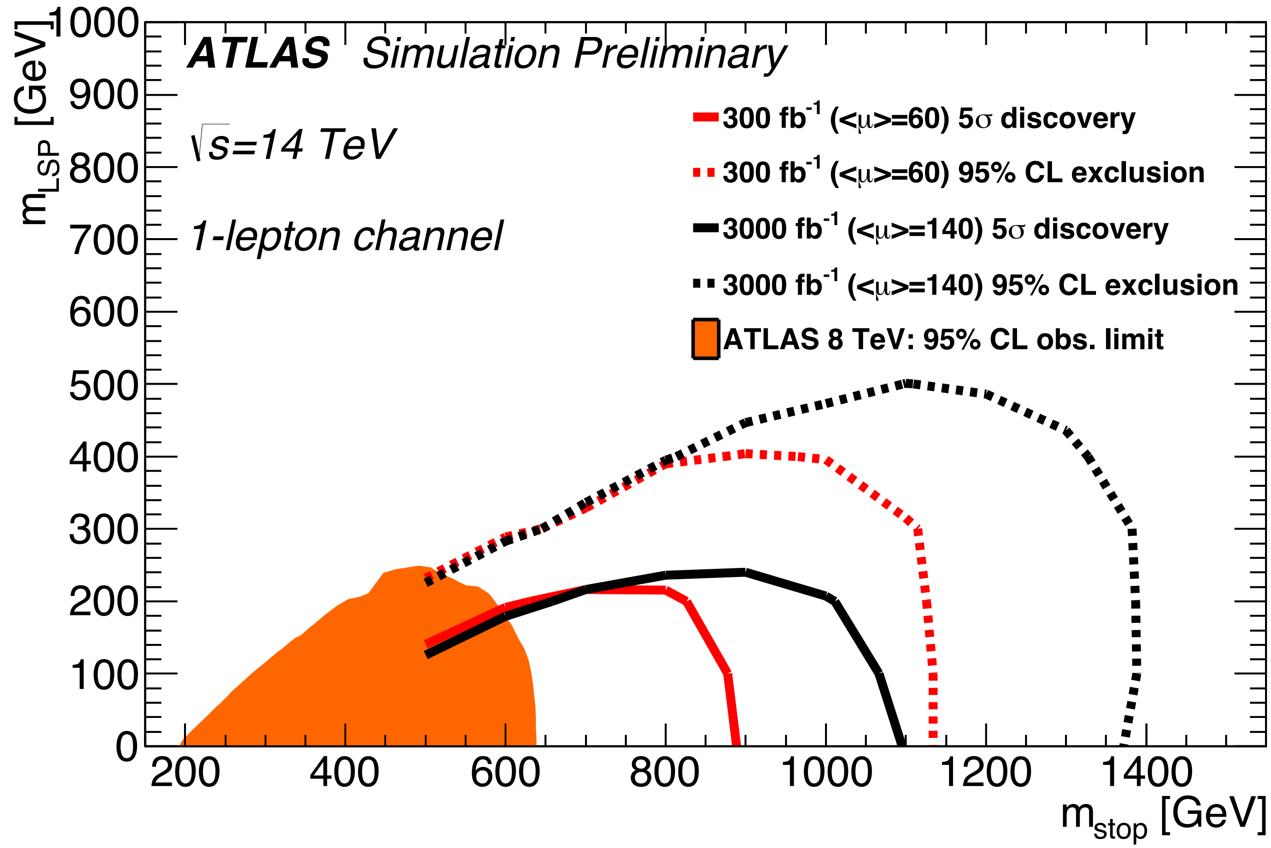


Searches for Scalar Top

- 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 **200 GeV** with 3000 fb^{-1} data, but sensitivity in plane increases even more dramatically

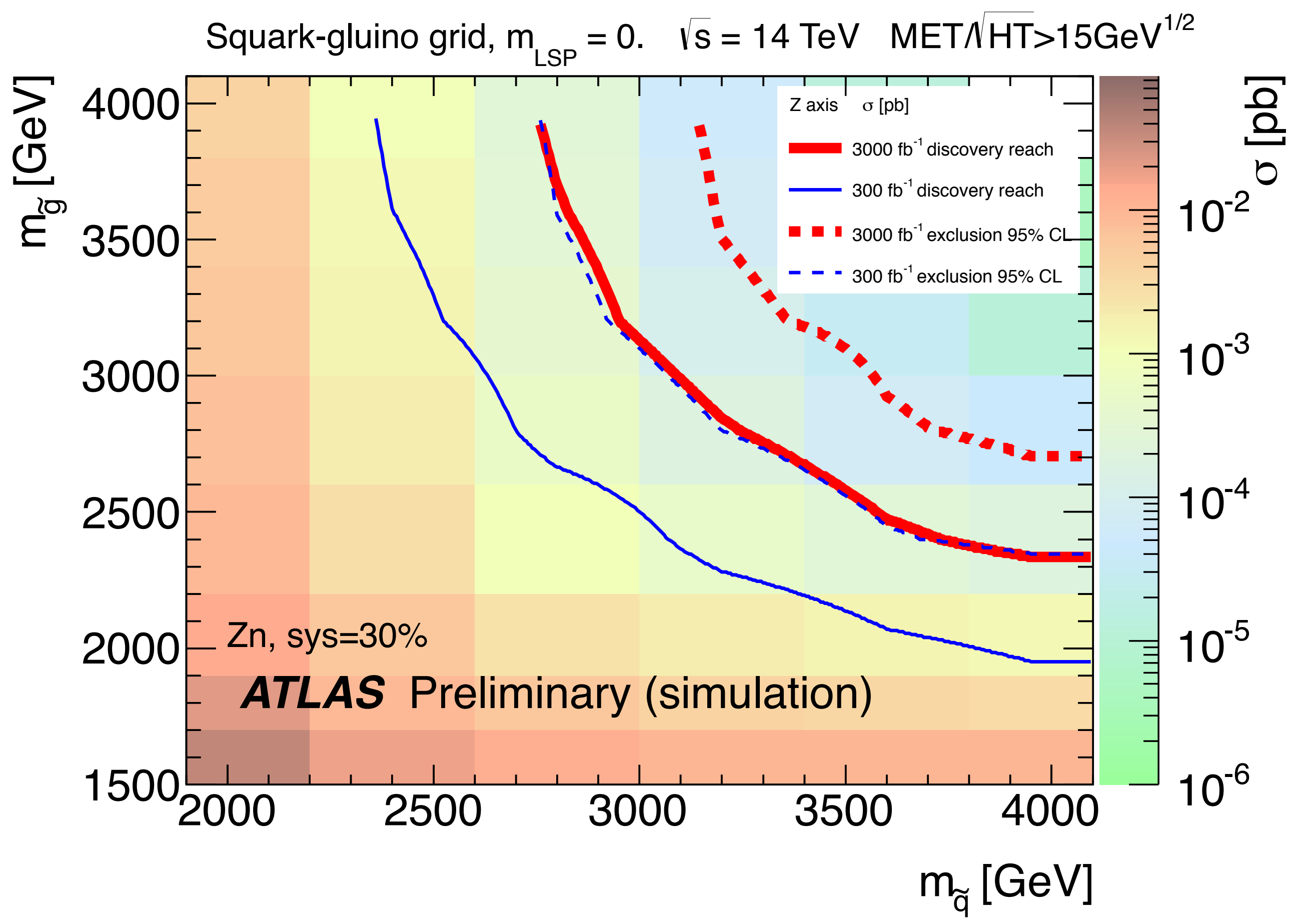


Searches for Squarks and Gluinos

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

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

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

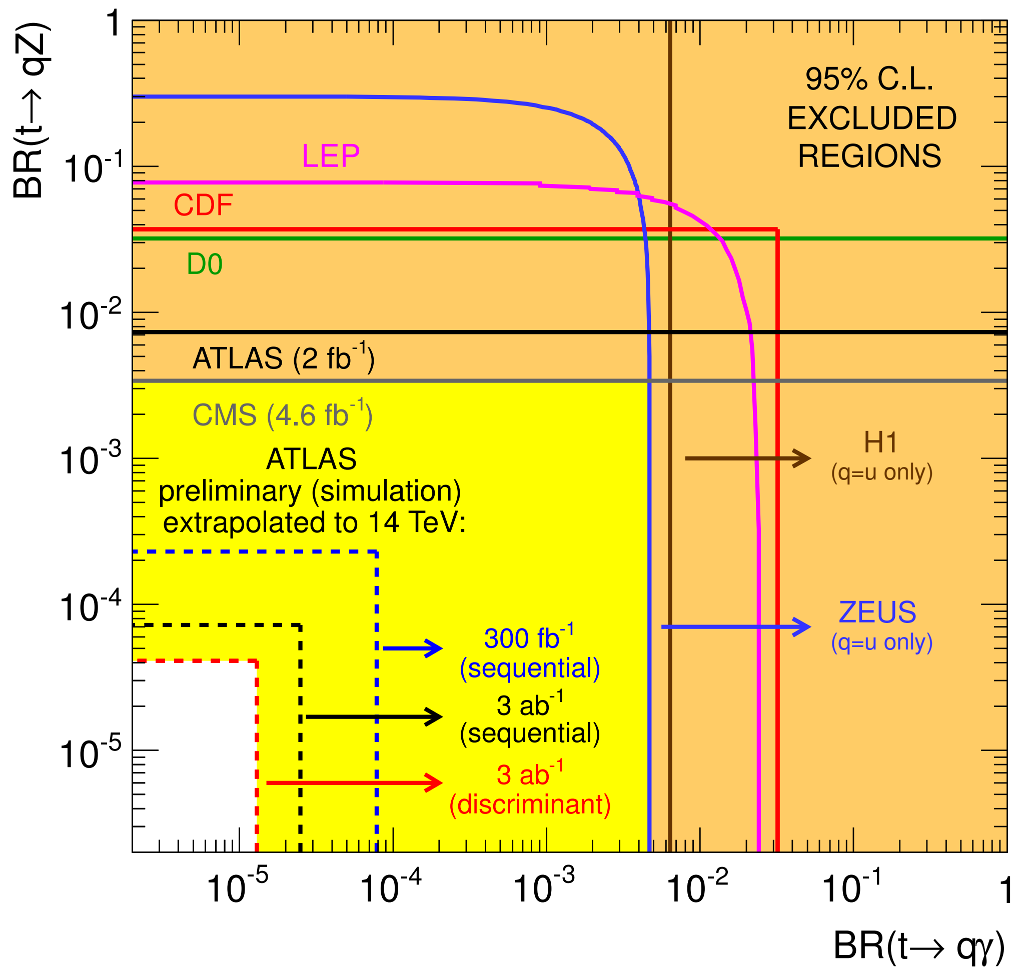


FCNC with Top Quarks

- 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}

<u>Extrapolation to 14 TeV</u>

- Based on 2 fb^{-1} result, using kinematic fit for top
- Limits on t->qγ and t->qZ are entering interesting range
- Dominant SM top background scales to 14 TeV

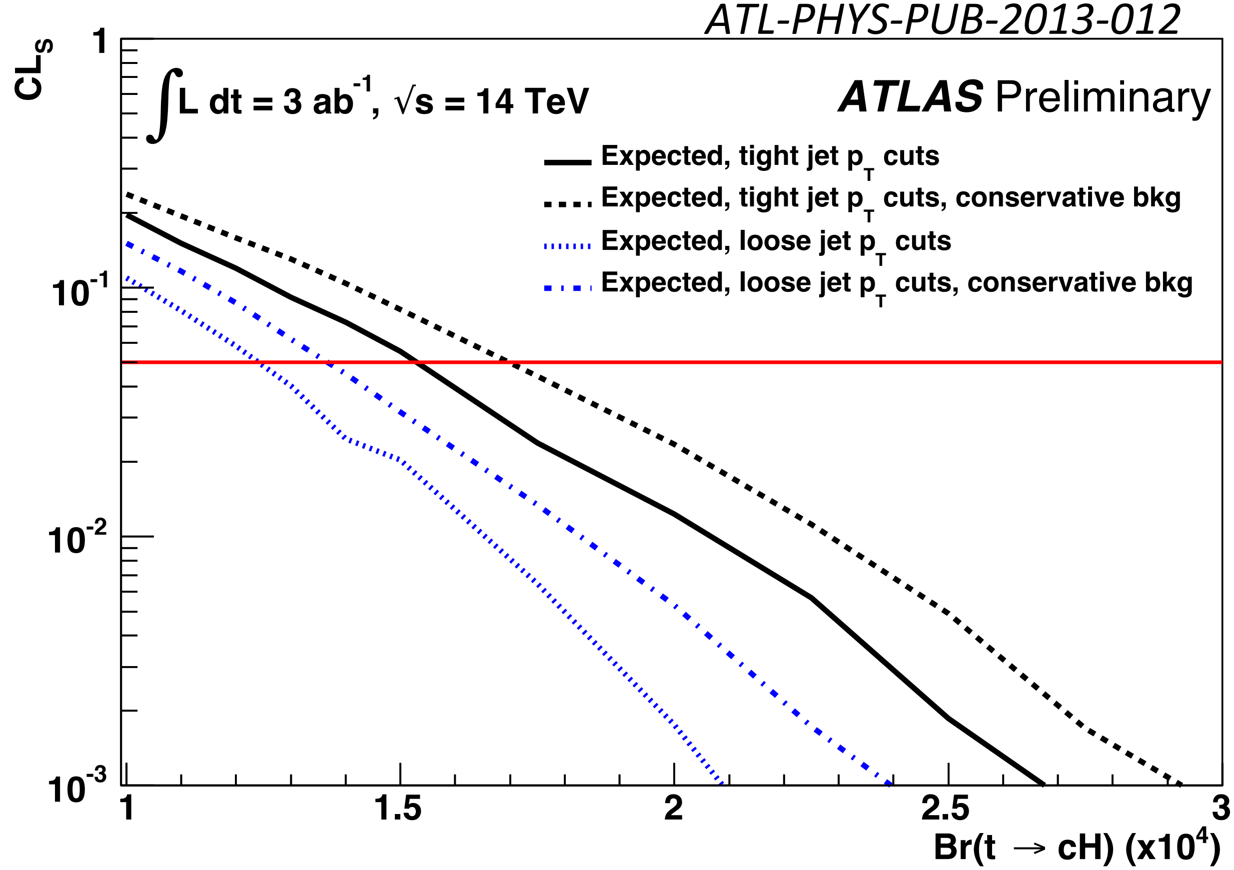


Improvements of 5x with respect to results at 300 fb^{-1}

FCNC Top Quark Decays to Higgs

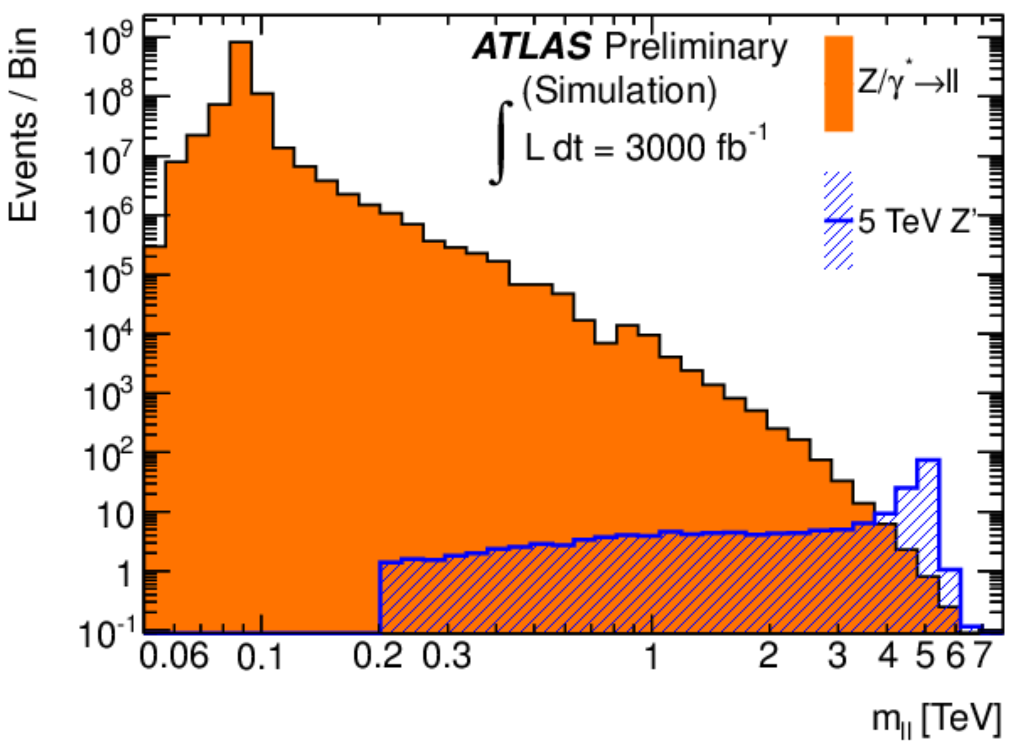
- In Type-III 2HDM (w/o flavor conservation), enhanced decay to cH
  - Branching ratio as large as 1.5×10^{-3} instead of 3×10^{-15} in Standard Model
- Identify Higgs decays in clean diphoton channel and reconstruct both hadronic and leptonic W decays (other channels to be added)

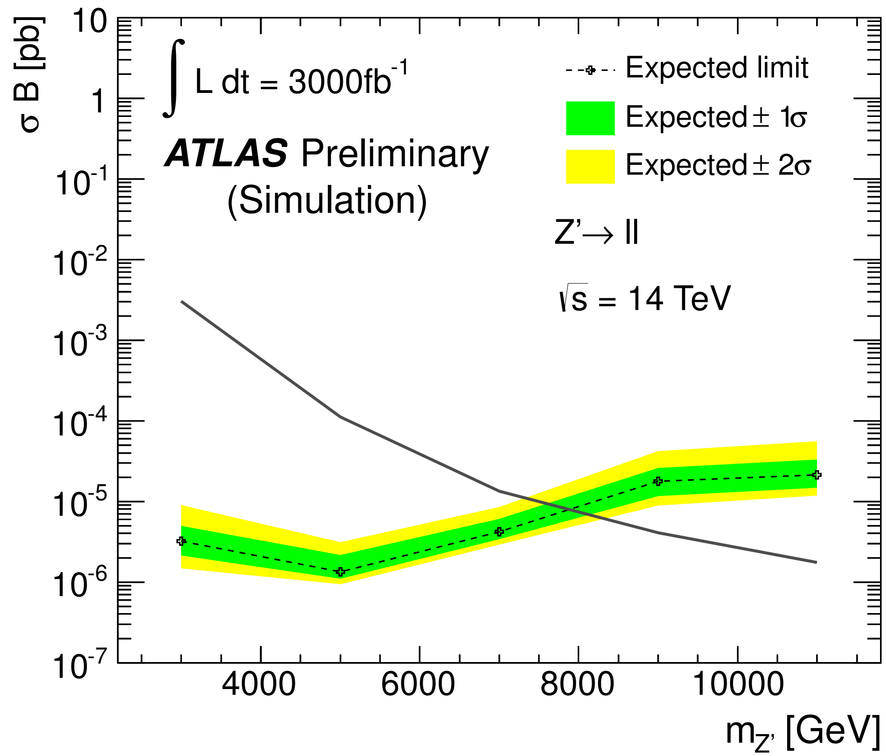
ATL-PHYS-PUB-2013-012



Exotic Resonances

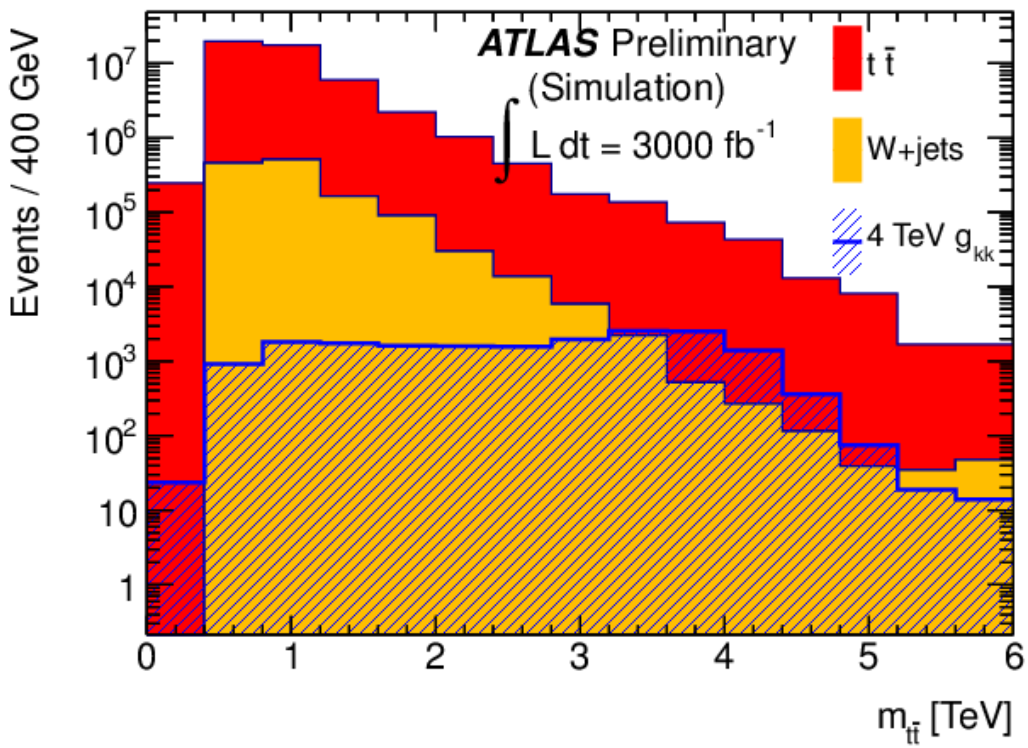
- Direct discovery probe of new physics at highest mass scales
  - Narrow weak resonances: Z' bosons in extended electroweak sectors
  - Broad strong resonances: KK gluons in models with extra dimensions
- For concrete comparisons, assume Z' with SM couplings
- Dielectron reach: 7.8 (6.5) TeV w/ 3000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

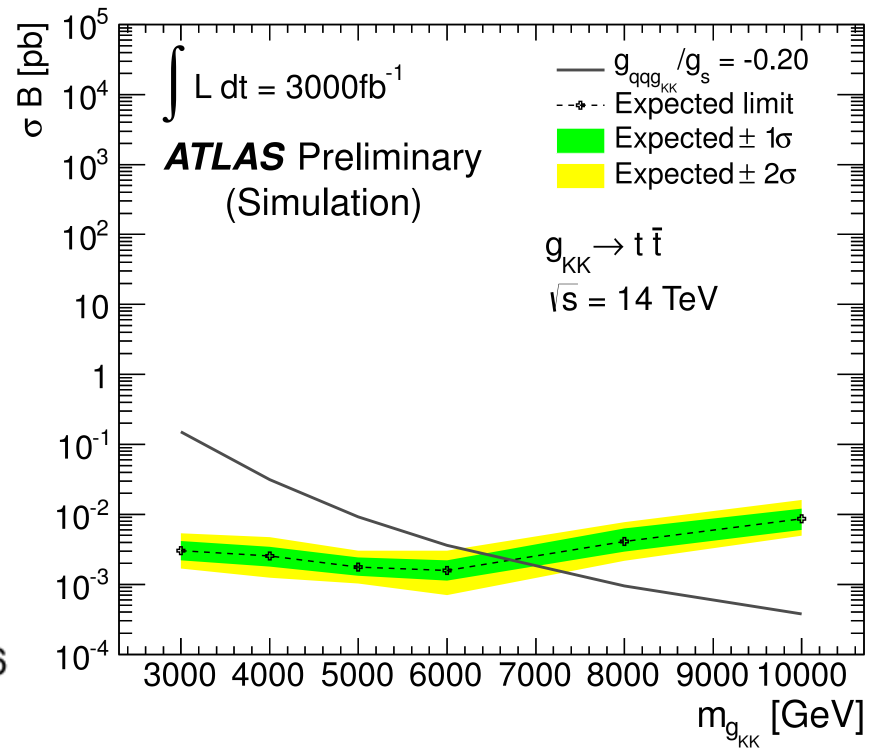




Exotic Top Quark Resonances

- 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) fb^{-1}
  - Typical observation that more complex signals benefit from larger dataset





Links to "ATLAS Future" Documentation

- All documentation collected on ATLAS Public Twiki
  - 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/
  - FTK TDR: https://cds.cern.ch/record/1552953
  - Muon New Small Wheel TDR: http://cds.cern.ch/record/1552862
  - Phase-I upgrade LoI: https://cds.cern.ch/record/1402470
  - Phase-II upgrade LoI: 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

- ATLAS has a rich physics program planned with 14 TeV pp collisions
  - Letter of Intent approved to collect 300 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 5×10^{34} $cm^{-2}s^{-1}$, integrated dataset of 3000 fb^{-1}
- Expanded physics reach with 3000 fb^{-1} relative to 300 fb^{-1}
  - Improved measurements of Higgs production in various channels (2-3x)
  - Measurements of rare Higgs decay to $\mu\mu$ and rare process of ttH($\gamma\gamma$)
  - 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 (~3 TeV)
- Energy frontier at LHC remains open to discovery and exploration of unexpected physics results at the highest energy scales