Physics Prospects for ATLAS at the HL-LHC

Jason Nielsen

Santa Cruz Institute for Particle Physics

University of California, Santa Cruz

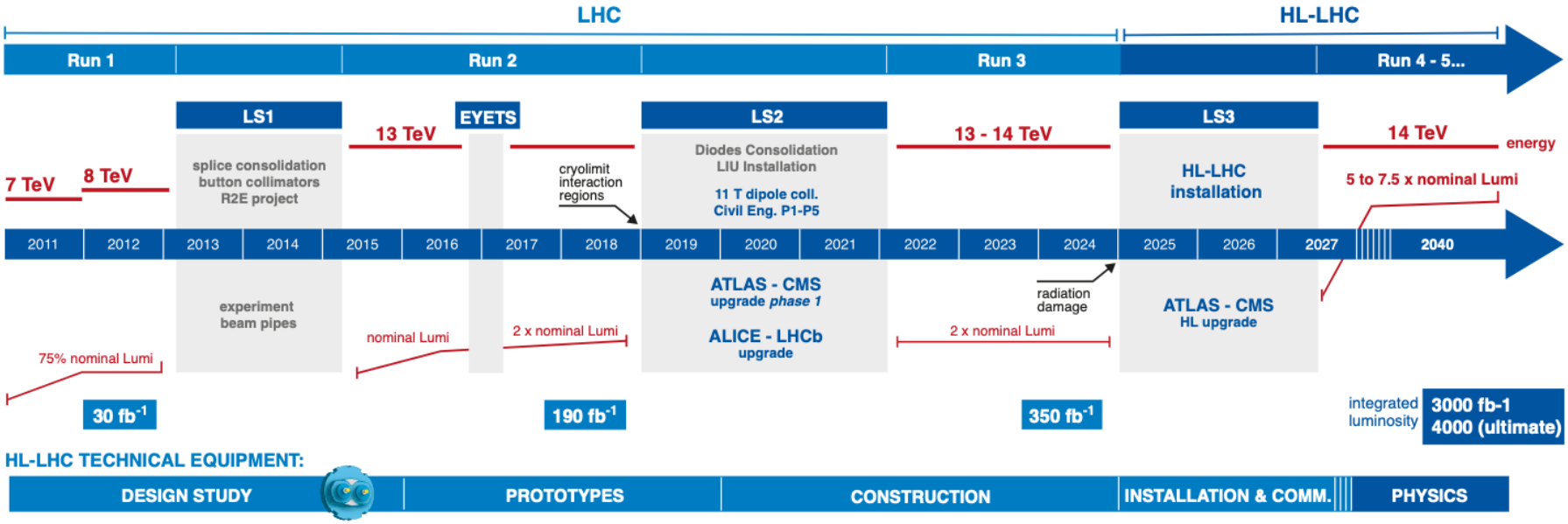
On behalf of the ATLAS Collaboration

5th International Conference on Particle Physics and Astrophysics

6 October 2020

ATLAS EXPERIMENT

High-Luminosity LHC Project



- HL-LHC is the culmination of the 27-km ring program at CERN
- Increase of √s to 14 TeV, integrated luminosity goal of 3000 fb^{-1}
  - Requires inst. lumi 7.5E34/cm^2/s, resulting in 200 pp collisions per crossing
- Challenging particle multiplicities and radiation environment
  - Requires new detector upgrades of the ATLAS experiment, as foreseen in the original LHC and ATLAS project plans

Experimental Challenges at High Lumi

- Large number of pp collisions ("pileup"), up to μ=200 per crossing
  - Higher hit occupancy in the detector, leading to higher rate of fake tracks
  - Stochastic accumulation into "pileup jets", especially in forward region
  - Additional energy in calorimeters degrades resolution
  - Increased radiation dose to sensitive detectors and electronics

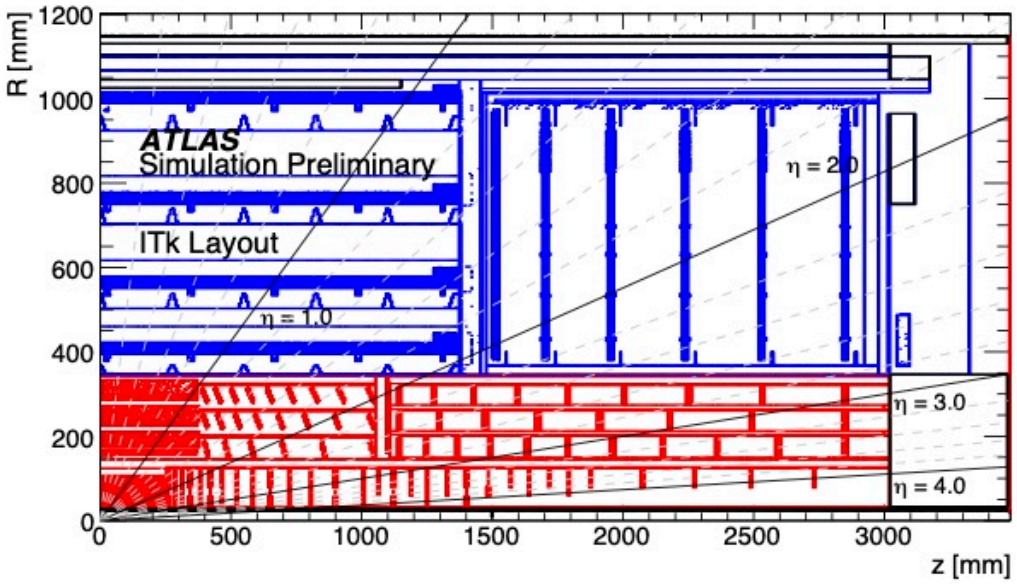
- Yet we would like to maintain current performance to be sensitive to rare processes and deliver precision measurements

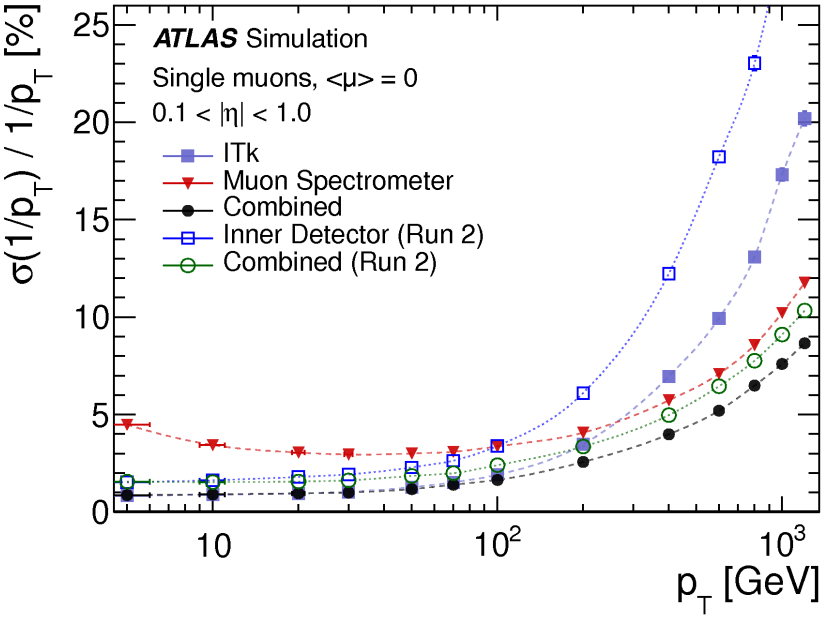
- Many improvements needed in detectors and software
  - Improved triggering using all detector information and improved resolution
  - Increased detector acceptance in forward regions
  - Better association of particles to primary vertex to reject pileup effects
  - Timing measurements for pileup rejection and particle flow

Overview of ATLAS Detector Upgrades

CERN-LHCC-2012-022
ATL-PHYS-PUB-2019-005

- All-silicon Inner Tracker replacement
  - Improved pseudorapidity coverage to $|\eta| < 4$
- New calorimeter front-end electronics to digitize signal at 40 MHz
- Muon electronics upgrade with additional trigger layer
- Trigger upgrade to use full detector information for 1 MHz decision
- Improved triggers are key to physics in many different signatures





ATLAS HL-LHC Physics Program

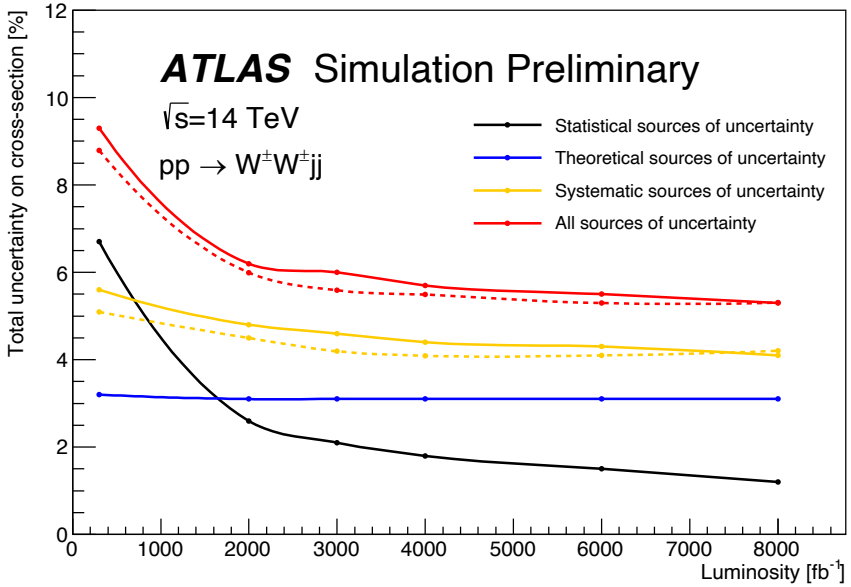
- Very broad program covering all areas of hadron collider physics
- Many studies performed for TDRs and European Strategy input
  - Measurement of **Higgs** boson properties: couplings, mass, width
  - Precision **electroweak** measurements: vector boson scattering, W mass, weak mixing angle, triboson couplings, rare processes
  - Searches for **Beyond Standard Model** physics: SUSY, dark matter
  - **QCD** measurements: precision PDF sets, especially in forward regions
  - **Flavor physics** studies: rare b-decays, constraints on CKM
  - **High-density QCD** measurements with heavy-ion and pp collisions
  - **Forward physics** with tagging of exclusive production processes
- Studies in ATLAS benefit from full HL-LHC simulation
  - Updated detector performance and systematic uncertainties

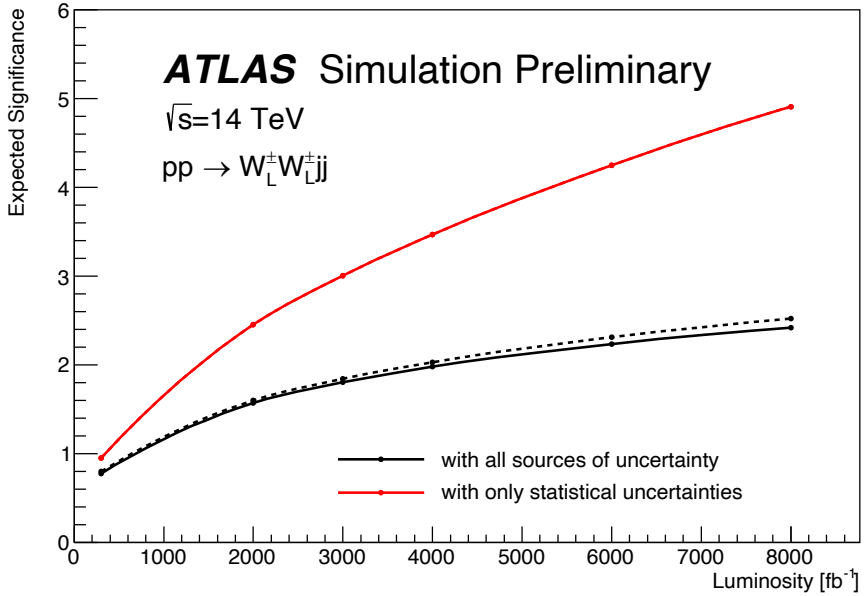
Focus on an interesting subset of the ATLAS results in my limited time

Vector Boson Scattering

ATL-PHYS-PUB-2018-022
ATL-PHYS-PUB-2018-023
ATL-PHYS-PUB-2018-029
ATL-PHYS-PUB-2018-052

- Three channels: WW, WZ, ZZ leptonic signatures
  - All observable at HL-LHC luminosities, but extracting the longitudinal scattering component to test unitarity is much more challenging
  - New forward tracking and jet-finding capabilities are key improvements
- WW scattering: <10% precision overall, 2σ sensitivity to $W_L W_L$
- WZ scattering: expect 6% precision overall
- ZZ scattering: 1-8σ overall, depends on theory uncertainties (ZZjj)

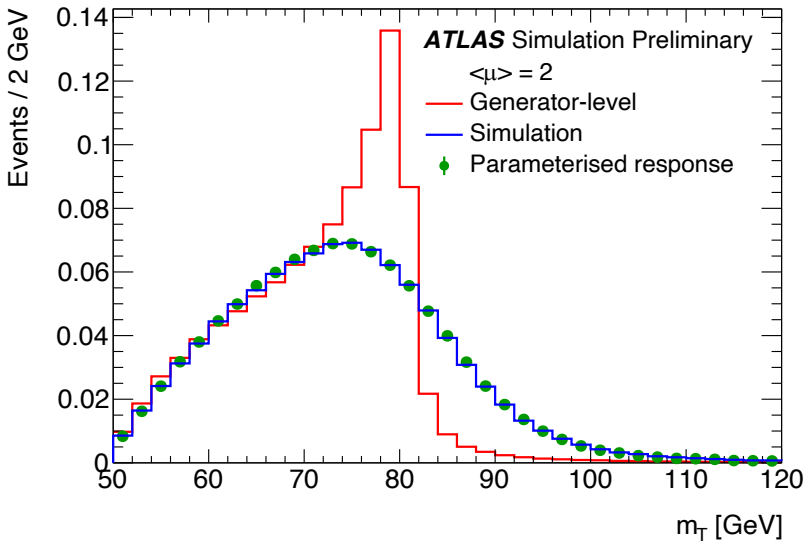


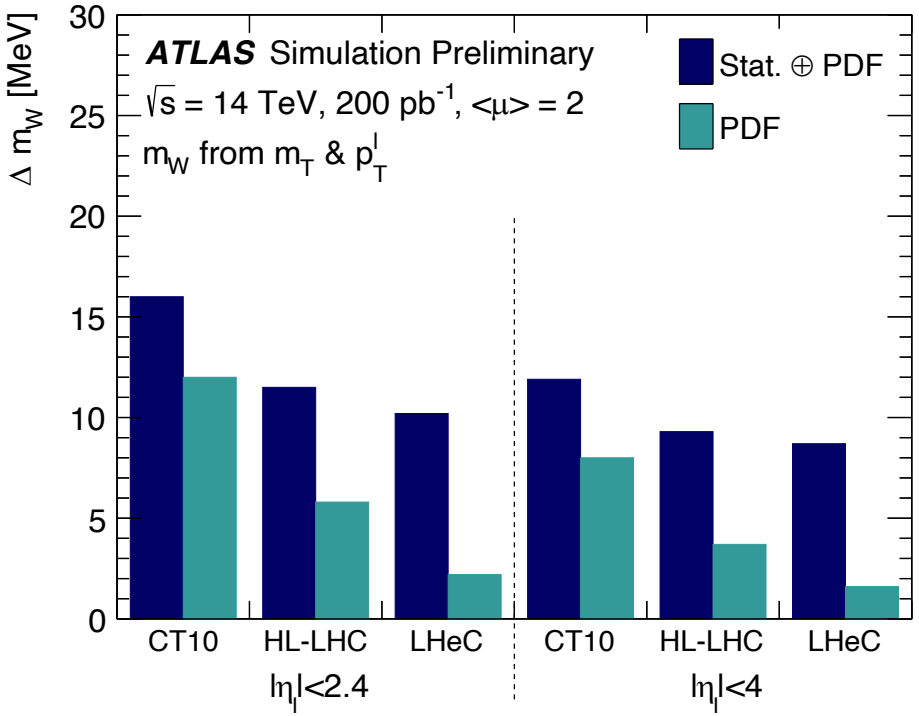


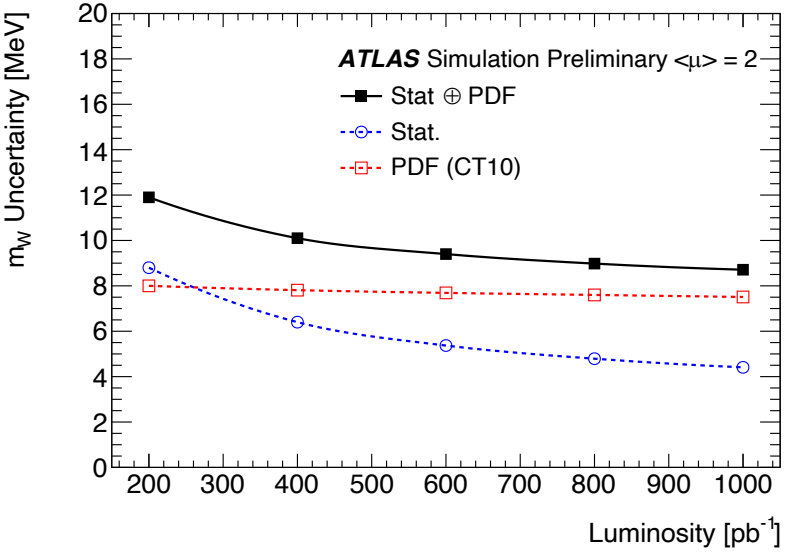
Precision W Boson Mass Measurement

- Leverage extended η coverage of upgraded detectors in low-lumi run
  - Still gives 10^6 W events in 1 week!
- Detector effects in m_T and p_T^{lepton} are dominated by recoil resolution

ATL-PHYS-PUB-2018-026



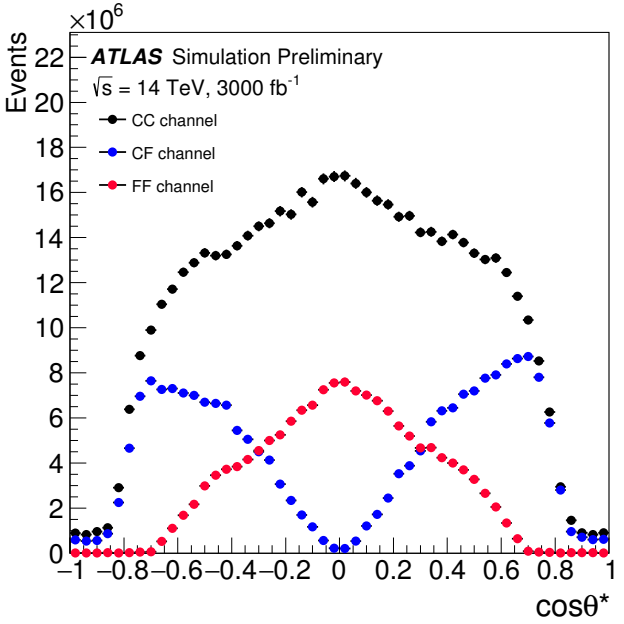


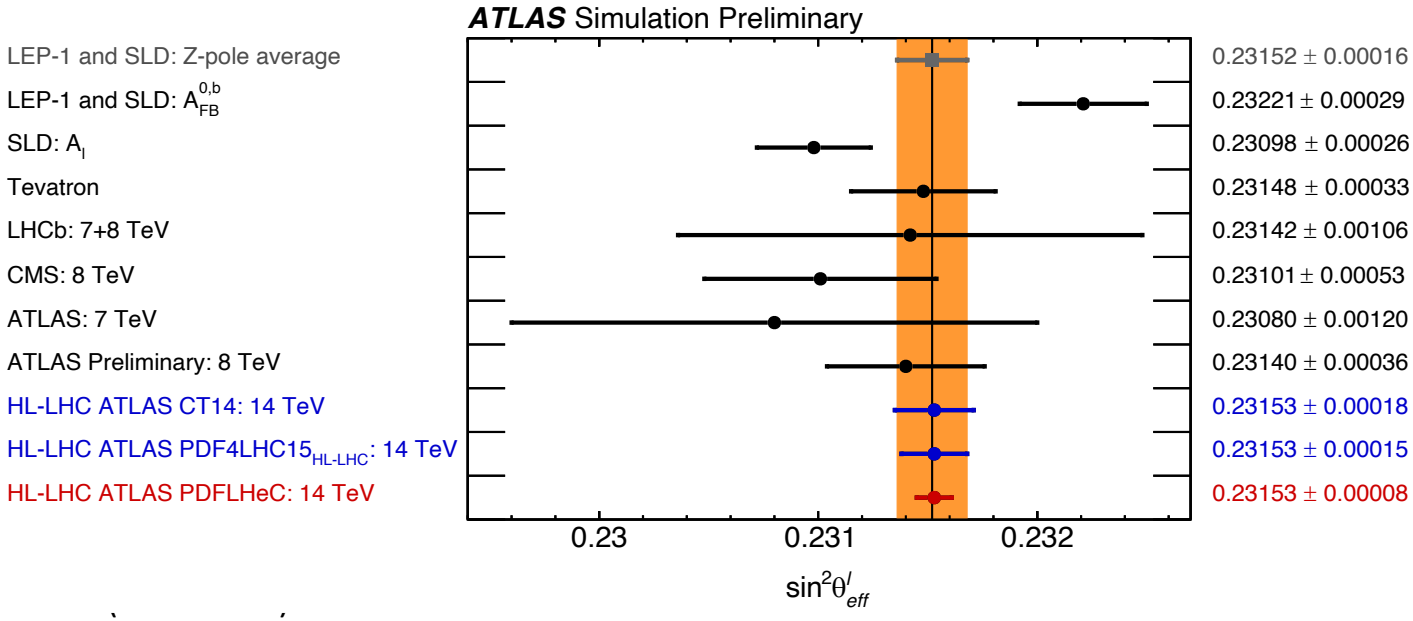


Precision $\sin^2\theta_W$ Measurement

ATL-PHYS-PUB-2018-037

- Z boson forward-backward asymmetry
  - Resolve discrepancy with SLD measurement
  - Relies on valence/sea quark momentum differences, upgraded detector acceptance
  - Ultra-high statistics electron sample uses timing information to reject tracks from pileup vertices
- Final result depends crucially on PDF uncertainties achieved at 14 TeV

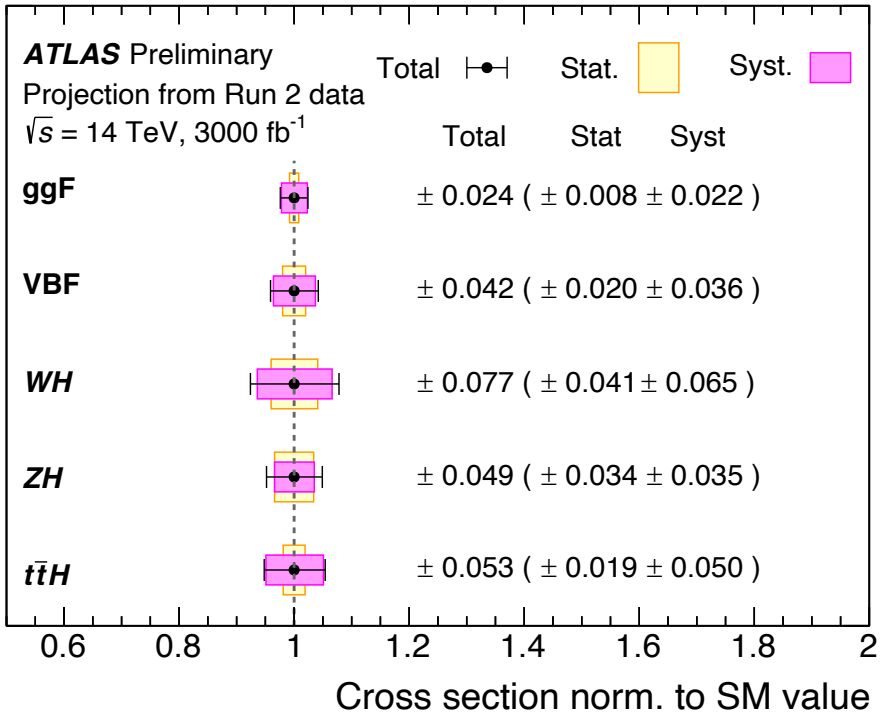


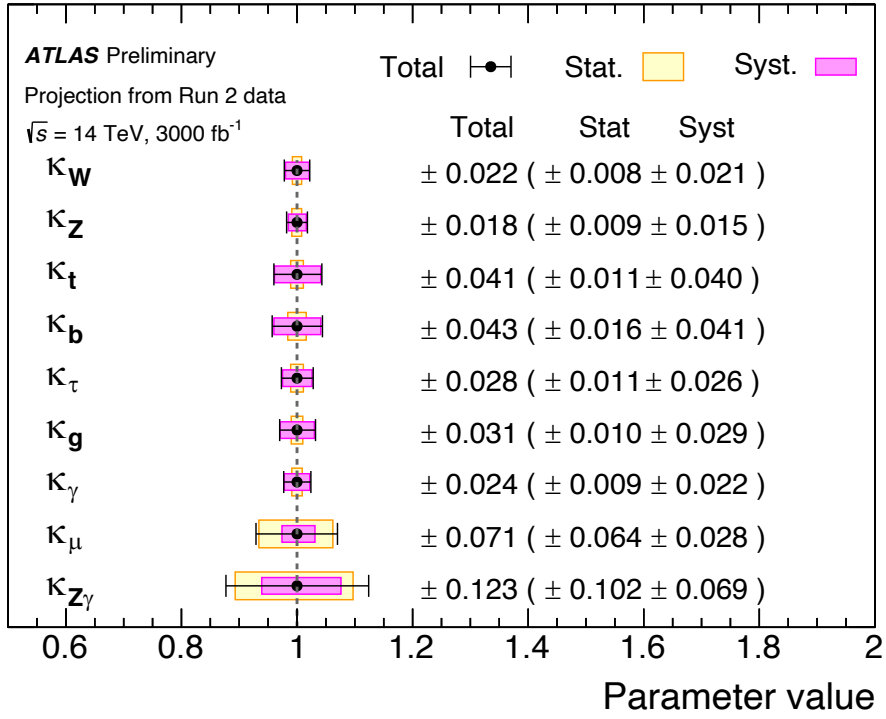


Higgs Boson Coupling Measurements

ATL-PHYS-PUB-2018-054

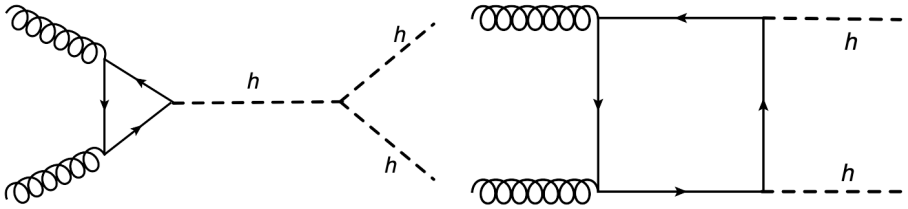
- Cross section measurements improve with high statistics
  - Projections assume systematic and theory uncertainties will be halved
- Measurements re-interpreted in coupling modifier κ framework
  - All of those couplings are constrained at the 2-7% level
  - Even μμ and Zγ couplings can be constrained at HL-LHC





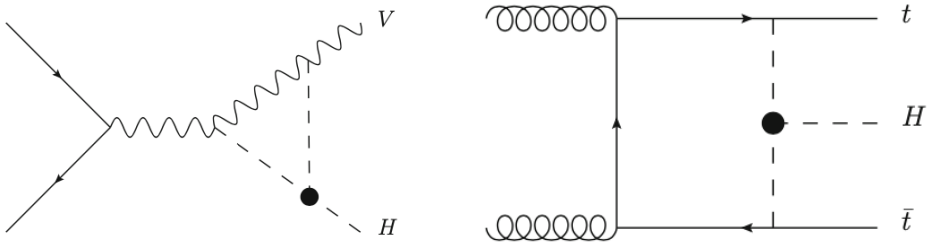
Higgs Boson Self Coupling

- Experimental access to the Higgs potential: is it the SM V(ϕ)?
  - May give hints of BSM physics with consequences for fate of universe!
- Directly accessible through HH production



But with destructive interference between diagrams

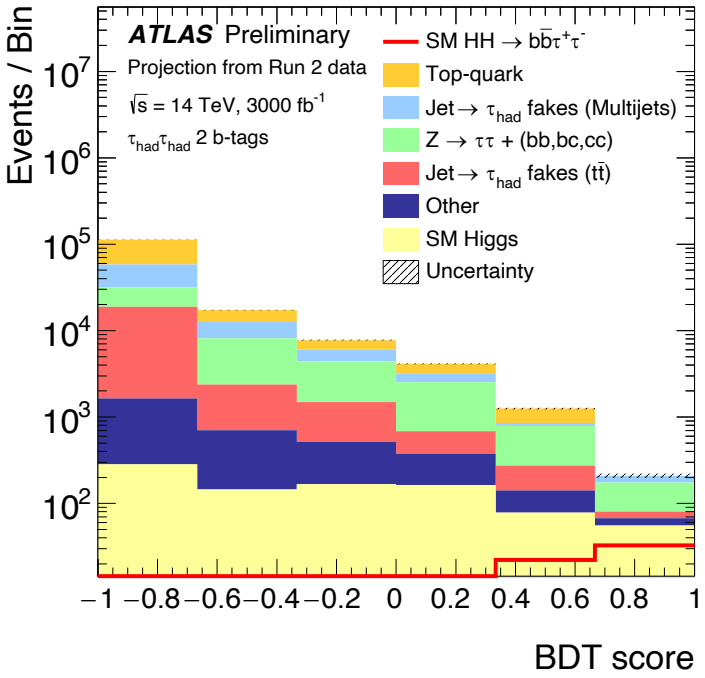
- But also indirectly through single Higgs production

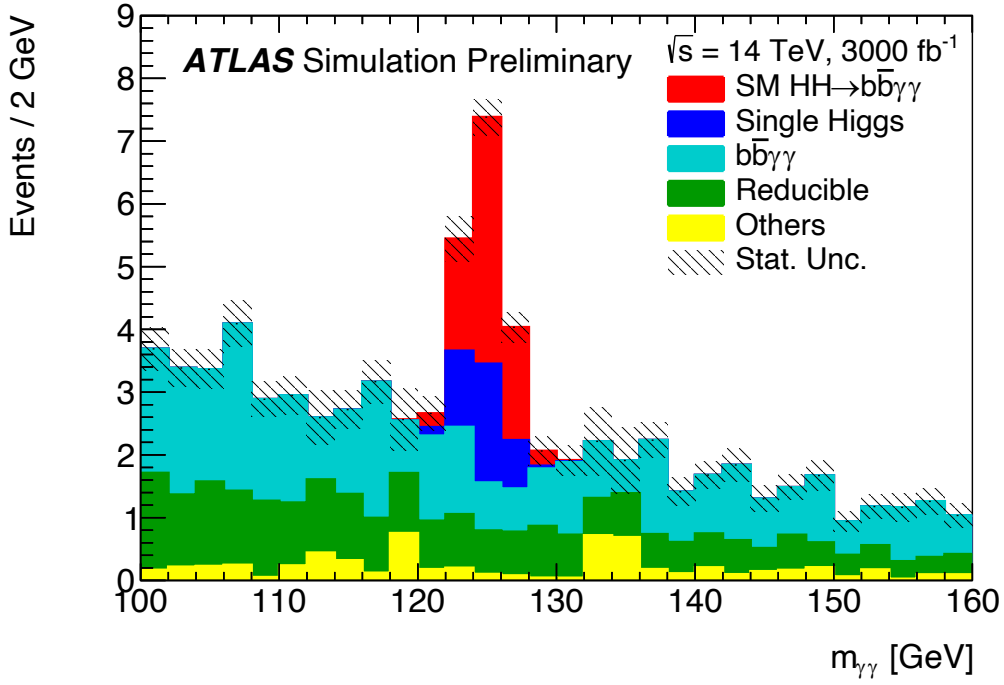


- Currently both approaches are used to constrain the coupling λ_{HHH}.
  - κ_{HHHH} will not be constrained at LHC or HL-LHC

HH Production Measurements

- Currently, ATLAS combined upper limit: 10 x SM [ATL-PHYS-PUB-2018-053]
- Most sensitive channel: bbττ uses fit to BDT score by category
- Second channel: bbγγ analysis w/ parameterized simulation: fit m_{HH}
- Third channel: bbbb result suffers large syst. uncertainties



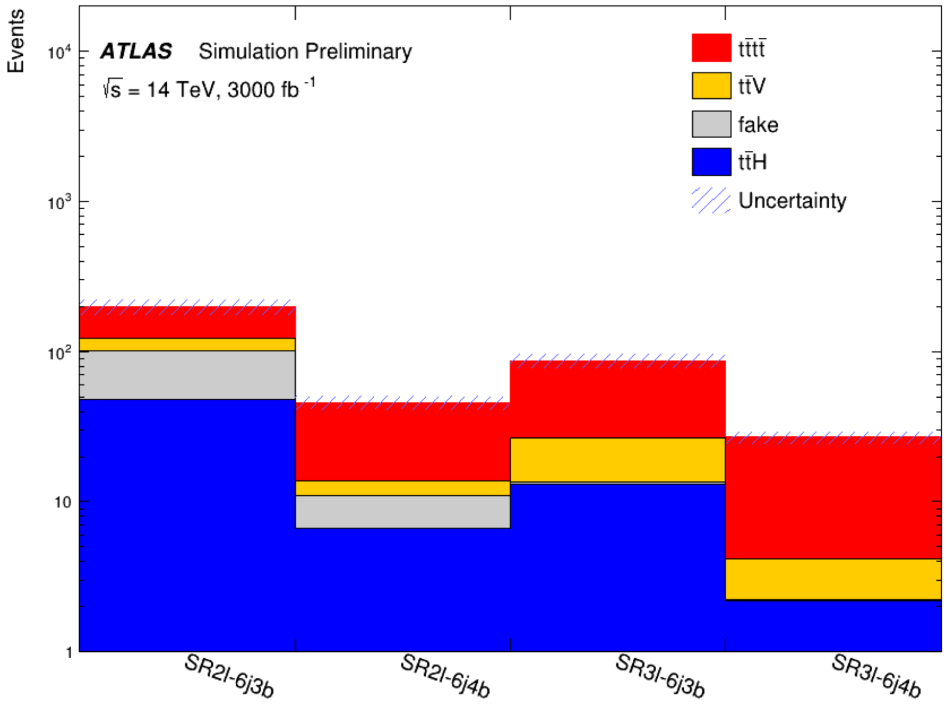


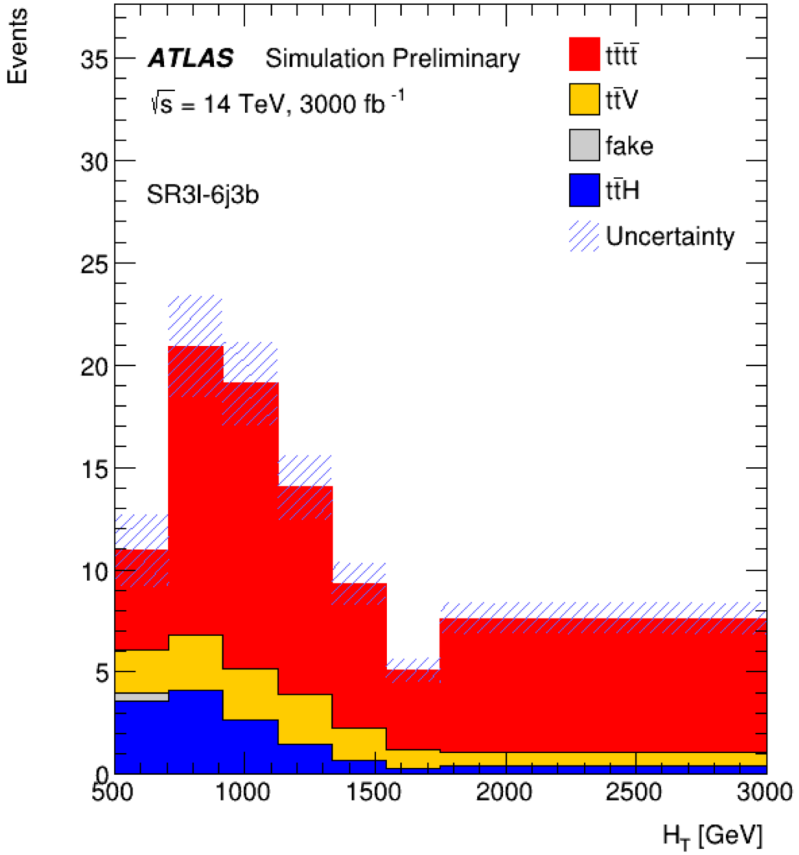
- ATLAS/CMS combination in arXiv:1902.00134: ~4σ for SM HH

Four-Top-Quark Production

- Recent ATLAS evidence for rare process (σ=16 fb)
  - Potential for BSM contributions, even DM mediators
- Define event categories based on number of jets, lepton, b-jets
  - Likelihood fit to H_T distributions
- Expect 11% precision on σ at HL-LHC

arXiv:2007.14858
ATL-PHYS-PUB-2018-047
ATL-PHYS-PUB-2018-027

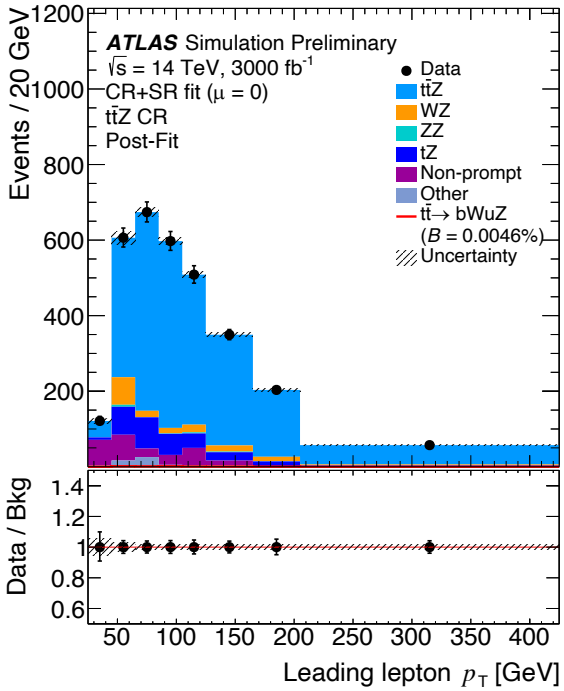


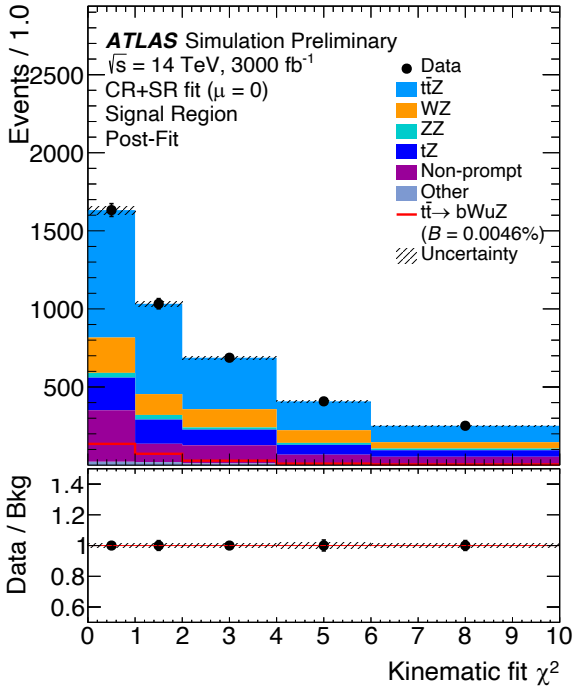


Searches for Top Quark FCNC Decays

- FCNC B(t →qZ)=10^{-14} in SM, but can be enhanced [ATL-PHYS-PUB-2019-001]
  - Quark-singlet model predicts values as high as 10^{-4}

- Kinematic fit tests compatibility with $t\bar{t}$ hypothesis
- Likelihood fit to lepton p_T in CRs and kinematic χ^2 in SR





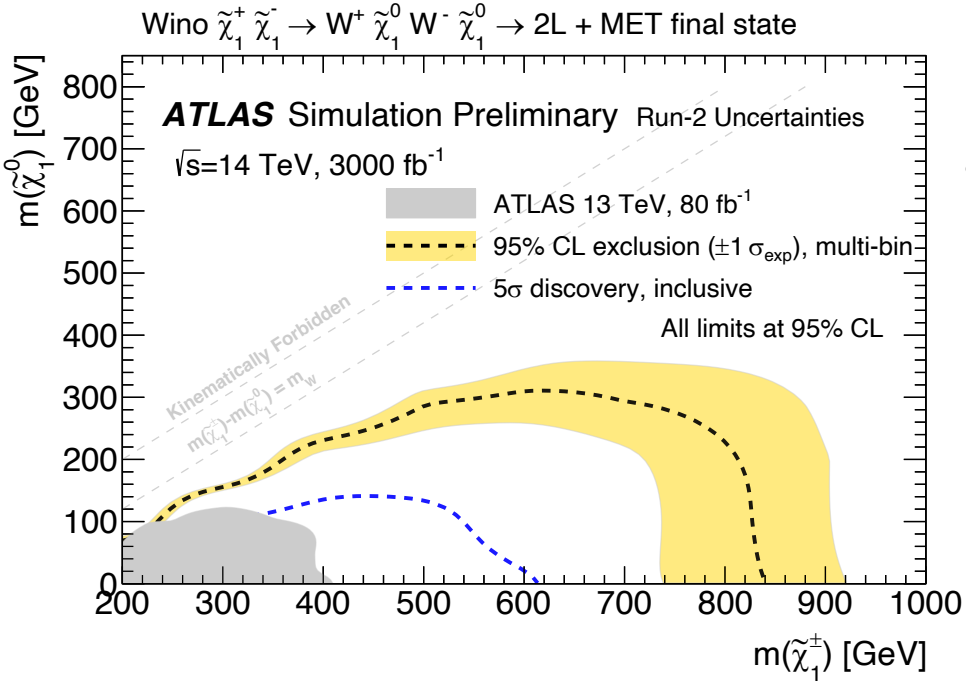
	-1σ	Expected	+1σ
$\mathcal{B}(t \to uZ)$	4.9×10^{-5}	6.9×10^{-5}	9.7×10^{-5}
$\mathcal{B}(t \to cZ)$	5.8×10^{-5}	8.1×10^{-5}	12×10^{-5}

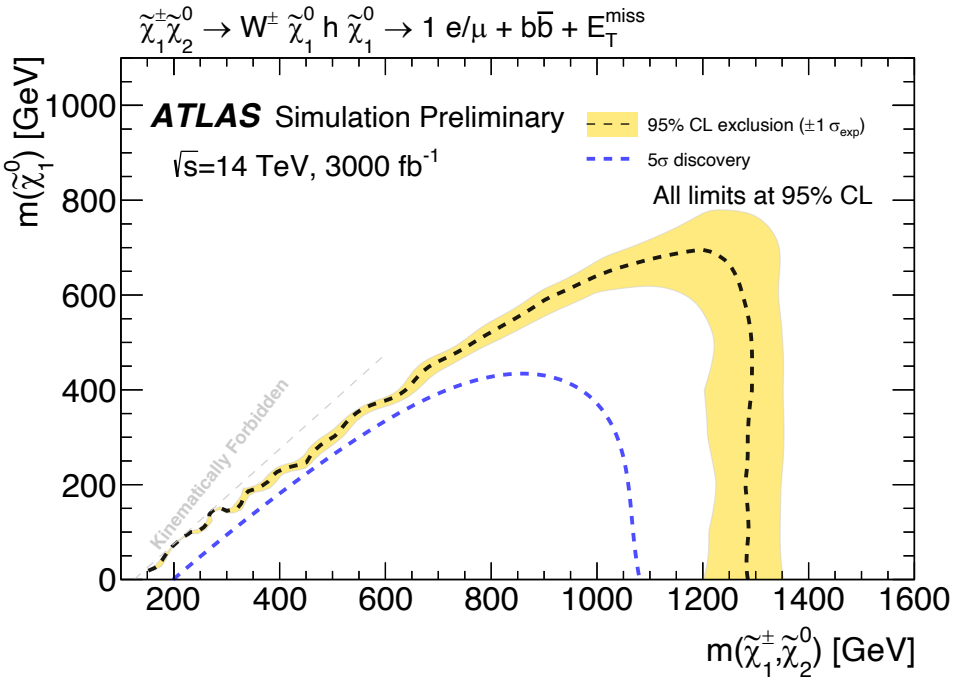
Compared to 10^{-6} in 2HDM, 10^{-5} in RS theories

Electroweak Supersymmetry Searches

ATL-PHYS-PUB-2018-048

- High-statistics HL-LHC dataset: an opportunity to test the TeV mass scale for electroweak SUSY, even for lowest cross sections
- Projections with full b-tagging simulation & realistic uncertainties



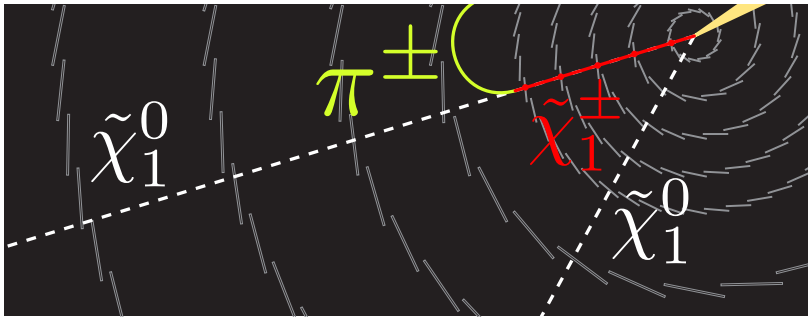


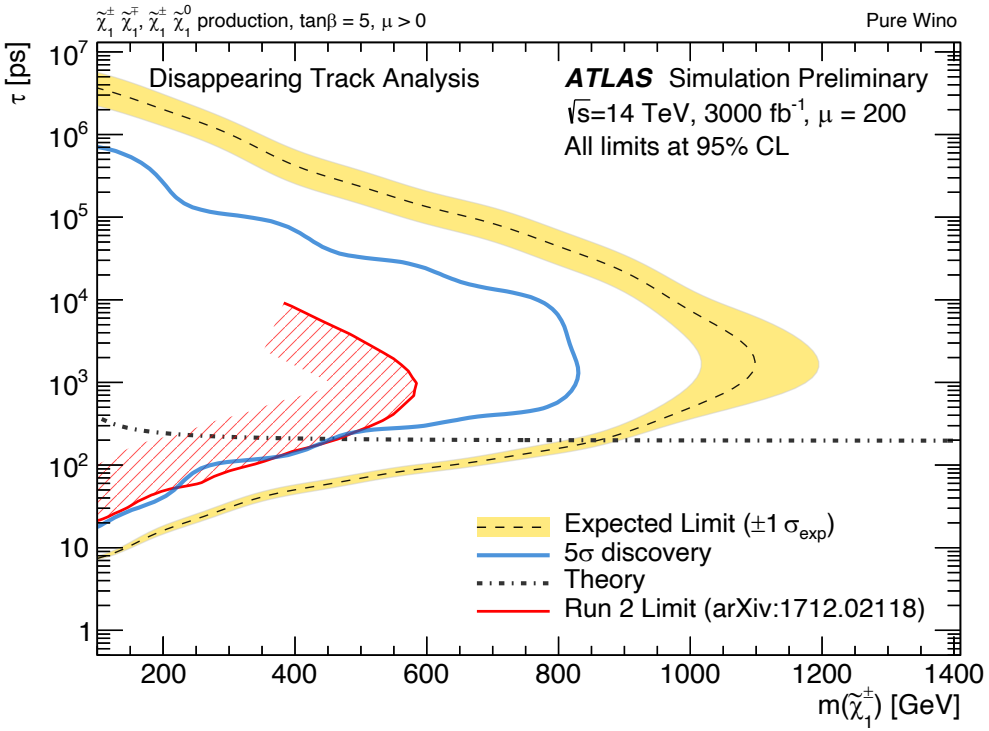
- Largest gains in statistics-limited searches with tight selections

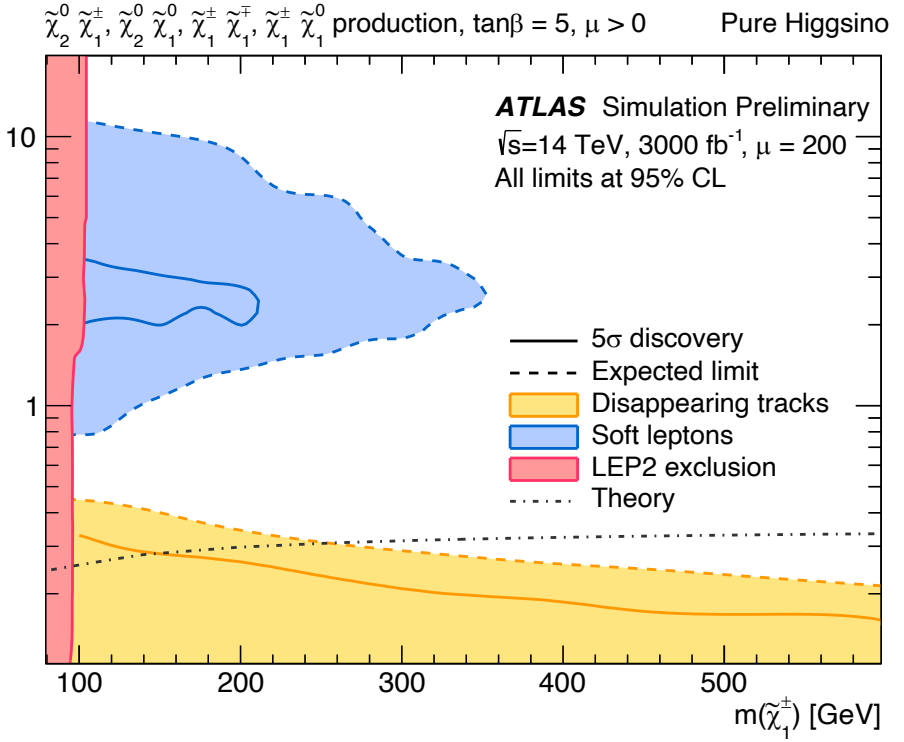
Compressed SUSY Searches

ATL-PHYS-PUB-2018-031

- Small χ_2^0/χ_1^0 mass splitting leads to soft leptons (down to p_T = 3 GeV)
- Tiny χ^+/χ^0 mass splitting leads to macroscopic χ^+ decay length, as a disappearing track





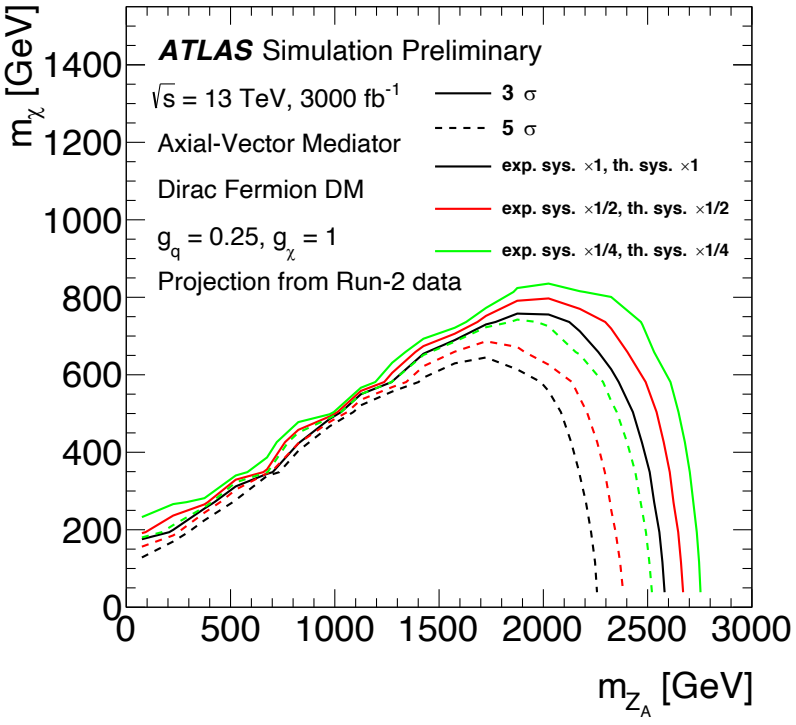


Dark Matter Searches

Jet + E_T^{miss} signature

ATL-PHYS-PUB-2018-043

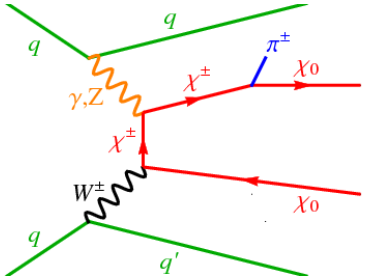
- E_T^{miss} as discriminating variable
- Even greater improvement expected with √s increase

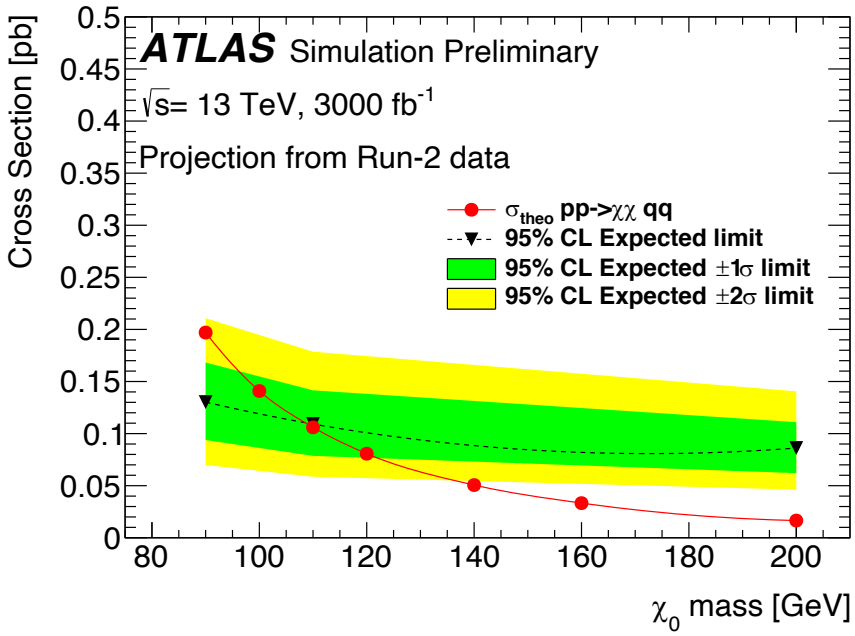


VBF + E_T^{miss} signature

ATL-PHYS-PUB-2018-038

- Context of electroweak fermionic triplet model

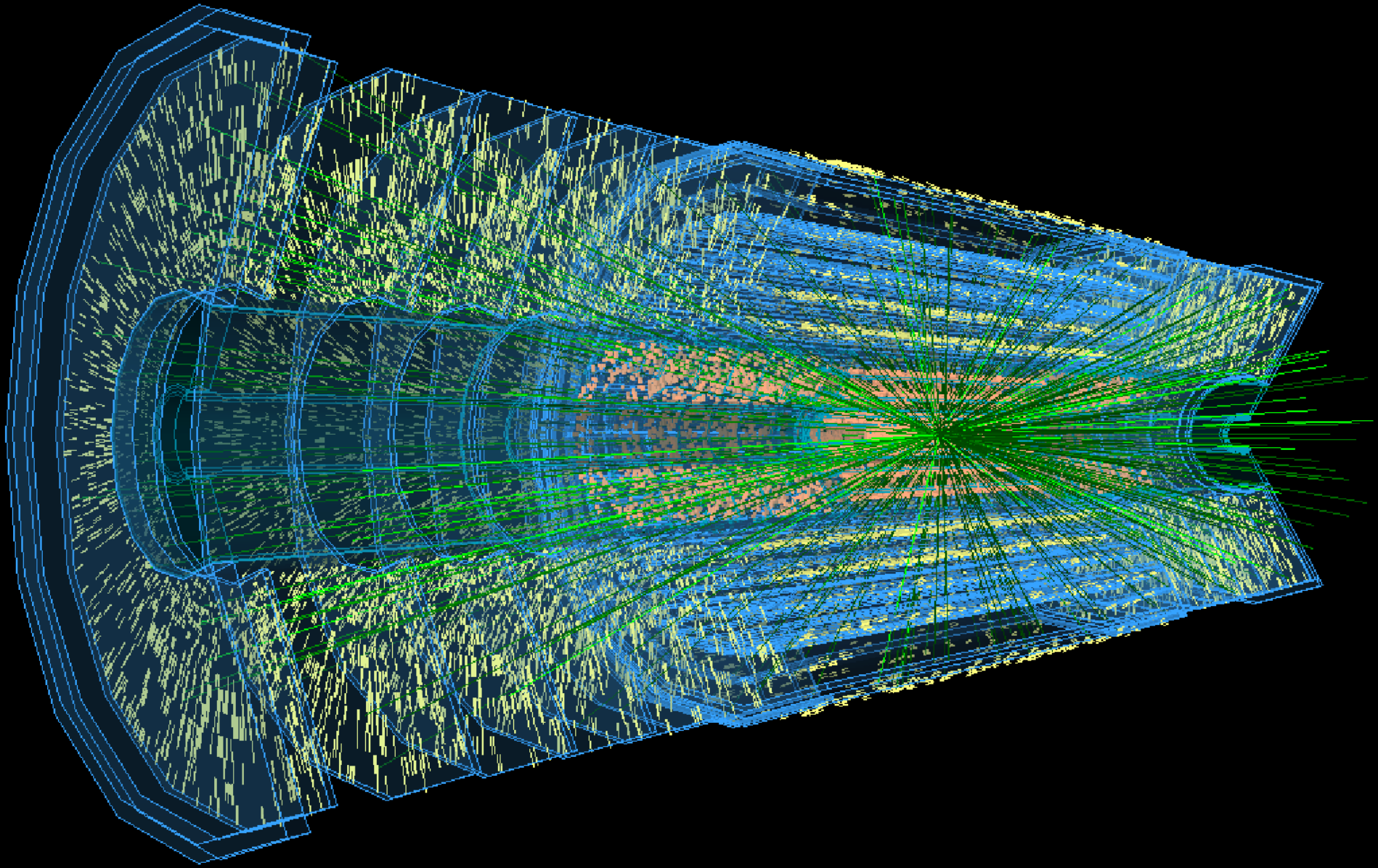




Summary and Conclusions

- ATLAS projects a broad and deep HL-LHC physics program
  - Precision Higgs, electroweak, and top measurements with large datasets
  - Improved PDF measurements with high lumi at 14 TeV
  - Searches for BSM physics, especially in small cross-section processes
  - High-density QCD studies in heavy-ion and pp collisions
- Detailed studies prepared both with full detector simulation and with extrapolated systematic uncertainties
- Challenging experimental conditions require new detector upgrade designs and improved reconstruction algorithms.
- These studies and improvements depend on continued progress in theoretical calculations and computational tools.

Already looking forward to 14 TeV data and lots of new data!



ATLAS HL-LHC Document Library

- More public ATLAS HL-LHC physics results available at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/UpgradePhysicsStudies

Other collections of HL-LHC studies

- High-Density QCD: arXiv:1812.06772
- Flavor Physics: arXiv:1812.07638
- BSM Physics: arXiv:1812.07831
- Higgs Physics: arXiv:1902.00134
- SM Physics: arXiv:1902.04070

Contributions to HL-LHC workshop

- Joint ATLAS-CMS addendum with collection of notes: arXiv:1902.10229 (Vol. 2 of Yellow Report)

ATLAS HL-LHC TDRs

- ITk Silicon Strips: https://cds.cern.ch/record/2257755
- Muon Spectrometer: https://cds.cern.ch/record/2285580
- LAr Calorimeter: https://cds.cern.ch/record/2285582
- Tile Calorimeter: https://cds.cern.ch/record/2285583
- ITk Silicon Pixels: https://cds.cern.ch/record/2285585
- High-Granularity Timing Detector: https://cds.cern.ch/record/2719855