Electroweak physics at the HL-LHC

Ultimate reaches and challenges

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ECFA WHF WG1

22 April 2022

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~~*Ultimate reaches*~~ *and challenges*

Reaches as currently estimated

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From HL-LHC to future colliders

- The success of the HL-LHC is a necessary condition for any future collider
  - LHC has been a tremendous success in discovering the Higgs boson and crystalizing the SM at our accessible energy scales
  - HL-LHC has the potential to break the SM paradigm and guide future explorations for BSM
    - Direct searches and SM measurements go hand-in-hand
  - The success of the HL-LHC will also demonstrate our ability as an international community to come together and accomplish a broad-spectrum and unique cutting-edge research
  - All international HEP planning processes (ESG, Snowmass etc.) are informed by the LHC results and any decision making is guided by LHC findings
- It is our responsibility to harvest the wealth of data that we expect at HL-LHC
  - No theoretical guidance of where new physics may hide → we have to rely on experimental data for such guidance
  - More tantalizing anomalies are popping up in precision measurements, e.g. W mass, rare processes, g-2

    ➔ HL-LHC can shed light to several of these anomalies

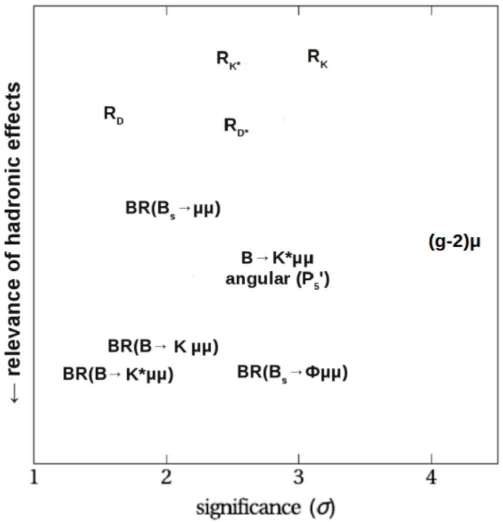
    ➔ We may expect more of anomalies at HL-LHC, thanks to larger datasets, higher reach in energy scales, and higher precision measurements

From HL-LHC to future colliders

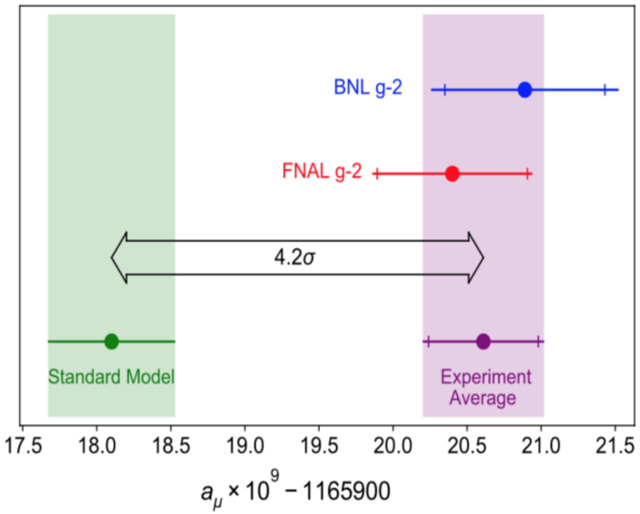
- Guidance to BSM will come from direct searches, and systematic tests of the SM paradigm

LHCb Flavour anomalies

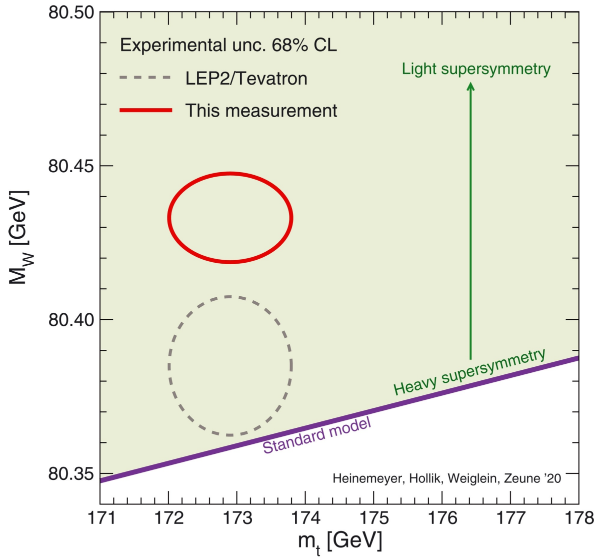
by Wolfgang Altmannshofer



g-2 anomaly



CDF II W mass



Prospects studies for HL-LHC

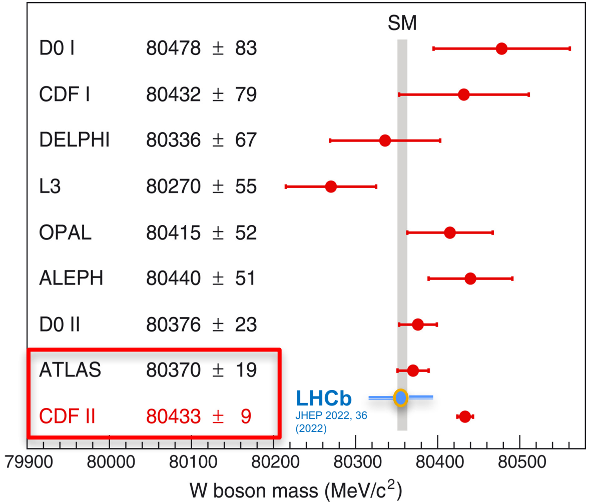
- LHC Collaborations have carried out several studies for the European Strategy (Yellow Report) and the US HEP planning (Snowmass)

- Snowmass Update in 2022:
  `ATL-PHYS-PUB-2022-018`
  `CMS PAS FTR-22-001`
- Yellow Report in 2018:
  `https://arxiv.org/abs/1902.04070`

- Electroweak measurements are the next frontier of precision physics
  - Low cross sections of EW processes benefit from the large HL-LHC dataset to go beyond the simple process observations
    - Detail studies of production properties, e.g. differential cross sections
    - Higher reach in energy scales, e.g. tails of distributions
    - Constraining of BSM scenarios
  - HL-LHC will enable currently unachievable measurements
  - Detector upgrades will allow for better forward jet and lepton reconstruction, essential to improve current measurements
  - Sophisticated analysis techniques (e.g. ML) are necessary to extract as much information as possible

W mass

- W mass is a key parameter of the standard model
  - 7.0 σ deviation from SM in latest CDF II measurement
- Precise W mass measurements at HL-LHC will be very important
  - To confront CDF measurement: ≤ 10 MeV precision is needed
  - To confront SM prediction: ≤ 6 MeV precision is needed (80,357 ± 6 MeV)



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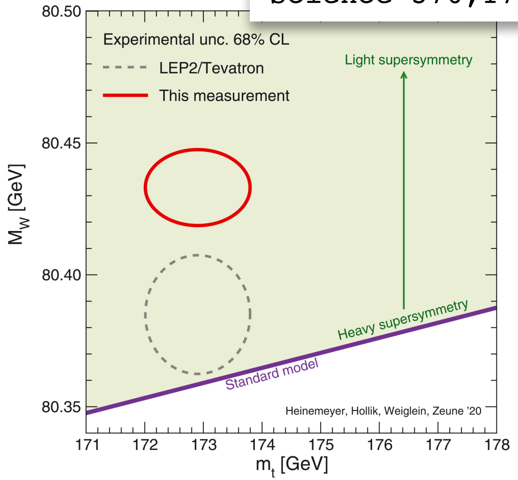
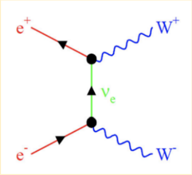


Lepton Collider Uncertainties on M_W :

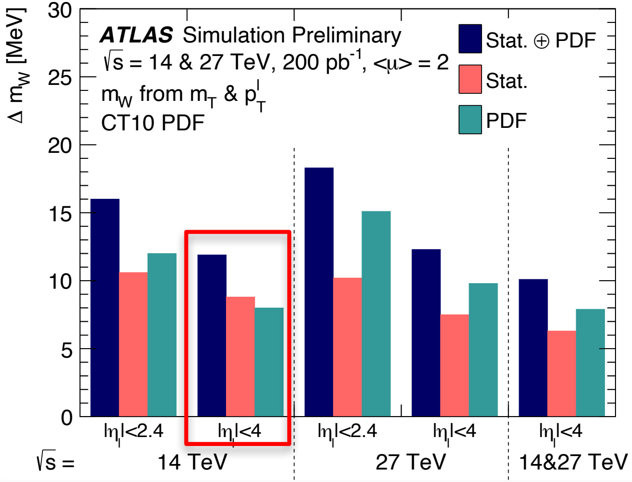
- **FCC-ee expected: ± 0.5 MeV**
  - WW threshold: ~10^8 WW boson pairs
  - scan of σ(WW) lineshape at √s= 157.5-162.5 GeV
- **ILC expected: ± 2.5 MeV**
  - combination of 5 complementary methods

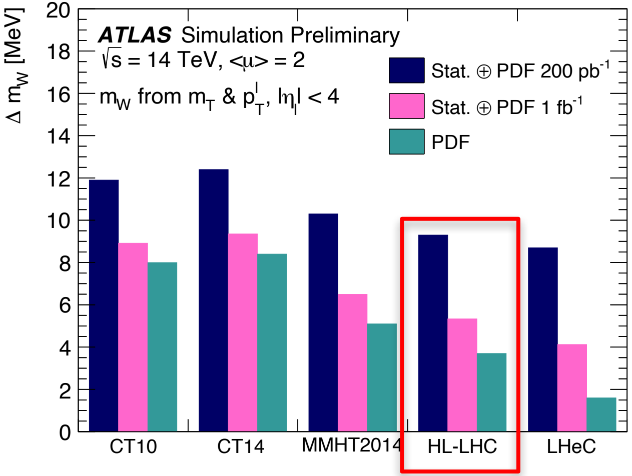


W mass at HL-LHC

- ≤10 MeV uncertainty at HL-LHC is challenging but achievable with exp. and theory improvements
  - Need to improve theoretical modelling (PDF, W p_T)
    → exploit extended lepton rapidity ($|\eta|<4$) and ancillary measurements (W, Z cross sections and p_T)
  - Special accelerator runs with low pileup (μ~2) to precisely measure missing energy, and collect at least $2x10^6$ W events (200 pb^{-1})

➔ ~5 MeV is a possible target with ≳ 1 fb^{-1} of low pileup data





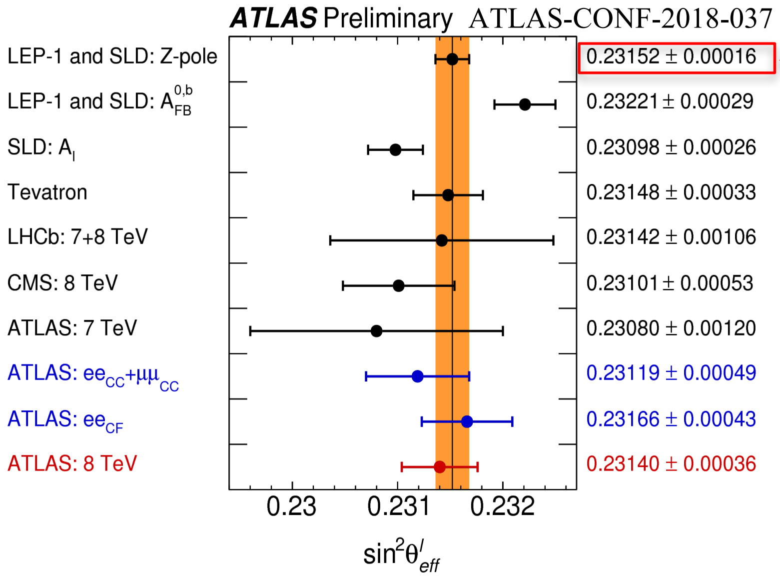
Experimental uncertainties not included (expected to be at the level of stat uncertainty)

Weak Mixing Angle

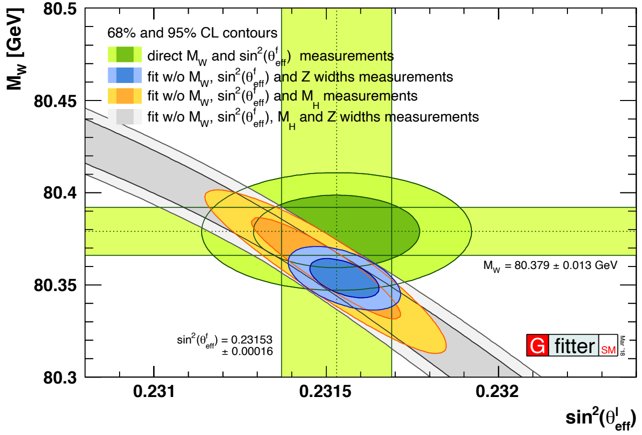
- Weak Mixing angle is another fundamental SM parameter
- Closely related to other SM parameters, e.g. W mass

$\sin^2\theta_W = 1 - M_W^2/M_Z^2$ Tree-level

$\sin^2\theta_{\rm eff}^{\rm f} = \kappa_{\rm f}\sin^2\theta_W$ w/ EW HO corrections



3σ tension b/w SLD and LEP



Lepton Collider Uncertainties on $\sin^2\theta_{W,eff}$ [x10^{-5}]:

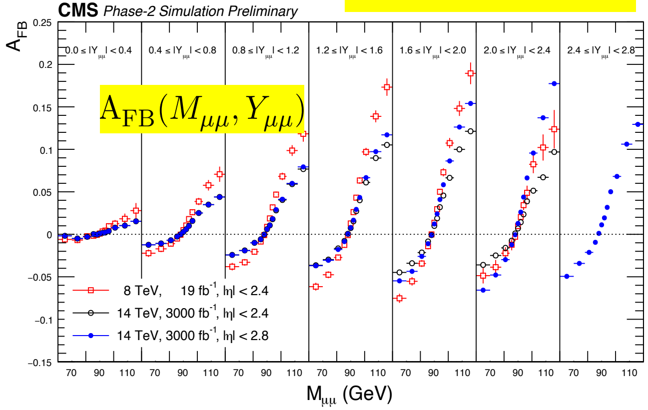
- LEP+SLD Combination........±16
- ILC Z pole - expected...........± 0.95
- FCC-ee Tera-Z - expected ....± 0.20

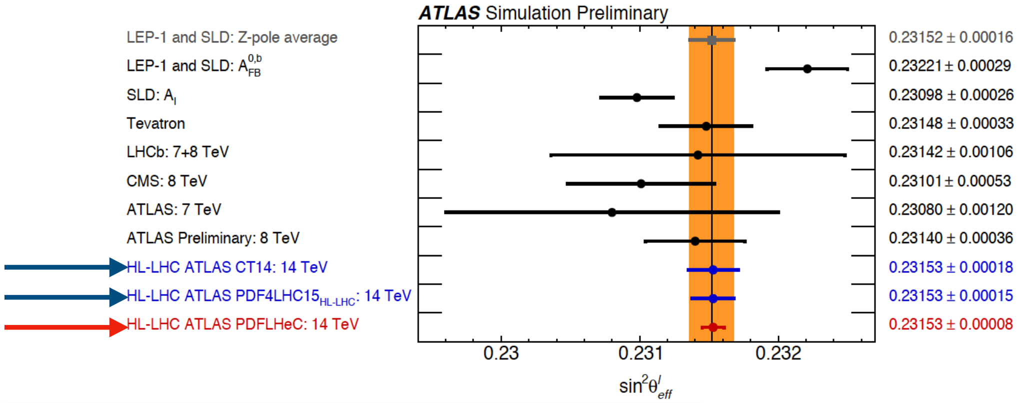
Weak Mixing Angle at HL-LHC

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

- The Weak Meeting angle is extracted from Forward-Backward Asymmetry in Drell-Yan events
  - Prospects analyses for HL-LHC done by **ATLAS, CMS and LHCb**
  - Essential to reduce PDF uncertainties, using ancillary measurements and in situ PDF profiling
  - Acceptance extension to higher lepton rapidity reduces PDF and stat uncertainties (extended trackers and fwd reconstruction with LHCb)

➔ Expected **HL-LHC precision similar to LEP+SLD combination**





Error projections (x10⁻⁵):

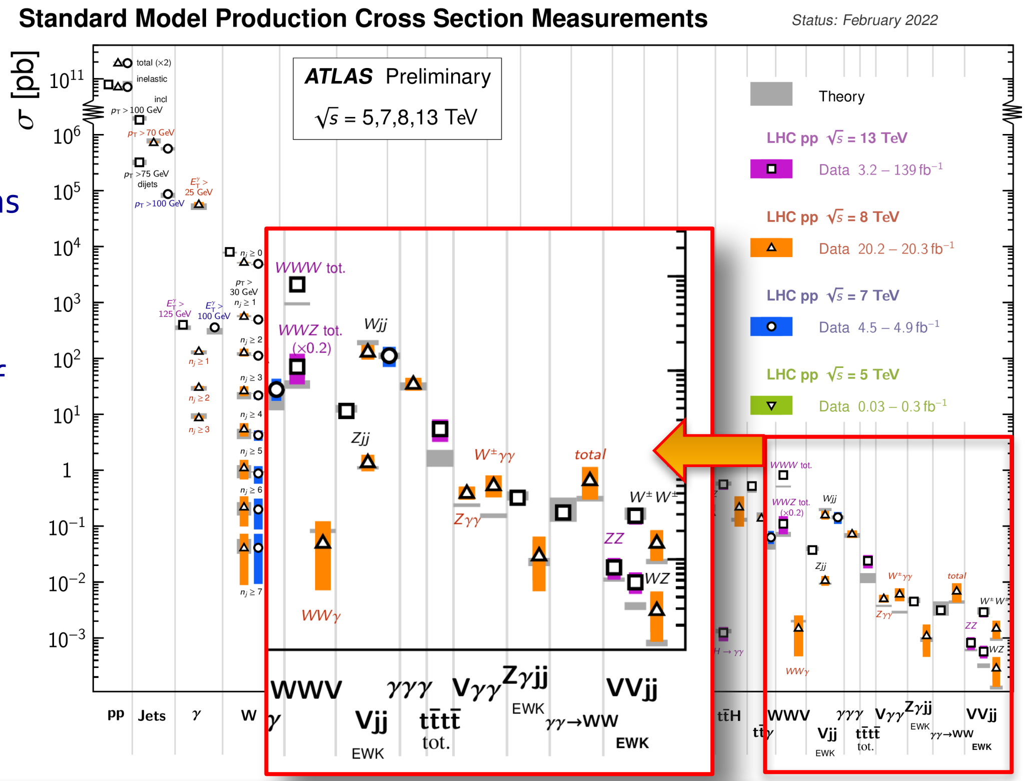
➔ **LHCb:** 5 (stat at 300 fb^{-1}), 10 (PDF)

➔ **CMS:** 3 (stat at 3000 fb^{-1}), 12 (PDF)

➔ **ATLAS:** 4 (stat at 3000 fb^{-1}), 13 (PDF), 5 (exp)

Multiboson production

- SM is very prescriptive on di- and multi-boson interactions
- Small and significant deviations from SM predictions in precision measurements would suggest new processes entering at loop level and produce anomalous triple or quartic gauge couplings
- LHC has already started a thorough investigation of multiboson production
  - Vector Boson Scattering (VBS) W±W±, W±Z, ZZ, Zγ,
  - WWV, Vγγ etc.
- Low cross-section processes that benefit from
  - Large HL-LHC dataset
  - HL-LHC detector upgrades enabling forward lepton reconstruction and pileup rejection in forward jets



VBS W±W± and W±Z at HL-LHC

- Same sign W±W± is the golden Vector Boson Scattering channel thanks to high S/B ratio
- ATLAS (CMS) expect to measure the EW production cross-section to 6% (3%) with 3000 fb^{-1} in the fully leptonic final state
- CMS: <8% precision in W±Z cross-section measurement achievable with 3000 fb^{-1}
  - Simultaneous measurement in CMS of EW W±W±, EW W±Z, and QCD W±Z
  - Binned maximum-likelihood fit of several distributions sensitive to these processes

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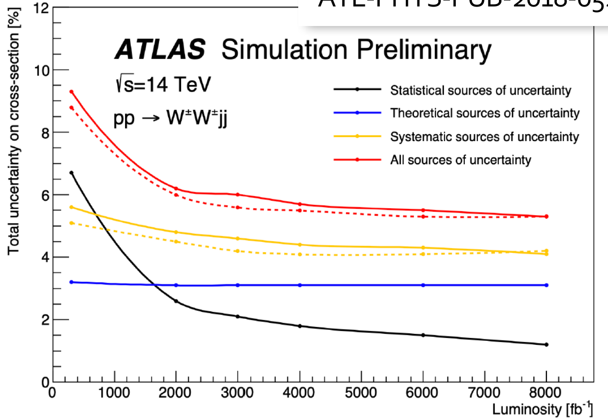

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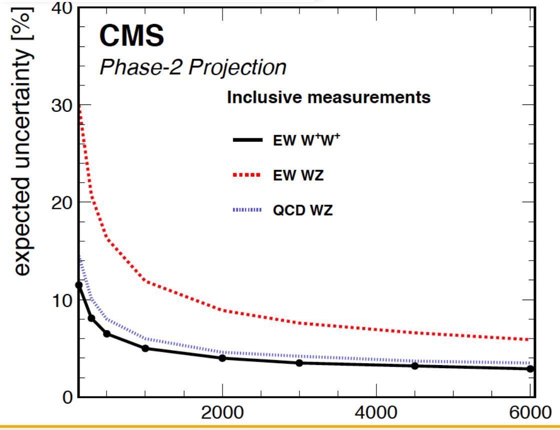
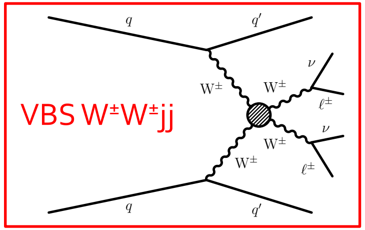
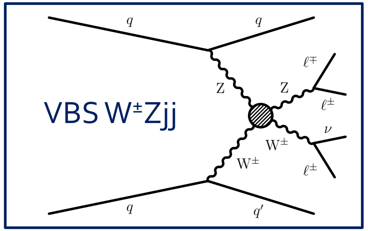
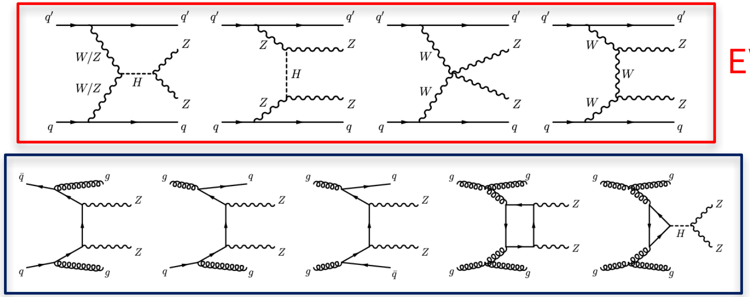




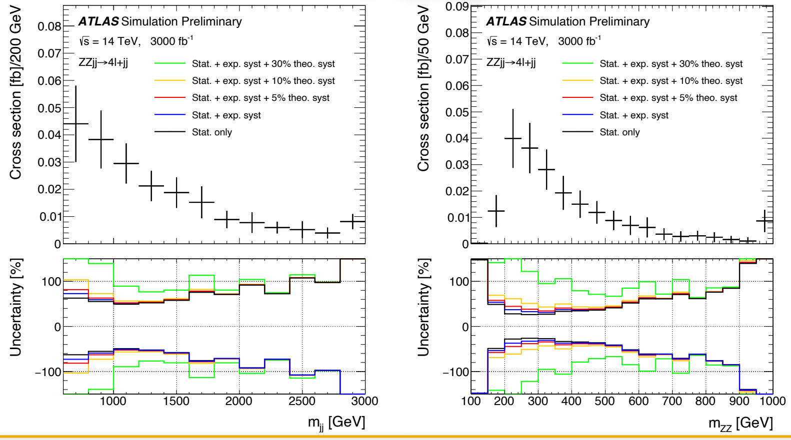


VBS ZZ at HL-LHC

- VBS ZZ is low cross section, but clean final state and possible reconstruction of the 4-lepton invariant mass
  - Observation of EW ZZ production at LHC with 5.5 σ significance
- Measurement precision depends on the modeling of QCD ZZjj processes
  - At HL-LHC statistical uncertainty (≲10%) subdominant wrt experimental systematics and theory modeling
    - Cross section uncertainty can reach 10-20% precision depending on background uncertainty

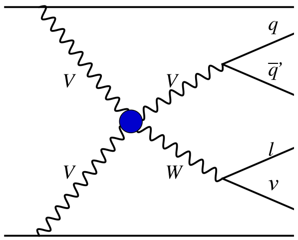


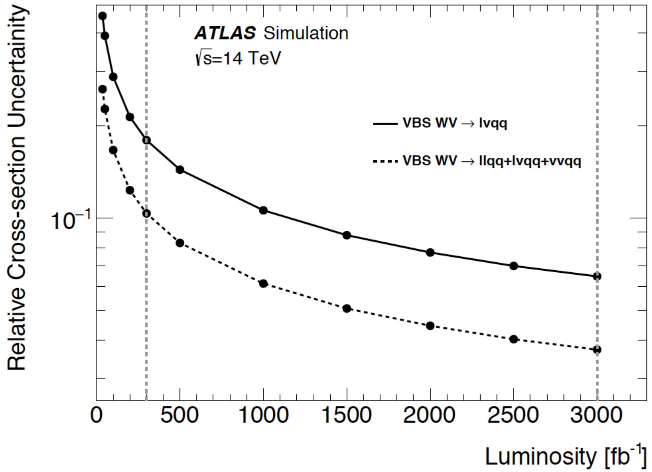
$$\sigma = \frac{N_{\text{pseudo-data}} - N_{\text{QCD}-ZZjj}}{L * C_{\text{EW}-ZZjj}}$$



Semileptonic VBS VV at HL-LHC

- Semileptonic VV final states are affected by larger background, but typically provide more stringent limits on anomalous couplings thanks to the larger branching ratios, thus higher event yield, and higher reach in energy scales
- Expected precision of 6.5% with 3000 fb^{-1} in semileptonic VBS WV→lνqq channel
- Greater precision (<3%) is reached when multiple channels are combined
  - Jet substructure technique necessary to control pileup
  - Multivariate analysis used to discriminate signal from backgrounds (W+jets and ttbar)





Longitudinal polarization ($V_L V_L$) at HL-LHC

- VV production cross sections are unitarized in SM thanks to the Higgs boson
- The extractions of longitudinally polarized $V_L V_L$ components are important tests of the SM
- Cross-section for the longitudinally polarized state is small (6–7% of total cross-section), making this a challenging but important part of the HL-LHC physics program
  - Extraction of longitudinal polarization contribution in fits of event kinematics, e.g. $\Delta\phi(j,j)$, or using machine learning

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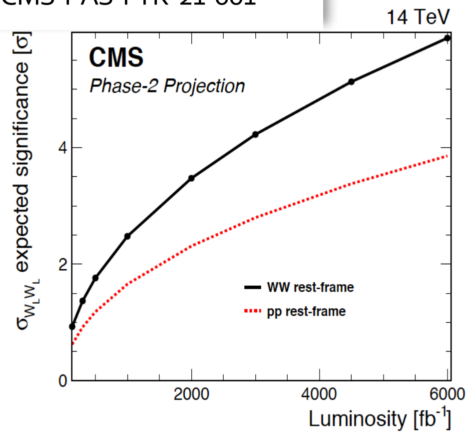


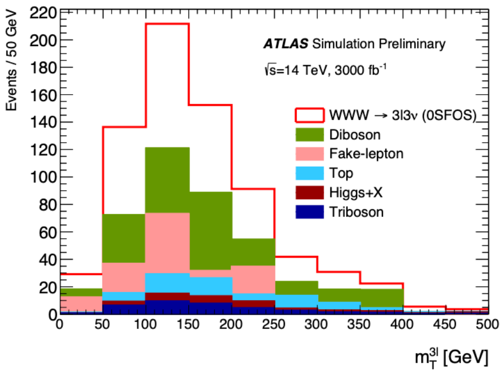
Longitudinally polarization the fully leptonic $W^{\pm}W^{\pm}$ final state

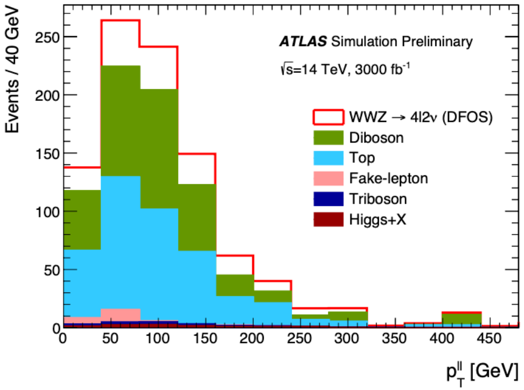
- Observation of $W^{\pm}_L W^{\pm}_L$ achievable by combining CMS and ATLAS measurements
- $W^{\pm}_L Z_L$ challenging: ~1.5σ sensitivity with 3000 fb^{-1} (ML techniques needed)
- In $Z_L Z_L$ 1.4σ is achievable with 3000 fb^{-1}

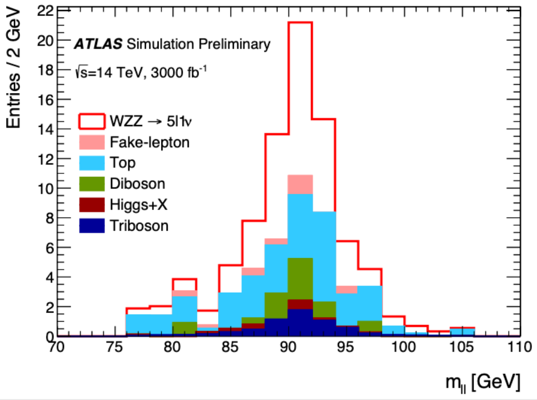
➔ Improving the sensitivity requires improved analysis techniques & combinations of results with several decay channels

Triboson production at HL-LHC

- HL-LHC offers a large improvement to multi-boson production

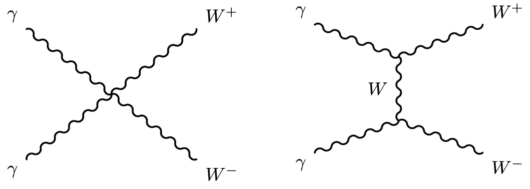




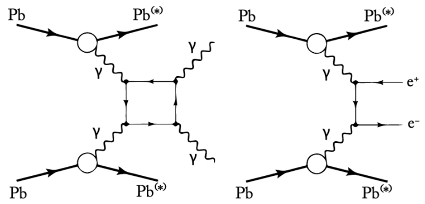


  - A cut-and-count projection study was performed
  - More sophisticated analysis techniques (ML) would significantly improve results
  - High level of background control (e.g diboson and instrumental background arising from fake-leptons) will be needed

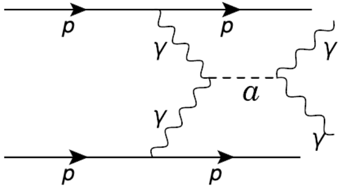
Photon-photon interactions



- Photon-photon interactions are very sensitive to anomalous triple and quartic gauge couplings
  - $\gamma\gamma \rightarrow \gamma\gamma$, $\gamma\gamma \rightarrow l^+l^-$, $\gamma\gamma \rightarrow VV$
  - clean signatures with no additional charged particles (tracks)
- Ongoing program at the LHC in pp and HI collisions
  - Light-by-Light scattering measured by both ATLAS and CMS in HI UPC
  - Observation of exclusive $\gamma\gamma \rightarrow$ WW production with 8.4 σ significance
- HL-LHC will increased statistical precision and will allow studies into the high-energy tails of the distributions
  - These are statistically limited processes that will benefit from larger datasets and improved trigger capabilities
- Sensitivity to BSM (e.g. axion-like particles)

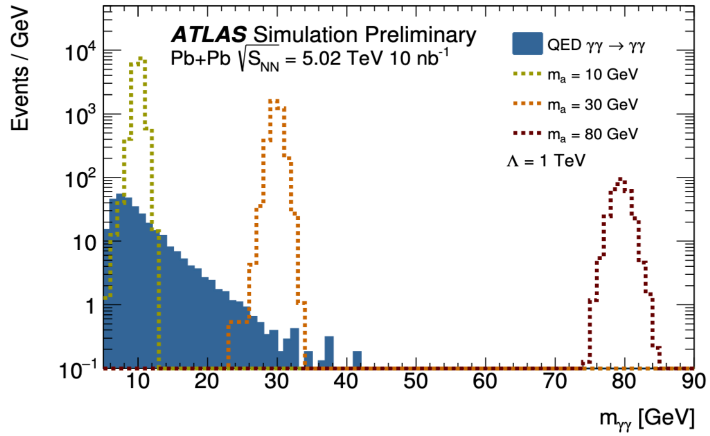


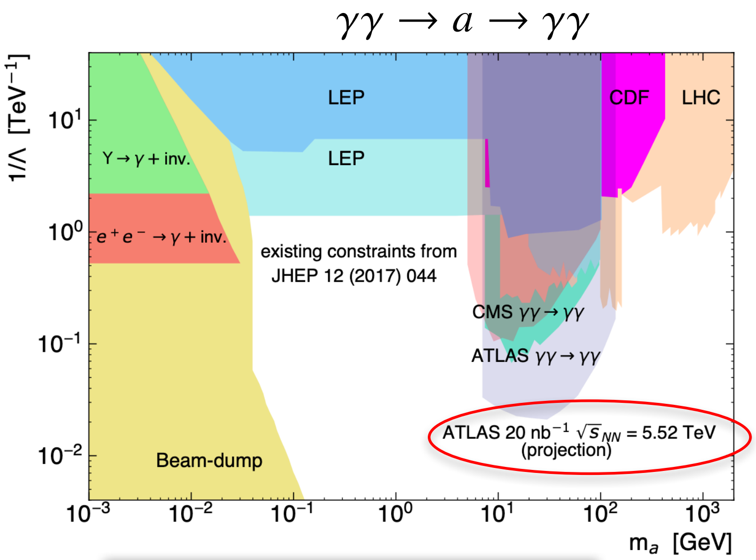
p-p collisions with p-tagging



Light-by-Light Scattering

- $\gamma\gamma \rightarrow \gamma\gamma$ has small cross-section $O(\alpha^4)$
- Special trigger and energy reconstruction (E_T<10 GeV)
- Sensitivity to BSM (e.g. axion-like particles)
  - Clean BSM signals over falling SM bkg
  - Light-by-Light interactions from Pb-Pb measured by both ATLAS and CMS already set the most stringent limits for m_a ~ 5 – 100 GeV and will improve with new data





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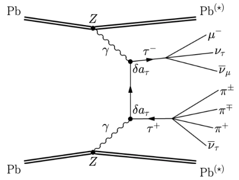
CMS PAS FTR-22-001

$\gamma\gamma \rightarrow l^{\pm}l^{\mp}$ in HI collisions

- UPC HI collisions provide a clean environment for $\gamma\gamma$-induced processes
- Exclusive production of dimuon pairs ($\gamma\gamma \rightarrow \mu^{\pm}\mu^{\mp}$) will be precision-like in HL-LHC
  - m_{dimuon}> 100 GeV, calibration of photon flux, constrain predictions for ditaus etc.
- $\gamma\gamma \rightarrow \tau^{\pm}\tau^{\mp}$ is sensitive to physics beyond the standard model: constraints on the anomalous magnetic moment of the τ lepton, currently known with poor precision from past lepton-lepton collider
  - 4x improvement wrt LHC measurements
  - Including more decay channels and improving analysis techniques, precision in anomalous magnetic moment of the τ lepton can surpass the existing lepton-lepton collider measurements



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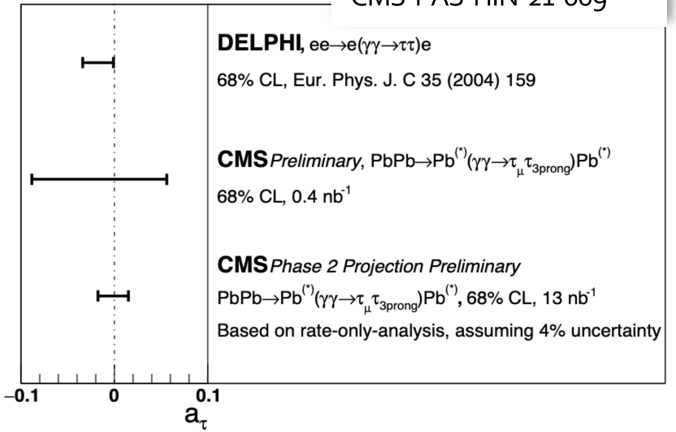

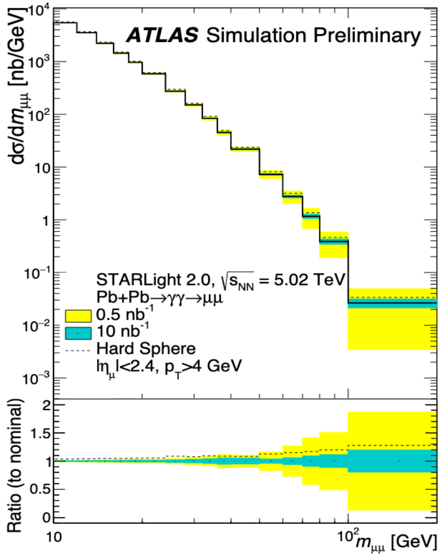

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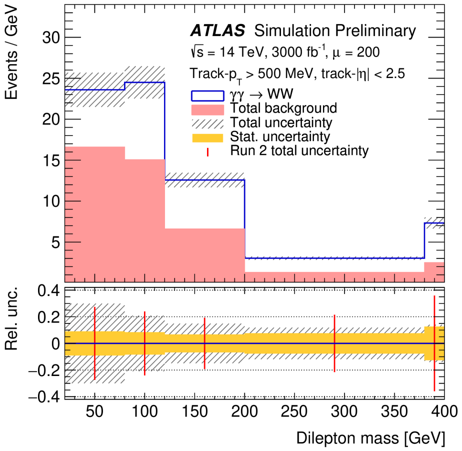
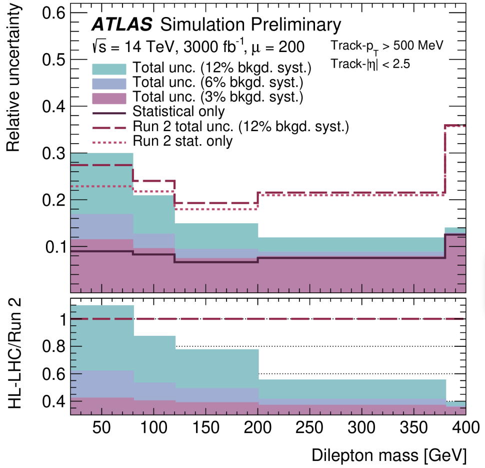
$\gamma\gamma \rightarrow W^{\pm}W^{\mp}$ in HL-LHC pp collisions

- HL-LHC prospect study for $\gamma\gamma \rightarrow W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu+\mu^{\mp}\nu$ is based on ATLAS Run-2 data analysis
  - Critical aspect of this analysis is impact of pileup
  - Improvements to track reconstruction will be important
    - Best performance is for central tracks, with a track p_T cut of 500 MeV
  - Background efficiency falls as dilepton mass increases → good for high-mass studies
  - HL-LHC analysis will have a reduced statistical uncertainty over what will be obtained from Run-2 and Run-3
  - Essential to reduce background modelling systematics to keep up with the increase in statistical precision



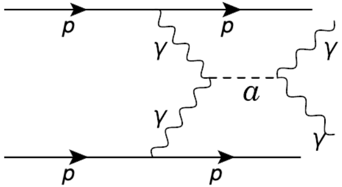


ATLAS-PHYS-PUB-2021-026

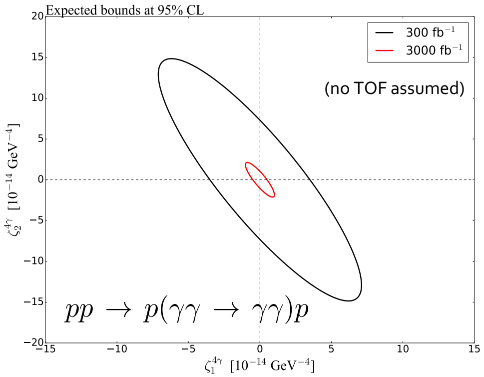
EW Physics with Forward p-tagging

- Central Exclusive Production to constrain anomalous quartic gauge coupling (dim-8 operators)
  - Peripheral (photon-induced) interactions
  - Clean environment with low QCD background at high-mass scales
  - Low cross sections → run in nominal HL-LHC running with tagged proton
  - Timing information (~10 ps) important to reduce background (pileup)

$pp \to p + X + p$ X = γγ, γZ, ZZ, ll, or BSM (ALP, Monopoles, SUSY)

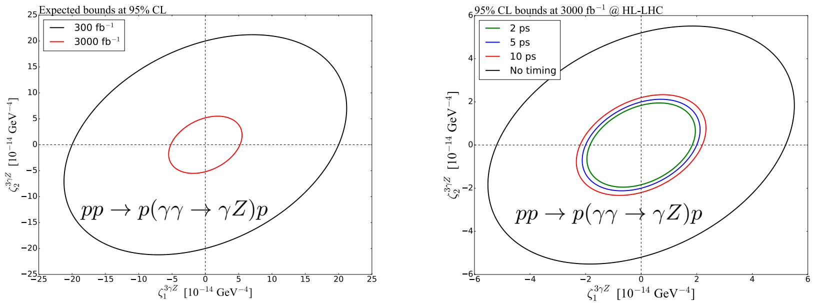


Light-by-light scattering → anomalous γγγγ quartic gauge coupling



$$\zeta_1^{4\gamma} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^{4\gamma} F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu}$$

γZ boson production → anomalous γγγZ quartic gauge coupling



$$\mathcal{L}_{\gamma\gamma\gamma Z} = \zeta_1^{3\gamma Z} F^{\mu\nu}F_{\mu\nu}F^{\rho\sigma}Z_{\rho\sigma} + \zeta_2^{3\gamma Z} F^{\mu\nu}\tilde{F}_{\mu\nu}F^{\rho\sigma}\tilde{Z}_{\rho\sigma}$$

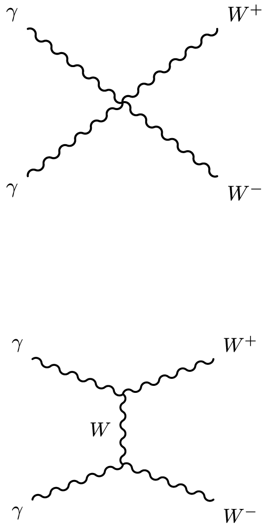
Conclusions

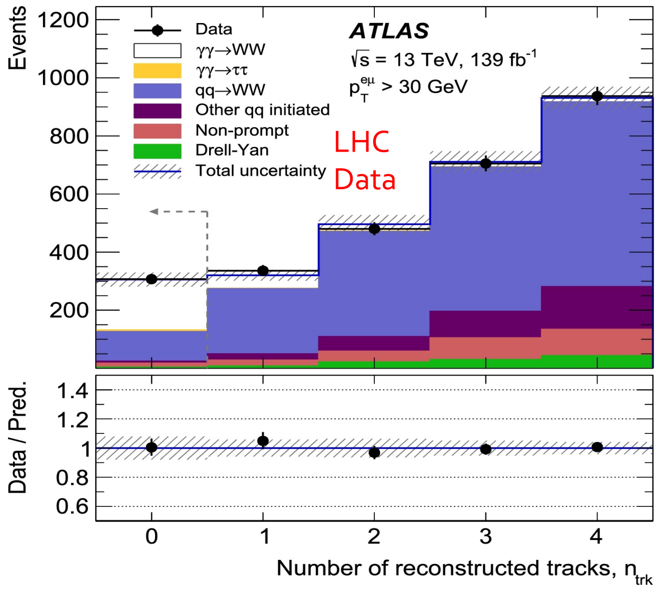
- The EW program at the HL-LHC is broad and versatile as well as critical to fully explore the SM and constrain or discover new physics
- Experimental challenges, e.g. pileup and data rate, can be overcome with upgraded detectors (e.g. tracking, timing, triggering), and advances in experimental techniques (ML, jet substructure etc.)
- Measurements of SM parameters (W mass, Weak Mixing angle) can approach precision of current world best measurements
- The large HL-LHC dataset will allow precision measurements of multiboson production and the extraction of longitudinal polarization in vector boson scattering cross sections
- The EW program at the HL-LHC can be carried out in central pp collisions, HI collisions as well as with forward proton-tagging, e.g. light-by-light scattering, photon-induced processes
- With no doubt we will do better than currently projected (see LHC experience)

Backup

Photon-photon interactions

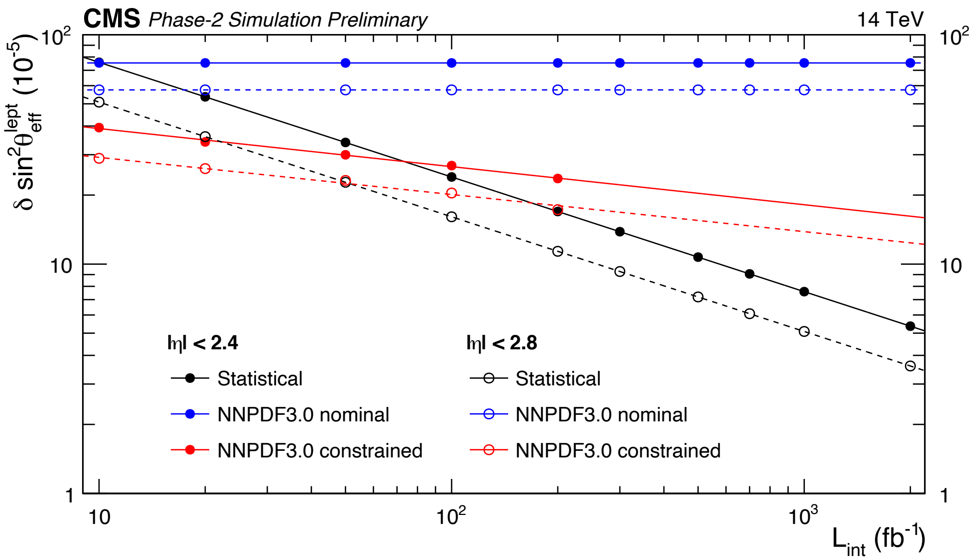
PLB 816 (2021) 136190





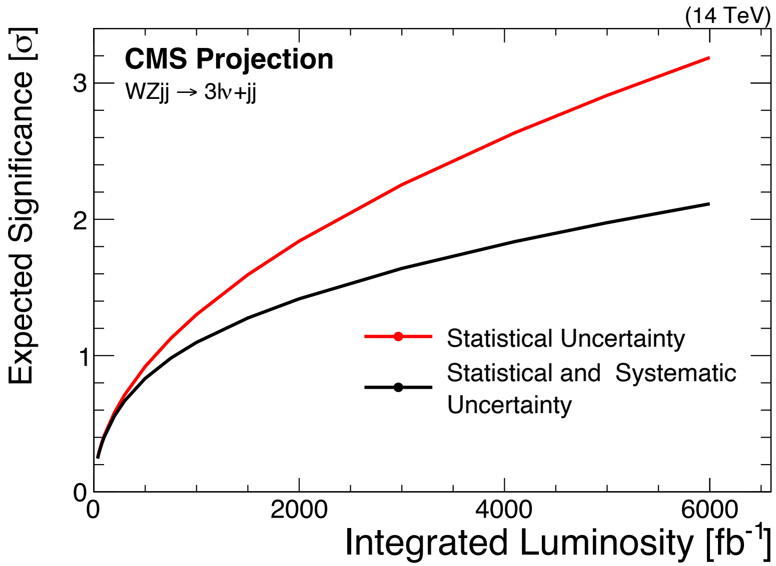
Weak Mixing Angle

- The extended lepton acceptance decreases the statistical uncertainties by about 30%, PDF uncertainties by about 20%.
- PDF uncertainty could be constrained to improve the precision of weak mixing angle

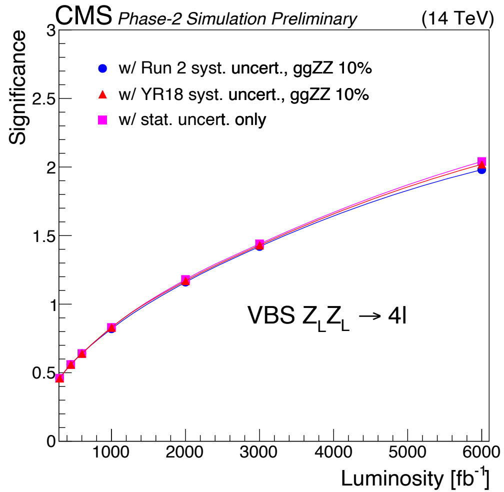


Longitudinal polarization ($W^{\pm}_L Z_L$, $Z_L Z_L$)

$W_L Z_L$ observation significance at HL-LHC



Longitudinally polarization significance in the fully leptonic ZZ final state



	significance		precision (%)	
	w/ syst. uncert.	w/o syst. uncert.	w/ syst. uncert.	w/o syst. uncert.)
HL-LHC	1.4σ	1.4σ	75%	75%
HE-LHC	5.2σ	5.7σ	20%	19%

Charged lepton flavor violation

- SM Charged Lepton Flavor Violation effects are too small to be observed at LHC, but limits on cross-section will provide constraints on BSM models
- $\tau \rightarrow 3\mu$ constrained in ATLAS with 8 TeV data using $W \rightarrow \tau\nu$ events
  - Sensitivity calculated using a profile likelihood fit of a BDT discriminant and 3-muon mass shape to the expected event yields in the signal region
- HL-LHC projection: analysis improvements will have a significant impact on the sensitivity of these results by up to a factor 50x
  - Further improvements may be possible using the τ leptons produced from heavy flavor meson decays, primarily from Ds decays, which provide around 40 times more τ leptons than the W-boson channel

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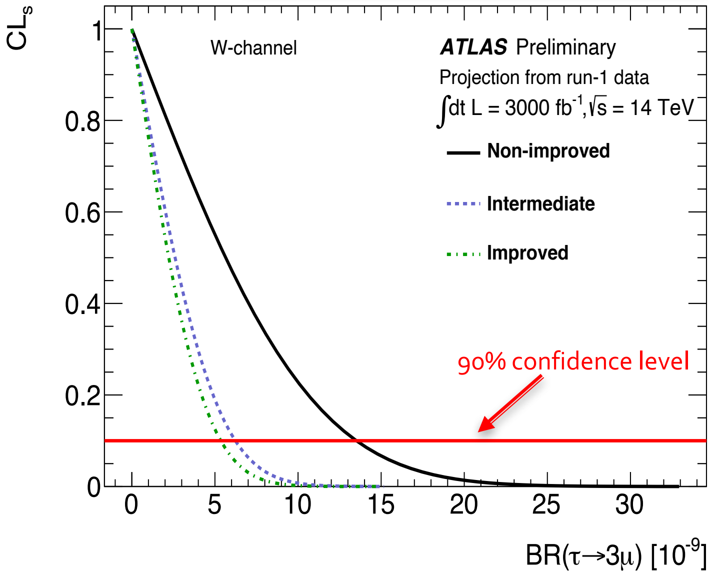

Three scenarios considered based on predicted changes to low-pT muon triggers and improvements in mass resolution from better tracking and vertexing in upgraded detector