Review of SM measurements (EF03-EF06)

On behalf of the ATLAS and CMS Collaborations

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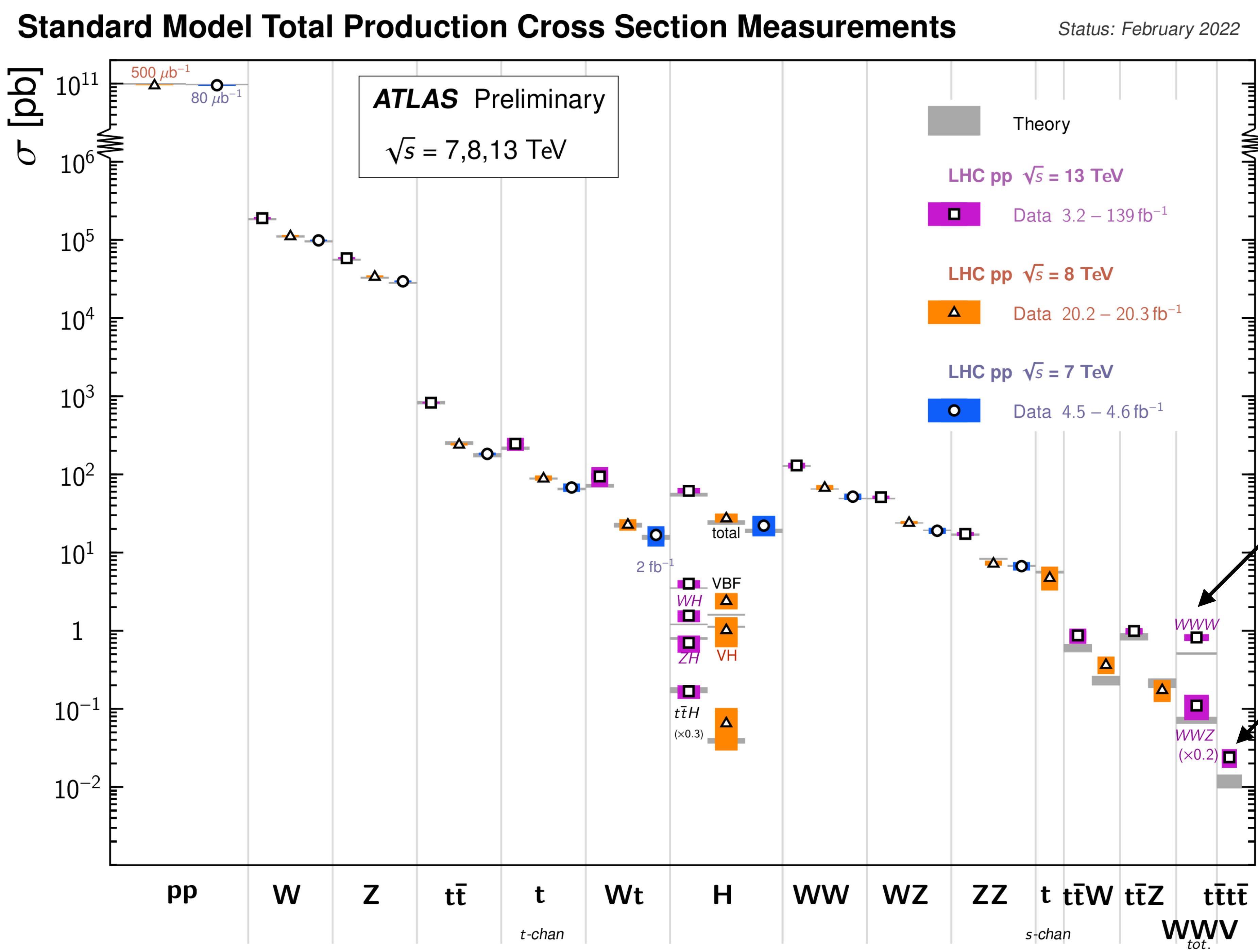
Energy Frontier Workshop- Brown University
29.03.2022

HARVARD
UNIVERSITY

Introduction

- We have been doing SM measurements for a long time!
- Run 2 brought us to an unprecedented centre-of-mass energy of 13 TeV
- Opened up measurements to new rare SM processes



First obs. in 2020

First evidence in 2020

Introduction

- Why keep doing SM measurements?
    - Teach us about the SM
    - Improves our theoretical calculations, MC modelling, and understanding of CP calibrations and uncertainties
    - Measurements will be important for constraining PDFs, understanding electroweak symmetry breaking (EWSB), and measuring fundamental properties of the SM
    - Can uncover unexpected deviations from the SM
- The HL-LHC will provide the opportunity for more precision, particularly at high energies which are currently limited by statistical uncertainties

Introduction

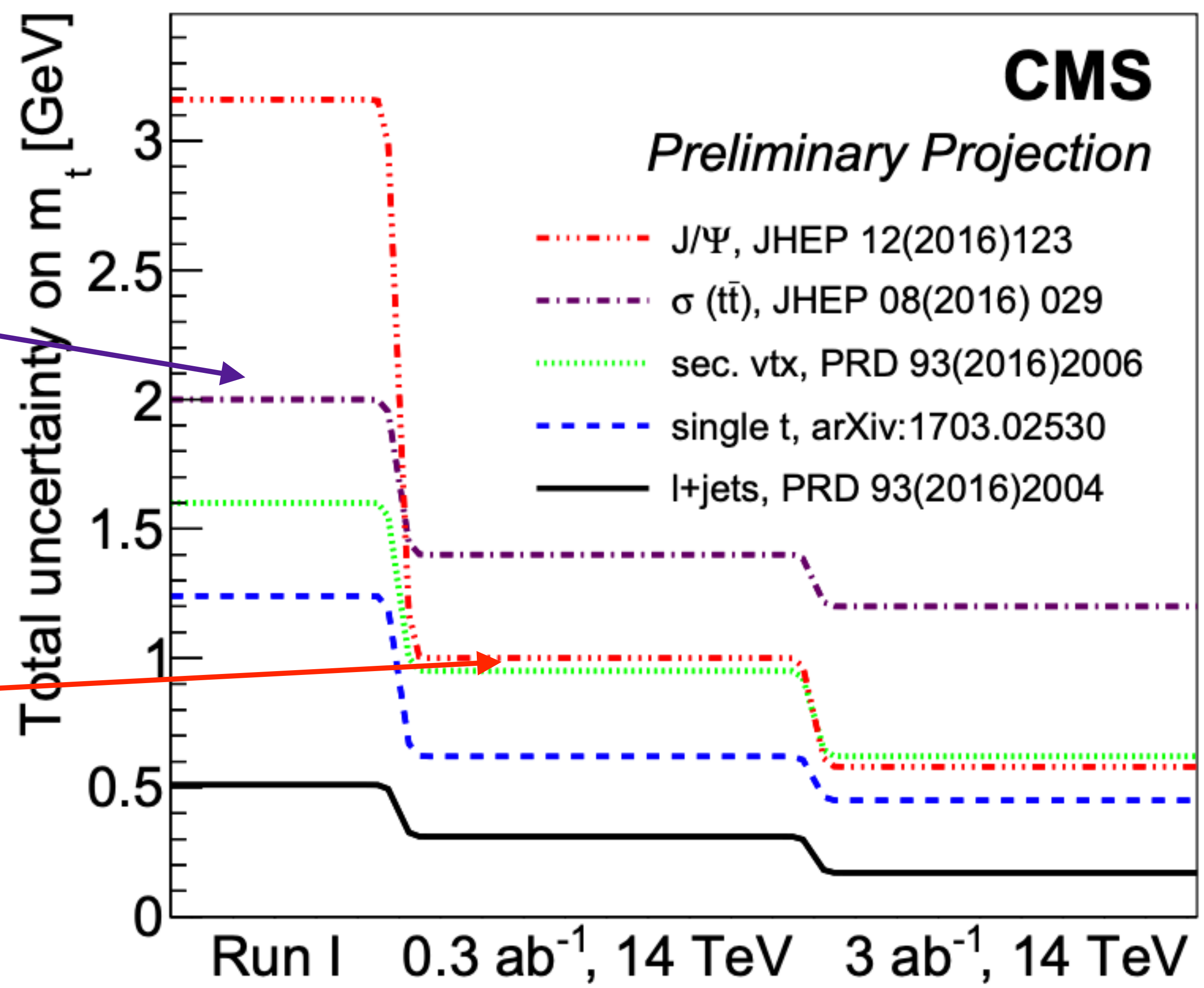
- Many interesting SM studies are highlighted in the White paper (EF03-EF06)
  - Many results were already included in the YR summary and summarised in the document
  - Many results to cover in 15 minutes!
    - A few results are only highlighted in this talk

Link to the Note:
ATL-PHYS-PUB-2022-018
CMS PAS FTR-22-001

EF03 - Heavy flavor and top quark physics

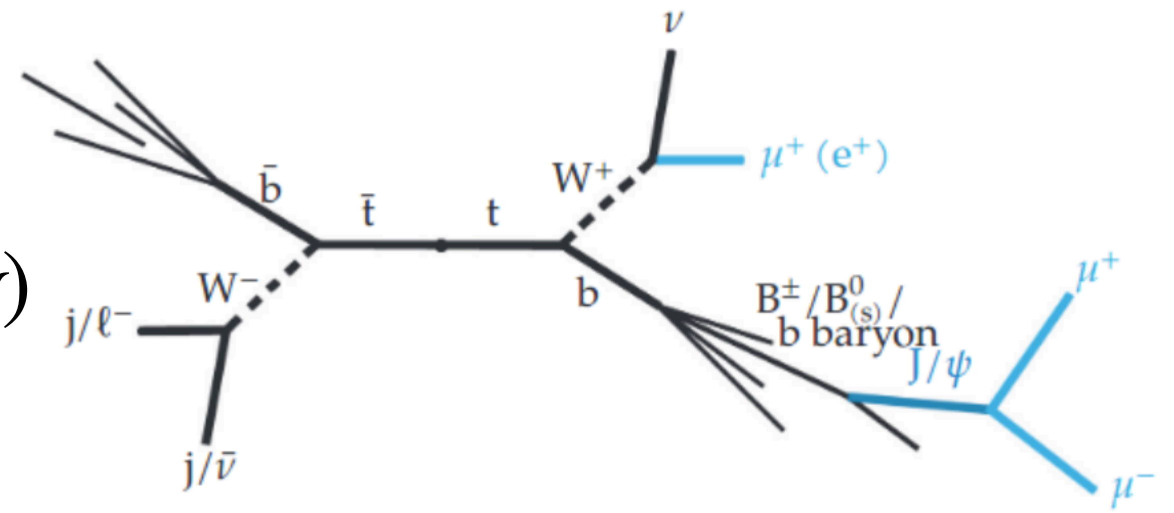
- Top quark plays a crucial role in EWSB and offers a gateway to searching for new physics beyond the SM
- m_{top} is a fundamental parameter related to other EWK parameters - stringent tests of SM
    - Most precise measurements exploit kinematic information of the decay products
- Current uncertainties are ~600 MeV, projected to be reduced to 200 MeV at the HL-LHC
- Indirect extraction of pole mass, e.g. $\sigma_{t\bar{t}}$
    - limited by theory uncertainty and lumi measurements
- less dependence on JES, e.g. $m(lJ/\psi)$
- Room for more reduction via future techniques

m_{top} measurement uncertainty for different methods as a function of integrated luminosity



CMS-PAS-FTR-16-006

Top quark mass measurement using $t\bar{t}$ pairs with a J/ψ



- Measurements using $t\bar{t}$ pairs with a $J/\psi \to \mu\mu$ in final state using the strong correlation between m_{top} and $m(lJ/\psi)$
  - BR $(b \to J/\psi(\to \mu\mu) + X)$ ~10^{-3}
    - Will benefit from larger data samples from the HL-LHC
- ATLAS [ATL-PHYS-PUB-2018-042]: **a statistical uncertainty of ~0.14 GeV is expected with a systematic uncertainty of 0.48 GeV**
  - Dominant uncertainties are from **signal modeling** (fragmentation functions / b-hadron fractions) and from **JES/JER**
- CMS [CMS-PAS-FTR-16-006]: **expected to yield an ultimate relative precision below 0.1% at the HL-LHC**

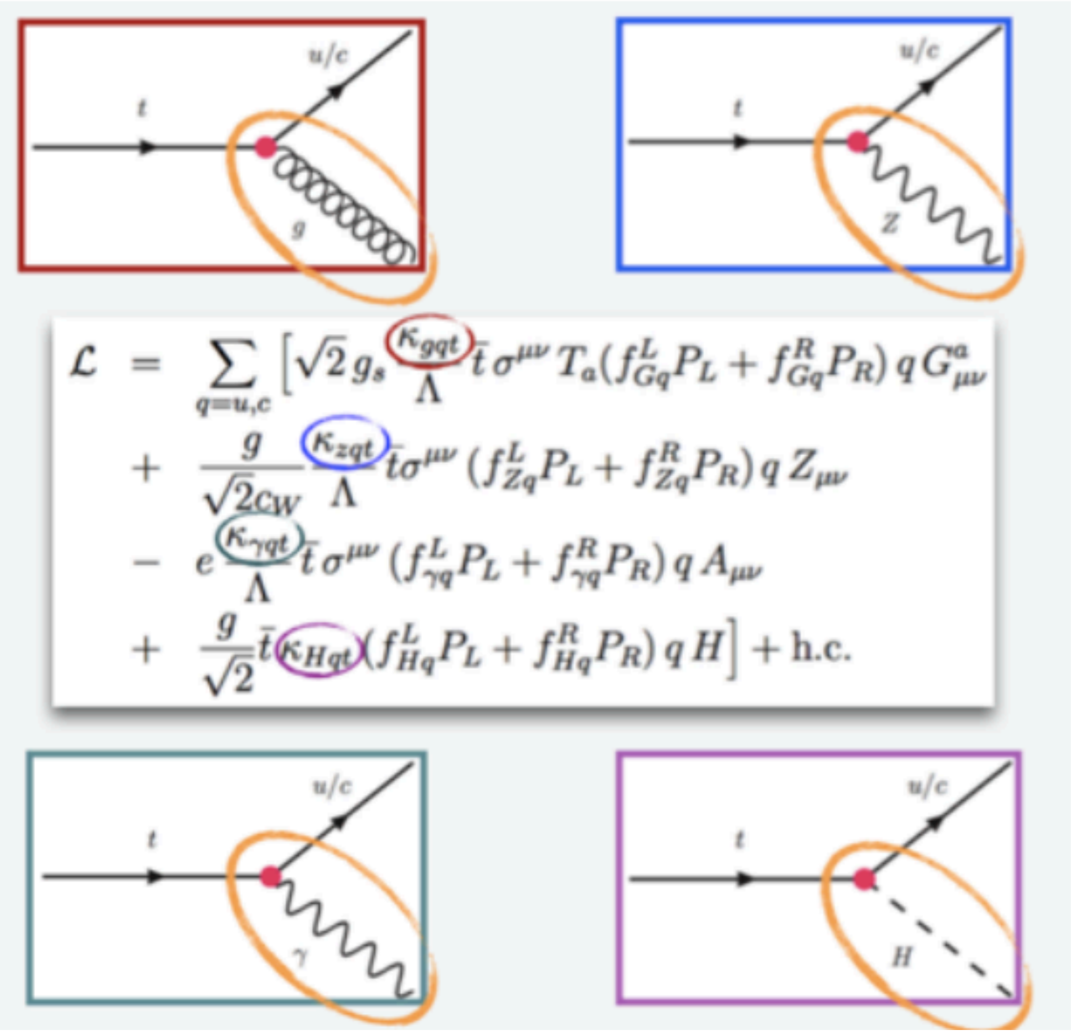
m_{top} measurements will be an important element of HL-LHC

Flavor Changing Neutral Currents (FCNC)

- FCNC in the SM is forbidden at tree-level: heavily suppressed in loops by GIM mechanism BRs ~10^{-14}
- BSM can enhance FCNC up to ~10^{-4}
  - Many potential models: 2HDM, MSSM, RPV SUSY, …
- Any observation of FCNC can hint to new physics
- FCNC probe can be done in both top quark **production**, and **decay**

top quark+ gluon

top quark+ Z boson



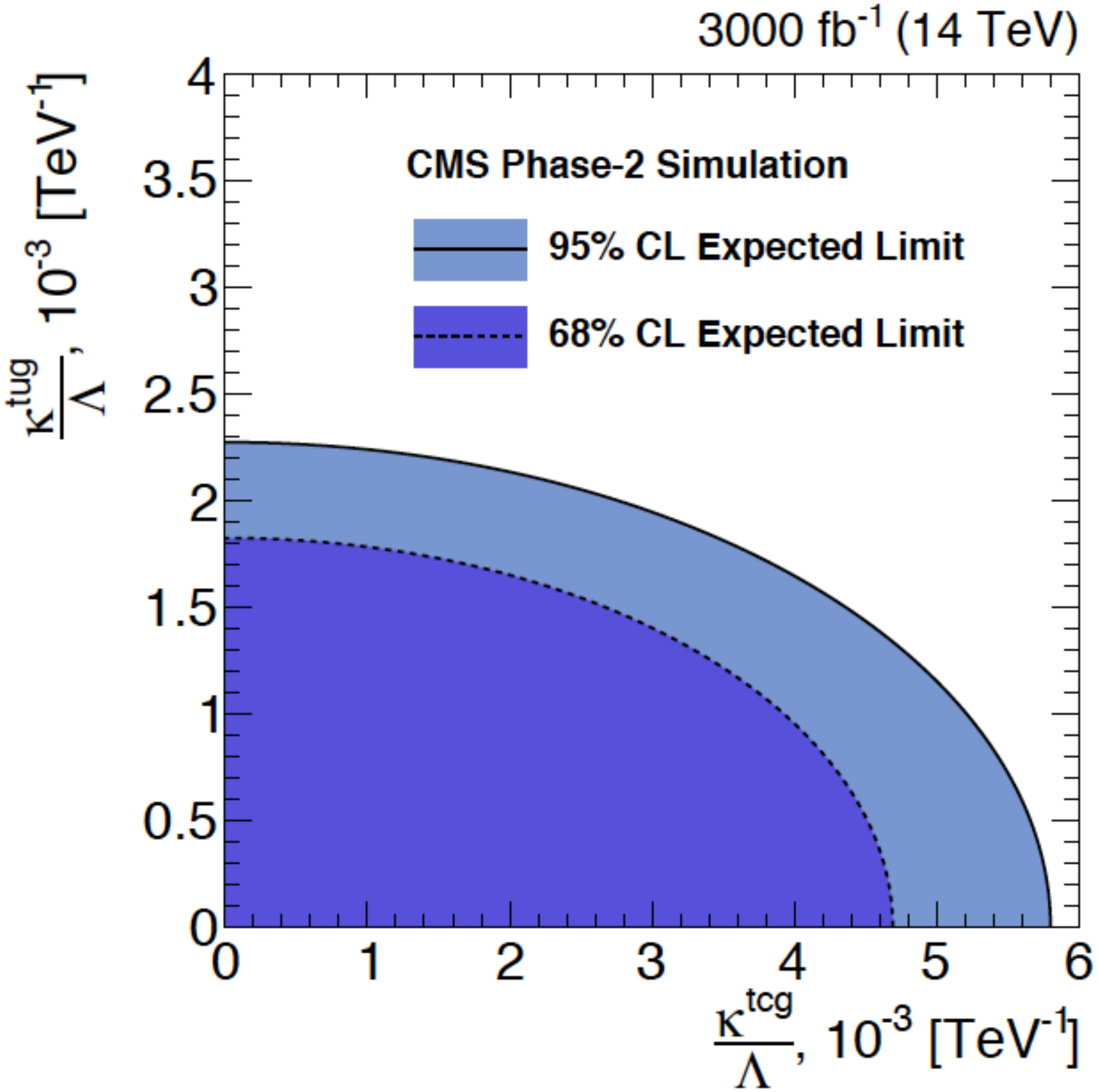
$$\begin{aligned}\mathcal{L} = \sum_{q=u,c} \Big[& \sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} T_a (f^L_{Gq} P_L + f^R_{Gq} P_R) q G^a_{\mu\nu} \\ & + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{Zq} P_L + f^R_{Zq} P_R) q Z_{\mu\nu} \\ & - e \frac{\kappa_{\gamma qt}}{\Lambda} \bar{t} \sigma^{\mu\nu} (f^L_{\gamma q} P_L + f^R_{\gamma q} P_R) q A_{\mu\nu} \\ & + \frac{g}{\sqrt{2}} \bar{t} \kappa_{Hqt} (f^L_{Hq} P_L + f^R_{Hq} P_R) q H \Big] + \text{h.c.}\end{aligned}$$

top quark+ photon

top quark+ Higgs

Flavor Changing Neutral Currents (FCNC)

- Search prospects for gluon-mediated FCNC in top quark production via *tug* and *tcg* vertices were studied with CMS HL-LHC detector
- Dominant uncertainty is normalization of multijet background
- Limits on branching fractions:
  - $B(t \to ug) < 3.8 \times 10^{-6}$
  - $B(t \to cg) < 32 \times 10^{-6}$



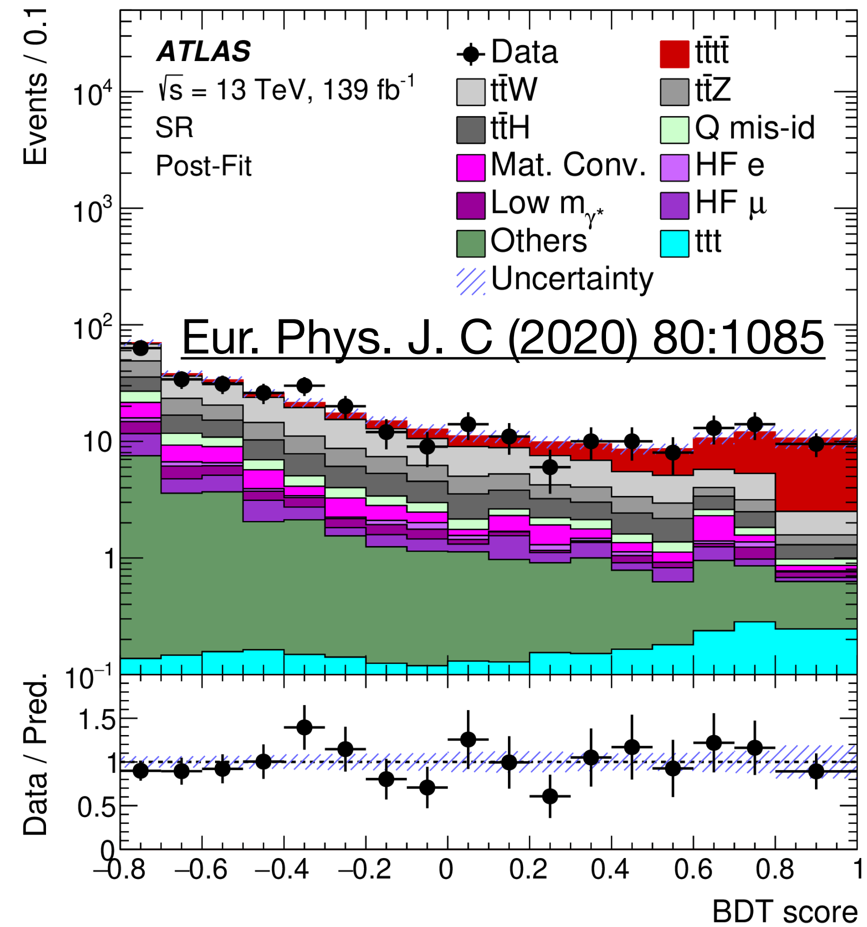
Exploiting full HL-LHC dataset will allow us to improve current limits by an order of magnitude

CMS-PAS-FTR-18-004

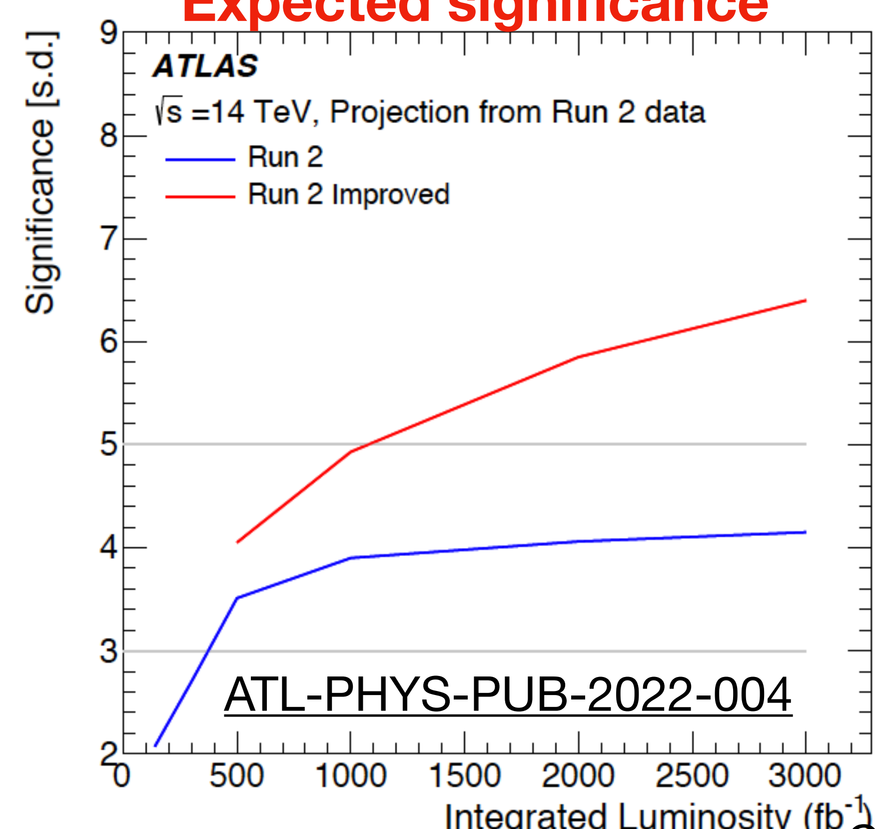
See back-up for more examples

Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

- Based on the recent evidence found in the SS/ML channel using the full run-2 dataset
- A significance of 6.4σ for the SM $t\bar{t}t\bar{t}$ process is expected in the **"Run 2 Improved"** scenario
  - Expecting total uncertainty on the cross section of ~14%
  - Experimental precision is expected to be significantly better than the precision of the current SM computation
- The better sensitivity is driven by:
  - Smaller theoretical uncertainties assumed in the $t\bar{t}t$ cross section
  - Better modeling of the $t\bar{t}W/t\bar{t}Z$ + HF jets
  - Smaller b-tagging experimental uncertainties



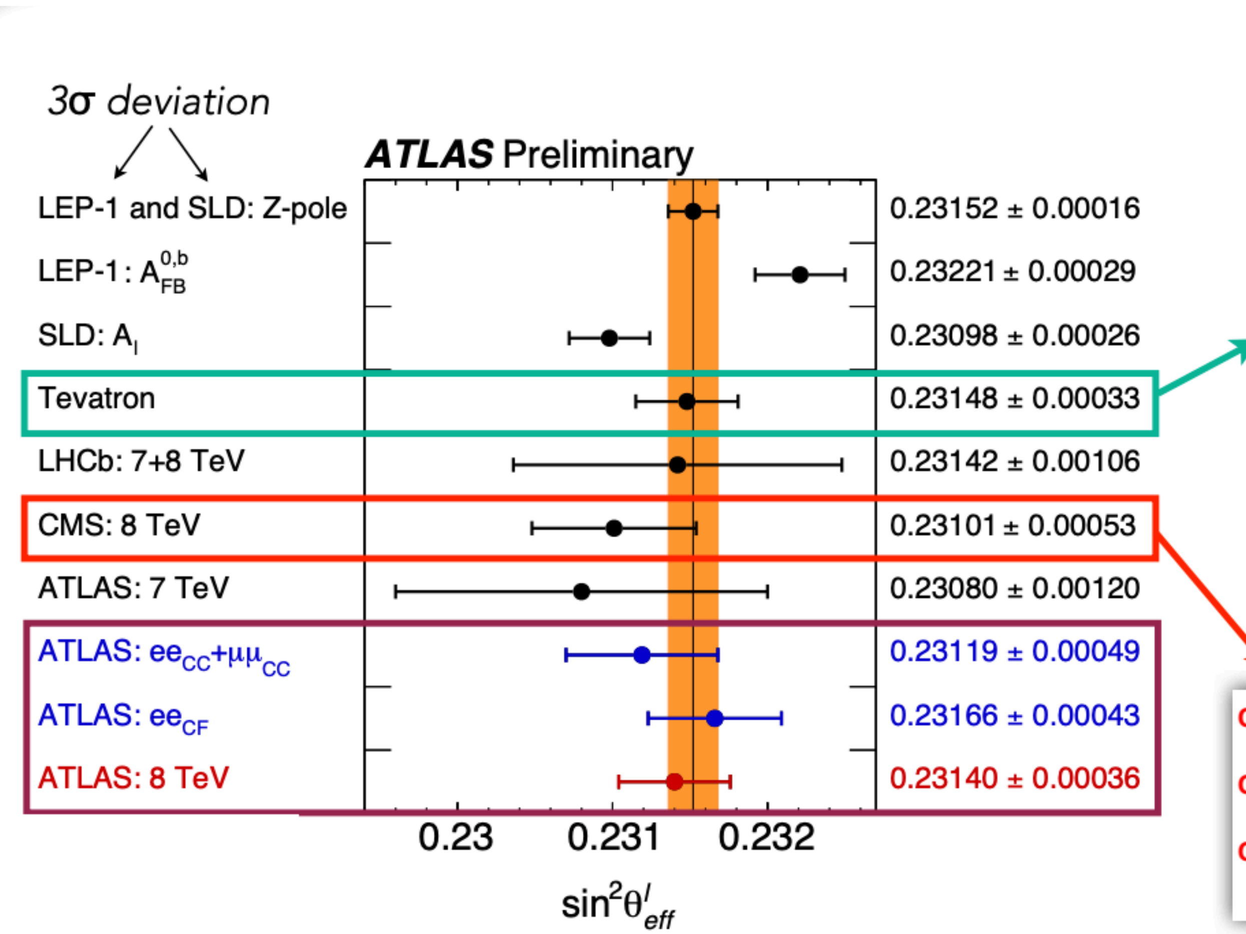
Expected significance

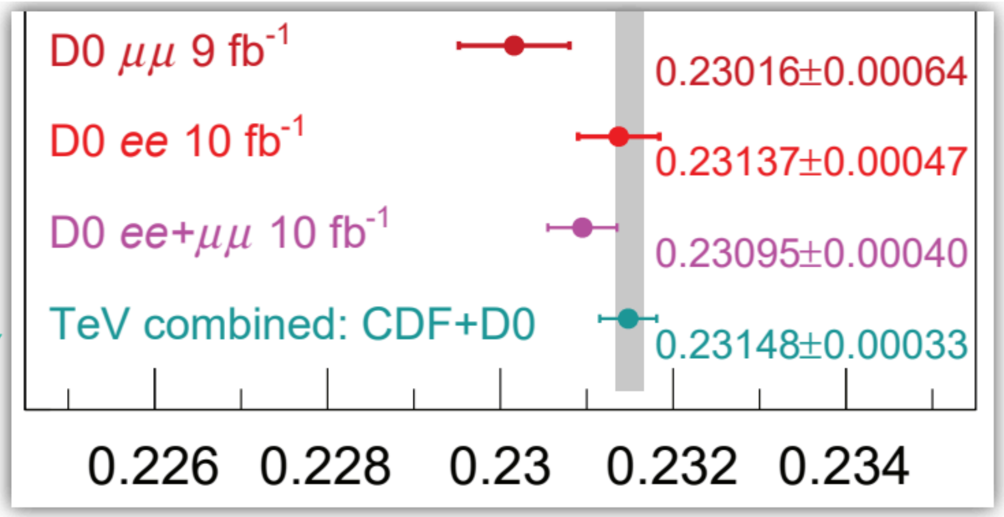


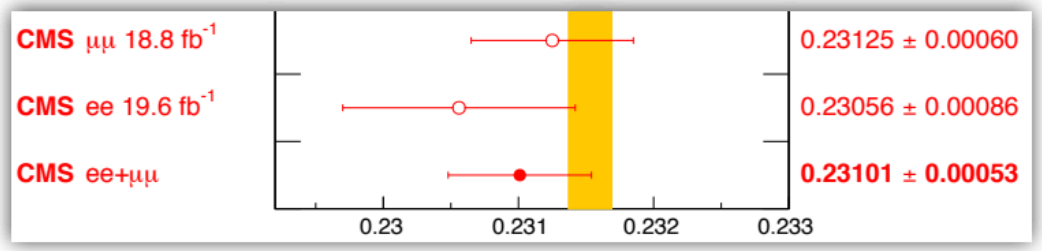
See back-up for CMS results

EF04 - EW precision physics and constraining new physics

- The large HL-LHC dataset will enable precision measurements of various electroweak processes
  - Many are currently limited by statistical uncertainties
- The tracking detector upgrades will allow for better forward jet and lepton reconstruction
- Weak mixing angle measurements ($sin^2\theta_{eff}$)
- The most precise measurements of $sin^2\theta_{eff}$ were performed by LEP and SLD with precision of 1.6×10^{-4}
  - Known tension of 3σ
- New analysis techniques, including *in situ* PDF profiling, significantly improve precision of measurements







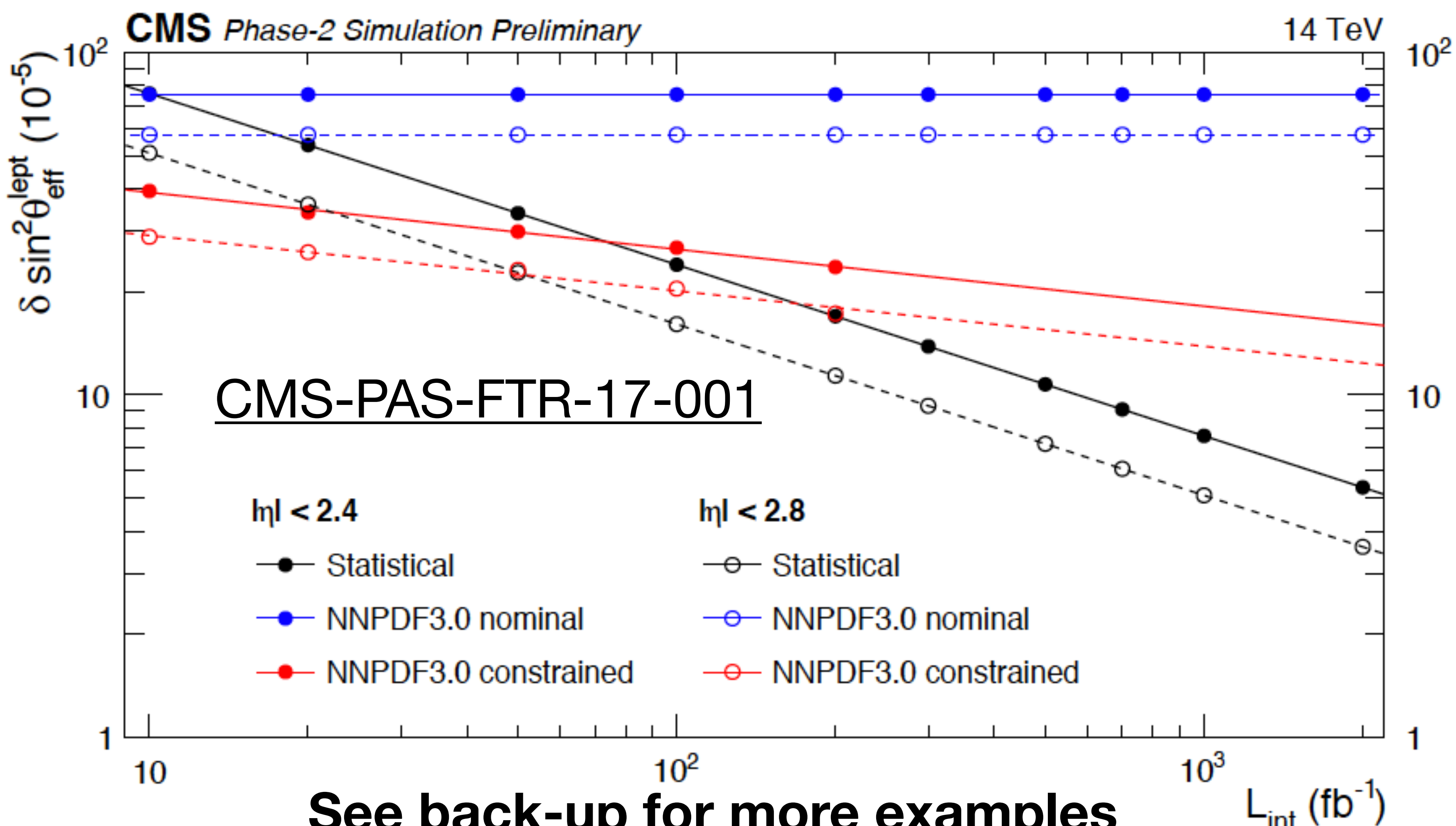
Weak mixing angle measurements

- Study performed in dimuon events, and will benefit both from the increased luminosity and the upgraded part of the CMS muon system that extends from $|\eta| < 2.4$ to $|\eta| < 2.8$ for muons

  - Extending the lepton acceptance decreases statistical uncertainties by ~30% and the PDF uncertainties by ~20%

  - PDF uncertainties could be constrained to improve the precision of $sin^2\theta_{eff}$

Projected statistical, nominal PDF and constrained PDF uncertainties

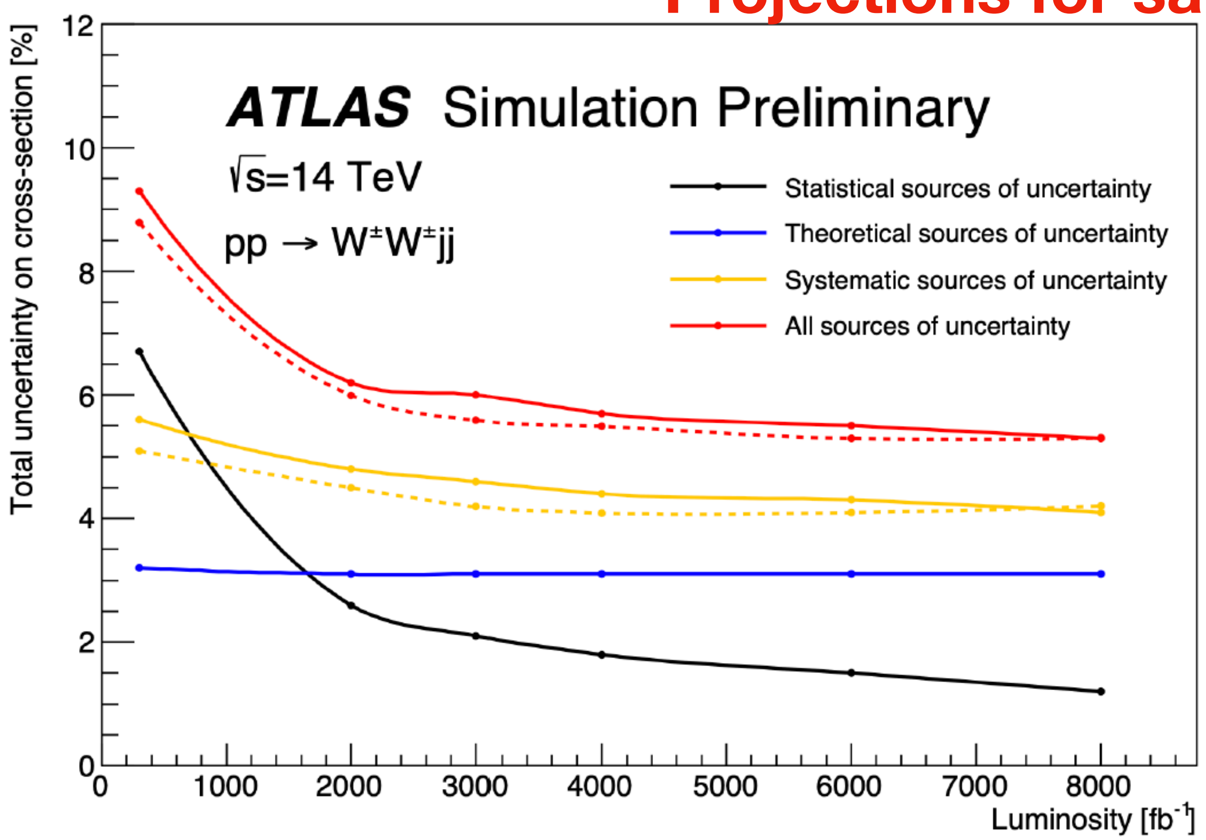


See back-up for more examples

VBS diboson measurements

- ATLAS and CMS found first observations of several EW diboson processes with 13 TeV data
  - VBS $W^{\pm}W^{\pm}$, VBS $W^{\pm}Z$, VBS ZZ, and VBS $Z\gamma$
  - These measurements will greatly benefit from larger HL-LHC dataset, detector upgrades enabling forward lepton reconstruction, and improved pile-up jet rejection for forward jets
  - ATLAS (CMS) expect to measure the cross-section of EW production of VBS $W^{\pm}W^{\pm}$ to 6%(2%) using 3000 fb^{-1}

Projections for same-sign WW



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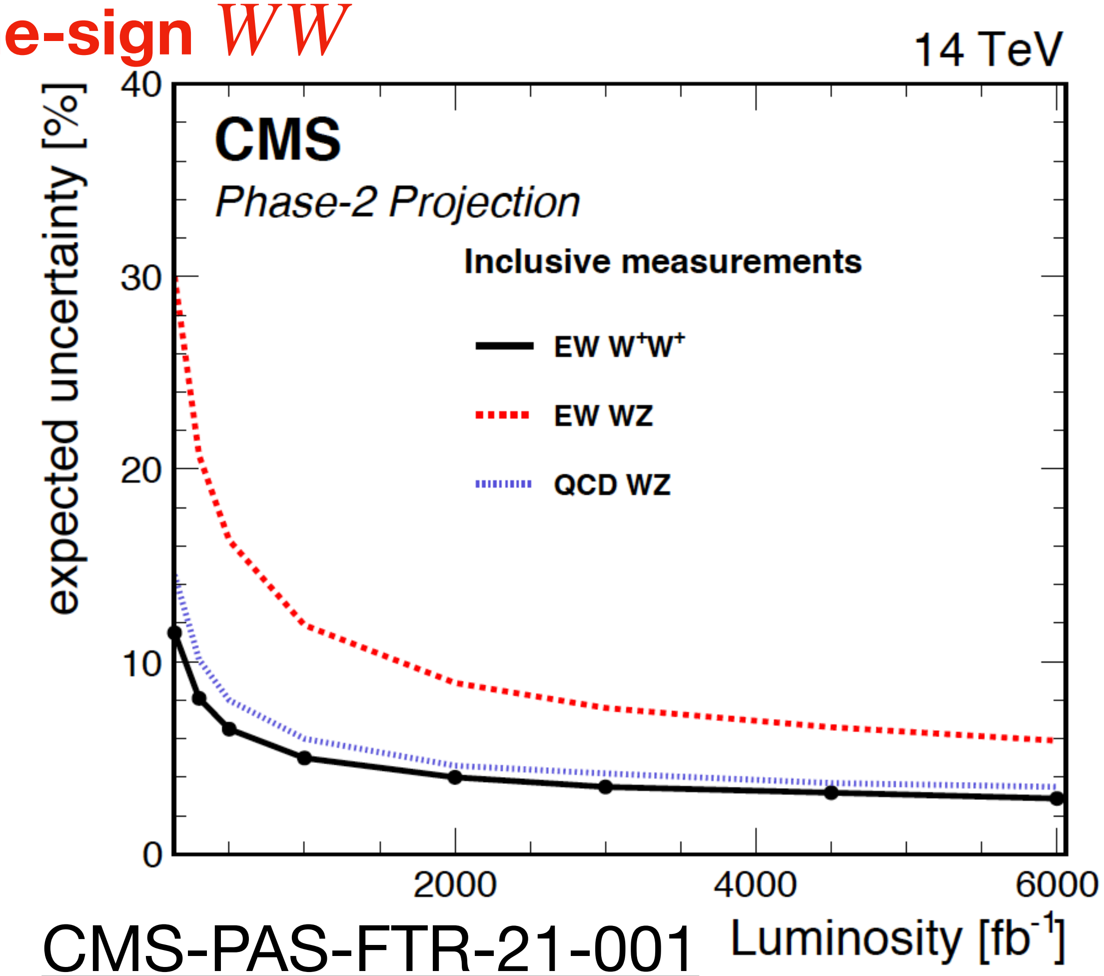


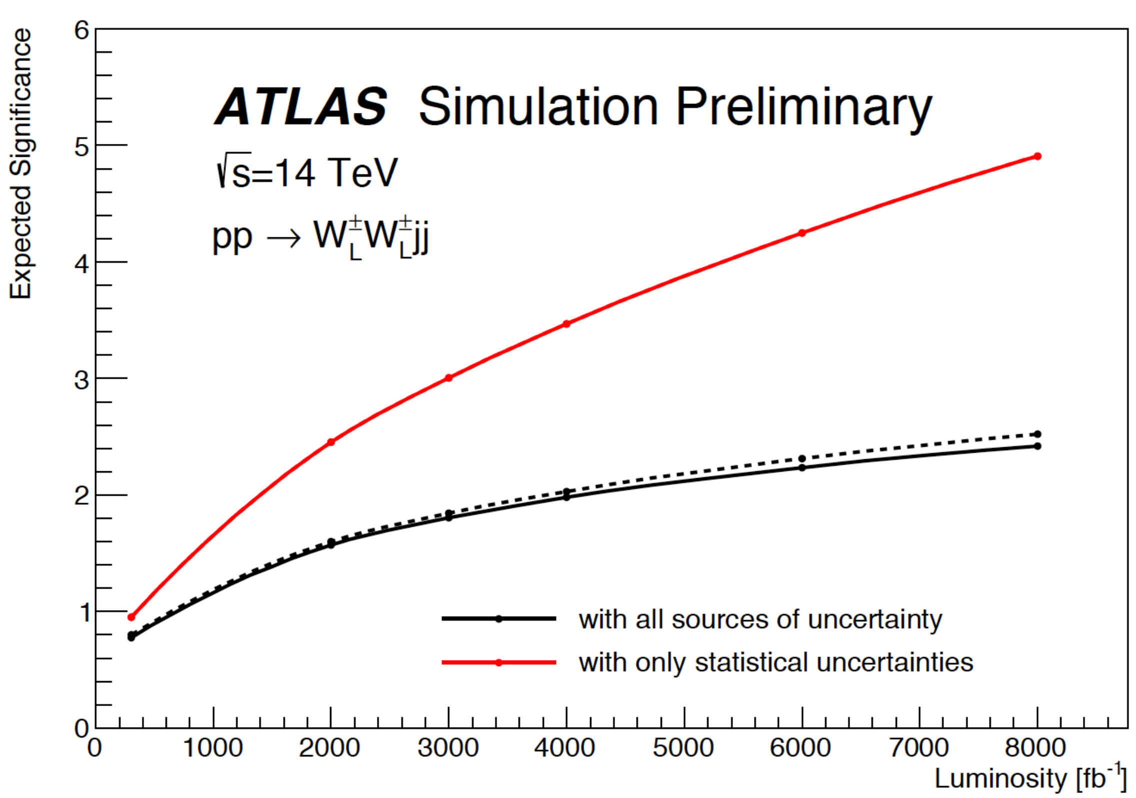
CMS-PAS-FTR-21-001

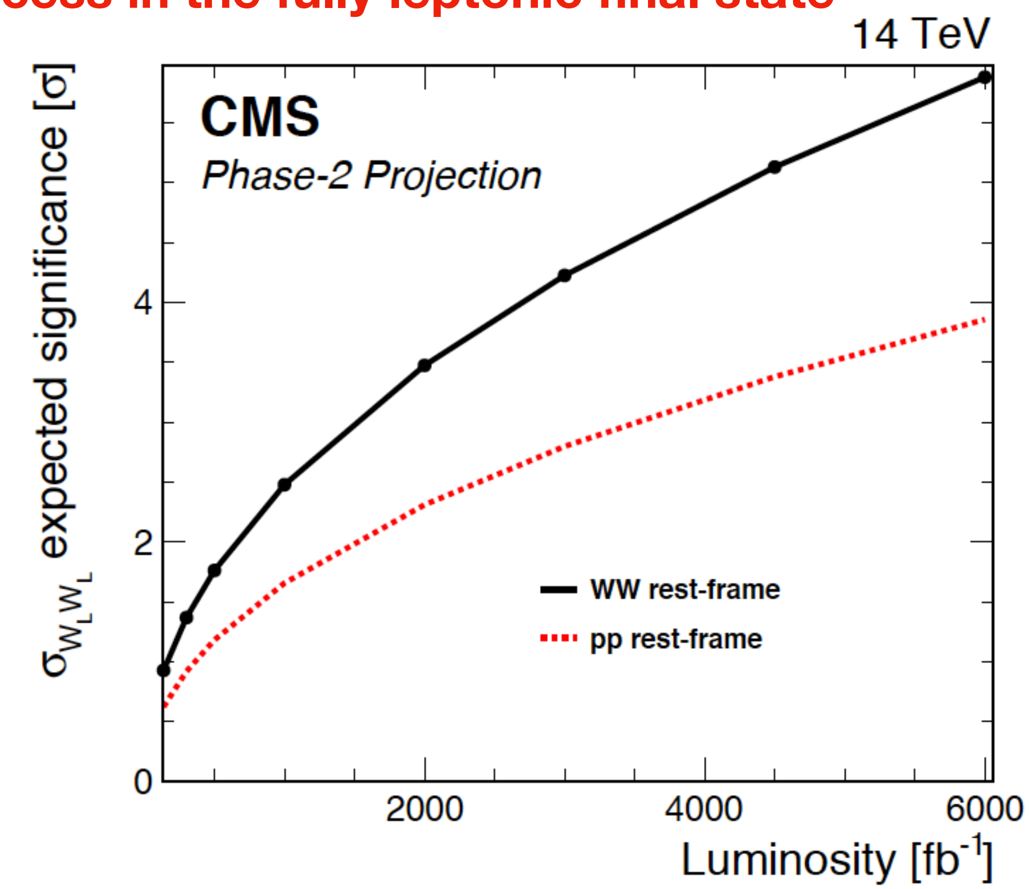
See back-up slides for results using semi-leptonic decays

VBS diboson measurements

- Measuring longitudinally polarized diboson processes ($V_L V_L$) are an important goal of HL-LHC
  - Unitarized process in the SM due to the presence of Higgs boson contributions
  - Any deviations would indicate the presence of BSM physics
- Cross-section for the longitudinally polarized state is small (6–7% of the total cross-section), making this a challenging but important part of the HL-LHC physics program
- Improving the sensitivity requires improved analysis techniques & combinations of results with other decay channels

Longitudinally polarized same-sign WW process in the fully leptonic final state





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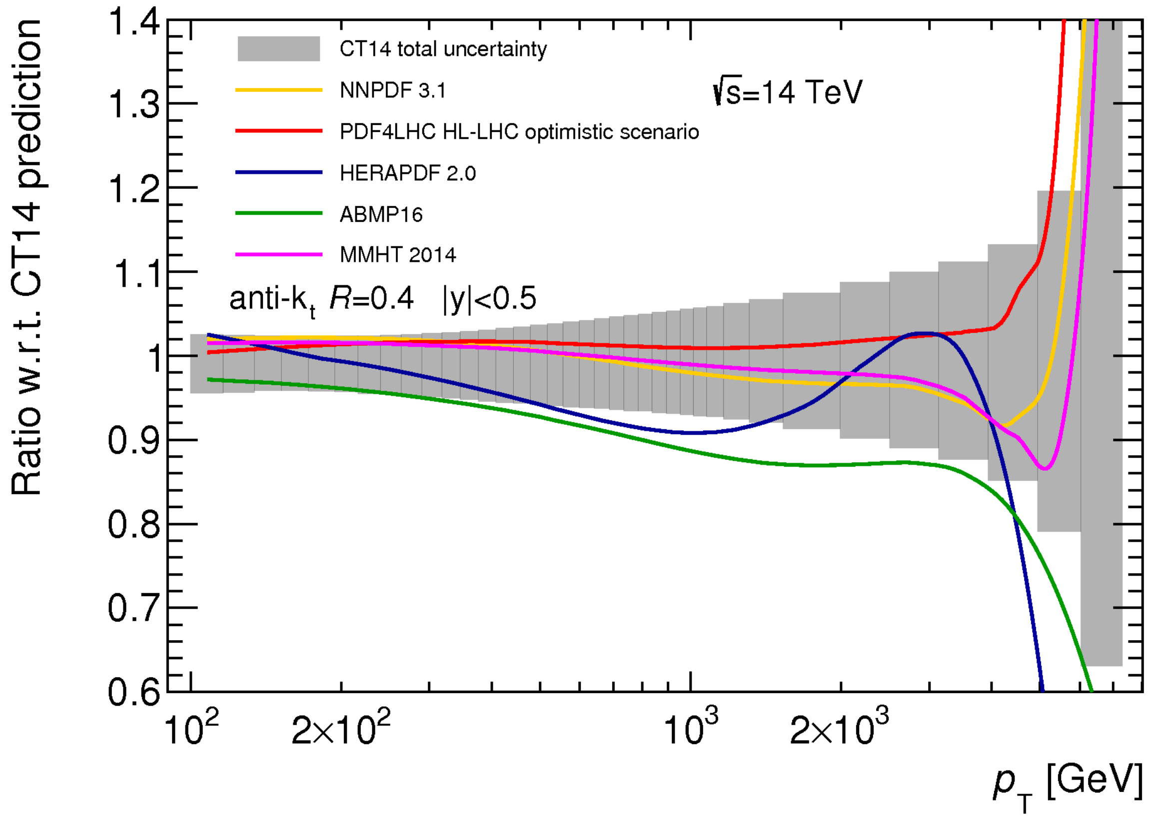
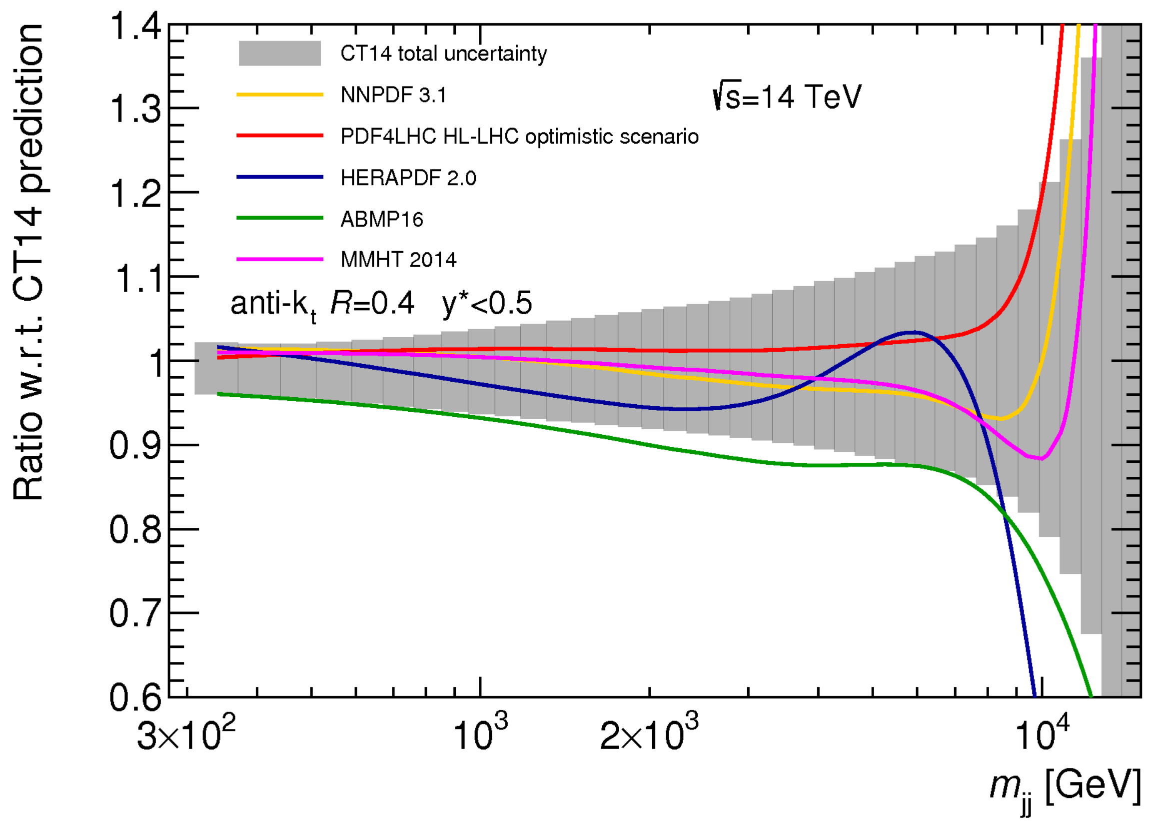
CMS-PAS-FTR-21-001

EF05 - Precision QCD

- Measurements of jet and photon cross-sections are able to constrain PDFs and measure the running of the strong coupling α_s
- Essential backgrounds for many measurements
- HL-LHC will provide opportunity to precisely test QCD at higher energies, currently limited by statistical uncertainties
- Prospects for inclusive and dijet cross-section measurements at the HL-LHC are studied
  - Large differences are seen between different PDF sets for the high-p_T and high-m_{jj} because of their sensitivity to the gluon density in the proton





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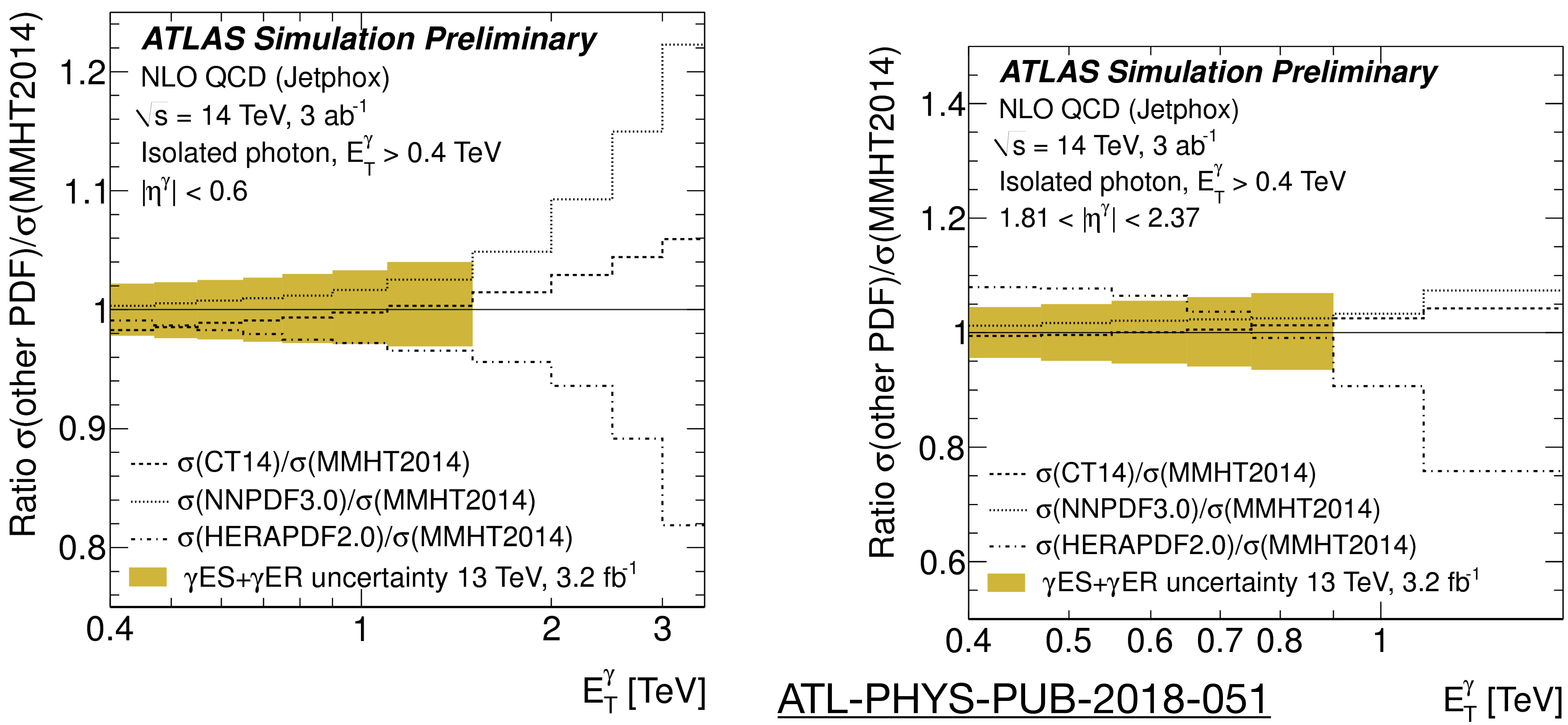
Photon cross-section measurements

- Studied the inclusive photon production differentially in E_T^γ and η^γ
- Large differences between PDF sets are seen for high values of E_T^γ , and the full HL-LHC dataset will enable measurements in these regions
- Improvements in the photon energy scale and resolution uncertainties will be important to improve the impact of this measurement on PDFs and tests of perturbative QCD

Ratios of inclusive isolated photon events for various PDFs as functions of E_T^γ

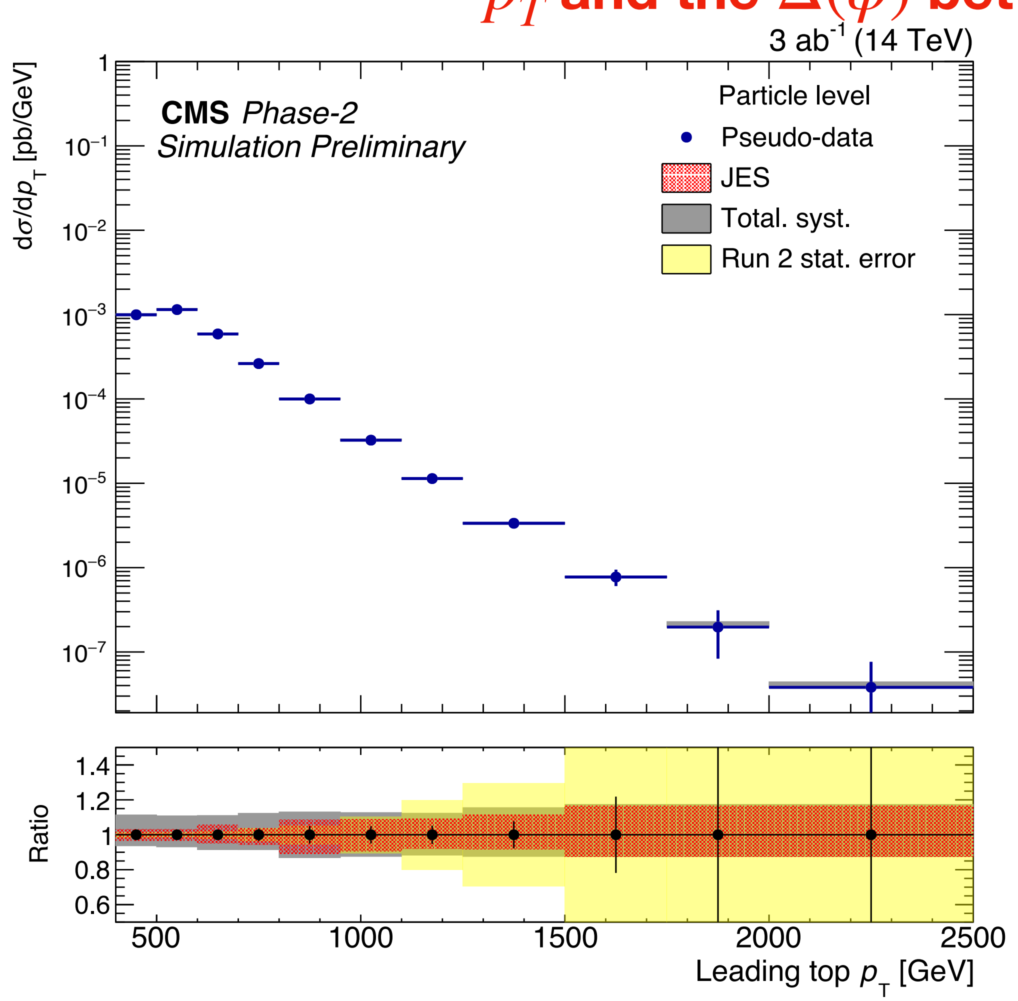


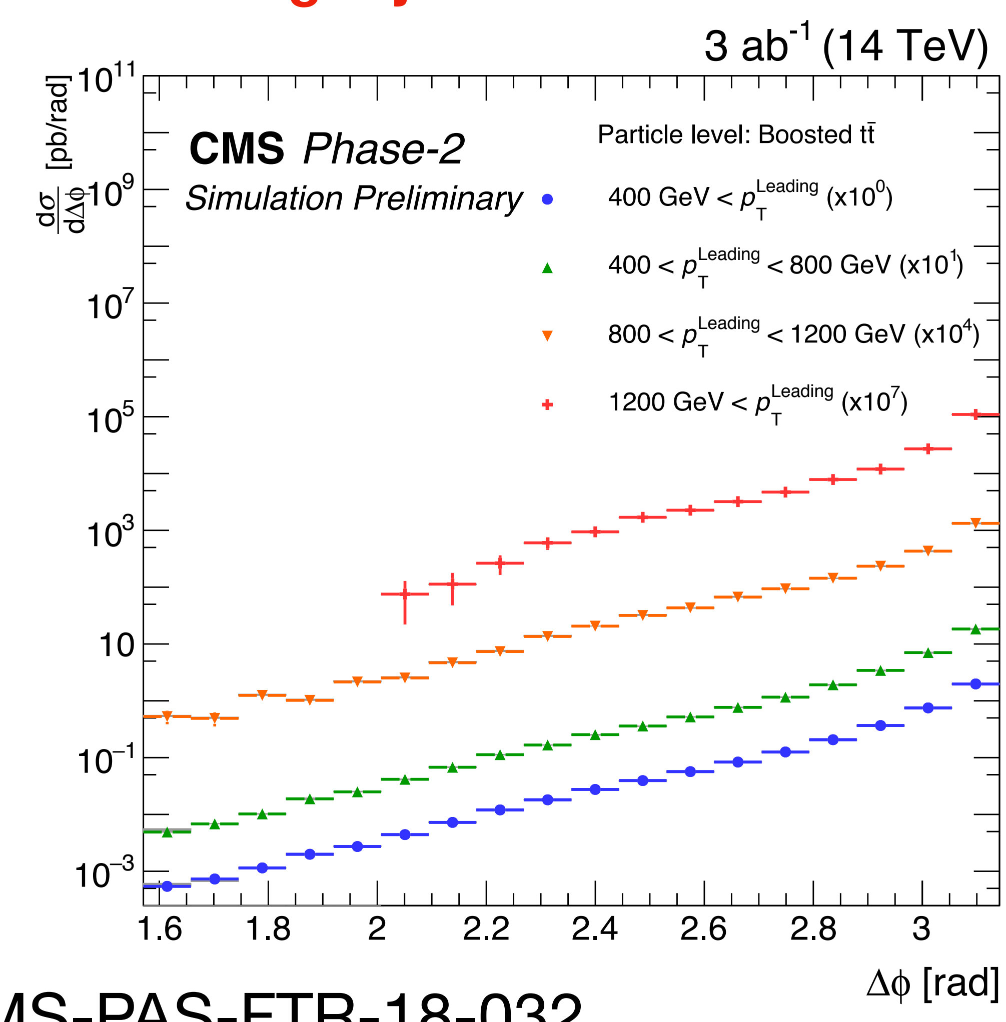
ATL-PHYS-PUB-2018-051

High-p_T jet measurements at the HL-LHC

- Studied kinematic distributions of jets in inclusive jet production, top quark jets and jets arising out of the hadronic decay of W-boson
- The azimuthal correlation between the two jets reflects interference effects from the color connection
- Efficiency for selecting $t\bar{t}$ jets ranges from 10% at small $\Delta\phi$ to ~20% at $\Delta\phi \sim \pi$ as obtained from the Delphes simulation

Particle level cross-section of the $t\bar{t}$ process as a function pf the leading top quark p_T and the $\Delta(\phi)$ between the two leading $t\bar{t}$ jets



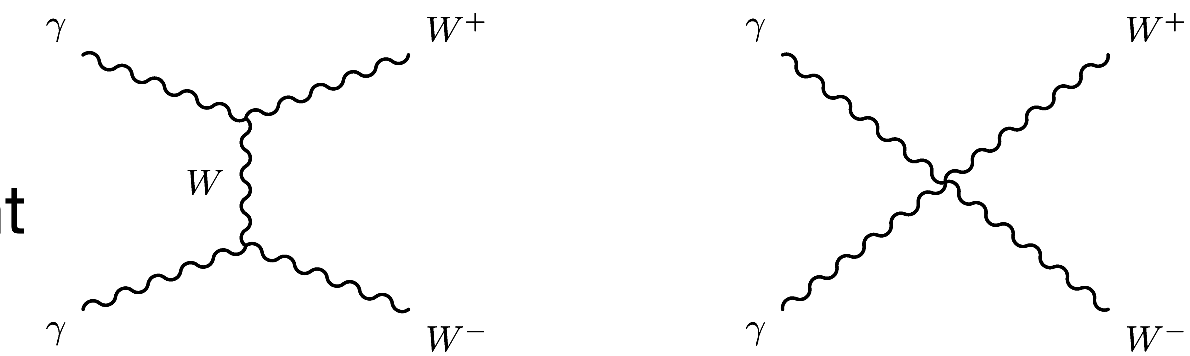


CMS-PAS-FTR-18-032

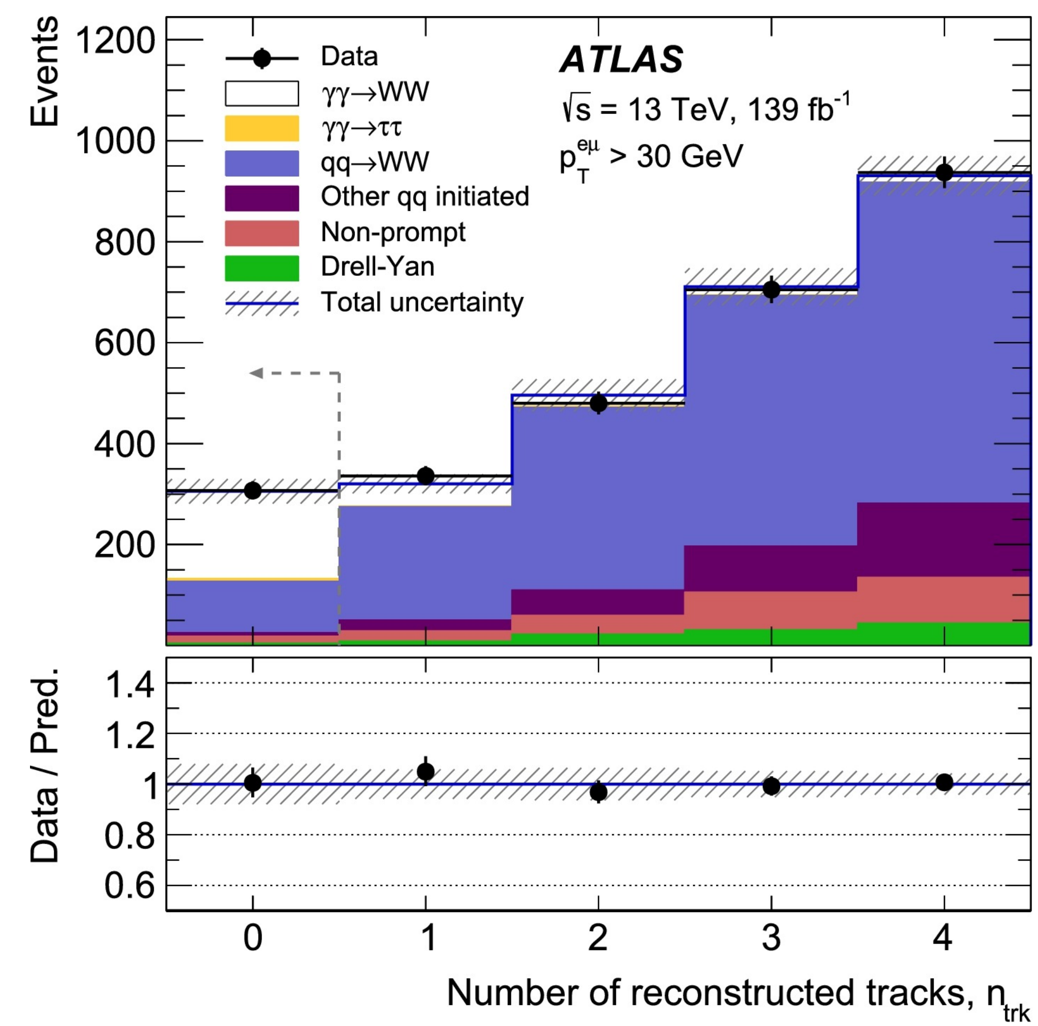
EF06 - Hadronic structure and forward QCD

- Photon-photon interactions can be studied at the LHC
  - used to observe processes such as light-light scattering and exclusive WW production
- First observation of $\gamma\gamma \rightarrow WW$ in 2020
  - Background hypothesis rejected with a significance of 8.4 standard deviations
  - **Clean signature**: zero additional charged particles
- Sensitivity to $\gamma\gamma \rightarrow W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ at the HL-LHC is performed following the run 2 analysis
- Increased statistical precision will allow studies into the high-energy tails of the distributions

Leading order Feynman diagrams contributing to the $\gamma\gamma \rightarrow WW$ process



Number of tracks associated with the interaction vertex



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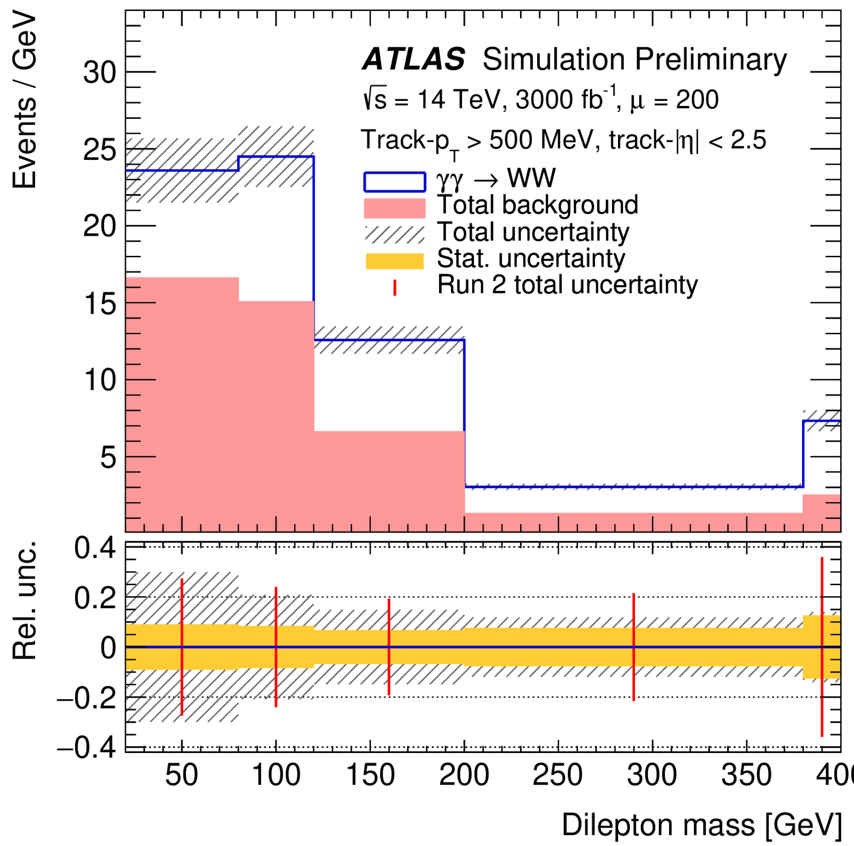
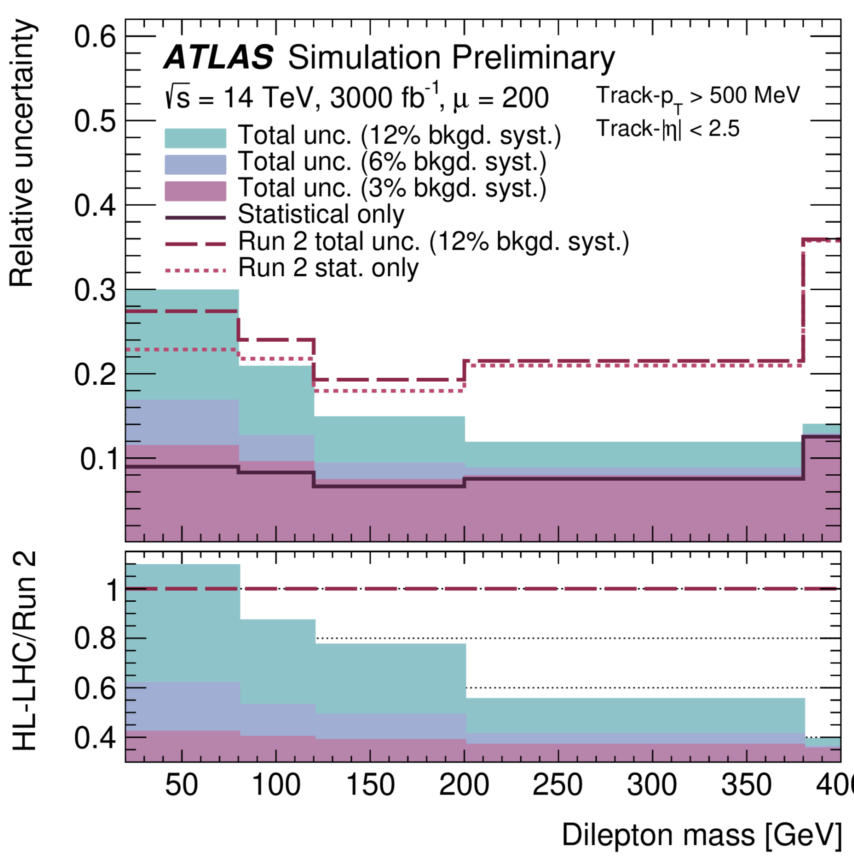
Sensitivity to $\gamma\gamma \to W^{\pm}W^{\mp} \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ at the HL-LHC

- Key part of this analysis is dealing with the impact of pileup at HL-LHC
- Background efficiency falls as dilepton mass increases; good for high-mass studies!
  - Can be important for certain EFT fits (sensitive to certain dimension-8 operators)
- HL-LHC analysis will have a reduced statistical uncertainty over what will be obtained from Run-II/ III
- Essential to reduce background modelling systematics to keep up with the increase in statistical precision
- Best performance is for central tracks, with a track p_T cut of 500 MeV
- The current HL-LHC baseline is to have a minimum track p_T of 900 MeV in the central region
  - Improvements to track reconstruction will be important for this analysis





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Conclusions

- HL-LHC will offer a great opportunity for many SM measurements
- Detector upgrades will allow for better forward jet and lepton reconstruction - essential to improve current measurements
- Will produce currently unachievable measurements
- Improve our understanding and learn more about the SM
- Can uncover unexpected deviations from the SM pointing to new physics
- Improving theoretical uncertainties is a key player to achieve better precision

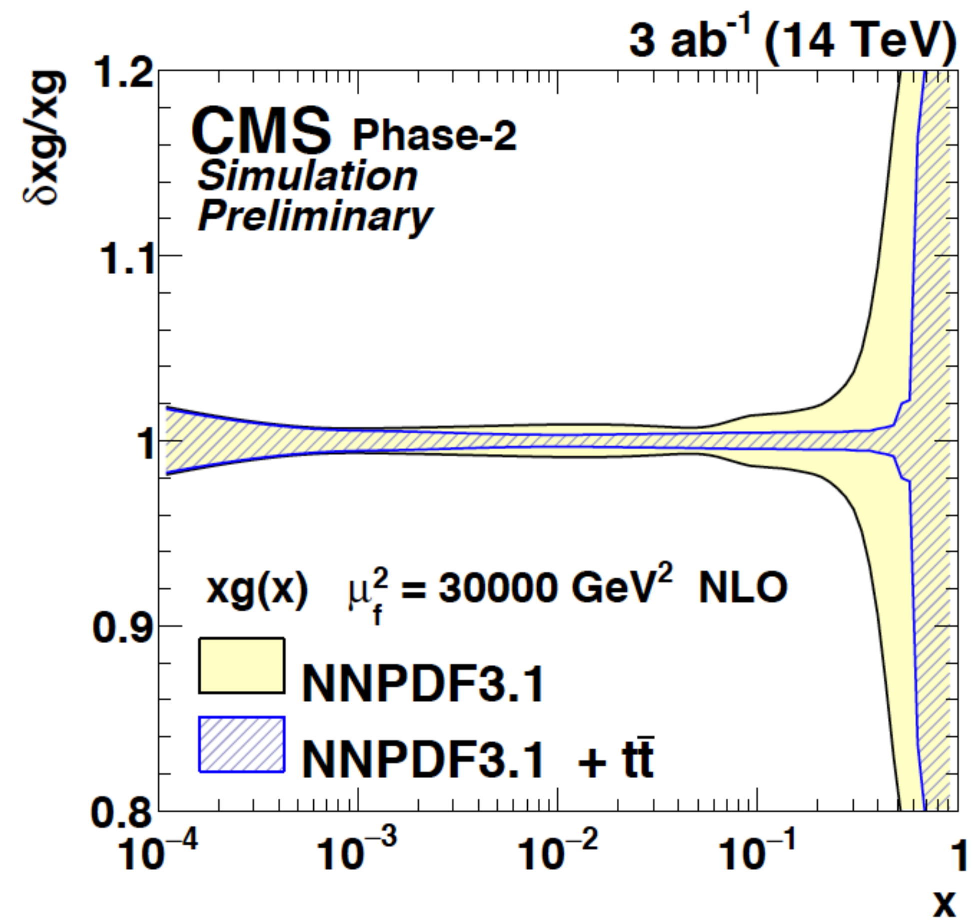
Thank you!

Extra Material

Differential $t\bar{t}$ cross-section measurements

- Done in e/μ+jets channels
- The most significant reduction of uncertainty is expected to come from:
  - an improved jet energy calibration
  - a reduced uncertainty in the b-jet identification
- The final projected uncertainty is estimated below 5%
- The precision in the measurement will profit from the **enormous amount of data** and the **extended η-coverage** of the Phase-2 CMS detector, which enables fine-binned measurements at high rapidity that are not possible with the current detector
- The uncertainties of the gluon distribution are drastically reduced and depend directly on the uncertainty of the integrated luminosity (assumed to be 1%)

Prospects at HL-LHC of the relative gluon uncertainties of the original and profiled NNPDF3.1 PDF set



CMS-PAS-FTR-18-015

FCNC - tZq

- Done in the three charged lepton final states
- The dominant sources of uncertainties, in both signal and background estimations, are from the theoretical normalization and the modeling of the background processes MC
- An improvement by a factor of four is expected over the current Run-2 analysis

	-1σ	Expected	$+1\sigma$
$\mathcal{B}(t \to uZ)$	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}

Table 6: The expected 95% confidence level upper limits on the top-quark FCNC decay branching ratios are shown together with the $\pm 1\sigma$ bands, which include the contribution from the statistical and systematic uncertainties. Presented limits are extracted from "Asimov data" in the signal and background control regions, defined as the total expected pre-fit background. Systematic uncertainty from the MC statistical uncertainty is considered as well.

Operator	Expected limit
$\lvert C_{uB}^{(31)} \rvert$	0.13
$\lvert C_{uW}^{(31)} \rvert$	0.13
$\lvert C_{uB}^{(32)} \rvert$	0.14
$\lvert C_{uW}^{(32)} \rvert$	0.14

Table 8: Expected 95% CL upper limits on the moduli of the operators contributing to the FCNC decays $t \to uZ$ and $t \to cZ$ within the TopFCNC model for a new-physics energy scale $\Lambda = 1$ TeV.

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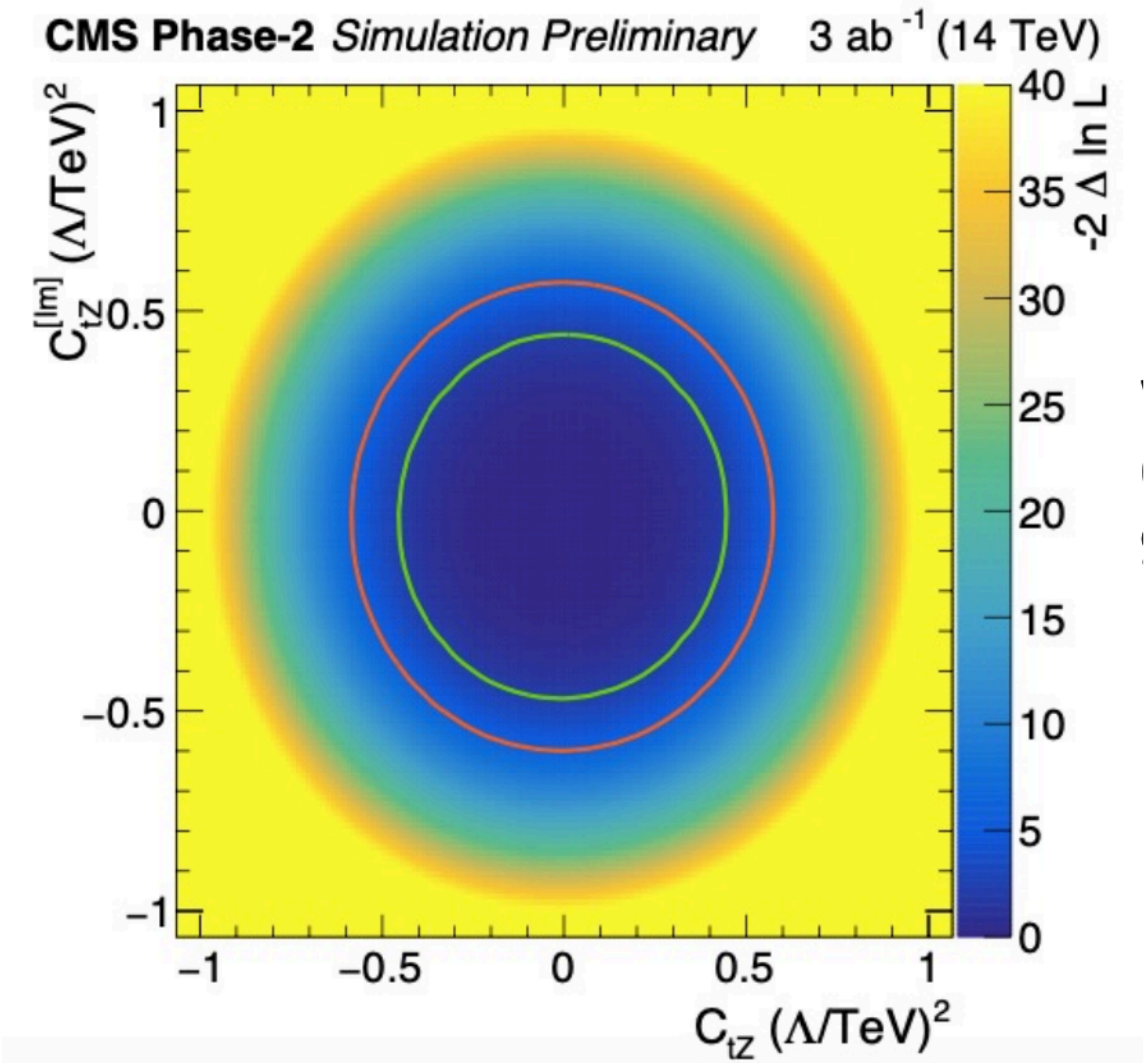
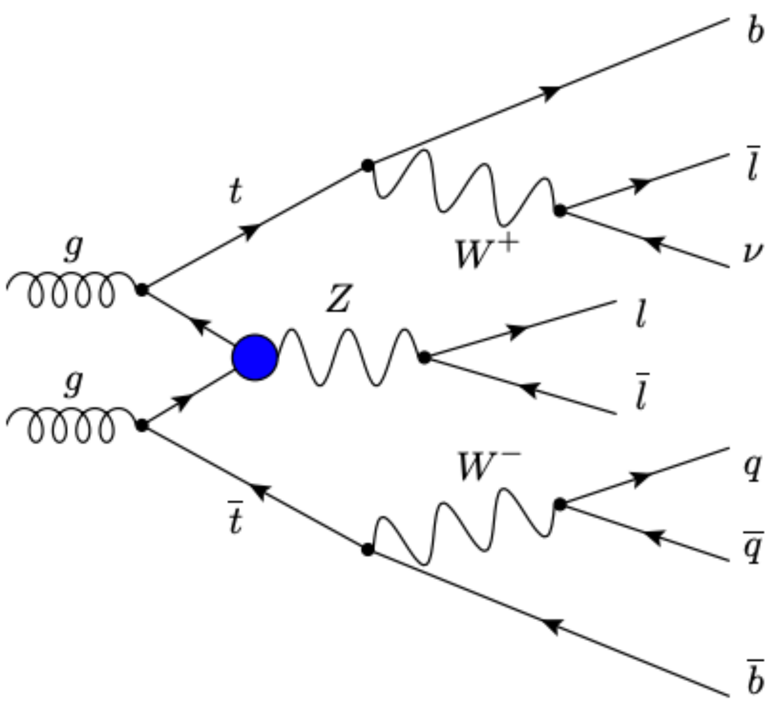
ttZ and EW top couplings at the HL-LHC

- Expected sensitivity to Wilson coefficients of top quark operators C_{tZ} in the ttZ process





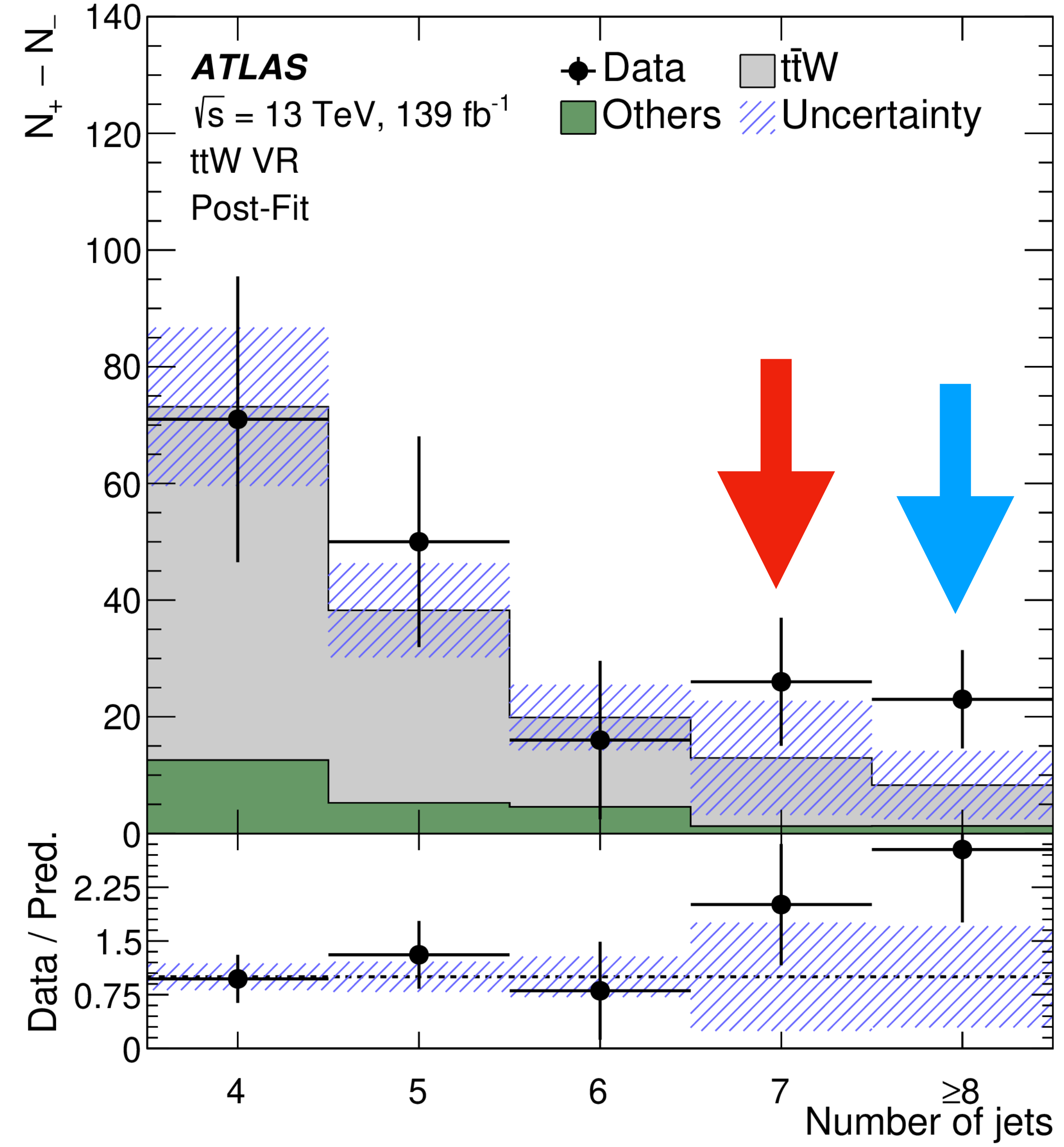
Wilson coefficient C_{tZ} in SMEFT
68 % CL $(\Lambda/\mathrm{TeV})^2$: [-0.37, 0.36]
95 % CL $(\Lambda/\mathrm{TeV})^2$: [-0.52, 0.51]

CMS-PAS-FTR-18-036

Run 2 SM $t\bar{t}t\bar{t}$ cross section

Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross section	+0.56	−0.31
$t\bar{t}t\bar{t}$ modelling	+0.15	−0.09
Background modelling		
$t\bar{t}W$ modelling	+0.26	−0.27
$t\bar{t}t$ modeling	+0.10	−0.07
Non-prompt leptons modeling	+0.05	−0.04
$t\bar{t}H$ modelling	+0.04	−0.01
$t\bar{t}Z$ modelling	+0.02	−0.04
Charge misassignment	+0.01	−0.02
Instrumental		
Jet uncertainties	+0.12	−0.08
Jet flavour tagging (light-jets)	+0.11	−0.06
Simulation sample size	+0.06	−0.06
Luminosity	+0.05	−0.03
Jet flavour tagging (b-jets)	+0.04	−0.02
Other experimental uncertainties	+0.03	−0.01
Jet flavour tagging (c-jets)	+0.03	−0.01
Total systematic uncertainty	+0.69	−0.46
Statistical	+0.42	−0.39
Non-prompt leptons normalisation(HF, material conversions)	+0.05	−0.04
$t\bar{t}W$ normalisation	+0.04	−0.04
Total uncertainty	+0.82	−0.62

$t\bar{t}W$ **Validation Region**: ≥4jets ≥2b-tagged



Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

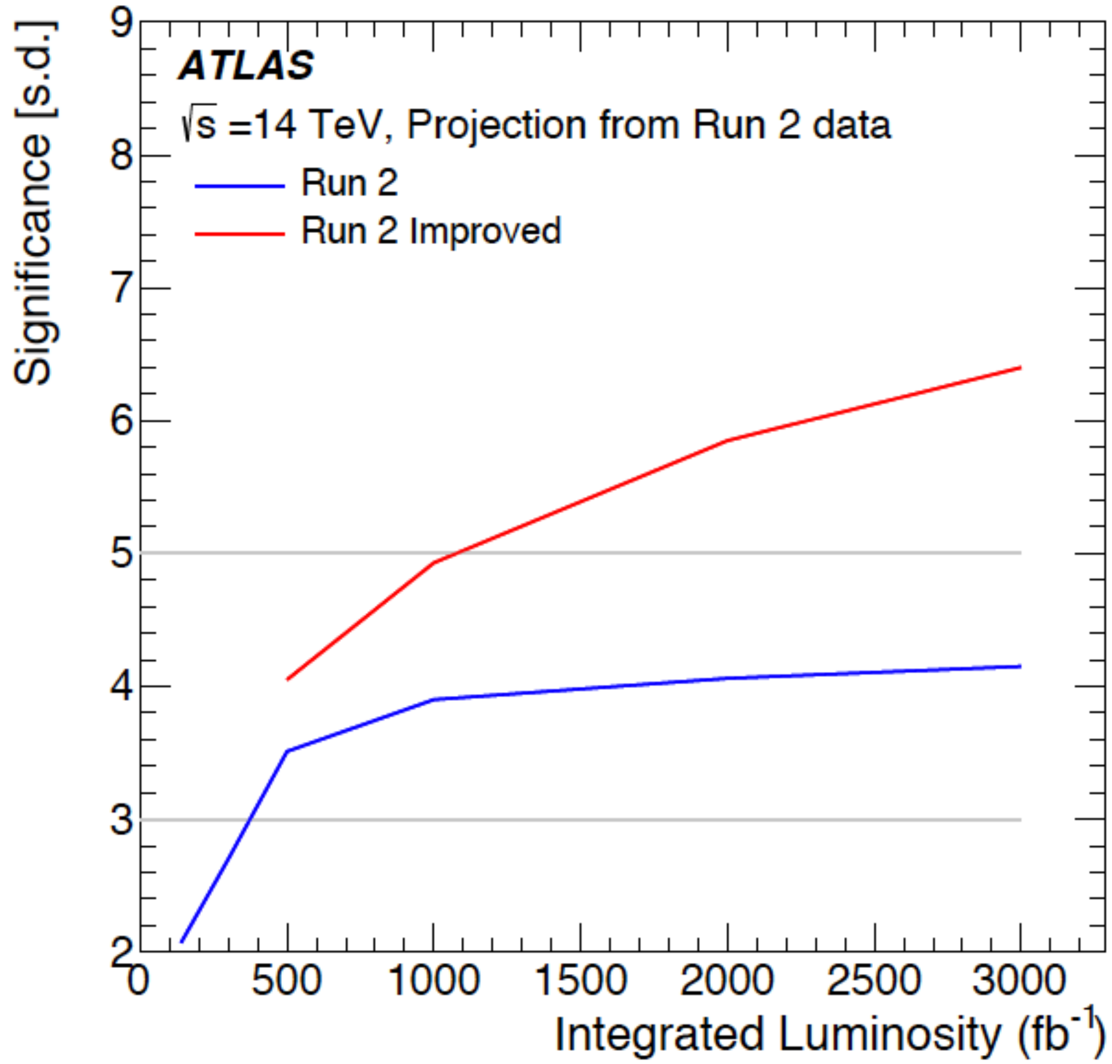
- The extrapolation is performed under two different scenarios of the evolution of detector performance and associated systematic uncertainties
- **“Run 2”** : systematic uncertainties are kept equal to their Run 2 values except uncertainties related to $t\bar{t}W + 7/8$jets (take the post-fit values of the corresponding nuisance parameters from the 139 fb^{-1} result)
- **“Run 2 Improved”**: includes the $t\bar{t}W + 7/8$jets scaling and includes a decrease of the systematic uncertainties based on the “YR18 systematic uncertainties”

Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

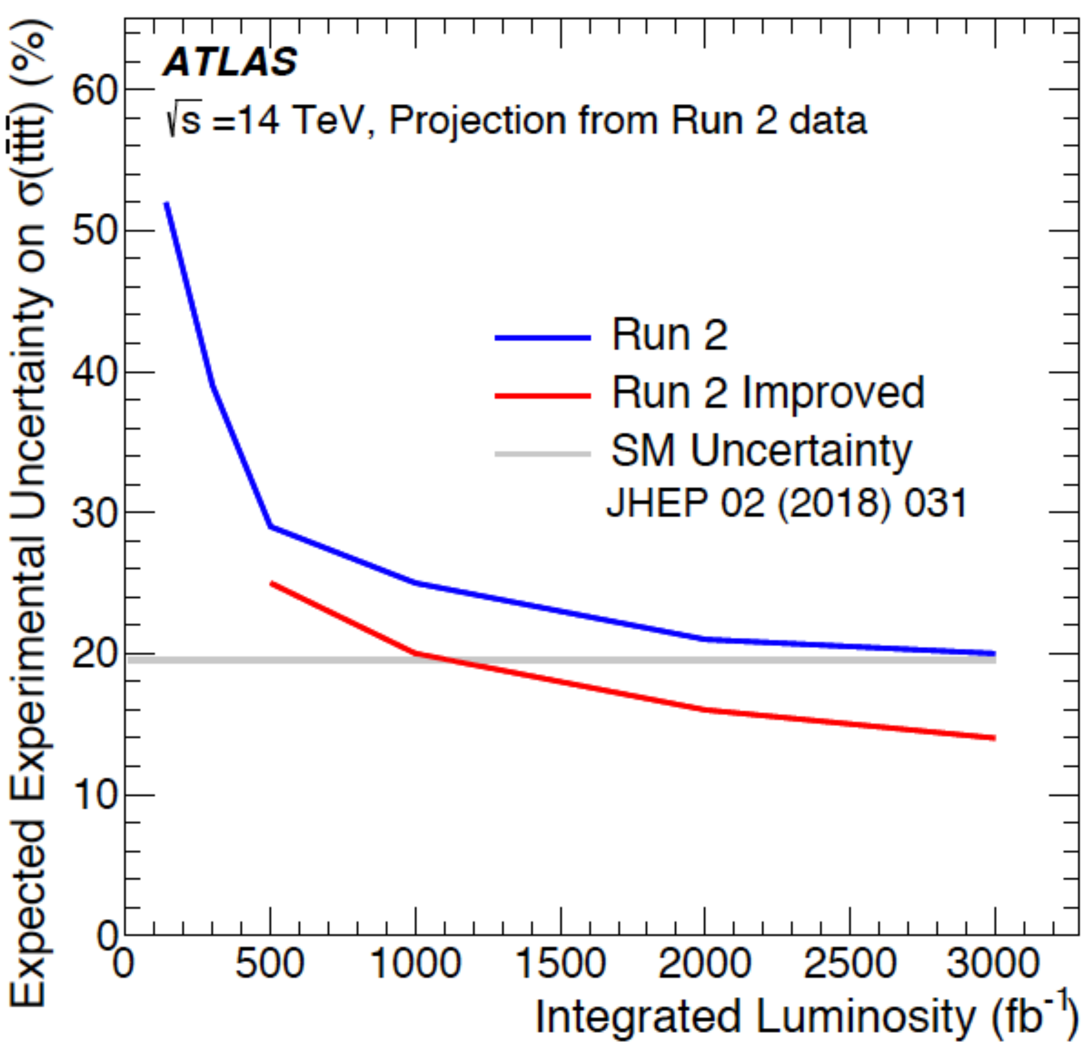
Uncertainty source	Treatment in the "Run 2 Improved" model
Signal modelling	
$t\bar{t}t\bar{t}$ cross section	Half of Run 2
$t\bar{t}t\bar{t}$ modelling	Half of Run 2
Background modelling	
$t\bar{t}W$+jets modelling	
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
Jets multiplicity modelling	Scaled by Run 2 pulls
Additional heavy flavour jets	Scaled by luminosity
$t\bar{t}t$ modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Non-prompt leptons modelling	Scaled by luminosity
$t\bar{t}H$+jets and $t\bar{t}Z$+jets modelling	
Cross section	Half of Run 2
Renormalisation and factorisation scales	Half of Run 2
Generator	Half of Run 2
PDF	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Other background modelling	
Cross section	Half of Run 2
Additional heavy flavour jets	Scaled by luminosity
Charge misassignment	Same as Run 2
Template fit shape uncertainties	
Mat. Conv., γ^*, and HF non-prompt leptons	Scaled by luminosity
Other fake leptons	Half of Run 2
Additional heavy flavour jets	Half of Run 2
Instrumental	
Jet uncertainties	Same as Run 2
Jet flavour tagging (light-flavour jets)	Half of Run 2
Luminosity	Same as Run 2
Jet flavour tagging (b-jets)	Half of Run 2
Jet flavour tagging (c-jets)	Half of Run 2
Other experimental uncertainties	Same as Run 2

Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

Expected significance



Expected experimental uncertainty



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Sensitivity of the SM $t\bar{t}t\bar{t}$ cross section at the HL-LHC

- The cross-section can be constrained down to 9% statistical uncertainty and 18% to 28% total uncertainty, depending on the considered systematic uncertainties, while a 4.5σ significance is expected with the most optimistic systematics scenario

- The expected sensitivity on the $t\bar{t}t\bar{t}$ cross-section is also used to provide constraints on EFT four top contact interaction operators, setting limits on their Wilson coefficients

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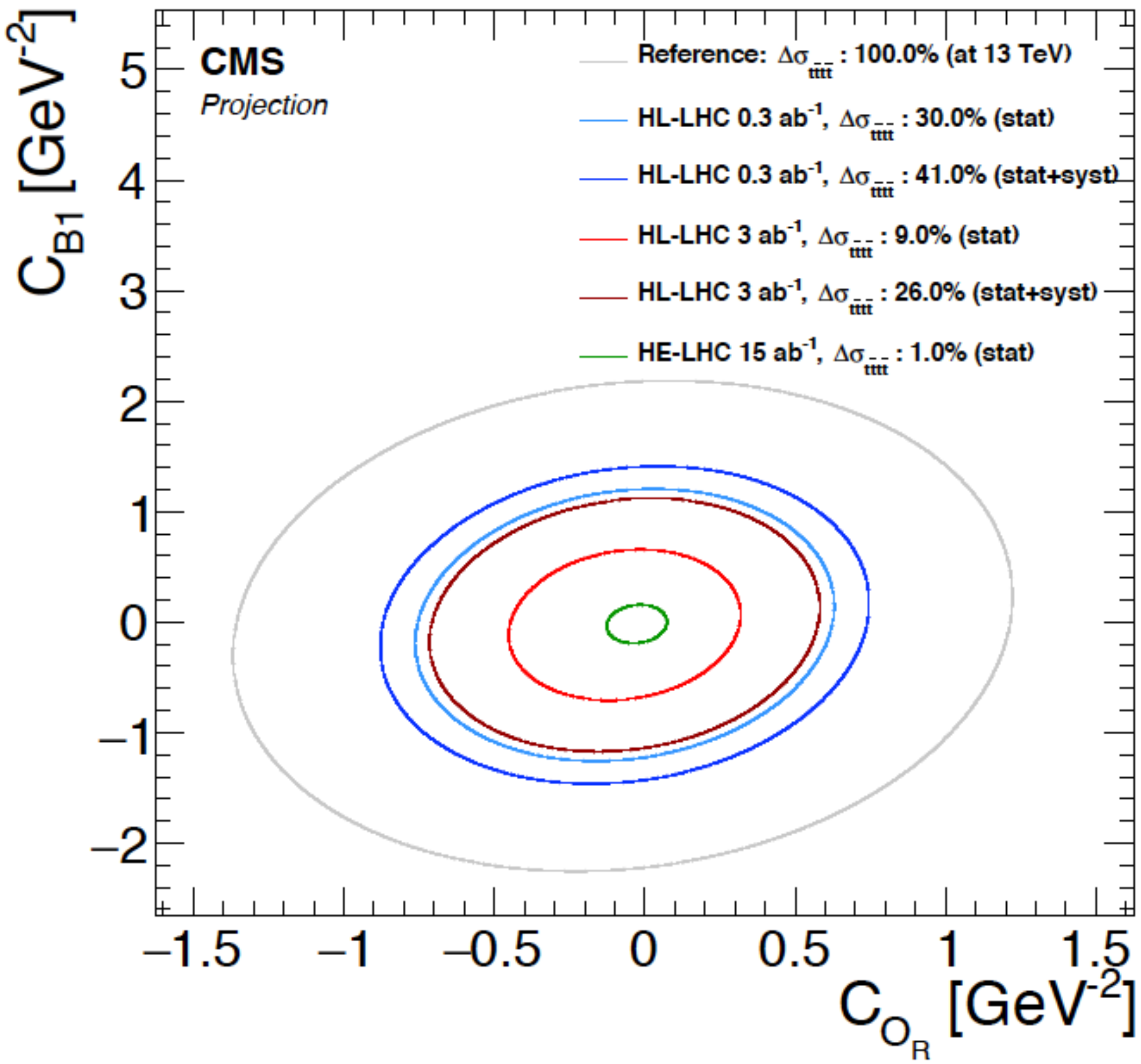
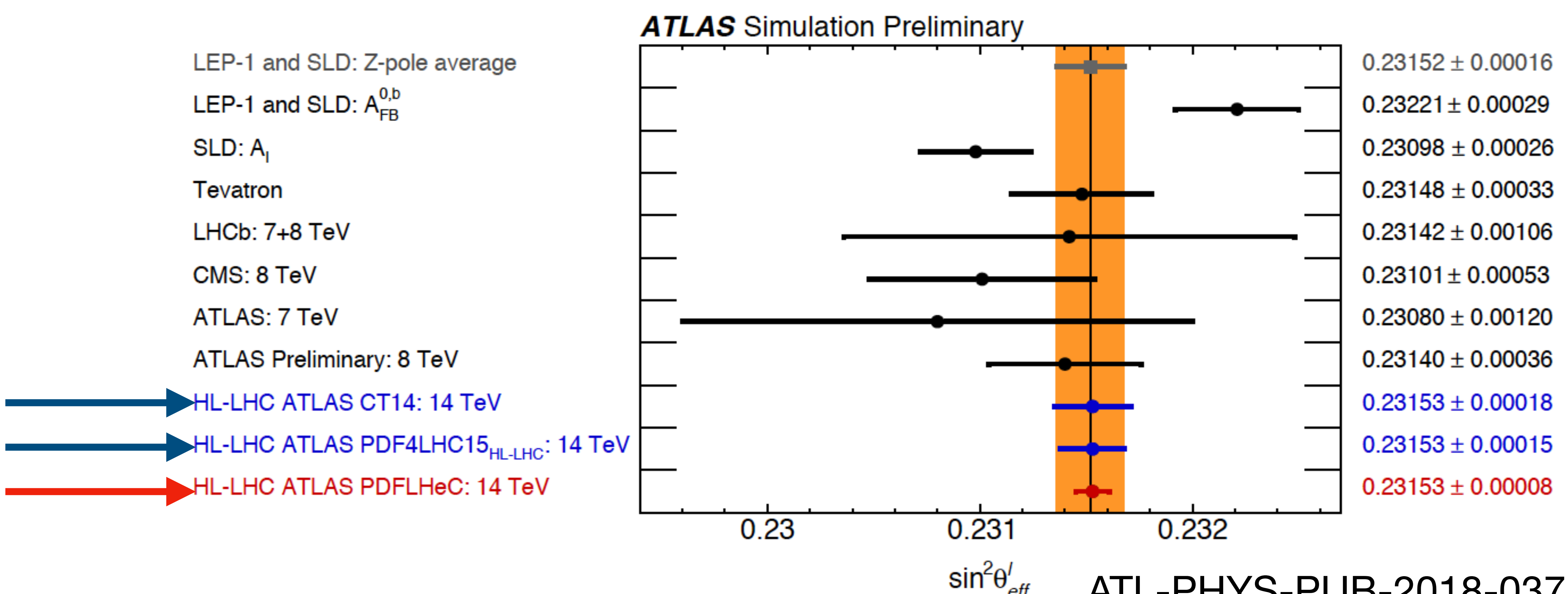


Weak mixing angle measurements

- Study performed in dielectron events, and will benefit from improved reconstruction of forward leptons from the extended reach of the ITk upgrade
  - This result will be dominated by the PDF uncertainties with the full HL-LHC dataset
    - Three different projected PDF sets are considered
    - The HL-LHC measurement will greatly improve the precision for any of the PDF choices, and is expected to achieve a precision similar to that of LEP and SLD
    - Further improvements to PDFs will be critical and can increase the sensitivity



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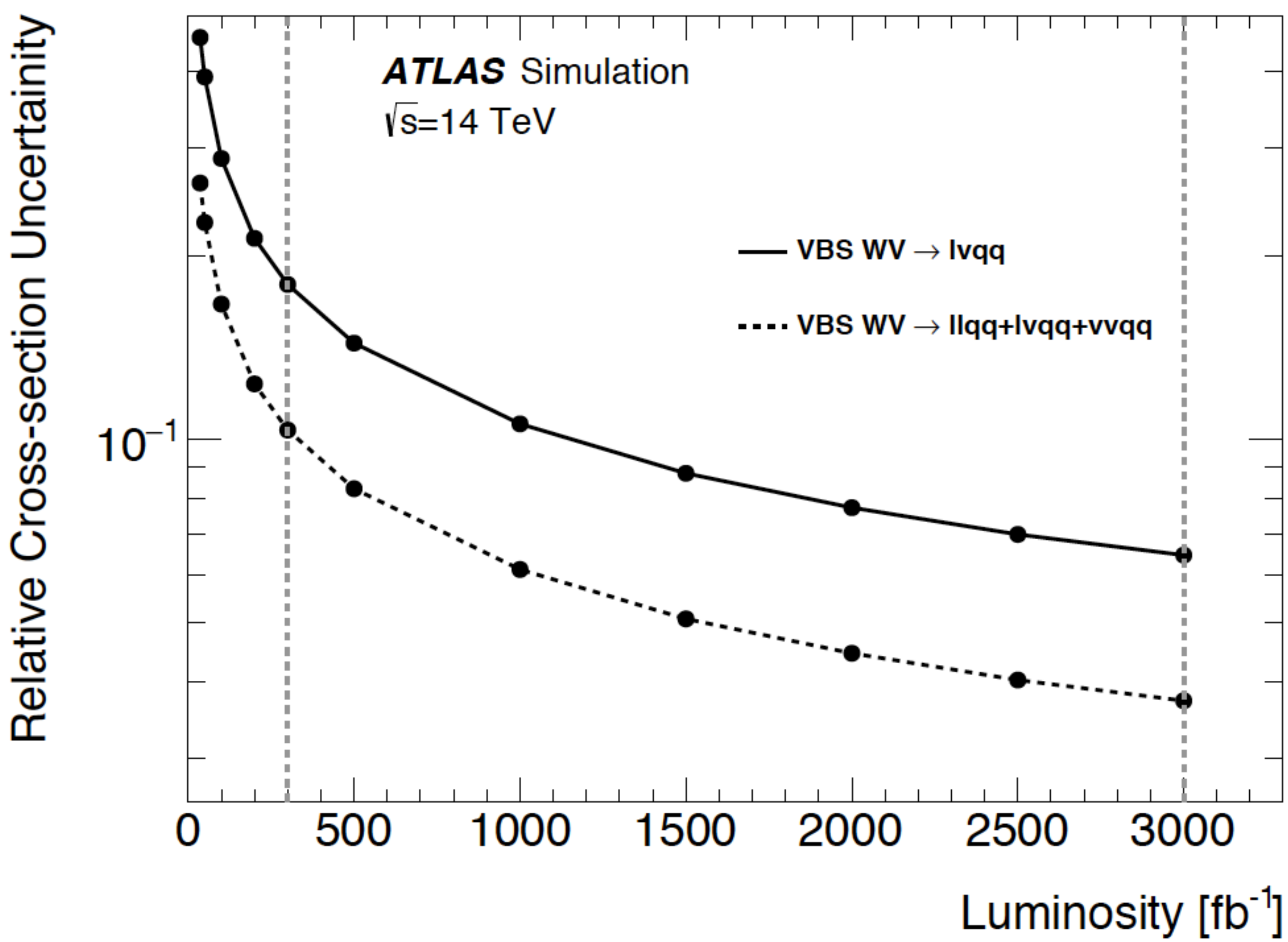
VBS diboson measurements

- Semi-leptonic decays are also able to provide sensitivity to EW VBS diboson processes
- The precision of this cross-section measurement is expected to be 6.5% with 3000 fb^{-1}

Expected cross-section uncertainty for the semileptonic WV analysis as function of integrated luminosity up to 3000 fb^{-1}



Charged lepton flavor violation (CLFV)

- SM CLFV effects are too small to be observed at LHC, but limits on the cross-section will provide constraints on several BSM models
- ATLAS experiment has constrained CLFV in 8 TeV search for $\tau \to 3\mu$ decays by using τ leptons originating from W bosons
- Three scenarios considered based on predicted changes to **low-p_T muon triggers** and improvements in **mass resolution** from better tracking and vertexing in upgraded detector
- Analysis improvements will have a significant impact on the sensitivity of these results by up to a factor of 50

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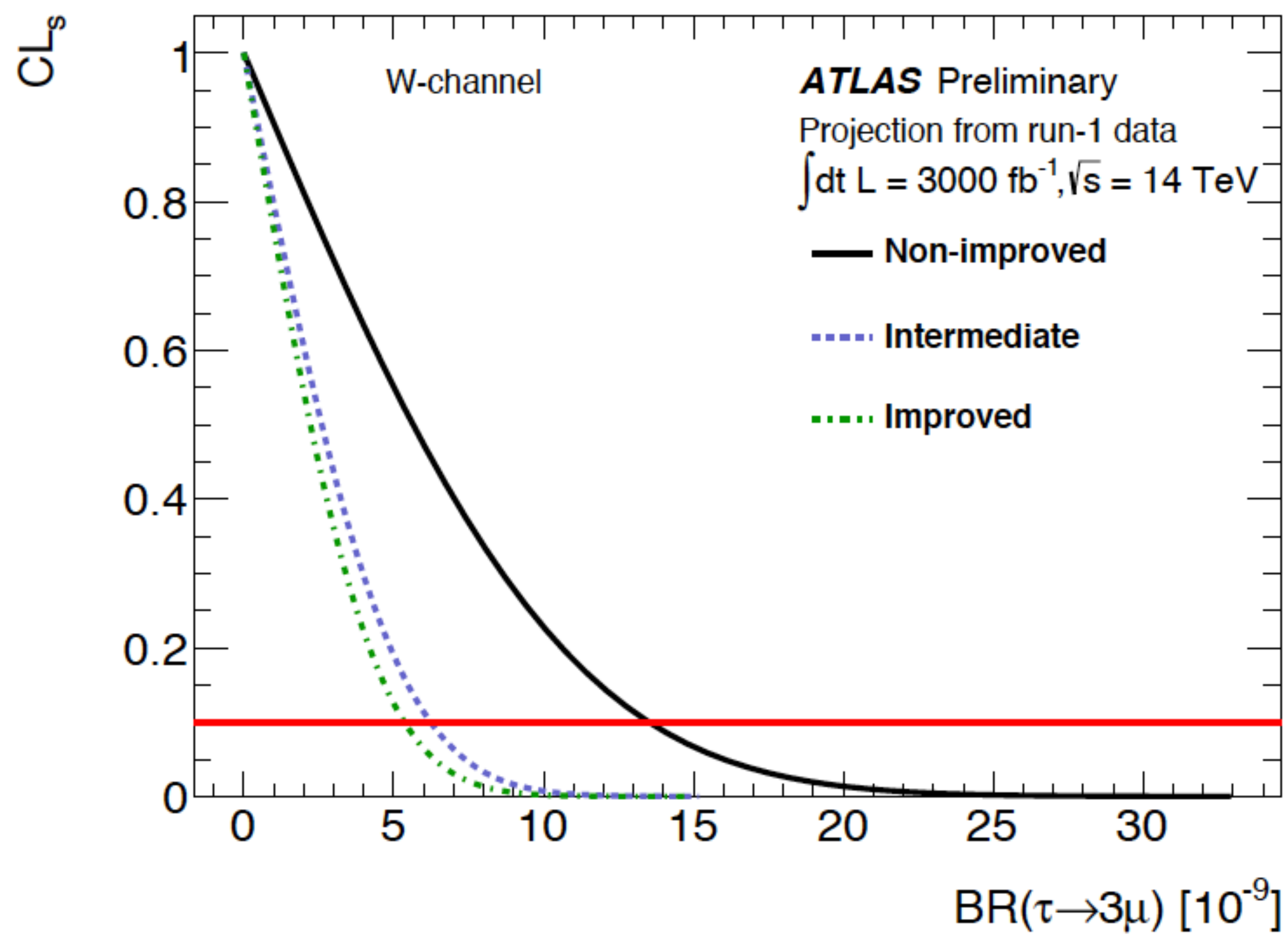
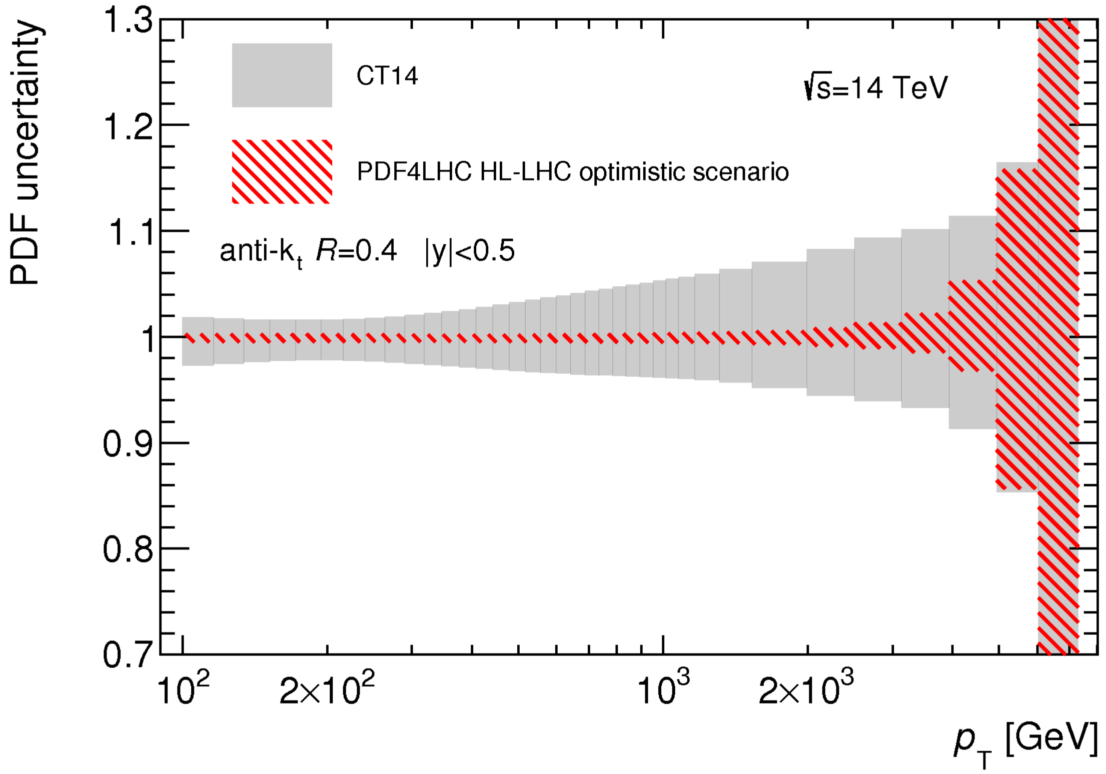
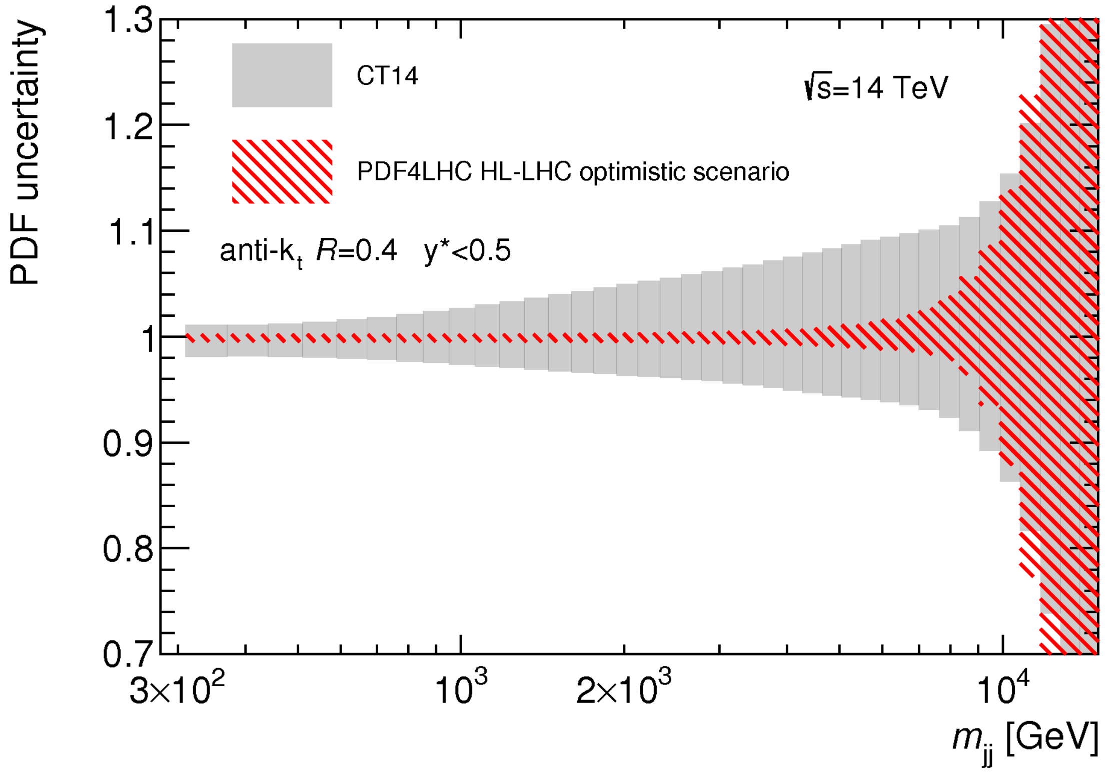


Prospects for jet cross-section measurements

- Including **HL-LHC** measurements in PDF fits, using projections of measurements of **jet cross section measurements**, inclusive **gauge boson** production, **top quark pair** production, W**-boson** production, and a measurement of $p_{T,Z}$
  - Significant reduction in the PDF uncertainties compared to the CT14 PDF set





Sensitivity to $\gamma\gamma \rightarrow W^{\pm}W^{\mp} \rightarrow e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ at the HL-LHC

- Key part of the analysis is dealing with the impact of pileup which will adversely affect the exclusivity criterion, which requires that the only tracks in the event come from the W boson decay products
- **Three HL-LHC configurations investigated**:
    - HL-LHC baseline, track-$|\eta| < 2.5$ - nominal analysis
    - HL-LHC baseline, track-$|\eta| < 4.0$ - forward tracking with the ITk
    - Track-pT > 500 MeV, track-$|\eta| < 2.5$ - dedicated low-pT reconstruction

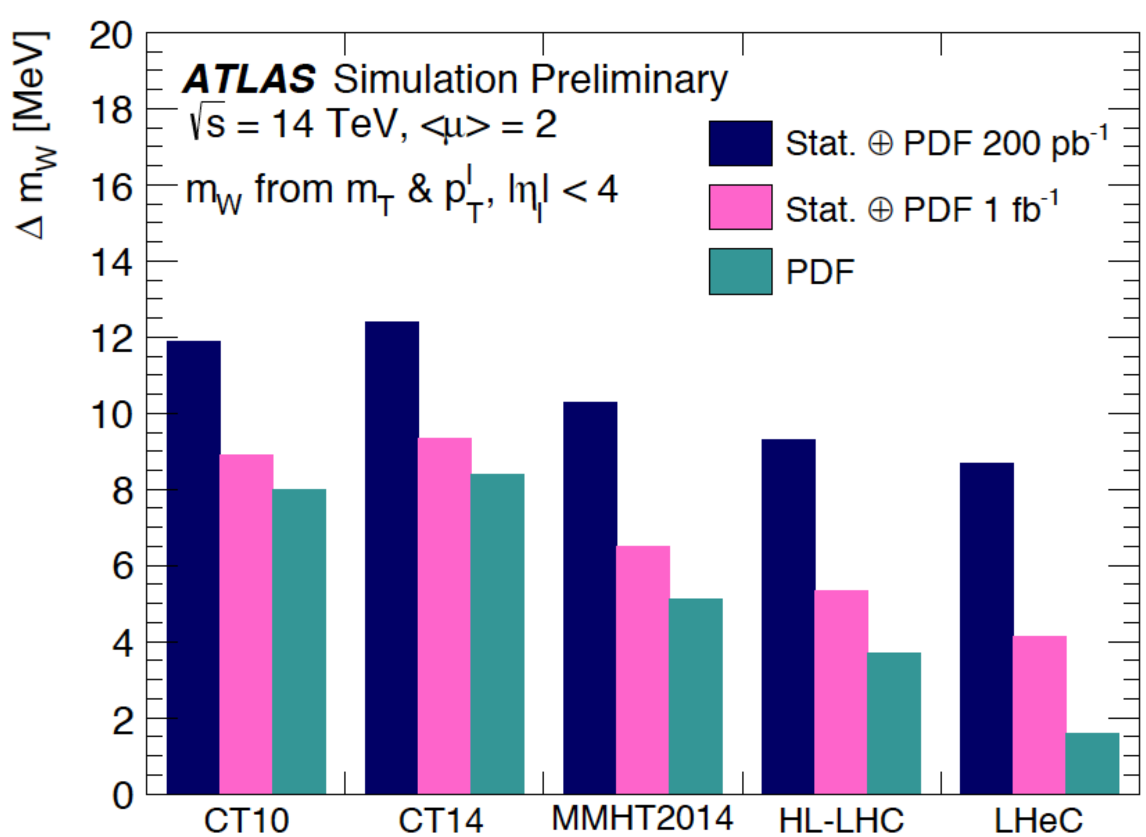
Backup: Sensitivity to $\gamma\gamma \to W^{\pm}W^{\mp} \to e^{\pm}\nu_e\mu^{\mp}\nu_\mu$ with ATLAS at the HL-LHC

- The reconstruction level selections that define the signal region

Reconstruction-level selection requirement	Reconstruction-level selection value
Single-lepton transverse momentum	$p_{\mathrm{T}} > 27$ GeV (leading), $p_{\mathrm{T}} > 20$ GeV (subleading)
Electron pseudorapidity	$\|\eta\| < 2.47$, excluding $1.37 < \|\eta\| < 1.52$
Muon pseudorapidity	$\|\eta\| < 2.4$
Dilepton selection	Exactly 2 leptons ($e^+\mu^-$ or $e^-\mu^+$)
Dilepton vertex	$z_{\mathrm{vtx}}^{\ell\ell} = (z_{\ell_1} \sin^2\theta_{\ell_1} + z_{\ell_2} \sin^2\theta_{\ell_2})/(\sin^2\theta_{\ell_1} + \sin^2\theta_{\ell_2})$
Lepton-vertex association	$\|z_\ell - z_{\mathrm{vtx}}^{\ell\ell}\| < 0.5$ mm
Dilepton mass	$m_{\ell\ell} > 20$ GeV
Dilepton transverse momentum	$p_{\mathrm{T}}^{\ell\ell} > 30$ GeV
Exclusivity definition	$n_{\mathrm{trk}} = 0$

W boson mass

- Measuring the W-boson mass requires a dedicated dataset collected at low instantaneous luminosity in order to reconstruct the missing transverse momentum with sufficient precision
- This measurement would benefit from forward lepton reconstruction enabled by the inner tracking detector upgrade, enhancing the current statistical precision of 7 MeV using 4.6 fb^{-1} of data
- The statistical precision could reach 10 MeV with 200 pb^{-1} and 3 MeV with 1 fb^{-1}
- The precision of this measurement depends on improvements to PDFs as well as the amount of data taken at low instantaneous luminosity



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