Theoretical Uncertainties in Searches for Heavy Gauge Bosons at the LHC

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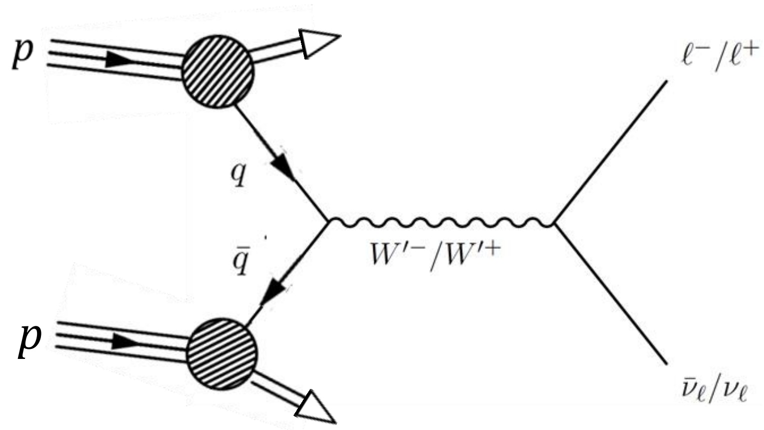
ATLAS EXPERIMENT

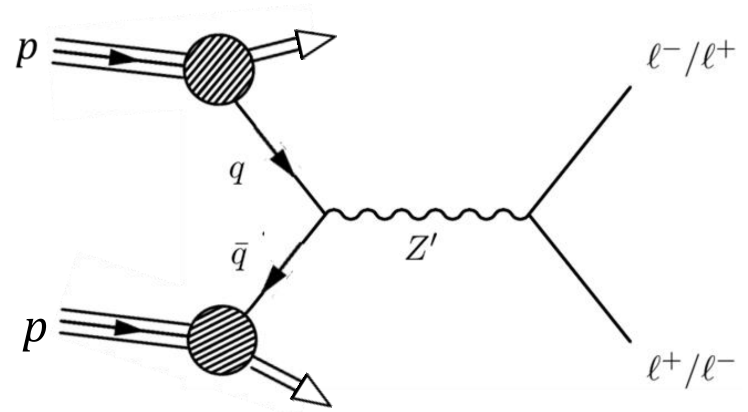
UNIVERSITY OF LIVERPOOL

Motivation

- The W′ and Z′ are new heavy gauge bosons arising from various extensions of the Standard Model.

- We consider s-channel W′ and Z′ in the context of the Sequential Standard Model (SSM):
  - Same couplings to fermions as SM W and Z but TeV scale masses.
  - Useful model used as a benchmark, other models may be studied:
    - Extra dimensions, E_6 GUTs…





- Searches by ATLAS using 20.3 fb^{-1} of $\sqrt{s}$ = 8 TeV data exclude W'_{SSM} masses below 3.24 TeV and Z'_{SSM} masses below 2.90 TeV at 95% CL.

First Run-2 Results

- First results at $\sqrt{s}$ = 13 TeV set preliminary W′ and Z′ limits of 4.07 TeV and 3.40 TeV, respectively.

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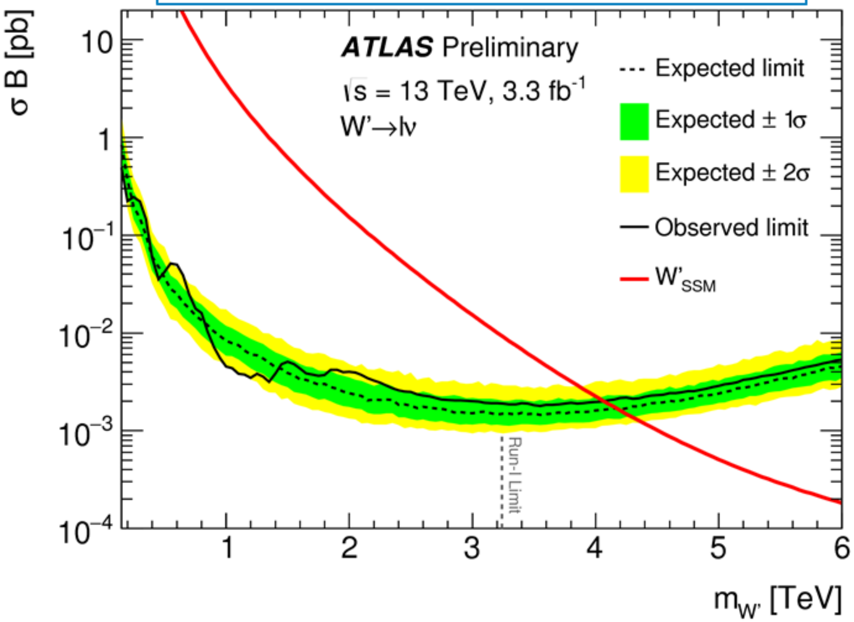

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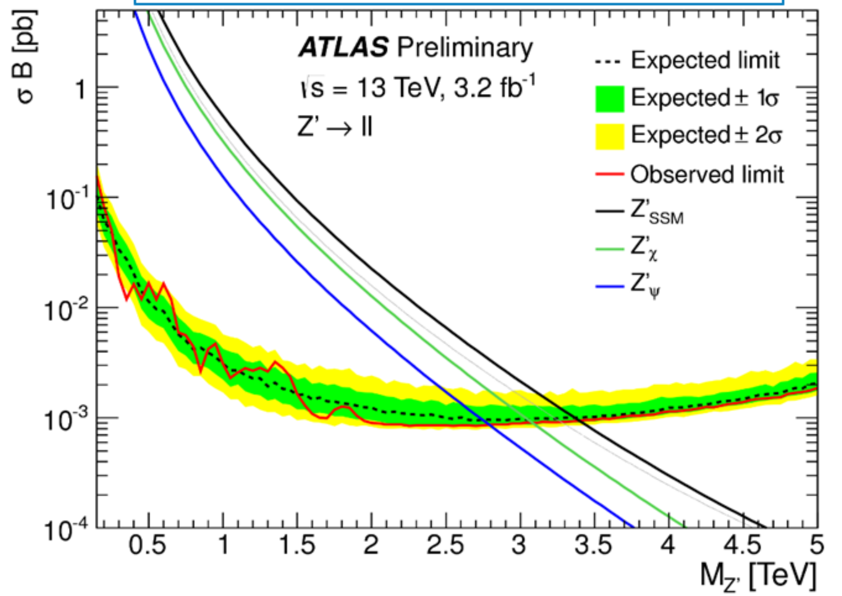

- For Z′, limits for GUT model with E_6 gauge group broken into SU(5) & two U(1) groups.
  - Z′ candidate from linear combination of corresponding gauge bosons Z'_χ & Z'_ψ

Data vs. Monte Carlo

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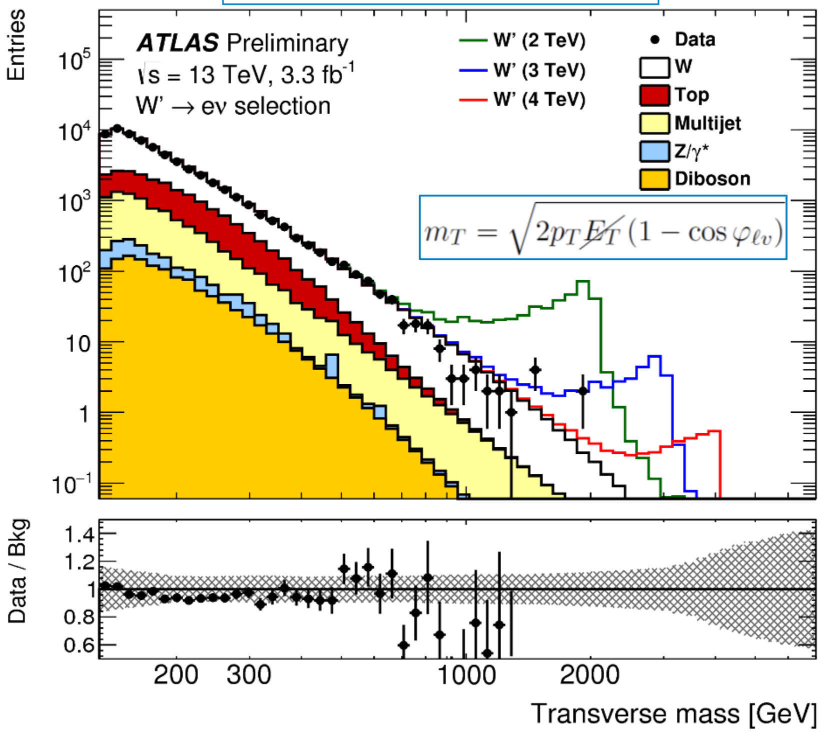

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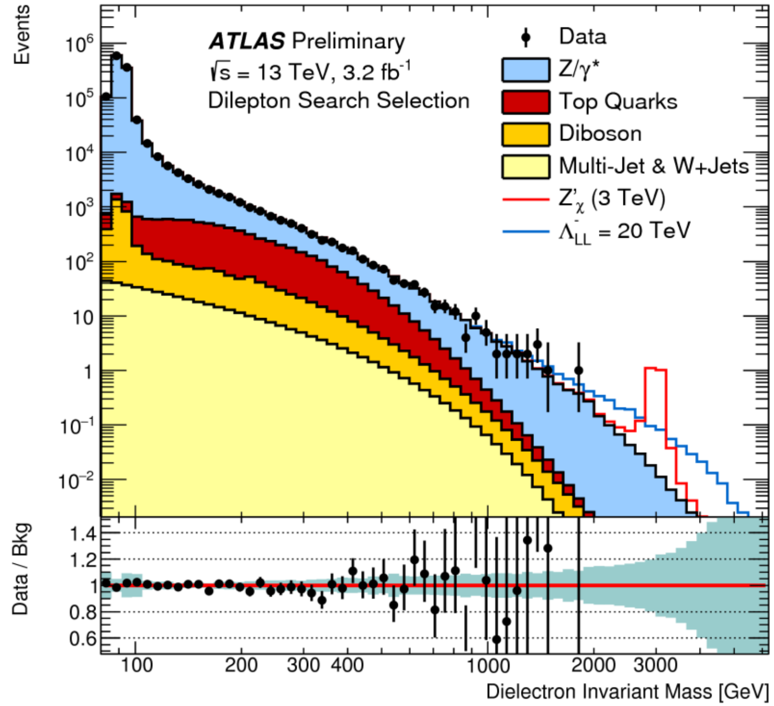

- For W′ and Z′ searches, Charged Current and Neutral Current Drell-Yan production are the dominant background sources.

- These backgrounds must be accurately modelled to reflect current knowledge.
  - This is achieved by applying theory corrections to the MC samples.

QCD @ NNLO
EW @ NLO

QCD @ NLO
EW @ LO

Systematic Uncertainties

- Lack of knowledge of the proton structure at large Bjorken x is the dominant source of theoretical uncertainty in high mass searches.

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- **W' 2(4) TeV**
– Systematics < 3% considered negligible

Source	Electron channel Background	Electron channel Signal	Muon channel Background	Muon channel Signal
Trigger	negl. (negl.)	negl. (negl.)	3% (3%)	3% (4%)
Lepton reconstruction and identification	negl. (negl.)	negl. (negl.)	6% (10%)	5% (8%)
Lepton isolation	negl. (negl.)	negl. (negl.)	5% (5%)	5% (5%)
Lepton momentum scale and resolution	3% (3%)	11% (6%)	49% (69%)	5% (21%)
E_T^{miss} resolution and scale	< 0.5% (< 0.5%)	< 0.5% (< 0.5%)	1% (1%)	1% (2%)
Jet energy resolution	< 0.5% (< 0.5%)	< 0.5% (1%)	1% (1%)	1% (1%)
Multijet background	3% (19%)	N/A (N/A)	negl. (negl.)	N/A (N/A)
PDF choice for DY production	3% (13%)	N/A (N/A)	2% (2%)	N/A (N/A)
PDF variation for DY production	8% (10%)	N/A (N/A)	6% (8%)	N/A (N/A)
Luminosity	8% (4%)	9% (9%)	9% (9%)	9% (9%)
Total	12% (26%)	14% (11%)	51% (71%)	13% (25%)

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- **Z' 2(3) TeV**

Source	Dielectron Signal	Dielectron Background	Dimuon Signal	Dimuon Background
Normalisation	4.0% (4.0%)	N/A	4.0% (4.0%)	N/A
PDF Choice	N/A	9.1% (17%)	N/A	5.3% (7.4%)
PDF Variation	N/A	5.3% (11%)	N/A	4.4% (6.5%)
PDF Scale	N/A	1.8% (2.3%)	N/A	1.7% (1.9%)
Photon-induced corrections	N/A	3.4% (5.4%)	N/A	3.2% (3.8%)
Efficiency	5.1% (5.0%)	5.1% (5.0%)	13% (19%)	13% (19%)
Scale & Resolution	<1.0% (<1.0%)	7.8% (9.1%)	20% (26%)	20% (46%)
Multi-jet & W+jets	N/A	<1.0% (<1.0%)	N/A	N/A
MC Statistics	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)	<1.0% (<1.0%)
Total	6.5% (6.4%)	15% (24%)	25% (32%)	26% (51%)

K-factor Approach

- Mass dependent $\boxed{\text{k-factors}}$ are applied to Monte Carlo in order to correct to current theory knowledge.

  Correction factors to shift MC to best theory predictions

- Theory cross sections are obtained through external calculations.
  - U. Klein Les Houches 2013: Physics at TeV Colliders Standard Model Working Group Report Chapter III.2, arXiv:1405.1067

- Theory systematics are included in the k-factor:
  - PDF & α_S uncertainty (90% CL) for nominal PDF.
  - PDF choice.

  Except QED FSR (already included in MC)

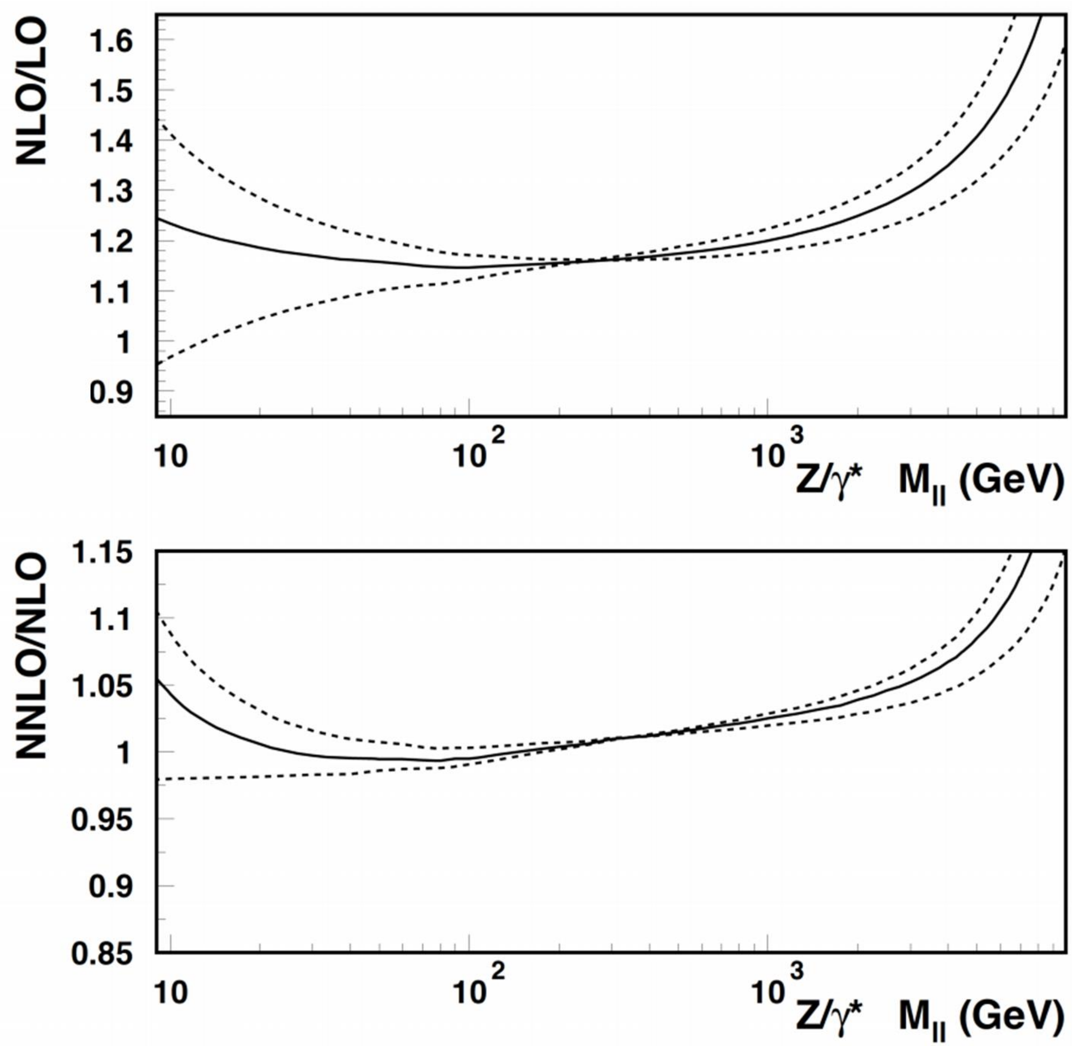
- Higher order QCD (NNLO) and EW (NLO) processes are included.
  - HO QCD corrections are also applied to signal.
- All fits for cross sections / systematics are described by functions:
  - Easily applied to Monte Carlo using ROOT.
  - Provide function with Born level invariant mass & obtain event weight.

  Before final state QED radiation

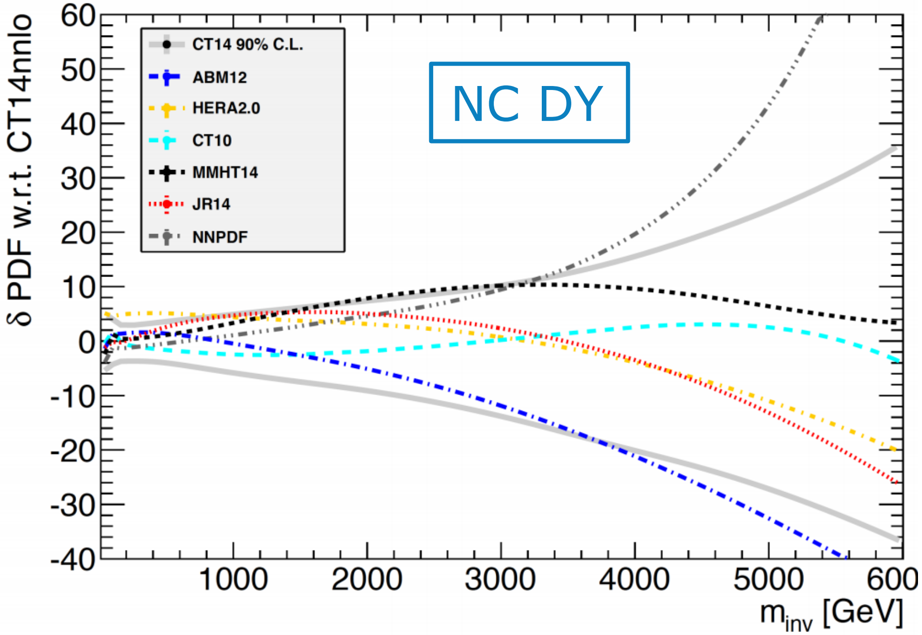
Size of QCD Corrections

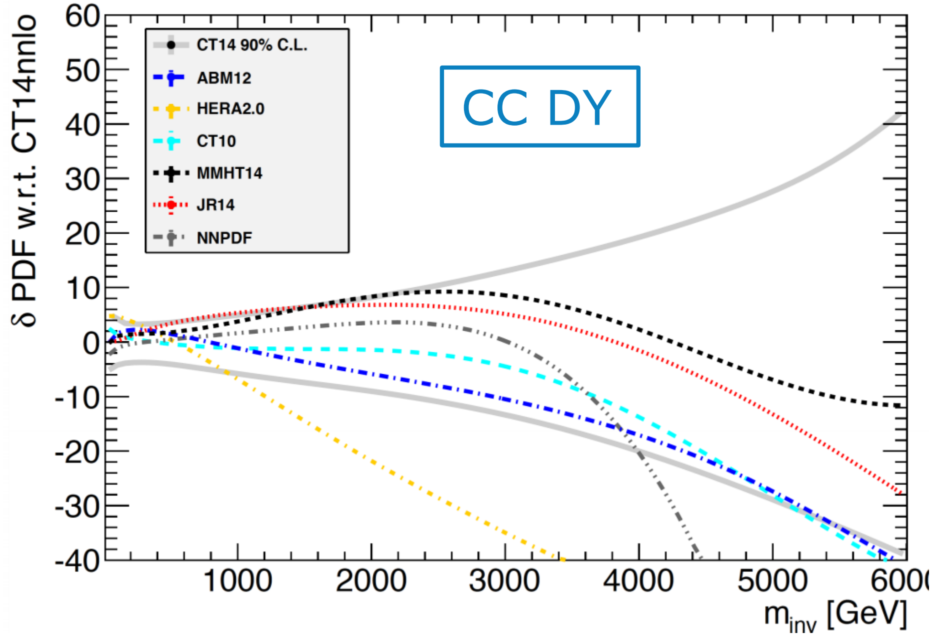
NC DY

- Using CT14nnlo (nominal) at all orders of QCD:
  - Strong mass dependence → large effects at high mass.

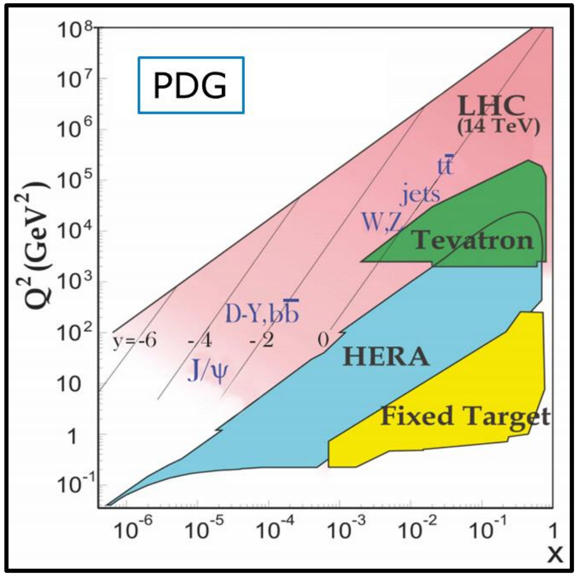


Summary of PDF Sets





- Considering all available modern PDF sets.
  - In the process of evaluating upper/lower estimates for all of these sets.
  - Currently focus on nominal (CT14).



PDF Uncertainty: Hessian Method

- Each PDF set has a set of mutually independent parameters formed by varying central PDF values by their systematic uncertainties.

- These parameters are known as the "eigenvectors" of the PDF set in function space, as they can be varied in orthogonal directions to quantify the systematic uncertainties associated with PDF variations.

- The asymmetric uncertainty is calculated as:

$$\Delta\sigma^+ = \sqrt{\sum_{i=1}^{N_{eig}} [\max(\sigma_i^+ - \sigma_0, \sigma_i^- - \sigma_0, 0)]^2}$$

$$\Delta\sigma^- = \sqrt{\sum_{i=1}^{N_{eig}} [\max(\sigma_0 - \sigma_i^+, \sigma_0 - \sigma_i^-, 0)]^2}$$

N_{eig} – Number of PDF EVs

σ_i^+ – σ for the higher value of i^{th} PDF EV

σ_i^- – σ for the lower value of i^{th} PDF EV

σ_0 – σ for the central value PDF

- CT14 NNLO PDF has a set of 28 eigenvectors.

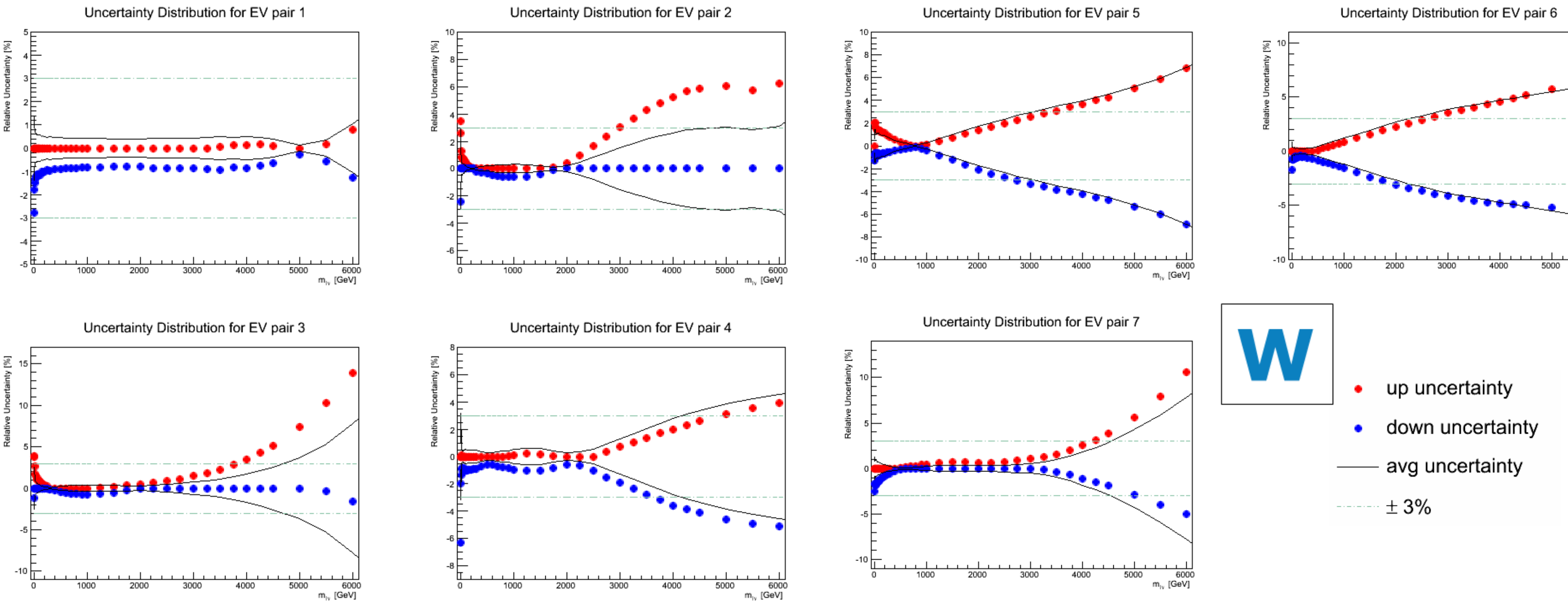
- Uncertainties are calculated for W^+, W^-, Z and combined W (where σ^{W+} and σ^{W-} are added for each EV).

CT14 NNLO Eigenvectors for W

- Symmetric (avg) uncertainties are calculated as a simple average of the up and down uncertainties.

$$\Delta\sigma^{symm} = \frac{1}{2}\sqrt{\sum_{i=1}^{N_{eig}}[\sigma_i^{+} - \sigma_i^{-}]^2}$$

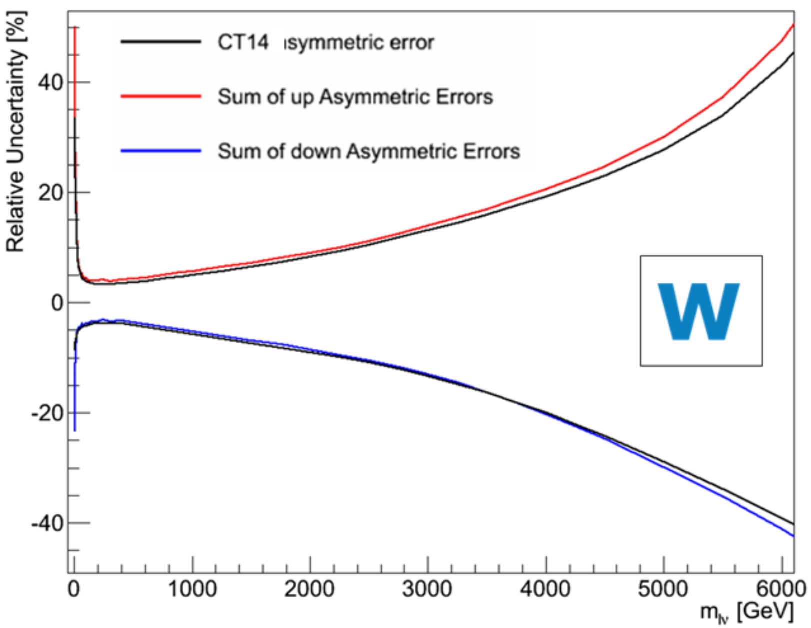
- e.g. first 7 of the 28 CT14 eigenvectors for W:

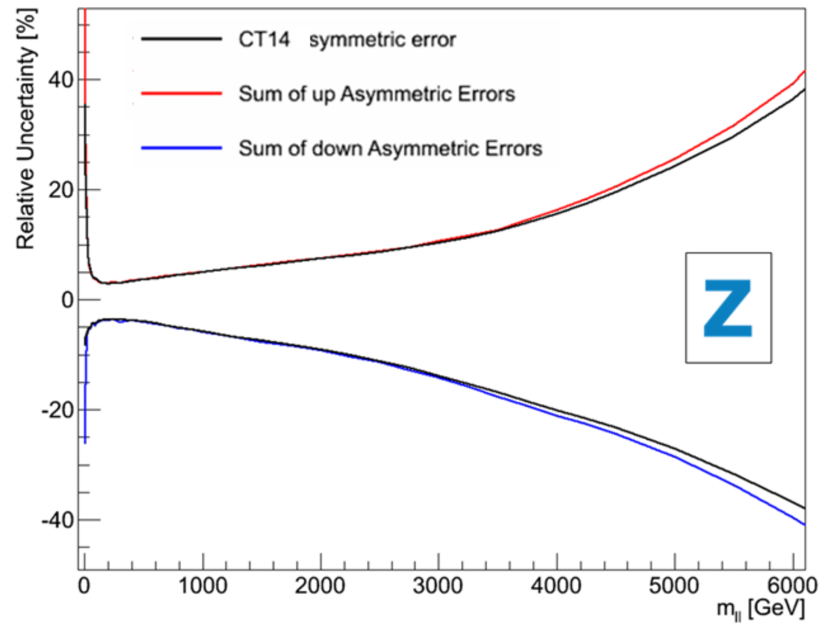


- Each EV has a distinct mass dependence.

Overall PDF Uncertainty

- Comparing quadratic sum of all asymmetric and symmetric CT14nnlo EVs:

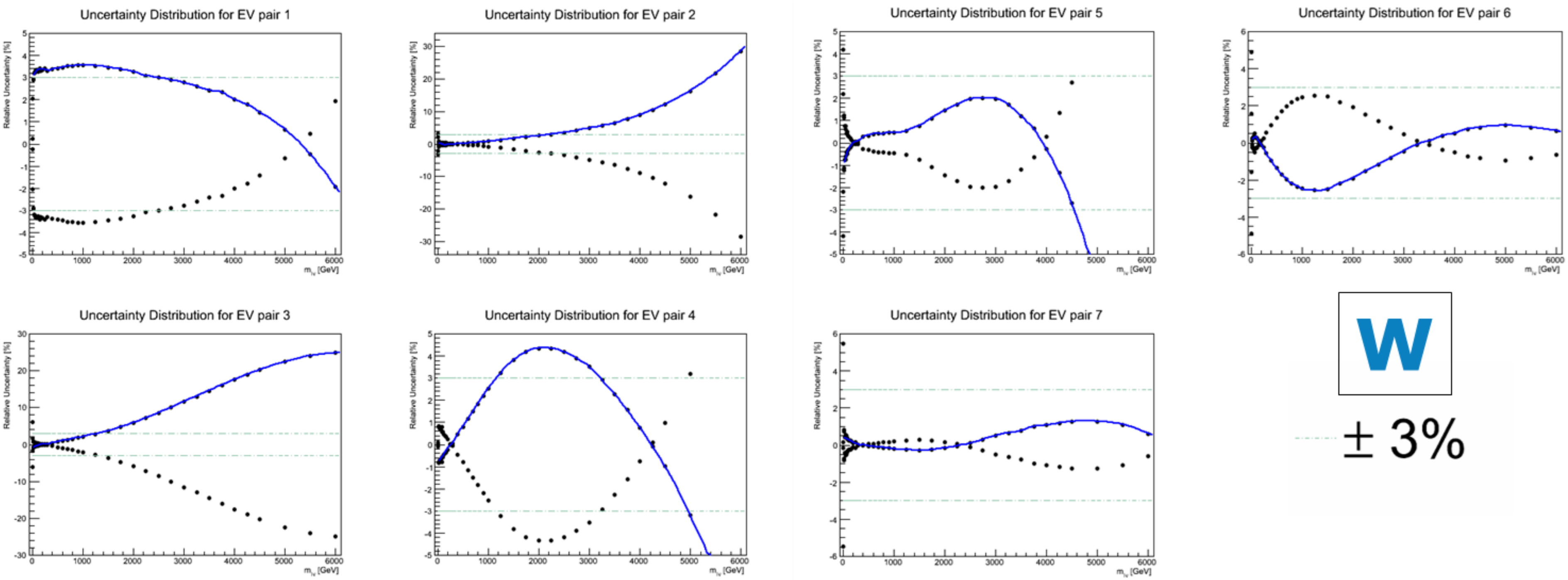




- Symmetrising errors only has a small effect.
- Usually this overall symmetric error is used as the single PDF error nuisance parameter for W′ and Z′ searches.
  - Easy to apply to Bayesian analysis tools for limit setting.
- This neglects the mass dependence exhibited by the separate EVs.
- For the Run-1 resonant Z′ search, EVs were grouped into bundles of similar mass dependence → a nuisance parameter for each bundle.

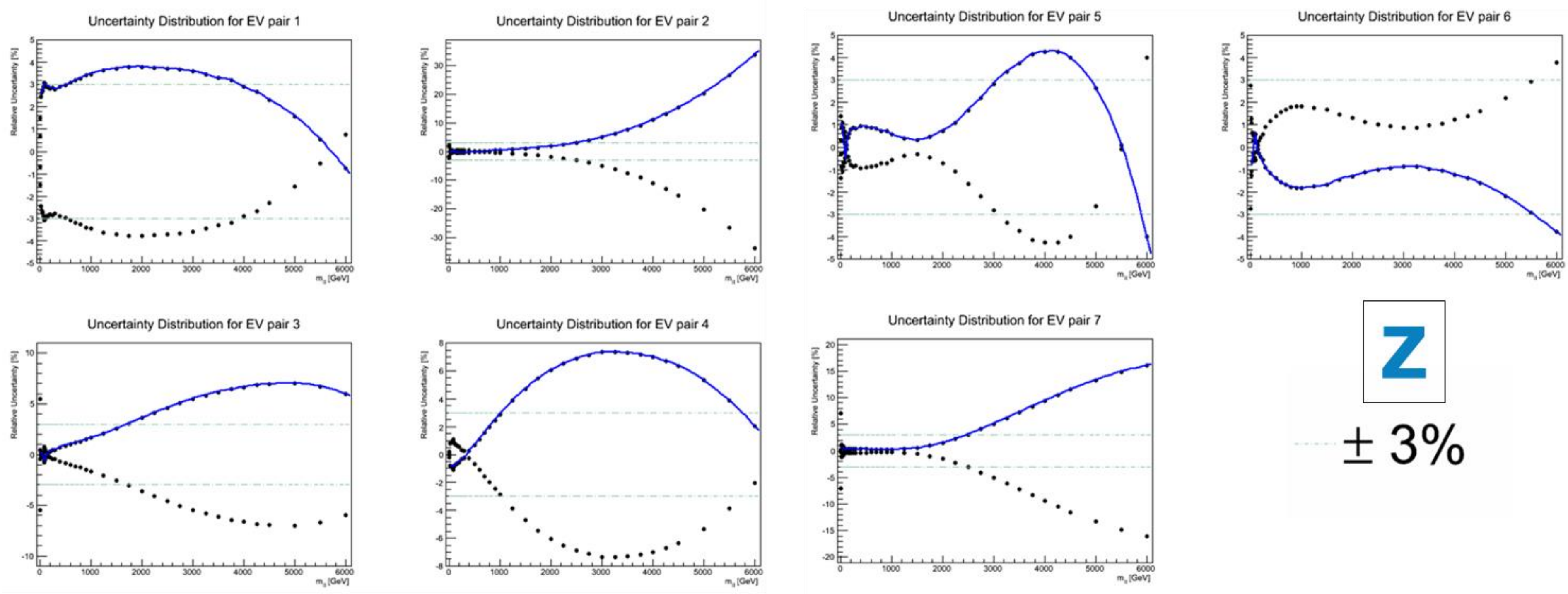
Reduced Set of Eigenvectors

- As an alternative to bundles produced with combinations of the 28 eigenvectors, 7 new eigenvectors for each VB (for DY production with mass > 120 GeV) were provided by CT14 authors.



- These eigenvectors are orthogonal between the W and Z boson, aiding any future combination effort between the W′ and Z′ searches.

Reduced Set of Eigenvectors



- Bundles which are considered to have a negligible effect (< 3%) are omitted from the analyses, with the rest added to statistical tools for limit setting.

- Bundles are provided as fits (blue) in the positive direction only as they are symmetric.

EW Corrections

- Two main methodologies exist for producing combined NNLO QCD and NLO EW cross sections: (1) factorised and (2) additive

1

$$\begin{aligned}\sigma_{NNLO\_QCD+NLO\_EW} &= k_{QCD} \times k_{EW} \times \sigma_{LO\_QCD} \\ k_{QCD} &= \frac{\sigma_{NNLO\_QCD}}{\sigma_{LO\_QCD}} \\ k_{EW} &= \frac{\sigma_{NLO\_EW,LO\_QCD}}{\sigma_{LO\_QCD}}.\end{aligned}$$

("EW" = HO EW except QED FSR)
– Include QED ISR, ISR & FSR interference

2

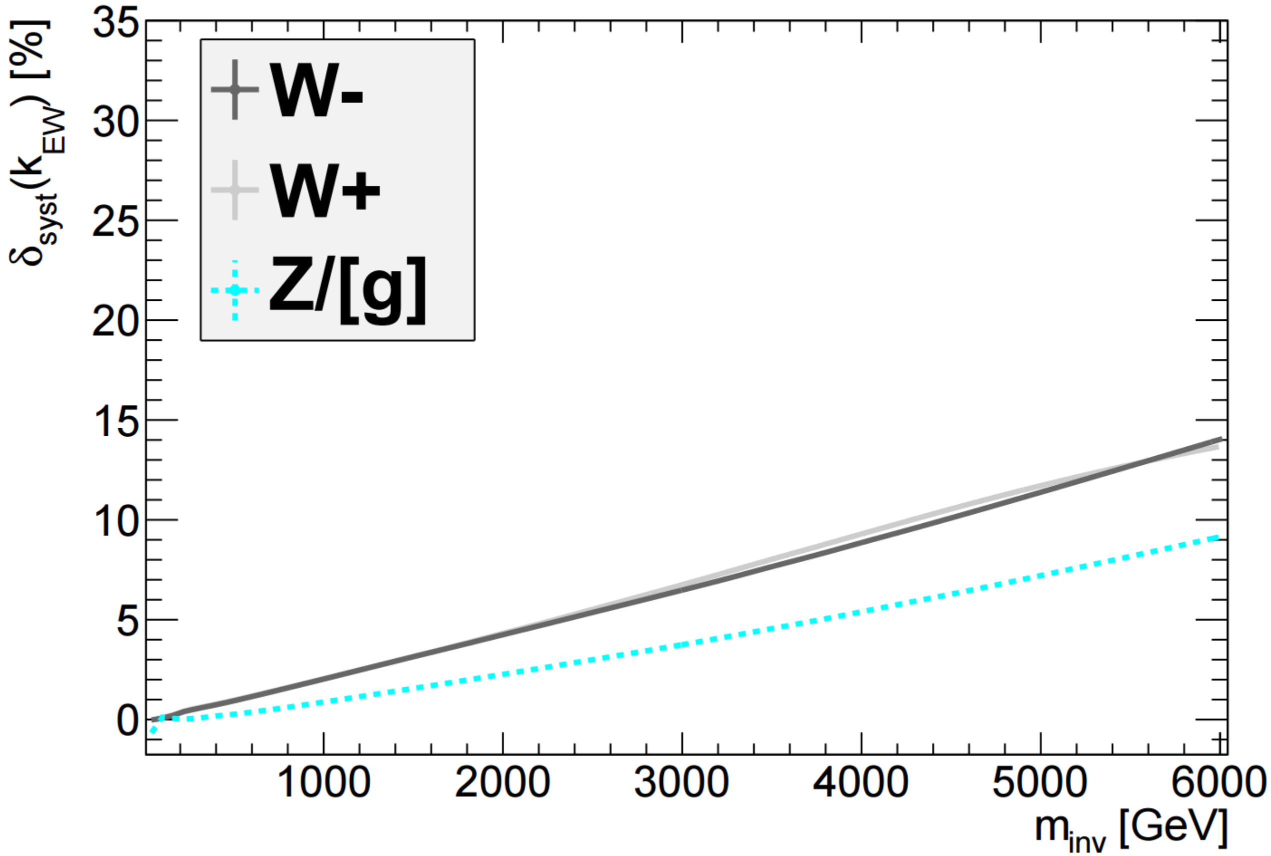
$$\begin{aligned}\sigma_{NNLO\_QCD+NLO\_EW} &= \sigma_{NNLO\_QCD} + \Delta\sigma_{LO\_QCD+NLO\_EW} \\ &= \sigma_{NNLO\_QCD}(1 + \frac{\Delta\sigma_{LO\_QCD+NLO\_EW}}{\sigma_{NNLO\_QCD}})\end{aligned}$$

1. HO EW corrections applied as factor which is the same for all QCD orders (∴ EW factor dependent on LO QCD).
2. HO EW corrections are a constant additional σ to be added to each order of QCD (∴ QCD order dependent factors).

- Additive approach is chosen to be the nominal one for these analyses.
  - Was also used in run-1 ATLAS exotics searches.
  - Found to be the more justified approach from discussions with SANC group.

EW Systematic

- Remaining NLO EW except QED FSR systematic for DY σ prediction:



- This systematic is particularly large for CC DY.
- Also becomes substantial (>3%) for NC DY in the higher mass range.
  - Must be accounted for in limit setting.

Summary

- First results at $\sqrt{s}$ = 13 TeV set preliminary W′ and Z′ limits of 4.07 TeV and 3.40 TeV, respectively.

- As these searches extend to hitherto unexplored high mass regions, higher order QCD and electroweak corrections become large & require accurate modelling.

- Approaches to modelling theoretical uncertainties arising from lack of understanding of the proton structure have been discussed.

- Fits for these systematic uncertainties are now being applied to the W′ and Z′ searches ready for next publications.
  - Applying HO QCD corrections to signal MC.
  - Applying other HO corrections (NNLO QCD & NLO EW) to DY background.

- Methods are constantly being refined to accommodate future combined W′ and Z′ limits.
  - Change to reduced set of orthogonal PDF eigenvectors.

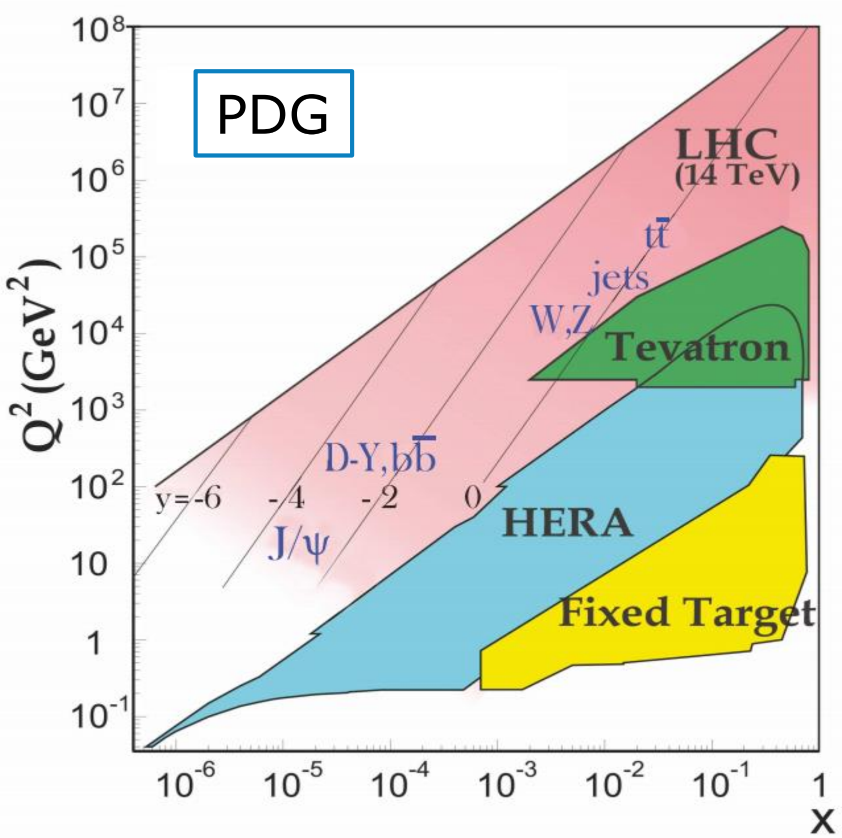
Backup

Parton Distribution Functions

- Parton Distribution Functions (PDFs) describe the probability of a struck parton that carrying fraction x of the collided proton's longitudinal momentum.

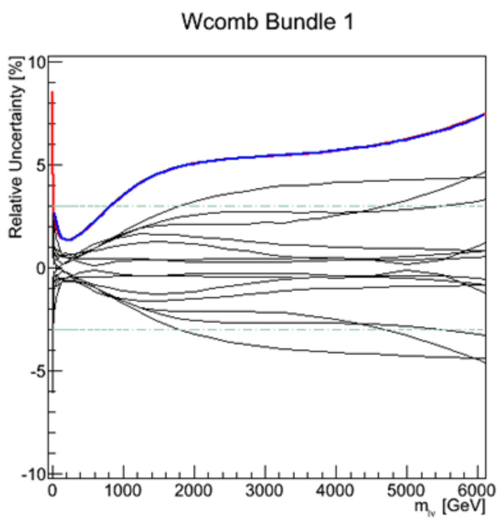
- PDF sets are produced by fitting cross section data in a grid of Q^2 and x values from various experiments.

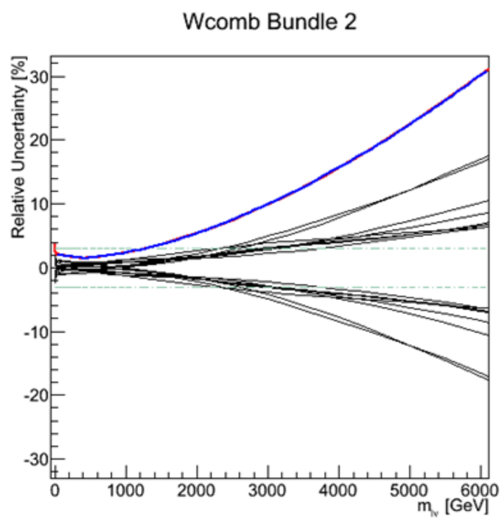
- NNLO PDF sets studied here include:
  - CT14 arXiv:1506.07443 (NOMINAL)
  - NNPDF 3.0 arXiv:1410.8849
  - HERAPDF 2.0 arXiv:1511.05402
  - abm12lhc arXiv:1310.3059
  - JR14 arXiv:1403.1852
  - MMHT2014 arXiv:1412.3989
  - MSTW2008 arXiv:0901.0002

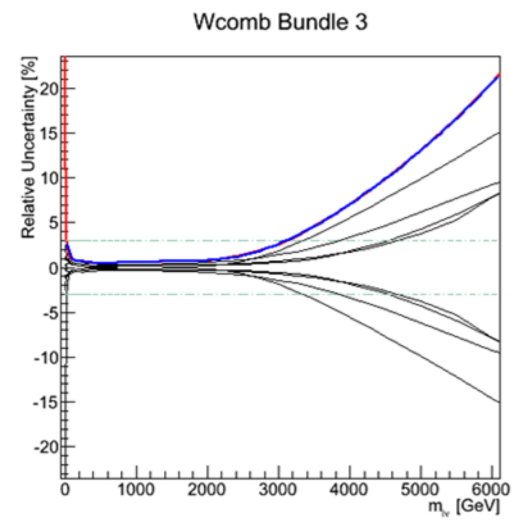


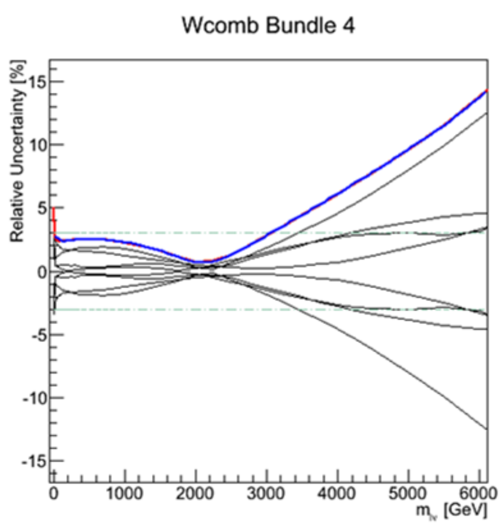
Bundling of 28 W Eigenvectors

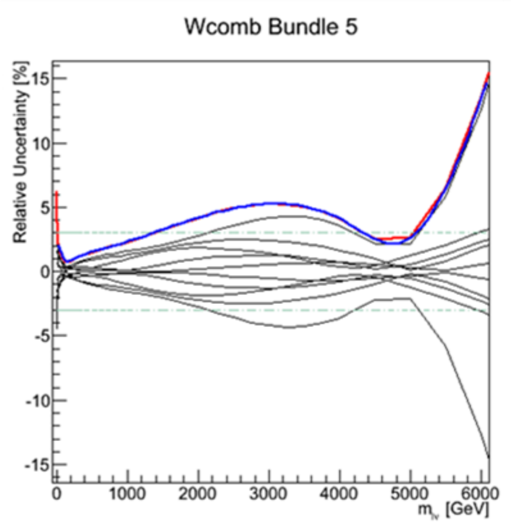
- These bundles are made ‘by hand’ through inspection of the plots for average uncertainty of the 28 eigenvectors.





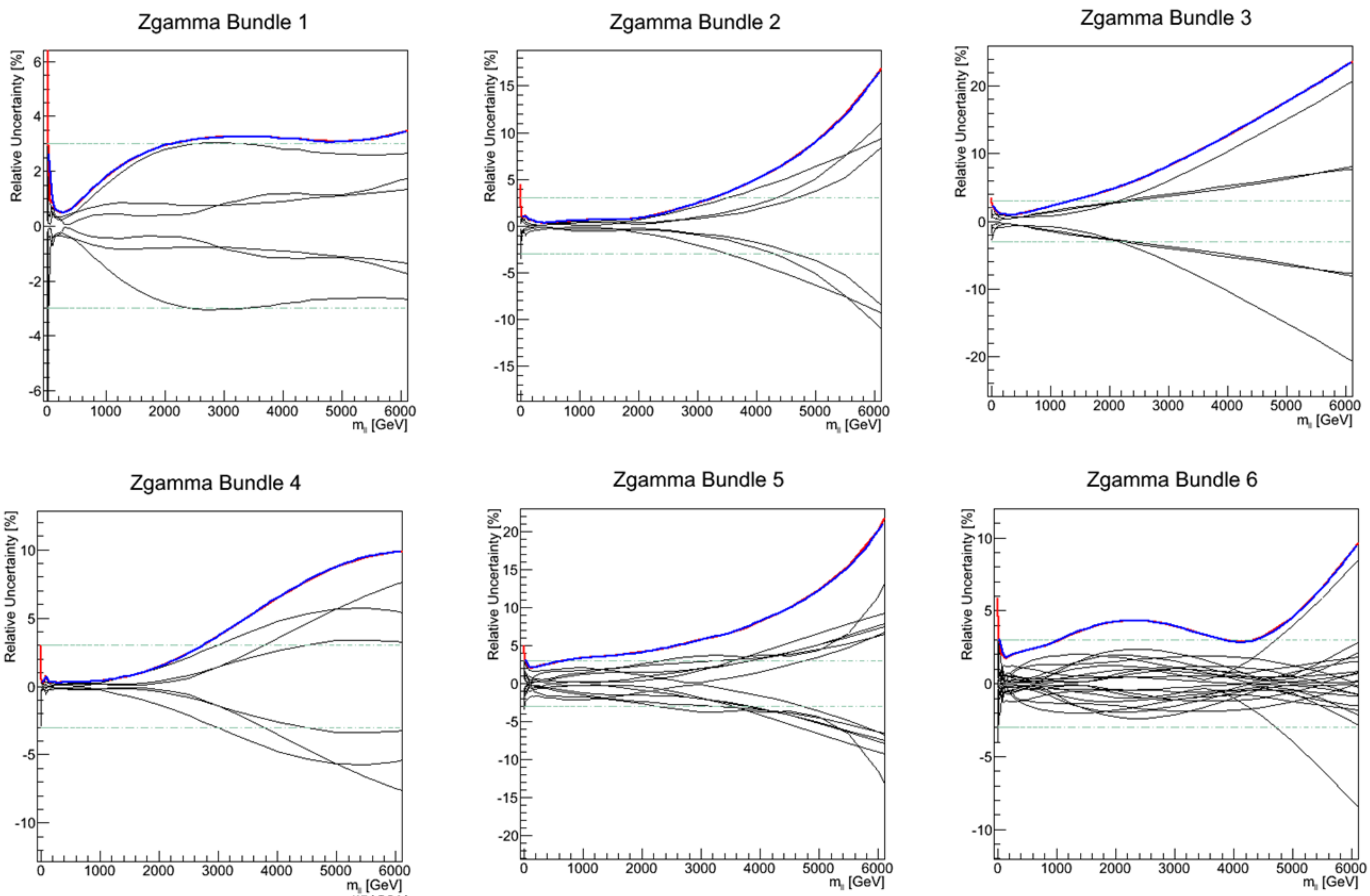






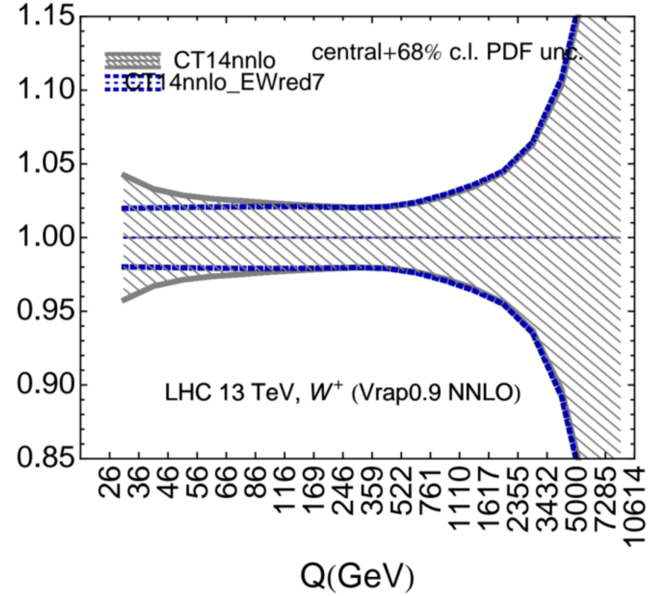
Bundling of 28 Z Eigenvectors

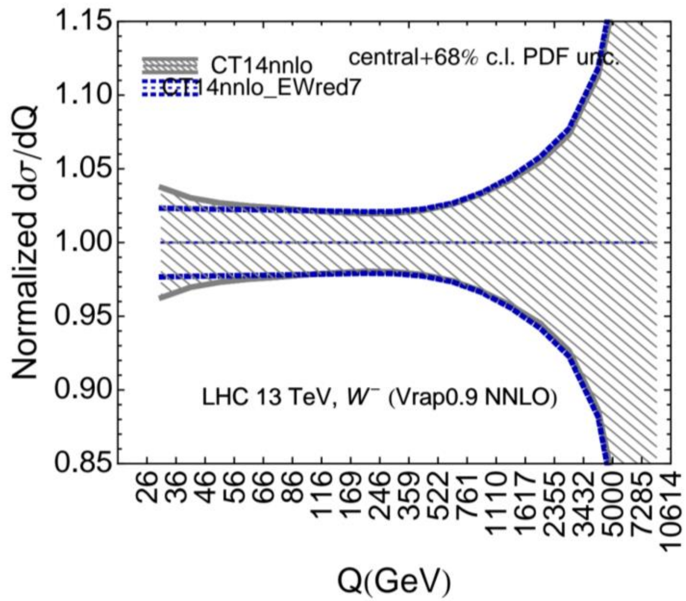
- This leads to 5 PDF nuisance parameters for W and 6 for Z.
  - Formed by fitting the quadratic sum of all EVs in the bundle.

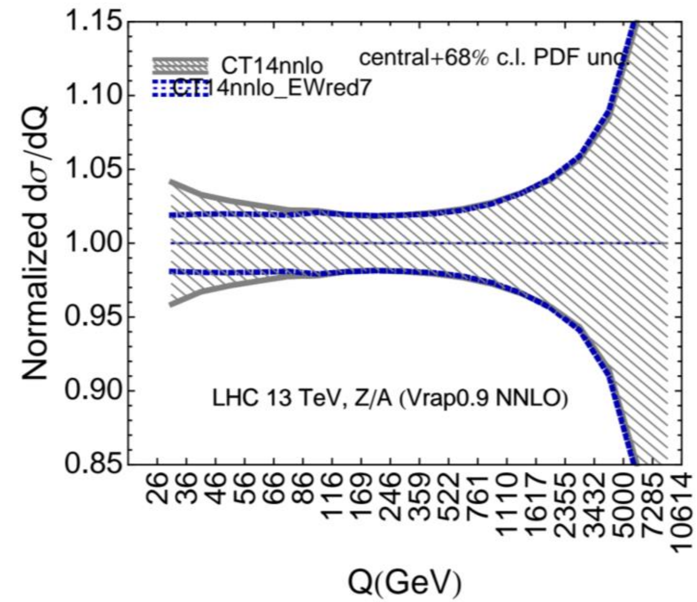


Reduced CT14nnlo EV Set

- From J.Gao (CT14 author):
- Constructed 7 EV directions/ nuisance parameters based on $W^{+/-}$ and Z σ.
- Validated by running independent VRAP calculations with slightly different Q values.
  - Calculate σ with original 28 EVs & new reduced set.
  - Compare symmetric PDF uncertainties (shown) & PDF correlation cosine.

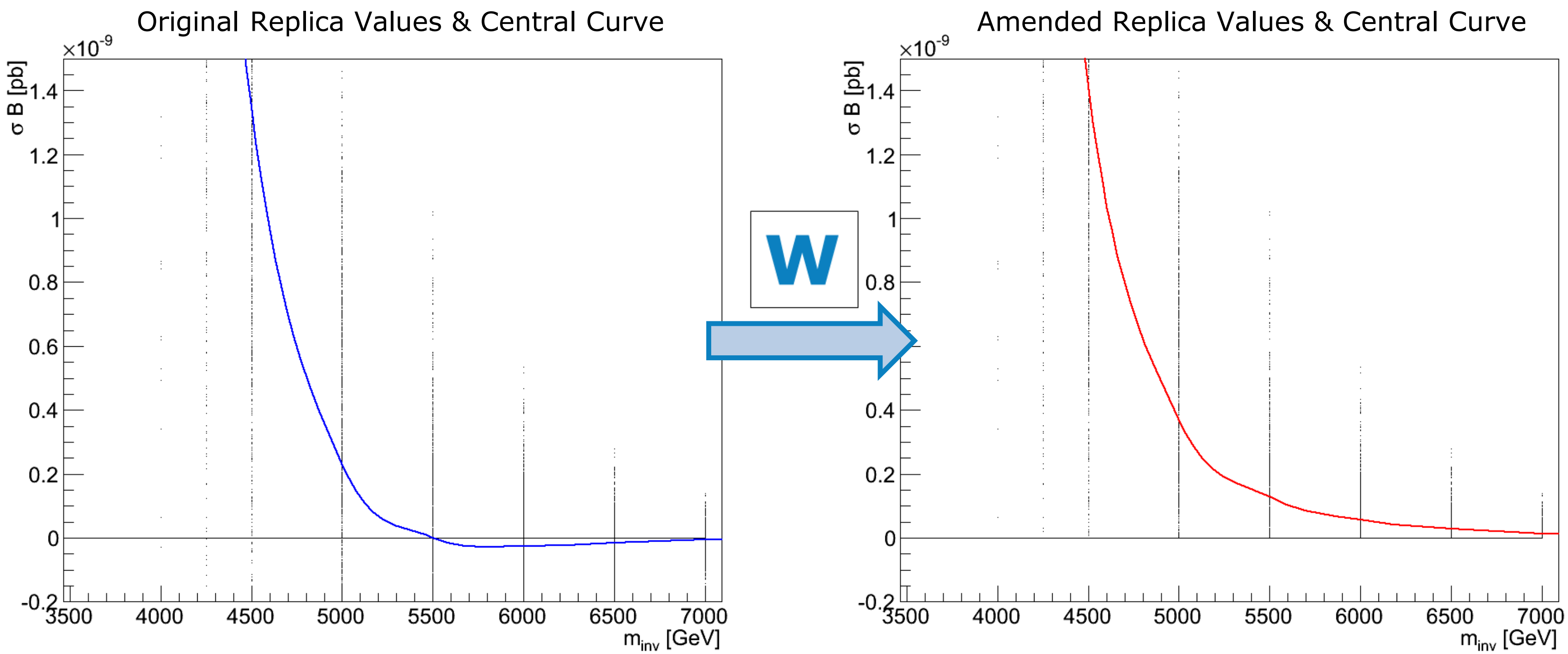






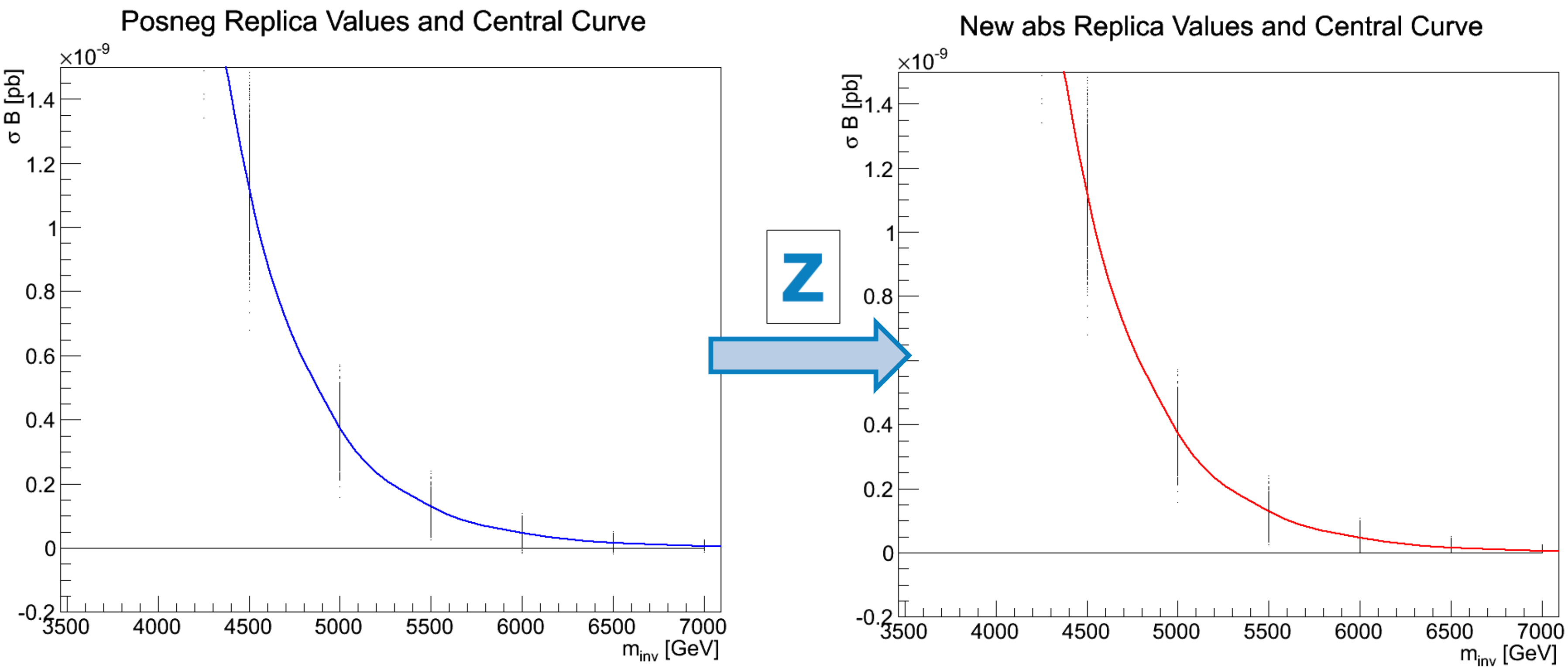
NNPDF3.0 Treatment

- NNPDF3.0 PDFs are provided as a nominal value with a set of 1000 pseudodata ‘replicas’ for each invariant mass.
- A central curve is constructed using a simple average of all replicas at each mass.
- For W^+ (and ∴ W) some replicas are negative and cause the central curve to dip below zero (> 4.5 TeV).
- New procedure (discussed with NNPDF authors) is to set negative replica values to zero.



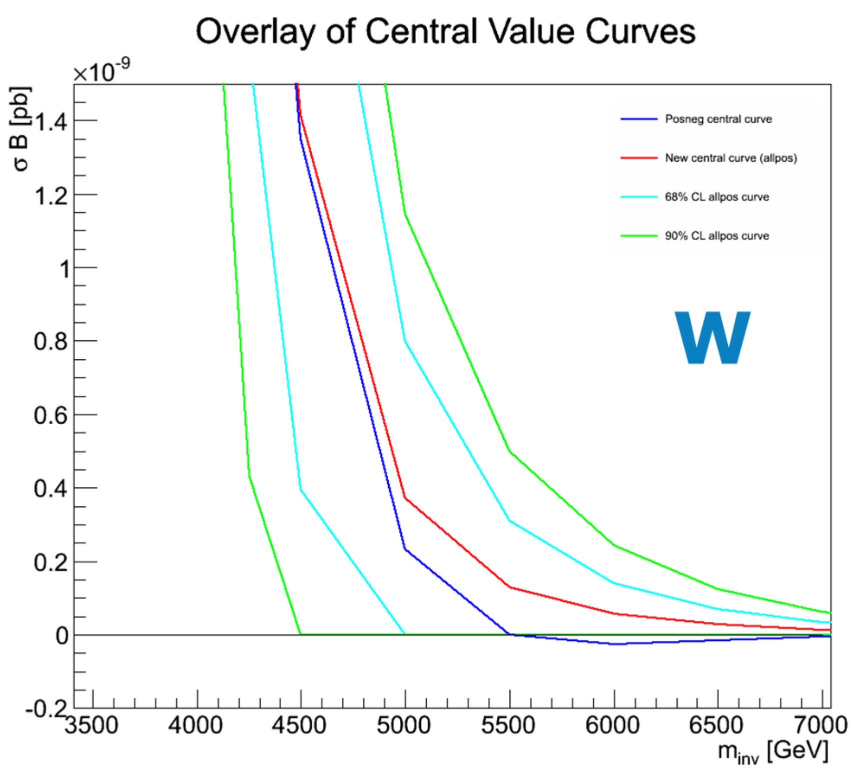
NNPDF3.0 Treatment

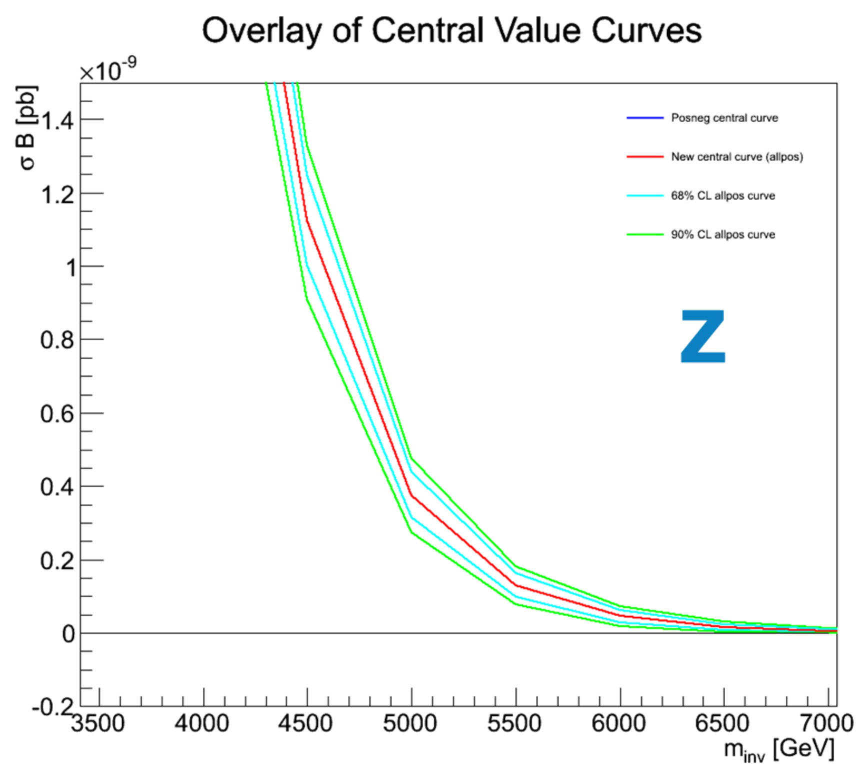
- For Z and W^- this problem is not observed, though a few replicas are negative and the same procedure is used for consistency.



W NNPDF Central Curve + CLs

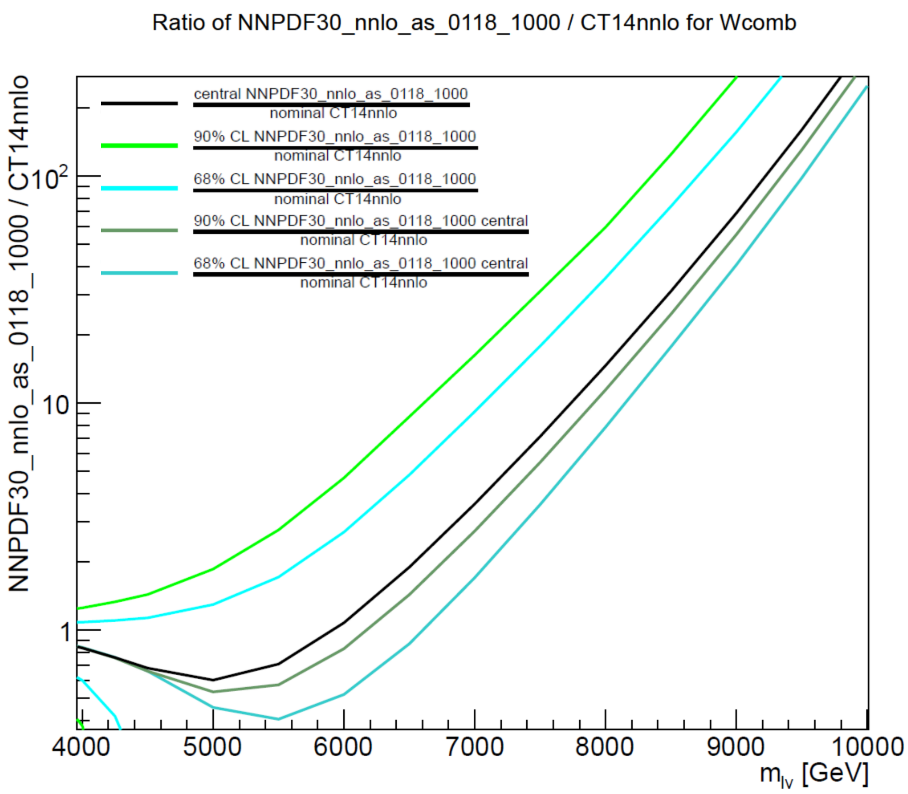
- Error bands for NNPDF3.0 are calculated at 90% CL and 68% CL.
- This is achieved by forming new curves with the highest/lowest replica values per mass bin, respectively.

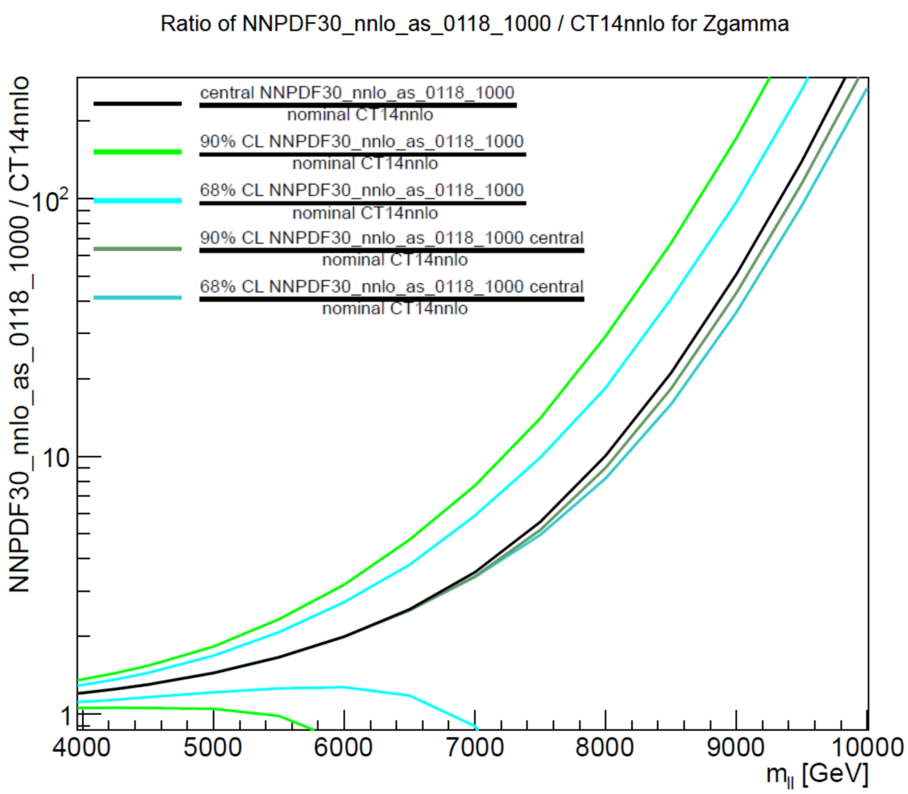




PDF Choice

- The effect of PDF choice is calculated using ratios of different PDF sets to the nominal.
- Fit $\frac{\sigma_{alternative}}{\sigma_{nominal}}$ over the search mass range.

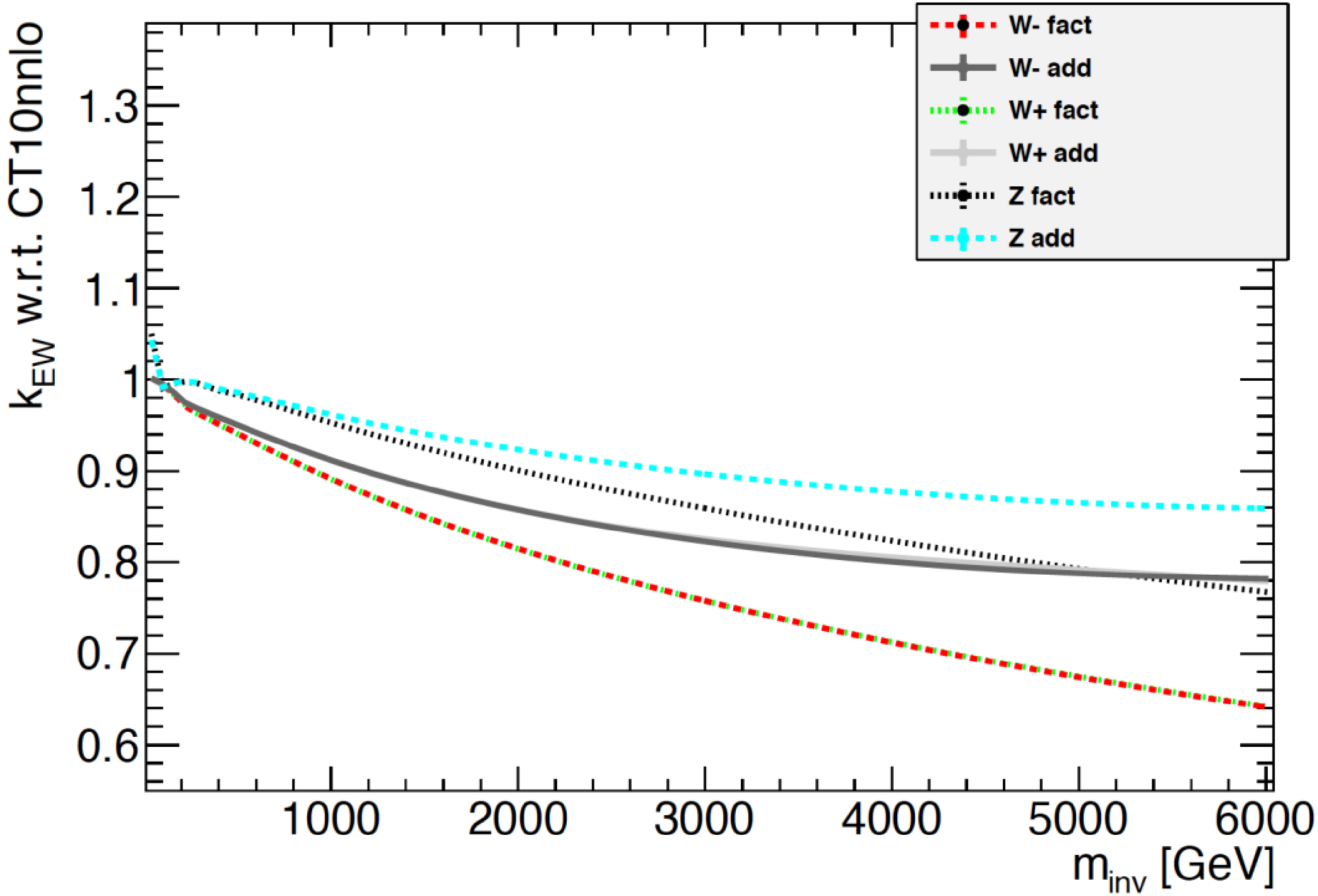




- Some ongoing discussion as to which central value for $\sigma_{alternative}$ to choose.

EW k-factors

- Comparing factorised and additive approaches for CT10nnlo:



α_S Uncertainty

- Study the effect of changing α_S by ±0.003 (from 0.118).
  - a conservative 90% CL in accordance with 68% CL recommendation of 0.0015 from PDF4LHC.

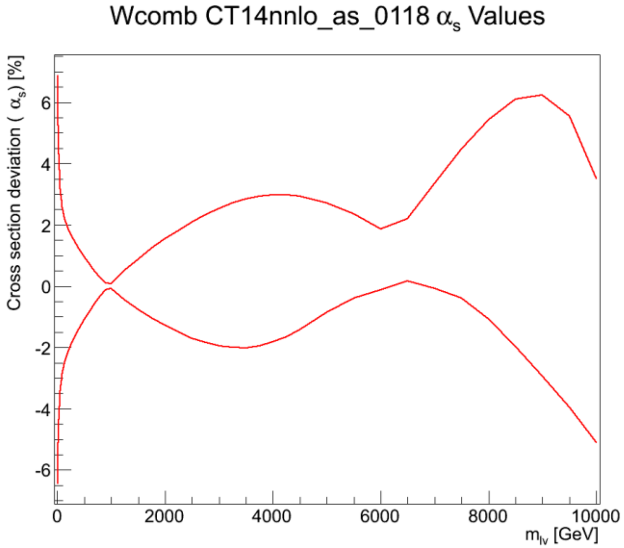
- Cross section calculated with VRAP 0.9 and PDFs CT14nnlo_as_0115 ... CT14nnlo_as_0121

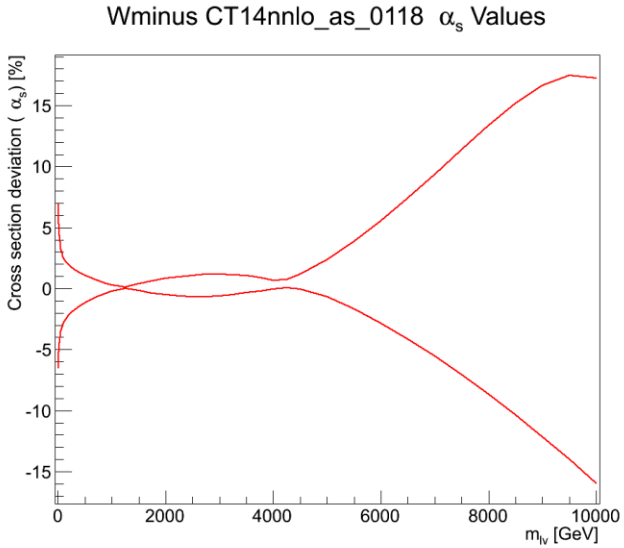
- The maximum and minimum deviating cross section is identified per mass bin and the resulting positive and negative deviations are plotted for each vector boson.

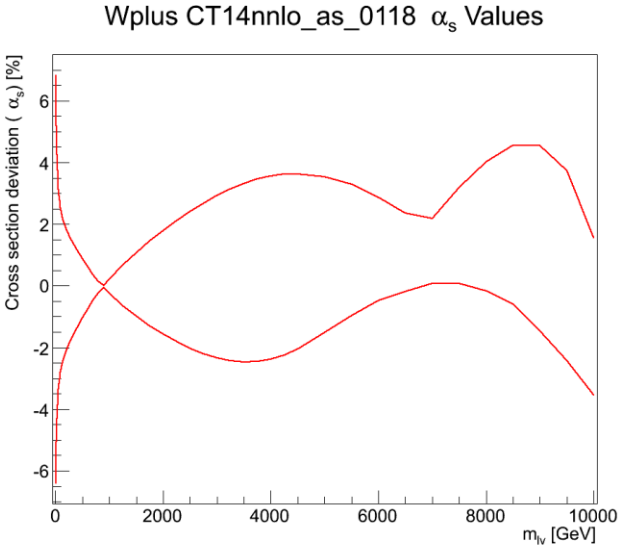
- The α_S uncertainty has to be added in quadrature to the PDF uncertainty.

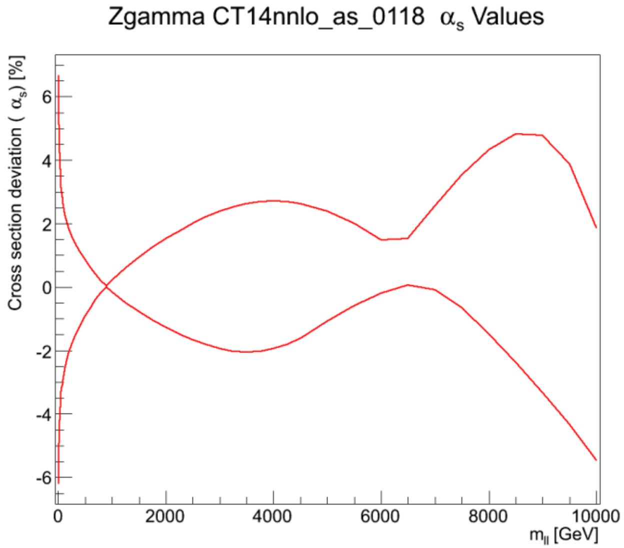
α_s Values

- Some erratic behaviour but overall effects are quite small.









Dilepton Correction Factors

$pp \to l^+l^- + X$ at $\sqrt{s} = 14\,\mathrm{TeV}$

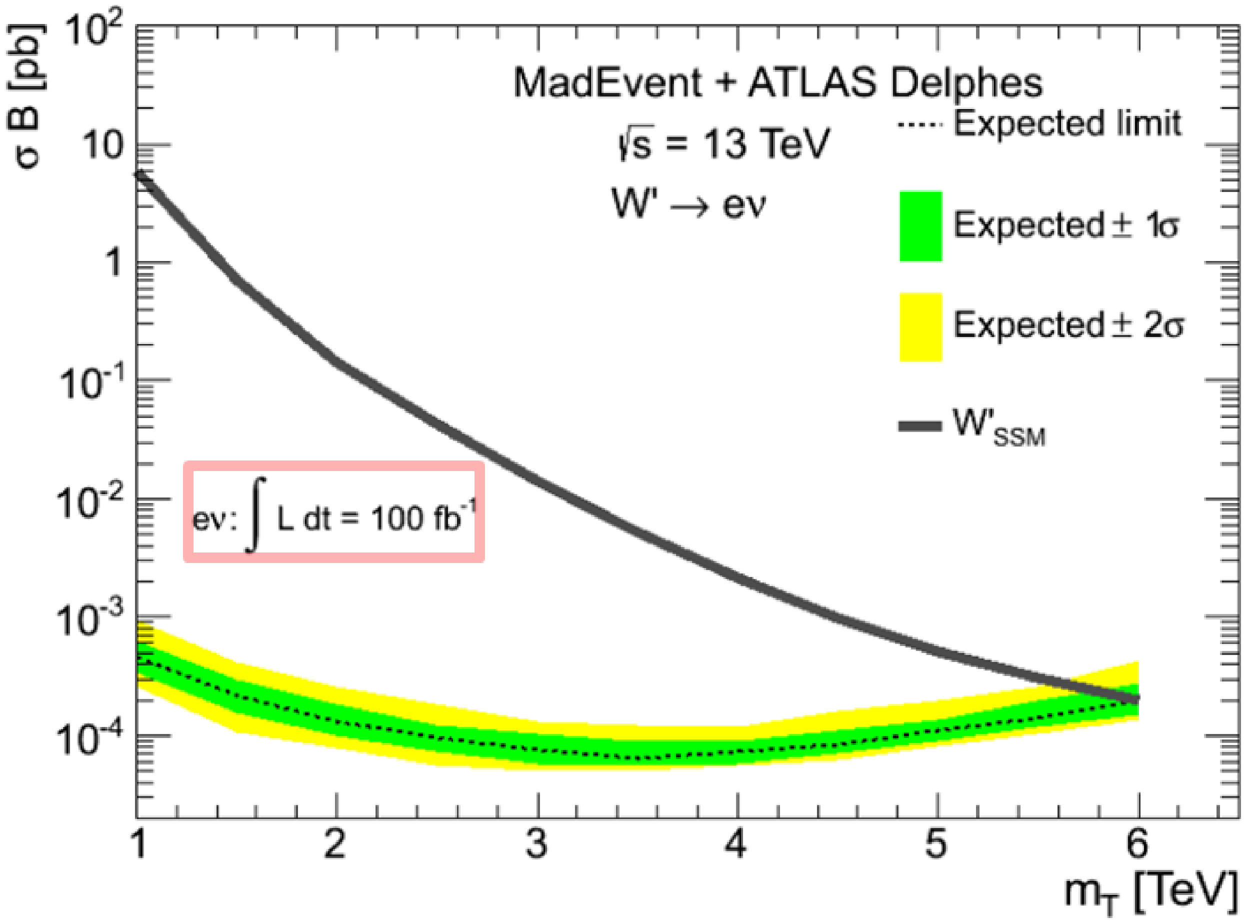
M_{ll}/GeV	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
σ_0/pb	738.733(6)	32.7236(3)	1.48479(1)	0.0809420(6)	0.00679953(3)	0.000303744(1)
$\sigma_0\vert_{\mathrm{FS/PS}}/\mathrm{pb}$	738.773(6)	32.7268(3)	1.48492(1)	0.0809489(6)	0.00680008(3)	0.000303767(1)
$\delta_{\gamma\gamma,0}/\%$	0.17	1.15	4.30	4.92	5.21	6.17
$\delta^{\mathrm{rec}}_{q\bar{q},\mathrm{phot}}/\%$	-1.81	-4.71	-2.92	-3.36	-4.24	-5.66
$\delta^{\mu^+\mu^-}_{q\bar{q},\mathrm{phot}}/\%$	-3.34	-8.85	-5.72	-7.05	-9.02	-12.08
$\delta^{\mu^+\mu^-}_{\mathrm{multi}-\gamma}/\%$	$0.073^{+0.027}_{-0.024}$	$0.49^{+0.18}_{-0.15}$	$0.17^{+0.06}_{-0.05}$	$0.23^{+0.07}_{-0.06}$	$0.33^{+0.09}_{-0.08}$	$0.54^{+0.13}_{-0.12}$
$\delta_{q\bar{q},\mathrm{weak}}/\%$	-0.71	-1.02	-0.14	-2.38	-5.87	-11.12
$\delta_{\mathrm{h.o.weak}}/\%$	0.030	0.012	-0.23	-0.29	-0.31	-0.32
$\delta^{(2)}_{\mathrm{Sudakov}}/\%$	-0.00046	-0.0067	-0.035	0.23	1.14	3.38
$\delta_{q/\bar{q}\gamma,\mathrm{phot}}/\%$	-0.11	-0.21	0.38	1.53	1.91	2.34
$\delta^{\mathrm{rec}}_{\gamma\gamma,\mathrm{phot}}/\%$	-0.0060	-0.032	-0.11	-0.14	-0.16	-0.23
$\delta^{\mu^+\mu^-}_{\gamma\gamma,\mathrm{phot}}/\%$	-0.011	-0.058	-0.22	-0.30	-0.39	-0.59
$\delta_{\gamma\gamma,\mathrm{weak}}/\%$	0.000045	0.00056	-0.025	-0.14	-0.31	-0.64
$\delta_{\mathrm{QCD}}/\%$	4.0(1)	13.90(6)	26.10(3)	21.29(2)	8.65(1)	$-11.93(1)$

Table 1: Integrated LO cross section and relative correction factors at the LHC for different values of the invariant mass cut M_{ll}.

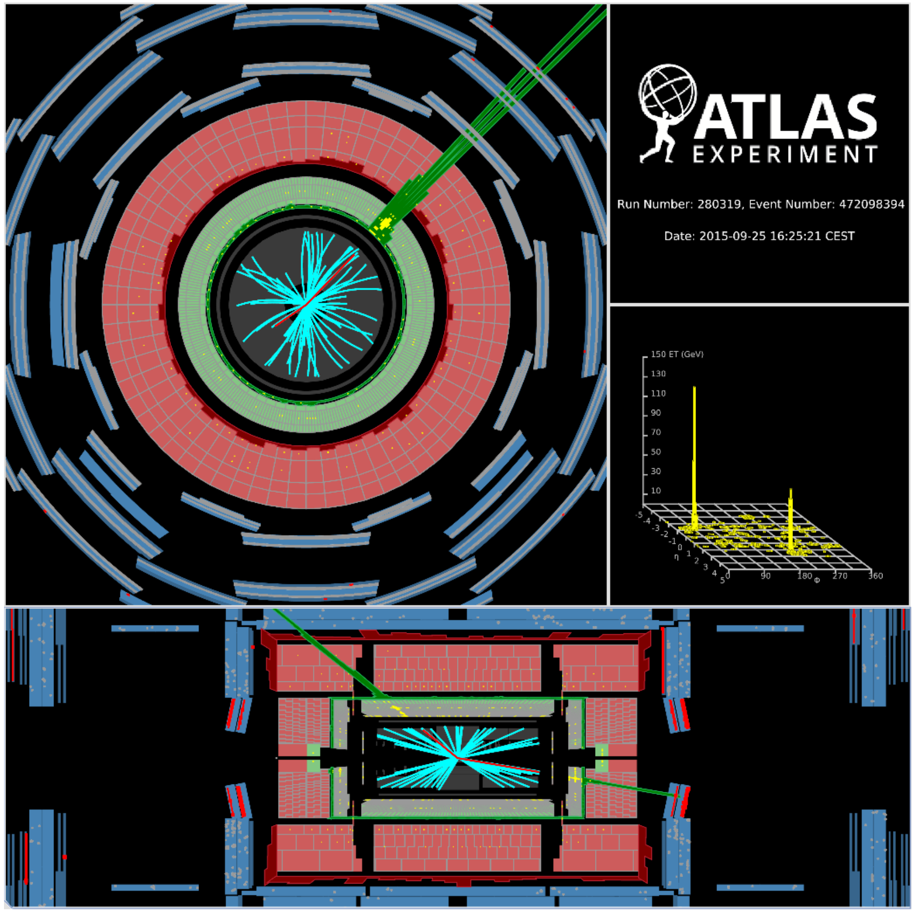
arXiv:0911.2329v2

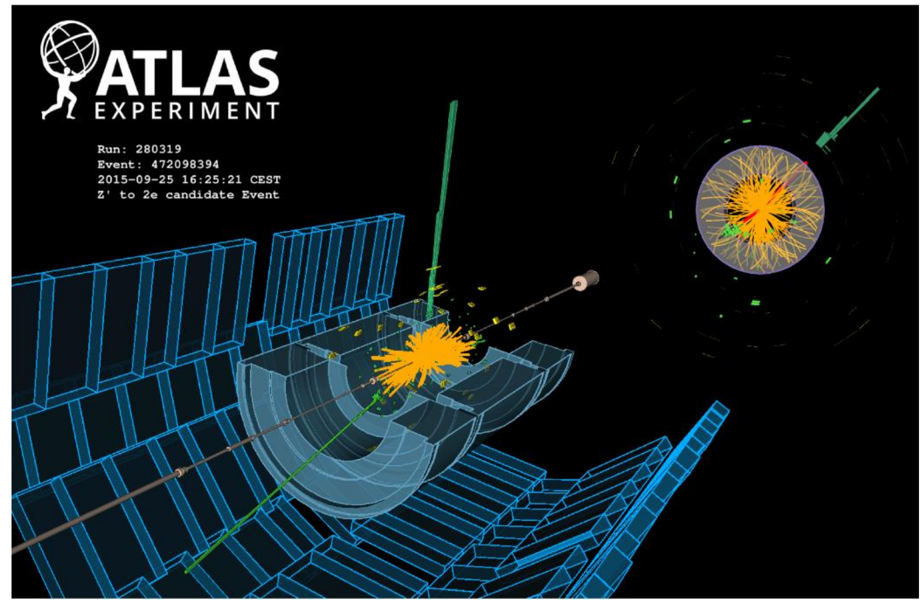
Outlook

- Optimistic plot without consideration of PDF uncertainty.
  - As the LHC approaches its expected integrated luminosity of 100 fb^{-1} in Run-2, limits for the W' could reach ~ 6 TeV!



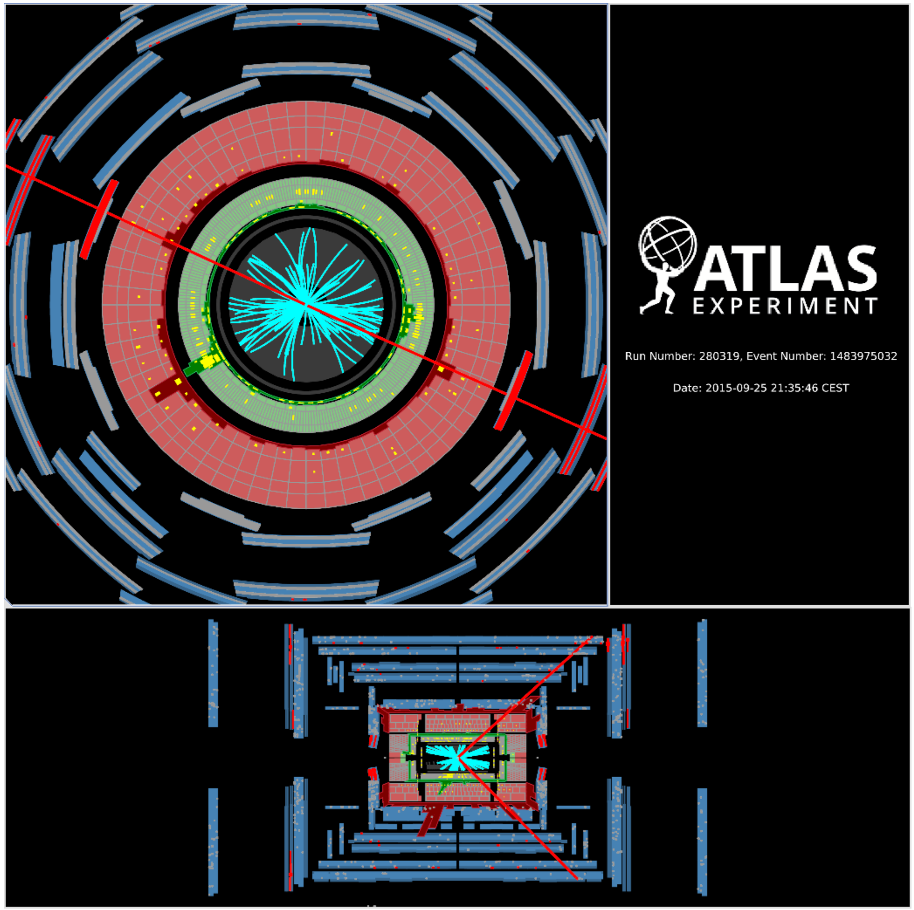
Event Displays: ee

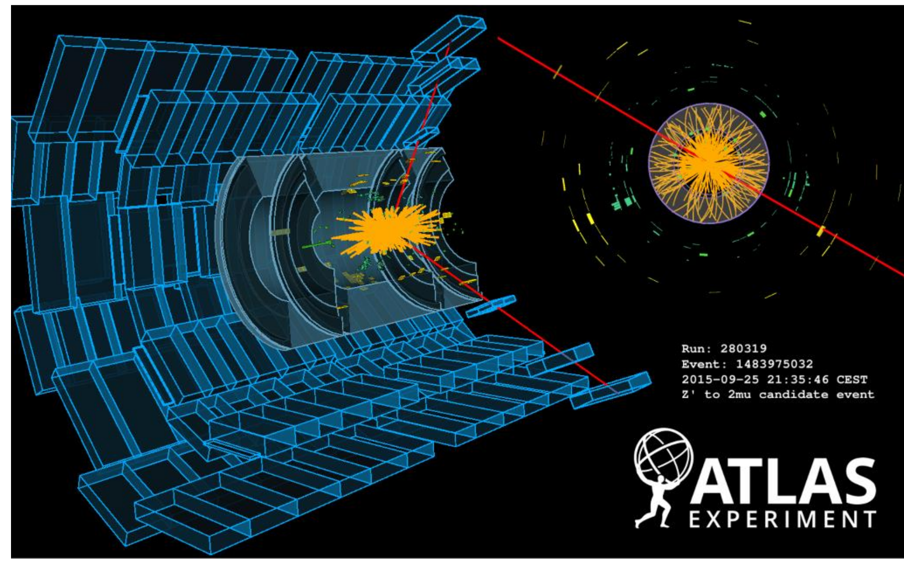




- Highest dielectron invariant mass event displayed in Atlantis and VP1. The highest momentum electron has an E_T = 373 GeV and an η = -1.03. The subleading electron has E_T = 246 GeV and η = 2.45. m_{ee} = 1775 GeV.

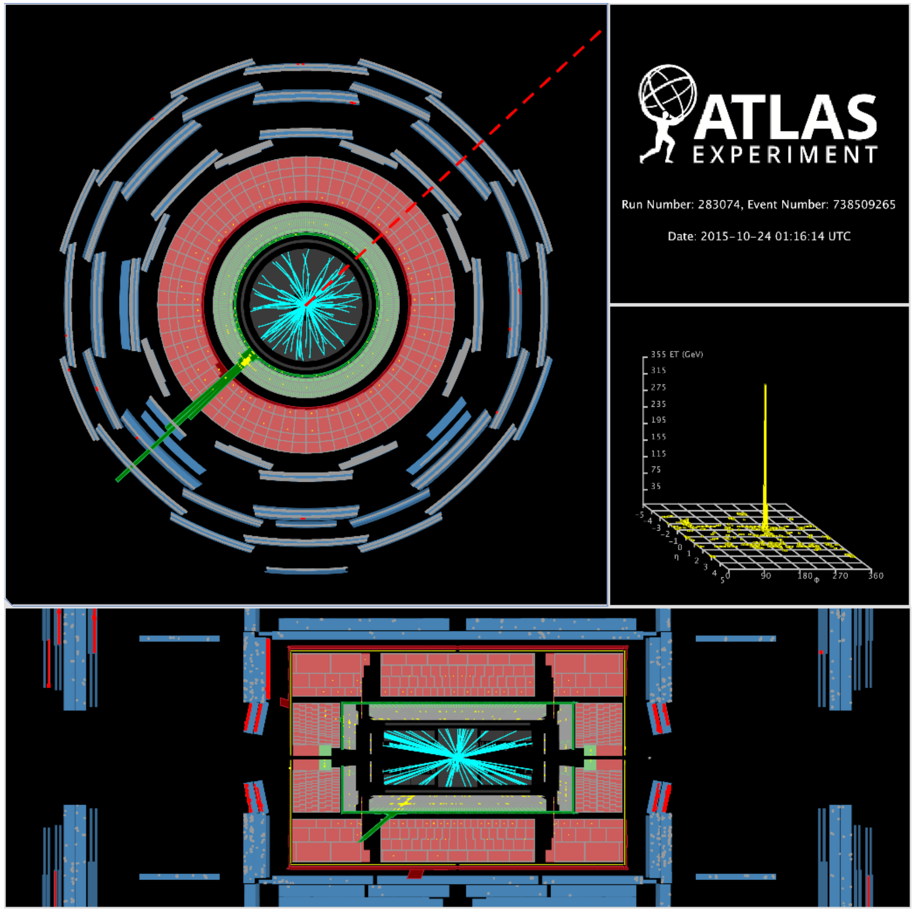
Event Displays: μμ





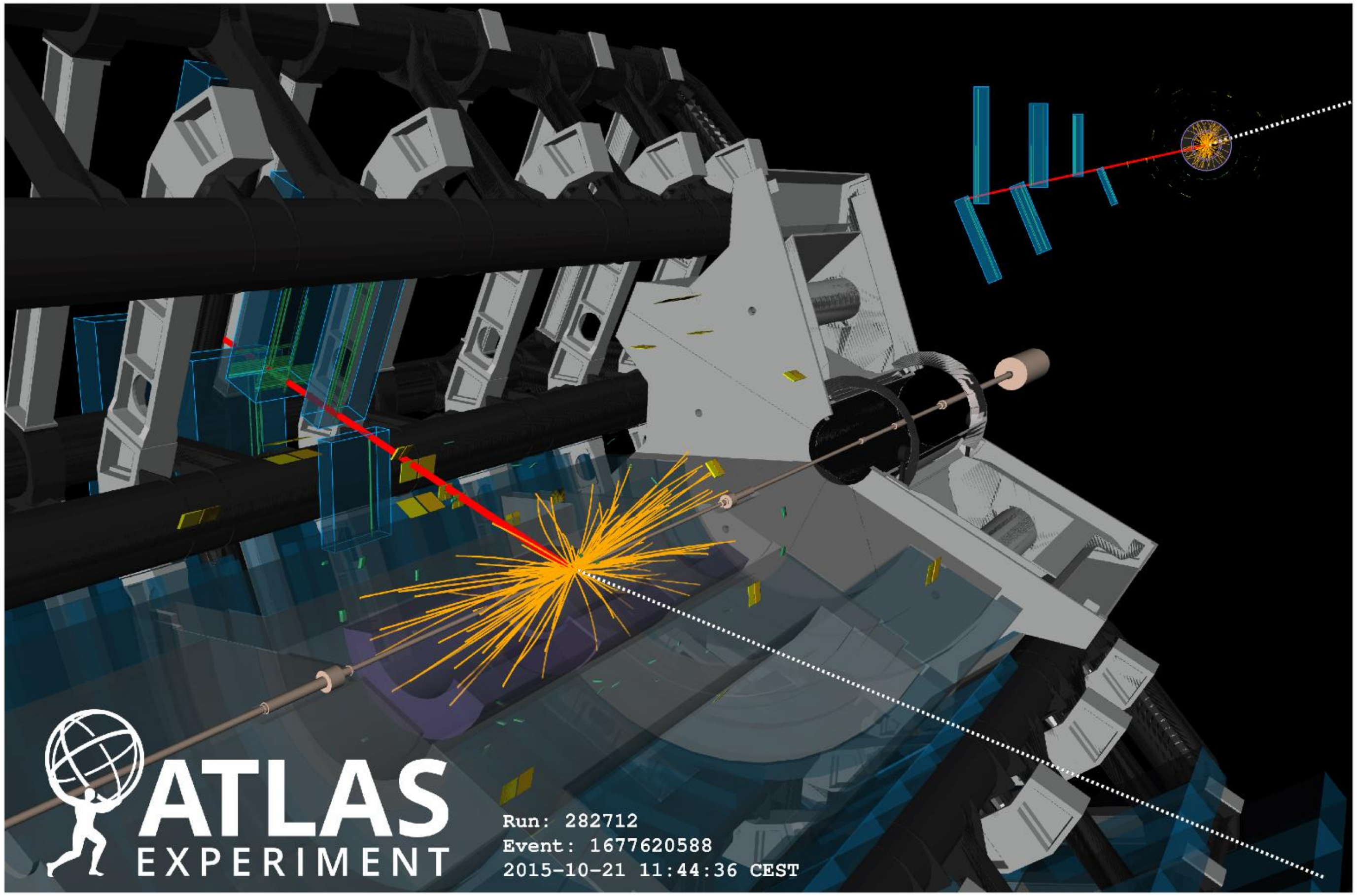
- Highest dimuon invariant mass event displayed in Atlantis and VP1. The highest momentum muon has p_T = 712 GeV and η = 0.87. The subleading muon has p_T = 676 GeV and η = 0.95. $m_{\mu\mu}$ = 1390 GeV.

Event Displays: High m_T (e)



- Event display for an event with high m_T in the electron channe. The event contains an electron with p_T = 1.01 TeV, η = -0.9, φ = -2.4, E_T^{miss}= 0.94 TeV, and m_T = 1.95 TeV.

Event Displays: High m_T (μ)



- Event display for an event with high m_T in the muon channel. The event contains a muon with p_T = 0.86 TeV, η = -0.2 , φ = -2.9, E_T^{miss}= 0.86 TeV, and m_T = 1.71 TeV.