Precision Electroweak Measurements: *CMS PERSPECTIVE*

Michael Schmitt*
on behalf of the CMS Collaboration

LHC EWWG Workshop
December 14, 2017

* Northwestern University

Contents

Recent CMS Results

- $\sin^2\theta_W$ from A_{FB}
- $d\sigma / dq_T$
- W helicity measurements

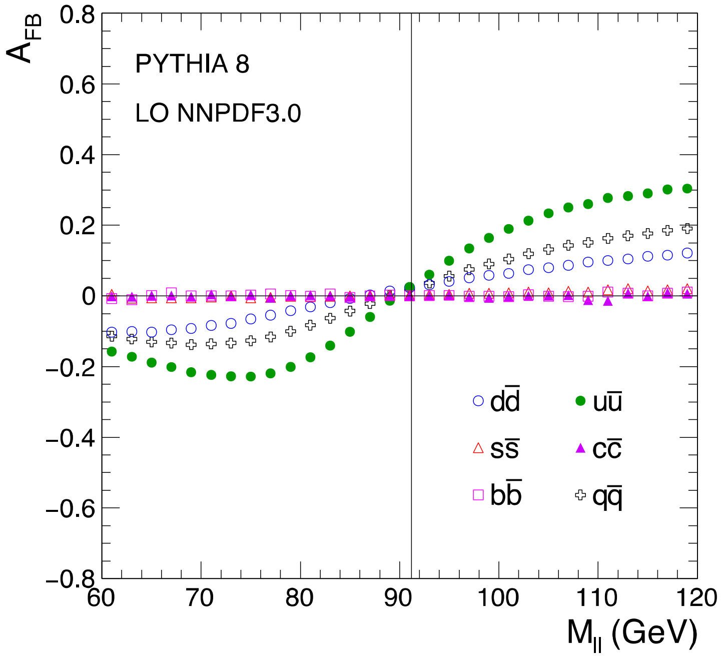
Issues

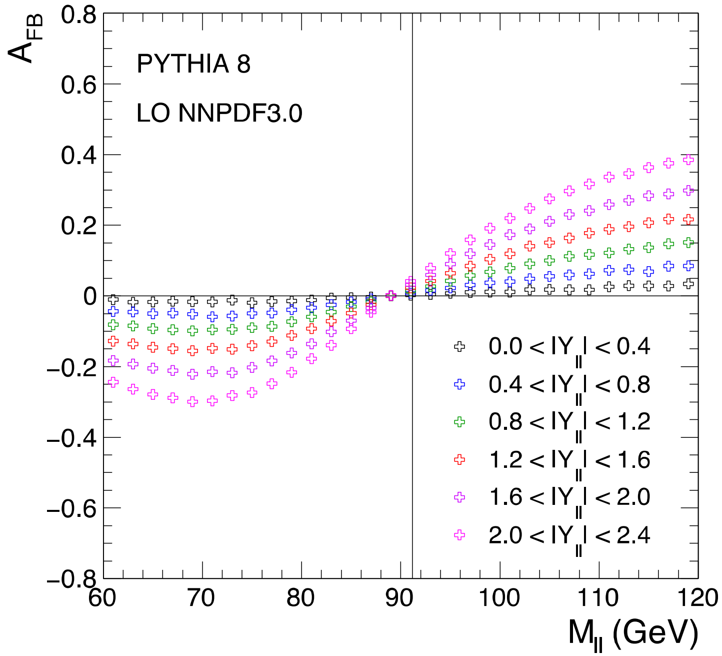
- POWHEG EW
- Transferring $d\sigma/dq_T$ from Z to W
- PDFs
- Improved experimental methods

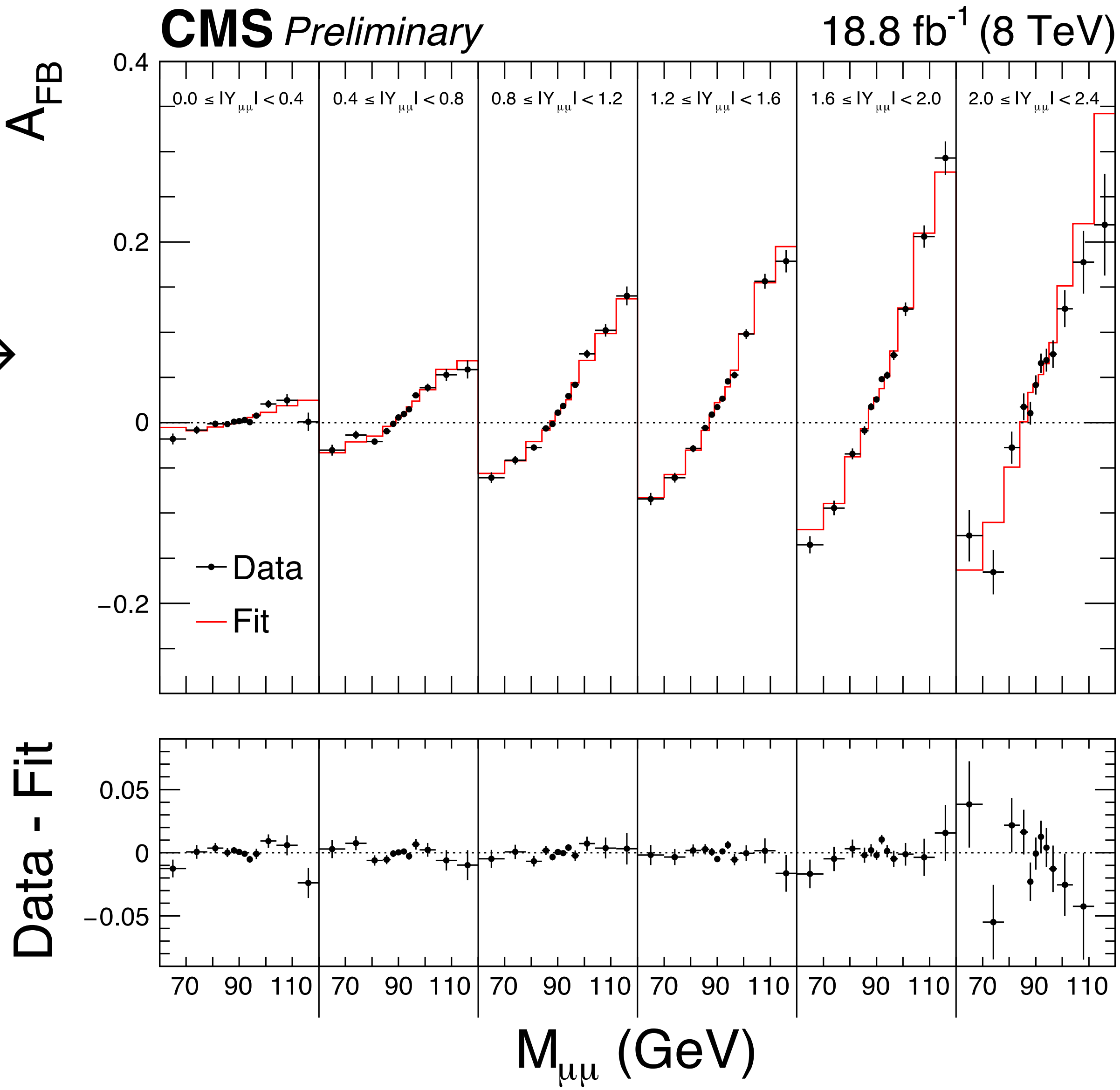
$\sin^2\theta_W$ (latest result)

- Known tension in $\sin^2\theta_W$ values from LEP+SLD.
- A_{FB} arises from nonzero axial coupling Zff and interference with vector coupling
- These couplings depend on $\sin^2\theta_W$
- Measure A_{FB} vs. M_{ll} in bins of rapidity
- $\sqrt{s}$ = 8 TeV 19 fb^{-1} electrons and muons

CMS PAS SMP-16-007





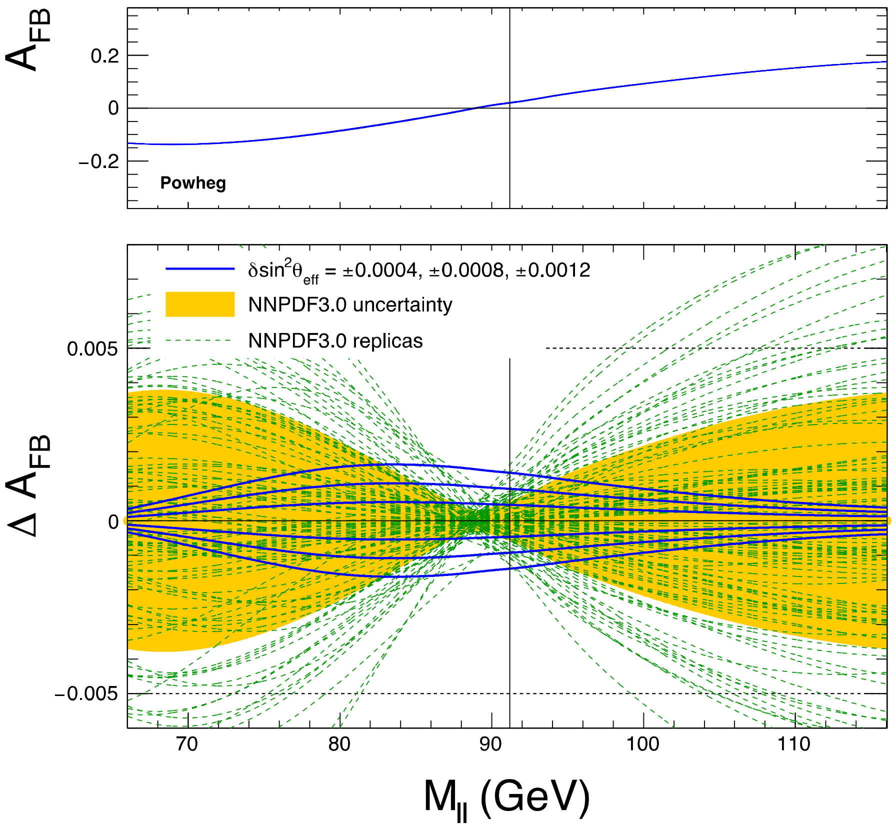


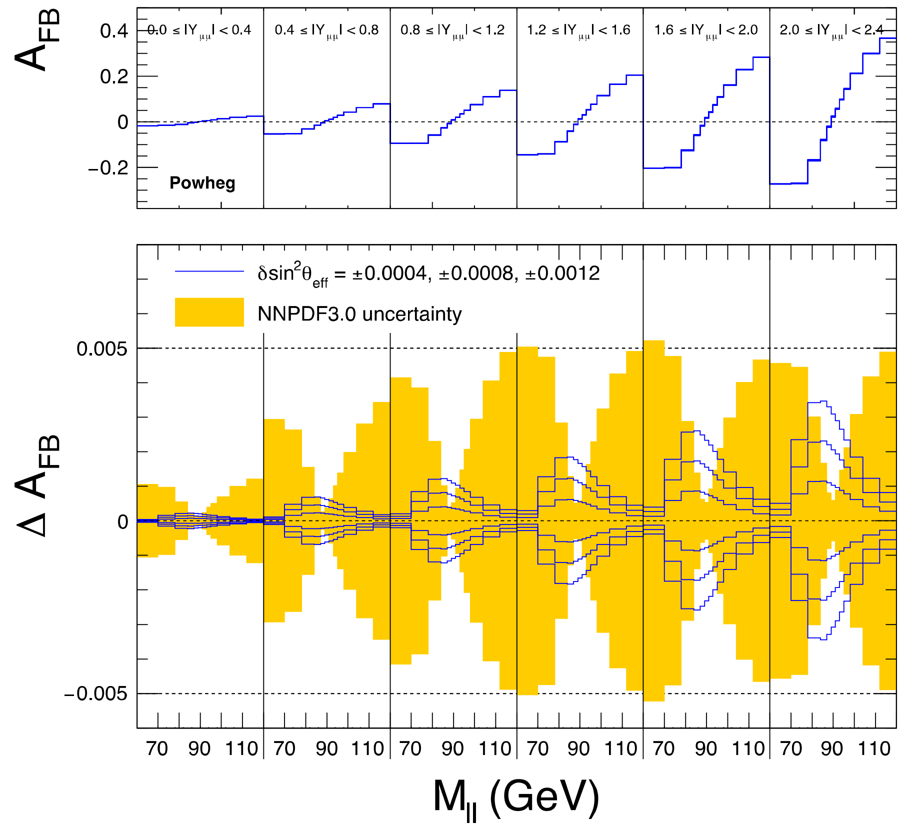
Smaller slope → greater dilution

Larger slope → greater sensitivity to $\sin^2\theta_W$

Results for electron channel are very similar.

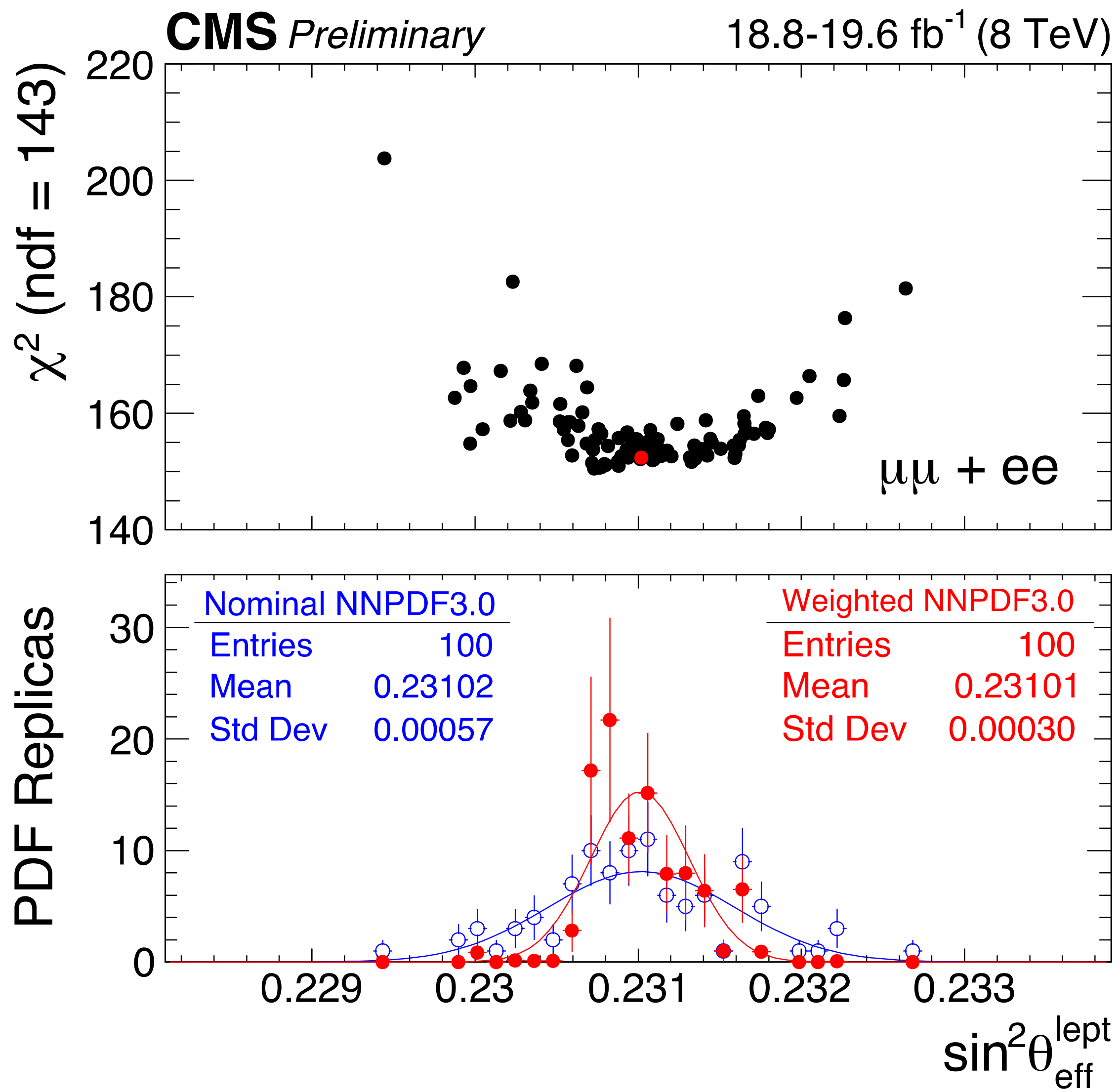
PDFs matter because: 1) up and down quarks produce the Ws
2) quark and anti-quark lead to dilution





NNPDF provides replicas that can be used to assess PDF uncertainties.
Apply weights according to the agreement with the data.
(Equivalently perform a Hessian error determination.)

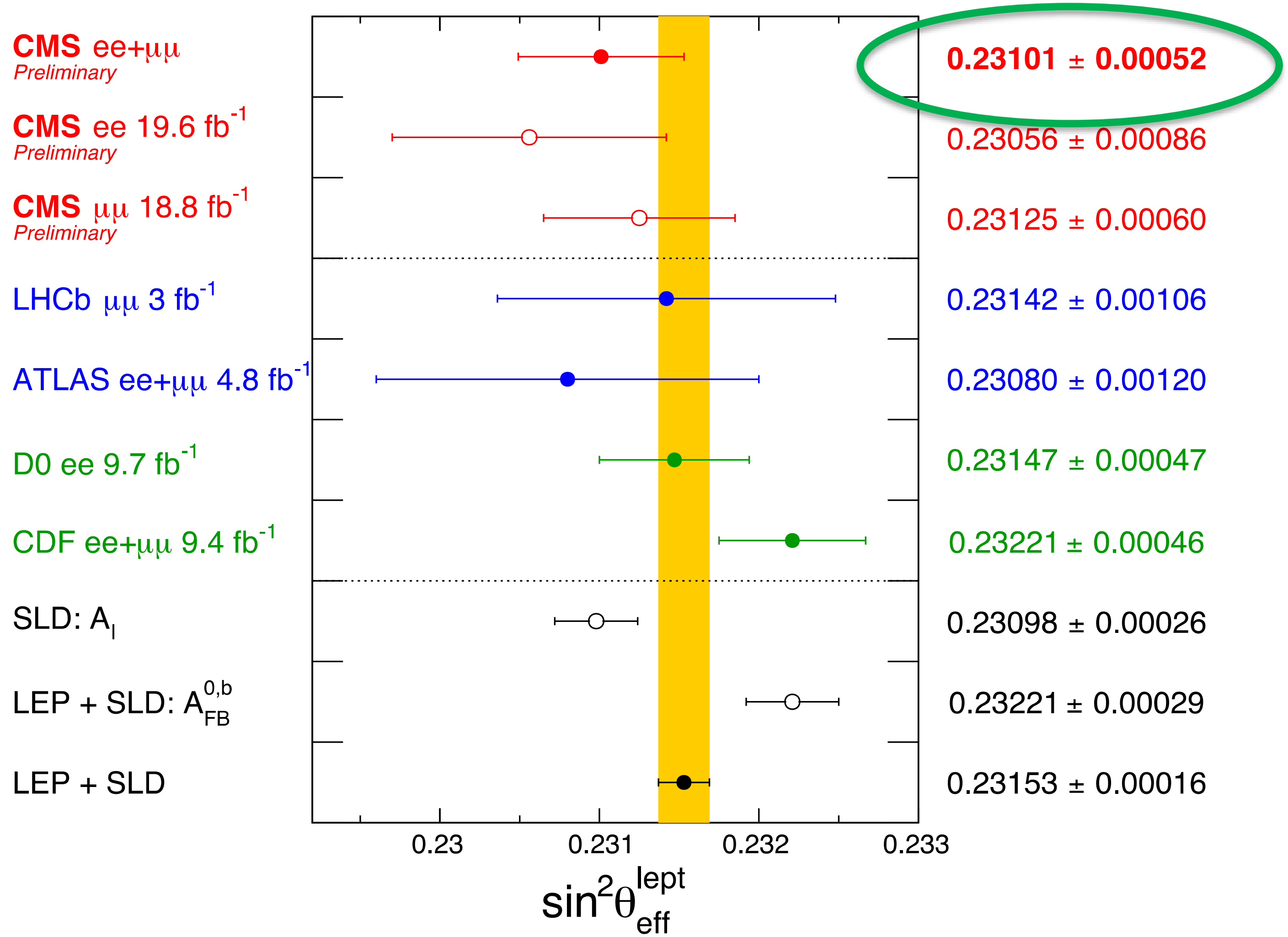
Replicas with larger χ^2 values receive a smaller weight.
Leads to a significant reduction in the uncertainty on $\sin^2\theta_W$



$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm \underline{0.00052}.$$

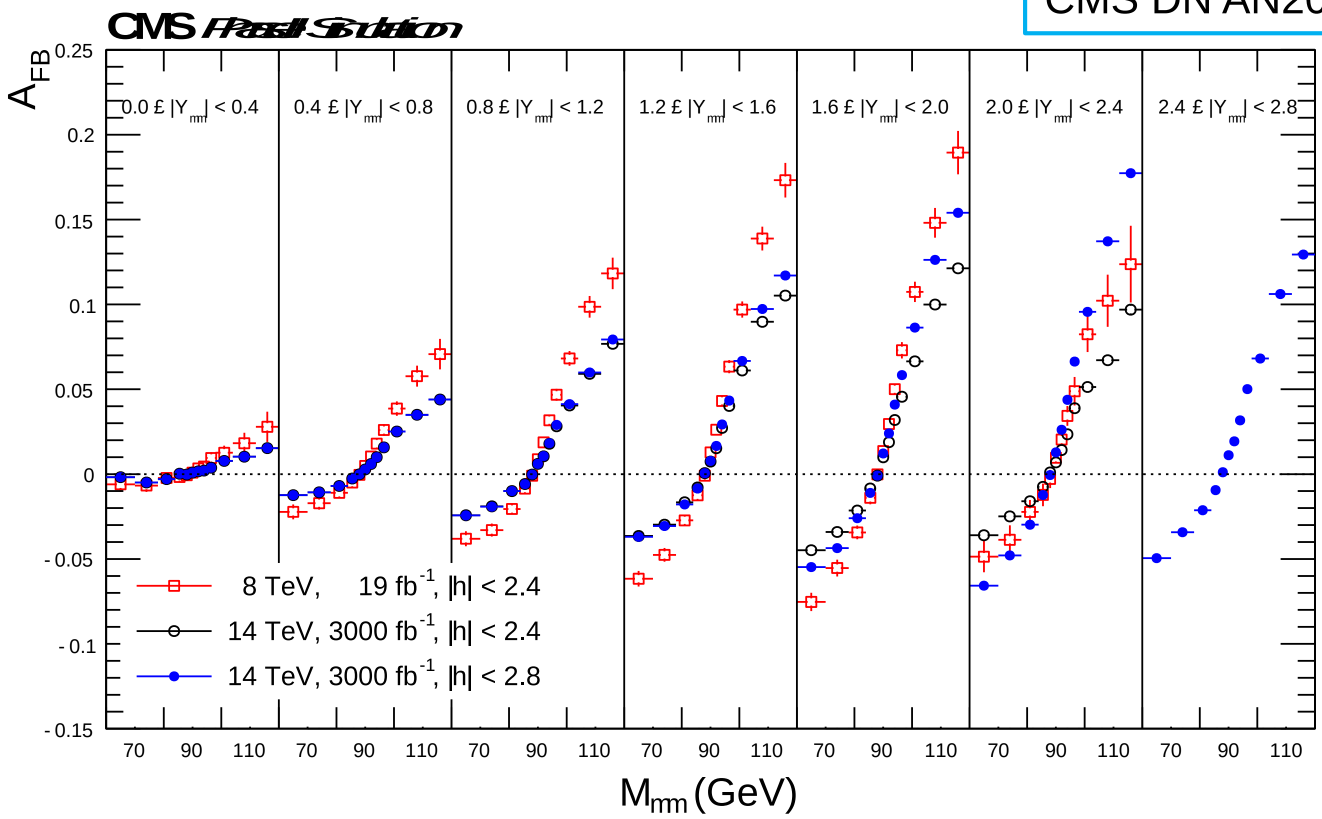
CMS PAS SMP-16-007

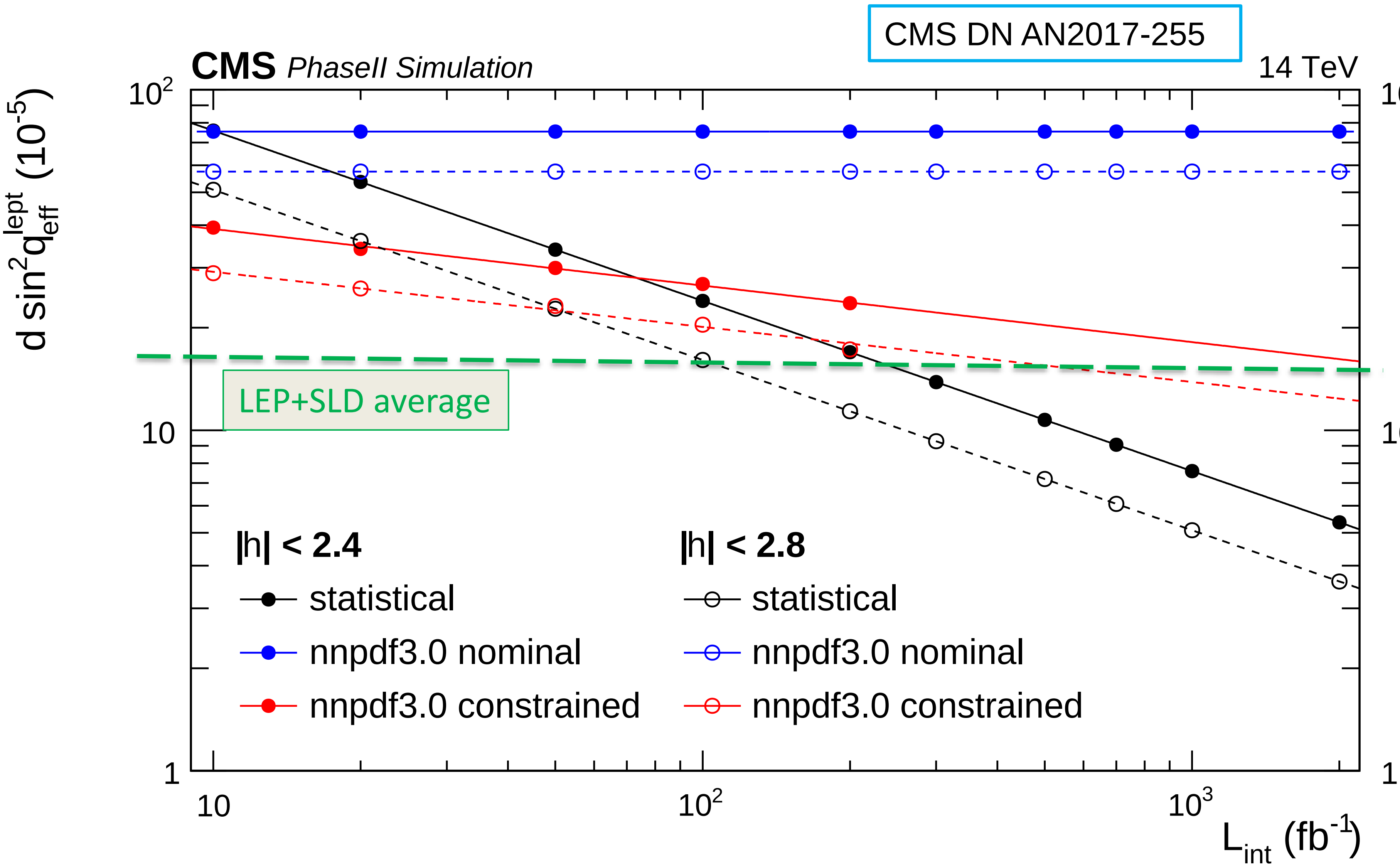


$\sin^2\theta_W$ (prospects for HL-LHC)

- Assume 3 ab^{-1} at 14 TeV
- Dilution is worse, but detector will have larger acceptance for leptons: $|\eta| < 2.8$

CMS DN AN2017-255





- Not a detailed simulation (for example, no pileup)
- Only PDF systematic uncertainty considered
- Negligible statistical uncertainty

$d\sigma / dq_T$

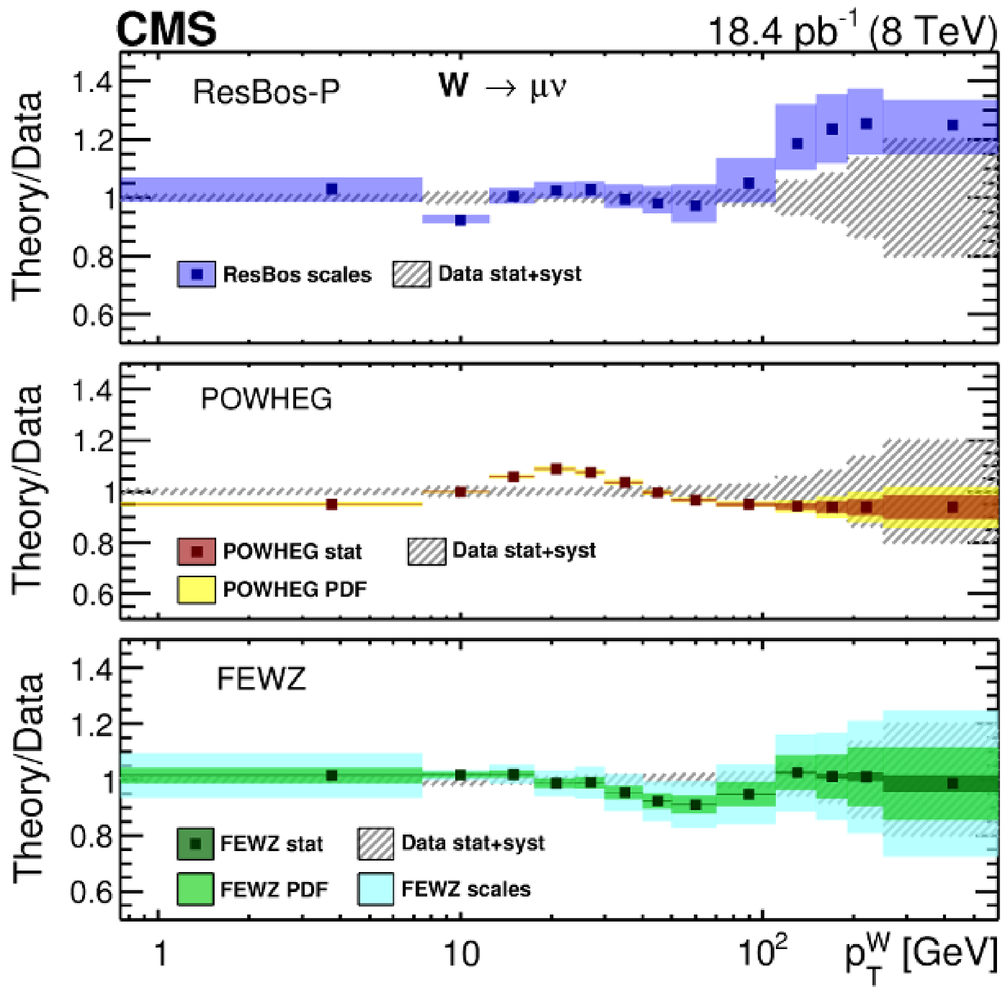
JHEP 02 (2017) 096

- New publication W and Z
- Low pileup run: 18 pb^{-1} at 8 TeV

Measurement precision:
roughly 1 – 2% systematic unc.
roughly 1 – 4% statical unc.
(worse at high q_T)

Largest systematic uncertainties:
unfolding
QCD background estimate (W)

Comparison to theoretical calculations
POWHEG does not match
FEWZ does well



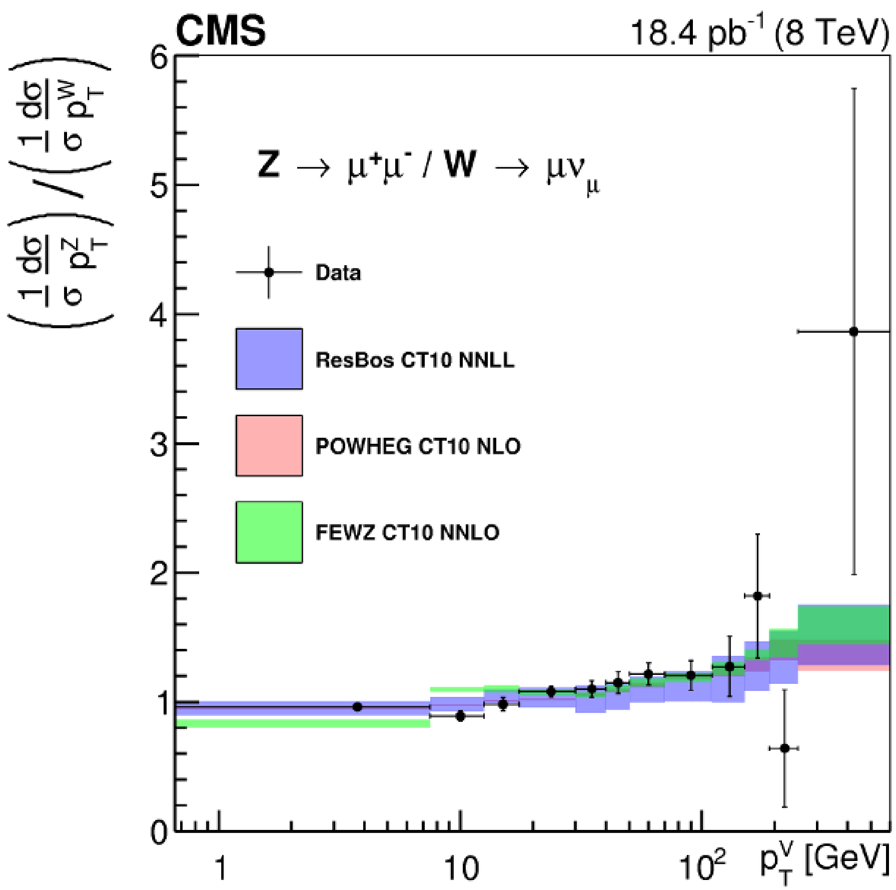
(Paper contains other comparisons.)

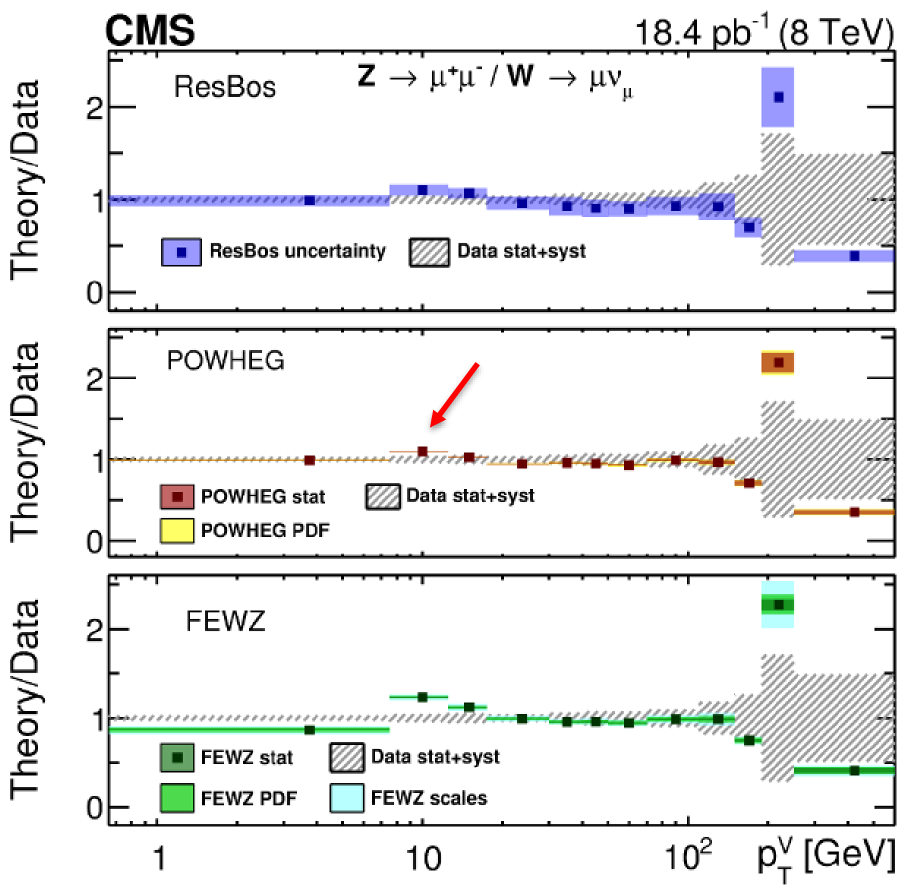
Theoretical and experimental systematics are reduced for the ratio.

Experimental precision 2 – 8% (expect at high q_T)

POWHEG generally OK though slightly off at q_T = 10 GeV.

JHEP 02 (2017) 096





M_W

- CMS is working on the *foundations* of the measurement.
- ATLAS measurement instructs us that:
  - PDF uncertainties are important
  - Modeling the q_T distribution is important
  - Theoretical uncertainties – “scales” – are tricky.
- The challenge ultimately is to reduce *all* systematic uncertainties.

CMS is pursuing analyses that attack the main systematic uncertainties:

- W helicity measurement: PDFs
- Better measurements of $d\sigma / dq_T$
- Better control over calibrations: hadronic recoil, leptons

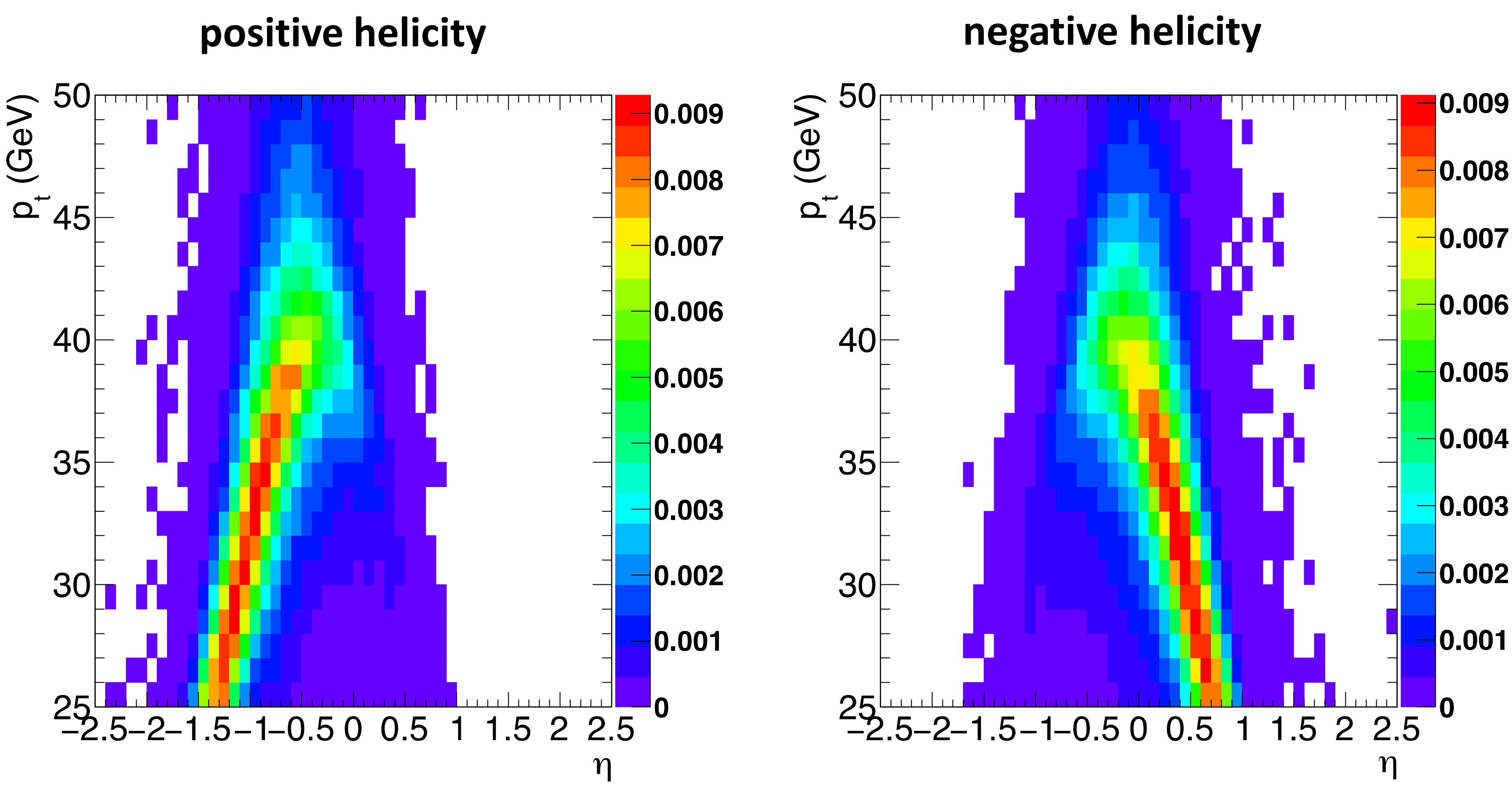
W Helicity Measurements

1707.09344

E. Manca et al.

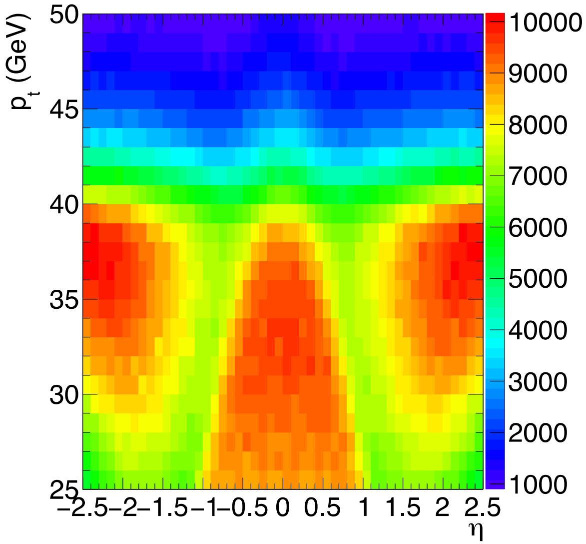
- Parity violation at production and decay:
- Strong angular asymmetry: $(1 - \cos\theta^{*})$ in W rest frame
  - Manifested in (p_T,η) plane (for a given charge)
- Strong dependence on u and d PDFs
- Weak / no dependence on M_W and q_T distribution
- Fit the W polarization and constrain the PDFs

Example: W^+ leptonic decays

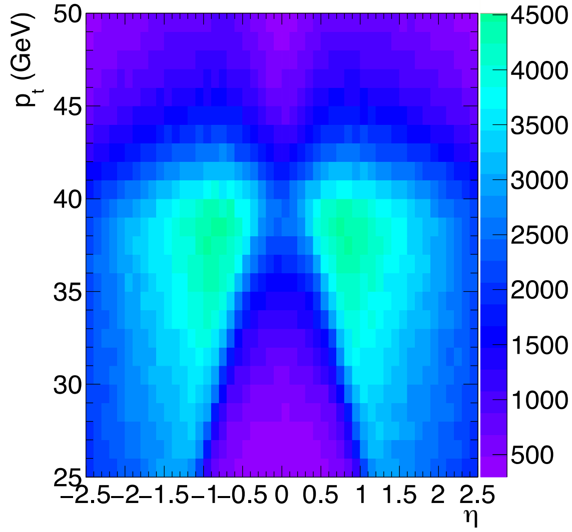


1707.09344

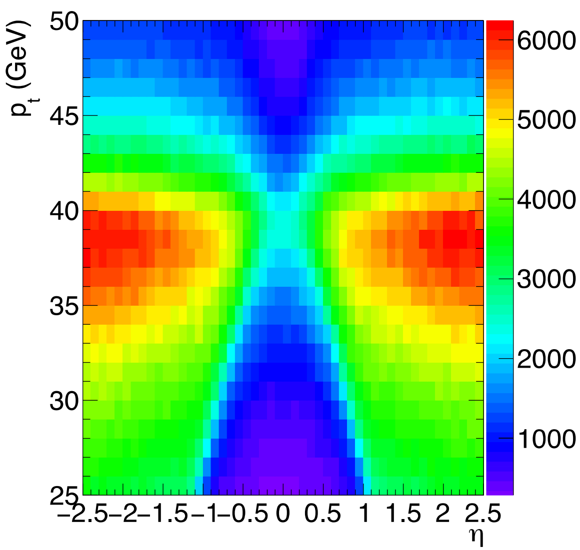
W+ negative helicity



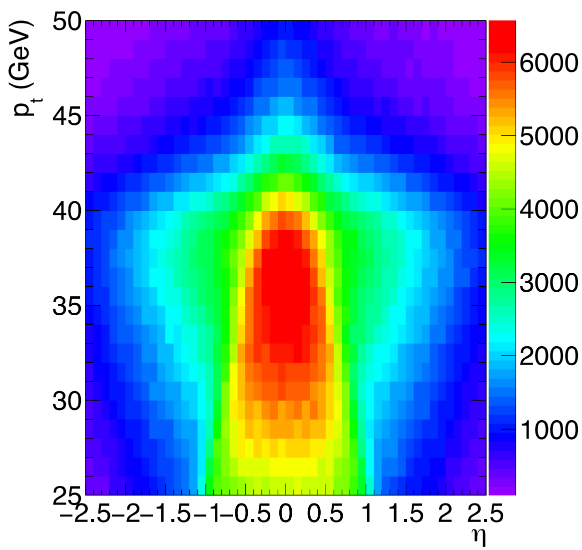
W+ positive helicity



W- negative helicity

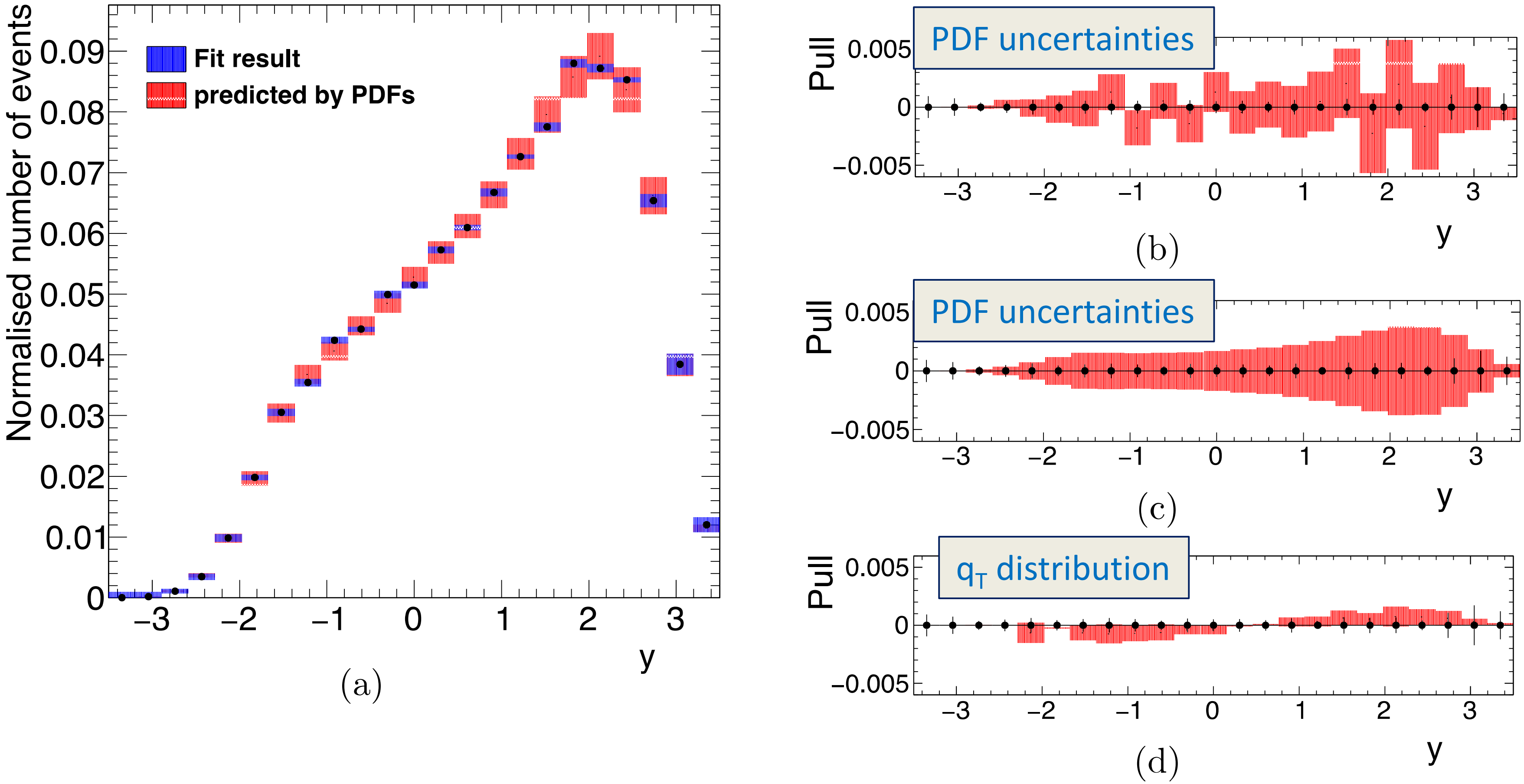


W- positive helicity



W^+ leptonic decays

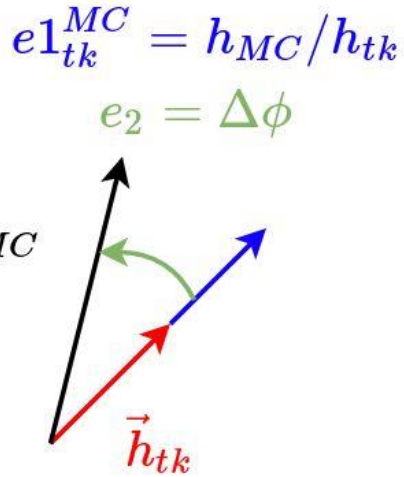
1707.09344



- Statistical uncertainties are much smaller than PDF uncertainty band.
- Rough studies show that detector effects are not a serious problem.
- Changes in boson p_T distribution have a different impact - Fig (d).
- The analysis with real data is under way.

M_W – hadronic recoil

Olmo Cerri & Nocolò Foppiani master's theses



- Reframe the calibration problem.
  - Correct magnitude and angle together.

- Employ machine learning techniques: semi-parametric regression (GMM)
  - extended list of input variables
  - obtain an event-by-event *pdf* for the recoil scale and angle
  - can use peak or mean of the *pdf*

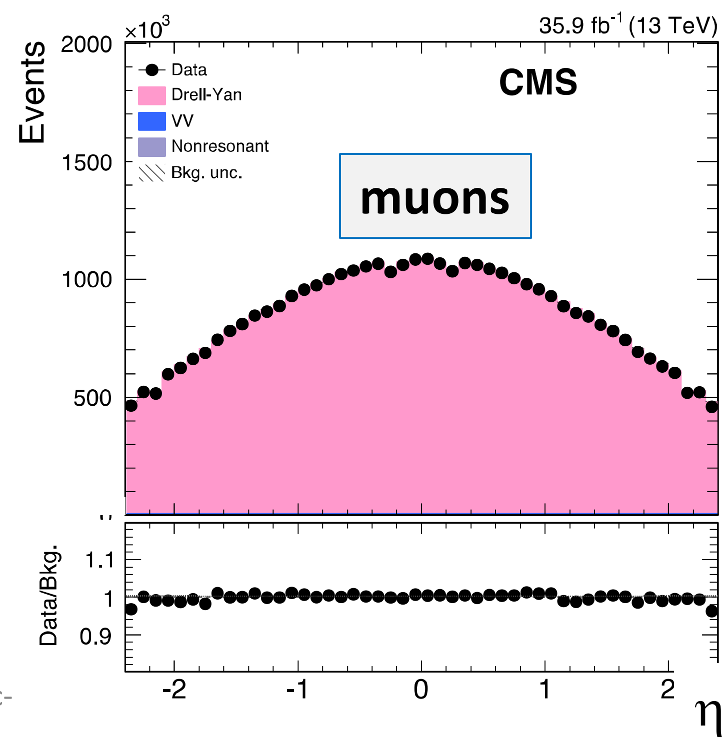
- Outperforms CMS best: Particle Flow
  - judged by the distribution of the errors on recoil *h*
  - judged by sensitivity to distortions of q_T distribution

M_W – better calibrations

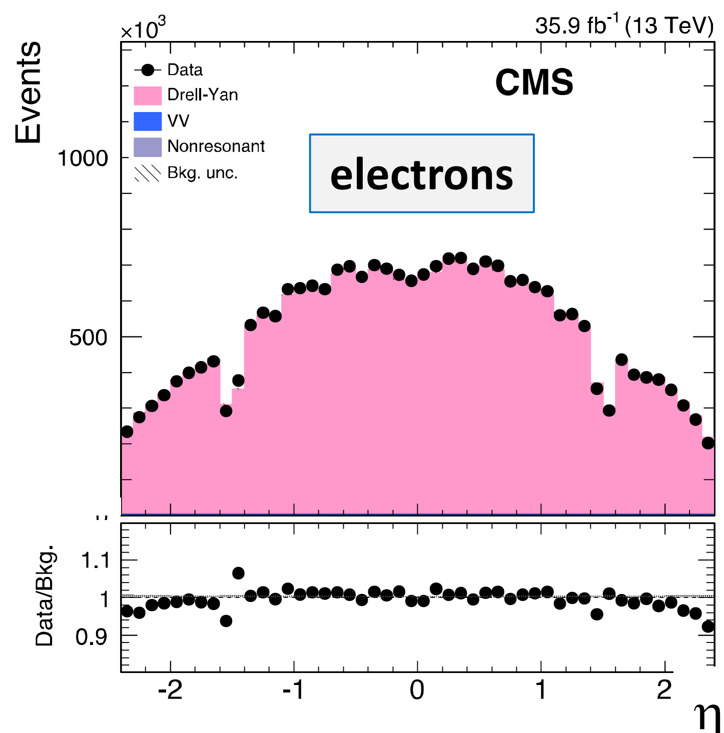
- Super-precise measurements (such as $d\sigma / dq_T$ and A_{FB}) pose greater challenges in controlling momentum calibrations, efficiencies, etc.
- Improved calibrations, efficiency measurements, support M_W measurement

Example: lepton efficiencies (28 η, 21 p_T, 7 y bins); closure test 0.1%, agreement 0.1%

η muons

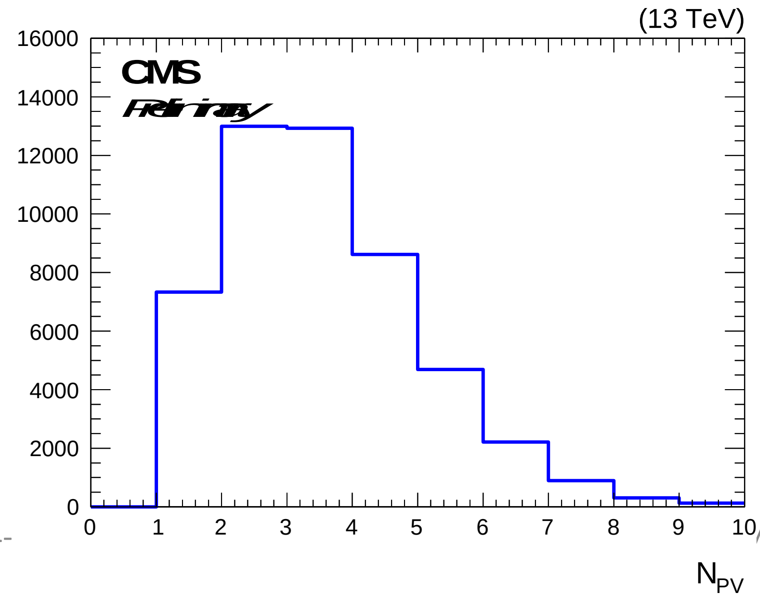


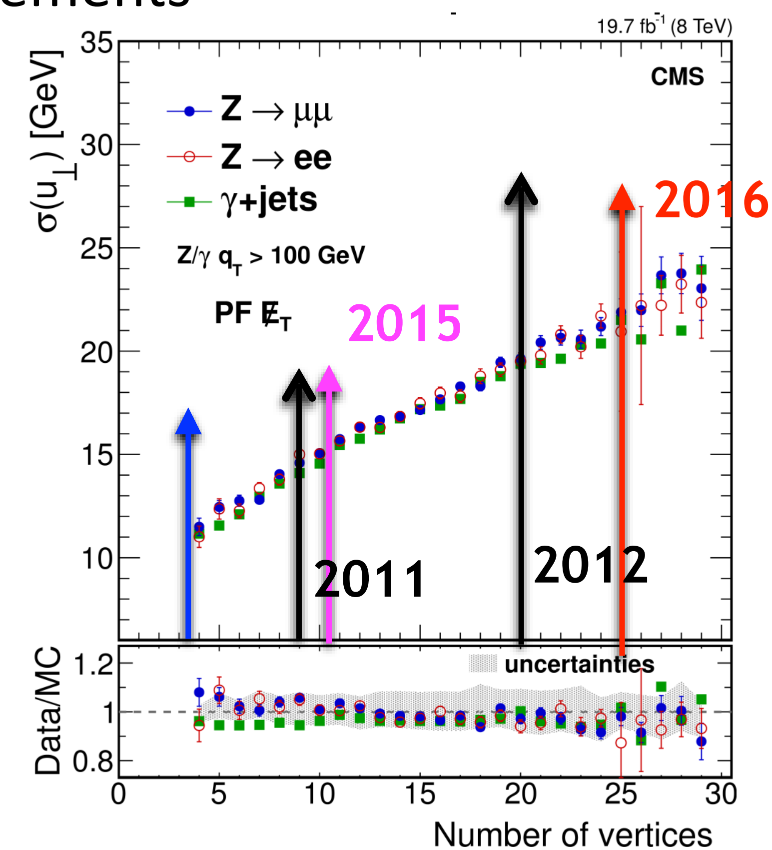
η electrons



M_W – low pile-up run

- 250 pb^{-1} recorded at 13 TeV this year
  - luminosity leveling giving average pileup = 3
  - lower lepton trigger thresholds (15 GeV)
- motivated by $d\sigma / dq_T$ and M_W measurements
- 300 pb^{-1} recorded earlier 5 TeV
- about 7M Ws in 13 and 5_TeV together
  - ATLAS used about 14 M



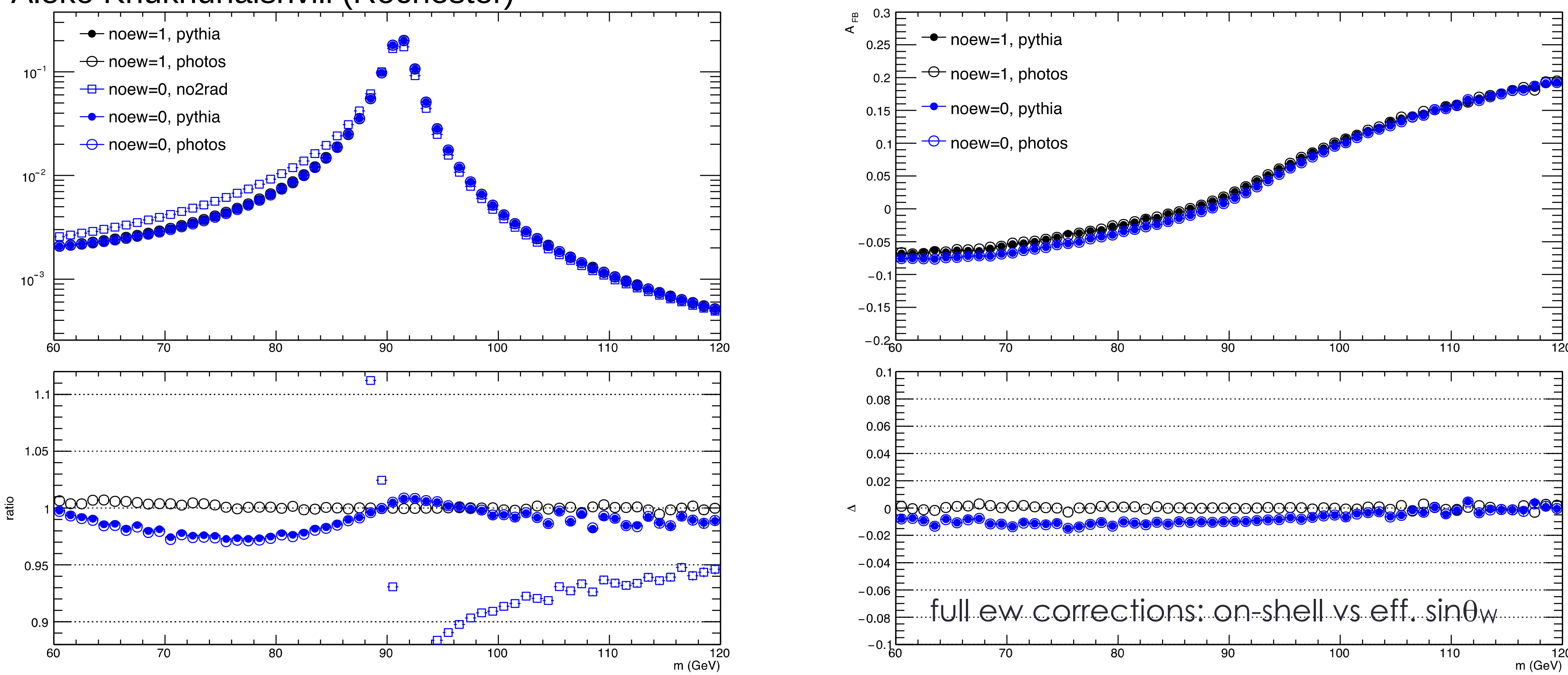


POWHEG with EW Corrections

- Proper EW corrections needed for POWHEG input parameters.
  - Need consistency between MW and sin2thetaW, for example.

- This has been provided, but we see some difficulties.
  - POWHEG authors have responded – close collaboration with CMS analyzers

Aleko Khukhunaishvili (Rochester)



Transferring $d\sigma/dq_T$ from Z to W

- Theoretical issues
  - Uncertainties are not small (Catani et al)
  - Non-perturbative pieces are not the same for W and Z
  - Different contributions from PDFs
  - Why is PYTHIA better than resummed calculations?
  - How to define and evaluate scale uncertainties for the ratio?
- Angular coefficients helpful – need NNLOJE – type calculations for Z and W (Gauld et a.)

- Experimental issues
  - Unfolding is not trivial. Smaller bins will require more sophisticated techniques such as likelihood unfolding.
  - How well can we measure the angular coefficients vs p_T?
    How do we propagate those uncertainties onto uncertainties for M_W?
  - Tuning MC event generators for underlying event, etc., needs extended effort.

PDFs

- Theoretical issues:
  - How to deal with HF?
    (Multi-scale problem)
  - Should QCD scale uncertainties for light and heavy flavor be correlated?
  - Should we work with PDFs that do **not** use the relevant measurements as input?
  - Does the photon PDF play any role?

- Experimental issues
  - Find ways to constrain PDFs that are insensitive to M_W, $\sin^2\theta_W$, etc.
  - Avoid "circular" tests – we don't want PDFs to absorb theoretical errors.
    - CMS is obtaining special sets from NNPDF that exclude CMS, ATLAS data
    - Can make this available to ATLAS & LHCb

Experimental Methods

- Issues
  - How can we maintain a low pT threshold for leptons?
  - How do we deal effectively with the impact of pileup on hadronic recoil?
  - Can we eliminate systematic uncertainties due to unfolding for the $d\sigma / dq_T$ measurements?
    - Exploring likelihood-based methods.

- Looking forward
  - Support that LHC experiments combine measurements for better precision on extracted parameters
  - Define first test case: AFB
    - Could use mock data
    - Define and test combination method
    - Define systematic uncertainties and correlations

Summary and Conclusions

- CMS making good progress on A_{FB} and differential cross sections
- Finding ways to pin down PDFs and q_T distribution –
  necessary for a good M_W measurement
- Significant progress on experimental issues (unfolding, calibrations, etc.)
- Further progress on theoretical side is crucial
  - calculations with resummed radiative, EW corrections
  - HF issues in PDFs
- Ultimately, LHC has potential to surpass both the Tevatron and LEP.

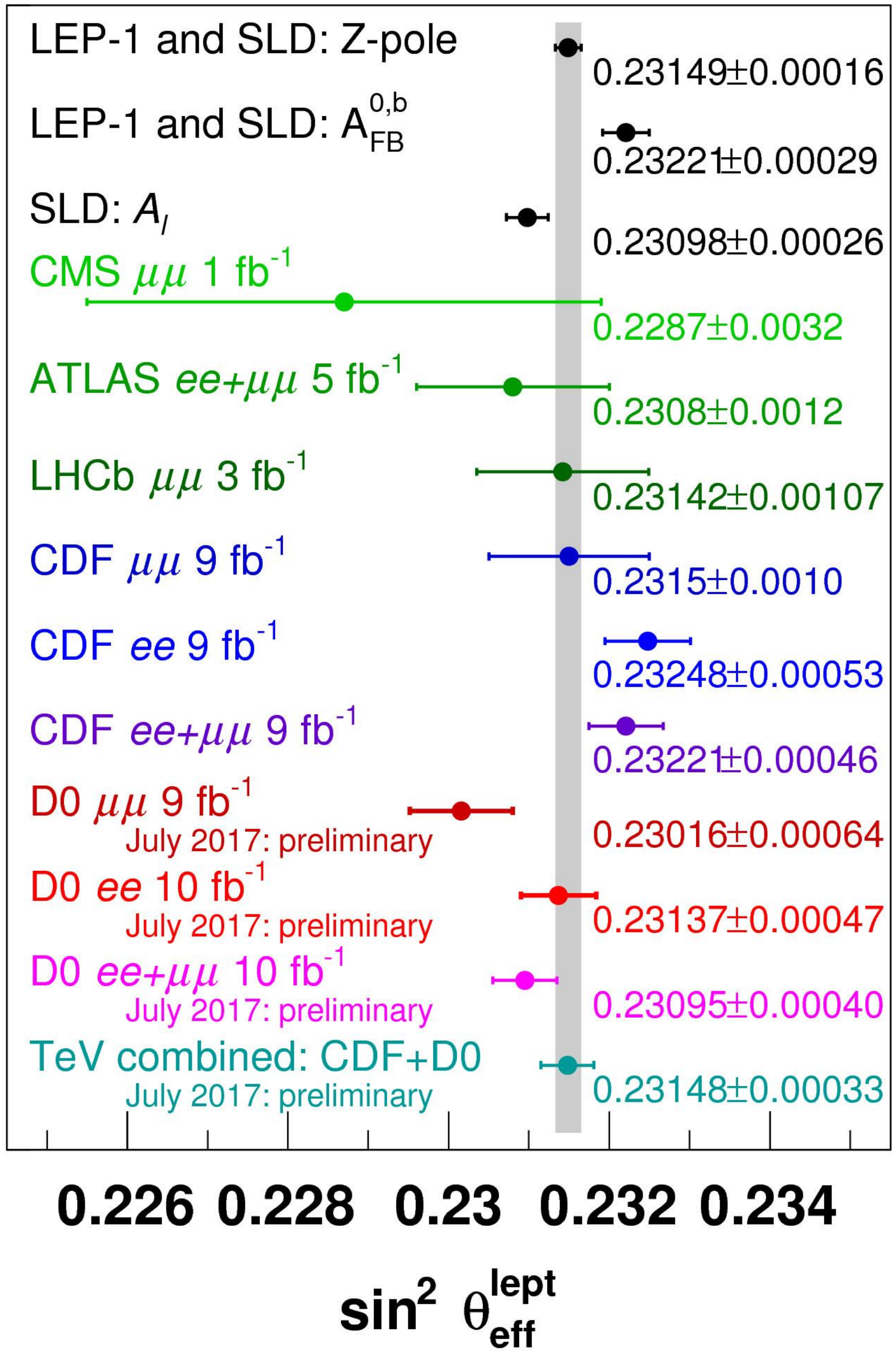
EXTRA SLIDES

CMS PAS SMP-16-007

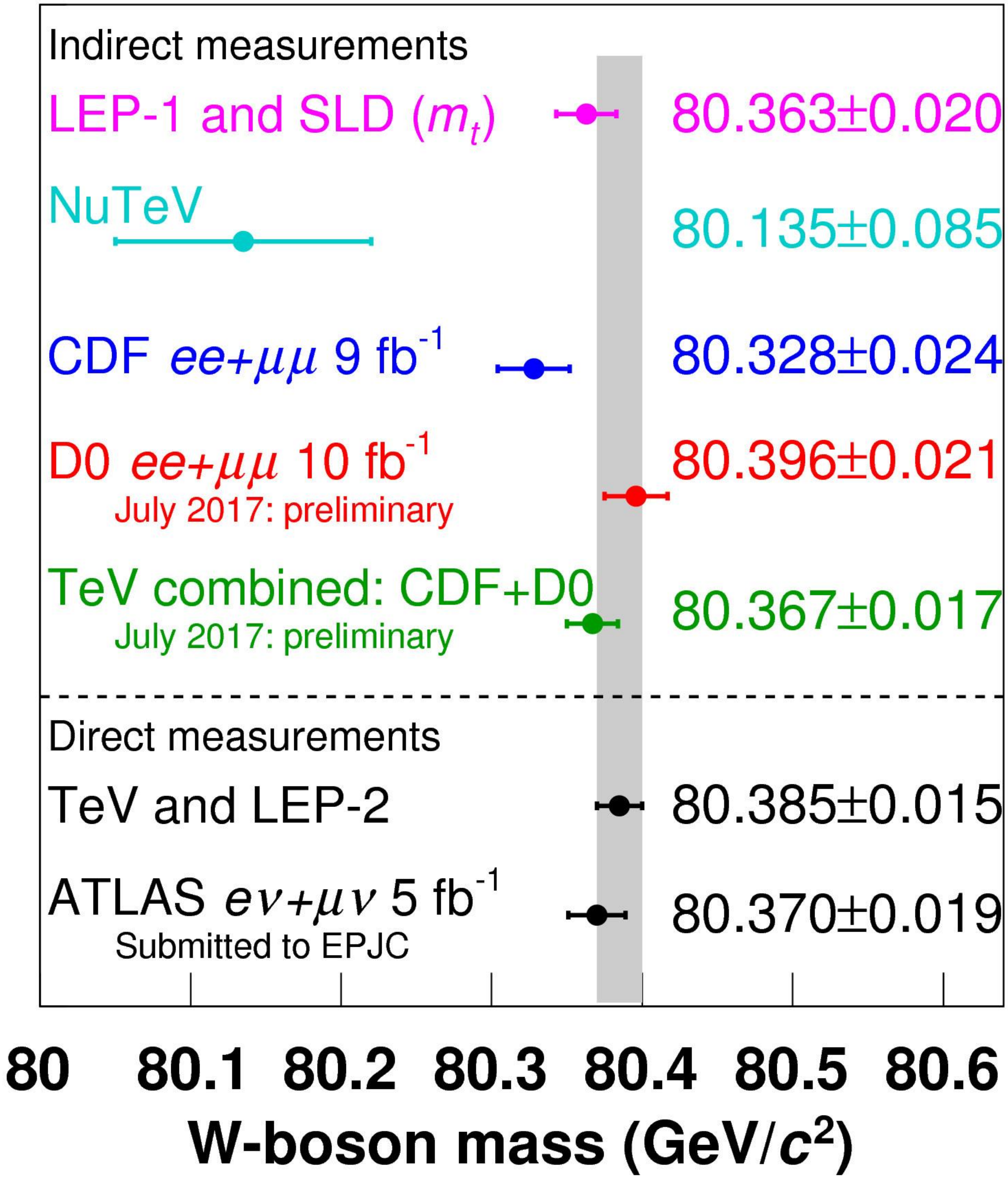
$$\sin^2\theta_{\text{eff}}^{\text{lept}} = 0.23101 \pm 0.00036(\text{stat}) \pm 0.00018(\text{syst}) \pm 0.00016(\text{theory}) \pm 0.00030(\text{pdf})$$

New combined D0 result (2017):

$$\sin^2\theta_{\text{eff}}^{\ell}[\text{comb.}] = 0.23095 \pm 0.00035(\text{stat.}) \pm 0.00007(\text{syst.}) \pm 0.00019(\text{PDF}).$$



Fermilab-Conf-17-201-E



Fermilab-Conf-17-201-E

$\sin^2\theta_W$ (8 TeV measurement)

CMS PAS SMP-16-007

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{8}\left(1+\cos^2\theta^* + \frac{A_0}{2}(1-3\cos^2\theta^*) + A_4\cos\theta^*\right)$$

$$A_{\mathrm{FB}} = \frac{3}{8}\frac{N_{\mathrm{F}}-N_{\mathrm{B}}}{D_{\mathrm{F}}+D_{\mathrm{B}}}$$

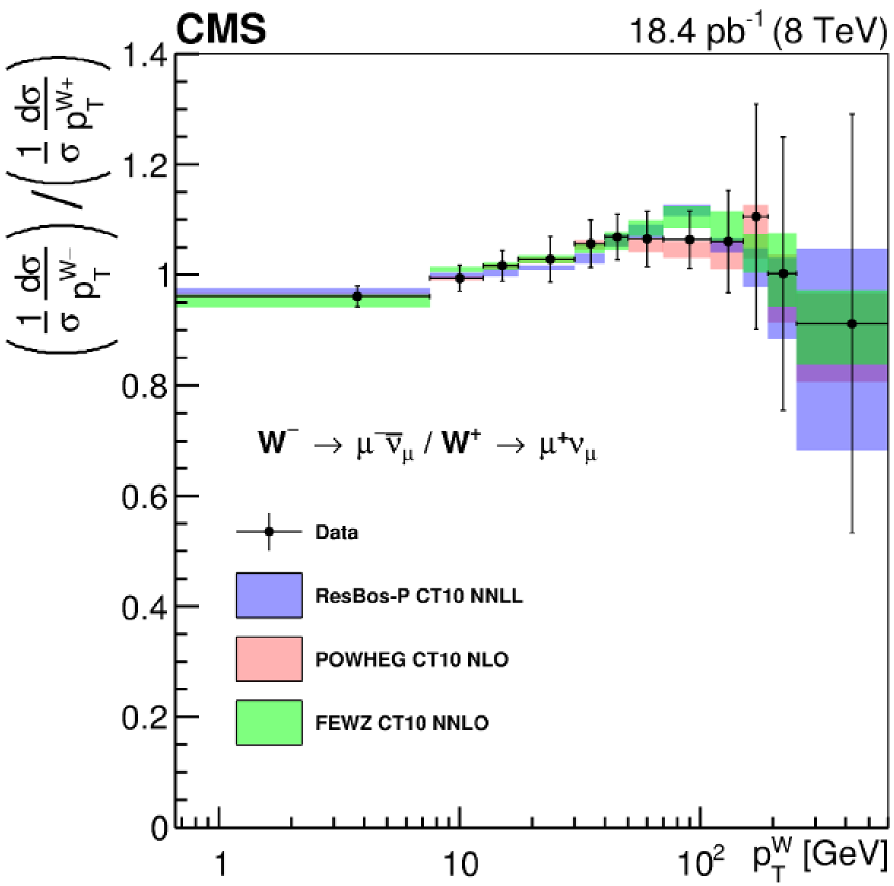
$$w_i = \frac{e^{-\frac{\chi^2_{\mathrm{min}}}{2}}}{\frac{1}{N}\sum_{i=1}^{N} e^{-\frac{\chi^2_{\mathrm{min}}}{2}}}$$

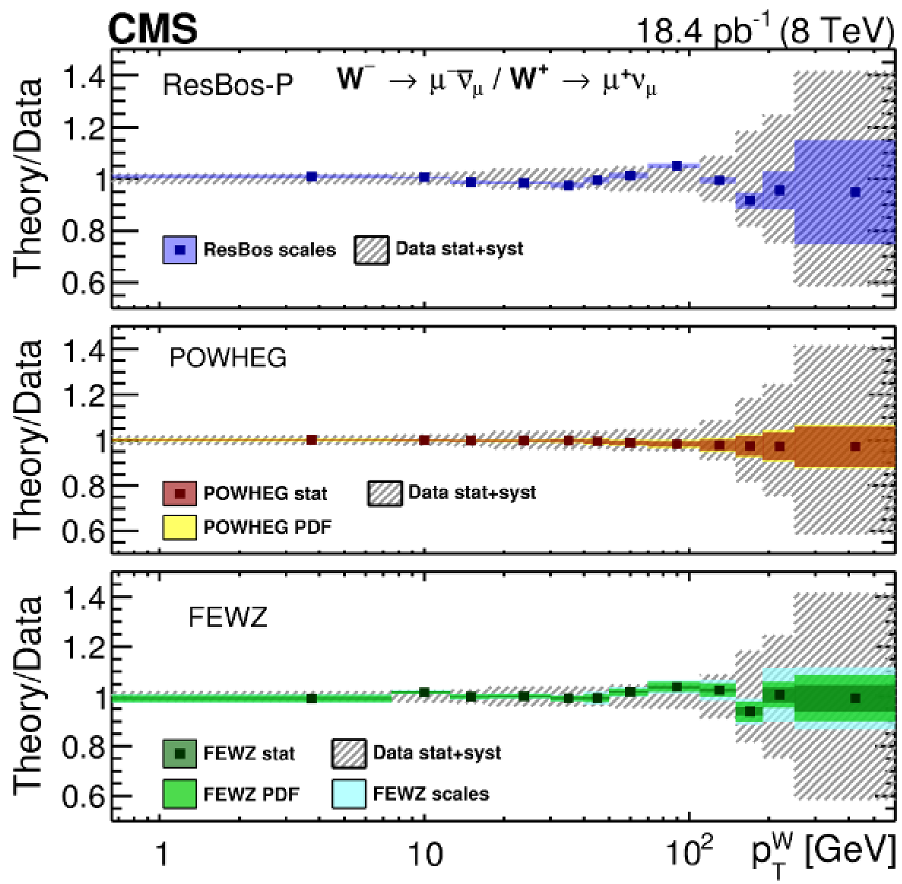
Table 2: Summary of experimental systematic uncertaintie

Source	muons	electrons
MC statistics	0.00015	0.00033
Lepton momentum calibration	0.00008	0.00019
Lepton selection efficiency	0.00005	0.00004
Background subtraction	0.00003	0.00005
Pileup modeling	0.00003	0.00002
Total	0.00018	0.00039

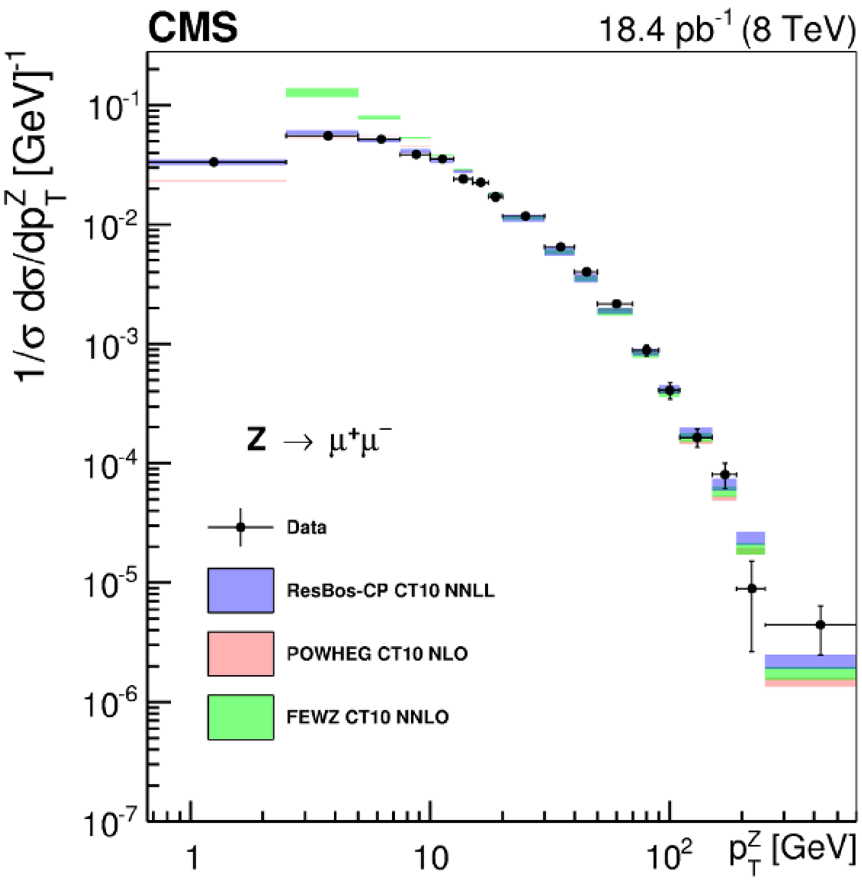
model variation	Muons	Electrons
Dilepton p_{T} reweighting	0.00003	0.00003
QCD $\mu_{R/F}$ scale	0.00011	0.00013
POWHEG MiNLO Z+j vs NLO Z model	0.00009	0.00009
FSR model (PHOTOS vs PYTHIA)	0.00003	0.00005
UE tune	0.00003	0.00004
Electroweak ($\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}} - \sin^2\theta^{\mathrm{u,d}}_{\mathrm{eff}}$)	0.00001	0.00001
Total	0.00015	0.00017

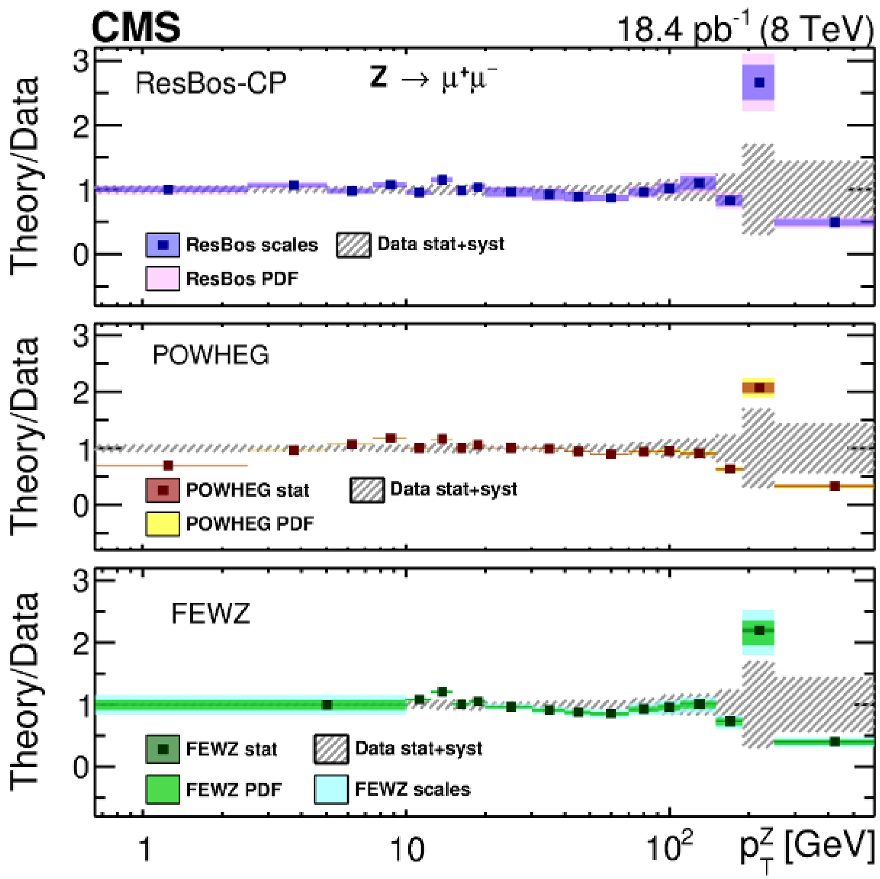
JHEP 02 (2017) 096



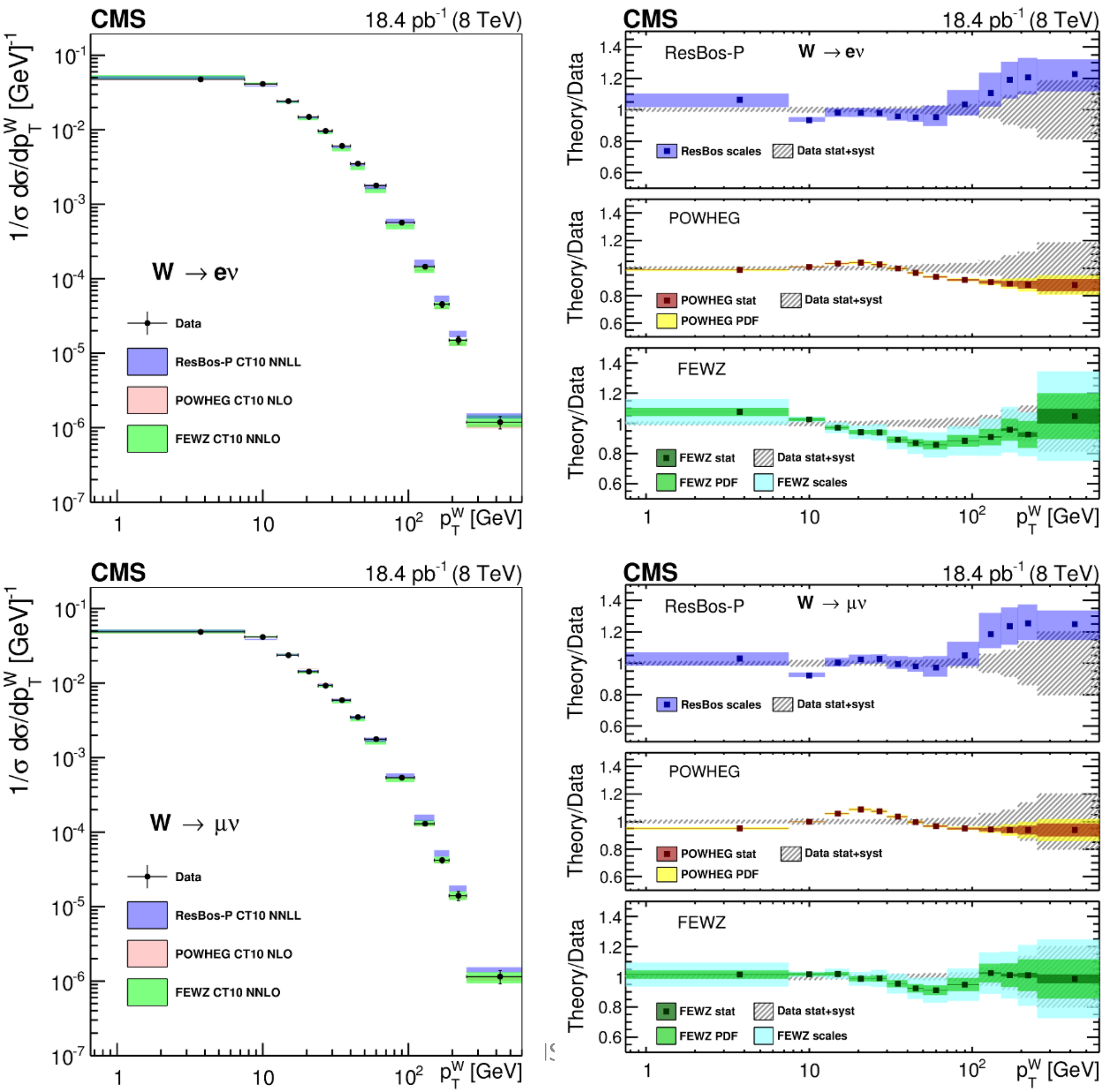


JHEP 02 (2017) 096

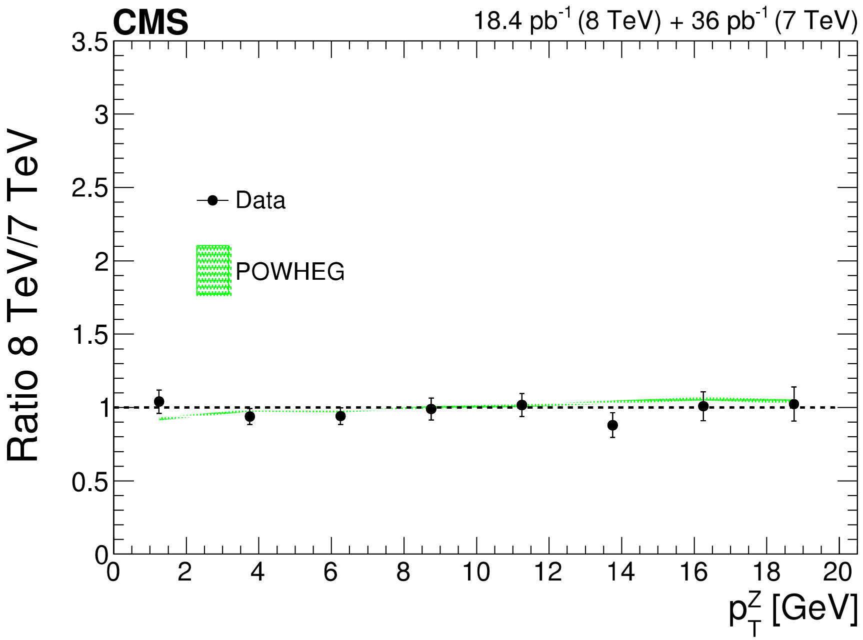


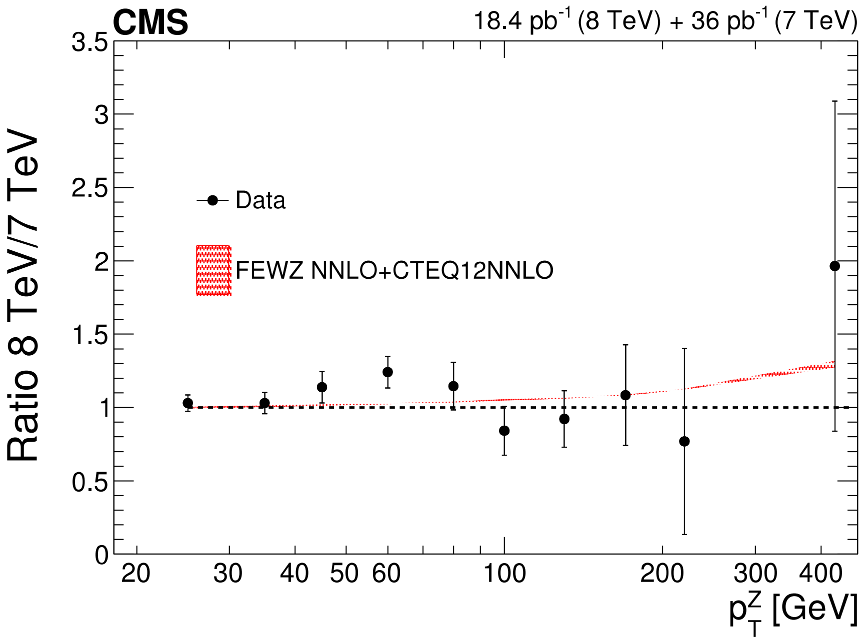


JHEP 02 (2017) 096



JHEP 02 (2017) 096

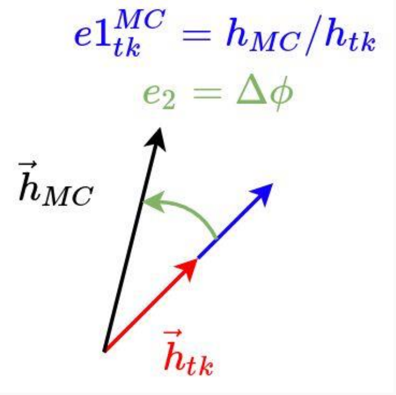




e1-e2 (i.e. scale-angle) regression

Target variables of which P(y|x) is fitted:

- ln(e1), ~scale
- e2, ~angle



Fitted pdf form:

➔ e1: Gaus + 2 expo tails
  - ◆ 4 pars = 4 DNN

➔ e2: Gaus + 2 expo tails + constant
  - ◆ 5 pars = 5 DNN

Input variables, *x previously*

Both:

- tk recoil: P_T, η, ϕ, mass, N_{tracks}
- Leading track P_T
- Tracks sphericity: $\frac{\sum \vec{P}_T^{(i)}}{\sum P_T^{(i)}}$
- neutral + tk not PV: P_T, η, ϕ
- Number of vetices

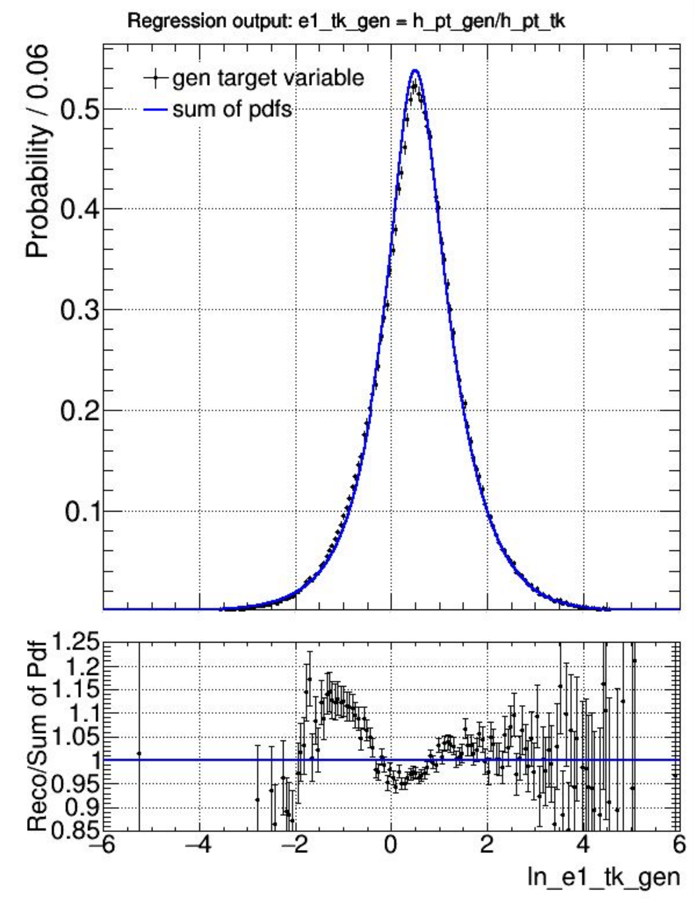
Only e1:

- $\cos(\phi_{ntnpv} - \phi_{tk})$

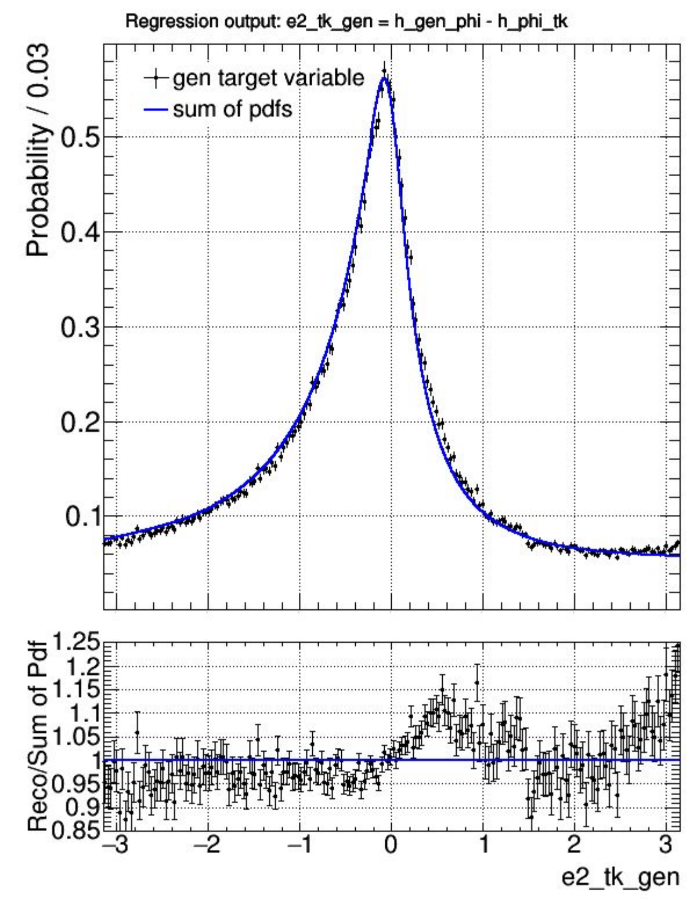
Only e2:

- $|\phi_{ntnpv} - \phi_{tk}|$
- $|\phi_{lead.tk} - \phi_{tk}|$

Sum of Pdf

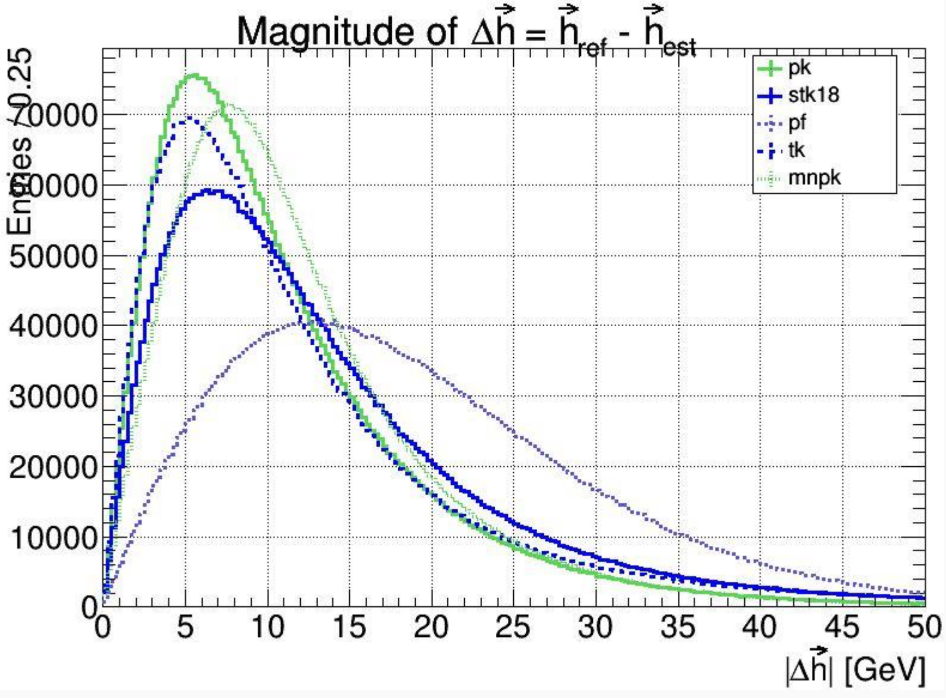


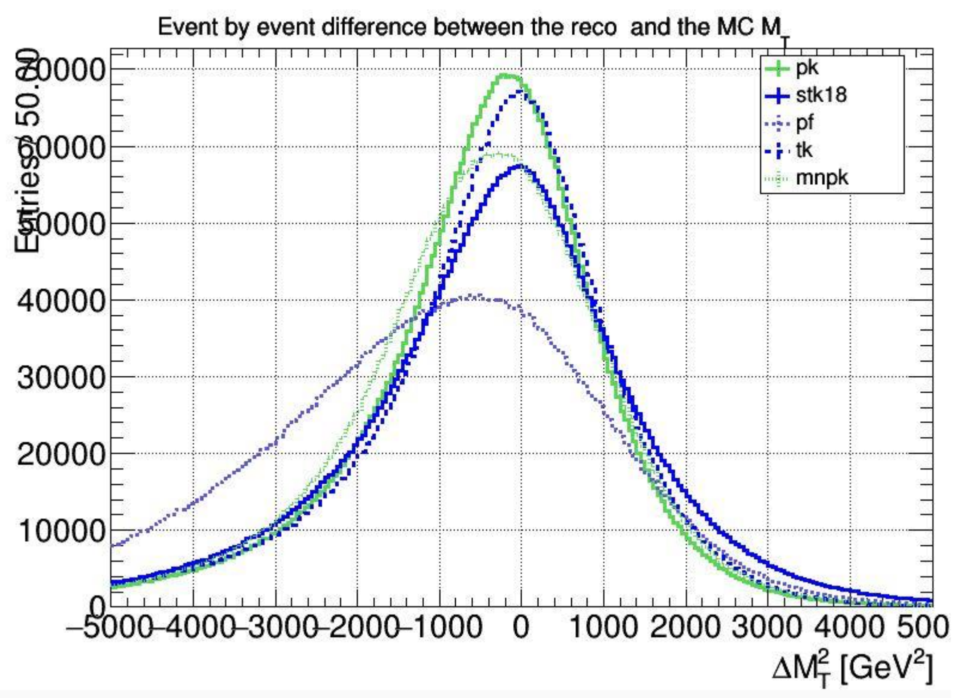
Regression output: e1_tk_gen = h_pt_gen/h_pt_tk
gen target variable
sum of pdfs
Probability / 0.06
Reco/Sum of Pdf
ln_e1_tk_gen



Regression output: e2_tk_gen = h_gen_phi - h_phi_tk
gen target variable
sum of pdfs
Probability / 0.03
Reco/Sum of Pdf
e2_tk_gen

Regression Control Plots - Z data sample (dimuon ~ gen)





The final rank

Summary:

- About **3 times less systematic** than tk (same stat.)
- About **30% less statistic** than PF (same sys.)

Although arbitrary variations are used, it has been tested that the ranking is reliable since it is independent of the shape of the variation.