Precision EW results from CMS

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On behalf of the CMS Collaboration

Alps2019:
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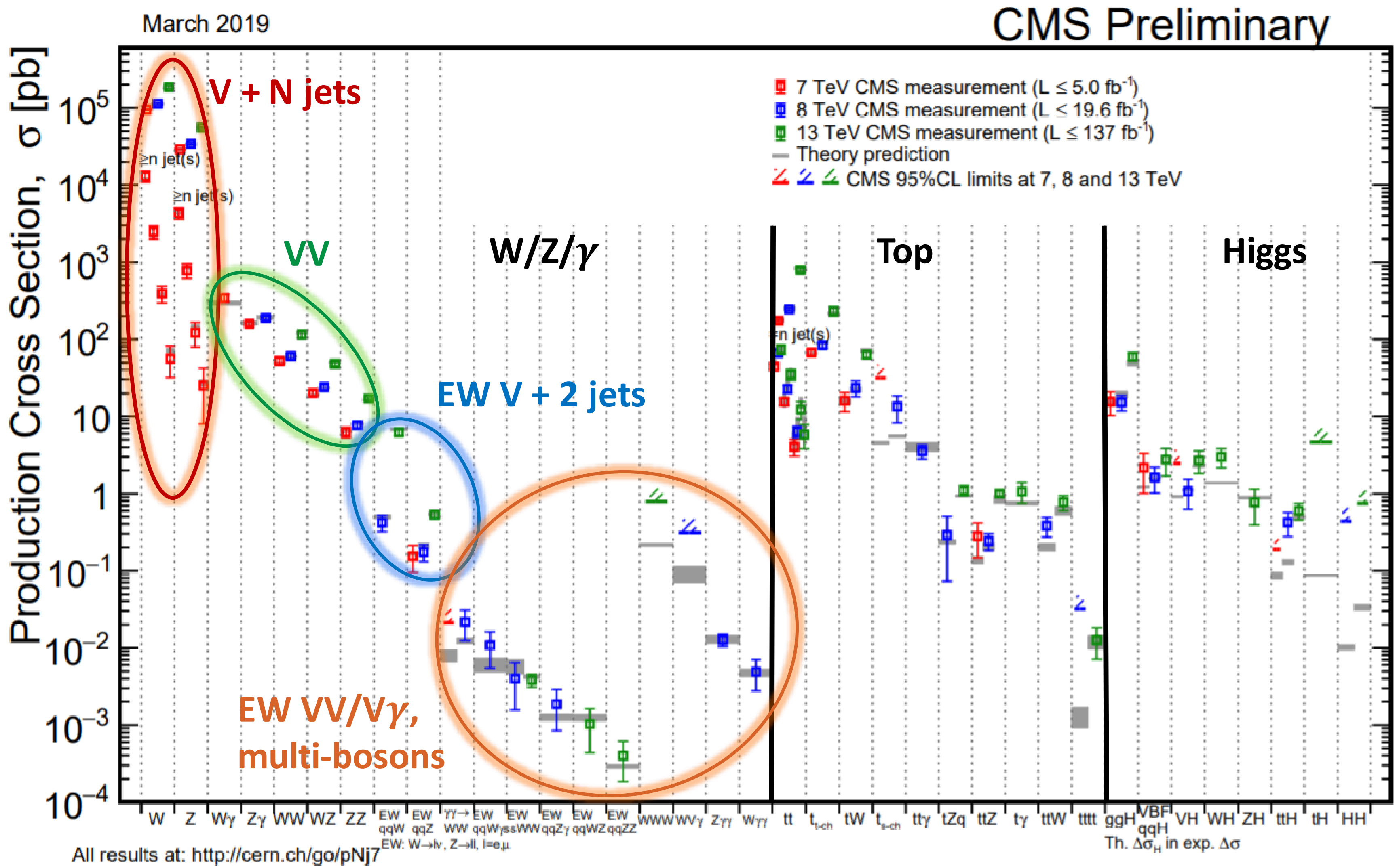
The success of the Standard Model (SM)

- **Experimental cross section measurements span over 9 orders of magnitude**
  - very good agreement with theoretical predictions at different energy scales

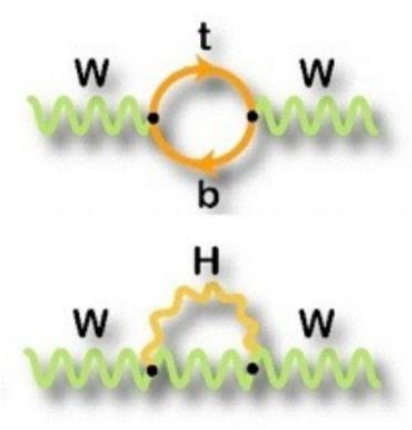


Exploring new physics through the EW sector

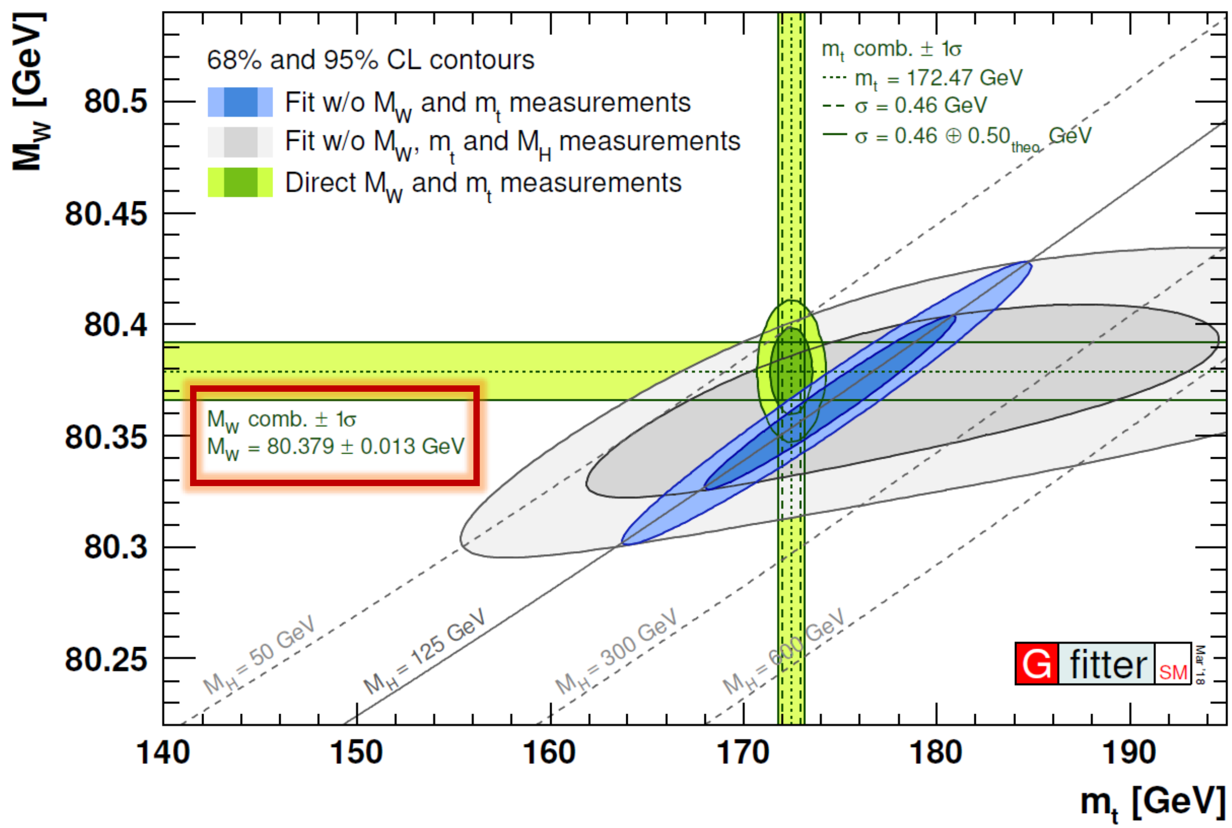
Z/W production important in many searches for new physics (NP)

- main source of background
- precision measurements of kinematic spectra and PDFs fundamental to discover NP
  - experiments must be supported by robust theoretical calculations

Knowledge of W/Z kinematics crucial to reach O(10) MeV precision on W-mass



δm_W^{SM} = 7 MeV from global EW fit to SM parameters



https://arxiv.org/abs/1803.01853

Effective weak mixing angle $\sin^2\theta^{f}_{eff}$

Forward-backward asymmetry A_{FB} in $q\bar{q} \rightarrow Z/\gamma^* \rightarrow \ell^+\ell^-$ sensitive to $\sin^2\theta^{f}_{eff}$

$$\frac{d\sigma}{d(\cos\theta^*)} \propto 1 + \cos^2\theta^* + A_4 \cos\theta^*$$

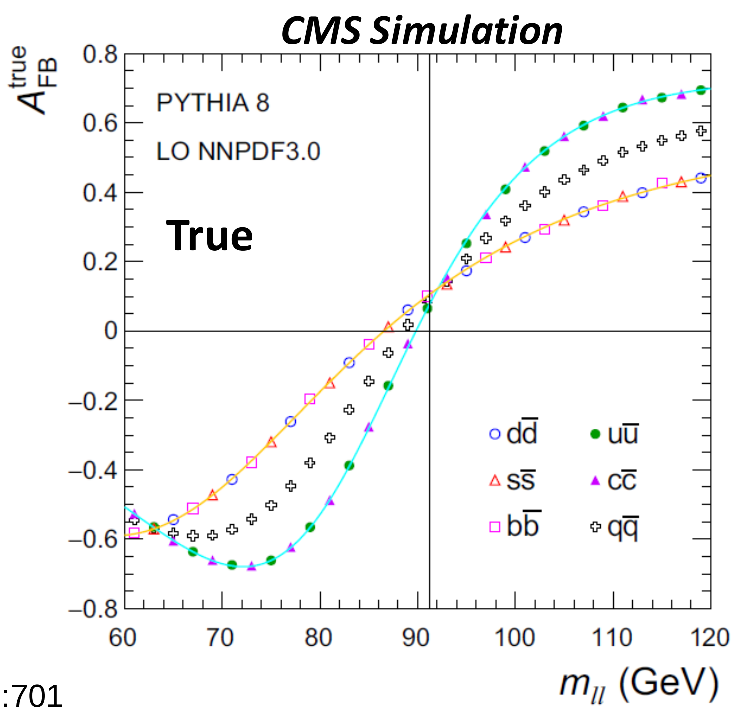
from interference of vector and axial-vector contributions (dependent on Z mass)

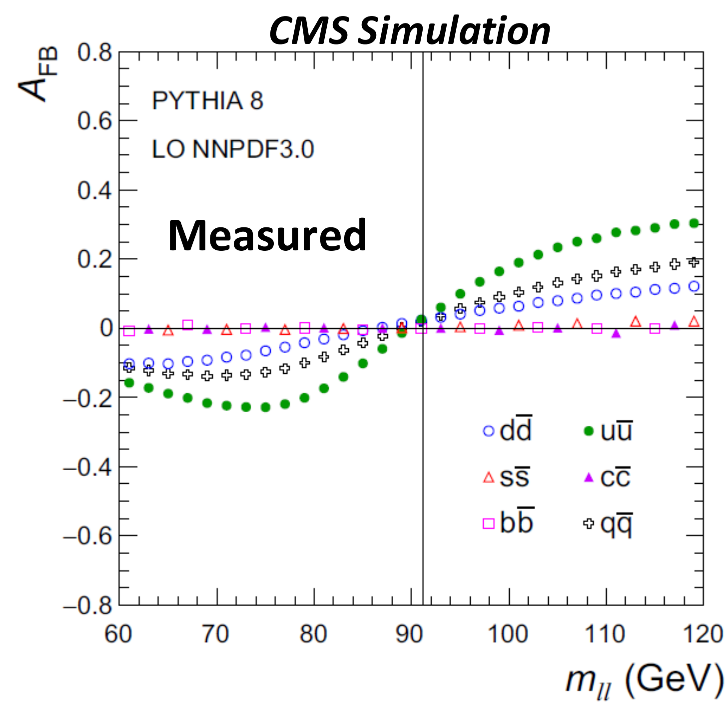
θ^* angle between ℓ^- and quark in Collins-Soper frame

- definition of θ^* assumes $\ell\ell$ pair produced along quark's direction
- quark's true direction unknown → dilution of A_{FB} → sensitivity to PDFs (large-x $\bar{q}$)

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

$F: \cos\theta^* > 0$
$B: \cos\theta^* < 0$





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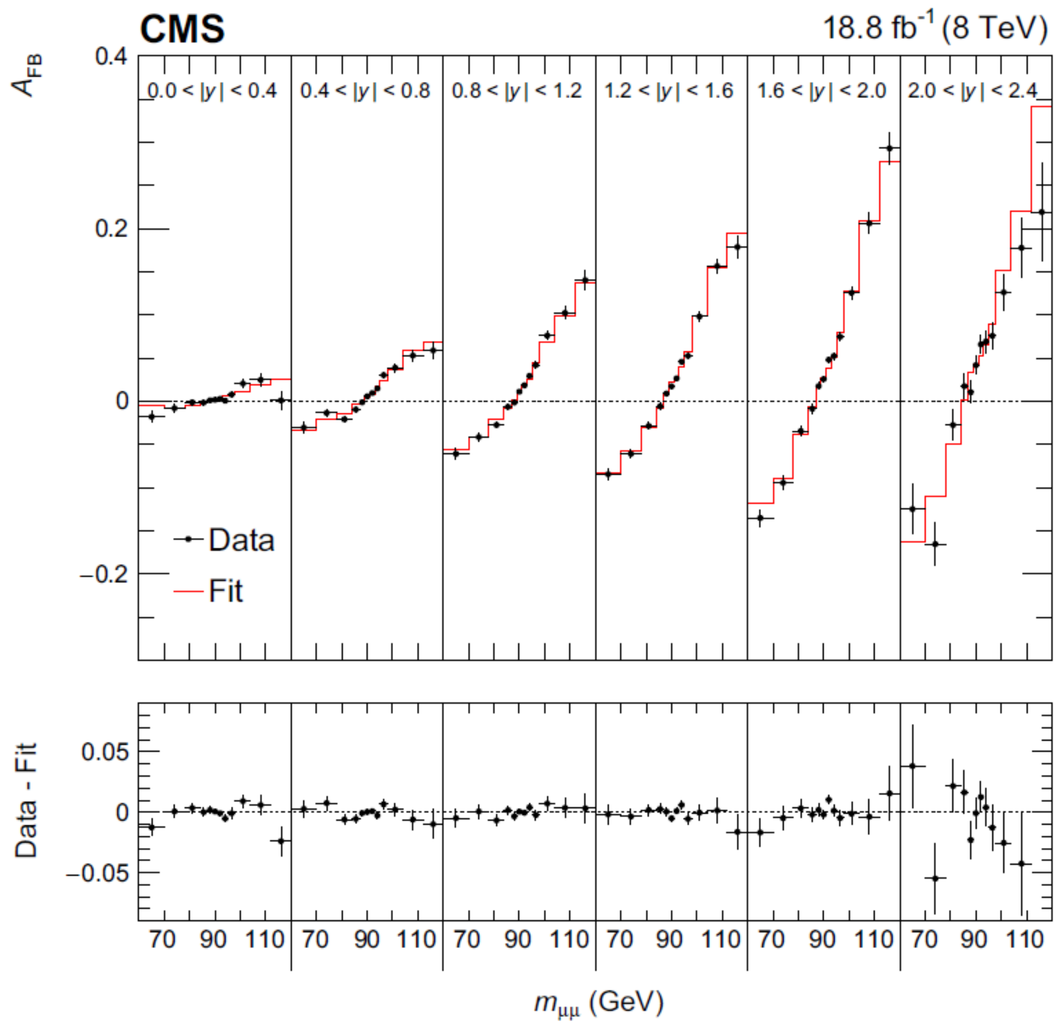
Measuring $\sin^2\theta^{f}_{eff}$ through A_{FB}

A_{FB} depends on both Z mass and rapidity Y

- $\sin^2\theta^{f}_{eff}$ measured by fitting $A_{FB}(m_{\ell\ell}, Y_{\ell\ell})$ in data to SM predictions obtained for different values of $\sin^2\theta^{f}_{eff}$
- signal templates from POWHEG
- using NNPDF3.0 PDF set

A_{FB} calculated with angular event weighting technique:

- measurement less sensitive to $\cos\theta^*$ acceptance modeling



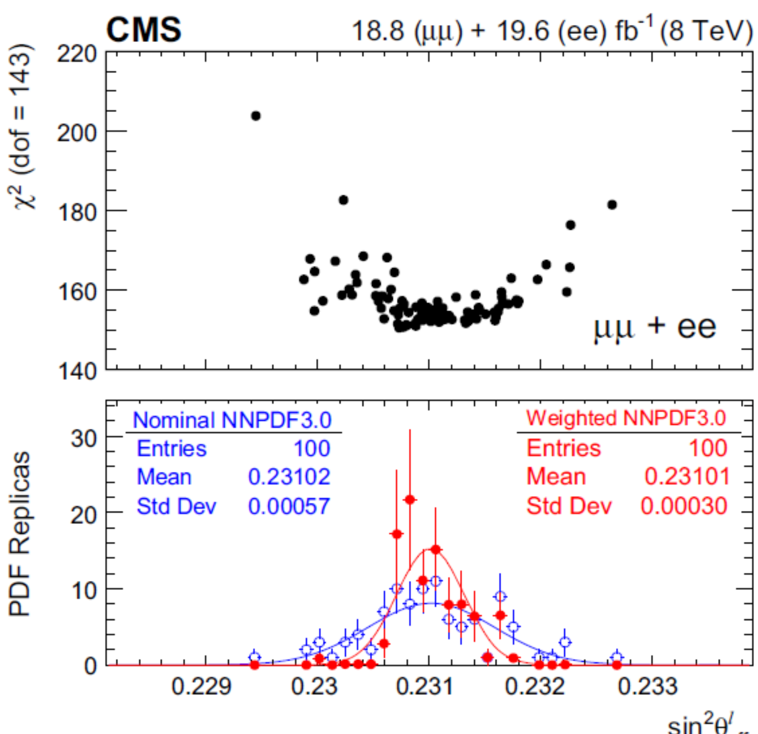
PDF uncertainty on $\sin^2\theta^{f}_{eff}$

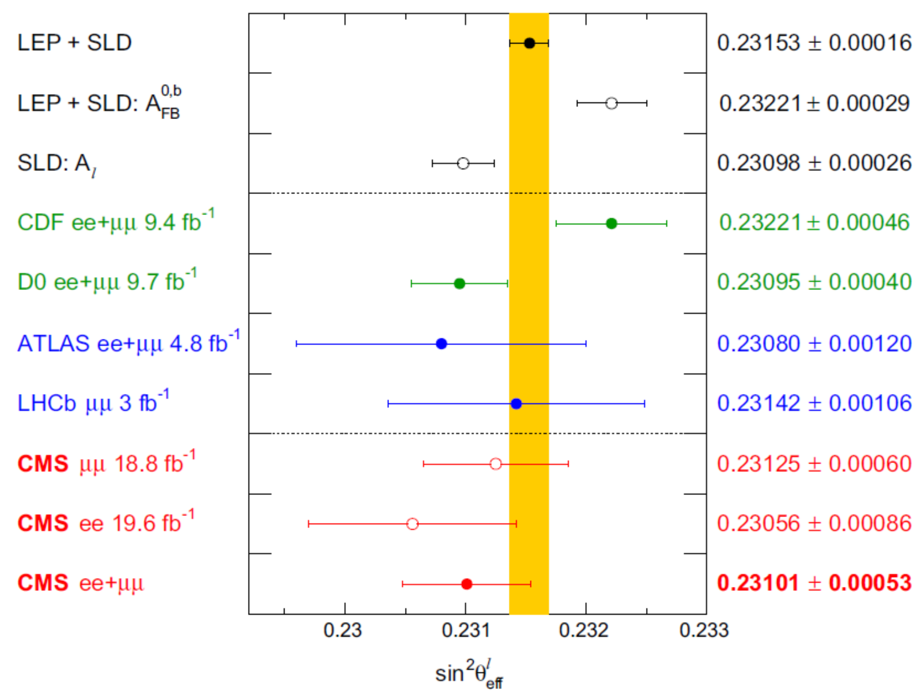
Bayesian χ^2 reweighing method used to constrain PDFs from data

- perform $\sin^2\theta^{f}_{eff}$ fit for each NNPDF3.0 replica (100) and assign weight $w \propto e^{-\chi^2/2}$
- measure $\sin^2\theta^{f}_{eff}$ as weighted sum over PDF replicas (PDF uncertainty reduced by ≈ 2)

Precision limited by statistical uncertainty and PDFs

- $\sin^2\theta^{f}_{eff} = 0.23101 \pm 0.00036\,(\mathrm{stat}) \pm 0.00018\,(\mathrm{syst}) \pm 0.00016\,(\mathrm{theory}) \pm 0.00031\,(\mathrm{PDF})$



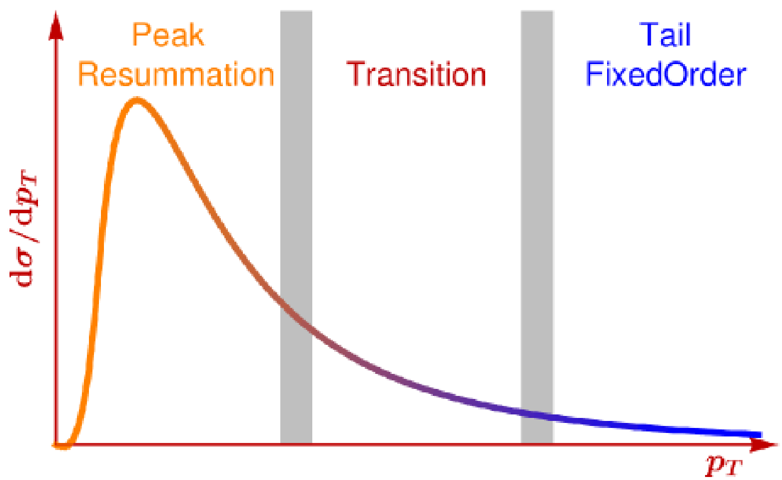


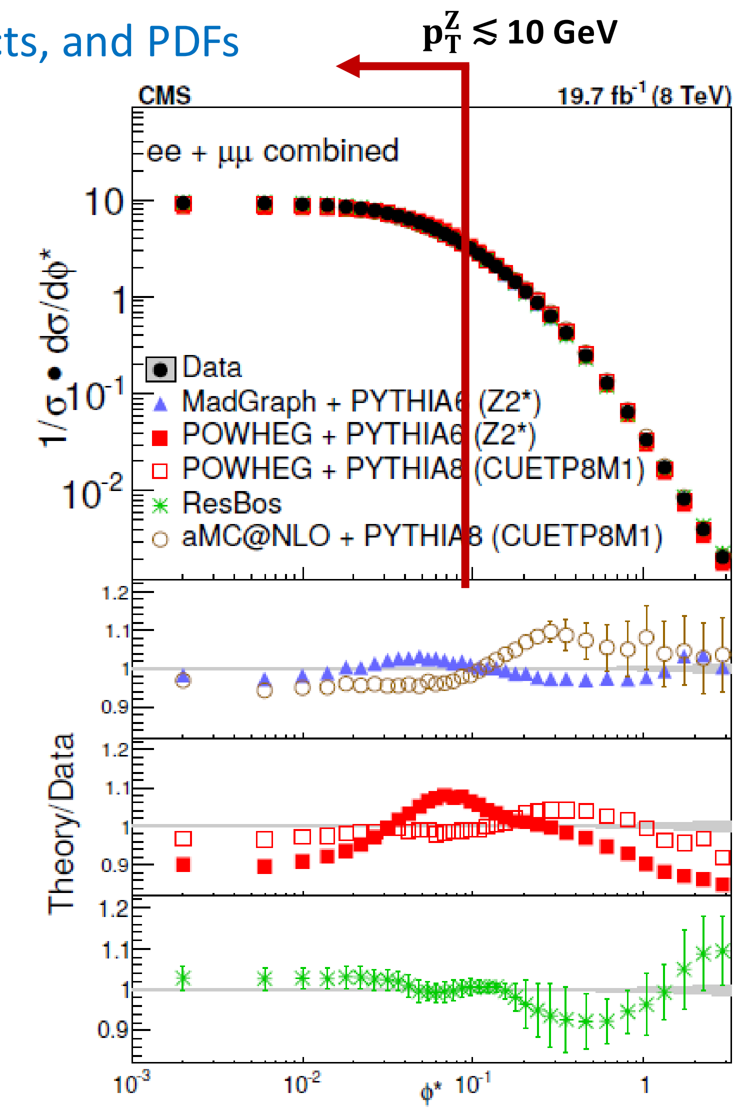
ATLAS [new meas. @8TeV]: $\sin^2\theta^{f}_{eff}$ = 0.23140 ± 0.00036

Z-boson $d\sigma/d\phi^*$

Fixed order perturbative QCD calculations do not work for $p_T \ll m_{Z,W}$

- $p_T^{W/Z}$ measurements test modeling of hard scattering/parton shower
- sensitive to higher orders, non-perturbative effects, and PDFs





ϕ^* correlated with p_T^Z, but depends only on $\ell\ell$ angular variables (better resolution)

$$\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta_\eta^*)$$

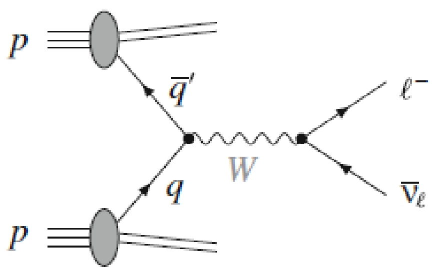
$$\phi^* \approx p_T^Z / m_{\ell\ell}$$

$$\cos(\theta_\eta^*) = \tanh(\Delta\eta/2)$$

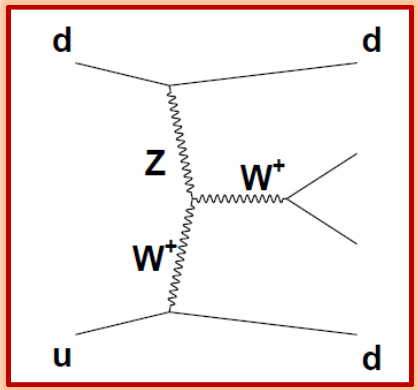
Electroweak production of W/Z + 2 jets

Distinctive signature with two forward jets with large dijet mass and $\Delta\eta(j1,j_2)$

- VBF understanding important for Higgs measurements and NP searches
- multivariate analysis to enhance signal

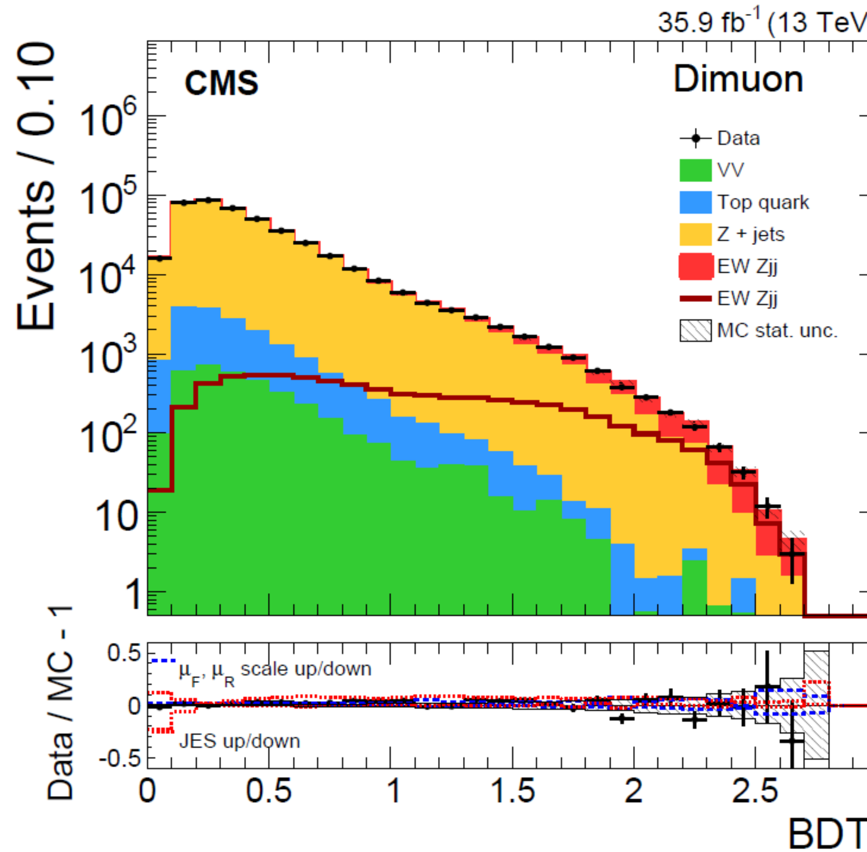


Drell-Yan (QCD) production



Pure EW production, vector boson fusion (VBF)

W+2jets: CMS-SMP-17-011 submitted to EPJC
Z +2jets: Eur. Phys. J. C 78 (2018) 589



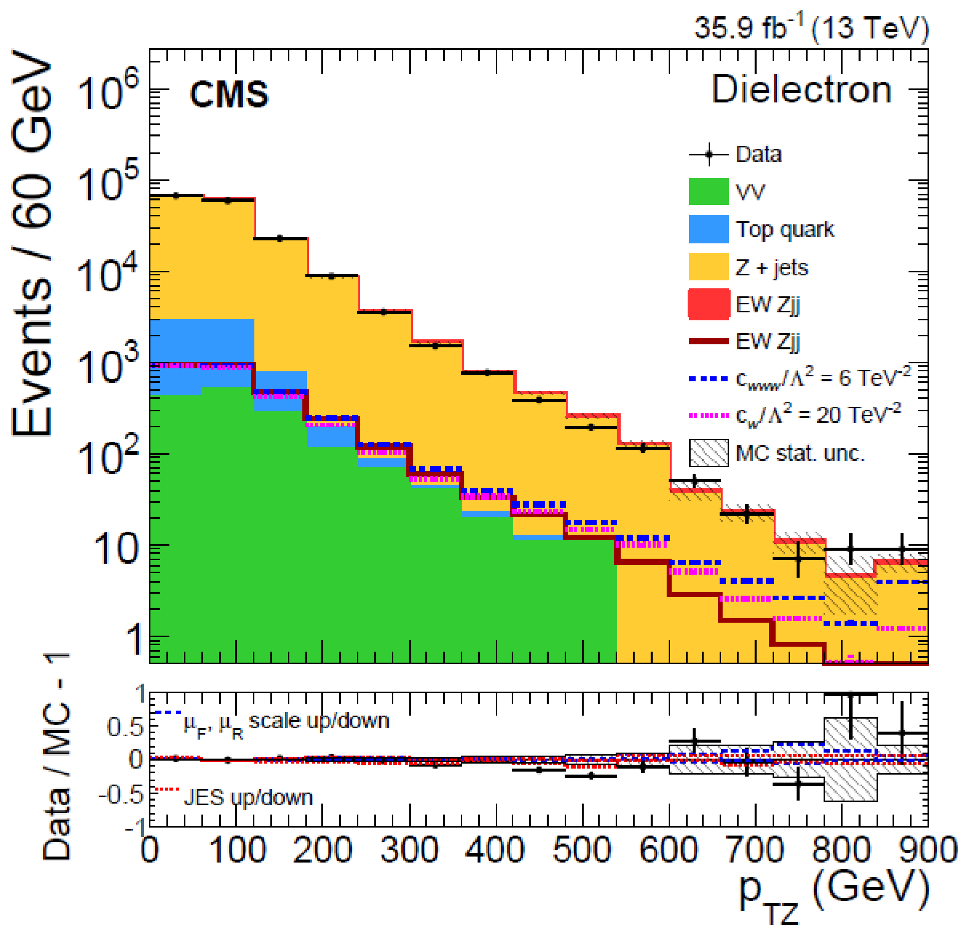
Cross section for combined e/μ channels in agreement with SM

- $\sigma_{\mathrm{EW}}(\mathrm{Wjj}) = 6.23 \pm 0.12\ (\mathrm{stat}) \pm 0.61(\mathrm{syst})\ \mathrm{pb}$
- $\sigma_{\mathrm{EW}}(\mathrm{Zjj}) = 534 \pm\ \ 20\ (\mathrm{stat}) \pm\ \ 57\ (\mathrm{syst})\ \mathrm{fb}$

Constraints on anomalous triple gauge couplings (ATPG)

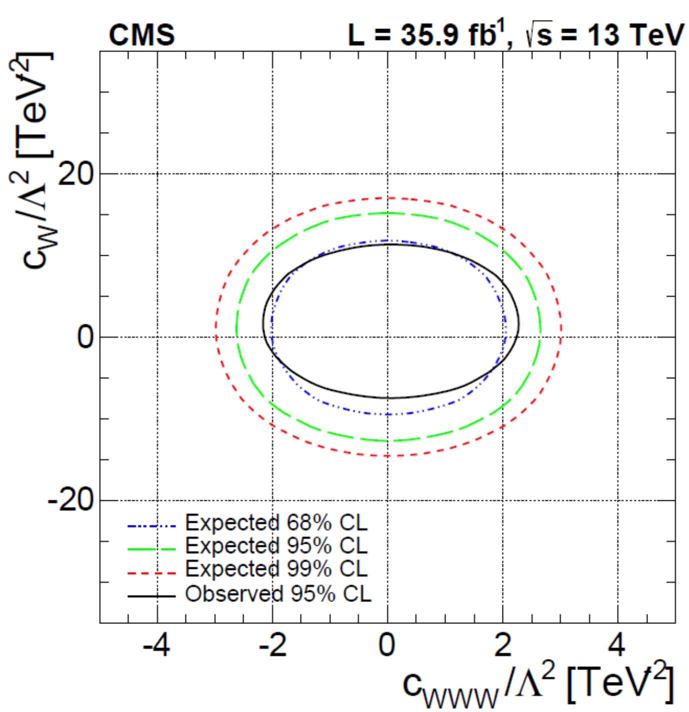
W/Z+2jets sensitive to ATPG induced by higher-dimension operators

- expect cross section enhancement at high p_T^{ℓ} or p_T^{Z}
- no sign of NP, **most stringent limits to date on c_{WWW}** from combination of W/Z



$$\mathcal{O}_{WWW} = \frac{c_{WWW}}{\Lambda^2} W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu},$$

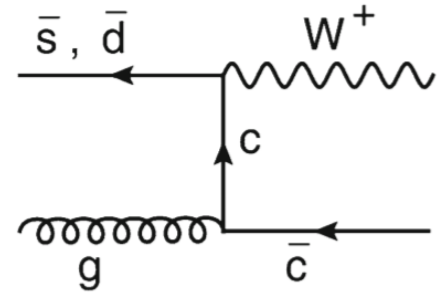
$$\mathcal{O}_{W} = \frac{c_W}{\Lambda^2} (D^{\mu}\Phi)^{\dagger} W_{\mu\nu} (D^{\nu}\Phi)$$



Production of a W boson and a charm quark

Probe s-quark content of the proton → sensitivity to PDF

- cross-check results from global PDF fits to deep inelastic scattering (DIS) data

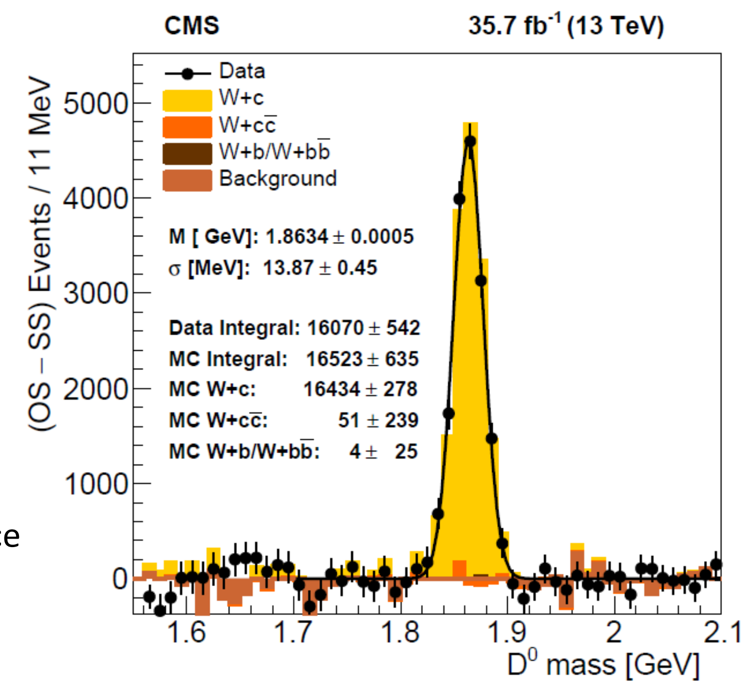


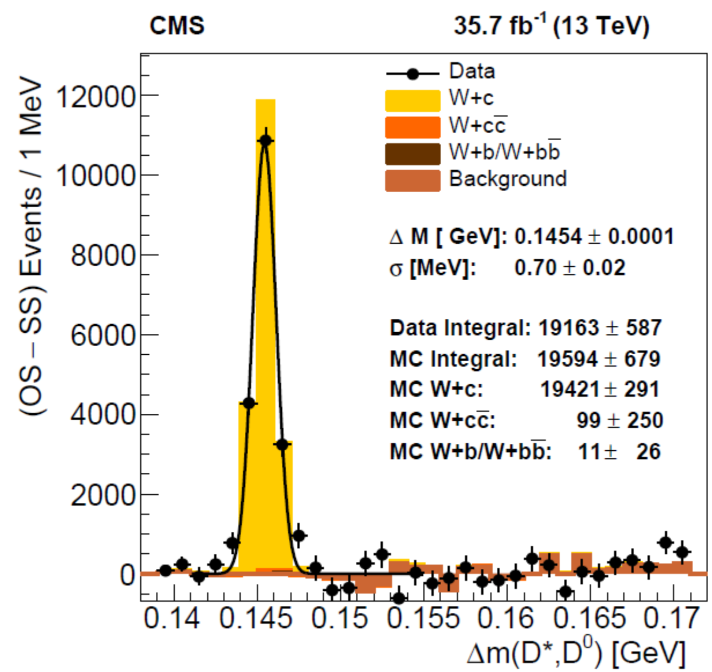
c-quark tagged by full reconstruction of charmed hadrons

- $c \rightarrow D^*(2010)^{\pm} \rightarrow D^0(1865) + \pi^{\pm}_{slow} \rightarrow K^{\mp} + \pi^{\pm} + \pi^{\pm}_{slow}$
- requires high performance in track reconstruction and secondary-vertex location

Left:
$K^{\mp}\pi^{\pm}$ mass in range $|\Delta m(D^*, D^0)$ - 0.1454$|$ < 1 MeV

Right:
reconstructed D mesons' mass difference





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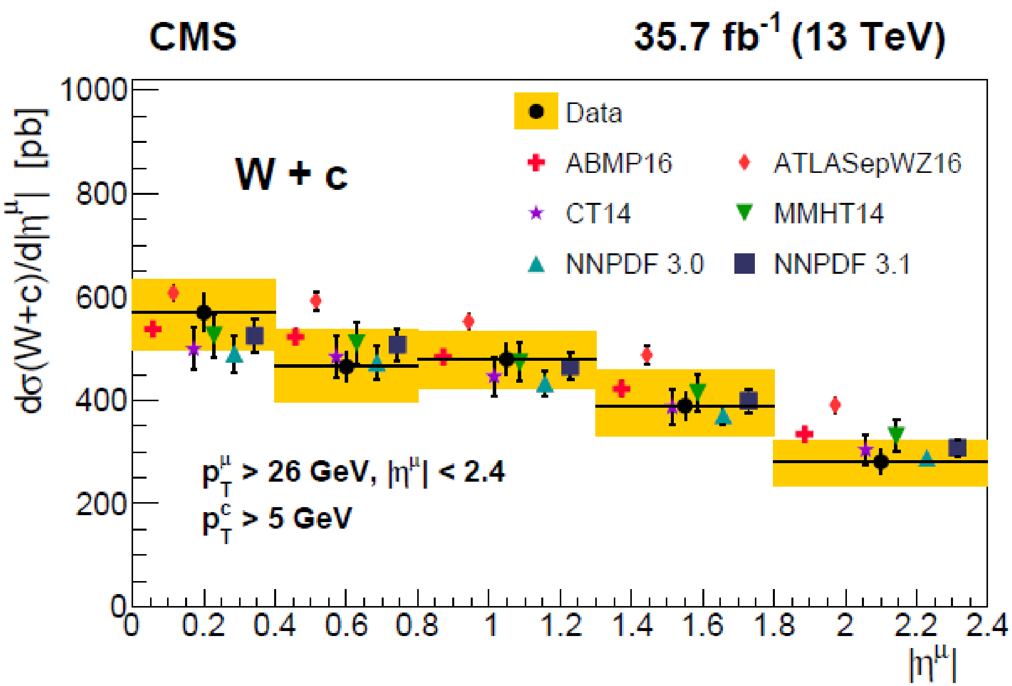
W+c cross section

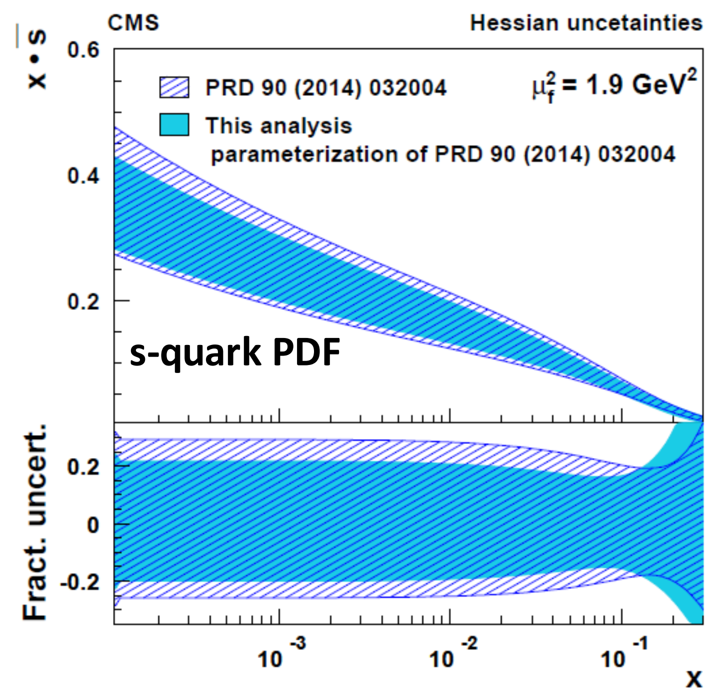
σ(W+c) measured inclusively/differentially in $|\eta^{\mu}|$

- results compared with NLO ($\mathcal{O}(\alpha_S^2)$) predictions using different PDF sets

Present measurement used in an NLO QCD analysis

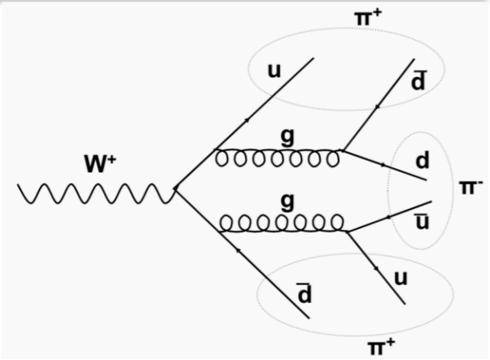
- combination of DIS measurements and earlier CMS W charge asymmetry and W+c
- determine s-quark PDF





Not only precision measurements

CMS-SMP-18-009
Submitted to PRL

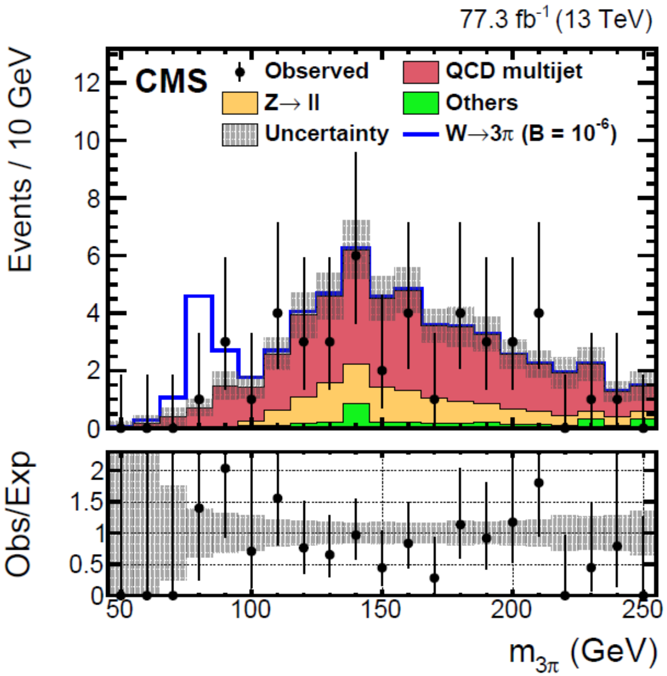


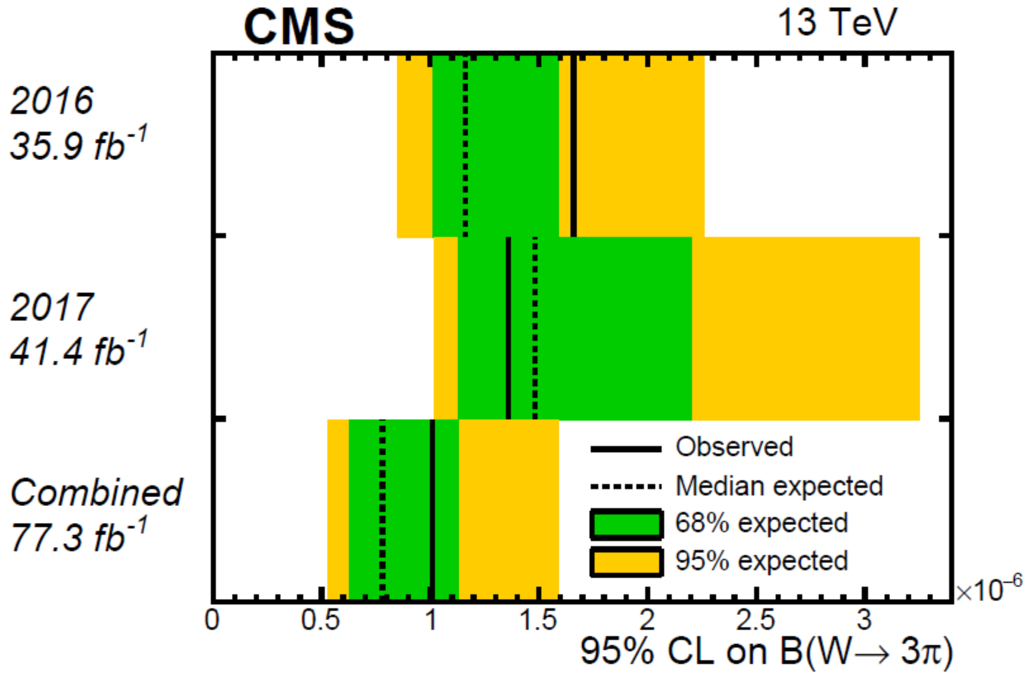
First search for rare decay $W \to 3\pi$

- **no theoretical prediction** exists for branching ratio!
- BR($W \to 3\pi$) thought to be between 10^{-8} and 10^{-5}

Innovative use of algorithms originally designed to trigger on and identify hadronically decaying τ leptons

- no excess found → upper limit set at 95% CL: **BR($W \to 3\pi$) < $1.01 \cdot 10^{-6}$**





Summary

- **Some of the most recent EW measurements from CMS presented**
  - fundamental to test perturbative QCD calculations and PDFs
  - precise knowledge of EW processes **vital in searches for new physics**

- **Excellent performance of the LHC and CMS detector during Run 2**
  - large amount of data allows to **probe SM with unprecedented precision** and **explore rare processes** (un)predicted by SM

- **Many analysis limited by theoretical systematic uncertainties**
  - devise new ideas and techniques to improve on precision
  - design new measurements to support more precise calculations

- **Collaboration between experimental and theoretical community paramount to exploit at best data collected during Run 2**

BACKUP

Forward–backward asymmetry of Drell–Yan events

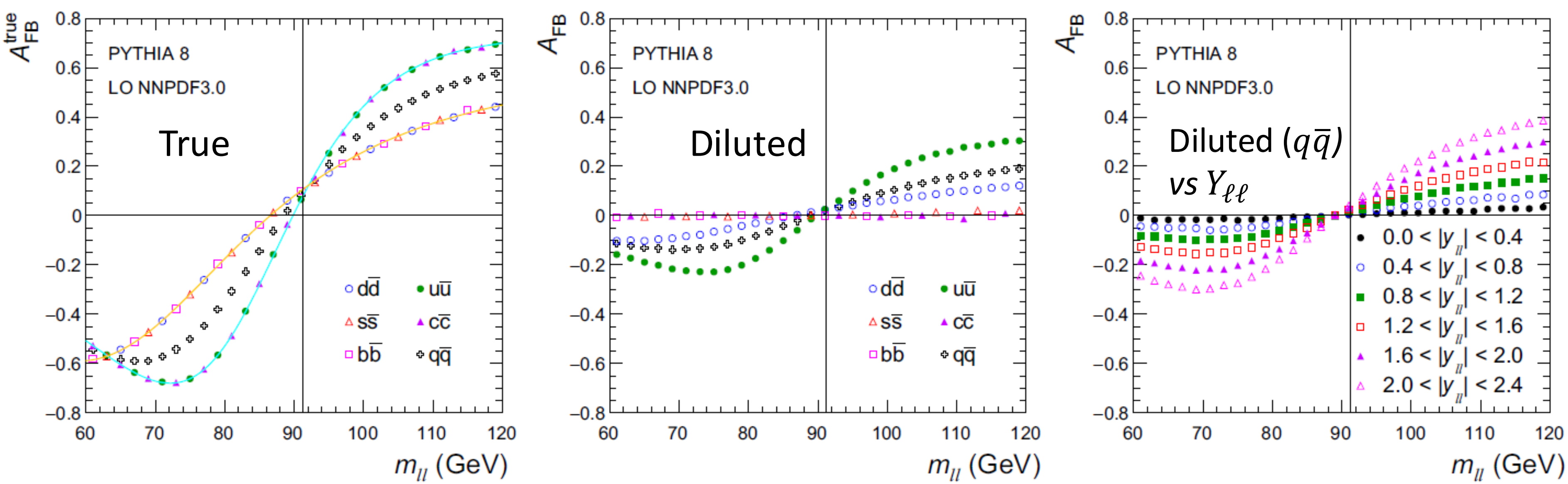
Forward-backward asymmetry A_{FB} in $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$

- Z couplings different for left and right-handed fermions

A_{FB} sensitive to $\sin^2\theta_W$ near Z peak

- at LO, $\sin^2\theta_W = 1 - m_W^2/m_Z^2$
- EW corrections can be absorbed in effective couplings k_f

$$v_f = T_3^f - 2Q_f \sin^2\theta_W,$$
$$a_f = T_3^f,$$
$$\boxed{\sin^2\theta_{eff}^f = k_f \sin^2\theta_W}$$



$\sin^2\theta^{f}_{eff}$ and PDF uncertainty

PDF uncertainty on A_{FB} larger far from Z peak (opposite behavior for $\sin^2\theta^{f}_{eff}$)

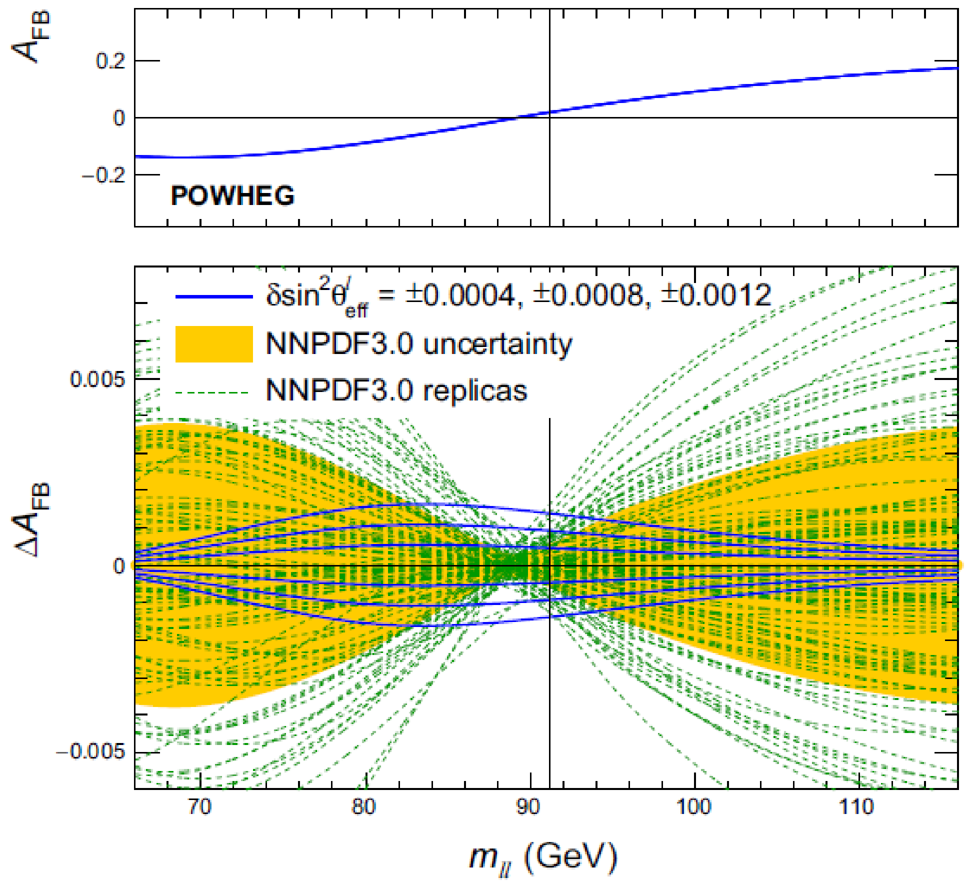
- each MC replica in the NNPD3.0 set corresponds to a measured value of A_{FB} cf
- PDF uncertainty on A_{FB} (from which $\sin^2\theta^{f}_{eff}$ is inferred) given by RMS of replicas
- one can reduce this spread by penalizing the replicas that are disfavoured by data

Bayesian χ^2 reweighing method

- perform $\sin^2\theta^{f}_{eff}$ measurement for each PDF replica (100) and get χ^2
- define a weight w_i for each replica
- measure $\sin^2\theta^{f}_{eff}$ as:

$$\boxed{\sin^2\theta^{\ell}_{\text{eff}} = \sum_{i=1}^{N} w_i s_i / N}$$

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



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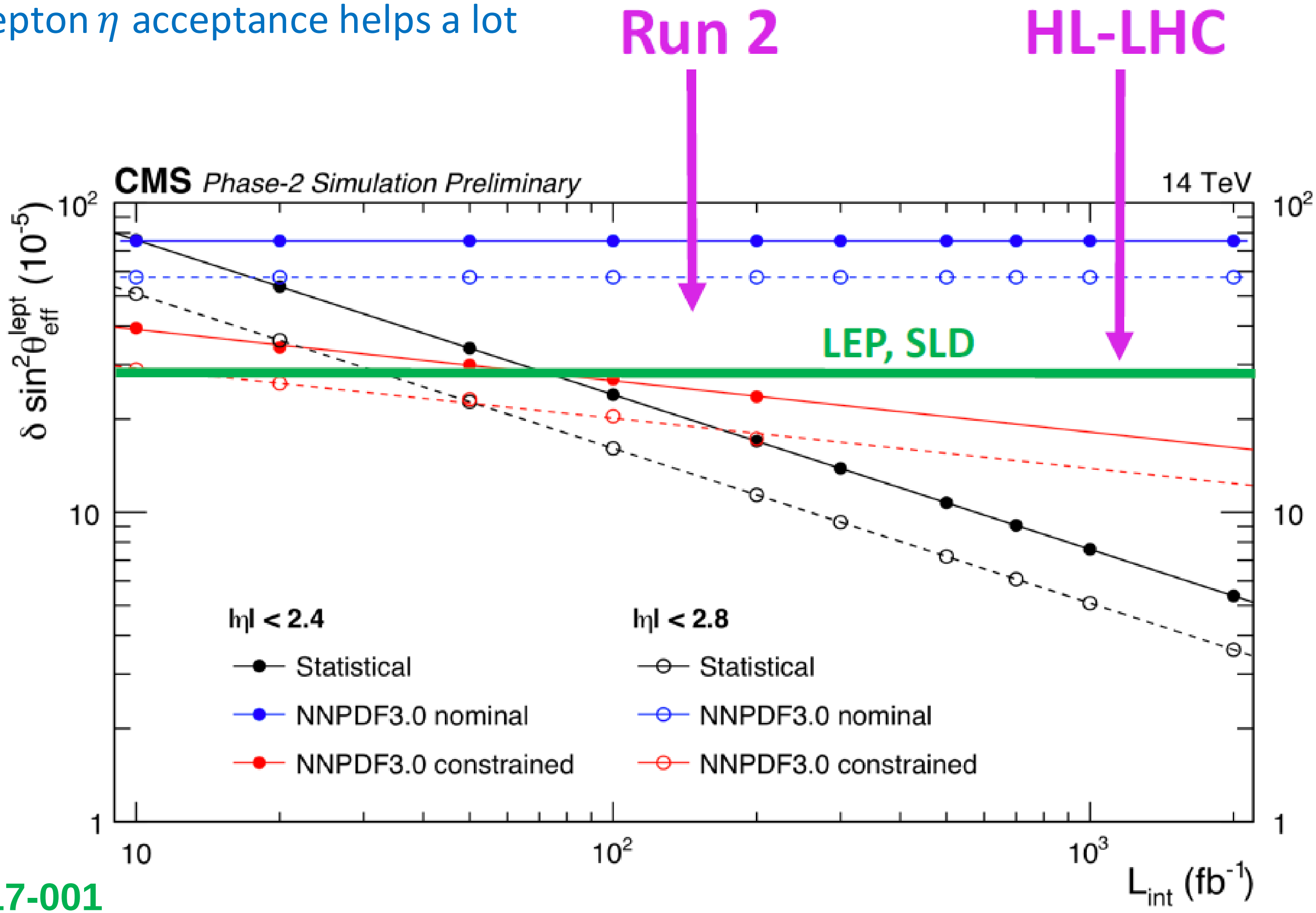
Projections for future measurements of $\sin^2 \theta^{f}_{eff}$

Statistical uncertainty (currently the dominant one) will be reduced using Run 2 data

- caveat: higher $\sqrt{s}$ implies A_{FB} dilution due to enhanced anti-quark PDF contribution
- PDF uncertainty could be reduced through global fits with recent LHC data
- extending lepton η acceptance helps a lot

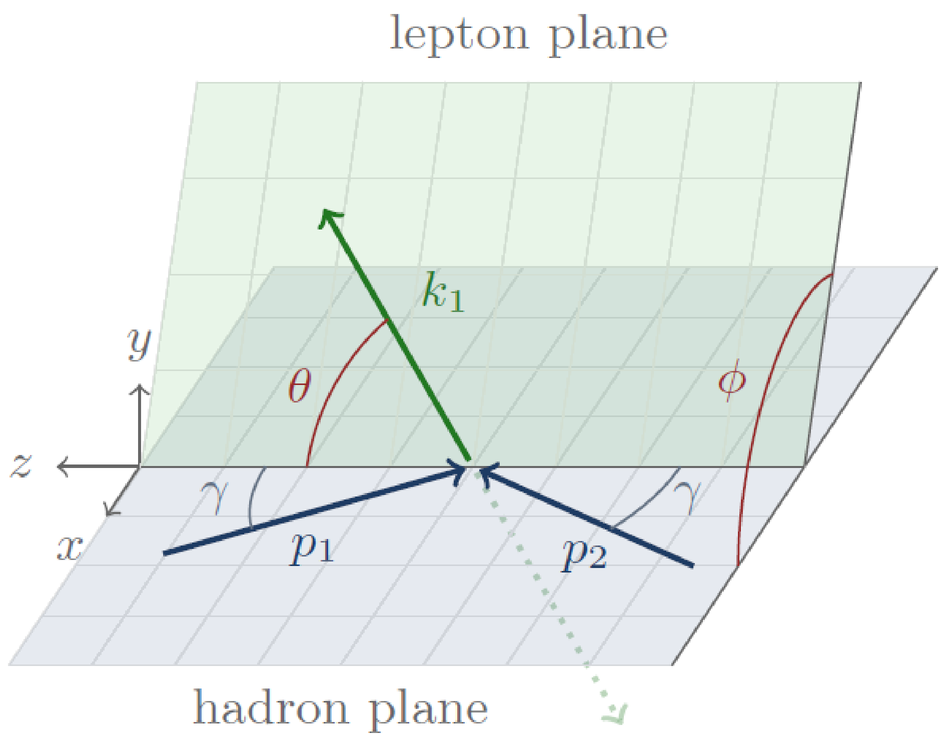


CMS PAS FTR-17-001

Collins-Soper frame

Z axis in CS frame defined as the axis that bisects the angle formed by the direction of the quark and the reversed direction of anti-quark

- minimize magnitude of partons' transverse momenta with respect to Z axis



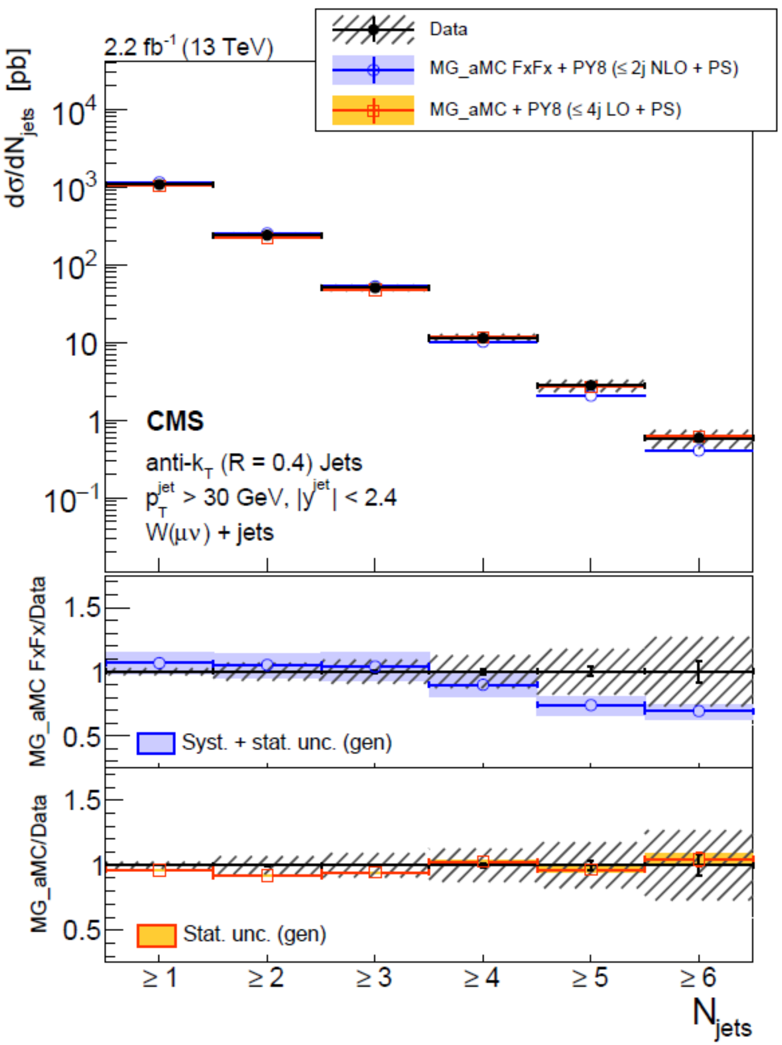
J.C. Collins, D.E. Soper, Angular distribution of dileptons in high energy hadron collisions. Phys. Rev. D **16**, 2219 (1977). https://doi.org/10.1103/PhysRevD.16.2219

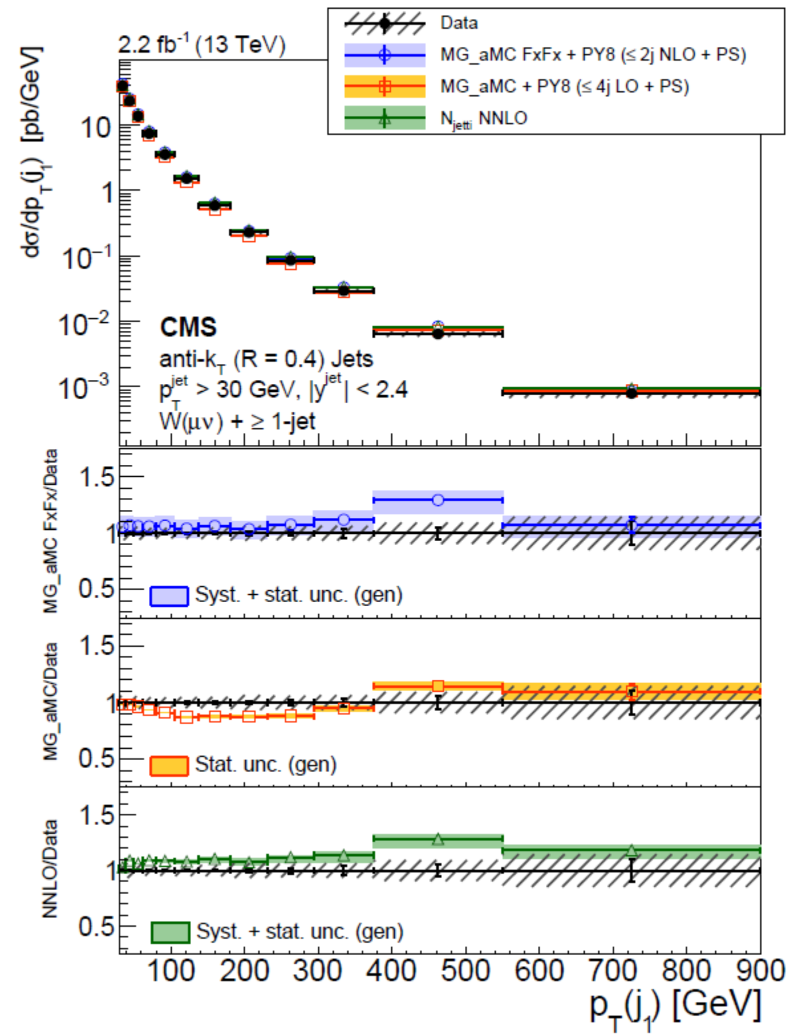
W+jets differential cross section

published in [Physical Review D](#)

Provide valuable tests of SM QCD sector and parton-shower models

- jet multiplicities sensitive to higher order terms and PDFs
- theory has O(1%) precision, experiments often sub-% level



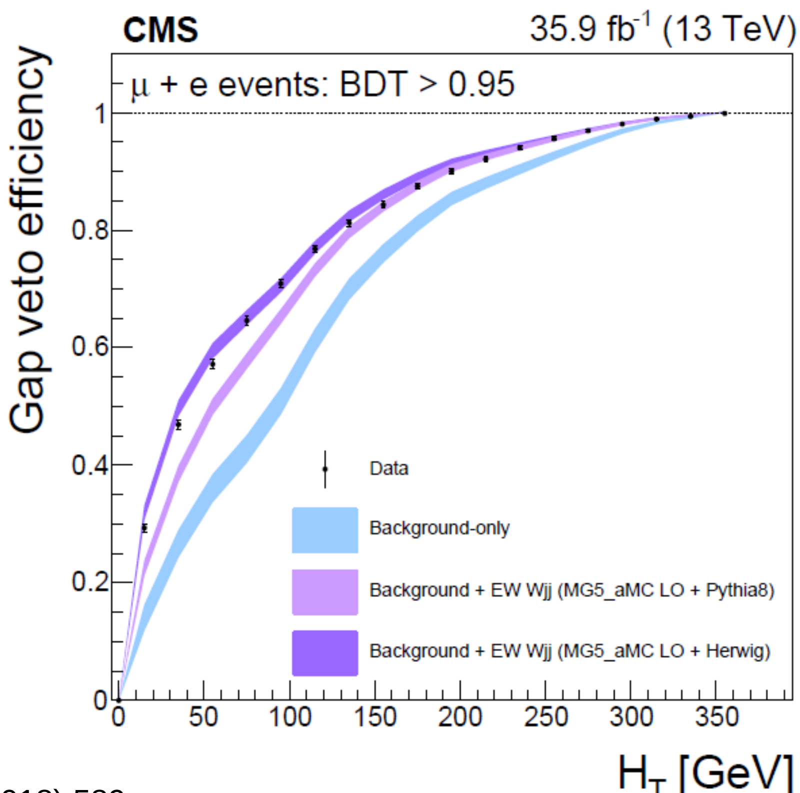


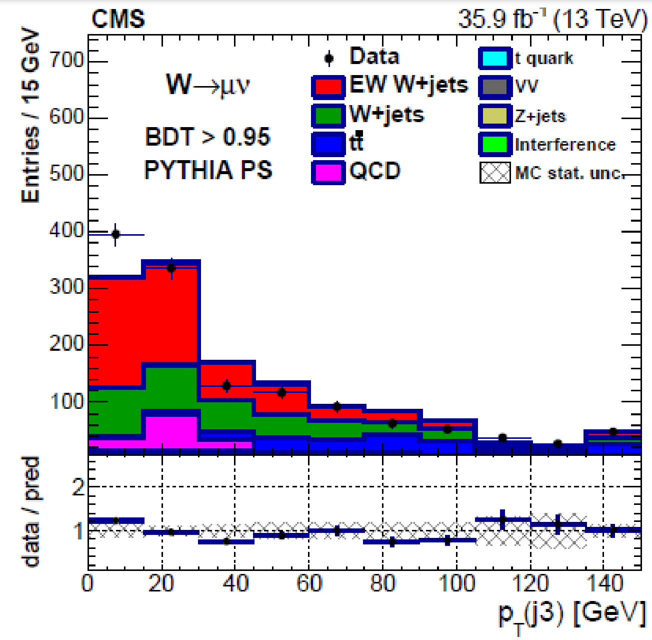
Jet activity in EW V + 2 jets production

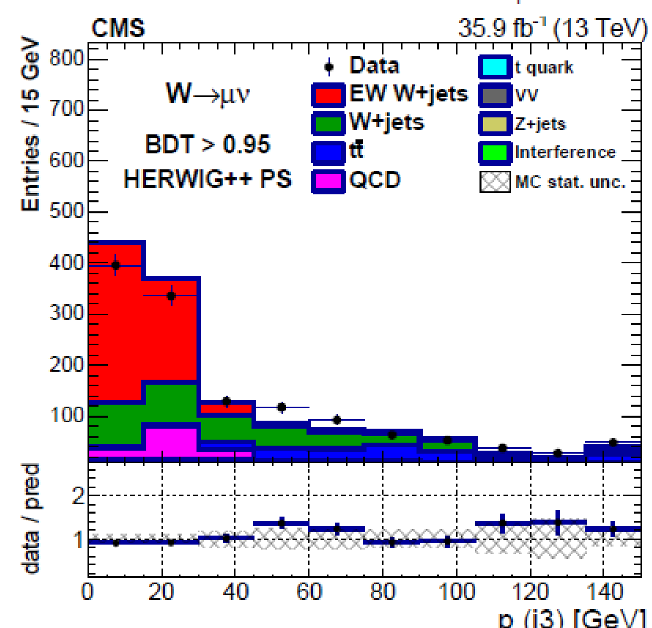
EW W/Z + 2 jets useful to study additional jet activity between forward jets

Can also study hadronic activity vetoes

- efficiency of hadronic activity veto corresponds to fraction of events with measured gap activity below a given threshold







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Z +2jets:
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