# ELECTROWEAK BOSON MEASUREMENTS IN PPB AND PBPB COLLISIONS WITH CMS

Ran Bi
for the CMS Collaboration

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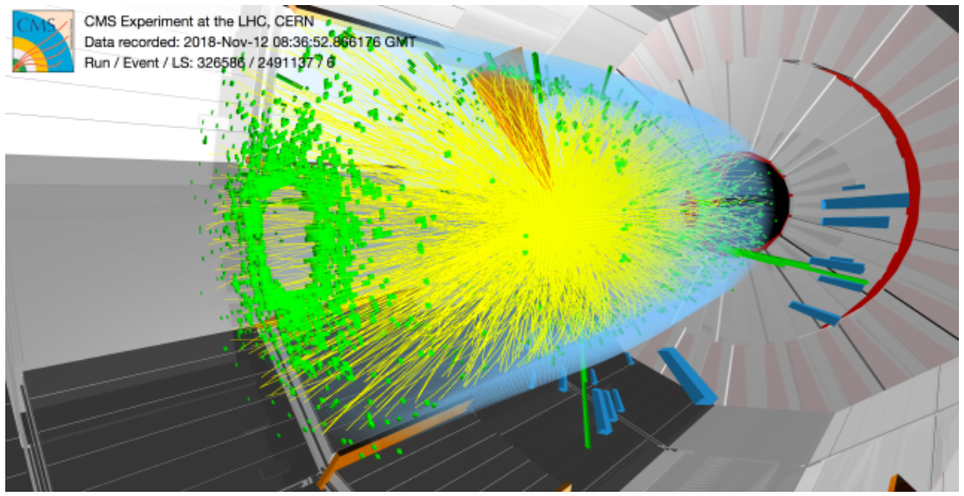
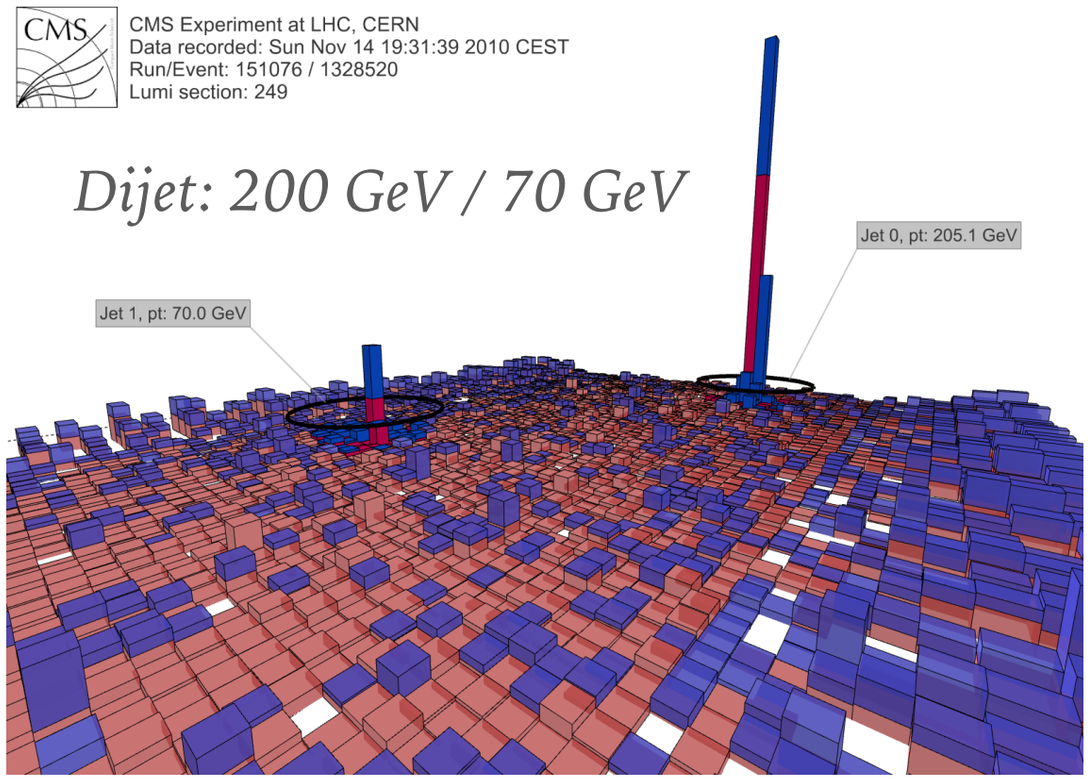
# HEAVY ION COLLISIONS

- Heavy ion collisions provide a glimpse of the early universe
  - hot, dense matter known as the quark-gluon plasma (QGP)
  - strongly interacting, deconfined medium of free quarks/gluons
- QGP exhibits interesting phenomena
  - jet quenching - medium-induced jet energy loss
- Study and extract properties of GQP
  - initial state effects: proton - lead (pPb)
  - medium effects: lead - lead (PbPb)

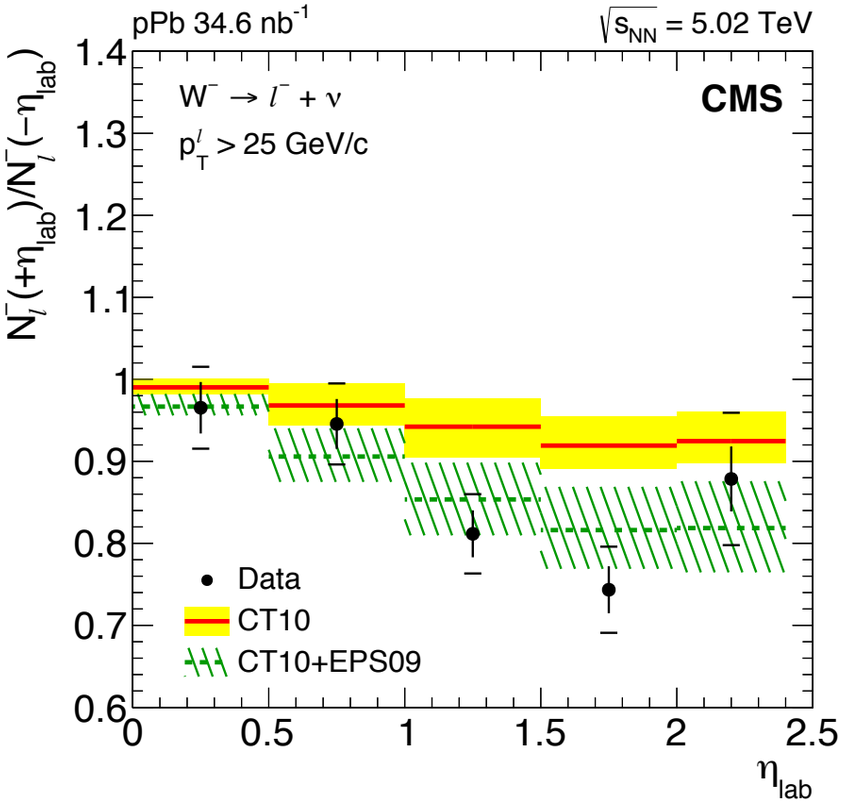


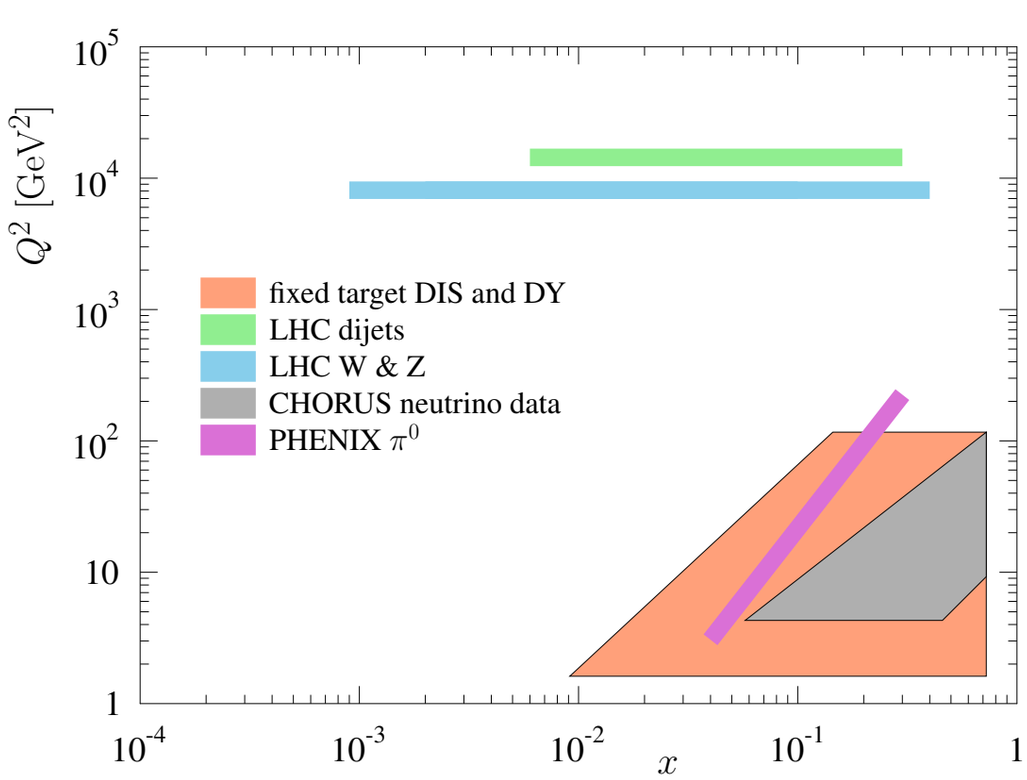
# INITIAL STATE EFFECTS

- Quarks behave differently inside bound nucleons vs. free nucleons
  - described by nuclear PDFs
- Measurements of electroweak boson cross sections provide input for nPDF calculations
  - probe nPDFs at high $Q^2$, $10^{-3} < x < 10^{-1}$
  - past measurements have helped to constrain nPDF sets
    - CMS dijet/Z,W measurements included in EPPS16

PLB 750 (2015) 565




EPJC 77 (2017) 163



# W BOSON MEASUREMENT IN PPB

- W boson yield increased by factor of ~10 compared to 2013 data
  - dominant production mode: ud → $W^+$, du → $W^-$
  - interactions between valence and sea quarks
    - probe quark nPDFs
- Signature: decay muon + missing momentum
  - muon isolation suppresses multi-jet background
  - veto Z → μμ events
  - remaining dominant backgrounds
    - muons from QCD jet
    - Z → μμ with 1 missing muon
- Signal extraction
  - fit missing $p_T$ distribution in bins of $\eta_{CM}$
  - signal, electroweak background:
    - templates from simulations
    - pPb NLO POWHEG v2, with CT14 + EPPS16 nPDF
  - QCD multi-jet background:
    - data-driven functional form

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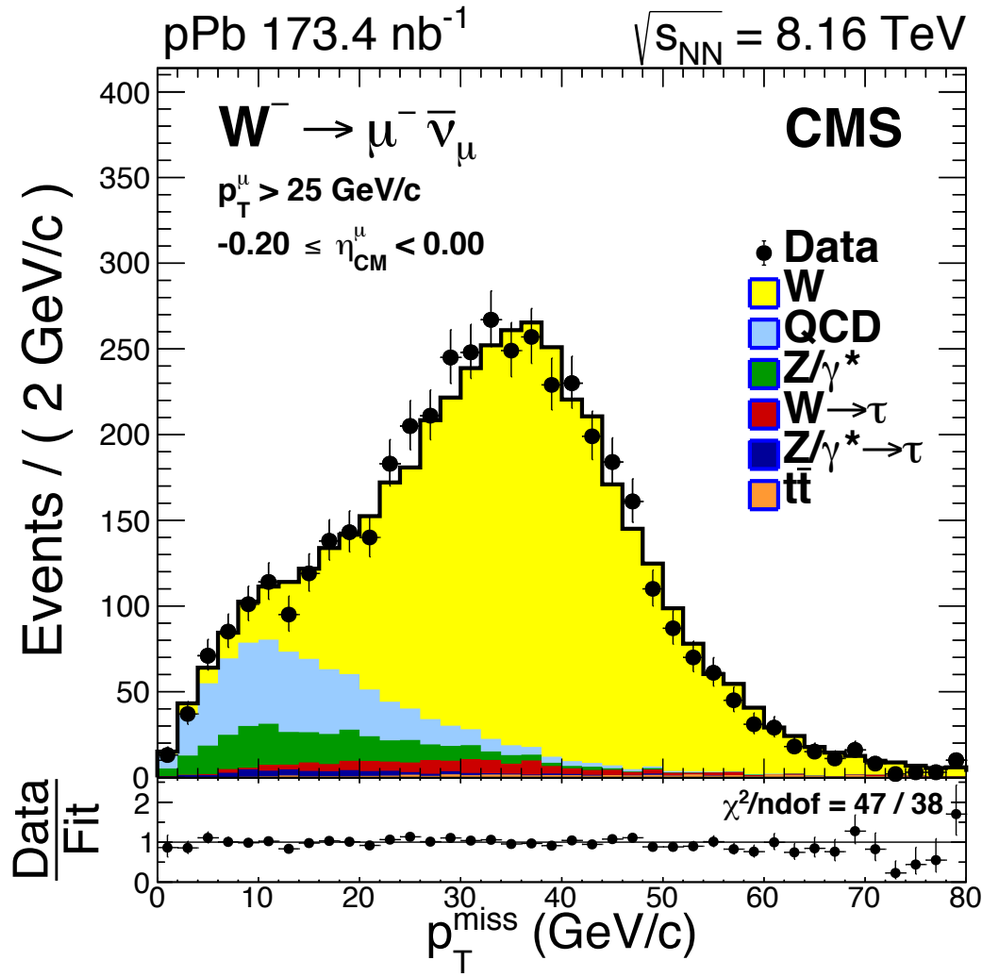
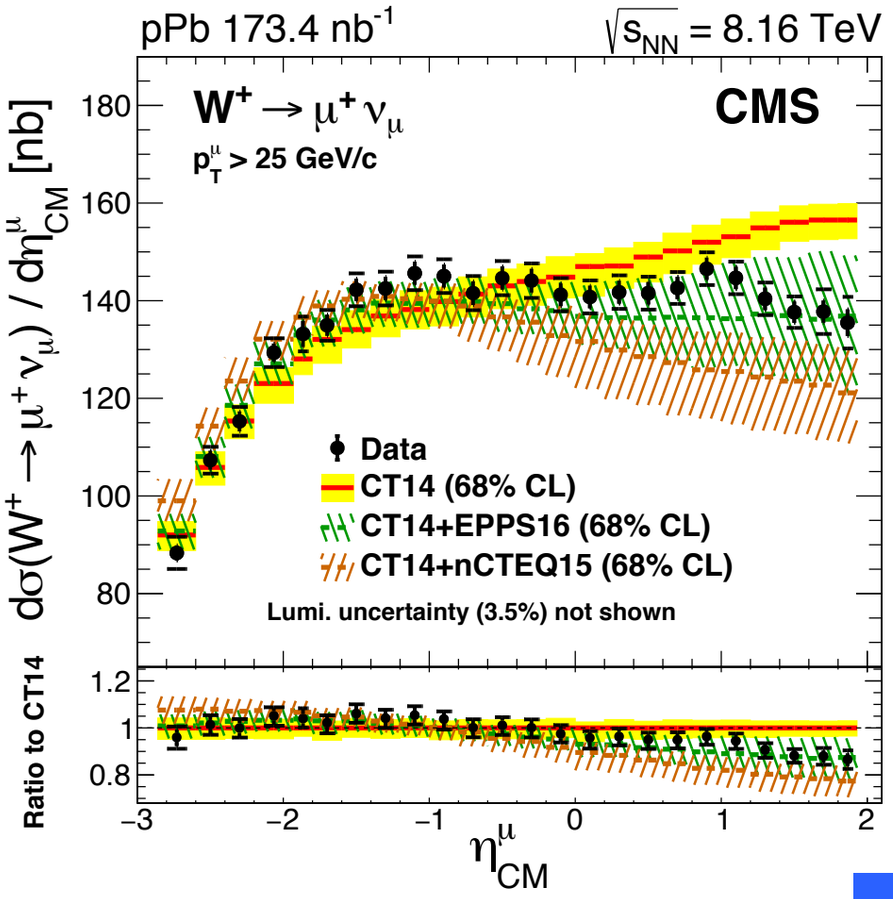
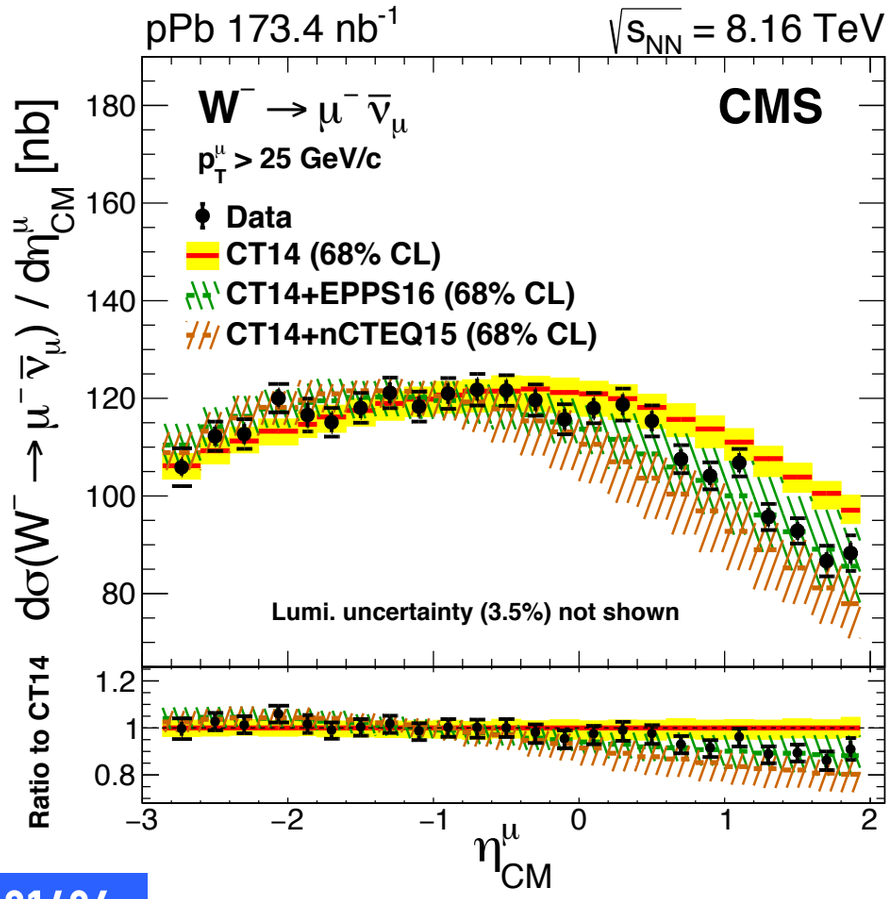


# W BOSON PRODUCTION CROSS SECTIONS

- $\eta_{CM} < 0$ (large $x_{Pb}$): results agree with both PDF and nPDF calculations
- $\eta_{CM} > 0$ (small $x_{Pb}$): results favour nPDF calculations
- $\chi^2$ probabilities: <0.01% (CT14) / 96% (CT14+EPPS16) / 79% (CT14+nCTEQ15)

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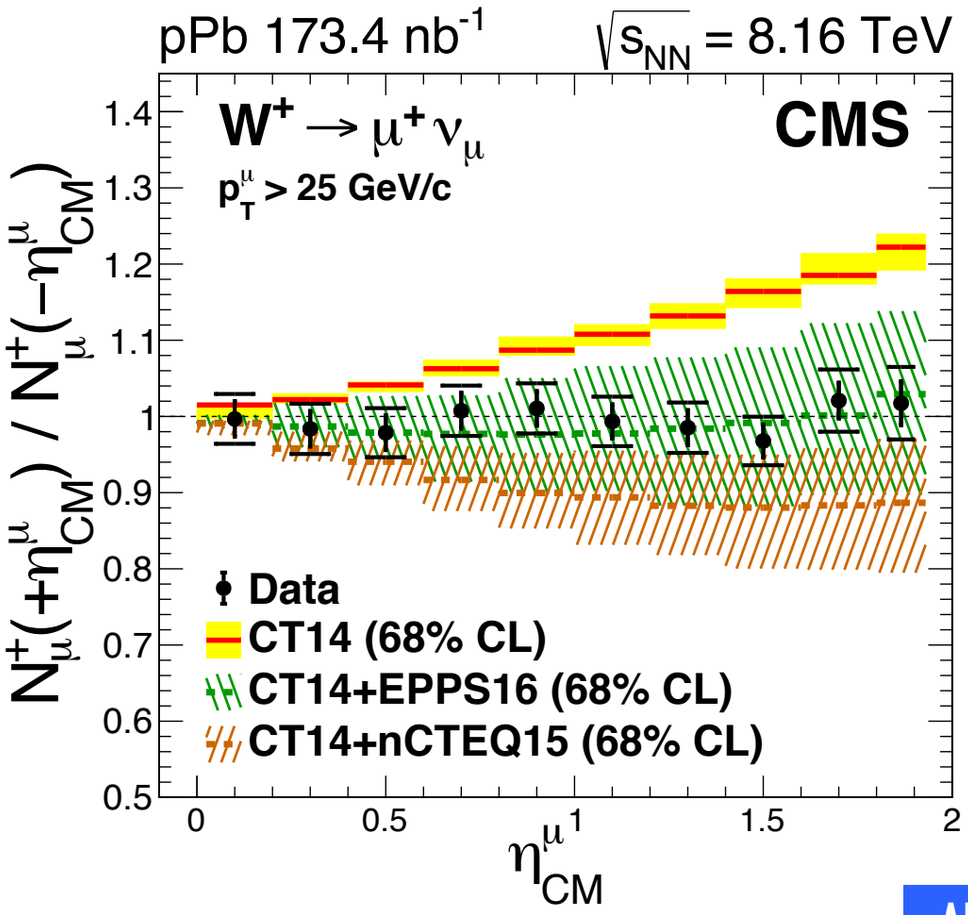
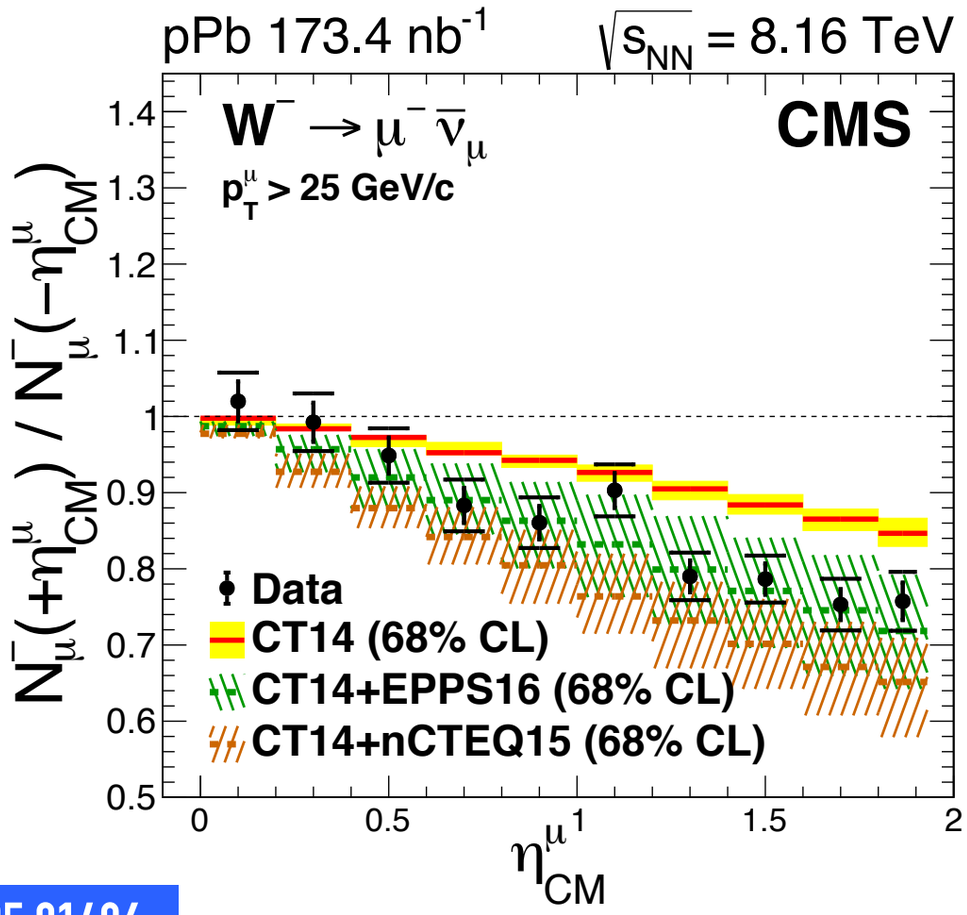
# W BOSON FORWARD/BACKWARD ASYMMETRY

- Cancel uncertainties fully correlated in $\eta_{CM}$
  - experimental uncertainties smaller than nPDF uncertainties
  - excludes free PDFs at 7σ
- $\chi^2$ probabilities: <0.01% (CT14) / 95% (CT14+EPPS16) / 83% (CT14+nCTEQ15)

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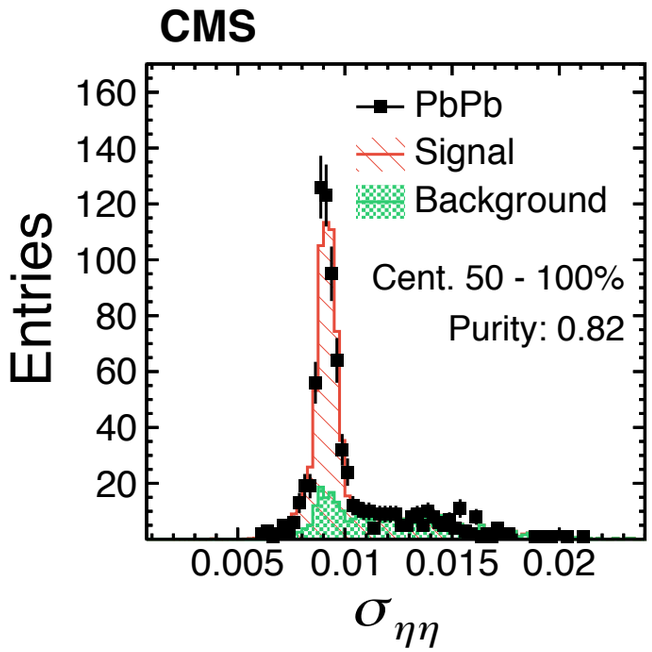
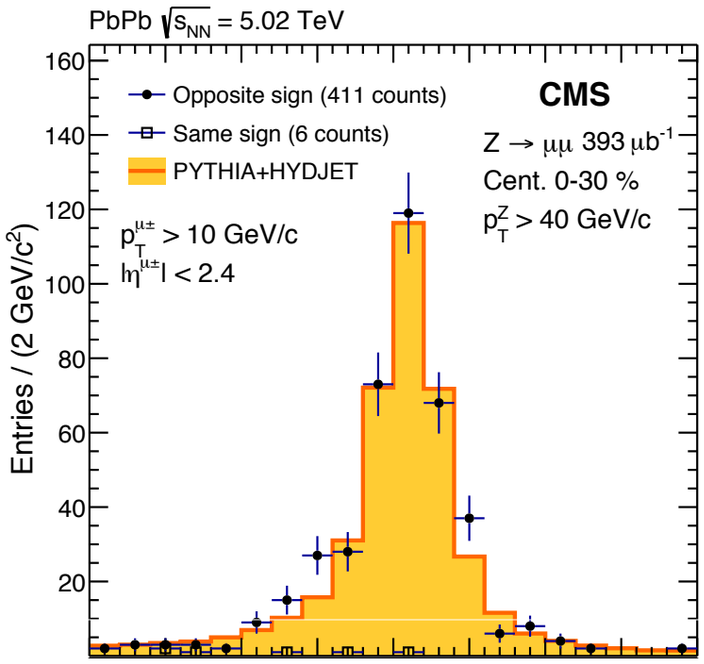
# ELECTROWEAK BOSONS IN PBPB COLLISIONS

- Electroweak bosons are good probes of the medium
  - colourless - not subject to medium-induced energy loss through the strong interaction
  - good proxy of the initial energy of the partons produced in the hard scattering
  - production processes constrain quark/gluon fraction of recoil parton
  - statistics: photons > Z bosons; background: photons > Z bosons
- Photons (isolated photons)
  - background mostly from boosted neutral meson decays
  - subtracted using a template fit method
    - signal template is extracted from simulated events
    - background is modelled using sideband region of data



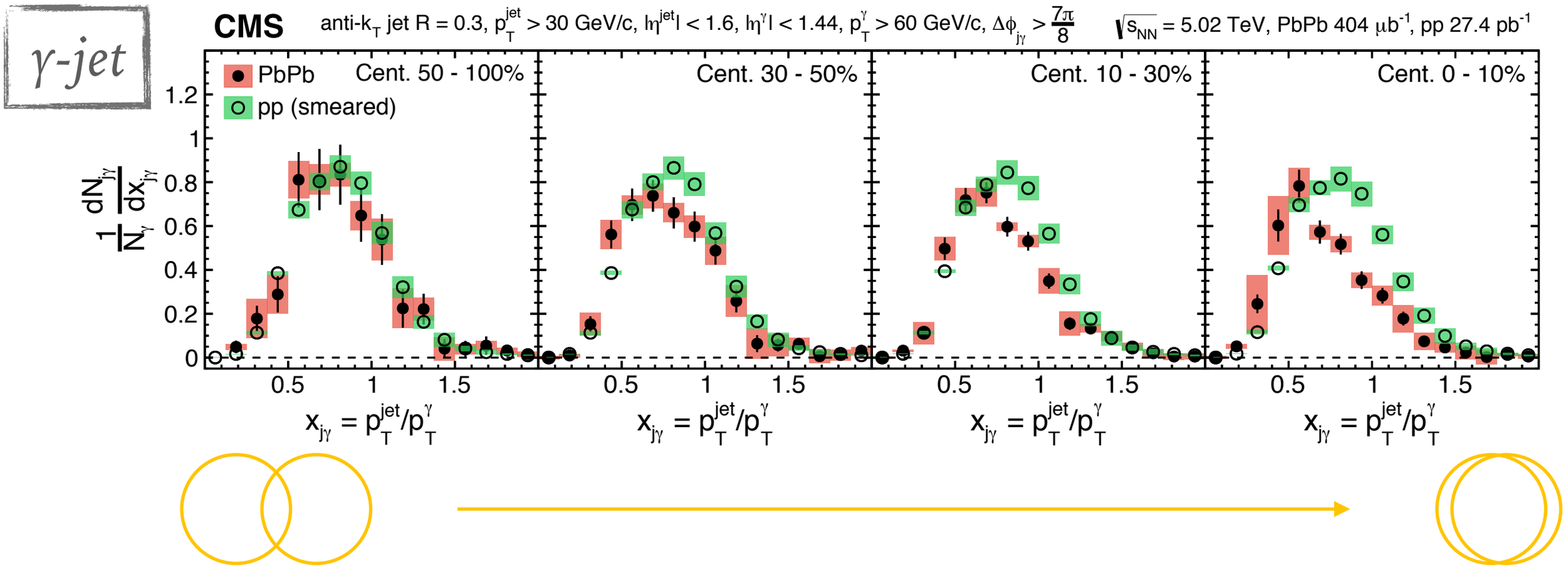




- Z bosons
  - reconstructed through dilepton channels
  - 2015: ~400 $\mu b^{-1}$; 2018: 1.5 $nb^{-1}$

# MOMENTUM IMBALANCE IN PBPB COLLISIONS

- Isolated-photon/Z-boson + jet correlations in PbPb @ 5.02 TeV
  - clear evidence for in-medium jet energy loss

PLB 785 (2018) 14

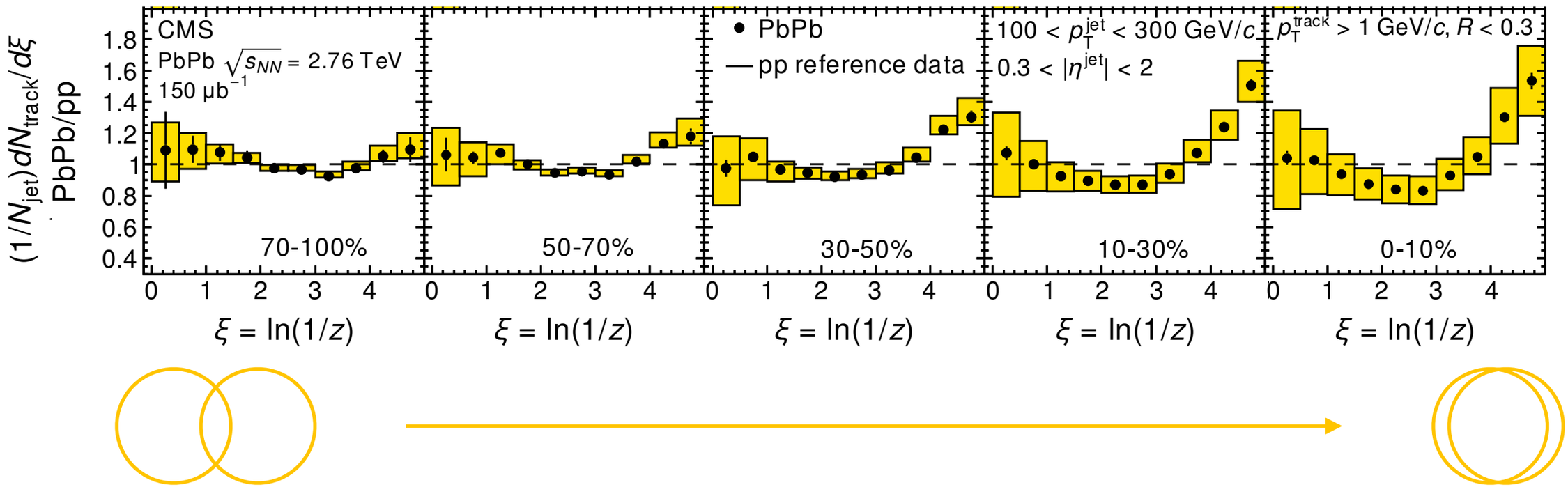



- Models with different descriptions of the energy loss mechanisms are able to predict the results within the experimental uncertainties
- Results give a crude picture of jet quenching
  - more detailed measurements required for a complete description

# JET SUBSTRUCTURE IN PBPB COLLISIONS (INCLUSIVE JETS)

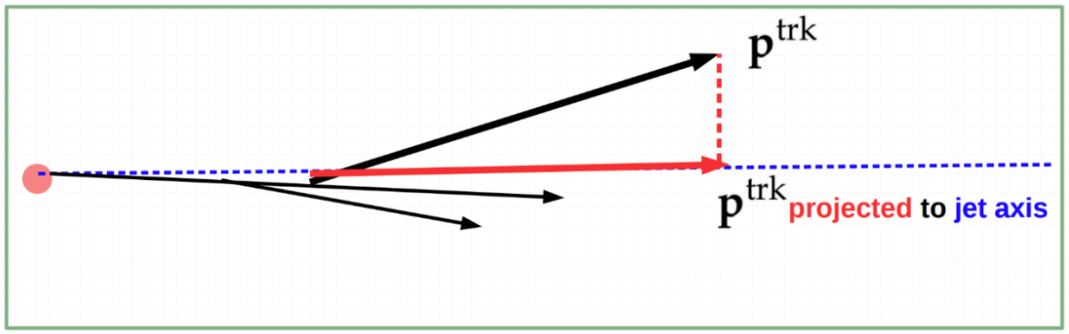
- Differentiate between different mechanisms by measurements of jet substructure
  - previous measurements with inclusive jets show some modification

PRC 90 (2014) 024908




- Jet fragmentation function

$$\xi^{\mathrm{jet}} = \ln \frac{|\mathbf{p}^{\mathrm{jet}}|^2}{\mathbf{p}^{\mathrm{trk}} \cdot \mathbf{p}^{\mathrm{jet}}}$$



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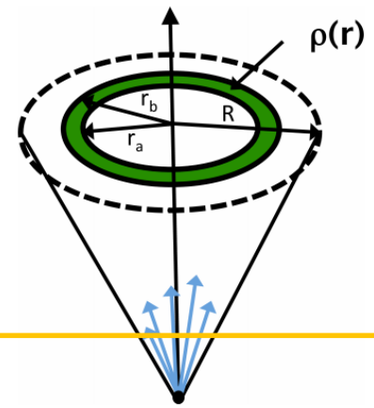
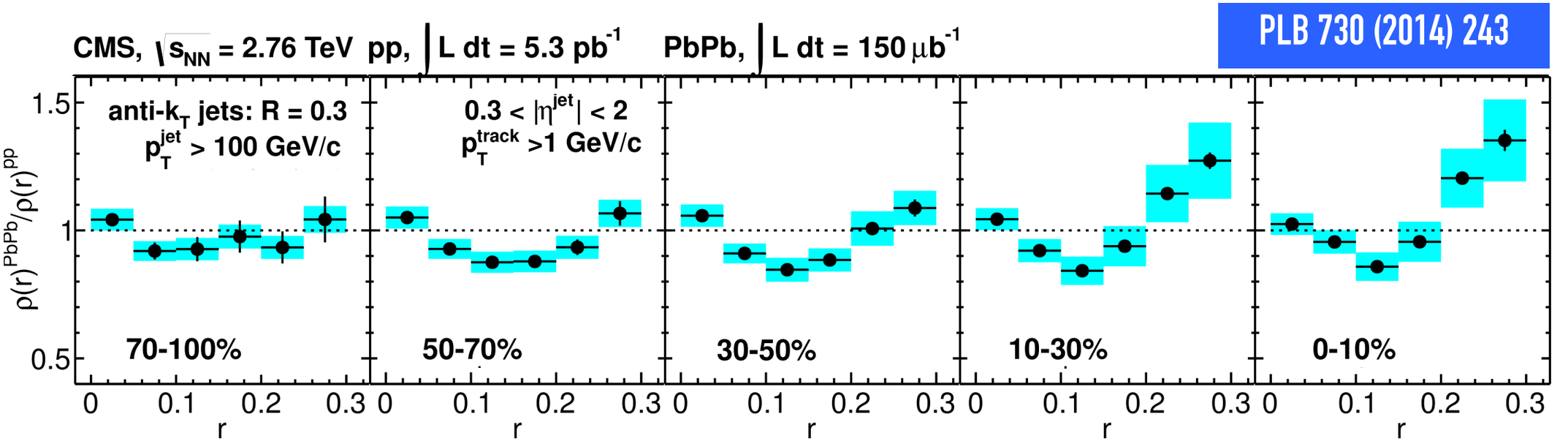
- Jet shape

$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{trk}\in[r_a, r_b)} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{\text{trk}\in[0, r_f)} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$



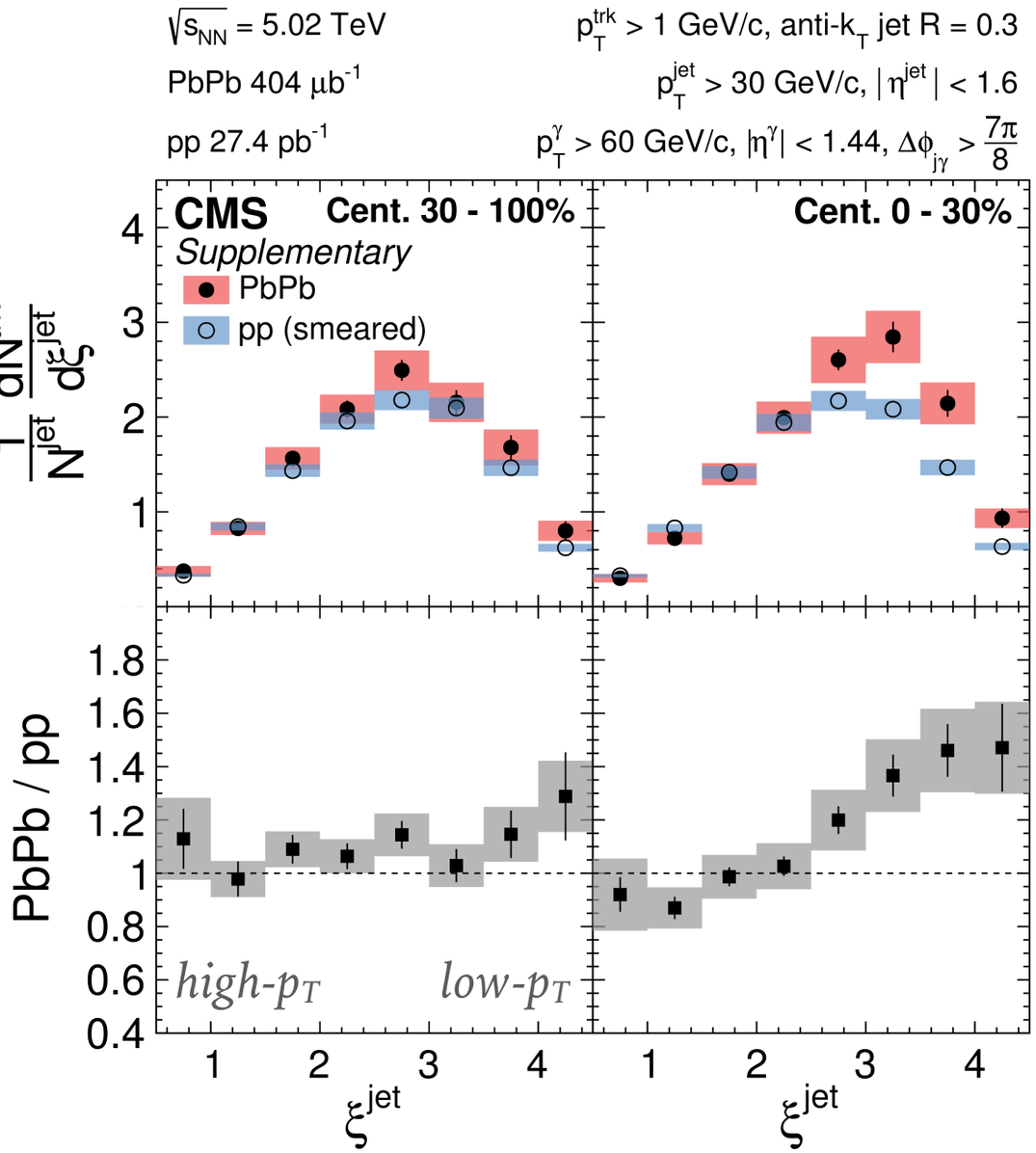




- Modifications to jet shape are interesting
  - may be because of kinematics and/or quark/gluon fractions

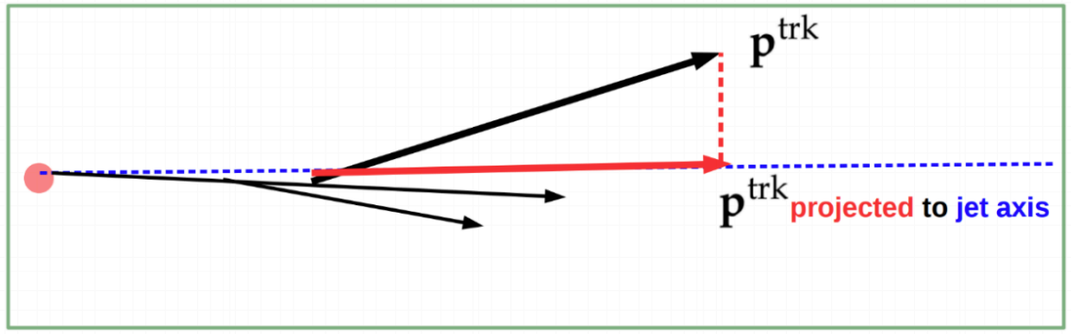
# PHOTON-TAGGED JET FRAGMENTATION FUNCTION

- Enhancement of low-pT particles, depletion of high-pT particles

PRL 121 (2018) 242301




$$\xi^{jet} = \ln \frac{|\mathbf{p}^{jet}|^2}{\mathbf{p}^{trk} \cdot \mathbf{p}^{jet}}$$



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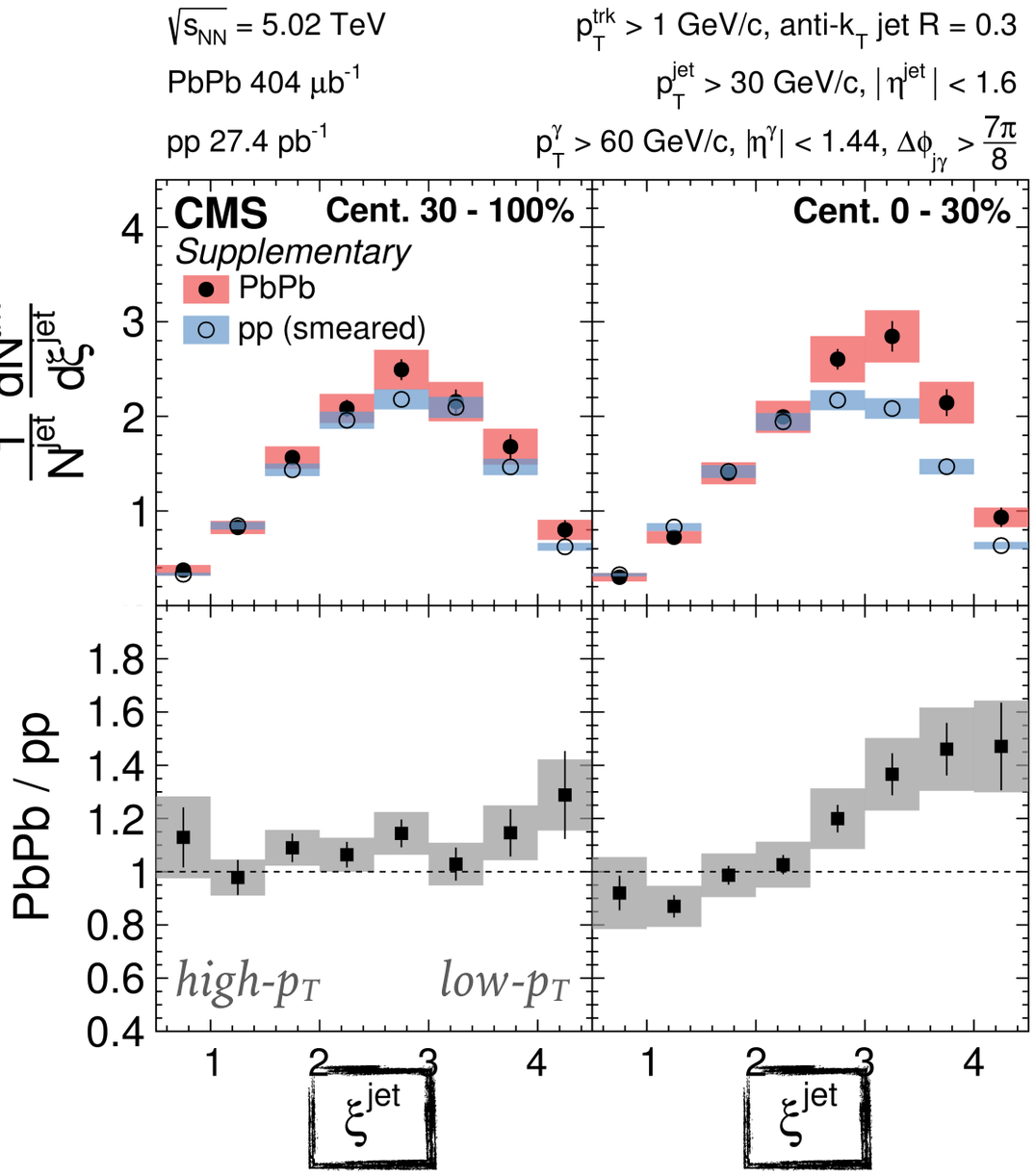


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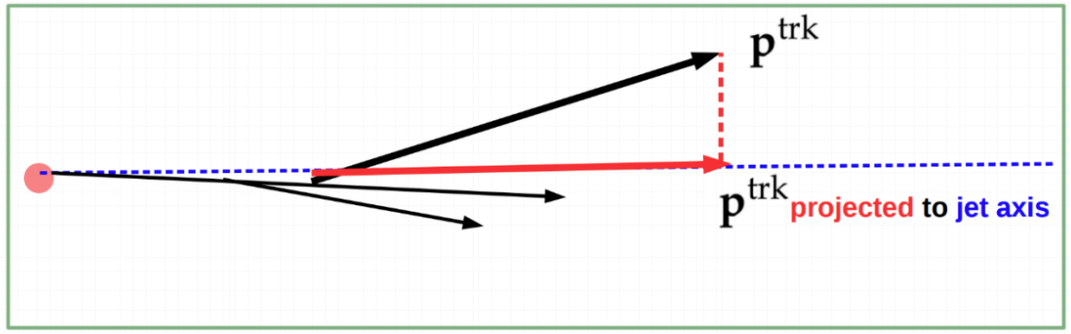
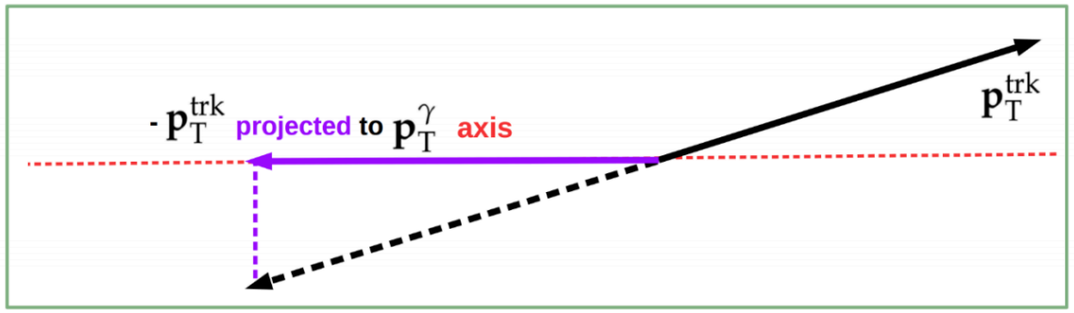



$$\xi_T^{\gamma} = \ln \frac{-|\mathbf{p}_T^{\gamma}|^2}{\mathbf{p}_T^{trk} \cdot \mathbf{p}_T^{\gamma}}$$



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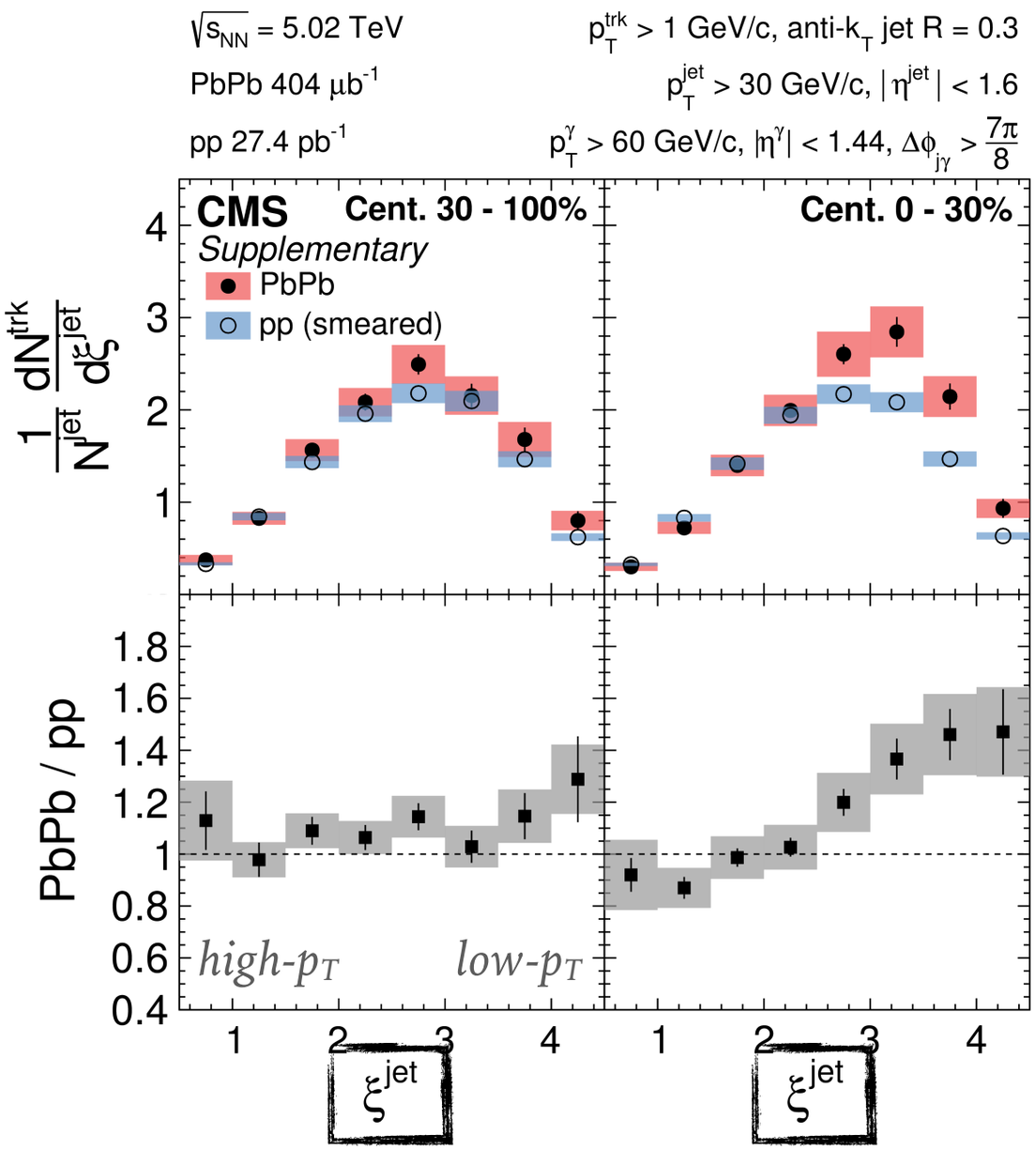
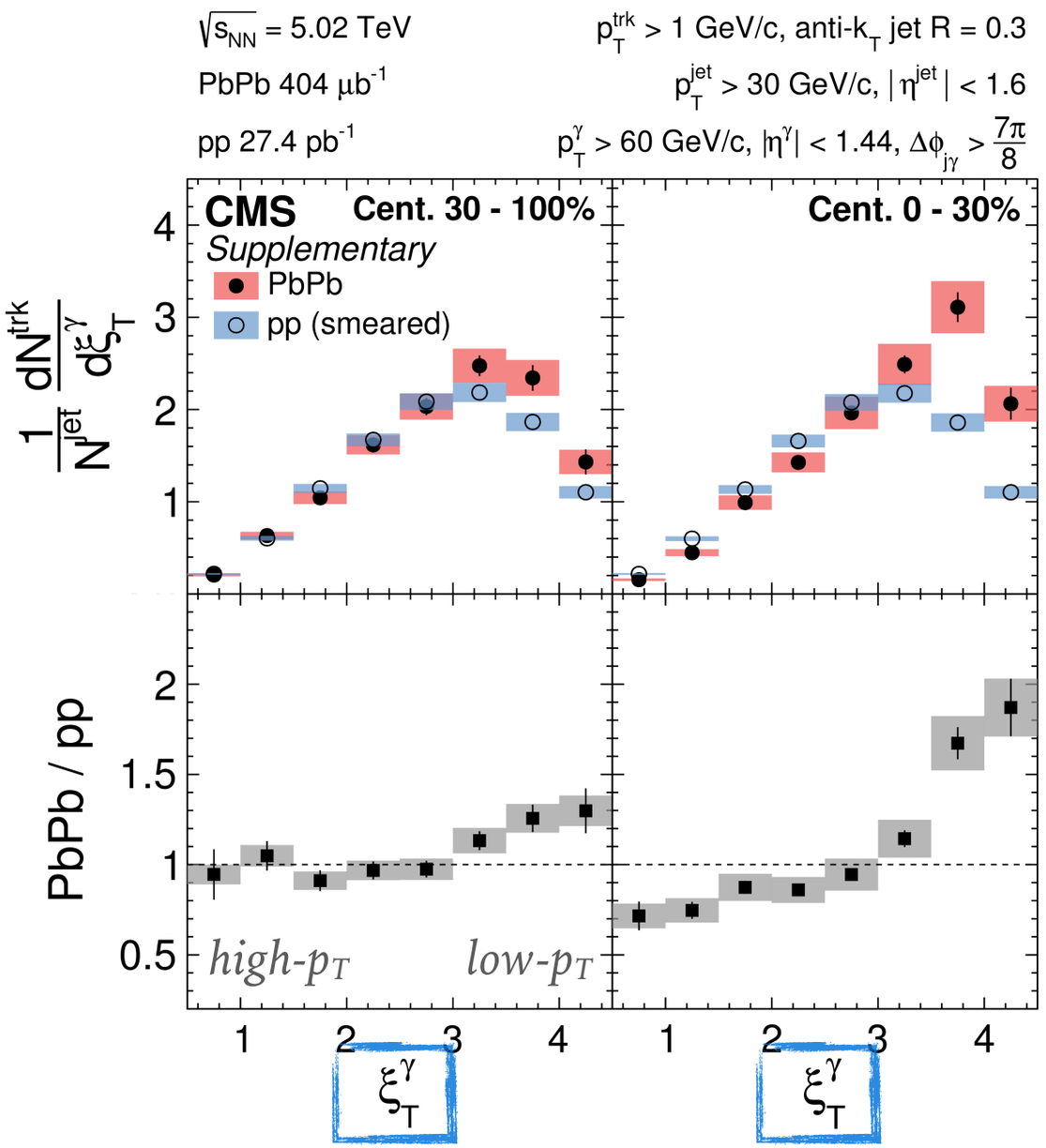


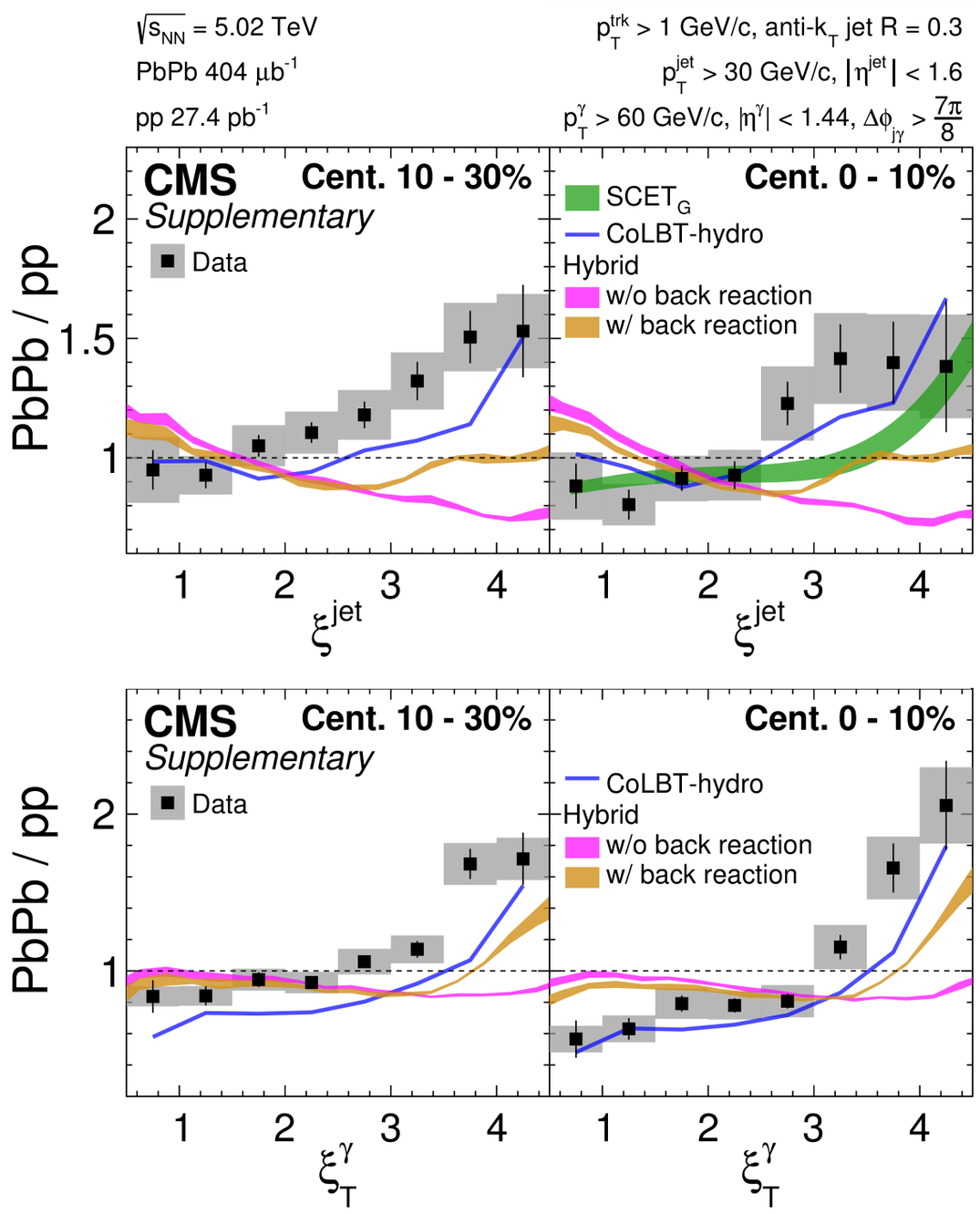



# MODEL PREDICTIONS (FRAGMENTATION FUNCTION)

- Stronger modification for $\xi_T^{\gamma}$ than for $\xi^{\mathrm{jet}}$
  - jet energy quenched

- Models describe data to different extents
  - both $\mathrm{SCET_G}$ and CoLBT-hydro models describe trend of both observables
  - hybrid model does not do well, but the addition of back reaction improves agreement with data
  - enhancement at large ξ (low-$p_T$ particles) underestimated by all models

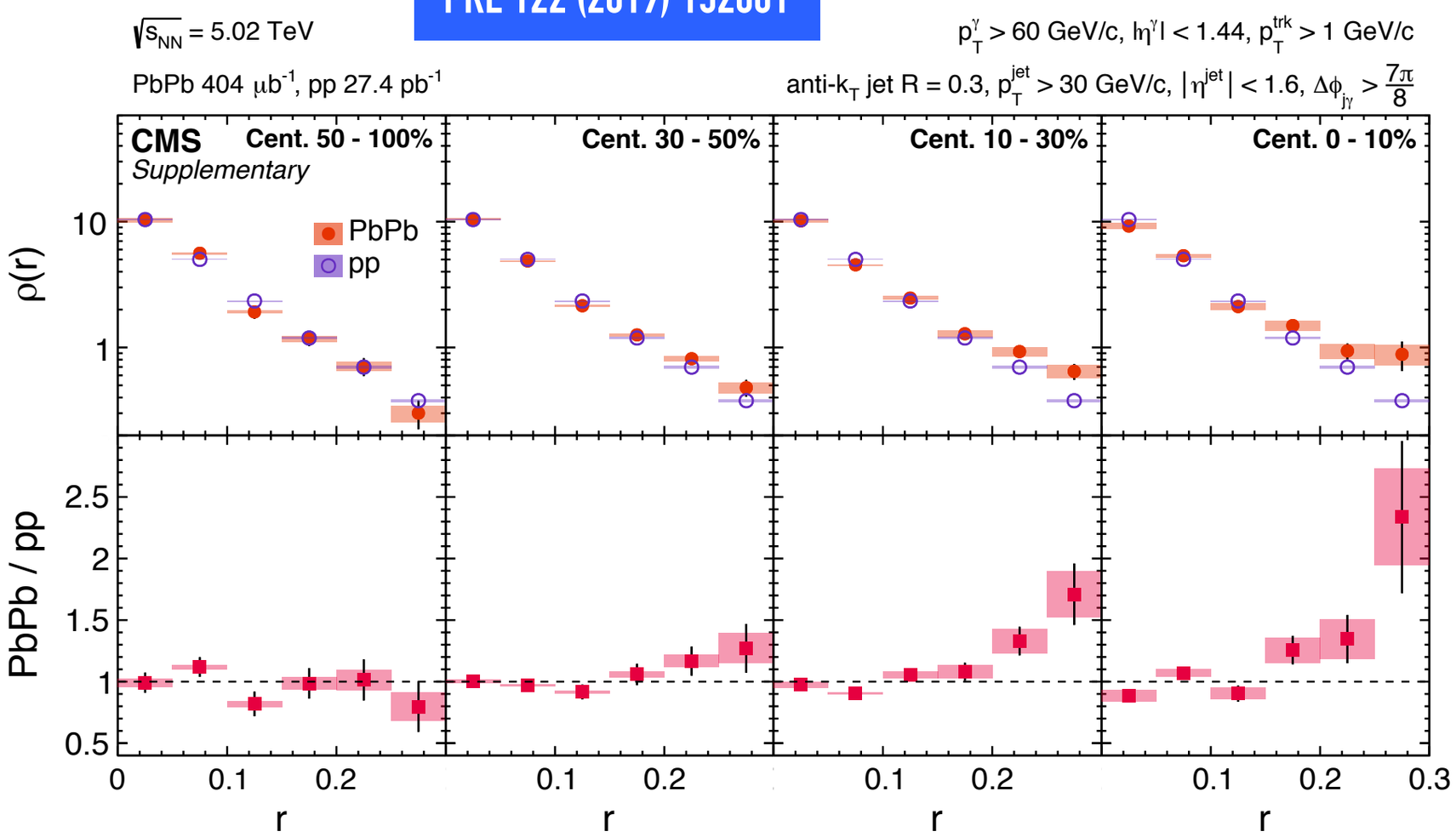
PRL 121 (2018) 242301

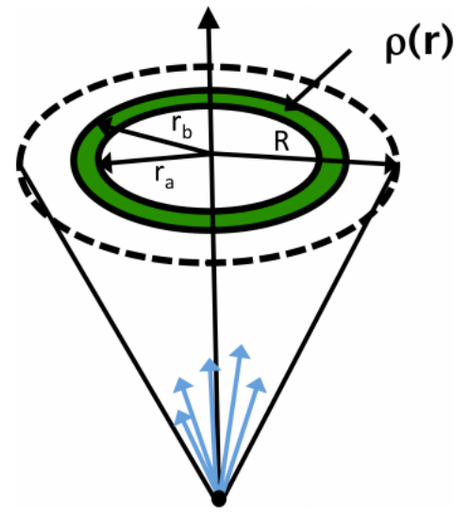


# PHOTON-TAGGED JET SHAPE

- Distribution of jet energy in transverse direction with respect to jet axis
  - complementary information to jet fragmentation function

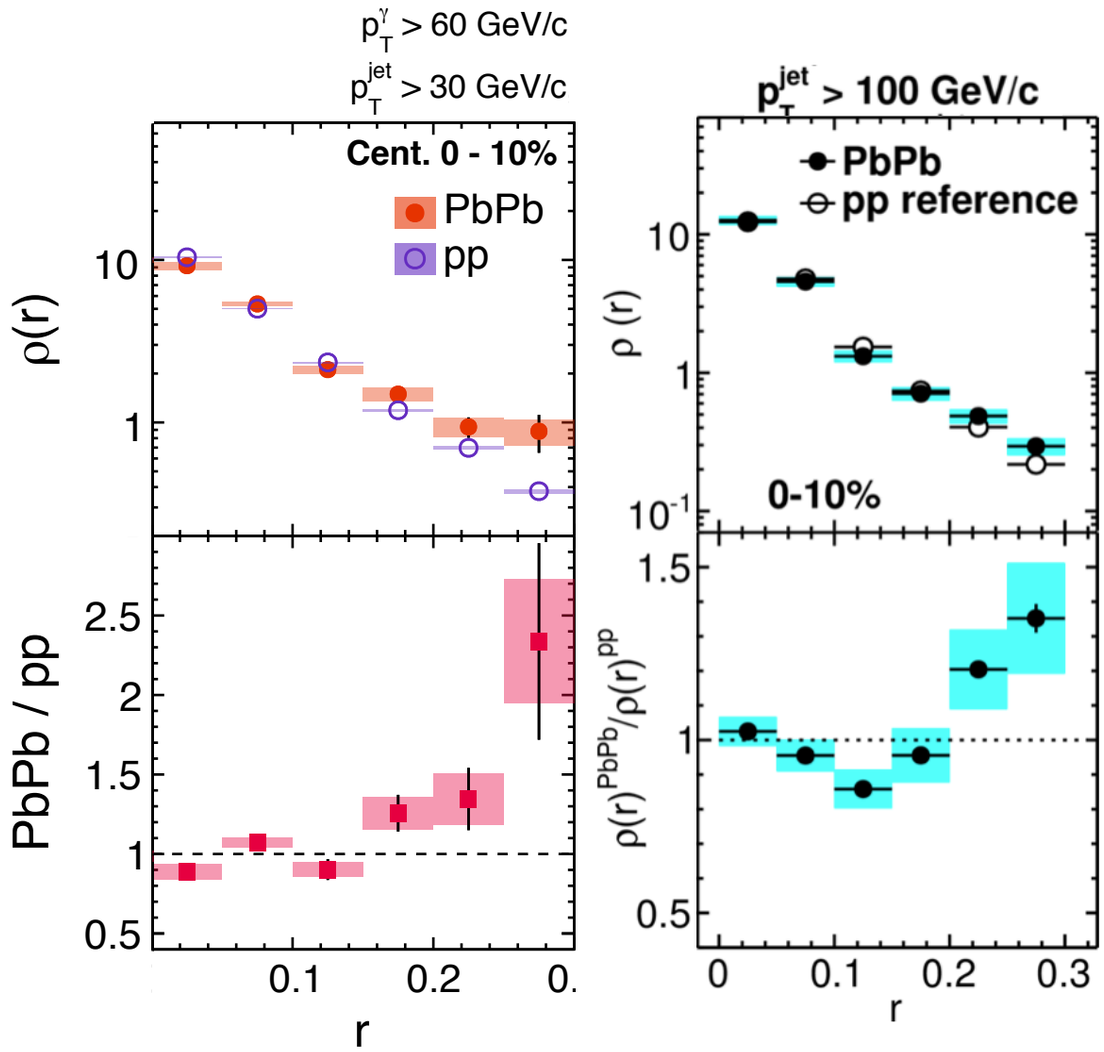
PRL 122 (2019) 152001



# PHOTON-TAGGED JET SHAPE

- Comparison to inclusive jet shapes
  - no depletion at intermediate r
    - increased quark/gluon ratio
    - lower jet $p_T$ threshold - jets lose more energy

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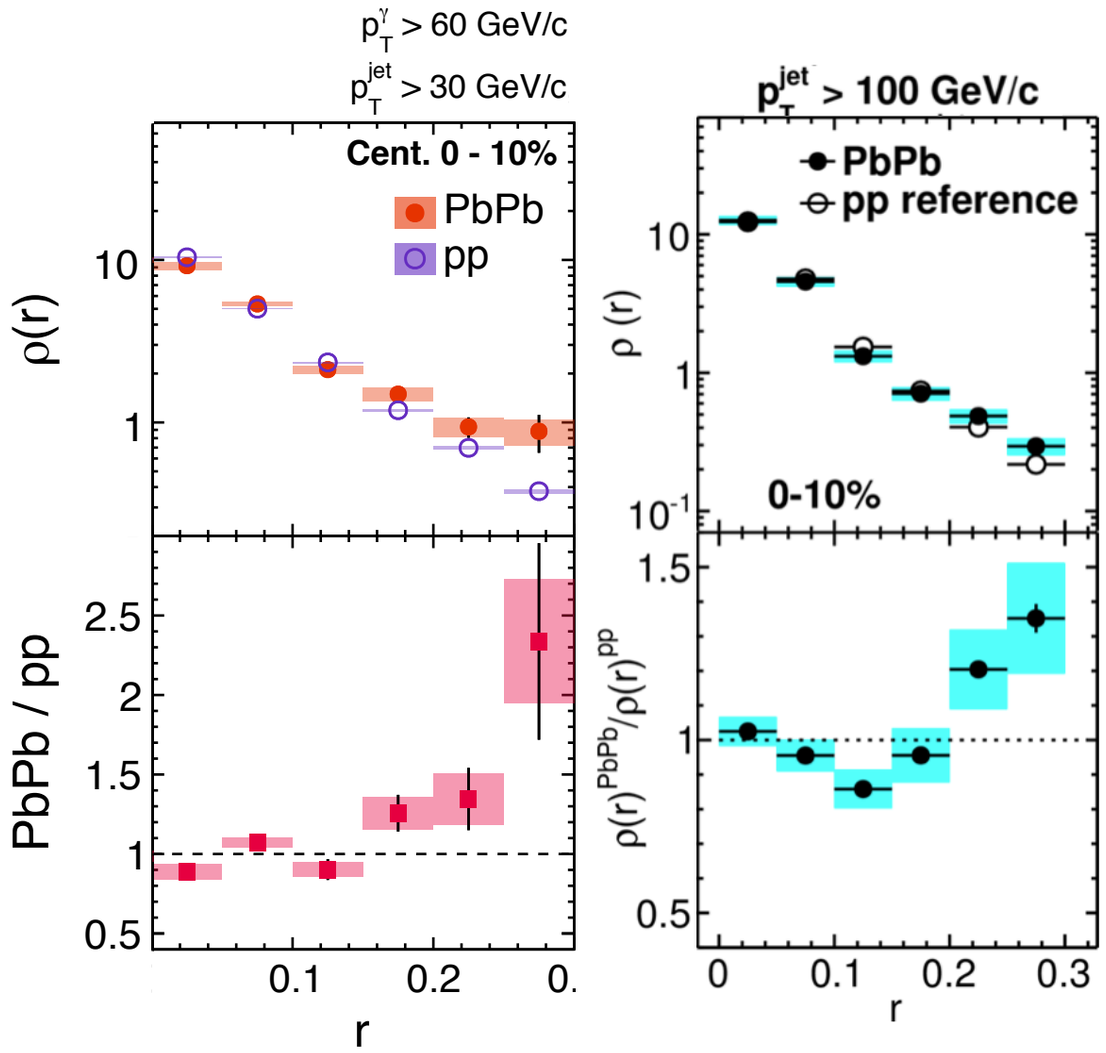
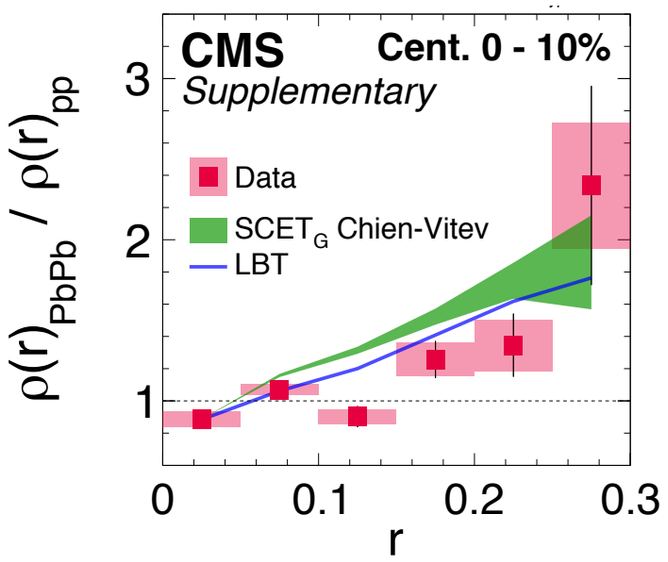



PRL 122 (2019) 152001

- Comparison to models
  - both $SCET_G$/LBT both describe trend



# SUMMARY

- Electroweak bosons probe initial state effects and medium interactions
  - W boson production measurements in pPb collisions help to constrain nuclear PDFs
  - boson-tagged jet measurements constrain recoil parton momentum and quark/gluon fractions
- Nuclear modification of quark PDFs observed with high significance
  - experimental uncertainties are smaller than PDF uncertainties
  - good agreement between data and EPPS16 nPDF sets
- In-medium jet energy loss and modification of jet fragmentation functions and jet shape
  - relatively unmodified jet core
  - suppression of intermediate $p_T$ particles
  - enhancement of low $p_T$ particles away from the jet axis

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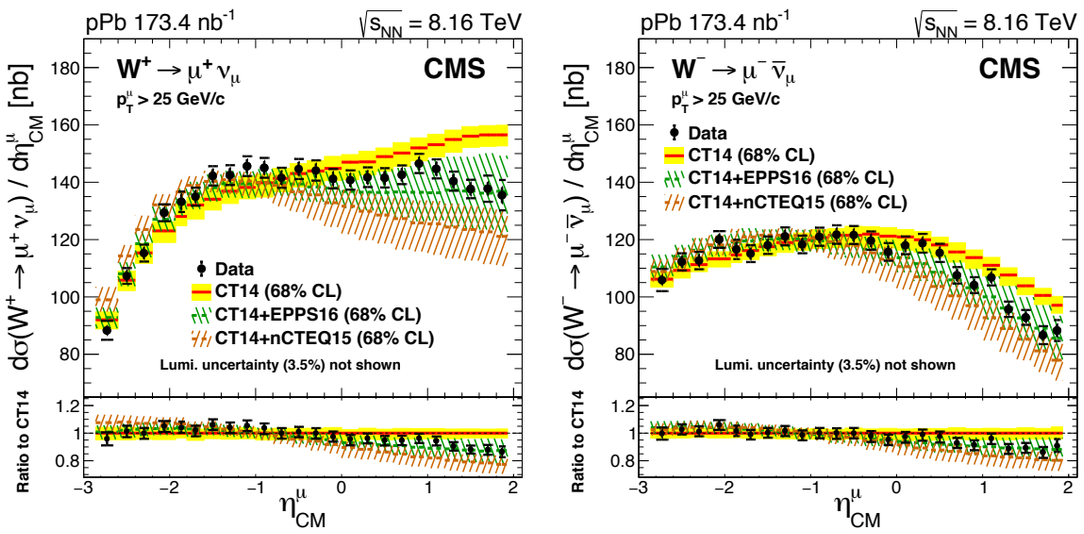


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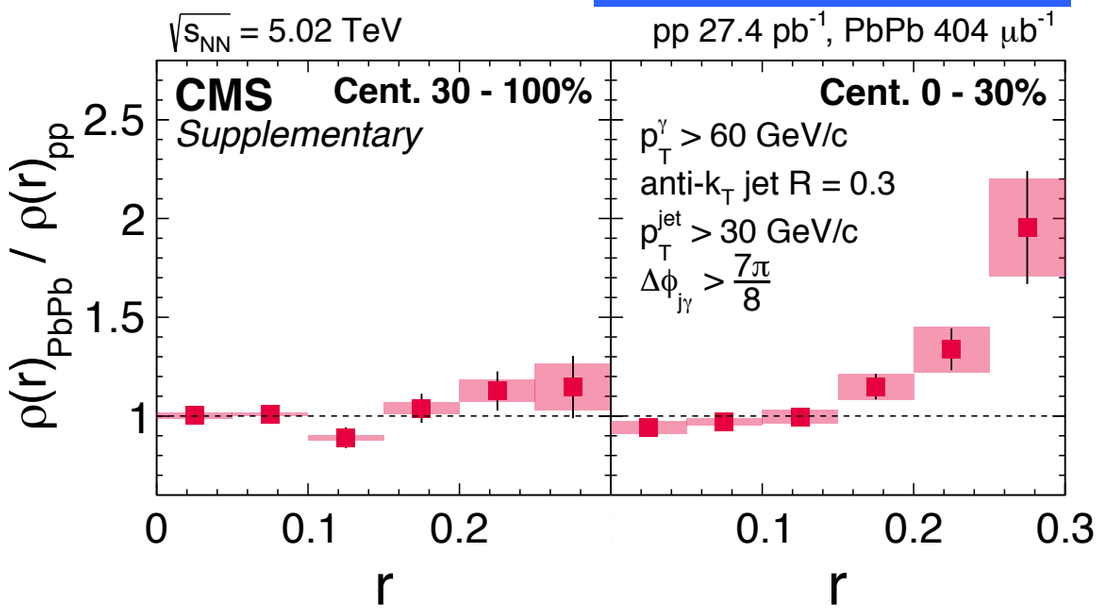
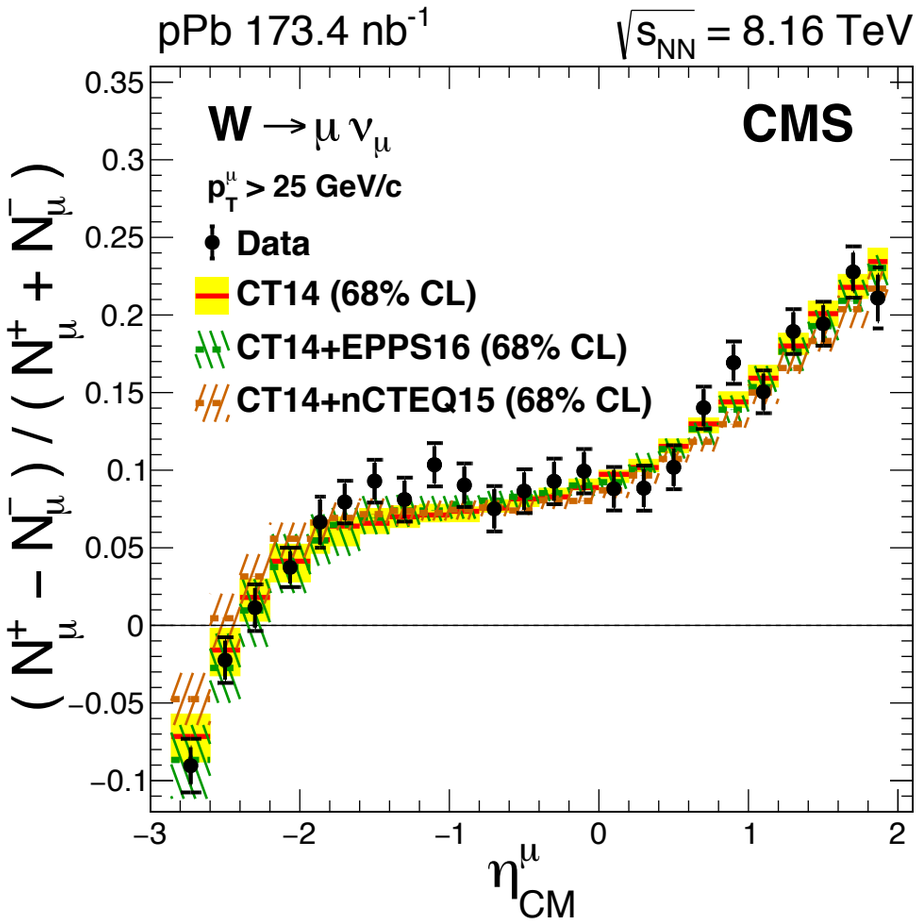
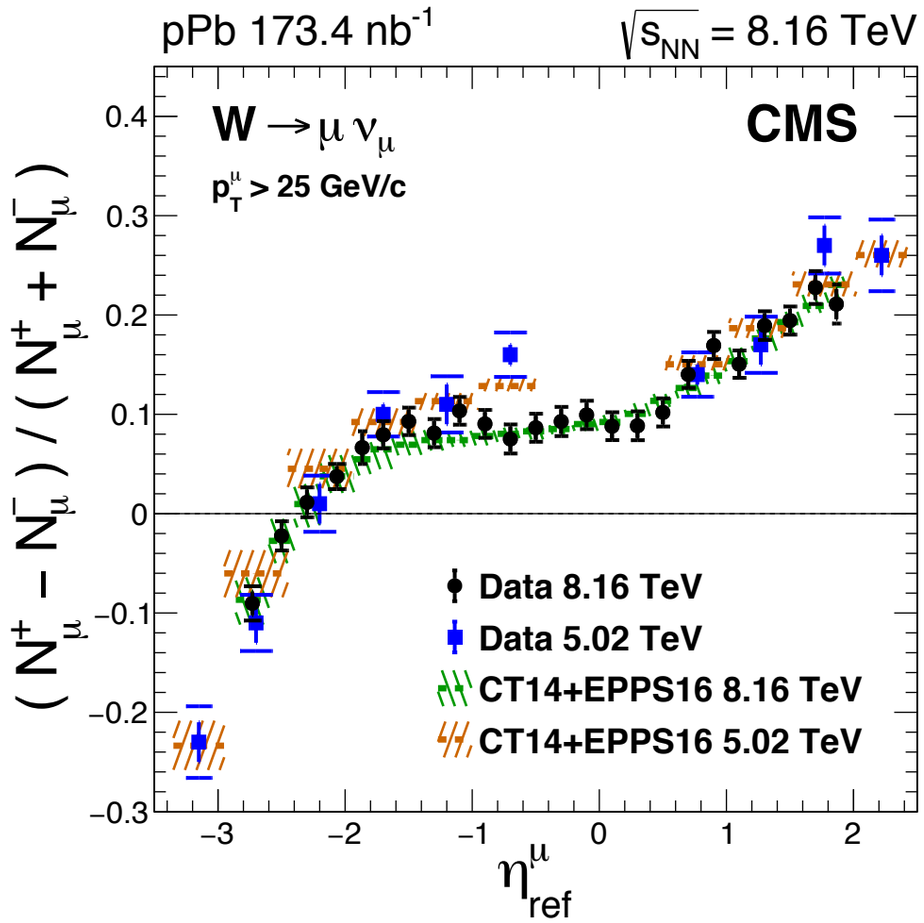



*This work is supported by the DOE Office of Science*

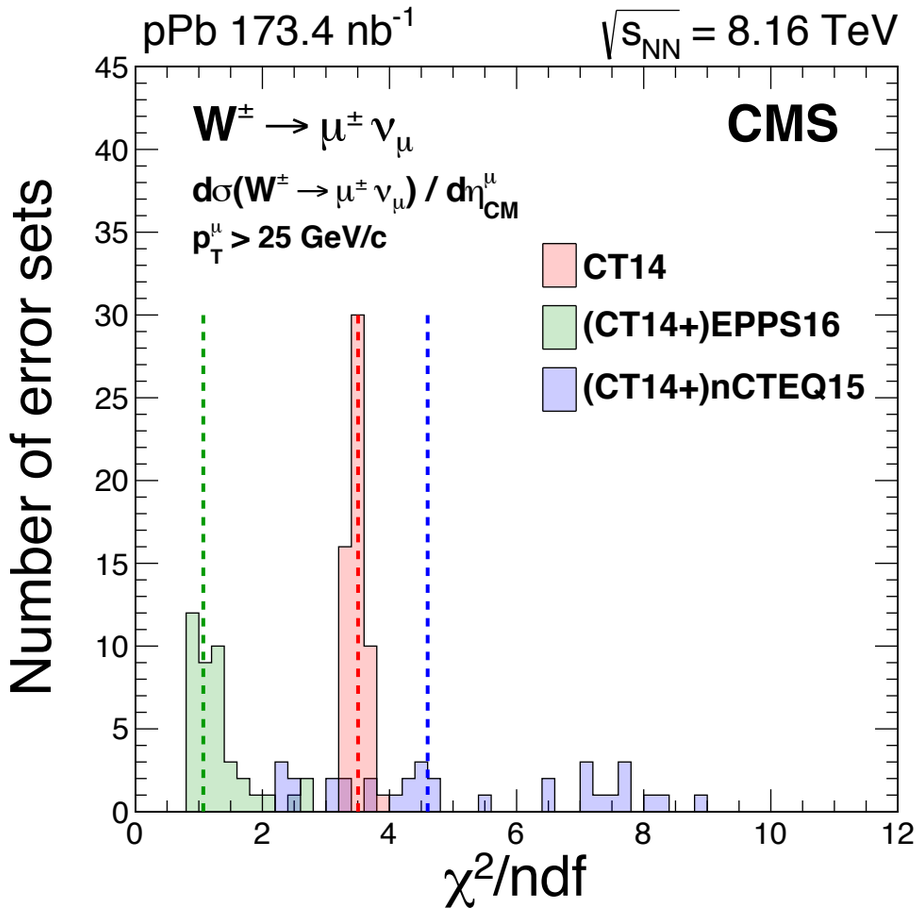
# BACKUP

# W BOSON CHARGE ASYMMETRY



# W BOSON CHI2 VALUES



# W BOSON CHI2 VALUES

Table 2: Results of the $\chi^2$ statistical test between the measurements and the nPDF calculations from the CT14 PDF, CT14+EPPS16 nPDF, and CT14+nCTEQ15 nPDF sets. The value of the $\chi^2$, the number of degrees of freedom (dof) and the $\chi^2$ probability (Prob.), are presented for the $W^{\pm}$ boson differential cross sections, the muon charge asymmetries, the charged muon forward-backward ratios, and the forward-backward ratios of all muons, respectively.

| Observable | CT14 | | | CT14+EPPS16 | | | CT14+nCTEQ15 | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\chi^2$ | dof | Prob. [%] | $\chi^2$ | dof | Prob. [%] | $\chi^2$ | dof | Prob. [%] |
| $d\sigma^{W^{\pm}\to\mu^{\pm}\nu_{\mu}}(\eta^{\mu}_{CM})/d\eta^{\mu}_{CM}$ | 135 | 48 | $3\times10^{-8}$ | 32 | 48 | 96 | 40 | 48 | 79 |
| $(N^{+}_{\mu}-N^{-}_{\mu})/(N^{+}_{\mu}+N^{-}_{\mu})$ | 23 | 24 | 54 | 18 | 24 | 80 | 29 | 24 | 23 |
| $N^{\pm}_{\mu}(+\eta^{\mu}_{CM})/N^{\pm}_{\mu}(-\eta^{\mu}_{CM})$ | 98 | 20 | $3\times10^{-10}$ | 11 | 20 | 95 | 14 | 20 | 83 |
| $N_{\mu}(+\eta^{\mu}_{CM})/N_{\mu}(-\eta^{\mu}_{CM})$ | 87 | 10 | $2\times10^{-12}$ | 3 | 10 | 99 | 5 | 10 | 90 |

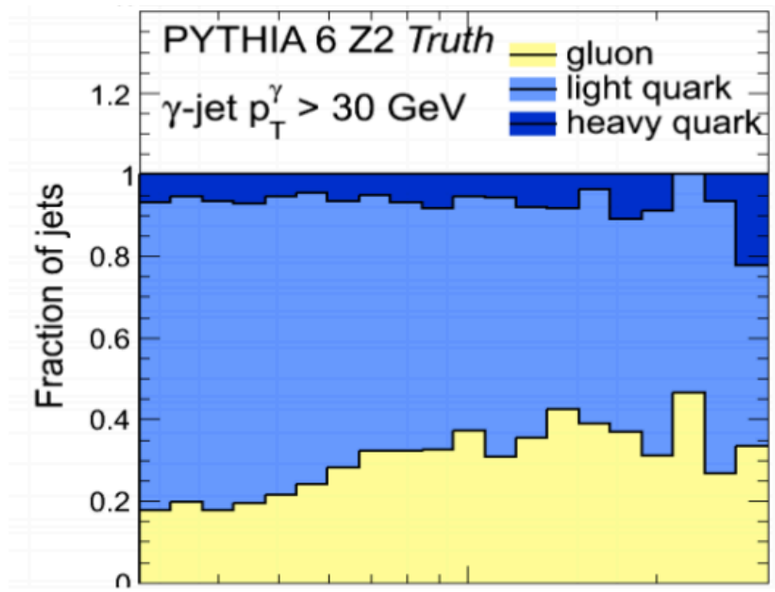
# W BOSON MEASUREMENT UNCERTAINTIES

Table 1: Maximum uncertainty in the measured observables among the $\eta^{\mu}_{\mathrm{CM}}$ bins determined for each source. The uncertainties in the cross sections are relative, whereas those for the asymmetries are absolute. The global integrated luminosity uncertainty of ±3.5% is not included in the total systematic uncertainty in the cross sections.

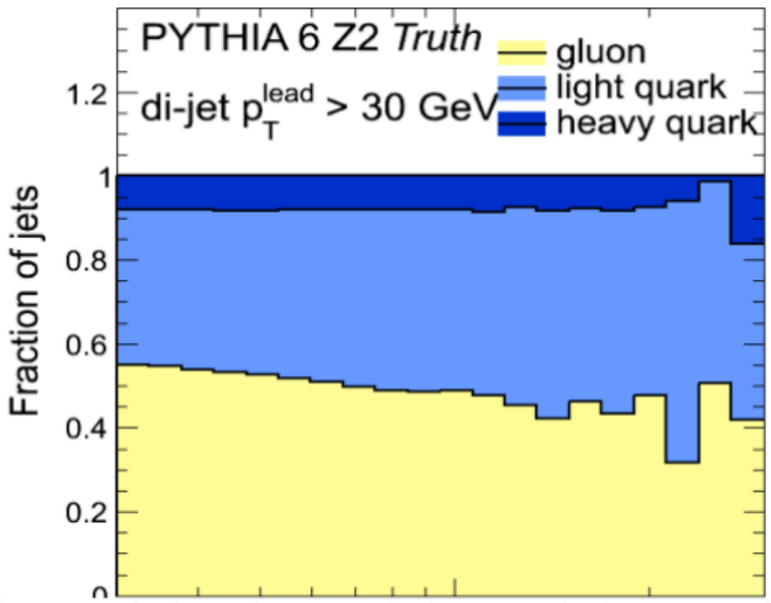
| Source | $\mathrm{W}^-$ $\frac{\mathrm{d}\sigma}{\mathrm{d}\eta_{\mathrm{CM}}}$ [%] | $\mathrm{W}^+$ $\frac{\mathrm{d}\sigma}{\mathrm{d}\eta_{\mathrm{CM}}}$ [%] | $\mathrm{W}^-$ $R_{\mathrm{FB}}$ | $\mathrm{W}^+$ $R_{\mathrm{FB}}$ | W $R_{\mathrm{FB}}$ | $\frac{N_{\mu}^{+}-N_{\mu}^{-}}{N_{\mu}^{+}+N_{\mu}^{-}}$ |
|---|---|---|---|---|---|---|
| Boson $p_{\mathrm{T}}$ reweighing | 0.5 | 0.4 | 0.001 | 0.001 | 0.001 | 0.001 |
| EW background | 0.4 | 0.3 | 0.002 | 0.001 | 0.001 | 0.000 |
| POWHEG EW correction | 0.9 | 0.5 | 0.007 | 0.004 | 0.006 | 0.003 |
| Efficiency | 3.0 | 3.2 | 0.026 | 0.037 | 0.030 | 0.011 |
| Event activity reweighing | 0.6 | 0.4 | 0.002 | 0.002 | 0.001 | 0.002 |
| $p_{\mathrm{T}}^{\mathrm{miss}}$ template binning | 0.1 | 0.1 | 0.002 | 0.001 | 0.001 | 0.001 |
| QCD background | 1.2 | 0.7 | 0.016 | 0.007 | 0.009 | 0.006 |
| Hadronic recoil correction | 0.2 | 0.3 | 0.002 | 0.004 | 0.002 | 0.002 |
| Total systematic uncertainty | 3.3 | 3.3 | 0.030 | 0.038 | 0.031 | 0.013 |
| Statistical uncertainty | 2.4 | 2.0 | 0.026 | 0.029 | 0.019 | 0.015 |

# QUARK/GLUON FRACTIONS

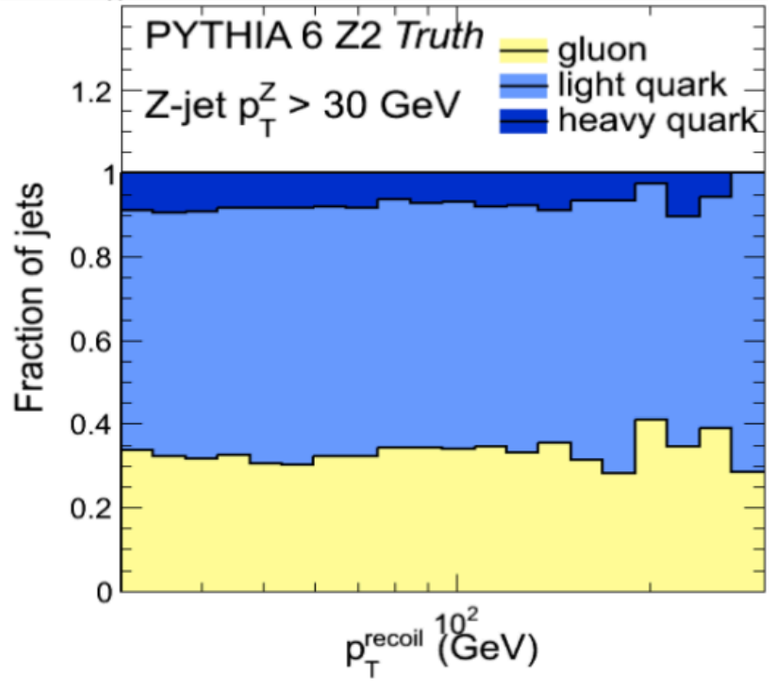
γ-jets




dijets



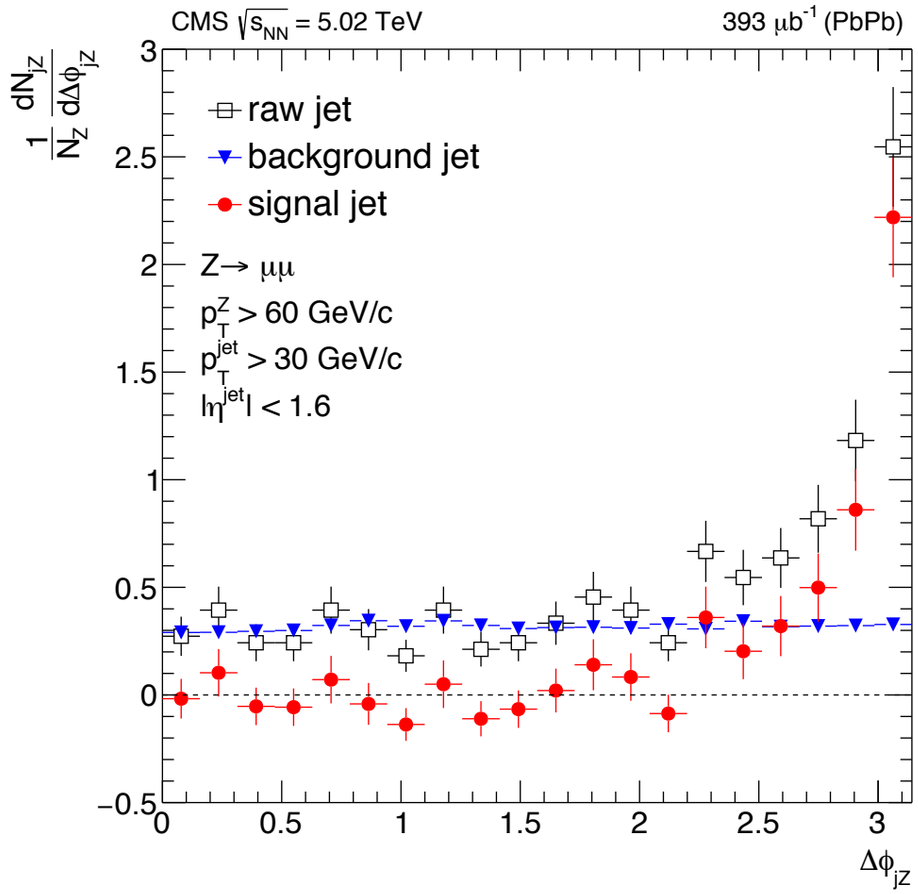

Z-jets

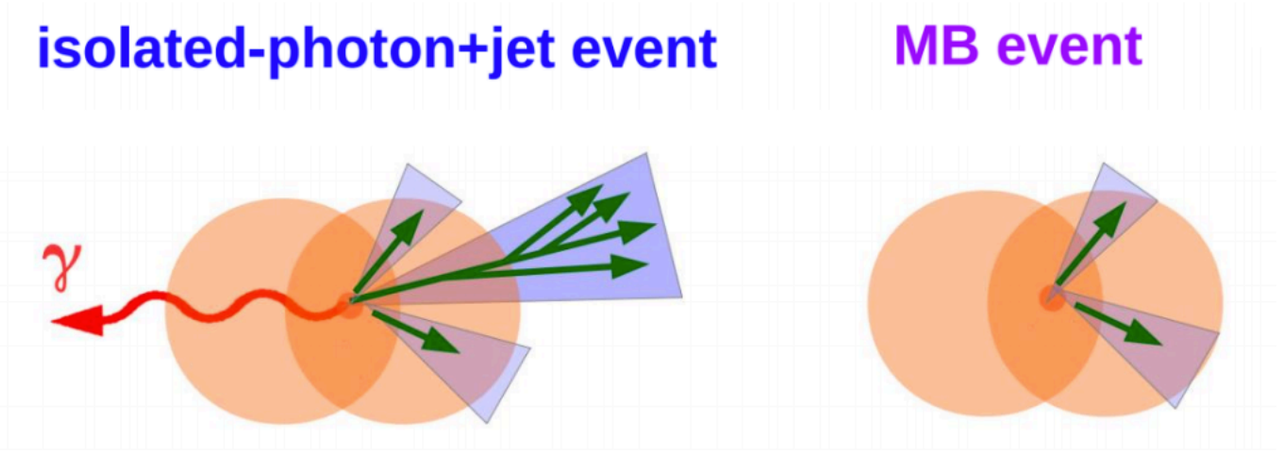


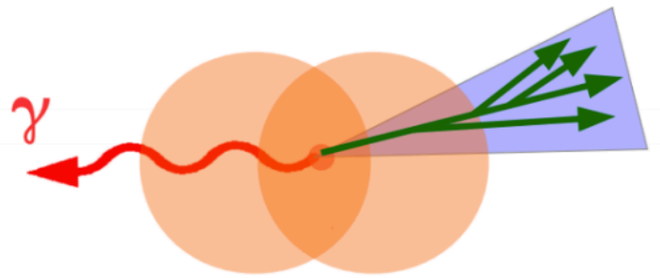
# BACKGROUND–JET SUBTRACTION IN PBPB COLLISIONS

- Large underlying event in PbPb collisions
  - also large fluctuations in the underlying event
  - upward fluctuations create ‘fake’ jets

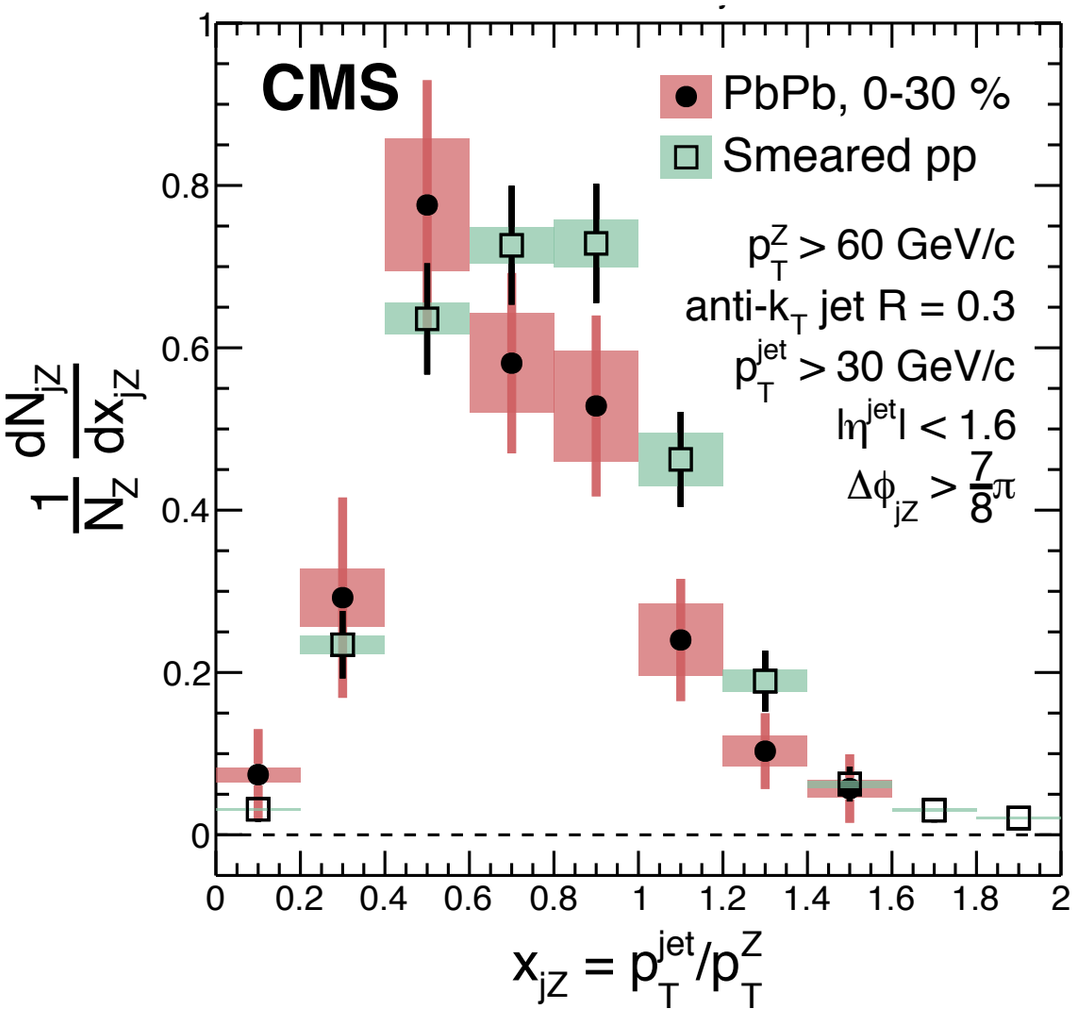
- Mixed-event background subtraction technique used for boson-jet correlation measurements
  - assume jets from the underlying event are uncorrelated with the signal
  - “embed” electroweak boson into minimum bias (MB) events with similar characteristics
  - subtract correlations of the embedded boson with jets from the MB events

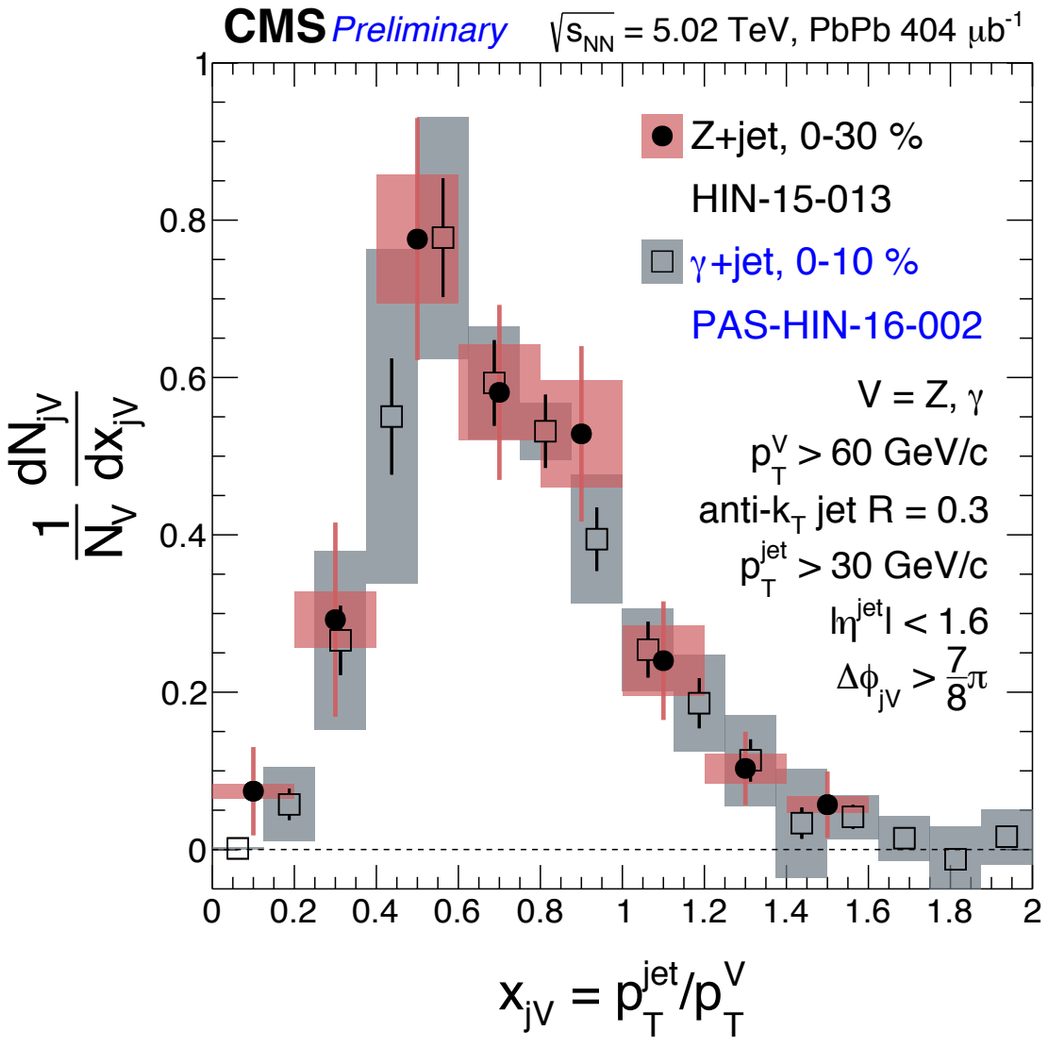


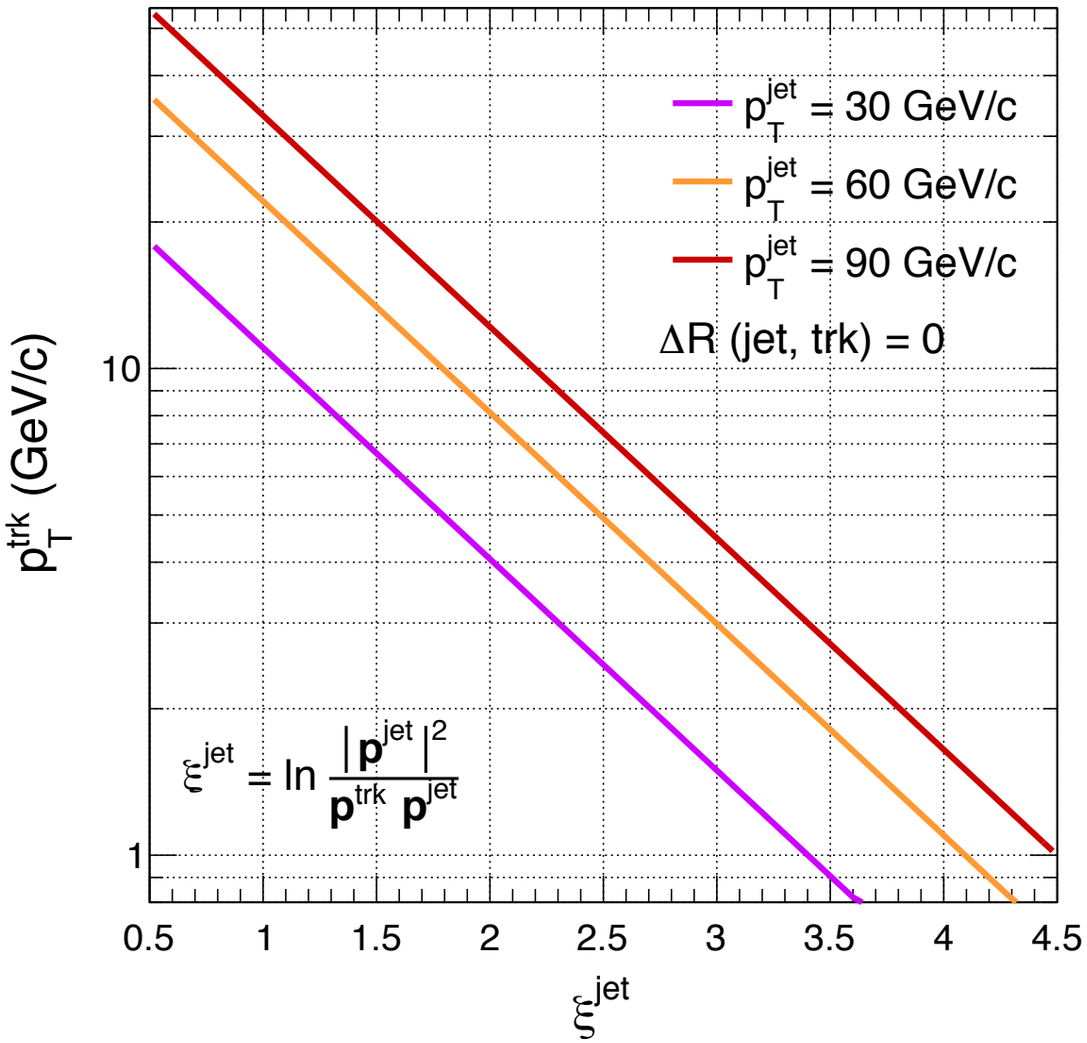



# Z-JET MOMENTUM IMBALANCE & Z/PHOTON-JET COMPARISON

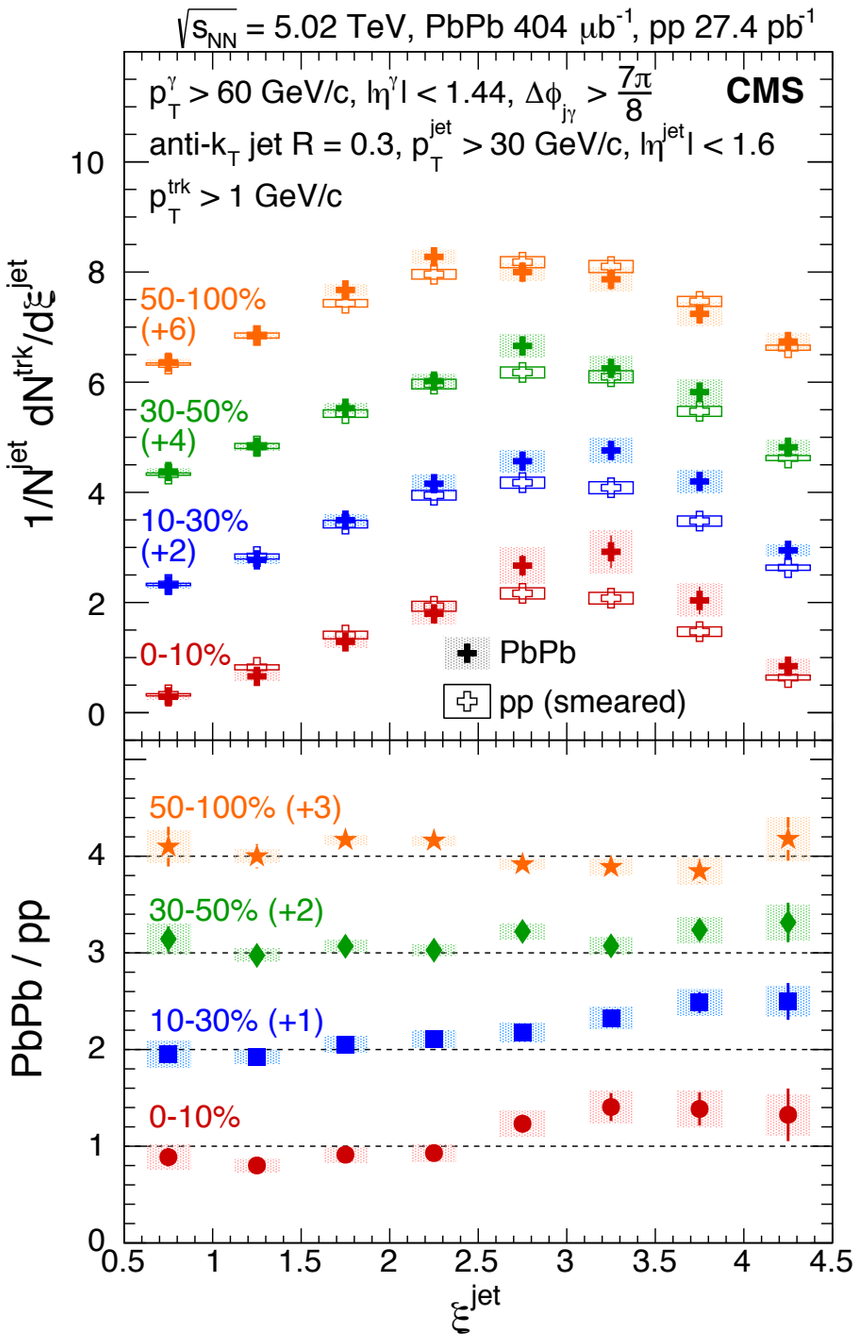


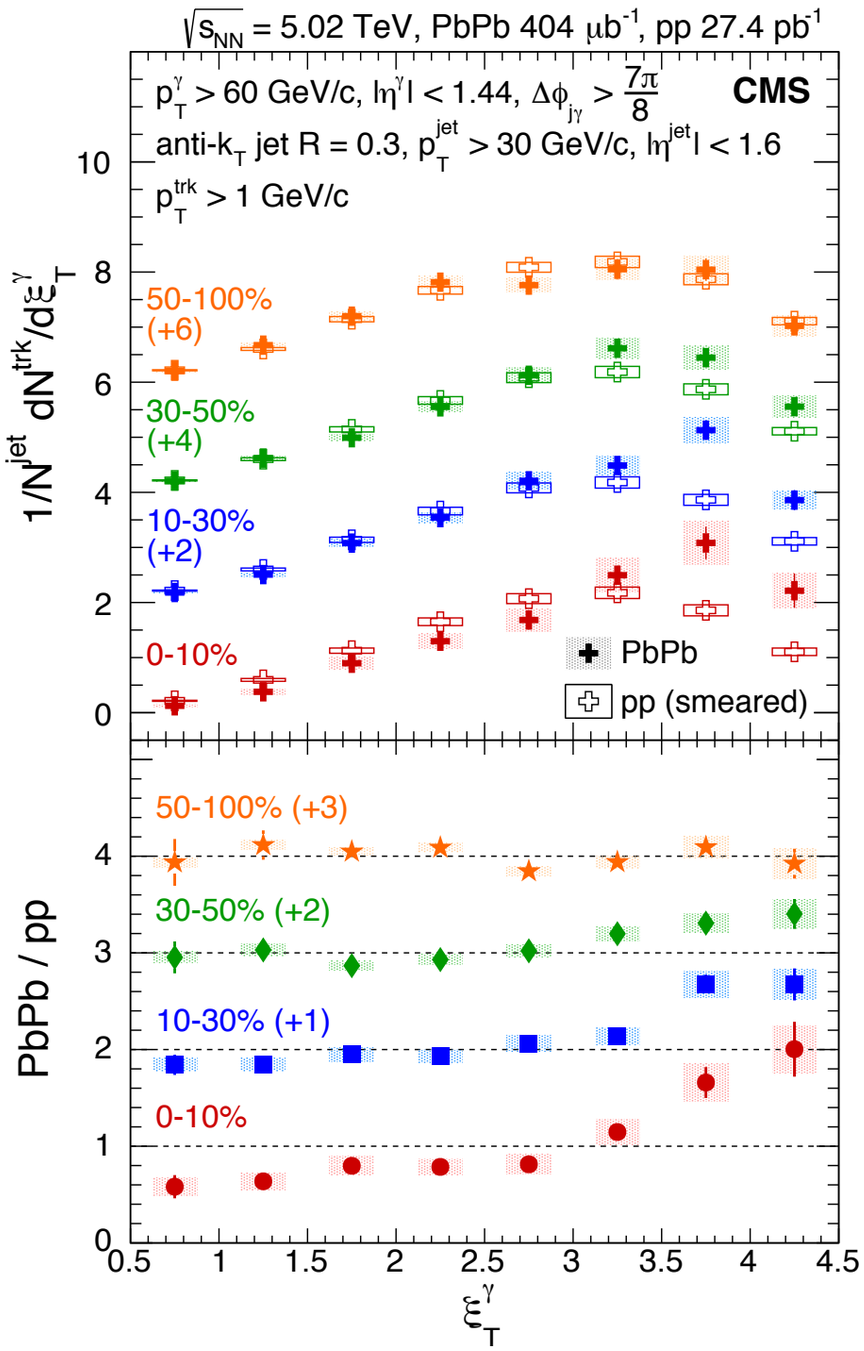



# HADRON PT AND XI



# PHOTON-TAGGED JET FRAGMENTATION FUNCTIONS



# ATLAS PHOTON-TAGGED JET FRAGMENTATION FUNCTIONS