STUDIES OF JET SUBSTRUCTURE IN HEAVY ION COLLISIONS WITH CMS

Ran Bi
for the CMS Collaboration

11th International Workshop on Boosted Object Phenomenology, Reconstruction and Searches in HEP (BOOST 2019)

22 July 2019

Cambridge, MA

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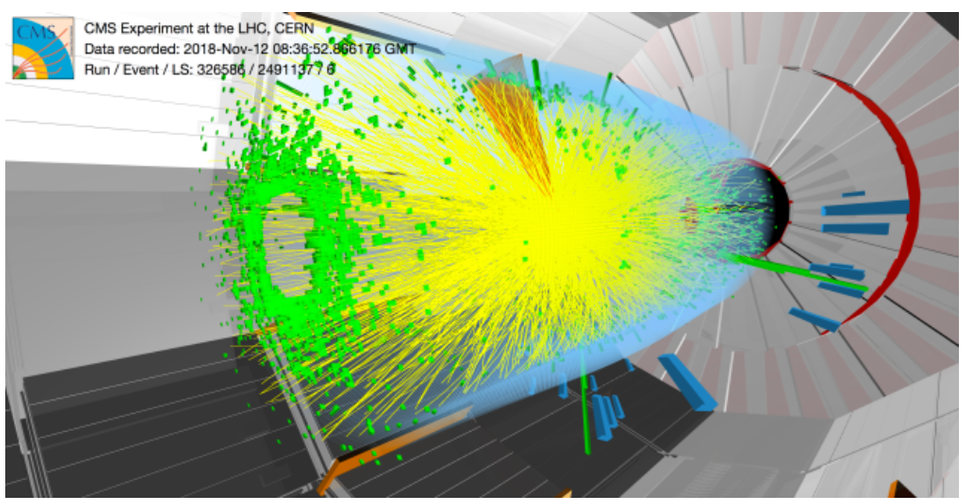
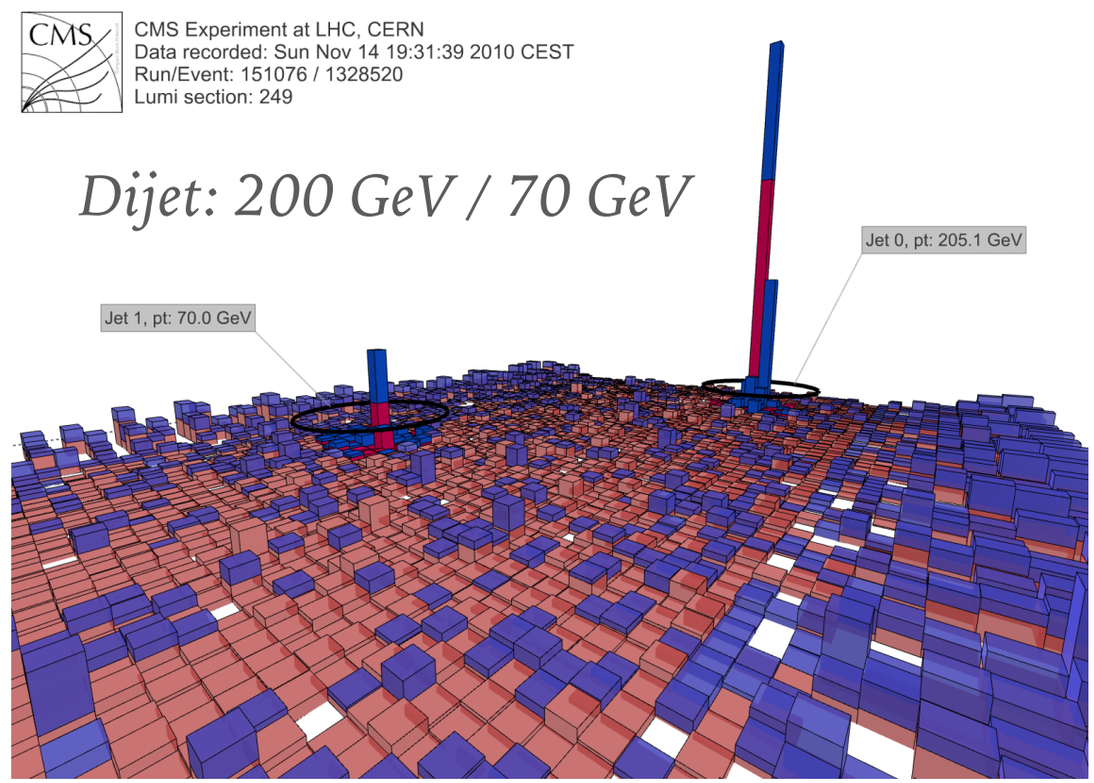
HEAVY ION COLLISIONS

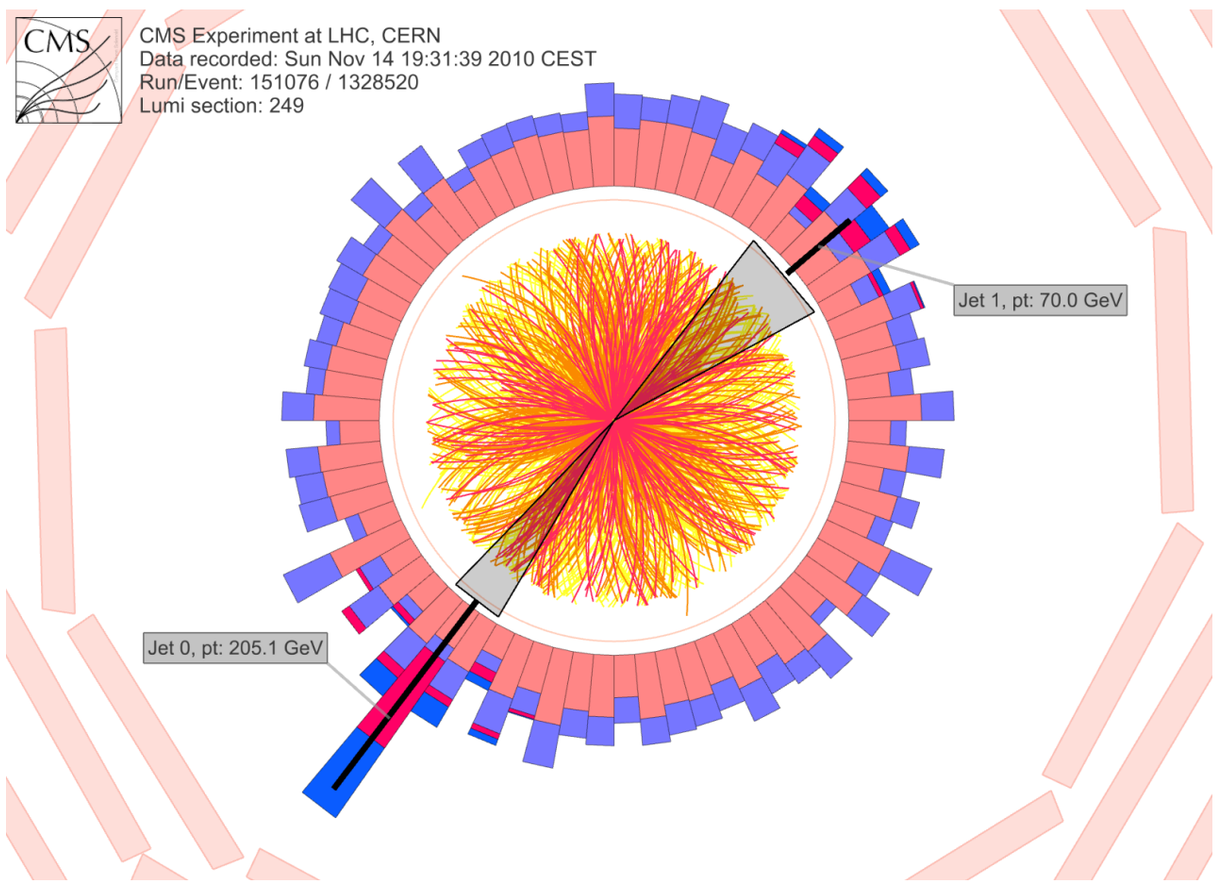
- Heavy ion collisions provide a glimpse of the early universe
  - hot, dense matter known as the quark-gluon plasma (QGP)
  - strongly interacting, deconfined medium of free quarks/gluons
  - large underlying event for the most head-on collisions - O(10^4) particles
- QGP exhibits interesting phenomena
  - jet quenching - medium-induced jet energy loss
- Study and extract properties of QGP



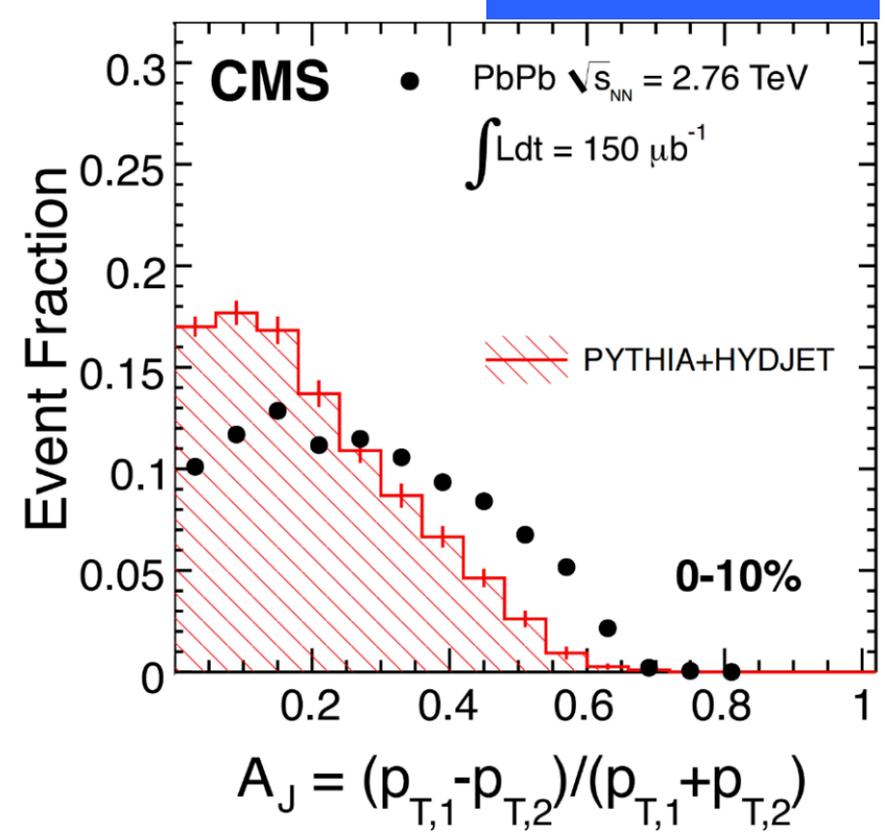


ENERGY LOSS IN DIJET EVENTS

- Jet quenching is a characteristic feature of the QGP
  - observed through measurements of jet energy loss in dijet systems
- Question: where does the jet energy go, how is it redistributed?
- Caveat: both jets can be modified when traversing the medium

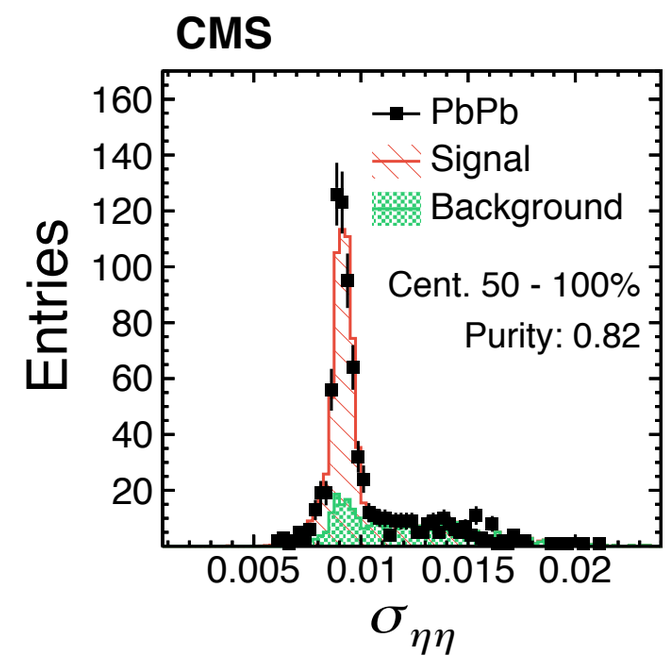


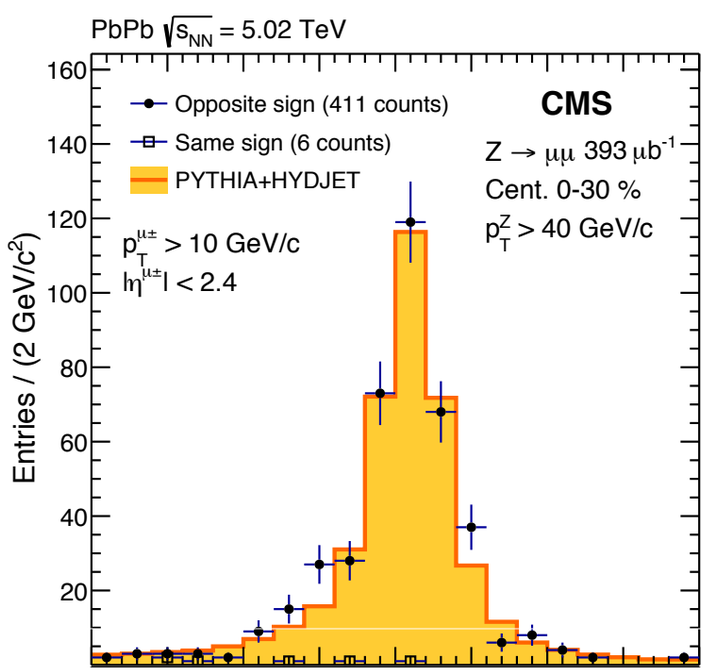
PLB 712 (2012) 176



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



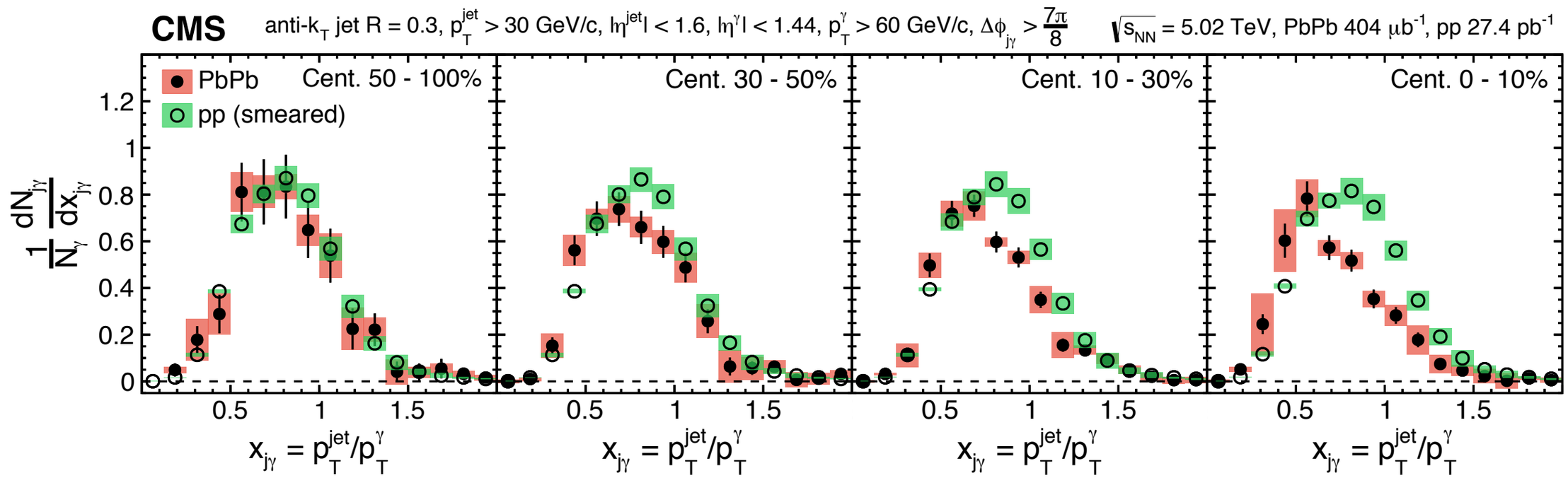


- Z bosons
  - reconstructed through dilepton channels
  - 2015: ~400 μb^{-1}; 2018: 1.5 nb^{-1}

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

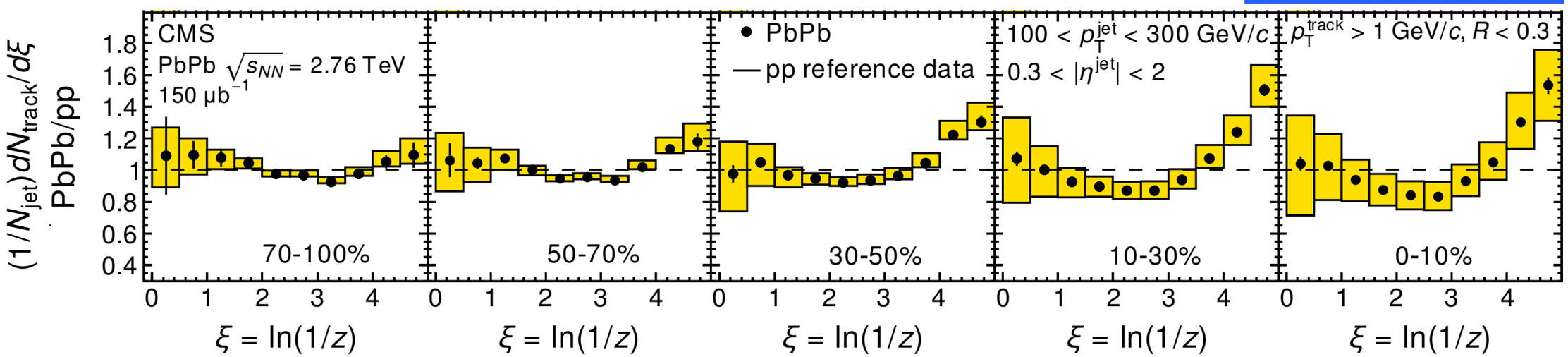


- Models with different descriptions of the energy loss mechanisms are able to predict the results within the experimental uncertainties
- Results give a crude picture of jet quenching
  - more detailed measurements required for a complete description

JET SUBSTRUCTURE IN PBPB COLLISIONS (INCLUSIVE JETS)

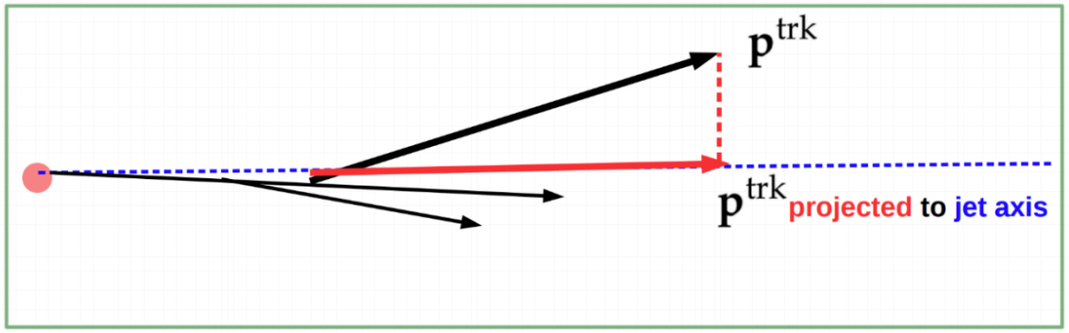
- Differentiate between different mechanisms by measurements of jet substructure
  - previous measurements with inclusive jets show some modification

PRC 90 (2014) 024908



- Jet fragmentation function

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

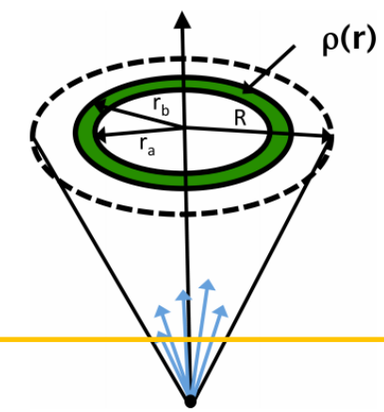


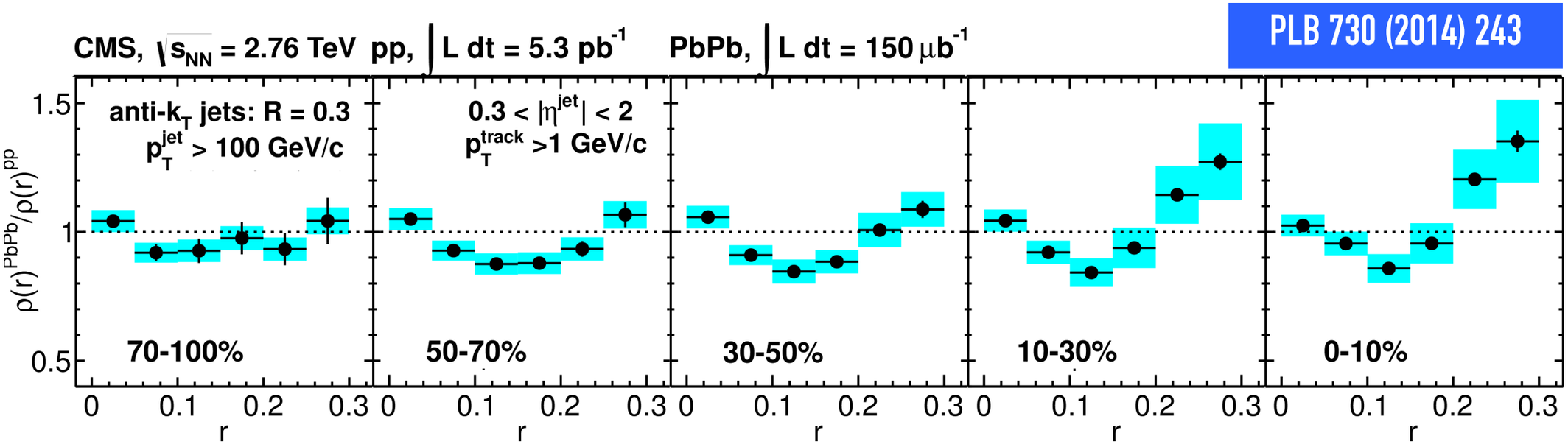
JET SUBSTRUCTURE IN PBPB COLLISIONS (INCLUSIVE JETS)

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

- Jet shape

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



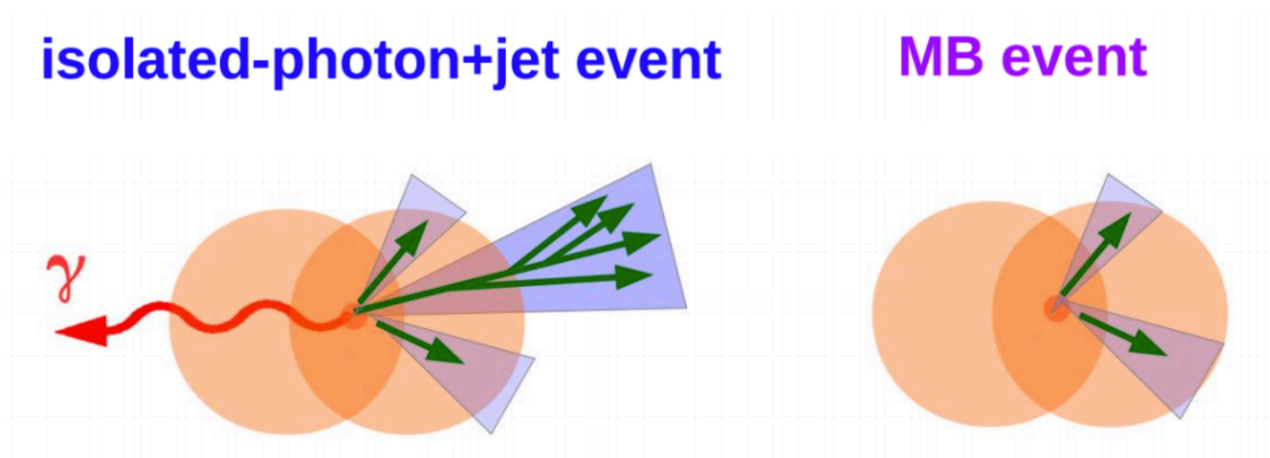


PLB 730 (2014) 243

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

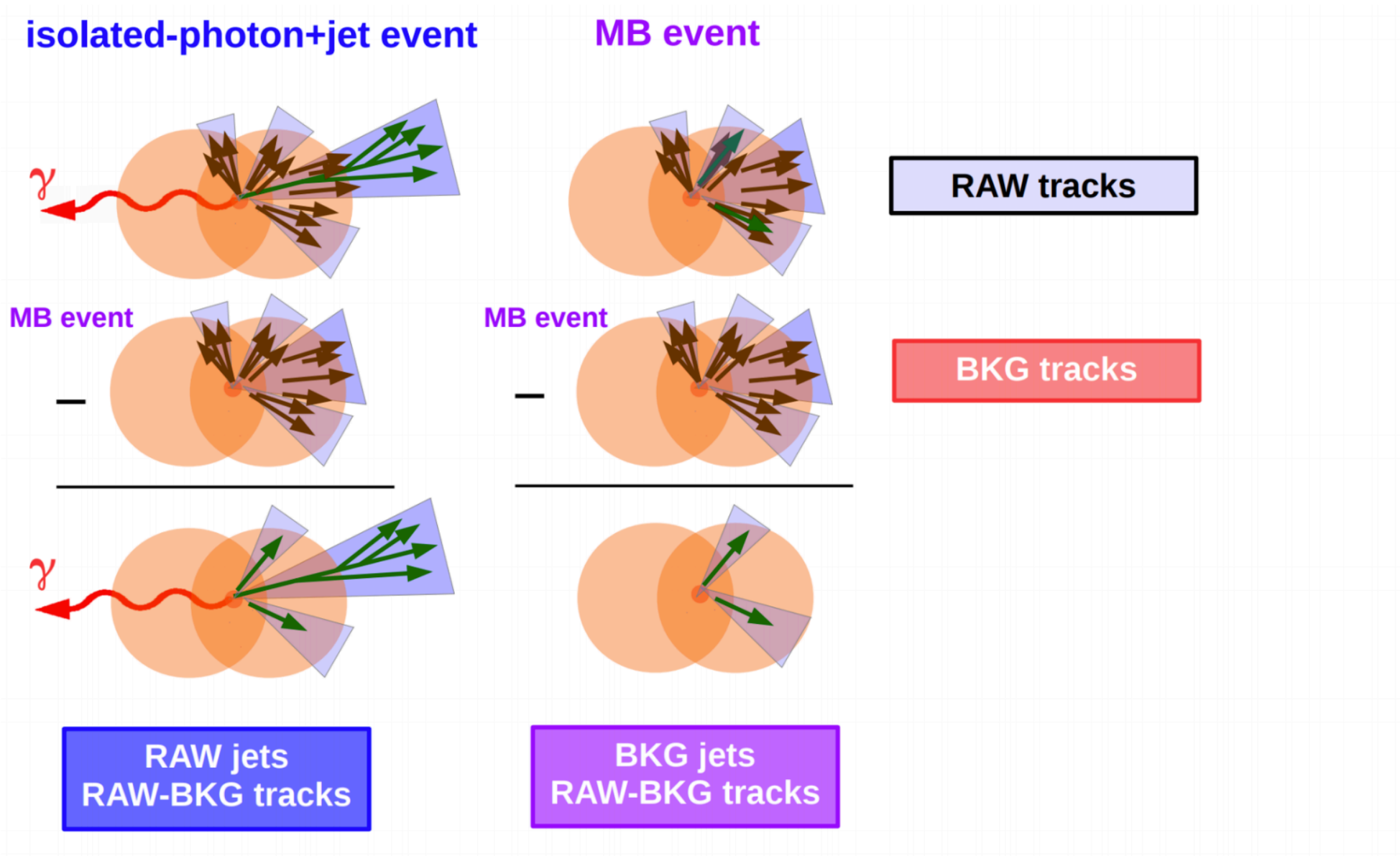
BACKGROUND SUBTRACTION (EVENT MIXING)

- Jets and tracks from the underlying event are uncorrelated with the photon
  - Estimate contribution of underlying event by embedding the photon into minimum bias (MB) events
  - Select MB events with similar event characteristics
    - Event activity (centrality), primary vertex position, event plane angle
- Subtraction for jet-based observables is straightforward



BACKGROUND SUBTRACTION (EVENT MIXING…)

- Contributions from background tracks (UE) and background jets (fake jets) must be subtracted



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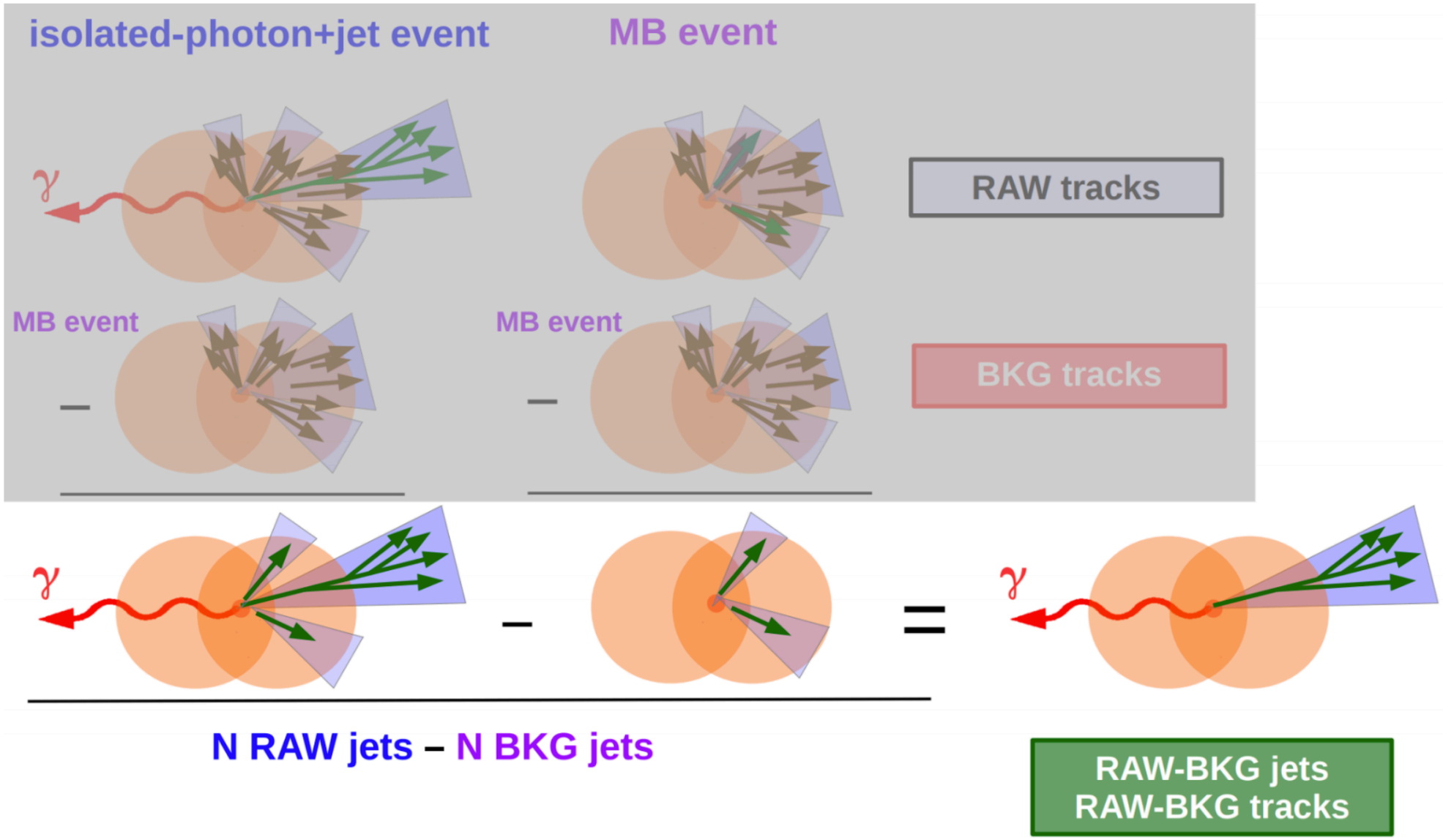
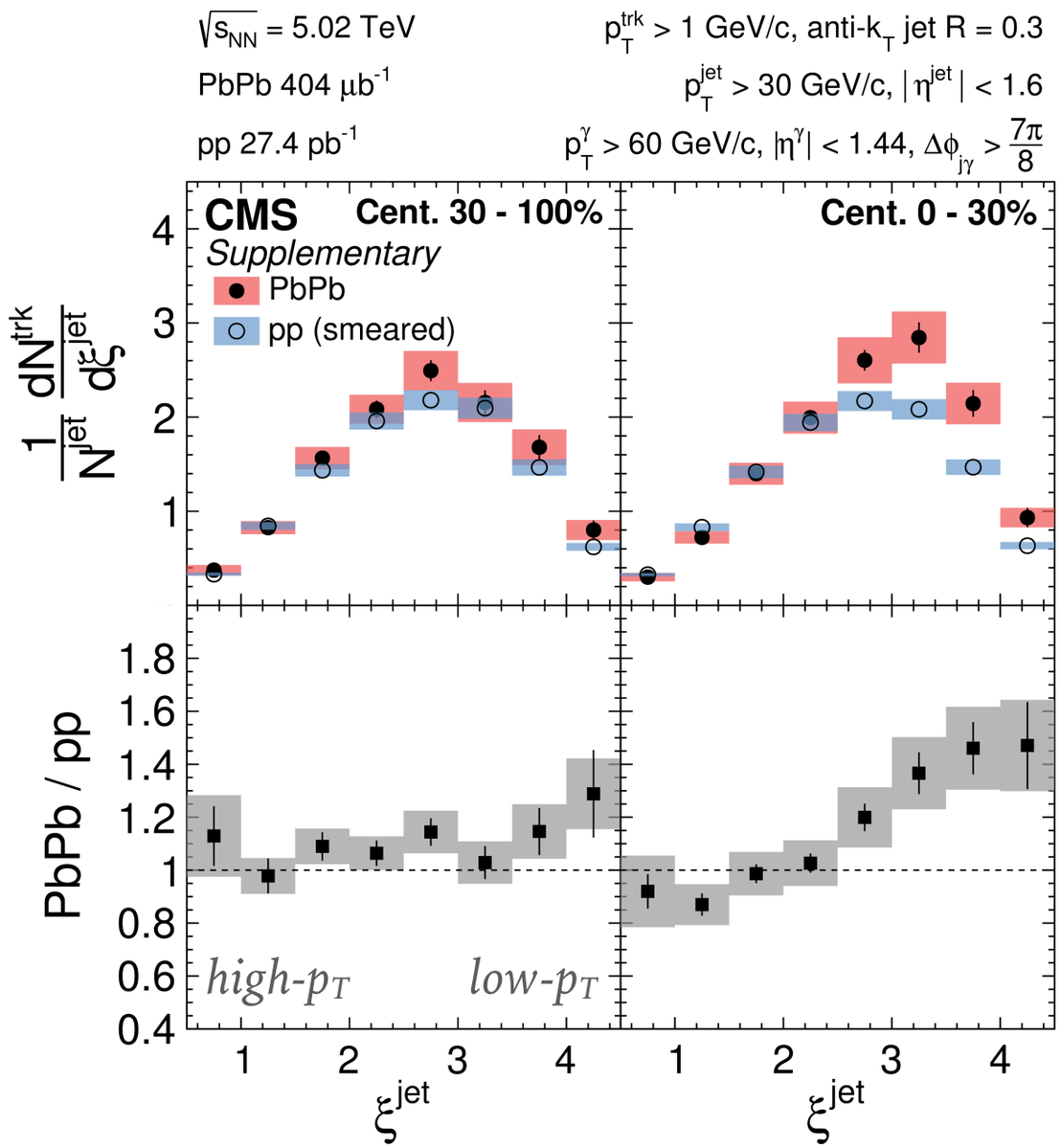


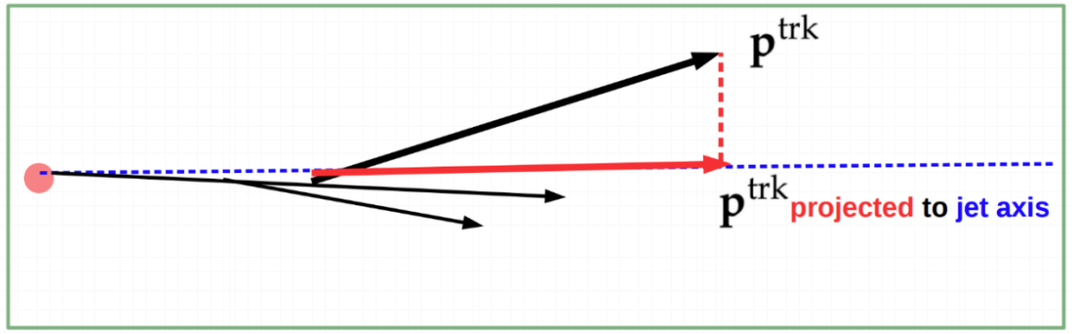
PHOTON-TAGGED JET FRAGMENTATION FUNCTION

- 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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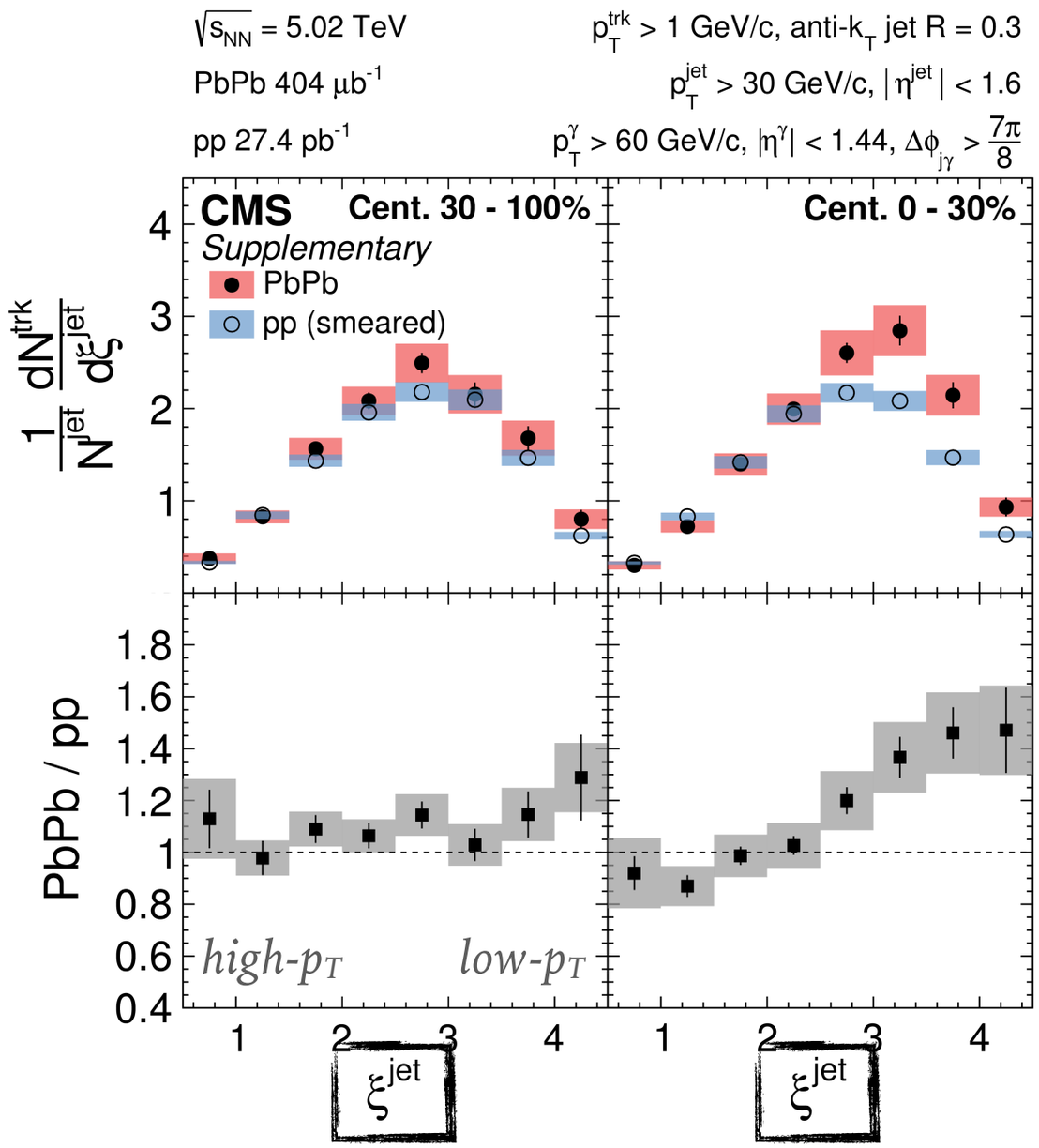

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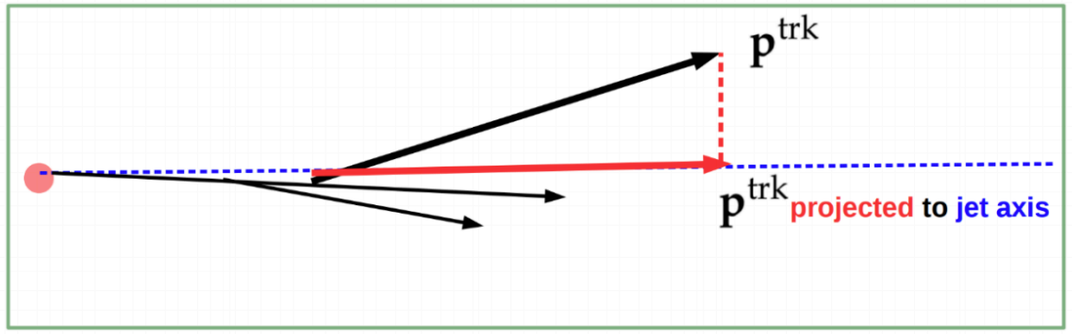
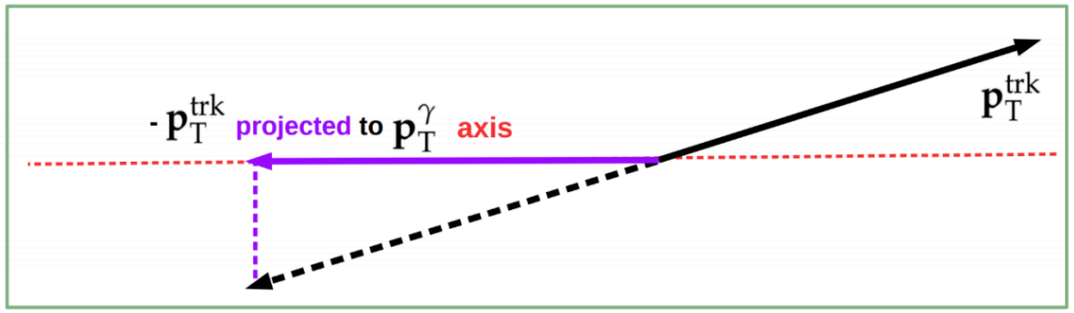


$$\xi_T^{\gamma} = \ln \frac{-|\mathbf{p}_T^{\gamma}|^2}{\mathbf{p}_T^{trk} \cdot \mathbf{p}_T^{\gamma}}$$



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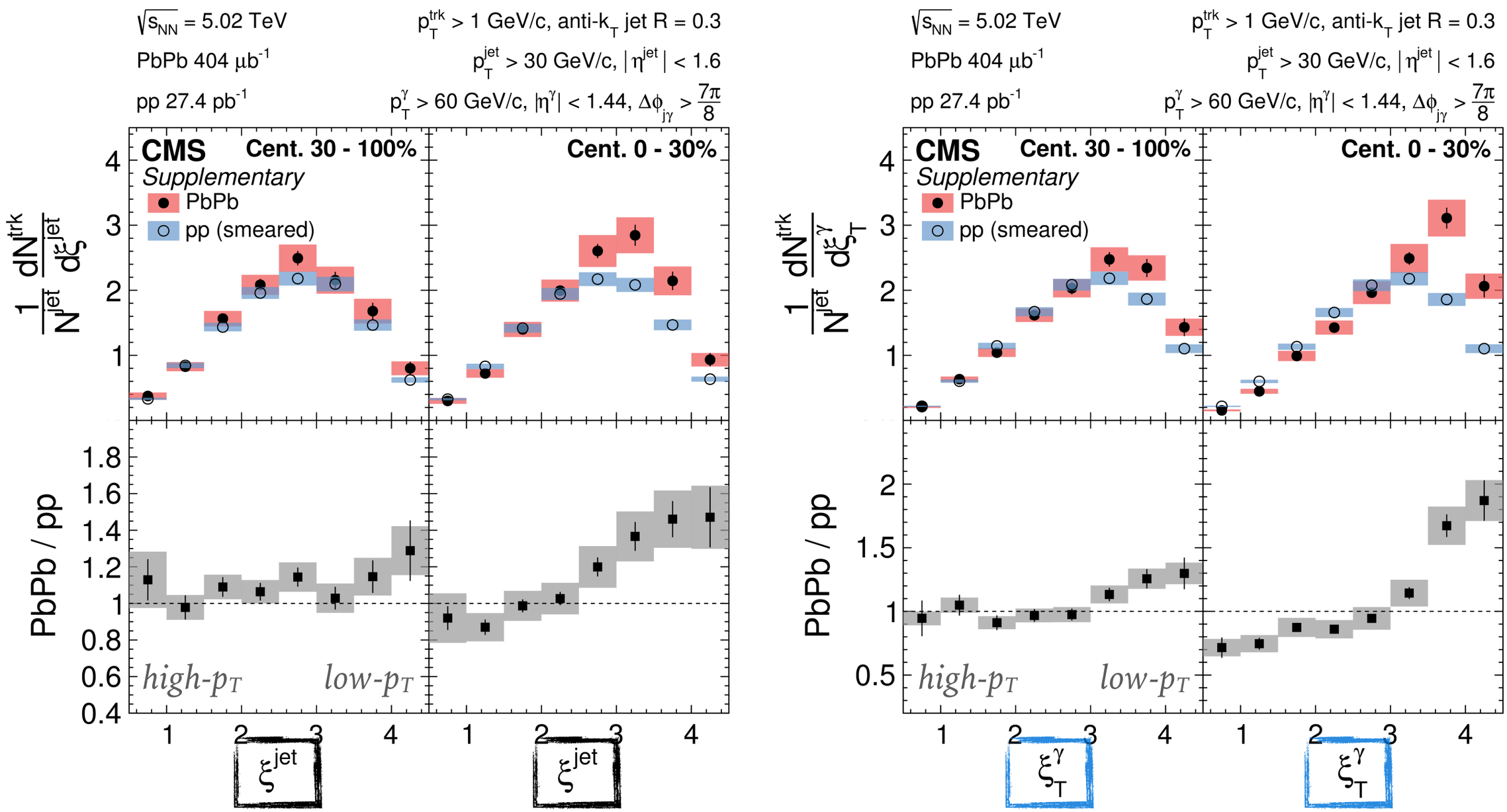
PRL 121 (2018) 242301



MODEL PREDICTIONS (FRAGMENTATION FUNCTION)

- Stronger modification for ξ_T^{γ} than for ξ^{jet}
  - jet energy quenched

- Models describe data to different extents
  - both $SCET_G$ 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

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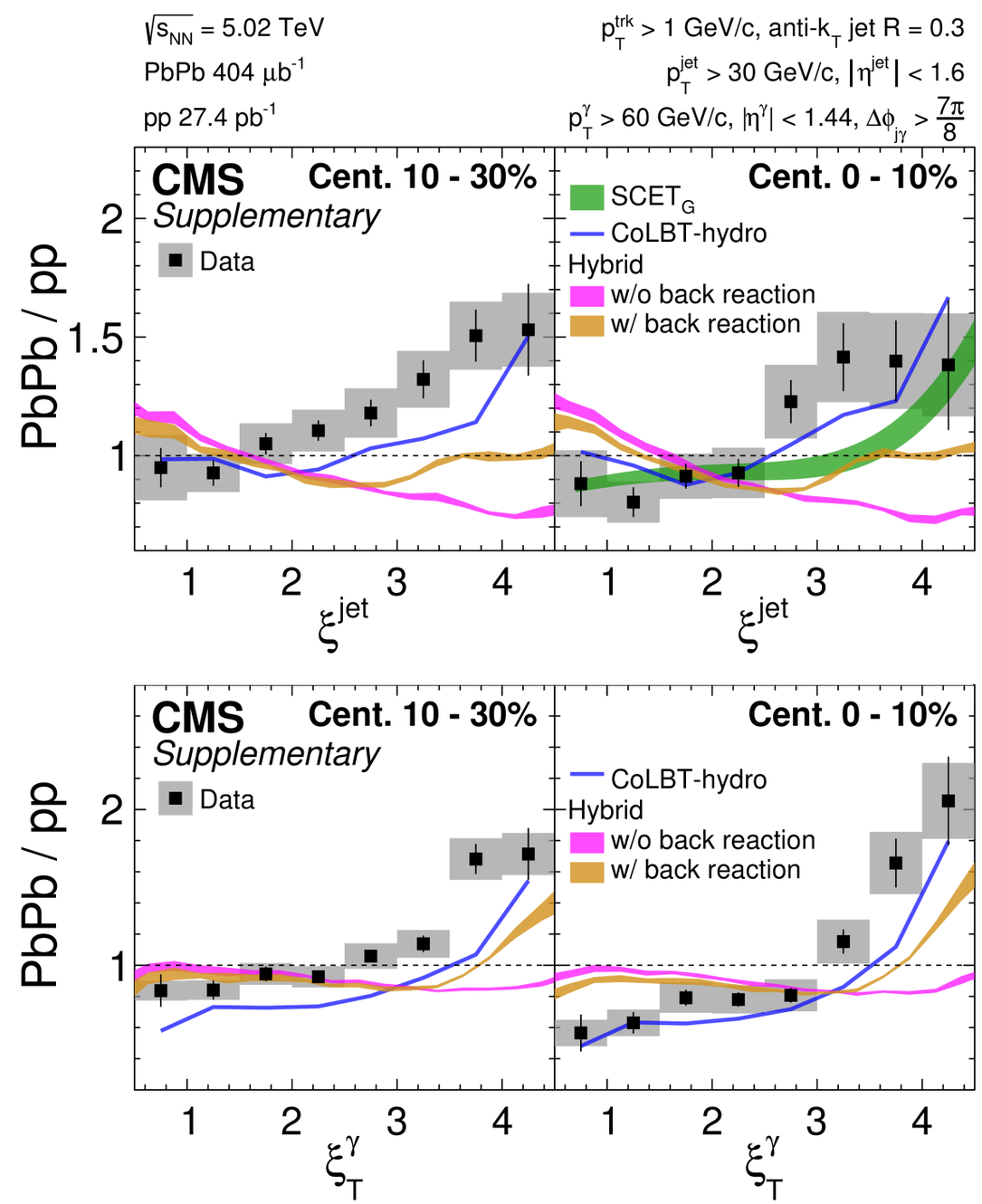
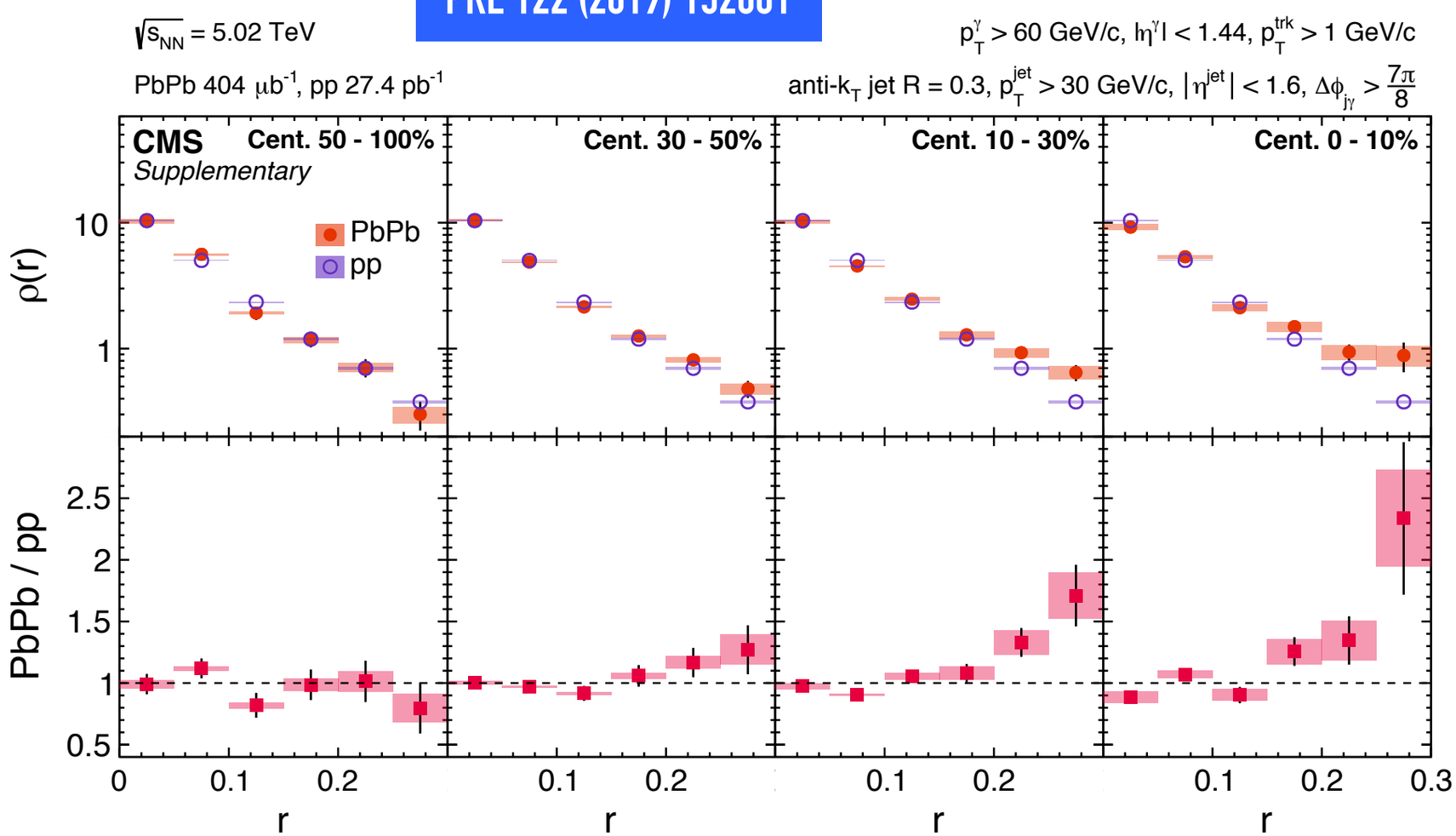
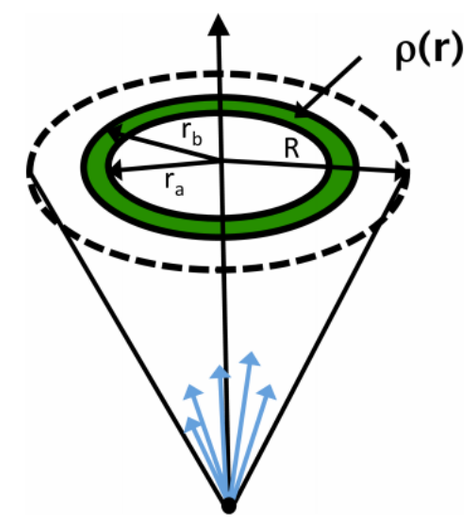


PHOTON-TAGGED JET SHAPE

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

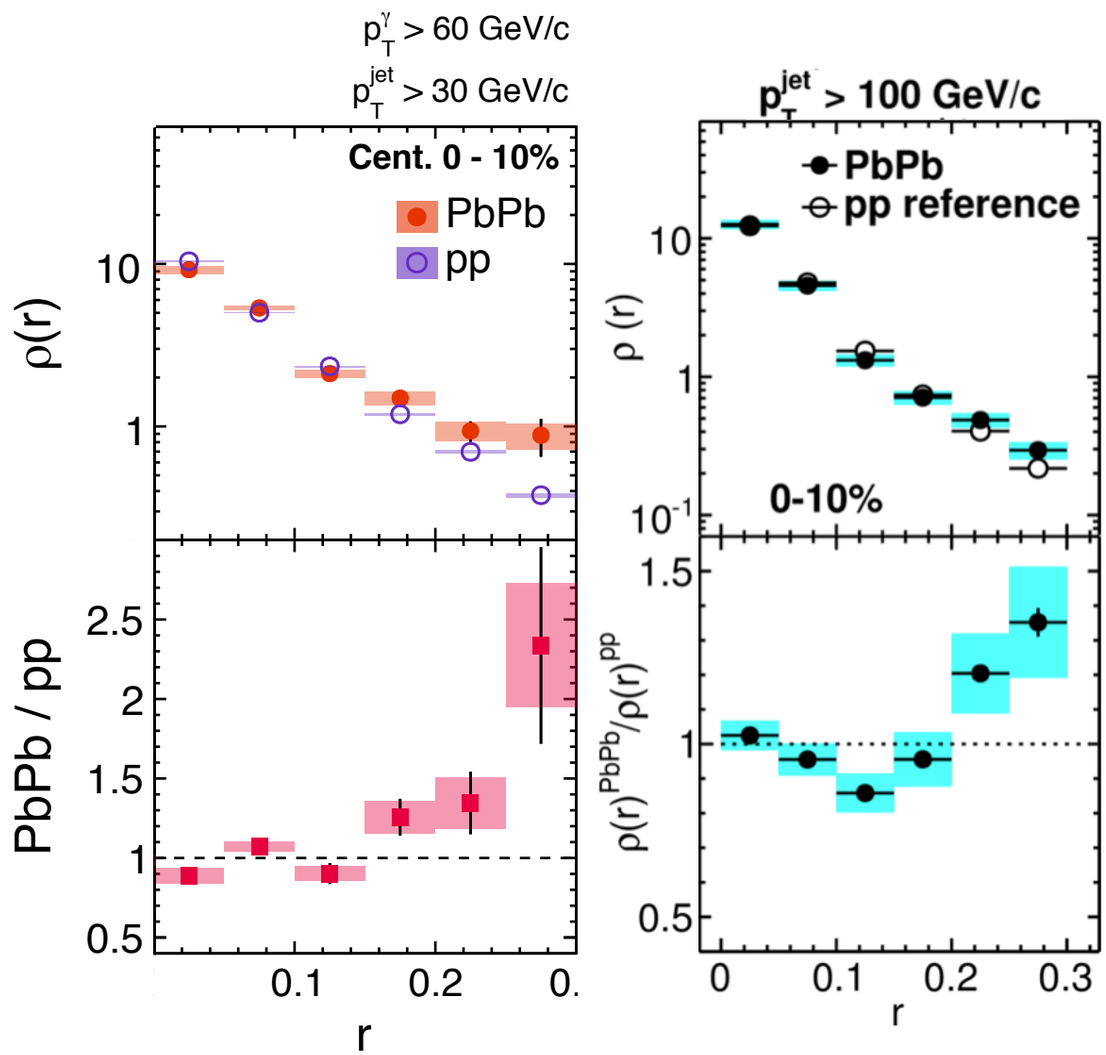
PRL 122 (2019) 152001





PHOTON-TAGGED JET SHAPE

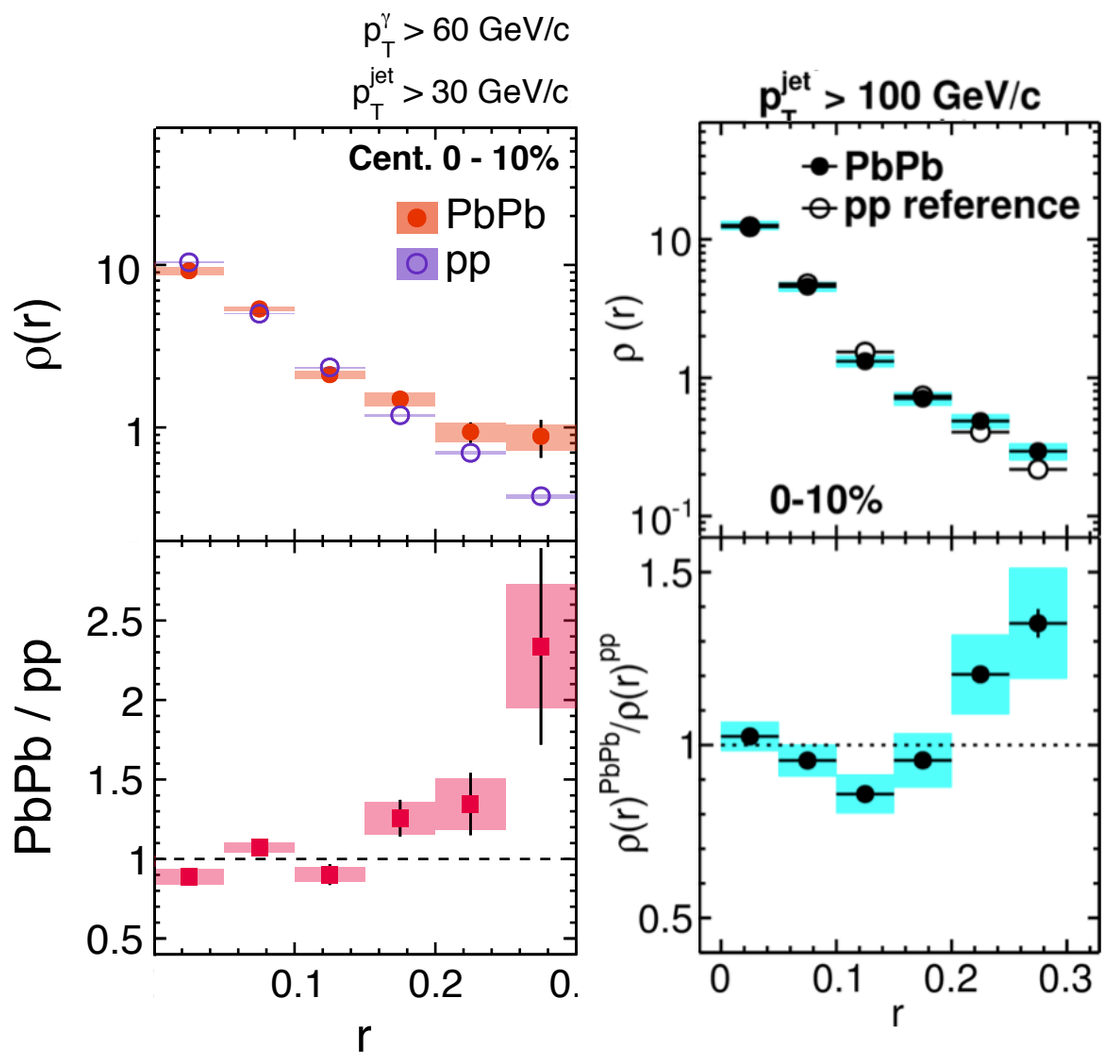
- Comparison to inclusive jet shapes
  - no depletion at intermediate r
    - increased quark/gluon ratio
    - lower jet p_T threshold - jets lose more energy



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
- Comparison to models
  - both $SCET_G$/LBT both describe trend
  - different mechanisms, interpretations



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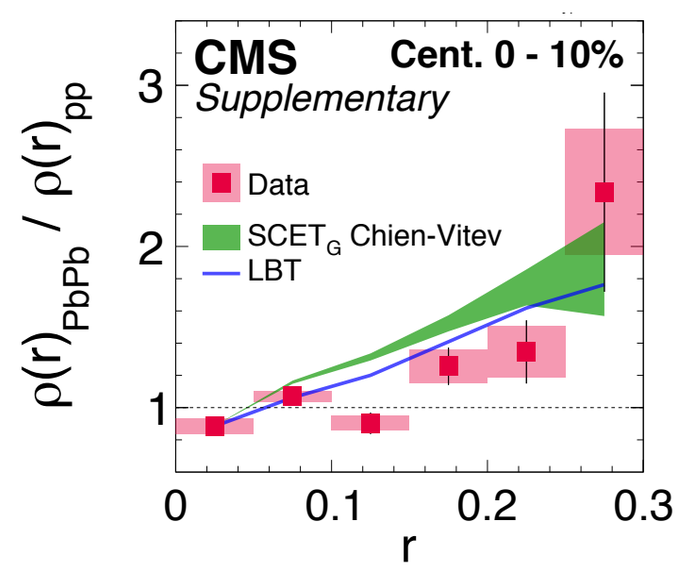
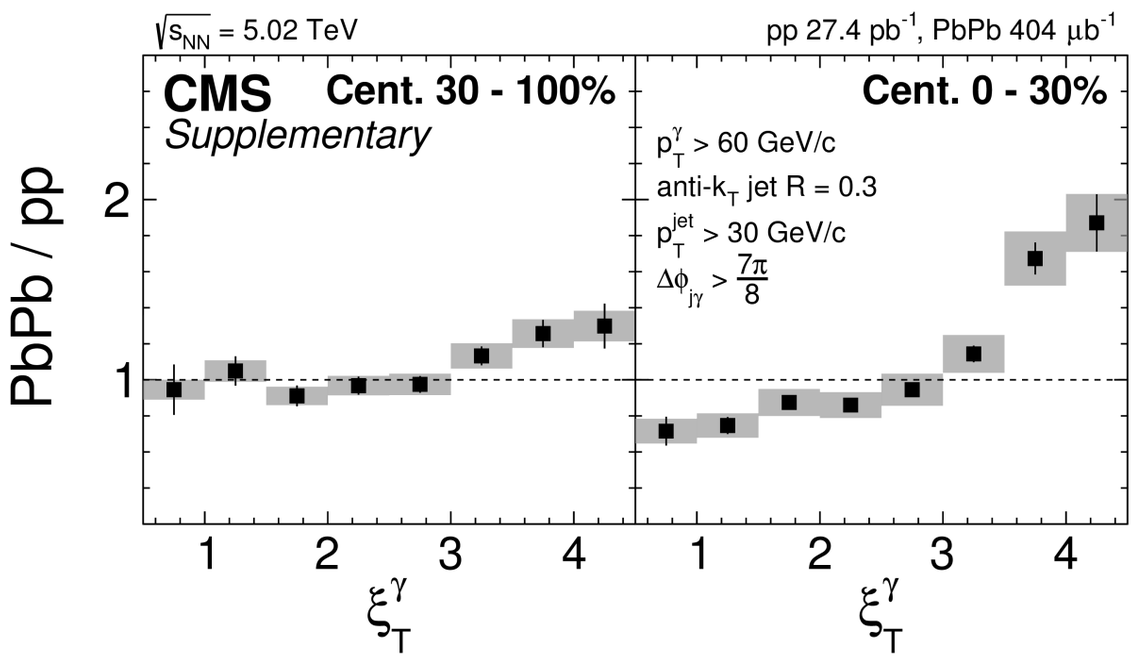


SUMMARY

- Jet substructure is a key probe of medium properties and interactions
  - boson-tagged jet measurements constrain recoil parton momentum and quark/gluon fractions
- 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

PRL 121 (2018) 242301



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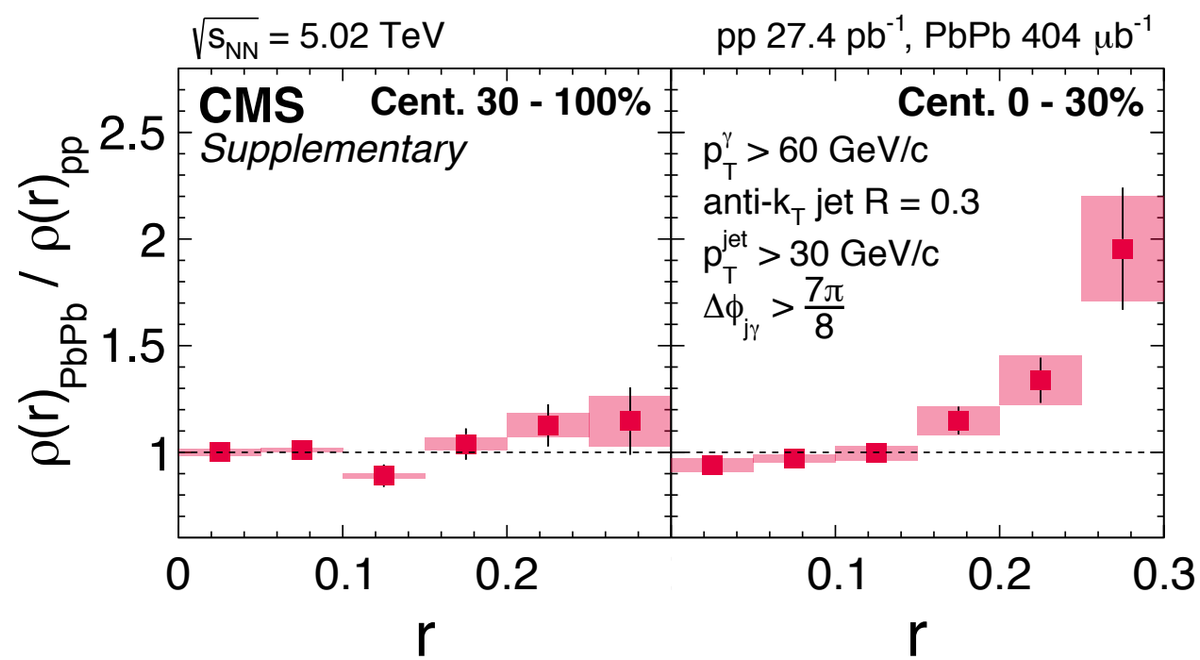
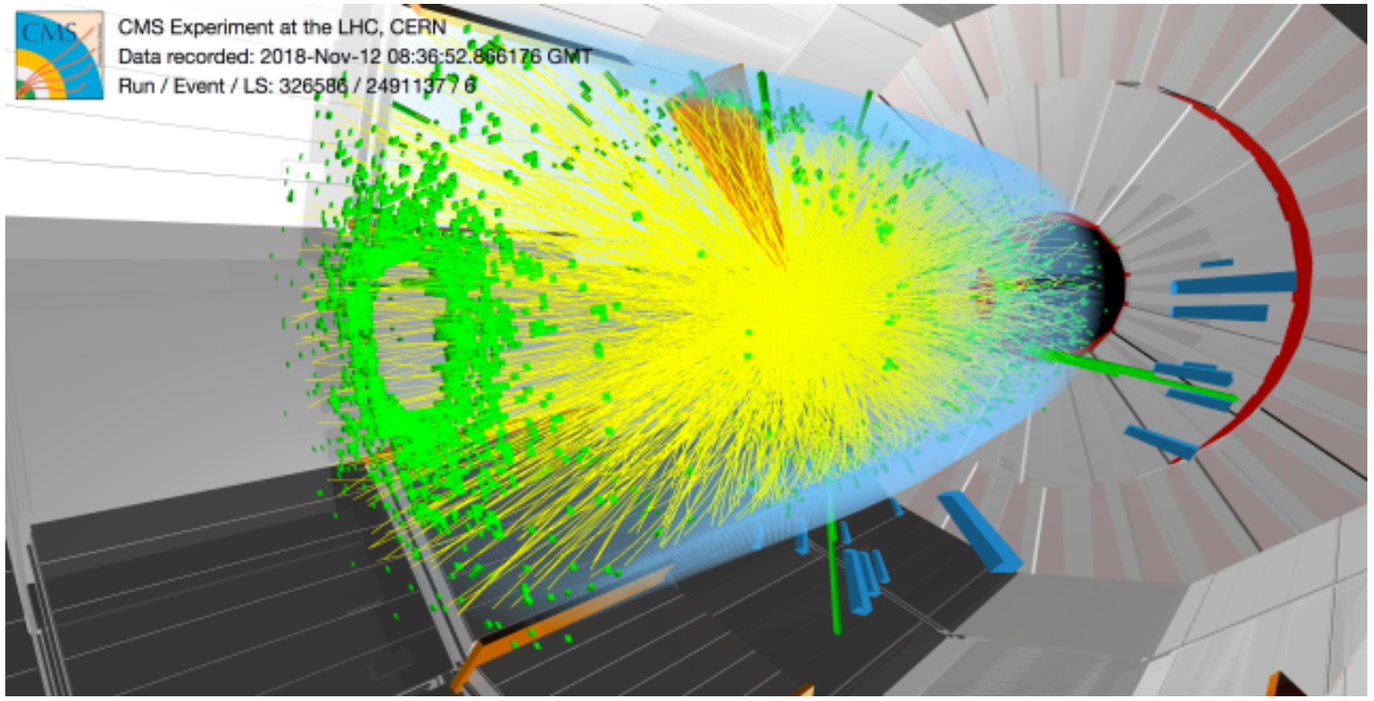


This work is supported by the DOE Office of Science

BACKUP

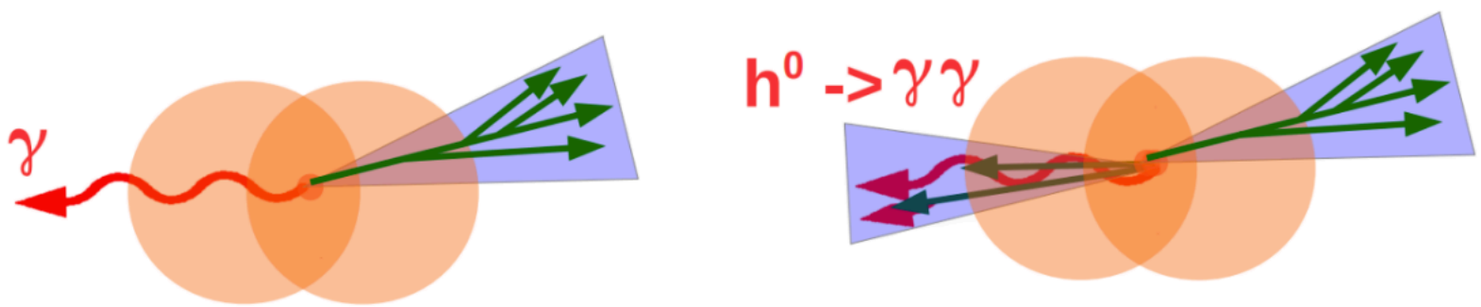
ANALYSIS TECHNIQUE

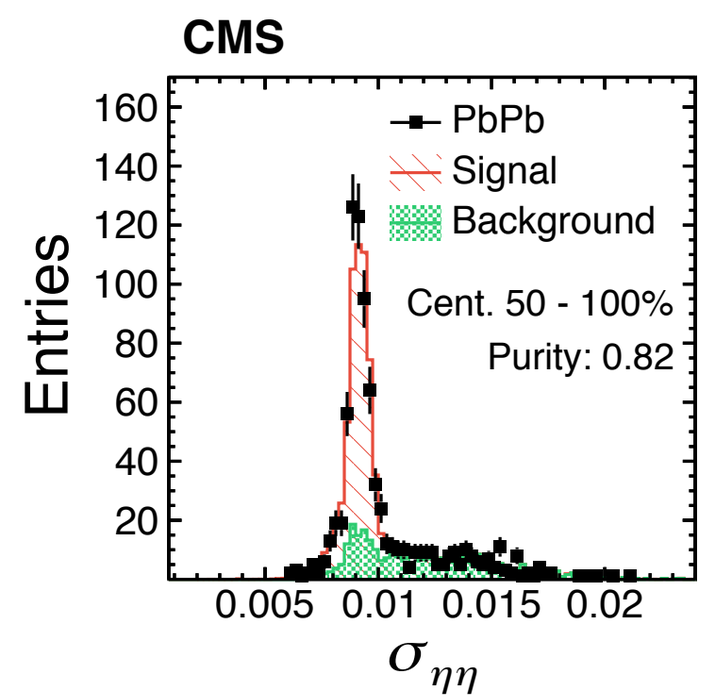
- Reconstruct photons, tracks, jets
- Correlate selected photons with all jets (back-to-back with the photon) within the event (inclusive jet measurement)
- Subtract backgrounds
  - Underlying event
  - Neutral meson decays
- Smear jet resolutions/ correct for resolution effects
  - Necessary for proper comparison between PbPb and pp data



BACKGROUND SUBTRACTION (NEUTRAL MESON DECAY)

- Photons produced from neutral meson decays mimic direct photons
  - Generally have wider shower shapes
  - Estimated and subtracted using a template fitting method
    - Signal template from simulation
    - Background template from data



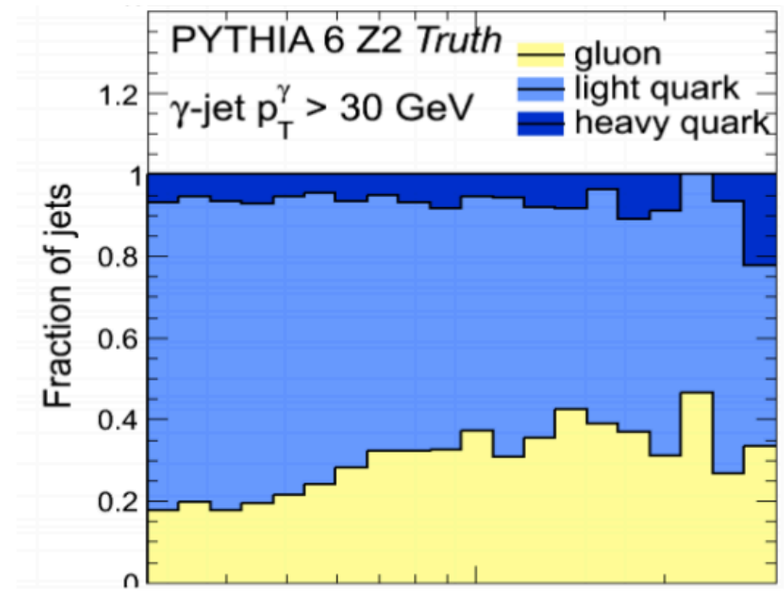


- Subtract distributions based on the relative fractions present

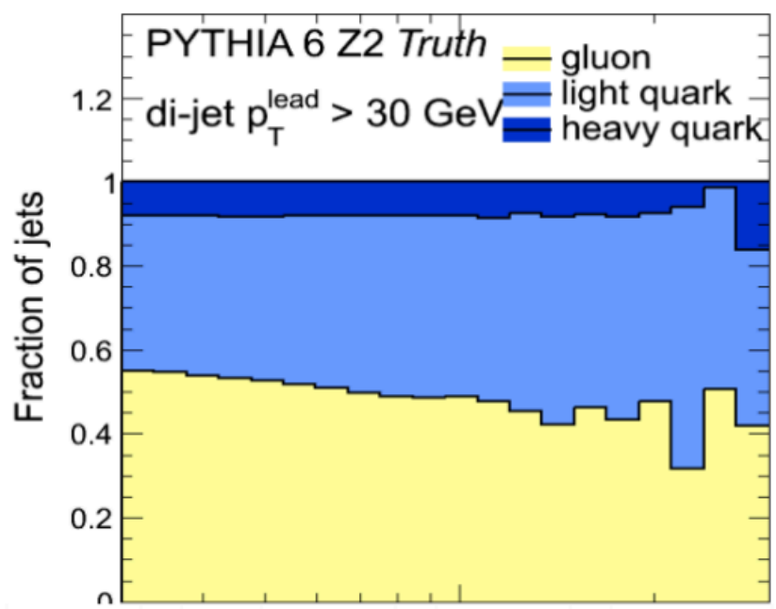
$$\text{Final result} = \frac{1}{\text{purity}} \times \text{Observable from all photon candidates} - \frac{1 - \text{purity}}{\text{purity}} \times \text{Observable from sideband photons}$$

QUARK/GLUON FRACTIONS

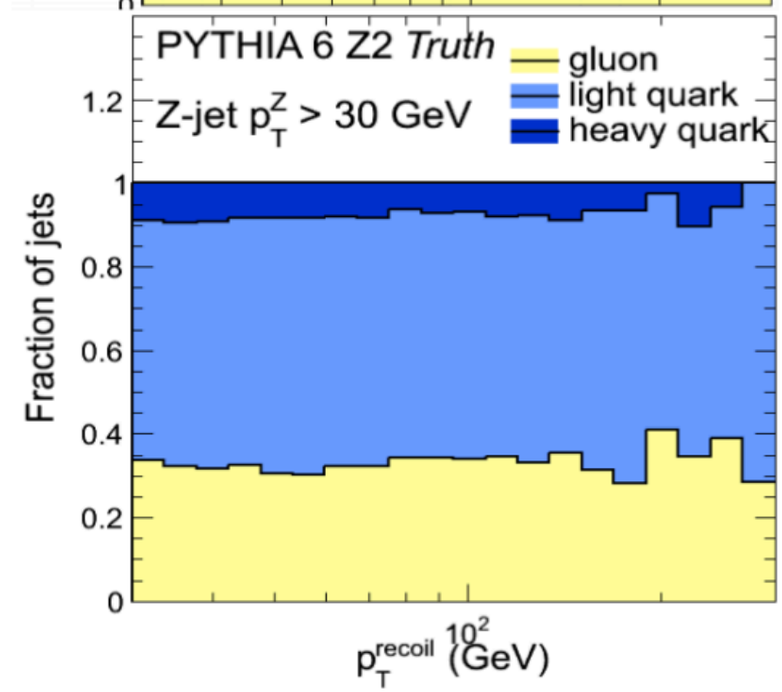
γ-jets



dijets



Z-jets

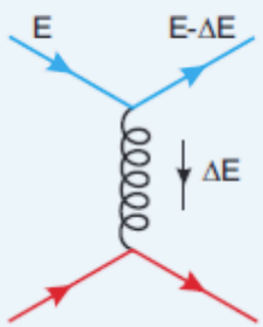


ENERGY LOSS MECHANISMS

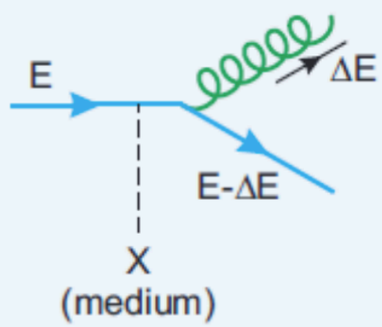
- Various models exist with different approaches to modelling the energy loss

Perturbative QCD
Weak coupling limit

Collisional energy loss

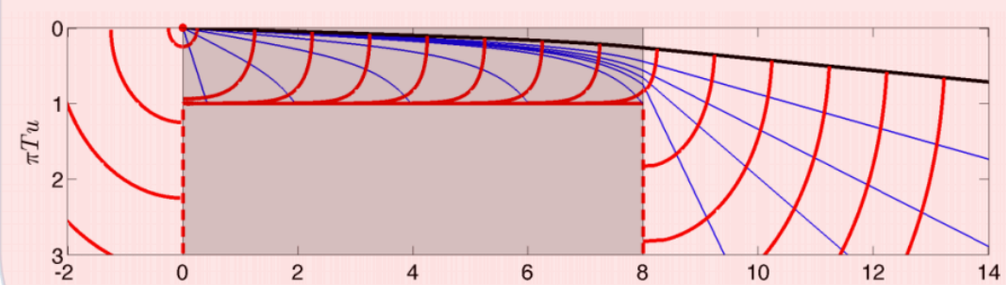


Radiative energy loss

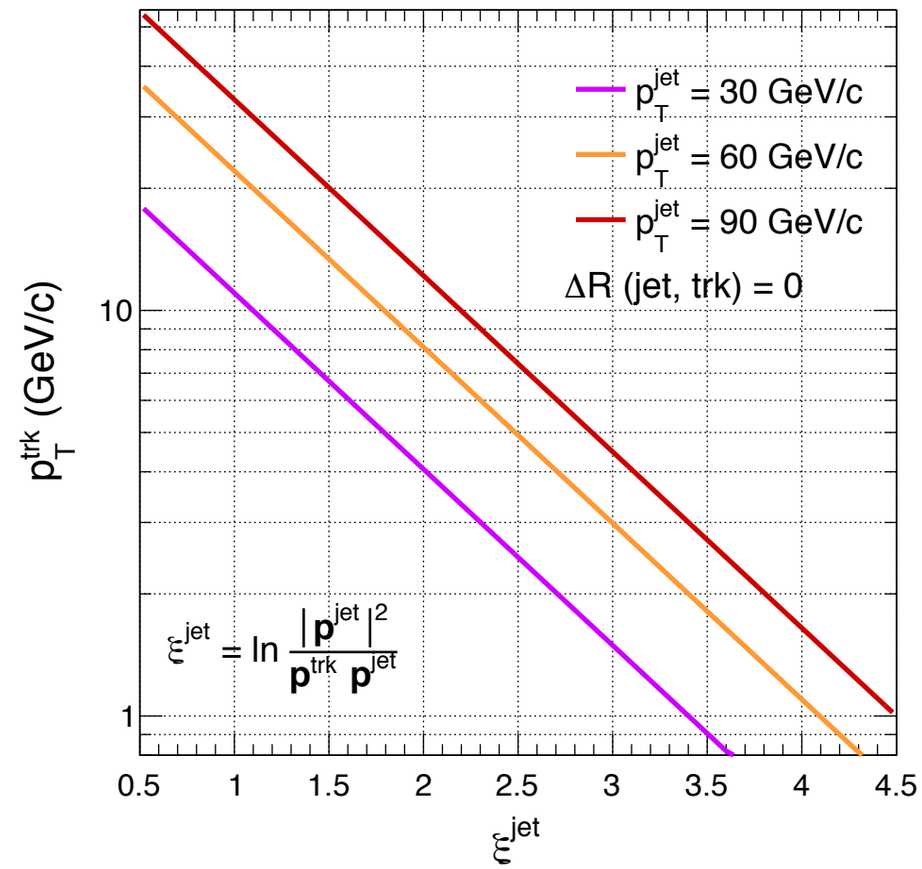


Holographic calculation
Strong coupling limit

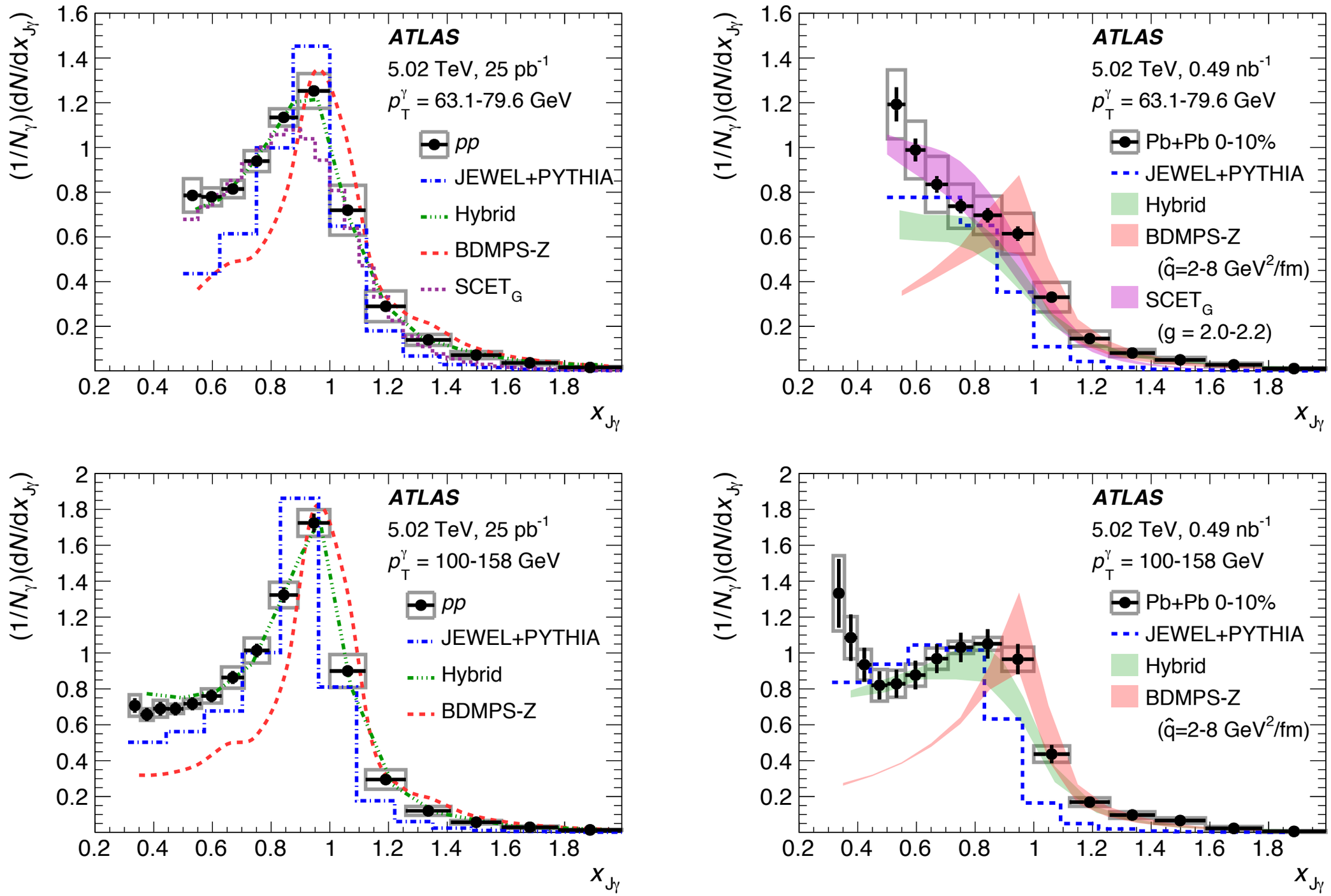
AdS/CFT "drag force"

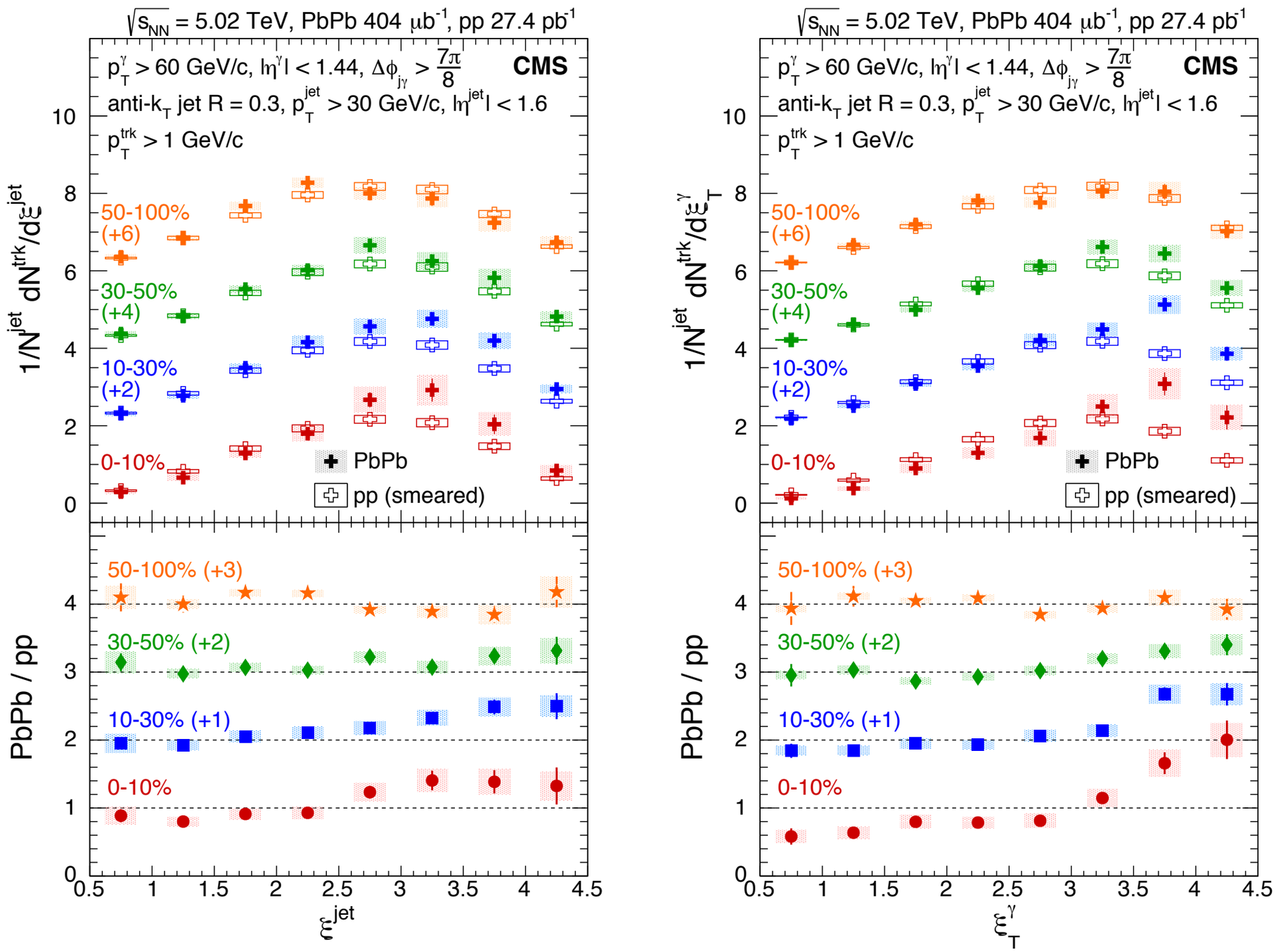


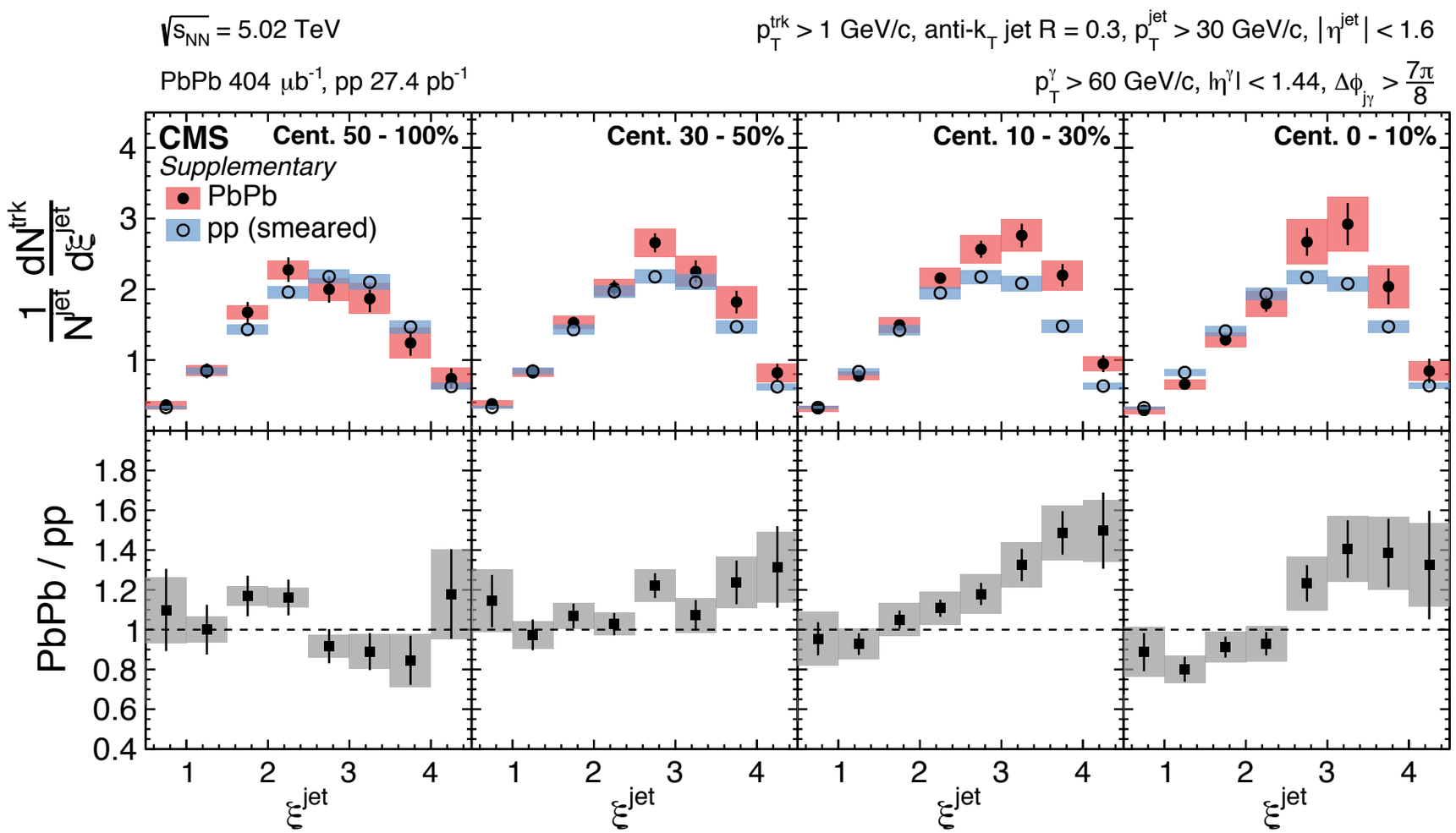
HADRON PT AND XI



ATLAS PHOTON-JET COMPARISON TO MODELS




$\sqrt{s_{NN}}$ = 5.02 TeV, PbPb 404 μb^{-1}, pp 27.4 pb^{-1}
p_T^{γ} > 60 GeV/c, $|\eta^{\gamma}|$ < 1.44, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$
CMS
anti-k_T jet R = 0.3, p_T^{jet} > 30 GeV/c, $|\eta^{jet}|$ < 1.6
p_T^{trk} > 1 GeV/c
50-100% (+6)
30-50% (+4)
10-30% (+2)
0-10%
PbPb
pp (smeared)
$1/N^{jet}\, dN^{trk}/d\xi^{jet}$
$1/N^{jet}\, dN^{trk}/d\xi_T^{\gamma}$
PbPb / pp
50-100% (+3)
30-50% (+2)
10-30% (+1)
0-10%
ξ^{jet}
ξ_T^{γ}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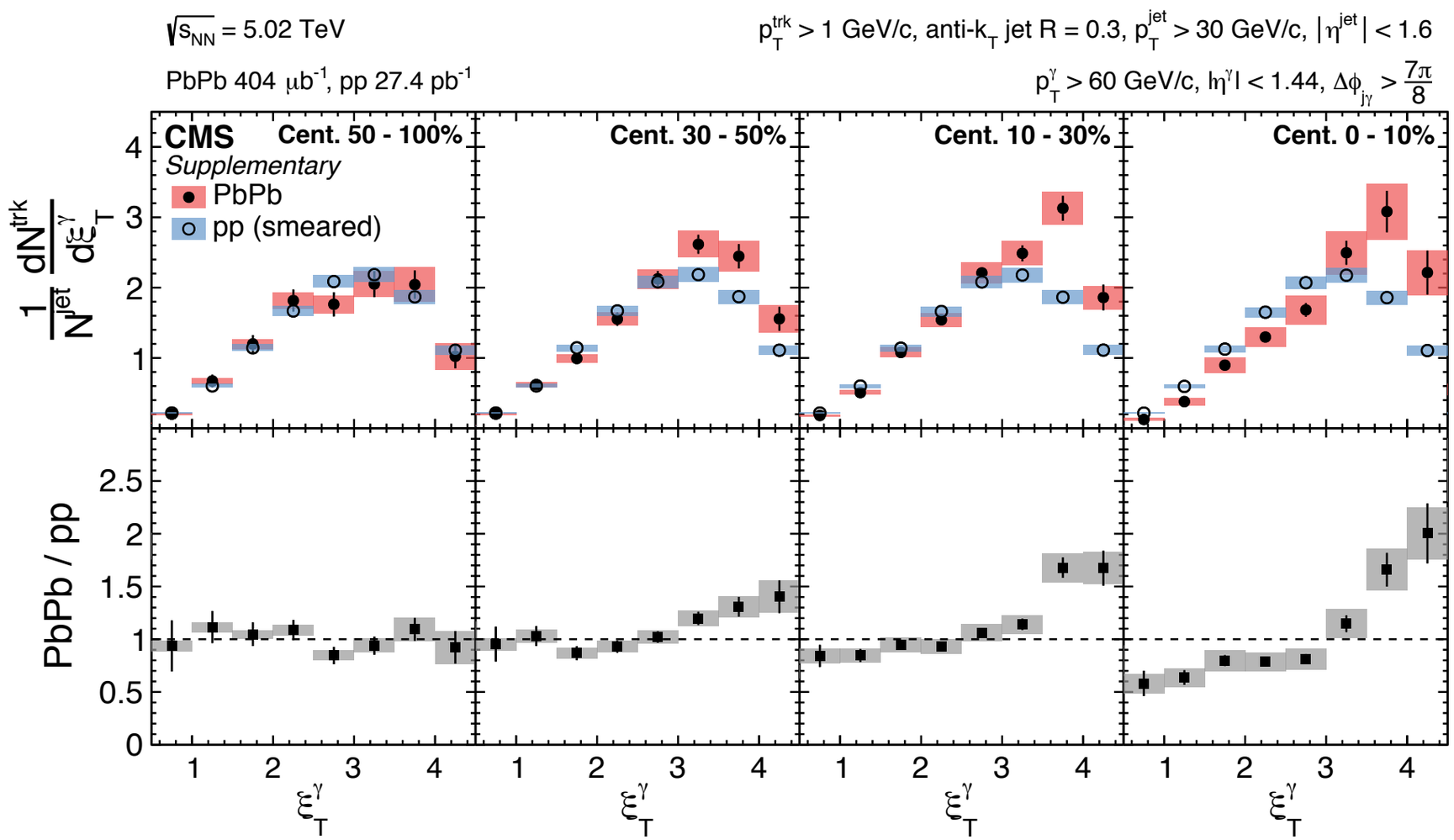
p_T^{γ} > 60 GeV/c, $|\eta^{\gamma}|$ < 1.44, $\Delta\phi_{j\gamma} > \frac{7\pi}{8}$
CMS
Supplementary
PbPb
pp (smeared)
Cent. 50 - 100%
Cent. 30 - 50%
Cent. 10 - 30%
Cent. 0 - 10%
$\frac{1}{N^{jet}}\frac{dN^{trk}}{d\xi^{jet}}$
PbPb / pp
ξ^{jet}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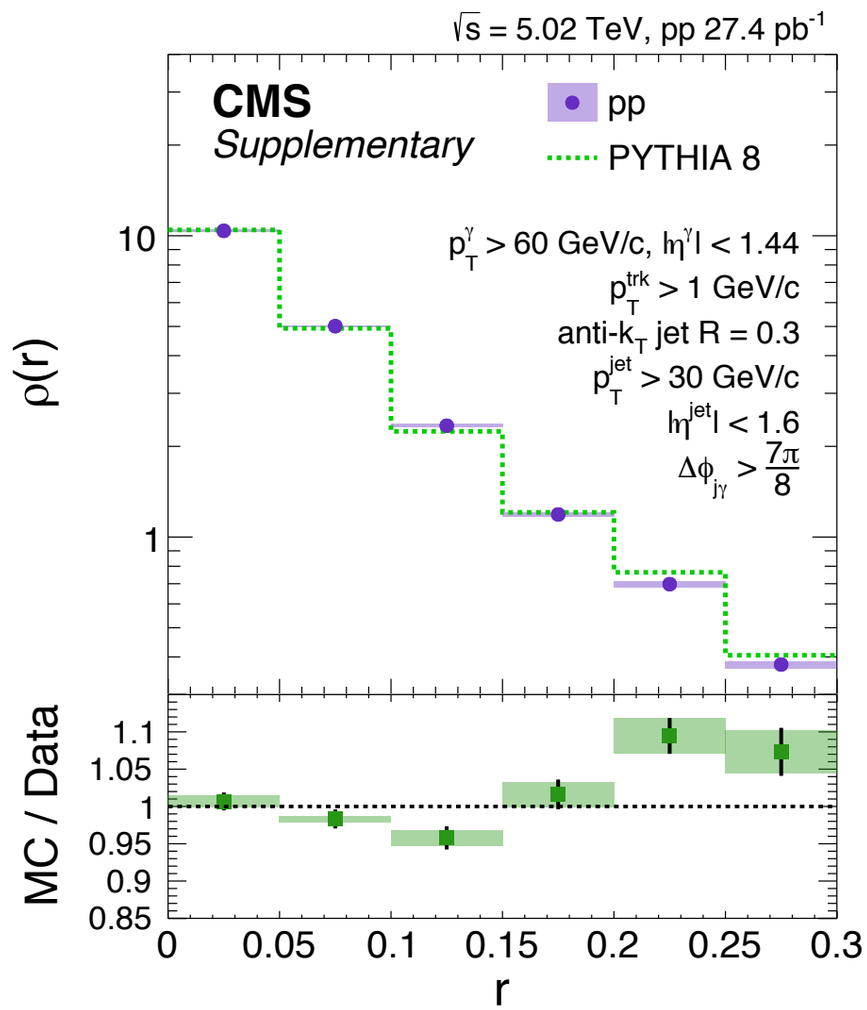
CMS
Supplementary
PbPb
pp (smeared)
Cent. 50 - 100%
Cent. 30 - 50%
Cent. 10 - 30%
Cent. 0 - 10%
$\frac{1}{N^{jet}}\frac{dN^{trk}}{d\xi_T^{\gamma}}$
PbPb / pp
ξ_T^{γ}


√s = 5.02 TeV, pp 27.4 pb-1
CMS
Supplementary
pp
PYTHIA 8
p_T^γ > 60 GeV/c, |η^γ| < 1.44
p_T^trk > 1 GeV/c
anti-k_T jet R = 0.3
p_T^jet > 30 GeV/c
|η^jet| < 1.6
Δφ_jγ > 7π/8
ρ(r)
MC / Data
r