Production of isolated photons and studies of photon-tagged jets in PbPb and pp at 5.02 TeV with CMS

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ICHEP 2022

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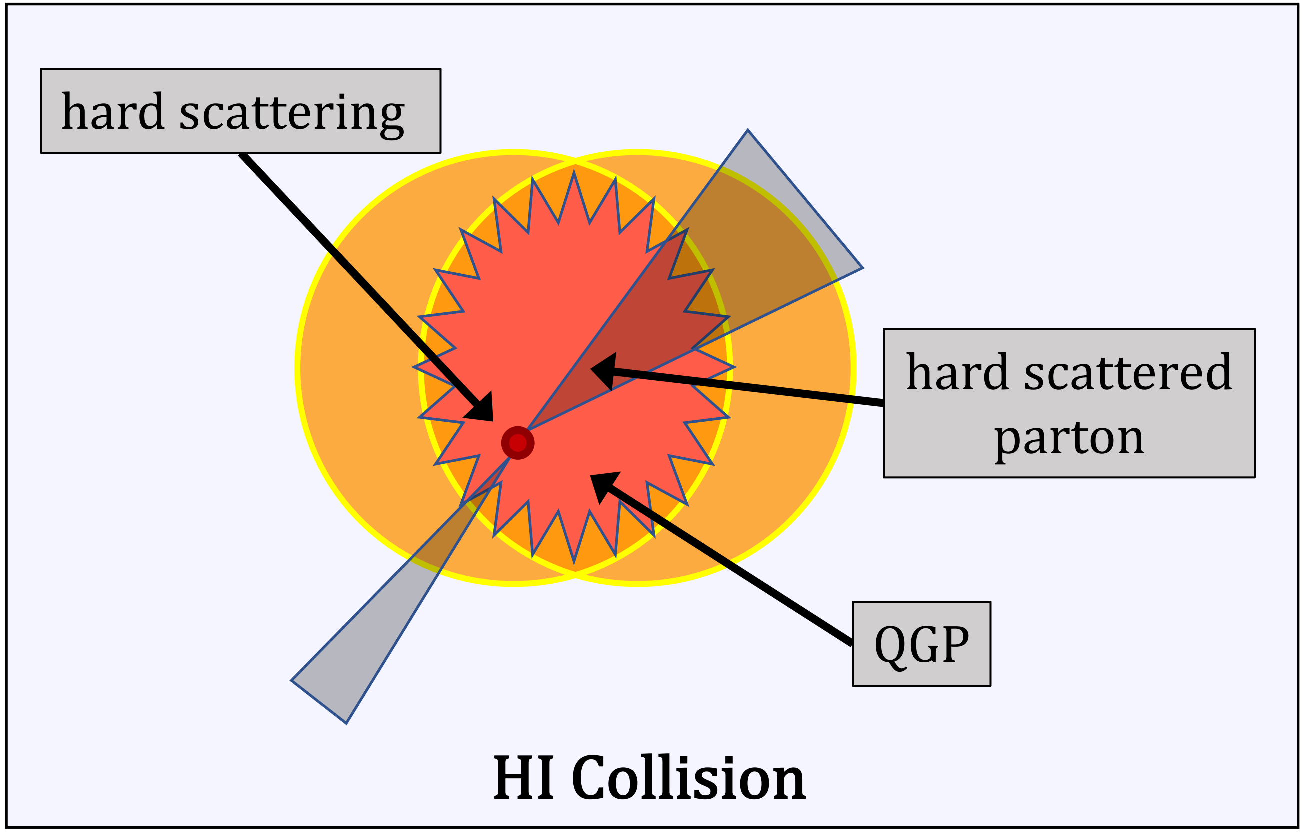
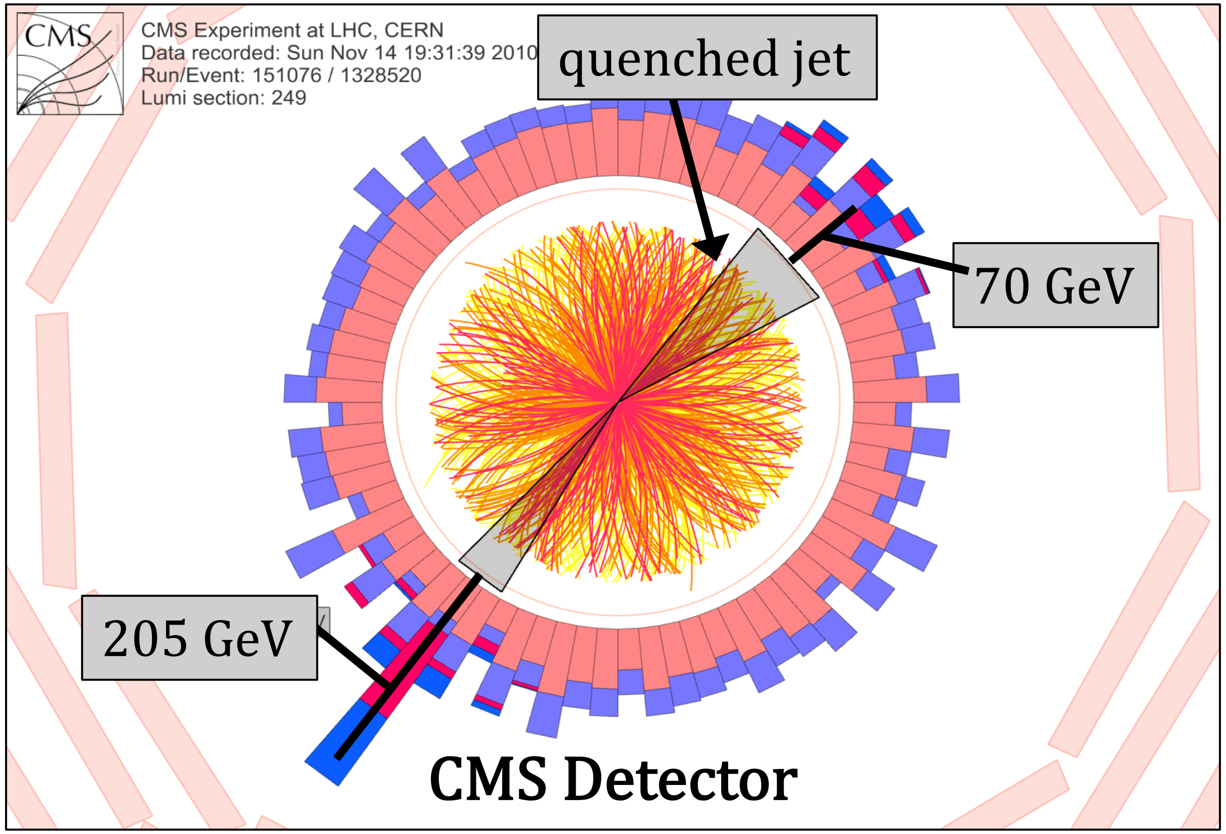
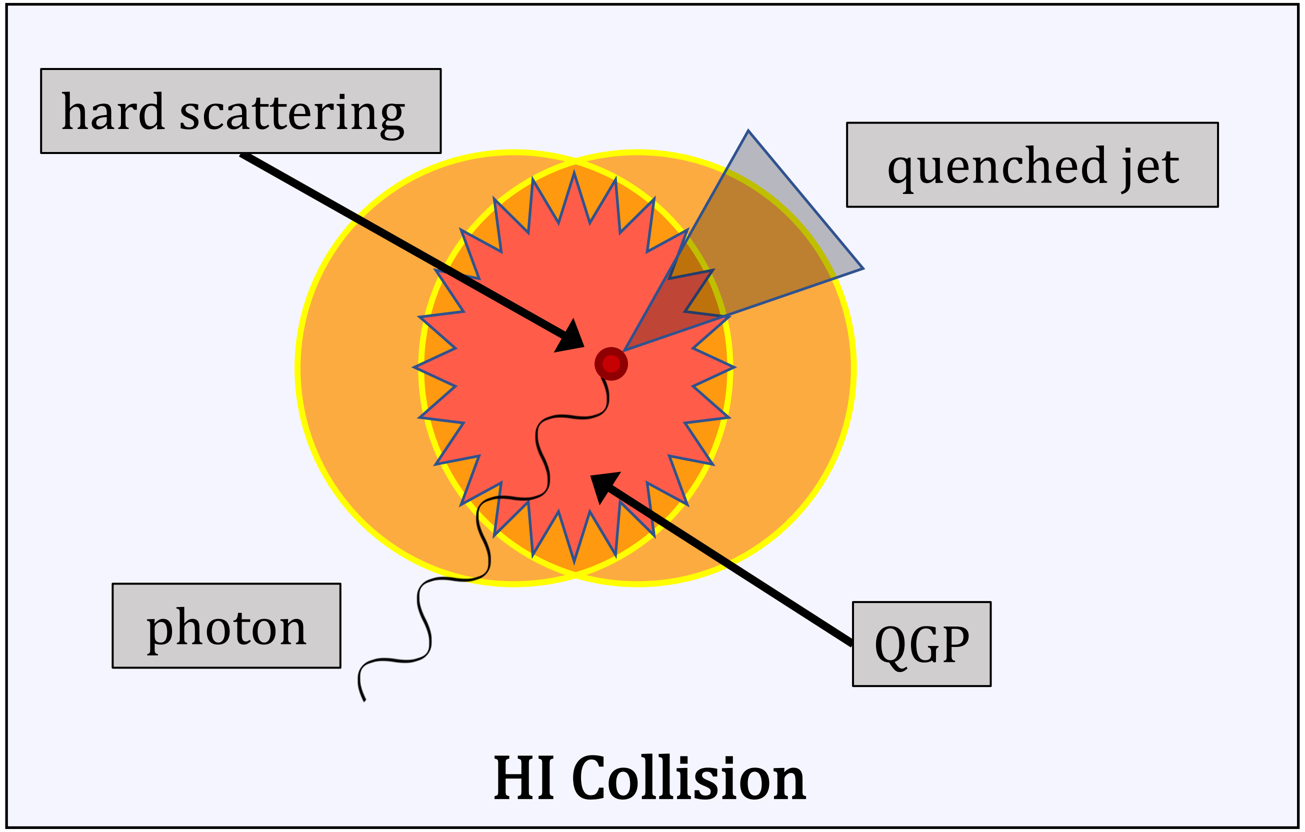
Jet quenching in heavy ion collisions





- QGP is formed when heavy ions collide
- Hard scattered partons interact with QGP and lose energy → **jet quenching**
- Studies of jet quenching can probe medium properties, such as transverse momentum broadening
- In dijet events there is a "surface bias" from jet p_T requirements, since both jets lose energy

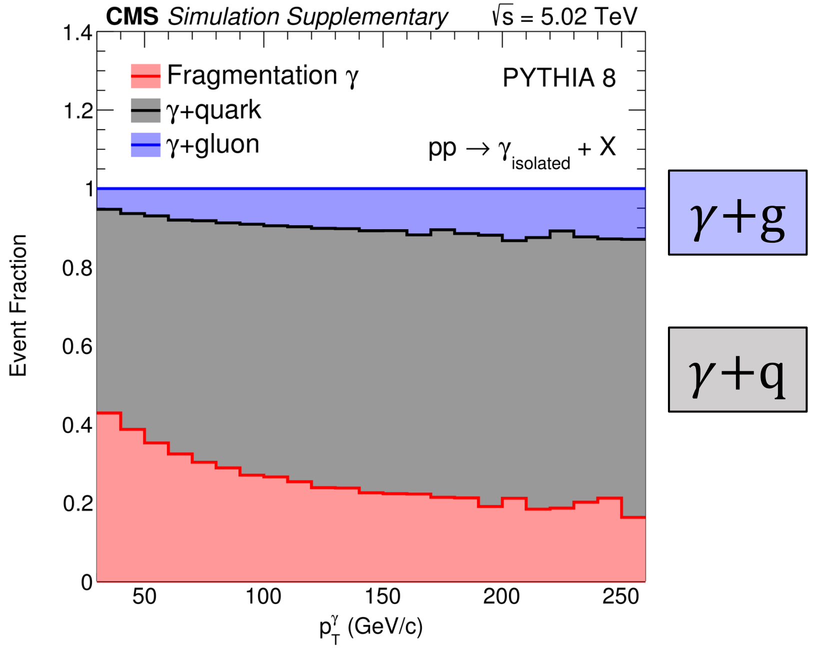
Using photon-tagged jets

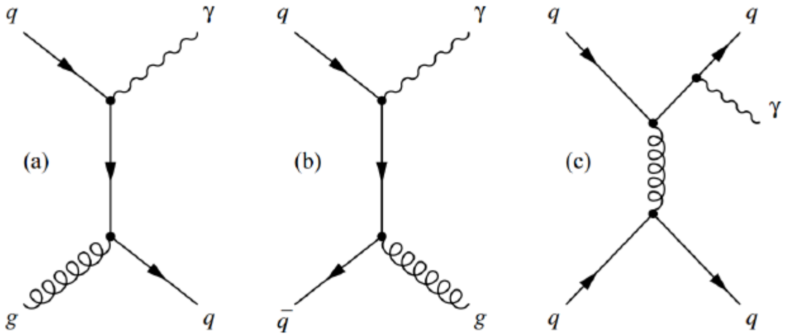


- Photon does not interact strongly with QGP

  => tags initial recoil parton p_T
- No surface bias from photon selection
- Good handle on q/g fraction of recoil parton

Composition of Events with Isolated Photons





PRL 122 (2019) 152001

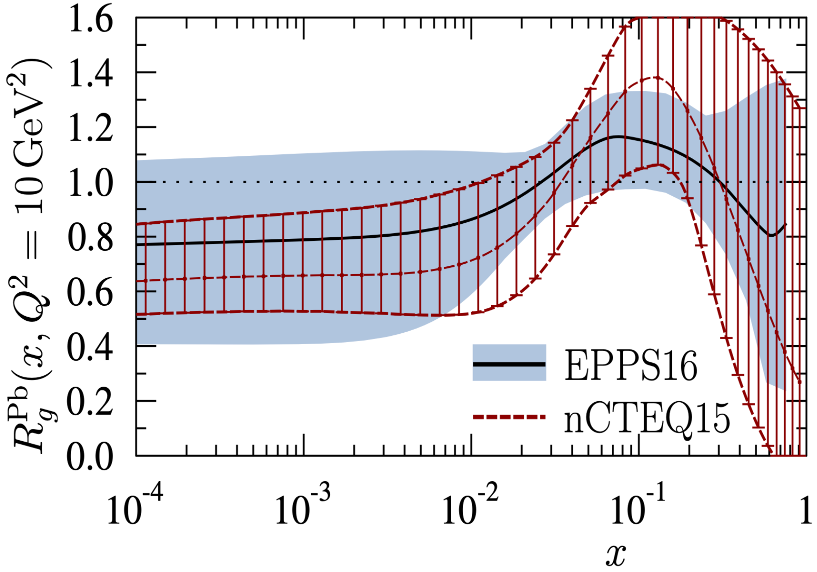
Isolated photon introduction

Isolated photons are those with generator-level energy < 5 GeV in $\Delta R = 0.4$ cone

Measurement of isolated photon spectrum and R_{AA}

- Establish that we understand photon production in PbPb collisions
- Verify that photons are not significantly affected by the QGP
- Provides a direct way to test perturbative QCD and nPDFs

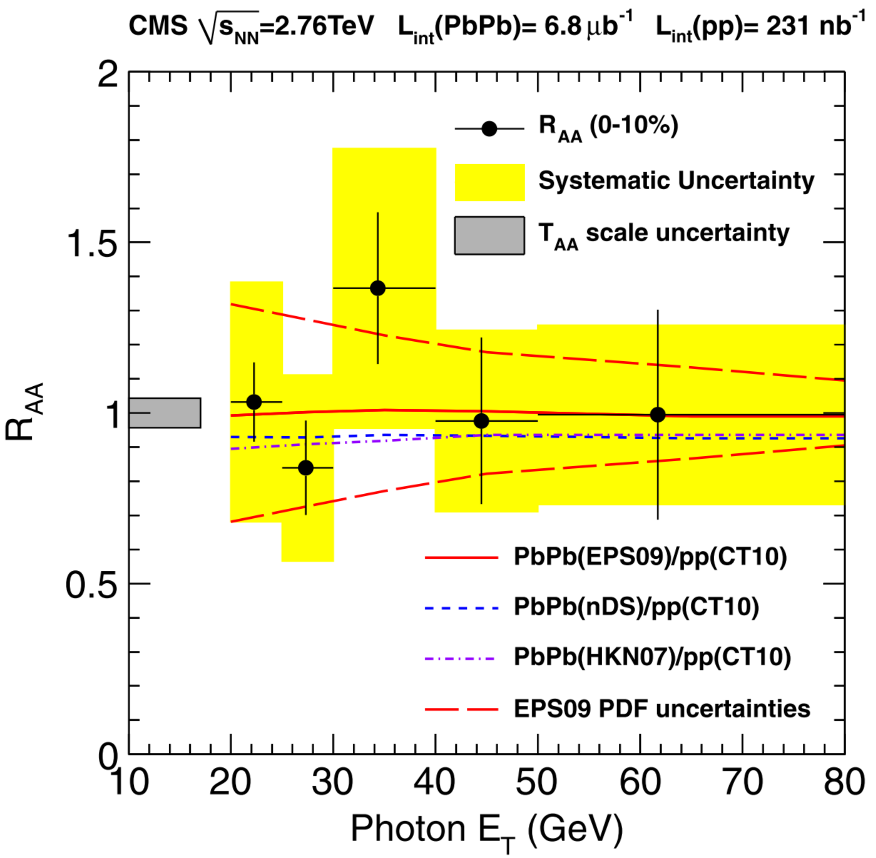
Gluon nPDF Modification



$$R_{AA} = \frac{1}{< T_{AA} >} \frac{1}{N_{MB}} \frac{d^2N^{\gamma}_{PbPb}/dE^{\gamma}_{T}d\eta}{d^2\sigma^{\gamma}_{pp}/dE^{\gamma}_{T}d\eta}$$

- $R_{AA} < 1 \Rightarrow$ suppression
- $R_{AA} = 1 \Rightarrow$ compatible with PP
- $R_{AA} > 1 \Rightarrow$ enhancement

CMS 2.76 TeV Isolated Photon R_{AA}



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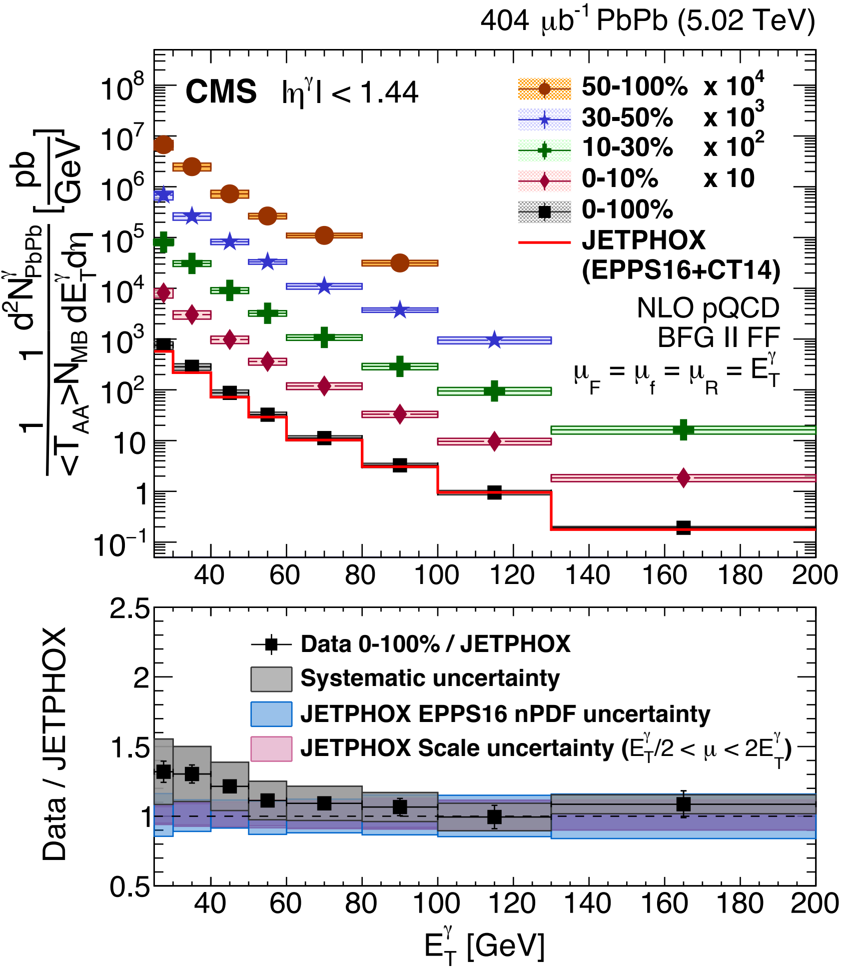
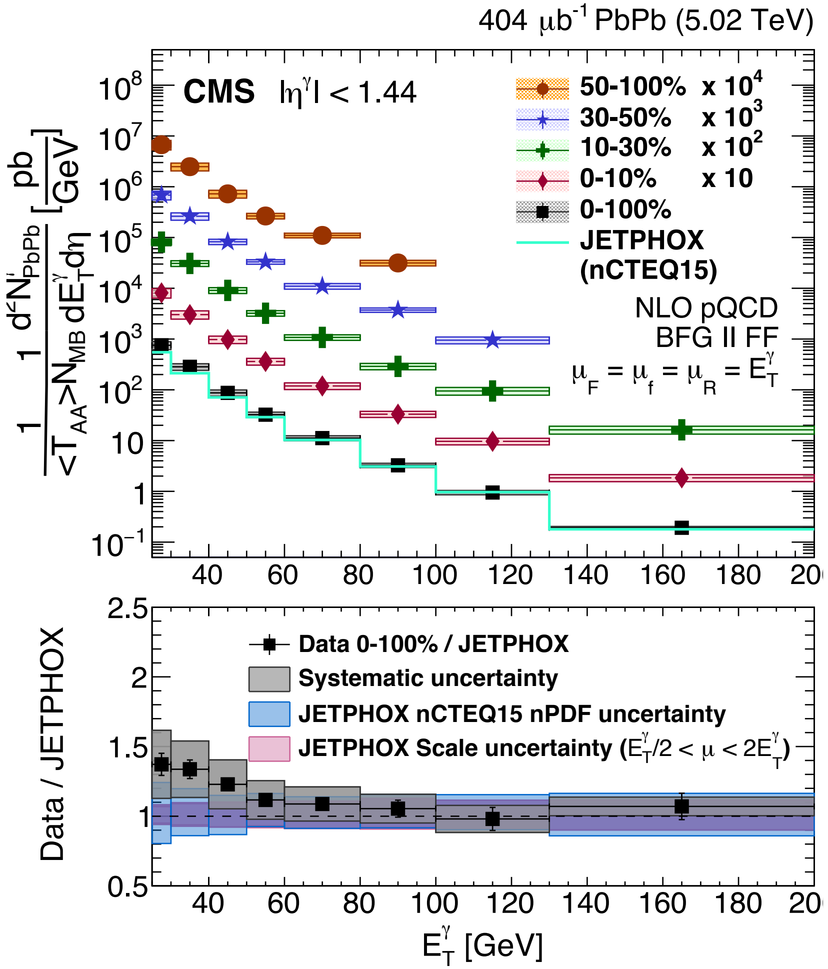
PLB 710 (2012) 256–277

Isolated photon spectra

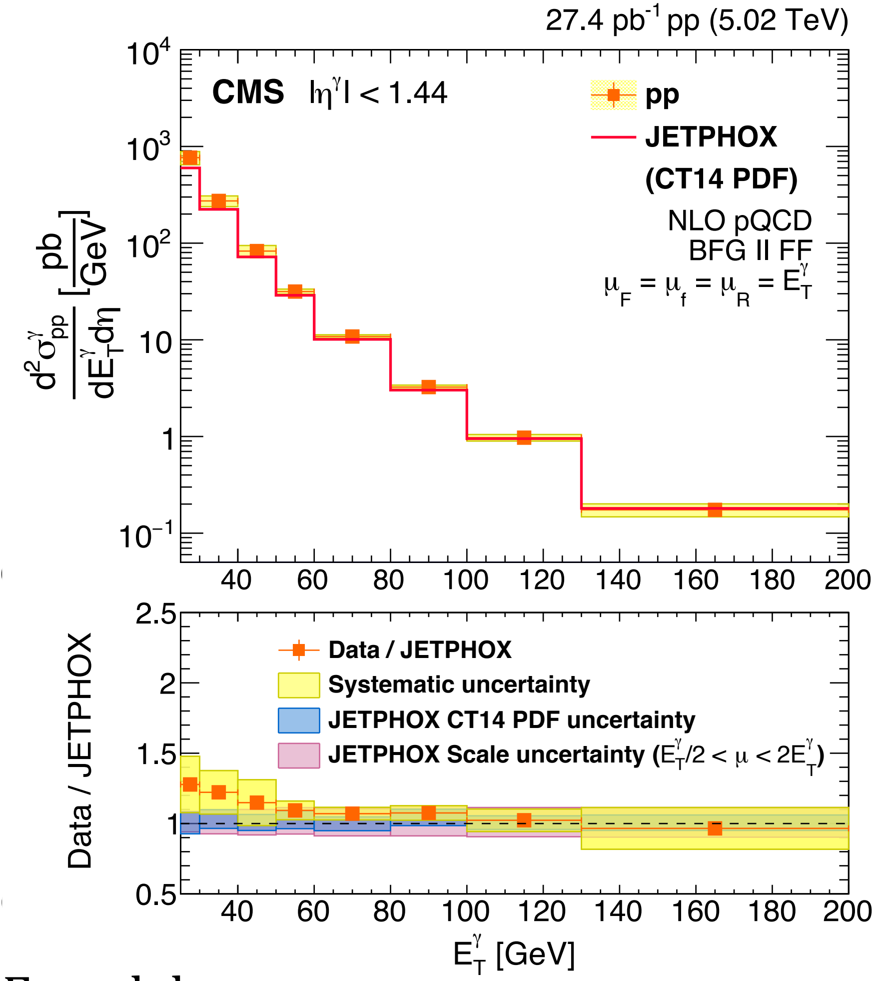
PbPb and JETPHOX with EPPS16+CT14 nPDFs



PbPb and JETPHOX with nCTEQ15 nPDFs



PP and JETPHOX with CT14 PDFs



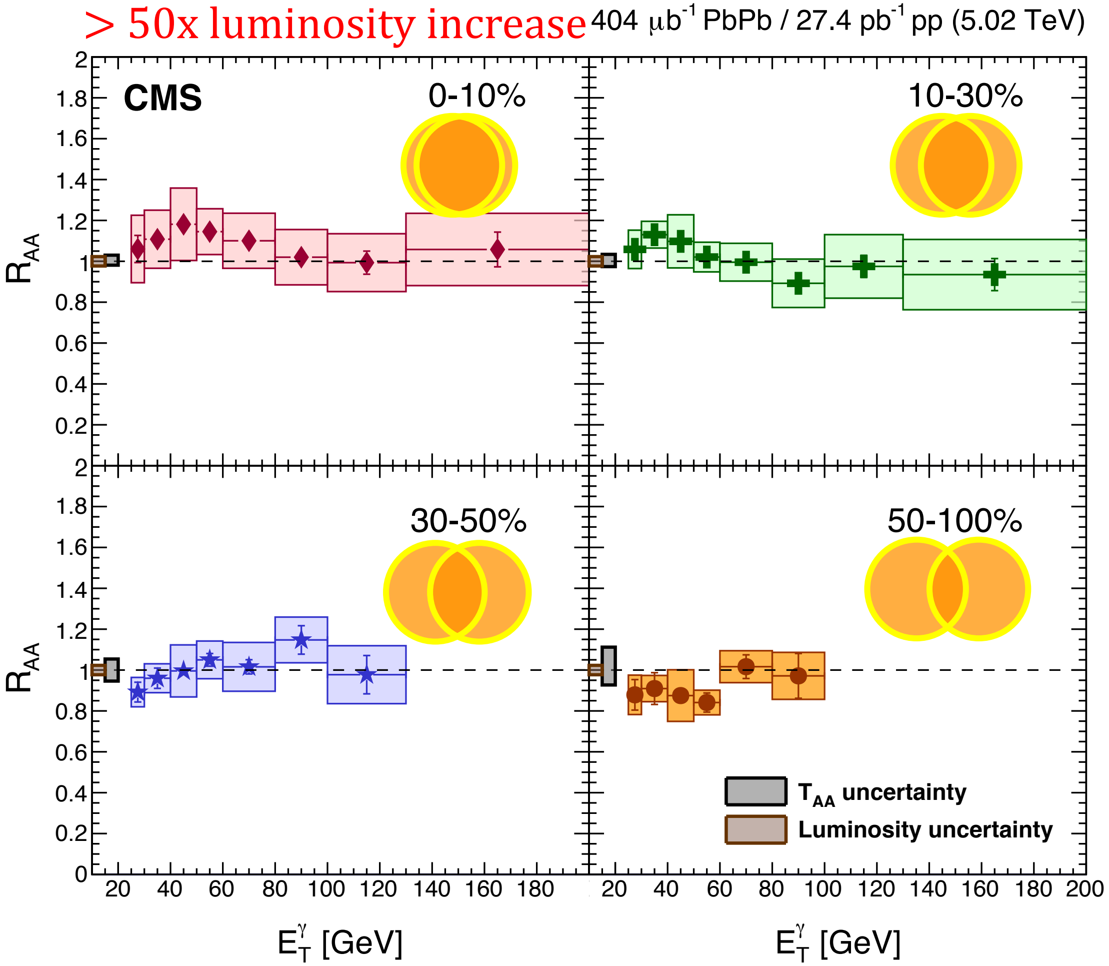
- PbPb data are consistent with JETPHOX predictions using both nPDF models

JHEP 2020, 116 (2020)

Isolated photon R_{AA}

5.02 TeV Isolated Photon R_{AA}

> 50x luminosity increase



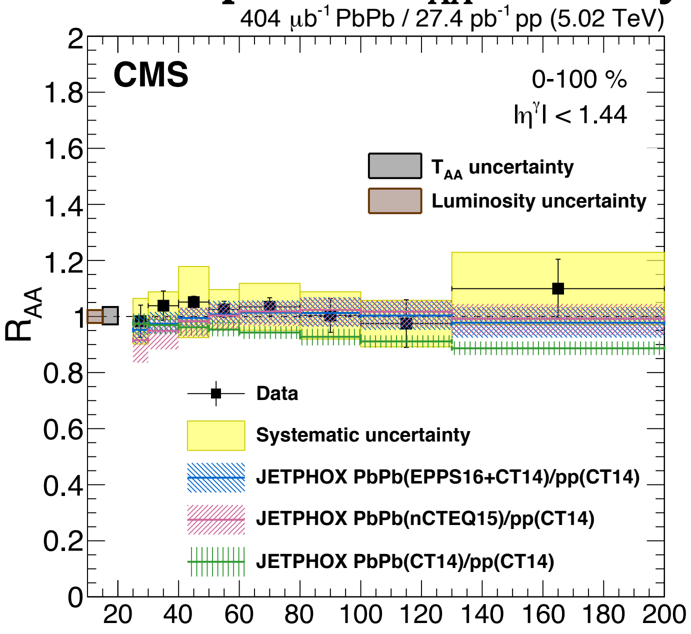
PLB 710 (2012) 256–277

- Dramatic improvement over previous measurement
- Photon production in PbPb is consistent scaled PP
  - Photons do not interact significantly in the QGP
  - Isolated photons can tag initial recoiling jet energy
- Need to reduce systematics to reach next level of accuracy

$$R_{AA} = \frac{1}{< T_{AA} >} \frac{1}{N_{MB}} \frac{d^2 N^{\gamma}_{PbPb}/dE^{\gamma}_T d\eta}{d^2 \sigma^{\gamma}_{pp}/dE^{\gamma}_T d\eta}$$

- $R_{AA} < 1 \Rightarrow$ suppression
- $R_{AA} = 1 \Rightarrow$ compatible with PP
- $R_{AA} > 1 \Rightarrow$ enhancement

Isolated photon R_{AA} + theory



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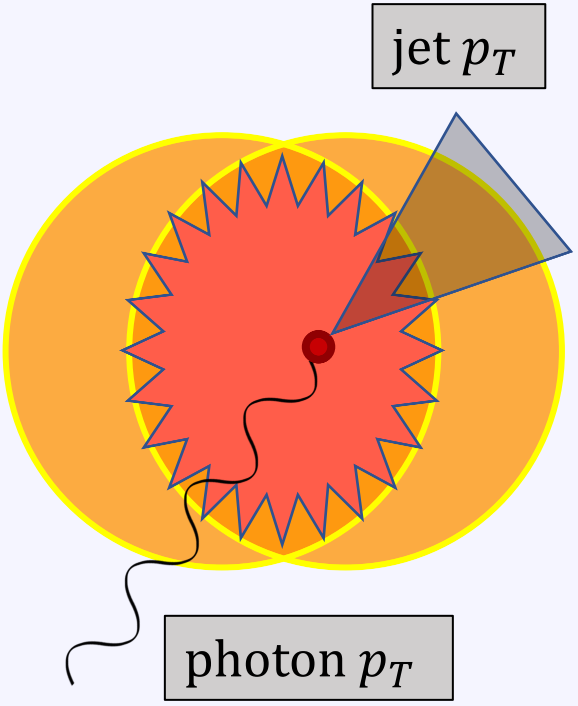
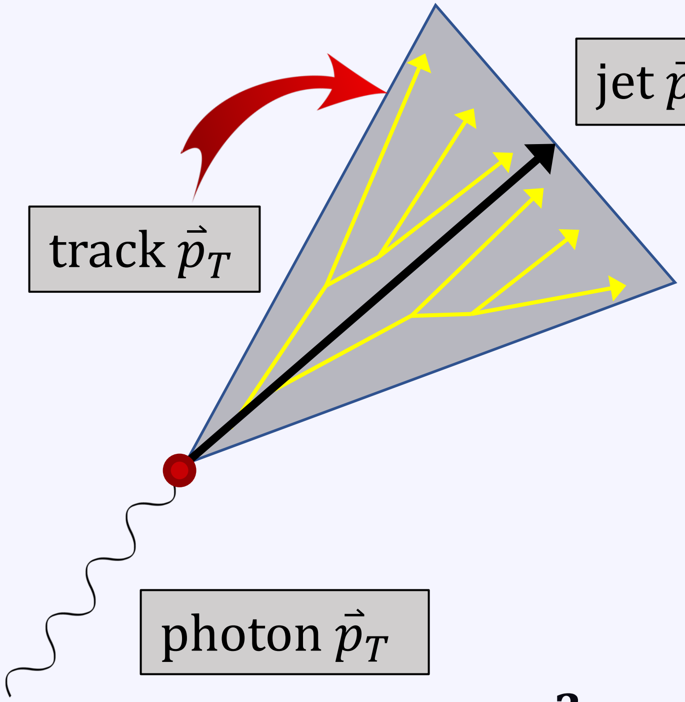
Photon-tagged jet results

Momentum Imbalance



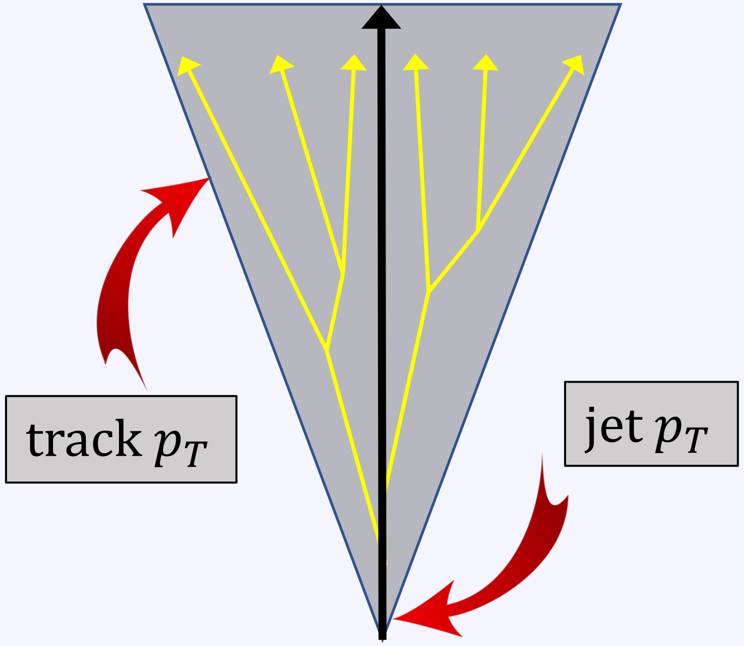
$$x_{jet,\gamma} = p_T^{jet}/p_T^{\gamma}$$

Fragmentation Function



$$\xi_T^{\gamma} = \ln \frac{-\left|\vec{p}_T^{\,\gamma}\right|^2}{\vec{p}_T^{\,trk} \cdot \vec{p}_T^{\,\gamma}}$$

Radial Momentum Density

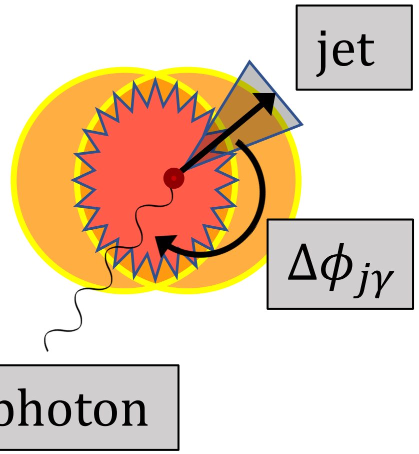


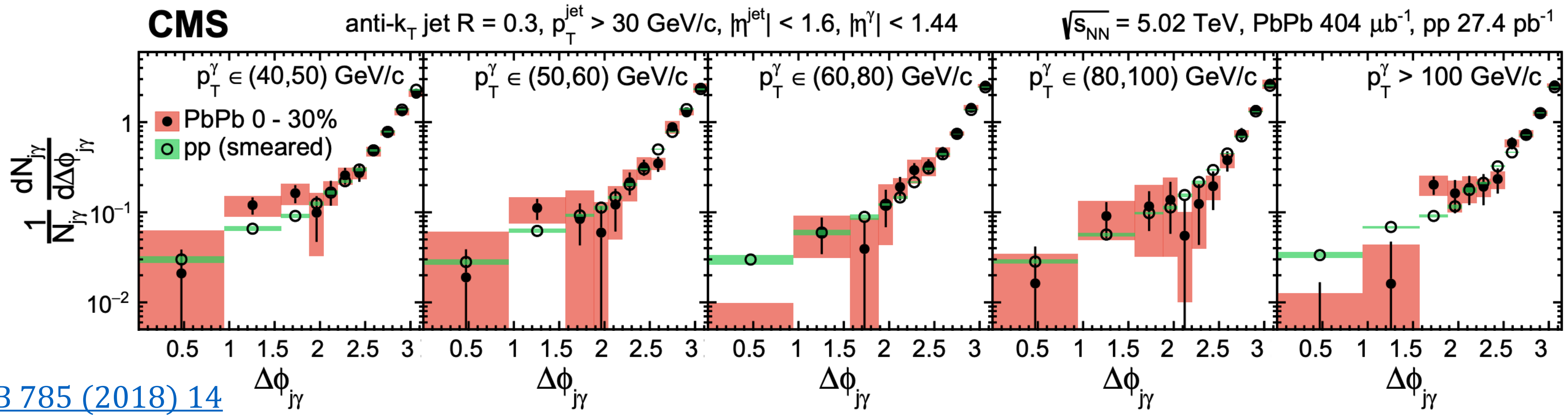
$$r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

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

Photon-jet azimuthal correlations

- Look at alignment of photon and recoiling jet
- PbPb result consistent with smeared PP data
- No significant modification at large angles
- No near side enhancement
- Is p_T broadening overshadowed by initial state radiation?

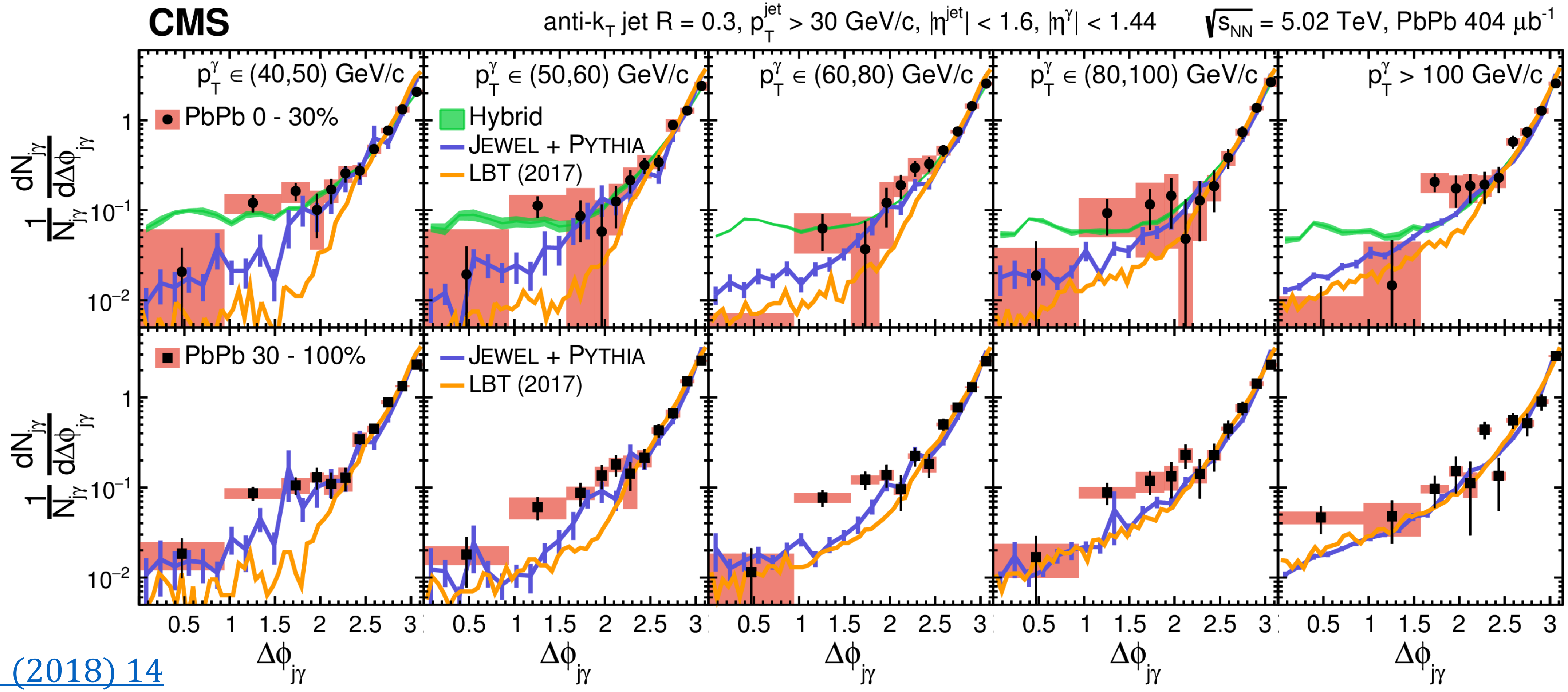




PLB 785 (2018) 14

Photon-jet azimuthal correlations theory

- The models don't show significant broadening effects compared to PP – ISR overshadows the effect?
- Will need increased statistics at small $\Delta\phi_{j\gamma}$ to constrain theory and see if we detect p_T broadening



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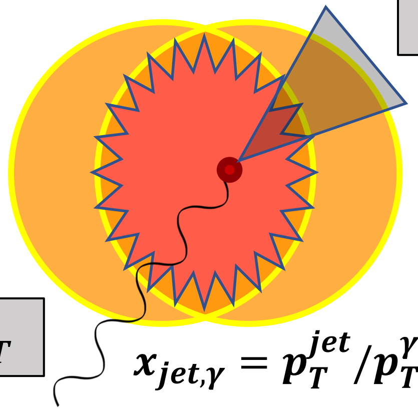
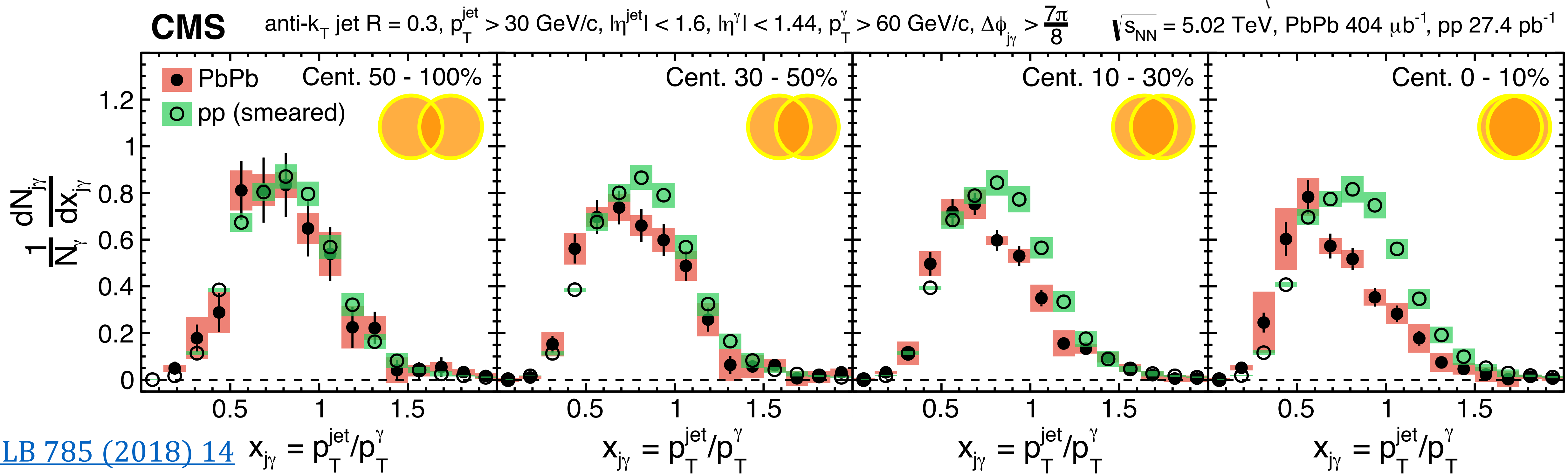
Photon-jet momentum imbalance

- Select jets with $p_T^{jet} > 30$ GeV and $\Delta\phi_{j\gamma} > 7\pi/8$
- Mean and yield shift to lower values in PbPb due a larger fraction of jets losing energy falling below the acceptance threshold
- Jets may lose more energy in central collisions because they travel longer or because QGP is denser





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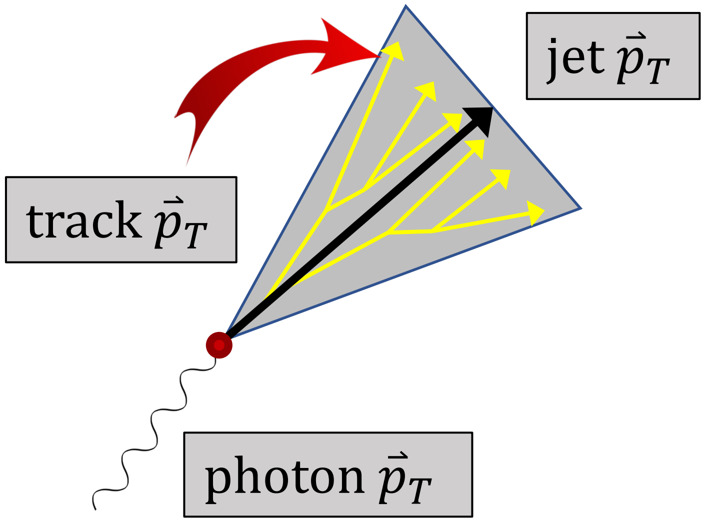
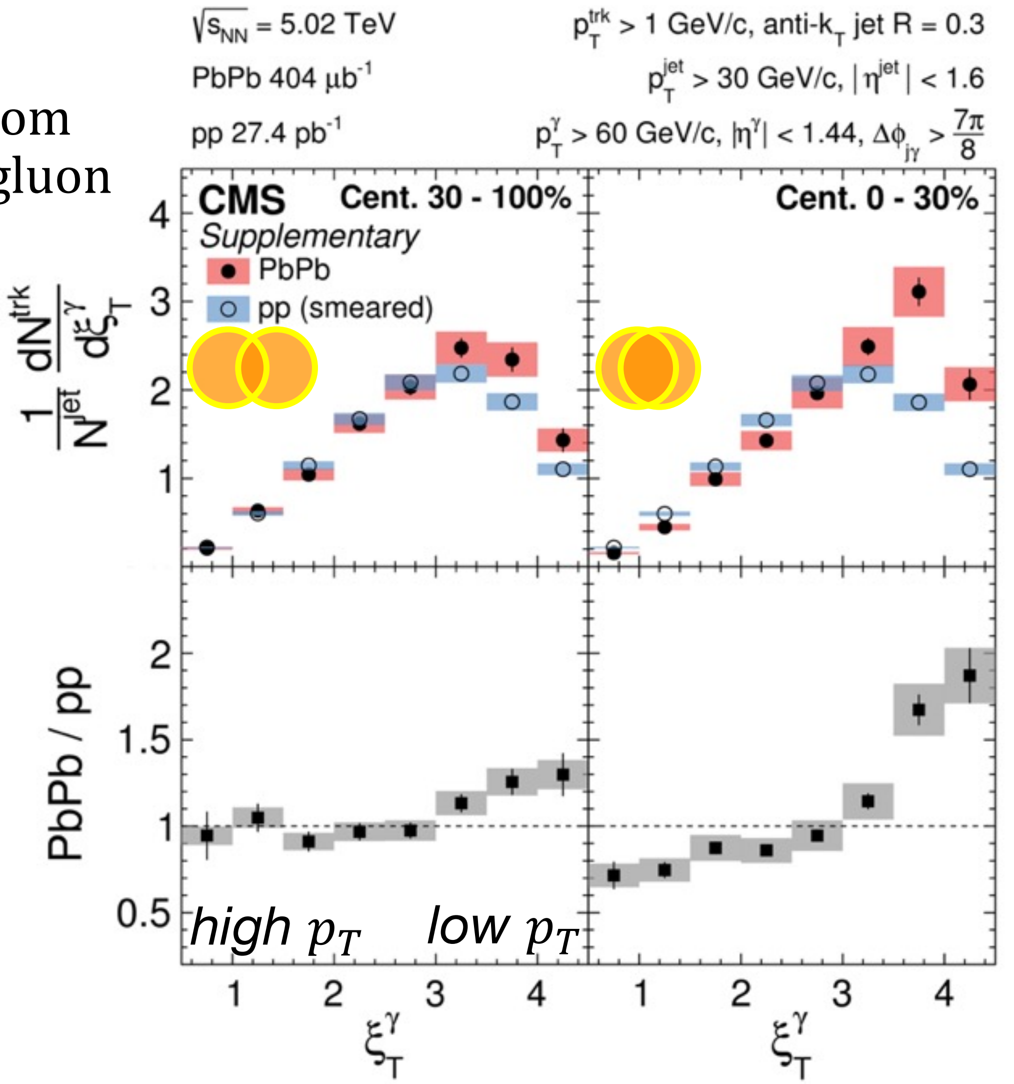
Photon-tagged jet fragmentation function

- ξ_T^γ characterizes fragmentation wrt photon kinematics
- Enhancement of low p_T particles and which may originate from medium response, higher p_T particles losing energy, or soft gluon radiation
- Depletion of high p_T particles in central collisions is direct evidence of jet quenching
- More significant effect than ξ^{jet} due to jet quenching effects



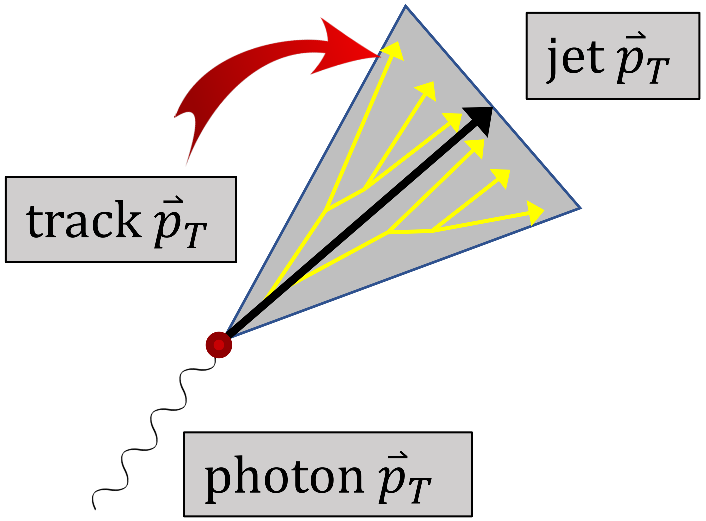
$$\xi_T^\gamma = \ln \frac{-\left|\vec{p}_T^{\,\gamma}\right|^2}{\vec{p}_T^{\,trk} \cdot \vec{p}_T^{\,\gamma}}$$



PRL 121 (2018) 242301

Photon-tagged jet fragmentation function theory

- Small excess of low p_T particles and depletion of high p_T particles
- Hybrid and CoLBT-hydro describe trend, both include medium back-reaction
- Back reaction improves agreement of Hybrid with data, indicating medium recoil is crucial to capture data



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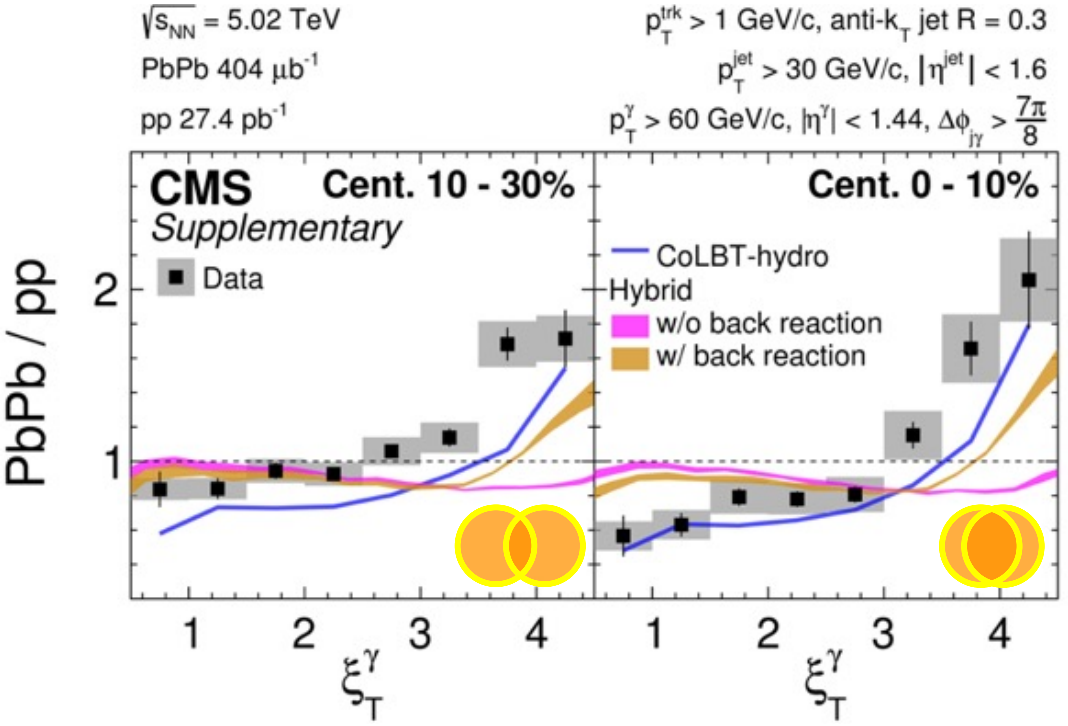
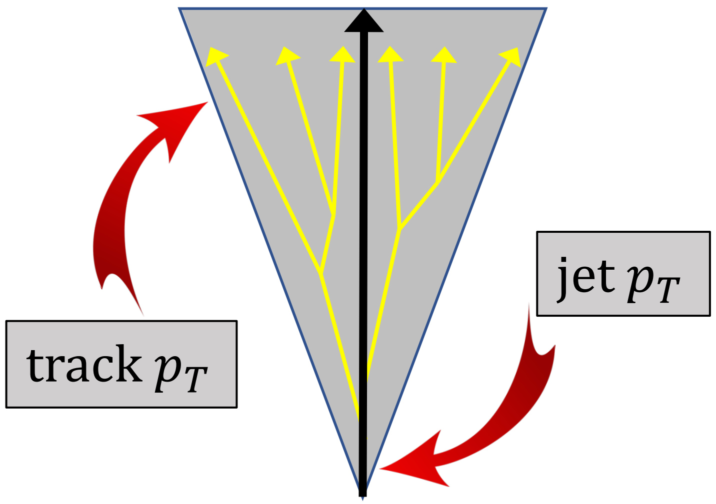


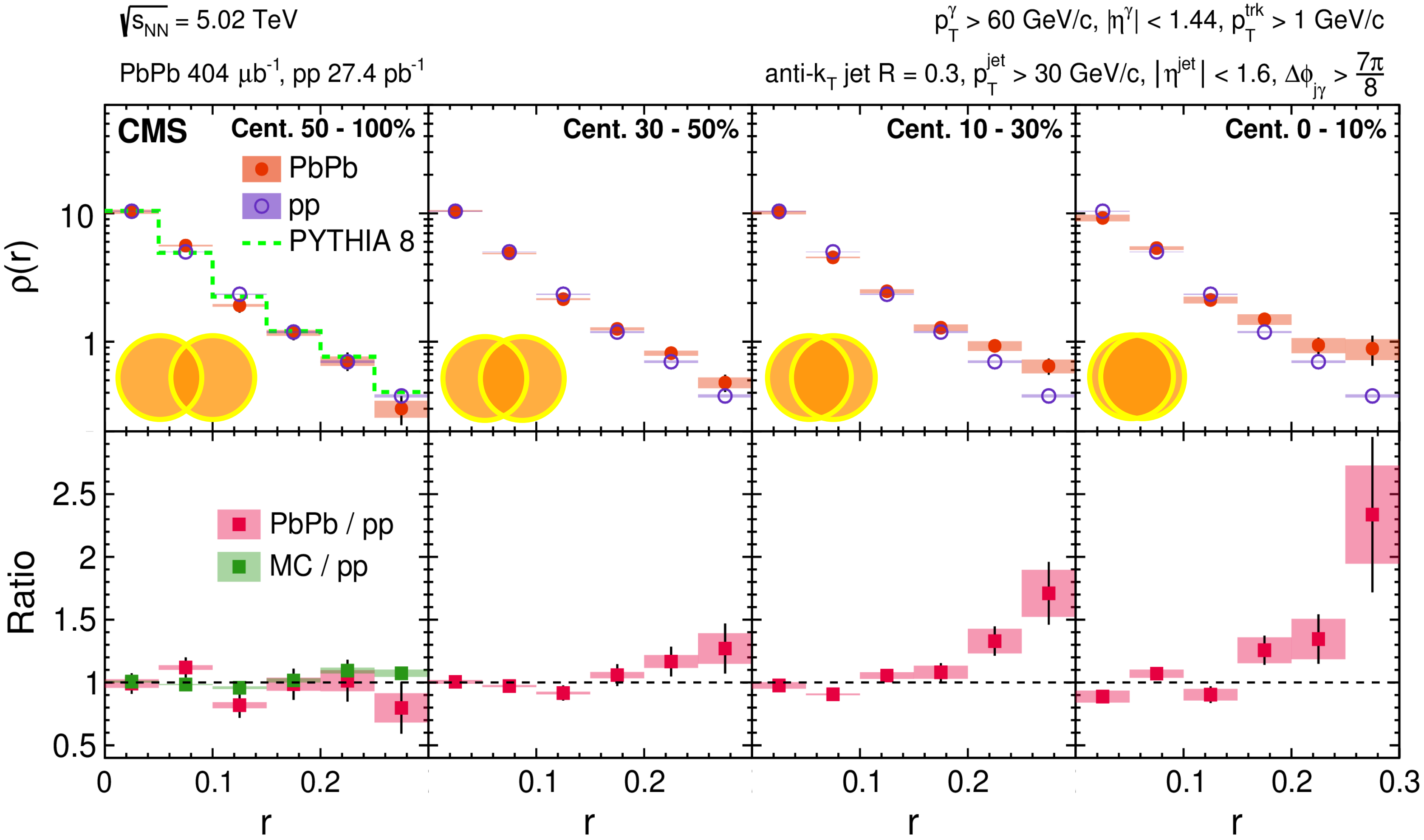
[PRL 121 (2018) 242301]

Photon-tagged jet radial momentum density



$$r = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

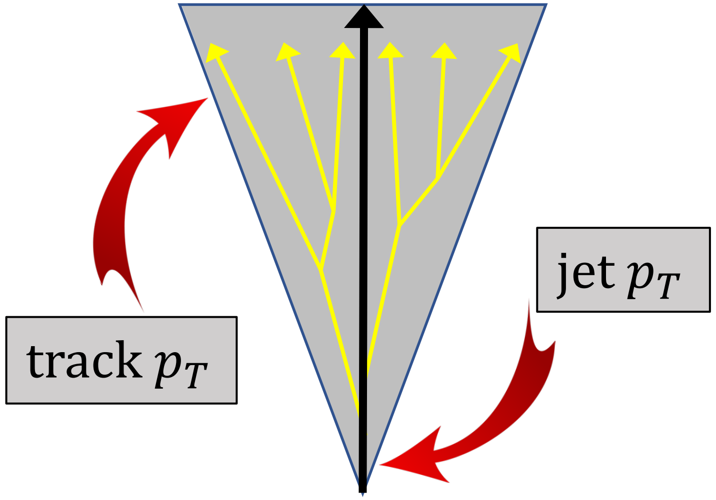
$$\boldsymbol{\rho(r)} = \frac{1}{\delta r} \frac{\sum_{jets} \sum_{r_a<r<r_b} p_T^{trk}/p_T^{jet}}{\sum_{jets} \sum_{0<r<r_f} p_T^{trk}/p_T^{jet}}$$



- Shows how the how the jet pT is distributed transverse to the jet axis, in both systems bulk is in core
- Small relative modification of jet core & enhancement of particles away from jet axis → broadening

PRL 122 (2019) 152001

Photon-tagged jet radial momentum density theory



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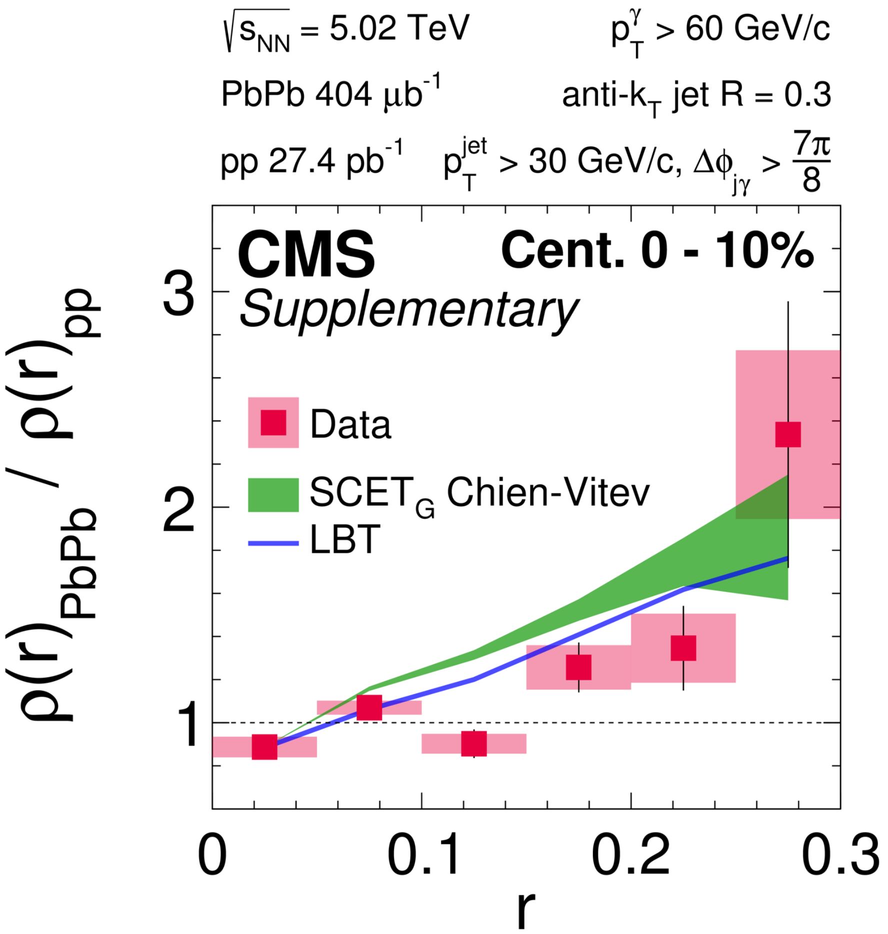


$SCET_G$
- EFT of QCD
- Glauber gluons mediate medium-jet interactions
- Includes medium modification but not medium response

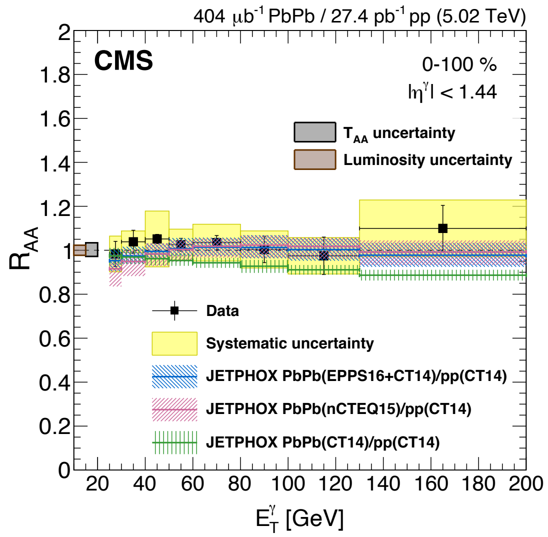
LBT
- Monte Carlo model
- Includes medium response

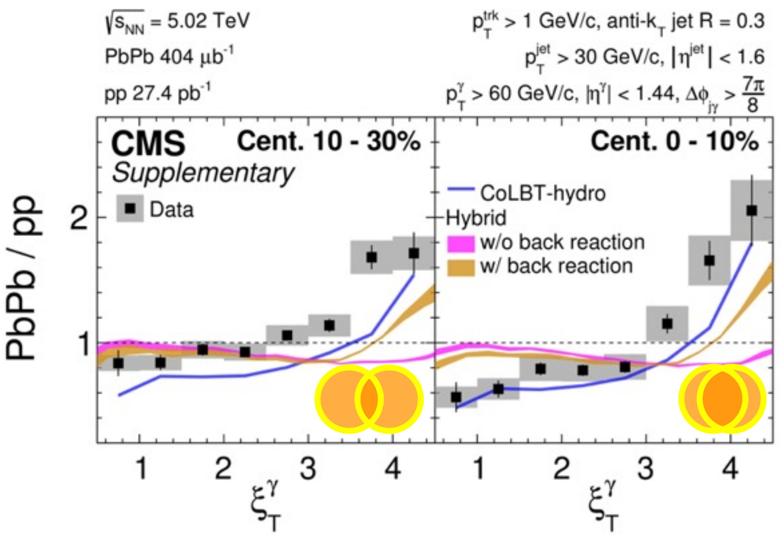
- Both models describe small relative modification of core & enhancement of particles away from jet axis

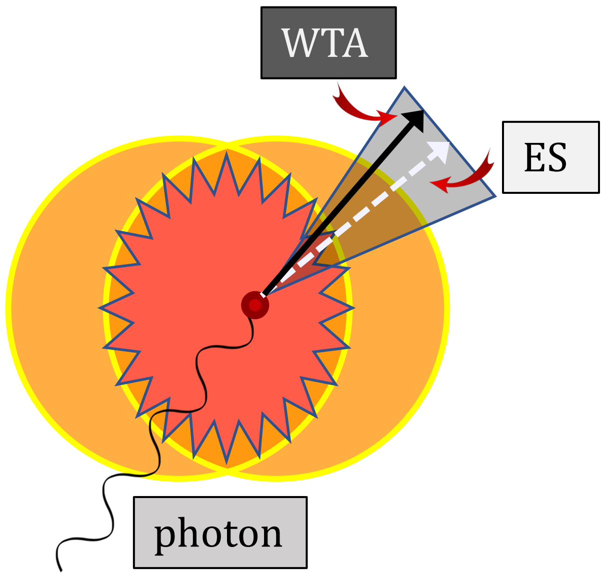
PRL 122 (2019) 152001

Summary

- Isolated photon production in PbPb events is not significantly modified by the QGP
  - Isolated photons can serve as reliable tags for the hard scattering
- Photon-jet results show hints of where energy loss is occurring
- Looking further at Z/γ-hadron correlations to learn about medium response
- Working on new photon-jet observable – the jet axis decorrelation δ_{jj}
- Excited to follow up with Run 3 data!







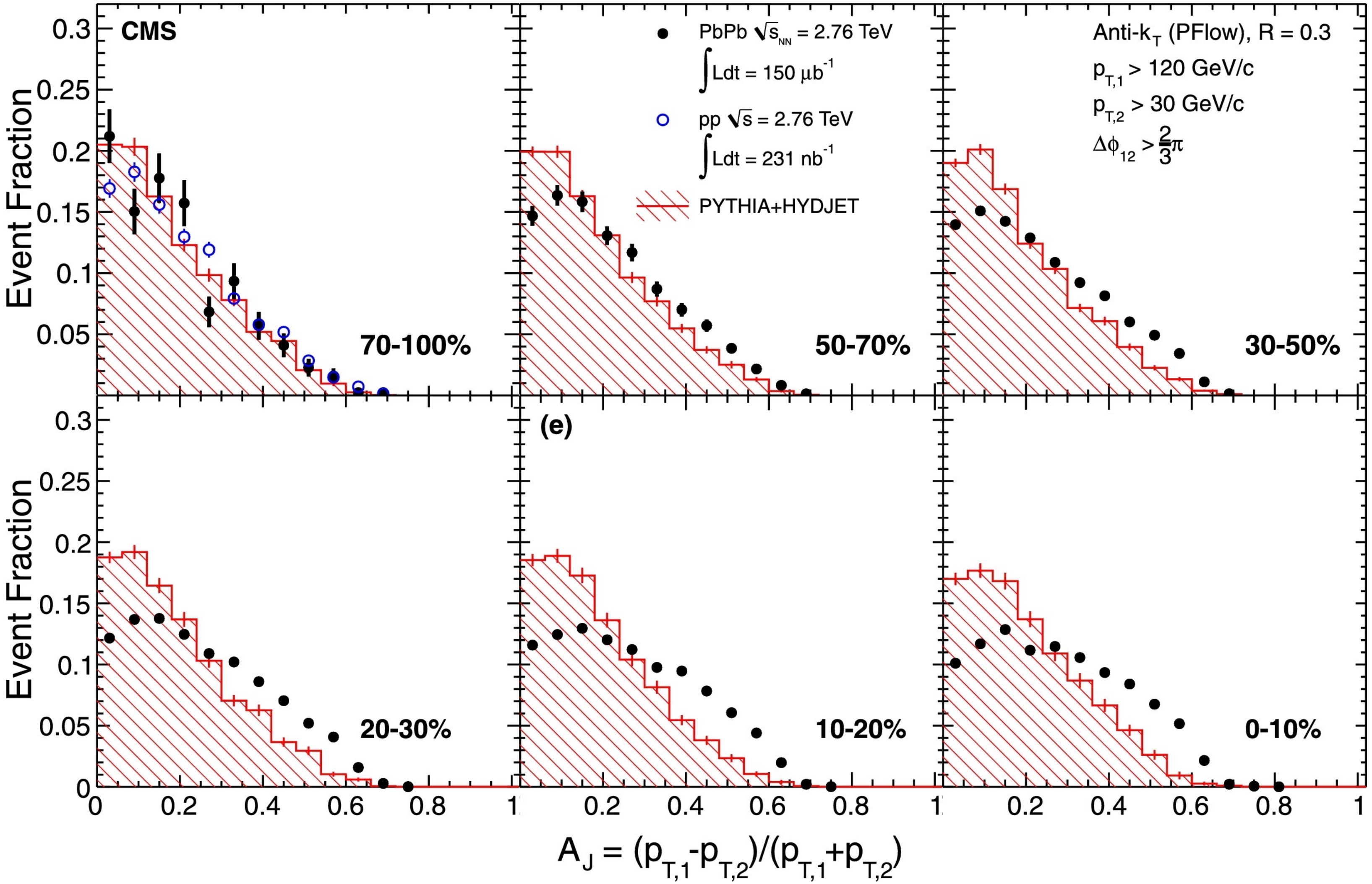
[JHEP 2020, 116 (2020)]

MITHIG group's work was supported by US DOE-NP

[PRL 121 (2018) 242301]

Backup

Dijet asymmetry



[PLB 712 (2012) 176](PLB 712 (2012) 176)

Prompt photon production

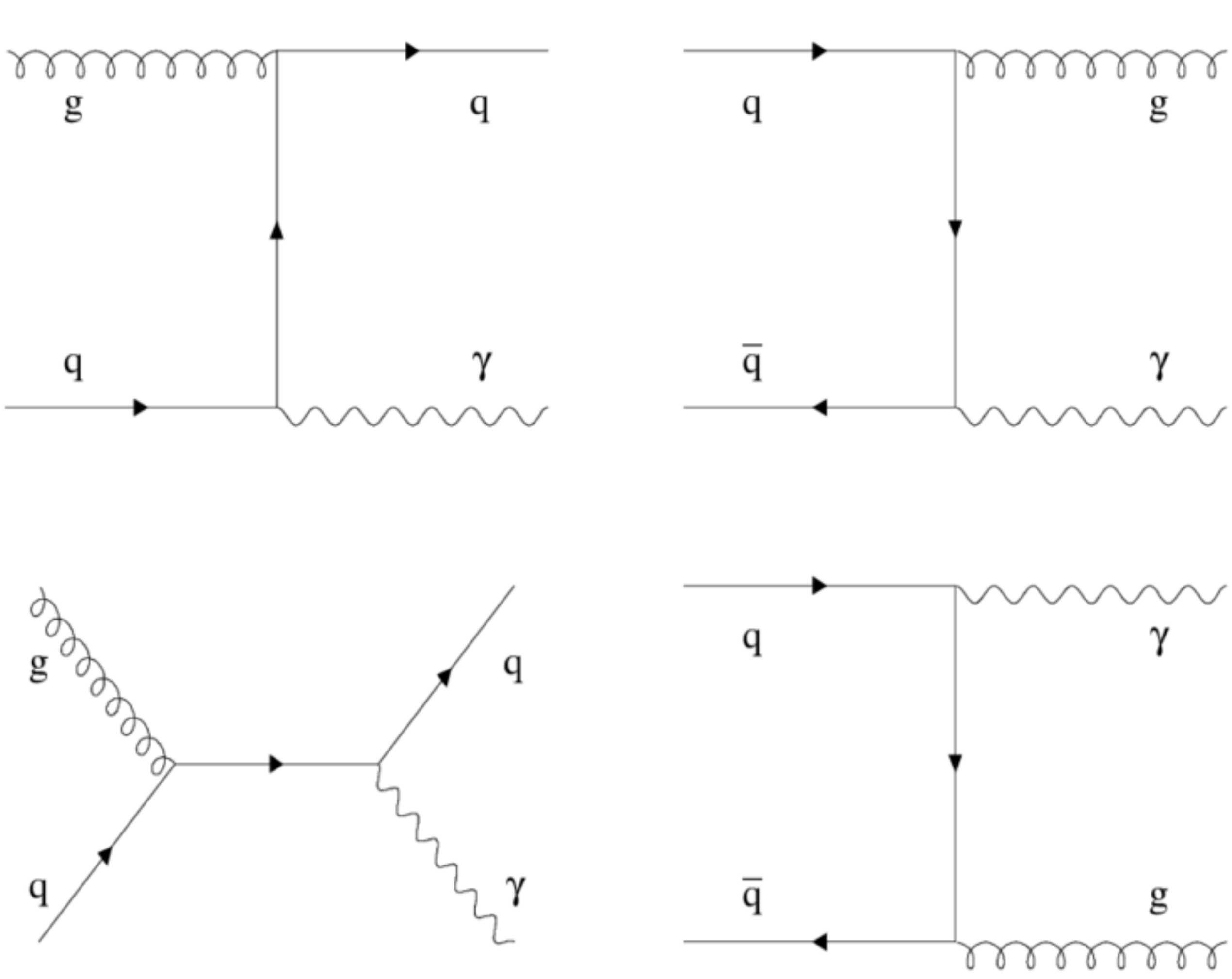


Figure: PLB 317 (1993) 250256

Isolation requirements and efficiency correction

Photon selections:

- $25 < E_T^{\gamma} < 200$ GeV and $|\eta| < 1.44$
- Reject if close to electron candidate track with $p_T > 10$ GeV

Isolation selections:

- HCal/ECal energy ratio < 0.1
- Shower shape $\sigma_{\eta\eta} < 0.01$
- sumIso (energy within $\Delta R = 0.4$) < 1 GeV

Efficiency correction:

- Efficiency of reconstructing photon candidates
- Selection efficiency
- Trigger efficiency

Results unfolded to correct for detector resolution

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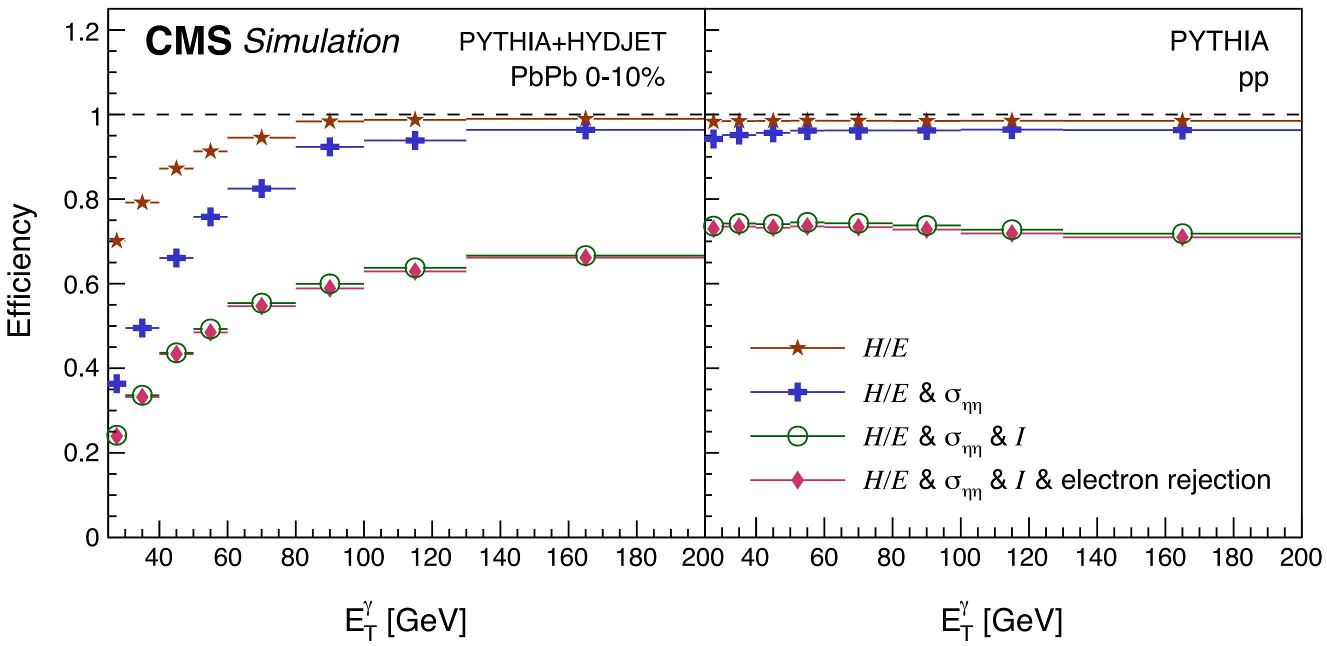
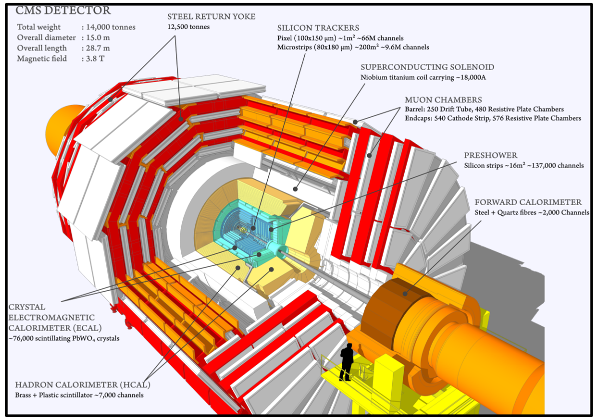
Selection Efficiency



$$N^{\gamma}_{corrected} = \frac{N^{\gamma}_{raw} P}{\epsilon}$$



Purity subtraction

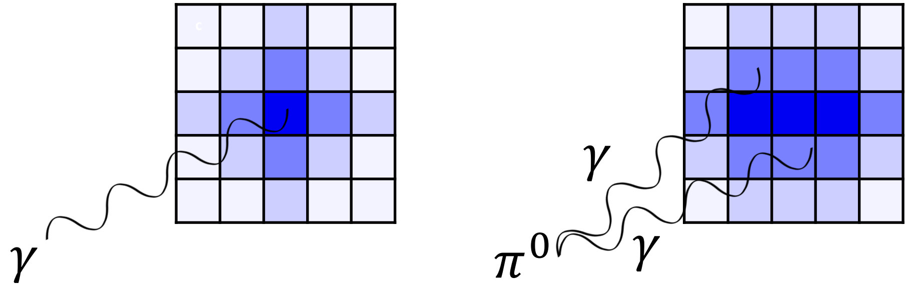
- After isolation requirements and electron rejection, dominant background is from neutral meson decay
- Use modified second moment of ECal distribution
- Most decay photons have larger values of $\sigma_{\eta\eta}$
- Estimate purity with a template fit method and subtract

Prompt Photons

small $\sigma_{\eta\eta}$

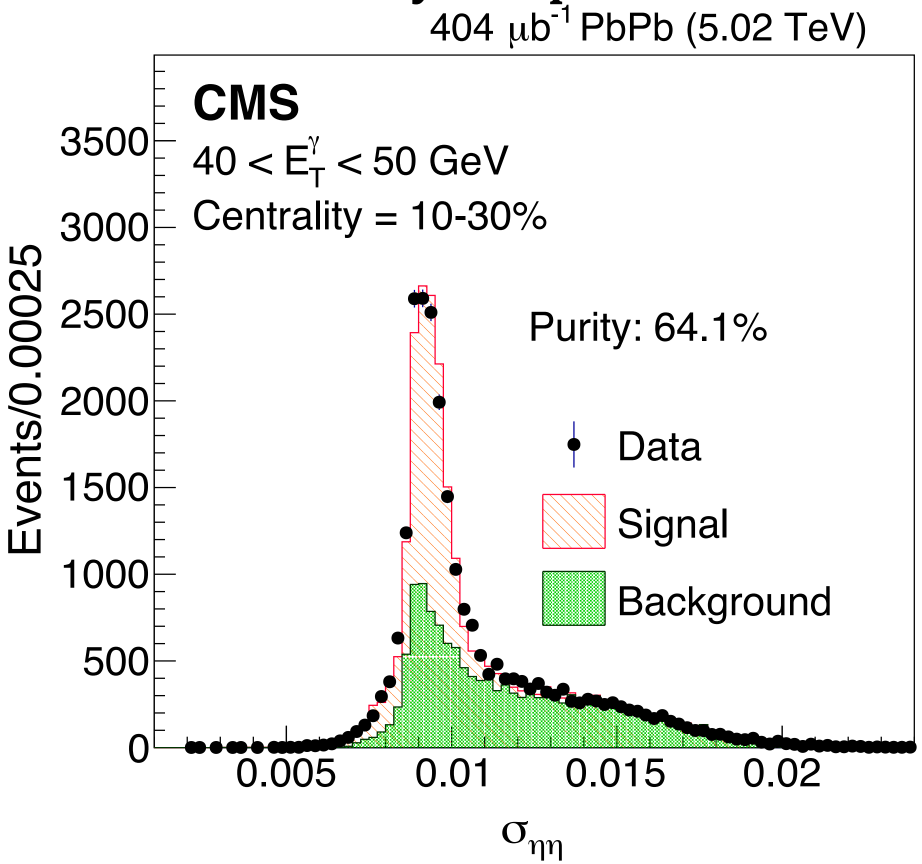
Decay Photons

large $\sigma_{\eta\eta}$



$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i} \qquad w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E_{5\times5}}\right)$$

Purity Template Fit



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Isolated photon systematic uncertainties

- Large source of uncertainty is the photon purity subtraction
- Residual photon energy scale also has a large effect, found using Z boson peak
- Pileup in PP collisions also adds significant uncertainty

	PbPb centrality				
Source	0–100%	0–10%	10–30%	30–50%	50–100%
Purity	6–9%	7–13%	3–12%	4–8%	2–7%
Electron rejection	1–2%	0–10%	1–6%	0–3%	0–7%
Pileup	0–10%	0–10%	0–10%	0–10%	0–10%
Energy scale	2–4%	3–6%	1–9%	2–7%	1–10%
Energy resolution	0–3%	1–7%	0–9%	1–8%	2–6%
Unfolding	1–4%	1–9%	1–5%	0–3%	0–1%
Efficiency	0–2%	0–5%	0–2%	0–1%	0–2%
Integrated luminosity	2.3%	2.3%	2.3%	2.3%	2.3%
T_{AA}	4%	3%	4%	6%	11%
Total	5–12%	10–17%	6–18%	7–15%	7–15%

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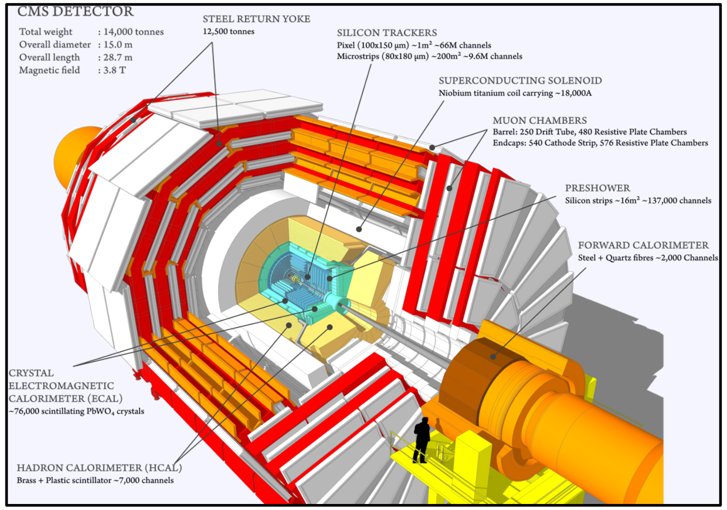
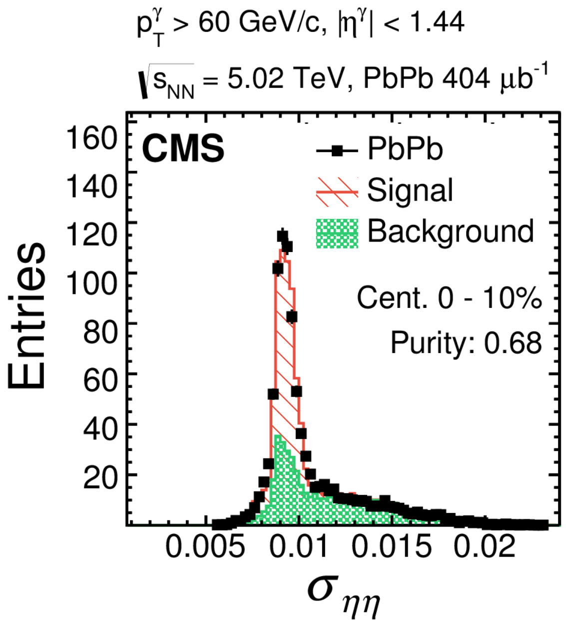
Object selections and analysis procedure

- Select events with $p_T^\gamma > 40$ GeV, $|\eta^\gamma| < 1.44$
- Cluster anti-kT R = 0.3 jets with FASTJET
- Subtract underlying event for PbPb collisions
- Find isolated photons with UE-subtracted energy sum < 1 GeV in R = 0.4 cone
- Reject photons close to electron tracks with $p_T^e > 10$ GeV/c
- Remove decay & fragmentation photons with purity subtraction
- Pair photons and jets to find photon-jet events
- Subtract combinatorial jet background via event mixing technique using MB events





[PLB 785 (2018) 14](#)

Mixed-event background subtraction

- Consider correlations between photon and all jets in event
- Subtract contributions from uncorrelated background jets and tracks
  - Statistically identical to jets in MB events, also uncorrelated
- Estimate background by embedding photon in MB events
- Done on aggregated basis

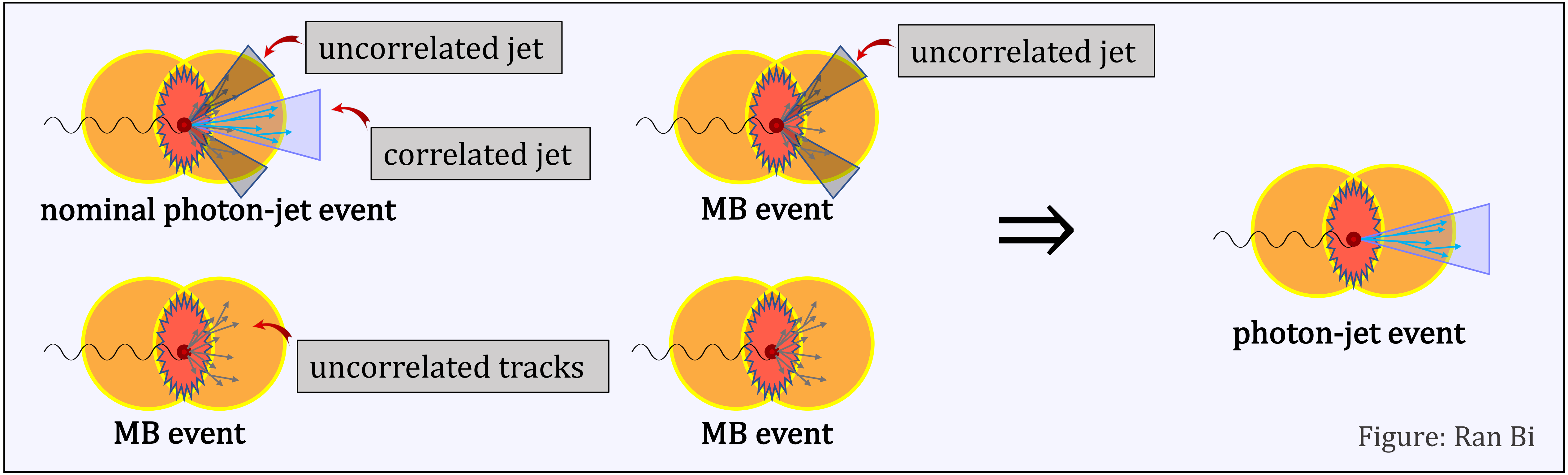
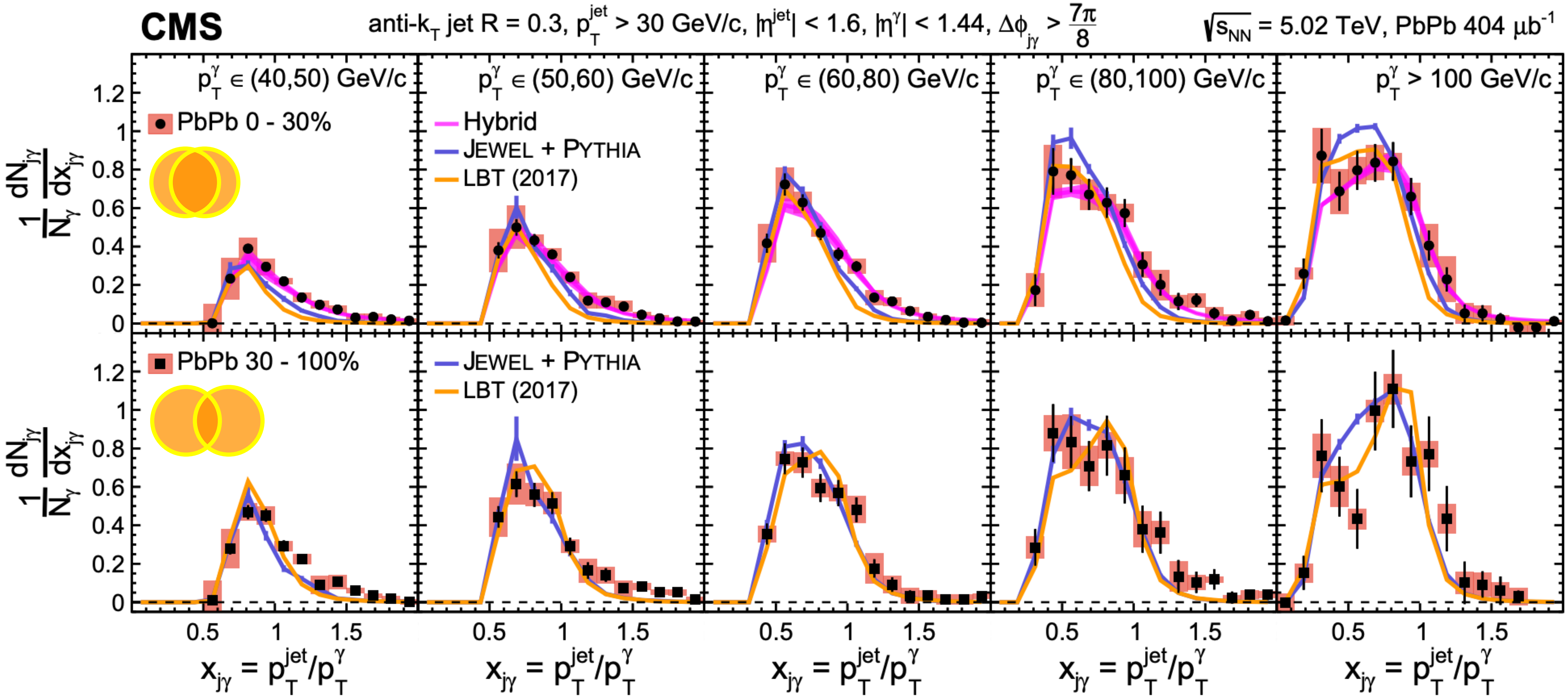


Figure: Ran Bi

Photon-jet momentum imbalance theory comparison



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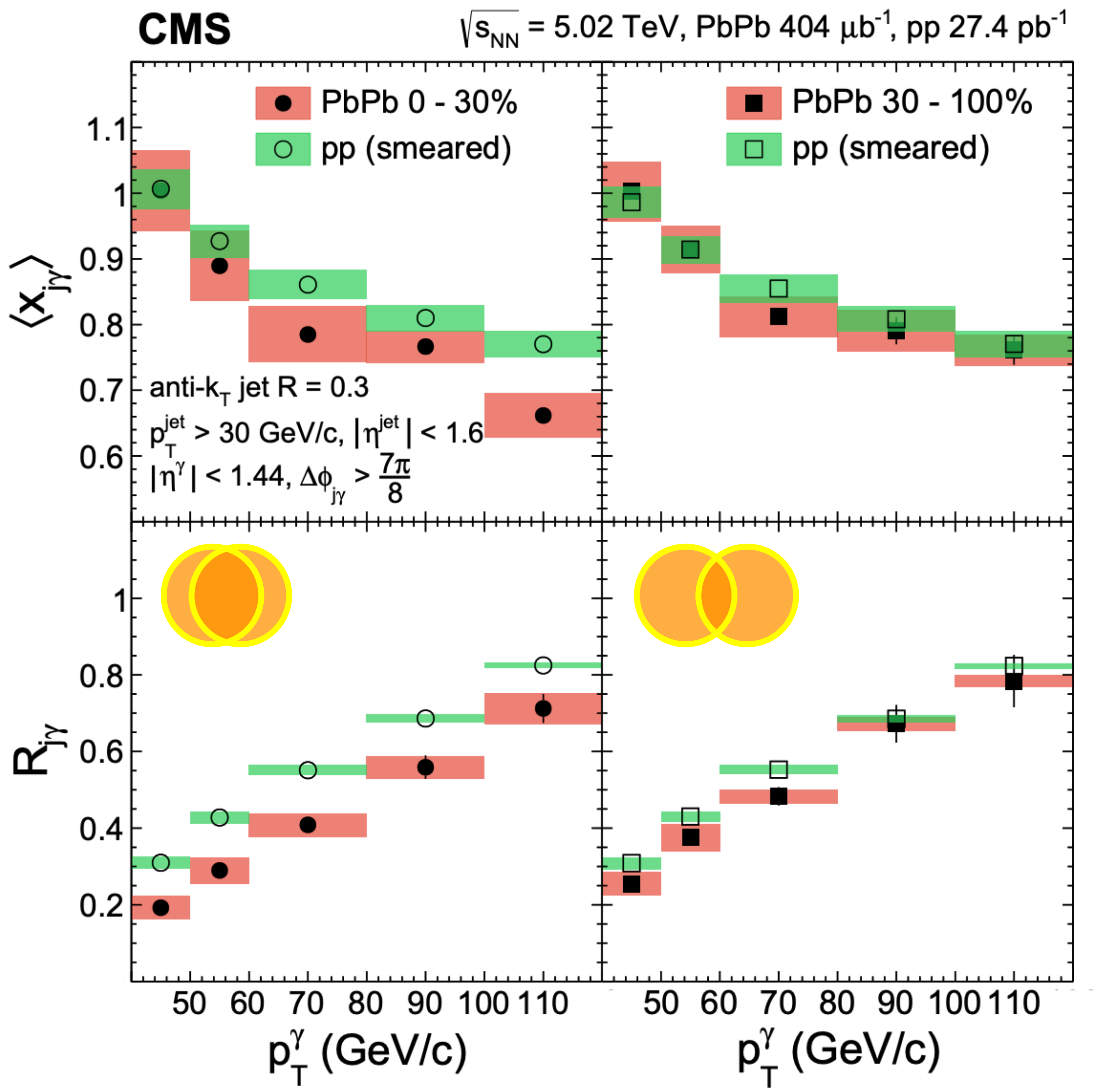
Photon-jet mean momentum imbalance



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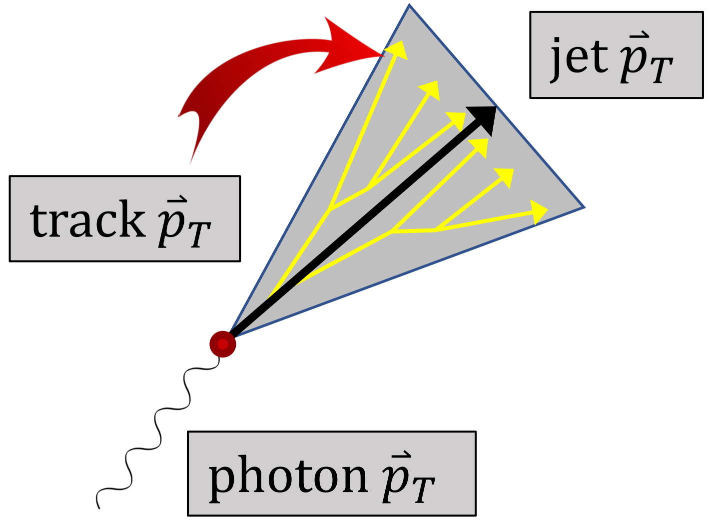
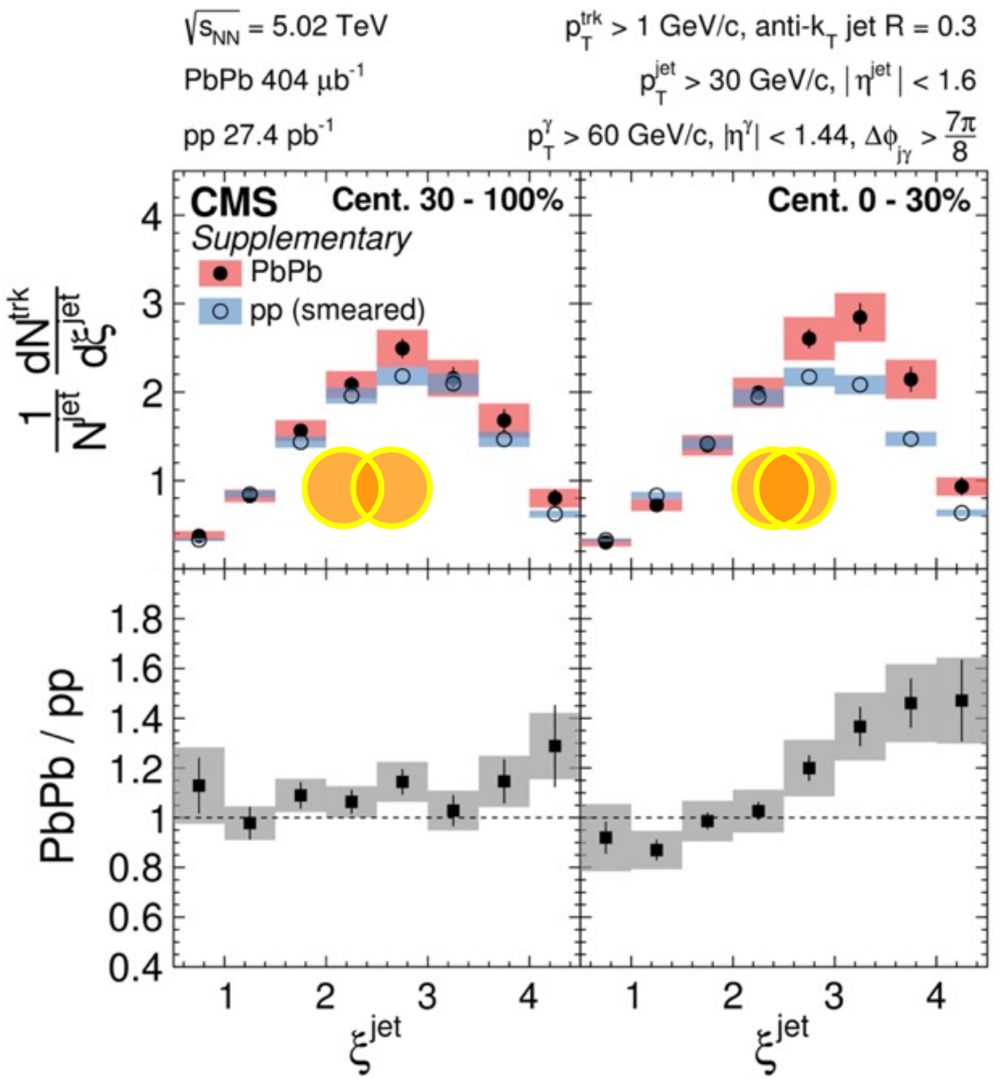
Photon-jet fragmentation function

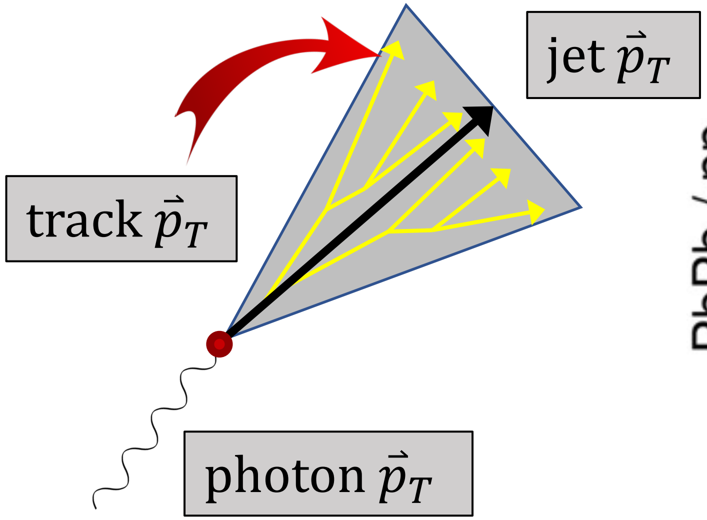


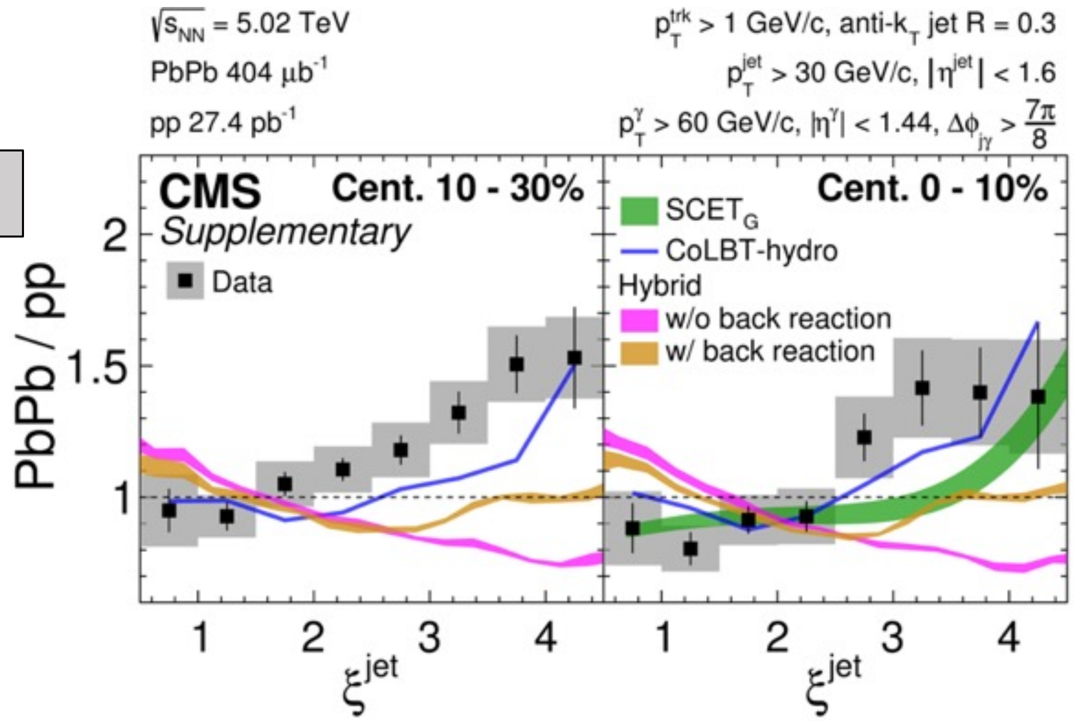


$$\xi^{jet} = \ln \frac{|\vec{p}^{\,jet}|^2}{\vec{p}^{\,trk} \cdot \vec{p}^{\,jet}}$$

[PRL 121 (2018) 242301](PRL 121 (2018) 242301)

Photon-jet fragmentation function theory comparison

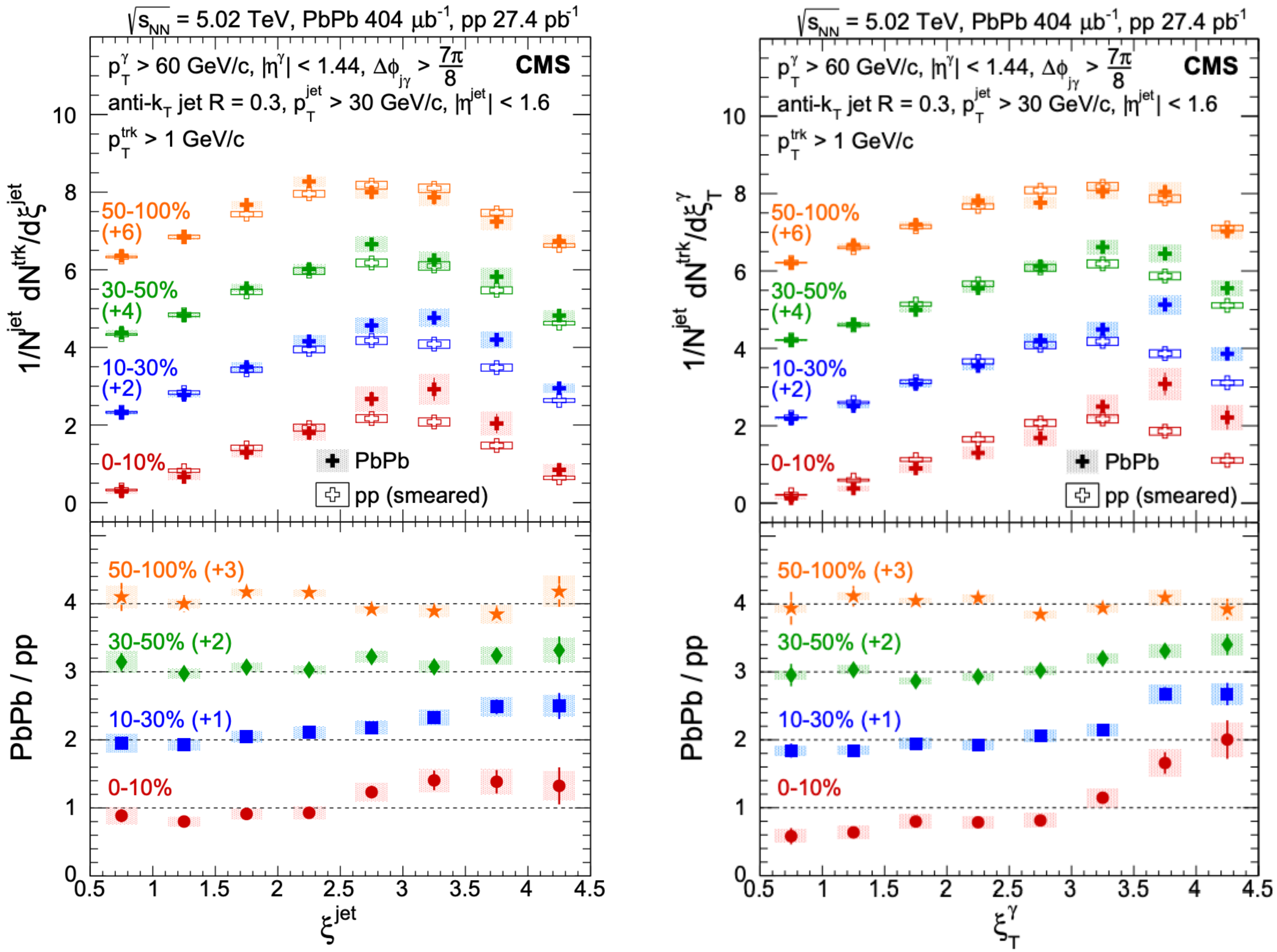




$$\xi^{jet} = \ln \frac{|\vec{p}^{\,jet}|^2}{\vec{p}^{\,trk} \cdot \vec{p}^{\,jet}}$$

PRL 121 (2018) 242301

Fragmentation function centrality dependence



$$\xi_{jet} = \ln \frac{\left|\vec{p}^{\,jet}\right|^2}{\vec{p}^{\,trk} \cdot \vec{p}^{\,jet}}$$

$$\xi_\gamma = \ln \frac{-\left|\vec{p}_T^{\,\gamma}\right|^2}{\vec{p}_T^{\,trk} \cdot \vec{p}_T^{\,\gamma}}$$

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