Photon-tagged Jet Fragmentation Functions in pp and PbPb Collisions at 5.02 TeV with CMS

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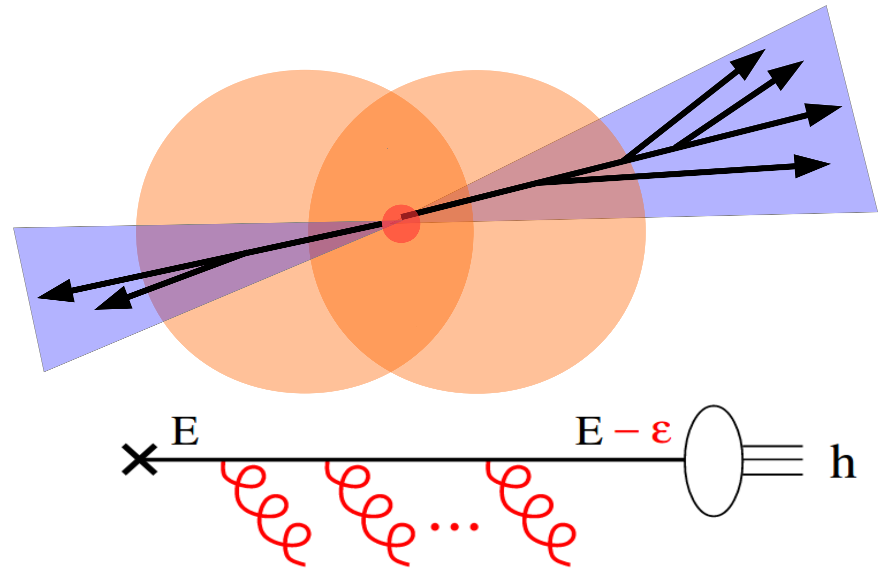
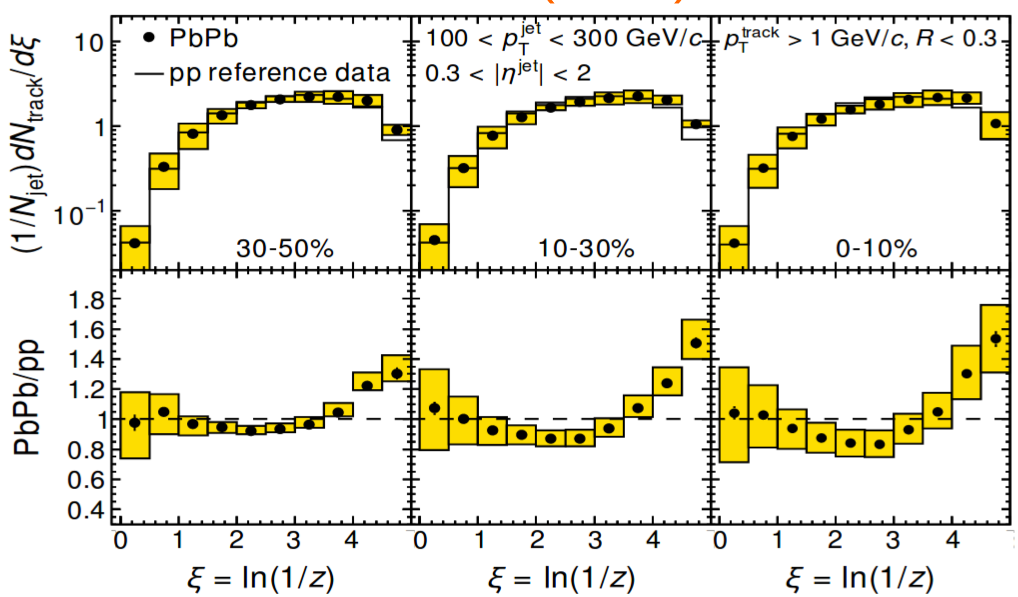
Introduction

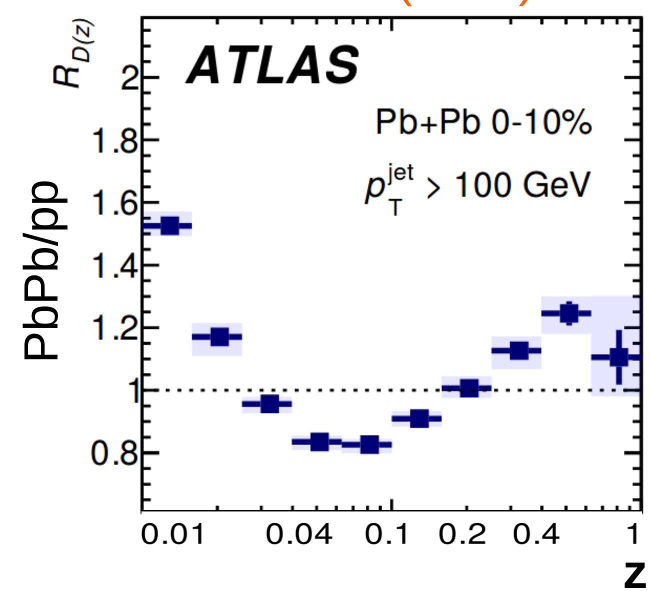
- The fragmentation pattern of a high energy parton is predicted and measured to be modified in A+A collisions.
- Jet fragmentation function (FF)
  - Info about longitudinal distribution of the momentum
  - Separate energy loss models
  - Sensitive to hadronization



CMS, PRC 90 (2014) 024908



EPJC 77 (2017) 379

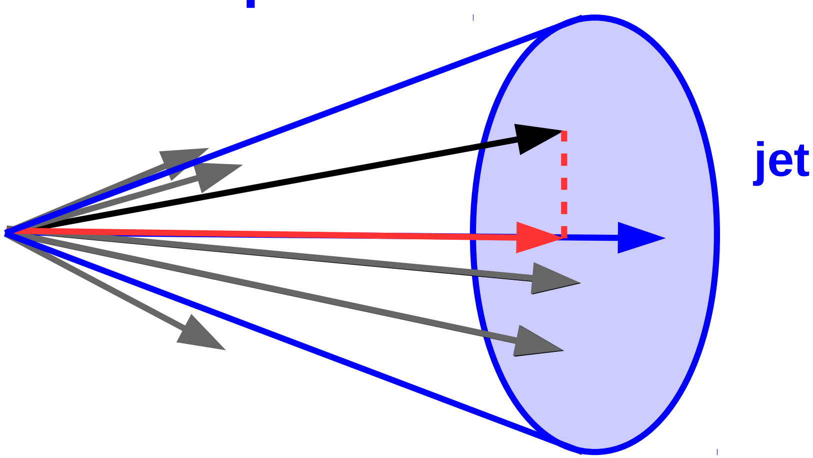


FF at LHC and RHIC so far

- jet+hadrons FF (at LHC)
- take hadrons inside the jet cone
- project p_T^h (or p^h) onto jet axis
- look at the fraction in p_T^{jet} (or p^{jet})

ATLAS : $z = \frac{p_T^h \cos \Delta R}{p_T^{jet}}$

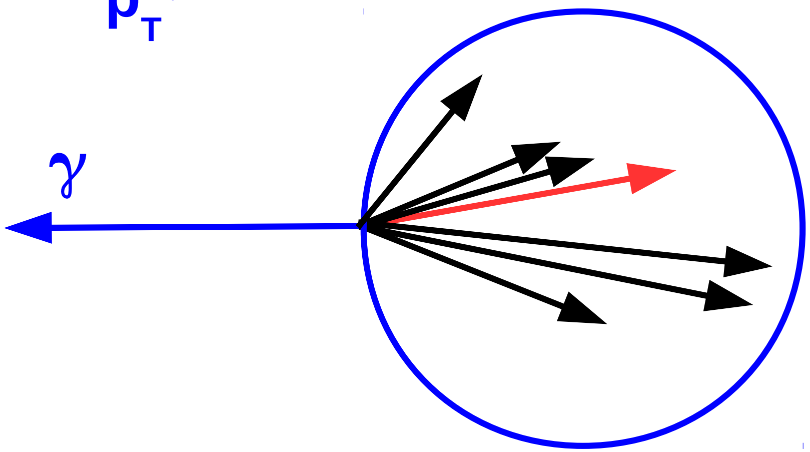
CMS : $z = \frac{p_{||}^h}{p^{jet}}$



p_t^{jet} ~100 GeV/c at sqrt(s) = 2.76, 5.02 TeV

- photon-hadrons FF (at RHIC), no reconstructed jets
- take hadrons away from the triggering object (photon)
- look at the fraction of hadron p_T in photon p_T

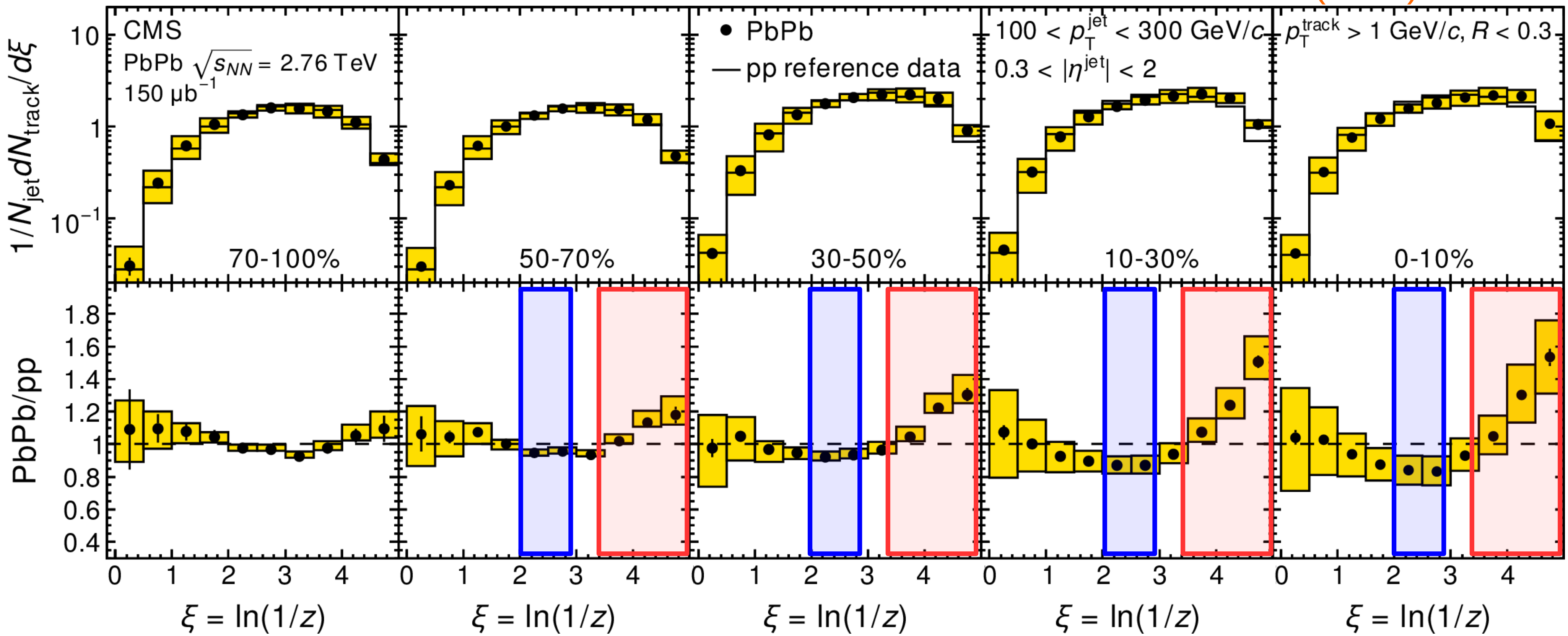
$z_T = \frac{p_T^h}{p_T^\gamma}$

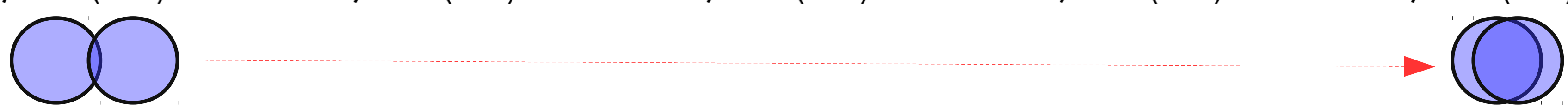


p_T^γ ~5 GeV/c at sqrt(s) = 0.2 TeV

Jet based FF at LHC - CMS

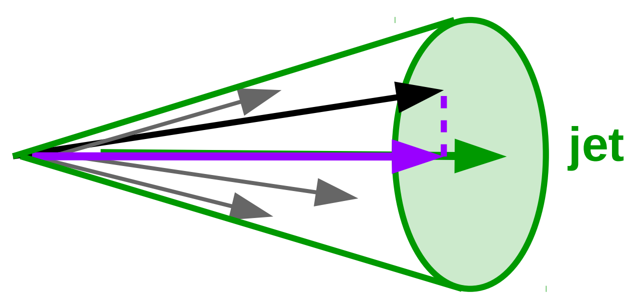
PRC 90 (2014) 024908





enhancement for ch. particles with 1 < pT < 3 GeV/c, ξ > 3.5

Small depletion in the intermediate pT range, 2 < ξ < 3



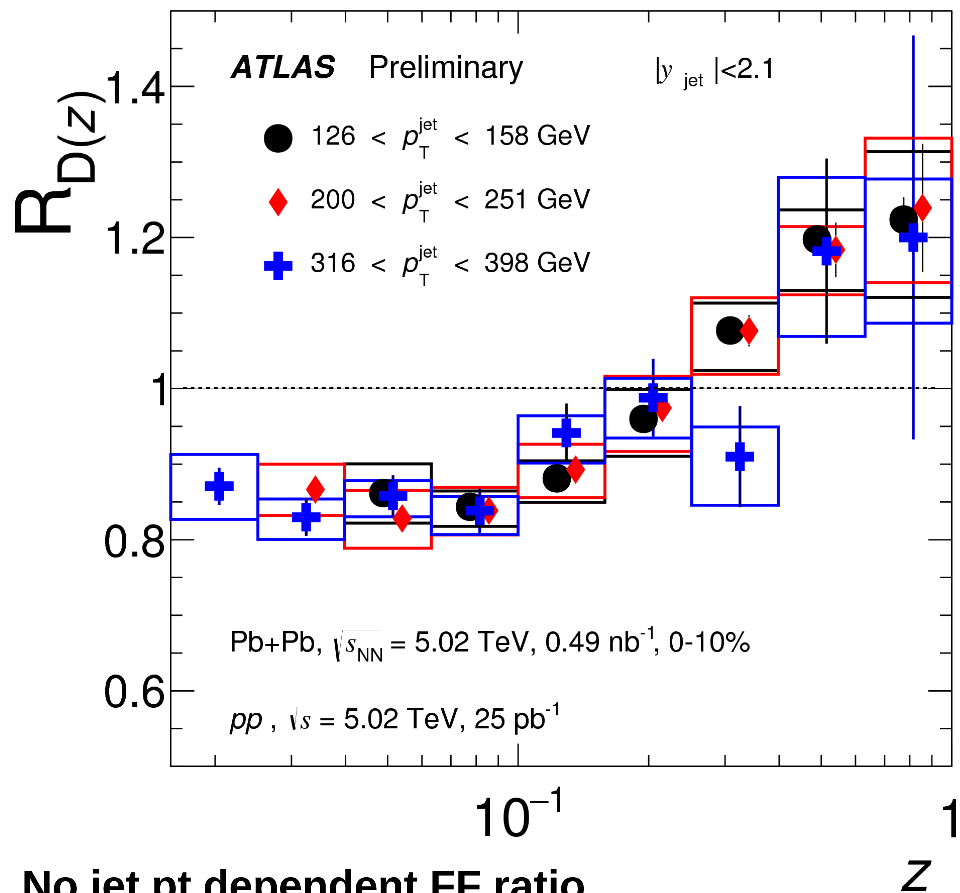
$$z = \frac{p_{||}^{trk}}{p^{jet}}$$

Jet based FF at LHC - ATLAS

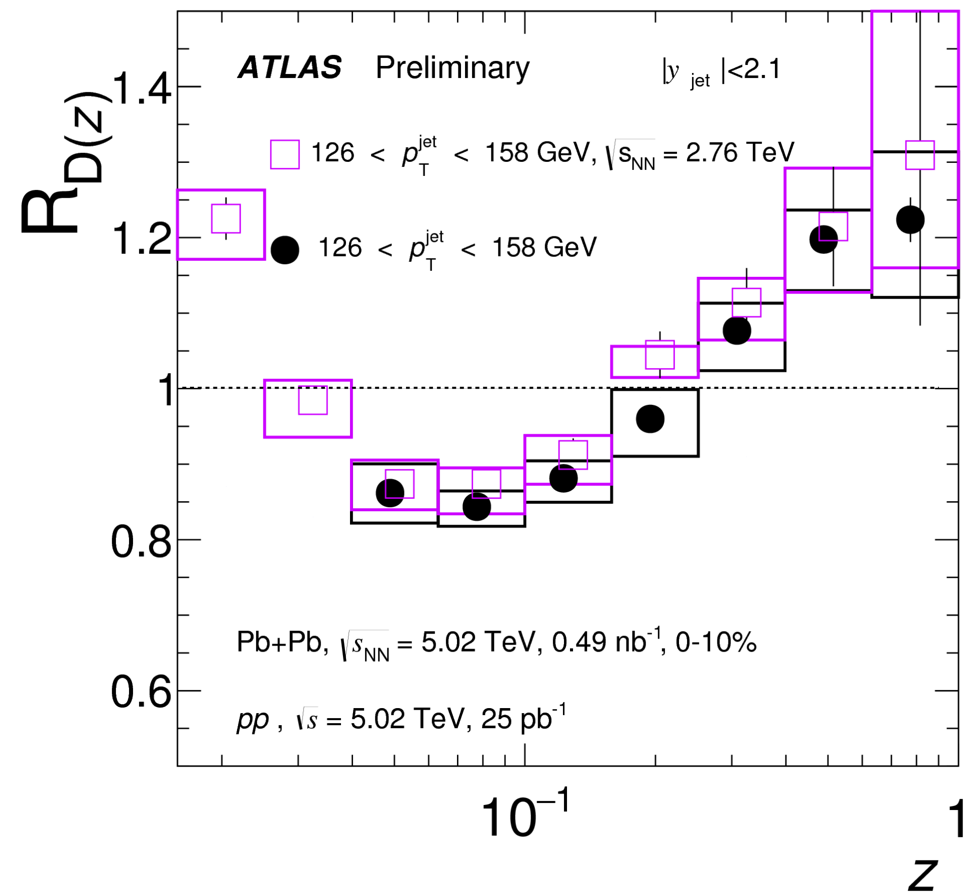
$$R_{D(z)} \equiv \frac{D(z)_{PbPb}}{D(z)_{pp}} \qquad D(z) = \frac{1}{N_{jet}} \frac{dN_{ch}}{dz} \qquad z = \frac{p_T}{p_T^{jet}} \cos \Delta R$$

ATLAS-CONF-2017-005

0-10%, 3 jet pt bins overlayed



0-10%, 5.02 vs 2.76 TeV



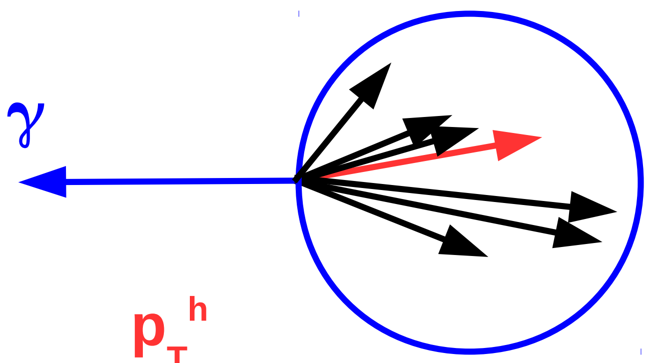
No jet pt dependent FF ratio
Enhancement at high z

ATLAS jet FF at 2.76 TeV EPJC 77 (2017) 379

Similar FF ratio between different $\sqrt{s_{NN}}$

5.02 (**2.76**) TeV result starts at z=**0.04** (**0.01**).

Photon based FF at RHIC



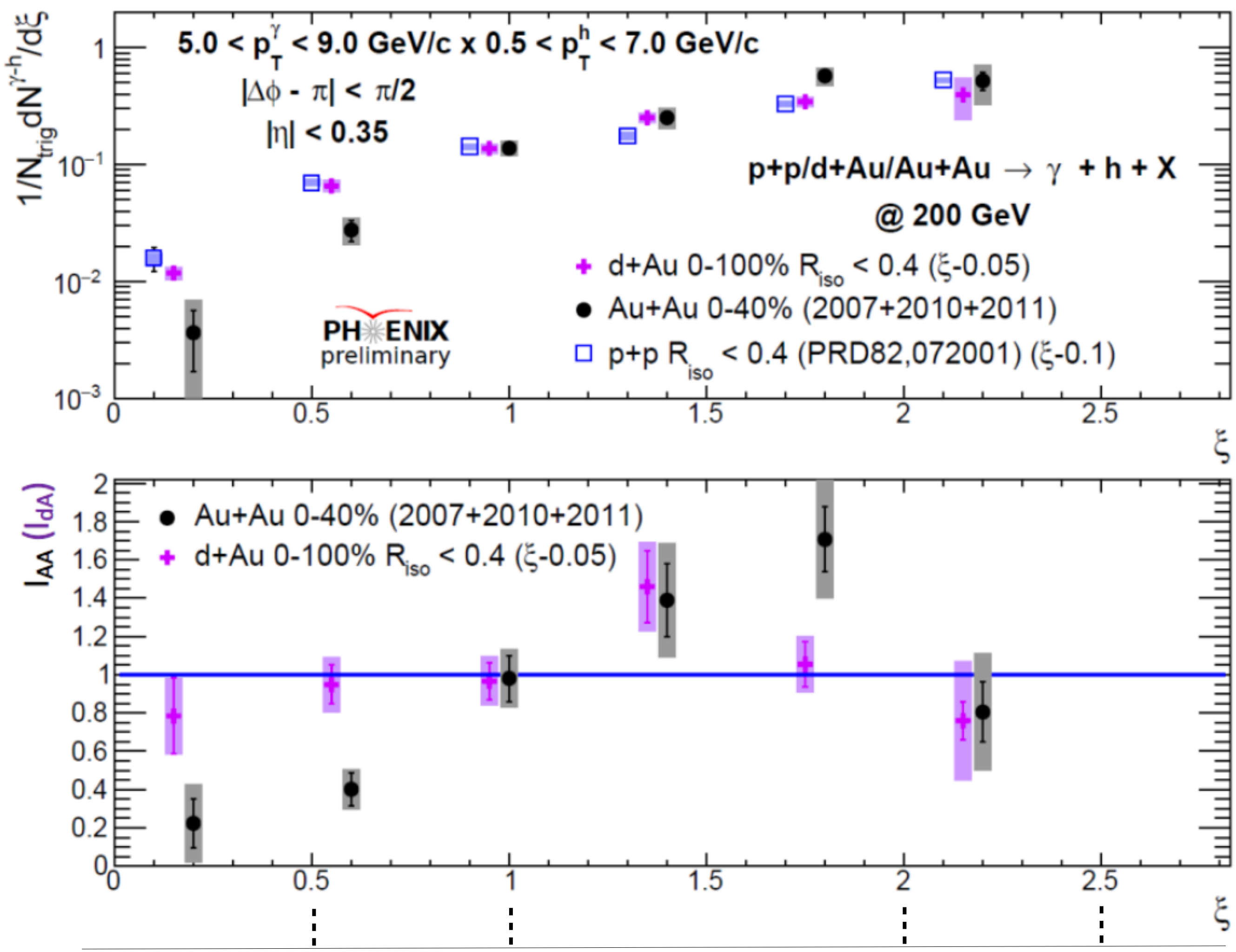
$$z_T = \frac{p_T^{\,h}}{p_T^{\,\gamma}}$$

$$\xi = \ln\left(\frac{1}{z_T}\right)$$

FF : $D(\xi) = \frac{1}{N_{event}} \frac{dN}{d\xi}$

FF ratio

$$I_{AA} = \frac{D_{AA}(\xi)}{D_{pp}(\xi)} \quad I_{dA} = \frac{D_{dA}(\xi)}{D_{pp}(\xi)}$$



z @ LHC	0.6	0.37	0.14	0.08

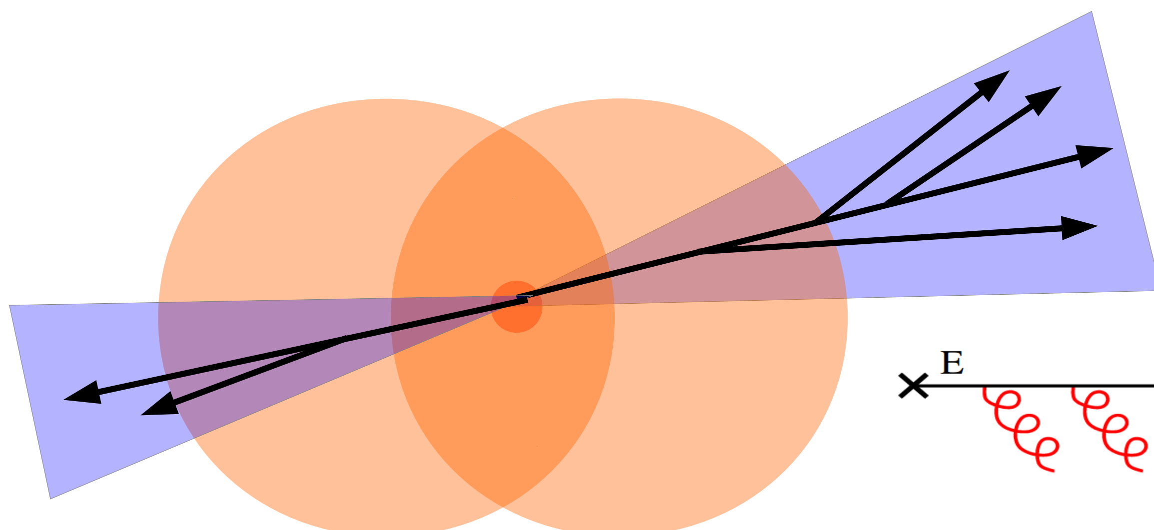
- No significant modification in **d+Au**
- Modification in **Au+Au**
  - suppression at small ξ (large $p_T^{\,h}$)
  - enhancement at large ξ (small $p_T^{\,h}$)

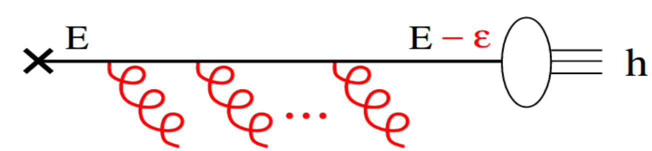
Joe Osborn @ QM 2017

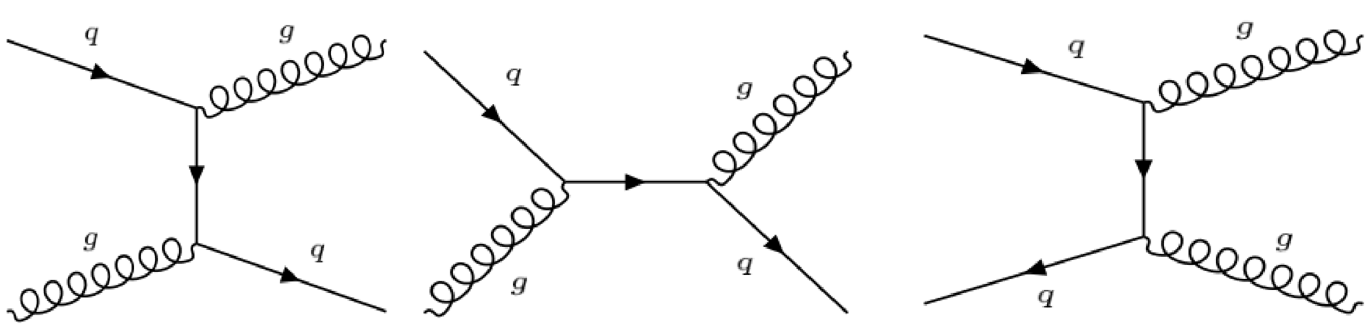
Jet FF with Dijets

Jet based FF measurements up to now were made with **dijet** samples.

- Pro : High statistics
- Con : Comparison is based on reconstructed jets (after suffering quenching). No control over initial kinematics





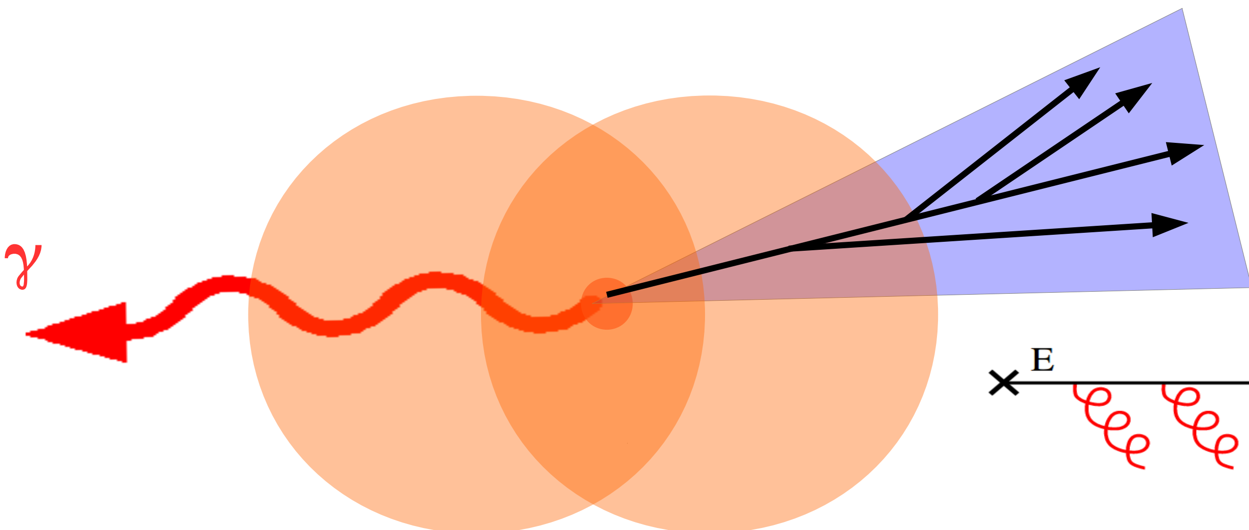


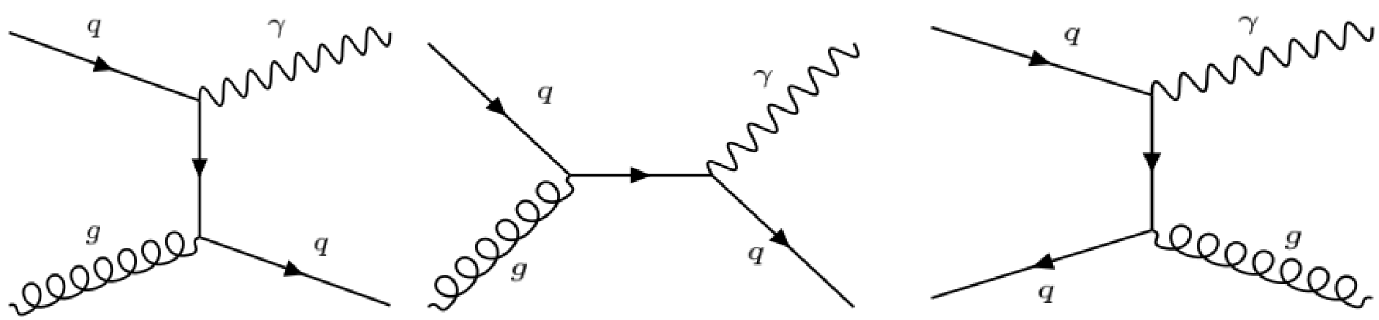
Jet FF with Photon+jet

One can **constrain the initial parton kinematics** if one of the hard scatterers is a **photon**. 5 TeV data set is large enough to perform this type of measurement.

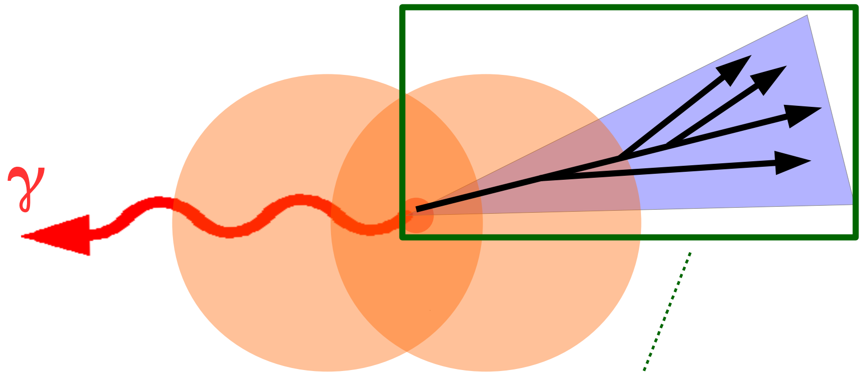
Motivation : understand QCD properties of the medium via longitudinal modification of parton shower

Goal : Measure **jet FF** in **isolated-photon+jet** events in PbPb and compare to pp





Observables - ξ^{jet}

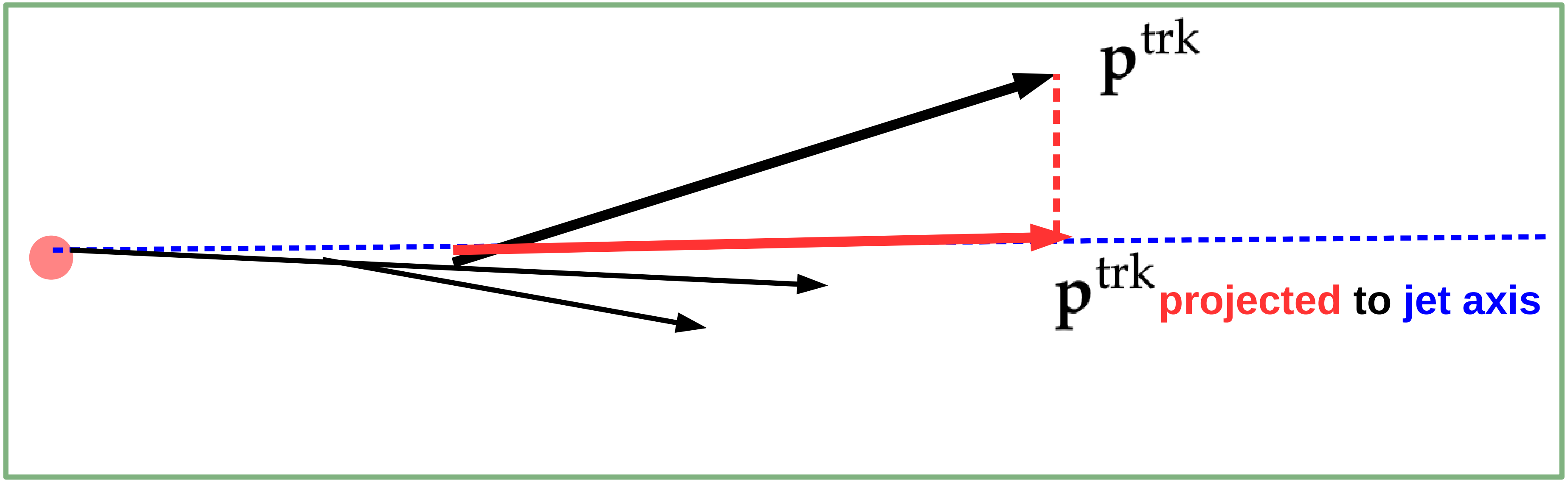


- Take tracks inside the jet cone.
- **Project** the track momentum to **jet axis**.
- Divide jet momentum by the projected track momentum.
- The natural log of this ratio is called ξ^{jet}.

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

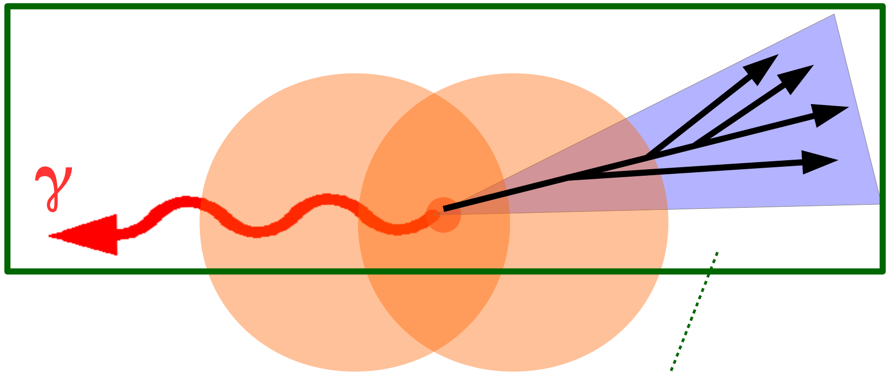
$\mathbf{p}^{jet}$: 3-momentum vector of the jet

$\mathbf{p}^{trk}$: 3-momentum vector of the track



Observables - ξ_T^γ

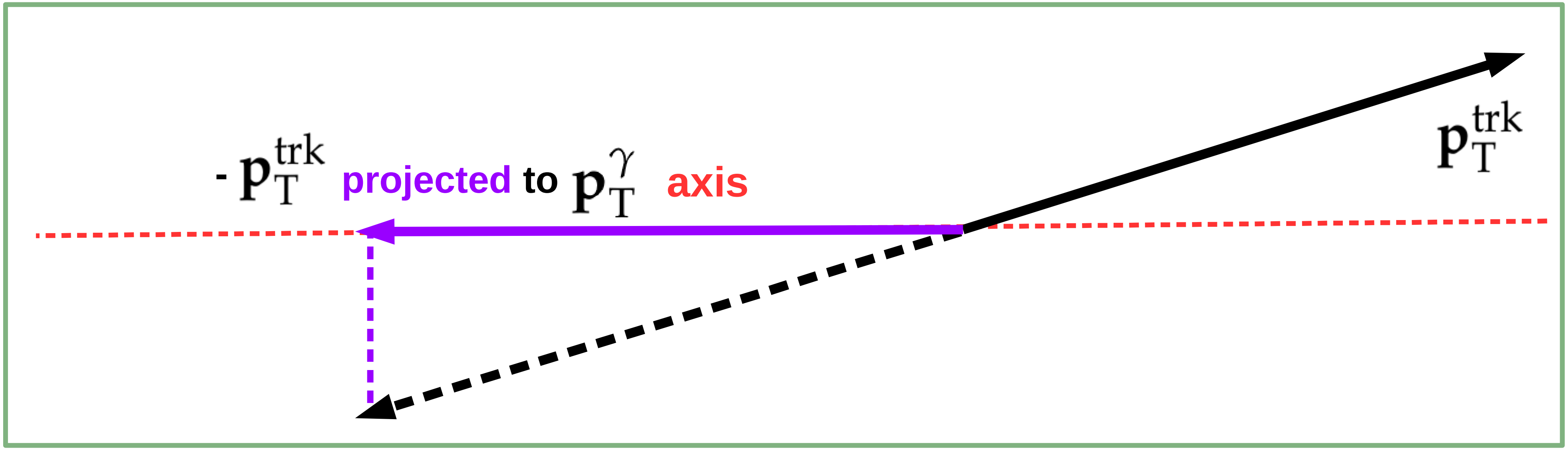
- Take tracks inside the jet cone.
- Construct transverse momentum vectors for track and photon
- Invert the track transverse momentum
- Follow the same logic as for ξ^{jet}.



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

$\mathbf{p}_T^\gamma$: transverse momentum vector of the photon

$\mathbf{p}_T^{trk}$: transverse momentum vector of the track

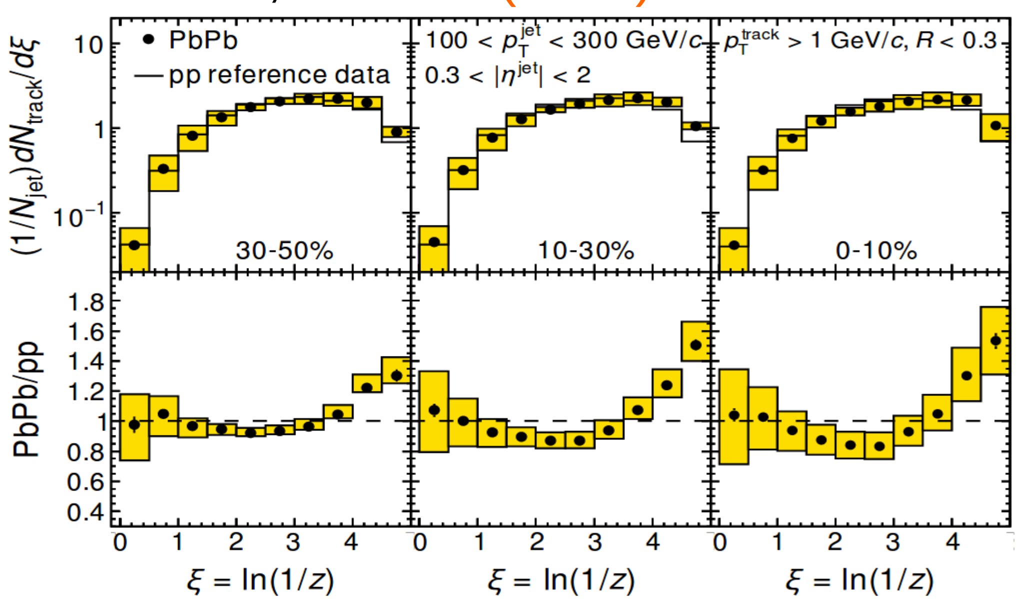


Observables

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

- Based on **reconstructed jet energy**
- Measured previously, eg.

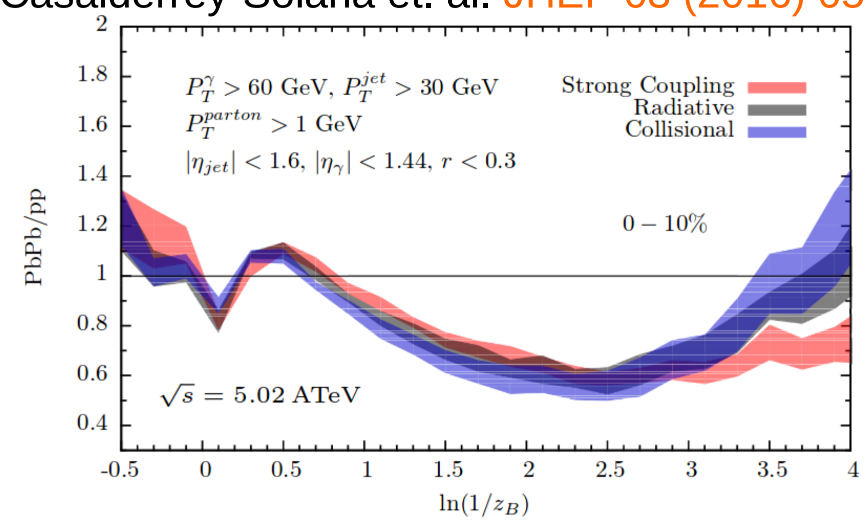
CMS, PRC 90 (2014) 024908



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

- Based on **photon energy**, proxy for the parton energy before jet quenching.
- Measured for the first time for reconstructed jets
  - only theoretical calculations so far
- $\xi^{\rm jet}$ and $\xi_{\rm T}^{\gamma}$ are measured **together for the first time**.

Casalderrey-Solana et. al. JHEP 03 (2016) 053



Object Selections

Photons

$p_T^{\gamma} > 60$ GeV/c

$|\eta^{\gamma}| < 1.44$

Jets

anti-kT, R=0.3

$p_T^{jet} > 30$ GeV/c

$|\eta^{jet}| < 1.6$

$\Delta\varphi$(photon, jet) > $7\pi/8$

inclusive jets, bkg jets **subtracted via MB event mixing**

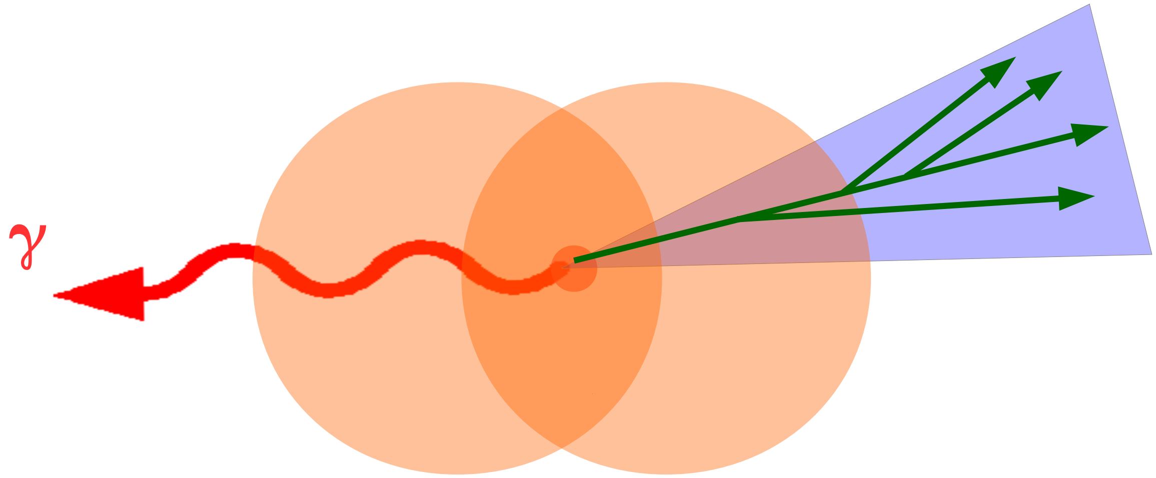
Tracks JHEP 04 (2017) 039

$p_T > 1$ GeV/c

$|\eta^{trk}| < 2.4$

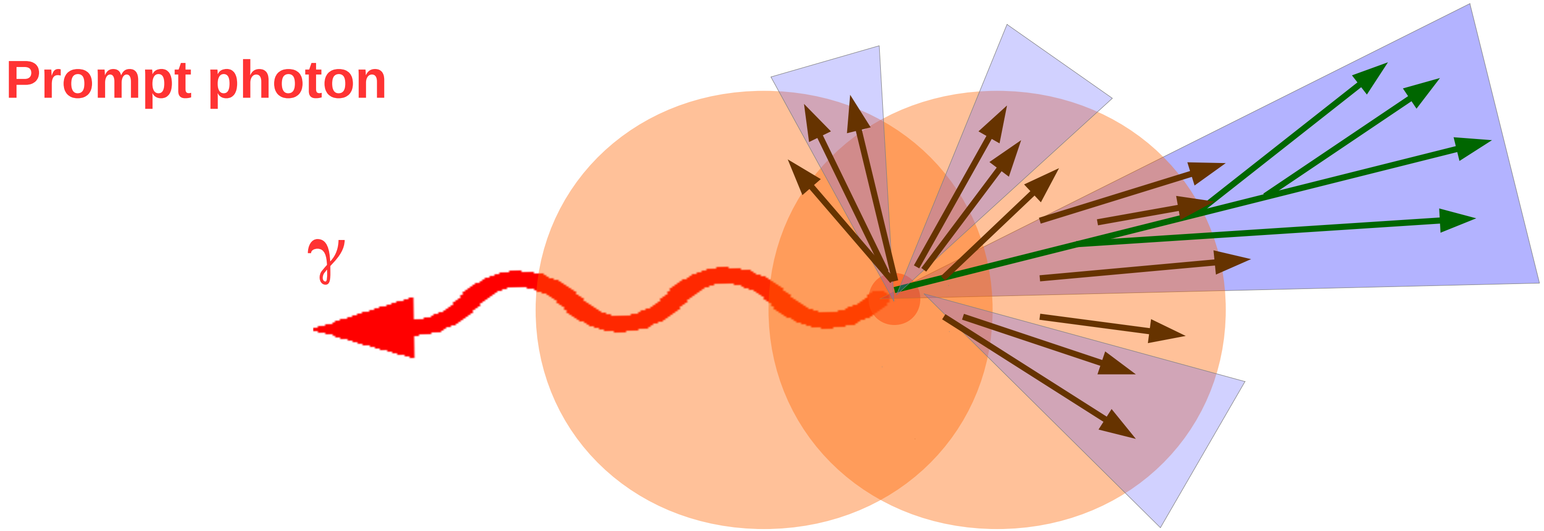
ΔR(jet, track) < 0.3

Bkg tracks **subtracted via MB event mixing**



Analysis

- Observables are constructed using photons, jets and tracks.



Background sources

Subtracted via Min Bias event mixing

Tracks from underlying event

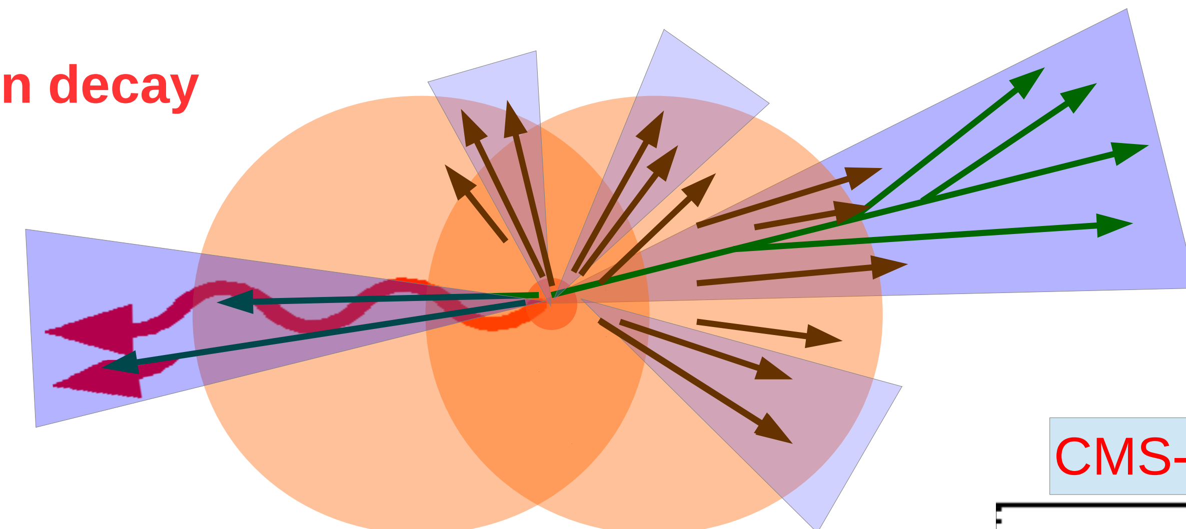
Mis-identified (fake) jets

Analysis

- Observables are constructed using photons, jets and tracks.

Neutral meson decay

$h^0 \to \gamma\gamma$

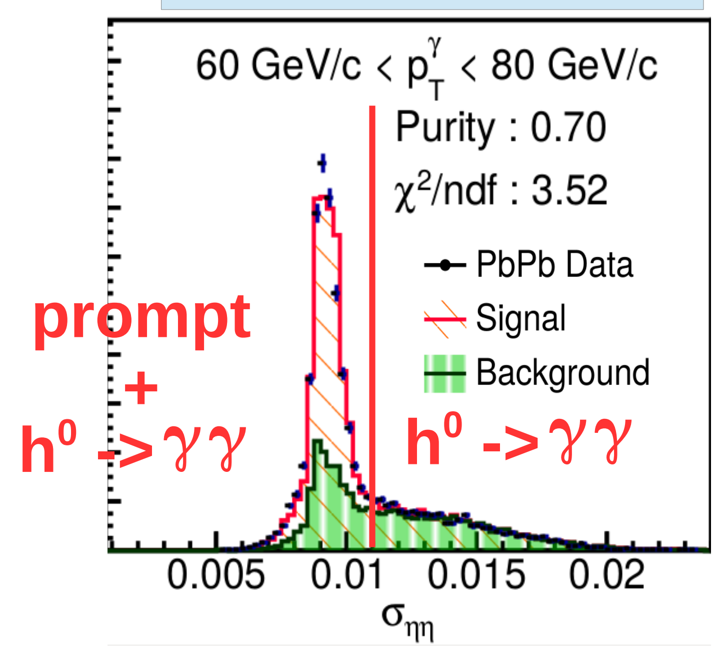


Background source

photons from neutral meson decays

- rejected with shower shape cut
- 2 photons are reconstruced as single with a **wider shower shape**
  - dominates the sideband region : $0.011 < \sigma_{\eta\eta} < 0.017$

CMS-PAS-HIN-16-002



shower shape

Energy weighted width of shower : $\sigma_{\eta\eta}$

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

Background from photons

- $\sigma_{\eta\eta} < 0.01$ selects narrow shower shape, supresses background from neutral meson decays, however there is still contamination.
- Purity = fraction of the prompt photons among candidates
  - Estimated using template fit method. Fit the distribution for $\sigma_{\eta\eta} < 0.01$ with

Signal (prompt photon) template from MC with isolated photon events

Bkg (neutral meson) template from non-isolated photons in data

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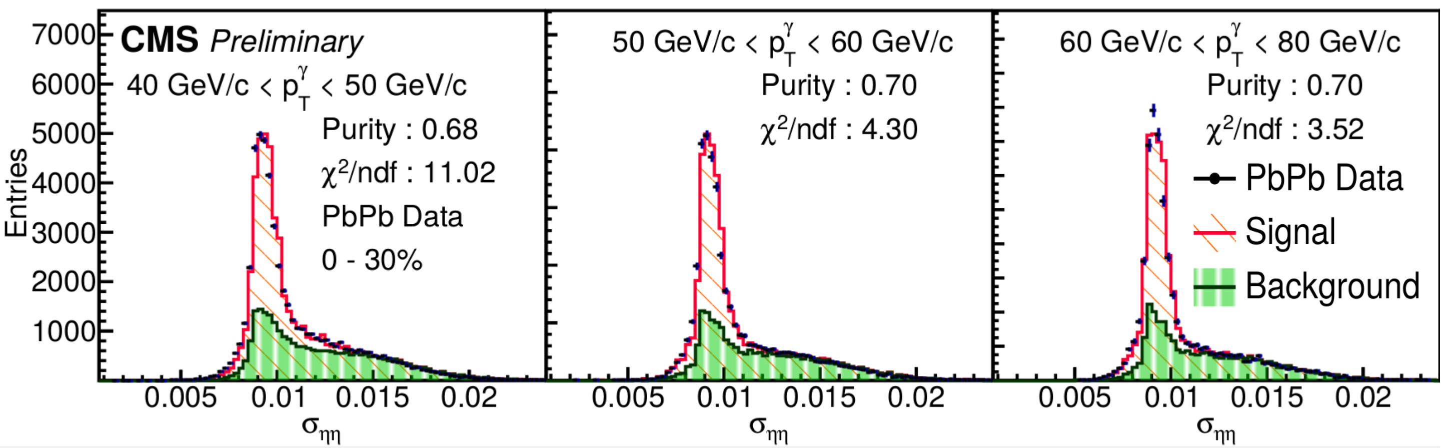
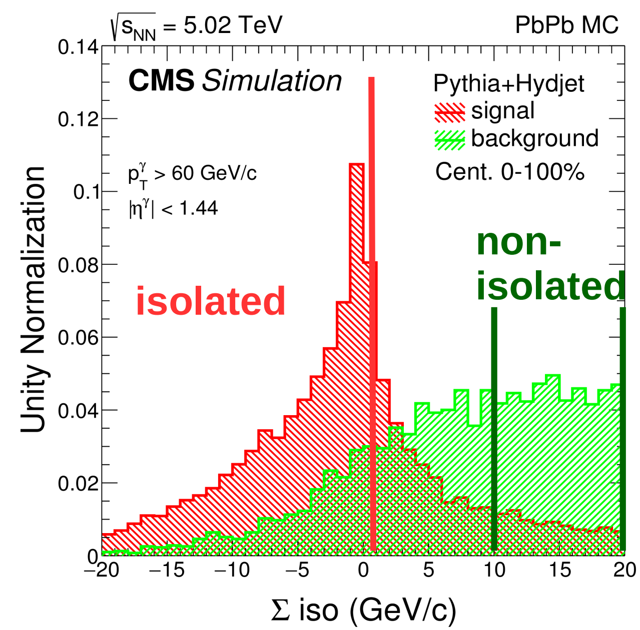
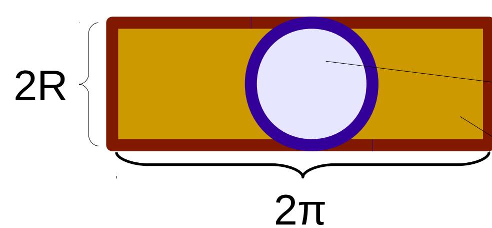




$$\sigma^2_{\eta\eta} = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i}$$

$$w_i = \max(0, 4.7 + \ln \frac{E_i}{E_{5\times5}})$$



Σ iso =
(tot energy in a cone of R=0.4 around the photon) -
(ave. energy from a strip of 2π x 2R)

Smearing jet spectra

- **Jet energy resolution** and **jet angular resolution** differ between pp and PbPb due to underlying event
  - Estimate relative resolution between pp and PbPb using simulations
  - Smear jet spectra in pp using this relative resolution
- Smearing **jet energy**
  - Parametrize jet energy resolution via

$$\sigma\left(\frac{p_T^{RECO}}{p_T^{GEN}}\right)=\sqrt{C^2+\frac{S^2}{p_T^{GEN}}+\frac{N^2}{(p_T^{GEN})^2}}$$

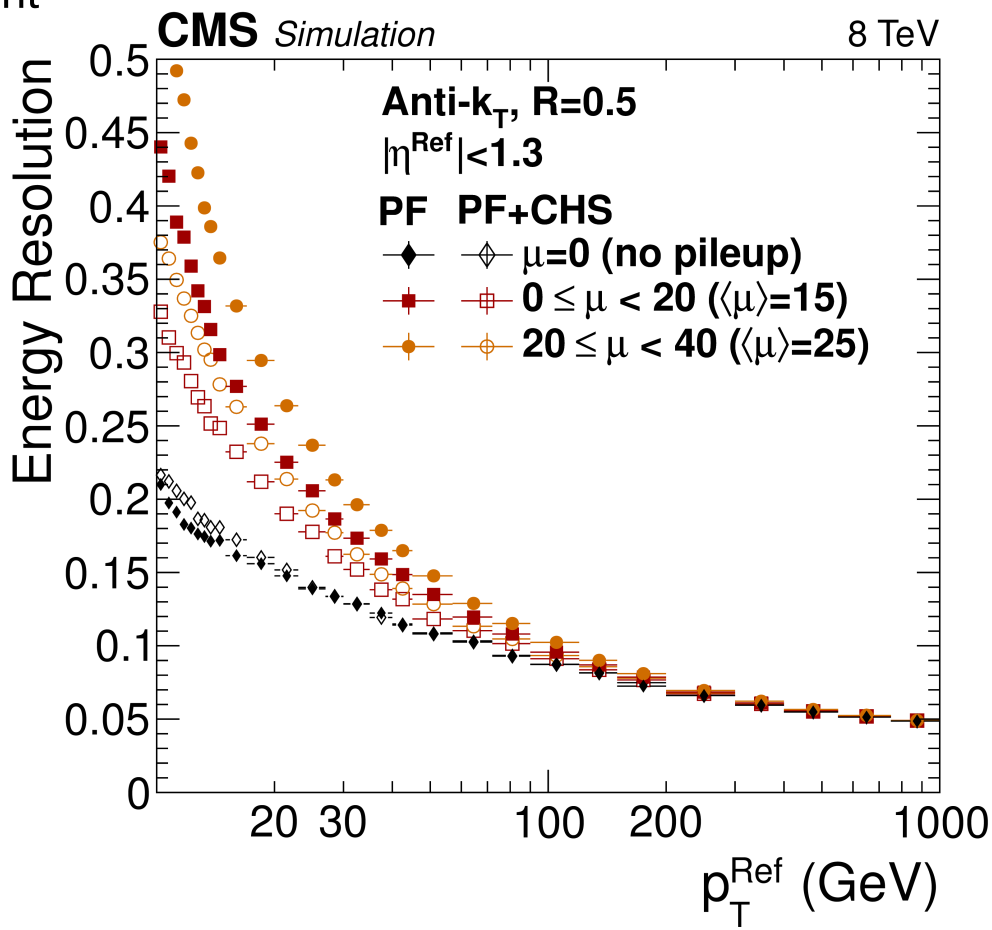
  - Fit C, S and N parameters and apply relative resolution via

$$\sigma_{rel}=\sqrt{(C_{PbPb}^2-C_{pp}^2)+\frac{(S_{PbPb}^2-S_{pp}^2)}{p_T^{GEN}}+\frac{(N_{PbPb}^2-N_{pp}^2)}{(p_T^{GEN})^2}}$$

- Smearing **jet azimuthal angle**
  - Use same parametrization as in jet energy resolution
  - Apply relative resolution in the same fashion

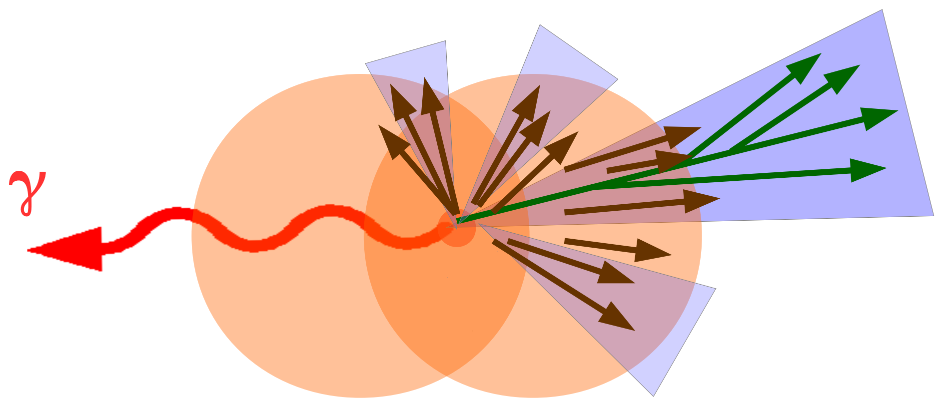
$$\sigma(|\phi^{RECO}-\phi^{GEN}|)=\sqrt{C^2+\frac{S^2}{p_T^{GEN}}+\frac{N^2}{(p_T^{GEN})^2}}$$

arXiv:1706.04965 submitted to JINST

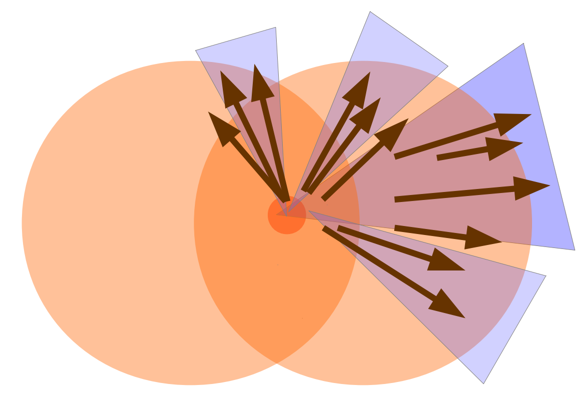


BKG subtraction for jets and tracks

isolated-photon+jet event



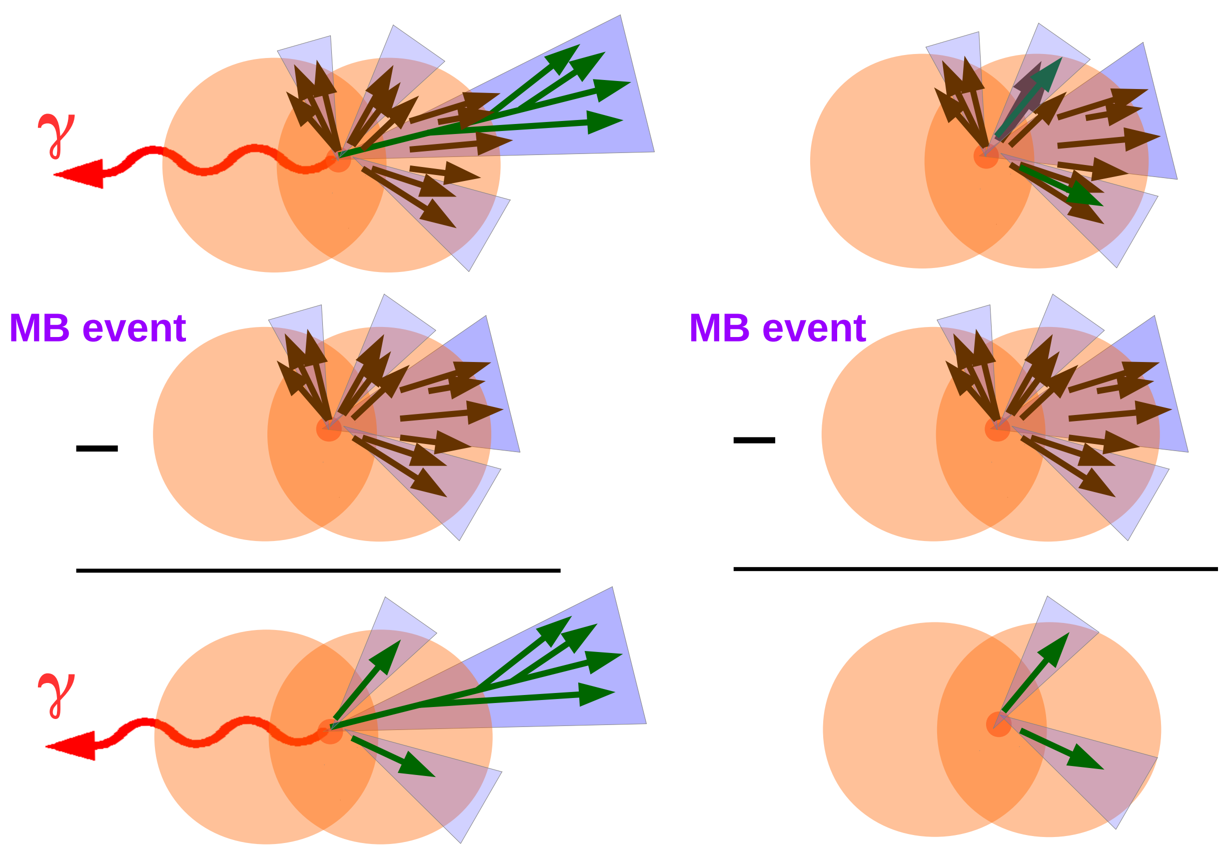
MB event



- MB event mixing technique
  - Estimate the bkg from fake jets and bkg tracks by constructing the observable using jets and tracks in matching MB events
- For each signal event find MB events with very close
  - centrality bin
  - vertex position in z-direction
  - event plane angle

Analysis steps – bkg tracks

isolated-photon+jet event **MB event**



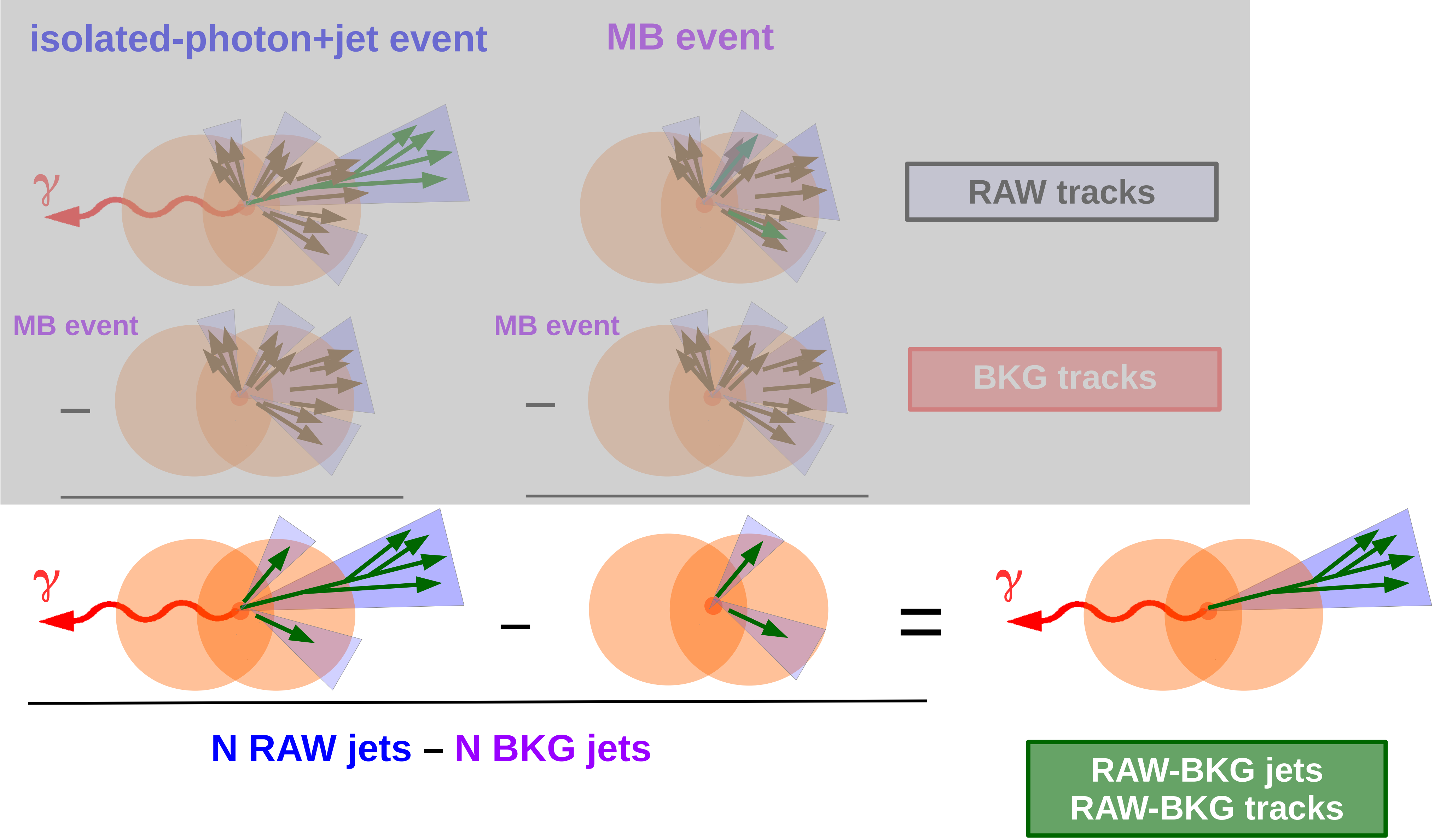
RAW tracks

BKG tracks

RAW jets
RAW-BKG tracks

BKG jets
RAW-BKG tracks

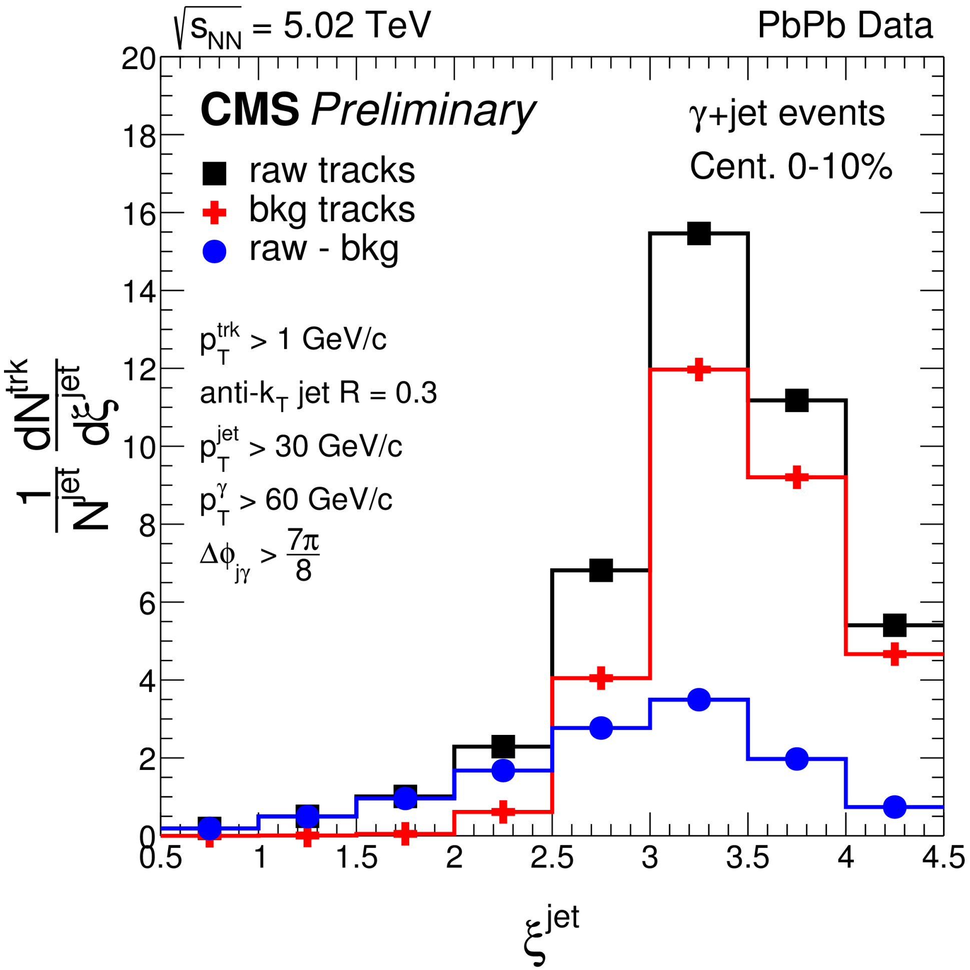
Analysis steps – bkg jets

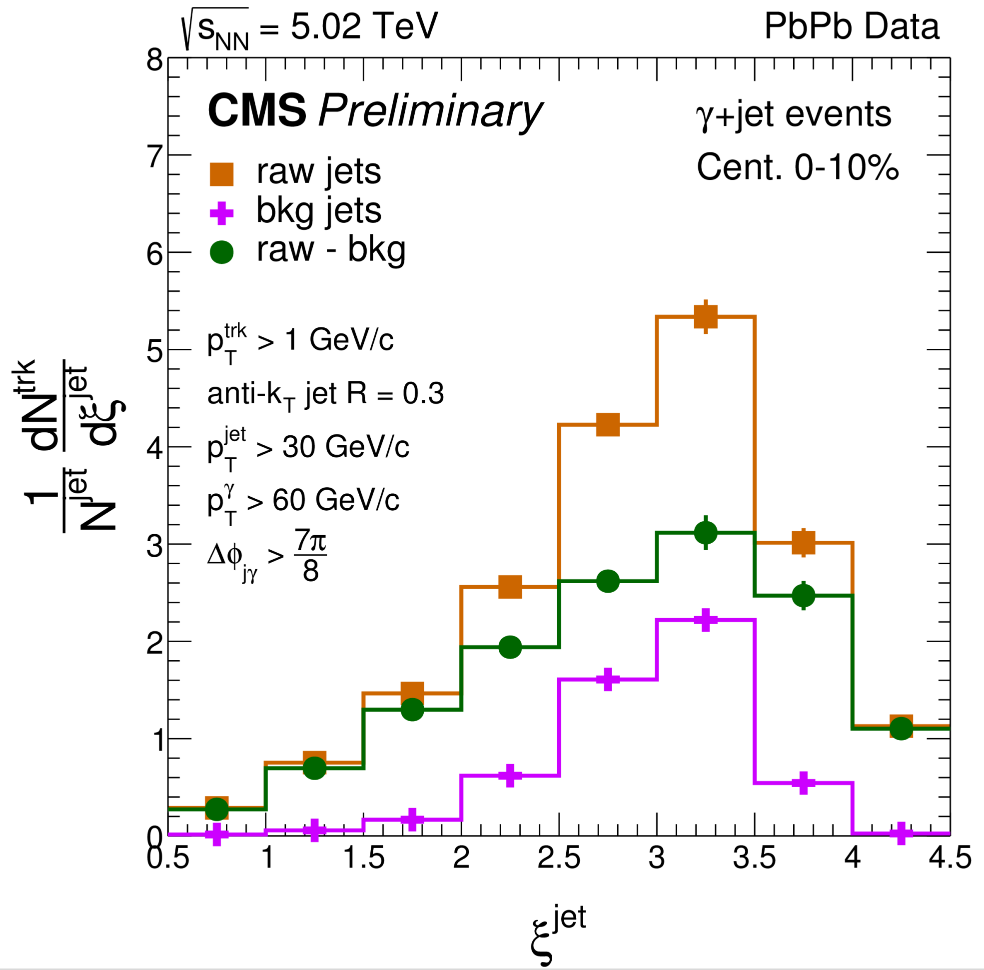


BKG subtraction – tracks and jets

Raw tracks inside jet cone
-
Bkg tracks inside jet cone
=
Raw – Bkg
(bkg track subtracted)

Raw jets
-
Bkg jets
=
Raw – Bkg
(bkg track and bkg jet subtracted)



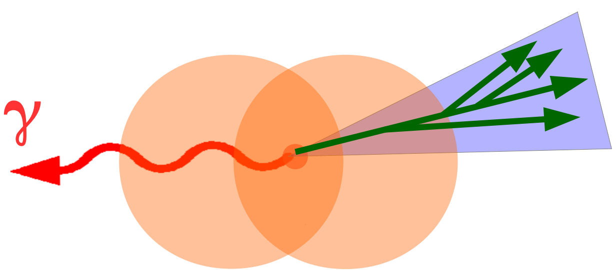


Analysis steps - photons

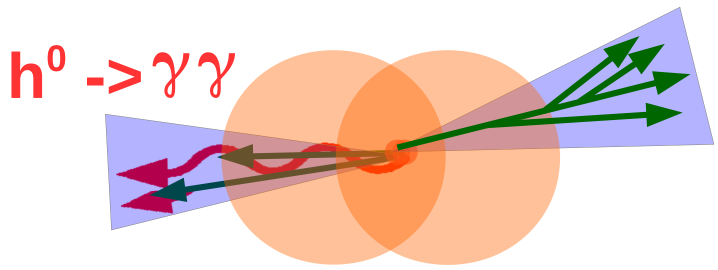
Repeat the previous steps for two photon selections

1. **photon candidate, $\sigma_{\eta\eta} < 0.01$**
2. **photon sideband, $0.011 < \sigma_{\eta\eta} < 0.017$**

photon candidate
$\sigma_{\eta\eta} < 0.01$



photon sideband
$0.011 < \sigma_{\eta\eta} < 0.017$



$$\frac{1}{\text{purity}} \times \boxed{\text{FF from photon candidates}} - \frac{1-\text{purity}}{\text{purity}} \times \boxed{\text{FF from photon sideband}} = \boxed{\text{FINAL RESULT}}$$

Results - ξ^{jet}

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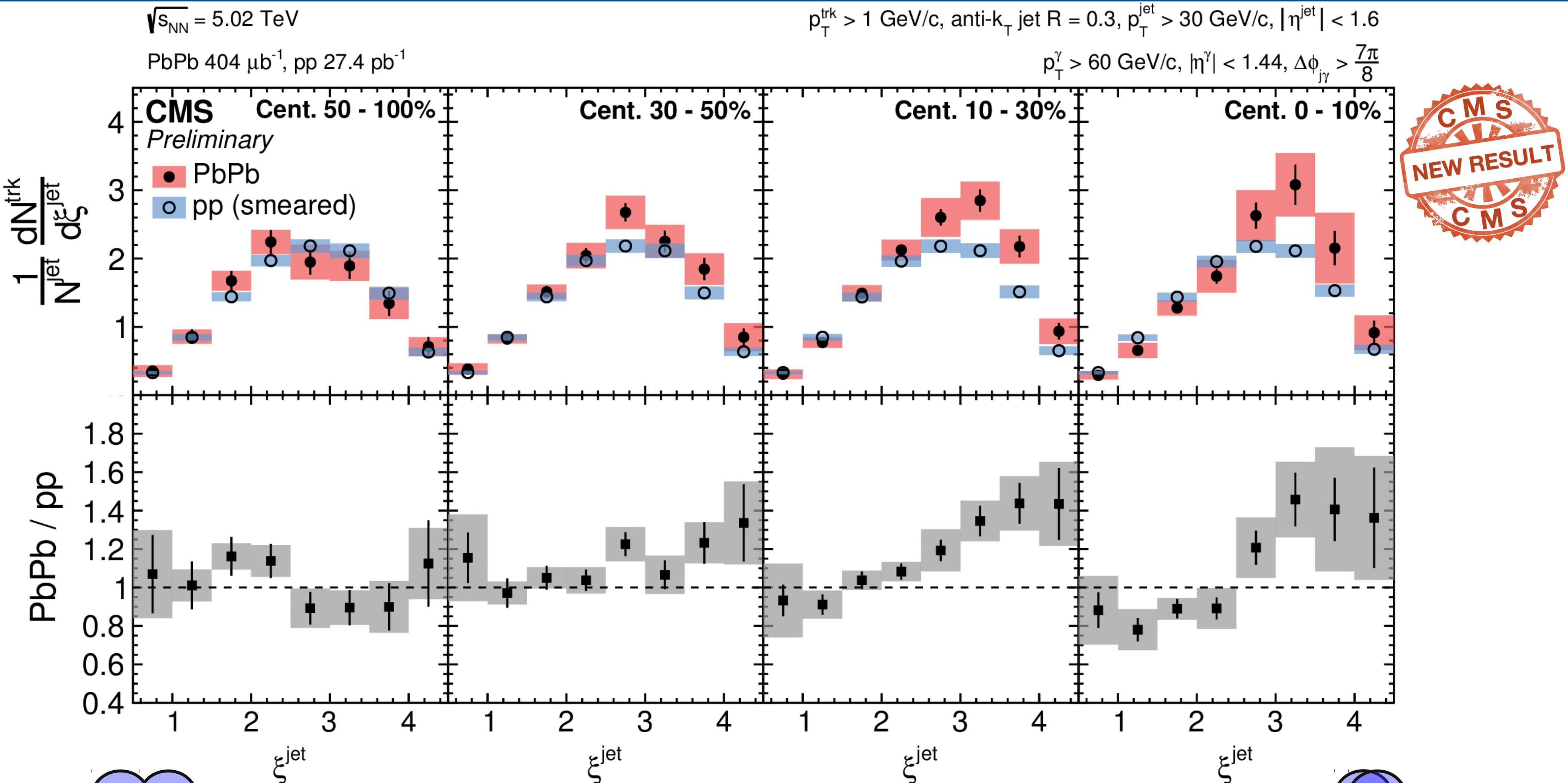
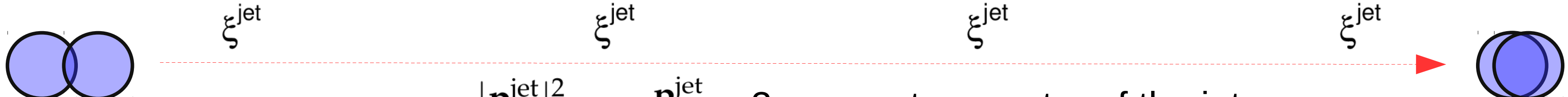




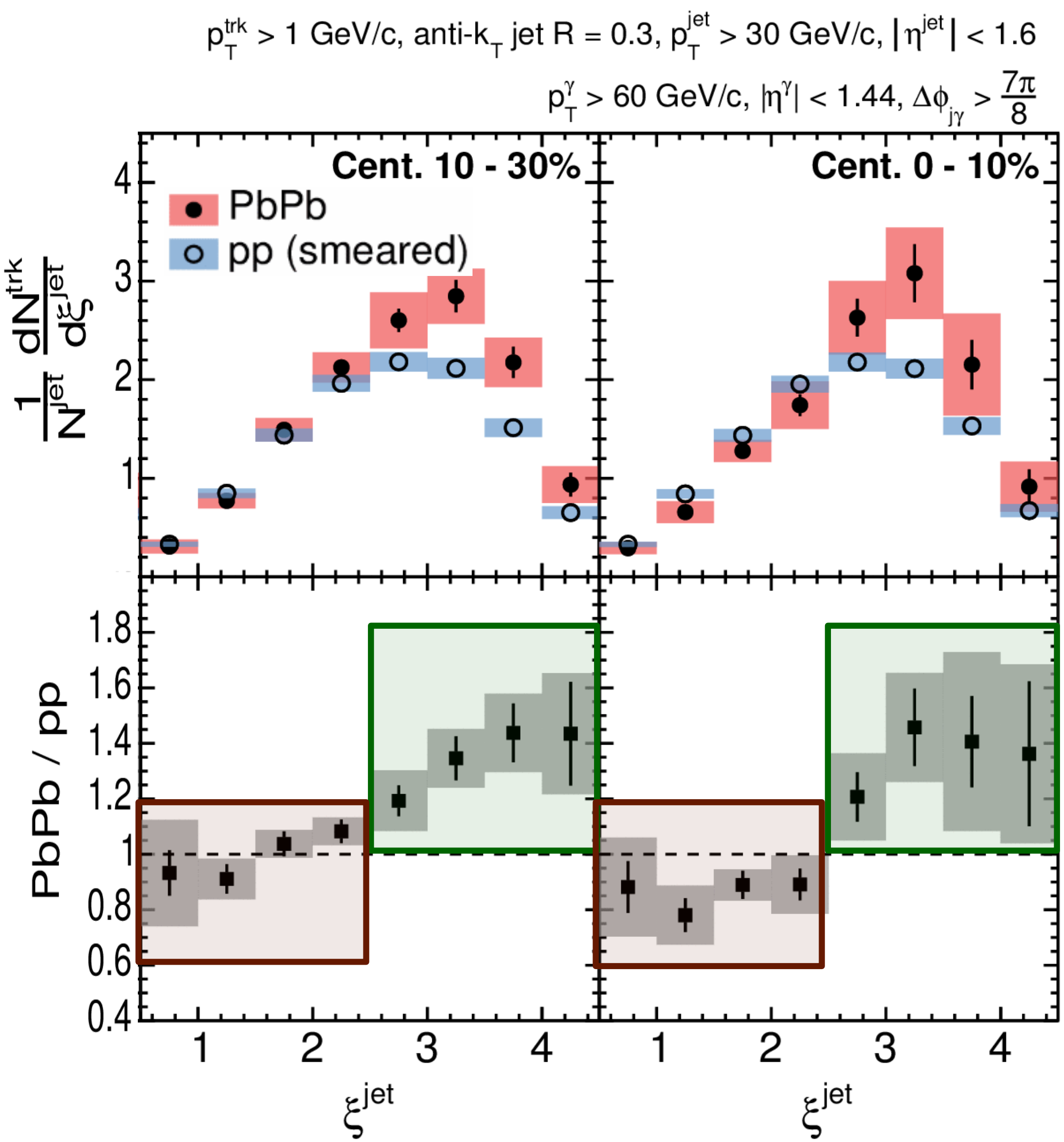
$$\xi^{jet} = \ln \frac{|\mathbf{p}^{jet}|^2}{\mathbf{p}^{trk} \cdot \mathbf{p}^{jet}}$$

$\mathbf{p}^{jet}$: 3-momentum vector of the jet
$\mathbf{p}^{trk}$: 3-momentum vector of the track

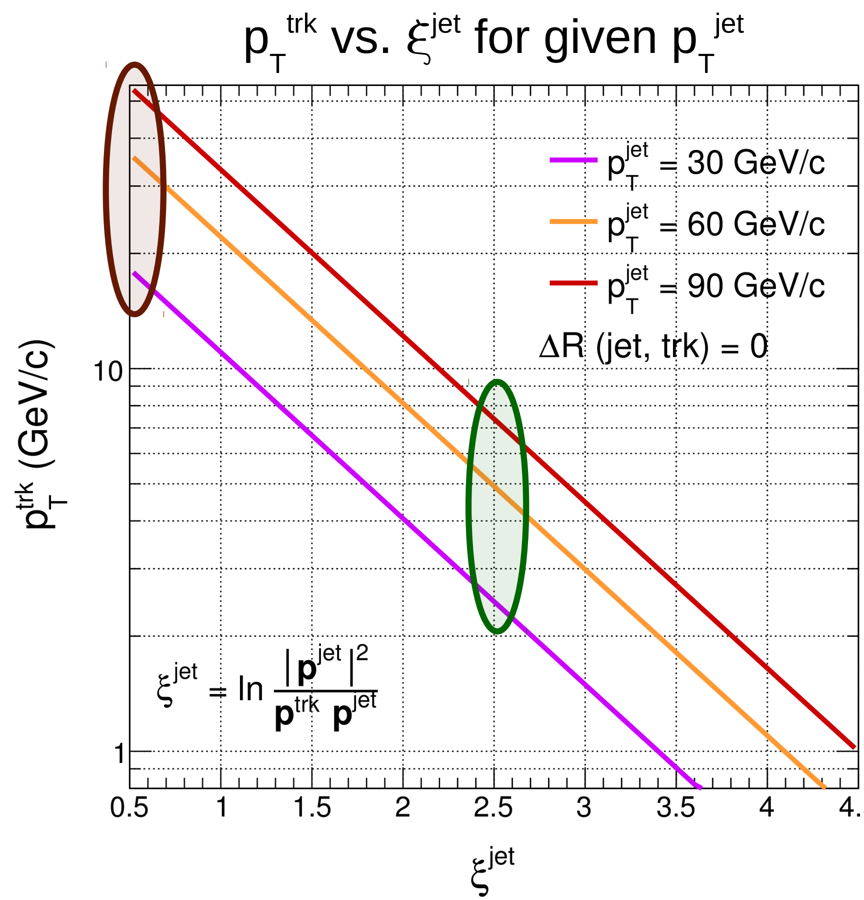
In central collisions, ξ^{jet} in PbPb is modified suggesting an **enhancement of low energy particles** and a **depletion of high energy particles**. Peripheral PbPb is consistent with pp.

Results - ξ^{jet}

CMS-PAS HIN-16-014



Based on reconstructed jet energy
(energy after quenching)



Transition at $\xi^{jet} \approx 2.5$ –> $p_T^{trk} \approx 3$ GeV

Enhancement for $\xi^{jet} > 2.5$

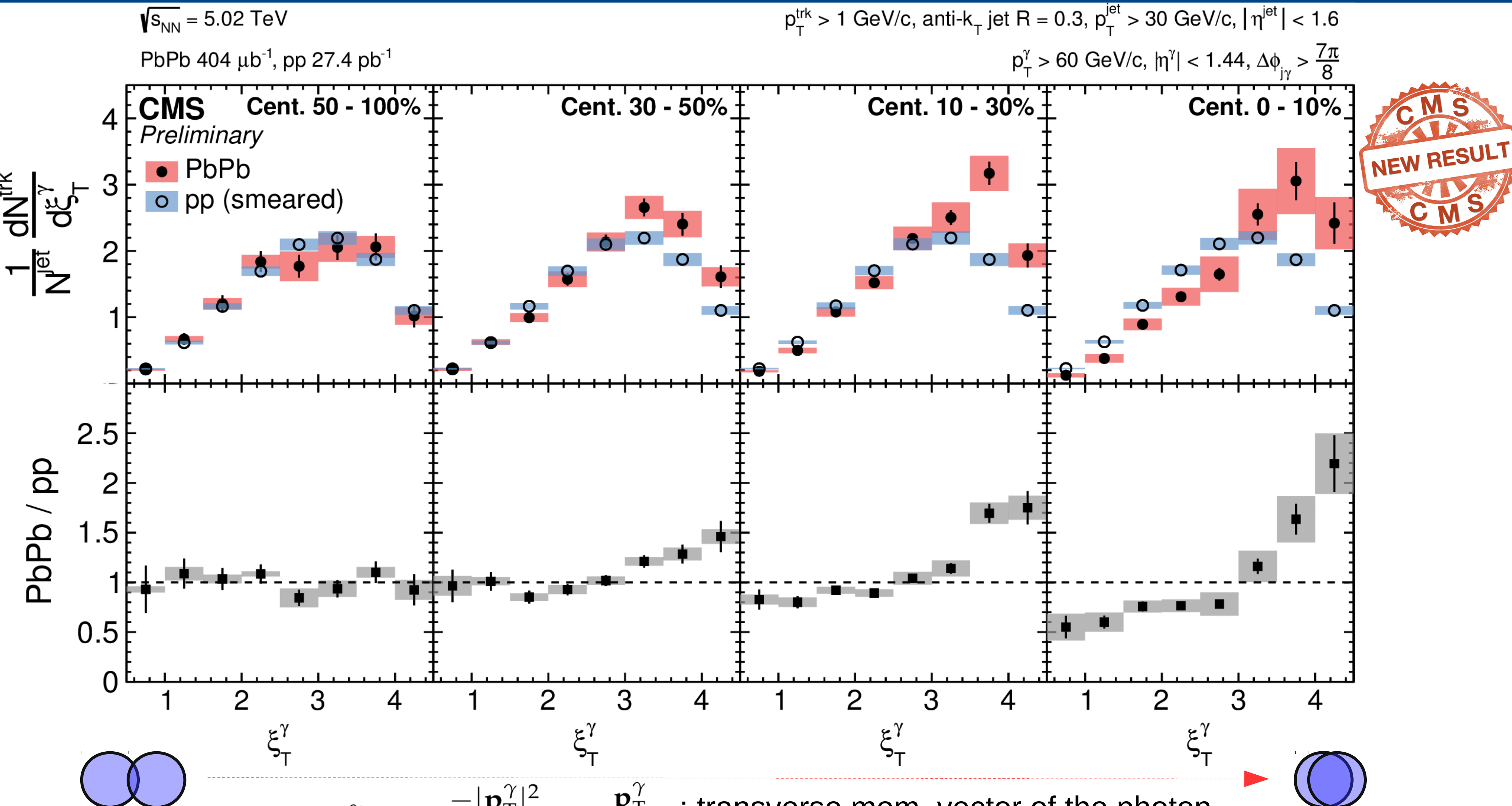
$p_T^{trk} \lesssim 2.5$ GeV/c for $p_T^{jet} \approx 30$ GeV/c

Slight depletion for $\xi^{jet} < 2.5$

$2.5 \lesssim p_T^{trk} \lesssim 18$ GeV/c for $p_T^{jet} \approx 30$ GeV/c

Results - ξ_T^{γ}

CMS-PAS HIN-16-014



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

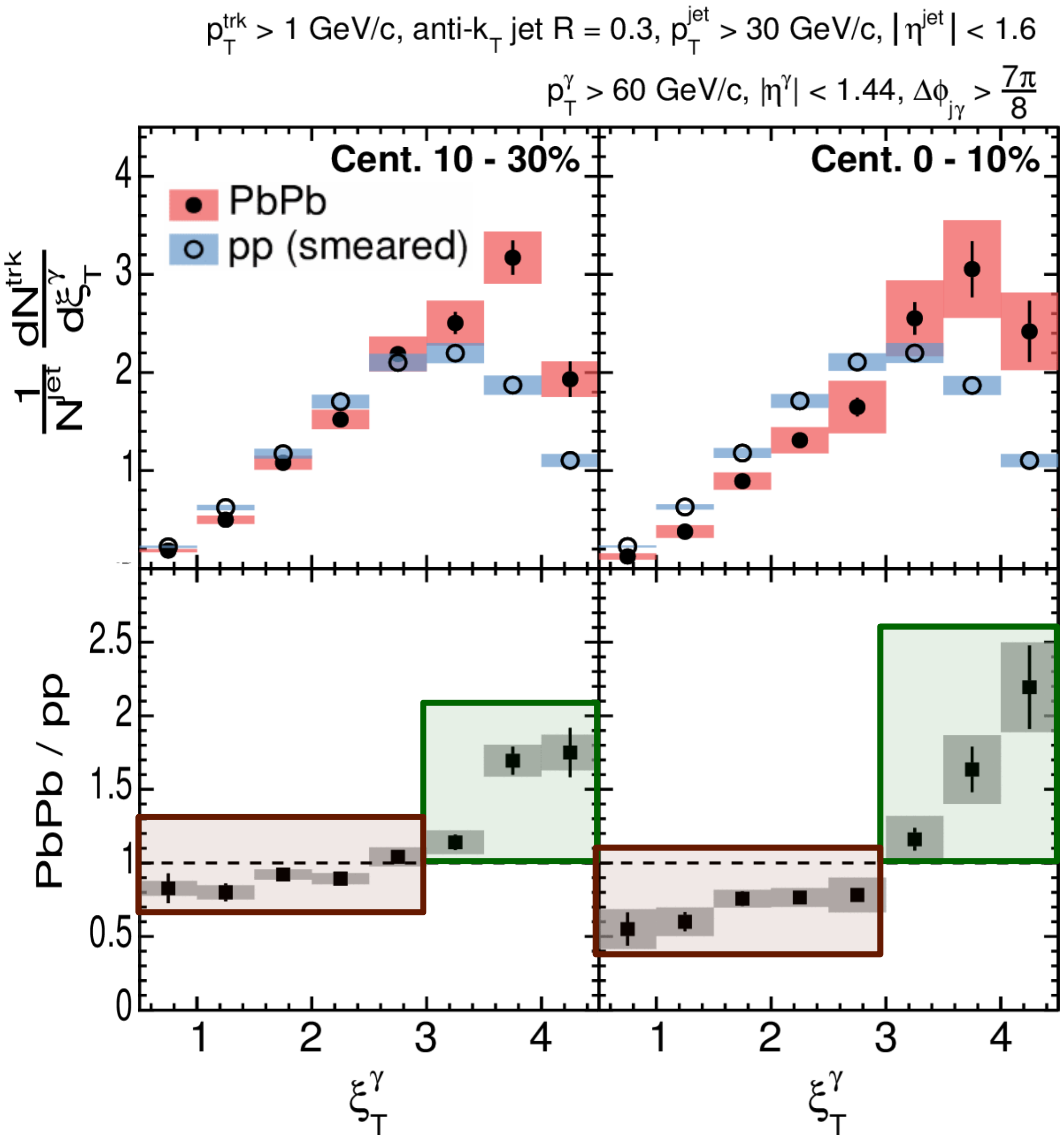
$\mathbf{p}_T^{\gamma}$: transverse mom. vector of the photon

$\mathbf{p}_T^{trk}$: transverse mom. vector of the track

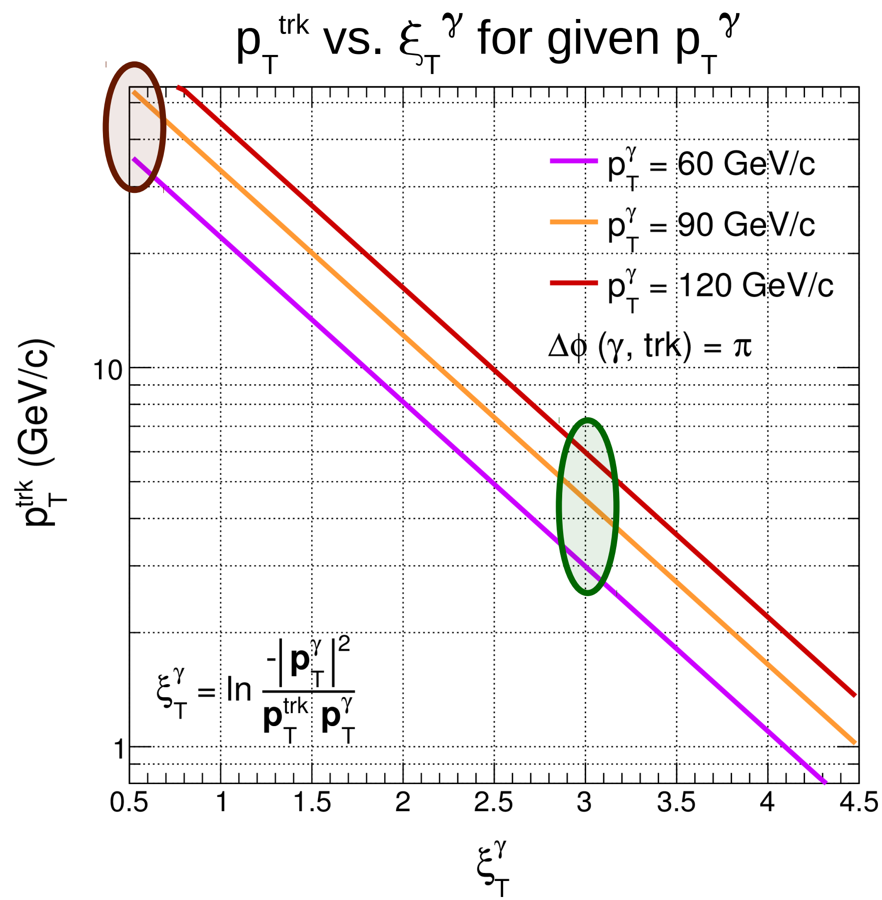
In central collisions, ξ_T^{γ} is modified suggesting an **enhancement of low energy particles** and a **depletion of high energy particles**. **More significant than** ξ^{jet}. Peripheral PbPb is consistent with pp.

Results - ξ_T^γ

CMS-PAS HIN-16-014



Based on initial parton energy (energy before quenching)



Transition at $\xi_T^\gamma \approx 3$ –> $p_T^{trk} \approx 3$ GeV

Enhancement for $\xi_T^\gamma > 3$

$p_T^{trk} \lesssim 3$ GeV/c for $p_T^\gamma \approx 60$ GeV/c

Depletion for $\xi_T^\gamma < 3$

$3 \lesssim p_T^{trk} \lesssim 36$ GeV/c for $p_T^\gamma \approx 60$ GeV/c

Results - ξ^{jet} vs ξ_T^{γ}

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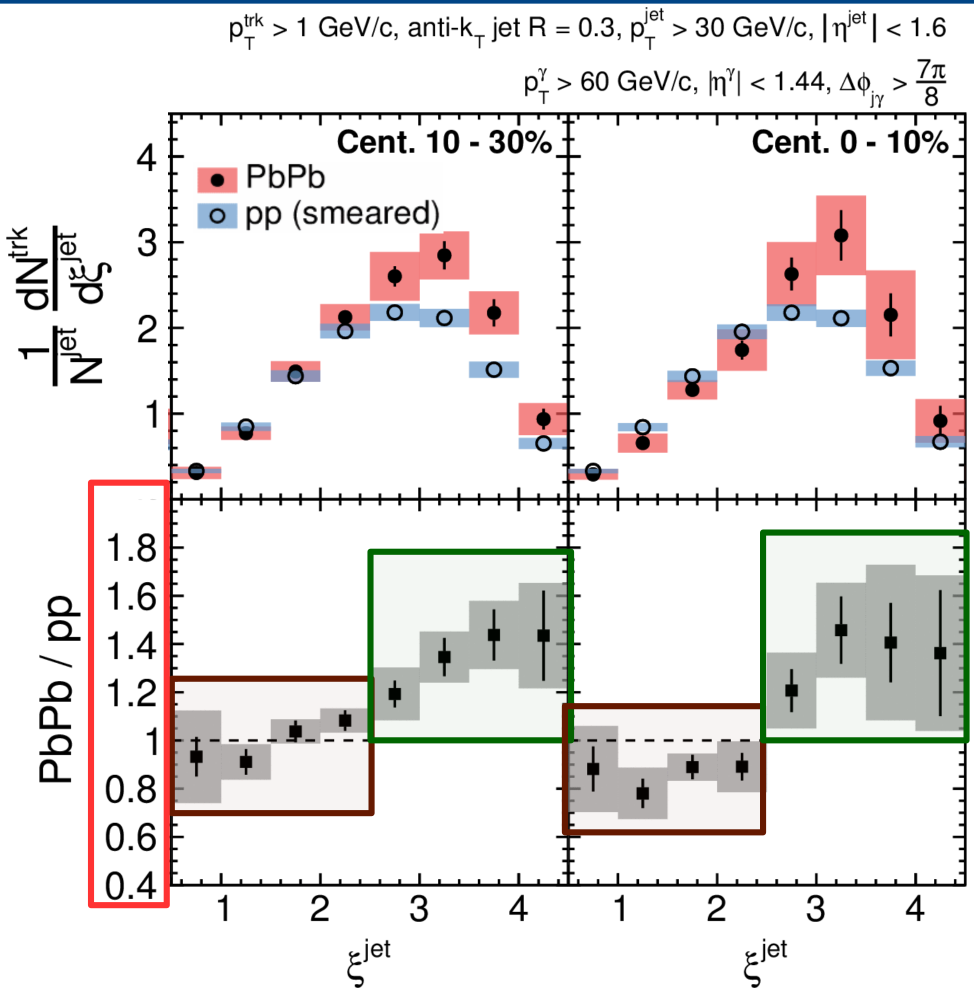
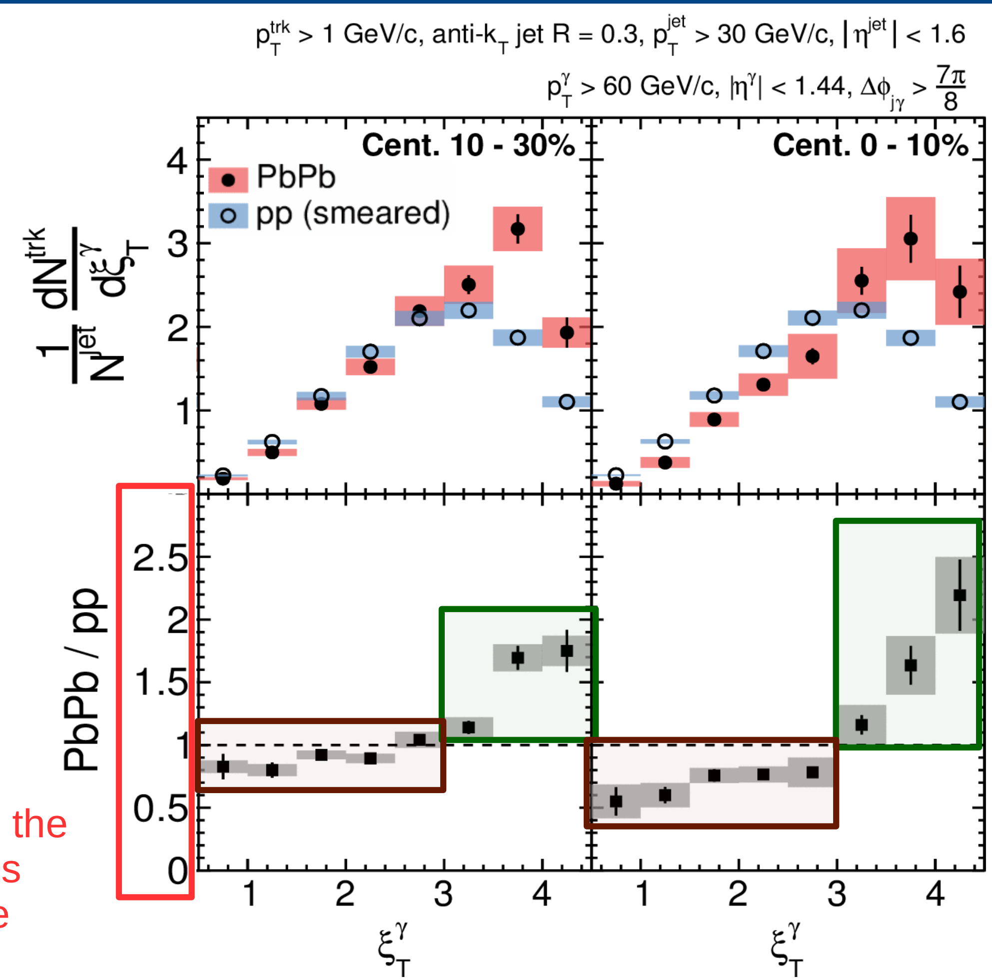


Note the y-axis scale



ξ^{jet} and ξ_T^{γ} are **measured together for the first time**.

ξ^{jet}

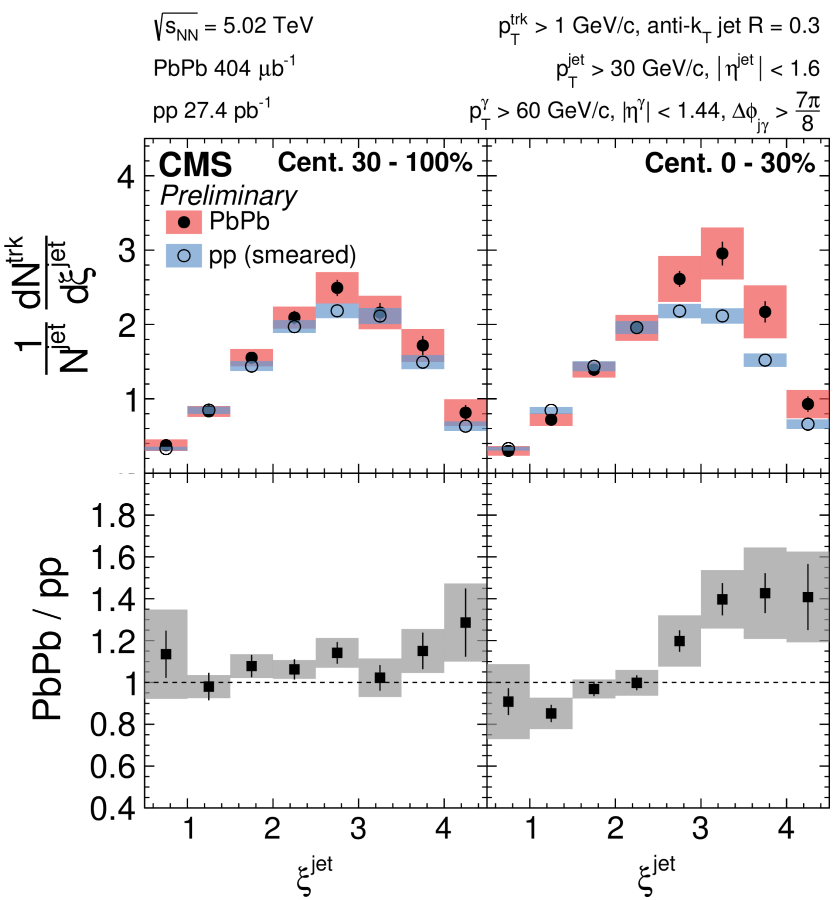
- Based on reconstructed jet energy (energy after quenching)
- Jets are tagged by photon.
- General shift to left compared to ξ_T^{γ}
  - Out-of-cone radiation, photon+>1 jet , quenching in PbPb

ξ_T^{γ}

- Based on initial parton energy
- Modification is relatively stronger.
- Centrality dependence is more clear.

Summary

- FF of jets associated with isolated-photons is measured for the **first time** in pp and PbPb collisions.
- Selection based on isolated photon provides helps **tagging the initial parton kinematics**.
- Study is done using jet momentum based and photon momentum based FF observables : ξ^{jet} and ξ_T^{γ}
- For both ξ^{jet} and ξ_T^{γ}, distributions in central collisions are modified indicating an **excess of low pt particles** and a **depletion of high pt particles** inside the jet cone. Relatively stronger picture with ξ_T^{γ}.



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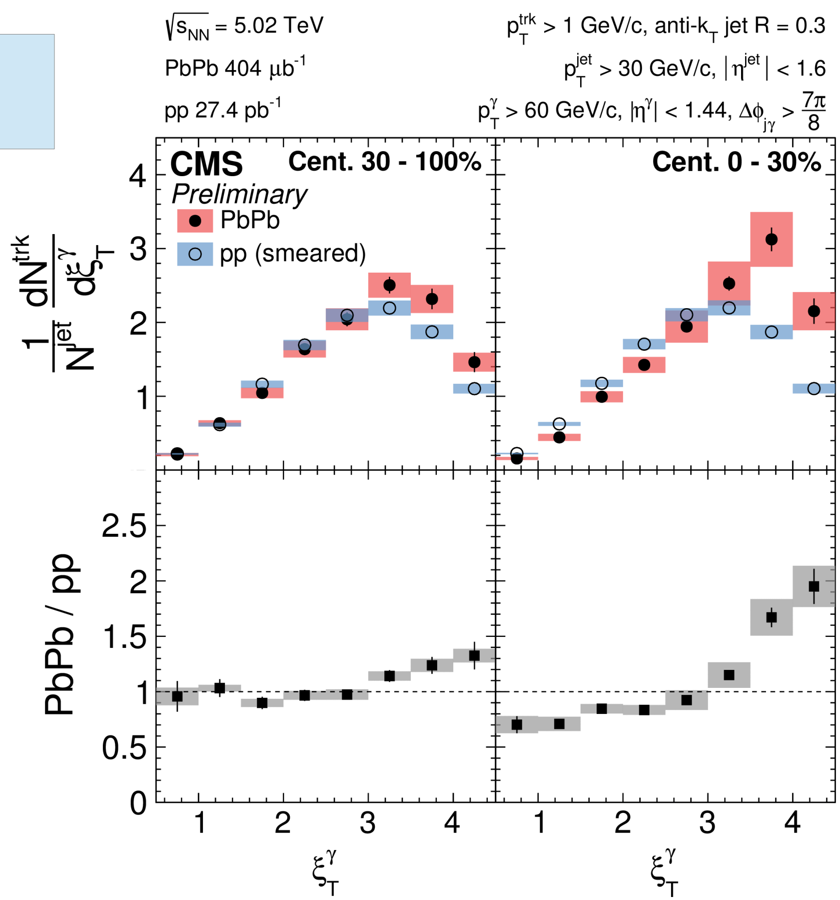
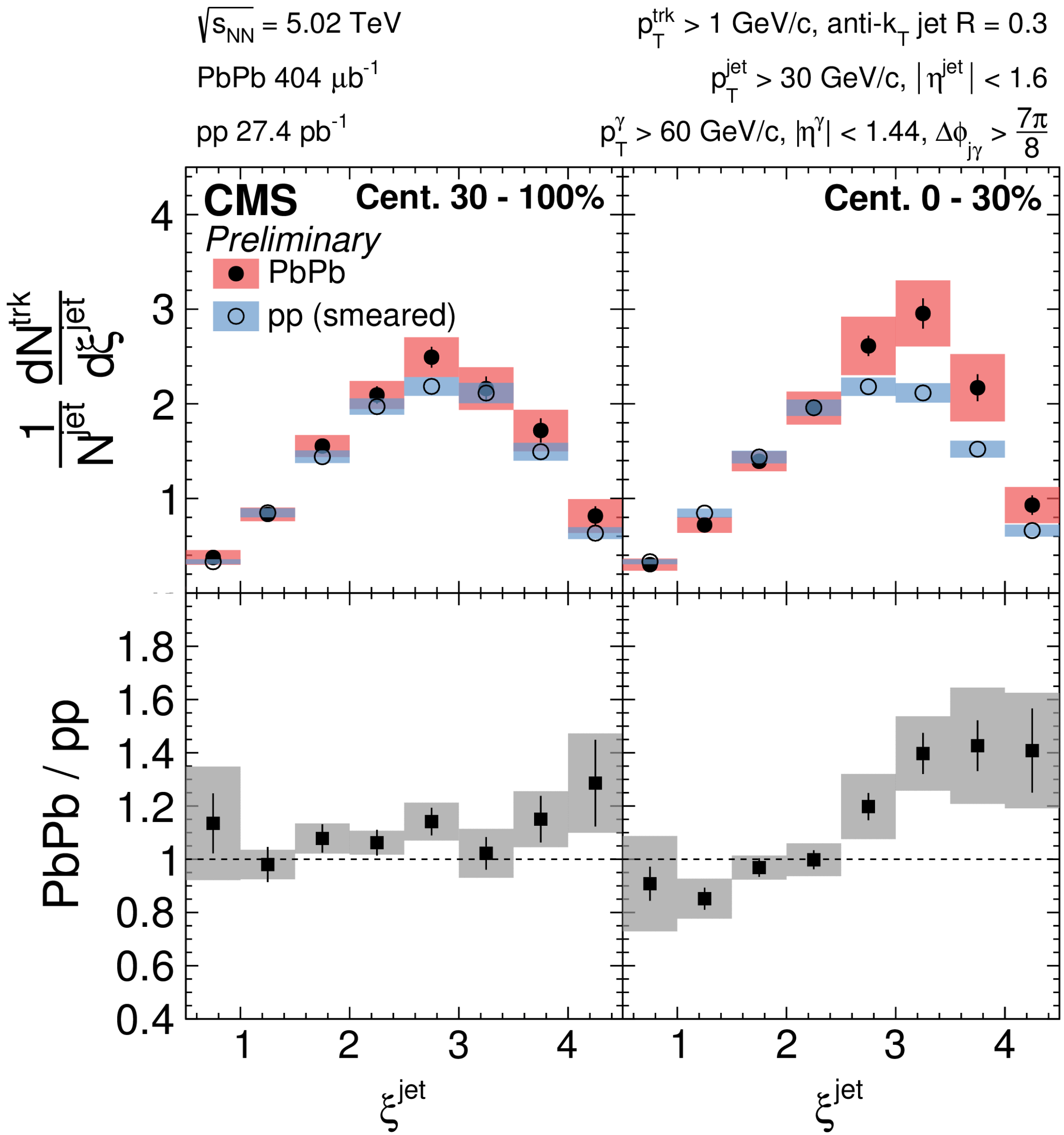
Results in 2 centrality bins



BACKUP

Results – ξ^{jet} : 30-100%, 0-30%



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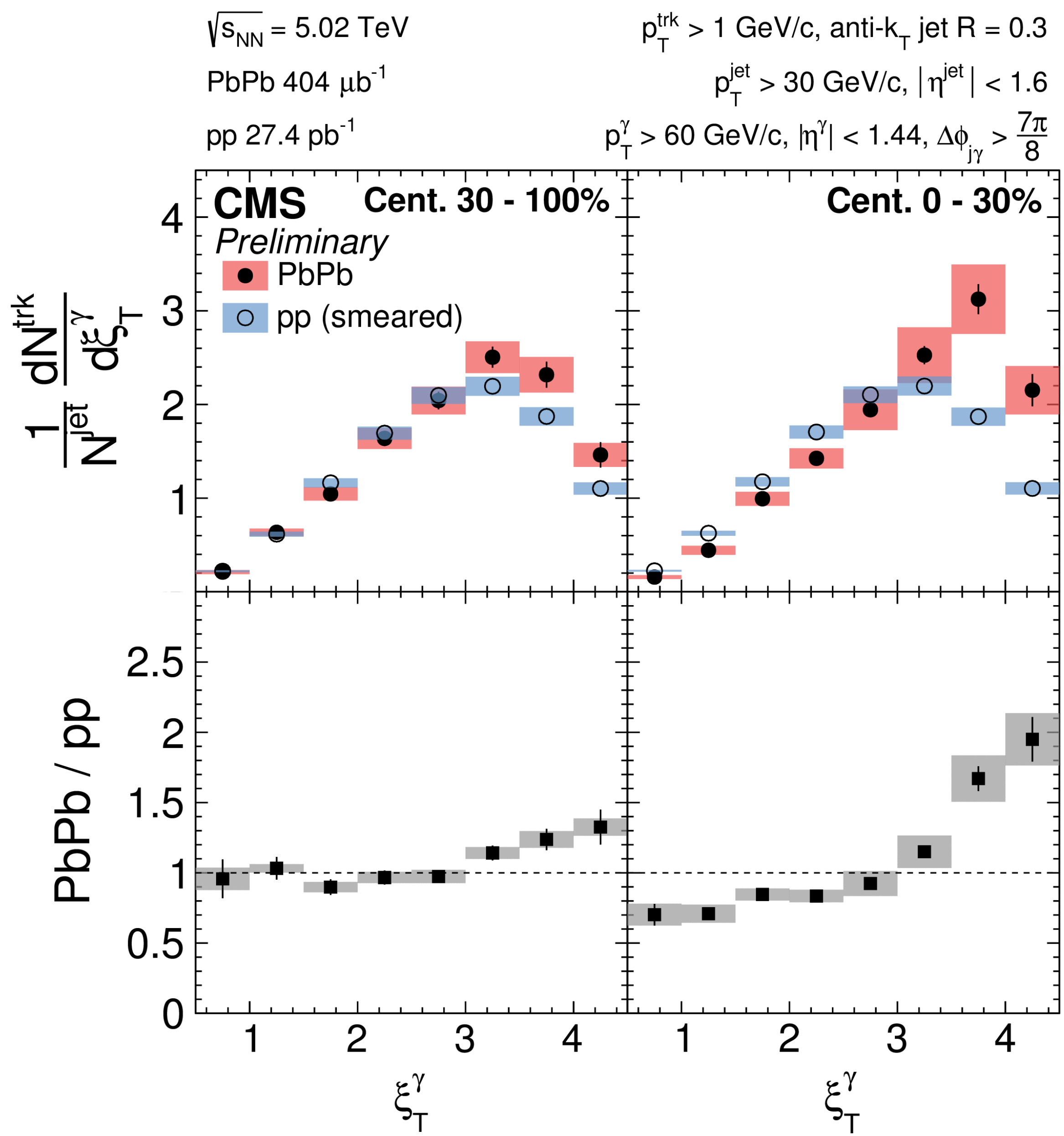
NEW RESULT

Perform measurement with coarser centrality binning

Increased significance

Results – ξ_T^γ : 30-100%, 0-30%



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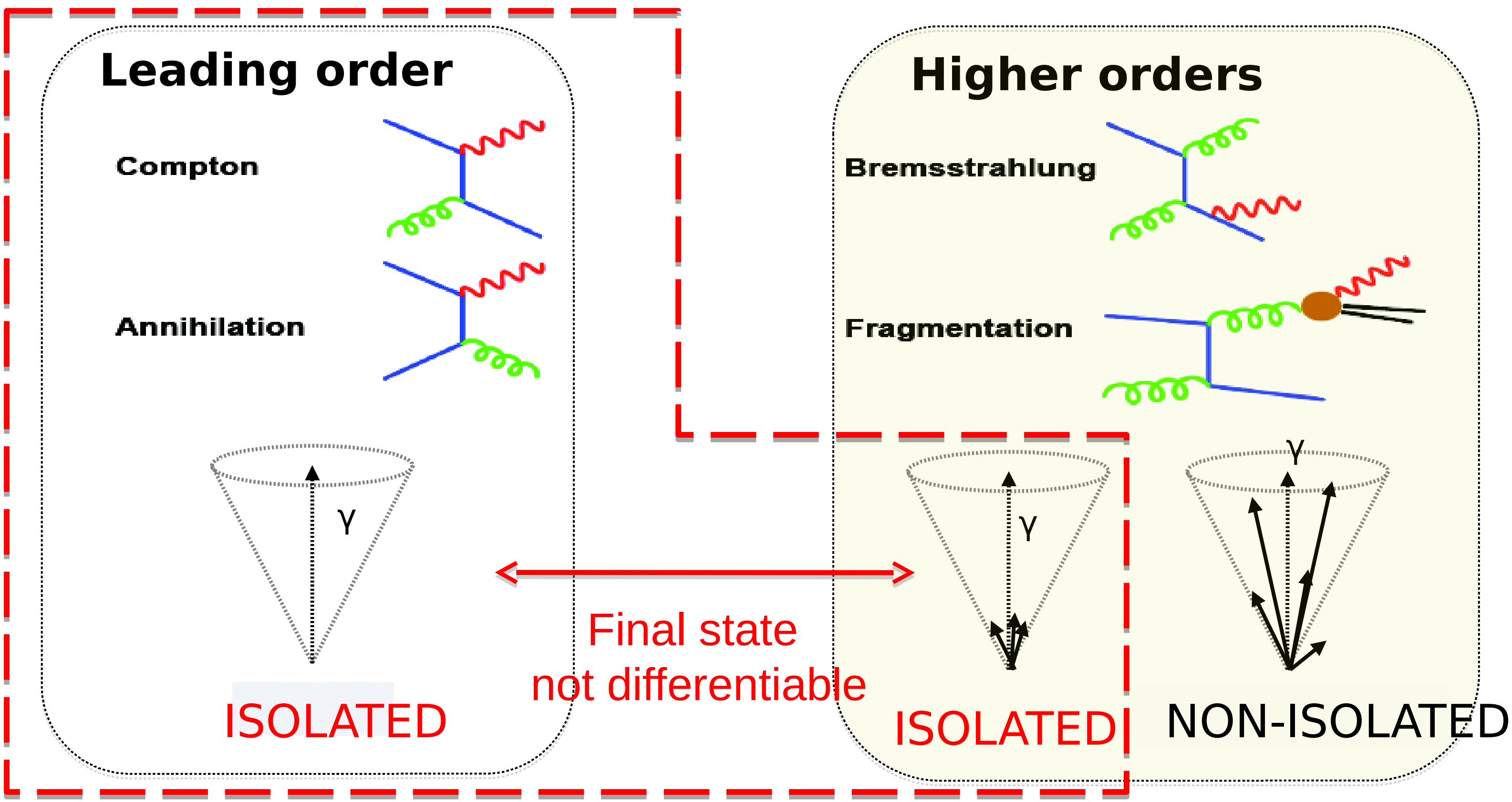
Perform measurement with coarser centrality binning

Increased significance

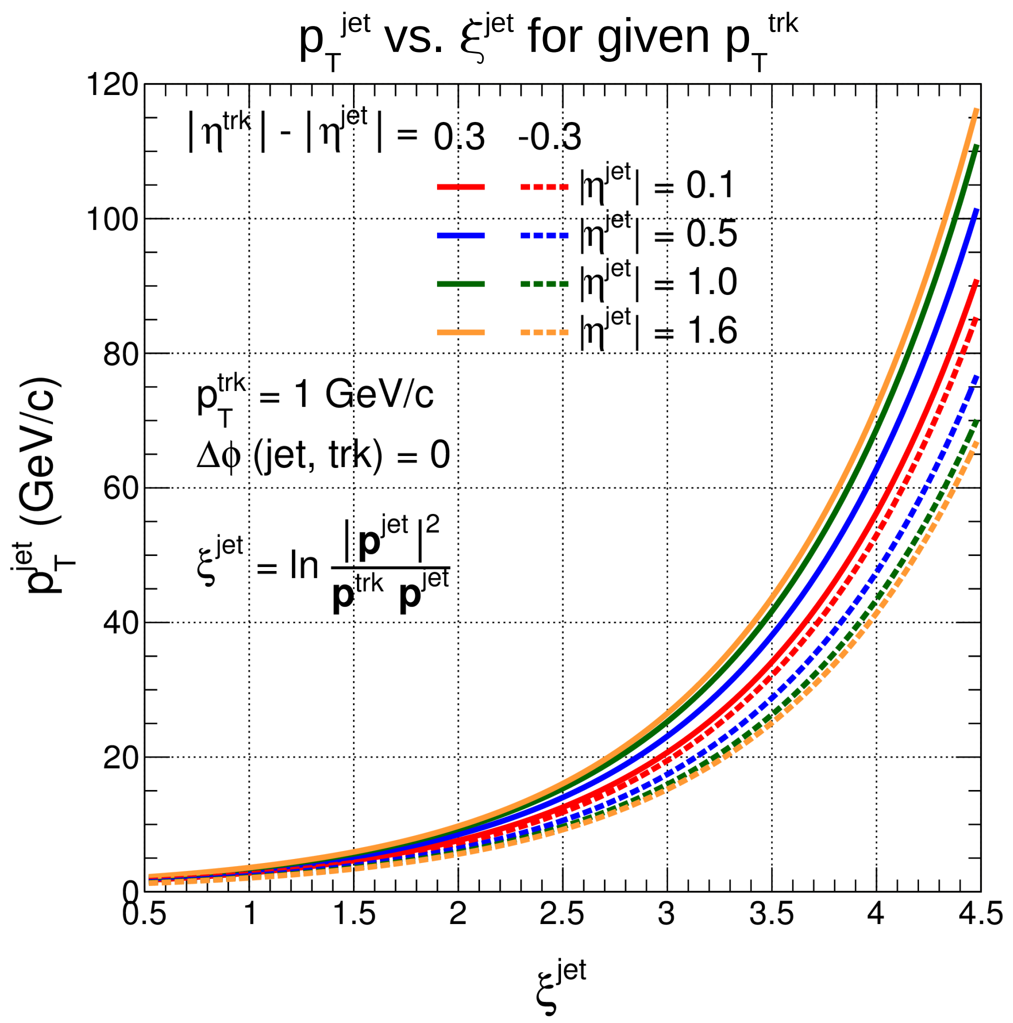
Signal Photon

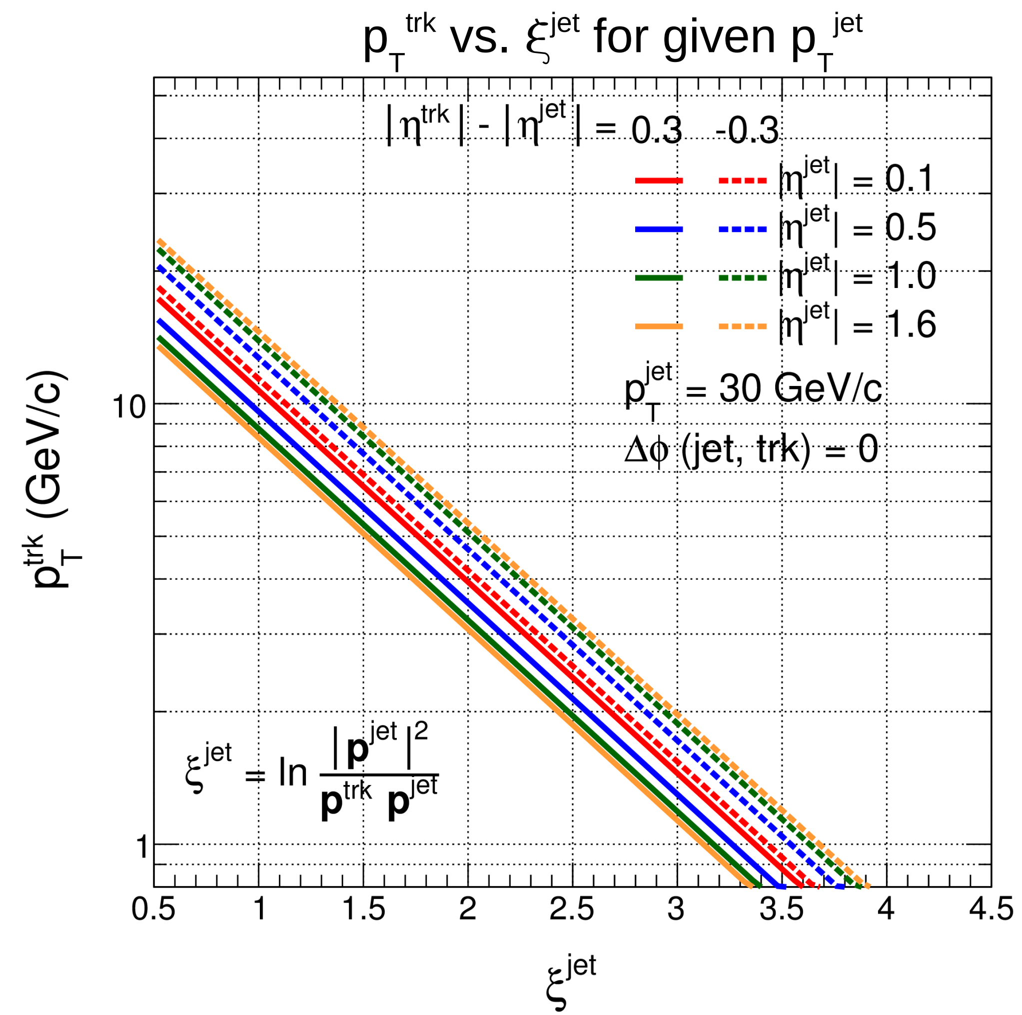
Identify signal photons by :

- Isolation requirement based on calorimeter deposits and tracks
- Extract fraction of signal photons based on shower shape



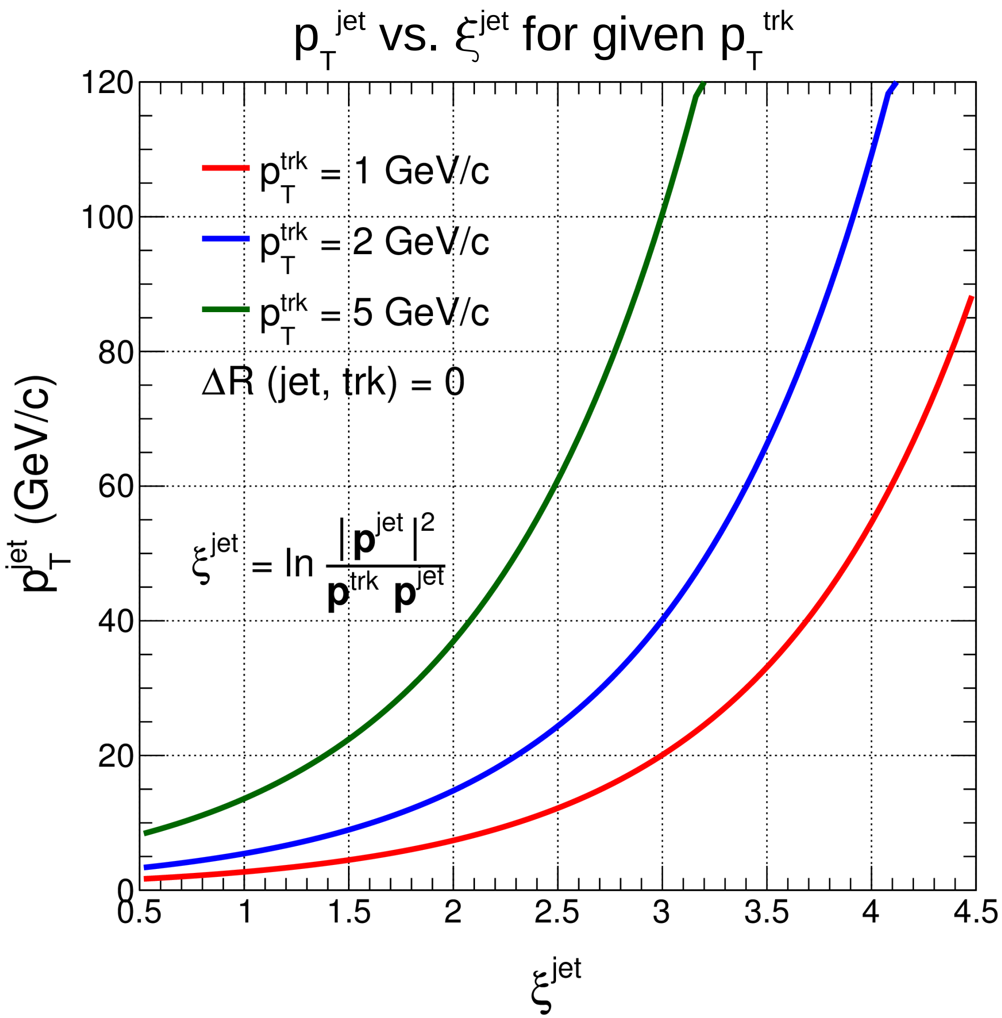
ξ^{jet} phase space

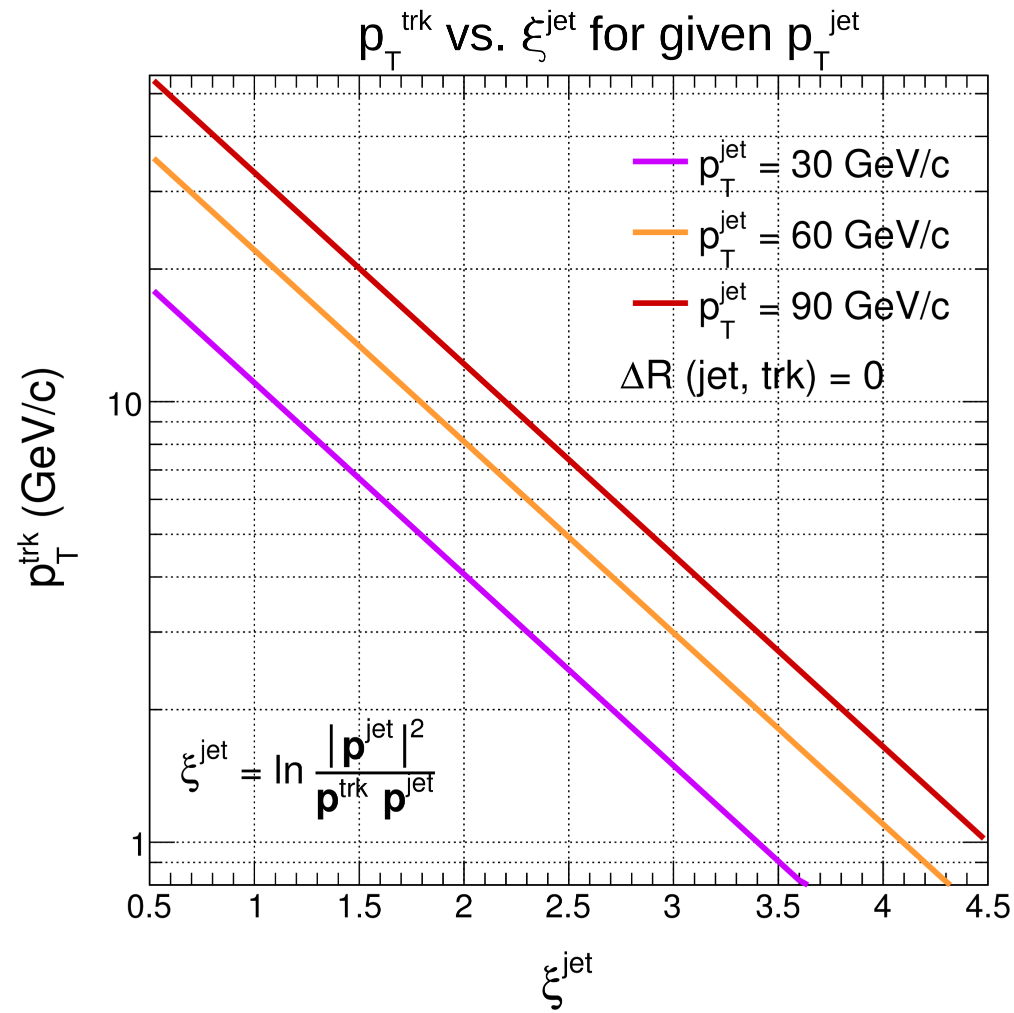




In general the mapping depends on $\boldsymbol{\eta^{jet}}$, $\boldsymbol{\eta^{trk}}$ and **ΔR (jet, trk)**.
The solid and dashed lines are the extreme cases for a given η^{jet}.

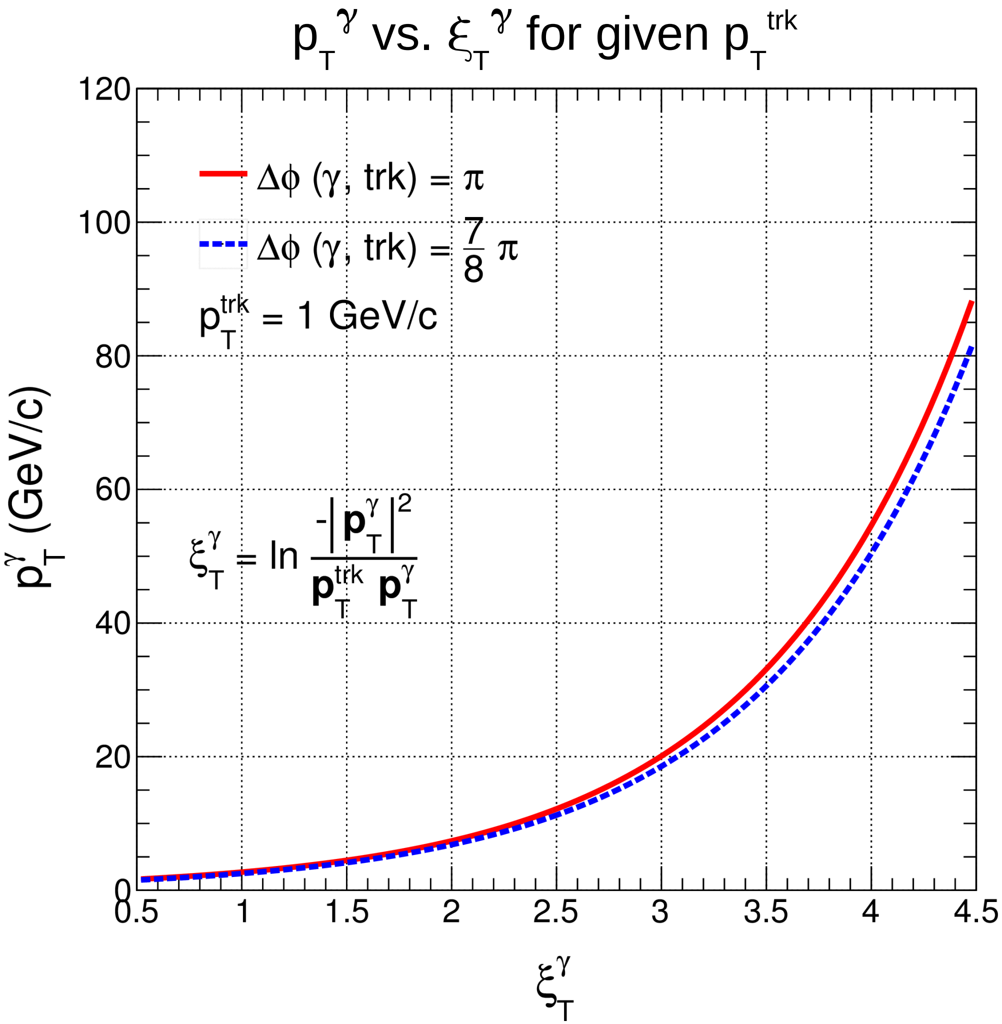
ξ^{jet} phase space

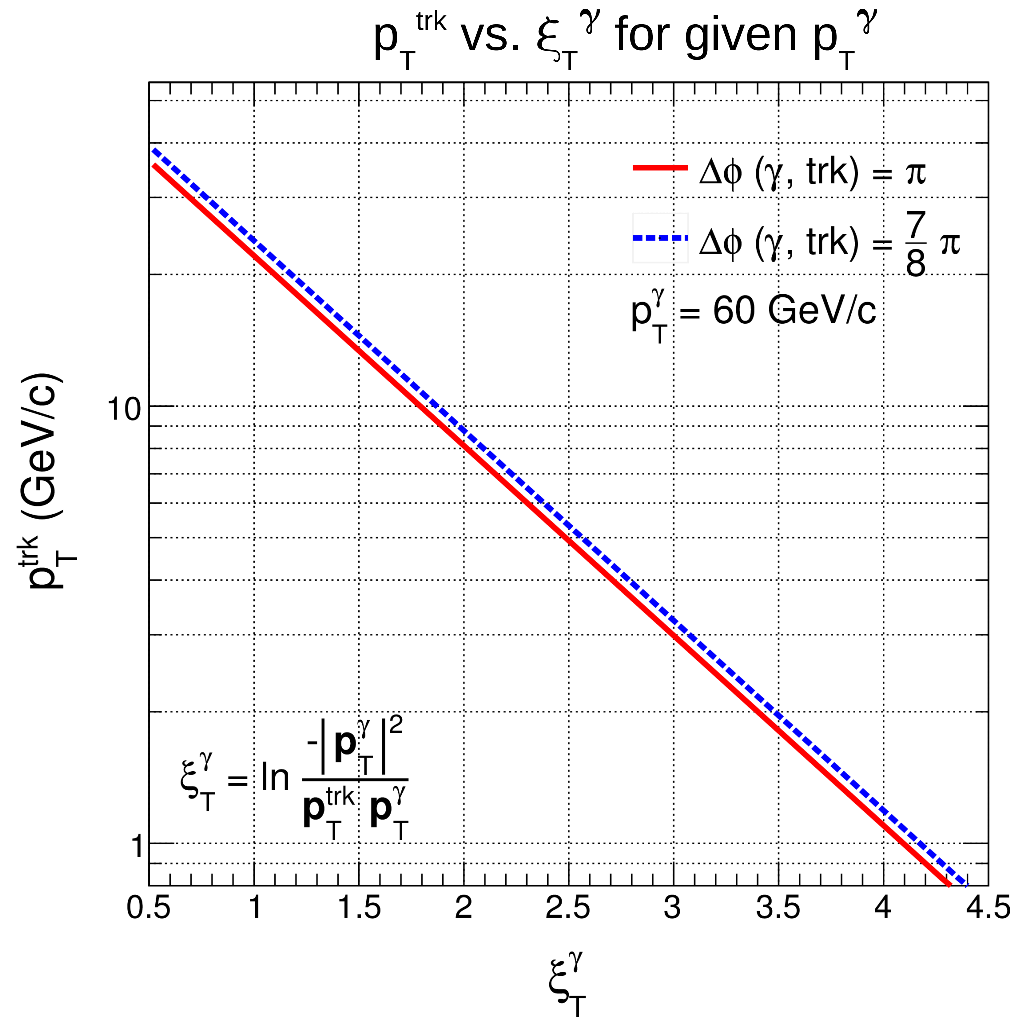




If **ΔR (jet, trk) = 0**, then the mapping becomes **η-indep**.

ξ_T^{γ} phase space



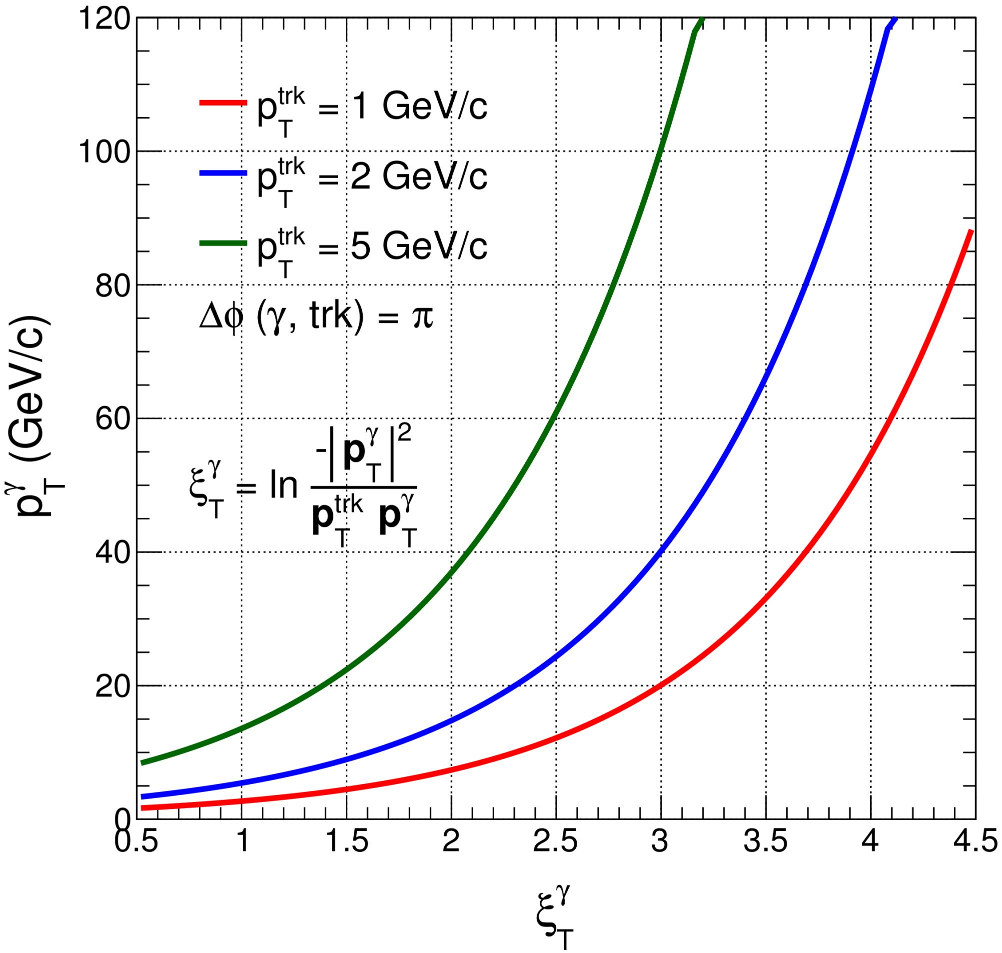


The mapping depends on **$\Delta\varphi\,(\gamma$, trk)**.

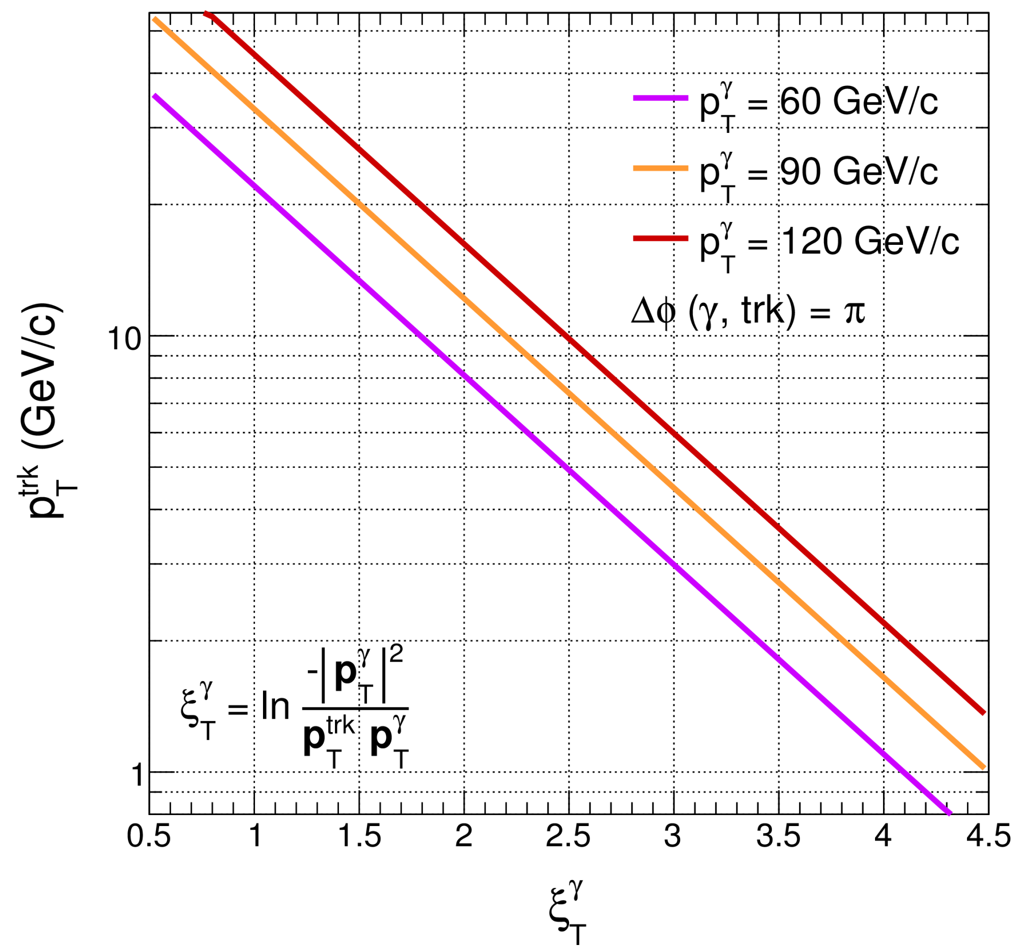
Phase space for ξ_T^{γ} tends to be narrower than for ξ^{jet} because **η** info is not used.

ξ_T^γ phase space

p_T^γ vs. ξ_T^γ for given p_T^{trk}

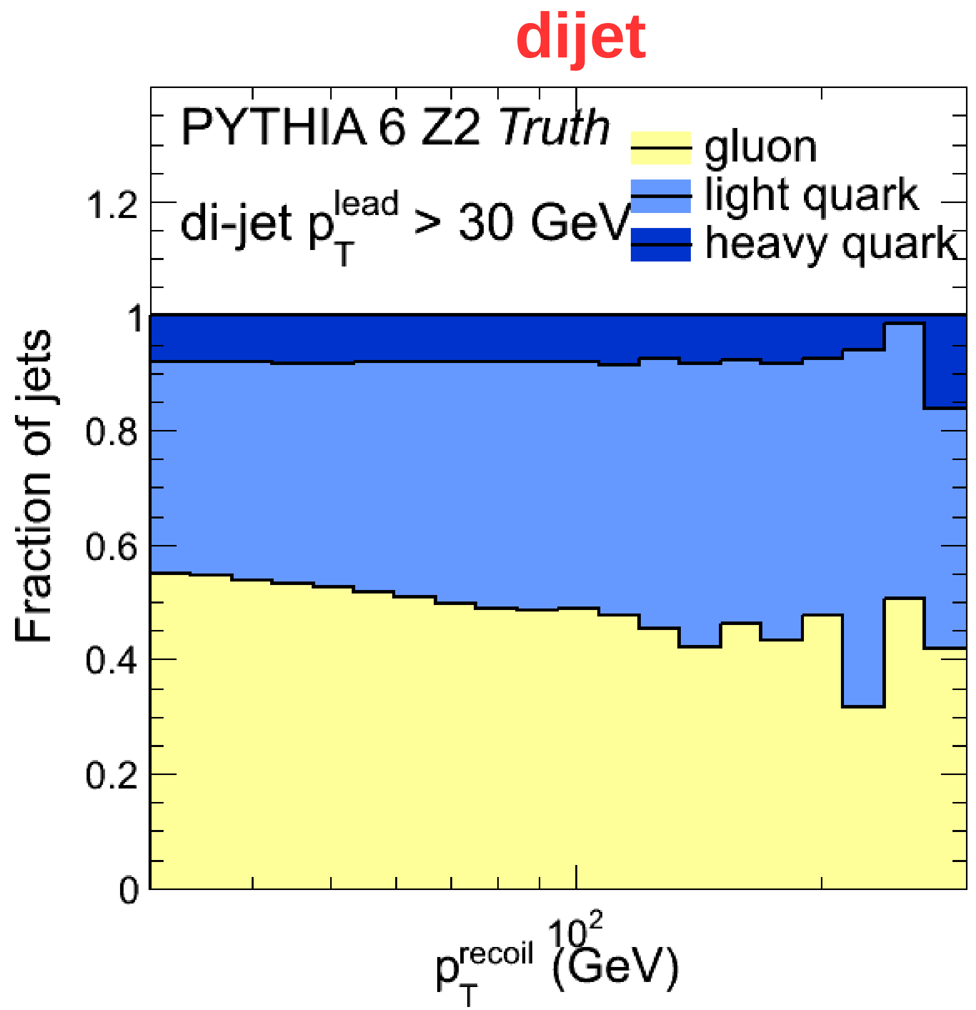


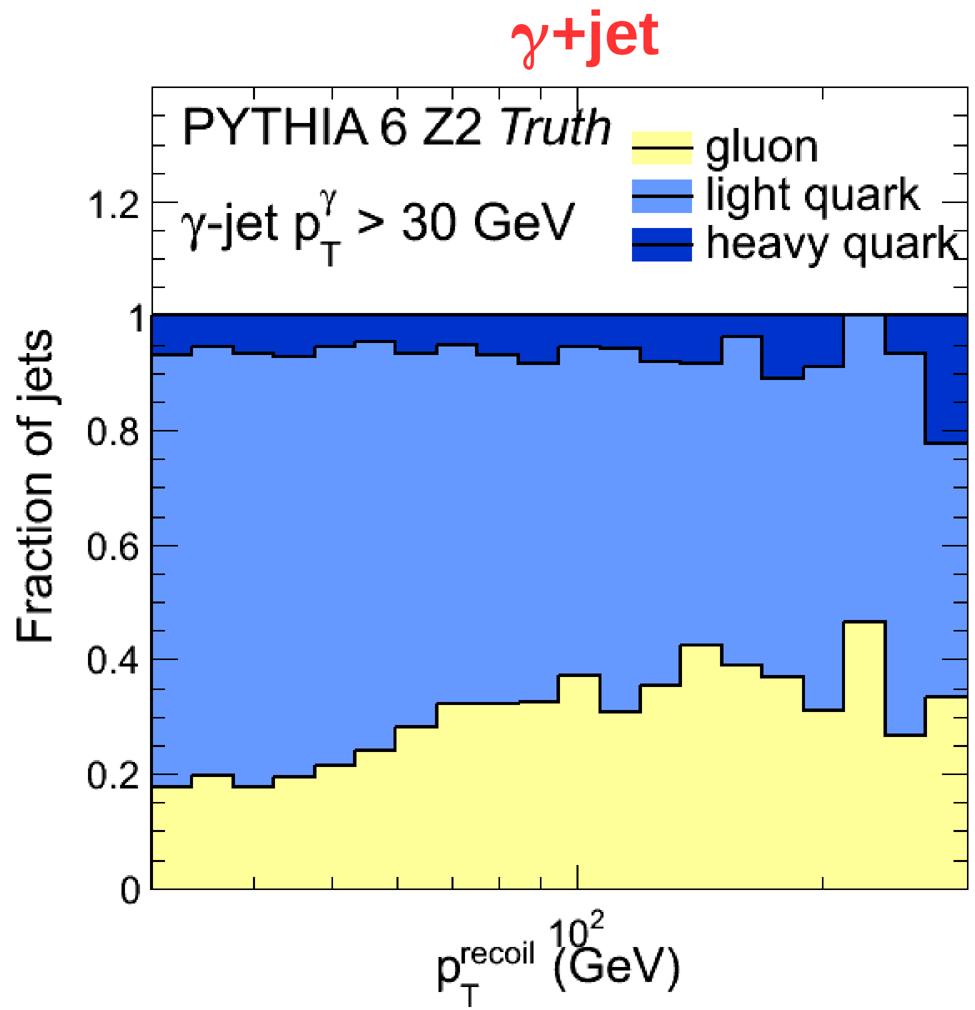
p_T^{trk} vs. ξ_T^γ for given p_T^γ



The **Δφ (γ, trk) = π** case of ξ_T^γ gives the same relation as the **ΔR (jet, trk) = 0** case of ξ^{jet}.

Q/G Fraction of Dijet and Photon+Jet





- Dijet has relatively larger fraction of gluon jets compared to photon+jet.
- Gluon fraction for photon+jet increases with p_T.

Photon+Jet Correlations - <Xjg>

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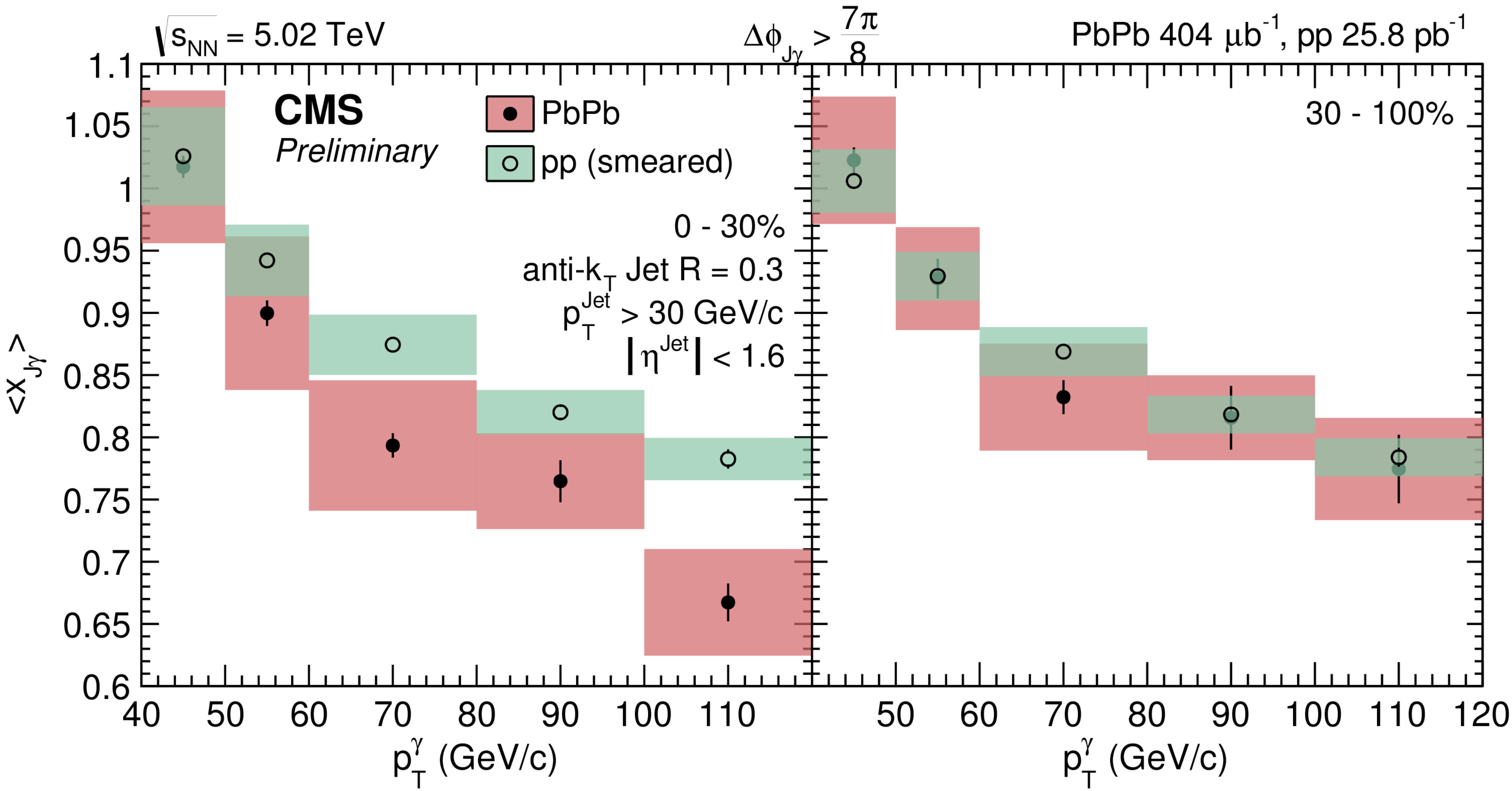
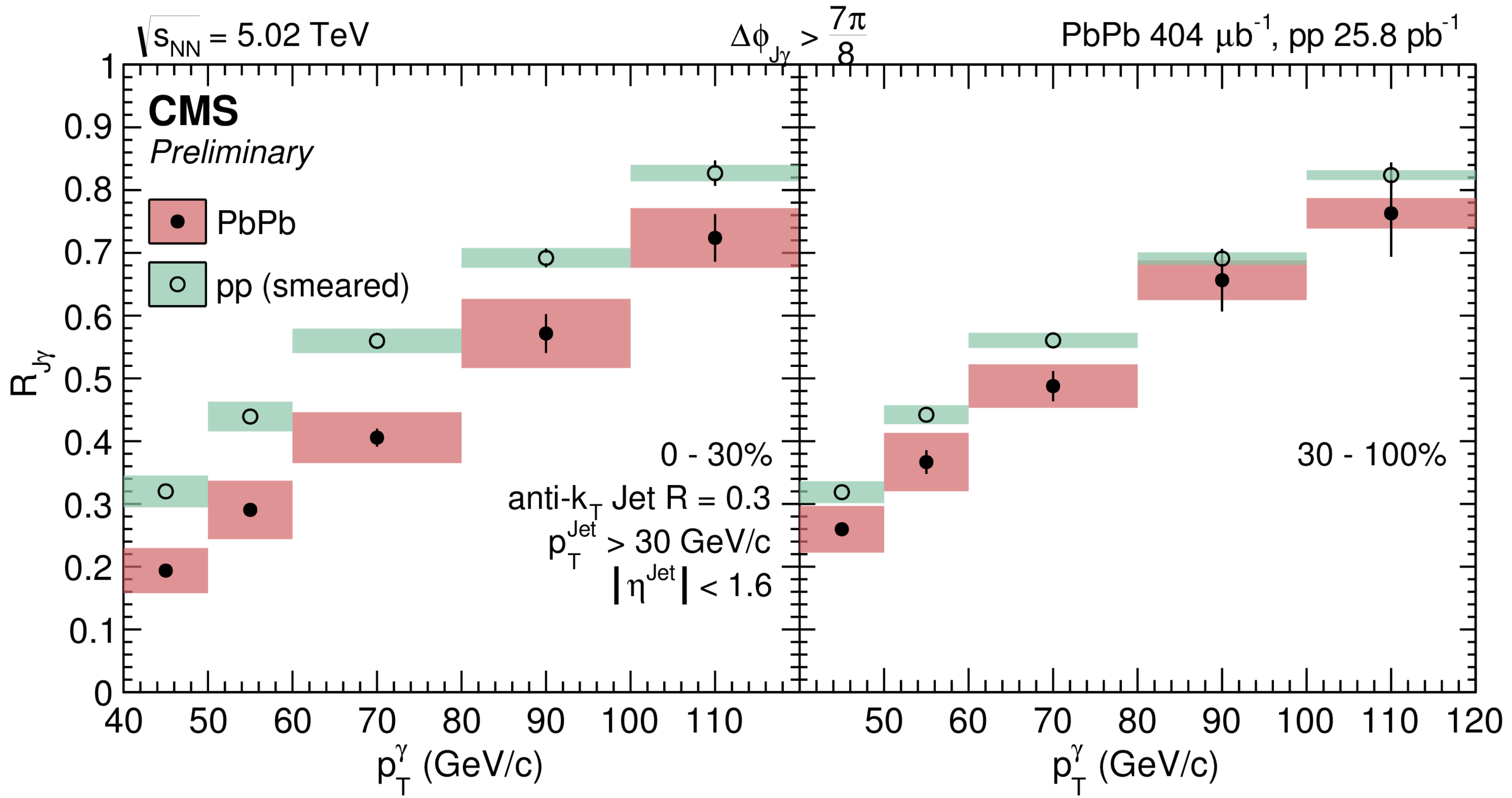


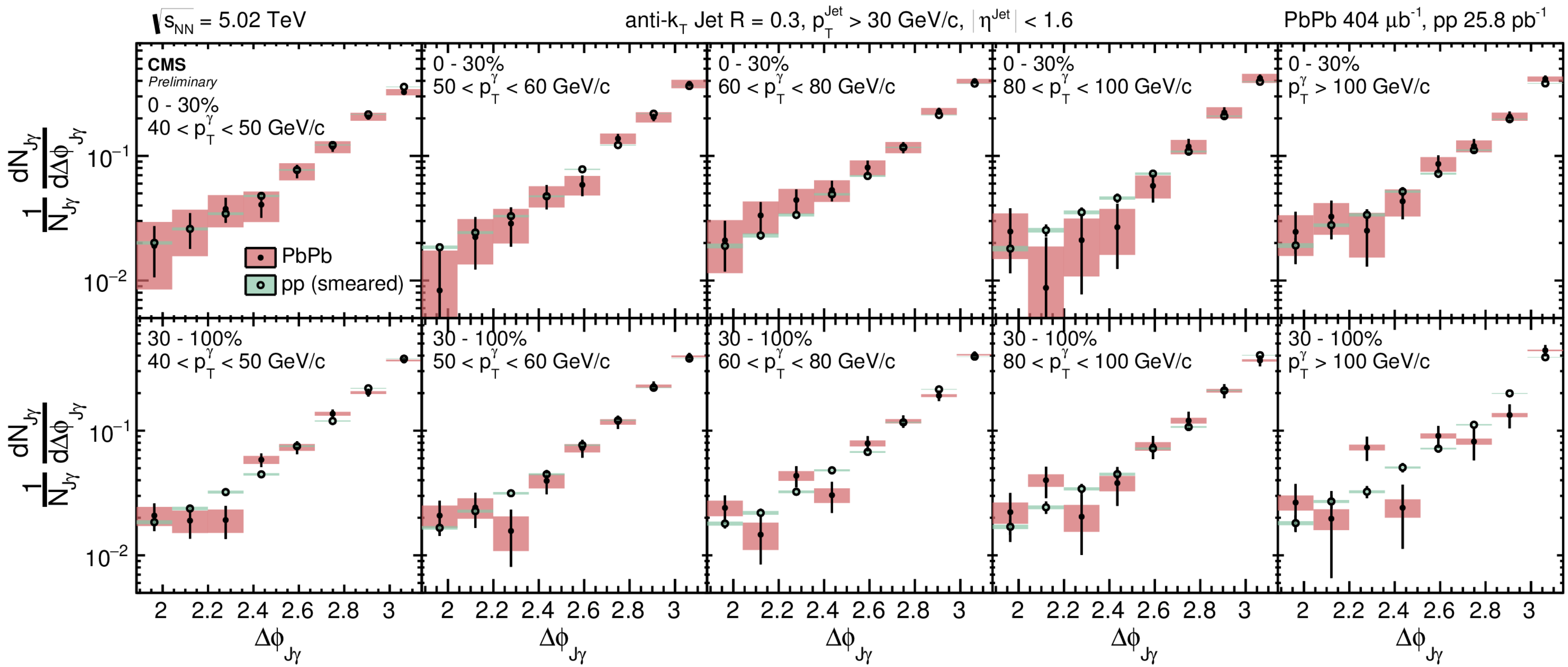
Photon+Jet Correlations - <Rjg>

CMS-PAS HIN-16-002



Photon+Jet Correlations - <dphijg>

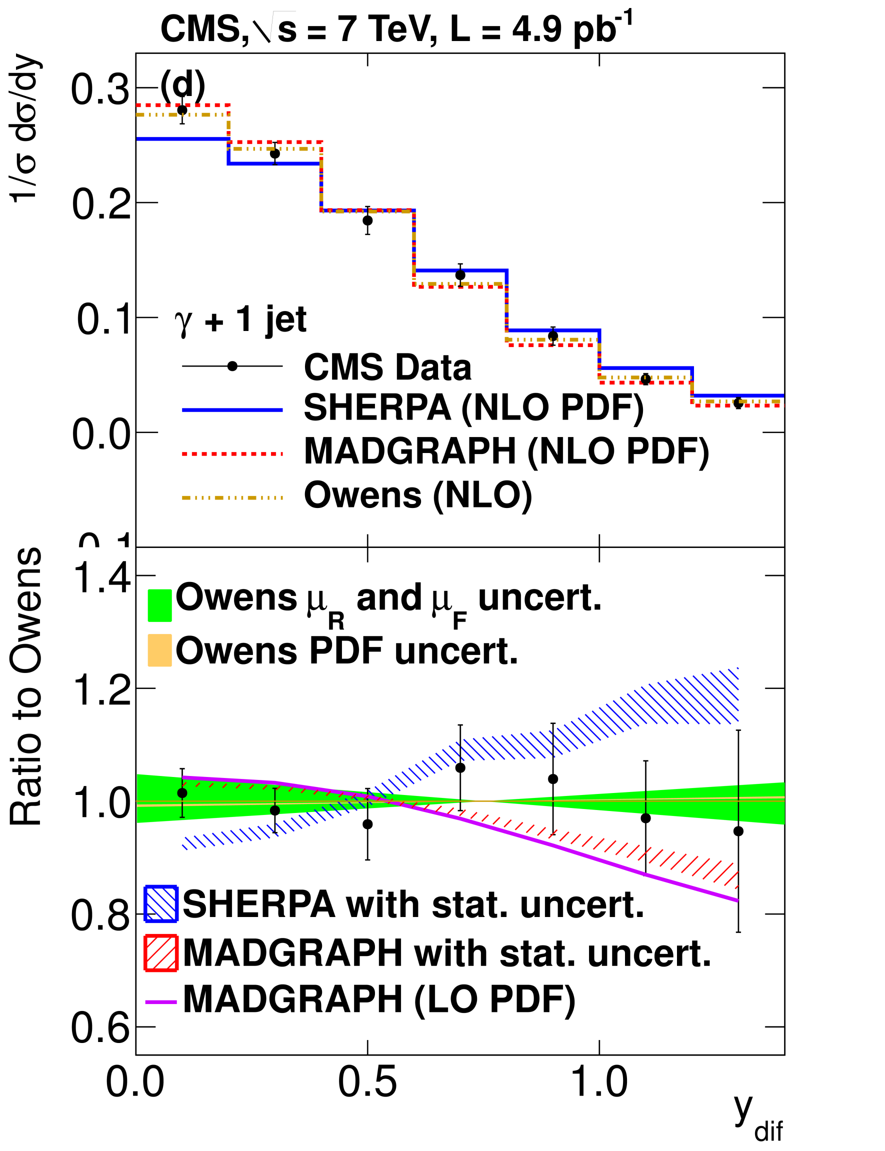
CMS-PAS HIN-16-002



deta (photon,jet)

- Distribution of rapidity difference, y_{dif}, between the photon and the jet, normalized to unity.
- Photon and jet does not necessarily share the same rapidity.
- Distribution decreases linearly with y_{dif}.

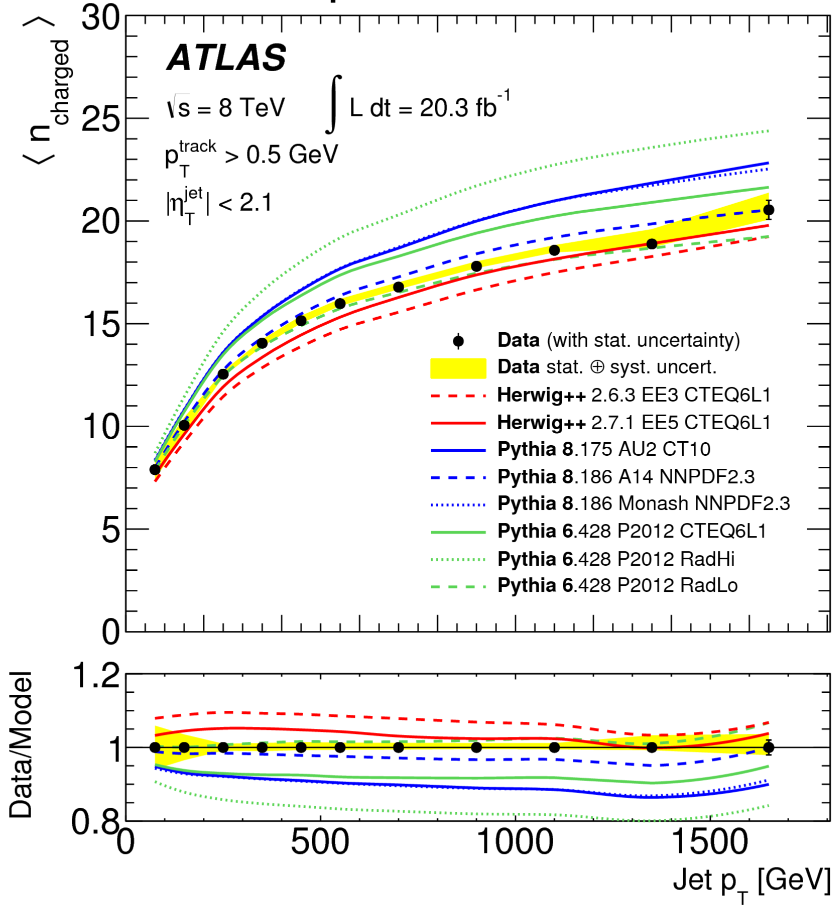
PRD 88 (2013) 112009



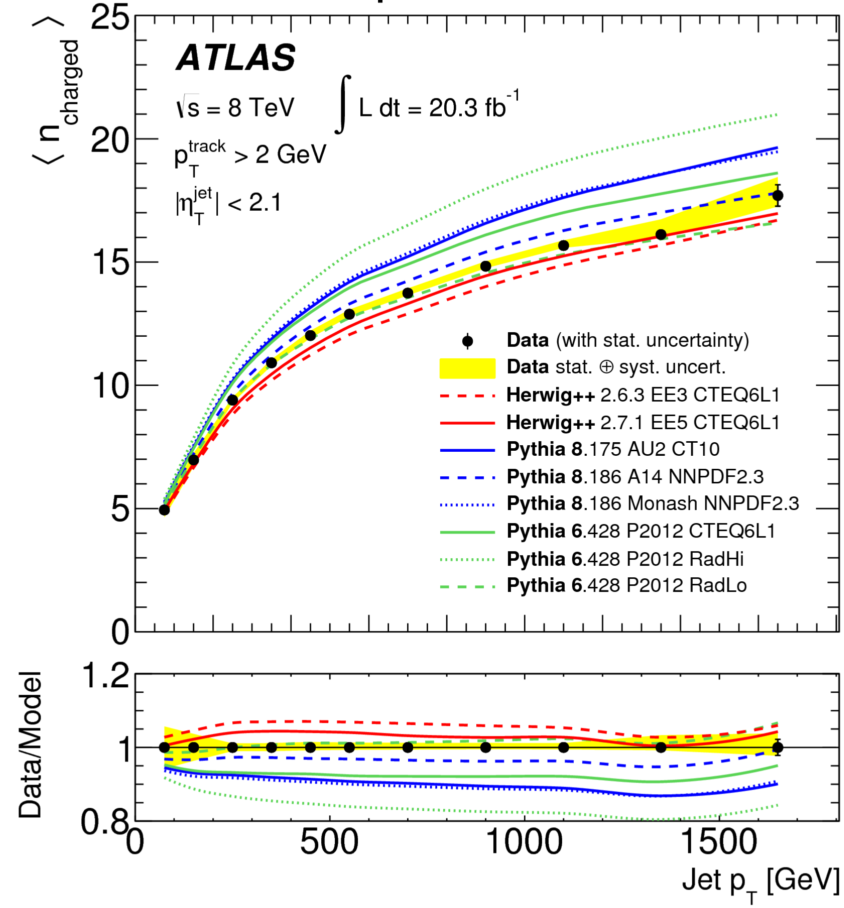
Number of charged particles inside jet

EPJC 76 (2016) 6

$p_T^{trk} > 0.5$ GeV



$p_T^{trk} > 2$ GeV



For $50 < p_T^{jet} < 300$ GeV range,

- there are 8-13 ch. with $p_T^{trk} > 0.5$ GeV
- there are 5-10 ch. with $p_T^{trk} > 2$ GeV

inside the jet.

Smearing jet spectra

- **Jet energy resolution** and **jet angular resolution** differ between pp and PbPb due to underlying event, so
  - Estimate relative resolution between pp and PbPb using simulations
  - Smear jet spectra in pp using this relative resolution
- Smearing **jet energy**
  - Parametrize jet energy resolution via

$$\sigma\left(\frac{p_T^{RECO}}{p_T^{GEN}}\right)=\sqrt{C^2+\frac{S^2}{p_T^{GEN}}+\frac{N^2}{(p_T^{GEN})^2}}$$

  - Fit C, S and N parameters and apply relative resolution via

$$\sigma_{rel}=\sqrt{(C_{PbPb}^2-C_{pp}^2)+\frac{(S_{PbPb}^2-S_{pp}^2)}{p_T^{GEN}}+\frac{(N_{PbPb}^2-N_{pp}^2)}{(p_T^{GEN})^2}}$$

- Smearing **jet azimuthal angle**
  - Use same parametrization as in jet energy resolution $\sigma\left(\left|\phi^{RECO}-\phi^{GEN}\right|\right)=\sqrt{C^2+\frac{S^2}{p_T^{GEN}}+\frac{N^2}{(p_T^{GEN})^2}}$
  - Apply relative resolution in the same fashion