Jet fragmentation and shapes for inclusive and photon-tagged jets in pp and PbPb collisions with the CMS detector

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Introduction

Study modification of parton shower

Gives info about the dynamics of hot QCD matter

Tools :

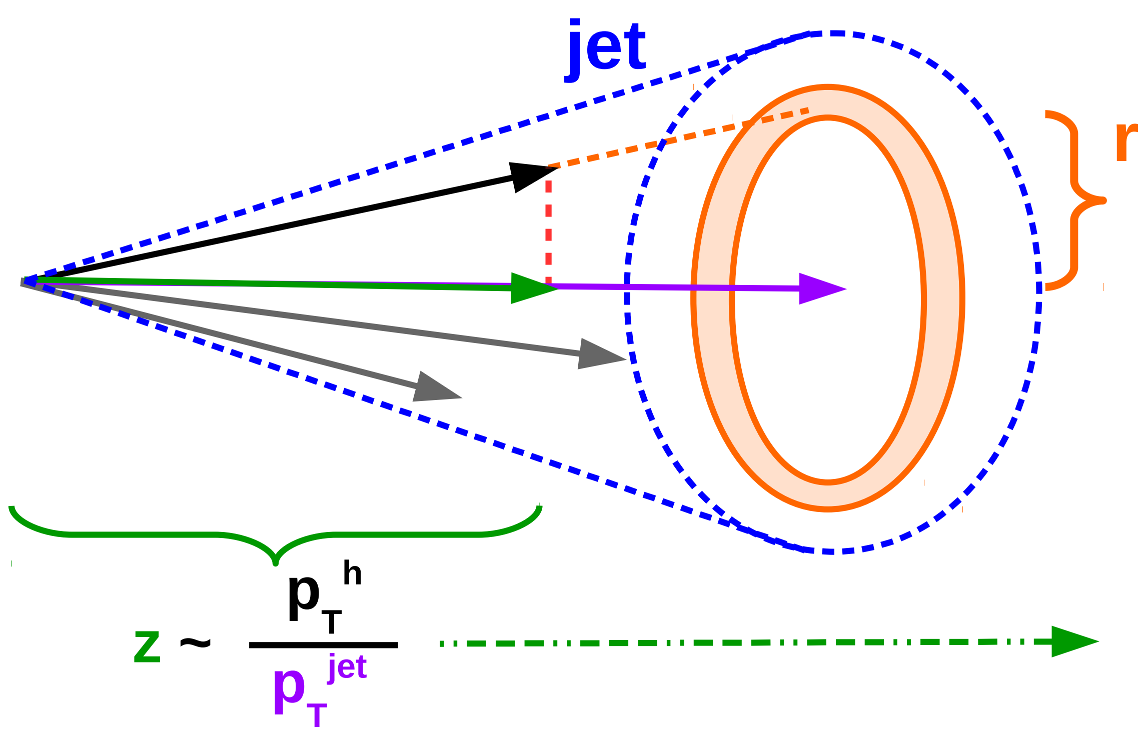
Jet fragmentation function (FF)

- Longitudinal distribution of momentum

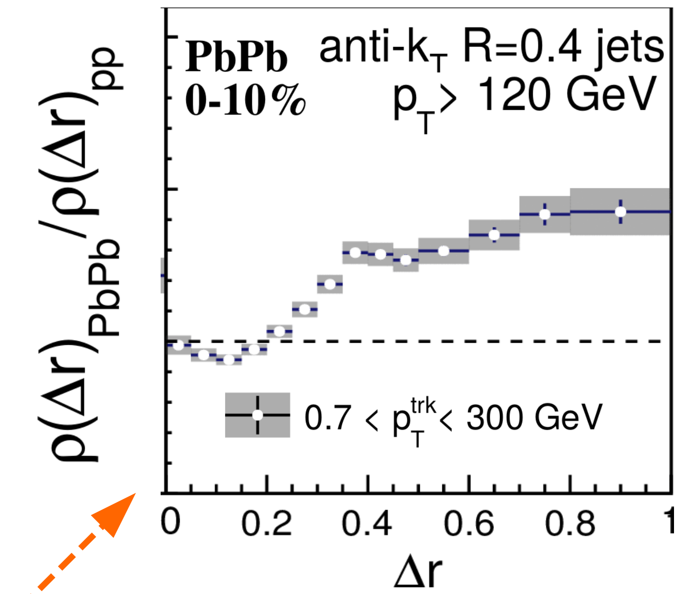
Jet shapes (JS)

- Distribution of jet energy in transverse direction

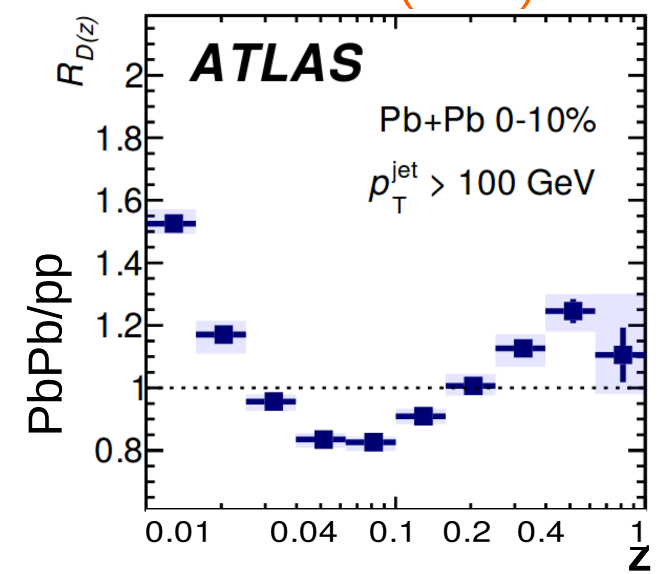
FF and JS provide different, but complementary info



arXiv:1803.00042



EPJC 77 (2017) 379

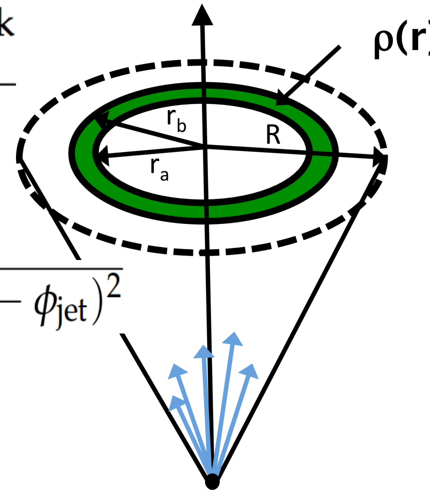


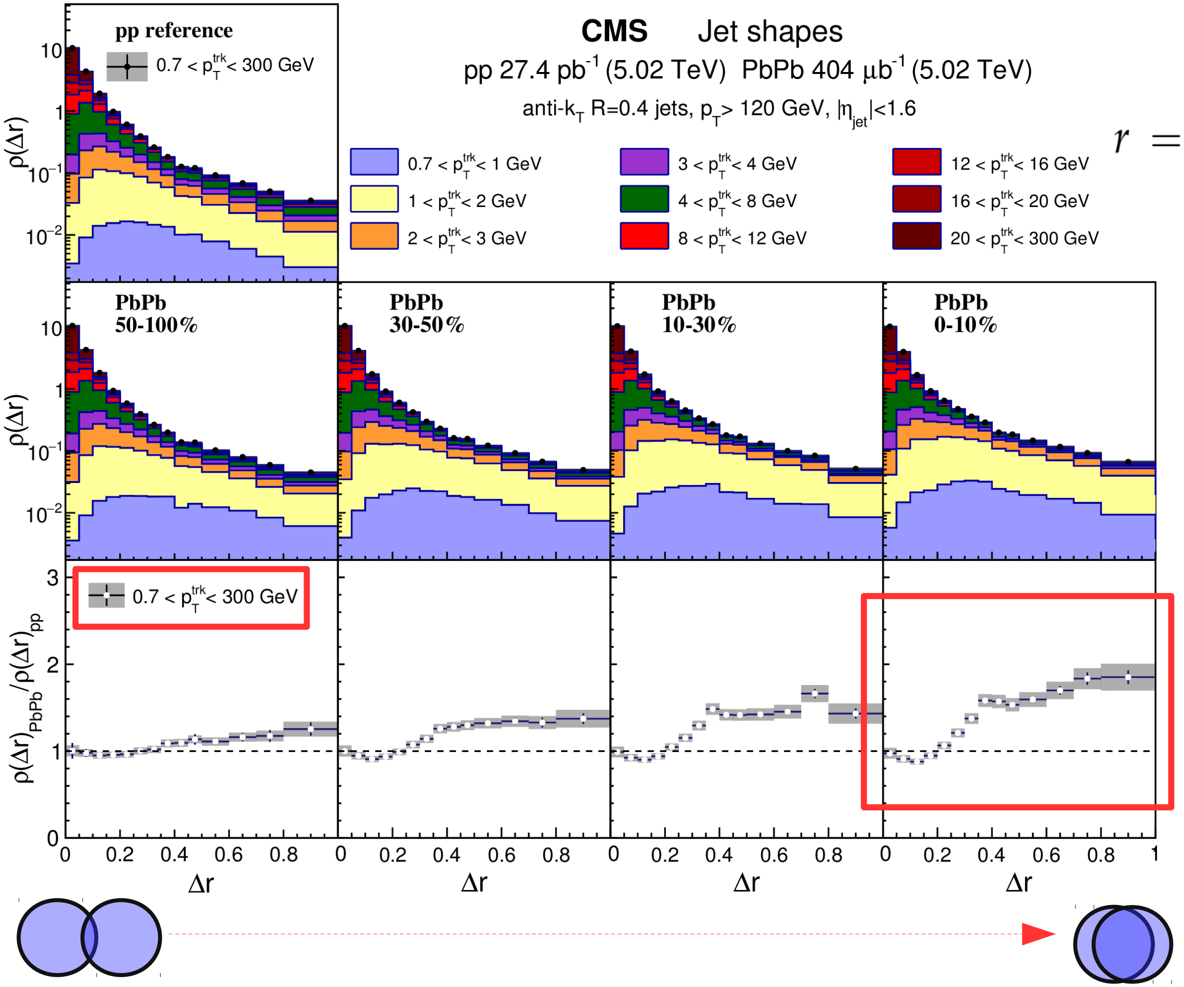
Inclusive jet shape

arXiv:1803.00042

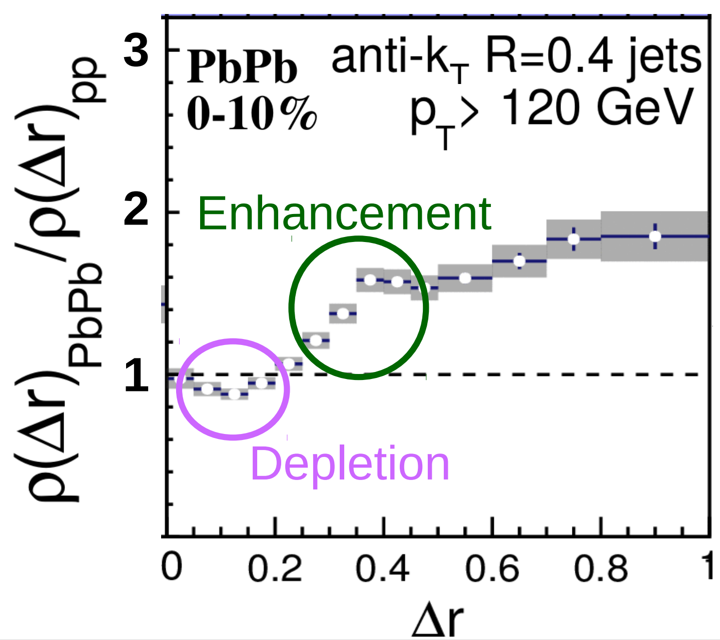
$$\rho(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\frac{\Sigma_{\text{tracks}\in(r_a,r_b)}p_T^{\text{trk}}}{\Sigma_{\text{tracks}}p_T^{\text{trk}}}$$

$$r = \sqrt{(\eta_{\text{track}}-\eta_{\text{jet}})^2+(\phi_{\text{track}}-\phi_{\text{jet}})^2}$$



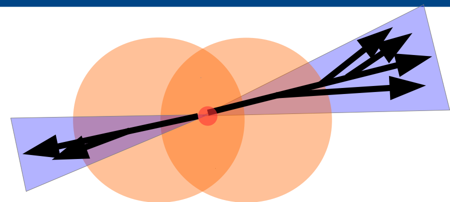


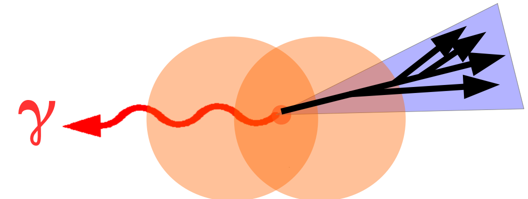
ρ(r) normalized to unity over **r < 1**.



PbPb – > A **larger fraction of jet energy** carried at **large distances** from the jet axis.

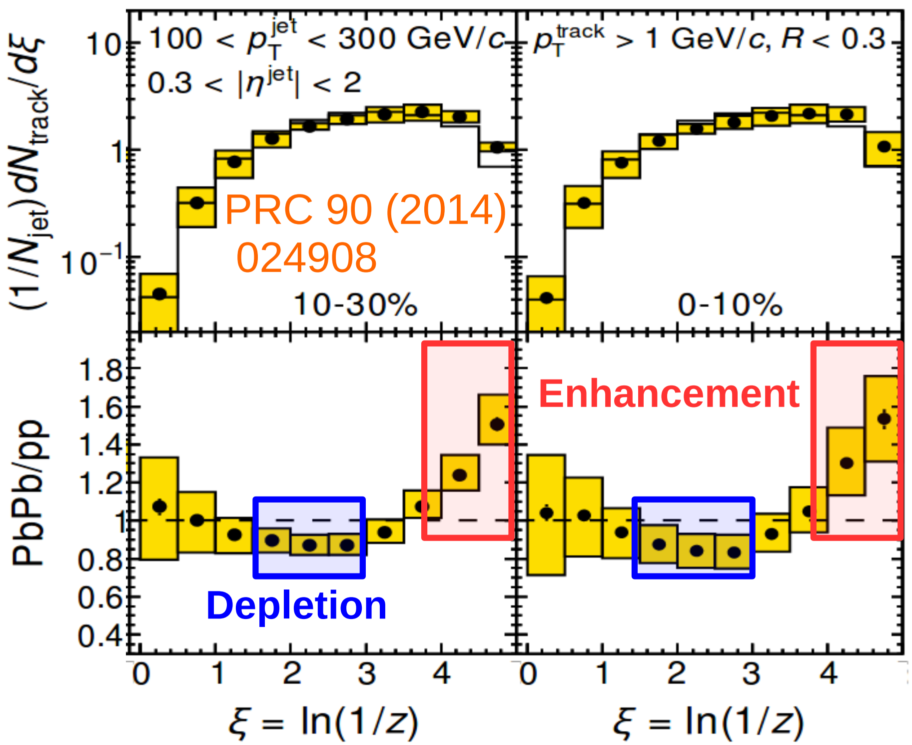
Inclusive jet vs photon+jet



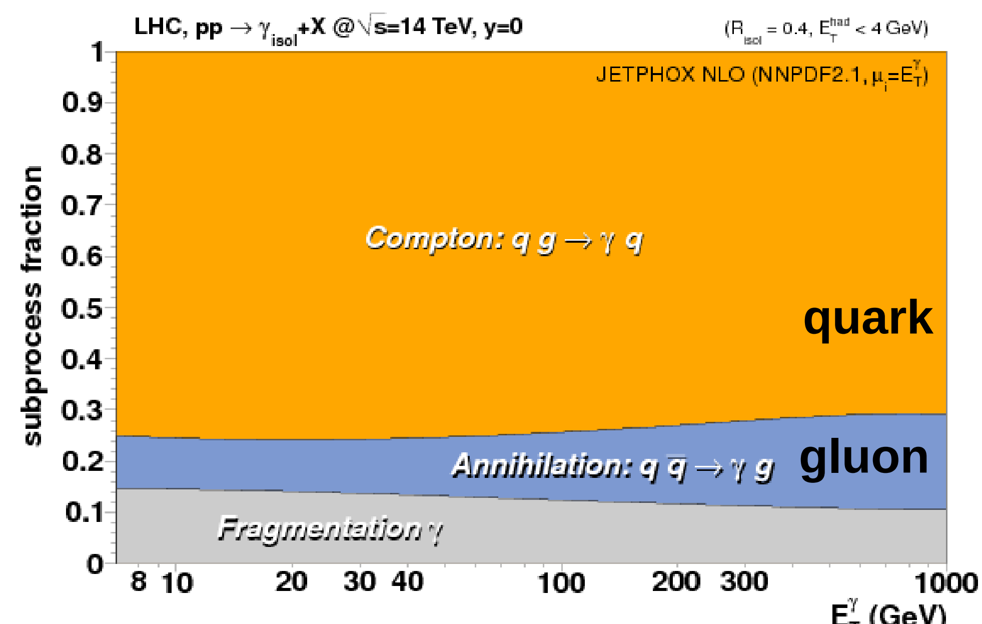


Inclusive jet
Compares samples with different initial states
Produced partons : mix of quarks and gluons

Photon+jet
Photon-tag **controls initial state**
Produced partons : is mostly quark
-- > Probe **quark jet** modification
-- > Insight for gluon modification when combined with inclusive jet



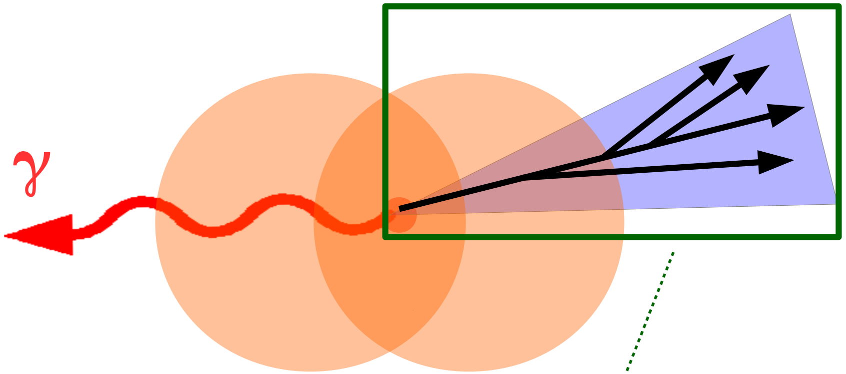
(high ξ – > low-pT particle)



Nucl.Phys. B860 (2012) 311

Observables : ξ^{jet}

- Take tracks (charged particles) 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}.

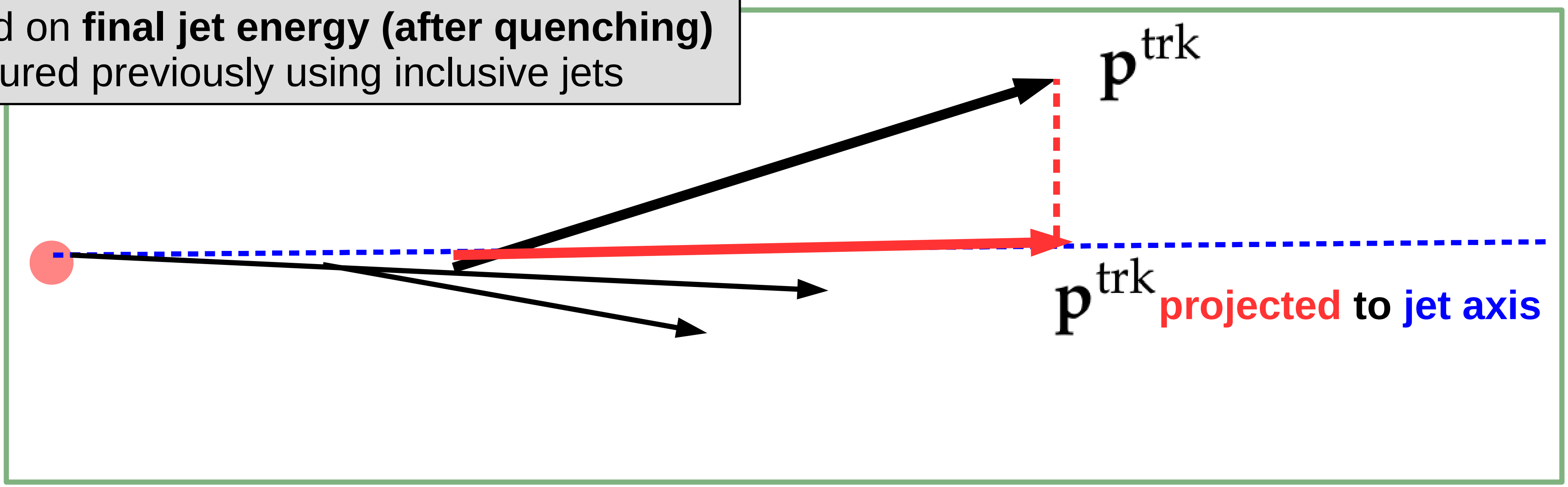


$$\xi^{\text{jet}} = \ln \frac{|\mathbf{p}^{\text{jet}}|^2}{\mathbf{p}^{\text{trk}} \cdot \mathbf{p}^{\text{jet}}}$$

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

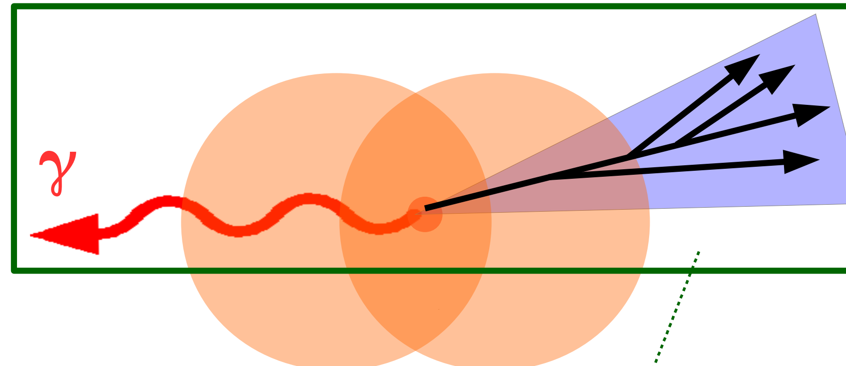
$\mathbf{p}^{\text{trk}}$: 3-momentum vector of the track

- Based on **final jet energy (after quenching)**
- Measured previously using inclusive jets



Observables : ξ_T^{γ}

- Take tracks (charged particles) 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}.

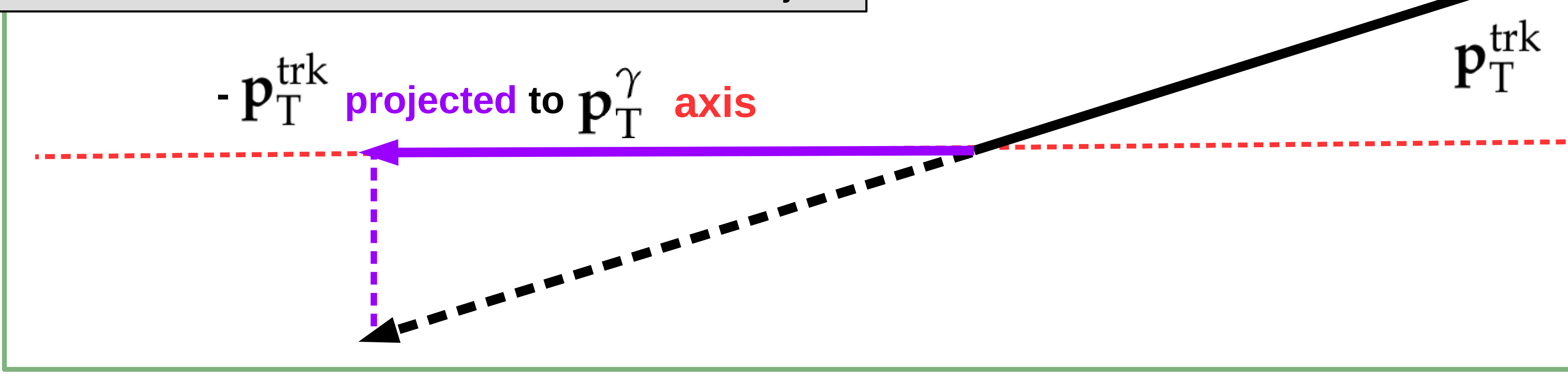


$$\xi_T^{\gamma} = \ln \frac{-|\mathbf{p}_T^{\gamma}|^2}{\mathbf{p}_T^{\text{trk}} \cdot \mathbf{p}_T^{\gamma}}$$

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

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

- Based on **photon energy**
- Measured for the **first time** for reconstructed jets



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**

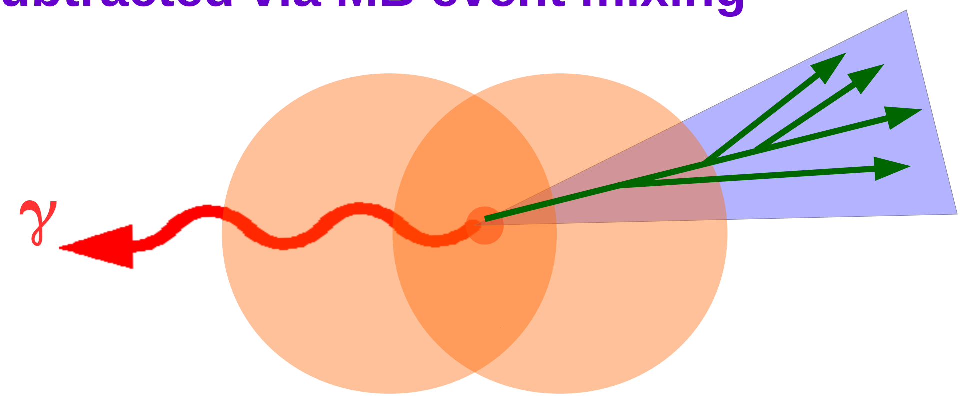
Tracks JHEP 04 (2017) 039

$p_T^{trk} > 1$ GeV/c

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

ΔR(jet, track) < 0.3

Bkg tracks **subtracted via MB event mixing**

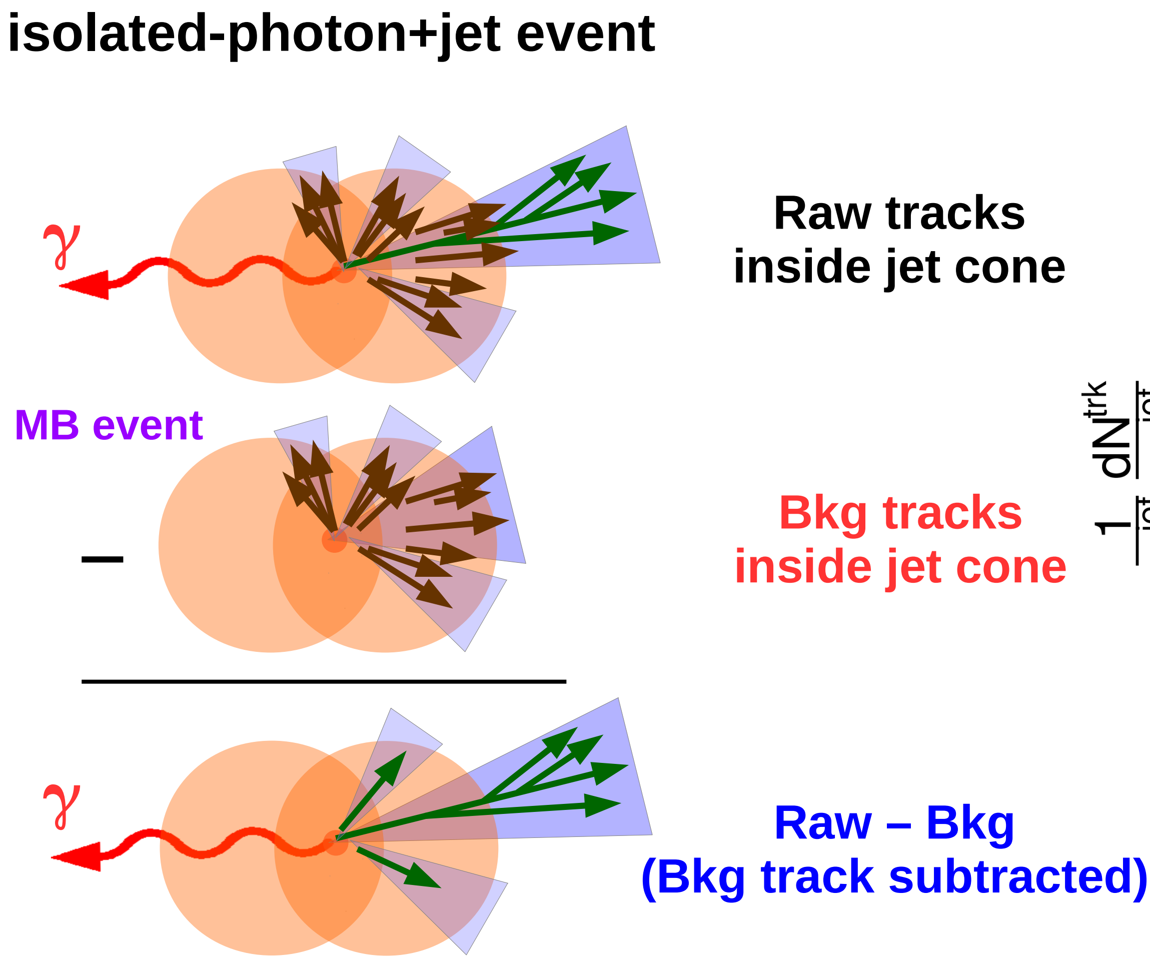


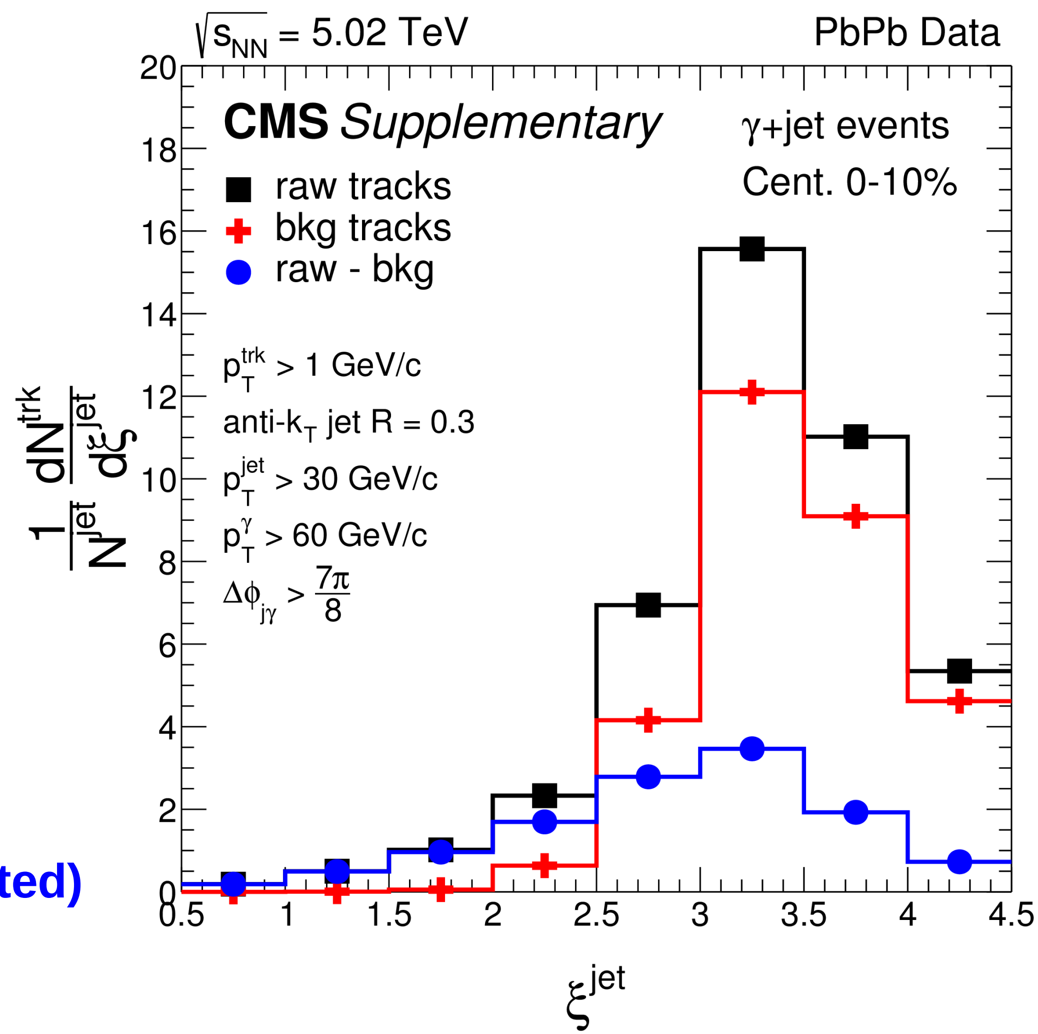
Background sources

- **Tracks from underlying event (UE) –>** Subtracted via Min Bias event mixing
- **Mis-identified (fake) jets –>** Subtracted via Min Bias event mixing
- **photons from neutral meson decays**
  rejected using shower shape cut, remaining bkg fraction estimated via template fit

Background subtraction for tracks

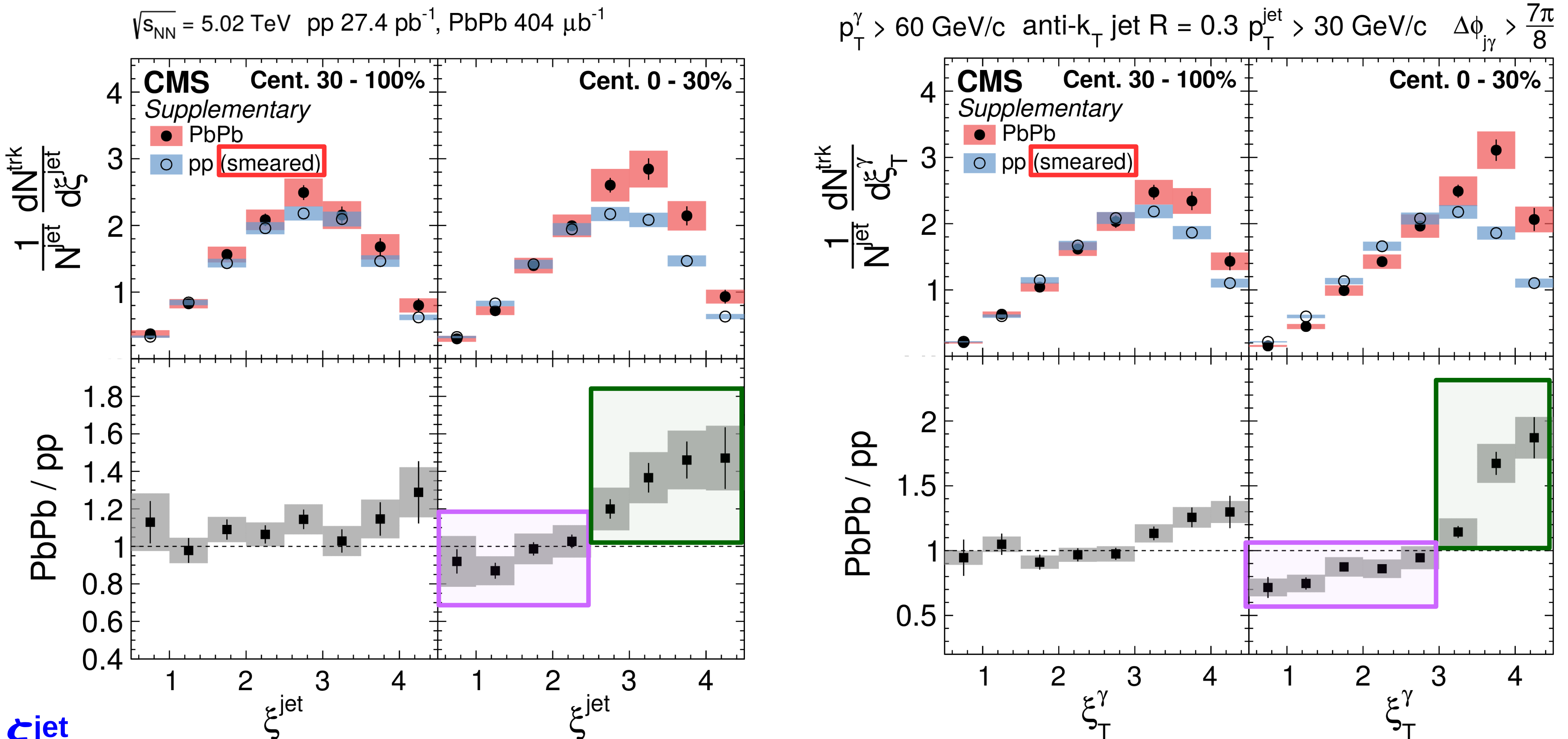
arXiv:1801.04895





Results : ξ^{jet} vs ξ_T^{γ}

arXiv:1801.04895



ξ^{jet}

- Based on reconstructed jet energy (energy after quenching)
- ξ^{jet} shifted to left compared to ξ_T^{γ}
  - Out-of-cone radiation, photon+multijet

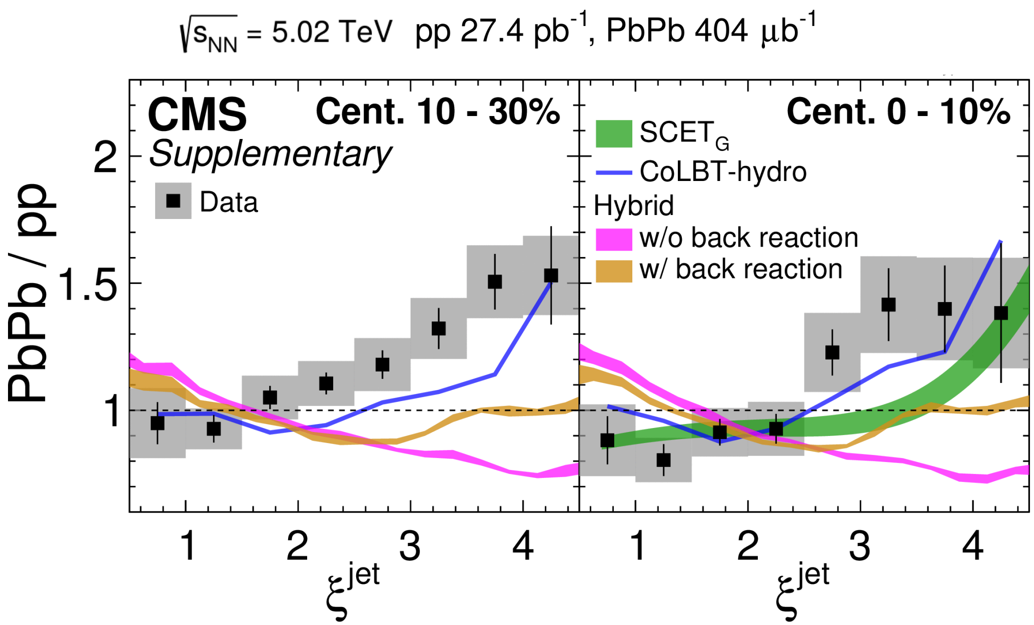
ξ_T^{γ}

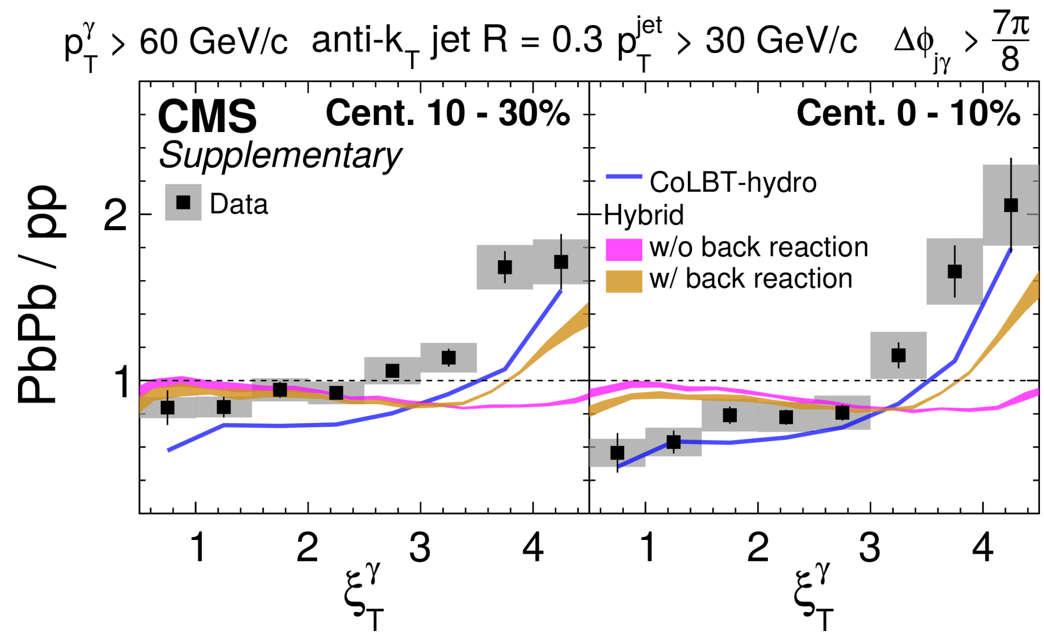
- Based on photon energy
- ξ_T^{γ} modified stronger compared to ξ^{jet}

Central PbPb collisions – > **enhancement of low-pT particles** and a **depletion of high-pT particles**

ξ^{jet} and ξ_T^{γ} vs Theory

arXiv:1801.04895





SCET$_G$ (JHEP 11 (2016) 155)

- Framework decomposing Soft Colliner and Glabuer modes

CoLBT-hydro (Phys. Lett. B, 777 (2018) 86)

- Couples LBT for jet evolution with (3+1)D hydrodynamics
- Combines pQCD approach with hydro simulation of medium.

Hybrid (JHEP 1410 (2014) 019, JHEP 1603 (2016) 053)

- Weak coupling : high-Q² processes using pQCD
- Strong coupling : low-Q² interactions between parton shower and medium
- Weak and strong coupling are combined

Turnover of PbPb/pp ratio at

$\xi^{jet} \approx 2.5$ and $\xi_T^{\gamma} \approx 3$ –> $p_T^{trk} \approx 3$ GeV

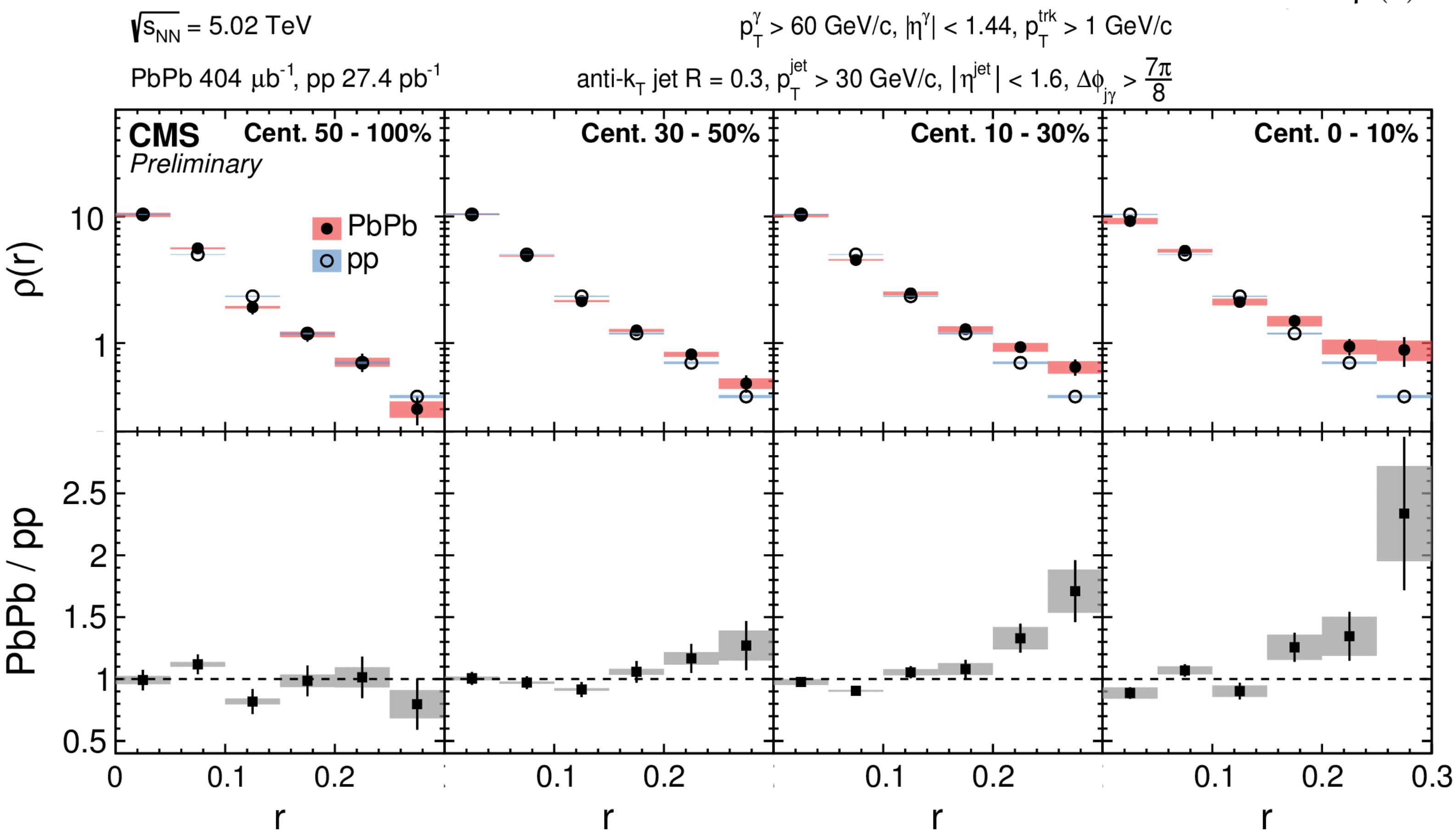
Large enhancement from particles with $p_T^{trk} \lesssim 3$ GeV

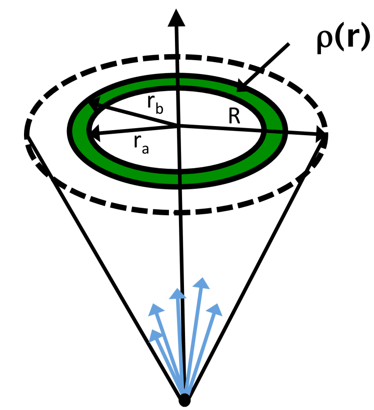
Some ingredients for theory models
- Medium-induced radiation
- Effects of medium on hadronization
- Medium response

γ-tagged jet shape

CMS-PAS HIN-18-006

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

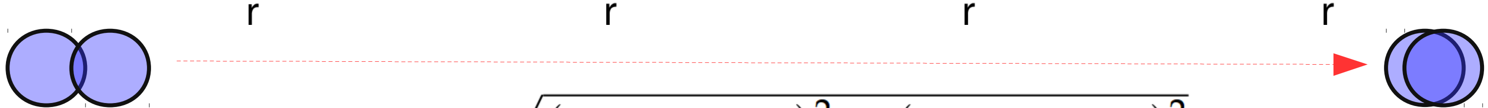




ρ(r) normalized to unity over **r < 0.3**.

Results are corrected for detector resolution, particle reco.

pp results are **NOT** smeared.



$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$

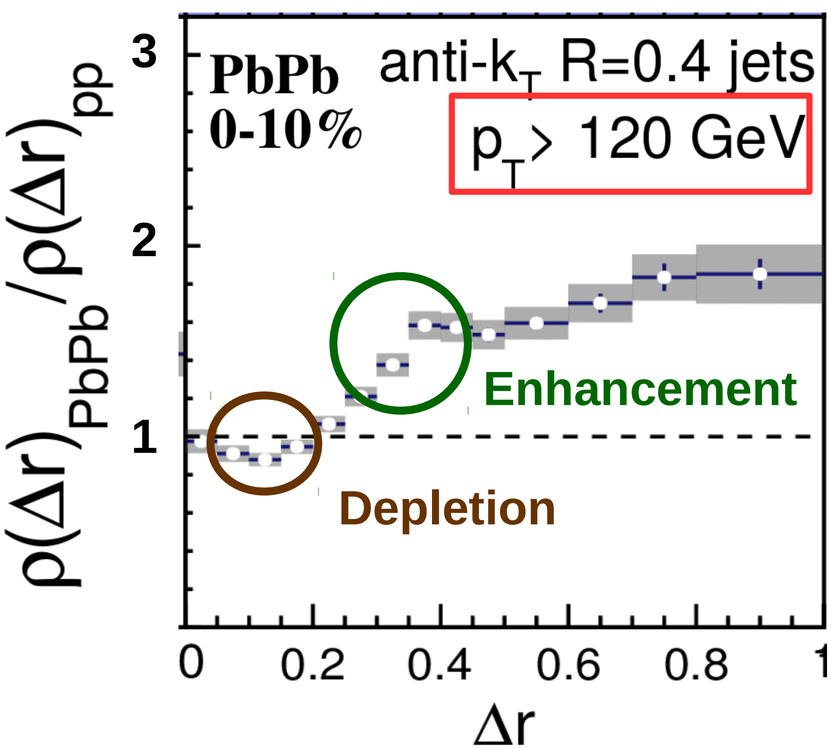
Central PbPb collisions – > a **larger fraction of jet energy** at **large distances** from the jet axis.

inclusive vs γ-tagged jet shape

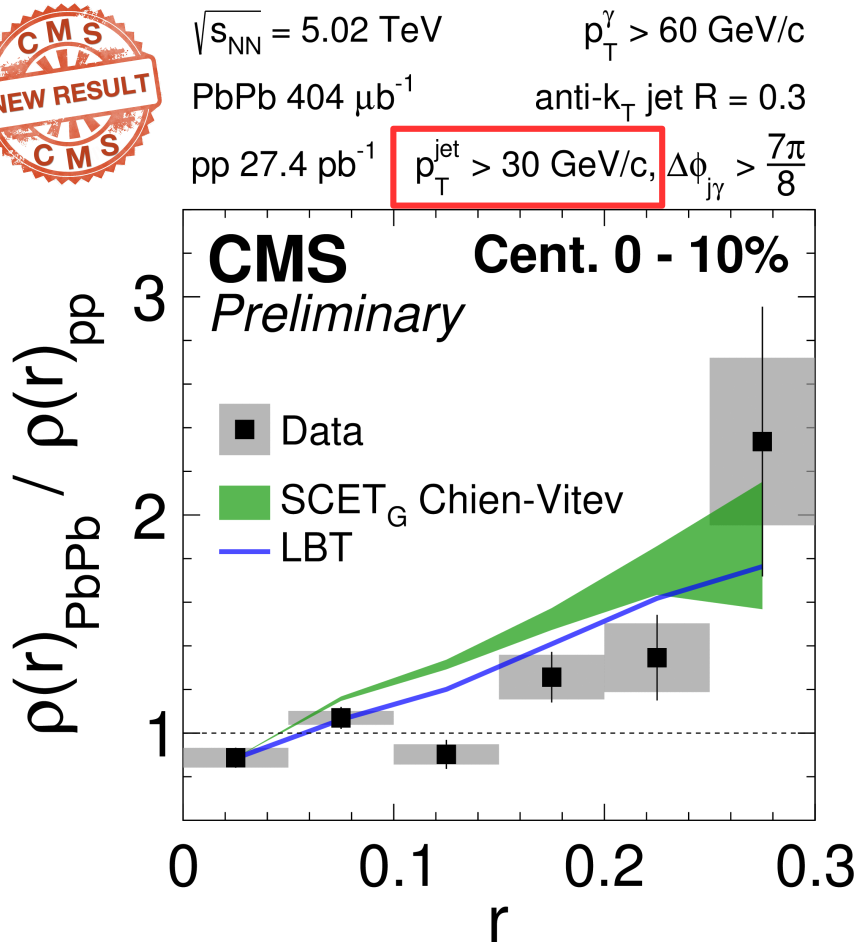
arXiv:1803.00042

CMS-PAS HIN-18-006

Inclusive jets



ρ(r) normalized to unity over
r < 1.0 (inclusive jets)
r < 0.3 (γ+jet)



SCET$_G$ [JHEP 05 (2016) 023]

LBT [arXiv:1803.06785]

γ+jet :

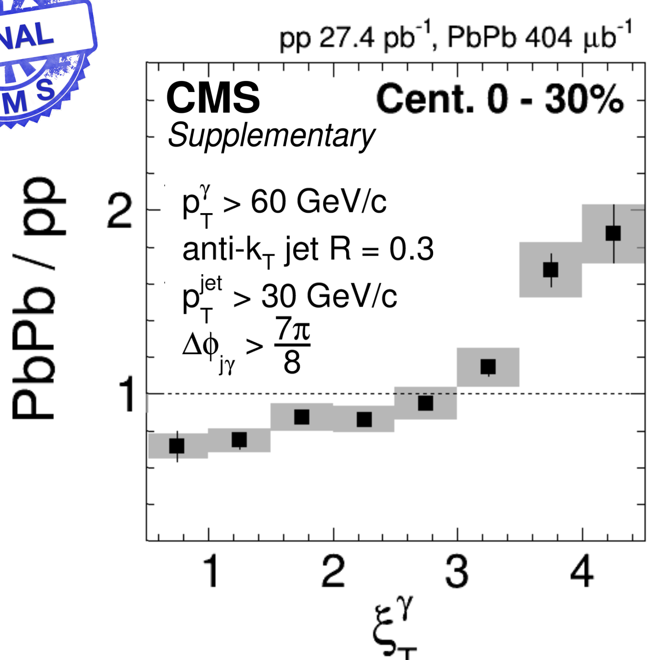
Larger enhancement at large r. **No depletion** at intermediate r.

- Increased quark fraction (70-80%) ?
- Lower jet p_T threshold (higher fraction of quenched jets) ?

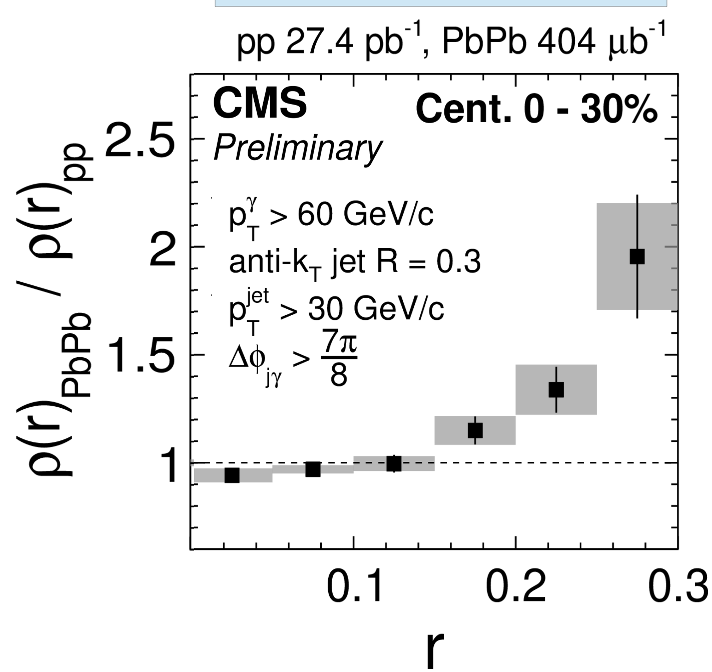
Summary

- FF and jet shapes (JS) measured for jets tagged with isolated-photons.
  - Constrains the **initial parton kinematics** and probes **quark-jet** modification.
- FF modification – > excess of low-pT particles and depletion of high-pT particles inside the jet cone.
  - FF observable wrt photon energy – > robust measurement, high significance
- JS modification – > a larger fraction of jet energy is carried at large distances from the jet axis.
  - A depletion for inclusive jets, while no significant depletion for photon-tagged jets.

arXiv:1801.04895



CMS-PAS-HIN-18-006

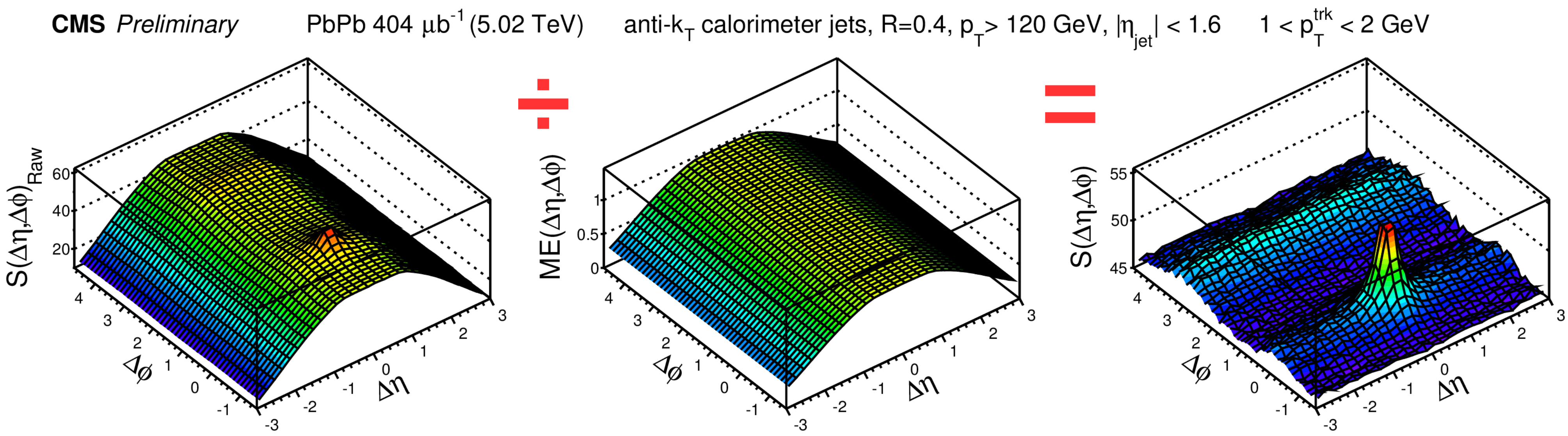


Acknowledgements : The MIT group's work was supported by US DOE-NP.

BACKUP

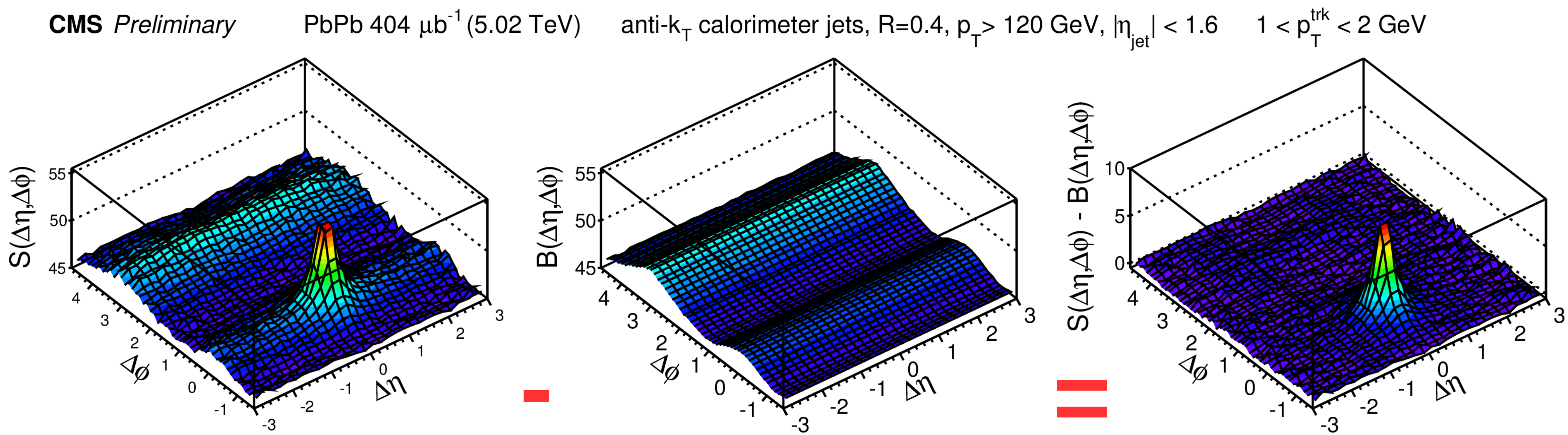
Inclusive jet shape : pair acceptance

CMS-PAS-HIN-16-020



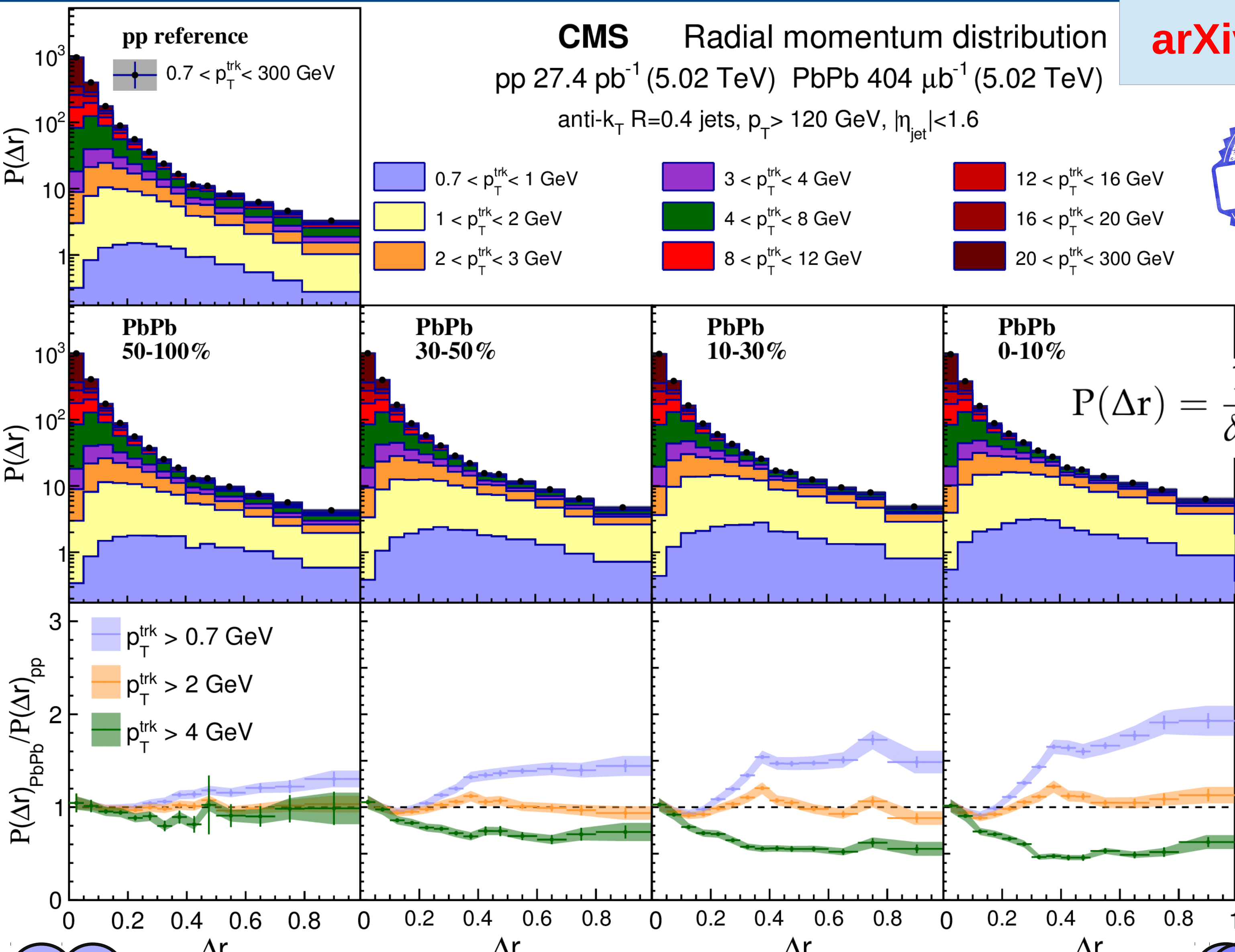
Inclusive jet shape : bkg subtraction

CMS-PAS-HIN-16-020



Radial momentum distribution

arXiv:1803.00042

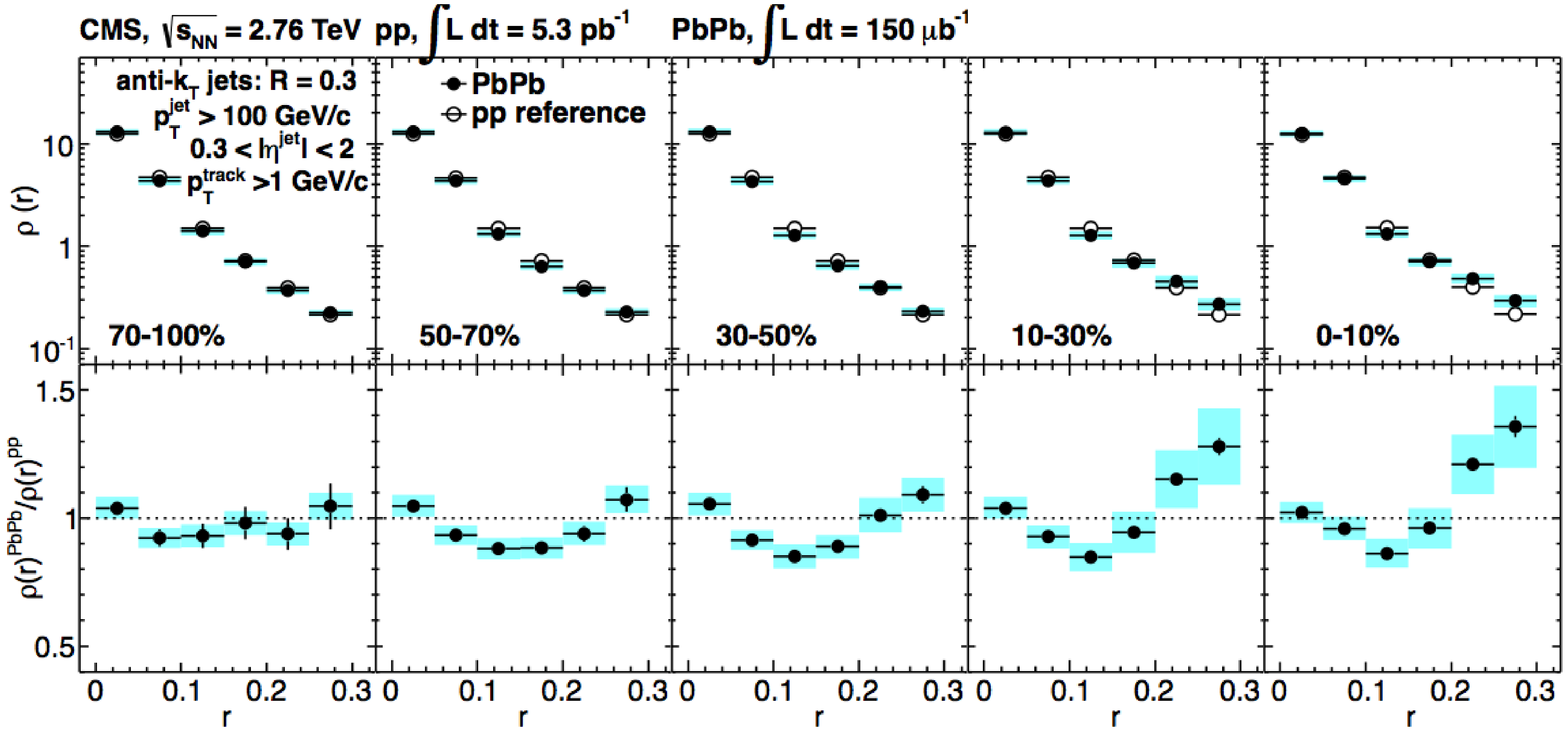


$$P(\Delta r) = \frac{1}{\delta r}\frac{1}{N_{jets}}\Sigma_{jets}\Sigma_{tracks\in(\Delta r_a,\Delta r_b)}\, p_T^{trk}$$

$$r = \sqrt{(\eta_{track}-\eta_{jet})^2 + (\phi_{track}-\phi_{jet})^2}$$

Inclusive jet shape

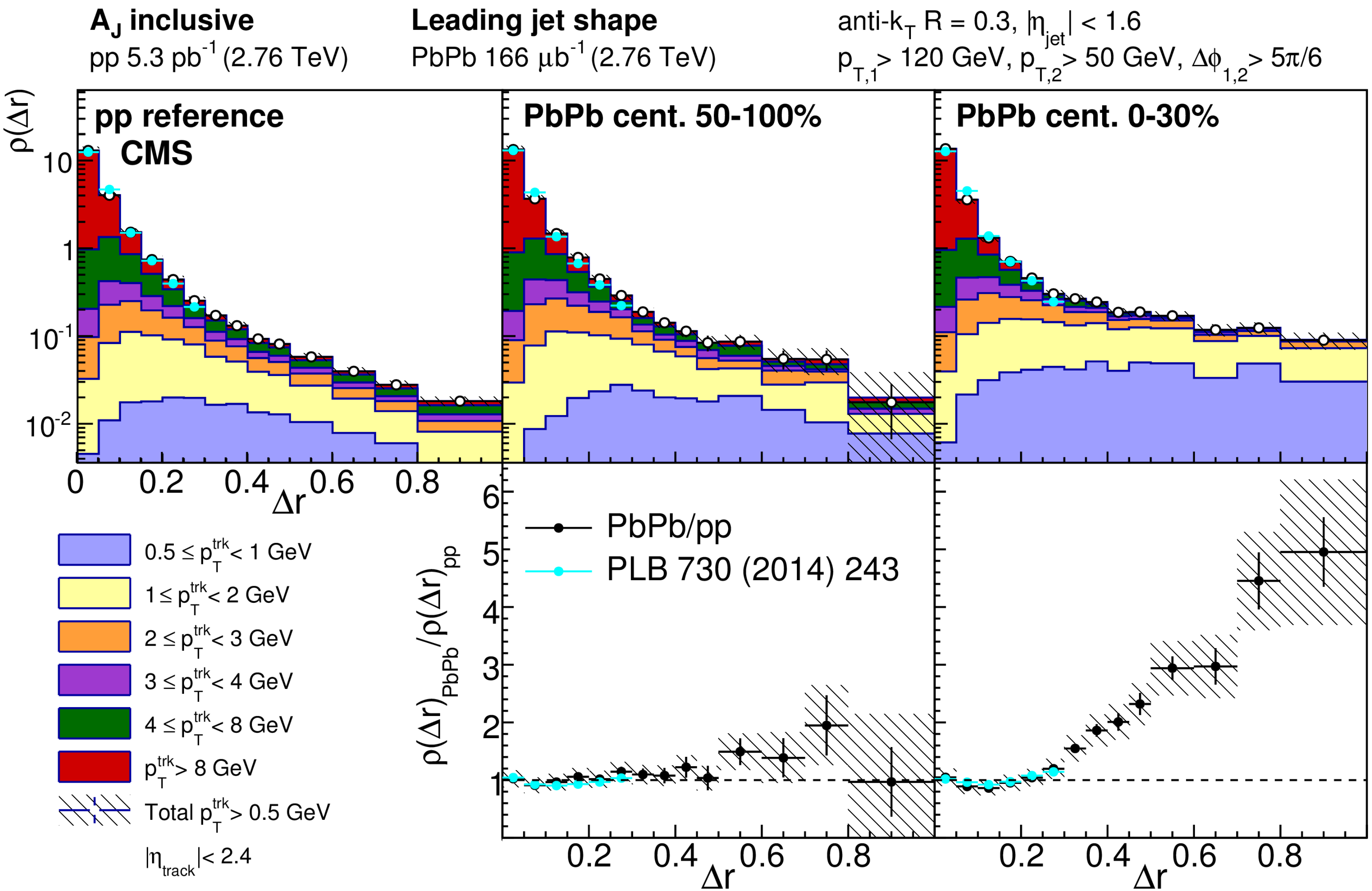
Phys. Lett. B 730 (2014) 243



$$r = \sqrt{(\eta_{\text{track}} - \eta_{\text{jet}})^2 + (\phi_{\text{track}} - \phi_{\text{jet}})^2}$$

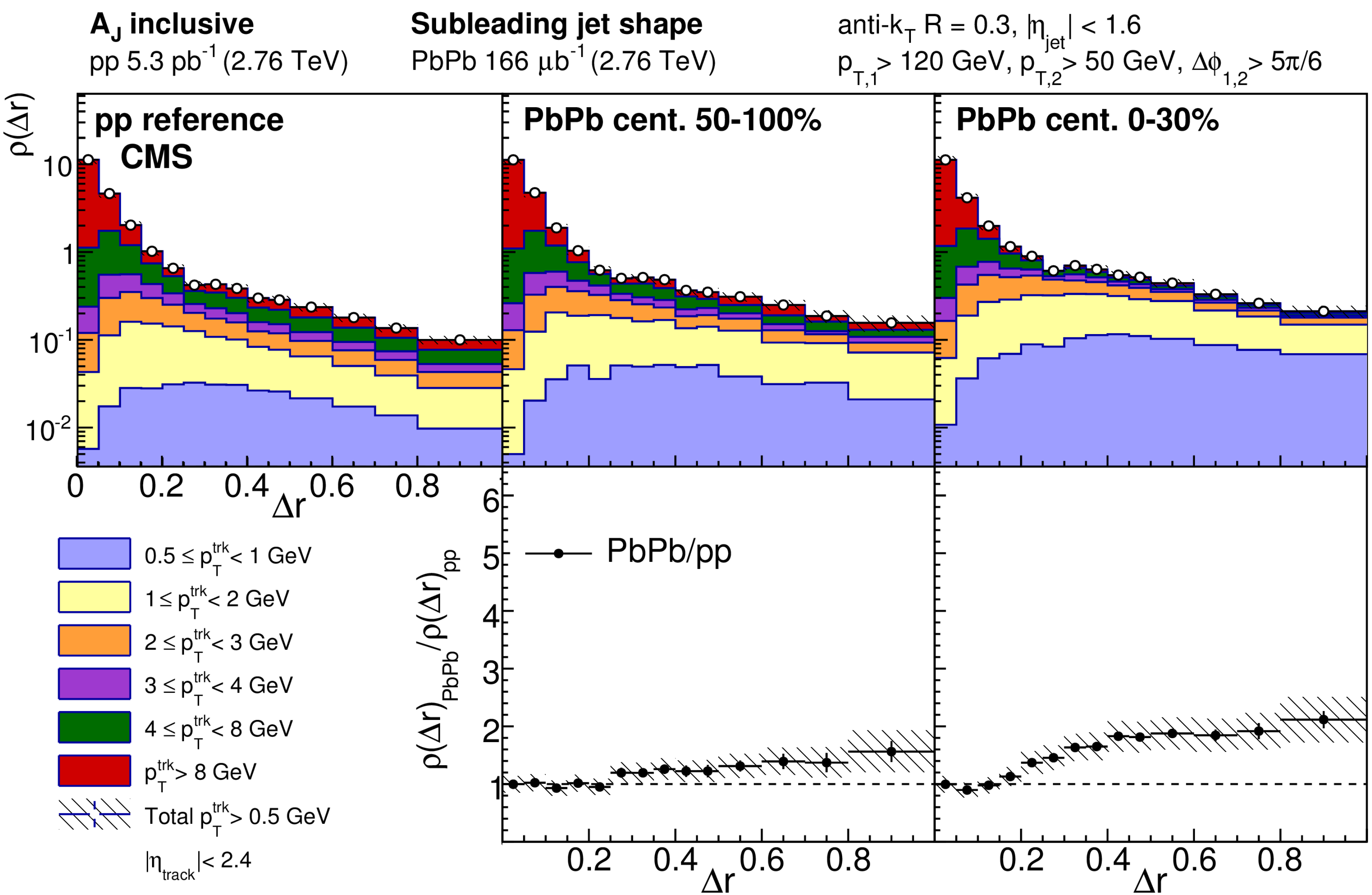
Leading jet shape

JHEP 11 (2016) 055



Subleading jet shape

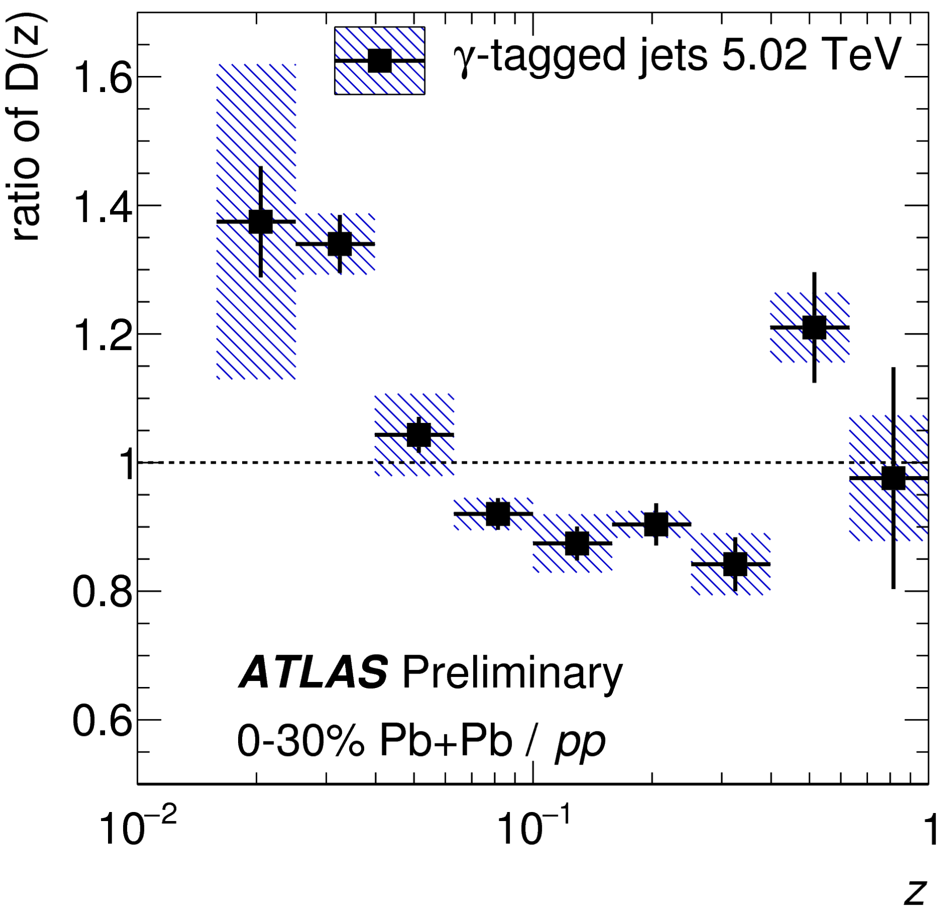
JHEP 11 (2016) 055



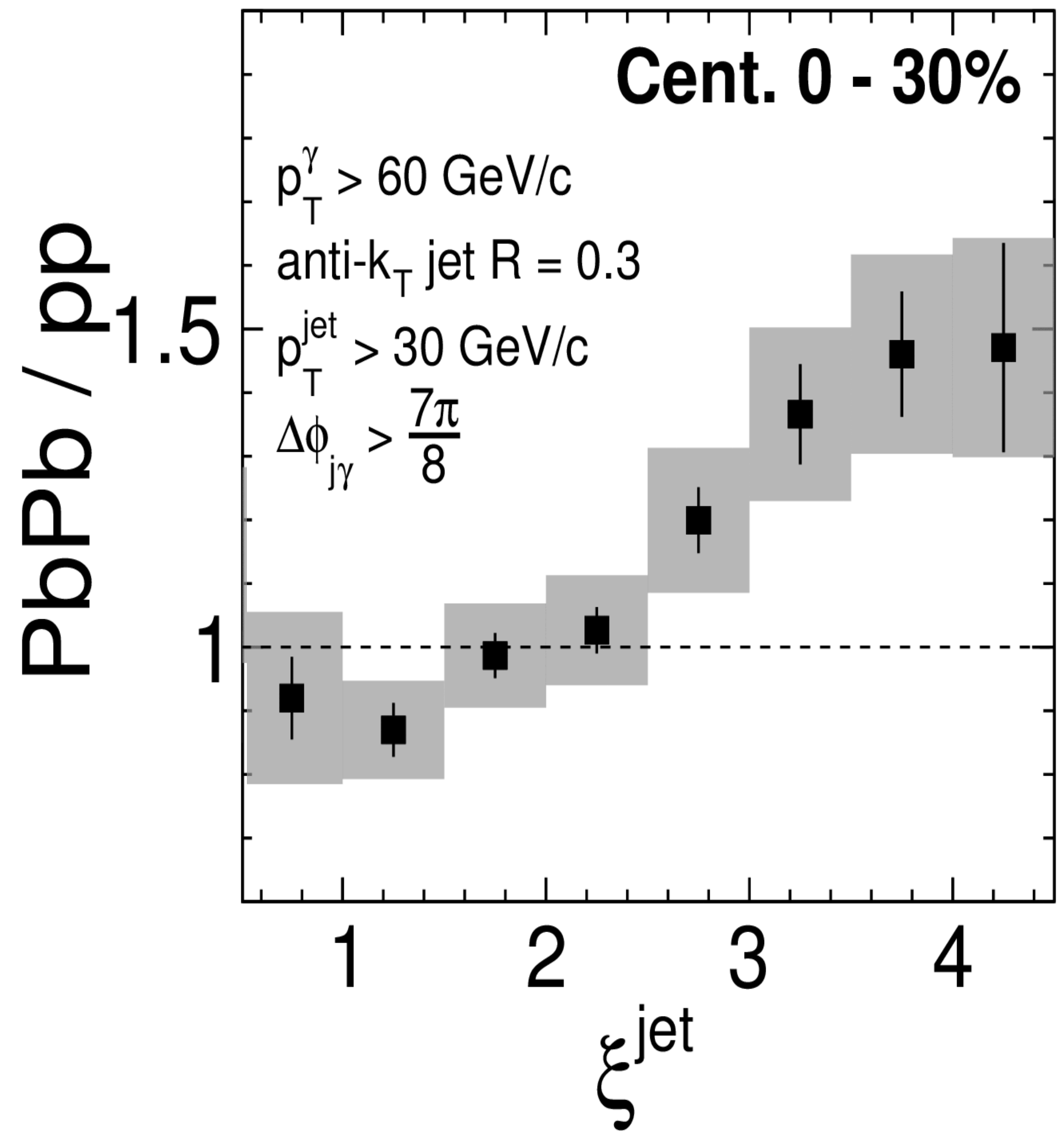
γ-tagged jet FF comparison

ATLAS-CONF-2017-074

CMS-PAS-HIN-18-006

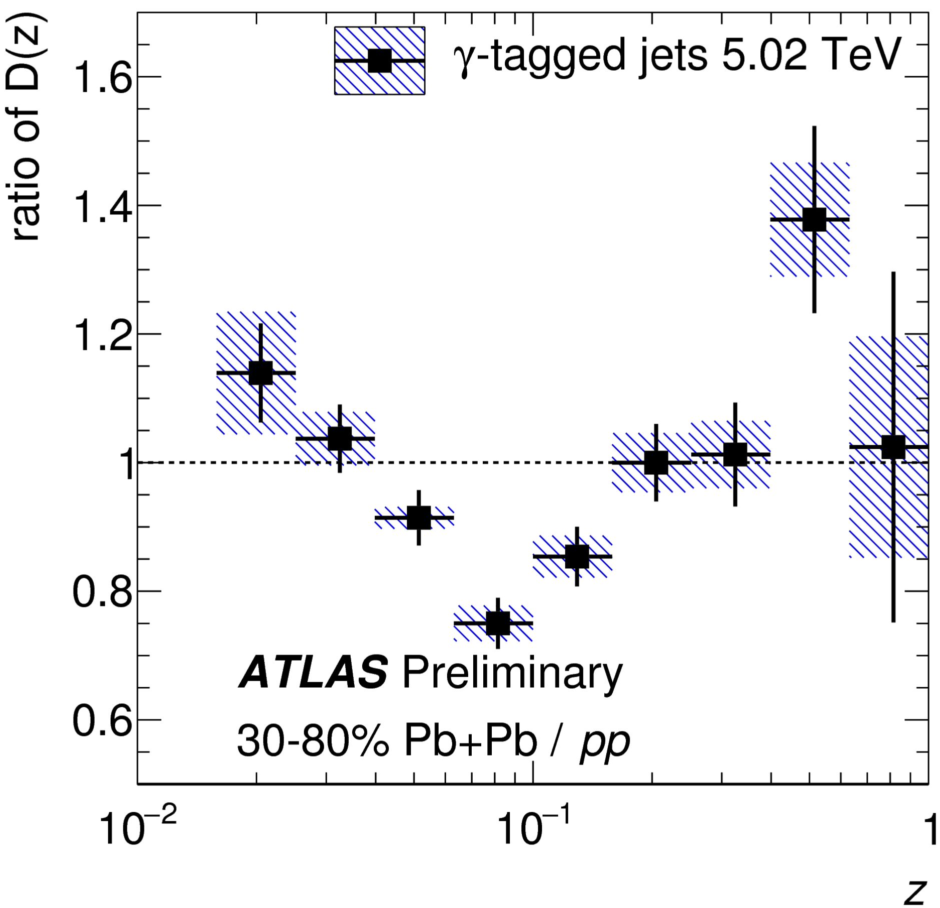


pp 27.4 pb^{-1}, PbPb 404 μb^{-1}

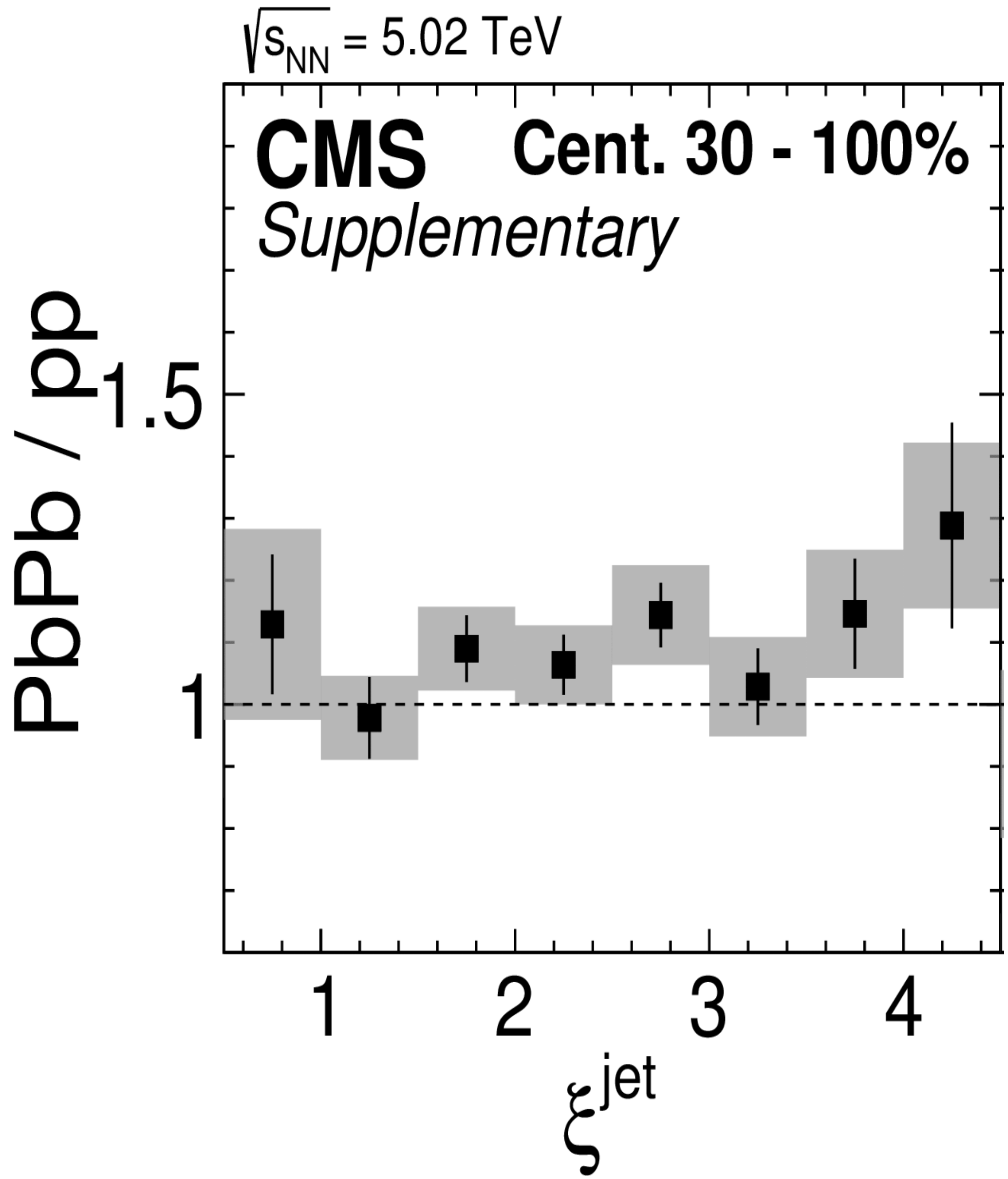


γ-tagged jet FF comparison

ATLAS-CONF-2017-074

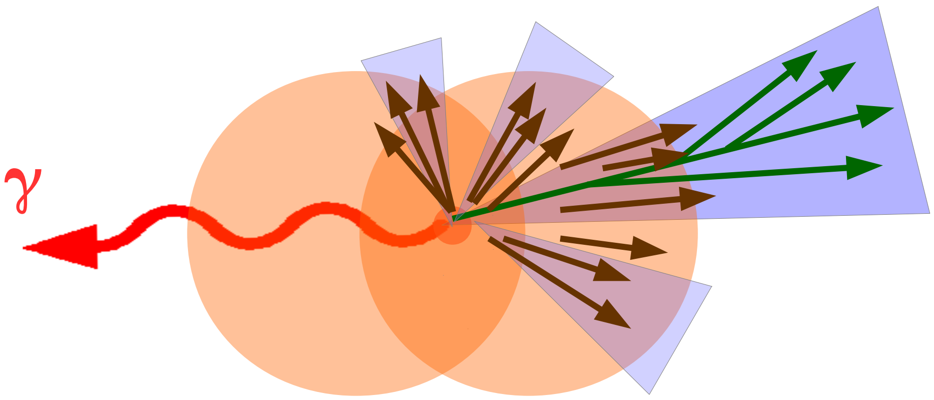


CMS-PAS-HIN-18-006

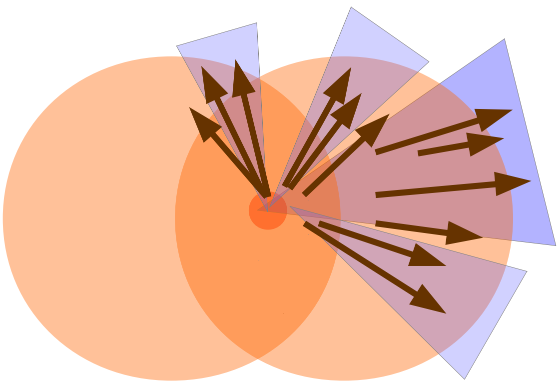


Bkg subtraction for jets and tracks

isolated-photon+jet event

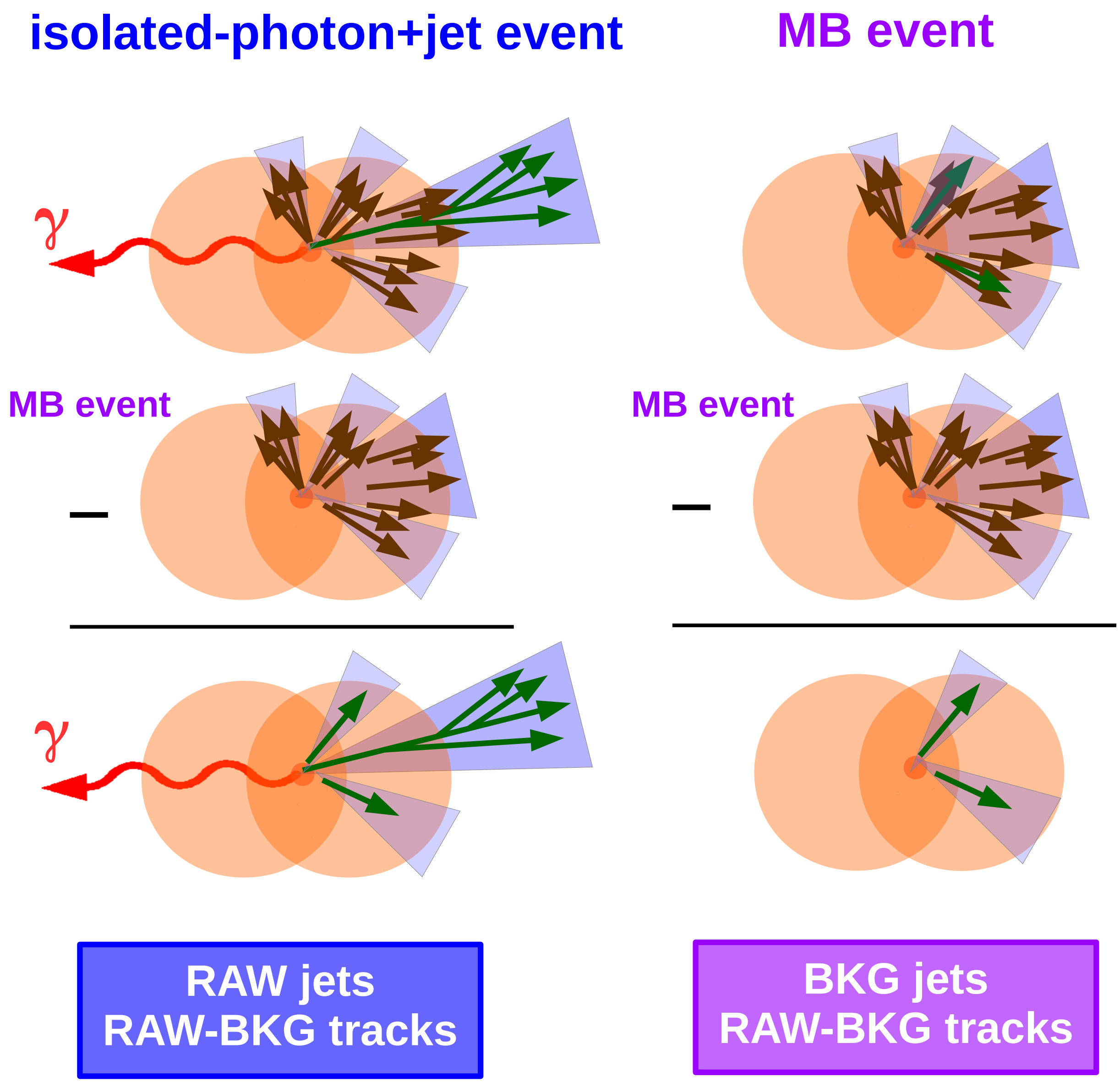


MB event



- 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



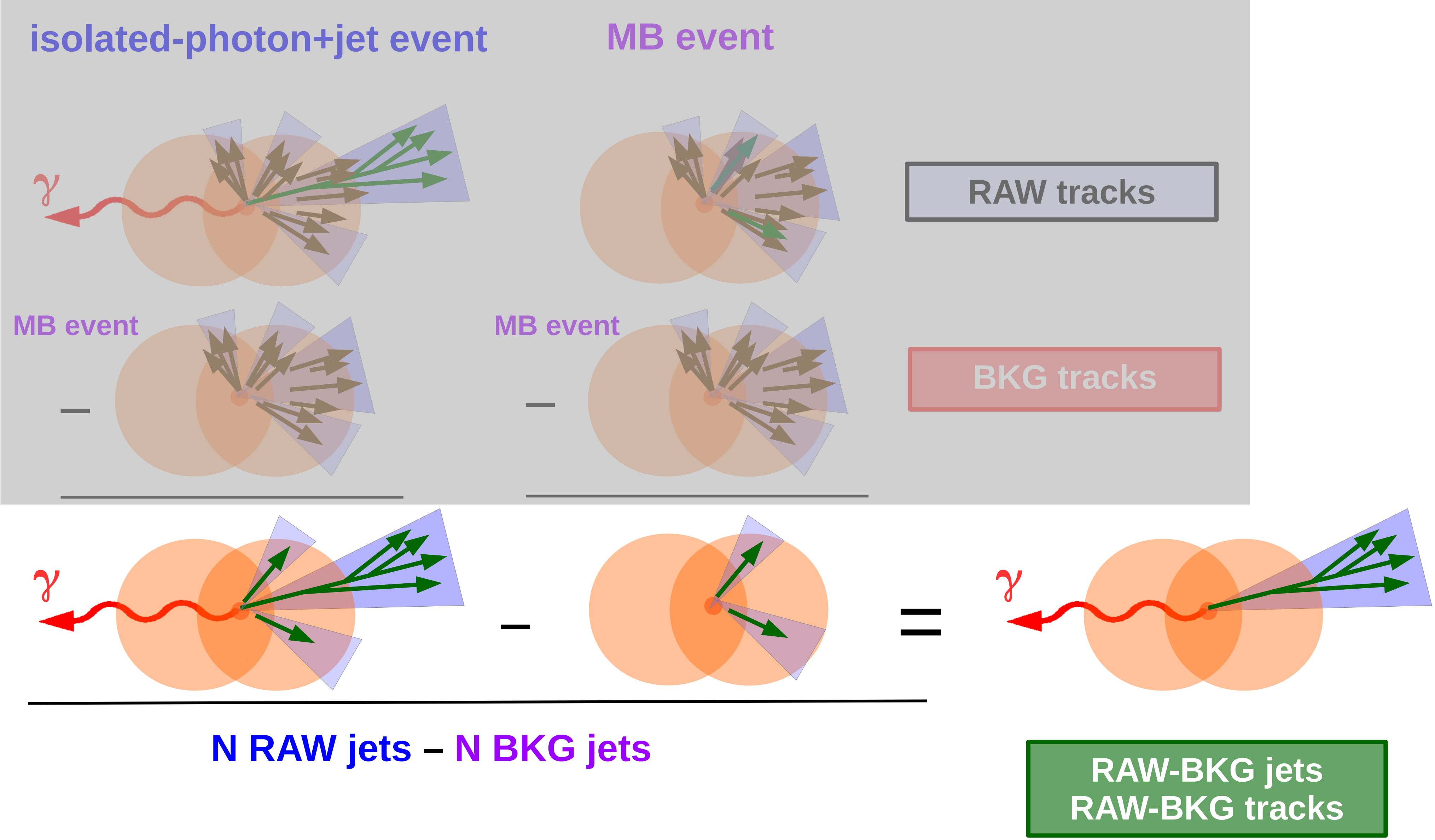
RAW tracks

BKG tracks

MB event mixing technique

How to estimate the bkg from jets/tracks ?
– construct the observable using jets/tracks in matching MB events

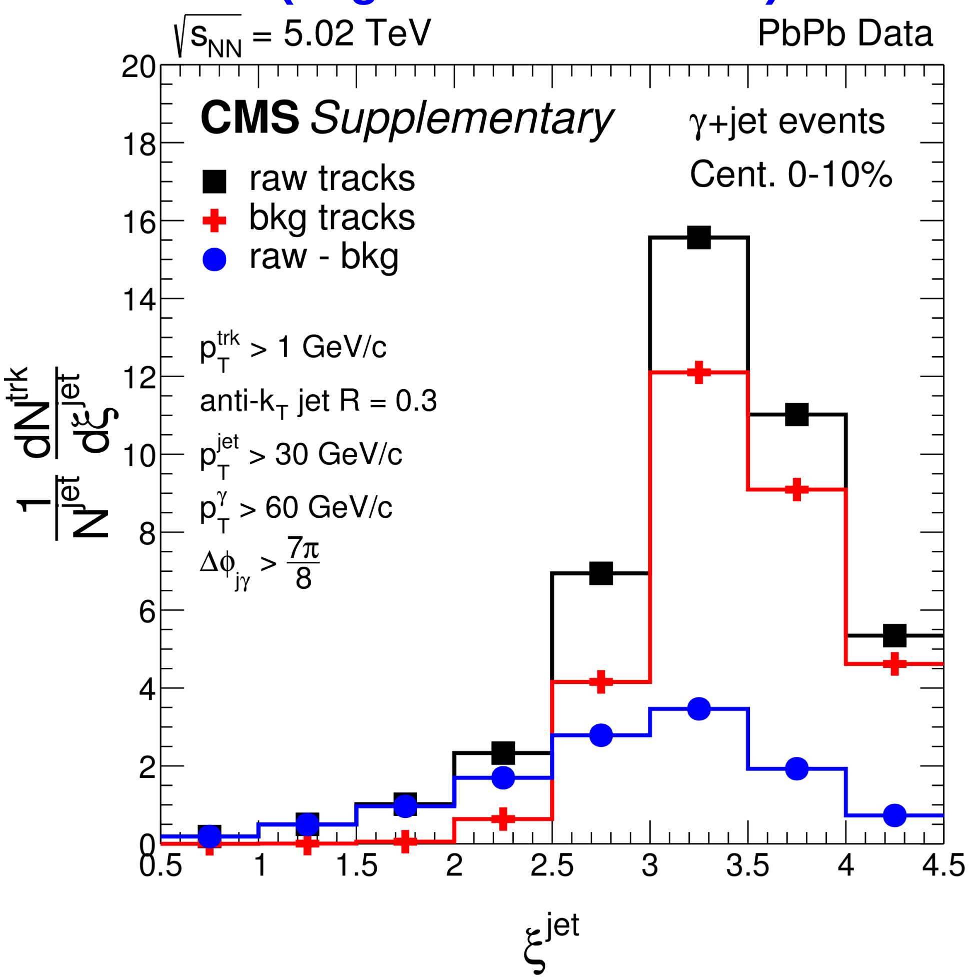
Analysis steps – bkg jets

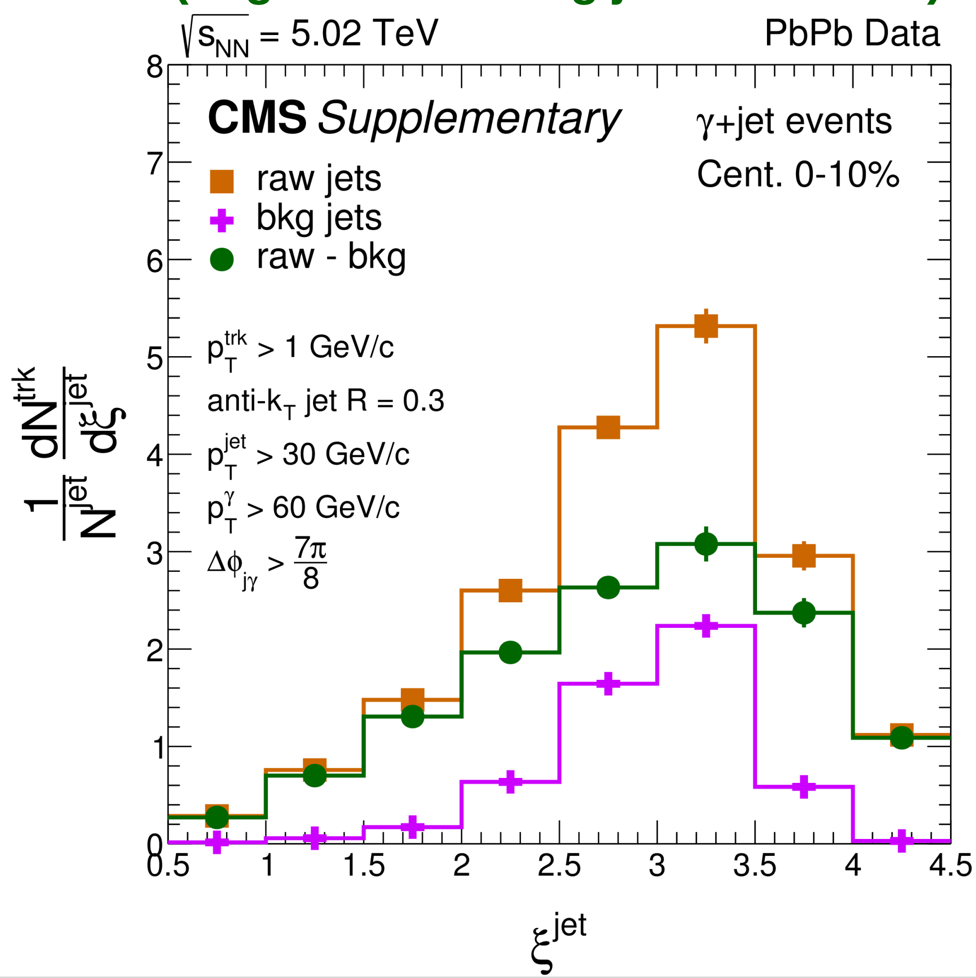


Bkg subtraction : tracks and jets

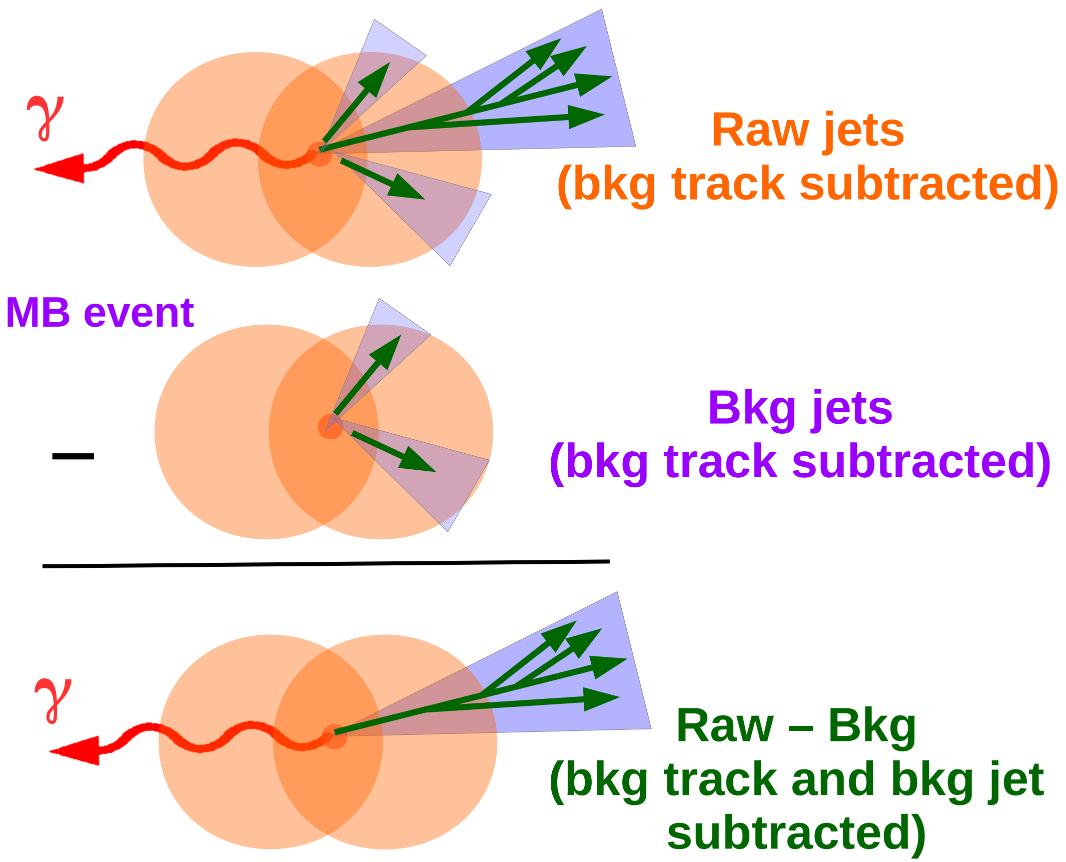
Raw tracks inside jet cone
-
Bkg tracks inside jet cone
=
Raw – Bkg
(bkg track subtracted)

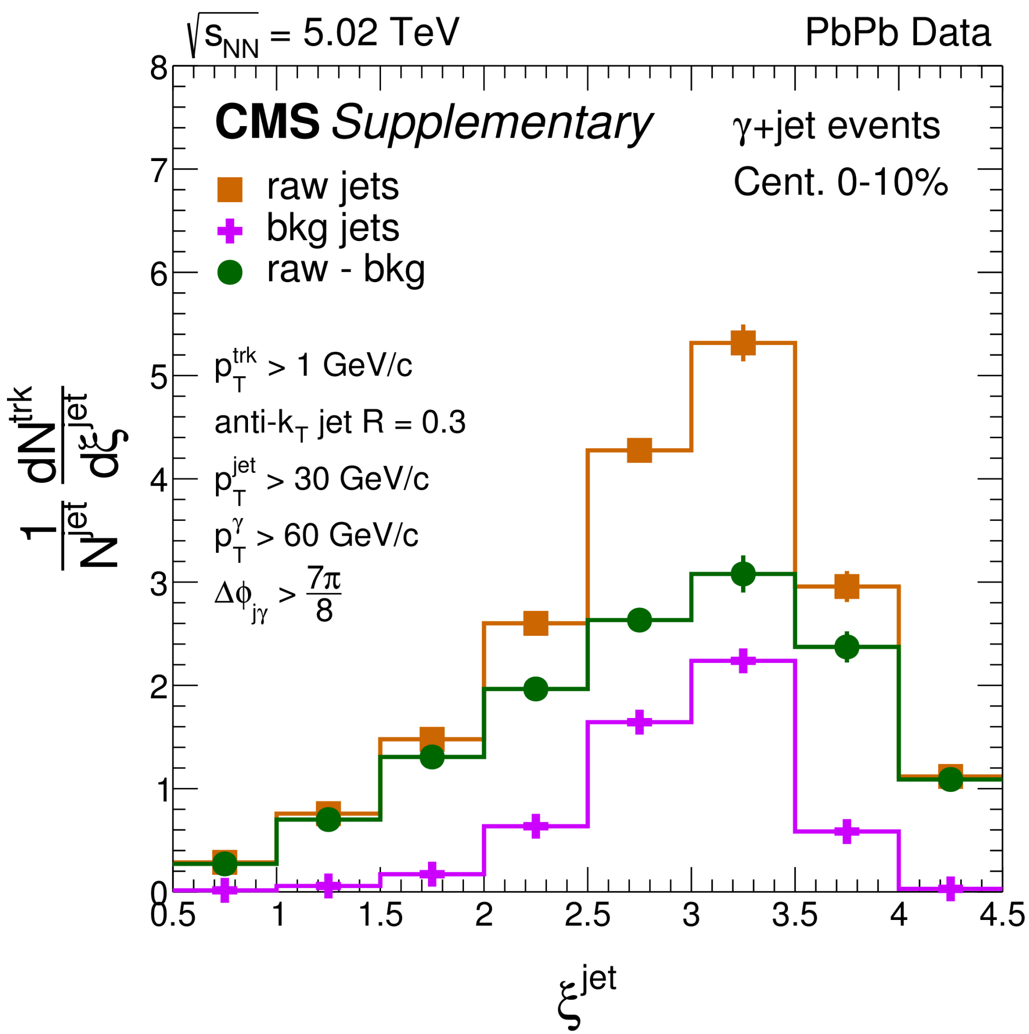
Raw jets
-
Bkg jets
=
Raw – Bkg
(bkg track and bkg jet subtracted)





Bkg subtraction for jets



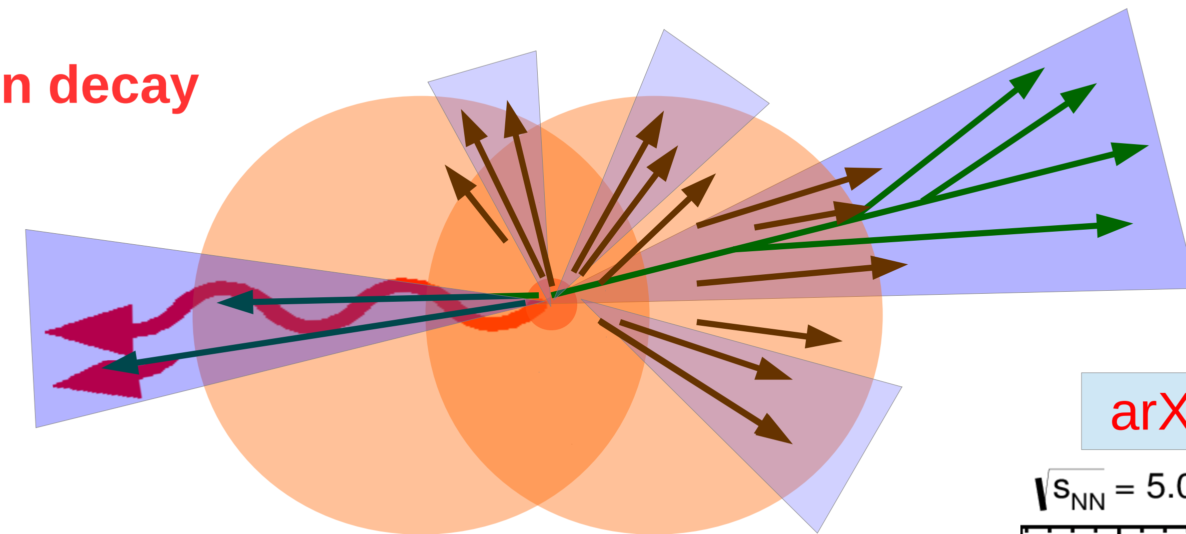


Analysis – bkg photons

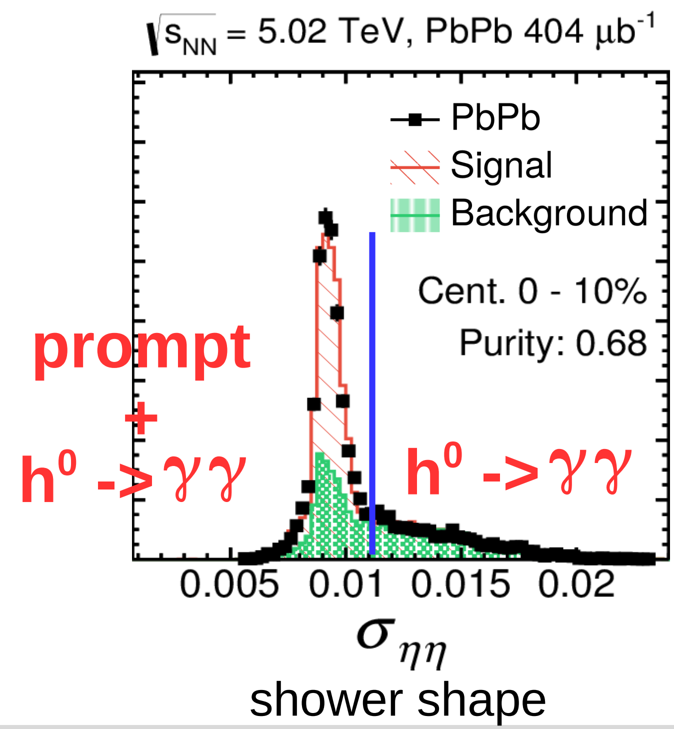
- Observables are constructed using photons, jets and tracks.

Neutral meson decay

$h^0 \rightarrow \gamma\gamma$



arXiv:1711.09738



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 : $0.011 < \sigma_{\eta\eta} < 0.017$

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

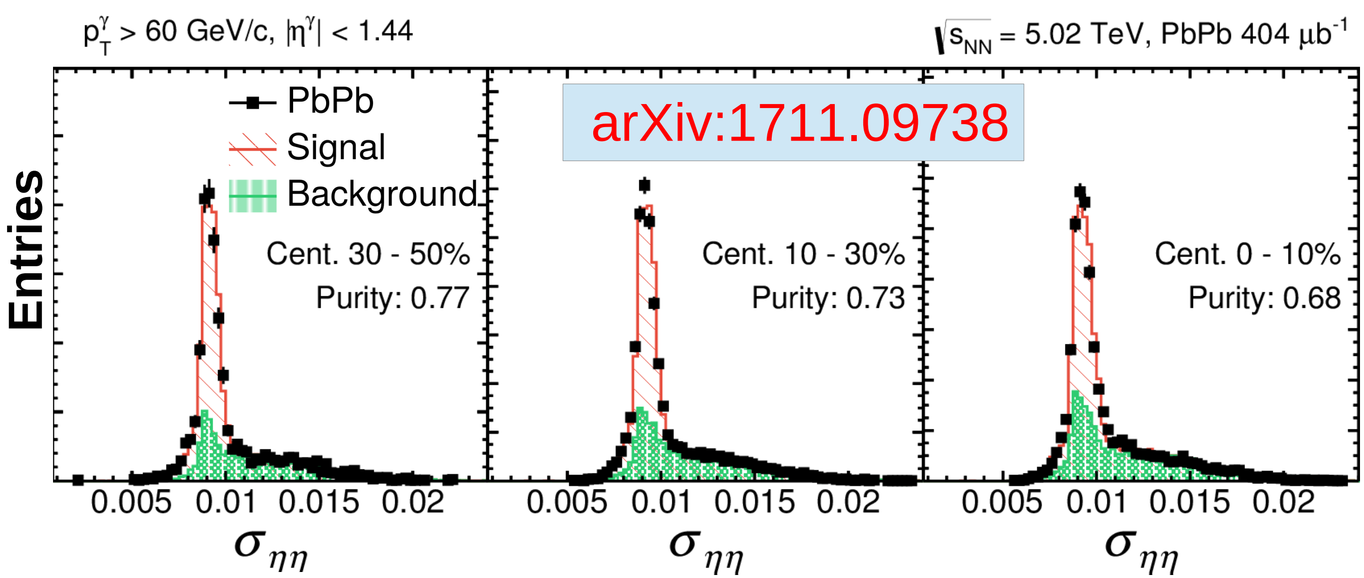
$$\sigma^2_{\eta\eta} = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i}, \qquad w_i = \max(0, 4.7 + \ln\frac{E_i}{E_{5\times5}}),$$

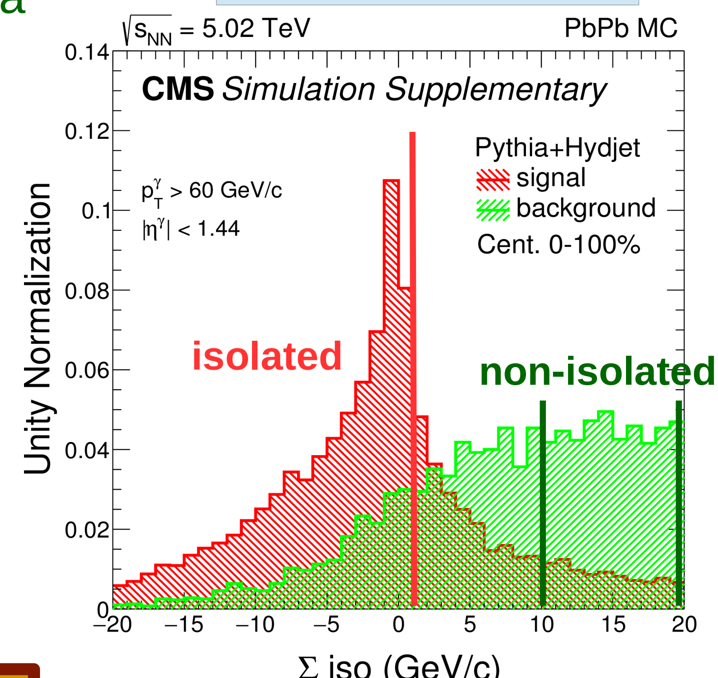
Background from photons

- $\sigma_{\eta\eta}$ < 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

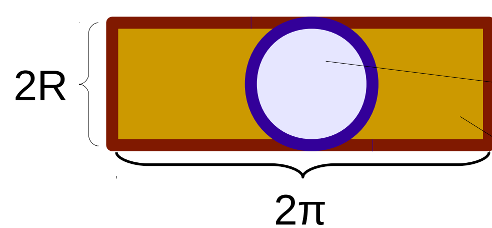
arXiv:1801.04895





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

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



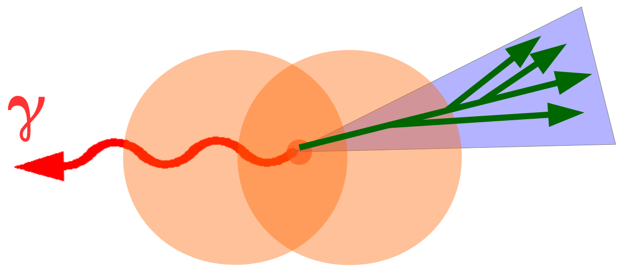
Σ iso =
(tot energy in a cone of R=0.4 around the photon) -
(ave. energy from a strip of 2π x 2R)

Analysis steps - photons

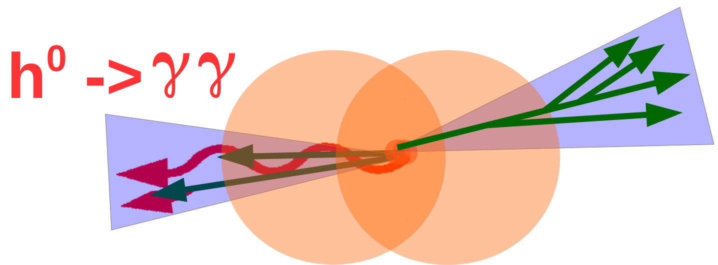
Repeat the previous steps for two photon selections

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



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

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

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

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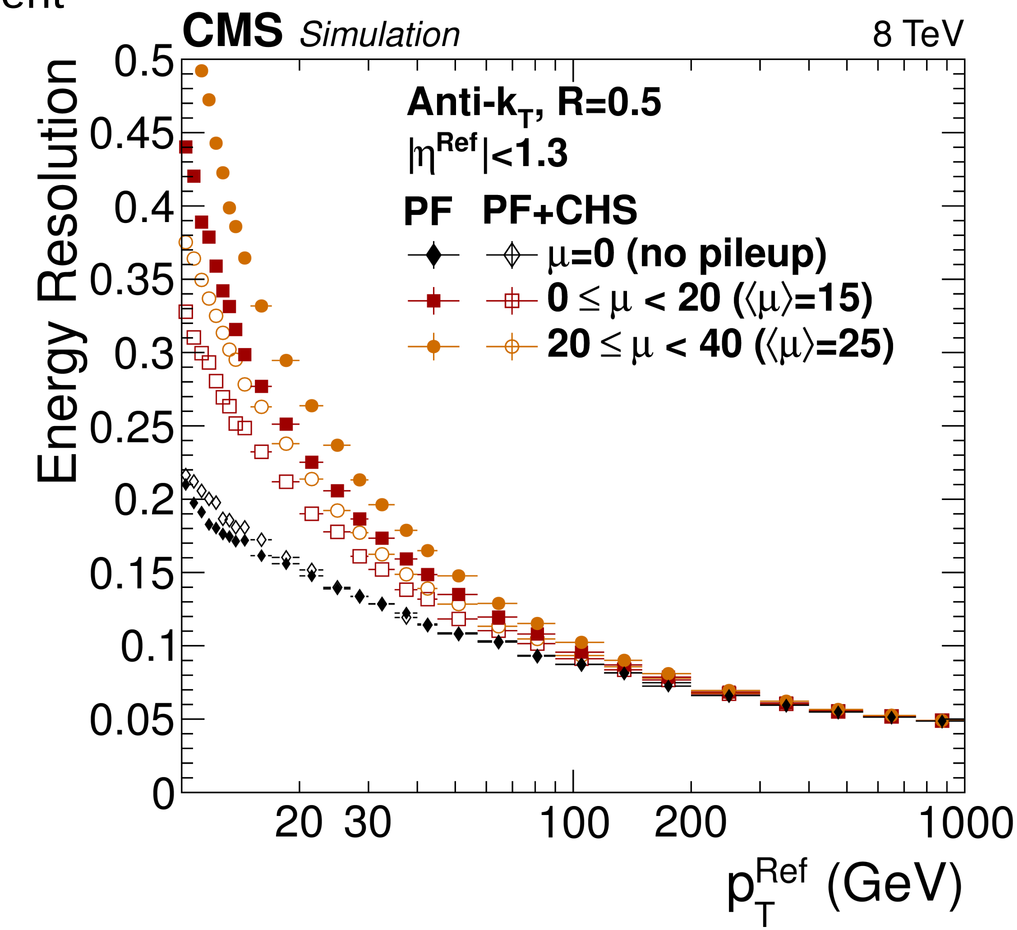


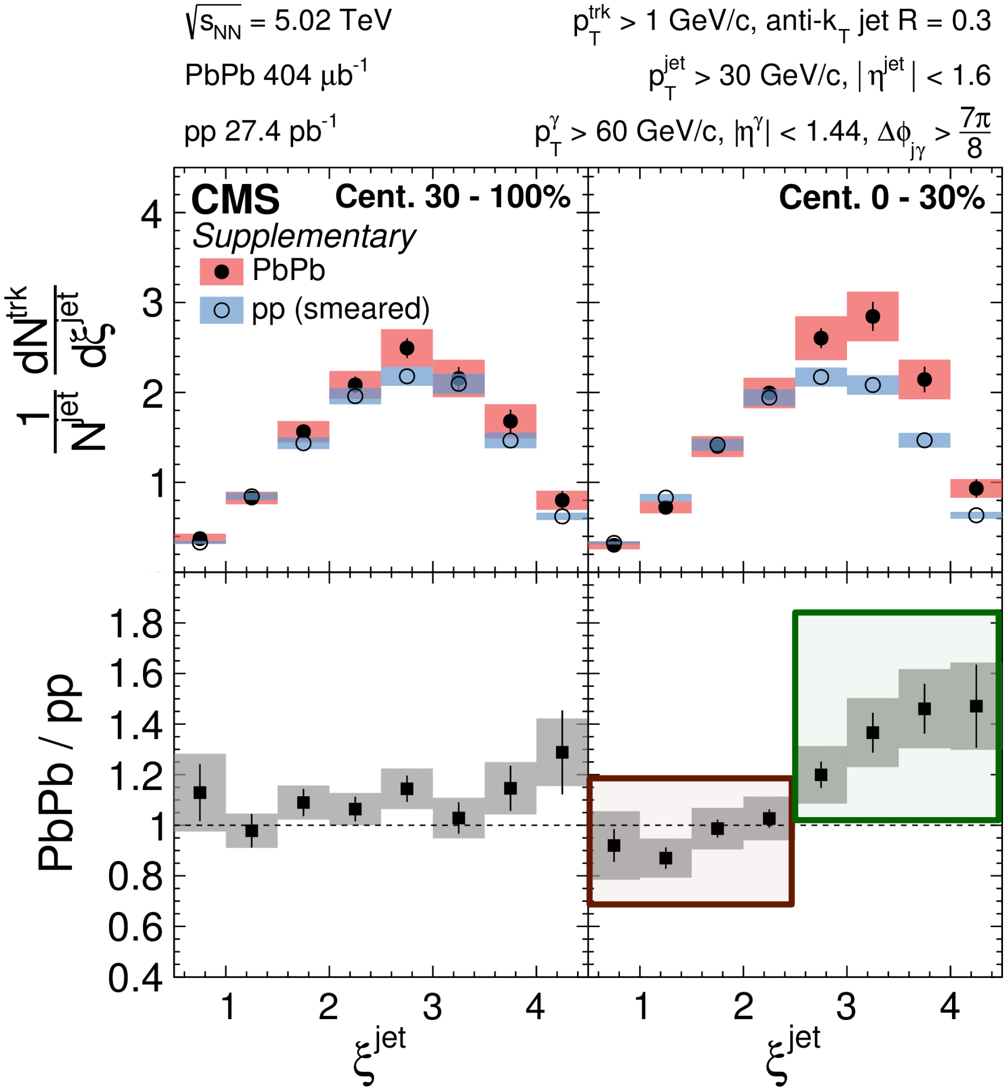
- Smearing **jet azimuthal angle**
  - Use same parametrization as in jet energy resolution

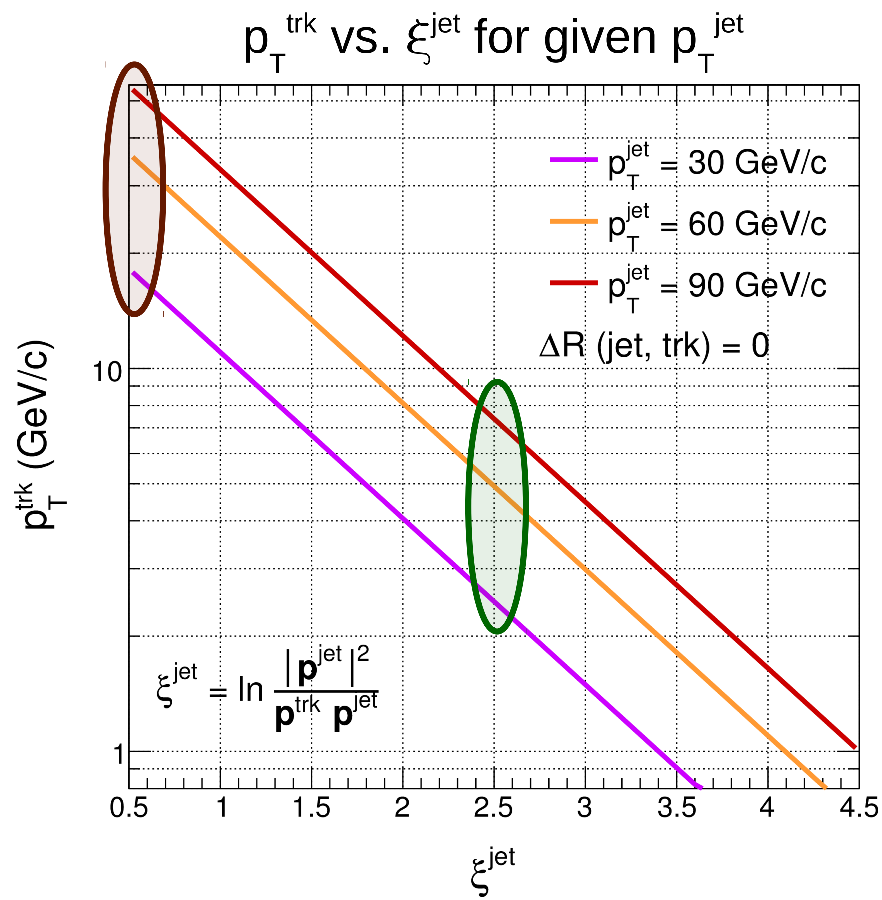
$$\sigma(|\phi^{RECO}-\phi^{GEN}|)=\sqrt{C^2+\frac{S^2}{p_T^{GEN}}+\frac{N^2}{(p_T^{GEN})^2}}$$

  - Apply relative resolution in the same fashion

Results - ξ^{jet}

arXiv:1801.04895





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

Enhancement for ξ^{jet} > 2.5

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

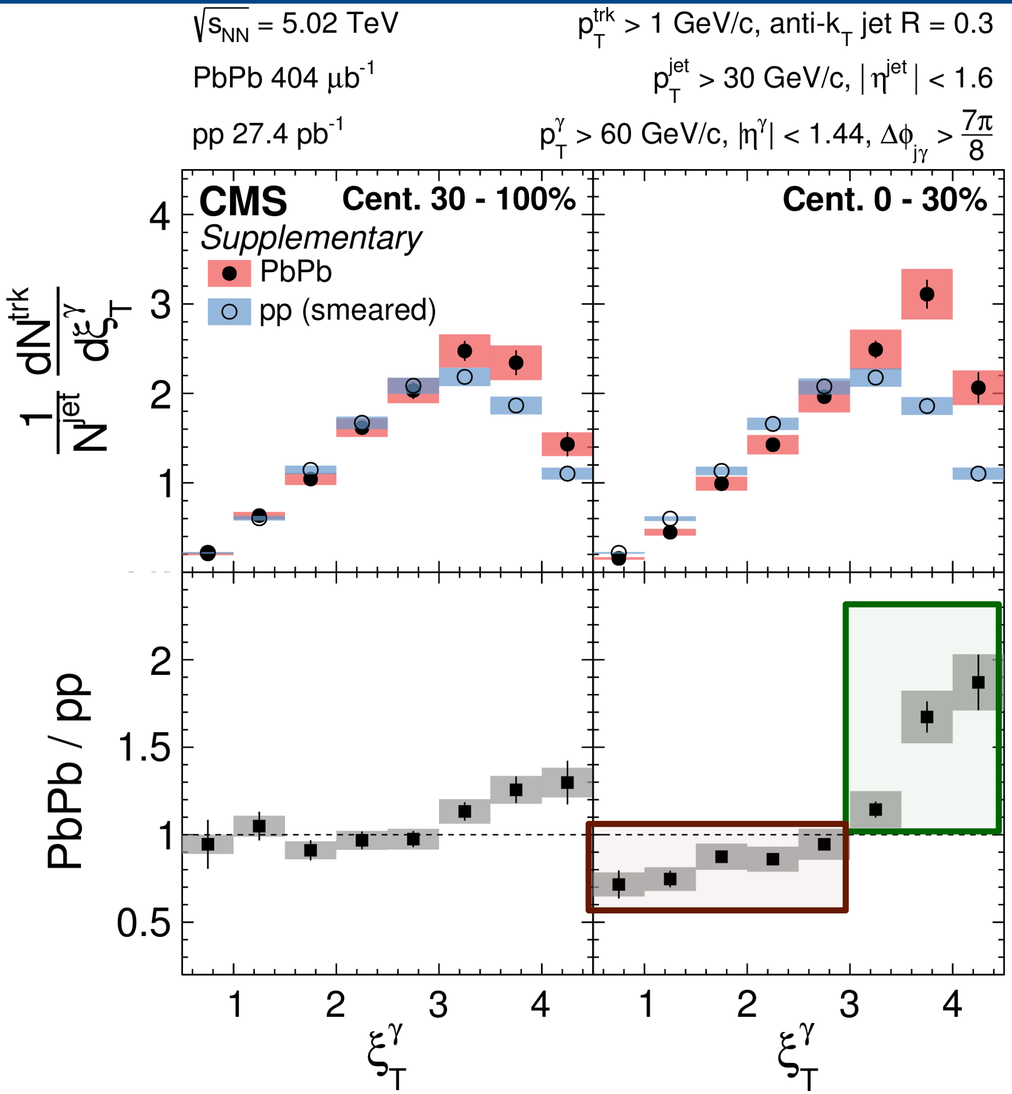
Slight depletion for ξ^{jet} < 2.5

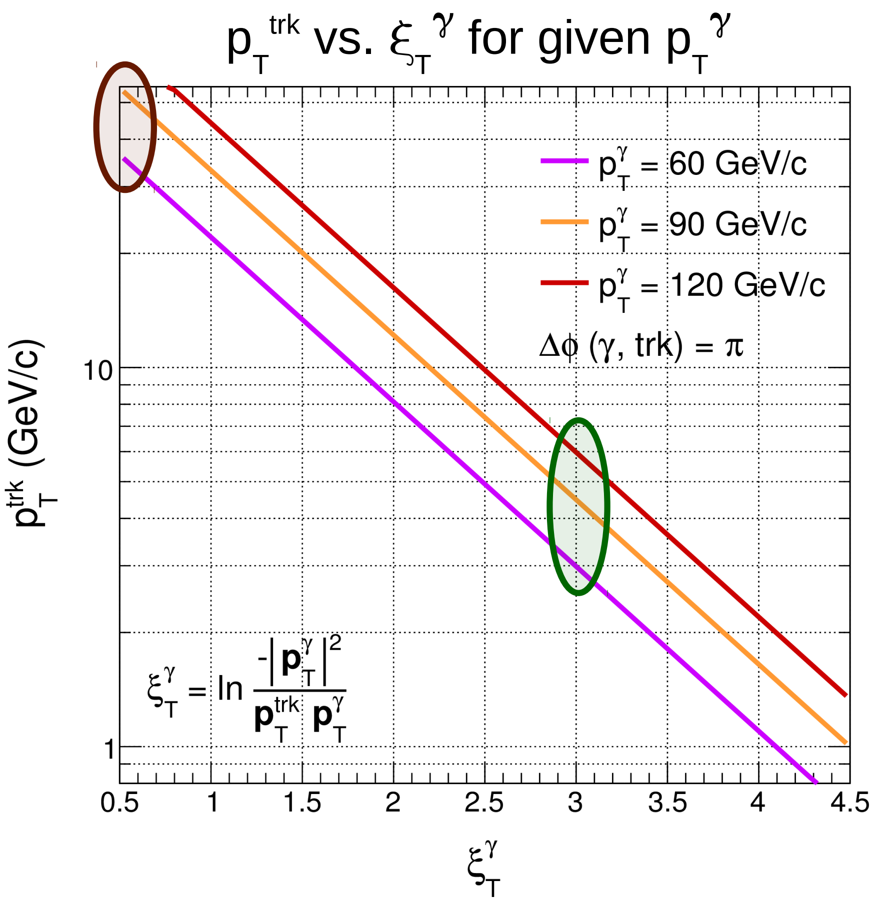
$2.5 \lesssim p_T^{trk} \lesssim 18$ GeV/c for $p_T^{jet} \approx 30$ GeV/c

Based on reconstructed jet energy
(energy after quenching)

Results - ξ_T^{γ}

arXiv:1801.04895





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

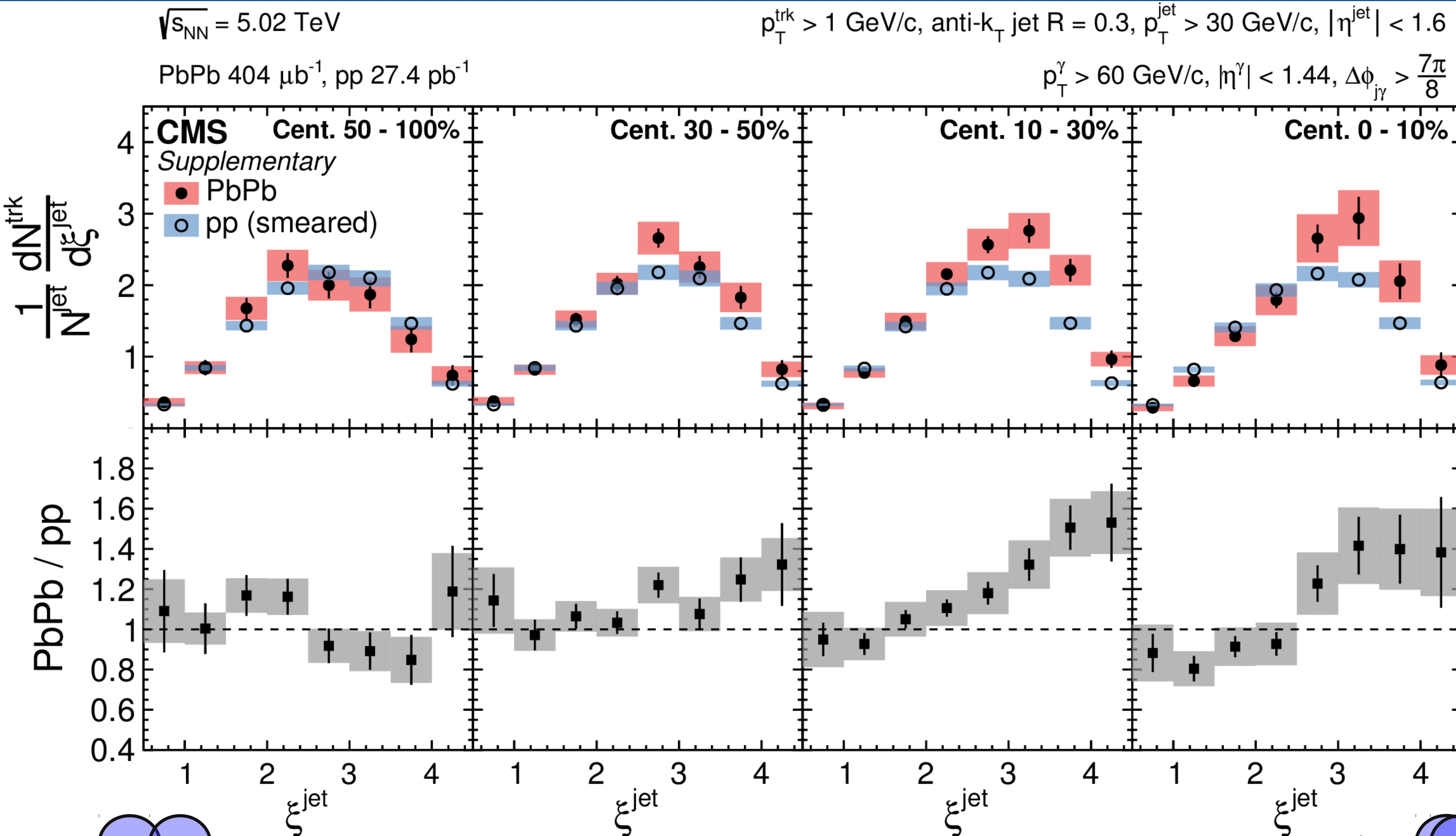
Depletion for $\xi_T^{\gamma} < 3$

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

Based on initial parton energy
(energy before quenching)

γ-tagged jet FF - ξ^{jet}

arXiv:1801.04895



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

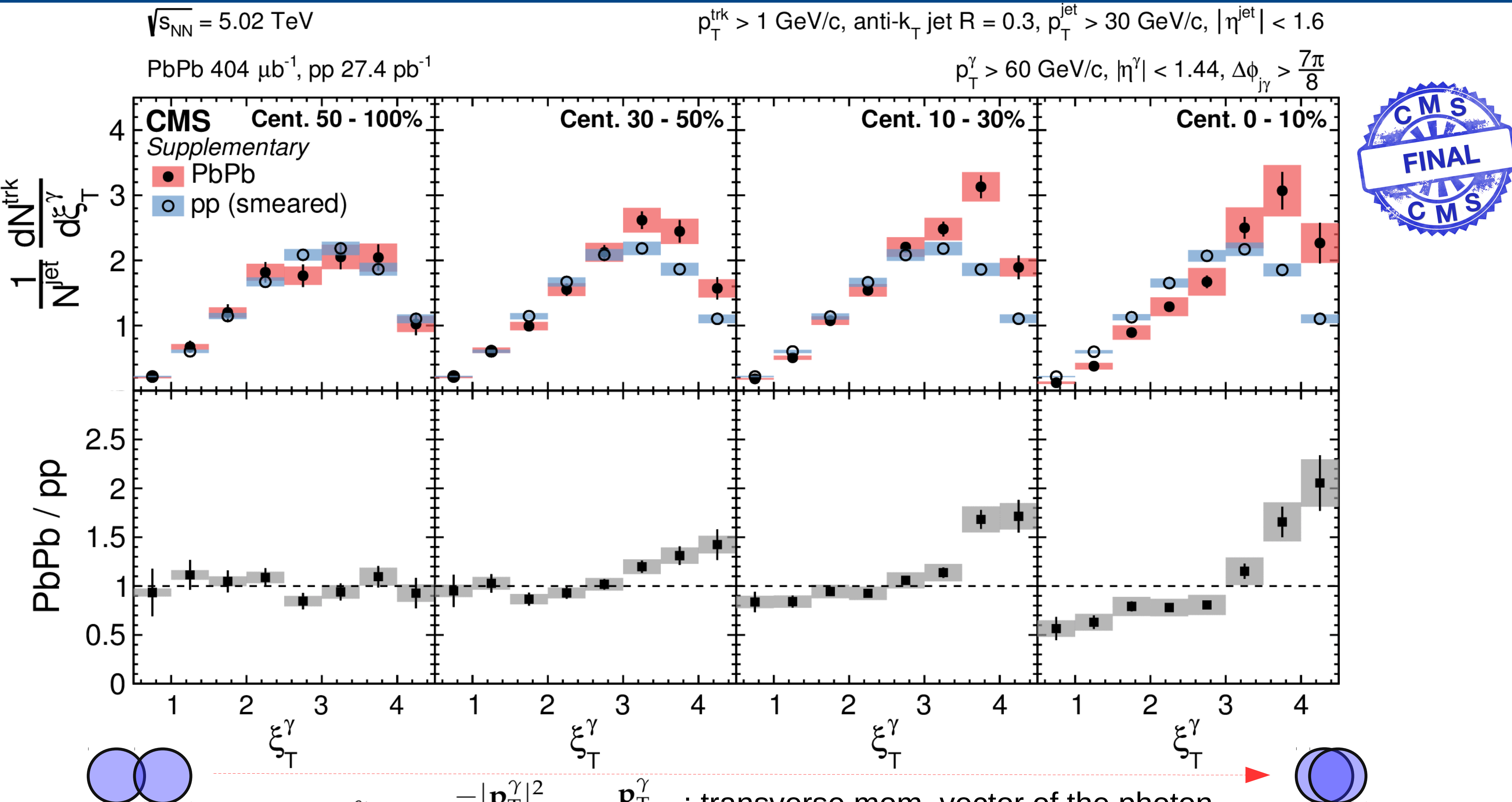
$\mathbf{p}^{jet}$: 3-momentum vector of the jet

$\mathbf{p}^{trk}$: 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.

γ-tagged jet FF - ξ_T^γ

arXiv:1801.04895



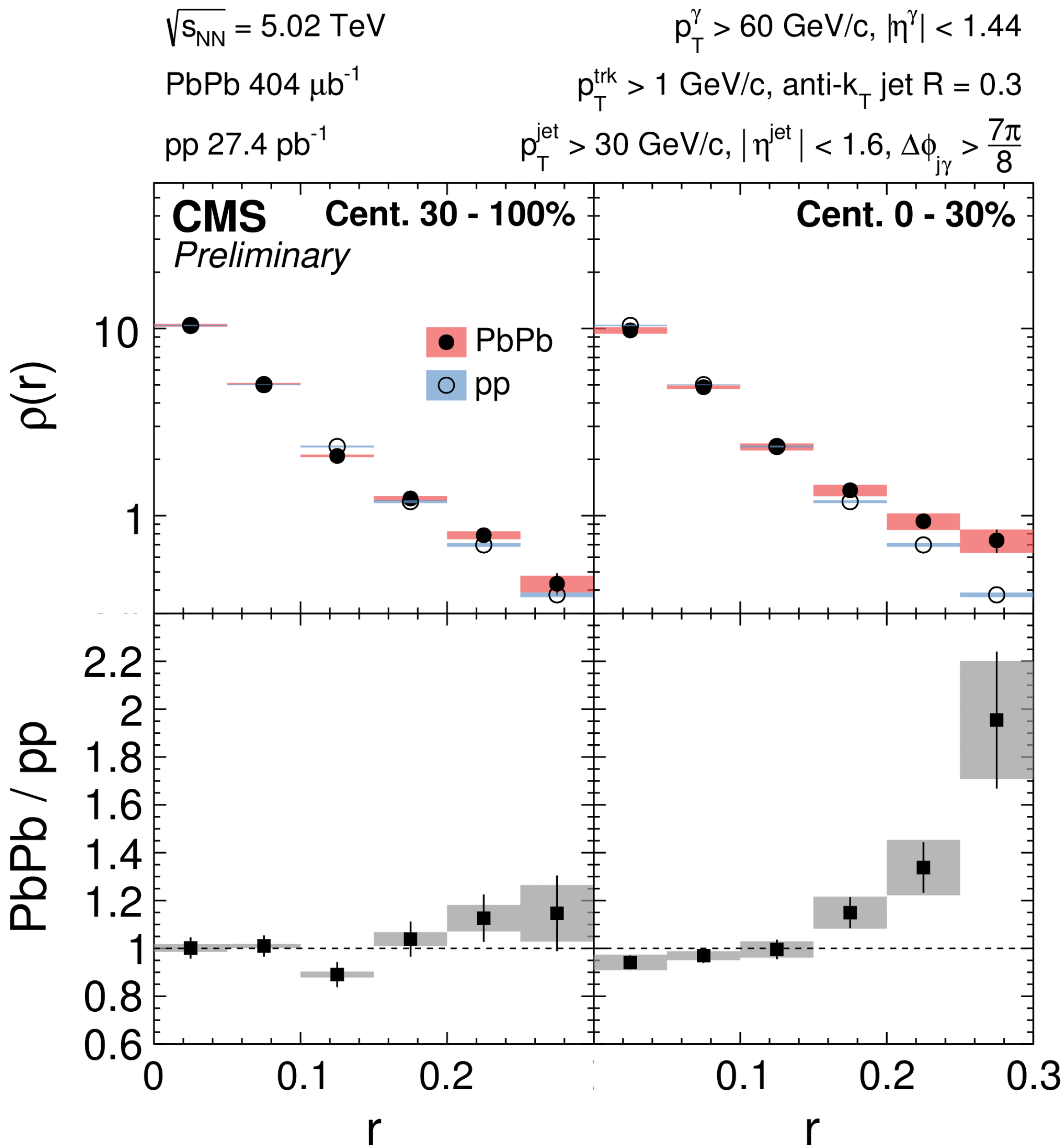
$$\xi_T^\gamma = \ln \frac{-|\mathbf{p}_T^\gamma|^2}{\mathbf{p}_T^{trk} \cdot \mathbf{p}_T^\gamma}$$

$\mathbf{p}_T^\gamma$: 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.

γ-tagged jet shape : 30-100%, 0-30%



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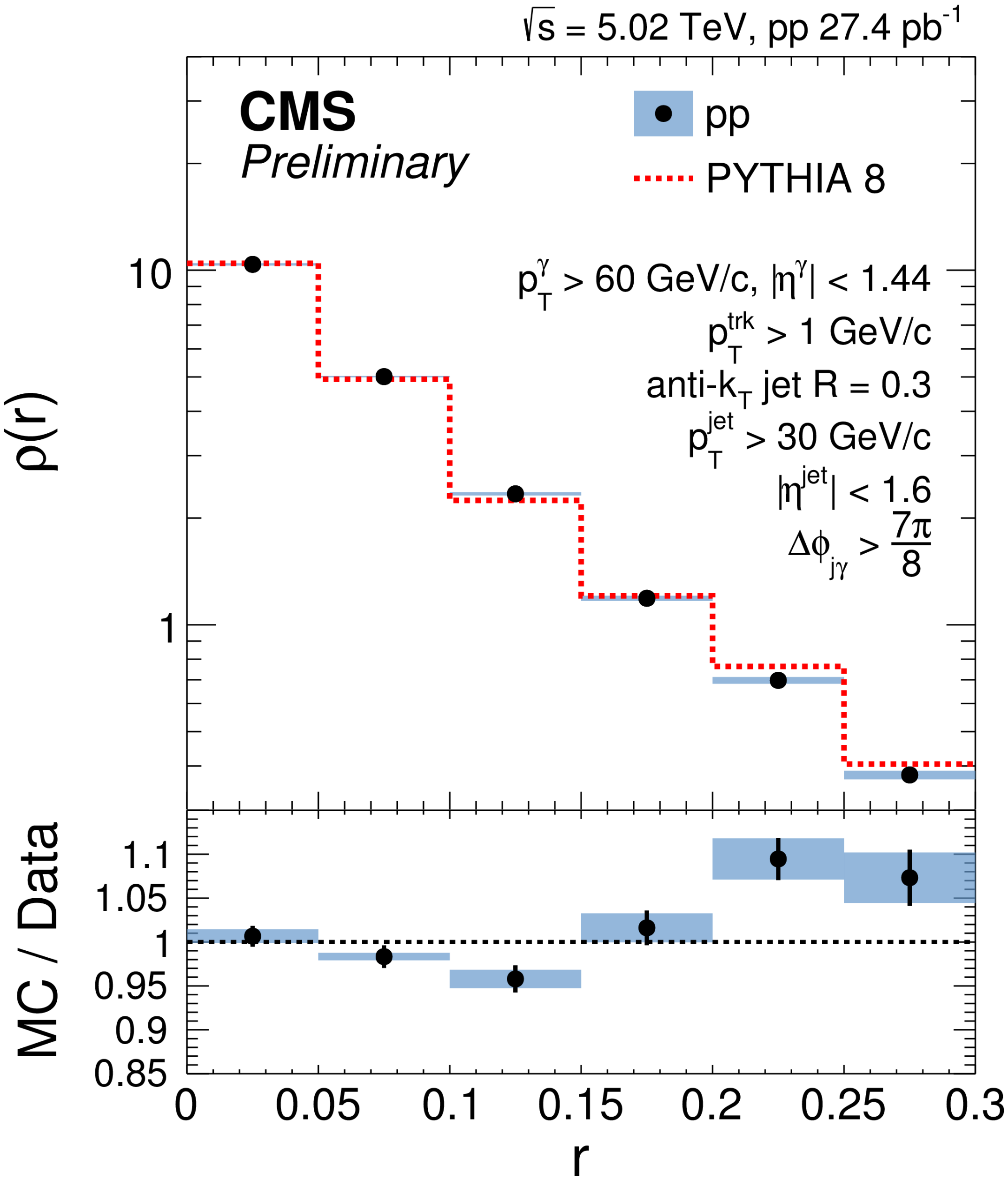
Measurement with coarser centrality binning

Increased significance

γ-tagged jet shape : pp vs MC



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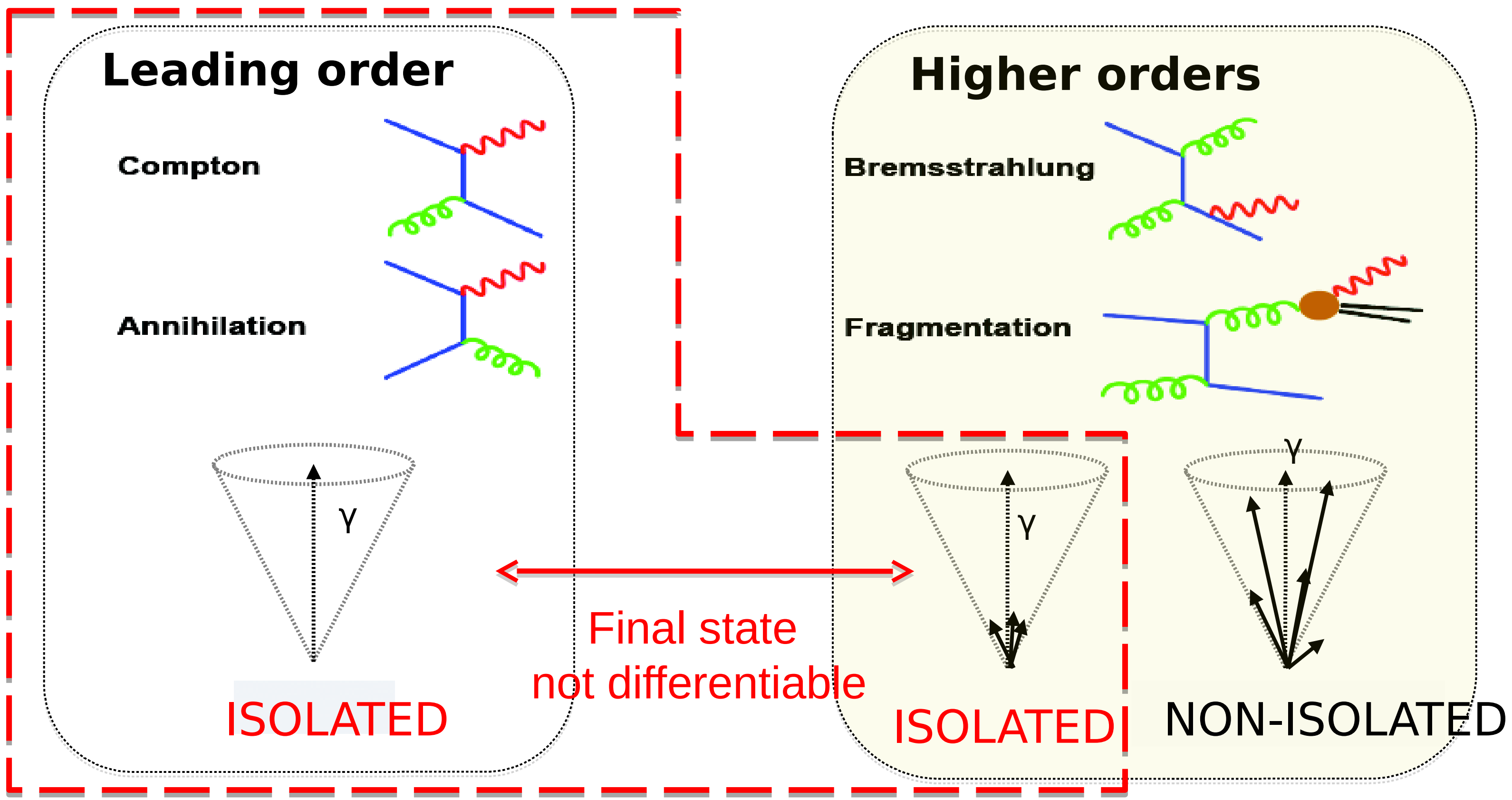
Signal Photon

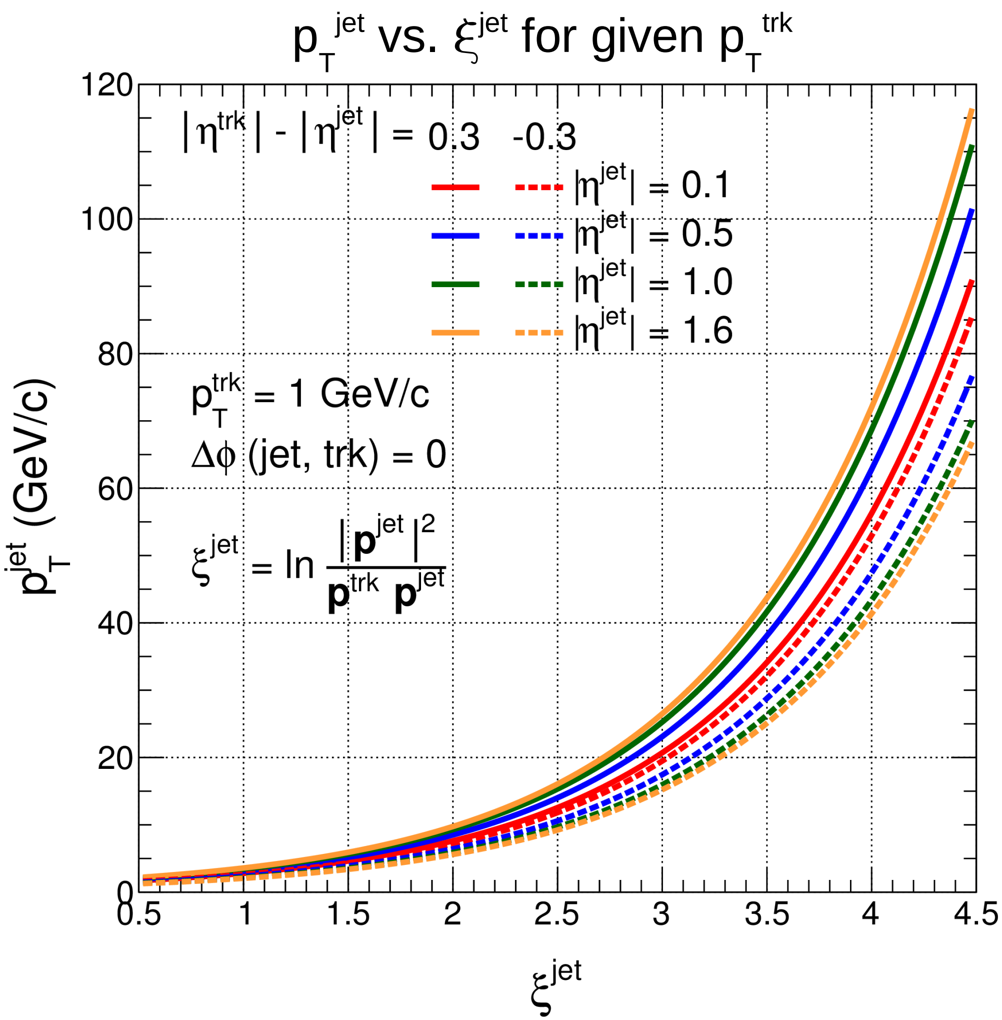
Identify signal photons by :

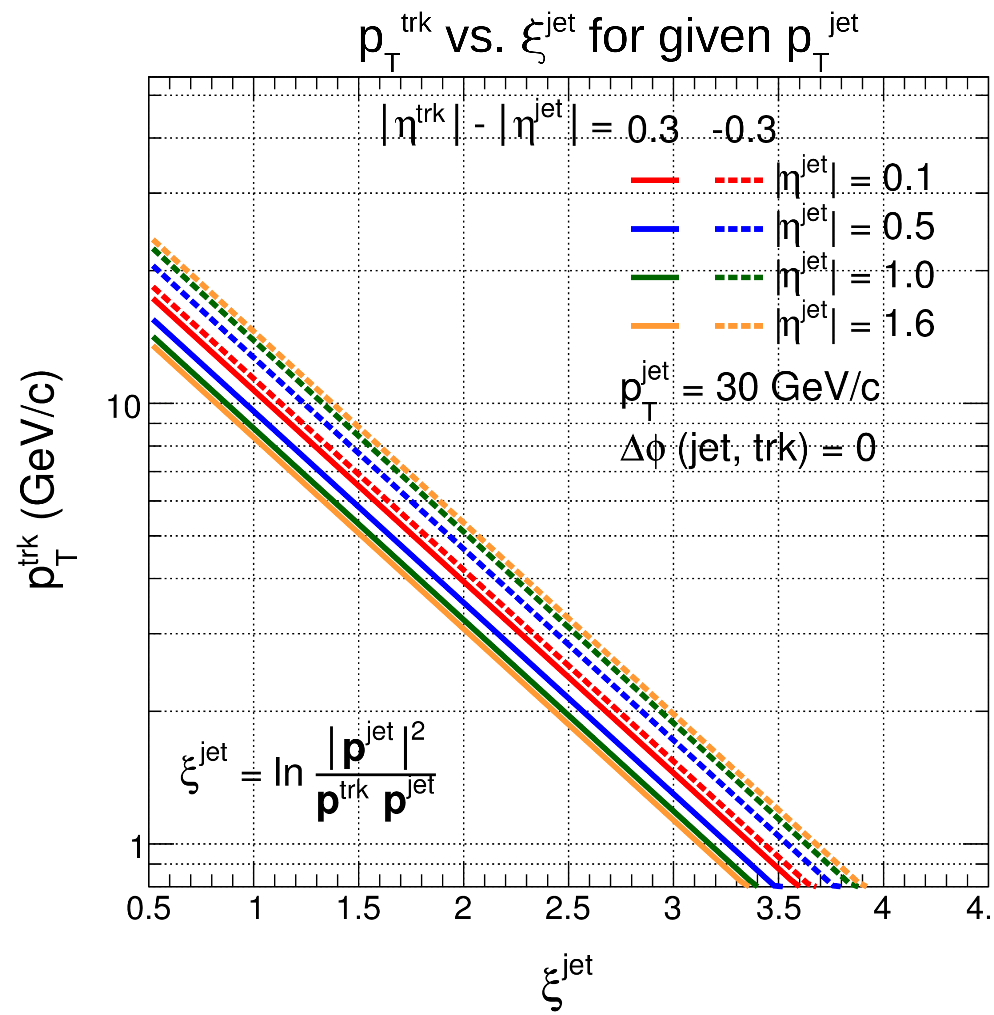
- Isolation requirement based on calorimeter deposits and tracks
- Extract fraction of signal photons based on shower shape



ξ^{jet} phase space

arXiv:1801.04895

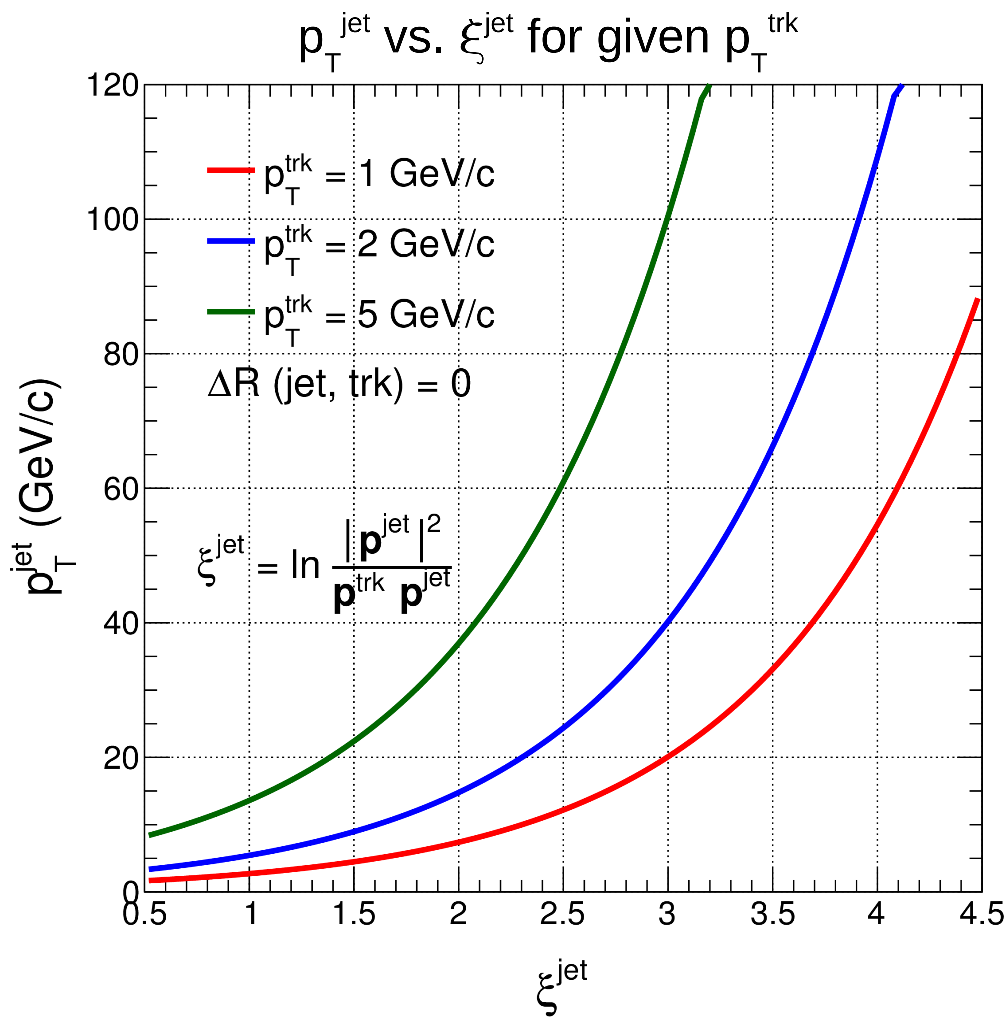


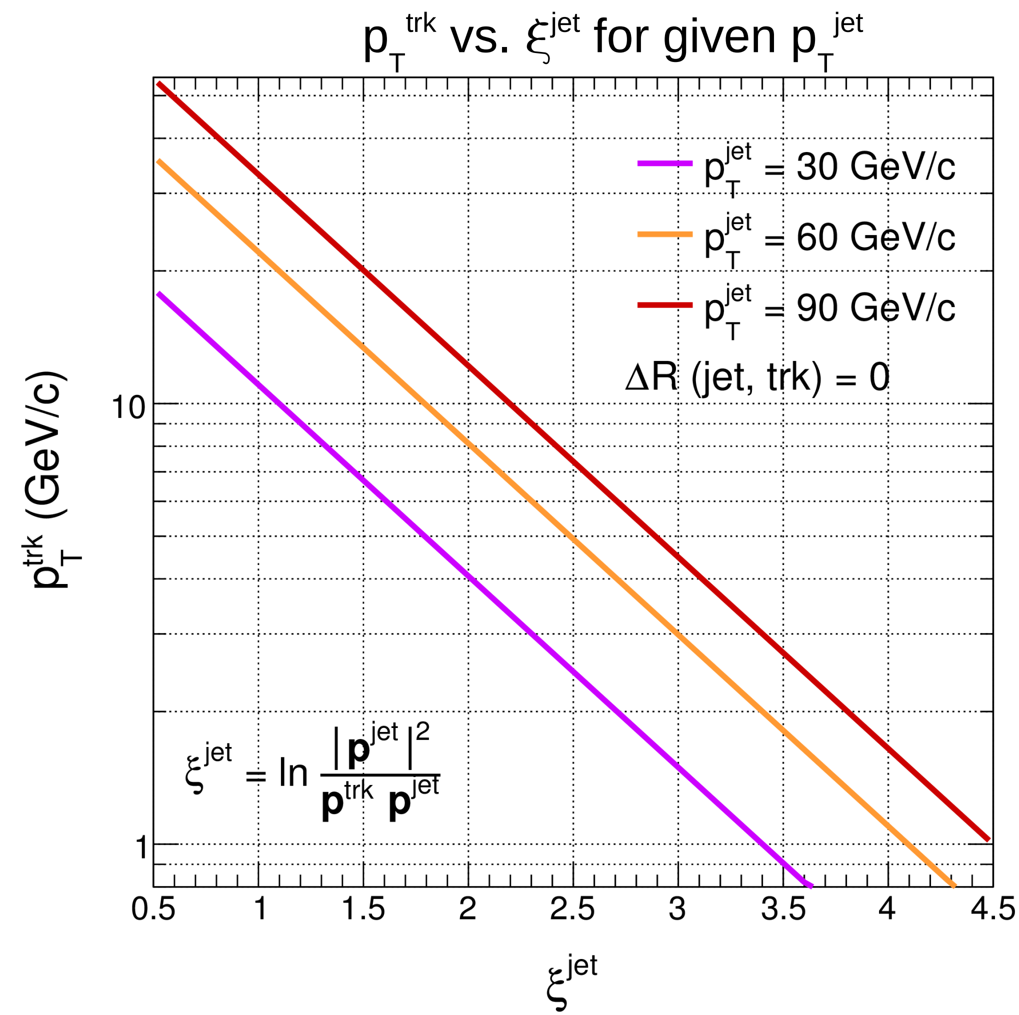


In general the mapping depends on $\boldsymbol{\eta^{jet}}$, $\boldsymbol{\eta^{trk}}$ and **ΔR (jet, trk)**.
The solid and dashed lines are the extreme cases for a given η^{jet}.

ξ^{jet} phase space

arXiv:1801.04895

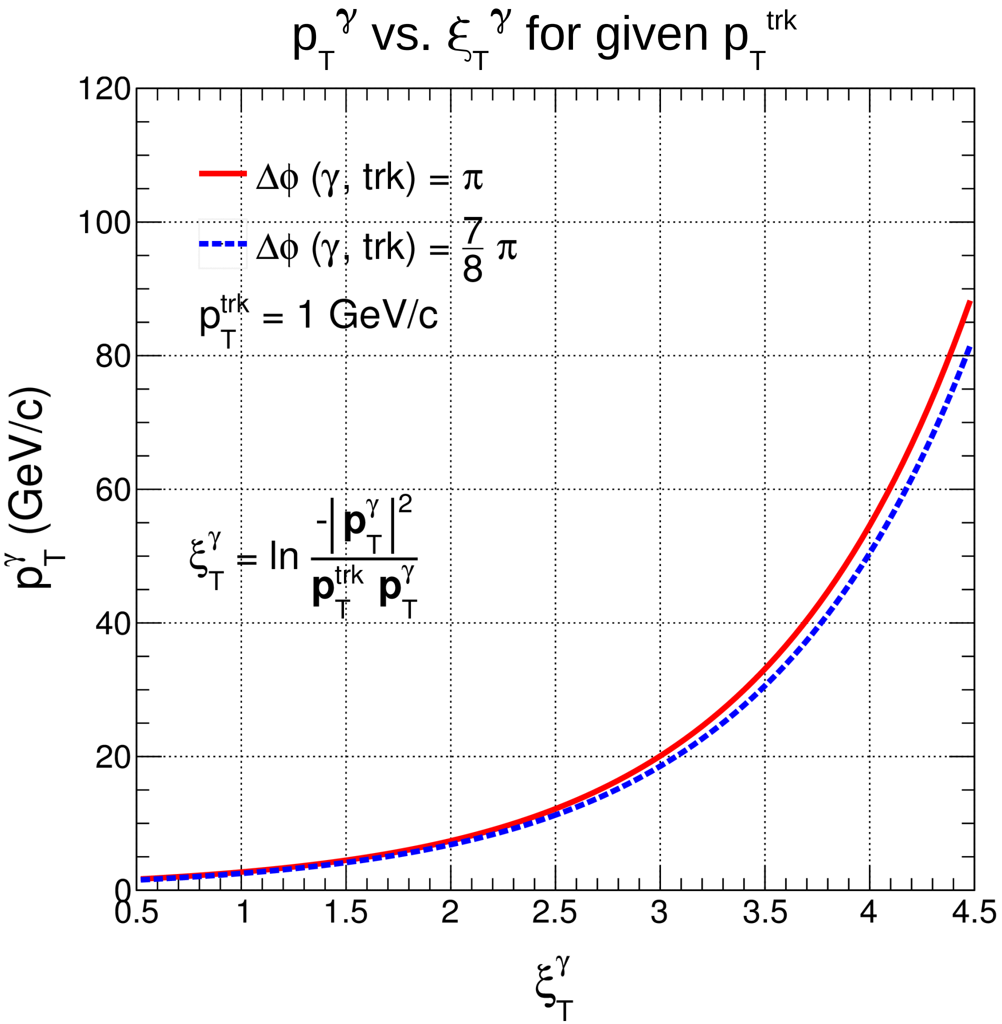


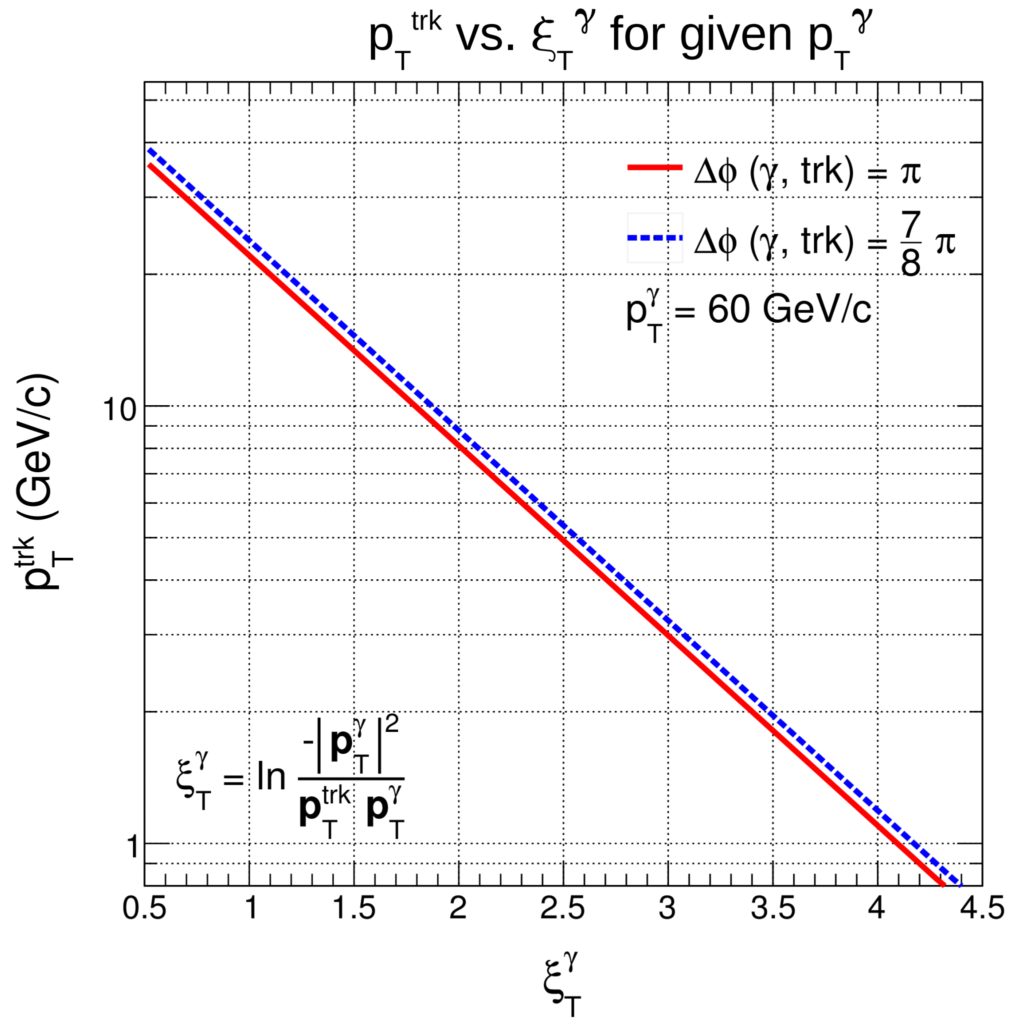


If **ΔR (jet, trk) = 0**, then the mapping becomes **η-indep**.

ξ_T^{γ} phase space

arXiv:1801.04895



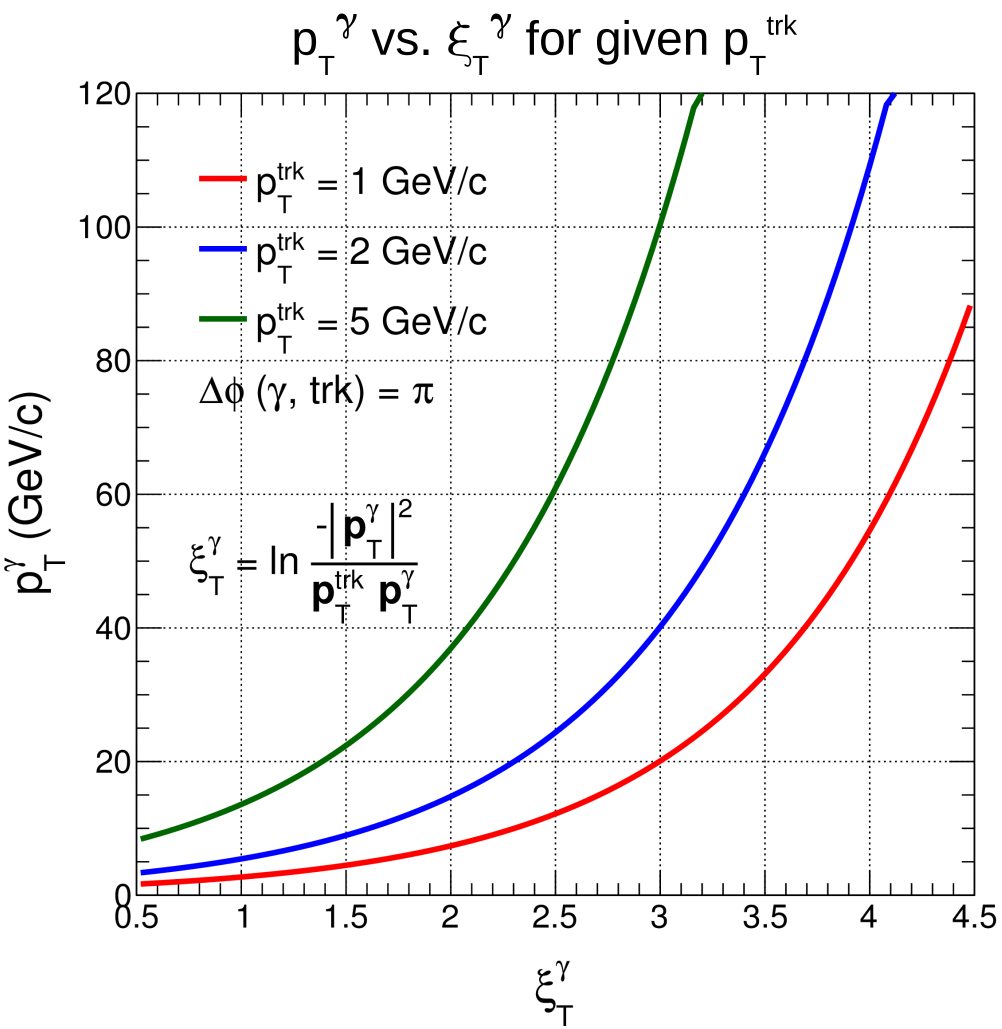


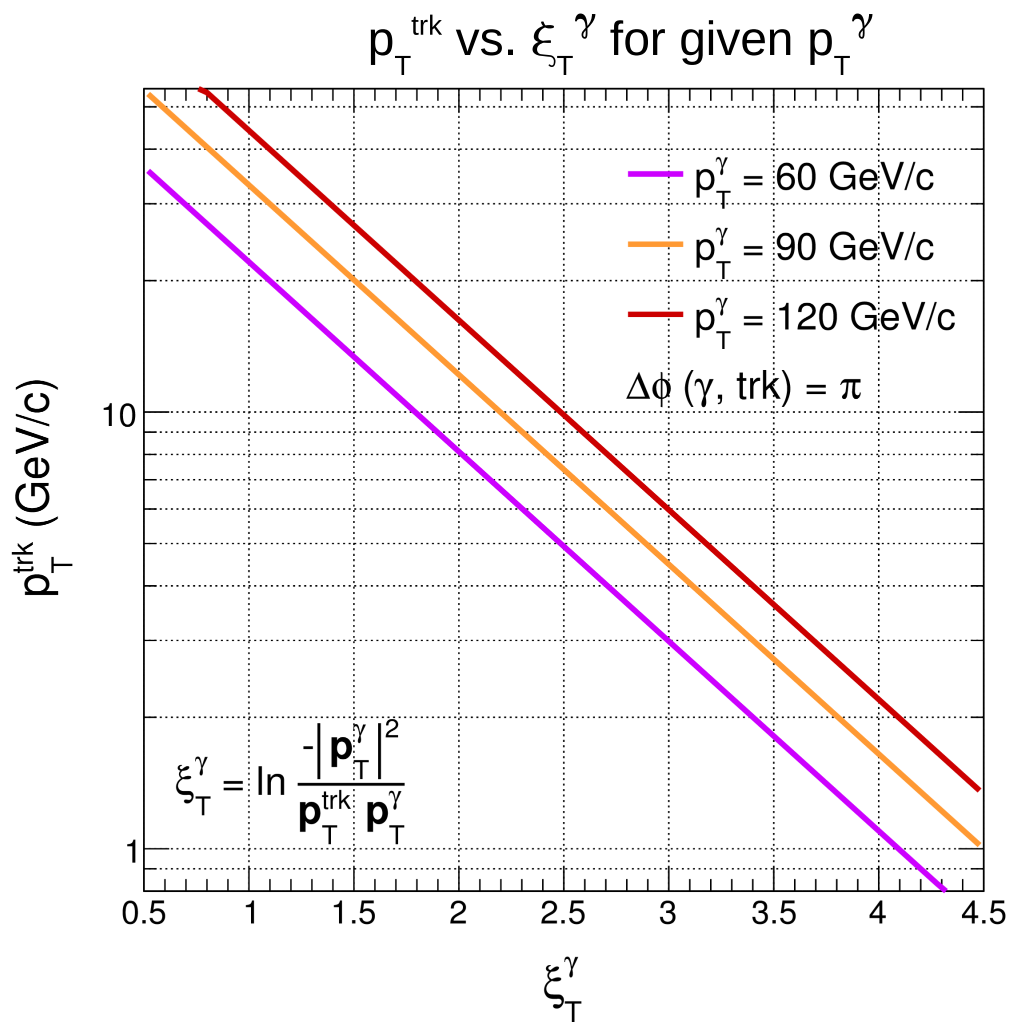
The mapping depends on **Δφ (γ, trk)**.

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

arXiv:1801.04895





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

Number of charged particles inside jet

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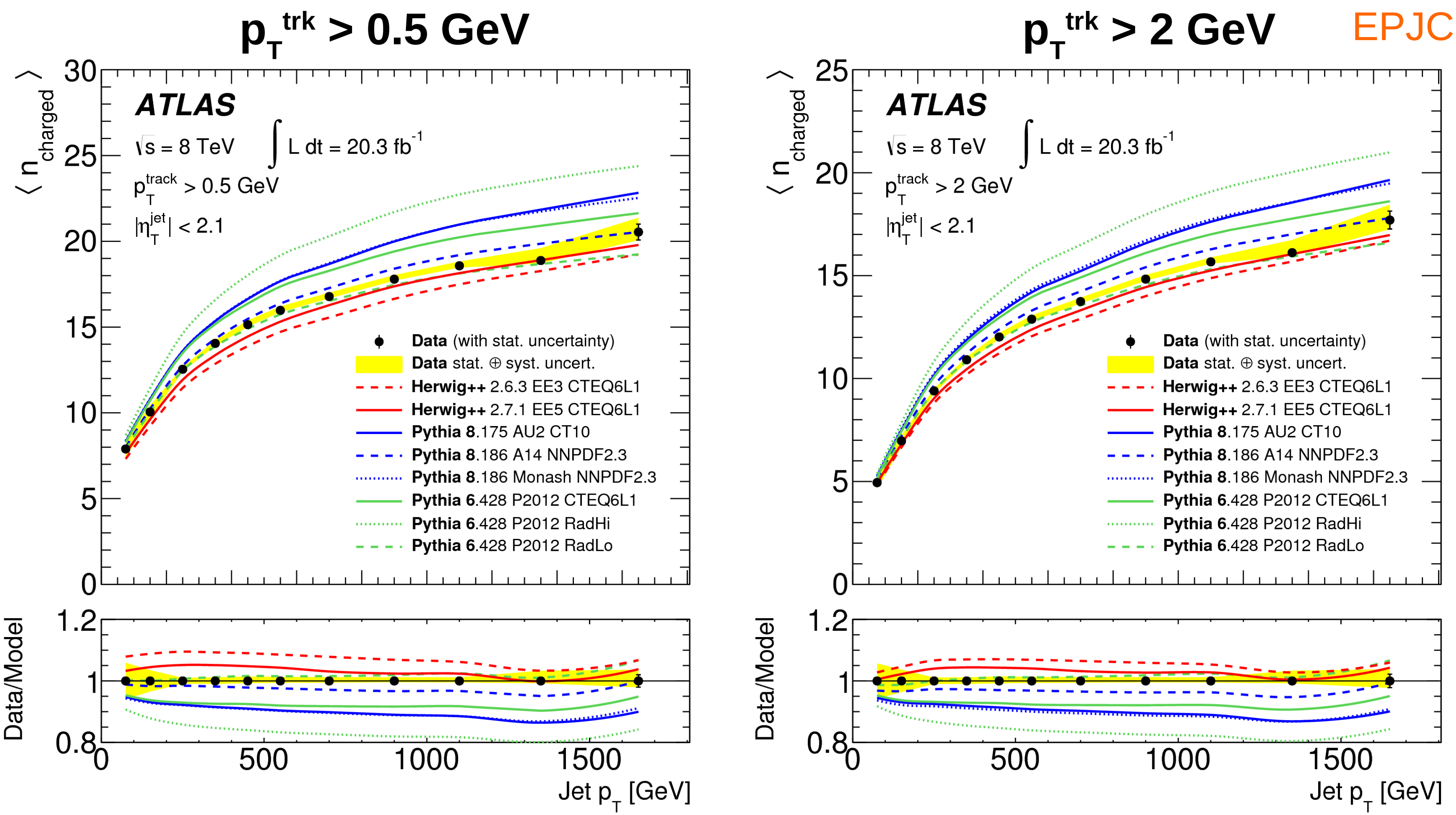

For 50 < p_T^{jet} < 300 GeV range,

- 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.