Boson-Jet Measurements in Heavy Ion Collisions at CMS

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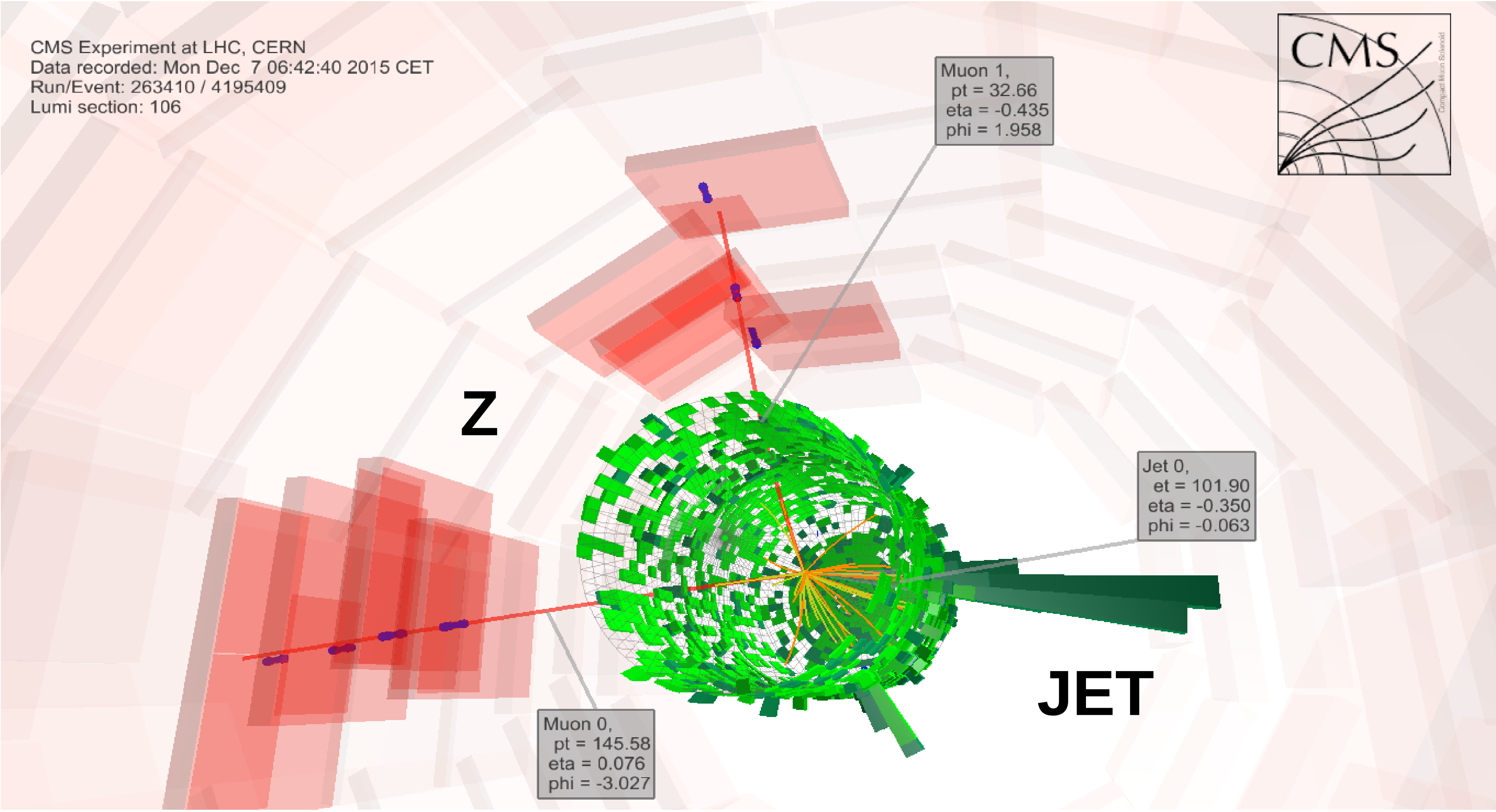
4th Heavy-Ion Jet Workshop, Paris
July 26, 2016

Introduction

Motivation : characterization of the jet energy loss using Z+jet pairs



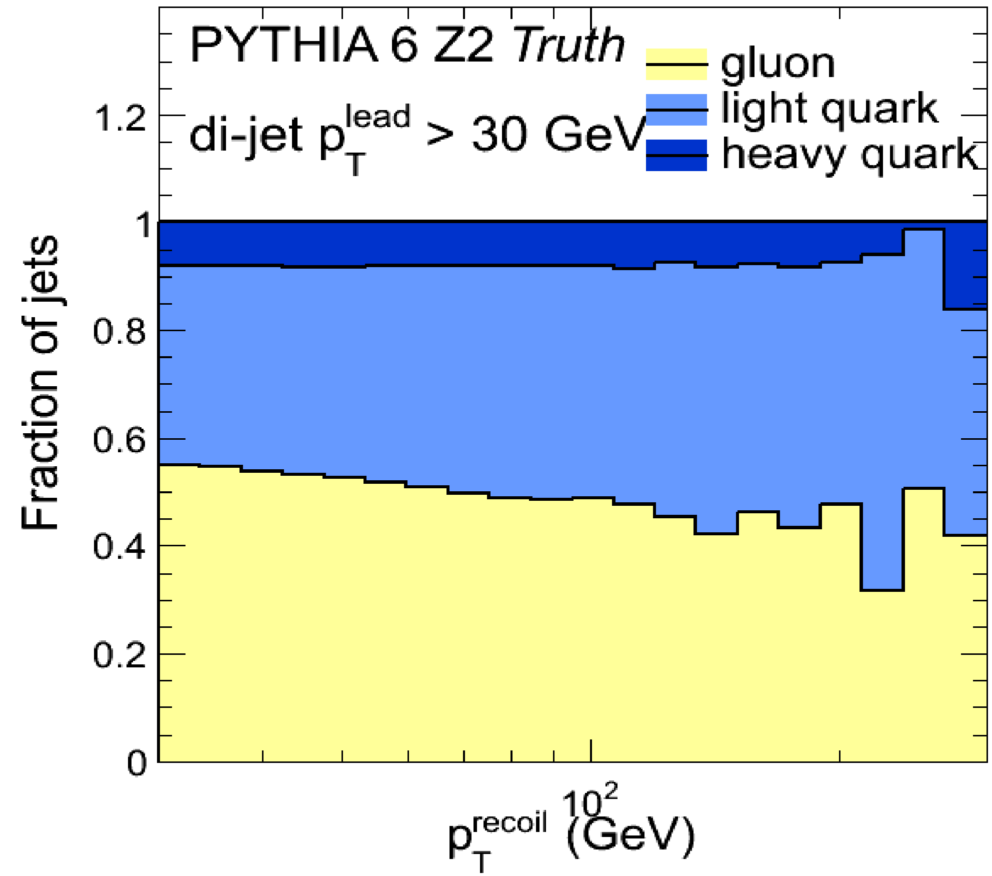
Jet energy loss - dijet

Typical way to study the medium produced in heavy ion collisions is to understand the passage of elementary particles through it.

Modification of high energy **quarks** and **gluons** enables the measurement of the transport properties of the strongly interacting medium.

One probe for this study is dijet events.

In this case both objects interact with the medium, only relative energy loss can be studied.



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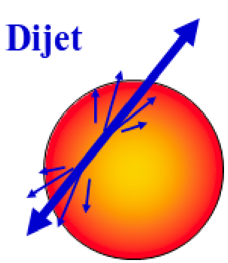
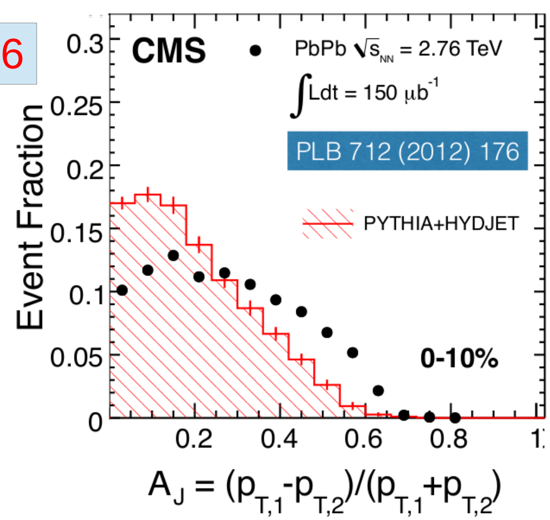
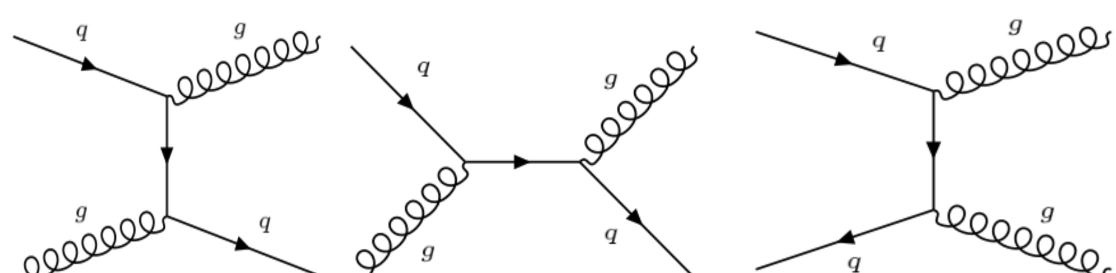






Jet energy loss - photon+jet

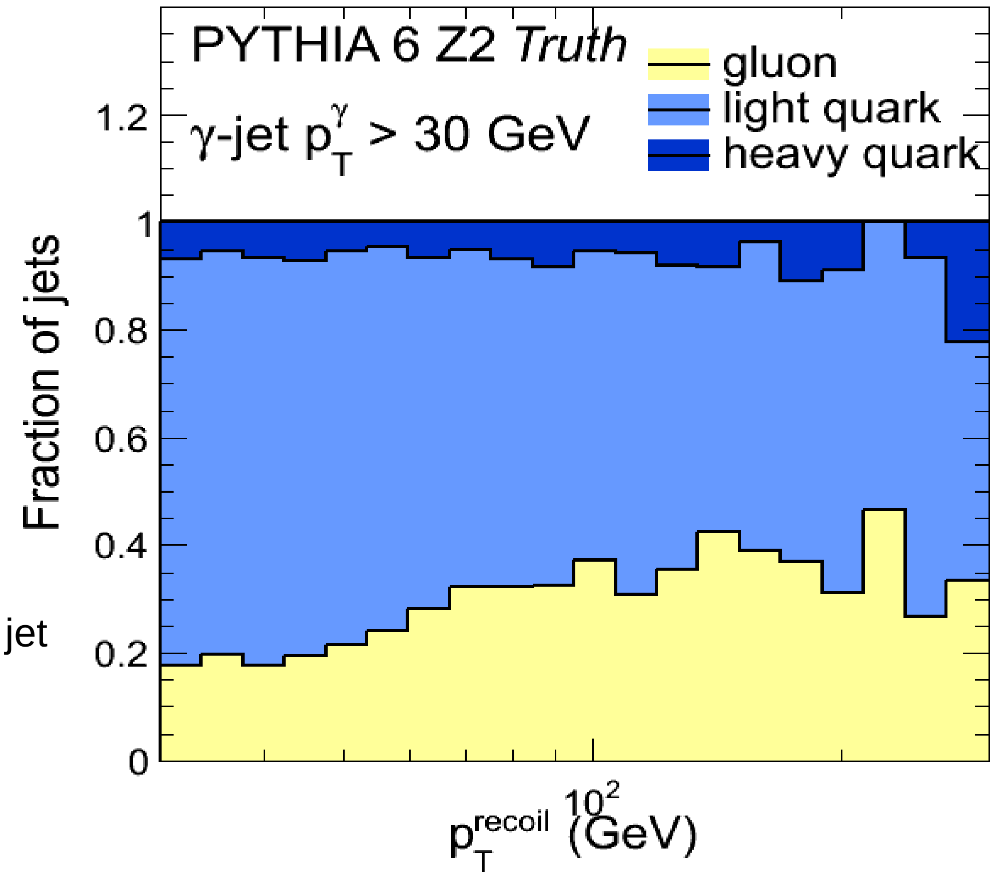
Photons do not undergo strong interaction.

Photon+jet events stand as clean probes to study the medium interaction mechanism of the partons.

Photon probes are contaminated by background processes:

- jet fragmentation
- neutral meson decay

Boson+jet events have higher quark jet fraction.



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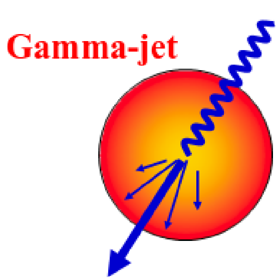
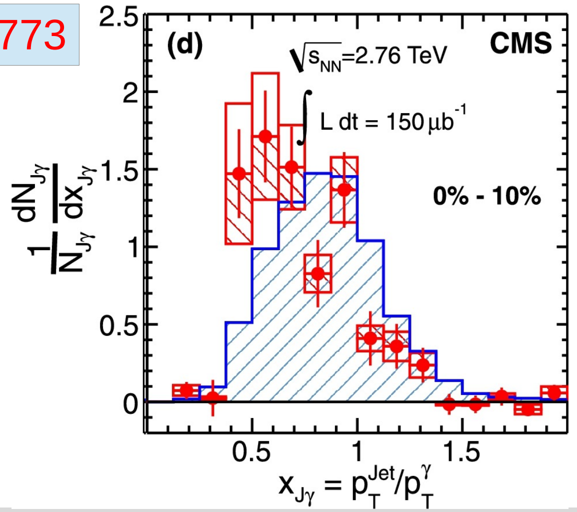
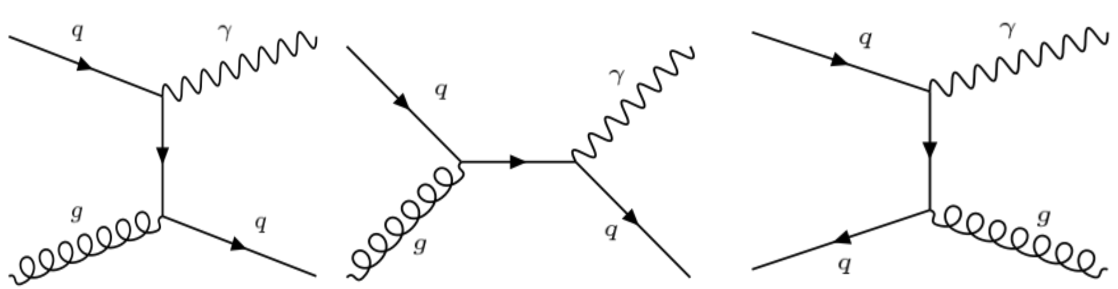






Jet energy loss - Z+jet

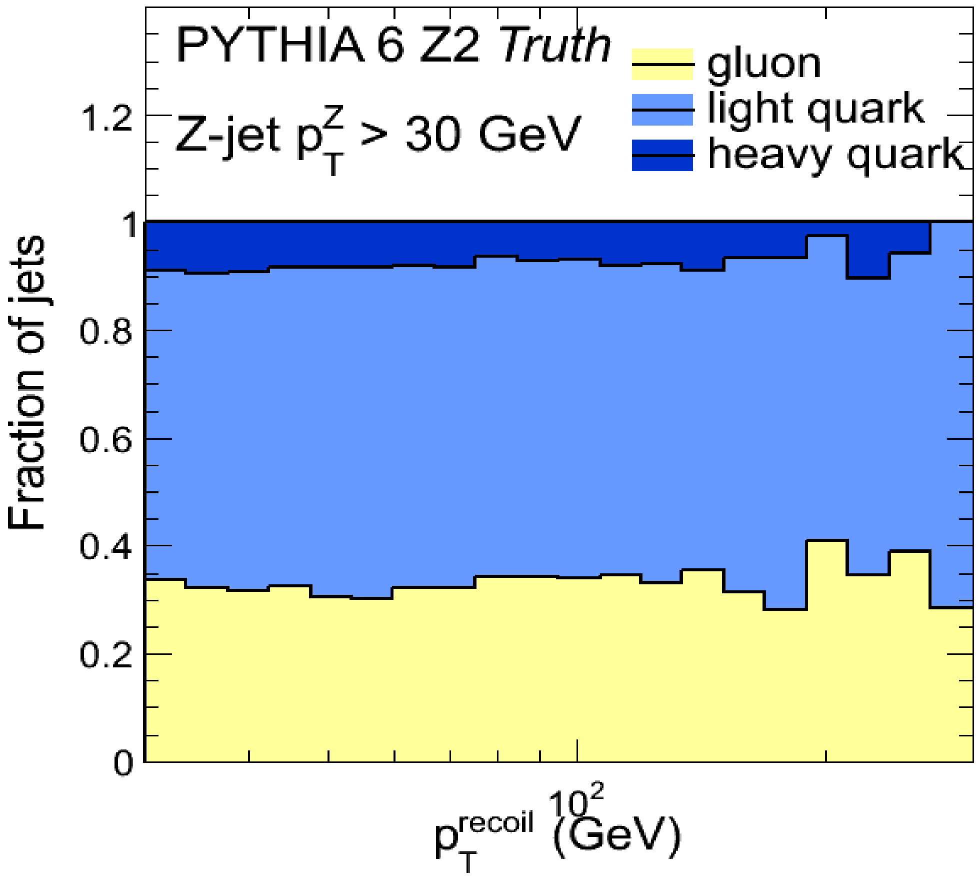
Quark fraction in Z+jet is larger than in dijet events.

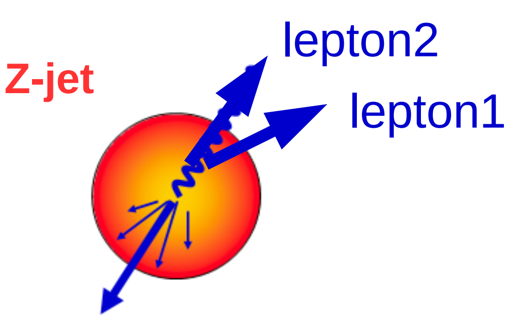
Z bosons do not undergo strong interaction.

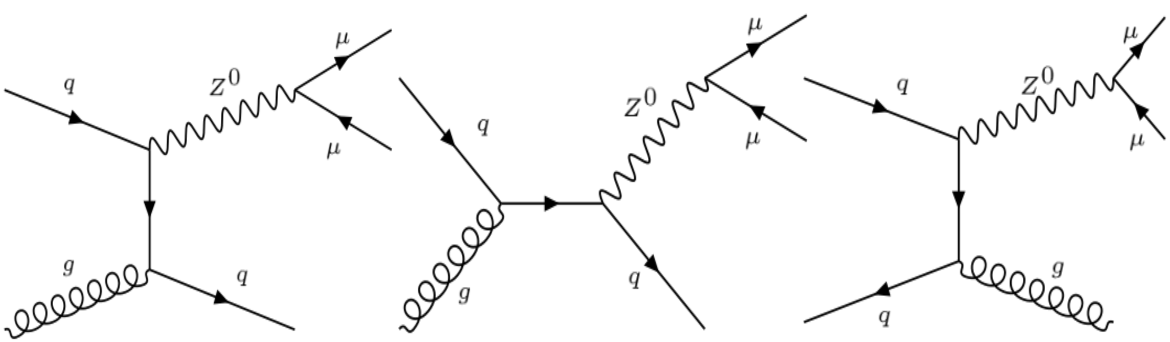
Z+jet events also stand as clean probes to study the medium interaction mechanism of the partons.

Z probes are **NOT** contaminated by background processes.

However, production cross-section of Z+jet process is **low**.







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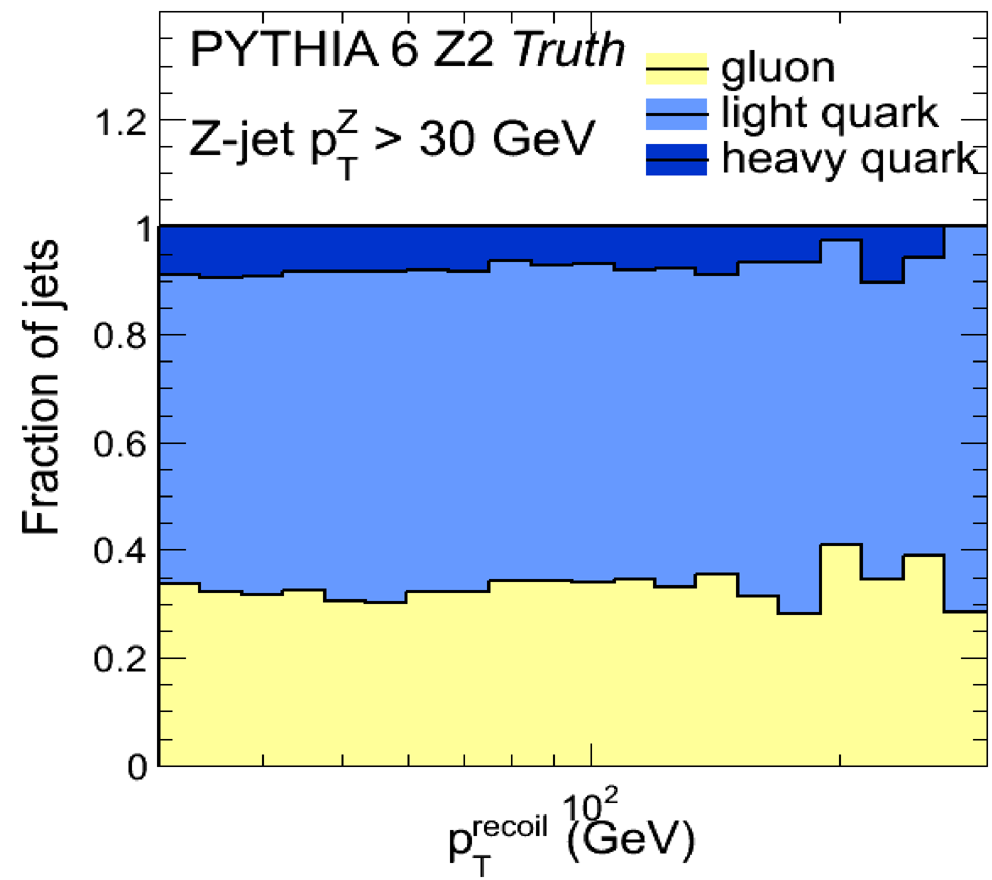
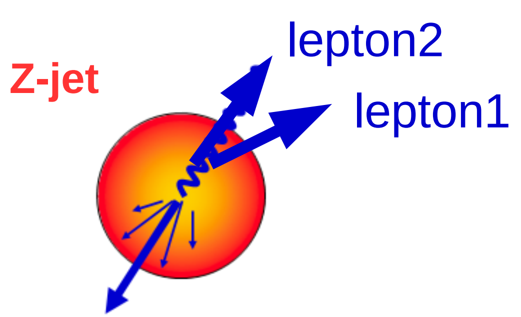
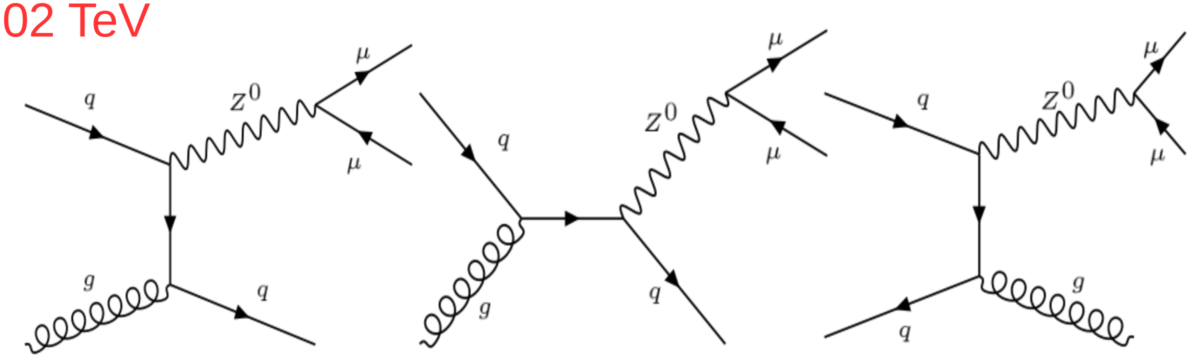


Possible with the high statistics PbPb and pp data at sqrt(s) = 5.02 TeV





Analysis : Z+jet

- Data used in Z+jet analysis:

  2015 PbPb data at 5.02 TeV, 404 μb^{-1}

  focus on 0-30 % centrality

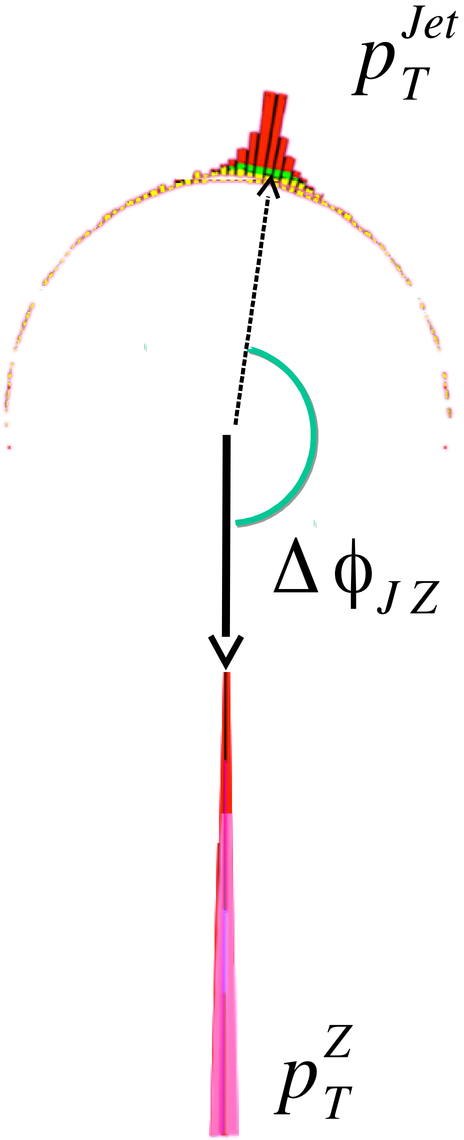
  2015 pp data at 5.02 TeV, 25.8 pb^{-1}

- Analysis steps :

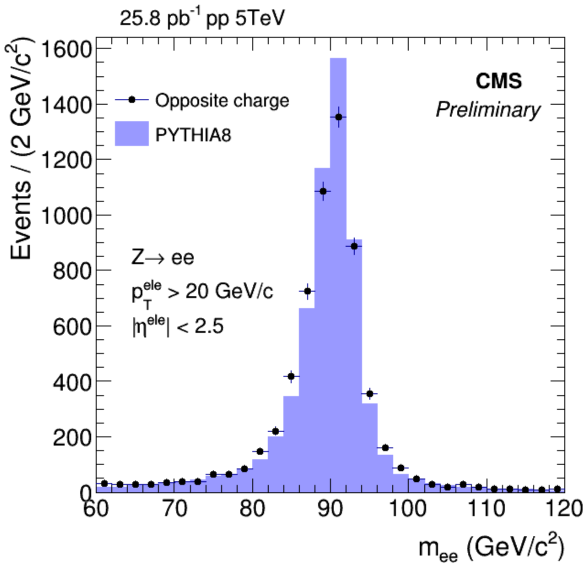
  1. Select electron and muon triggered data
  2. Reconstruct Z bosons, reconstruct jets
     - Smear jet spectra in pp
  3. Make Z+jet pairs
     - Background subtraction (for PbPb only)
  4. Combine Z+jet pairs from muon and electron channels

  Final plots :

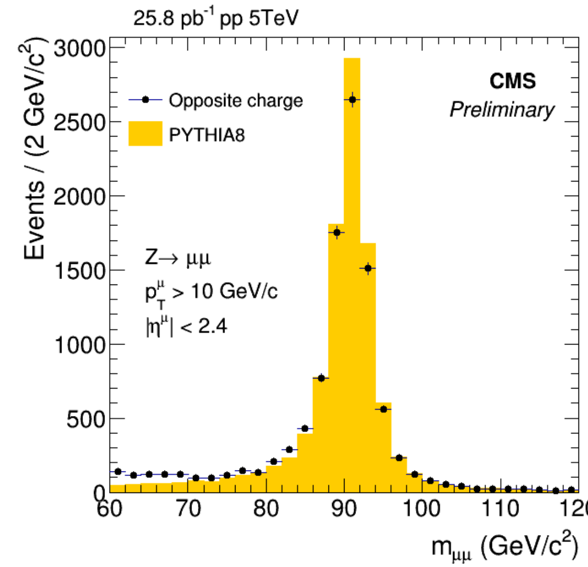
  Distributions are normalized by number of Z events.

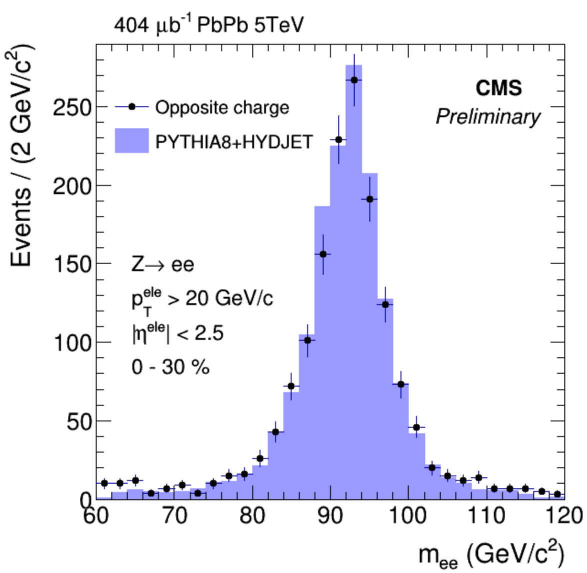


Z Boson reconstruction

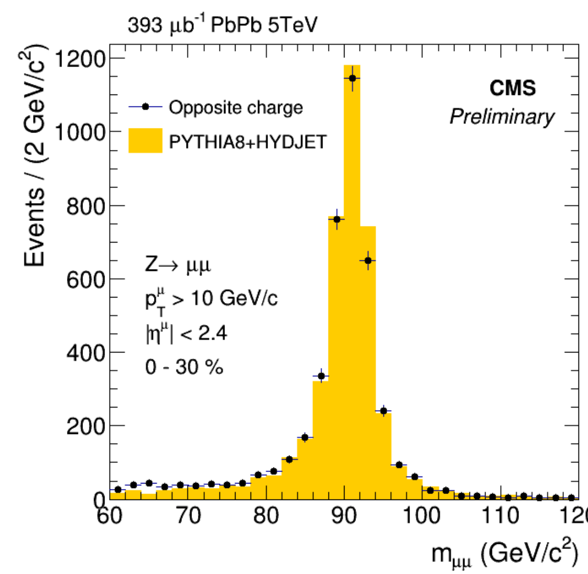


pp





PbPb



electron channel

muon channel

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

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

    Apply relative resolution in the same fashion

Kinematics

Z Bosons

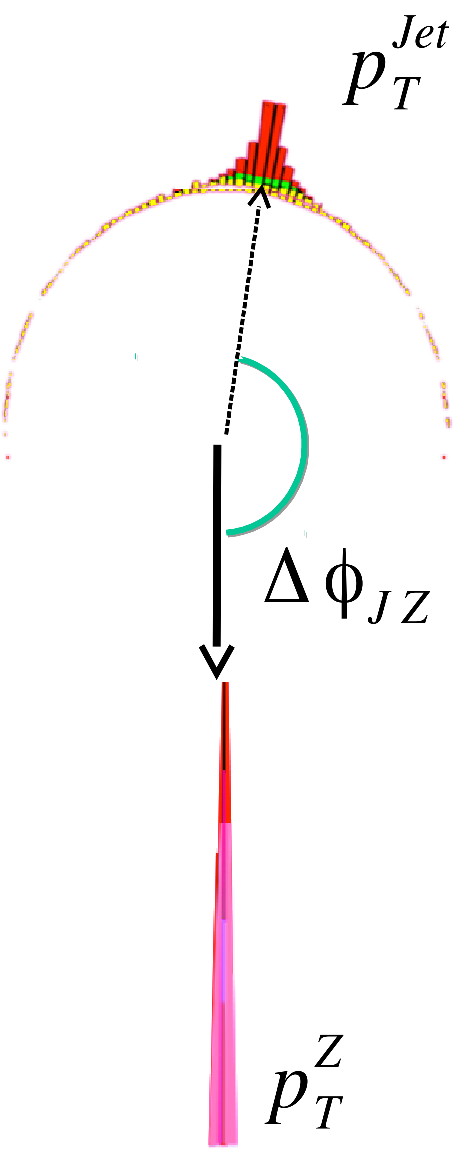
- electron channel : $p_T^e > 20$ GeV/c², $|\eta^e| < 2.5$
- muon channel : $p_T^\mu > 10$ GeV/c², $|\eta^\mu| < 2.4$
- opposite charge pairs
- $p_T^Z > 60$ GeV/c (for $\Delta\varphi_{JZ}$ and x_{JZ} distributions)
- $70 < M_Z < 110$ GeV/c² ==> 232 Z boson events in PbPb
  673 Z boson events in pp

Jets

- Anti-k_T jets, R=0.3
- $p_T^{Jet} > 30$ GeV/c
- $|\eta^{Jet}| < 1.6$

Z+jet pairs

- **All** jets which meet the given kinematics are included, **not just leading**.
  - Apply MinBias event mixing to subtract background (PbPb only)

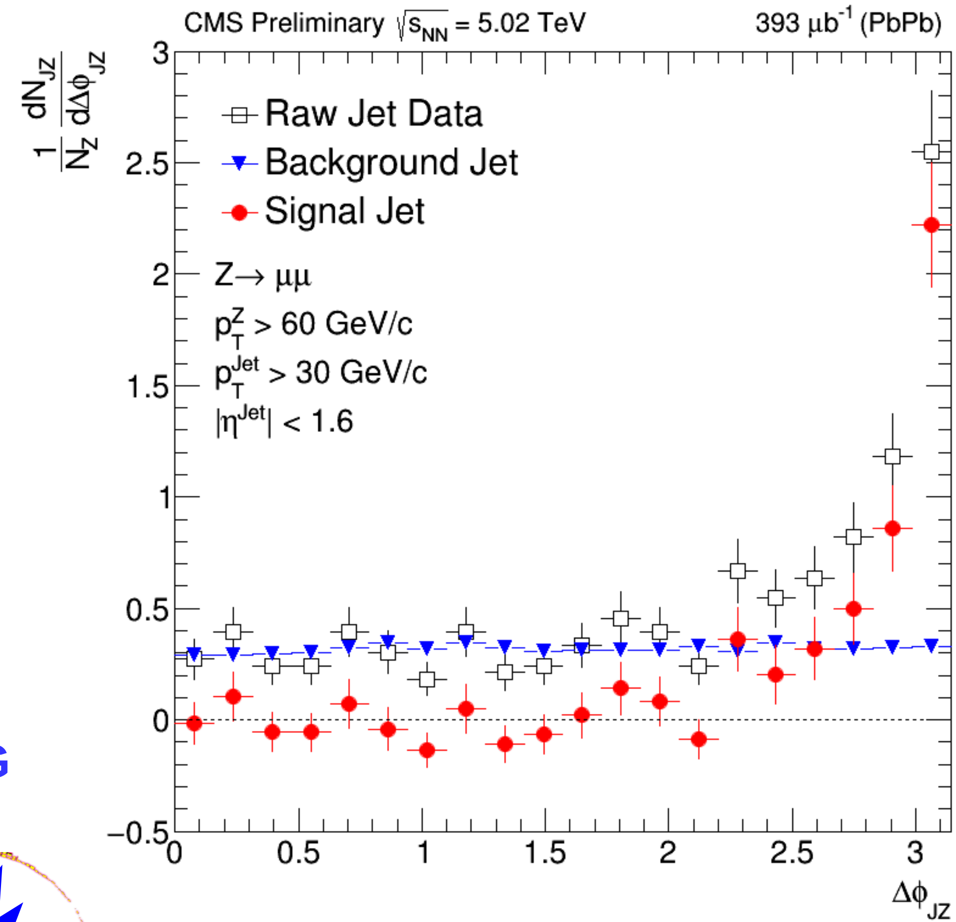


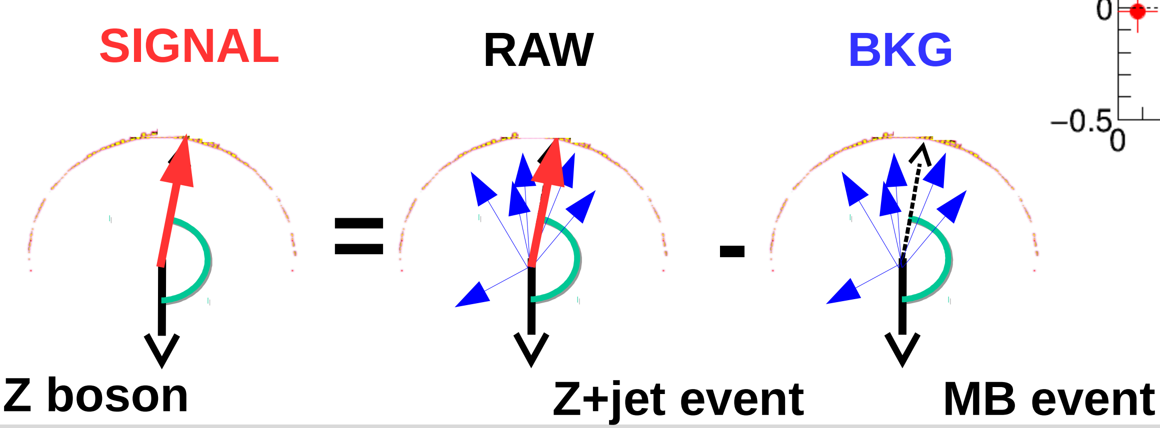
Background Subtraction

Background source : jets from underlying event

Subtraction method : Minimum bias event mixing technique

- Background contribution is by definition not correlated to the Z boson
- Estimate this contribution by correlating the Z boson to jets from matching minbias events





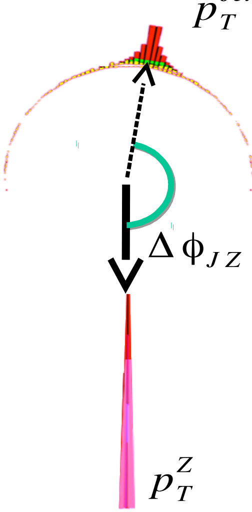
Azimuthal Correlation

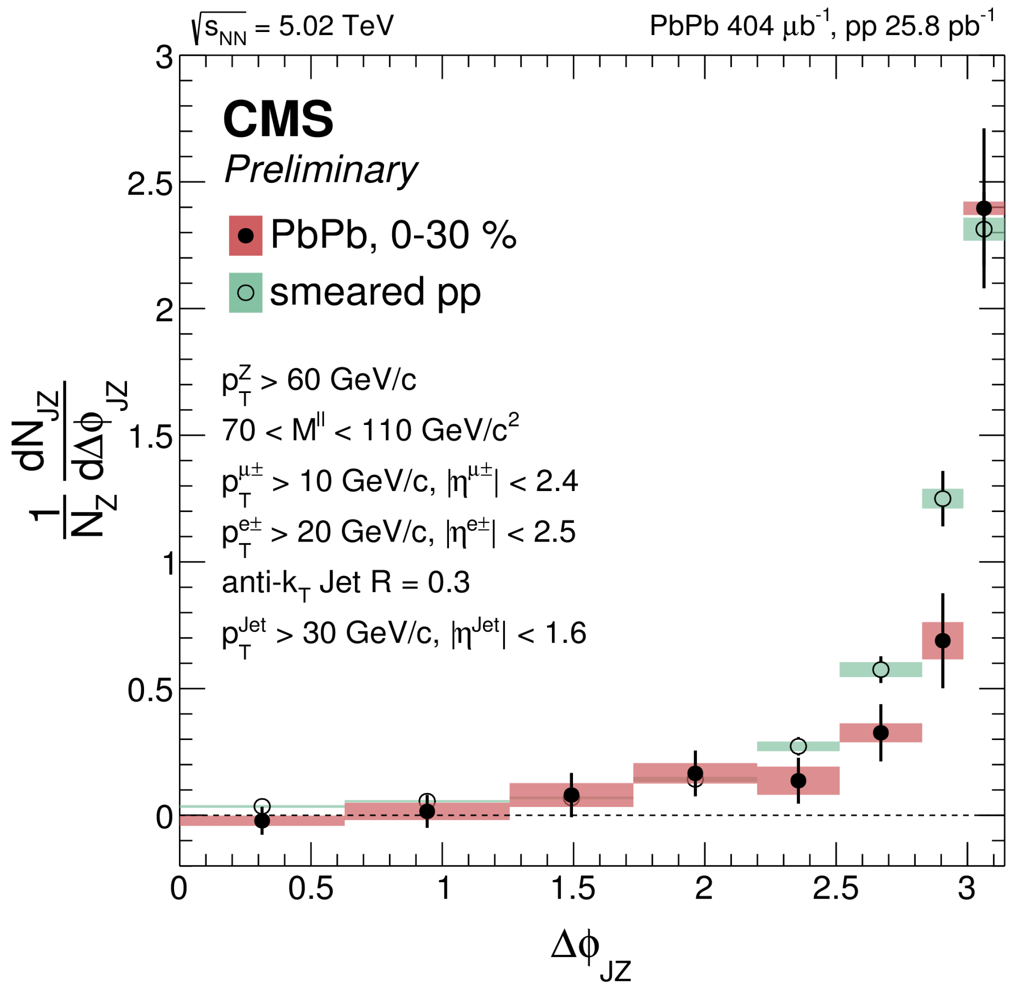
Azimuthal correlation

Deflection of jet ?

$$\Delta\phi_{JZ} = |\phi^{Jet} - \phi^{Z}|$$

The shape in PbPb is slightly narrower for large $\Delta\varphi_{JZ}$.





"smeared pp" means that jet spectra in pp data is modified to match the resolution in PbPb data

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Transverse Momentum Imbalance

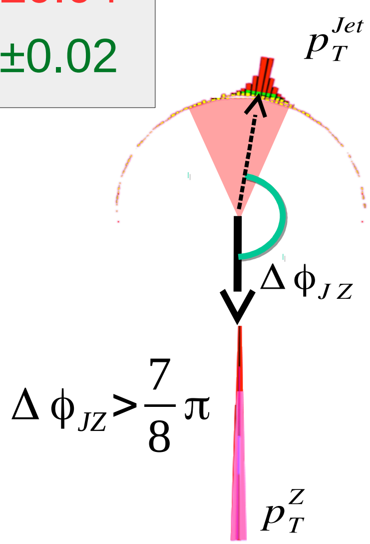
Transverse momentum imbalance

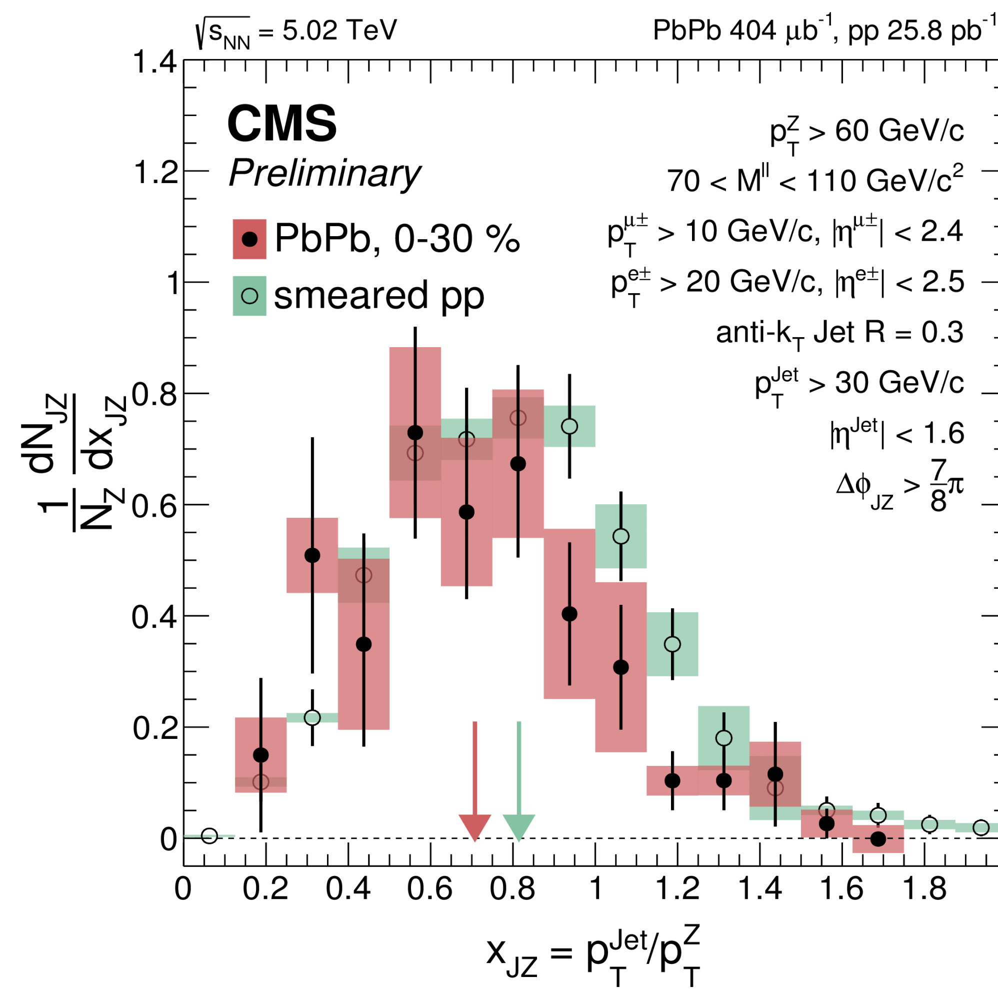
energy loss ?

$$x_{JZ} = \frac{p_T^{Jet}}{p_T^Z}$$

x_{JZ} in 0-30% centrality PbPb collisions is shifted to lower values with respect to pp collisions.

PbPb, 0-30%	: $\langle x_{JZ} \rangle = 0.71 \pm 0.04$
pp	: $\langle x_{JZ} \rangle = 0.81 \pm 0.02$





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Mean Value of Momentum Imbalance

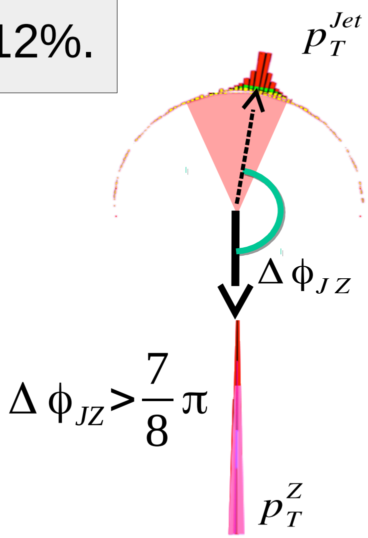
$\langle x_{JZ} \rangle$: Mean value of transverse momentum imbalance

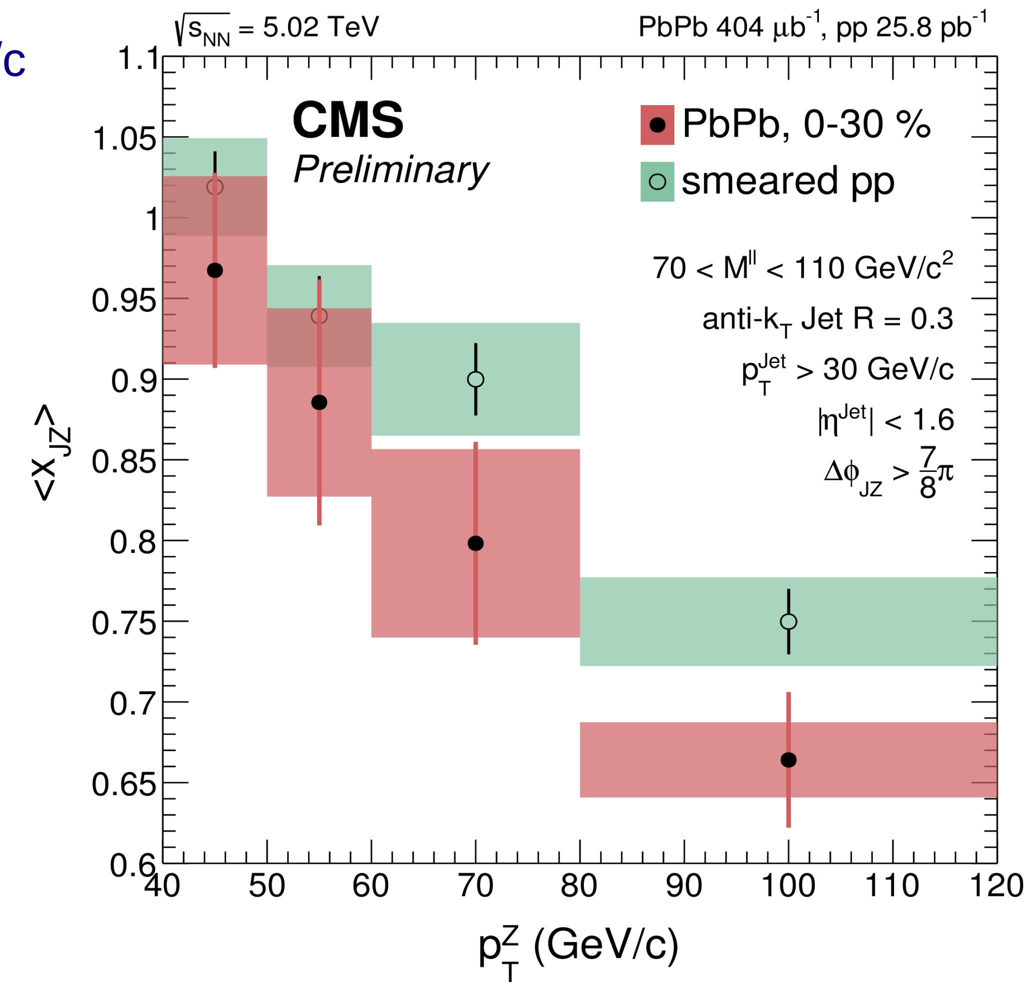
p_T^Z bins: [40-50], [50-60], [60-80], [80+] GeV/c

$\langle x_{JZ} \rangle$ in 0-30% centrality PbPb collisions is smaller than in pp

in agreement with jet quenching effects

[80+] GeV/c bin :
$\langle x_{JZ} \rangle$ in PbPb is lower by 12%.





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Average Number of Jets per Z Boson

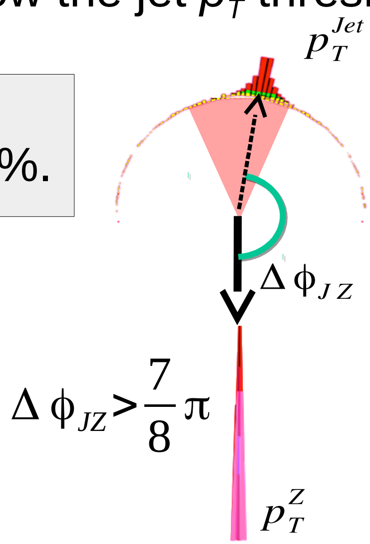
$\mathbf{R_{JZ}}$: average number of jets per Z boson
(fraction of Z bosons with an associated jet)

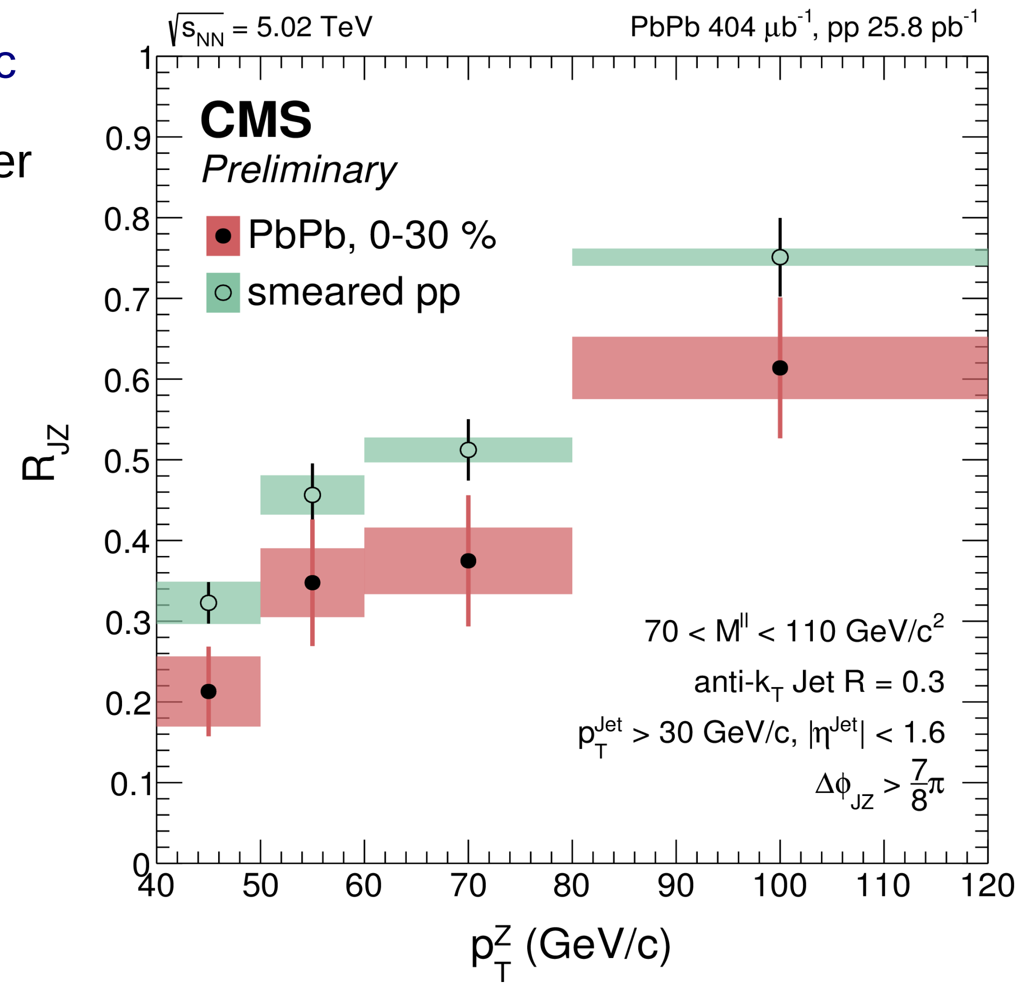
p_T^Z bins: [40-50], [50-60], [60-80], [80+] GeV/c

R_{JZ} in 0-30% centrality PbPb collisions is lower than in pp

suggests that in PbPb larger fraction of jets associated with the Z boson lost energy and fell below the jet p_T threshold

[80+] GeV/c bin :
R_{JZ} in PbPb is lower by 19%.





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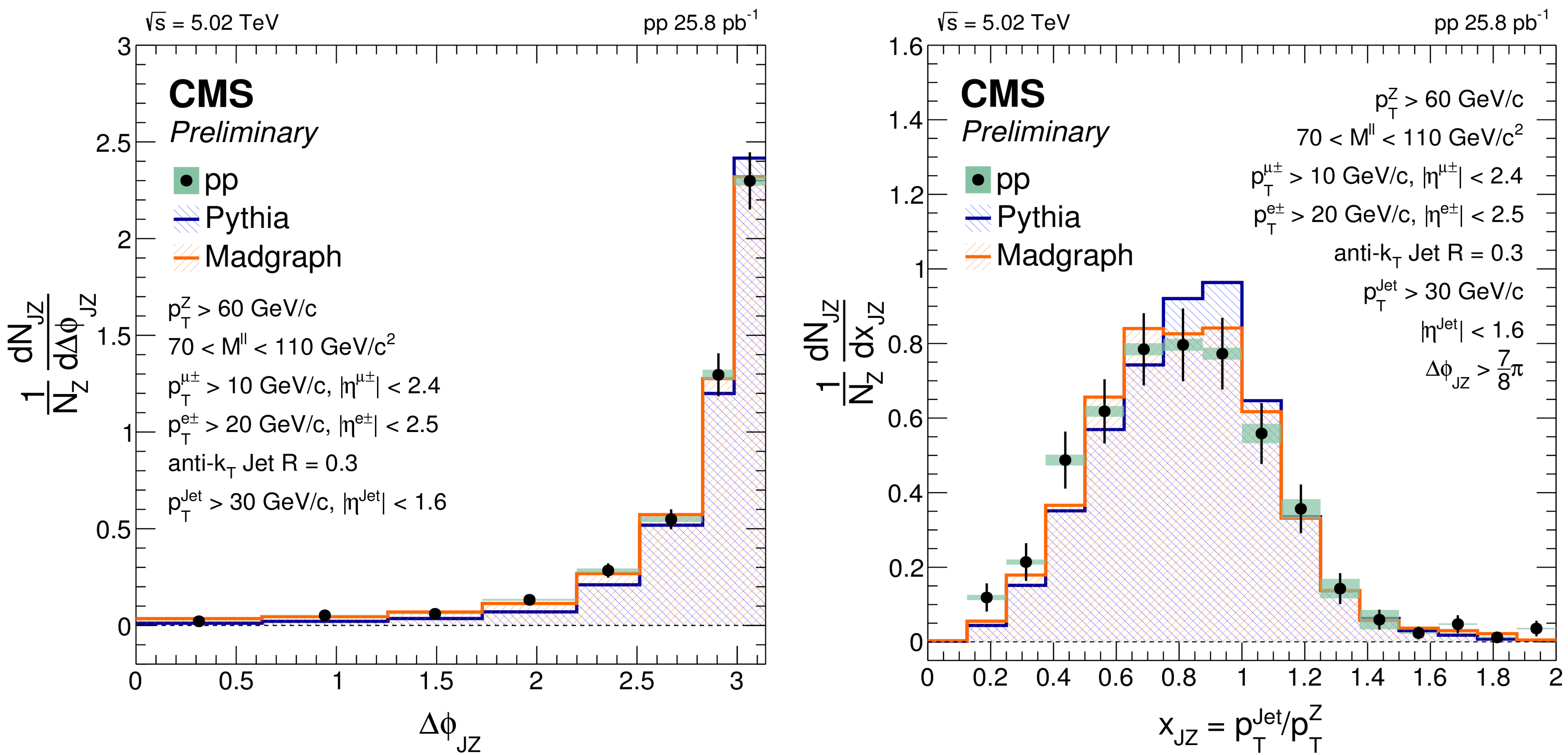
Comparison between pp and MC



Compared pp data to PYTHIA and MADGRAPH NLO models.
MADGRAPH NLO is in good agreement with data

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Analysis : photon+jet

Z+jet CMS-PAS-HIN-15-013

Data used in the analysis :

2015 PbPb data at 5.02 TeV, 404 μb^{-1}

focus on 0-30 % centrality

2015 pp data at 5.02 TeV, 25.8 pb^{-1}

Analysis steps :

1. Select **electron/muon** triggered data
2. Reconstruct **Z bosons**, reconstruct jets

   Smear jet spectra in pp

3. Make Z+jet pairs

   Background subtraction

   1. jets from UE

photon+jet CMS-PAS-HIN-13-006

Data used in the analysis :

2011 PbPb data at 2.76 TeV, 150 μb^{-1}

not just 0-30%, whole centrality

2013 pp data at 2.76 TeV, 5.3 pb^{-1}

2013 pPb data at 5.02 TeV, 30.4 nb^{-1}

Analysis steps :

1. Select **photon** triggered data
2. Reconstruct **photons**, reconstruct jets

   Smear jet spectra in pp

3. Make photon+jet pairs

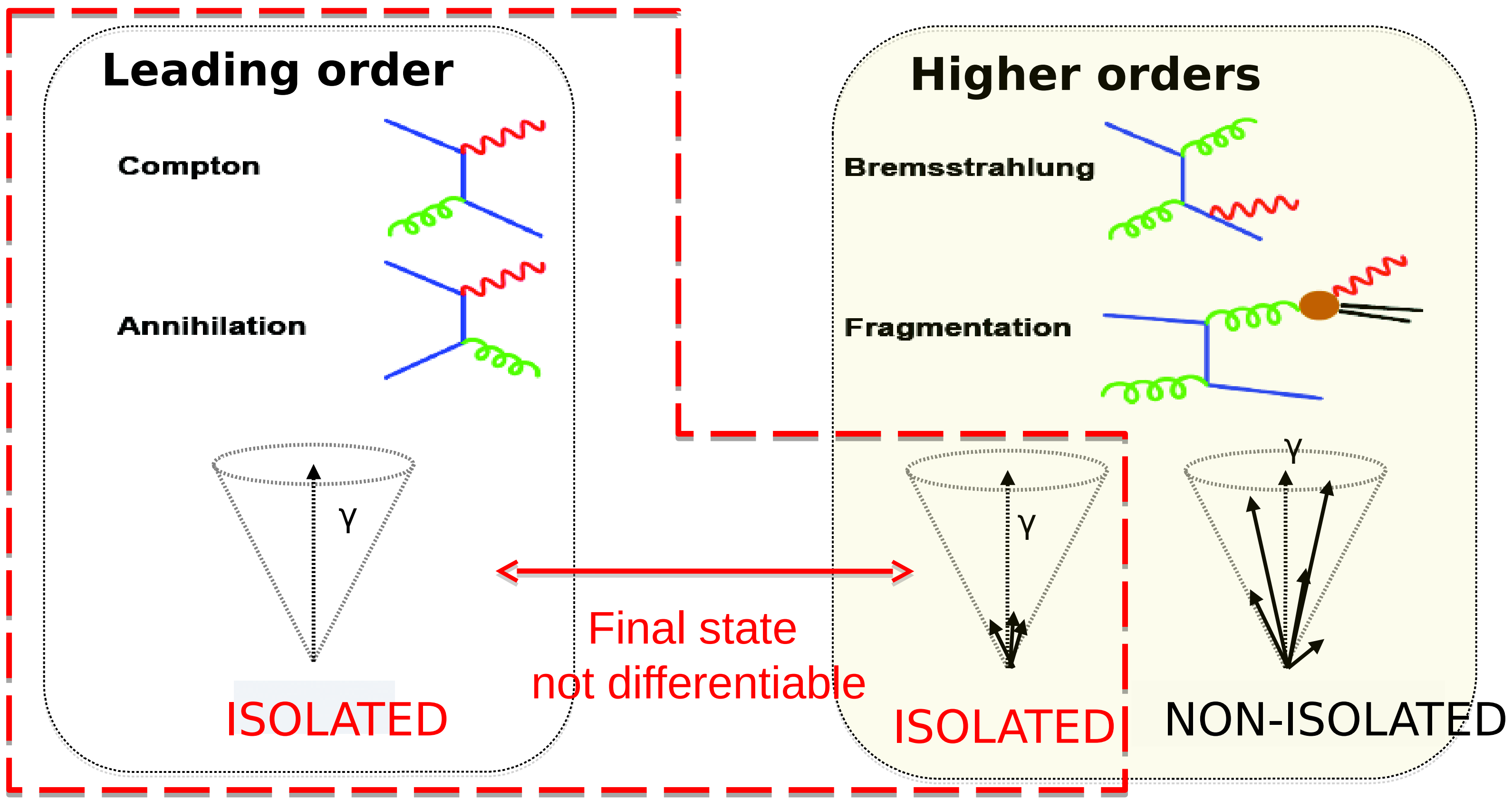
   Background subtraction

   1. jets from UE
   2. **decay/fragmentation photons**

Signal Photon

Identify signal photons by :

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



Azimuthal Correlation

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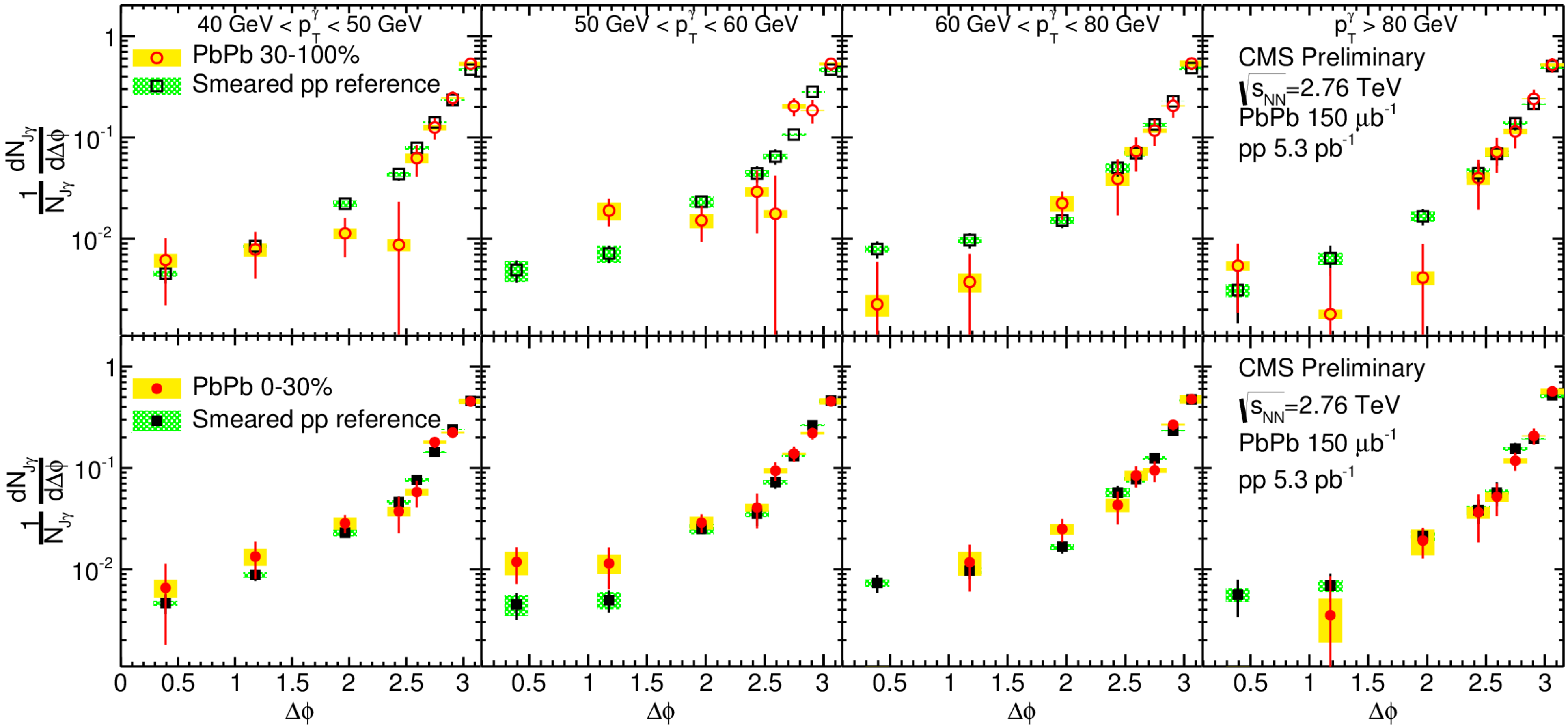

In bins of centrality (split into rows) and in bins of photon pt (split into columns)

Distributions are normalized by number of photon+jet pairs, not by number of photons

No jet deflection observed

Momentum Imbalance

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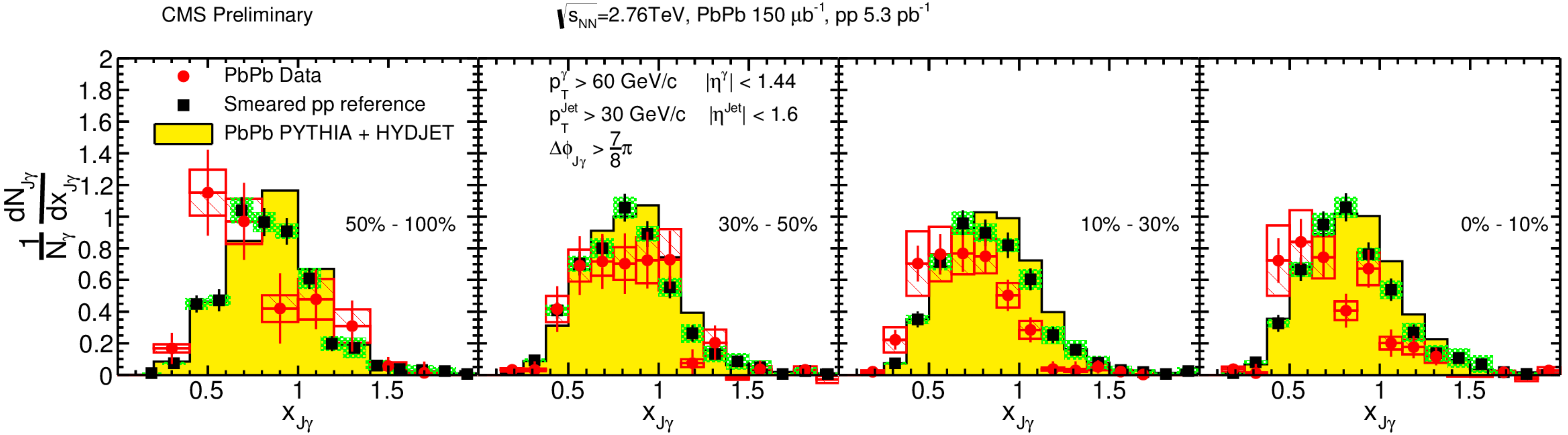

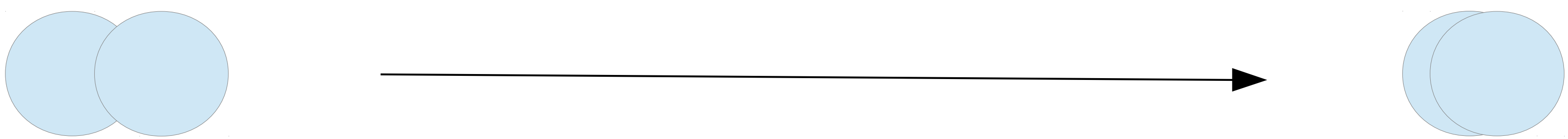

In bins of centrality (peripheral on the left, central on the right)

Distributions are normalized by number of photons

$x_{J\gamma}$ in PbPb is shifted to left with centrality.

Comparison between Z+jet and photon+jet

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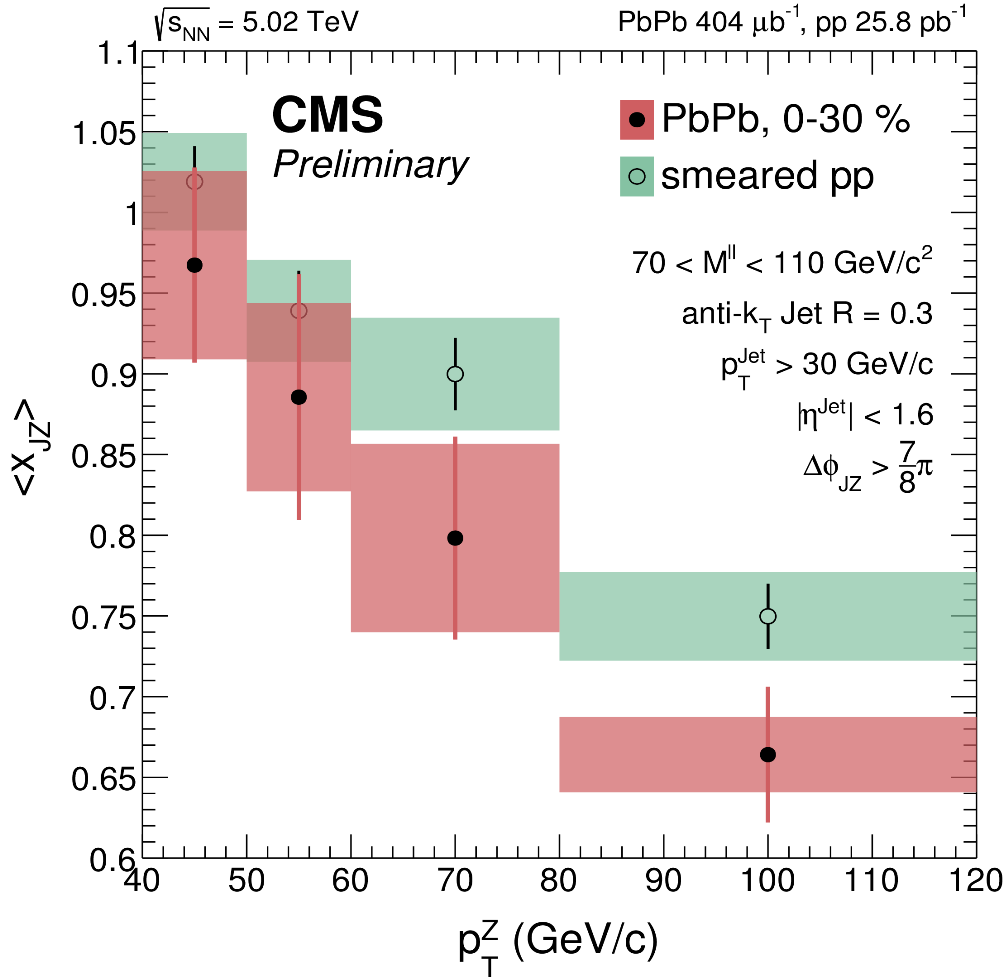

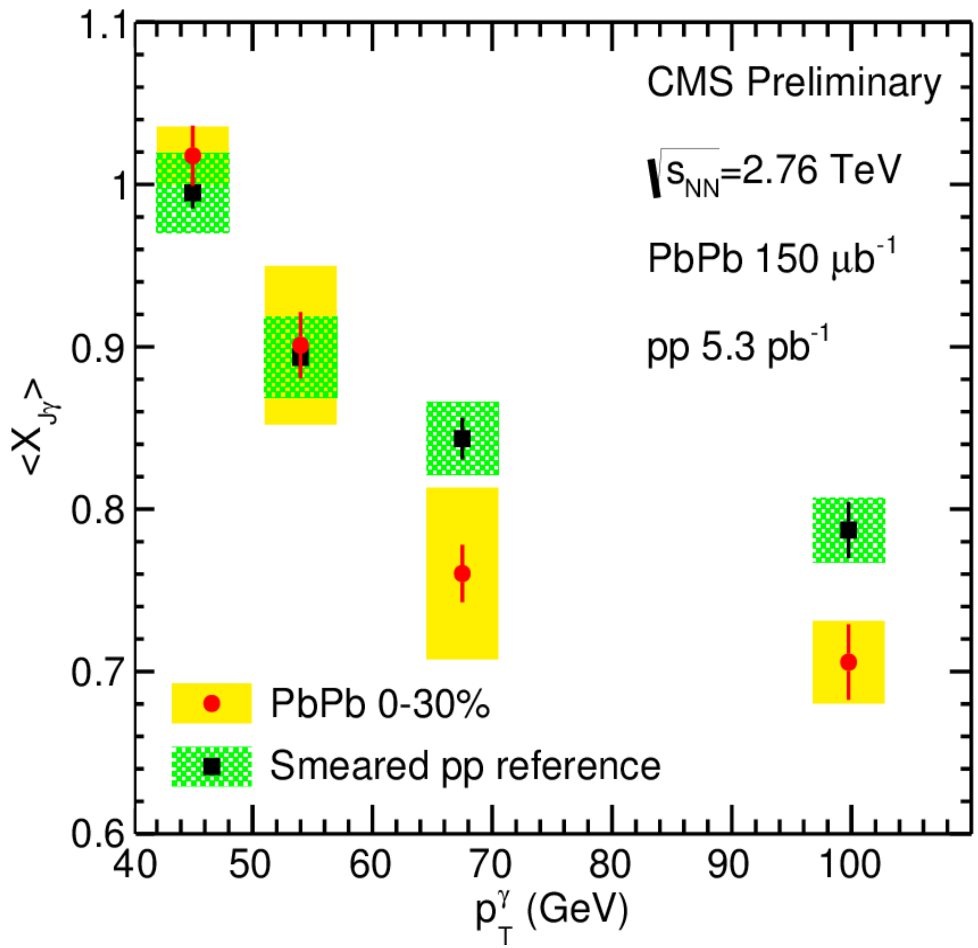

Z+jet at 5.02 TeV vs photon+jet at 2.76 TeV

- Same kinematic selections for jets. Photon pseudo-rapidity : $|\eta^{\gamma}| < 1.44$
- agreement within statistical uncertainties

Comparison between Z+jet and photon+jet

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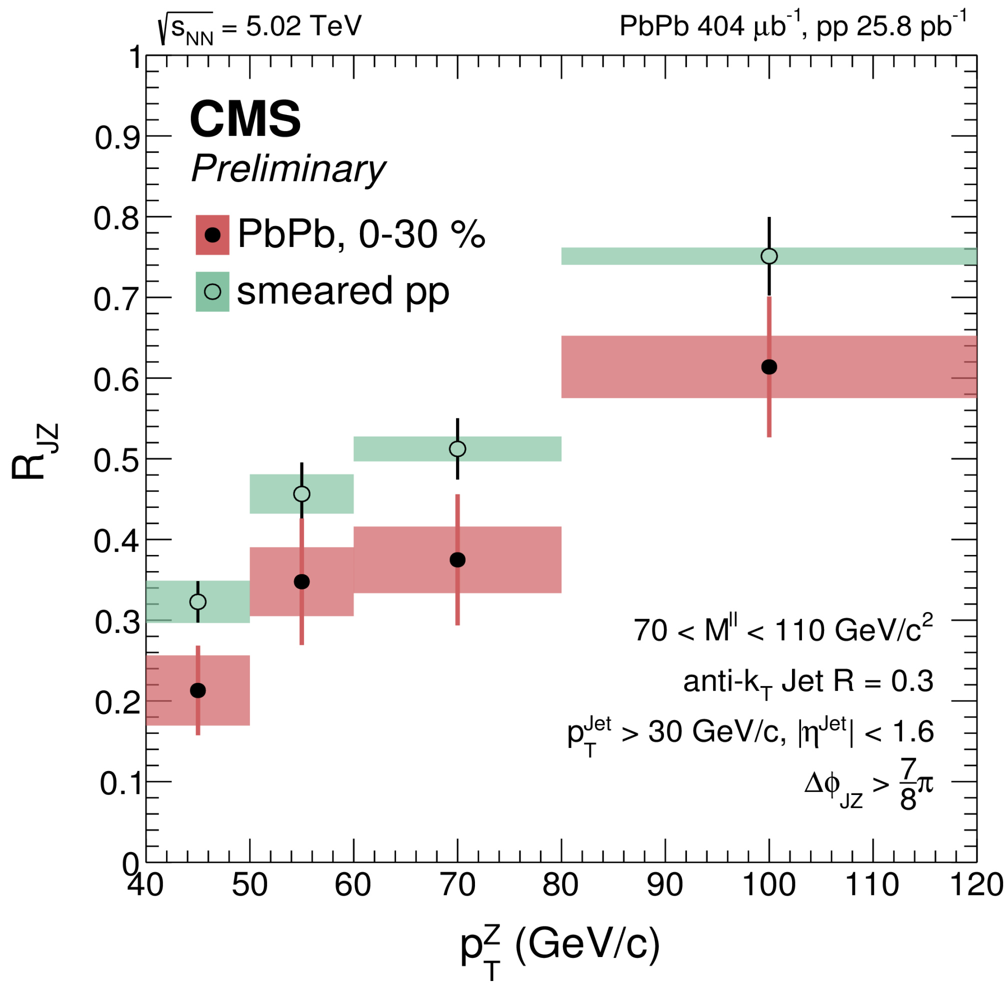

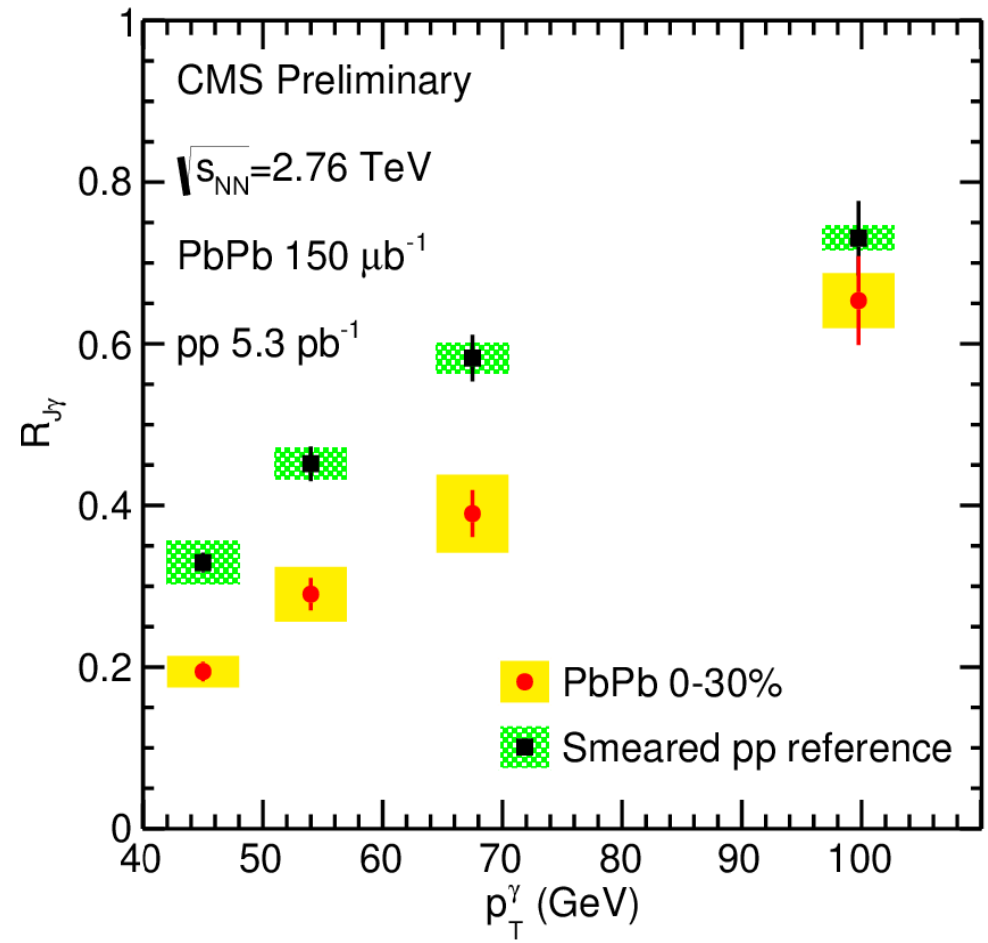

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agreement within statistical uncertainties

Summary

Studied Z+jet pairs in 0-30% centrality PbPb and pp data at 5.02 TeV

Comparison between pp data and MC model :

- MADGRAPH NLO is in good agreement with data

Characterization of jet energy loss using Z+jet pairs :

- Compared PbPb data with pp data

Azimuthal correlation :

- Shape in PbPb is slightly narrower for large $\Delta\varphi_{JZ}$.

Transverse momentum imbalance :

- x_{JZ} in PbPb has a shift to lower values with respect to pp.
- $\langle x_{JZ} \rangle$ in PbPb is lower than in pp.

  in agreement with jet quenching effects

Average number of jets per Z boson :

- R_{JZ} in PbPb is lower than in pp.

  suggests that in PbPb larger fraction of jets associated with the Z boson lost energy and fell below the jet p_T threshold

Comparison with photon+jet results at 2.76 TeV

- agreement within statistical uncertainties

Links

Z+jet at 5.02 TeV

CMS-PAS-HIN-15-013

photon+jet at 2.76 TeV

CMS-PAS-HIN-13-006

Outlook

2011 PbPb data

~3K isolated photons with pt > 60 GeV/c

~1.5K photon+jet events

No Z+jet analysis at CMS

2015 PbPb data

12K-15K isolated photons with pt > 60 GeV/c

6K-10K photon+jet events

~200 Z bosons with pt > 60 GeV/c, 0-30% centrality

With 2015 data :

Number of photon events increased by a factor of 4 to 5

- Study photon+jet events at higher pt
- Make the analysis more differential in pt, centrality, rapidity
- Go down to smaller objects : jet shape, photon+jet fragmentation, photon+track correlation

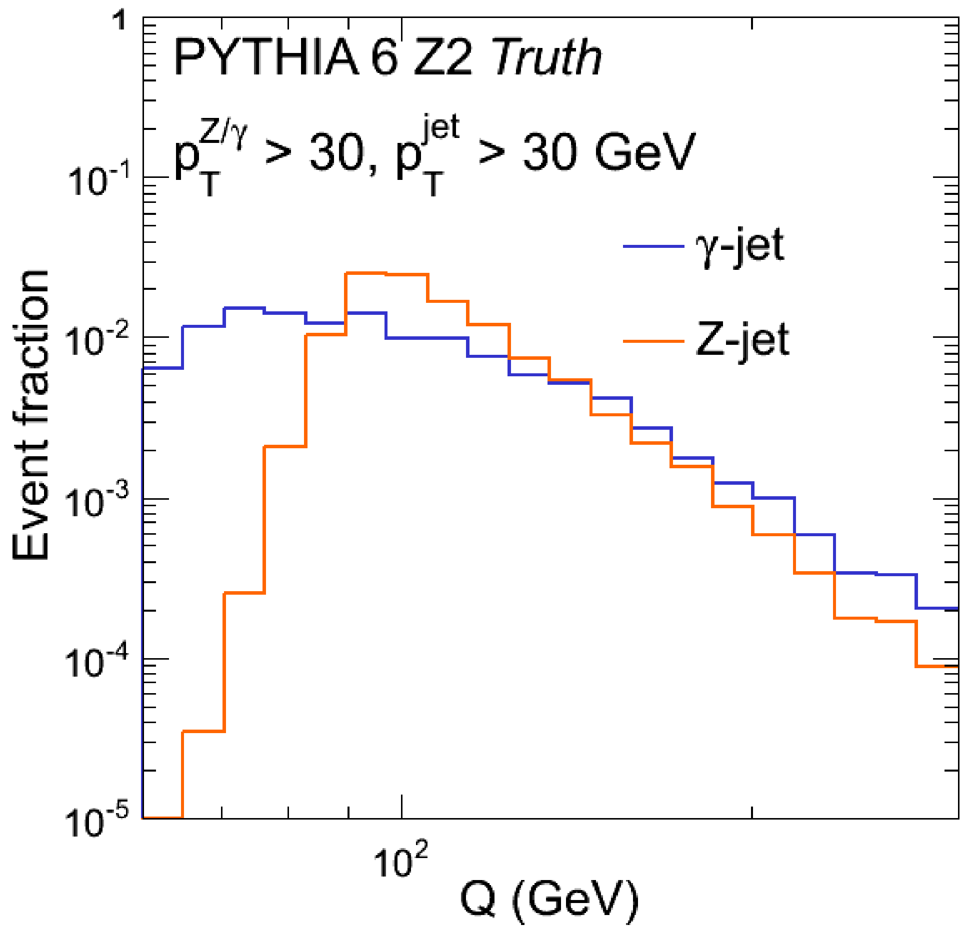
Z+jet analysis became possible

- Still not enough statistics to go as detailed as photon+jet
- But can go down to low pt (5-15 GeV/c) more reliably than with photons
- Perform low pt boson+track correlations with Z bosons.

BACKUP

Q scale

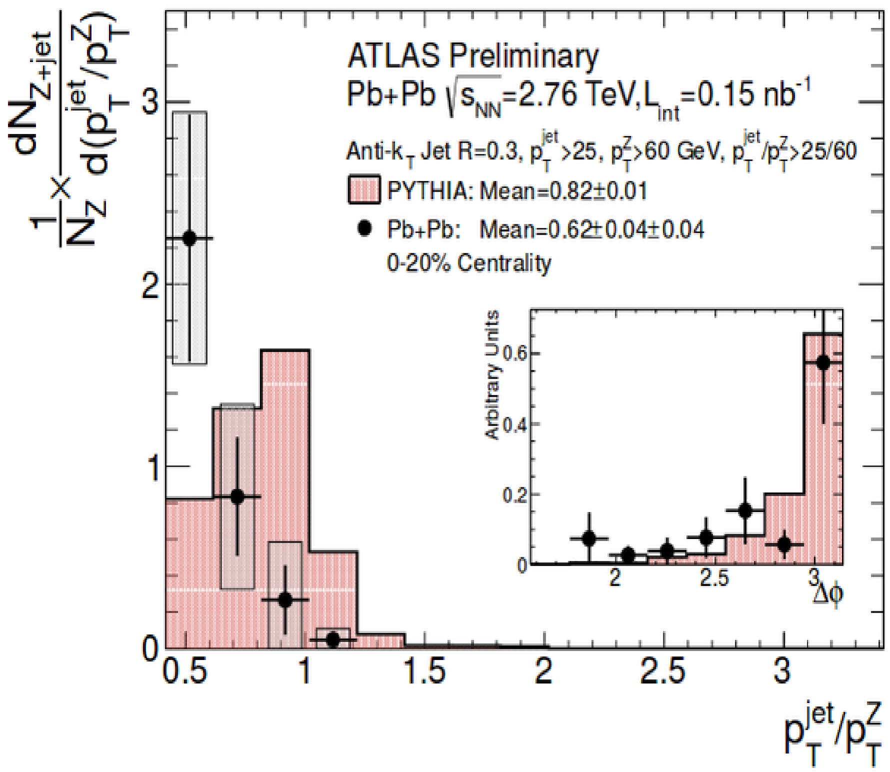
Z+jet events have higher Q scale than photon+jet.

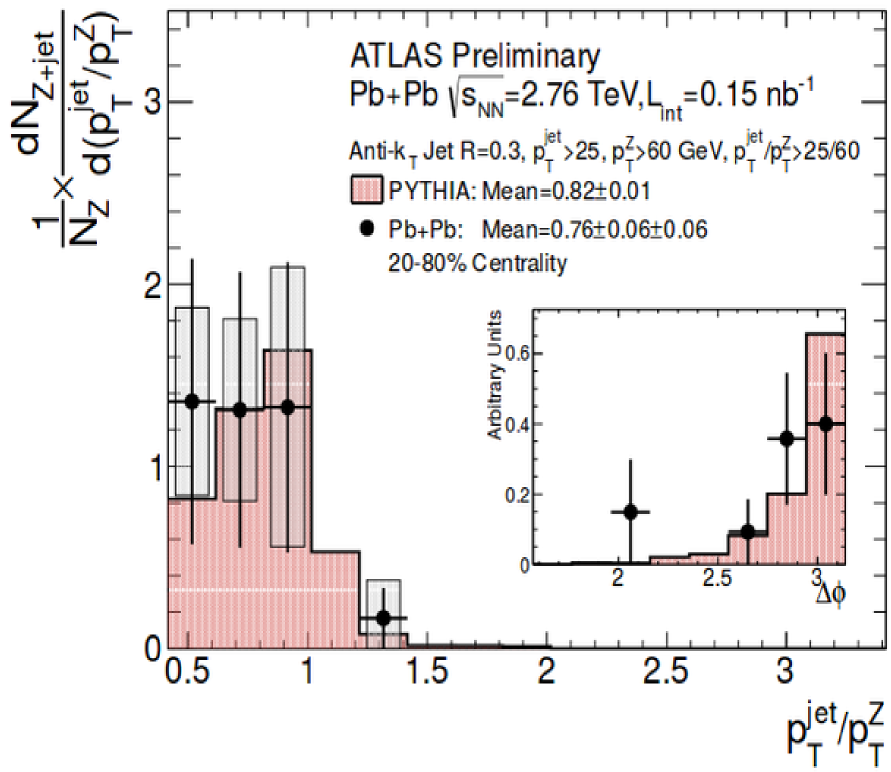


Relevant Results

- ATLAS collaboration
- 2011 PbPb, 2.76 TeV
- 36 **Z+jet** events

ATLAS-CONF-2012-119





Relevant Results

Studies of jet quenching using isolated-photon + jet correlations in PbPb and pp collisions at sqrt(s[NN]) = 2.76 TeV

- CMS collaboration
- 2011 PbPb, 2.76 TeV
- **photon+jet** events

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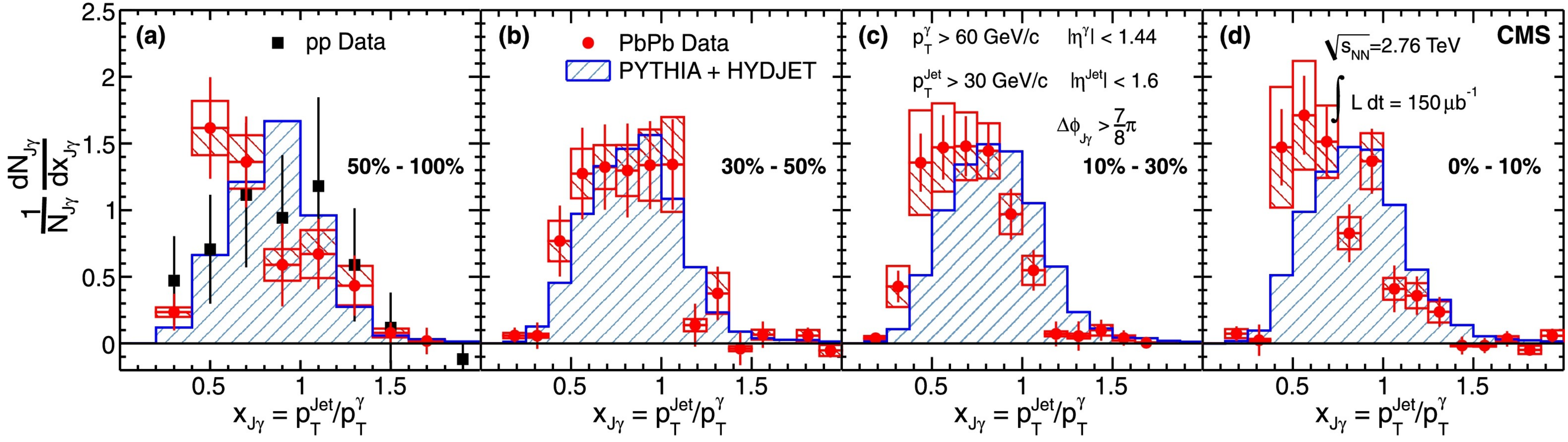

Relevant Results

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- PbPb and pp, 2.76 TeV
- **photon+jet** events

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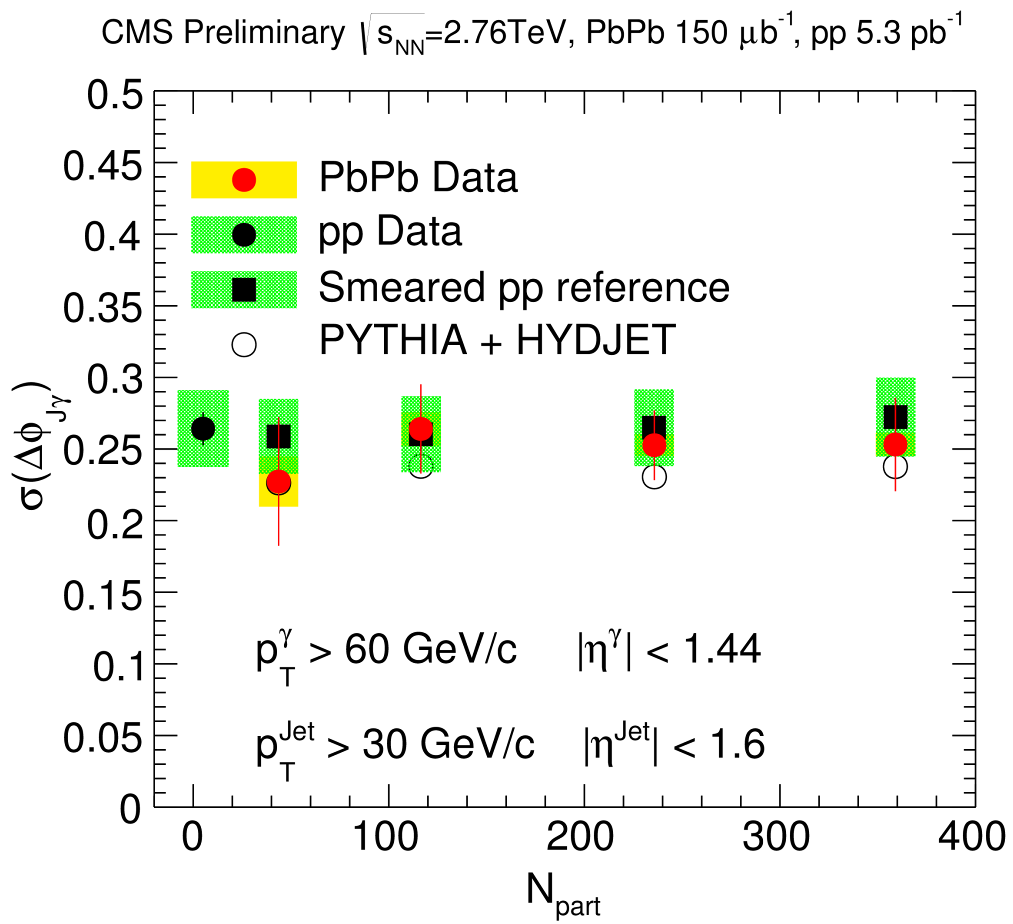

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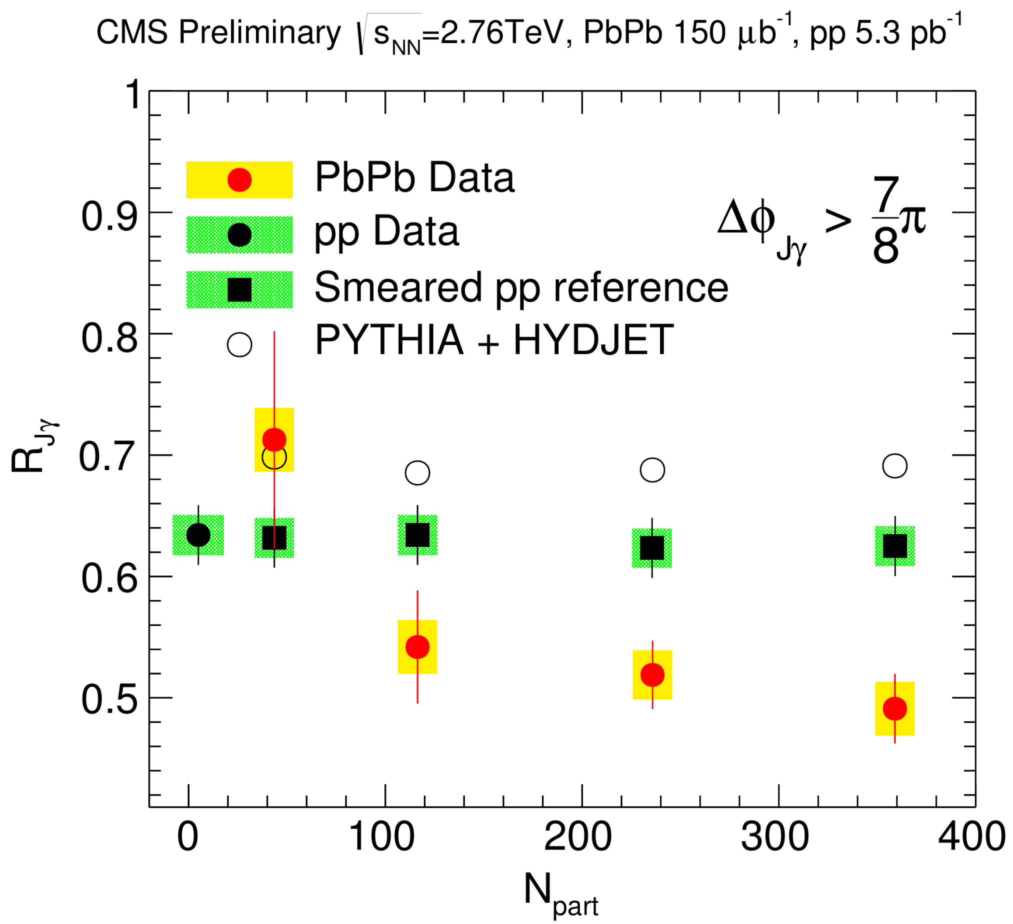

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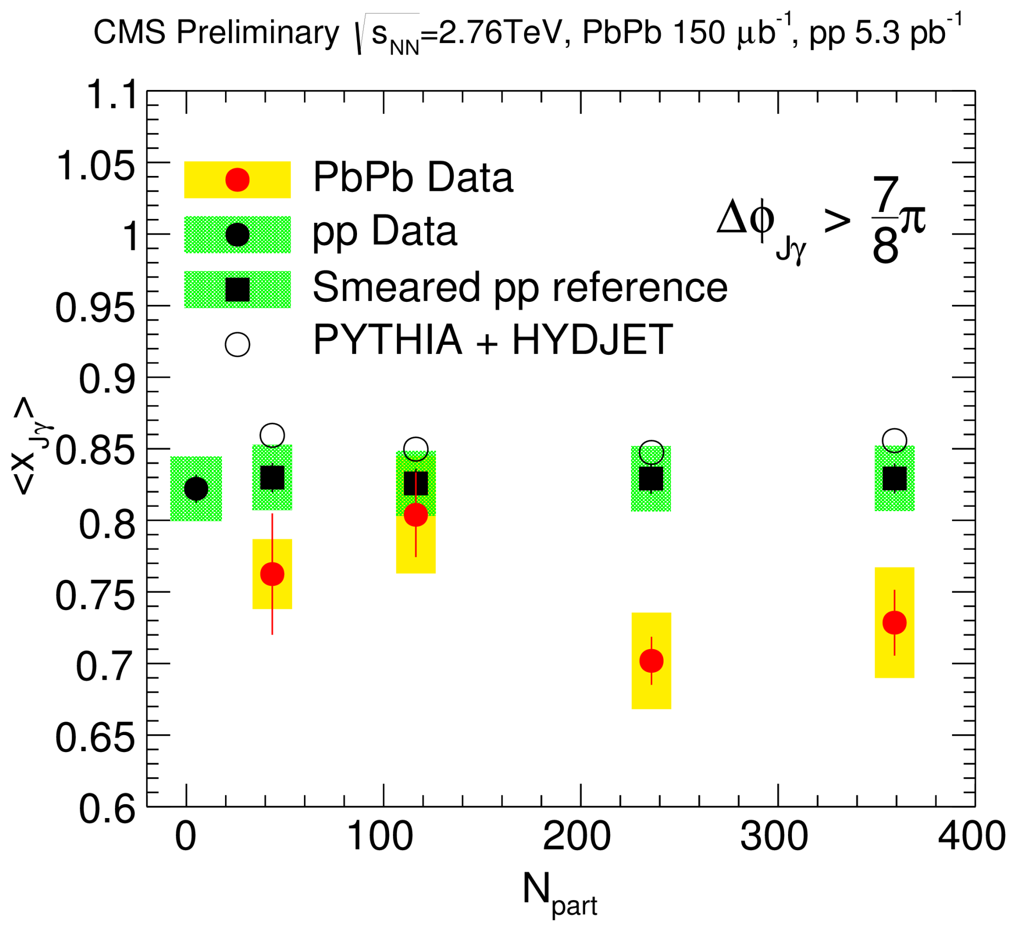
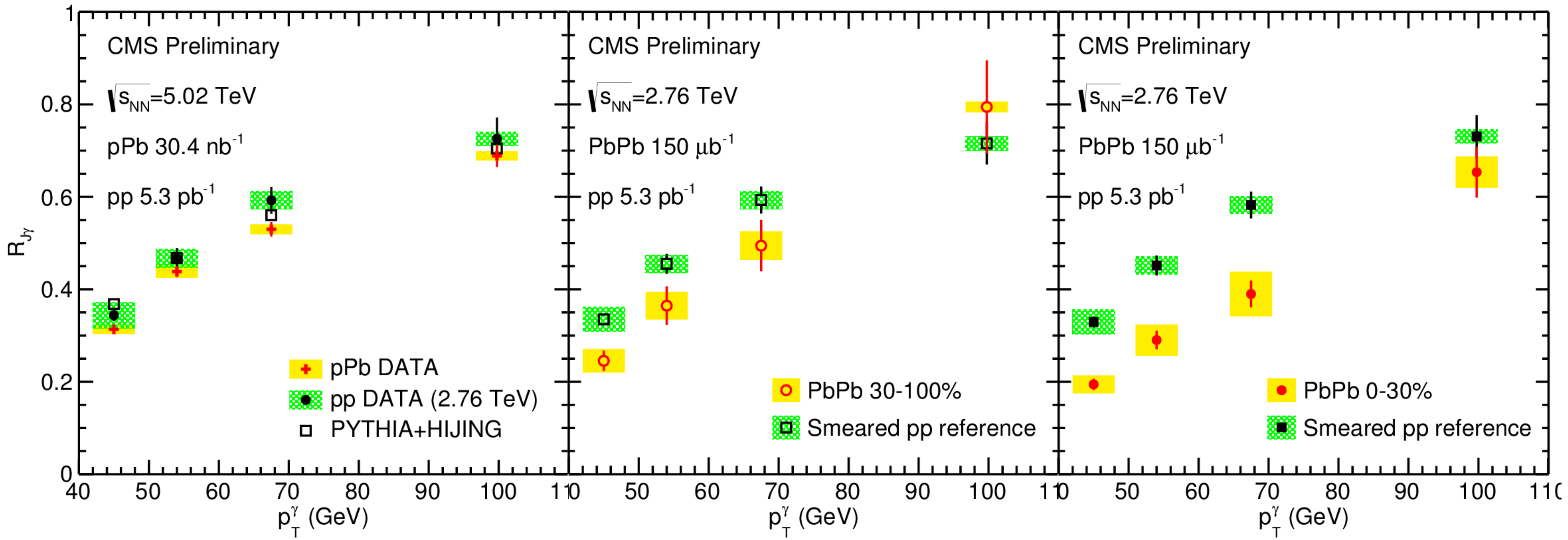
CMS-PAS-HIN-13-006



Relevant Results

- CMS collaboration
- PbPb and pp, 2.76 TeV
- **photon+jet** events

CMS-PAS-HIN-13-006



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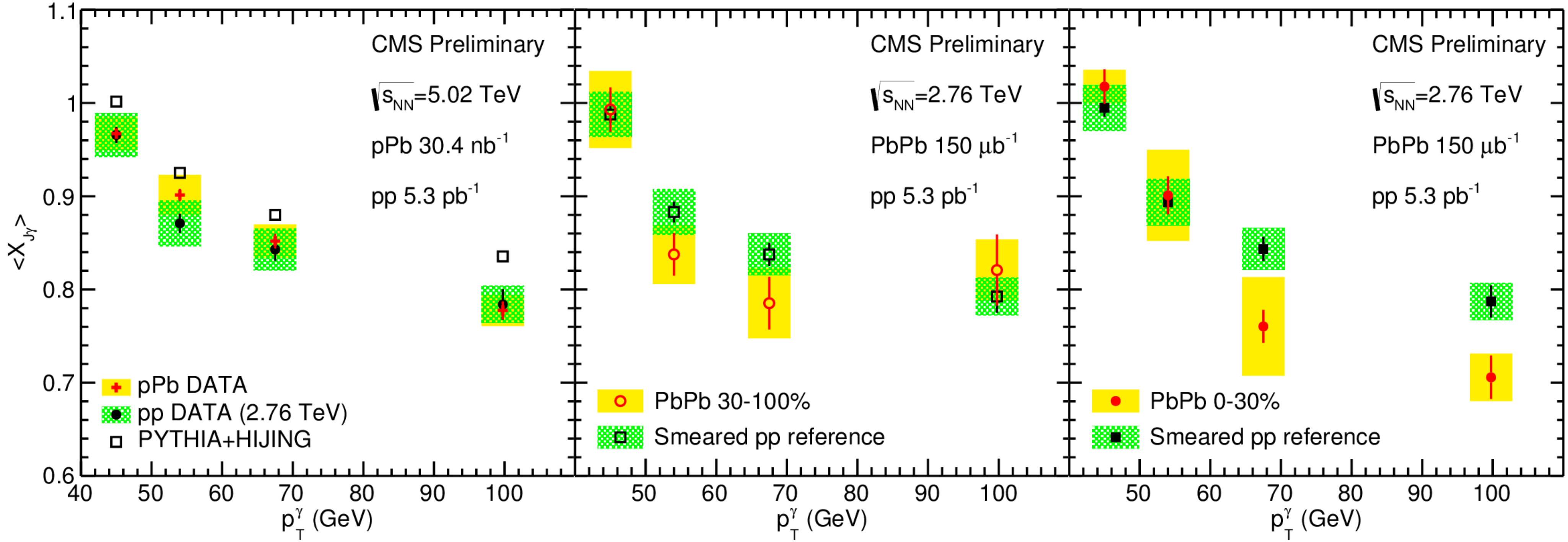

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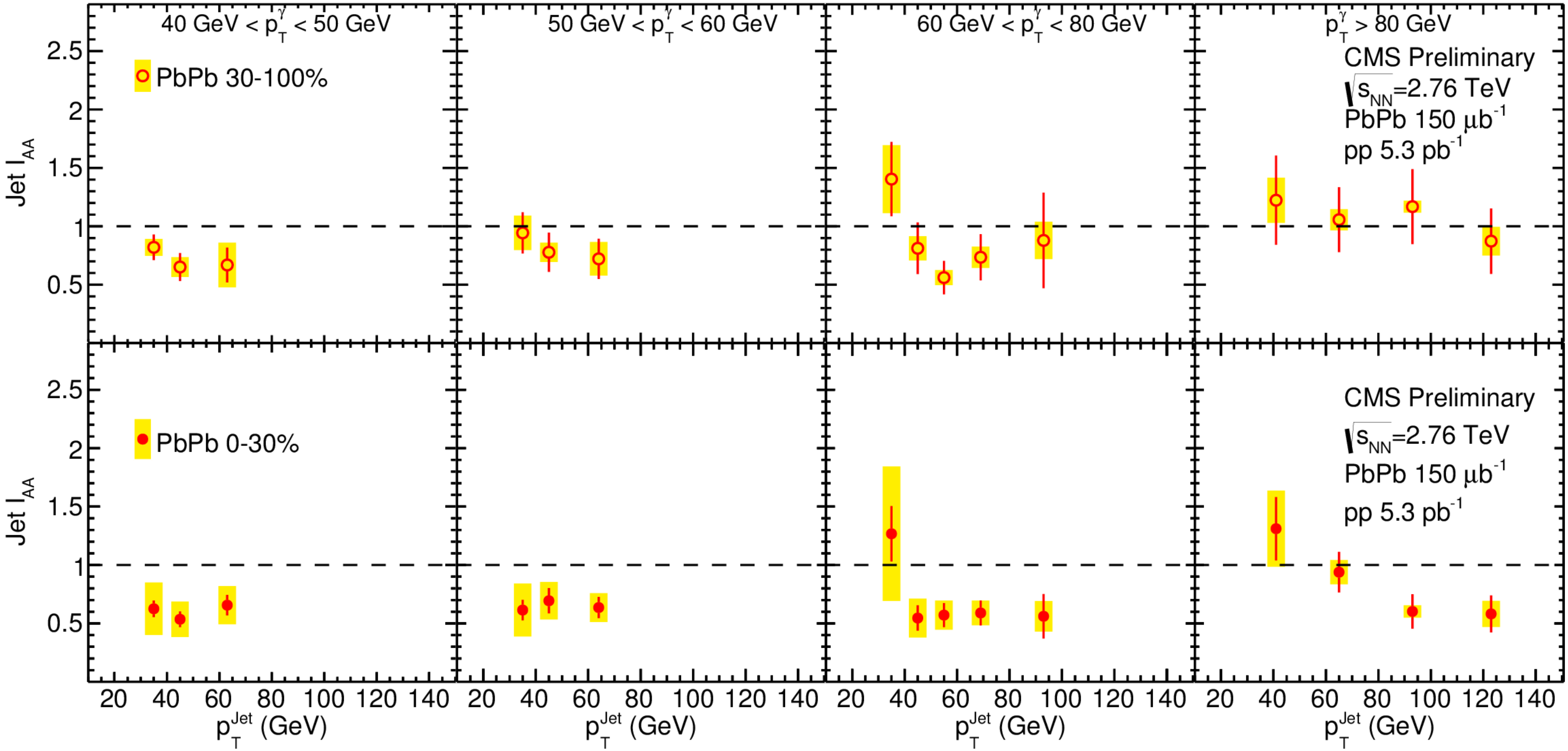
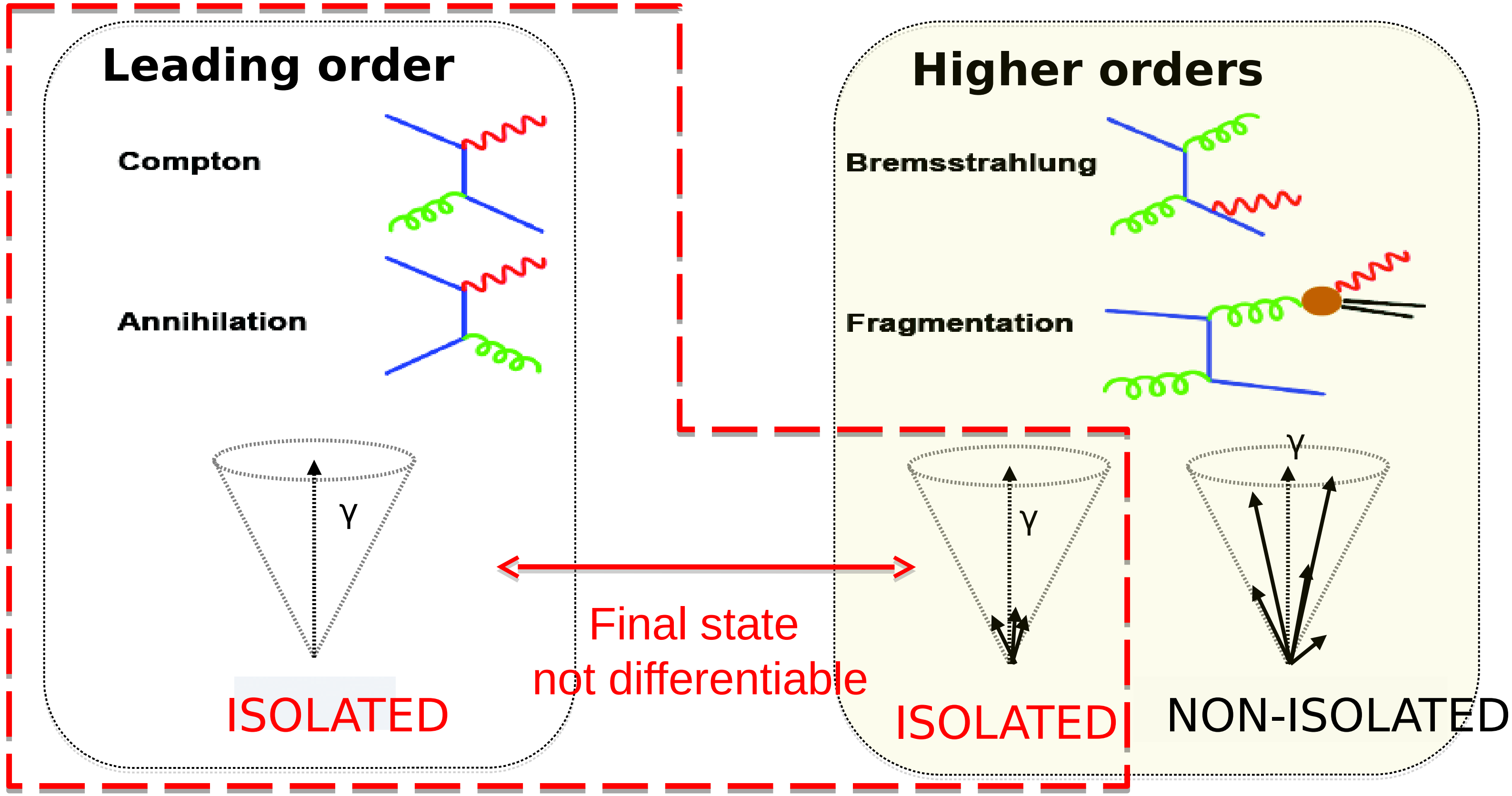


Signal Photon

Identify signal photons by :

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



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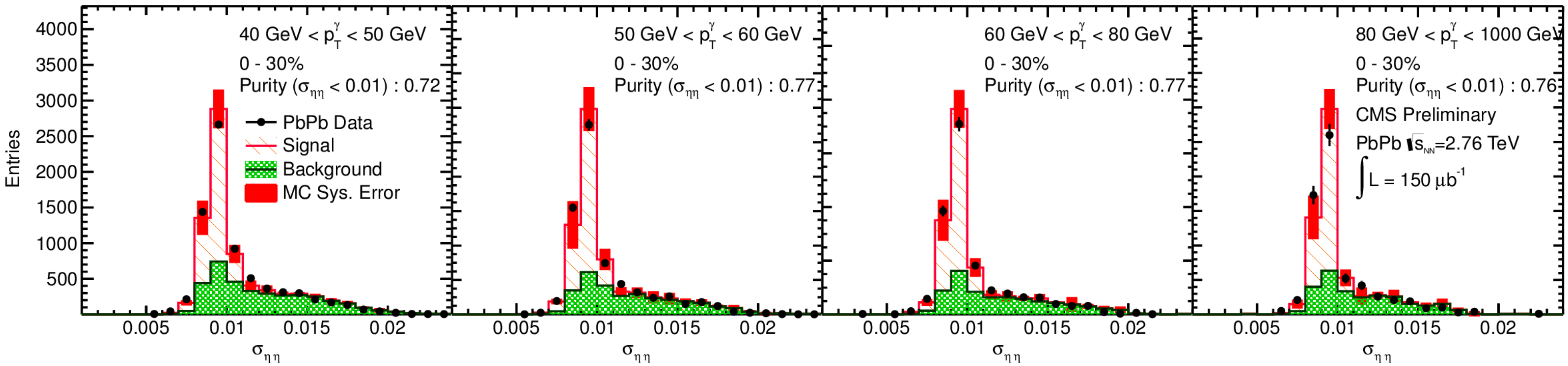
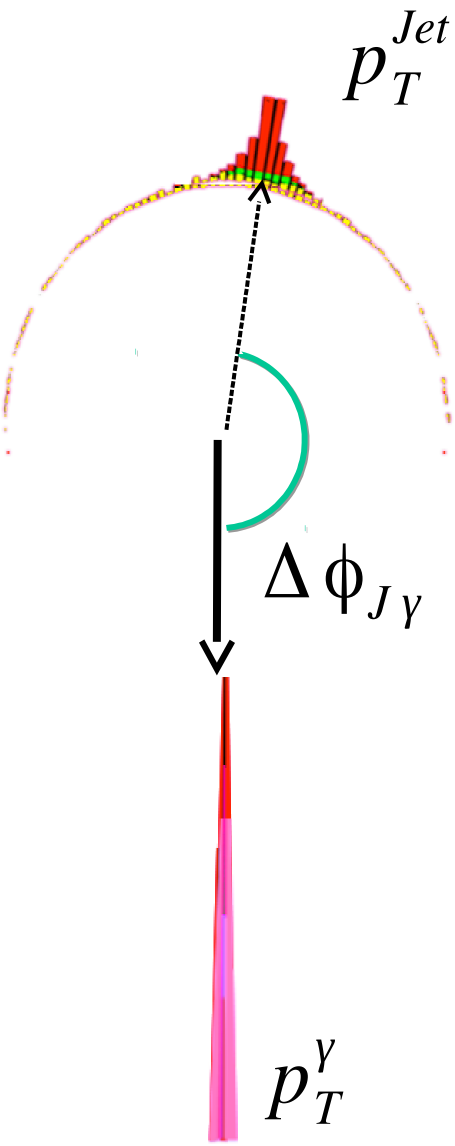


Kinematics : photon+jet

Photons

- $|\eta^{\gamma}| < 1.44$
- $p_T^{\gamma} > 60$ GeV/c (for $\Delta\varphi_{J\gamma}$ and $x_{J\gamma}$ distributions)
- Isolated photons



Jets

- Anti-k_T jets, R=0.3
- $p_T^{Jet} > 30$ GeV/c
- $|\eta^{Jet}| < 1.6$

photon+jet pairs

- **All** jets which meet the given kinematics are included, **not just leading**.

  Apply MinBias event mixing to subtract background (PbPb only)