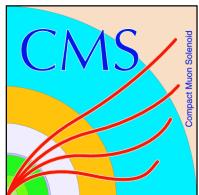


# Parton modification studies using EW-boson-tagged hadrons with pp and PbPb collisions at 5.02 TeV with the CMS experiment



Kaya Tatar  
Massachusetts Institute of Technology  
*for the CMS Collaboration*



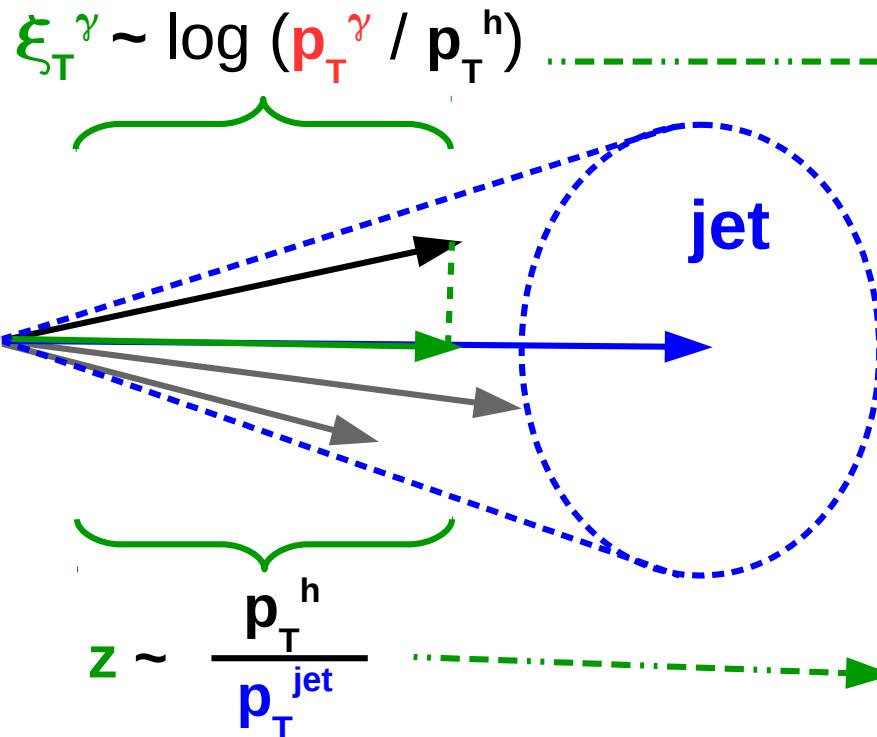
Hard Probes, Online  
June 4, 2020

# Parton-medium interactions - I

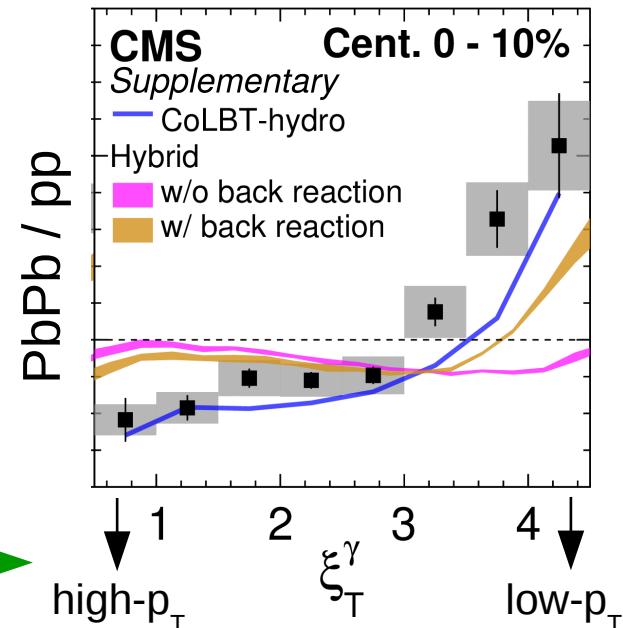
- $\gamma/Z + \text{jet}$  → Constrain initial parton kinematics and flavor
- Direct measure of parton-medium interactions via Jet fragmentation functions (FF)

Parton shower modified :

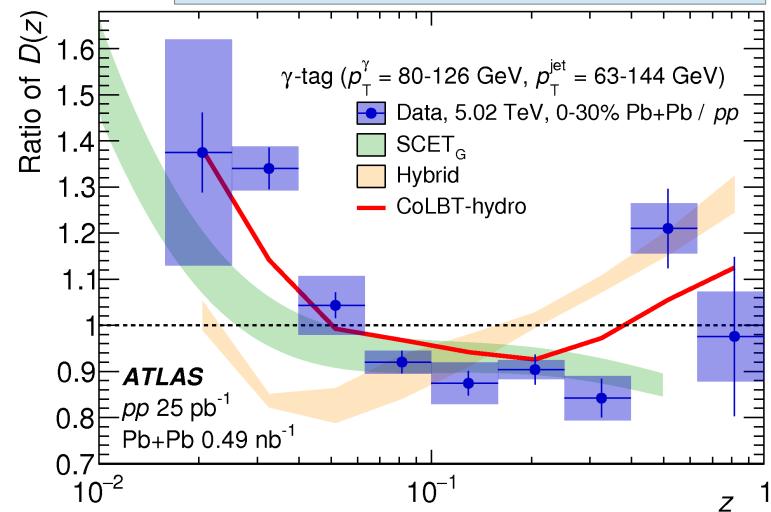
**More low-energy and less high-energy particles**



PRL 121 242301 (2018)



PRL 123 042001 (2019)

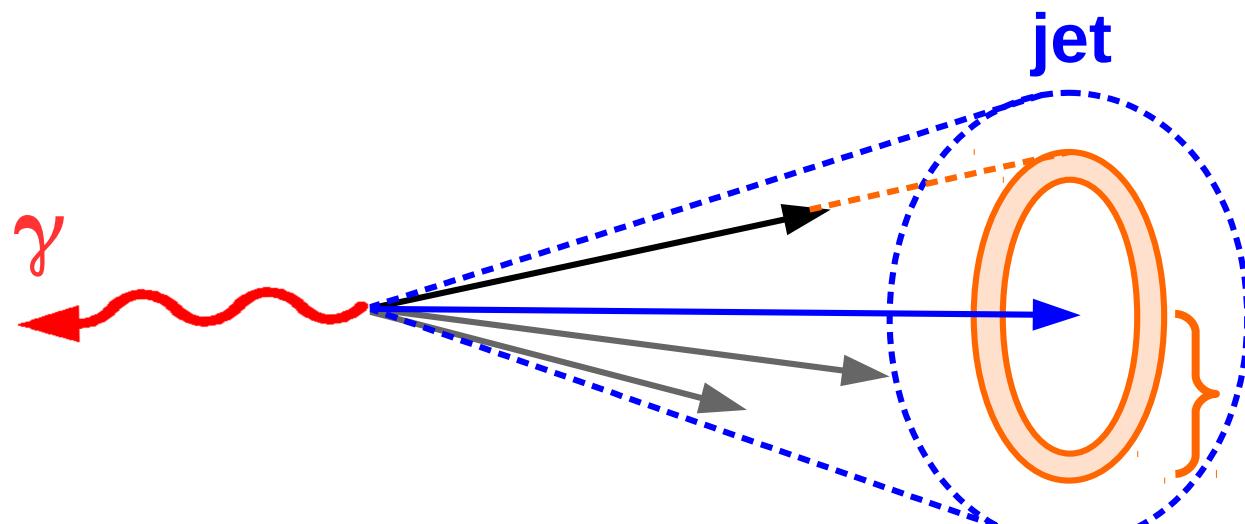


# Parton-medium interactions - II

- $\gamma/Z + \text{jet}$  → Constrain initial parton kinematics and flavor  
→ Direct measure of parton-medium interactions via jet radial density profile, i.e. jet shapes

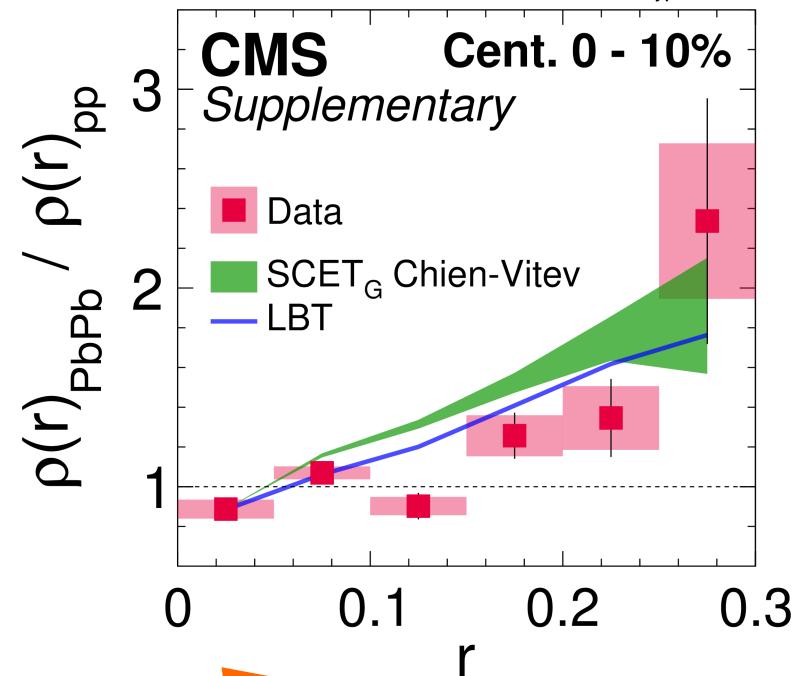
Parton shower modified :

**Larger energy fraction at large angles**



PRL 122 152001 (2019)

$\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$        $p_T^\gamma > 60 \text{ GeV/c}$   
 $\text{PbPb } 404 \mu\text{b}^{-1}$       anti- $k_T$  jet  $R = 0.3$   
 $\text{pp } 27.4 \text{ pb}^{-1}$        $p_T^{\text{jet}} > 30 \text{ GeV/c}$ ,  $\Delta\phi_{\gamma\text{jet}} > \frac{7\pi}{8}$



# Parton-medium using Z+hadron - I

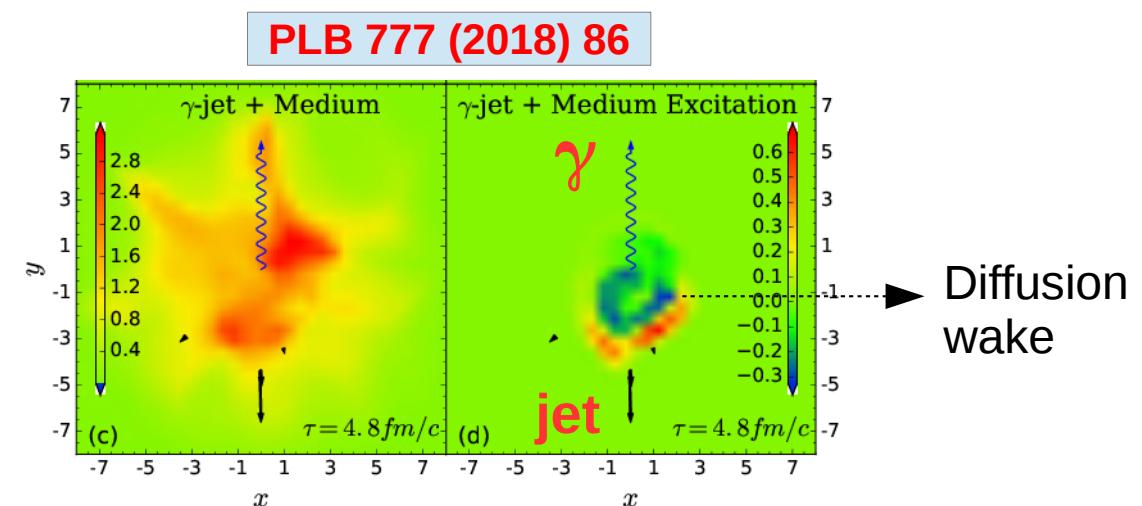
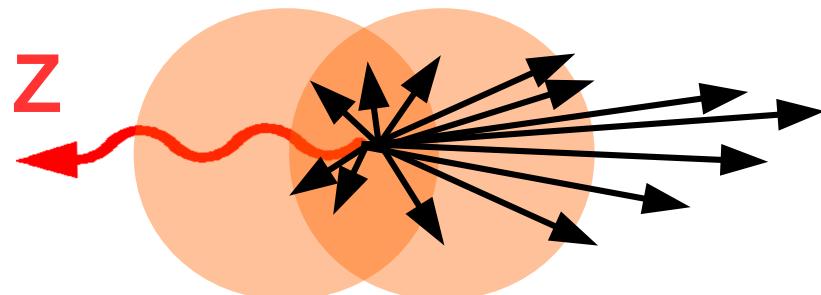
## Z+jet vs $\gamma$ +jet

Pro : No background process, i.e. no Z from fragmentation/radiation/decay  
Con : Lower cross-section  
→ But, large PbPb sample ( $1700 \mu b^{-1}$ ) collected in 2018

This talk : Expand parton-medium interaction studies via correlations between Z bosons and charged particles

## Measure

1) Angular correlation :  $\Delta\phi_{\text{trk},Z} = |\phi^{\text{trk}} - \phi^Z|$



# Parton-medium using Z+hadron - II

## Z+jet vs $\gamma$ +jet

Pro : No background process, i.e. no Z from fragmentation/radiation/decay

Con : Lower cross-section

→ But, large PbPb sample ( $1700 \mu\text{b}^{-1}$ ) collected in 2018

**This talk** : Expand parton-medium interaction studies via correlations between Z bosons and charged particles

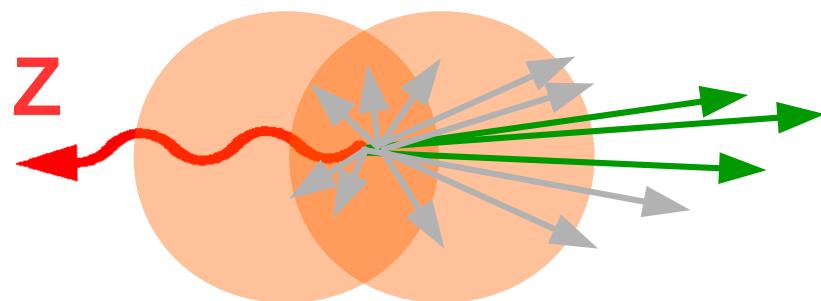
## Measure

1) Angular correlation :  $\Delta\phi_{\text{trk},Z} = |\phi^{\text{trk}} - \phi^Z|$

2) Z-tagged FF :  $\xi_T^{\text{trk},Z} = \ln \frac{-|\vec{p}_T^Z|^2}{\vec{p}_T^{\text{trk}} \cdot \vec{p}_T^Z}$

3)  $p_T$  spectrum :  $p_T^{\text{trk}}$

in the recoil region :  $\Delta\phi_{\text{trk},Z} > 7\pi/8$



# Z+hadron analysis

Dataset :

2018 PbPb data at 5.02 TeV,  $1.7 \text{ nb}^{-1}$

2017 pp data at 5.02 TeV,  $304 \text{ pb}^{-1}$

Event sample :

Electron or muon triggered data

## Step 1 : Reconstruction

### Z boson

electron pairs :  $p_T^e > 20 \text{ GeV}/c$ ,  $|\eta^e| < 2.1$

muon pairs :  $p_T^\mu > 20 \text{ GeV}/c$ ,  $|\eta^\mu| < 2.4$

$60 < M_Z < 120 \text{ GeV}/c^2$

opposite charge pairs

$p_T^Z > 30 \text{ GeV}/c$

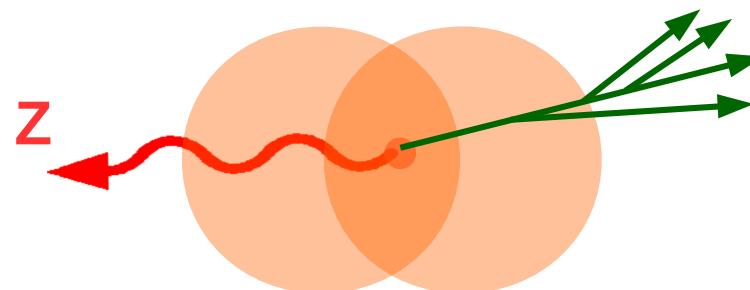
Tracks JHEP 04 (2017) 039

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

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

No jet reco !

## Step 2 : Make Z+track pairs



## Step 3 : Background subtraction

Tracks from PbPb underlying event (UE) → Subtracted via event mixing

QCD background events → Subtract events with same charge lepton pairs

# Z boson reconstruction - PbPb

Electron pairs

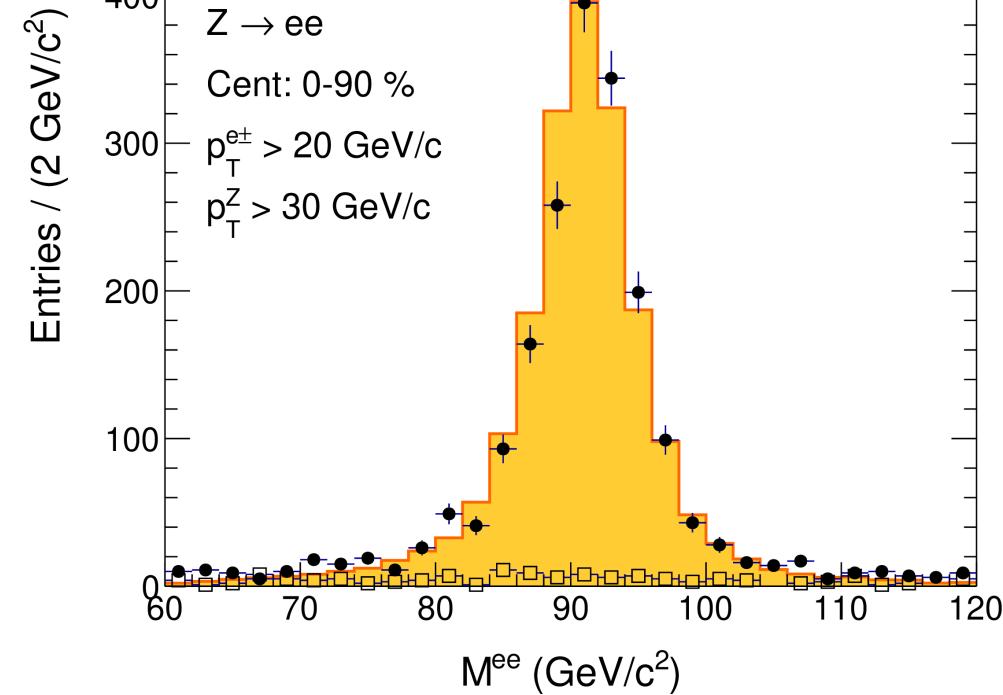
CMS-PAS-HIN-19-006

Muon pairs

PbPb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

1.7 nb<sup>-1</sup>

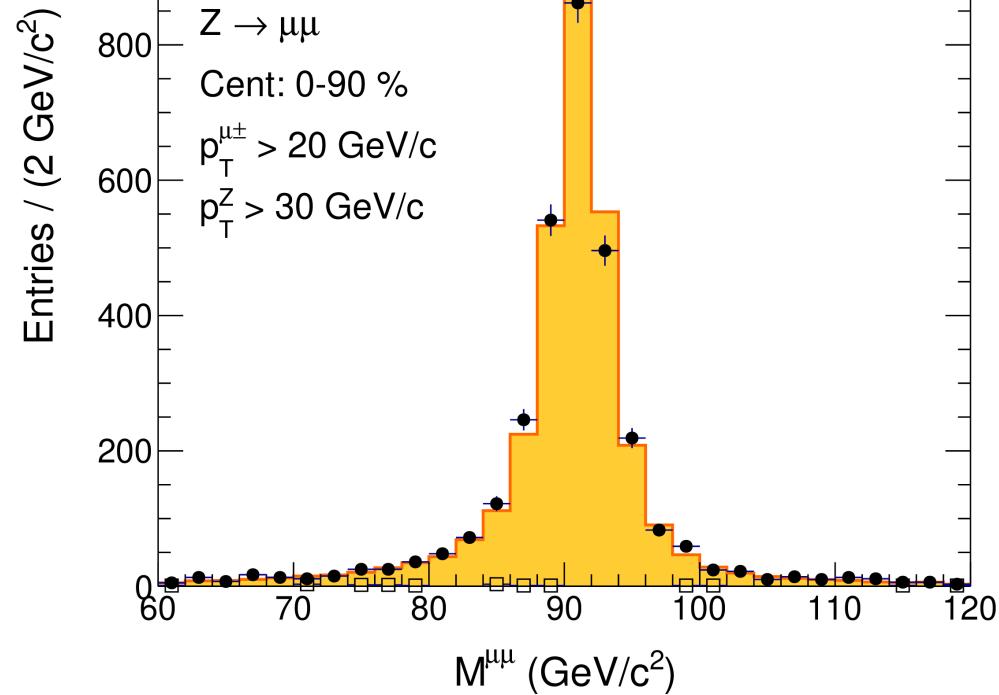
CMS  
Preliminary



PbPb  $\sqrt{s_{NN}} = 5.02 \text{ TeV}$

1.7 nb<sup>-1</sup>

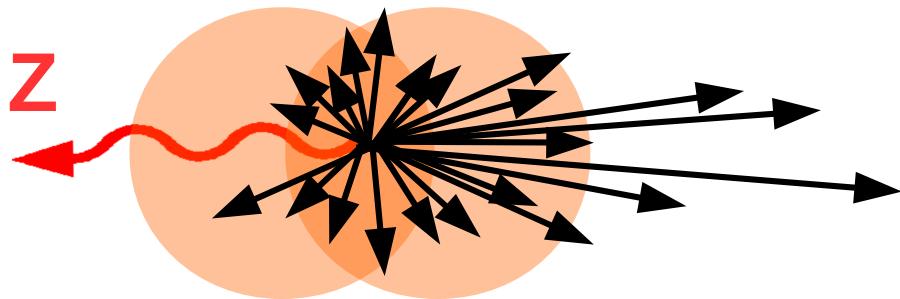
CMS  
Preliminary



~ 5000 Z candidate events

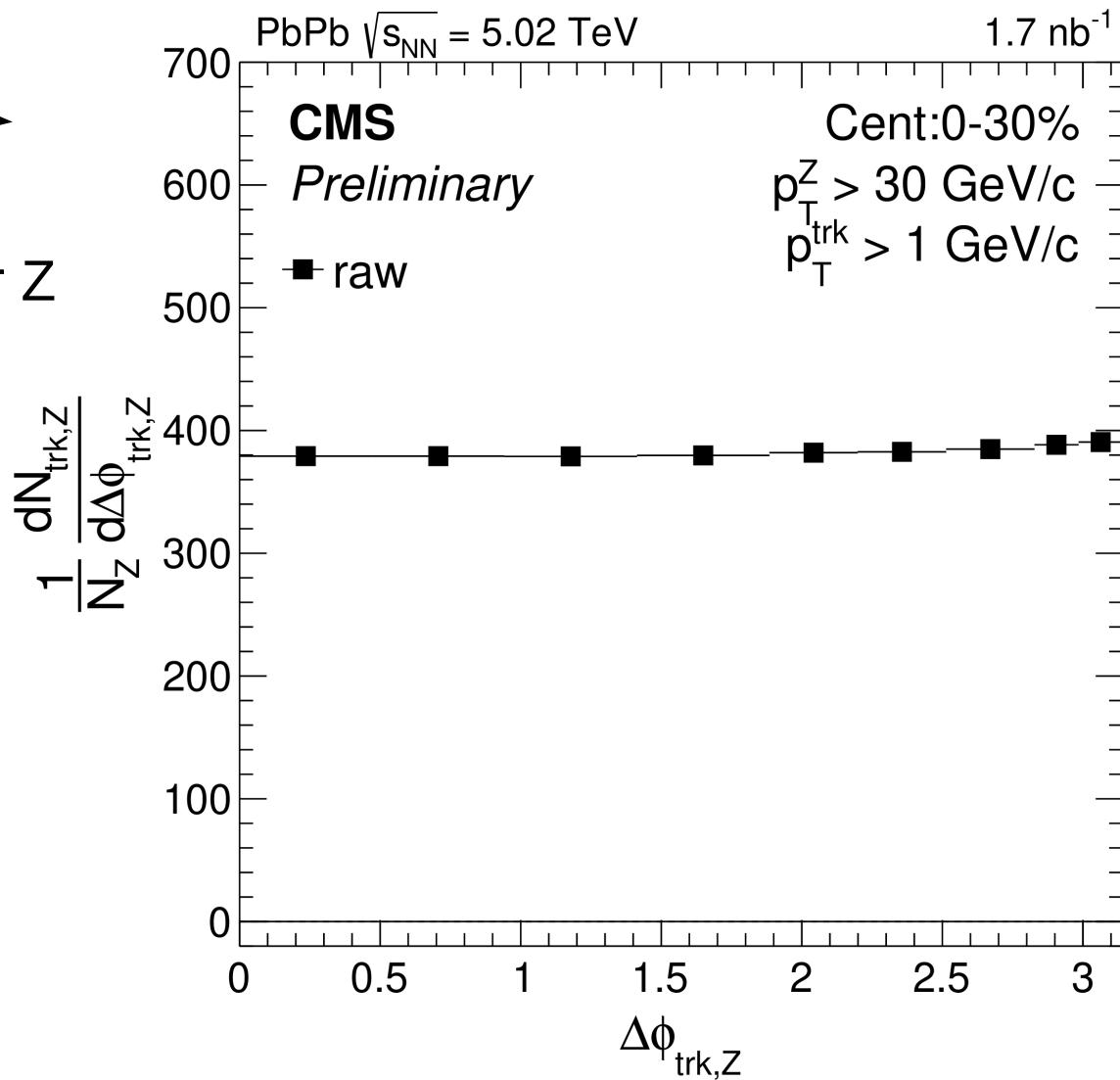
# Z+track pairs in PbPb - I

CMS-PAS-HIN-19-006



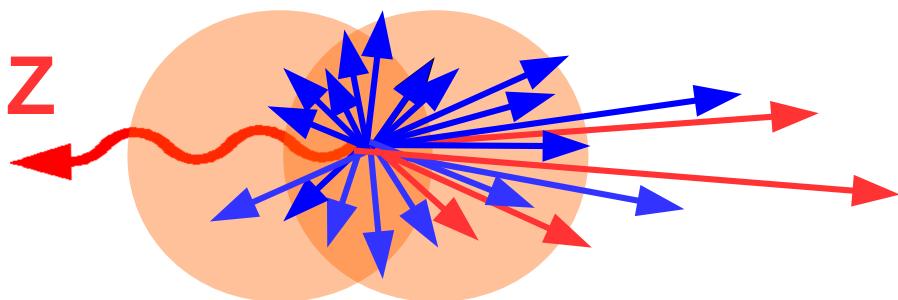
A huge yield  $\rightarrow \sim 1000$  particles per Z

Recall : No particle tagging via jets



# Z+track pairs in PbPb - II

CMS-PAS-HIN-19-006



A huge yield composed of

## 1.) Signal

The NN collision producing the Z

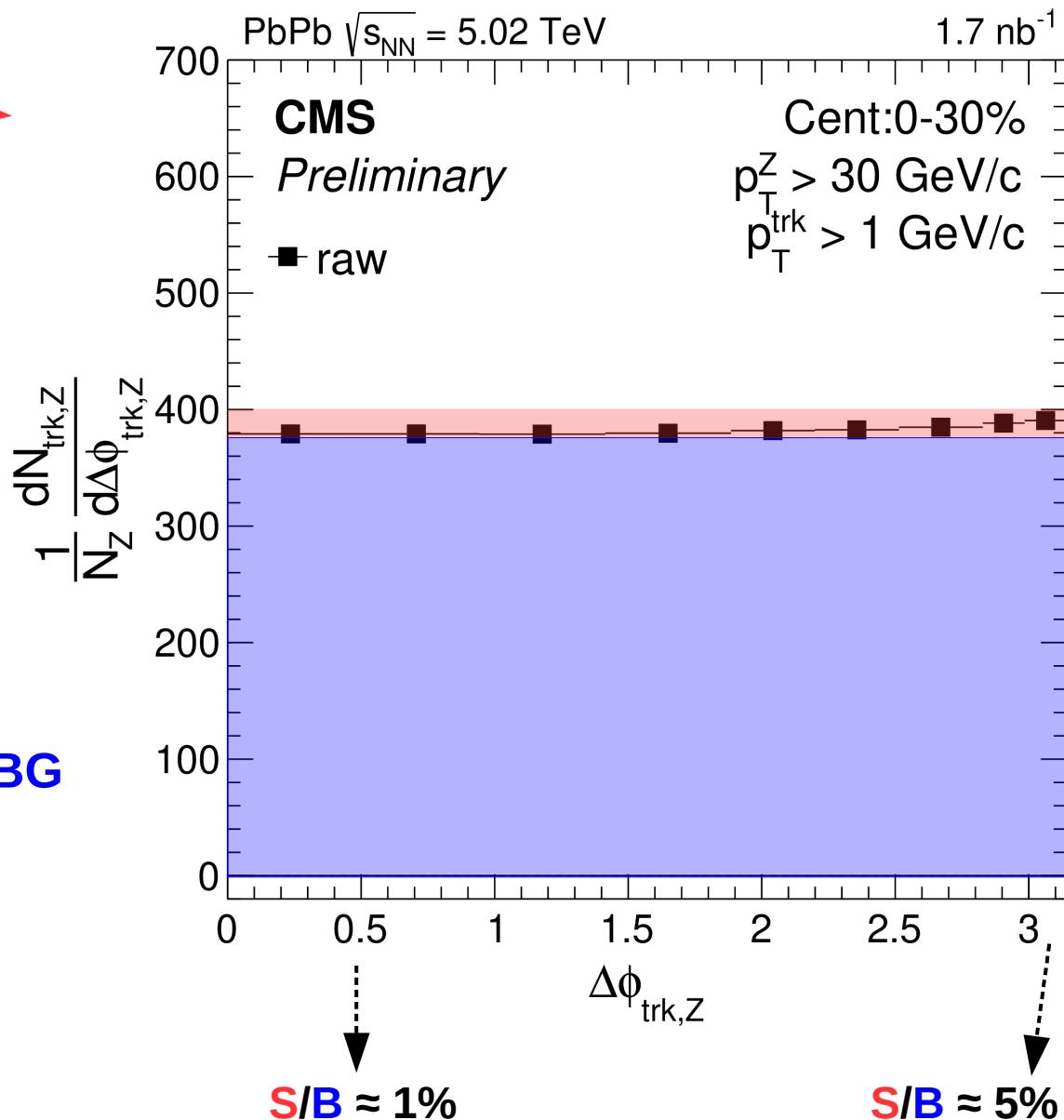
## 2.) Background from PbPb UE

Other NN collisions

How to estimate the **BG** precisely?

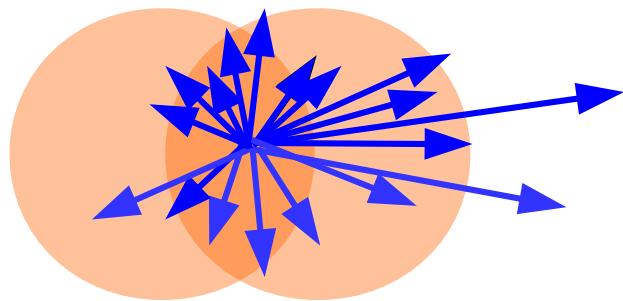
**Assumption :**

The energy in forward rap. ( $3 < |\eta| < 5$ )  
composed of **UE from Z process** and **BG**  
i.e.  $E^{HF} = E^{HF, Z} + E^{HF, BG}$



# Mixed event selection - I

CMS-PAS-HIN-19-006



A huge yield composed of

## 1.) Signal

The NN collision producing the Z

## 2.) Background from PbPb UE

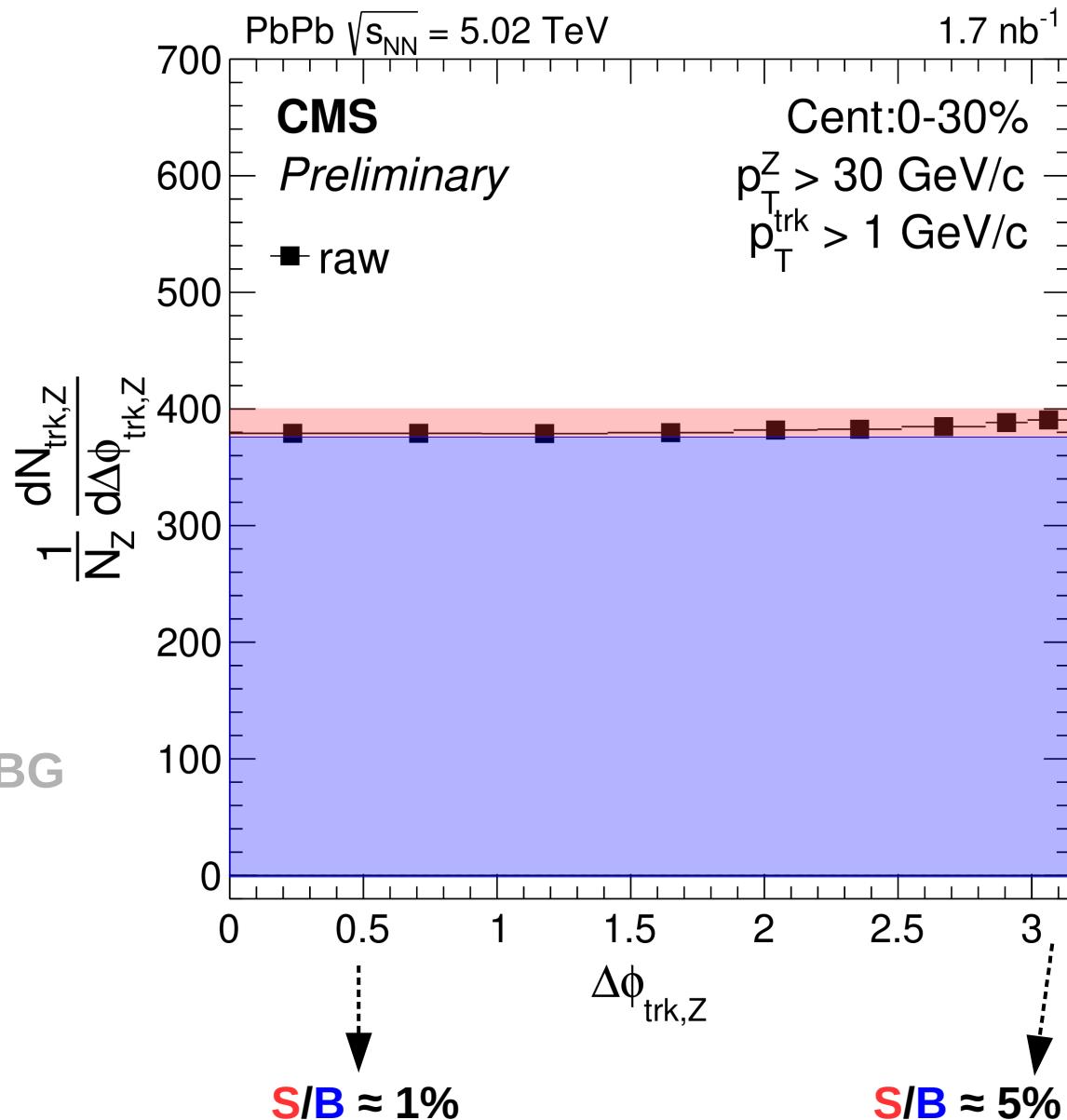
Other NN collisions

How to estimate the BG precisely?

Assumption :

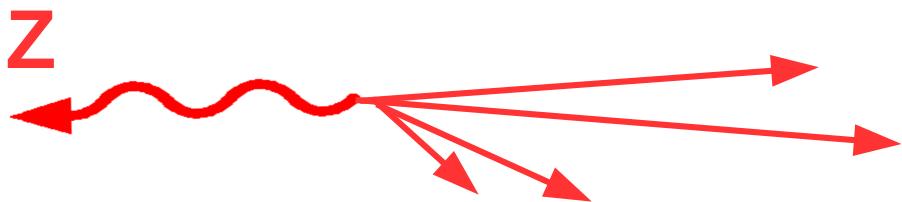
The energy in forward rap. ( $3 < |\eta| < 5$ )  
composed of UE from Z process and BG  
i.e.  $E^{HF} = E^{HF, Z} + E^{HF, BG}$

Subtract BG using MB events matched  
with forward energy  $E^{HF, MB} = E^{HF} - E^{HF, Z}$



# Mixed event selection - II

CMS-PAS-HIN-19-006



A huge yield composed of

## 1.) Signal

The NN collision producing the Z

## 2.) Background from PbPb UE

Other NN collisions

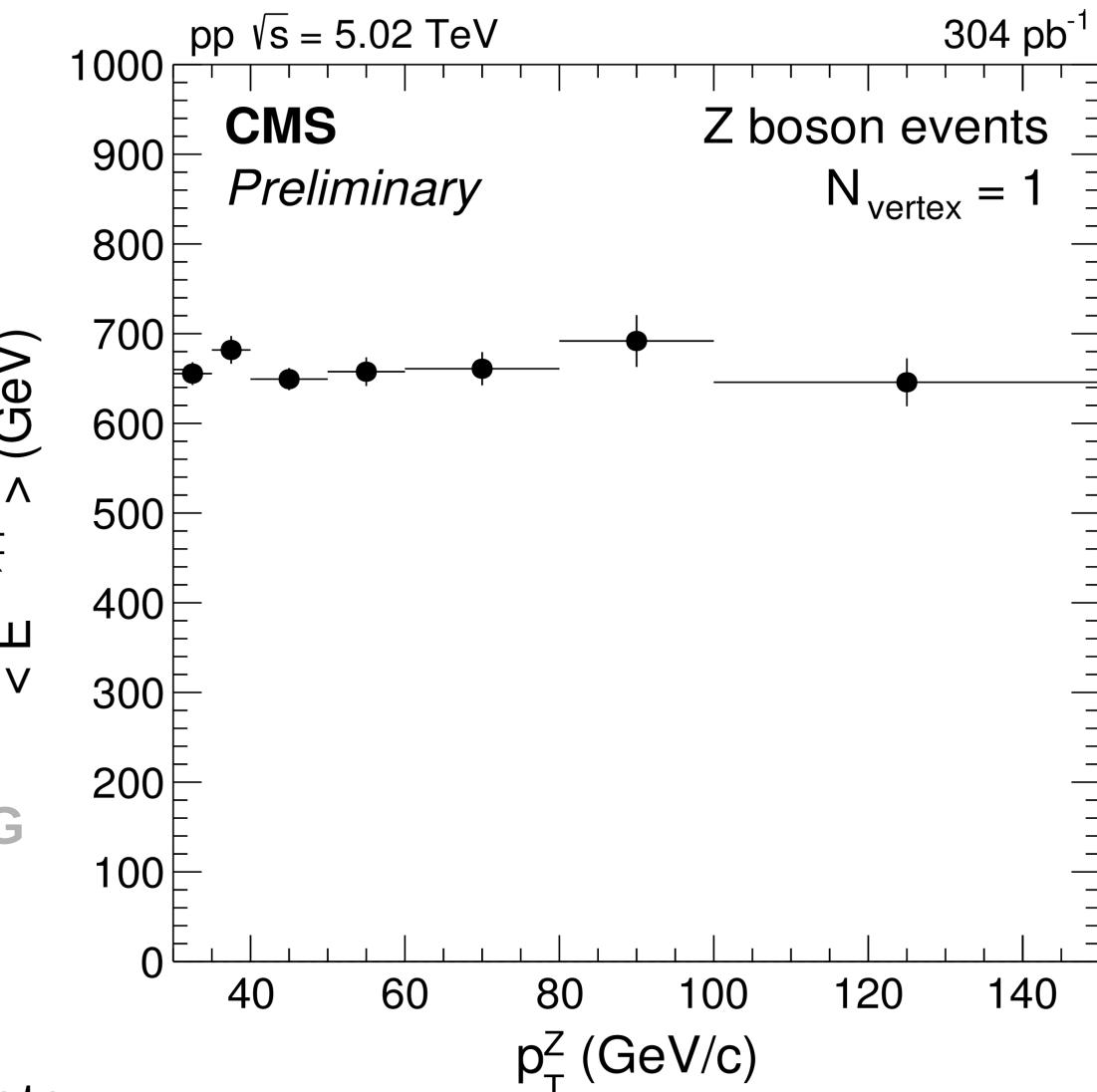
How to estimate the BG precisely?

Assumption :

The energy in forward rap. ( $3 < |\eta| < 5$ )  
composed of UE from Z process and BG  
i.e.  $E^{HF} = E^{HF, Z} + E^{HF, BG}$

Subtract BG using MB events matched  
with forward energy  $E^{HF, MB} = E^{HF} - E^{HF, Z}$

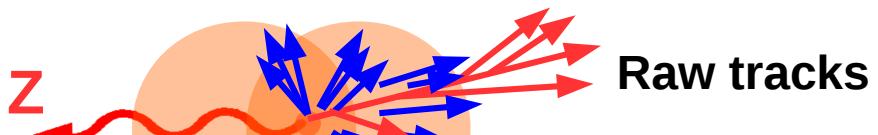
$E^{HF, Z}$  estimated from Z events in pp data



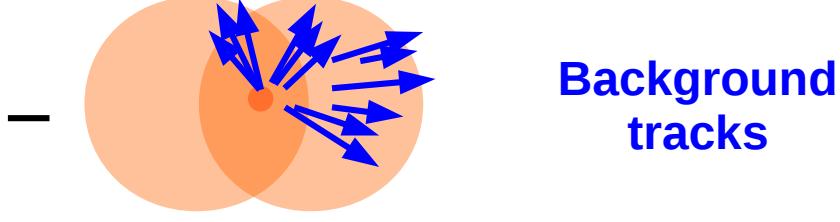
# Background subtraction for tracks

CMS-PAS-HIN-19-006

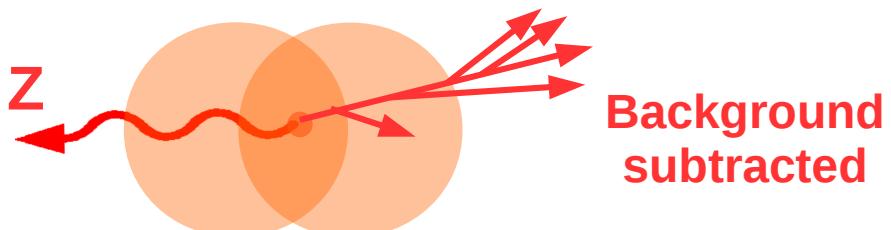
Z+jet event



MB event

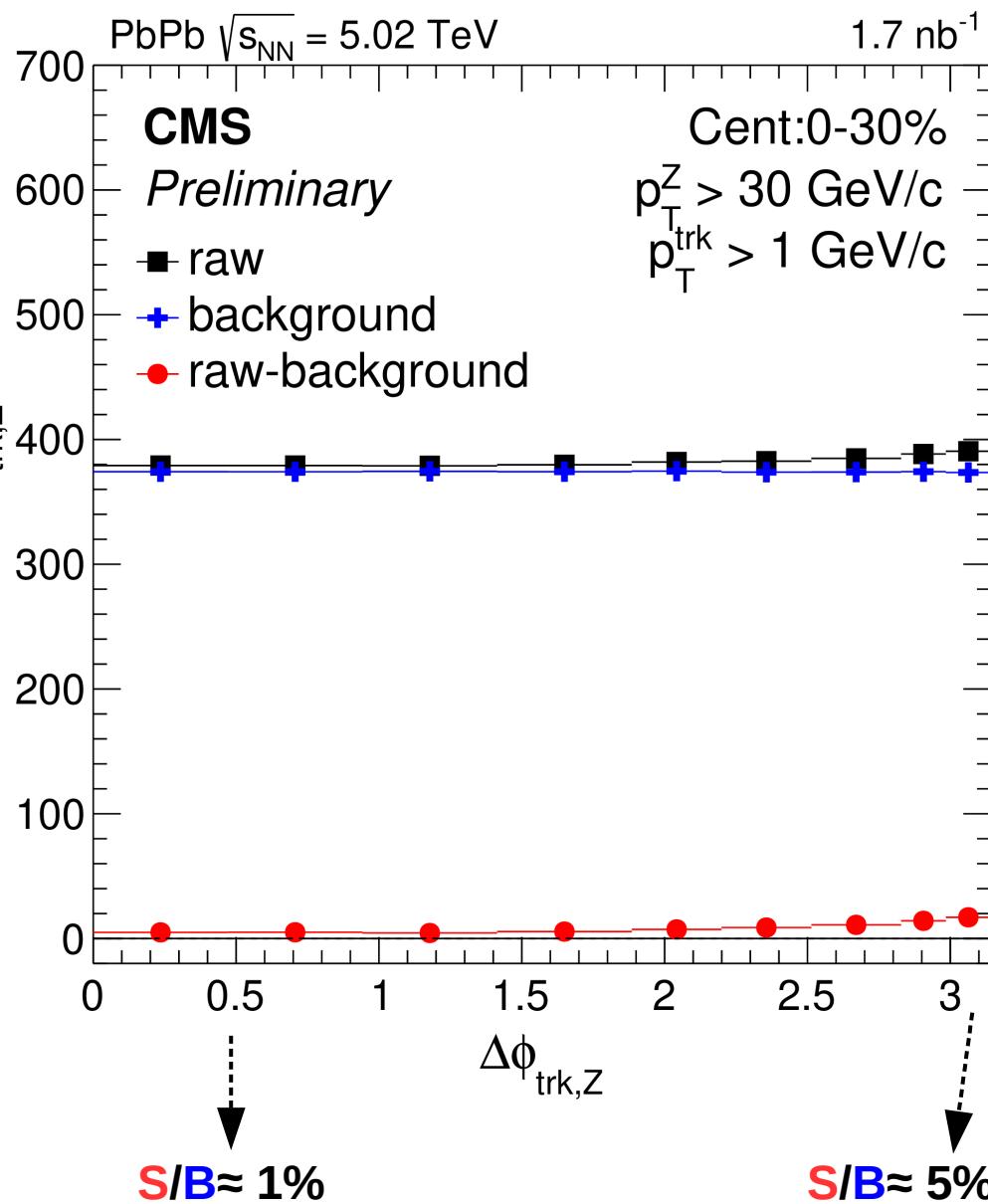


Background tracks



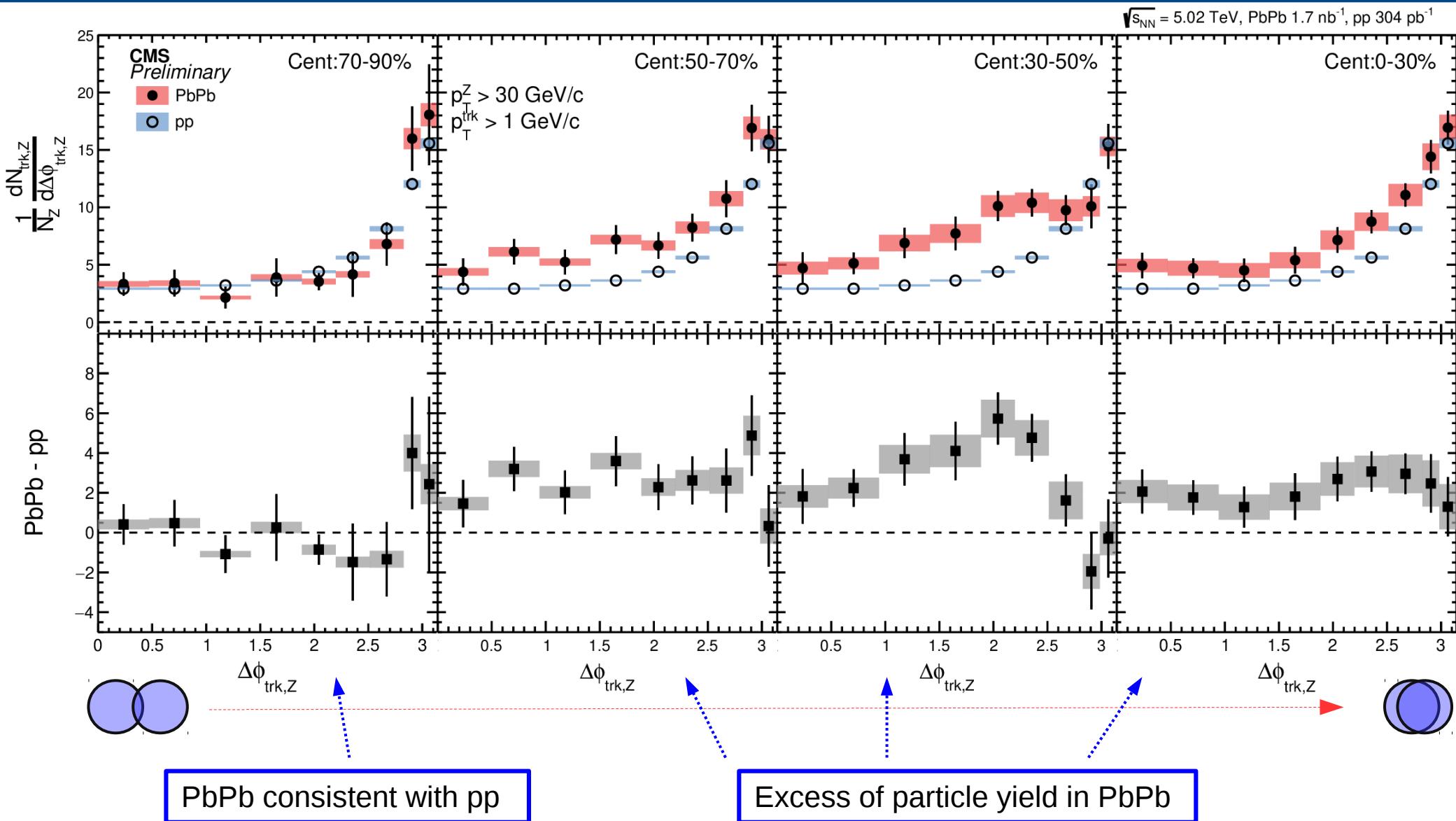
Background  
subtracted

Background subtraction verified  
via Pythia+Hydjet simulation



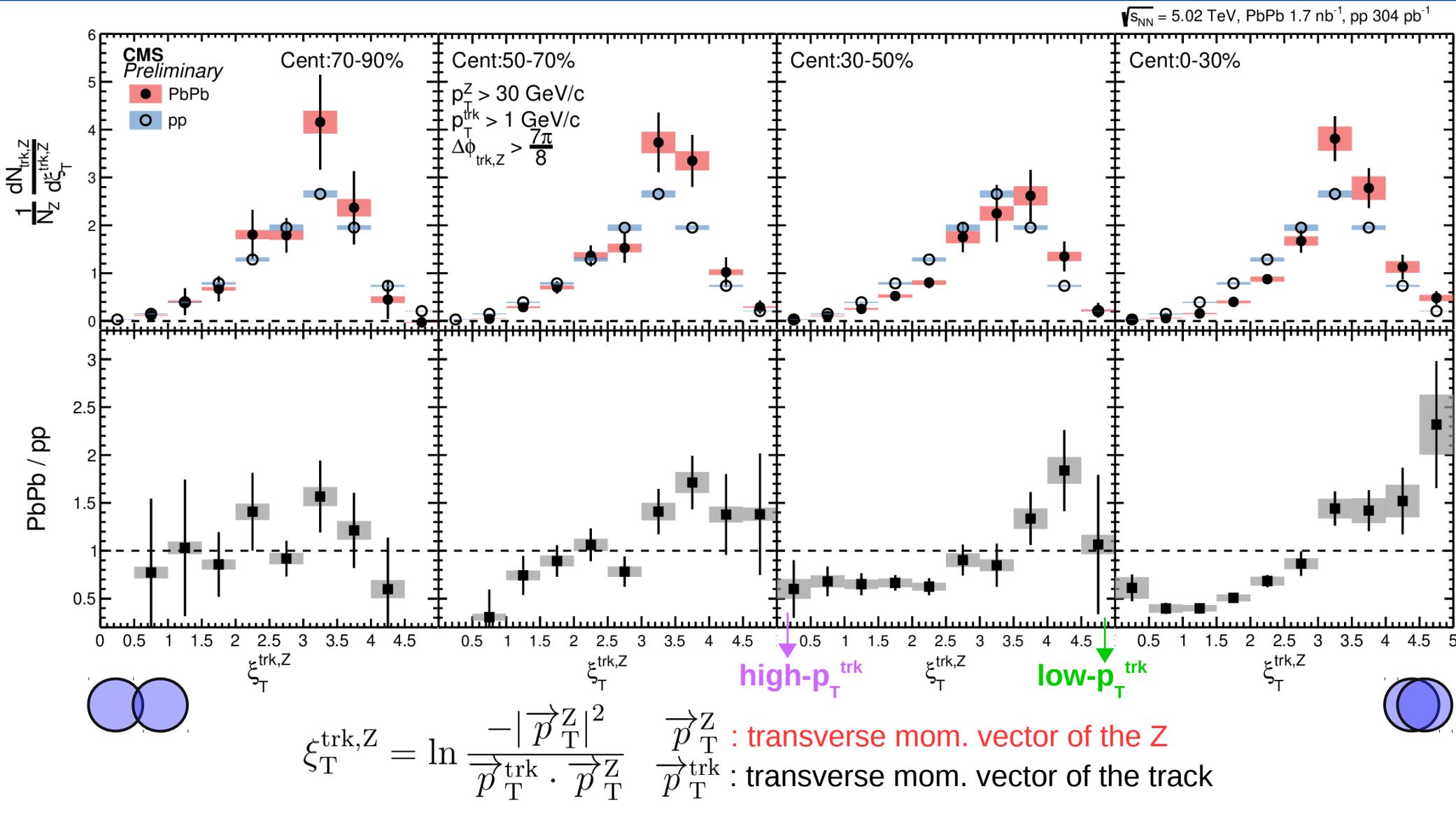
# Results : $\Delta\phi_{\text{trk},Z}$

CMS-PAS-HIN-19-006



# Results : $\xi_T^{\text{trk},Z}$

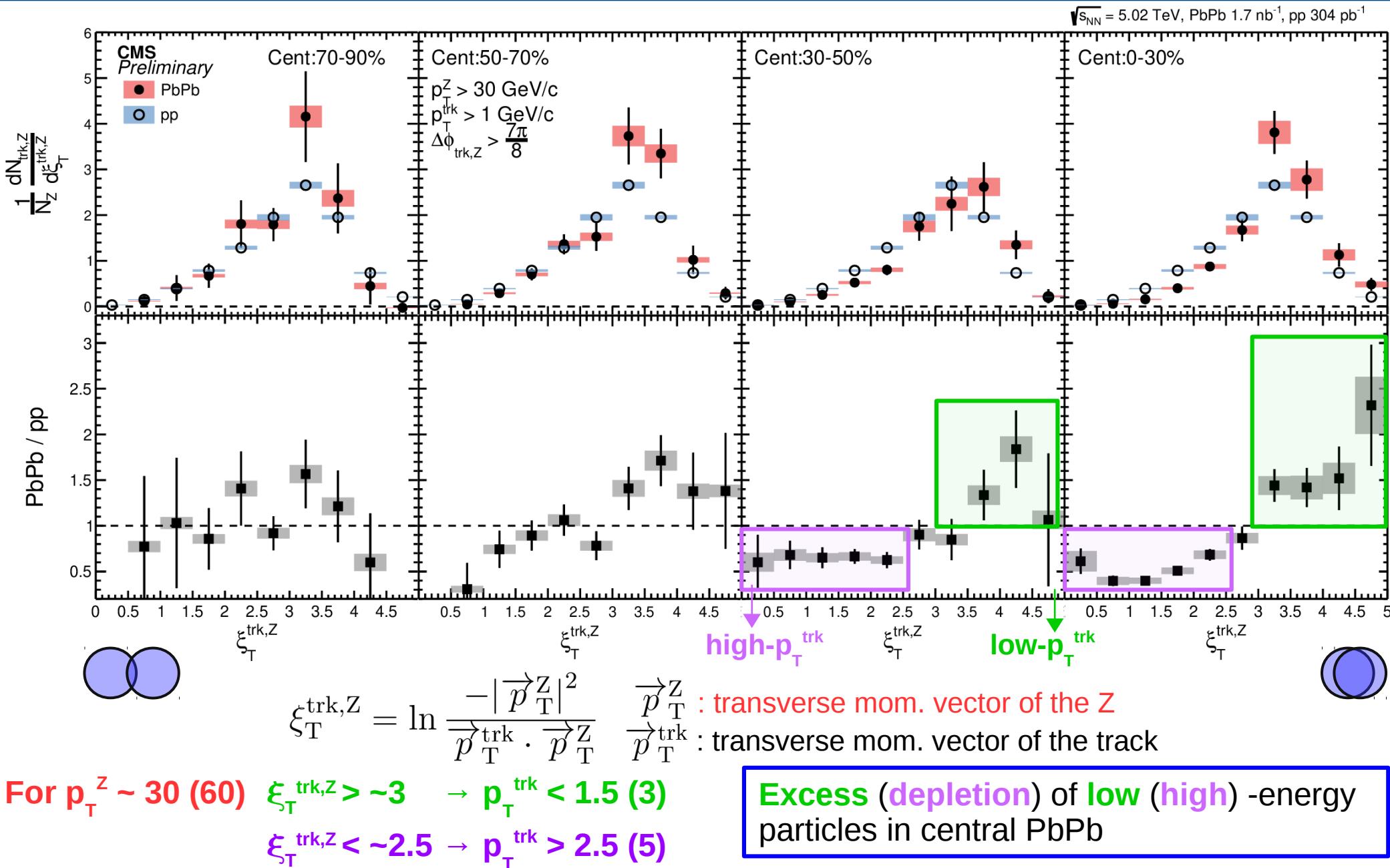
CMS-PAS-HIN-19-006



Peripheral PbPb consistent with pp

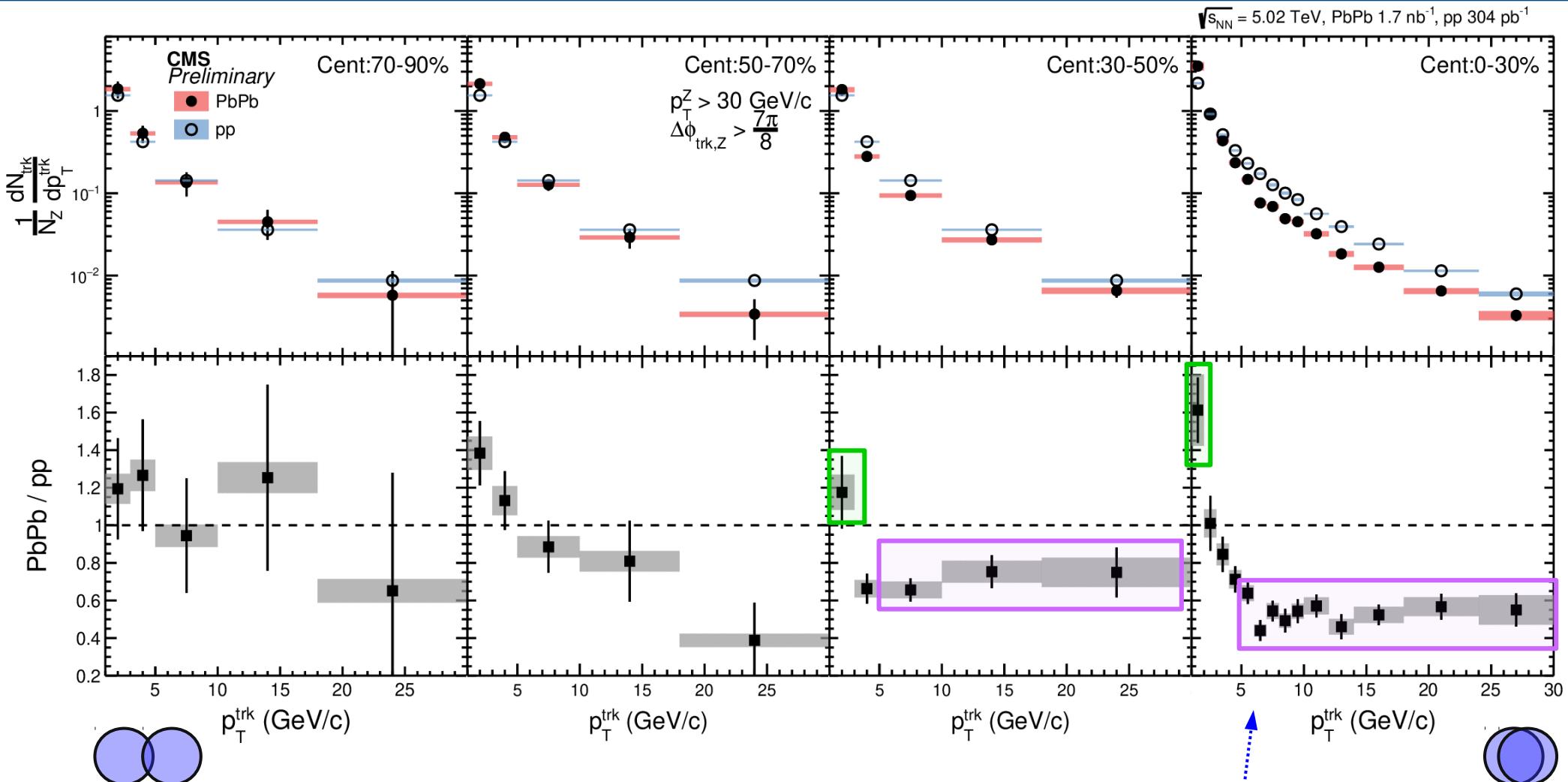
# Results : $\xi_T^{\text{trk},Z}$

CMS-PAS-HIN-19-006



# Results : $p_T^{\text{trk}}$

CMS-PAS-HIN-19-006



Peripheral PbPb consistent with pp

**PbPb / pp**

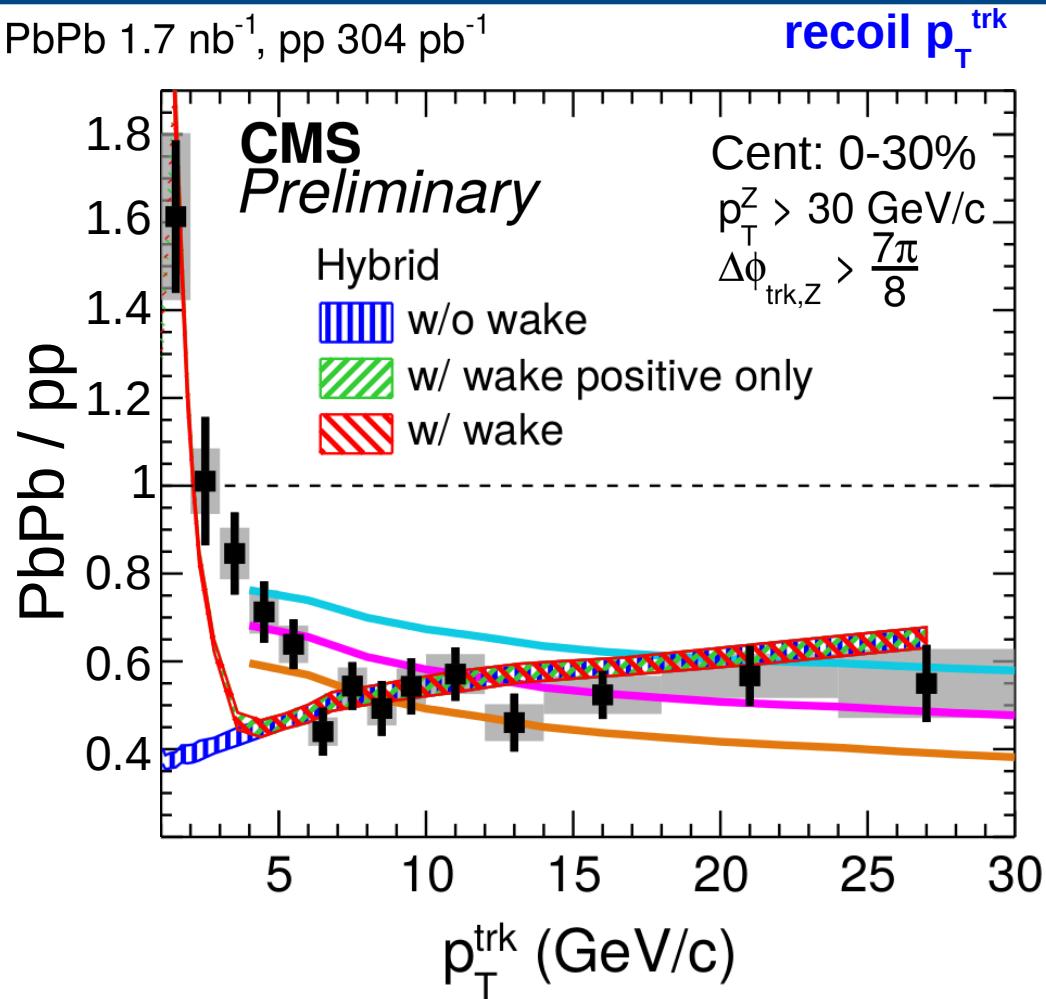
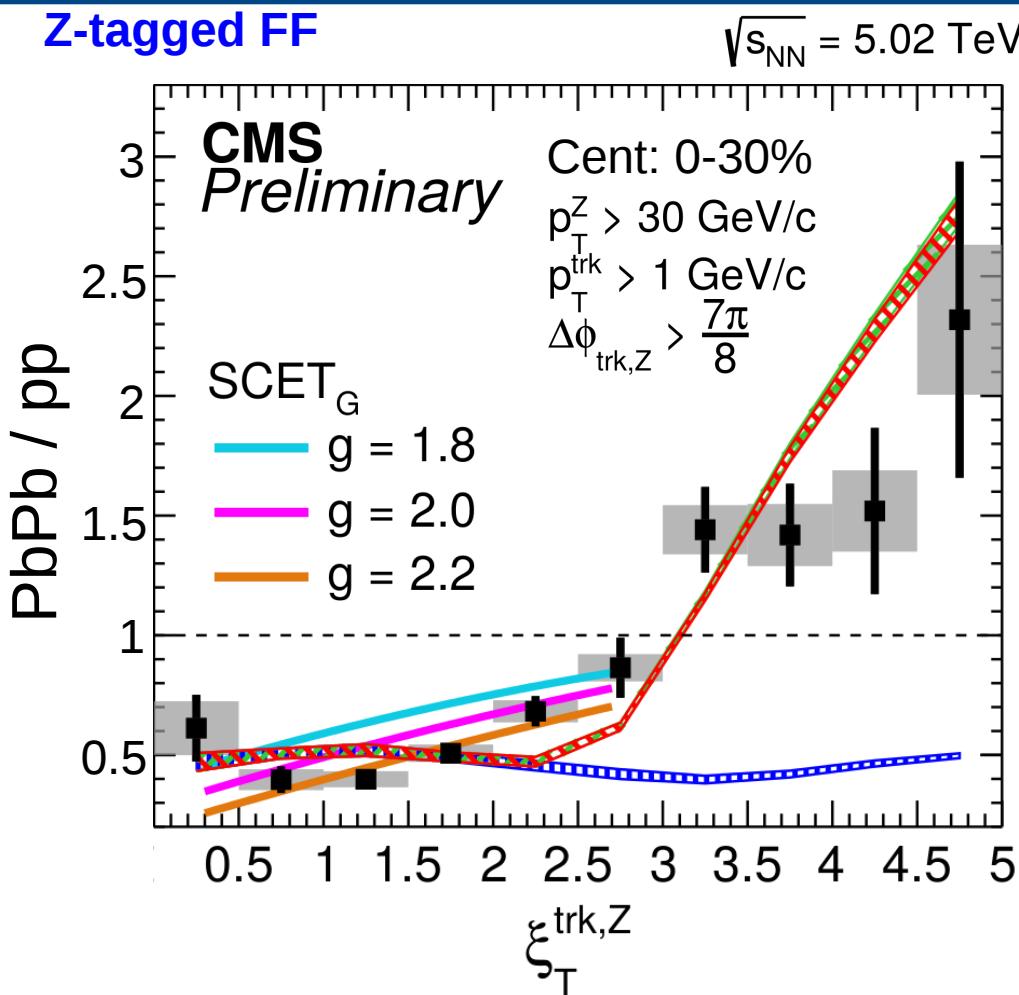
( $1 < p_T^{\text{trk}} < 2 \text{ GeV}$ )  $\sim 1.6$

( $p_T^{\text{trk}} > 5 \text{ GeV}$ )  $\sim 0.4 - 0.6$

# FF and $p_T^{\text{trk}}$ vs theory - I

CMS-PAS-HIN-19-006

Z-tagged FF



**SCET<sub>G</sub>** includes Glabuer gluons into soft-collinear effective theory.  
g : parton-medium coupling strength

Curves based on [PRD 93 074030 (2016), PRD 101 076020 (2020)]

**Hybrid** (JHEP 1410 (2014) 019) combines weak and strong coupling regimes

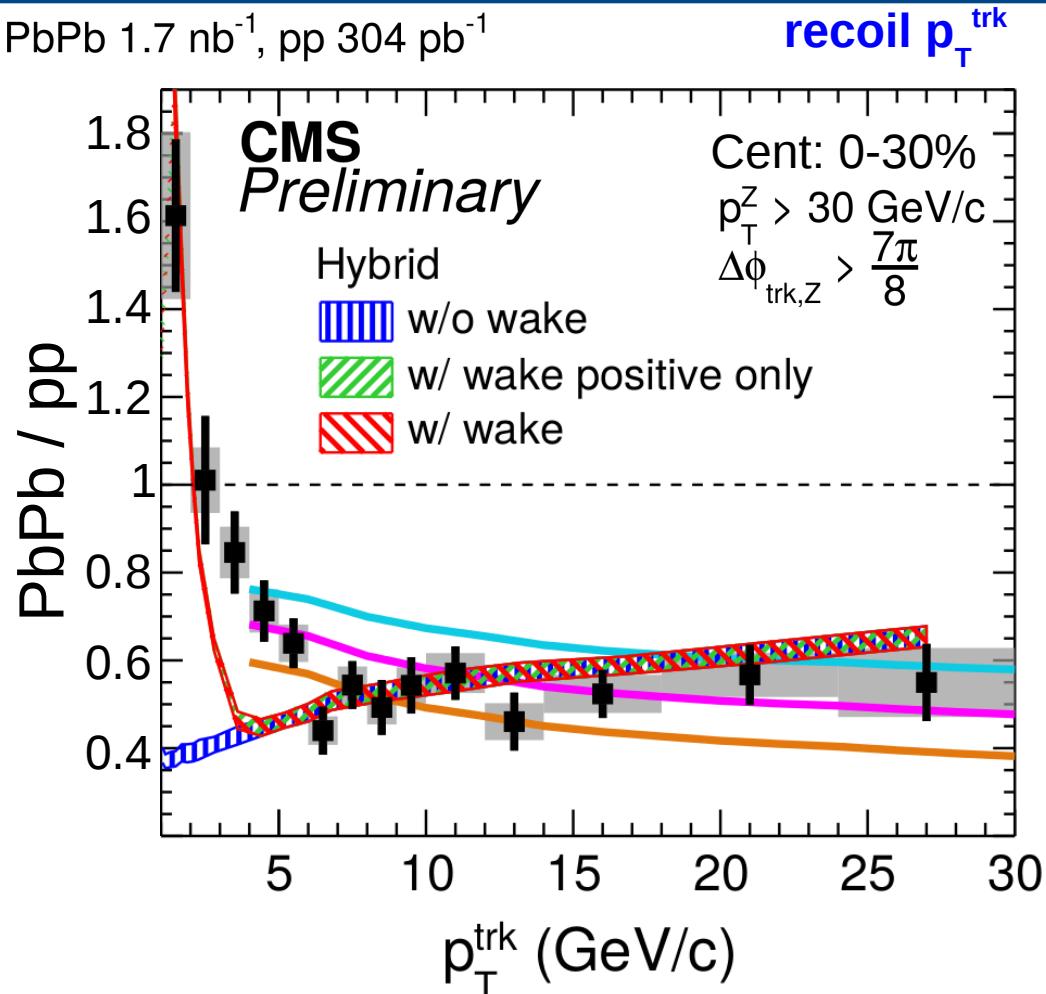
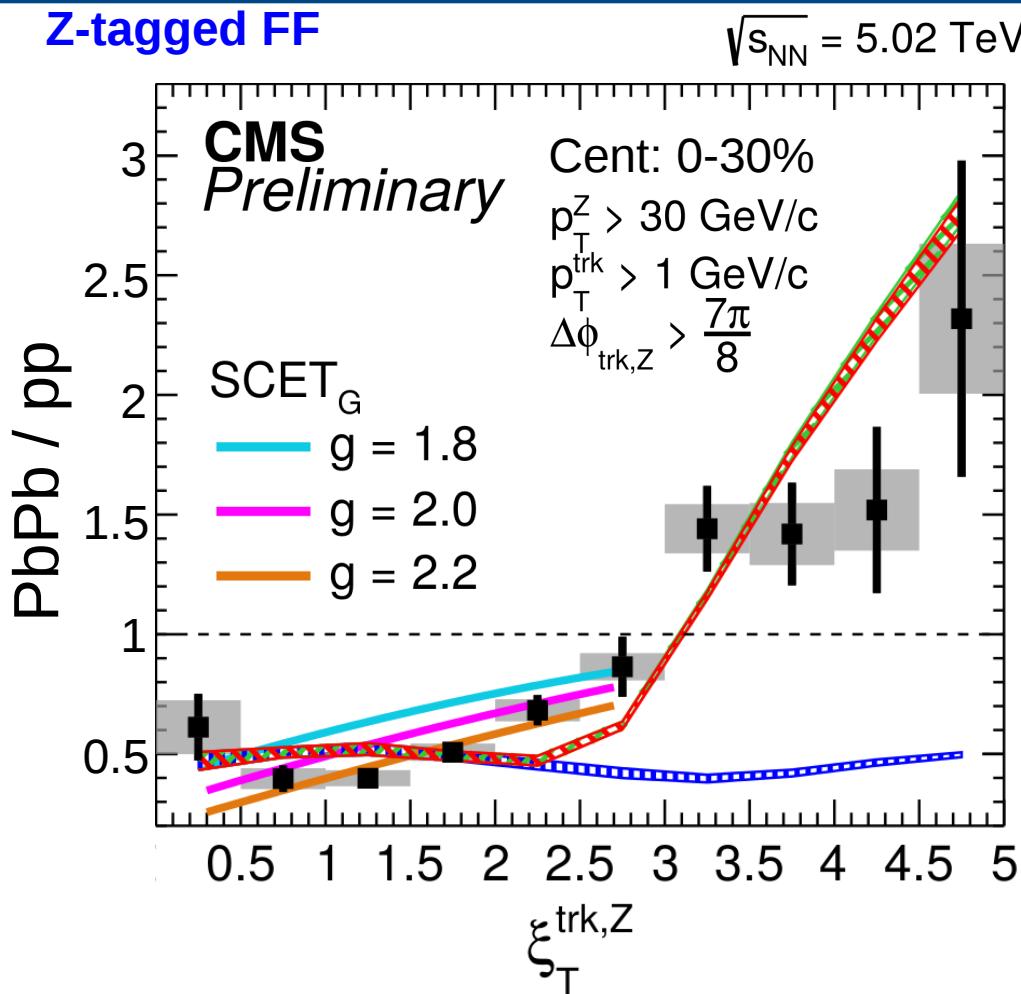
wl (w/o) wake : do (do not) include medium response

Weak (high-Q<sup>2</sup>) via pQCD  
Strong (low-Q<sup>2</sup>) via gauge/gravity

# FF and $p_T^{\text{trk}}$ vs theory - II

CMS-PAS-HIN-19-006

Z-tagged FF

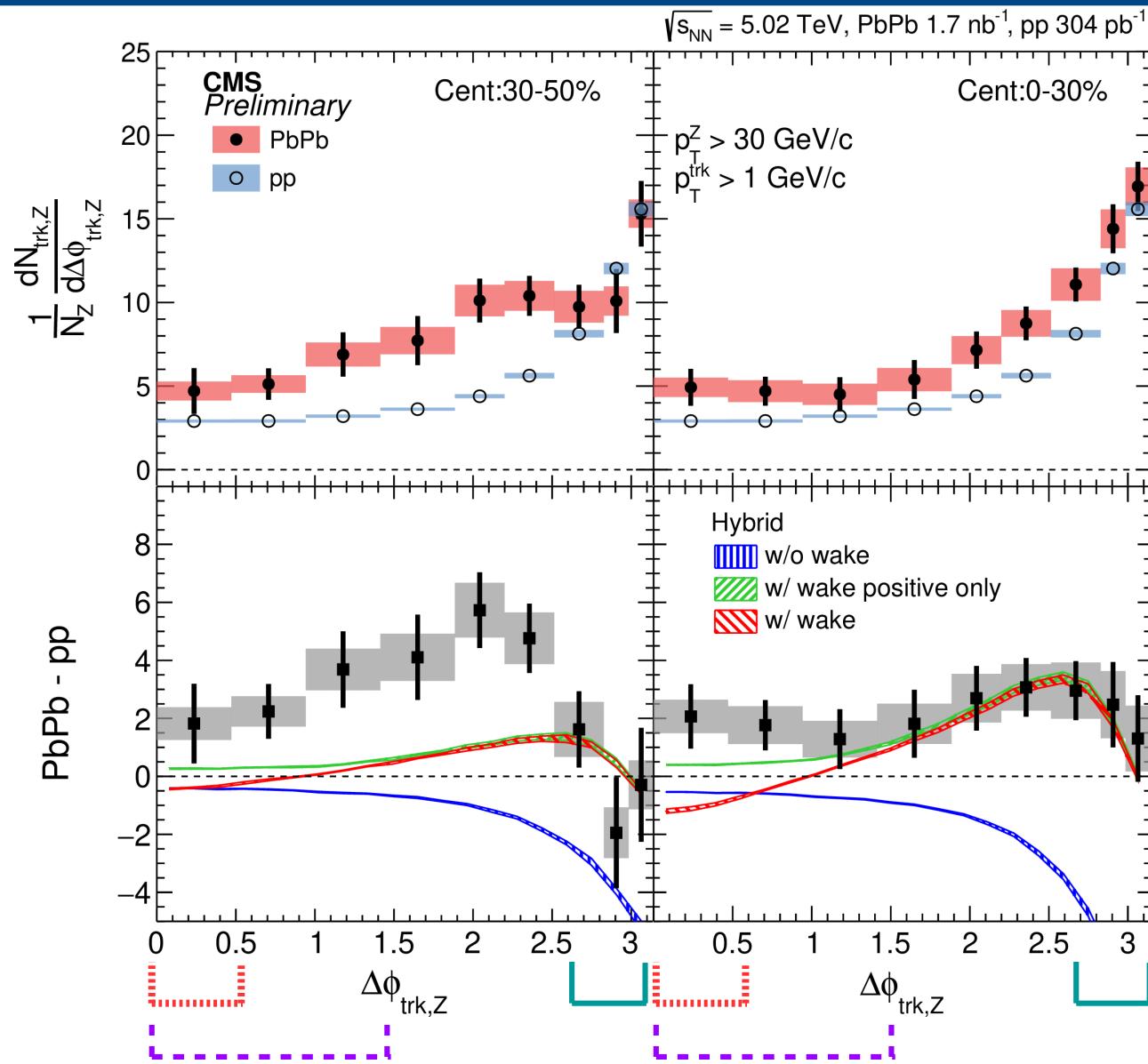


The **g=2.0** describes data better than other **scet<sub>G</sub>** curves

**Hybrid** with medium response **included** captures enhancement at low- $p_{\text{T}} \sim 1 \text{ GeV}$   
undershoots intermediate- $p_{\text{T}} \sim 3-5 \text{ GeV}$

# $\Delta\phi_{\text{trk},Z}$ vs theory

CMS-PAS-HIN-19-006

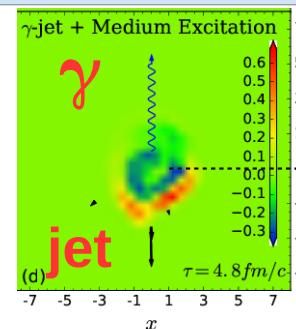


$\Delta\phi_{\text{trk},Z} \sim \pi$  trend similar when **including** medium response

$\Delta\phi_{\text{trk},Z} < \pi/2$  underestimated

Full wake negative at  $\Delta\phi_{\text{trk},Z} \sim 0$  (w/ diffusion)

PLB 777 (2018) 86



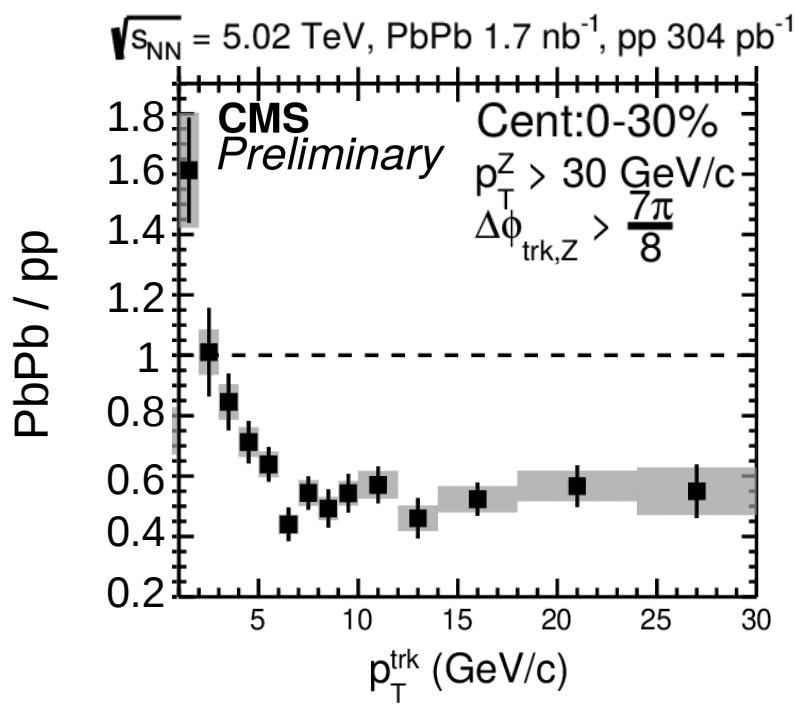
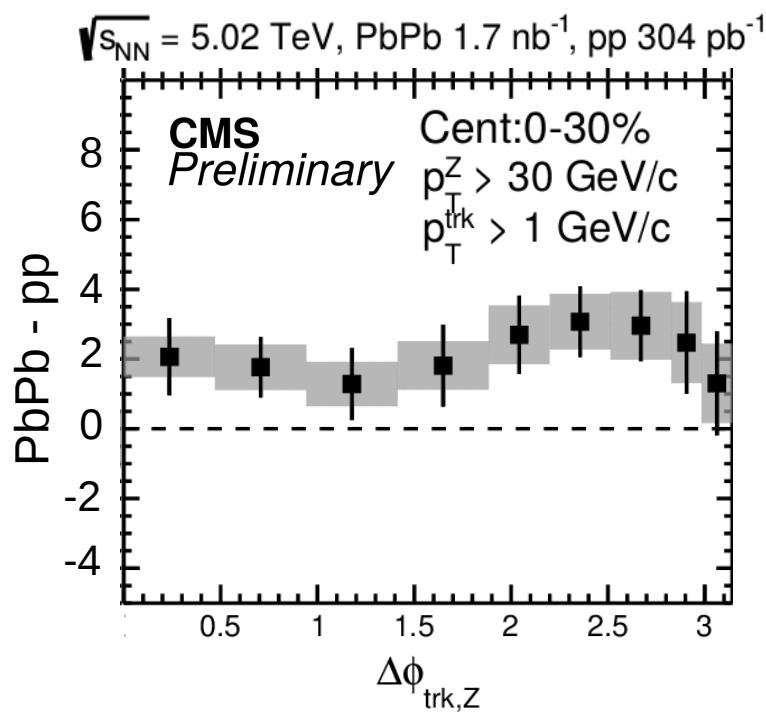
Medium response treatment may be too simple

Improvements presented in J. Casalderrey-Solana's talk

# Summary

CMS-PAS-HIN-19-006

- Parton-medium studies expanded to large angles using Z+hadron correlations
- First hint of particle excess across the azimuthal space up to  $\Delta\phi_{\text{trk},Z} = 0$
- Excess (depletion) of low (high) energy particles in the parton shower
- Unique input for microscopic understanding of QCD medium dynamics

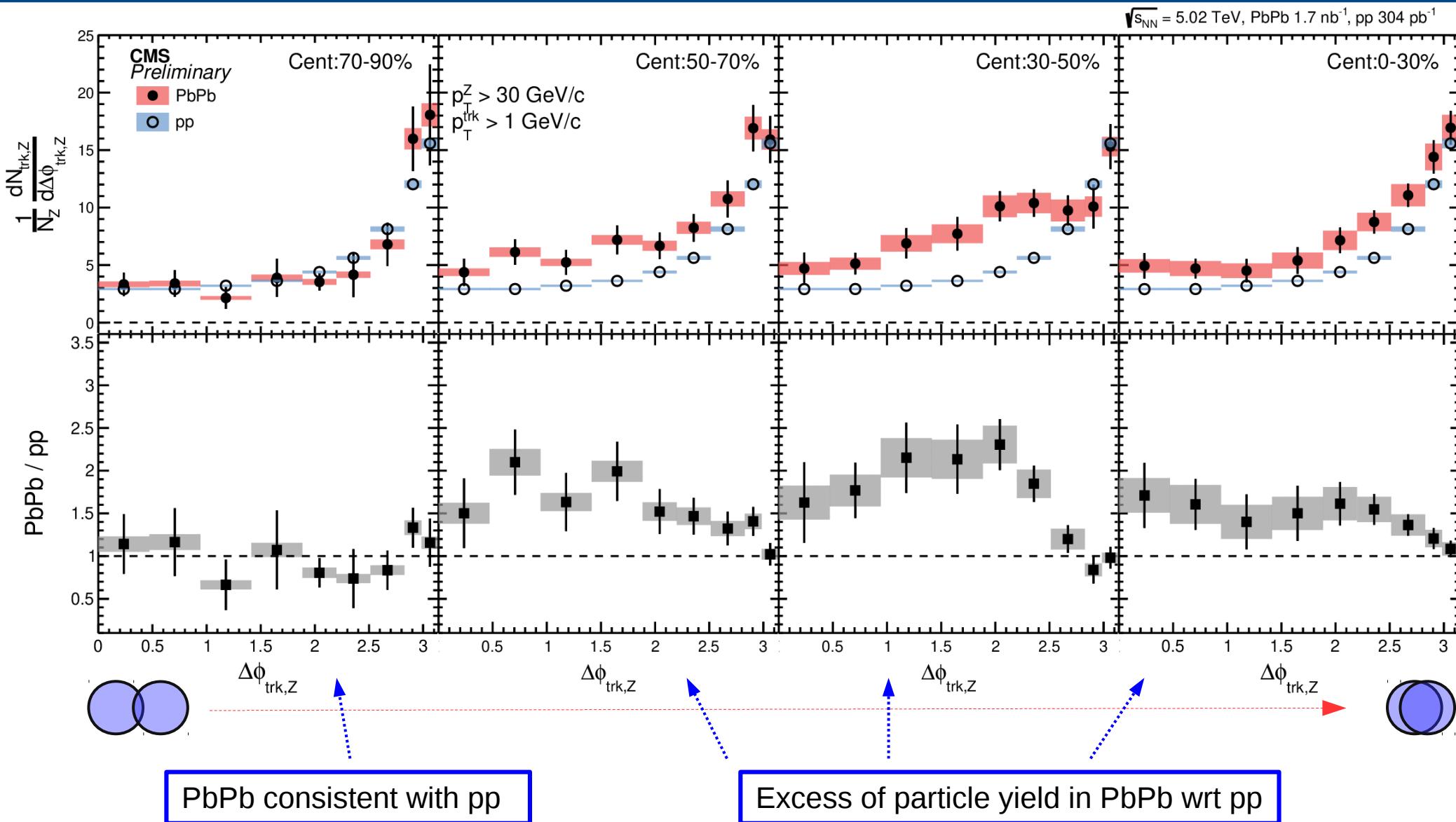


**Acknowledgements :** The MIT group's work was supported by US DOE-NP.

# BACKUP

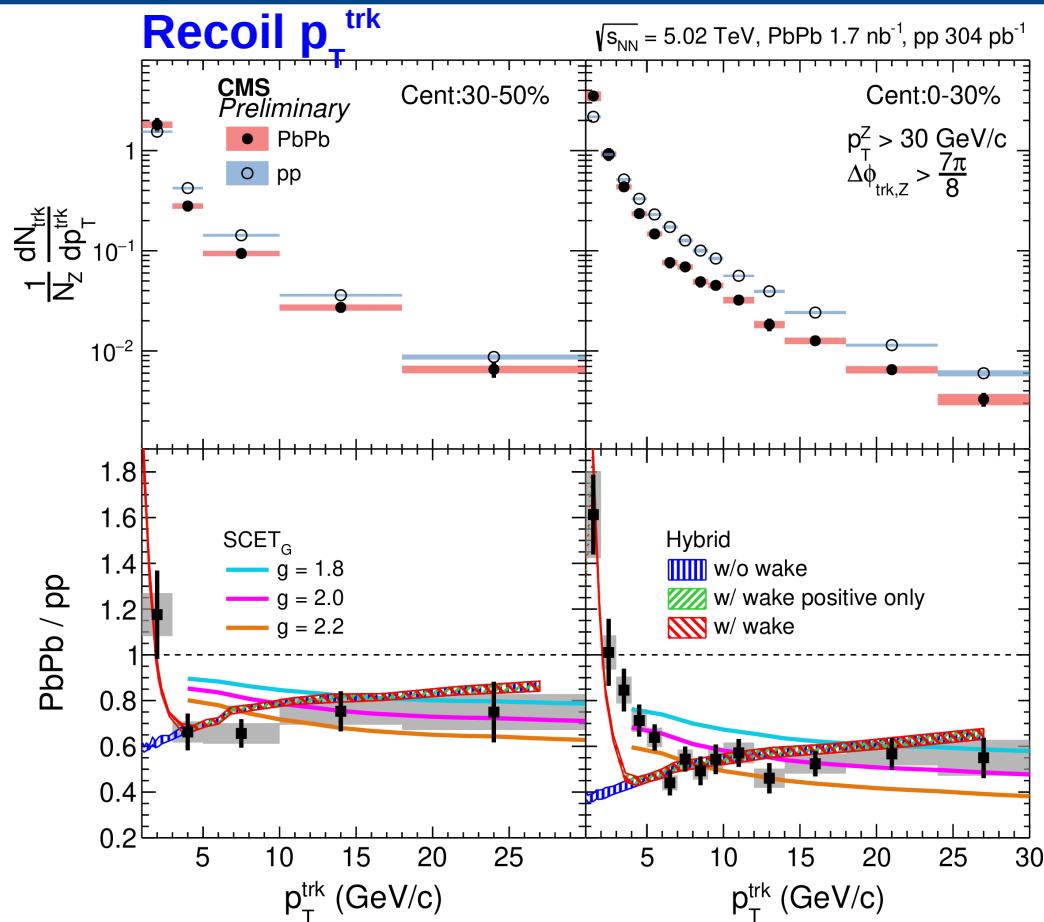
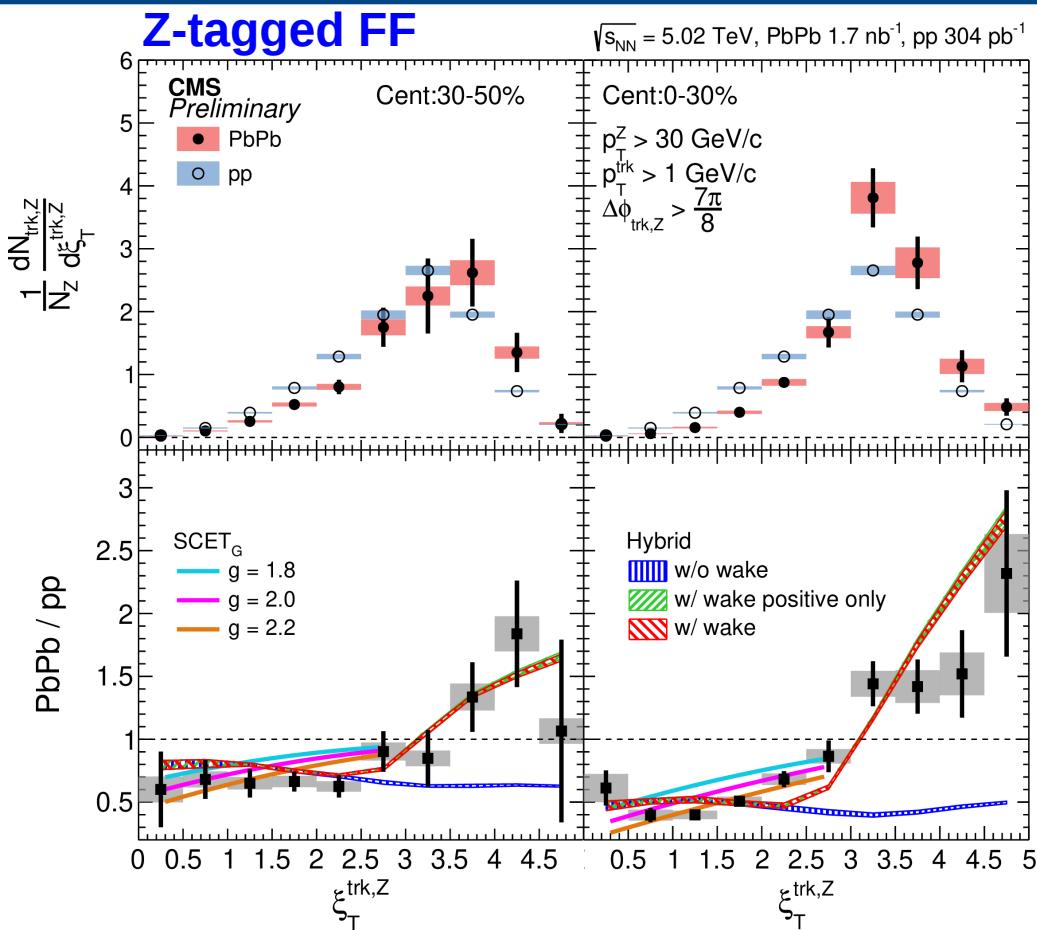
# Results : $\Delta\phi_{\text{trk},Z}$ ratio

CMS-PAS-HIN-19-006



# FF and $p_T^{\text{trk}}$ vs theory - I

CMS-PAS-HIN-19-006



**SCET<sub>G</sub>** includes Glabuer gluons into soft-collinear effective theory.  
**g** : parton-medium coupling strength

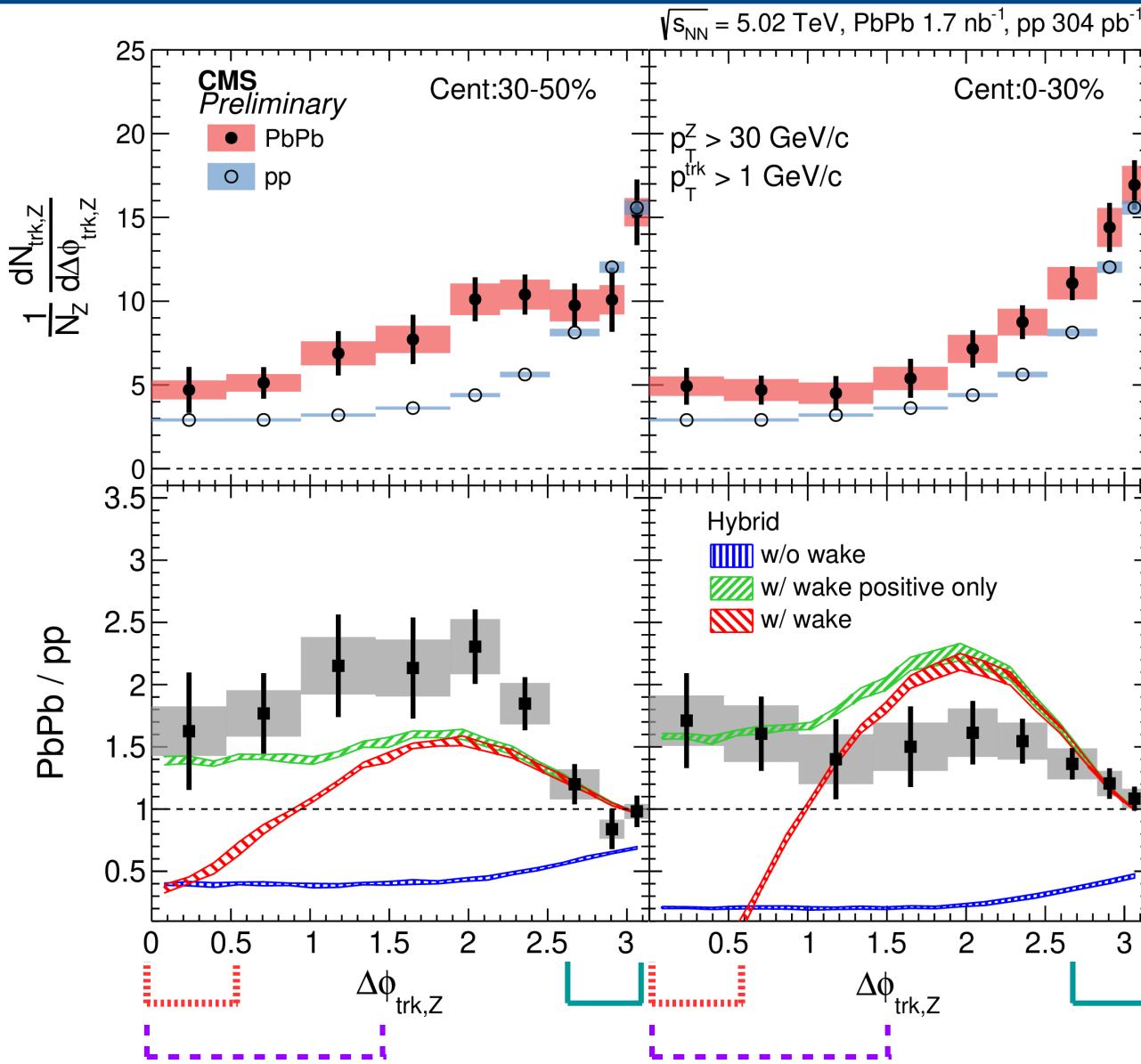
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**wl (w/o) wake** : do (do not) include medium response

Weak (high- $Q^2$ ) via pQCD  
 Strong (low- $Q^2$ ) via gauge/gravity

# $\Delta\phi_{\text{trk},Z}$ vs theory

CMS-PAS-HIN-19-006



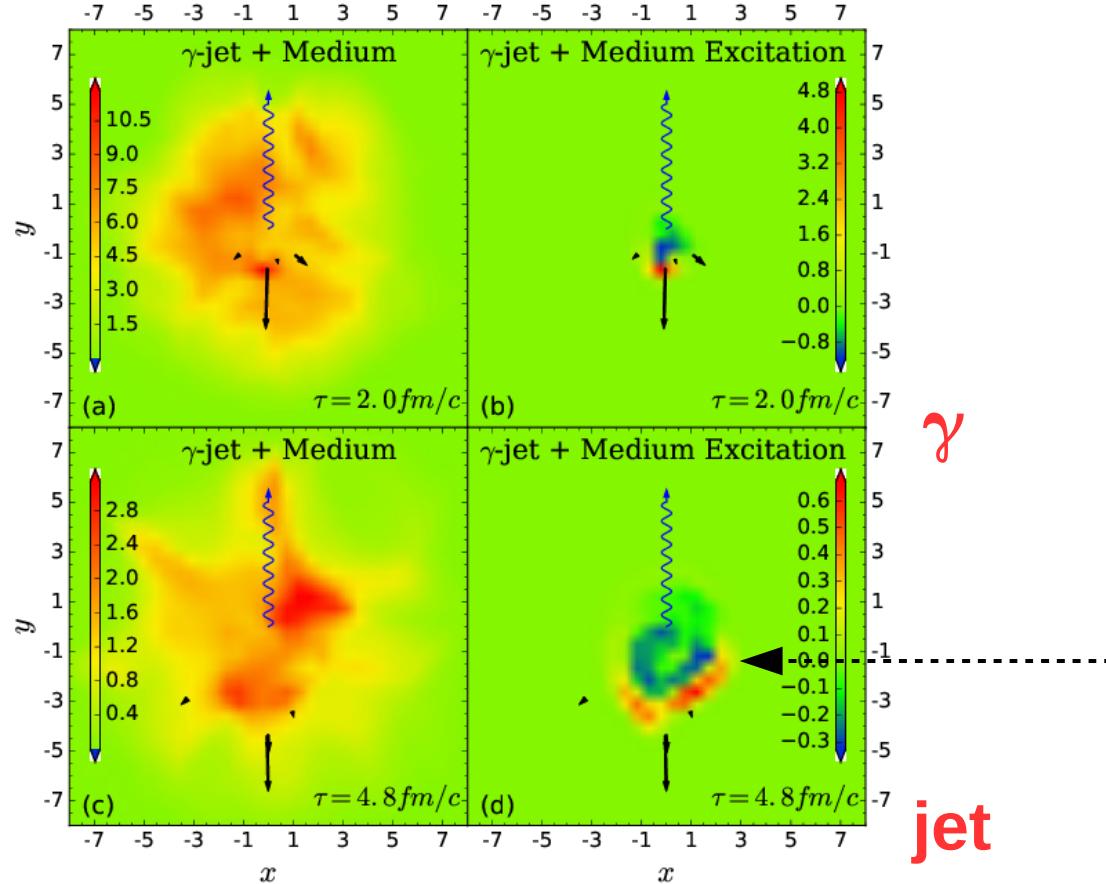
$\Delta\phi_{\text{trk},Z} \sim \pi$  trend similar when  
**including** medium response

$\Delta\phi_{\text{trk},Z} < \pi/2$  underestimated

Full wake < 1 at  $\Delta\phi_{\text{trk},Z} \sim 0$

# Diffusion Wake

PLB 777 (2018) 86

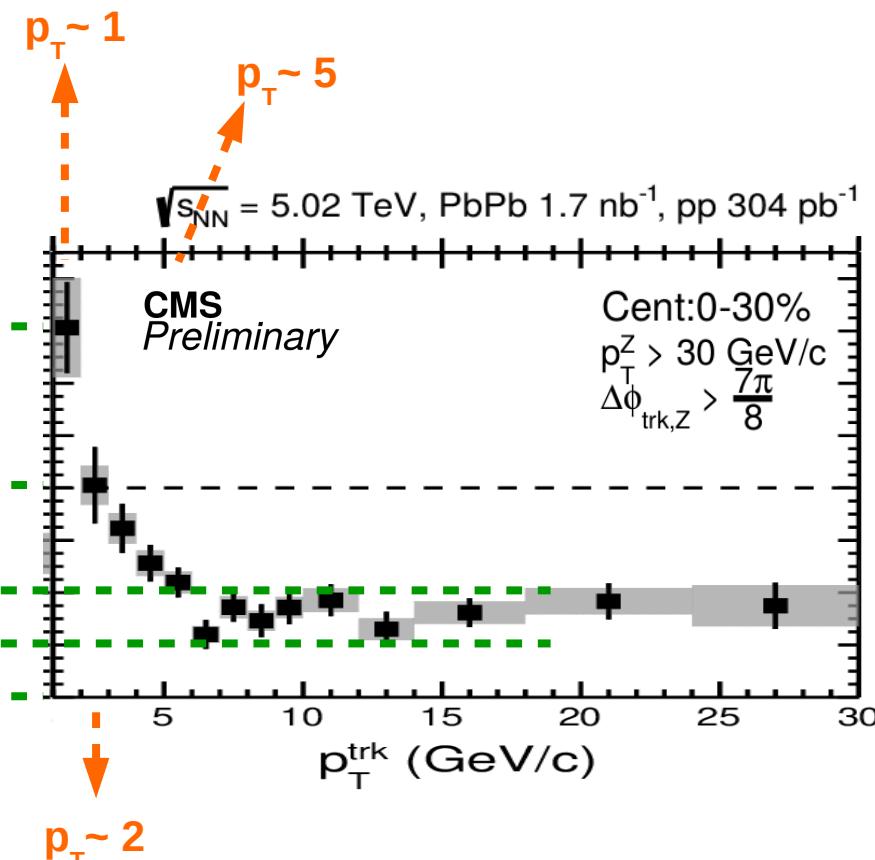
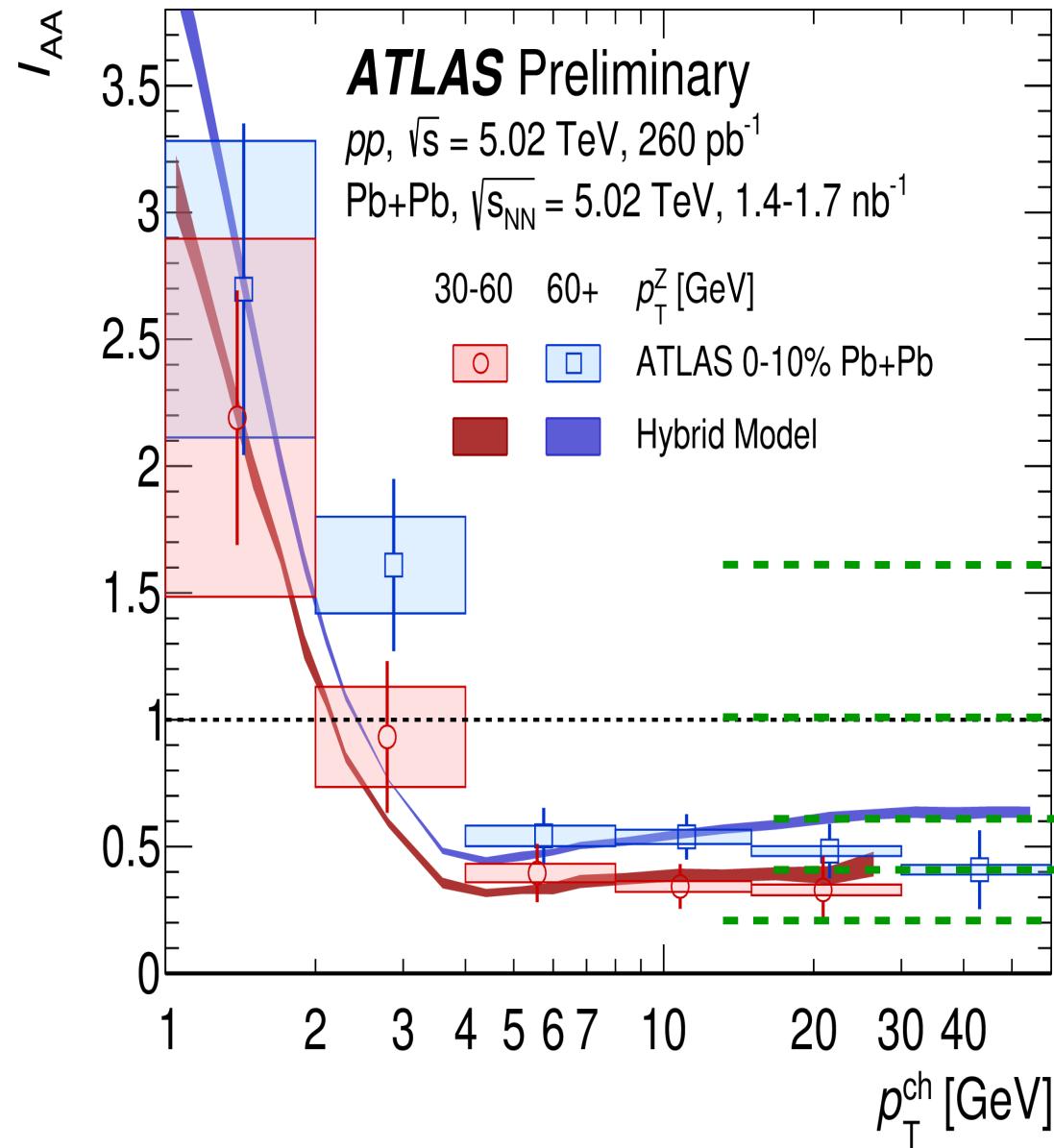


Medium-parton interactions  
“Mach-cone like”  
→  
diffusion wake behind the jet

# Z+hadron Atlas vs CMS

ATLAS-CONF-2019-052

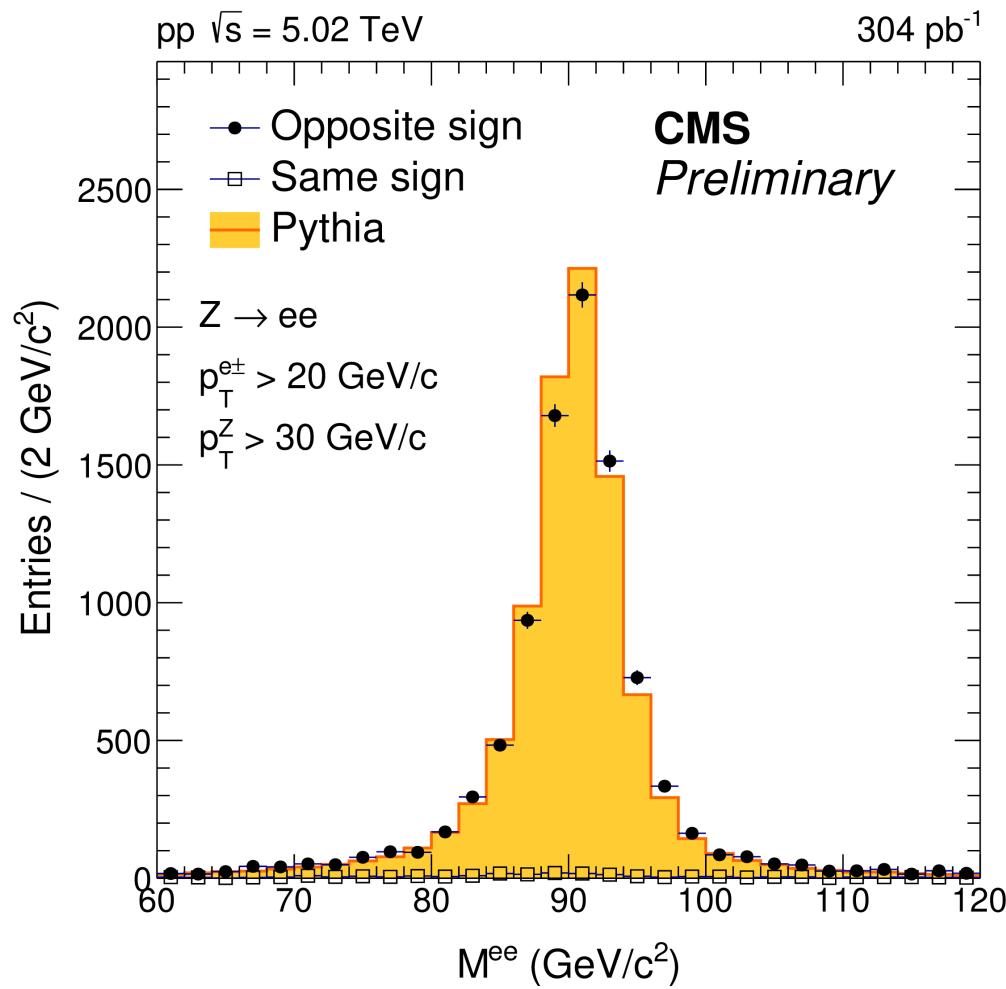
CMS-PAS-HIN-19-006



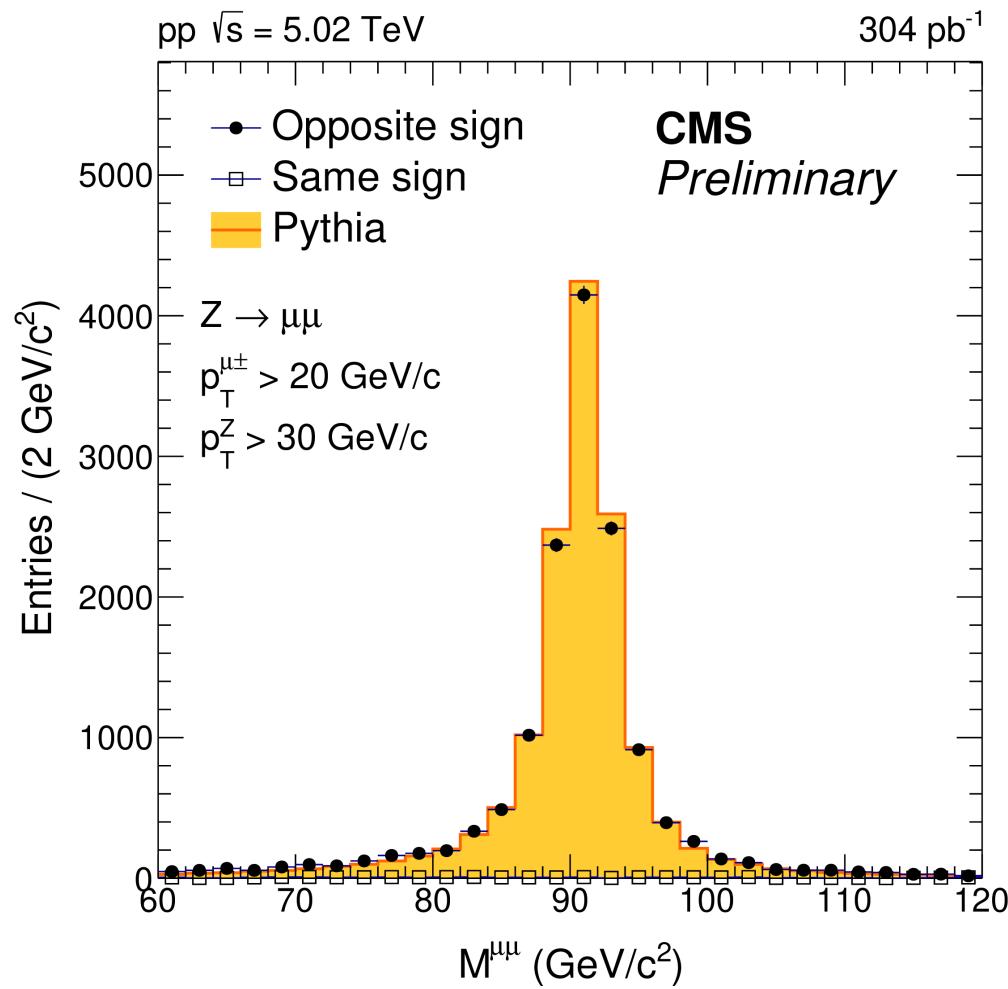
# Z boson reconstruction - pp

CMS-PAS-HIN-19-006

Electron pairs



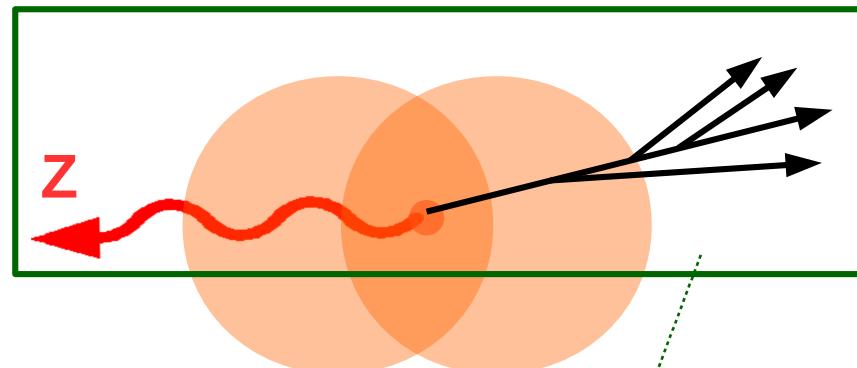
Muon pairs



~ 23500 Z candidate events

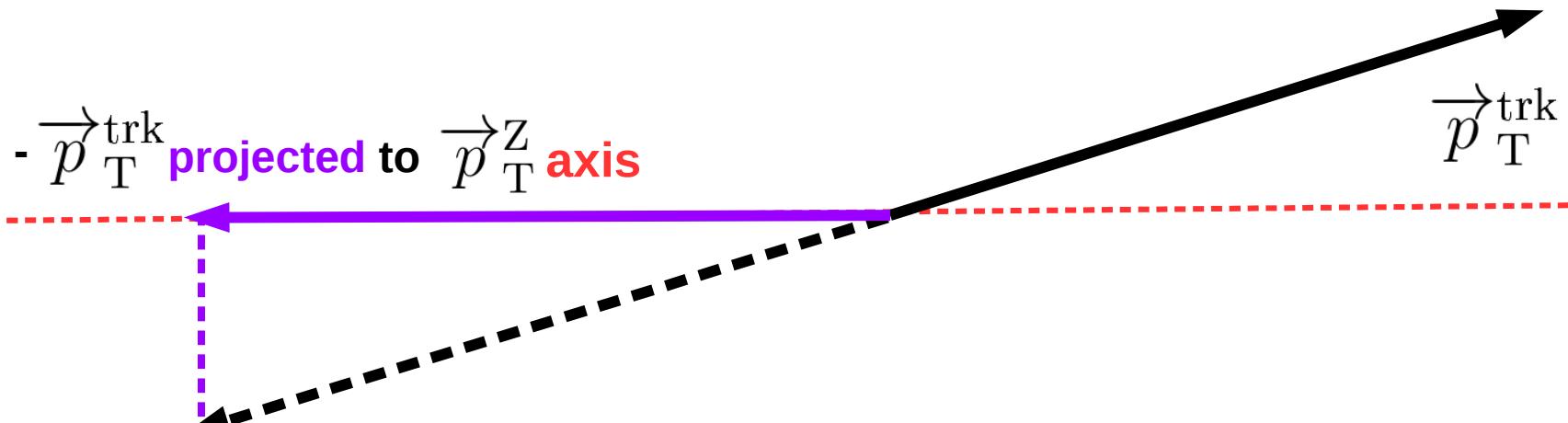
# Observable : $\xi_T^{\text{trk},Z}$

- Take tracks (charged particles) recoiling from the Z
- Construct transverse momentum vectors for track and Z
- Invert the **track** transverse momentum, **project** to the axis of **Z boson** momentum.
- Natural log of the momentum ratio is  $\xi_T^{\text{trk},Z}$ .



$$\xi_T^{\text{trk},Z} = \ln \frac{-|\vec{p}_T^Z|^2}{\vec{p}_T^{\text{trk}} \cdot \vec{p}_T^Z}$$

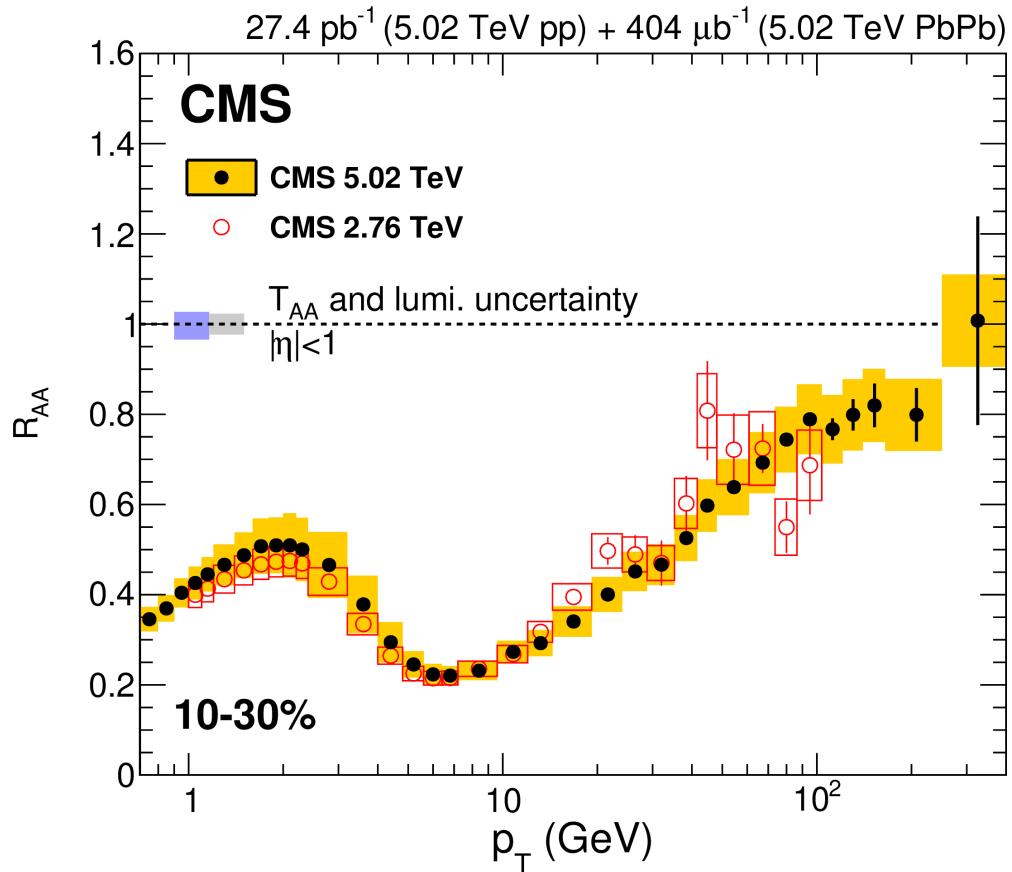
$\vec{p}_T^Z$  : transverse momentum vector of the Z boson  
 $\vec{p}_T^{\text{trk}}$  : transverse momentum vector of the track



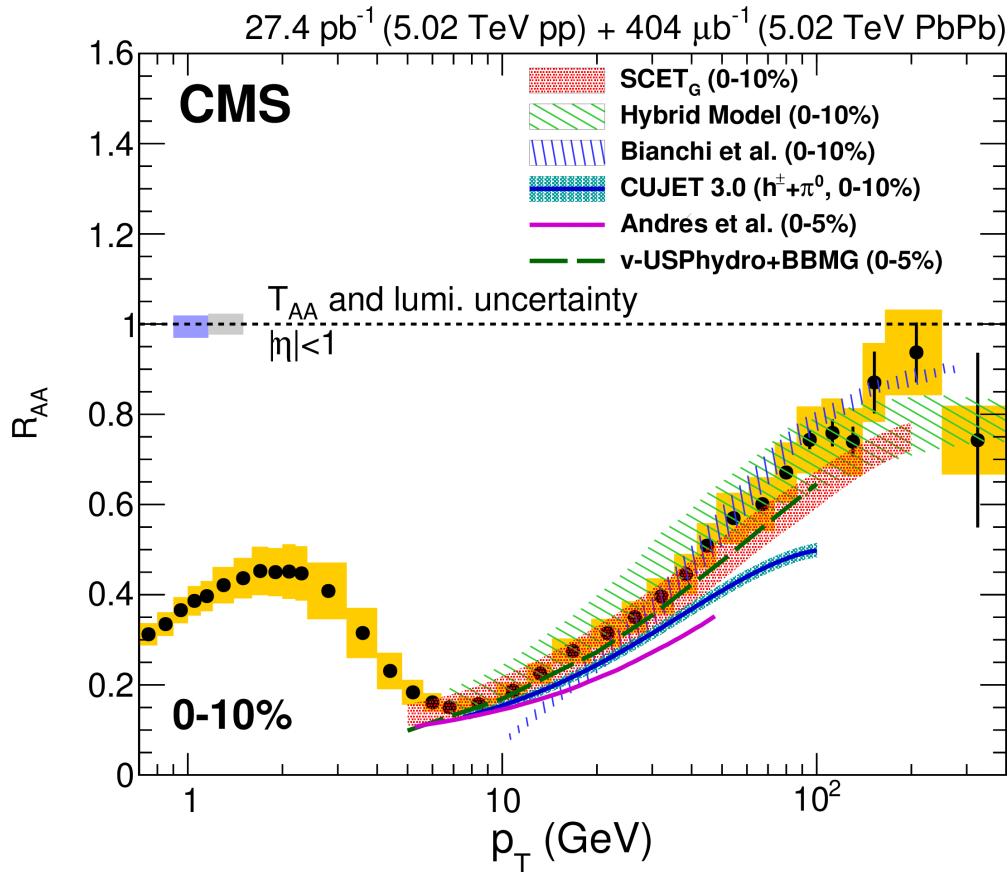
# Ch hadron RAA - I

JHEP 04 (2017) 039

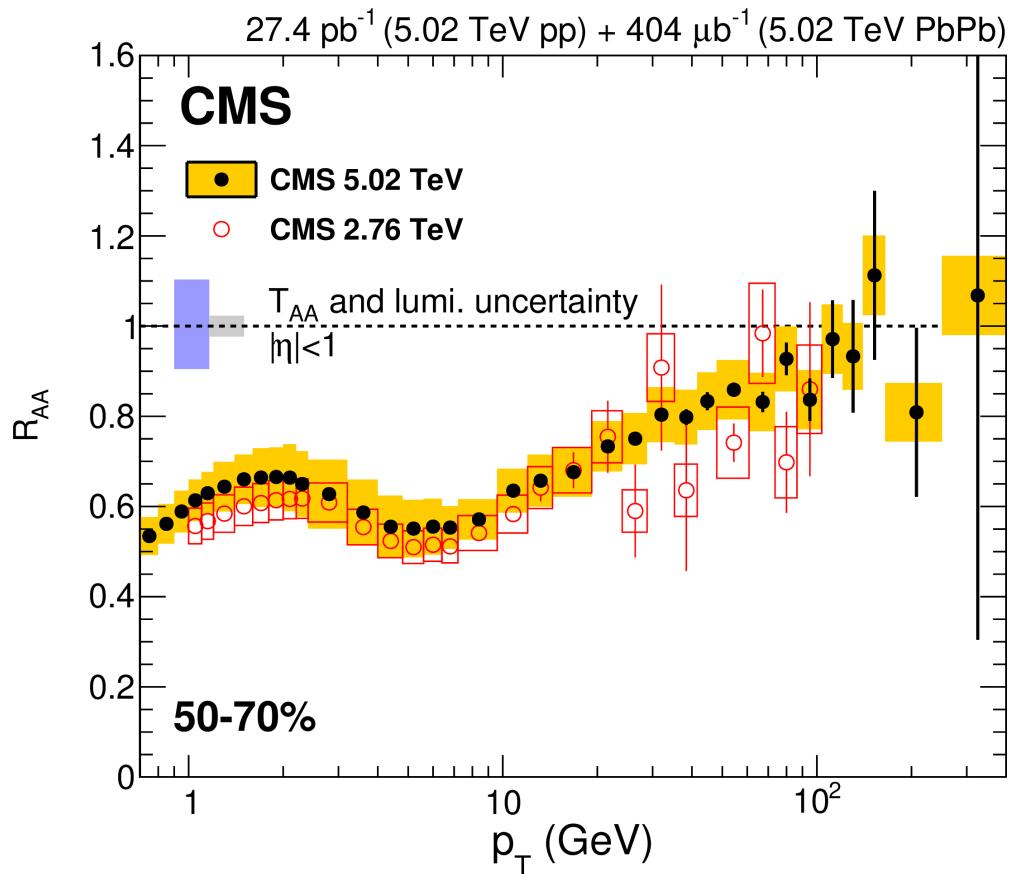
Cent:10-30%



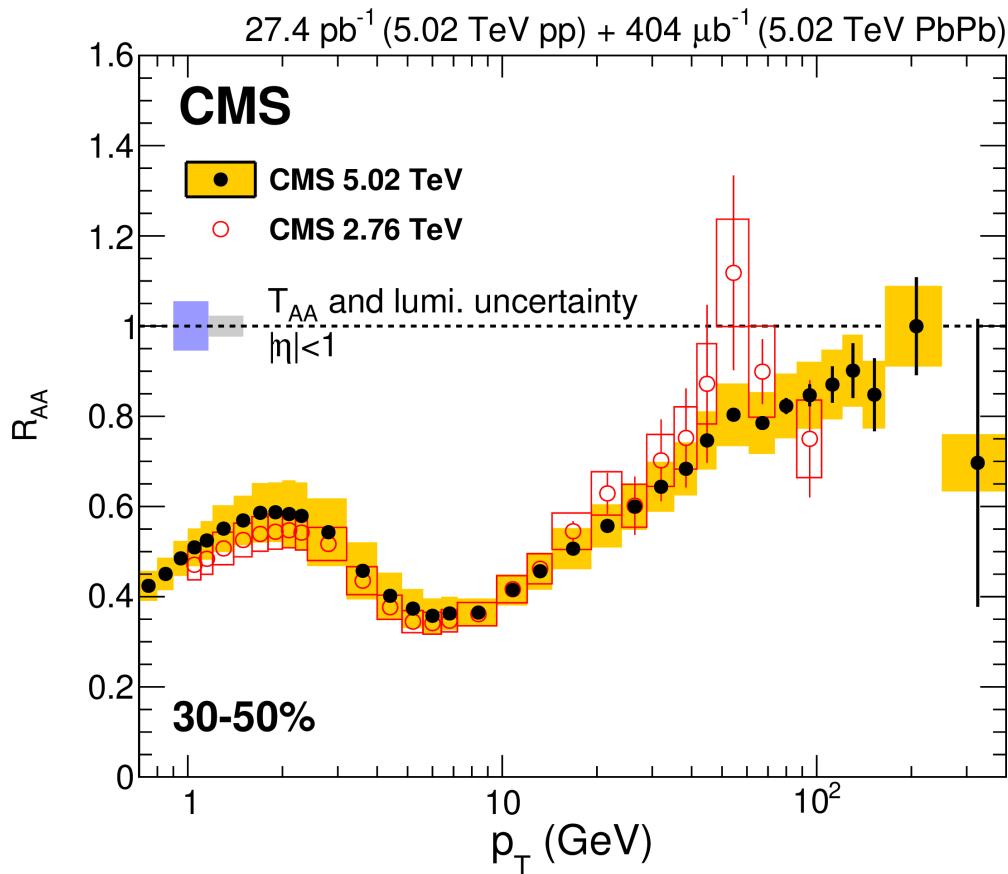
Cent:0-10%



Cent:50-70%



Cent:30-50%



# Ch hadron RAA - III

JHEP 04 (2017) 039

Cent:70-90%

