High p_T flow and jet quenching at CMS

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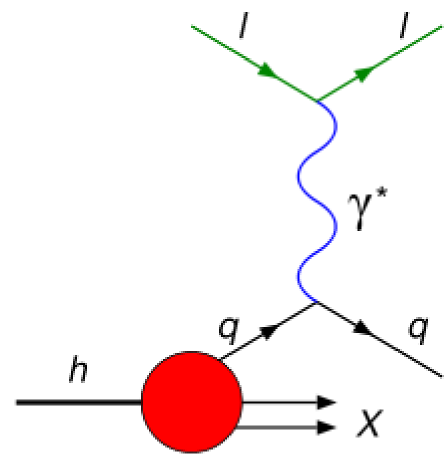
Inha University, Incheon, Korea

Overview

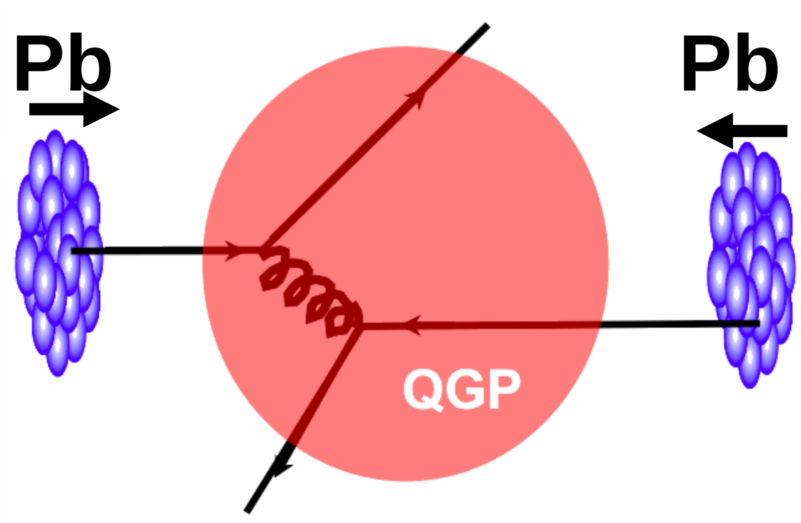
- Motivation of Probing QGP by high energy partons
- Reconstruction of particles, jets and photons in CMS
- Analysis and results
  - Hard probe scale 1 :   100 - 300GeV ➔ Di-jet counting
  - Hard probe scale 2 :   60 - 100GeV ➔ Gamma-jet counting
  - Hard probe scale 3 :   10 - 60GeV ➔ Particle correlation
- Summary

Probing QGP with a high energy parton

- Study of QED using Deep inelastic scattering using a charged particle as a probe
- Analogy for a QCD system
  - Charge :
    - QCD (EM) ➔ QCD (color)
  - Probe :
    - Electron ➔ Parton (q,g)
  - Observable
    - Modification of momentum of probe



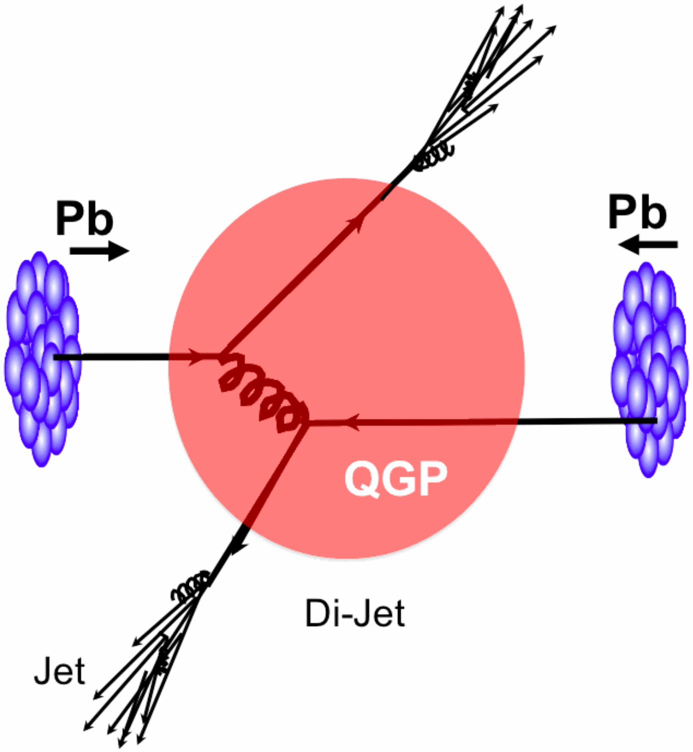
Probe from outside



Probes from inside

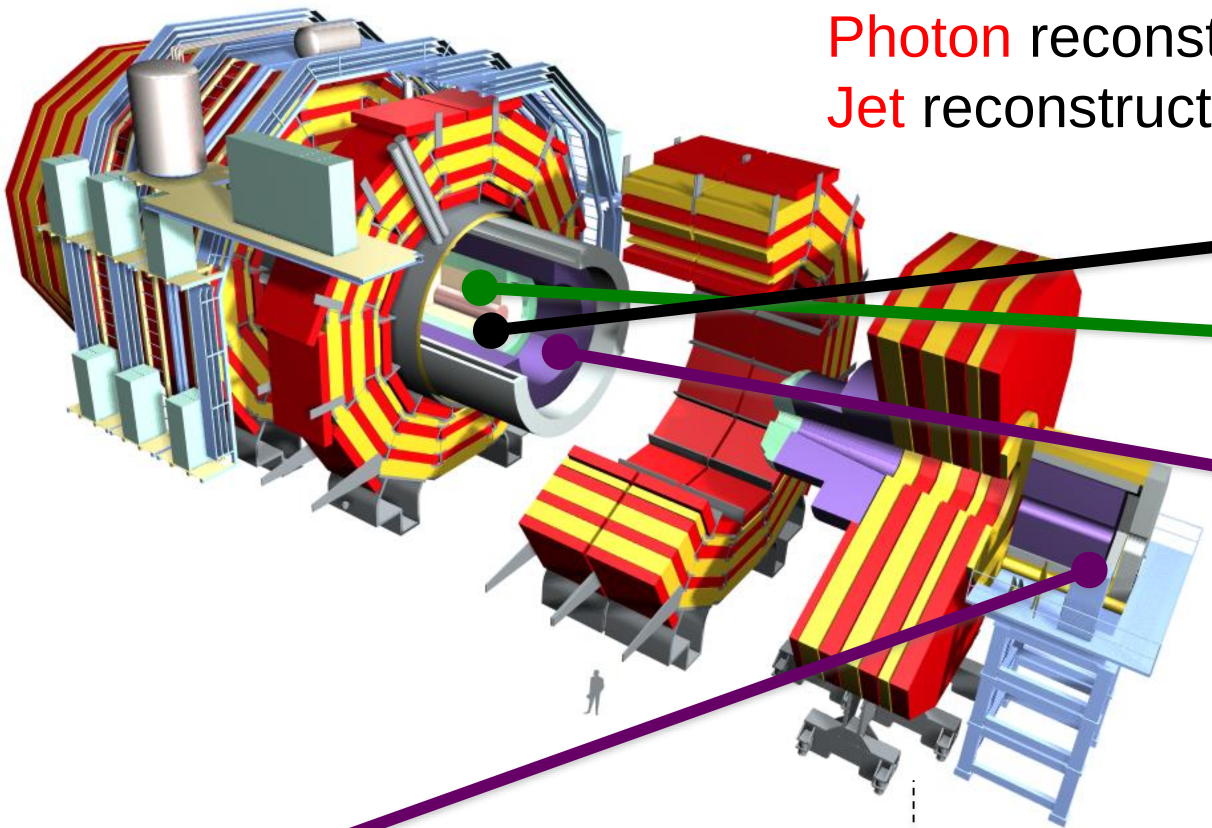
But, we can not directly measure partons

- Problem : Quarks and gluons can not be detected in isolated state
- Solution : Jet
  - Indirect measurement of partons
  - Bunch of fragmentation of high energy partons
  - SNOWMASS accords, including Collinear, infrared safety.
- High p_T hadrons
  - Most of them are from jet fragmentation
  - Indirect probe for quenching



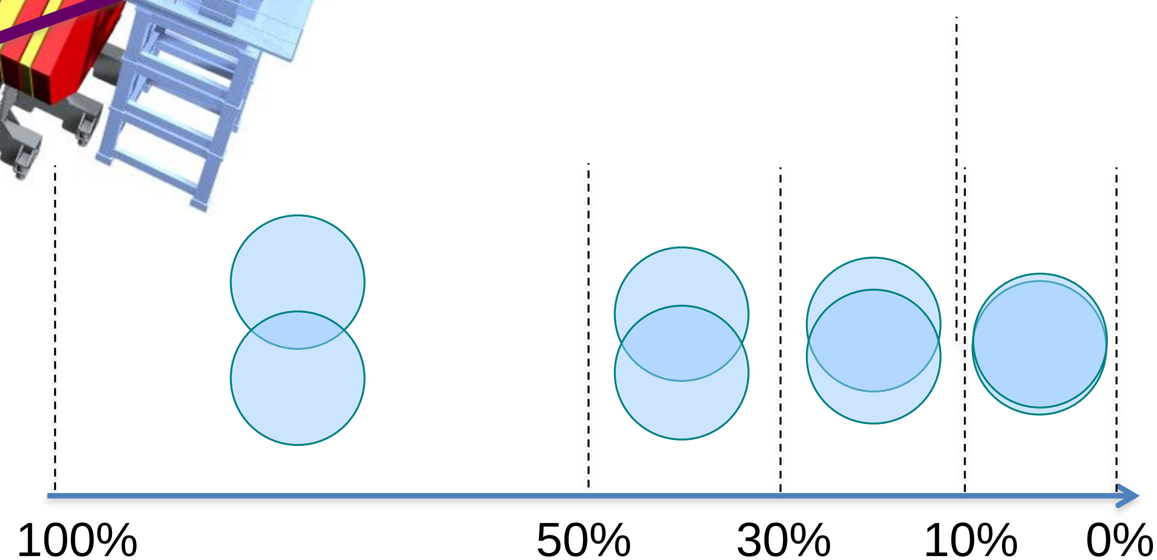
CMS Detector

Charged particles reconstructed by tracker
Photon reconstructed by Ecal
Jet reconstructed by tracker + Ecal + Hcal



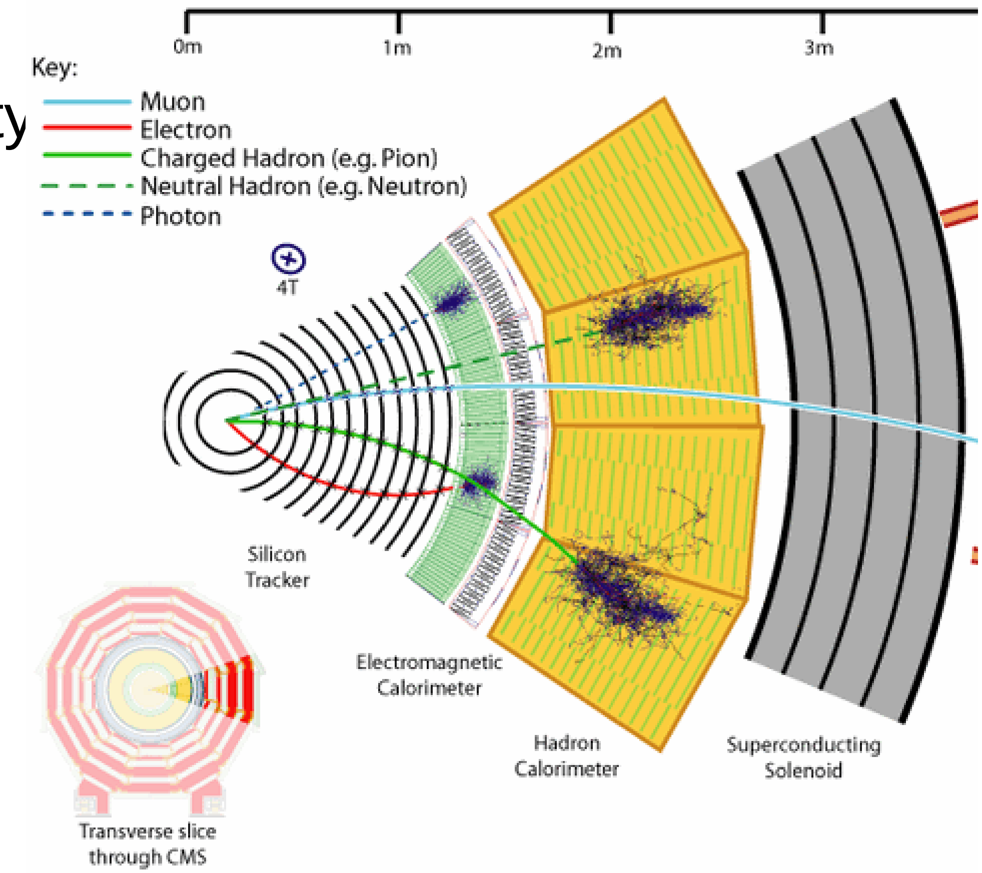
Determines

Impact parameter



Reconstruction of hadrons in CMS

- Individual objects sorted into 3 classes
  - Particle Flow in CMS terminoloty
- Charged particles
  - Silicon Tracker
  - Nice momentum resolution
    - < 2% for 100GeV
- Neutral hadrons
  - Energy in Calorimenter but no tracks
- Photons (neutral meason)
  - Energy concetrated in ECAL

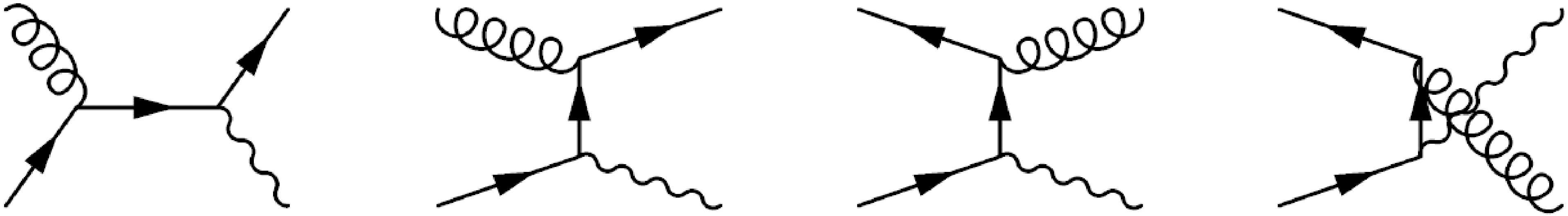


Reconstruction of Jet in CMS

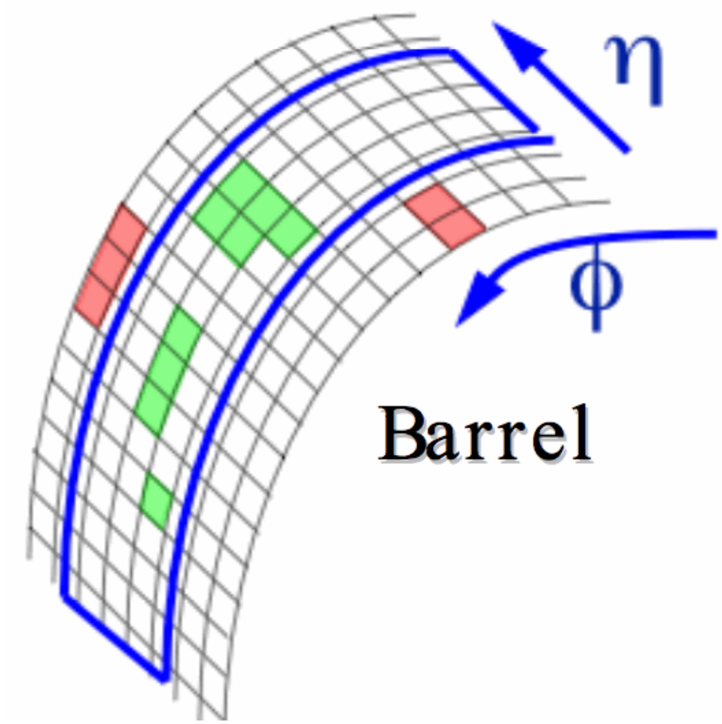
JHEP 0804 (2008) 063

- Anti-kt jet algorithm
  - A sequential clustering algorithm, but shaped in a circular cone
  - Infrared- & Collinear- safe (by construction)
  - Only single parameter. R = Jet Resolution (or radius)
  - Known to be favored by theorists (P. Schieferdeckers in lecture)
- Particle flow objects are uses as the ingredients
- Background subtraction algorithm for PbPb and pPb
  - To subtract the energy piled up from underlying events
  - UE subtracted tower-by-tower (size = 0.087 x 0.087) before jet clustering
- In CMS heavy ion group, R = 0.3 (relatively small) is used to reduce the fluctuation of underlying events

Reconstruction of isolated photon in CMS



- Isolated photons comes from hard scattering.
  - Not decayed from neutral meson
  - Not thermal photon
- Superclustering algorithm in CMS
  - Find the EM shower and recover the bremsstrahlung energy
- In pp, energy resolution < 1% for photon p_T > 100GeV



Analysis/results

- Jets in 100GeV < p_T < 300GeV
  - Correlation of Di-jet events
- Charged particles in O(1) GeV < p_T < 60GeV
  - Correlation of particles
- Jets around 50 GeV
  - Gamma-jet correlation

Correlation of di-jets

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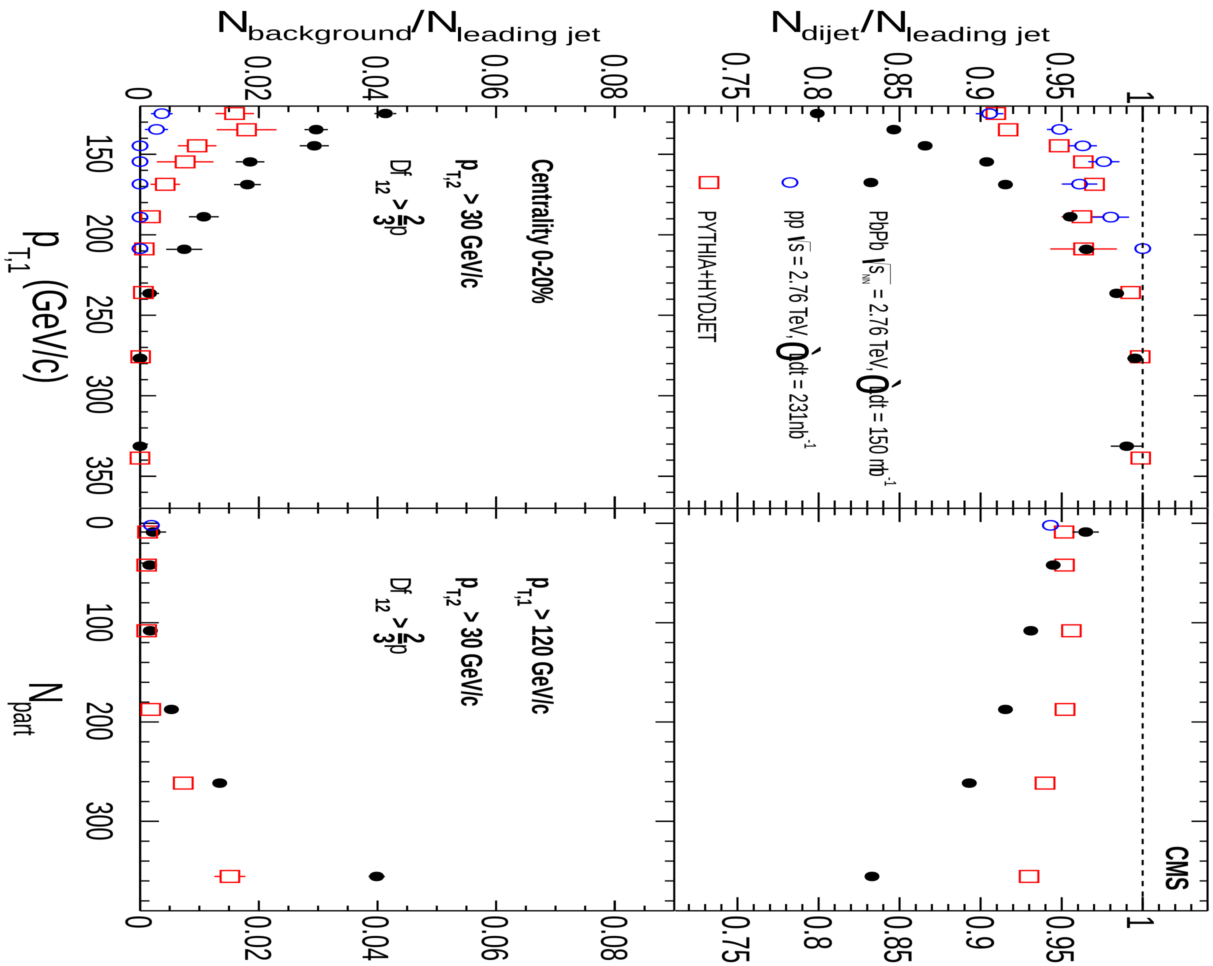

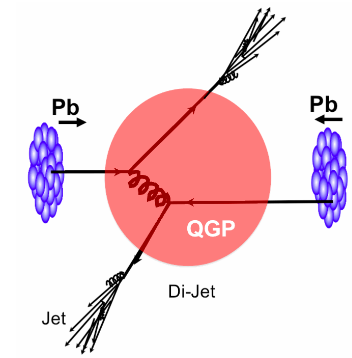

Increase of mono-jet events in central collisions compared to pp, while the angular correlation is consistent with pp

Leading jet p_T > 100GeV
Sub-leading jet p_T > 30GeV
$\Delta\Phi > 2\pi/3$

Correlation of di-jets : Momentum ratio

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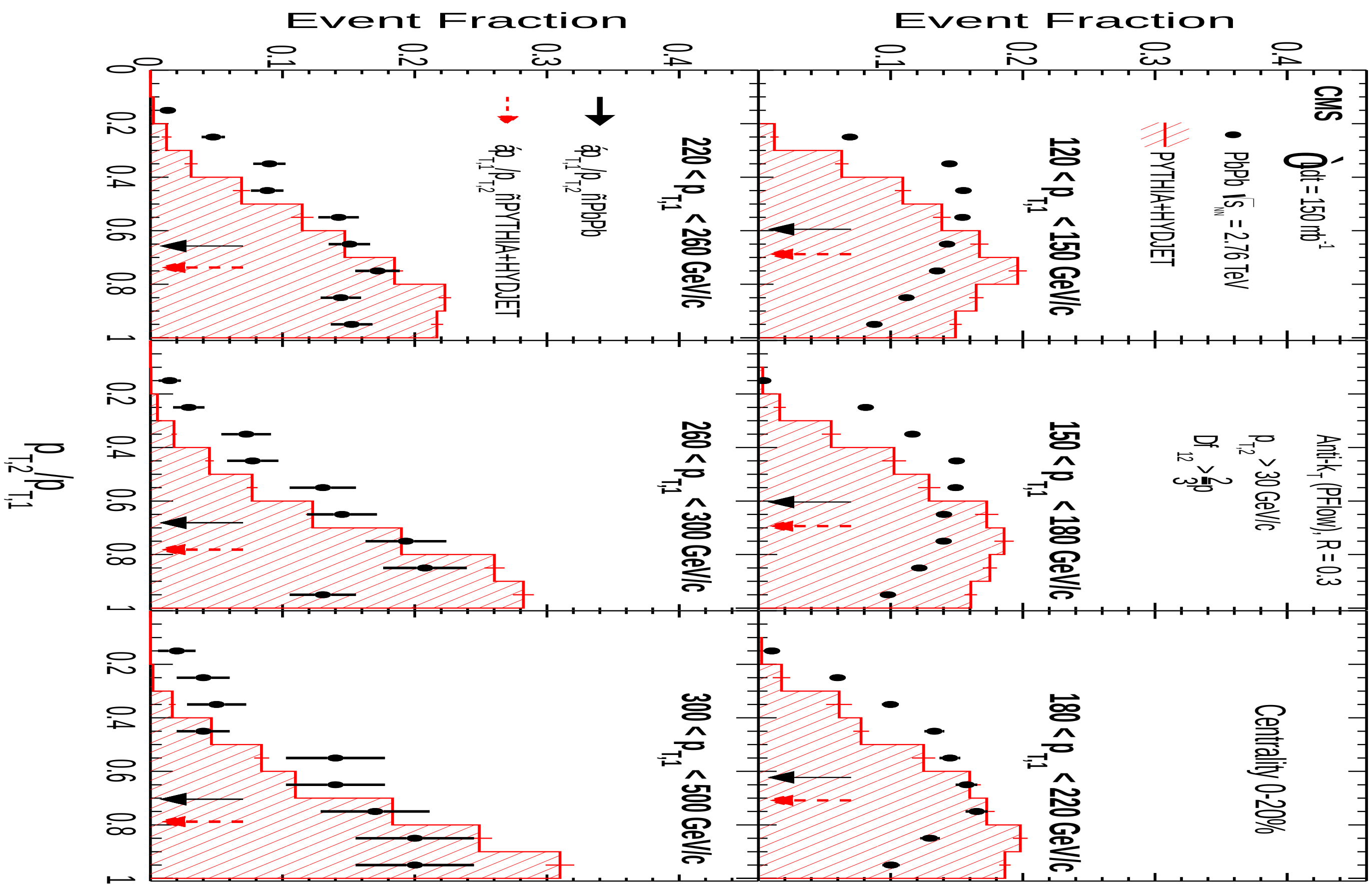

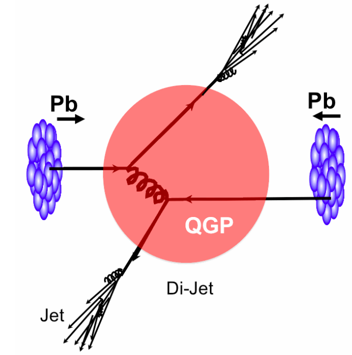

- Asymmetry of p_T^1/p_T^2 gradually increases by collision centrality

Momentum correlation of di-jets

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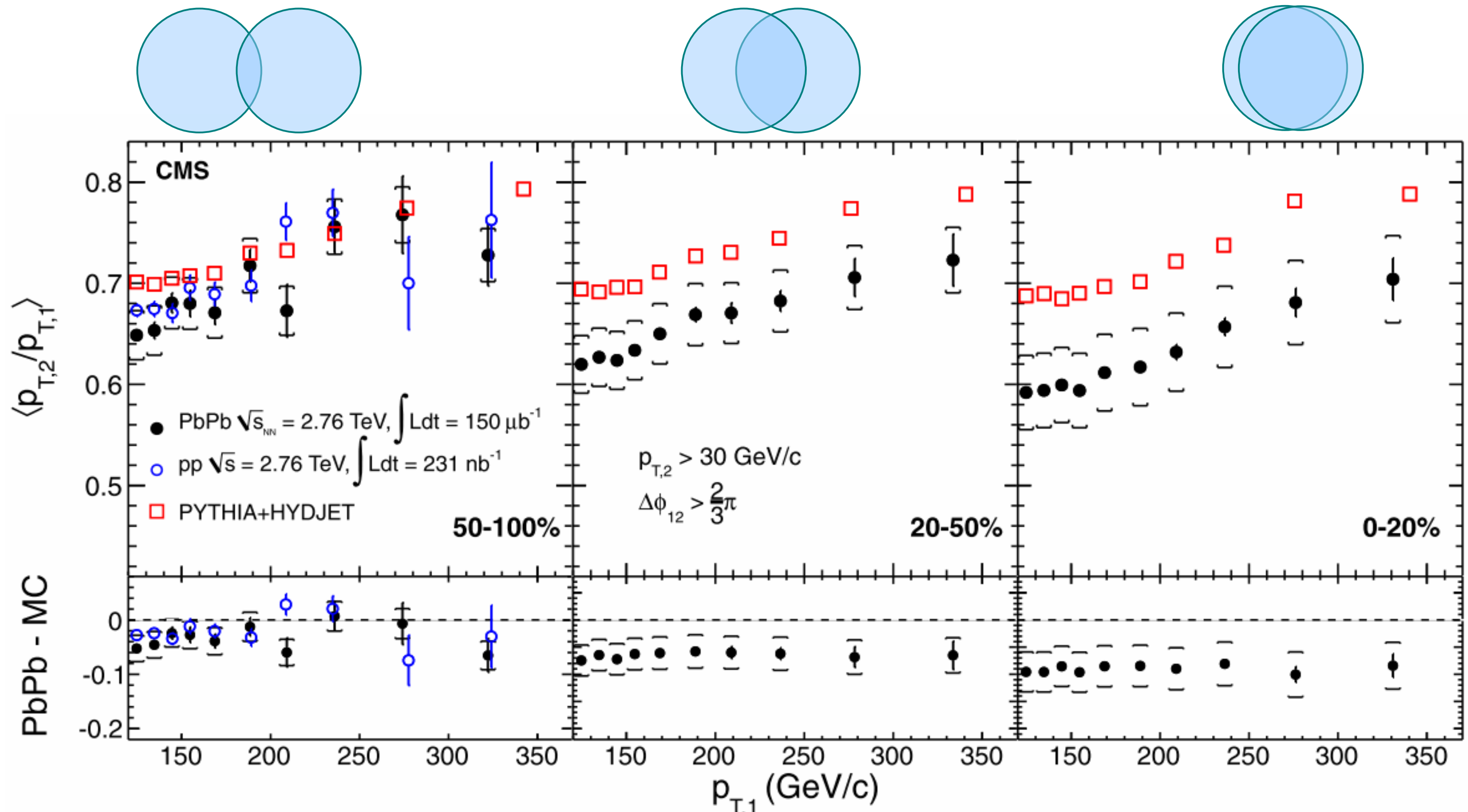
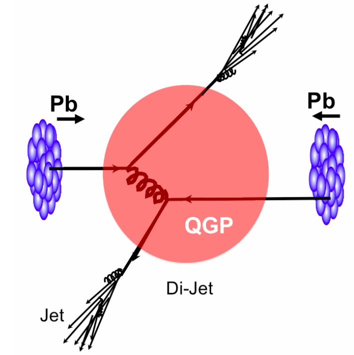




Compared with (Unquenched) PYTHIA embedded in HYDJET (uncerlying events) simulation to exclude detector bias and generic asymmetry from initial state in pp(or pn, nn) collision.

DATA – MC of the ratio was flat as a function of $p_T^{leading}$

Jet fragmentation

Jet fragmentation
- Energy fraction and momentum direction of each hadrons in the jet

Gluon radiation by QGP modifies the virtuality of parton can modify the Fragmentation pattern

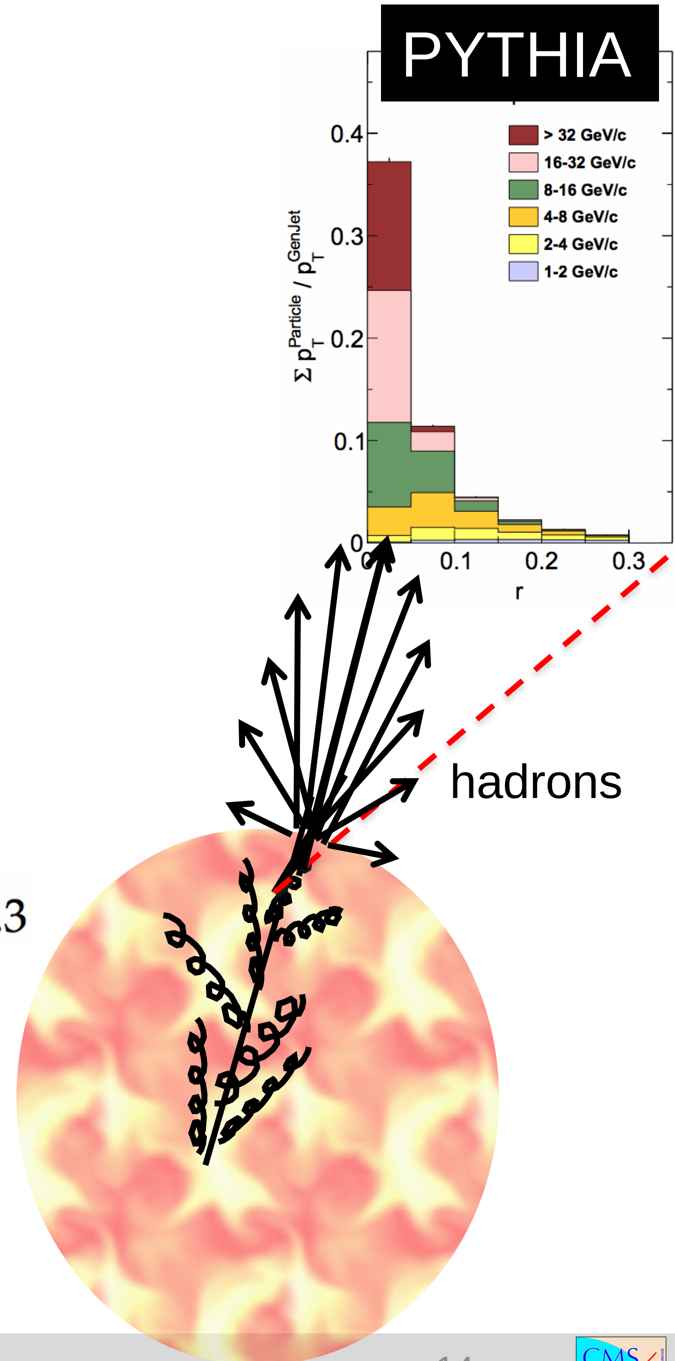
CMS measured the inclusive jets above 100TeV in PbPb and compared with pp

Observable 1 : Fragmentation function

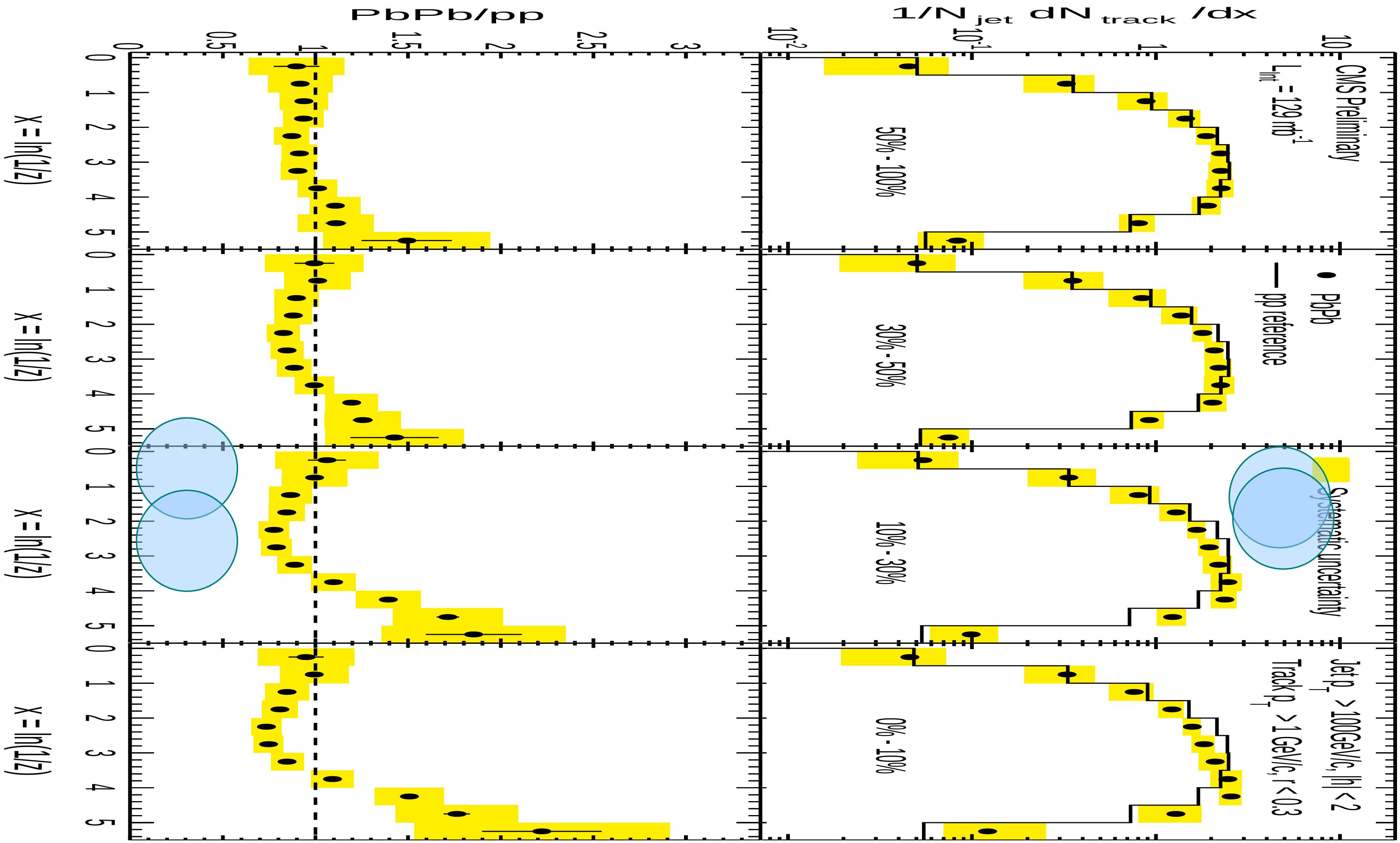
$$\xi = \ln \frac{1}{z}; \quad z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}, \quad \text{in a cone of } \Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.3$$

Observable 2 : Jet shape   (arxiv:1310.0878)

$$\rho(r) = \frac{1}{\delta r} \frac{1}{N_{\text{jet}}} \sum_{\text{jets}} \frac{\sum_{r-\delta r/2}^{r+\delta r/2} p_{\text{T}}^{\text{track}}}{p_{\text{T}}^{\text{jet}}}$$



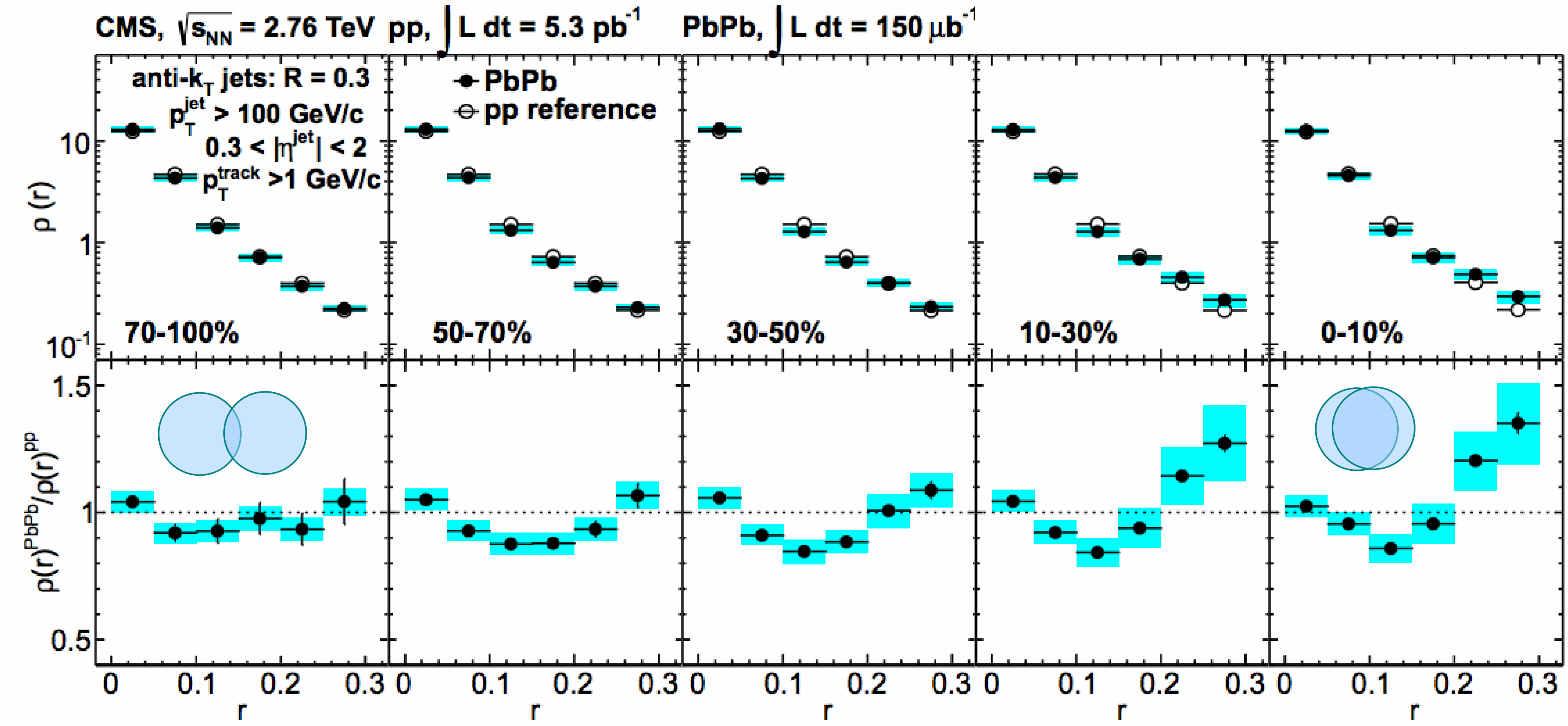
Modification of jet fragmentation -1



$$\xi = \ln\frac{1}{z}\ ;\quad z = \frac{p_{\parallel}^{track}}{p^{jet}},$$

Significant excess of low energy hadrons observed and the effect gradually increases in more central collisions.

Modification of jet fragmentation -2

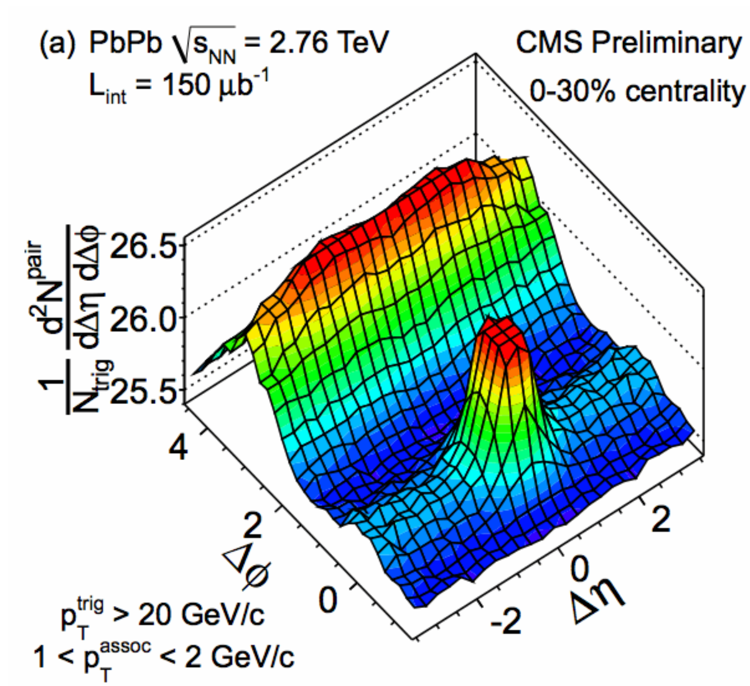


Re-distribution of jet energy observed.
Depletion of intermediate radii (0.1 < r < 0.2) and
Excess of distant fragmentation (r > 0.2)

Two Particle correlation

PRL 109 (2012) 022301

- In the traditional particle correlation, the low p_T particle correlation characterizes the collective particle dynamics
- In high p_T trigger particle correlation, jet plays the major role

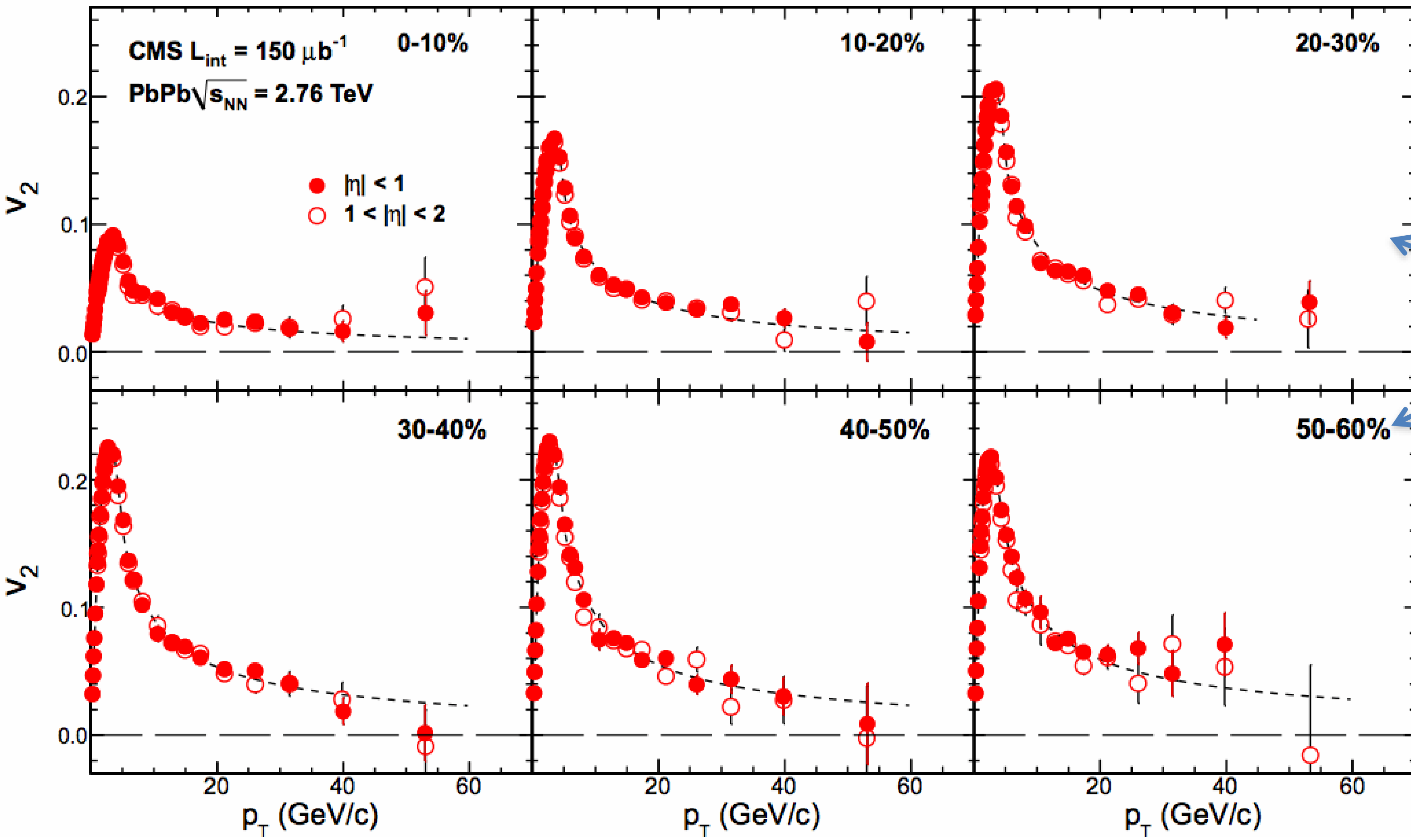


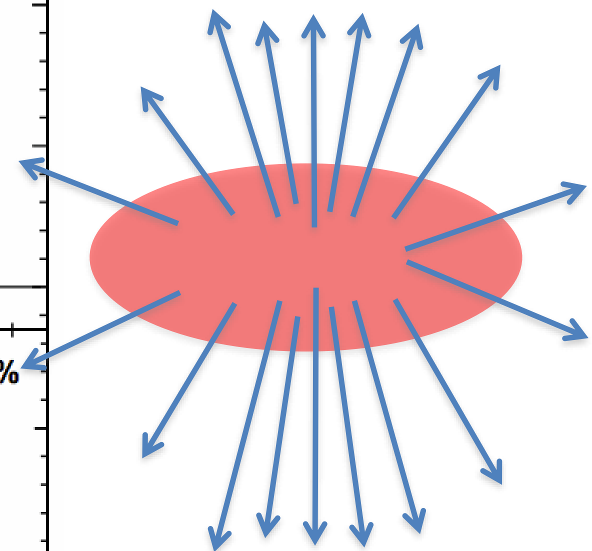
$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} = \frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}_{sub}}{d\Delta\phi} + a_0\left(1+2\sum_n v_n(p_{\rm T}^{\rm trig})v_n(p_{\rm T}^{\rm assoc})\cos(n\Delta\phi)\right)$$

Total | Jet | Anisotropy harmonics

Both Jet and harmonics delivers jet quenching message, but in different ways

1. Observation of anisotropy





- Event plane method using HF calorimeter
- Non-zero v_2 of High p_T particles (10 - 30GeV) implies the path length dependence of jet quenching

2. Extraction of jet-like 2 particle correlation

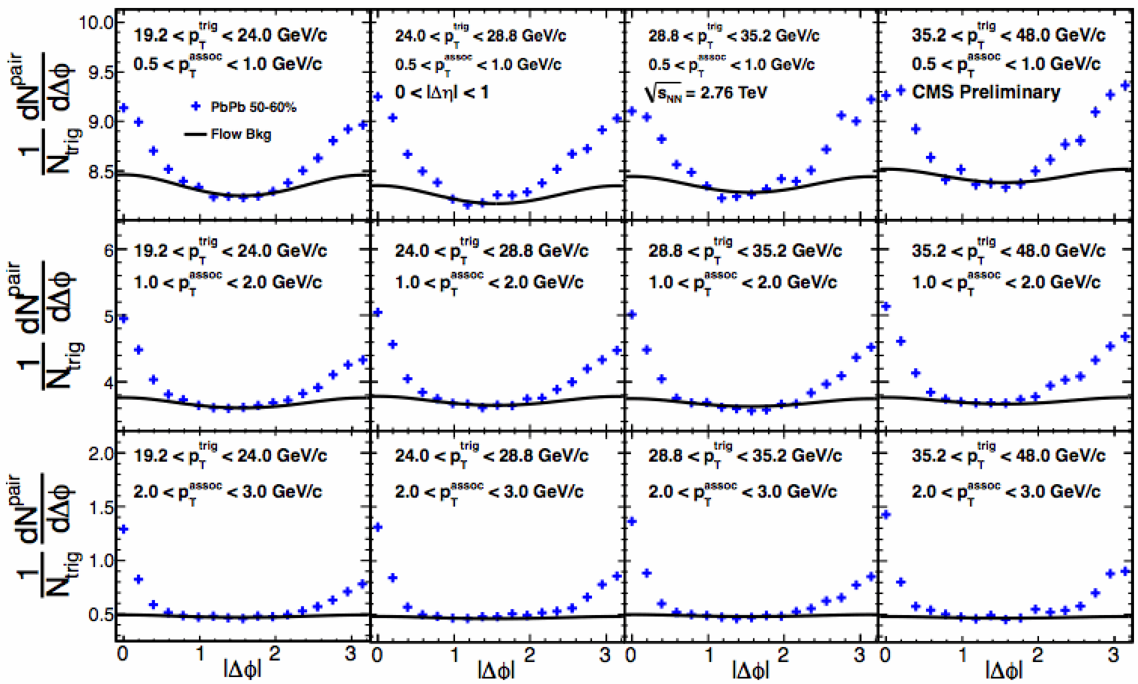
$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}_{sub}}{d\Delta\phi} = \frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} - a_0\left(1+2\sum_n v_n(p_{\rm T}^{\rm trig})v_n(p_{\rm T}^{\rm assoc})\cos(n\Delta\phi)\right)$$

Jet

Total

Anisotropy harmonics

- ZYAM procedure used to determine a_0 coefficient
  - Assumed Jet-like correlation is 0 around $\Delta\Phi = \pi/2$



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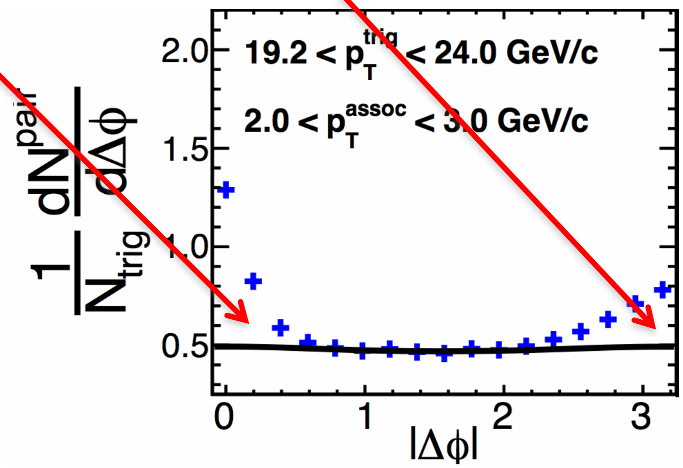
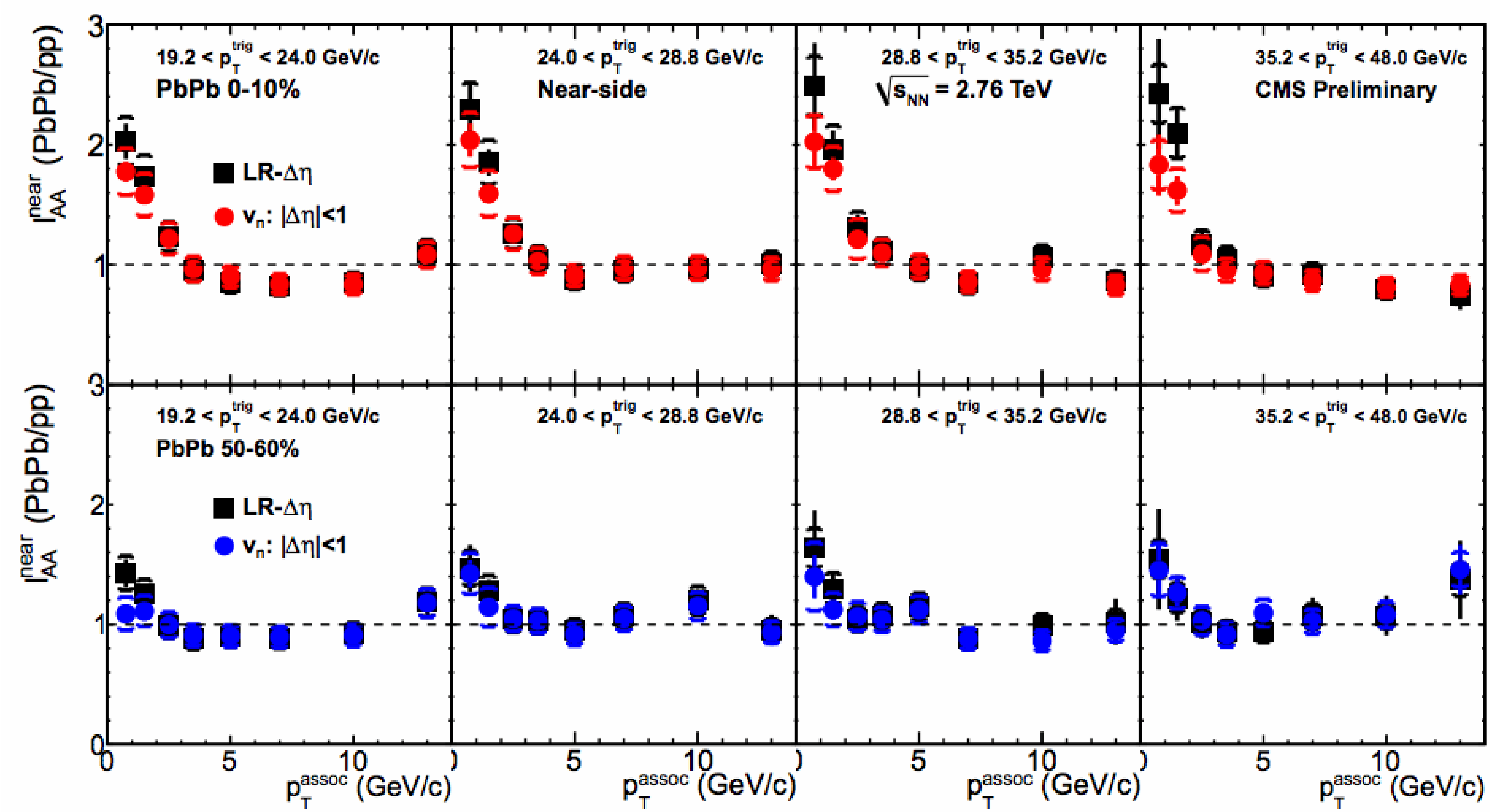
Jet | Total | Anisotropy harmonics

- Then integrated the yield in near side and away side



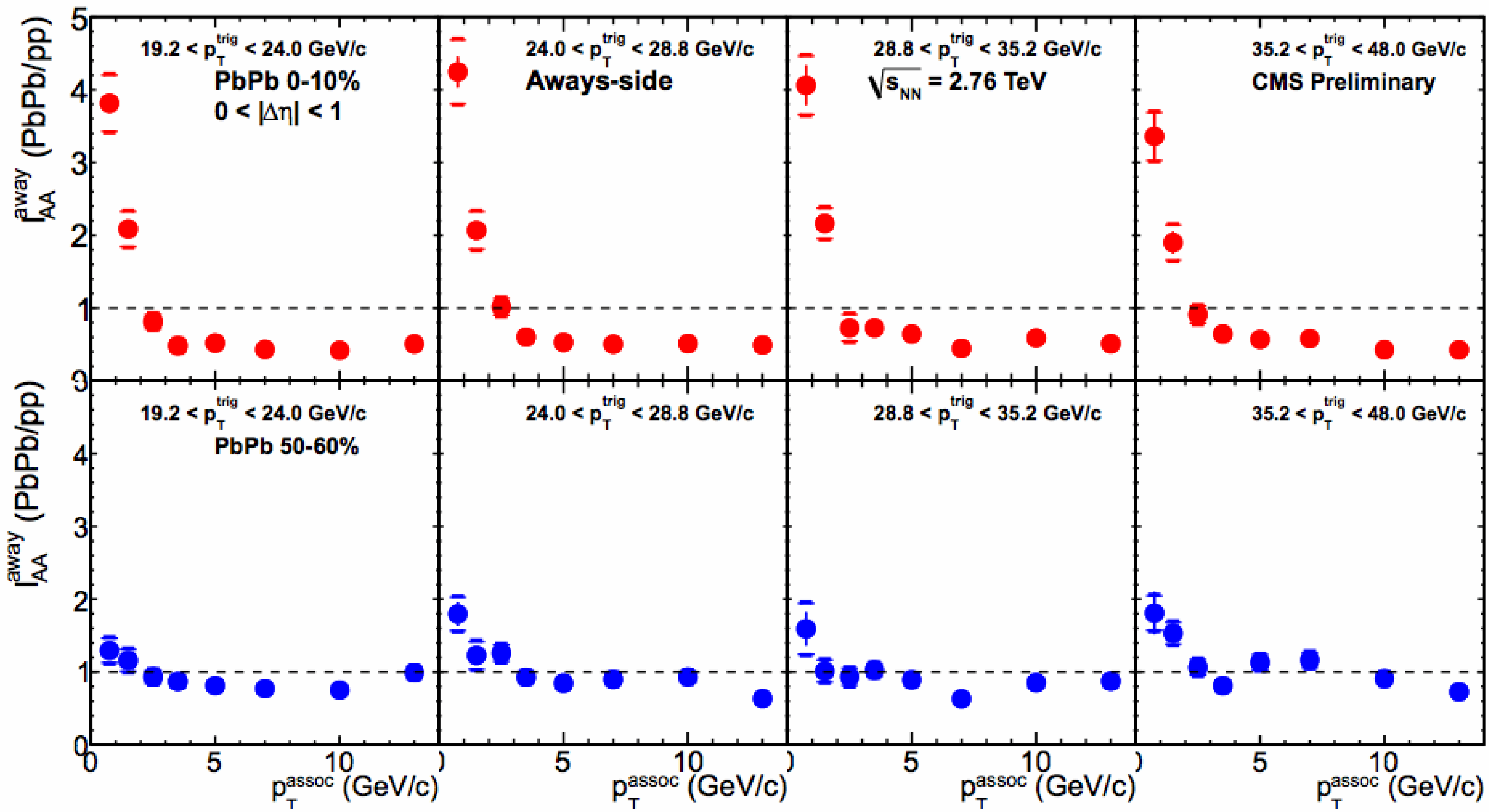
- Definition of I_{AA}
  - PbPb/pp Ratio of yield of associated particles in a same p_T trigger bin

Near side I_{AA} ($\Delta\Phi$ <1)



- Excess of low p_T particles <2GeV
- Energy lost by jet quenching transforms into multiple low energy particles

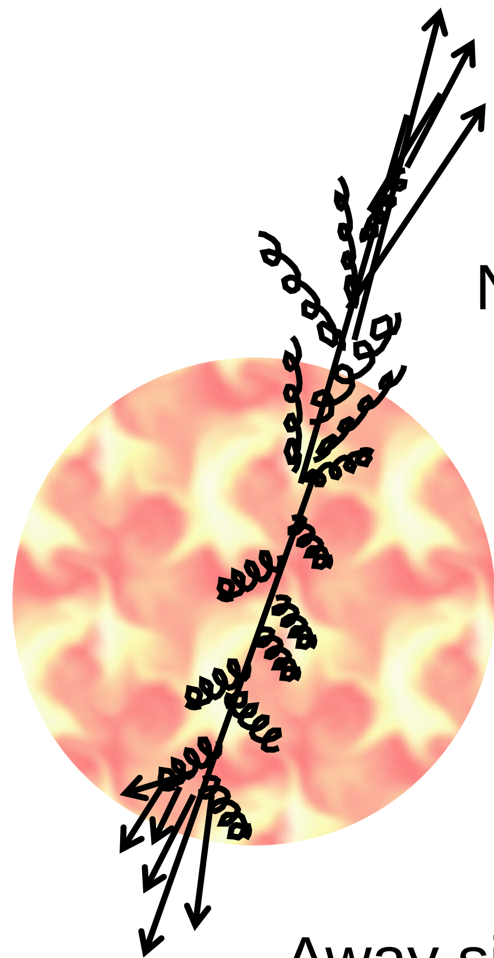
Away side I_{AA} ($\Delta\Phi$ >1)



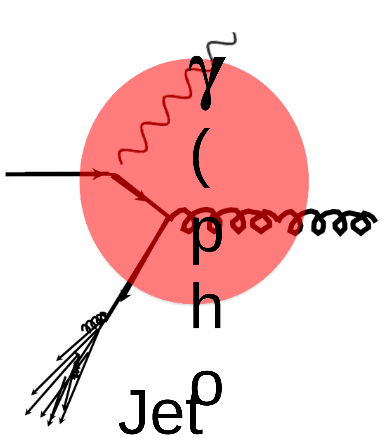
- Even more excess of low p_T particles <2GeV and suppression of high p_T particles
- Jet quenching happened for the away side jet

Lessons from particle correlation analysis

- Suppression of high p_T particles in the away side
  - Trigger particle selection has a surface bias
  - path length dependence of energy loss
- Energy lost by quenching transforms into low p_T particles

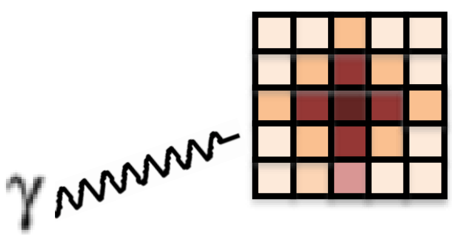


Can we remove the surface bias?

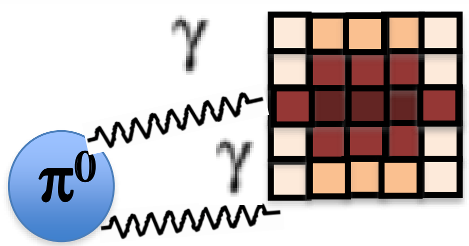


YES
using photon-jet!

CMS has excellent photon isolation power to control S/(S+B) to be 70% - 90%. Remaining background photons are statistically subtracted using shower shape fitting



Smaller width



Larger width

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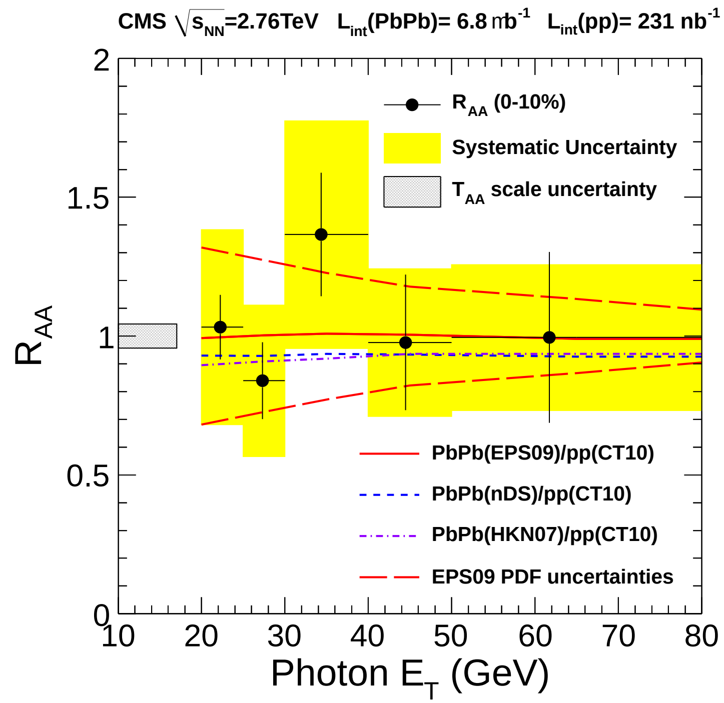
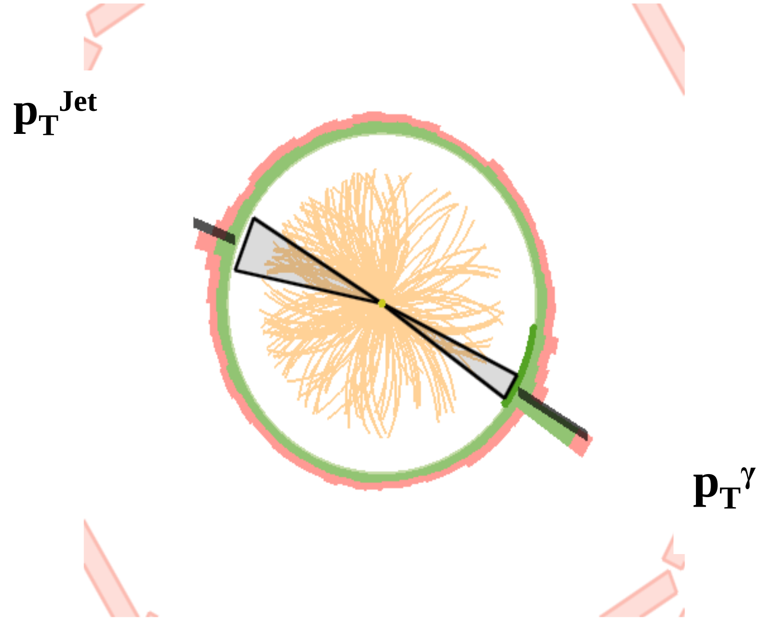


R_{AA} : ratio of cross sections of heavy ion collision to pp after binary collision scaling

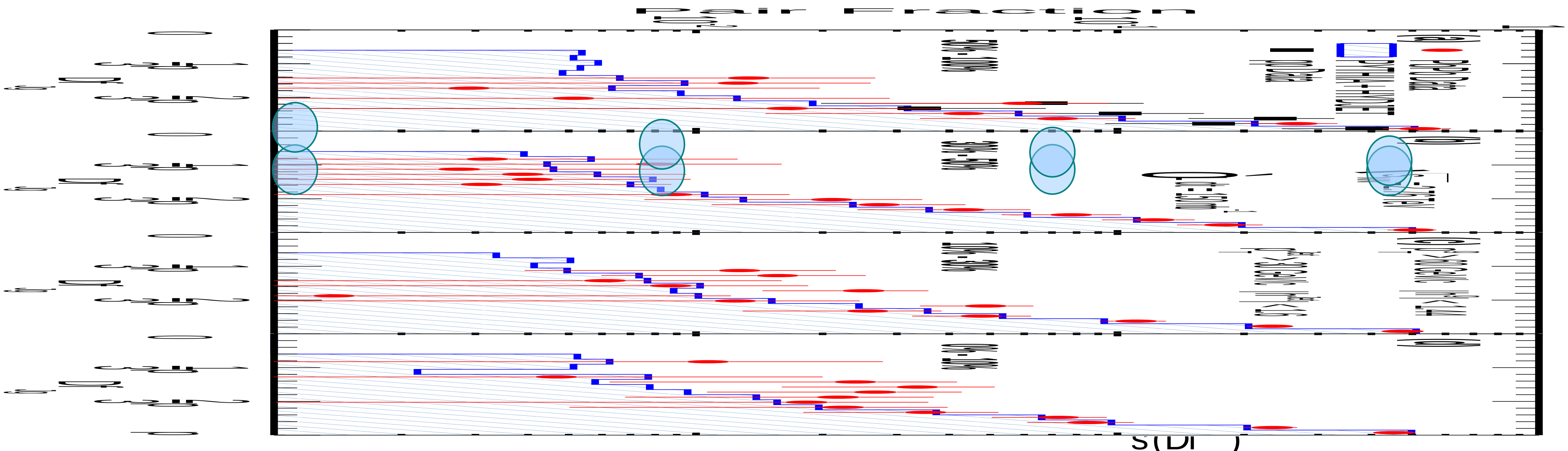
γ-jet correlations

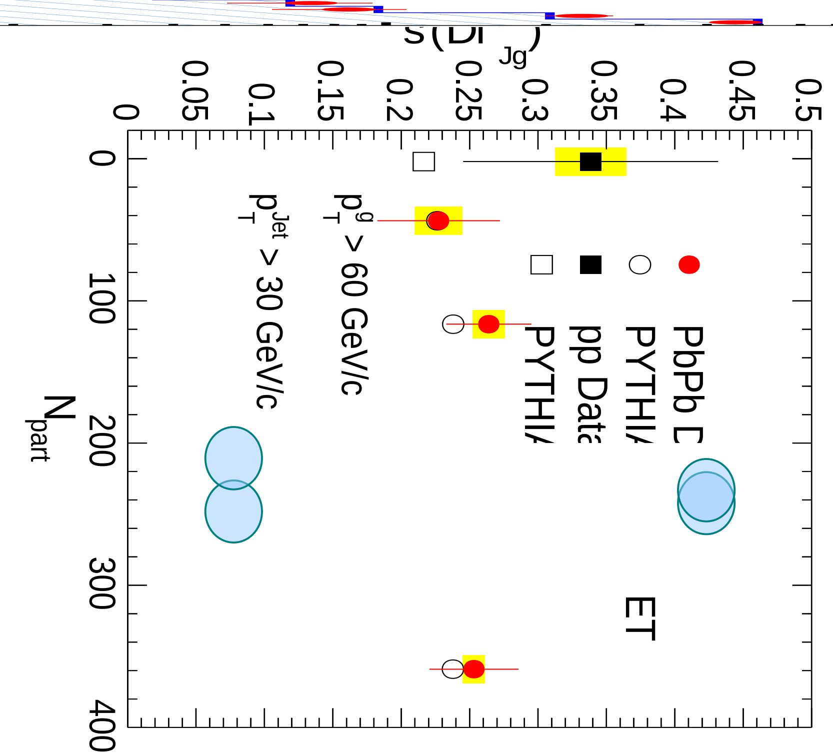
- Event selection
  - Photon p_T > 40GeV
  - Jet p_T >30GeV
  - Back-to-Back : $\Delta\Phi > 7\pi/8$
- Observables
  - 1. Angular correlation
  - 2. Rate of finding Jets
  - 3. Momentum correlation
  - 4. Yield of jets per photon
  - 5. p_T dependence of each observables



Combinatorial backgrounds are subtracted
1. Jets from underlying events
2. Photons from neutral meson

1. Angular Correlation





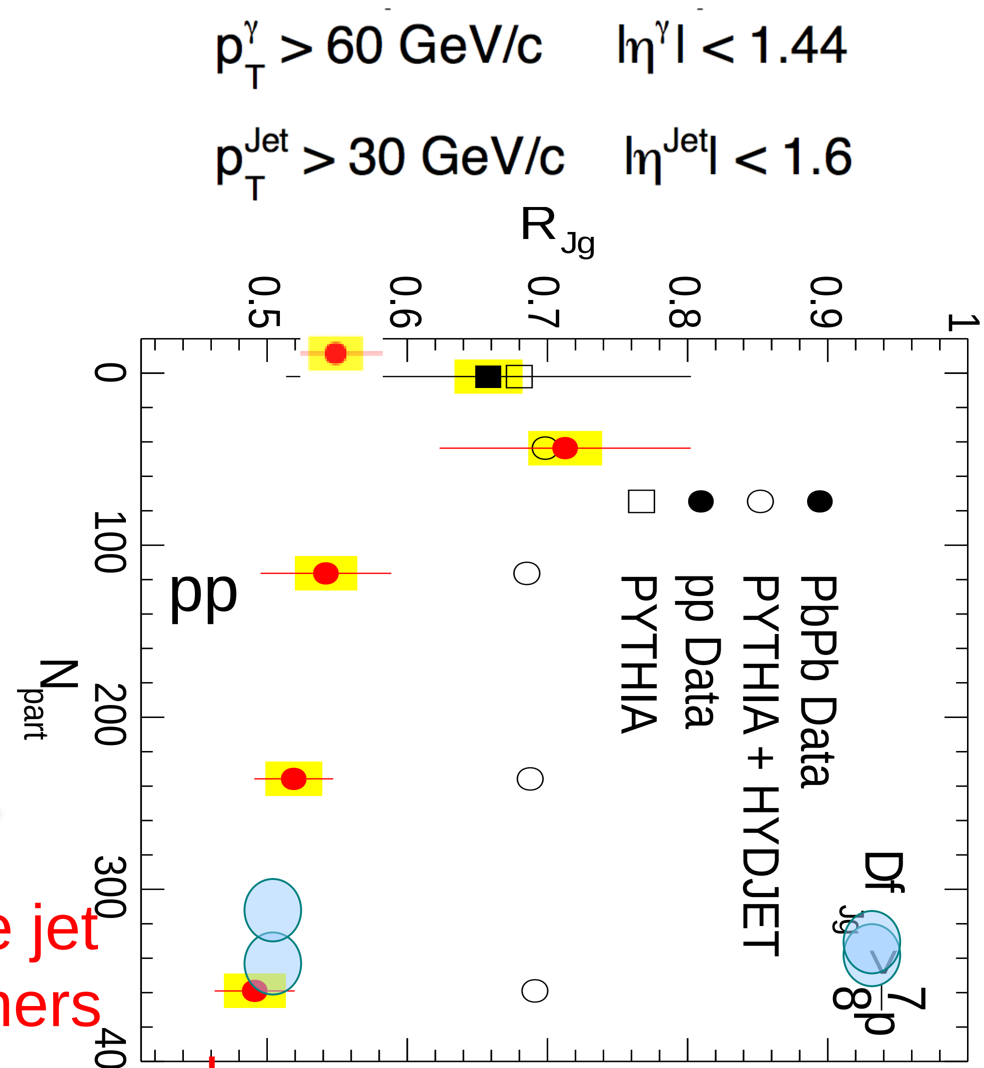
$$f(\Delta\phi) = Ae^{\frac{(\pi-\phi)}{\sigma}}, \quad \left(\frac{2\pi}{3} < \Delta\phi < \pi\right)$$

All data points and MC reference have consistent width around 0.25

2. Rate γ-jet / γ

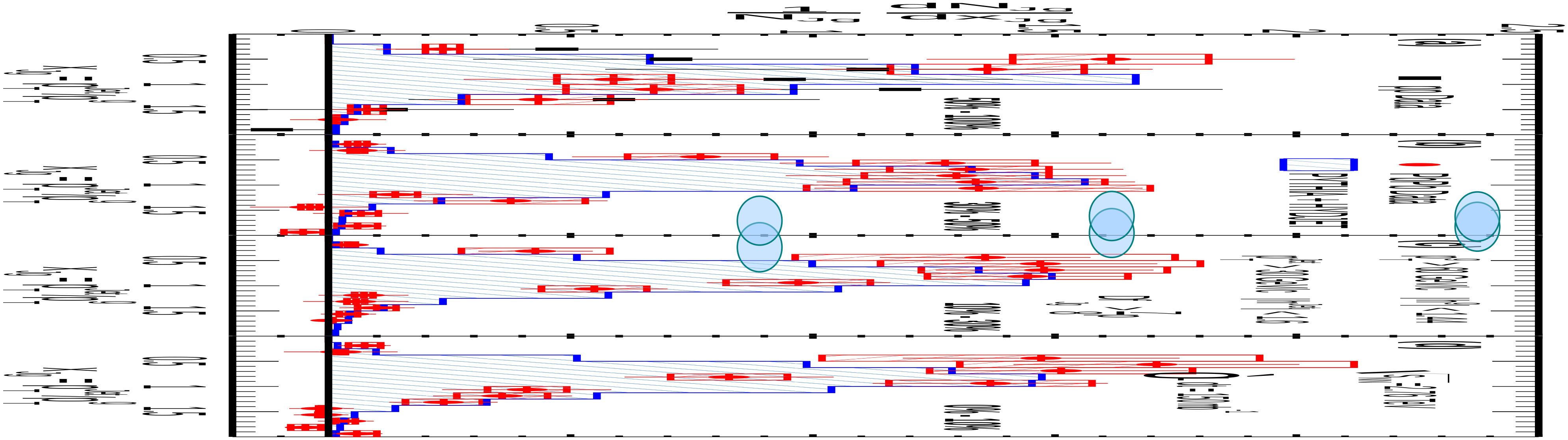
$$R_{J\gamma} = \frac{\text{Number of associated jets}}{\text{Number of triggering } \gamma\text{'s}}$$

- In Pb+Pb data, number of jet partners are significantly less than in MC reference
- Indicates that the jet lost energy and goes below 30GeV threshold



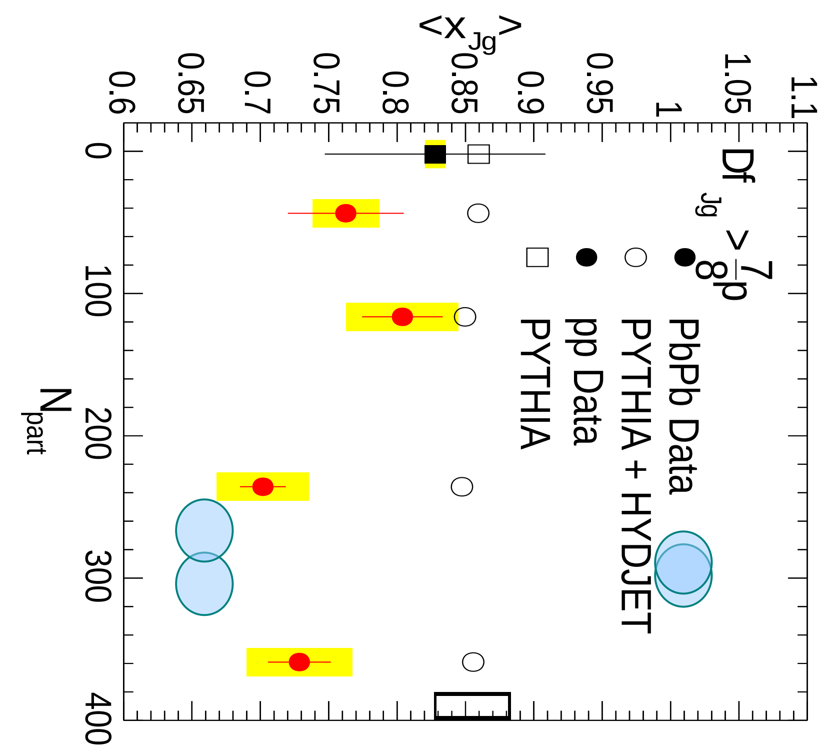
More jet partners disappeared

3. Momentum Ratio



$$x_{J\gamma} \equiv \frac{p_T^{jet}}{p_T^{\gamma}}$$

- Gradual shift of to lower x was observed



Summary of γ-jet correlation

- Observation 1

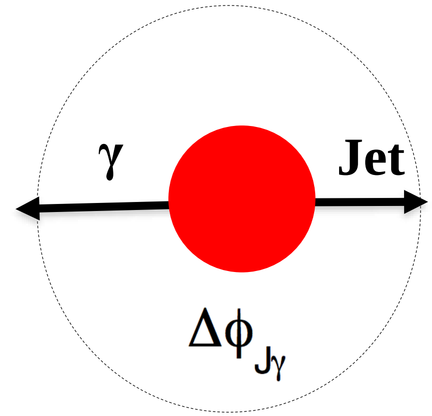
High momentum parton is NOT distracted by the medium

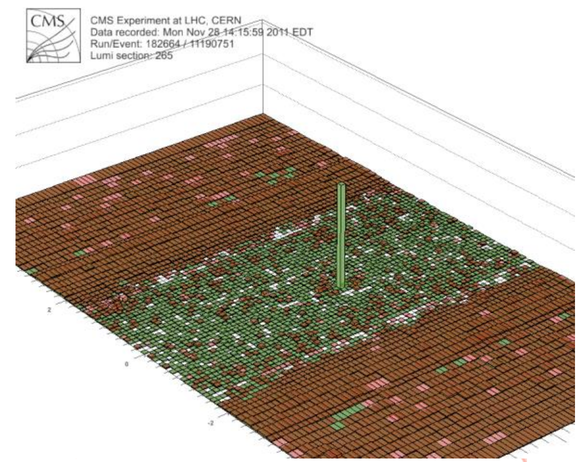
- Observation 2

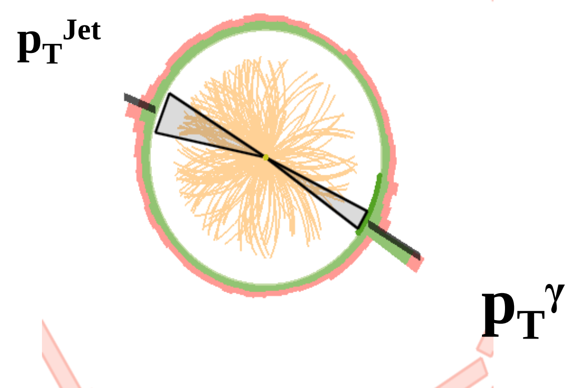
Significant number of jet partners are submerged (below the jet p_T threshold)

- Observation 3

Overall momentum ratio p_T^{Jet}/p_T^{γ} are reduced





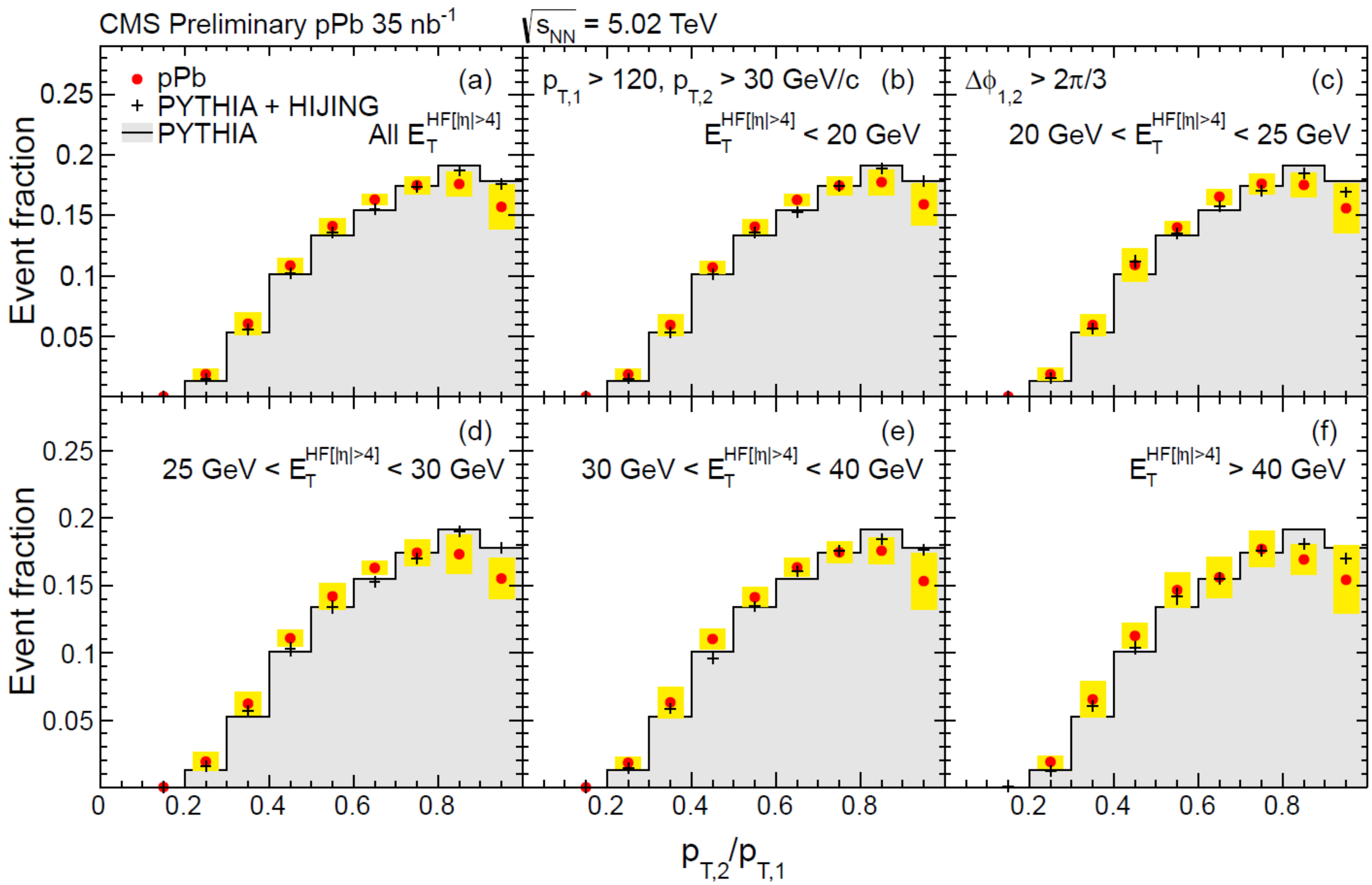


pPb collision

- First jet anlaysis in pPb
  - Di-jet correlation in pPb collisions

- pPb collsions at LHC
  - March 2013
  - Sqrt(s_{NN}) = 5.02 TeV
- Di-jet selection
  - $p_T^{leading}$ > 120GeV
  - p_T^{subl} > 30GeV
  - back-to-back : $\Delta\Phi = 2\pi/3$

Exclusion of cold nuclear effect in quenching



Events divided into 5 bins by Forward energy activity

- Momenta of di-jet pairs are balanced
- Confirms that the momentum asymmetry in PbPb is not from initial state

Di-jet pesudo-rapidity constrains nPDF

CMS Preliminary

pPb 35 nb^{-1}

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

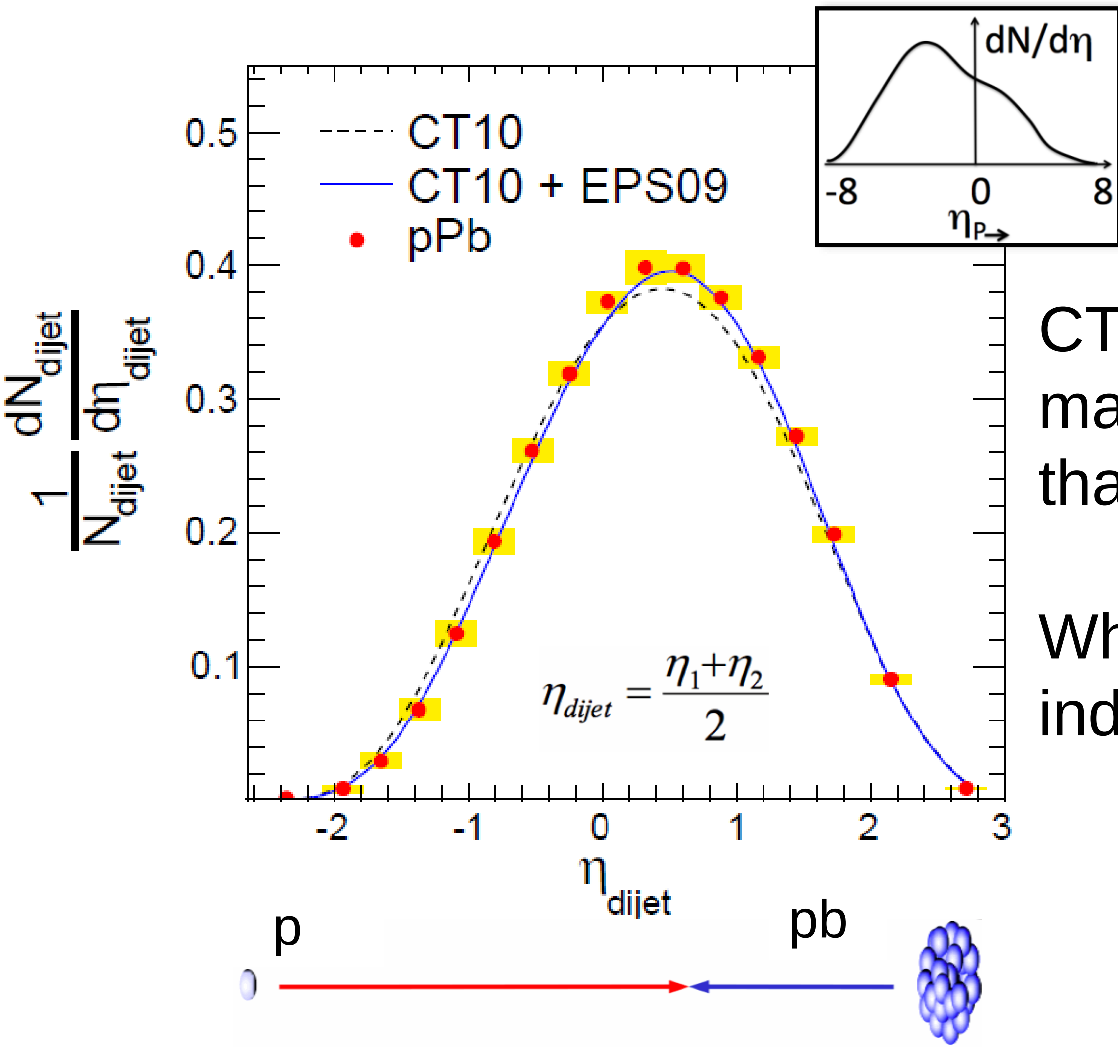
$p_{T,1}$ > 120 GeV/c

$p_{T,2}$ > 30 GeV/c

$\Delta\phi_{1,2} > 2\pi/3$

All $E_T^{HF[|\eta|>4]}$

Escola, Paukkunen, Salgado. arxiv:1308.6733



CT10+EPS09 matches better than CT10.

What does this indicate?

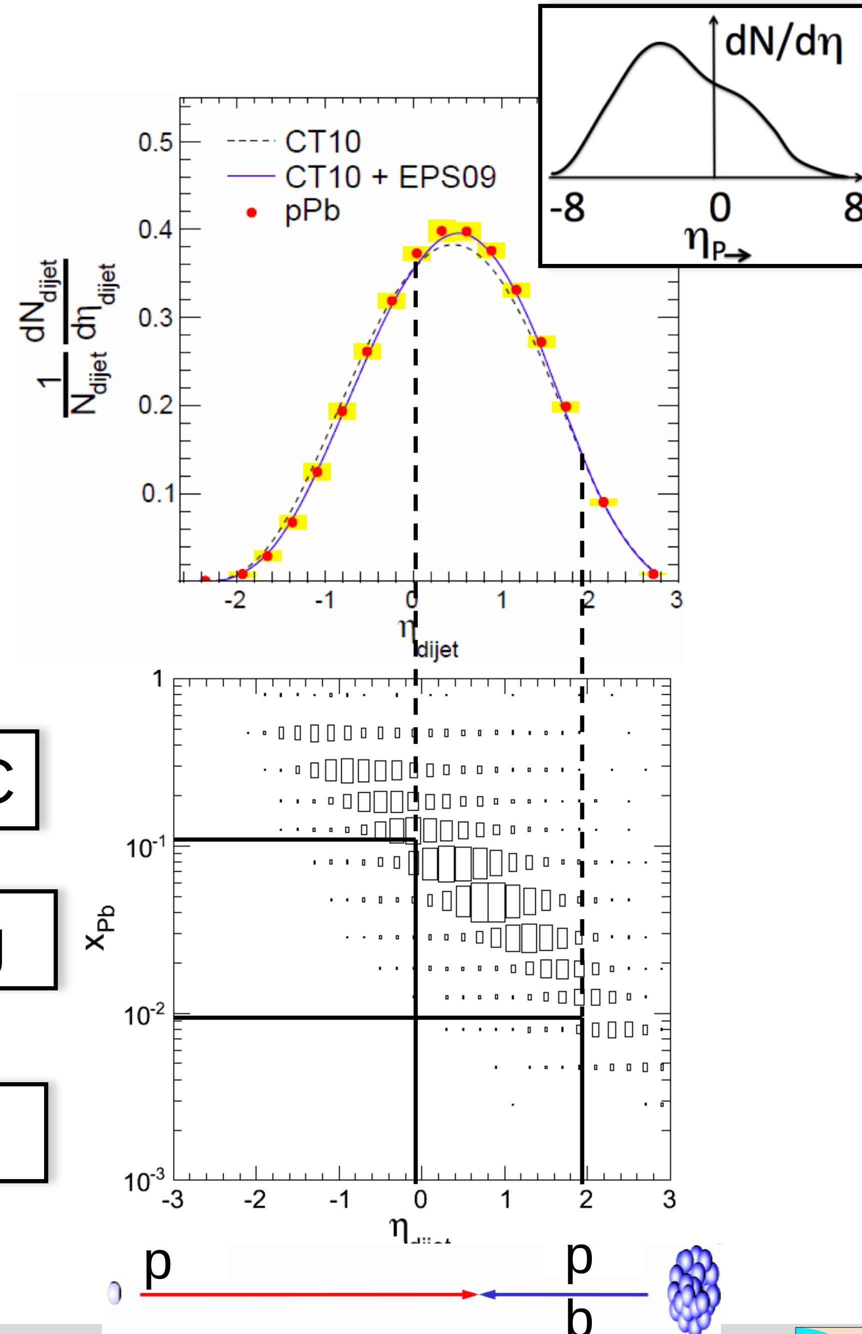
Di-jet pesudo-rapidity constrains nPDF

- Pseudo-rapidity of di-jet reflects the parton momentum fraction in Pb ion
- Modification indicates the EMC, Anti-shadowing and shadowing effect in various momentum fraction regimes

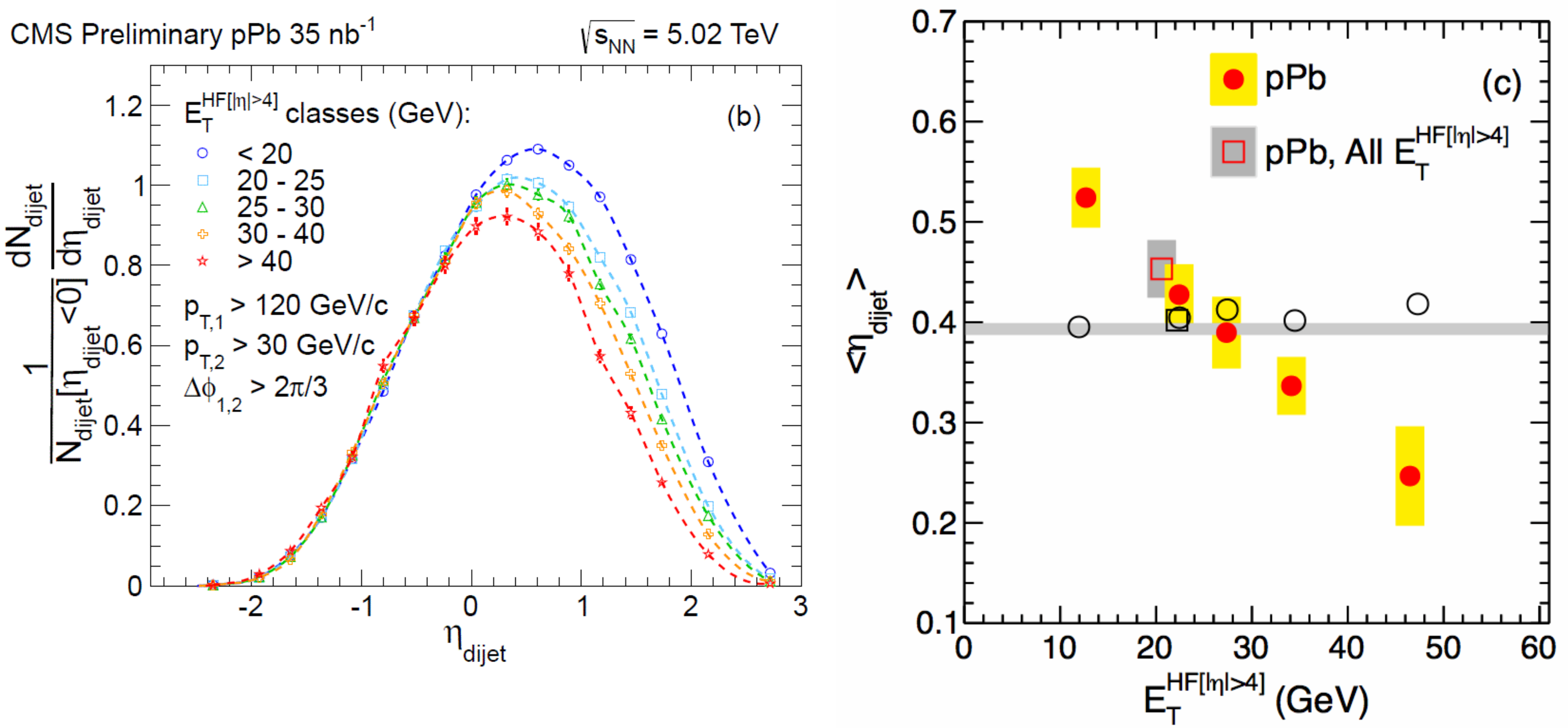
EMC

Anti-shadowing

Shadowing



Di-jet η modification vs HF energy



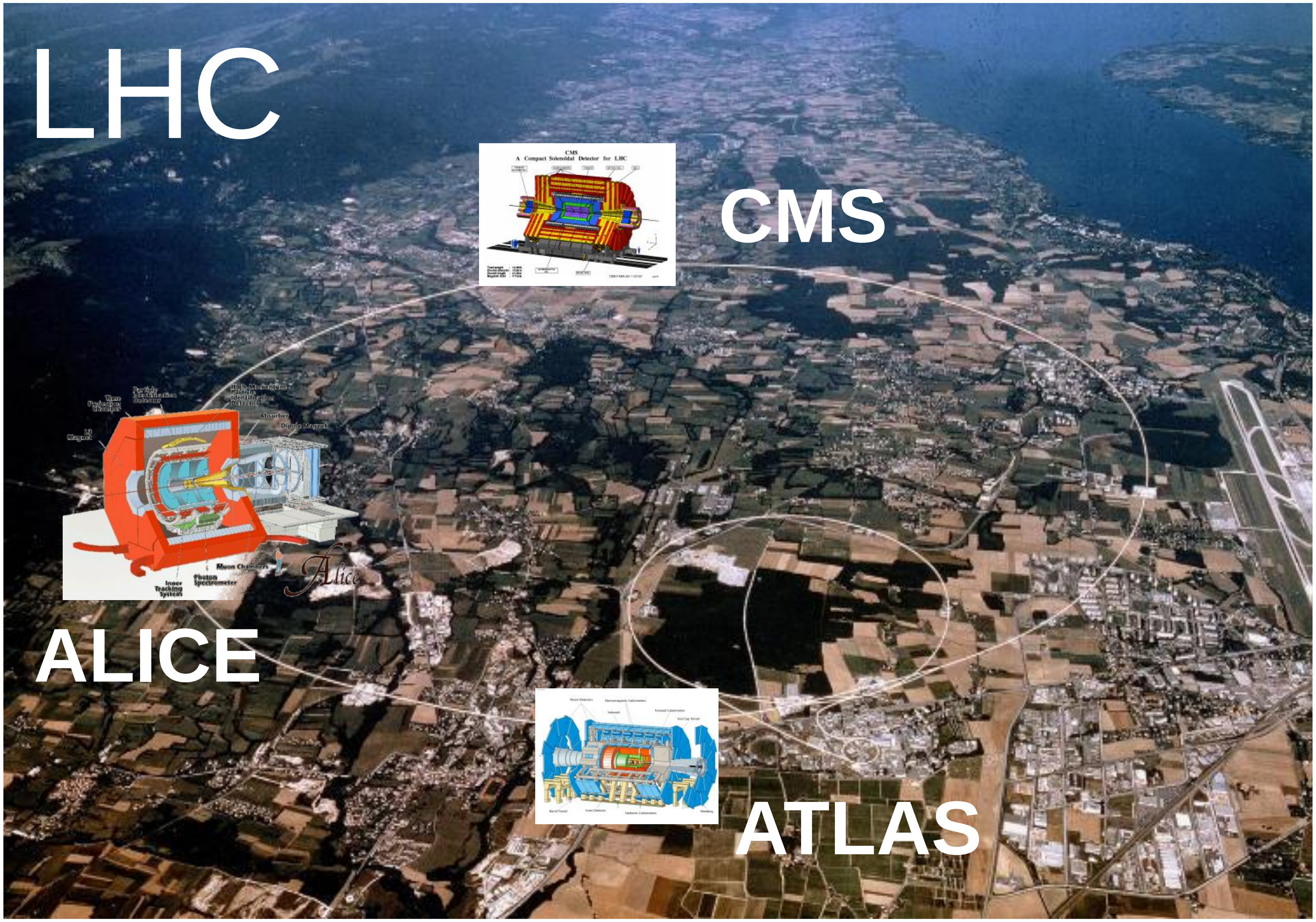
- Strong modification of di-jet pseudo-rapidity distribution
  - longitudinal momentum fraction tends to be larger as proton scatters the Pb ion near the center.

Summary

- Hard probes in heavy ion experiments are very useful to understand the QCD interaction of the hot and dense matter
- CMS has excellent apparatus to reconstruct hard probes and has carried out heavy ion collision experiments with PbPb at 2.76TeV from 2010 and pPb in 2013
- Significant energy loss of partons in PbPb collisions were observed in di-jet, gamma-jet and particle correlation study
- Those effects were confirmed not to be initial state modification by analyzing pPb collisions at 5.02TeV
- Modification of momentum fraction in Pb ions were measured which provides strong constraints of nPDF
- New Hard Probe results will be public soon ➔

BACK UP

LHC Heavy Ion Program



Heavy ion (Pb) beam began to circulate the LHC ring from Nov. 2010
$\sqrt{s_{NN}}$ = 2.76TeV.