Recent Heavy Ion Results with the CMS Detector
Hard and EM Probes

Yen-Jie Lee (MIT)

for the CMS Collaboration

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Chicago, USA

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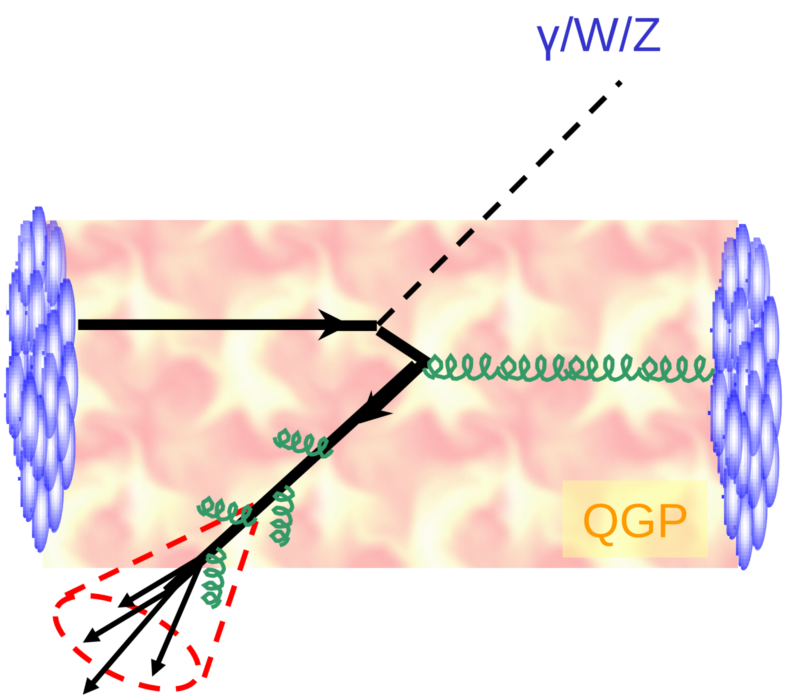
Probe the medium

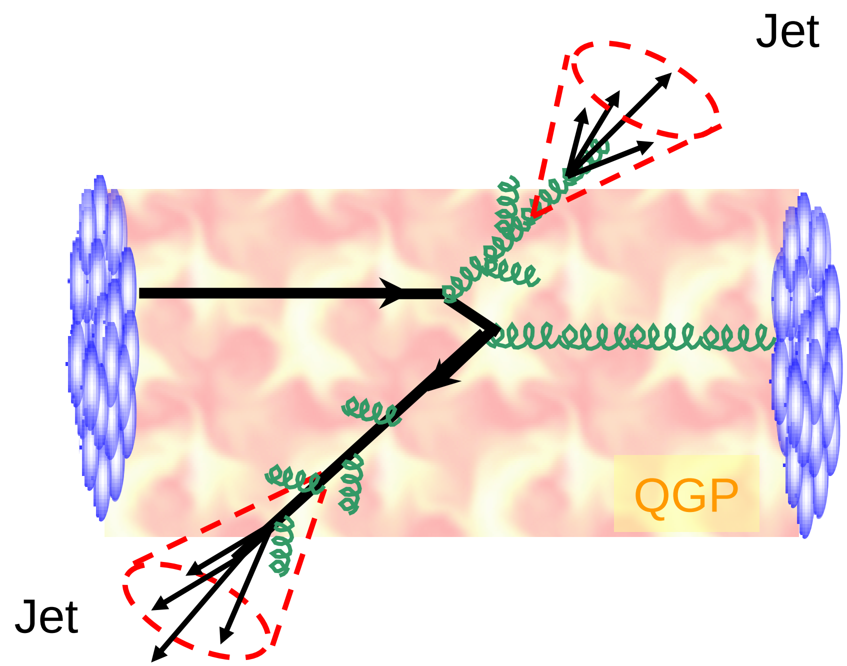
Use the hard probes produced with the collisions

Colorless probes: γ, W/Z bosons



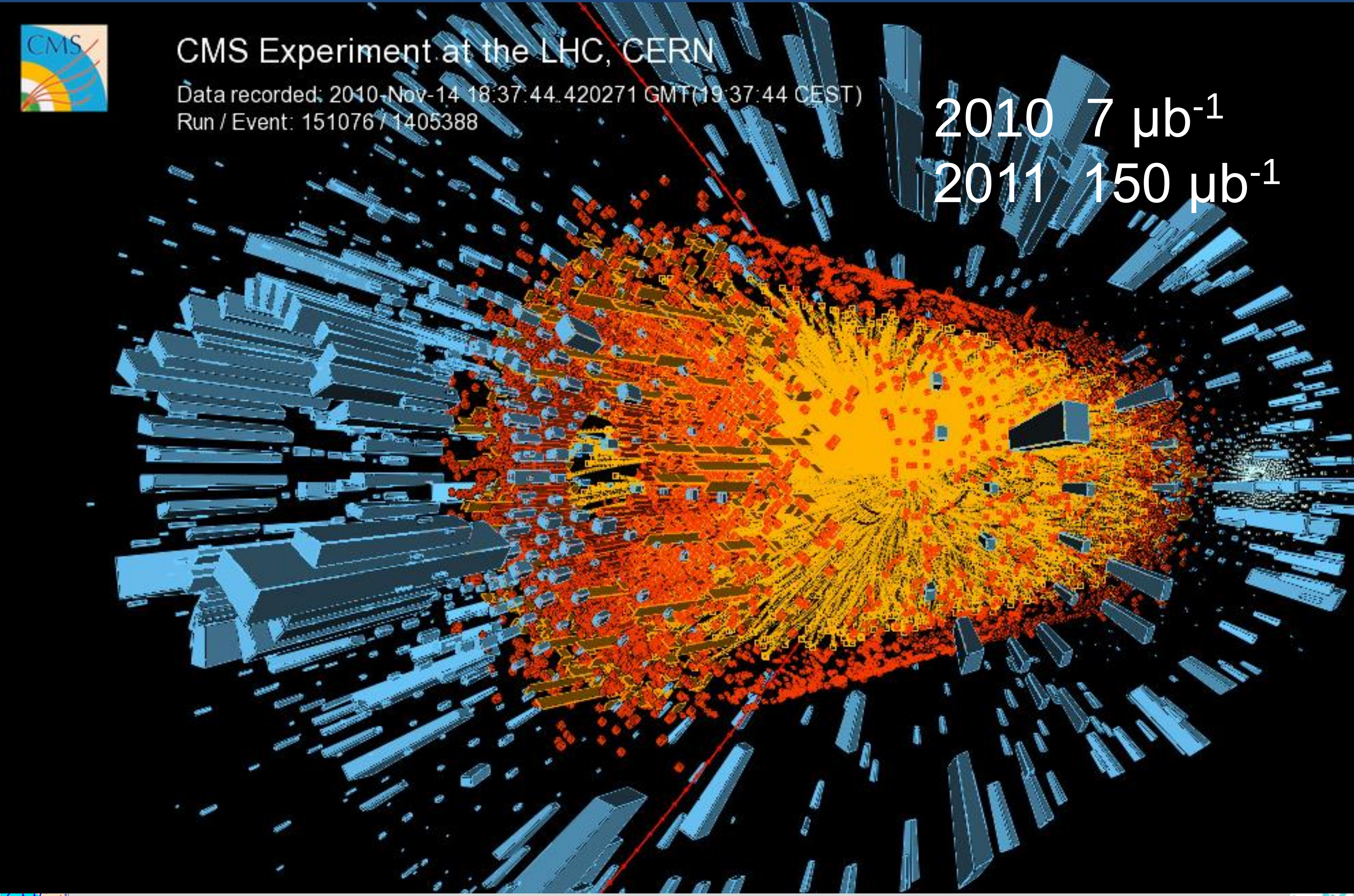
Probe the initial state
Number of NN scattering

Jets: originating from **quarks and gluons**



In medium parton energy loss
→ "Jet quenching"
(Bjorken, 1982)

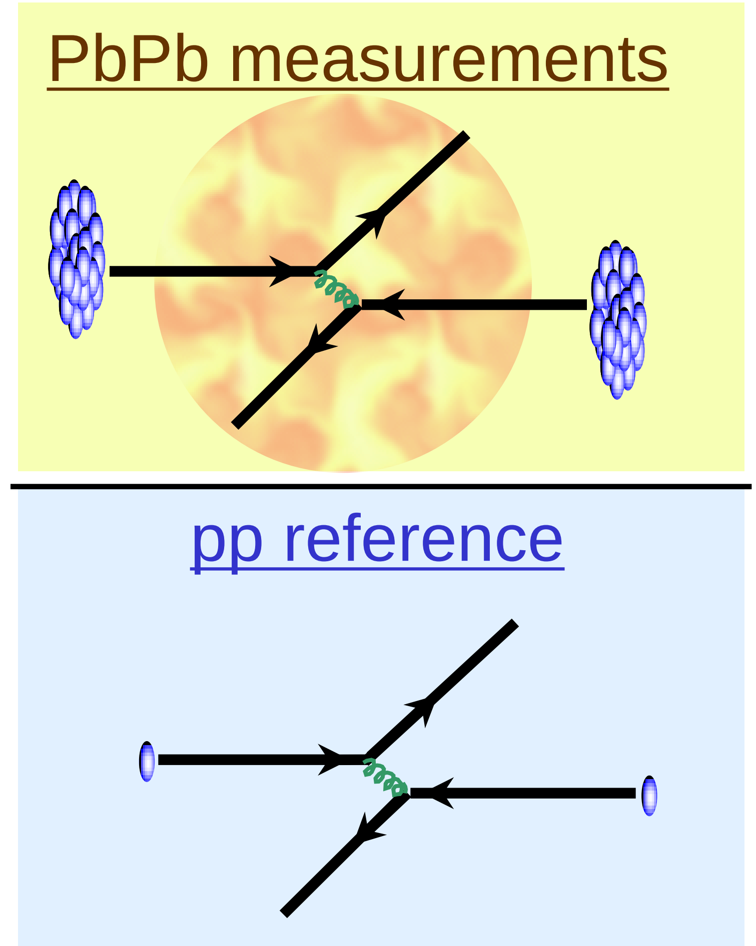
Heavy Ion Collision Recorded by the CMS Detector



How Do We Extract Medium Effects?

Compare PbPb measurements to pp reference

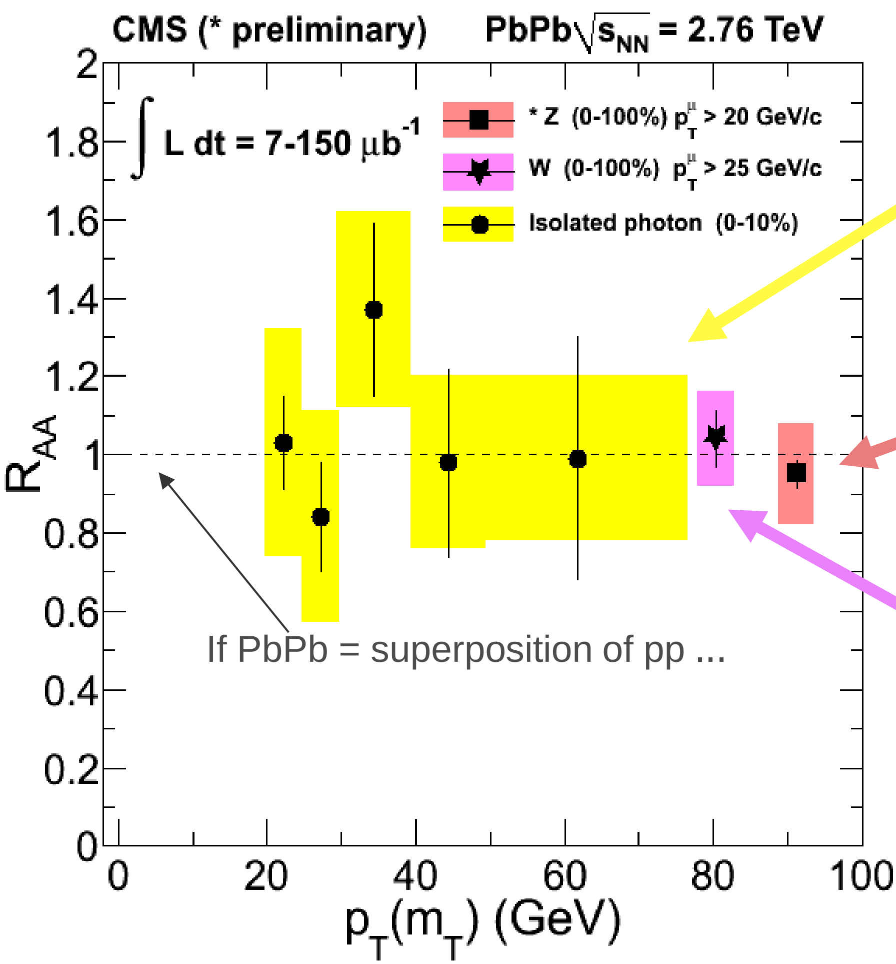
$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 \sigma_{pp} / dp_T d\eta} \leftarrow$$



Number of nucleon-nucleon collisions per event

(Non-) Suppression of Colorless Probes

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

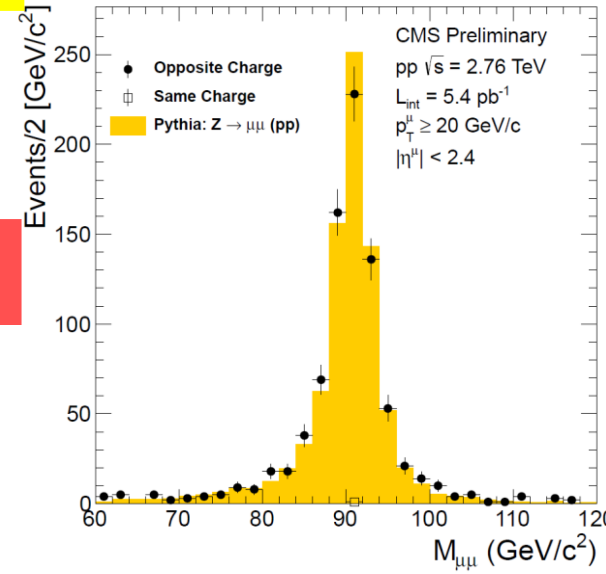


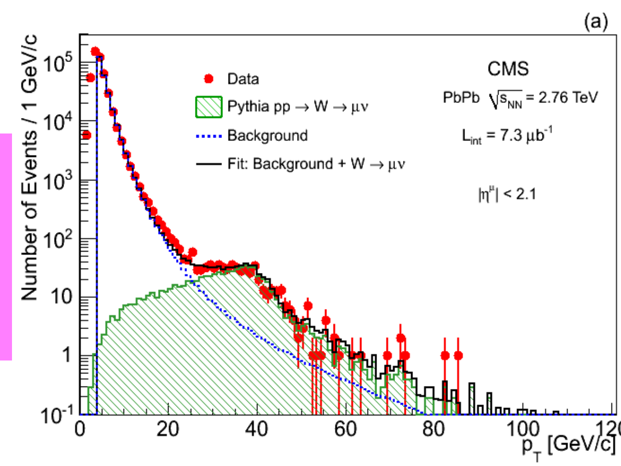
Isolated photon
PLB 710 (2012) 256

$Z^0 \rightarrow \mu^+\mu^-$

$W \rightarrow \mu\nu$ using single muon recoil against missing p_T

PRL 106 (2011) 212301
CMS-PAS HIN-12-008
CMS-PAS HIN-13-004





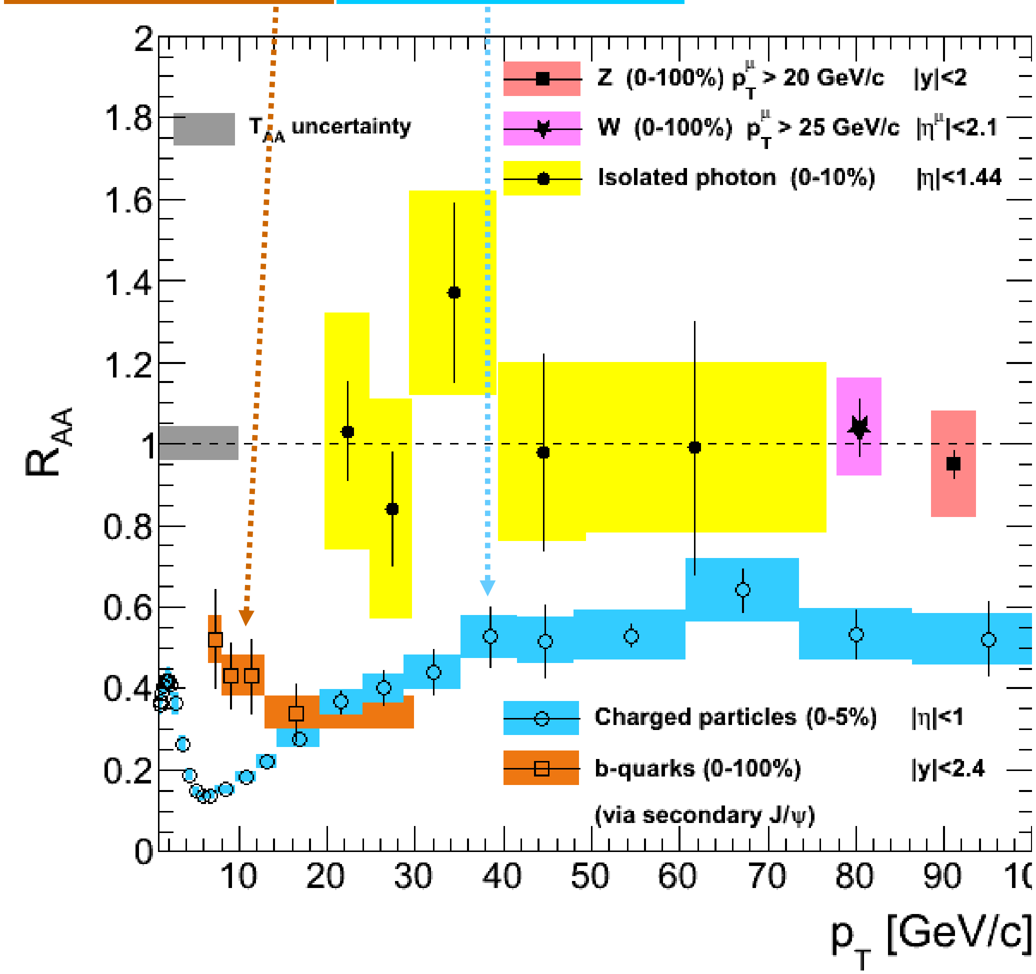
arXiv:1205.6334
PLB 715 (2012) 66

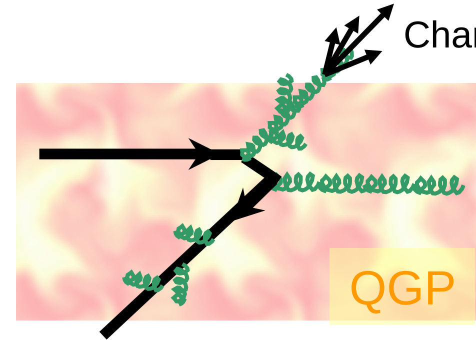
N_{coll} scaling confirmed in PbPb collisions at 2.76 TeV

Track and secondary J/ψ (from b-quark)

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 \sigma_{pp} / dp_T d\eta}$$

JHEP 05 (2012) 063 EPJC 72 (2012) 1945





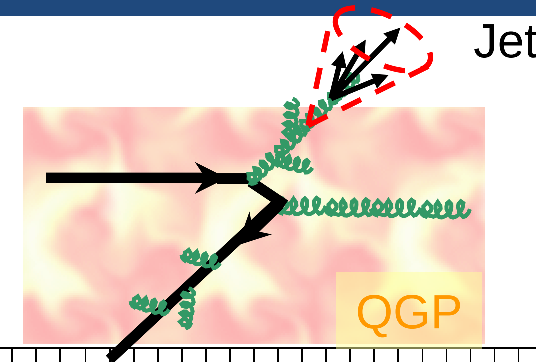
Jet quenching without jet

Strong suppression of **charged particles** and **secondary J/ψ(←b)**

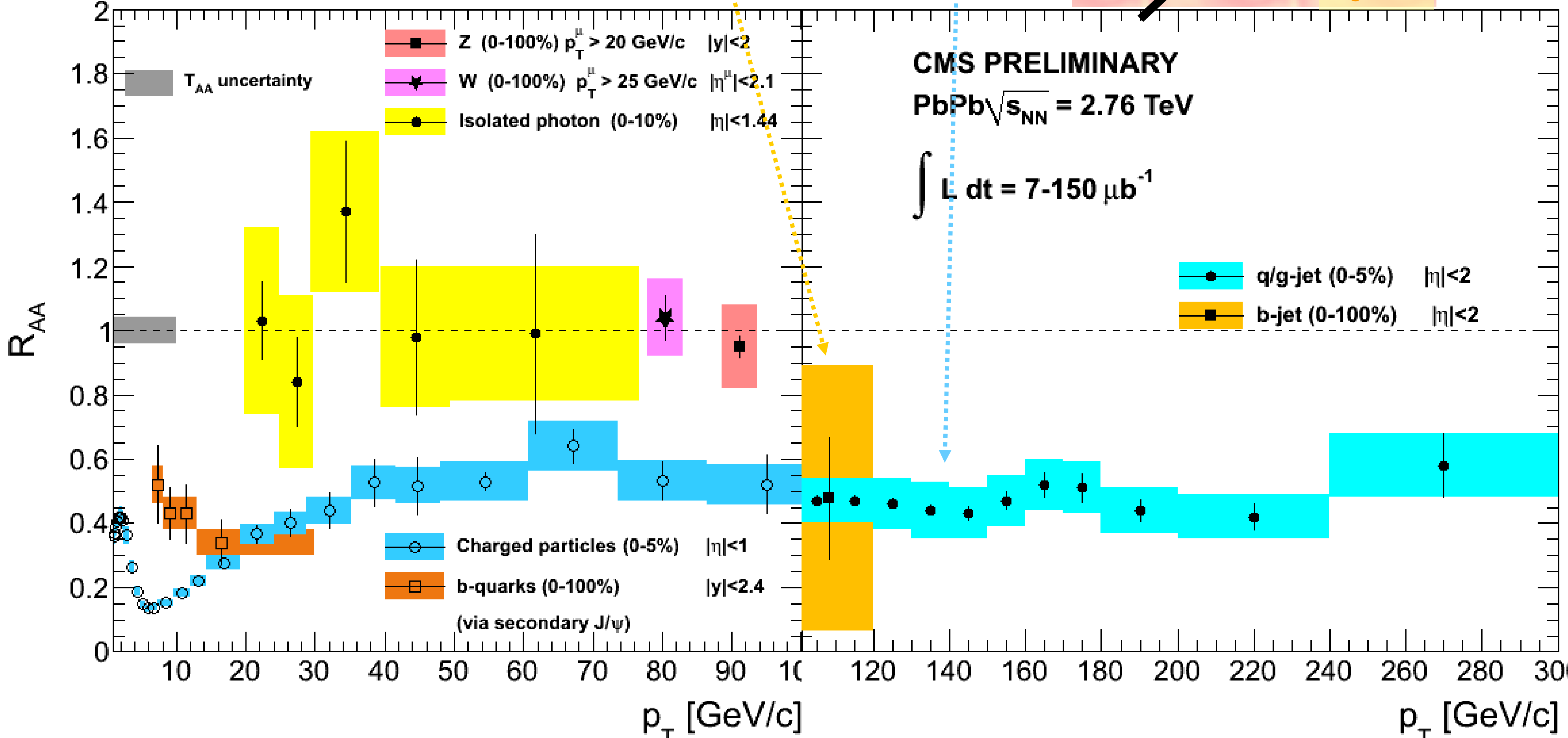
Can we collect the radiated energy back by jet reconstruction algorithm?

Inclusive jet R_{AA}

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$



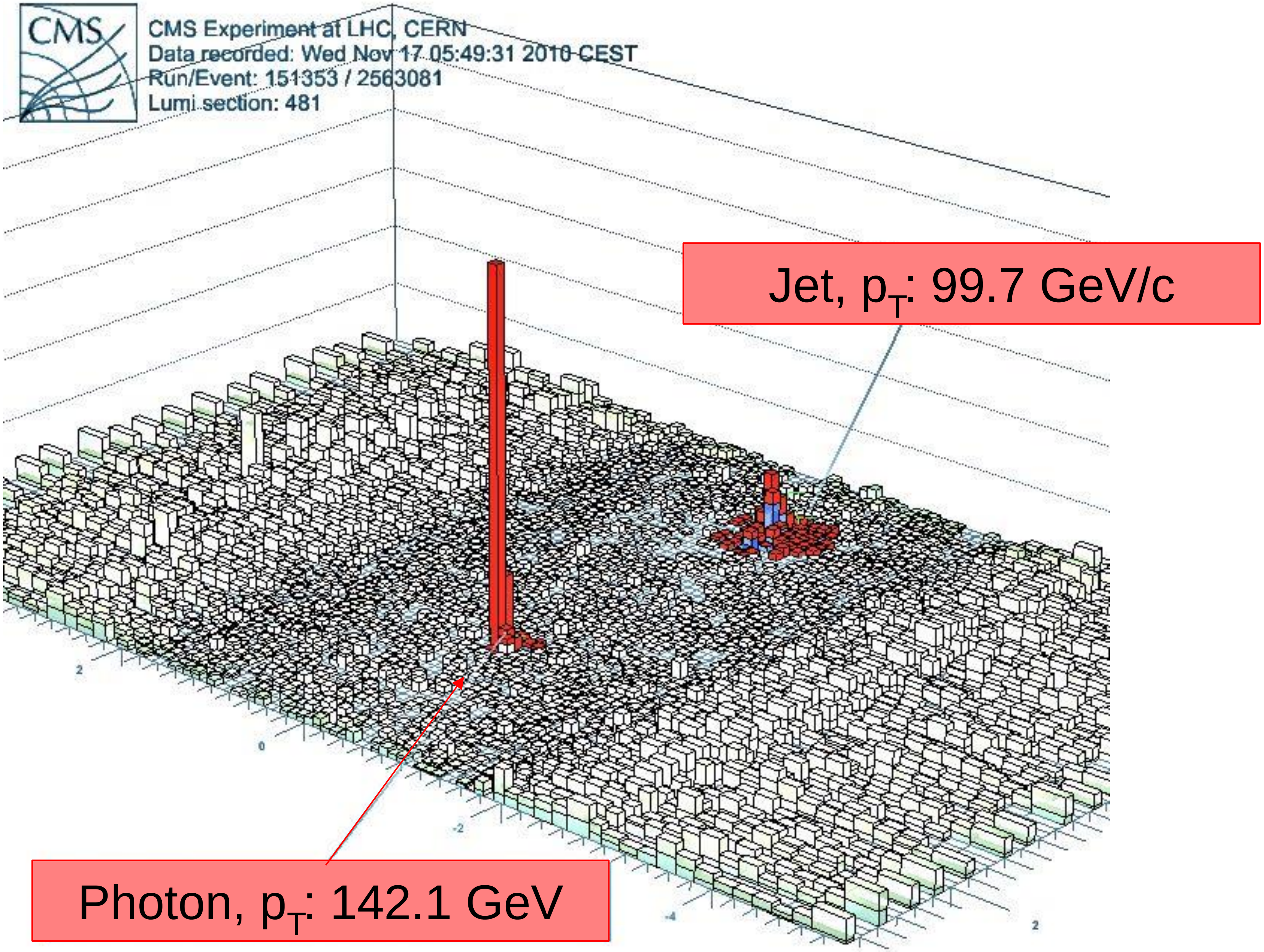
JHEP 05 (2012) 063 | EPJC 72 (2012) 1945 | HIN-12-003 b-jet | HIN-12-004 Jet R_{AA}



Suppression of high p_T jet! Indication of b-jet suppression.

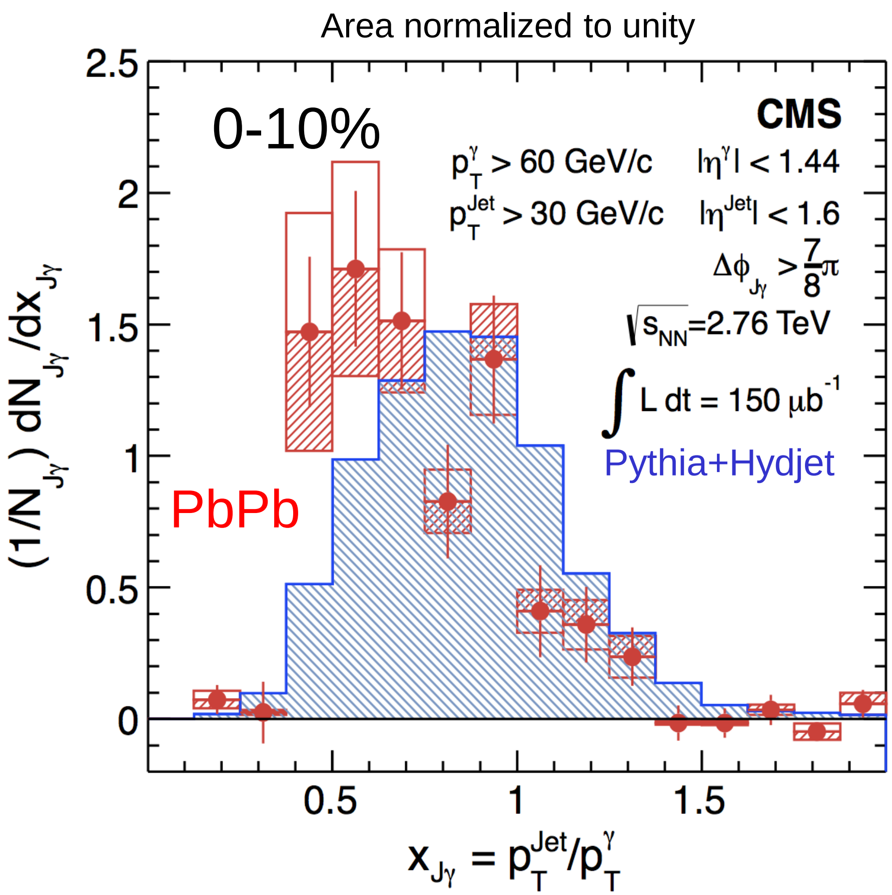
Jet reconstruction algorithm (Anti-k_T) does not collect all the radiated energy back

Photon-Jet in PbPb Collisions

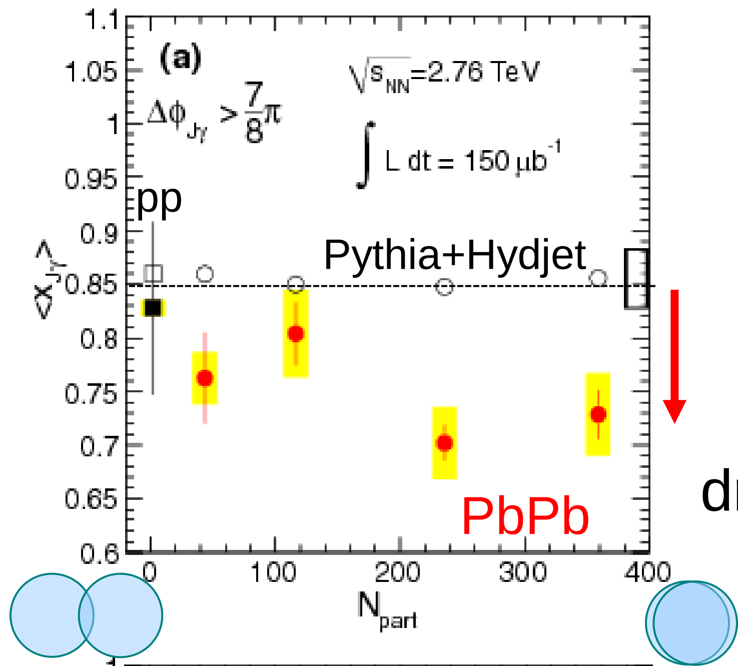


γ+Jet: u,d Quark "Absolute Energy Loss"

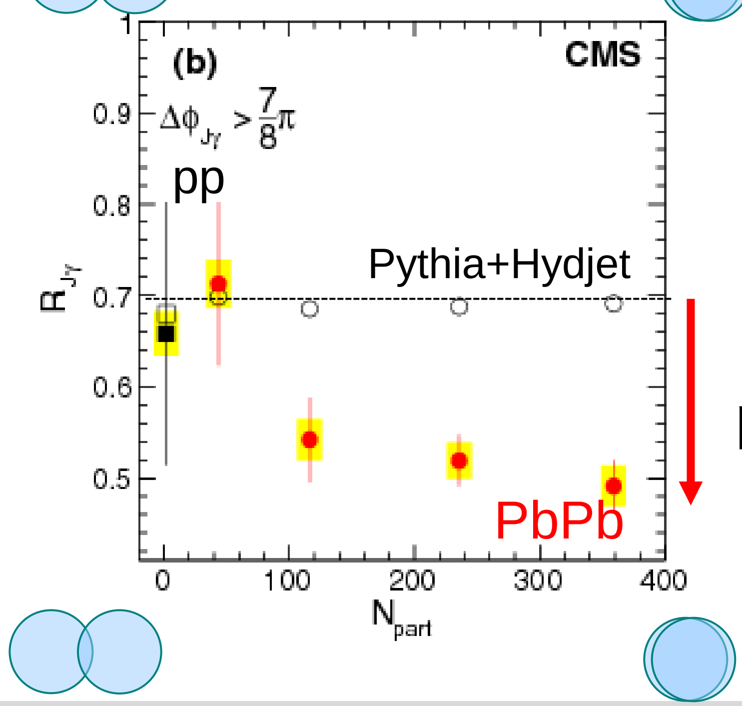
PLB 718 (2013) 773



Photon-jet
momentum balance
Jet p_T / Photon p_T



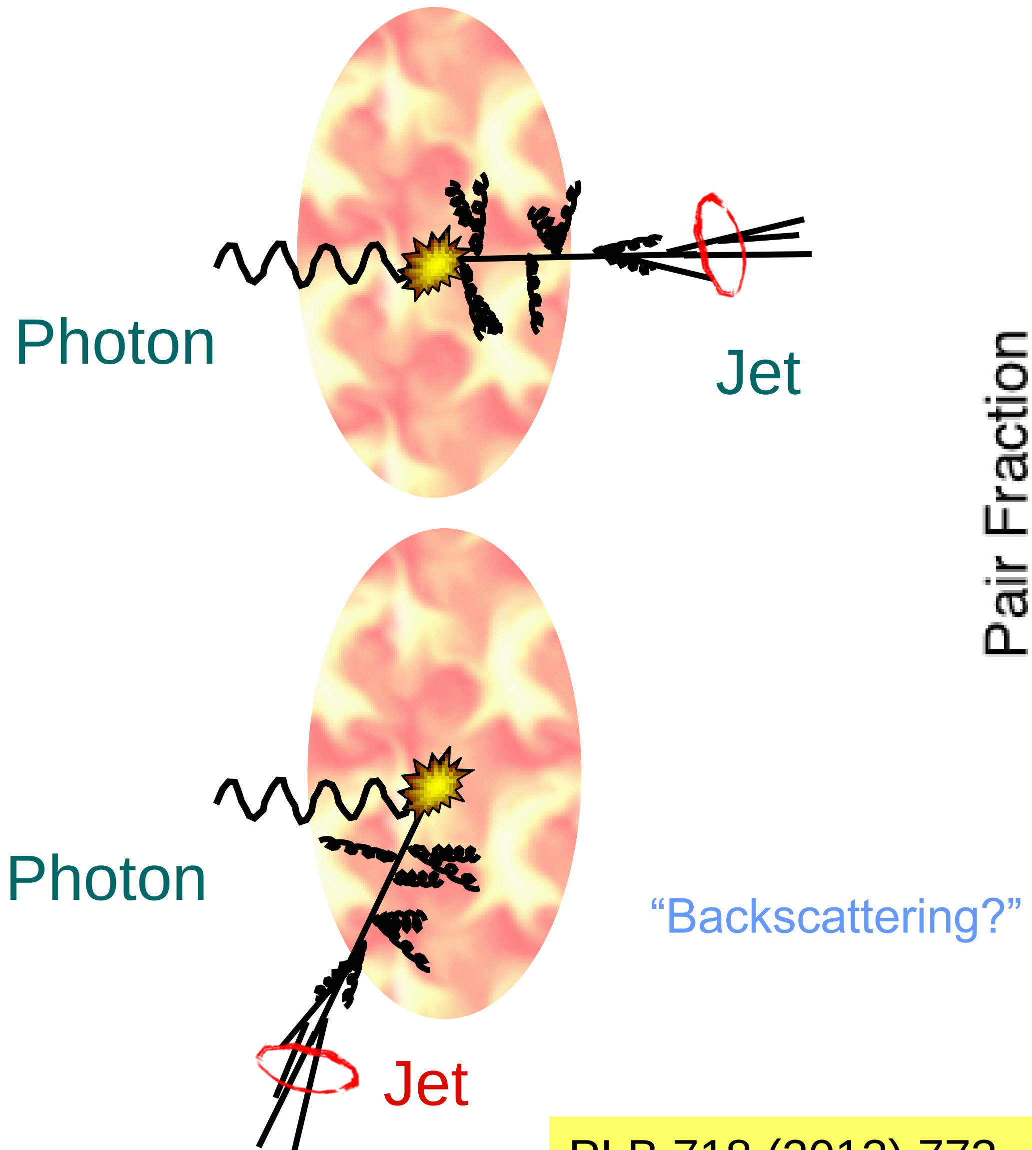
Jet-photon
p_T balance
drops by 14%



20% of
photons lose
jet partner

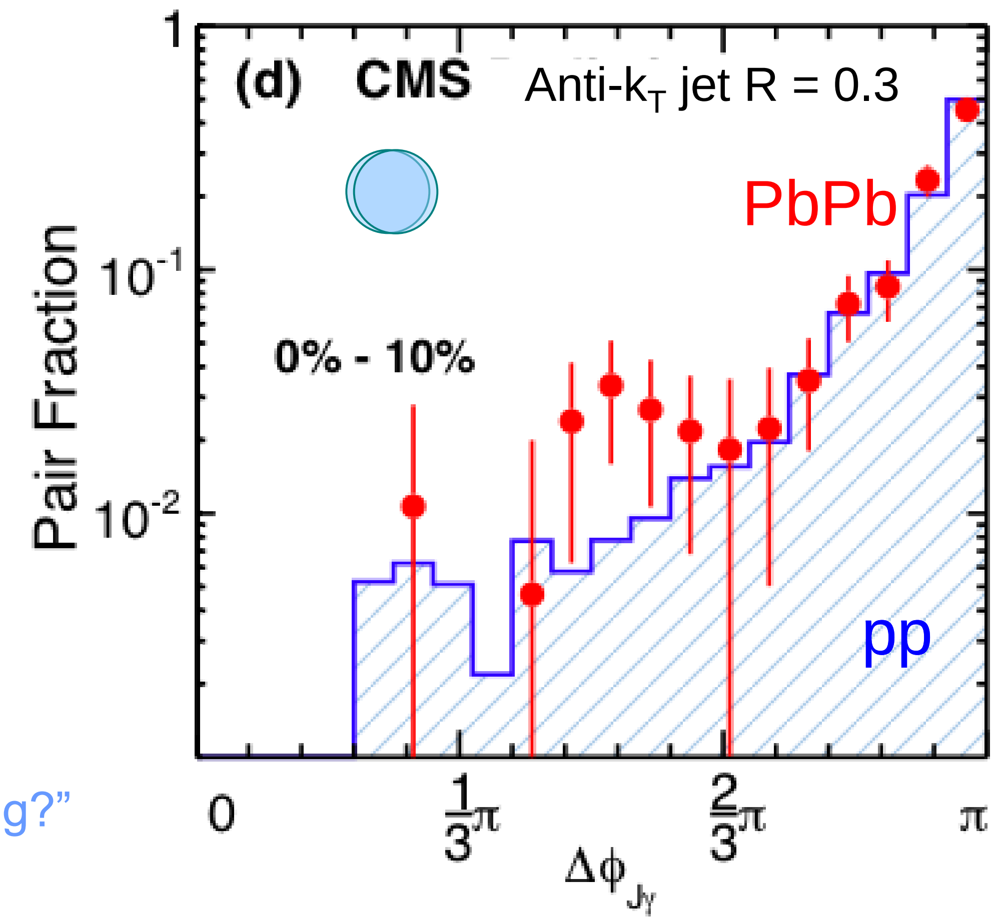
γ+Jet Azimuthal Angular Correlation

The first photon-jet correlation measurement in heavy ion collisions



PLB 718 (2013) 773

"QGP Rutherford experiment"

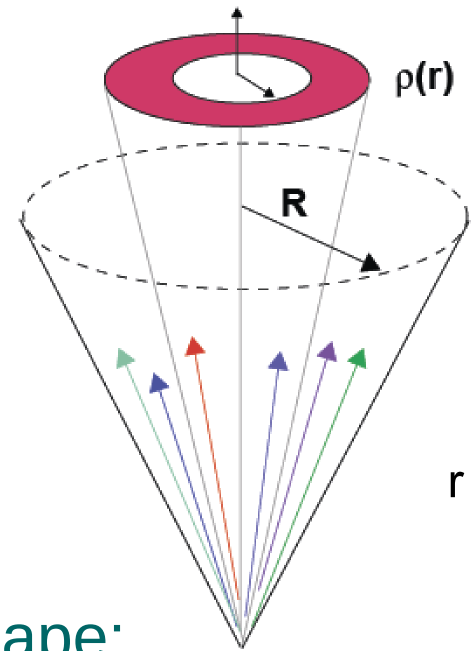


Azimuthal angle difference between photon and jet

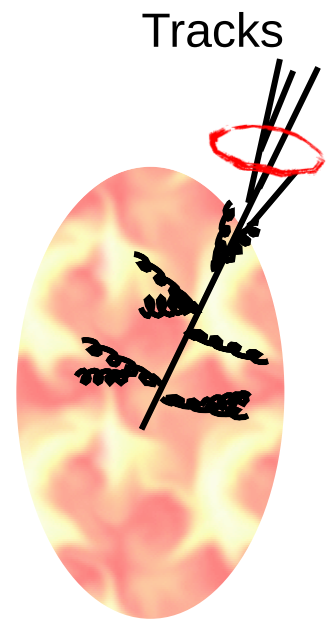
Jet Shape and Fragmentation Function

Large parton energy loss (O(10GeV)) in the medium, out of jet cone → What about jet structure?

Anti-k_T R=0.3
Jet p_T > 100 GeV/c
Jet $|\eta|<2$
Track p_T > 1 GeV/c



$r = (\Delta\eta^2+\Delta\varphi^2)^{1/2}$



Jet shape:

shape of the jet as a function of radius (r)

$$\rho(r) = \frac{1}{f_{ch}}\frac{1}{\delta r}\frac{1}{N_{jet}}\sum_{jets}\frac{p_T(r-\delta r/2, r+\delta r/2)}{p_T^{jet}}$$

$$f_{ch} = \frac{1}{N_{jet}}\sum_{jets}\frac{p_T(0,R)}{p_T^{jet}}$$

Jet fragmentation function:

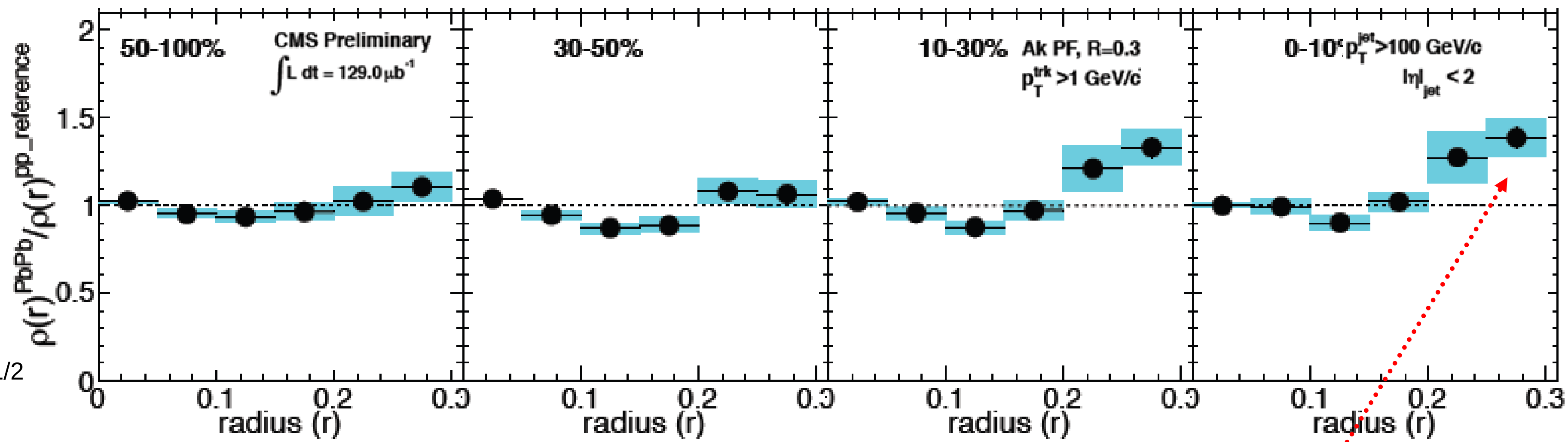
how transverse momentum is distributed inside the jet cone

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

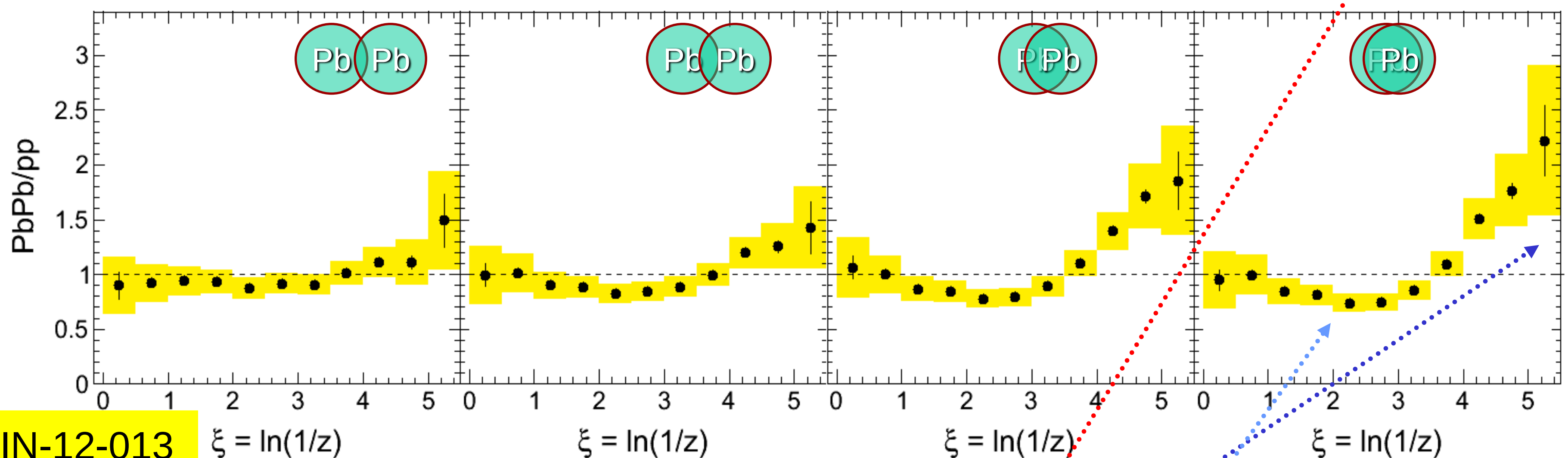
Jet Shape and Fragmentation Function

PbPb / pp
Jet shape
Ratio

$r = (\Delta\eta^2+\Delta\varphi^2)^{1/2}$



PbPb / pp
Fragmentation
Function Ratio



CMS PAS HIN-12-013

High p_T particles

Low p_T particles

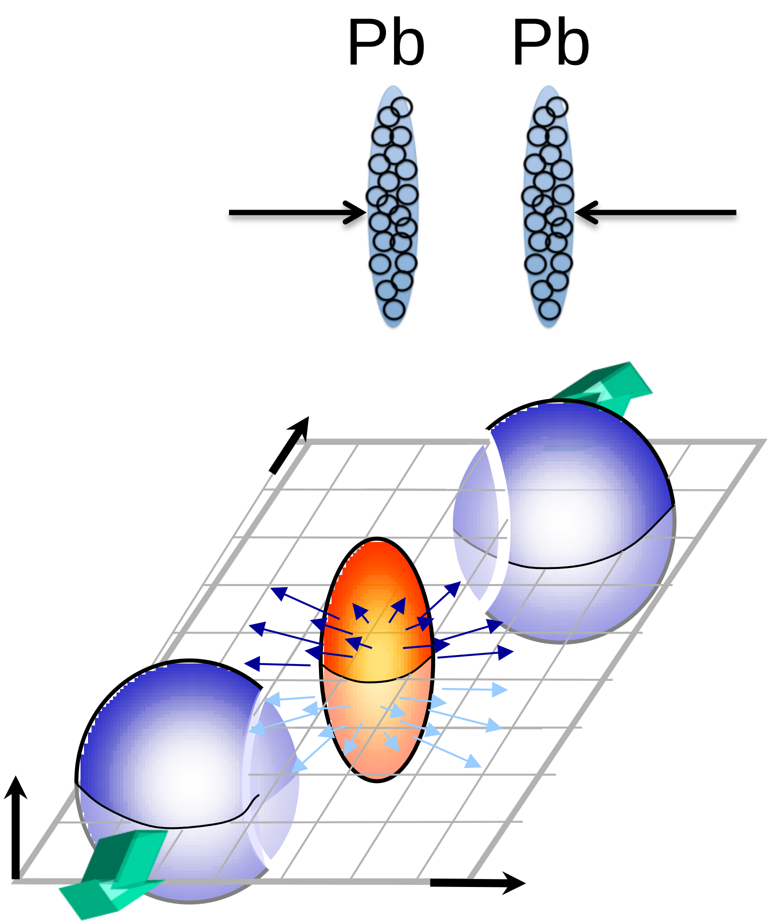
Significant modification at large radius (r)

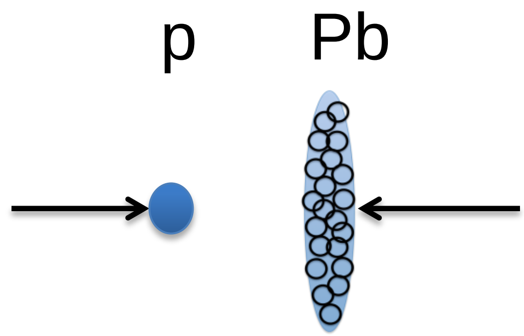
Enhancement of low p_T particle in cone

Suppression of intermediate p_T particles in cone

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

Missing Link: pPb Collisions

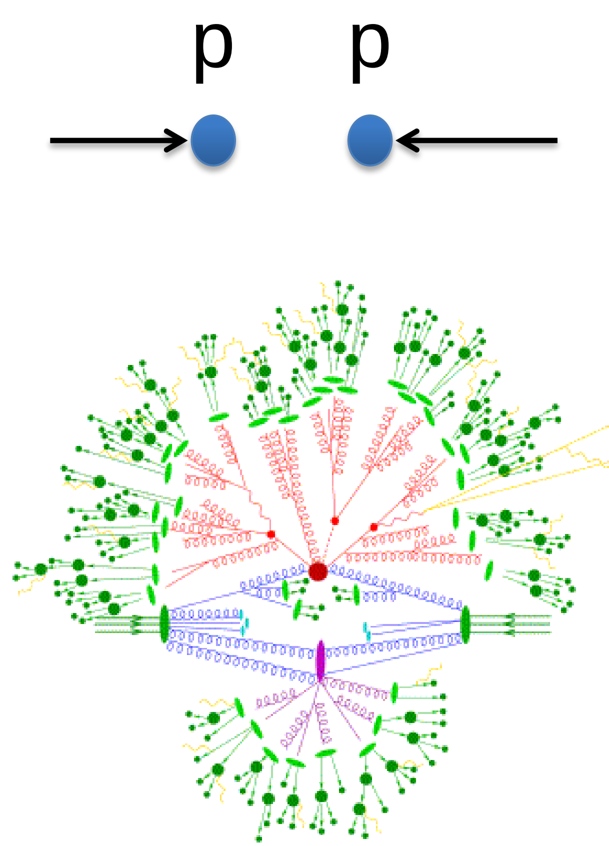




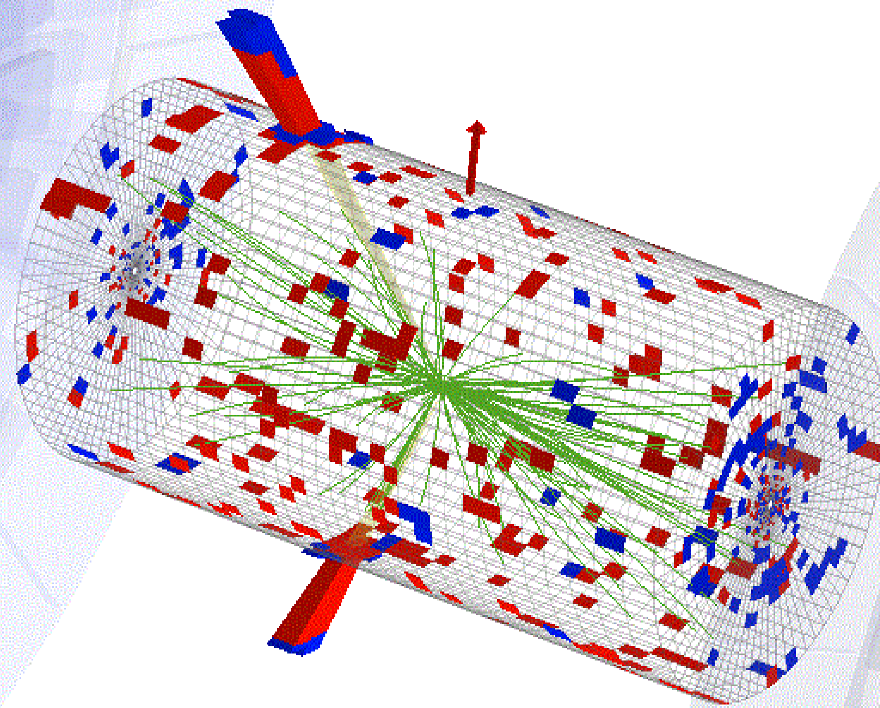
?

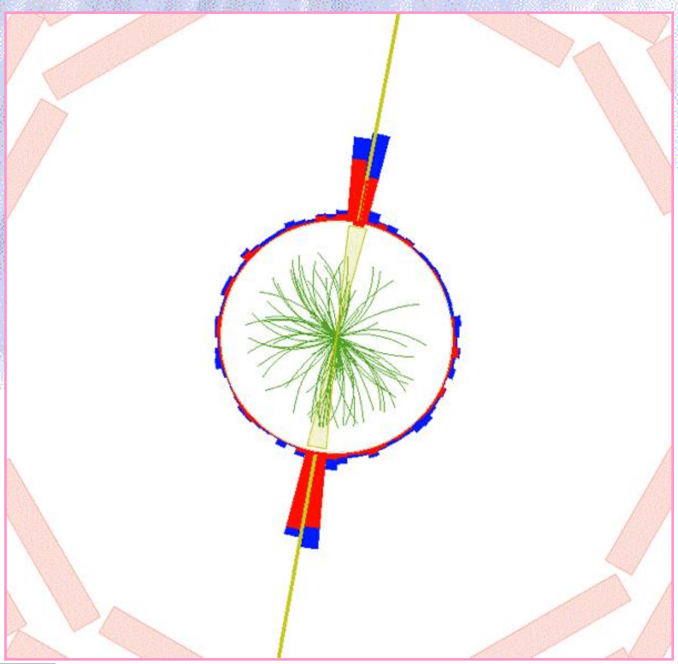
Missing link between pp and PbPb

Are there "Cold nuclear effect" or "initial state" effects for the understand of PbPb?



Dijet in pPb Collisions Recorded by CMS



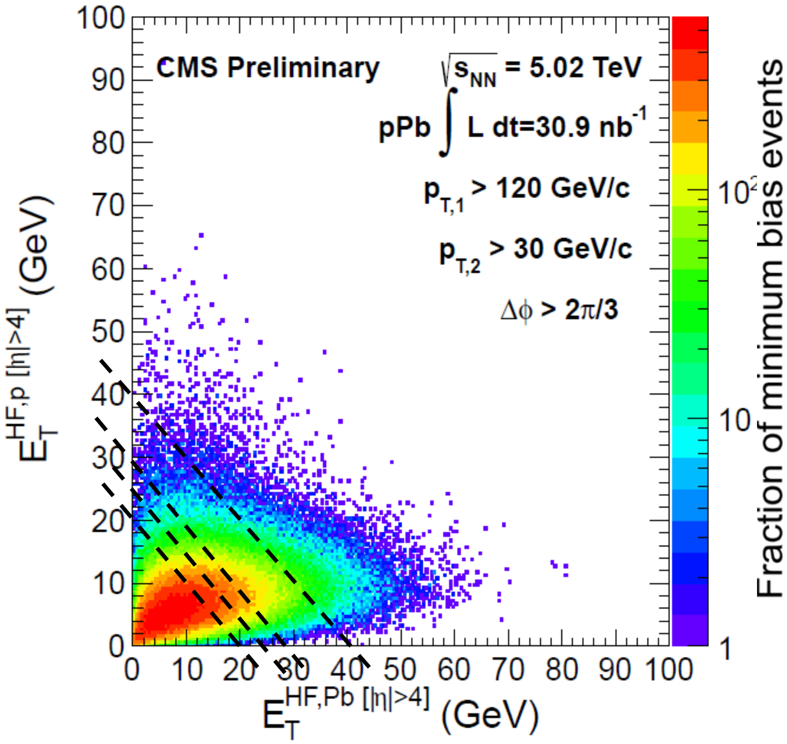


2012 pPb	1 μb^{-1}
2013 pPb	31 nb^{-1}

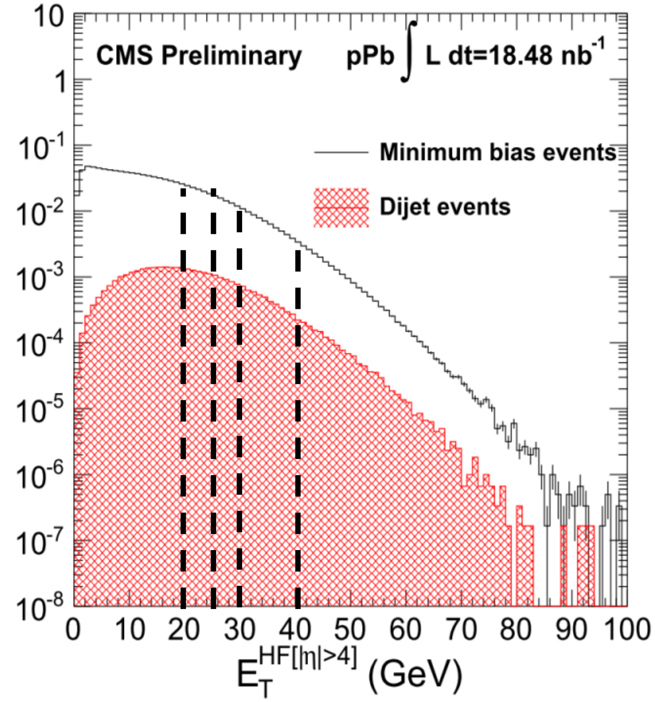
pPb Event Classification

CMS PAS HIN-13-001

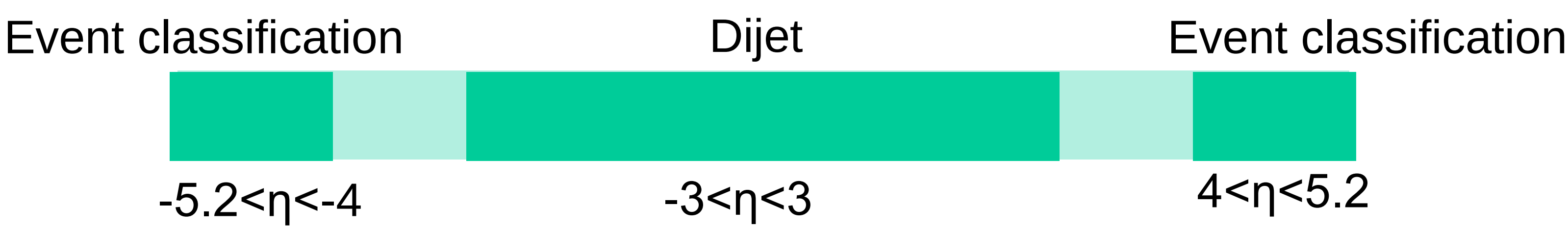
Proton Side Energy



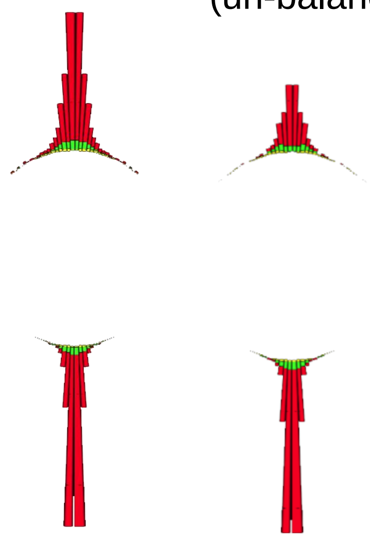
Pb Ion Side Energy

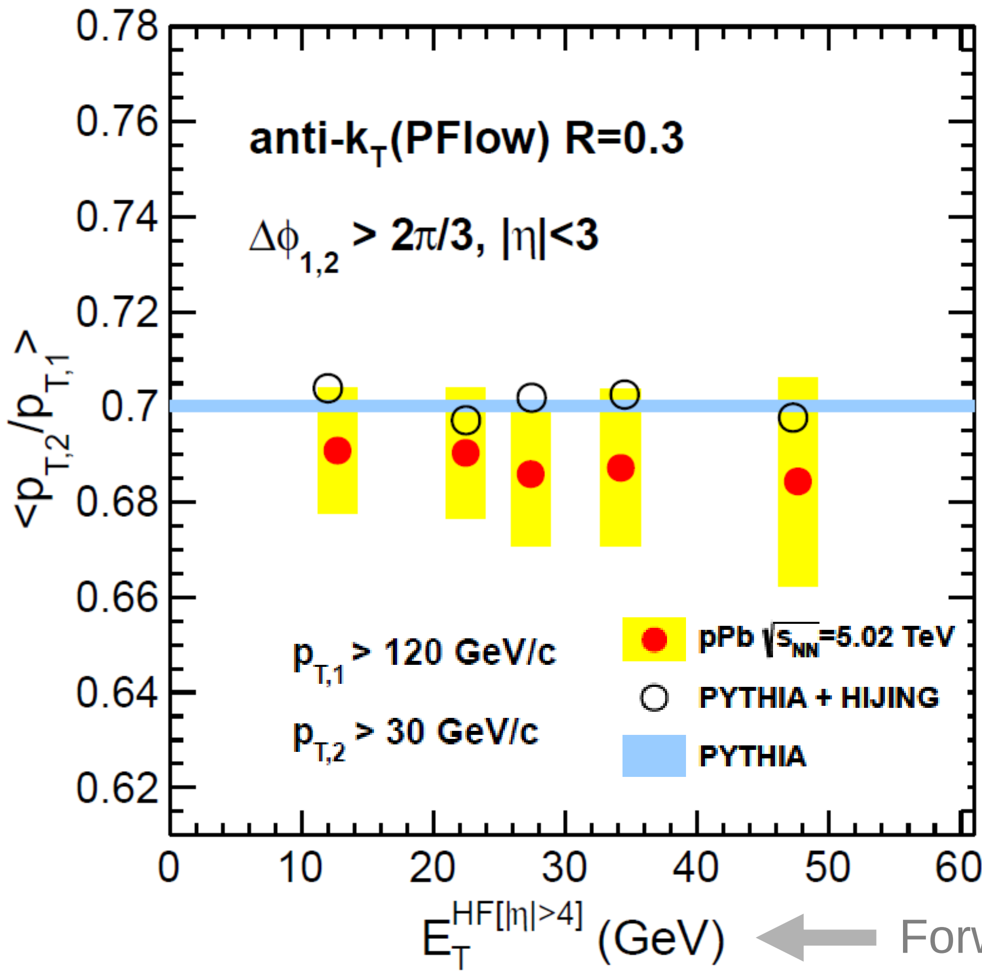


Minimum bias selection:
At least one particle with E>3 GeV in the pseudorapidity range -5 < η< -3 and one in the range 3 < η < 5



Dijet p_T Ratios in pPb Collisions





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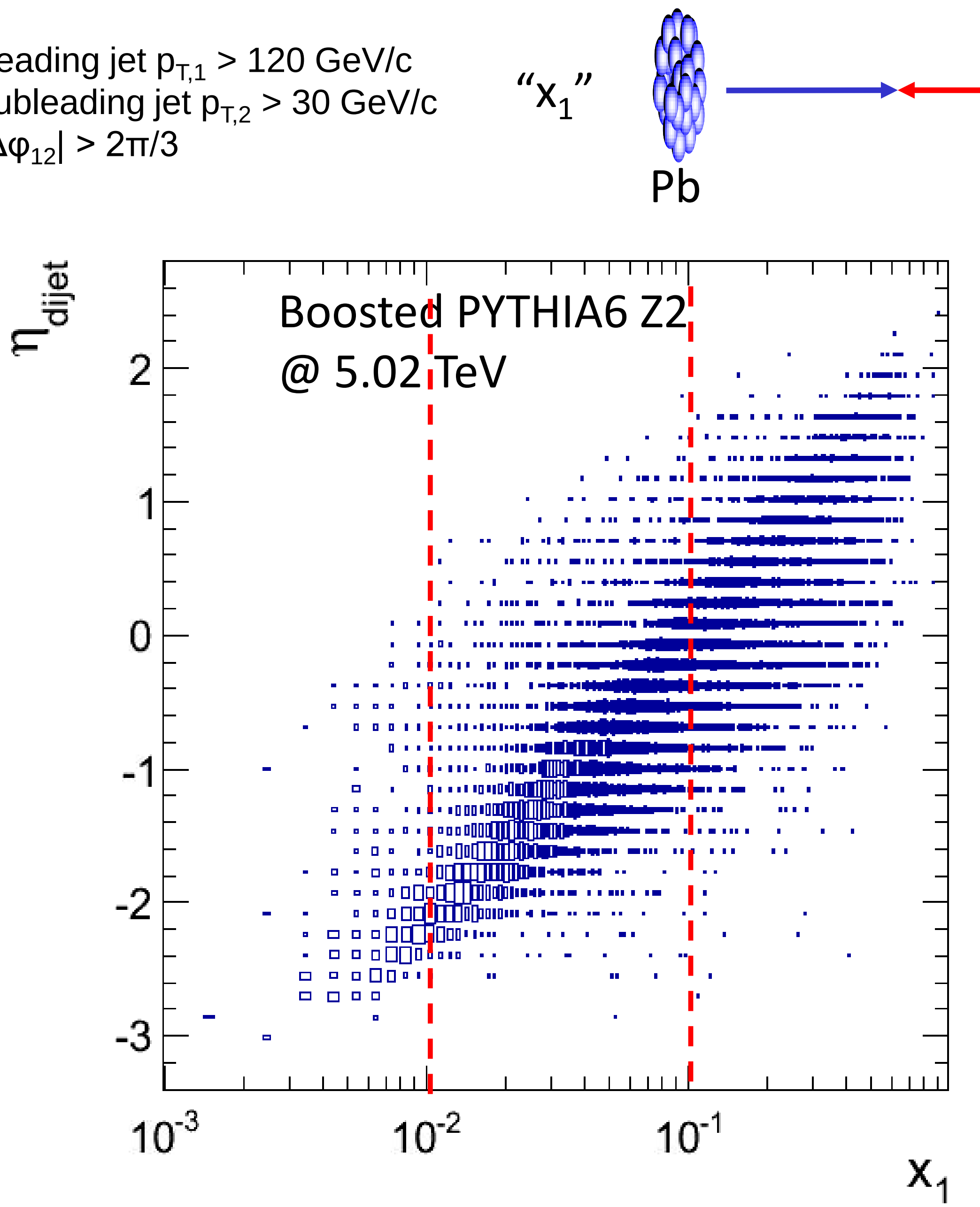
$$< \frac{\text{Subeading jet } p_T}{\text{Leading jet } p_T} >$$

- A ~10% drop in dijet pT ratio was observed in PbPb 0-10% central collisions
- In pPb collsions: With the current systematic uncertainty, no detectable change in $<p_{T,2}/p_{T,1}>$ as a function of forward calorimeter energy
- **Establish the basis to use the jets for nPDF determination**

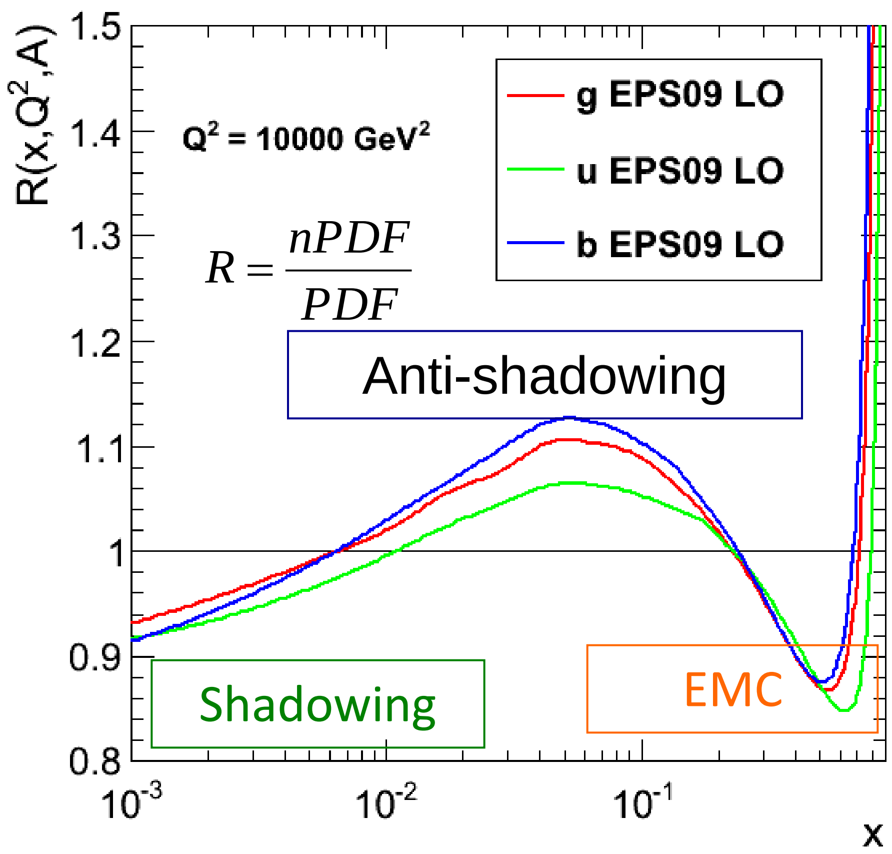
Dijet η_{dijet} Distributions

Leading jet $p_{T,1}$ > 120 GeV/c
subleading jet $p_{T,2}$ > 30 GeV/c
$|\Delta\varphi_{12}| > 2\pi/3$

$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$



Lead nucleus PDF / Nucleon PDF



Compare to NLO Calculations

Escola, Paukkunen, Salgado. arxiv:1308.6733

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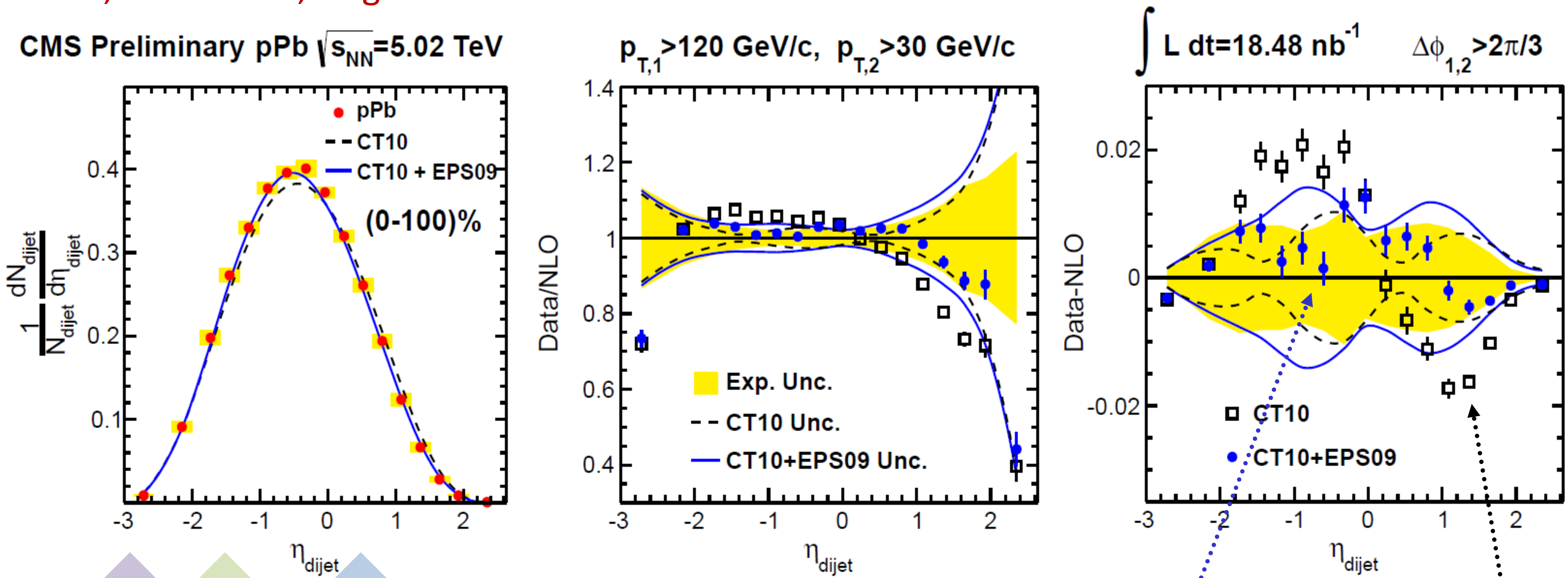

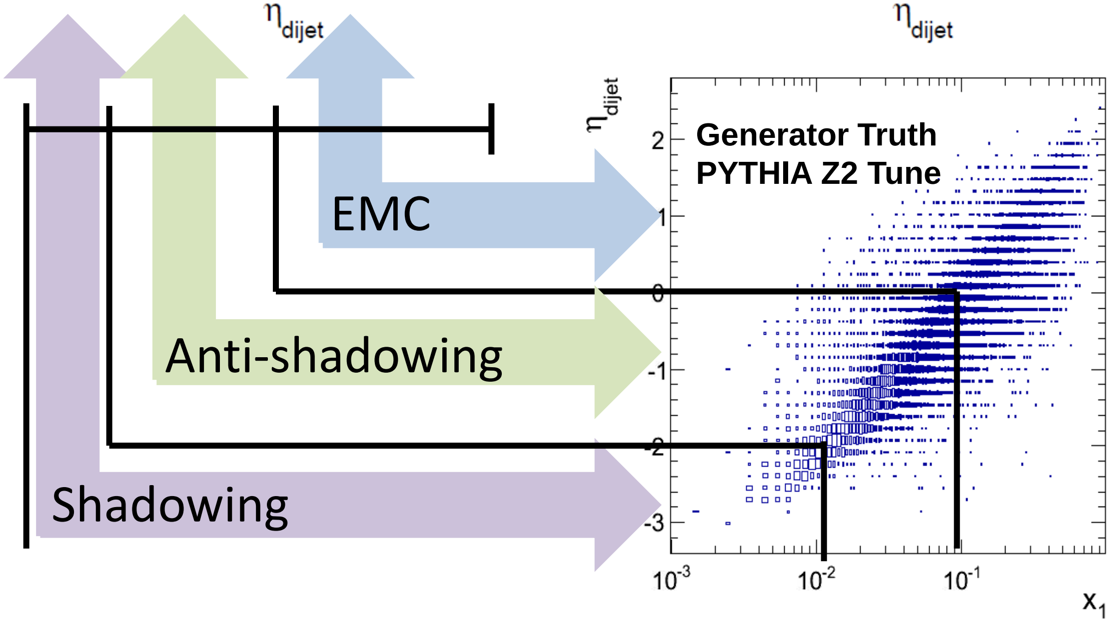

CT10 nucleon PDF

CT10 x EPS09 nPDF

Agreement between data with EPS09 within systematical uncertainty

Dijet η in different event classes

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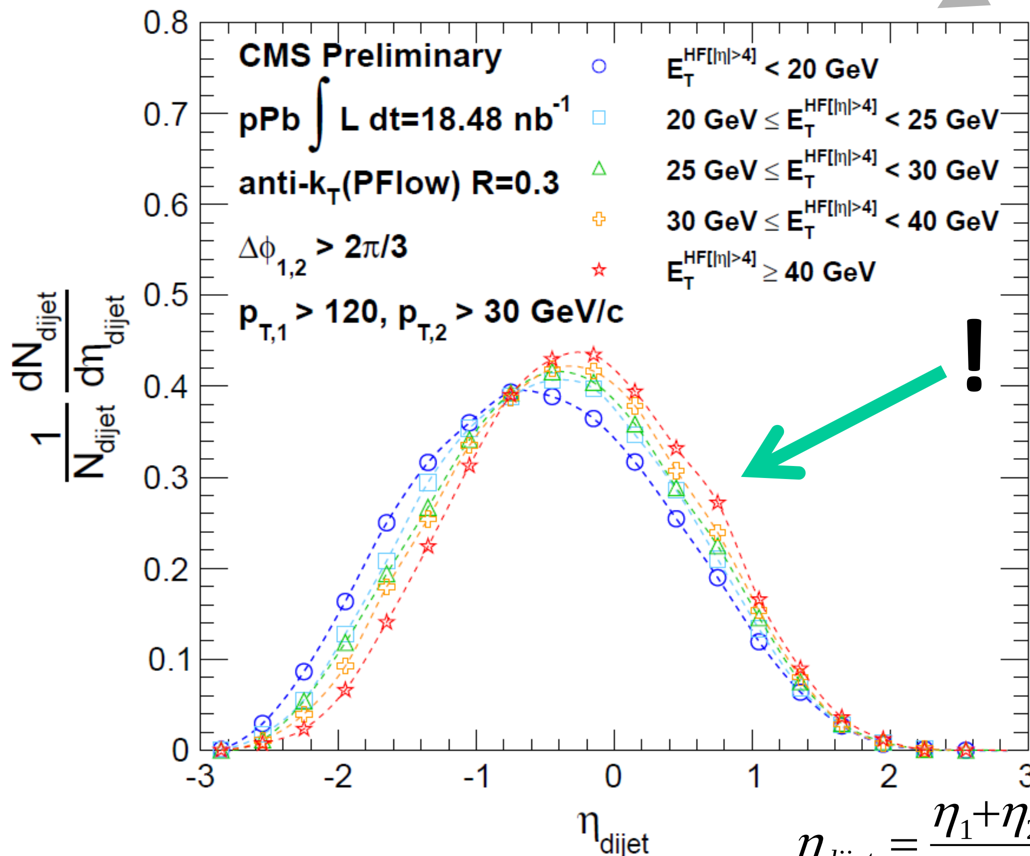
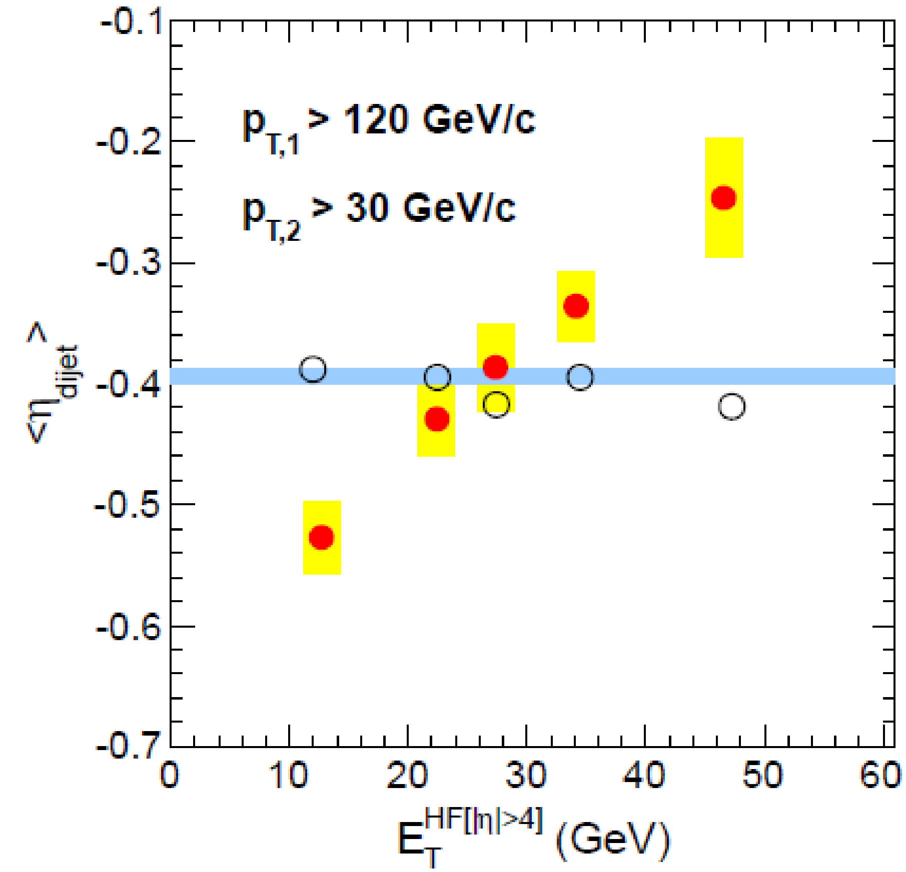
Normalized by N_{dijet}

Event Classes with Different Forward Calorimeter E_T



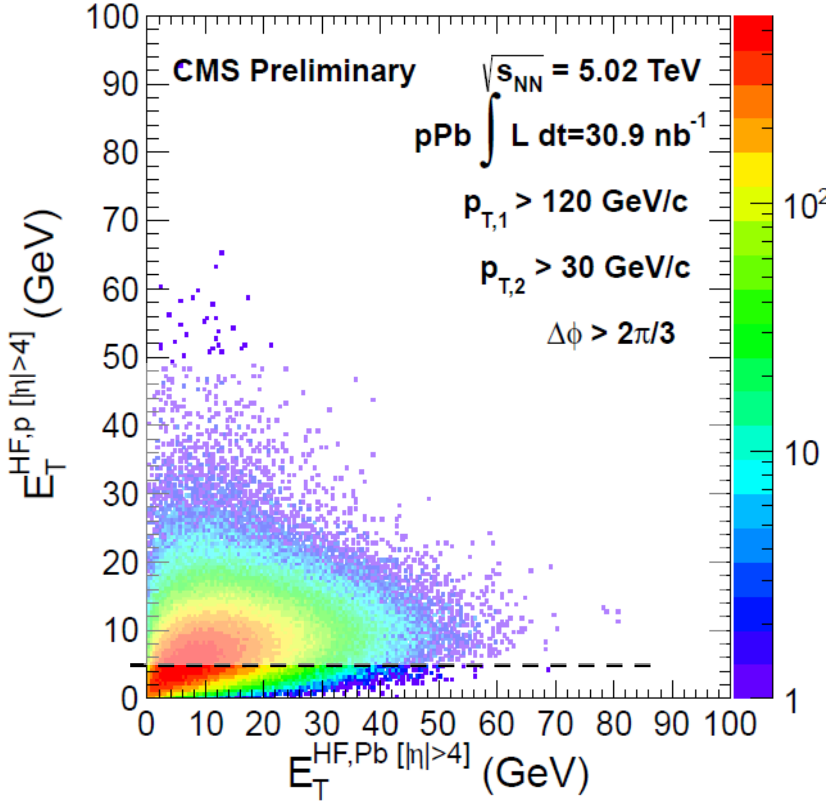
$$\eta_{dijet} = \frac{\eta_1 + \eta_2}{2}$$



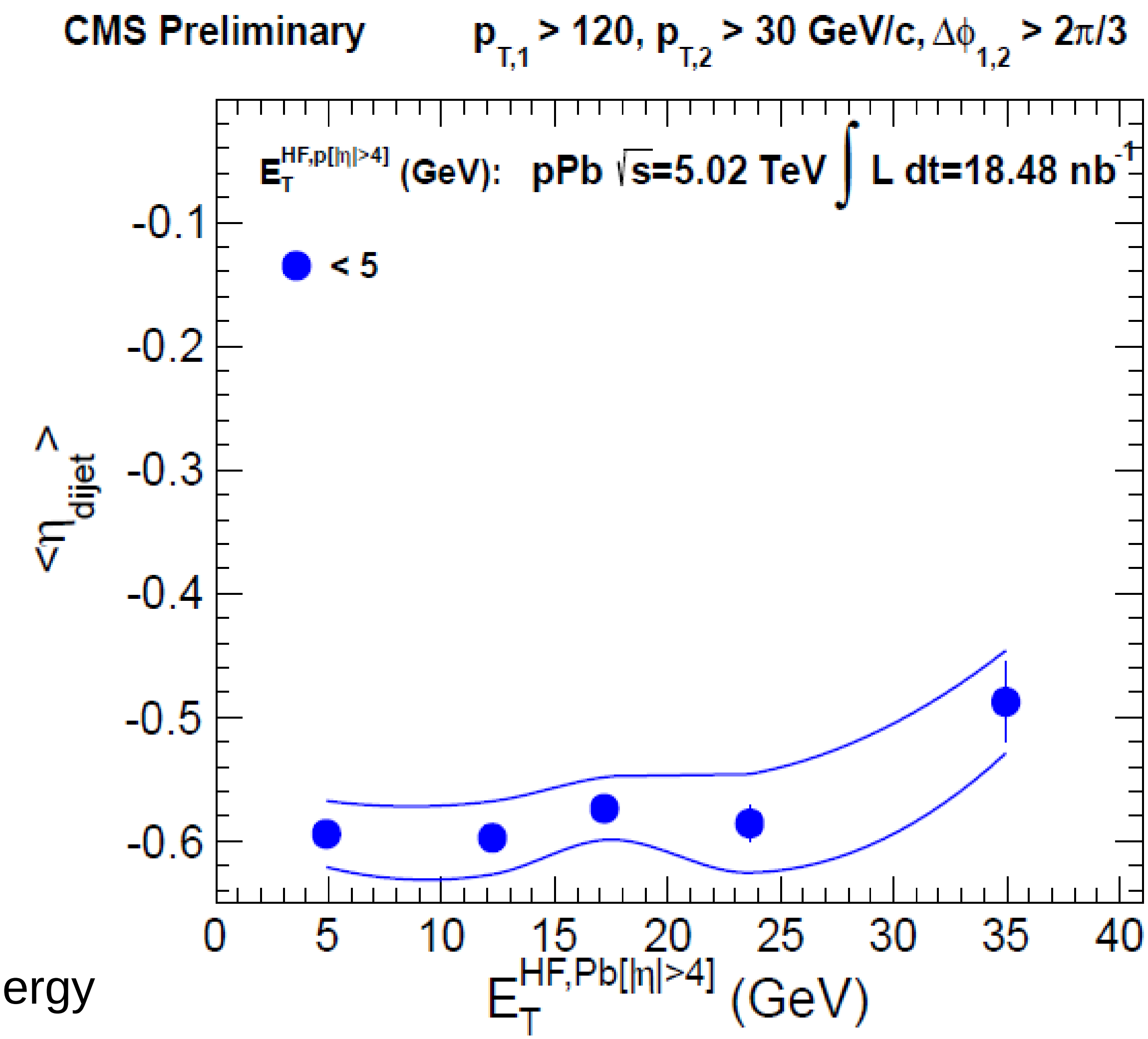
- Dijet η distribution changes as a function of forward calorimeter energy.
- The large modification can not be explained by shadowing effect or centrality dependent PDF

Dijet η At Fixed Proton Side Activity

Proton Side Energy



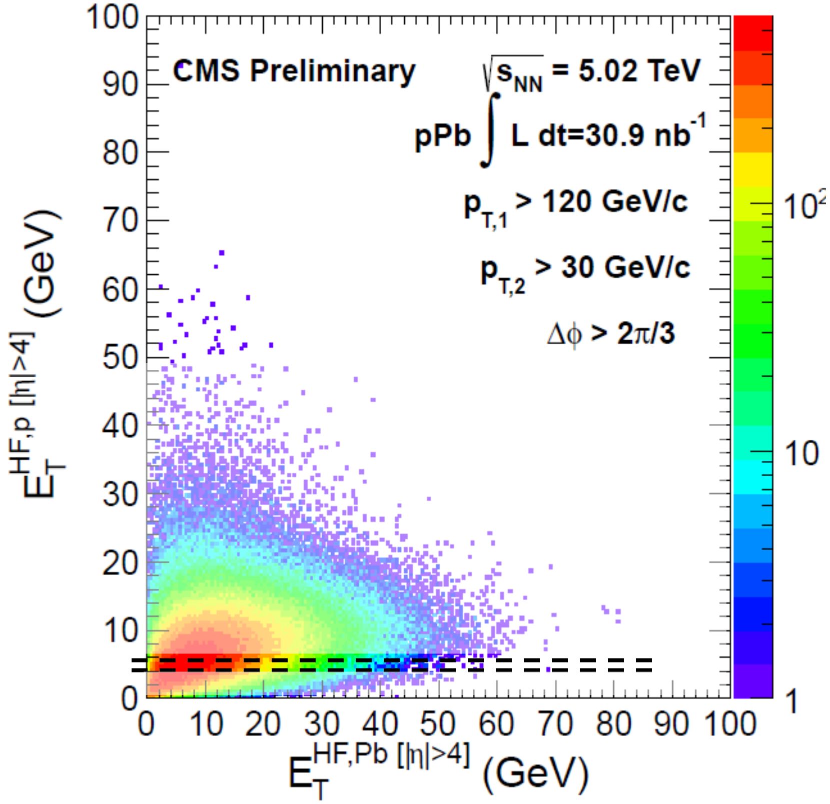
Pb Ion Side Energy

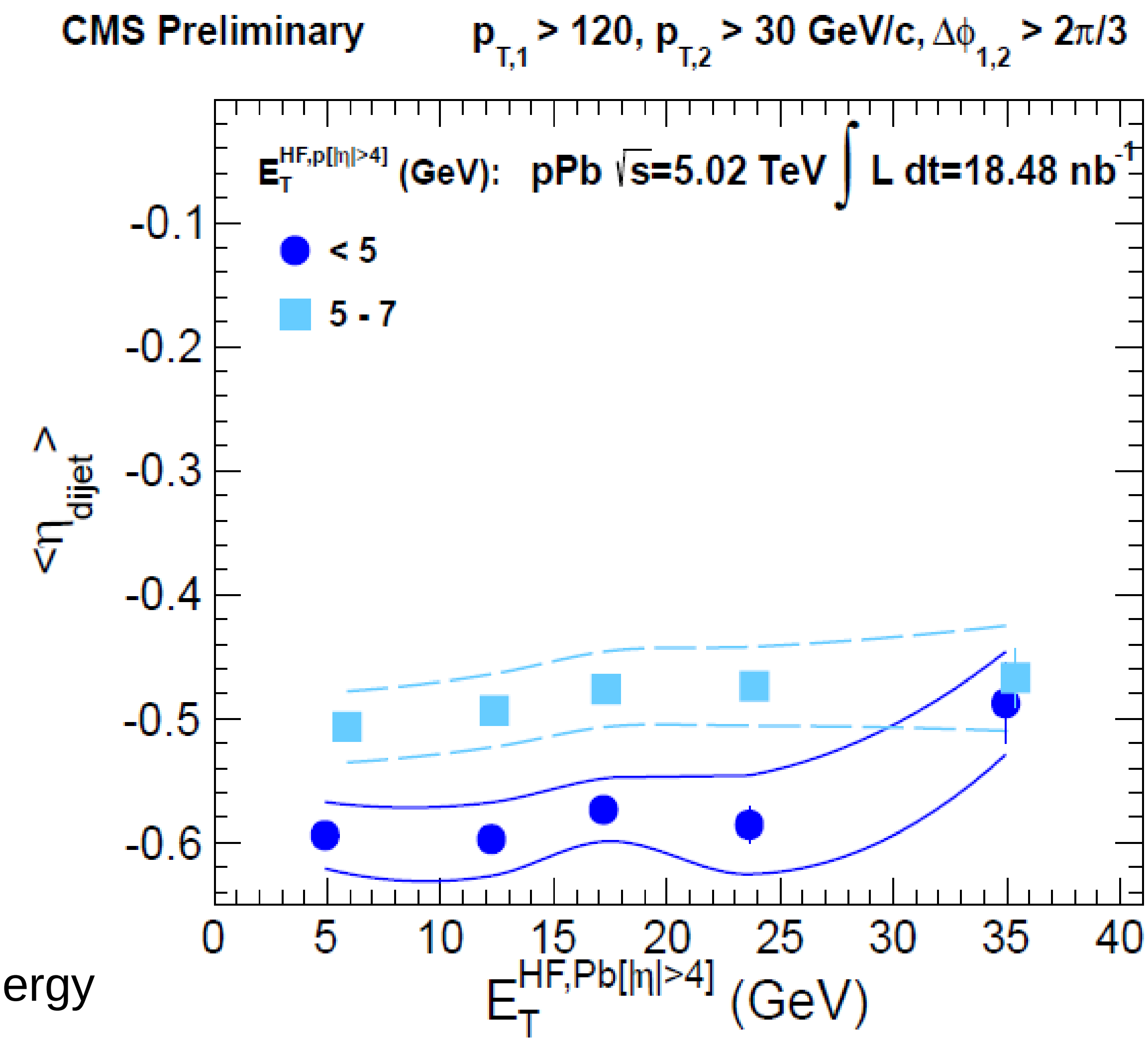


- When energy on proton side is small $<\eta_{dijet}>$ almost flat as a function of forward activity on Pb side.

Dijet η At Fixed Proton Side Activity

Proton Side Energy



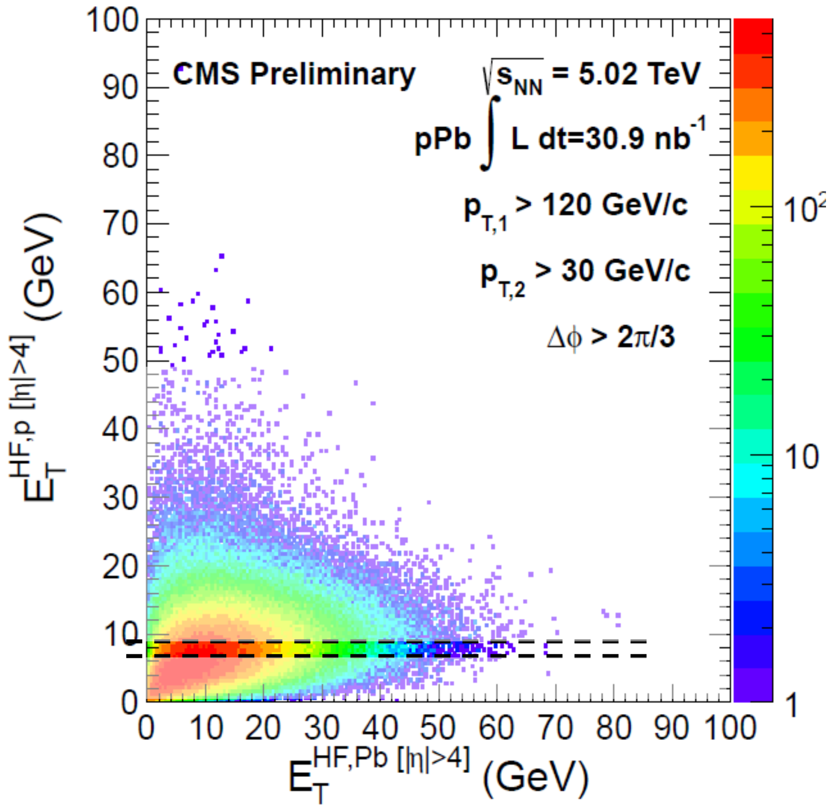


Pb Ion Side Energy

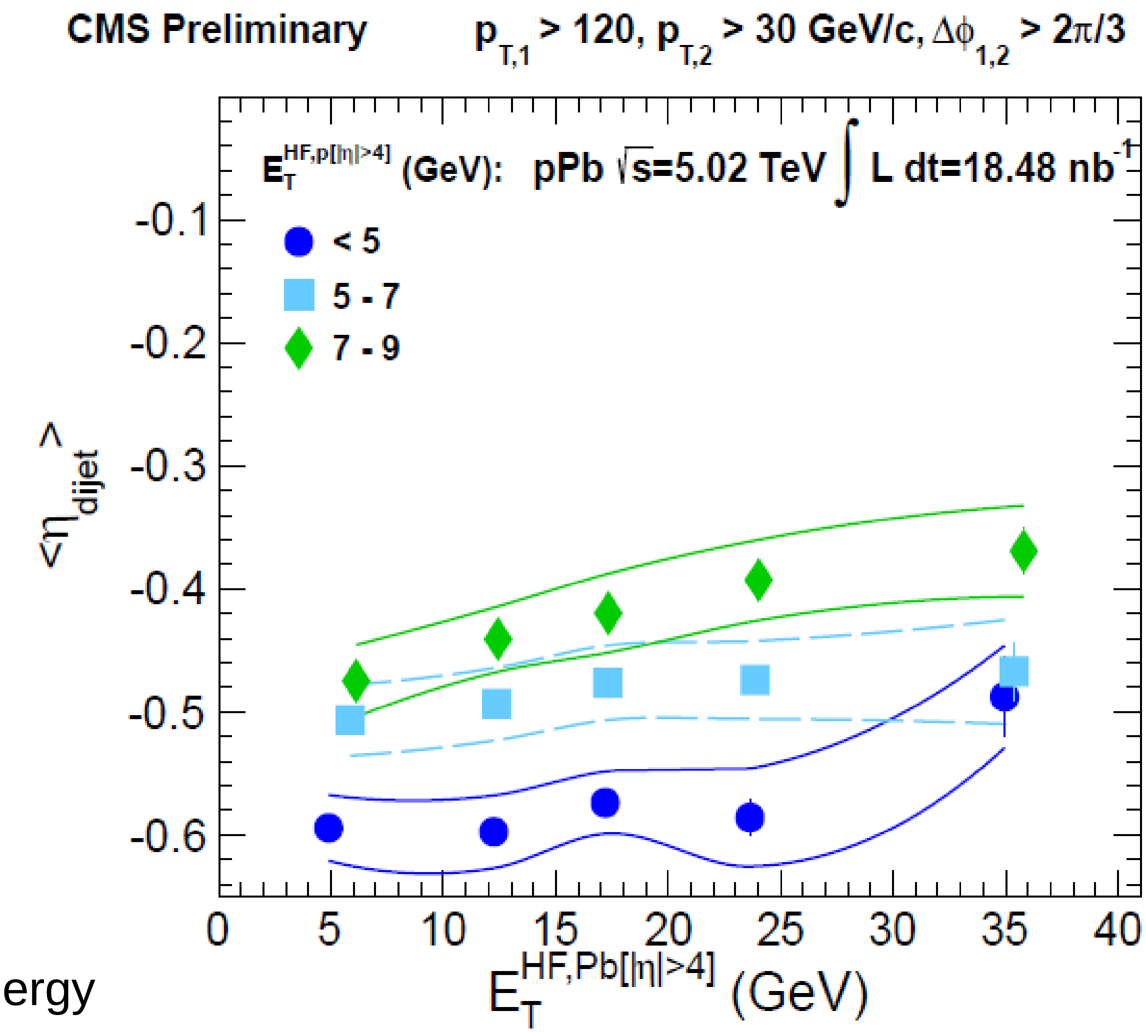
Still flat..

Dijet η At Fixed Proton Side Activity

Proton Side Energy

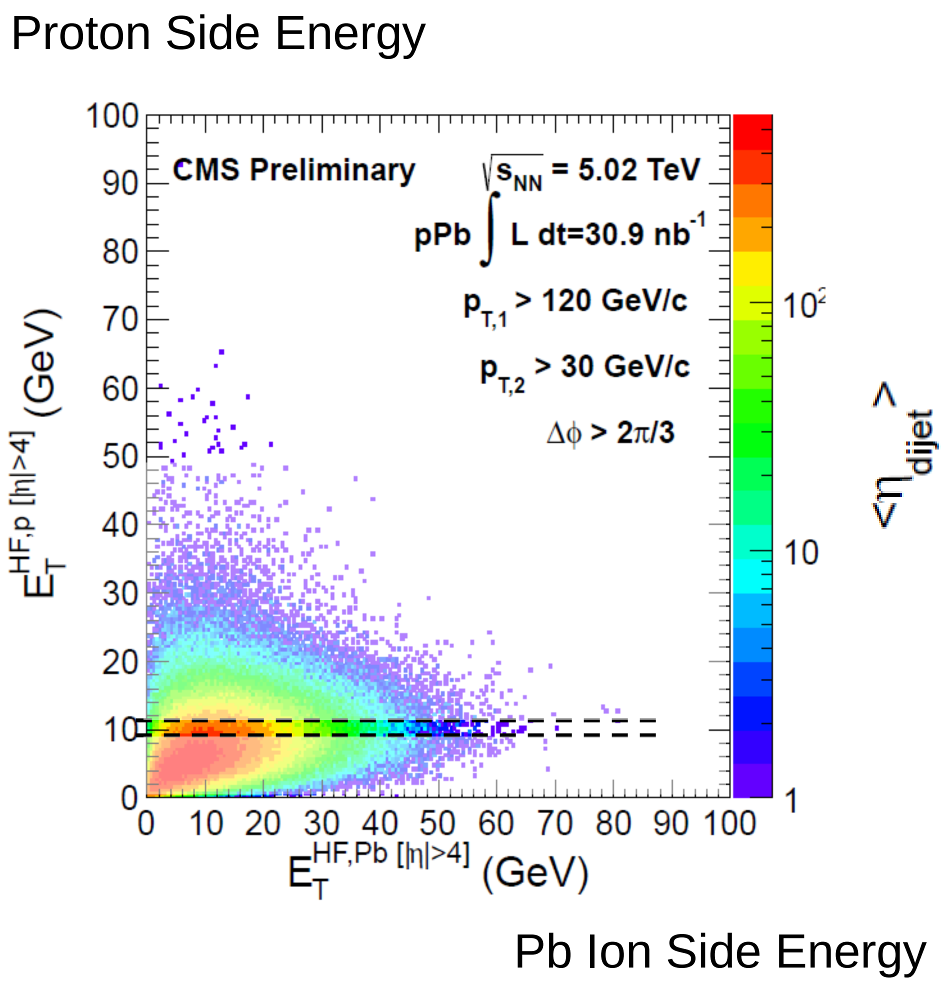


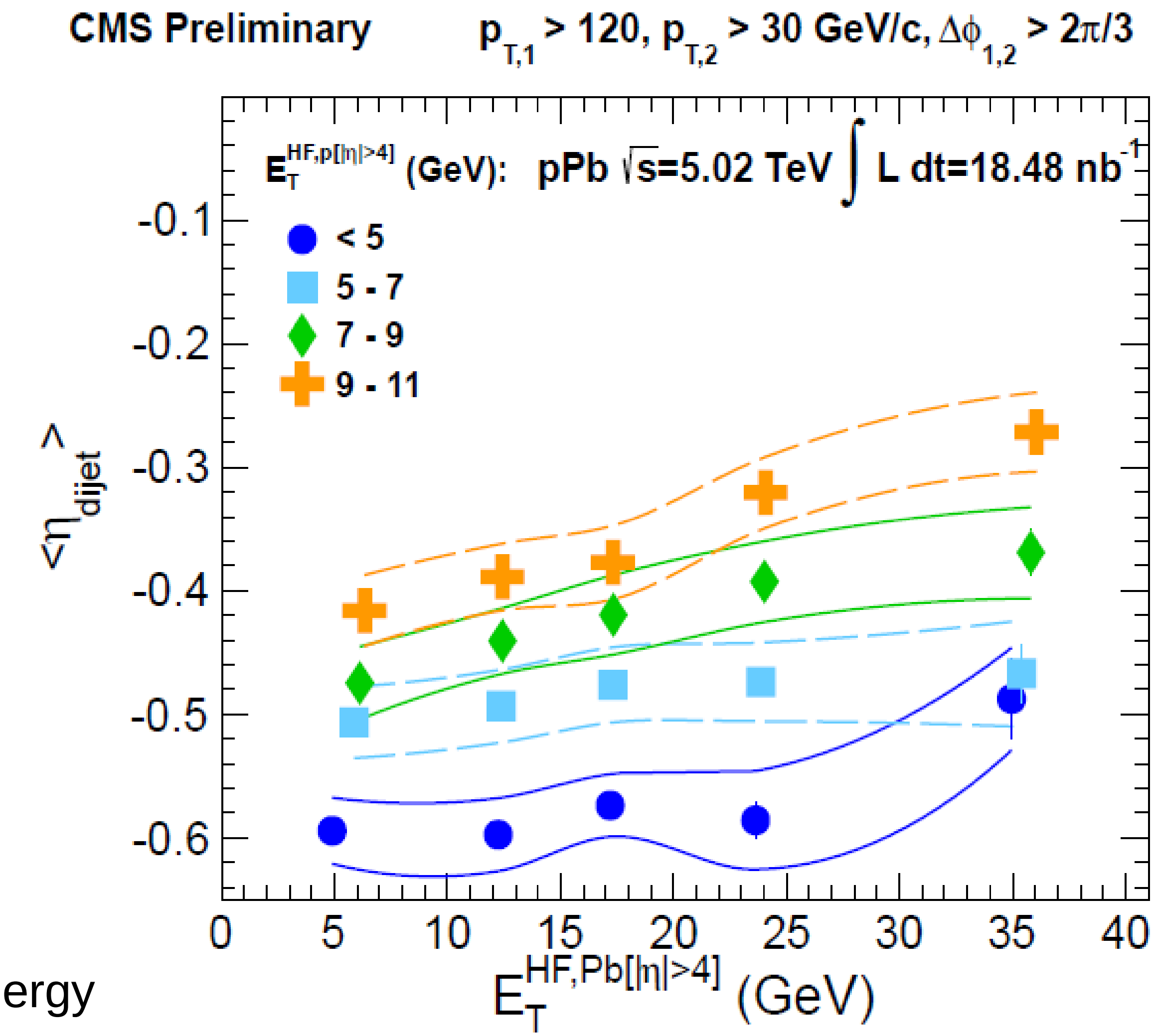
Pb Ion Side Energy



Slope starts to increase..

Dijet η At Fixed Proton Side Activity

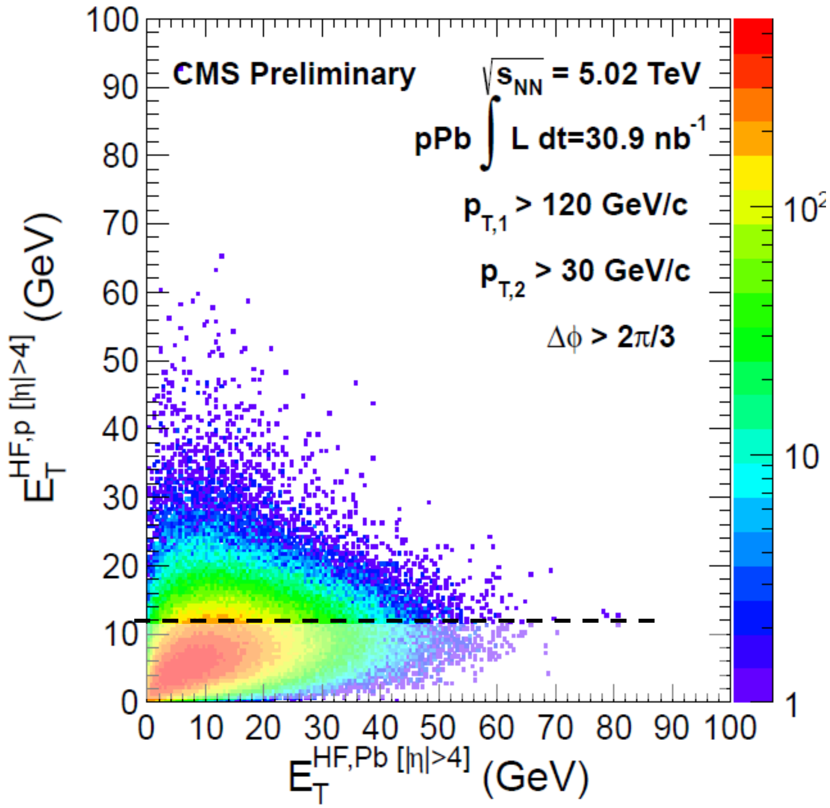


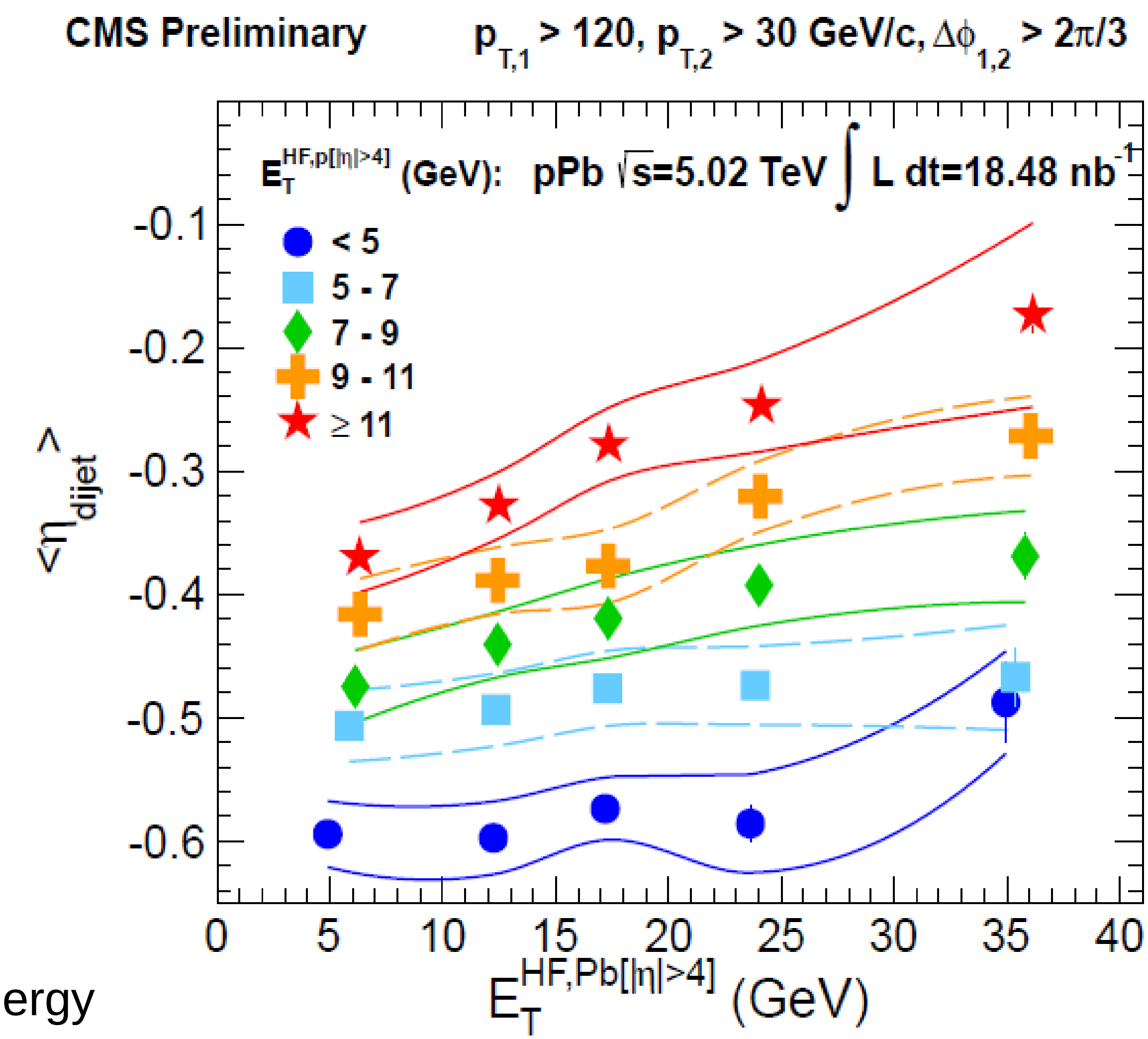


Slope increases even more..

Dijet η At Fixed Proton Side Activity

Proton Side Energy





Pb Ion Side Energy

And even more..

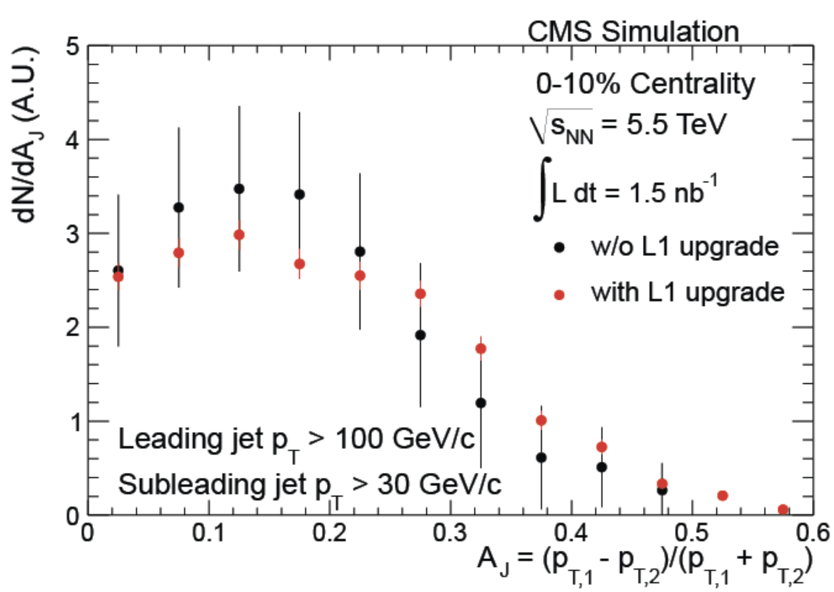
Summary

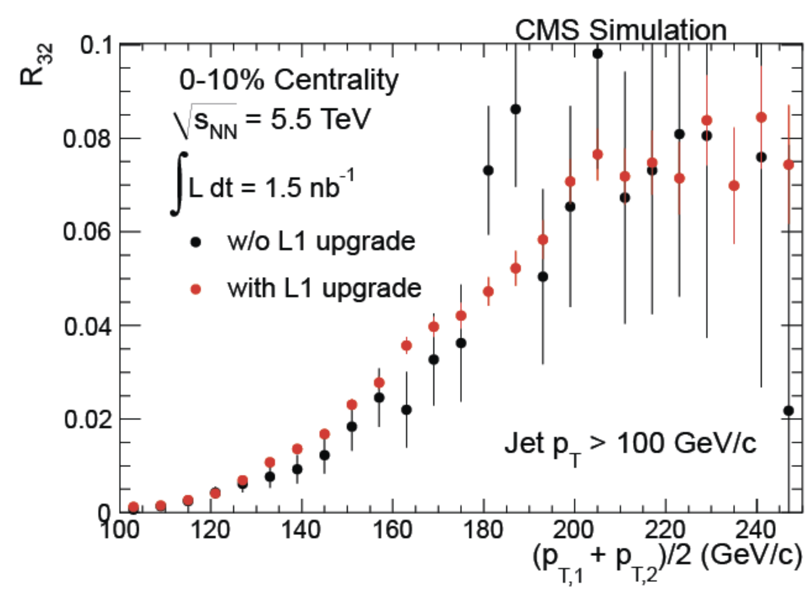
- CMS has presented interesting results using tracks, photons, muons and jets in heavy ion collisions
  - Confirmed N_{coll} scaling using colorless probes
  - An unprecedented picture of jet quenching is emerging
- Jet quenching in pPb collisions:
  - No significant modification observed in dijet p_T ratio (shift in dijet p_T ratio < 2%)
- Dijet pseudorapidity distributions in pPb collisions:
  - Provide useful constraints for nPDF determination
  - Strong correlation between η_{dijet} v.s. forward calorimeter energy is observed
- A lot of exciting analyses on the high statistics data expected in 2015
  - Parton flavor dependence of jet quenching
  - High statistics photon-jet and Z-jet events

Backup slides

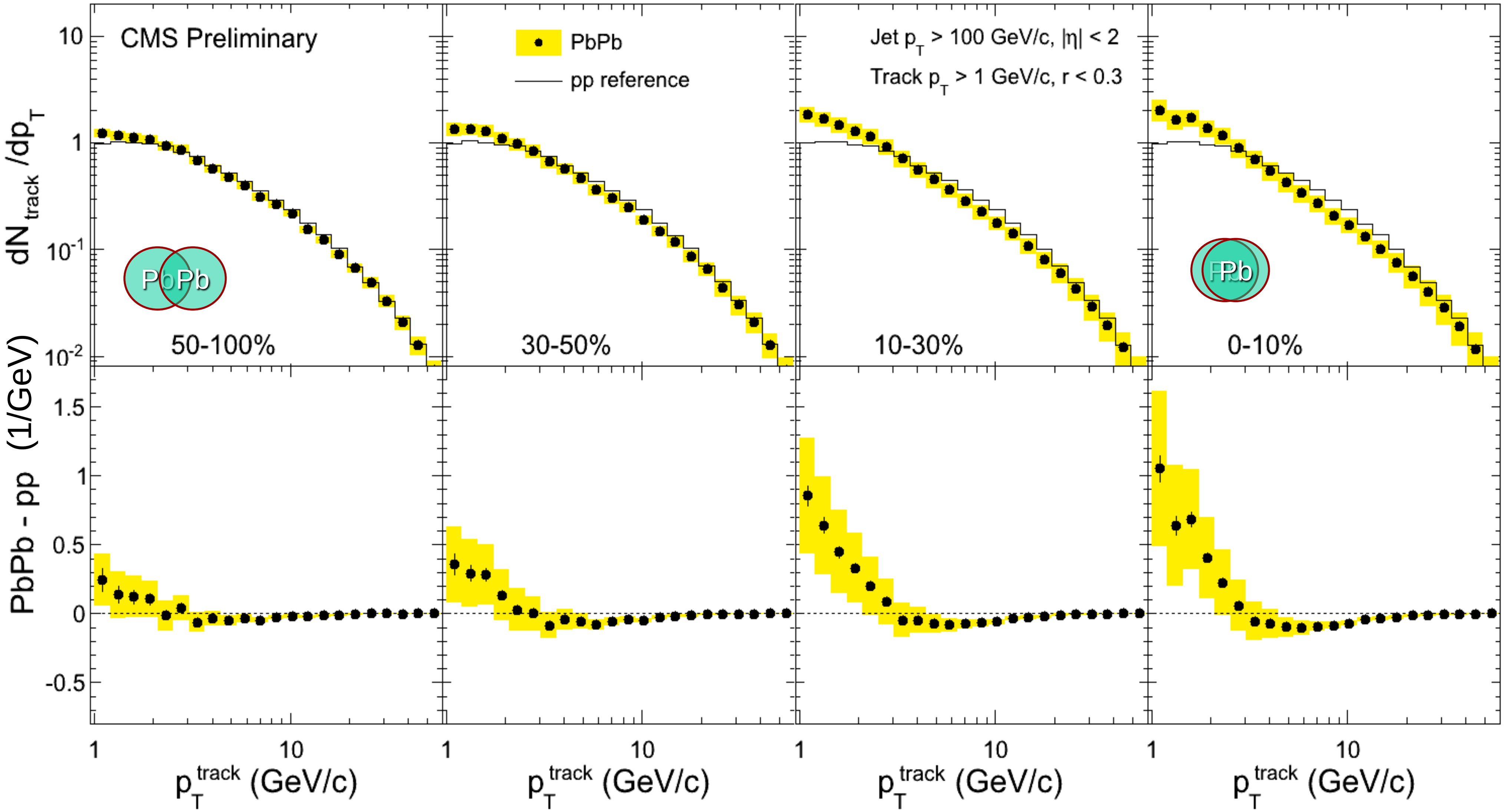
Outlook

- Level-1 online trigger system upgrade: permit high luminosity data taking and efficient online jet trigger
- Extension of the existing analysis in 2015
  - Photon-track and Z-track correlation
  - Flavor dependence of jet quenching:
    - b jet tagging and di-b-jet asymmetry
    - Gluon jet quenching: 3-jet to 2-jet ratio
    - Identified heavy flavour meson





Track p_T distributions in jet cones (R=0.3)

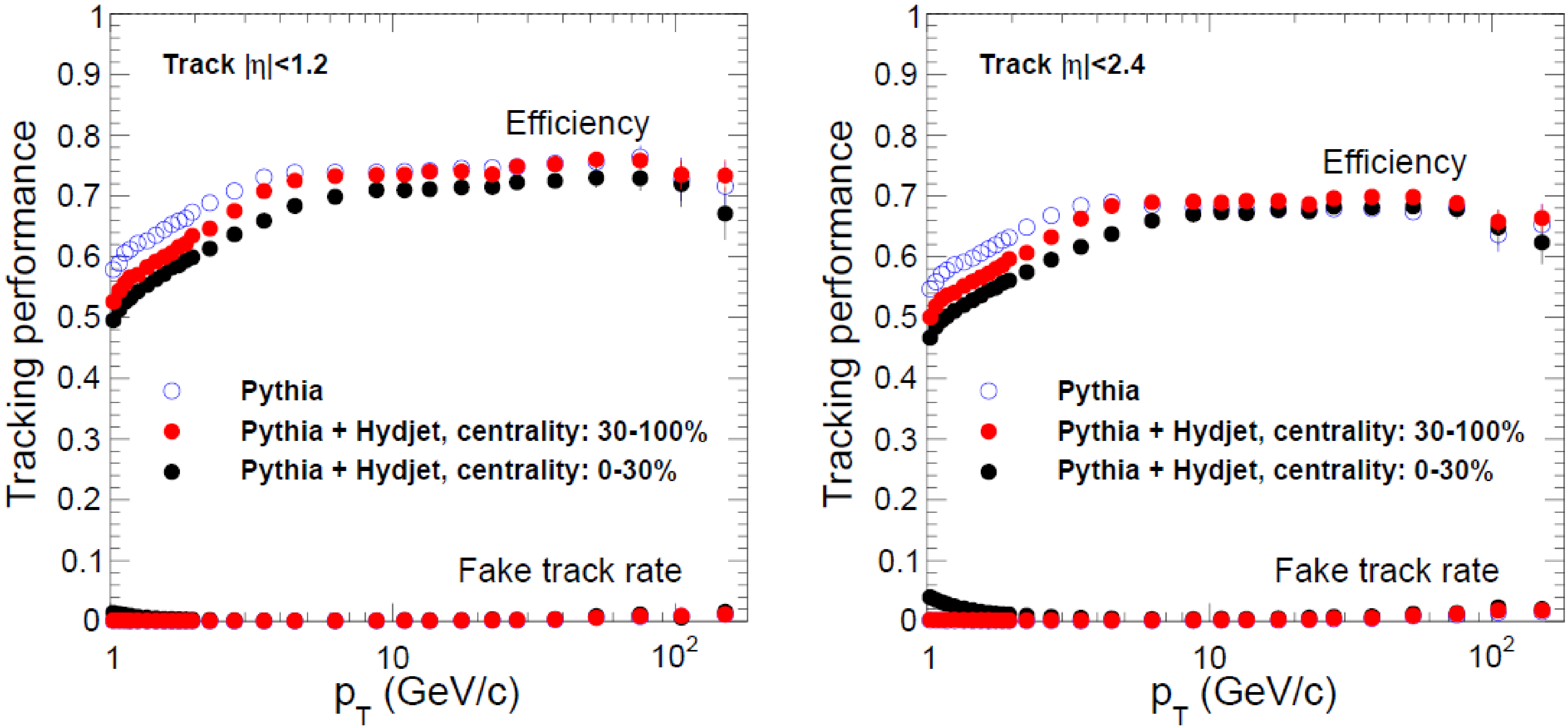


High p_T : **no change** compared to jets in pp collisions

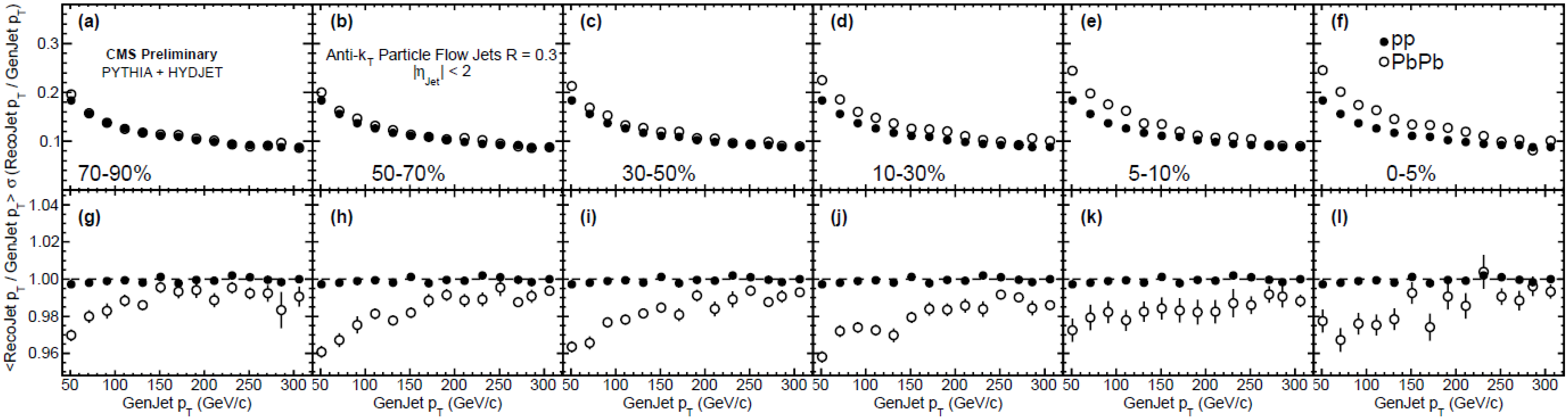
In (central) PbPb: **excess** of tracks compared to pp at low p_T

CMS PAS HIN-12-013

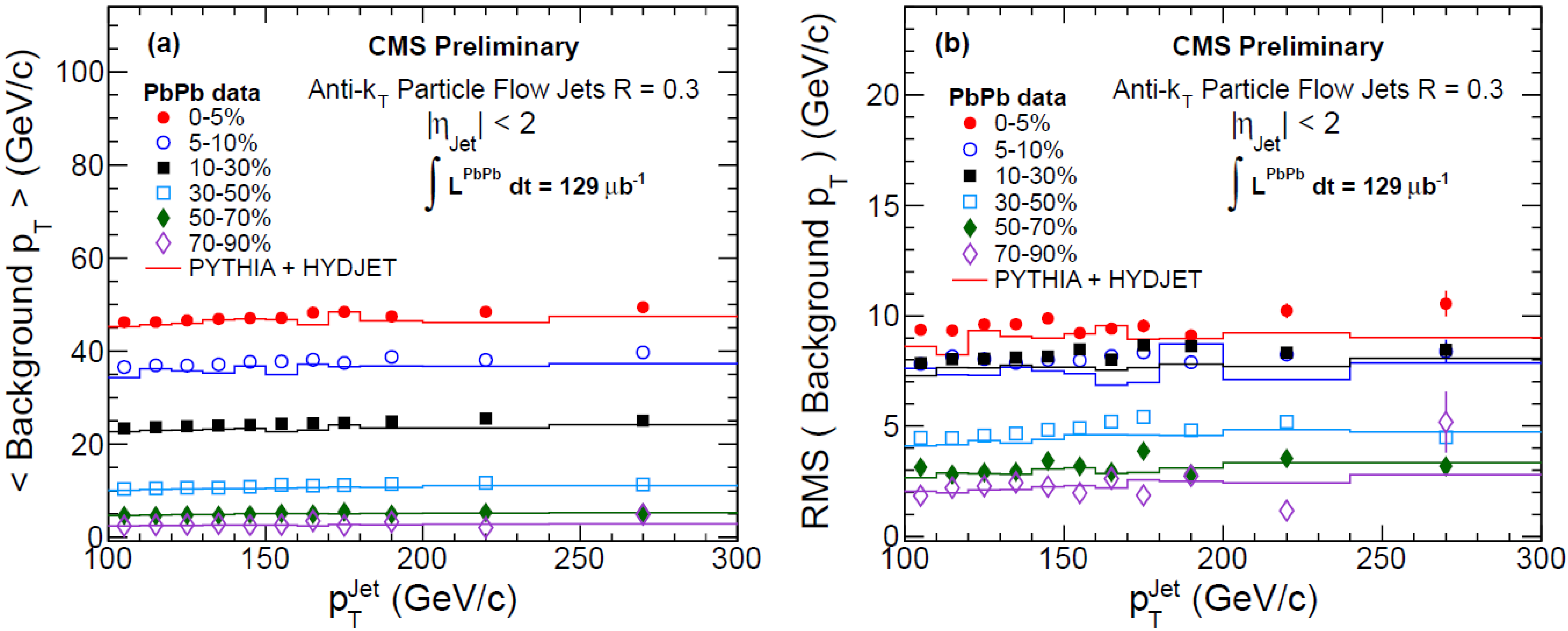
Tracking efficiency



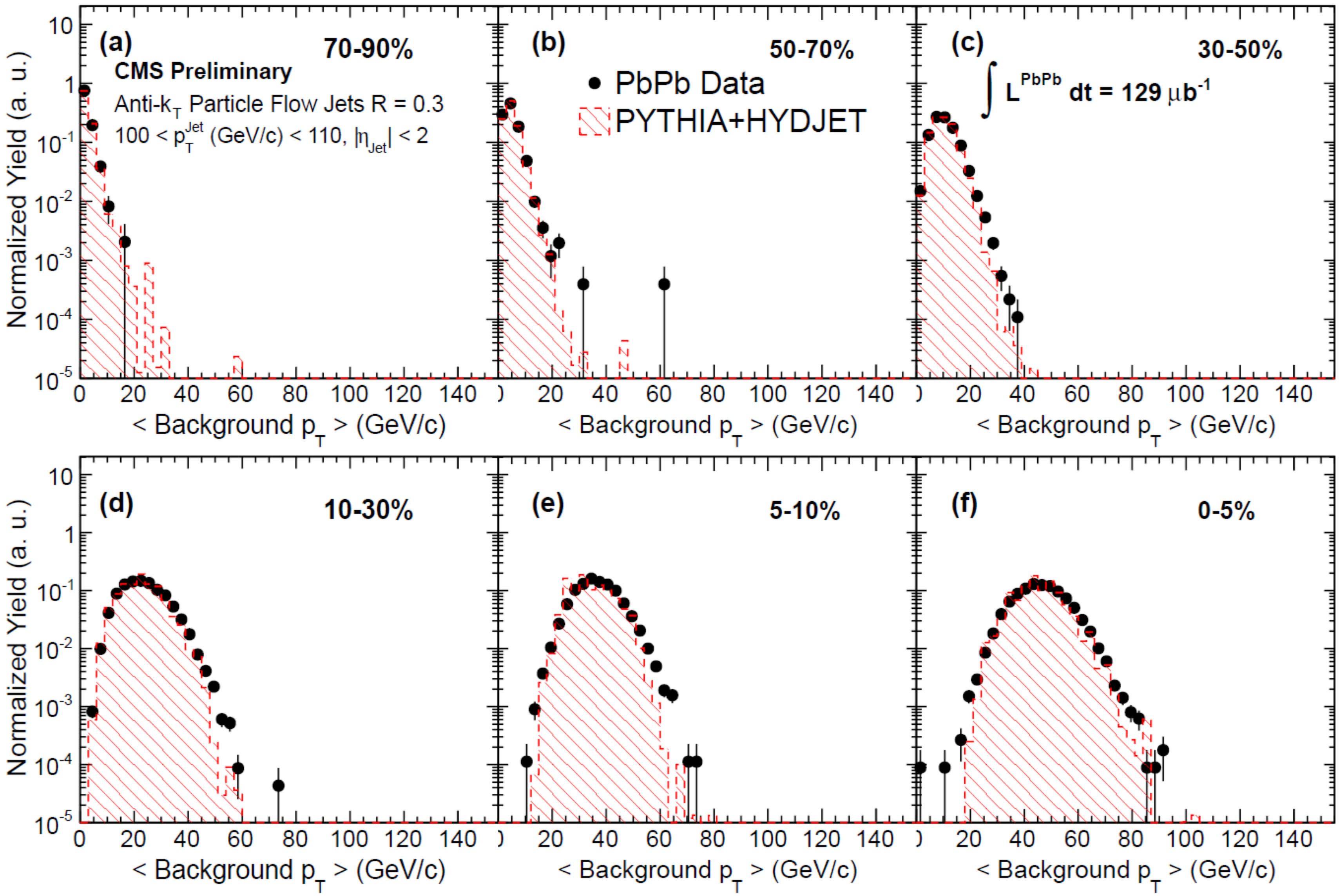
Jet resolution and enery scale



Subtracted background



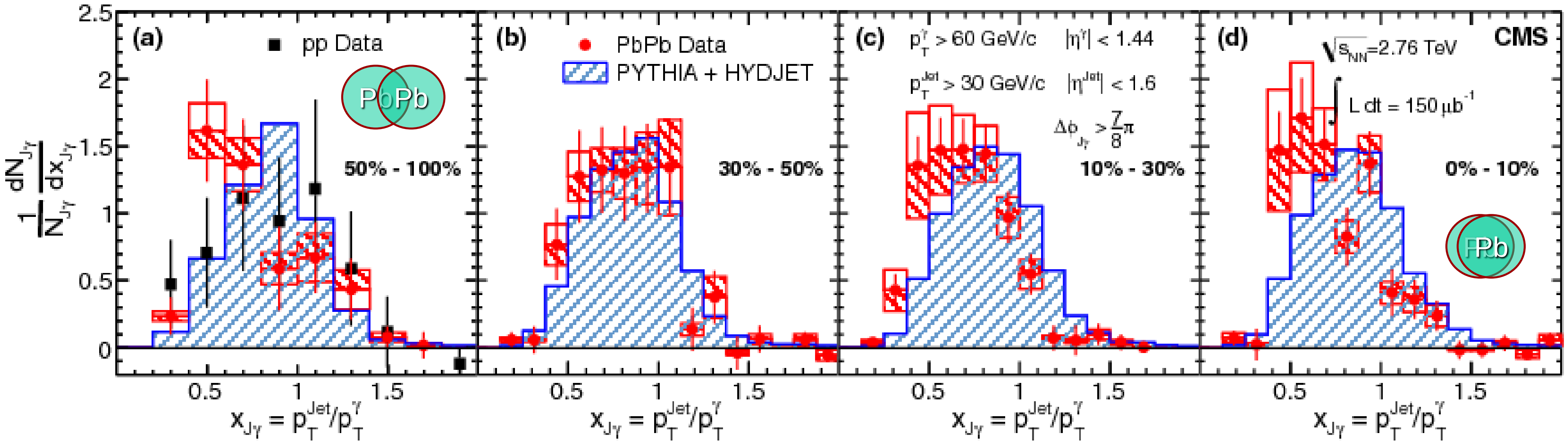
Subtracted background



γ-jet correlations

- Photons serve as an unmodified energy tag for the jet partner
- Ratio of the p_T of jets to photons ($x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$) is a direct measure of the jet energy loss
- Gradual centrality-dependence of the $x_{J\gamma}$ distribution

Anti-k_T jet R = 0.3



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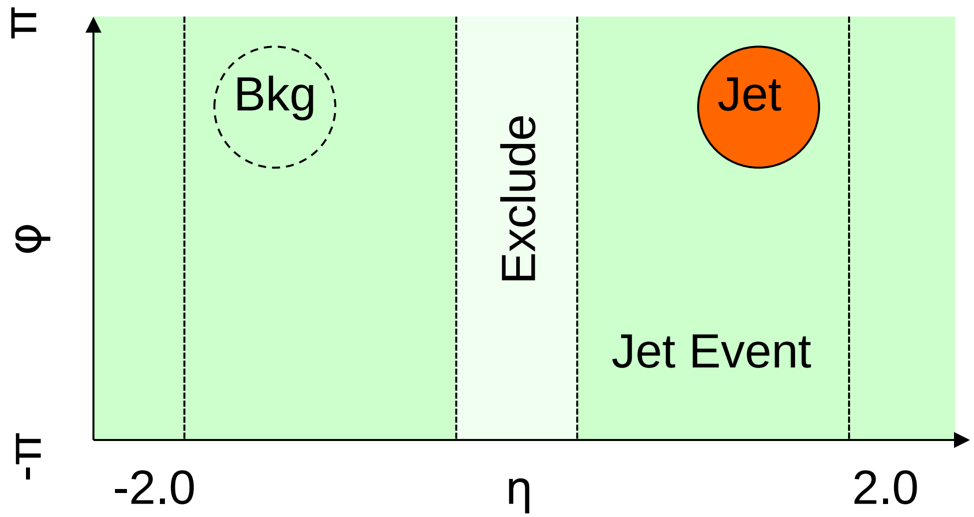
Background subtraction



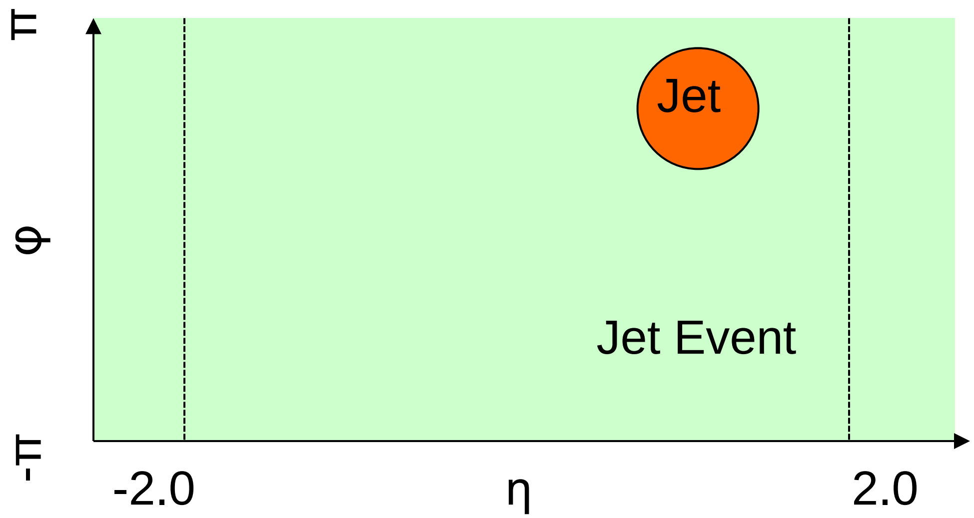
η reflection Method

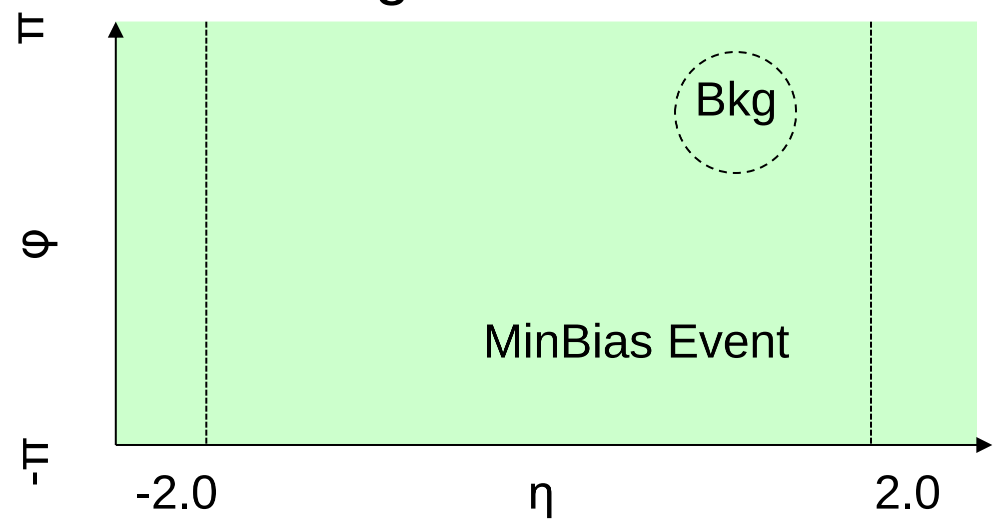
Main result

Same technique

Used in FF and jet shape

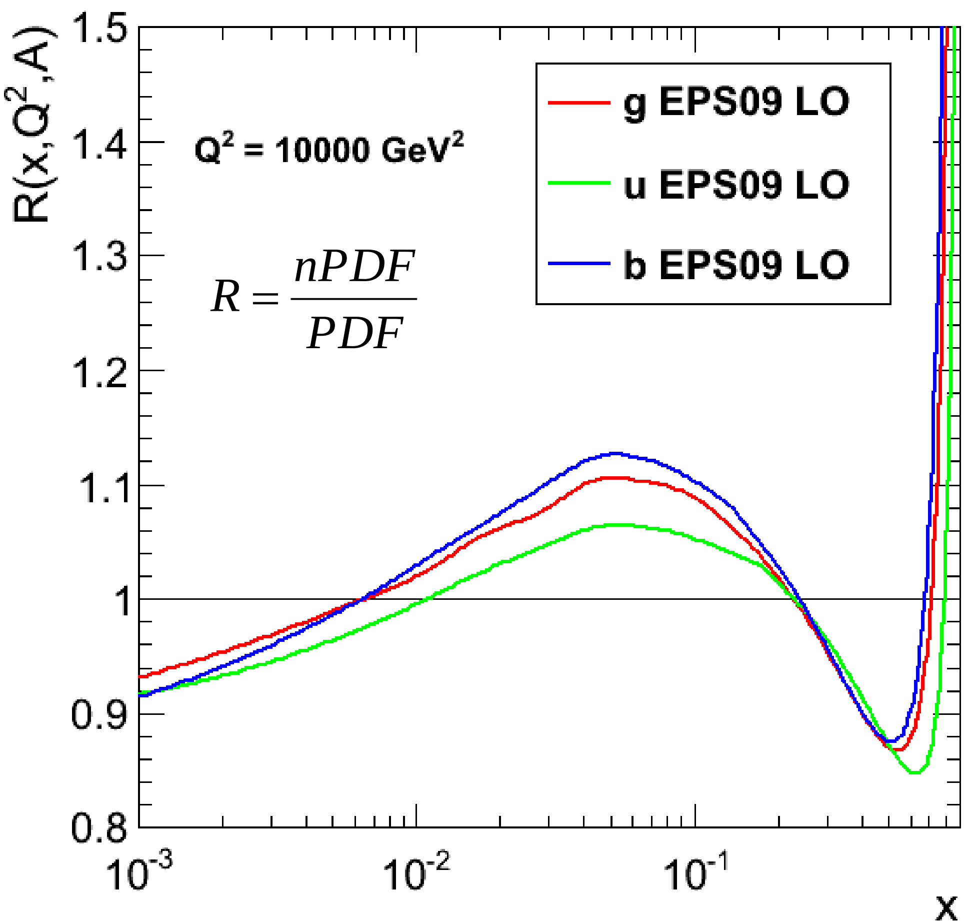
Event Mixing Method (Cross-checks)



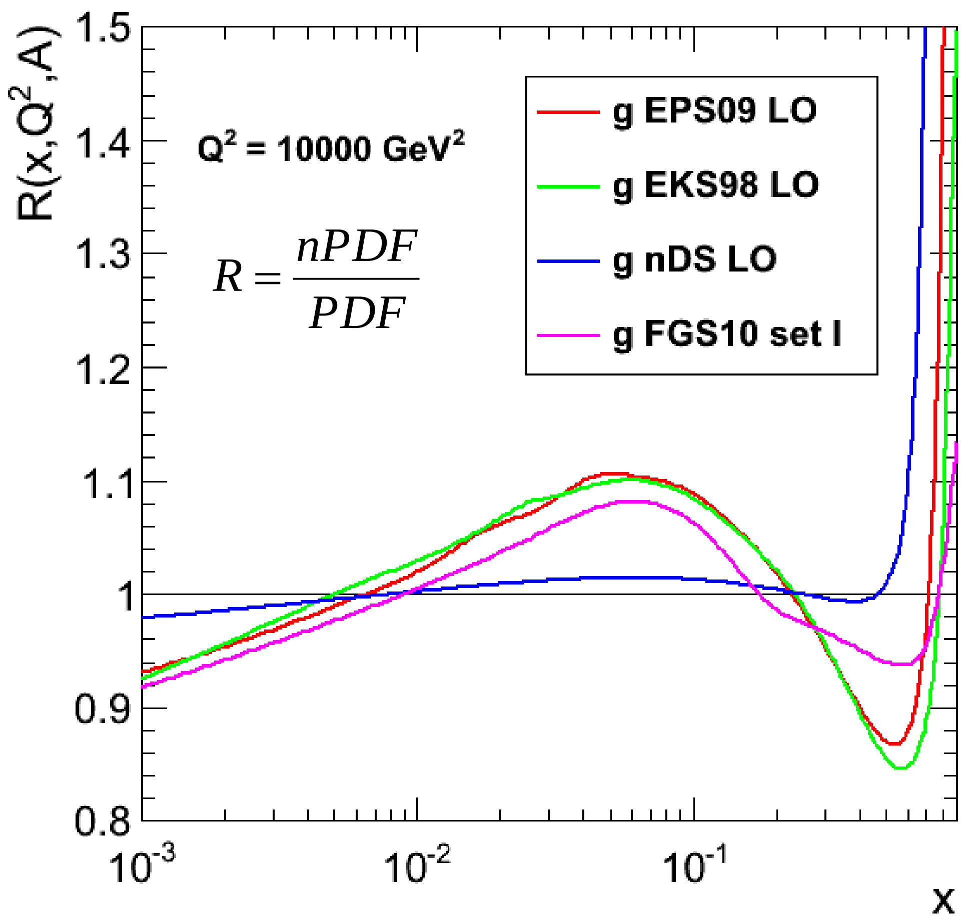


Nuclear Parton Distribution Function

Gluon and Quark nPDF/PDF in EPS09 LO

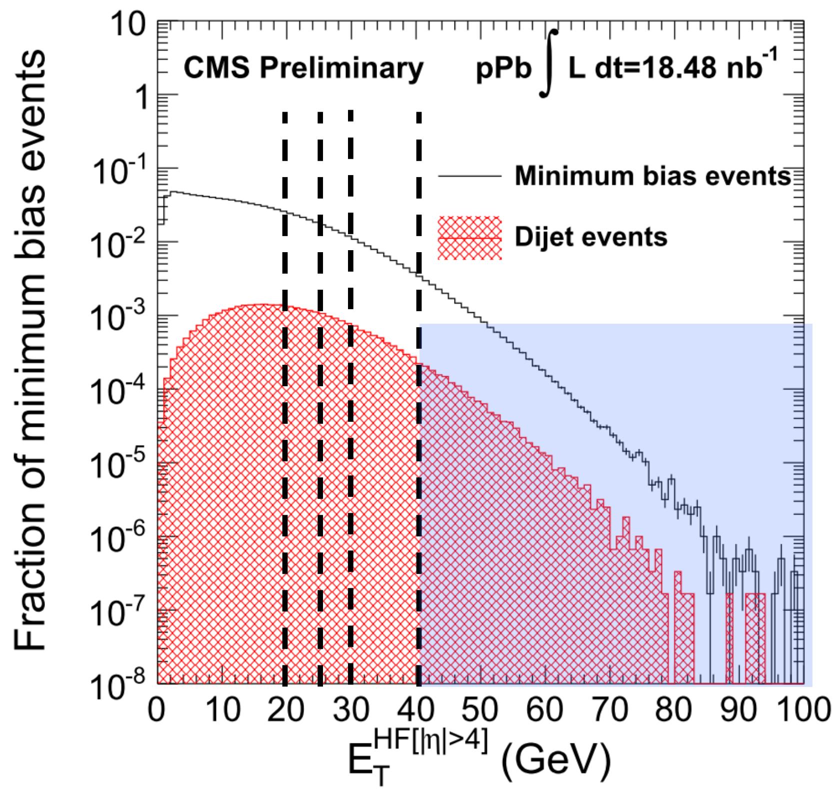


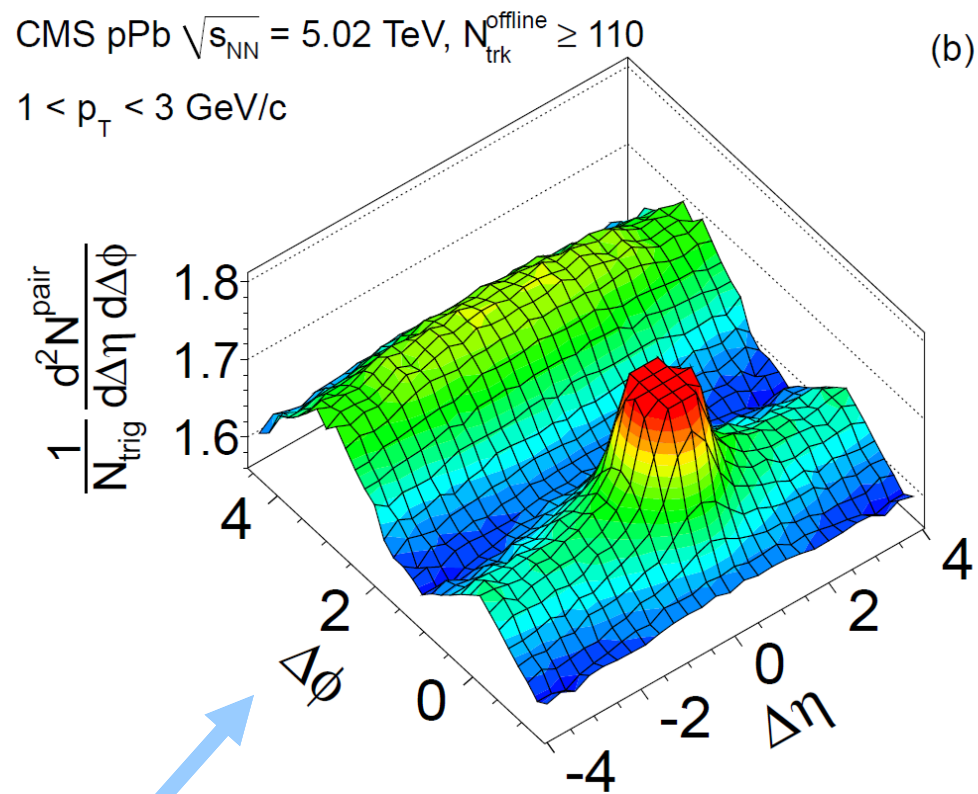
Gluon nPDF/PDF comparison between EPS09, EKS98, nDS and FGS10



François Arleo and Jean-Philippe Guillet http://lapth.cnrs.fr/npdfgenerator/

Event classes



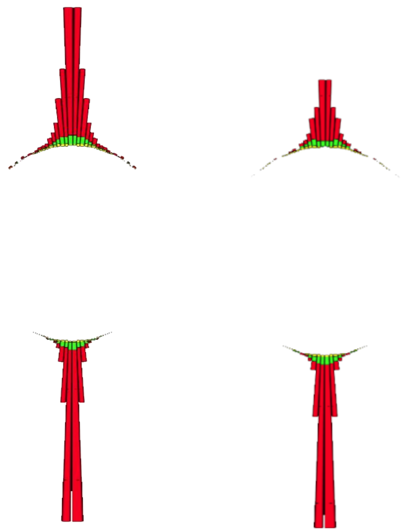


"**roughly**" correspond to $N_{trk}^{Offline}$>110 bin, given the caveat HF energy is loosely correlated with N

$E_T^{HF[\|\eta\|>4]}$ range (GeV)	Fraction of DS events	Fraction of dijet events	$\langle N_{trk}^{corrected} \rangle$ in DS events
0-20	73.1%	52.6%	33±2
20-25	10.5%	16.8%	74±3
25-30	7.1%	12.7%	88±4
30-40	6.8%	13.0%	106 ±5
40-100	2.5%	4.9%	135 ±6

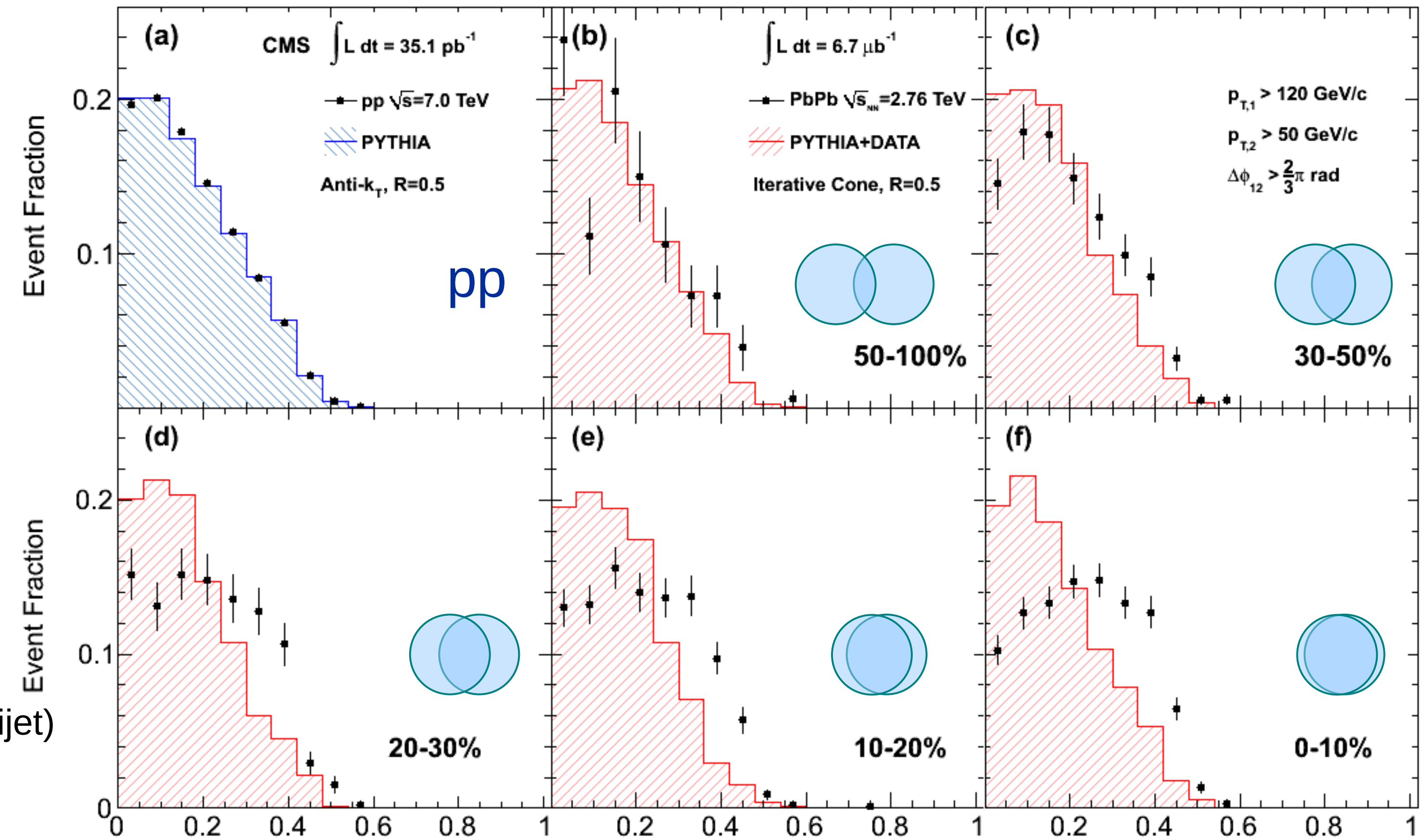
Dijet momentum imbalance

Jet Cone size R = 0.5



Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)

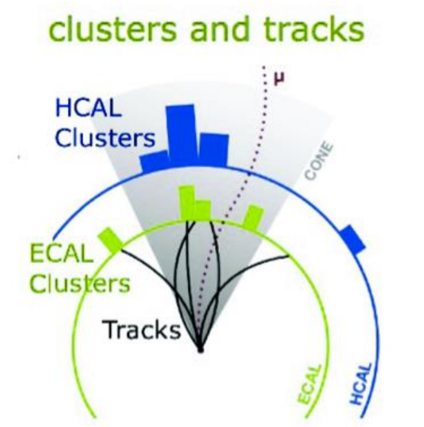


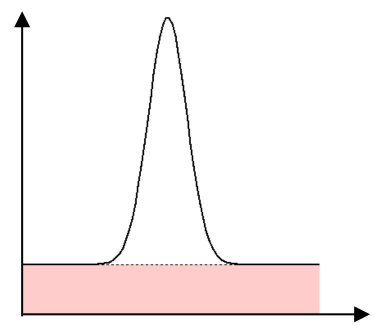
PRC 84 (2011) 024906

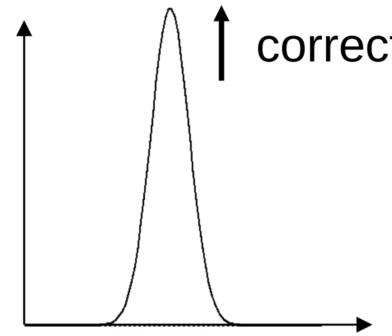
$$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$$

Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions

Jet energy correction







Raw jet energy → Background subtraction → Jet energy correction

Anti-k_T algorithm with R=0.3
"Particle Flow" reconstruction

Remove underlying events contribution

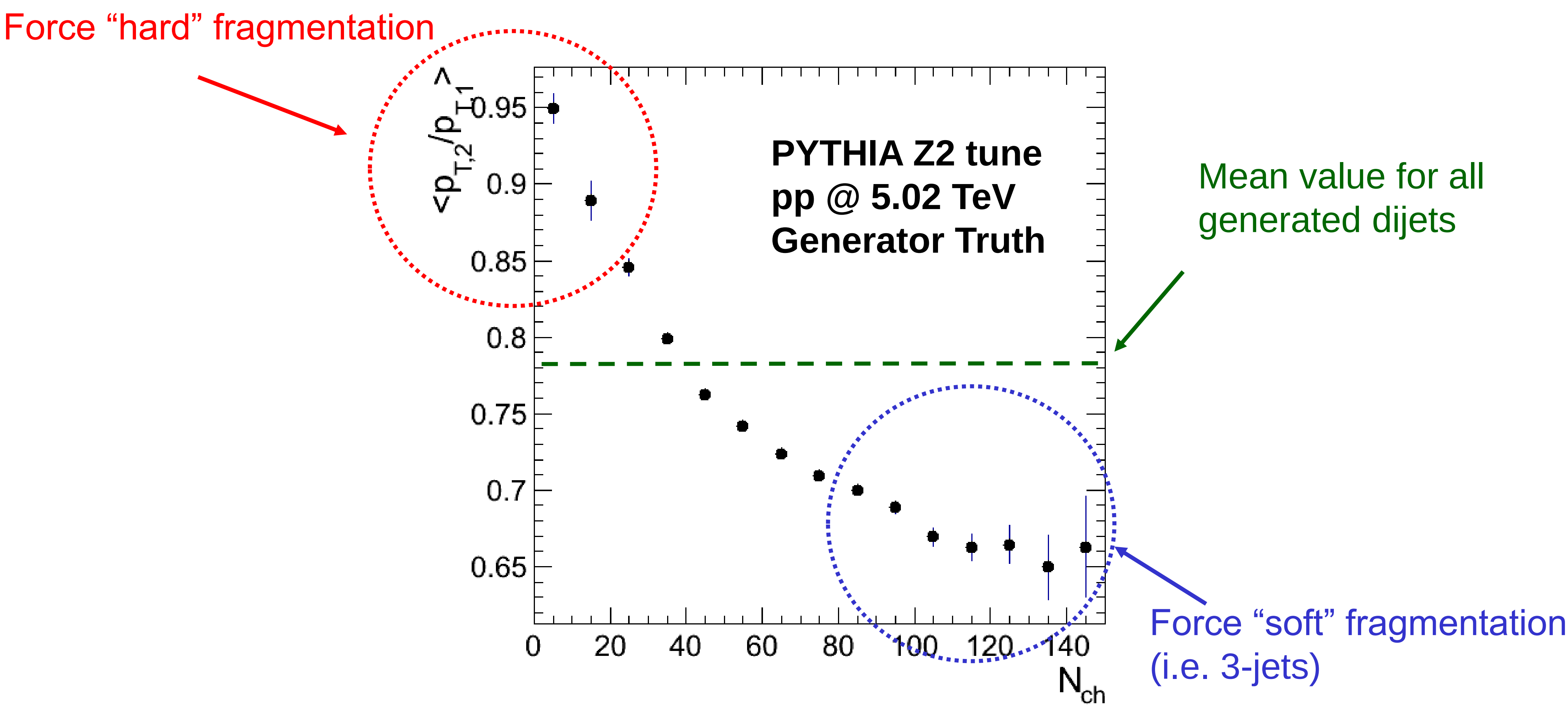
PYTHIA MC
Residual correction from dijet and photon-jet

- Data-driven jet energy correction from dijet and photon-jet events (method described in **JINST 6 (2011) P11002**)
- Jet with background subtraction used as the main result
- Cross-check with jets without background subtraction

Looking at high multiplicity event

Leading jet $p_{T,1}$ > 120 GeV/c
subleading jet $p_{T,2}$ > 30 GeV/c $|\Delta\varphi_{12}| > 2\pi/3$

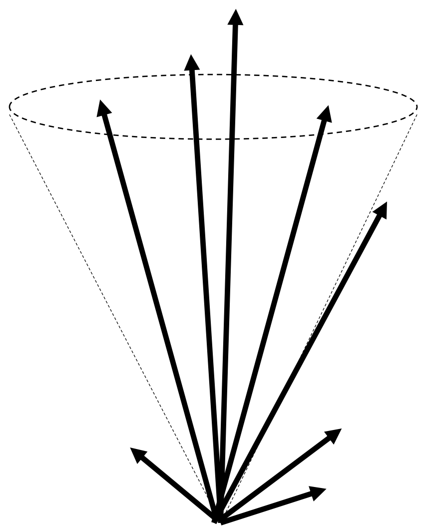
N_{ch}: Number of charged particles with $|p_T|$>0.4 and $|\eta|$<2.4



- Number of charged particles produced in pPb << in PbPb
- **Slicing on N_{ch} may cause bias on jet fragmentation pattern**

Inclusive jet spectra: jet R_{AA}

Anti-k_T jets with
R = 0.3



If PbPb = superposition of pp

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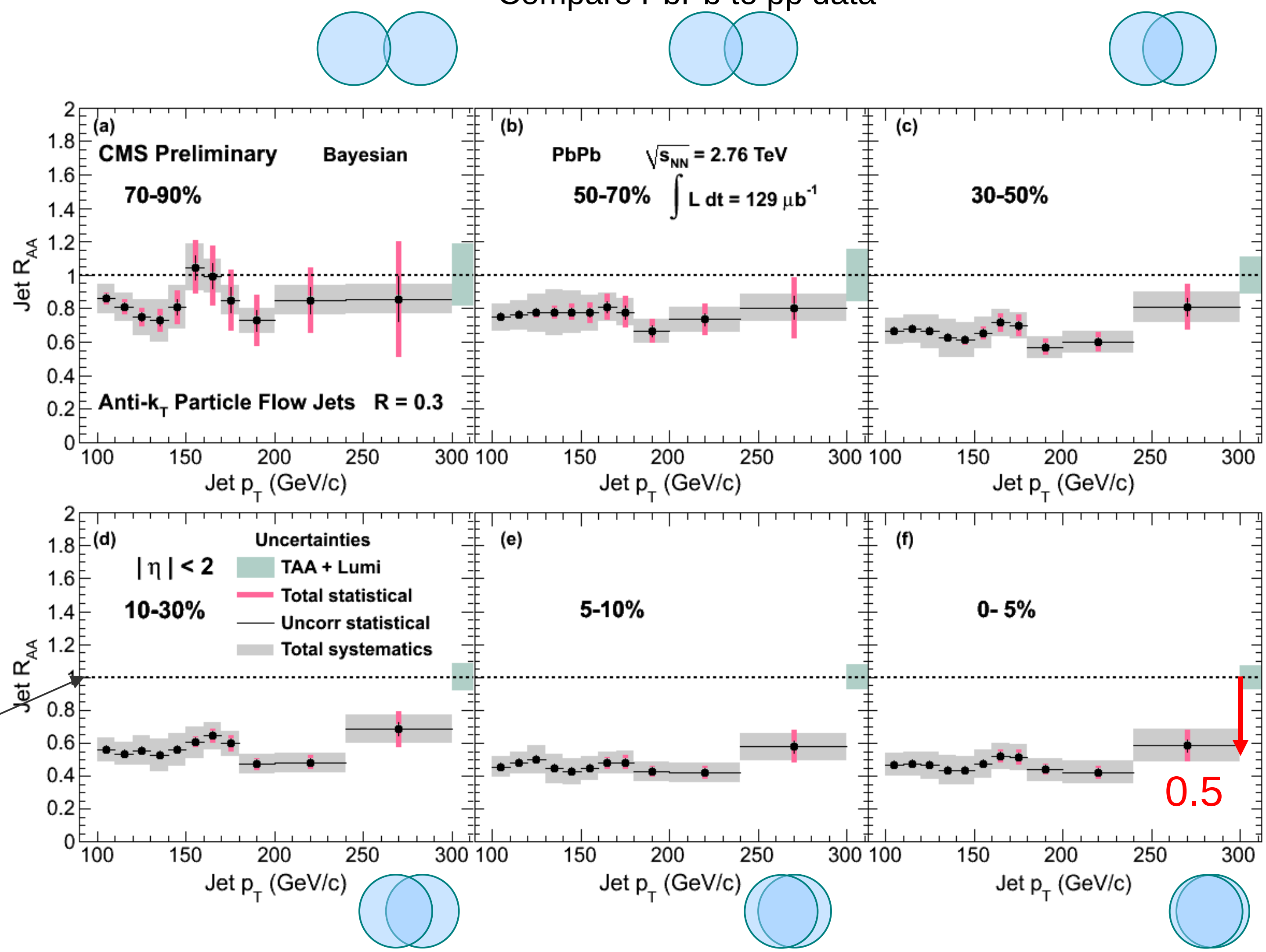
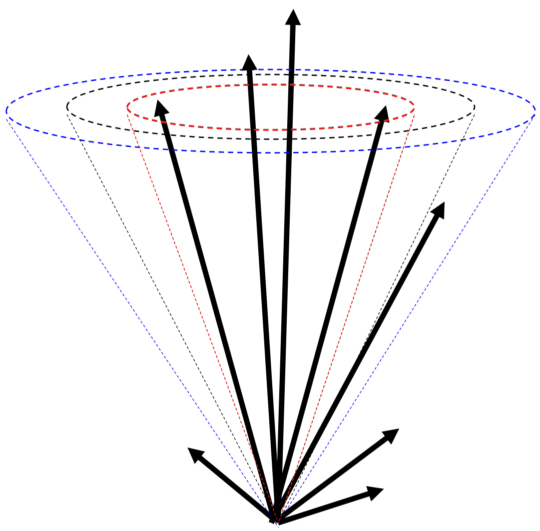
Compare PbPb to pp data



Strong suppression of inclusive high p_T jets

Inclusive jet spectra: jet R_{AA}

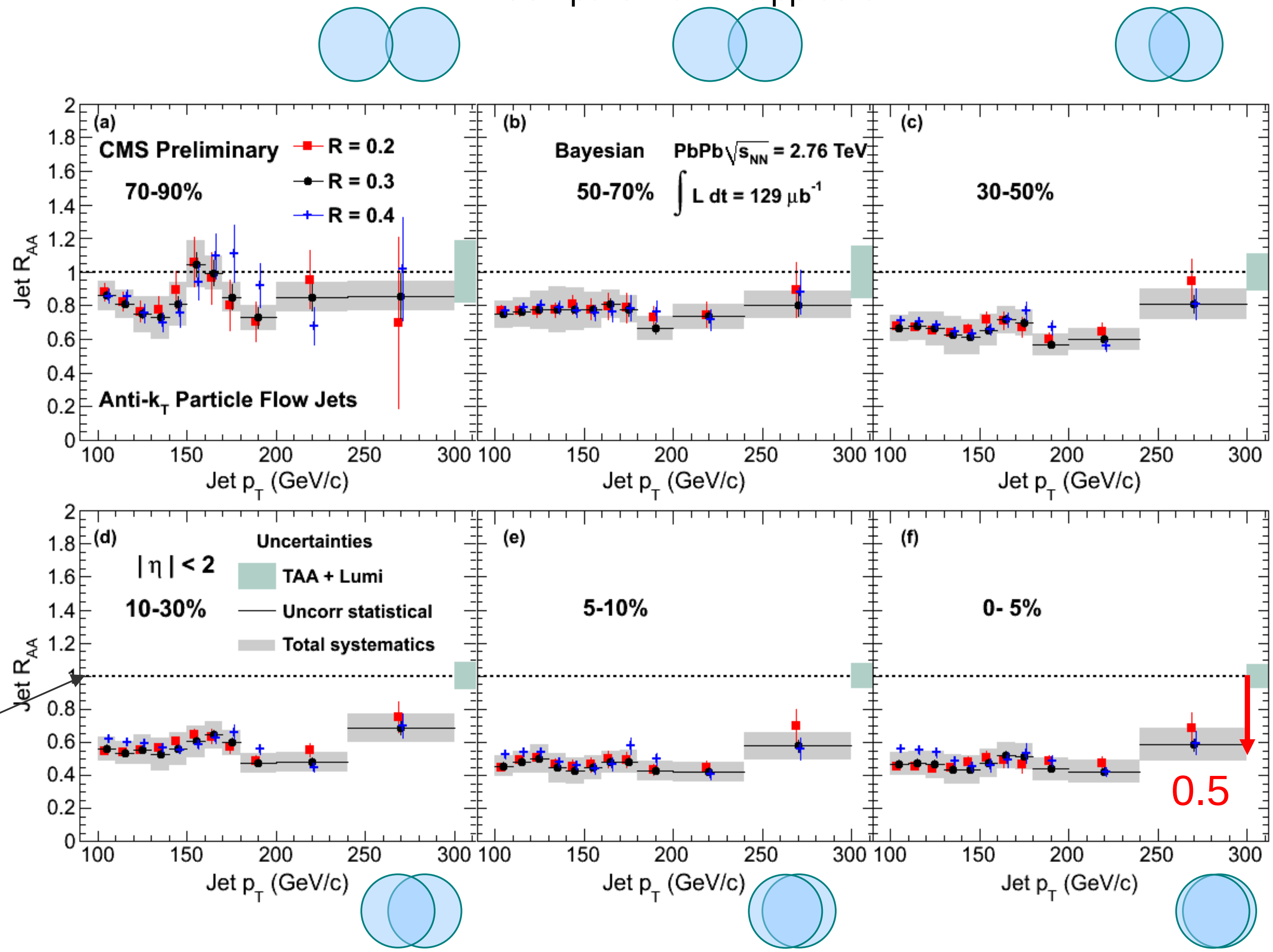
Anti-k_T jets with
R = 0.2, 0.3, 0.4



If PbPb = superposition of pp

CMS PAS HIN-12-004

Compare PbPb to pp data



Strong suppression of inclusive high p_T jets

A cone of R=0.2, 0.3, 0.4 doesn't catch all the radiated energy

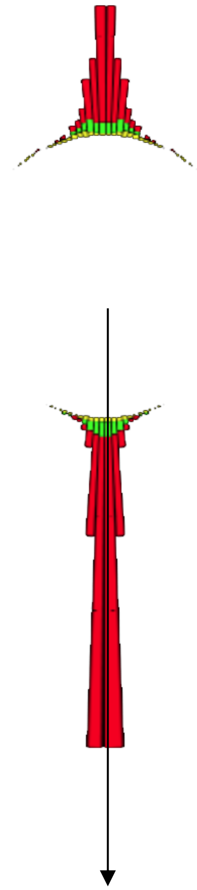
Are those high p_T jets "**completely absorbed**" by the medium?

Where does the energy go?

- Suppression of high p_T jets
- Large dijet (photon-jet) energy (momentum) imbalance

$\Delta E_T \sim O(10)$ GeV,
~10% shift in <dijet p_T ratio>

Where does the energy go?



Missing-$p_T^{||}$

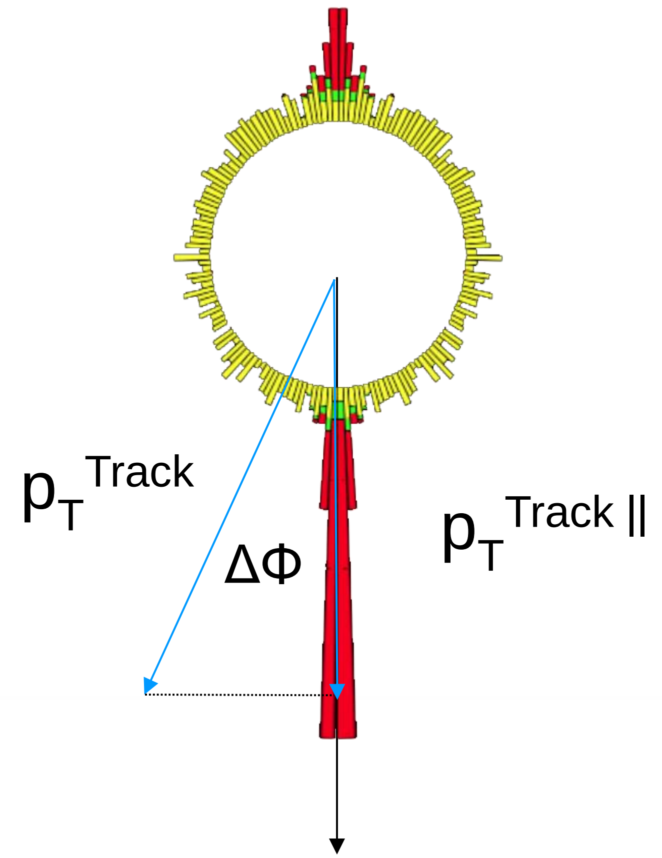
Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\mathrm{Tracks}} -p_T^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

Where does the energy go?

Calculate projection of p_T on leading jet axis and average over selected tracks with

$p_T > 0.5$ GeV/c and
$|\eta| < 2.4$

Underlying events cancels

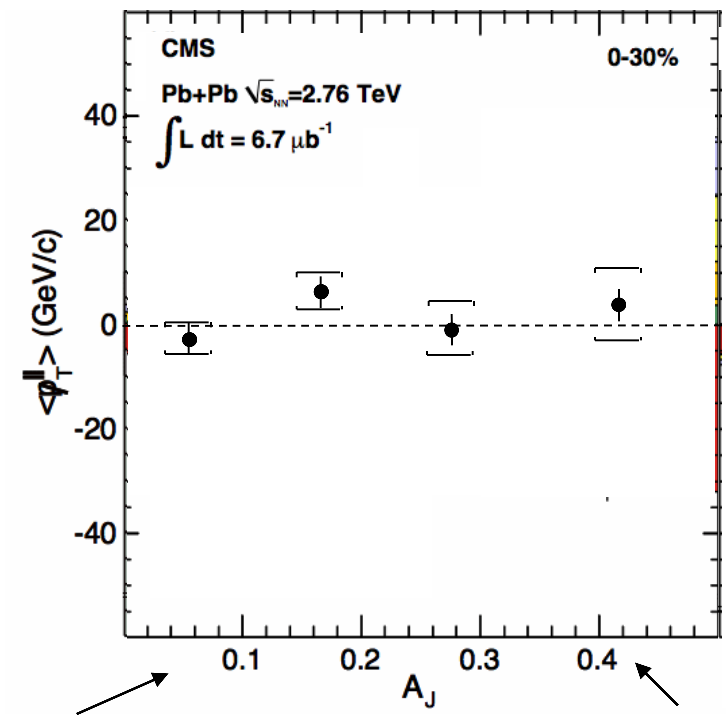


Sum over all tracks in the event

Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\mathrm{Tracks}} -p_T^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

0-30% Central PbPb



balanced jets

unbalanced jets

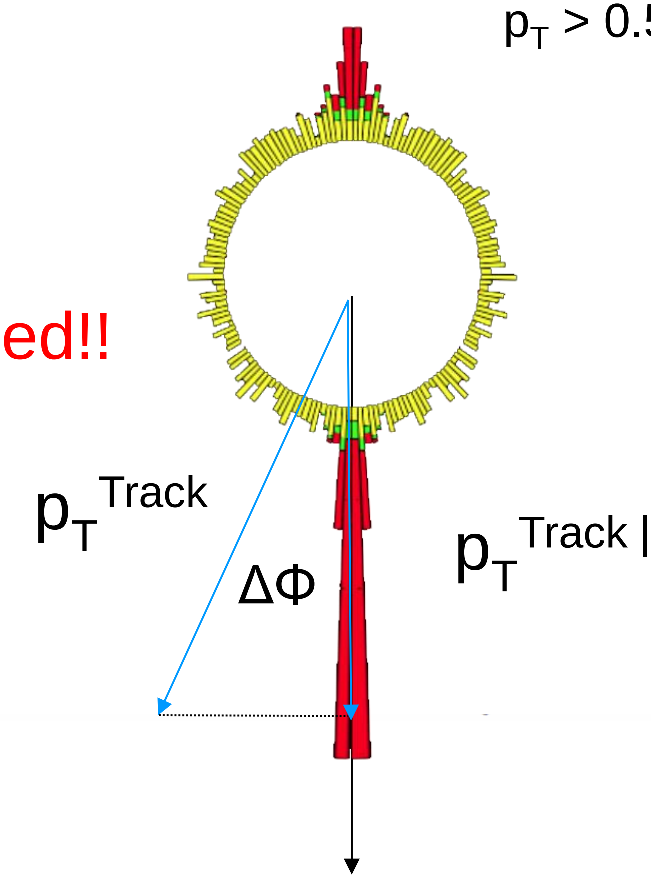
$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

excess away from leading jet

Balanced!!

excess towards leading jet

Track p_T > 0.5 GeV/c



Integrating over the whole event final state

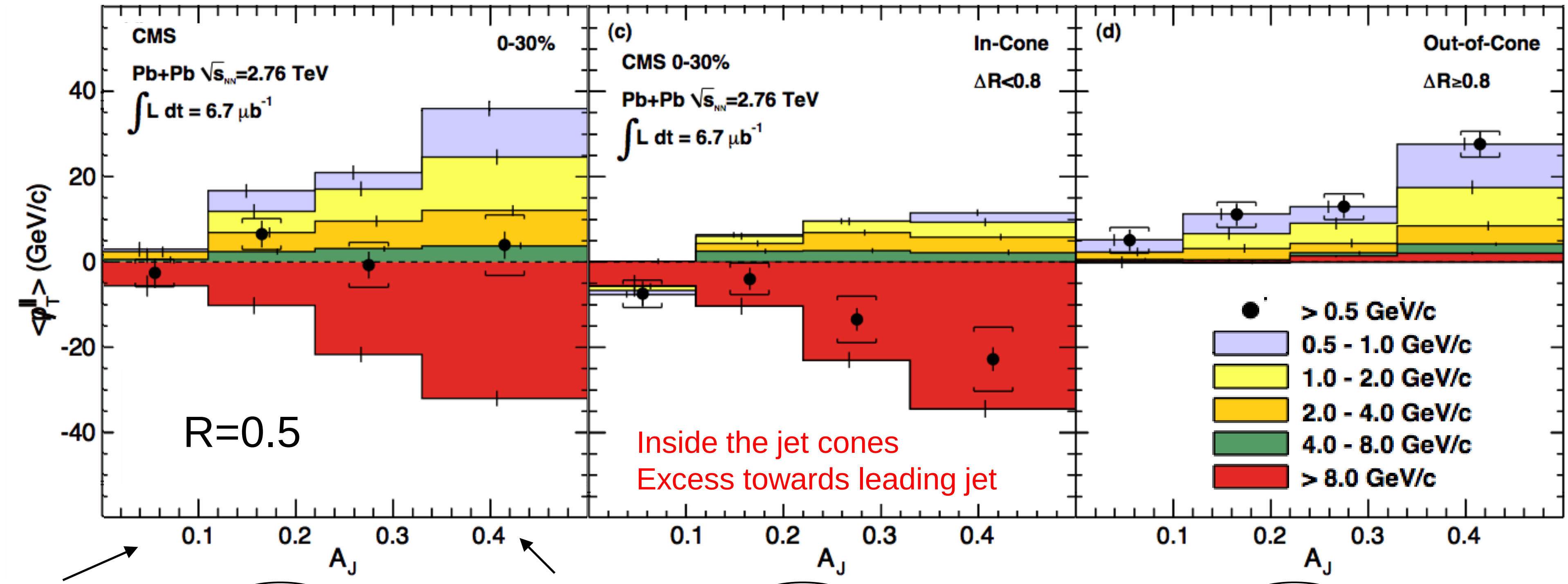
the dijet momentum balance is restored

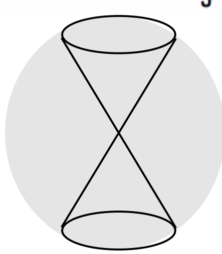
Missing-$p_T^{||}$

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

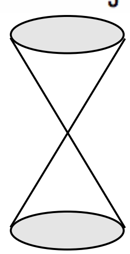
0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet

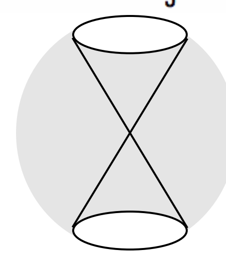




All tracks



Tracks in
the jet cone
ΔR<0.8



Tracks out of
the jet cone
ΔR>0.8

The momentum difference in the dijet is balanced by low p_T particles outside the jet cone

Fraction of leading jets with an away side jet

- Given a leading jet with p_T > 150 GeV/c, >90% of them has a away side partner

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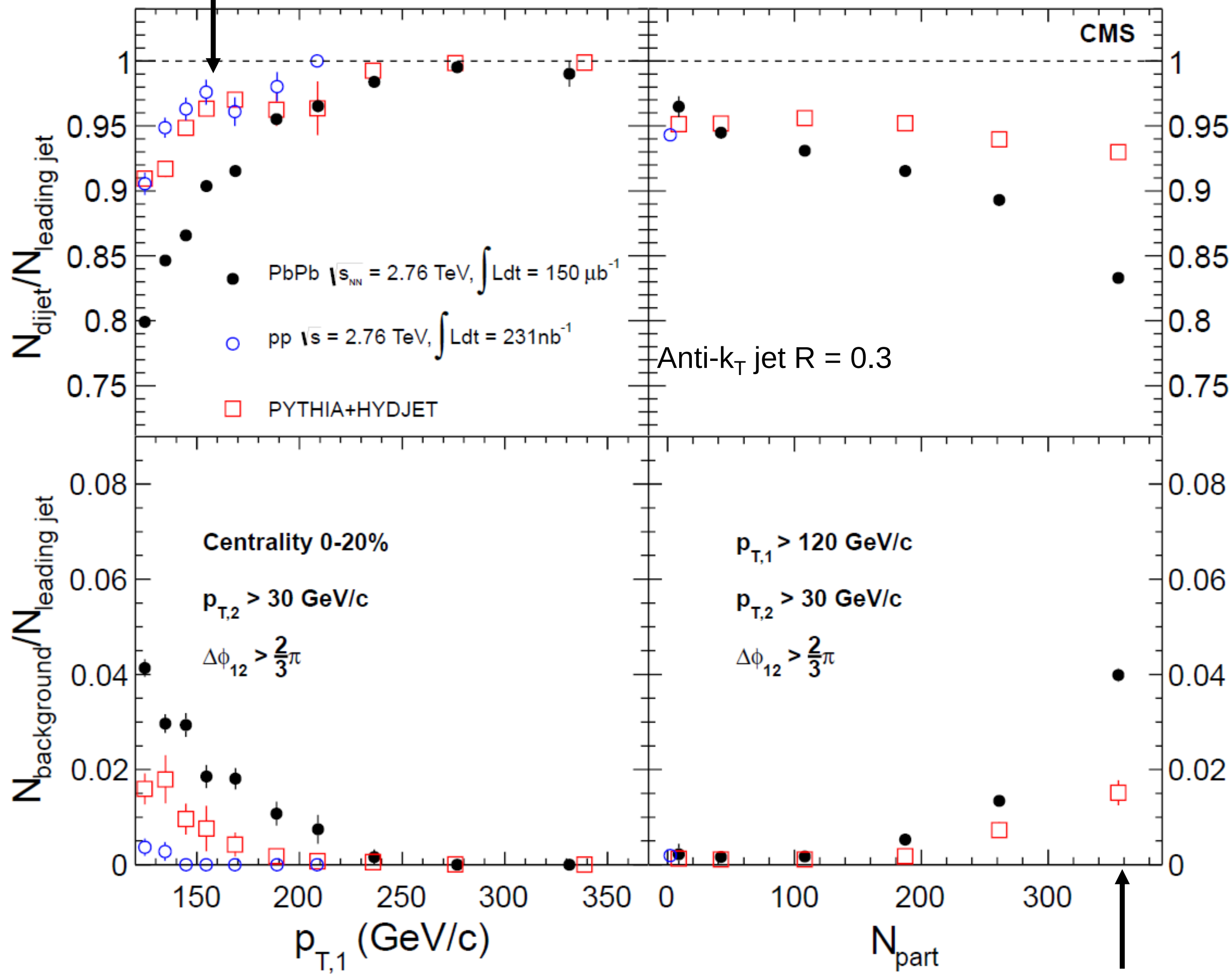
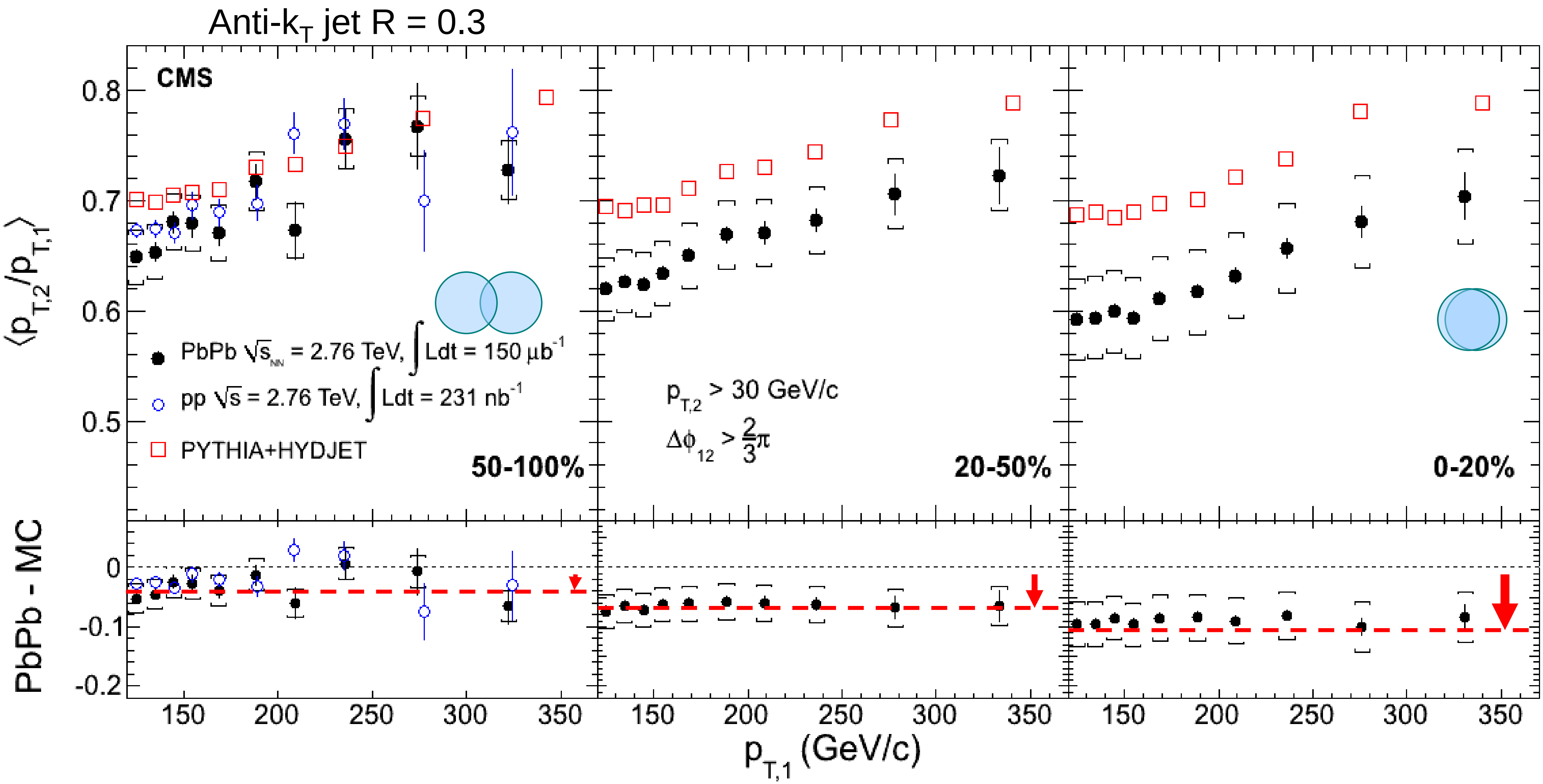


- Fake away side jet rate is < 4%

Dijet p_T Ratio (p_{T2}/p_{T1})



- Energy imbalance increases with centrality
- Very high p_T jets are also quenched

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Dijet η in different event classes

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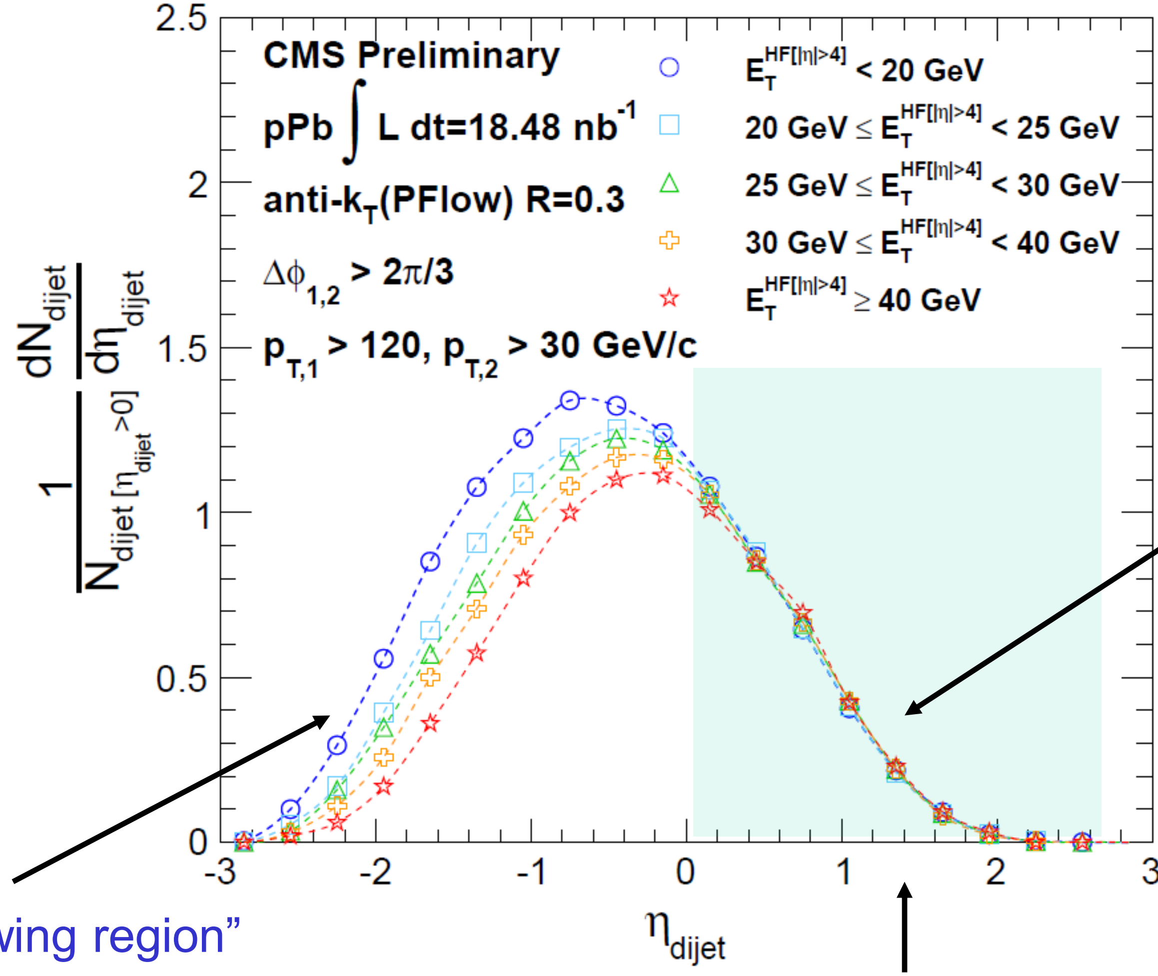
Normalized by N_{dijet} with $\eta_{dijet}>0$



The same shape in "EMC region"?

Evolving "shadowing region"

$$\eta_{dijet} = \frac{\eta_1+\eta_2}{2}$$

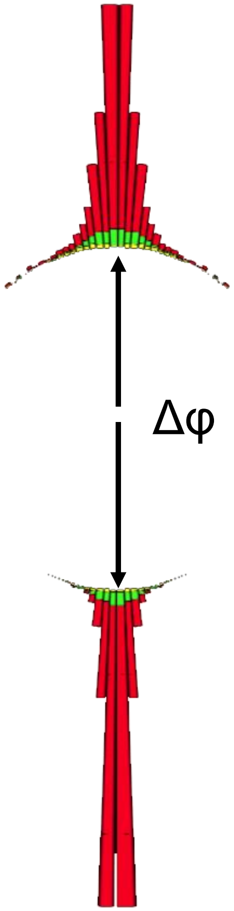
If we normalize the distribution by the area in the interval $\eta_{dijet} > 0$

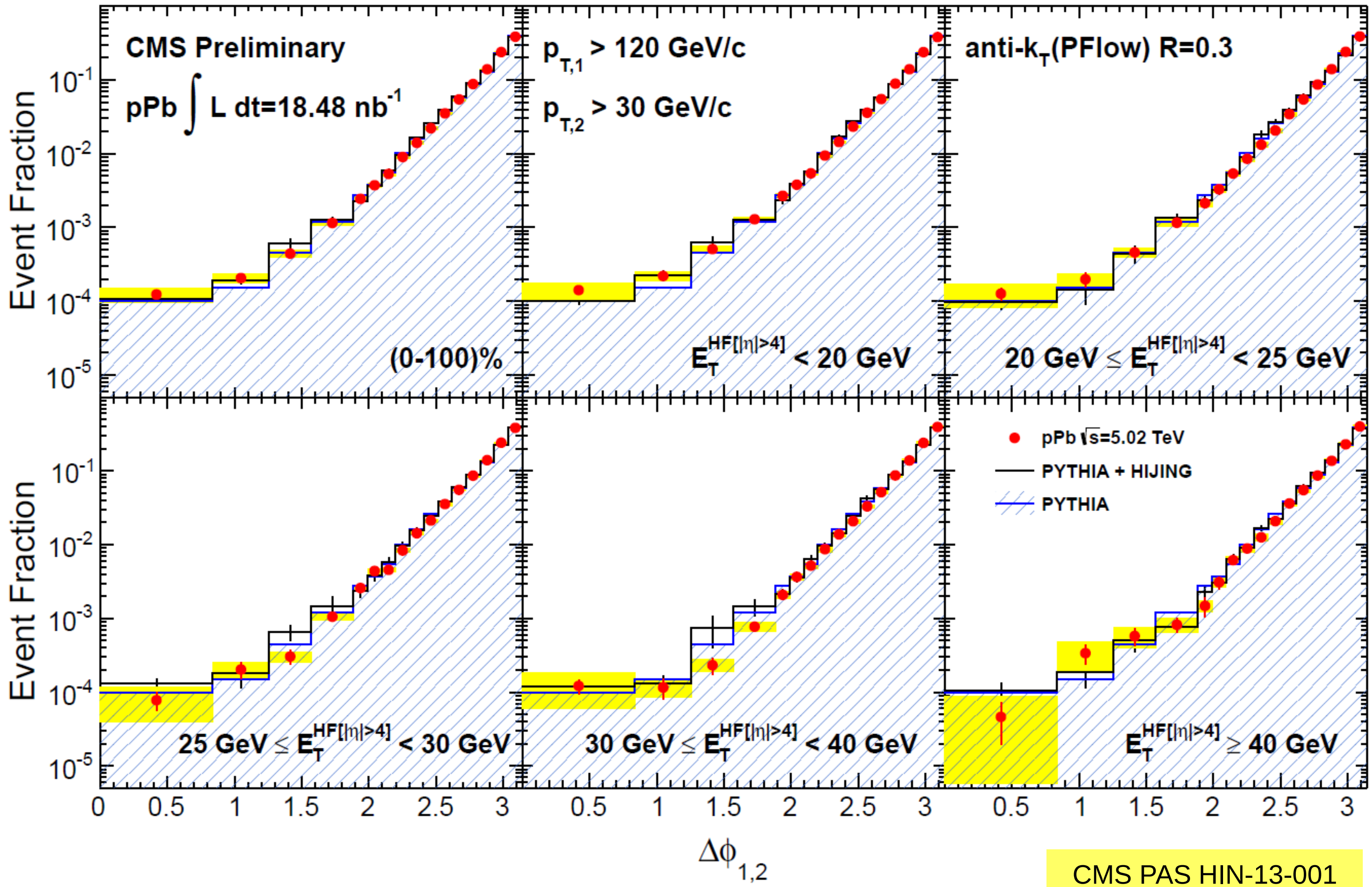
Looking at high multiplicity event

- Several options tested:
  - Tracker based variables:
    - Number of pixel hits
    - Number of pixel tracks, or number of tracks
    - Introduce fragmentation bias as demonstrated before
  - ZDC based variables:
    - Doesn't have good enough resolution to go to very high multiplicity events
- Final choice:

E_T measured in $4<|\eta|<5.2$ by forward calorimeter ($E_T^{HF[|\eta|>4]}$)

Dijet Δφ





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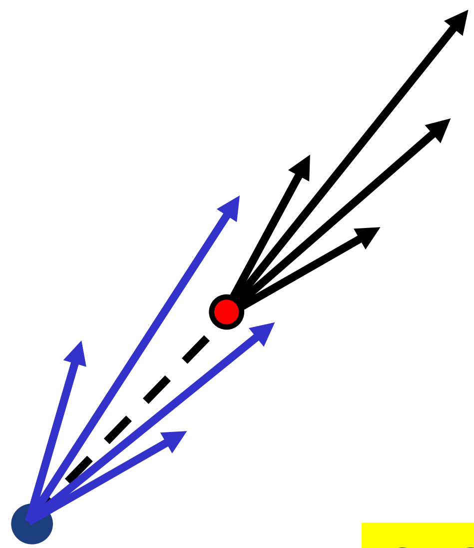
Δϕ distribution is unchanged w.r.t. HF energy

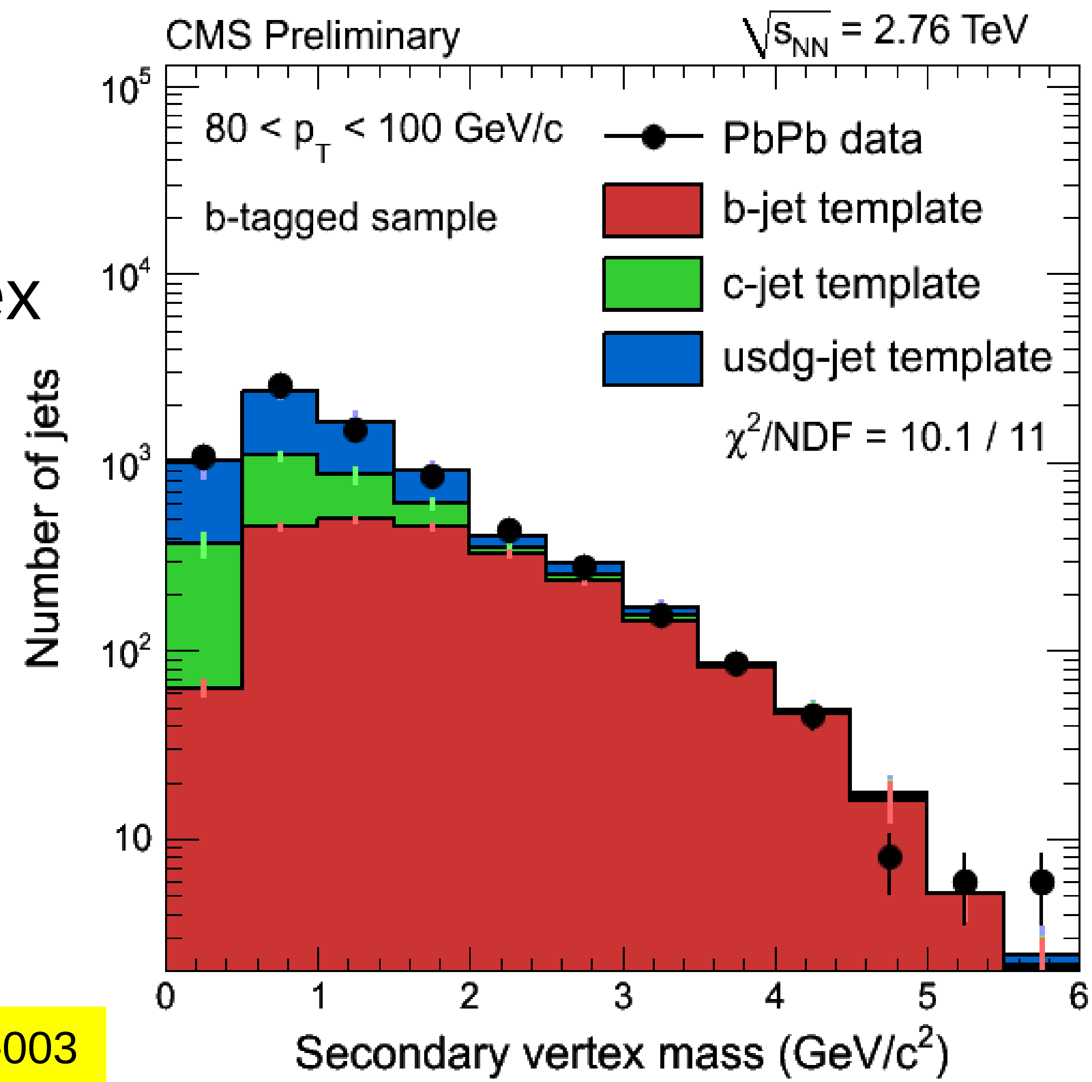
Tagging and counting b-quark jets

Secondary vertex tagged using flight distance significance

Tagging efficiency estimated
in a **data-driven** way

Purity from **template fits**
to (tagged) secondary vertex
mass distributions





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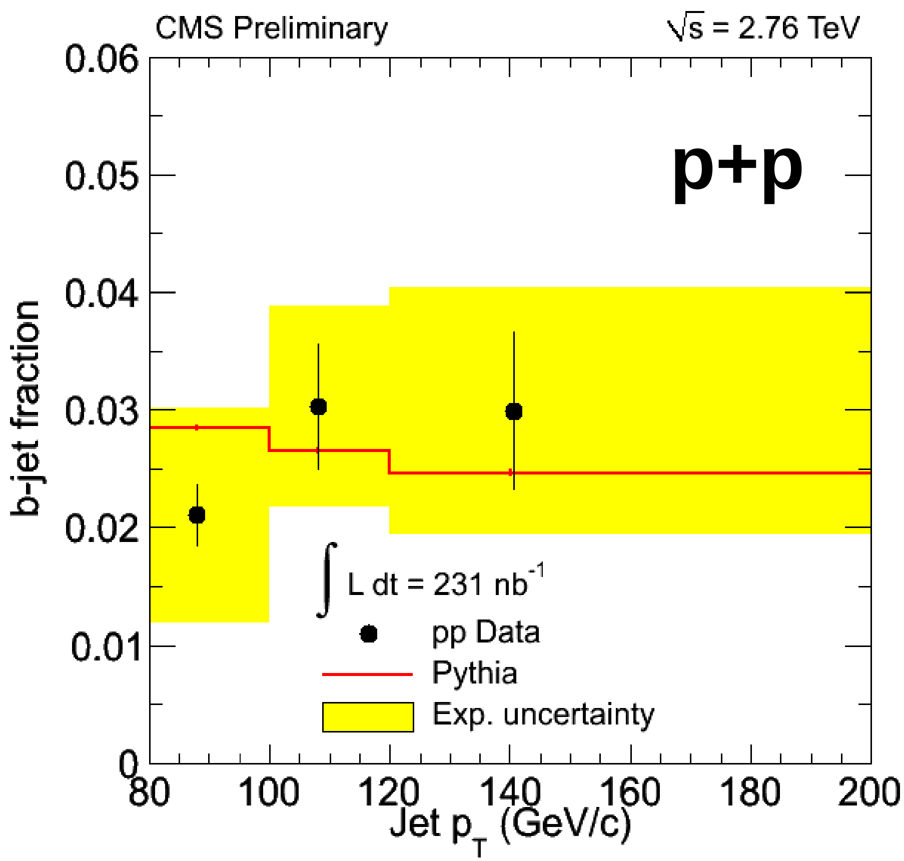
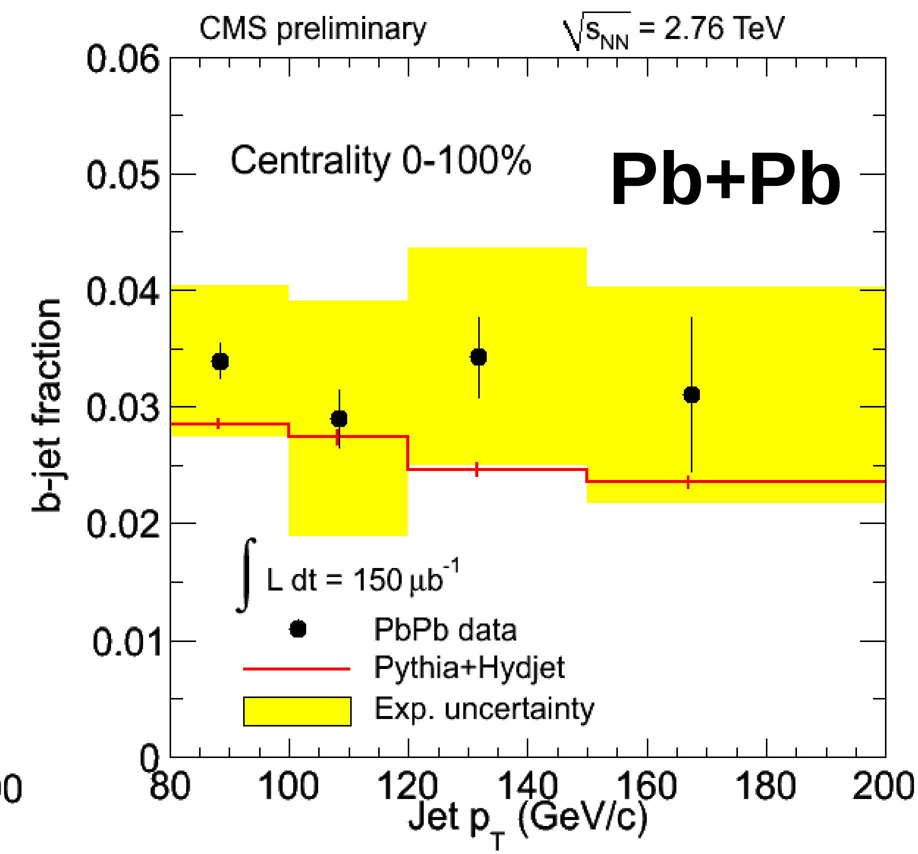
Fraction of b-jets among all jets

b-jet fraction: similar in pp and PbPb
→ b-jet quenching is comparable to light-jet quenching (R_{AA}≈0.5), within present systematics





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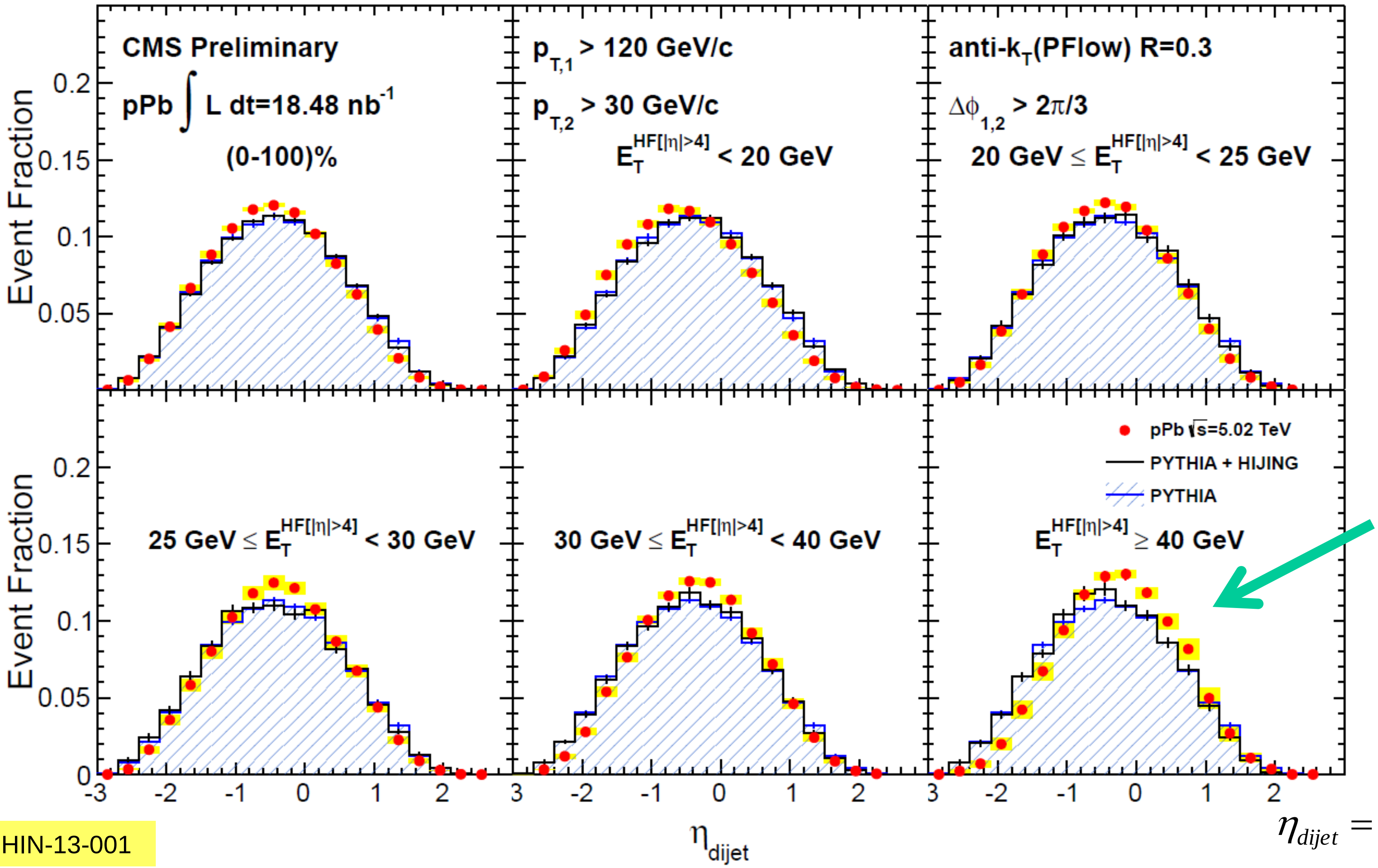
Dijet η v.s. Forward Calorimeter Energy



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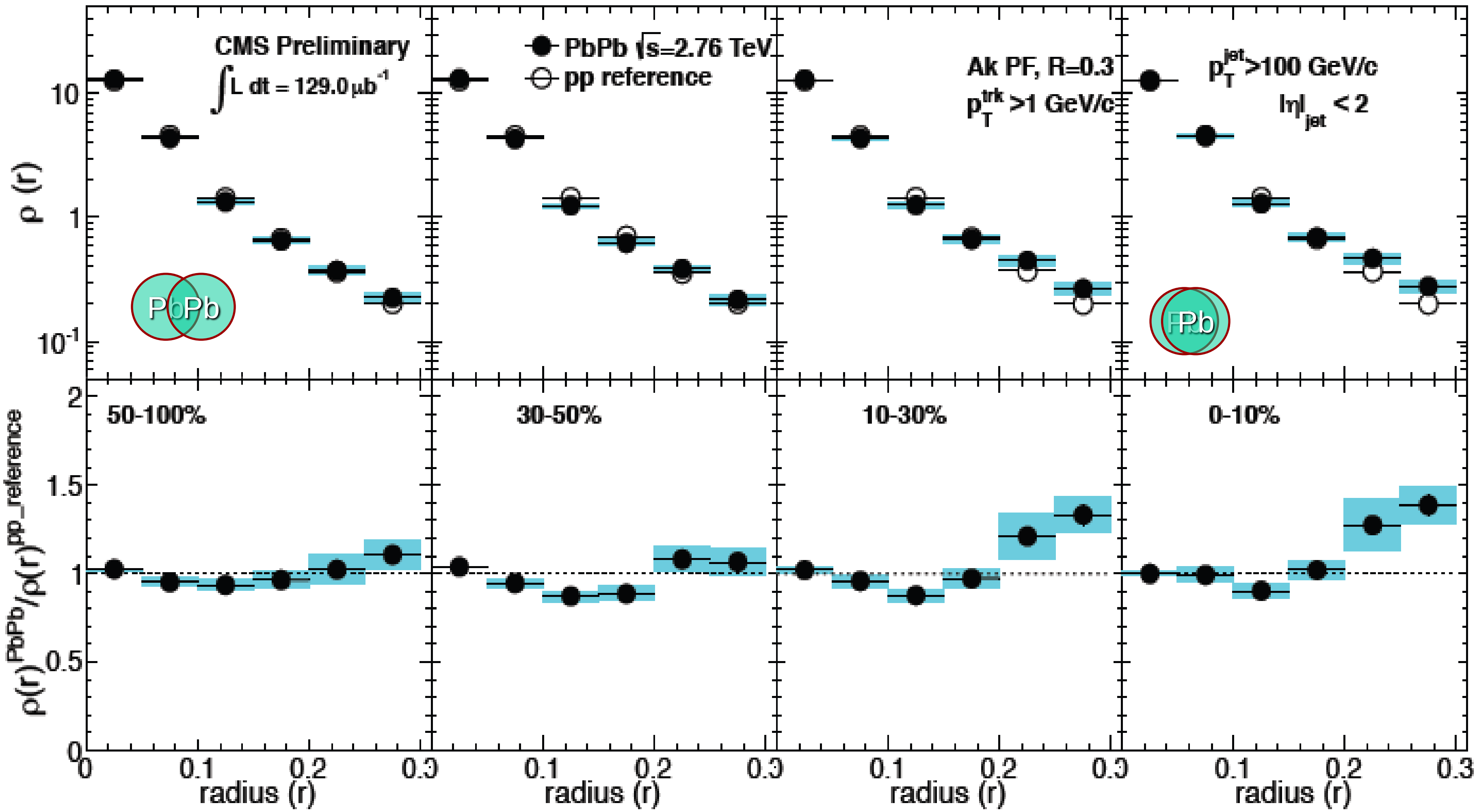
$$\eta_{dijet} = \frac{\eta_1+\eta_2}{2}$$

- η_{dijet} distributions plotted against PYTHIA references
- A systematic shift in the positive η direction vs HF energy

Jet Shapes



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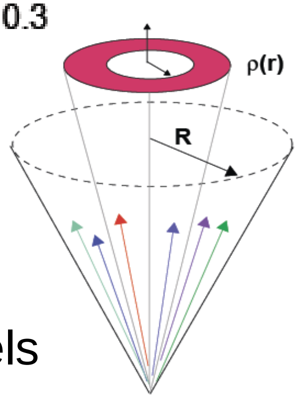
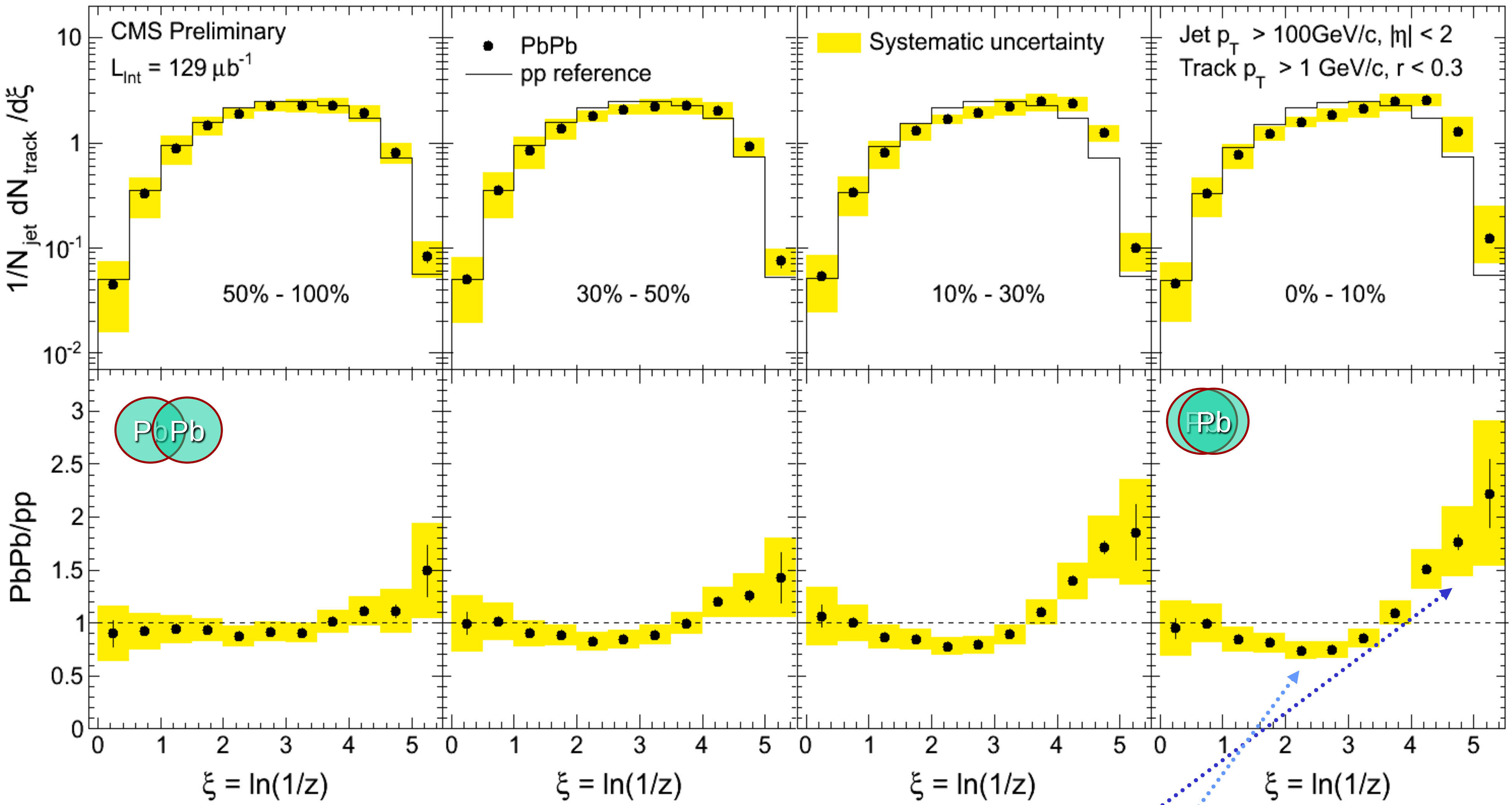
$r = (\Delta\eta^2+\Delta\varphi^2)^{1/2}$



Significant modification at large radius (r) with respect to the jet axis, looking at tracks with p_T> 1 GeV/c

However, the modification is smaller than prediction from most of the models

Jet Fragmentation Functions



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Inside the jet cone: Enhancement of low p_T particle

Suppression of intermediate p_T particles in cone

High p_T particles

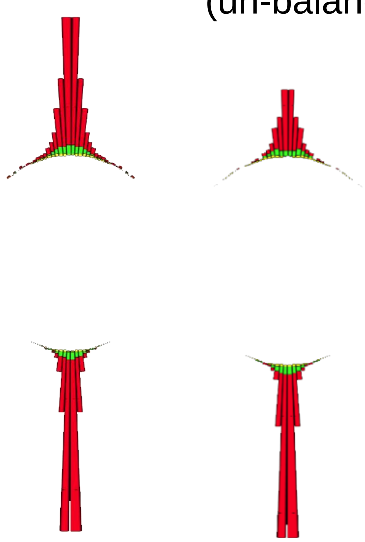
Low p_T particles

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

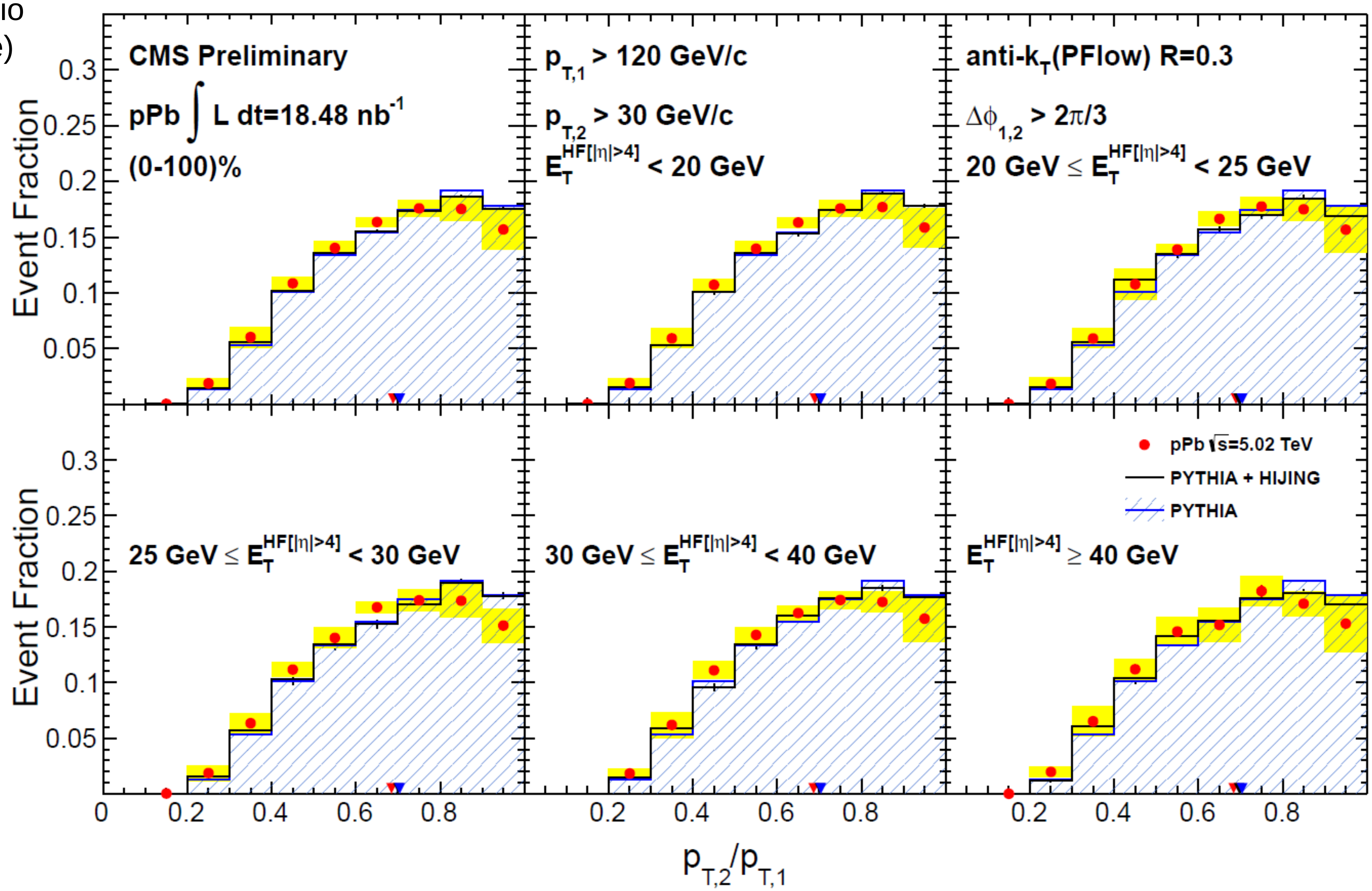
Dijet p_T Ratios in pPb Collisions

CMS PAS HIN-13-001

Small p_T ratio (un-balance)



Large p_T ratio (balanced)



No modification is observed in dijet p_T ratio up to $E_T^{HF[|\eta|>4]} > 40$ GeV (top 0-2.5%)

(Did not have enough statistics to check PbPb collisions in the same $E_T^{HF[|\eta|>4]}$ interval)