Recent results on the modifications to hard probes in PbPb collisions from the CMS Collaboration

Yen-Jie Lee (CERN)

for the CMS Collaboration

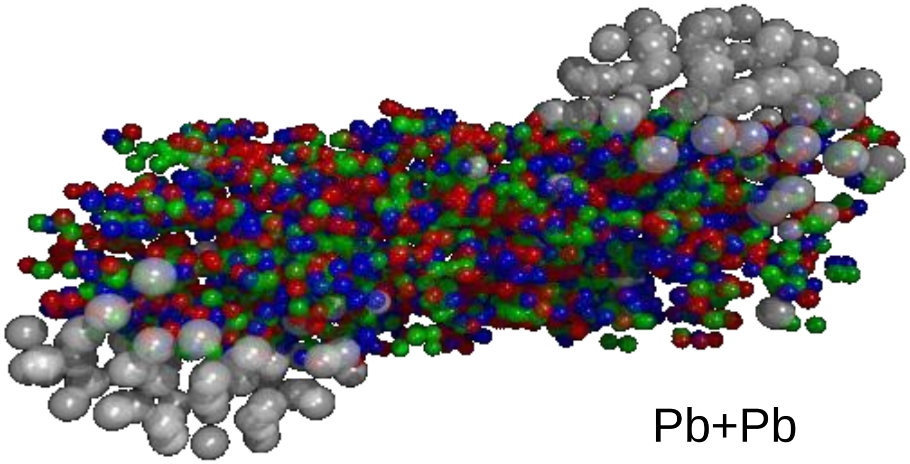
Zimanyi Winter School 2012,

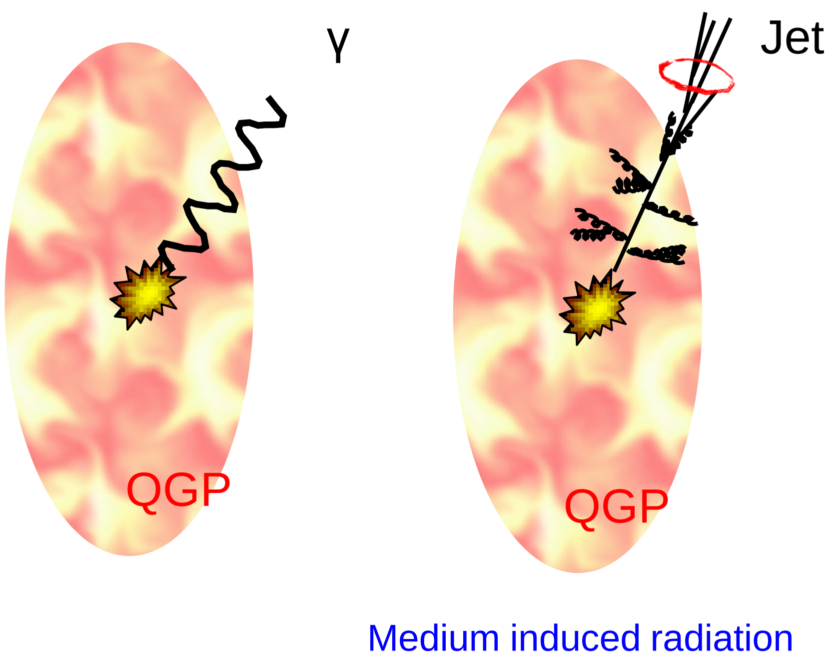
Wigner Center and Eotvos University

5th Dec, 2012

Introduction

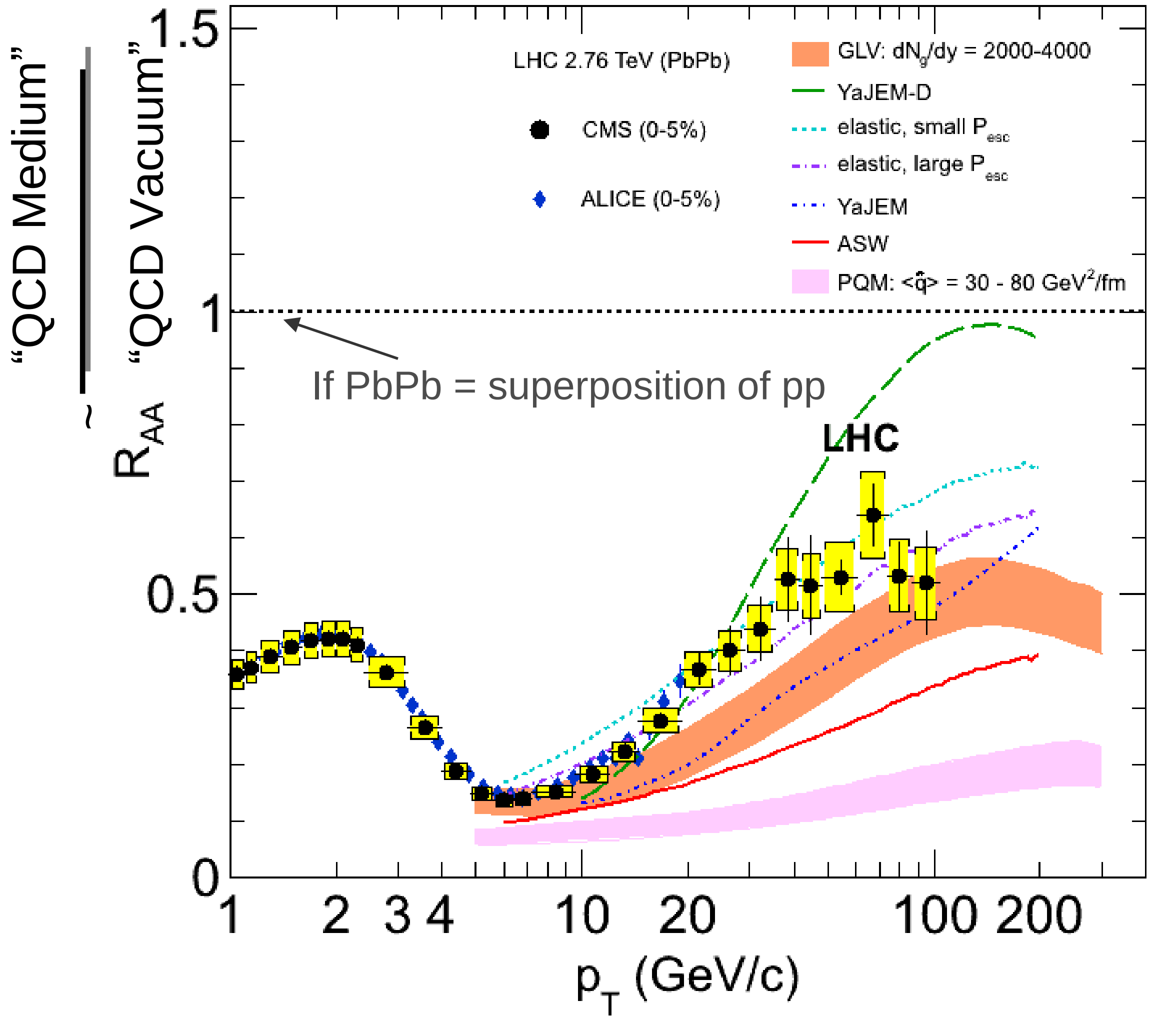
- Goal: Understand the properties of QGP
- Challenges: the lifetime of QGP is so short (O(fm/c)) such that it is not feasible to probe it with an external source
- Solution: use high p_T jets, photons produced with the collisions
- Extract medium properties by comparing the results from PbPb collisions (QCD in medium) and pp collisions (QCD in vacuum)





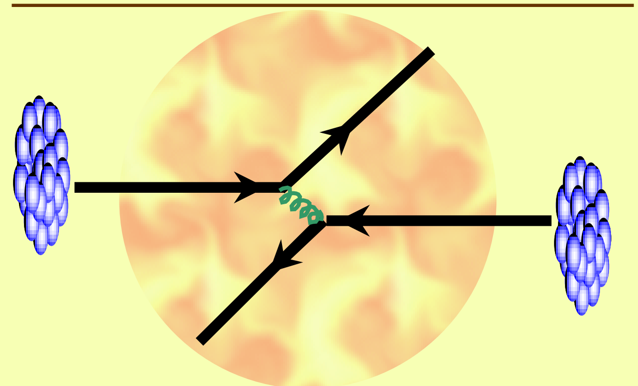
Jet quenching: strong suppression of high p_T particles

EPJC 72 (2012) 1945

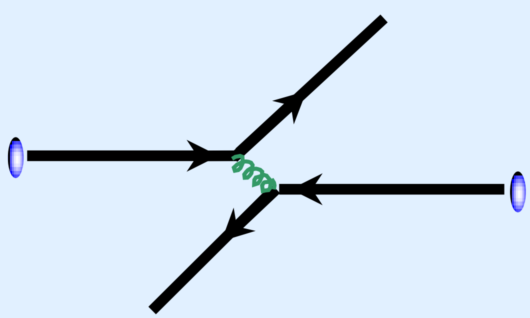


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

PbPb measurements



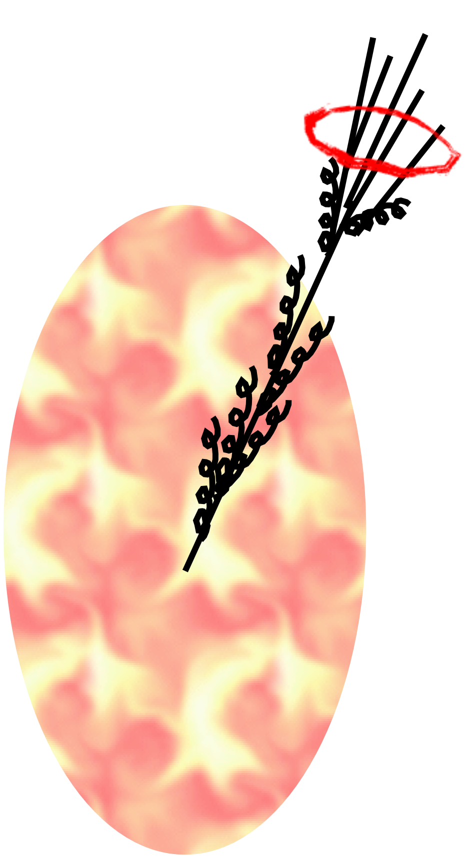
pp reference



High p_T reach up to 100 GeV/c

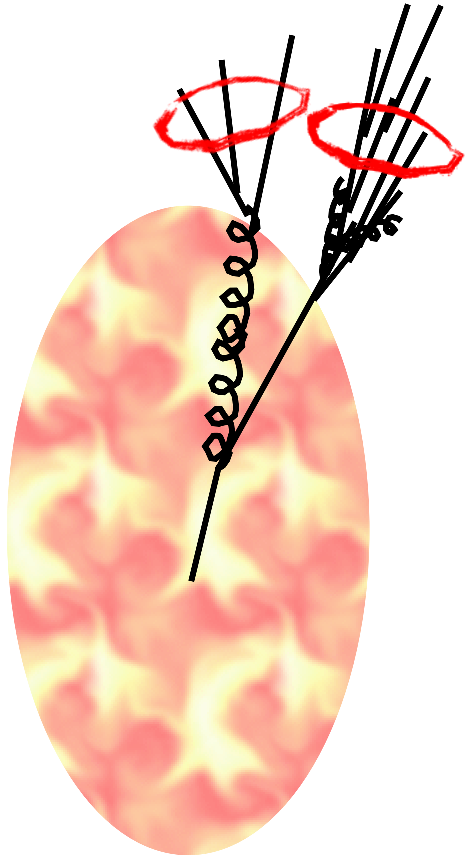
Constraints on the parton energy loss models

To explain the suppression of high p_T particles



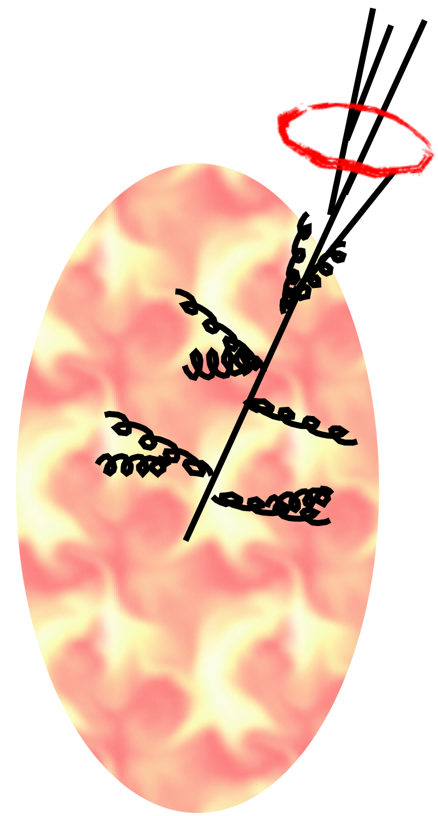
Soft collinear radiation

GLV + others
(pre-LHC models)



Hard radiation

PYTHIA inspired models
Modified splitting functions



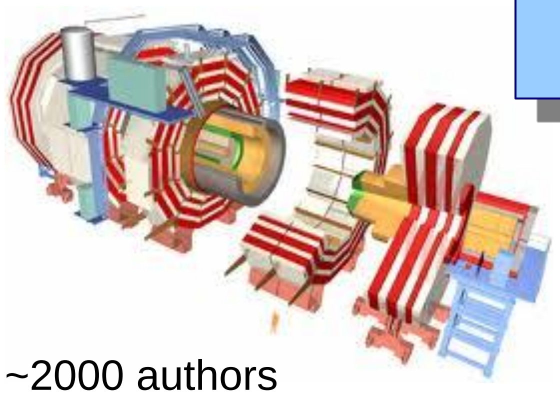
Large angle soft radiation
“QGP heating”

AdS/CFT
Interference

Do we see strong suppression of high p_T jets?
Can we collect the radiated energy back?

CMS detector: optimized for high p_T physics

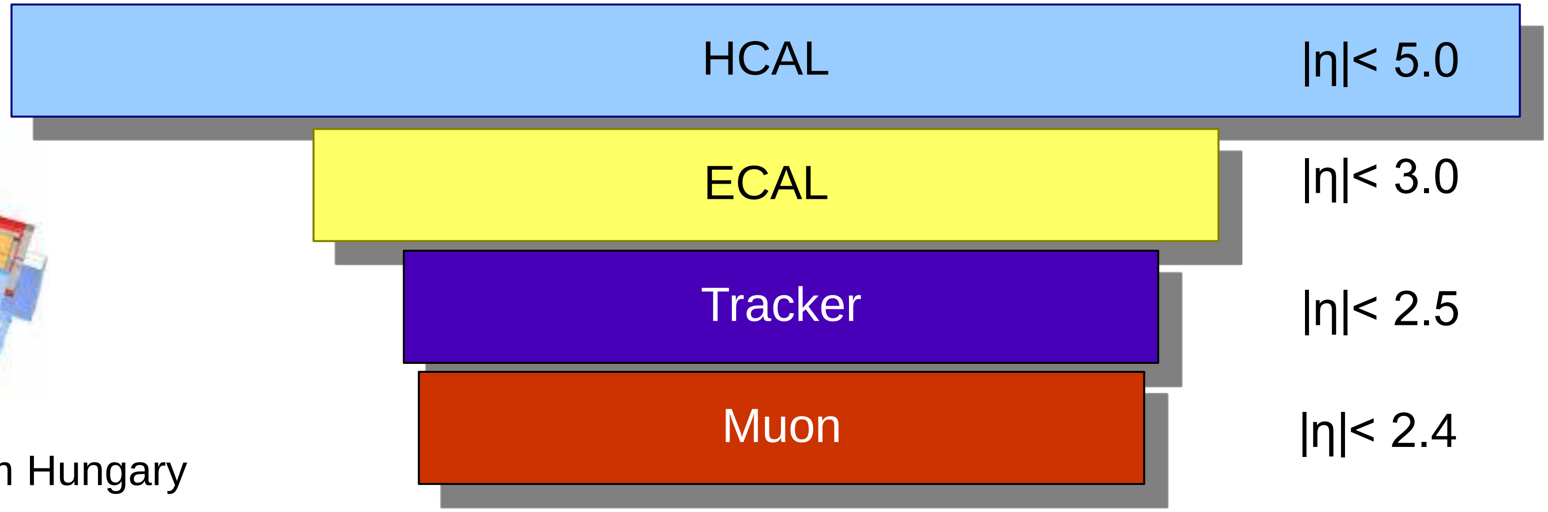
CMS



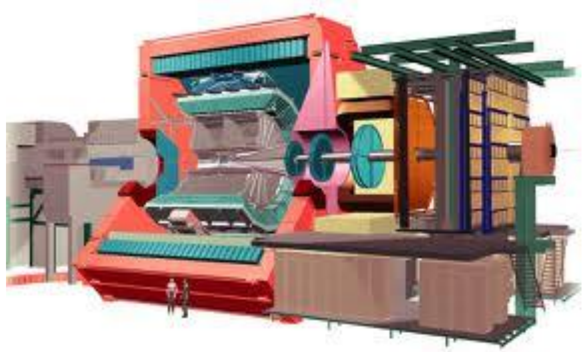
~2000 authors

~100 working on HI, 4 from Hungary

High p_T, large acceptance and excellent calorimeter resolution

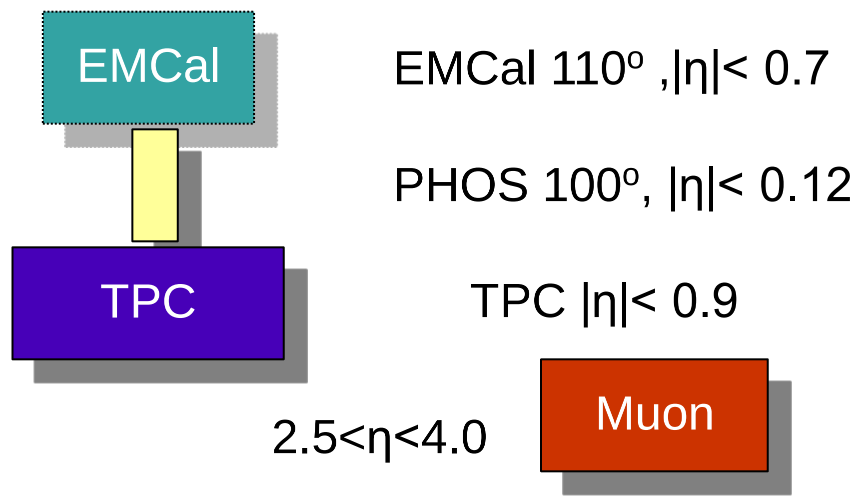


ALICE

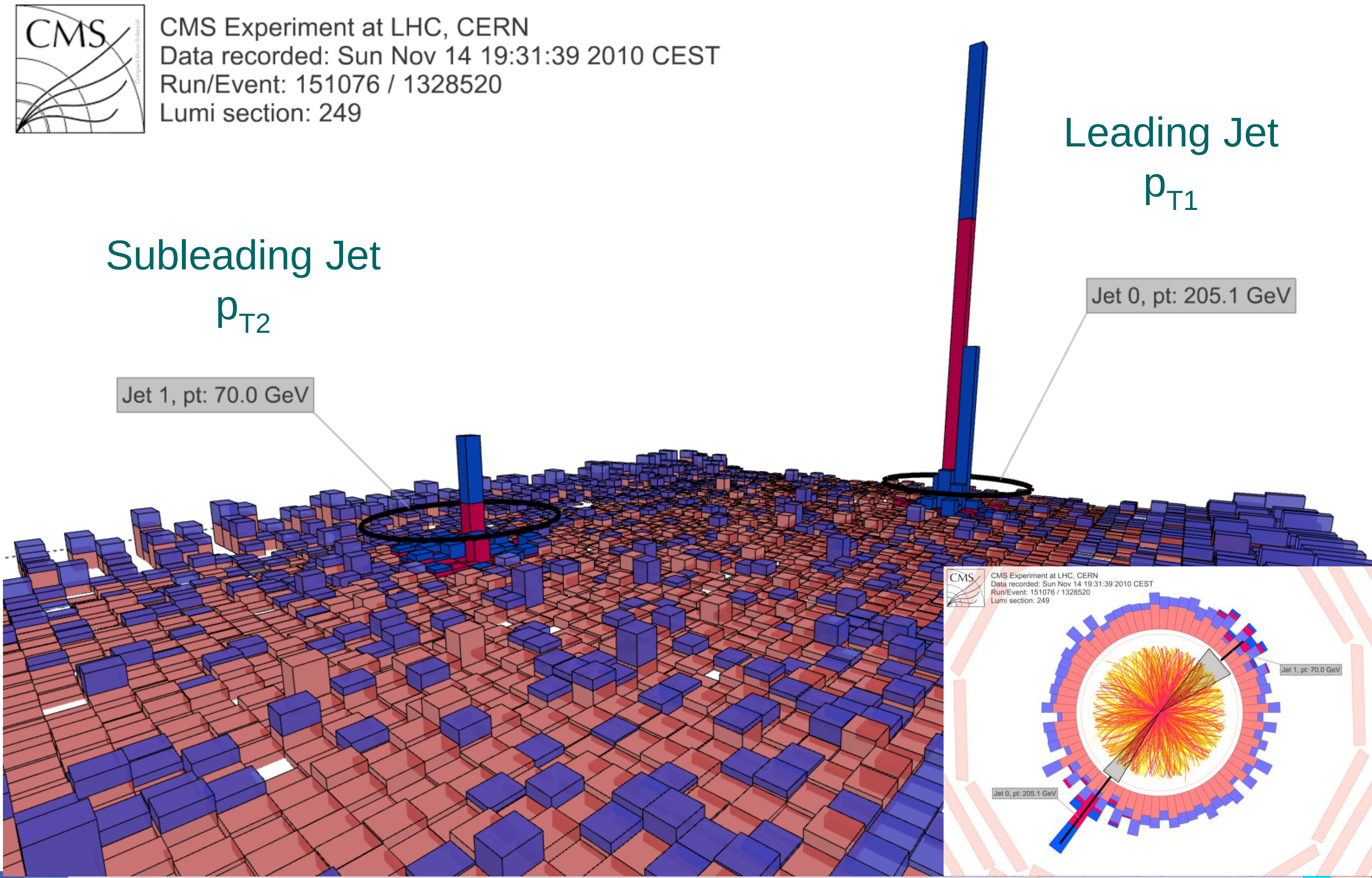


~1000 authors

Excellent particle ID capability and low p_T reach to ~0 GeV/c

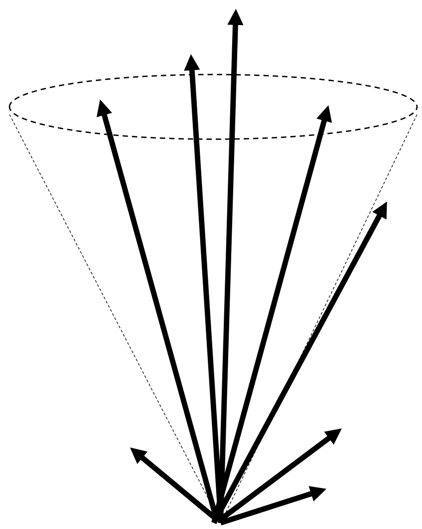


Direct jet reconstruction with CMS



Inclusive jet spectra: jet R_{AA}

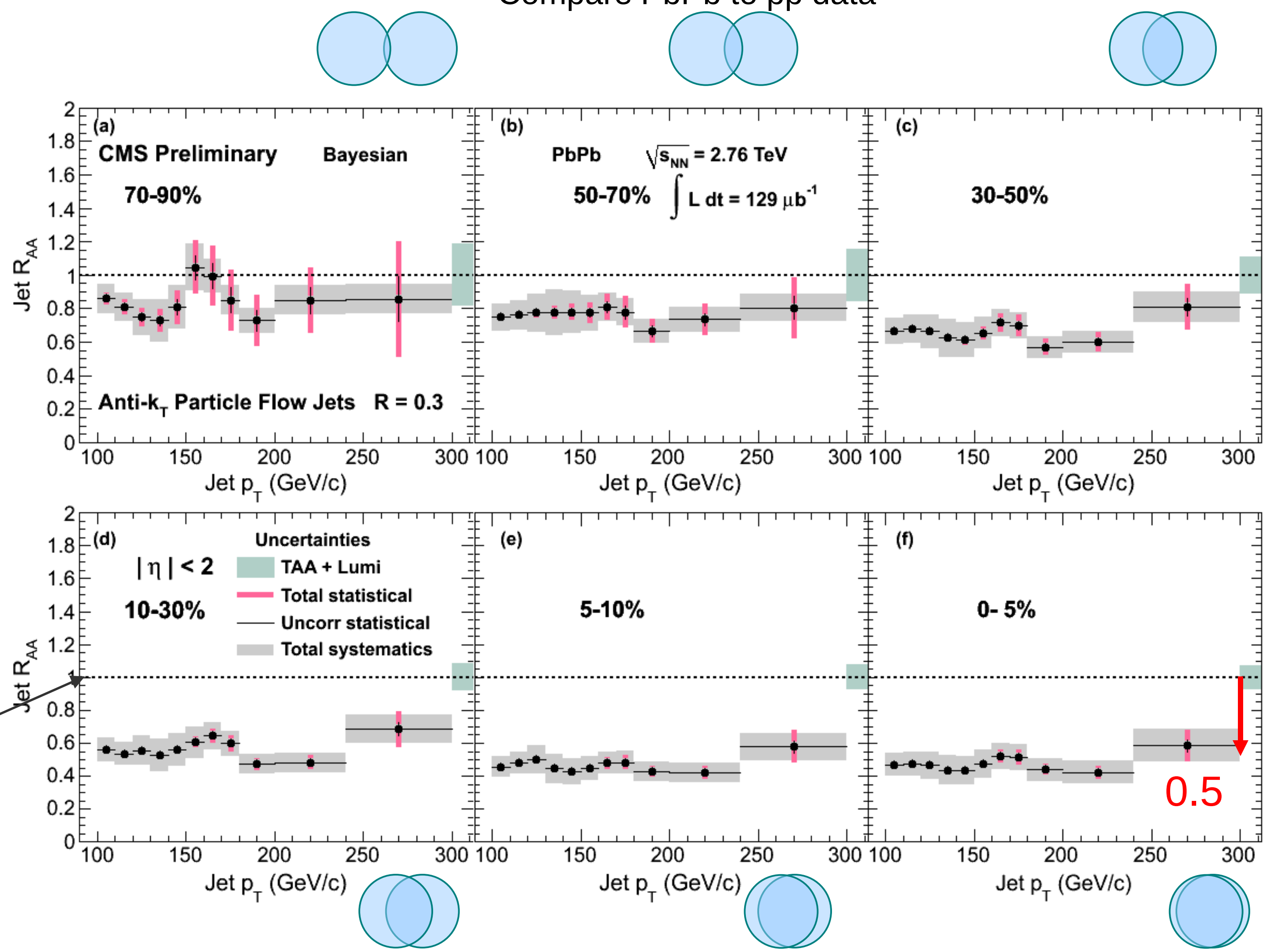
Anti-k_T jets with
R = 0.3



If PbPb = superposition of pp

CMS PAS HIN-12-004

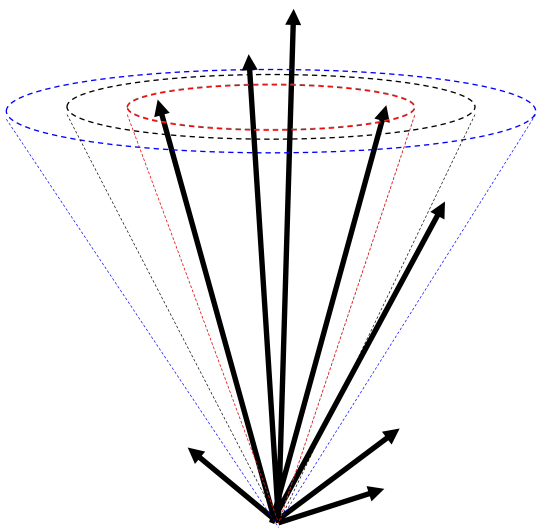
Compare PbPb to pp data



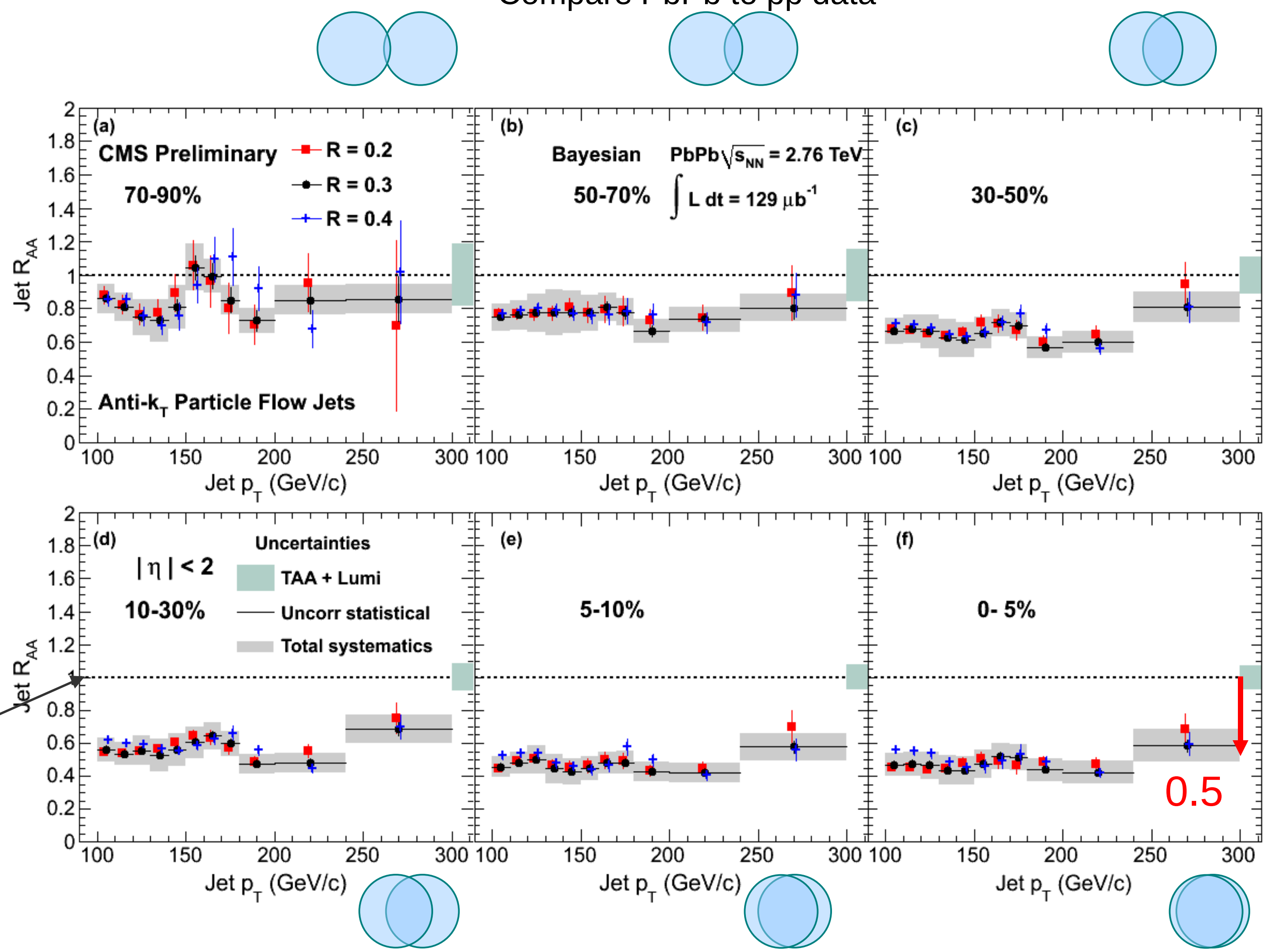
Strong suppression of inclusive high p_T jets

Inclusive jet spectra: jet R_{AA}

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



Compare PbPb to pp data



If PbPb = superposition of pp

CMS PAS HIN-12-004

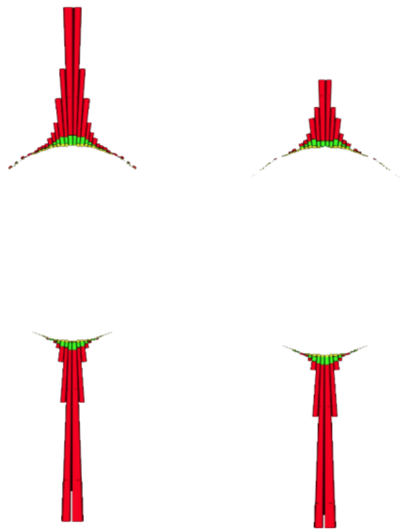
Strong suppression of inclusive high p_T jets

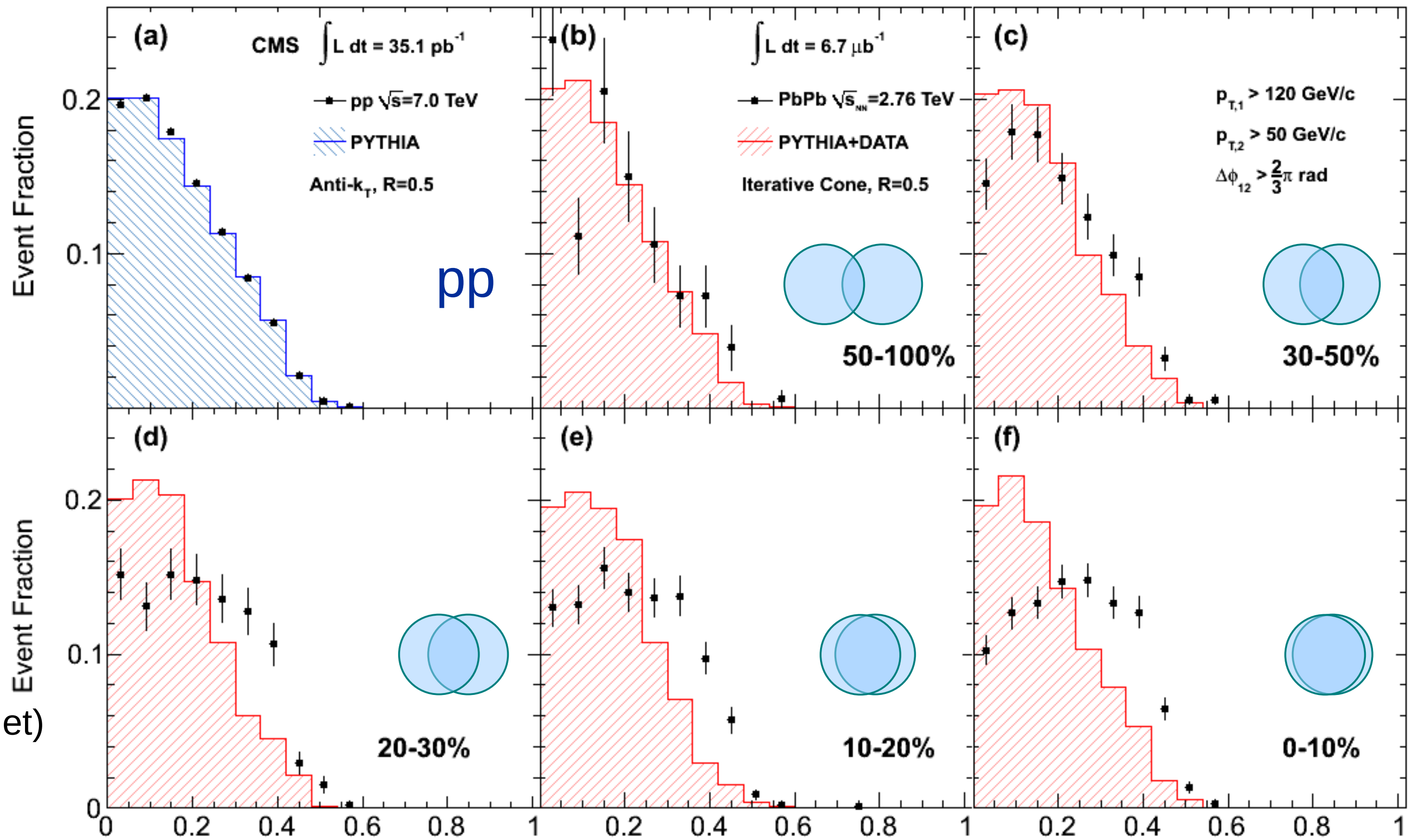
A cone of R=0.2, 0.3, 0.4 doesn't catch all the radiated energy

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

Di-jet momentum imbalance

Jet Cone size R = 0.5





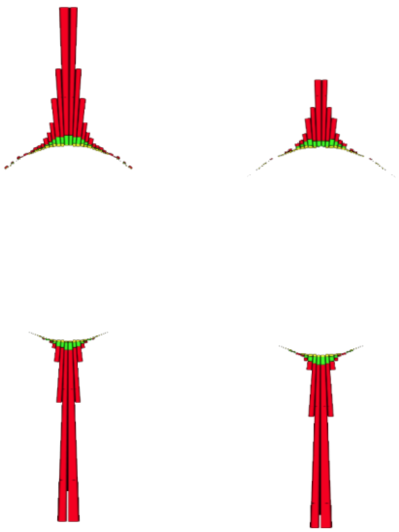
PRC 84 (2011) 024906

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

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

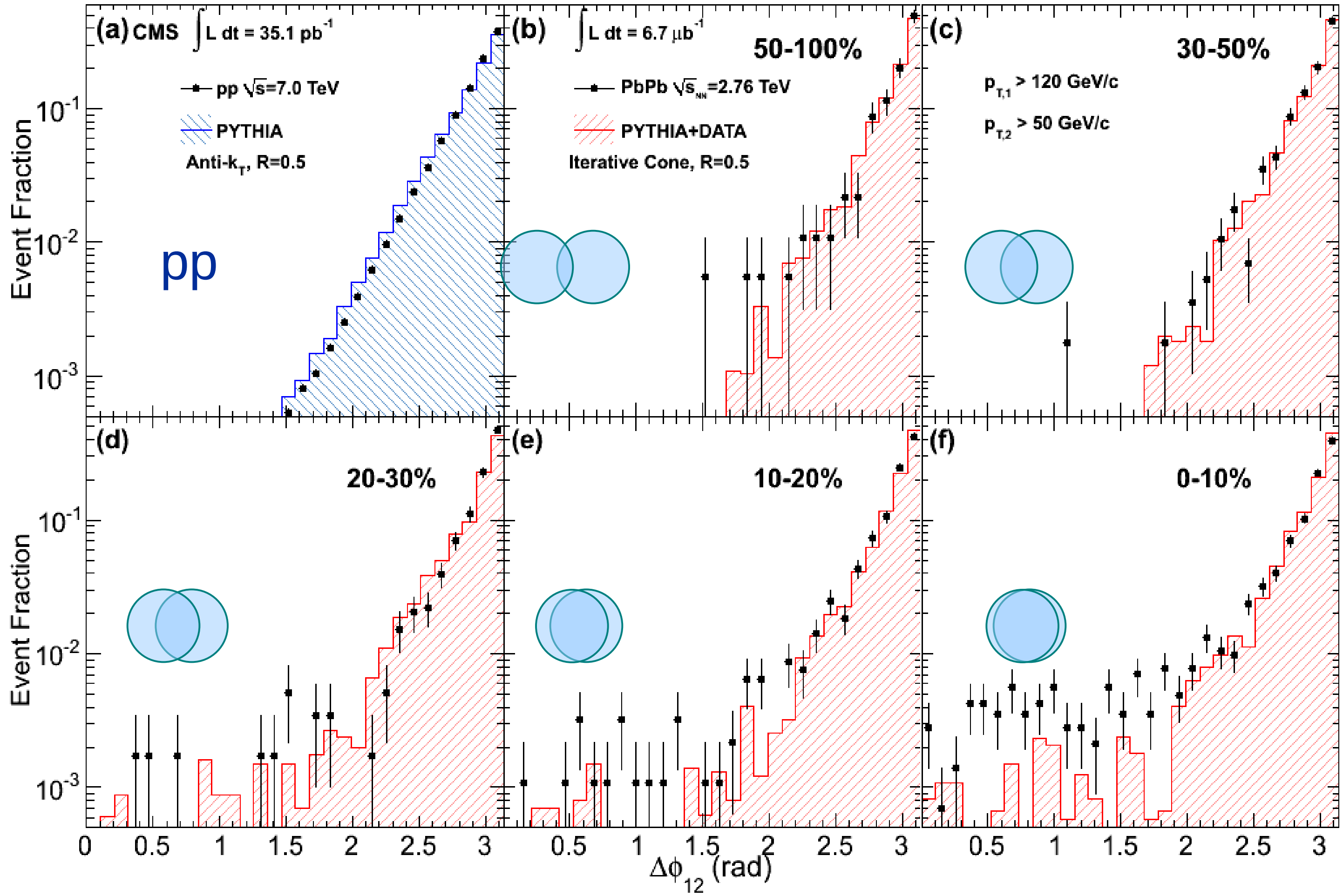
Dijet azimuthal angle correlations

Jet Cone size R = 0.5



Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)

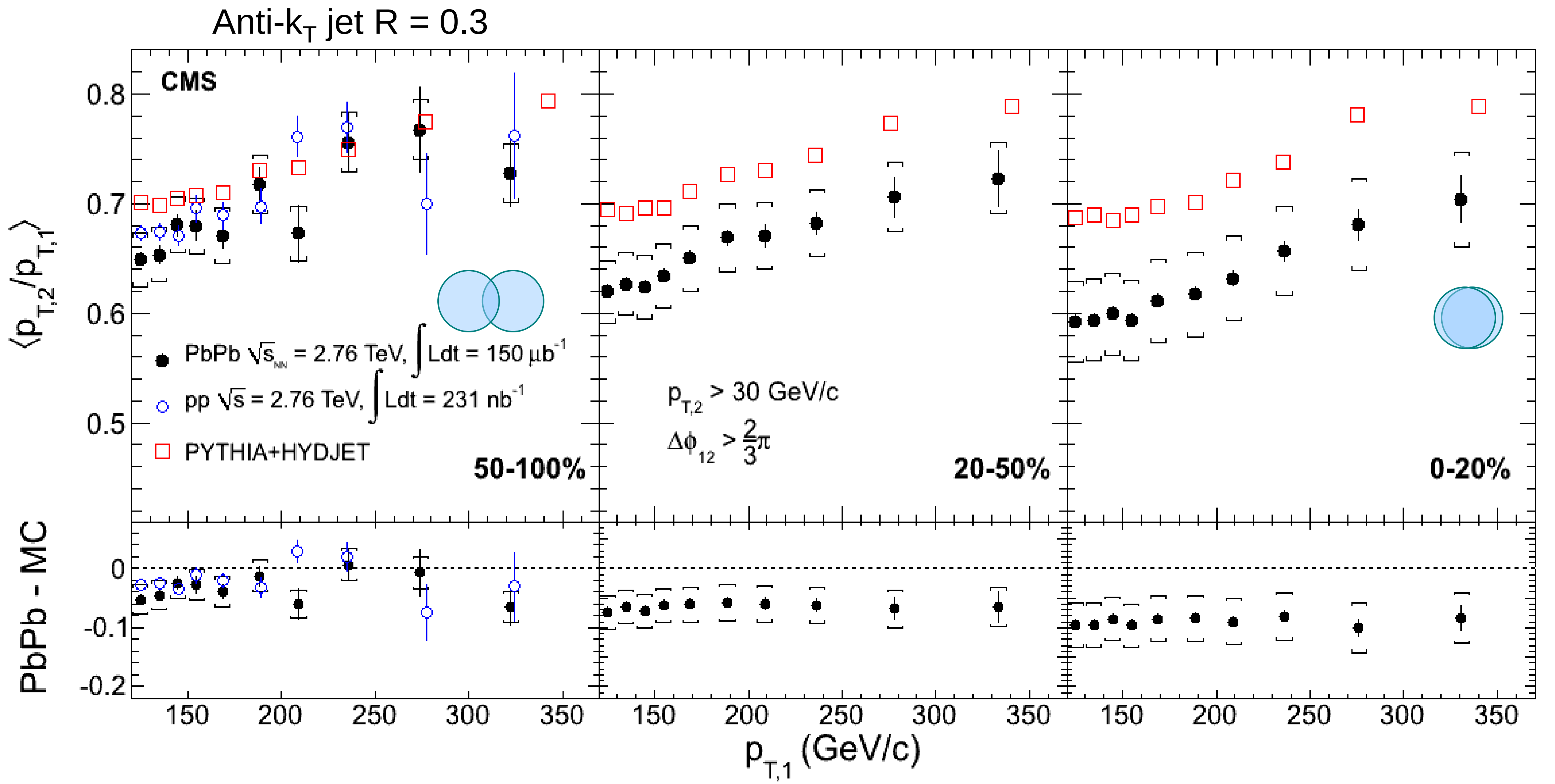


PRC 84 (2011) 024906

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

No apparent modification in the dijet Δφ distribution
(still back-to-back)

Dijet energy ratio (imbalance)

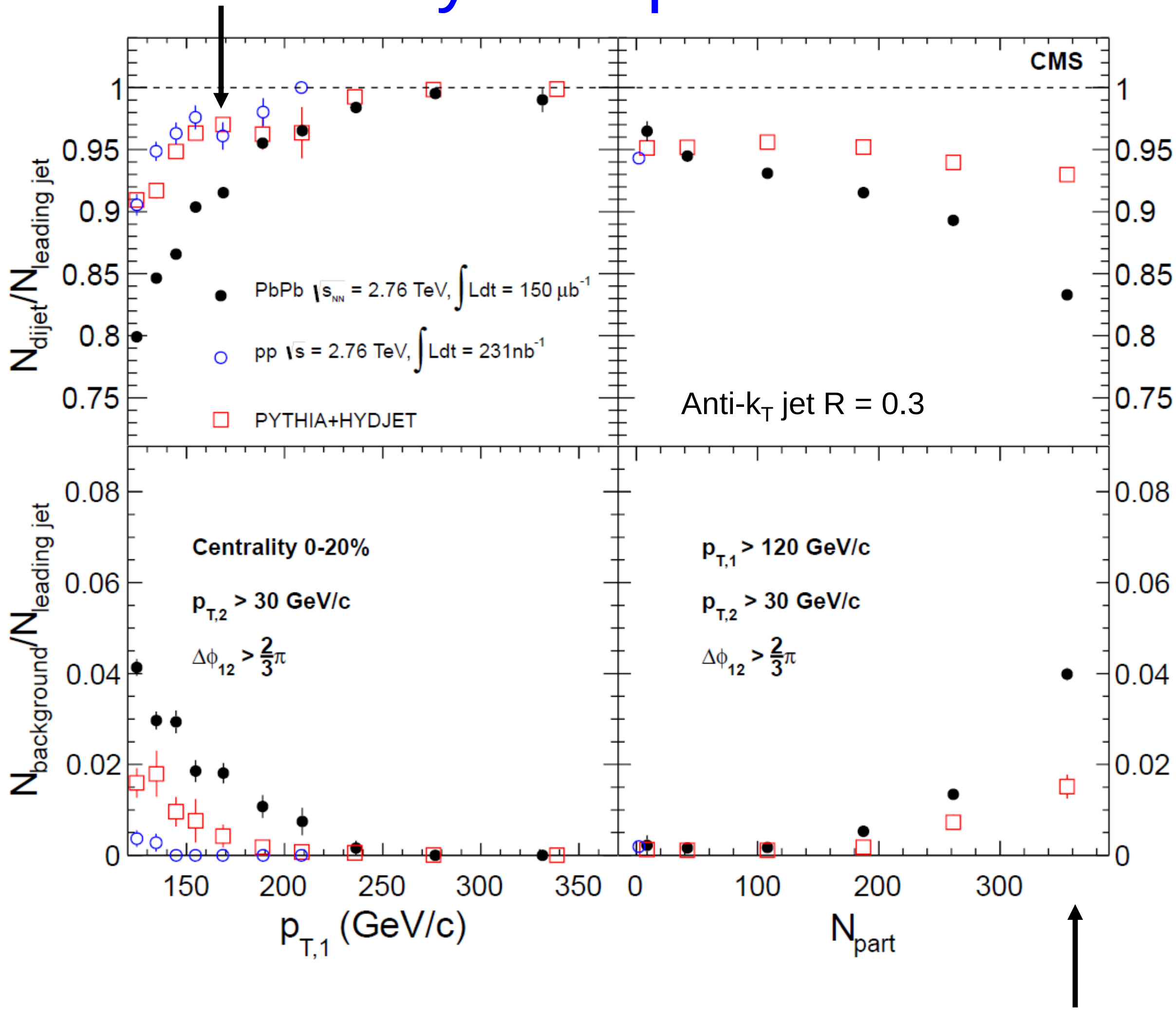


- Energy imbalance increases with centrality
- Very high p_T jets are also quenched

PLB 712 (2012) 176

Fraction of jets with an away side jet

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

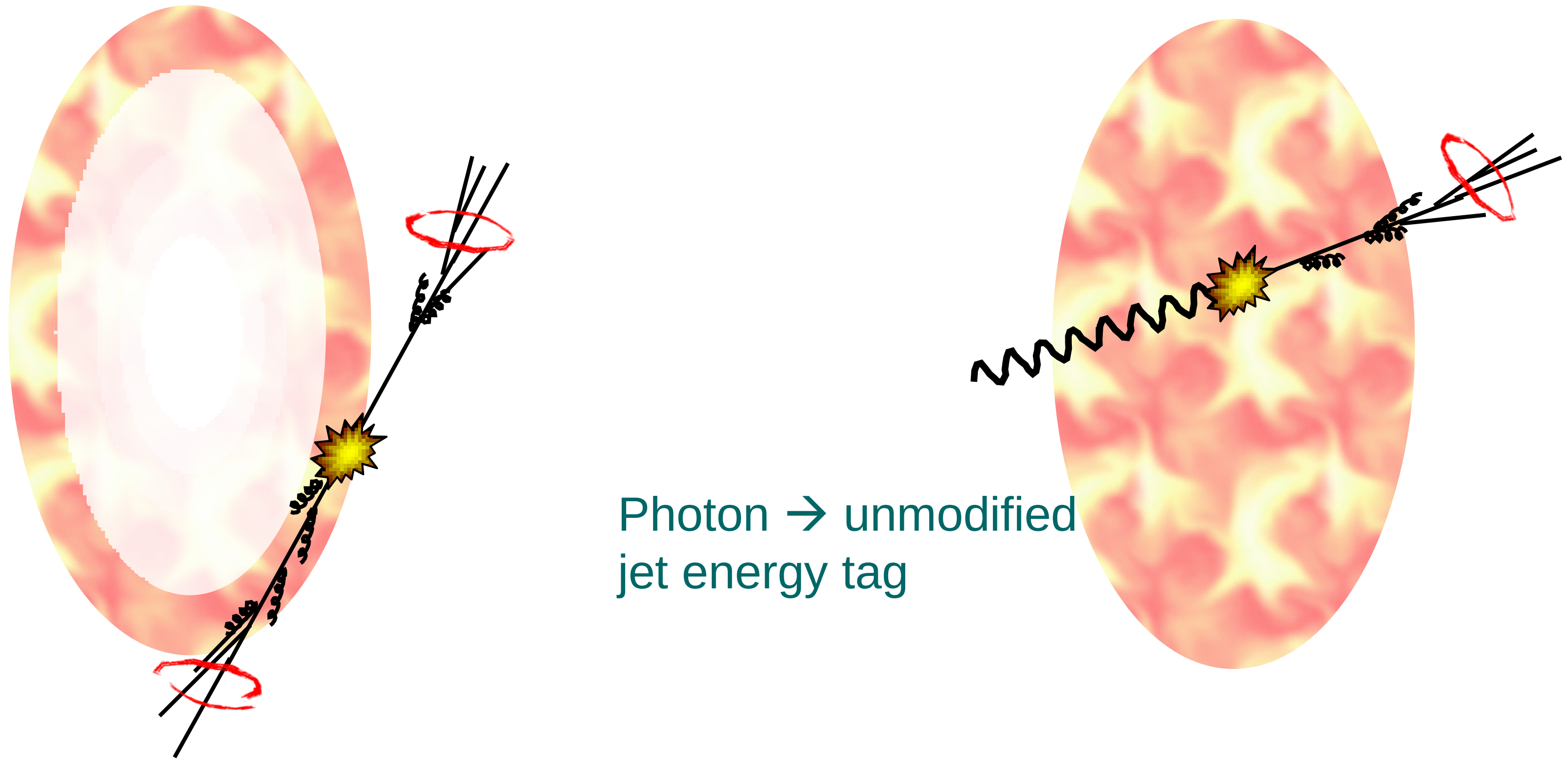


- Fake away side jet rate is < 4%

Photon-jet

Selection on a high p_T leading jet may bias the position of the hard scattering in the QGP

Solution → trigger on high p_T photon



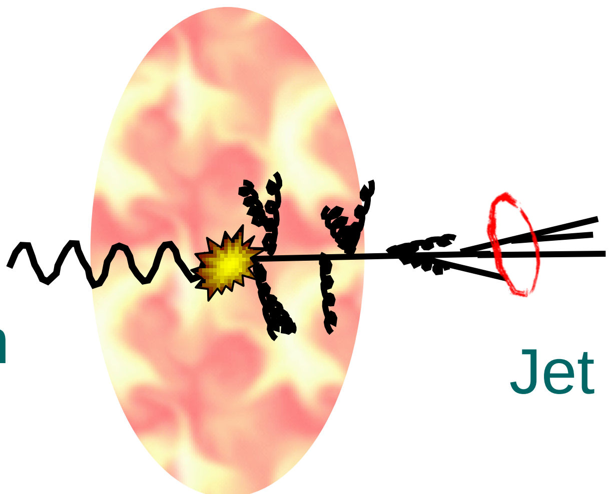
Photon → unmodified jet energy tag

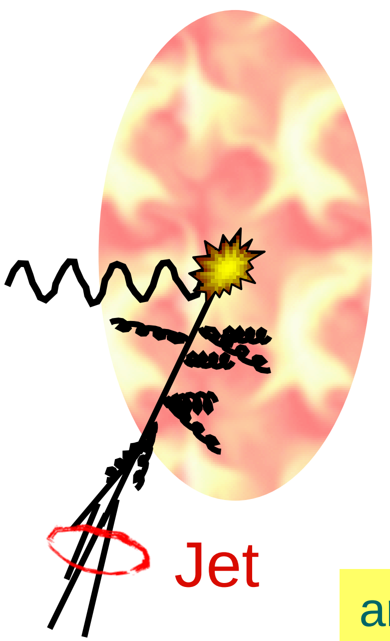
High p_T leading jet triggered sample

High p_T photon triggered sample

Photon-jet angular correlation

The first photon-jet correlation measurement in heavy ion collisions

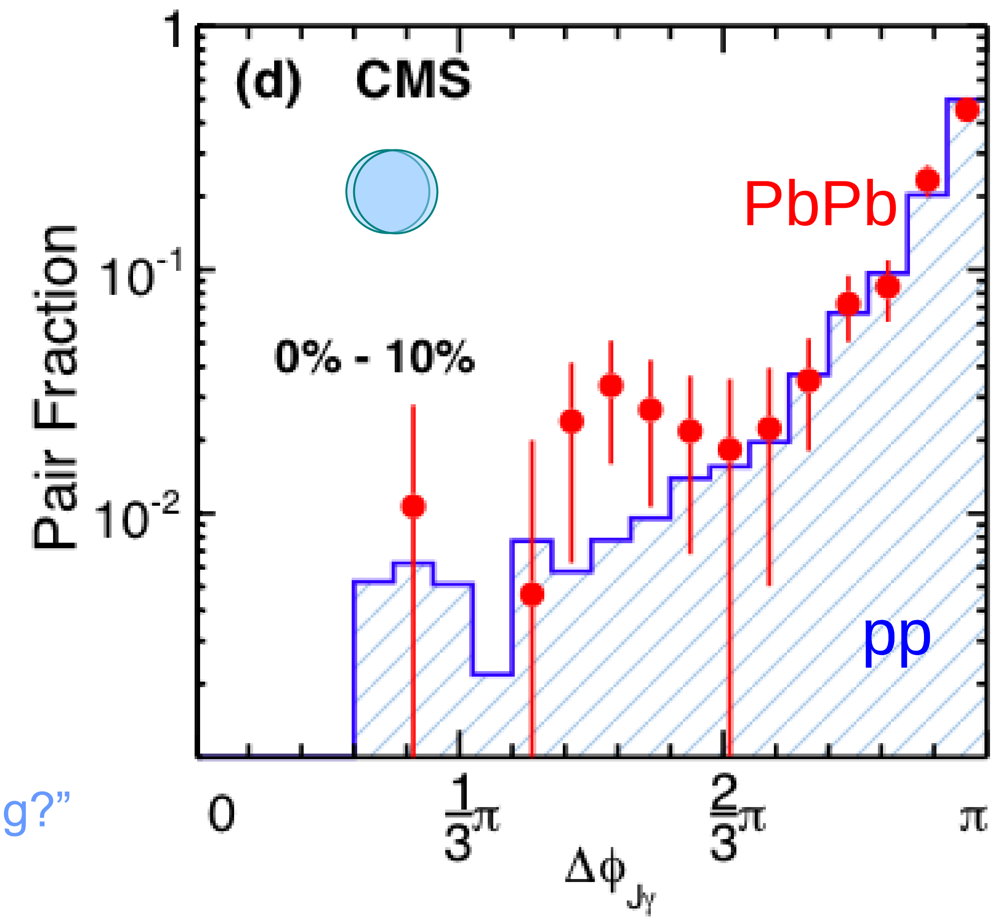




"Backscattering?"

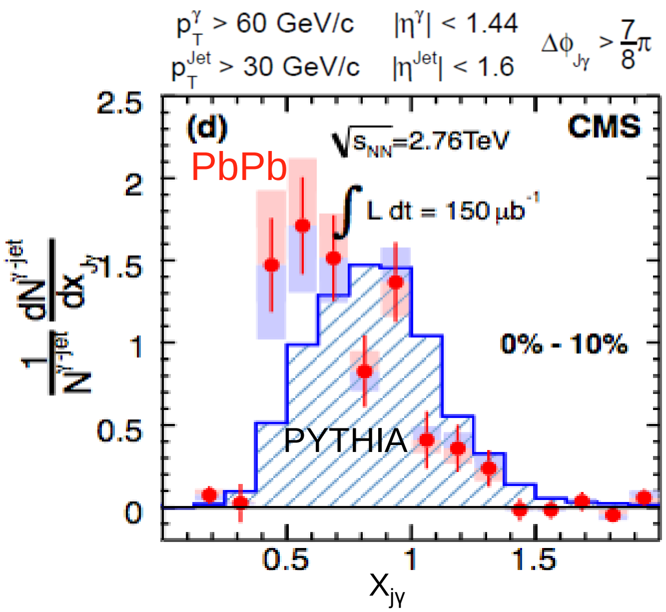
arXiv:1205.0206
Accepted by PLB

"QGP Rutherfold experiment"



Azimuthal angle difference between photon and jet

Photon-jet momentum balance



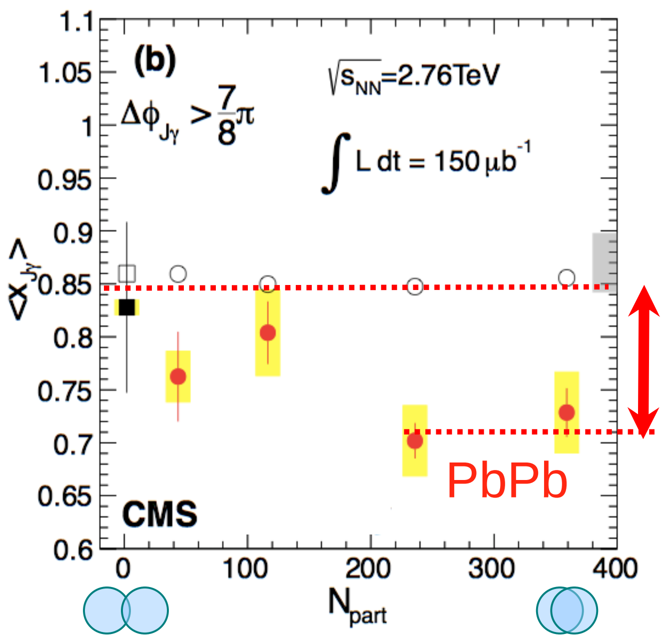
Compare photon-jet momentum balance

$x_{j\gamma} = p_T^{Jet}/p_T^{photon}$

in **vacuum** (pp collision) to the **QGP** (PbPb collision)

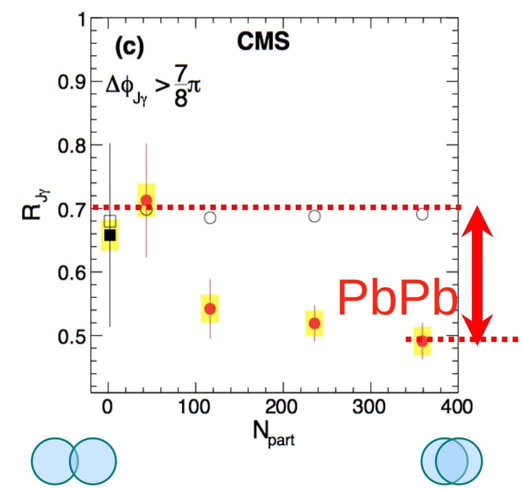
In addition, 20% of photons lose their jet partner (jet p_T> 30 GeV/c)

R=0.3

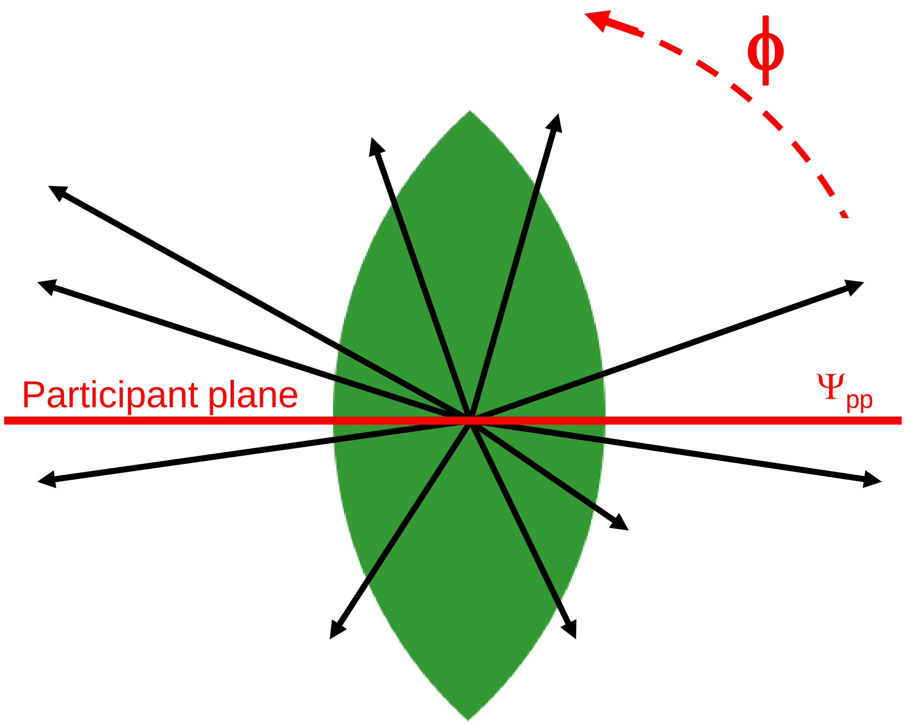


Jets lose about 15% of their initial energy

arXiv:1205.0206
Accepted by PLB



Path length dependence of jet energy loss?

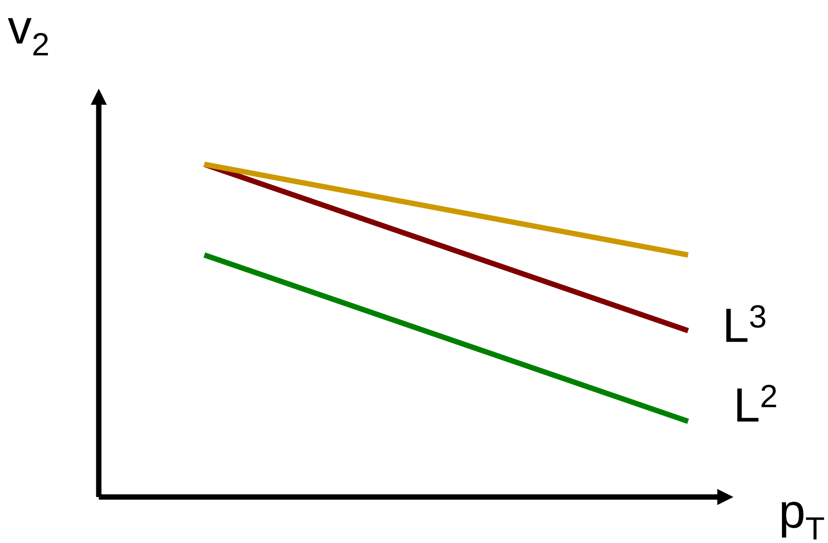


Overlap zone is almond-shaped
→ Parton energy loss is smaller along the short axis
→ More high-p_T tracks and jets closer to the event plane

→ Azimuthal asymmetry (v_2):

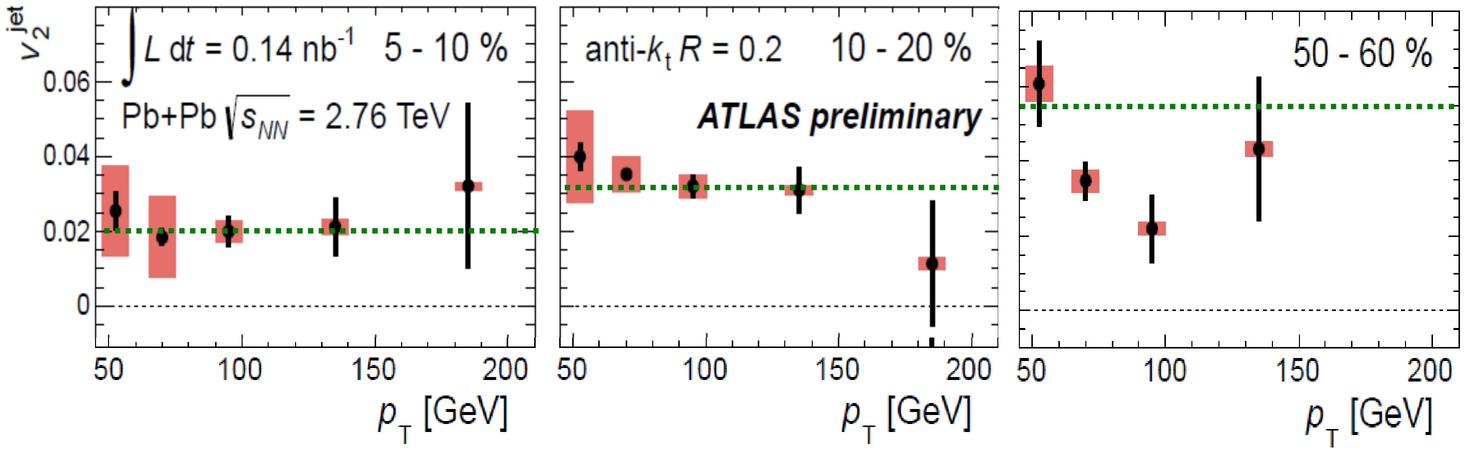
$$dN/d\phi \propto 1 + 2v_2 \cos(2(\phi - \Psi_{EP}))$$

→ v2 is sensitive to the path-length dependence of the energy loss

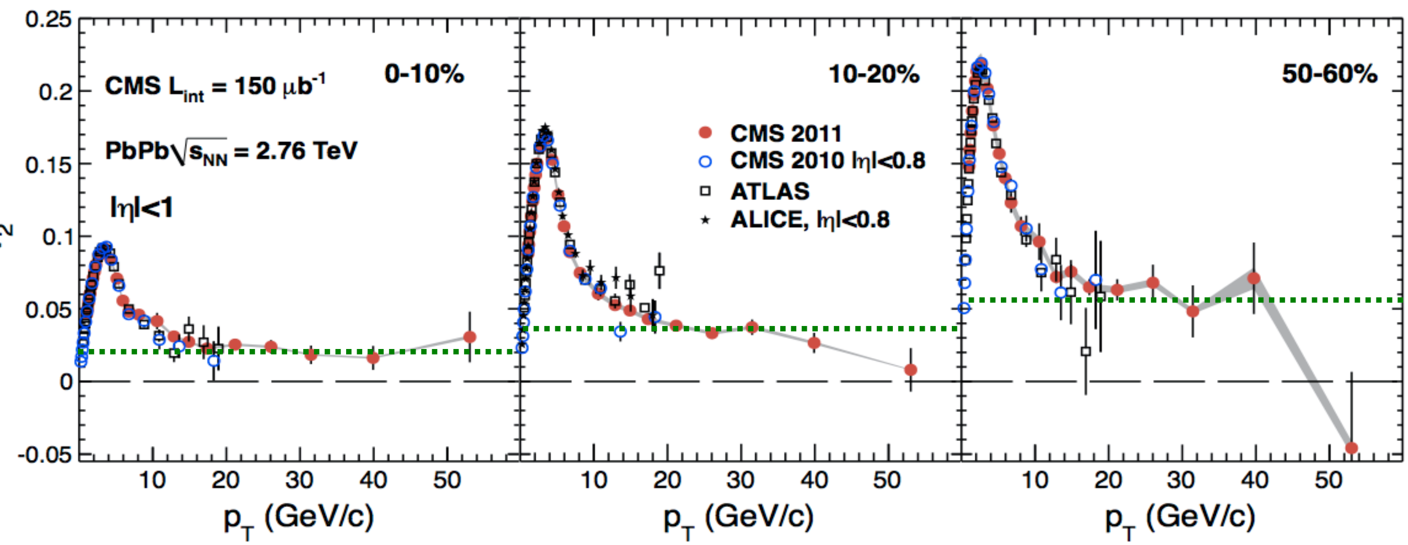


Jet and high p_T track v_2 at the LHC

Jet v_2



High p_T track v_2



PRL 109 (2012) 022301

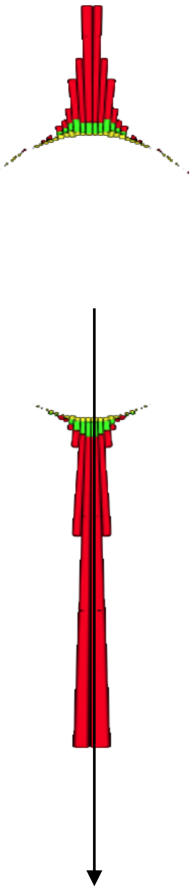
- Jet and high p_T track v_2 : non-zero up to very high p_T
- Sensitive to the path length dependence of energy loss

Where does the energy go?

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

ΔE_T ~ O(10) GeV,
~10% shift in <dijet p_T ratio>

Where does the energy go?



Missing-$p_T^{||}$

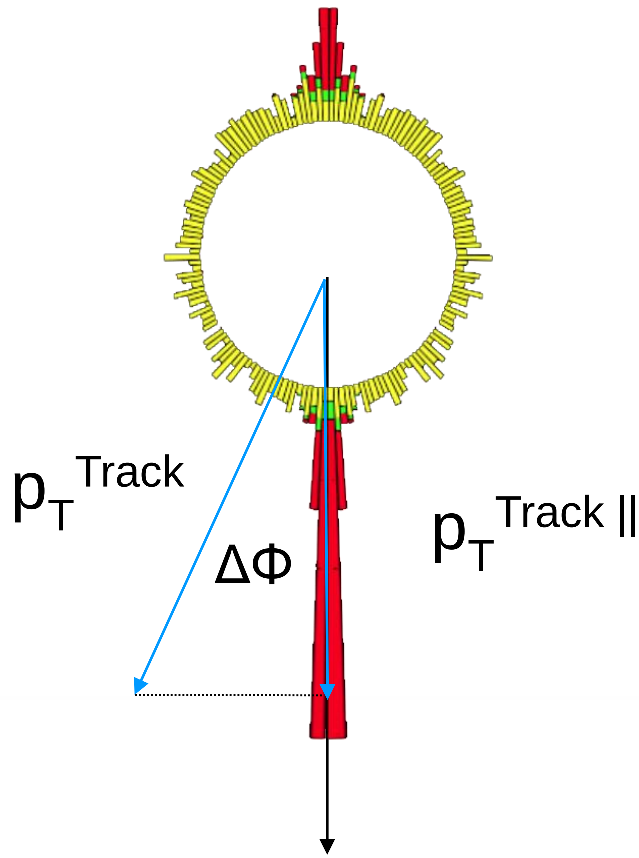
Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

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

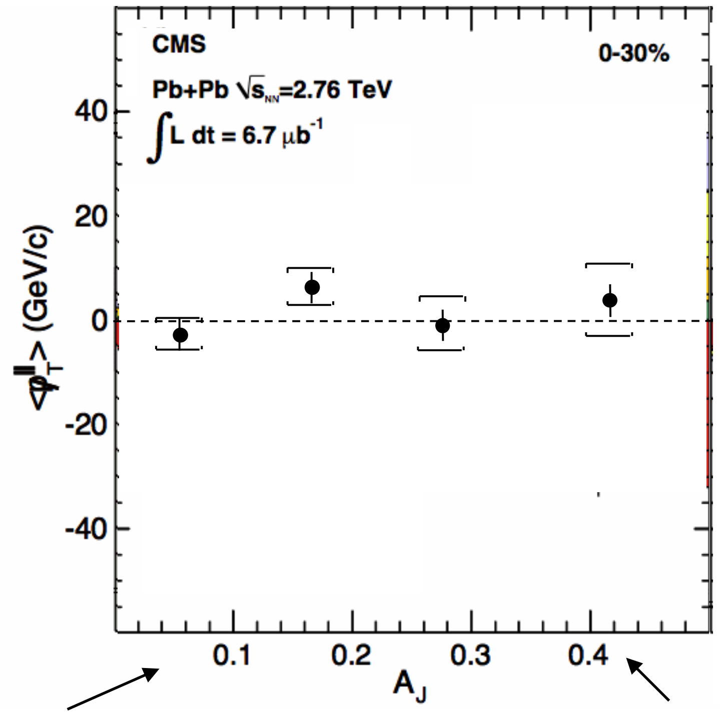


Sum over all tracks in the event

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

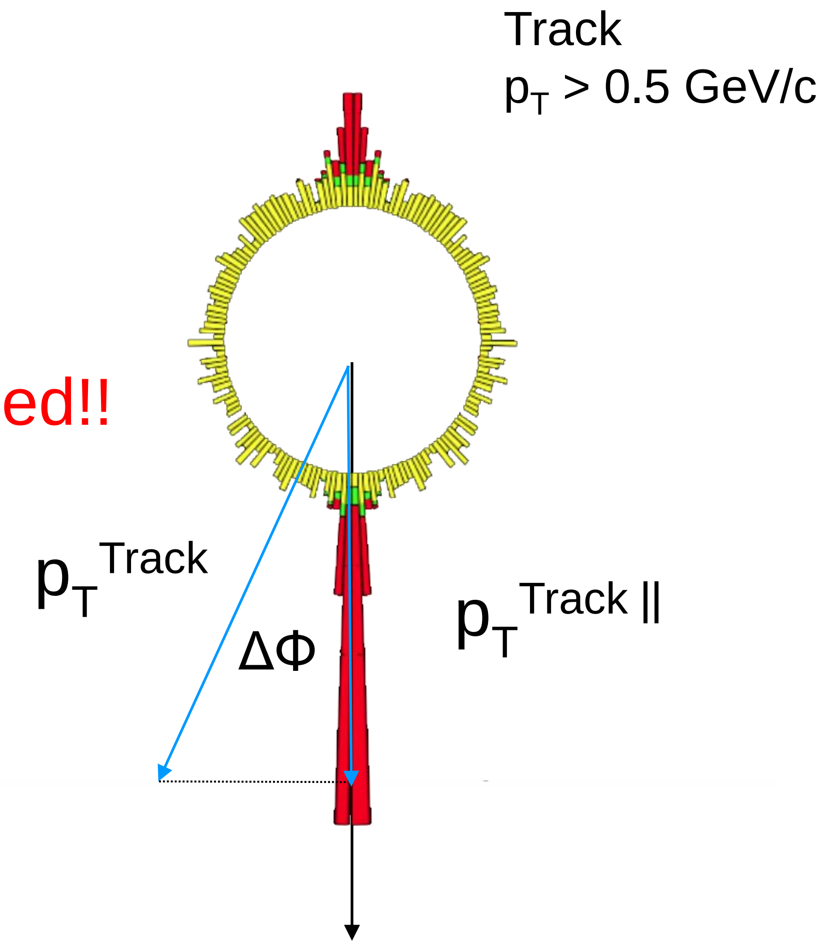
unbalanced jets

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

excess away from leading jet

Balanced!!

excess towards leading jet



Integrating over the whole event final state

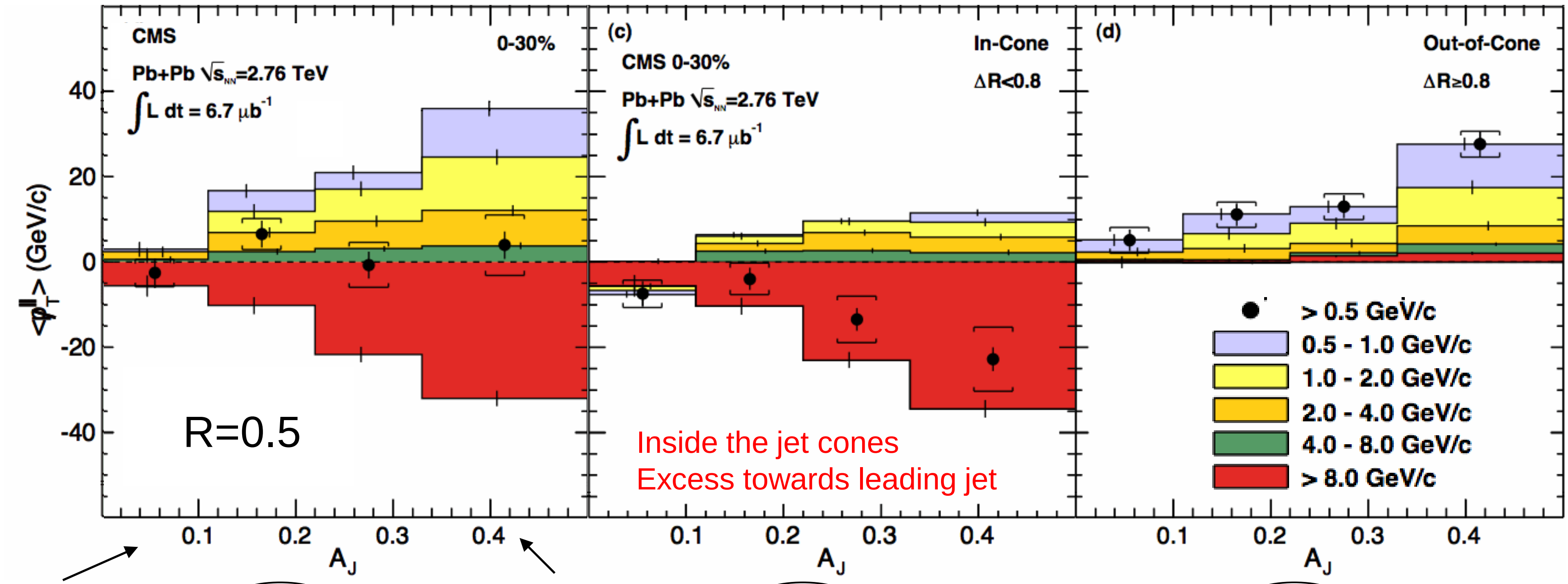
the dijet momentum balance is restored

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

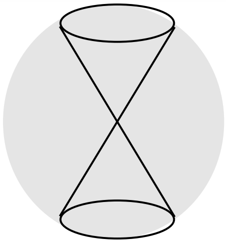
Out of the jet cones
Excess towards sub-leading jet



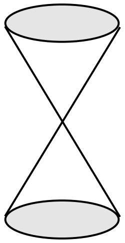
Inside the jet cones
Excess towards leading jet

balanced jets

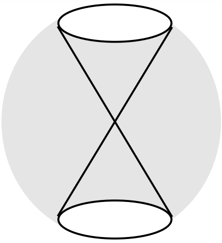
unbalanced jets



All tracks



Tracks in
the jet cone
ΔR<0.8



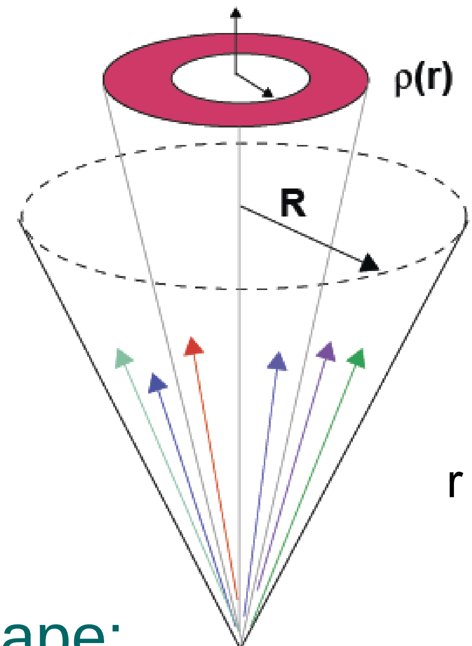
Tracks out of
the jet cone
ΔR>0.8

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

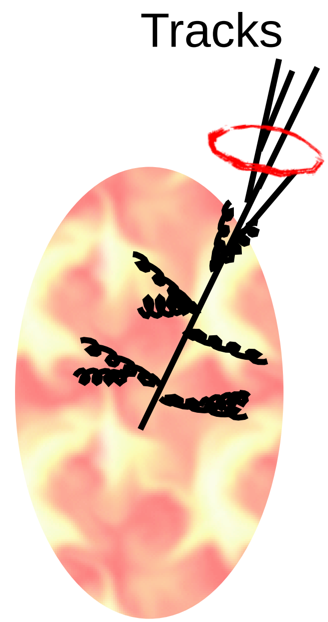
Jet shape and fragmentation function

Large parton energy loss (O(10GeV)) in the medium, out of jet cone

→ What about jet structure?



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



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

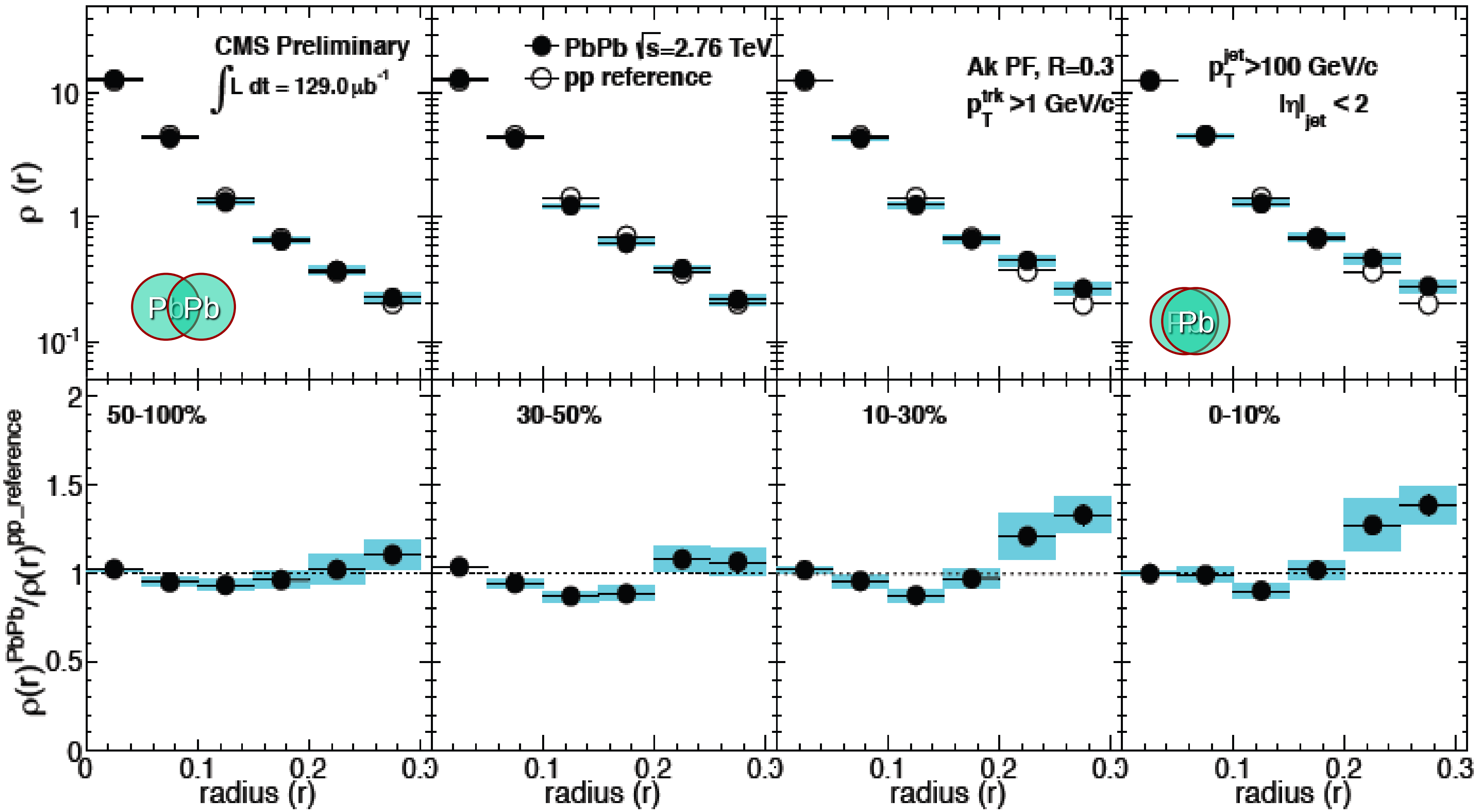
$$\rho(r) = \frac{1}{f_{\text{ch}}}\frac{1}{\delta r}\frac{1}{N_{\text{jet}}}\sum_{\text{jets}}\frac{p_{\text{T}}(r-\delta r/2, r+\delta r/2)}{p_{\text{T}}^{\text{jet}}}$$

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

Jet fragmentation function:
how transverse momentum is distributed inside the jet cone

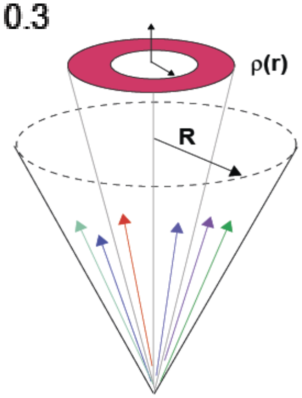
$$\xi = \ln\frac{1}{z}\ ;\quad z = \frac{p_{\parallel}^{\text{track}}}{p^{\text{jet}}}$$

Jet shapes



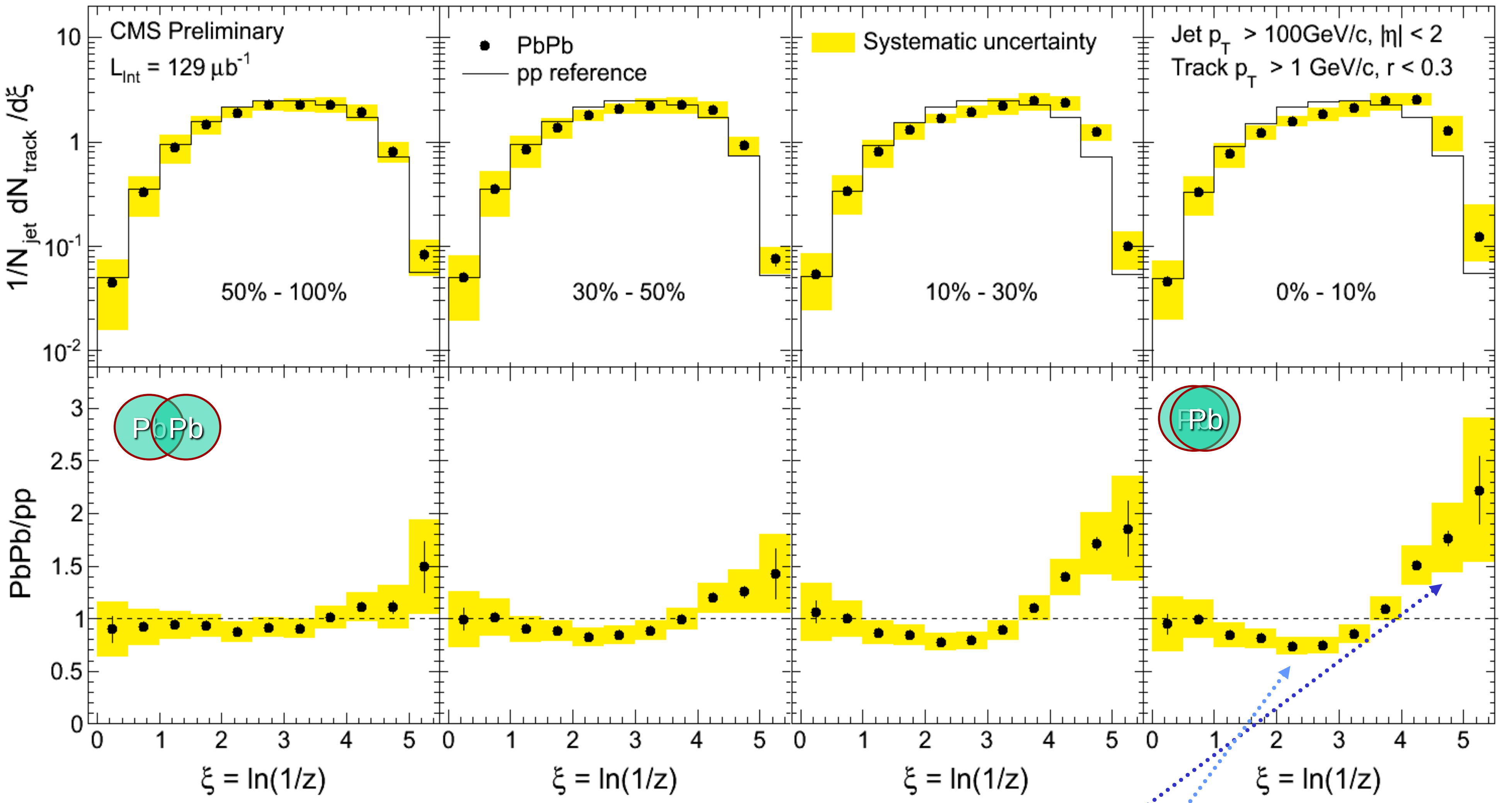
CMS PAS HIN-12-013

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



Significant modification at large radius (r) with respect to the jet axis

Jet fragmentation functions



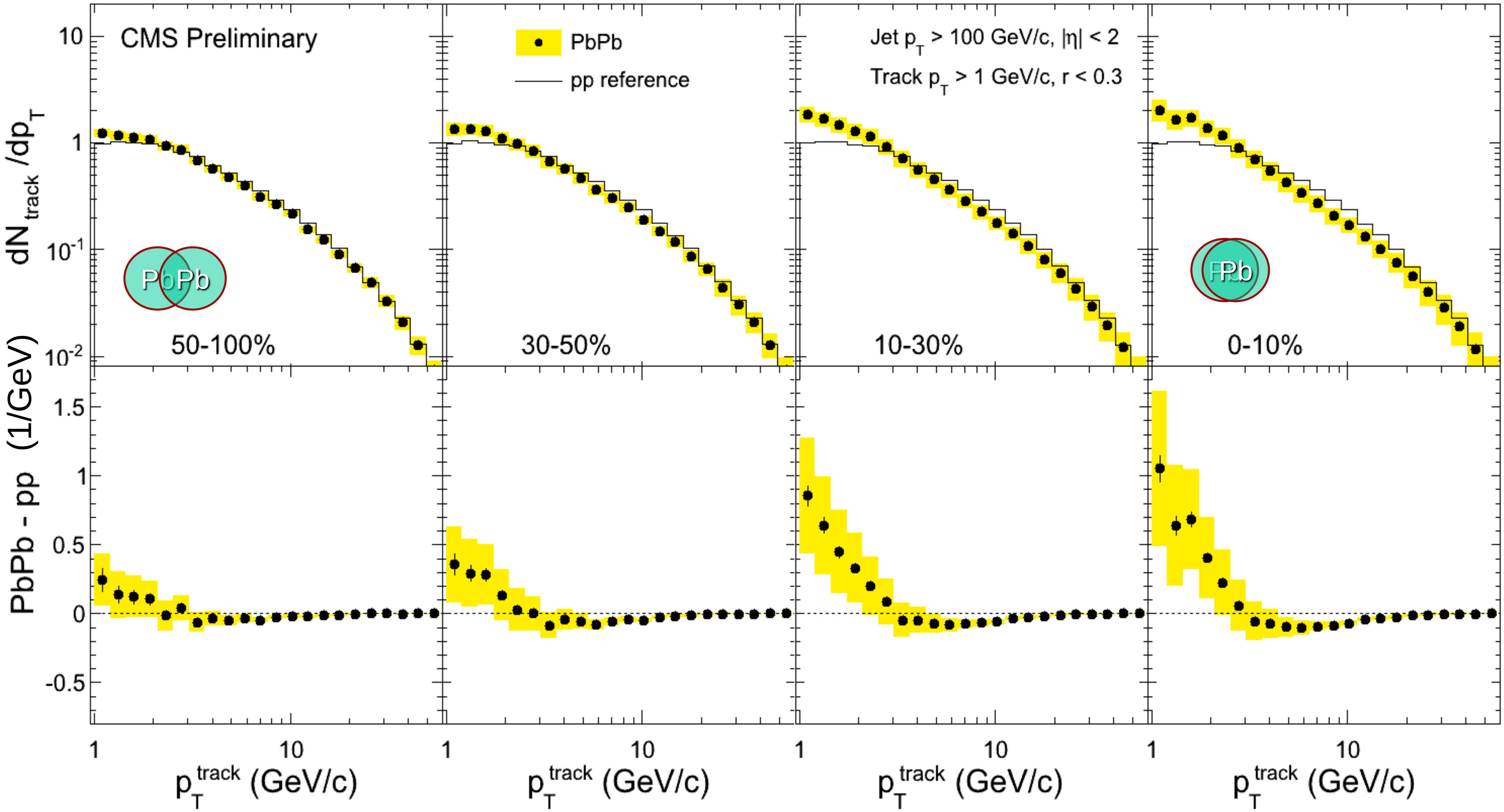
CMS PAS HIN-12-013

Inside the jet cone: Enhancement of low p_T particle

Suppression of intermediate p_T particles in cone

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

Track p_T distributions in jet cones (R=0.3)

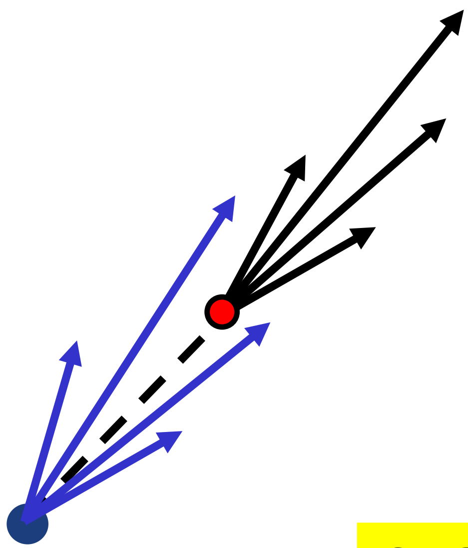


High p_T : **no change** compared to jets in pp collisions
In (central) PbPb: **excess** of tracks compared to pp at low p_T

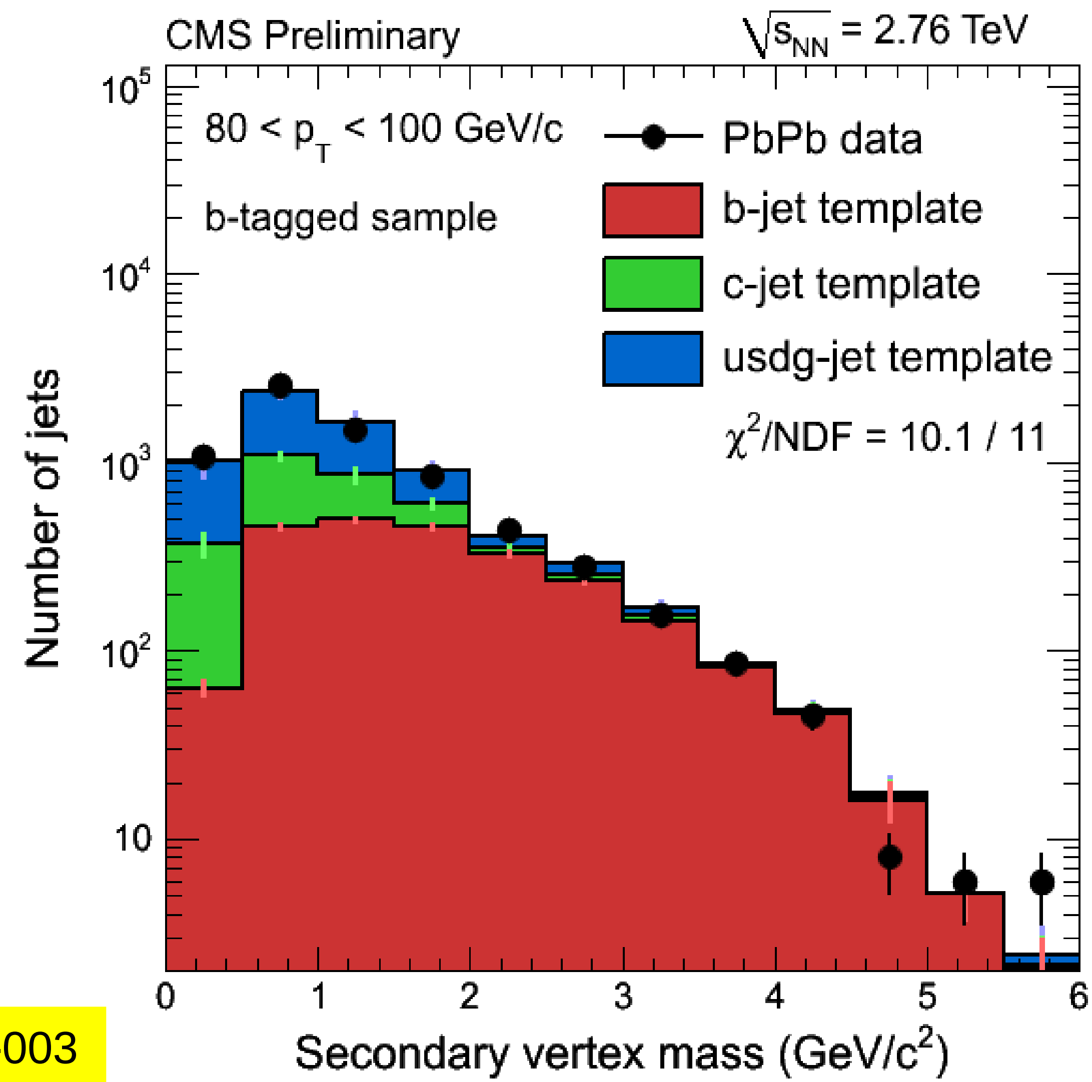
Tagging and counting b-quark jets

Secondary vertex tagged using flight distance significance

- Tagging efficiency estimated in a **data-driven** way
- Purity from **template fits** to (tagged) secondary vtx mass distributions

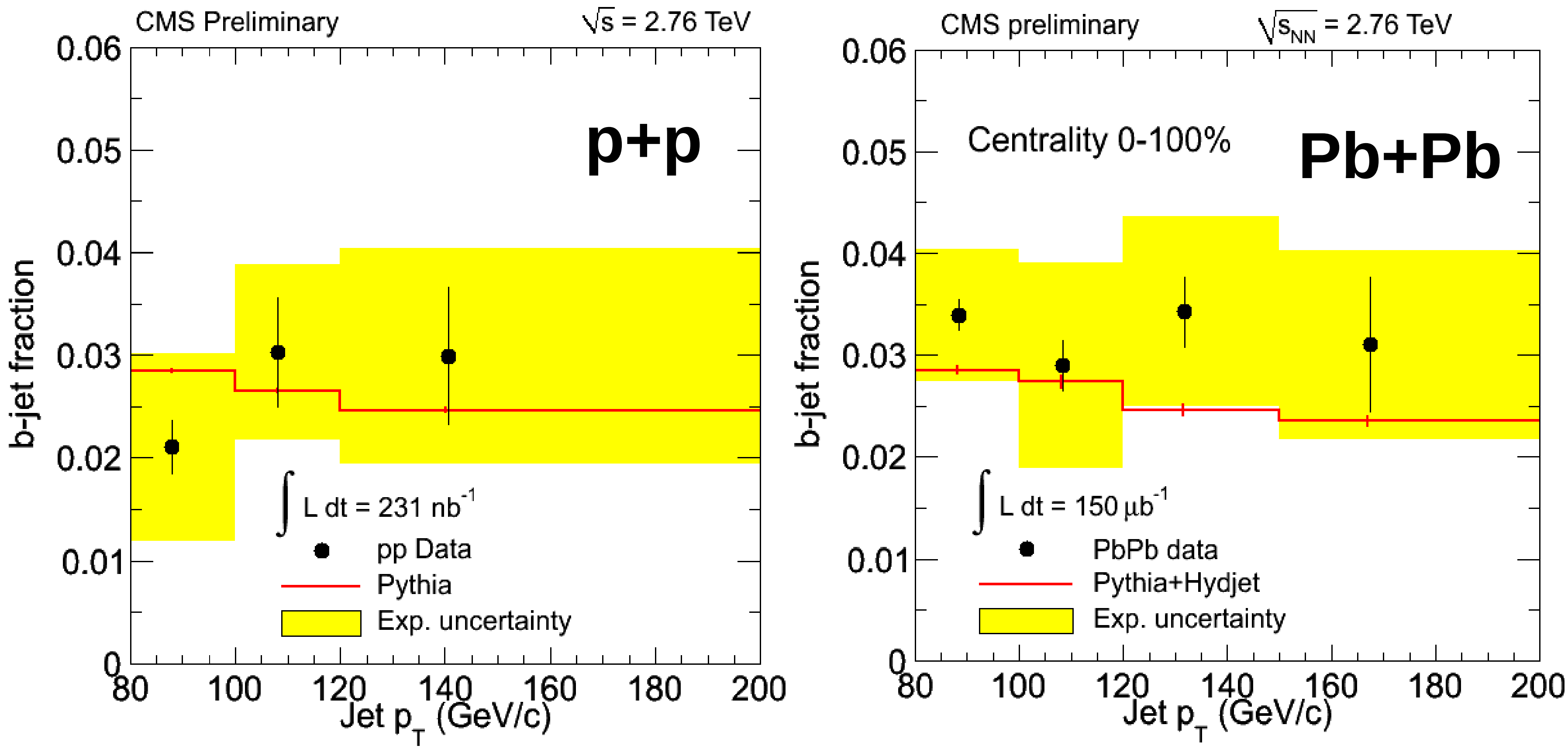


CMS PAS HIN-12-003



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

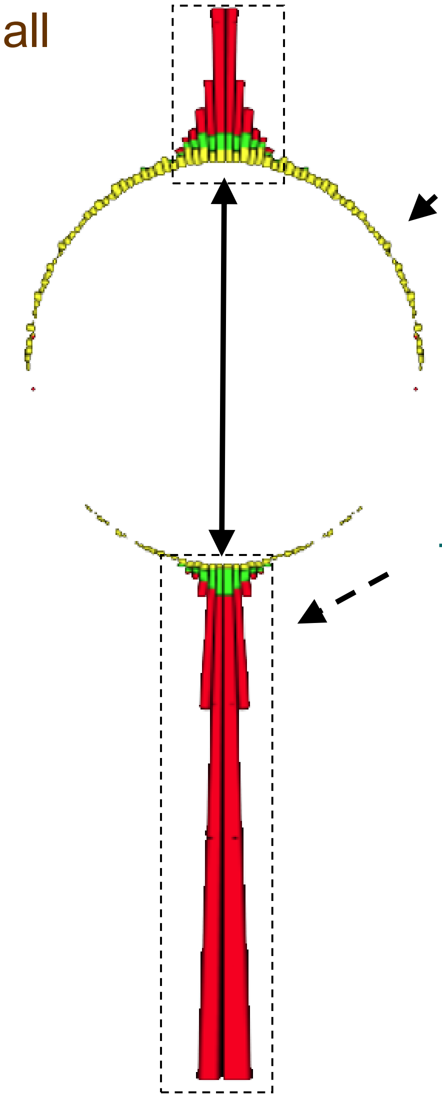


CMS PAS HIN-12-003

What have we learned with CMS PbPb data?

1. High p_T jet suppression
→ΔR = 0.2 - 0.5 doesn't capture all the radiated energy

4. p_T difference found at low p_T particles far away from the jets



2. Large average dijet and photon-jet p_T imbalance

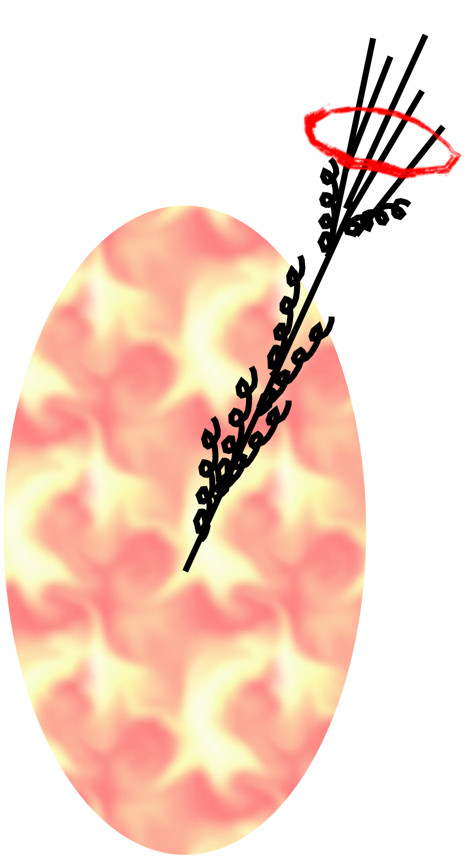
5. First observation of modified fragmentation function and jet shape

6. b-jets are also quenched

3. Angular correlation of jets not largely modified

challenges to theory community!

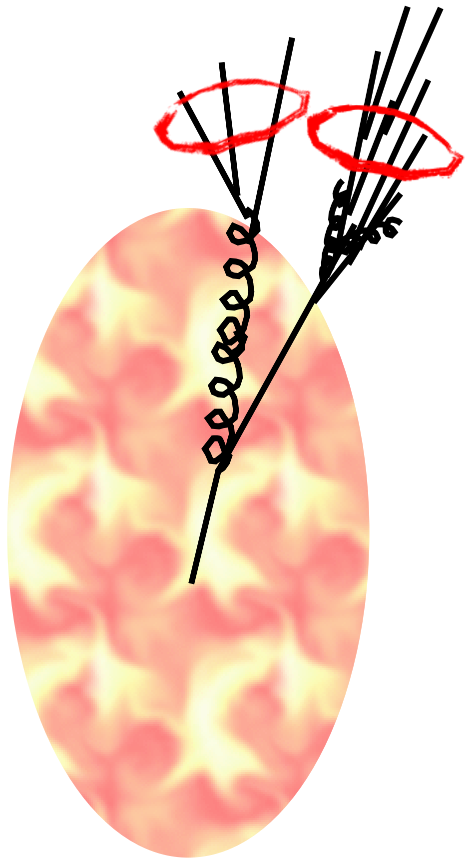
To explain the suppression of high p_T particles



Soft collinear radiation

GLV + others

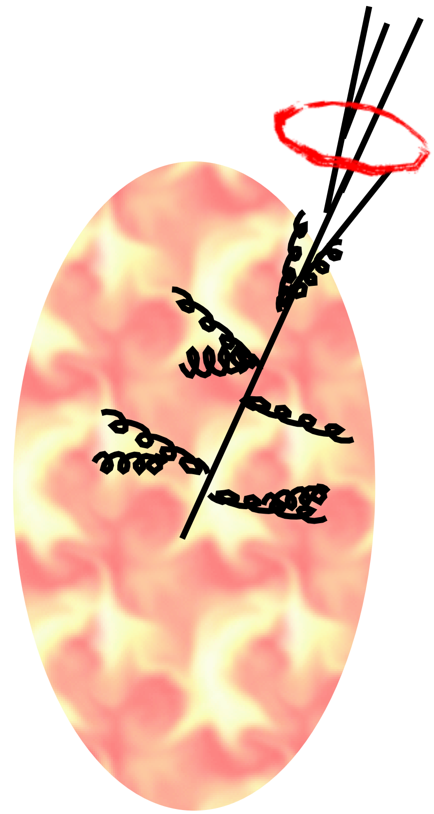
(pre-LHC models)



Hard radiation

PYTHIA inspired models

Modified splitting functions



Large angle soft radiation

“QGP heating”

AdS/CFT

Interference

Can we collect the in-medium radiated energy back? → Need a large jet cone

Do we see strong suppression of high p_T jets? → Yes

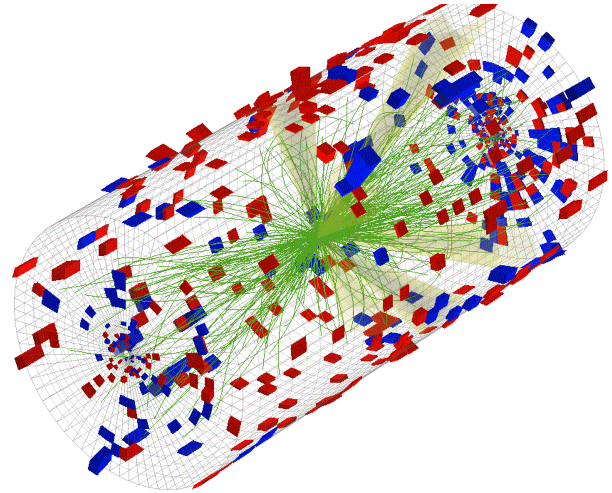
pPb pilot run

Successful pPb data-taking with physics object triggers fully deployed on Sep 2012!

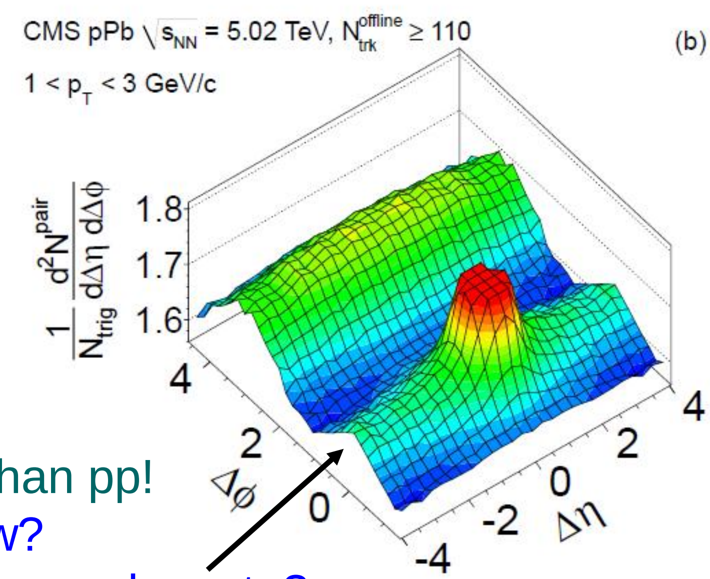
• The first unexpected result already came out:

Observation of long-range near-side angular correlations in proton-lead collisions at the LHC

arXiv:1210.5482v2, accepted by PLB



Two particle correlation function



5x larger than pp!

Elliptic flow?

Color glass condensate?

Modified jet structure?

pp ridge paper: JHEP 1009 (2010) 091

2013 pPb run:

• Jet quenching in pPb collisions?

• Are jets modified in pPb collisions?

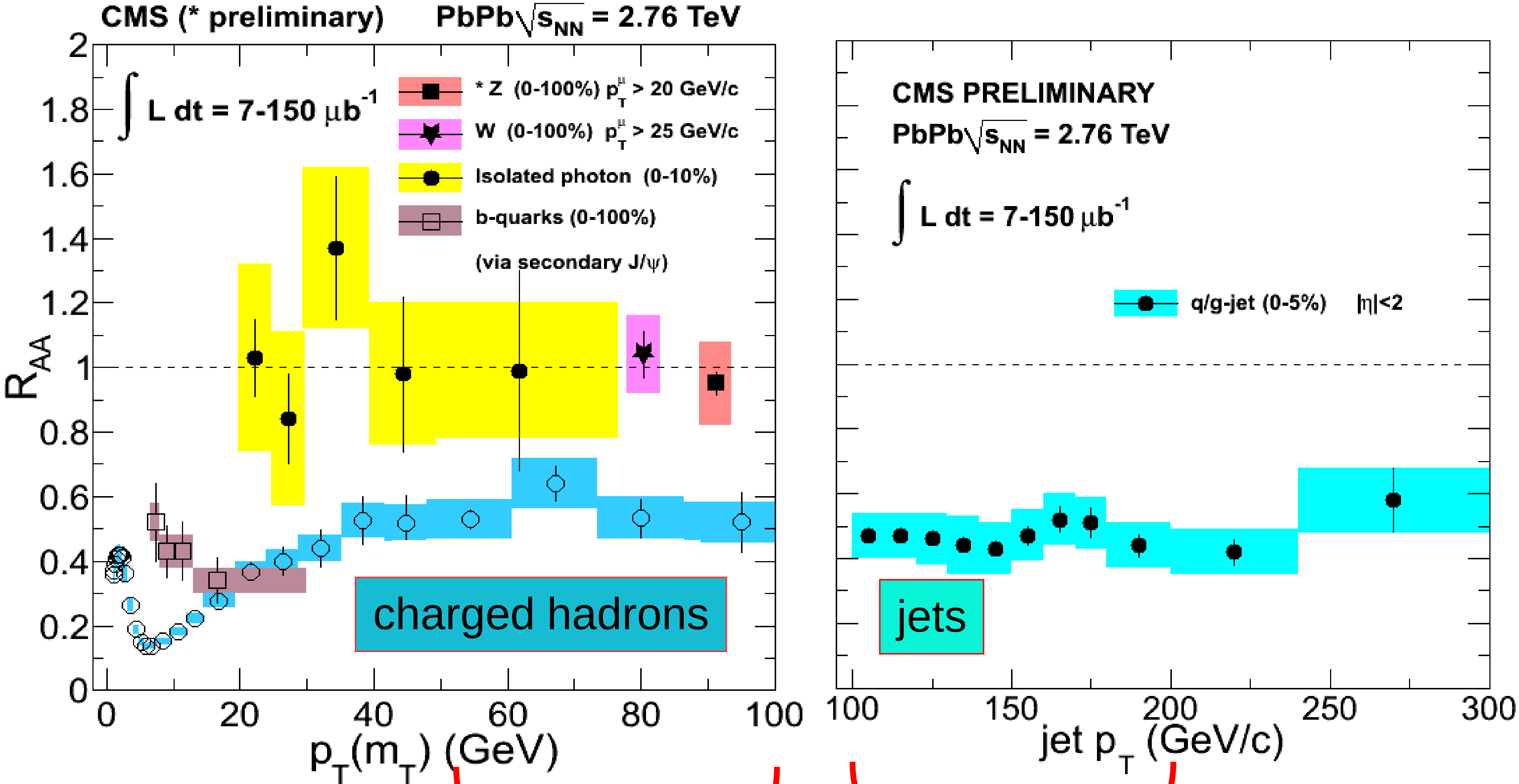
• Are nuclear parton distribution functions modified with respect to nucleons?

Summary

- Exciting LHC era:
  - Strongly interacting QGP is produced
  - High performance CMS detector
- Results from those high p_T hard probes are interesting!
  - Post challenges to the theoretical community
- Smooth pPb pilot run in 2012. Expect to learn more with 2013 data!
- A lot of future measurements to be done with high statistics PbPb data at nominal collision energy

Backup slides

Nuclear modification factors

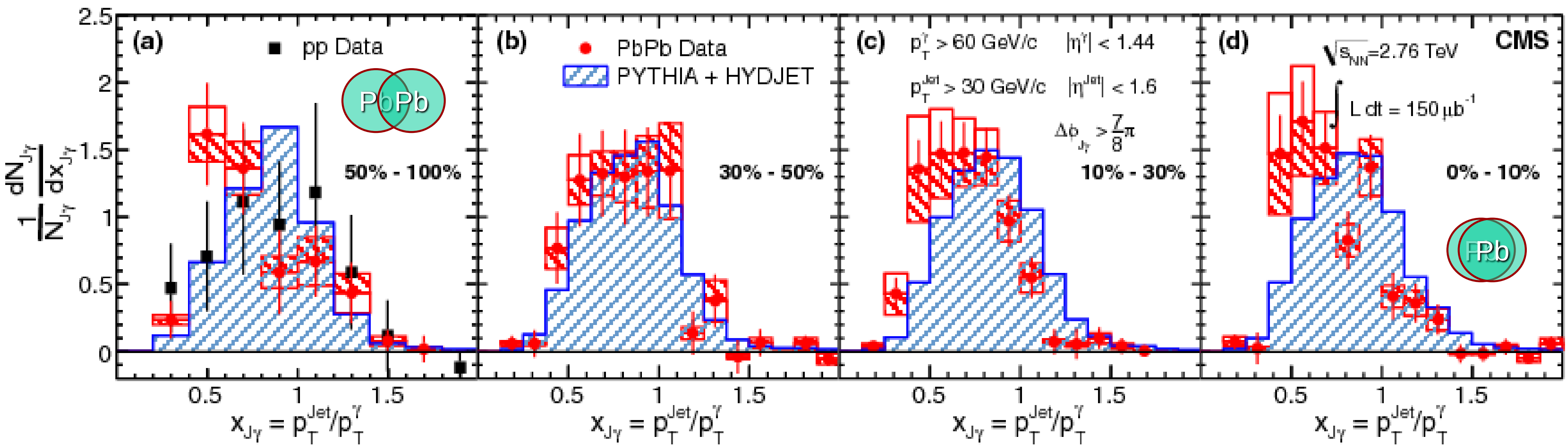


Sampling the ~same parton p_T range

Note: jets fragment into high-p_T particles in pp and PbPb the same way – *see later…*

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

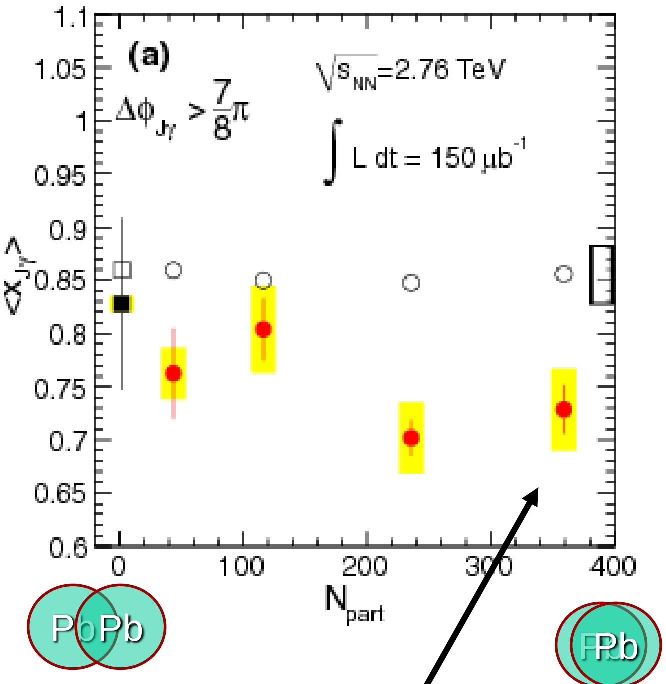


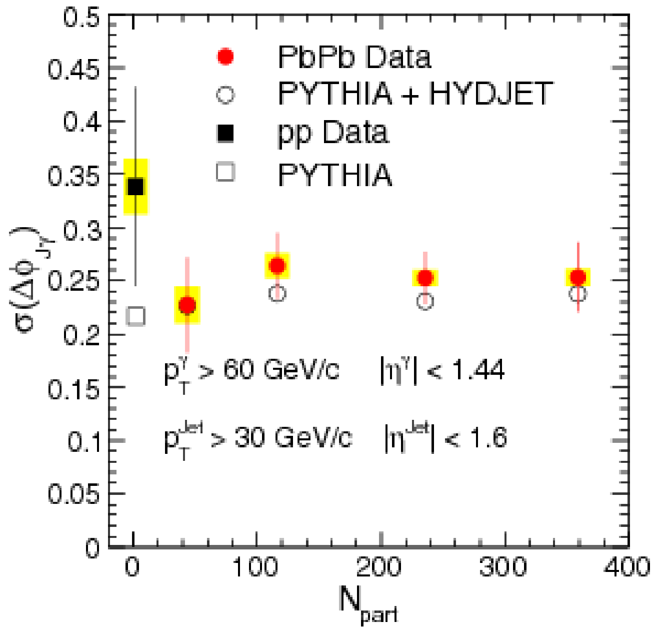
arXiv:1206.0206

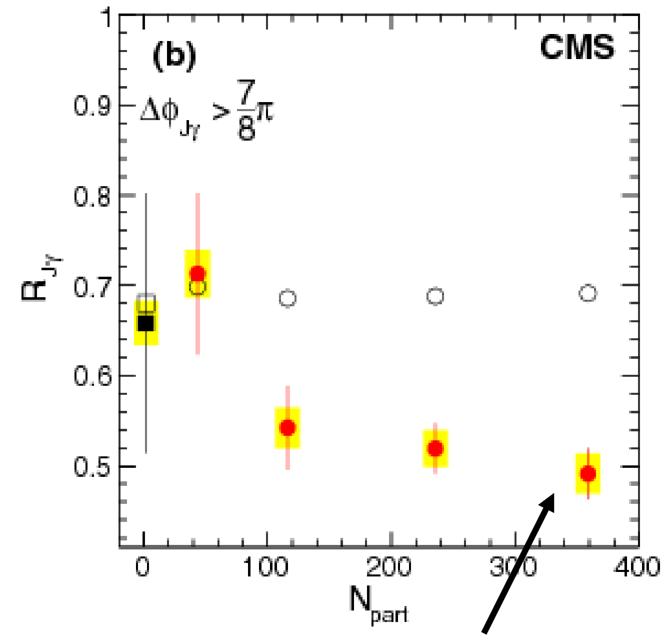
γ-jet correlations

$x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$

$R_{J\gamma}$ = fraction of photons with jet partner >30 GeV/c







Increasing p_T-imbalance

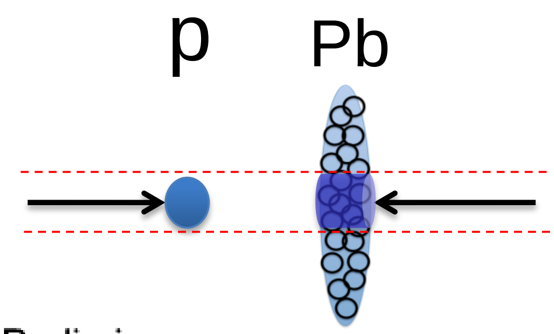
Jets lose ~14% of their initial energy

No φ-decorrelation

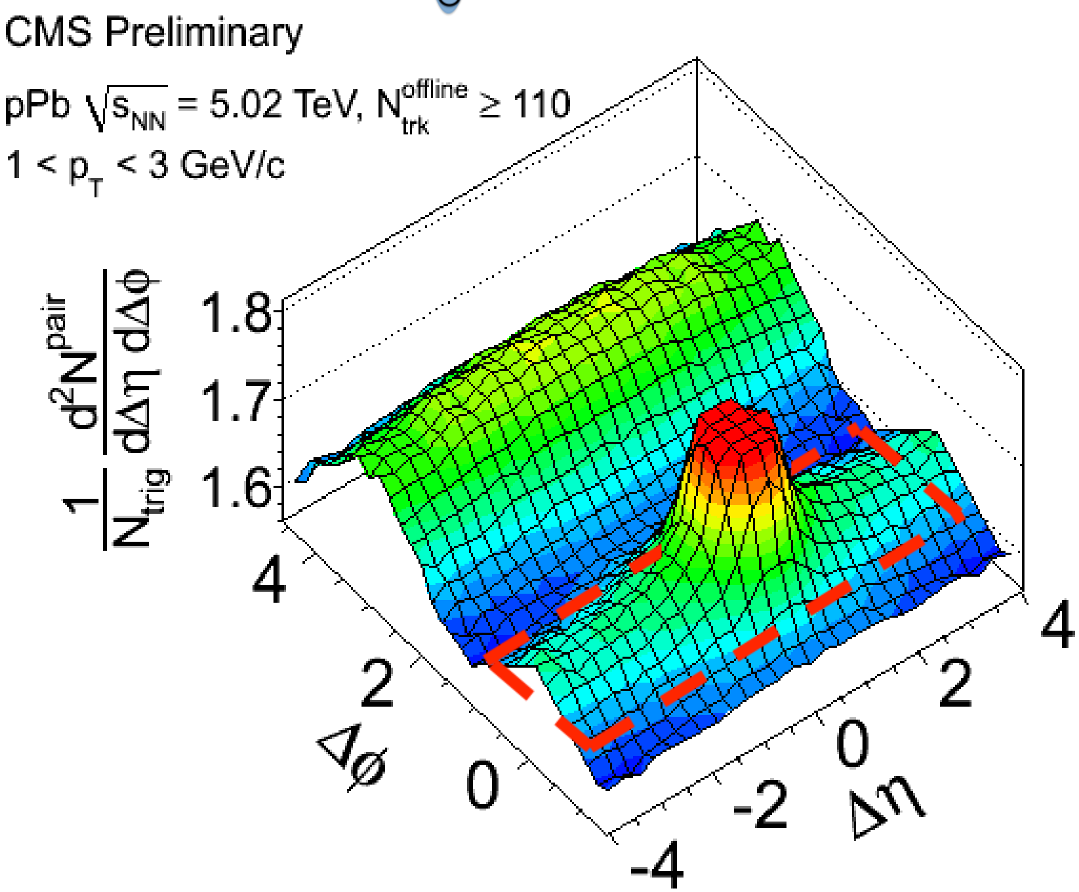
Less jet partners above threshold

~20% of photons lose their jet partner

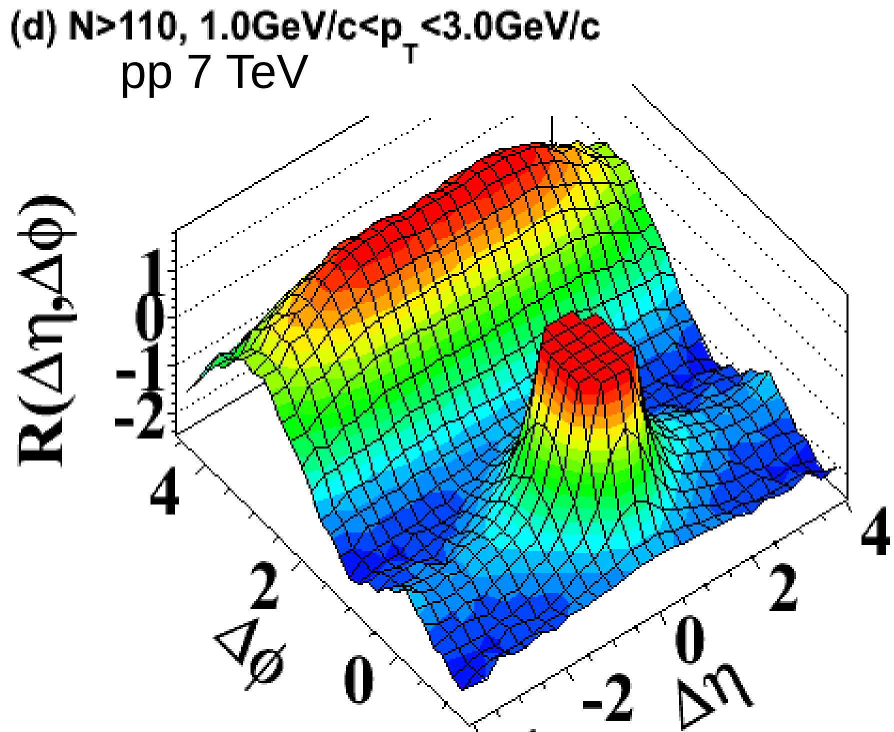
arXiv:1206.0206



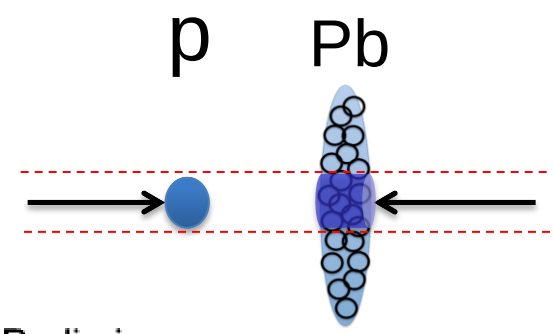
Phisical origin still unclear



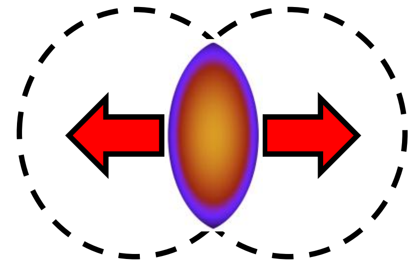
Much bigger than pp

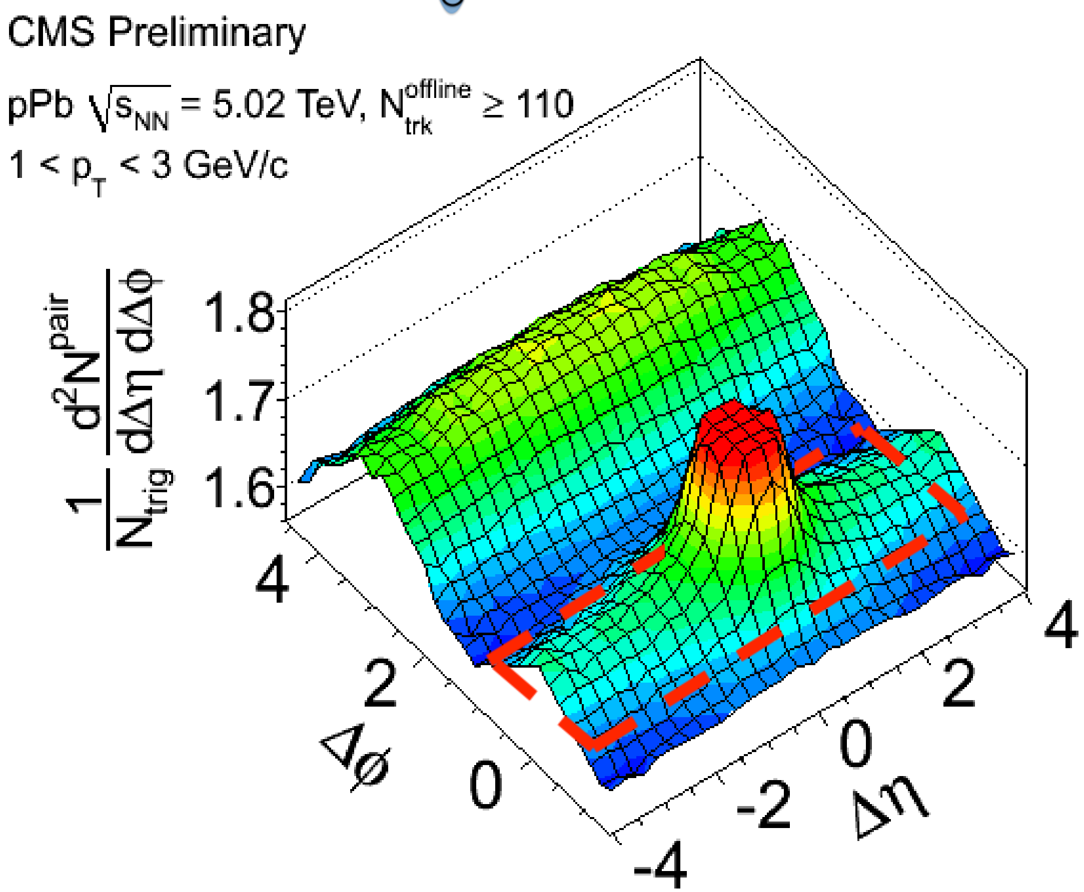


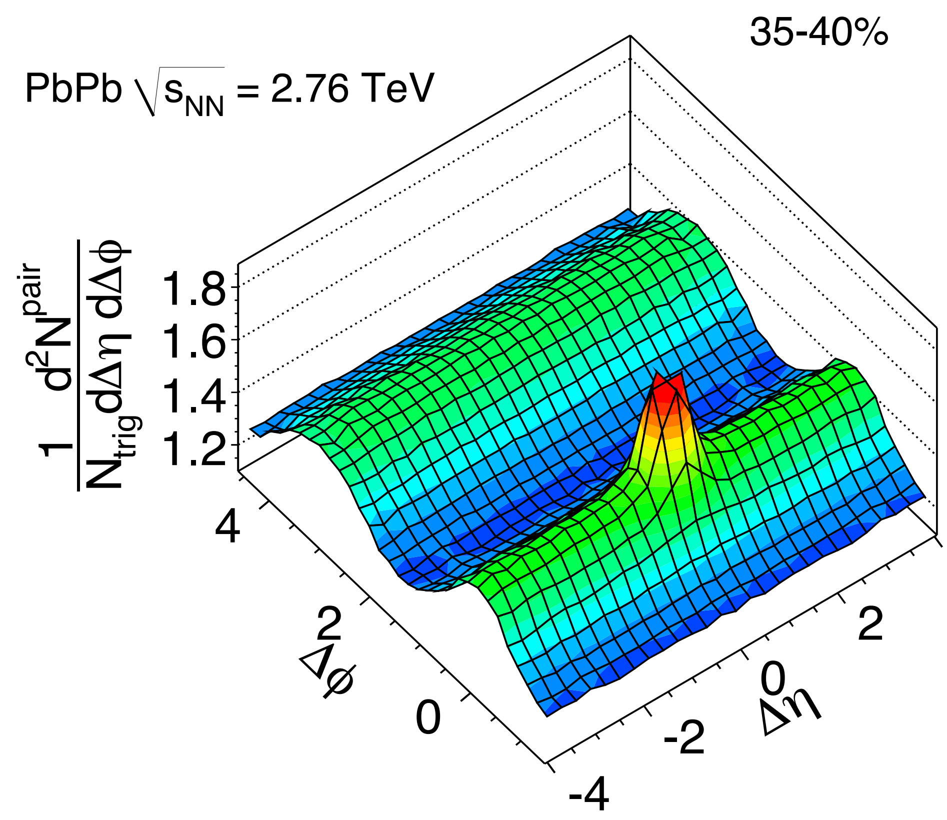
JHEP 09 (2010) 091



Initial-state geometry
+
collective expansion

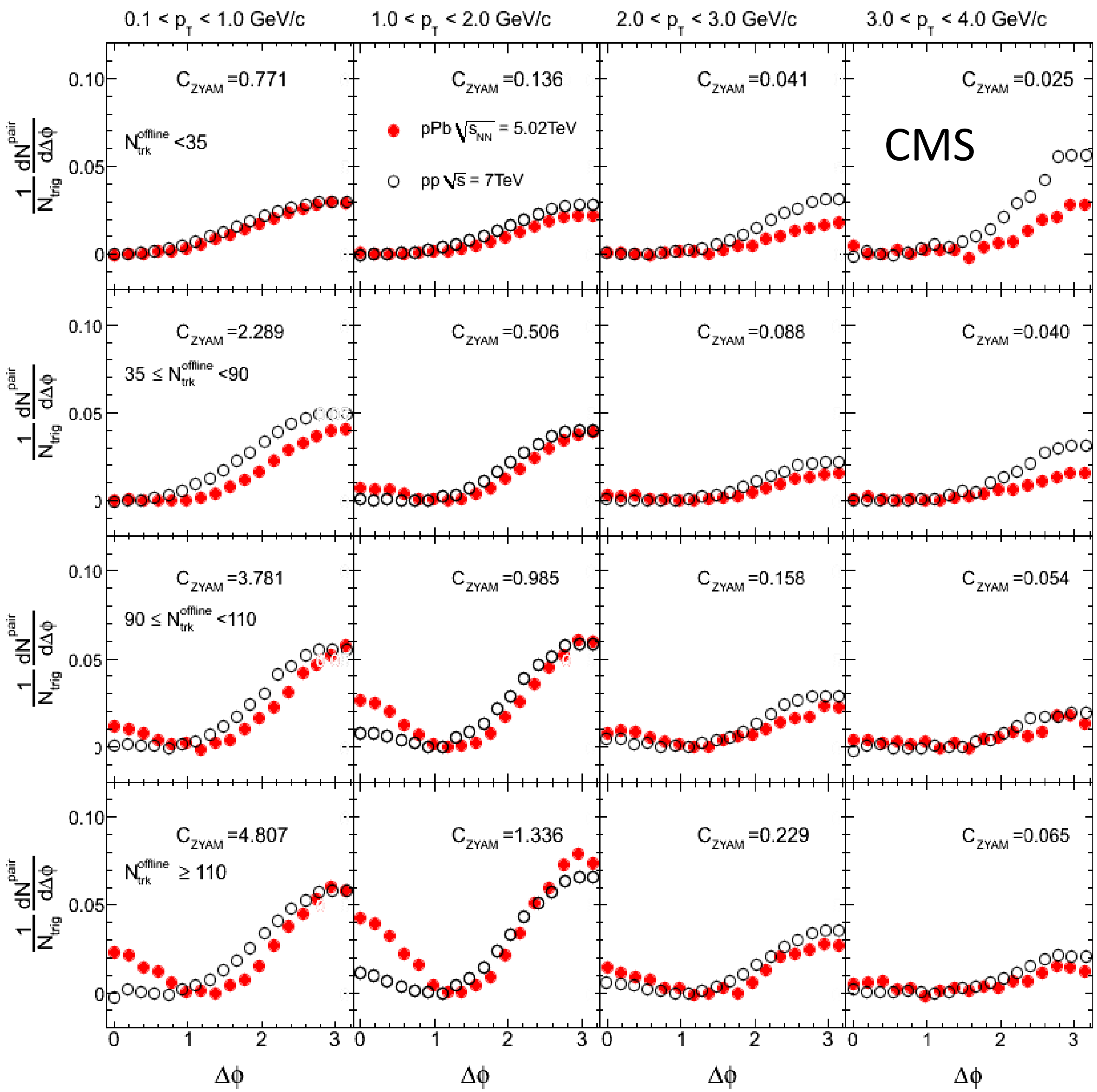






Multiplicity

	0 – 1	1 – 2	2 – 3	3 – 4	p_T (GeV/c)
N<35					
35<N<90					
90<N<110					
N>110					



Yen-Jie Lee (CERN) Zimanyi Winter School 2012 38