Status of jet measurements in CMS

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for the CMS Collaboration

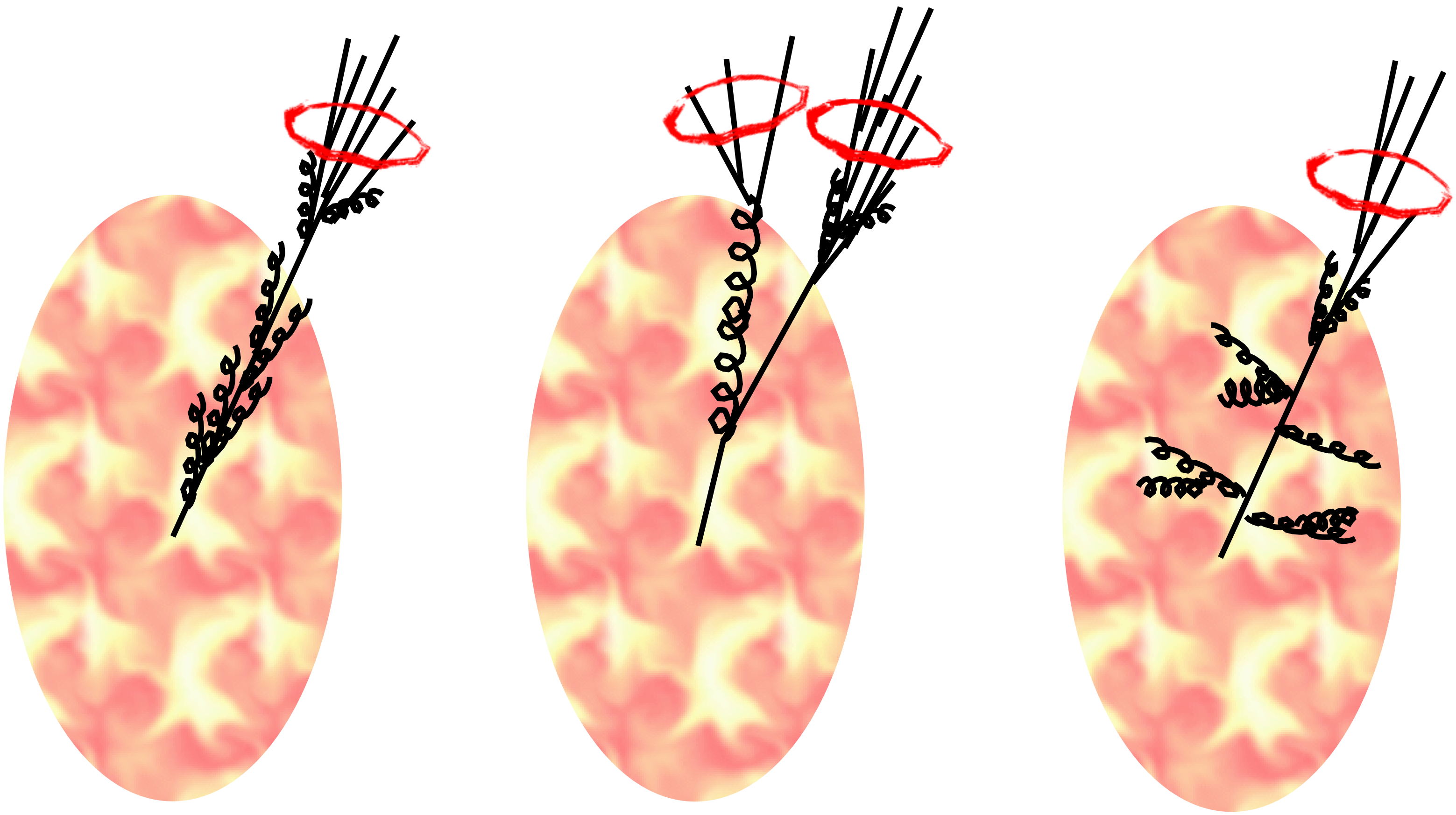
Jet Quenching:

the interface between theory and experiment

CERN

11 Feb, 2013

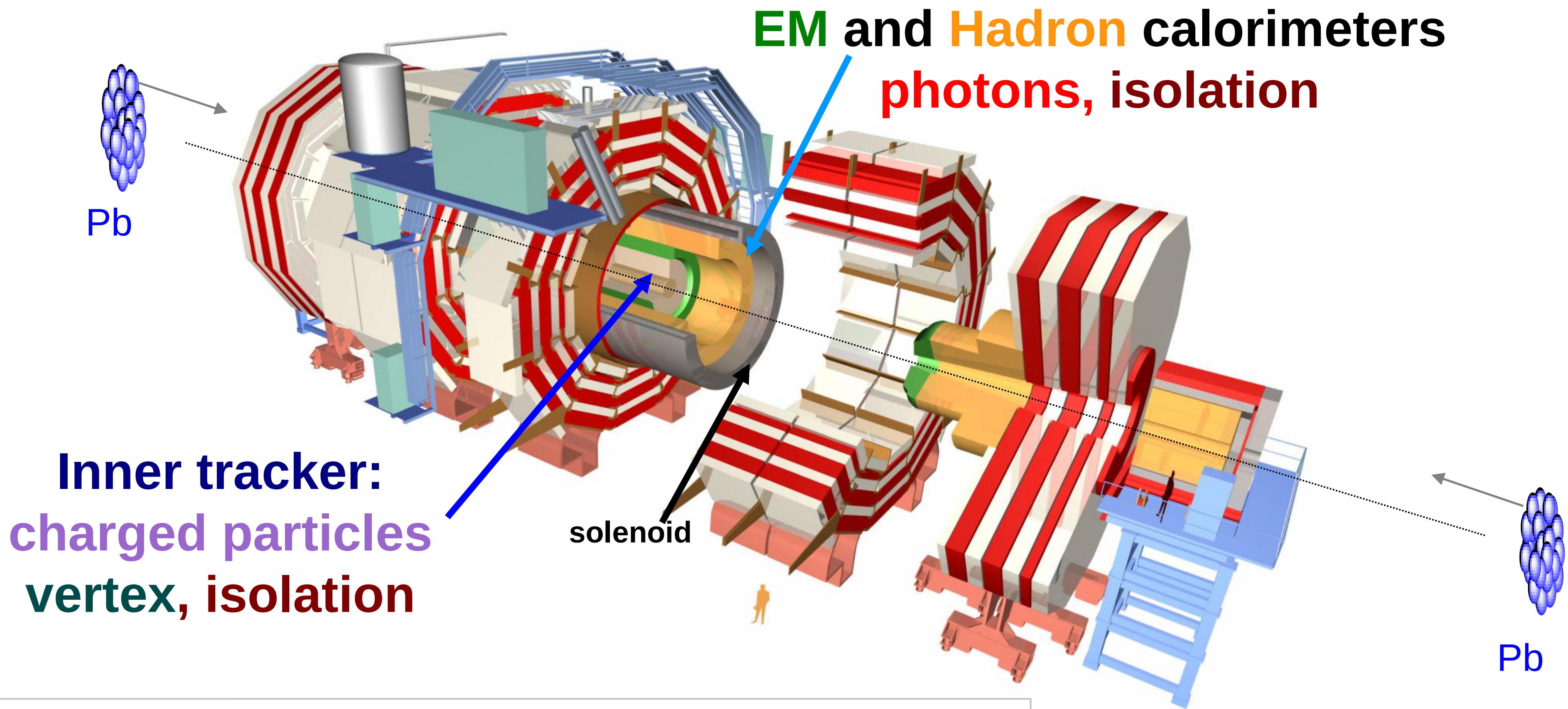
Study of jet quenching in heavy ion collisions

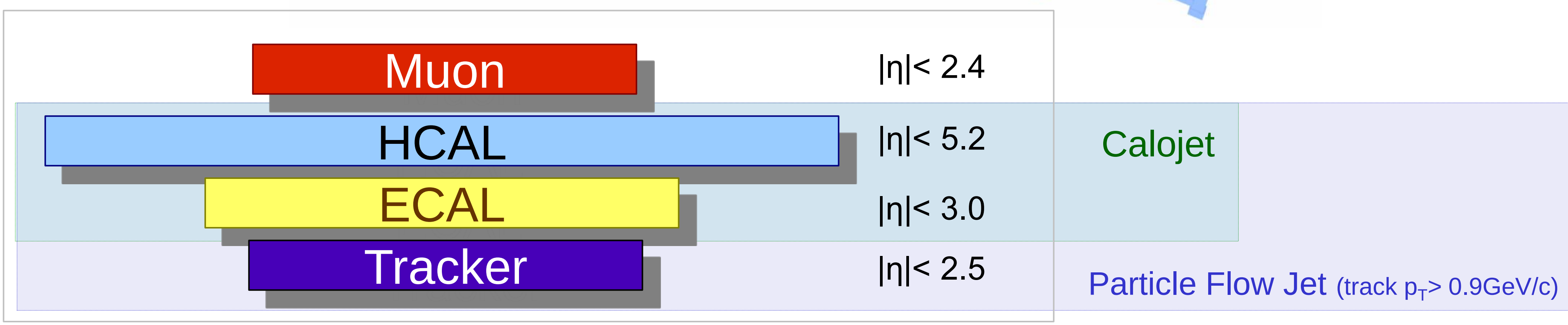


Soft collinear radiation	Hard radiation	Large angle soft radiation "QGP heating"
GLV + others (pre-LHC models)	PYTHIA inspired models Modified splitting functions	AdS/CFT Interference

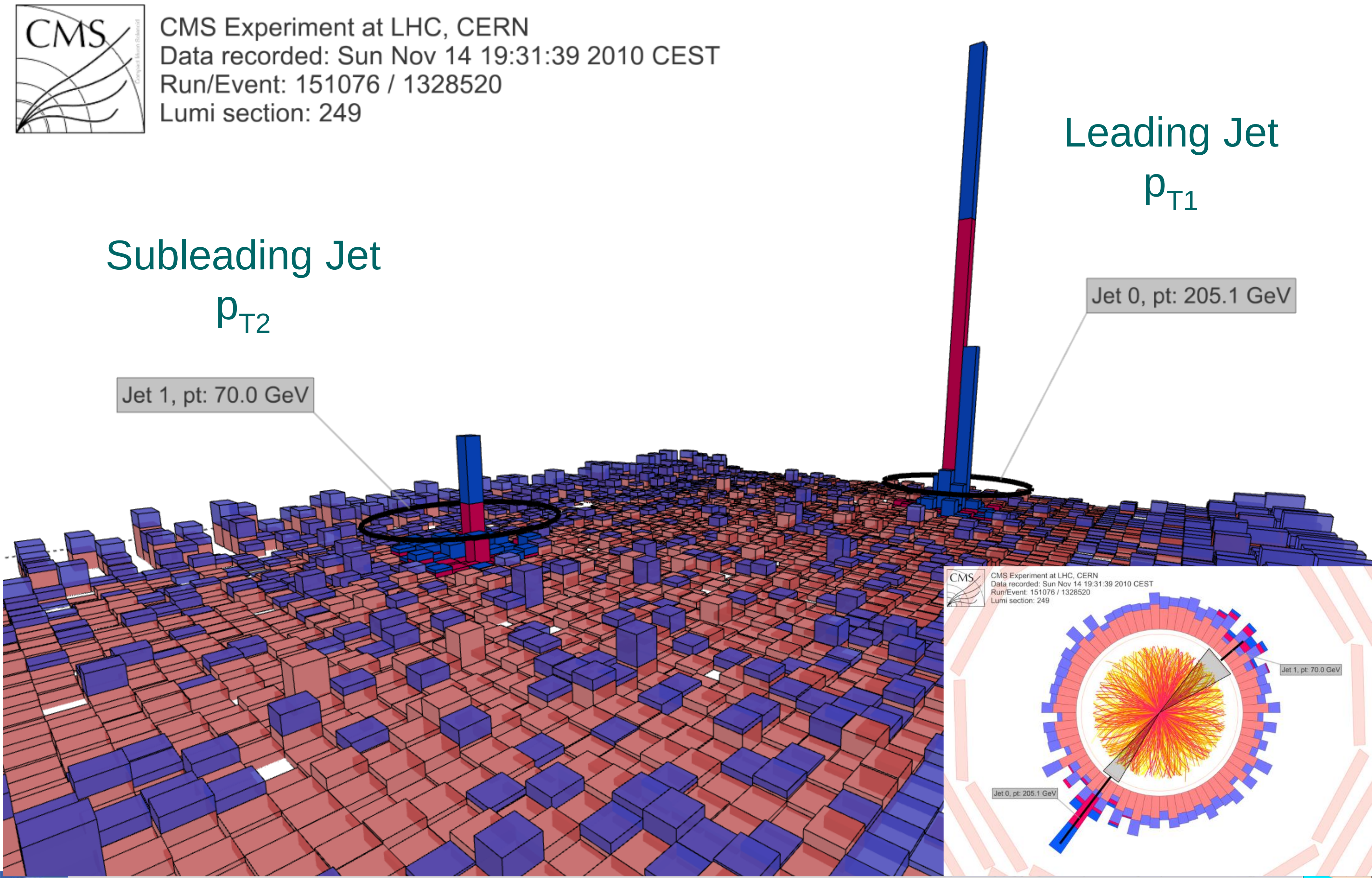
Focus on the dijet energy imbalance, azimuthal correlation, missing transverse momentum, jet shape and fragmentation function measurements

CMS detector





Dijet event in CMS



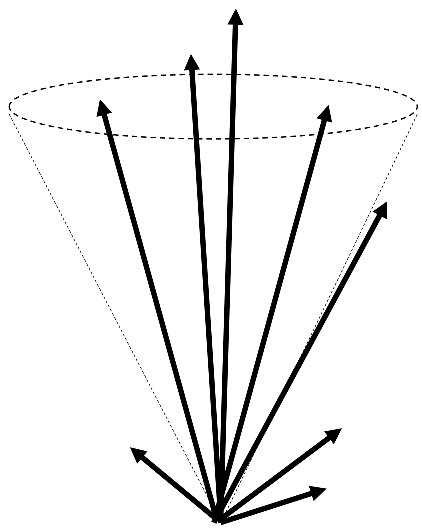
List of CMS jet analysis in HI collisions

Analysis	Jet algorithm	Radius	Jet Energy Resolution	Track p_T (GeV/c)	Reference
Dijet momentum imbalance	Iterative Cone calojet	0.5	No unfolding	-	PRC 84 (2011) 024906
Dijet azimuthal correlation	Iterative Cone calojet	0.5	-	-	PRC 84 (2011) 024906
Dijet missing p_T analysis	Iterative Cone calojet	0.5	Included in systematics	>0.5	PRC 84 (2011) 024906
Dijet momentum imbalance v.s. leading jet p_T	Anti-kT Particle Flow (Calo&Tracker)	0.3	Included in systematics	-	PLB 712 (2012) 176
Dijet azimuthal correlation v.s. leading jet p_T	Anti-kT Particle Flow (Calo&Tracker)	0.3	-	-	PLB 712 (2012) 176
Dijet fragmentation analysis	Anti-kT Particle Flow (Calo&Tracker)	0.3	Included in systematics	>4.0	JHEP 10 (2012) 087
γ -jet momentum imbalance	Anti-kT Particle Flow (Calo&Tracker)	0.3	Included in systematics	-	PLB 718 (2013) 773
γ -jet azimuthal correlation	Anti-kT Particle Flow (Calo&Tracker)	0.3	-	-	PLB 718 (2013) 773
Inclusive jet R_{AA}	Anti-kT Particle Flow (Calo&Tracker)	0.2,0.3,0.4	Corrected	-	CMS PAS HIN-12-004
Inclusive jet shape and fragmentation function	Anti-kT Particle Flow (Calo&Tracker)	0.3	Included in systematics	>1.0	CMS PAS HIN-12-013
Inclusive b-jet fraction	Anti-kT Particle Flow (Calo&Tracker)	0.3	Corrected	-	CMS PAS HIN-12-003

* Reconstructed jet energy is always corrected to generator-level jet using the same algorithm (including both charged and neutral particles) **without** constituent p_T cut using PYTHIA

Inclusive jet spectra: jet R_{AA}

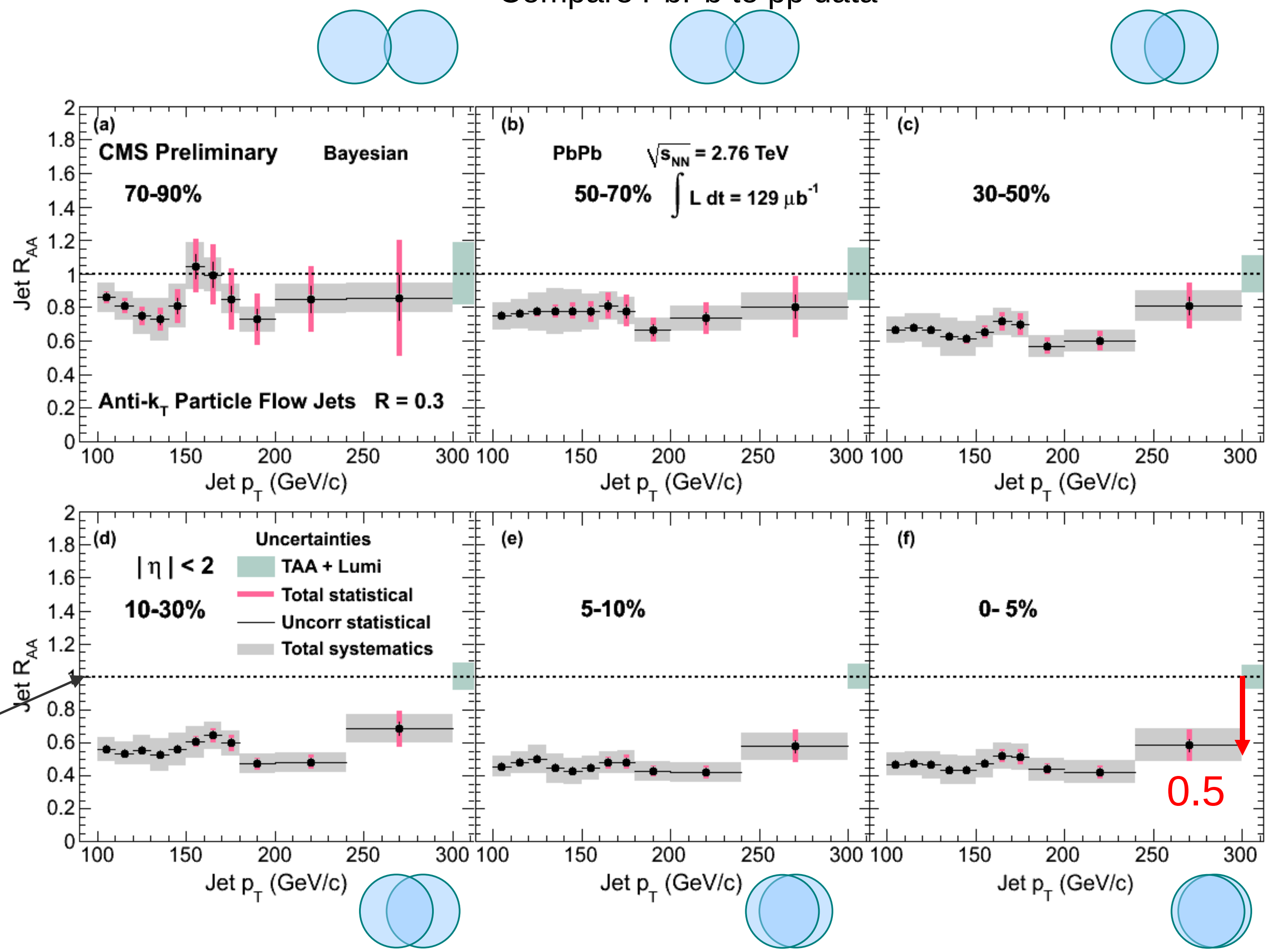
Anti-k_T jets with
R = 0.3



If PbPb = superposition of pp

CMS PAS HIN-12-004

Compare PbPb to pp data

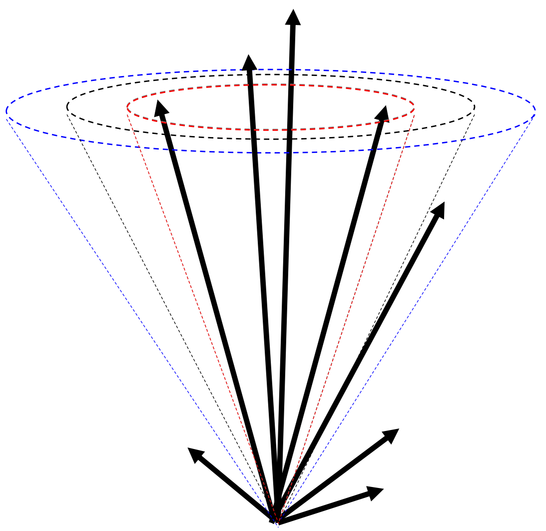


Strong suppression of inclusive high p_T jets

Inclusive jet spectra: jet R_{AA}

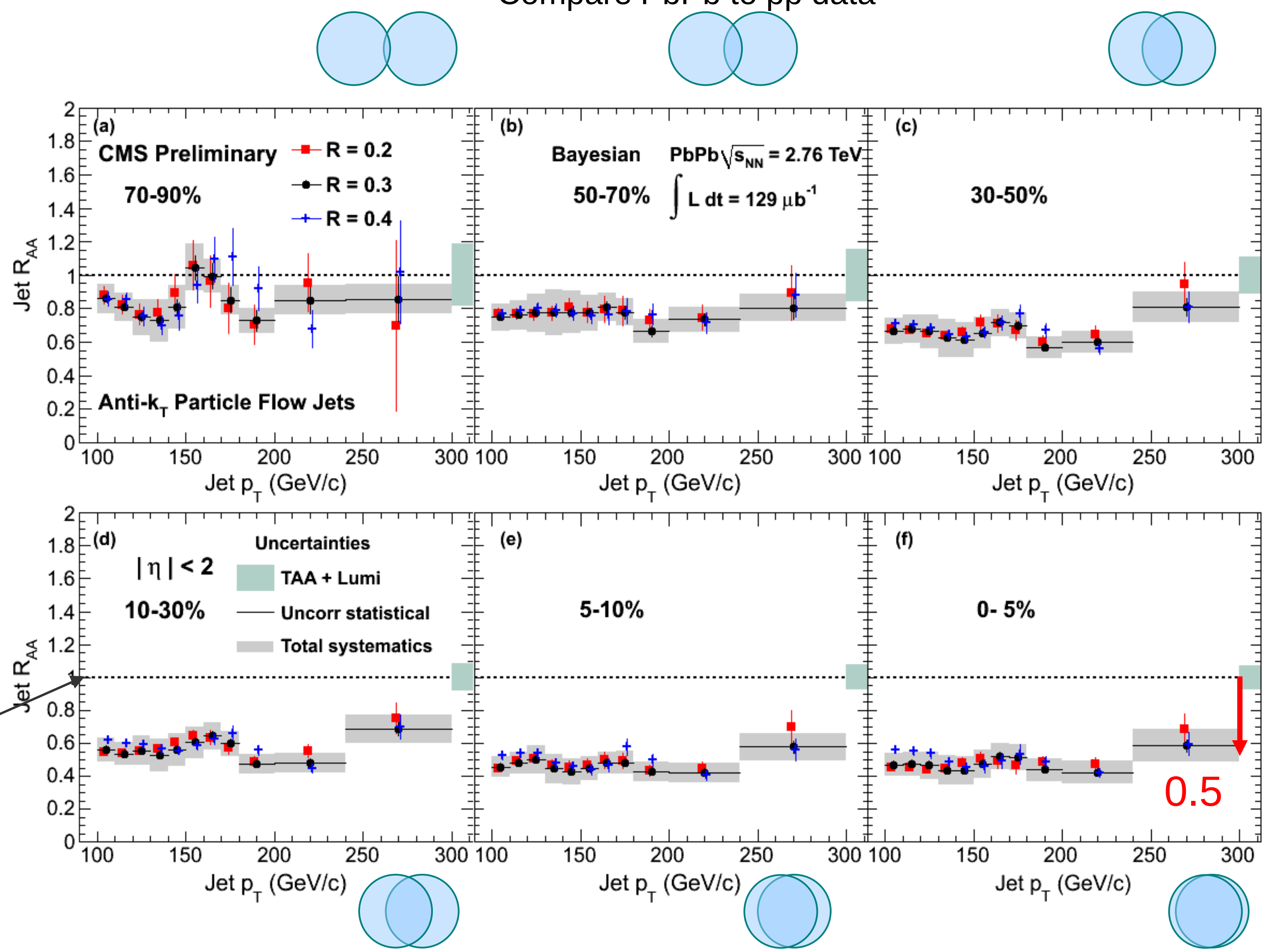
Compare PbPb to pp data

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



If PbPb = superposition of pp

CMS PAS HIN-12-004



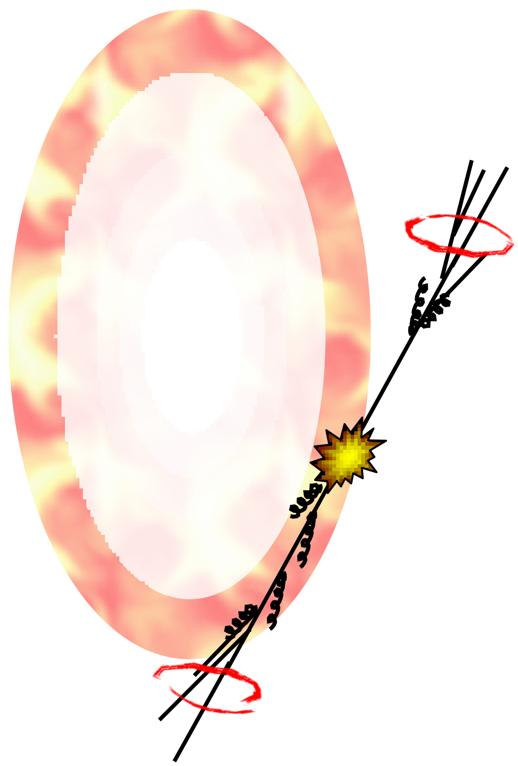
Strong suppression of inclusive high p_T jets

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?

Dijet and photon-jet energy imbalance

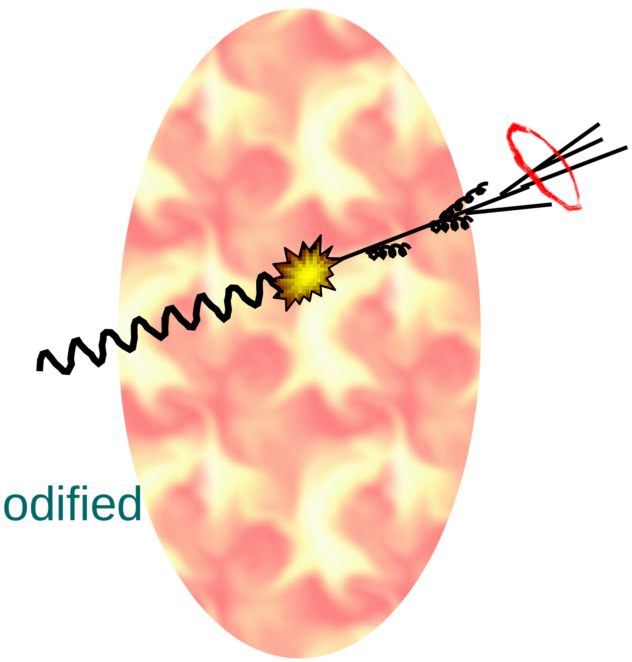
Dijet



High p_T leading jet triggered sample

High statistics, with surface bias

Photon-jet



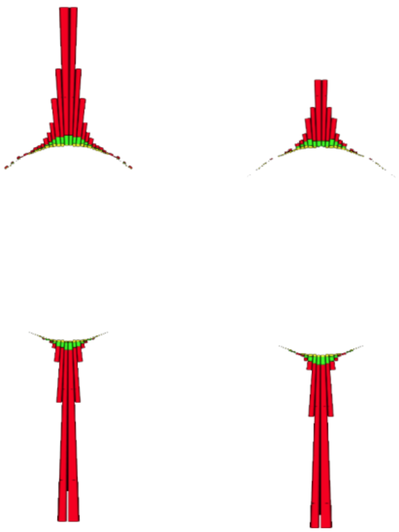
Photon → unmodified jet energy tag

High p_T photon triggered sample

Lower statistics, without surface bias

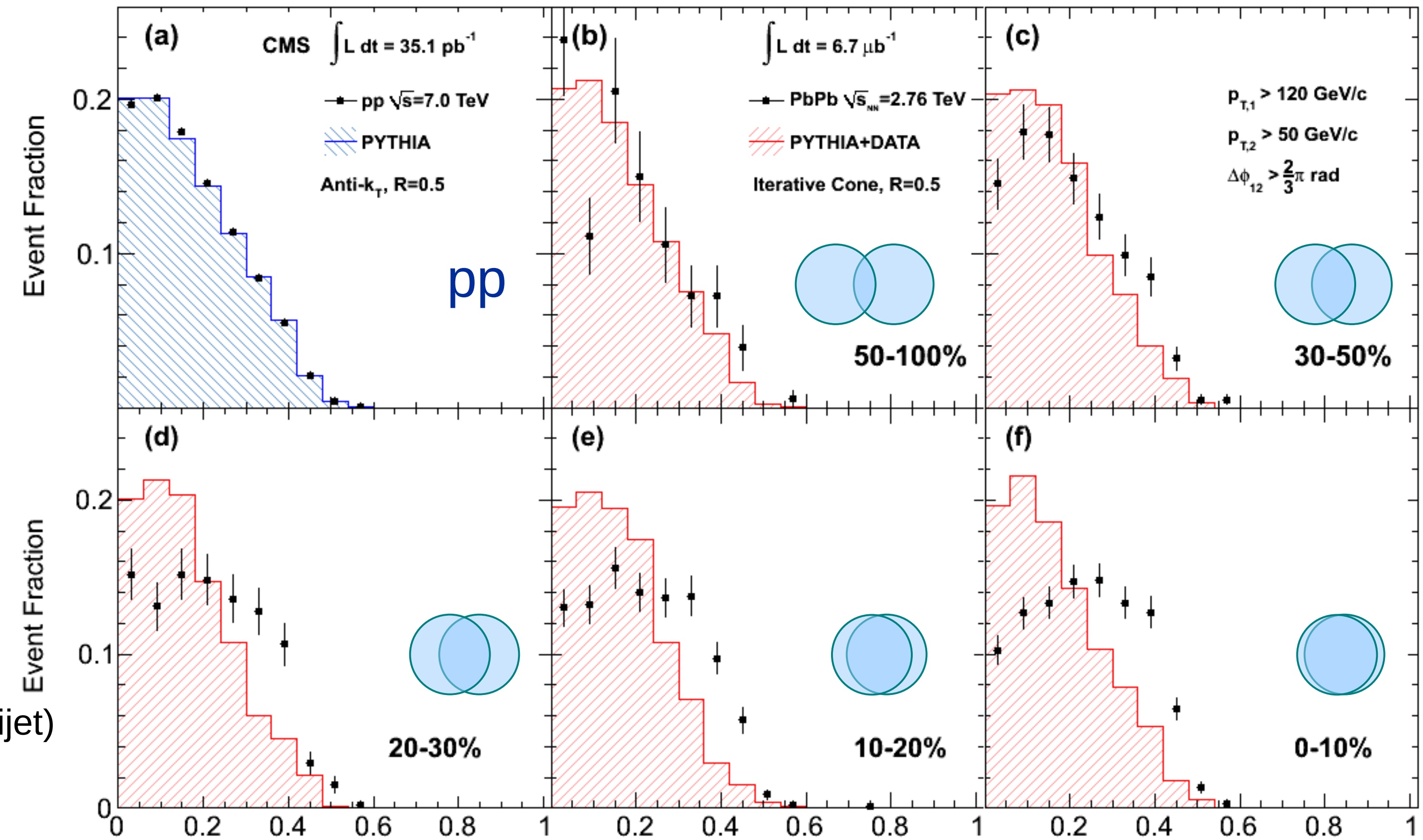
Dijet momentum imbalance

Jet Cone size R = 0.5



Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)

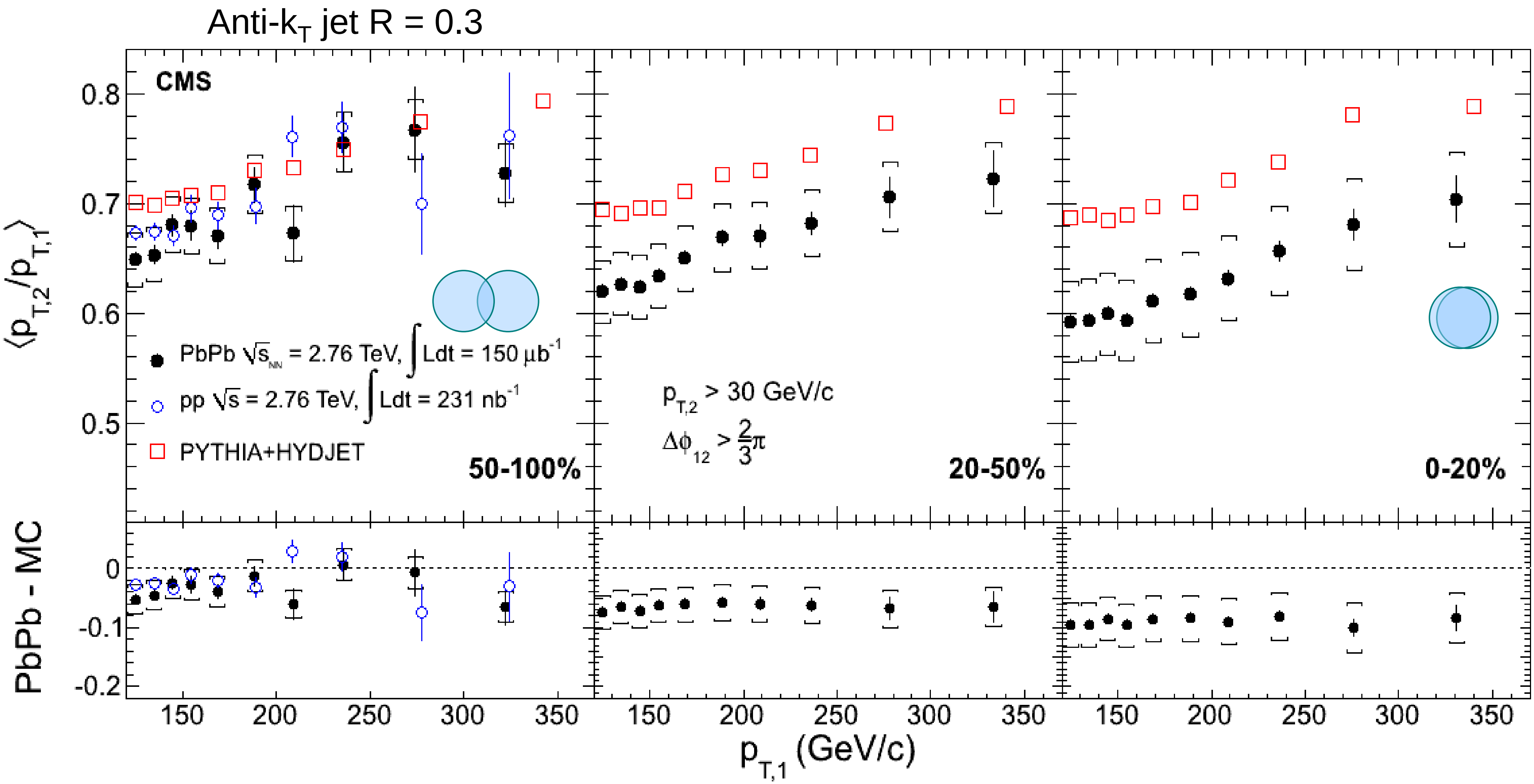


PRC 84 (2011) 024906

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

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

Dijet energy ratio (imbalance)

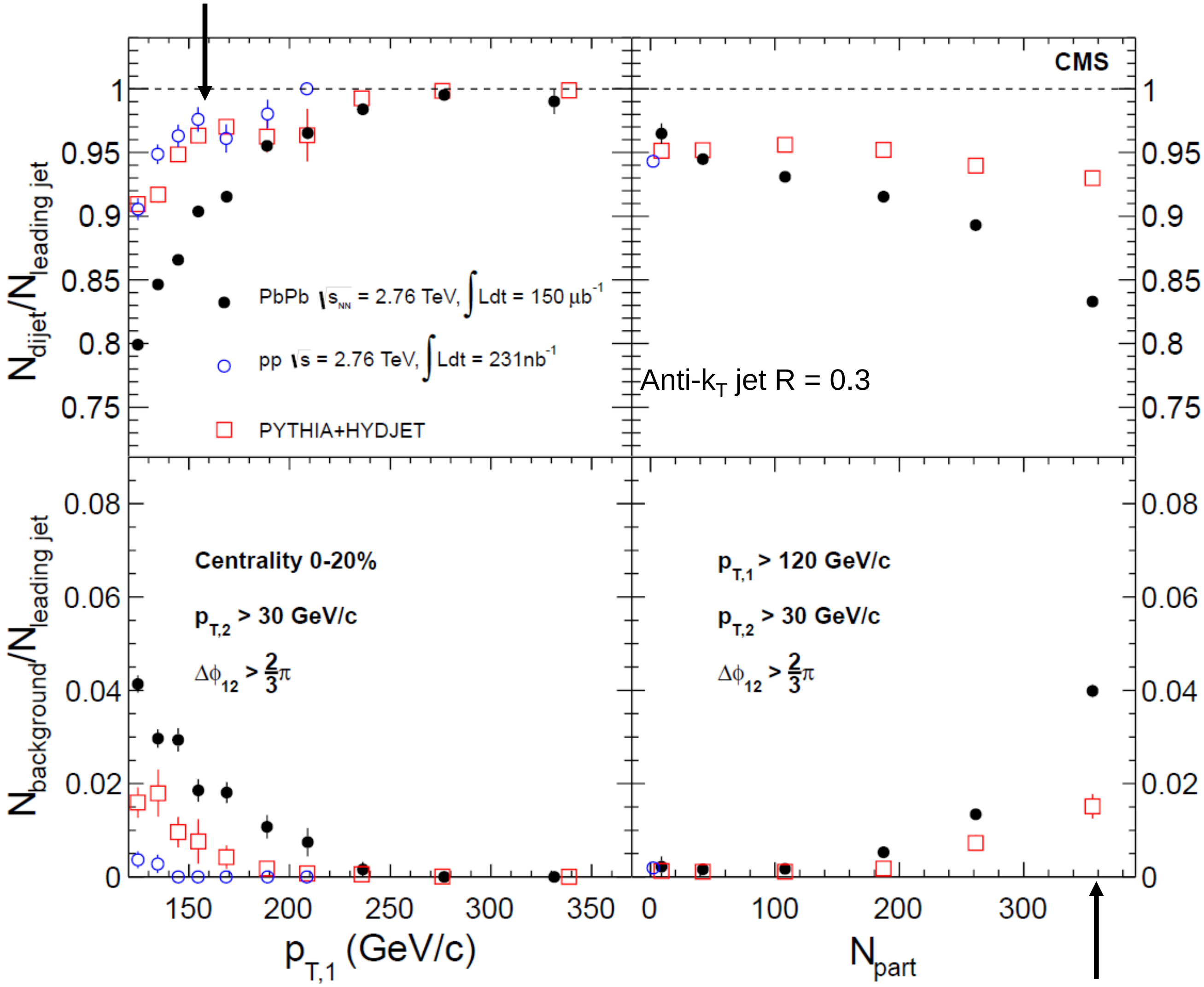


- Energy imbalance increases with centrality
- Very high p_T jets are also quenched

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

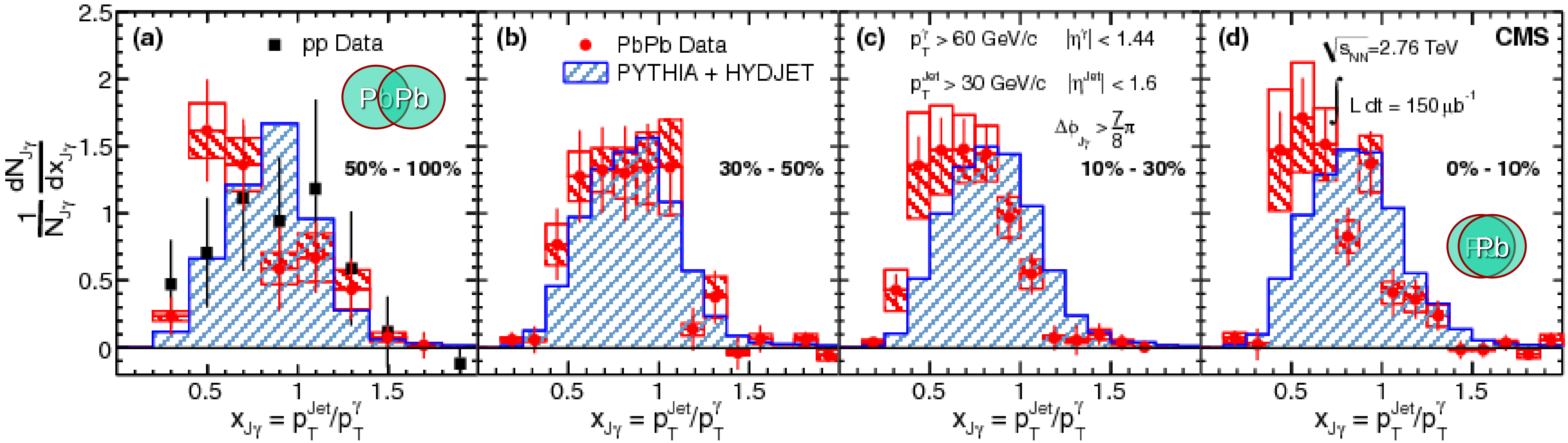


- Fake away side jet rate is < 4%

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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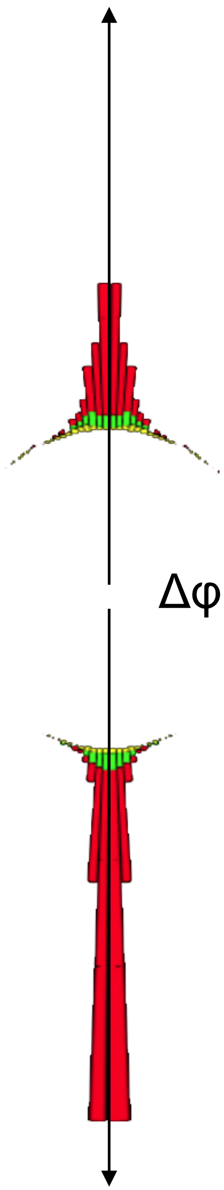
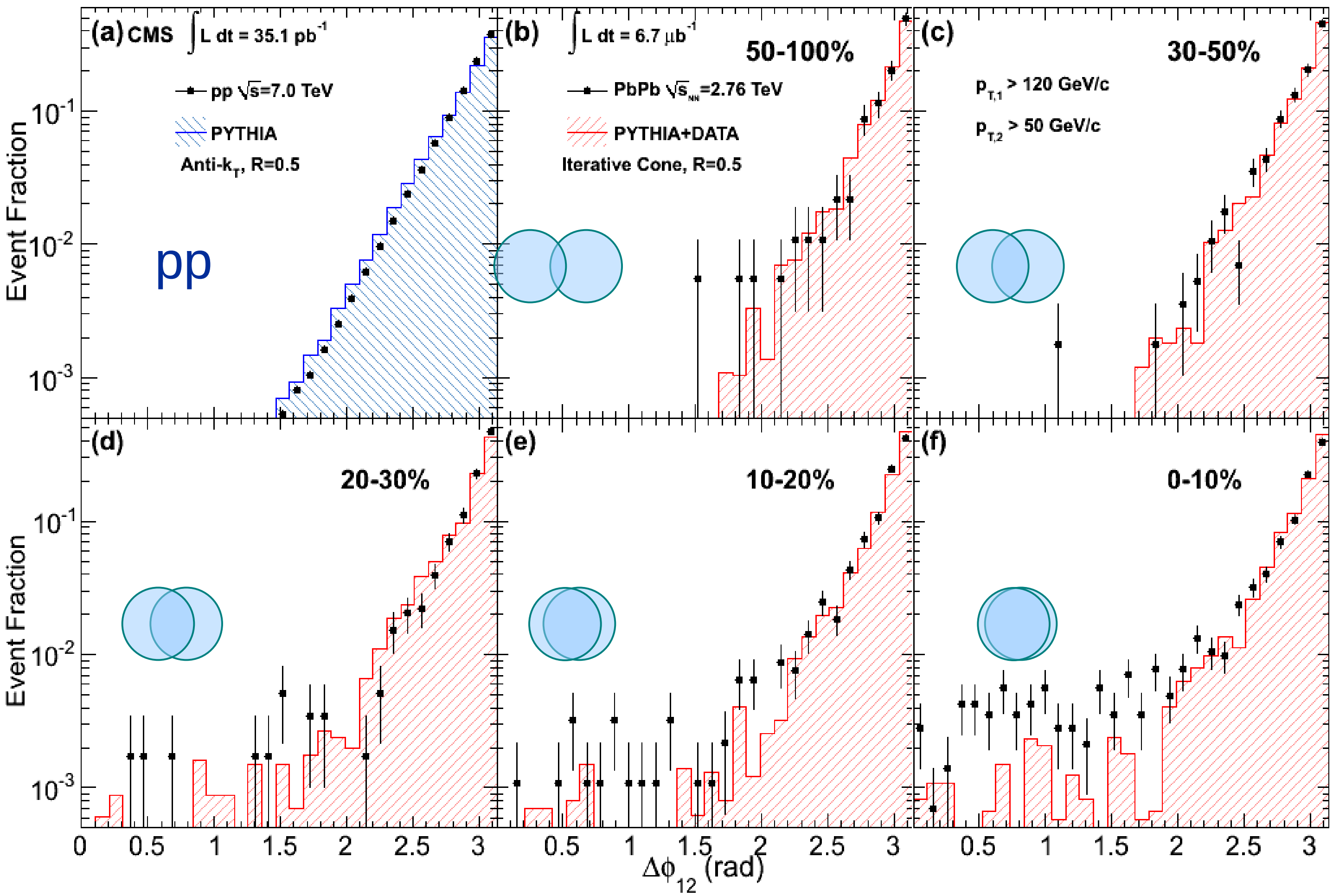
Dijet and photon-jet azimuthal correlation

Given the large momentum imbalance seen in dijet and photon-jet events

Is the azimuthal correlation modified?



Dijet azimuthal angle correlations



Jet Cone size R = 0.5

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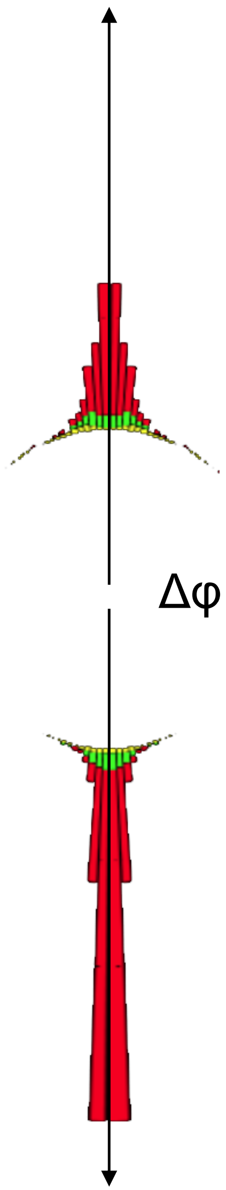
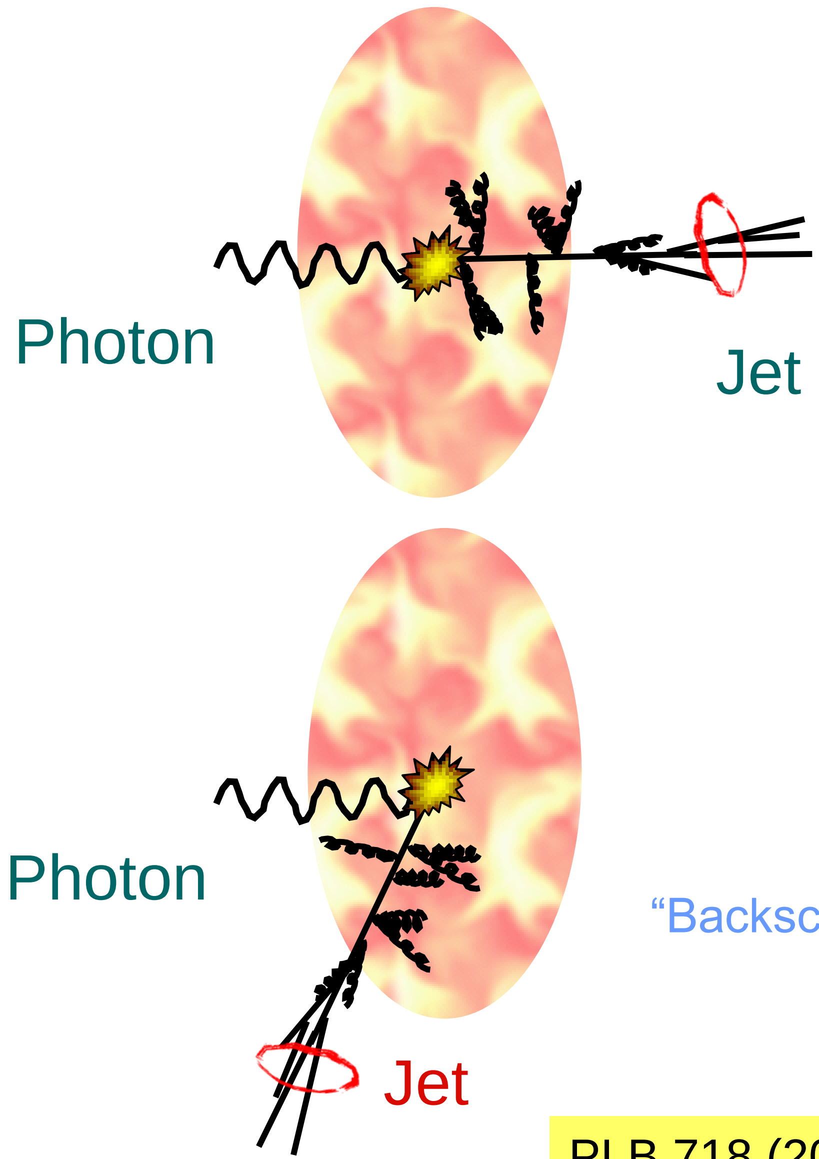


No apparent modification in the dijet Δφ distribution
(still back-to-back)

Photon-jet angular correlation

The first photon-jet correlation measurement in heavy ion collisions



"Backscattering?"

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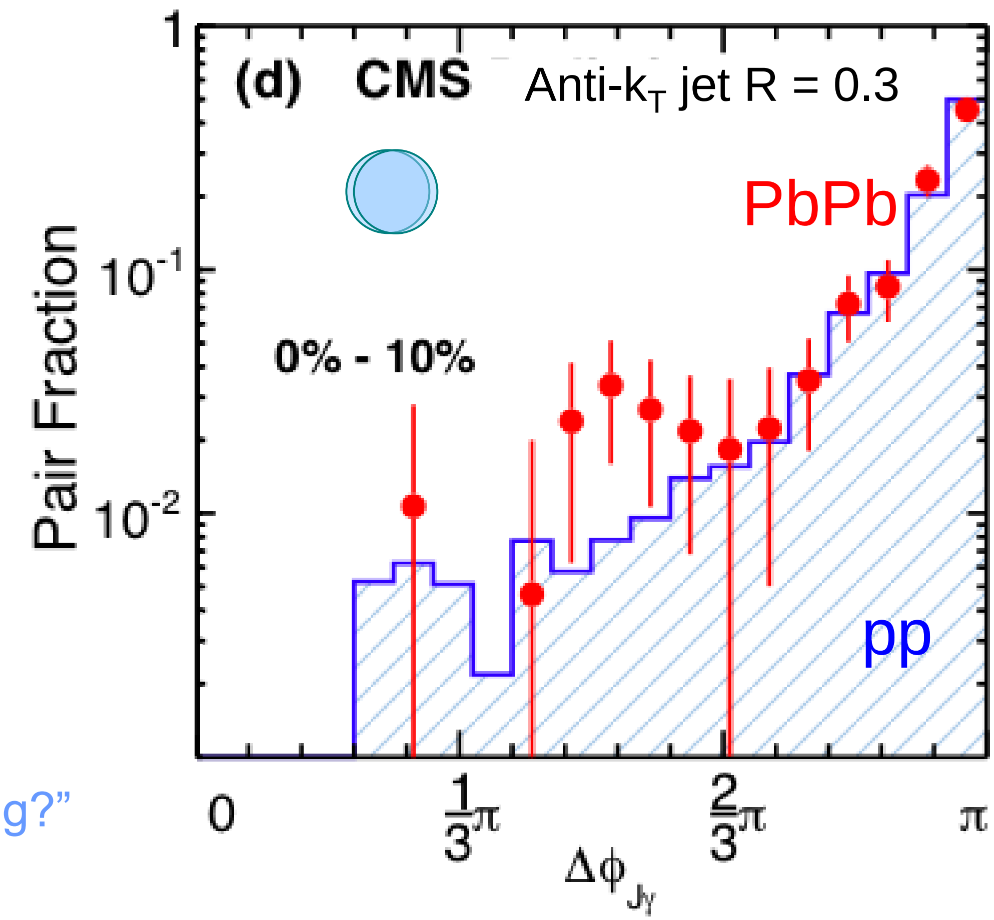
"QGP Rutherfold experiment"



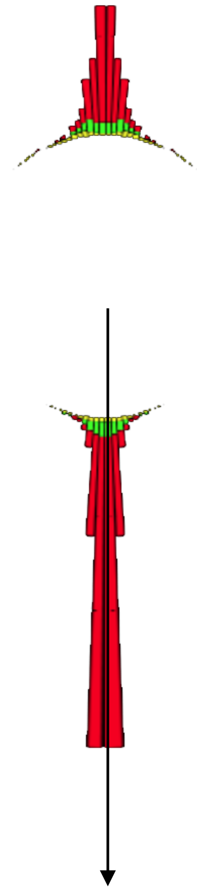
Azimuthal angle difference between photon and jet

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?

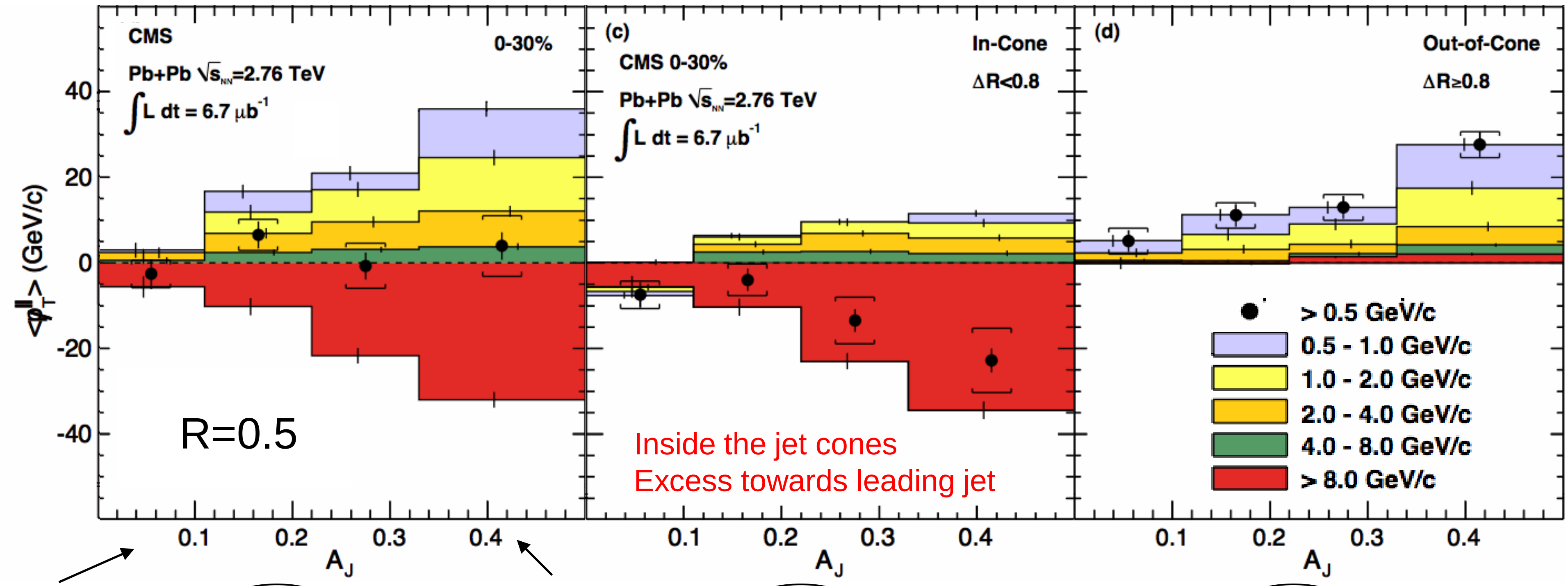


Missing-$p_T^{||}$

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

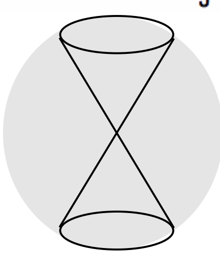
0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet

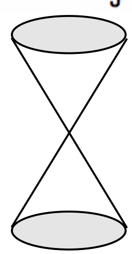


balanced jets

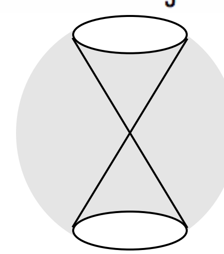
unbalanced jets



All tracks



Tracks in
the jet cone
ΔR<0.8



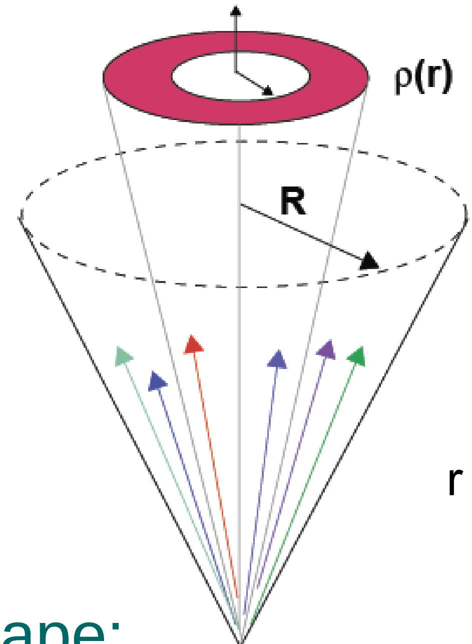
Tracks out of
the jet cone
ΔR>0.8

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

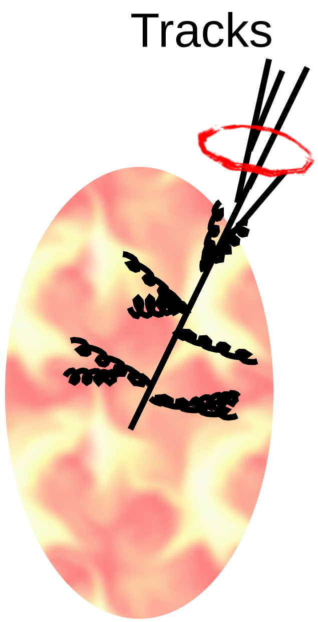
Jet shape and fragmentation function

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)

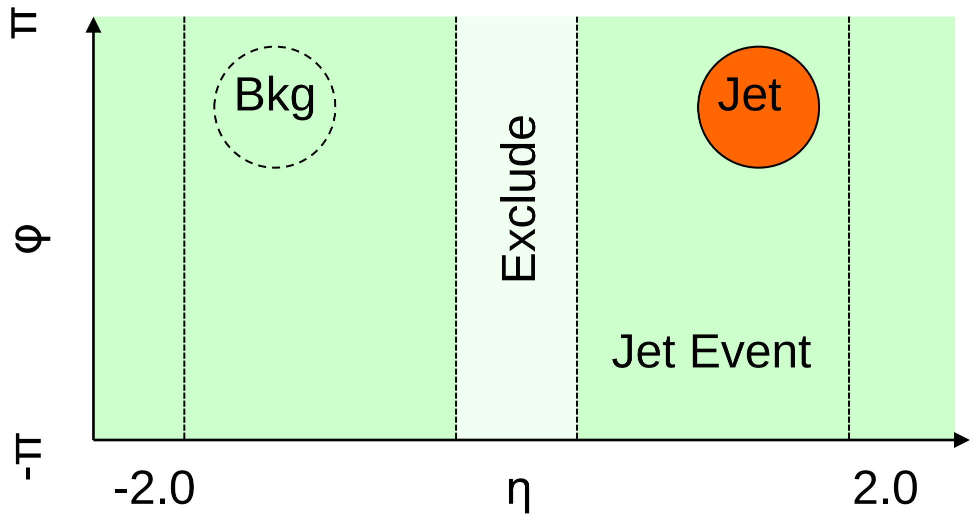
$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{jet}}$$

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

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

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

Background subtraction



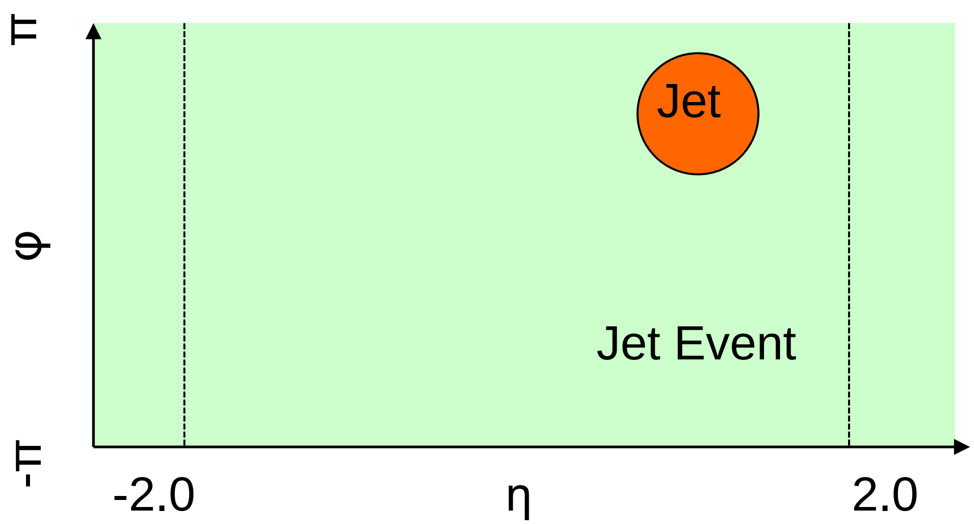
η reflection Method

Main result

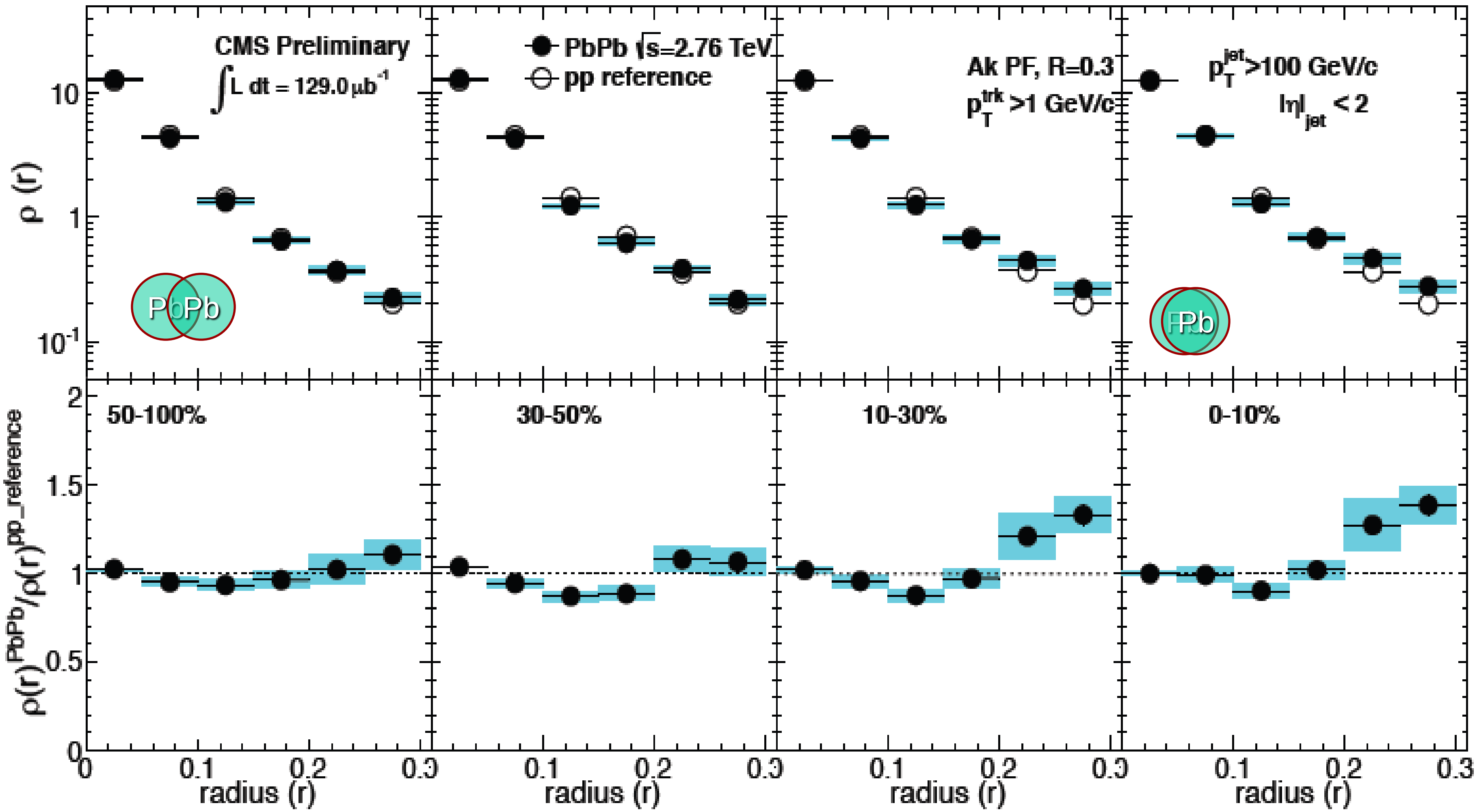
Same technique

Used in FF and jet shape

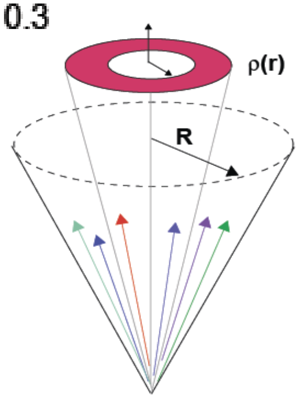
Event Mixing Method (Cross-checks)



Jet shapes



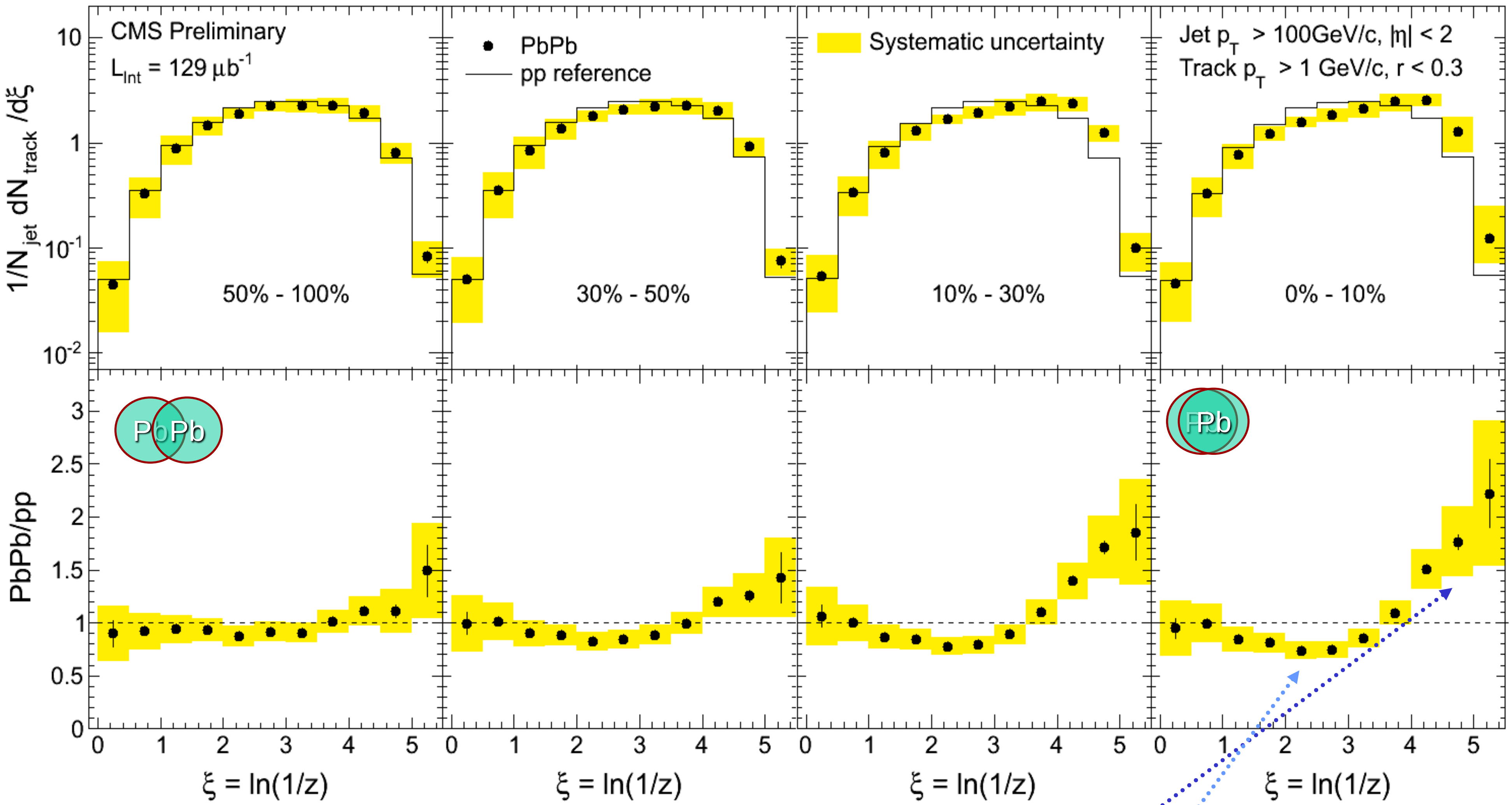
CMS PAS HIN-12-013



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

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

Jet fragmentation functions



CMS PAS HIN-12-013

High p_T particles ← → Low p_T particles

Inside the jet cone: Enhancement of low p_T particle

Suppression of intermediate p_T particles in cone

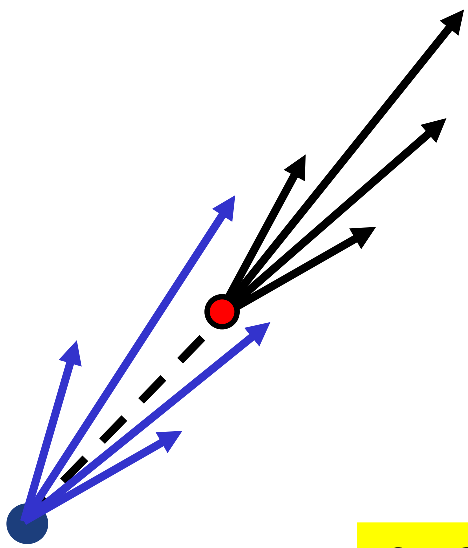
$$\xi = \ln\frac{1}{z}\ ;\ \ z = \frac{p_{\parallel}^{track}}{p^{jet}}$$

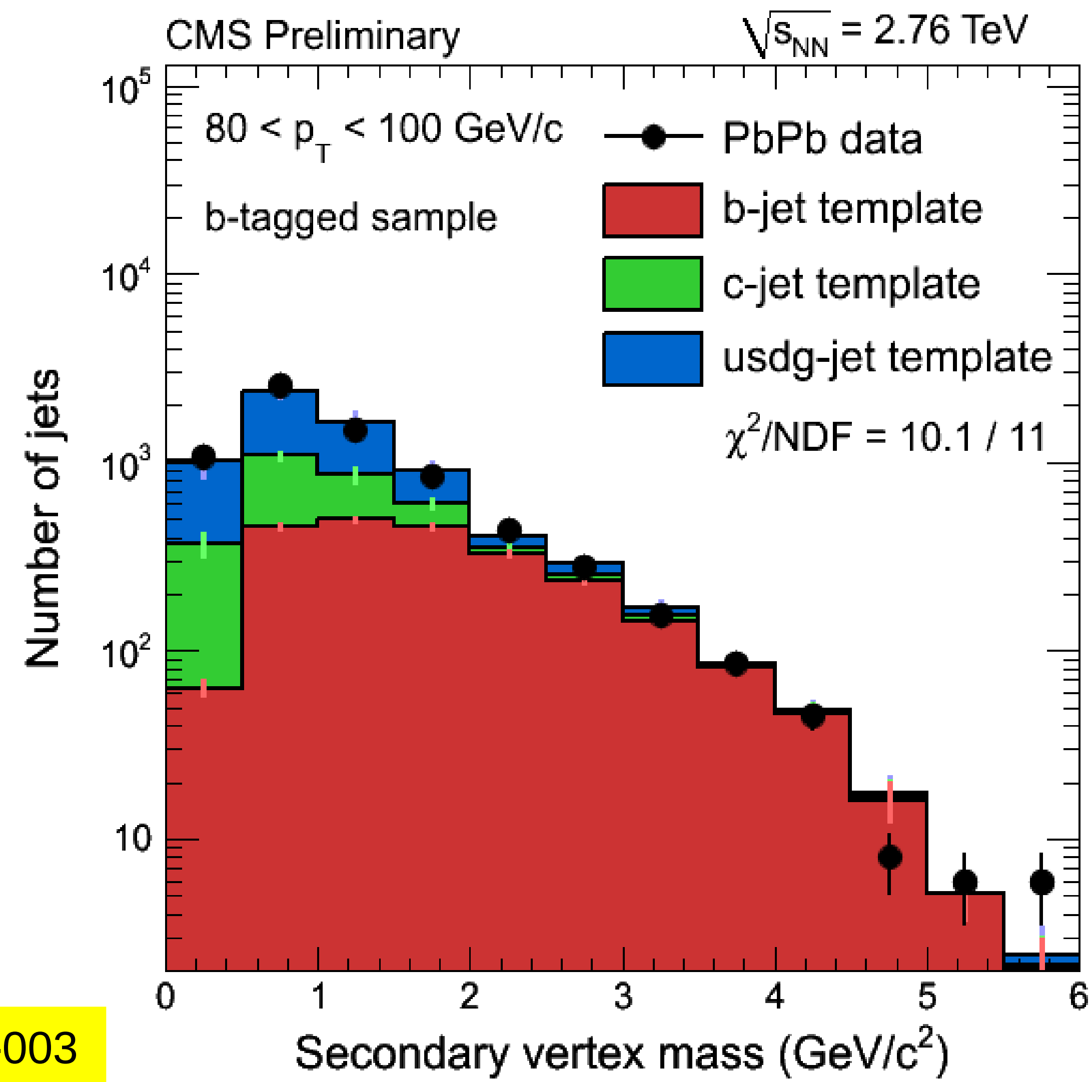
Tagging and counting b-quark jets

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

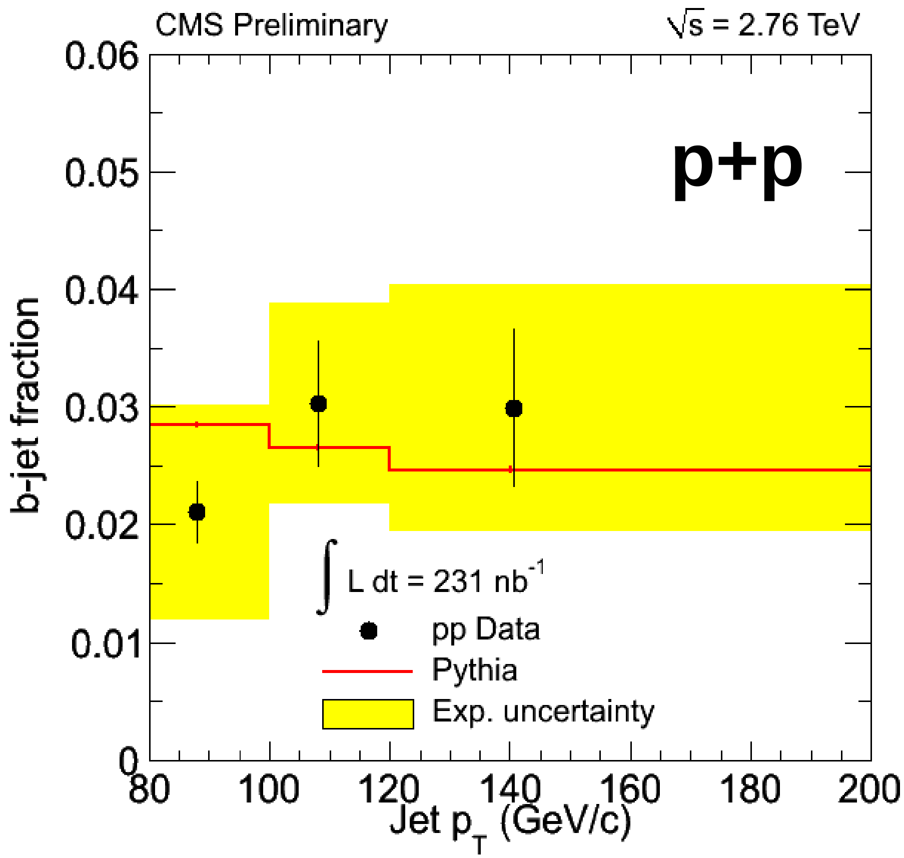


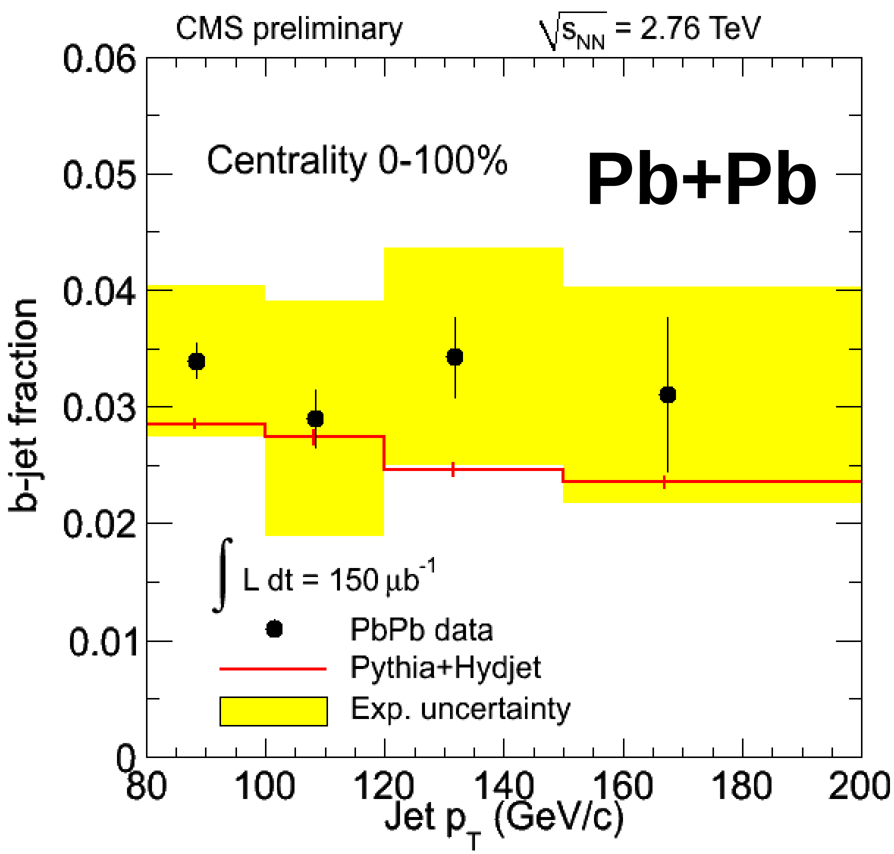


CMS PAS HIN-12-003

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





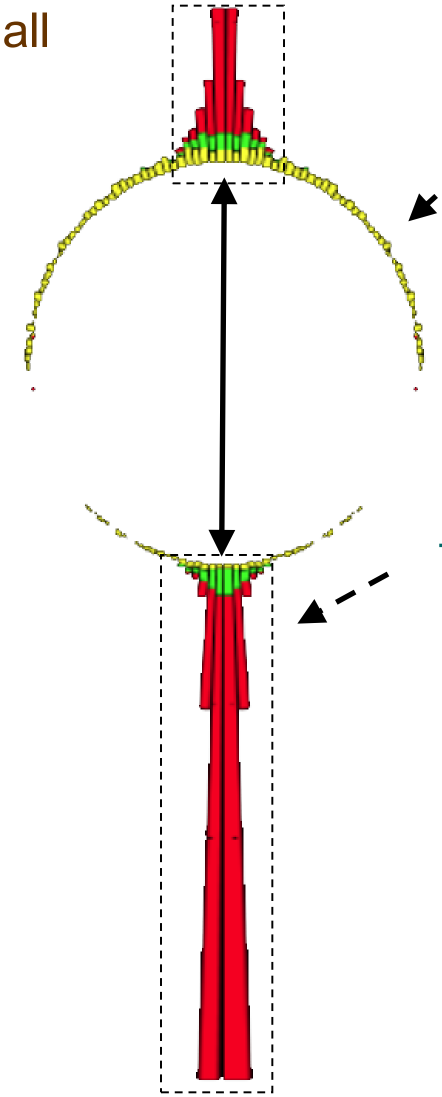
CMS PAS HIN-12-003

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

2. Large average dijet and photon-jet p_T imbalance

3. Angular correlation of jets not largely modified



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

5. Observation of modified jet fragmentation function and jet shape

6. b-jets are also quenched

Effects to be considered in analysis

- **Impact of background subtraction**
  - Jet response dependence on the jet event configuraiton (ex: 3-jet v.s. 2-jet event)
  - Jet flavour dependence (Quark v.s. gluon, modified jet shape and FF)
  - Shape of medium response
  - Sensitivity to tracking efficiency (and fluctuation)
- **Impact of jet energy resolution**
  - Resolution of calorimeter resolution
  - Possible bias toward positive UE fluctuation
  - Impact to jet energy and pointing resolution
  - Fake jets from UE fluctuation
  - Inefficiency due to downward UE fluctuation
  - Impact of flow and event plane dependence
- **Detector related effects**
  - Calorimeter noise
  - Fake tracks
- **Centrality determination**
  - Inference of the jet to centrality determination

See Yetkin Yilmaz's talk on 2/12(Tue)

Effects to be considered in analysis

	Jet energy scale	Jet pointing resolution	Jet energy resolution	Fake jets / Noise	Track UE background subtraction	Tracking efficiency
Dijet (γ-Jet) pT Imbalance	*	N/A	**	X	N/A	X
Dijet (γ-jet) Azimuthal Correlation	*	**	**	X	N/A	X
Dijet Missing p_T	*	*	*	X	N/A	**
Inclusive Jet Fragmentation	**	N/A	**	X	**	**
Inclusive Jet Shape	*	*	*	X	**	**
Inclusive Jet R_{AA}	*	N/A	**	*	N/A	X
Inclusive Jet Spectra	**	N/A	**	*	N/A	X
b-jet Fraction	**	N/A	**	*	N/A	**

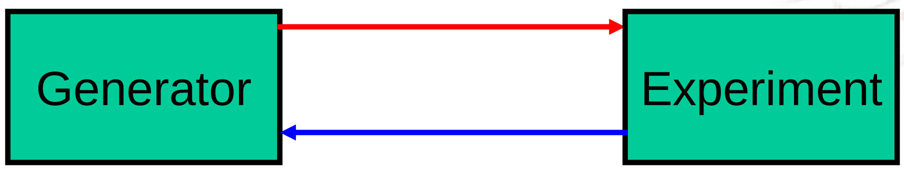
X → negligible/small effect, * → important systematics, **→ dominant systematics

See Yetkin Yilmaz's talk on 2/12 (Tue)

Inputs to the MC discussion

- **Need realistic MC generator (for both jet and UE)**
  - Iterative feedback cycle is very important (like PYTHIA v.s pp data in high energy community)
  - CMS is willing to use and check the simulated results if you offer a jet event generator

Used to derive correction or to compare with data



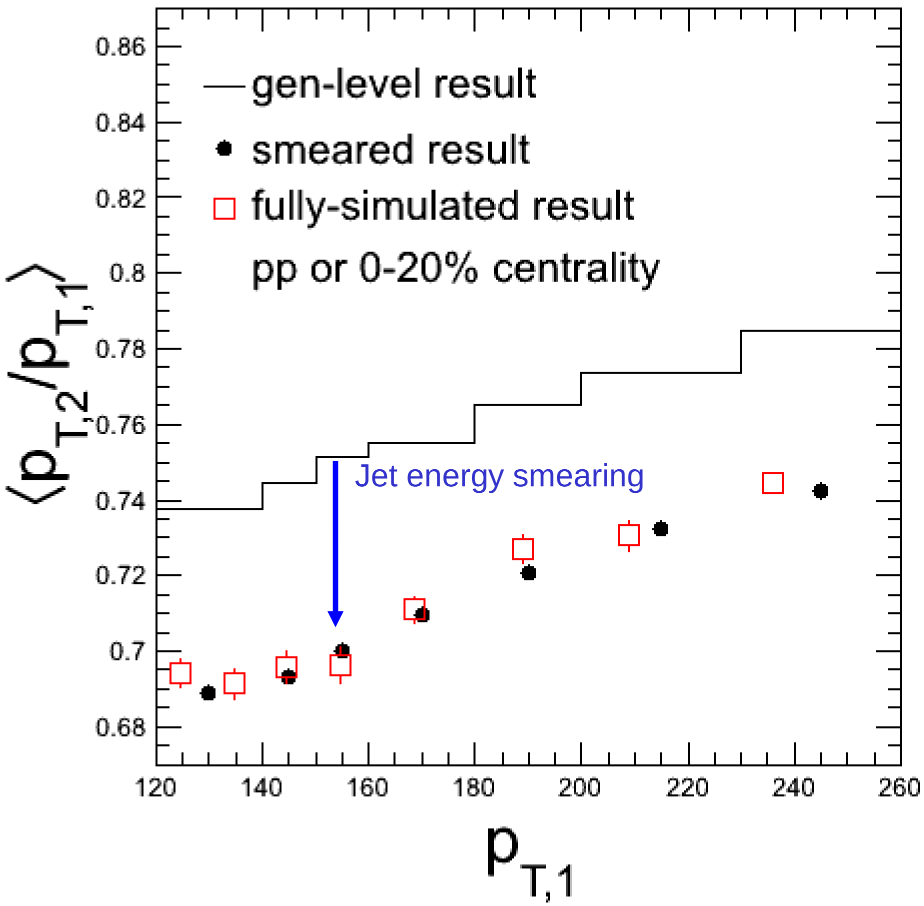
Feedback and improve the generator

- **Need to include reconstruction effect before comparing to data**
  - Genjet → energy loss → apply jet energy smearing → apply jet selection → compare the result

Impact of jet energy smearing

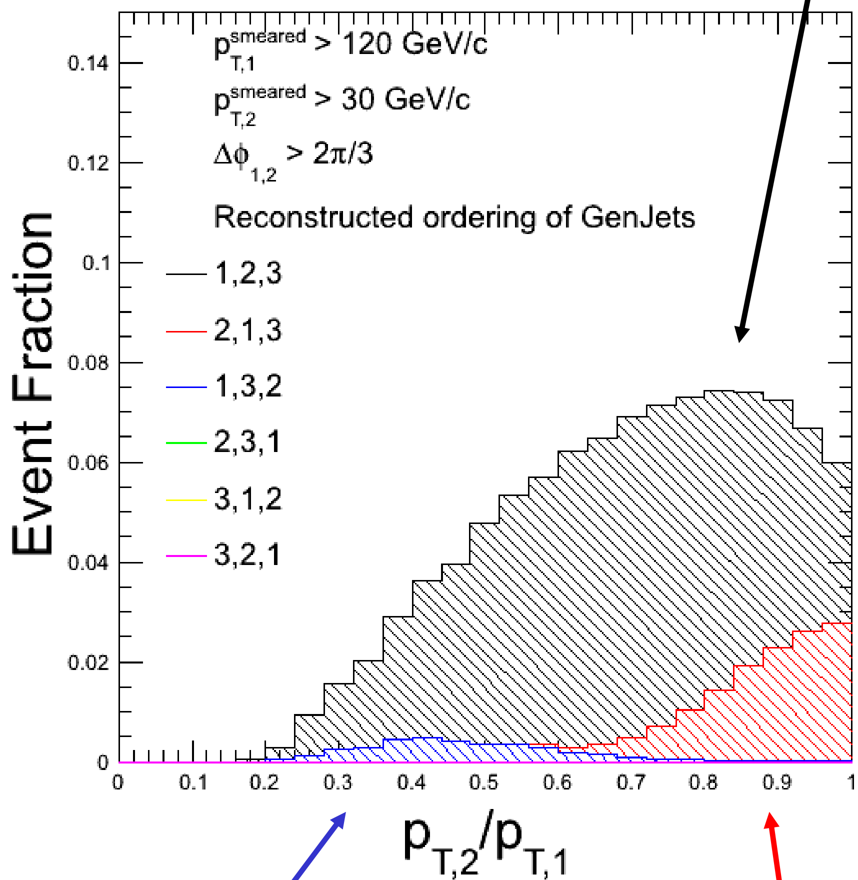
Dijet p_T ratio
Generator level jets from PYTHIA

Anti-k_T jet R = 0.3



Smearing function from PLB 718 (2013) 773

Generator level leading and subleading jets matches reco level



Subleading jet is replaced by third jet

Swapped leading and subleading jet

Summary

- CMS has presented interesting results from dijet, photon-jet and inclusive jet analyses in heavy ion collisions

- To go beyond qualitative observation:
  - **An iterative feedback cycle** between theory (in the form of MC generator) and experiment is very important

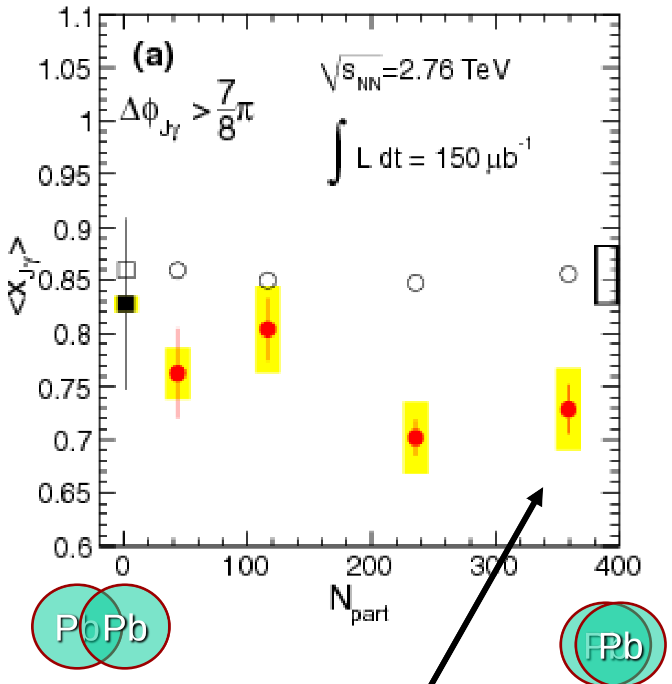
- To compare between data and theory:
  - **A proper smearing procedure** for theorist (**a proper unfolding procedure** for experimentalist when applicable) is needed

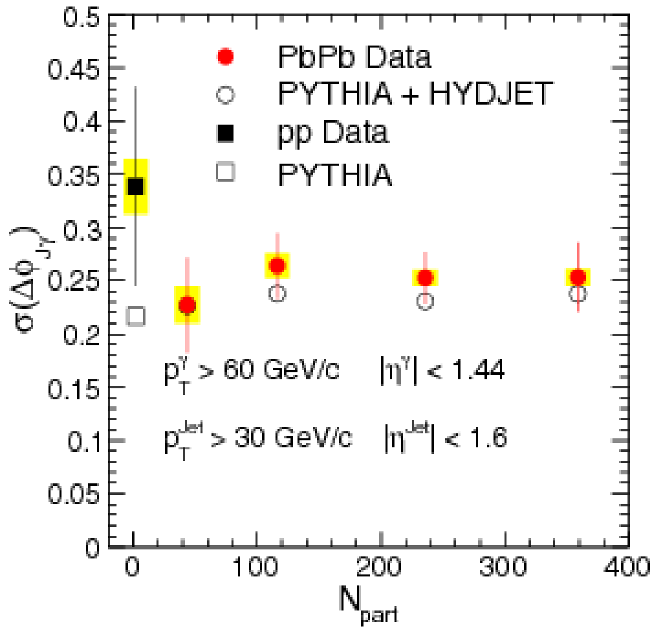
- Working Plan:
  - Jet quenching in pPb collisions?
  - Shadowing effects in pPb collisions?
  - Corrected inclusive jet spectra in pPb and PbPb collisions
  - Further studies on dijet and photon-jet events
  - W/Z+jet analysis
  - Study of multijet production

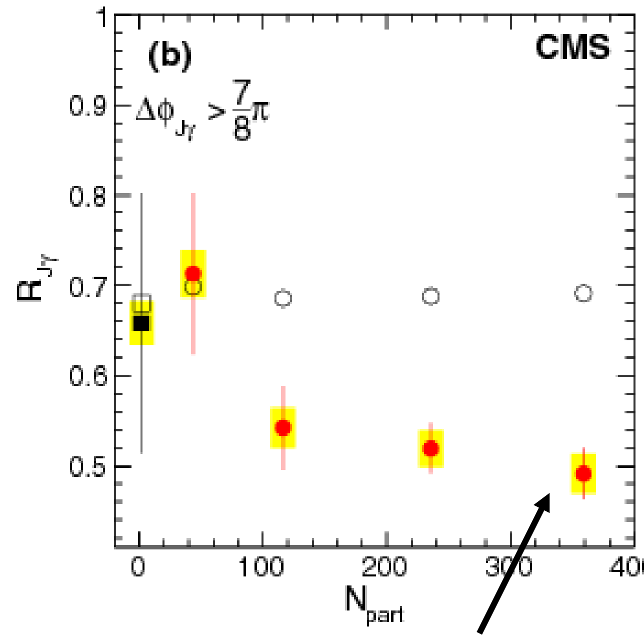
Backup slides

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

$R_{J\gamma}$ = 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

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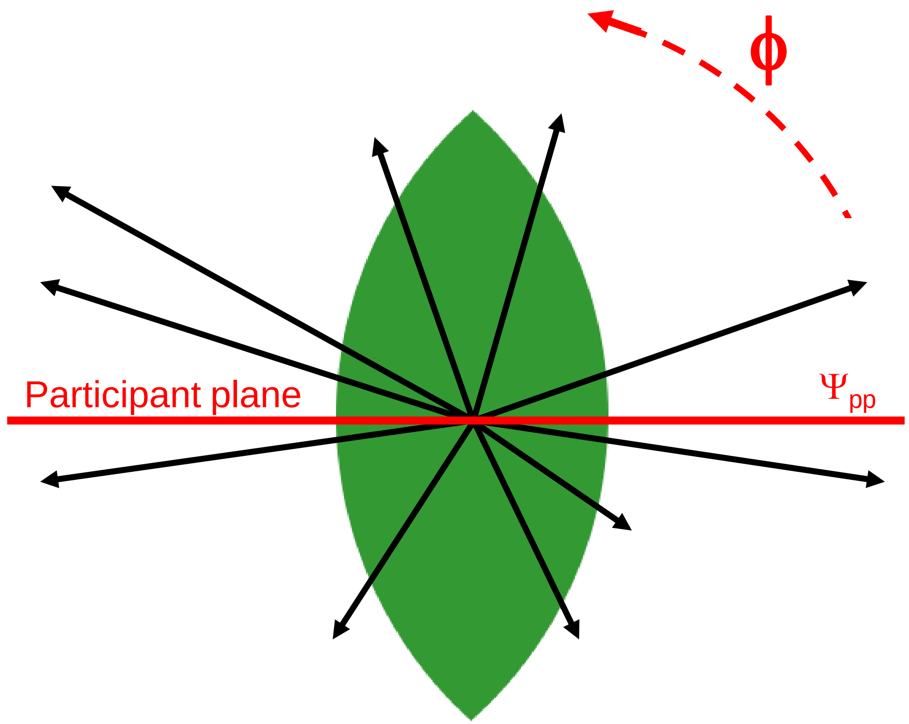
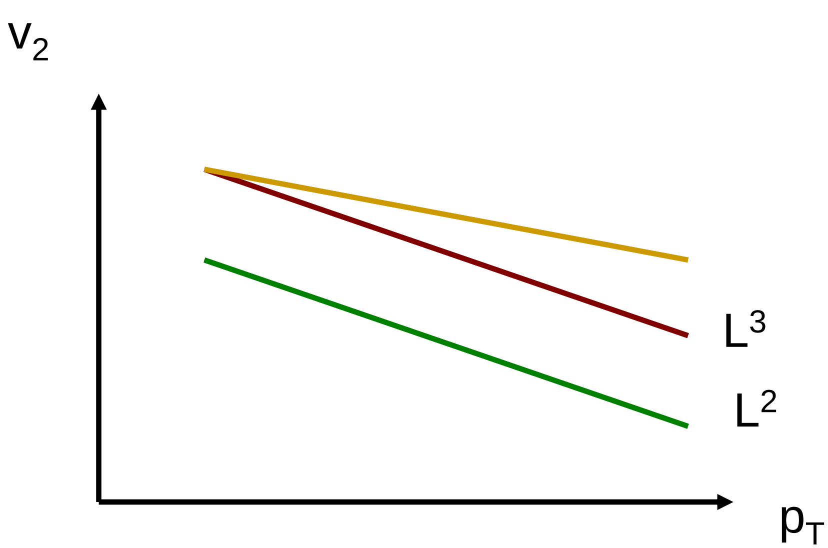
Path length dependence of jet energy loss?



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):

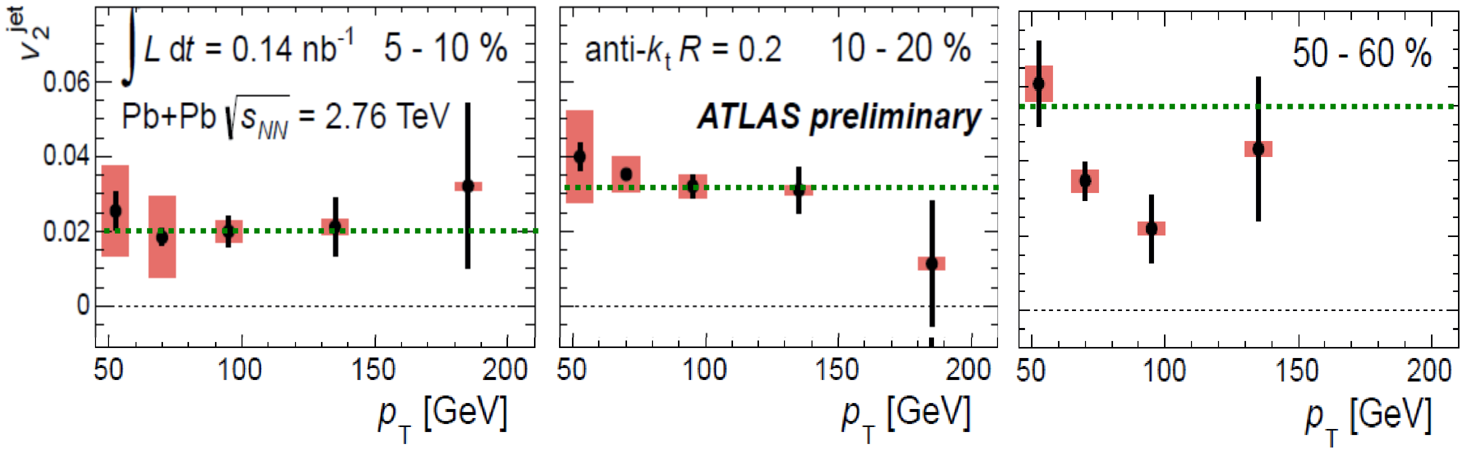
$$dN/d\phi \propto 1 + 2v_2\cos(2(\phi - \Psi_{EP}))$$



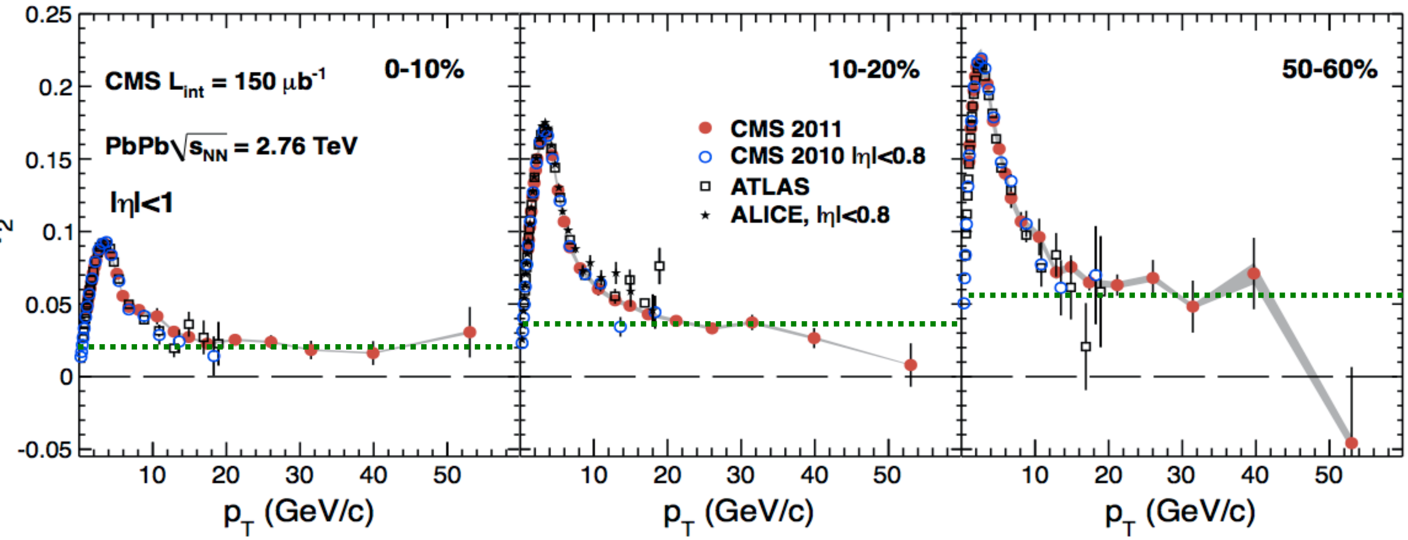
→ v2 is sensitive to the path-length dependence of the energy loss

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

Missing-$p_T^{||}$

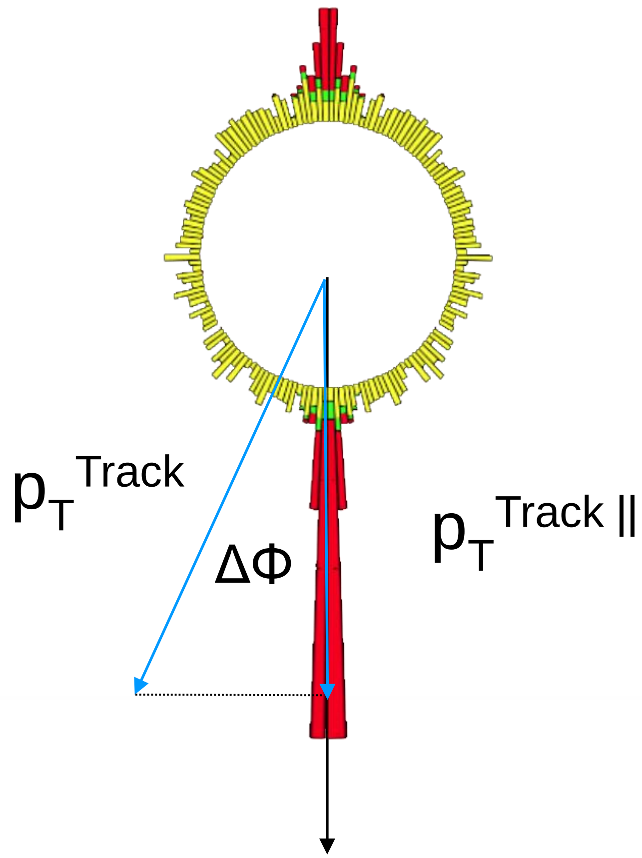
Missing $p_T^{||}$: $\displaystyle \not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$

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

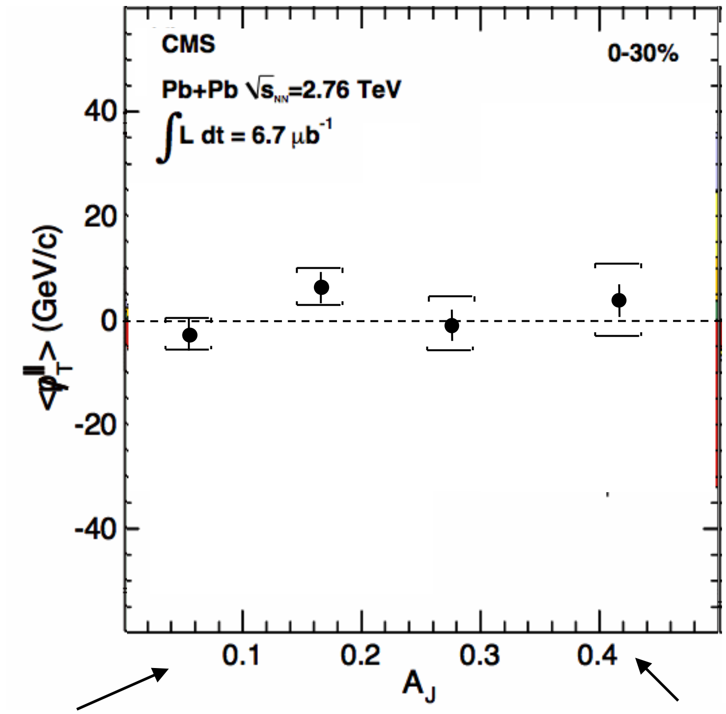


Sum over all tracks in the event

Missing-$p_T^{||}$

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

0-30% Central PbPb



balanced jets

unbalanced jets

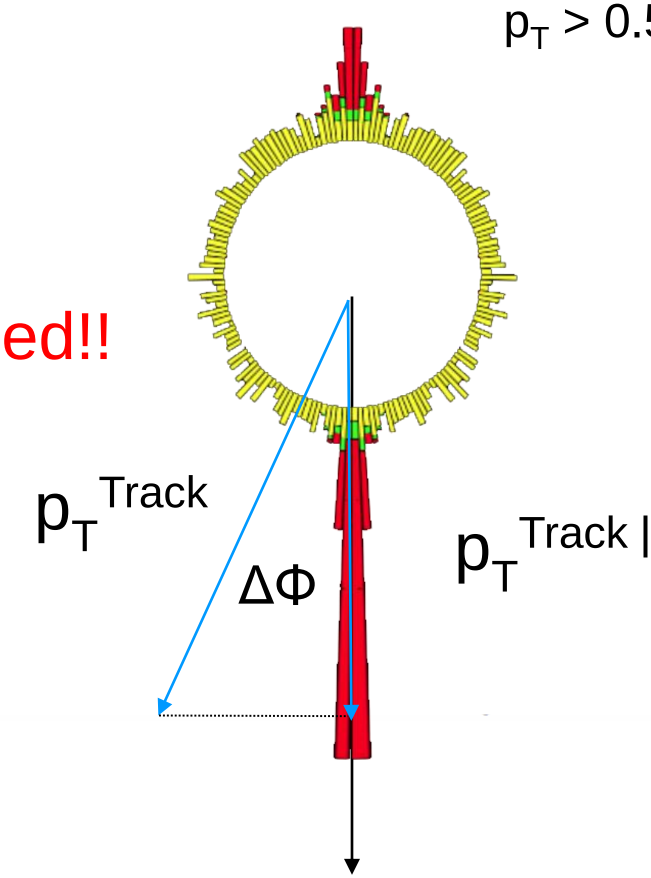
$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

excess away from leading jet

Balanced!!

excess towards leading jet

Track
$p_T > 0.5$ GeV/c

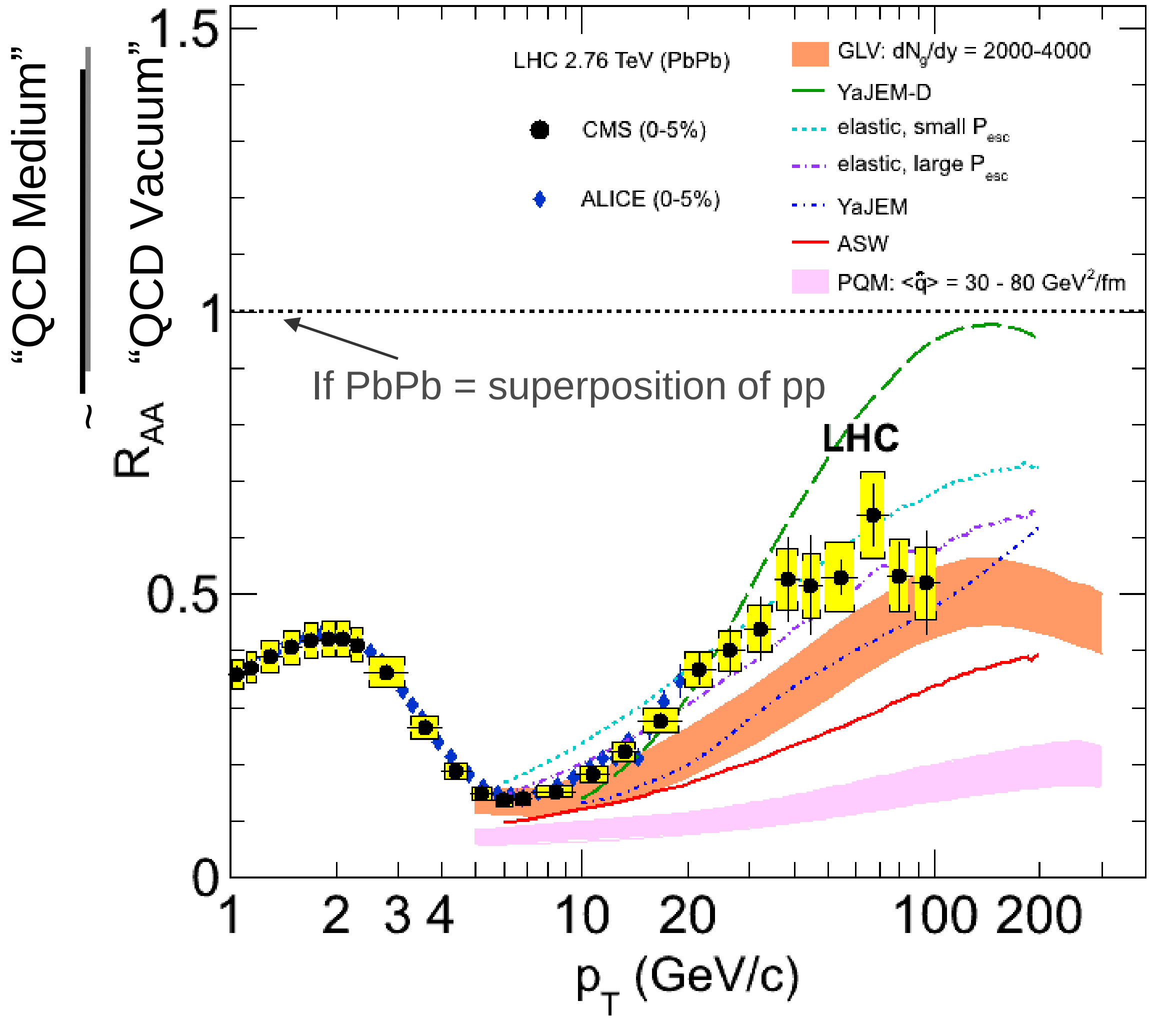


Integrating over the whole event final state

the dijet momentum balance is restored

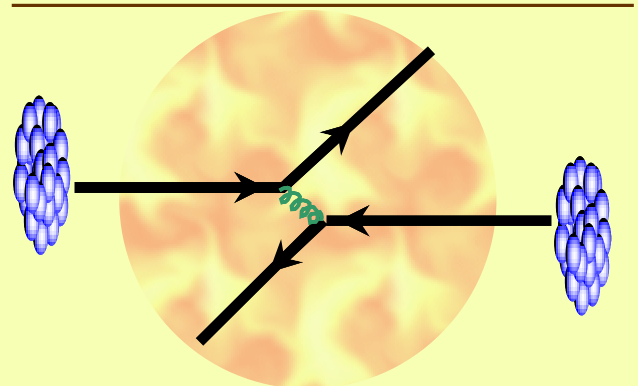
Jet quenching: strong suppression of high p_T particles

EPJC 72 (2012) 1945

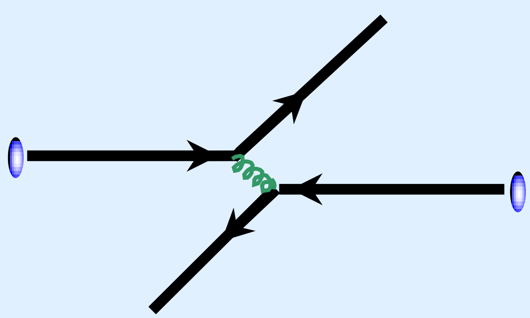


$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

PbPb measurements



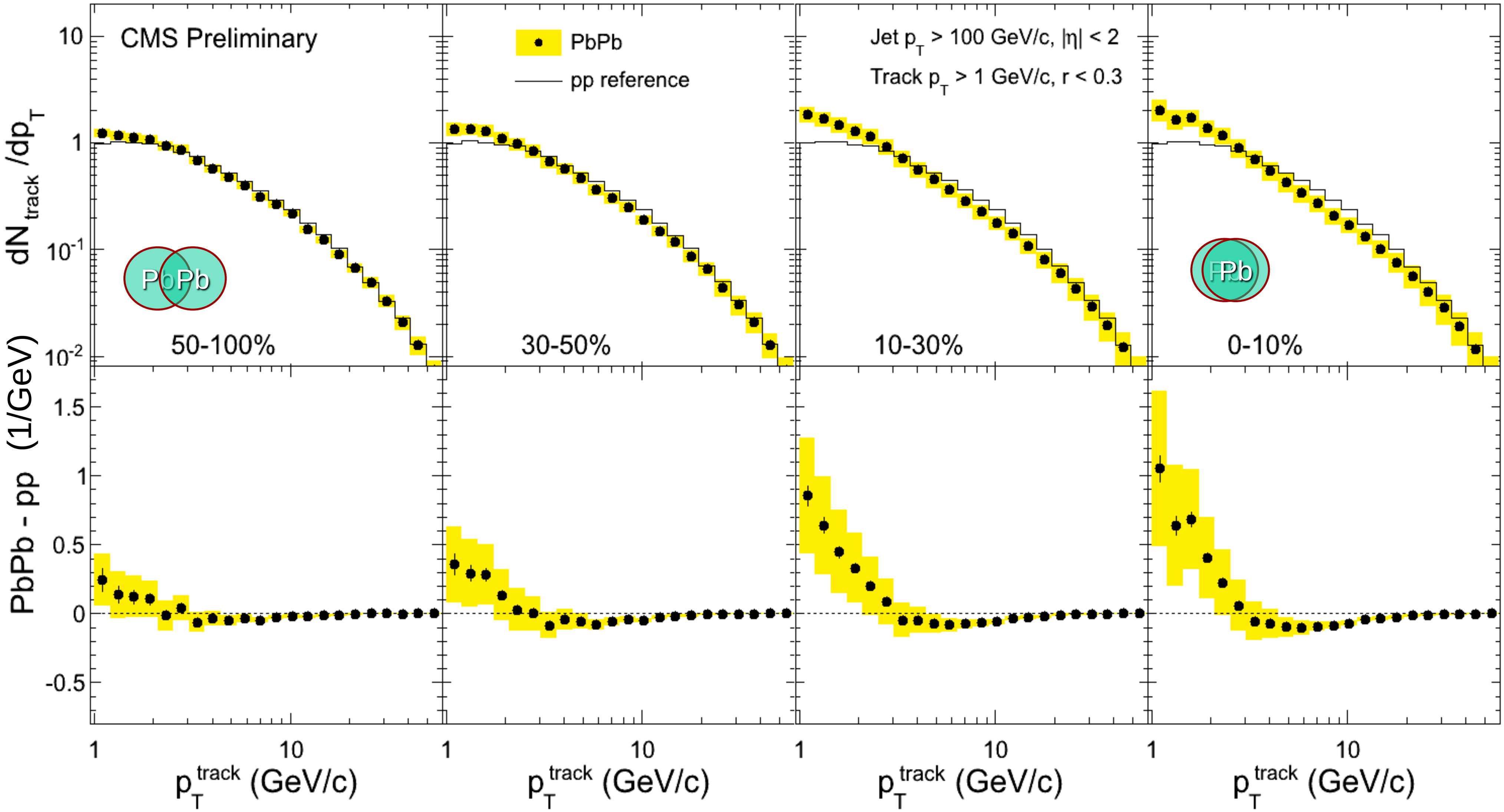
pp reference



High p_T reach up to 100 GeV/c

Constraints on the parton energy loss models

Track p_T distributions in jet cones (R=0.3)



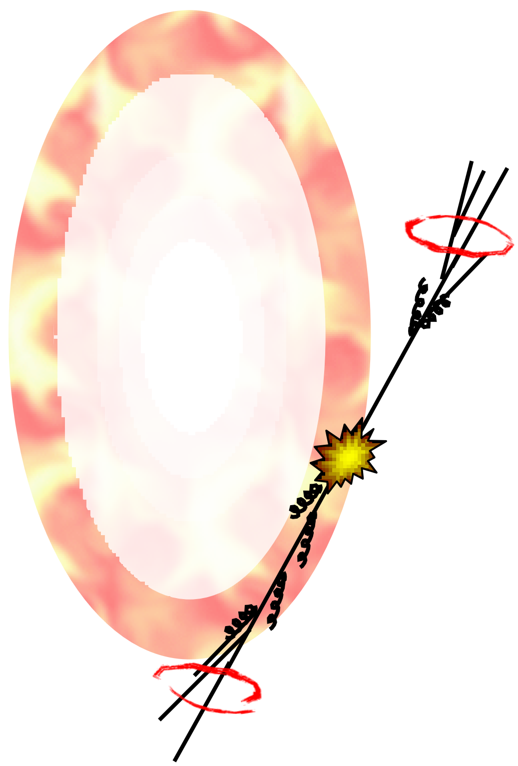
High p_T : **no change** compared to jets in pp collisions

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

Photon-jet

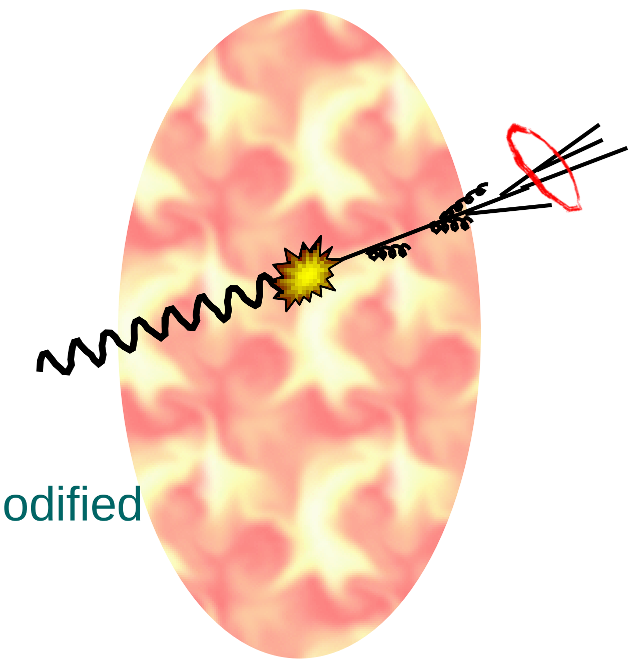
Selection on a high p_T leading jet may bias the position of the hard scattering in the QGP

Solution → trigger on high p_T photon



High p_T leading jet triggered sample

Photon → unmodified jet energy tag



High p_T photon triggered sample

Status of CMS jet measurement

- **Dijet analysis**
  - Dijet energy balance and azimuthal angle correlation
  - Missing p_T analysis
  - Fragmentation function
- **Photon-jet analysis**
  - Photon-jet energy balance and azimuthal angle correlation
- **Inclusive jet analysis**
  - Jet R_{AA} and jet spectra
  - Inclusive jet shape and fragmentation function
- **b-jet analysis:**
  - b-jet fraction

pPb 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

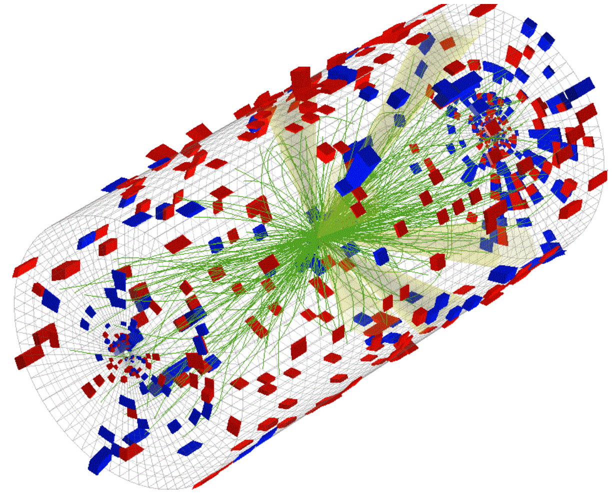
PLB 718 (2013) 795

2013 pPb run: >30/nb recorded!

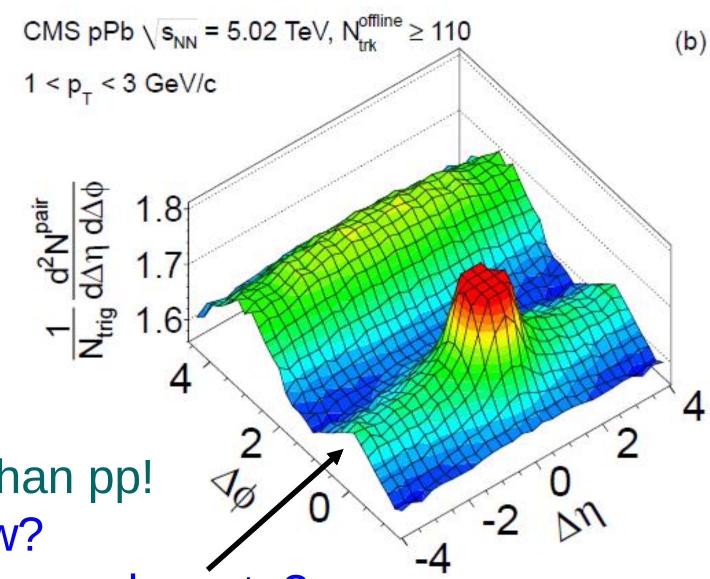
• Jet quenching in pPb collisions?

• Are jets modified in pPb collisions?

• How shadowing effect and modification on the jet observables?



Two particle correlation function



5x larger than pp!

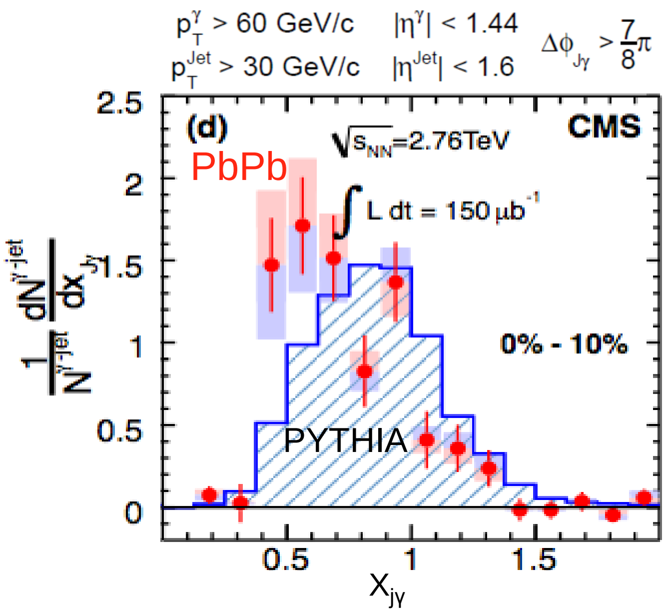
Elliptic flow?

Color glass condensate?

Modified jet structure?

pp ridge paper: JHEP 1009 (2010) 091

Photon-jet momentum balance

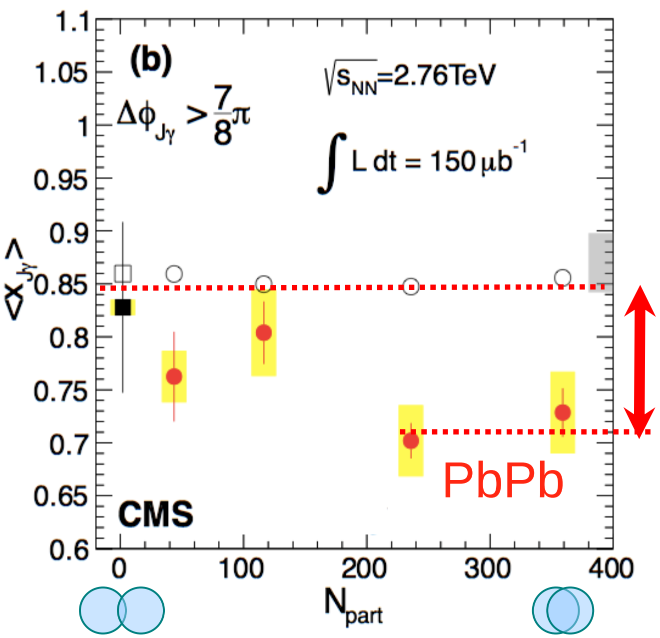


Compare photon-jet momentum balance

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

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

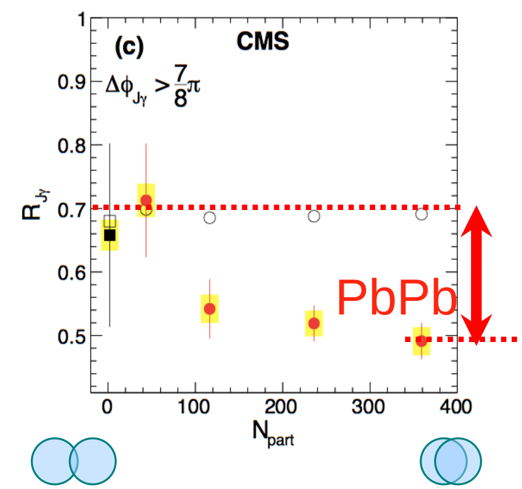
R=0.3



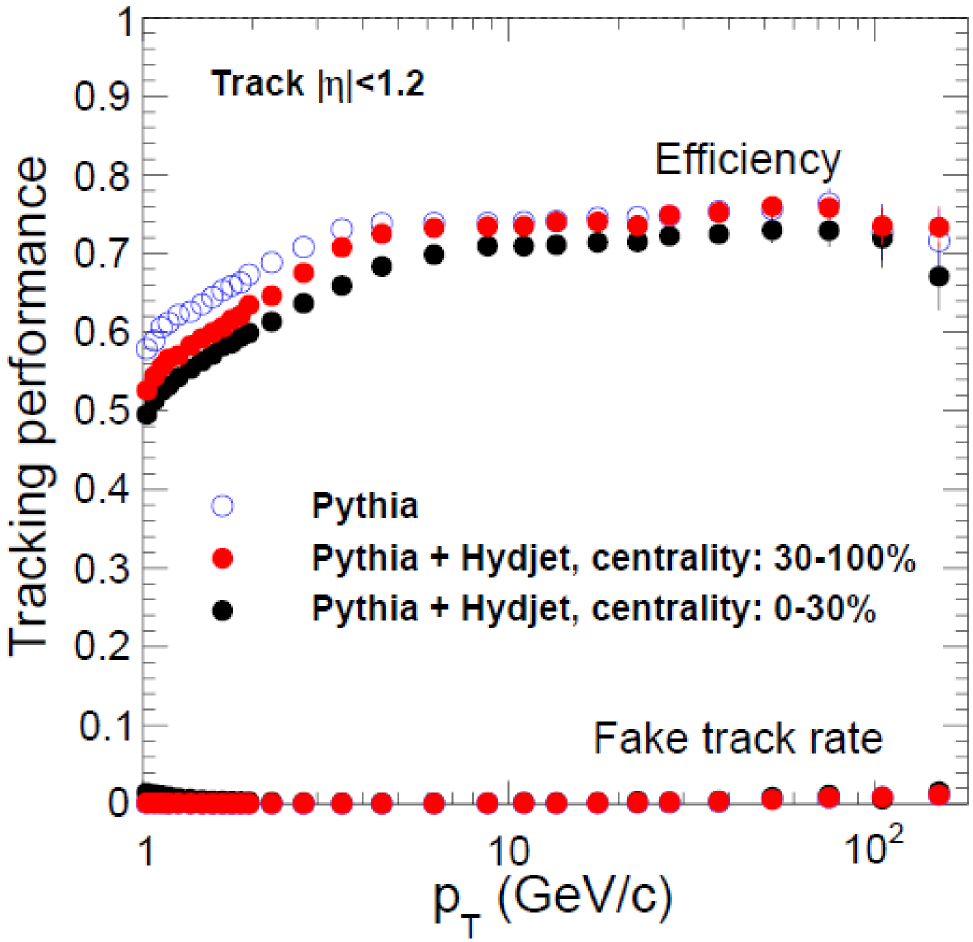
Jets lose about 15% of their initial energy

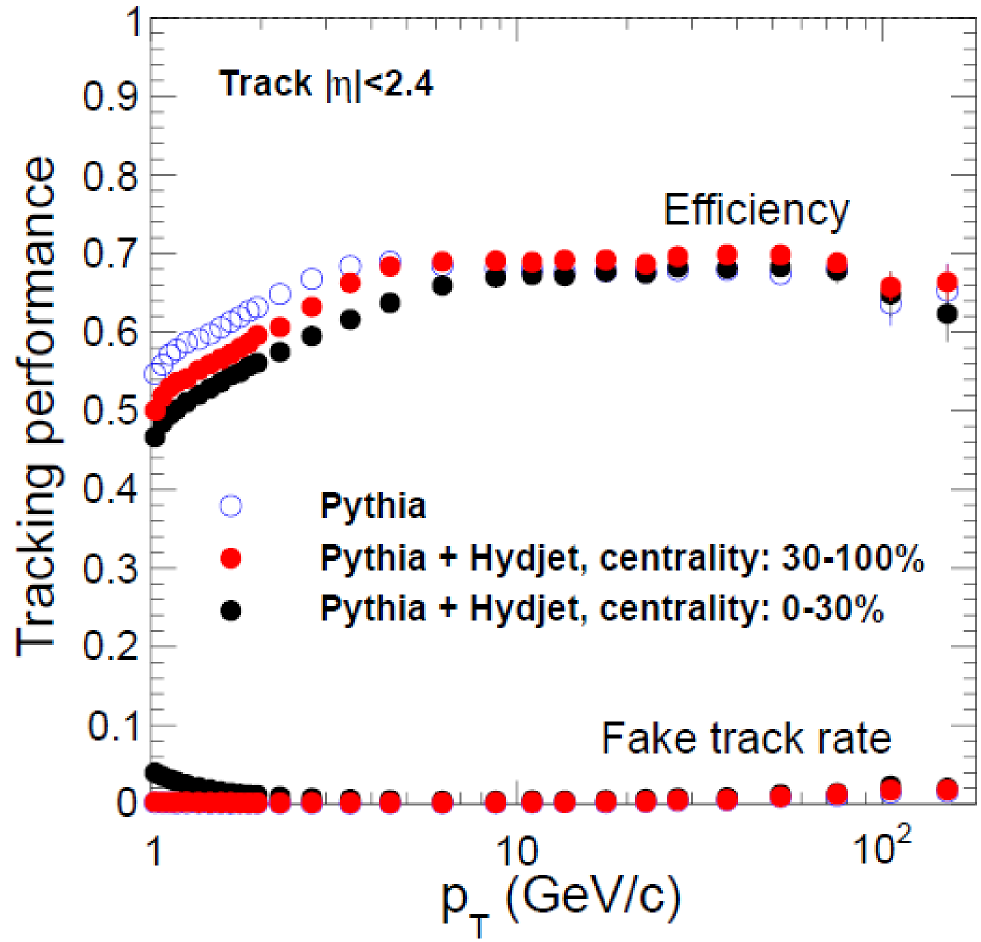
PLB 718 (2013) 773

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

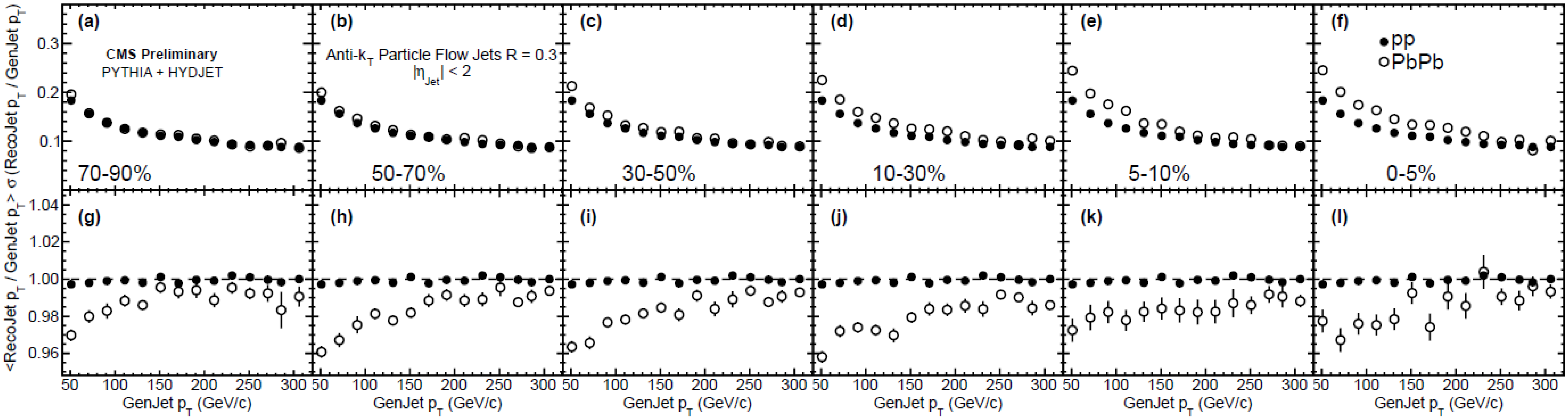


Tracking efficiency

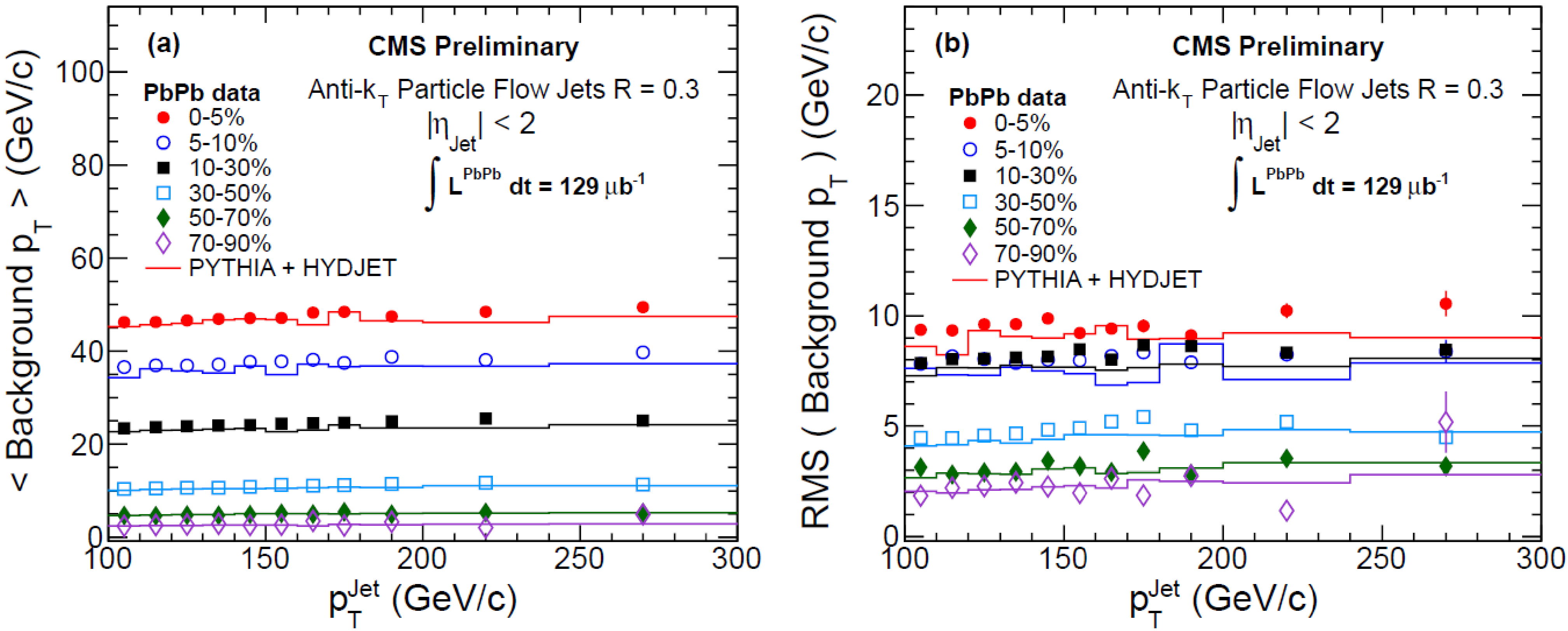




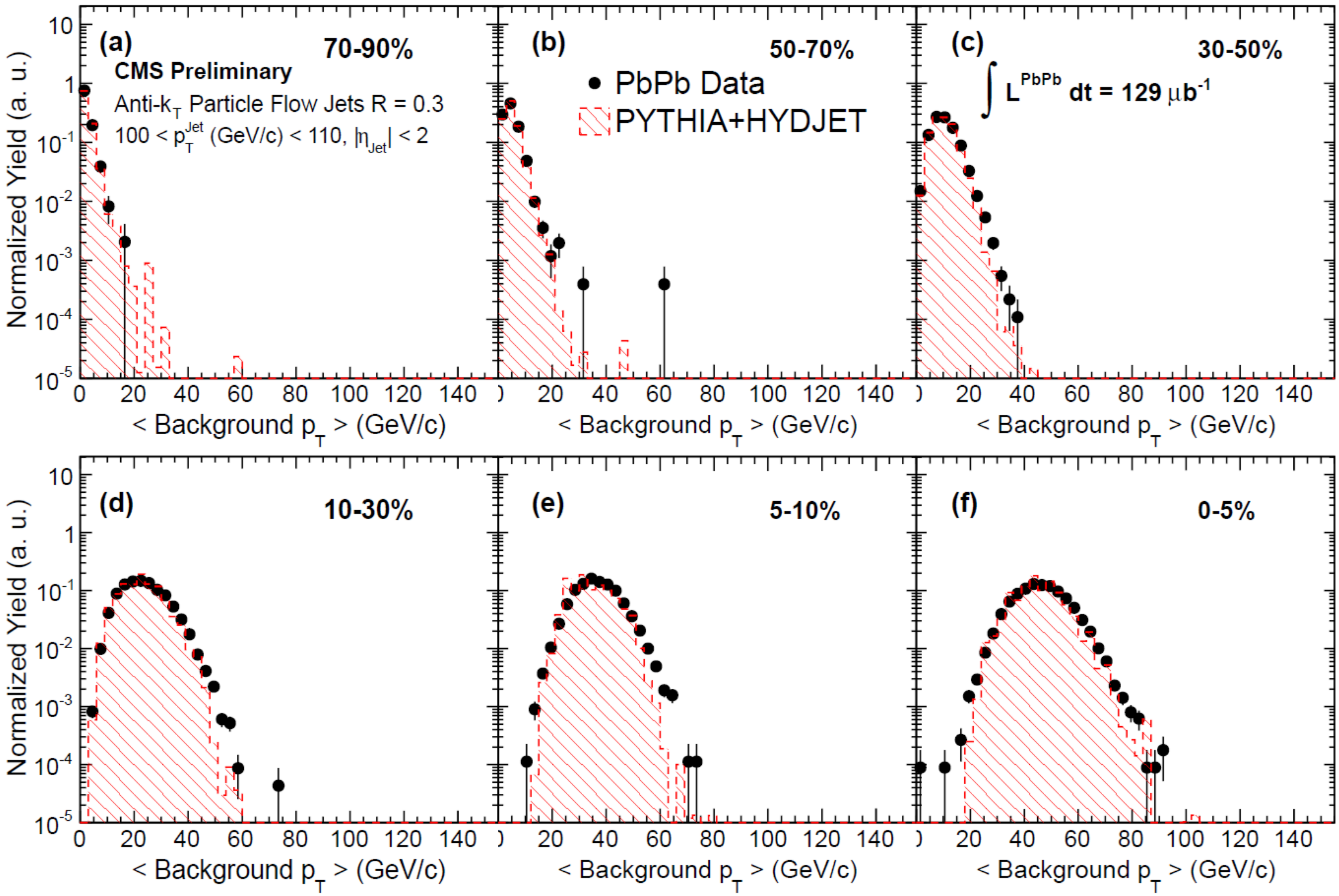
Jet resolution and enery scale



Subtracted background



Subtracted background



Effects to be considered in analysis

- Impact of background subtraction
  - Jet response dependence on the jet event configuraiton (ex: 3-jet v.s. 2-jet event) → studied with PYTHIA & PYTHIA+HYDJET MC
  - Jet flavour dependence (Quark v.s. gluon, modified jet shape and FF pattern) → studied PYTHIA & PYTHIA+HYDJET MC, cross-check with PYQUEN generator
  - Shape of medium response (?)
  - Sensitivity to tracking efficiency (and fluctuation) → studied with PYTHIA+HYDJET
- Impact of jet energy resolution
  - Resolution of calorimeter resolution → studied PYTHIA & PYTHIA+HYDJET MC, cross-check with PYQUEN generator
  - Possible bias toward positive UE fluctuation → Random cone & PYTHIA+HYDJET
  - Impact to jet energy and pointing resolution → PYTHIA+HYDJET
  - Fake jets from UE fluctuation → PYTHIA+HYDJET, data driven from dijet $\Delta\varphi$ correlation
  - Inefficiency due to downward UE fluctuation → PYTHIA+HYDJET
  - Impact of flow and event plane dependence → PYTHIA+HYDJET
- Centrality determination
  - Inference of the presence of a jet to centrality determination → PYTHIA+HYDJET, cross-checks with other detectors
- Detector related effects
  - Calorimeter noise → data driven rejection studied with dijet $\Delta\varphi$ correlation
  - Fake tracks → PYTHIA+HYDJET, studied with dijet $\Delta\varphi$ correlation

See Yetkin Yilmaz's talk on Tueday

Dijet azimuthal correlation v.s. leading jet p_T