Results on jet quenching from the CMS experiment

Bożena Boimska
National Centre for Nuclear Research

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Outline

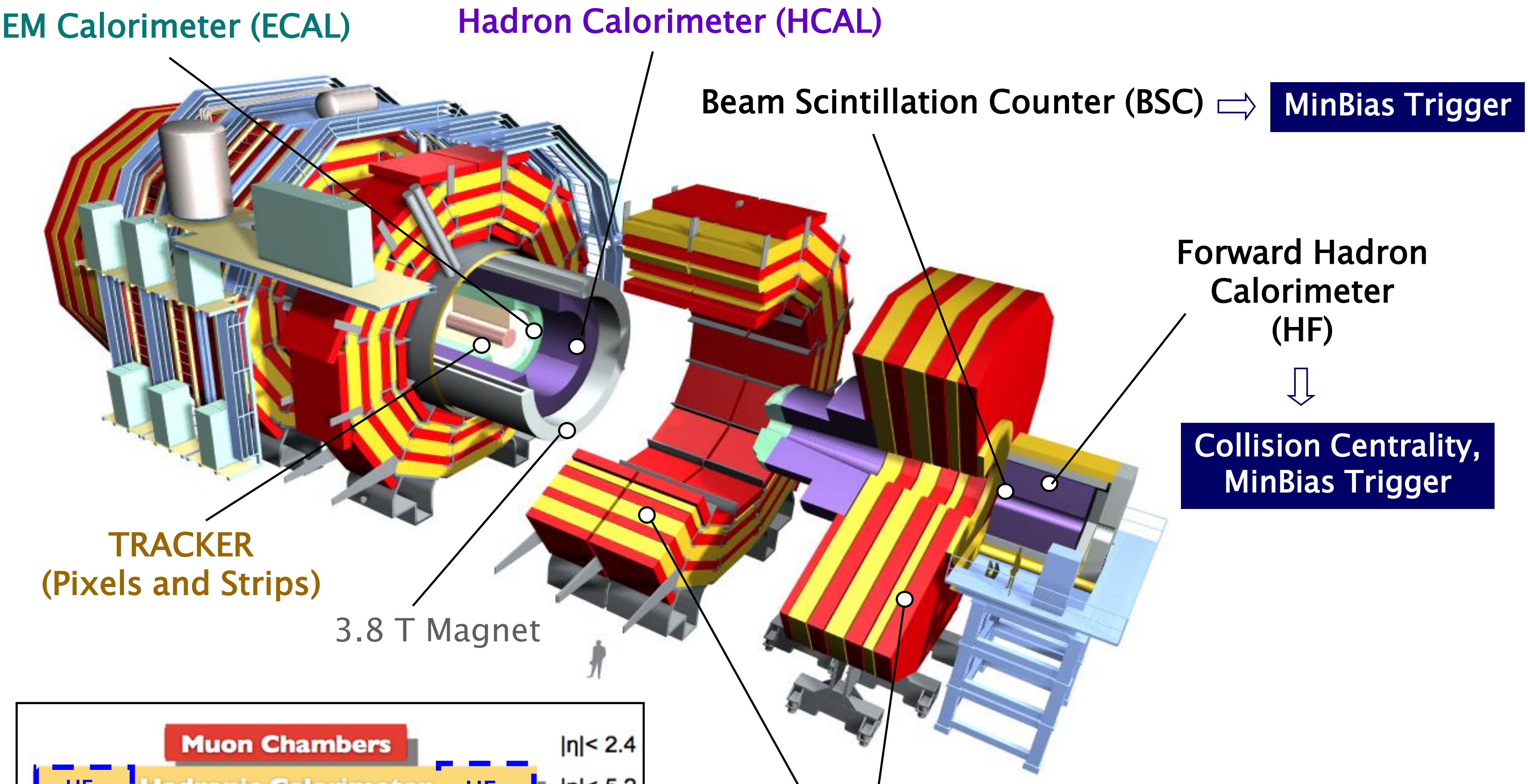
- Introduction
- Jet-quenching effect
- Experimental results
  - Study of dijet events
  - Nuclear modification factor
- Summary

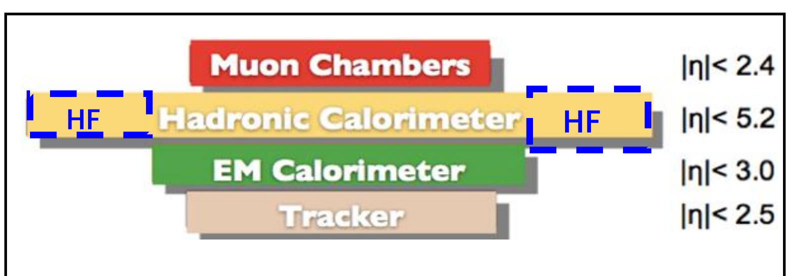
31 published/submitted papers
19 Physics Analysis Summaries (PAS)
http://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN

CMS studies both 'soft' and '**hard**' observables

Only some selected results presented today ...

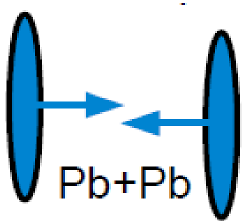
CMS detector



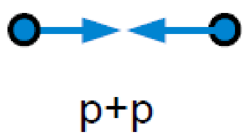


$\eta = -\ln(\mathrm{tg}\,\theta/2)$

Data for HI analyses



$\sqrt{s_{NN}}$= 2.76 TeV



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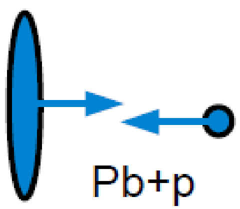


$\sqrt{s_{NN}}$= 5.02 TeV

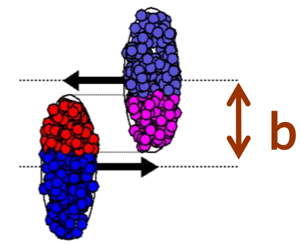
System & Energy	Year	Integrated luminosity
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV	2010	8.3 μb^{-1}
	2011	150 μb^{-1}
pp $\sqrt{s}$ = 2.76 TeV	2011	231 nb^{-1}
	2013	5.4 pb^{-1}
pPb $\sqrt{s_{NN}}$ = 5.02 TeV	2012 (pilot run)	1 μb^{-1}
	2013	35 nb^{-1} (pPb) + (Pbp)

Different trigger selections used

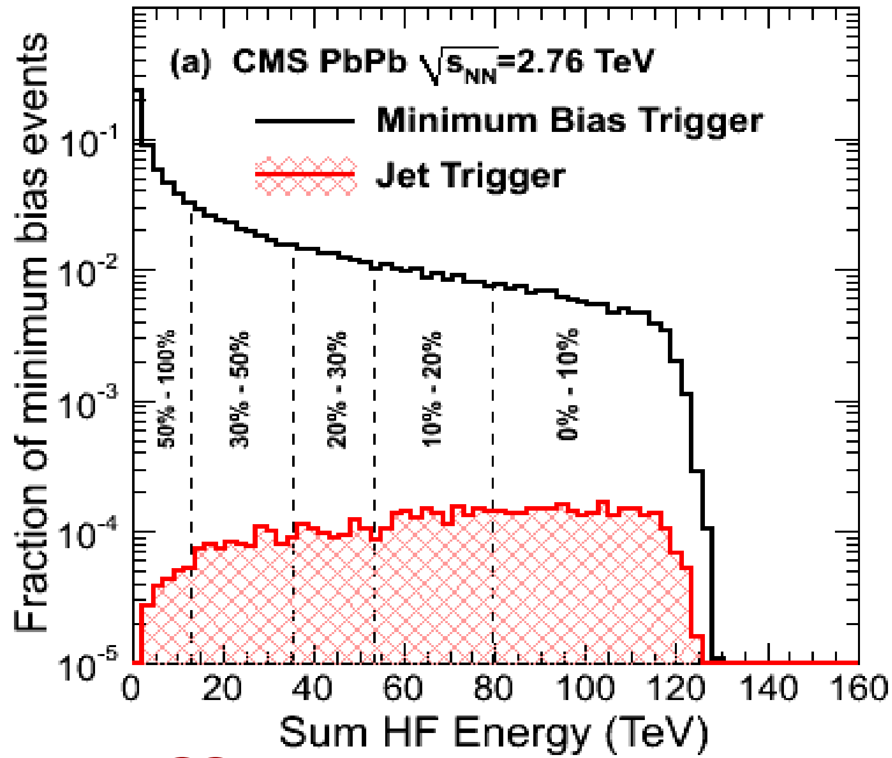
- MinBias Trigger
- Photon Trigger
- Jet Trigger
- (Di)Muon Trigger
- High-multiplicity Trigger

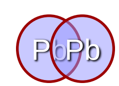
Centrality determination

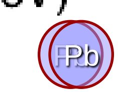
- Energy deposit in forward calorimeters (HF) used to determine centrality of PbPb and pPb collisions



- Example distribution of the total HF energy used to divide PbPb sample into centrality bins



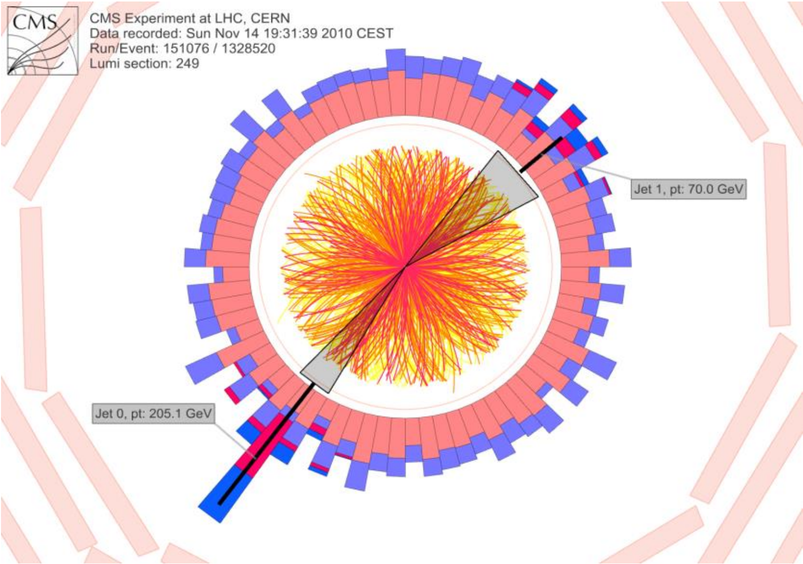




Collision centrality is related to geometrical quantities:

- N_{part} – number of participating nucleons
- N_{coll} – number of elementary NN collisions

Jet reconstruction in PbPb collisions



$dN_{charged}/d\eta \approx 1600$

(for 5% most central PbPb collisions)

Jet cone radius:

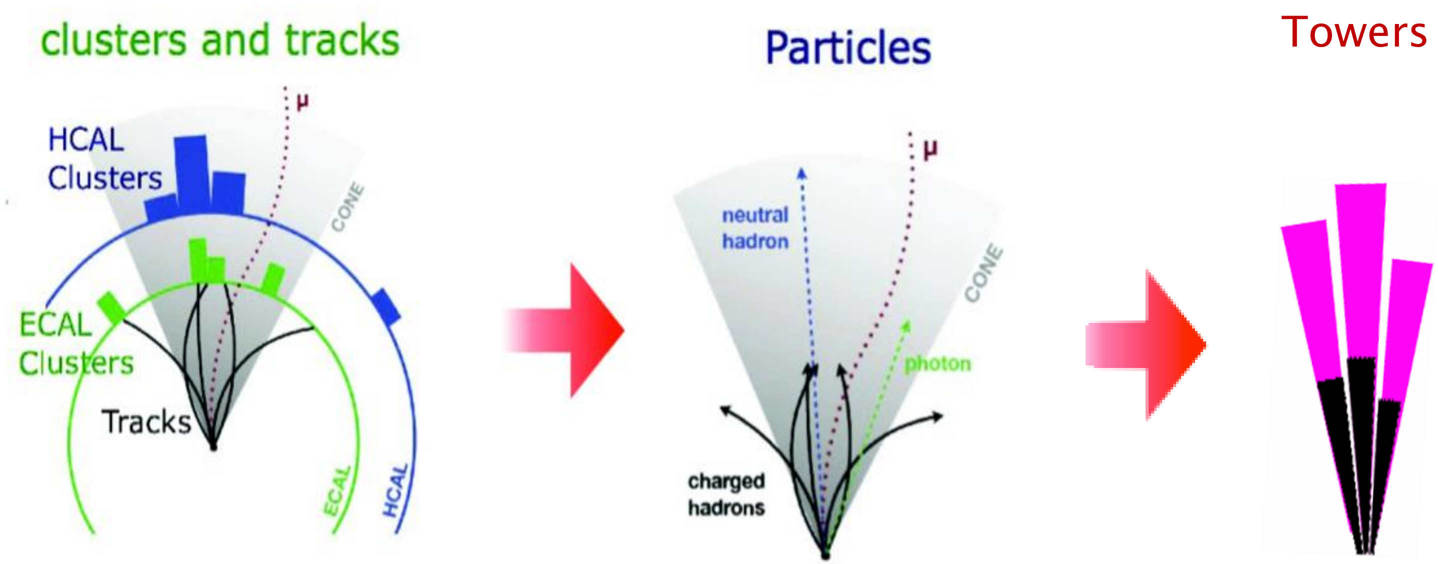
$$R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Jets are accompanied by large "soft underlying event"
→ jet reconstruction difficult

- **Use event-by-event background subtraction procedures**
  → In CMS iterative PileUp subtraction method employed [Eur. Phys. J. C50 (2007) 117]

- Jet finding algorithms used in CMS
  - Iterative Cone
  - Anti-k_T
- Jets are found using different sets of detectors
  - Calorimetric Jets: use ECAL and HCAL
  - **Particle Flow Jets**: use Tracker and Calorimeters

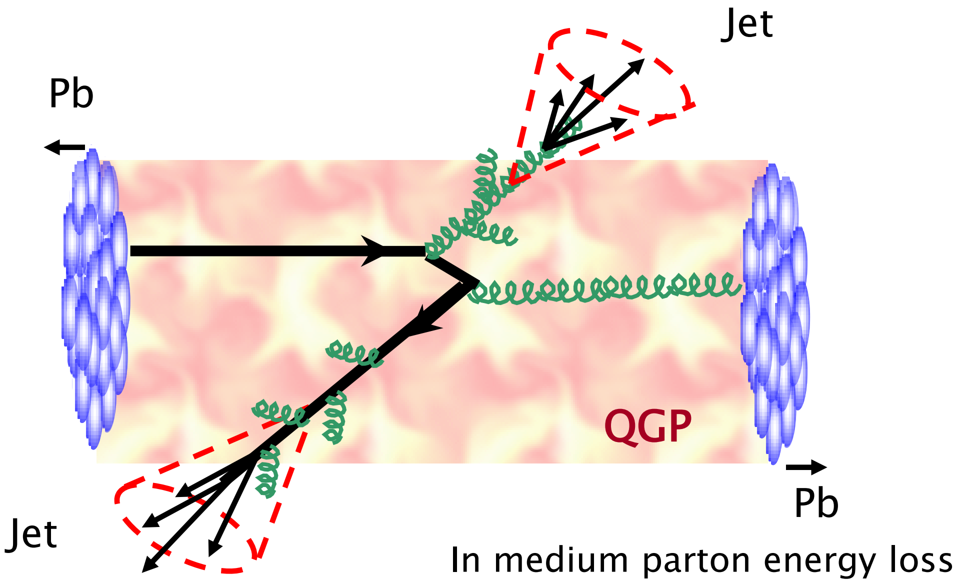
Particle Flow Jets



- HCAL, ECAL and Tracker information used
- Particle flow reconstructs all stable particles in the event: $h^{+/-}$, γ, h^0, e, μ
- Individual particles are then used to build jets
- Particle flow event reconstruction applied in AA collisions for the 1st time

Jet quenching

signature of QGP – J.D.Bjorken (1982)



In medium parton energy loss
→ "Jet quenching"

Energy loss of high energy quarks and gluons propagating through Quark-Gluon Plasma (QGP) leads to the depletion of jet yields at high transverse momenta (p_T).

Parton flavor dependence is predicted.

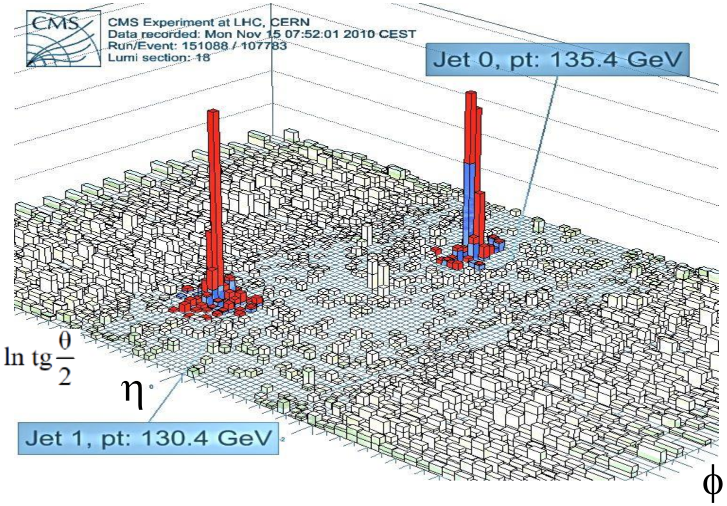
Energy loss of heavy quarks expected to be smaller than for light quarks and gluons.

Dijet events in PbPb collisions

First hours of LHC running

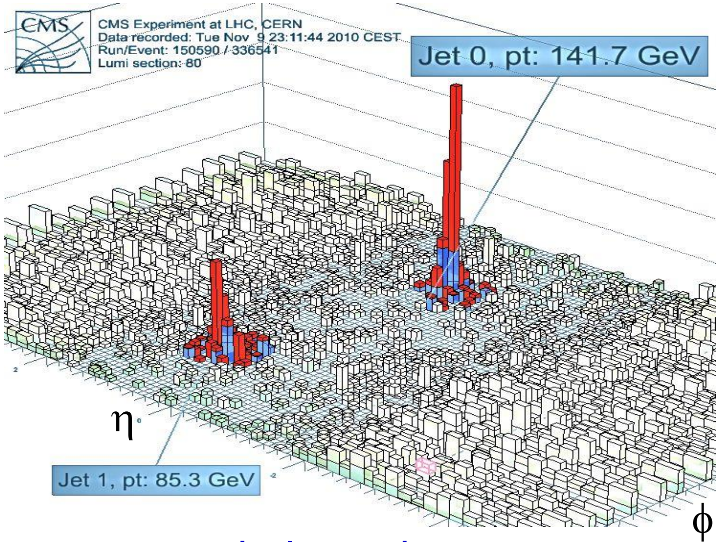
- Dijet events seen
- Dijets with unbalanced energy also observed

Energy deposits in calorimeters:



$\eta = -\ln \mathrm{tg}\frac{\theta}{2}$

Balanced jets



Unbalanced jets

Manifestation of jet quenching effect

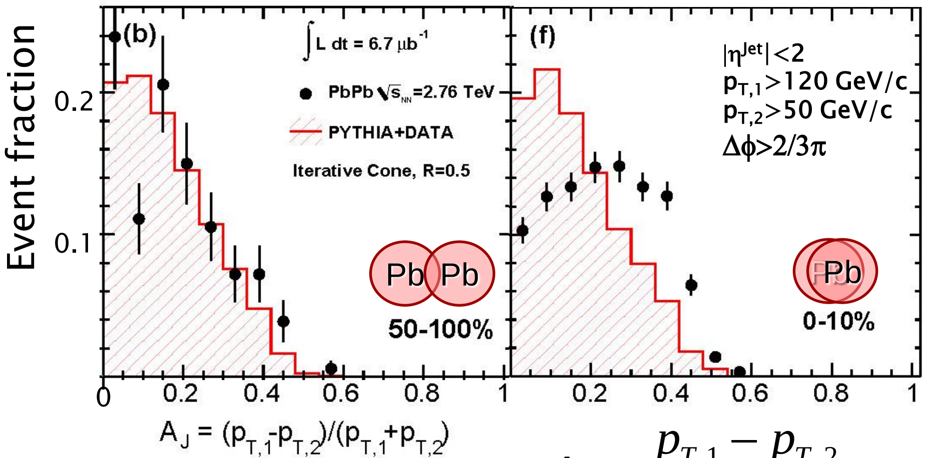
Dijet p_T imbalance quantified by asymmetry ratio:

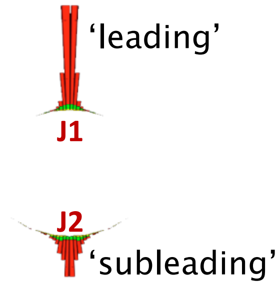
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$ – leading
$p_{T,2}$ – subleading

Dijet events in PbPb collisions

Dijet Imbalance





PRC 84 (2011) 024906

PLB 712 (2012) 176

• exp. DATA

– ref. DATA

Asymmetry: $$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

➡ Dijet p_T imbalance (A_J) increases with centrality

→ Direct observation of jet quenching in central PbPb collisions

Dijet events in PbPb collisions

PRC 84 (2011) 024906

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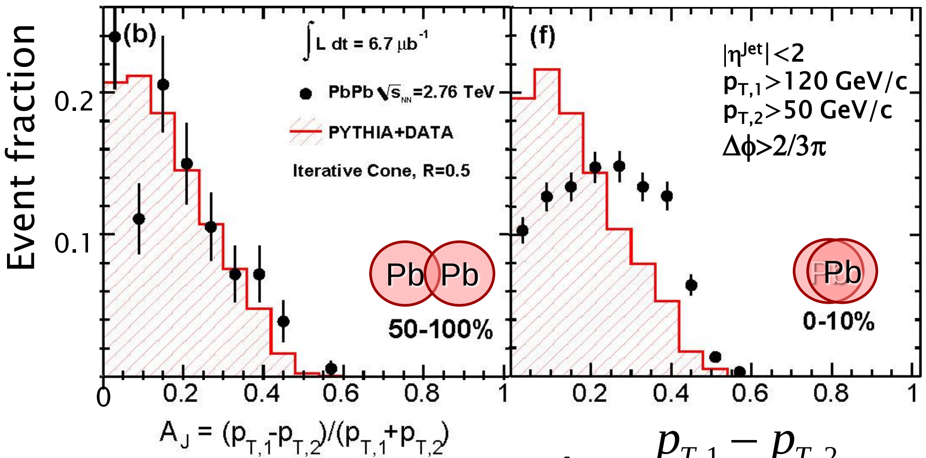

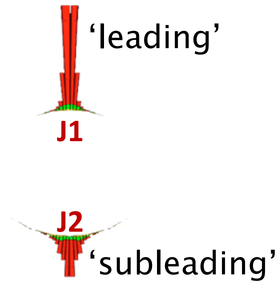

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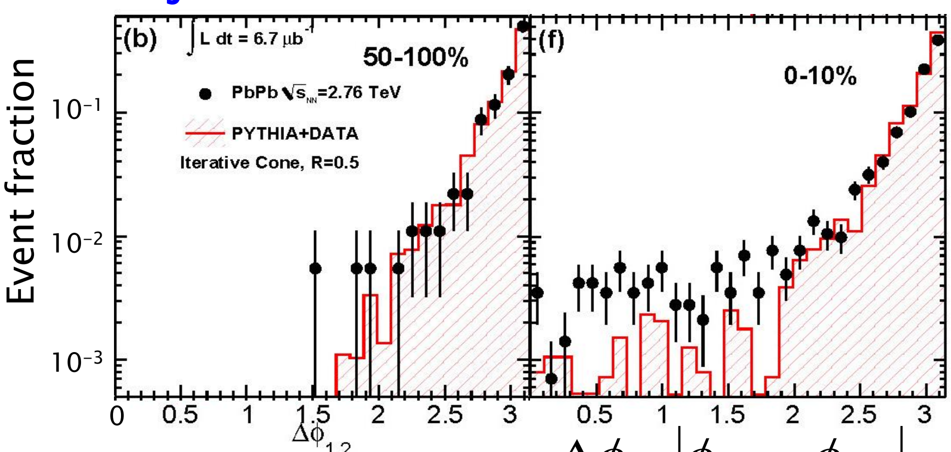
→ **Direct observation of jet quenching in central PbPb collisions**

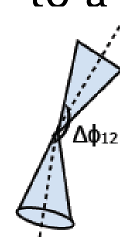
Dijet Azimuthal Correlation



$\Delta\phi = \left|\phi_{jet1} - \phi_{jet2}\right|$

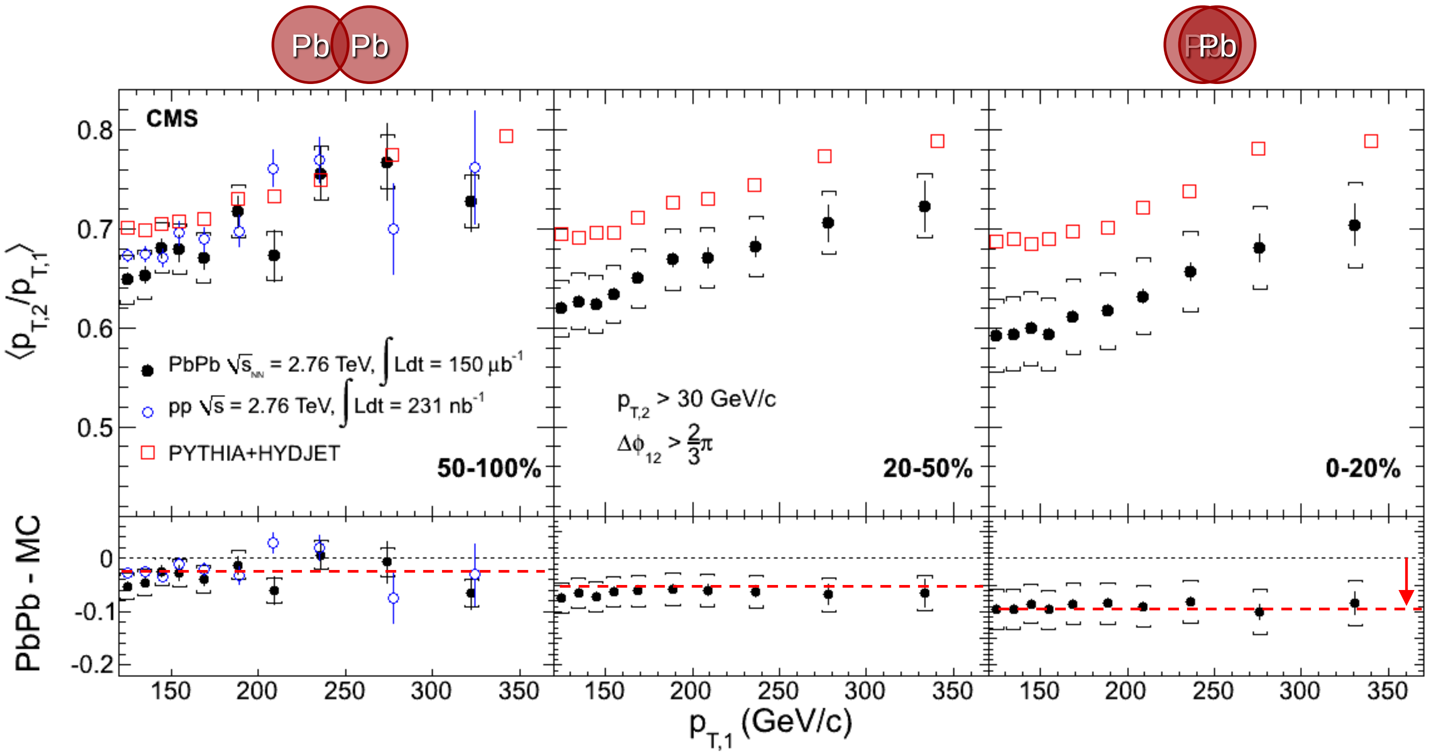
➡ Jets remain essentially back-to-back ($\Delta\phi \sim \pi$) for all centralities

→ Propagation of high p_T partons in dense nuclear medium does not lead to a strong angular decorrelation



Dijet events in PbPb collisions

Average dijet momentum ratio $<p_{T,2}/p_{T,1}>$



PLB 712 (2012) 176

□ ref. DATA (MC)

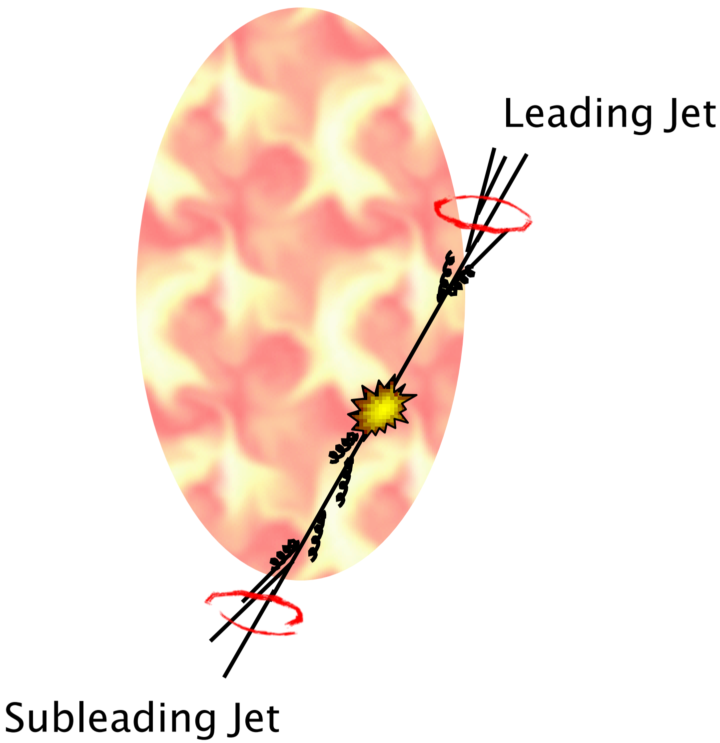
• exp. DATA

$p_{T,1}$ – leading
$p_{T,2}$ – subleading

- For mid-central and central PbPb events $<p_{T,2}/p_{T,1}>$ significantly lower than in MC simulation
- Effect stronger for more central collisions

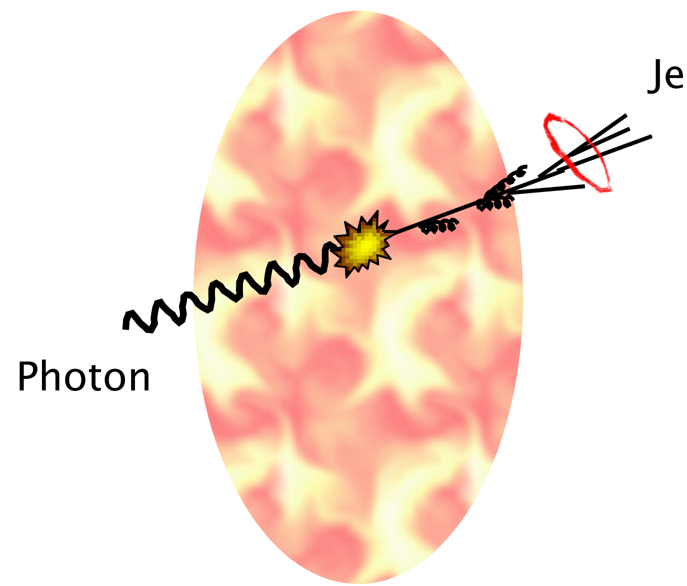
Photon-jet events in PbPb collisions

Jet-Jet



Initial parton for leading jet could also lose some energy
→ analysis is biased

Photon-Jet

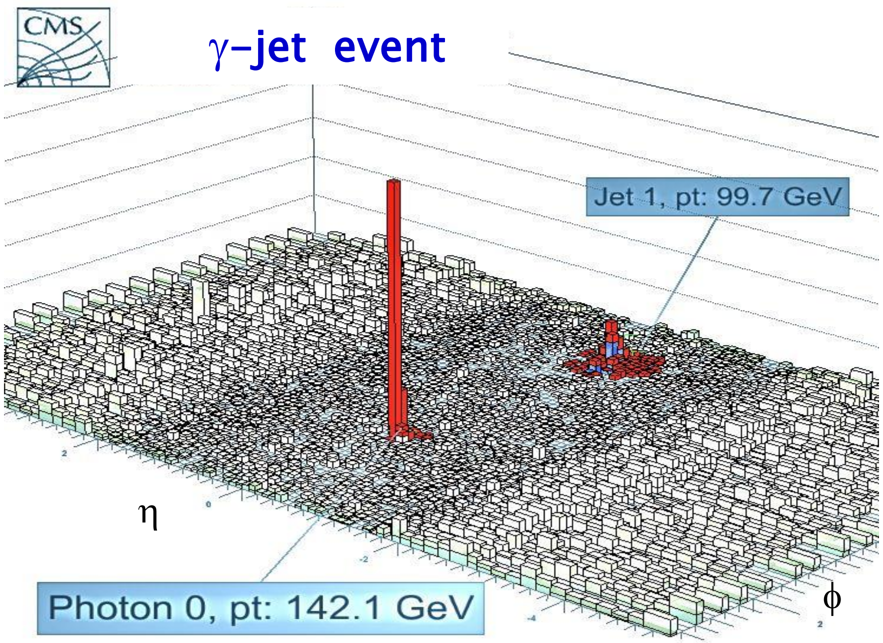


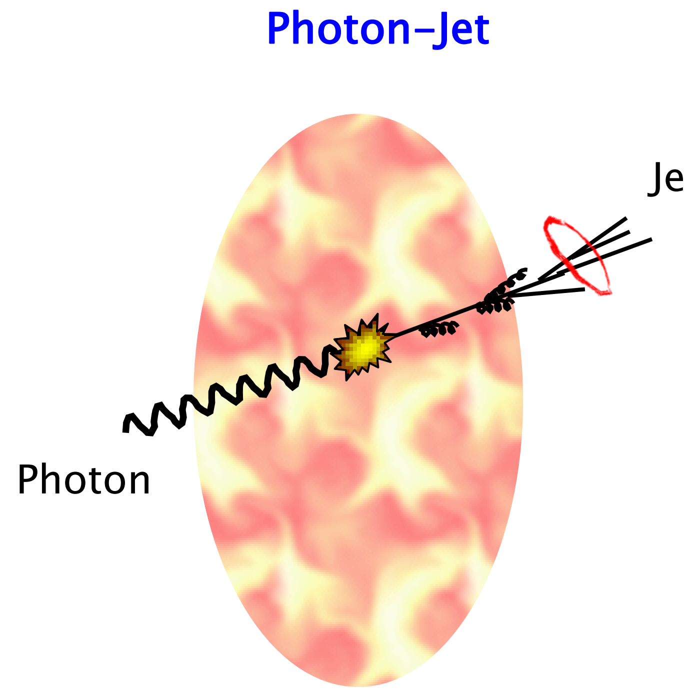
'Prompt' photon does not interact with the medium:

→ provides initial parton direction

→ provides initial parton p_T

Photon–jet events in PbPb collisions





⇩

Direct measurement of parton energy loss in the medium

'Prompt' photon does not interact with the medium:

→ provides initial parton direction

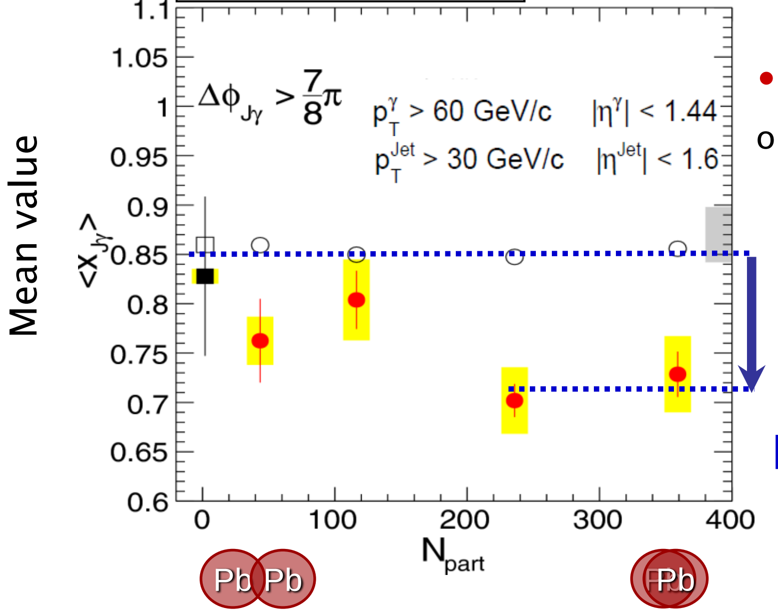
→ provides initial parton p_T

Photon–jet events in PbPb collisions

Direct measure of the jet energy loss is **the ratio of jet to photon p_T**:

PLB 718 (2013) 773

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



• exp. DATA

o ref. DATA (PYTHIA+HYDJET)

Jets lose about 15% of their initial energy

p_T imbalance larger for more central collisions

Photon–jet events in PbPb collisions

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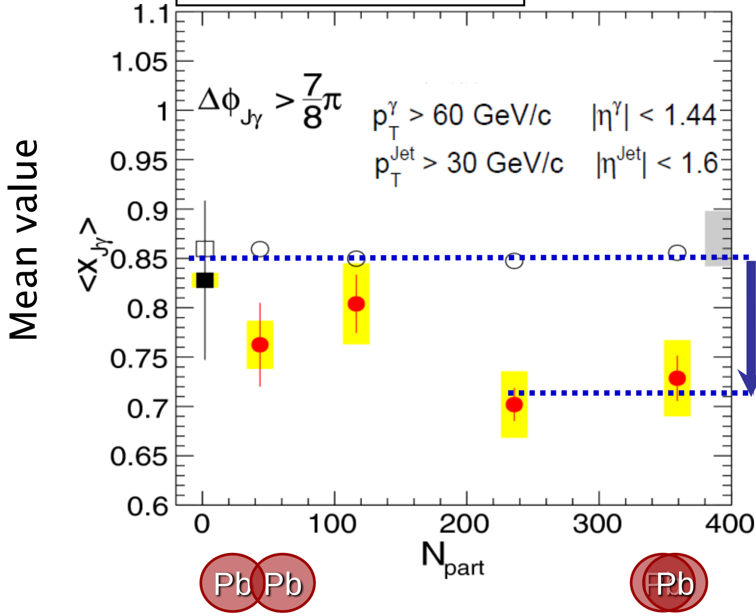
PLB 718 (2013) 773



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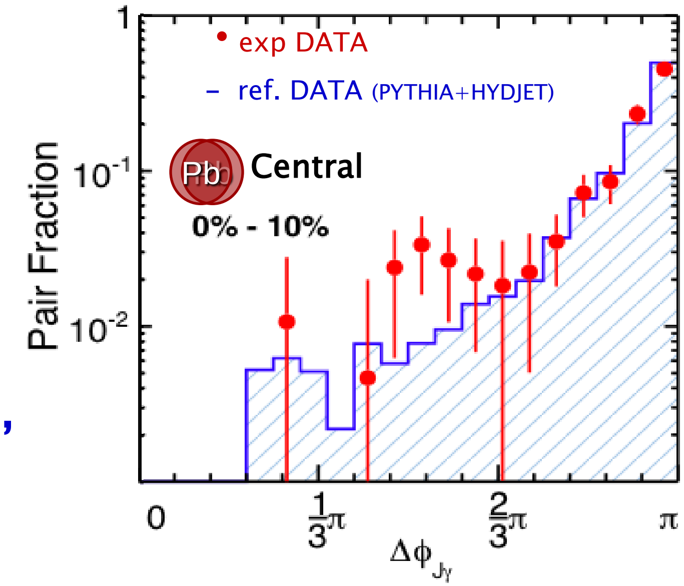
p_T imbalance larger for more central collisions

Azimuthal Correlation:

$$\Delta\phi_{J\gamma} = \left|\phi^{Jet} - \phi^{\gamma}\right|$$

Photon and jet are 'back-to-back' ($\Delta\phi_{J\gamma} \sim \pi$), also for other centralities.



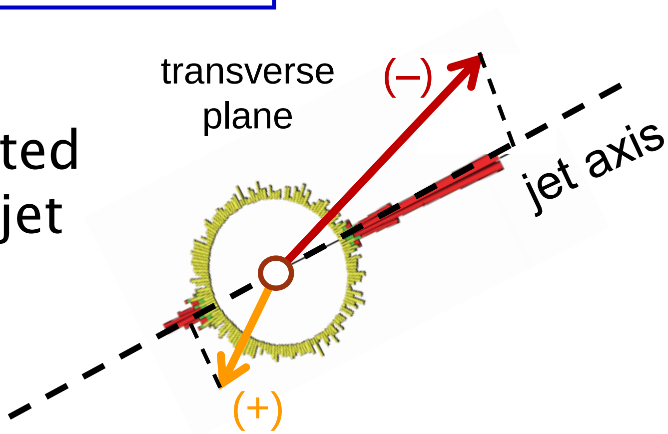
Dijet events in PbPb collisions

Where does the lost energy go?

„missing" $p_T^{||}$:

$$\not{p}_{\mathrm{T}}^{\|} = \sum_{\mathrm{Tracks}} -p_{\mathrm{T}}^{\mathrm{Track}} \cos\left(\phi_{\mathrm{Track}} - \phi_{\mathrm{Leading\ Jet}}\right)$$

Sum the projections of p_T of all reconstructed charged tracks (in the event) onto leading jet axis



Study dependence of mean „missing" $<p_T^{||}>$ on dijet asymmetry A_J

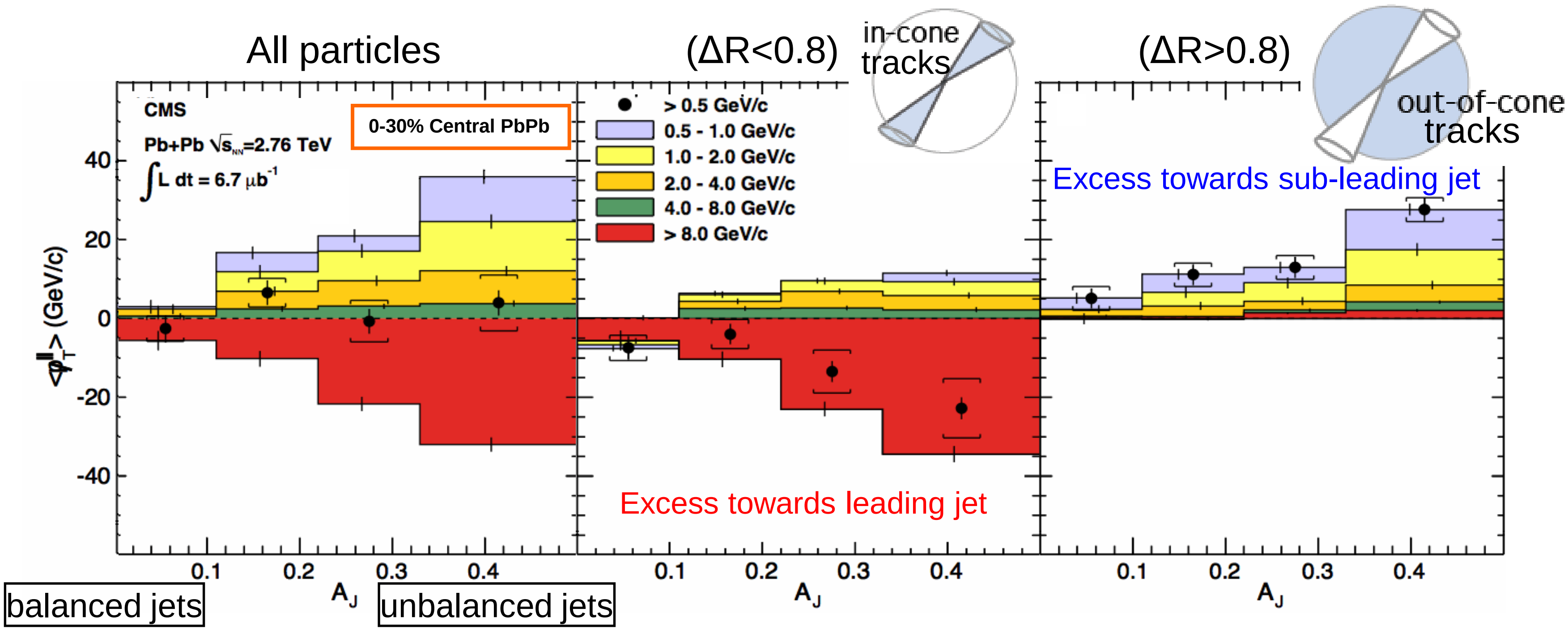
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

$p_{T,1}$ – leading jet
$p_{T,2}$ – subleading jet

"Missing" $p_T^{||}$ vs. A_J

PRC 84 (2011) 024906

Radial dependence of the momentum balance:



Momentum balance restored when summing over all particles in the event, independently of A_J

In-cone excess of high p_T tracks is balanced by out-of-cone low p_T tracks.

Momentum difference in the dijet is balanced by low p_T particles at large angles relative to the jet axis.

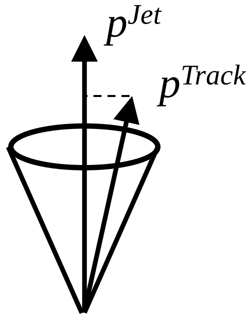
Is jet fragmentation affected?

Measure Fragmentation Functions to check if energy loss mechanisms modify fragmentation of partons.

Jet Fragmentation Function: $\frac{1}{N_{Jet}} \frac{dN_{Track}}{d\xi}$

$$\xi = \ln(1/z) = \ln(\frac{p^{Jet}}{p_{\parallel}^{Track}})$$

z– fraction of parton's momentum carried by hadron



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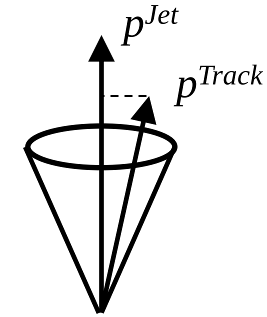
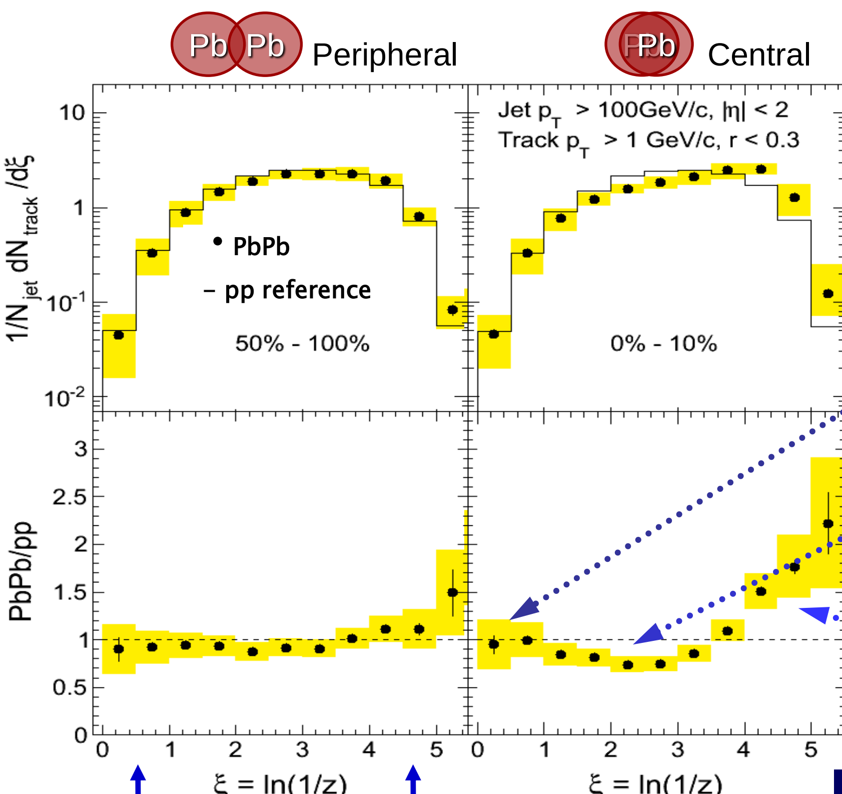


PRC 90 (2014) 024908



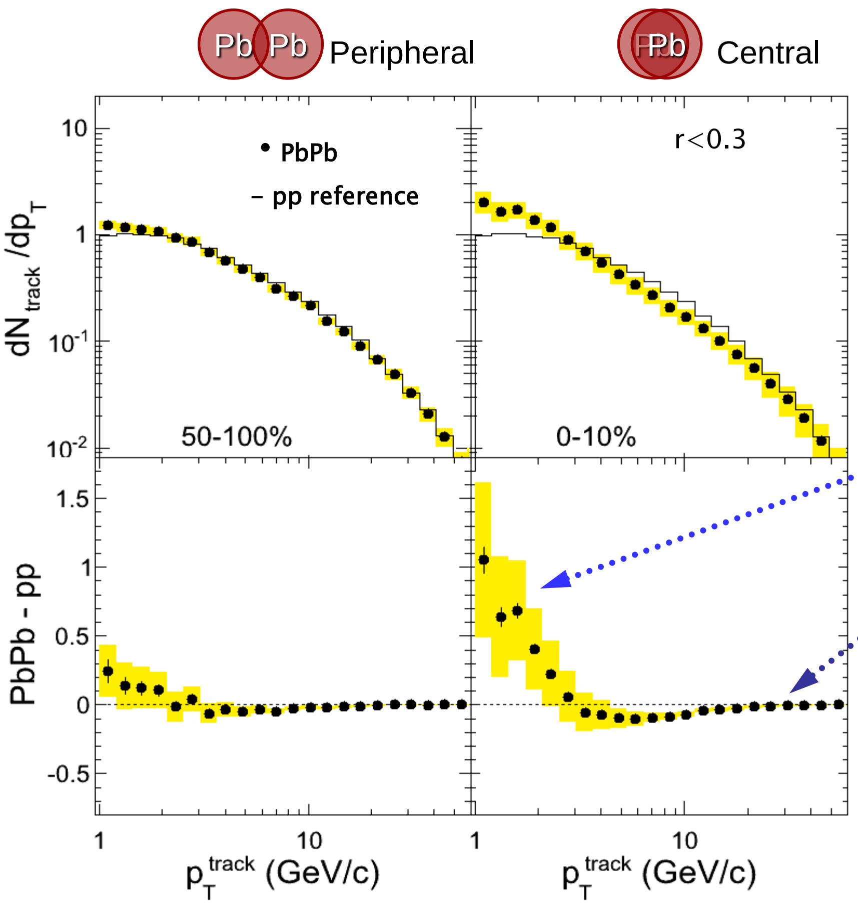
Central PbPb:

- For high p_T particles (in jet cone) fragmentation as in pp
- Suppression of intermediate p_T particles
- Enhancement of low p_T particles

Centrality dependent modification of jet fragmentation functions in PbPb collisions

Is jet fragmentation affected?

Track p_T distributions in jets:



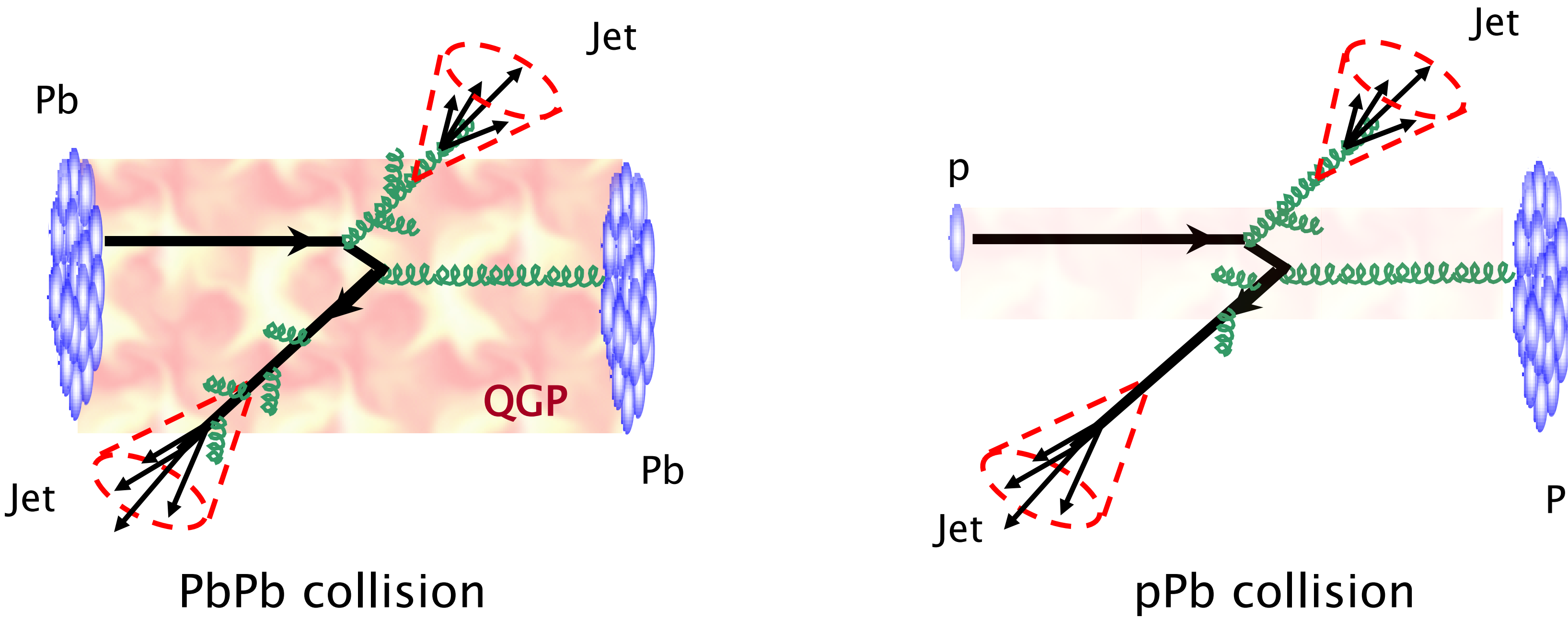
PRC 90 (2014) 024908

Central PbPb:

Low p_T: excess of charged particles (quenched jets)

High p_T: no change compared to track distribution in pp jets

Dijet events in HI collisions



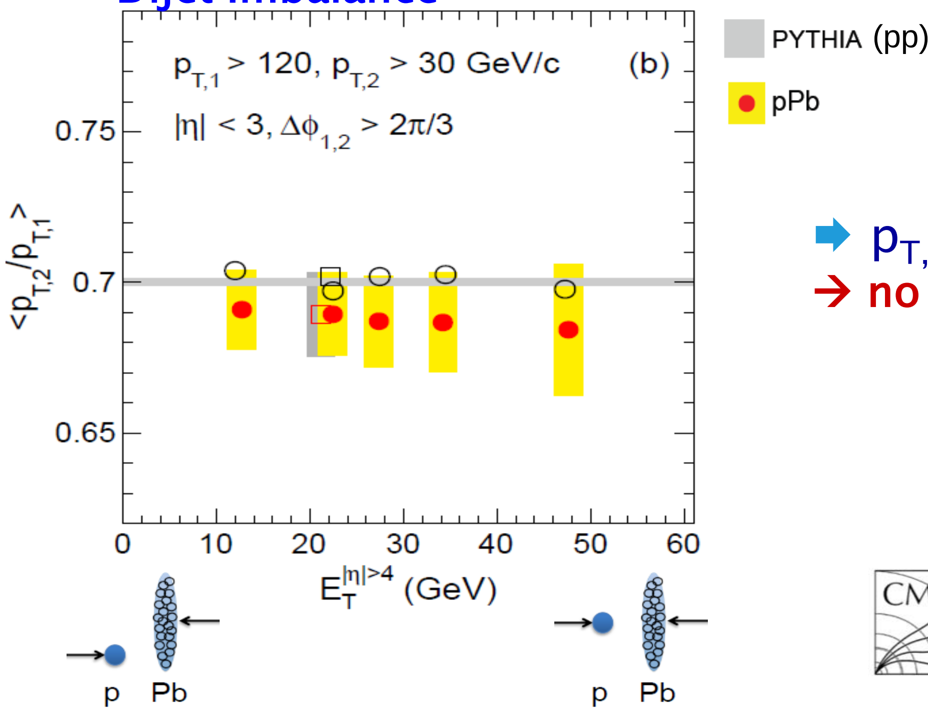
- **Strong jet quenching in central PbPb collisions**
- **Observed as a pronounced dijet p_T imbalance**
  (measurement of dijet asymmetry A_J)
- **No azimuthal decorrelation of jets**
  (jets are “back-to-back”)

Is there jet quenching in pPb collisions?

Is there jet quenching in pPb for dijets?

EPJC 74 (2014) 2951

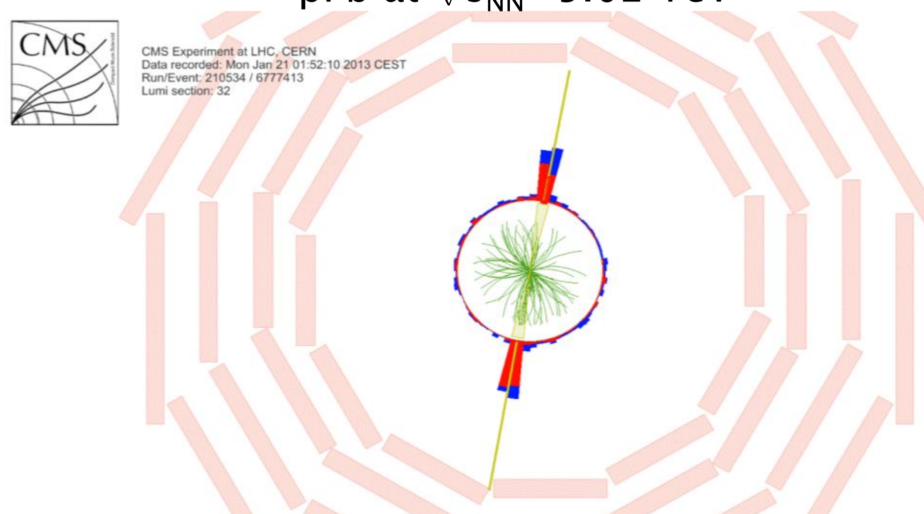
Dijet Imbalance



Centrality characterized by E_T at large $|\eta|$

- $p_{T,2}/p_{T,1}$ for pPb dijets the same as in pp
- → no jet quenching observed

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



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EPJC 74 (2014) 2951

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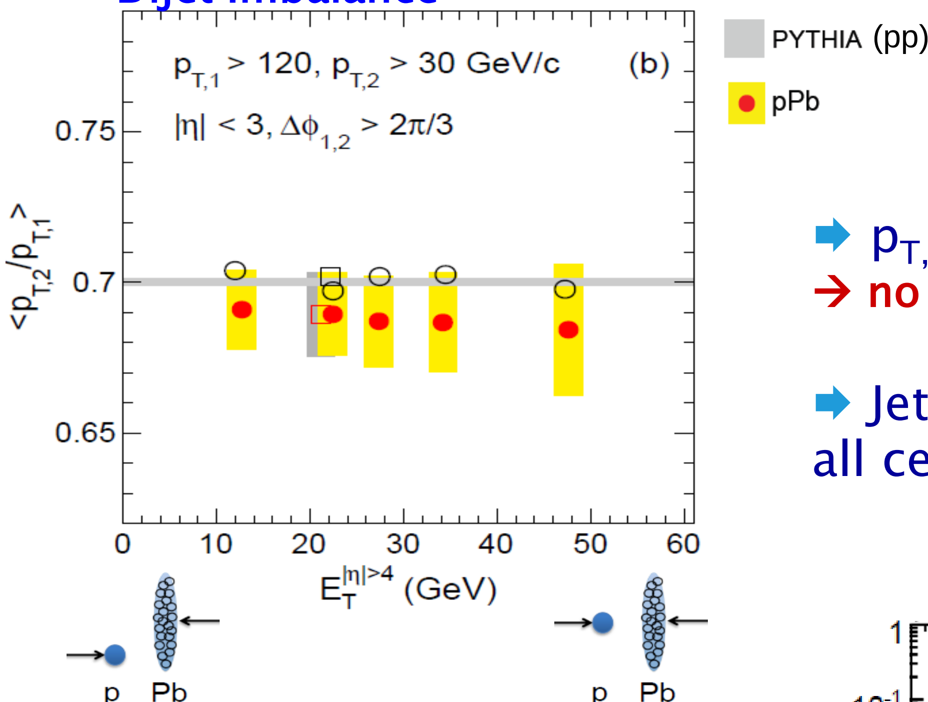
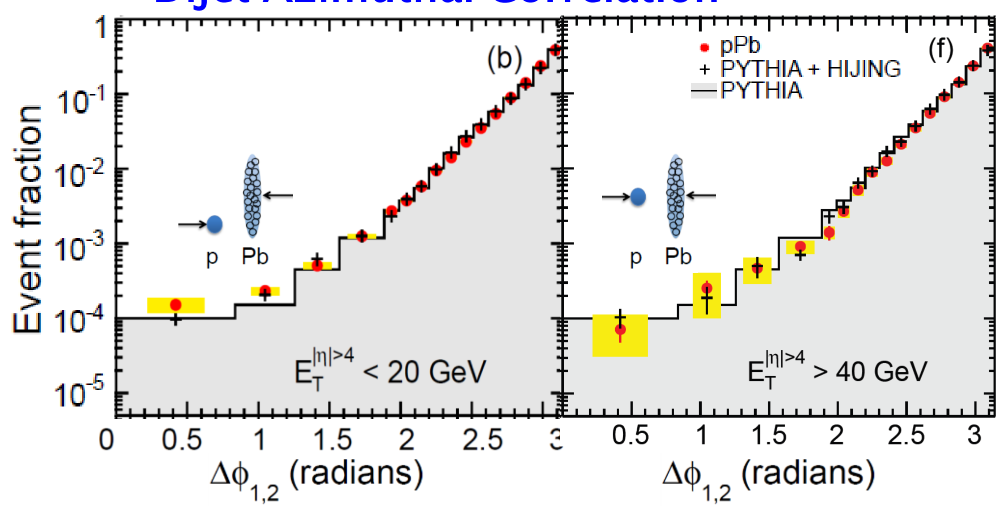


Centrality characterized by E_T at large $|\eta|$

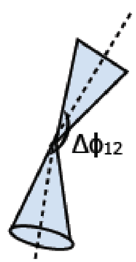
- $p_{T,2}/p_{T,1}$ for pPb dijets the same as in pp
→ **no jet quenching observed**

- Jets remain back-to-back ($\Delta\phi$~π) for all centralities

Dijet Azimuthal Correlation



$$\Delta\phi_{1,2} = |\phi_{jet1} - \phi_{jet2}|$$



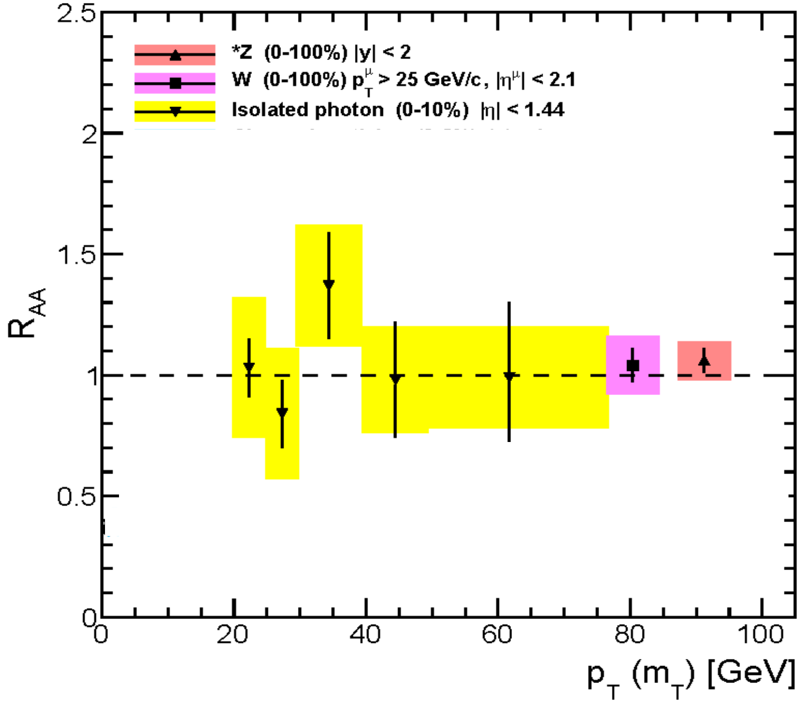
Nuclear modification factor

Study of jet quenching by looking at magnitude of particle yield suppression.

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{d^2 N_{AA} / dp_T d\eta}{d^2 N_{pp} / dp_T d\eta}$$

- $R_{AA} > 1$ enhancement
- $R_{AA} = 1$ no medium effects
- $R_{AA} < 1$ suppression

PbPb 2.76 TeV



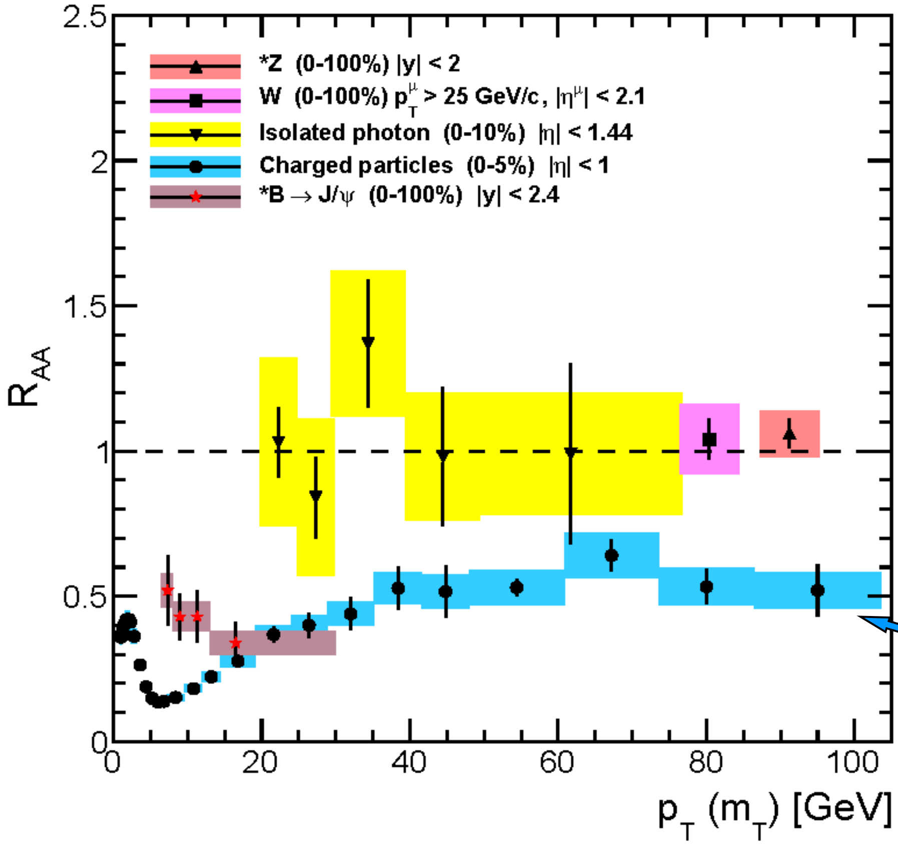
Prompt γ	PLB 710 (2012) 256
$W \to \mu\nu$	PLB 715 (2012) 66
$Z^0 \to \mu^+\mu^-$	PAS-HIN-13-004

Colorless probes (control probes) are not modified by the medium

Production scales with N_{coll}, $R_{AA} \approx 1$

Nuclear modification factor

PbPb 2.76 TeV



EPJC 72 (2012) 1945

JHEP 05 (2012) 063

charged hadrons & b-quarks

are suppressed, $R_{AA}<1$

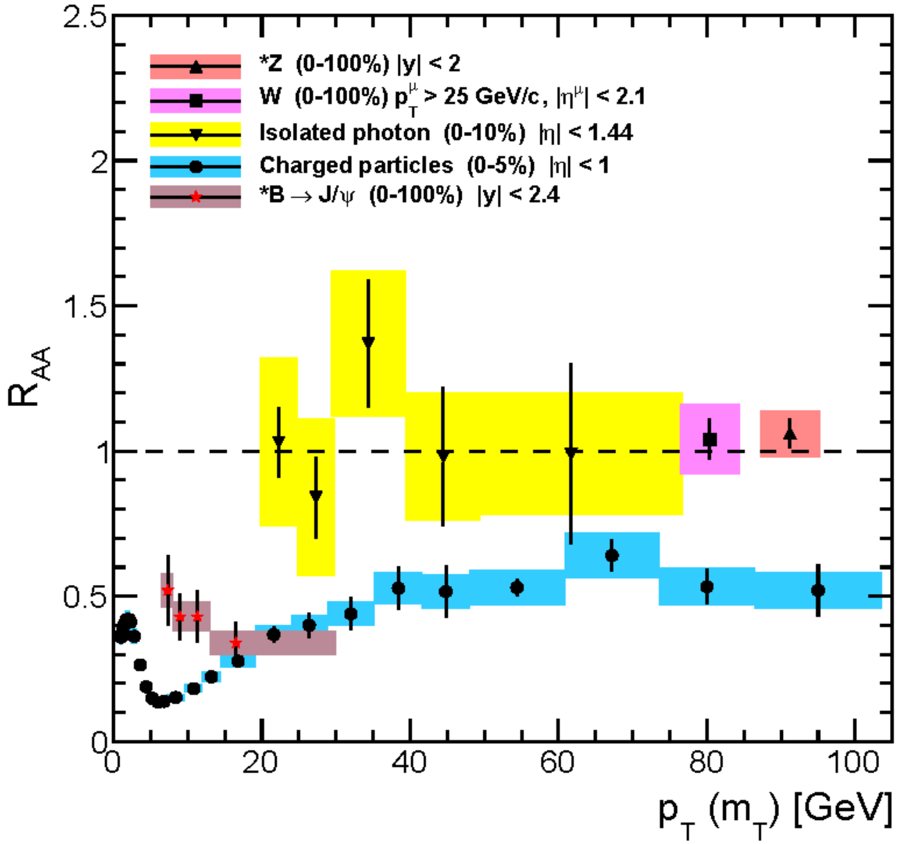
high p_T reach

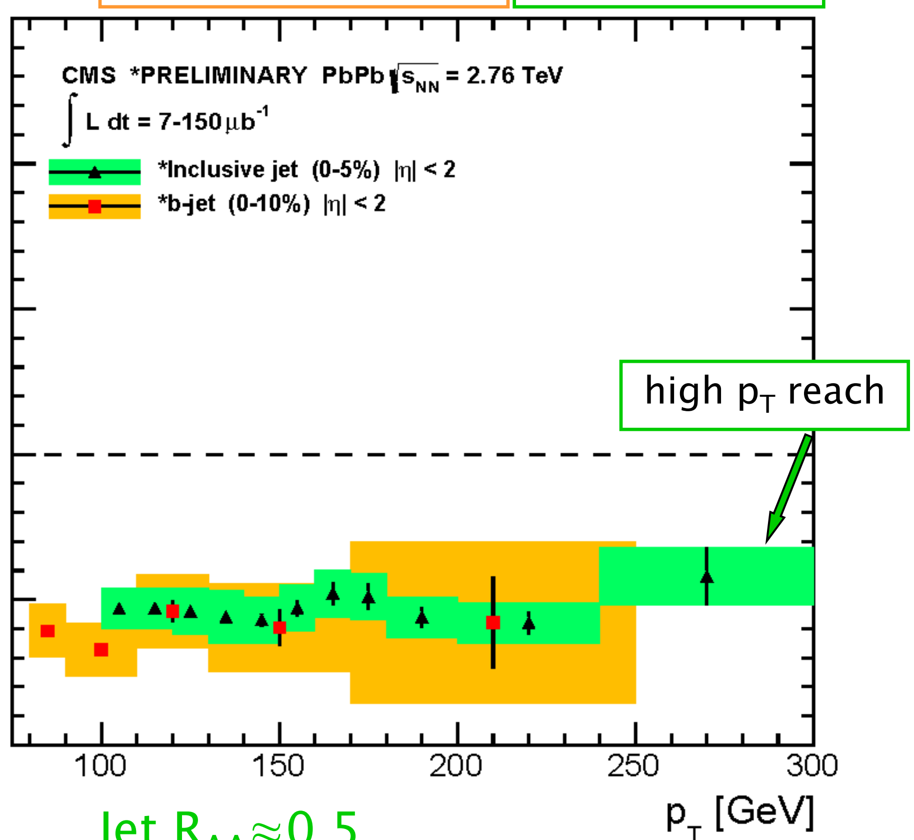
- Colorless probes are unsuppressed
- Hadrons are modified (jet quenching)
- Less b-hadron suppression at low p_T

Nuclear modification factor

PbPb 2.76 TeV

PRL 113 (2014) 132301 | PAS-HIN-12-004





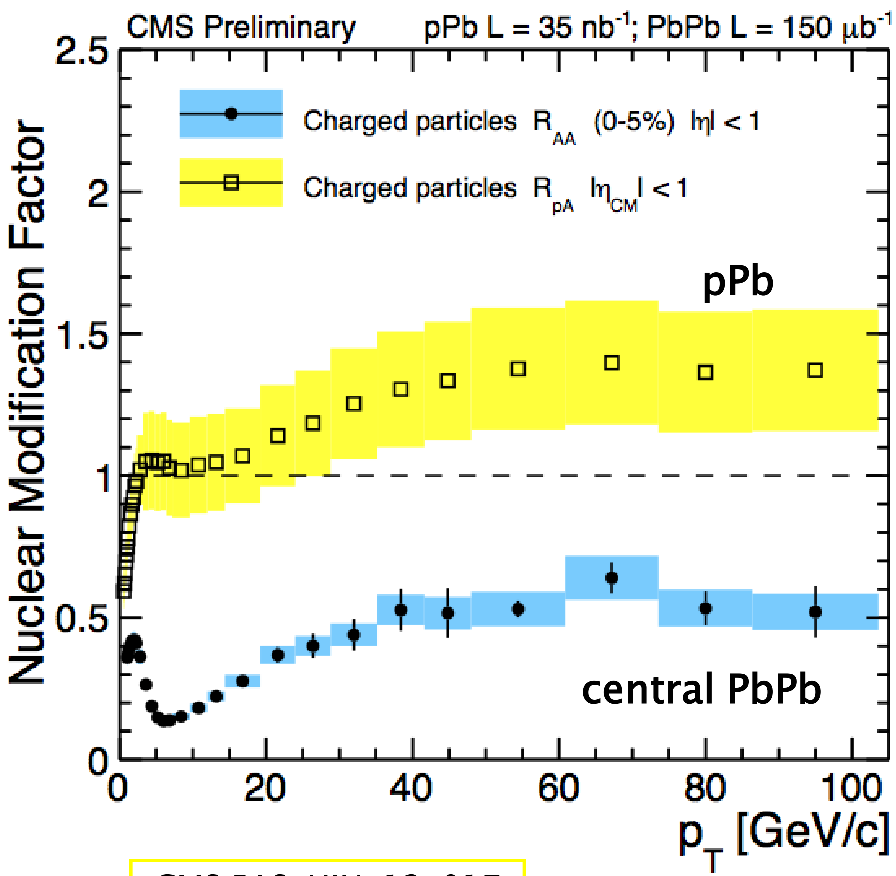
Jet $R_{AA} \approx 0.5$

First measurement of b-jet R_{AA} !!

- Colorless probes are unsuppressed
- Hadrons and jets are modified (jet quenching)
- Less b-hadron suppression at low p_T; b-jets are similar to q/g jets

Nuclear modification factor: PbPb vs. pPb

Charged particles



CMS PAS-HIN-12-017

EPJC 72 (2012) 1945

At high p_T:

Enhancement in pPb collisions, $R_{pA}>1$

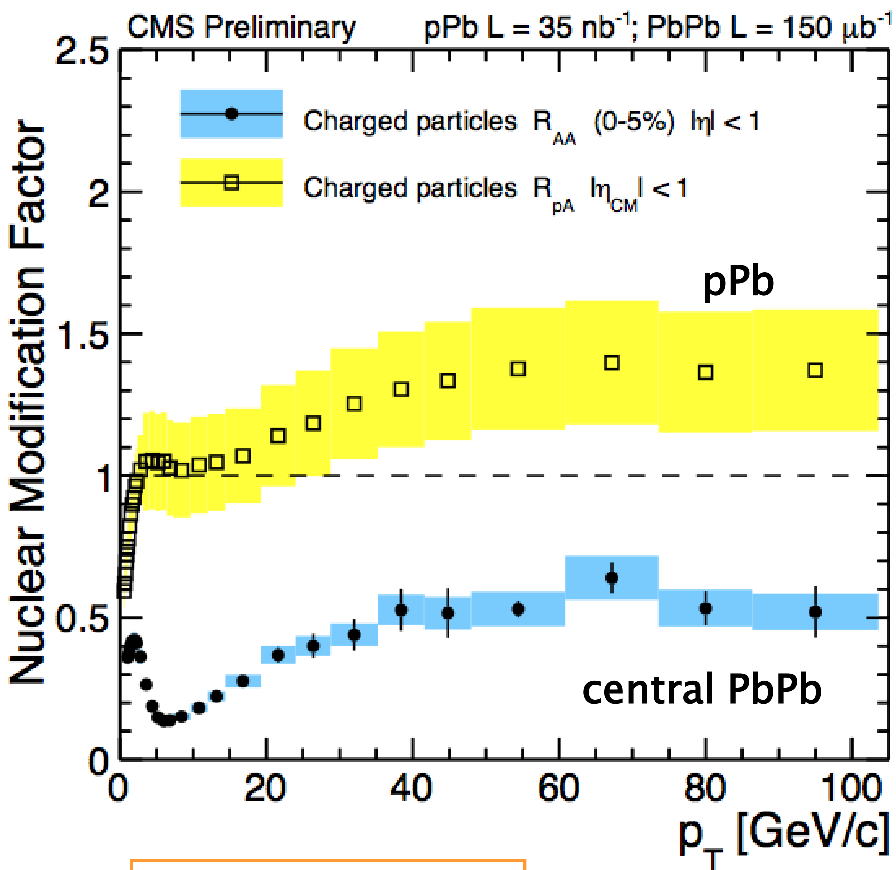
Suppression in PbPb collisions, $R_{AA}<1$

Similar trend in R_{pA} and R_{AA} as a function of p_T

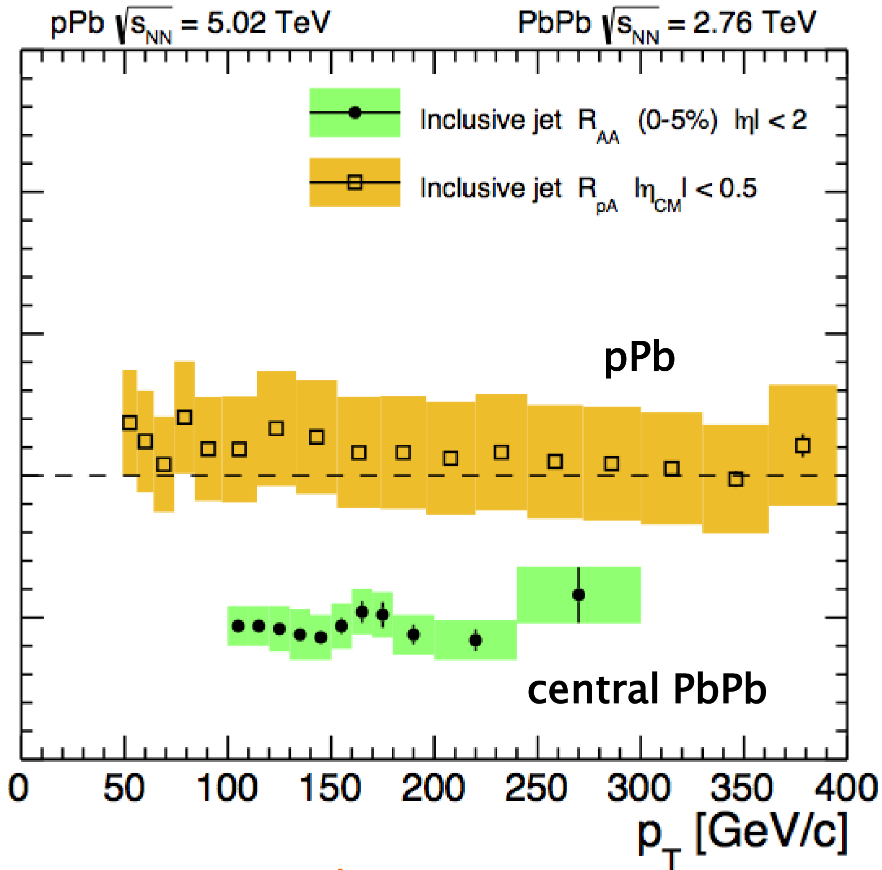
Need pp reference data at 5.02 TeV to reduce systematics

Nuclear modification factor: PbPb vs. pPb

Charged particles



Jets



CMS PAS-HIN-14-001

CMS PAS-HIN-12-004

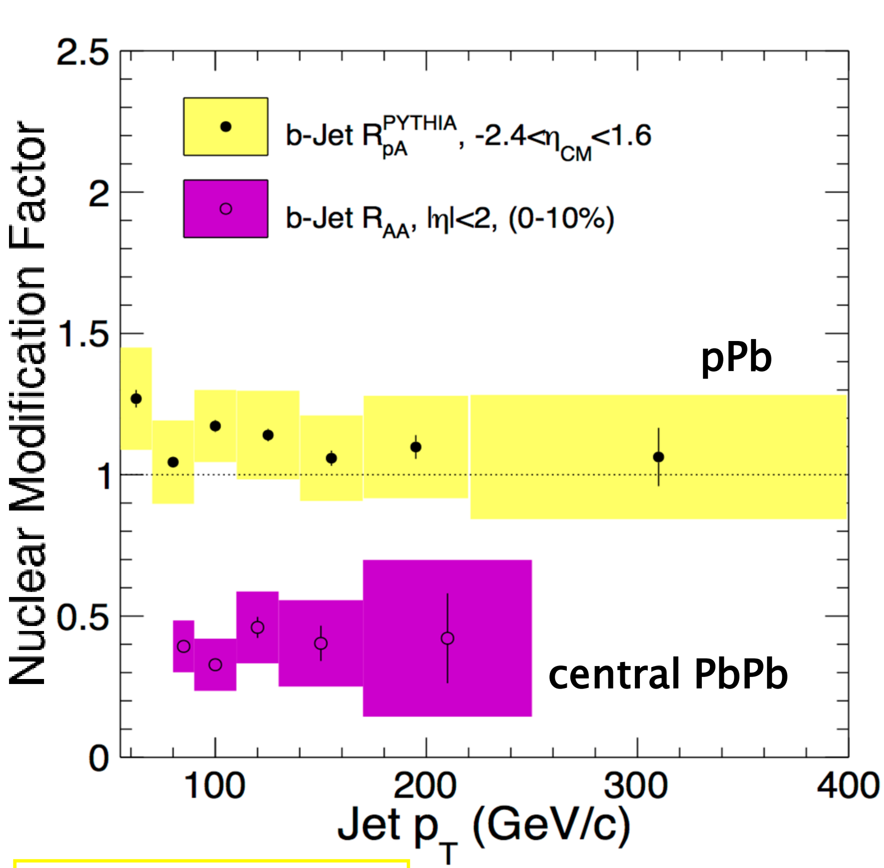
For pPb $R_{pA} \approx 1$

For PbPb $R_{AA} < 1$

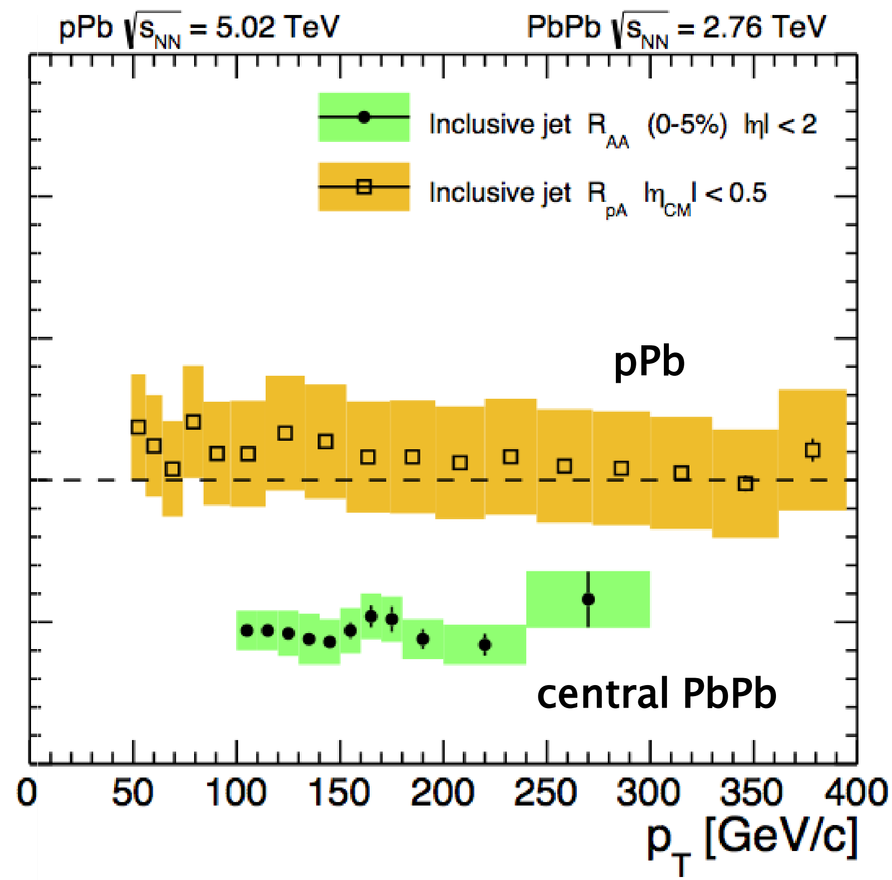
Jet suppression observed in PbPb collisions is the final state effect (QGP)

Nuclear modification factor: PbPb vs. pPb

b-Jets



Inclusive Jets



CMS PAS-HIN-14-007

PRL 113 (2014) 132301

For central PbPb: b-jets show similar suppression to inclusive jets, $R_{AA}\approx 0.5$

For pPb: inclusive and b-jets are not suppressed, $R_{pA}\approx 1$

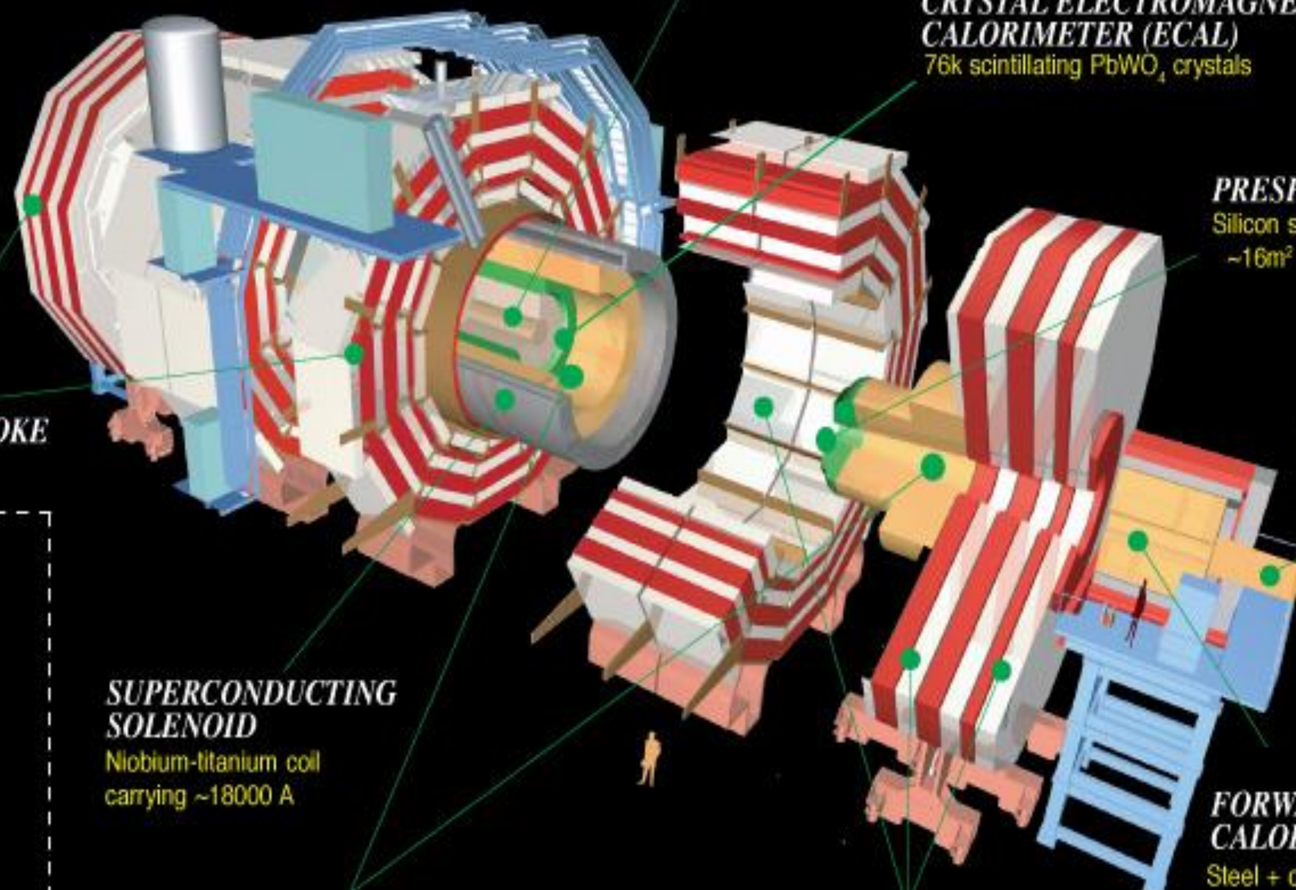
No jet flavor dependence is observed

Summary

- Medium created in PbPb collisions:
  - Does not quench control probes (γ, W, Z)
  - Strongly quenches partons, including b-quarks
  - Causes dijet and photon-jet p_T imbalance, but does not modify their angular correlation
  - Modifies fragmentation functions of jets (enhancement at low p_T)
- Energy lost in the medium redistributed into low p_T particles at large angles (far away from the jet cone)
- Hint of parton flavor dependence of the energy loss at low p_T, disappearance at high p_T
- No jet quenching for pPb collisions → the effect observed for PbPb is a final state effect

Backup

CMS Detector

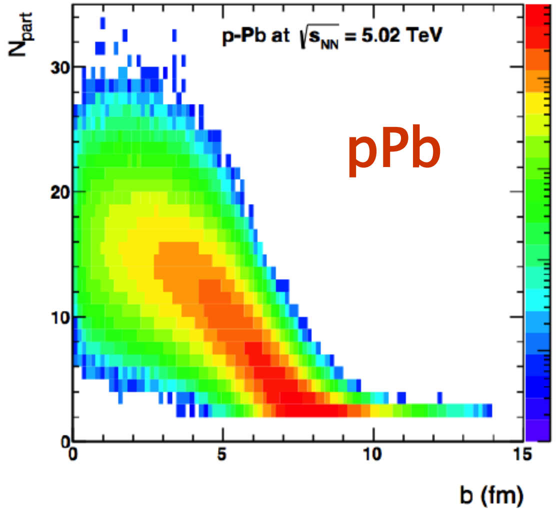


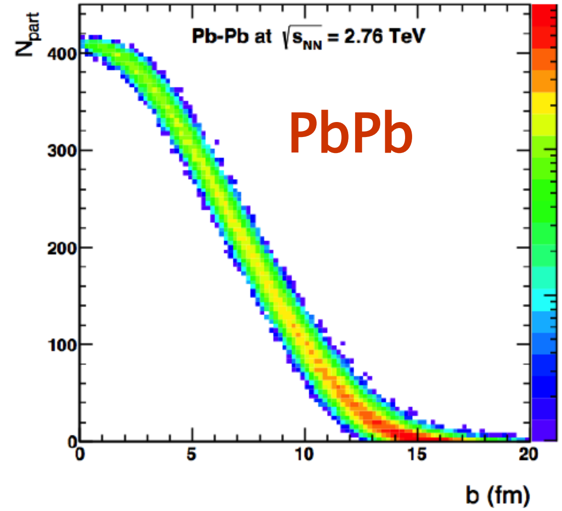
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Collision centrality

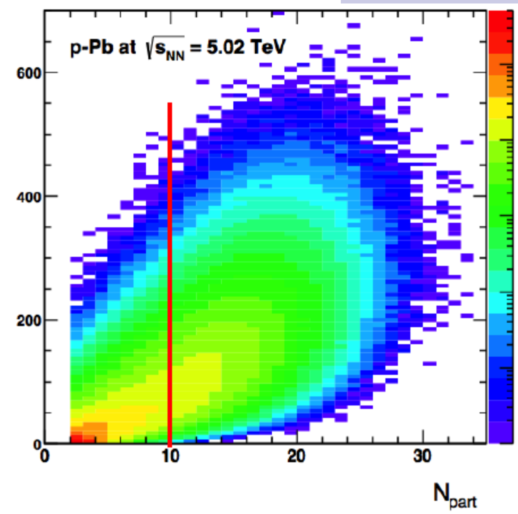
- Weak correlation observed for pPb collisions
- Given N_{part} (N_{coll}) value can belong to different multiplicity classes
- Large multiplicity fluctuations observed for pPb collisions introduce ‘bias’

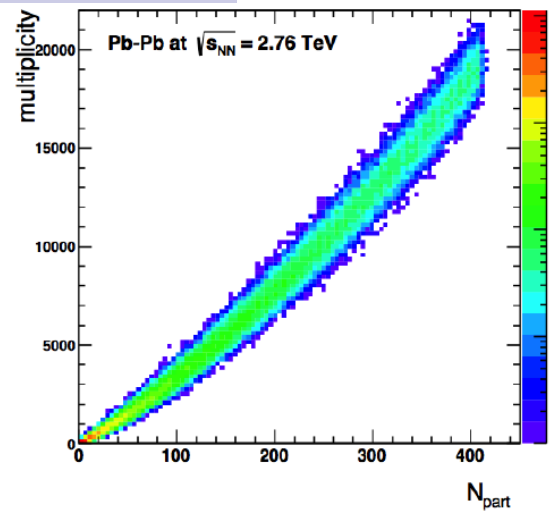
N_{part} vs. b





multiplicity vs. N_{part}

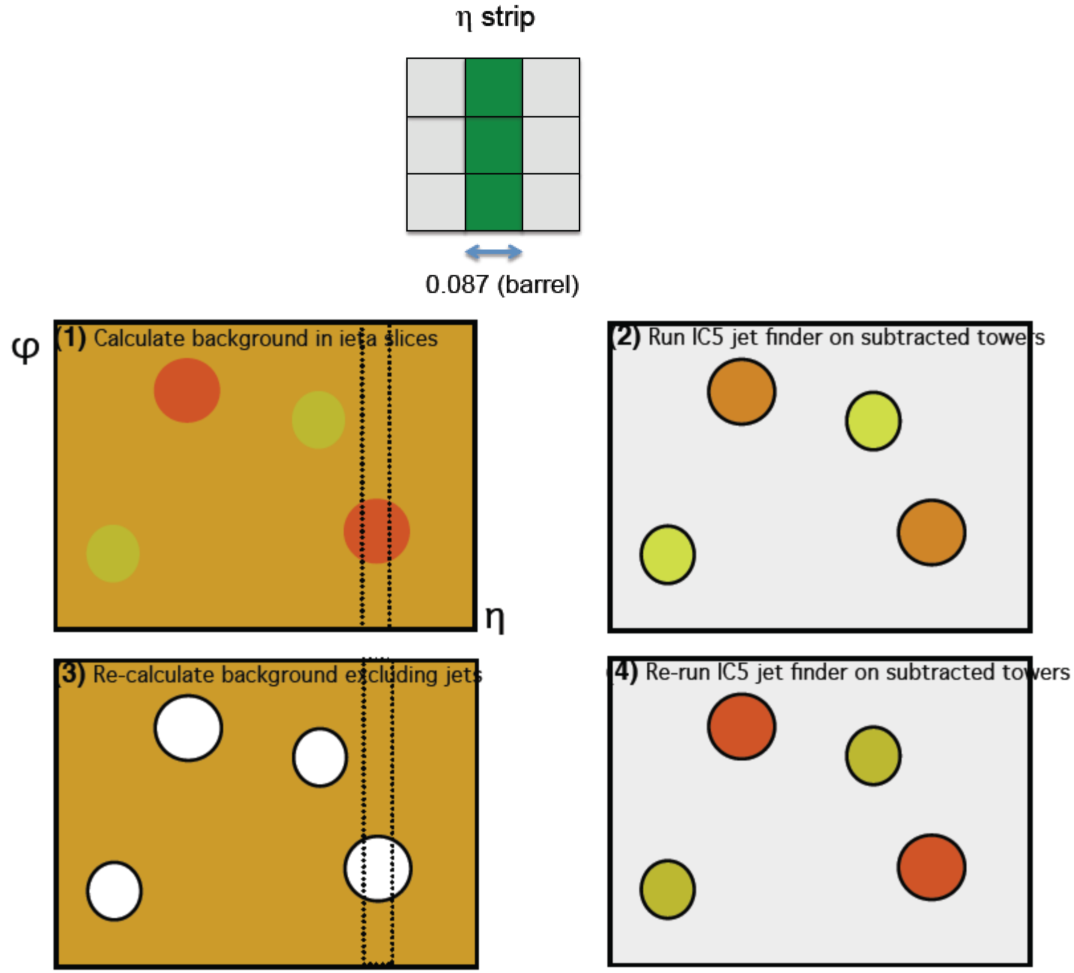




Background subtraction method

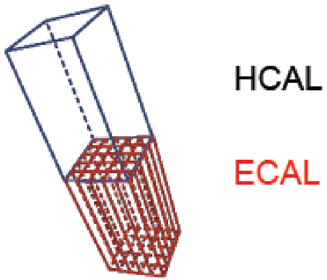
O. Kodolova et al., Eur. Phys. J. C50 (2007) 117

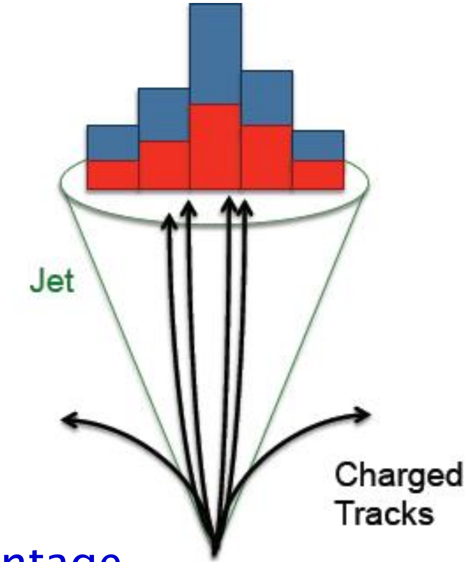
1) Background energy per tower calculated in strips of η. Pedestal subtraction.
2) Jet finding algorithm run on background subtracted towers.
3) Exclude reconstructed jets. Recalculate the background energy.
4) Jet algorithm rerun on background subtracted towers to obtain final jets



Calorimetric Jets

- ECAL and HCAL used
- „Traditional" jet reconstruction
- Calorimeter Towers
  - 1 HCAL cell ~0.1 ($\Delta\phi$ x $\Delta\eta$)
  - 25 ECAL crystals ~0.01 ($\Delta\phi$ x $\Delta\eta$)
- Does not make use of ECAL granularity
- Jet resolution driven by HCAL
  ~100%/$\sqrt{E(\mathrm{GeV})}$
- Low p_T charged hadrons bent outside jet



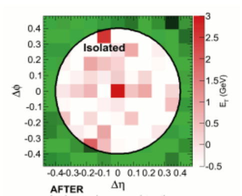


Calorimetric jet reconstruction does not take full advantage of the versatility of CMS

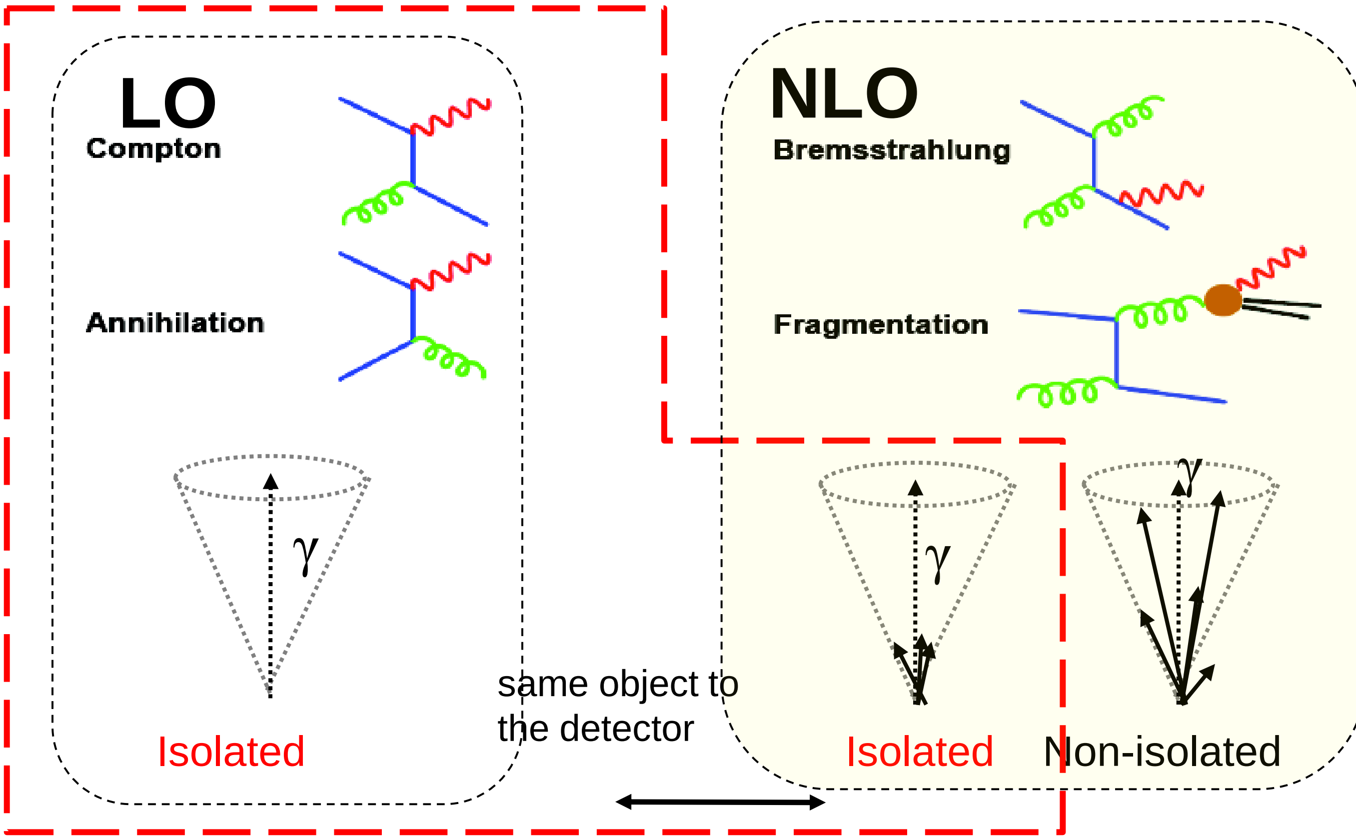
Isolated high-p_T photons

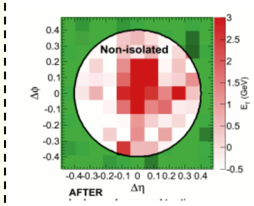
Decay photons from hadrons in jets such as π^0, $\eta \to \gamma\gamma$ are largely suppressed

UE subtracted isolation variables are developed



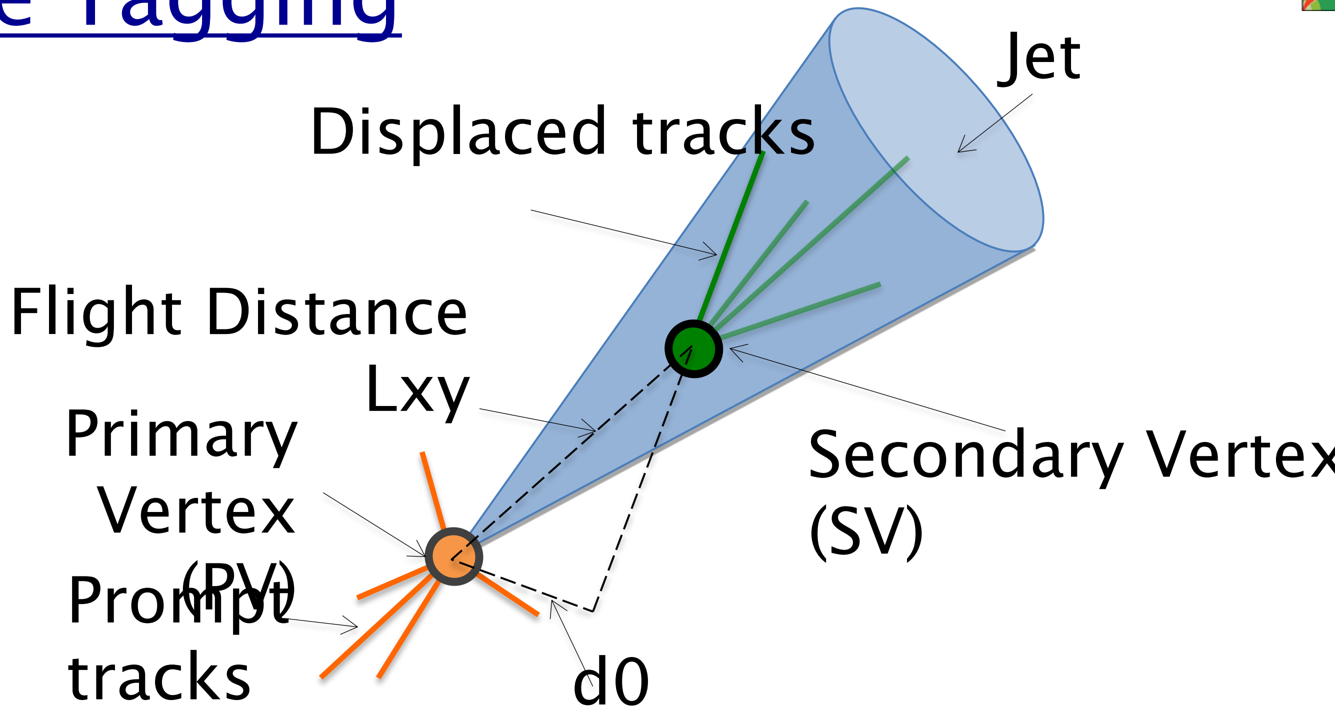
Isolated





Non-isolated

Lifetime Tagging



- Long B-hadron lifetime (~1.5 ps) → decays mm – cm from PV
- *Lifetime tagging* based on
  - Reconstructed secondary vertices (SV)
  - Impact parameter (IP) of displaced tracks
- Jet measurement is identical to inclusive jets

Collision energy (in the N-N centre of mass system)

$$\sqrt{s_{NN}} = 2\cdot\sqrt{E_{Beam1}\cdot E_{Beam2}}$$

For E_p=7 TeV:

PbPb collisions

Pb-beam energy: $E_{Pb} = \frac{Z}{A}E_p = \frac{82}{208}\cdot 3.5\,[TeV] = 1.38\,[TeV/nucleon]$

$$\sqrt{s_{NN}} = 2\cdot\sqrt{(1.38)\cdot(1.38)} = 2\cdot 1.38\,[TeV] = 2.76\,[TeV]$$

5.52 TeV

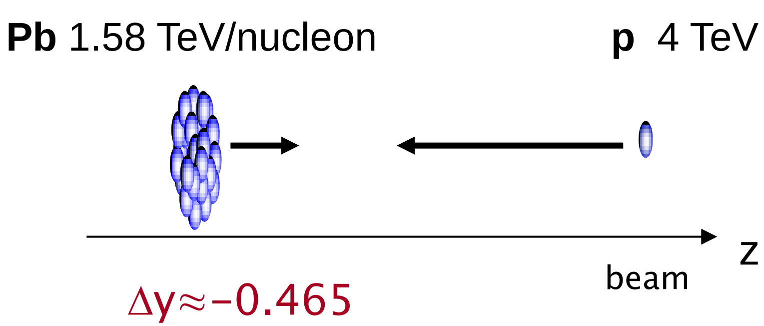
pPb collisions

p-beam energy: $E_p = 4\,[TeV]$

Pb-beam energy: $E_{Pb} = \frac{Z}{A}E_p = \frac{82}{208}\cdot 4\,[TeV] = 1.58\,[TeV/nucleon]$

$$\sqrt{s_{NN}} = 2\cdot\sqrt{(4)\cdot(1.58)} = 5.02\,[TeV]$$

8.8 TeV



LAB system is different than **CM** system → rapidity shift:

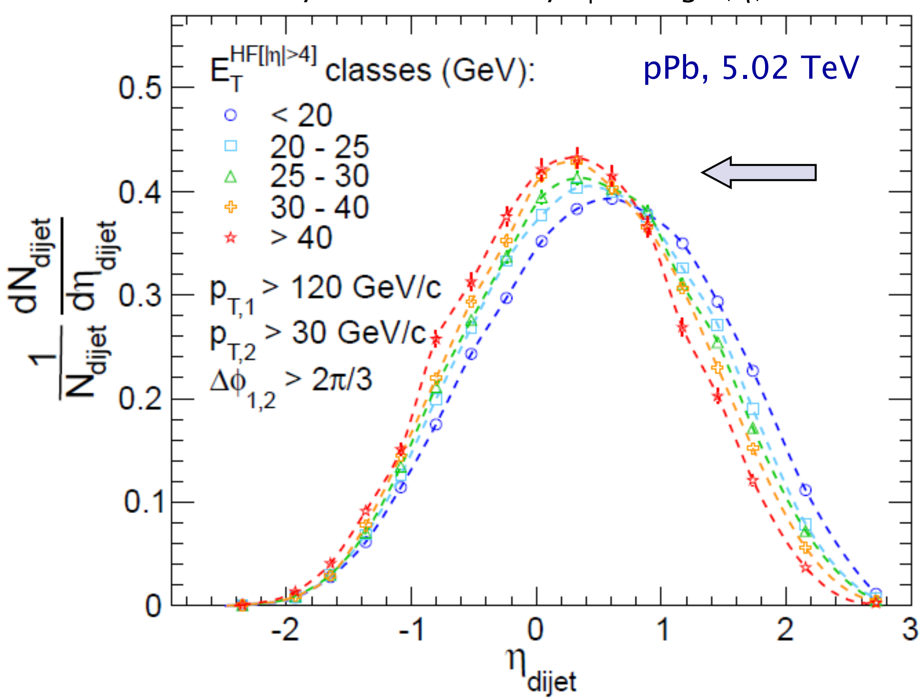
$$\Delta y \approx \frac{1}{2}\ln\left(\frac{Z_1 A_2}{Z_2 A_1}\right) = \frac{1}{2}\ln\left(\frac{82\cdot 1}{1\cdot 208}\right) = -0.465$$

Dijet η distribution

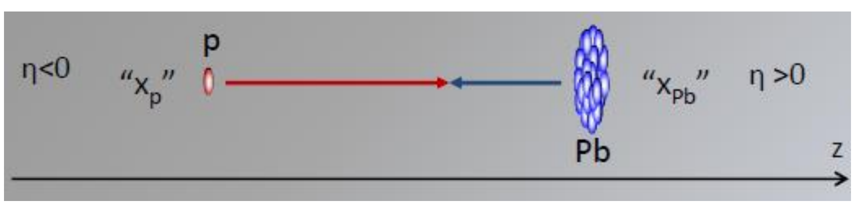
For different centrality classes:

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

Centrality characterized by E_T at large $|\eta|$



EPJC 74 (2014) 2951



Backward direction

Forward direction

For more central collisions:

- η_{dijet} distribution shifts towards Pb-going side (negative values)
- shape of η_{dijet} distribution also changes – it gets narrower