Hard Probes in CMS

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for the CMS Collaboration

VANDERBILT
UNIVERSITY

Moriond QCD and High Energy Interactions
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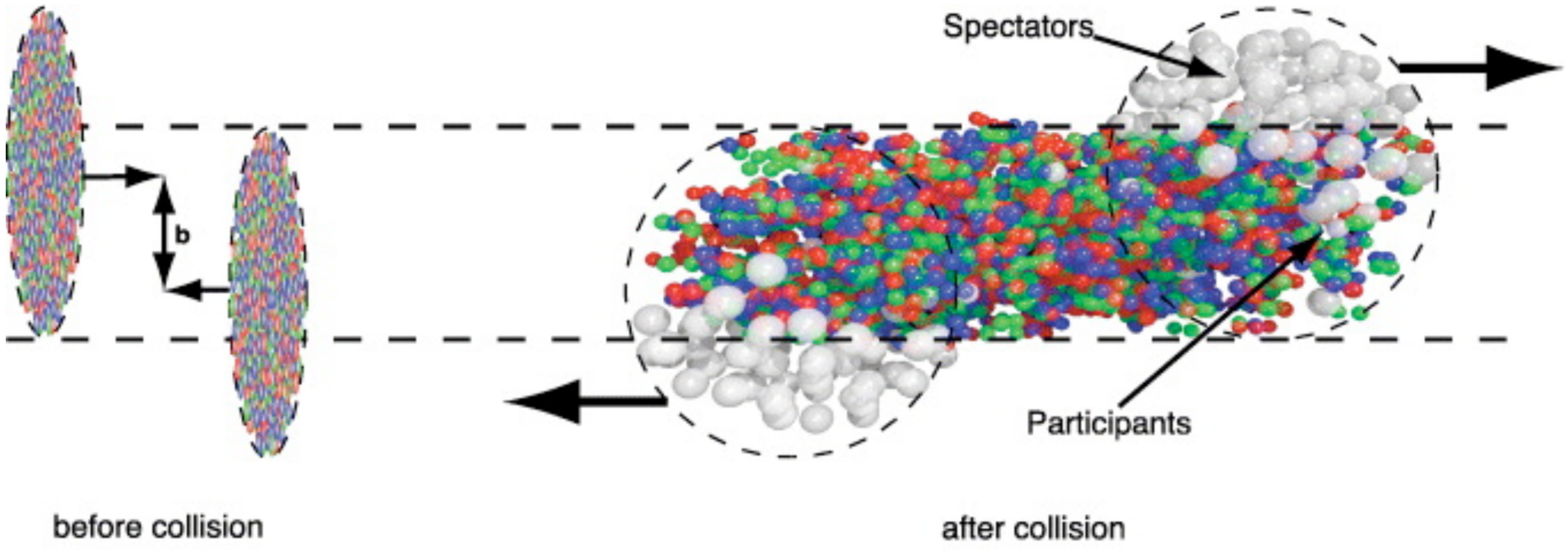
Objectives

Study the transport properties of the QGP

a color charge (g, q, Q) in a colored medium



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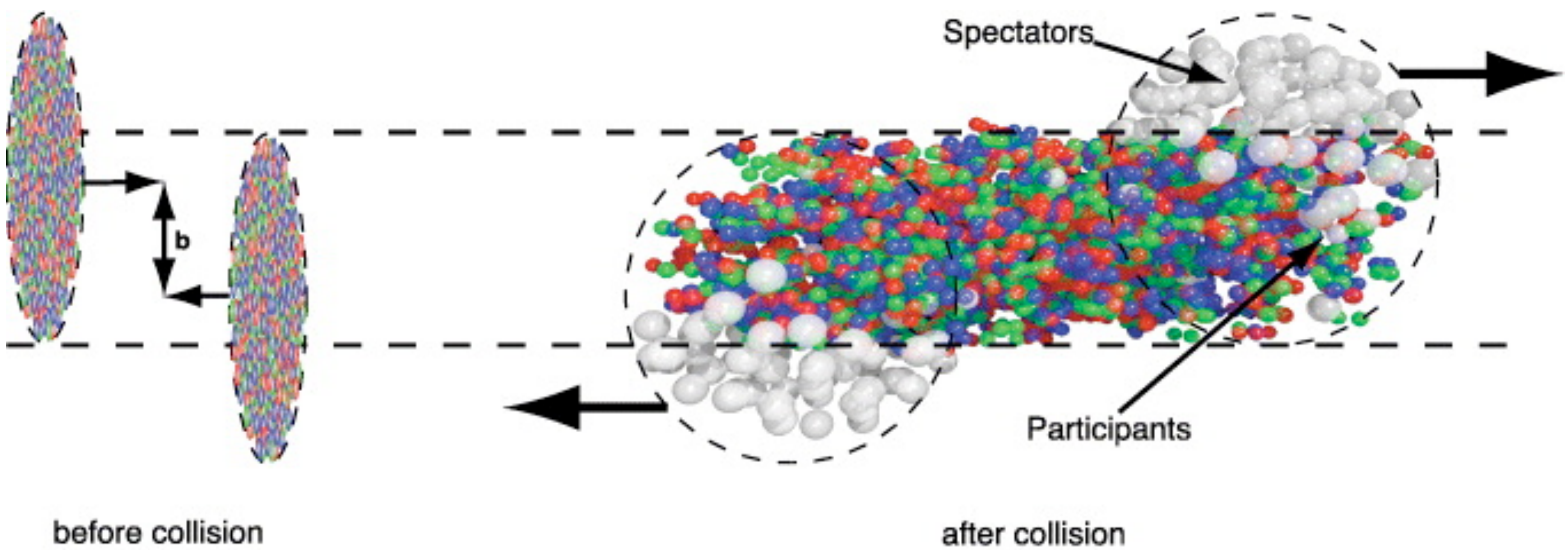
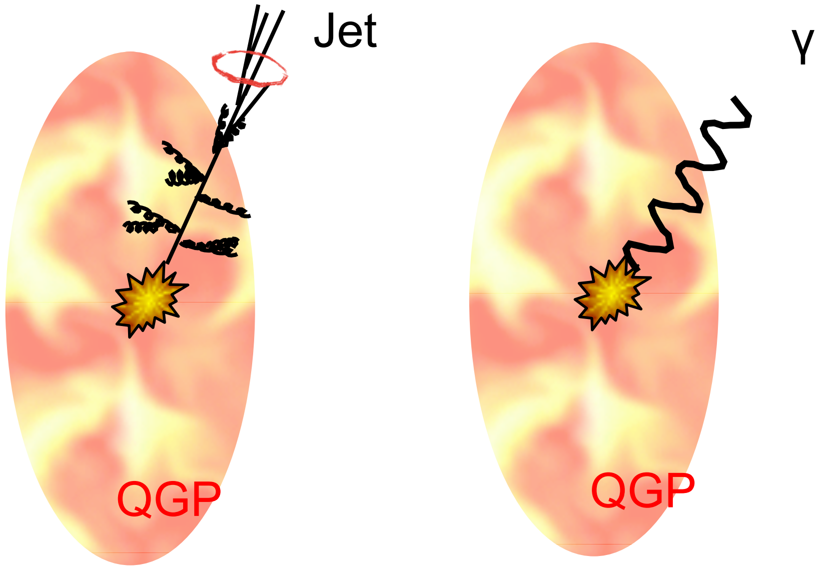
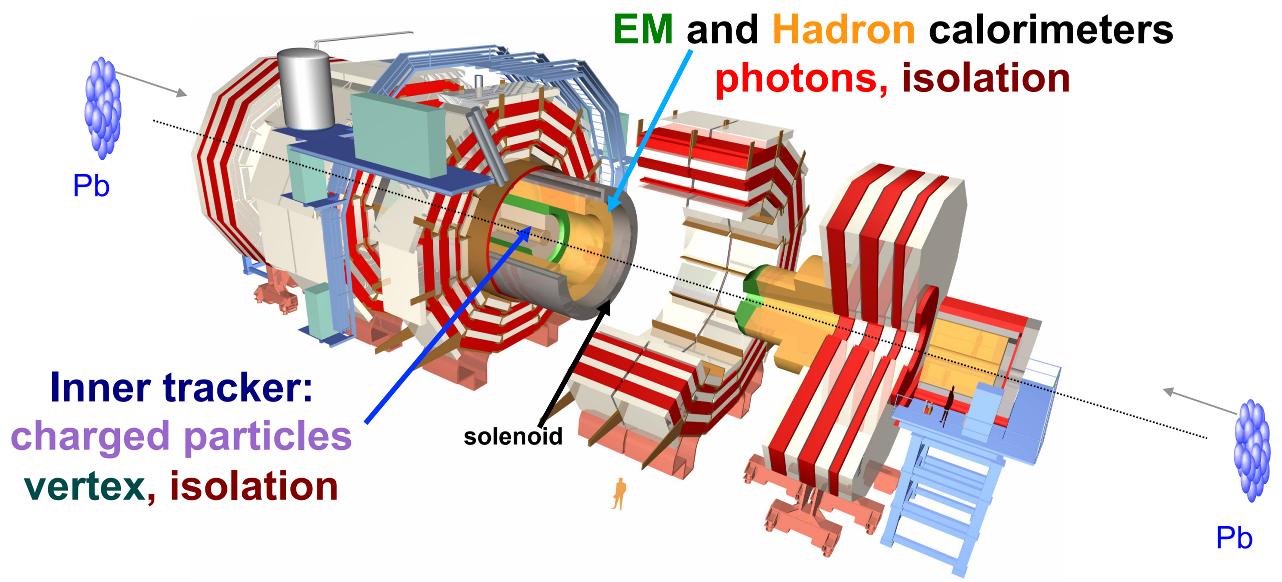


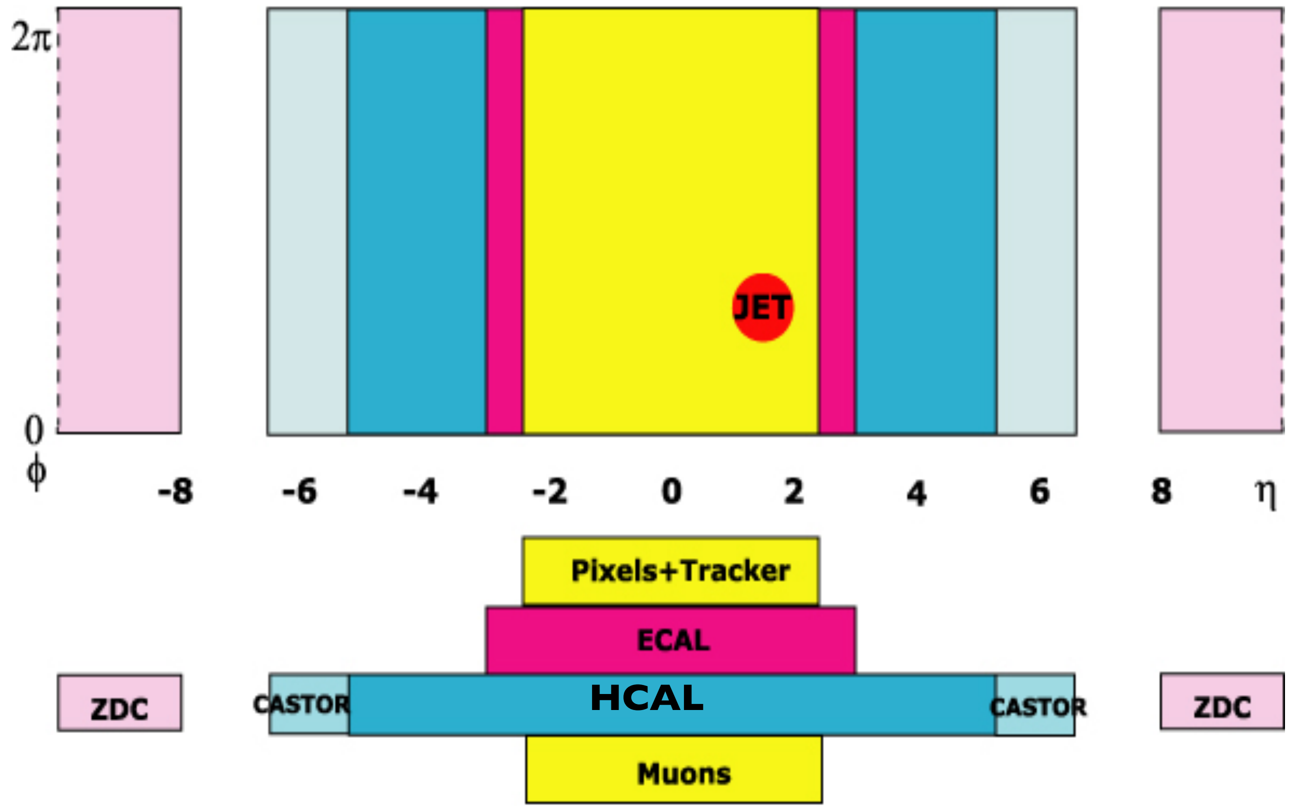
Observables:

- high p_T hadrons R_{AA}
- inclusive jet (udsg and cb) R_{AA}
- di-jet and γ-jet momentum imbalance
- jet fragmentation and structure
- high p_T charged particle v_2



CMS detector: optimized for heavy ion physics

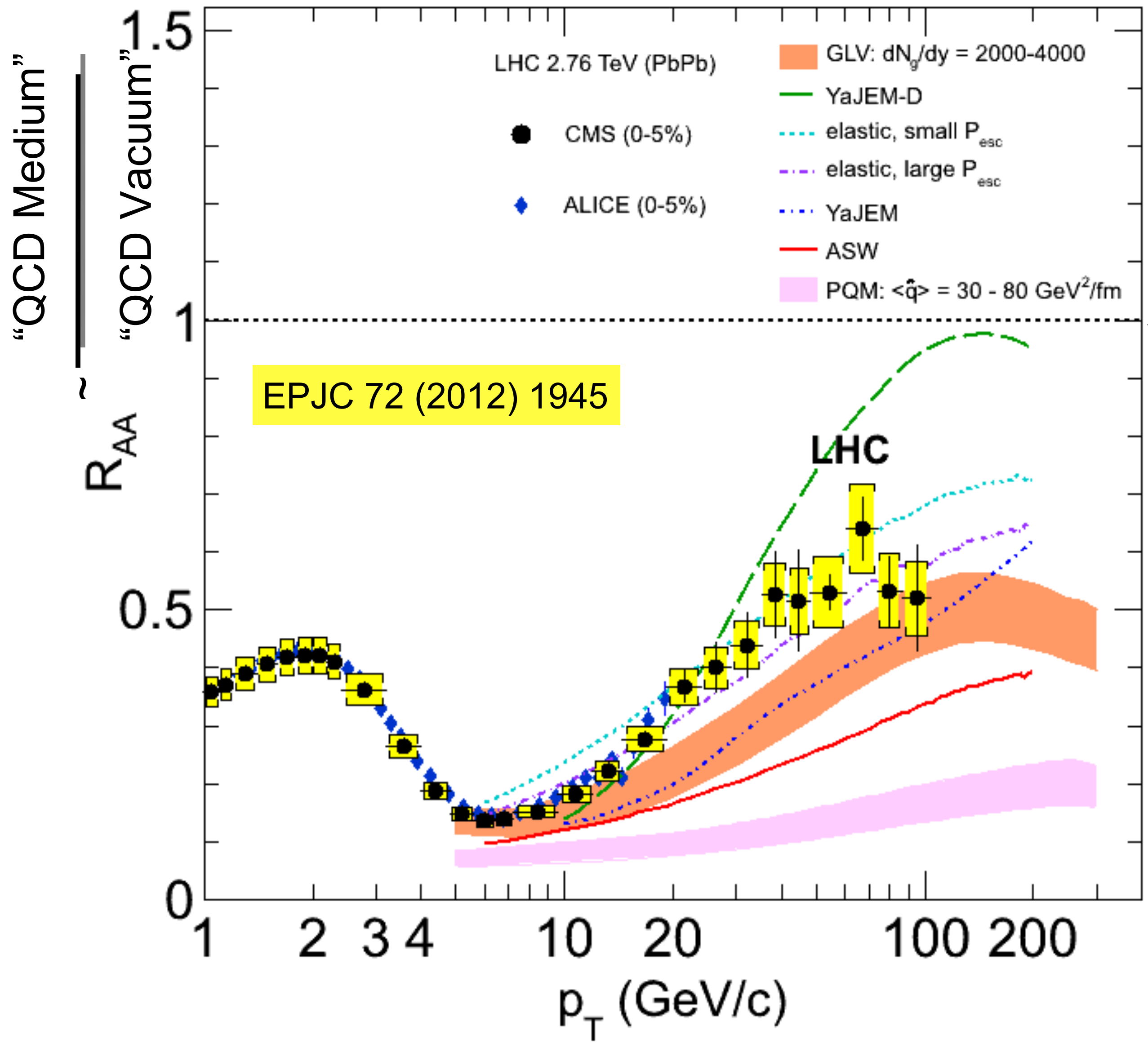




- Large acceptance and excellent resolution for high p_T probes
  - Jet finder coverage up to | η |<5 and photons coverage up to | η |<3
  - Good efficiency and low fake rate for track p_T>1 GeV/c
  - Low occupancy of pixel detectors – 1-2% with PbPb central events
  - High level trigger capable of full reconstruction of most of HI events

Jet quenching: suppression of high p_T particles

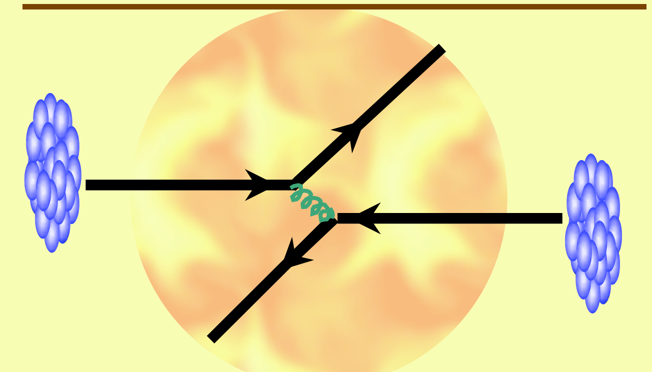
B. Hippolyte's talk, Fri, morning



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

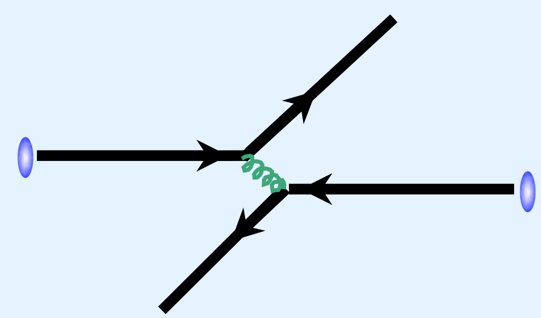
If PbPb = superposition of pp

PbPb measurements



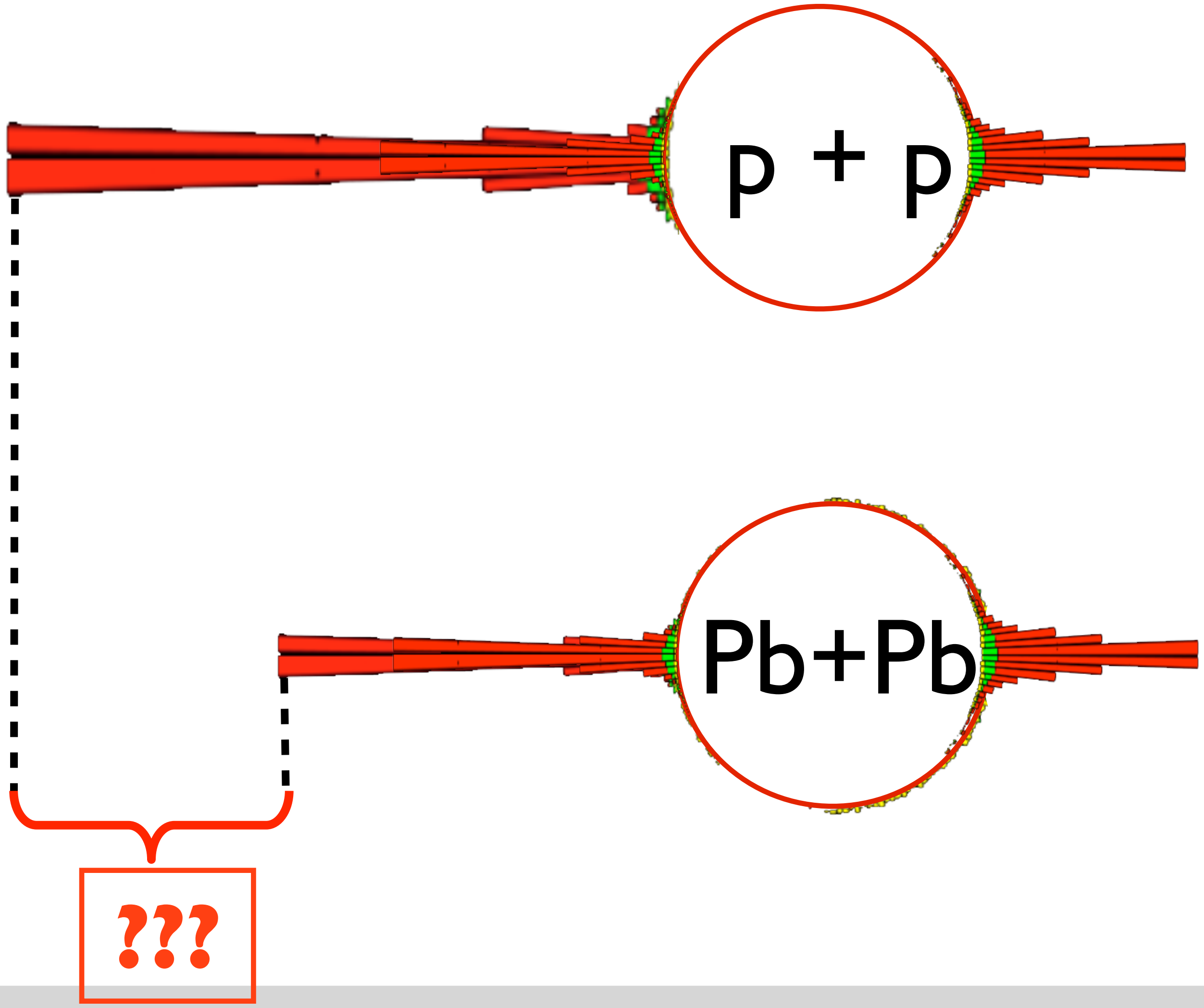
R_{AA}=

scaled pp reference



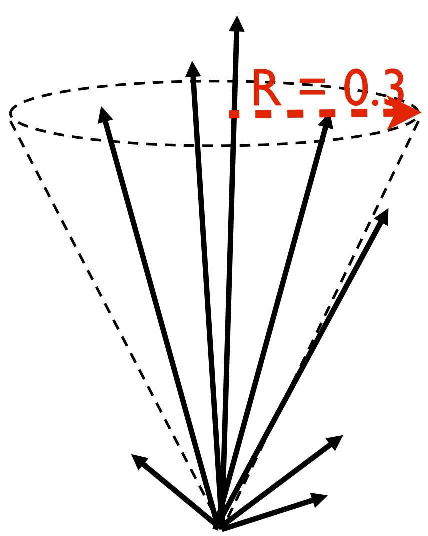
- Constraints on the parton energy loss in QGP

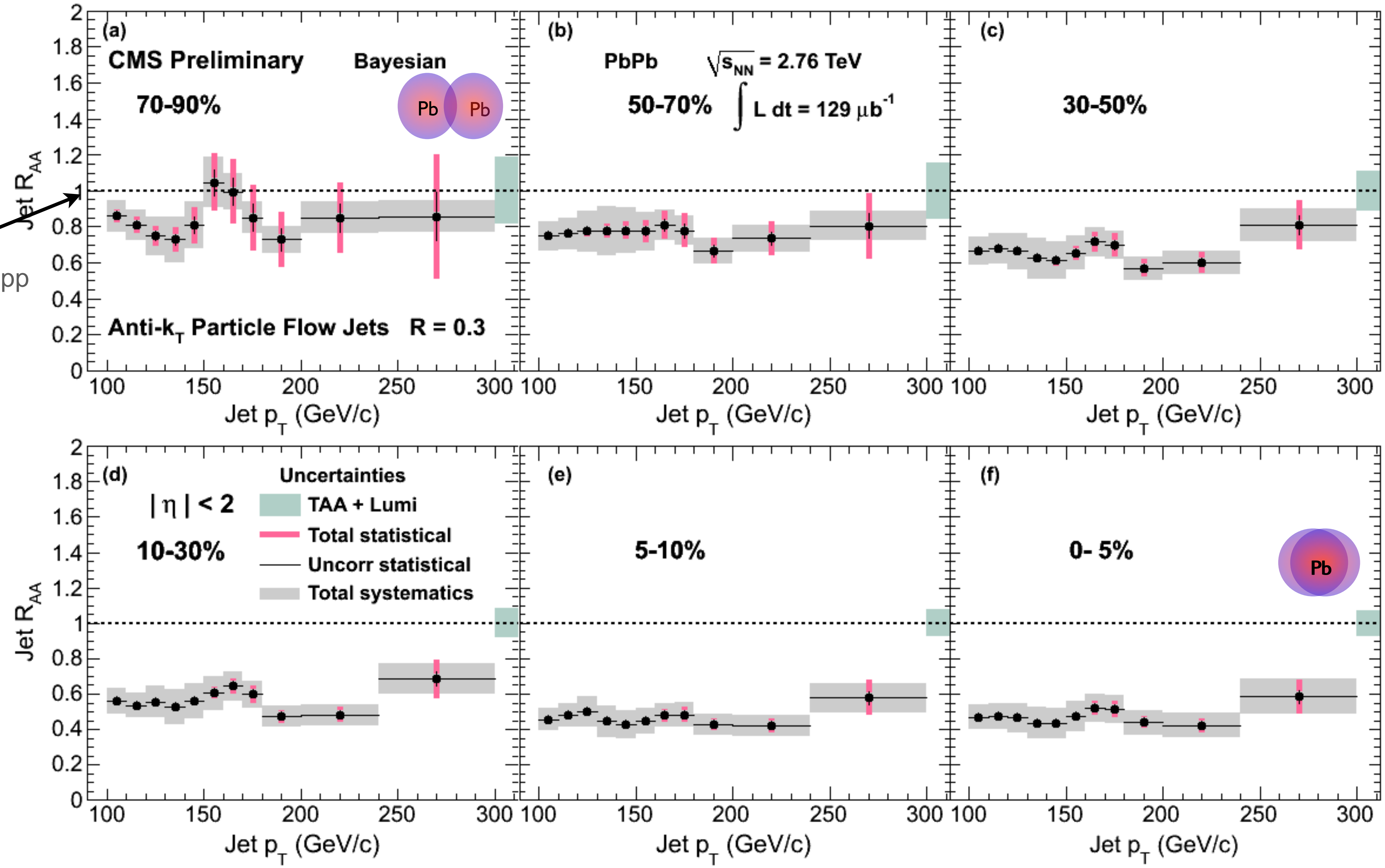
How much energy do single jets lose?



Nuclear modification factors of jets

If PbPb = superposition of pp





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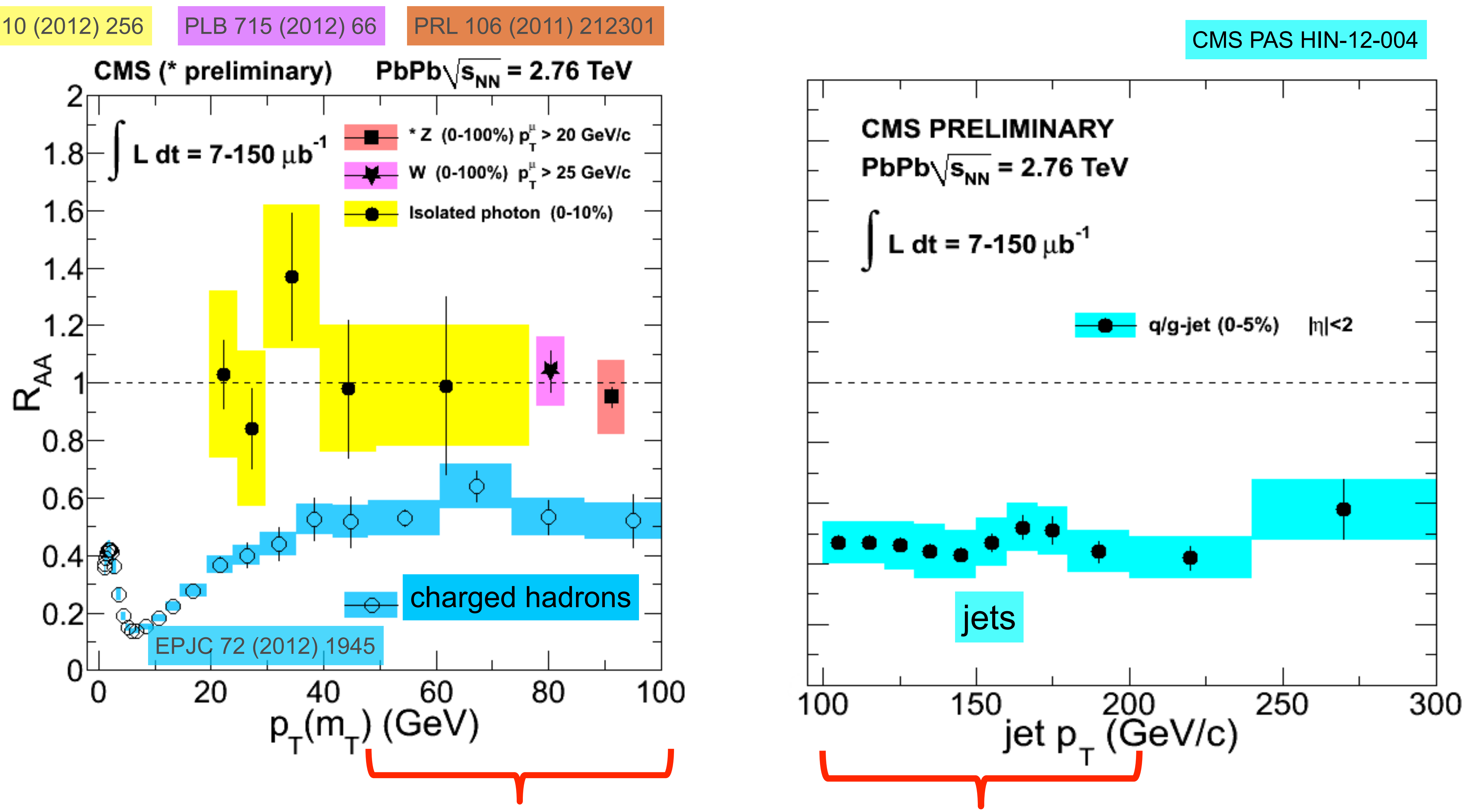
- Suppression: no significant p_T–dependence

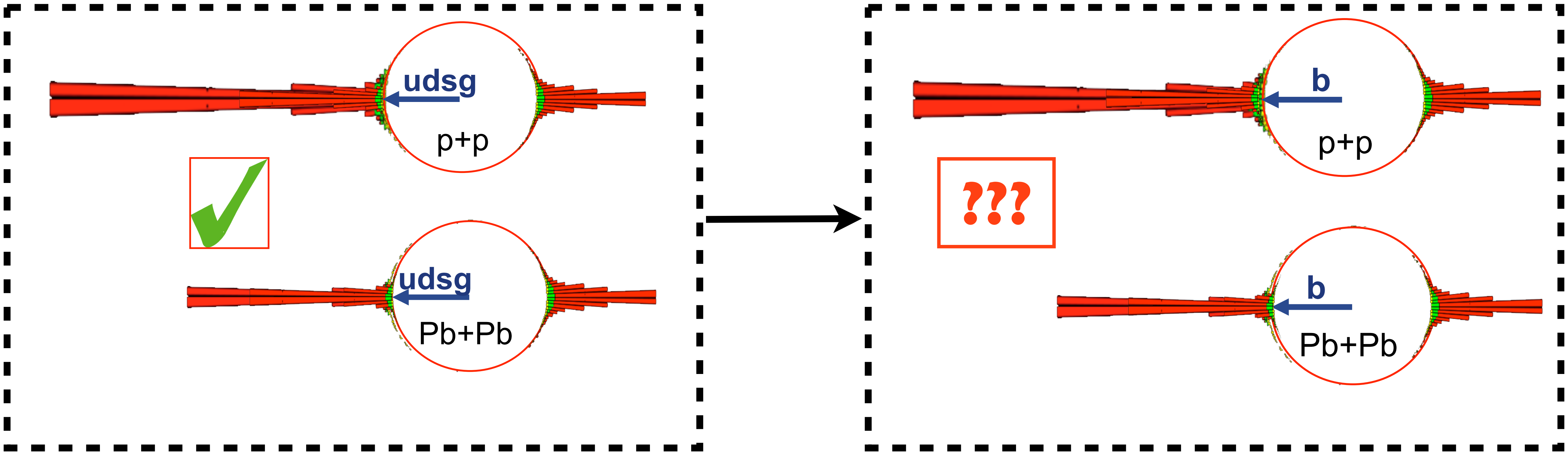
Charged hadron R_{AA} to jet R_{AA}



Sampling the ~same parton p_T range

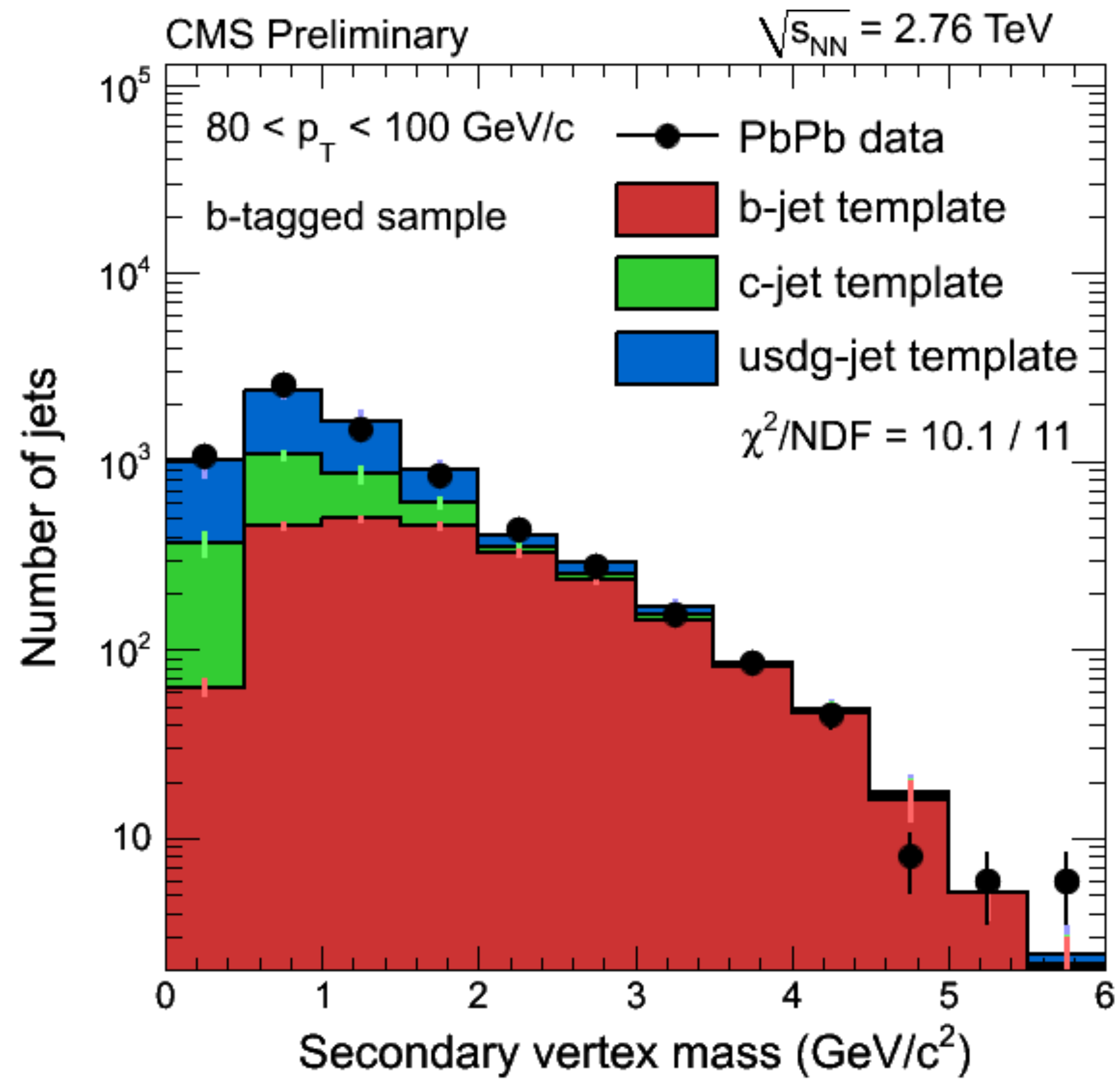
- Note: jets fragment into high-p_T particles in pp and PbPb the same way – see later…

Are heavy-quark jets quenched differently?



Tagging and counting b-quark jets

- Long lifetime of b (~1.5 ps) leads to measurable displaced secondary vertices (SV)
- Subsequent charm decay may lead to a tertiary vertex (TV)
- B-jets are tagged using reconstructed SV's based on flight distance
- Tagging efficiency estimated in a data-driven way
- b-jet fraction (purity) is extracted by a template fit to the (tagged) SV mass



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Fraction of b-jets among all jets

b-jet fraction = # of tagged jets * purity / efficiency

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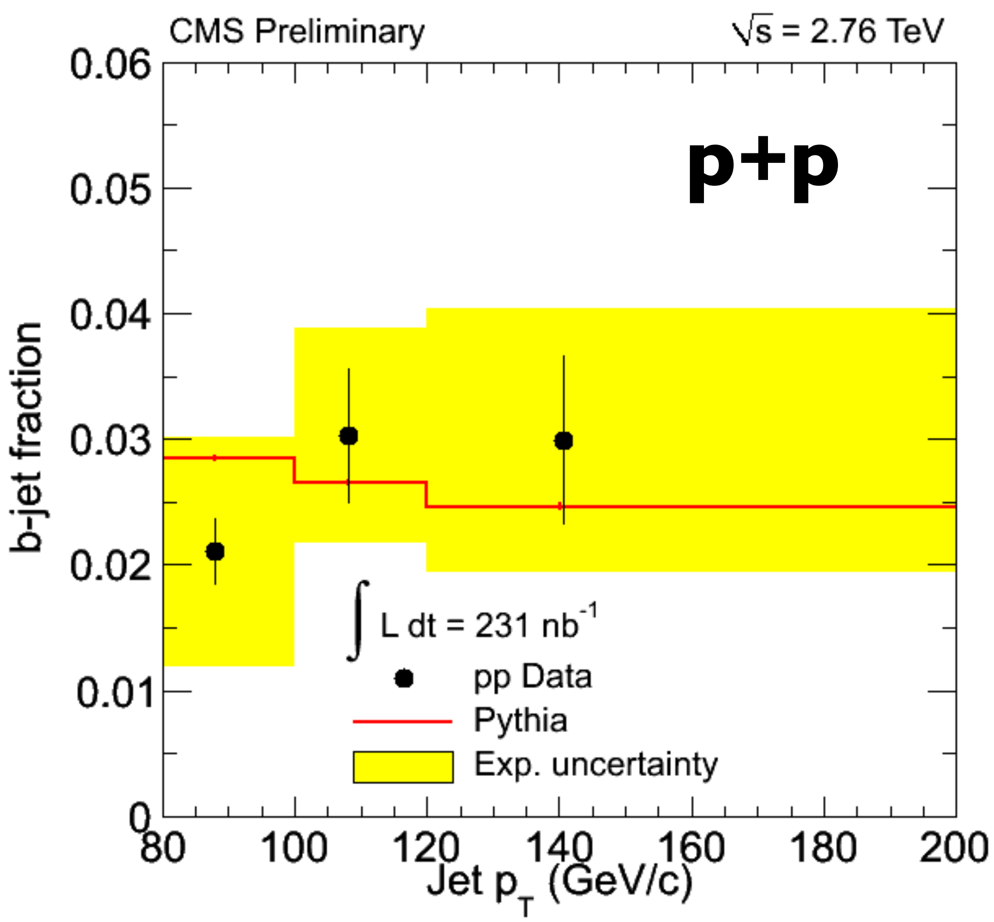
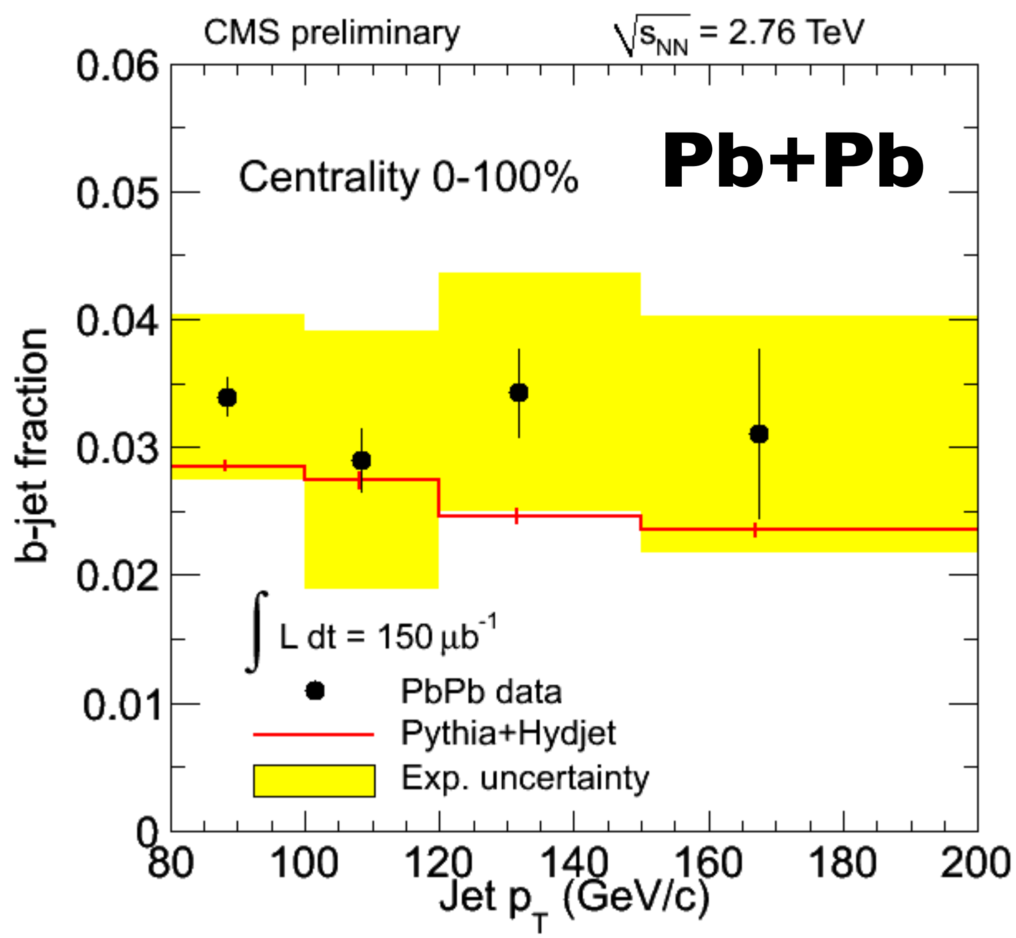
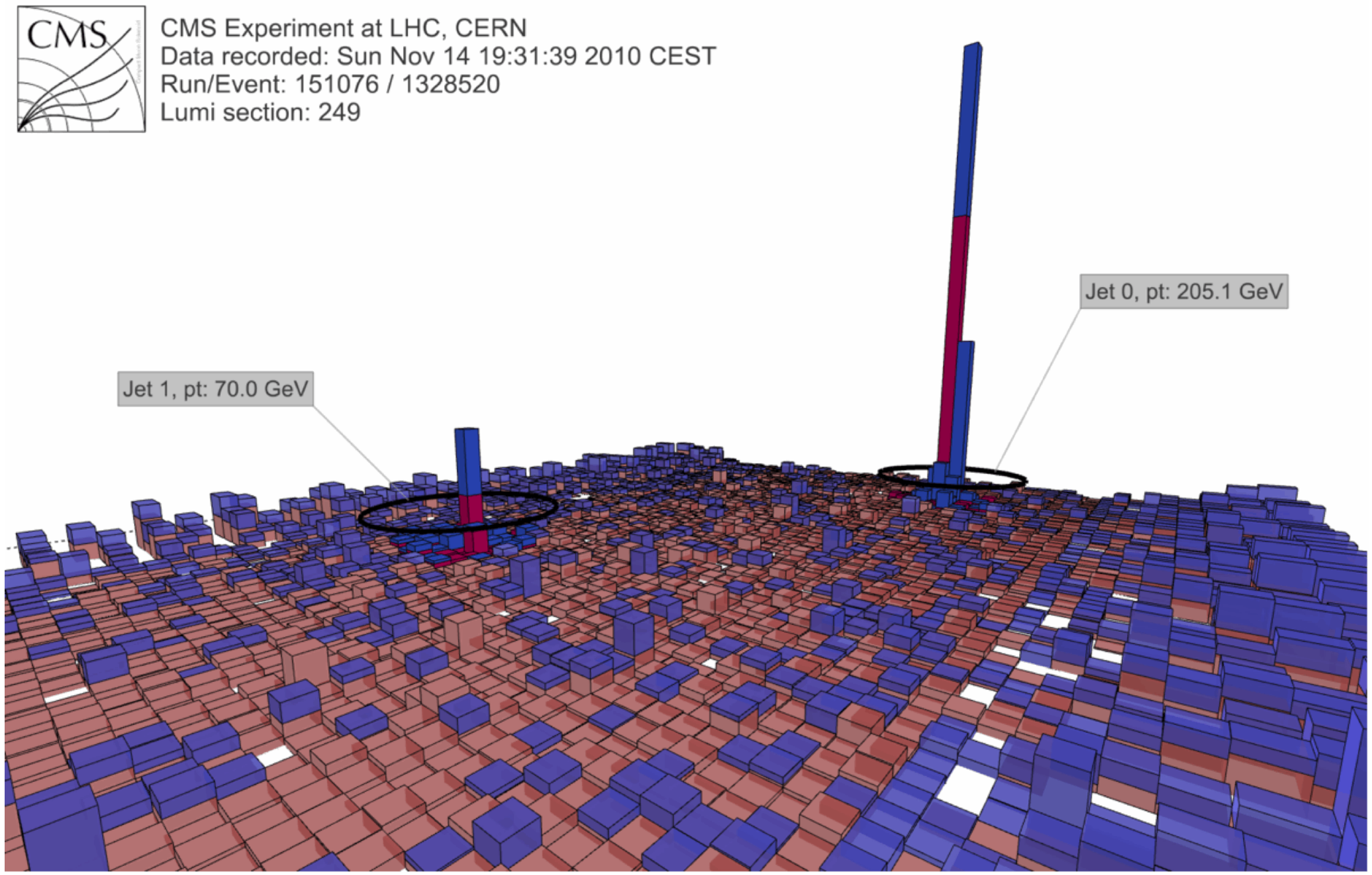




- b-jet fraction: similar in pp and PbPb

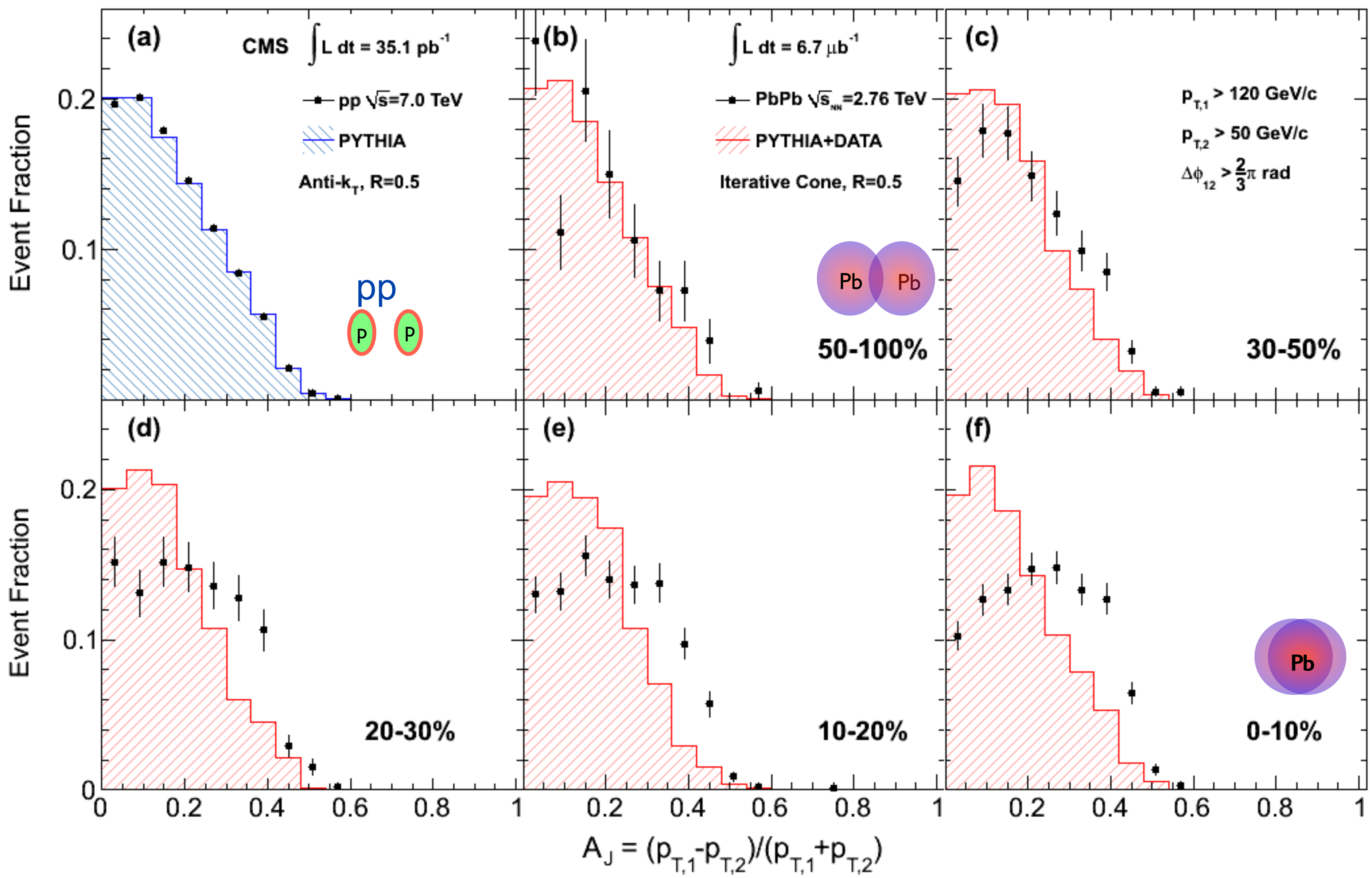
→ b-jet quenched like light-jet (R_{AA} ~ 0.5)

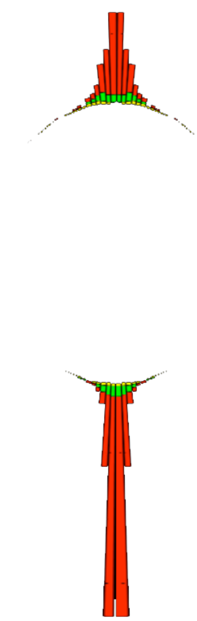
More exclusive observables: di-jets



Jet energy imbalance

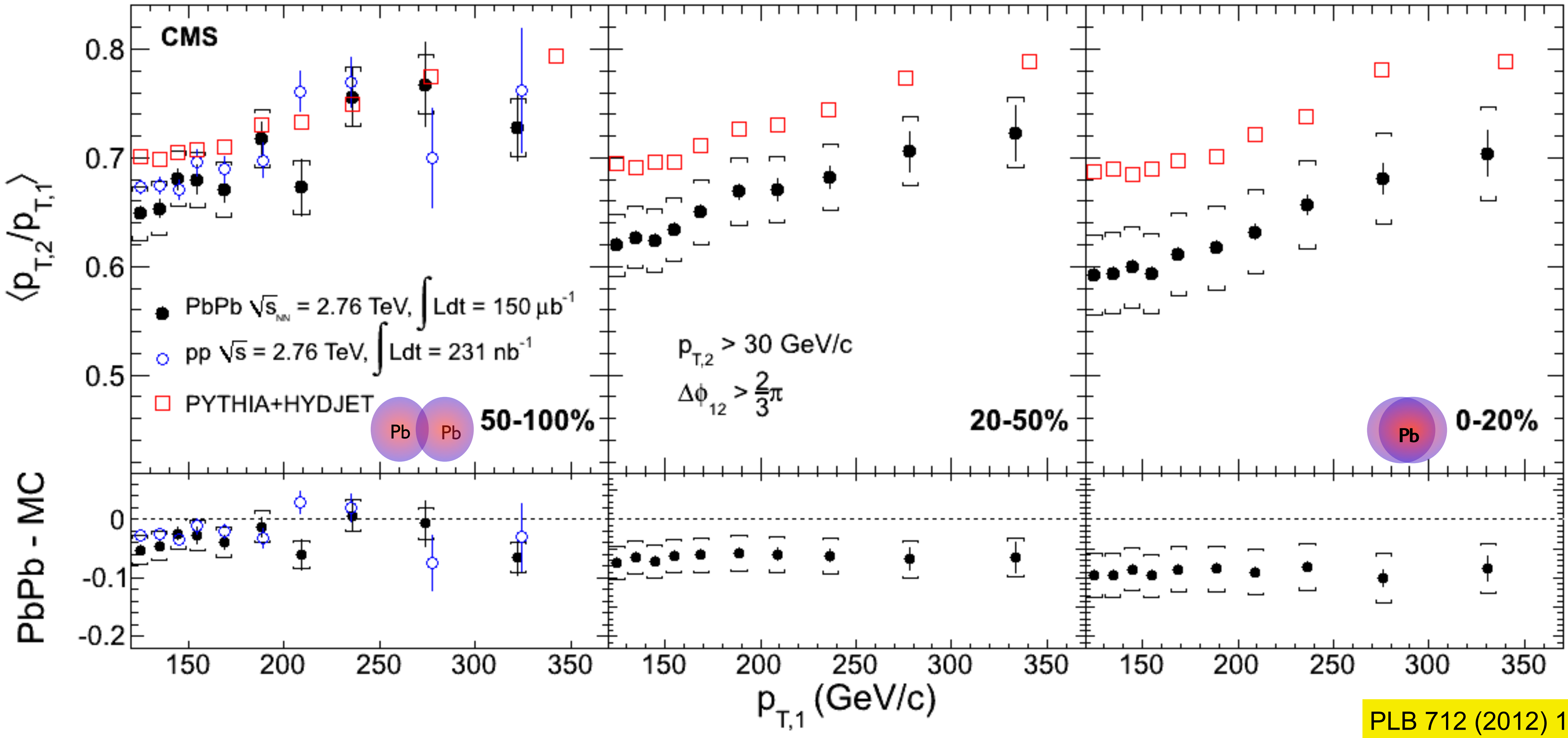
- Parton energy loss is observed as a pronounced dijet energy imbalance in central PbPb collisions





PRC 84 (2011) 024906

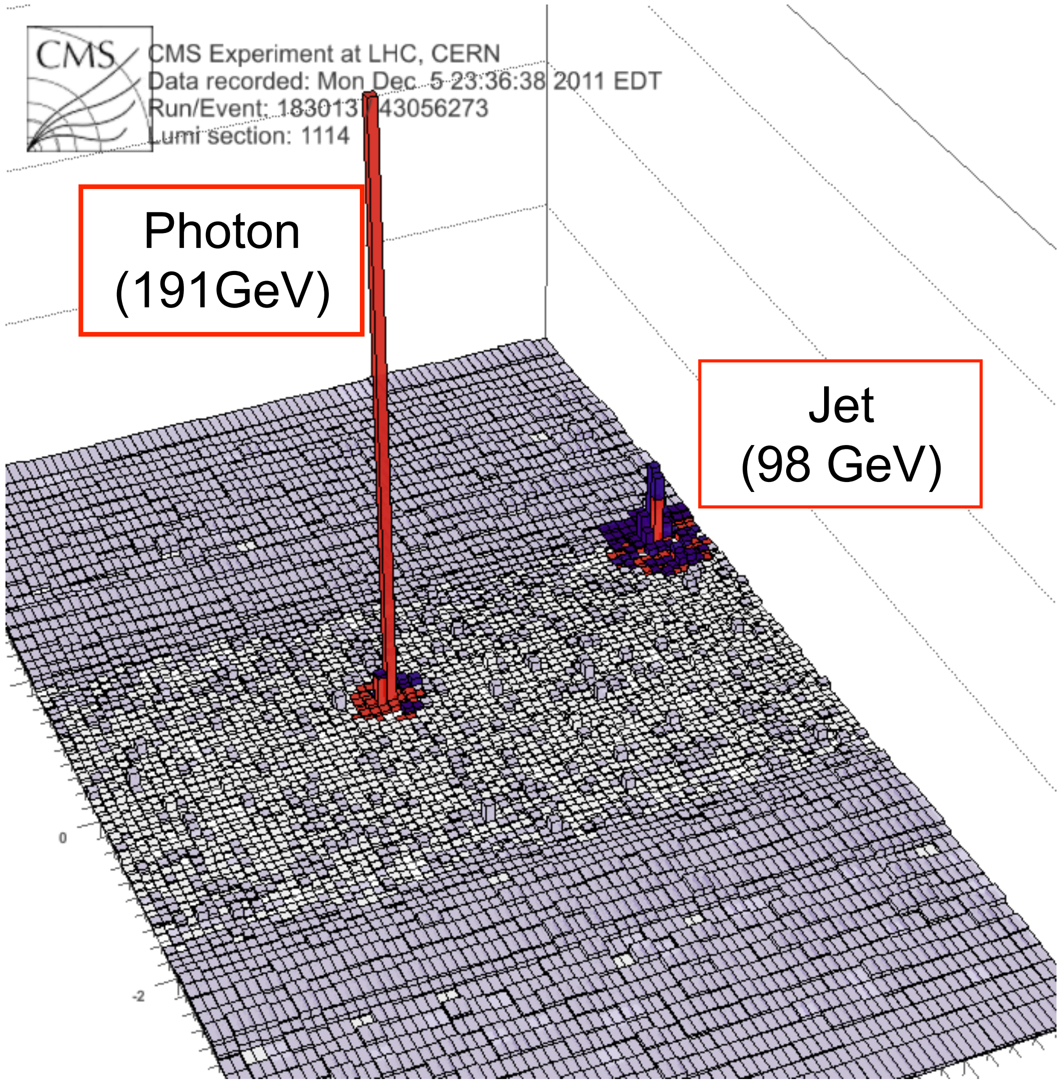
Dijet imbalance (p_T)

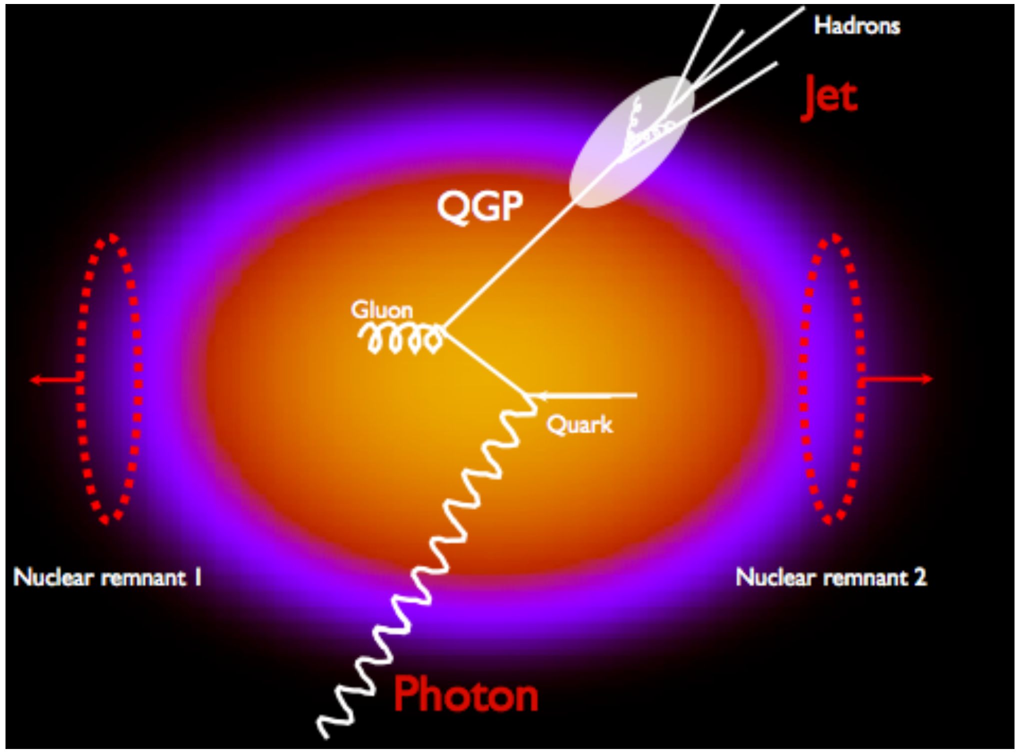


PLB 712 (2012) 176

- Energy imbalance increases with centrality
- p_T-ratio deviates from the unquenched reference in a p_T-independent way

γ+jet: "golden" probe for energy loss

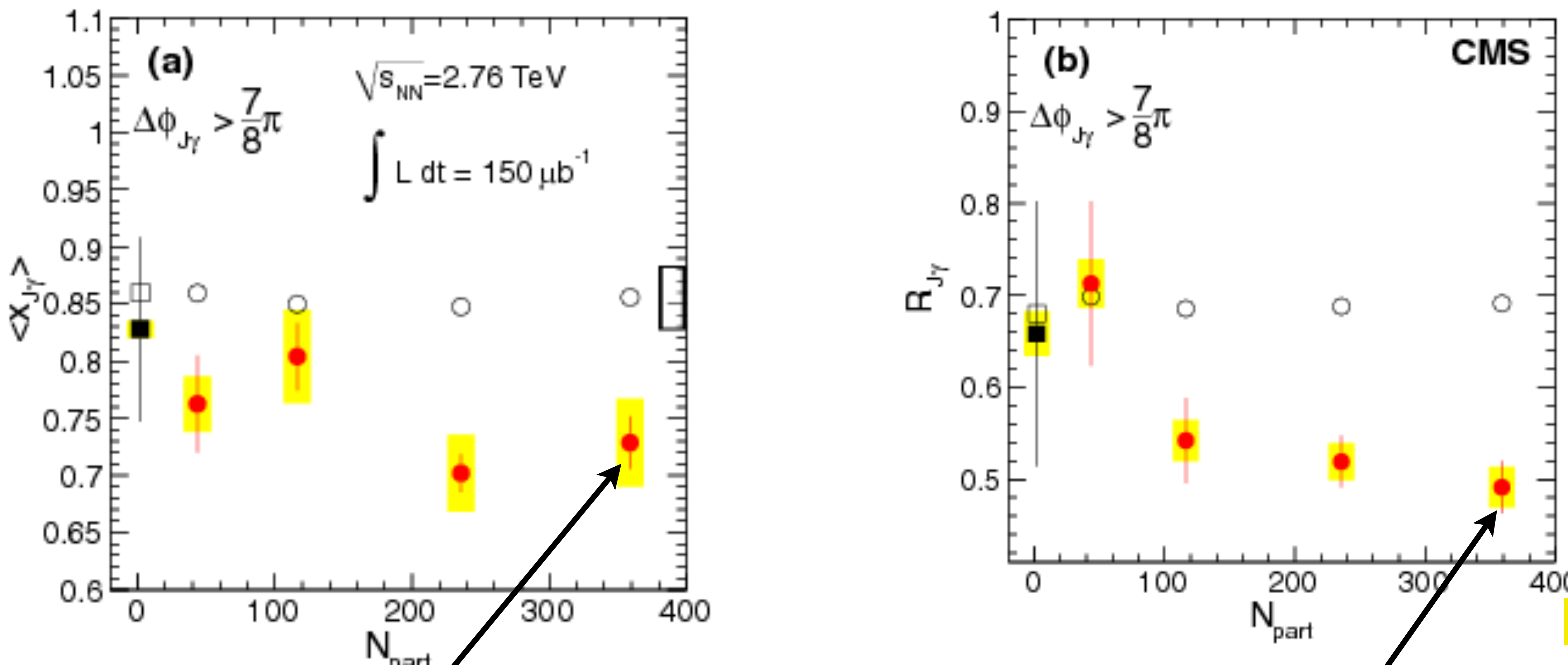




- Photon tag:
  - Identifies jet as quark jet (mainly)
  - Provides initial quark direction
  - Provides initial quark energy

γ-jet correlations

- Ratio of jet to photon p_T ($x_{J\gamma} = p_T^{jet}/p_T^{\gamma}$) is a direct measure of the jet energy loss: gradual centrality-dependence of $x_{J\gamma}$
- Fraction of isolated photon-jet pair ($R_{J\gamma}$): less jet partners above threshold (> 30 GeV/c)



PLB 718 (2013) 773

Increasing p_T-imbalance

Jets lose ~14% of their initial energy

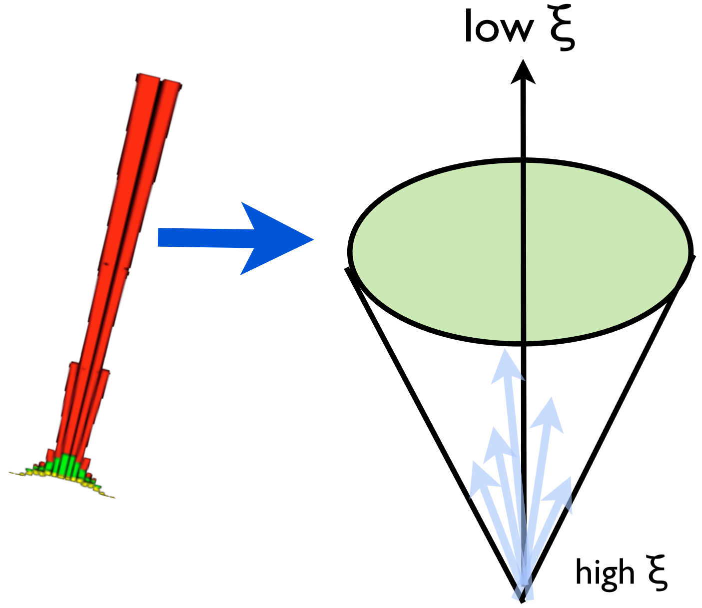
~20% of photons lose their jet partner

Is jet fragmentation and shape modified?

Jet fragmentation function:

- particle momenta projected onto the jet axis

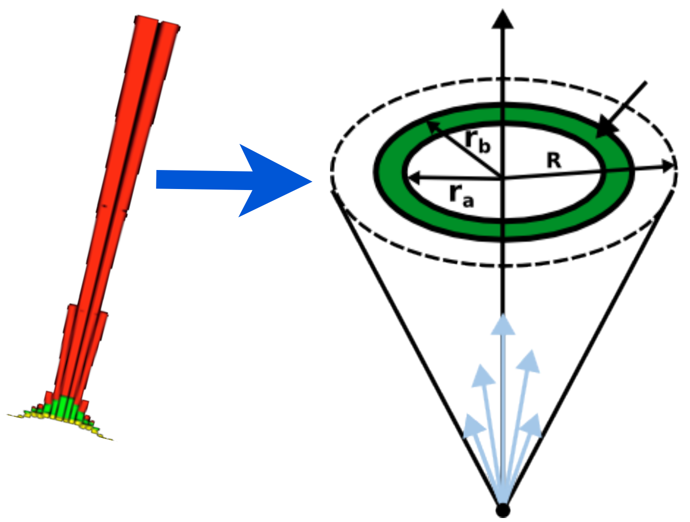
$$\xi = \ln(1/z) = \ln(p^{jet}/p_{||}^{track})$$



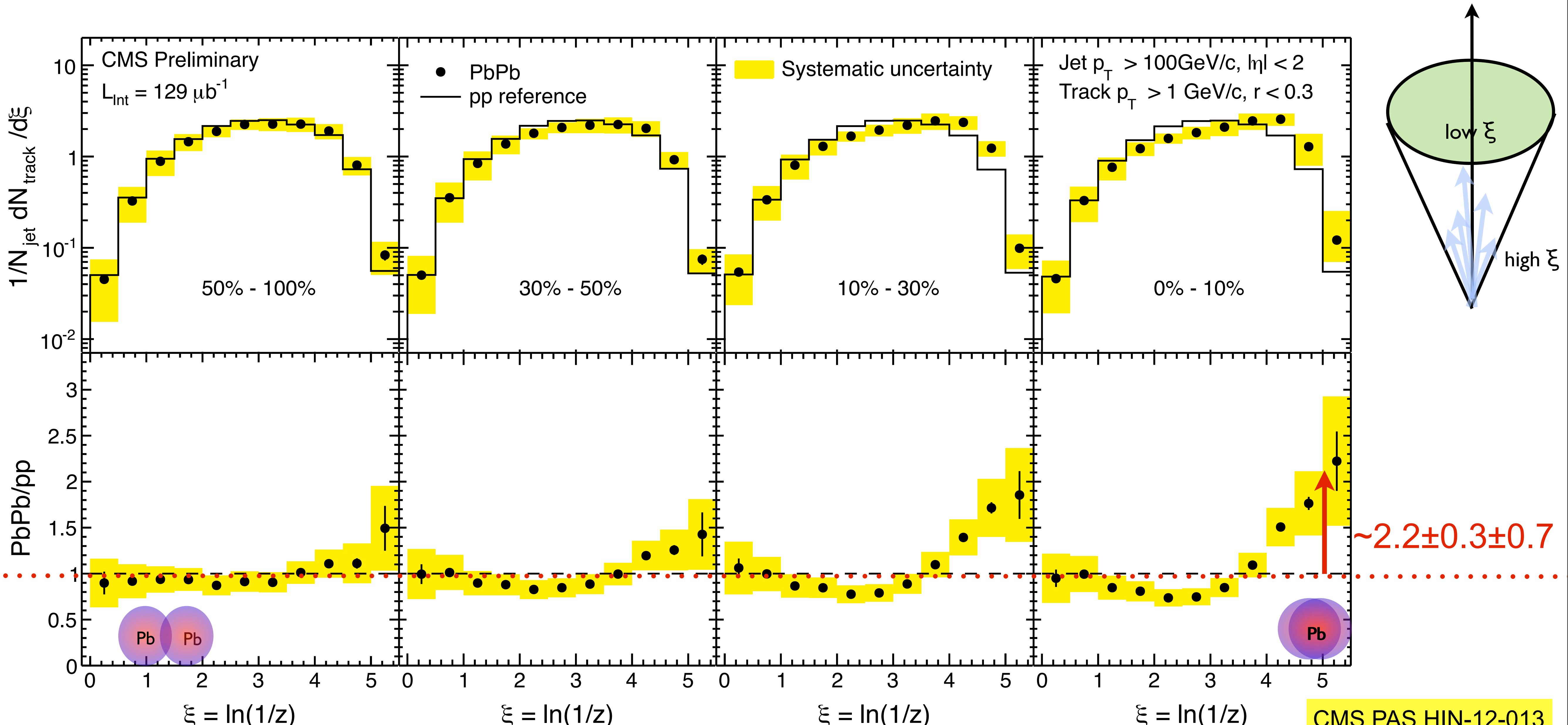
Jet shape:

- transverse momenta-flow as a function of the distance from the jet axis (r) in the η-φ plane

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



Jet fragmentation functions



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$\xi = \ln(p^{jet}/p_{||}^{track})$

- Peripheral PbPb similar to pp
- Up to factor of 2 excess at $\xi > 4$ ($p_T < 3$ GeV/c) in most central collisions
- Excess complemented by deficit at ξ = 1-3 in most central collisions
- High p_T tracks ($\xi < 1$; $p_T > 10$ GeV/c) unmodified even in most central events

Differential jet shapes

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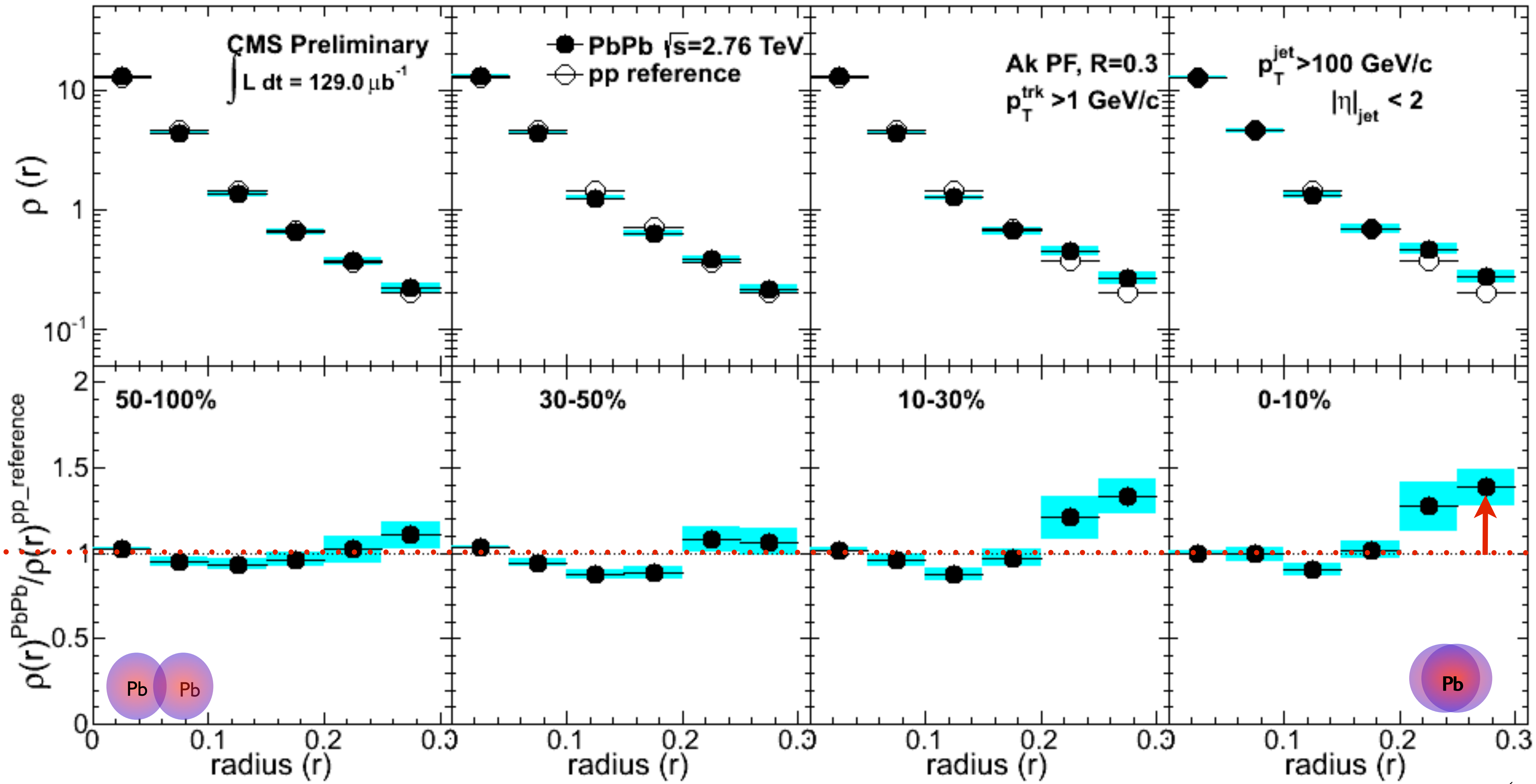
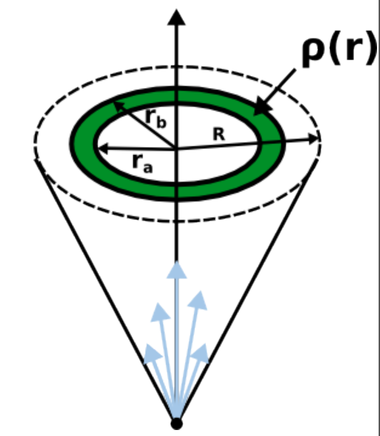
In presence of medium effect ➔ ratio expected to deviate from 1

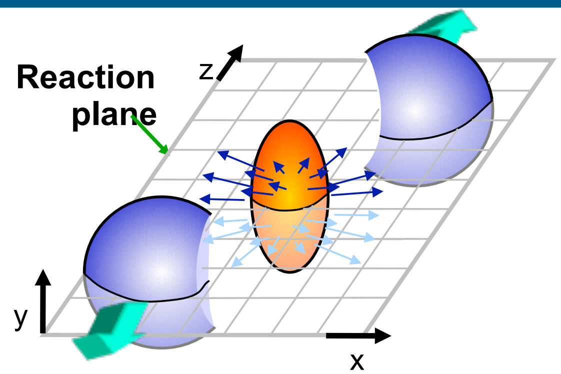


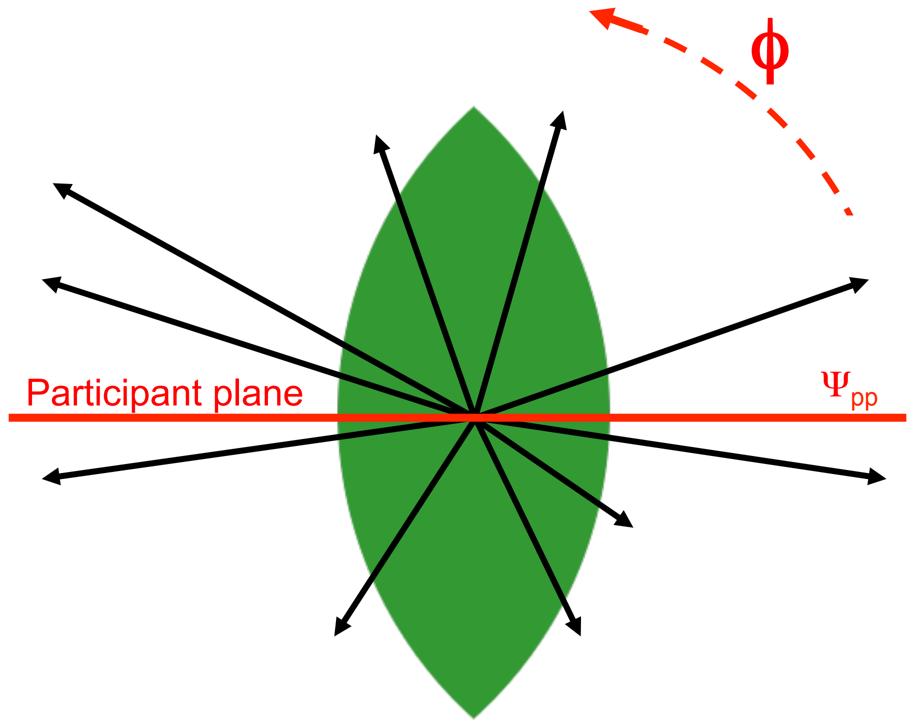


$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{jet}},$$

- Ratio close to unity for non-central (50-100%) collisions
- Shape broadening for mid-central (10-30%) and most central (0-10%) collisions

Path length dependence of jet energy loss?





$$\Delta E \propto \begin{cases} L & \text{pQCD, collisional} \\ L^2 & \text{pQCD, radiative} \\ L^3 & \text{AdS/CFT} \end{cases}$$

Overlap zone is almond-shaped

→ Parton energy loss is smaller along the short axis

→ More high-p_T tracks expected closer to the event plane

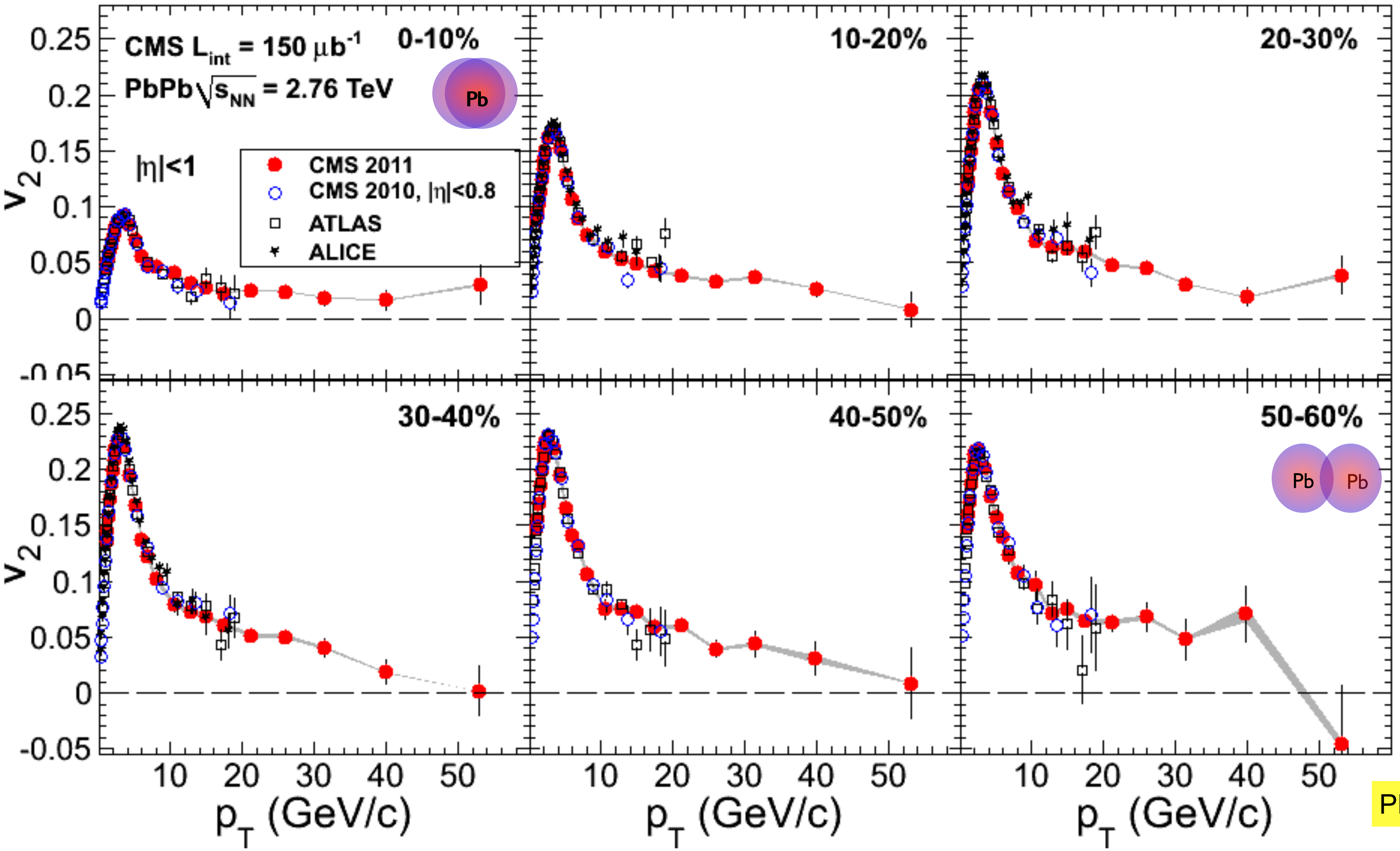
→ Azimuthal asymmetry (v_2):

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

→ v_2 is sensitive to the path-length dependence of the energy loss

Charged hadron v_2 at very high p_T

Q. Wang's talk, Fri, morning

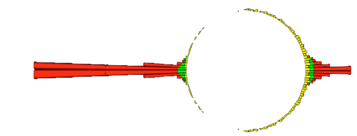


PRL 109 (2012) 022301

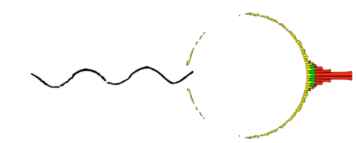
- v_2 is non-zero up to very high p_T
- Sensitive to the path length dependence of energy loss

Summary

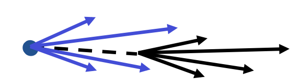
- Energy imbalance and jet R_{AA} independent of jet p_T



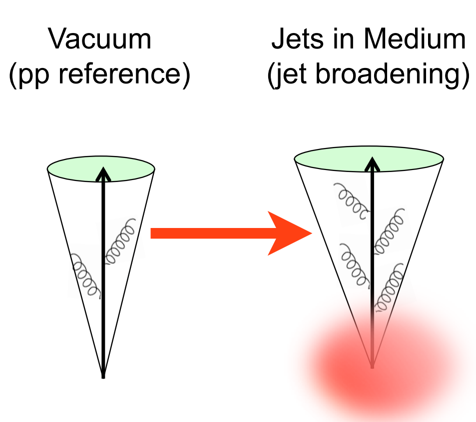
- First γ-jet measurement shows consistent energy loss as di-jets



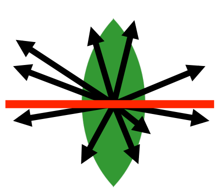
- b-quark jets are quenched similarly to light quarks



- Jet shapes and fragmentation functions: structure modified



- High p_T particle v_2 is non-zero: path length dependence of quenching



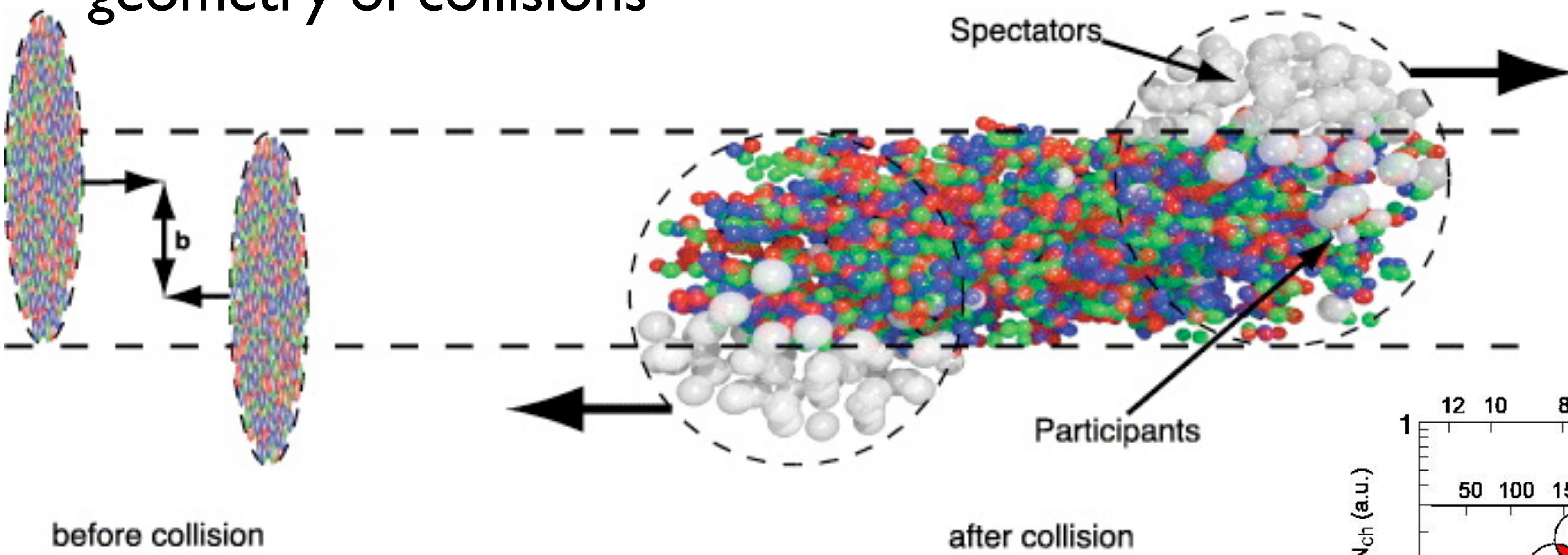
Jet-quenching picture is made more precise and quantitative!

backup

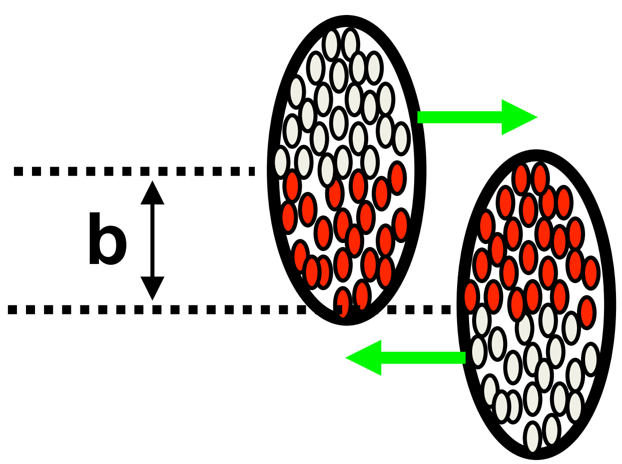
Heavy ion collision centrality

Controls the volume and shape of the system

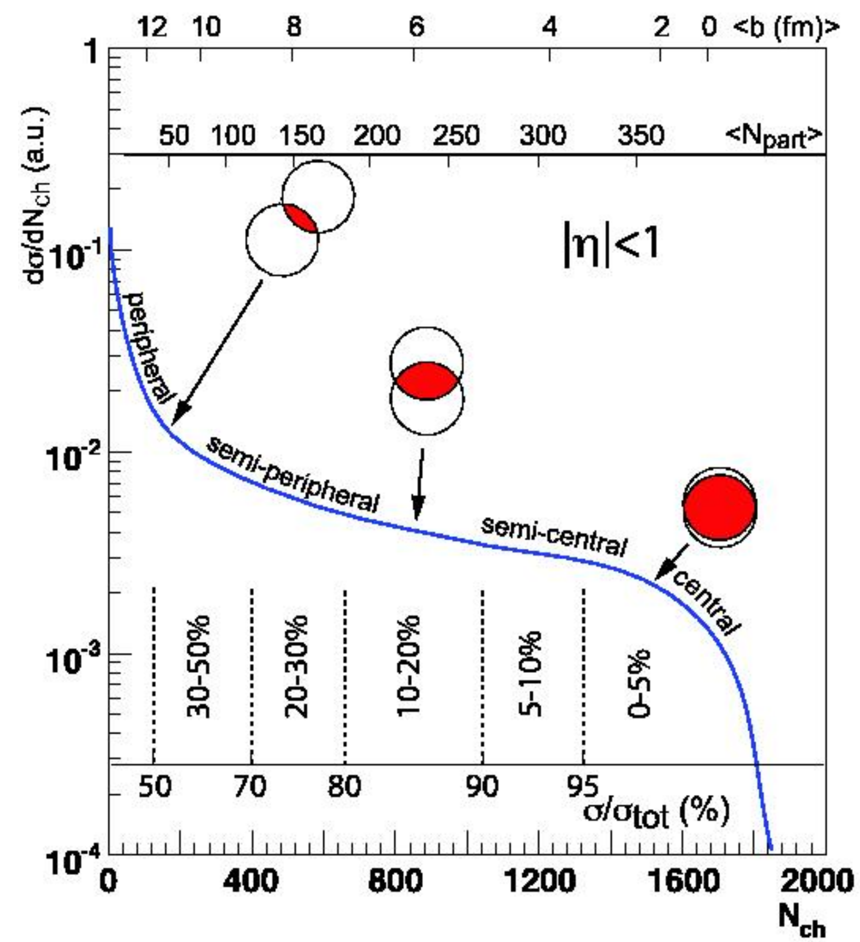
➡ Multiplicity and energy of produced particles are correlated with geometry of collisions



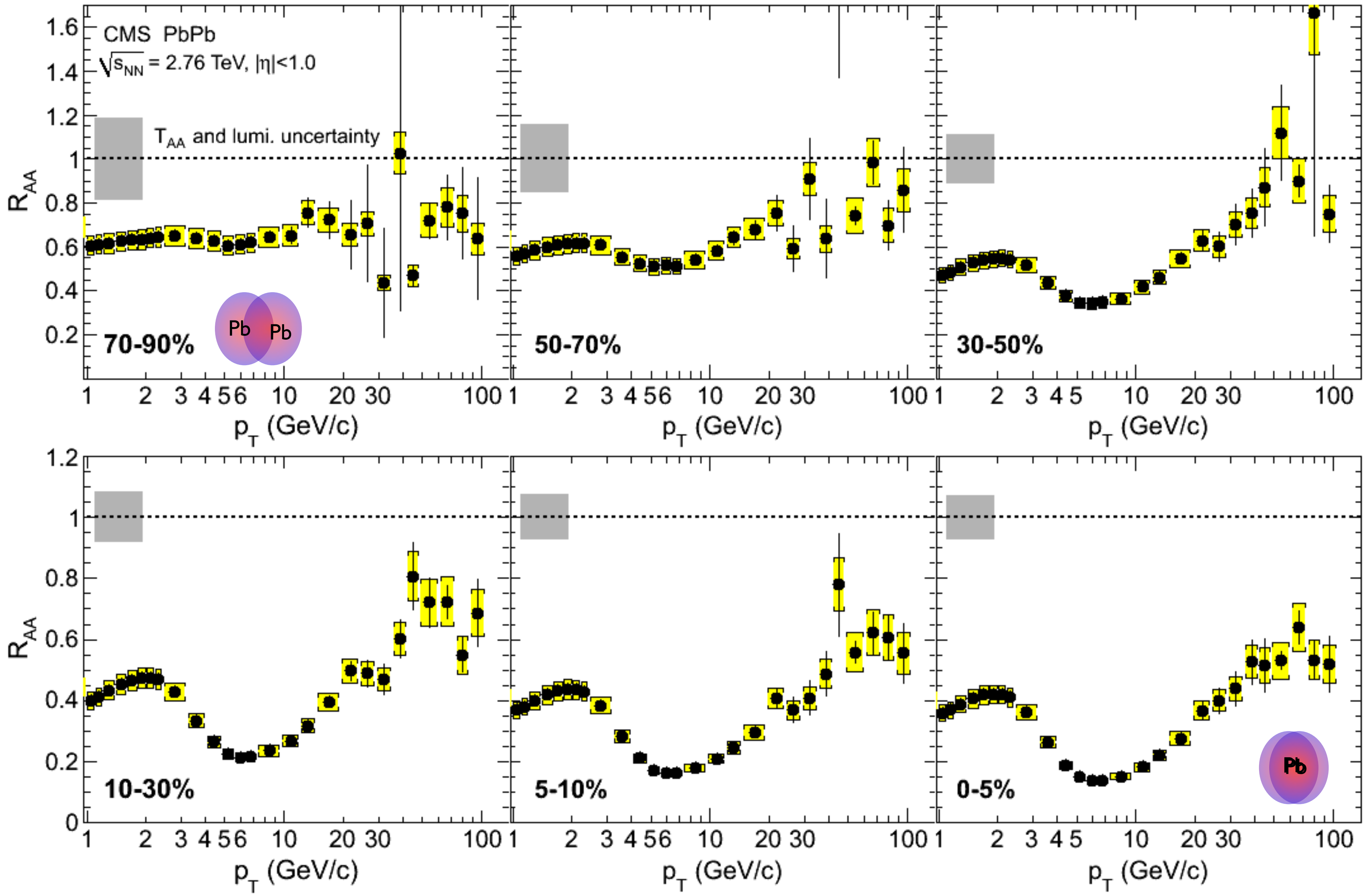
N_{part} Participants



$N_{part}/2 \sim A$



Charged hadron R_{AA}

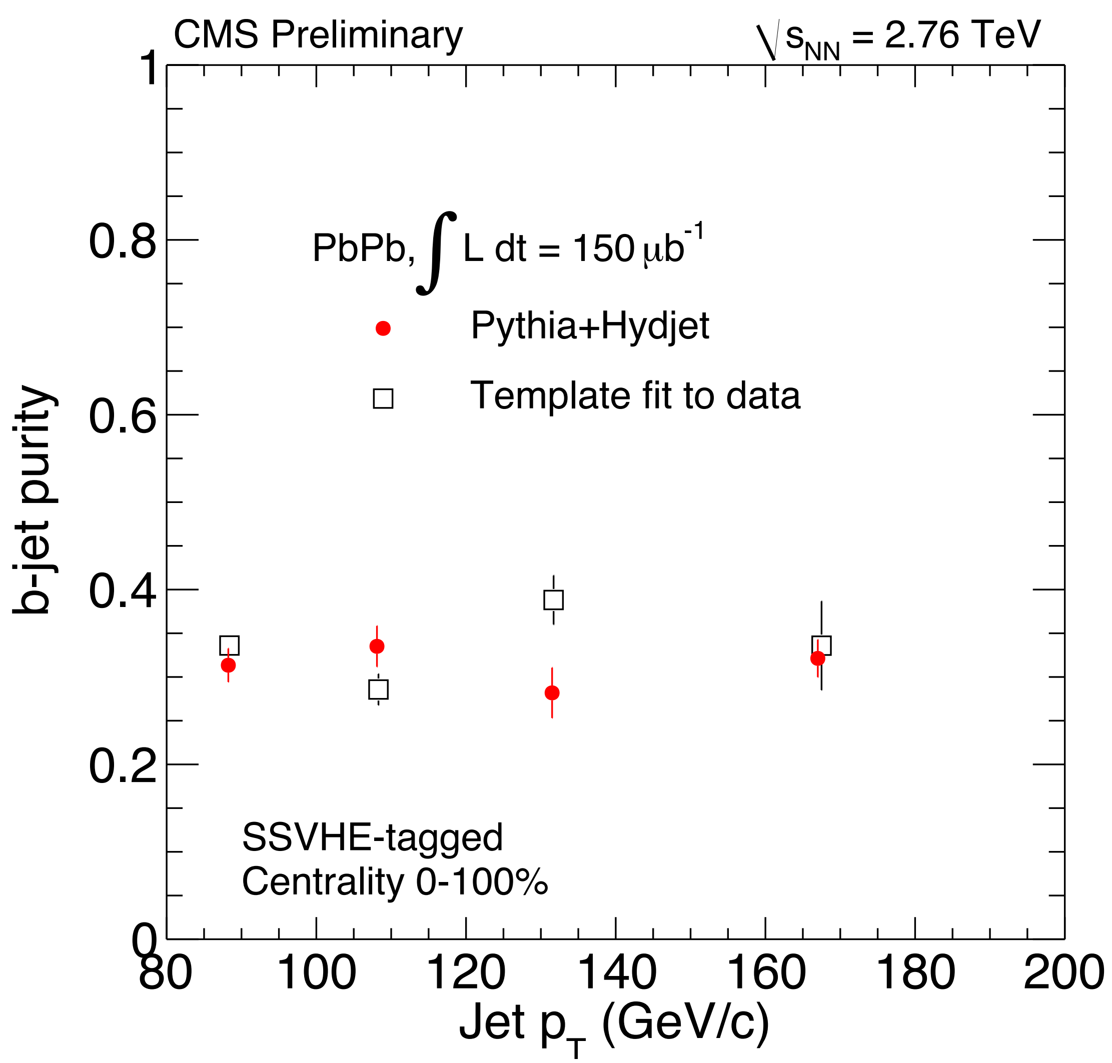


→ what is the connection to jet R_{AA}?

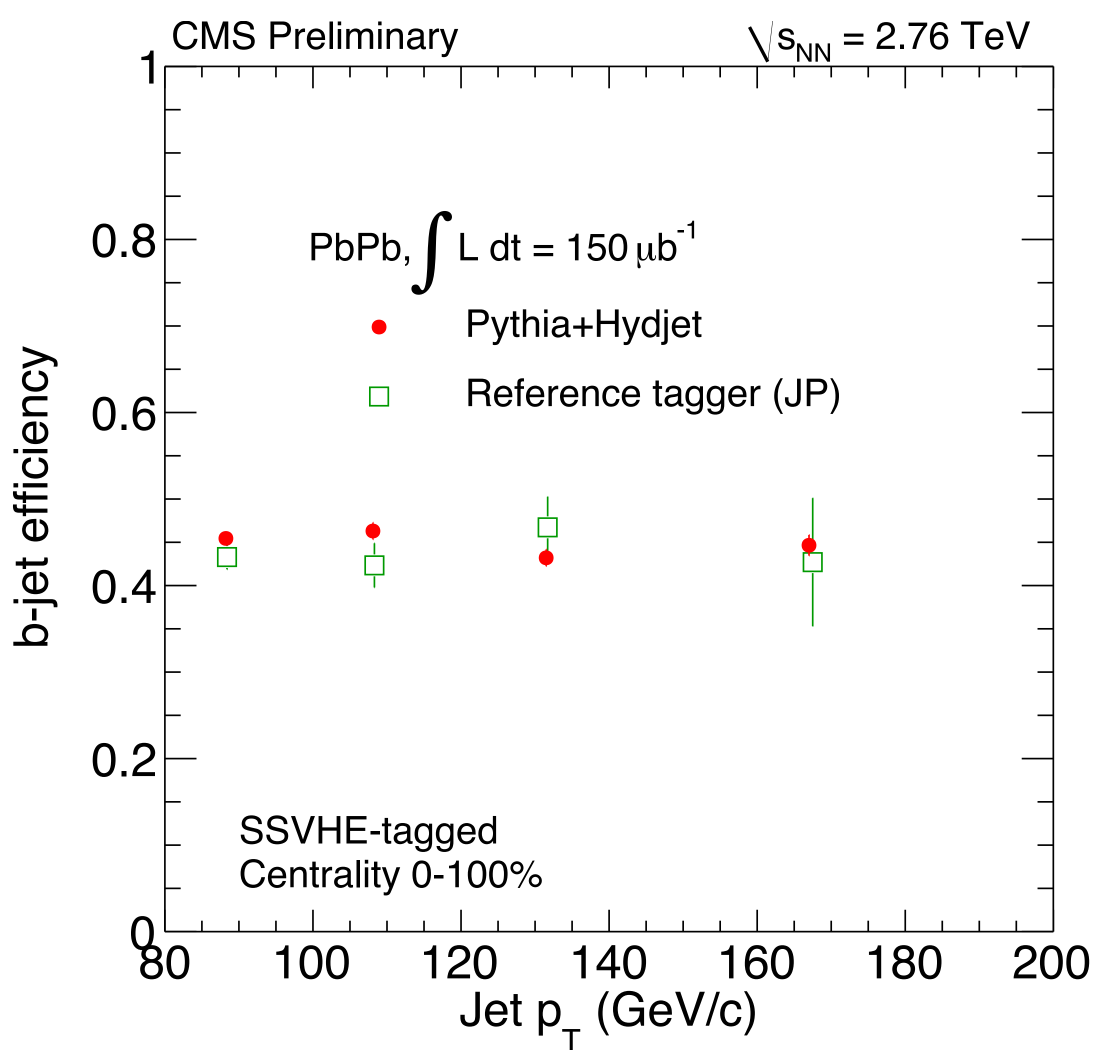
EPJC 72 (2012) 1945

b-Tagging Purity and Efficiency

Purity: b-jet fraction in SV tagged sample extracted from SV mass fit



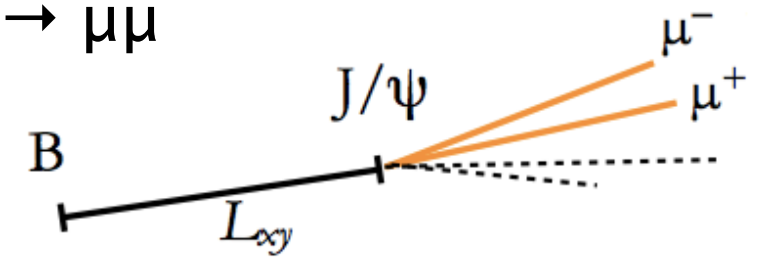
Efficiency: Fraction of b-jets which are tagged by their SV



- Efficiency is extracted from simulation and with a data-driven method using the JP tagger, i.e., w/o requiring a SV
- For both efficiency and purity, MC is fairly close to data "out of the box"

A new kind of PID

$6.5 < p_T < 30$ GeV:
Displaced $J/\psi \rightarrow \mu\mu$



Obtain *B* R_{AA}

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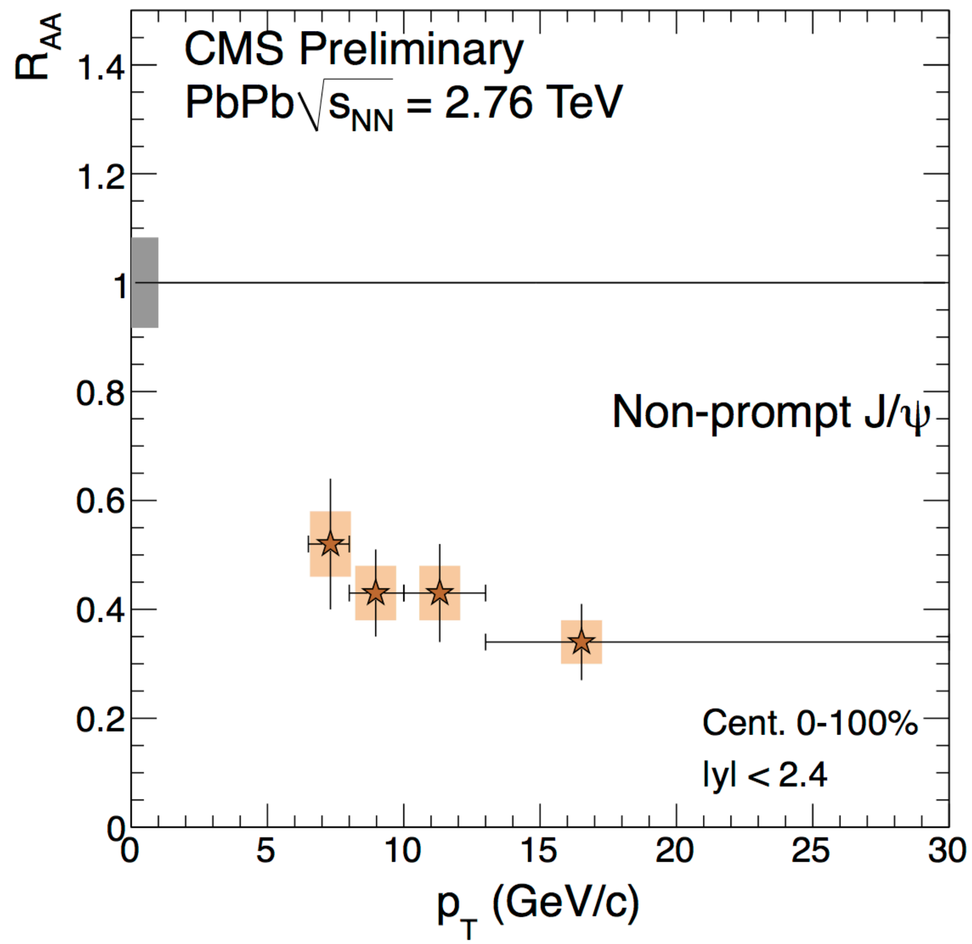
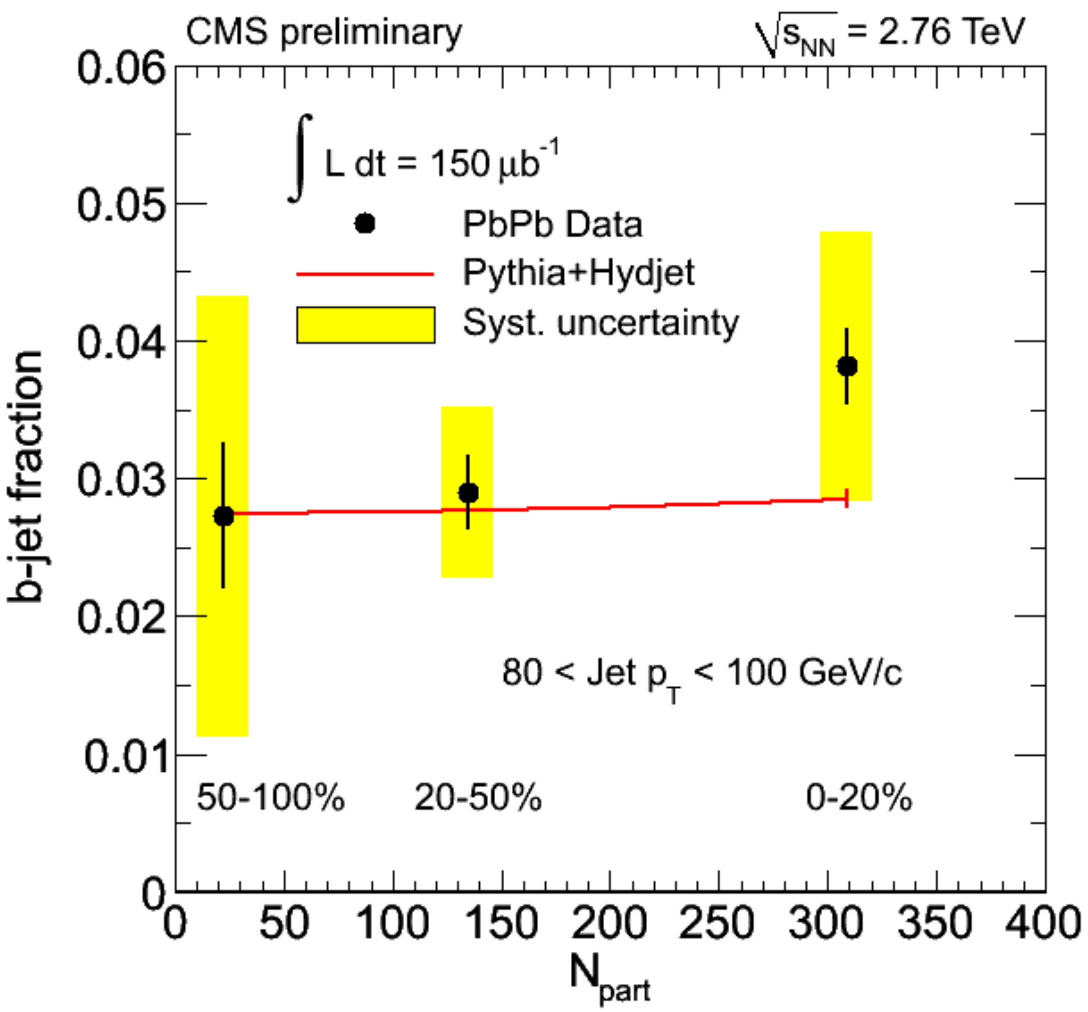


$p_T > 80$GeV:
Jet + high mass secondary vertex

Obtain *b-jet fraction*

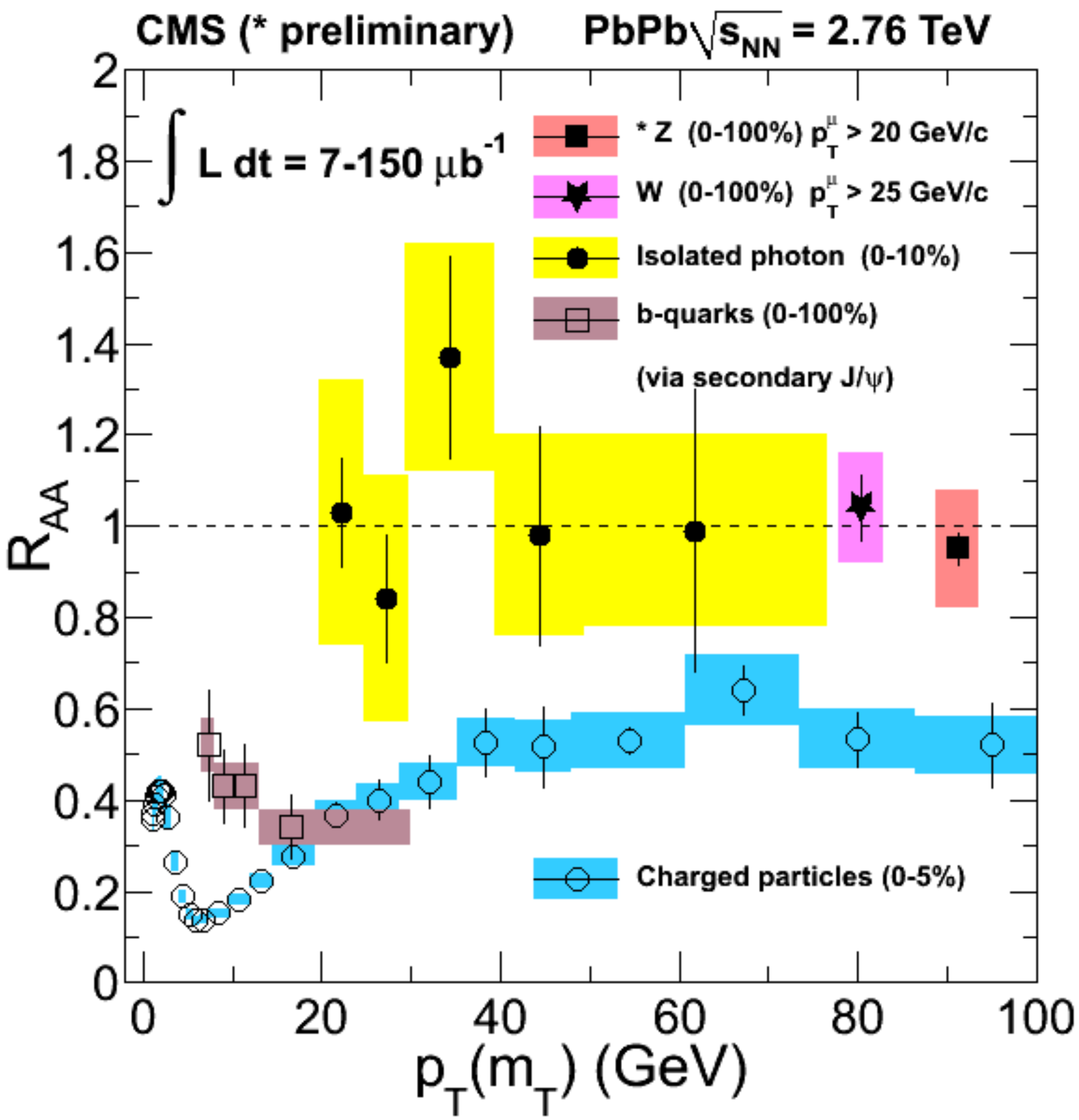
CMS PAS HIN-12-003

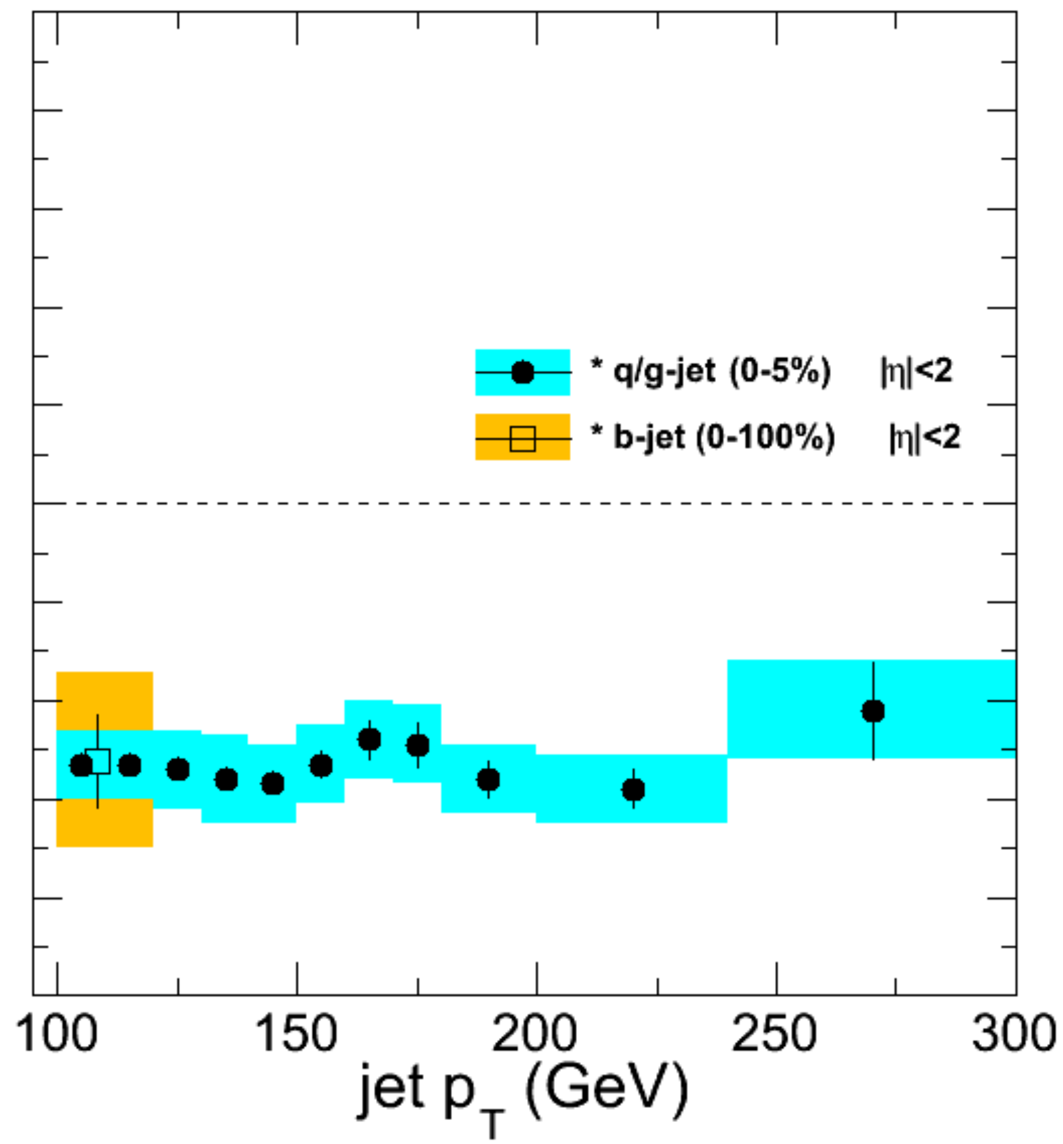


Parton ID: b-quarks

PLB 710 (2012) 256 PLB 715 (2012) 66 PRL 106 (2011) 212301 CMS PAS HIN-12-003 CMS PAS HIN-12-004

CMS-PAS HIN-12-014



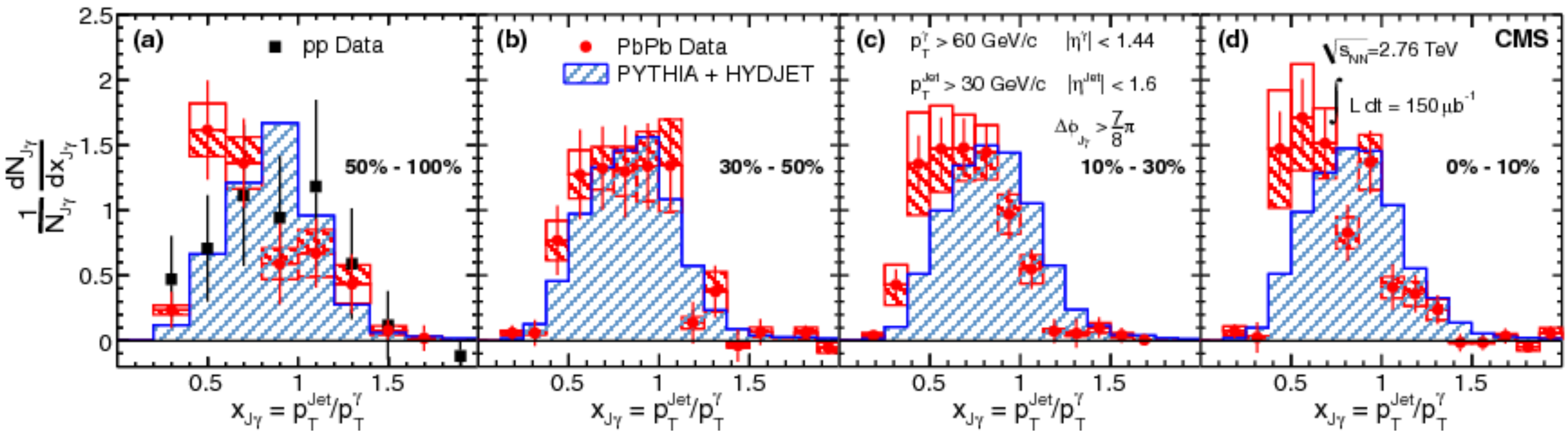


Distinct b-quark suppression pattern at low pT

First observation of b-jet suppression at high pT

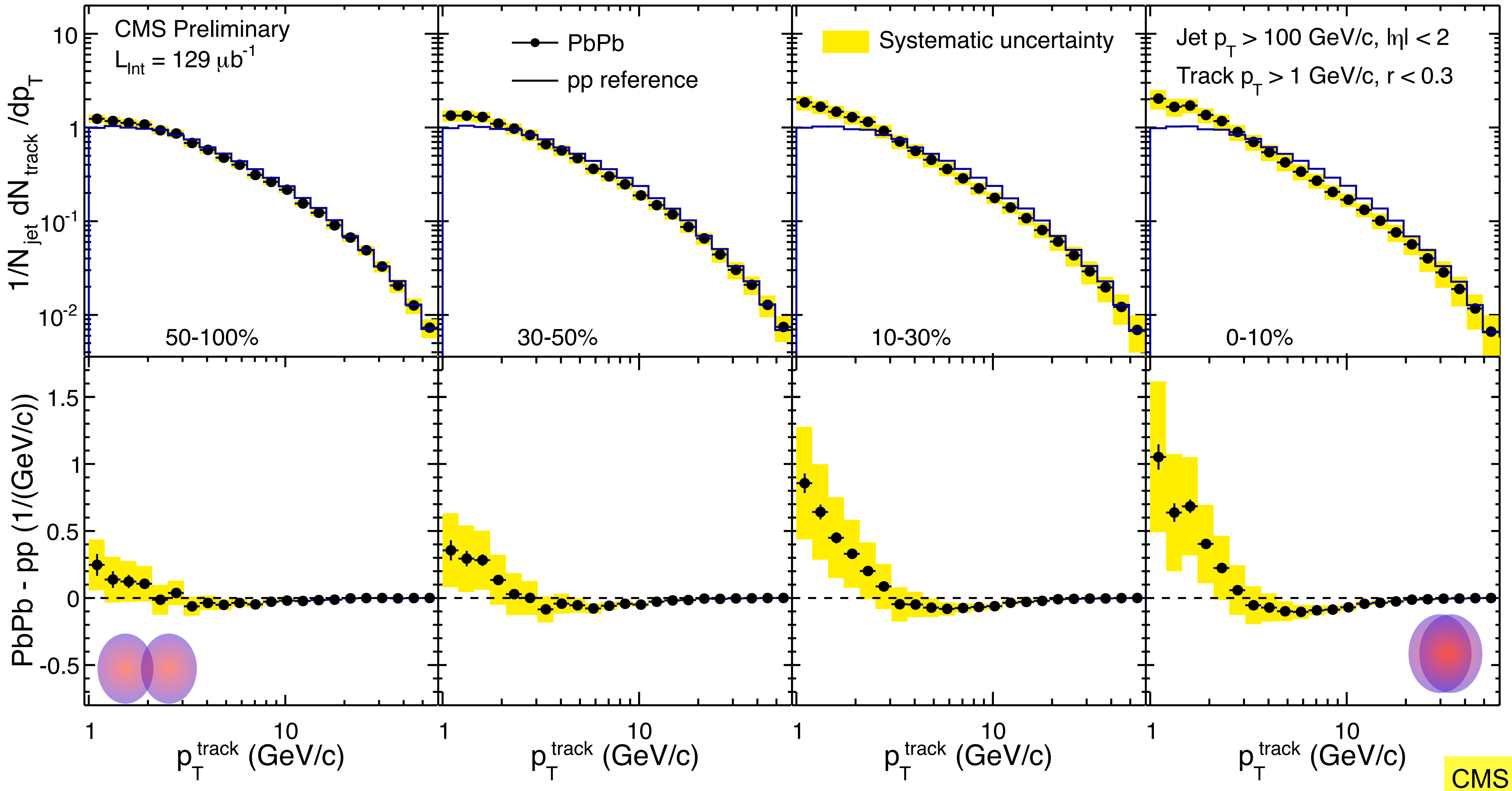
γ-jet correlations

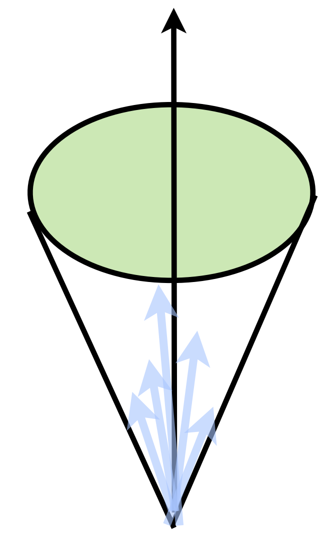
- Ratio of jet to photon p_T ($x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$)
  is a direct measure of the jet energy loss
- Gradual centrality-dependence of $x_{J\gamma}$



PLB 718 (2013) 773

Track p_T distribution inside jet: pp and PbPb





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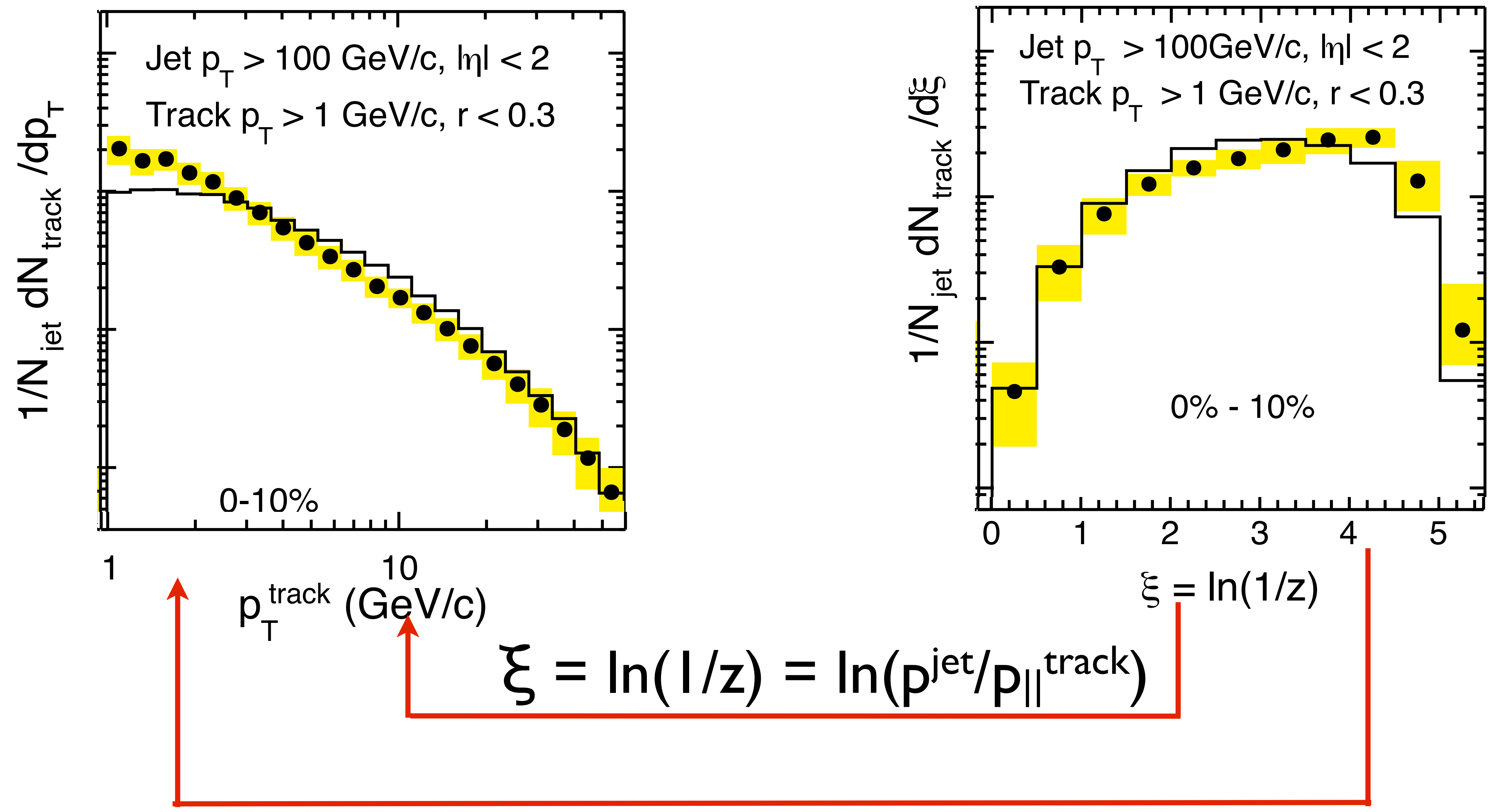
- High p_T (low ξ): no change compared to jets in pp collisions
- In (central) PbPb: excess of tracks compared to pp at low p_T (high ξ)

Connection between p_T and ξ distributions

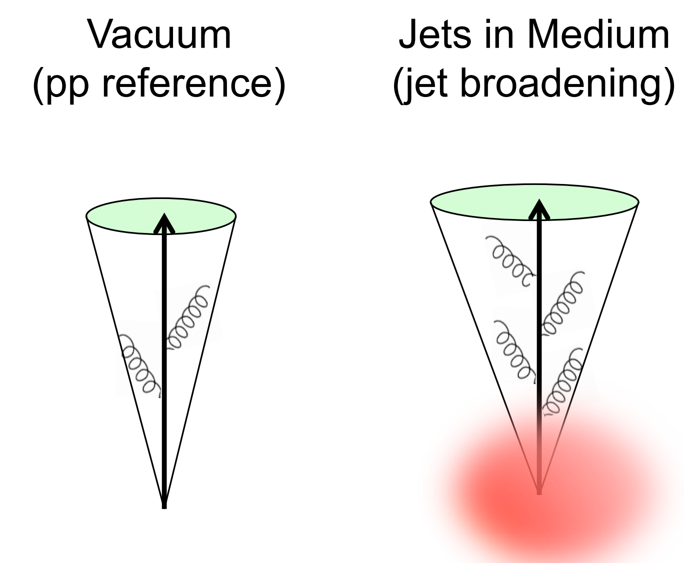
- From traditional p_T distribution to jet fragmentation function variables ξ

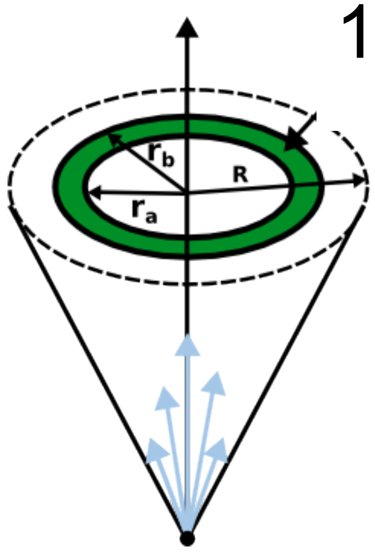


$$\xi = \ln(1/z) = \ln(p^{jet}/p_{||}^{track})$$

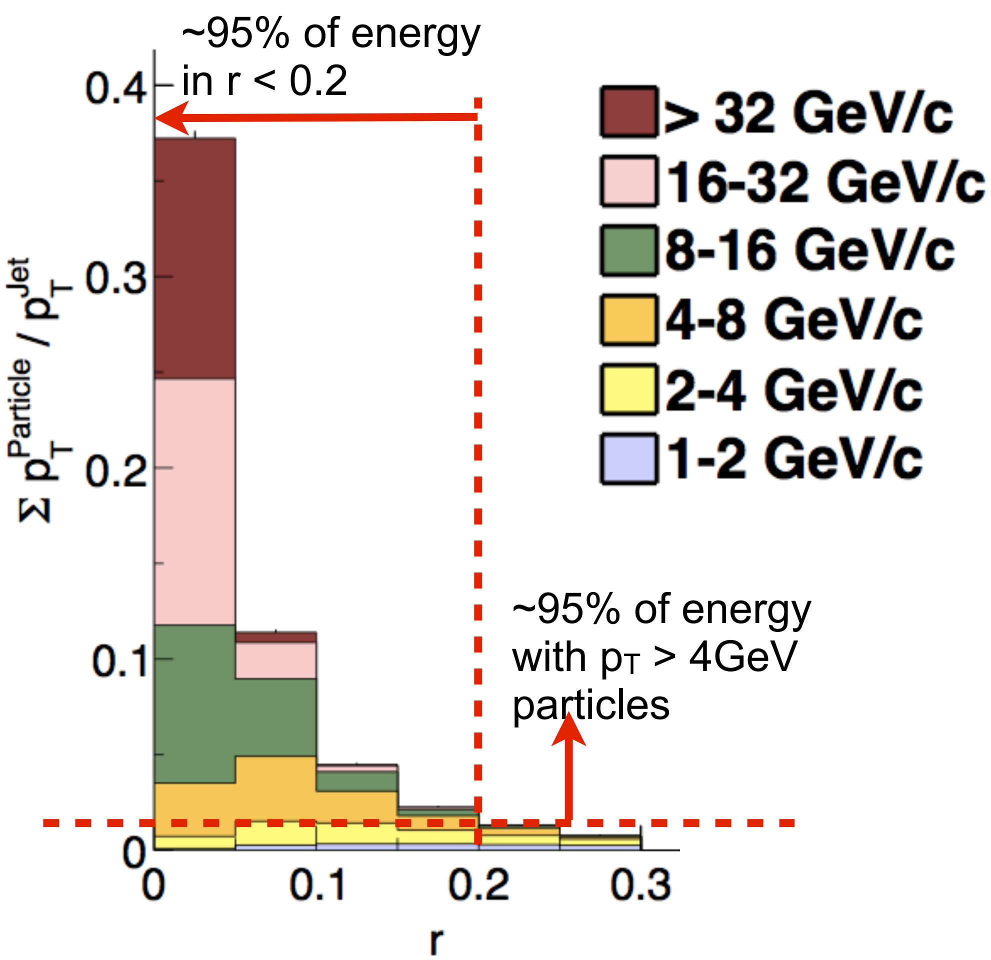
From jet fragmentation to jet shape

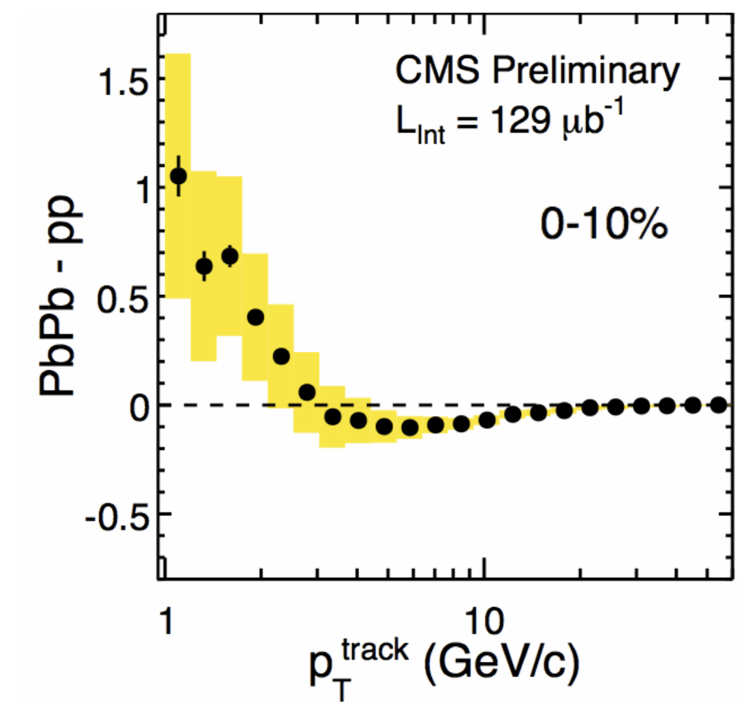
- How is the jet energy redistributed radially in PbPb?
  - Charged particle energy fraction from PYTHIA 100 GeV inclusive jet (anti-kT, R = 0.3)





$$r = \sqrt{(\eta_{jet}-\eta_{ch})^2+(\varphi_{jet}-\varphi_{ch})^2}$$





- High p_T particles close to jet axis → slight change in PbPb?
- Low p_T particles dominate away from jet axis

→ more particles at large radii in PbPb?