Probe QGP properties using jet observables at LHC

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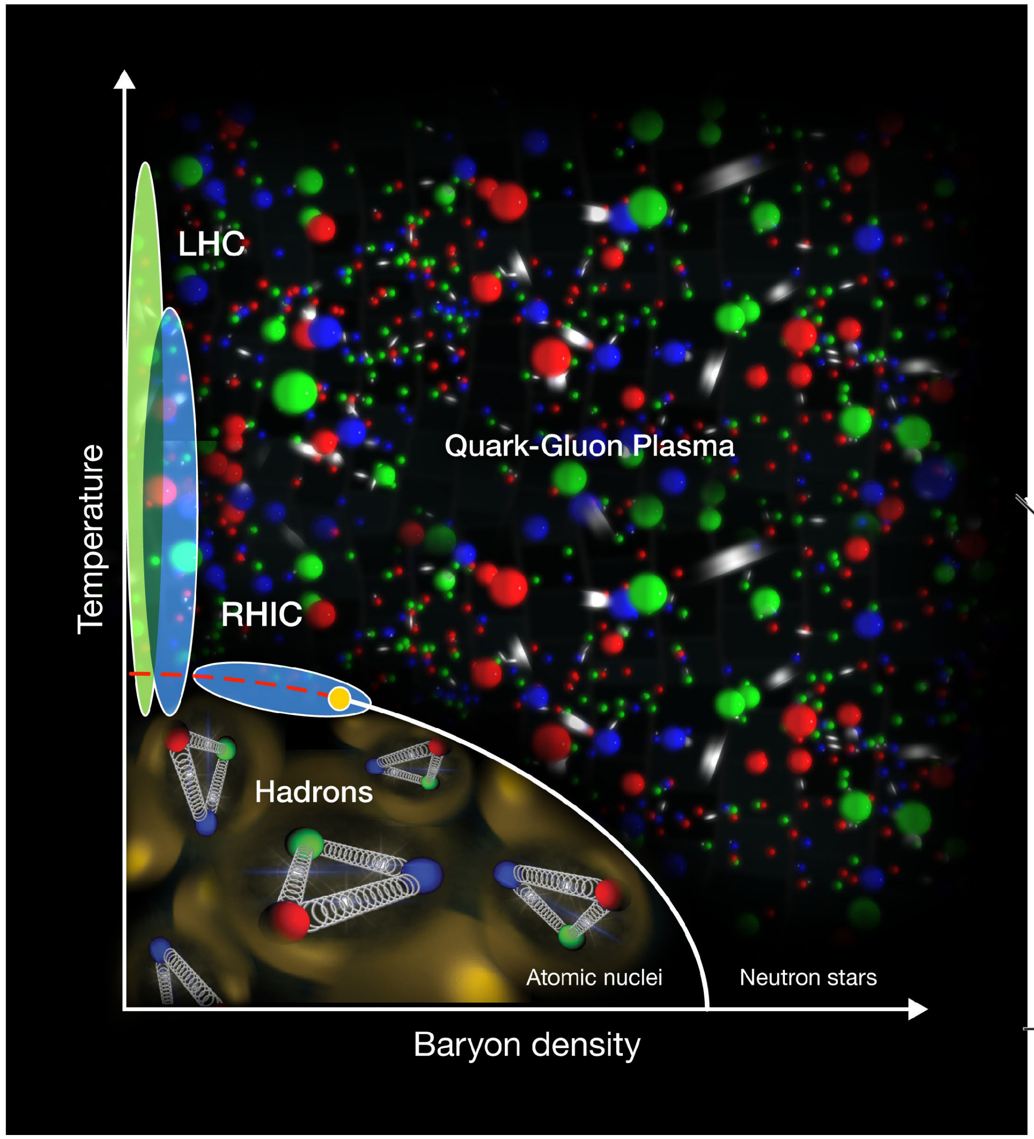
QCD phase transition and HI collision

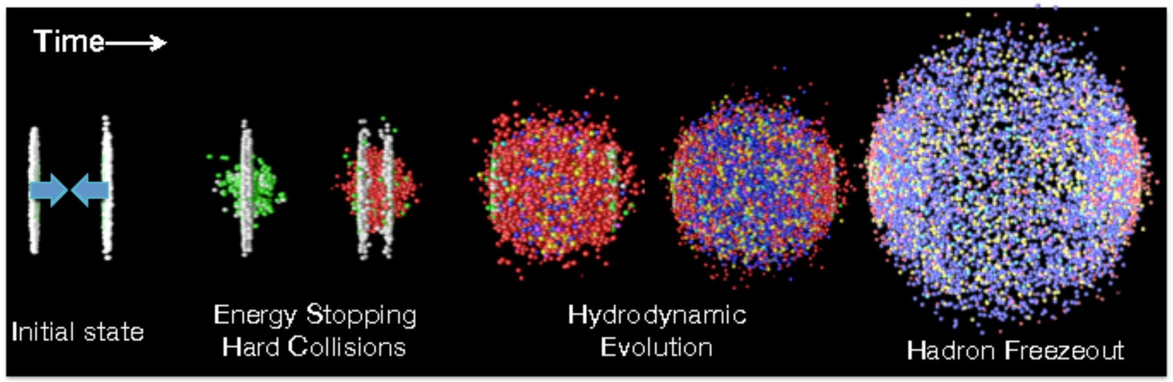
- QCD calculations (on the lattice) indicate that the phase transition occurs at a critical energy density

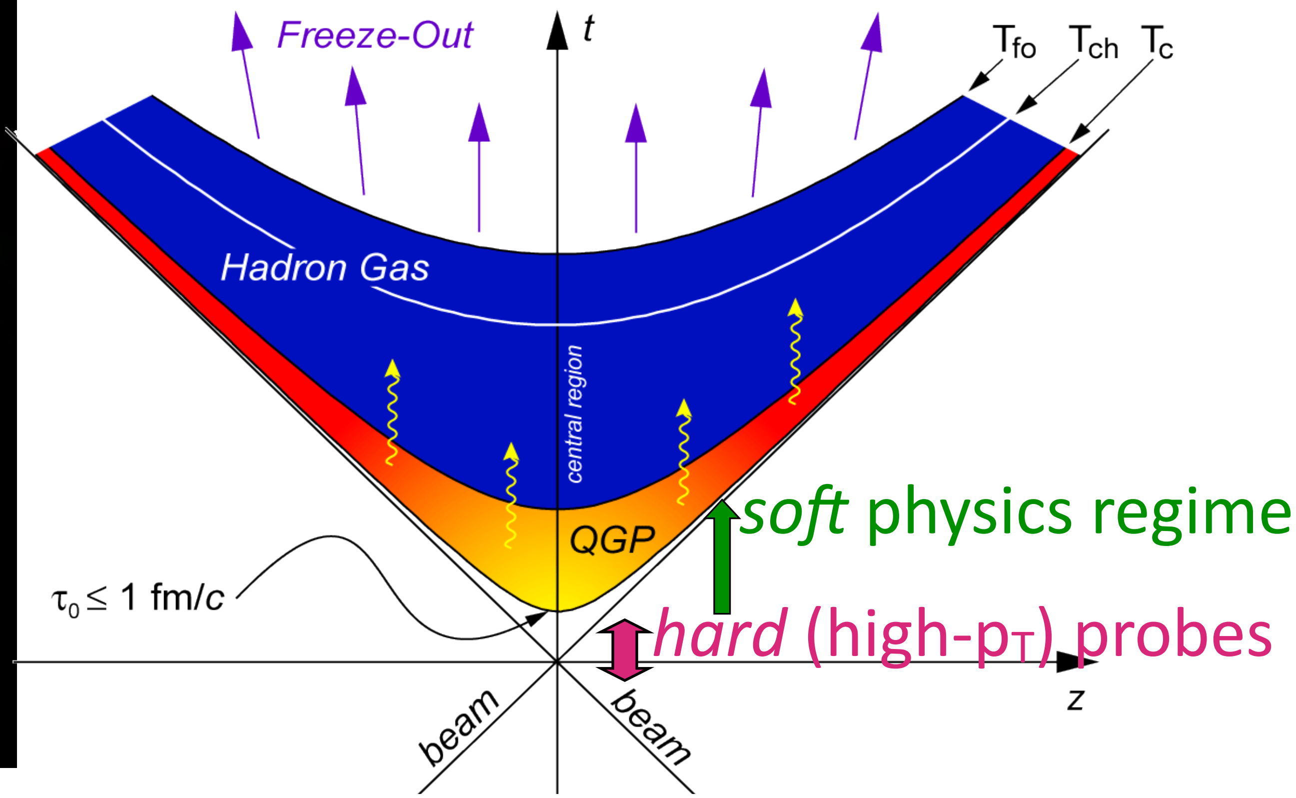
We can thus create a system of deconfined quarks and gluons

➡ by heating (T)

➡ by compression (matter density)

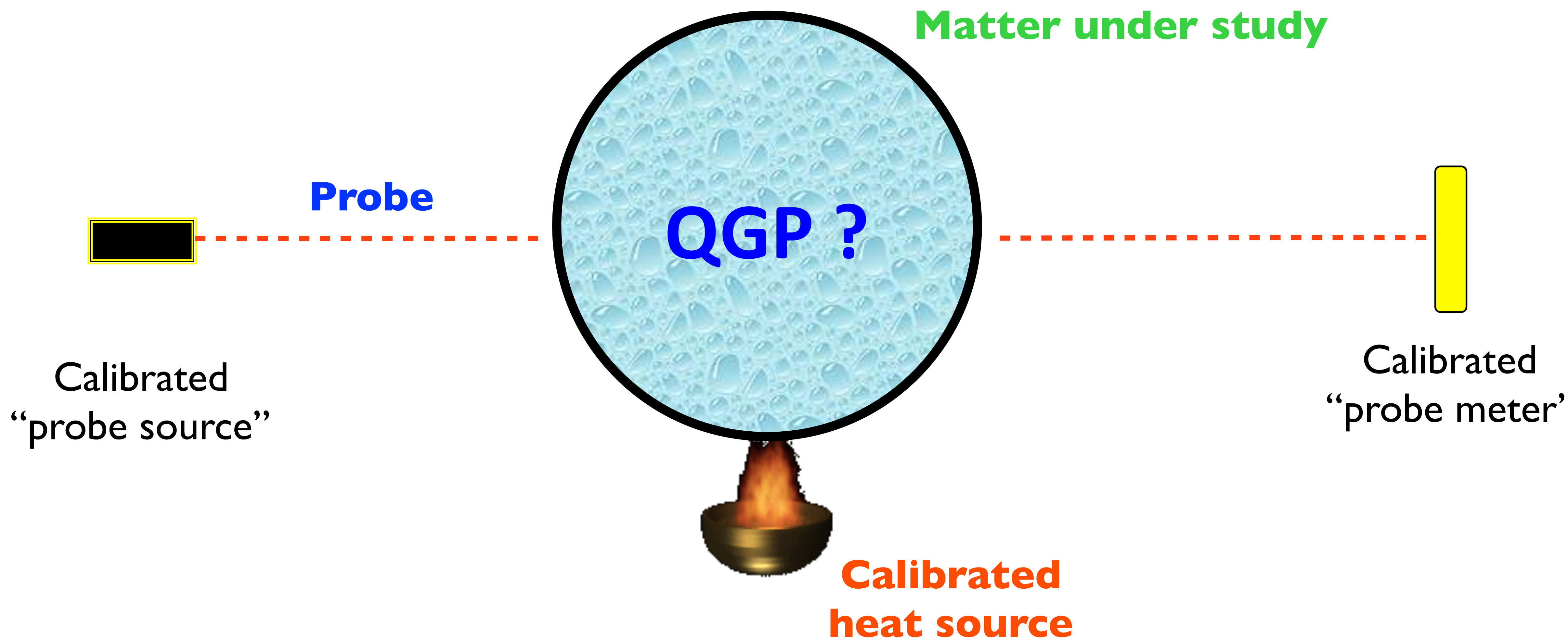




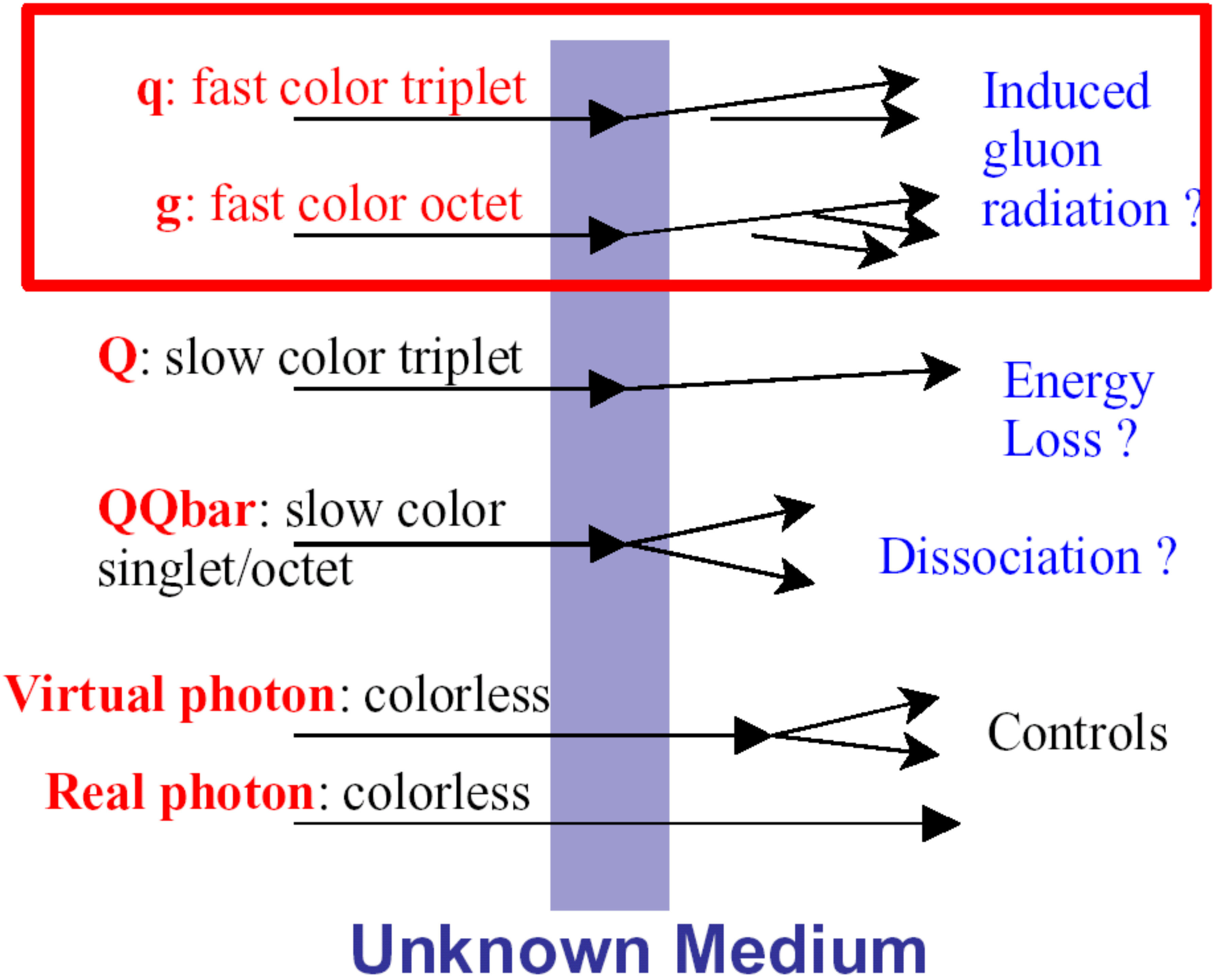


Probing QGP

We study the QCD matter produced in HI collisions by looking how well understood probes are modified, as a function of temperature (centrality of the collisions)



The Probes Gallery



Jet Suppression

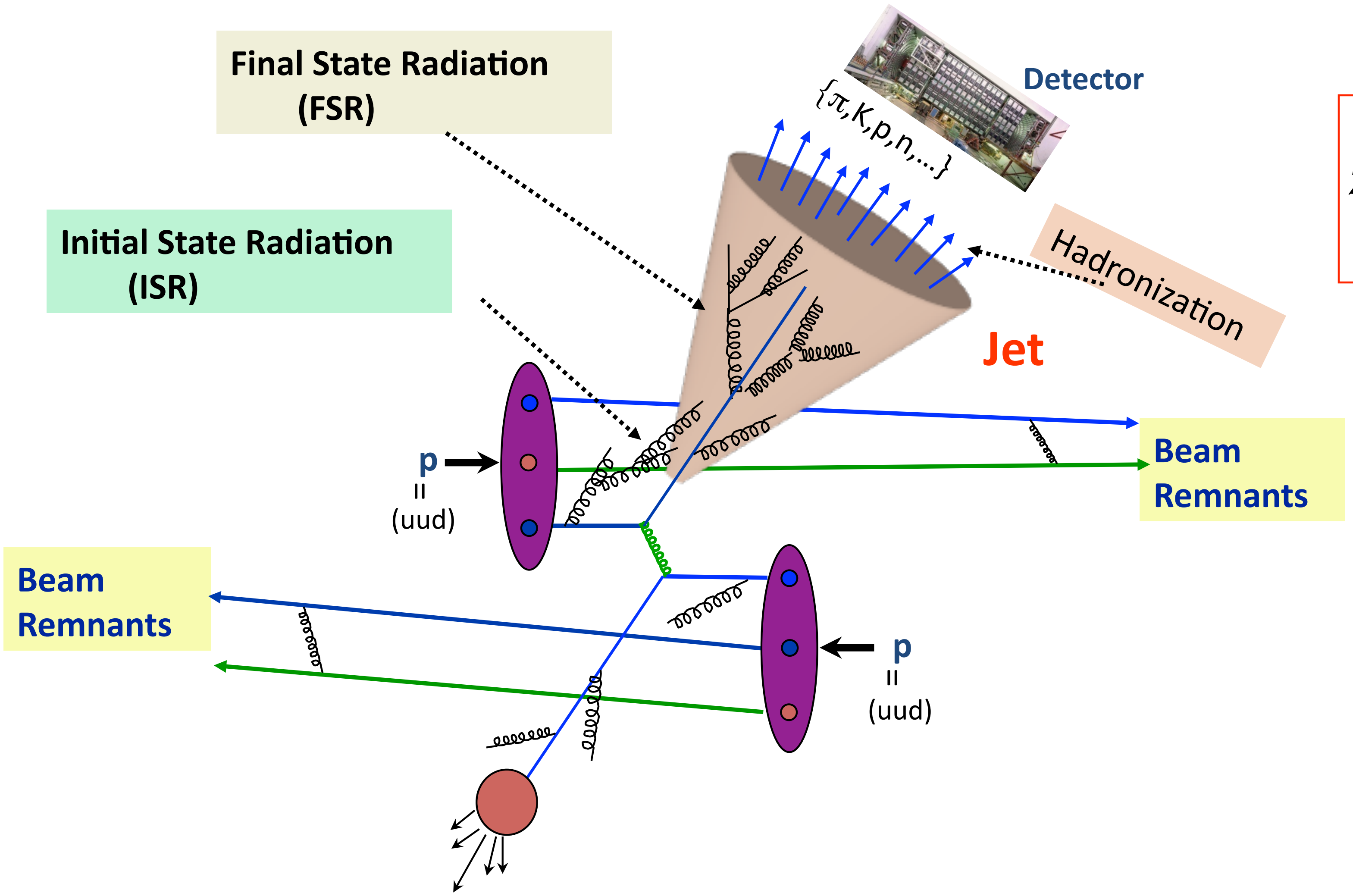
charm/bottom dynamics

J/Ψ & ϒ

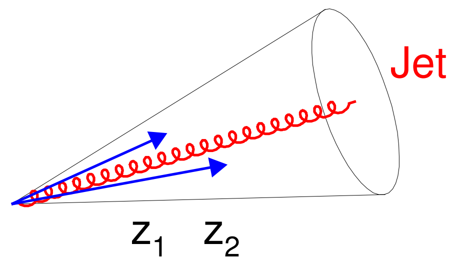
direct photons CONTROL

The importance of the control measurement(s) cannot be overstated!

Jets: a tomographic probe of the medium



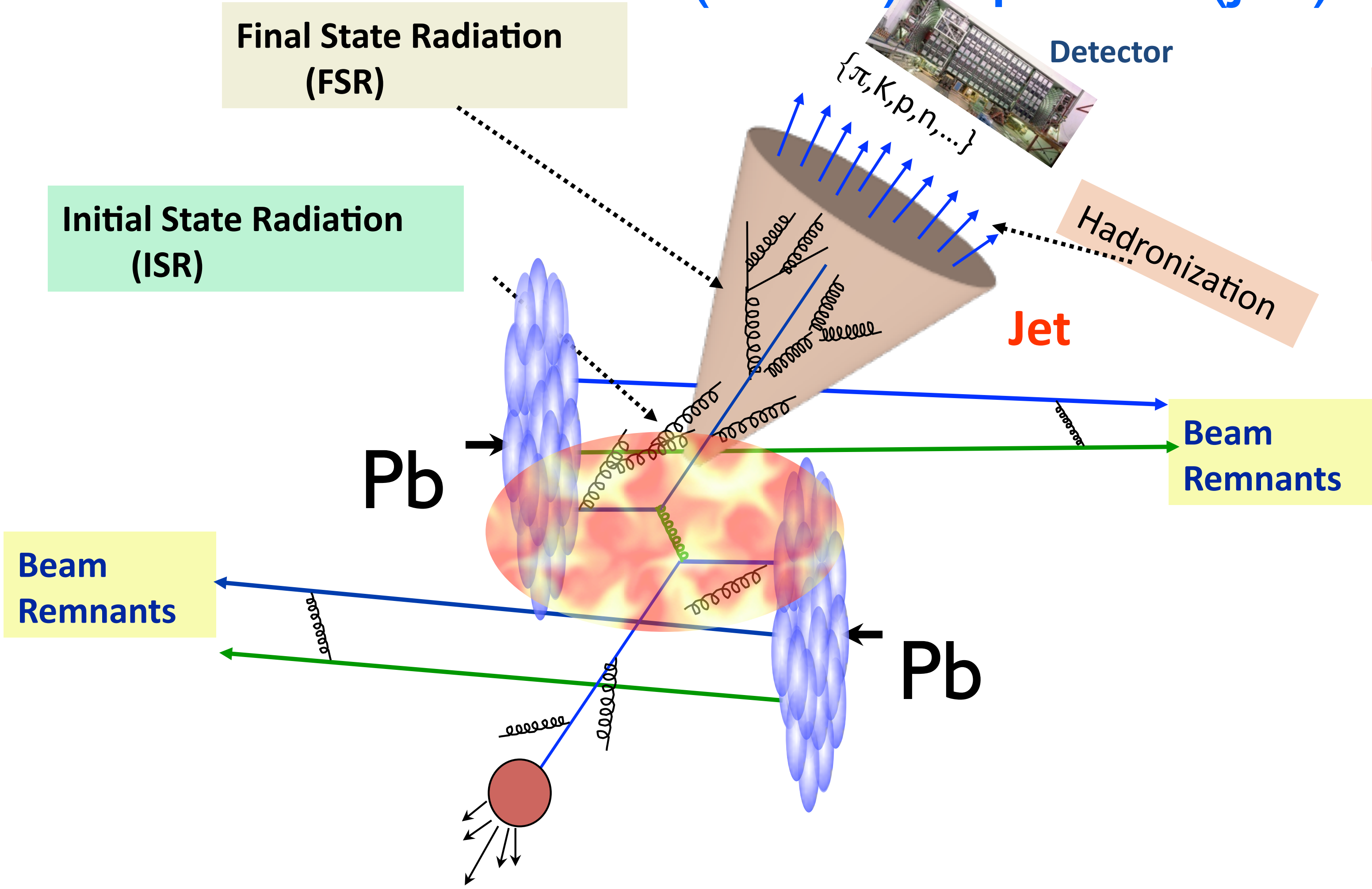
$$z = \frac{p_{\mathrm{hadron}}}{p_{\mathrm{jet}}}$$



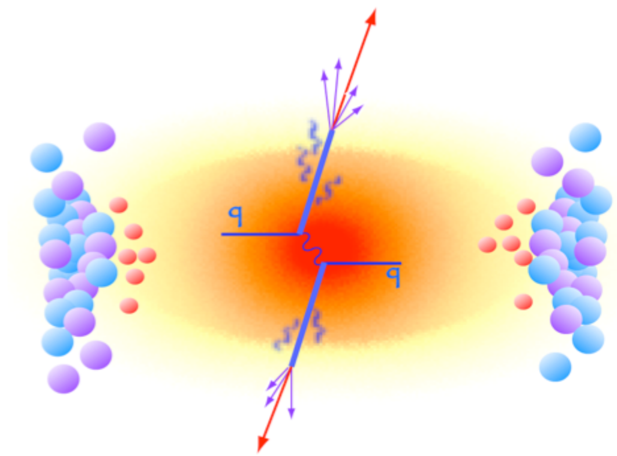
- High momentum transfer scattering in 2→2 process (LO pQCD) develops a partonic shower and hadronizes into final state particles (non pQCD) collimated in a spray of hadrons (jet)

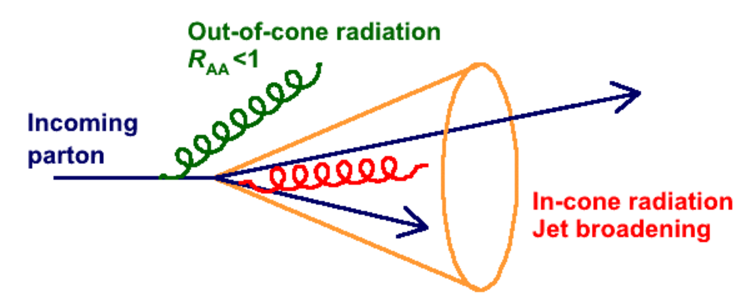
Jets: a tomographic probe of the medium

Probe source(QCD) + probe (jet) → QGP properties



$$z = \frac{p_{\text{hadron}}}{p_{\text{jet}}}$$

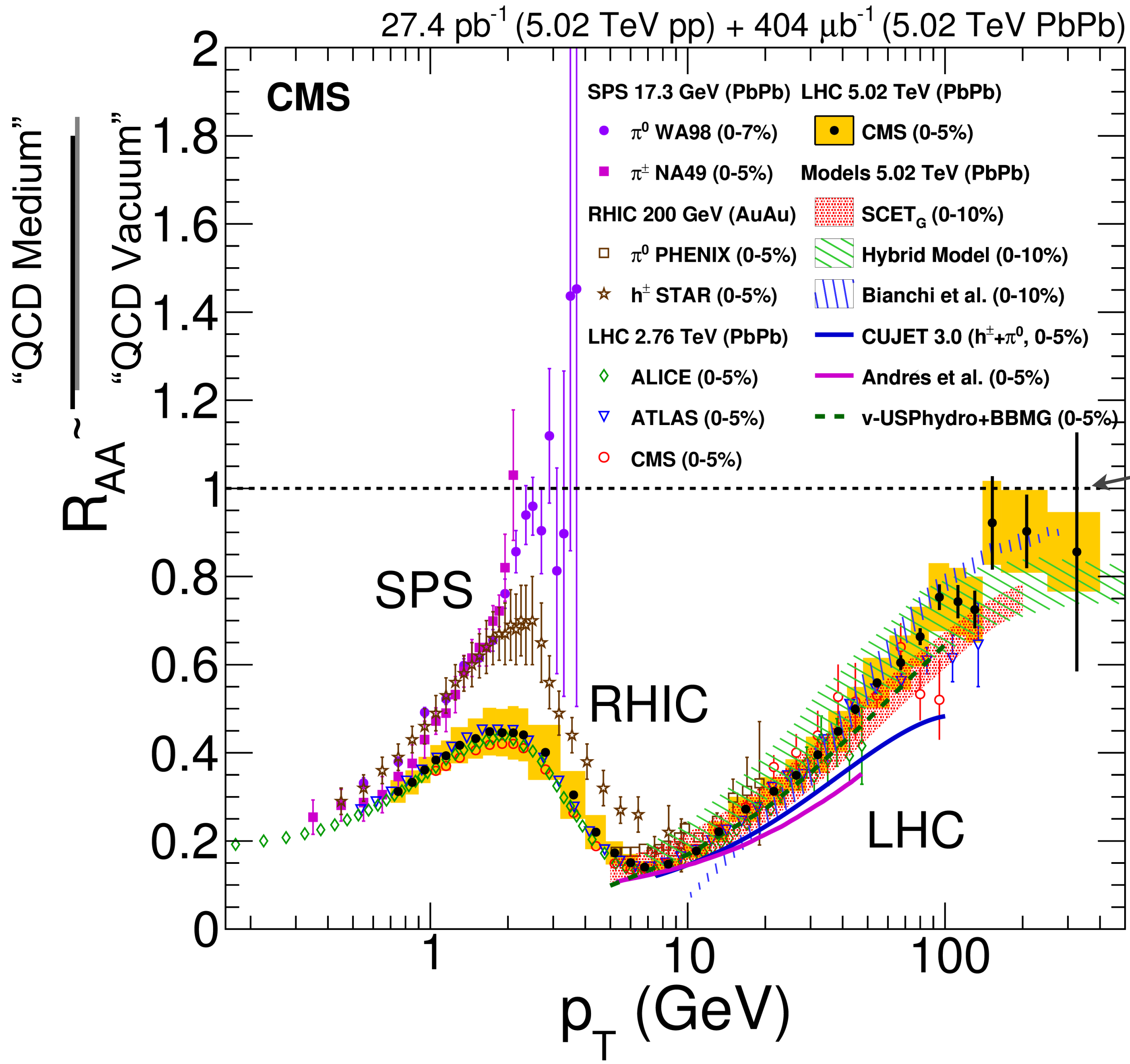




- High momentum transfer scattering in 2→2 process (LO pQCD) develops a partonic shower and hadronizes into final state particles (non pQCD) collimated in a spray of hadrons (jet)
- Partons loose energy ΔE (collision + radiation) when traversing the medium

$$\text{Jet(E)} \rightarrow \text{Jet (E' = E-}\Delta\text{E) + soft particles(}\Delta\text{E)}$$

Jet quenching: suppression of high p_T particles

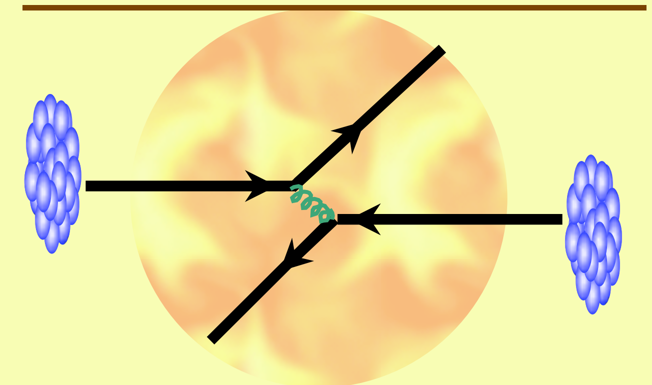


$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{d^2N_{AA}/dp_T d\eta}{d^2\sigma_{pp}/dp_T d\eta}$$

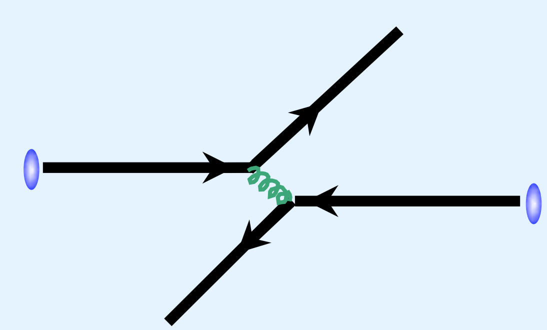
If AA = superposition of pp

R_{AA}=

PbPb measurements

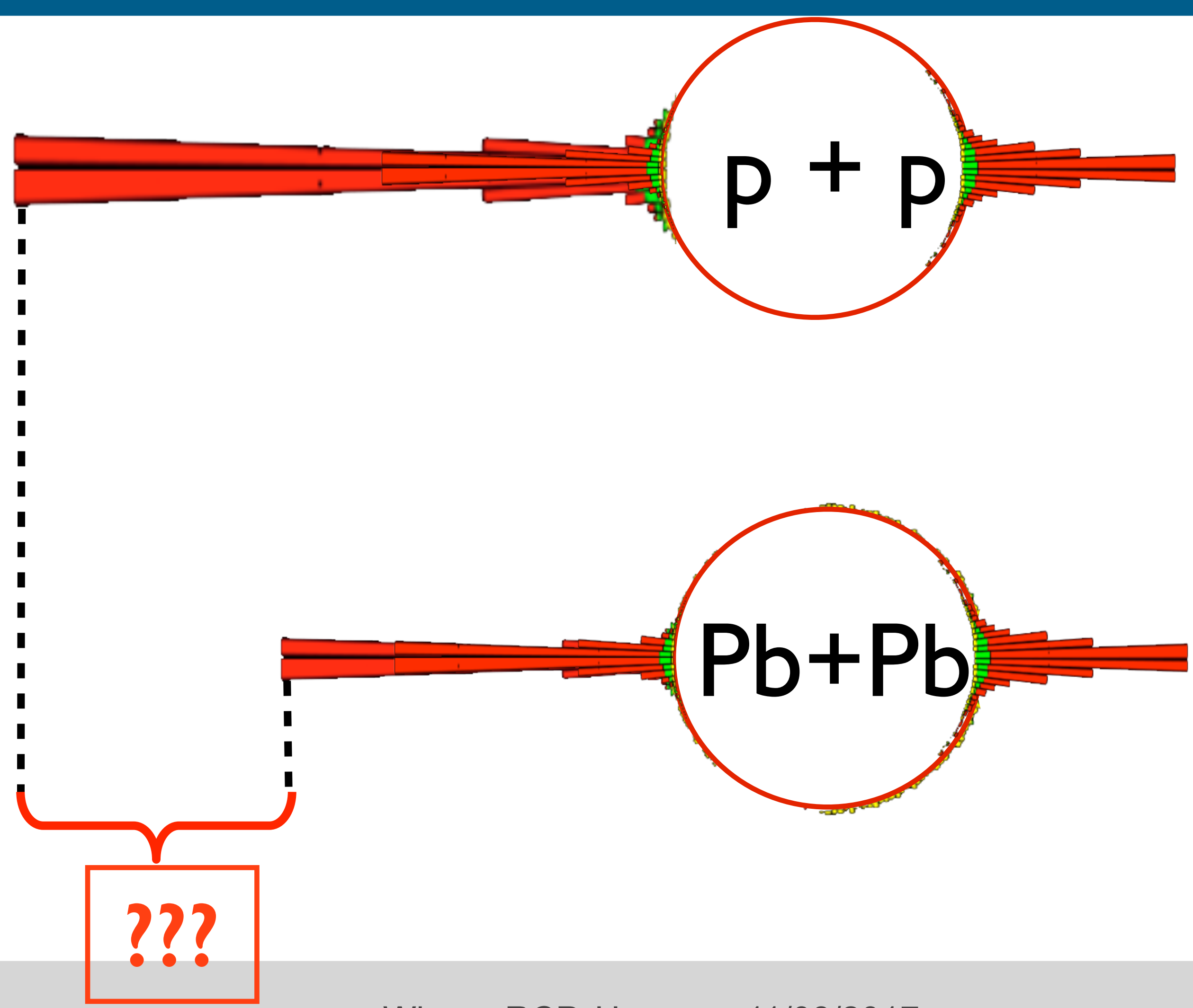


scaled pp reference

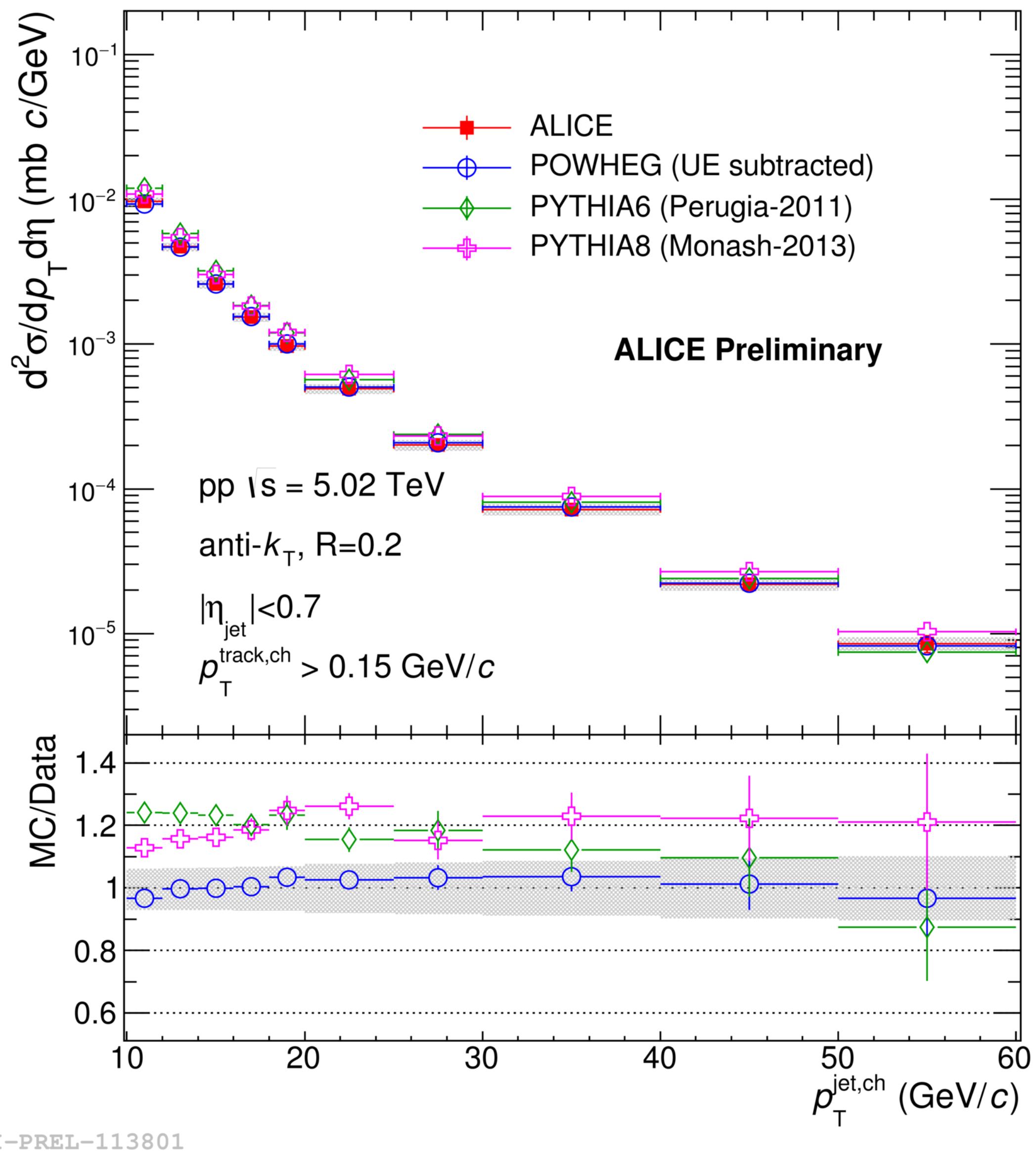


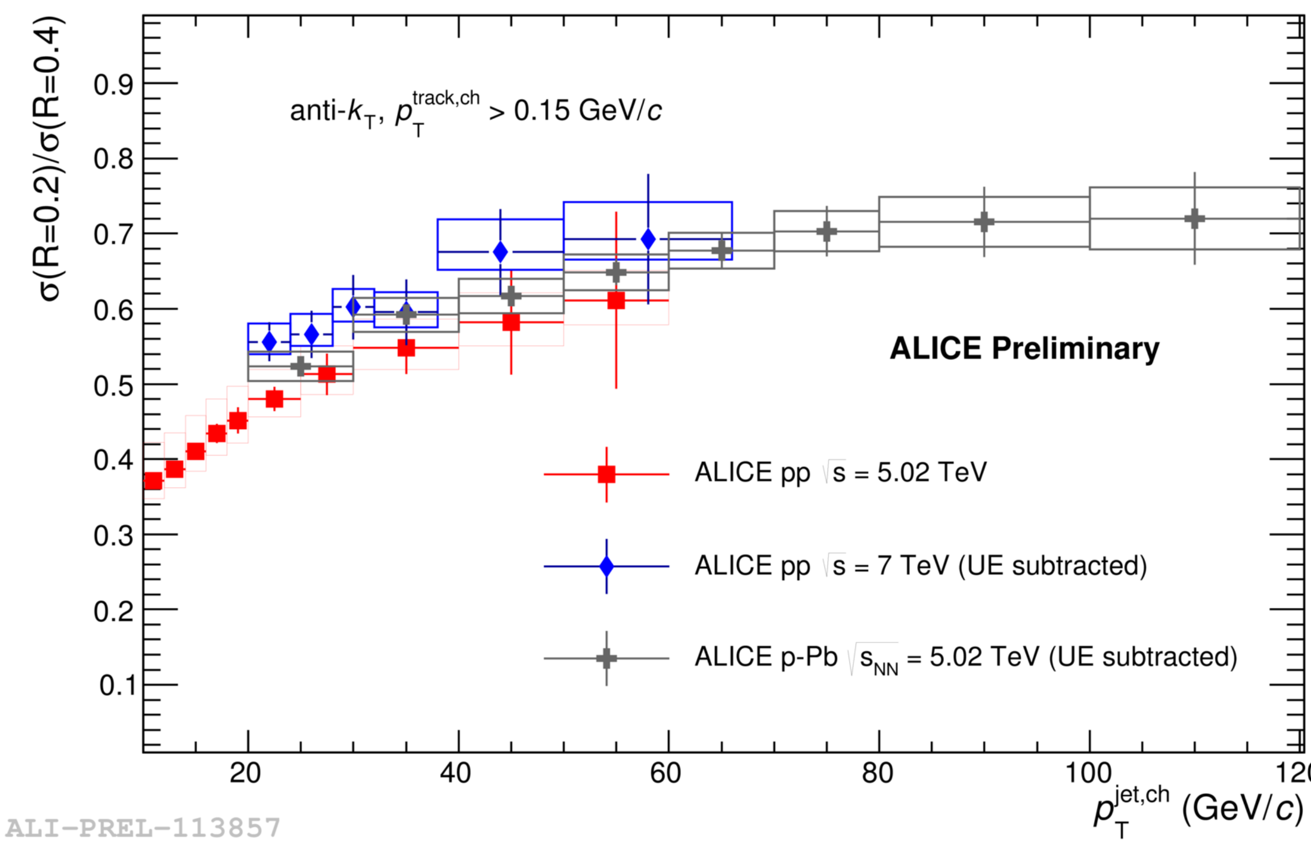
- Constraints on the parton energy loss in QGP

How much energy do single jets loose?



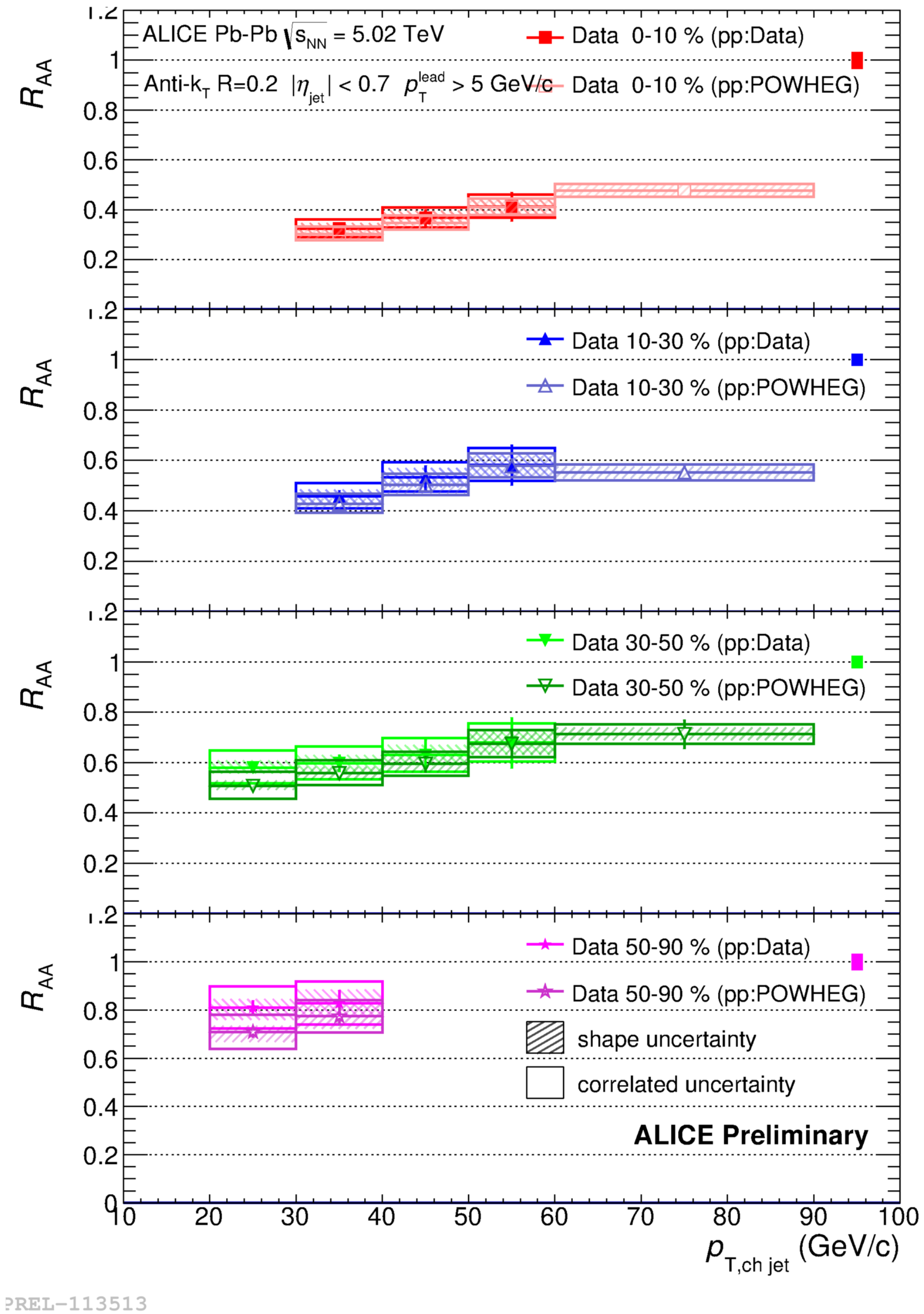
Jet cross section in pp collisions





- Jet cross section is well described by POWHEG+PYTHIA8 NLO calculations within systematic uncertainties
- Cross section ratio between R = 0.2/R = 0.4 consistent with different $\sqrt{s}$, slightly increasing with jet p_T → reflects jet collimation

Jet nuclear modification factor R_{AA}



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

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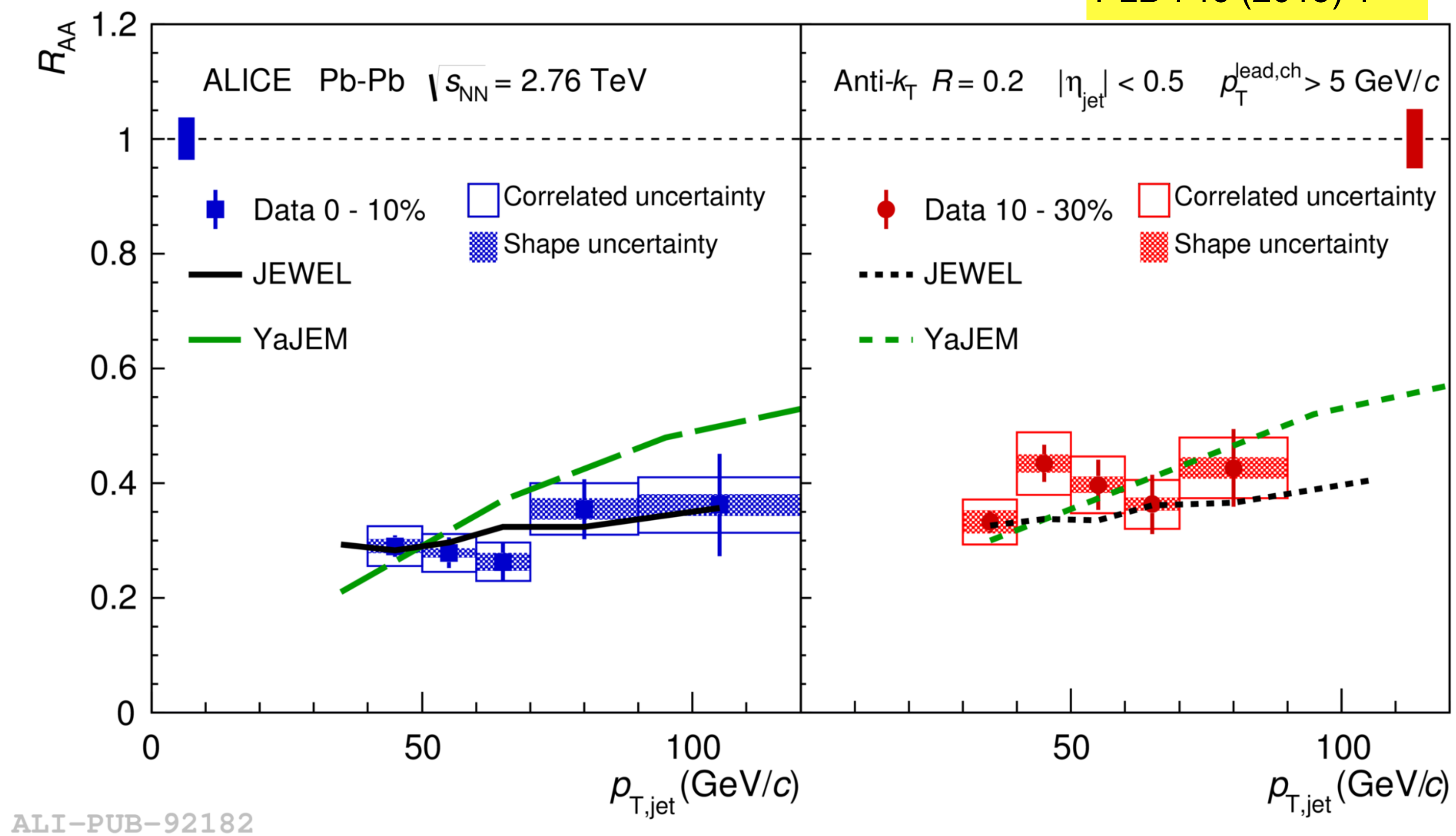
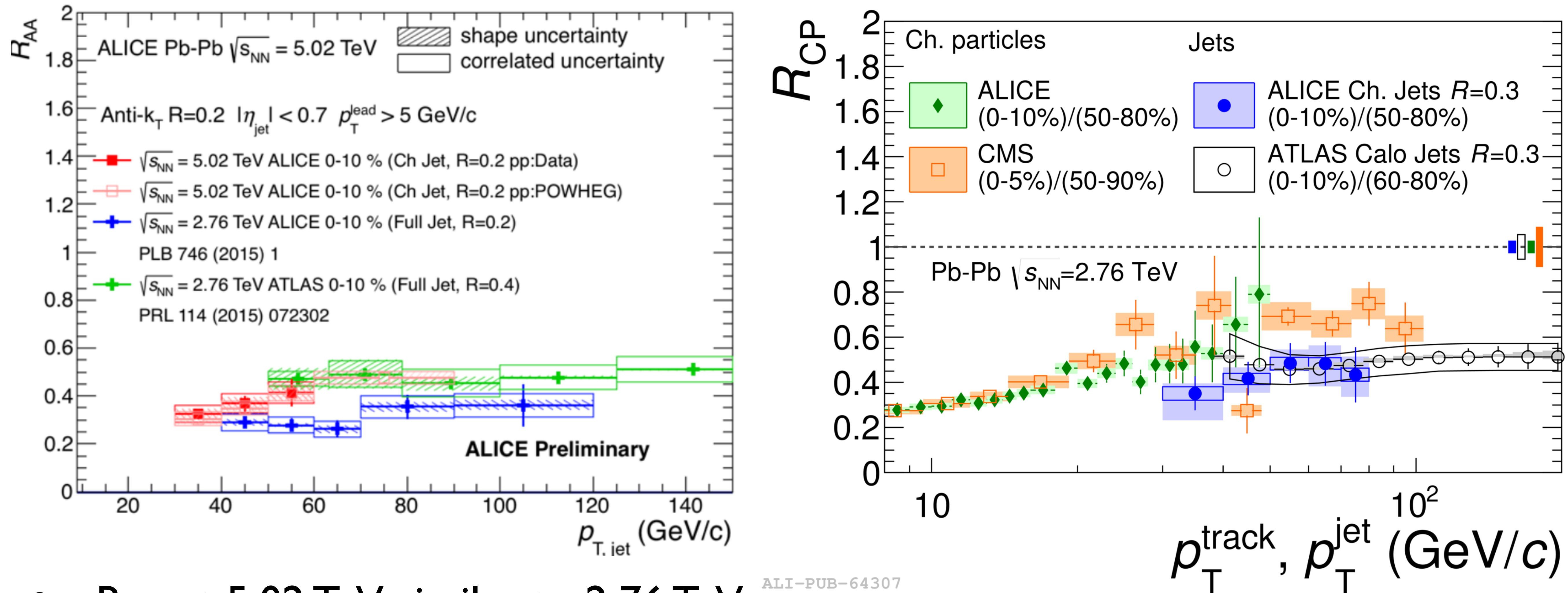


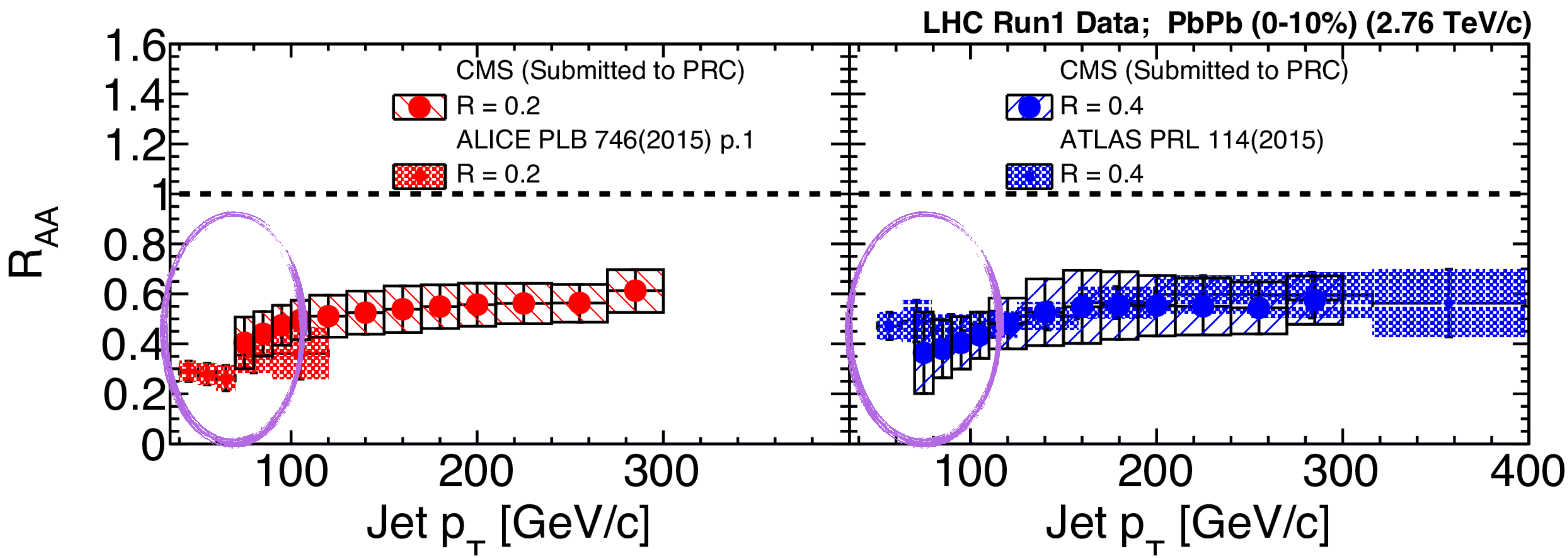
- Strong suppression of jet yield in most central collisions
- JEWEL models the suppression as observed in data

Jets and hadrons R_{AA}



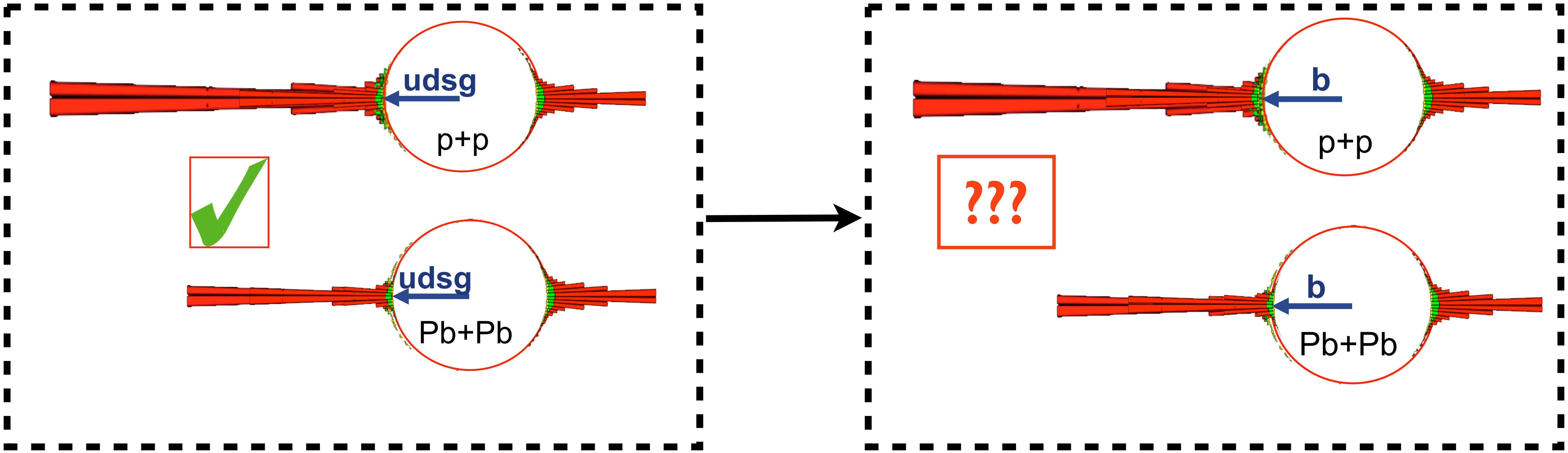
- R_{AA} at 5.02 TeV similar to 2.76 TeV
  - ➡ "compensation" between increasing suppression and modification of the shape of the spectra
- Charged jet and Calo jets have similar features of jet quenching
- Suppression of jet yield and charged particles are quite similar
  - ➡ jets fragment into high-p_T particles in pp and PbPb the same way

How low p_T jet quenched?



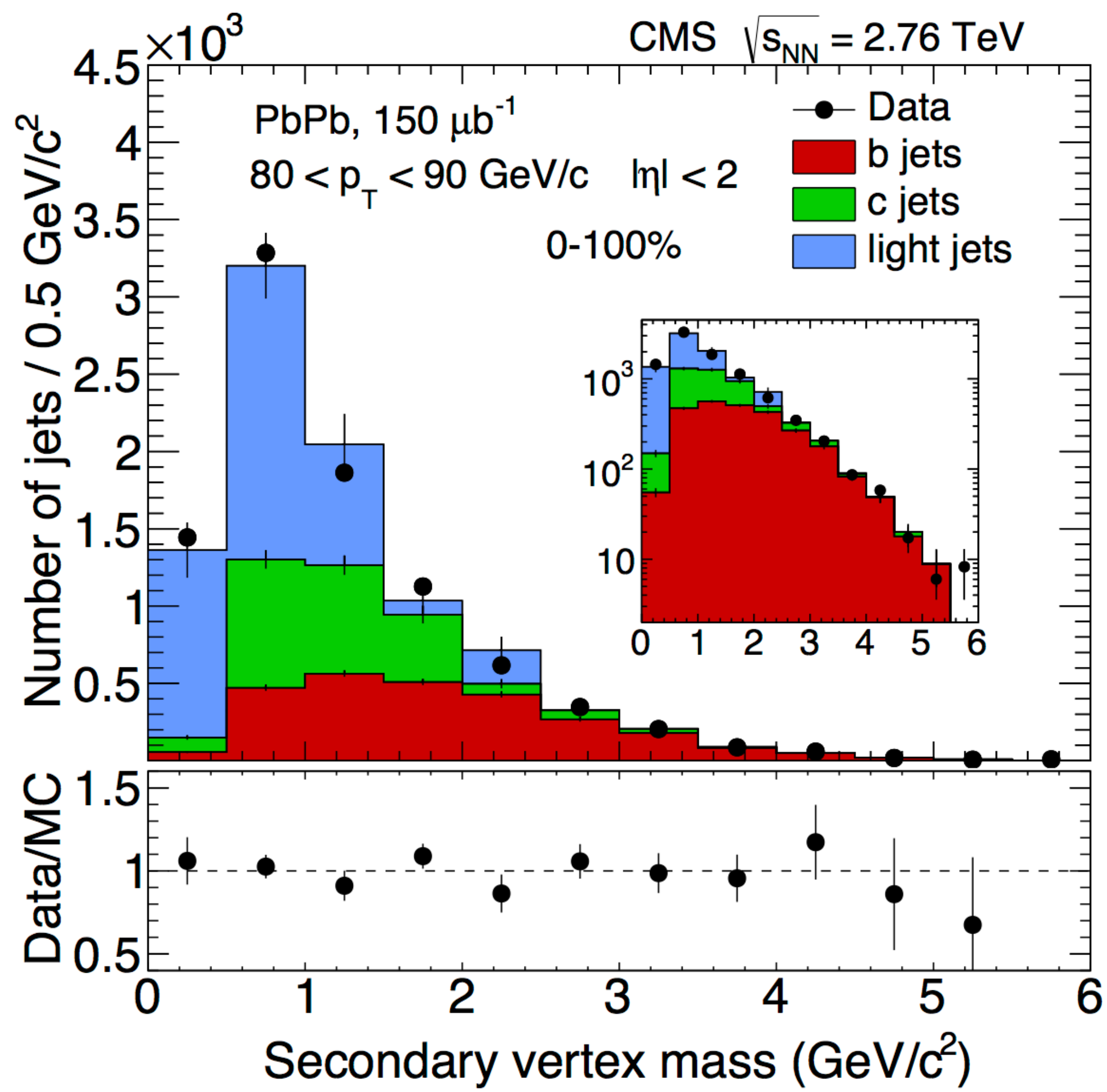
- High p_T jet R_{AA} is in good agreement, however low p_T behavior is different
  - ➡ different jet cone size, precise low p_T measurements quite important

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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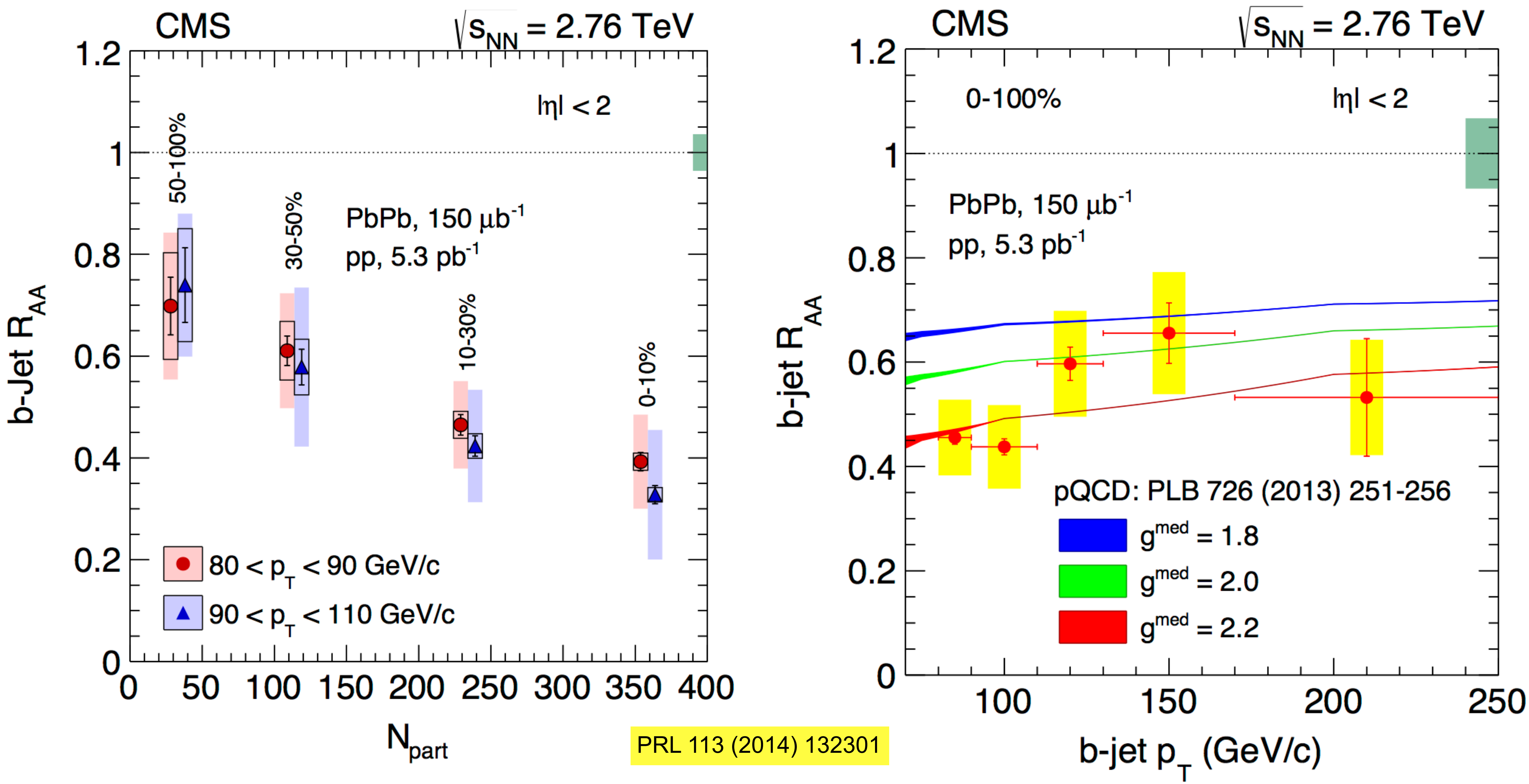
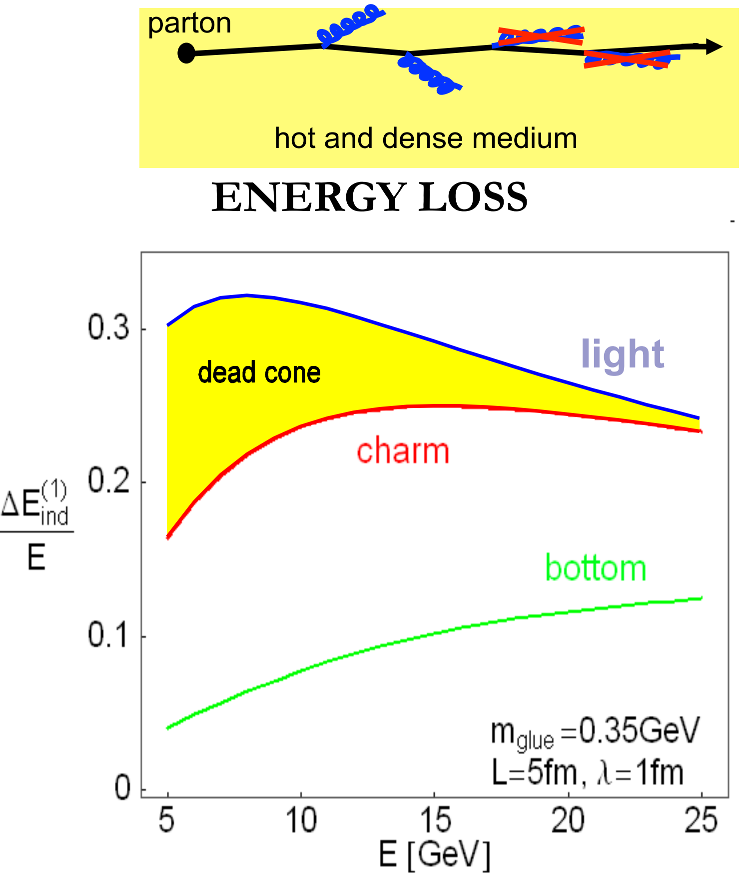
b-jet suppression

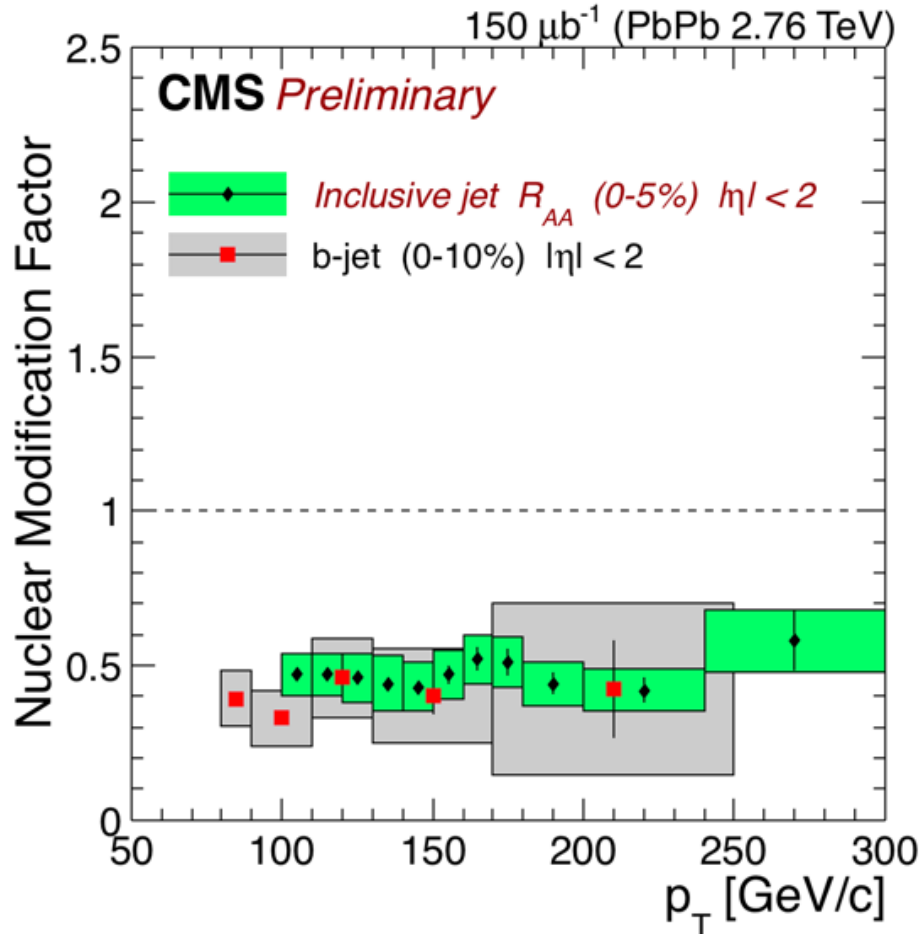


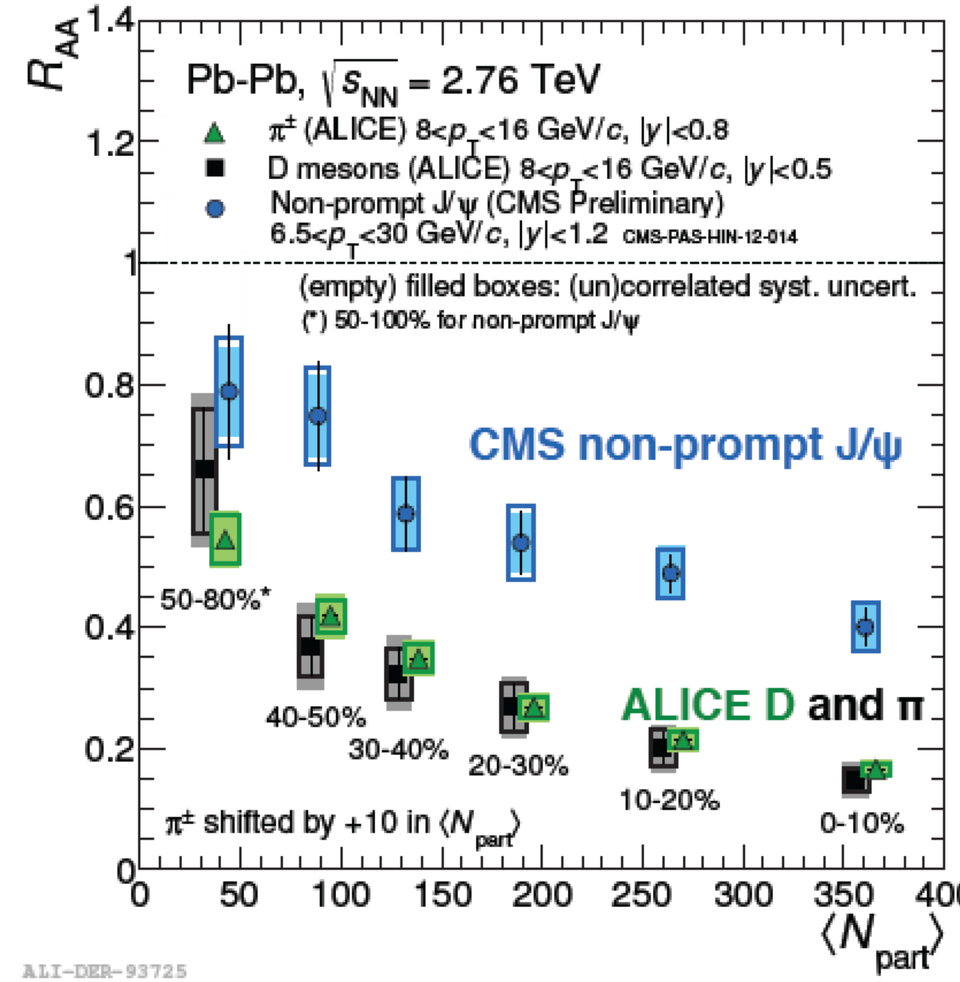
- Evidence of b-jet suppression in central PbPb collisions
- b-jet RAA favours pQCD models that include strong jet-medium coupling

Flavour/mass dependence: yes, no, maybe?



M.Djordjevic PRL 94 (2004)



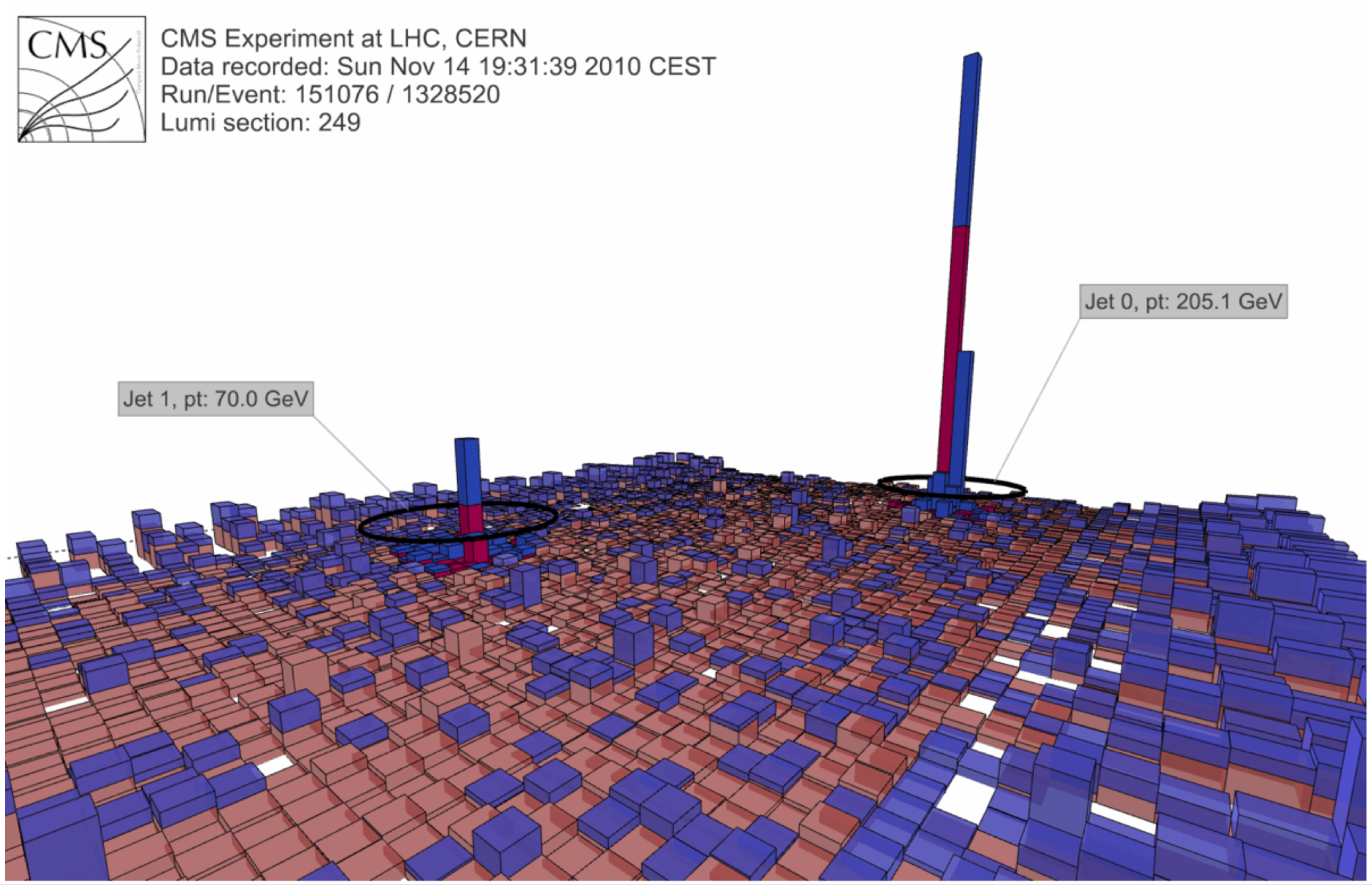


- R_{AA}(b-jet) ≃ R_{AA}(inclusive-jet) at high p_T, no strong flavour dependence
- $R_{AA}(J/\psi \leftarrow B) > R_{AA}(D) \simeq R_{AA}(\pi)$

Is the energy loss depending on the quark mass as predicted?

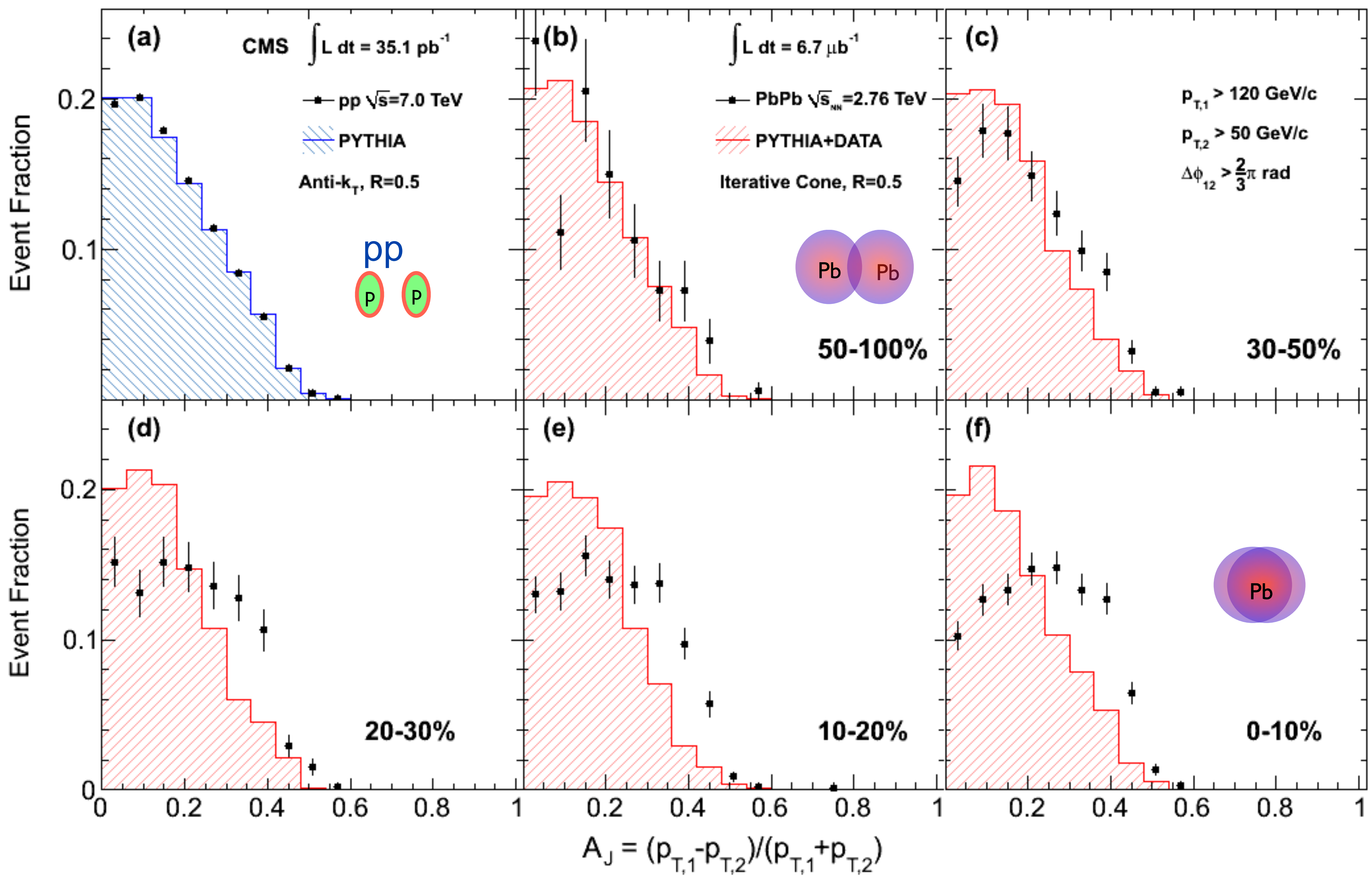
➡ Precise measurements down to low p_T are needed to conclude

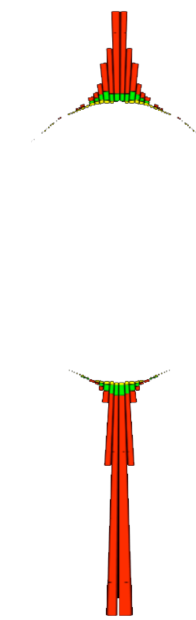
More exclusive observables: di-jets



Jet energy imbalance

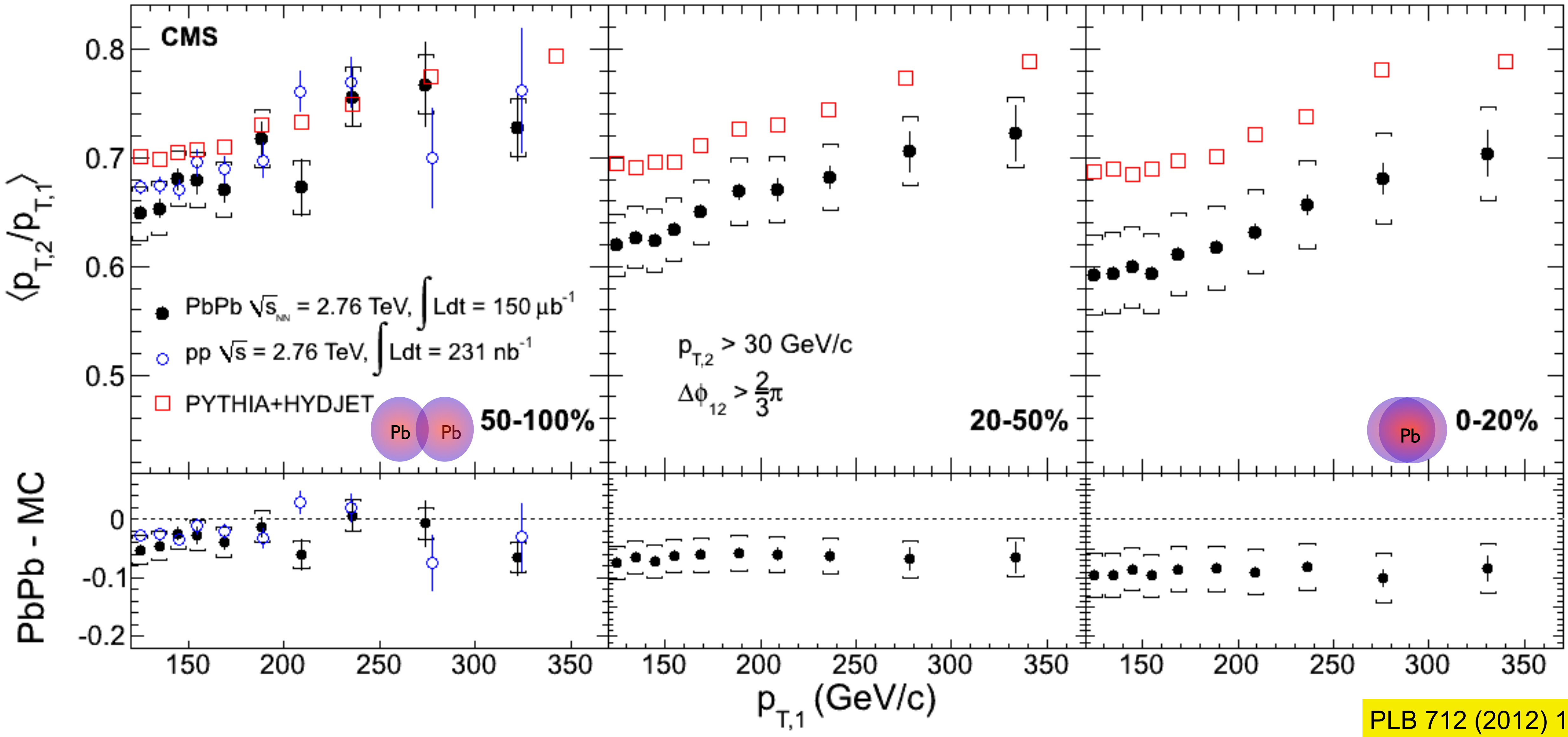
PRC 84 (2011) 024906





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

Dijet p_T imbalance



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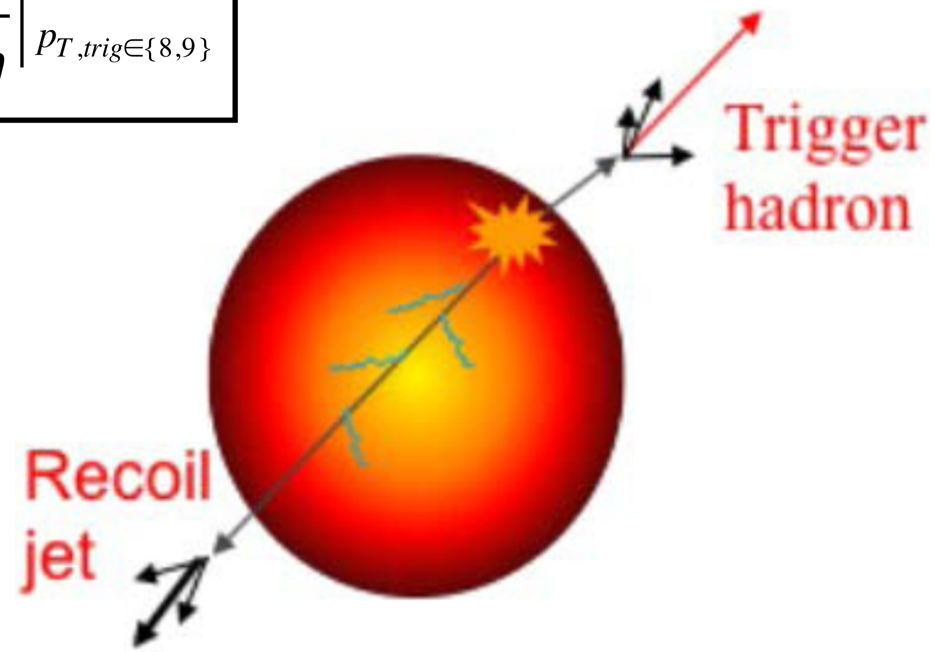
- Energy imbalance increases with centrality
- p_T-ratio deviates from the unquenched reference in a p_T-independent way

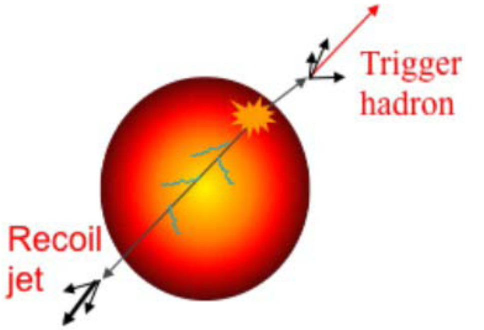
Semi-exclusive measurements: recoil jets

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\eta}\Bigg|_{p_{T,trig} \in \{20,50\}} - c_{\mathrm{Ref}} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp_{T,jet}^{ch} d\eta}\Bigg|_{p_{T,trig} \in \{8,9\}}$$



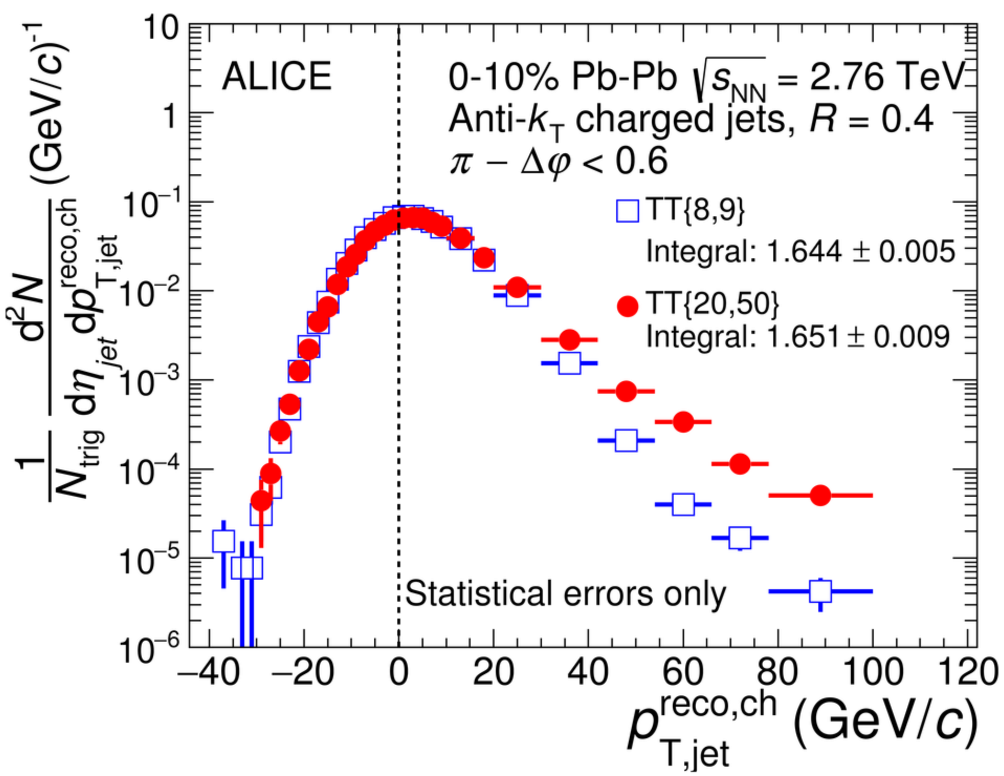
Semi-inclusive hadron-jet correlations

- New observables of recoil jet measurements:
  - pp: calculable via pQCD
  - AA: a good handle on the combinatorial background by varying $p_{T,trig}$ →systematically well-controlled at low p_{Tjet}, large R
  - Trigger hadron close to surface, but no bias on recoil jets



$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\eta}\Bigg|_{p_{T,trig} \in \{20,50\}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\eta}\Bigg|_{p_{T,trig} \in \{8,9\}}$$

c_{Ref}: accounts for invariance of jet density with TT-class ($c_{Ref} \approx 0.94$)



TT = Trigger Track

TT{X,Y} means $p_{T,trig} \in$ {X,Y} GeV/c

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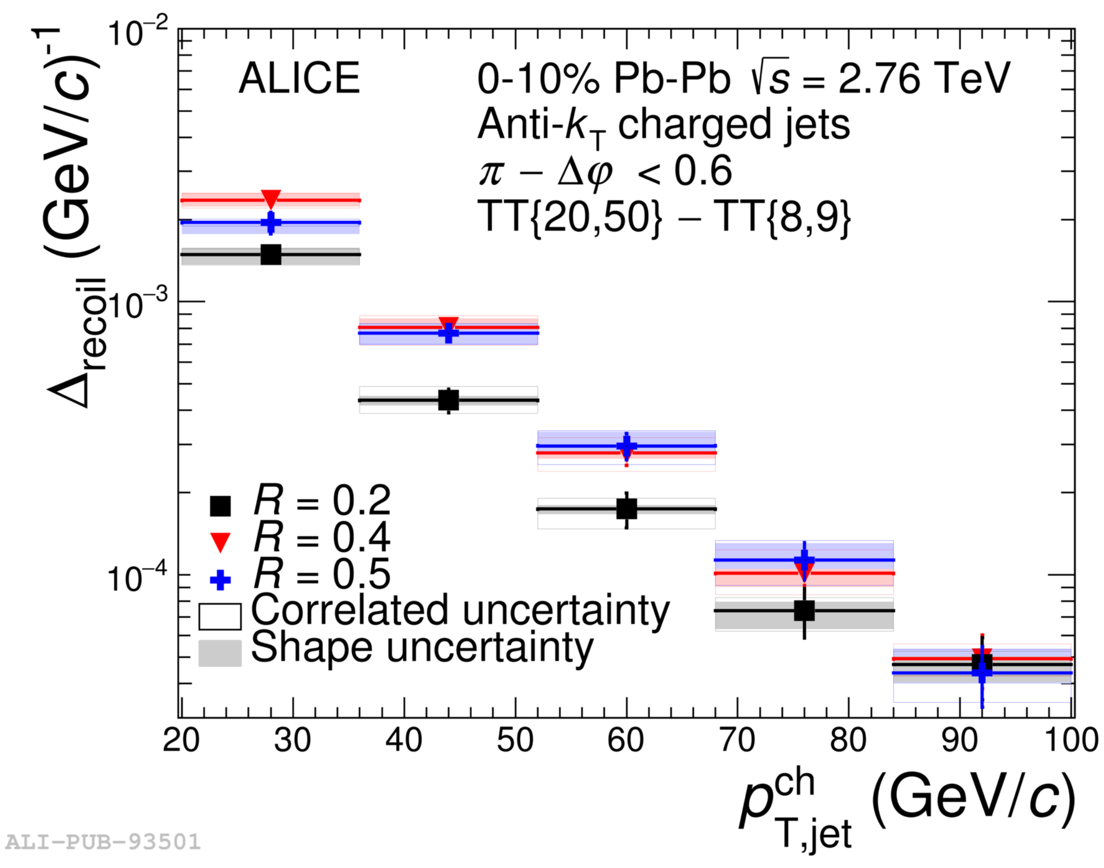
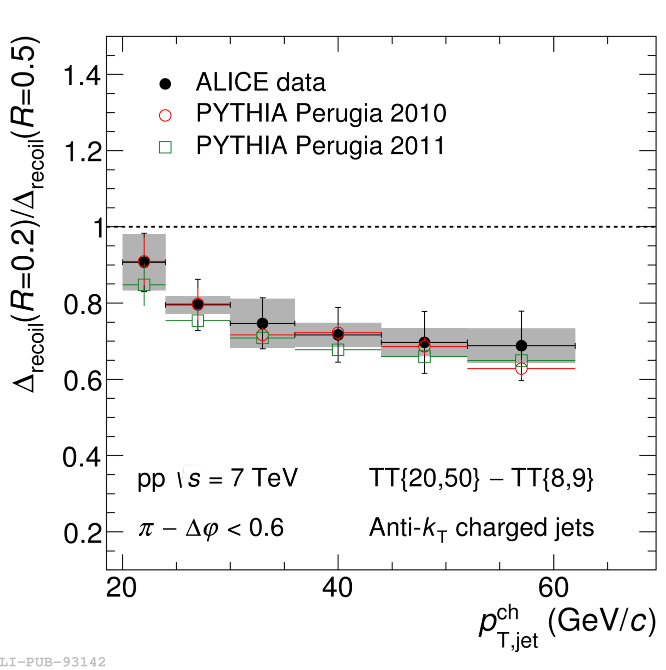
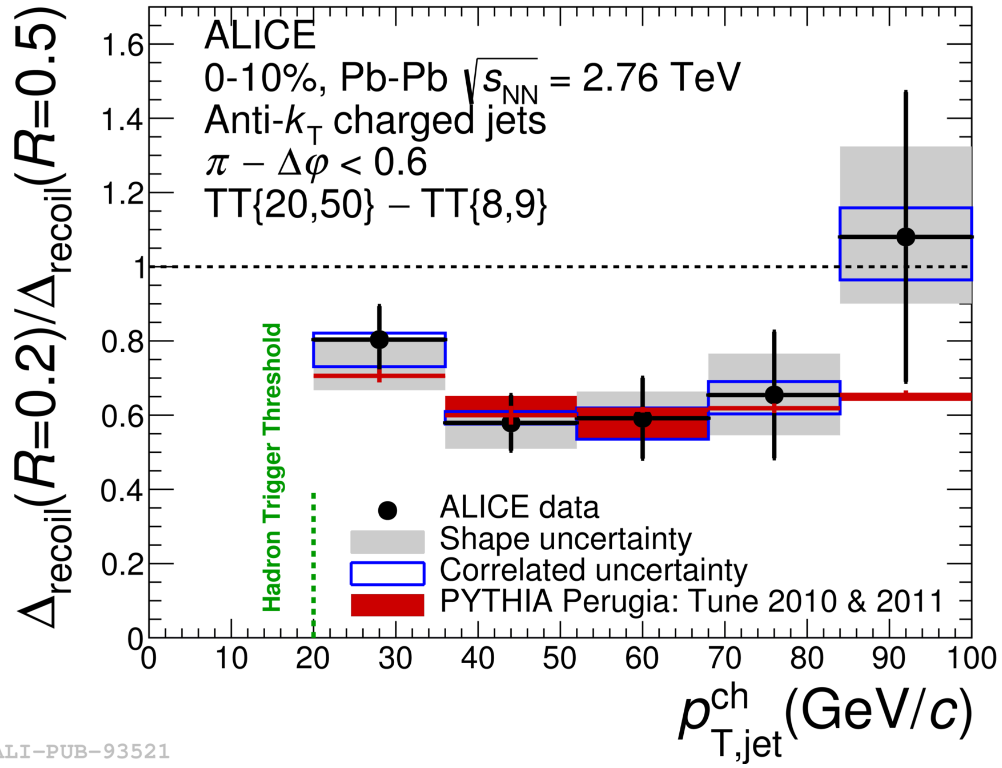
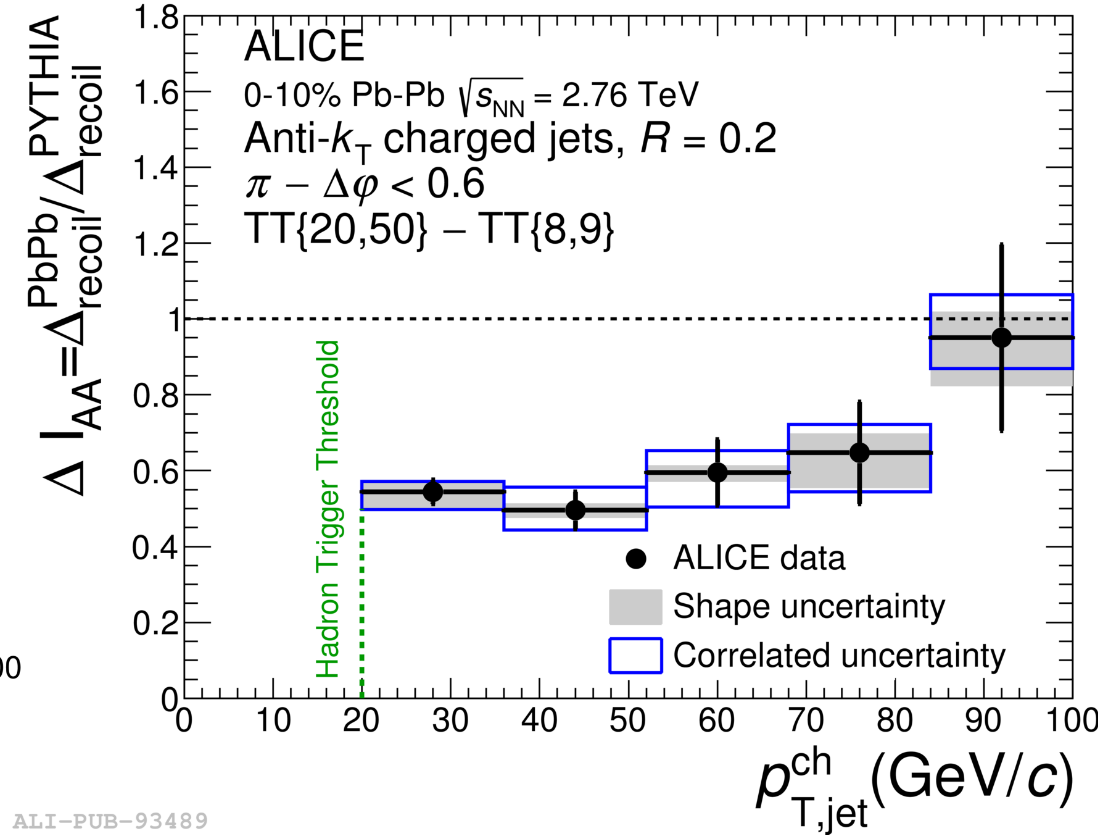


Recoil jet yield measurements

- Trigger-normalized yield of jets recoiling from a high p_T trigger



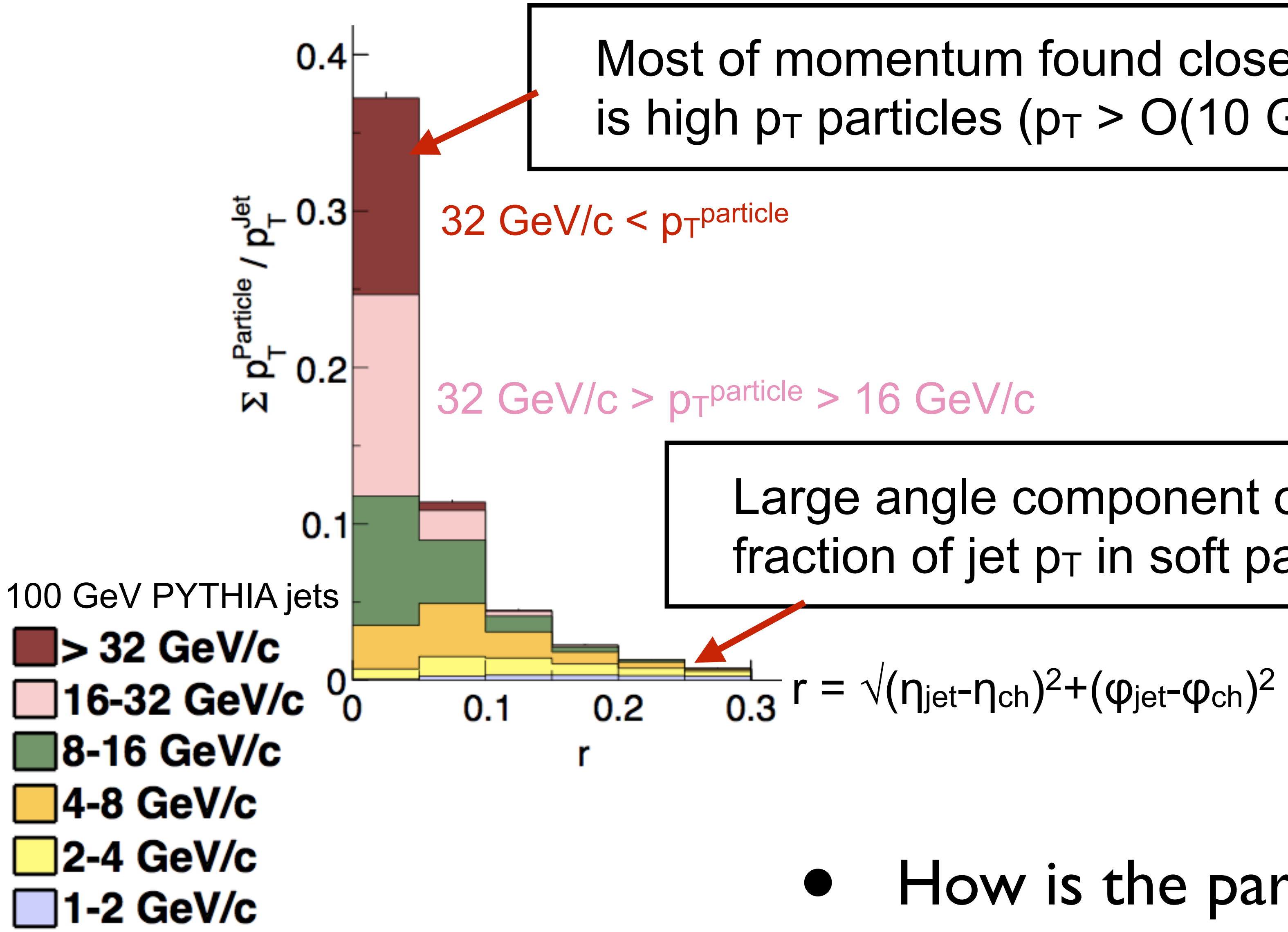


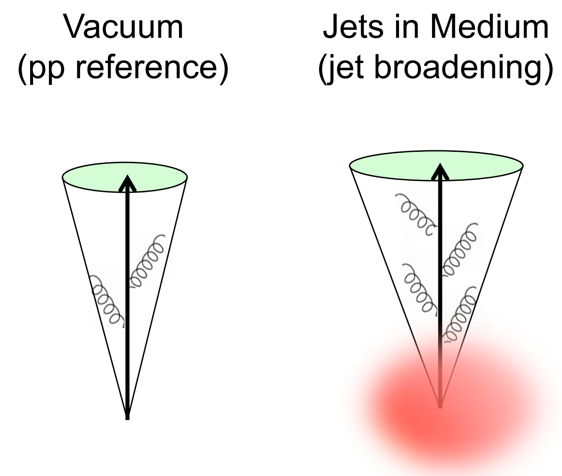


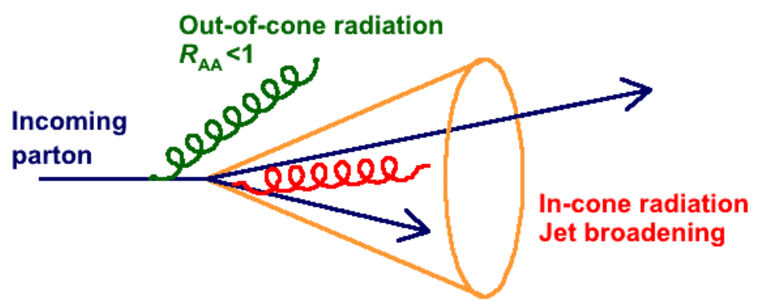
- Recoil jet yield ratio between different Rs well described by PYTHIA Perugia tune → reflects jet collimation
- Recoil jet yield suppressed in central PbPb compared to PYTHIA reference → jet quenching
- No jet broadening observed

Jet anatomy

- Jet are extended objects with momentum and angular structure







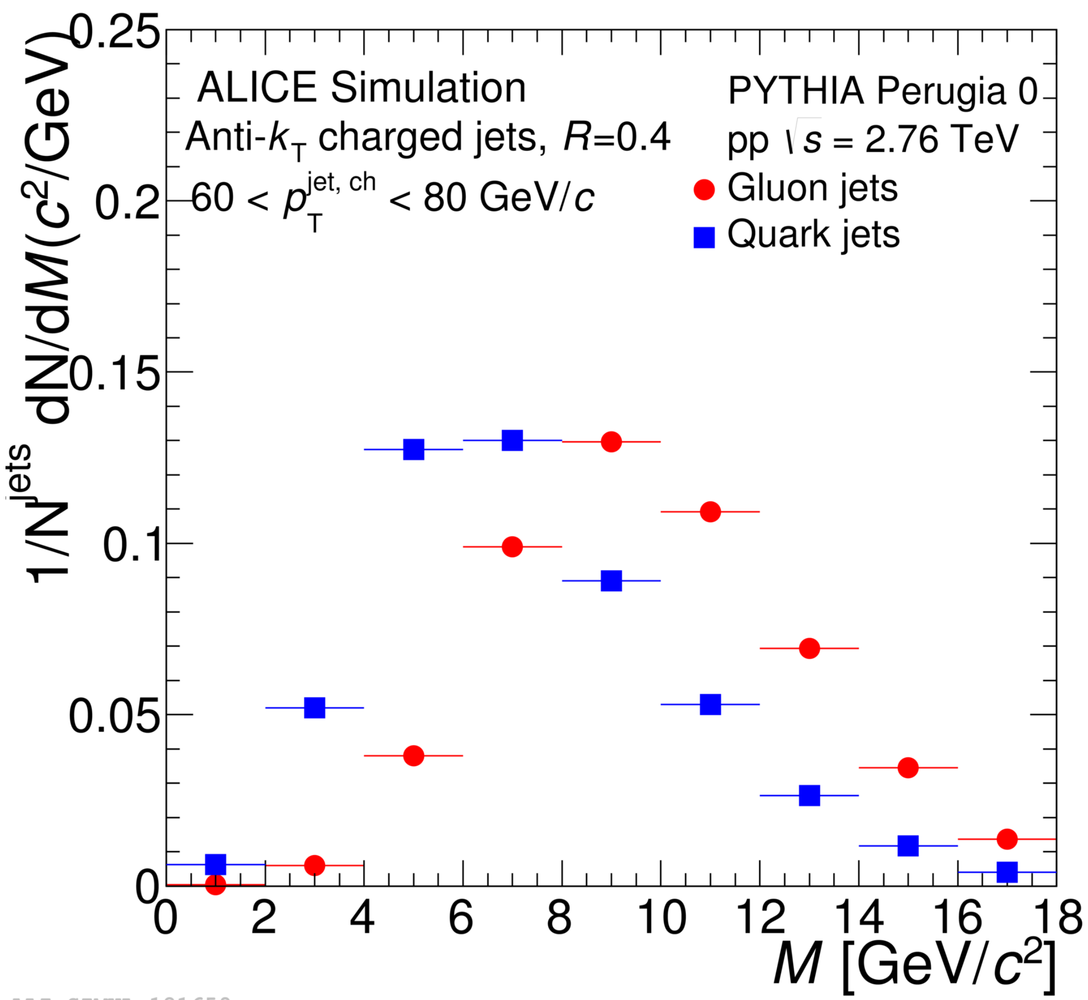
- How is the parton shower modified?
- What is the mechanism modifying the shower?
- Can we relate shower modifications to medium properties?

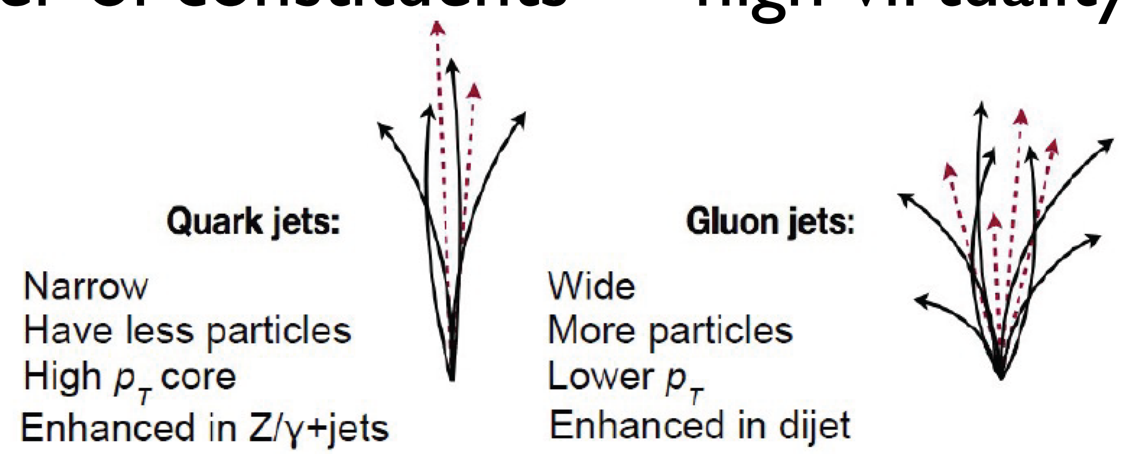
Jet mass

- Difference of the momentum of the jets and the energy of its constituents weighted by their pseudo-rapidity

$$M = \sqrt{p^2 - p_T^2 - p_z^2} \qquad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i. \qquad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i$$

- Related to the virtuality of the parton traversing the medium
  - small mass: collimated jet, small number of constituents → low virtuality
  - large mass: broad jet, large number of constituents → high virtuality



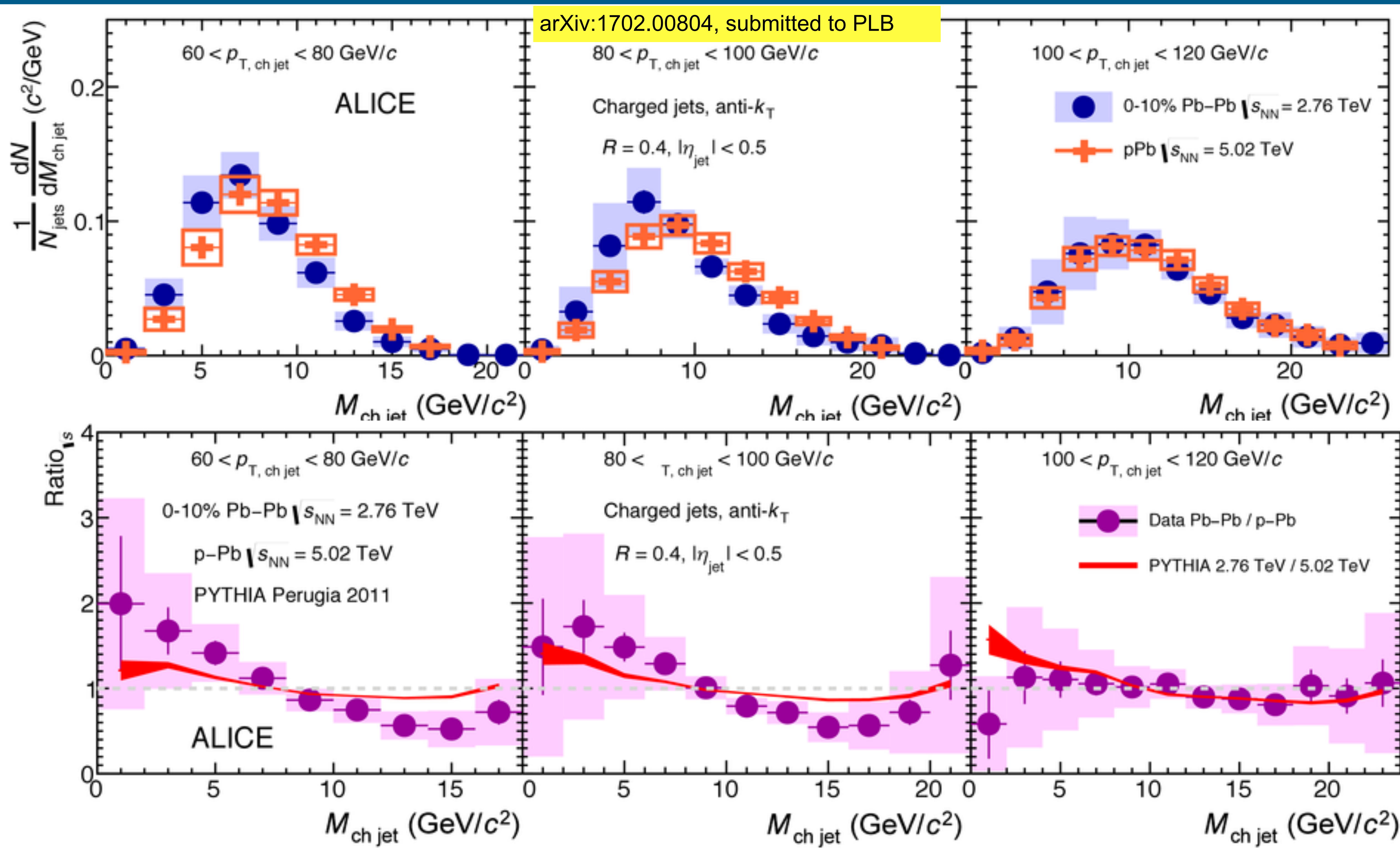


Gluon jets are wider than quark jets

↓

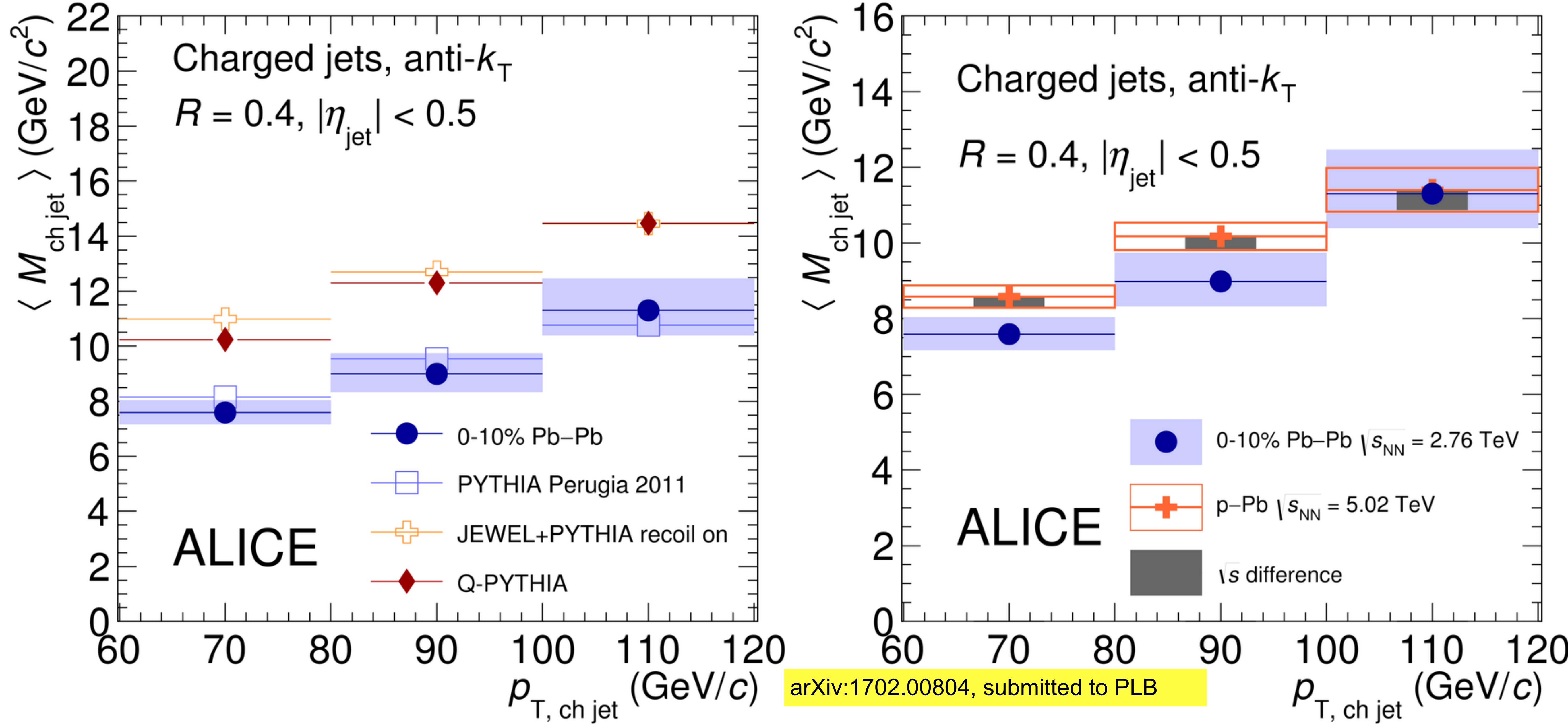
Jet mass of gluon jets is larger than for quark jets

Charged jet mass in different collision systems



- Difference observed between pPb and Pb-Pb jet mass distribution
- Shift also quantified in the ratio Pb-Pb/pPb and PYTHIA at the two energies

Charged jet mass comparison



- Model without quenching describes Pb-Pb data, quenching generates larger mean jet mass
- Small difference between p-Pb and Pb-Pb observed in mean jet mass for low p_T jets

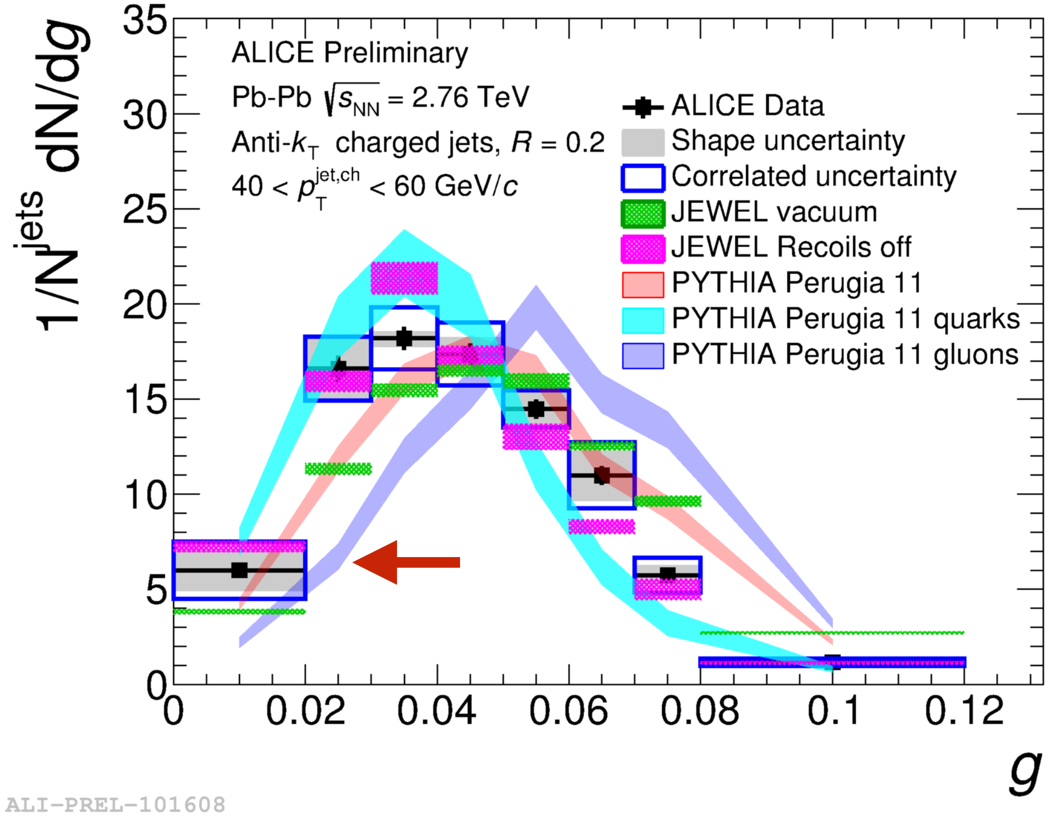
Jet angularity and p_T dispersion

- Probe angular and momentum scale of quenched jets

jet width:
momentum redistribution of jet constituents weighted by distance

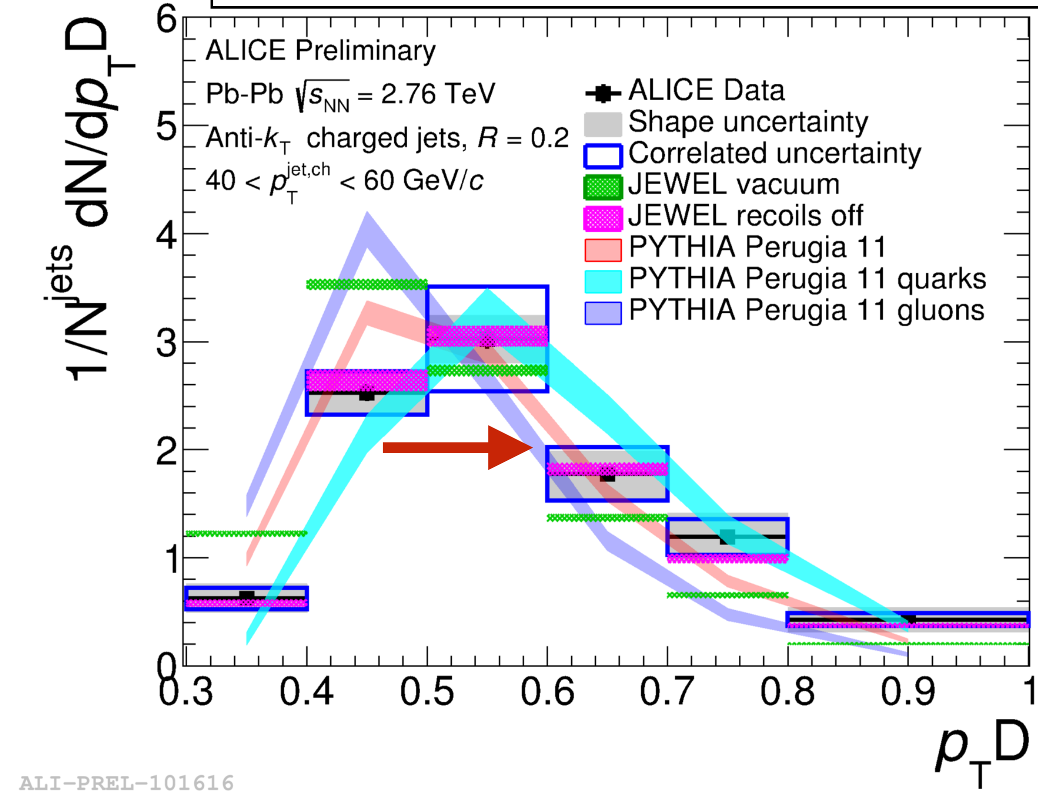
anti-k_T, charged jets
R = 0.2

p_T-dispersion p_TD:
momentum redistribution of jet constituents



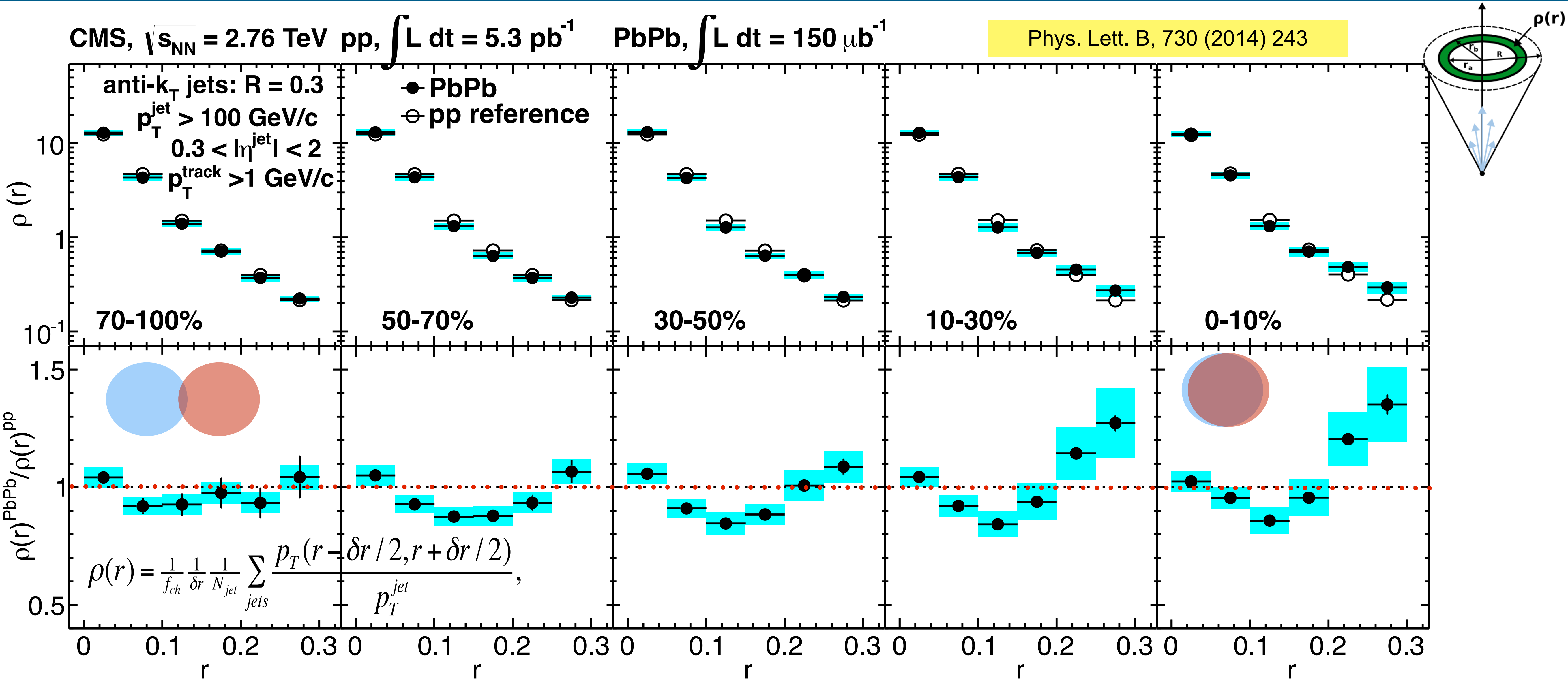
$$g = \sum_{i \in \mathrm{jet}} \frac{p_T^i}{p_T^{\mathrm{jet}}} |r_i|$$

$$p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}}$$



- Accelerated shower leads to higher angularities (broader) and small p_TD (more constituents)
- Qualitatively consistent with collimation of the jet core
- g and p_TD qualitatively described by JEWEL model with recoils off

Jet shapes



- Ratio close 1 for most peripheral collisions → no jet shape modification
- Depletion in the intermediate radius (0.1<r<0.2) → jet quenching
- Excess at large radius (r>0.2) for most central PbPb collisions → jet broadening

Broadening observed in two particle correlations

- Probe angular scale of quenched jets

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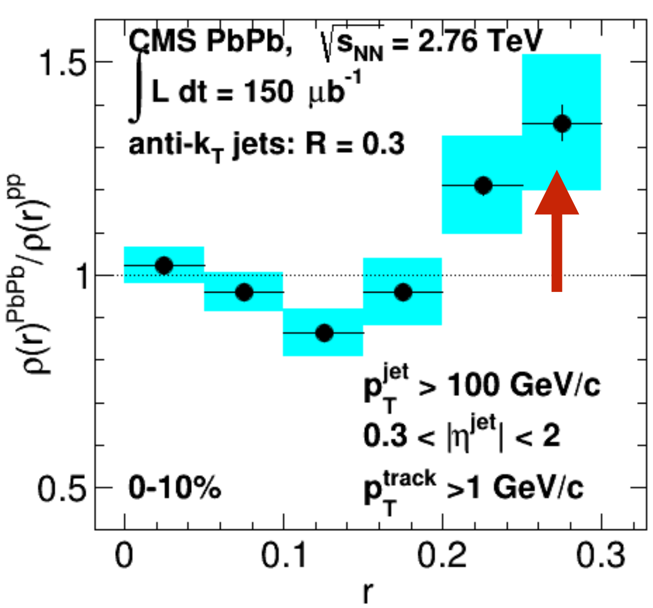
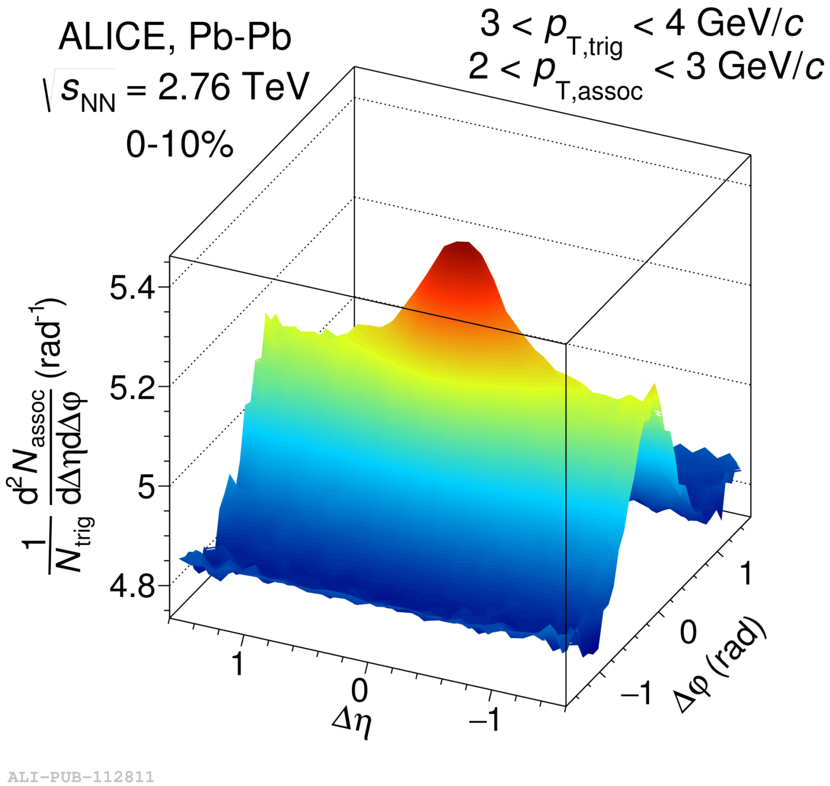
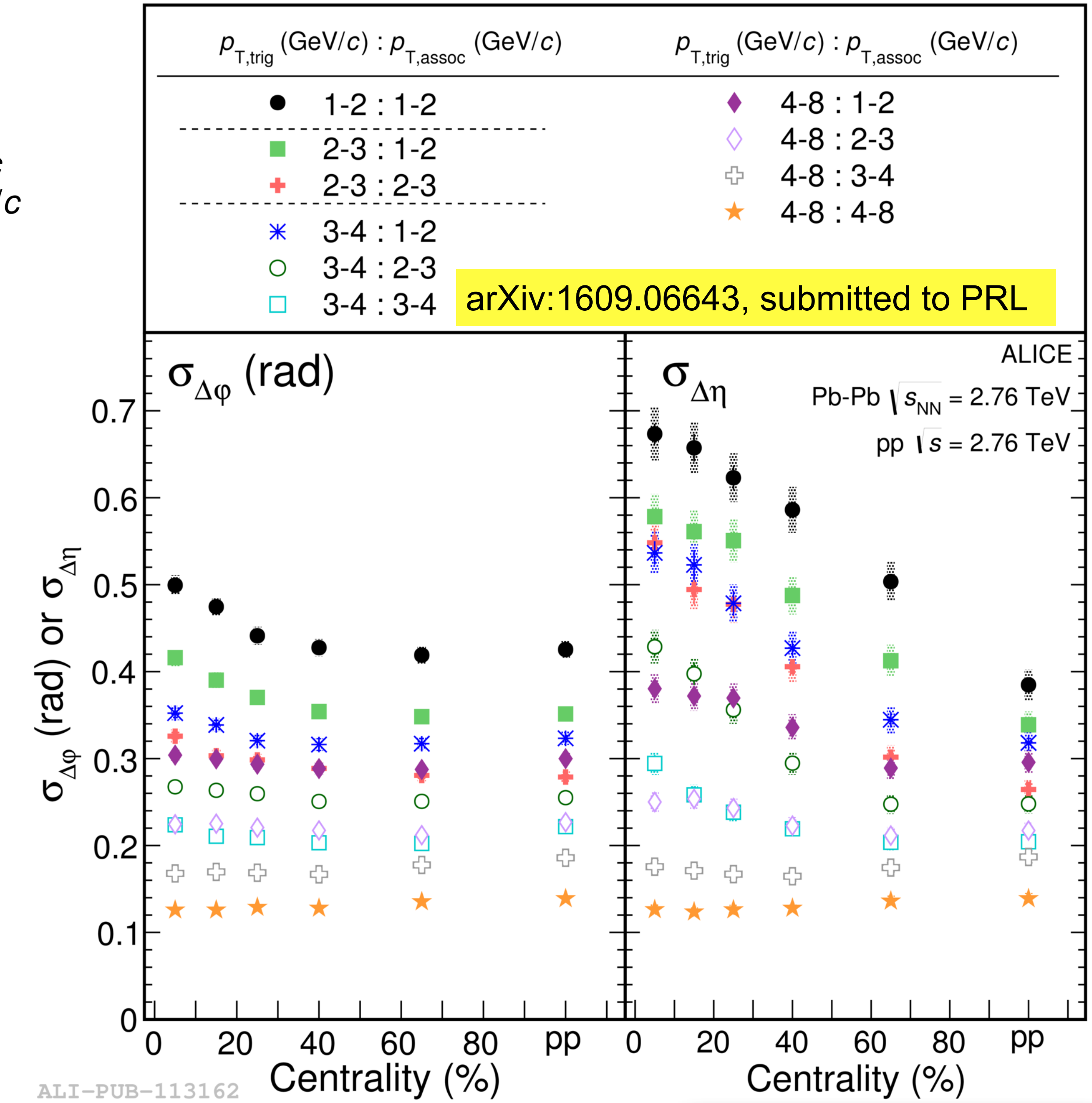
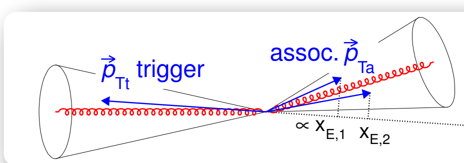




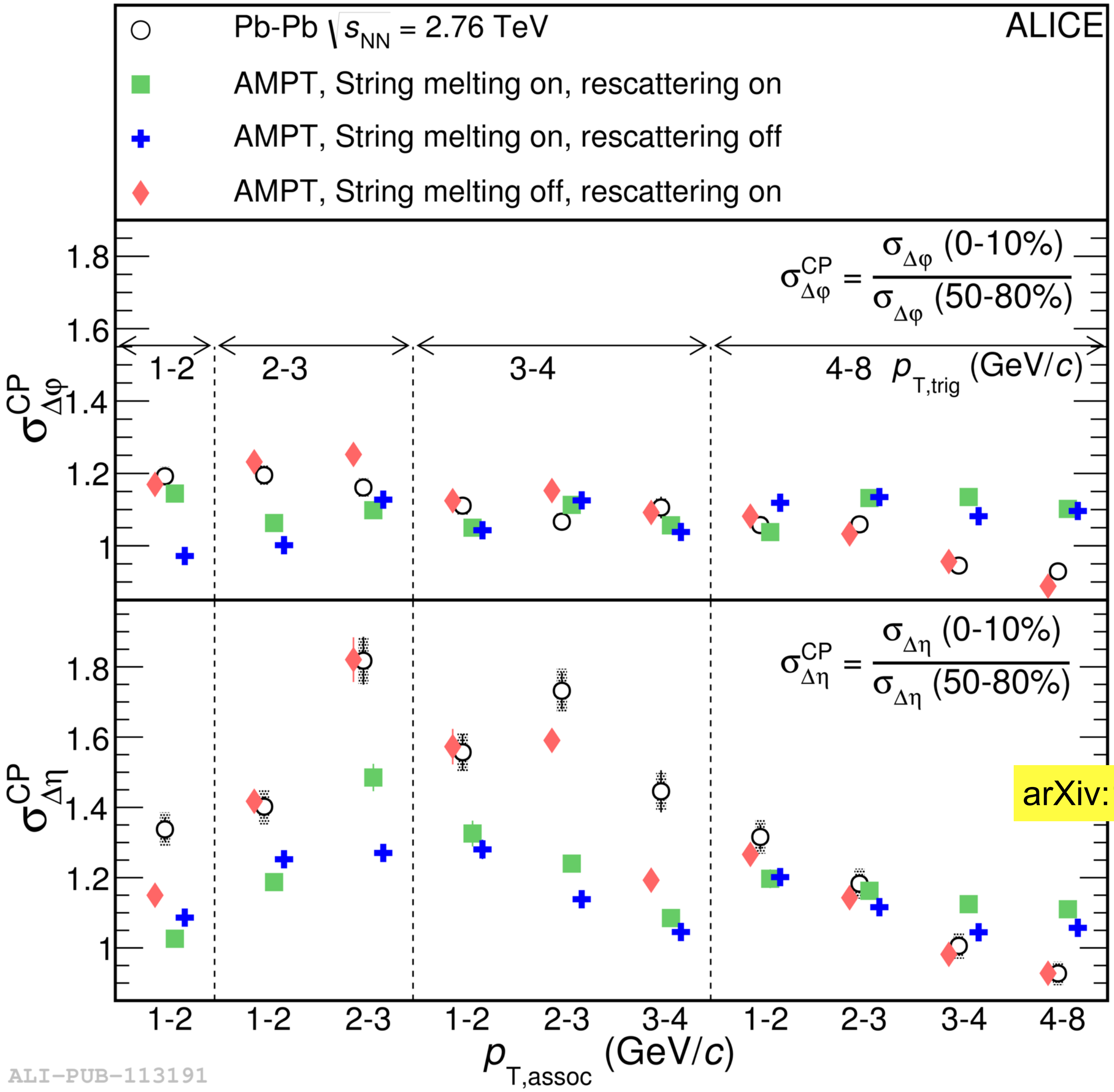


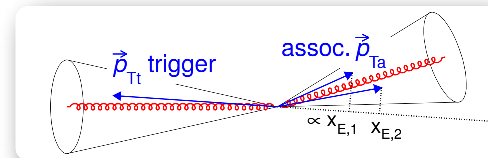
- Excess at large angular distance → jet broadening

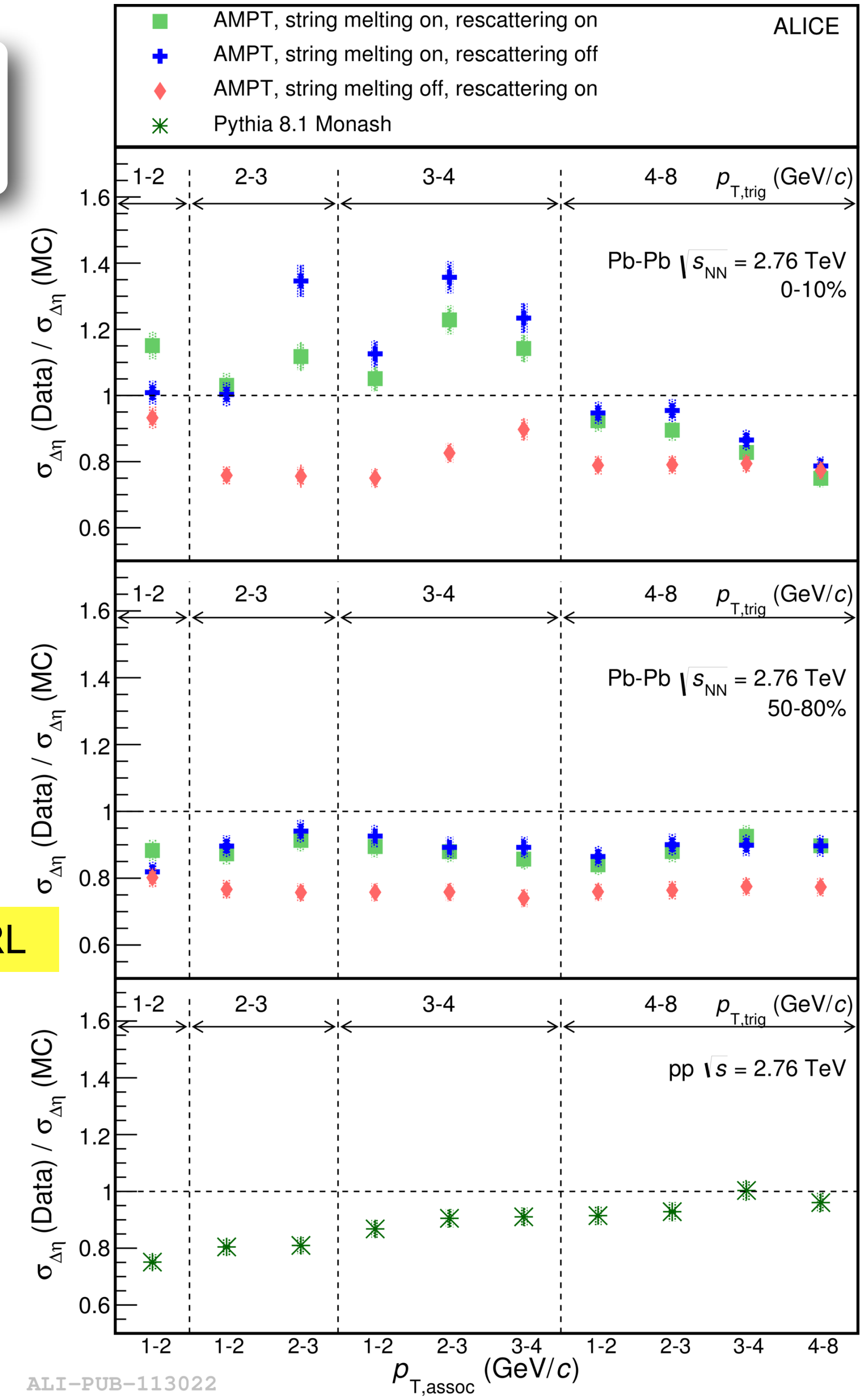


- Jet broadening quantified using two particle correlations:
  - ➡ Small broadening in Δφ, significant broadening in Δη ($p_{T,trig}$ ↑, width ↓)

Near side jet peak broadening



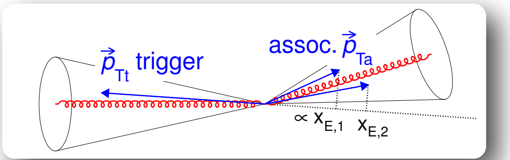




arXiv:1609.06643, submitted to PRL

- Small broadening in Δφ, significant broadening in Δη
- Broadening vanished at high p_T ($p_{T,trig}$ ↑, width ↓)
- None of model settings describe the absolute width

Low p_T broadening observed in π^0-h correlations



near side

$$I_{AA} = \frac{Y_{\text{Pb-Pb}}}{Y_{\text{pp}}} \qquad Y = \int \frac{dN_{assoc}}{d\Delta\varphi}\, d\Delta\varphi$$

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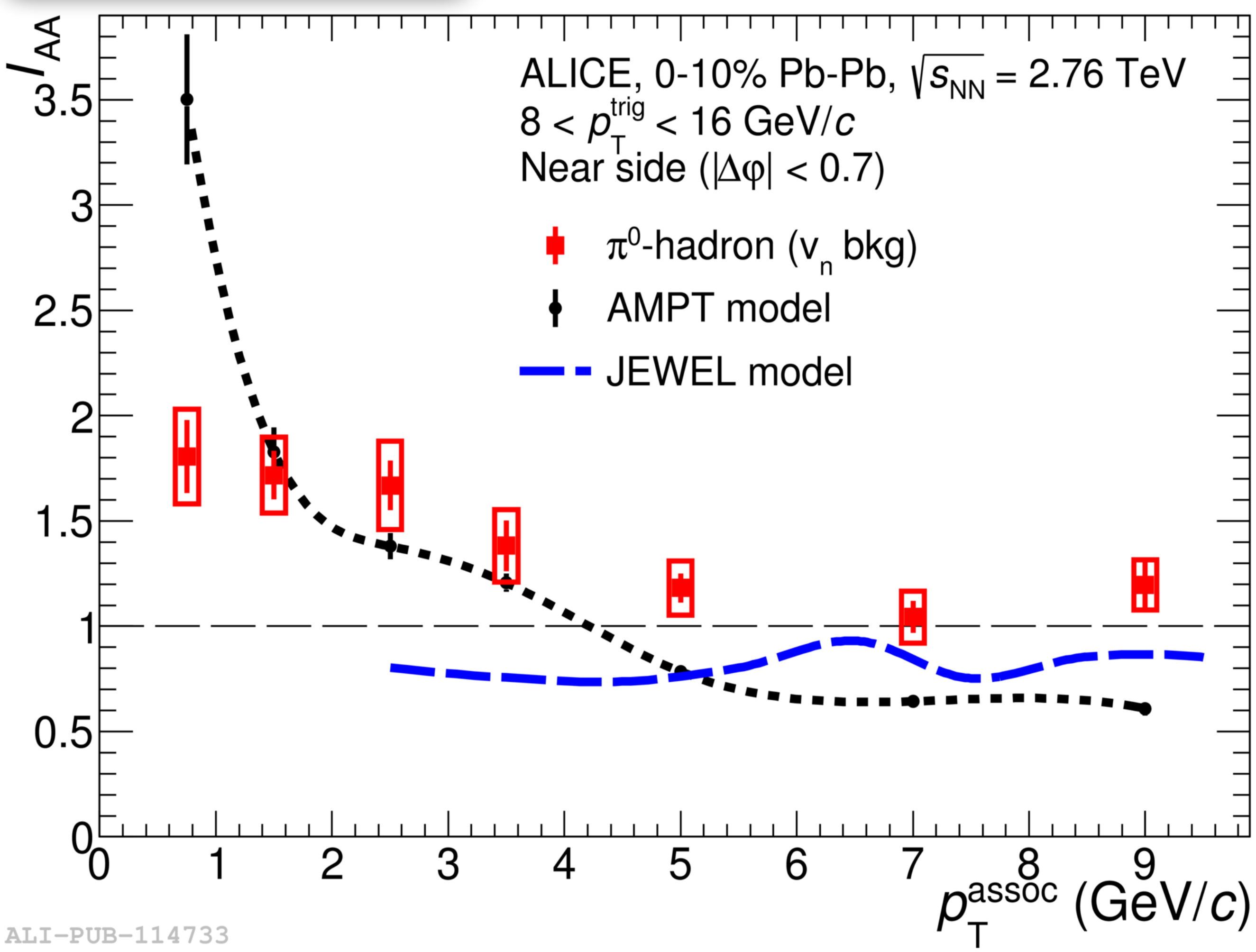
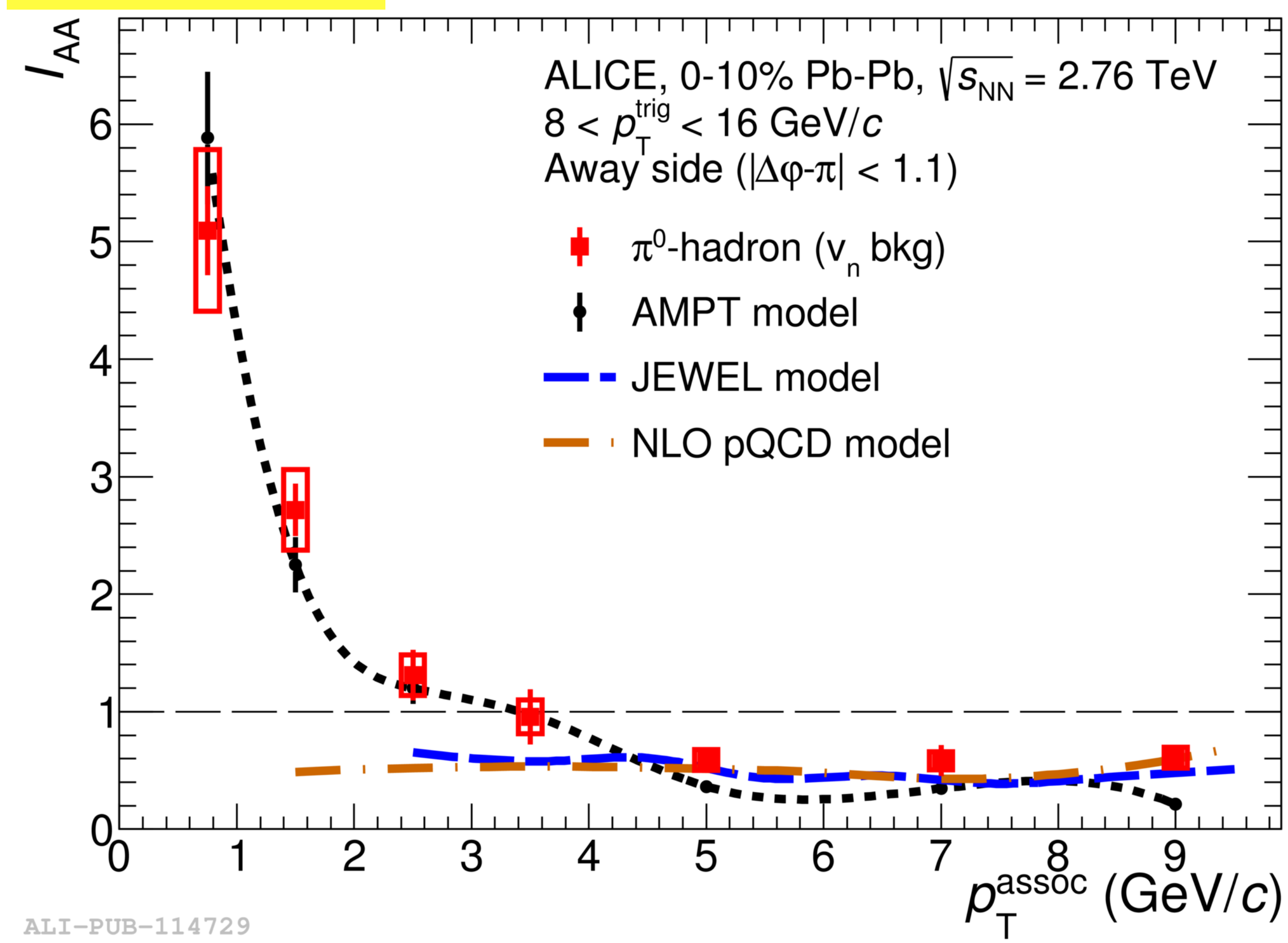
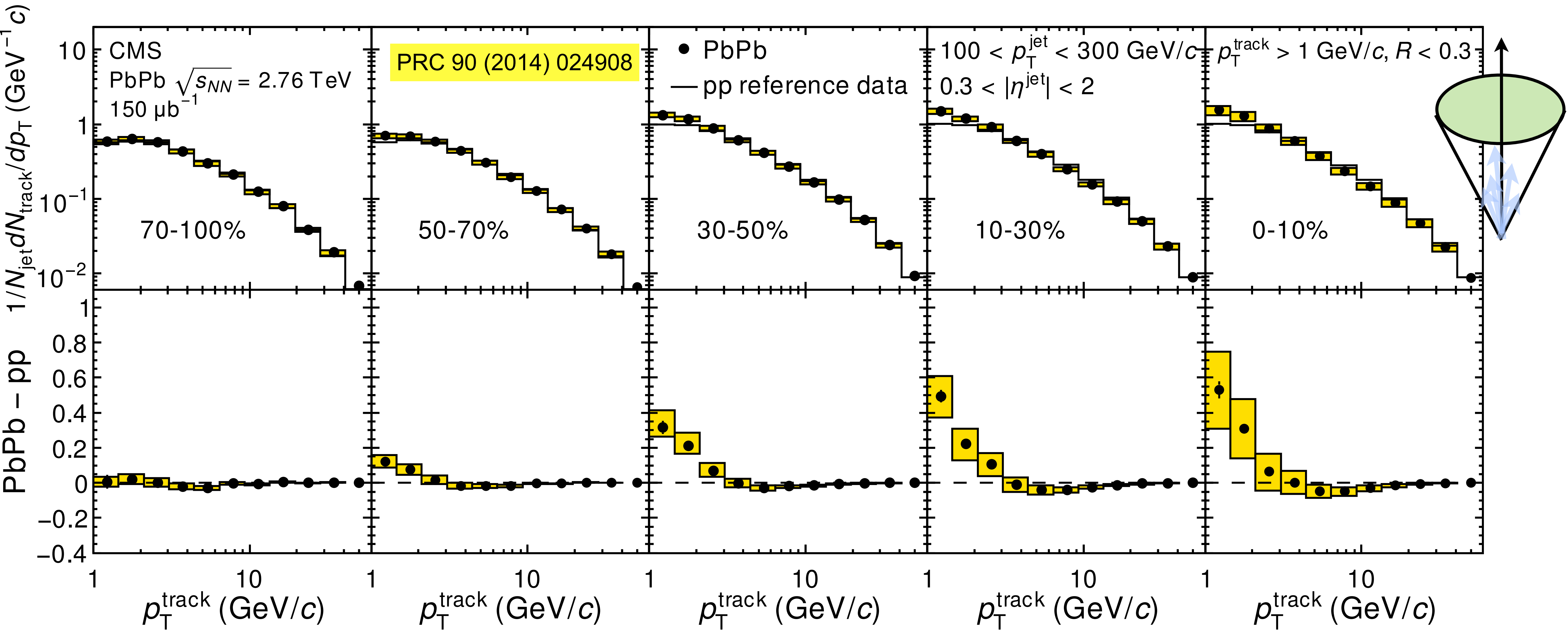
away side





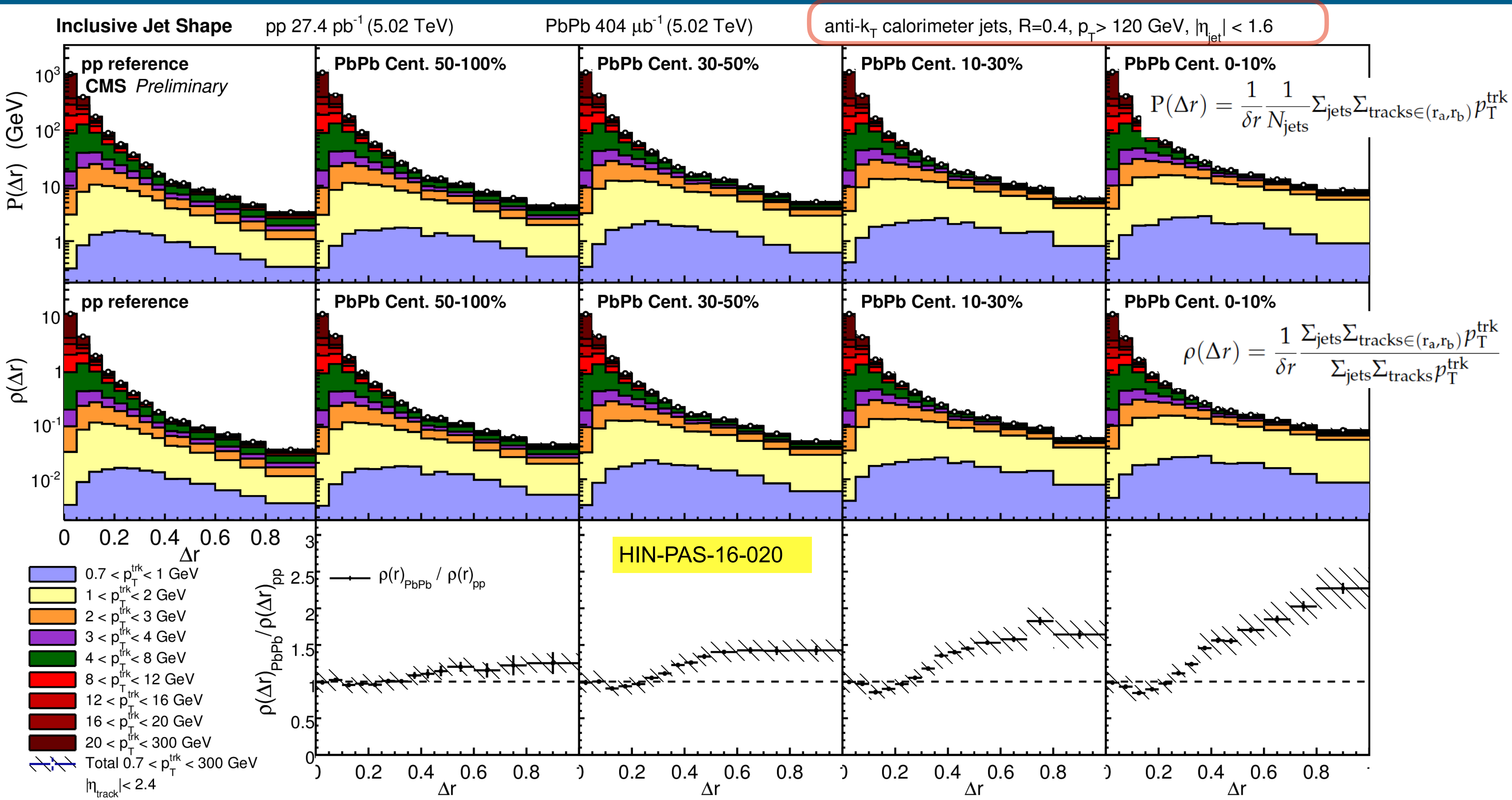
- Enhancement at very low p_T, indicating extra particles excess → consistent with low p_T broadening (soften of fragmentation functions? excited by medium?)
- Suppression on the away side for high p_T → consistent with jet quenching

Jet fragmentation function



- Peripheral PbPb similar to pp → no jet FF modification
- Excess at low p_T (< 4 GeV/c) in most central collisions → jet broadening
- Suppression at 4 < p_T < 20 in more central collisions → jet quenching

Jet shape measurements to larger distance

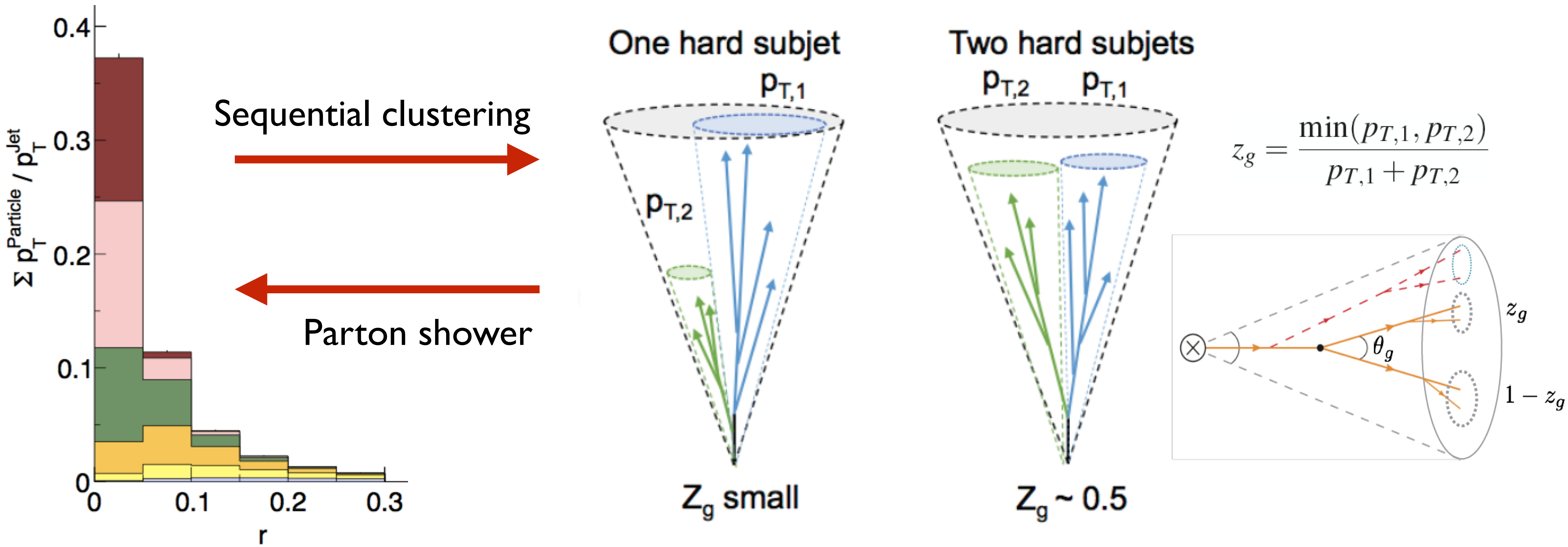


- Extend jet shape analysis to large R using 2-d correlation methods
- Large angle broadening becomes stronger

➡ decouple such broadening in Δη and Δφ directions for low p_T jets in ALICE

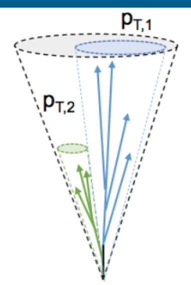
Jet substructure

- Using clustering+jet grooming techniques to map structure of final state jets to evolution of parton shower (e.g. "splitting function")

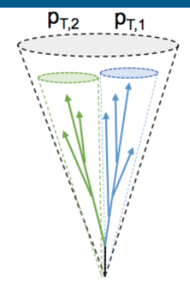


- Splitting function z_g: observable connected to the hardest splitting
- Measure the momentum balance of the two hard sub-jets
- Looking for modifications of the jet hard substructure

Splitting function in p-Pb collisions

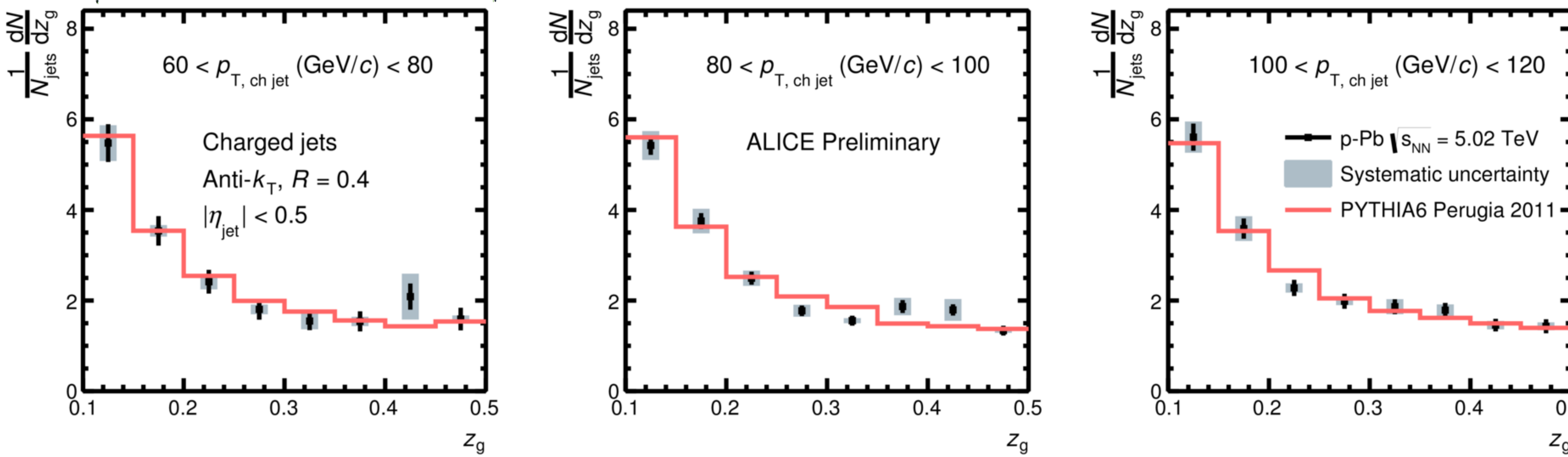


$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



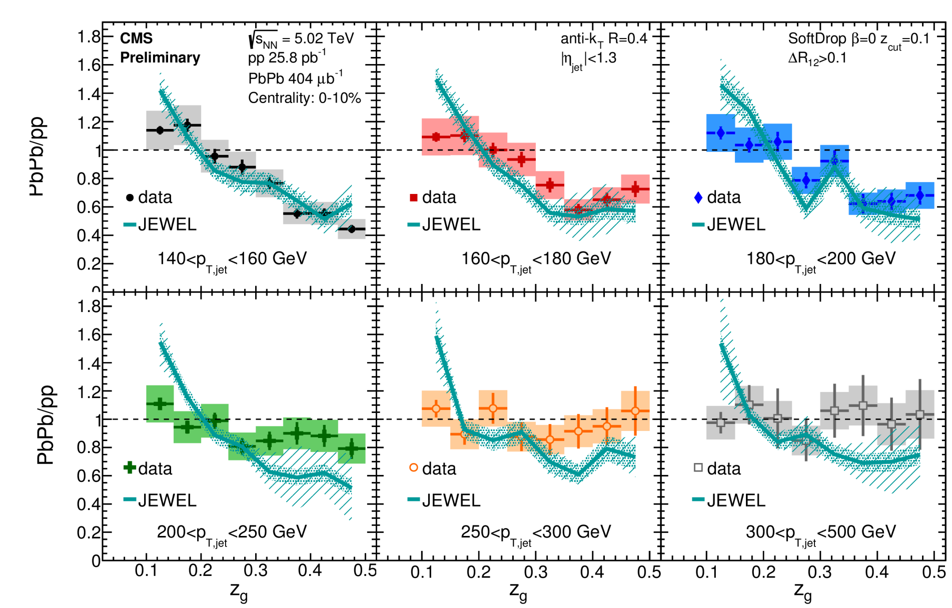
anti-k$_T$, charged jets

R = 0.4, $|\eta_{jet}| < 0.5$

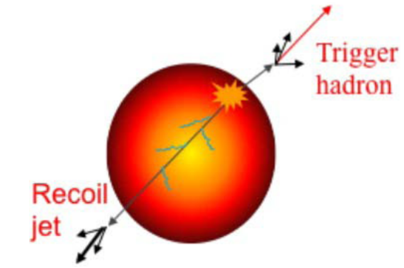


ALI-PREL-120123

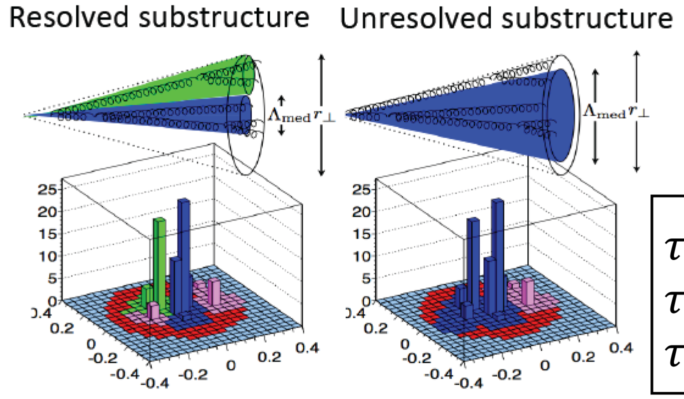
- First measurement of z_g in p-Pb collisions at 5.02 TeV
- No modification observed in minimum-bias p-Pb data compared to PYTHIA
- Next: redo the analysis in multiplicity classes, measurements in pp and PbPb collisions



Nsubjettiness measurements



- Nsubjettiness jet shape τ_N: study how N pronged a jet substructure using recoil jets measurement
  - → suppresses combinatorial background, explore low $p_{T\text{jet}}$, large R

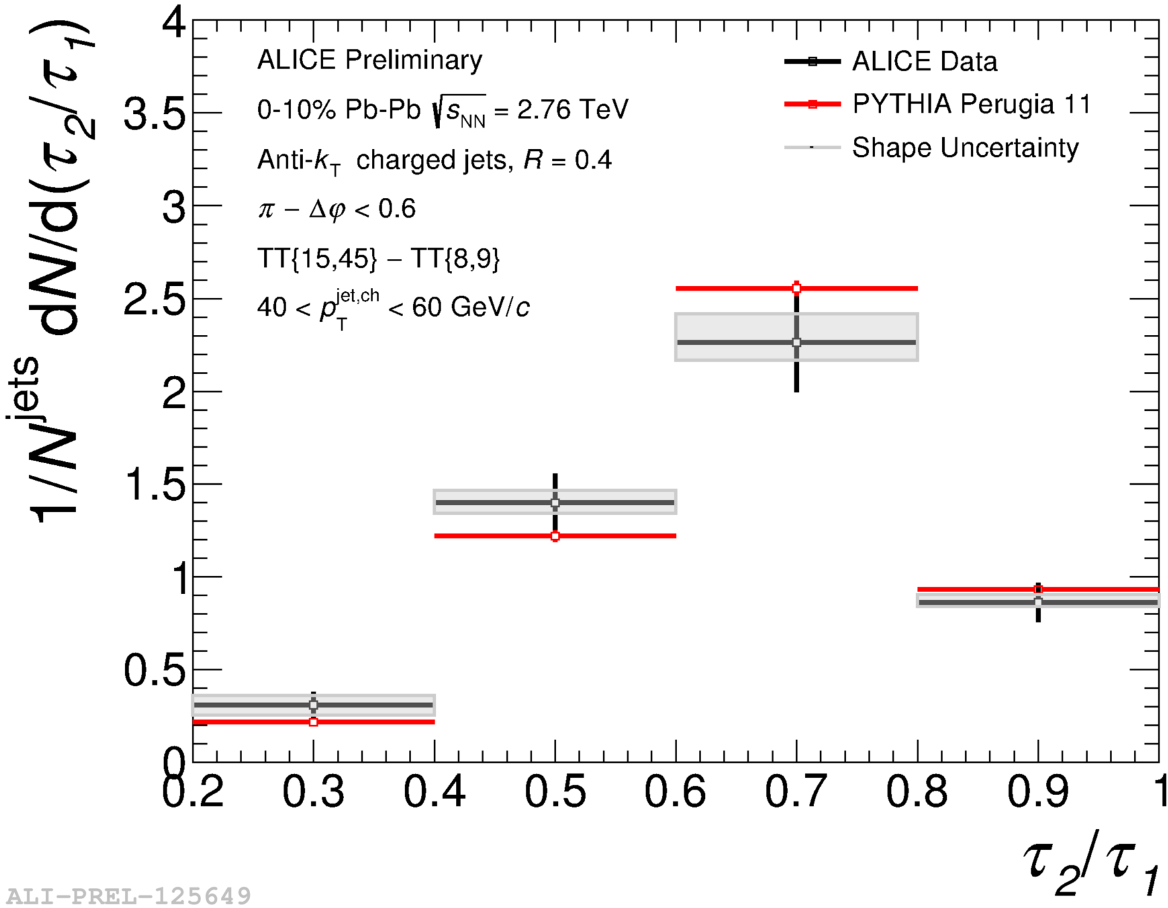


Casalderrey-Solana, Mehtar-Tani, Salgado, Tywoniuk Phys.Lett.B ***725*** *(2013) 357–360*

$$\tau_N = \frac{\sum_{i=1} p_{T,i} Min(\Delta R_{i,1}, \Delta R_{i,2}, \ldots, \Delta R_{i,N})}{R_0 \sum_{i=1} p_{T,i}}$$

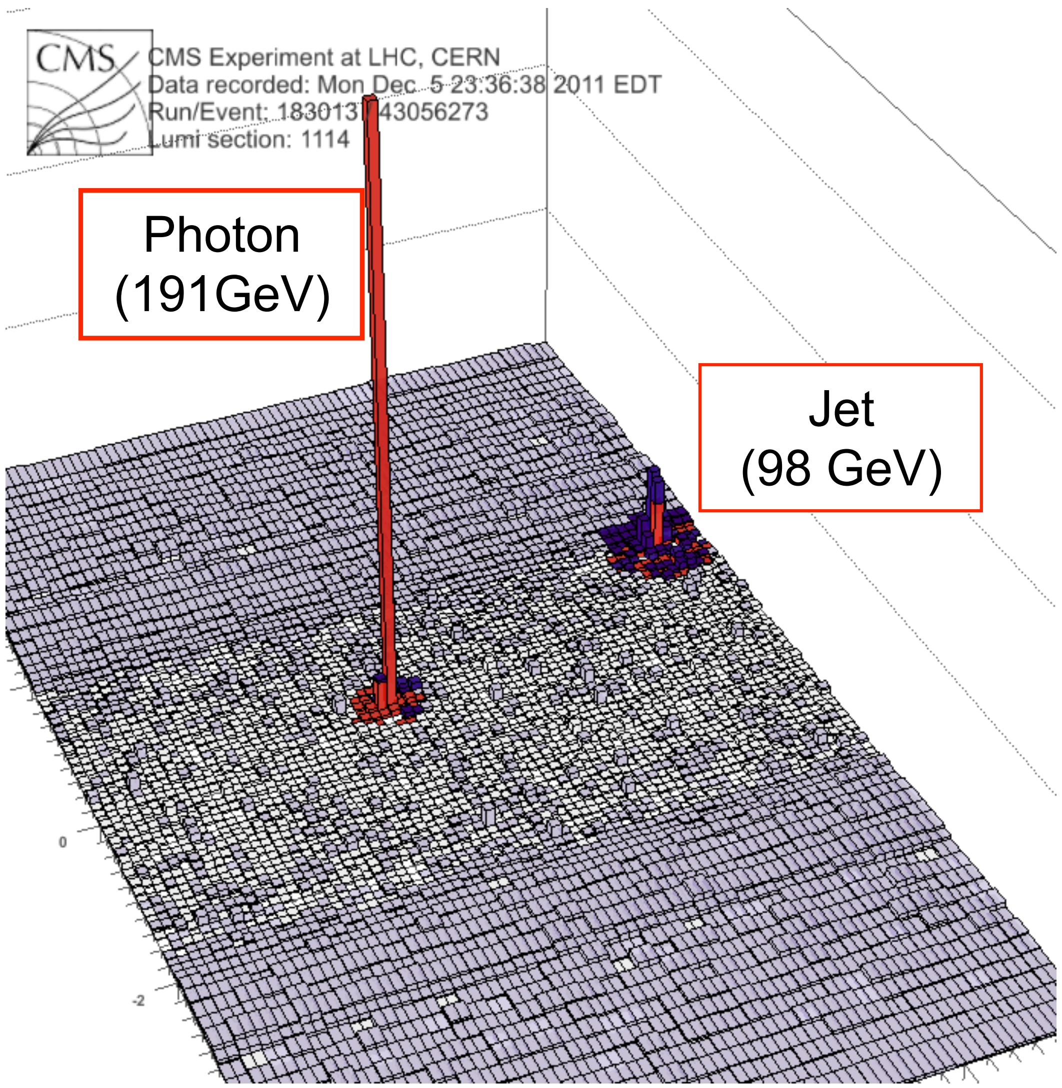
$\tau_N \to 0$: jet has N or fewer well defined cores
$\tau_N \to 1$: jet has at least N+1 cores
$\tau_N/\tau_{N-1} \to 0$: jet has N cores

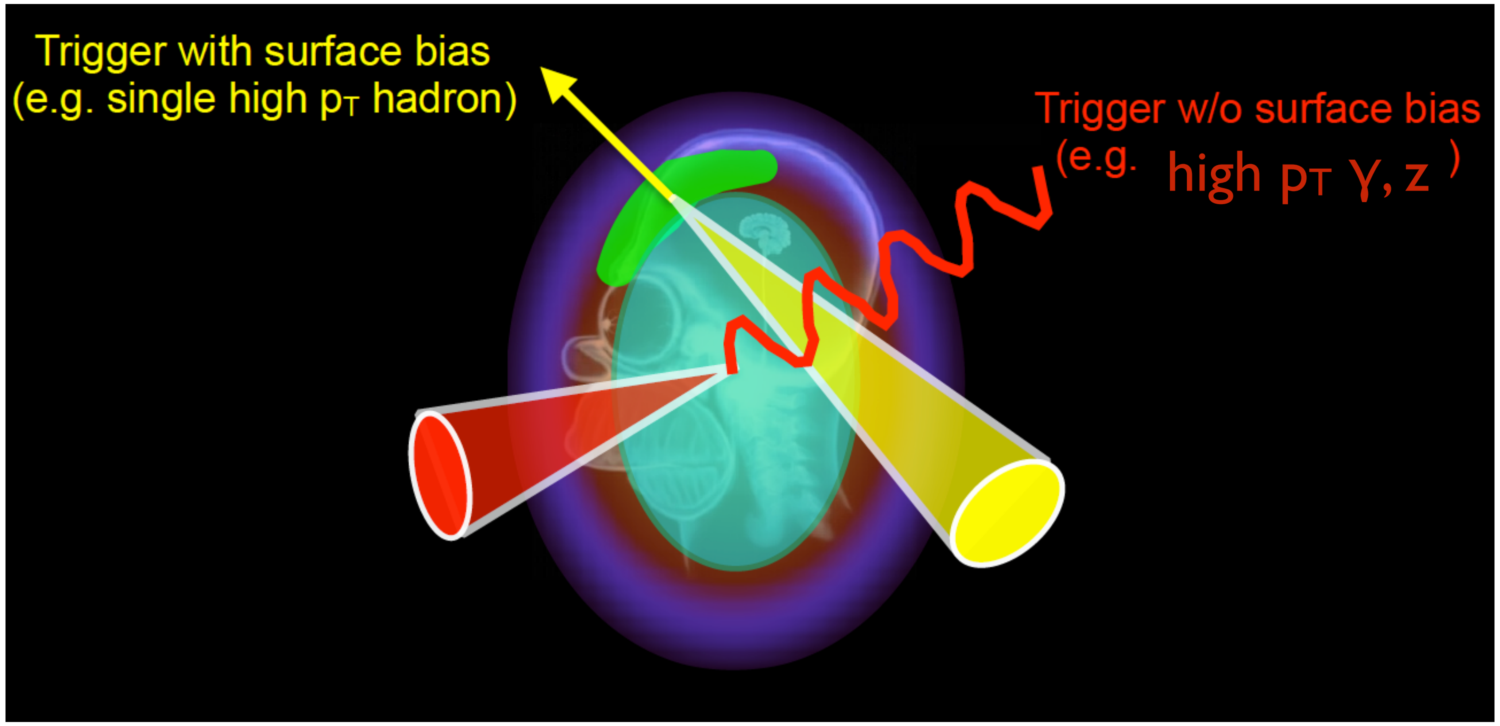
$\Delta R_{i,j}$: η-φ distance between track i and subject j
$p_{T,i}$: p_T of the ith jet constituent
R_0: jet resolution parameter



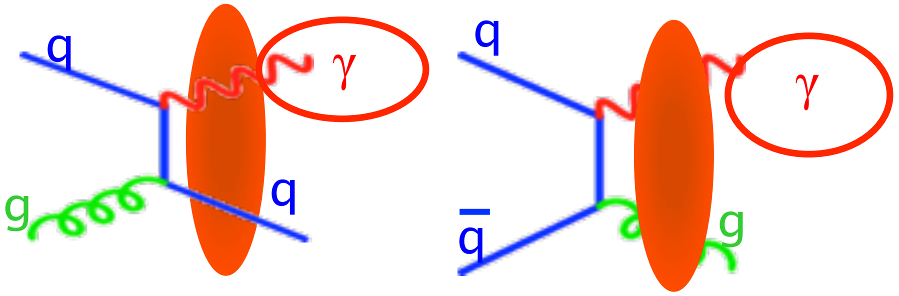
- τ_2/τ_1: measures the two prongness of the jet
  - ➡ Small τ_2/τ_1 related to leading parton splitting into 2 resolvable partons
  - ➡ Medium modifications can shift τ_2/τ_1 to a higher value
- Data comparable with PYTHIA prediction without quenching effect

γ+jet: "golden" probe for energy loss

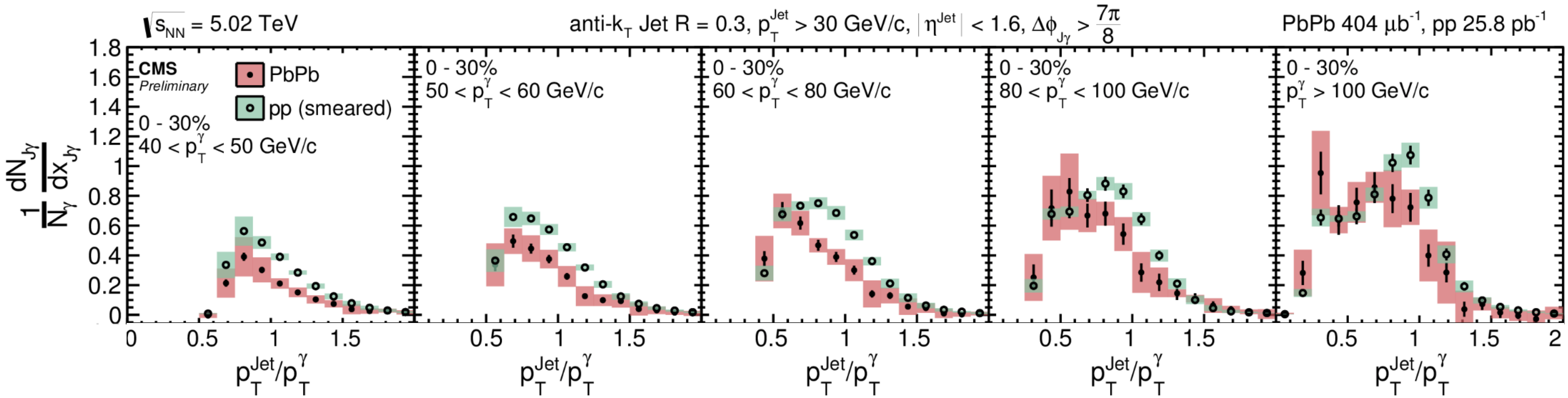




- Photon tagging:
  - Sets the reference of the hard process
  - Provide the calibrated energy of the jet opposite
  - Identify quark jets by photon tagging
  - Allows to measure jets in an energy domain where jet cannot be fully reconstructed

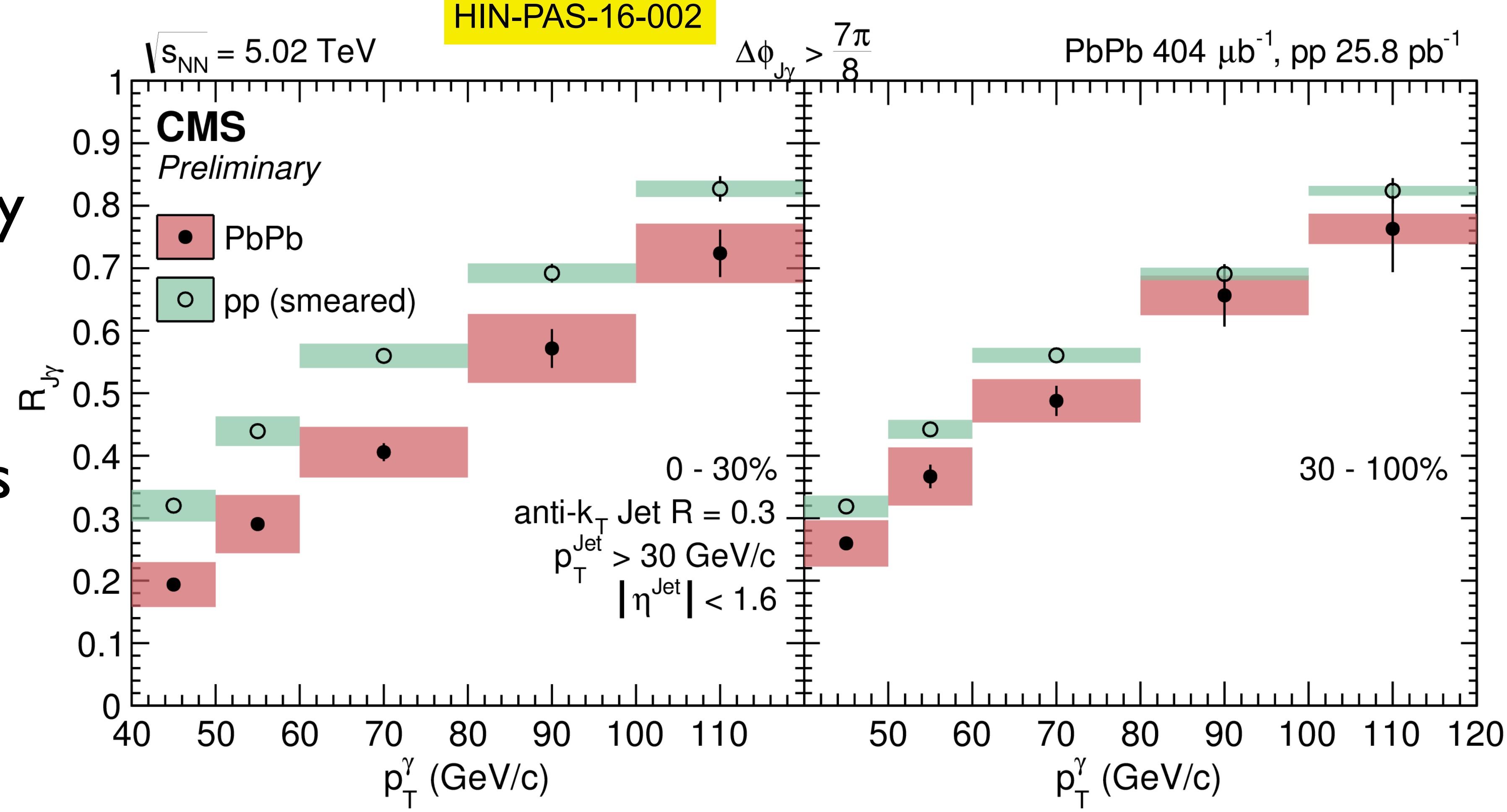


γ-jet correlations

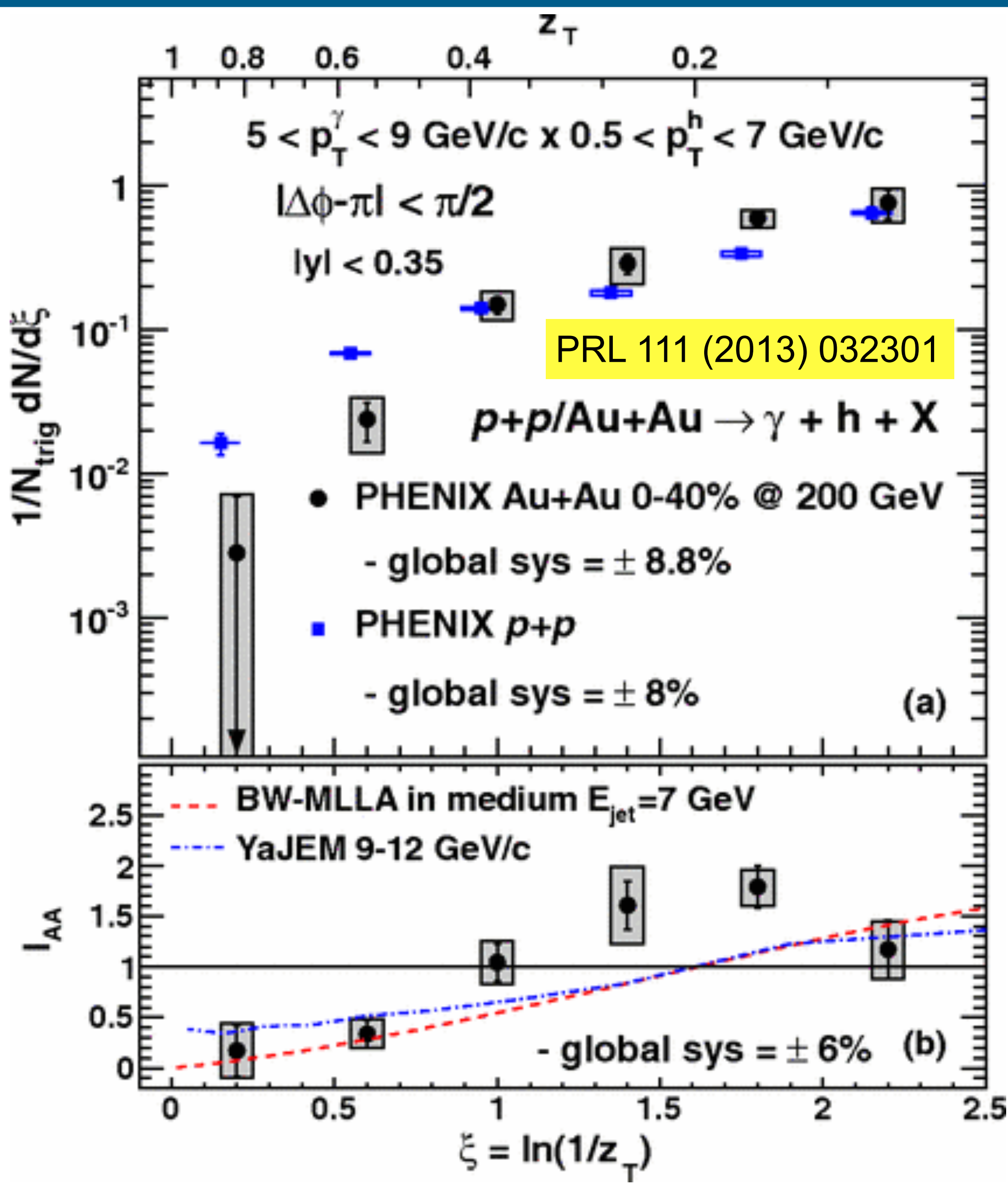


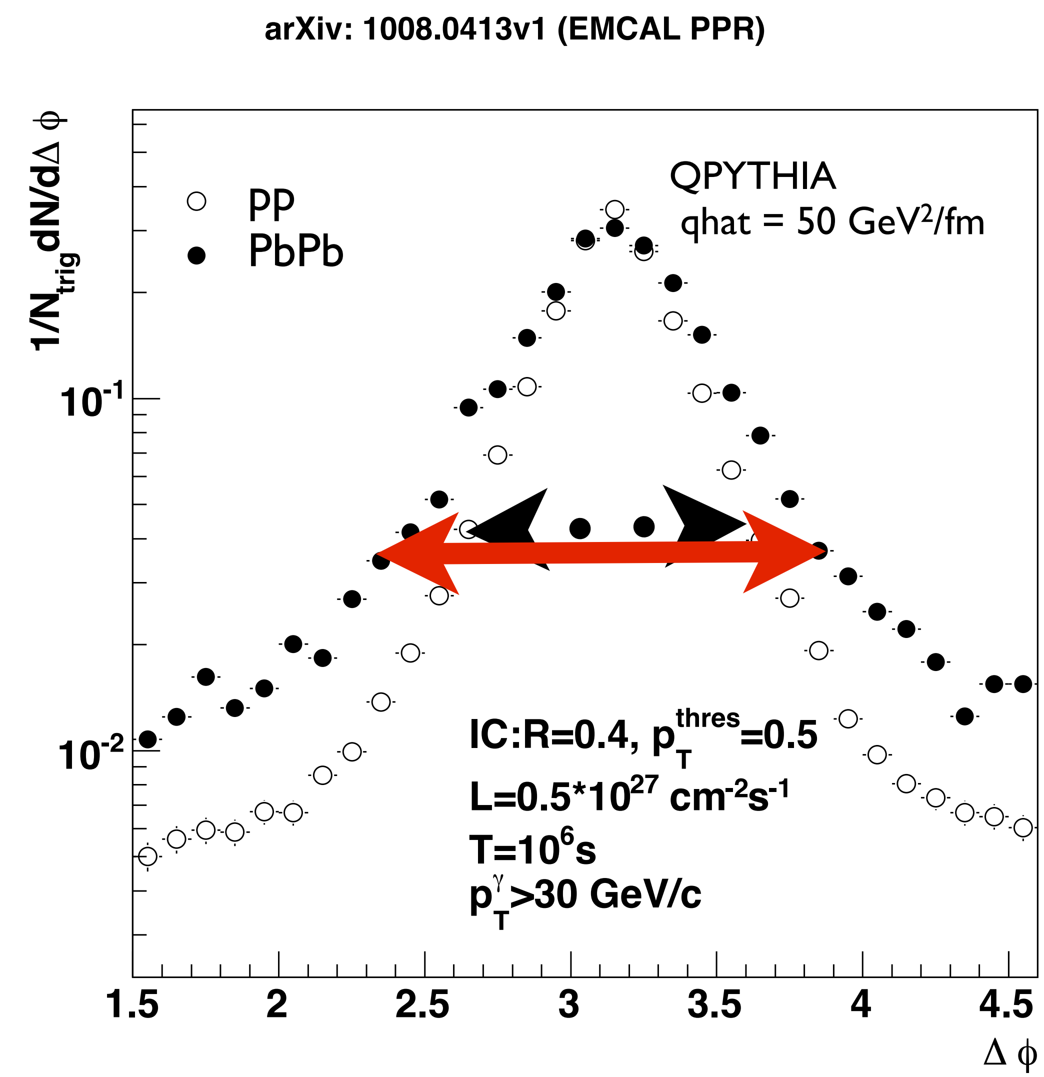
HIN-PAS-16-002

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



γ-triggered hadron correlations

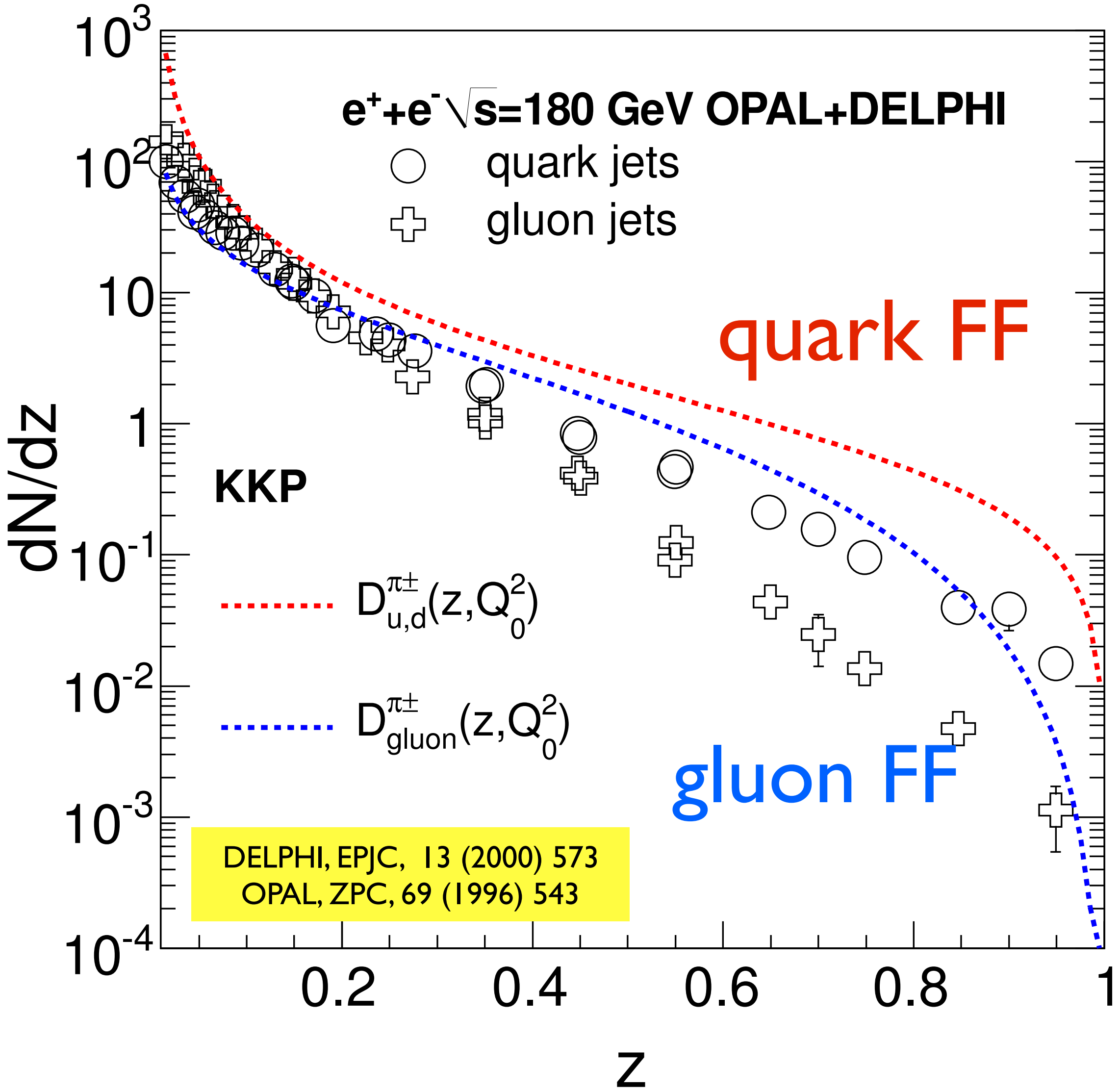


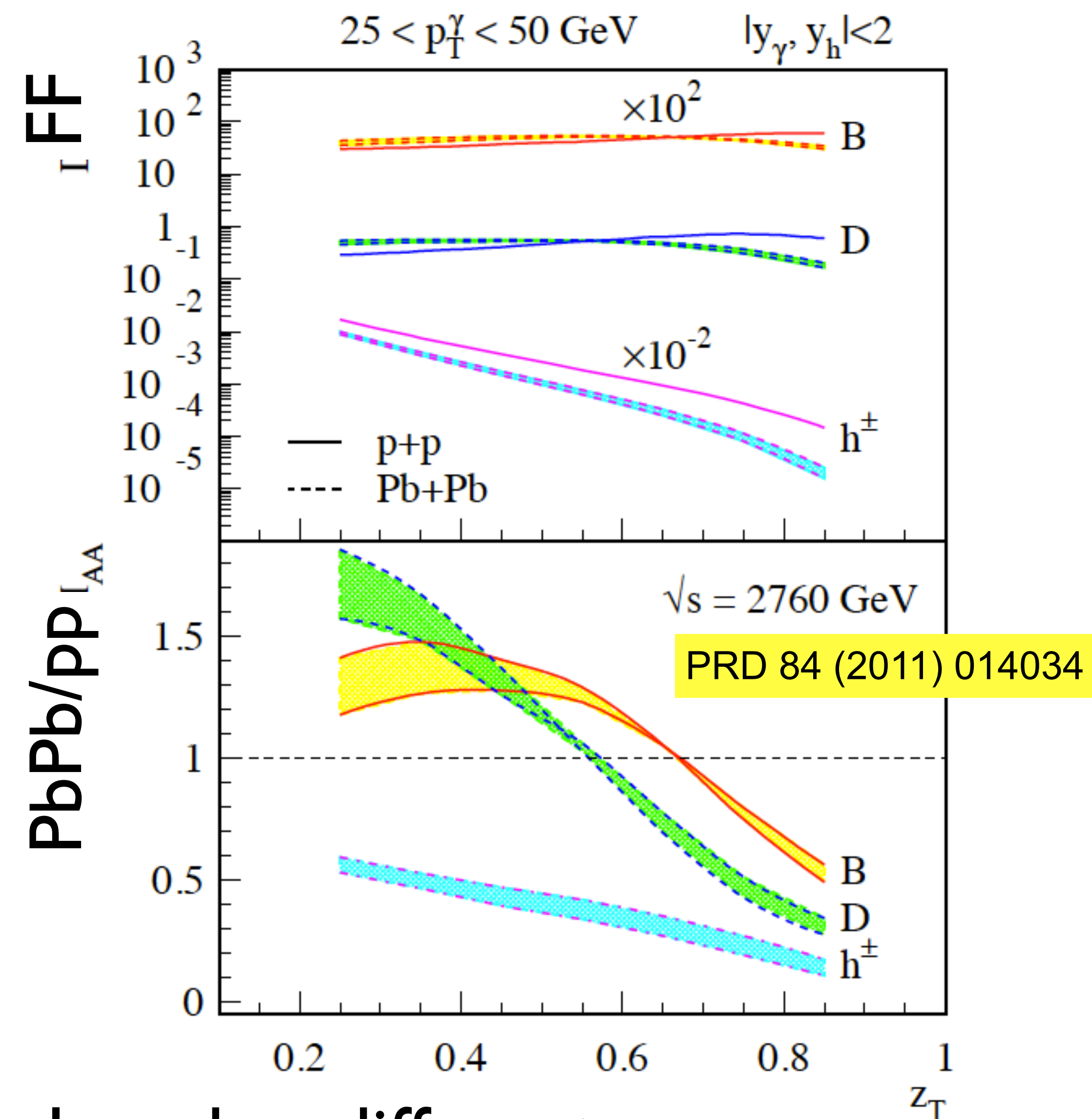


- Provide sensitive measurements of medium effects modifying the away side jet structure
  - probe jet fragmentation modifications
  - Study broadening in azimuthal correlations

Color and mass dependence by tagging

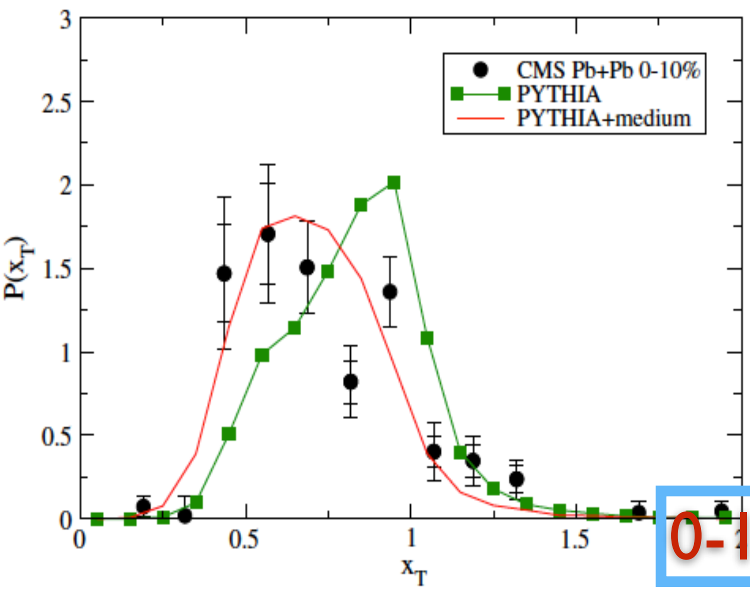
Tagging jets by different triggered-particle correlations





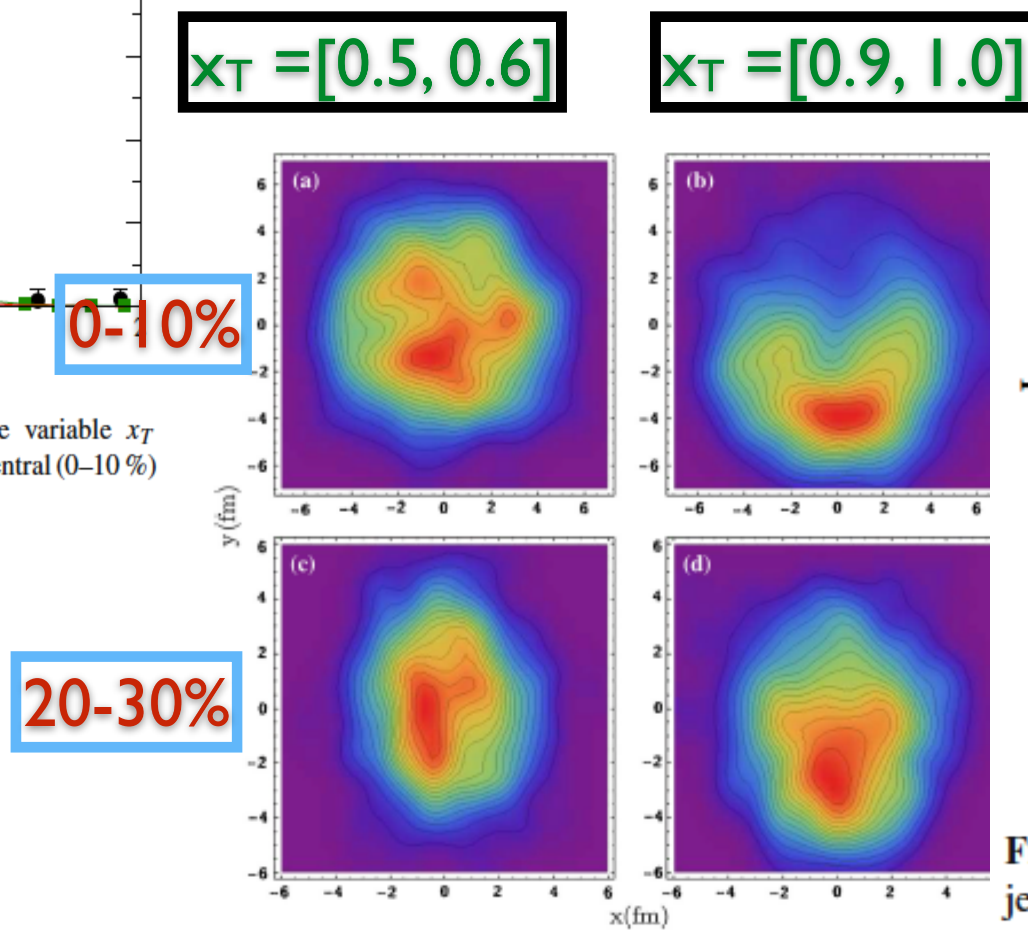
- OPAL and DELPHI measured quark and gluon has different fragmentation pattern in e+e-
- Theory predicted jet fragmentation pattern modified differently for g, q and Q
    - ➡ can be studied at LHC with Run2&3 data

Path length dependent medium effect by tagging



ig. 3 The distribution of the momentum imbalance variable x_T between triggered photons and associated jets for most central (0–10 %) b+Pb collisions at the LHC. The jet size is $R = 0.3$

Feasible to probe medium density experimentally?



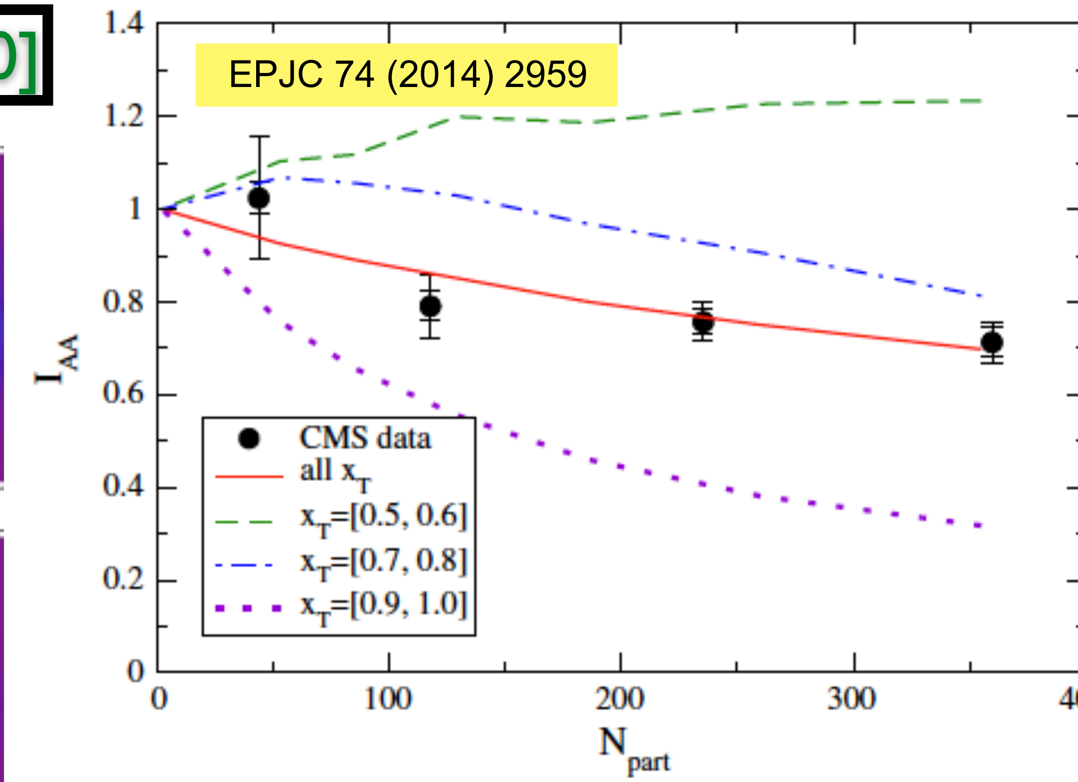


Fig. 8 The nuclear modification factor I_{AA} for the photon-triggered jets as a function of centrality for Pb+Pb collisions at the LHC. The results for different x_T values are compared. The jet size is $R = 0.3$

- By selecting jet pair events using different asymmetry (x_T) value, one can probe different medium lengths and density profile, and result different modification patterns

➡ can be studied at LHC with Run2&3 data

Summary and outlook

- So far so good…
  - consistent picture about jet quenching in PbPb collisions from different experiments
    - high p_T jets/particles strongly suppressed
    - Dijet imbalance and asymmetric
    - Jet structure modified with low p_T and large angle broadening
  - New sets of jet observables probing additional aspects of QCD developed
    - sophisticated measurements (g, p_TD, z_g, τ_{2}/τ_{1}, …)
    - improving understanding on jet thermalization and resolving power of jets
- But…still left with questions…
  - can be addressed and checked by high statistics LHC RunII and RunIII data

Thank you for your attention!

Please stay tuned...

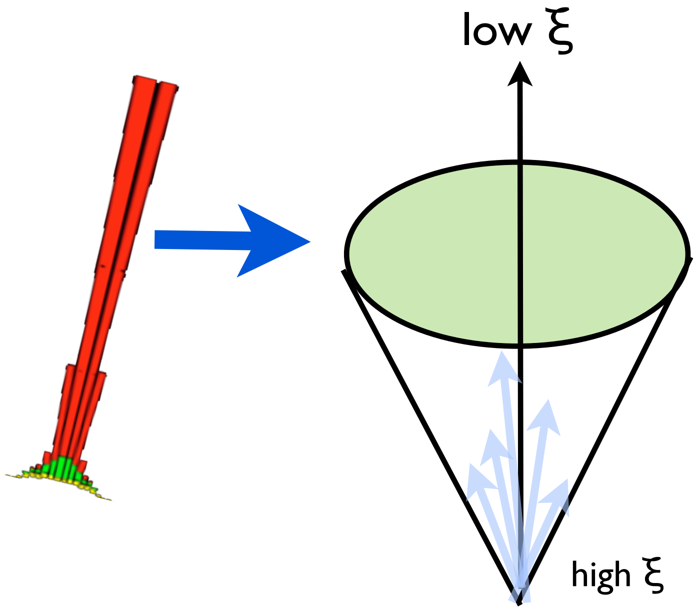
backup

Jet fragmentation and shape

Jet fragmentation function:

- particle momenta projected onto the jet axis

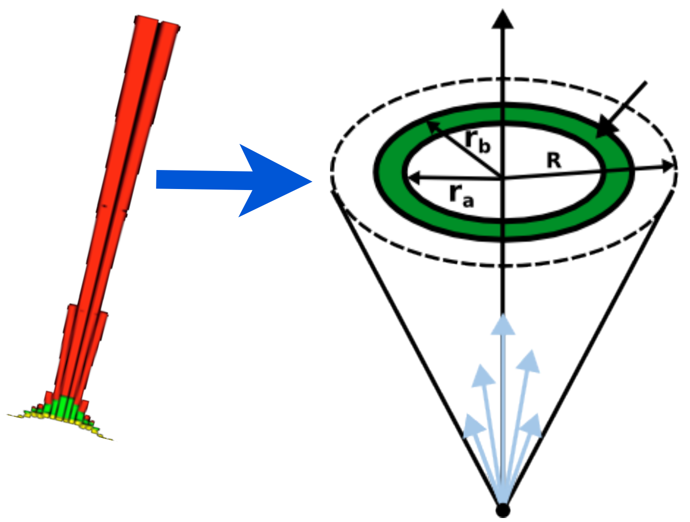
$$\xi = \ln(1/z) = \ln(p^{jet}/p^{track})$$



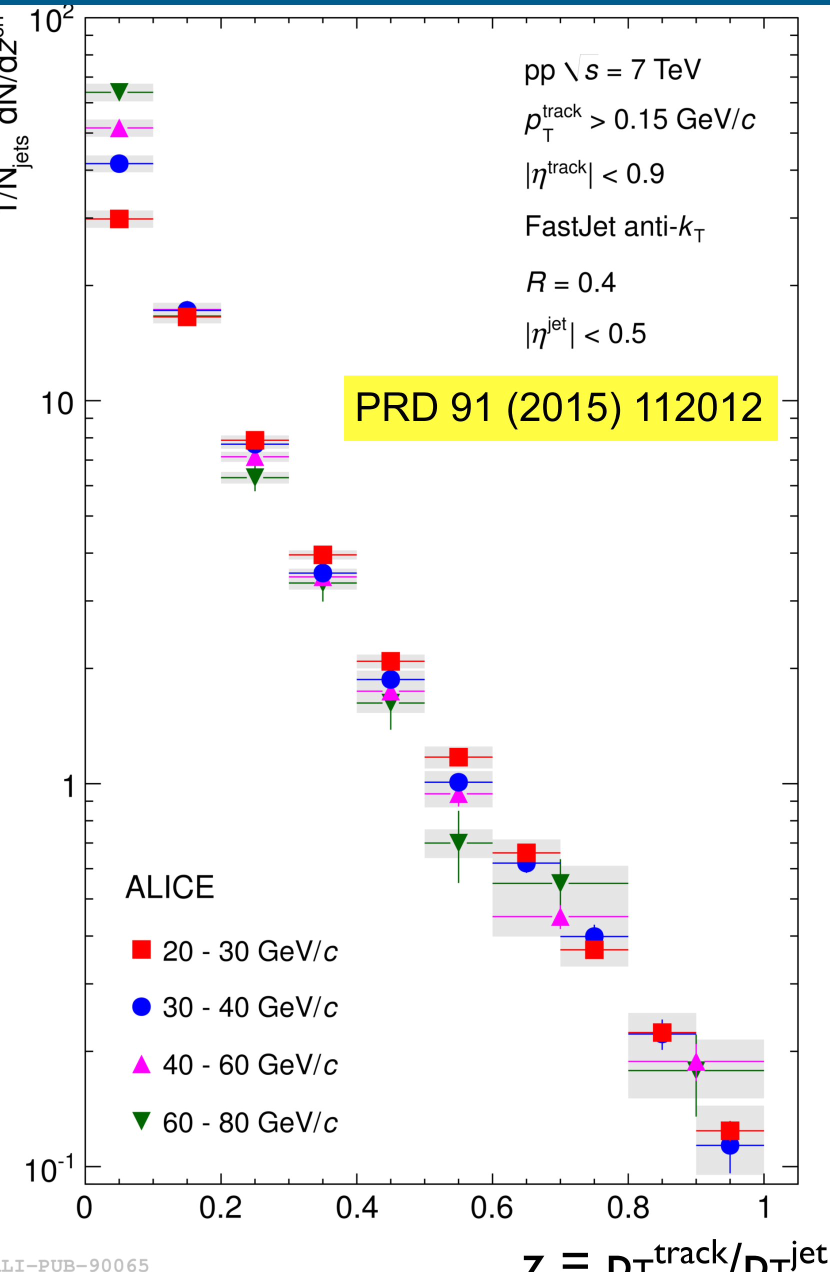
Jet shape:

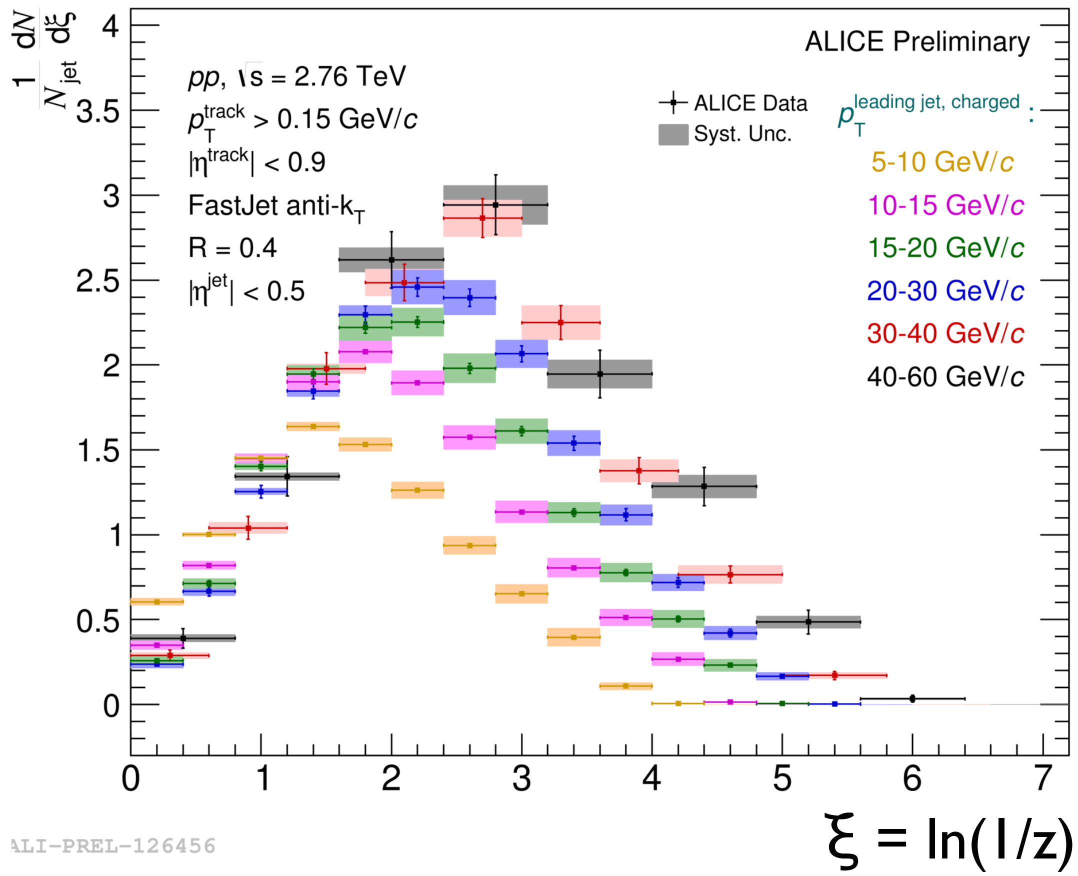
- transverse momenta-flow as a function of the distance from the jet axis (r) in the η-φ plane

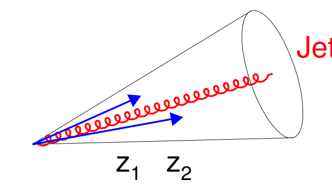
$$\rho(r) = \frac{1}{f_{ch}} \frac{1}{\delta r} \frac{1}{N_{jet}} \sum_{jets} \frac{p_T(r - \delta r/2, r + \delta r/2)}{p_T^{jet}},$$



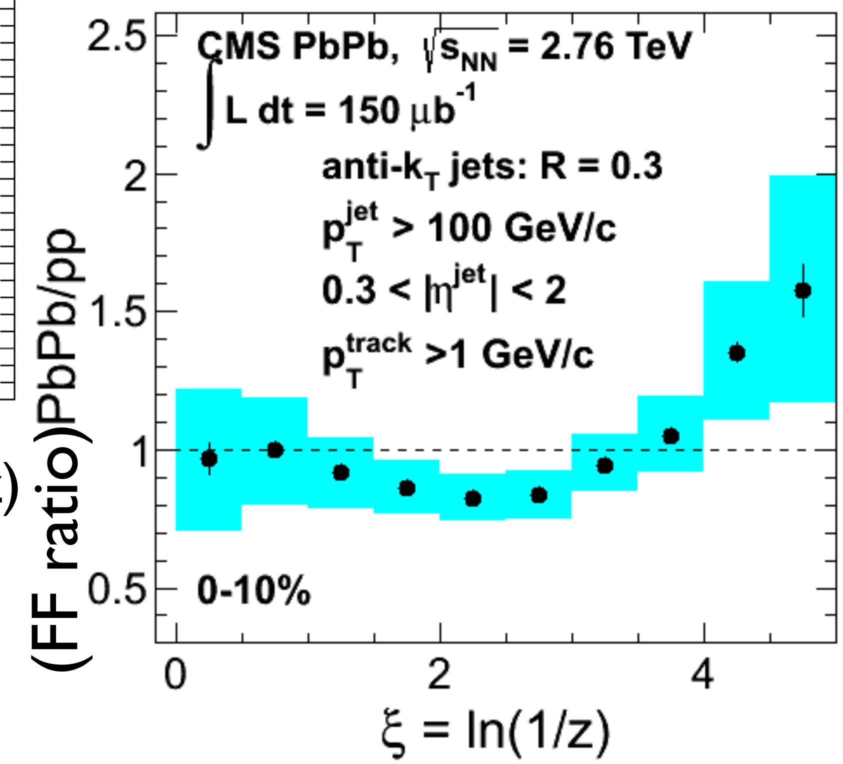
Jet fragmentation function







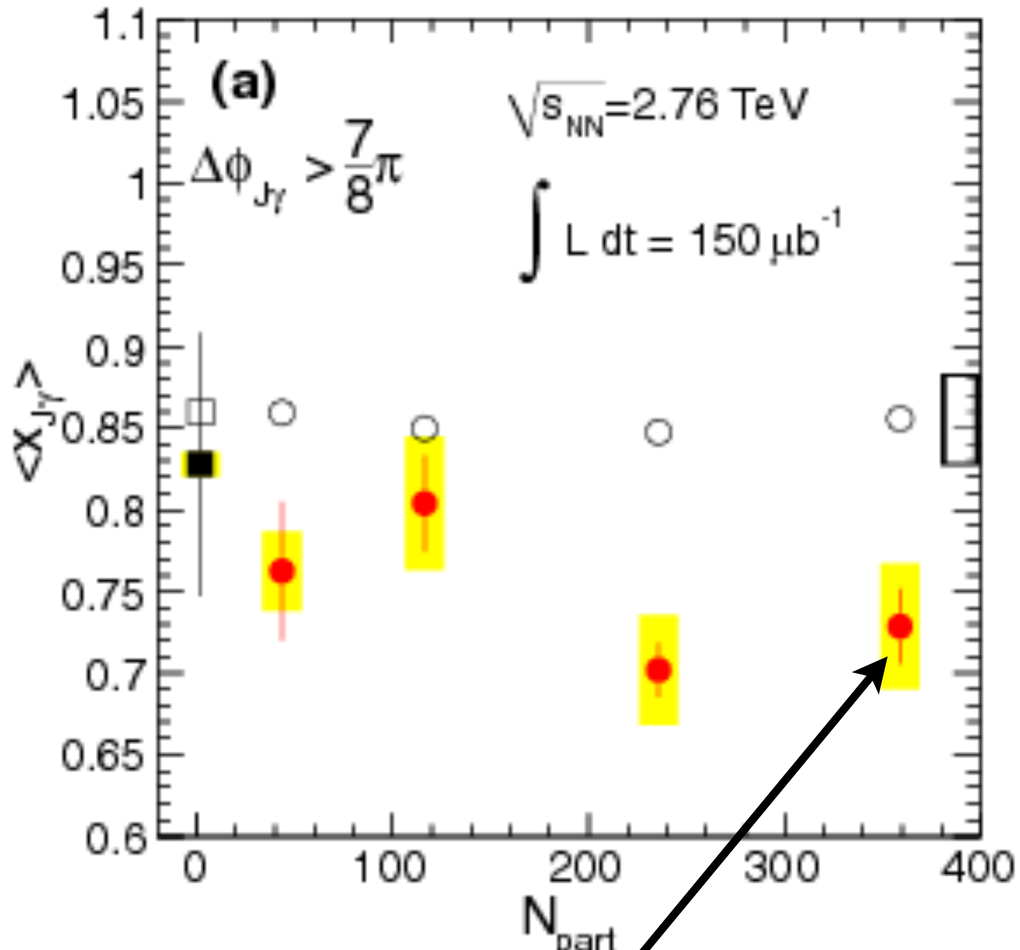
$$z = \frac{p_{hadron}}{p_{jet}}$$

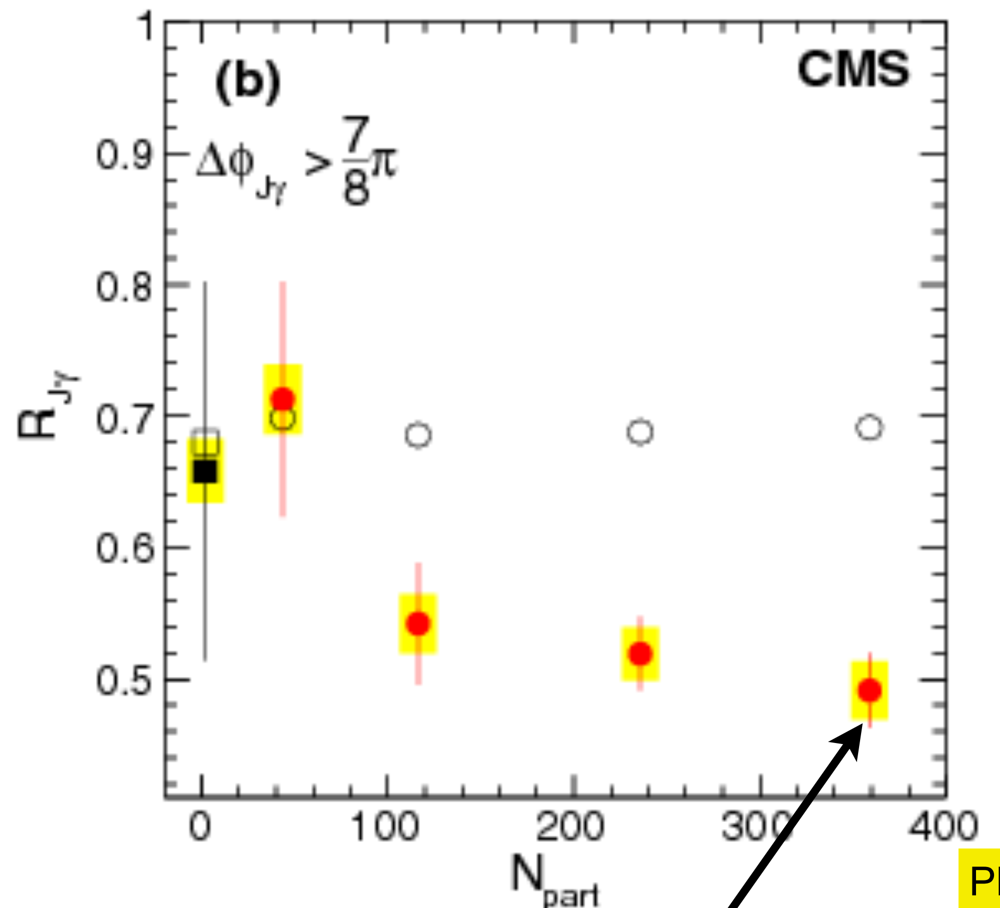


- No strong jet p_T dependent fragmentation pattern
- difference observed at very low z (high ξ), especially for low p_T jets
- Next: do the analysis in PbPb collisions and study FF modification for low p_T jets

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)





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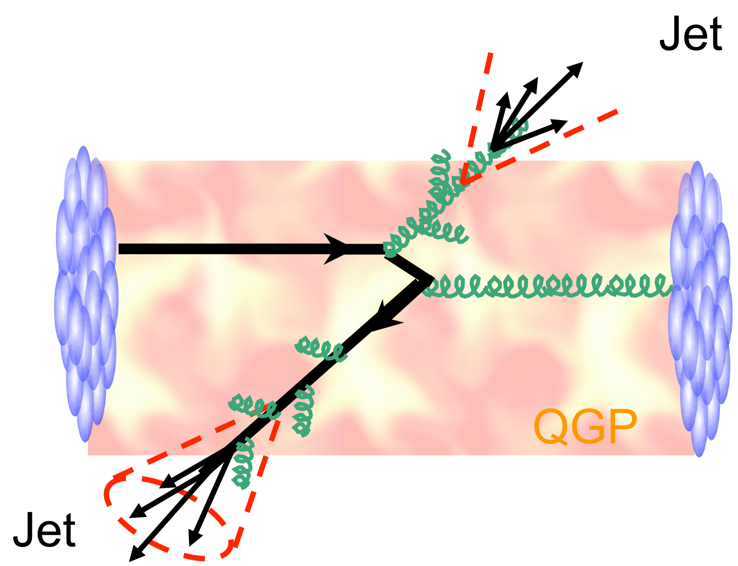
Increasing p_T-imbalance

Jets lose ~14% of their initial energy

~20% of photons lose their jet partner

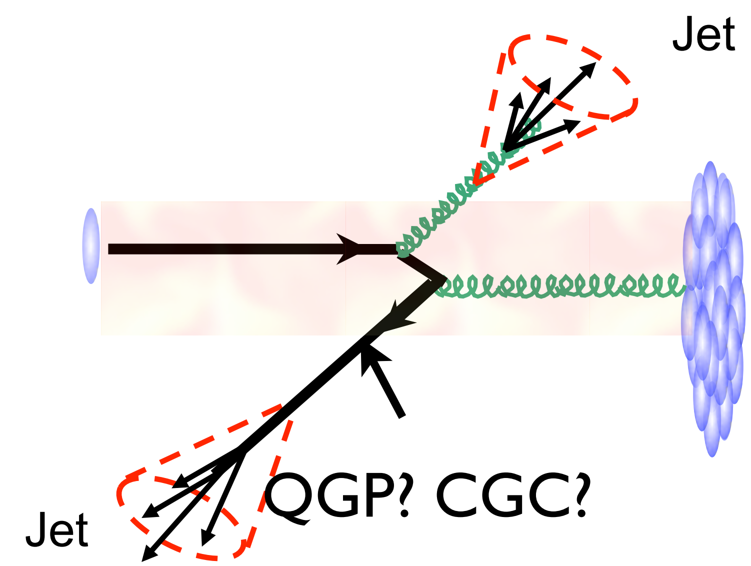
Controlled Experiment: p + Pb ?

PbPb collisions



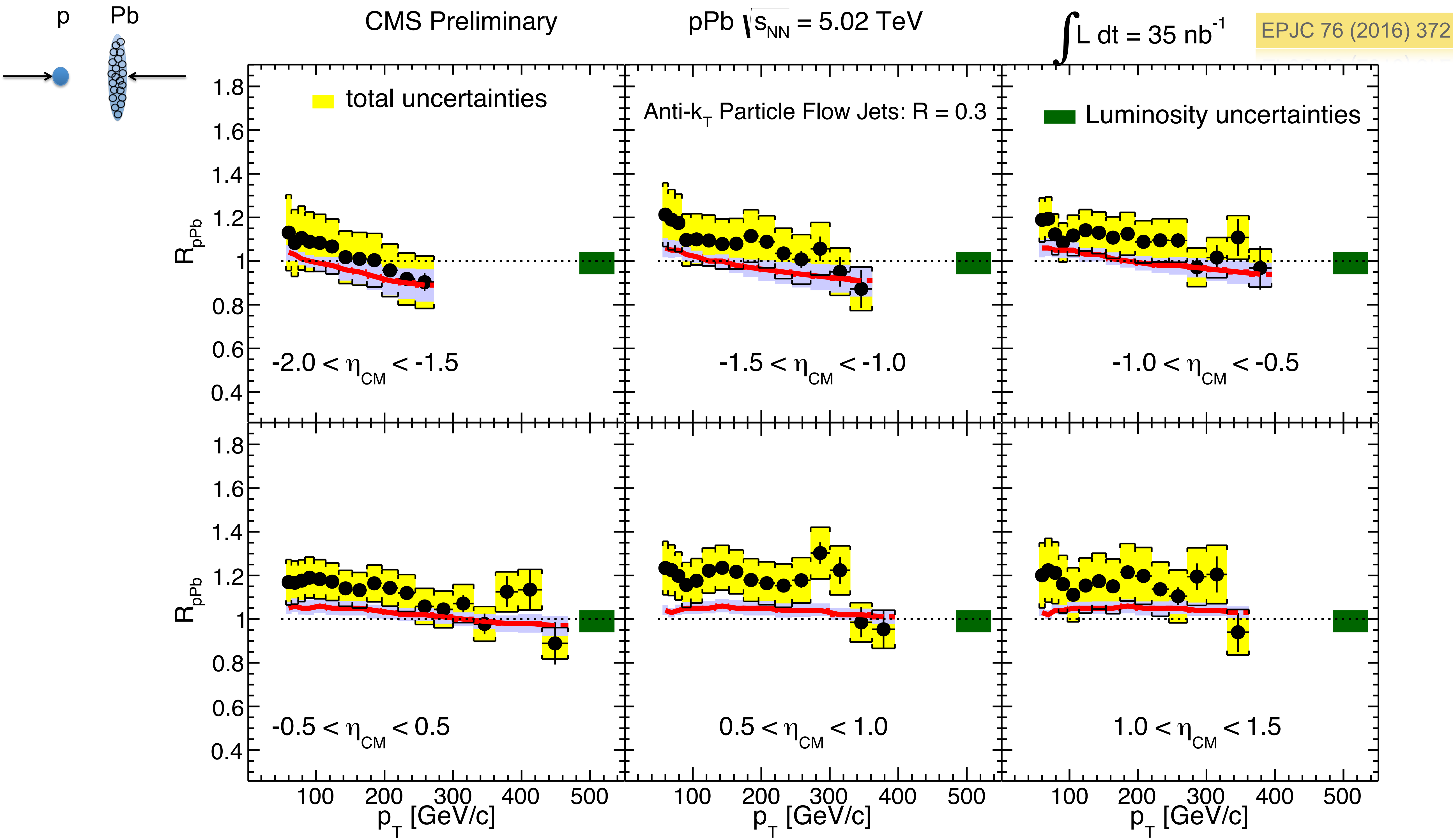
- Clear signs of Quark-Gluon Plasma (QGP)
- Strongly interacting particles affected by the presence of QGP
  - quenched jets and high p_T
  - modified jet structure

pPb collisions



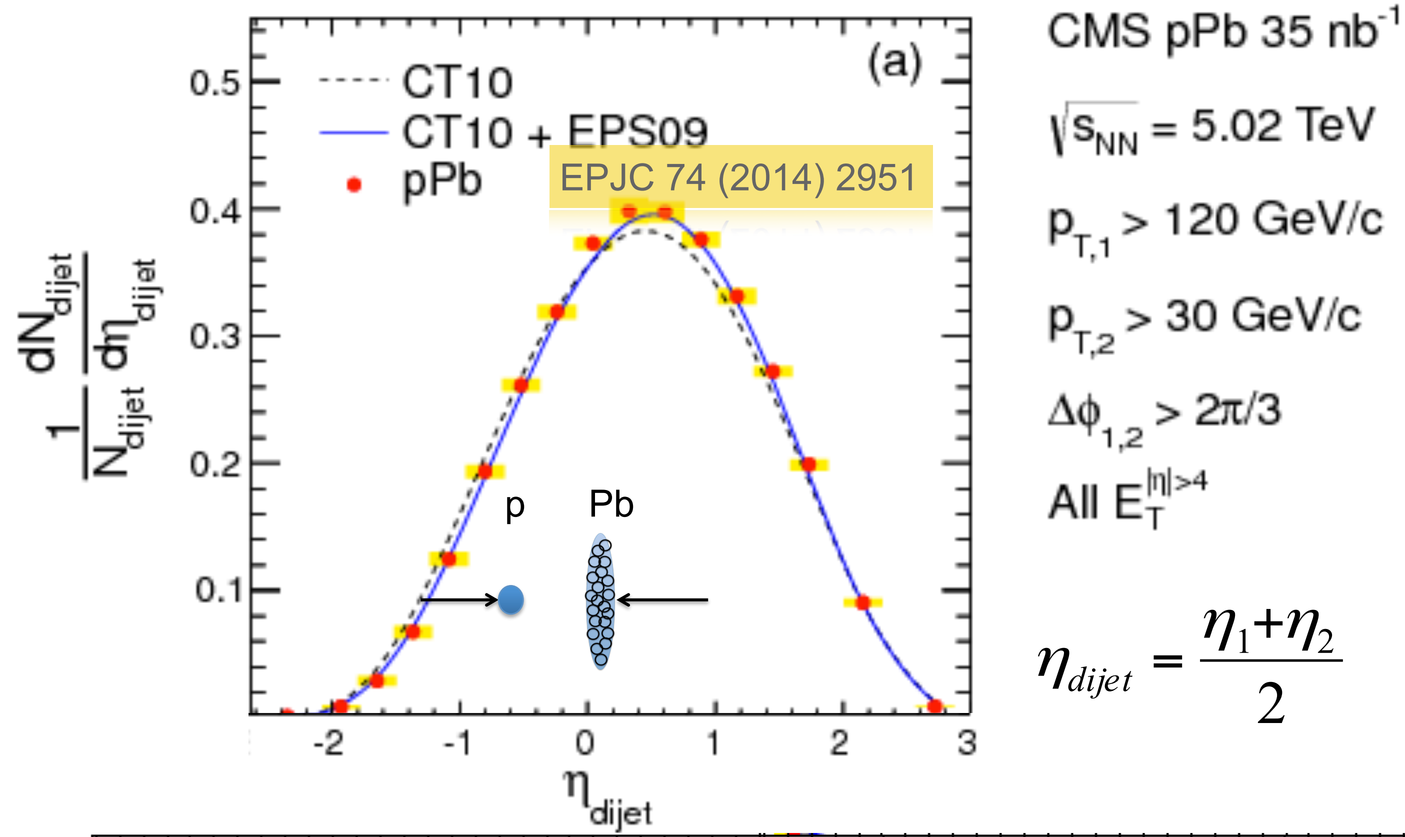
- Can we understand the baseline for PbPb?
- How do strongly interacting particles behave in cold nuclear matter? quenching?
- Can we see nuclear structure?

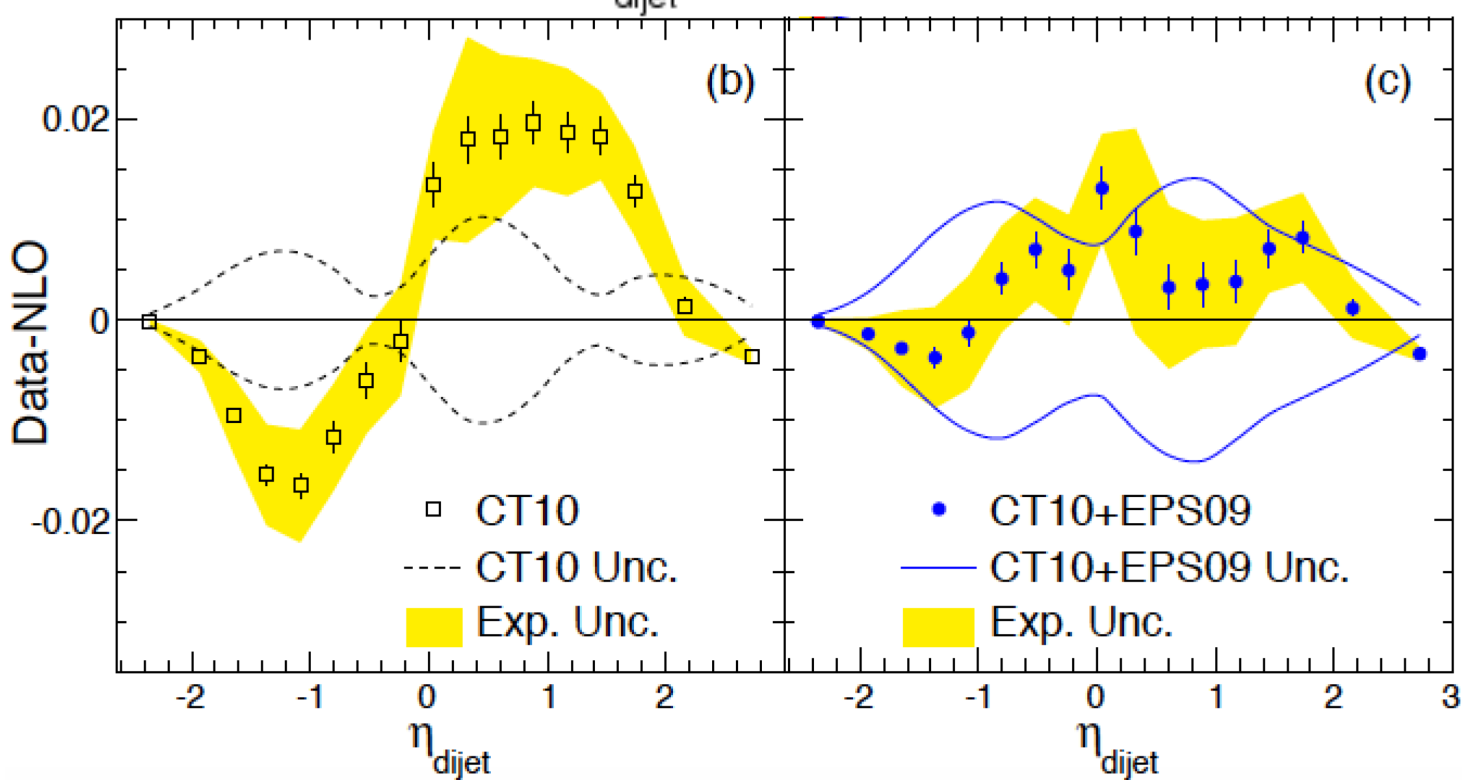
Jet quenching in p + Pb?

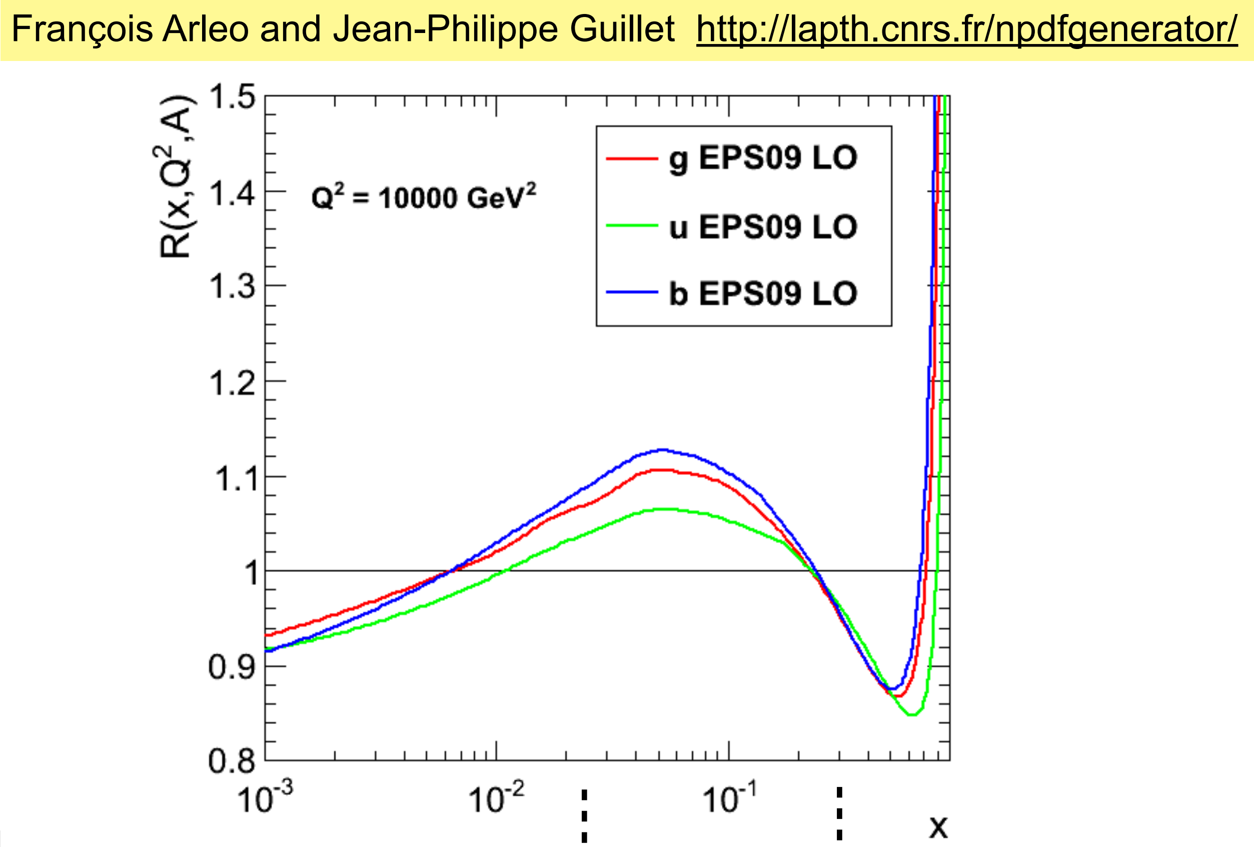


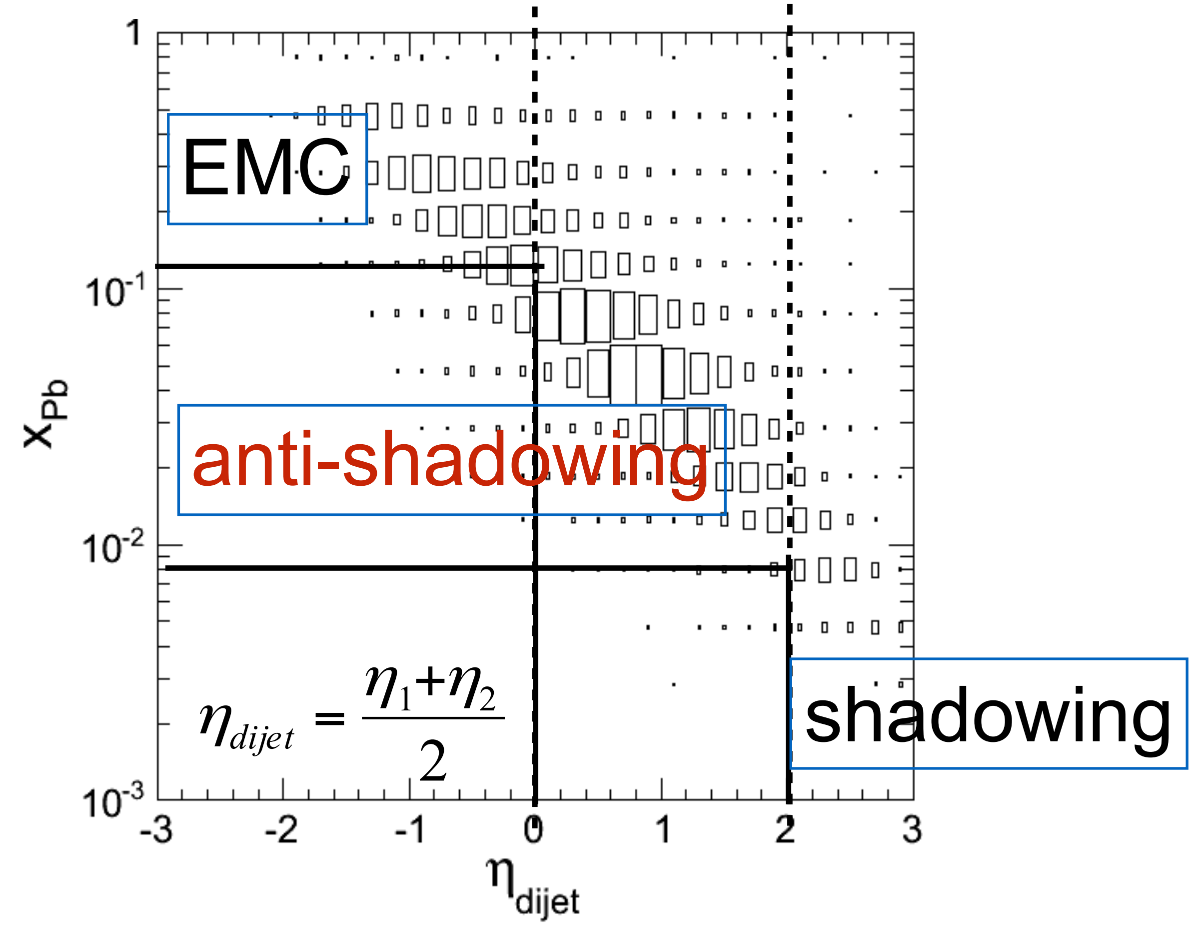
- No strong jet p_T dependence observed
- Consistent with EPS09 description

Dijet η asymmetry







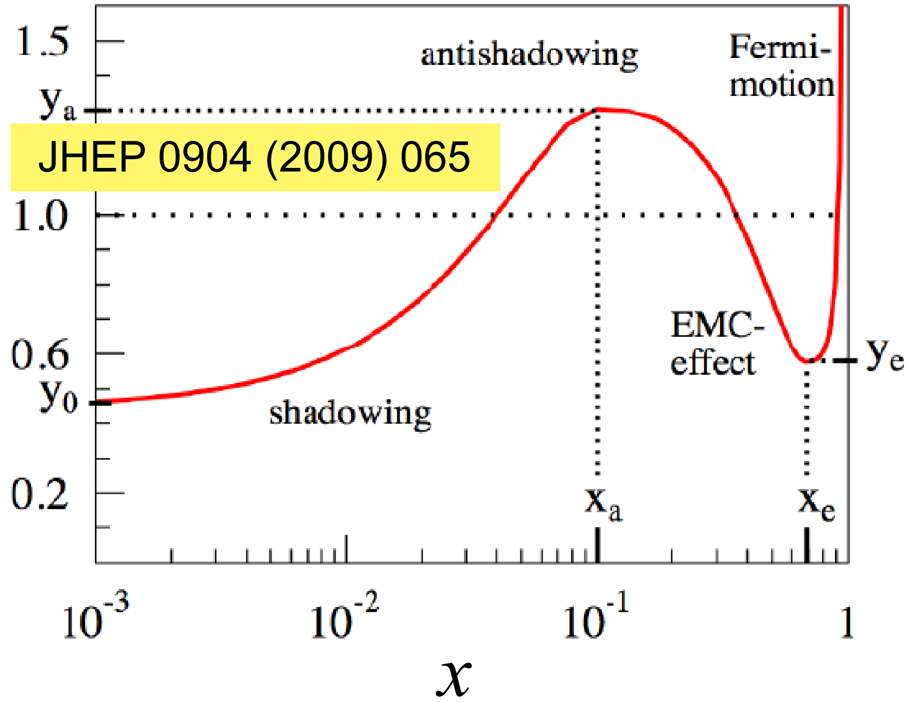


- Agreement between data and EPS09 calculation with systematics

Probing nPDF with jets and hadrons

x - fractional momentum from a colliding nucleon carried by the parton

$$R = \frac{nPDF}{PDF}$$



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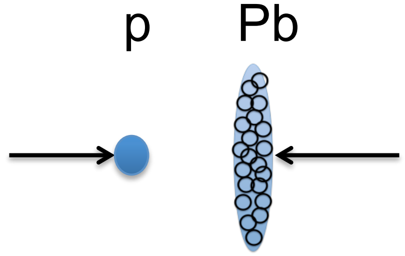
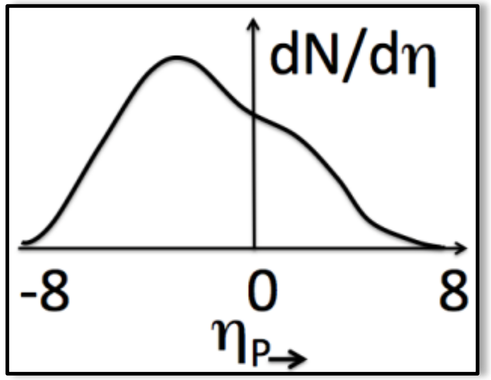
"backward"

large x from Pb



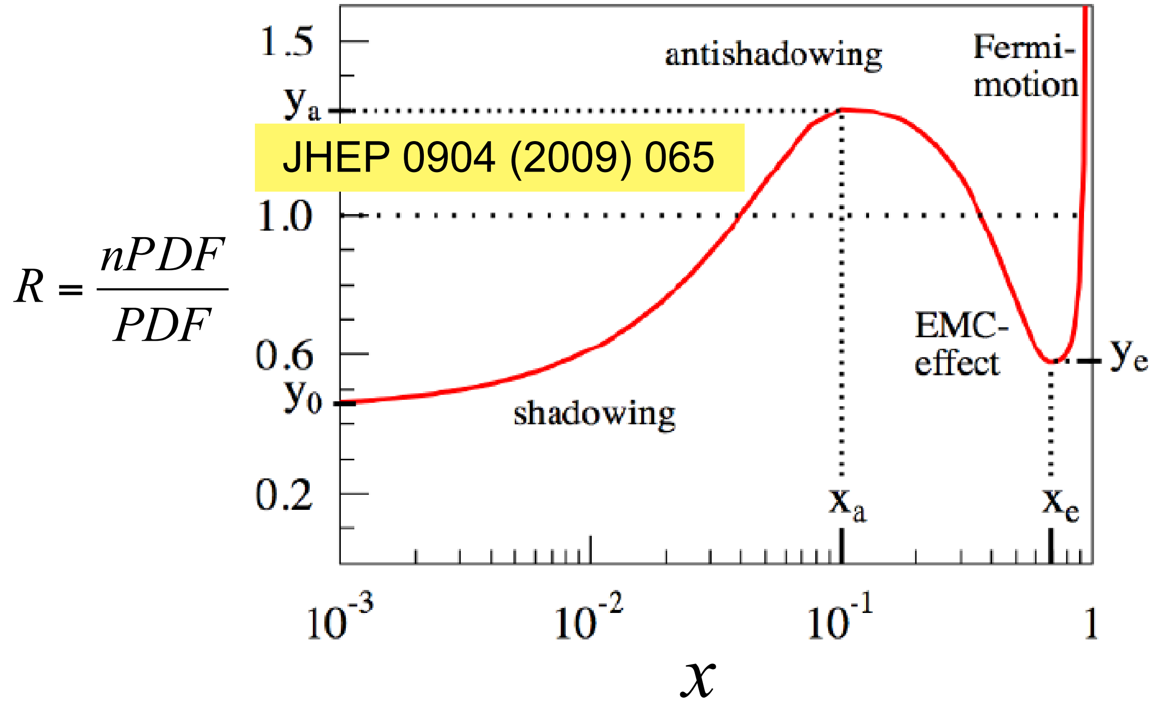
"forward"

small x from Pb



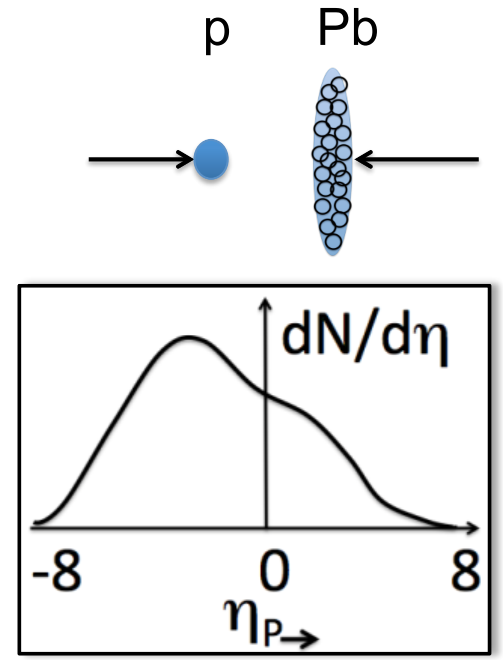
- Different p_T and η region can probe different x-range

x - fractional momentum from a colliding nucleon carried by the parton



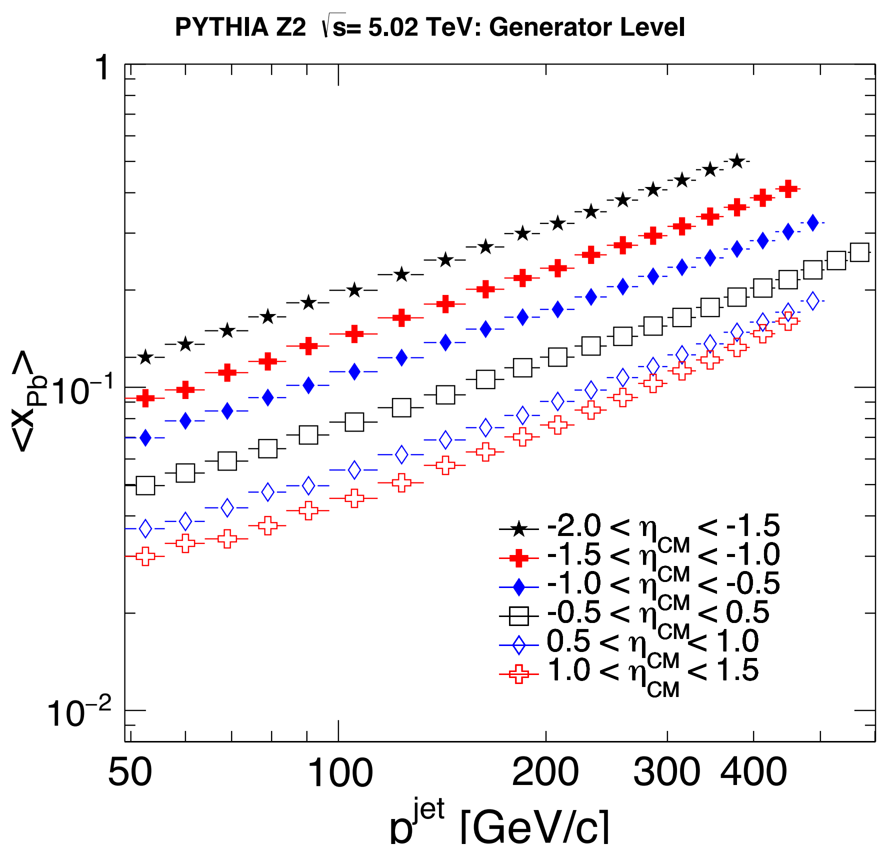
"backward"

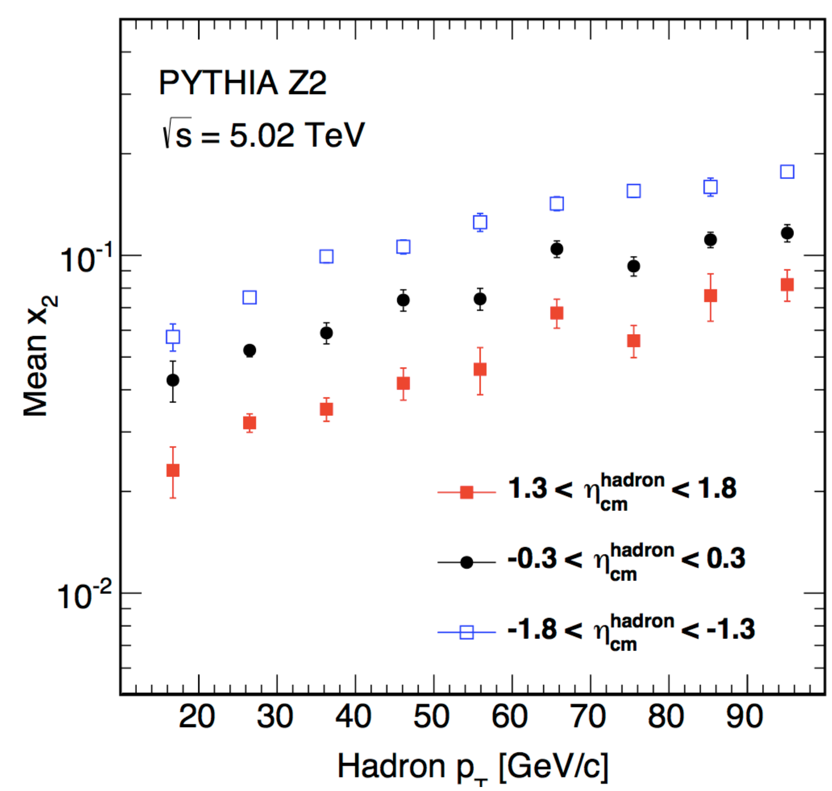
large x from Pb



"forward"

small x from Pb

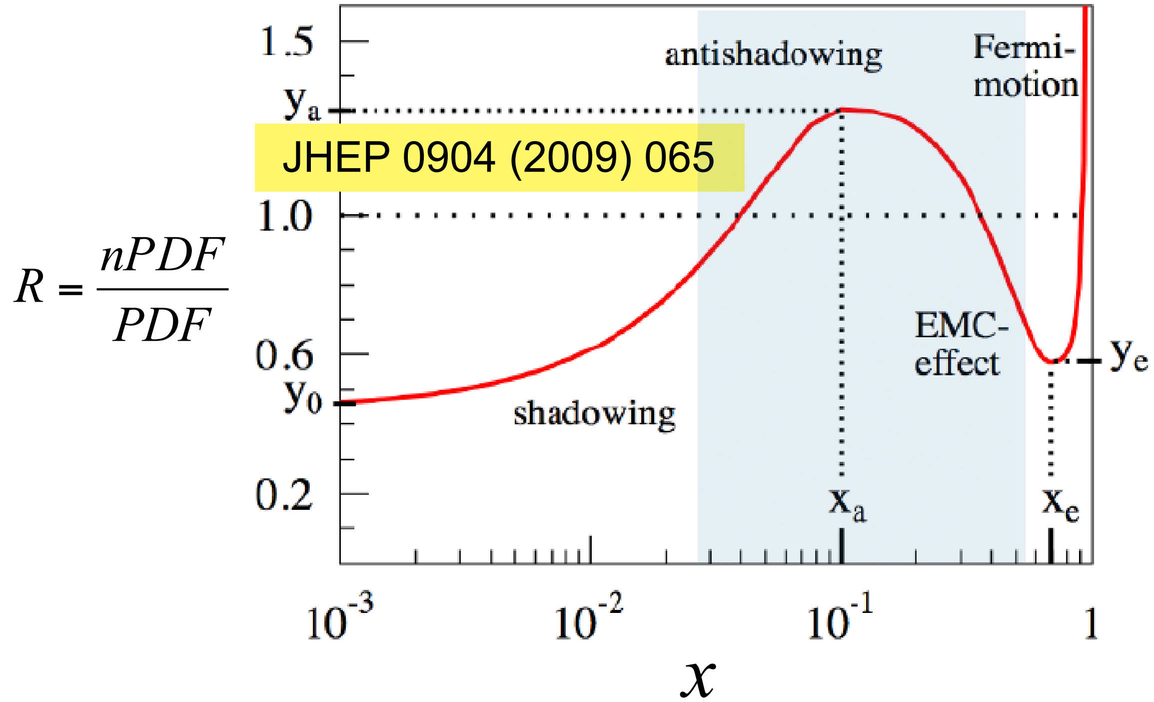


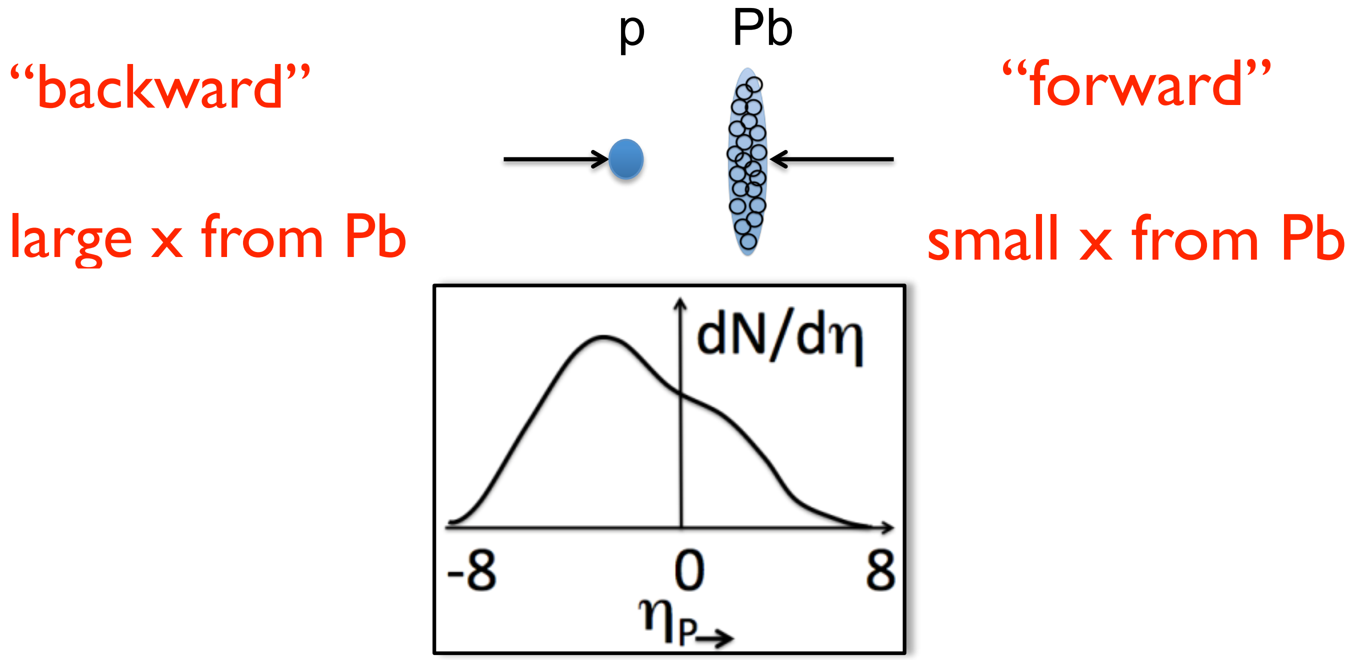


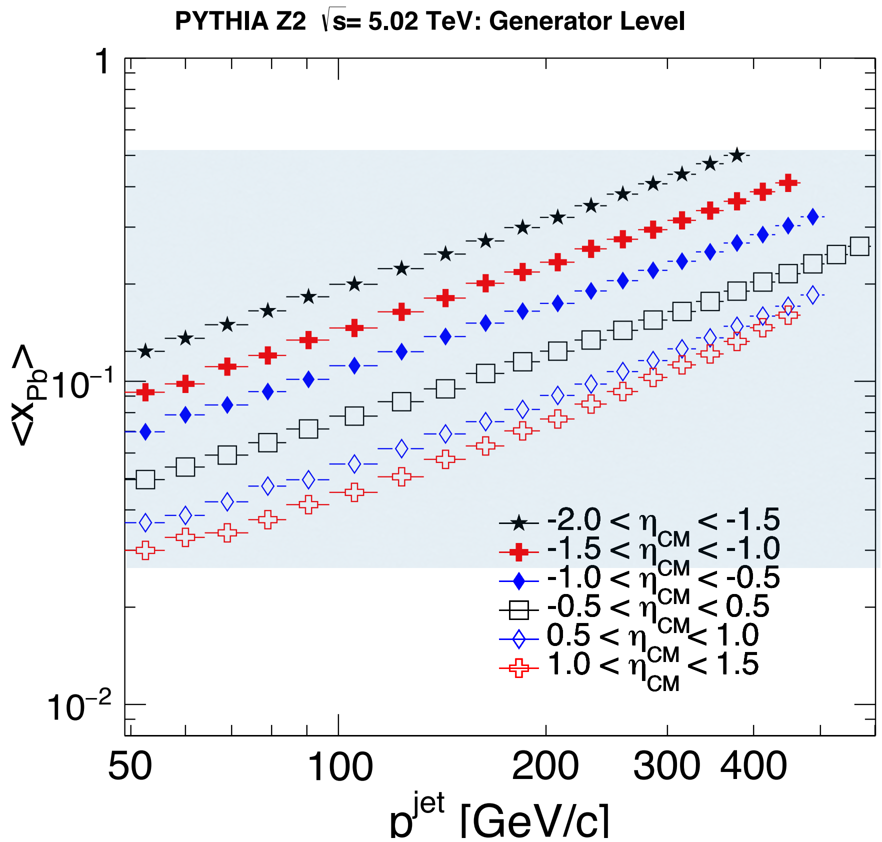
- Different p_T and η region can probe different x-range

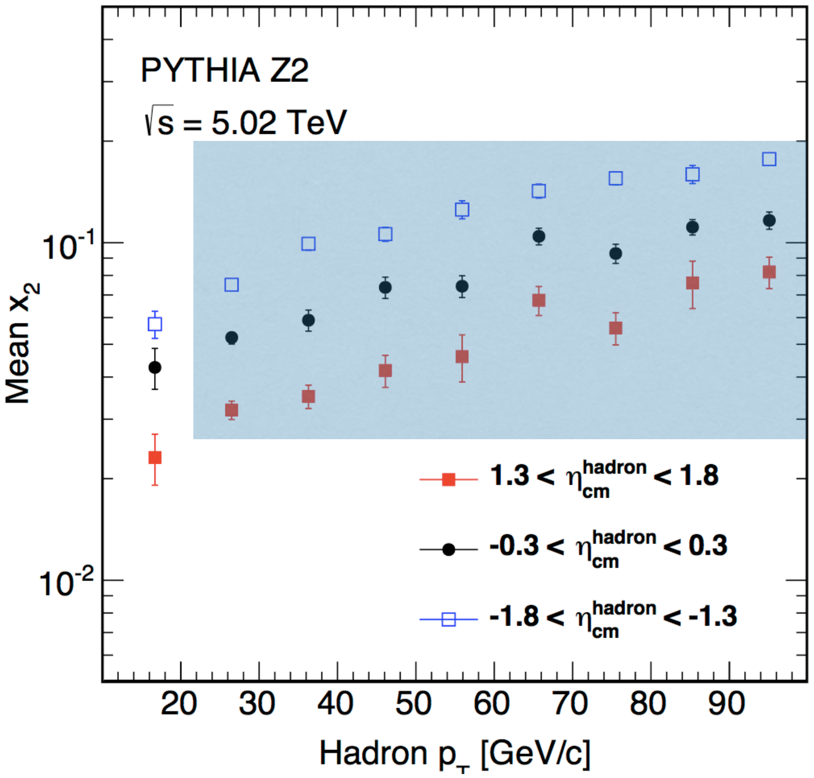
Probing nPDF with jets and hadrons

x - fractional momentum from a colliding nucleon carried by the parton



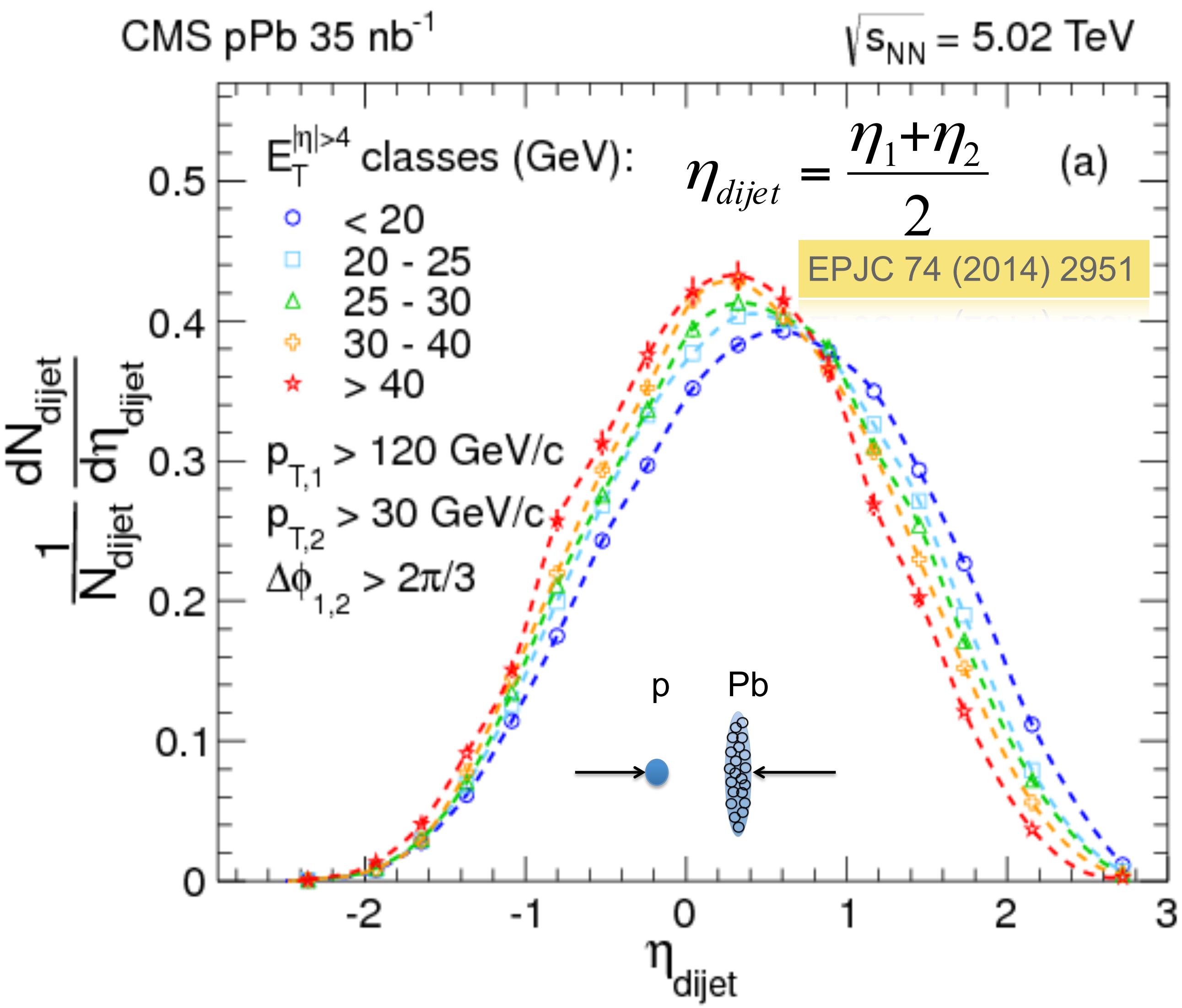


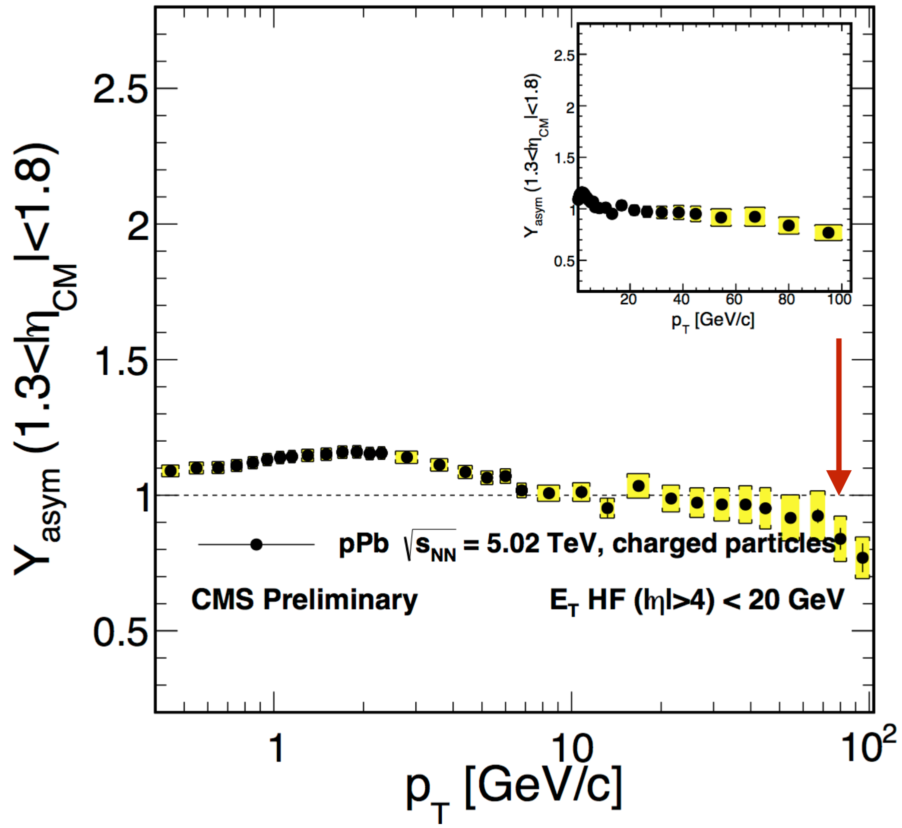


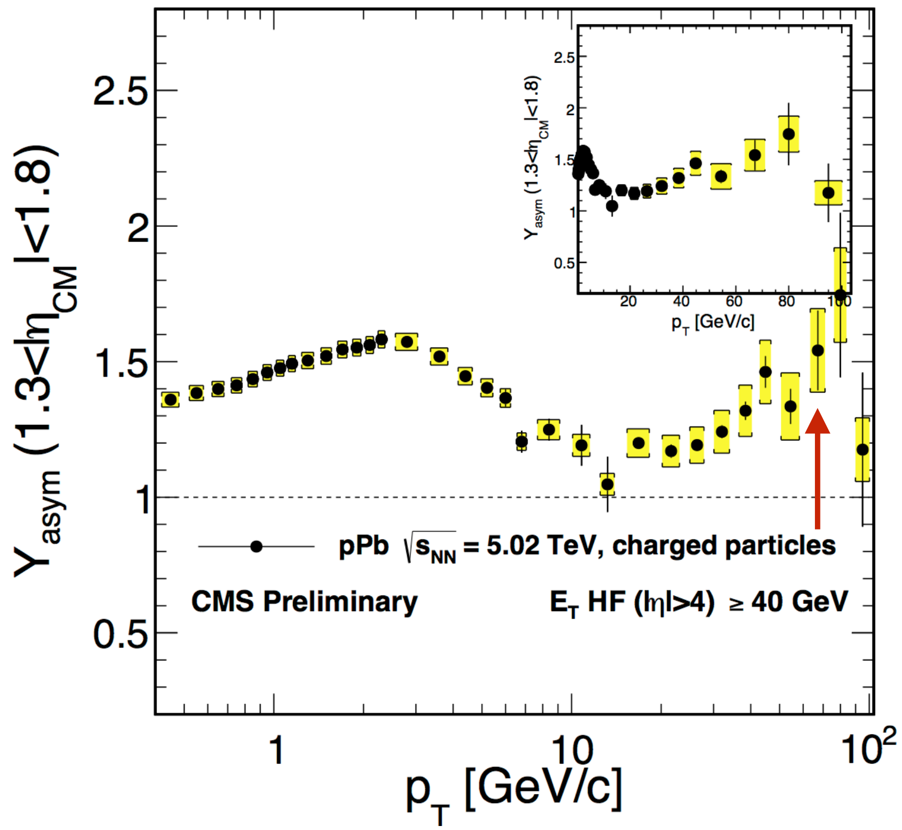


- Different p_T and η region can probe different x-range

dijet η and charged hadron asymmetry



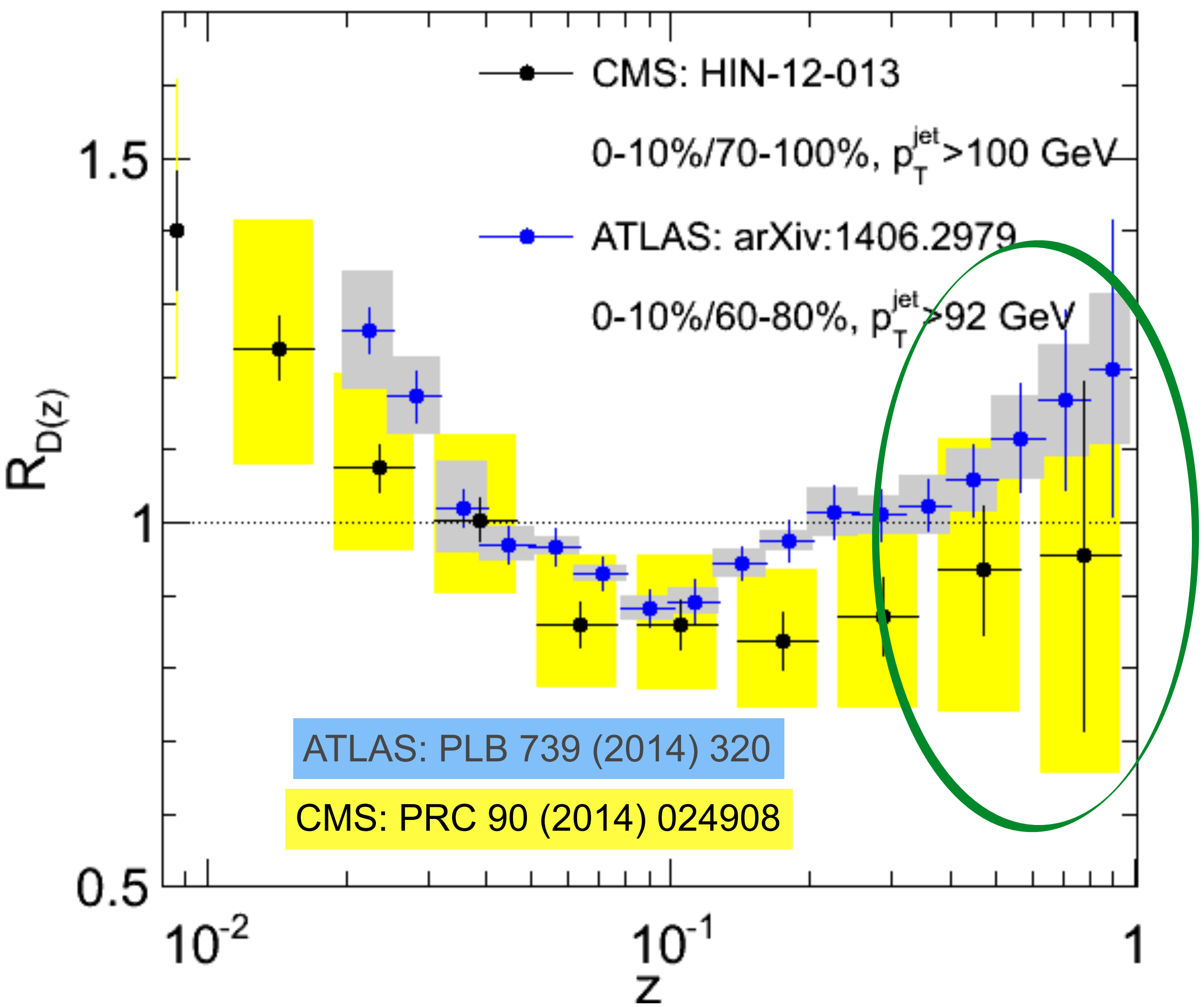


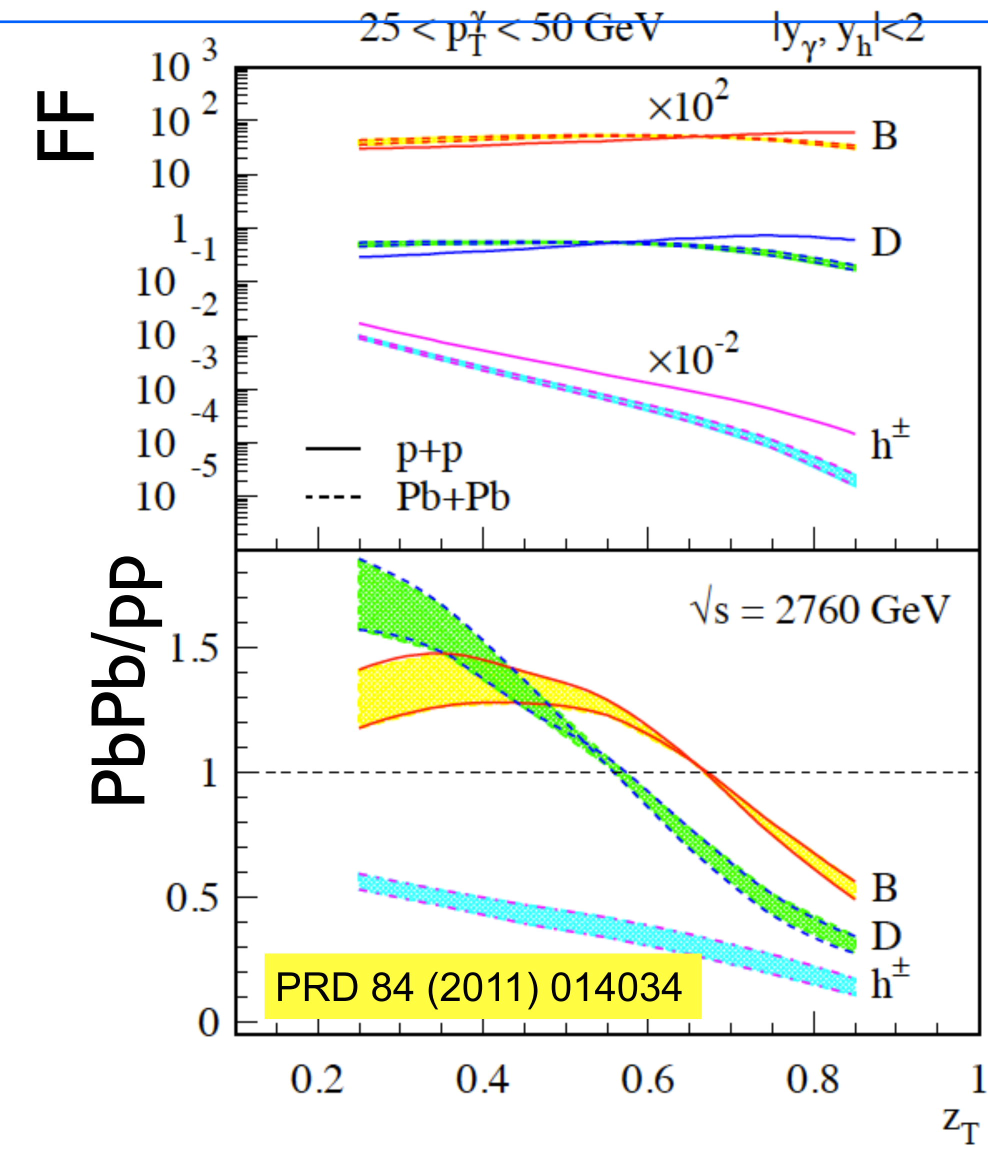


- "Peripheral" events with low HF activity: dijets shifted to p-going side, expect $Y_{asym} < 1$
- "Central" events with high HF activity: dijets shifted to Pb-going side, expect $Y_{asym} > 1$

Color charge dependent jet FF and modifications?

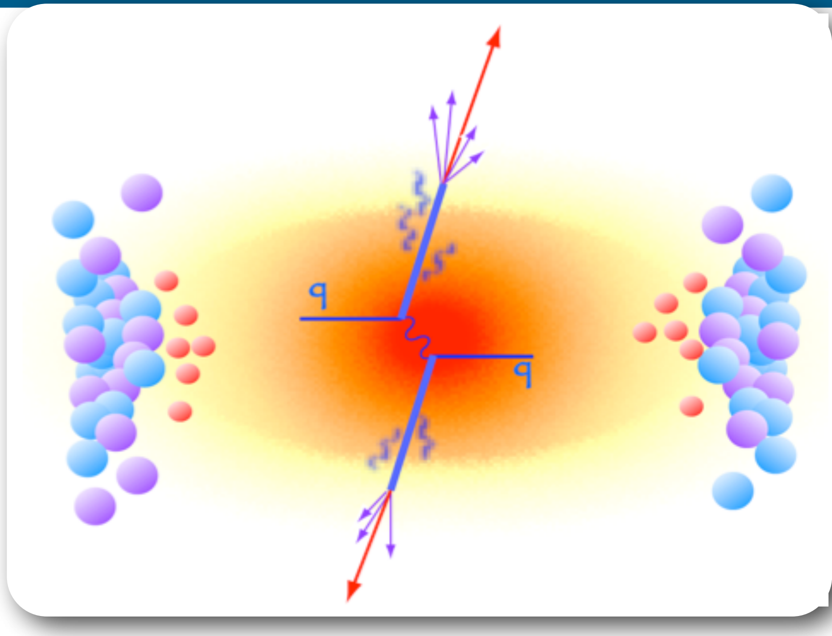
High z fragments modified? Different partons have different modification?



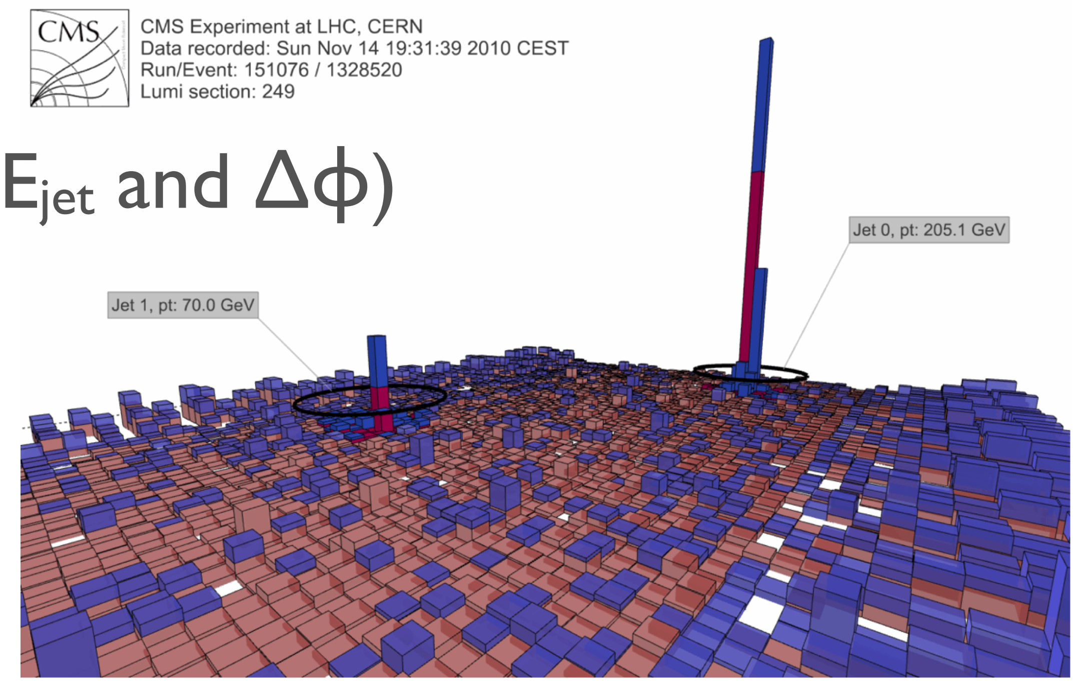


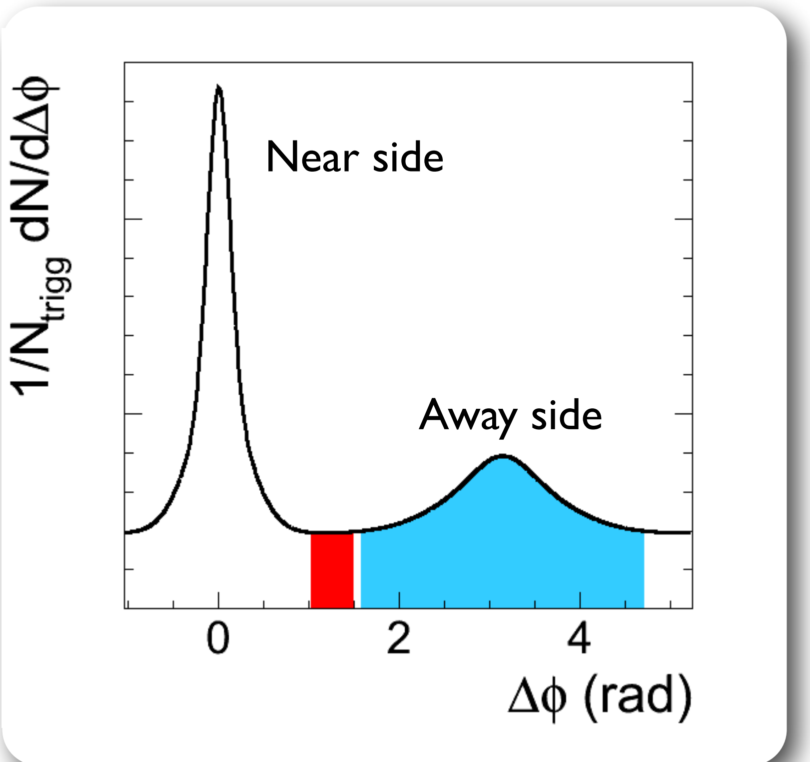
- FF Rcp shows difference hints at high z between experiments
  - ➡ need precise measurements with coming LHC data
- Theory predicted jet fragmentation pattern modified differently for different parton mass
  - ➡ can be checked at LHC with coming data

Di-jet and di-hadron correlations

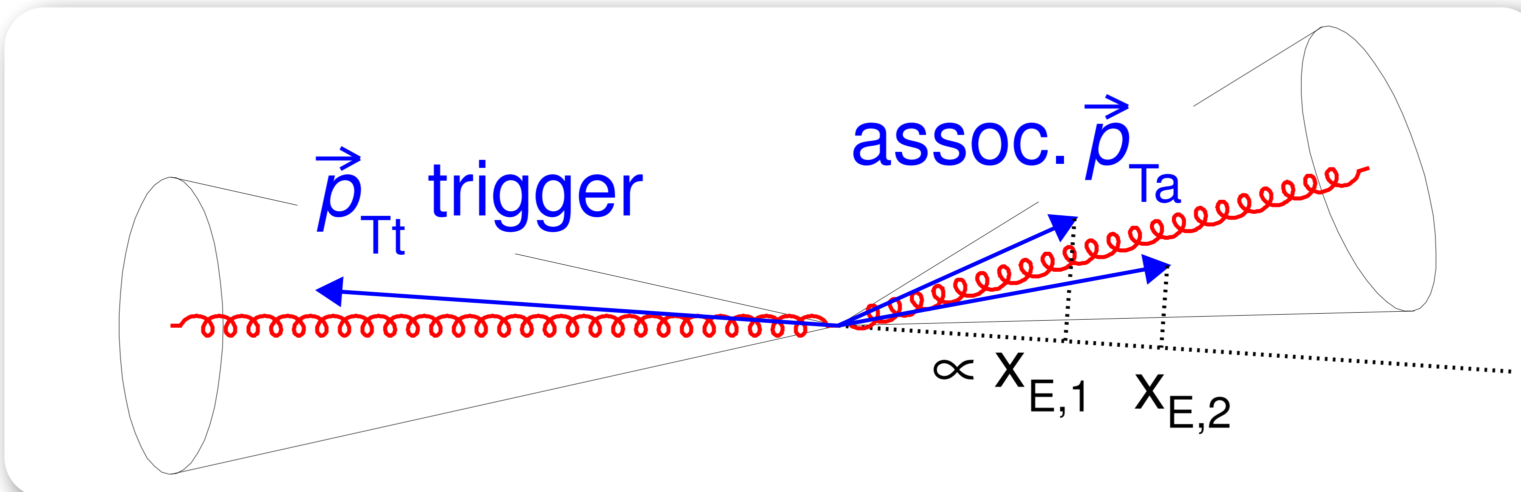


- hard scattered parton looses energy while traversing the medium
  - di-jet (im)balance (E_{jet} and $\Delta\phi$)

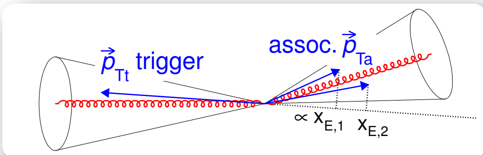




  - di-hadron correlation pattern
    - Inter-jet properties ($\Delta\phi$, away side x_E)



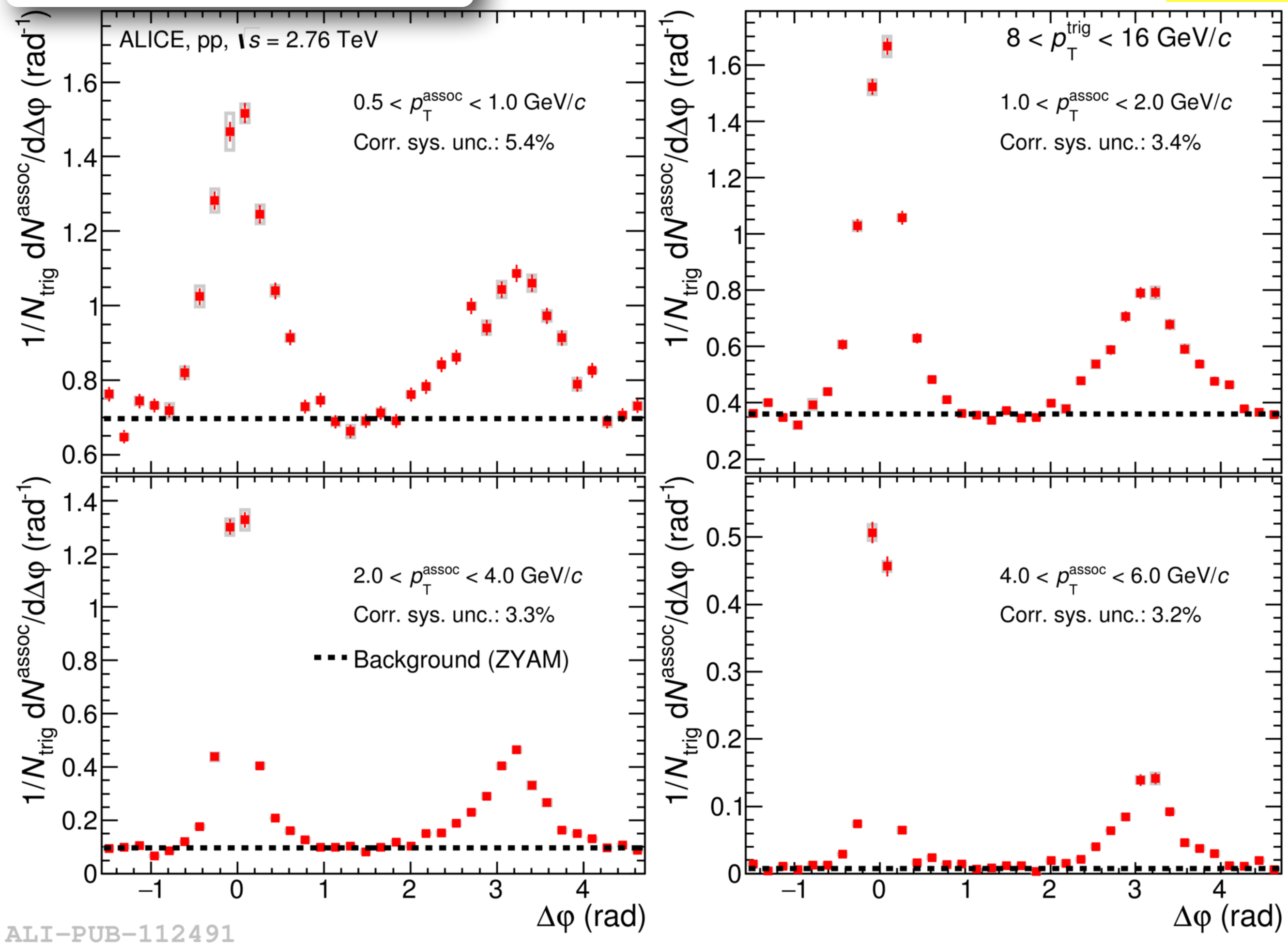
π⁰-hadron azimuthal correlations

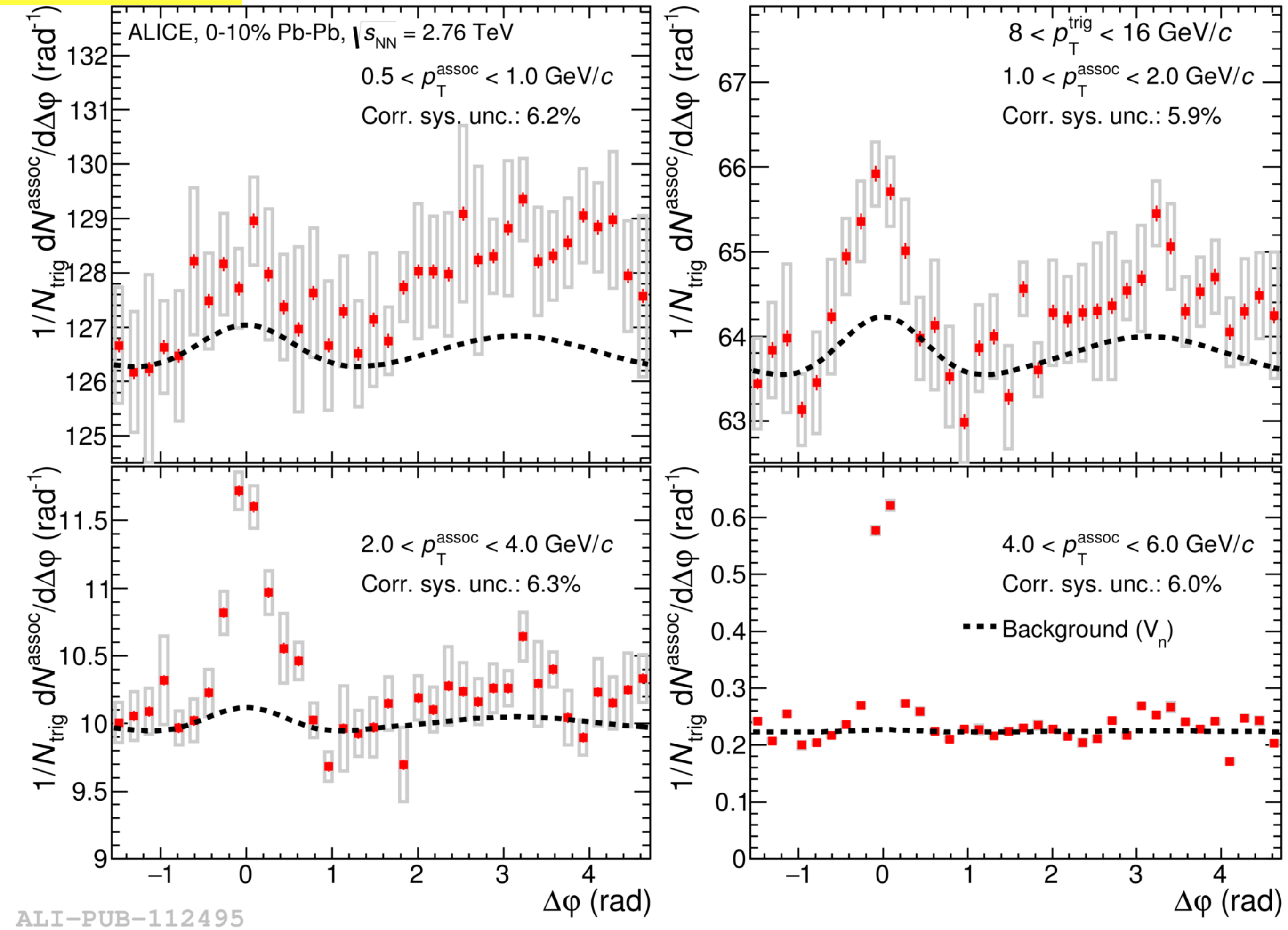


pp

PLB 763 (2016) 238

PbPb



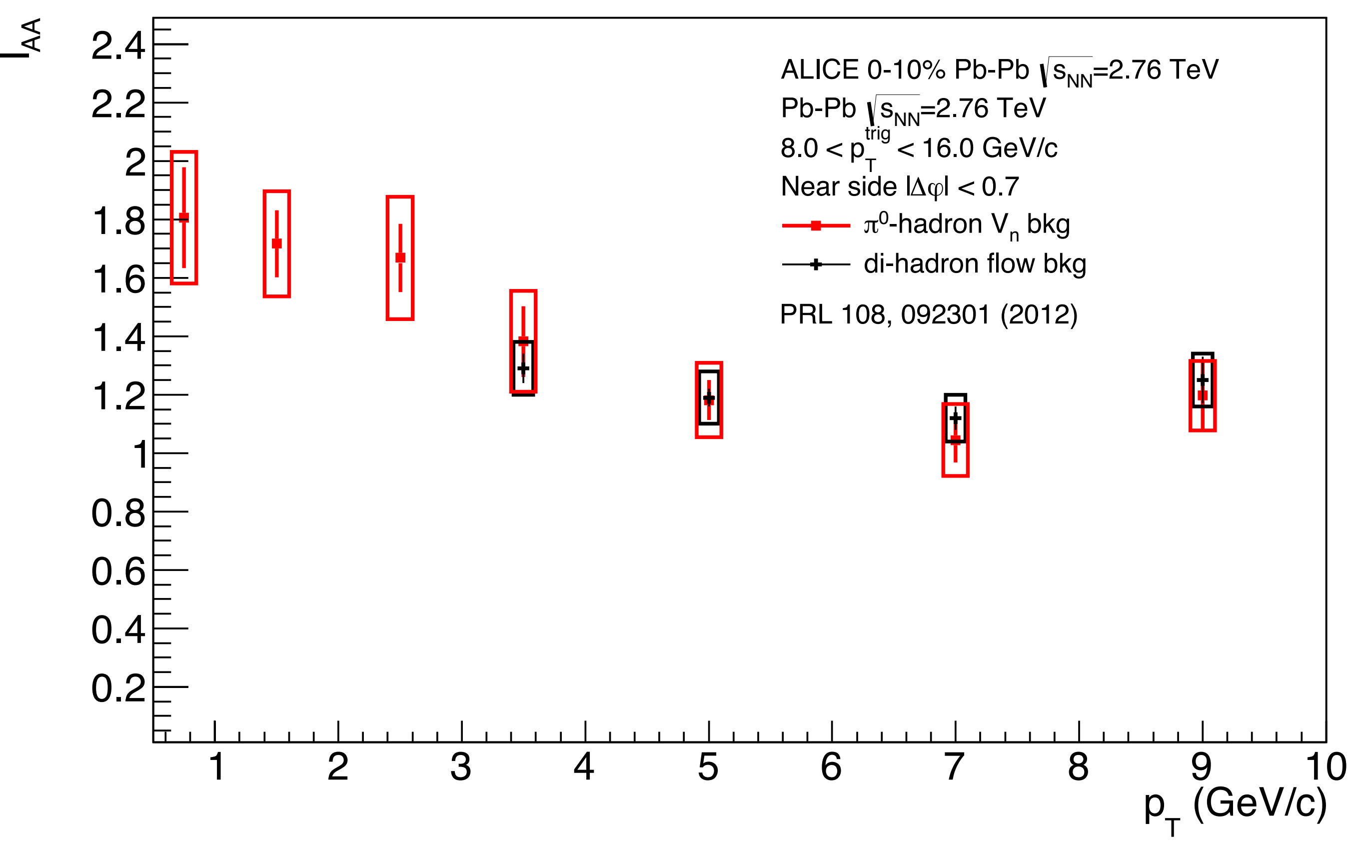


- Double peaks observed → di-jet structure
- Near side peak width broader in PbPb compared to pp → jet broadening
- Away side peak in central PbPb collision is strongly suppressed → jet quenching

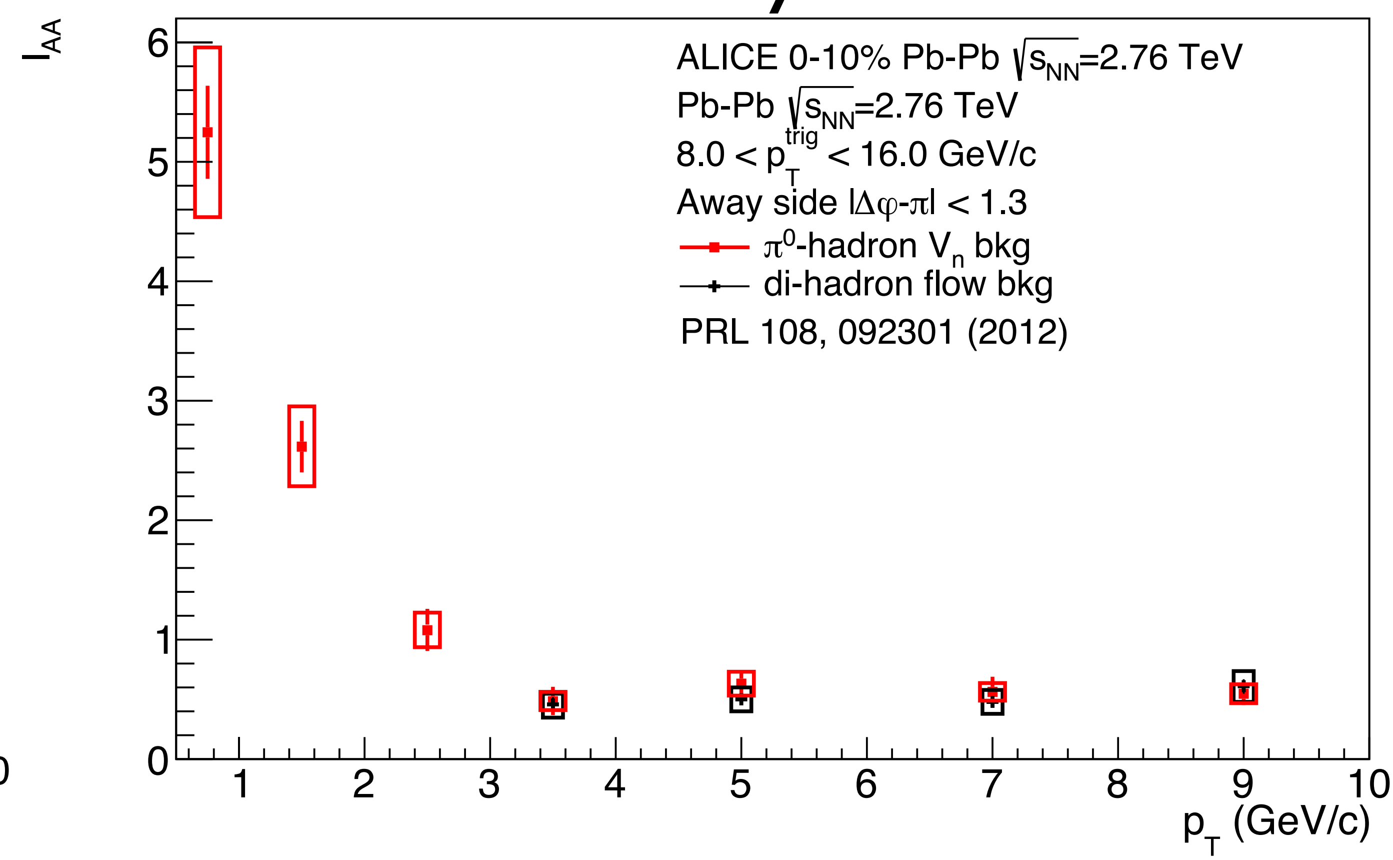
Yield modification I_{AA}

$$I_{AA}\left(p_T^{\pi^0}, p_T^{h^\pm}\right) = \frac{Y_{PbPb}\left(p_T^{\pi^0}, p_T^{h^\pm}\right)}{Y_{pp}\left(p_T^{\pi^0}, p_T^{h^\pm}\right)} \qquad Y = \int \frac{1}{N_{trig}} \frac{dN_{assoc}}{d\Delta\varphi\varphi} d\Delta\varphi$$

near side

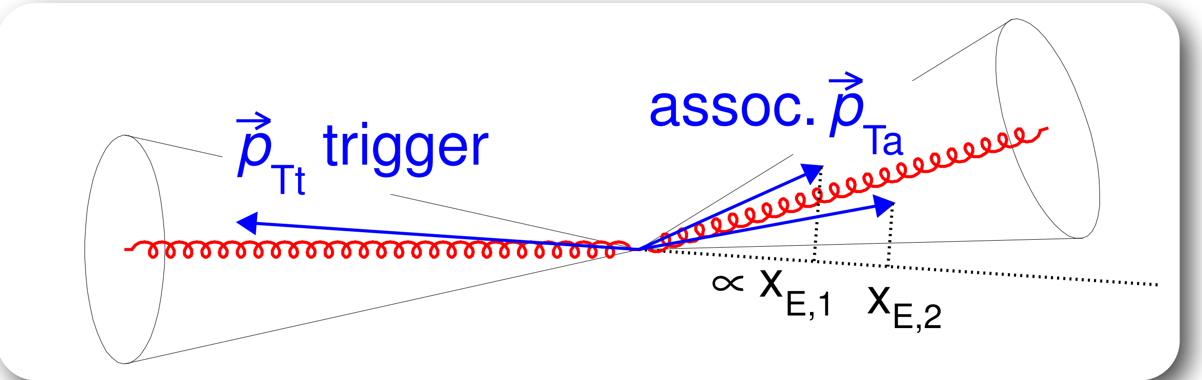


away side



- π^0 triggered correlation identical to non identified di-hadron correlations
- No or little yield modification in the near side and yield suppression in the away side for high p_T particles
- Yield enhancement observed at very low p_T for both near and away side

x_E kinematics



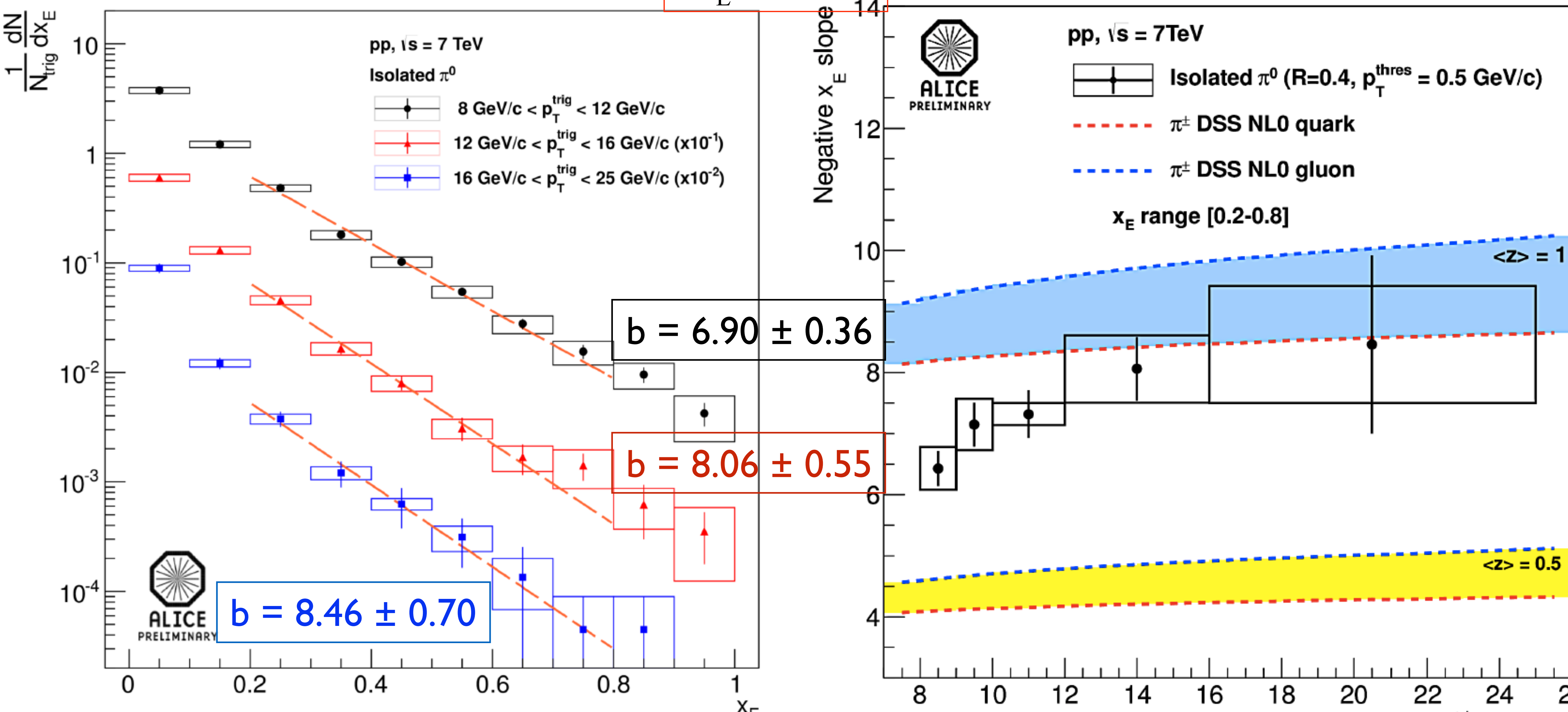
$$z_t = \frac{p_{Tt}}{p_{jet}^{near}} \qquad z_a = \frac{p_{Ta}}{p_{jet}^{away}}$$

$$x_E = -\frac{\vec{p}_{Tt} \cdot \vec{p}_{Ta}}{\left|\vec{p}_{Tt}\right|^2} = -\frac{p_{Ta}}{p_{Tt}} \cos(\Delta\phi)$$

- $\Delta\phi = \phi_{trigger} - \phi_{associate} \sim \pi \quad \Rightarrow \quad x_E \approx \dfrac{z_a \cdot p_{jet}^{away}}{z_t \cdot p_{jet}^{near}}$
- No k_T (di-jet balance) $\quad \Rightarrow \quad x_E \approx \dfrac{z_a}{\langle z_t \rangle}$
  - Charged/neutral trigger: $\langle z_t \rangle < 1 \Rightarrow x_E \neq z_a$
  - Isolated trigger: $\langle z_t \rangle \to 1 \Rightarrow x_E \to z_a$
  - Direct Photon-jet : $\langle z_t \rangle = 1 \Rightarrow x_E \approx z_a$

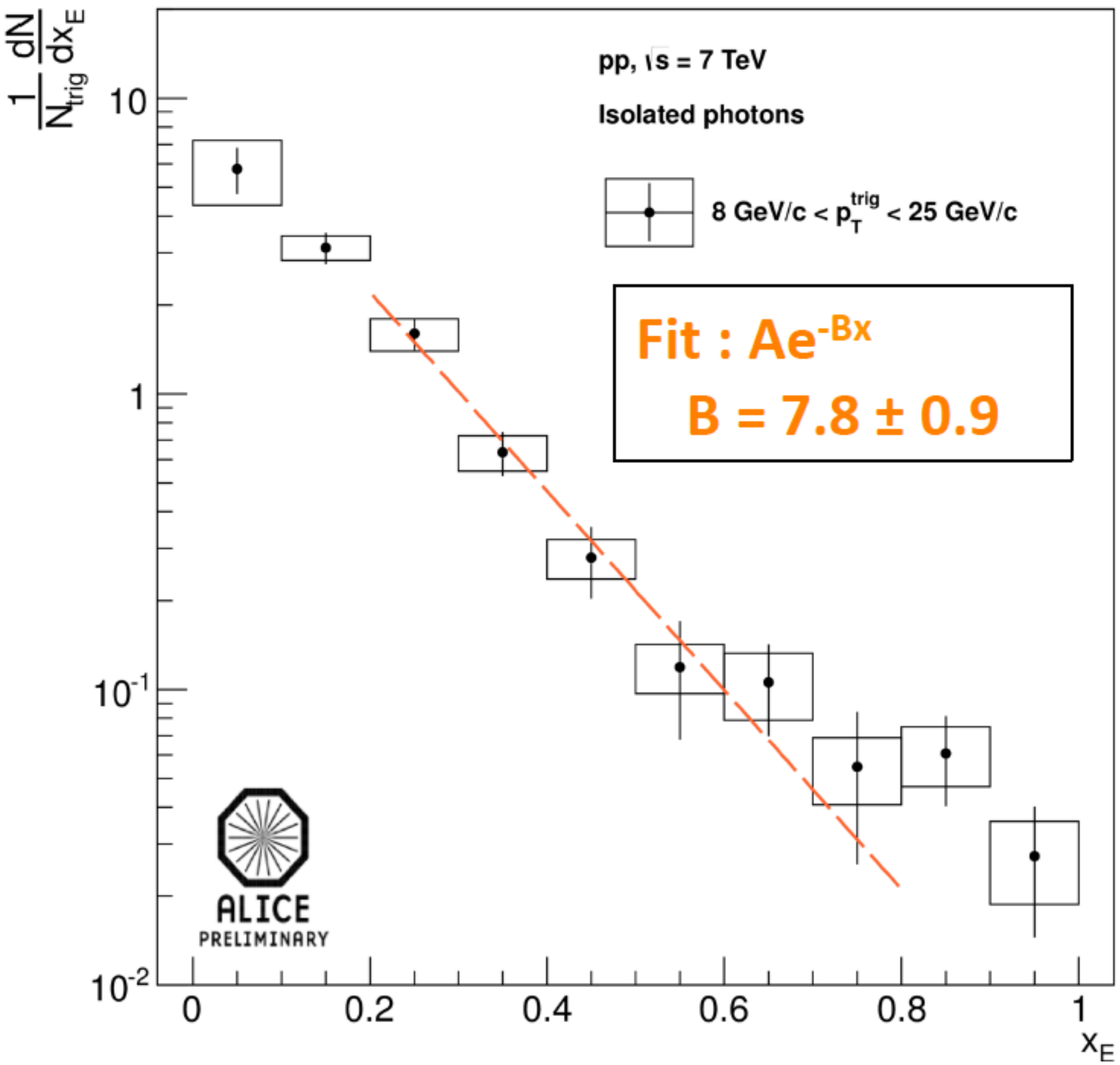
Isolated π^0-hadron x_E distributions

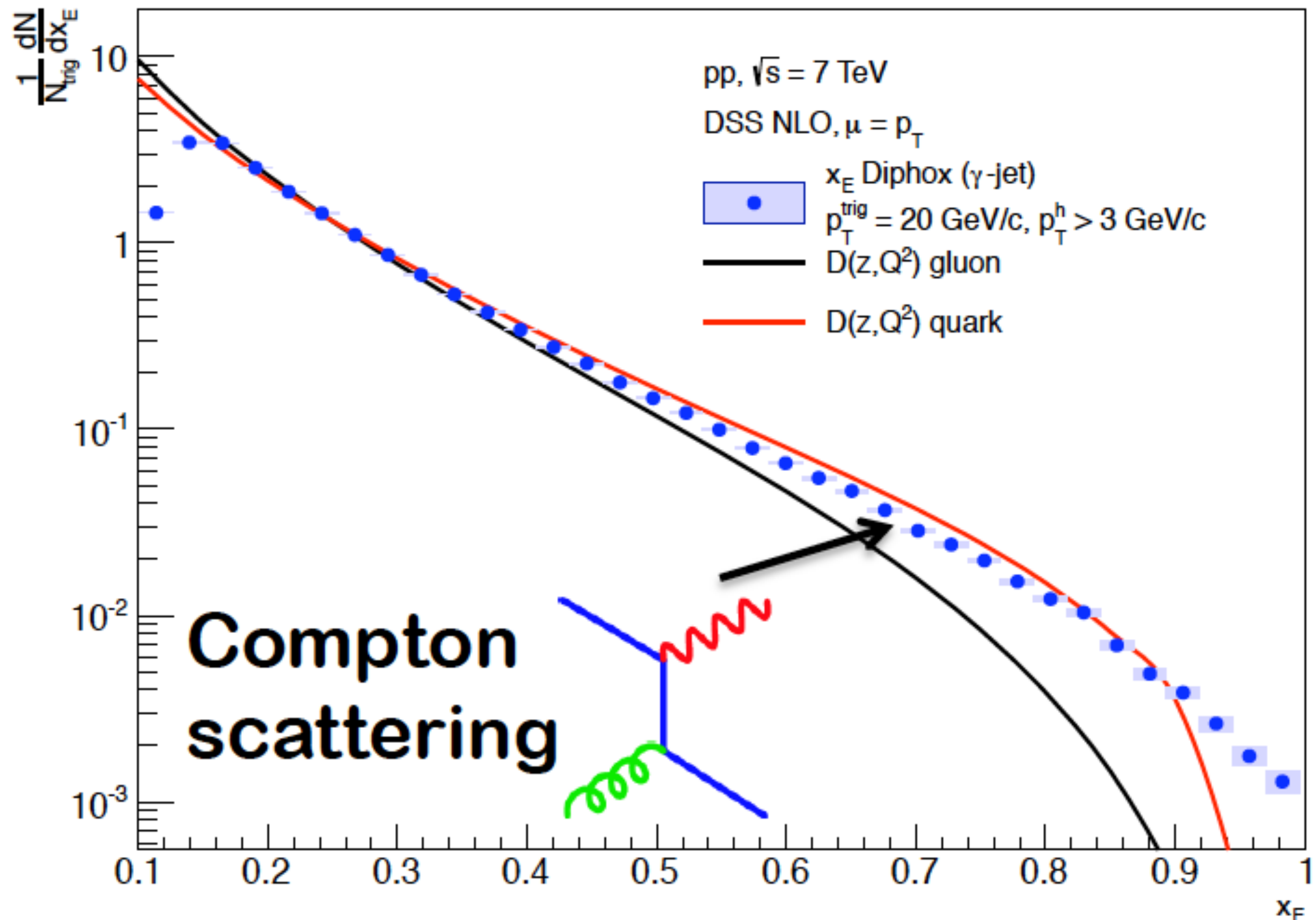
$$\frac{dN}{dx_E} = N e^{-b x_E}$$



- x_E slope moves towards to <z> =1 direction → isolated π^0 samples a large fraction of jet energy
- Very limited statistics and large uncertainties from Run1 analysis

Isolated γ-hadron x_E distributions





- Isolated γ-hadron x_E distributions seems in favour of quark jet FF
- Detailed tagging study limited by Run I statistics

Path length dependent medium effect

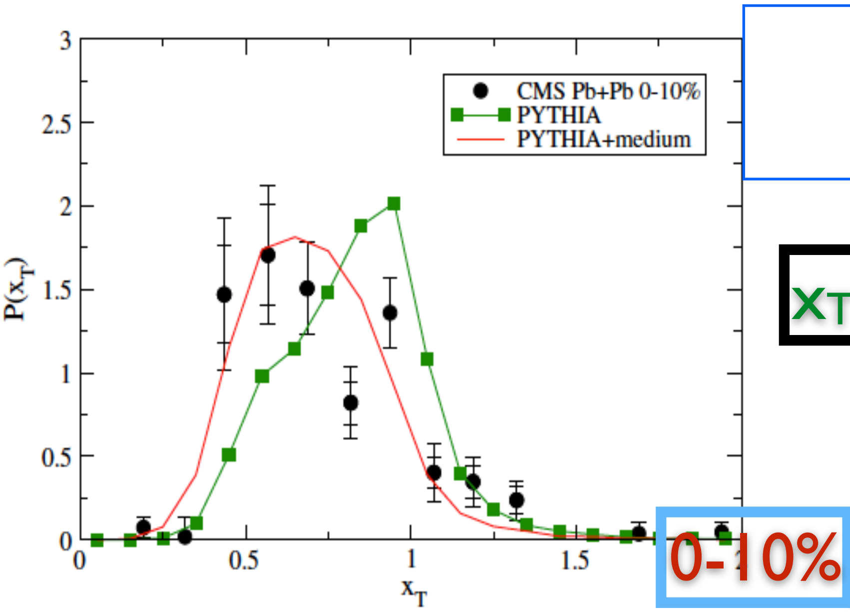
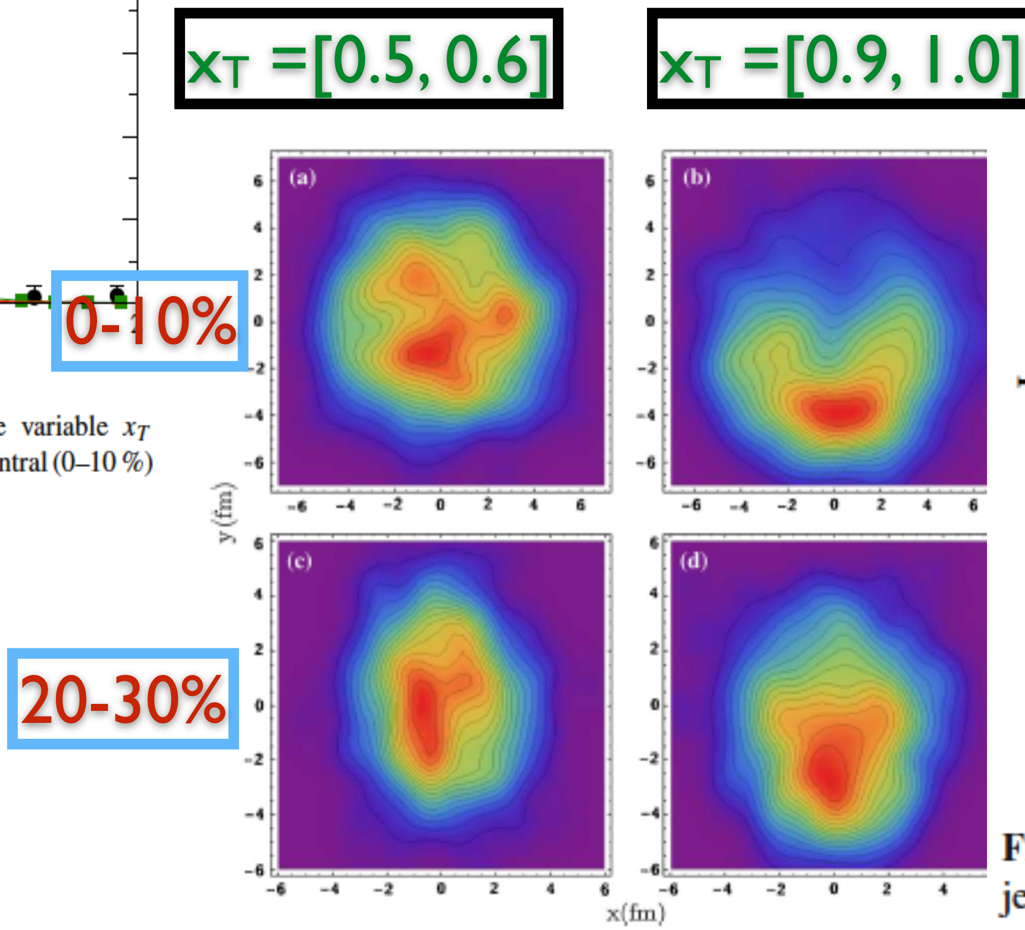


Fig. 3 The distribution of the momentum imbalance variable x_T between triggered photons and associated jets for most central (0–10 %) Pb+Pb collisions at the LHC. The jet size is $R = 0.3$

Probe medium density by asymmetric γ-jet events



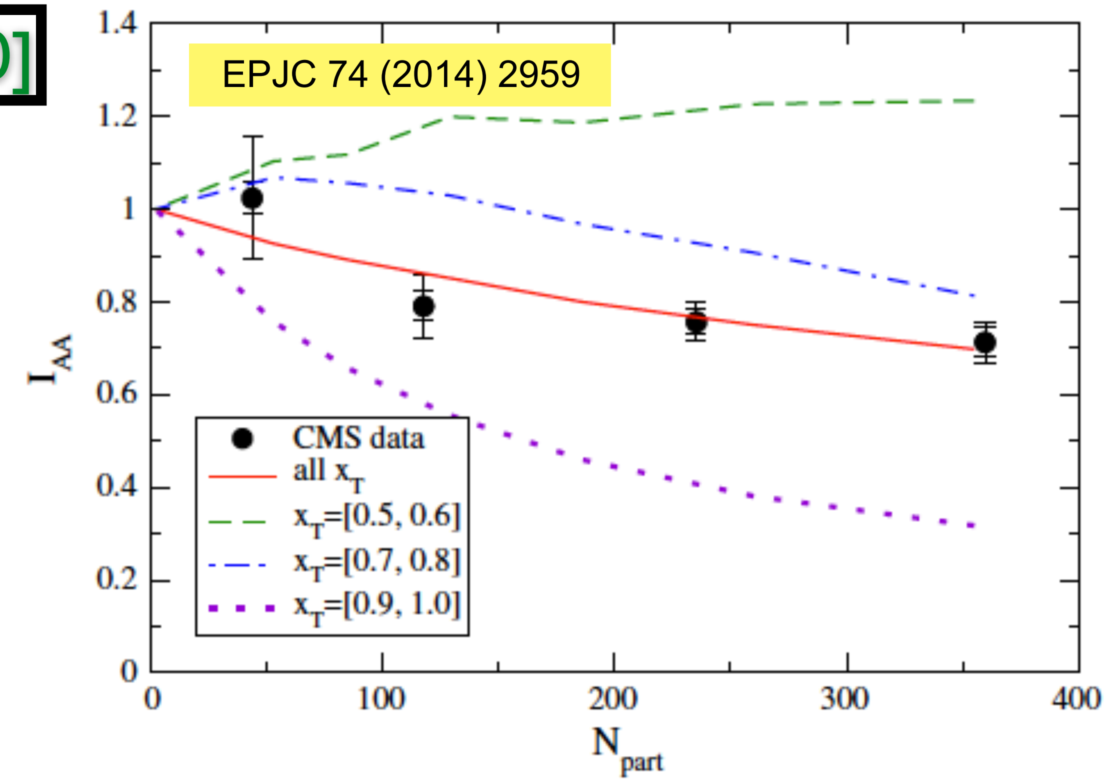


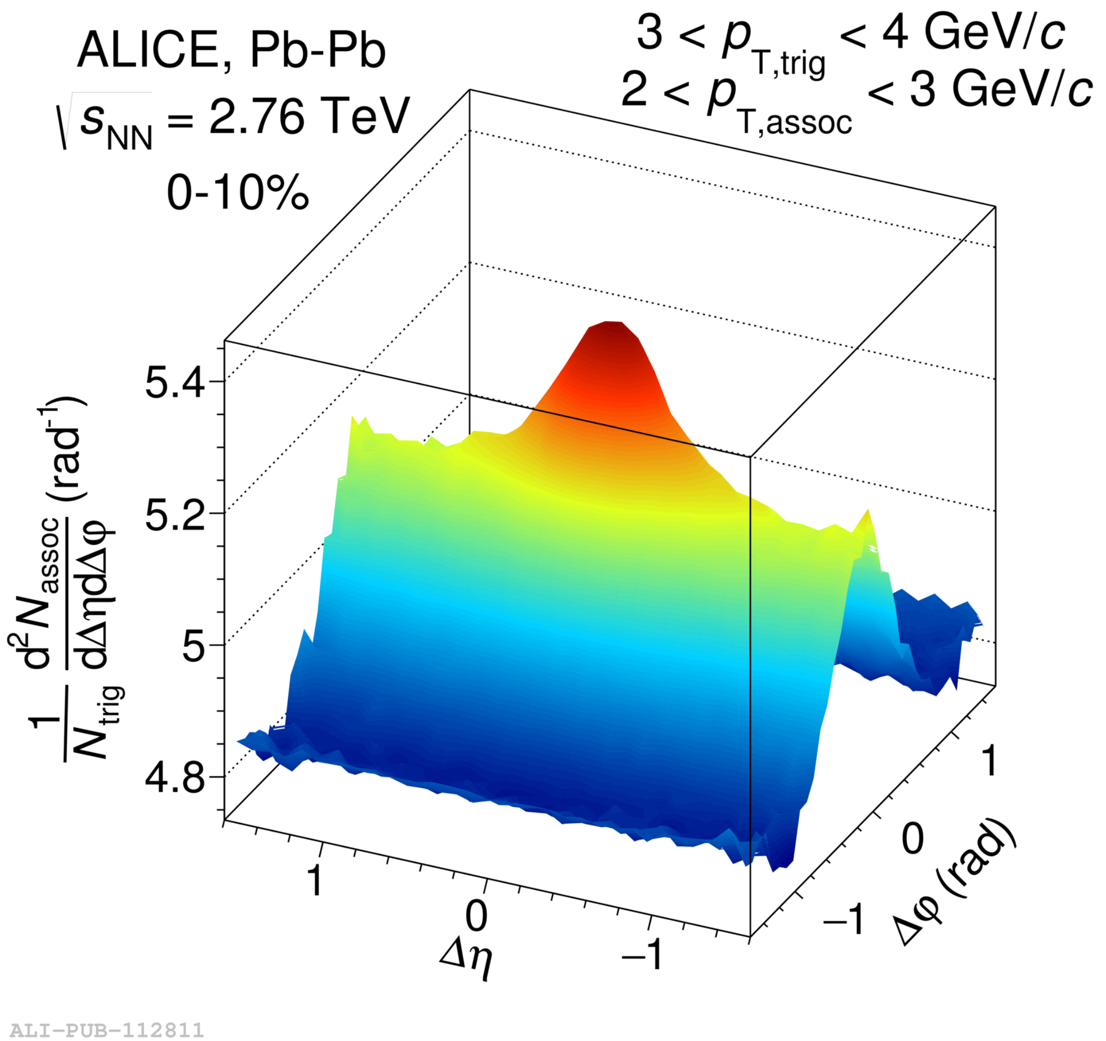
Fig. 8 The nuclear modification factor I_{AA} for the photon-triggered jets as a function of centrality for Pb+Pb collisions at the LHC. The results for different x_T values are compared. The jet size is $R = 0.3$

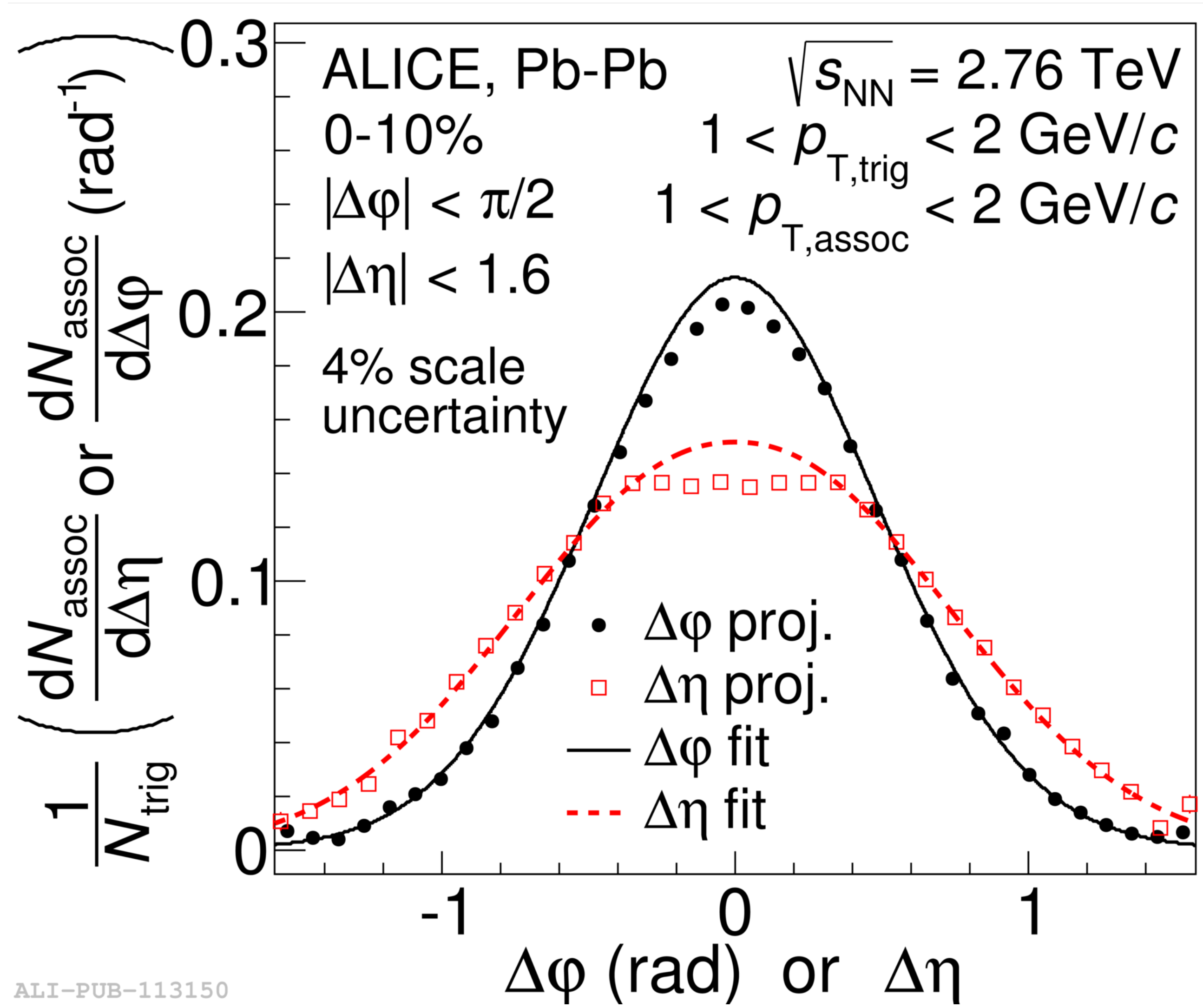
- By selecting jet pair events using different asymmetry (x_T) value, one can probe different medium lengths and density profile, and result different modification patterns

  ➡ can be studied at LHC with coming data

Jet peak from di-hadron correlations

arXiv:1609.06643, submitted to PRL

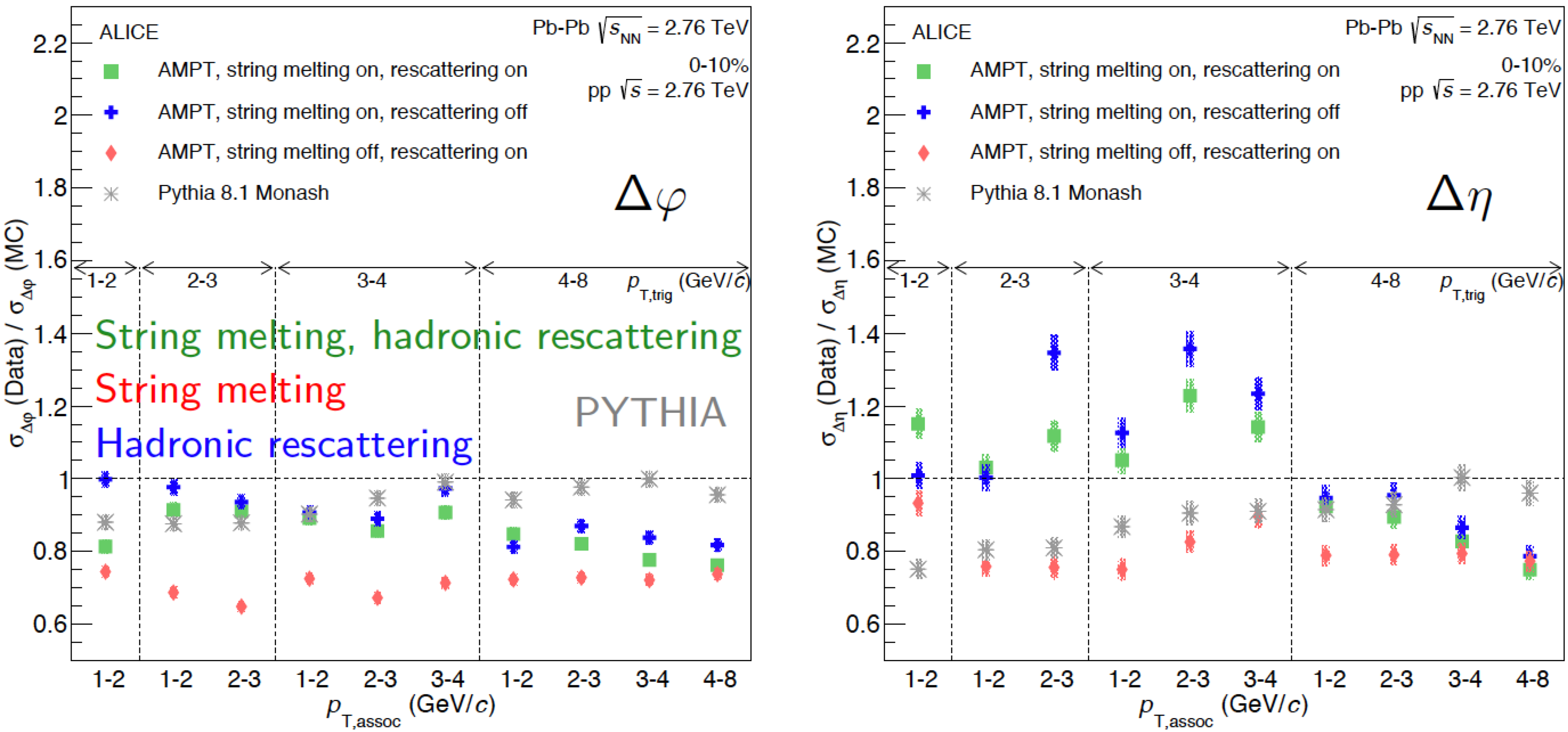




- Jets distributed much wider in Δη than in Δφ
- Near side peak is fitted to characterize its shape evolution
- Fit function: background + generalized Gaussian

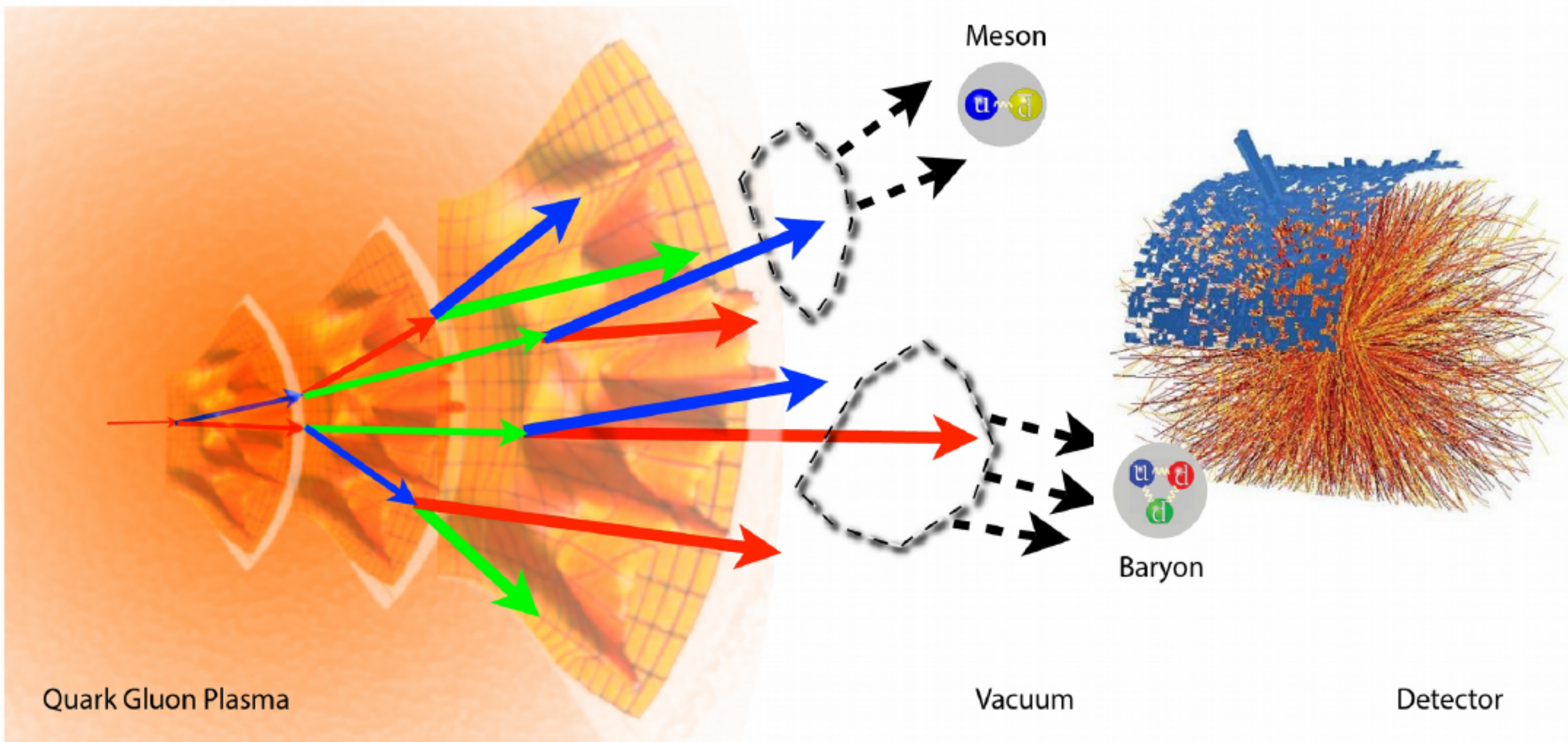
Comparison to MC — absolute width in central

- Absolute width described by $\frac{\sigma_{\Delta\varphi}(\mathrm{Data})}{\sigma_{\Delta\varphi}(\mathrm{MC})}$, $\frac{\sigma_{\Delta\eta}(\mathrm{Data})}{\sigma_{\Delta\eta}(\mathrm{MC})}$

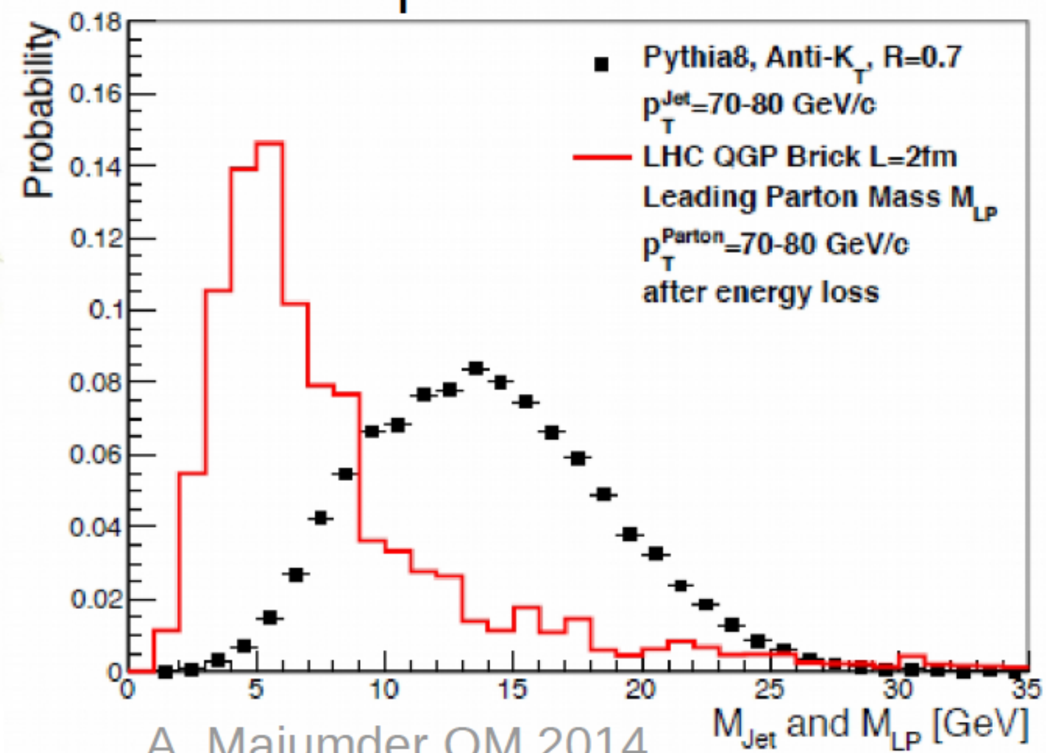


- None of the AMPT settings describe all p_T bins

Virtuality evolution



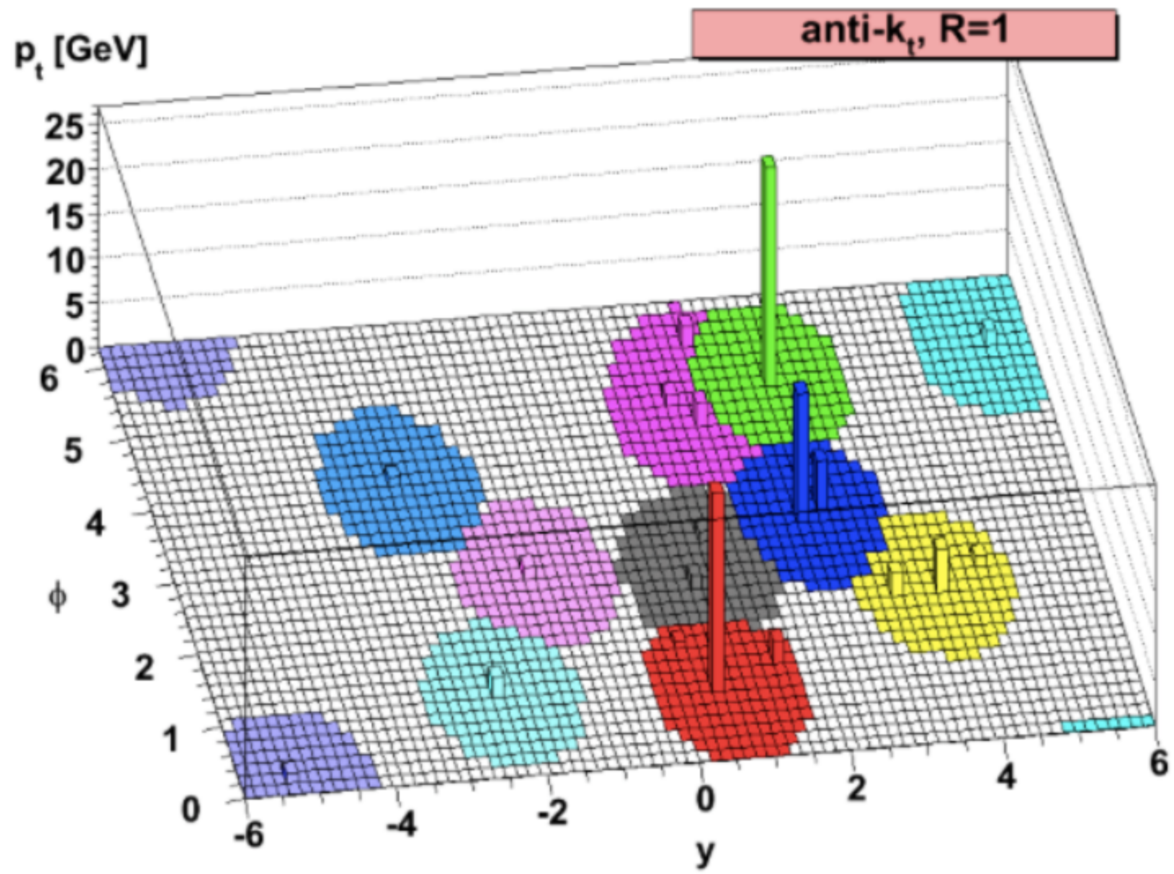
Mass of the LP in a medium in case of radiation at large angle compared to vacuum



A. Majumder QM 2014

- In hard scattering processes the leading parton (LP) is usually produced off-shell, its off-shellness is the **virtuality ~ jet mass**
  - In vacuum, parton virtuality decreases at each emission
  - In a medium, parton virtuality can rise due to scatterings

Jet reconstruction



2008: Fastjet revolution

Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

"anti-kT" replaced zoo of prior algorithms:

- conceptually simple
- theoretically sound
  - infrared safe
  - collinear safe
- computationally efficient & robust
- part of Fastjet package

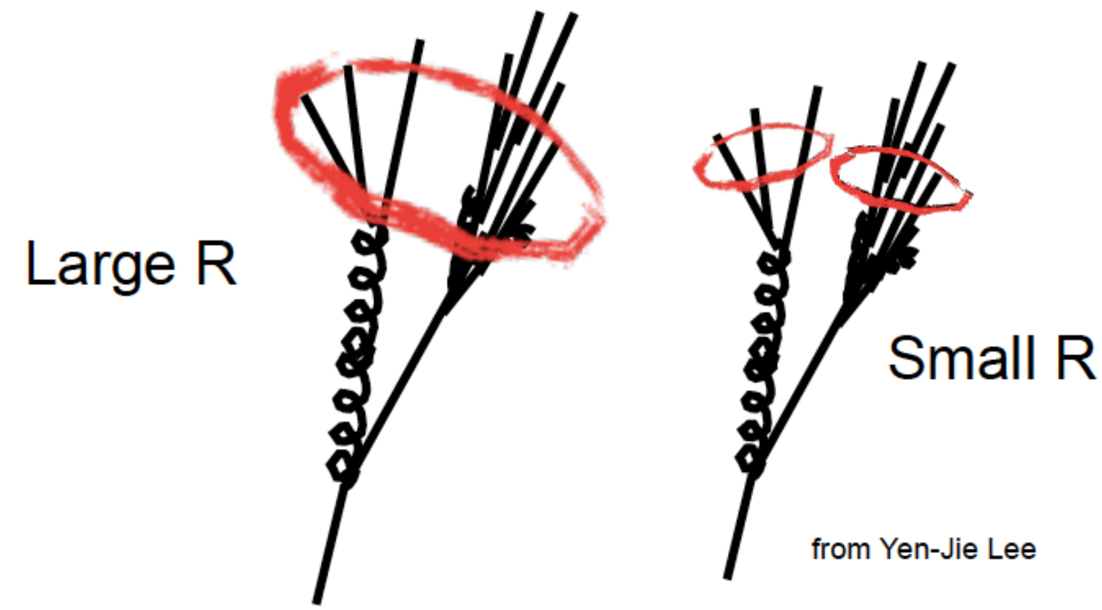
Anti-k$_T$:

Sequential clustering of objects in event (calo towers, tracks etc) with a particular distance measure:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$

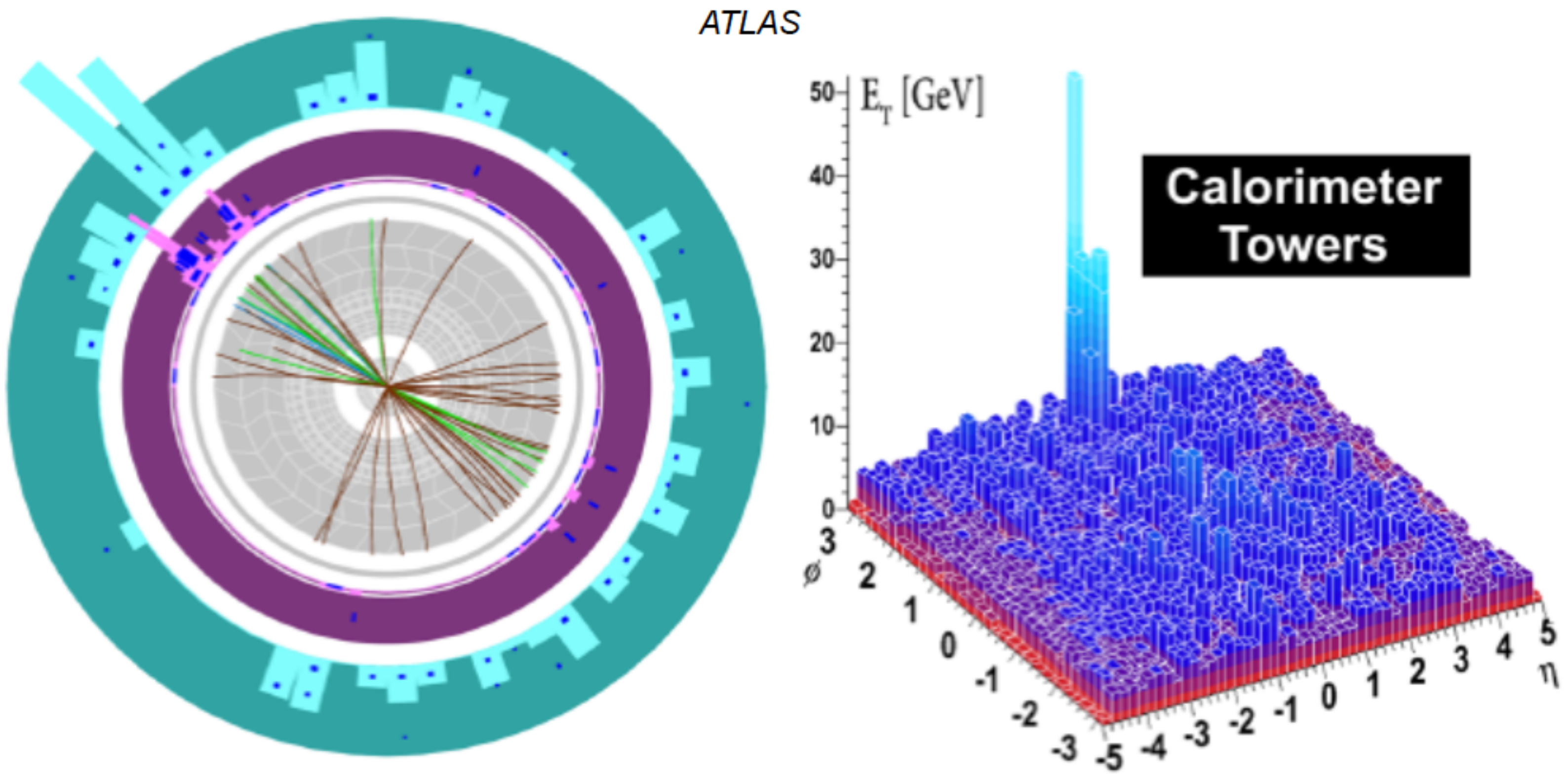
$$d_{iB} = k_{ti}^{2p}, \quad \boxed{p=-1}$$

Results in cone-shaped, approximately R-sized jets



Which jets are found depends on anti-k$_T$ resolution parameter

Jet and underlying event



Jets in heavy-ion collisions sit on top of large underlying event (UE)
Need to ***decide*** which particles are part of jet and which belong to UE: **UE subtraction**

Current methods assume that local UE (under jet) is the same as elsewhere in the event
I.e., UE modification due to jet would manifest as modification of observed jet