Hard probes
(jet quenching, energy loss)

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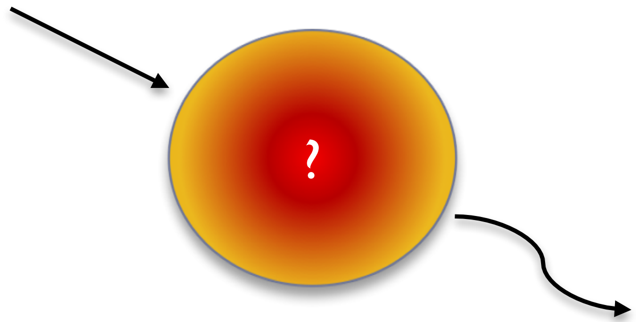
Hard probes

- Investigate inside of matter
  - Use well known probes
    - Looks modification of probes before/after probing matter



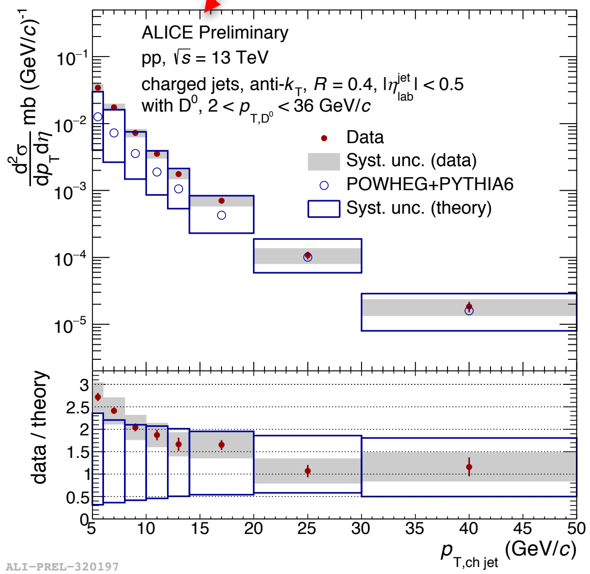
- “Hard” probes
  - Jet, heavy flavours (charm & beauty), high p_T particles
  - Originally from partonic scatterings with large momentum transfer Q^2
    - Large transverse momentum, Large mass (> Λ_{QCD} ~ 200 MeV)
    - Applicable perturbative QCD
  - Time scale : example (heavy flavours) :
    - $\tau \sim 1/2\, m_q \sim 0.07$ fm < QGP (~0.1-1 fm)
    - Produced before QGP
  - Constrain medium properties : transport coefficient, η/s

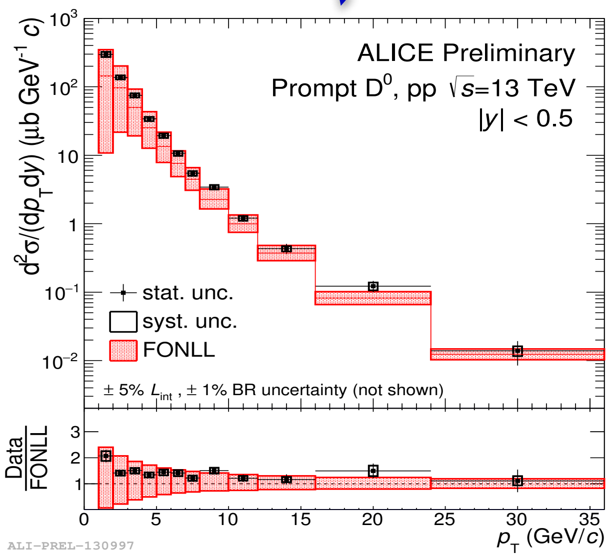
Hard probe productions in pp collisions

$$d\sigma^{hard}_{AB\to h} = f_{a/A}(x,Q^2)\otimes f_{b/B}(x,Q^2)\otimes d\sigma^{hard}_{ab\to c}\otimes D_{c\to h}(z,Q^2)$$

parton ~ jet

hadronization

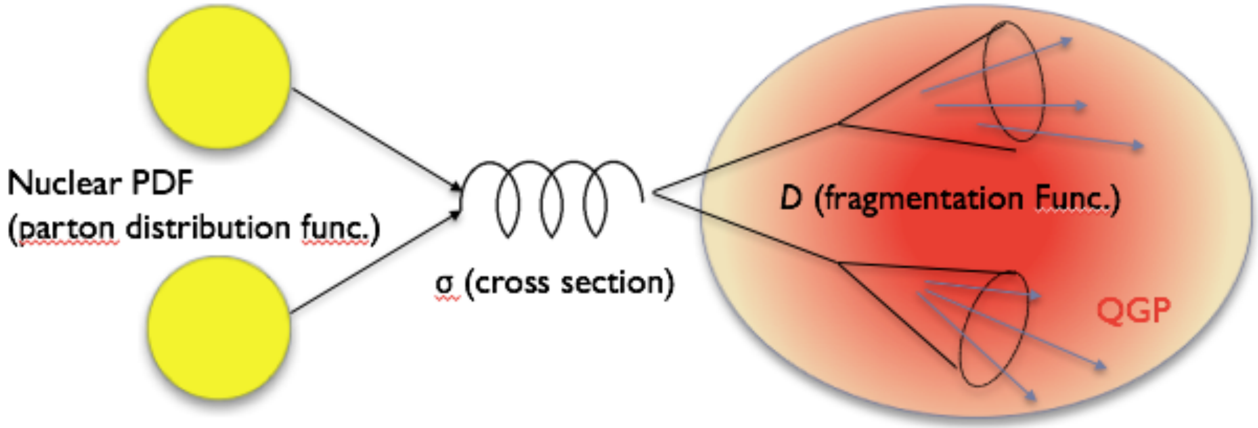




Charm quark (c-jet) → D mesons

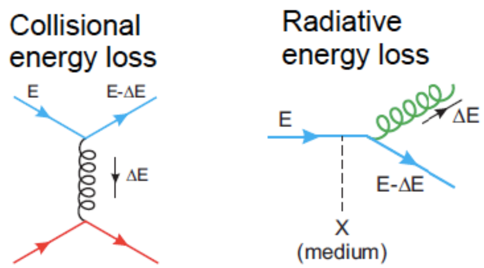
- Comparison of hard probes, c-jets (left) and D mesons (right), with pQCD predictions
  - Consistent with uncertainties in data and pQCD

Hard probes in AA collisions



$$d\sigma_{AB\to h}^{hard} = f_{a/A}(x,Q^2) \otimes f_{b/B}(x,Q^2) \otimes d\sigma_{ab\to c}^{hard} \otimes D_{c\to h}(z,Q^2)$$

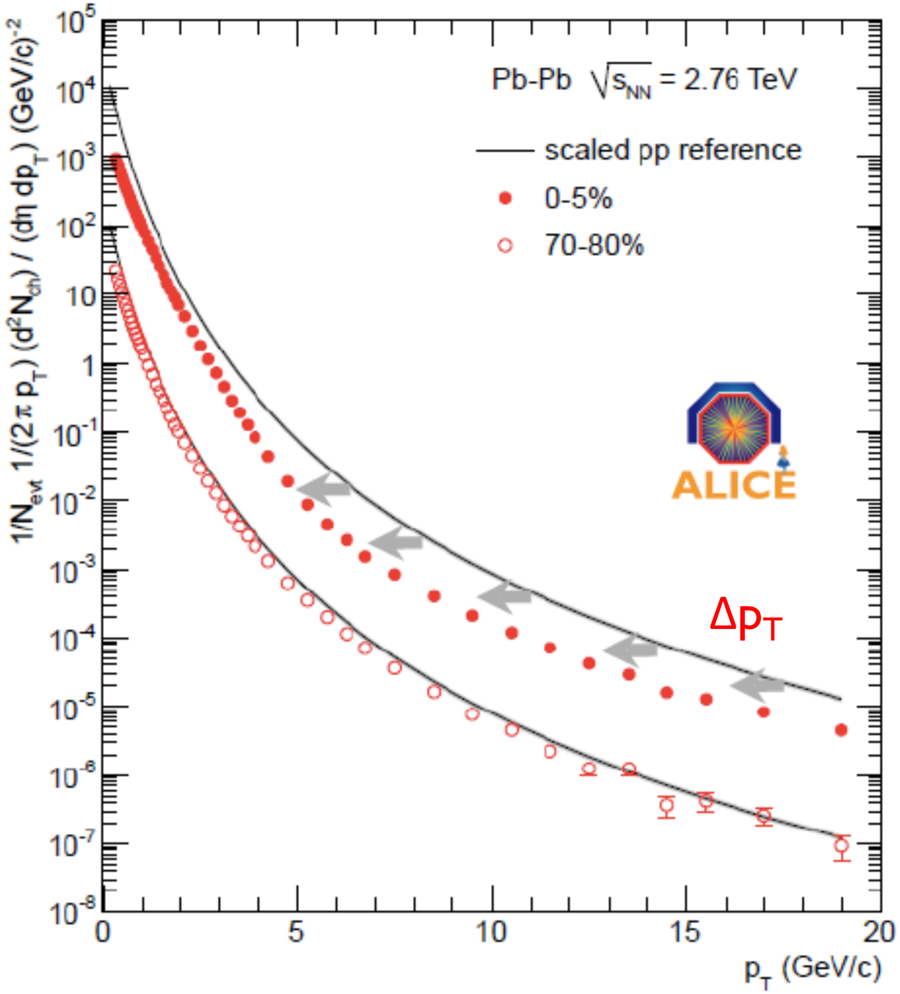
- Interact between parton and QGP
  - elastic scattering -> collisional energy loss (low p_T)
  - gluon bremsstrahlung -> radiative energy loss (high p_T)
    - Modify hadronization process
- In experiment
  - Suppression of yields (Di-jet imbalance)
  - Modification of fragmentation functions



Energy loss in QCD matter

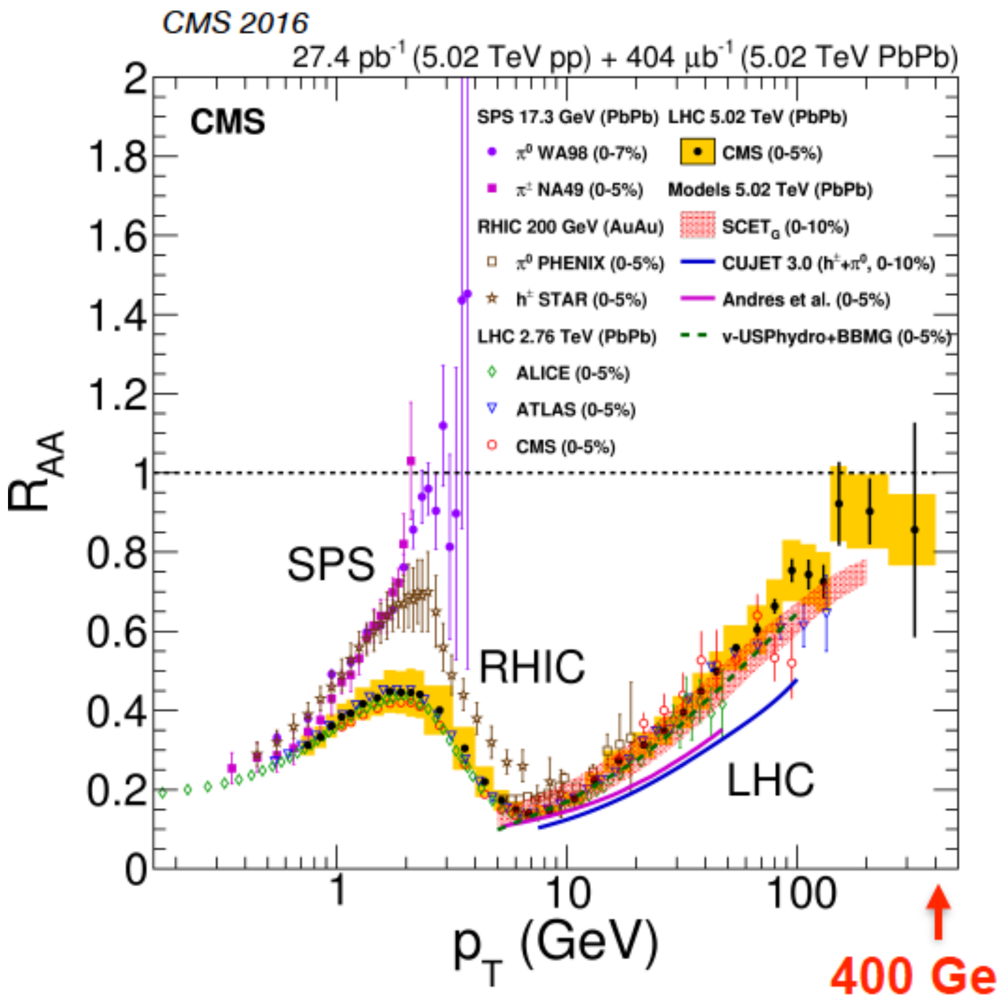
- Properties of radiative energy loss
  - 1. $\langle \Delta E \rangle \propto C_R L^2 q$
    - Depend on color charge : quark vs. gluon
    - Proportional to path-length (L^2)
    - Sensitive to transport coefficient : $q = \mu^2/\lambda$
  - 2. Dead cone effect
    - Probability of radiation ; $1/(\theta^2 + (m/E)^2)^2$
    - Lose less energy for heavier partons
    - $E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b)$

Charged particle spectrum in AA



- Scaled pp reference
  - without energy loss
- Yields in 70-80%
  - Same as without energy loss
- Yields in 0-10%
  - Spectrum shift to lower p_T
    - Due to energy loss
    - $p_T \rightarrow (1-\varepsilon_{loss})p_T$
    - $\varepsilon_{loss} = \Delta p_T / p_T$

Charged hadron R_{AA}



- Nuclear modification factor

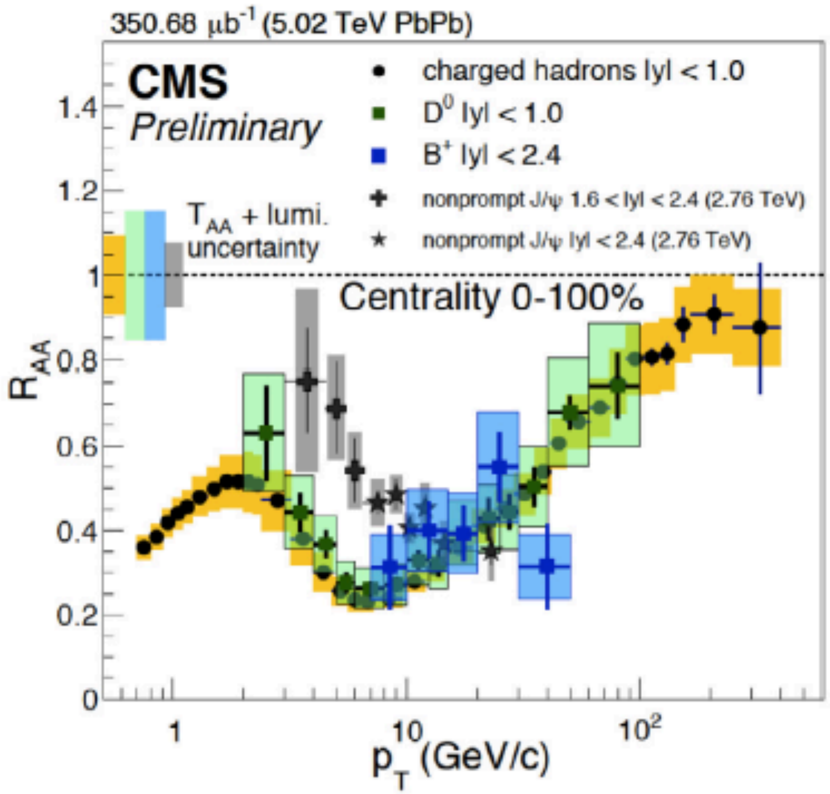
$$R_{AA}(p_T) = \frac{d^2N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle d^2N_{pp}/d\eta dp_T}$$

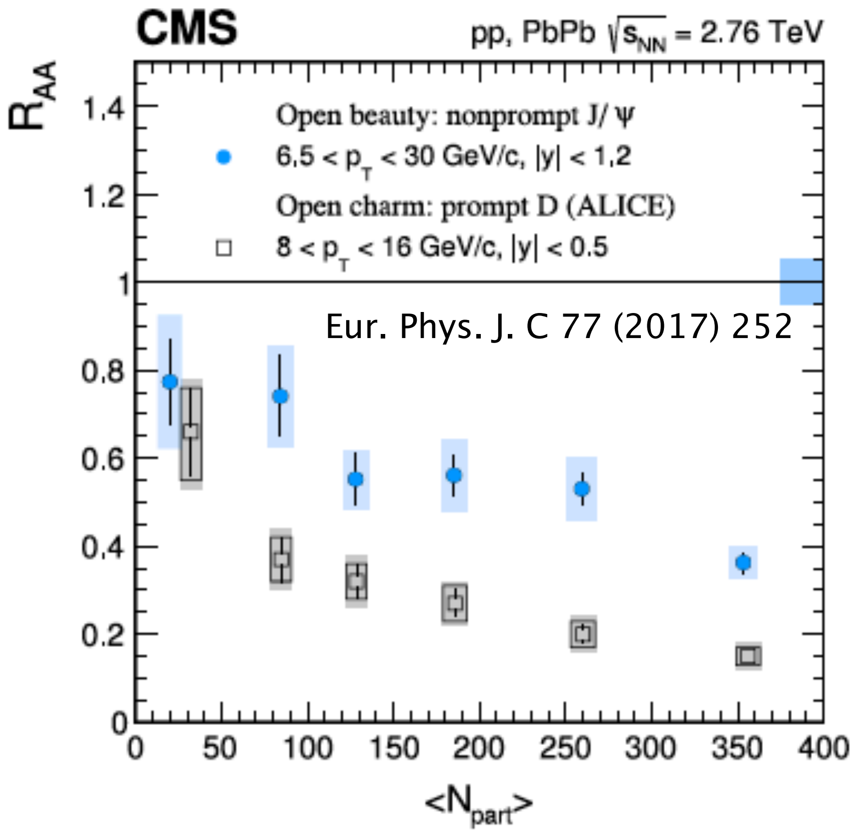
$R_{AA} > 1$: enhancement
$R_{AA} = 1$: no medium effect
$R_{AA} < 1$: suppression

- Strong suppression of charged particle production in RHIC & LHC
  - Minimum $R_{AA} \sim 0.1$
  - ~90% charged hadrons are suppressed w.r.t. pp collisions

- $R_{AA} \leftrightarrow \varepsilon_{loss}$
  - $\varepsilon_{loss} = 1 - R_{AA}^{1/(n-2)}$
  - Example : π0 @ RHIC (n=8)
    - $\varepsilon_{loss} = 0.2$ for $R_{AA} \sim 0.25$

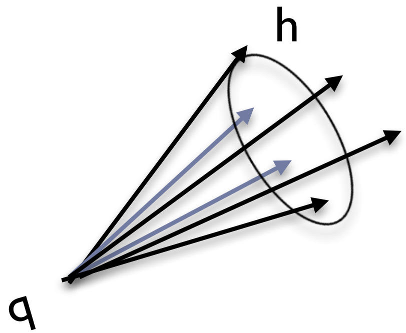
Flavour dependence of R_{AA}

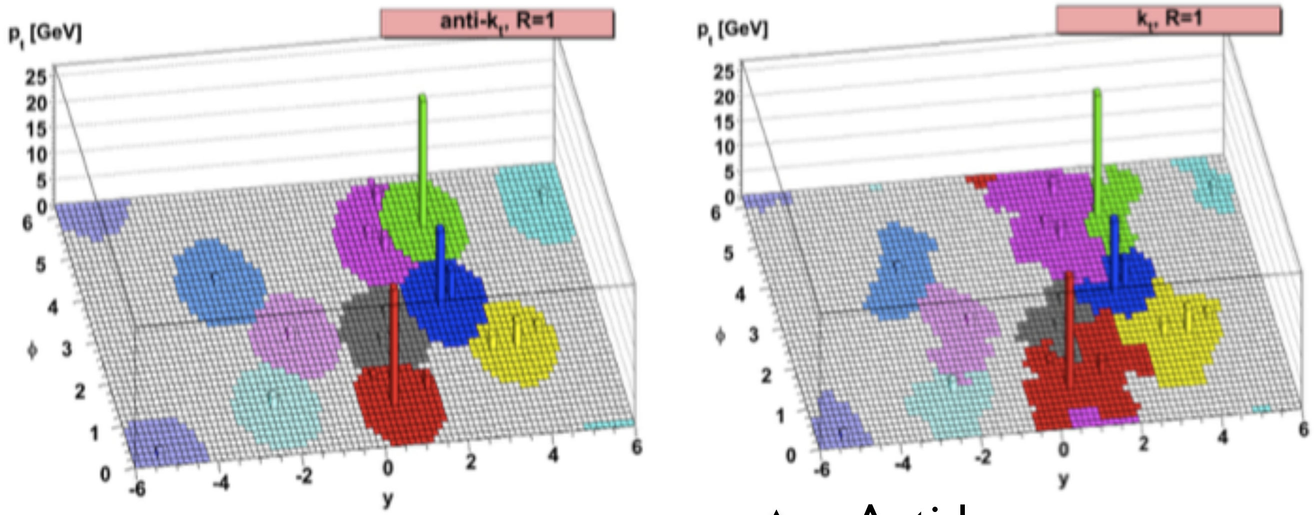




- Both charm and beauty lose energy in QGP
- $E_{loss}(g) > E_{loss}(u,d,s) > E_{loss}(c) > E_{loss}(b) \Rightarrow R_{AA}(c) < R_{AA}(b)$
- Smaller R_{AA} of B mesons than D mesons
  - Indicate smaller energy loss of beauty than charm

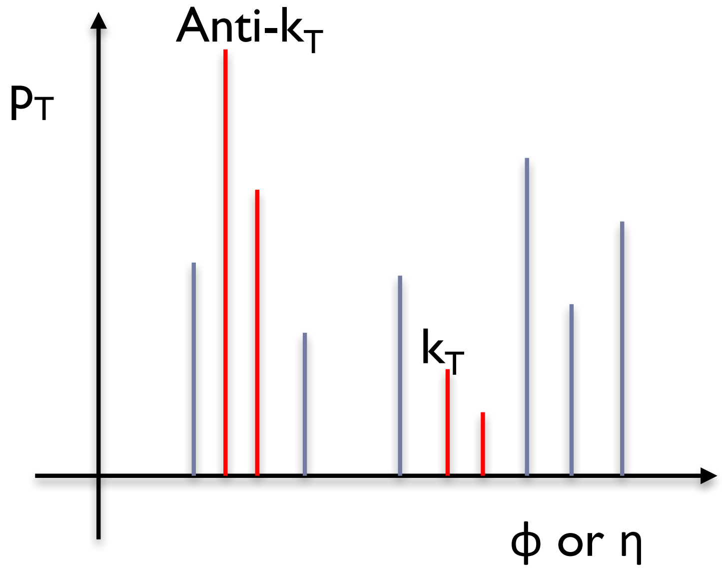
Jet reconstruction



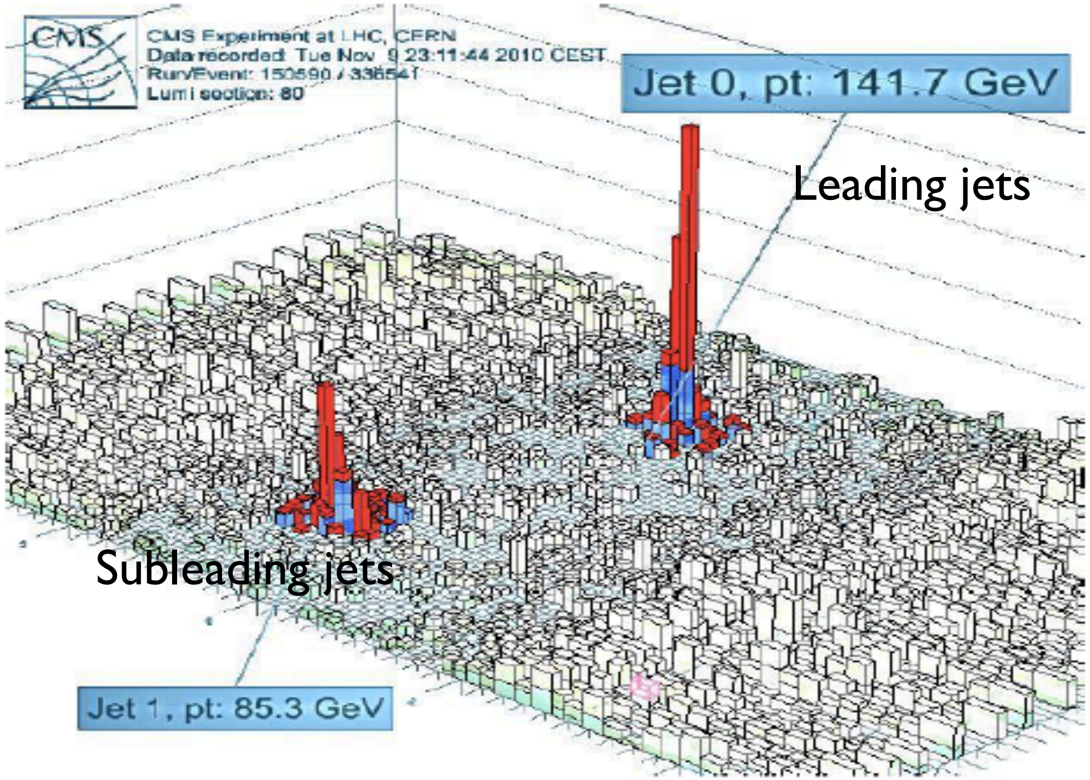


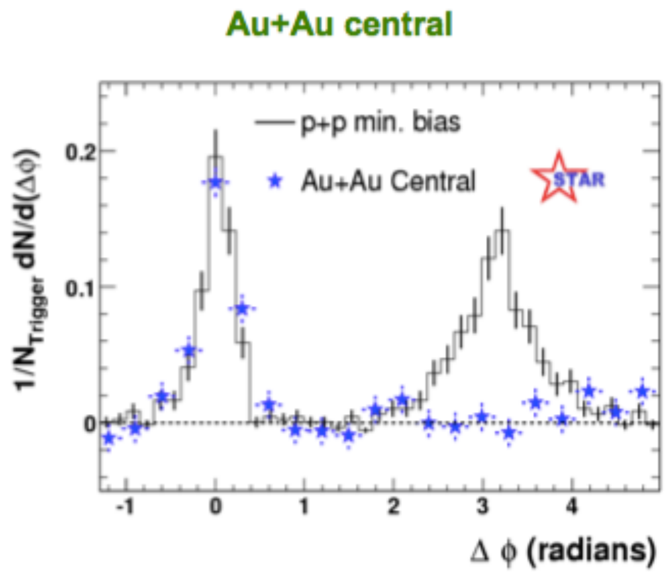
- "Jet" : defined by "Fastjet"
  - (Cacciari et. al. JHEP 0804 (2008) 063)
- k_T algorithm: start from low p_T
  - not bound to a circular structure
- Anti-k_T algorithm: start from high p_T
  - Circulate shape, "cone" radius
  - Expected to be less sensitive to underlying event

  ->Suitable to heavy-ion collisions



Jet quenching !

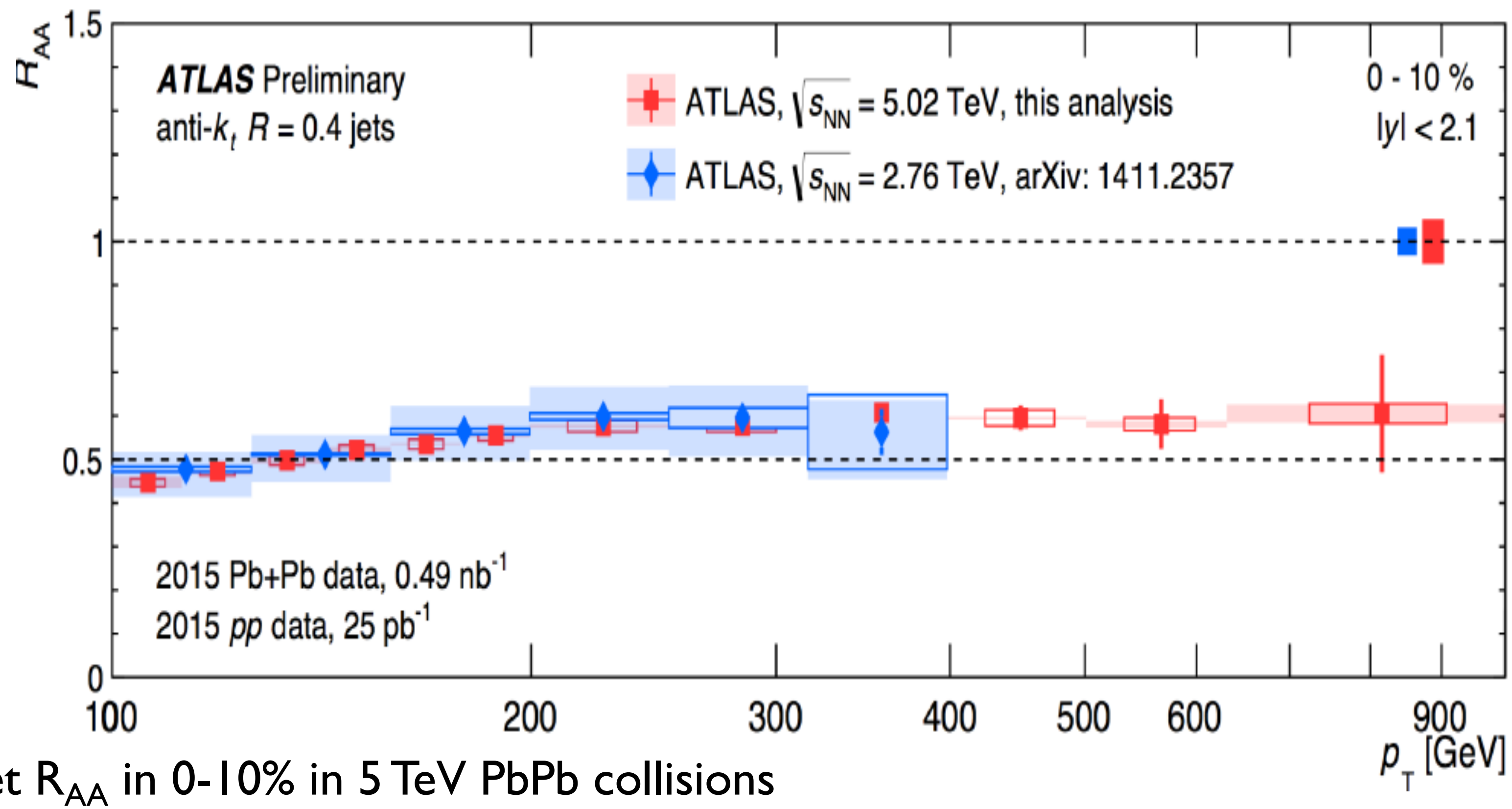




- Jets are produced back-to-back
  - Recoil jets (subleading) have originally same energy as leading jets
  - Clear suppression of recoil jet
    - Energy loss of parton in QGP

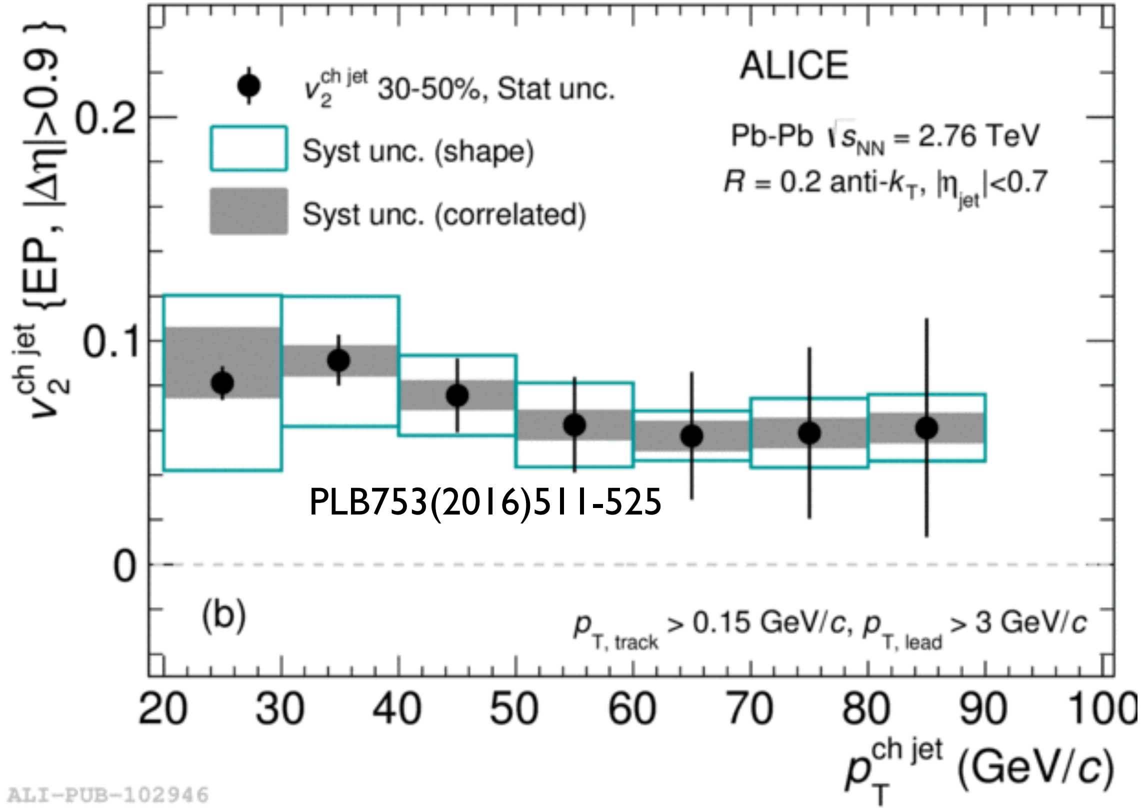
Jet R_{AA} in PbPb at 5.02 TeV (0-10%)

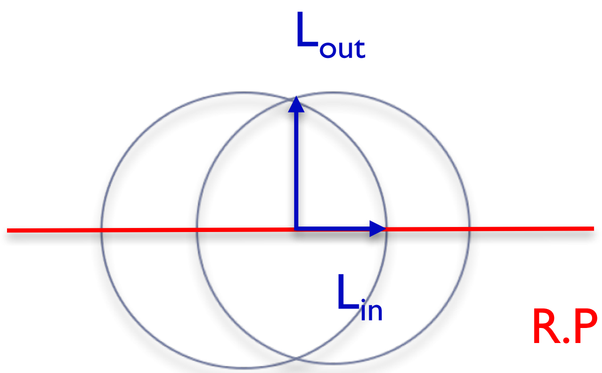
ATLAS-CONF-2017-009, M. Spouta



- Jet R_{AA} in 0-10% in 5 TeV PbPb collisions
  - R_{AA} < 1 ; Observed suppression up to 1 TeV
    - 2.76 TeV up to 400 GeV/c
  - Suppression of jet productions in Pb-Pb collisions

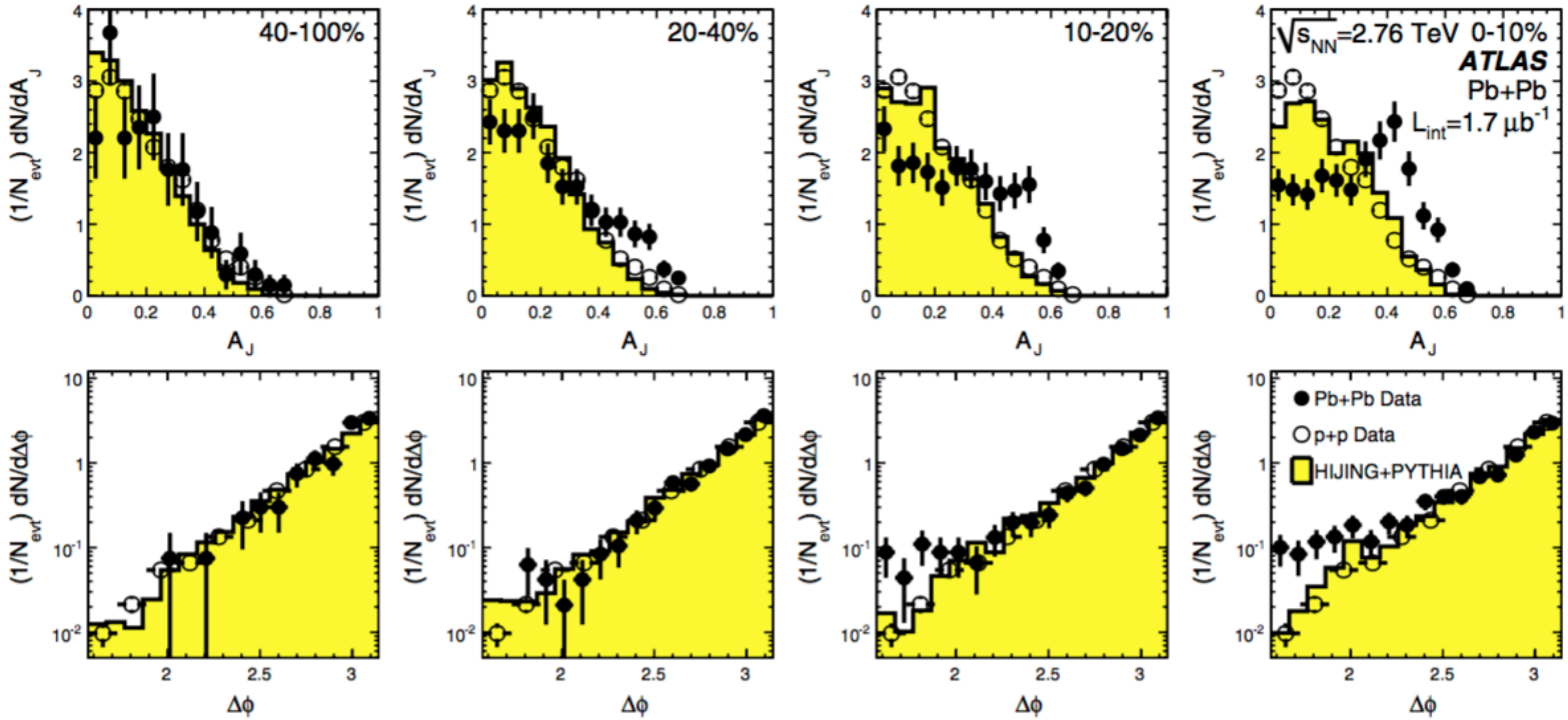
v_2 (path-length dependence of energy loss)





- $v_2 \propto (N_{in}-N_{out})/(N_{in}+N_{out})$
  - $L_{out} > L_{in}$
  - $v_2 > 0$; jets in out-plane is more suppressed than in in-plane

Di-jet momentum balance



PRL105, 252303 (2010)

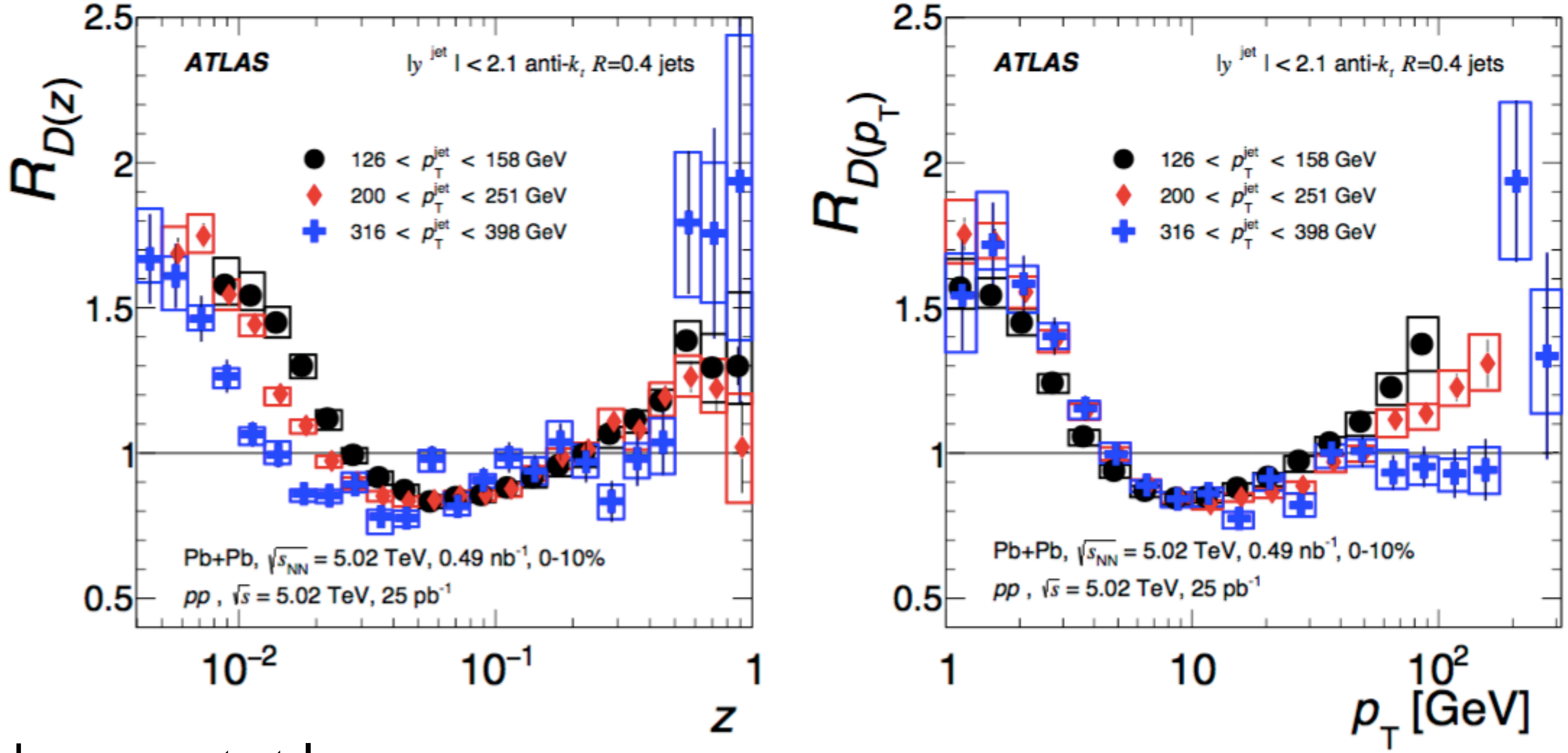
- Excess of imbalanced jets from peripheral to central
  - Aj->0 : balance / Aj->1 : imbalance

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

Jet Fragmentation in PbPb

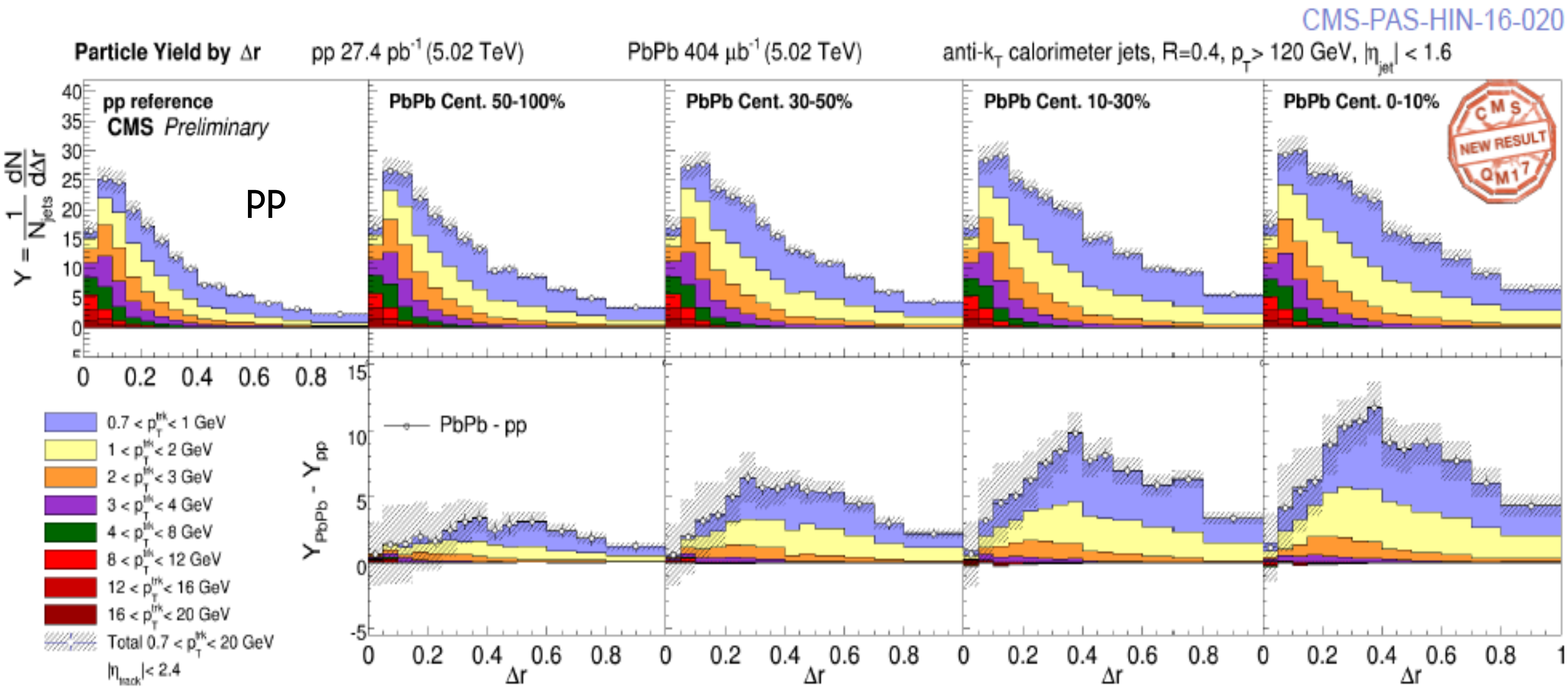
$$D(z) \equiv \frac{1}{N_{\text{jet}}}\frac{dn_{\text{ch}}}{dz} \quad [z \equiv p_{\text{T}}\cos(\Delta R)/p_{\text{T}}^{\text{jet}}]$$

Phys. Rev. C 98, 024908



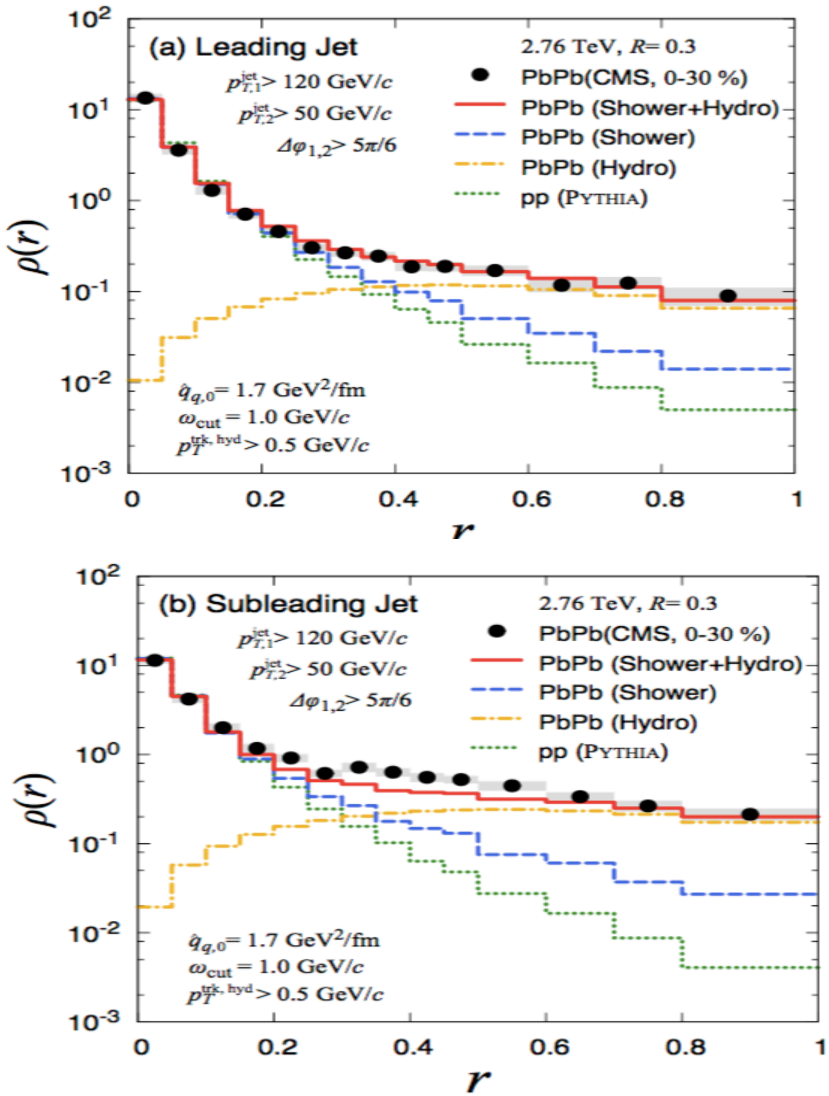
- Enhancement at low z
  - Due to energy loss by partons is transferred predominantly to soft particles
- Enhancement at high z
  - Large quark jet contribution in PbPb, and quark jets likely to produce high-z particles

Jet-track correlation



- Particle distribution w.r.t. axis of leading jets (>120 GeV/c) *H. Trauger*
- A excess of low p_T particles (p_T < 3 GeV/c) extending to large Δr from jet axis is found
- ΔE uses to produce lower p_T particles at large R

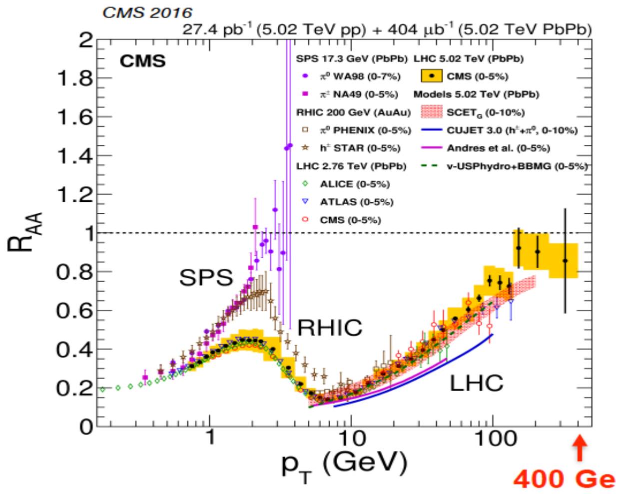
Jet – medium interaction

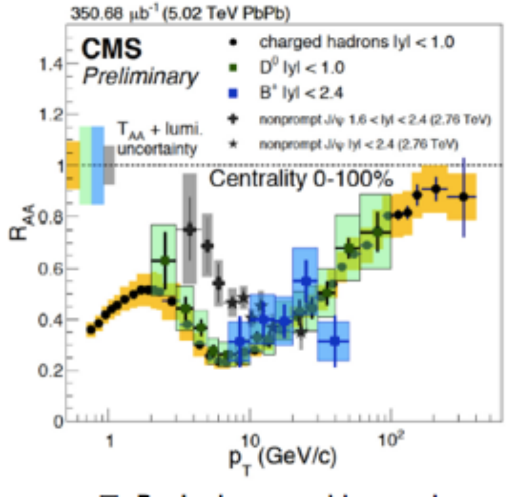


- Enhancement at large R due to jet – medium interaction ?
- A model with energy loss + hydrodenamical model well represents the enhance
  - Full jets shower interact with medium by radiative & collisional process
  - Deposit the energy to the medium and then evolve with the medium hydrodynamically.

Phys. Rev. C 95, 044909 (2017)
V. Khachatryan et al. (CMS Collaboration) Report No. CMS-PAS-HIN-15-011 (2015).

Summary

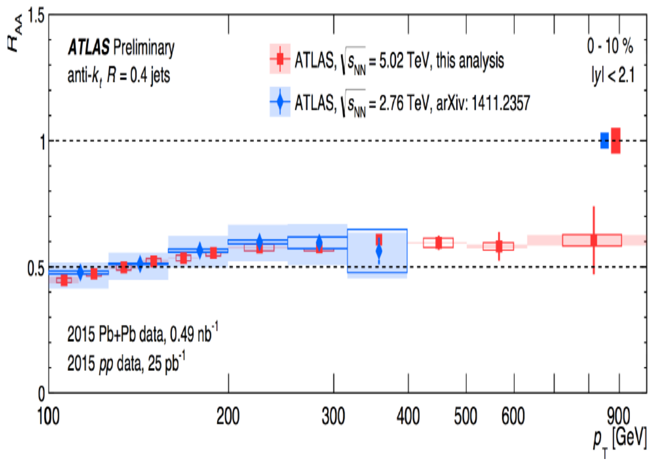


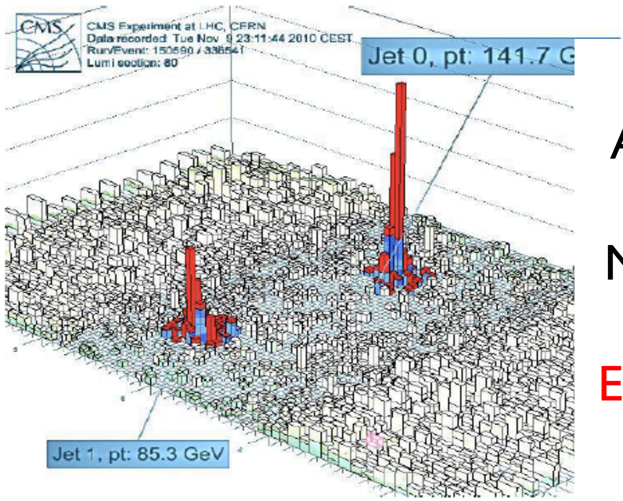


Single particle

$R_{AA}<1$

Strongly suppression productions





jet

Address kinematics of parton

$R_{AA}<1$

Mometum imbalance of Di-jet

Energy loss of partons in QGP