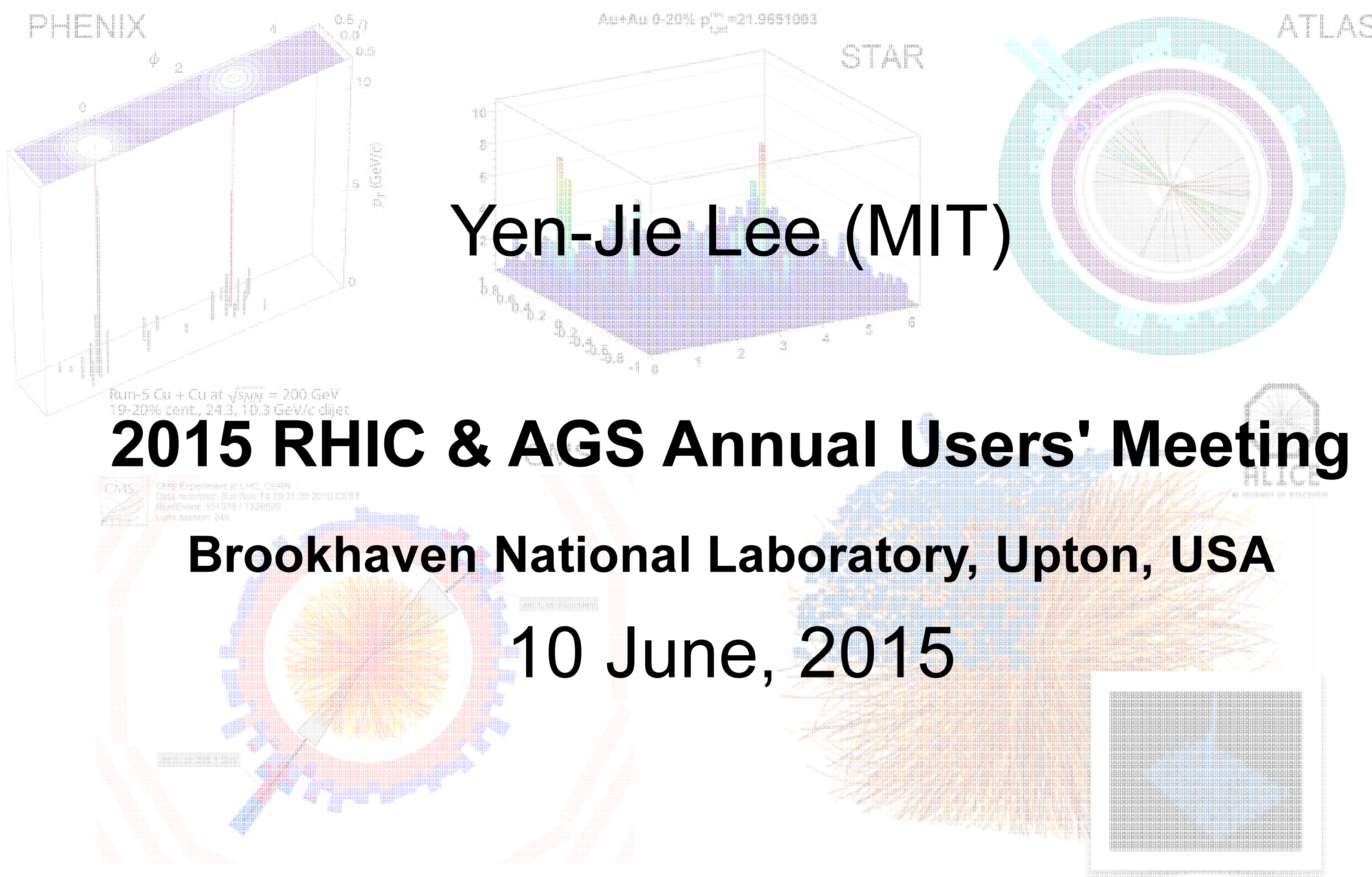
Experimental results on jets from RHIC and LHC



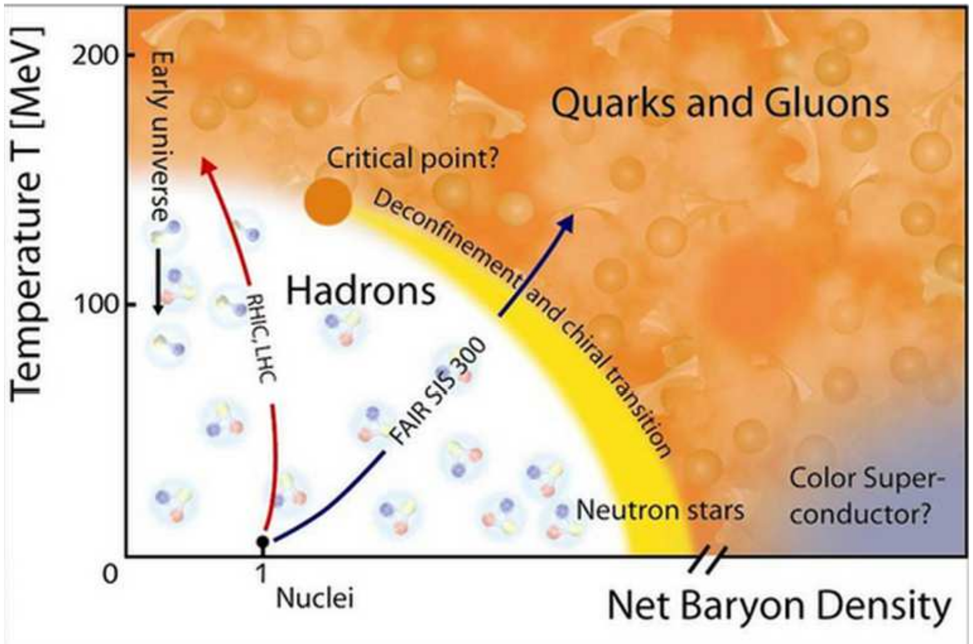
Yen-Jie Lee (MIT)

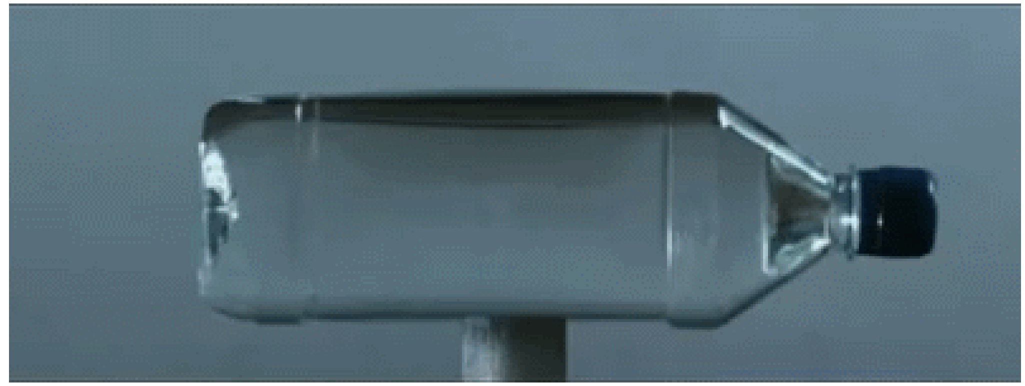
2015 RHIC & AGS Annual Users' Meeting

Brookhaven National Laboratory, Upton, USA

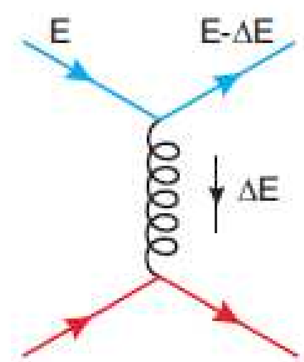
10 June, 2015

Probing the property of the medium

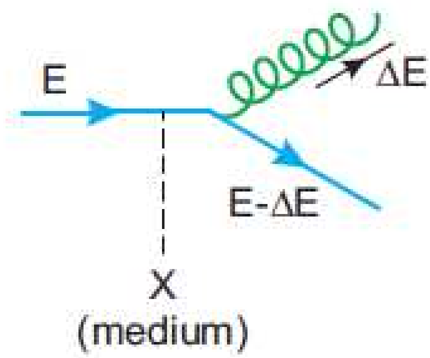


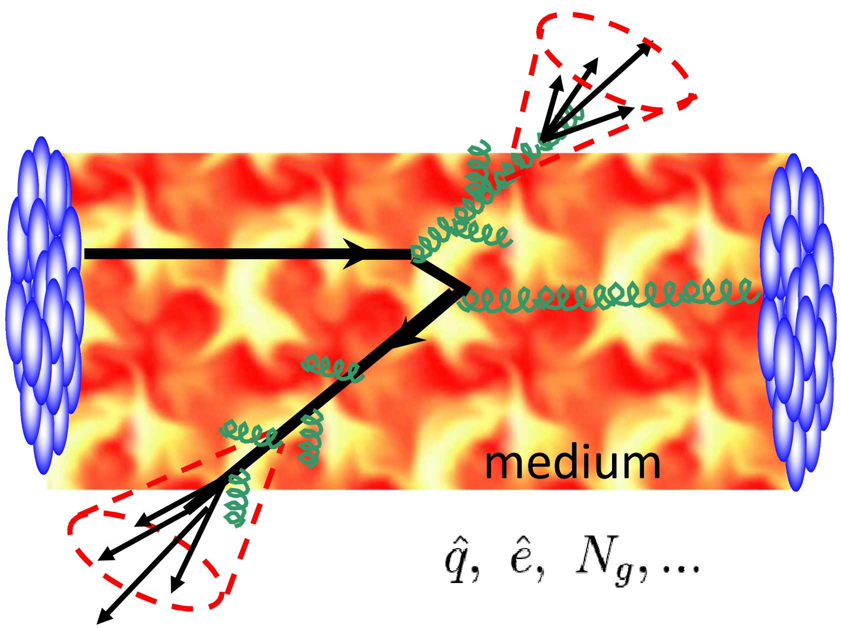


Collisional energy loss



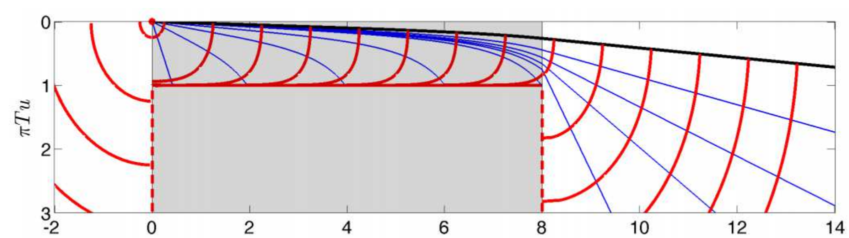
Radiative energy loss



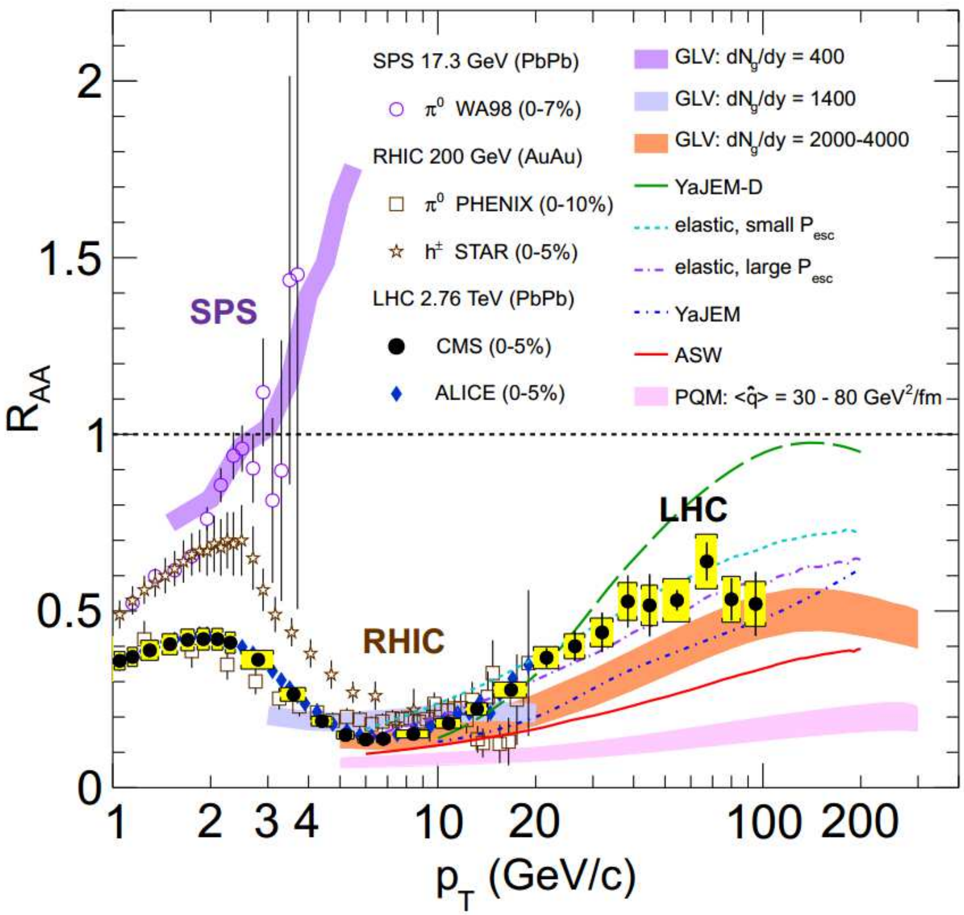


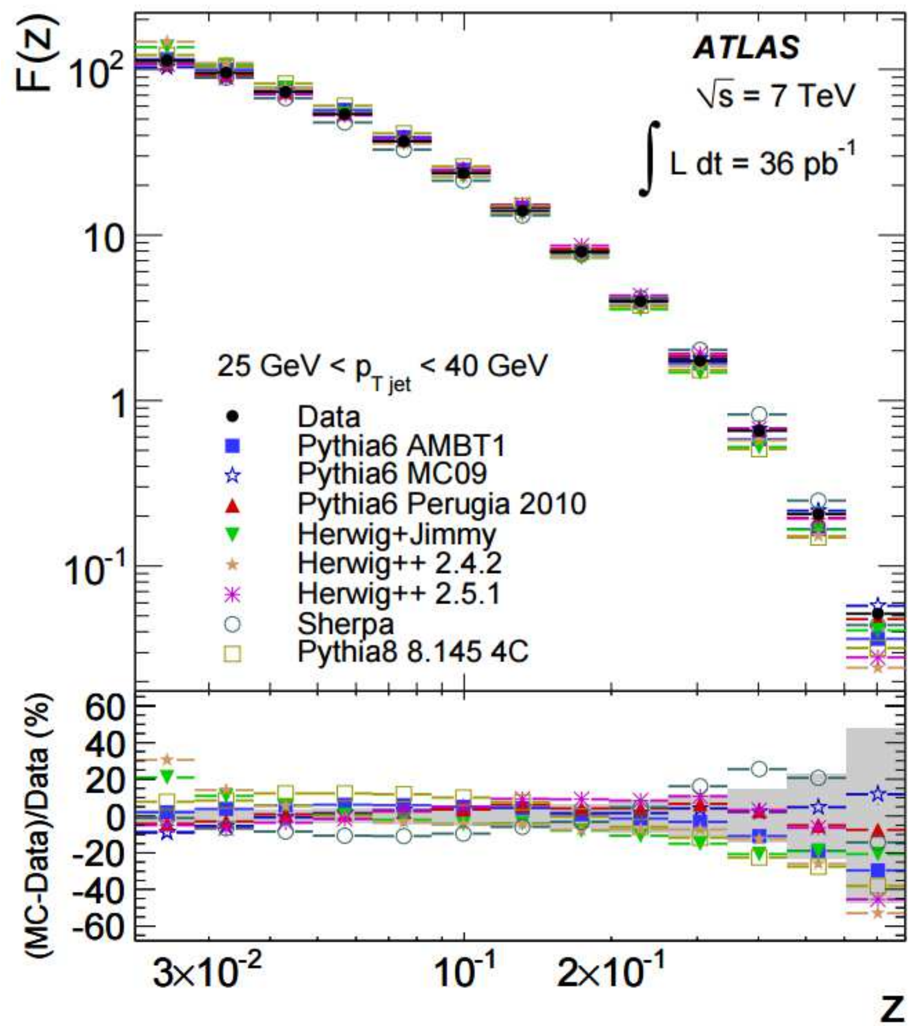
$\hat{q},\ \hat{e},\ N_g, \ldots$

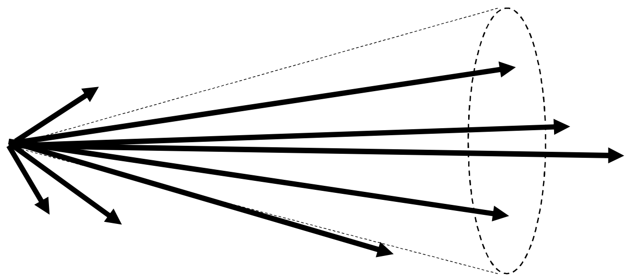
Strong coupling: “AdS drag force”



Why do we study jet quenching with jets?





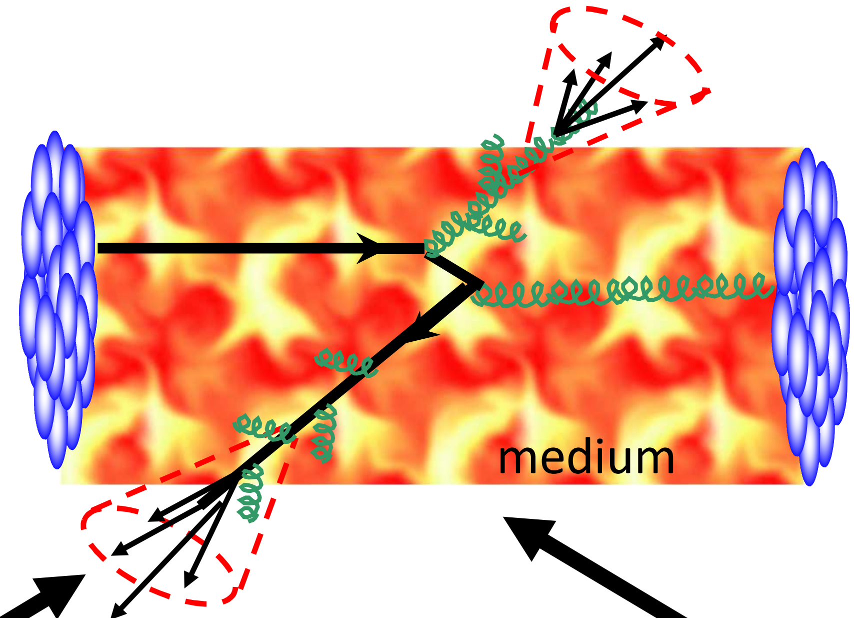


$$z = \frac{\mathbf{p}_{jet} \cdot \mathbf{p}_{ch}}{|\mathbf{p}_{jet}|^2}$$

EPJC 71 (2011) 1795

Jet as a versatile probe

Probe the Initial State Effects:
Extraction of nPDF

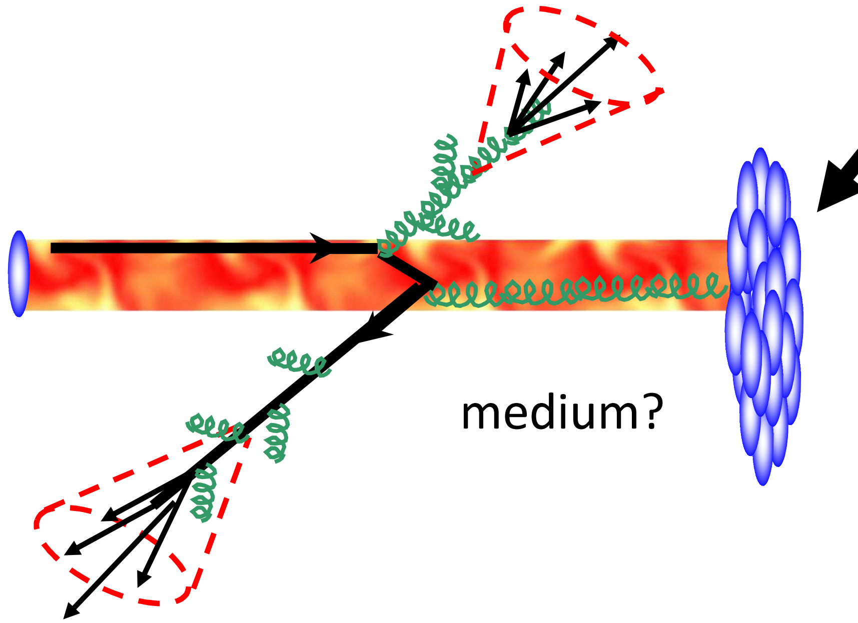


Probe the Final State
Modification of Jets

Search for medium response
Where does the quenched energy go?

Jet as a versatile probe

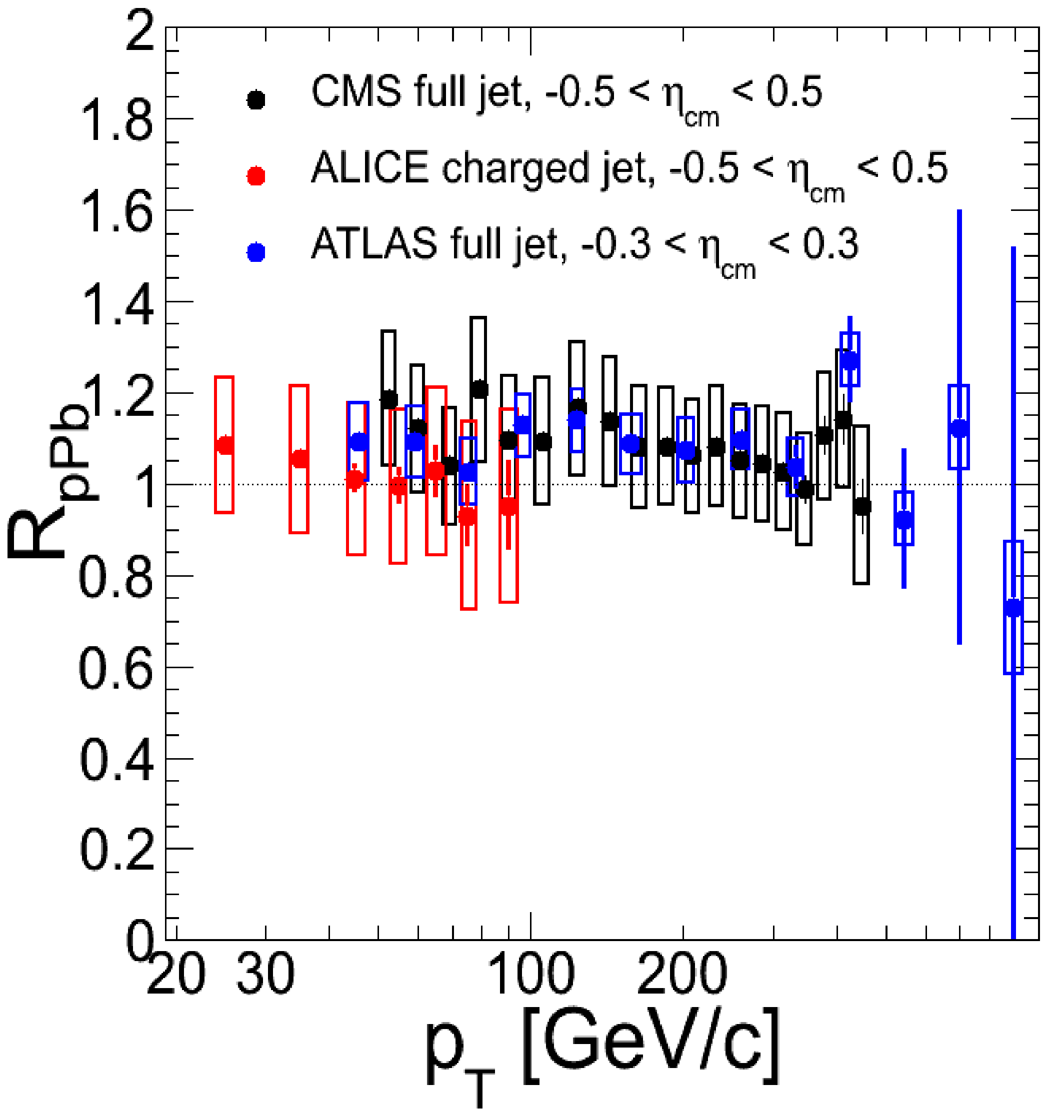
Probe the Initial State Effects:
Extraction of nPDF



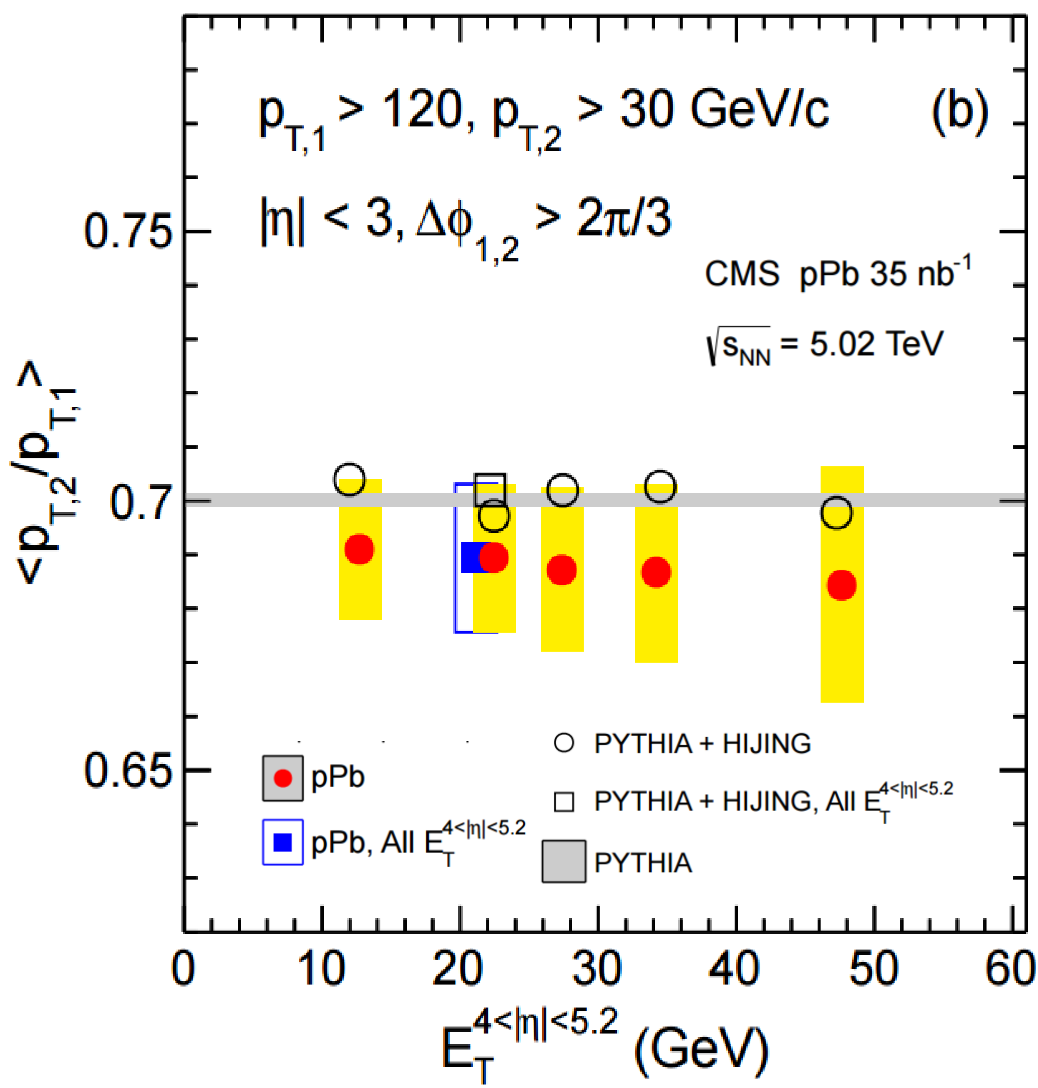
→ p(d)A collisions

(Di-)Jet production in pPb collisions at 5.02 TeV

Inclusive (charged) jet R_{pPb}



Subleading Jet p_T / leading jet p_T



Jet R_{pPb} ~ 1.1 ± 0.2, Consistent with pQCD calculation with EPS09 nPDF

Dijet p_T ratio compared to PYTHIA from CMS. No significant reduction of dijet p_T ratio (<2%)

Dijet dN/dη in pPb collisions at 5.02 TeV

CMS pPb 35 nb^{-1}

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

$p_{T,1}$ > 120 GeV/c

$p_{T,2}$ > 30 GeV/c

$\Delta\phi_{1,2} > 2\pi/3$

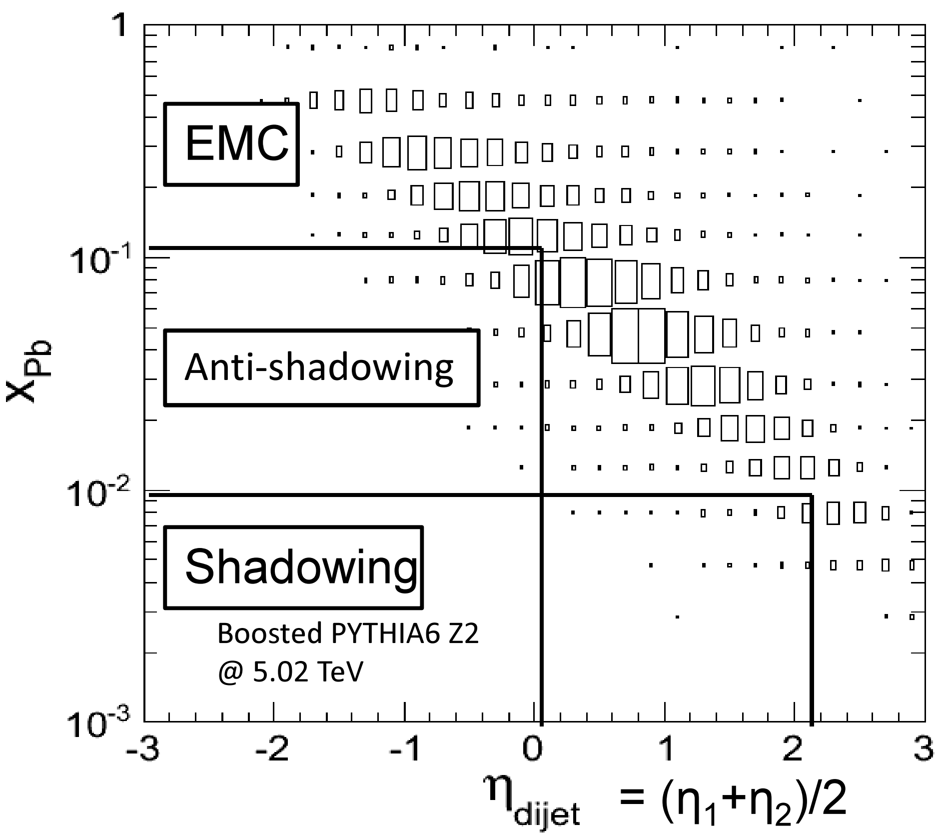
All $E_T^{|\eta|>4}$

Jet quenching from dijet analysis in pPb:

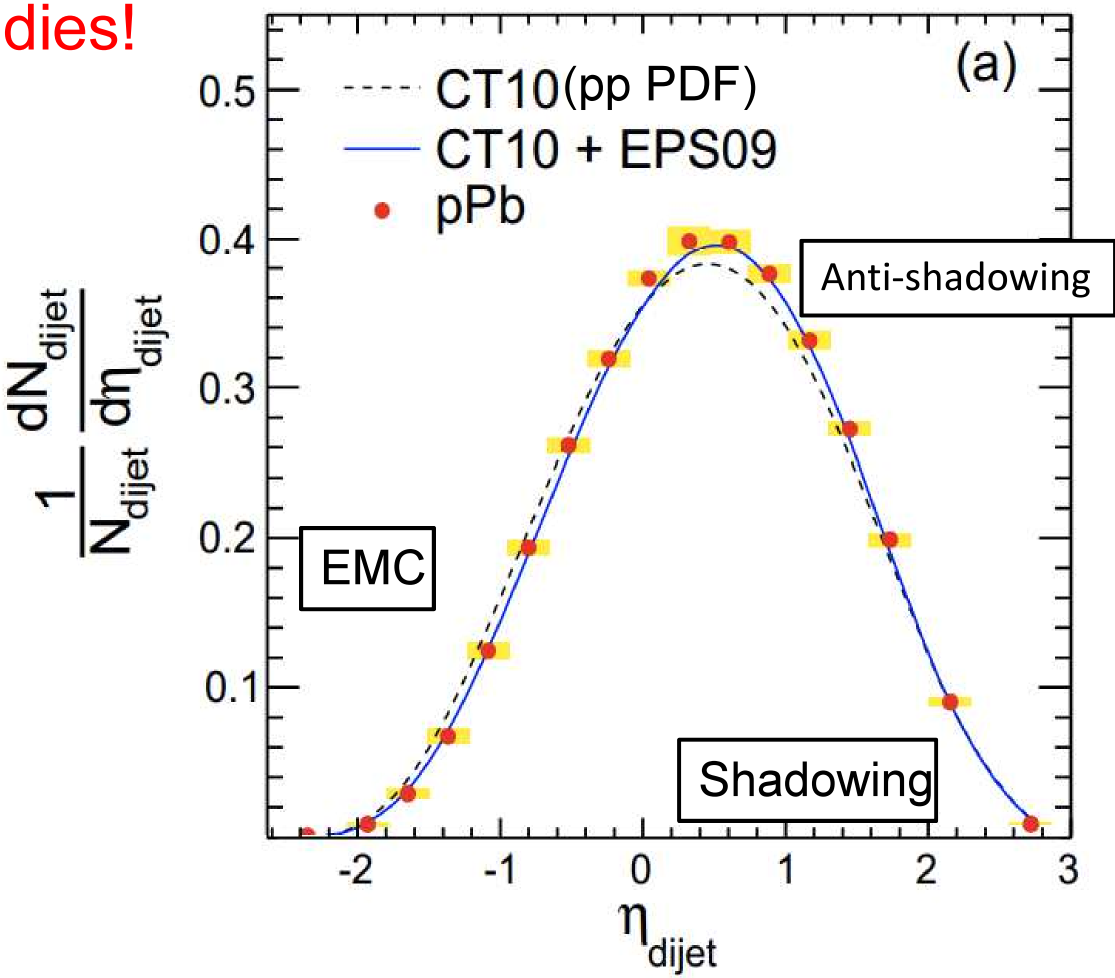
Dijet asymmetry <2%

No sizable deviation from unity found in jet R_{pPb}

→ Jets for nPDF studies!

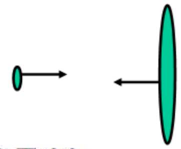


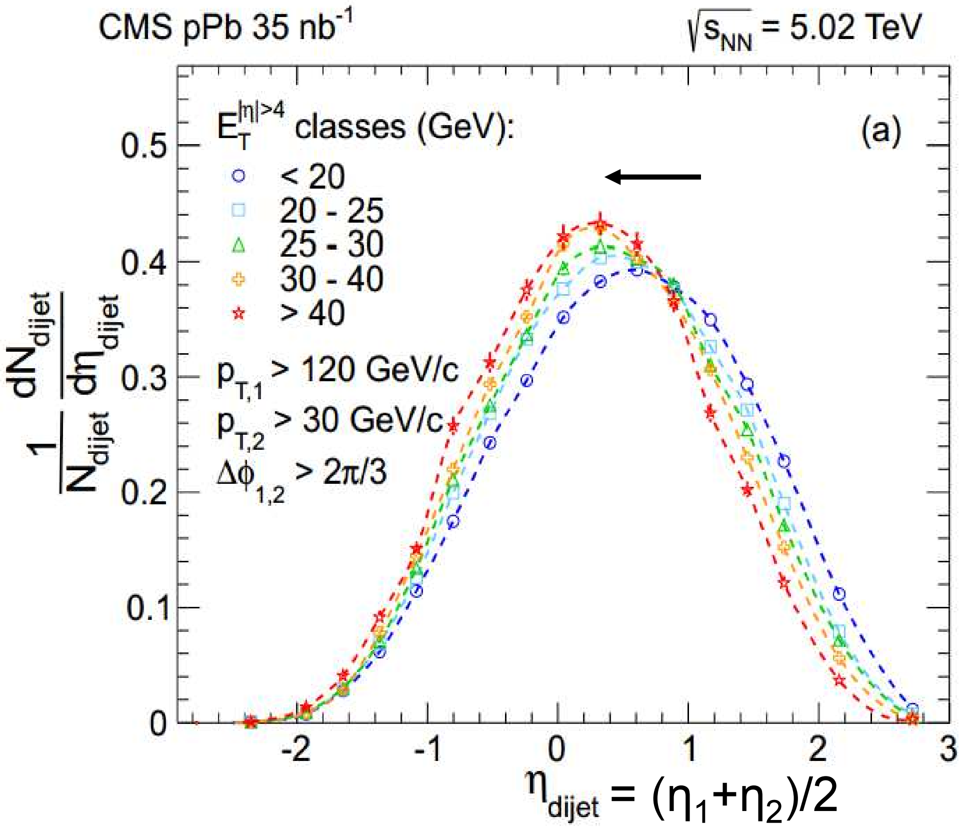
(In the lab frame)



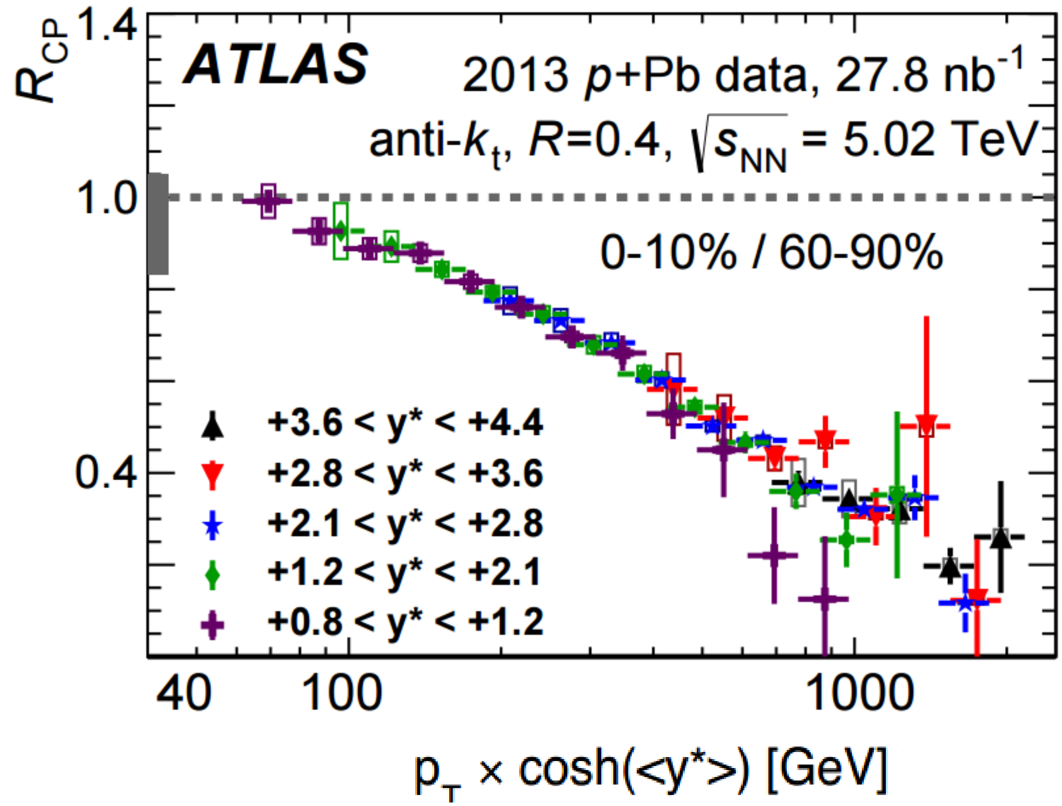
Dijet dN/dη vs. event activity and Jet R_{CP}

Red: event with **large** forward energy
Blue: event with **small** forward energy





y* > 0 (proton going data)



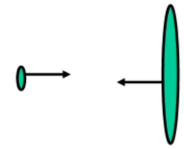
Jet momentum

(Too) large modification vs. event activity. Can not be explained by centrality dependent nPDF

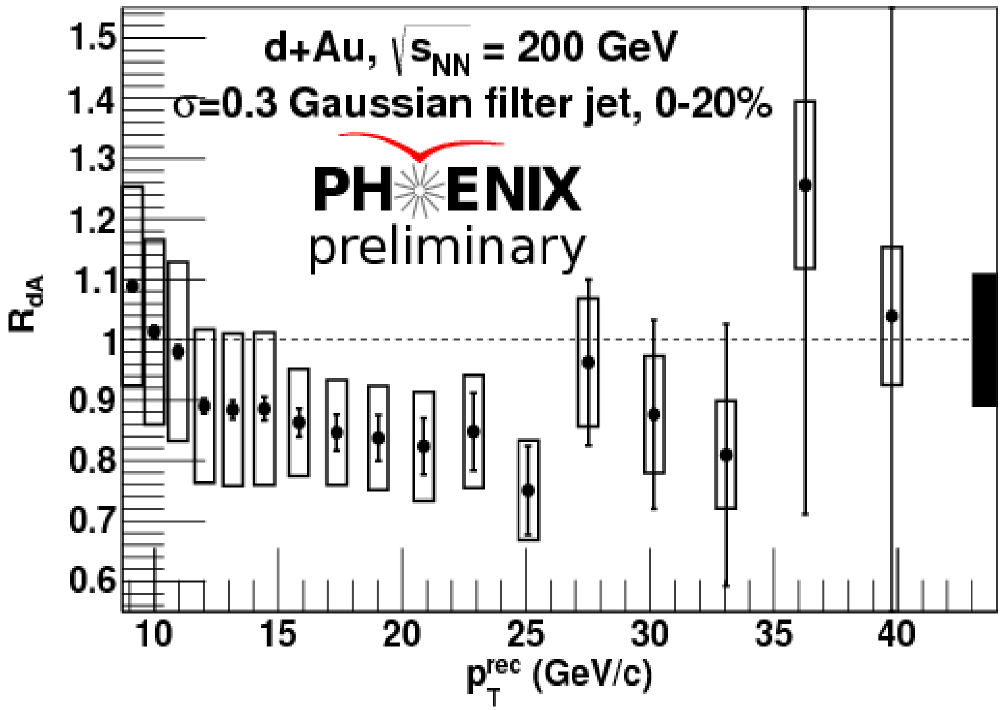
R_{CP} scaling vs. jet momentum in y*>0 data (proton going side)

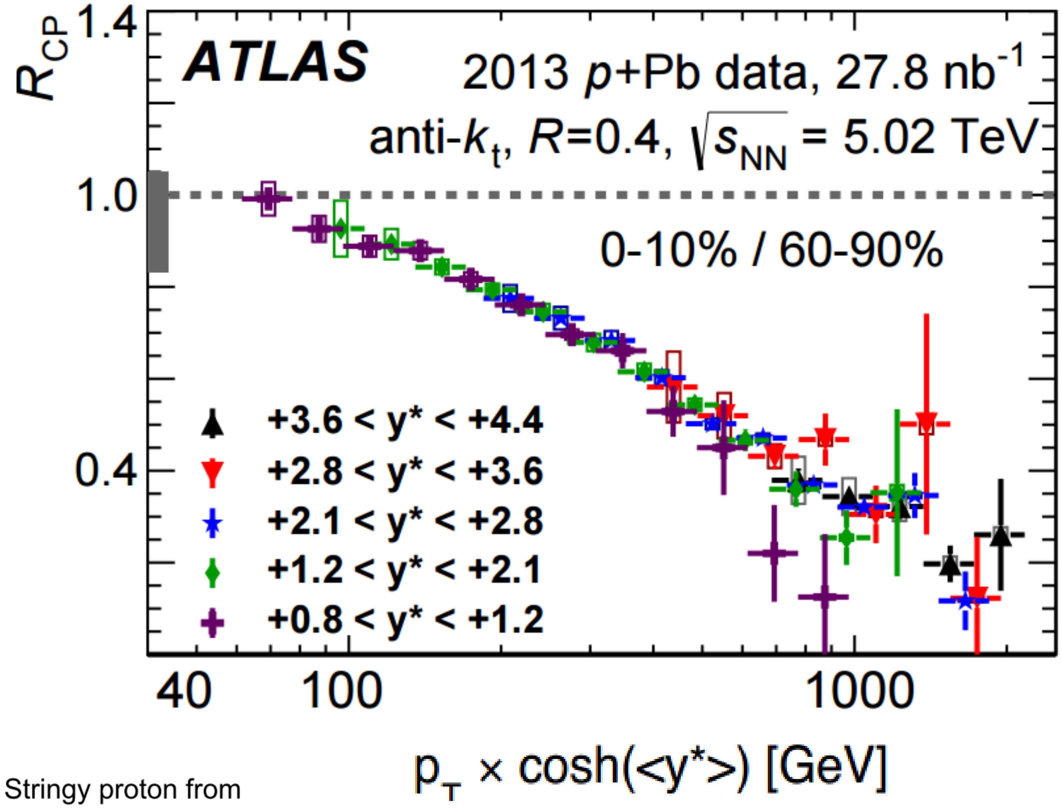
Jet R_{dAu} and Jet R_{CP}

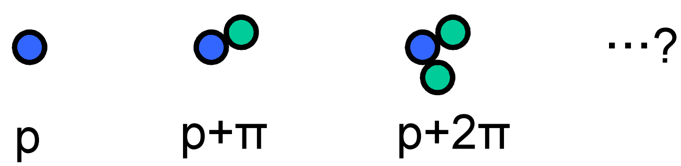
Jet R_{dA} in 0-20% central dAu collisions



y* > 0 (proton going data)







Stringy proton from quantum fluctuations caughter by a nucleus?

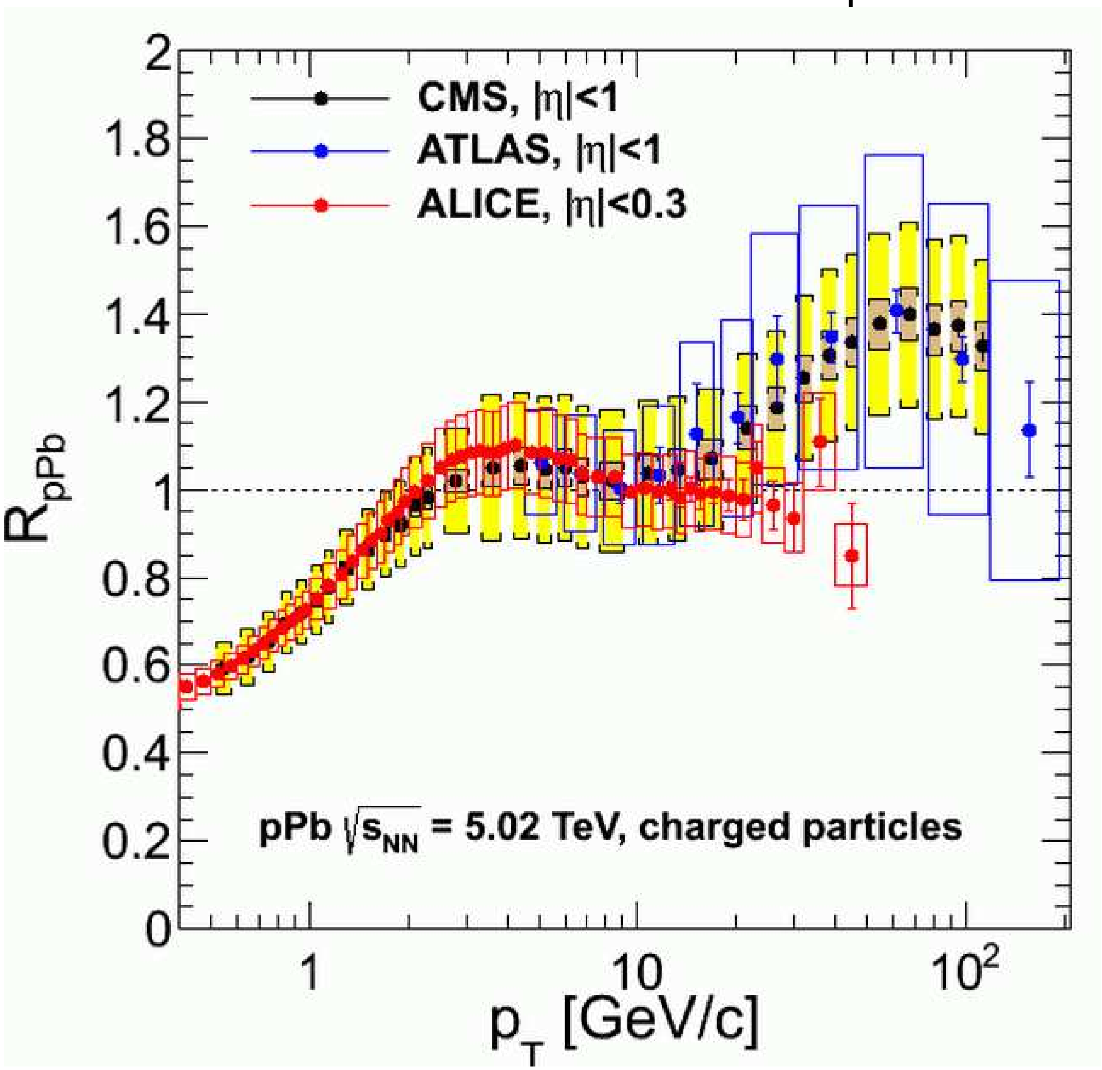
PRD 89, 025019 (2014)

Jet momentum

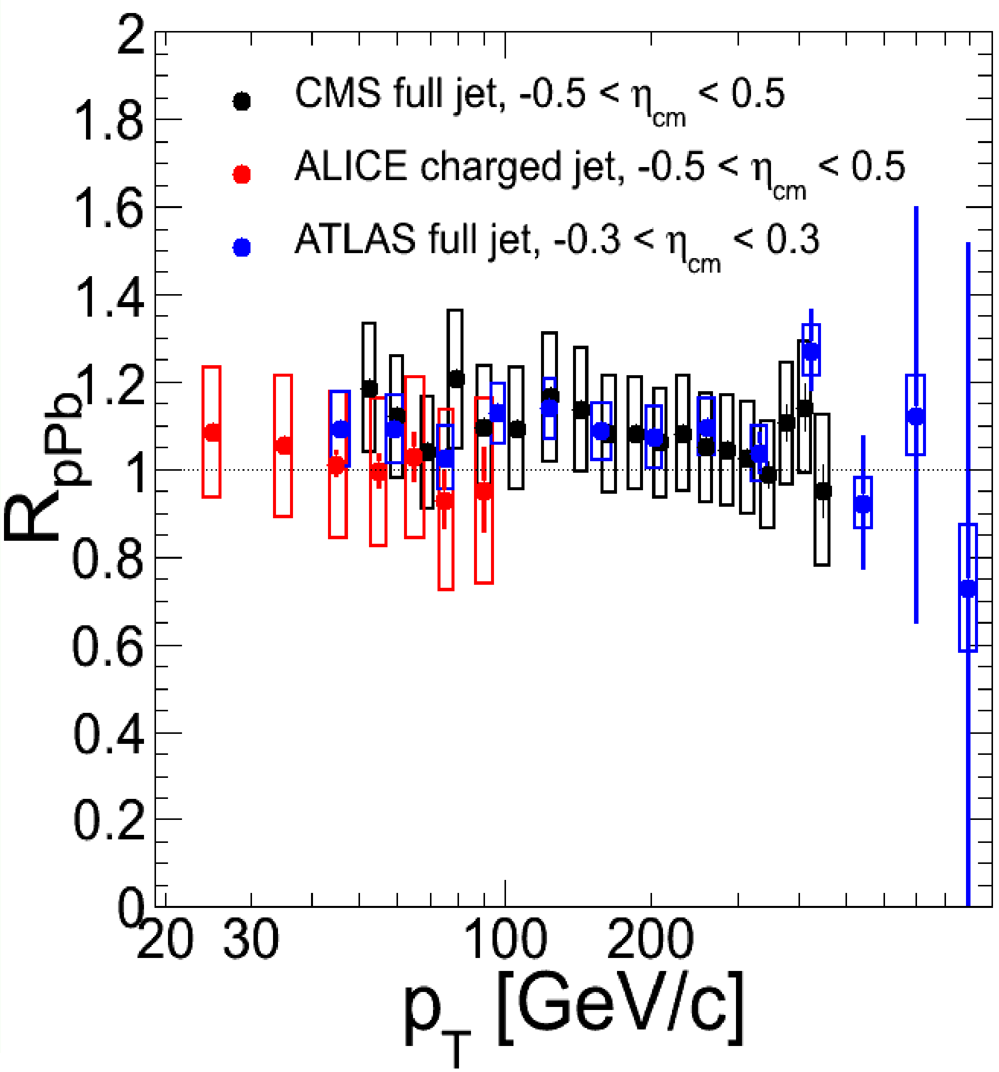
- Studies in bins of event activity in dAu, pPb collisions: interesting effects such as energy conservation, fluctuating proton size come into play

Charged particle and jet R_{pPb}

Charged hadron R_{pPb}



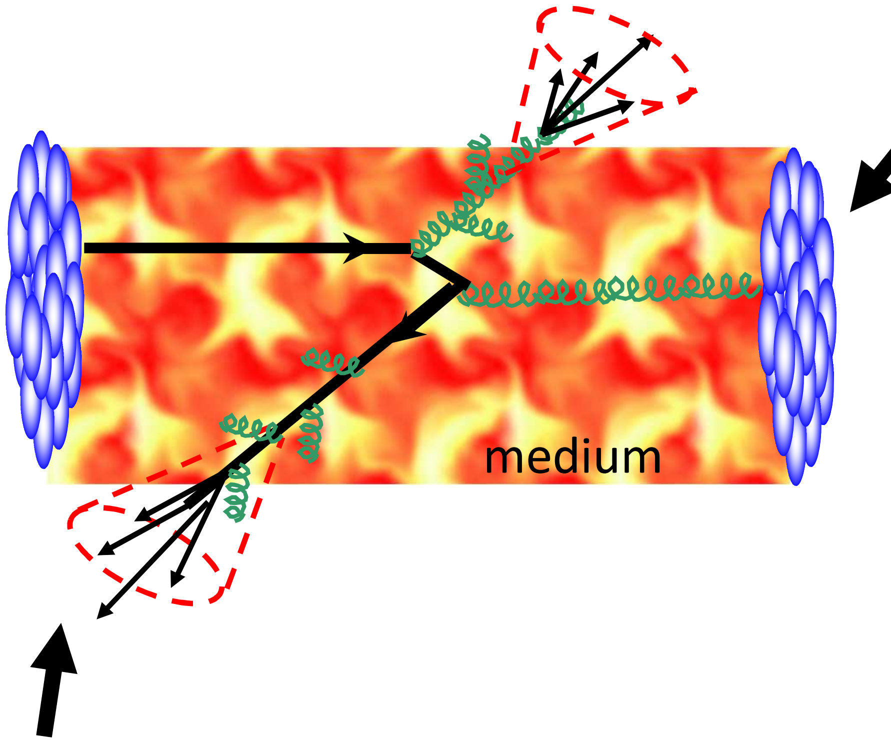
(Charged) Jet R_{pPb}



Large enhancement of charged hadron R_{pPb} ! Jet RpPb ~ 1.1, consistent with pQCD calculation with EPS09 nPDF. Need to check jet fragmentation function..

Jet as a versatile probe

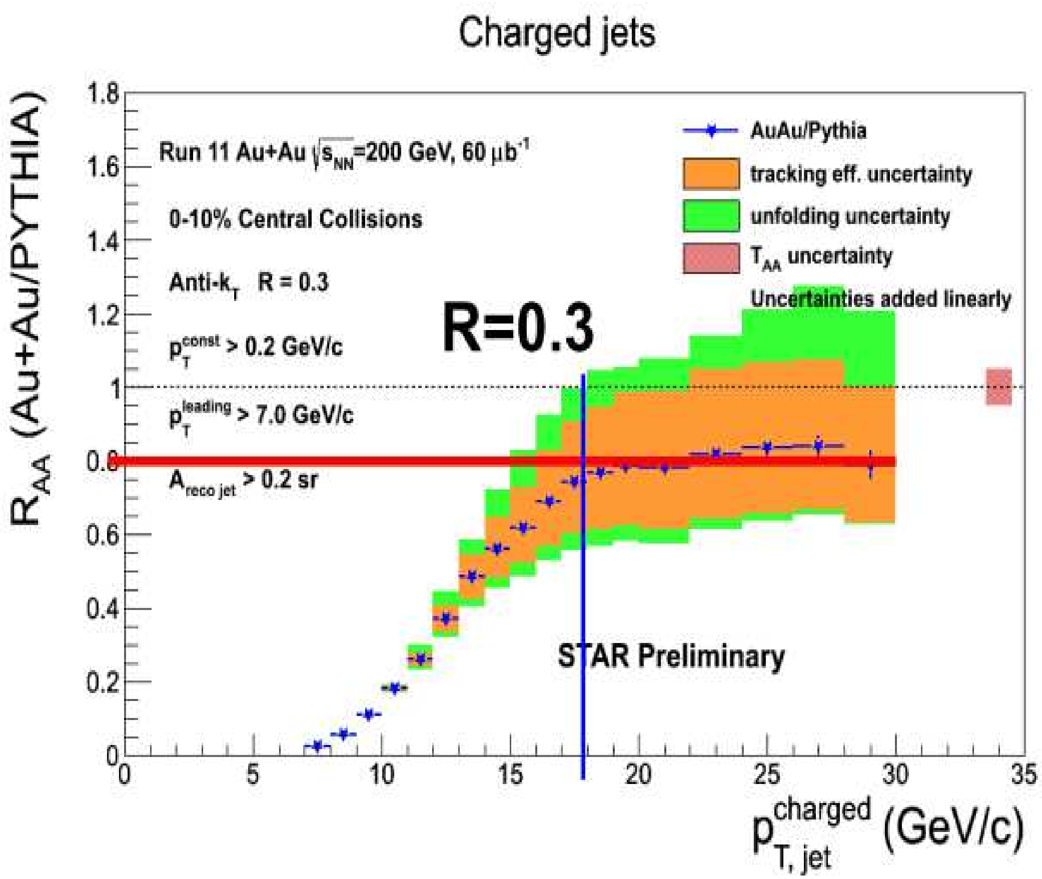
Probe the Initial State Effects:
Extraction of nPDF



Probe the Final State
Modification of Jets

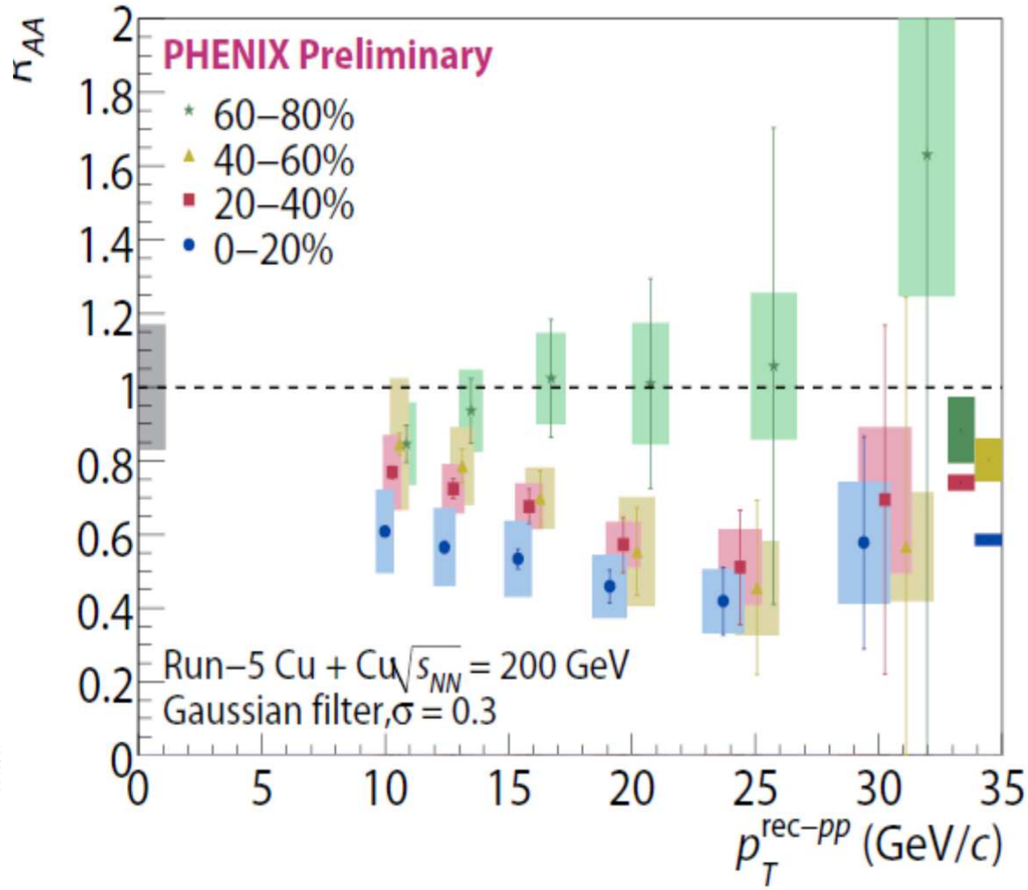
Inclusive Jet R_{AA} at the RHIC

STAR (Anti-k_T R=0.3)
Compare 0-10% AuAu to pp



PHENIX (Gaussian Filter r=0.3)

Compare CuCu to pp

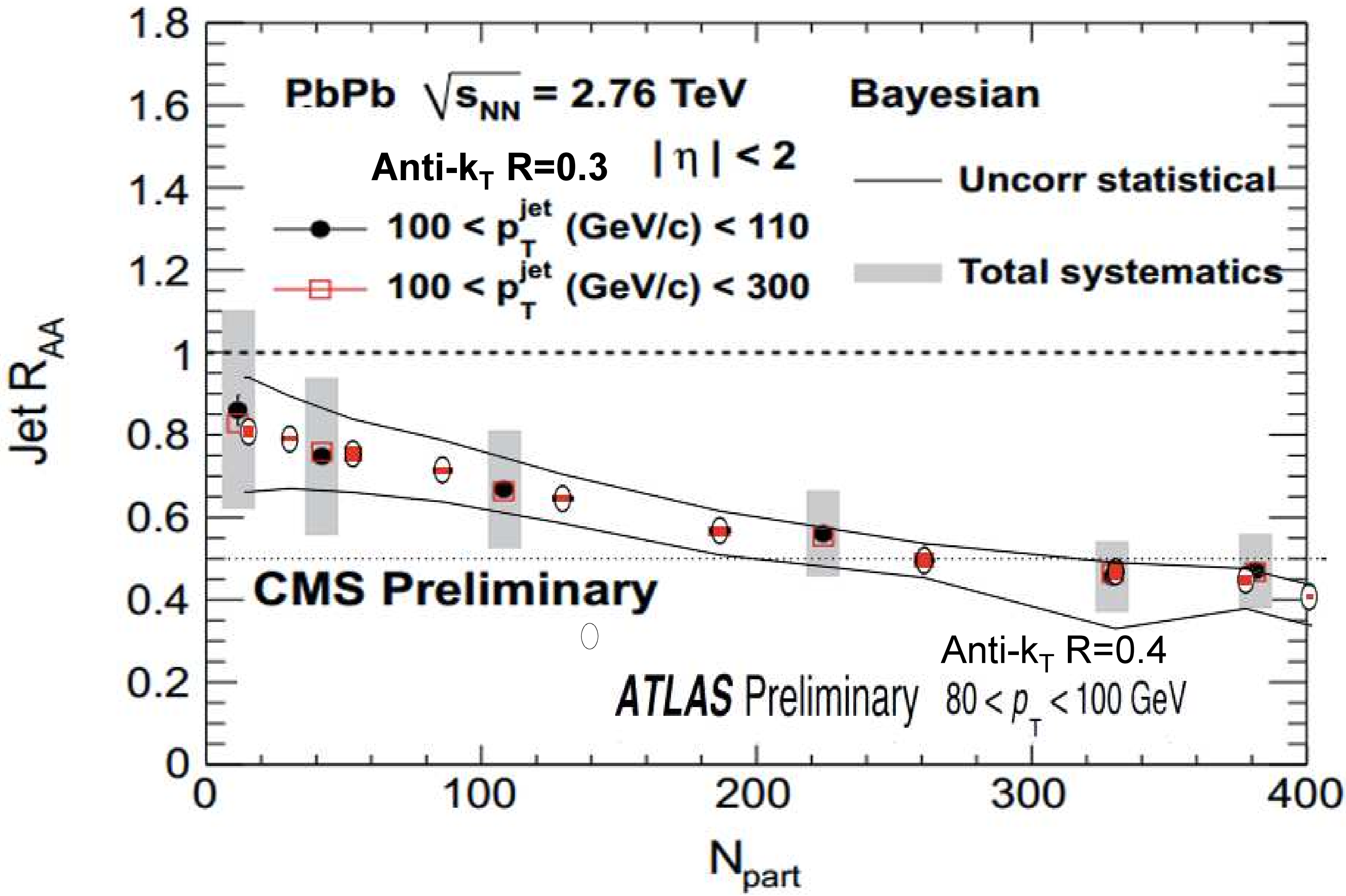


Strong suppression of inclusive high p_T jets!

Different results from STAR and PHENIX (different systems, jet algorithms and selection)

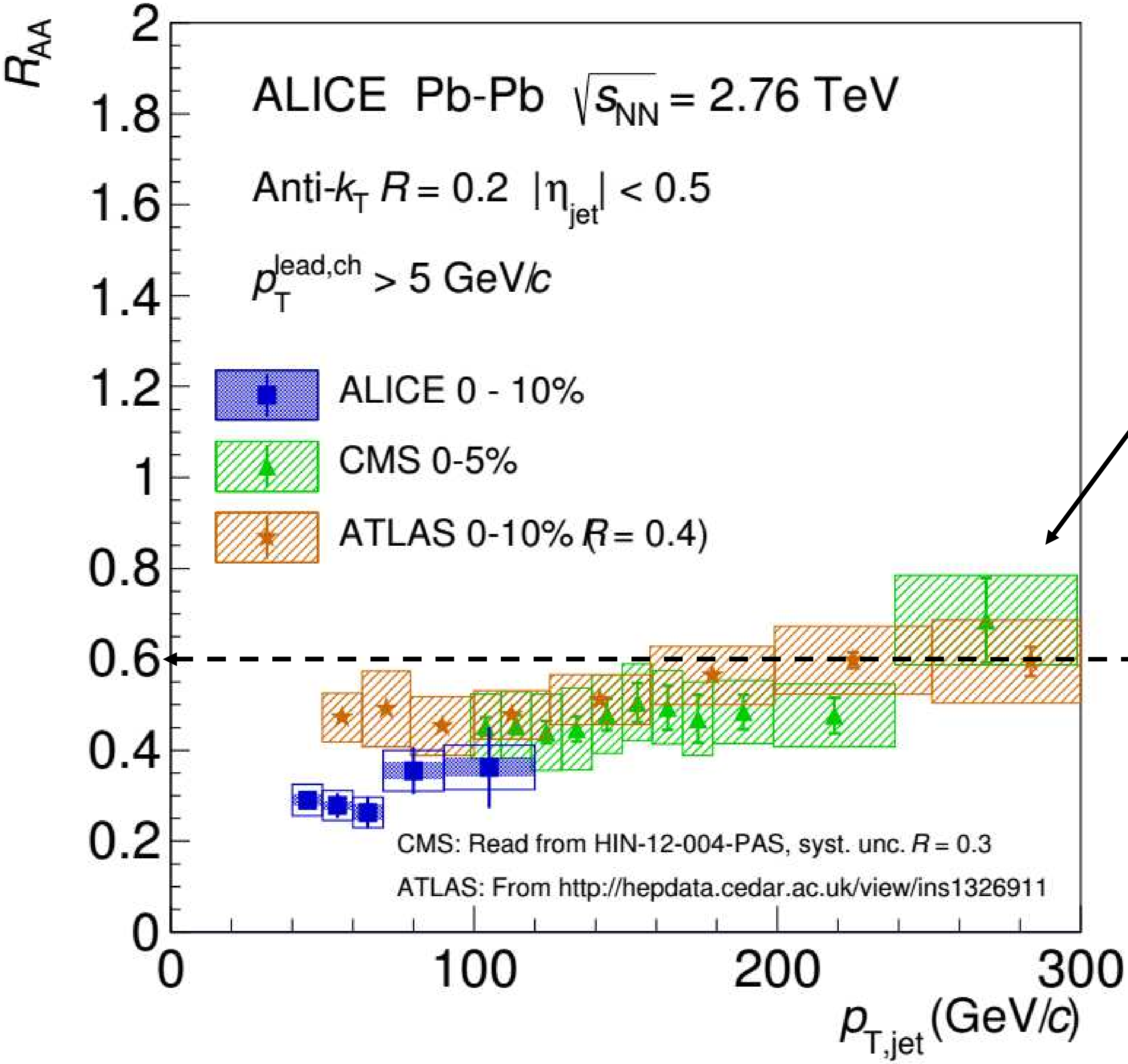
A cone of R~0.3 doesn't catch all the radiated energy

Jet R_{AA} at the LHC



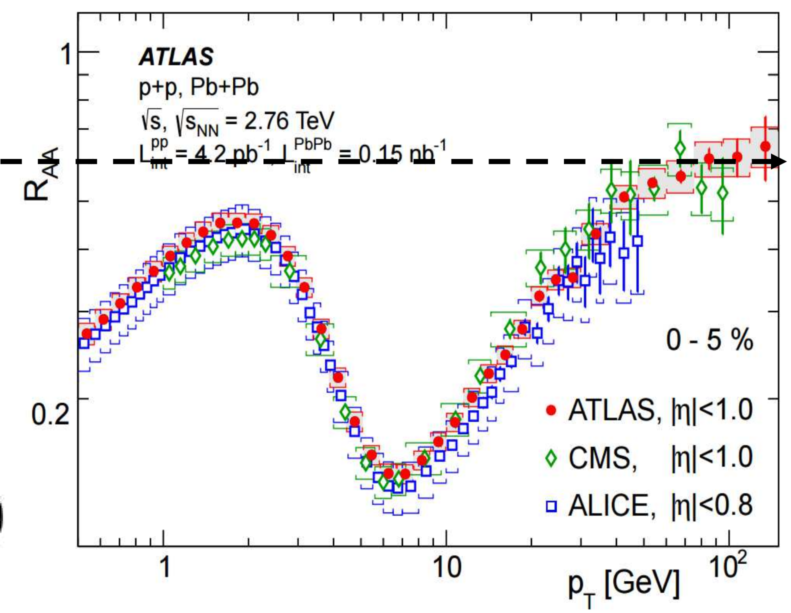
Strong suppression of inclusive high p_T jets in central PbPb collisions

Jet R_{AA} in PbPb collisions at LHC



~ Agreement between CMS and ATLAS at high jet p_T

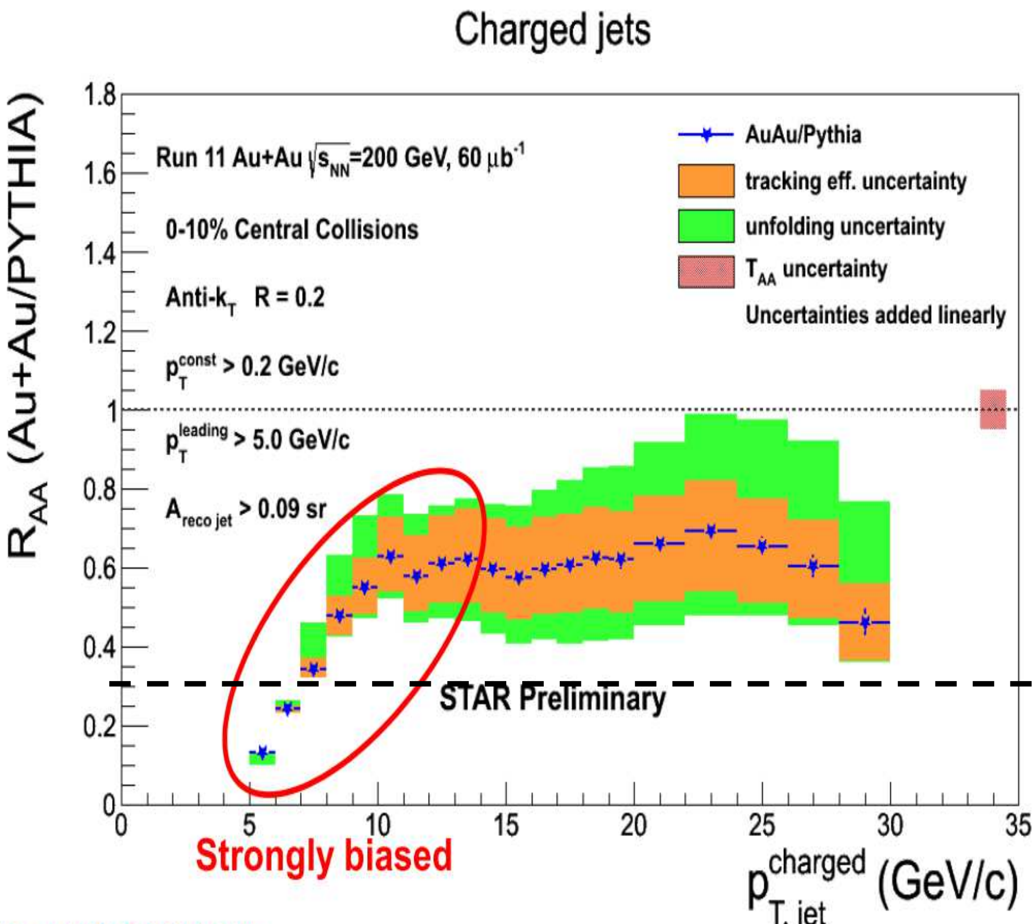
Agree with charged particle R_{AA} at high p_T

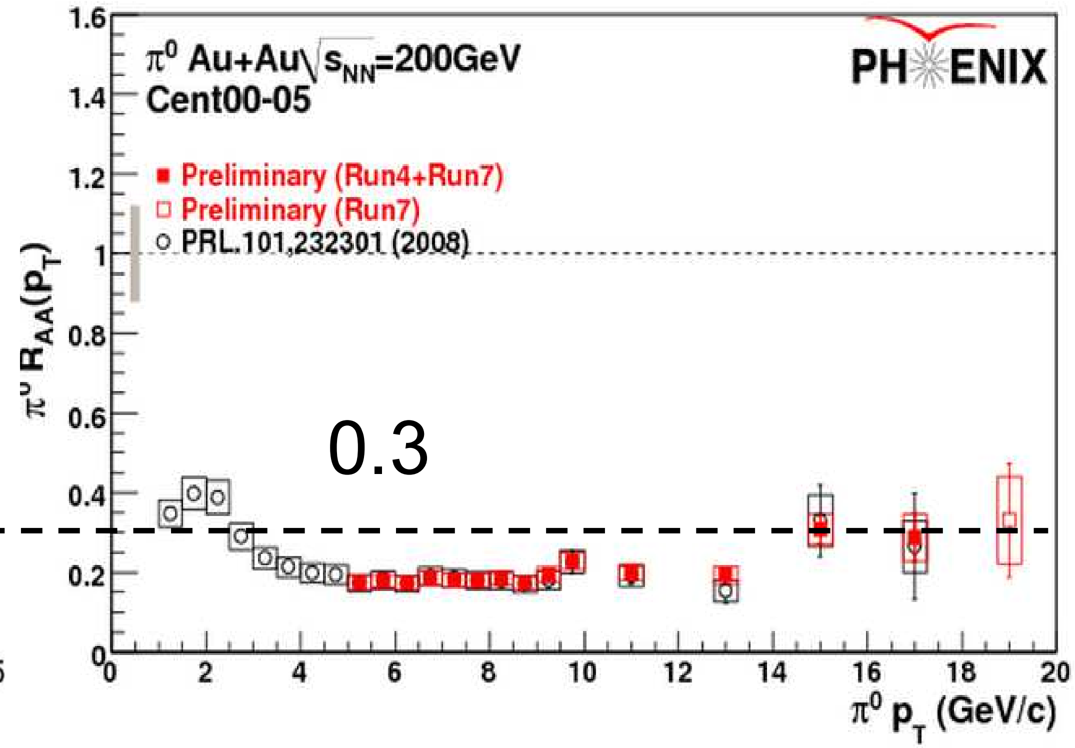


It would be nice to have low p_T CMS data / ATLAS R_{AA} with R=0.2 / ALICE high p_T data

Charged Jet R_{AA} v.s π^0 R_{AA} at RHIC

STAR





IR cutoff: 200MeV/c

Charged jet R_{AA} results: different from single particle R_{AA}

Indication of modification of jet fragmentation function?

Selection bias? Due to the steeply falling p_T spectra?

Jet Fragmentation at LHC

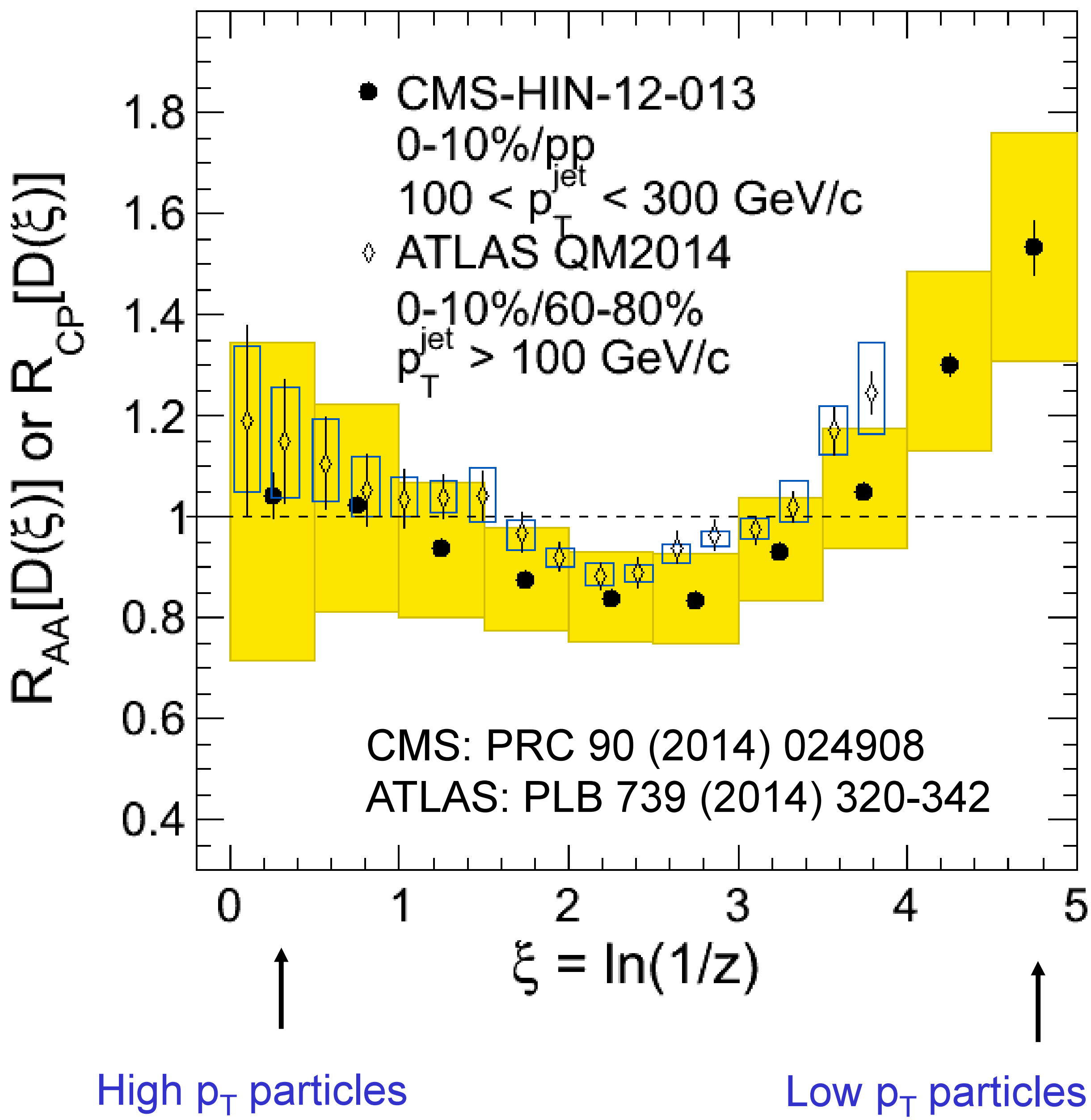
Using **Jet Energy** as a reference

CMS FF R_{AA} compared to ATLAS FF R_{CP}

$Z = p_{||}^{Trk} / p^{Jet}$

Qualitative consistent results between CMS and ATLAS

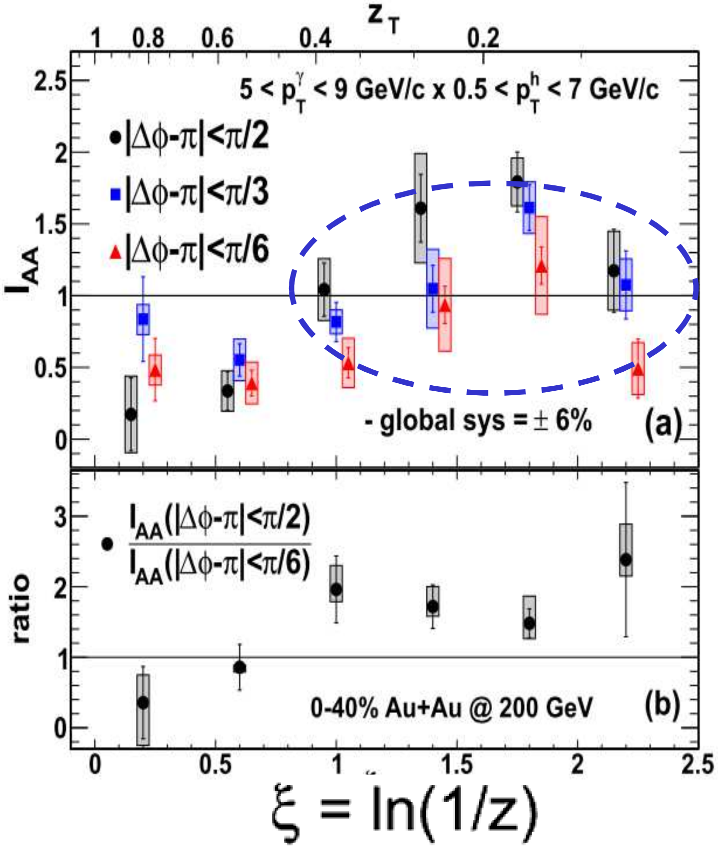
ATLAS update: indication of enhancement of low ξ (high z) particles in the jet cone



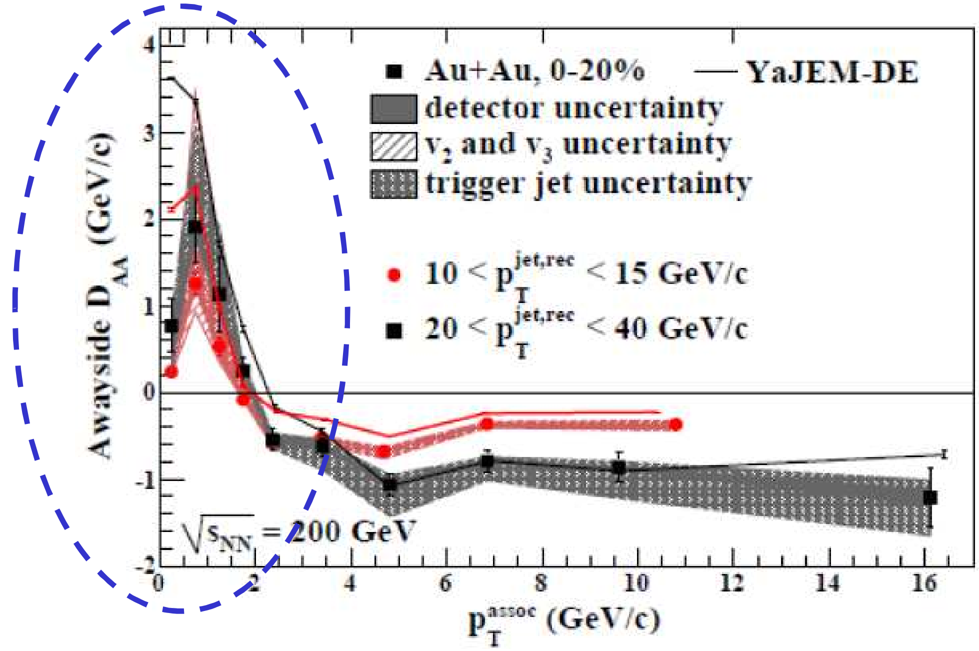
Consistent picture: excess of low p_T particle in the jet cone

PHENIX

Photon-tagged Hadron I_{AA}

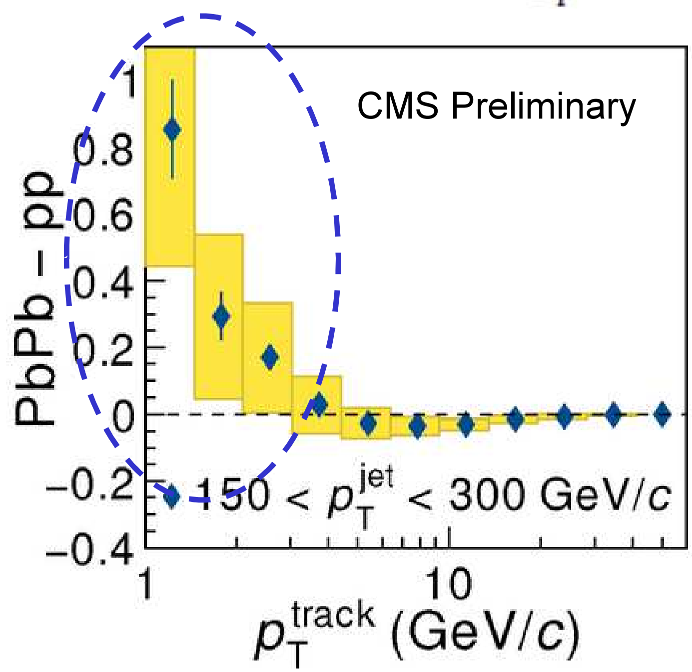


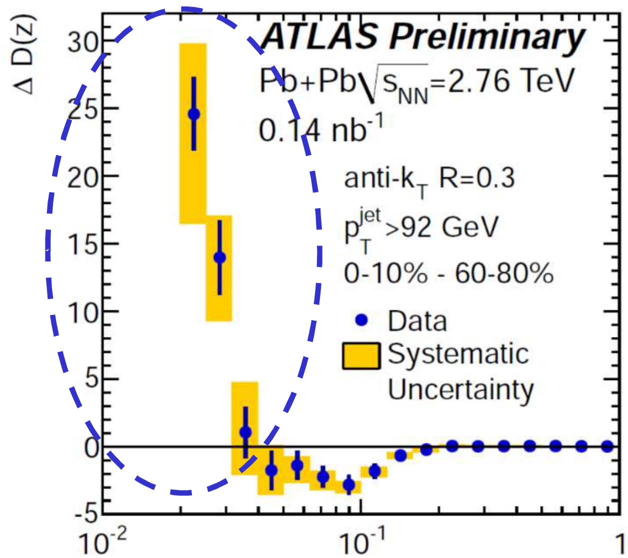
$$Z = p_{||}^{Trk} / p^{Jet}$$



STAR

Jet-Hadron



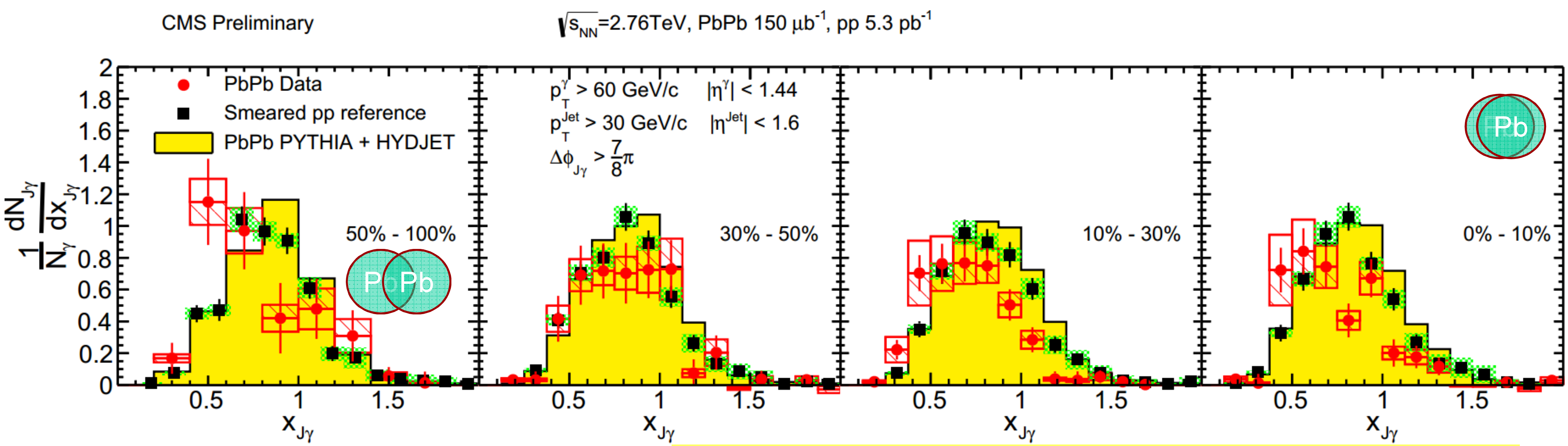


$$Z = p_{||}^{Trk} / p^{Jet}$$

γ-"inclusive jet" correlations

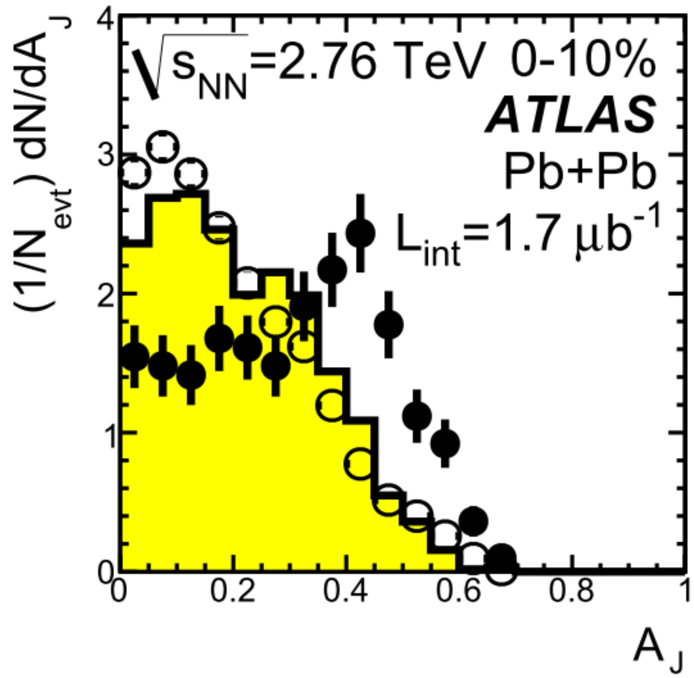
- Photons serve as an unmodified energy tag for the jet partner
- Ratio of the p_T of jets to photons ($x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$) is a direct measure of the jet energy loss
- Gradual centrality-dependence of the $x_{J\gamma}$ distribution

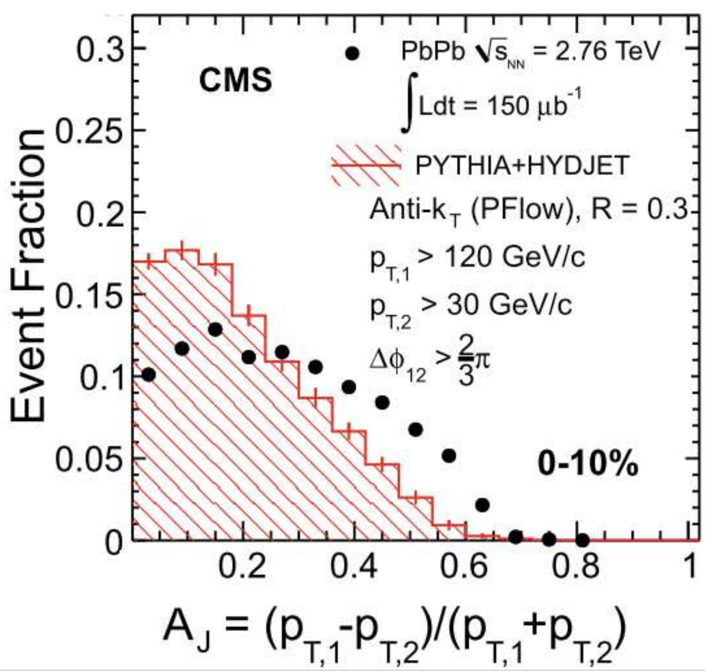
Anti-k_T jet R = 0.3



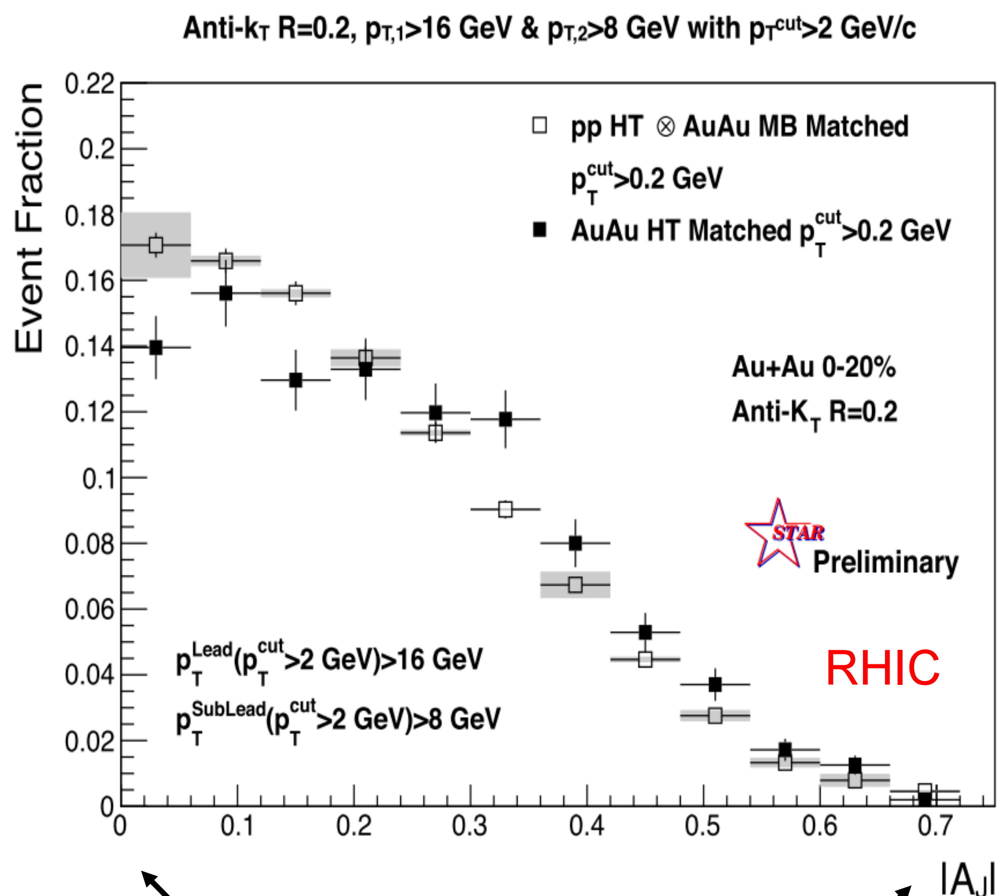
PLB 718 (2013) 773 CMS-PAS-HIN-13-006

Dijet asymmetry A_J in RHIC and LHC





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

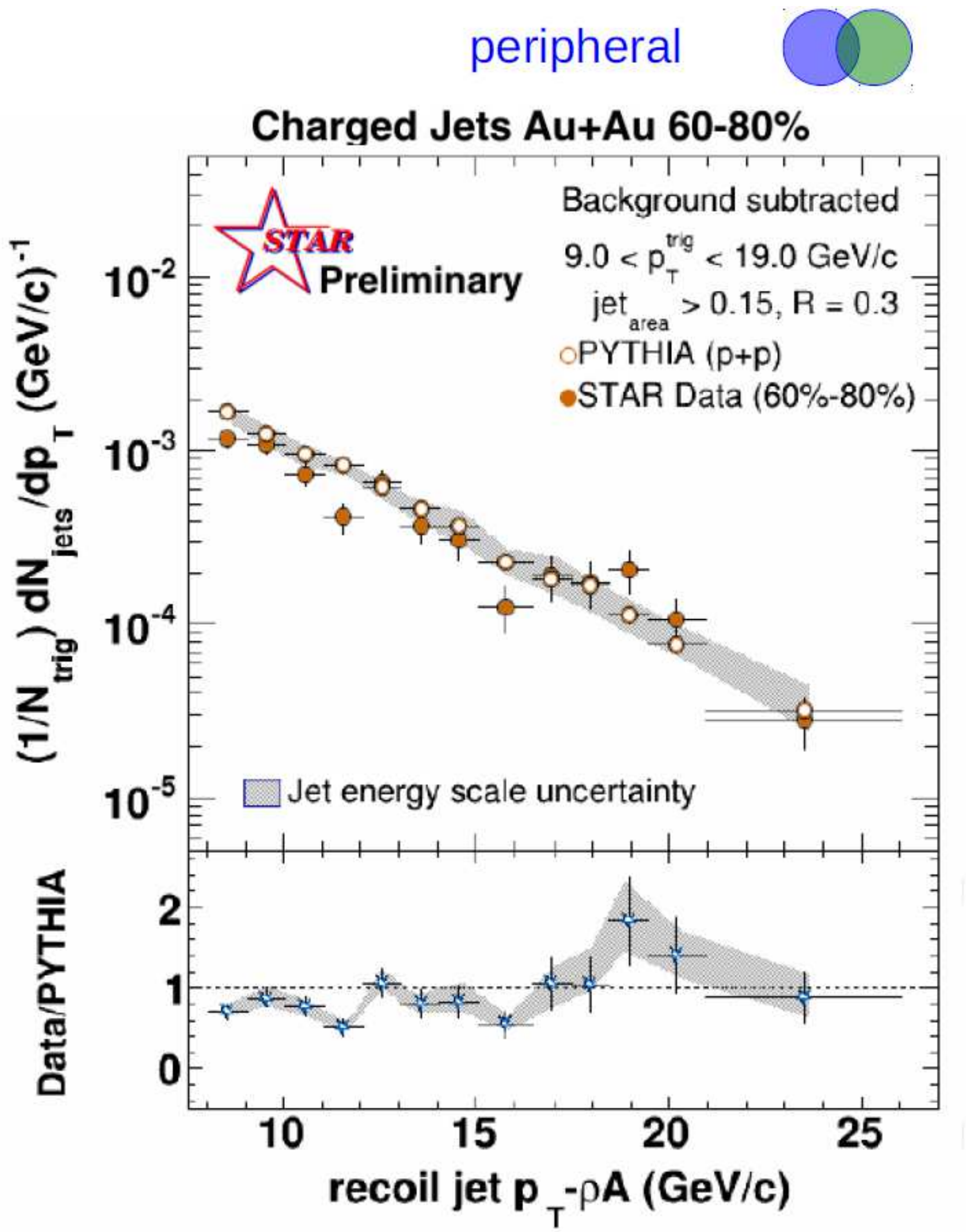


Balanced dijet

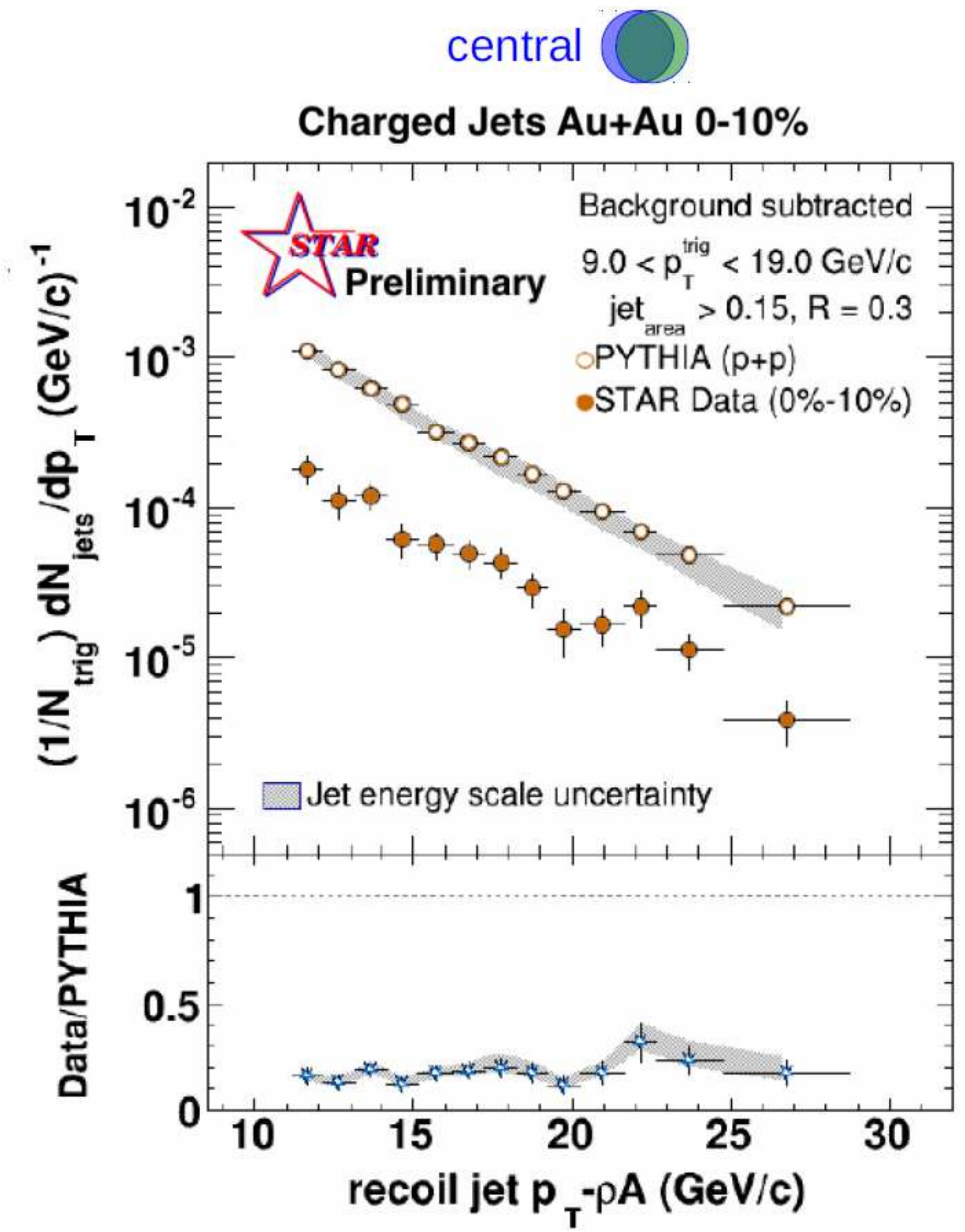
Imbalanced dijet

Hadron-Jet correlation

peripheral

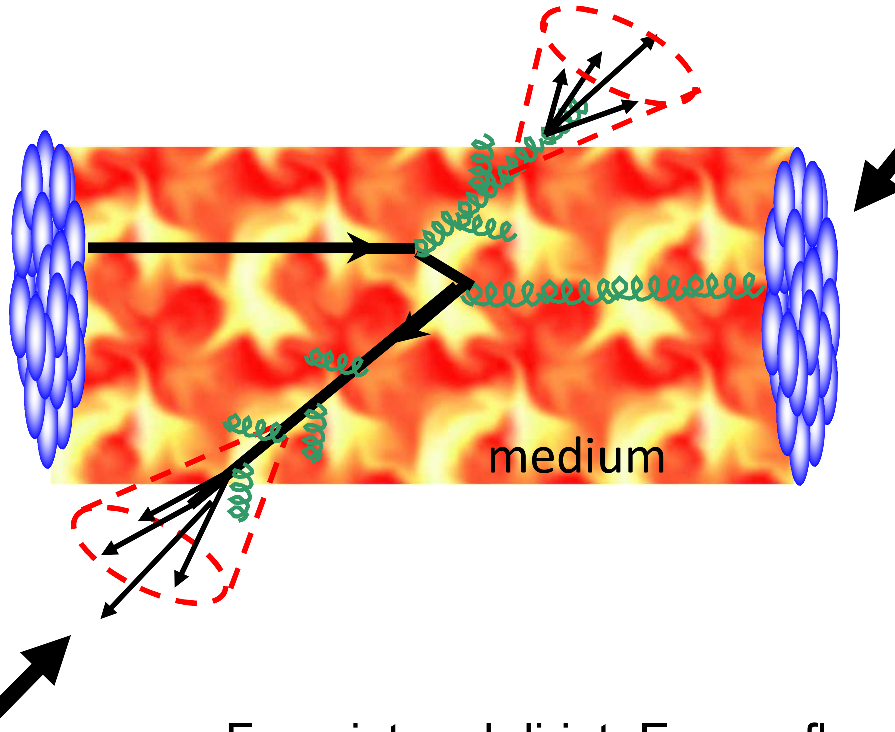


central



Jet as a versatile probe

Probe the Initial State Effects:
Extraction of nPDF



Probe the Final State
Modification of Jets

From jet and di-jet: Energy flow out of the jet cone

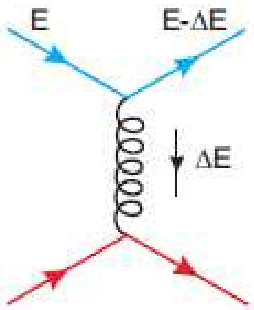
Flavor dependence of parton energy loss?

Flavor dependence of parton energy loss

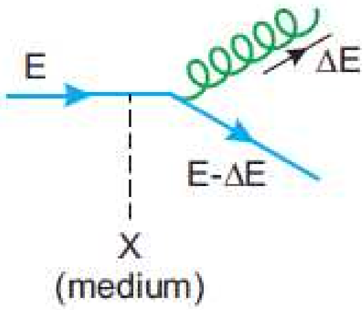
- From QCD
  - Color charge:
    E_{loss} in gluons > E_{loss} in quarks
  - Kinematics: "Dead cone effect":
    E_{loss} in quarks > E_{loss} in heavy quarks

Heavy Quark vs. Light Quark:
Changing the ratio of
collisional and radiative energy loss
→ Determination of the
elastic energy loss coefficient ($\hat{e}$)

Collisional energy loss



Radiative energy loss



Heavy flavor jet and hadron analyses cover a wide kinematics range
→ Suppression of induced radiation at low p_T and
the disappearance of this effect at high p_T

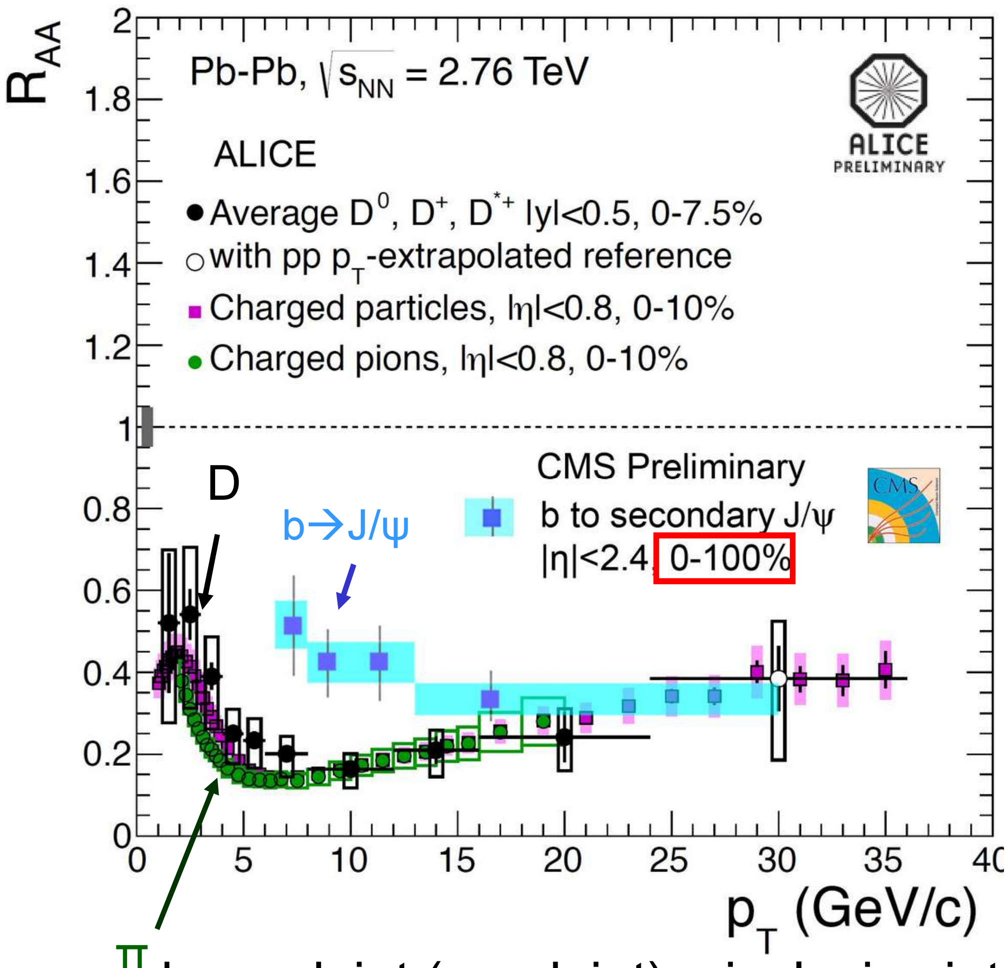
Flavor Dependence of Jet Quenching

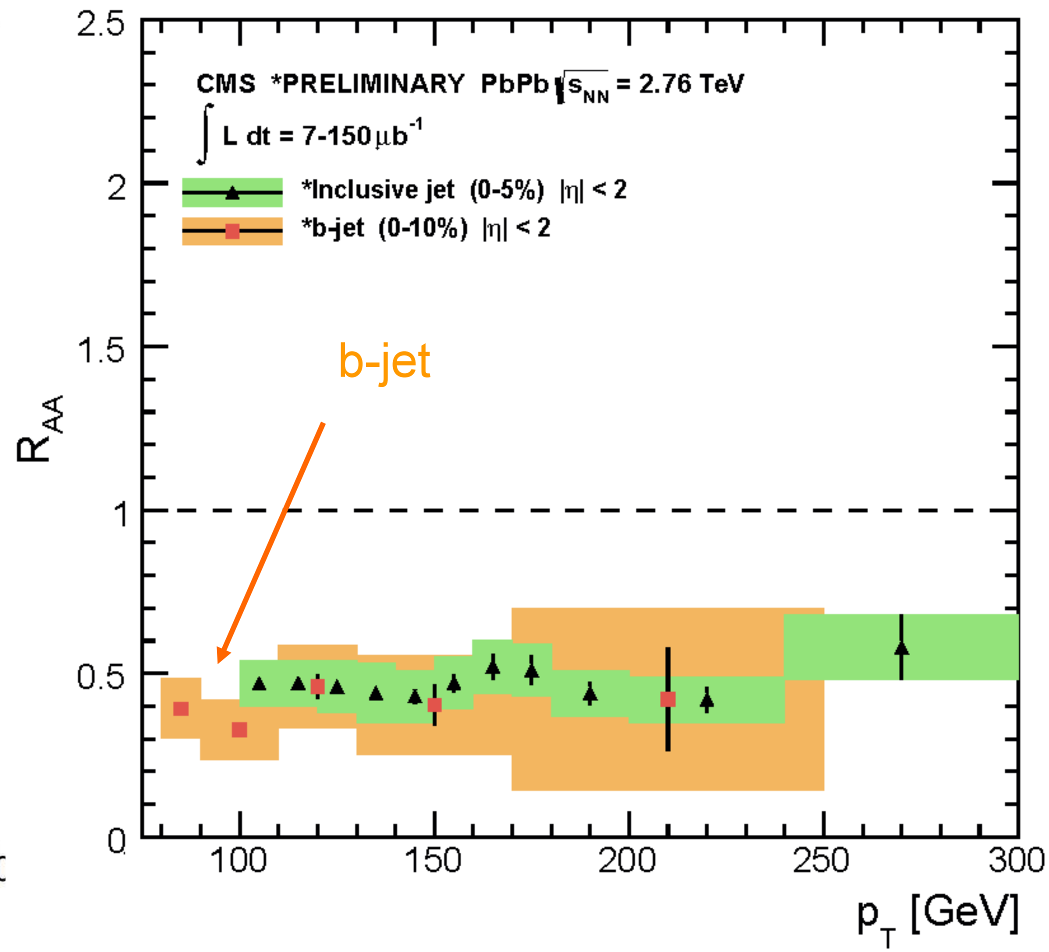
Indication of $R_{AA}(B) > R_{AA}(D) > R_{AA}(\pi)$ at low p_T

(However, spectra slope are different)

Indication of R_{AA}(b-jet) ~ R_{AA}(all jets) at high jet p_T

Pb+Pb

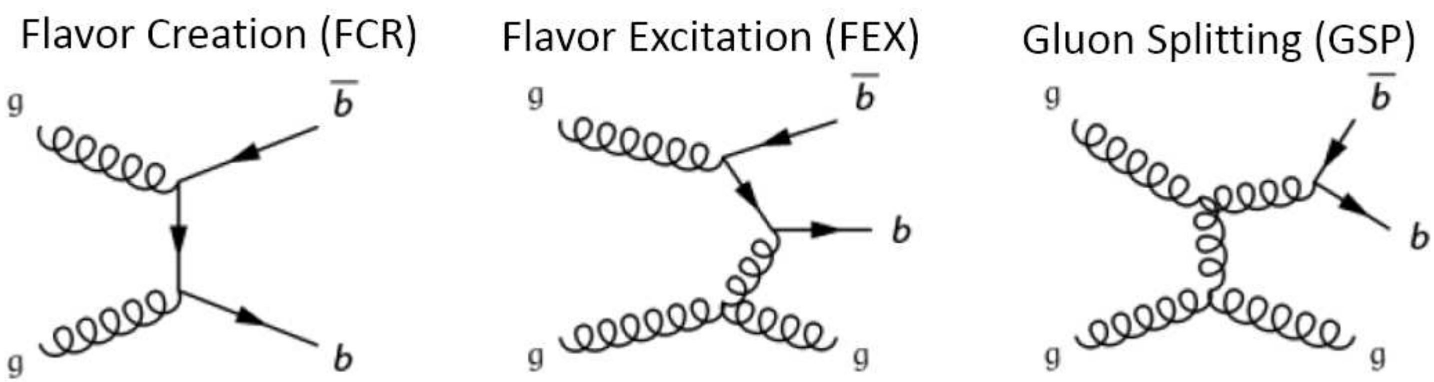




b quark jet (quark jet) ~ inclusive jet (dominated by gluon jets)?

Are we really studying heavy flavor parton energy loss with D, b→J/ψ and b-jet?

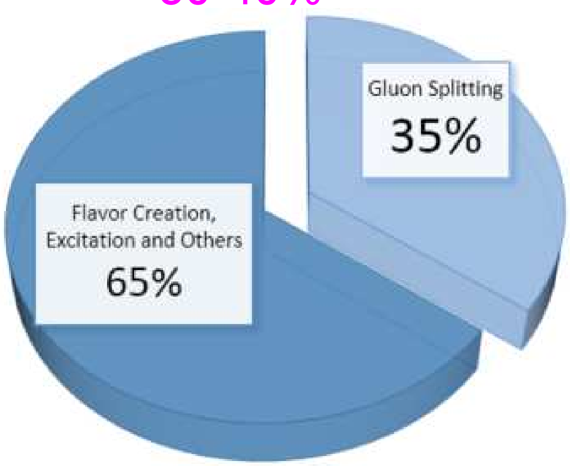
Gluon Splitting Contribution



- HF studies: matched partons are not necessary heavy quarks!

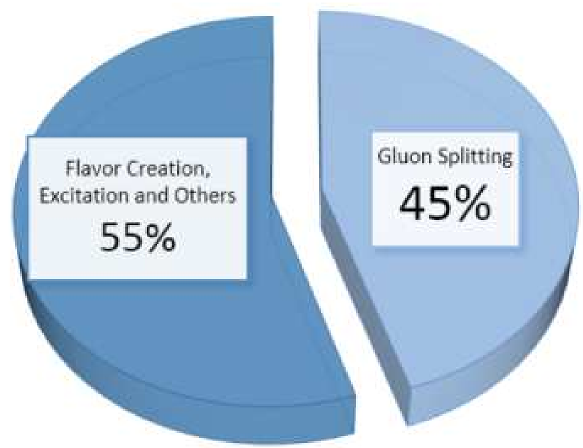
b jets

~30-40%



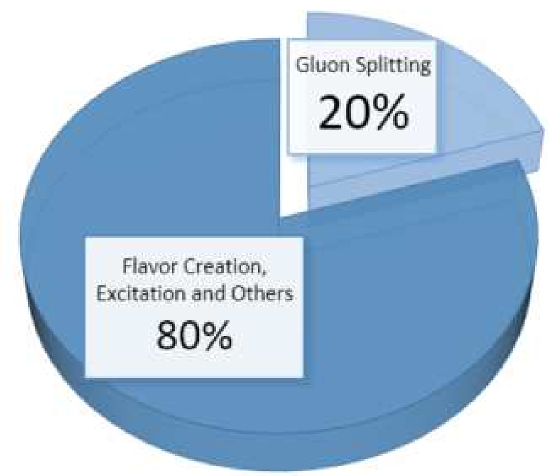
D mesons

~40-50%



Non-Prompt J/ψ

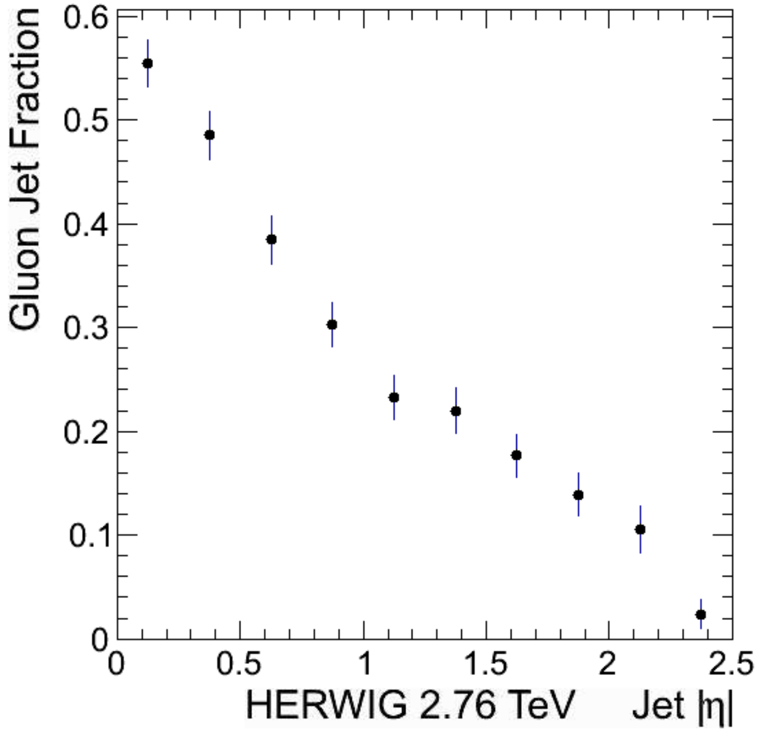
~20%

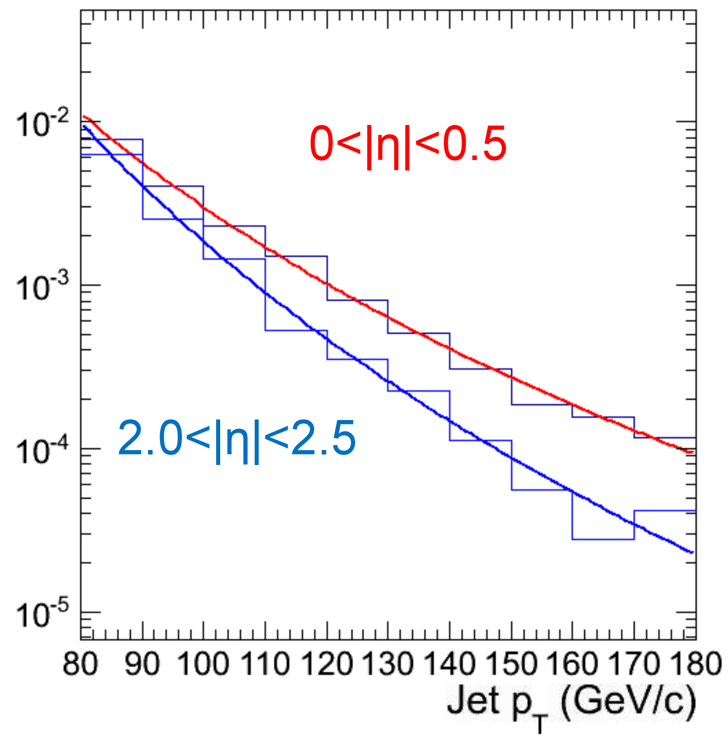


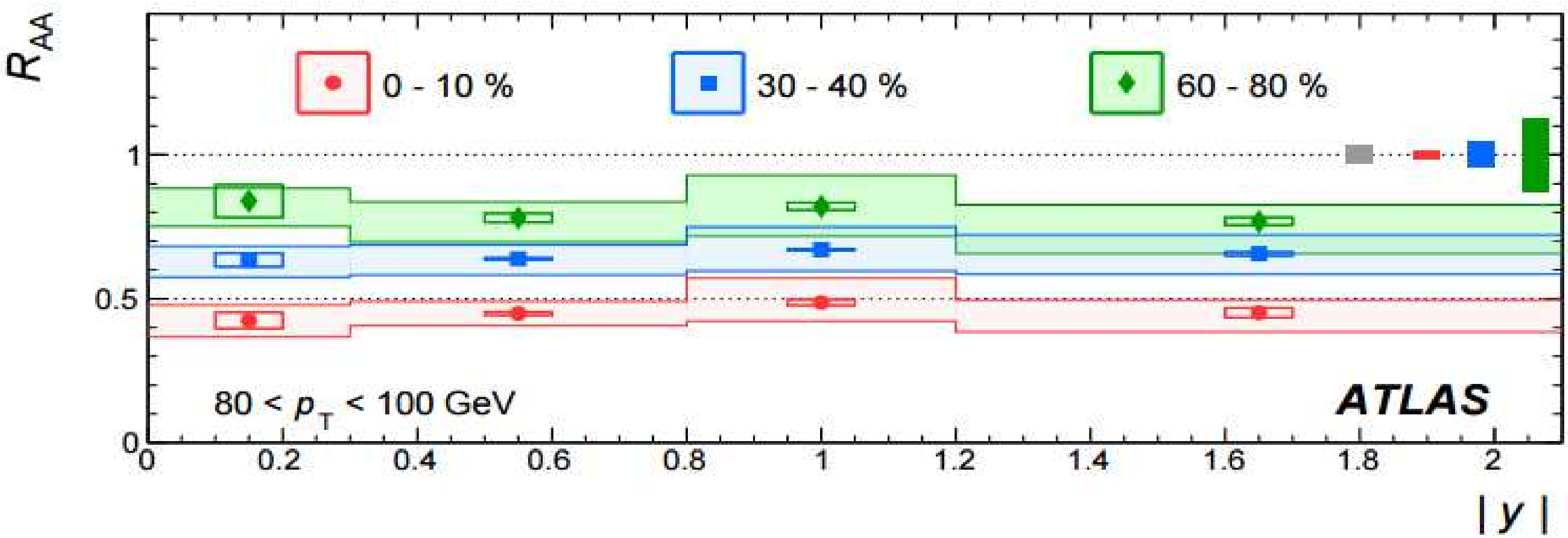
Estimated from PYTHIA 6

- **Non-negligible for both jets and hadrons!**
- Even more important for charm than for bottom at LHC energy!

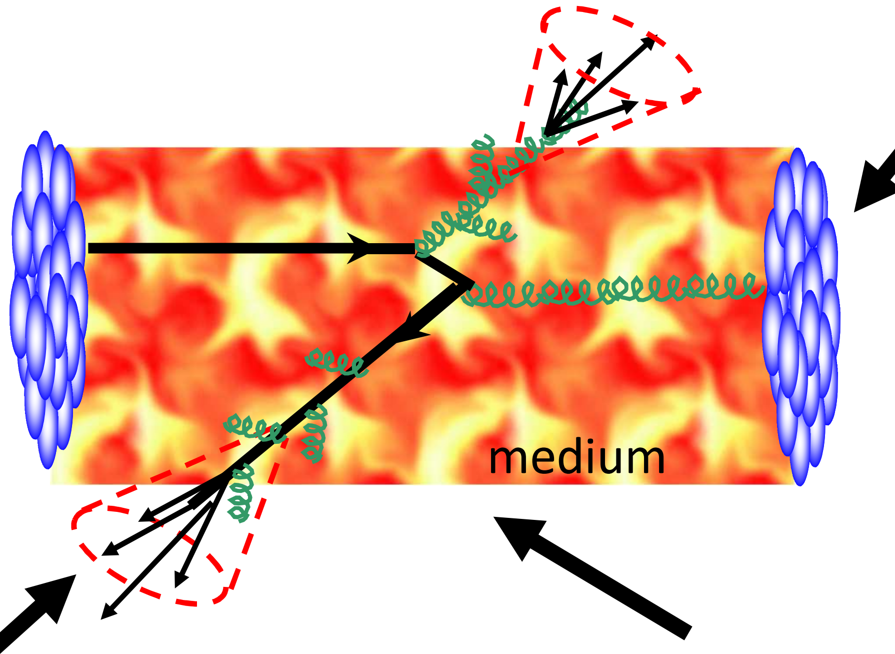
Gluon jet fraction and jet p_T spectra







Jet as a versatile probe

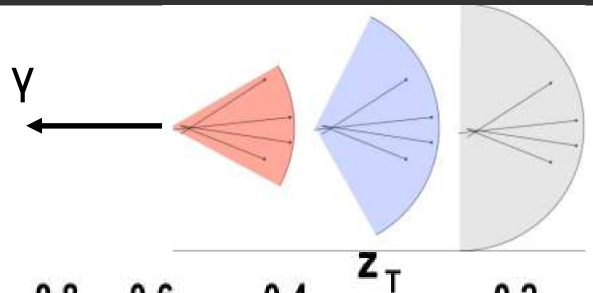


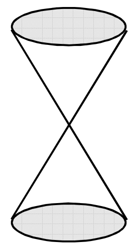
Probe the Initial State Effects: Extraction of nPDF

Probe the Final State Modification of Jets

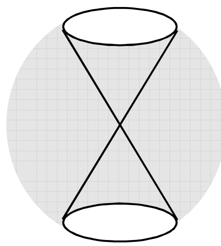
Search for medium response
Where does the quenched energy go?

Lost energy at RHIC and LHC

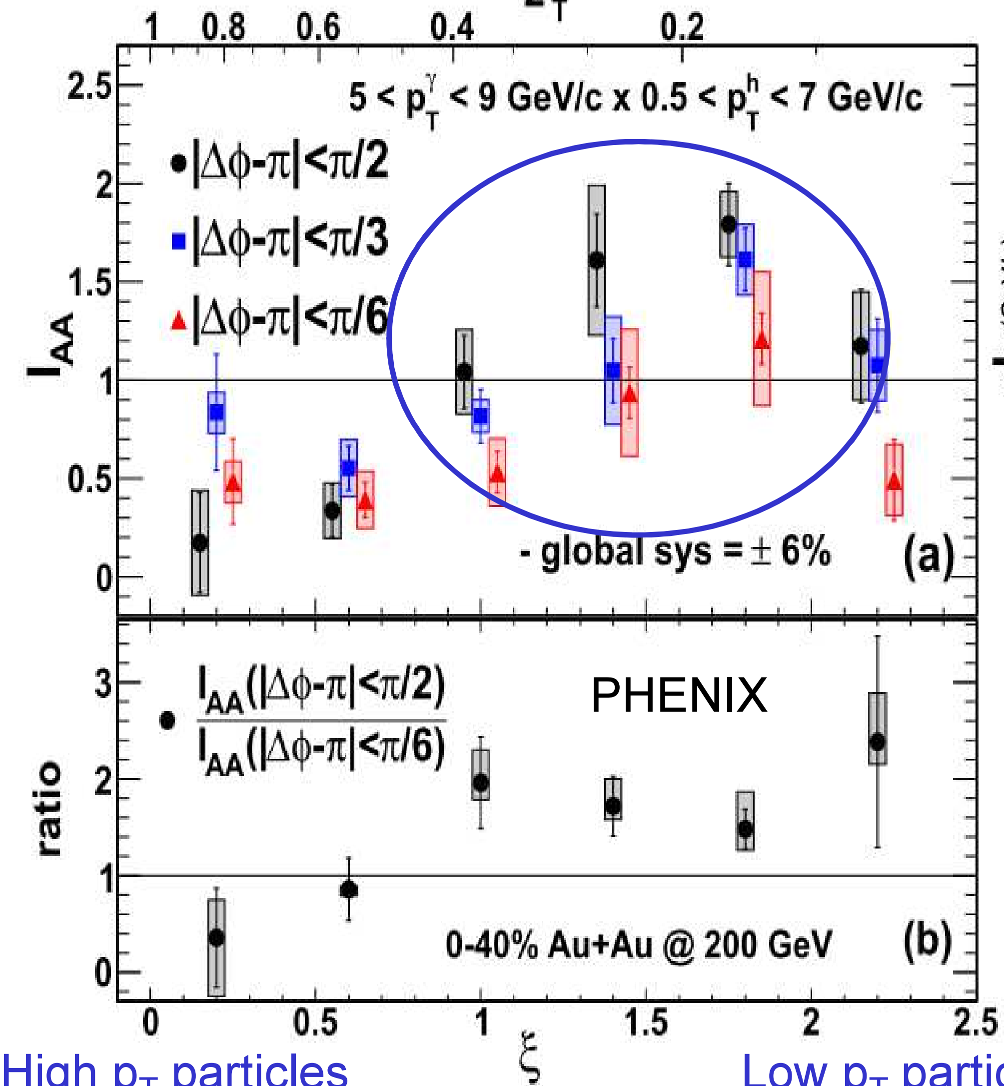


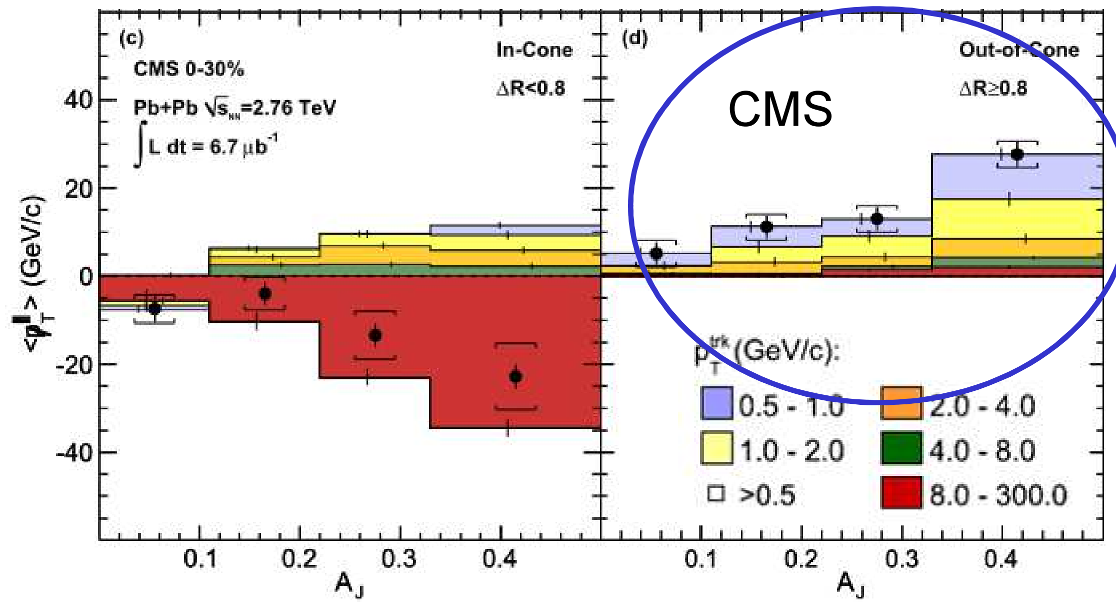


Tracks in the jet cone ΔR<0.8



Tracks out of the jet cone ΔR>0.8



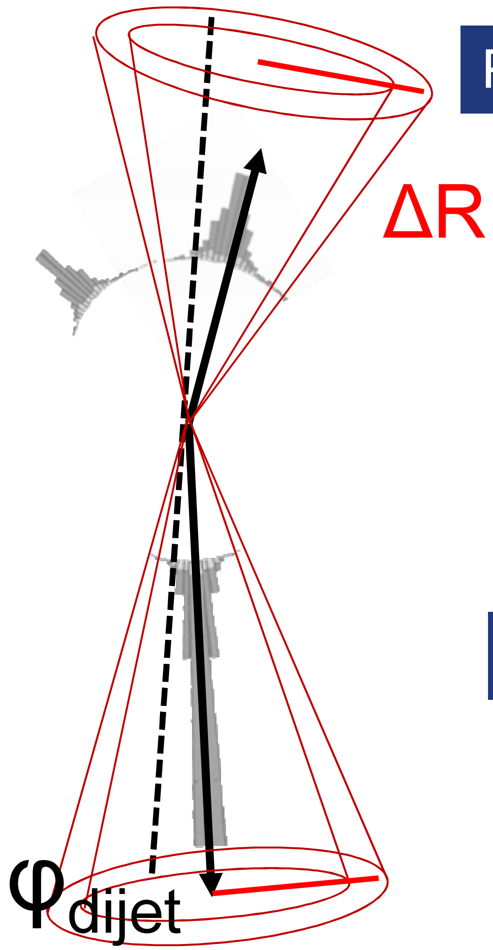


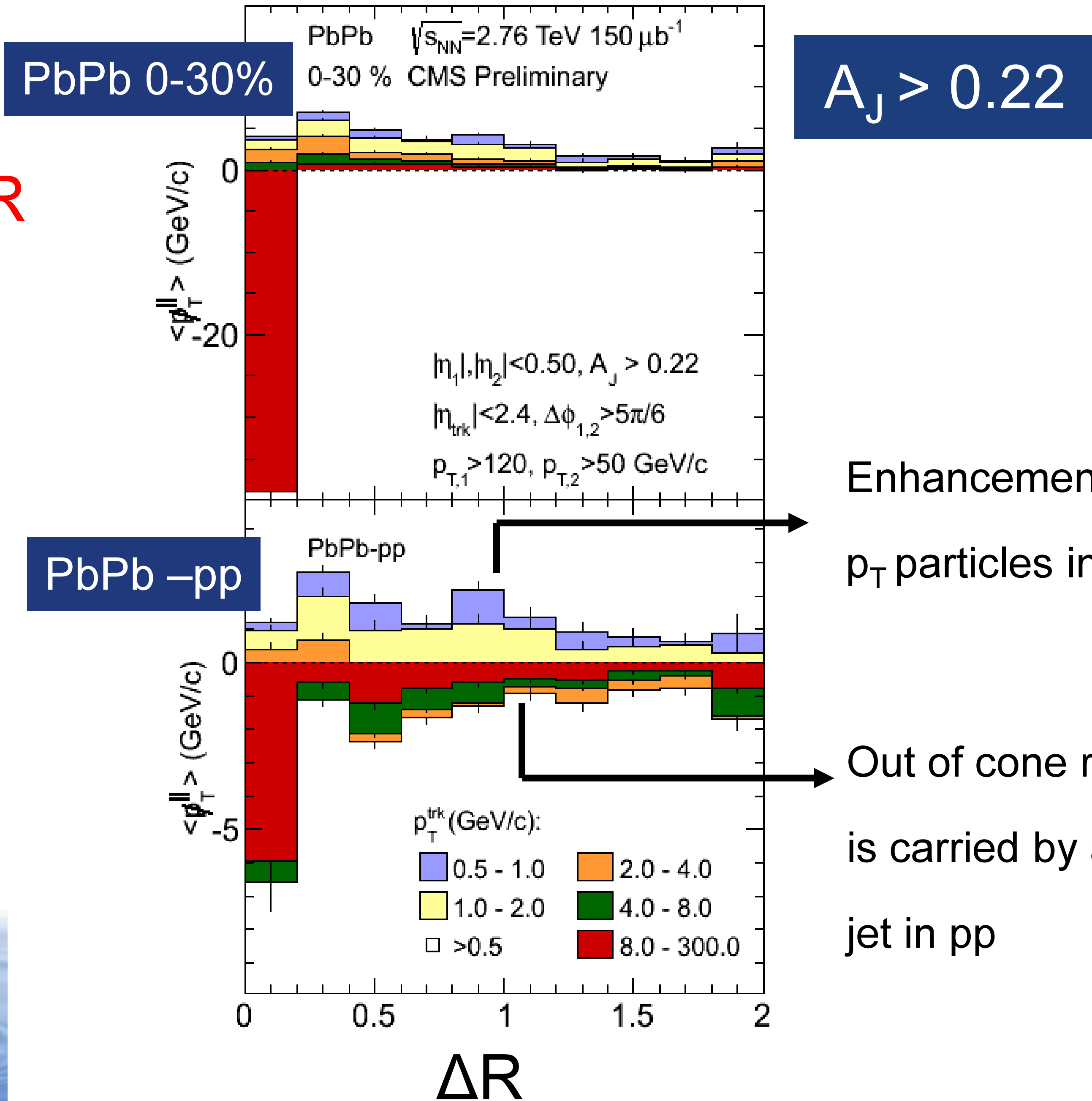
Lost energy: found in large Δφ(ΔR) with respect to the away-side jet, converted to low p_T particles.

High p_T particles

Low p_T particles

Results - Missing p_T vs. ΔR



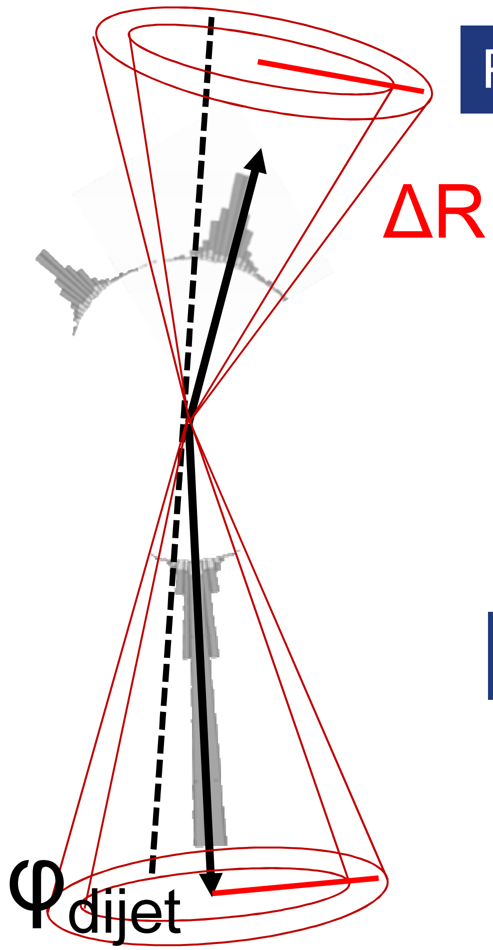


$A_J > 0.22$

Enhancement of low p_T particles in PbPb

Out of cone radiation is carried by a third jet in pp

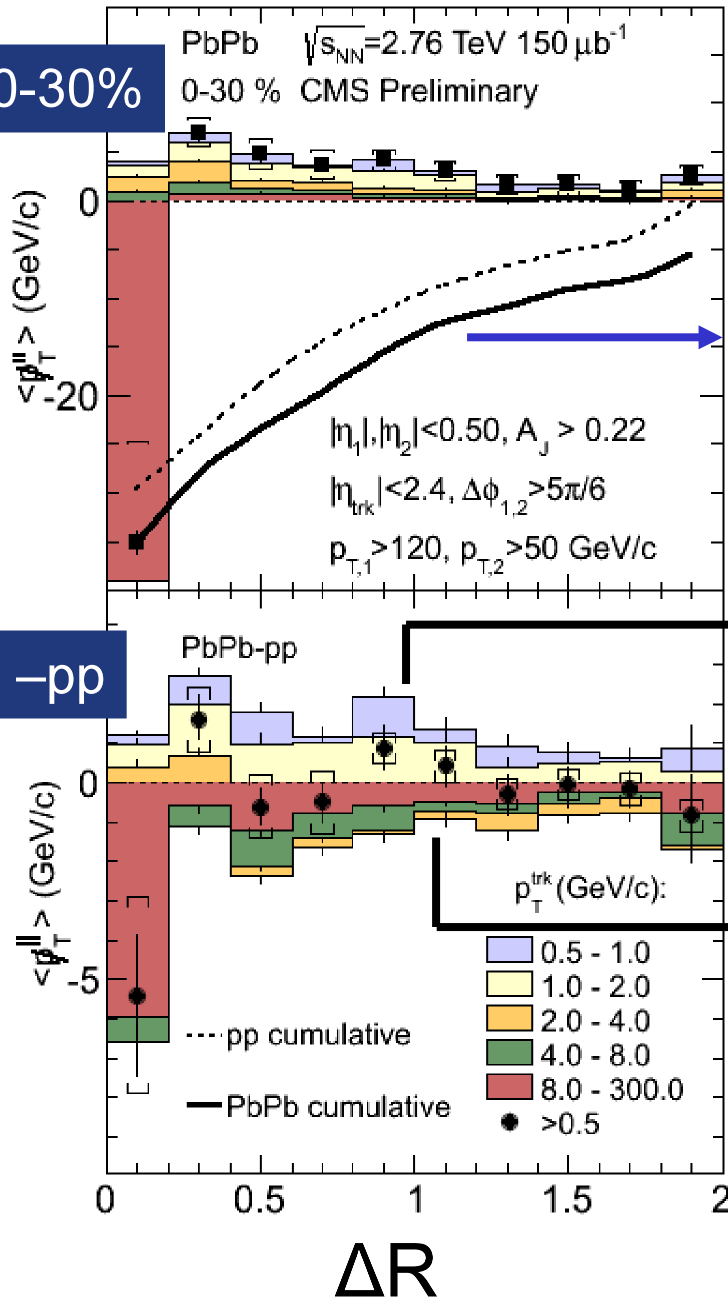
Results - Missing p_T vs. ΔR



ΔR

PbPb 0-30%

PbPb –pp



$A_J > 0.22$

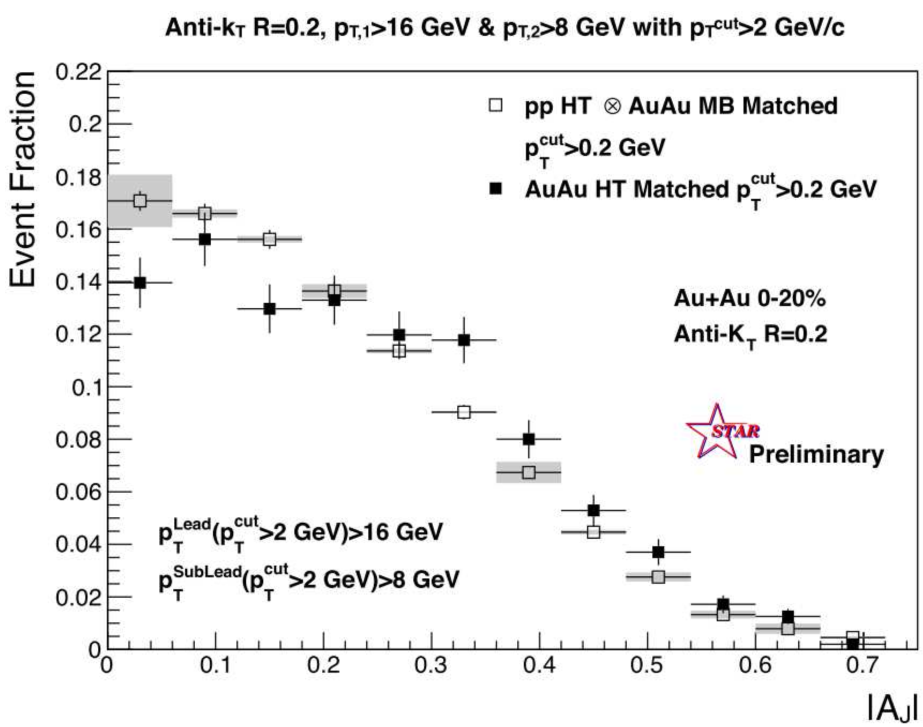
Similar shape of the balancing distribution in pp and PbPb

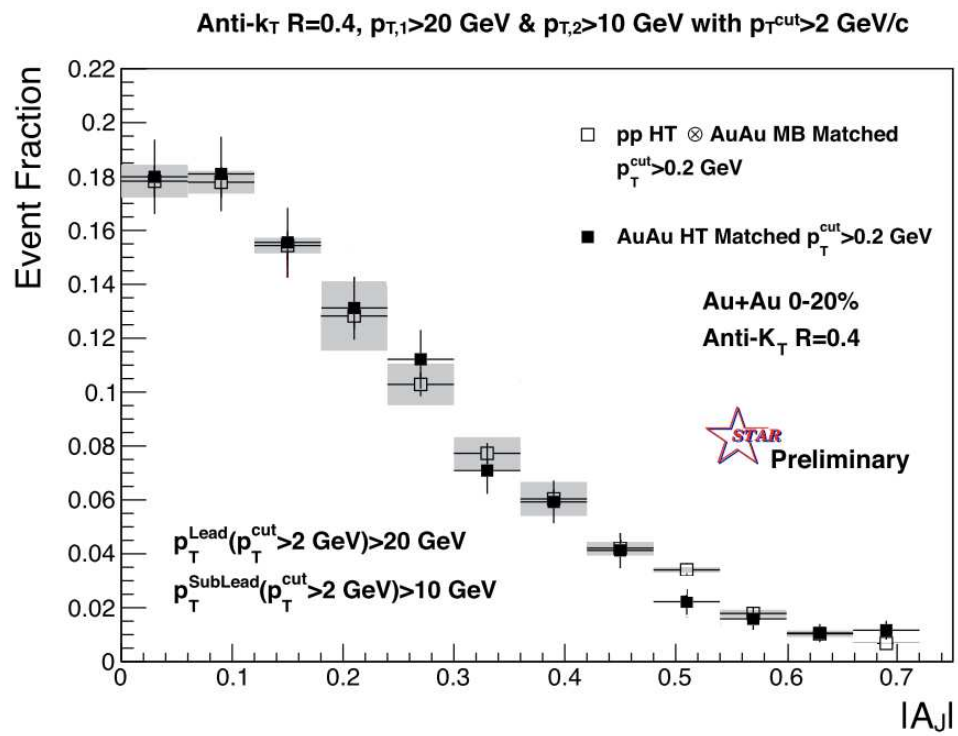
Enhancement of low p_T particles in PbPb

Out of cone radiation is carried by a third jet in pp

Lost energy at RHIC from dijet asymmetry

R=0.2 cone → R=0.4 cone

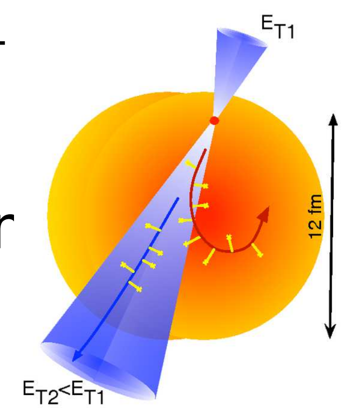




Dijet transverse momentum balance is recovered with anti-k$_T$ R=0.4 jet reconstruction in 0-20% AuAu collisions!

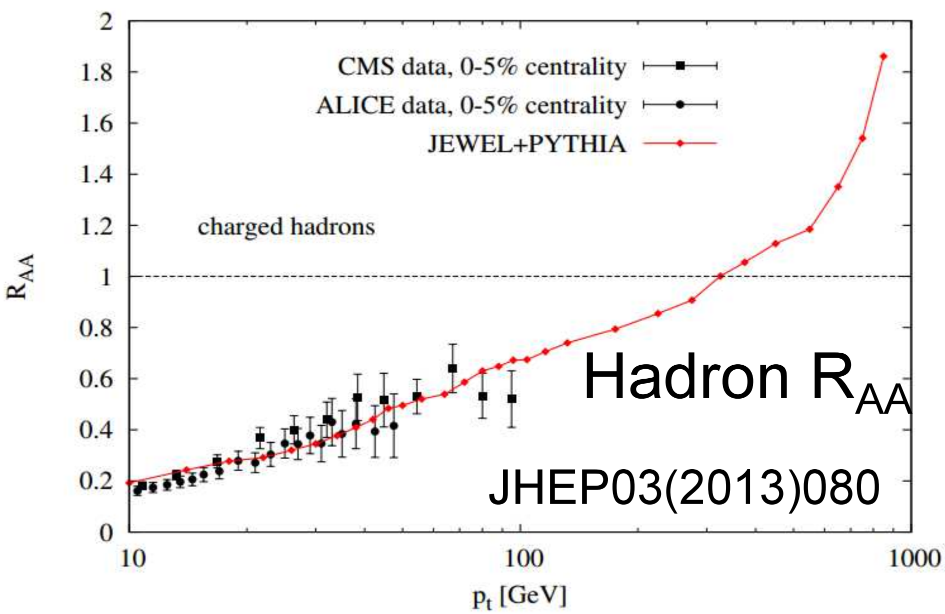
Selection on the hard fragmenting jet may bias the productior vertex of the jets toward the surface of the medium

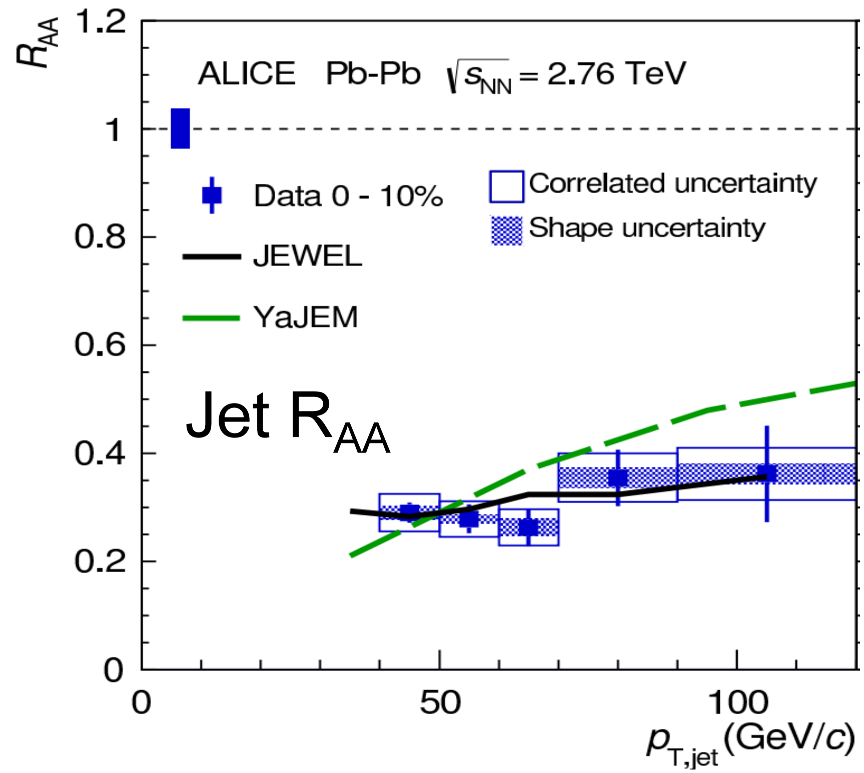
→ interesting to see what we get when implementing similar bias at the LHC

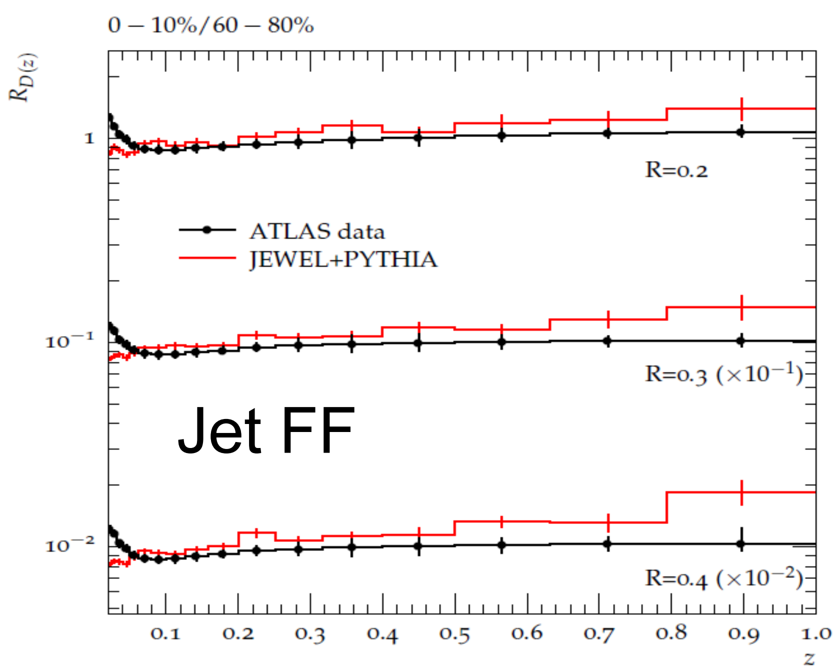


sPHENIX upgrades to look at fully reconstructed jets at RHIC

Jet data vs. JEWEL and YaJEM



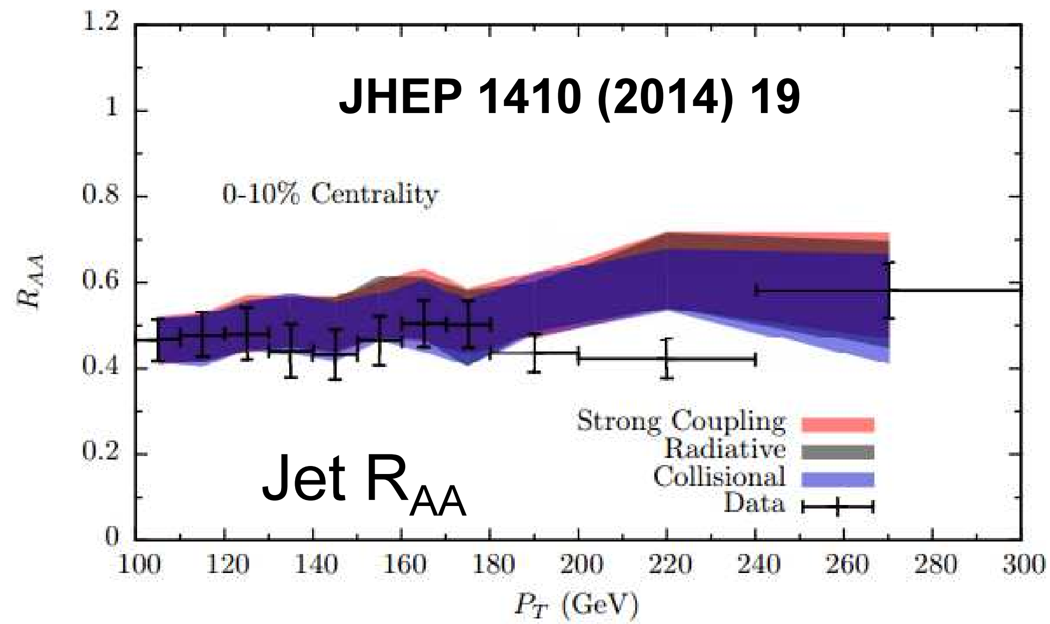


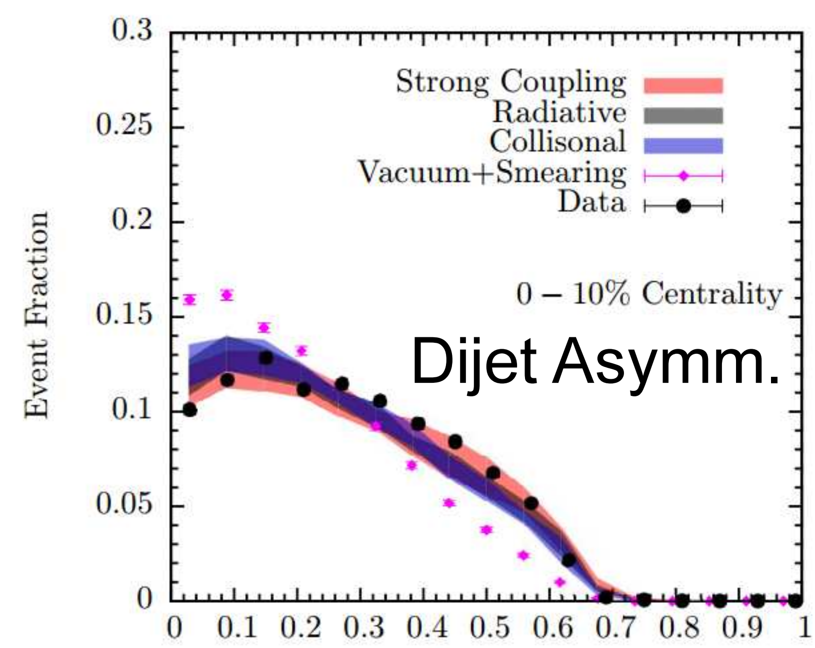


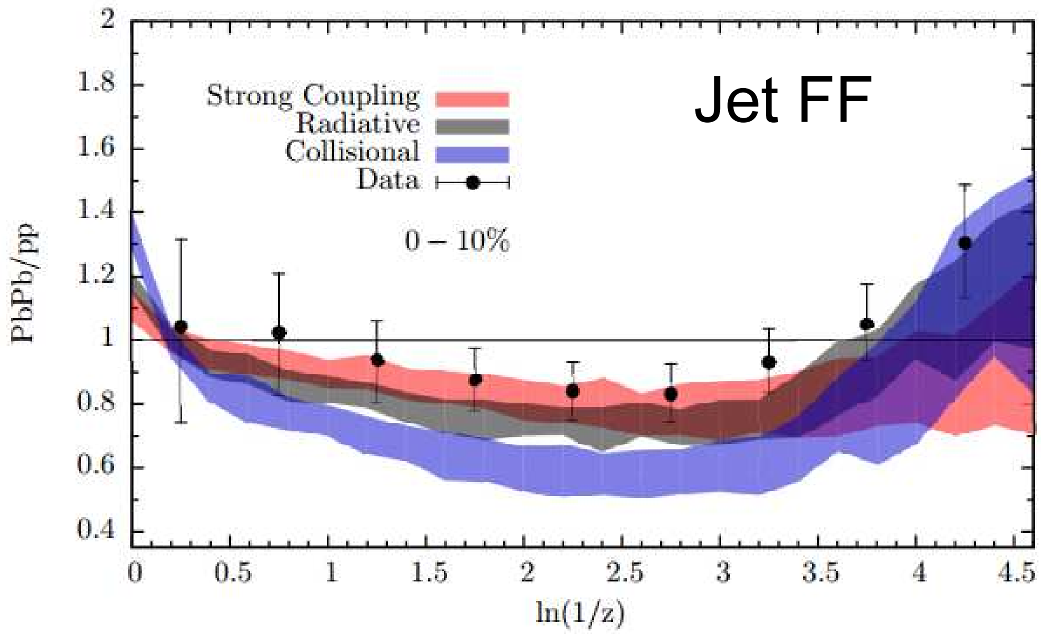
Jet Quenching Monte Carlo based on weak coupling approach:

Reasonable description of jet FF, jet R_{AA} and charged hadron R_{AA}

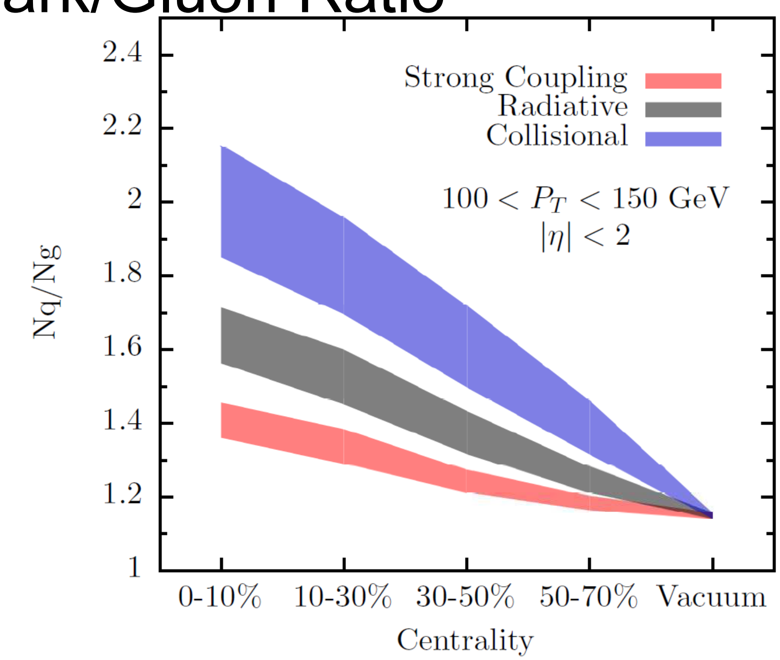
Description of the jet data with strong coupling approach







Quark/Gluon Ratio



Summary

- Before extracting medium properties with jet data:
  - We are at the stage of testing our theoretical understanding of jet production and modification
- Jet data in pA and dA collisions
  - Constraint nPDF, reveal "PDF fluctuation"
- Jet data in AA:
  - Quenched jet energy goes out of the jet cone
  - Enhancement of soft particle inside the jet cone
  - LHC: The radiated energy goes far away from the jet axis
  - RHIC: R=0.4 can recover the lost energy if hard fragmenting jet selection is applied
  - Mild or no sign of flavor dependence of parton energy loss at high p_T.
- Quenched jet Monte Carlo:
  - Allow detailed comparisons between data and models
  - Both weak and strong coupling approaches describe the data … (!)
  - Study of exclusive processes and jet substructure may help to separate models