Jets at the LHC:
Where does the lost energy go?

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3rd Workshop on Jet Modification in the RHIC and LHC Era

Wayne State University, Detroit, USA

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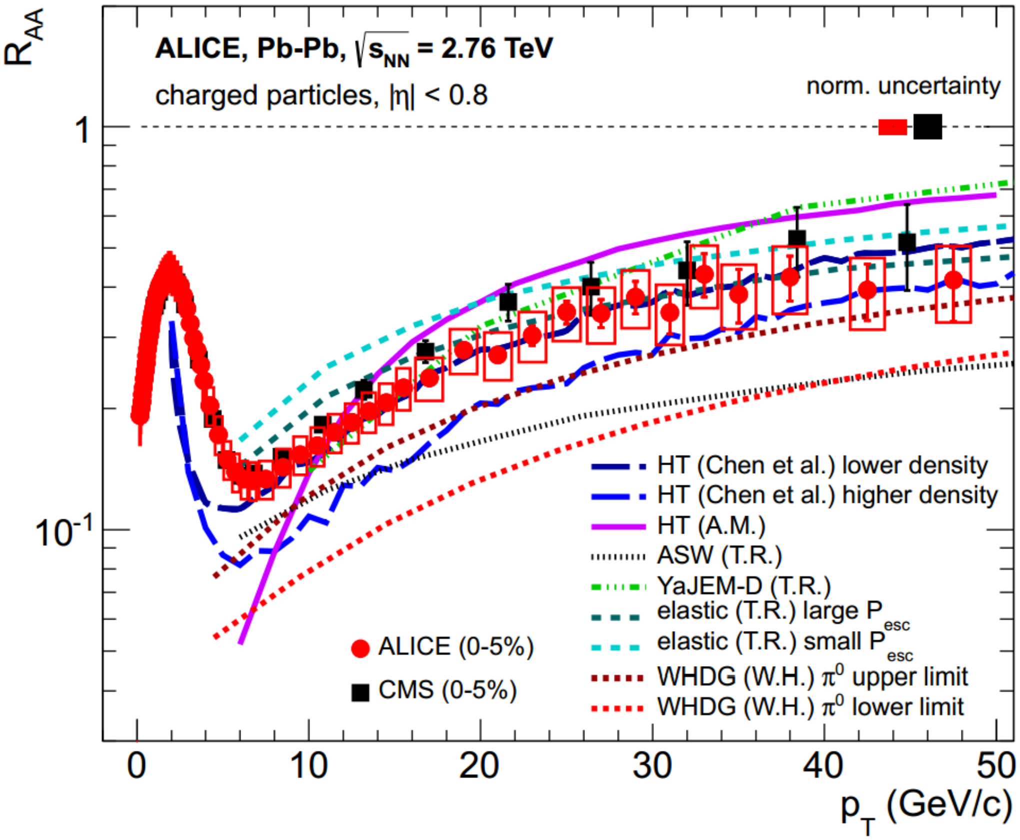
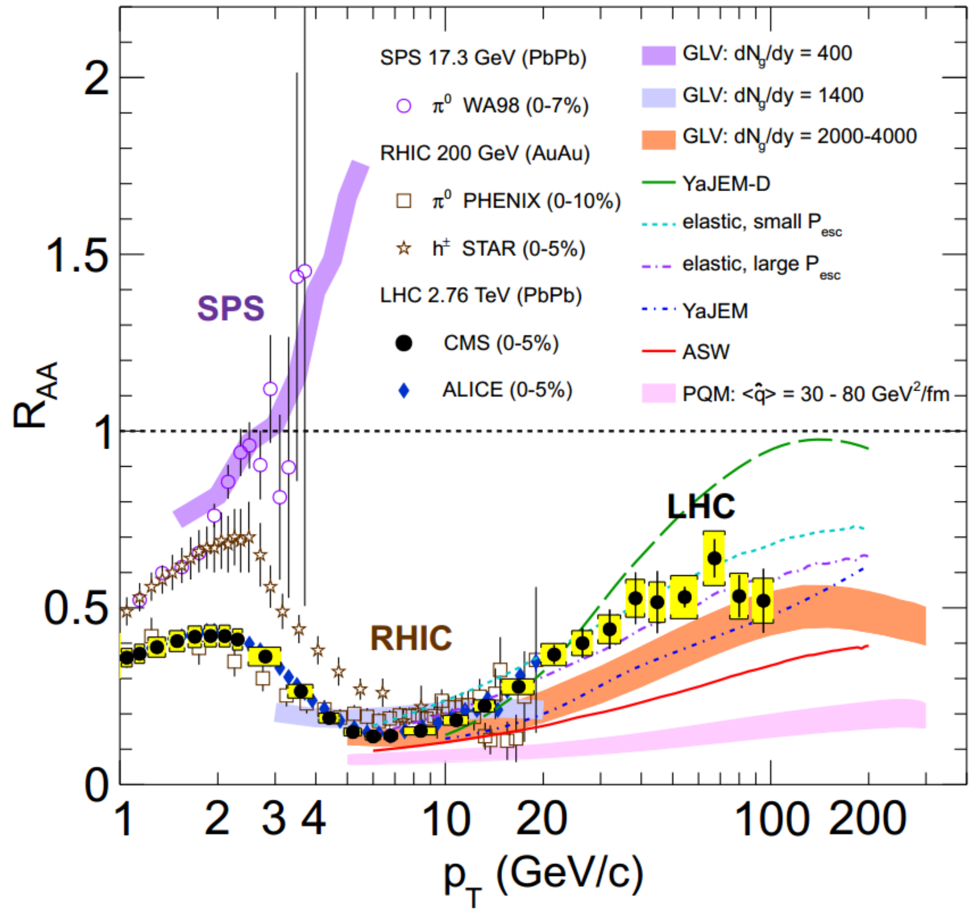
High p_T charged particles





Suppression of high p_T particles in AA collisions

Why do we study jet quenching with jets?

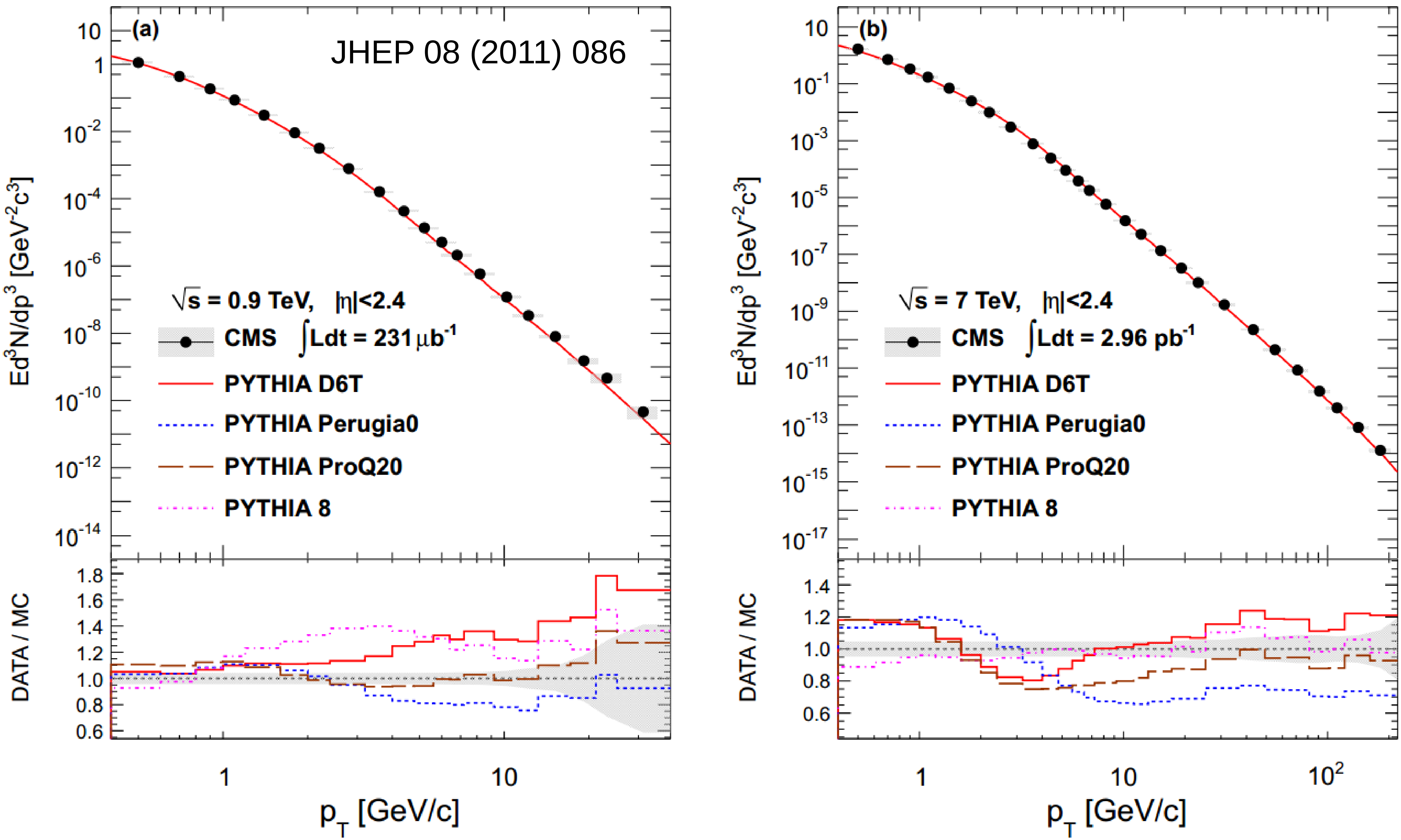
- Theoretically calculable,
  infra-red/collinear safe

- Allow the use of a well defined object (by algorithm) to study "the final parton energy" and how the energy is distributed with respect to the direction of the out-going parton

http://www.digitalpicturezone.com/digital-pictures/30-colorful-examples-of-high-speed-bullet-photography/

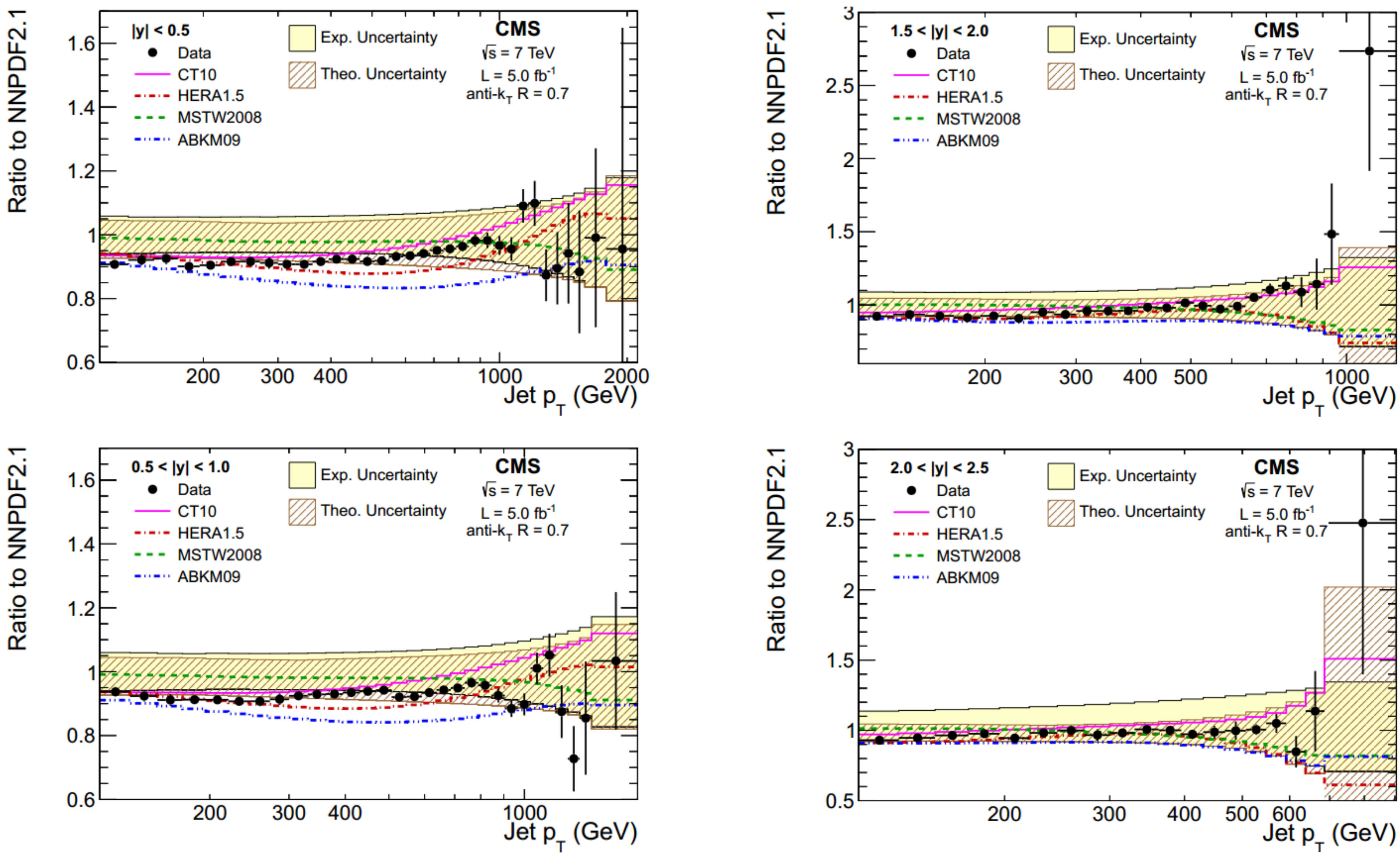
- Allow us to select quenched jets (i.e., jets from partons which have lost a lot of energy when passing through the medium)

Charged particle spectra in pp



Charged particle spectra in pp and PYTHIA agree within 20-60%

Jet spectra in pp

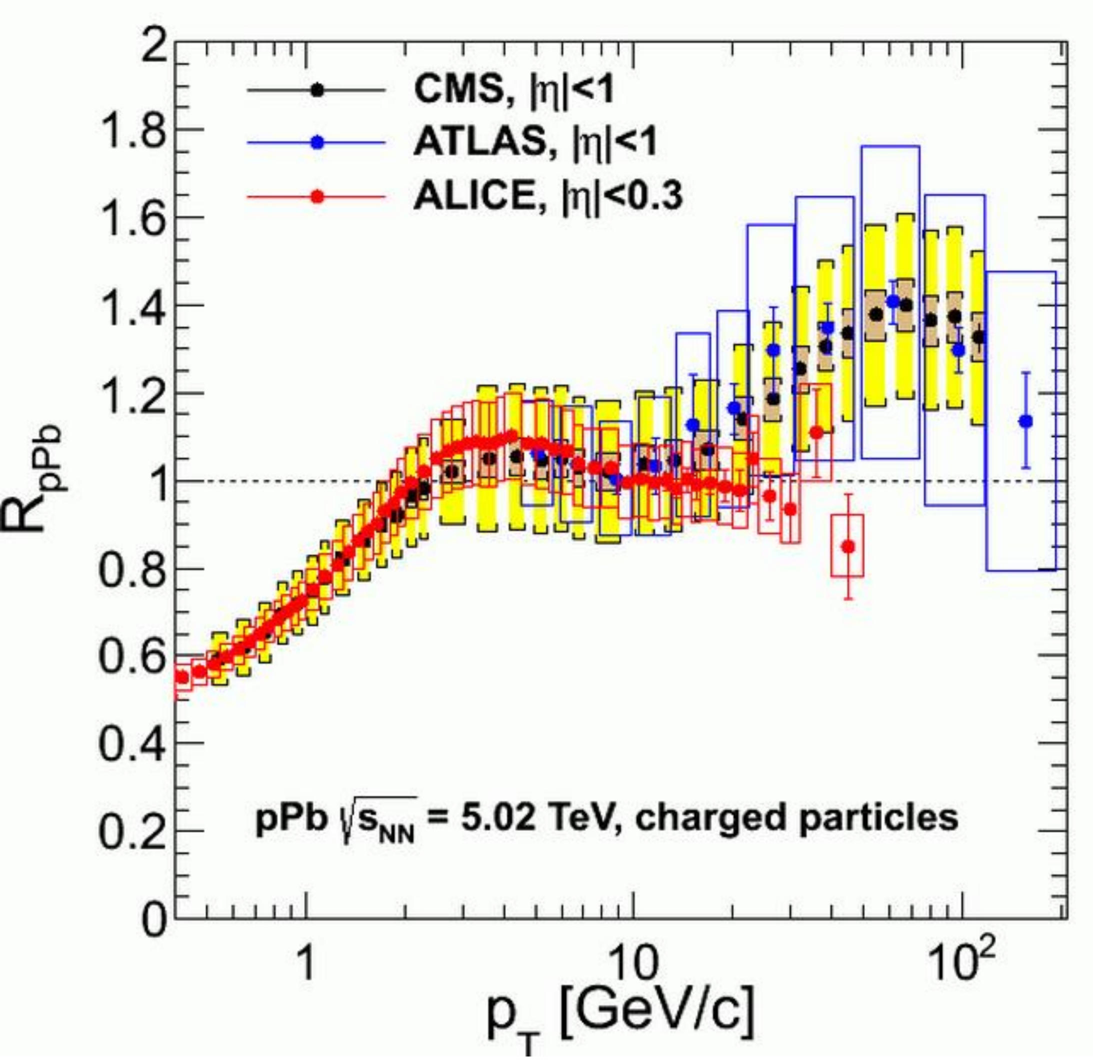


Where does the lost energy go?

- Reconstructed jet analysis
  - Jet spectra / R_{AA}
  - Dijet / photon-jet asymmetry
- Energy redistribution inside the jet cone:
  - Jet FF and jet shape
- Energy distribution out of the jet cone
  - Missing p_T measurements

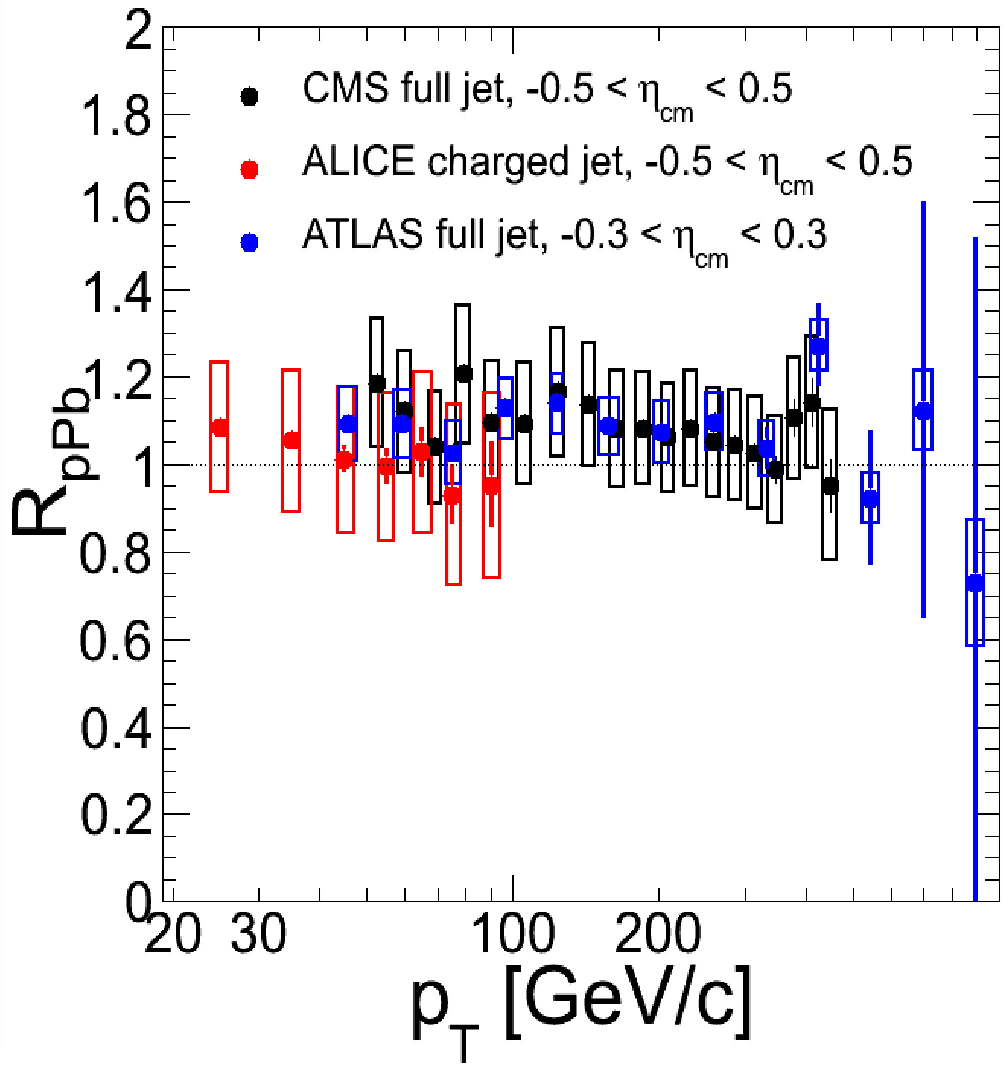
Charged particle and jet R_{pPb} (QM2014)

Charged particle R_{pPb}



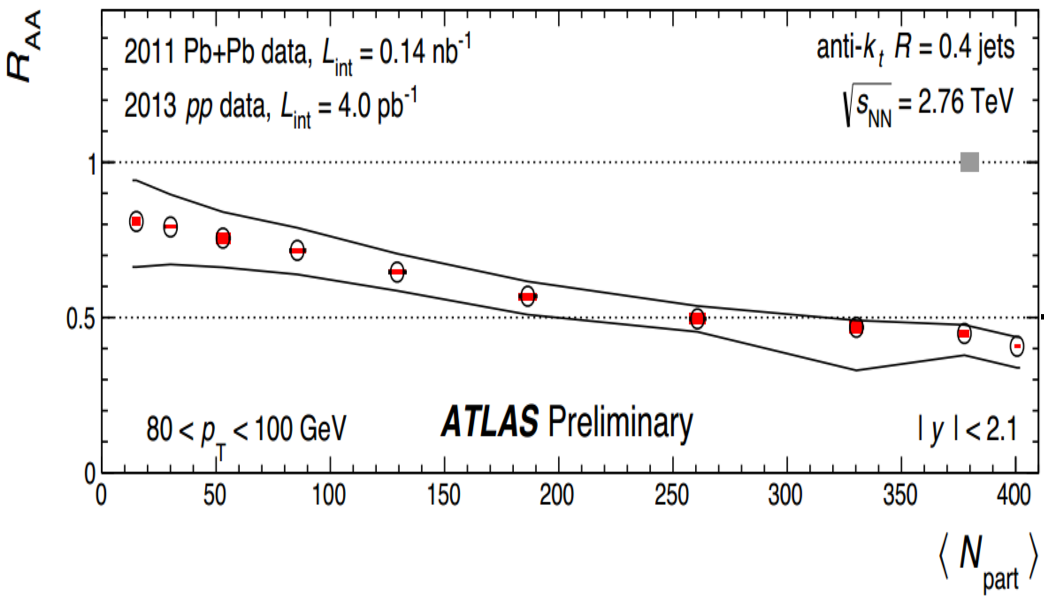
Need to check jet fragmentation function

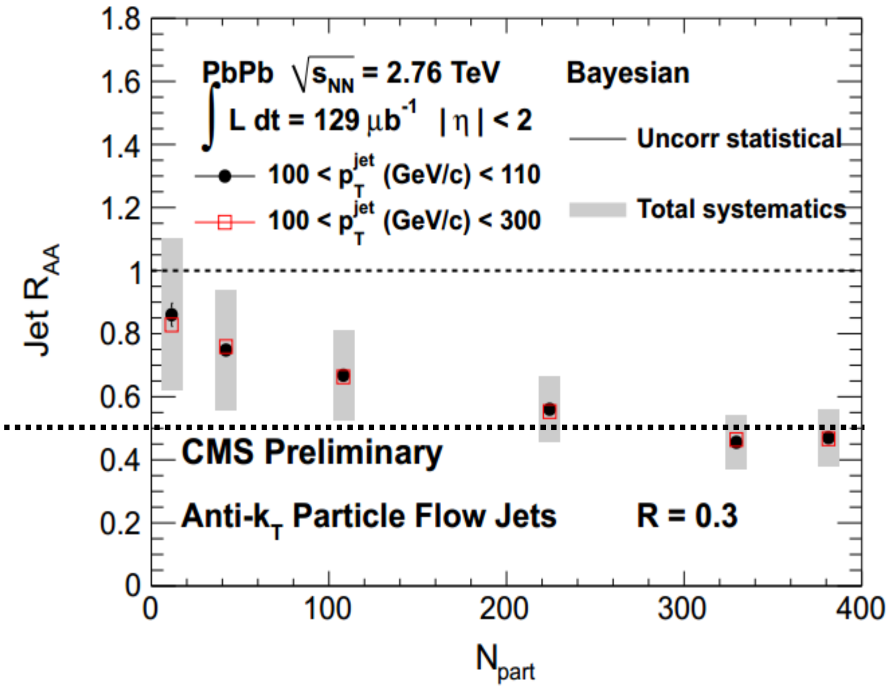
(Charged) Jet R_{pPb}



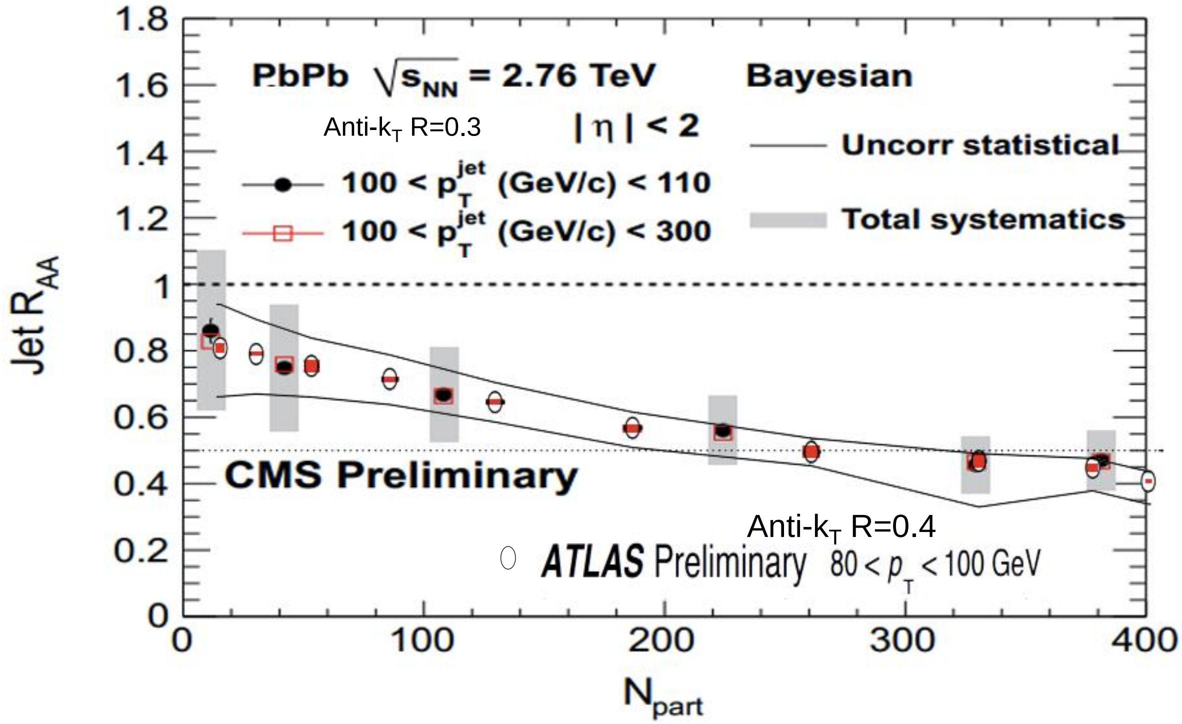
Jet spectra seem to be under control

Preliminary ATLAS and CMS R_{AA}

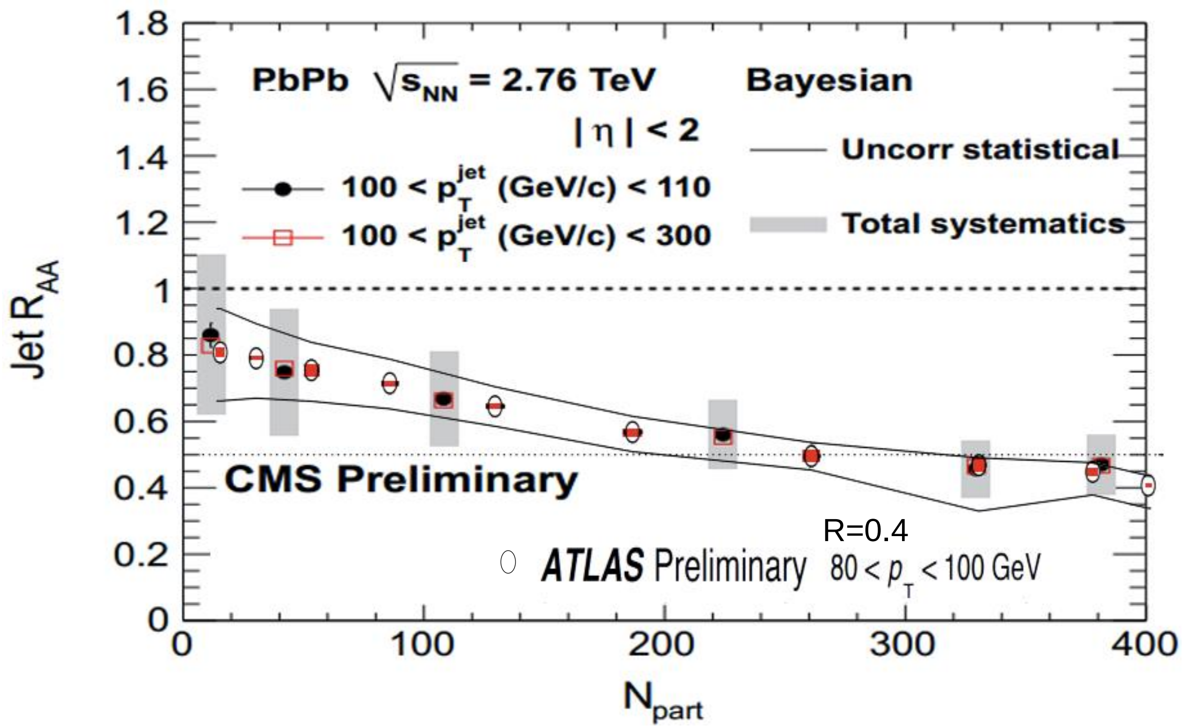


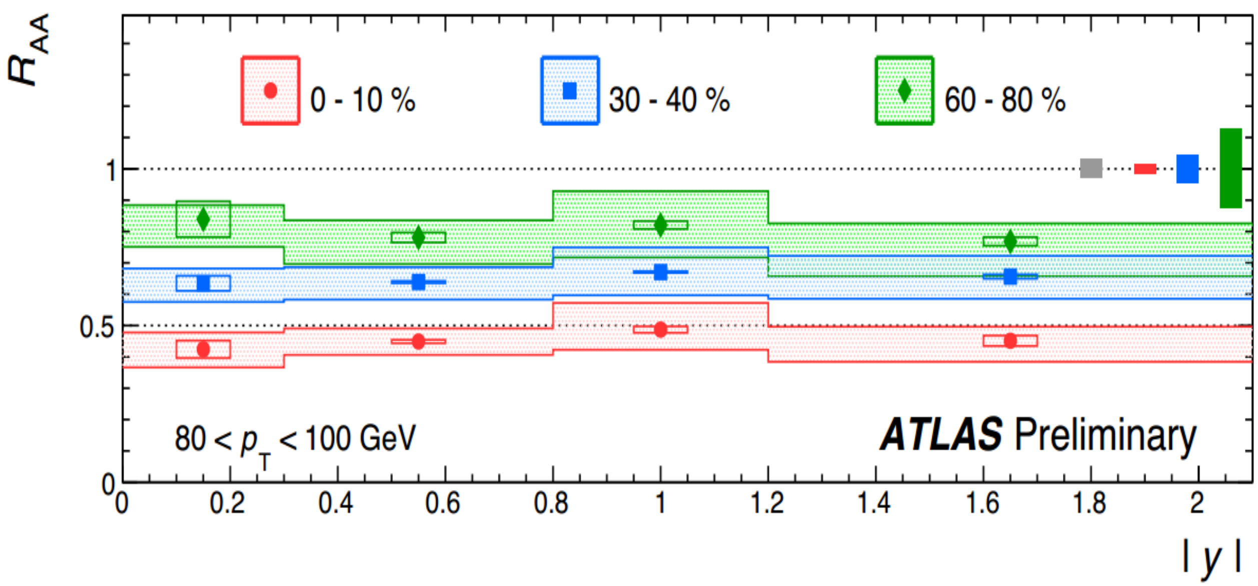


Preliminary ATLAS and CMS R_{AA}



Preliminary ATLAS and CMS R_{AA}



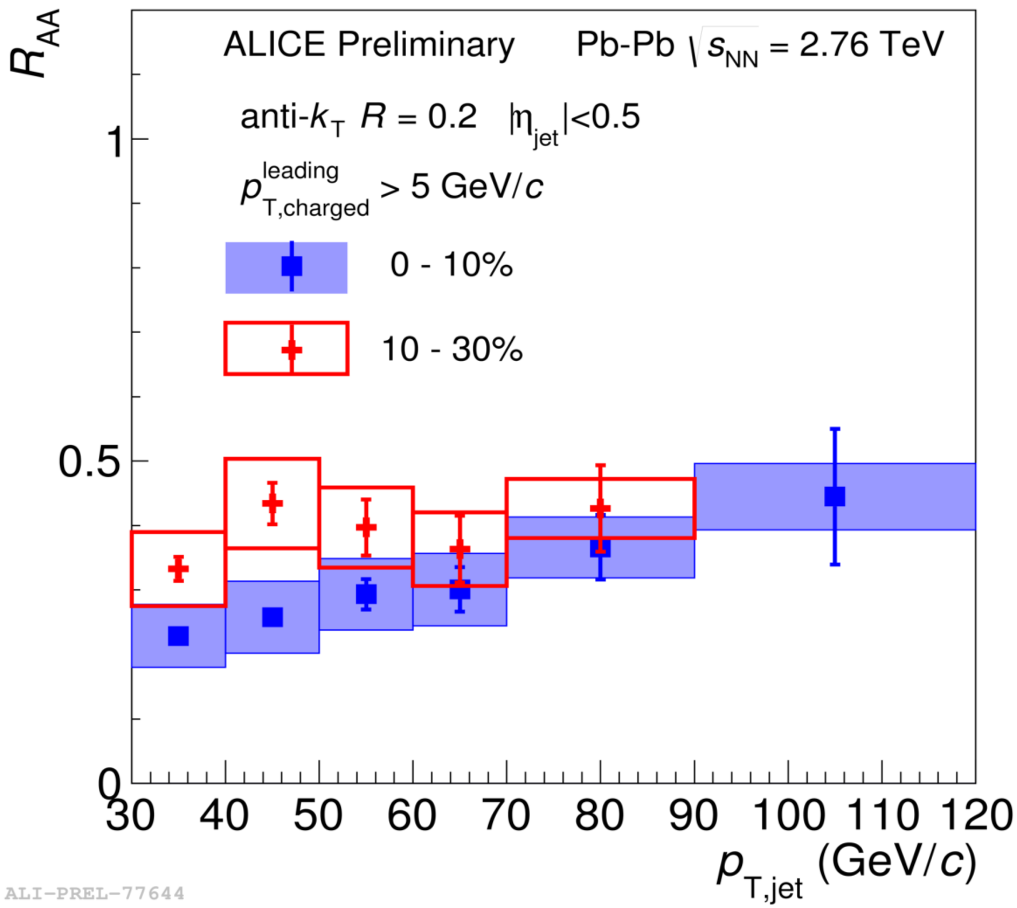


Weak dependence on jet rapidity

Quark/gluon fraction (as well as the slope of the jet pT spectra) changes v.s. y

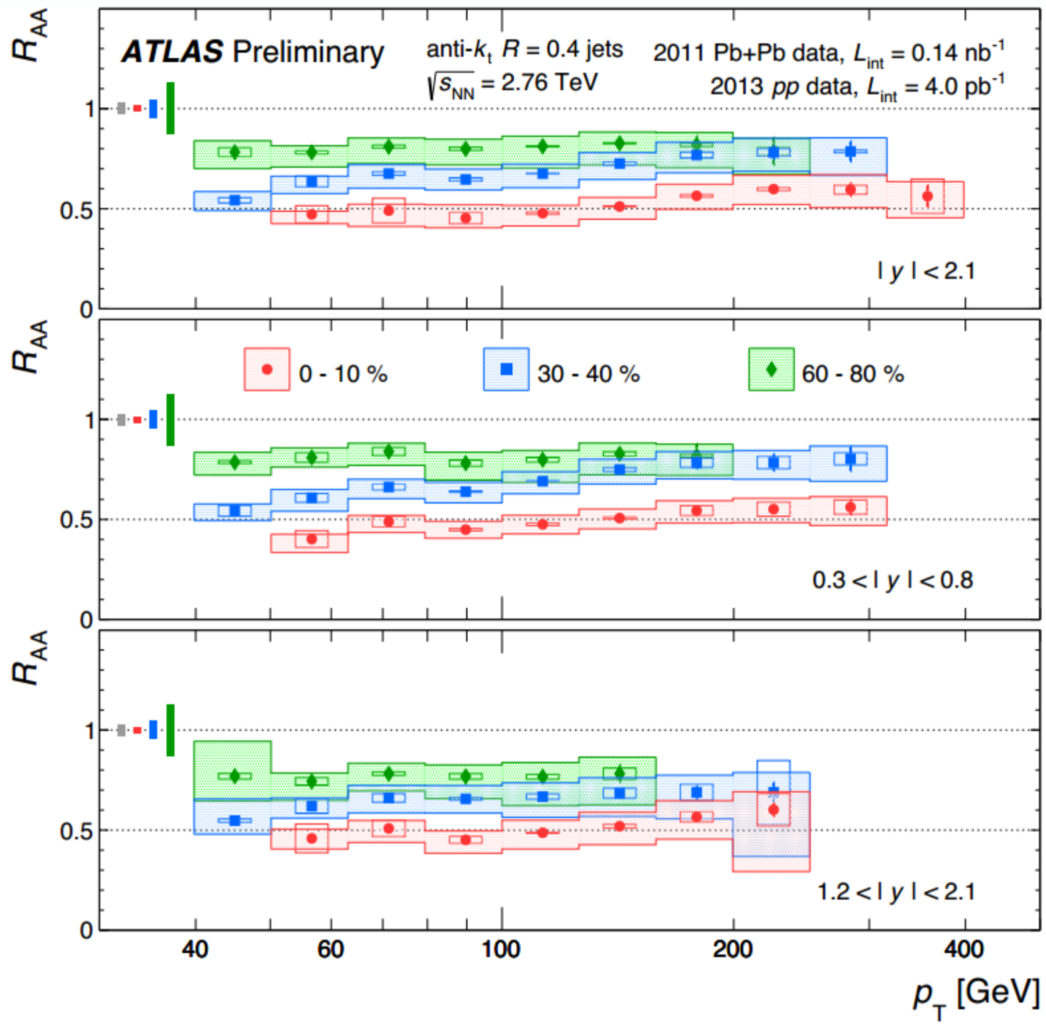
Preliminary Jet R_{AA} at LHC

ALICE new result 10-30%



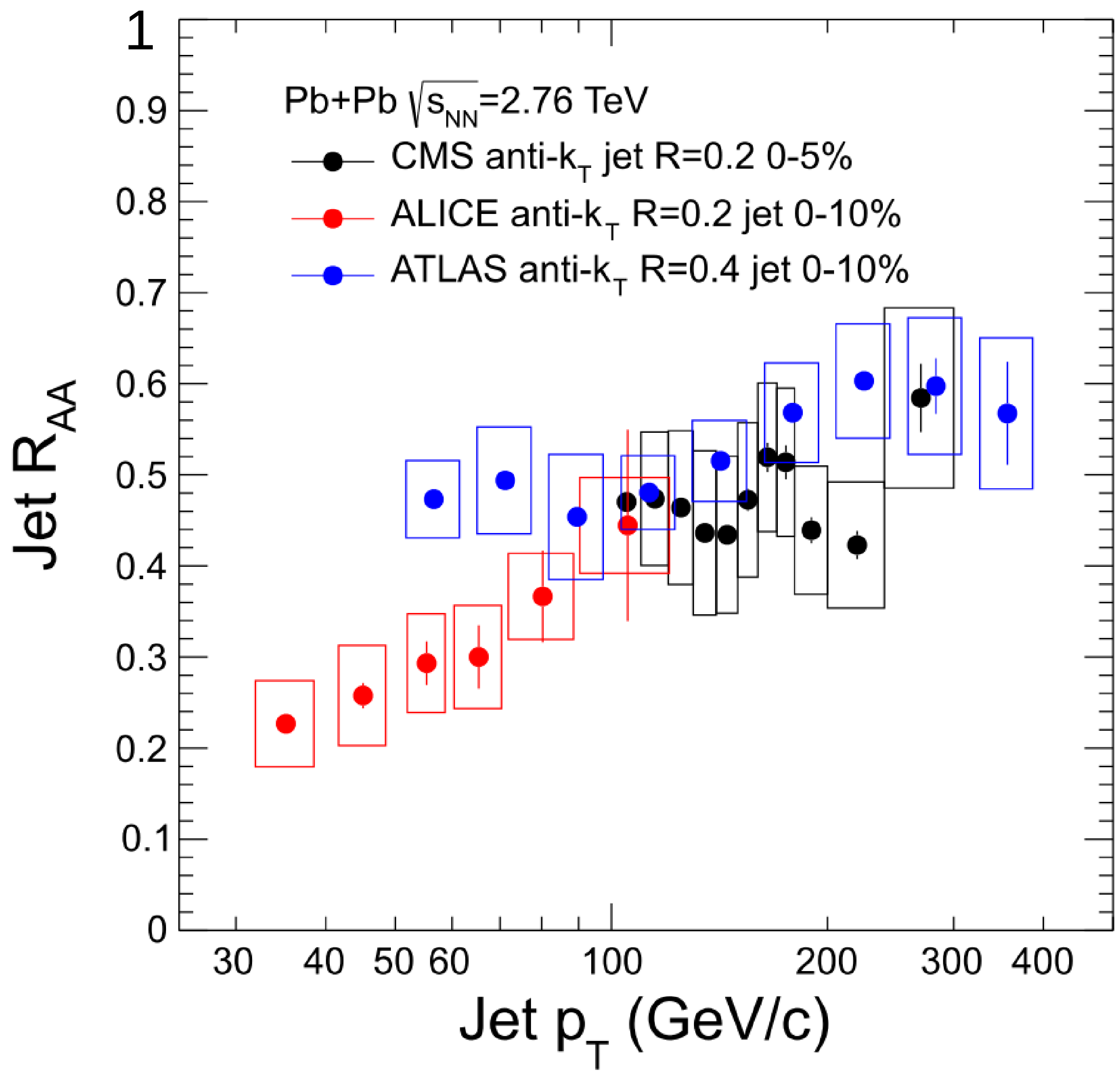
R_{AA} raises as a function of jet p_T

ATLAS new results on jet R_{AA}



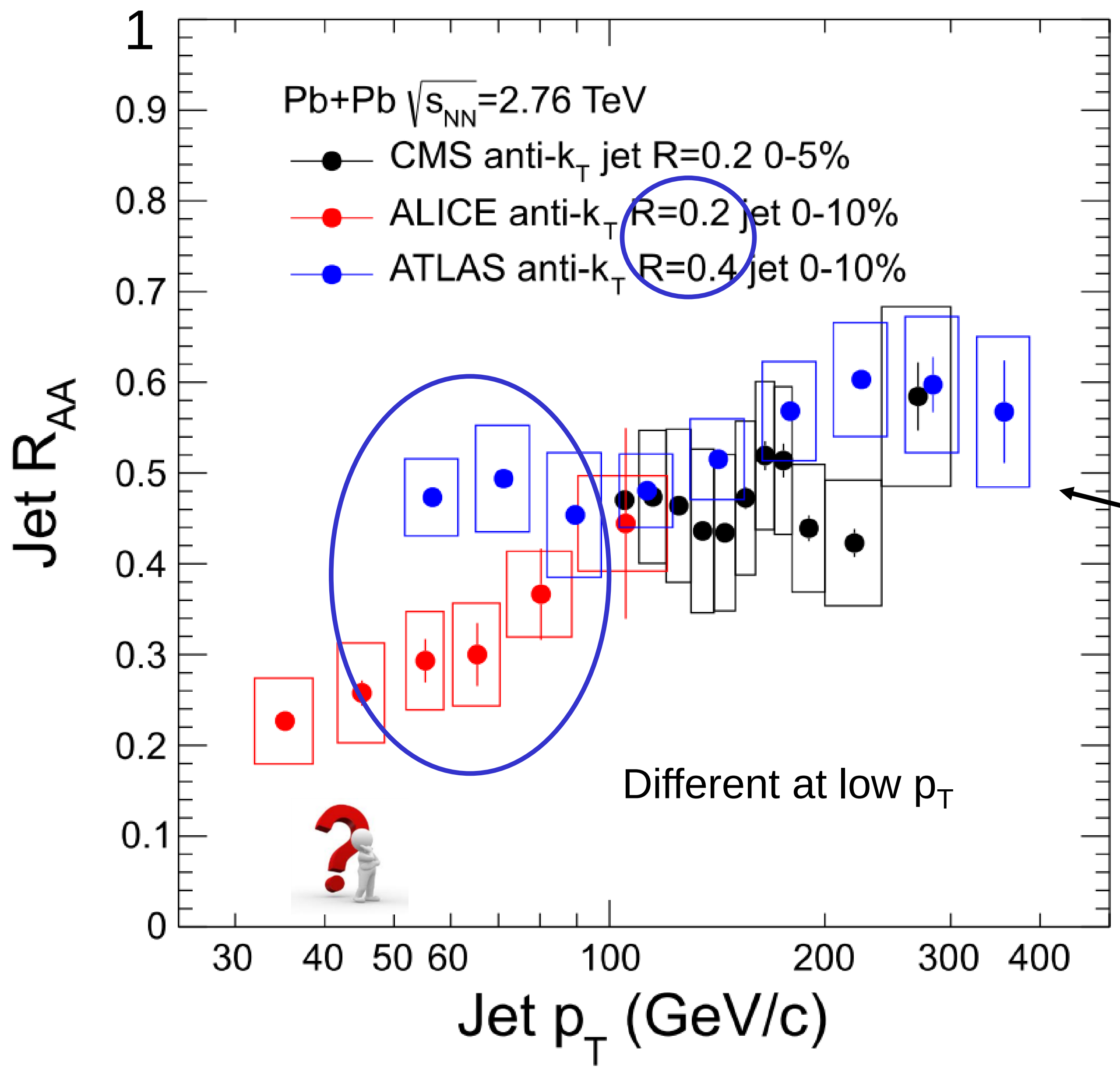
R_{AA} v.s p_T & y

Jet R_{AA} in PbPb collisions at LHC



Establish a rising trend from low to high jet p_T

Jet R_{AA} in PbPb collisions at LHC

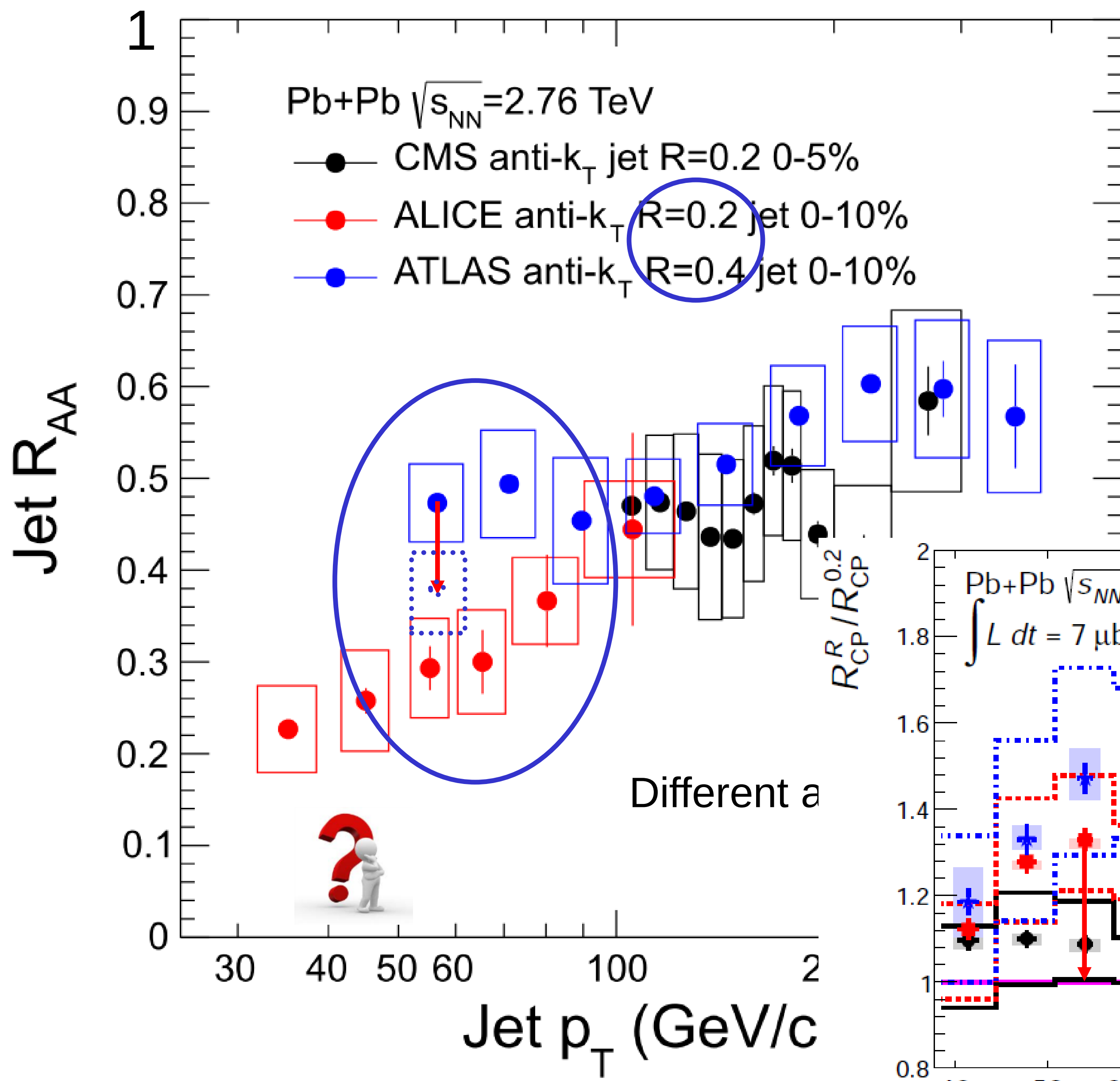


~ Agreement between CMS and ATLAS at high jet p_T

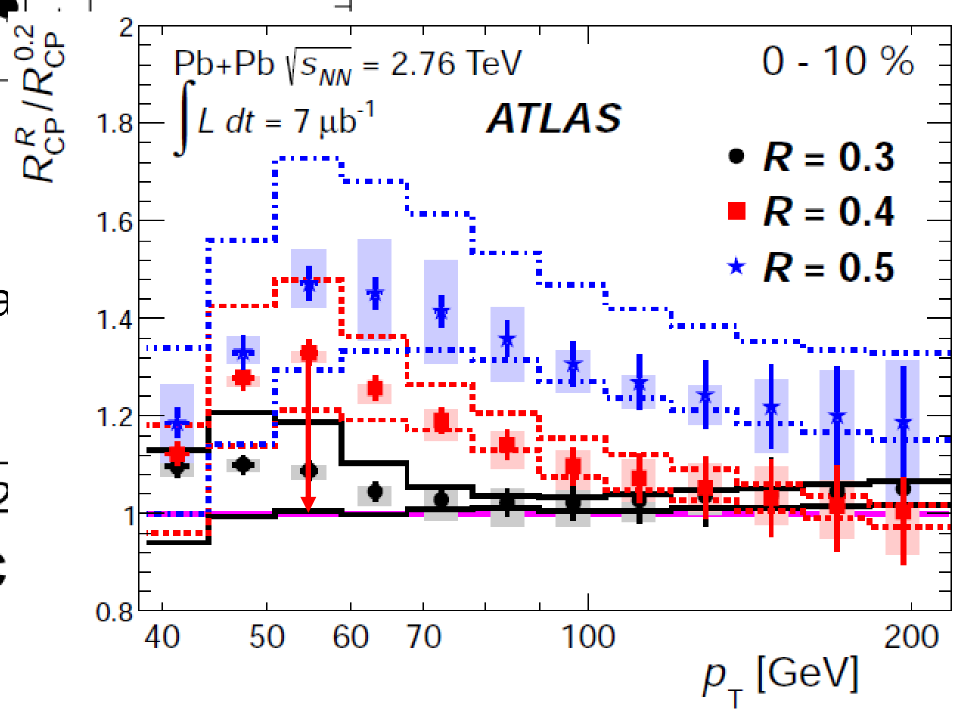
Agree with charged particle R_{AA} at high p_T

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

Jet R_{AA} in PbPb collisions at LHC



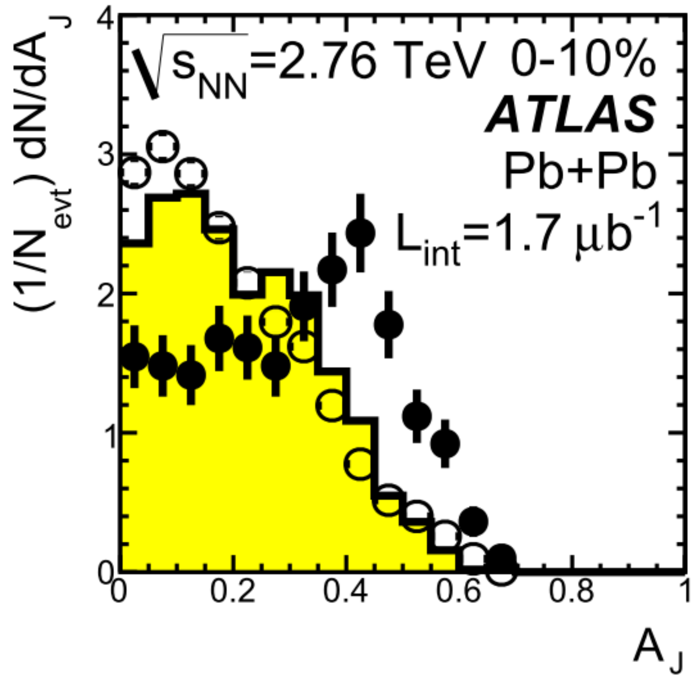
ATLAS R_{CP} ratio
PLB 719 (2013) 220-241

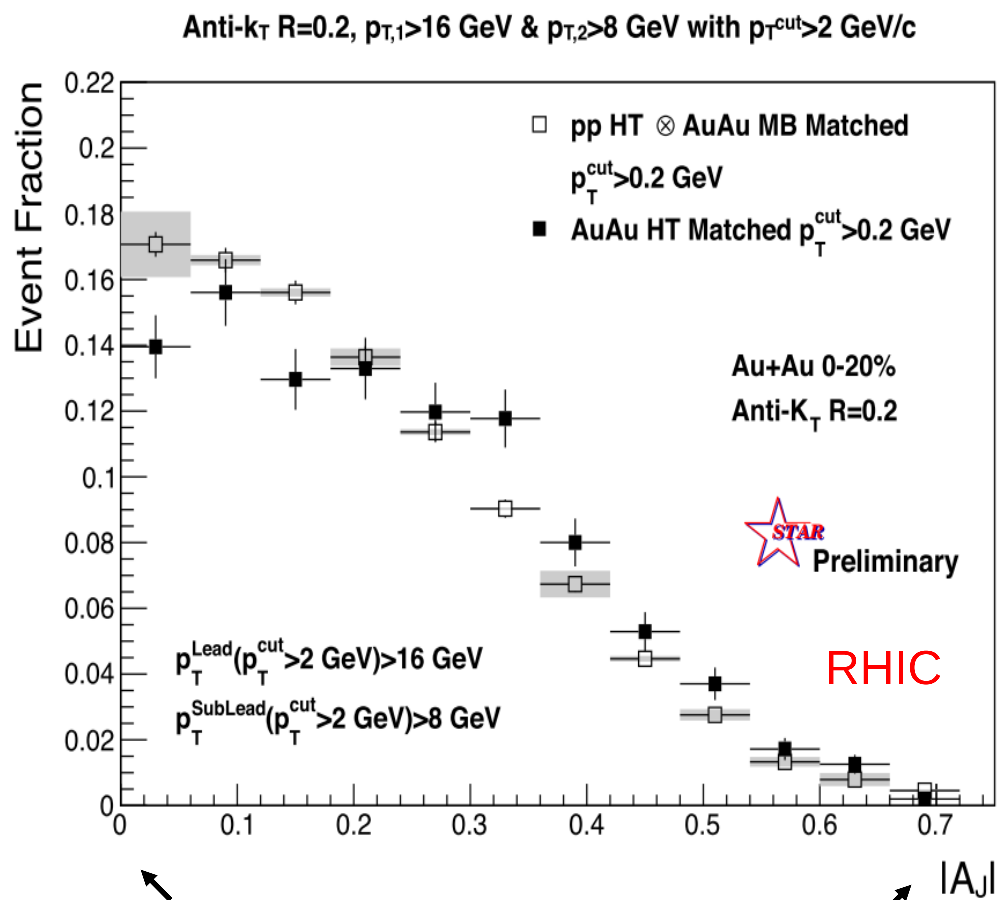


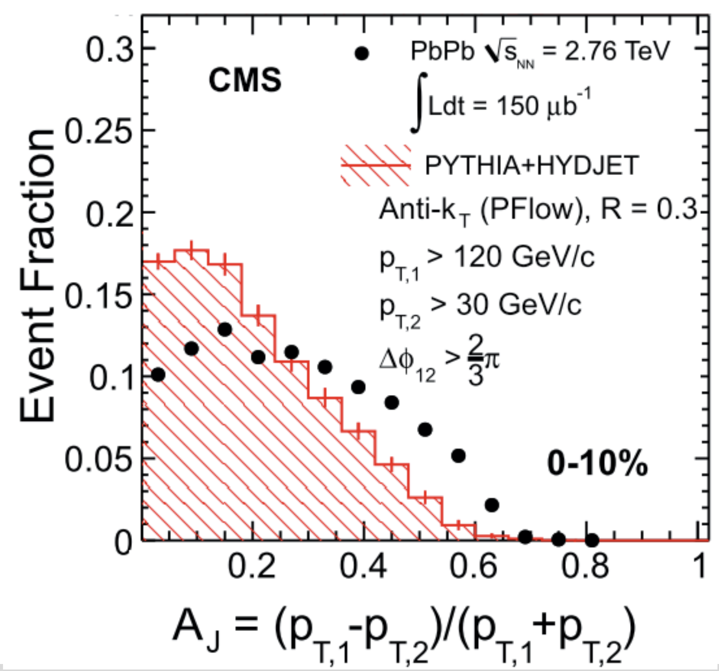
It would be nice to have low p_T CMS data / ATLAS

Dijet asymmetry A_J in RHIC and LHC

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

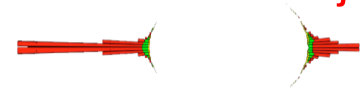




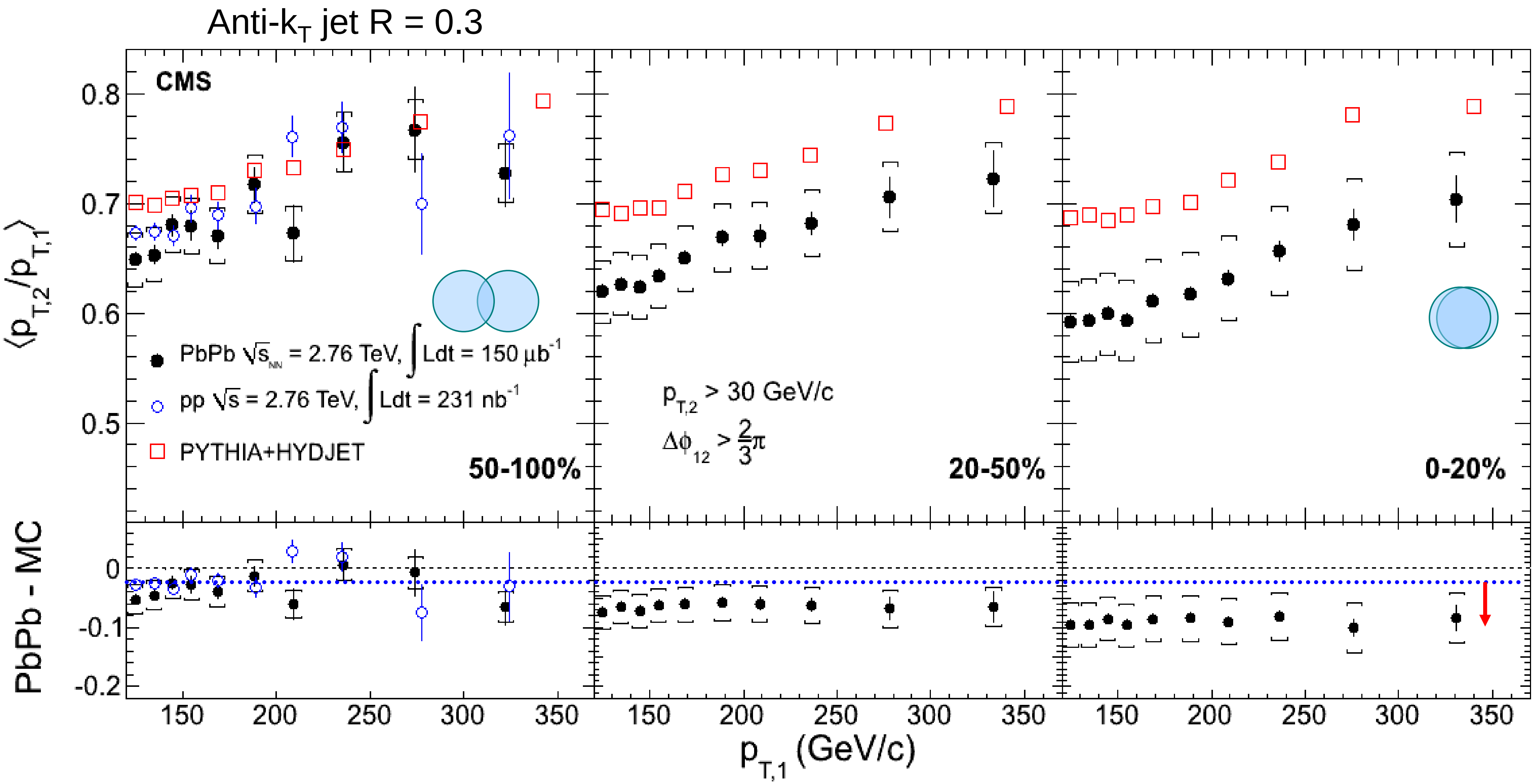


Balanced dijet

Imbalanced dijet



Dijet energy ratio (imbalance)

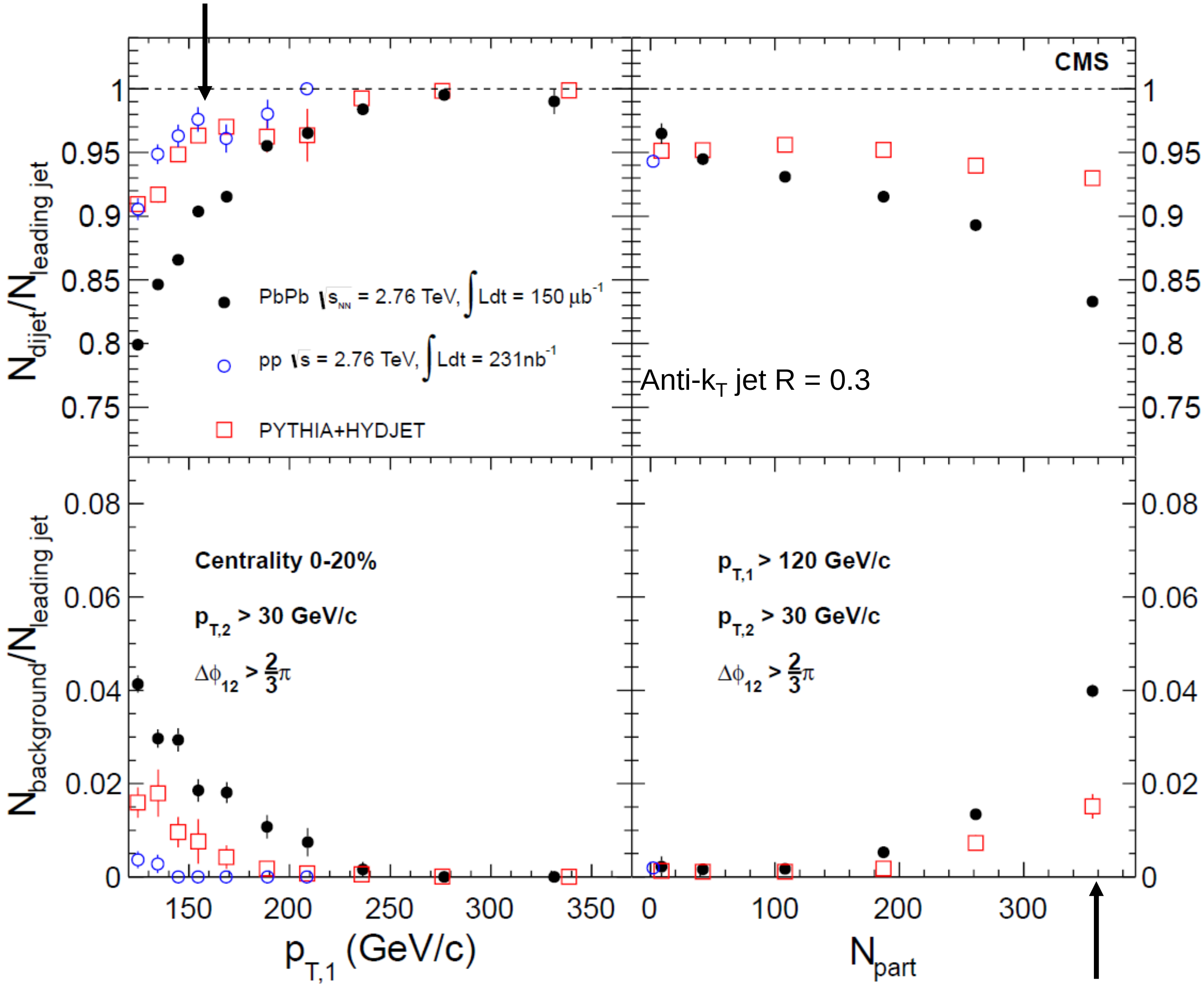


- Energy imbalance increases with centrality
- Very high p_T jets are also quenched

PLB 712 (2012) 176

Fraction of jets with an away side jet

- Given a leading jet with p_T > 150 GeV/c, >90% of them has an away side partner

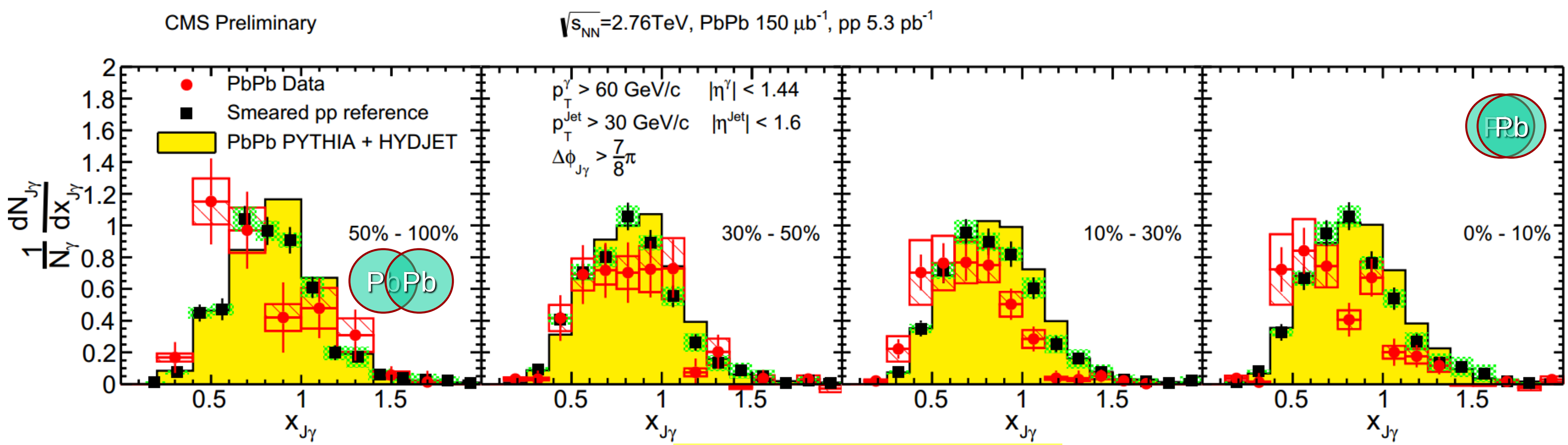


- Fake away side jet rate is < 4%

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

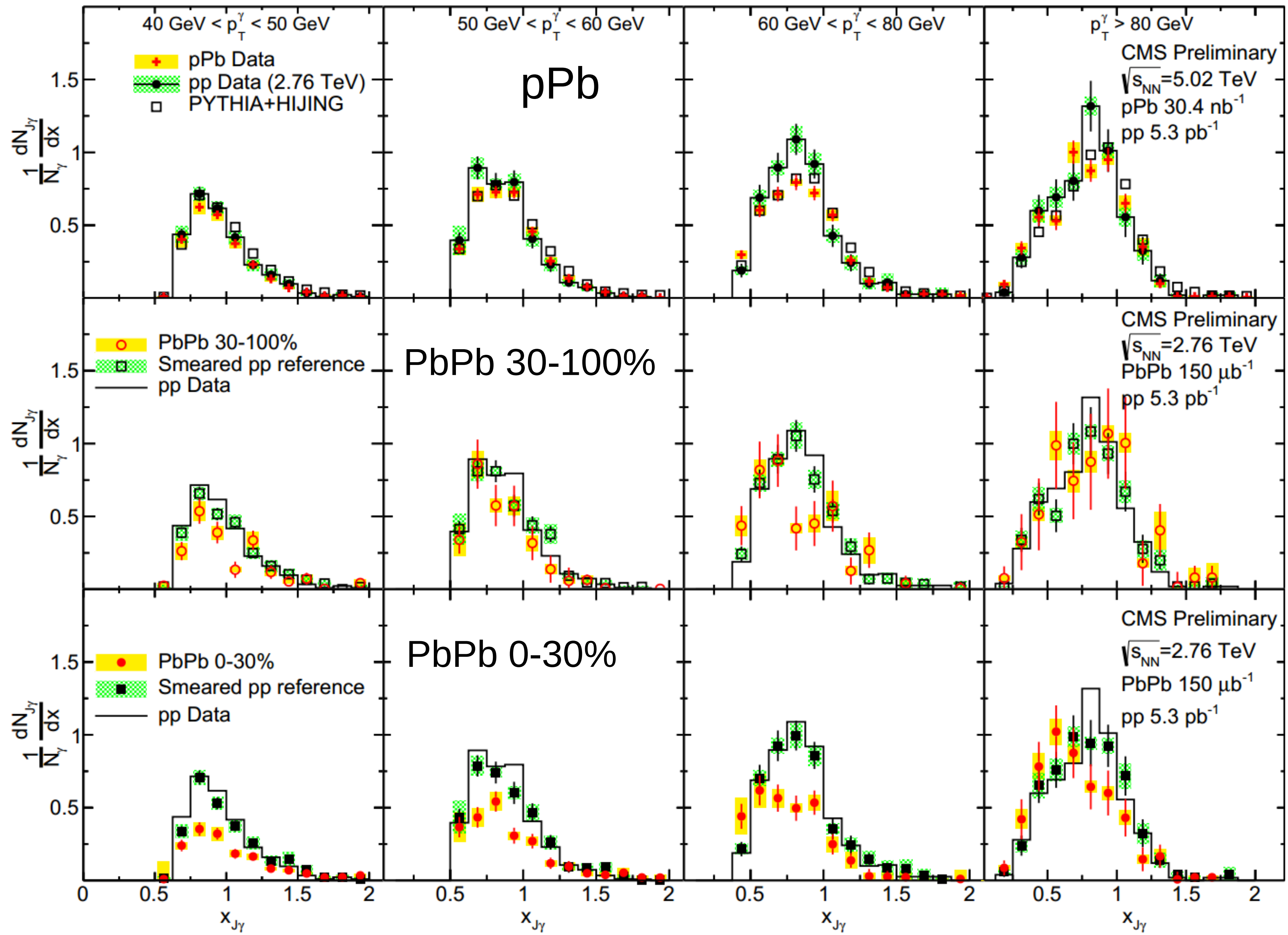
Anti-k_T jet R = 0.3



PLB 718 (2013) 773

CMS-PAS-HIN-13-006

Xj$_g$ spectra vs photon p$_T$

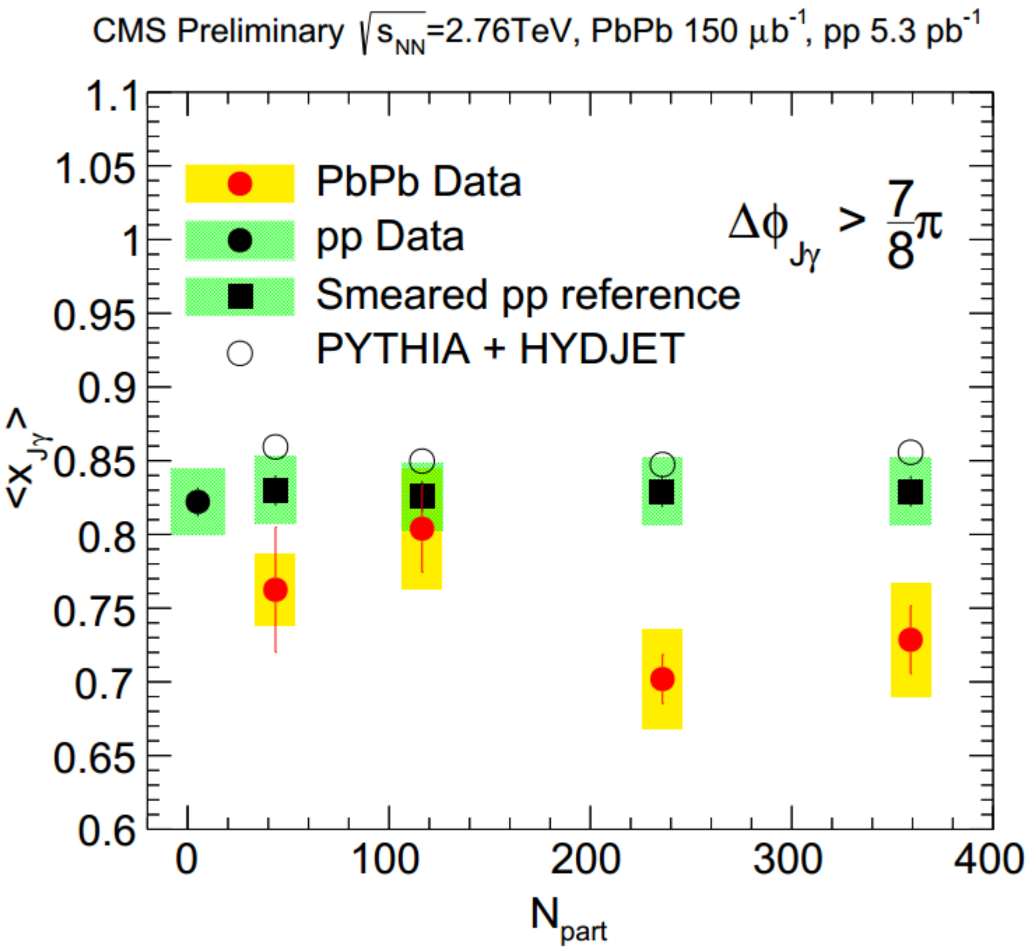


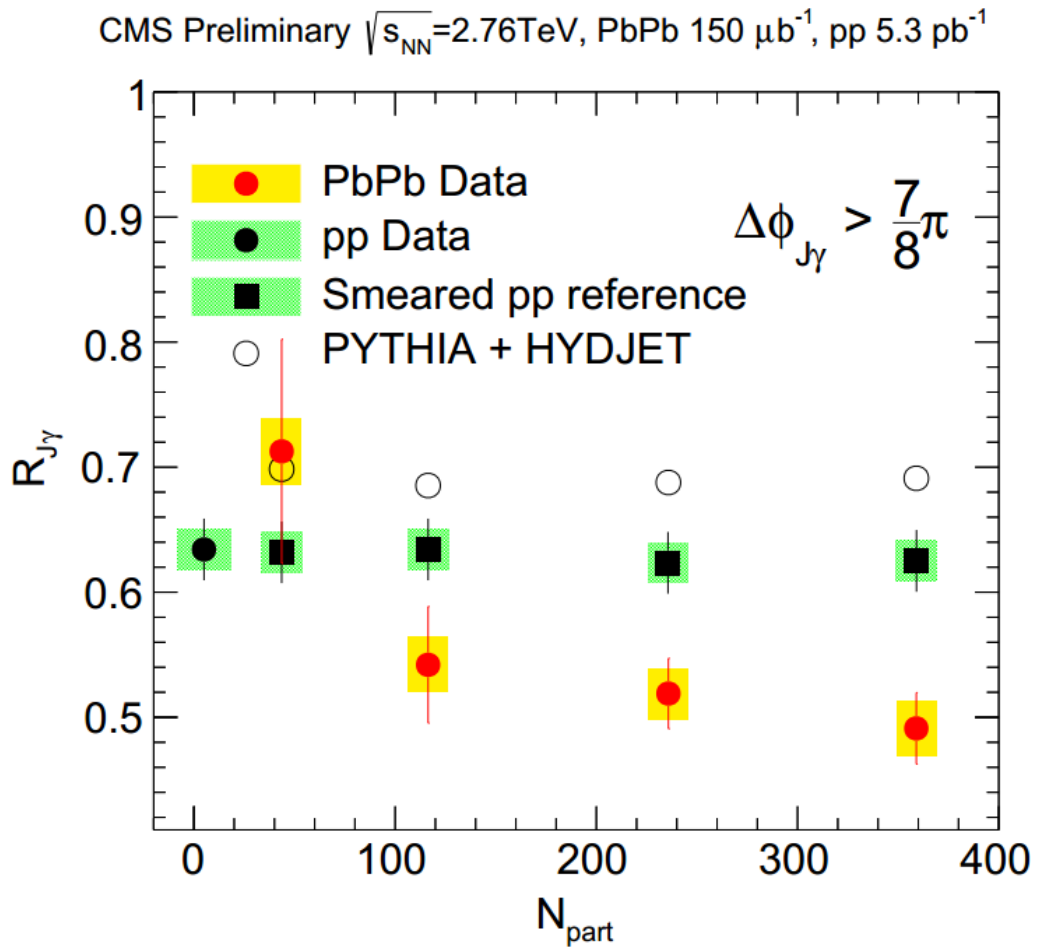
Updated pp reference for photon-jet analysis

PLB 718 (2013) 773

CMS-PAS-HIN-13-006

Photon pT > 60 GeV/c, Jet pT > 30 GeV/c





Away size jet lose ~10% of the energy or ~ O(10 GeV) in 0-10% PbPb collisions

14% of the photons lose their away-side partner

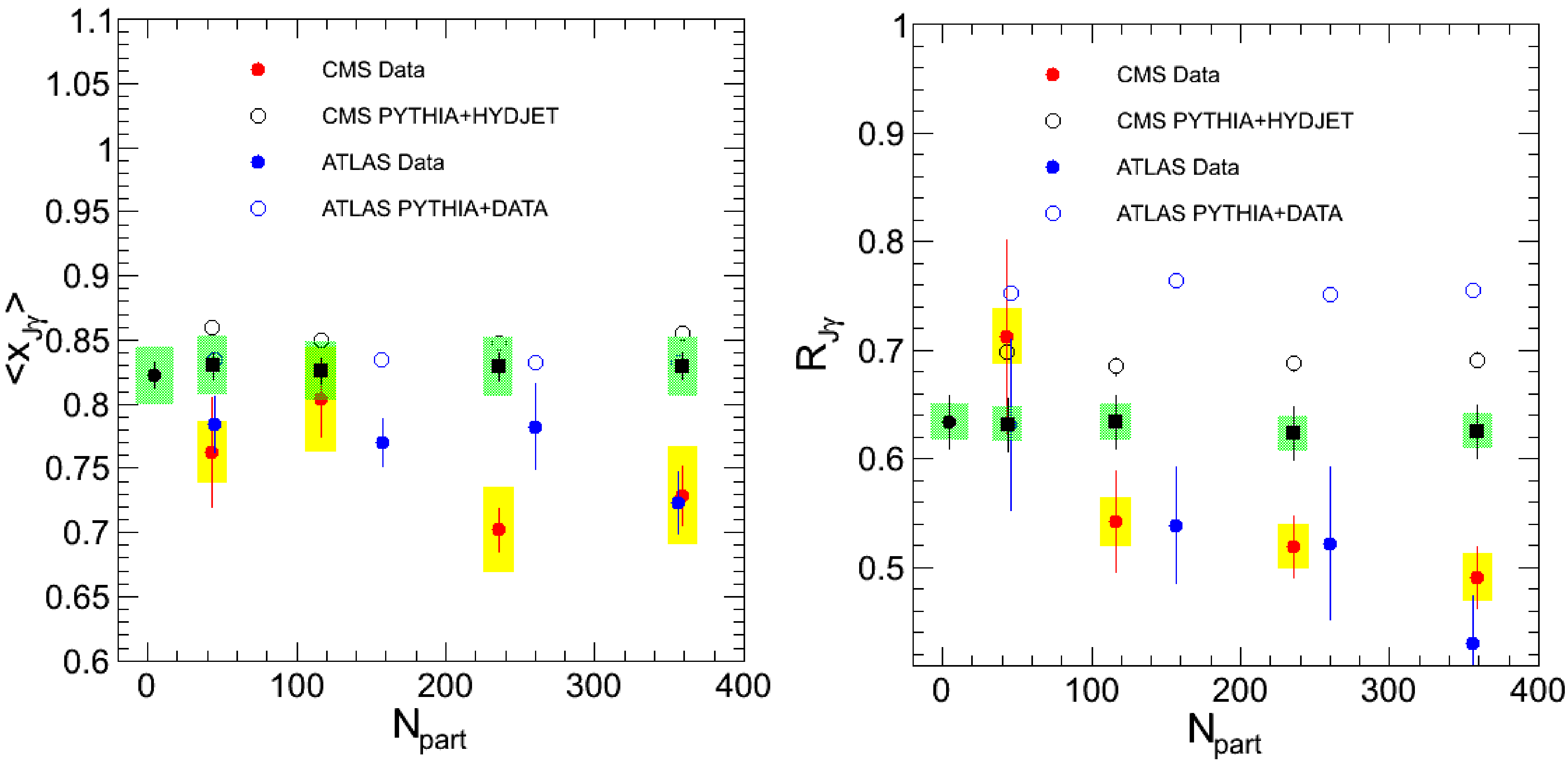
Photon+jet correlation at LHC

CMS published result photon+inclusive jet

Photon p_T > 60 GeV/c, Jet p_T > 30 GeV/c

ATLAS preliminary photon+leading jet

60 < Photon p_T <90 GeV/c, Jet p_T/Photon p_T > 0.4

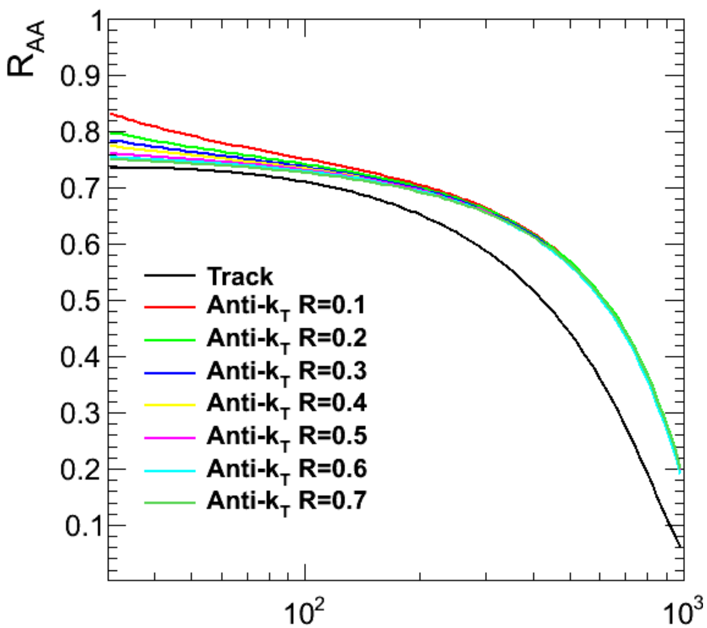


Qualitative consistent result between ATLAS and CMS

Lose constant fraction of energy

What will happen if we take the amount of lost energy (O(10%)) from photon-jet / dijet measurement and use that to modify PYTHIA jet p_T spectra?

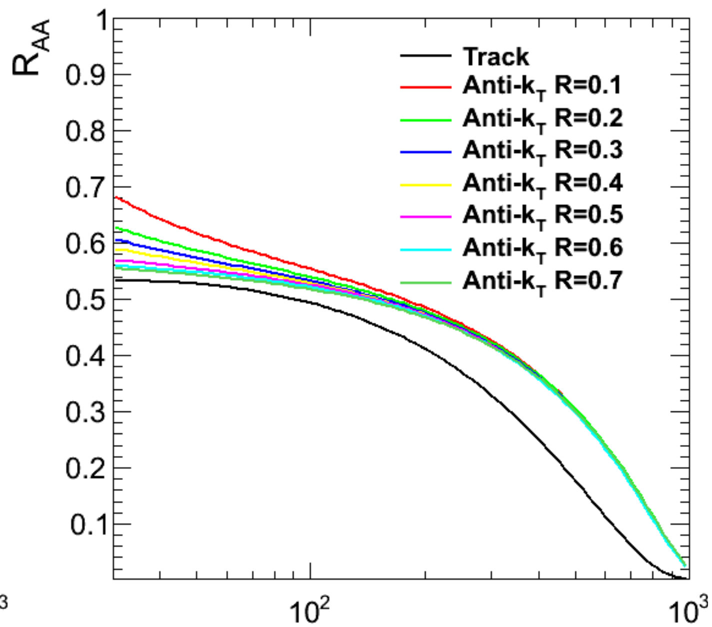
5% energy



Jet (Track) p_T (GeV/c)

$p_T \rightarrow 0.95\ p_T$

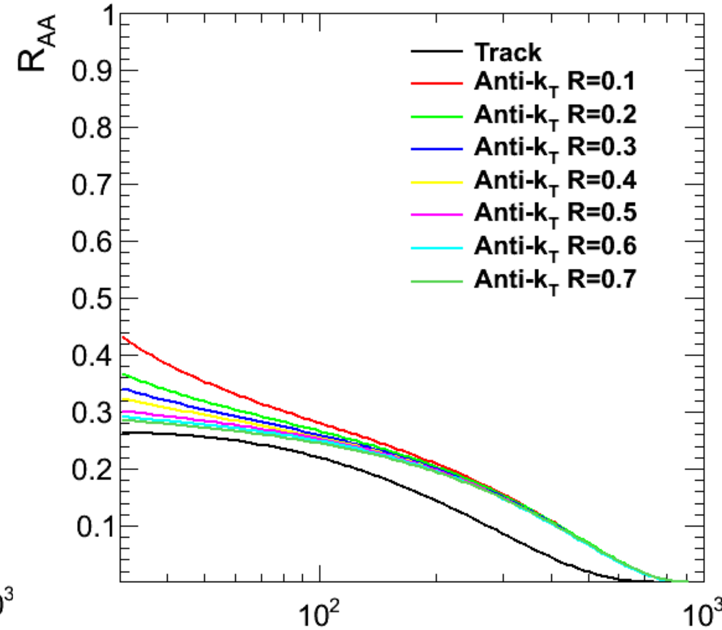
10% energy



Jet (Track) p_T (GeV/c)

$p_T \rightarrow 0.90\ p_T$

20% energy



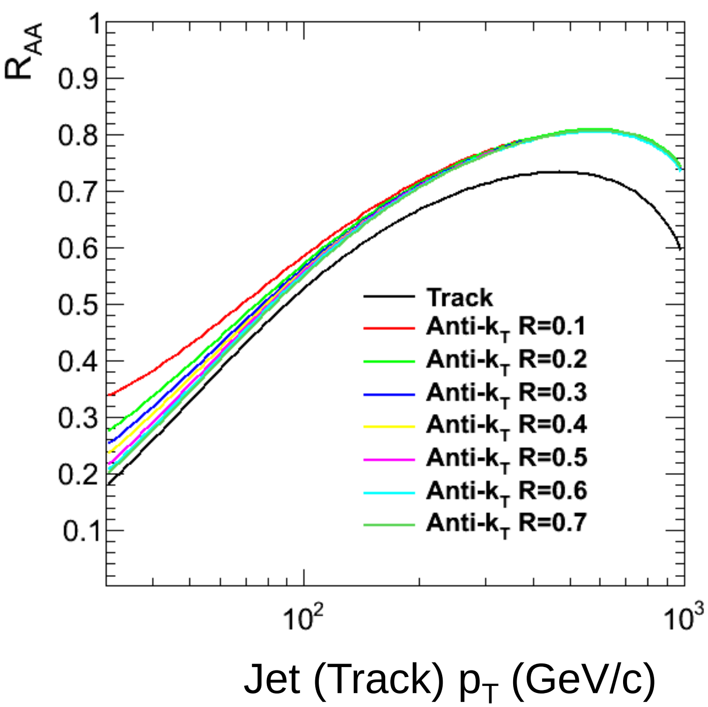
Jet (Track) p_T (GeV/c)

$p_T \rightarrow 0.80\ p_T$

Lose constant amount of energy

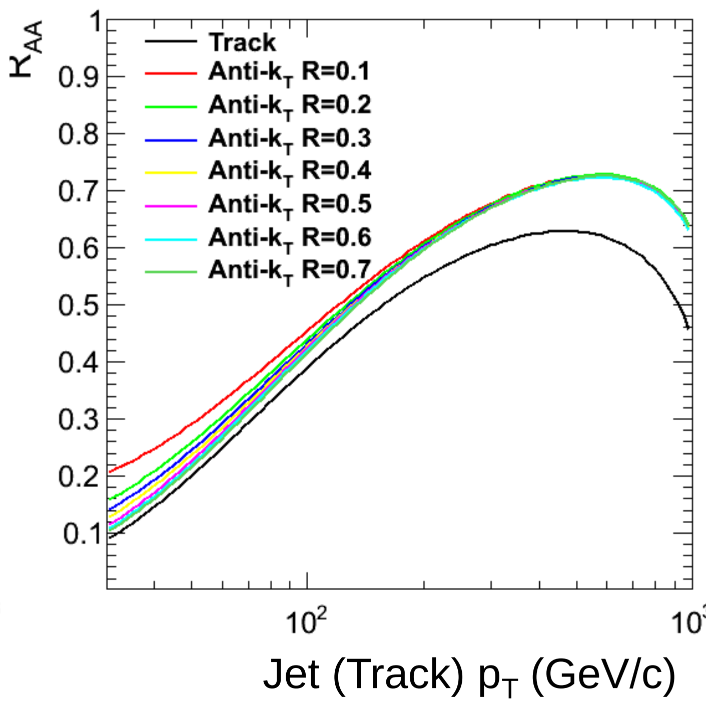
What will happen if we take the amount of lost energy (O(10GeV)) from photon-jet / dijet measurement and use that to shift PYTHIA jet p_T spectra?

10 GeV shift



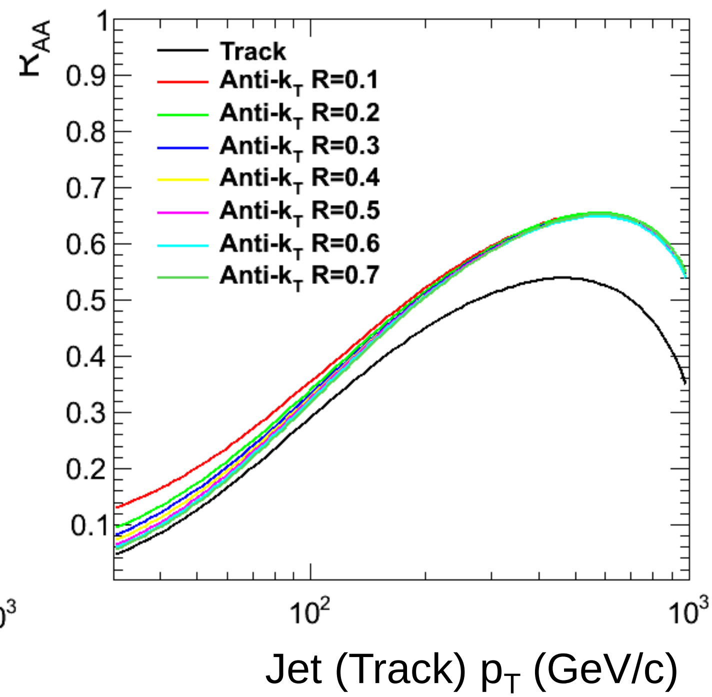
$p_T \rightarrow p_T - 10$ GeV

15 GeV shift



$p_T \rightarrow p_T - 15$ GeV

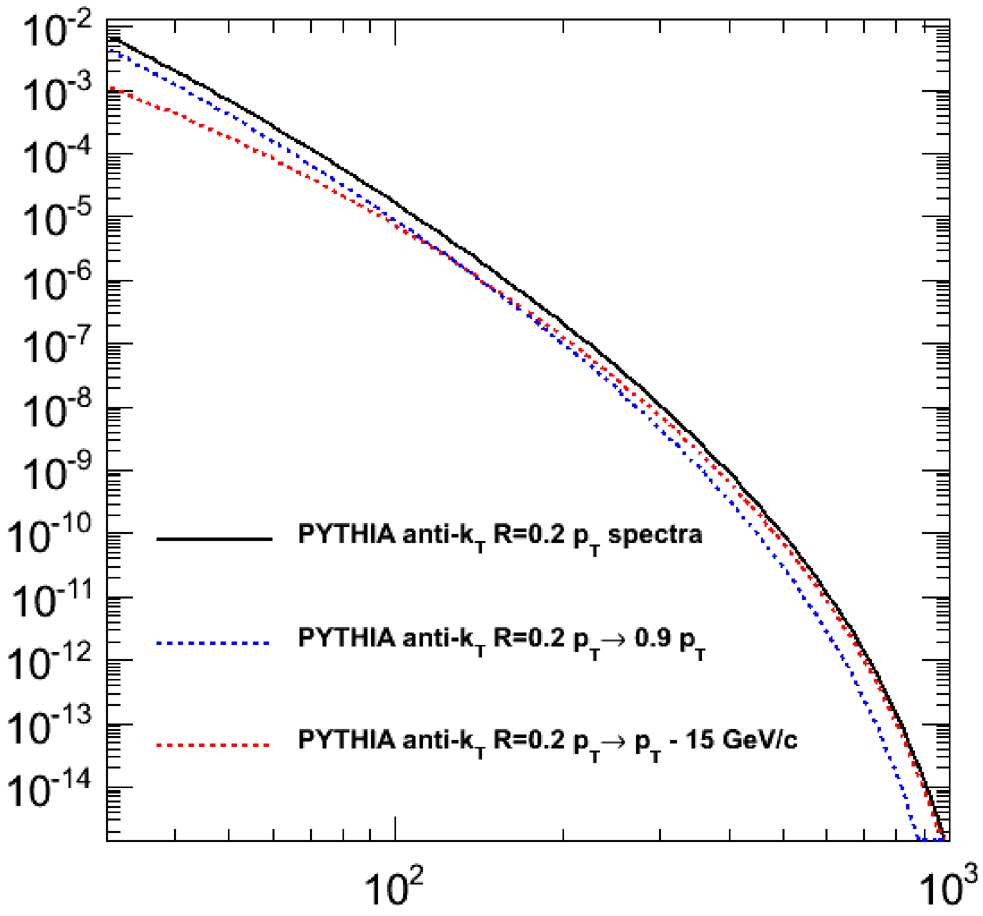
20 GeV shift

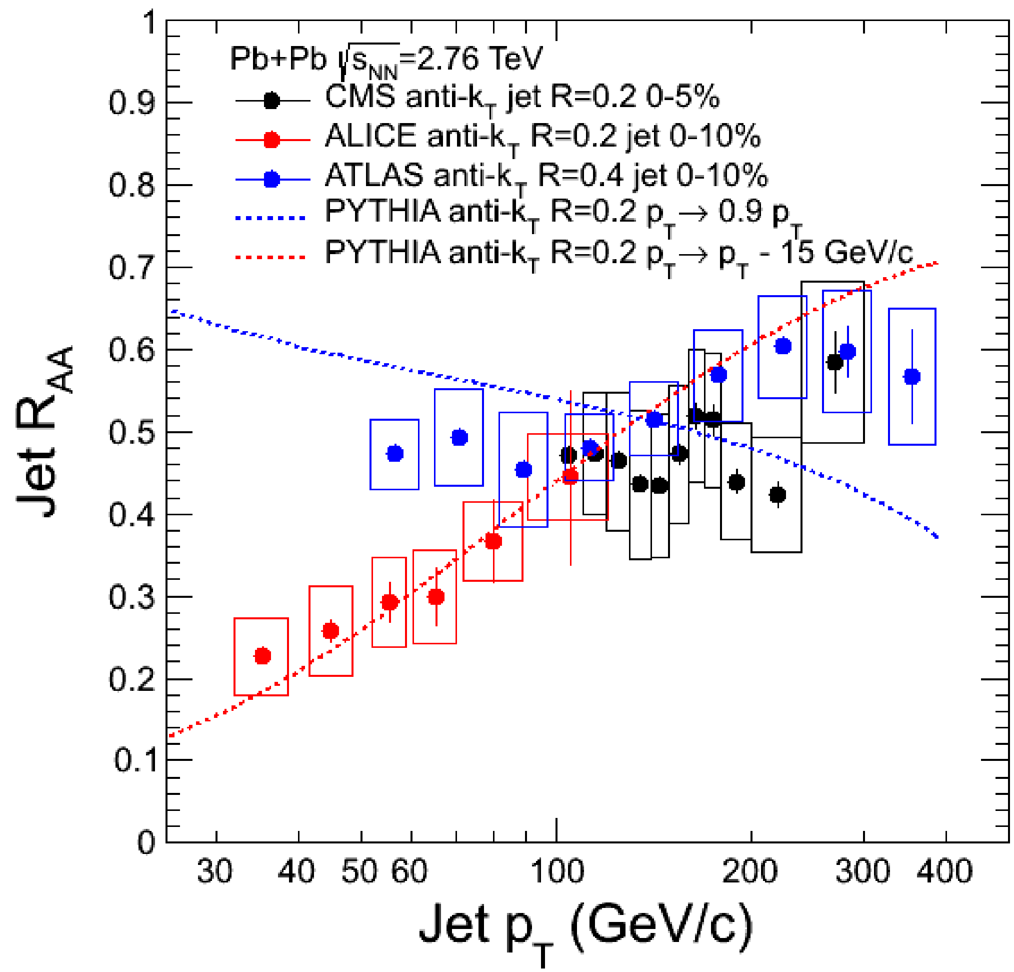


$p_T \rightarrow p_T - 20$ GeV

Compared to LHC data

Blue dashed line: jet $p_T \rightarrow 0.9\, p_T$ Red dashed line: jet $p_T \rightarrow p_T - 15$ GeV



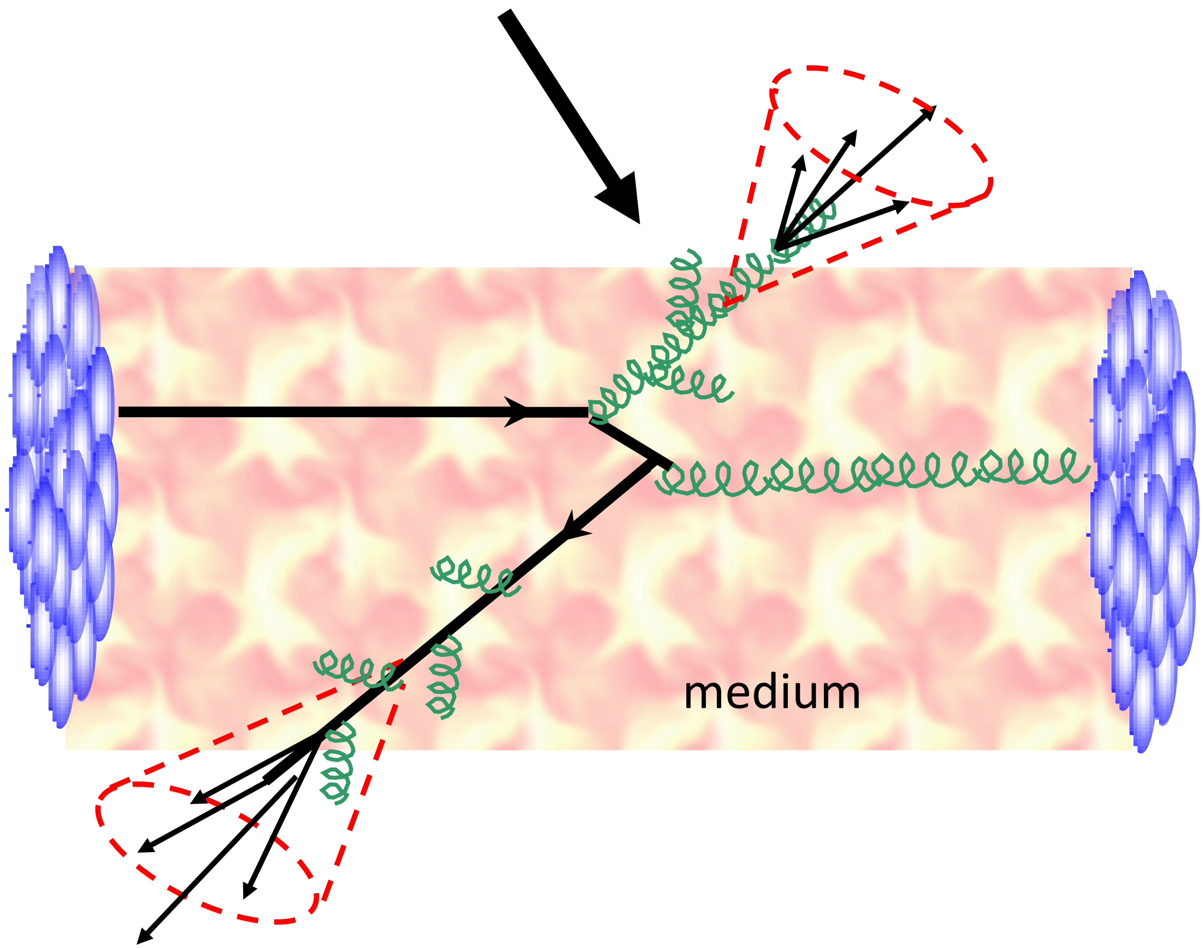


Constant fractional energy loss doesn't describe the trend established by ALICE+CMS data

The resulting jet R_{AA} could be reproduced by shifting the jet spectra by -15 GeV

Jet quenching with jets

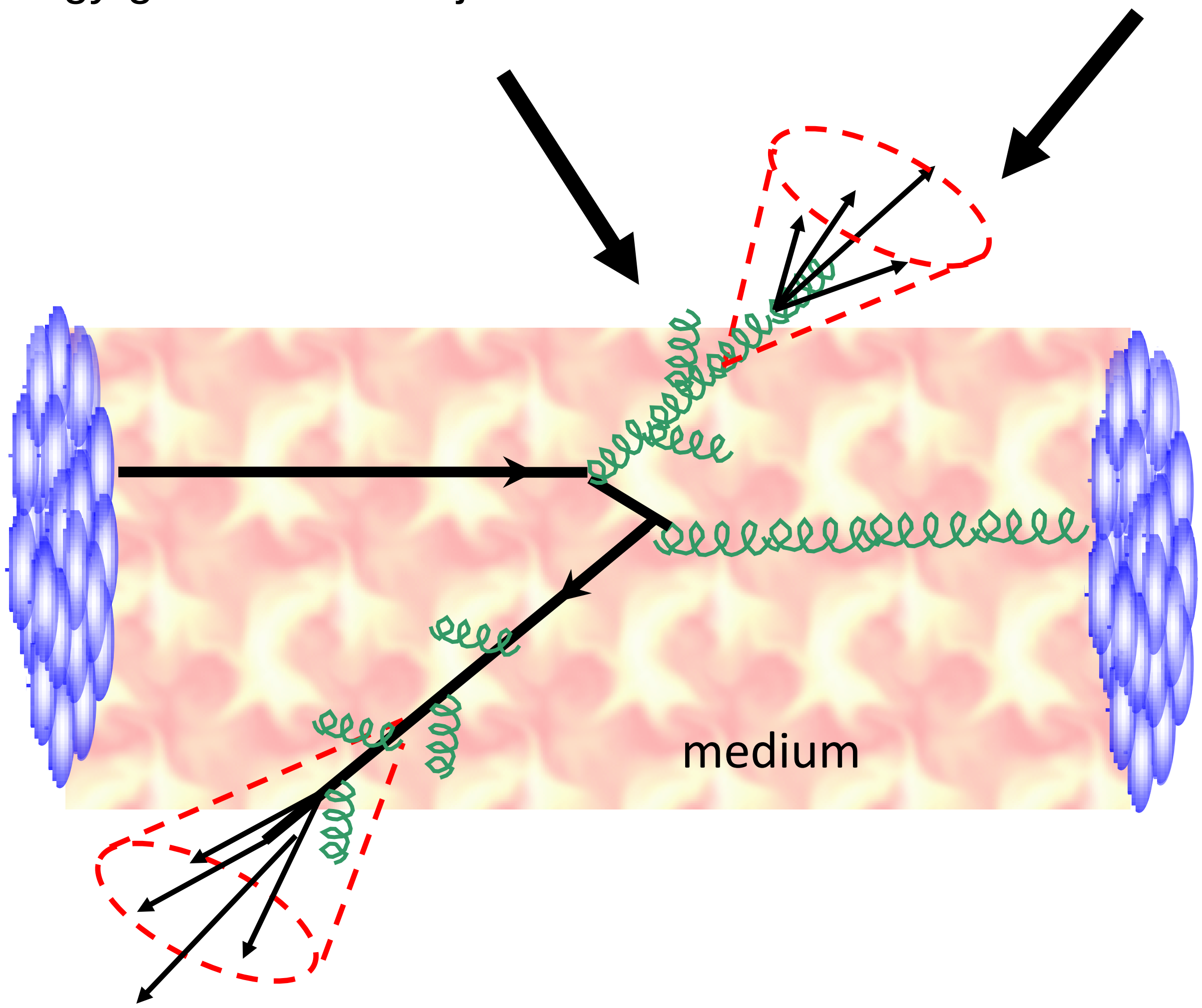
O(10 GeV) energy goes out of the jet cone



Jet quenching with jets

Inside the jet cone?

O(10 GeV) energy goes out of the jet cone



Jet Fragmentation at LHC

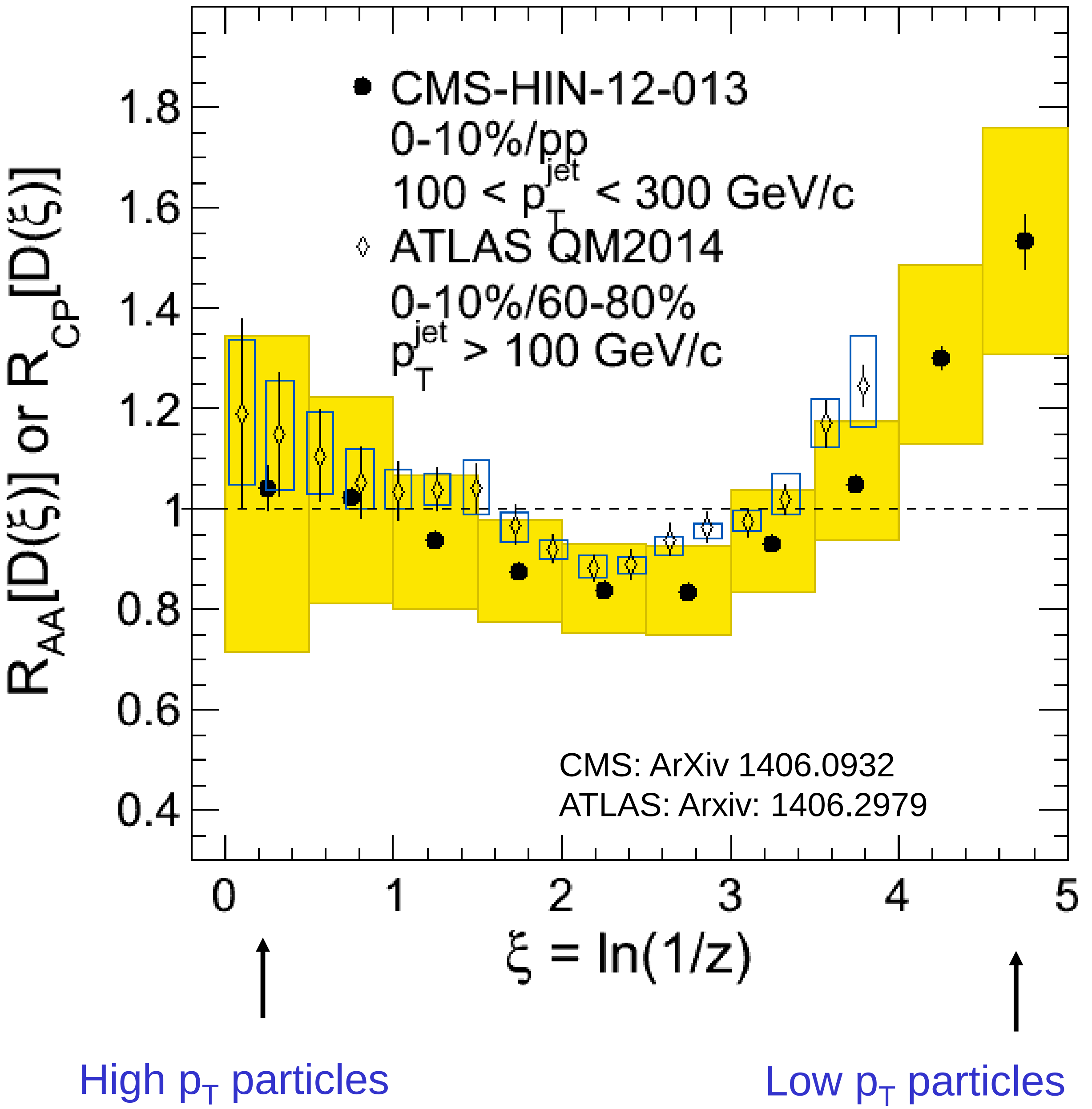
Using **Jet Energy** as a reference

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

$Z = p_T^{Trk} / p_T^{Jet}$

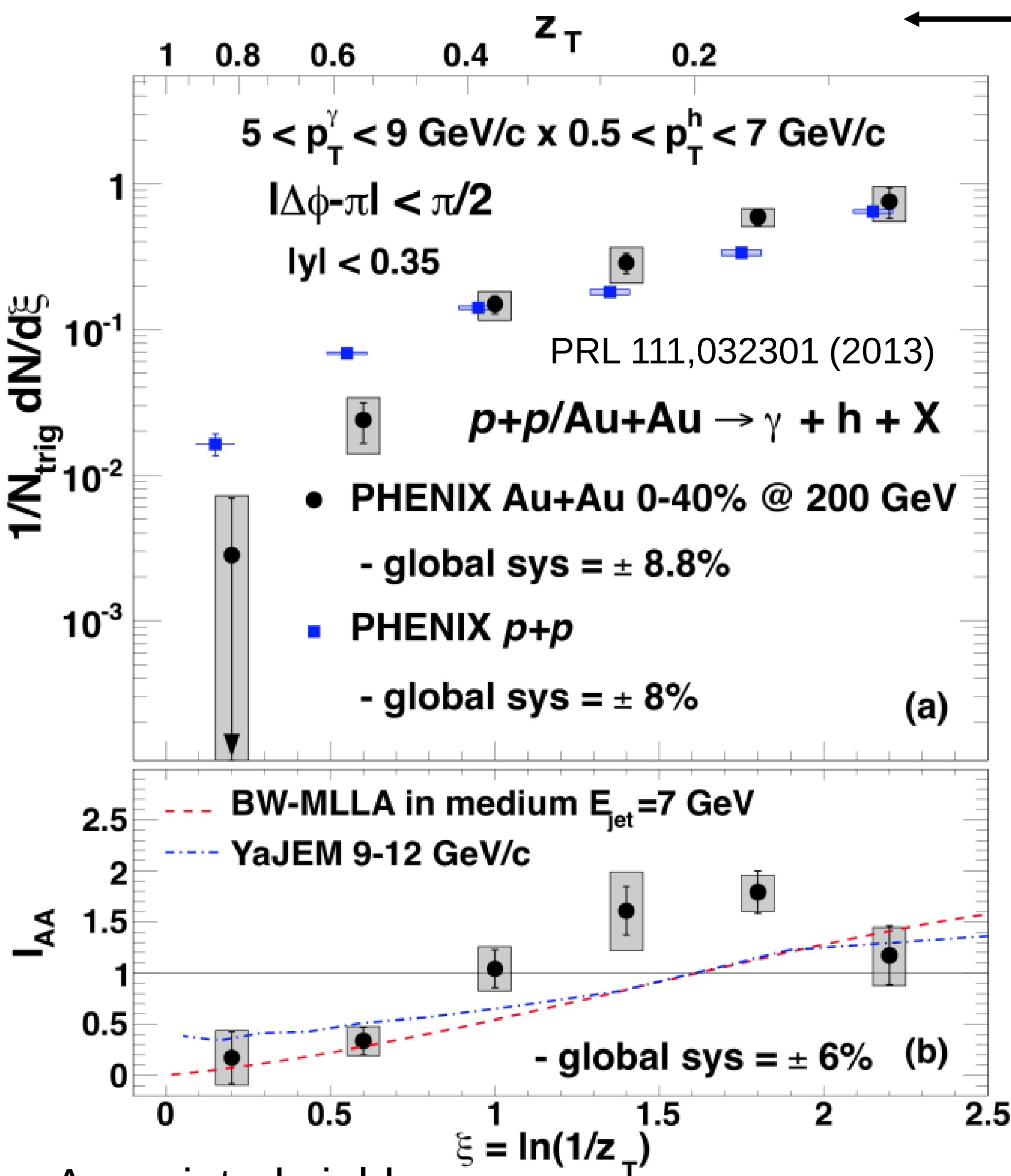
Qualitative consistent results between CMS and ATLAS

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

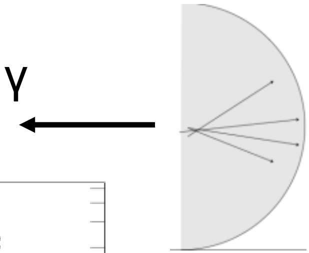


Photon-hadron correlation

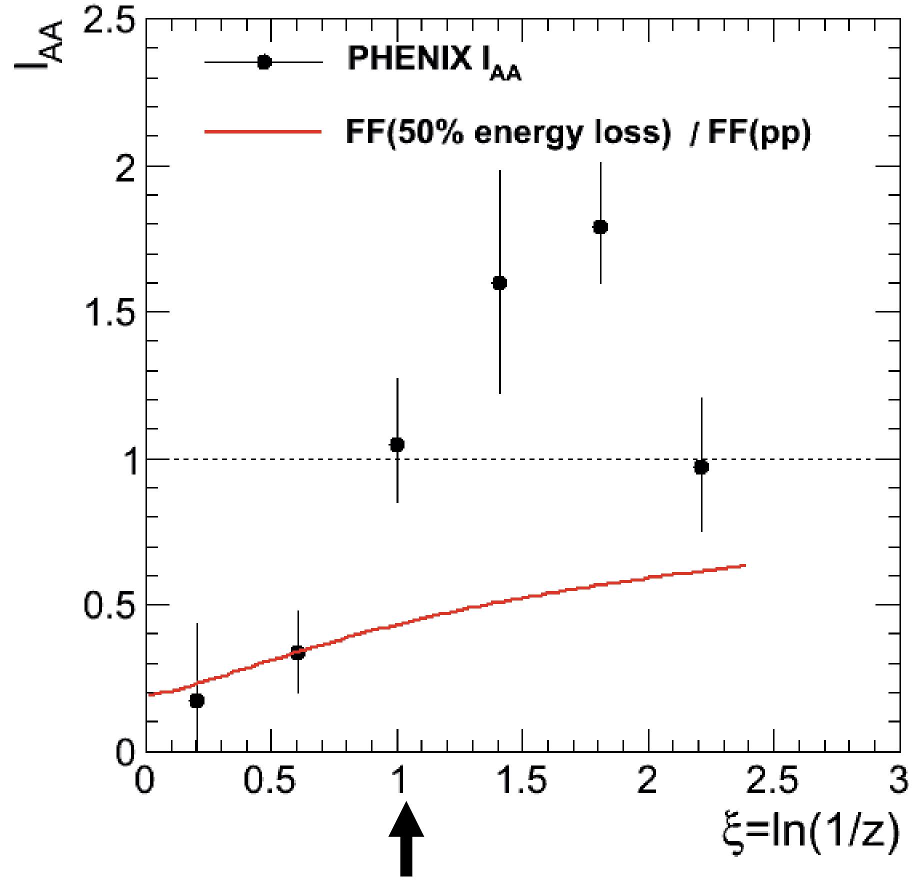
Using **Photon Energy** as a reference



Associated yield



The FF shape can not be explained by simple shift of pp fragmentation function

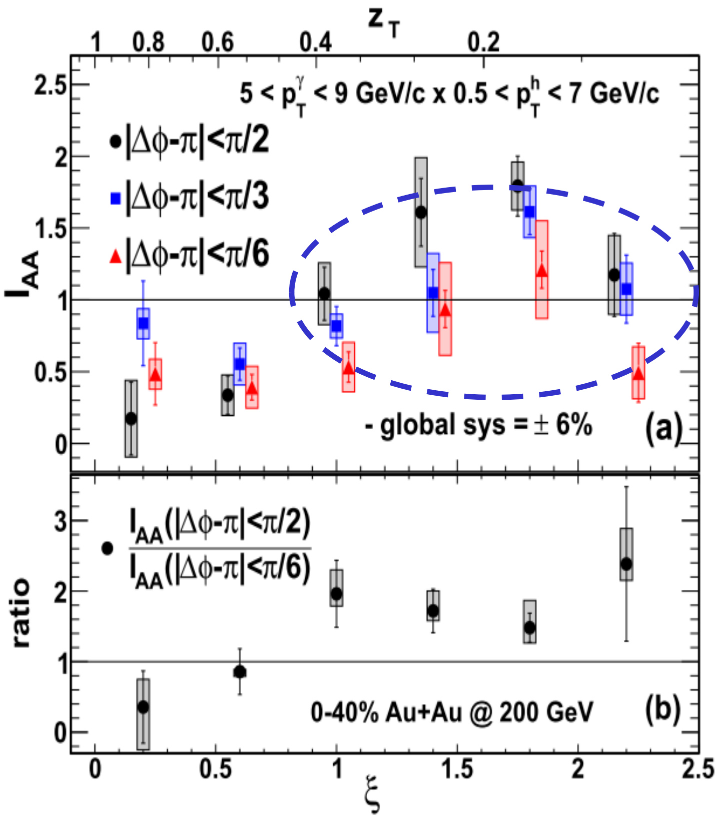


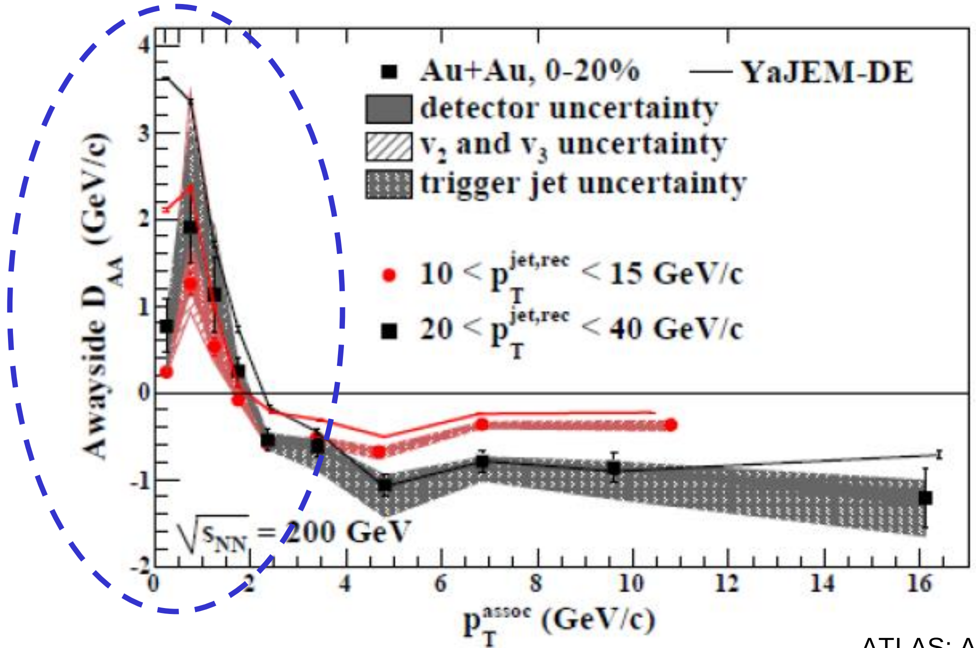
Track p_T ~2 GeV

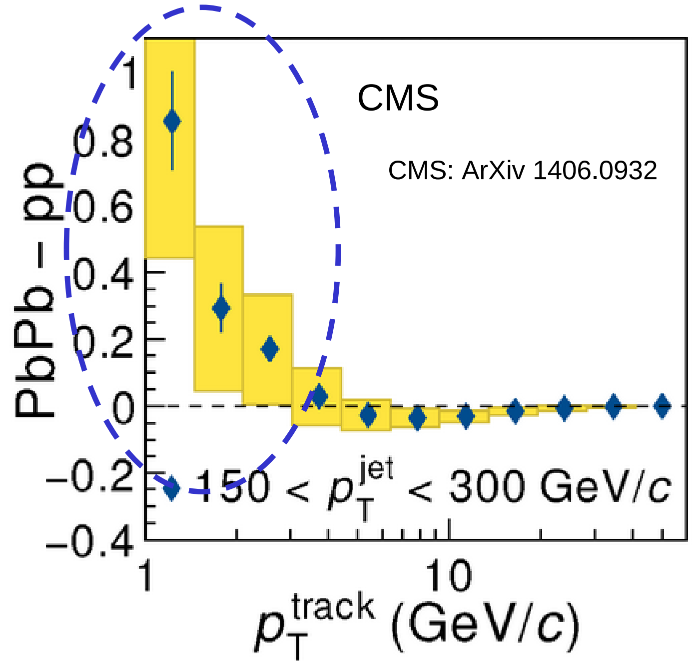
Enhancement of low p_T particles

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

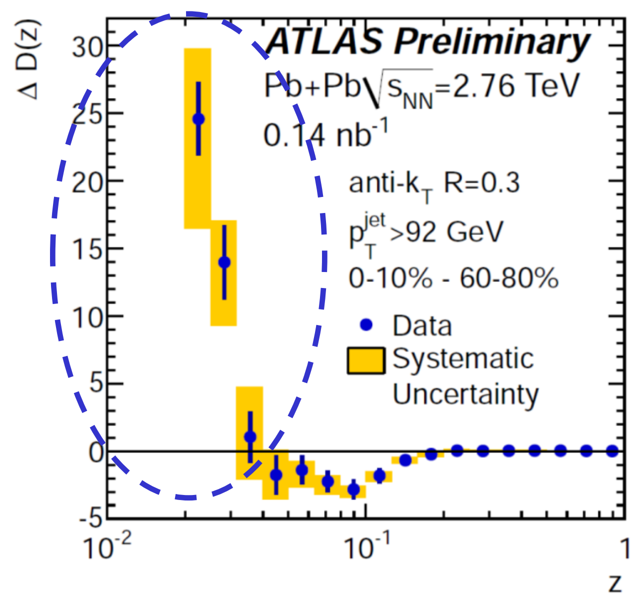
PHENIX







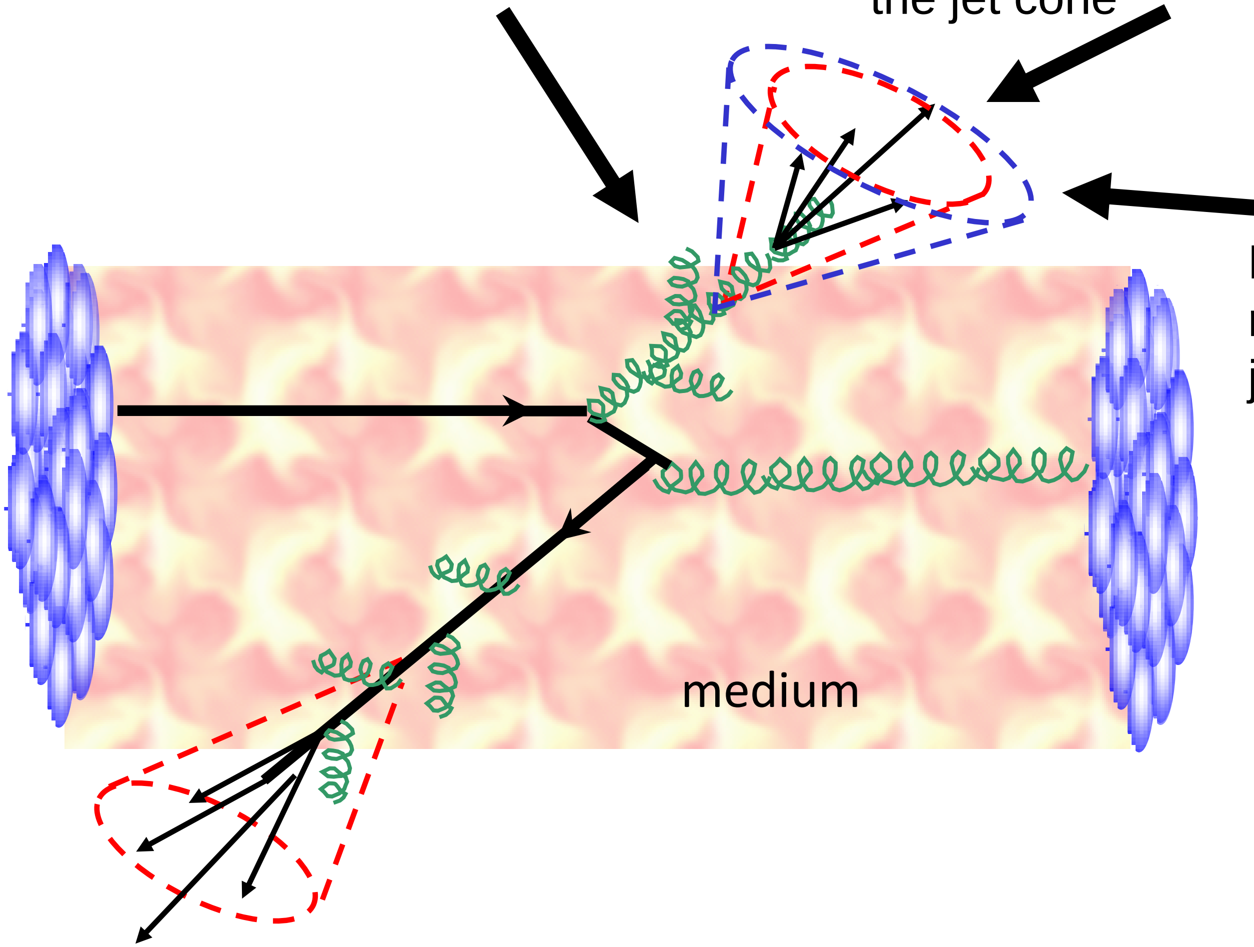
ATLAS: Arxiv: 1406.2979



Jet quenching with jets

O(10 GeV) energy goes out of the jet cone

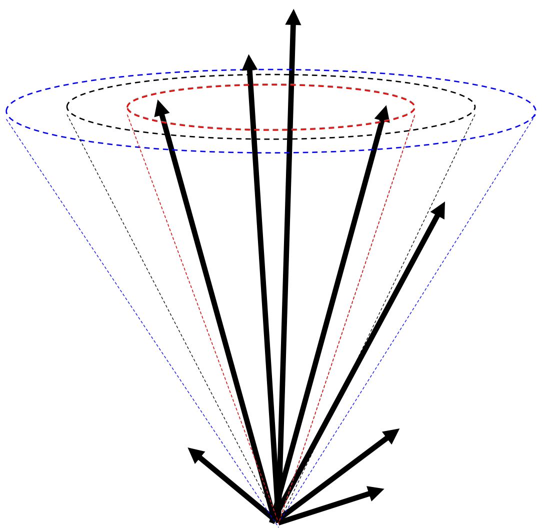
O(1 GeV) “radiated energy” or “medium recoil” carried by low p_T particles inside the jet cone



How about the region close to the jet axis?

Inclusive jet spectra: jet R_{AA}

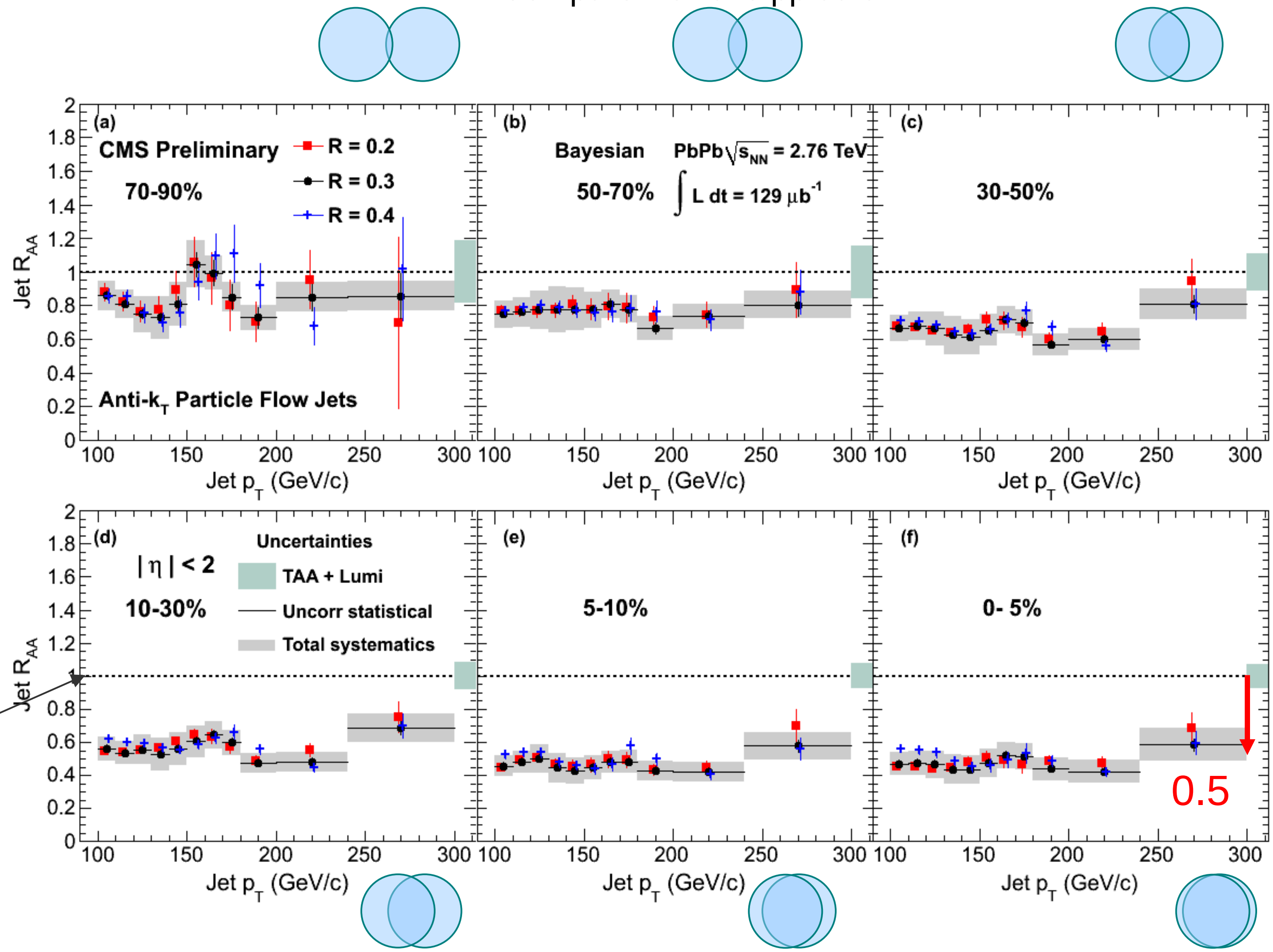
Anti-k_T jets with
R = 0.2, 0.3, 0.4



If PbPb = superposition of pp

CMS PAS HIN-12-004

Compare PbPb to pp data

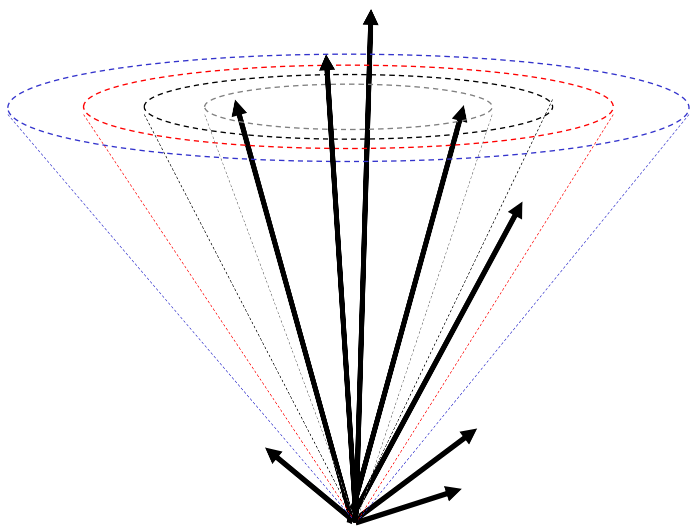


Strong suppression of inclusive high p_T jets

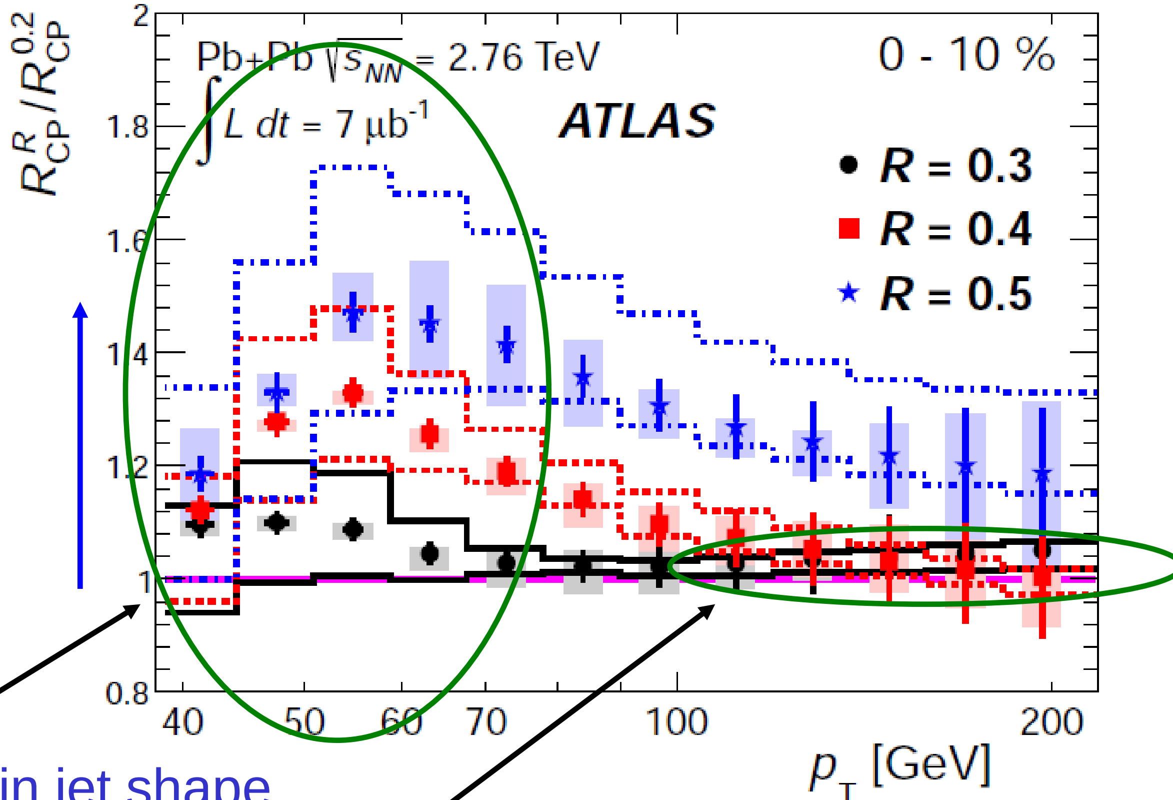
A cone of R=0.2, 0.3, 0.4 doesn't catch all the radiated energy

Do we collect the radiated energy with large cone size?

Anti-k_T jets with
R = 0.2, 0.3, 0.4, 0.5



Ratio of R_{CP} with different cone sizes

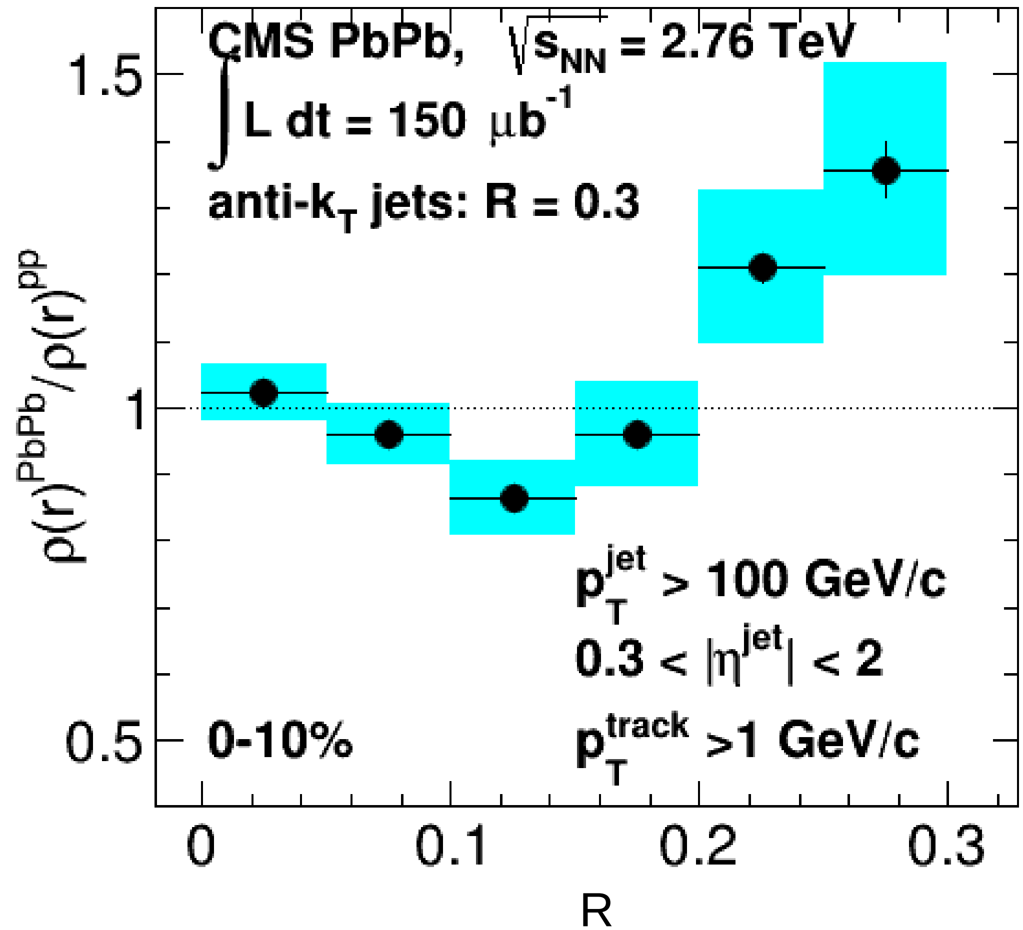


$R_{CP}^{(R=0.5)} / R_{CP}^{(R=0.2)} > 1$
→ recovery of lost energy, change in jet shape
with respect to the pp reference

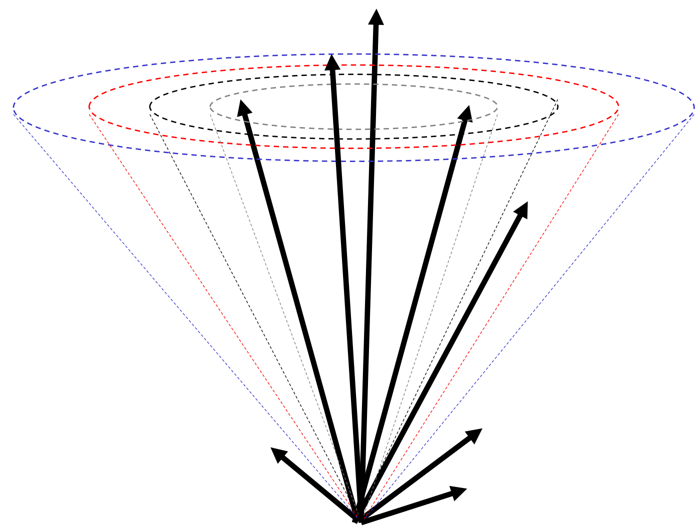
ATLAS Jet $R_{CP}^{(R=0.3)} / R_{CP}^{(R=0.2)} \sim 1.0 \pm 0.2$
Allows to recover up to 0-4% more jet energy when moving from R=0.2 → R=0.3
in PbPb collisions than pp reference

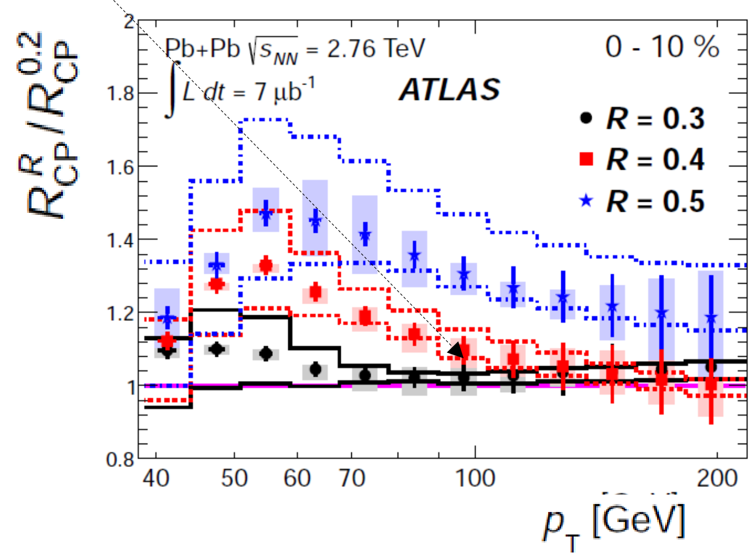
Jet shape vs. R_{AA} ratio

Ratio of jet shapes in PbPb and pp collisions



Jet shapes: how the energy is distributed as a function of R (distance between jet and track)

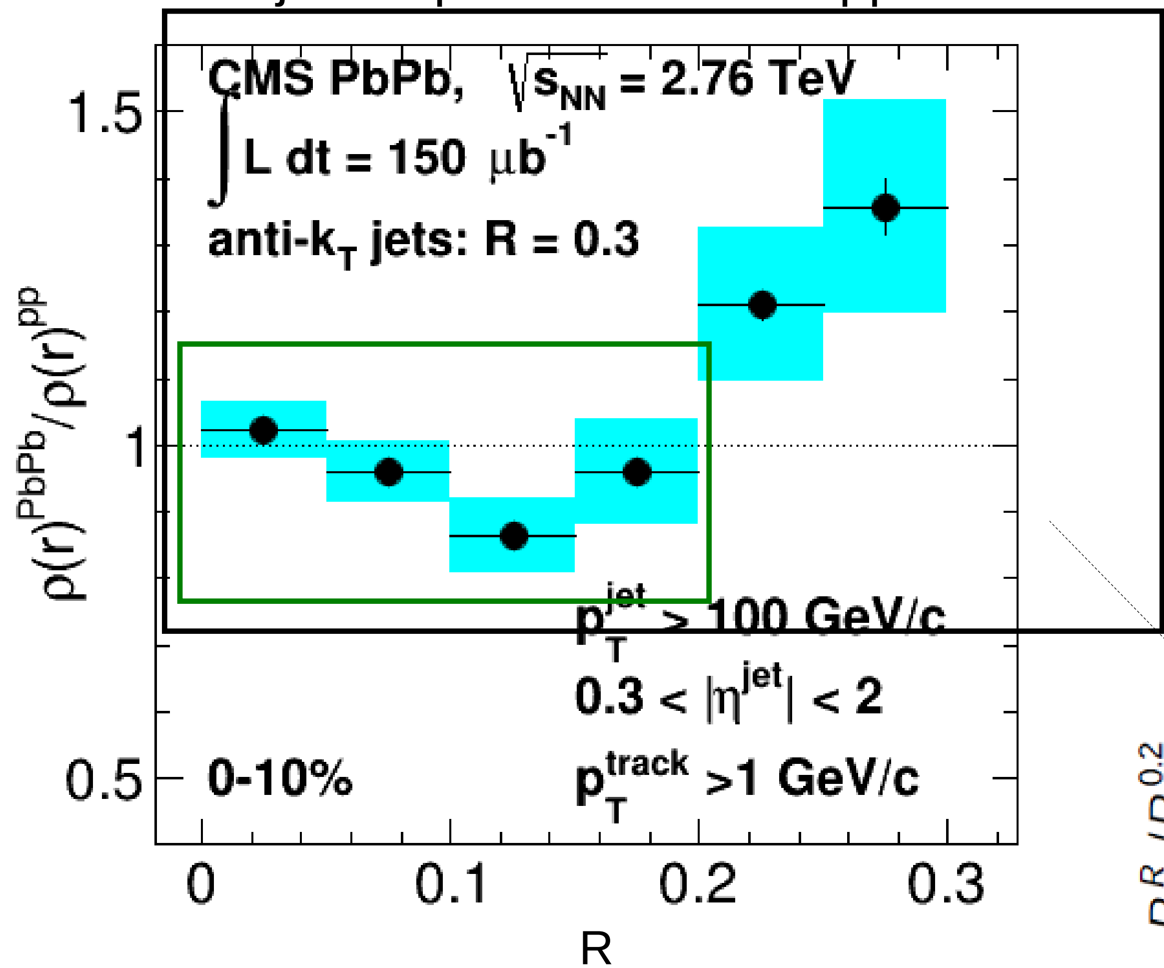




ATLAS Jet R_{CP} (R=0.3) / R_{AA} (R=0.2) ~ 1.0 ±0.2
Allows to recover up to 0-4% more jet energy than pp reference

Jet shape vs. R_{AA} ratio

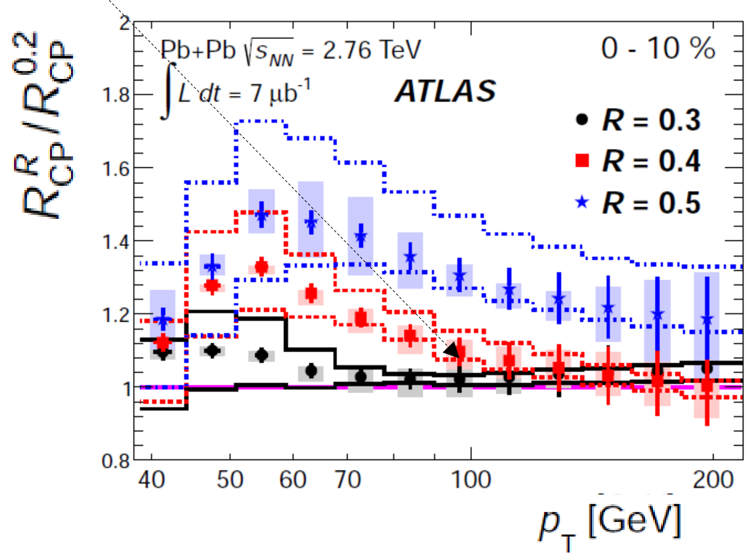
Ratio of jet shapes in PbPb and pp collisions



Changing the R from 0.2 to 0.3→ recover more radiated energy

CMS observed this change in R recover ~1% more energy in PbPb than pp

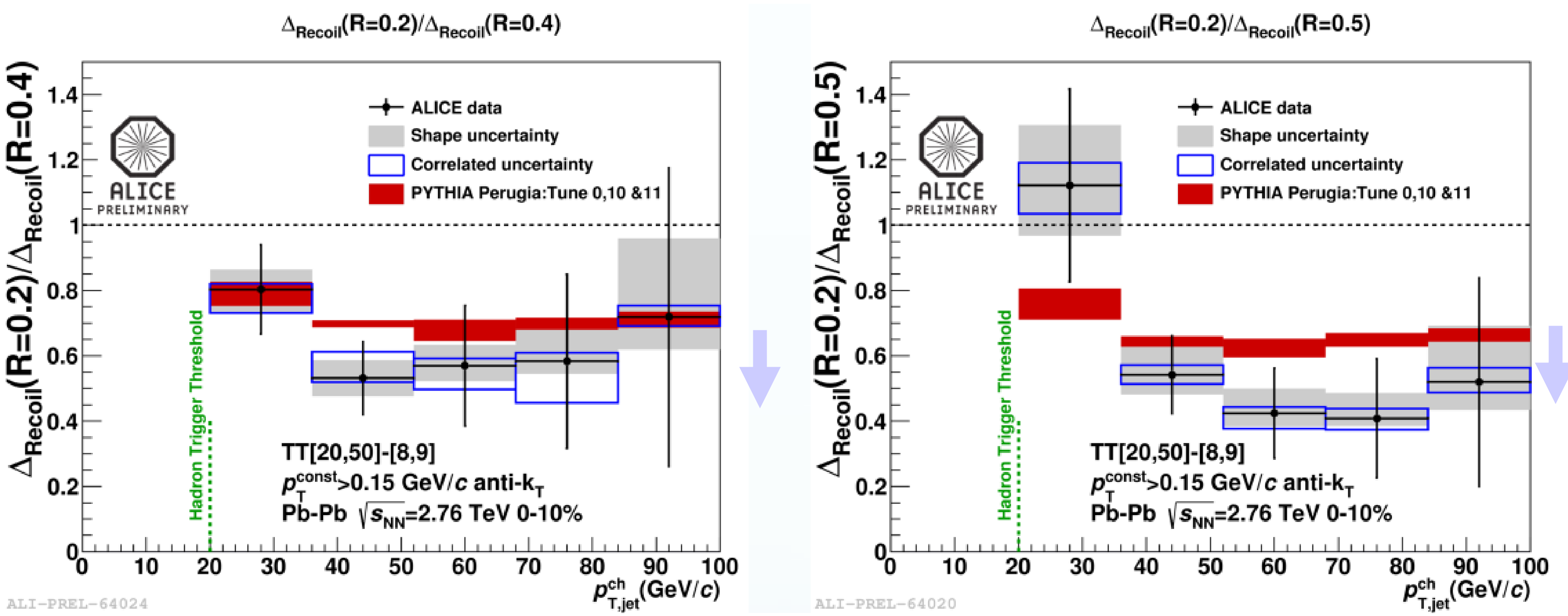
CMS and ATLAS results are roughly compatible



ATLAS Jet R_{CP} (R=0.3) / R_{AA} (R=0.2) ~ 1.0 ±0.2
Allows to recover up to 4% more jet energy than pp reference

Δ_{Recoil} Ratio

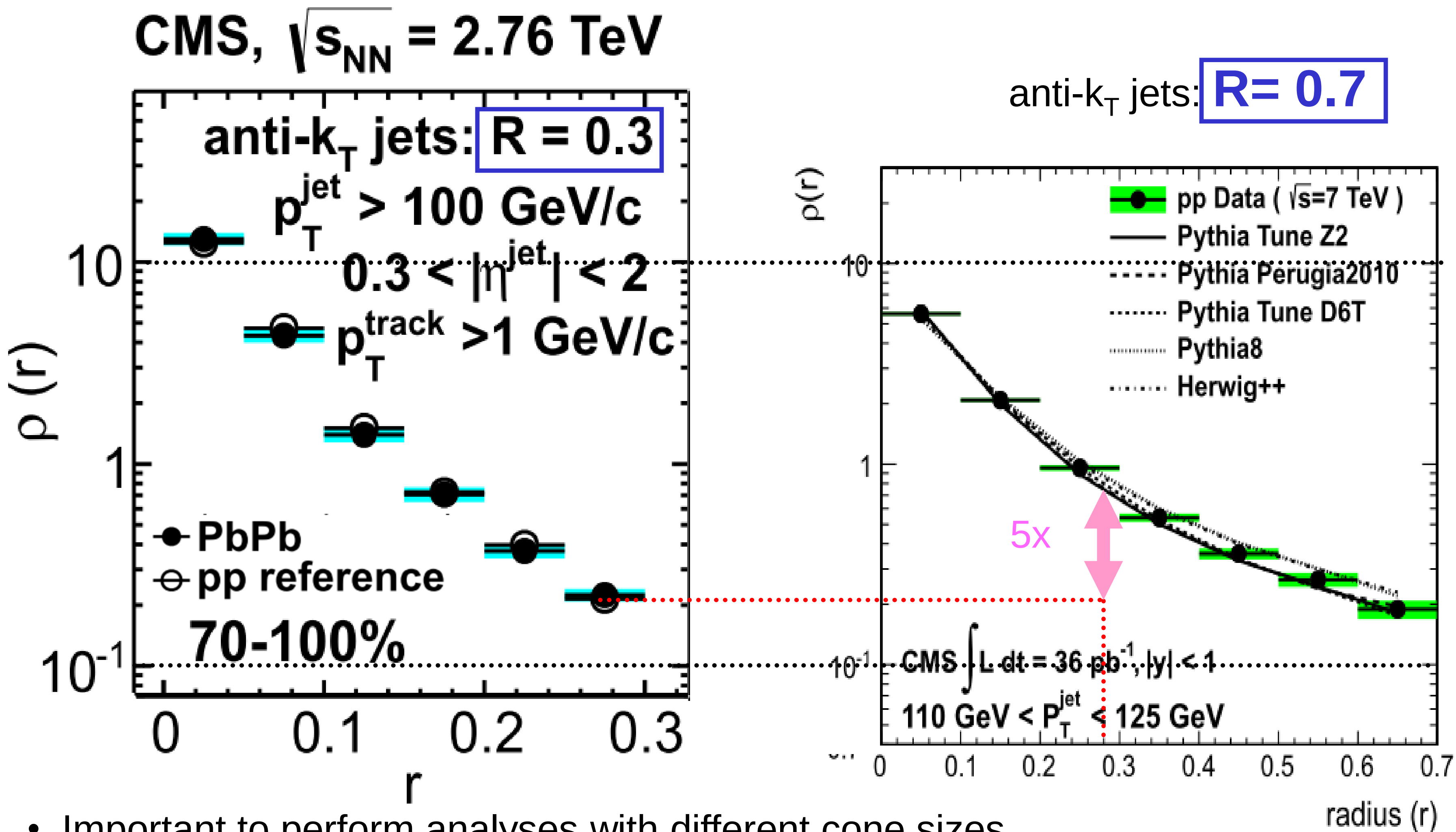
$$\Delta_{recoil} = \left(\frac{1}{N_{trig}}\frac{dN}{dp_{T,jet}}\right)_{20-50} - \left(\frac{1}{N_{trig}}\frac{dN}{dp_{T,jet}}\right)_{8-9}$$



Indication of recovery of the lost parton energy
with larger cone size
(also consistent with no energy redistribution)

Consistent picture between CMS, ATLAS and ALICE

Caveat: jet shape depends on jet distance parameter

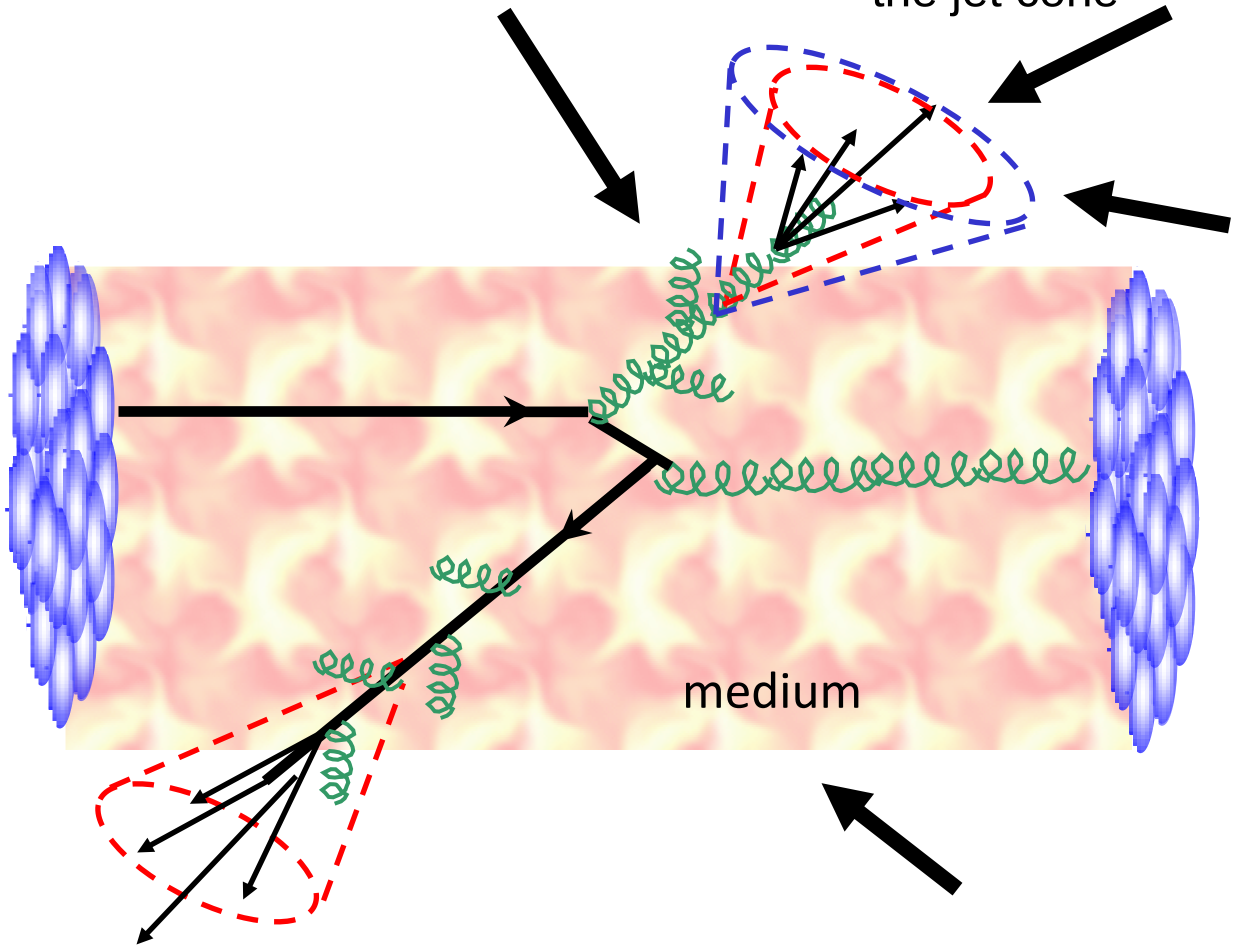


- Important to perform analyses with different cone sizes
- Comparison between jets reconstructed with different cone size is tricky
  - At the same jet p_T: Essentially comparing a different set of jets
  - Small distance parameter + cut on jet p_T → selecting on narrow jets

Jet quenching with jets

O(10 GeV) energy goes out of the jet cone

O(1 GeV) “radiated energy” or “medium recoil” carried by low p_T particles inside the jet cone



Hint of less quenching with larger R

R=0.5 can’t capture all the radiated energy

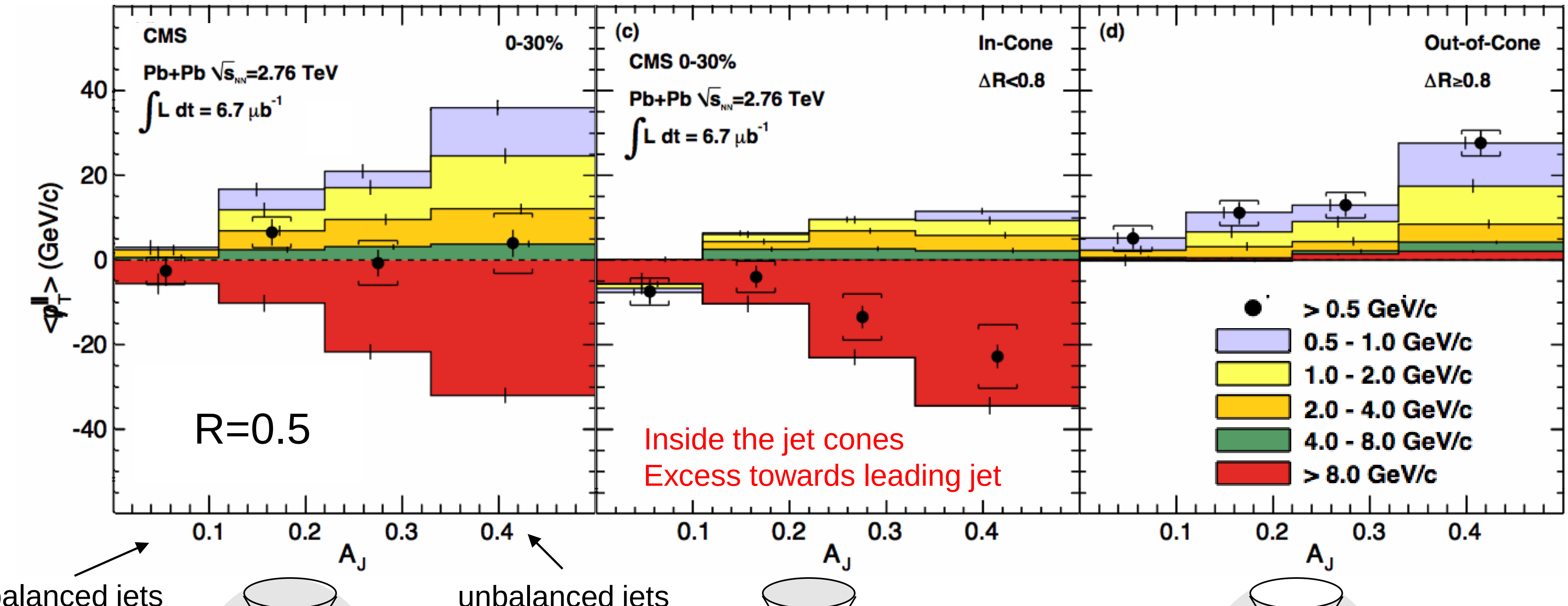
How far does the lost energy go?

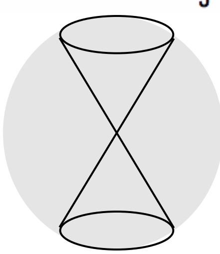
Missing $p_T^{||}$ in 2010 (IC5 calojet)

Missing $p_T^{||}$: $$\not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

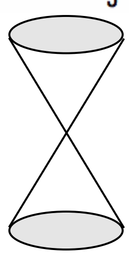
0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet

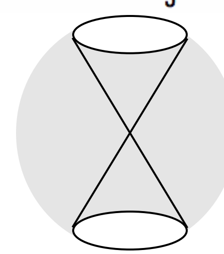




All tracks



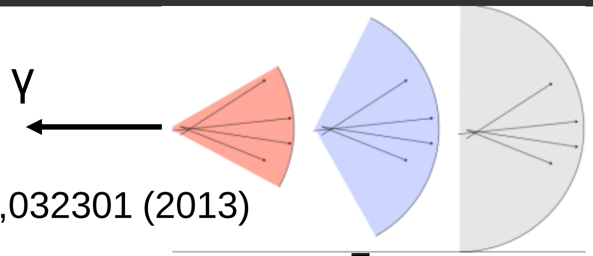
Tracks in
the jet cone
ΔR<0.8



Tracks out of
the jet cone
ΔR>0.8

The momentum difference in the dijet is balanced by low p_T particles outside the jet cone

Lost energy at RHIC and LHC



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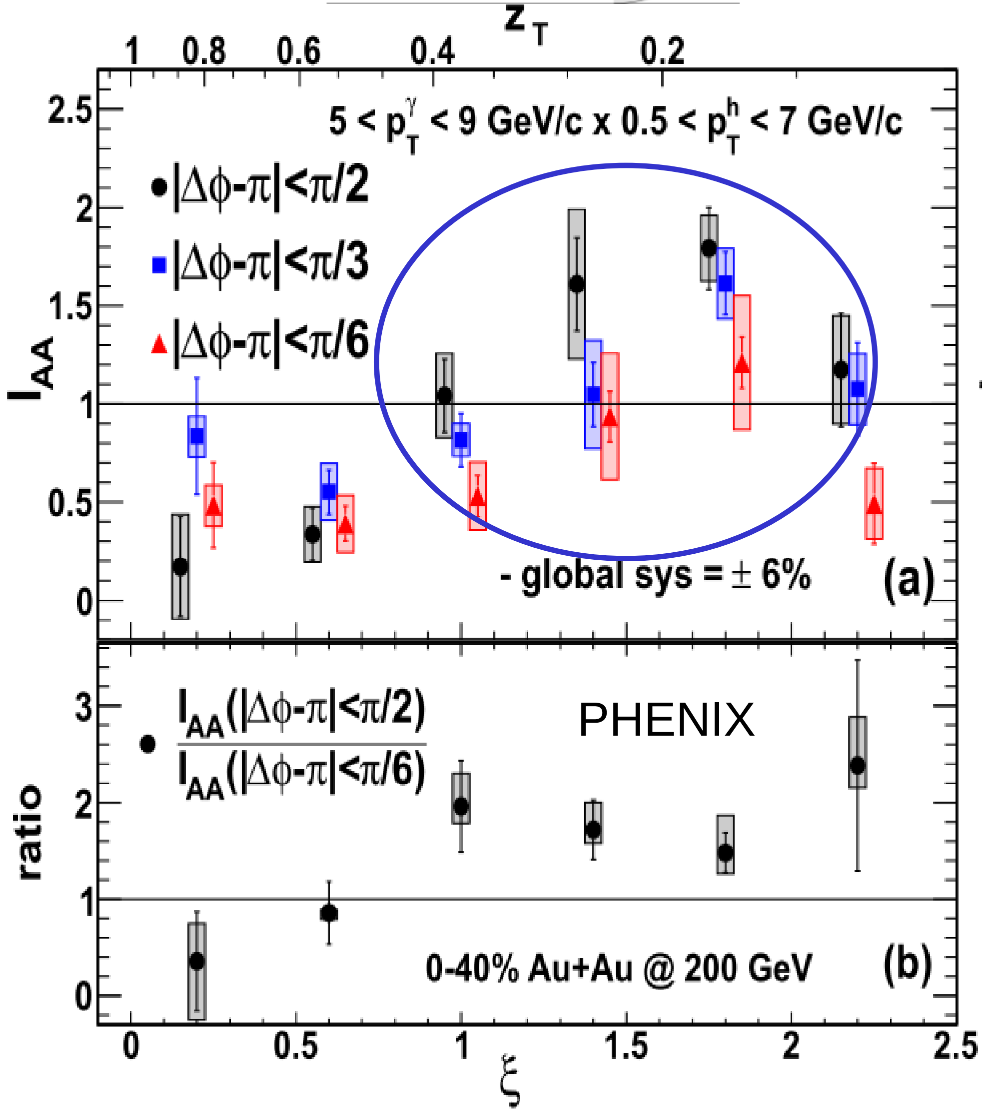
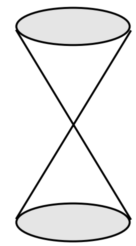
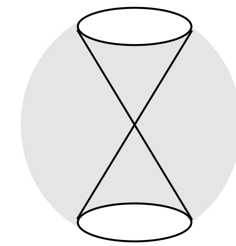
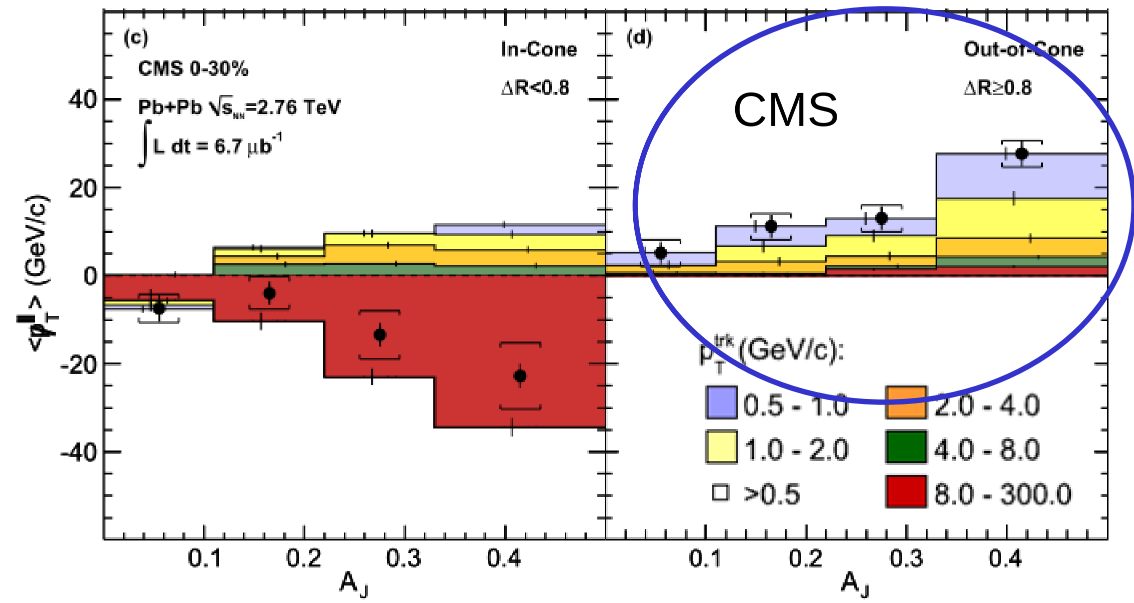




Tracks in
the jet cone
ΔR<0.8



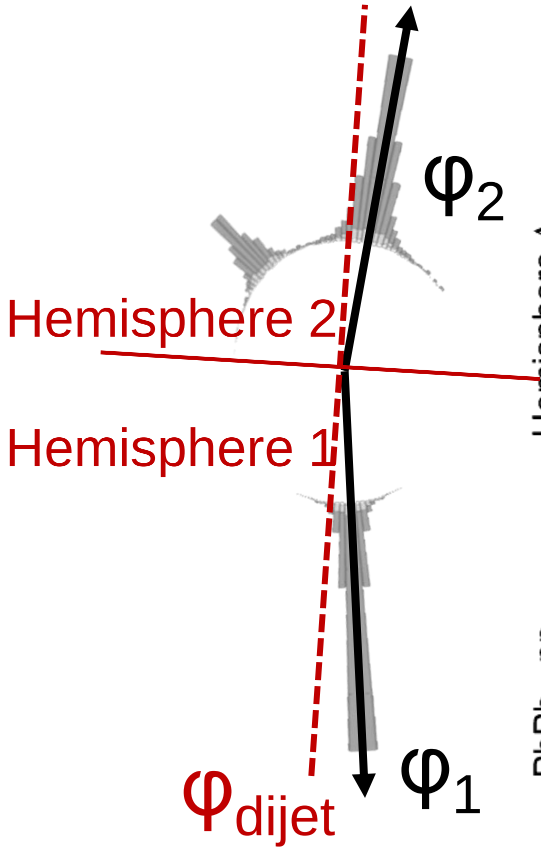
Tracks out of
the jet cone
ΔR>0.8

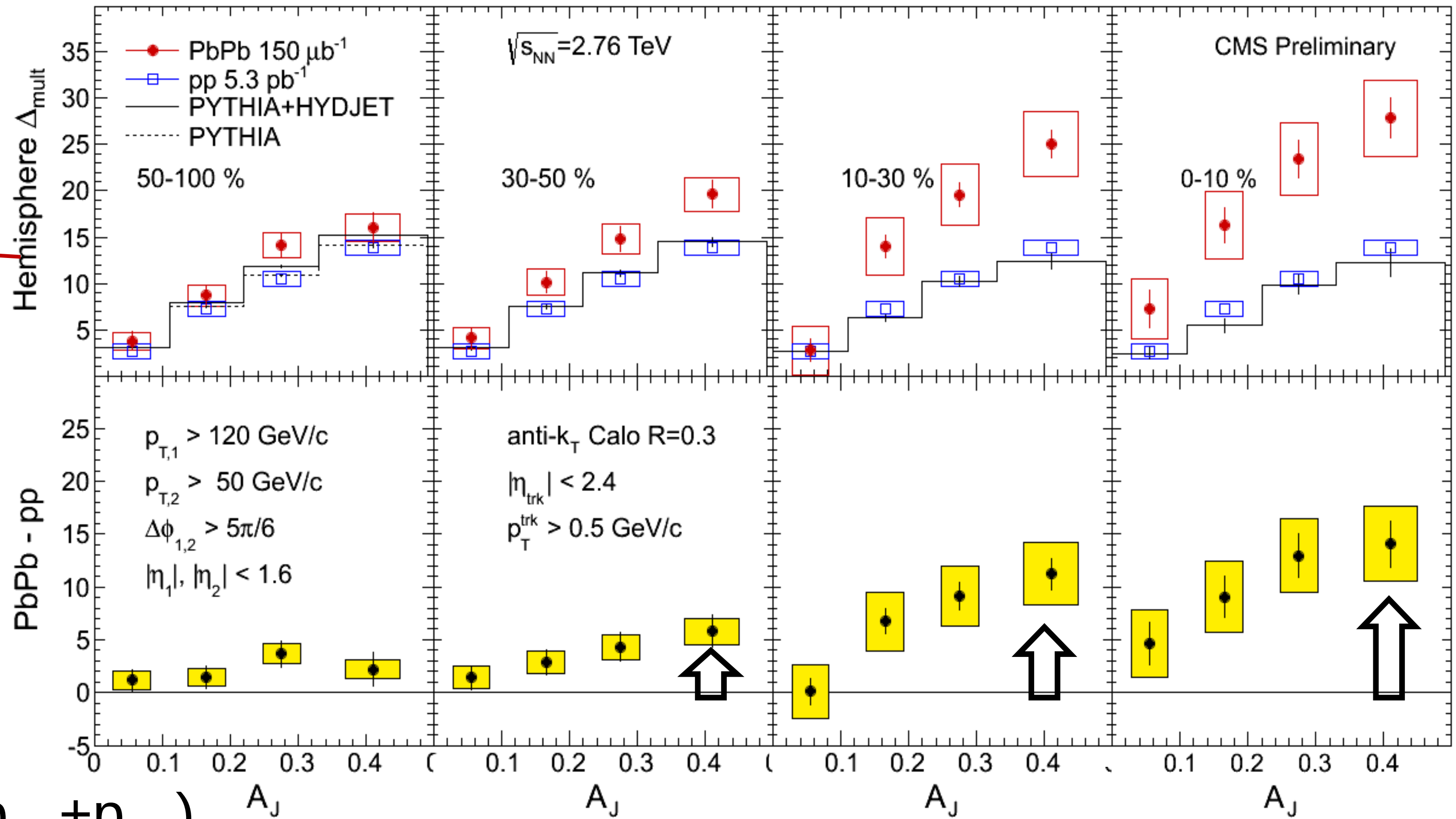


Lost energy: found in large $\Delta\varphi(\Delta R)$ with respect to the away-side jet axis, converted to low p_T particles.

2014: Multiplicity difference vs. A_J

CMS-PAS-HIN-14-010





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

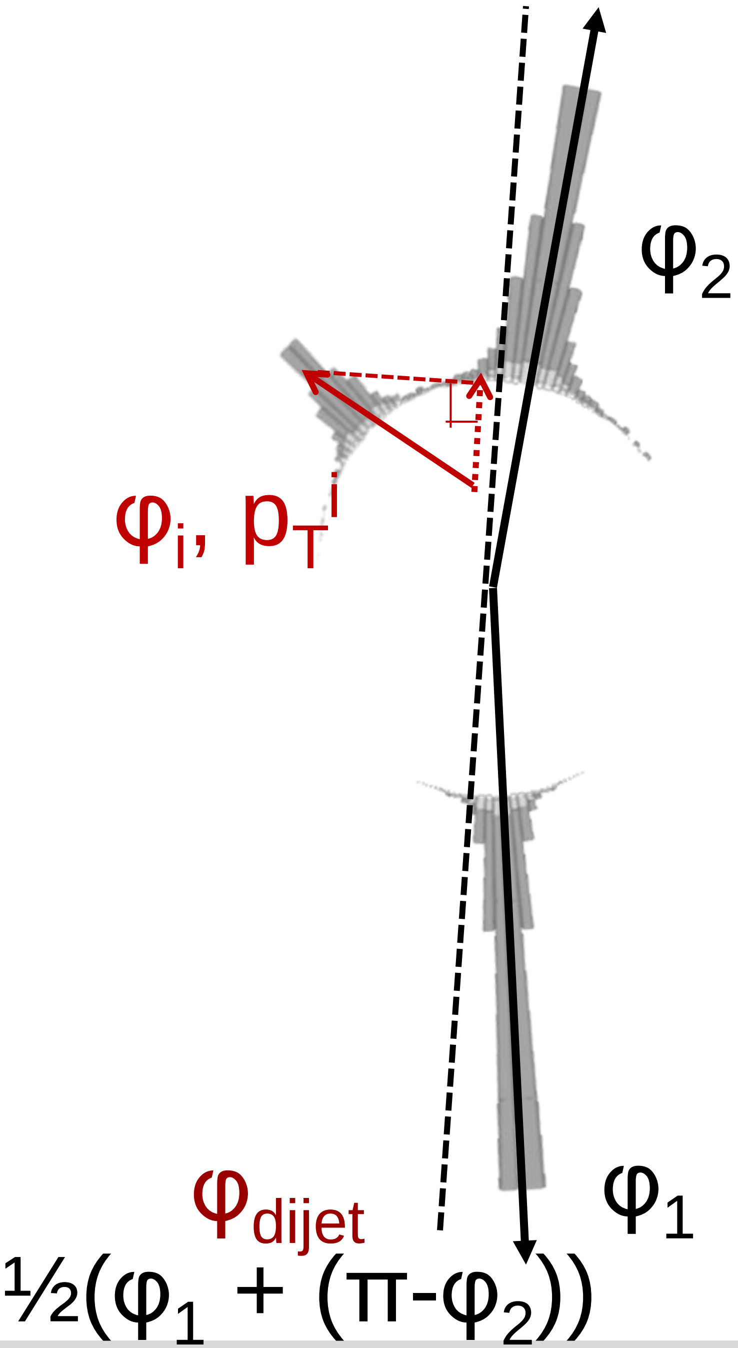
Multiplicity difference (in acceptance) increases as a function of A_J

The increase is larger in PbPb

The enhancement in PbPb compared to pp increases with centrality

Large A_J, 0-10% → 15 extra particles

2014 Missing p_T



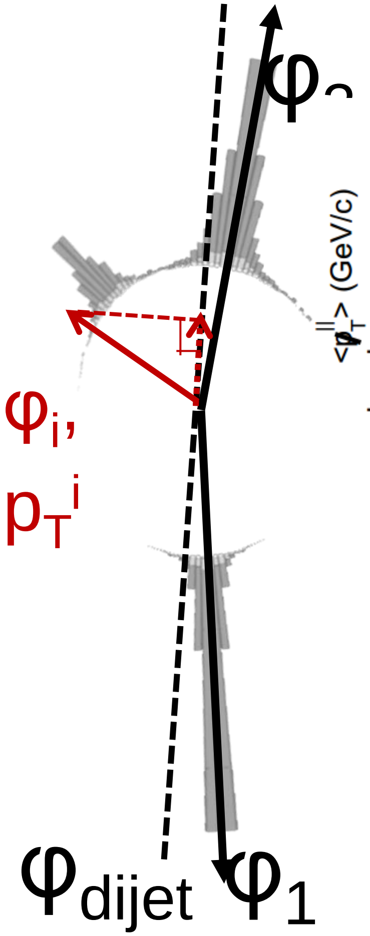
What is the multiplicity and **spectrum** of particles that balance the “extra” lost p_T?

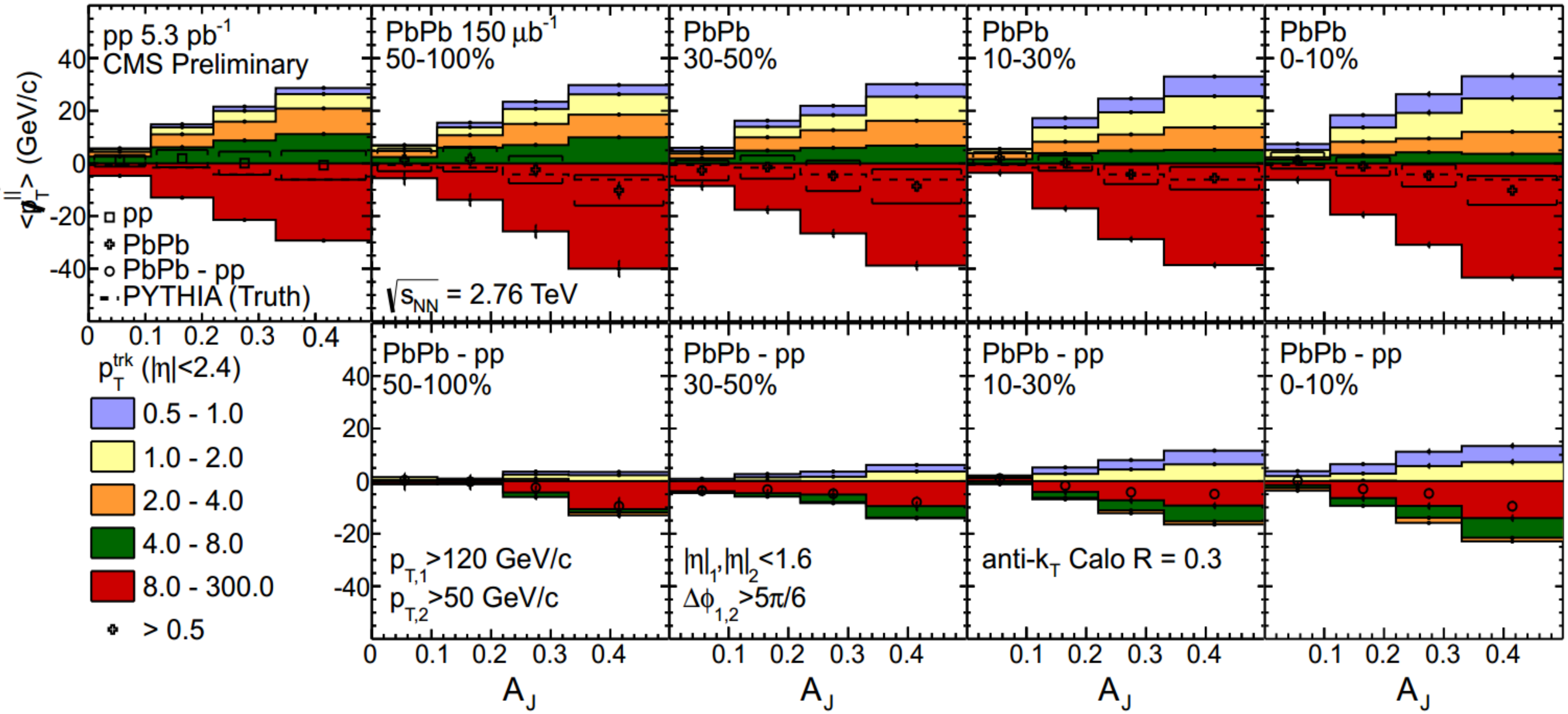
Calculate the missing p_T for charged particles in different p_T ranges

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\mathrm{Dijet}}\right)$$

Results - Missing p_T vs. A_J

CMS-PAS-HIN-14-010



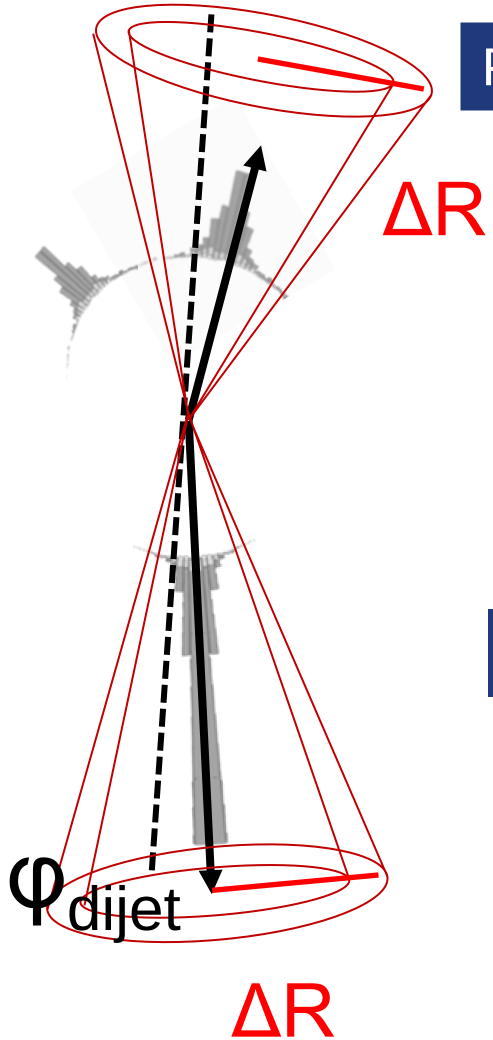


Access to high p_T particles increases as a function of A_J

In pp ⟶ Balanced by 2-8 GeV/c particles

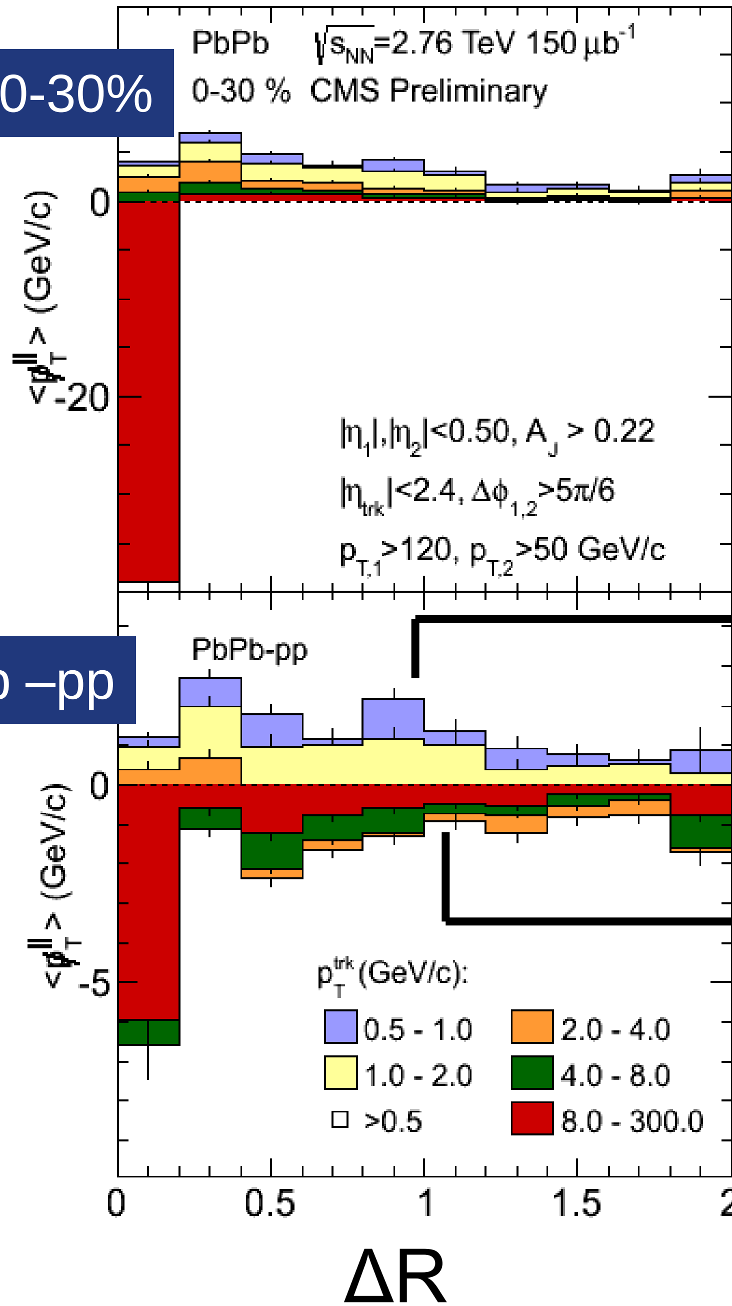
In PbPb ⟶ Balanced by particles with p_T < 2 GeV/c

Results - Missing p_T vs. ΔR



PbPb 0-30%

PbPb –pp



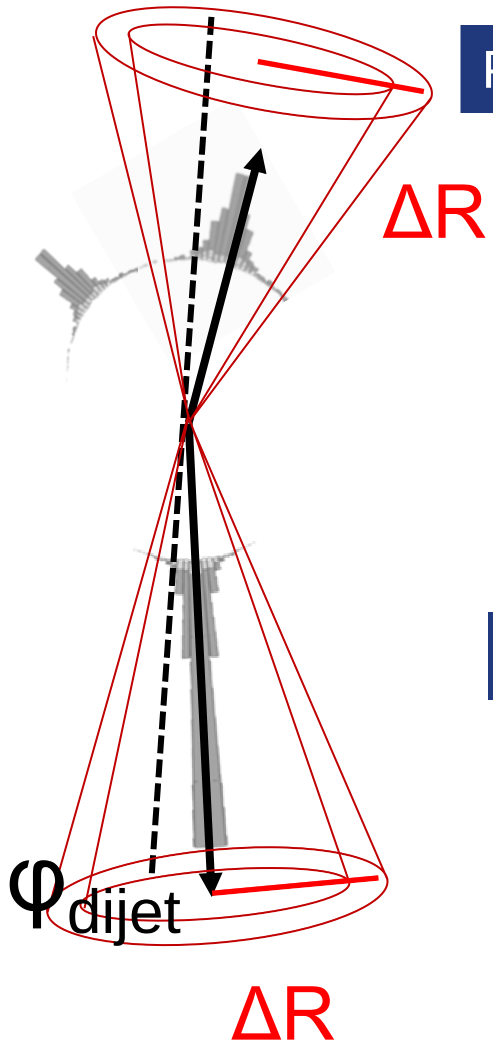
$A_J > 0.22$

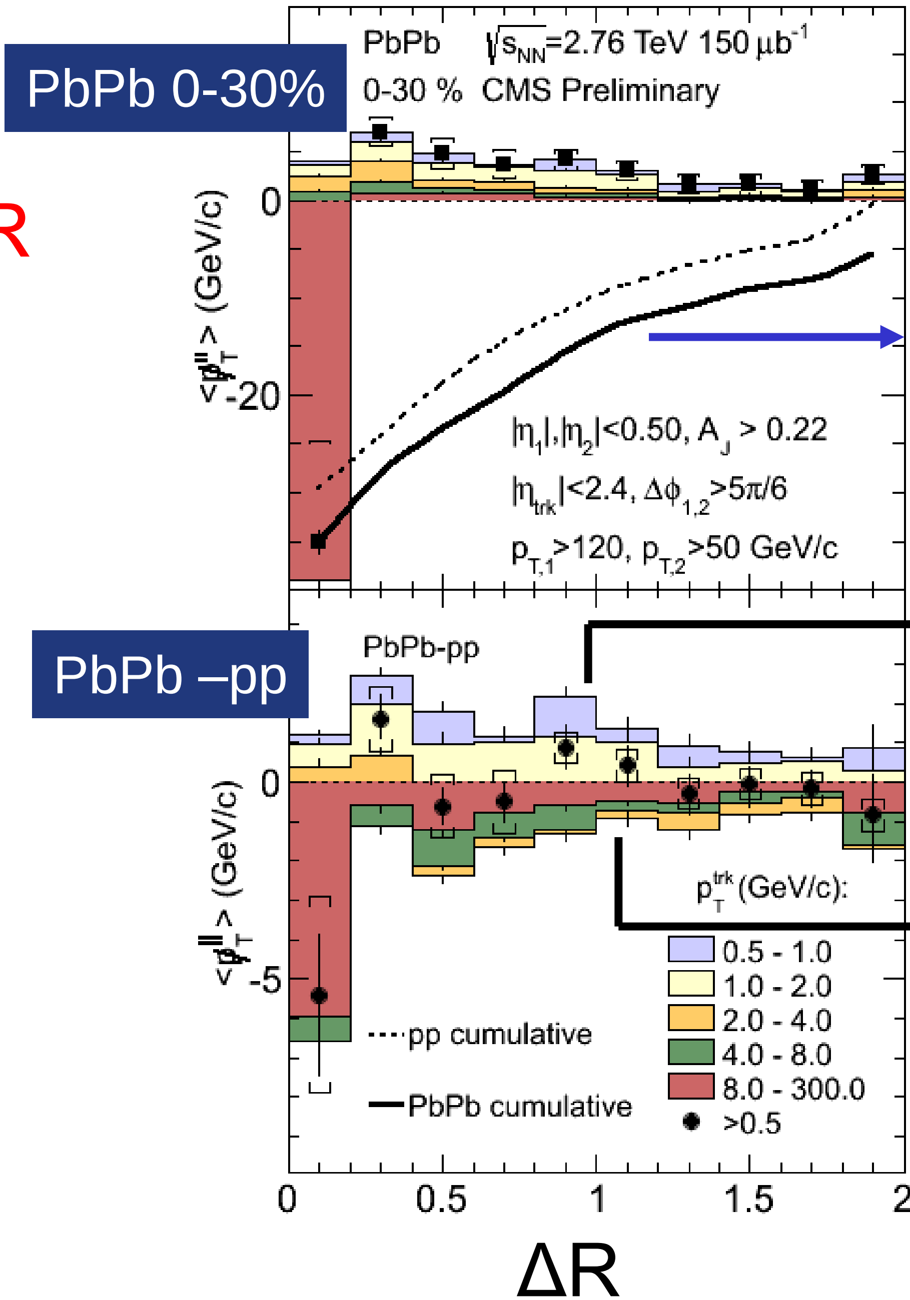
Enhancement of low p_T particles in PbPb

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

CMS-PAS-HIN-14-010

Results - Missing p_T vs. ΔR





$A_J > 0.22$

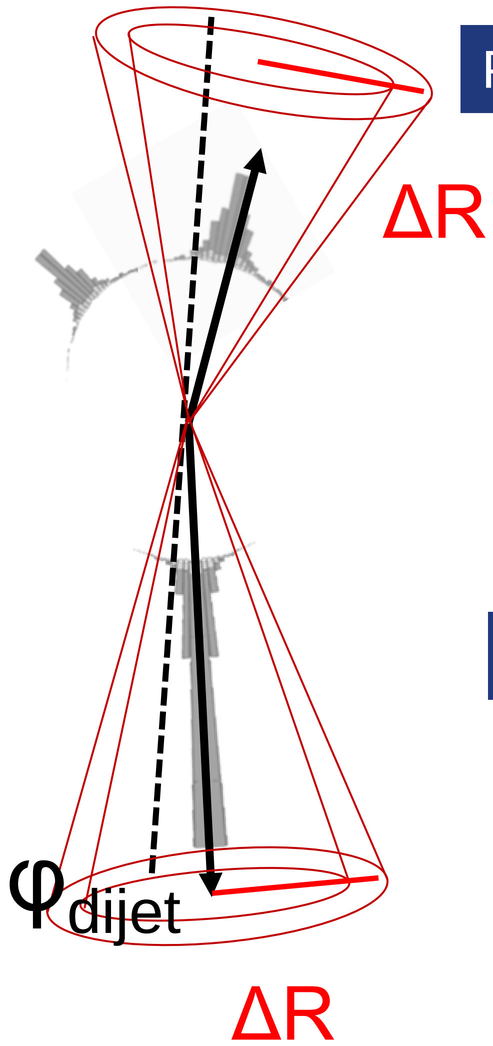
Similar shape of the balancing distribution in pp and PbPb

Enhancement of low p_T particles in PbPb

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

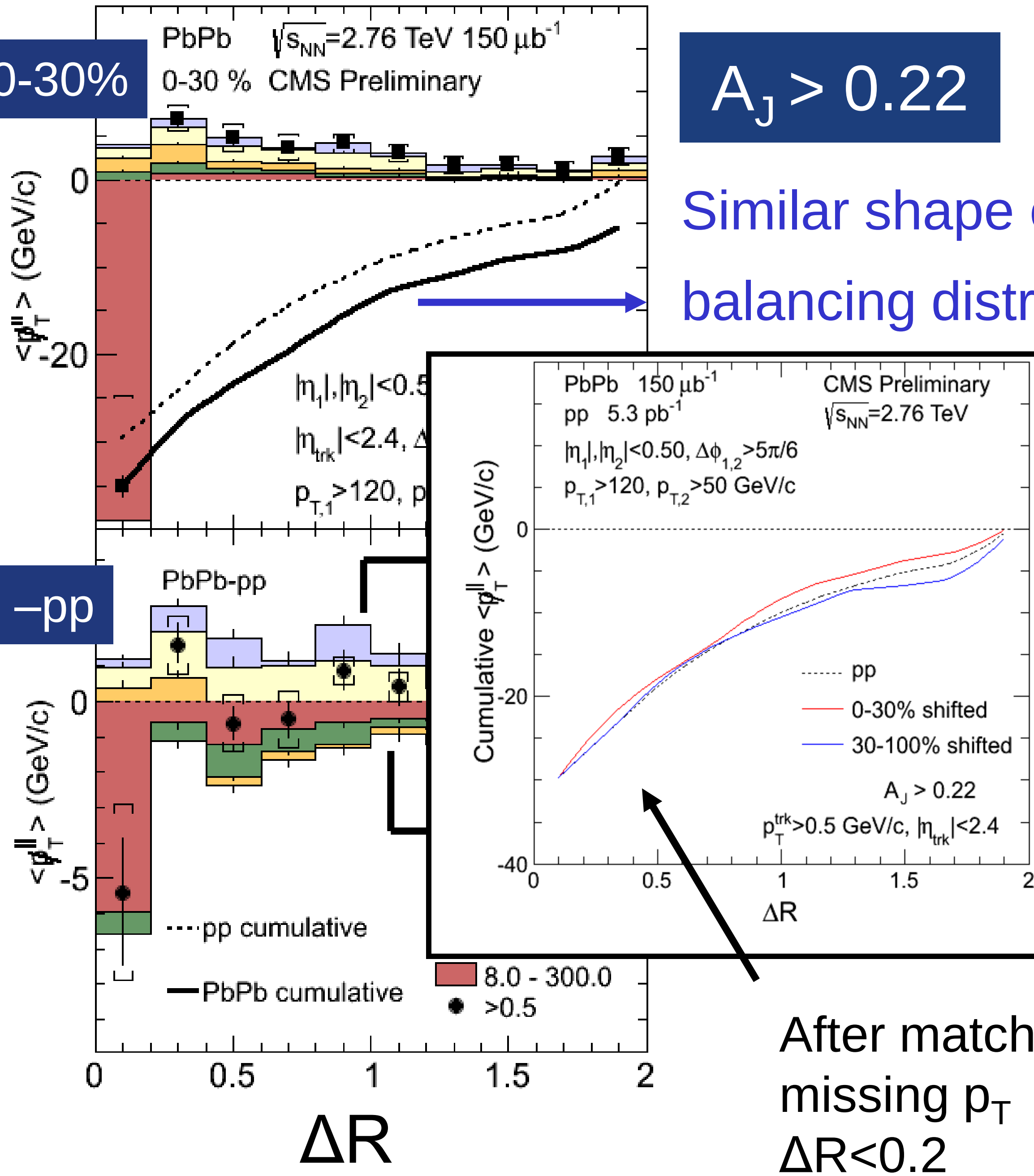
CMS-PAS-HIN-14-010

Results - Missing p_T vs. ΔR



PbPb 0-30%

PbPb –pp



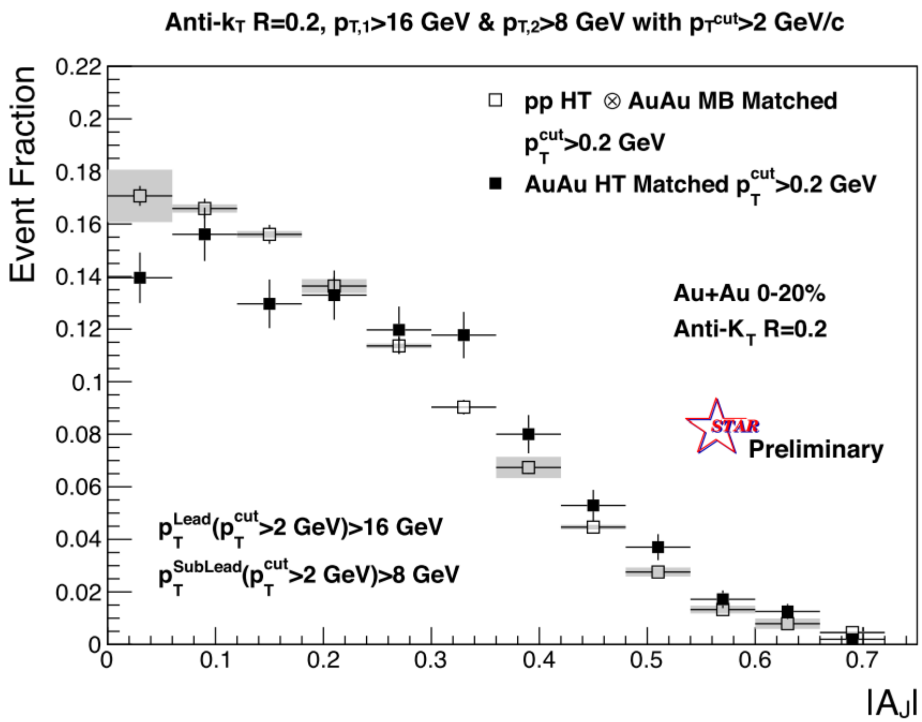
$A_J > 0.22$

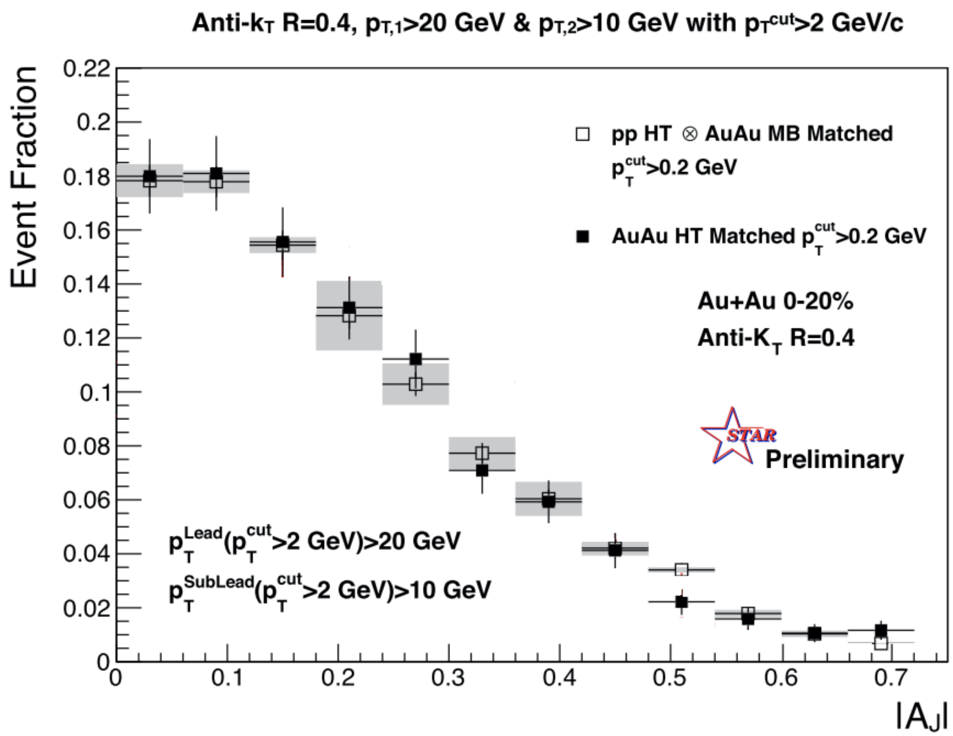
Similar shape of the balancing distribution in

After matching the missing p_T at $\Delta R<0.2$

Lost energy at RHIC

R=0.2 cone → R=0.4 cone





Dijet transverse momentum balance is recovered with anti-k_T R=0.4 jet reconstruction!!

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

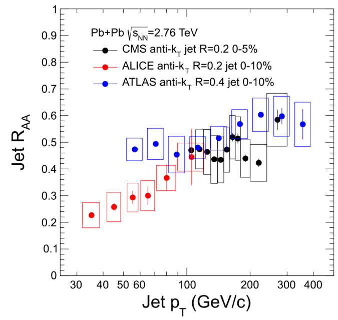
→ interesting to see what we get when implementing similar bias at the LHC

Jet quenching at LHC

Artist's view of a di-bullet event

Summary and outlook (1/2)

What's the fraction energy radiated out of the jet cone?



From jet R_{AA} and photon-jet: ~10% of the jet energy go out of the jet cone at high p_T, O(10 GeV)

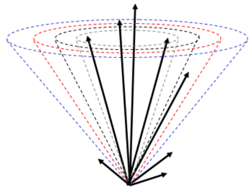
To figure out the $\Delta E(p_T)$ directly from data:

→ Important to measure triggered jet differential cross-section using different trigger objects (using ideally isolated photons for CMS+ATLAS / leading hadron in ALICE)

→ Measurements with different distance parameters

→ Measure jets from gluon, quark and heavy quark separately using W+jet, Z+jet, photon+jet and dijet events

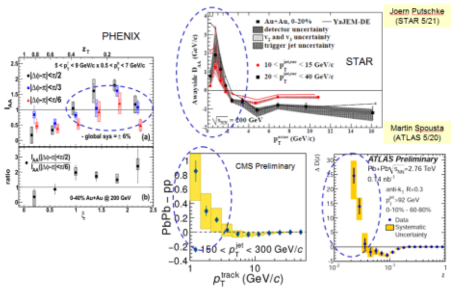
Can we recover the lost energy by jet reconstruction with large R?



Lost energy is recovered slowly, R=0.2-0.5 doesn't recover all the lost energy

Different behavior observed (in STAR) if biased jet fragmentation selection is used

Summary and outlook (2/2)



Jet structure modified?

Excess of low p_T particles inside the jet cone.

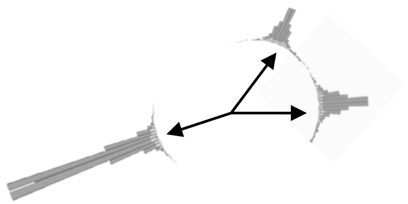
Modified jet FF and/or jet shapes can be explained by different classes of models

Which part of it is coming from the changing q/g fraction?

How does parton energy loss depend on the fragmentation pattern?

Can we learn more using sub-jet reconstruction?

Fluctuation of jet fragmentation modification?



Where does the lost energy go?

The lost energy is carried by low p_T particles far away from the jet cone

Distribution of lost energy: Initial configuration (2/3/multi-jet) + medium effects?

Can we kill the effect by biasing the jet fragmentation?

Can we kill / enhance the effect by requiring / rejecting a third jet in the event?

What are the alternative way to select quenched jets?

Backup slides