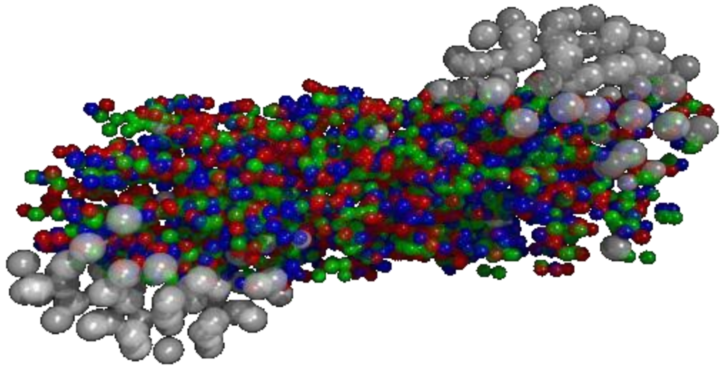
Jets in high-energy heavy ion collisions

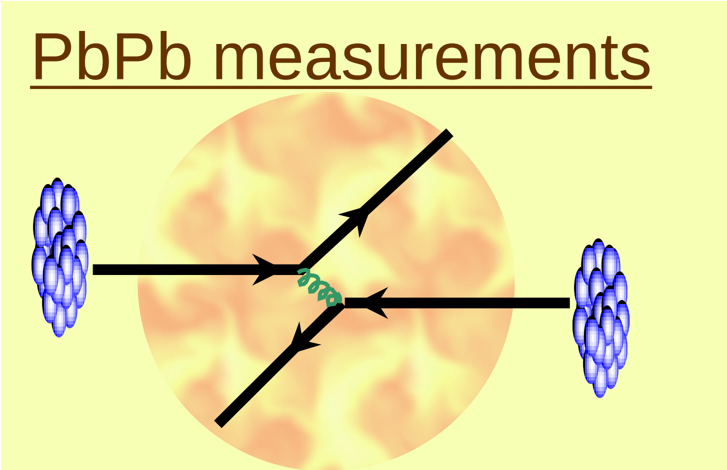
Yen-Jie Lee (CERN)

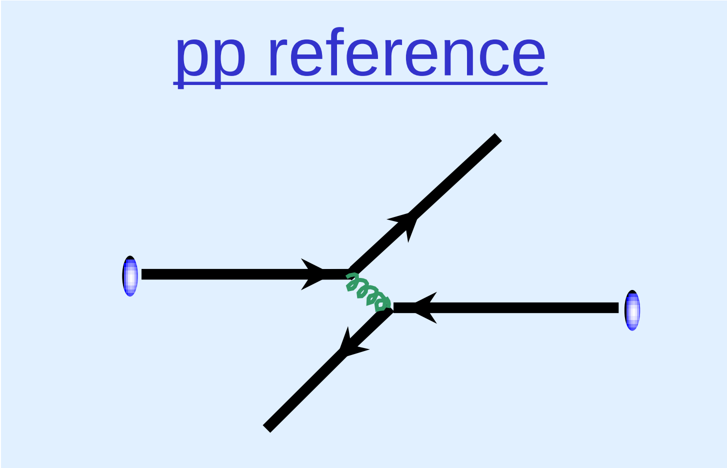
Hot Quarks 2012

Probe the medium

- Goal: Understand the property of QGP
- Problem: the lifetime of QGP is so short (O(fm/c)) such that it is NOT feasible to probe it with an external source
- Solution: use high p_T jets, γ/Z boson produced with the collisions
- Extract medium property by comparing the results from AA (QCD in medium) and pp collisions (QCD in vacuum)



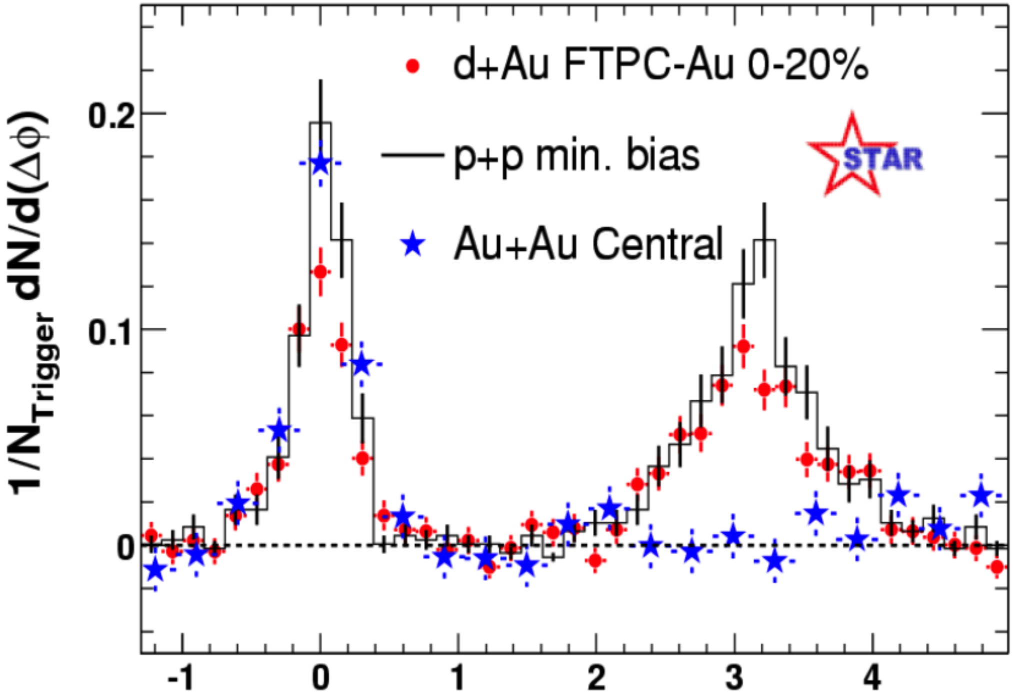




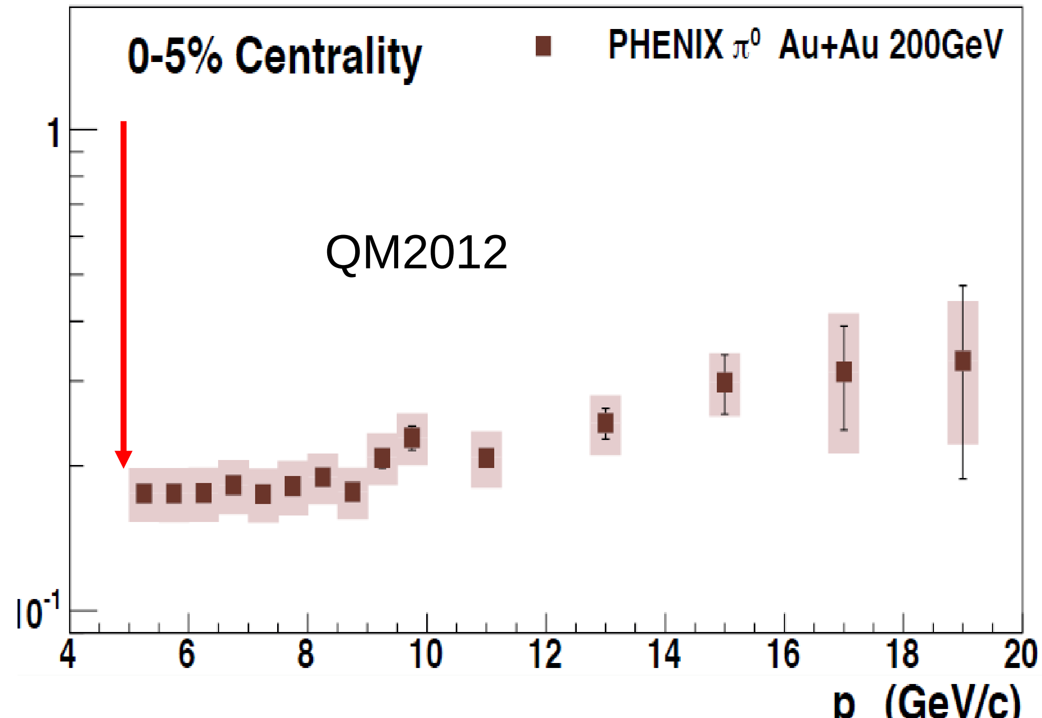
Jet quenching at RHIC

Observation of jet quenching without jet reconstruction

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



Phys. Rev. Lett. 91 (2003) 072304
Phys. Rev. Lett. 97 (2006) 162301

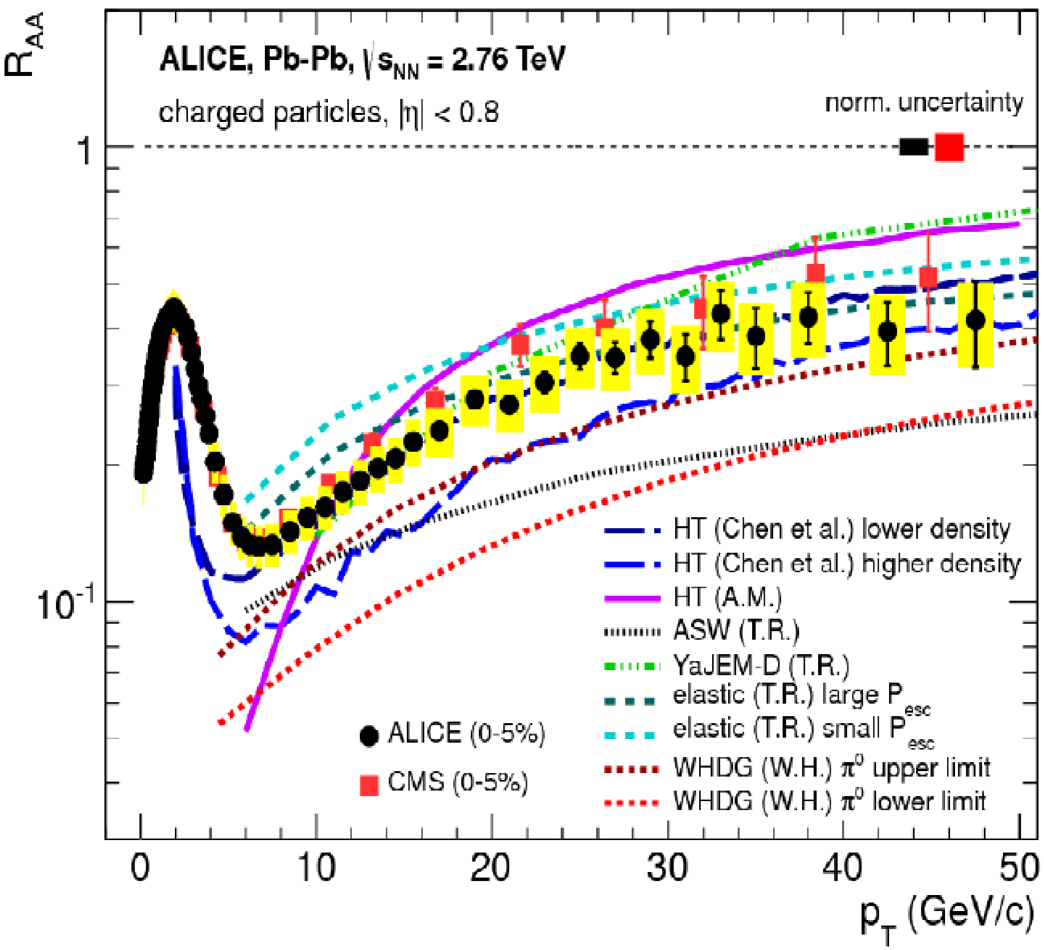


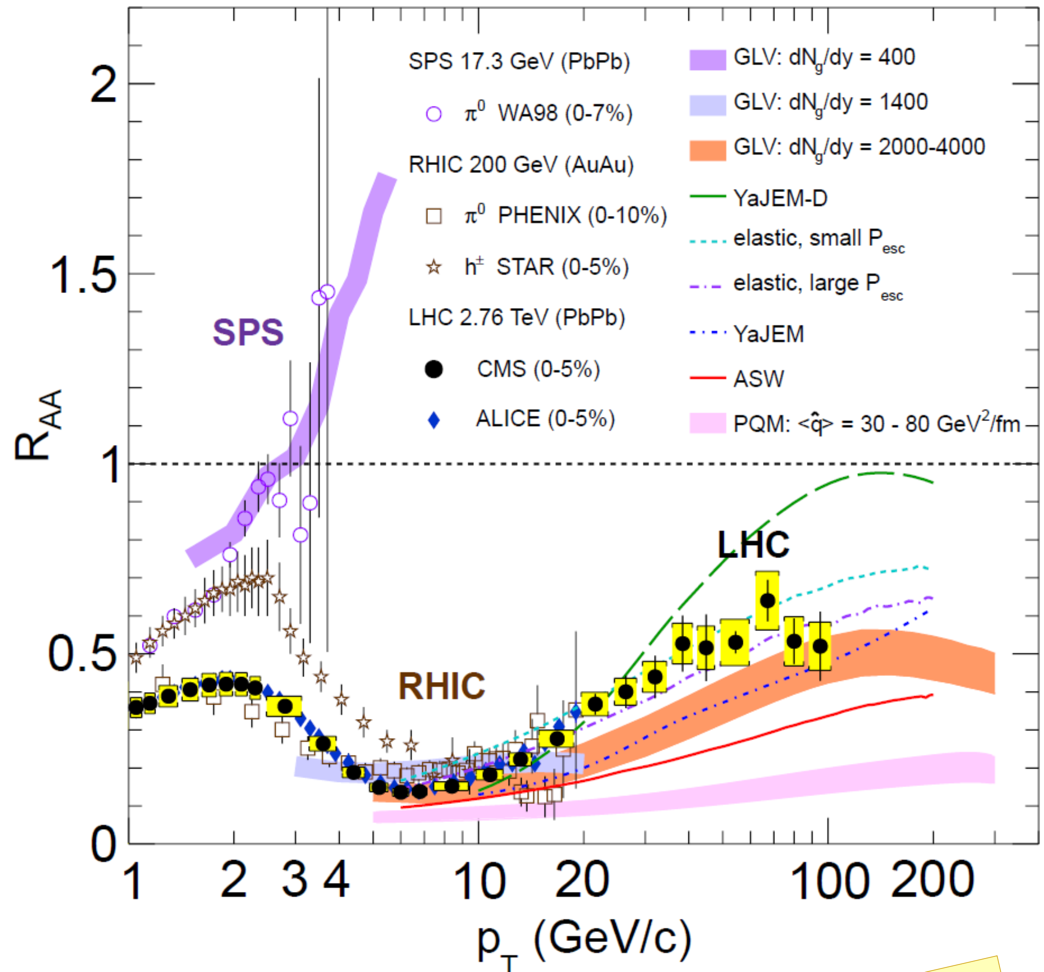
2003: Disappearance of the away side jet

Quark Matter 2012: raising R_{AA} at high p_T

Charged particle R_{AA} at the LHC

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



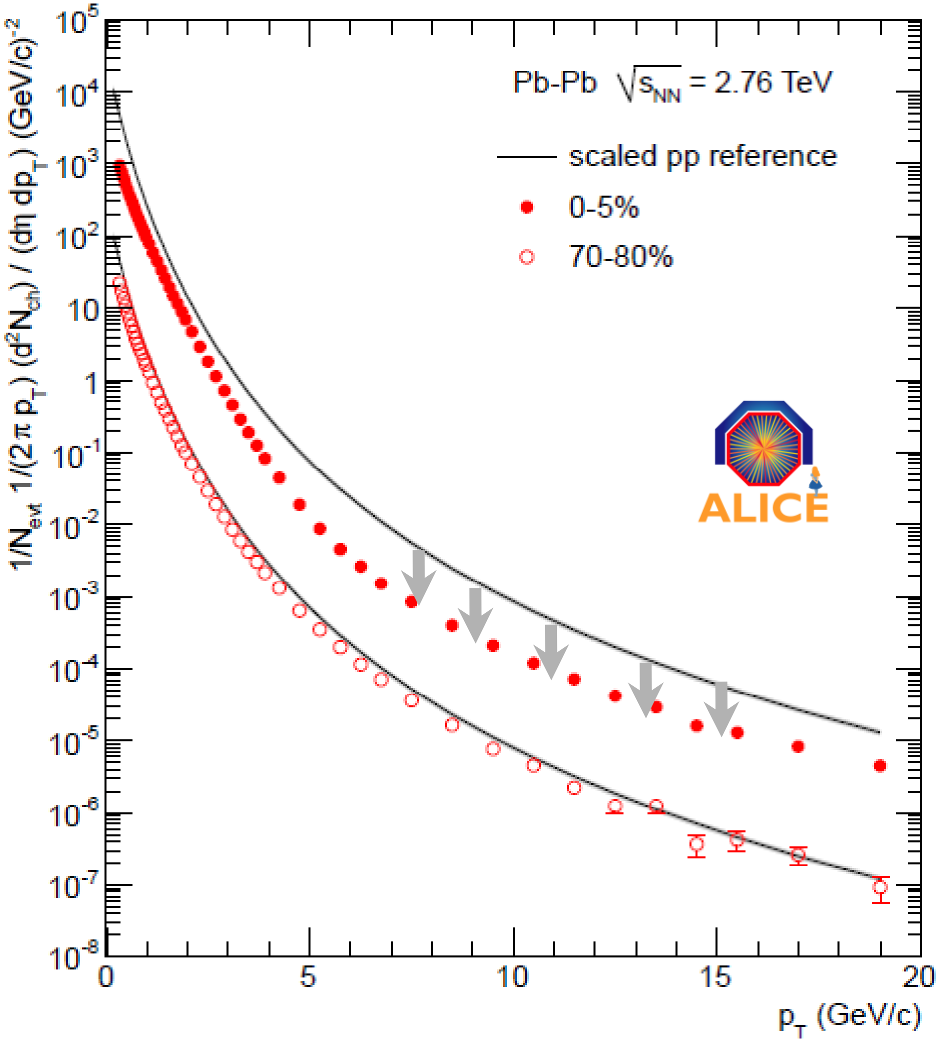


Provide constraints on the parton energy loss models

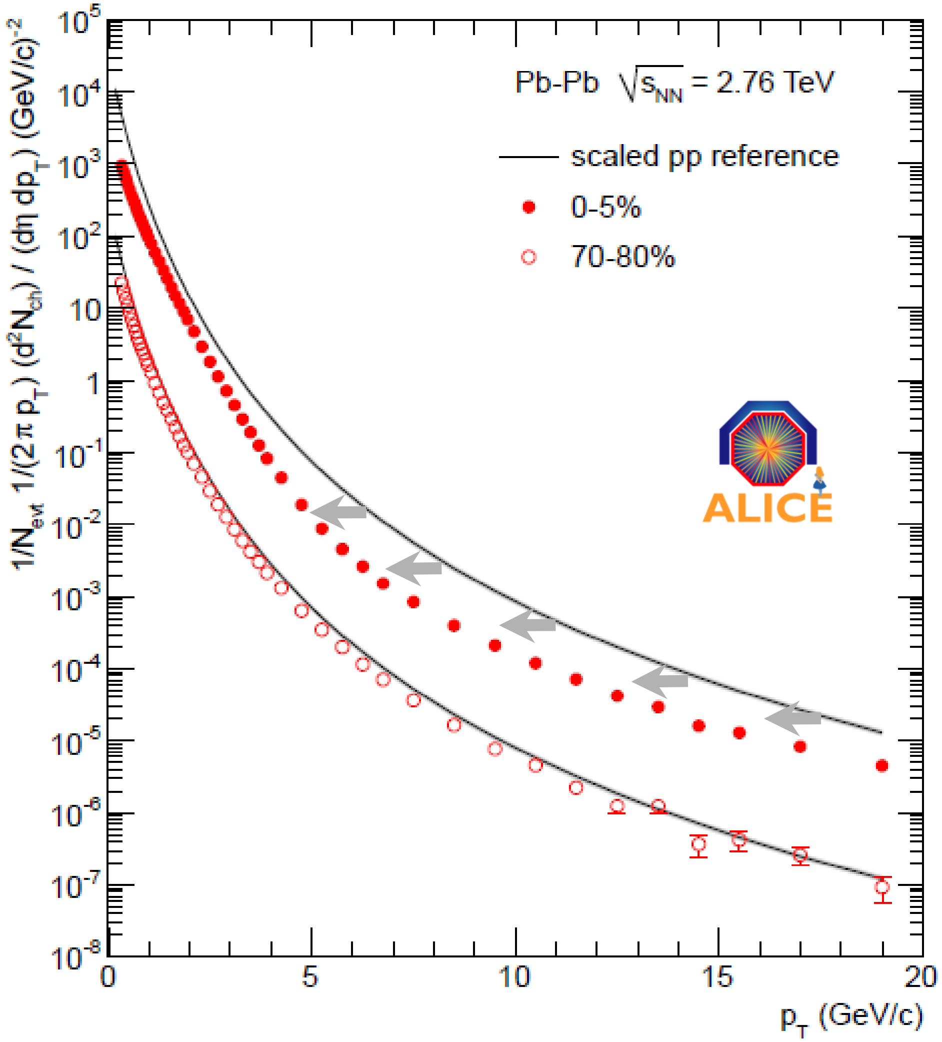
Yongsun Kim

Charged particle spectra

Absorption?



Energy loss?

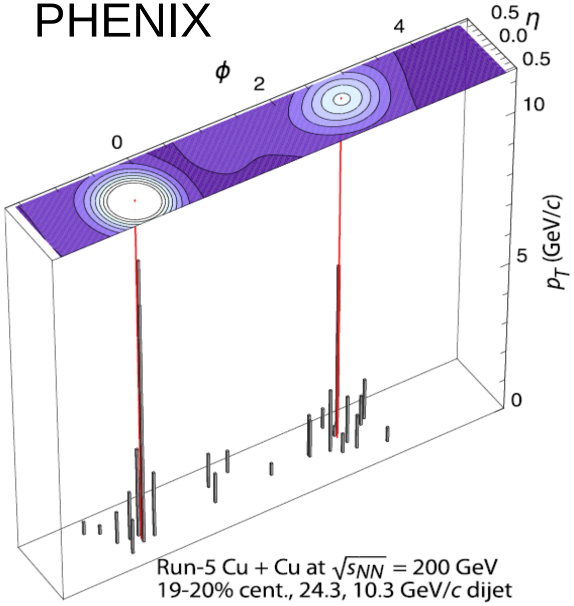


Single hadron spectra itself do not provide details of the underlying mechanism

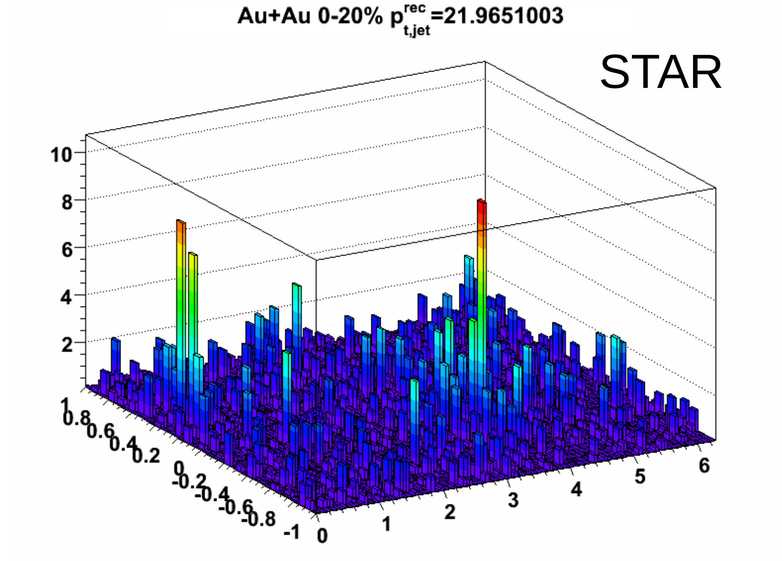
→ Need direct jet reconstruction and correlation studies!

Jet events in heavy ion collisions

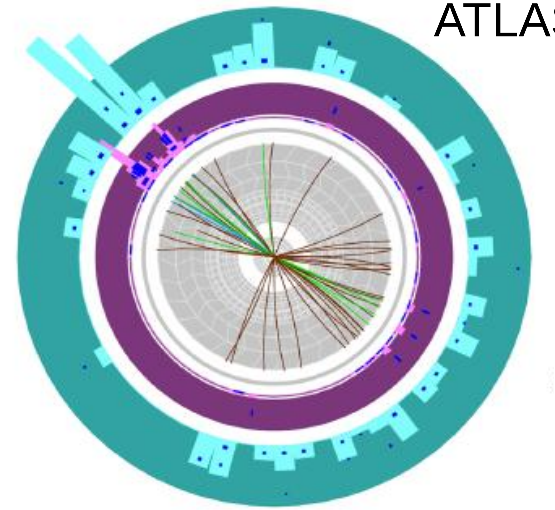
PHENIX



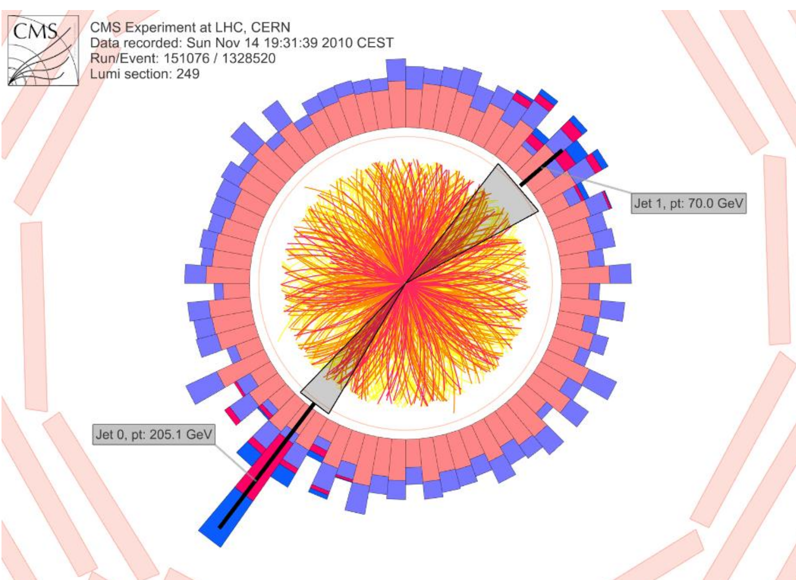
STAR

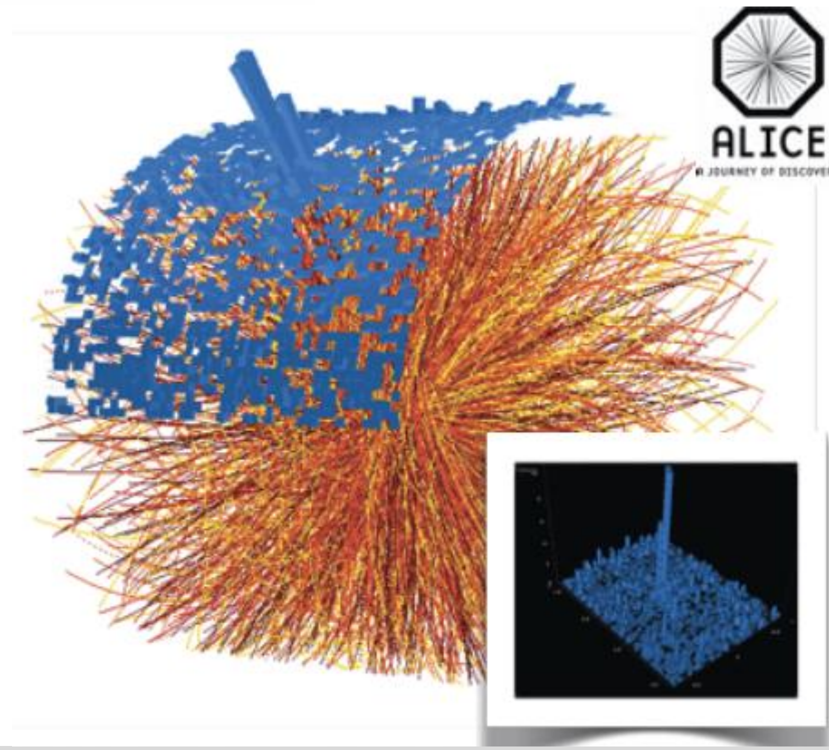


ATLAS



CMS





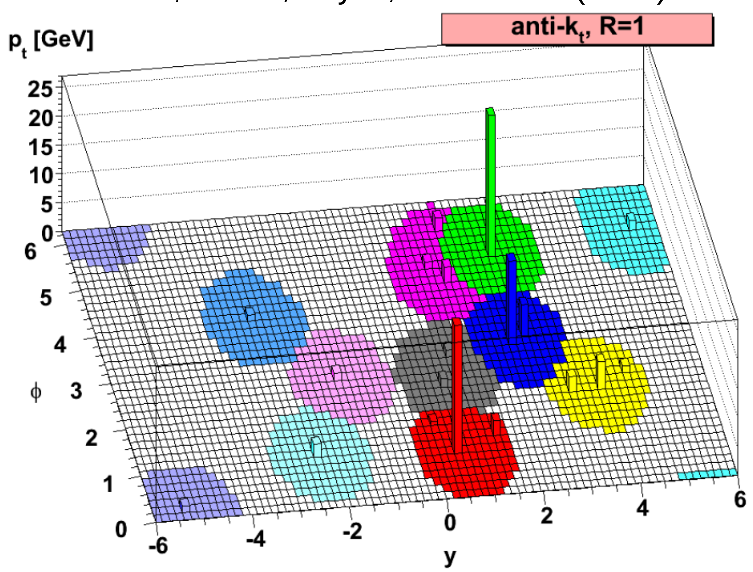
From particles to jets

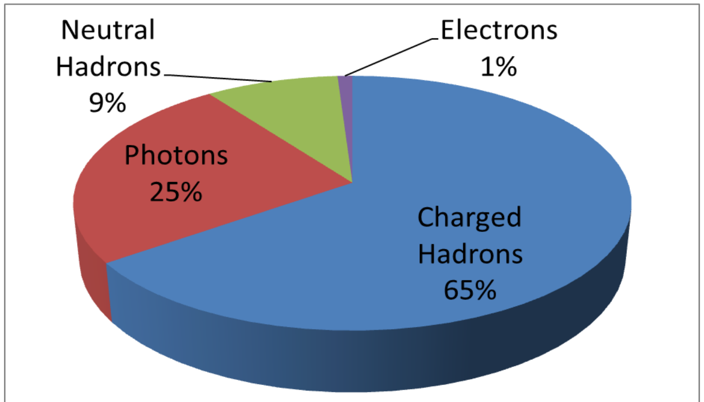
Need rules to group the particles

A popular algorithm is anti-k_T algorithm
Used in STAR, PHENIX, ALICE, ATLAS and CMS analyses

Other algorithms: k_T (used in STAR) and Gaussian filter (used in PHENIX)

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



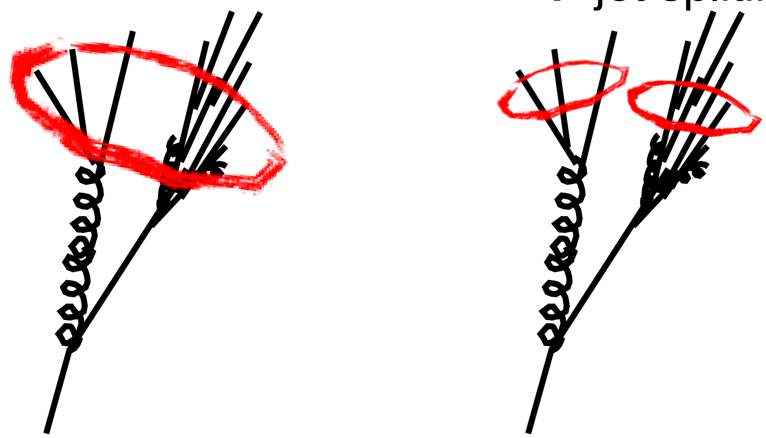


A typical high p_T jet

Radius parameter: decide the resolution scale

Large radius parameter

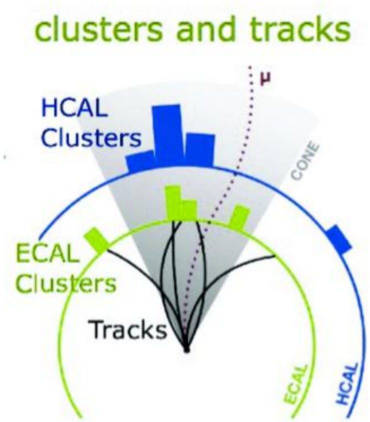
Small radius parameter → jet spliting



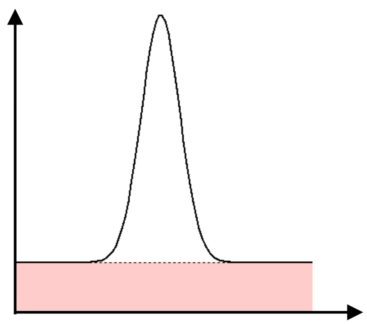
ΔR = 0.2, 0.3, 0.4, 0.5 are used in RHIC and LHC analyses

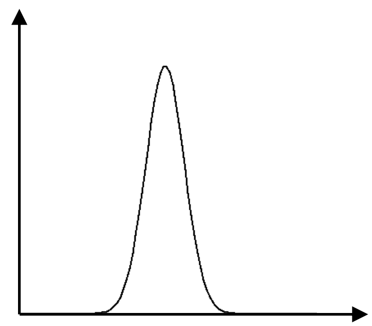
Jet reconstruction in heavy ion collisions

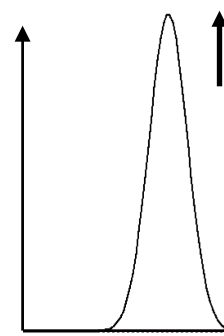
Track only
Calorimeter only
Or Calo+Track



Either correct to track jet level
(ex. ALICE)
Or including neutral component
(ex. CMS, ATLAS)







Raw jet energy → Background subtraction → Jet energy correction → Jet energy

Background subtraction: Remove underlying events contribution

Jet energy correction: MC Simulation ex: PYTHIA

Rosi Reed
Betty Bezverkhny Abelev
Michal Vajzer

Three possible scenarios

To explain the suppression of high p_T particles

Ads/CFT: Andrej Ficnar

Interference effect
Mauricio

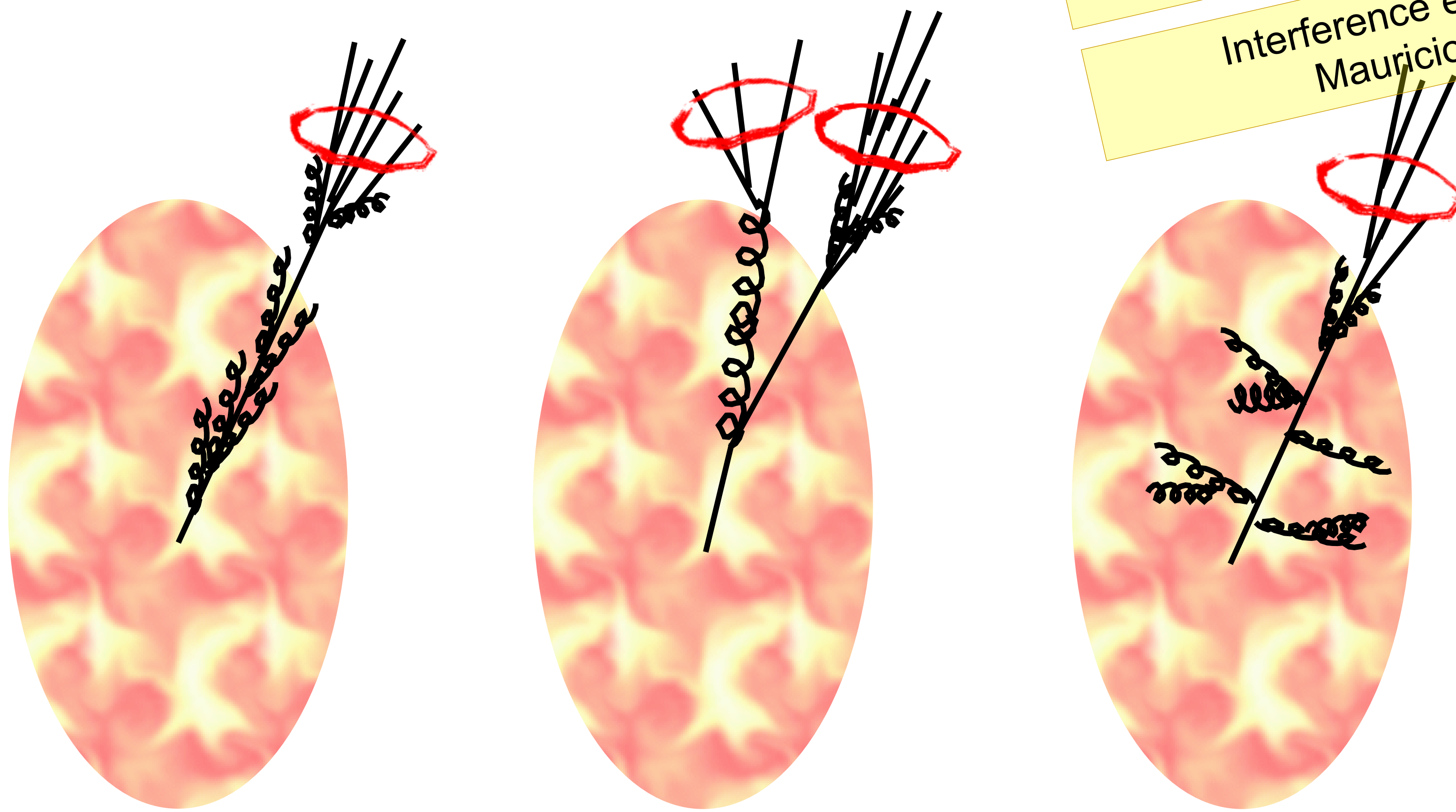
Soft collinear radiation	Hard radiation	Large angle soft radiation "QGP heating"
GLV + others	PYTHIA inspired models Modified splitting functions	AdS/CFT Interference

Three possible scenarios

Can we collect the radiated energy back?
Do we see strong suppression of high p_T jets?

Ads/CFT: Andrej Ficnar

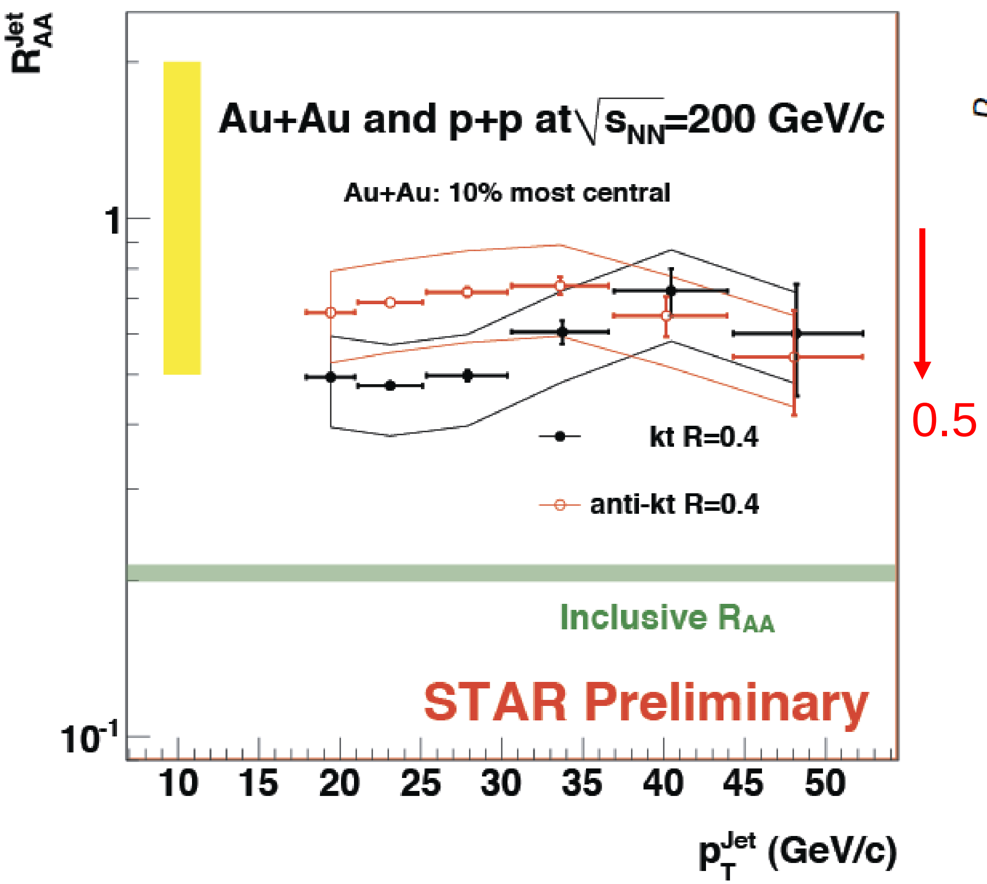
Interference effect
Mauricio



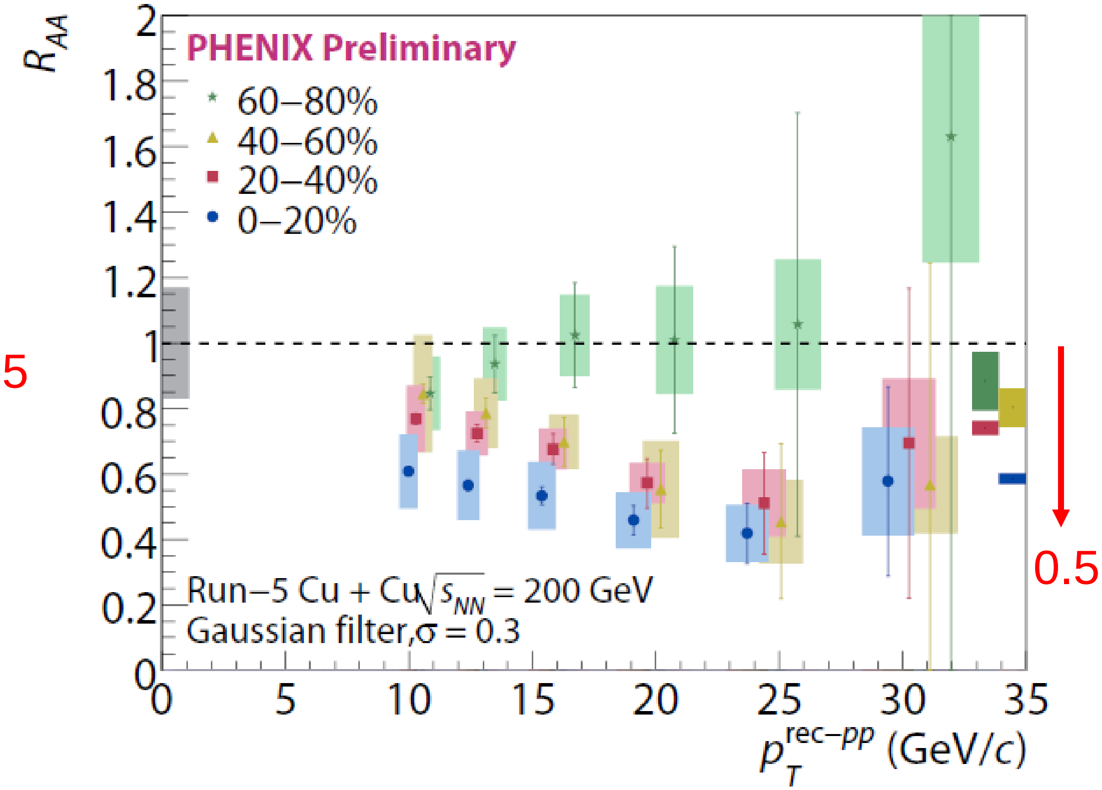
Soft collinear radiation	Hard radiation	Large angle soft radiation "QGP heating"
GLV + others	PYTHIA inspired models Modified splitting functions	AdS/CFT Interference

Inclusive Jet R_{AA} at the RHIC

Compare AuAu to pp



Compare CuCu to pp



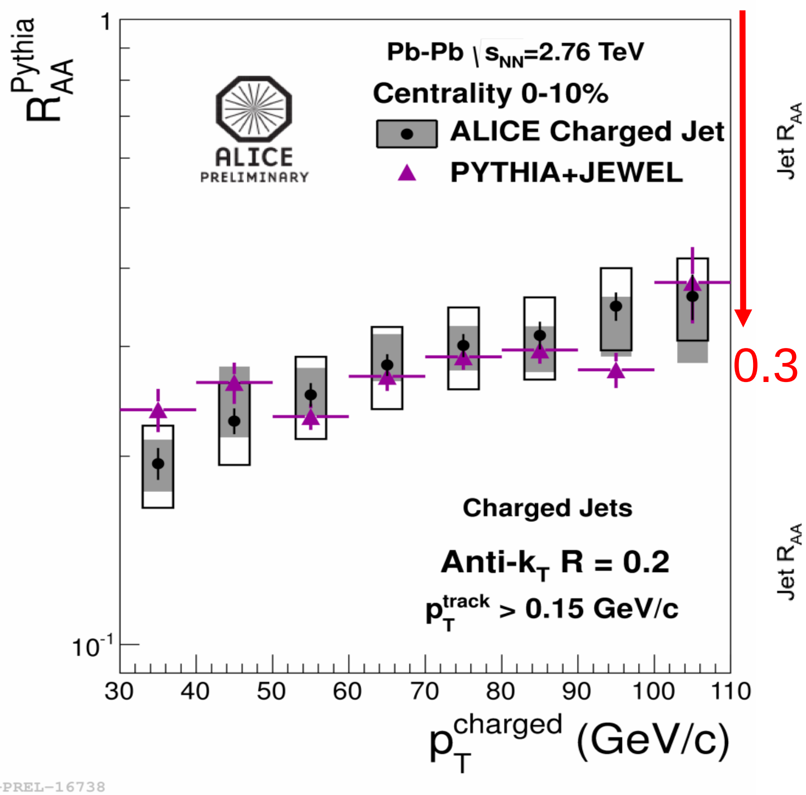
Strong suppression of inclusive high p_T jets!

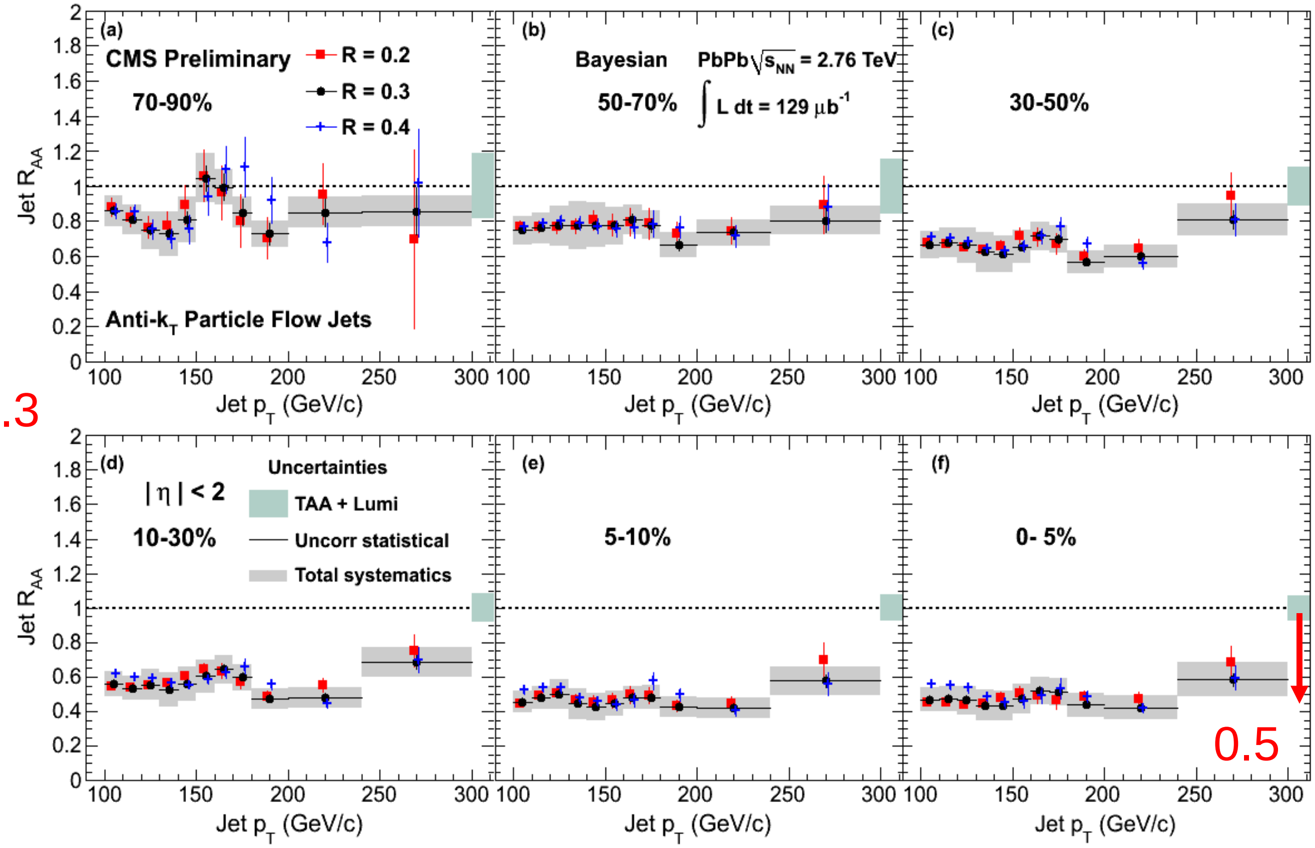
A cone of R=0.3, 0.4 doesn't catch all the radiated energy

Inclusive jet R_{AA} at the LHC

Compare PbPb to PYTHIA (pp generator)

Compare PbPb to pp data





Track Jet

Rosi Reed
Salvatore Aiola

Particle Flow Jet (Calo+track)

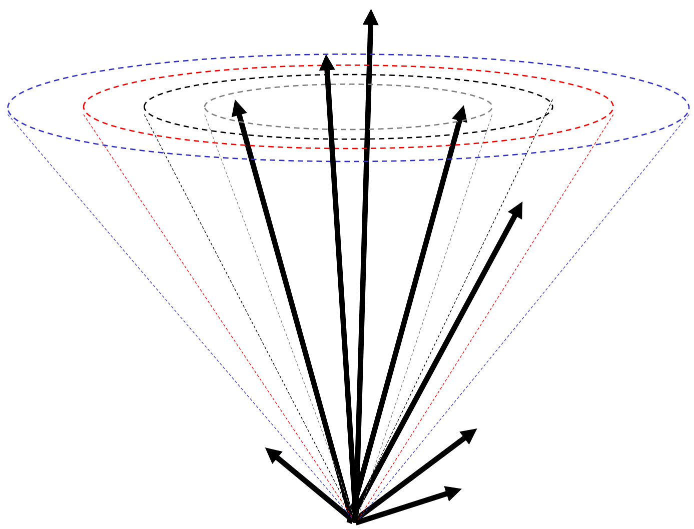
Yongsun Kim

Strong suppression of inclusive high p_T jets!

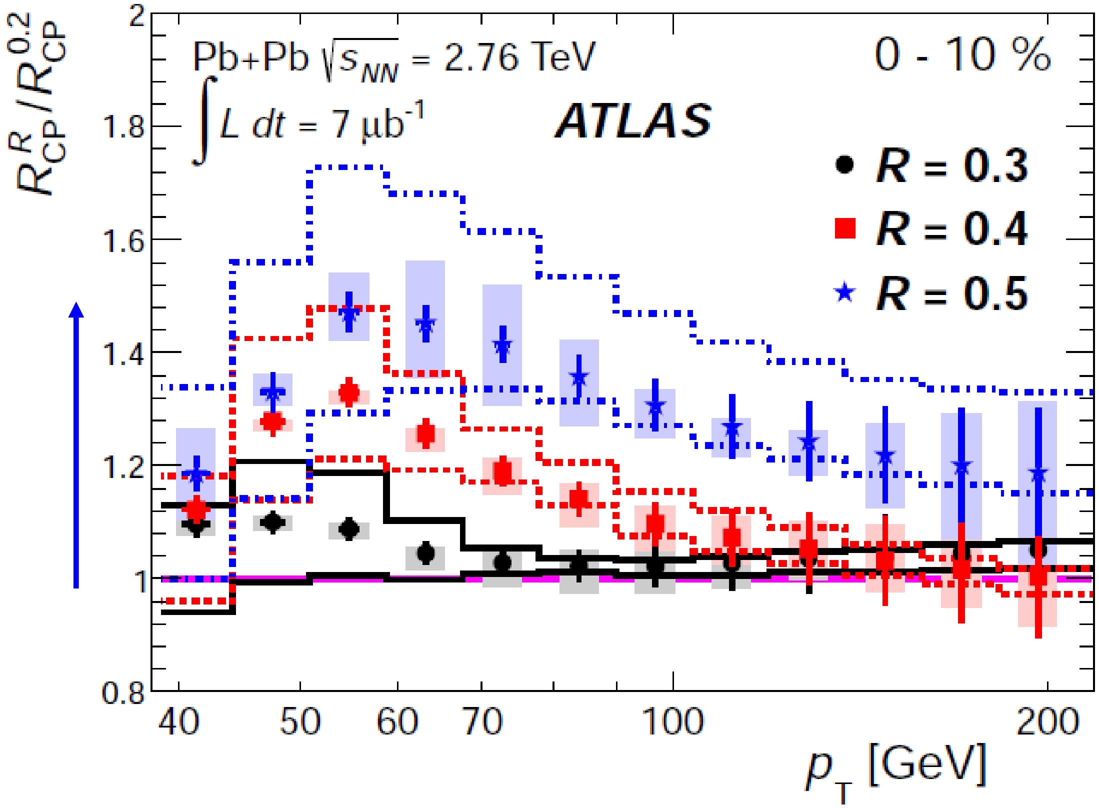
A cone of R=0.2, 0.3, 0.4 doesn’t catch all the radiated energy

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



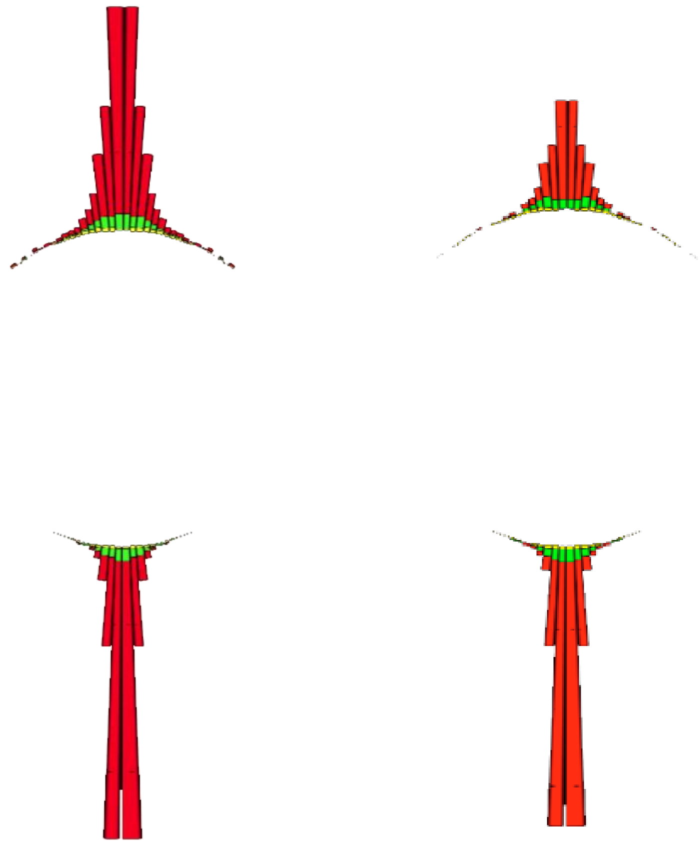
Hint of less suppression with large cone!

Motivate detailed studies on jet shapes

Martin Spousta

Correlation study: Di-jet imbalance

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

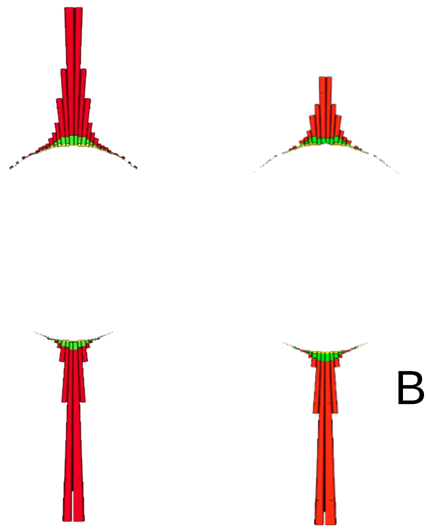


Small A_J
(Balanced dijet)

Large A_J
(Un-balanced dijet)

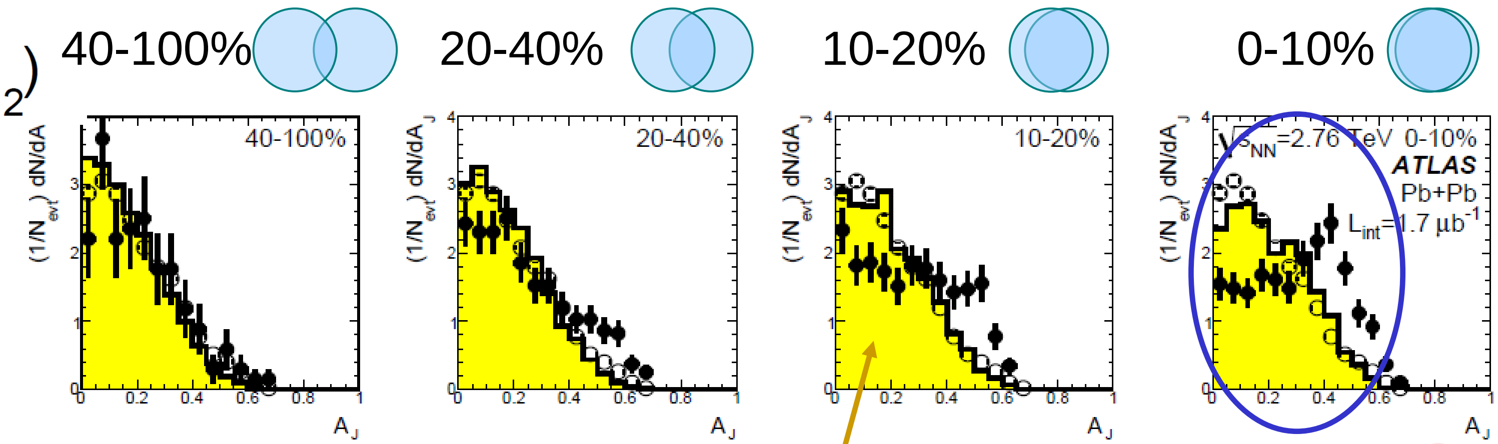
First observation: Di-jet imbalance

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



Small A_J (Balanced dijet)

Large A_J (Un-balanced dijet)



← Balanced dijet

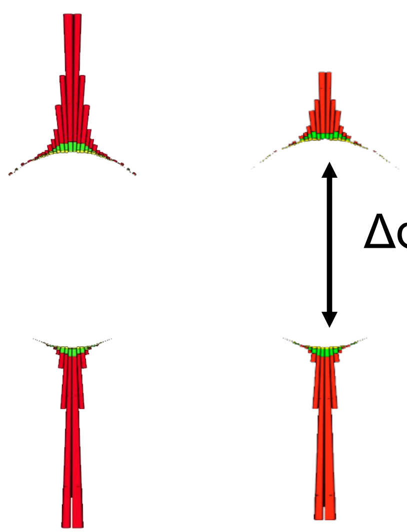
→ Asymmetric dijet

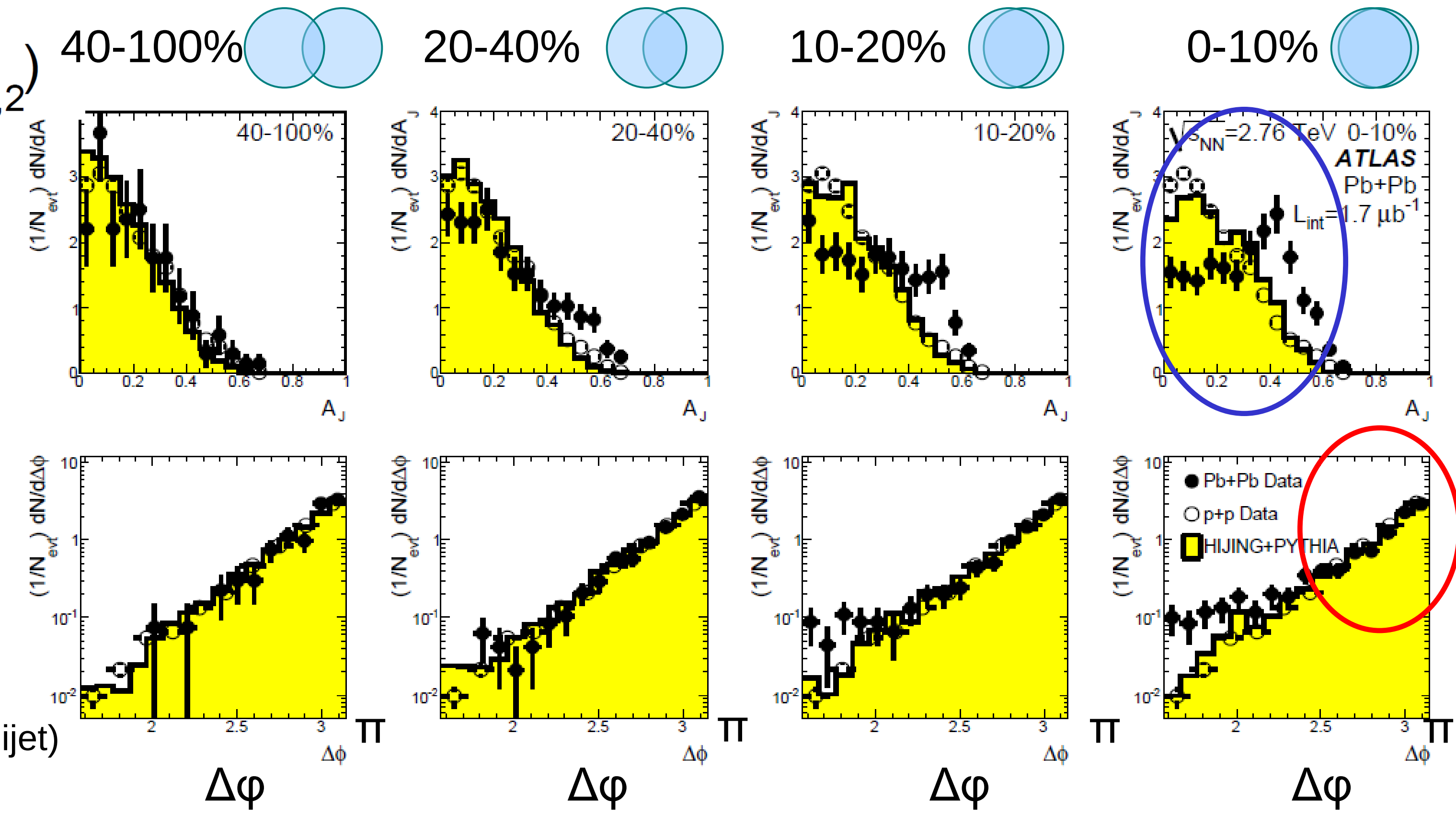
pp reference

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

Martin Spousta

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



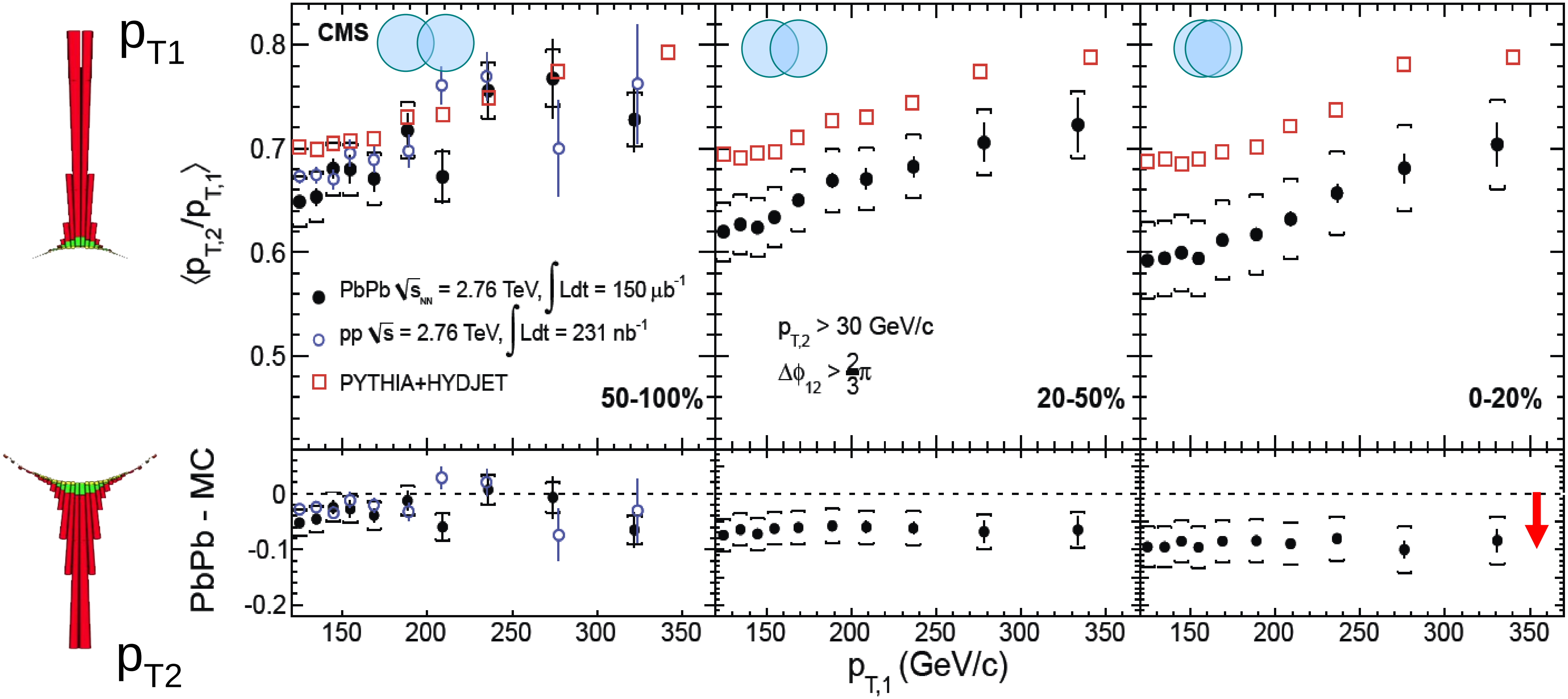


Parton energy loss is observed as a pronounced energy imbalance in central PbPb collisions

No apparent modification in the dijet Δφ distribution
(Dijet pairs are still back-to-back!)

Martin Spousta

Leading jet and subleading jet p_T ratio

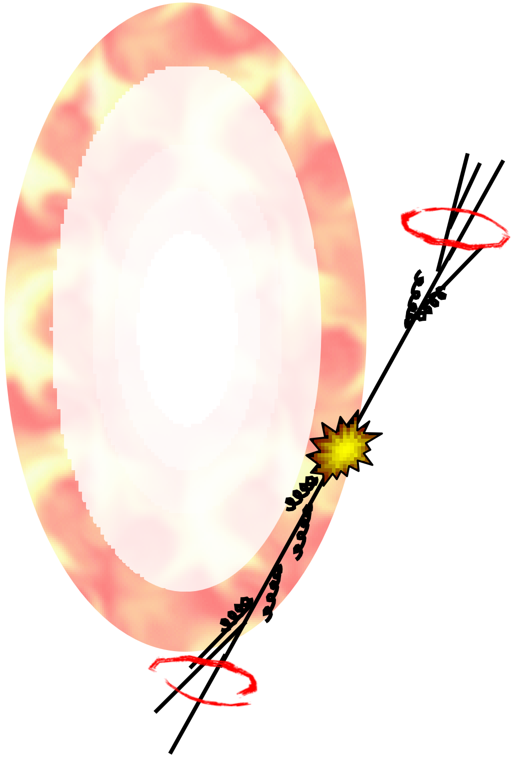


The shift in <p_{T2}/p_{T1}> increases monotonically with collision centrality, and is largely independent of the leading jet p_T at high jet p_T

Problem of jet as a trigger: surface bias

Selection on a high p_T leading jet (charged particle) may bias the position of the hard scattering in the QGP

All hard collisions
Can happen in any place in the QGP

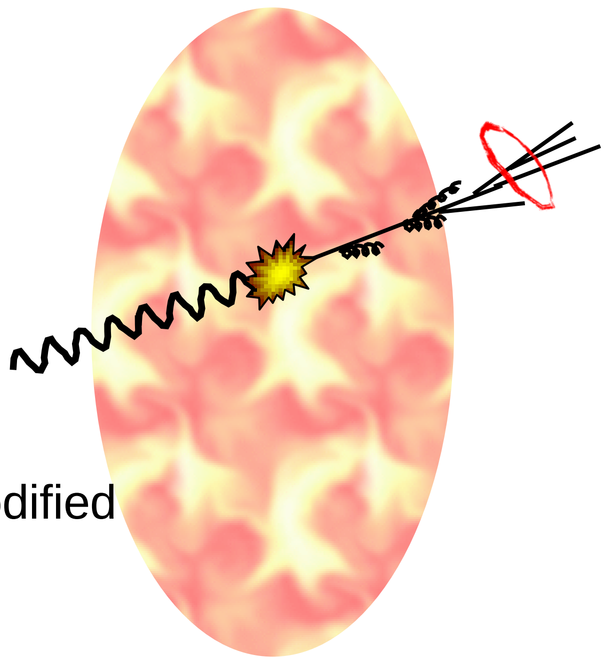


High p_T leading jet
triggered sample

Photon-jet: bias removed

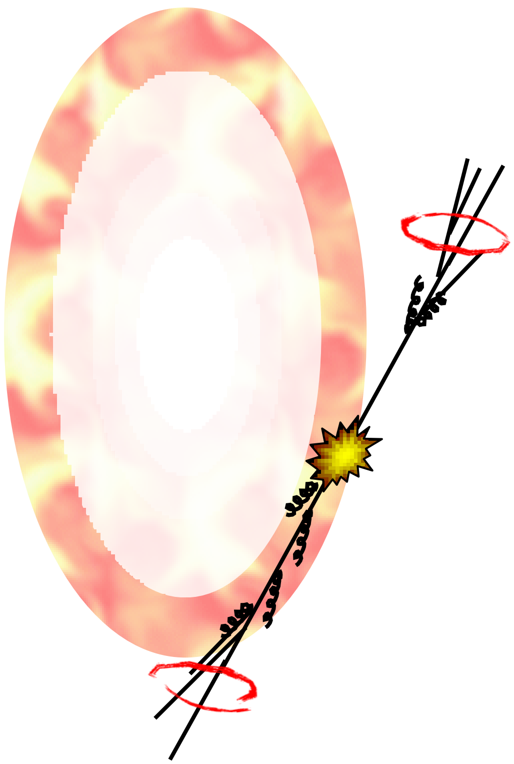
Selection on a high p_T leading jet (charged particle) may bias the position of the hard scattering in the QGP

Solution → trigger on high p_T photon



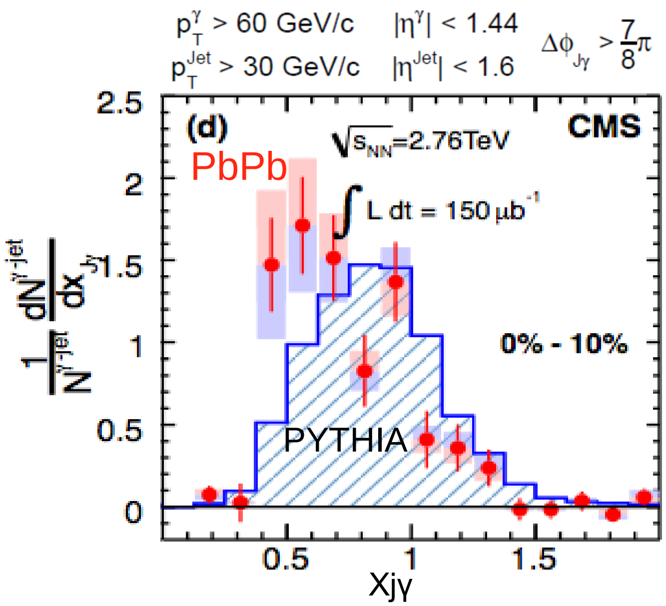
Photon → unmodified jet energy tag

High p_T photon triggered sample



High p_T leading jet triggered sample

Photon-jet momentum balance

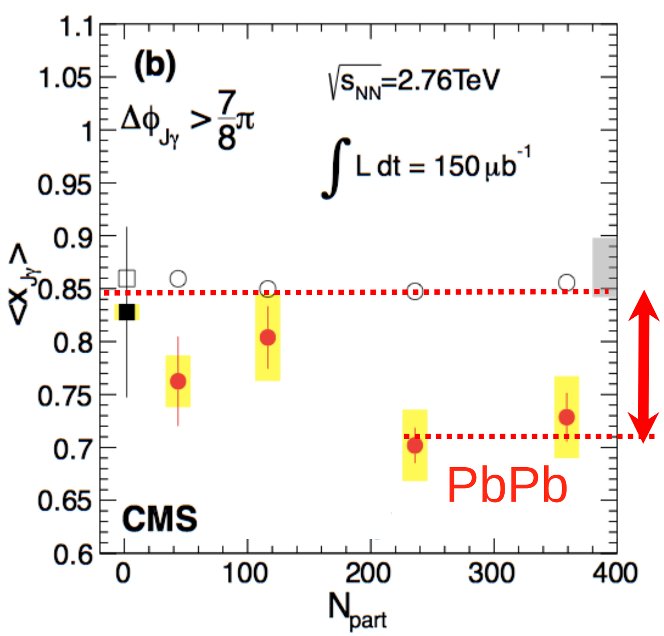


Compare photon-jet momentum balance

$X_{j\gamma} = p_T^{Jet}/p_T^{photon}$

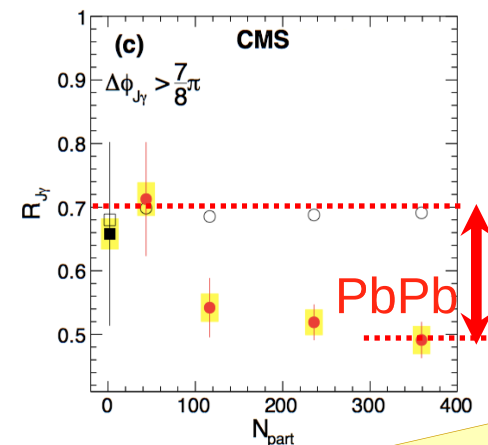
in **vacuum** (pp collision) to the **QGP** (PbPb collision)

R=0.3



Jets lose about 15% of their initial energy

In addition, 20% of photons lose their jet partner (jet p_T> 30 GeV/c)

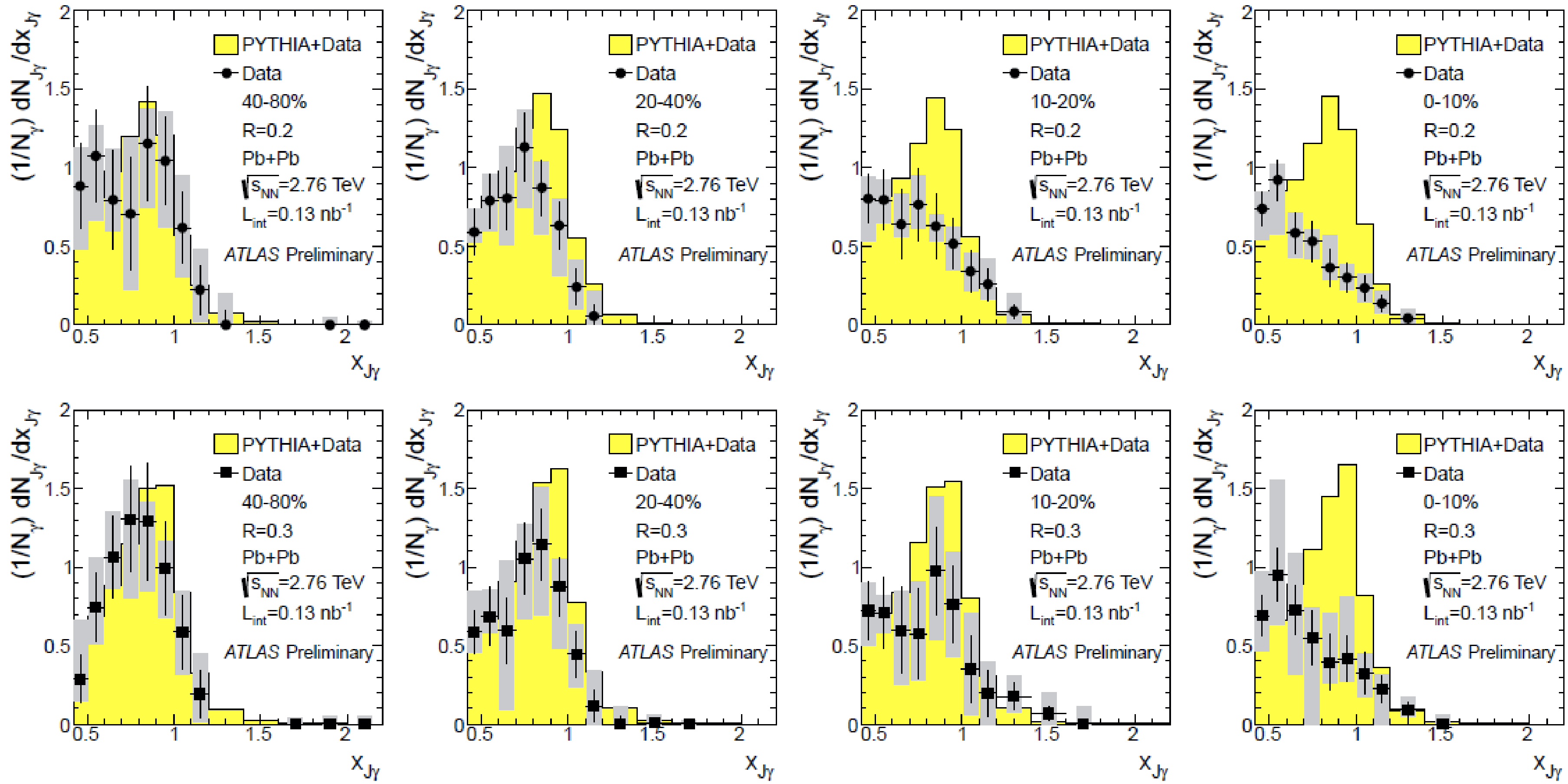


Yongsun Kim

Photon-jet momentum balance

R=0.2

R=0.3



- Ratio of the p_T of jets to photons ($x_{J\gamma}=p_T^{jet}/p_T^{\gamma}$)
- Large momentum imbalance in central PbPb collisions
- Detector effects unfolded

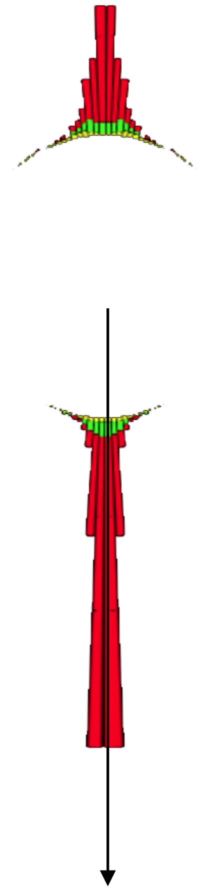
Martin Spousta

Where does the energy go?

- Suppression of high p_T jets
- Large dijet (photon-jet) energy (momentum) imbalance

ΔE_T ~ O(10) GeV,
~10% shift in <dijet p_T ratio>

Where does the energy go?



Missing-$p_T^{||}$

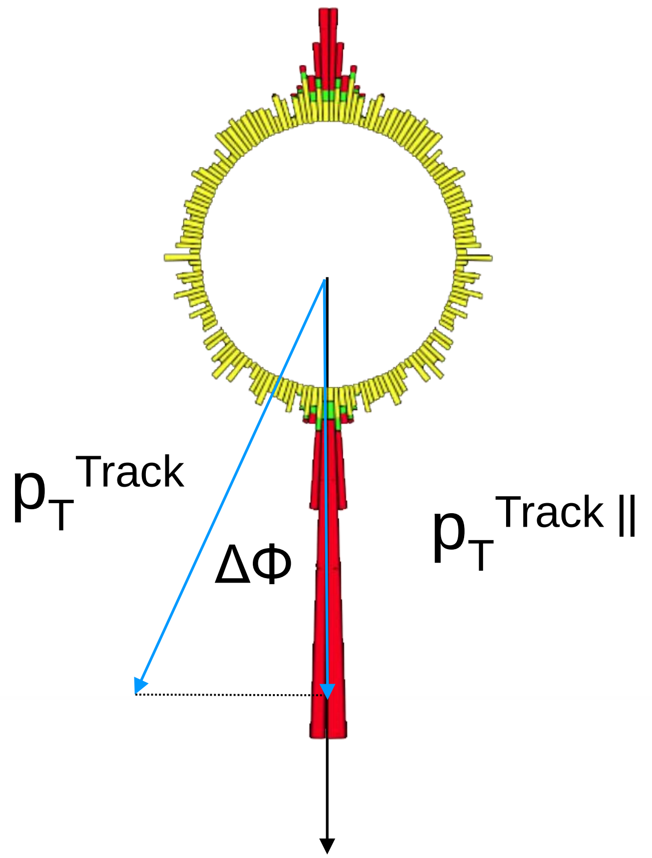
Missing $p_T^{||}$: $\displaystyle \not{p}_T^{||} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$

Where does the energy go?

- Calculate projection of p_T on leading jet axis and average over selected tracks with

  $p_T > 0.5$ GeV/c and
  $|\eta| < 2.4$

Underlying events cancels

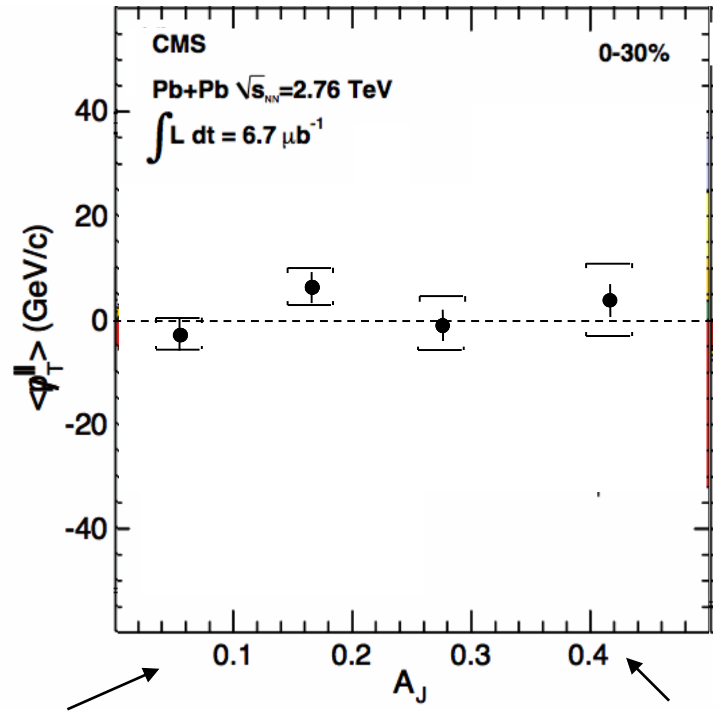


Sum over all tracks in the event

Missing-$p_T^{||}$

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



balanced jets

unbalanced jets

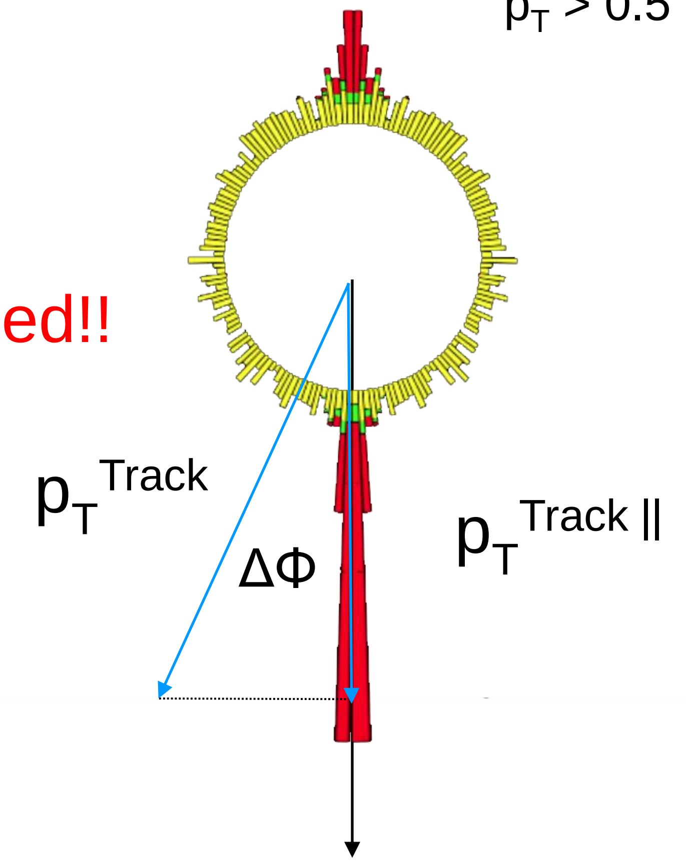
$A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$

excess away from leading jet

Balanced!!

excess towards leading jet

Track $p_T > 0.5$ GeV/c



Integrating over the whole event final state

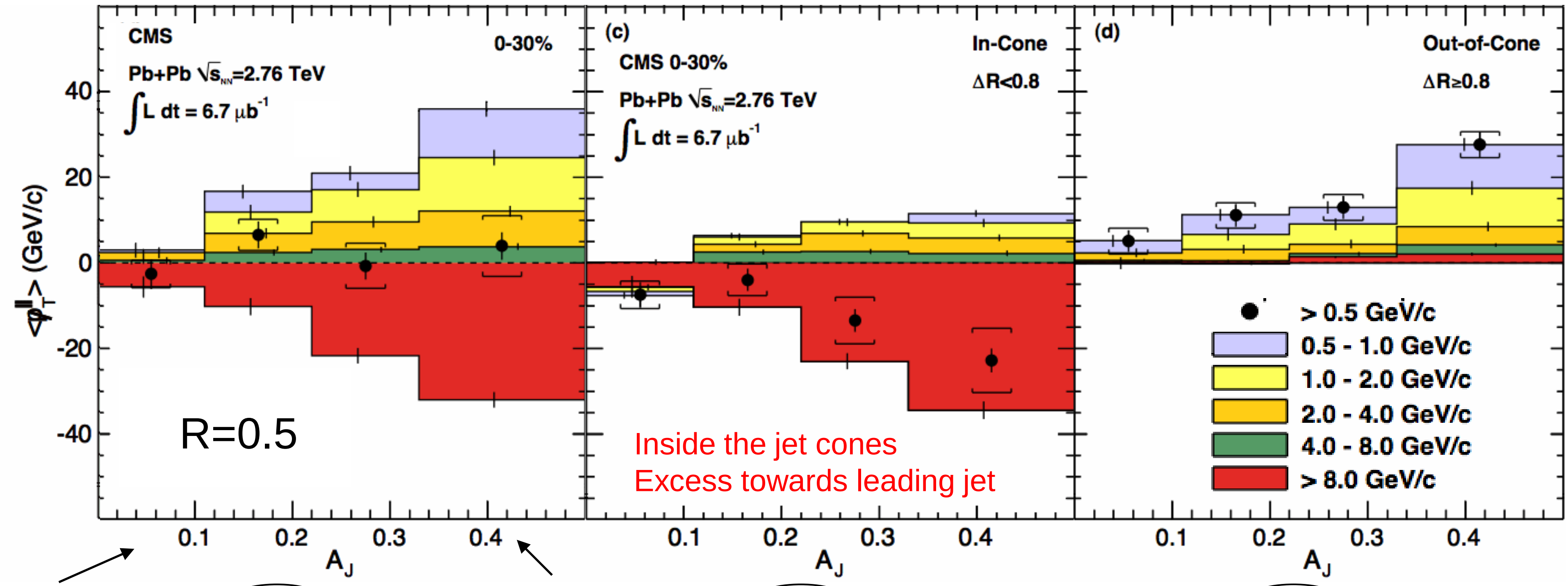
the dijet momentum balance is restored

Missing-$p_T^{\parallel}$

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

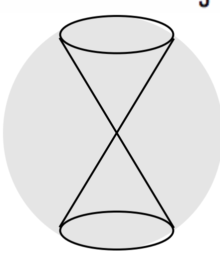
0-30% Central PbPb

Out of the jet cones
Excess towards sub-leading jet

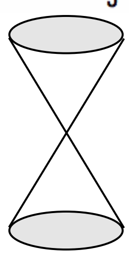


balanced jets

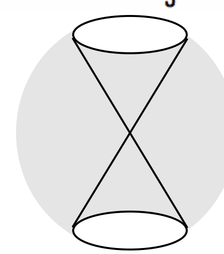
unbalanced jets



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

Associated p_T weighted yield in RHIC

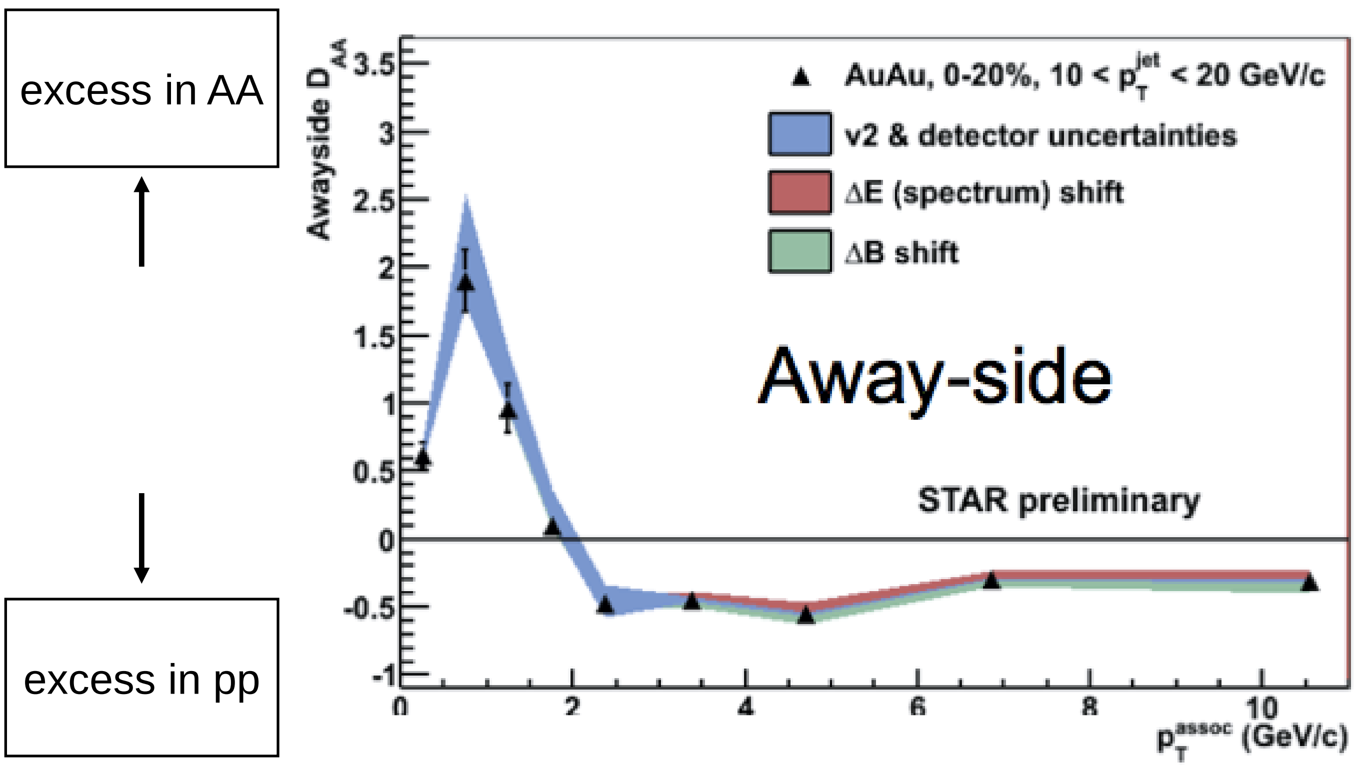
Look at jet triggered events

$Y_{AA}P_T$: "associated sum p_T"

D_{AA}: The difference between AA and pp collisions

$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$

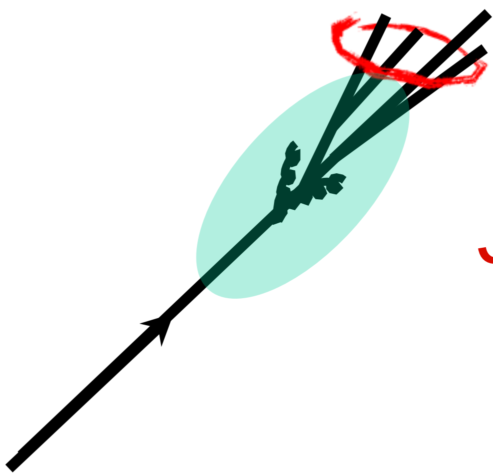
$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$

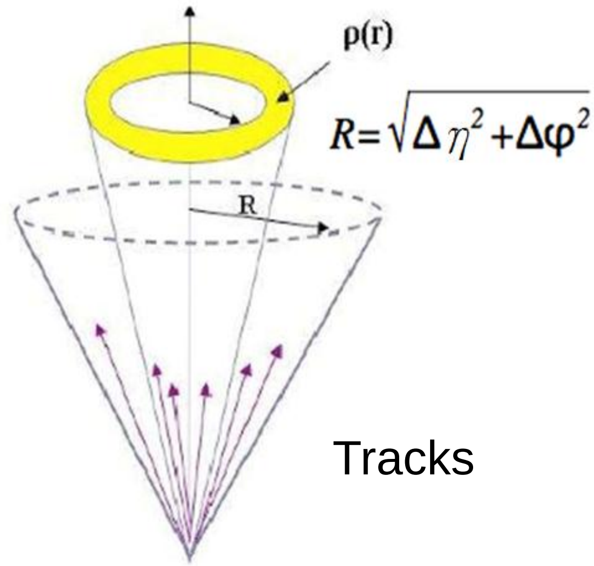


$\Delta B = 1.5\ ^{+1.7}_{-0.4}\ ^{+0.5}_{-0.4}$ (sys) GeV/c

Energy lost at high p_T approximately recovered at low p_T and high R

Jet shape and fragmentation function





Jet Fragmentation function:
how transverse momentum is distributed inside the jet cone

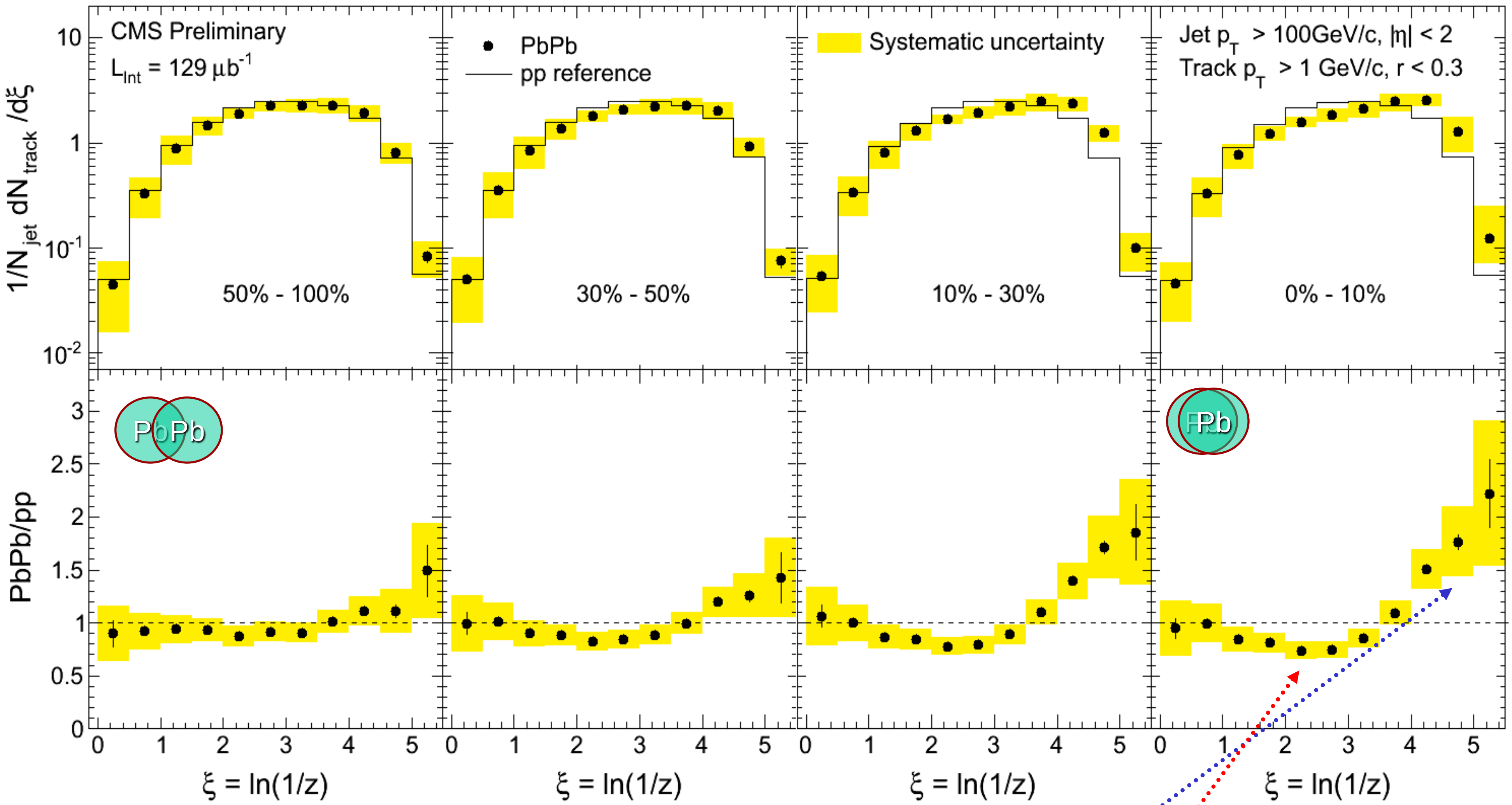
$$\xi = \ln\frac{1}{z} \;\; ; \;\; z = \frac{p_{\parallel}^{\mathrm{track}}}{p^{\mathrm{jet}}},$$

Jet shape:
shape of jet as a function of ΔR

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

$$f_{\mathrm{ch}} = \frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jets}}\frac{p_{\mathrm{T}}(0,R)}{p_{\mathrm{T}}^{\mathrm{jet}}}$$

Jet fragmentation functions



Inside the jet cone: Enhancement of low p_T particle

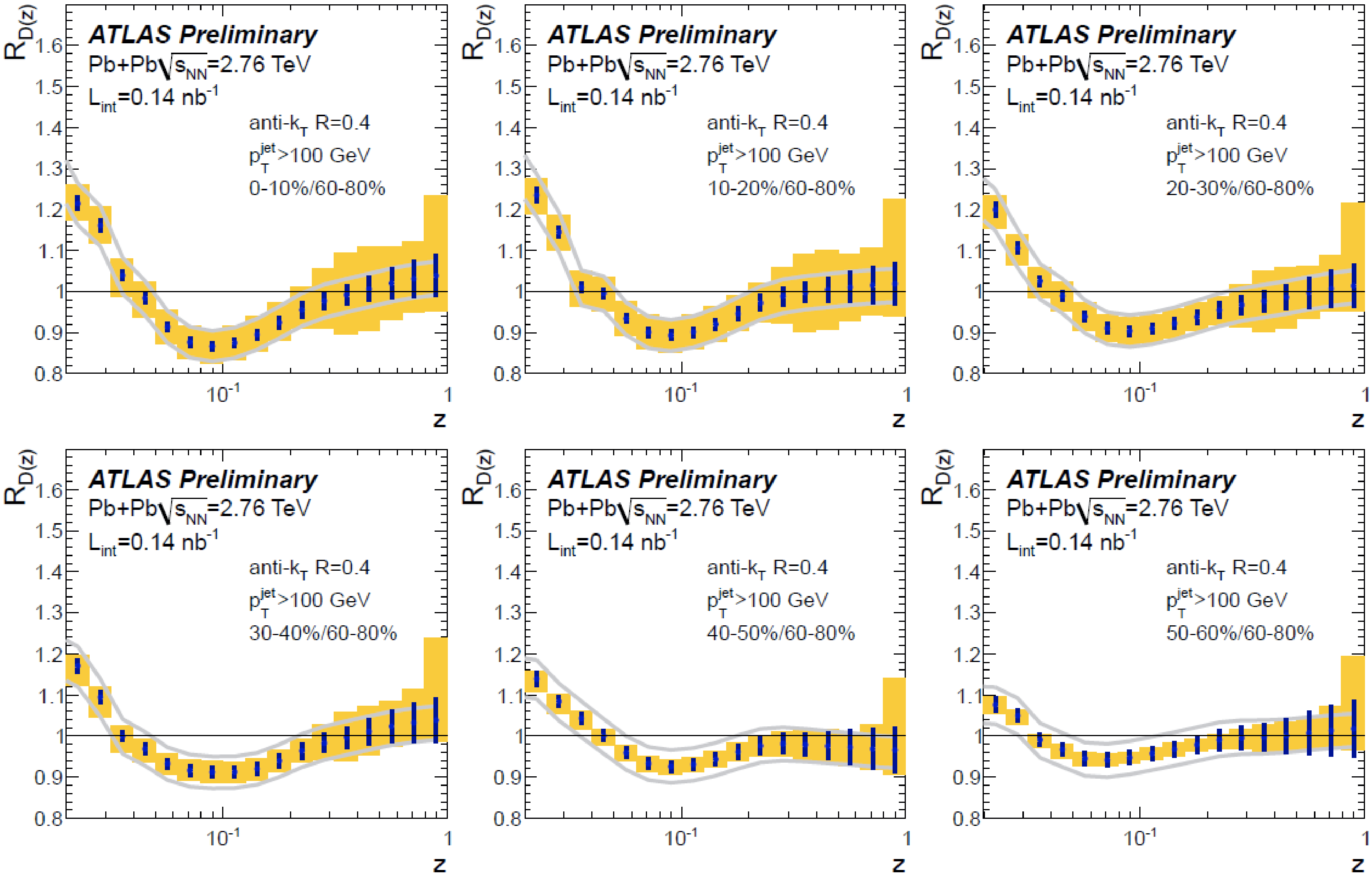
Suppression of intermediate p_T particles in cone

High p_T particles

Low p_T particles

$$\xi = \ln\frac{1}{z} \quad ; \quad z = \frac{p_{\parallel}^{track}}{p^{jet}},$$

Jet fragmentation functions



← Low p_T particles

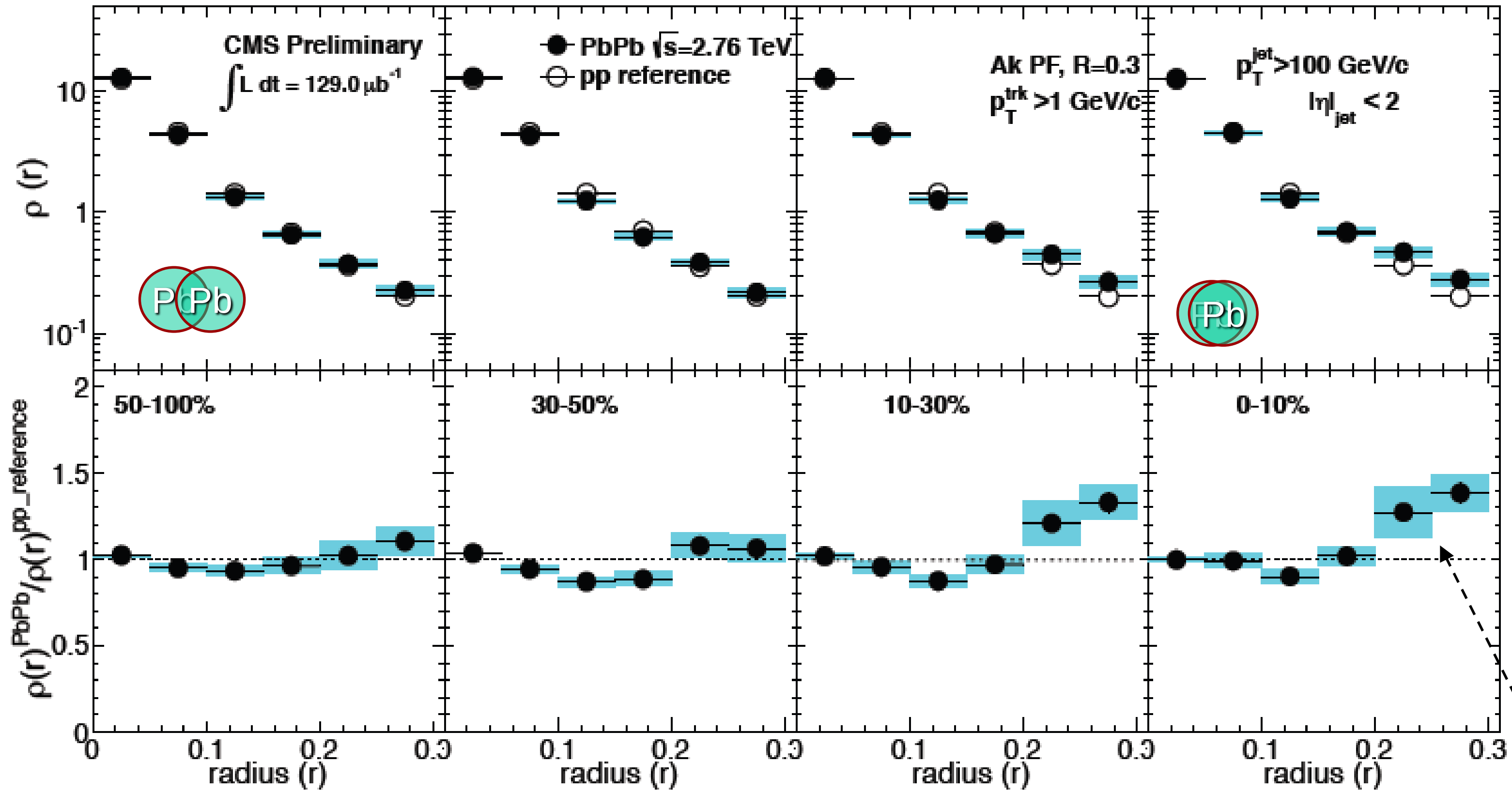
High p_T particles →

Track p_T > 2 GeV/c

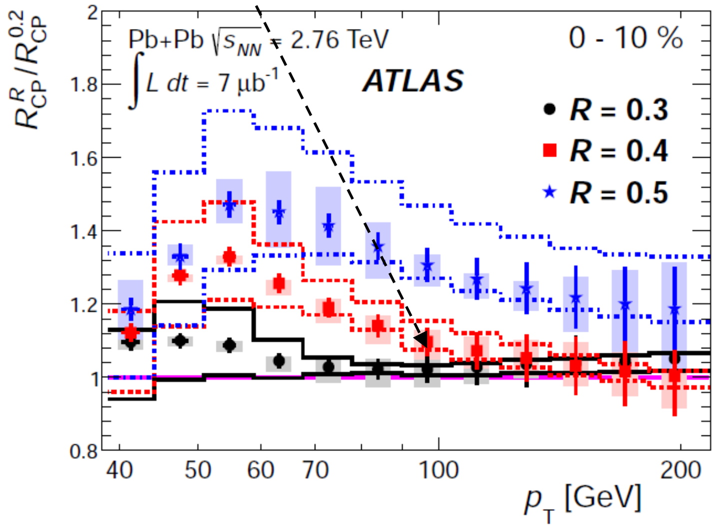
Detector effects unfolded

Martin Spousta

Changing jet shapes vs. centrality



Compatible with ATLAS results?

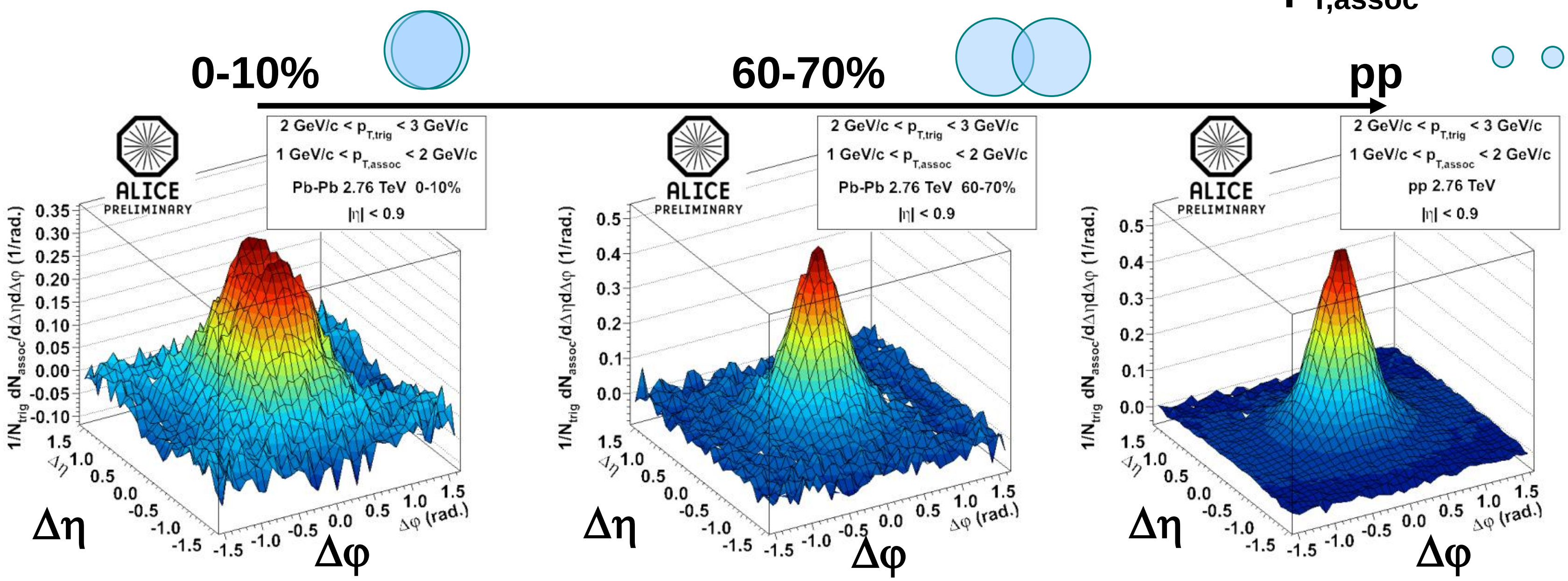


Significant modification at large radius

Low p_T jets in PbPb collisions

Two particle correlation from ALICE:
Jet like near side correlation with background subtraction (Δη sideband)
Widening of the angular correlation

$2 < p_{T,trig} < 3$ GeV/c
$1 < p_{T,assoc} < 2$ GeV/c



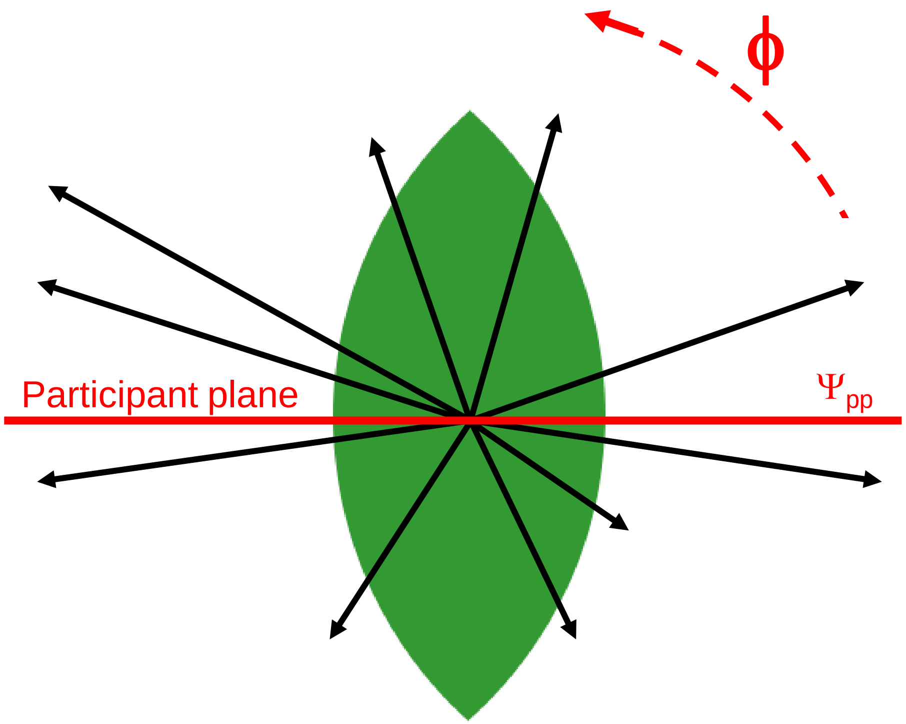
Flow?

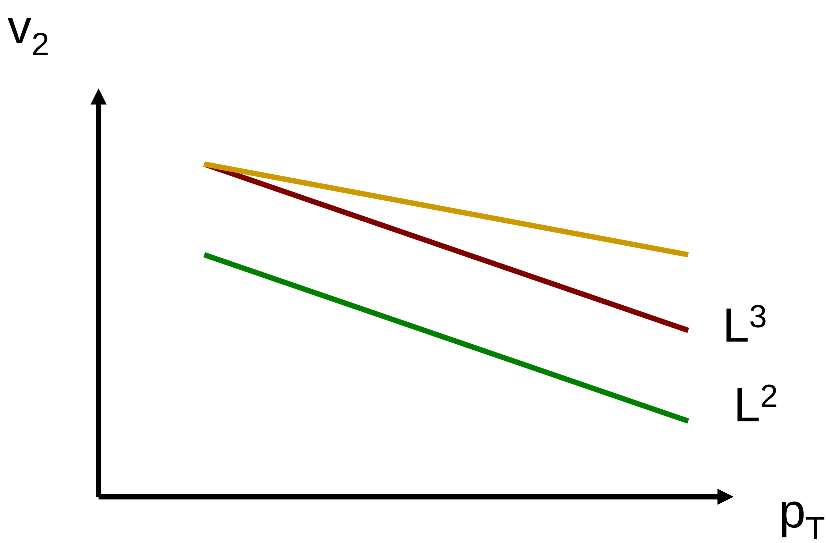
→Motivates jet shape analysis and fragmentation function with low p_T particles

→ Look at low p_T reconstructed jet

ALICE jet-hadron
Megan Elizabeth Connors

Path length dependence of jet energy loss?





Overlap zone is almond-shaped
→ Parton energy loss is smaller along the short axis
→ More high-pT tracks and jets closer to the event plane

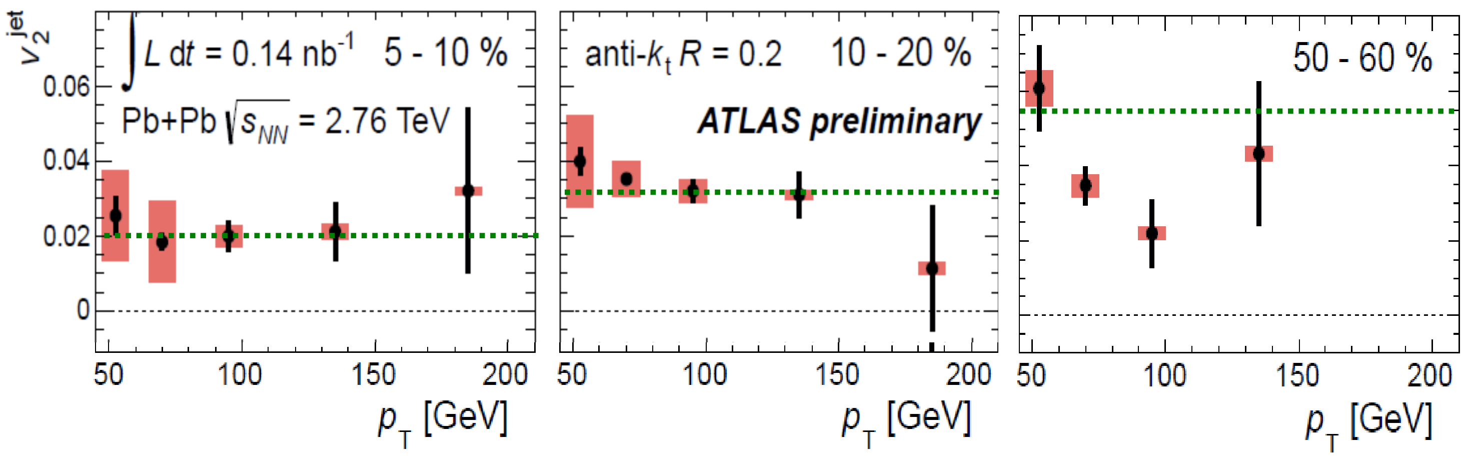
→ Azimuthal asymmetry (v2):

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

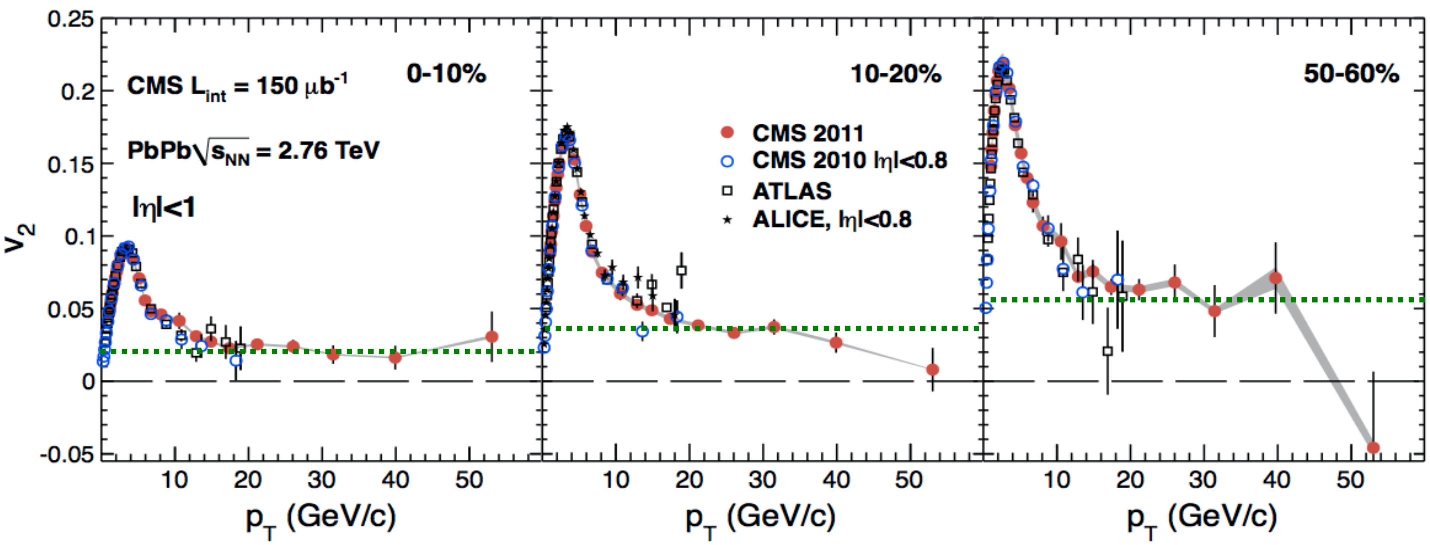
→ v2 is sensitive to the path-length dependence of the energy loss

Jet and high p_T track v_2 at the LHC

Jet v_2



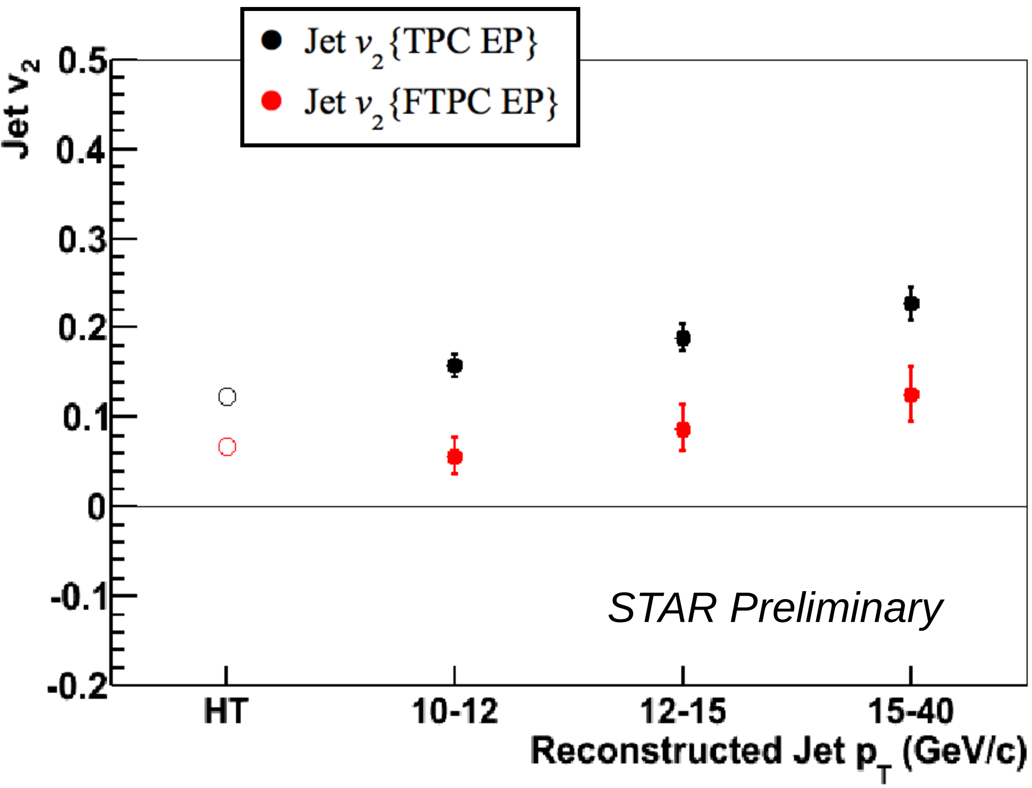
High p_T Track v_2



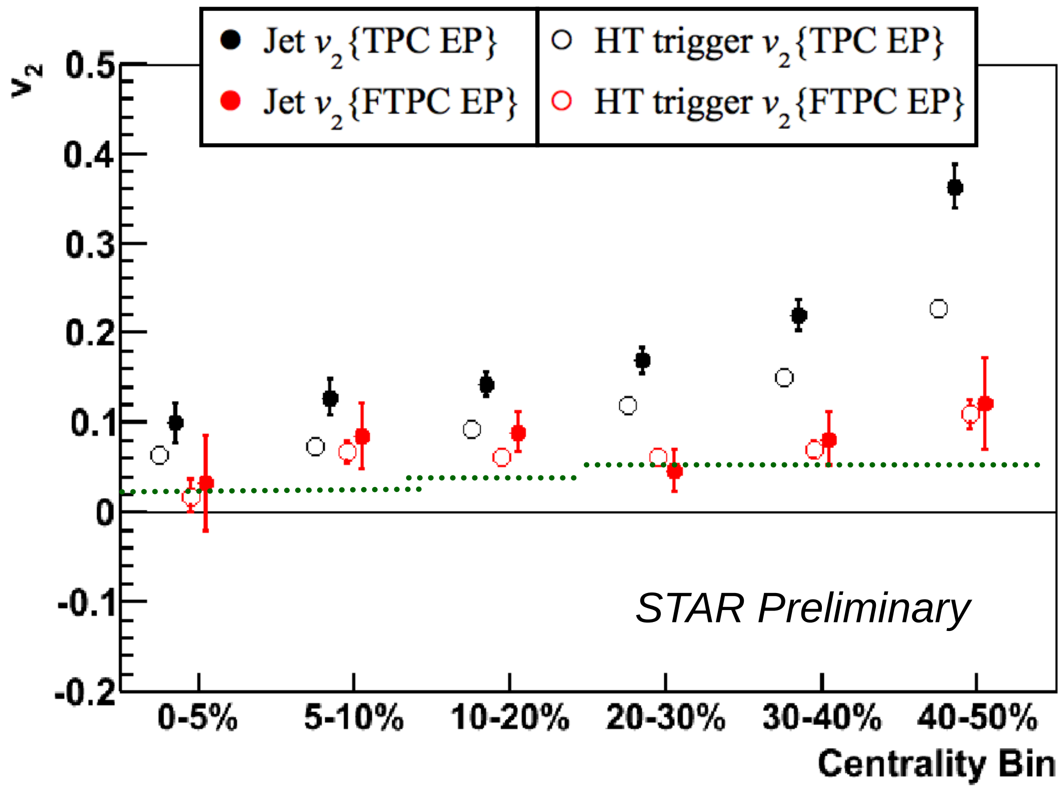
- Jet and high p_T track v_2 : non-zero up to very high p_T
- Sensitive to the path length dependence of energy loss

Jet v_2 at the RHIC

Jet Definition:
HT trigger $E_T > 5.5$ GeV
constituent $p_T^{cut} = 2$ GeV/c



Jet p_T: 10-40 GeV/c



- Jet v_2 is non-zero up to high p_T
- Similar jet v_2 observed in RHIC compared to LHC results (Different jet p_T ranges)

Summary (1/2)

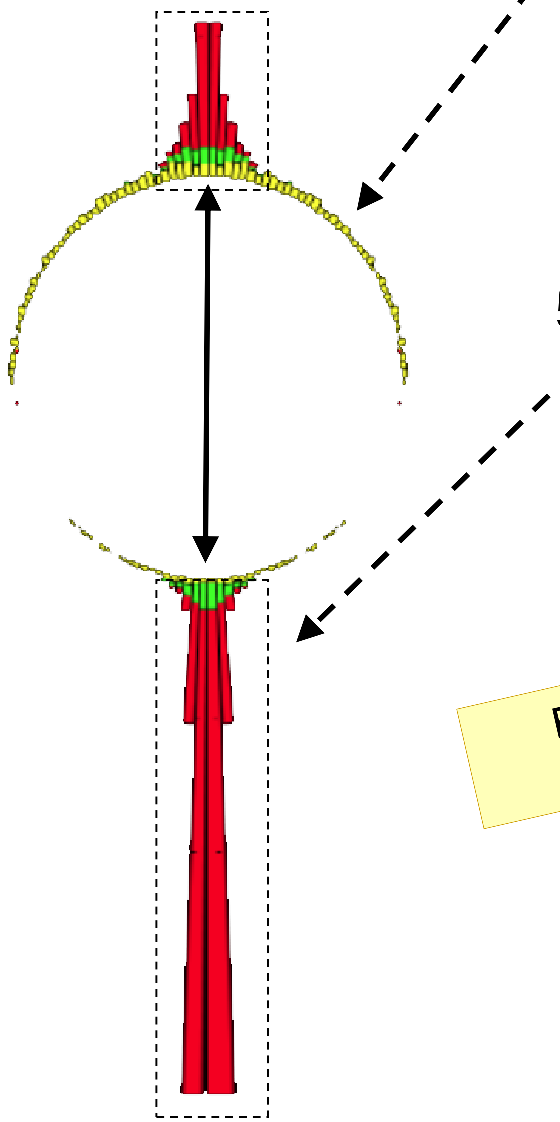
1. High p_T jet suppression
→ΔR = 0.2 — 0.5 doesn't capture all the radiated energy

2. Large average dijet p_T imbalance

3. Angular correlation of jets not largely modified

4. p_T difference found at low p_T particles far away from the jets

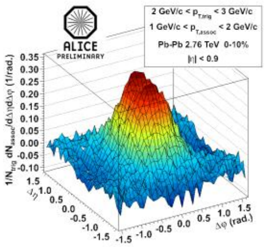
5. Observation of modified FF and jet shape

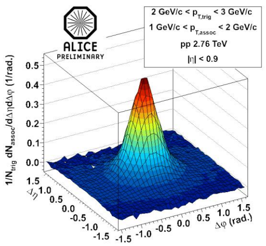


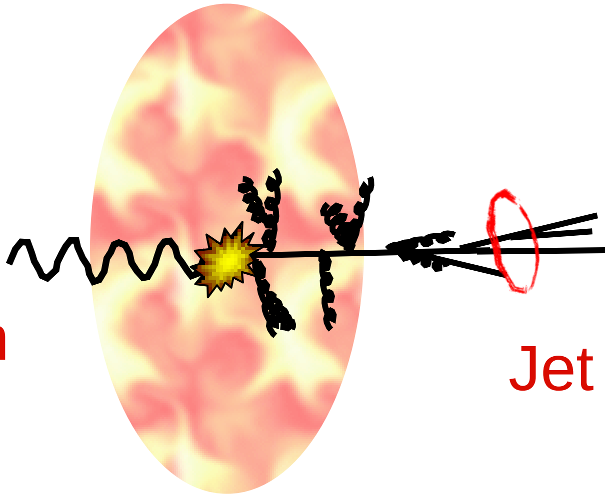
VNI/BMS:
Christopher Colemansmith

Fluctuating background:
Ricardo Rodriguez

6. Jet shape “broadening” seen in low p_T two particle correlation

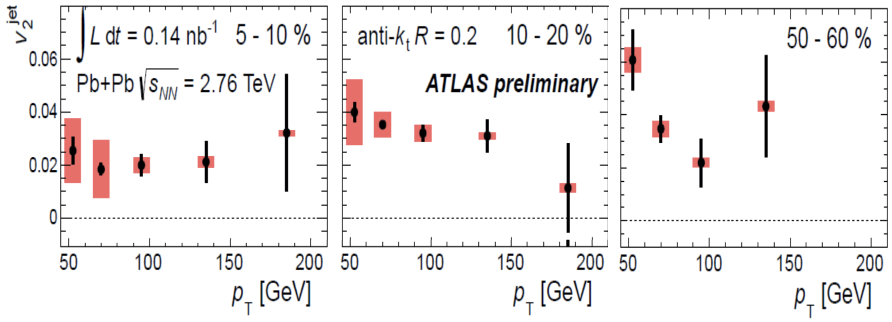






7. Large photon-jet p_T imbalance > dijet p_T imbalance

8. Non-zero jet (high p_T hadron) v_2



Many interesting results from RHIC and LHC
Challenges to our theory community!

Coming back to three possible scenarios

To explain the suppression of high p_T particles

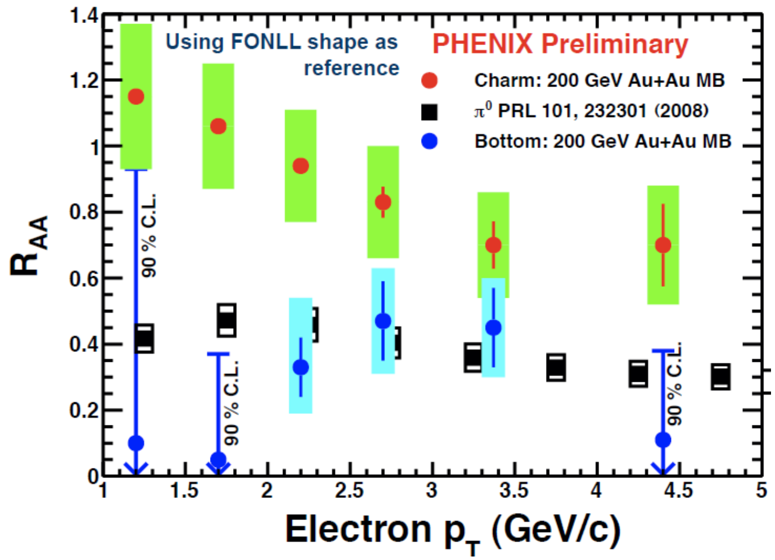
Ads/CFT: Andrej Ficnar

Interference effect
Mauricio

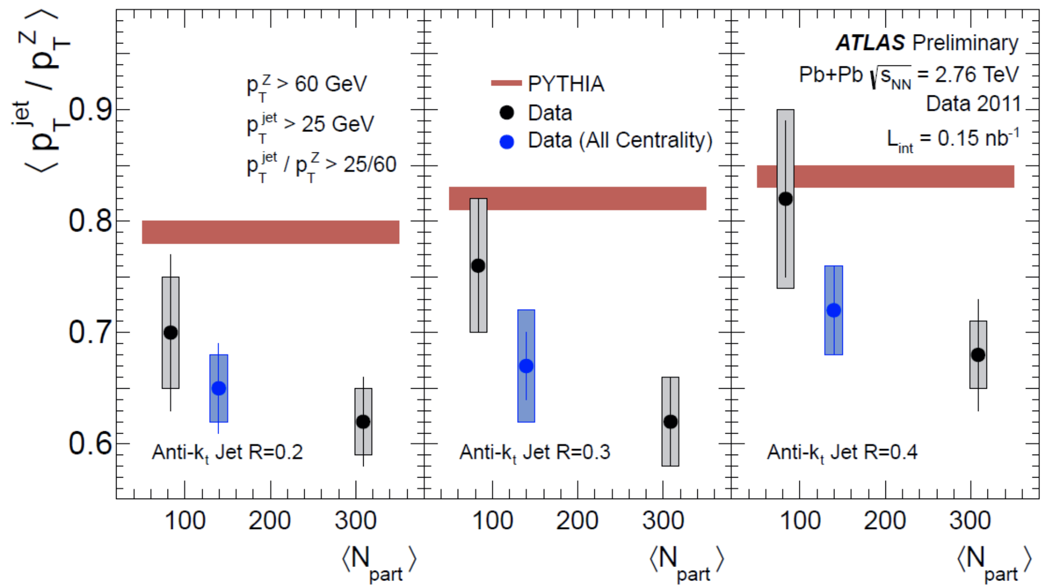
Soft collinear radiation	Hard radiation	Large angle soft radiation “QGP heating”
GLV + others	PYTHIA inspired models Modified splitting functions	AdS/CFT Interference

Things are getting very interesting!

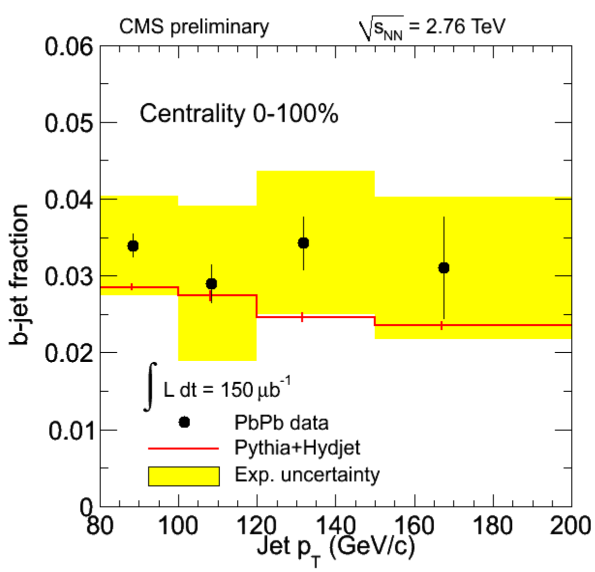
Strong b-jet suppression in PHENIX ?!



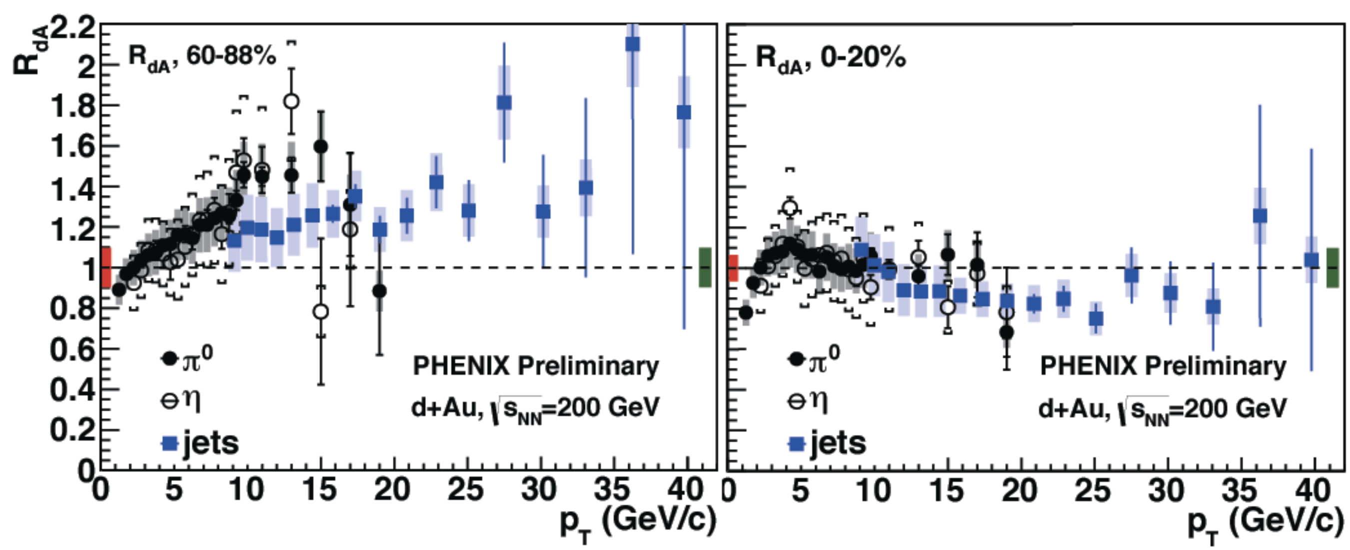
First Z-jet analysis from ATLAS!



b-jet tagging from CMS!



$R_{dA} > 1$ in peripheral dAu collisions from PHENIX ?!



And the pPb run at the LHC…!

Backup slides