Lecture 3: Jets

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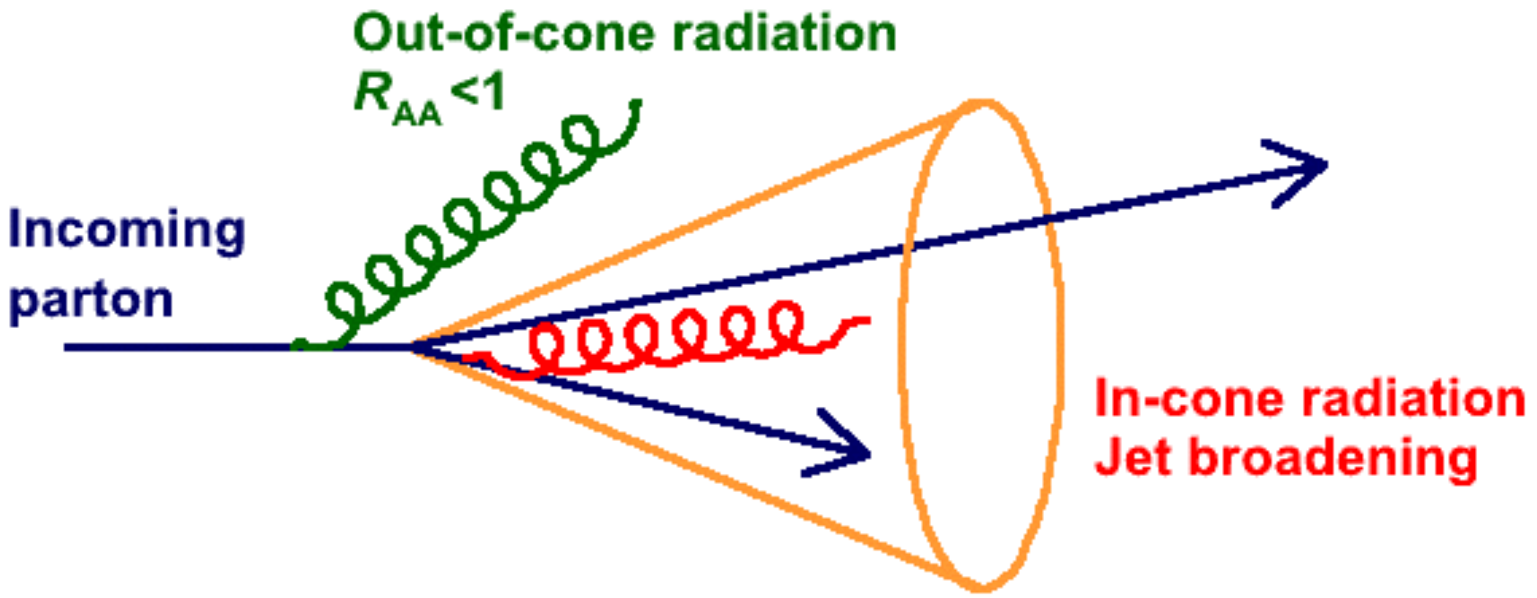
NIKHEF

Jets and parton energy loss

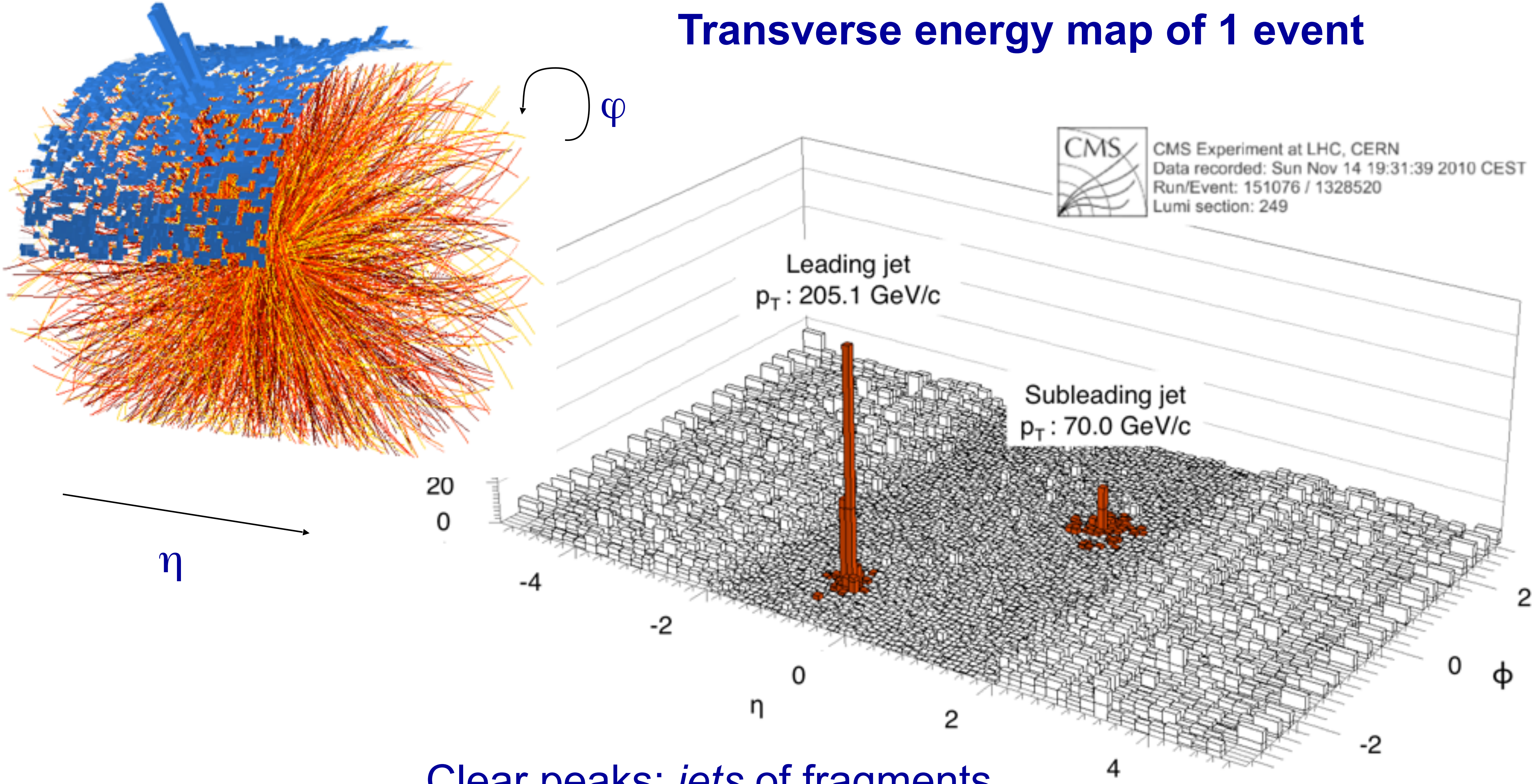
Motivation: understand parton energy loss by tracking the gluon radiation



Qualitatively two scenarios:

1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$

Jets at LHC



Transverse energy map of 1 event

Clear peaks: *jets* of fragments
from high-energy quarks and gluons

And a lot of uncorrelated ‘soft’ background

Jet reconstruction algorithms

Two categories of jet algorithms:

- Sequential recombination k_T, anti-k_T, Durham
  - Define distance measure, e.g. $d_{ij} = \min(p_{Ti}, p_{Tj}) * R_{ij}$
  - Cluster closest
- Cone
  - Draw Cone radius R around starting point
  - Iterate until stable $\eta, \varphi_{jet} = \langle \eta, \varphi \rangle_{particles}$

Sum particles inside jet

Different prescriptions exist, most natural: E-scheme, sum 4-vectors

Jet is an object defined by jet algorithm
If parameters are right, may approximate parton

For a complete discussion, see: http://www.lpthe.jussieu.fr/~salam/teaching/PhD-courses.html

Collinear and infrared safety

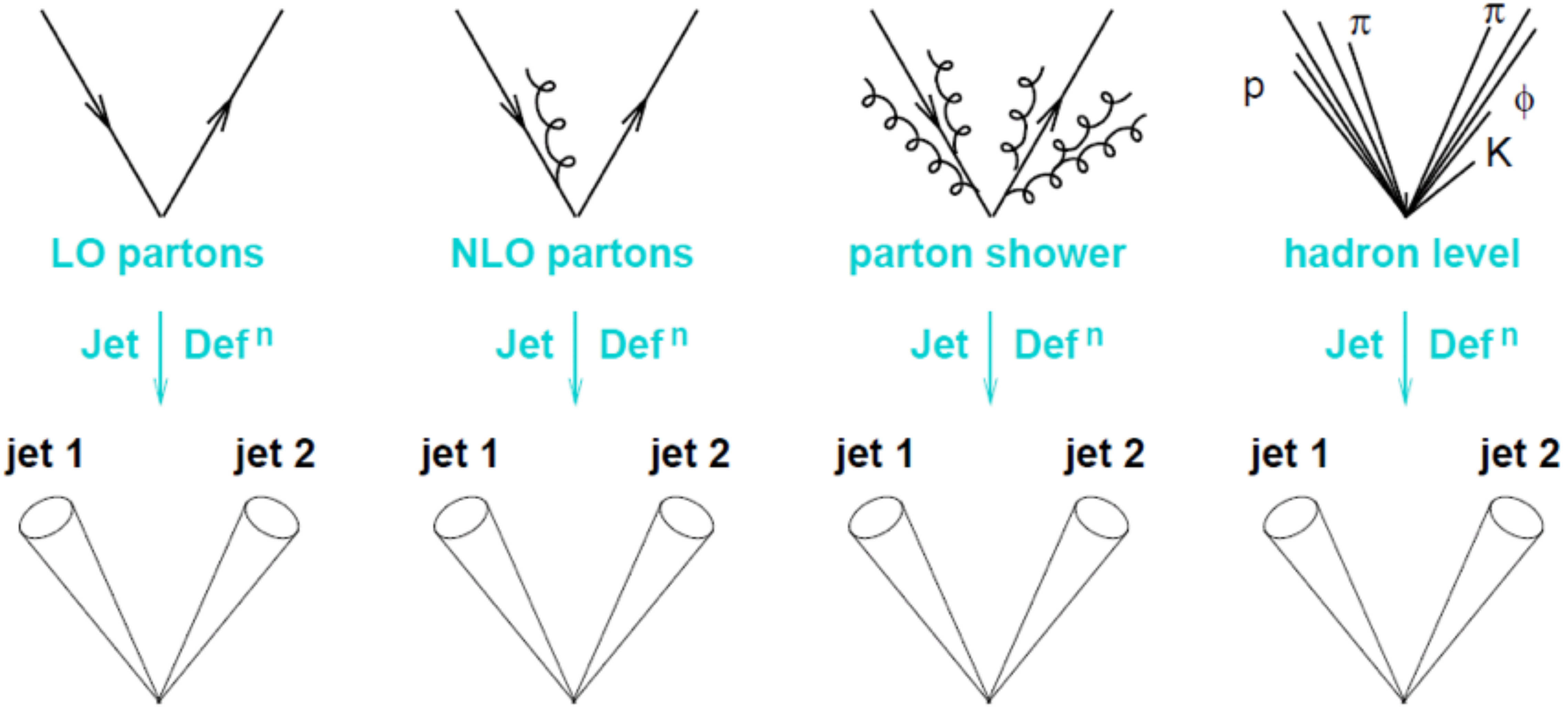


Illustration by G. Salam

Jets should not be sensitive to soft effects (hadronisation and E-loss)

- Collinear safe
- Infrared safe

Collinear safety

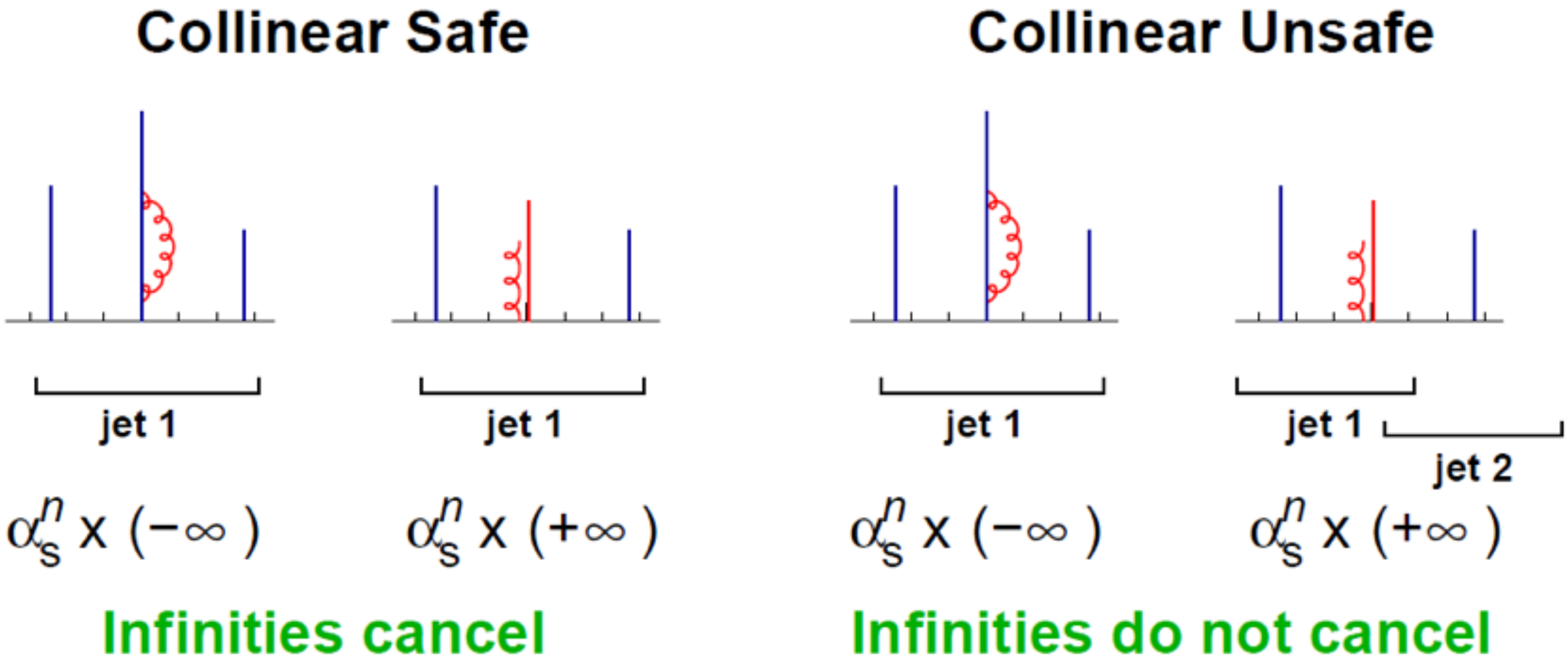


Illustration by G. Salam

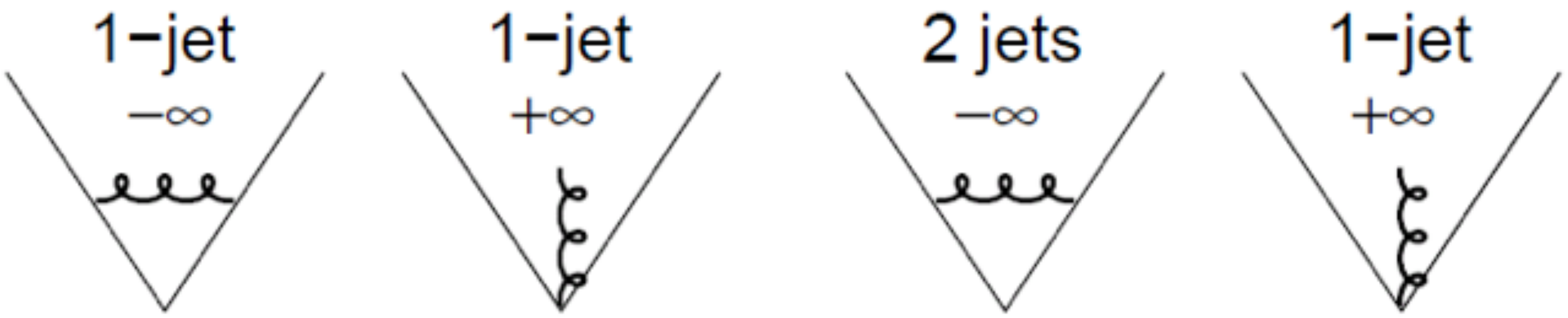
Note also: detector effects,
such as splitting clusters in calorimeter (π^0 decay)

Infrared safety

Soft emission, collinear splitting are both **infinite** in pert. QCD.

Infinities **cancel** with loop diagrams if jet-alg IRC safe

IRC safe **IRC unsafe**



sum is finite sum is infinite

Illustration by G. Salam

Some calculations simply become **meaningless**

Infrared safety also implies robustness
against soft background in heavy ion collisions

Clustering algorithms – k_T algorithm

Majority of QCD branching is soft & collinear, with following divergences:

$$[dk_j]|M^2_{g\to g_i g_j}(k_j)| \simeq \frac{2\alpha_s C_A}{\pi}\,\frac{dE_j}{\min(E_i,E_j)}\,\frac{d\theta_{ij}}{\theta_{ij}}\,, \qquad (E_j \ll E_i\,,\ \ \theta_{ij} \ll 1)\,.$$

To invert branching process, take pair with strongest divergence between them — they're the most *likely* to belong together.

This is basis of **k_t/Durham algorithm** (e^+e^-):

1. Calculate (or update) distances between all particles i and j:

$$y_{ij} = \frac{2\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{Q^2}$$

NB: relative k_t between particles

2. Find smallest of y_{ij}
   - If $> y_{cut}$, stop clustering
   - Otherwise recombine i and j, and repeat from step 1

Catani, Dokshitzer, Olsson, Turnock & Webber '91

Slide by G. Salam

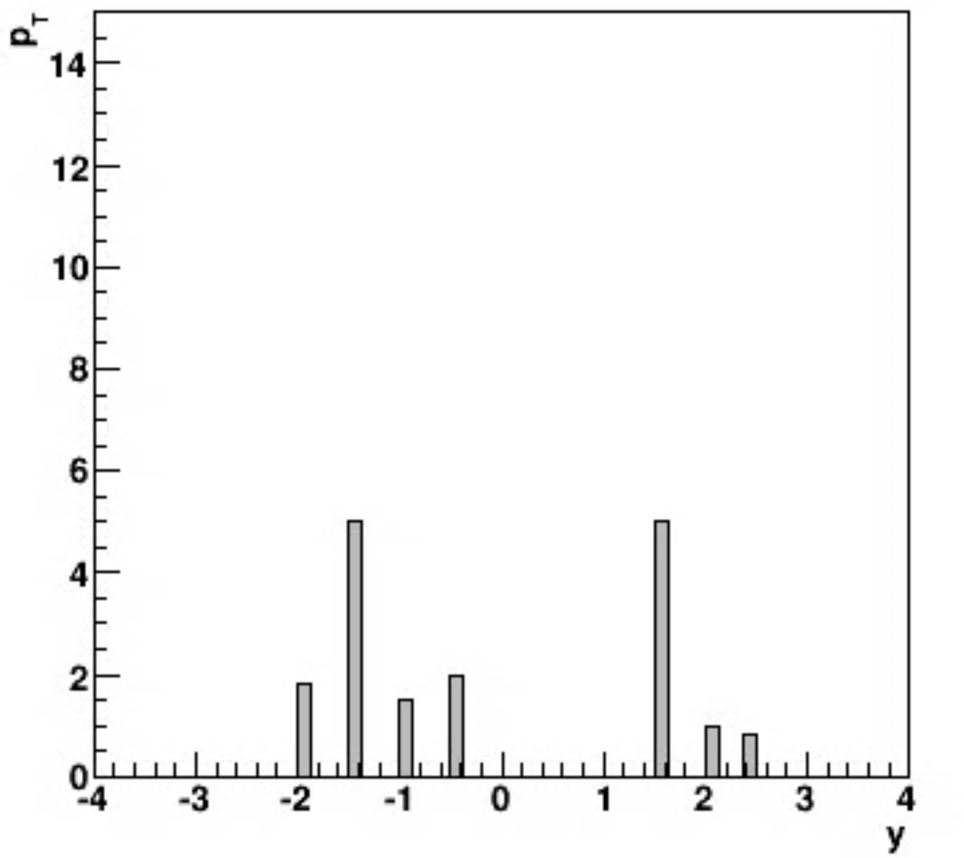
k_T algorithm

Various distance measures have been used,
e.g. Jade, Durham, Cambridge/Aachen

Current standard choice:

- Calculate
  - For every particle *i*: distance to beam $d_{iB} = p_{t,i}^2$
  - For every pair *i*,*j* : distance $d_{ij} = \min(p_{t,i}^2, p_{t,j}^2)\frac{R_{ij}^2}{R^2}$
- Find minimal *d*
  - If d_{iB}, *i* is a jet
  - If d_{ij}, combine *i* and *j*
- Repeat until only jets

k_T algorithm demo



k_T algorithm properties

- Everything ends up in jets
- k_T-jets irregular shape
  - Measure area with ‘ghost particles’
- k_T-algo starts with soft stuff
  - ‘background’ clusters first, affects jet
- Infrared and collinear safe
- Naïve implementation slow (N^3). Not necessary → Fastjet

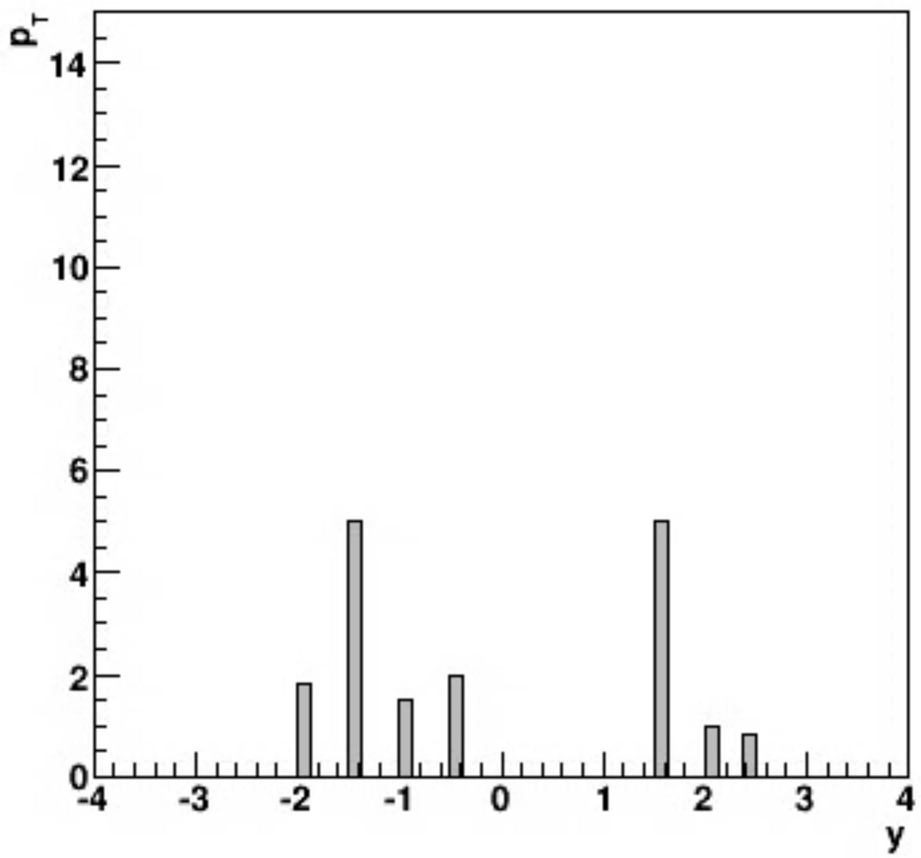
Alternative: anti-k_T $d_{ij} = \min\left(\frac{1}{p_{t,i}^2}, \frac{1}{p_{t,j}^2}\right)\frac{R_{ij}^2}{R^2}$ $d_{iB} = \frac{1}{p_{t,i}^2}$

Cambridge-Aachen: $d_{ij} = \frac{R_{ij}^2}{R^2}$

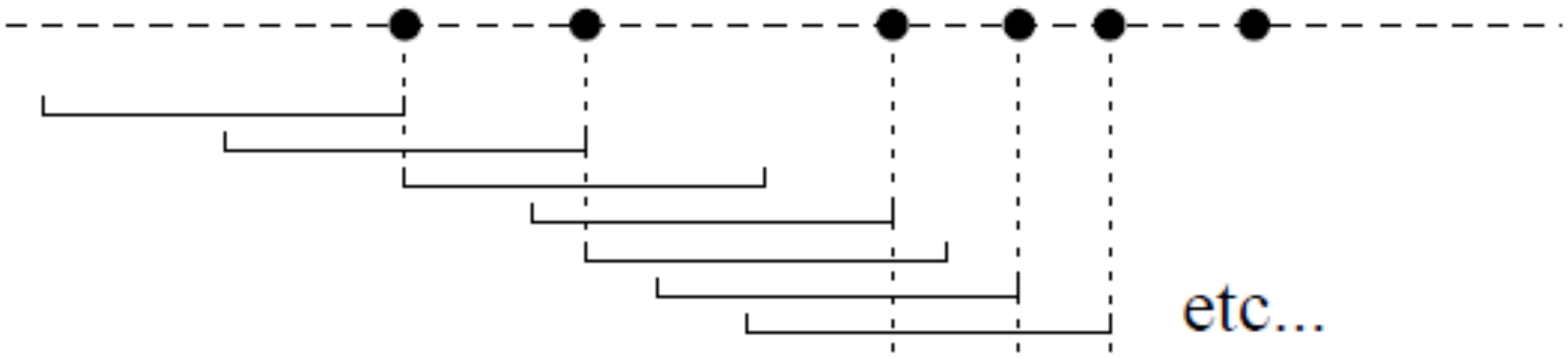
Cone algorithm

- Jets defined as cone
- Iterate until stable:
  $(\eta,\varphi)_{\mathrm{Cone}} = \langle\eta,\varphi\rangle_{\text{particles in cone}}$
- Starting points for cones, seeds, e.g. highest p_T particles
- Split-merge prescription for overlapping cones

Cone algorithm demo

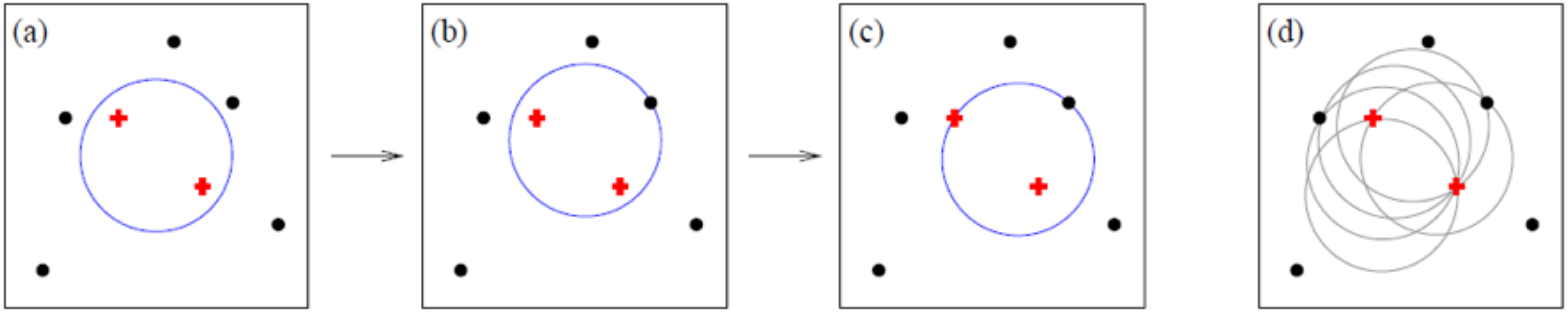


Seedless cone



1D: slide cone over particles and search for stable cone
Key observation: content of cone only changes when the cone boundary touches a particle

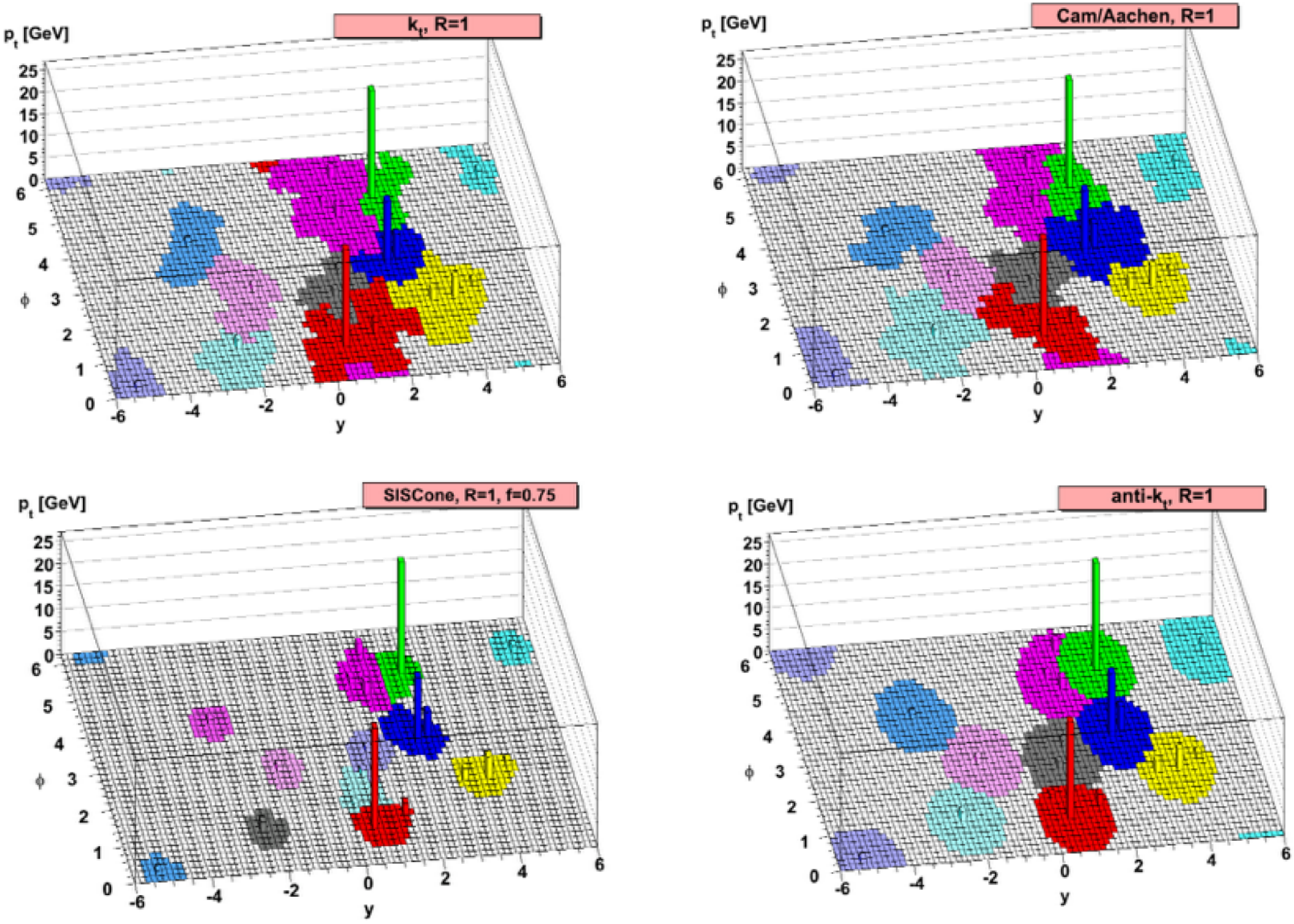
Extension to 2D (η,φ)



Limiting cases occur when two particles are on the edge of the cone

Jet algorithm examples

simulated p+p event

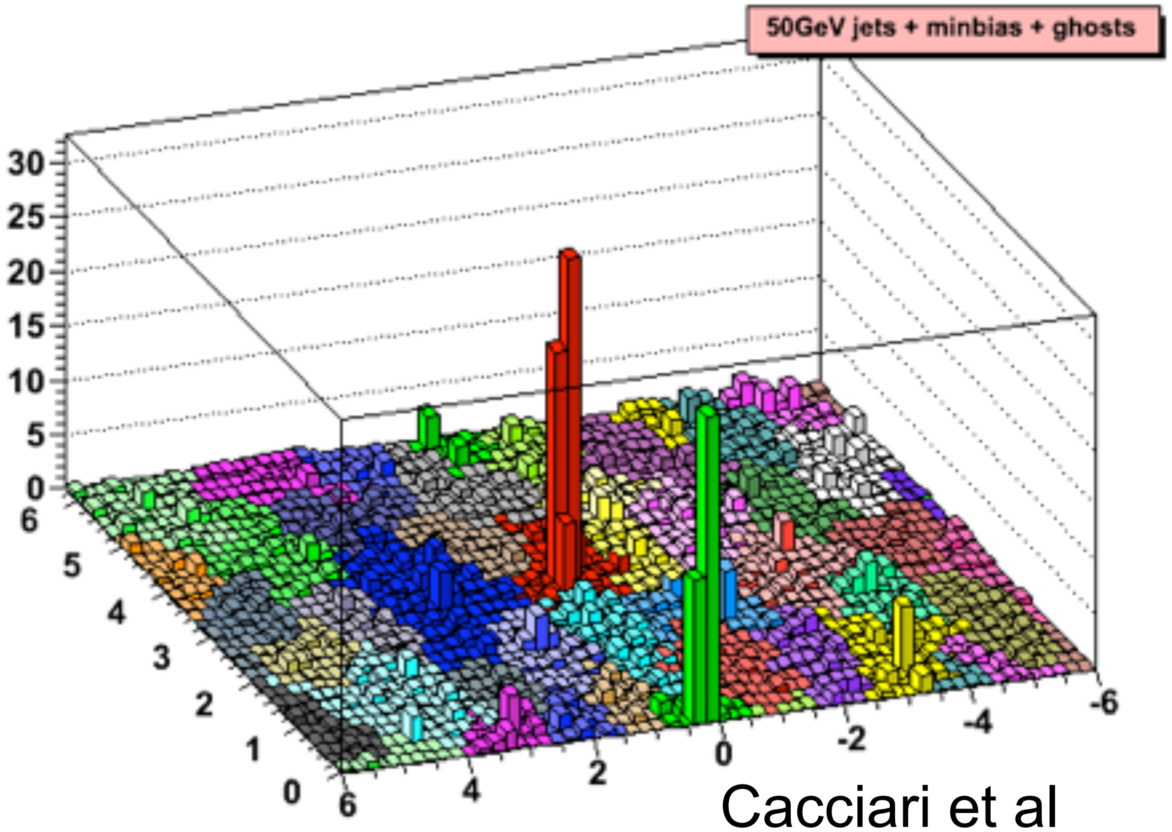


Cacciari, Salam, Soyez, arXiv:0802.1189

Measuring the jet spectrum

PbPb jet background

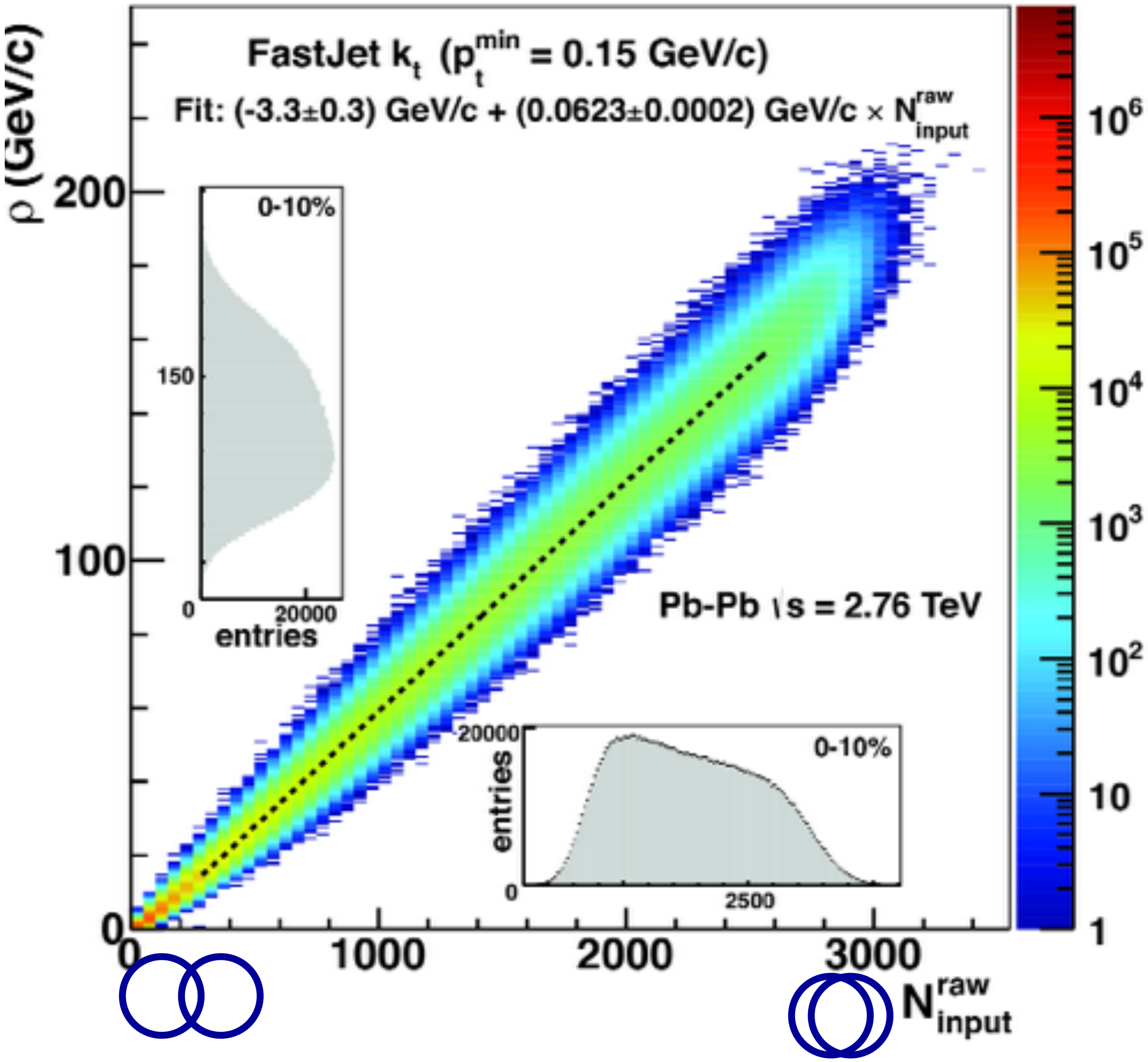
Jet finding illustration



Cacciari et al

η-φ space filled with jets
Many ‘background jets’

Background density vs multiplicity

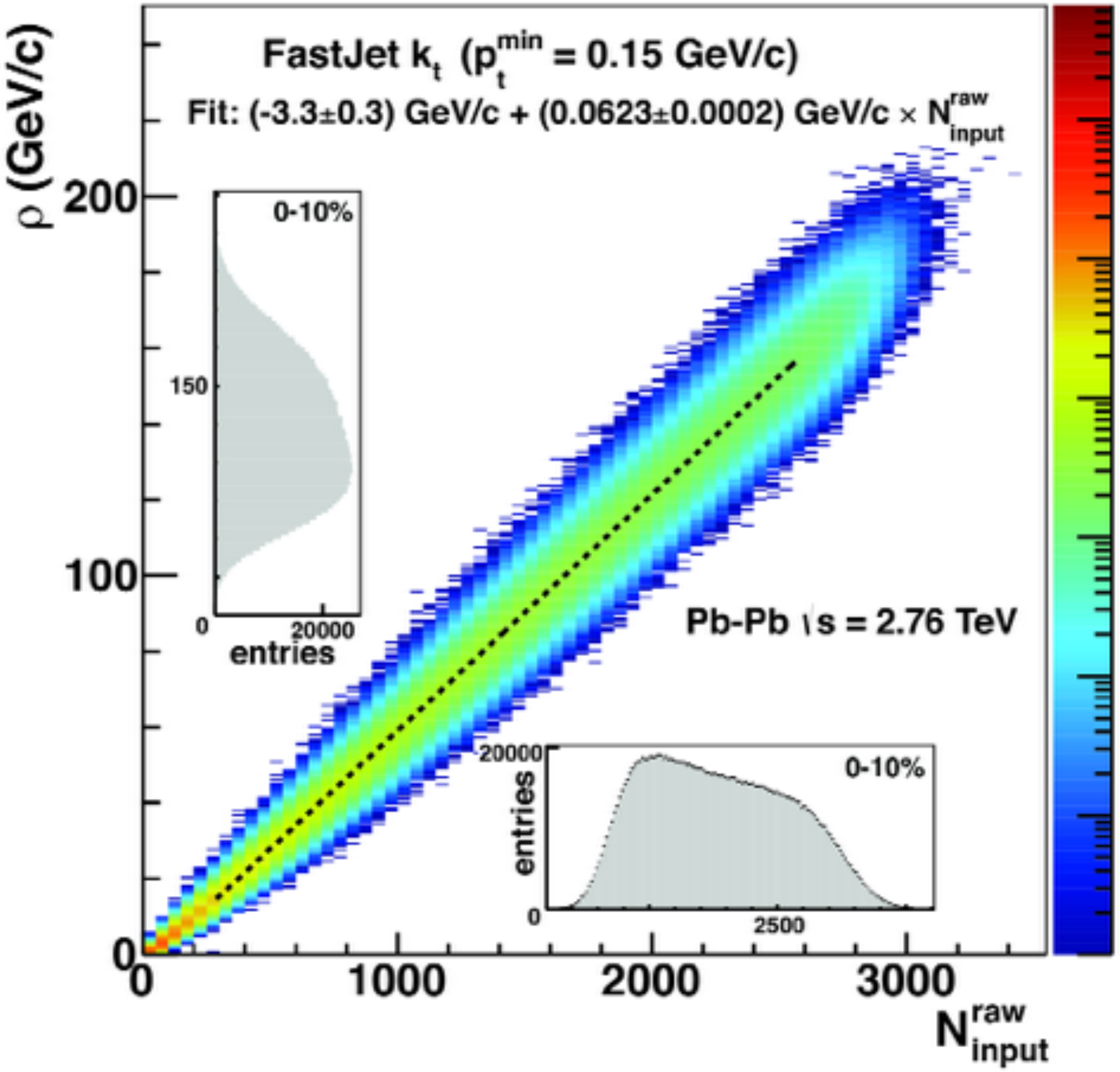


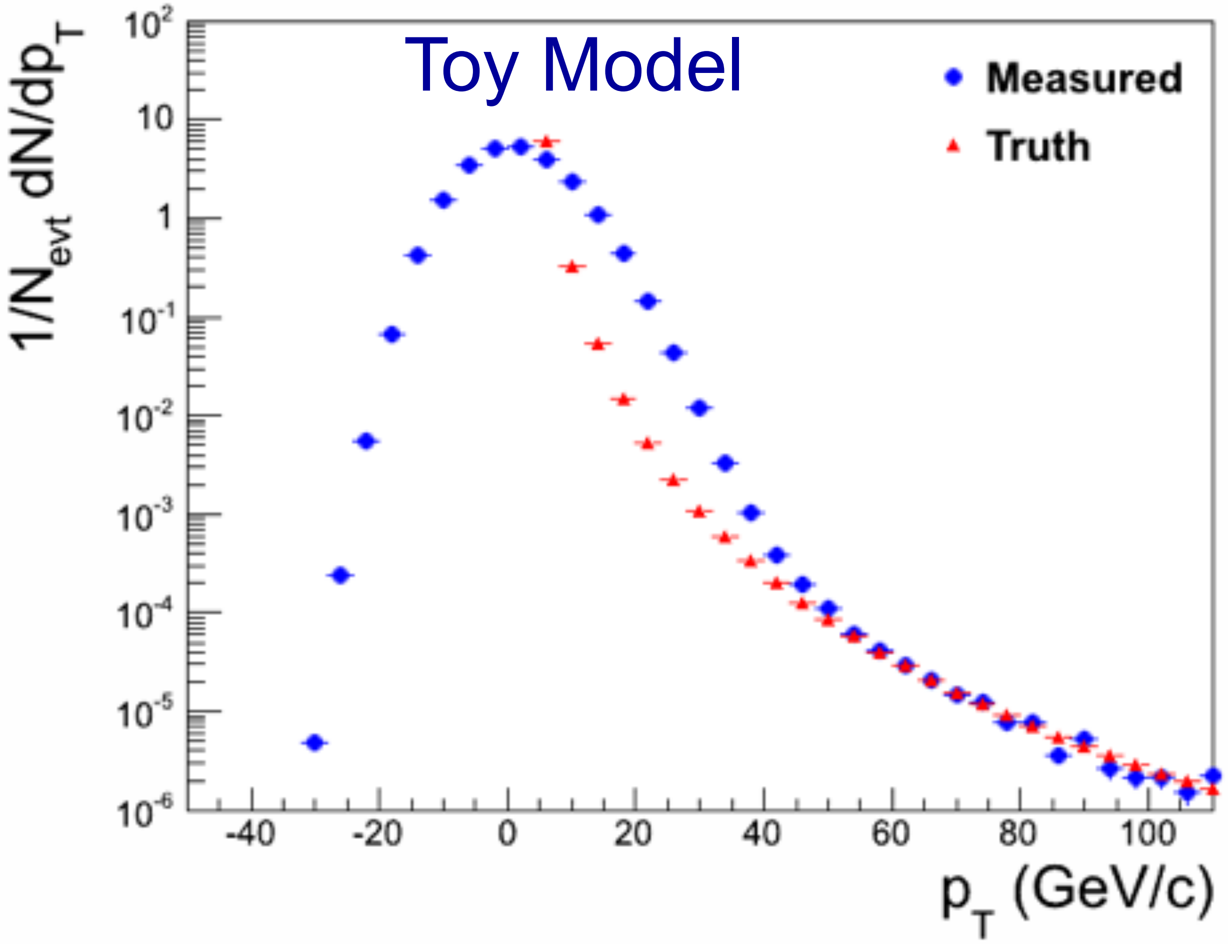
Background contributes up to ~180 GeV per unit area

Subtract background: $p_{T,jet}^{sub} = p_{T,jet}^{raw} - \rho\ A$

Statistical fluctuations remain after subtraction

PbPb jet background





Main challenge: large fluctuations of uncorrelated background energy

Size of fluctuations depends on p_T cut, cone radius

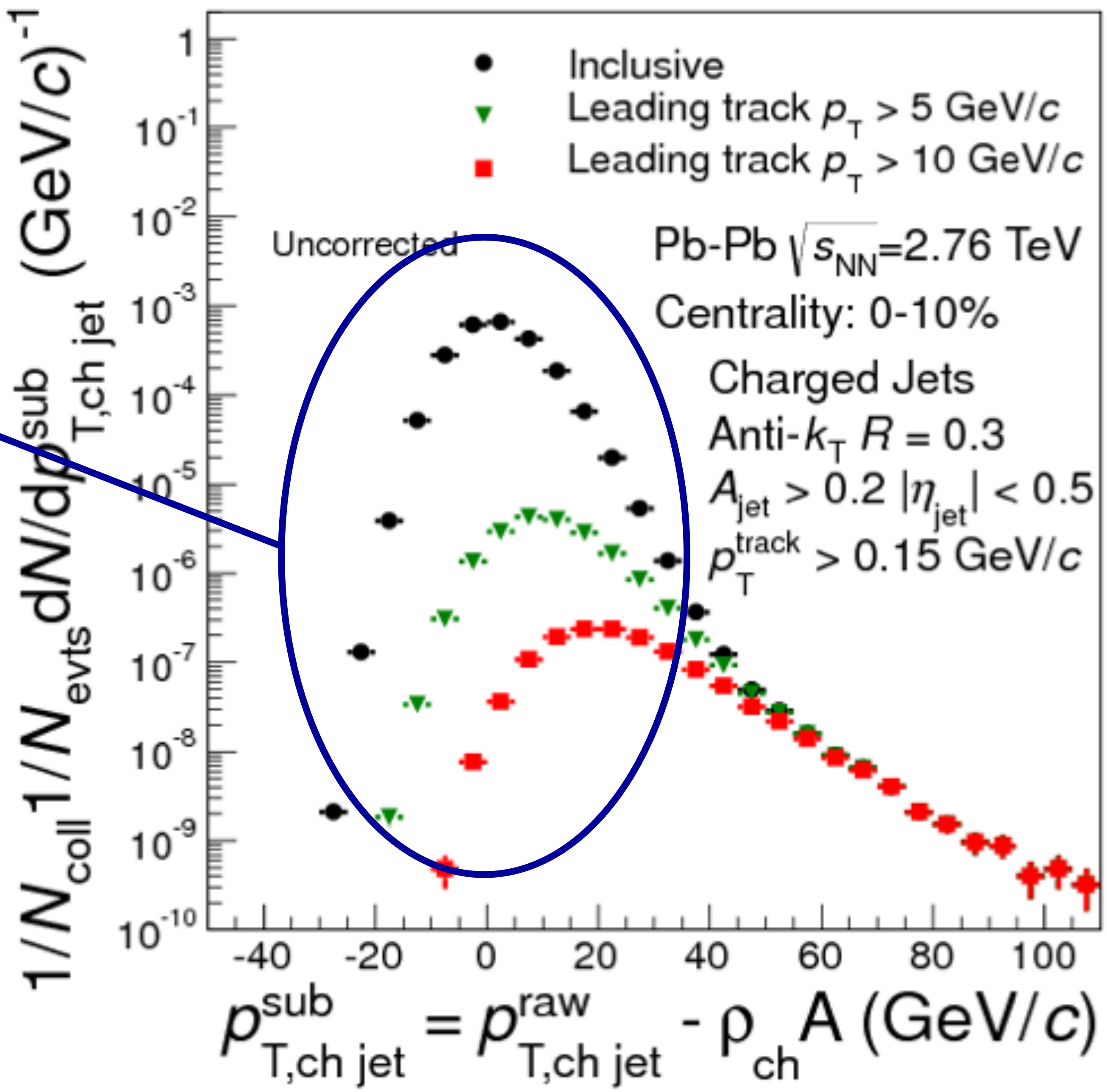
Background jets

Low p_T: ‘combinatorial jets’

- Can be suppressed by requiring leading track
- However: no strict distinction at low p_T possible

Raw jet spectrum

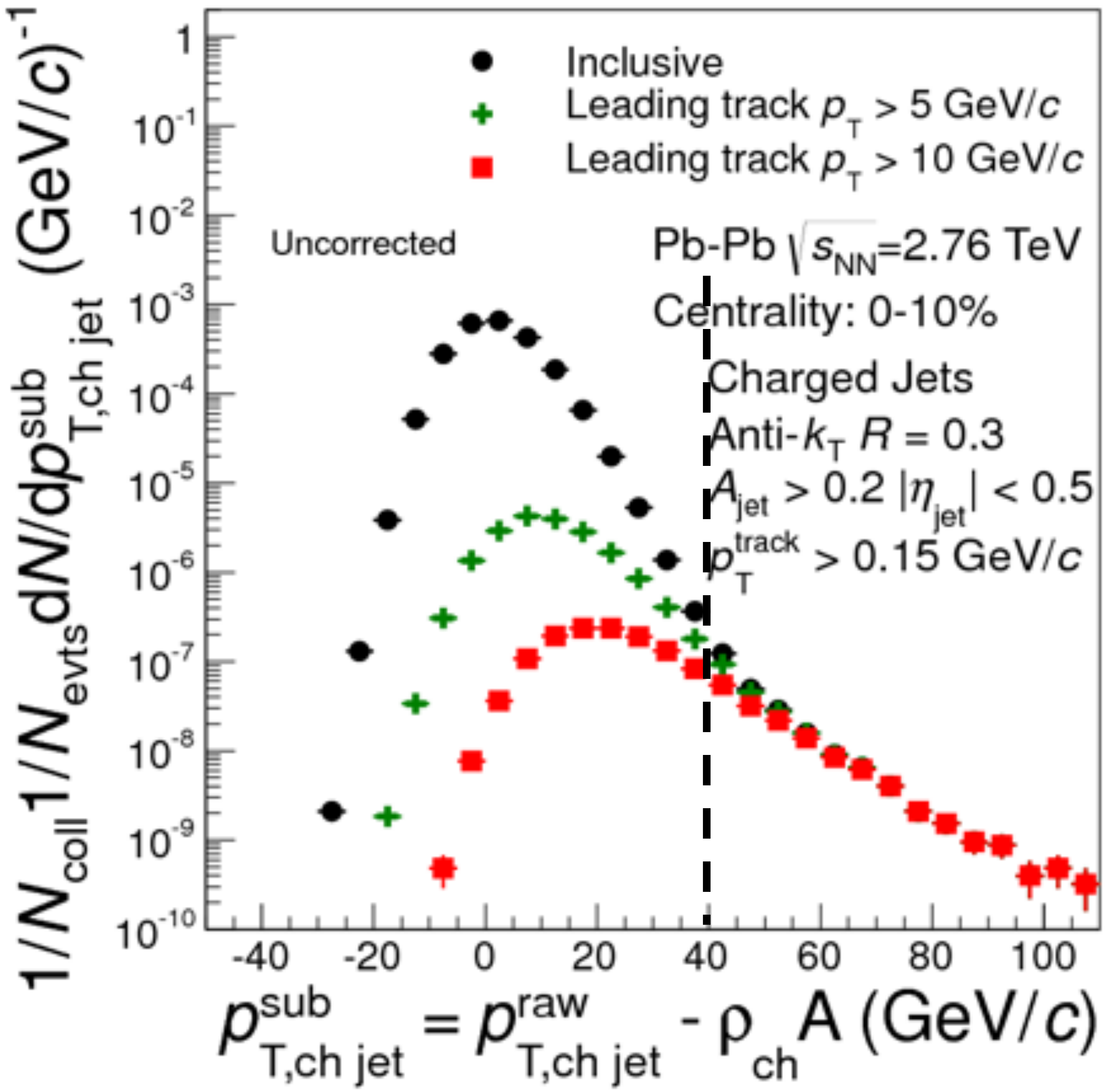
Event-by-event background subtracted



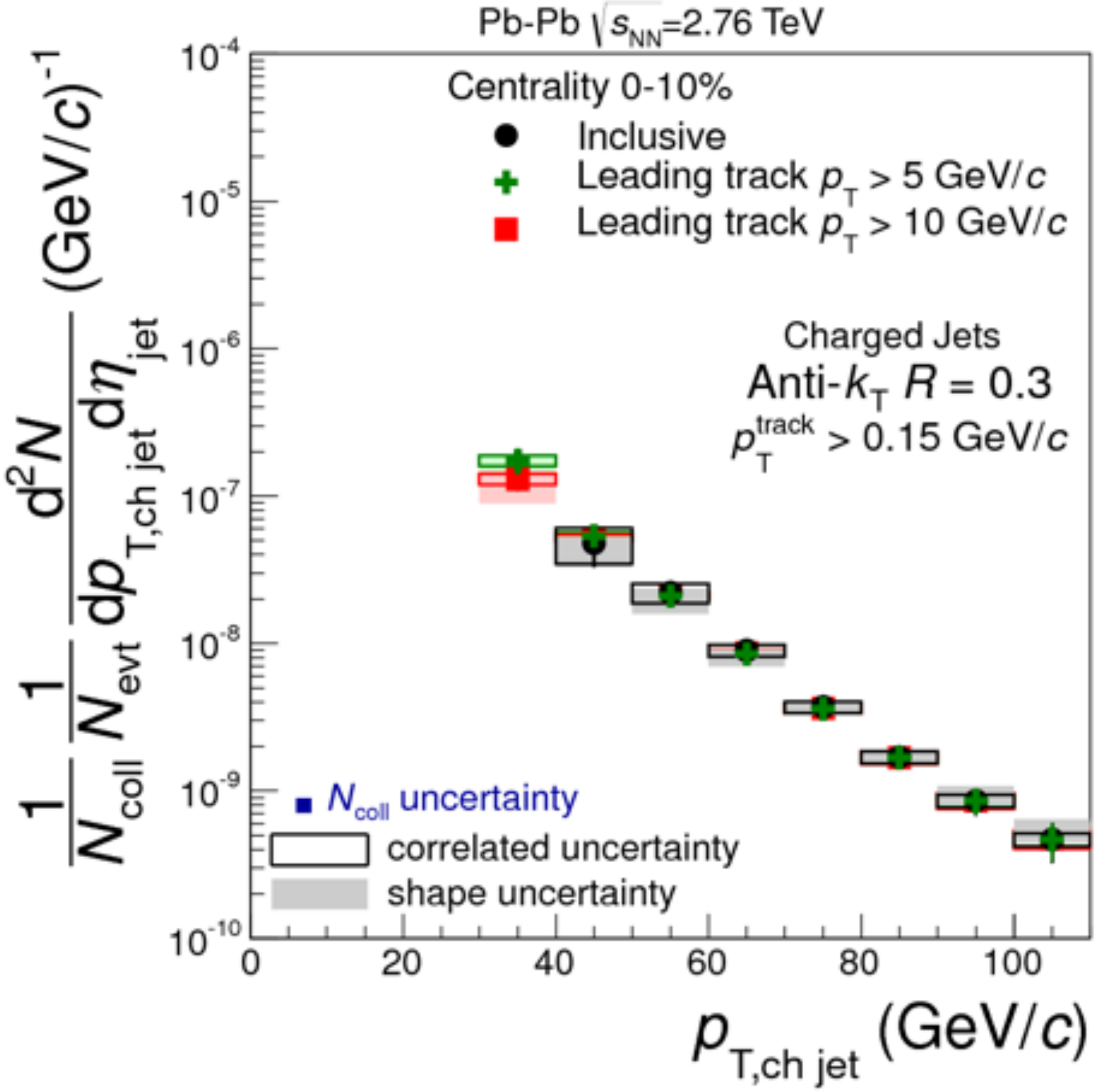
Next step: Correct for background fluctuations and detector effects by unfolding/deconvolution

Removing the combinatorial jets

Raw jet spectrum



Fully corrected jet spectrum



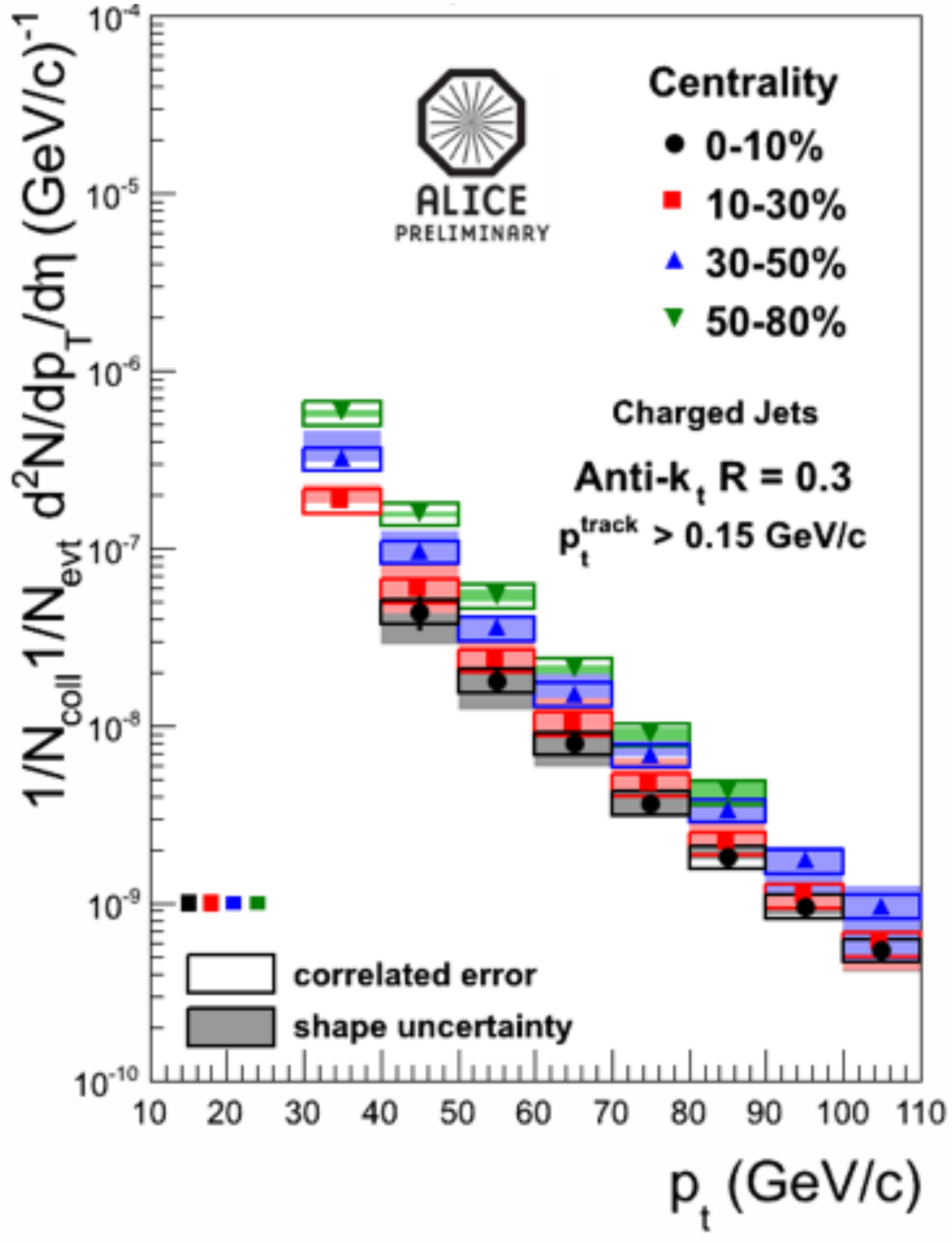
ALICE arXiv:1311.0633

Correct spectrum and remove combinatorial jets by unfolding

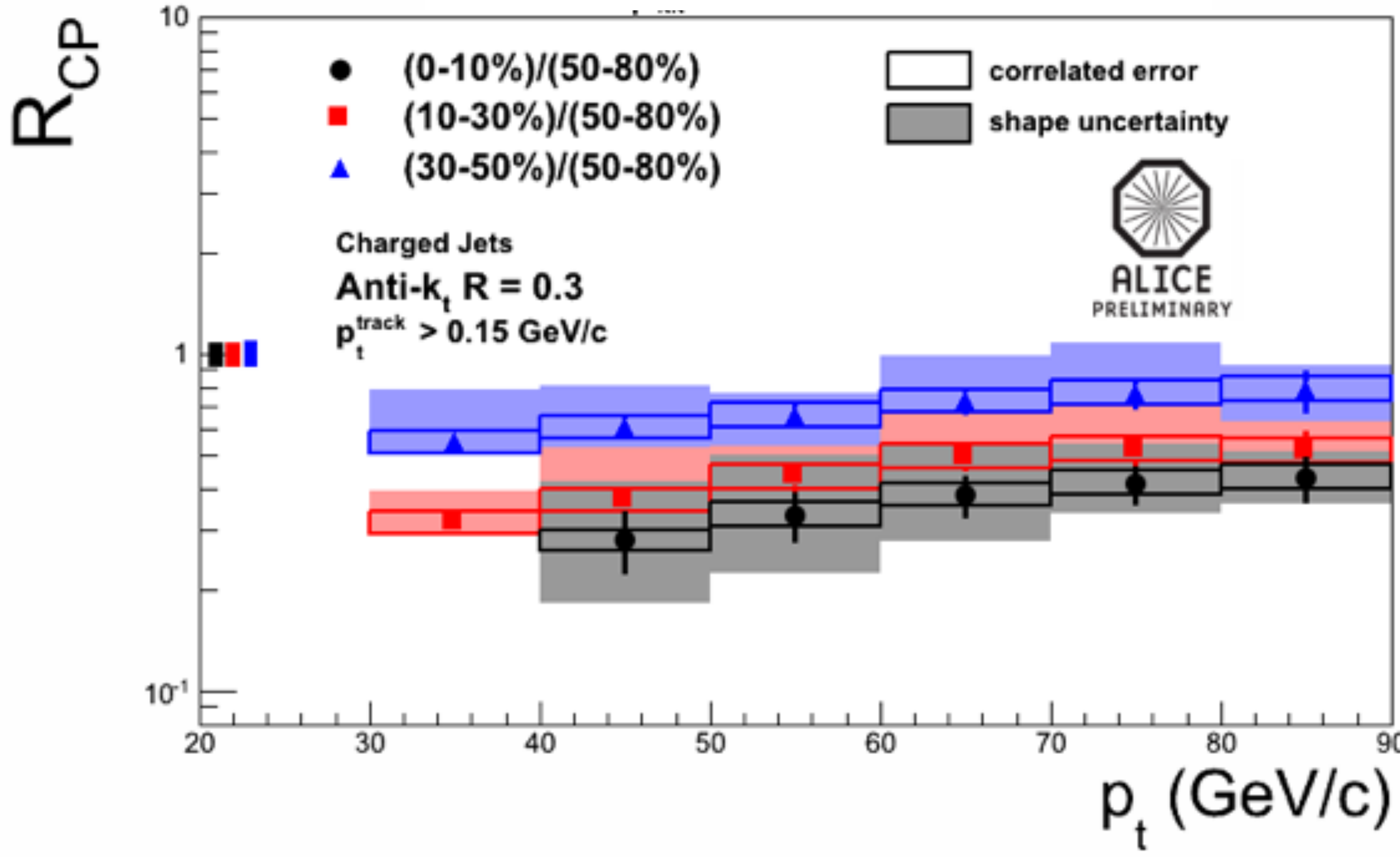
Results agree with biased jets: reliably recovers all jets and removed bkg

PbPb jet spectra

Charged jets, *R*=0.3



R_{CP}, charged jets, *R*=0.3



ALICE arXiv:1311.0633

Jet reconstruction does not
‘recover’ much of the radiated energy

Jet spectrum in Pb+Pb: charged particle jets
Two cone radii, 4 centralities

Pb+Pb jet R_{AA}

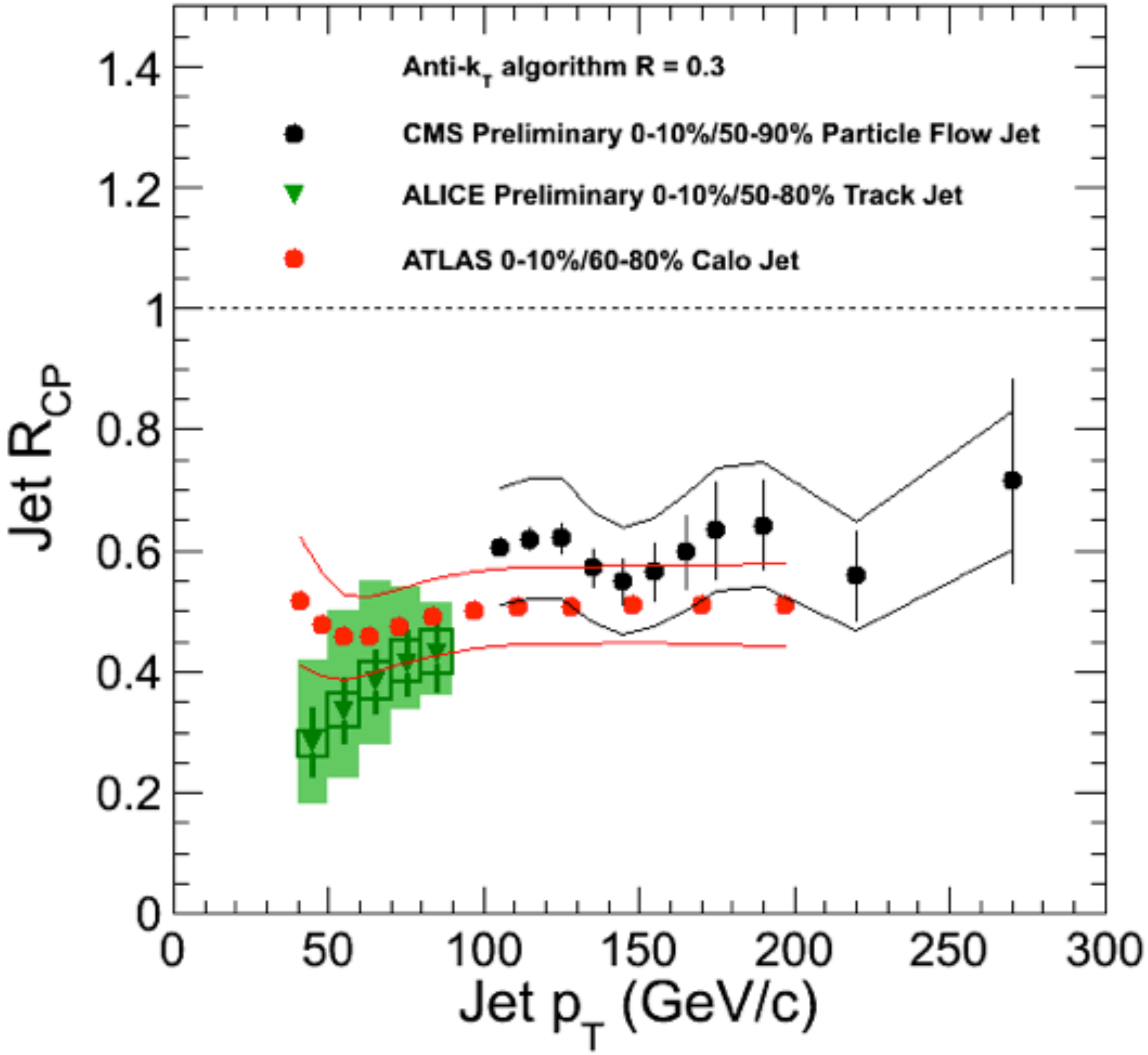
Jet R_{AA} measured by
ATLAS, ALICE, CMS

Good agreement
between experiments

Despite different methods:

ATLAS+CMS: hadron+EM jets

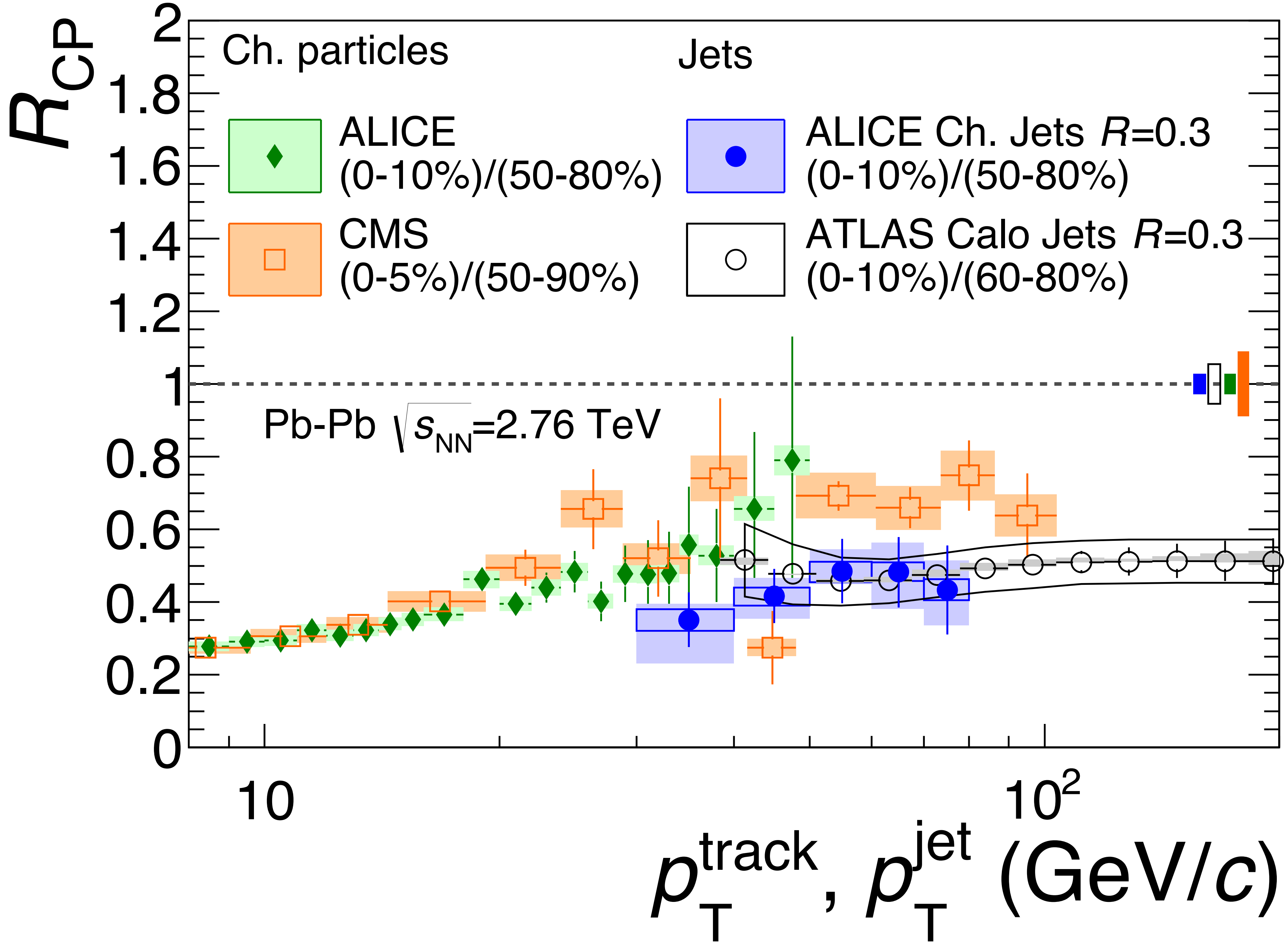
ALICE: charged track jets



$R_{AA} < 1$: not all produced jets are seen;
out-of-cone radiation and/or ‘absorption’

For jet energies up to ~250 GeV; energy loss is a very large effect

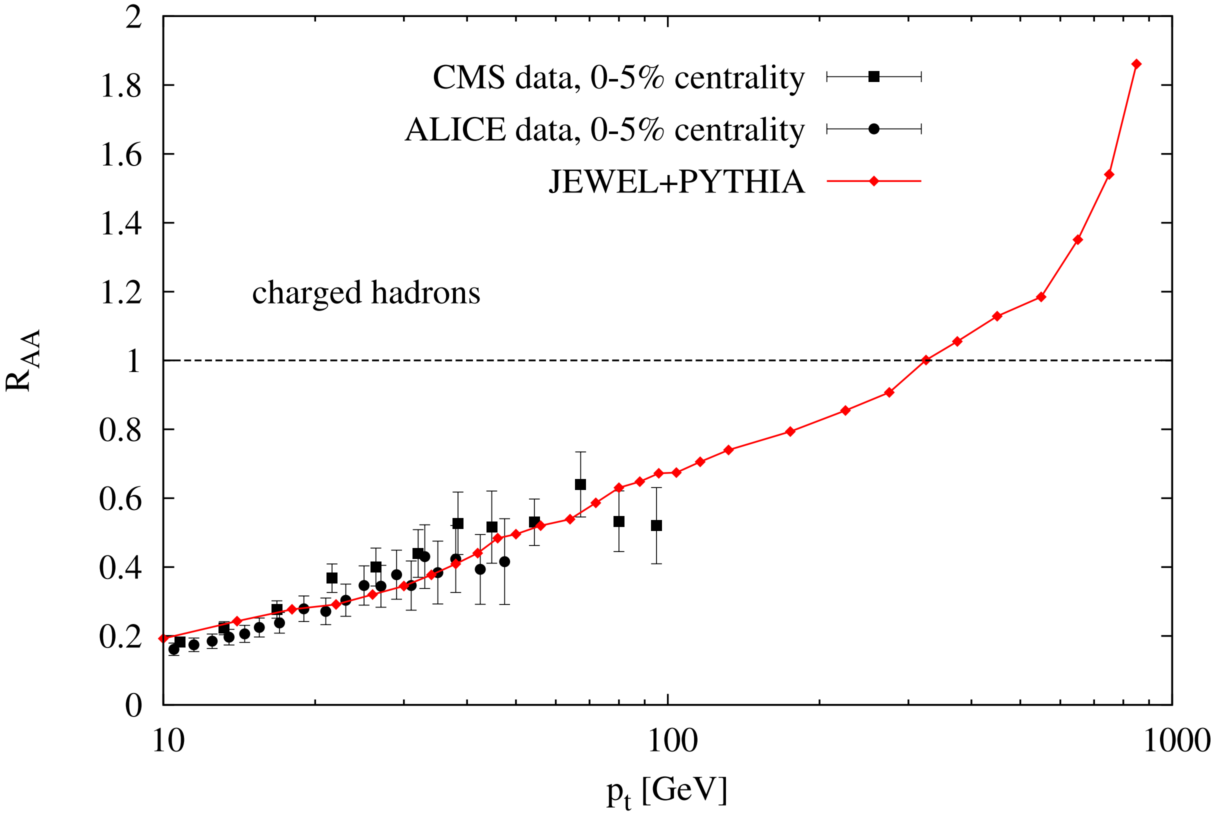
Comparing hadrons and jets

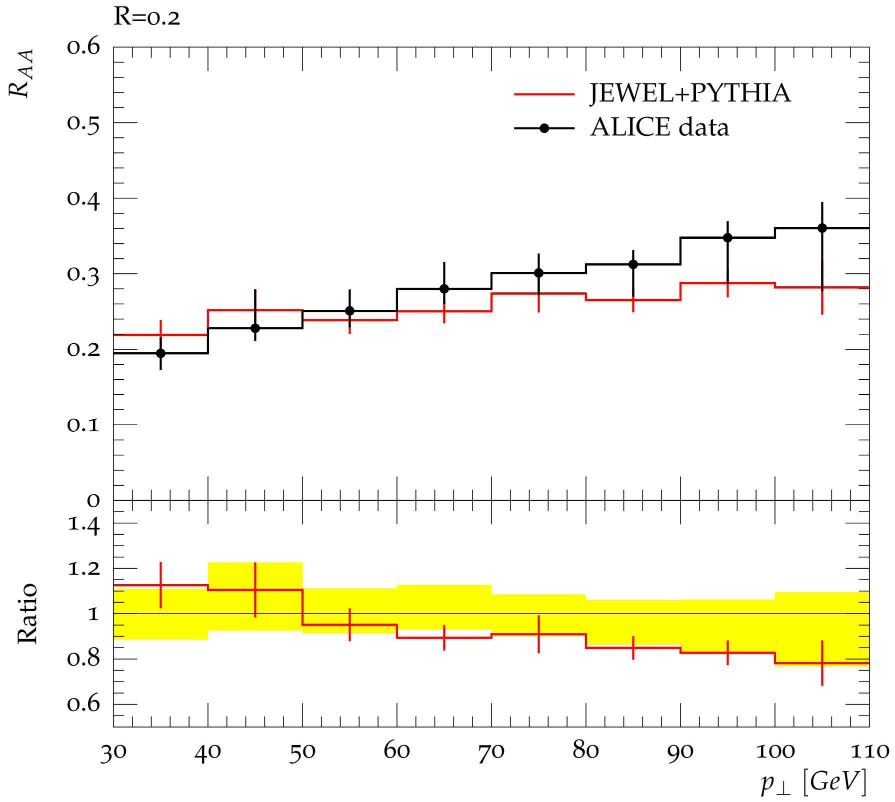


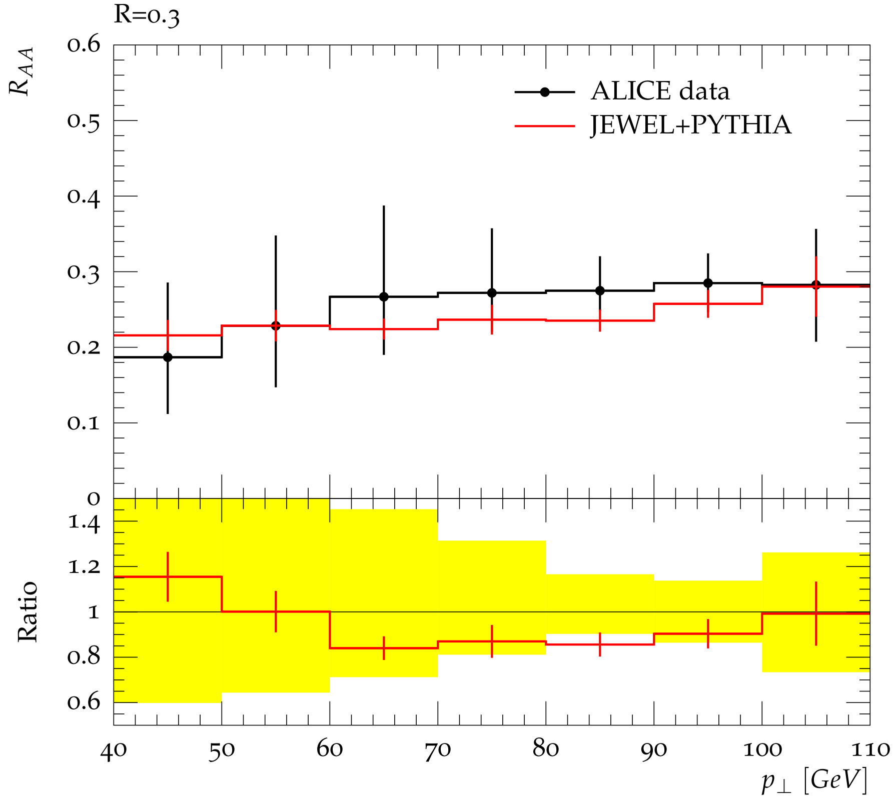
Suppression of hadron (leading fragment) and jet yield similar

Is this 'natural'? No (visible) effect of in-cone radiation?

Comparison to JEWEL energy loss MC

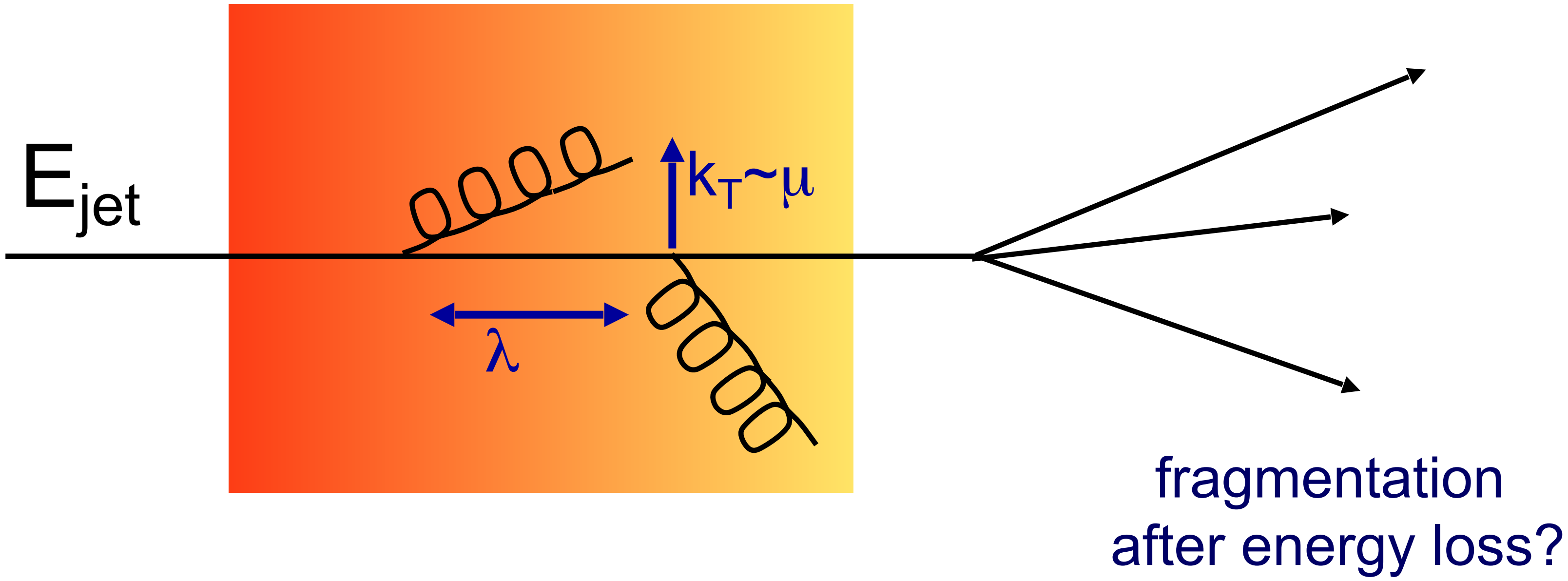






JEWEL shows the same feature:
jet R_{AA} ~ hadron R_{AA}

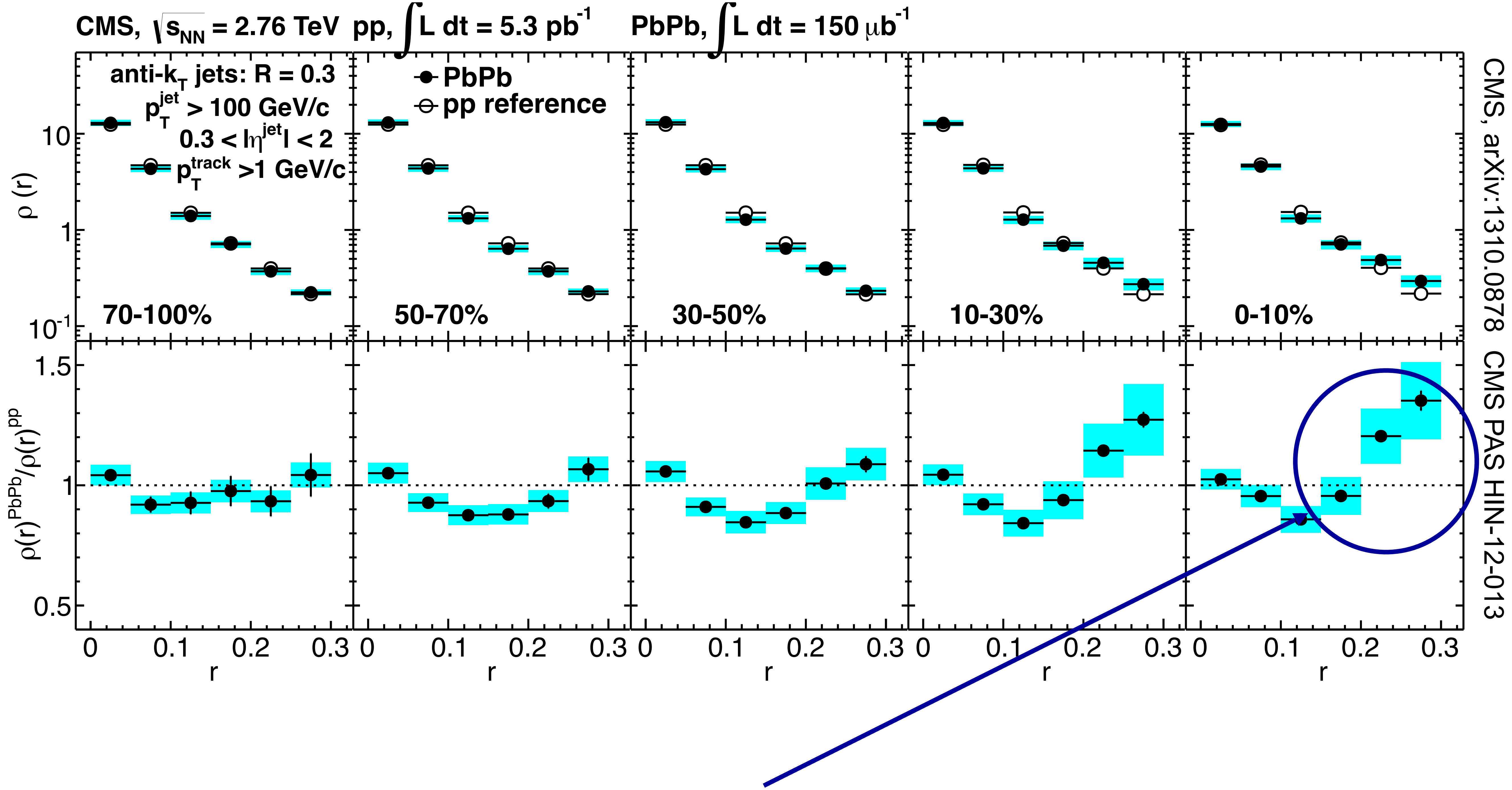
Generic expectations from energy loss



fragmentation
after energy loss?

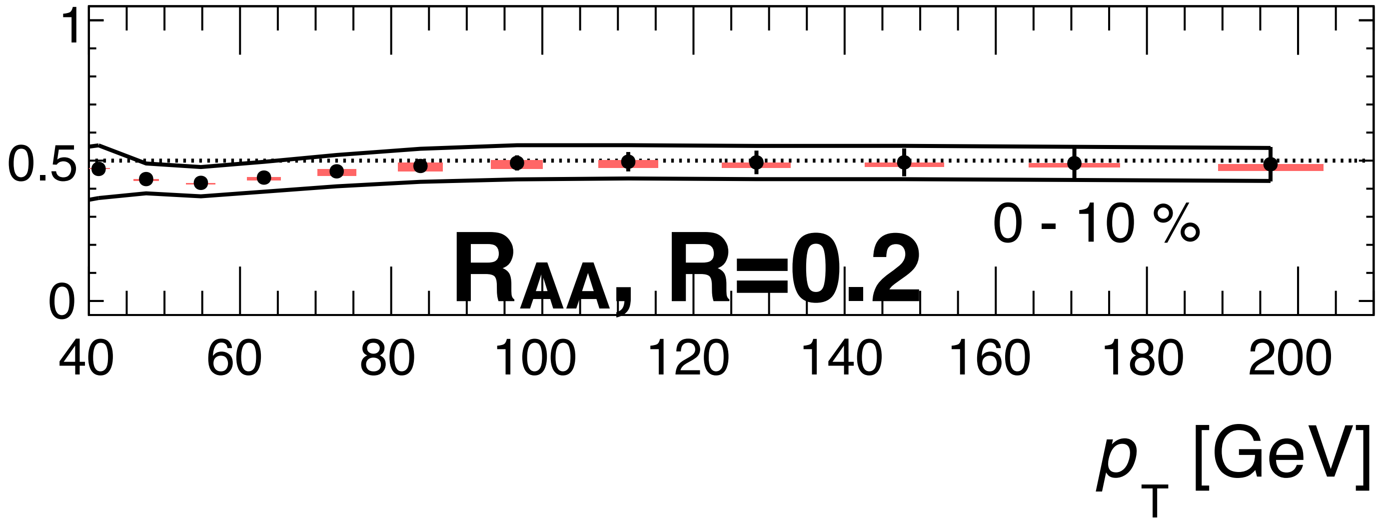
- Longitudinal modification:
  - out-of-cone ⇒ energy lost, suppression of yield, di-jet energy imbalance
  - in-cone ⇒ softening of fragmentation
- Transverse modification
  - out-of-cone ⇒ increase acoplanarity k_T
  - in-cone ⇒ broadening of jet-profile

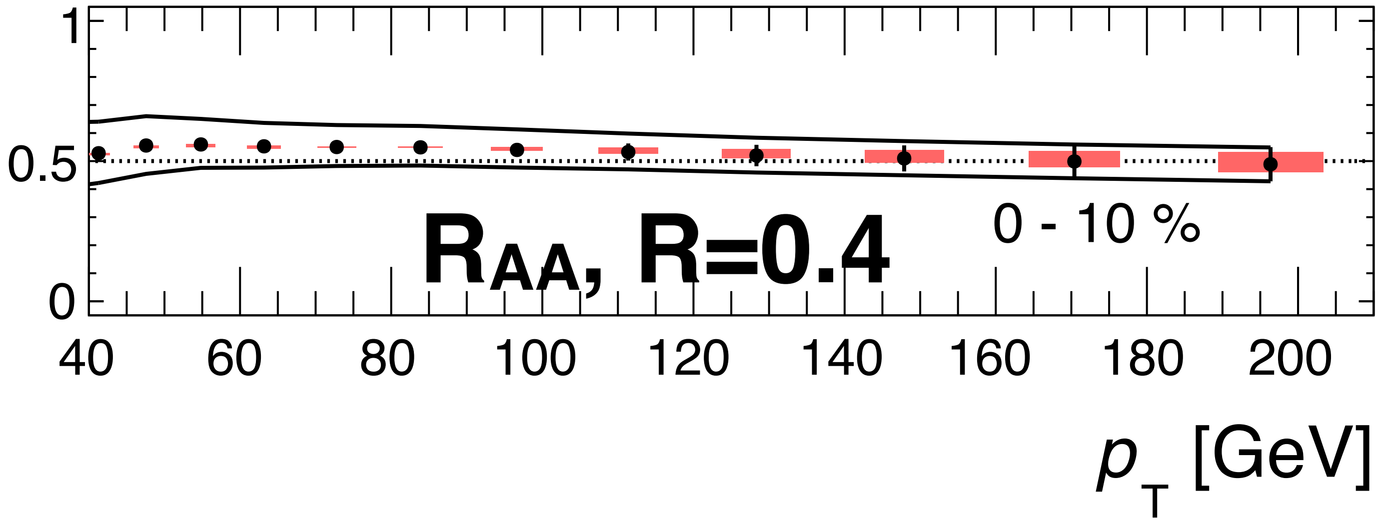
Jet broadening: transverse fragment distributions

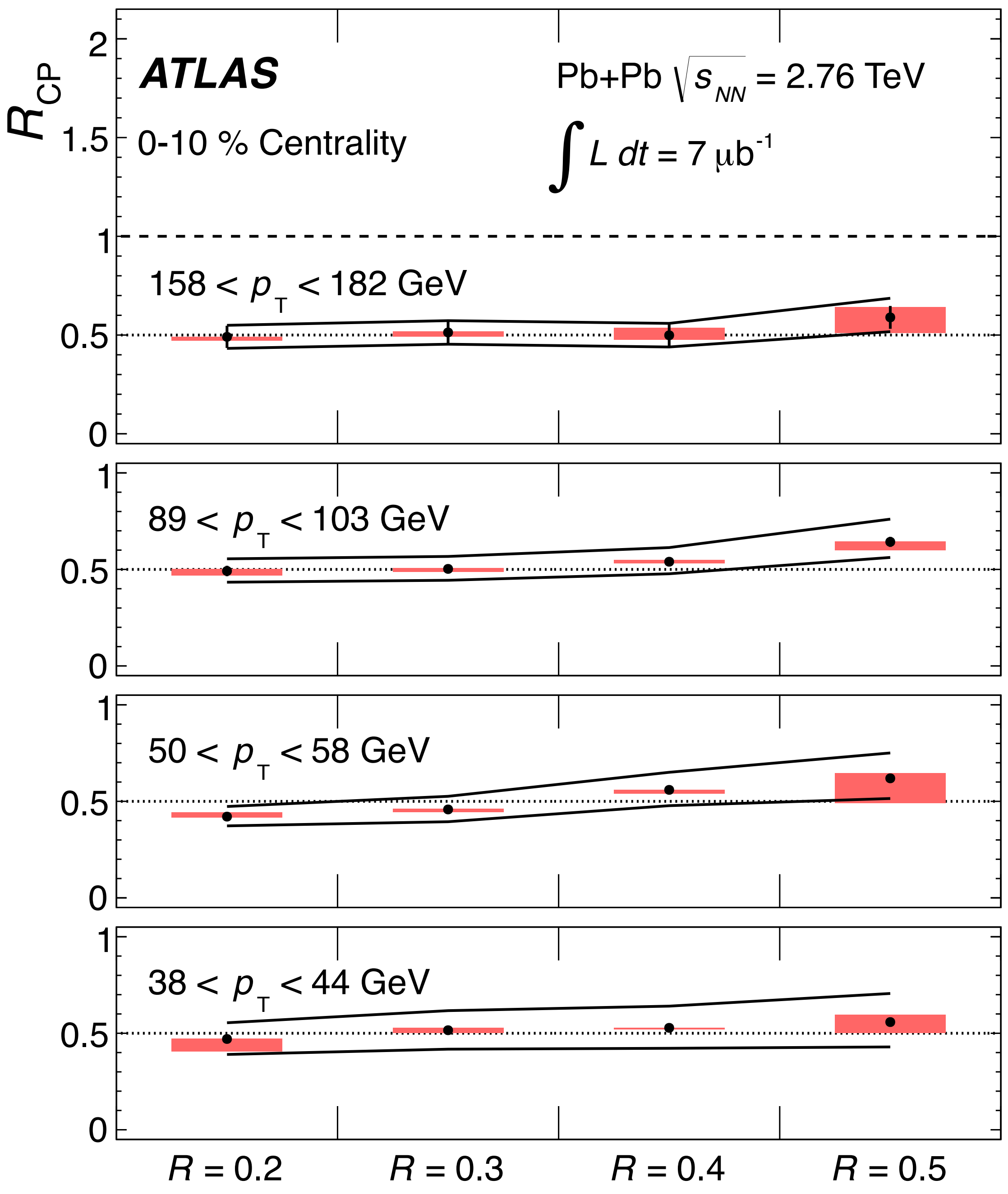


Jet broadening: radiation at large angles

Jet broadening: R dependence of R_{AA}



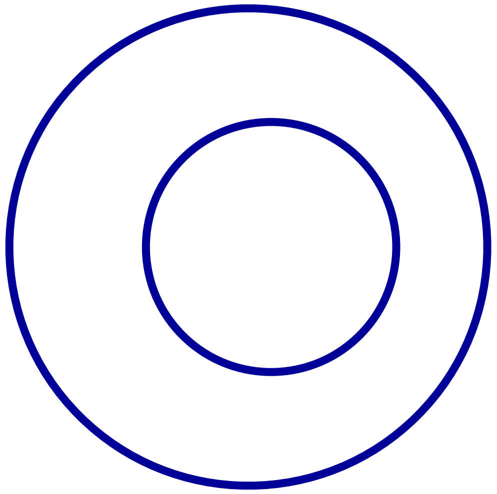




ATLAS, arXiv:1208.1867

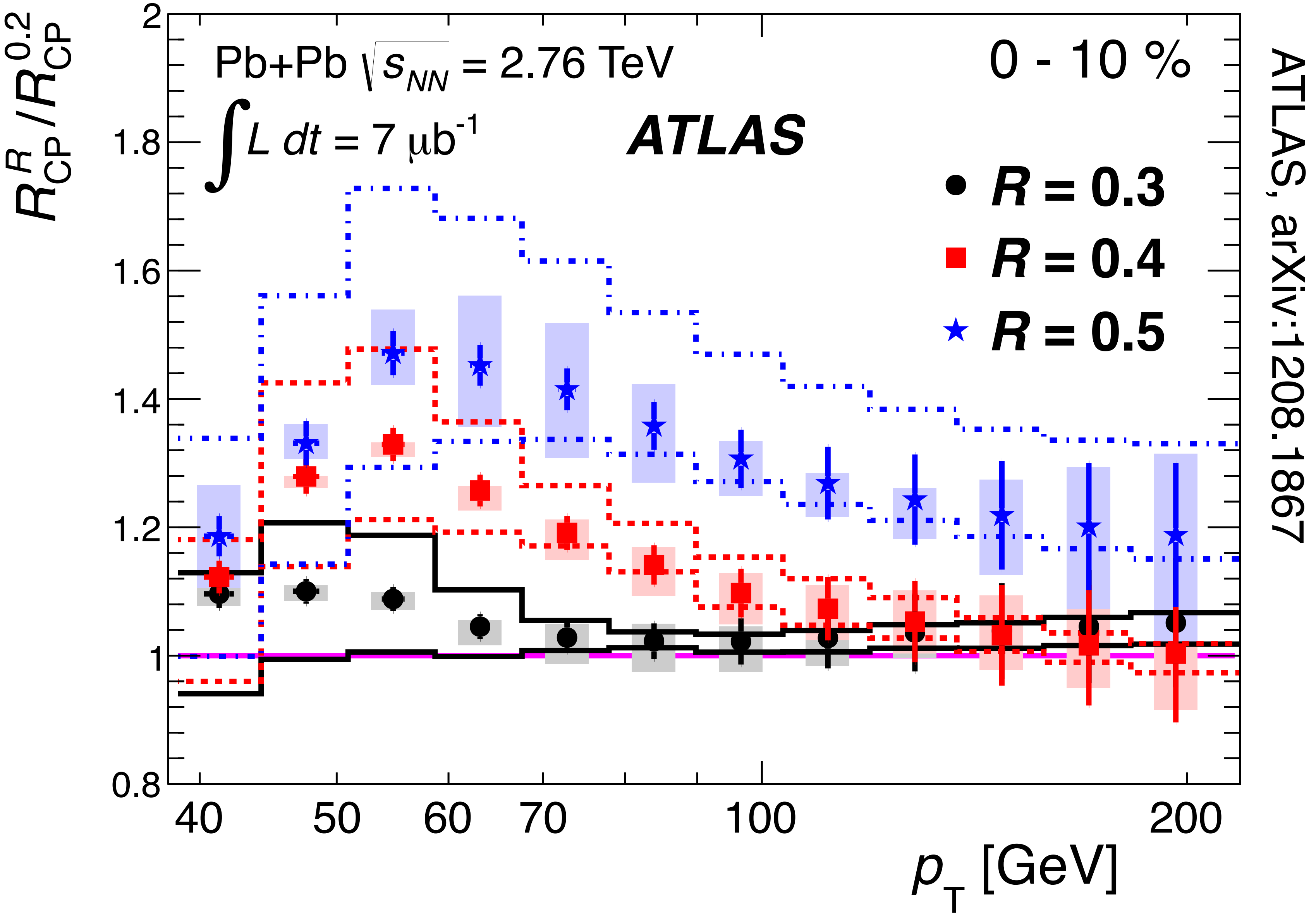
Jet R_{AA} increases with R (but slowly)

Jet broadening: *R* dependence



Larger jet cone:
'catch' more radiation
→ Jet broadening

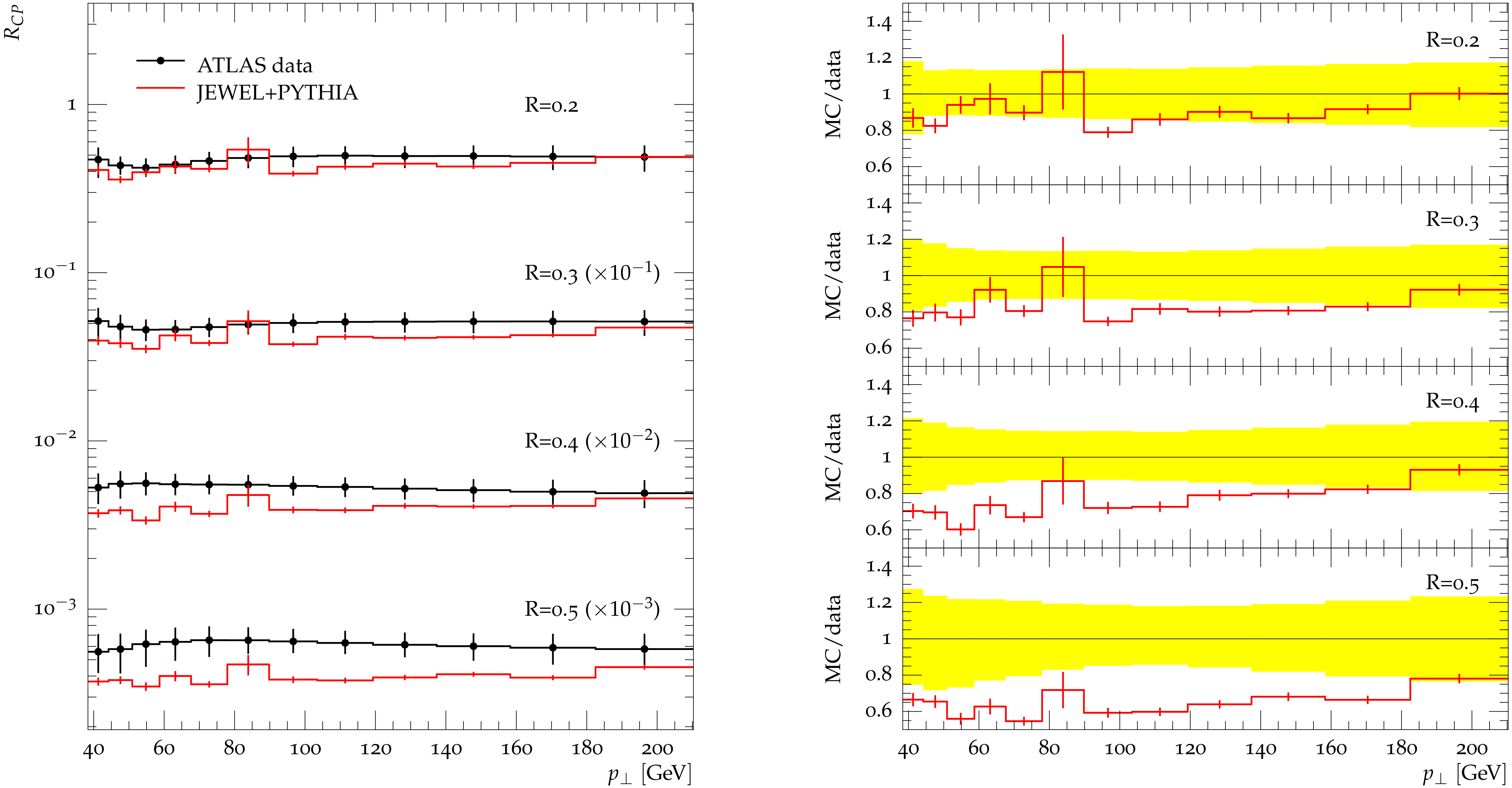
Ratio of spectra with different *R*



ATLAS, arXiv:1208.1867

However, R = 0.5 still has $R_{AA} < 1$
– Hard to see/measure the radiated energy

Comparing to JEWEL energy loss MC



K. Zapp et al, arXiv:1212.1599

JEWEL gets the right suppression for R=0.2,

but not the increase with R

May be treatment of recoil patrons

Recap

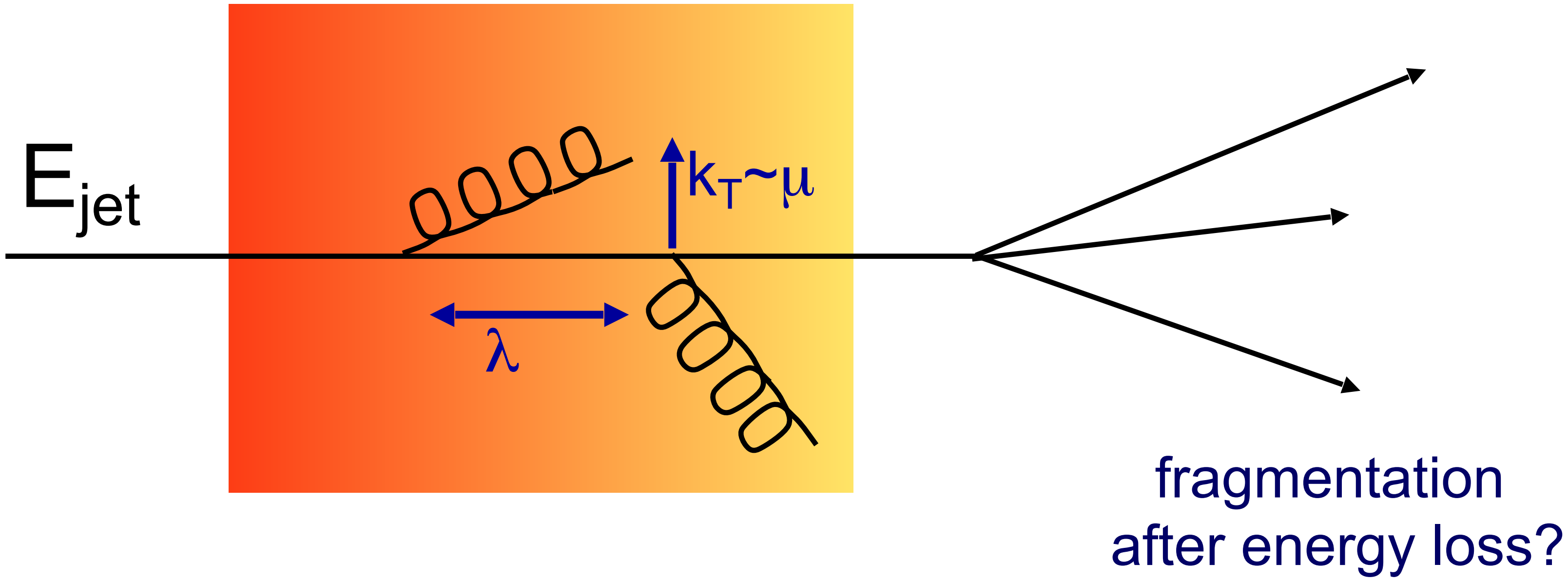
- So, jet R_{AA} is not close to 1
- Large out-of-cone radiation
- Also means: measured jet energy ≠ initial parton energy!

Next sections: more jet measurements

Why so many?

- Different observables sensitive to different aspects of energy loss
- Finding a balance between what you want to know and what you can measure

Generic expectations from energy loss



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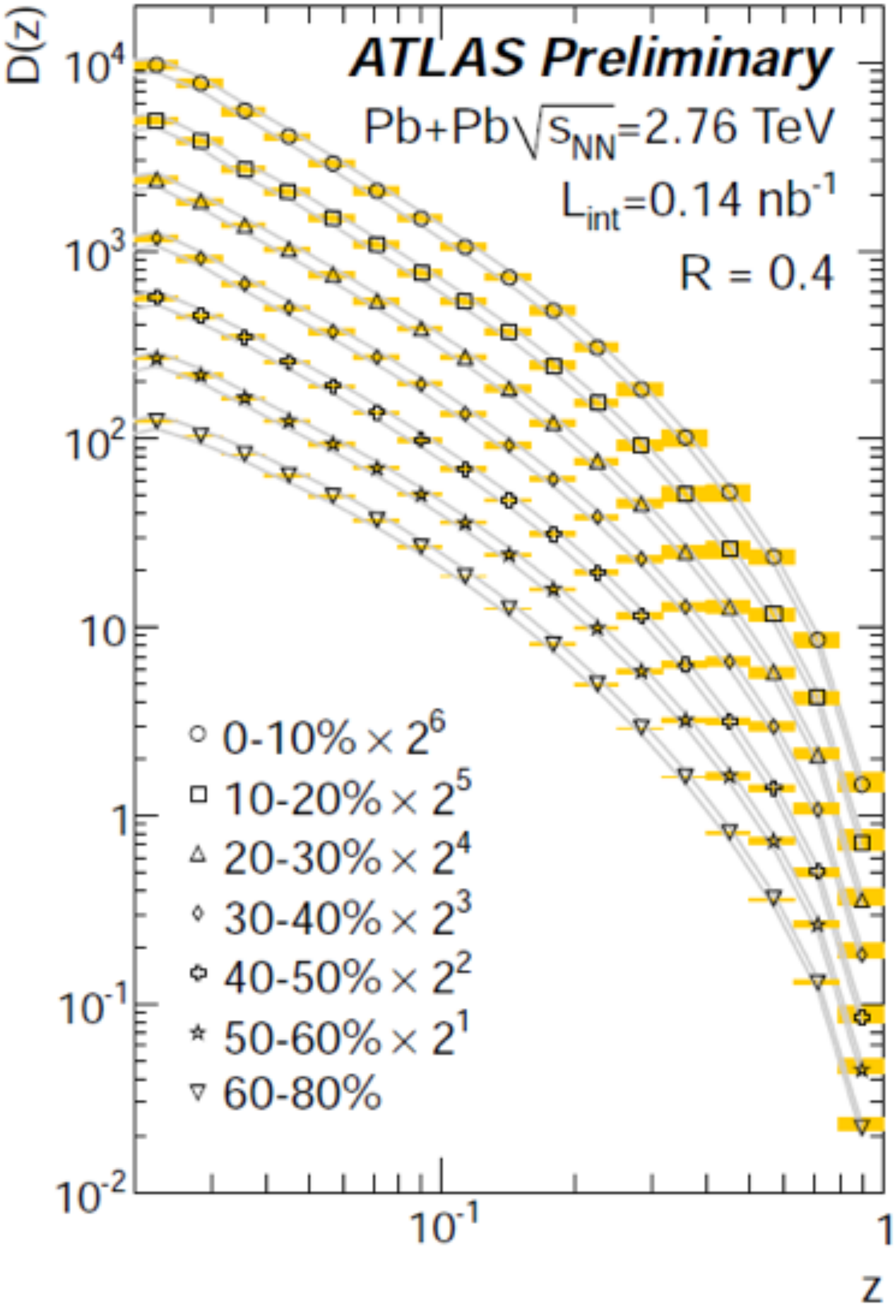
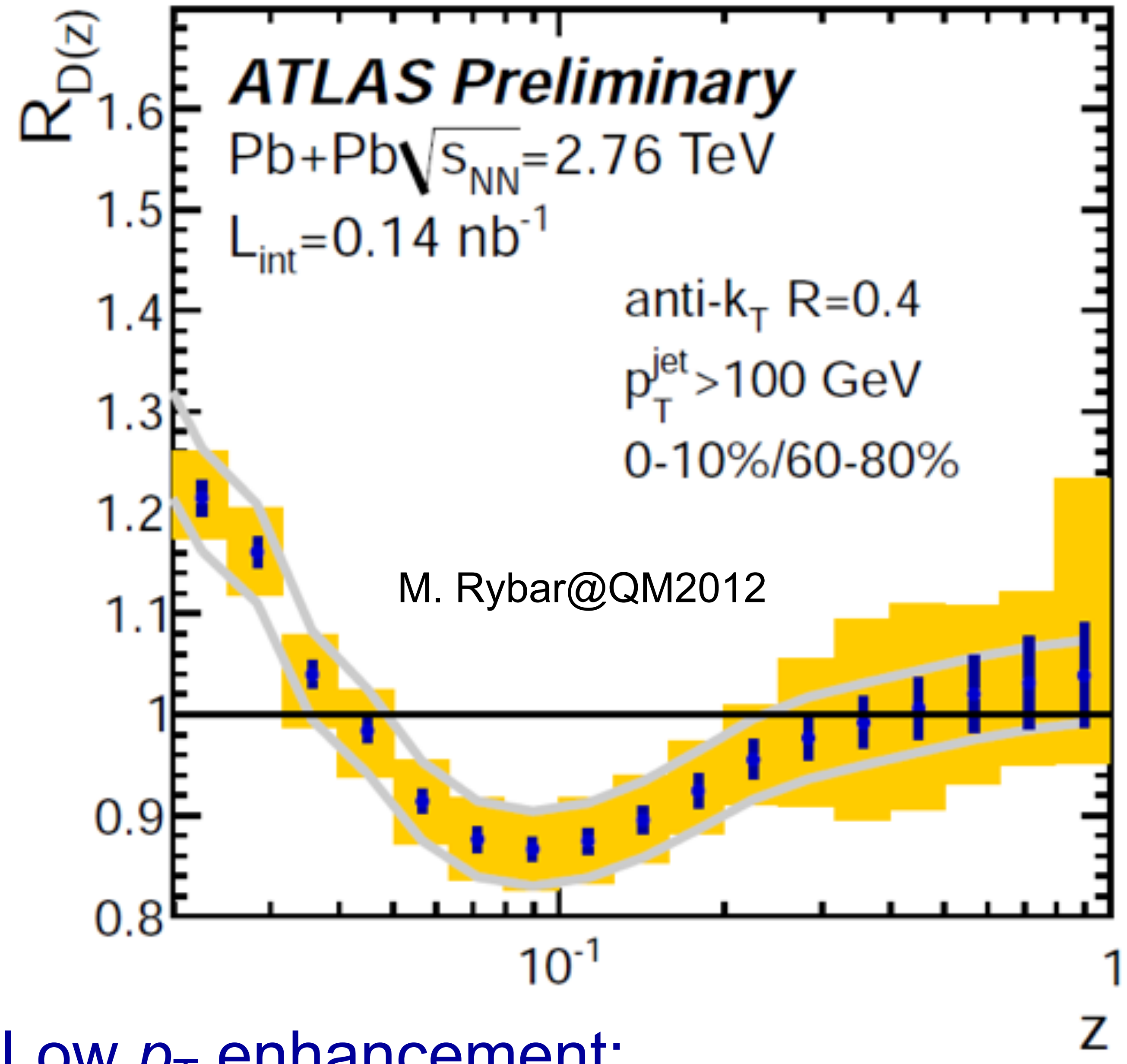
Jet fragment distributions

PbPb measurement



ATLAS M.Rybar@QM12

Ratio to pp



M. Rybar@QM2012

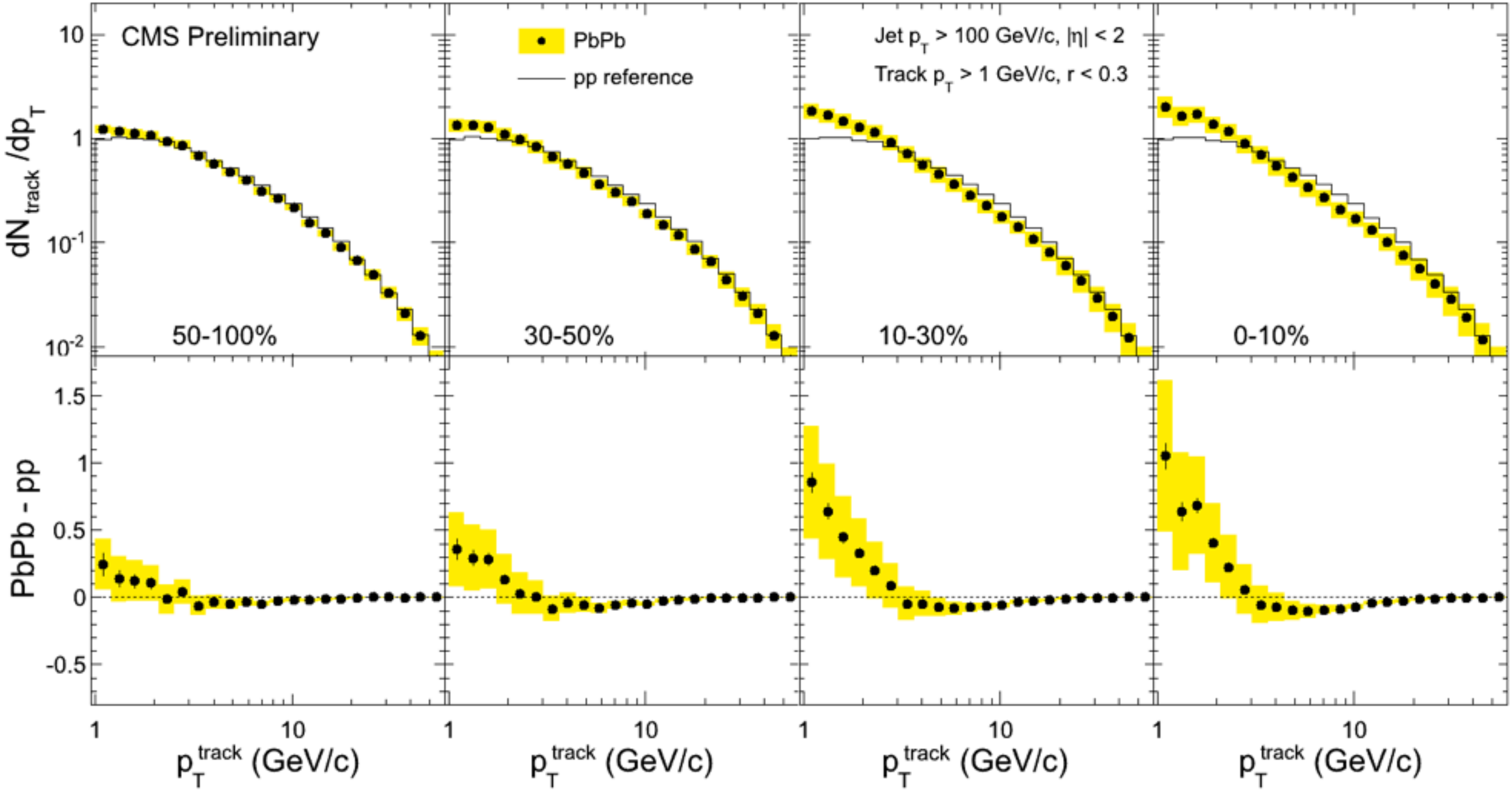
Low p_T enhancement:
soft radiation

Intermediate z:
depletion: E-loss

NB: z is wrt *observed* $E_{\text{jet}} \neq$ initial E_{parton}

Jet fragment distributions

CMS, Frank Ma@QM12

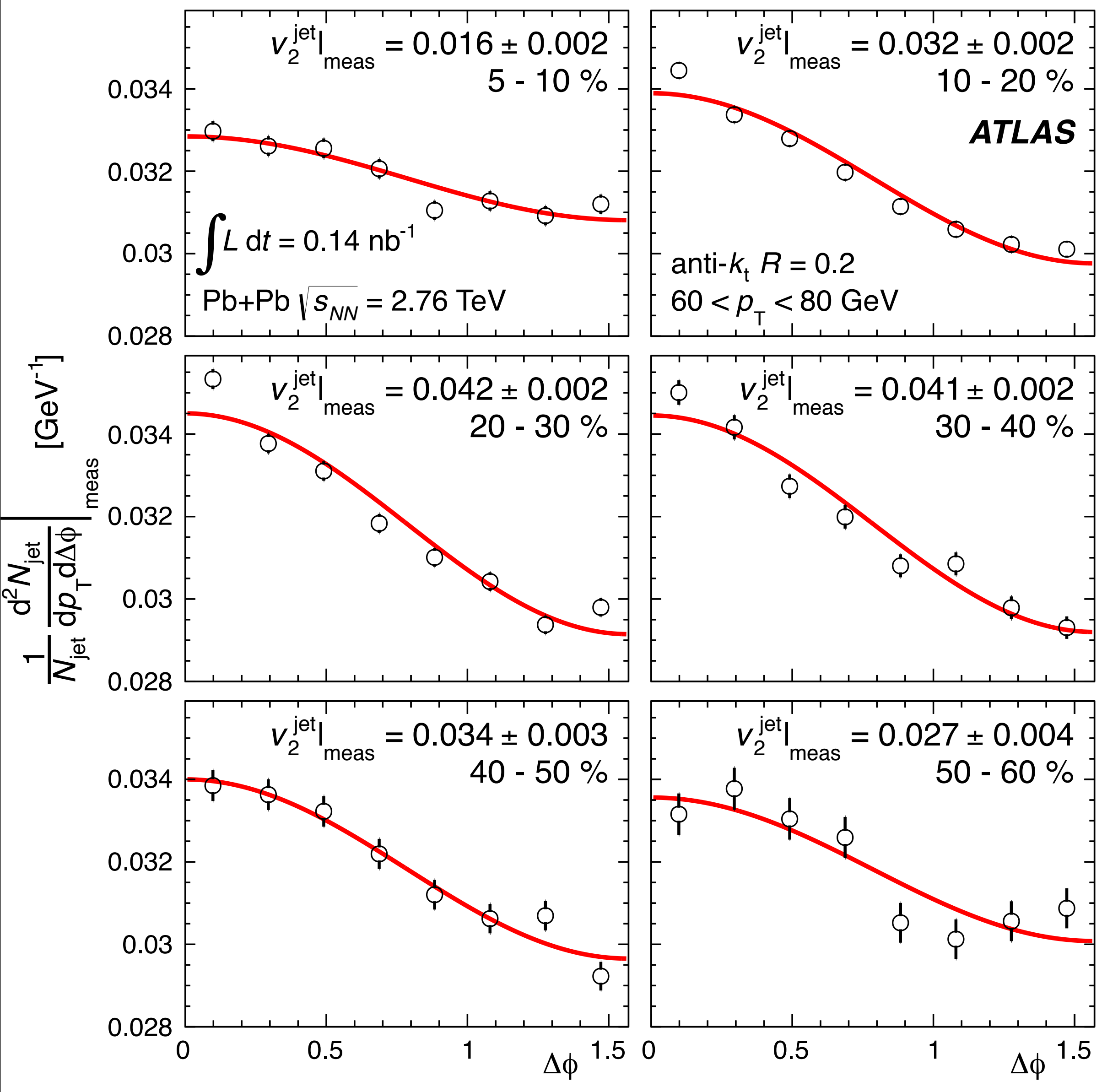


Low p_T enhancement:
soft radiation

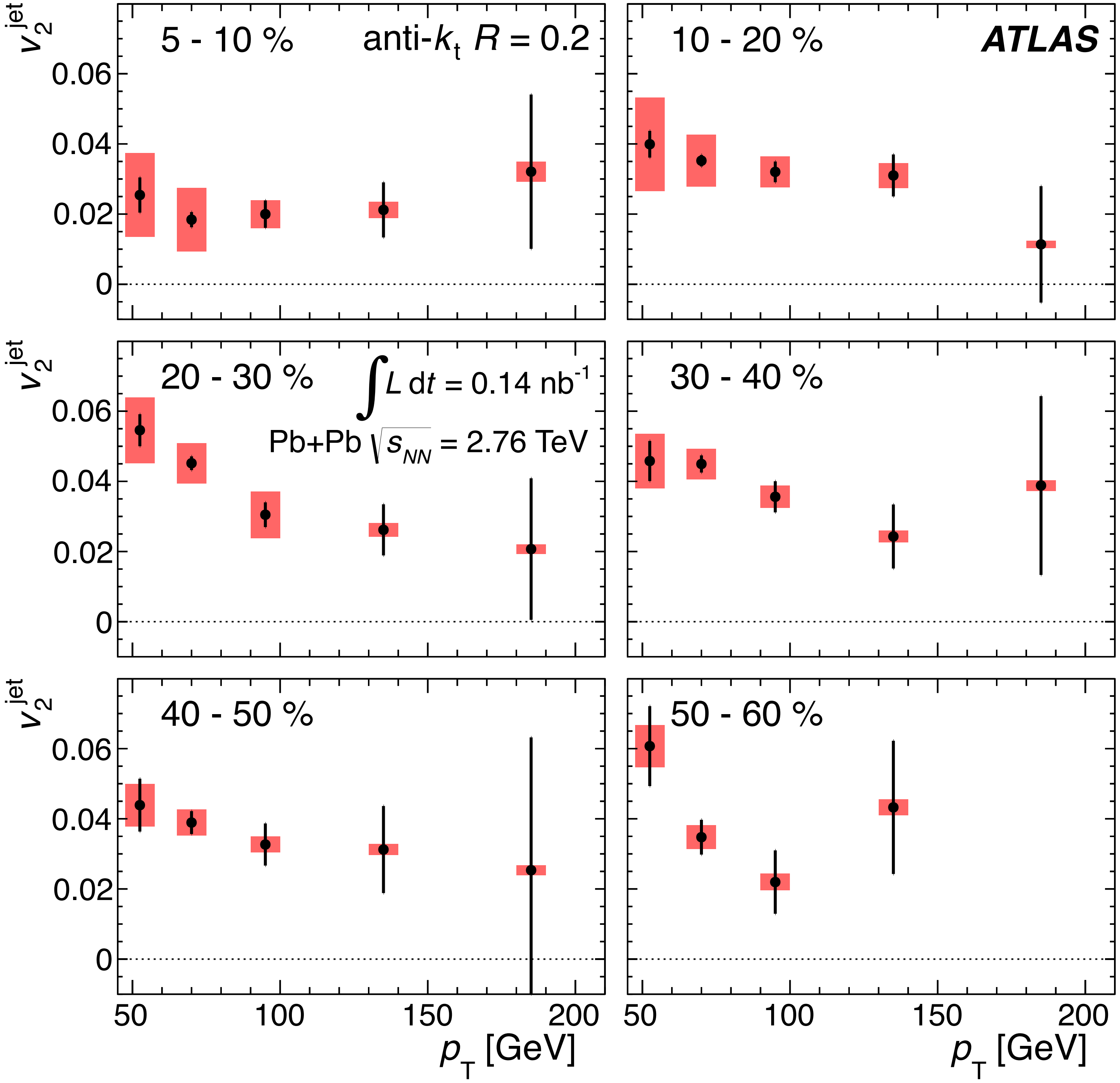
Intermediate z, p_T:
depletion: E-loss

Azimuthal modulation of R_{AA} ‘jet flow’

Path length dependence: elliptic flow of Jets



ATLAS, arXiv:1306.6469

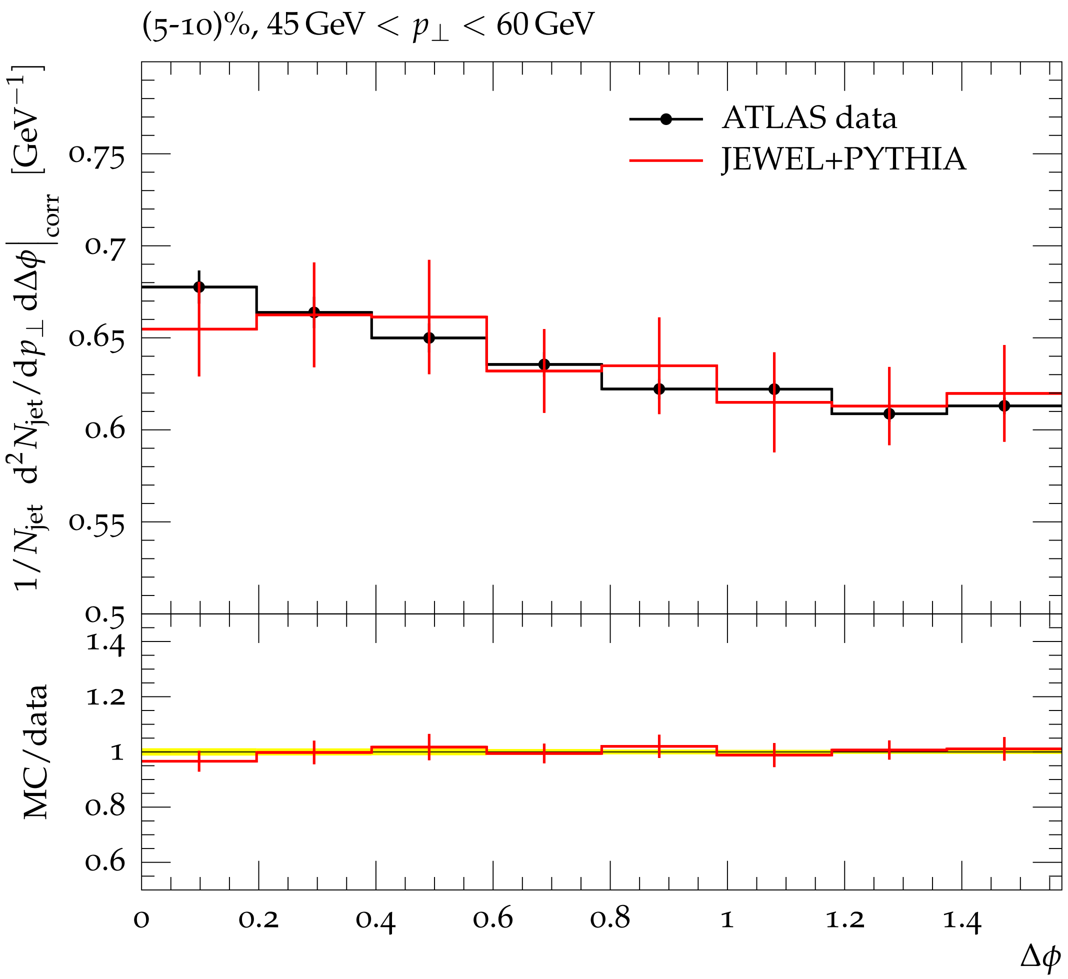


Significant azimuthal modulation of jet yield

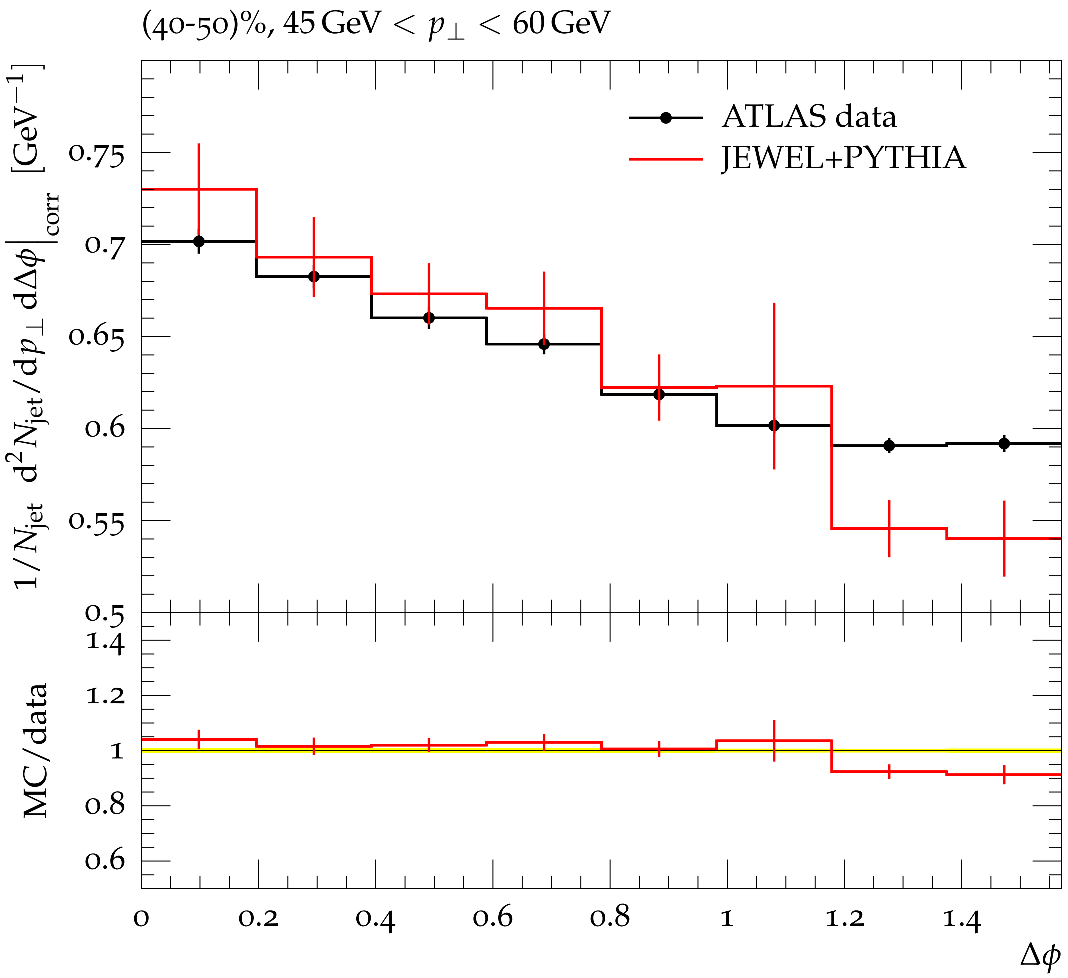
jet v_2 ~ 0.03 at high p_T

Comparing to JEWEL energy loss MC

5-10% centrality



40-50% centrality



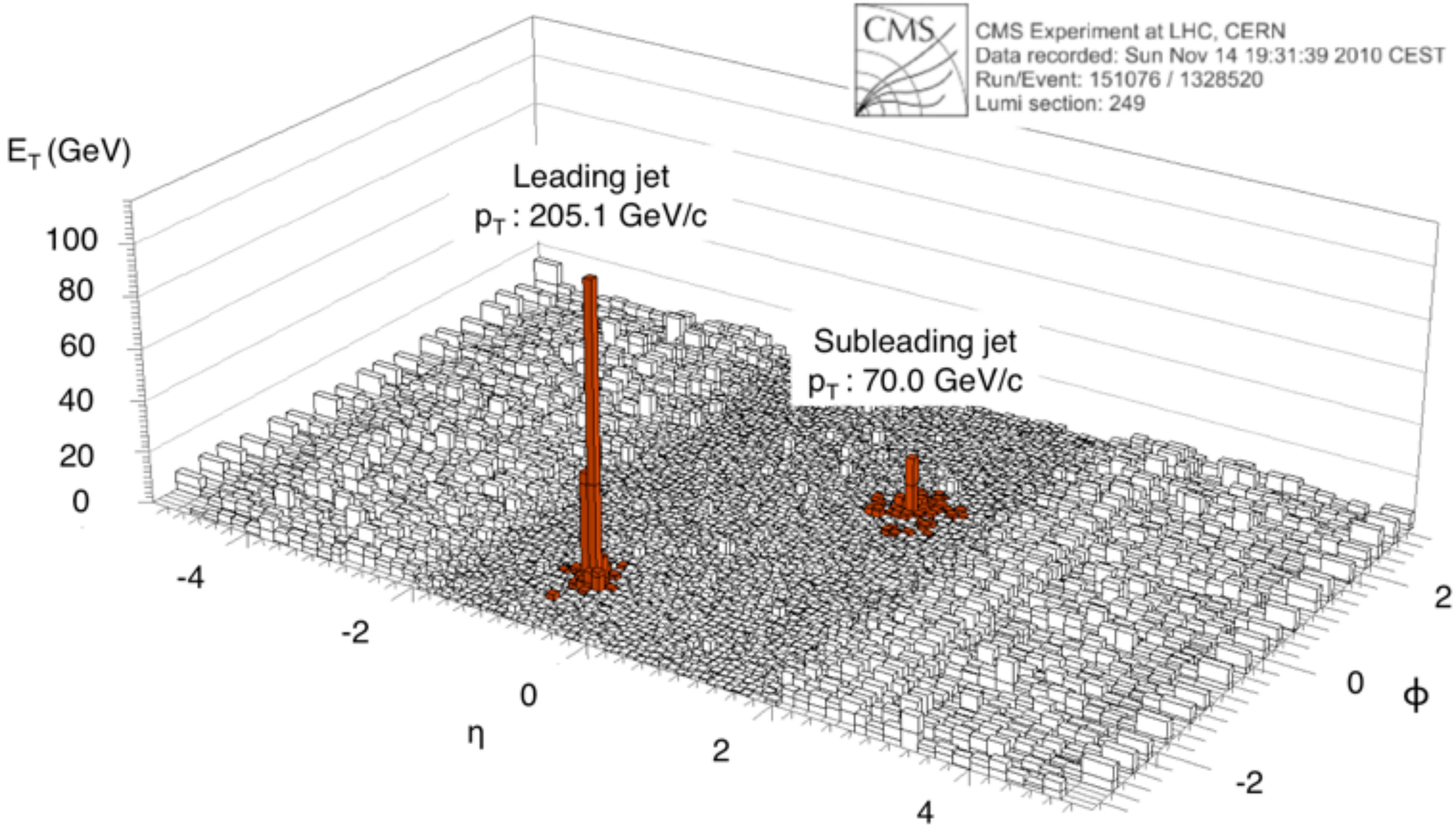
K. Zapp, arXiv:1312.5563

Good agreement between JEWEL and jet v_2 results

Geometry: Glauber overlap with Bjorken expansion

Di-jet imbalance measurements

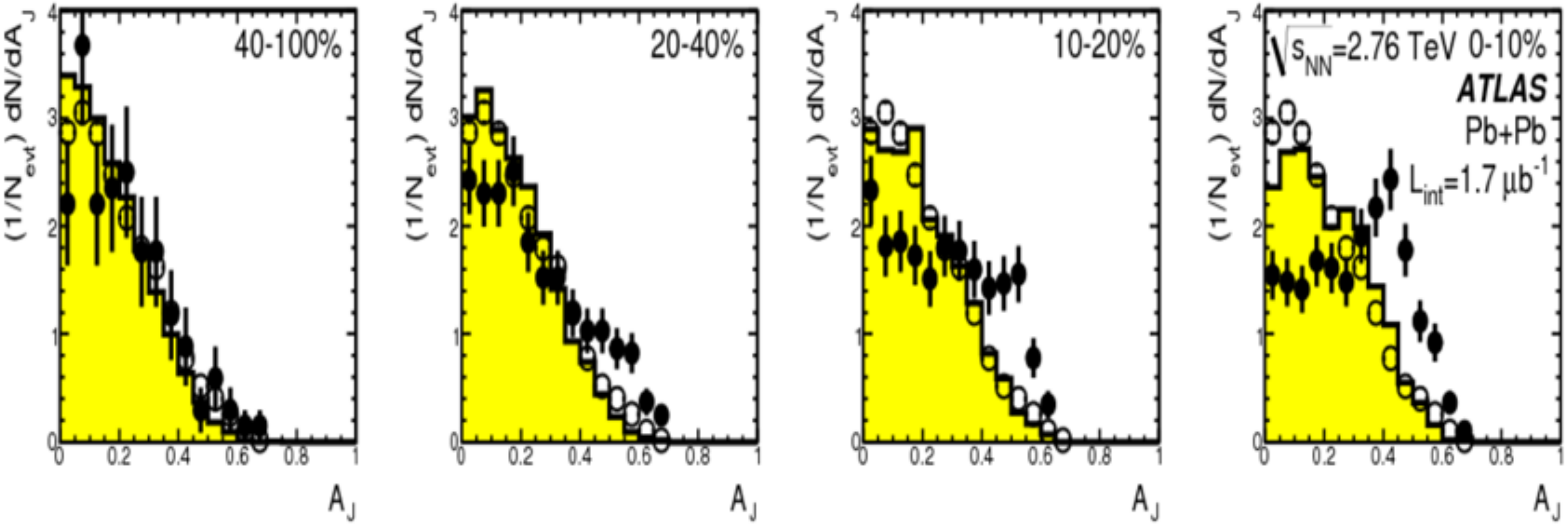
Di-jet asymmetry



Observation: some events have two jets with different energy
(However: one swallow does not make spring)

Jet energy asymmetry

Centrality



ATLAS, arXiv:1011.6182 (PRL)

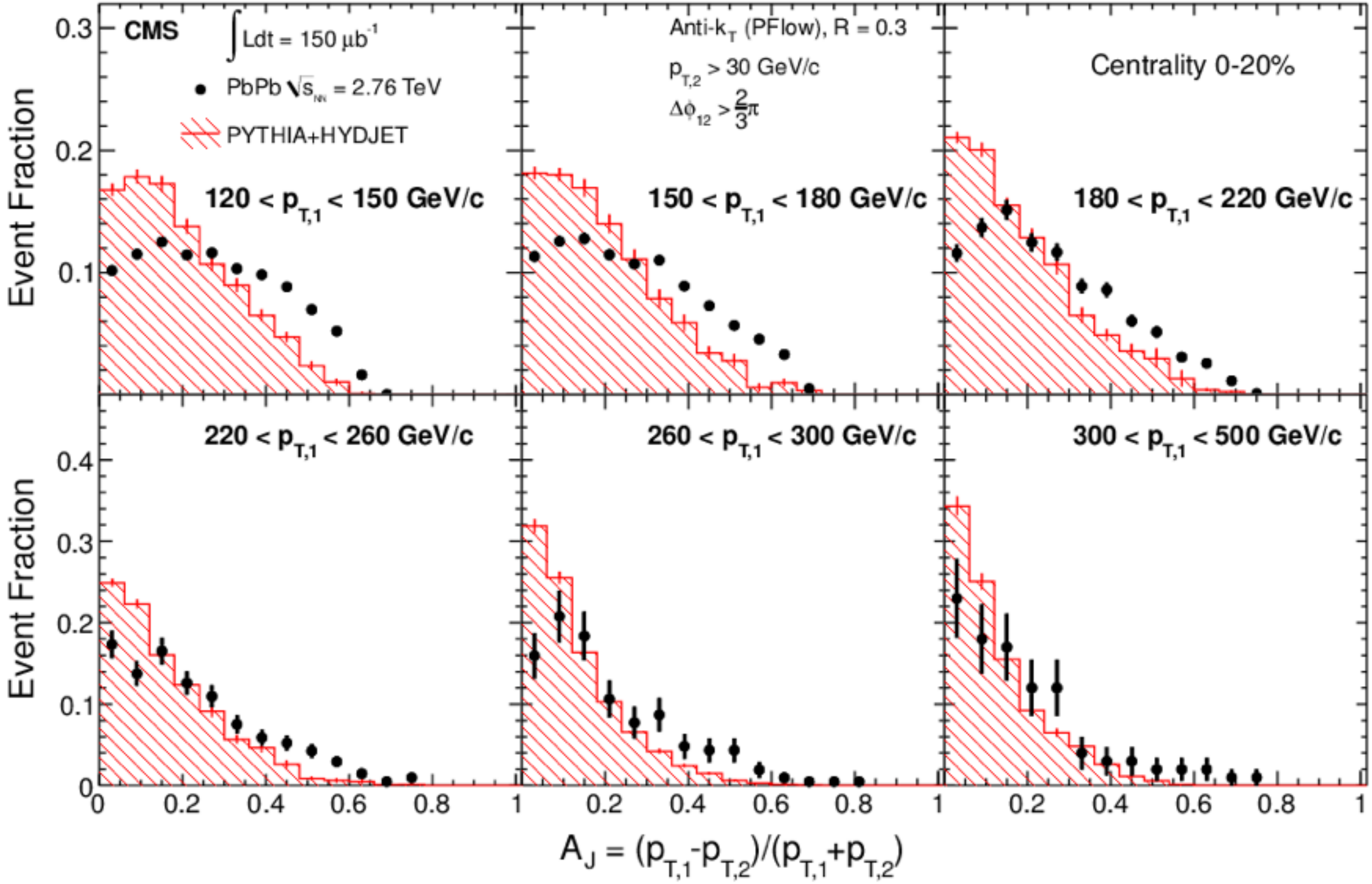
Jet-energy asymmetry $$A_J = \frac{E_2 - E_1}{E_2 + E_1}$$

Large asymmetry seen
for central events

Suggests large energy loss: many GeV
~ compatible with expectations from RHIC+theory

However:
- Only measures reconstructed di-jets (don’t see lost jets)
- Not corrected for fluctuations from detector+background
- Both jets are interacting – Not a simple observable

Energy dependence of asymmetry



CMS, arXiv:1202.5022

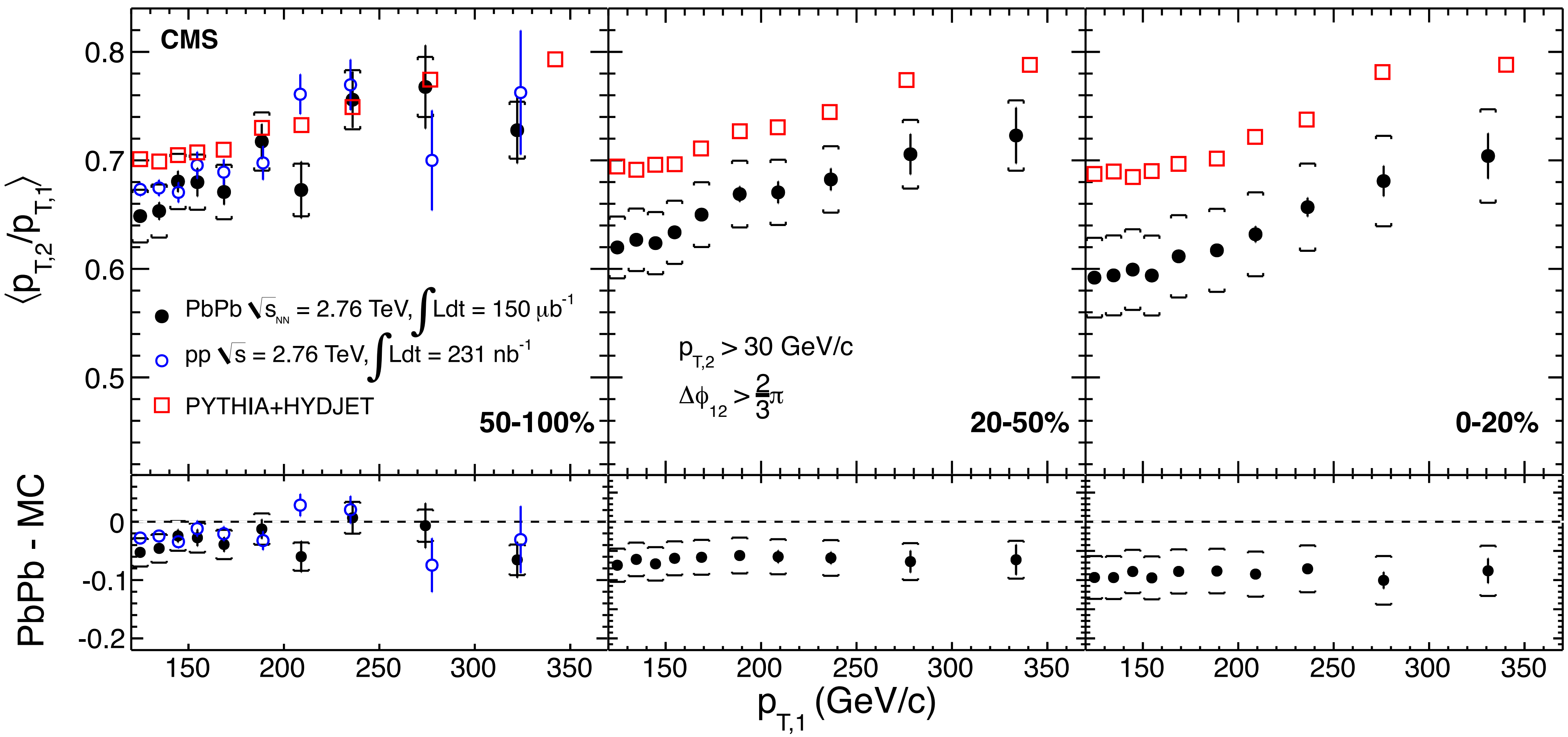
(Relative) asymmetry decreases with energy

However: difference pp vs PbPb remains – energy loss finite at large E

Energy dependence of A_J

Peripheral

Central



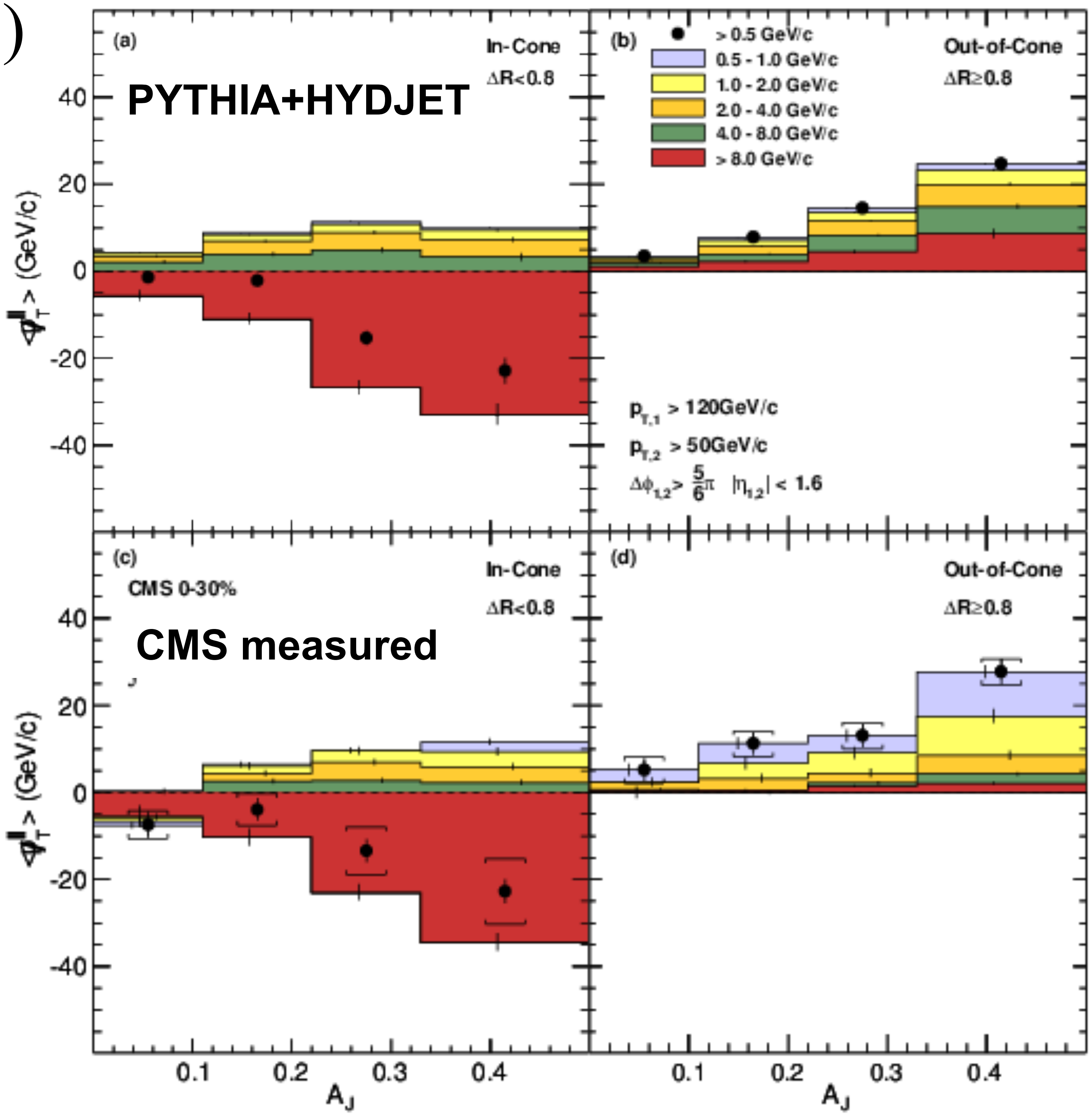
Asymmetry decreases for larger jet energy

Similar effect in pp (Pythia): difference stays ~constant

Studying the imbalance

$$p^{//}_{T,miss} = \sum_{tracks} p_T \cos(\varphi - \varphi_{jet})$$

In Cone R<0.8 Out of Cone R>0.8



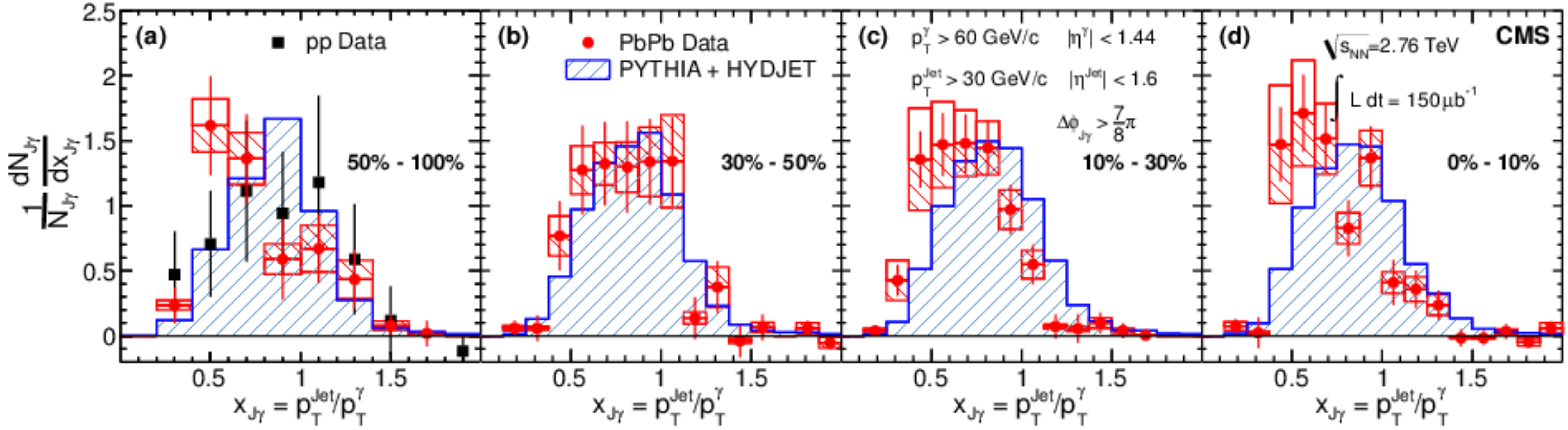
Momentum imbalance restored by hadrons at large angle R>0.8 and small p_T < 2 GeV/*c*

CMS, arXiv:1102.1957

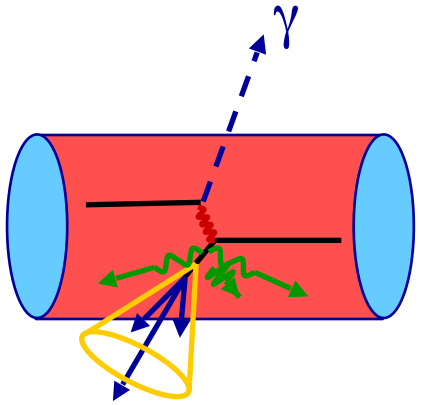
γ-jet imbalance

Centrality

CMS, arXiv:1502.0206



γ-jet asymmetry $x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$



Advantage: γ is a parton: know parton kinematics

Disadvantage: low rate (+background $\pi^0 \rightarrow \gamma\gamma$)

Translates into: low $p_{T,\gamma}$ cut > 60 GeV

Dominant contibution: qg → qγ

Hadron-recoil jet measurements

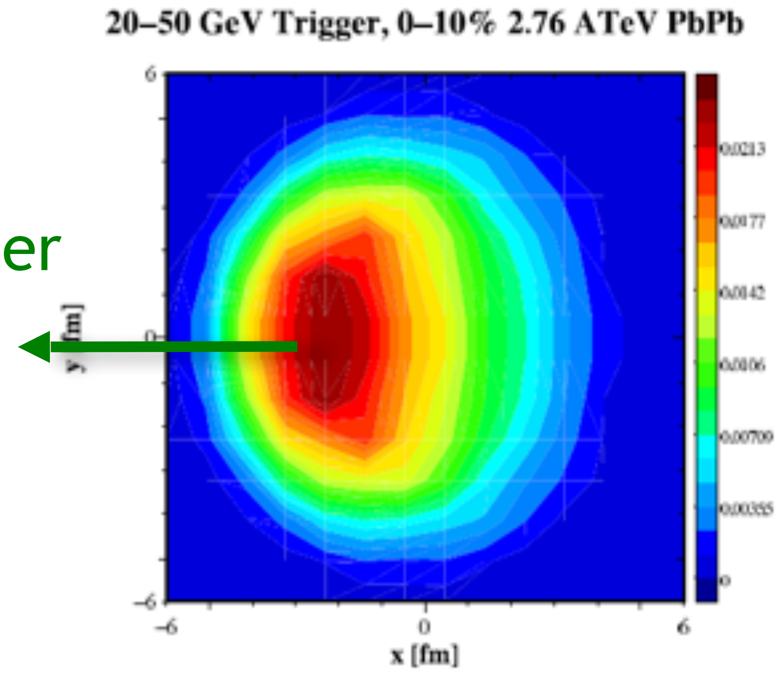
Hadron trigger vs jet trigger

Hadron trigger: strong "surface bias"

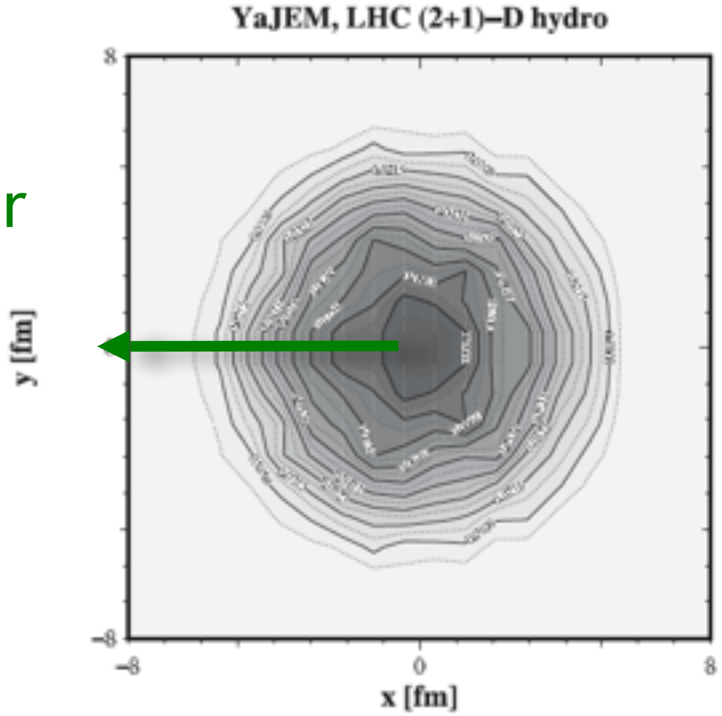
maximizes recoil path length

(T.Renk, private com.)

Hadron trigger



Jet trigger



T.Renk, PRC85 064908

Full jet trigger: no geom. bias

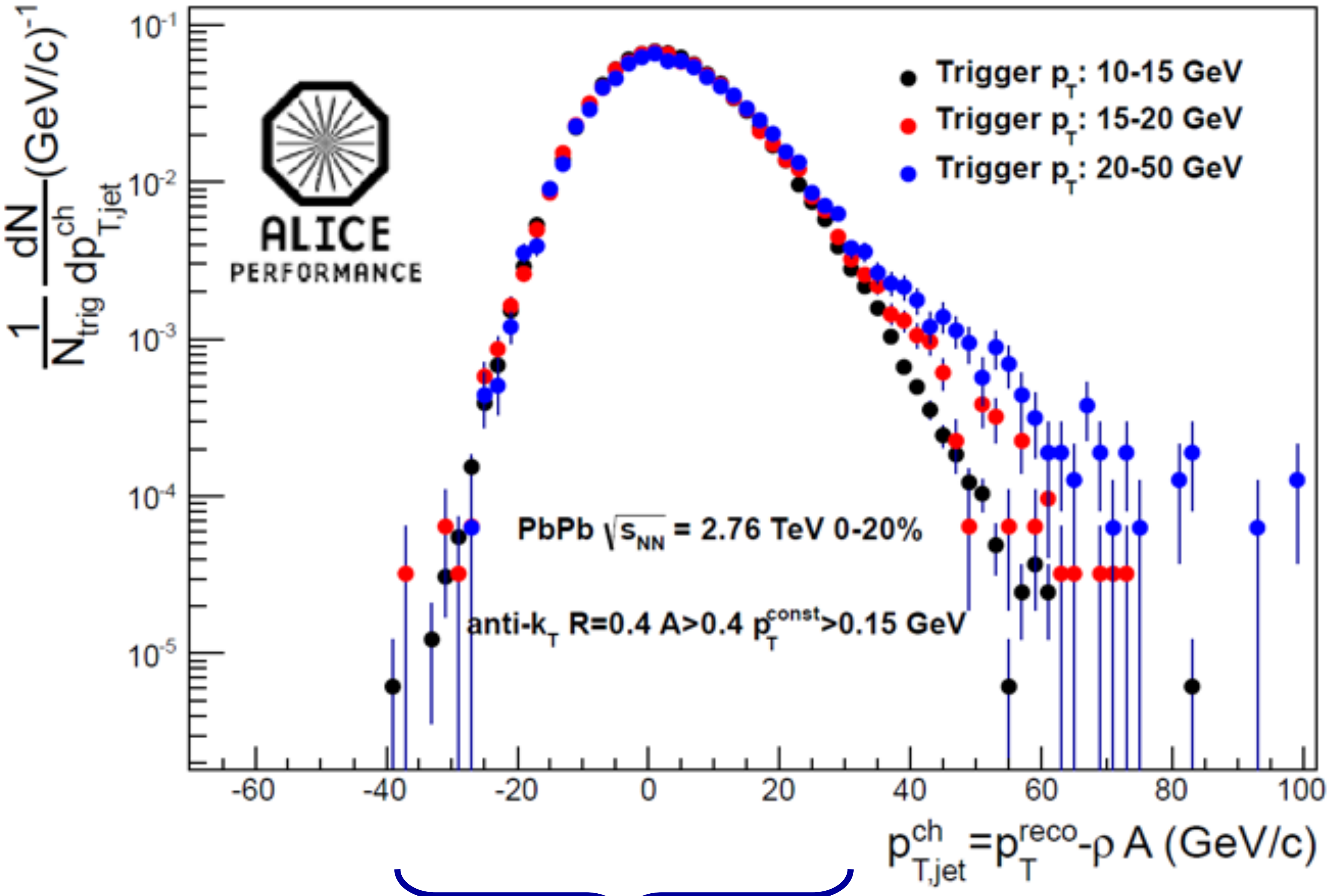
partially cancelled by bkg fluctuations

Centrality and reaction plane biases:

- Finite, but only weak trigger p_T dependence for high p_T^{trig}

Hadron-triggered recoil jet distributions

G. de Barros et al., arXiv:1208.1518



$$\underbrace{\hspace{6cm}}$$

$p_{T,jet}$< 20 GeV/c:
No change with trigger p_T
Combinatorial background

$$\underbrace{\hspace{6cm}}$$

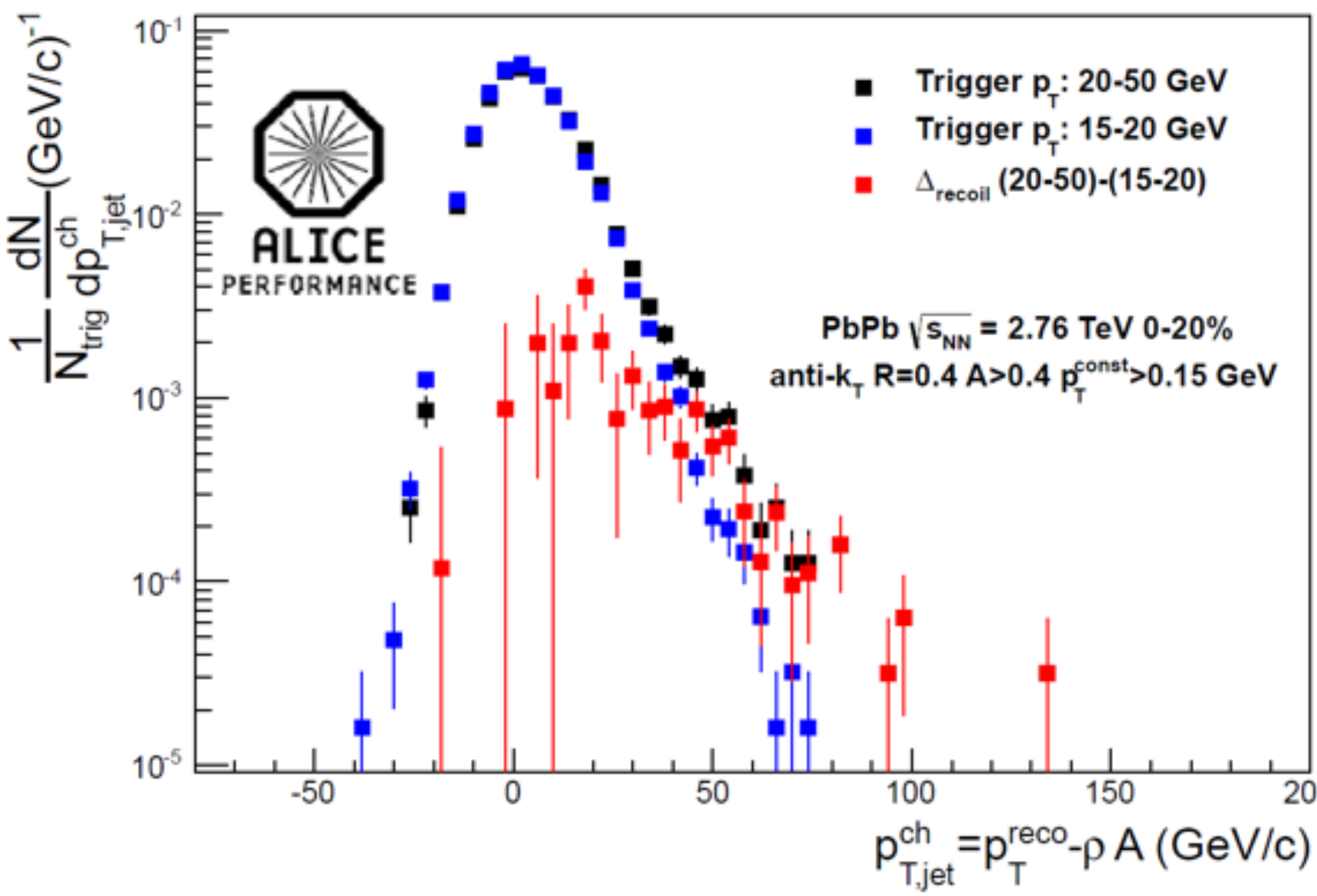
$p_{T,jet}$> 20 GeV/c:
Evolves with trigger p_T
Recoil jet spectrum

Background subtraction: Δ_{recoil}

Remove background by subtracting spectrum with lower p_T^{trig}:

Δ_{recoil} =[(20-50)-(15-20)]

Reference spectrum (15-20) scaled by ~0.96 to account for conservation of jet density



Δ_{recoil} measures the change of the recoil spectrum with p_T^{trig}

Unfolding correction for background fluctuations and detector response

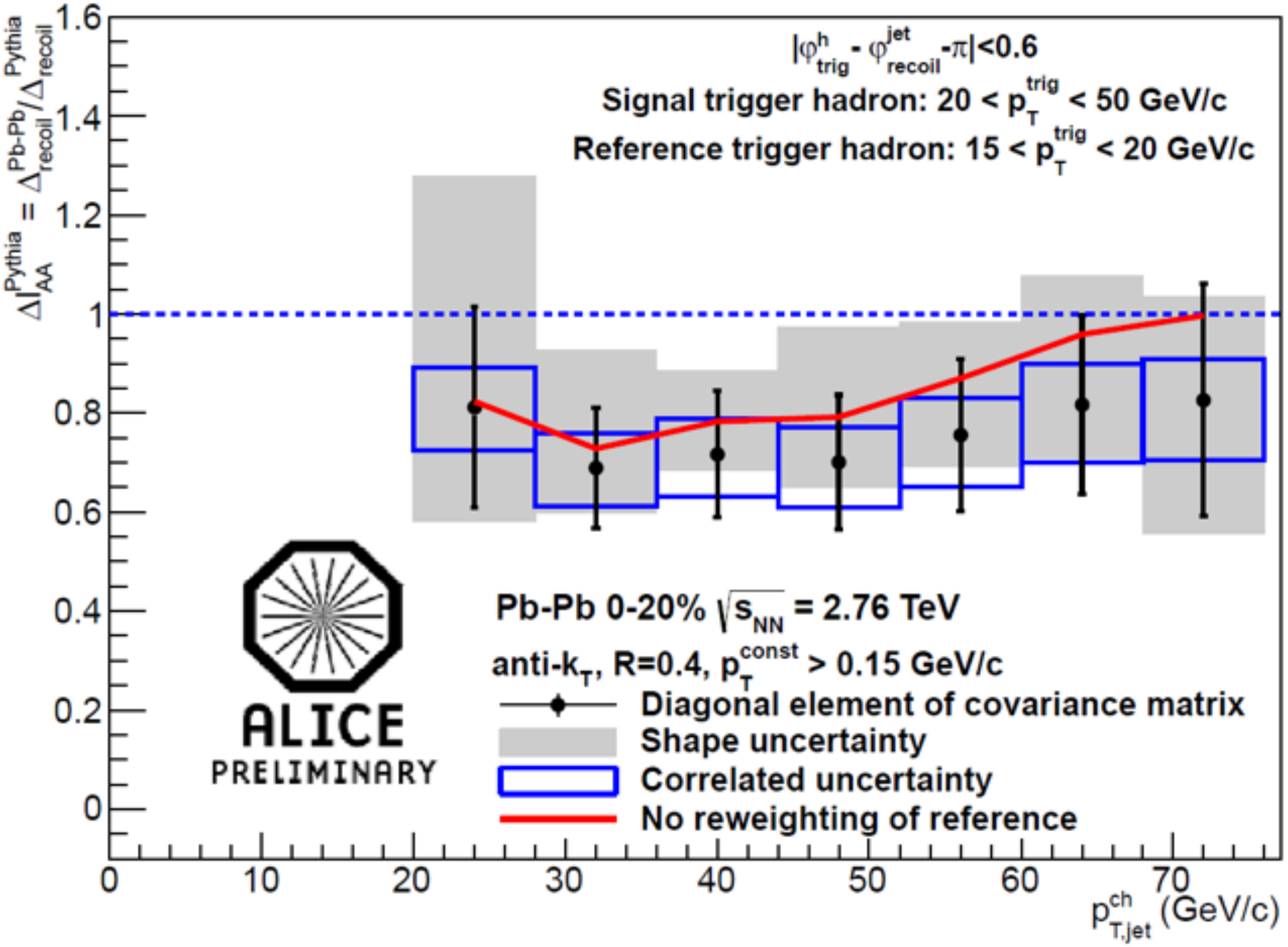
Ratio of Recoil Jet Yield ΔI_{AA}^{PYTHIA}

pp reference: PYTHIA (Perugia 2010)

R=0.4

Constituents:
p_T^{const} > 0.15 GeV/c

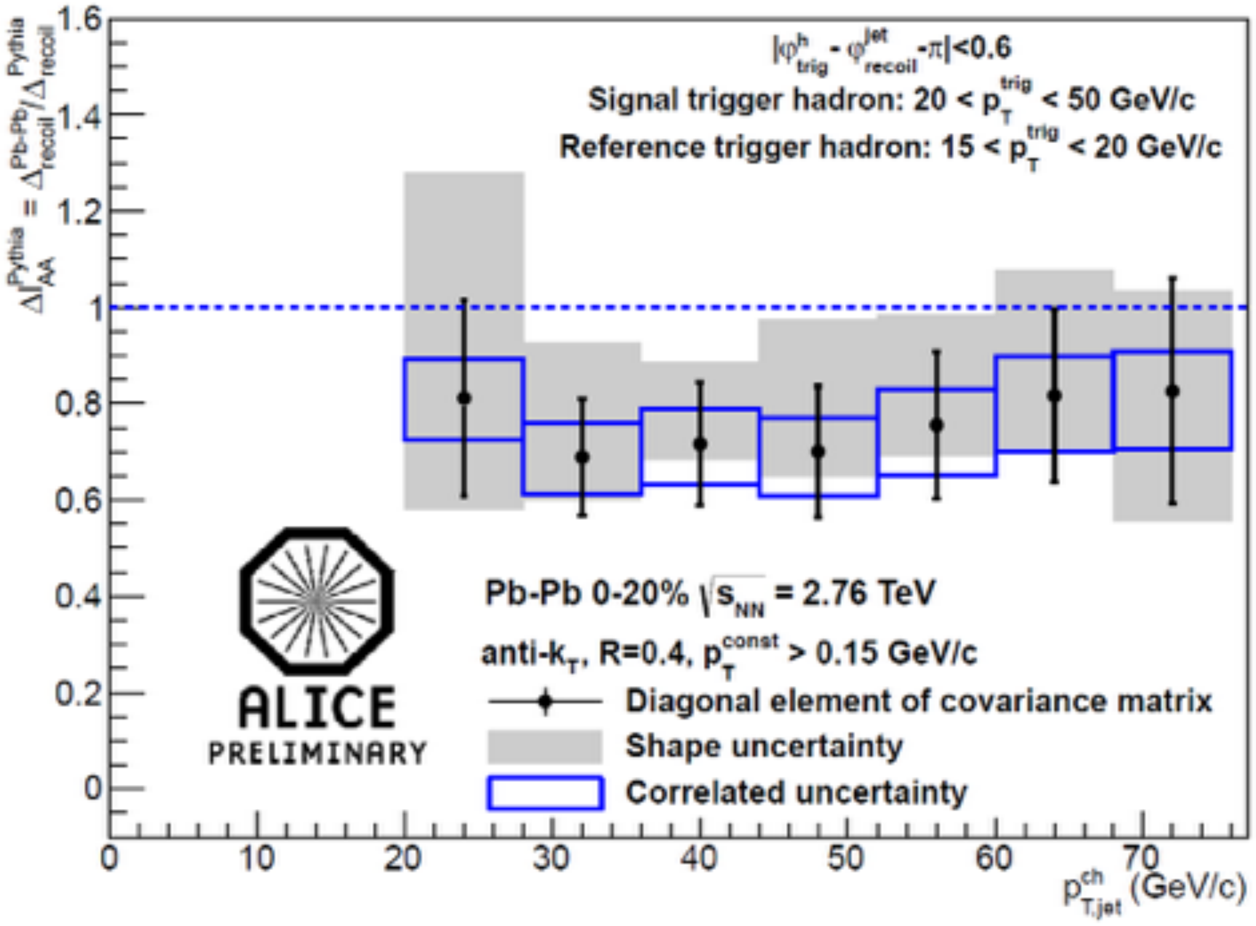
no additional cuts (fragmentation bias) on recoil jets



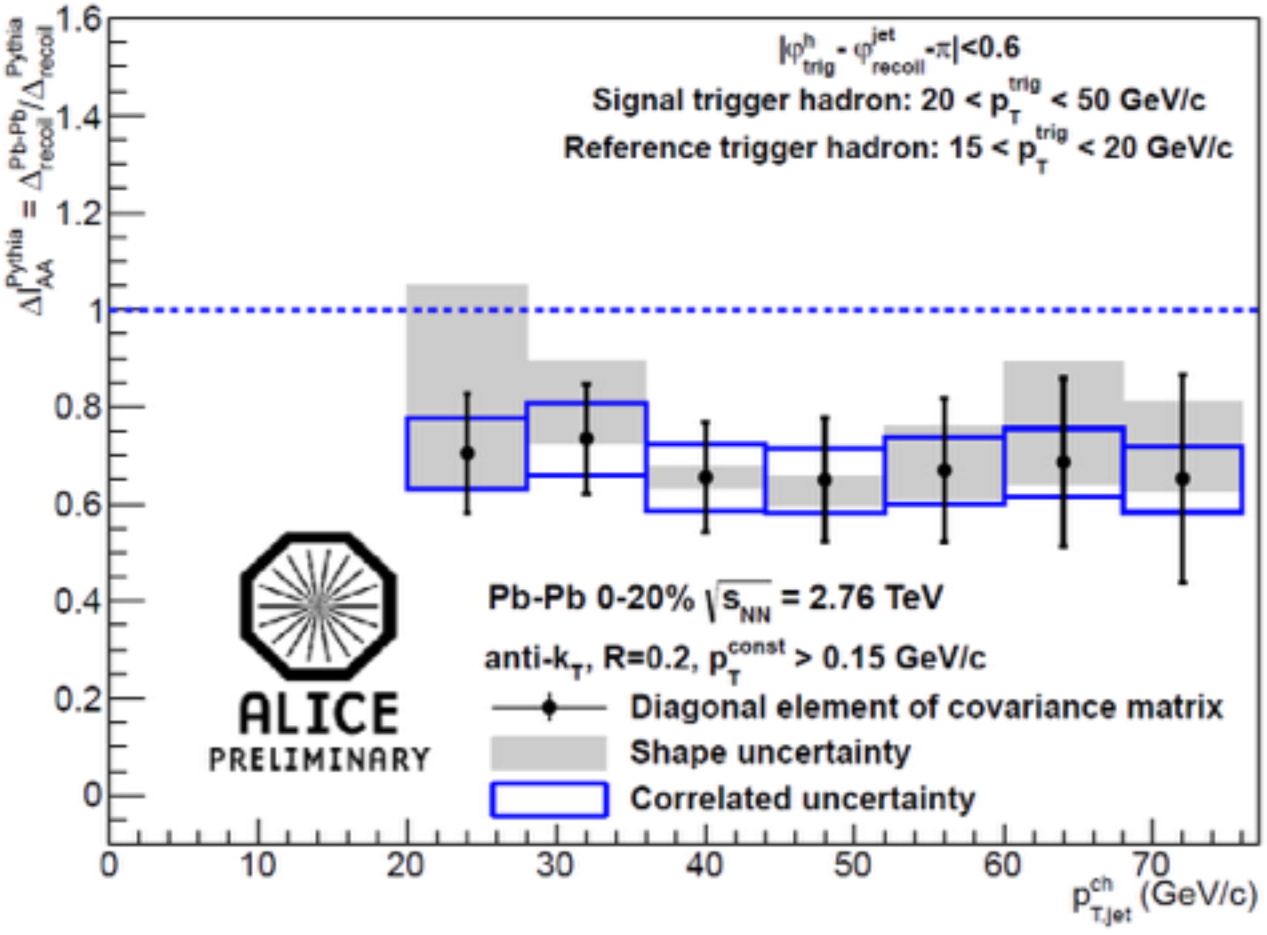
Recoil jet yield $\Delta I_{AA}^{PYTHIA} \approx 0.75$, approx. constant with jet p_T

Recoil Jet ΔI_{AA}^{PYTHIA}: R dependence

R=0.4



R=0.2



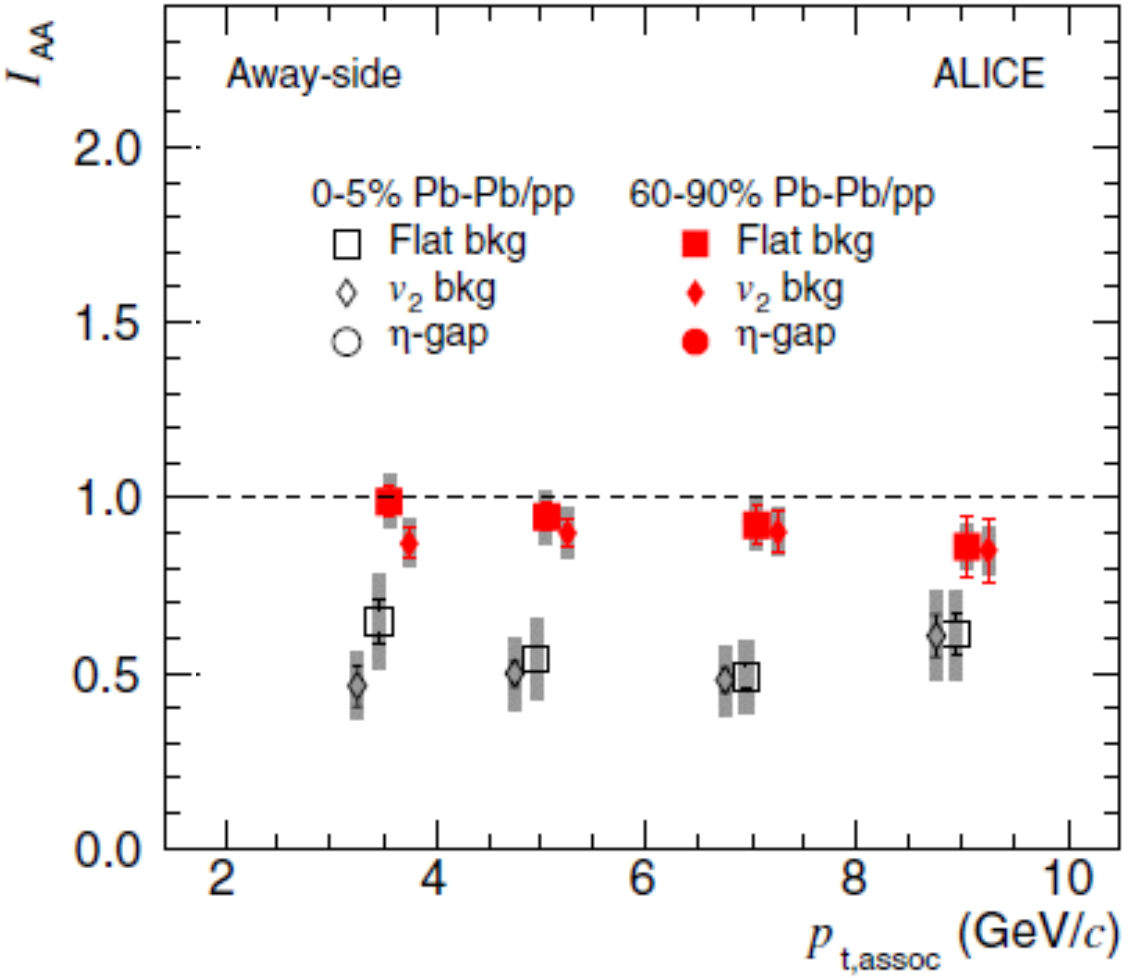
Similar ΔI_{AA}^{PYTHIA} for R=0.2 and R=0.4

No visible broadening within R=0.4

(within exp uncertainties)

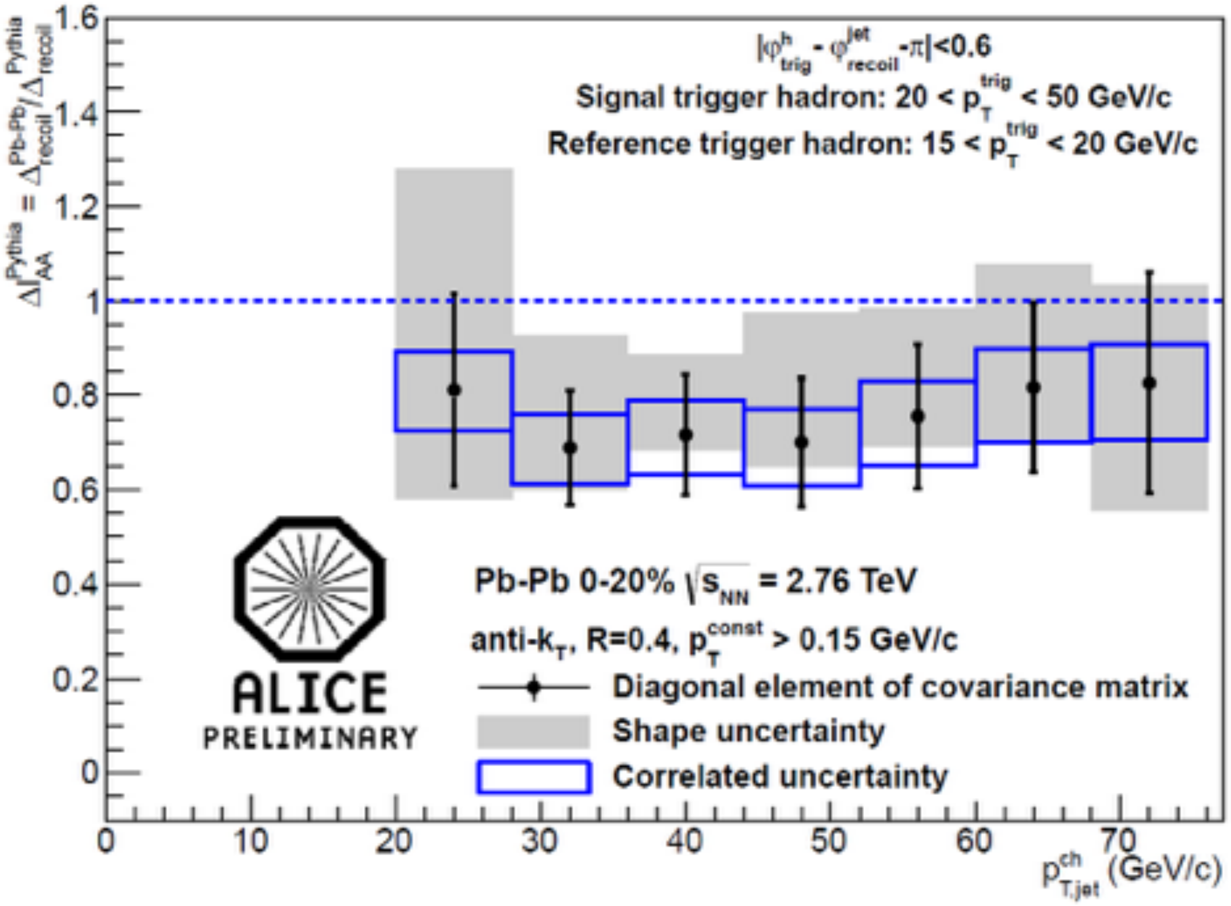
Hadrons vs jets II: recoil

Hadrons



PRL108 092301

Jets



Hadron I_{AA} = 0.5-0.6

In approx. agreement with models;
elastic E-loss would give larger I_{AA}

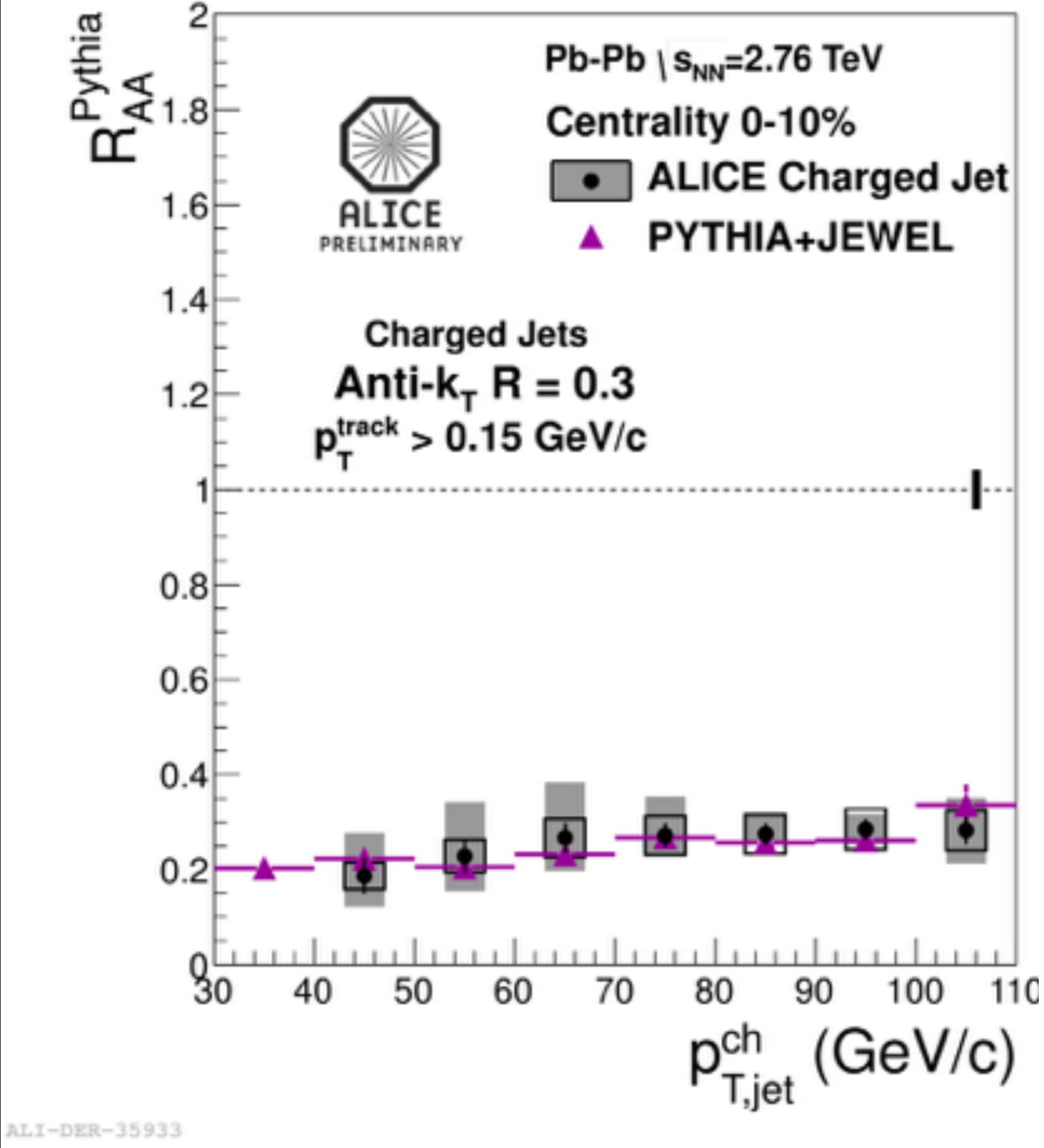
Jet I_{AA} = 0.7-0.8

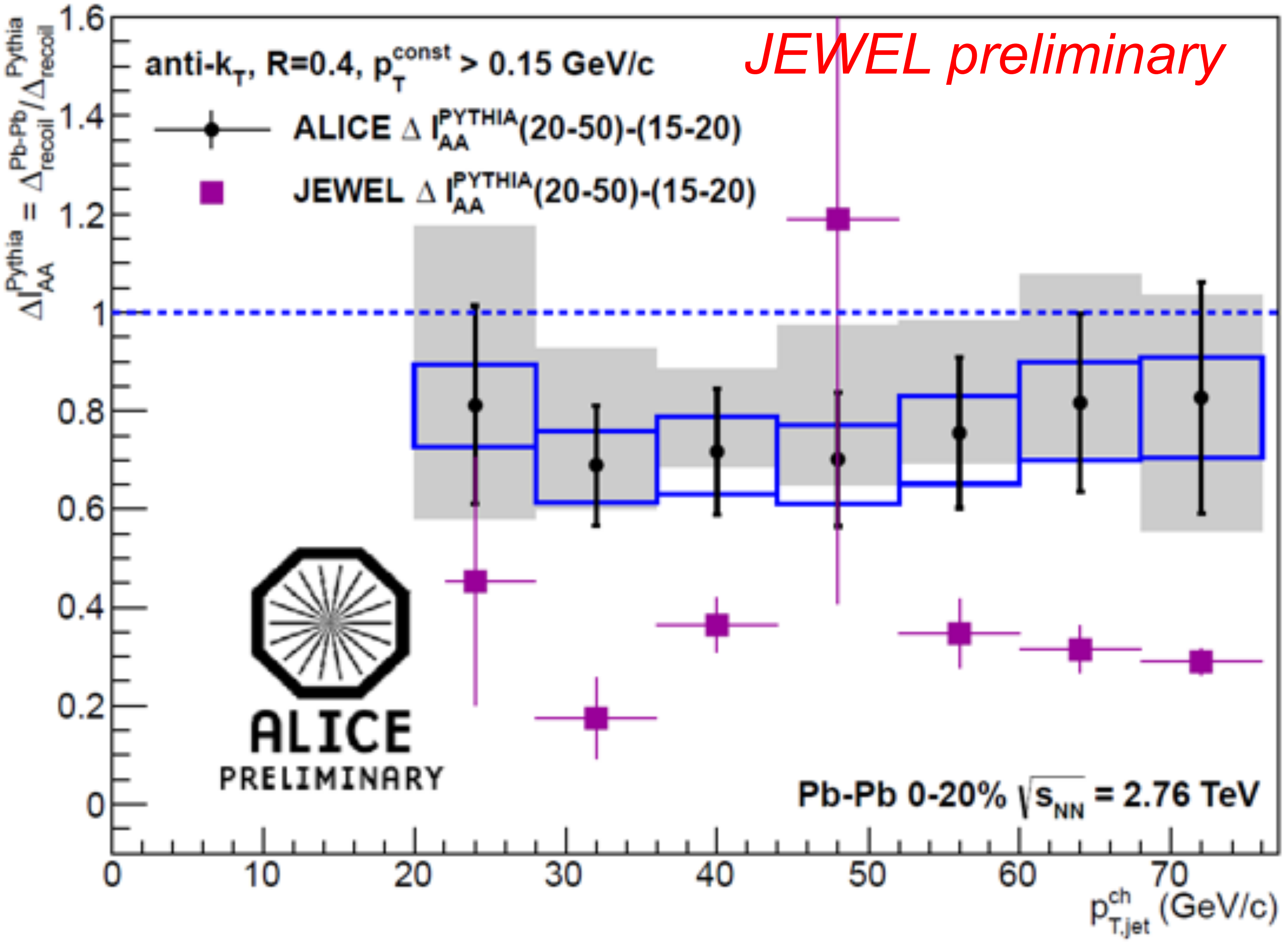
Jet I_{AA} > hadron I_{AA}
Not unreasonable

NB/caveat: very different momentum scales !

Model comparison I_{AA}

JEWEL: Zapp et al., EPJ C69, 617





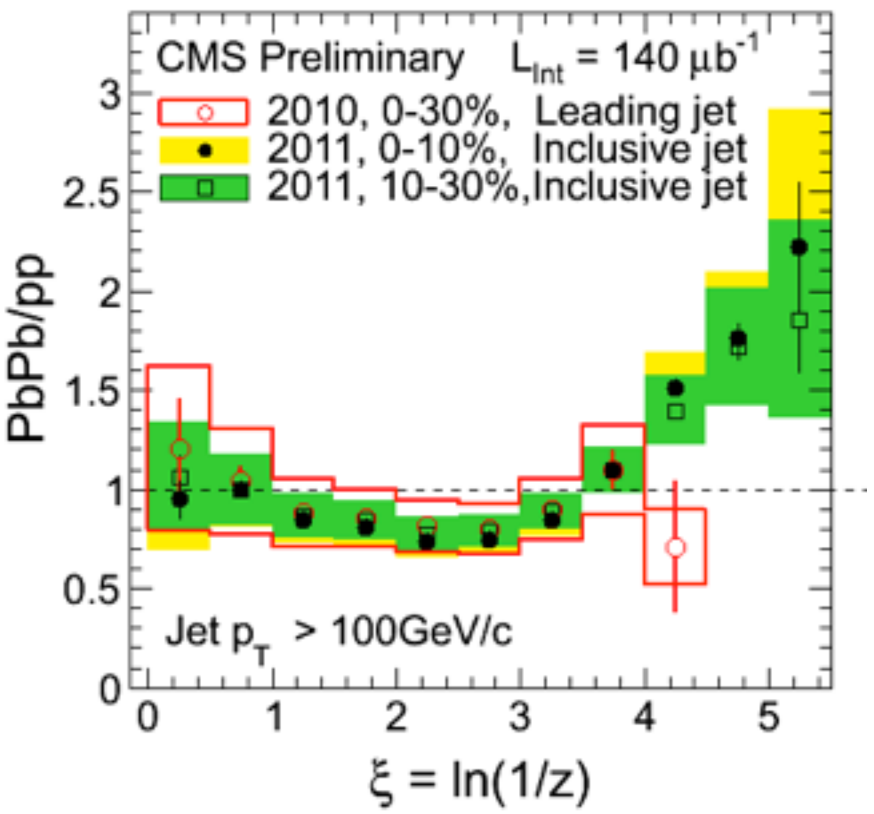
JEWEL correctly describes inclusive jet R_{AA}

Predicts ΔI_{AA}~0.4, below measured

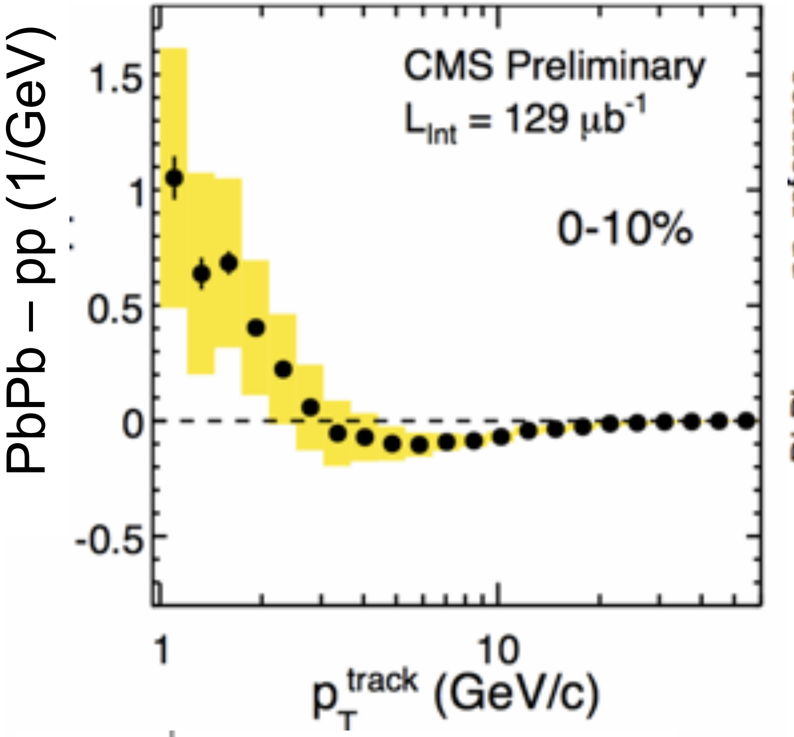
A consistent view of jet quenching

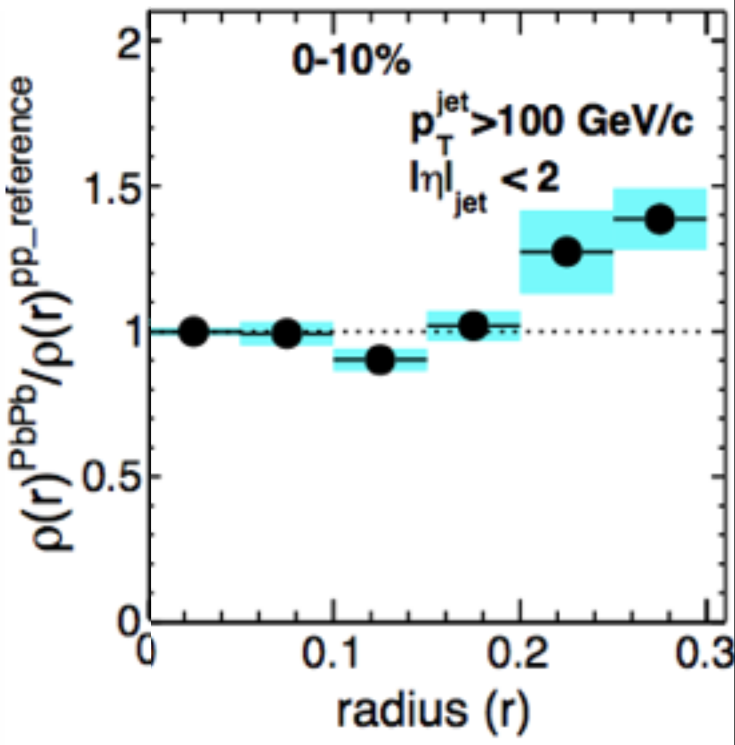
G. Roland@QM2012

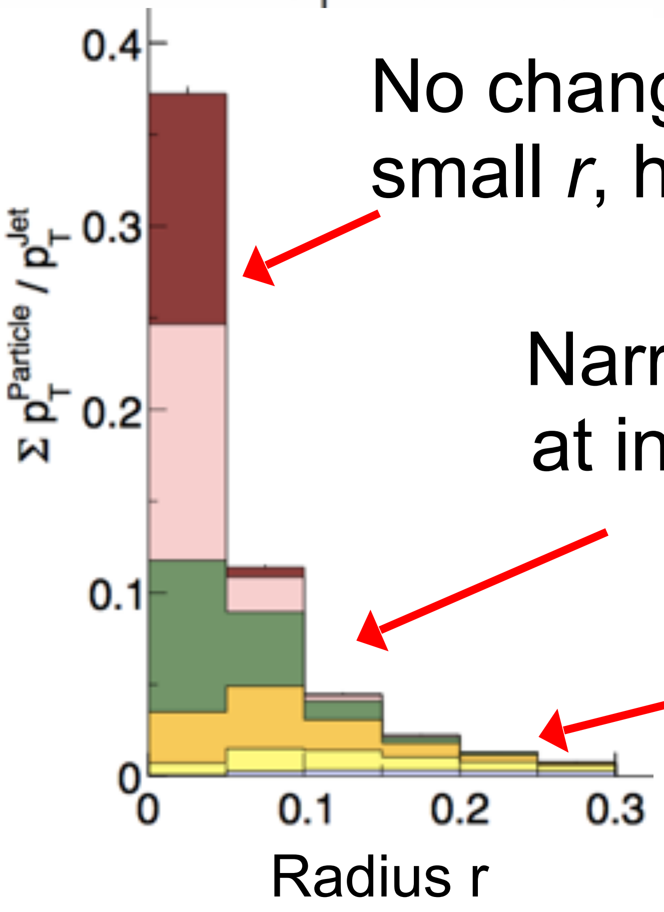
arXiv:1205.5872



Change from "ξ" to "p_T"







No change at small *r*, high p_T

Narrowing/depletion at intermediate *r*, p_T

Broadening/excess at large *r*, low p_T

(~2% of jet energy)

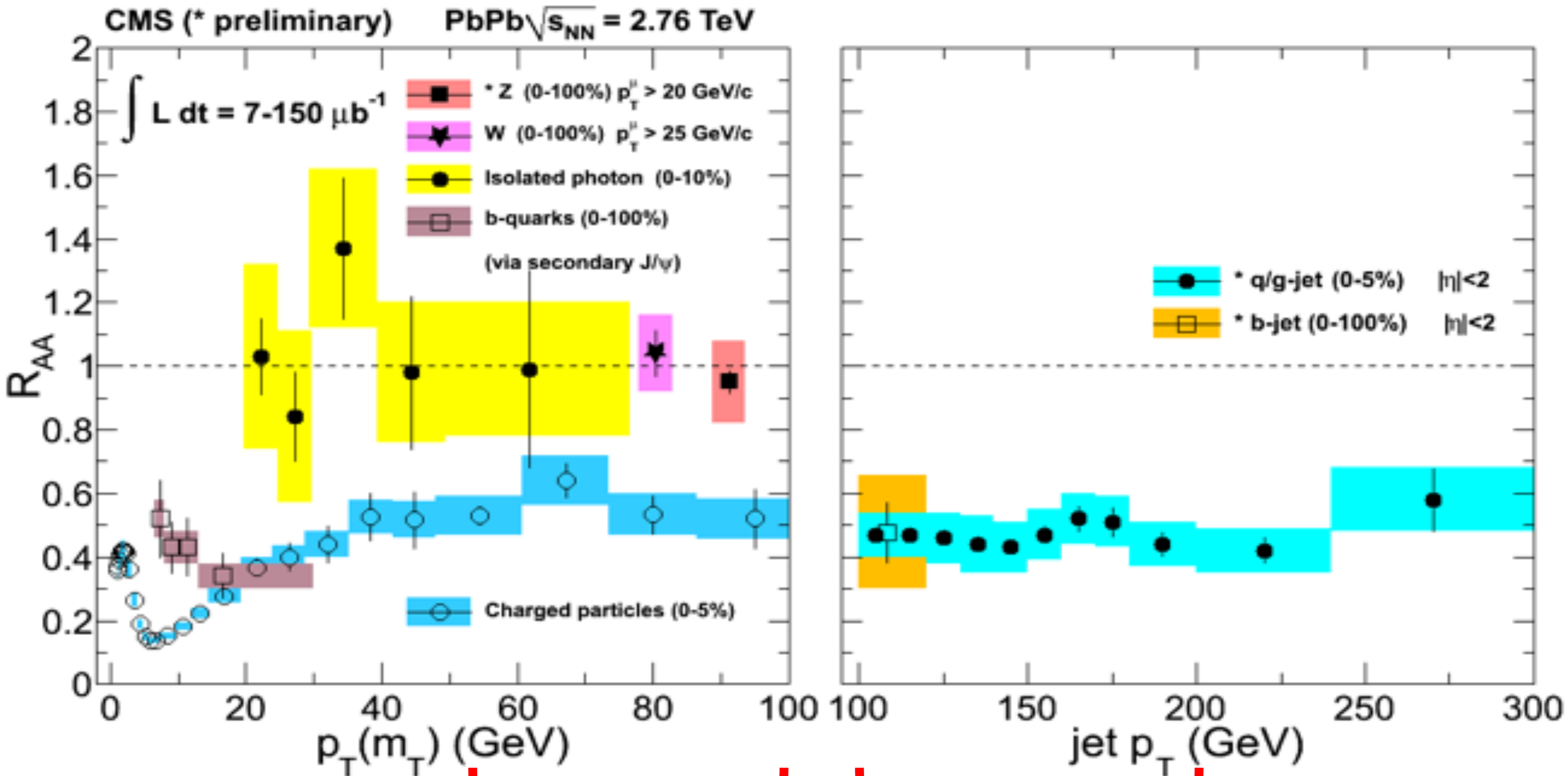
Consistent with 2010 result

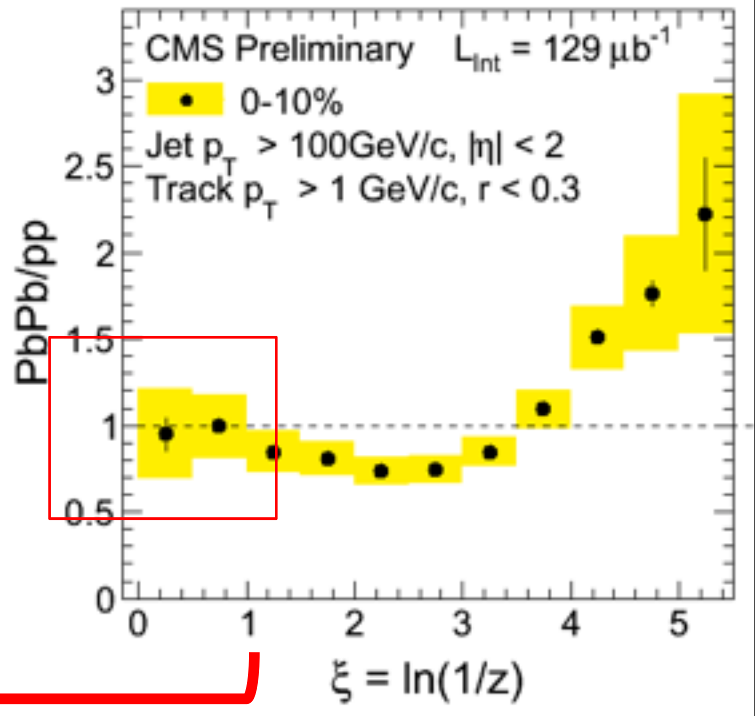
Recall (2010 vs 2011):

- Track p_T > 4 GeV vs p_T > 1 GeV
- Leading vs inclusive jet
- 0-30% vs 0-10% and 10-30%

A consistent view of jet quenching

G. Roland@QM2012





Looking at the same parton p_T range

Charged particles from p_T =50-100 GeV:
z = p_T(track)/p_T(jet) = 0.4-0.6
→ ξ < 1

PbPb fragmentation function = pp for ξ <1

Consistent message from charged hadron R_{AA}, inclusive jet R_{AA} and fragmentation functions!

Summary

- Jets: a new tool for parton energy loss measurements
  - Large out-of-cone radiation (R = 0.2-0.4)
    - Energy asymmetry
    - $R_{AA} < 1$
    - $I_{AA} < 1$
    - Radial shapes
  - Remaining jet is pp-like:
    - Fragment distribution at large *z* same as pp
    - R_{AA} similar for jets and hadrons
  - Most of the radiation is at low p_T
    - Scale set by medium temperature?
- Direct photons
  - γ-jet allows to measure initial parton energy; jet asymmetry seen

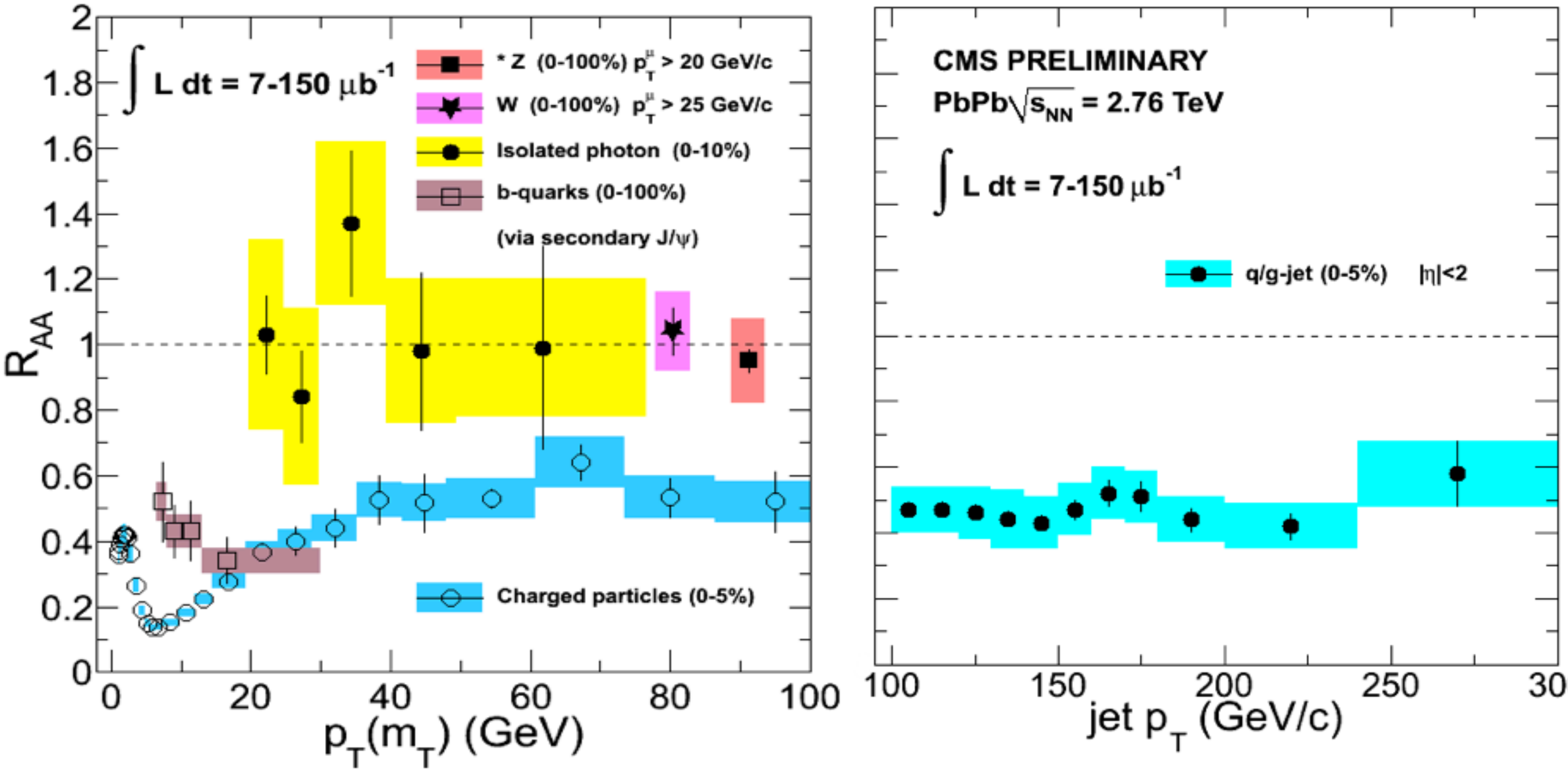
JEWEL energy loss MC agrees with many of the observed effects
Does this constrain the energy loss mechanism(s)?
Need to test for kinematic effects/alternative explanations (e.g. YaJEM)

Extra slides

γ, hadrons, jets compared

γ, hadrons

Jets

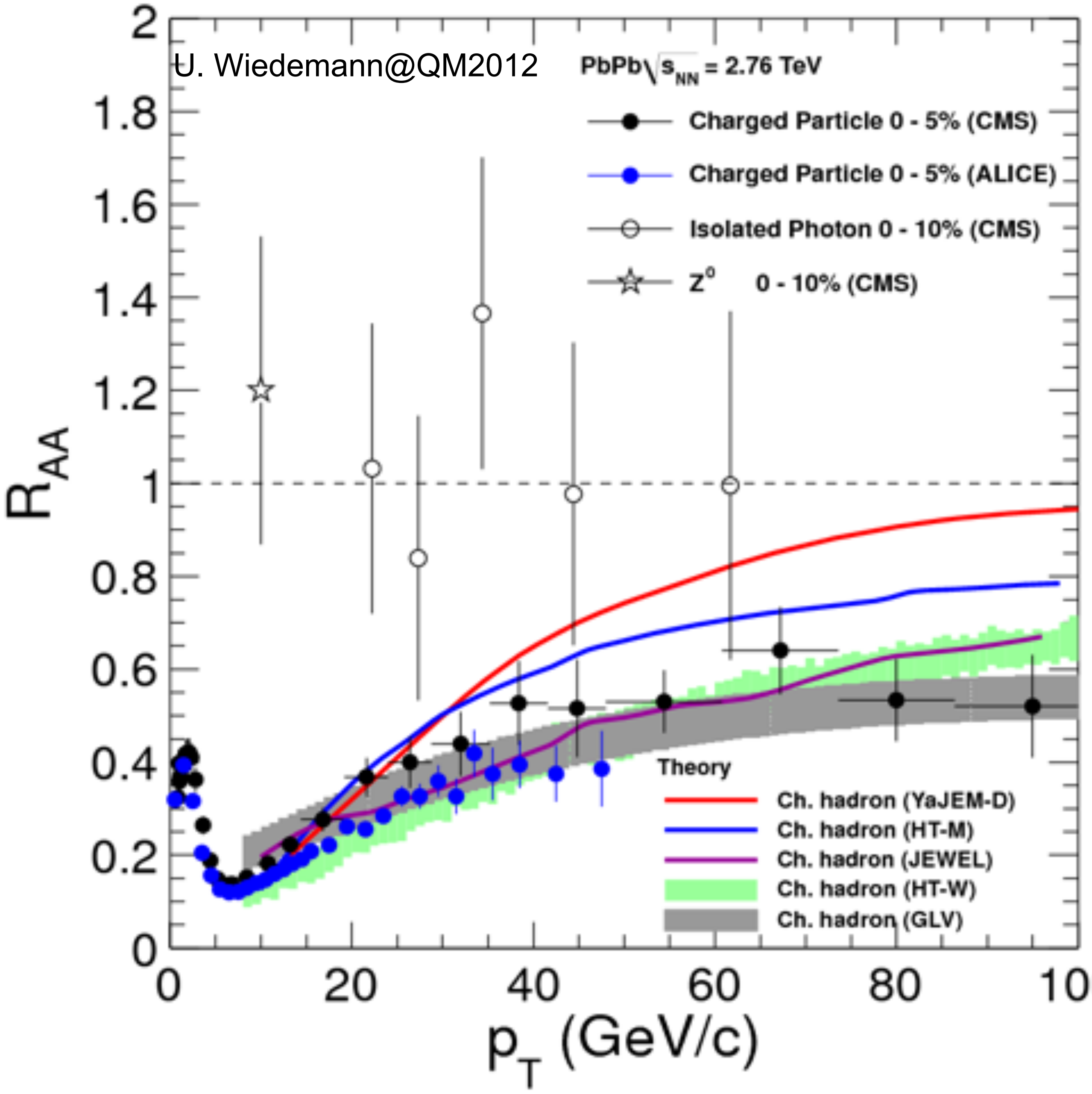


Suppression of hadron (leading fragment) and jet yield similar

Is this ‘natural’? No effect of in-cone radiation?

Model comparison

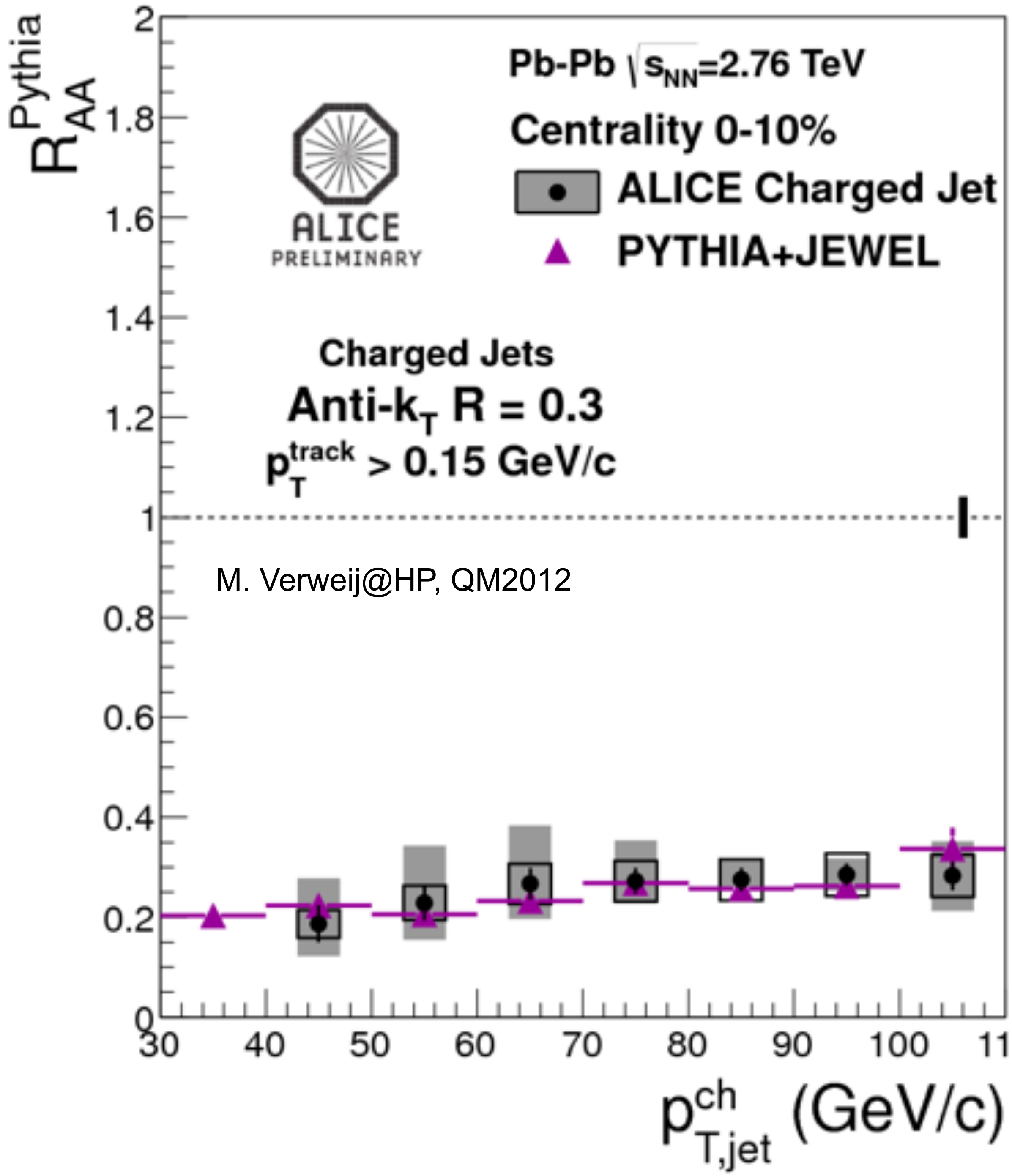
Hadron R_{AA}



U. Wiedemann@QM2012

Schukraft et al, arXiv:1202.3233

Jet R_{AA}



M. Verweij@HP, QM2012

JEWEL: K. Zapp et al, Eur Phys J C69, 617

At least one model calculation reproduces the observed suppression
⇒ Understand mechanism for out-of-cone radiation?