Lecture 3: jets in heavy ion collisions

Marco van Leeuwen,
Nikhef and Utrecht University

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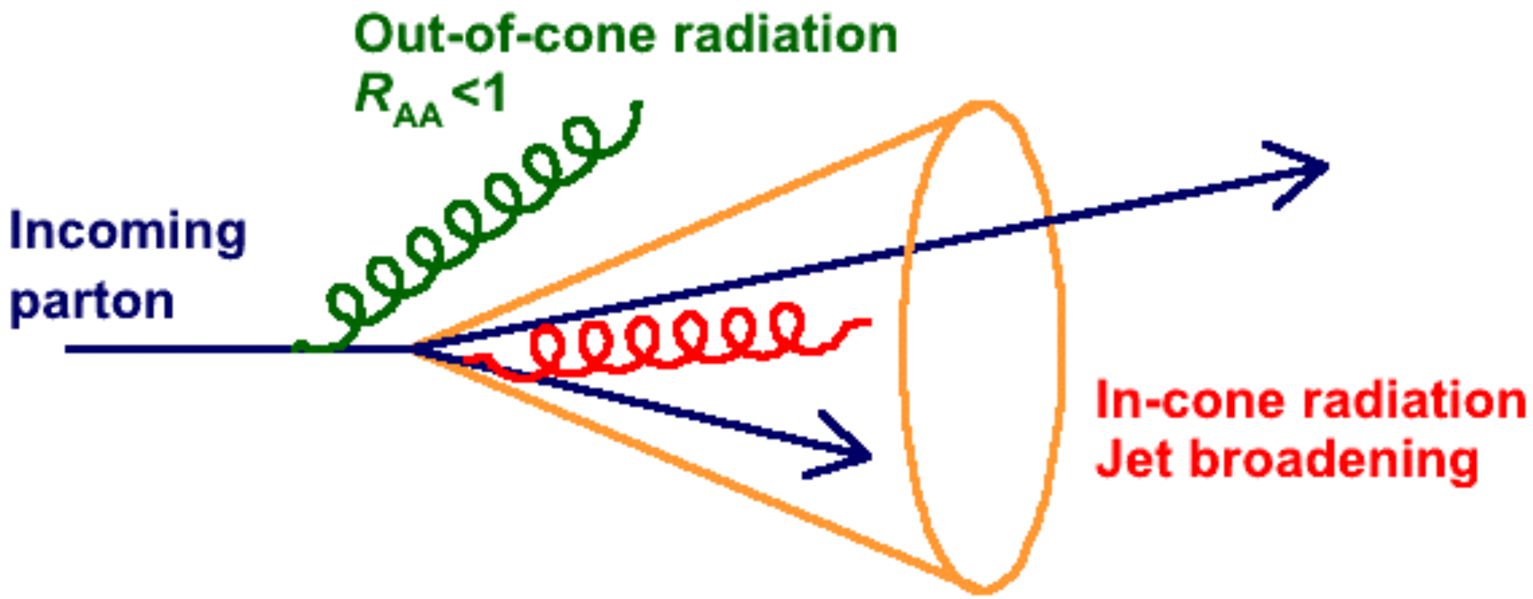
Universiteit Utrecht

NIKHEF

Jets and parton energy loss

Motivation: understand parton energy loss by tracking the lost energy

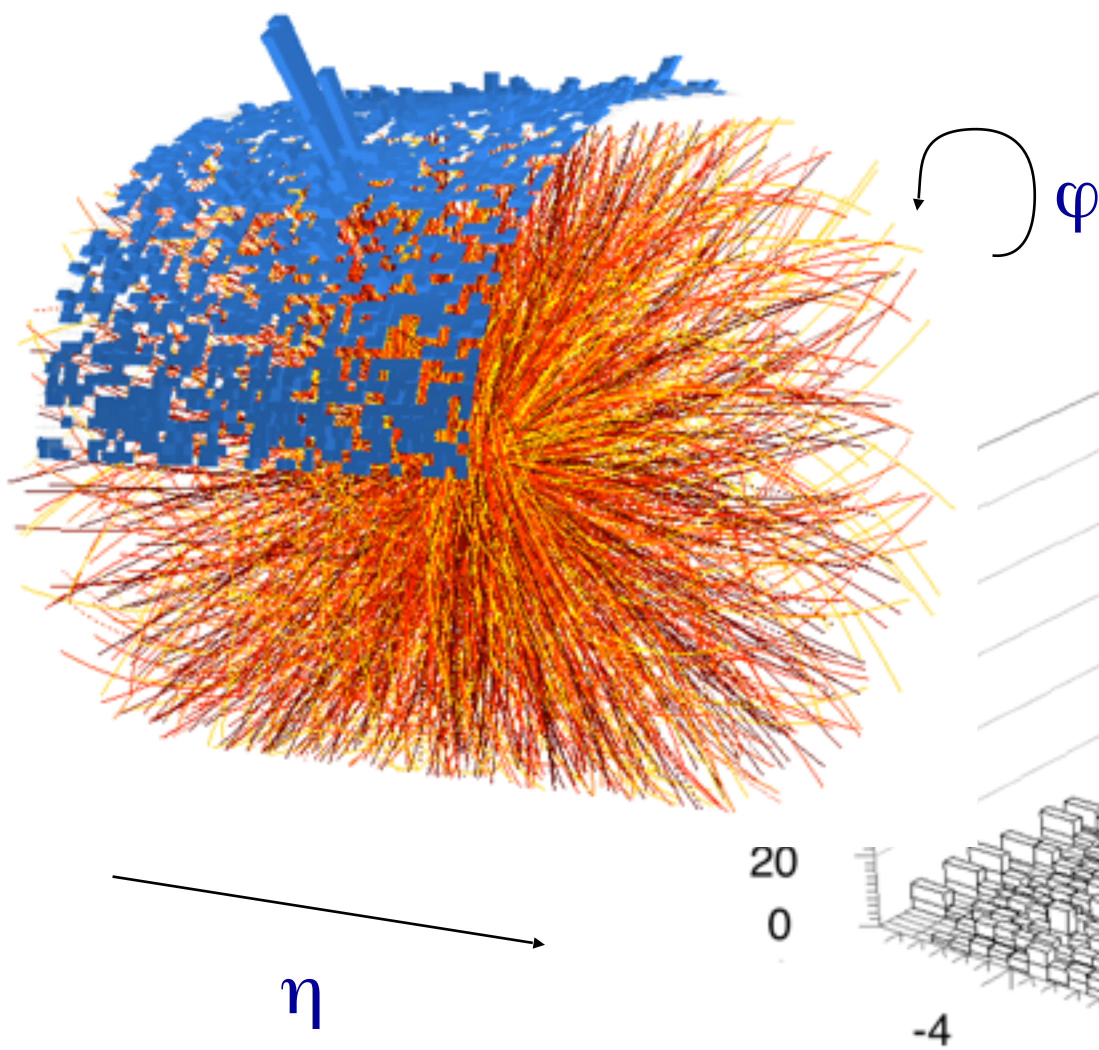


Qualitatively two scenarios:

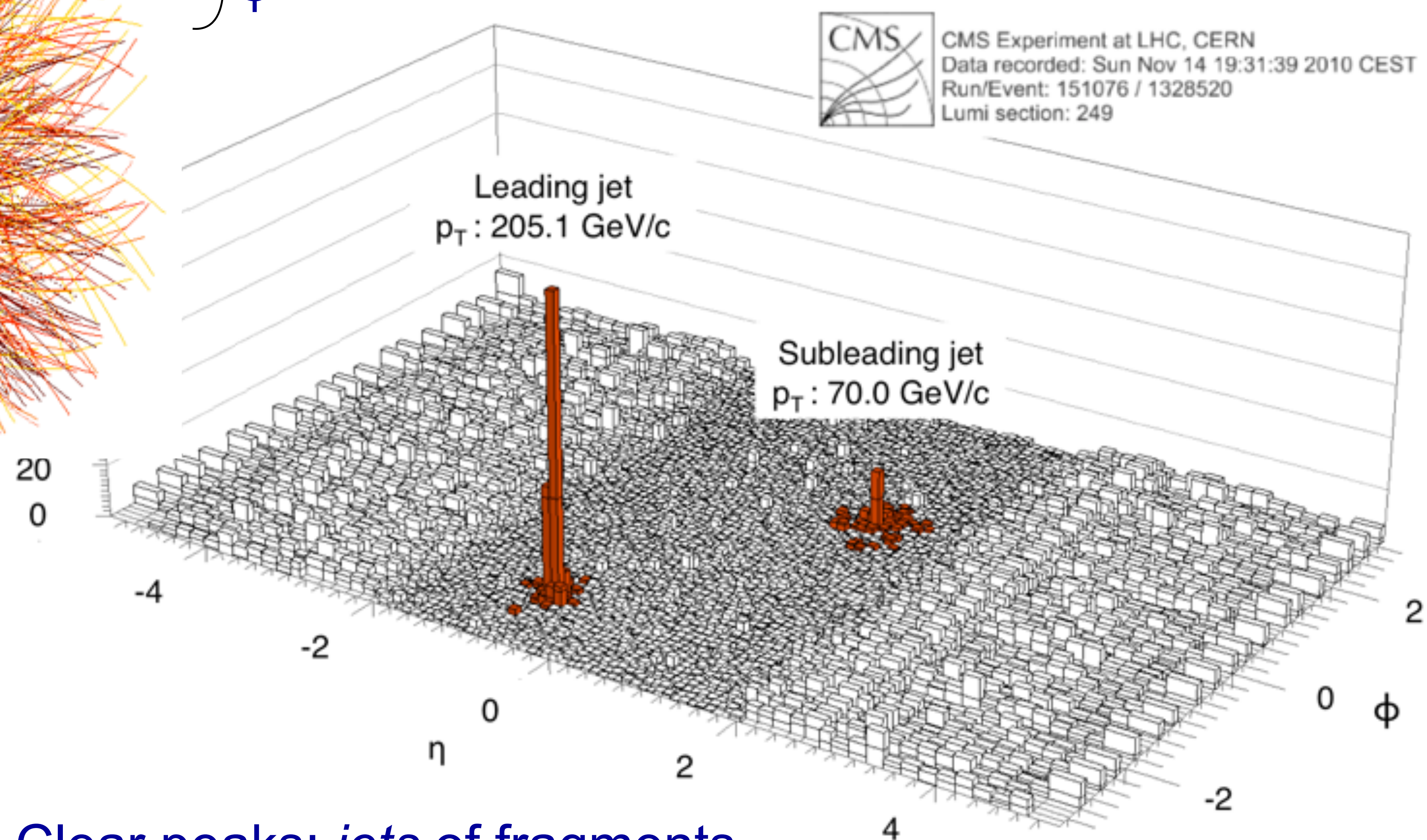
1) In-cone radiation: R_{AA} = 1, change of fragmentation
2) Out-of-cone radiation: R_{AA} < 1

Jets at LHC

ALICE



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

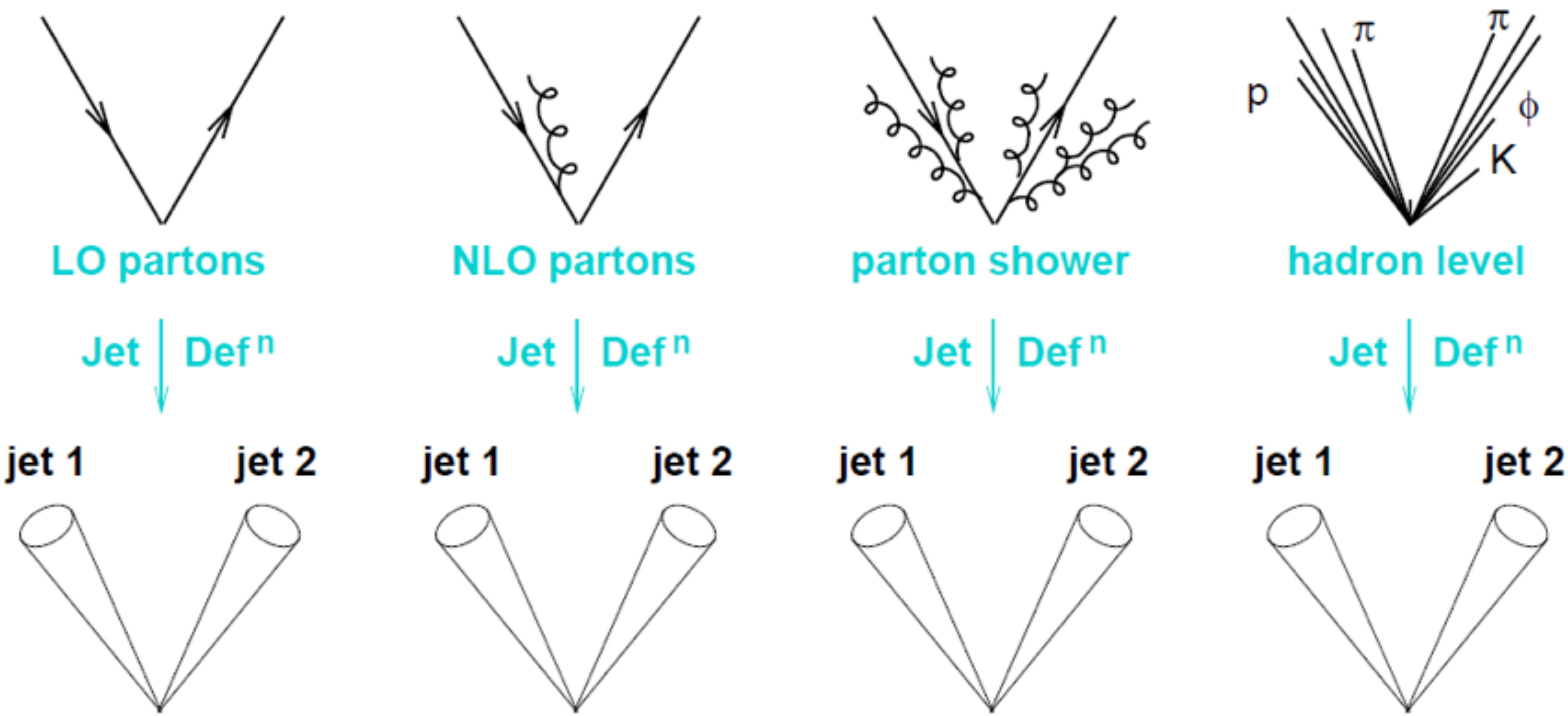


Illustration by G. Salam

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

- Collinear safe
- Infrared safe

Collinear safety

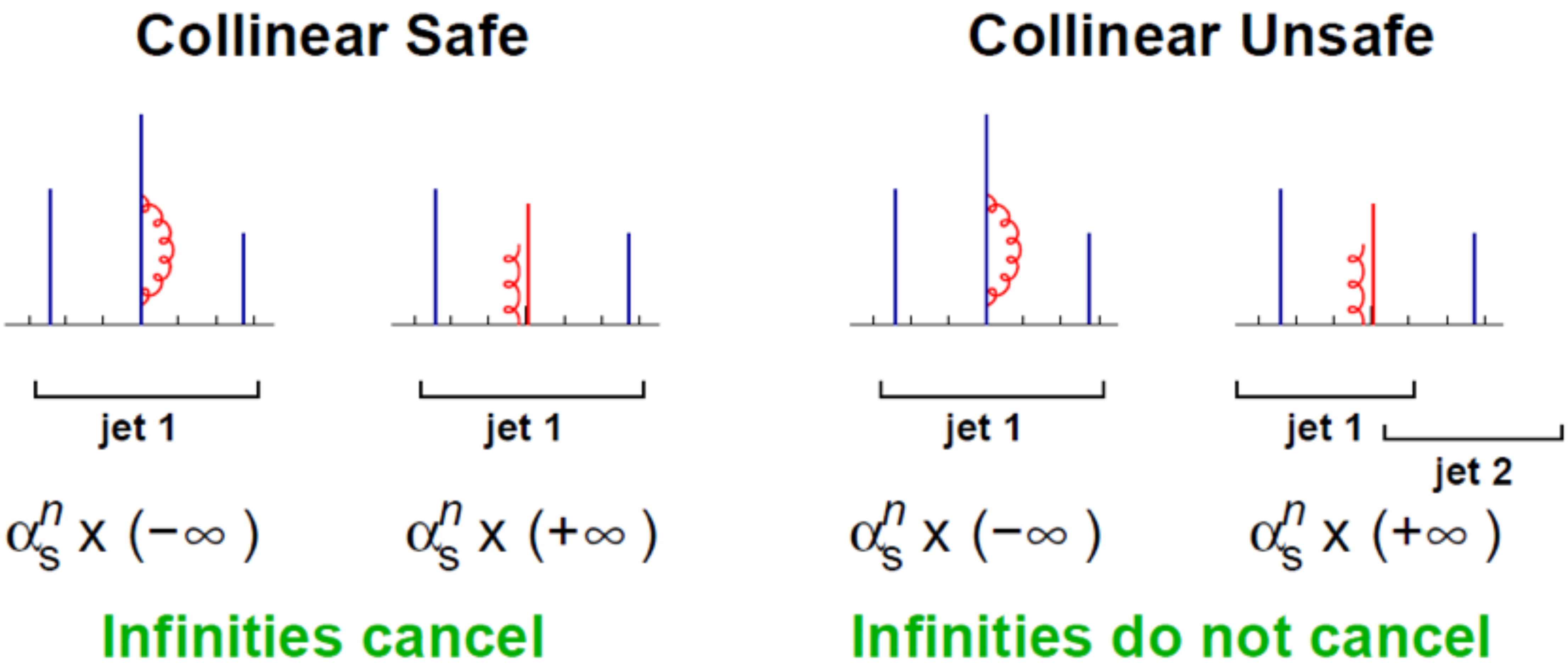


Illustration by G. Salam

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

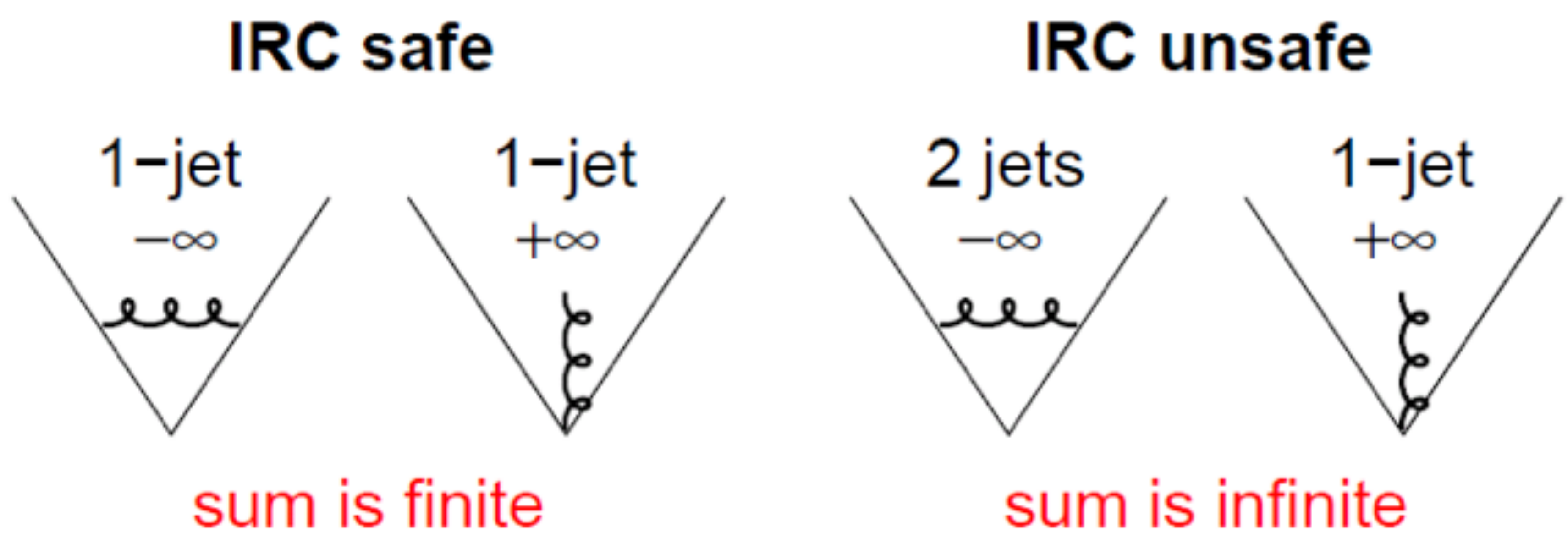


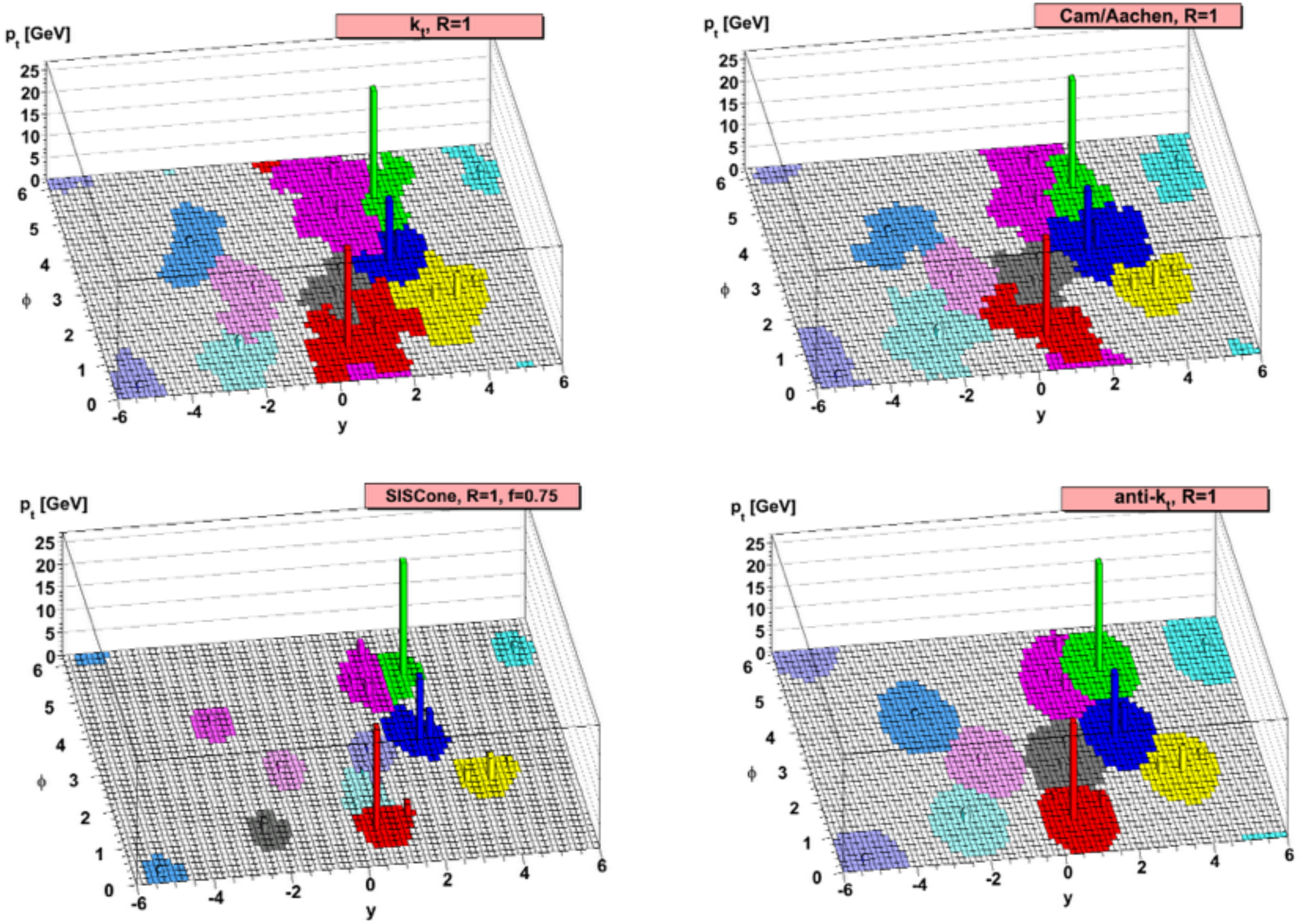
Illustration by G. Salam

Some calculations simply become **meaningless**

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

Jet algorithm examples

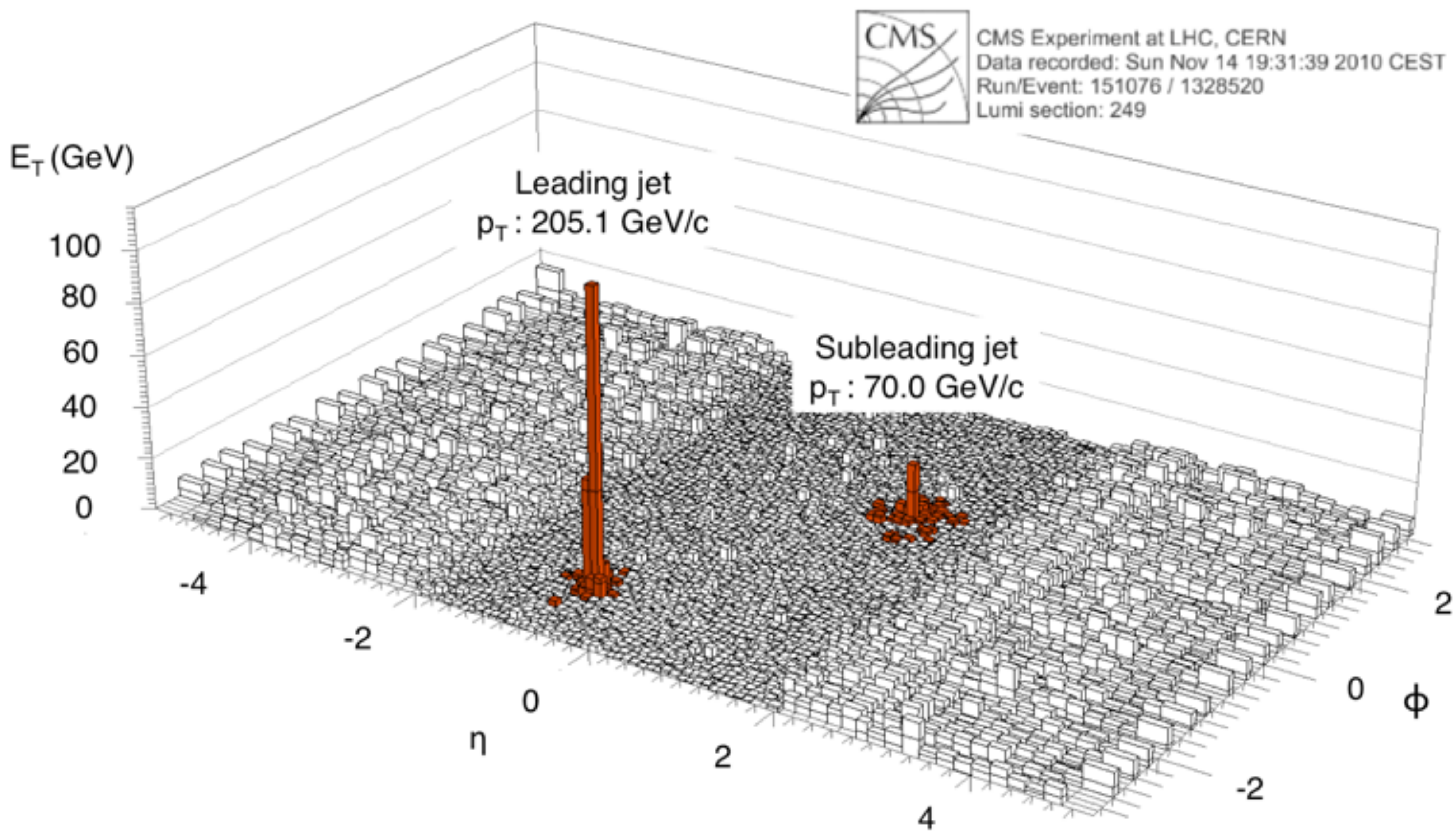
simulated p+p event



Cacciari, Salam, Soyez, arXiv:0802.1189

Di-jet imbalance measurements

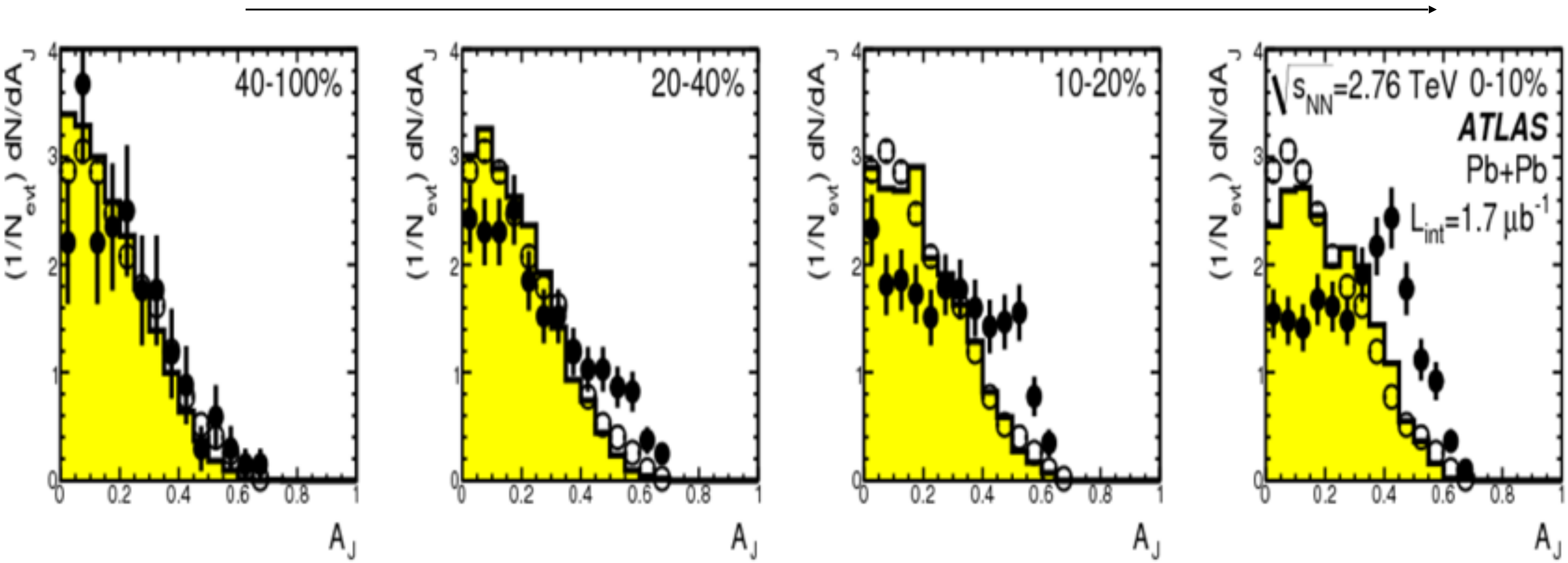
Di-jet asymmetry



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 $A_J = \frac{E_2 - E_1}{E_2 + E_1}$

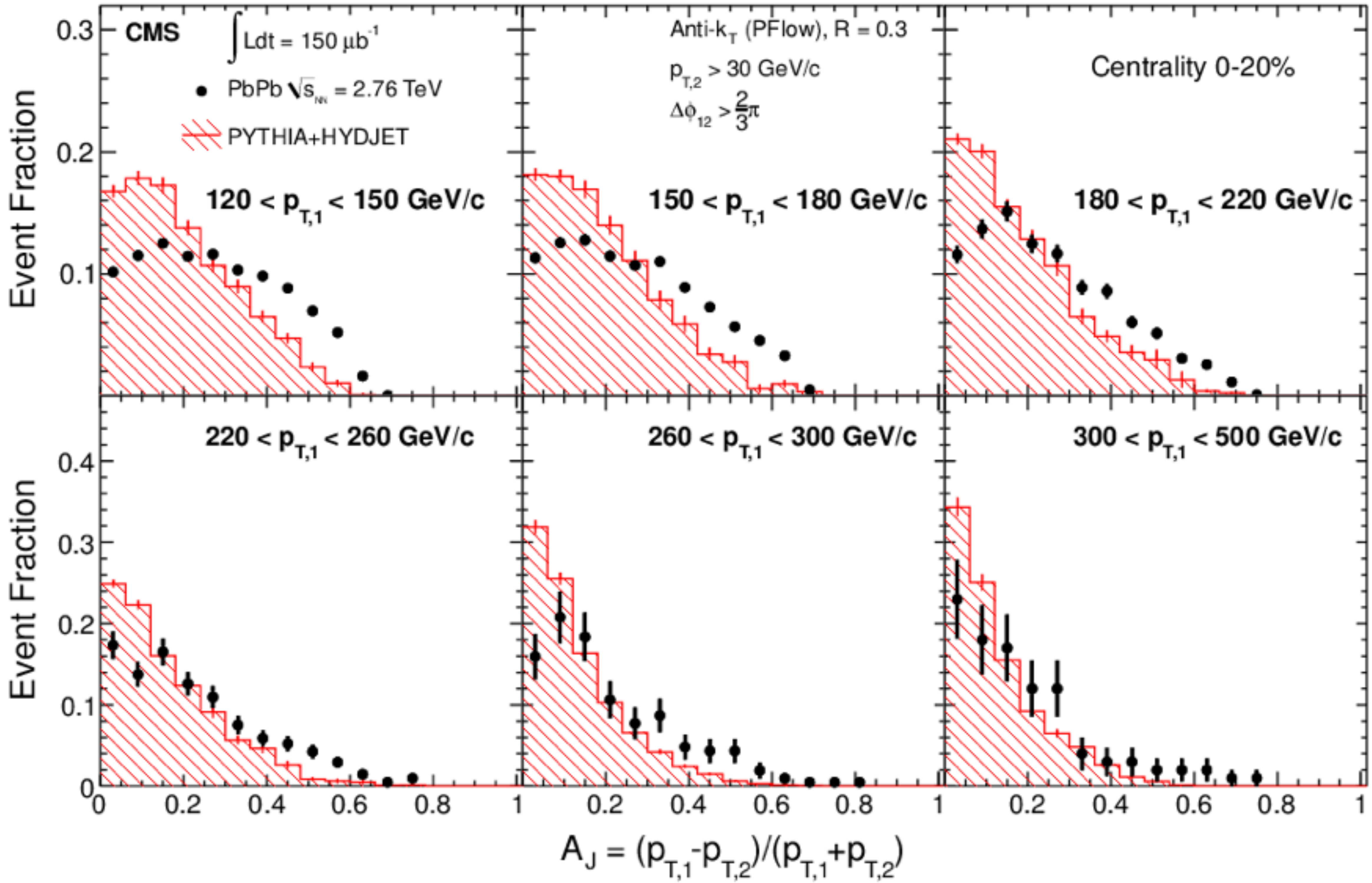
Large asymmetry seen for central events

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

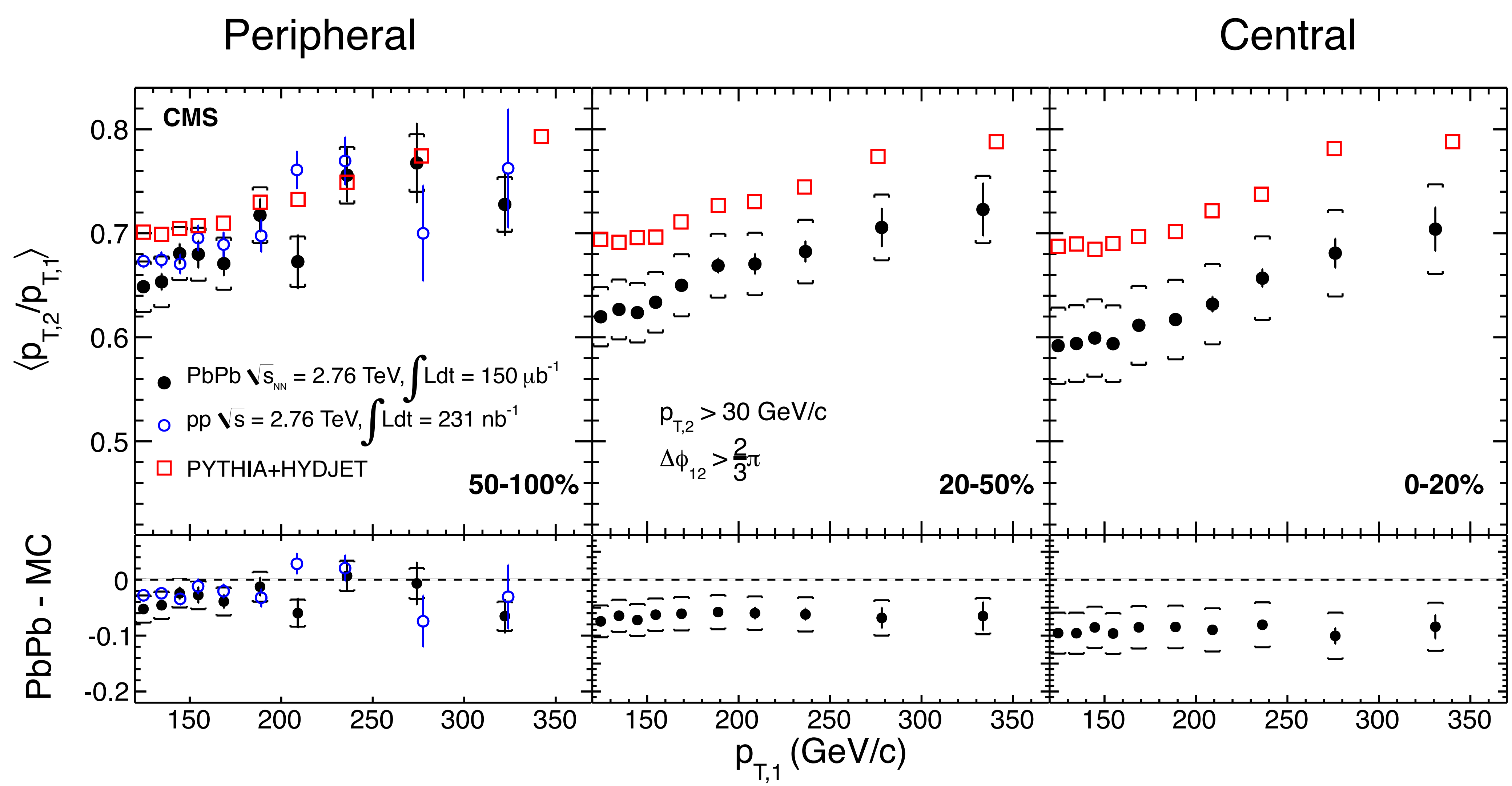


CMS, arXiv:1202.5022

(Relative) asymmetry decreases with energy

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

Energy dependence of A_J



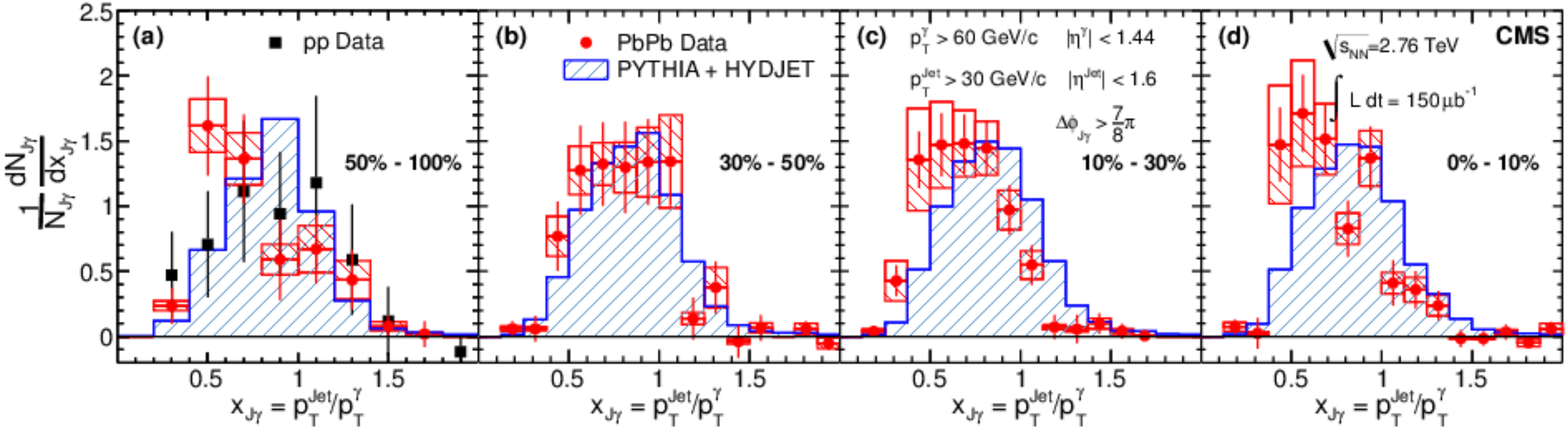
Asymmetry decreases for larger jet energy

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

γ-jet imbalance

Centrality →

CMS, arXiv:1502.0206



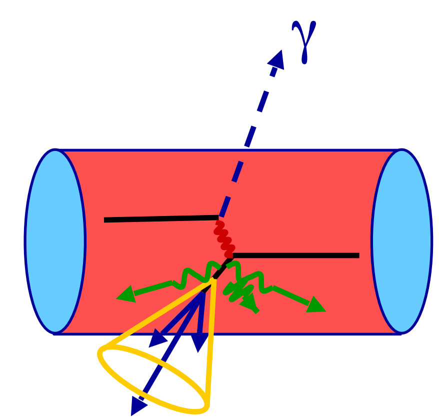
γ-jet asymmetry $$x_{J\gamma} = \frac{p_T^{jet}}{p_T^{\gamma}}$$

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: $qg \rightarrow q\gamma$



Potentially important observable — more stats in next run(s)

Corrections

Always ask: for which effects is the measurement corrected?
Important for any measurement, but in particular for jets!

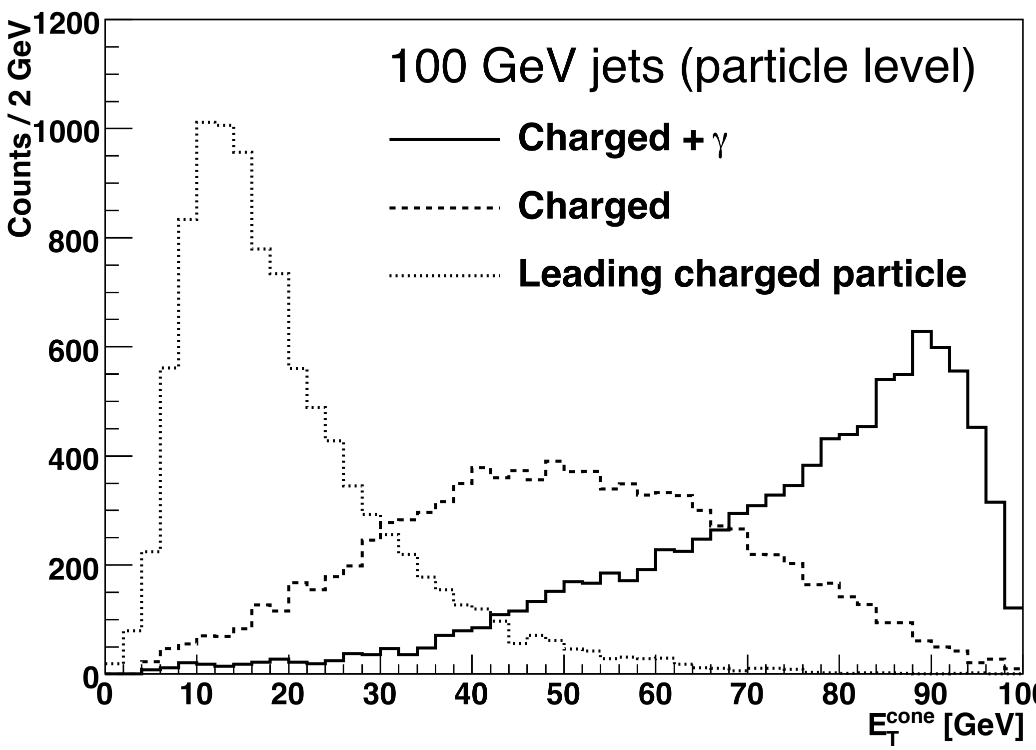
- A_J is basically uncorrected
  - Background subtracted, detector effects corrected on average
  - Hard to correct for detector effects+fluctuations
- Spectra and recoil measurements are corrected for
  - Detector effects
  - Background:
    - Overall background, measured outside jet cone, details differ between experiments
    - Background fluctuations
  - Motivation: compare to theory without detector effects and without background (may be ill-defined)

Measuring the jet spectrum

Charged and full jets

- Full jets: charged + neutral particles (except neutrinos)
  - Hadronic + Electromagnetic Calorimetry (ATLAS)
    - + tracking (particle flow; CMS)
  - Tracking + EMCal (ALICE)
- Charged jets: only charged particles
  - Used by ALICE because of limited acceptance of EMCal

Reconstructed energy



Charge to neutral fluctuations!

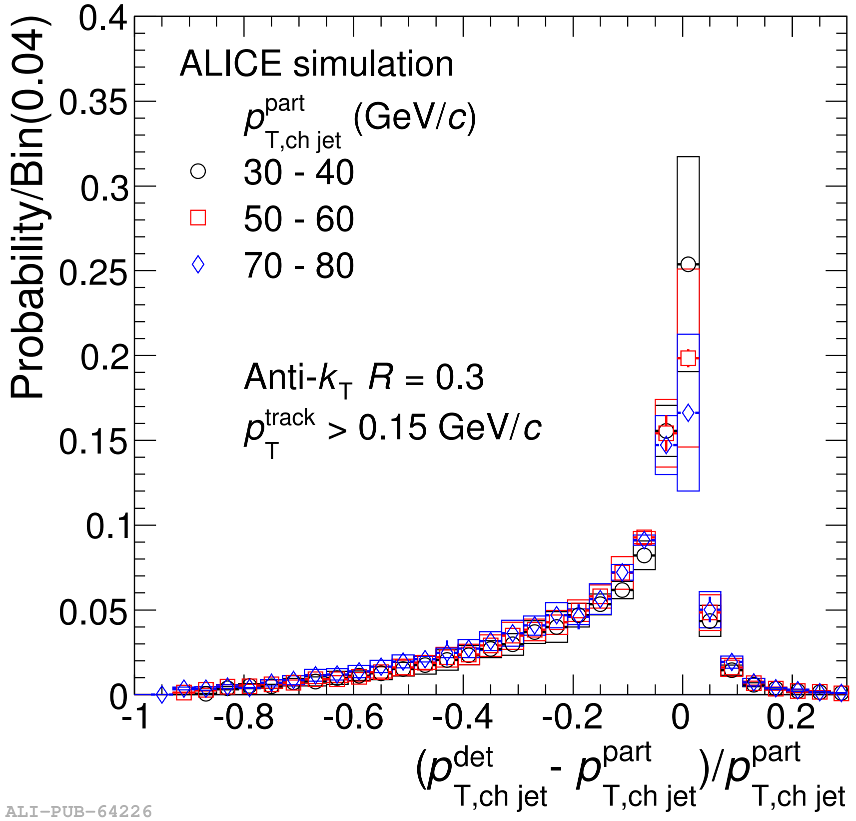
Full jets strongly preferred for original goal: recover jet energy

Detector corrections

Definitions:
Particle level: as generated by event generator, e.g. Pythia
Detector level: as reconstructed (Pythia+detector simulation)
(**Parton level**: parton energy; ill-defined?)

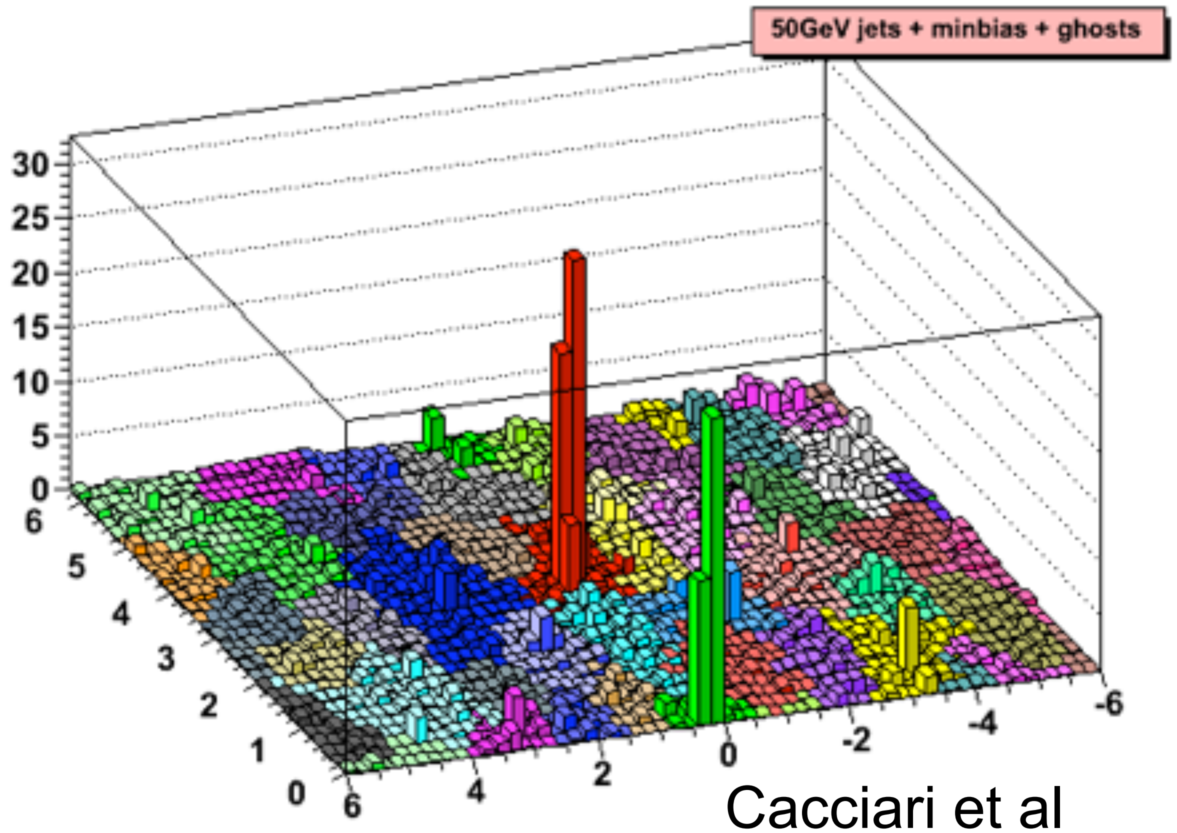
Standard practice:

- Charged jets are corrected to charged jets at the particle level
  - main effect: tracking efficiency
- Full jets are corrected to full jets at the particle level
  - Calorimetric jets: HCal response
  - Tracking+EMCal: Unmeasured hadrons (neutrons, K^0_L, tracking efficiency)



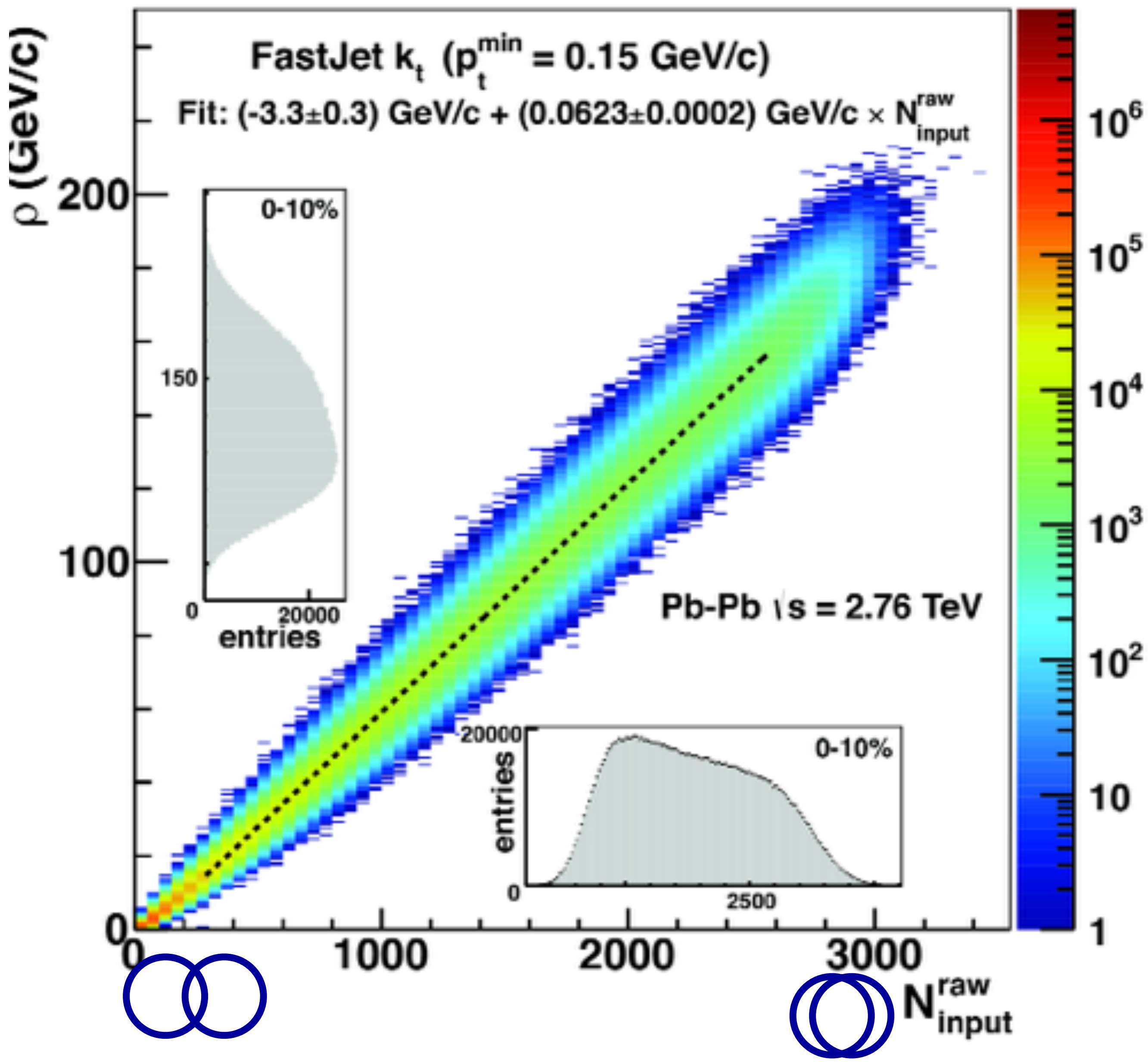
PbPb jet background

Jet finding illustration



η-φ space filled with jets
Many 'background jets'

Background density vs multiplicity

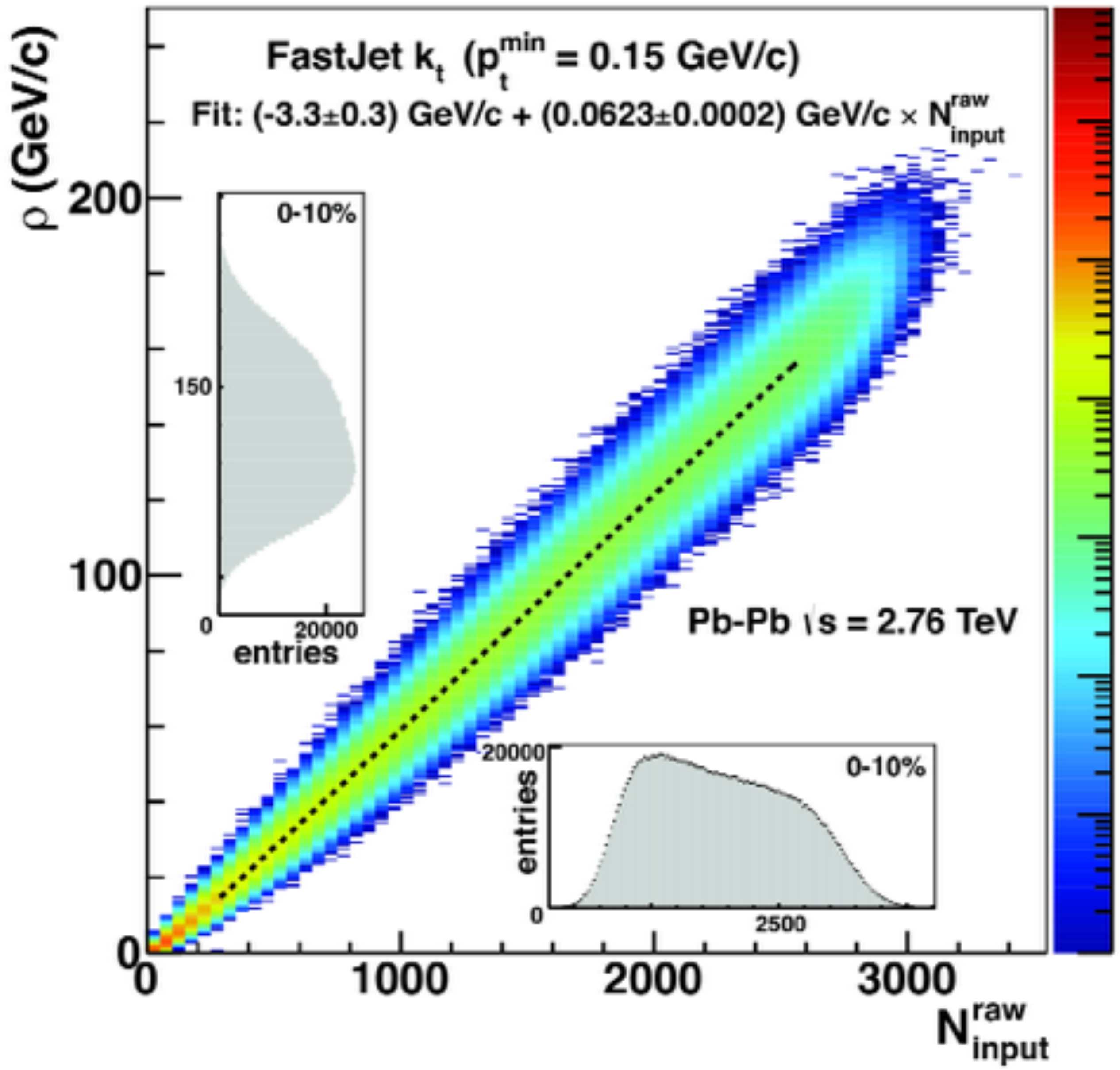


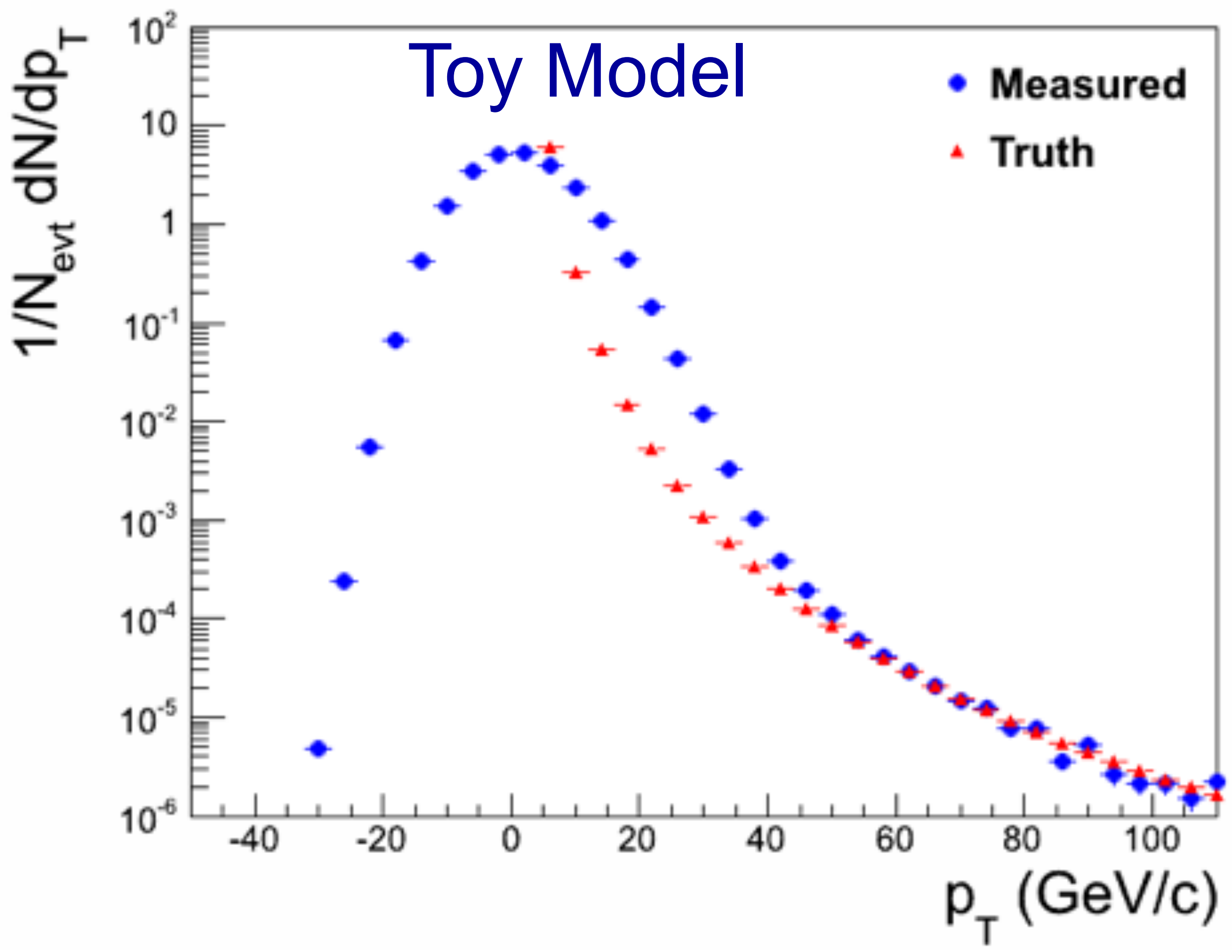
Background contributes up to ~180 GeV per unit area

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

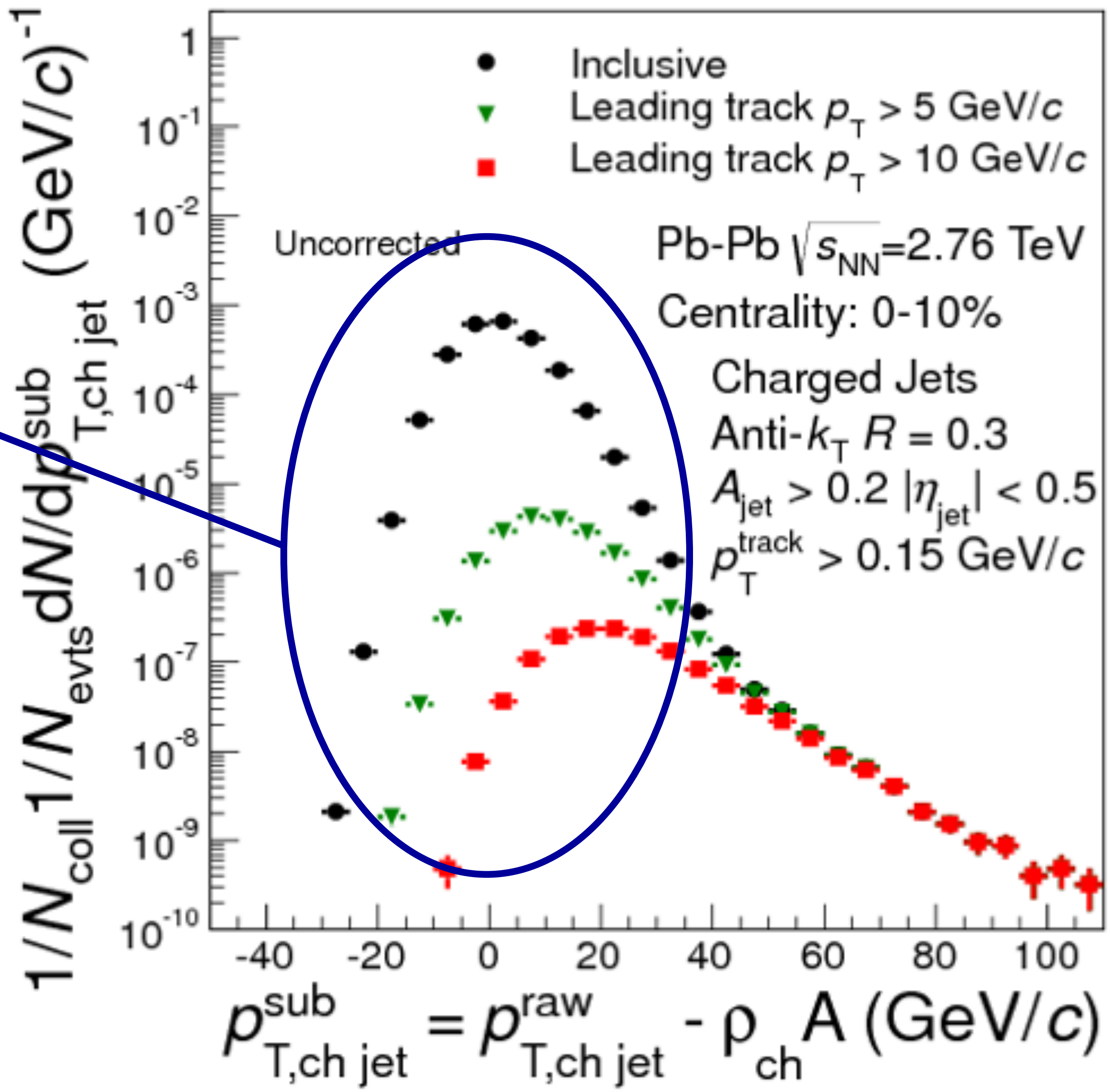
Background jets

Low p_T: 'combinatorial jets'

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

Raw jet spectrum

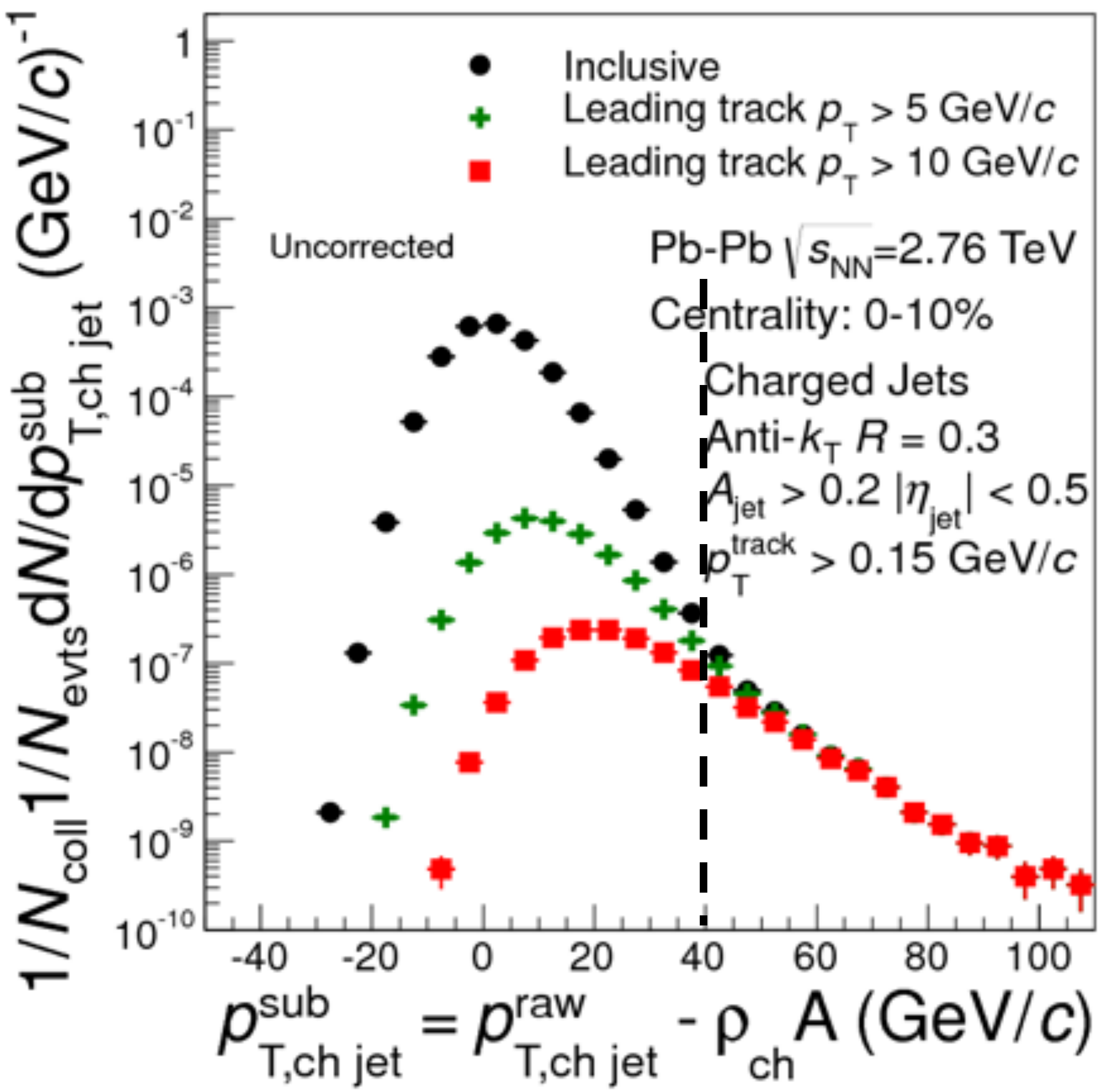
Event-by-event background subtracted



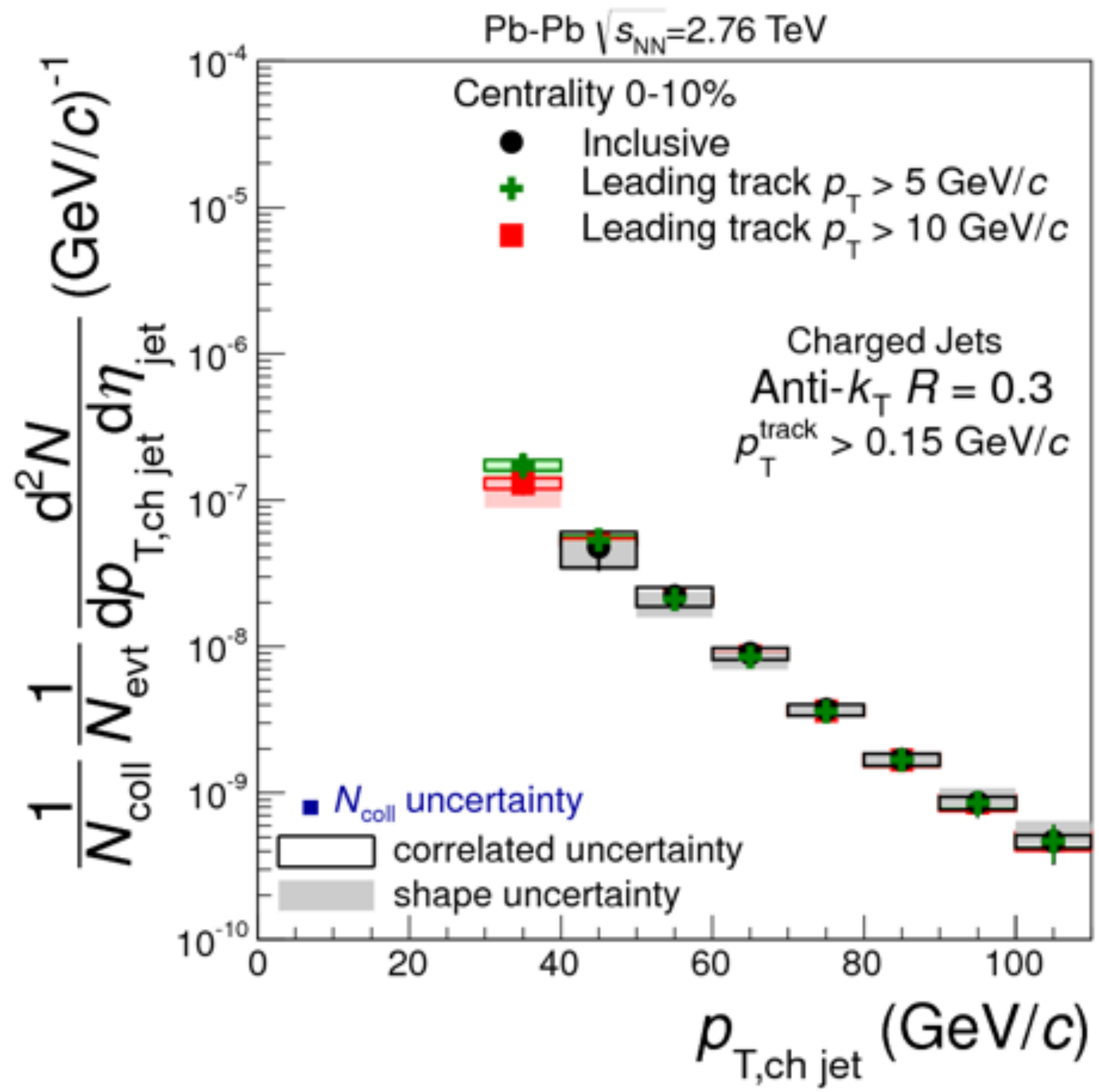
Next step: Correct for background fluctuations and detector effects by unfolding/deconvolution

Removing the combinatorial jets

Raw jet spectrum



Fully corrected jet spectrum



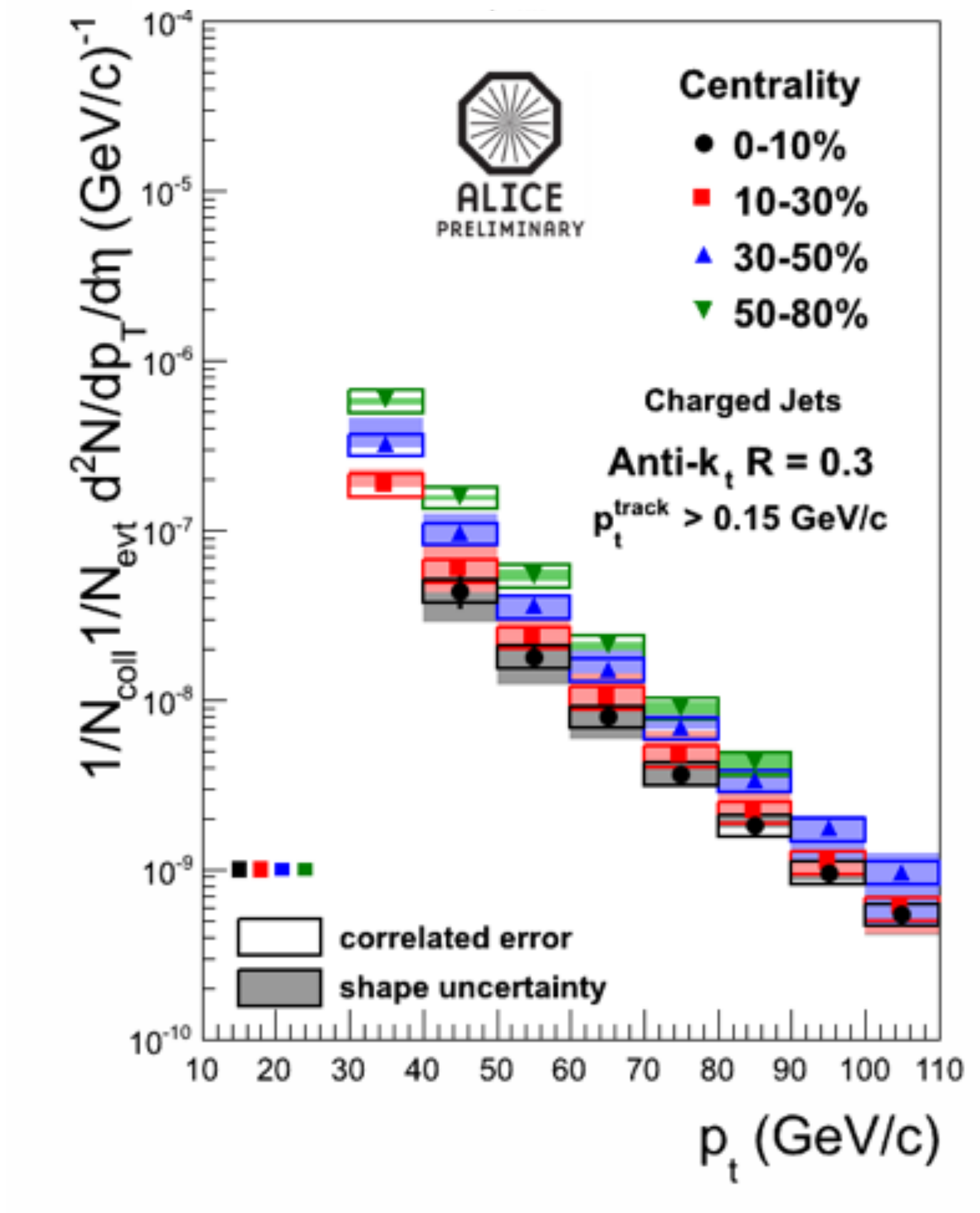
ALICE arXiv:1311.0633

Correct spectrum and remove combinatorial jets by unfolding

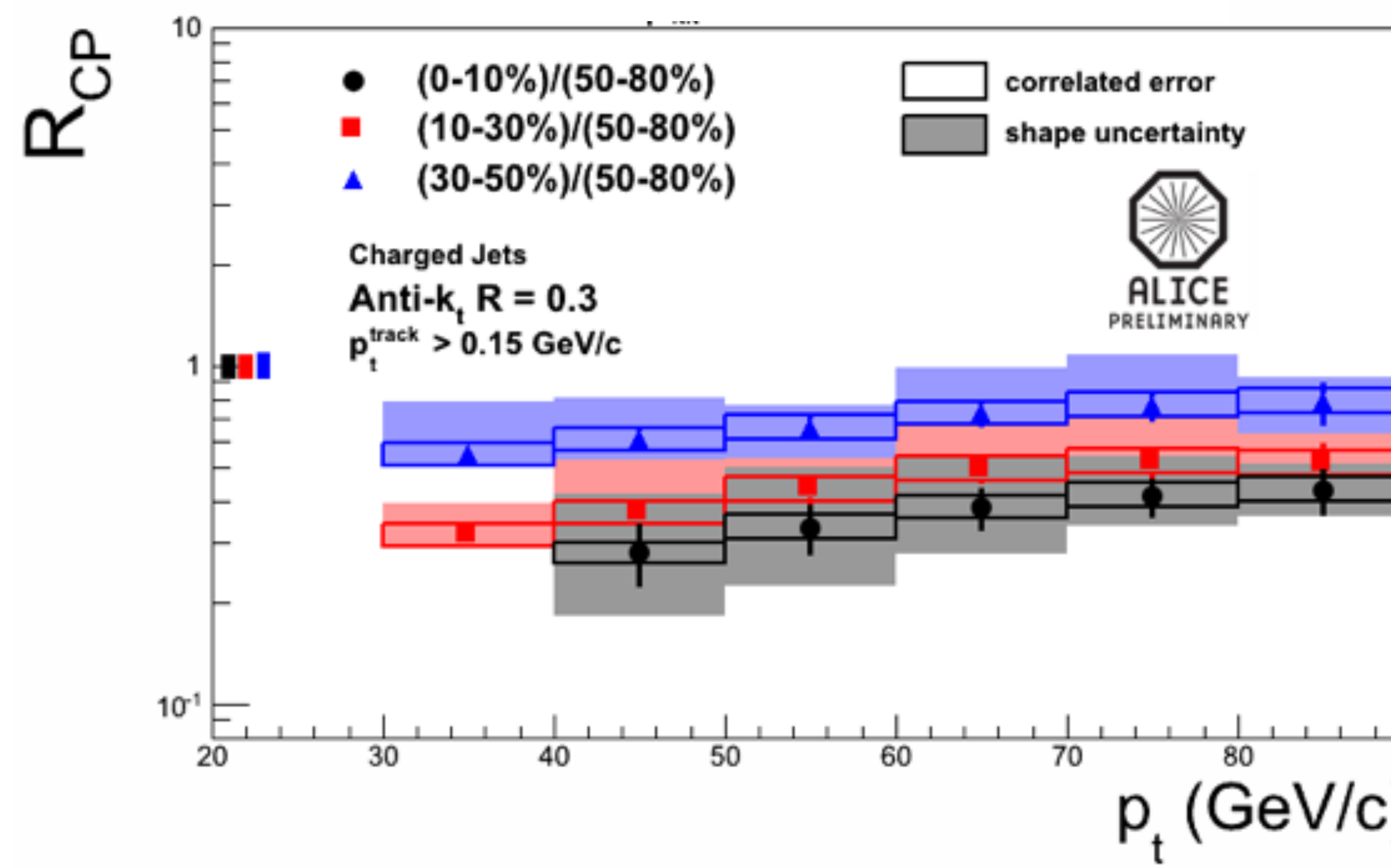
Results agree with biased jets: reliably recovers all jets and removed bkg

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}

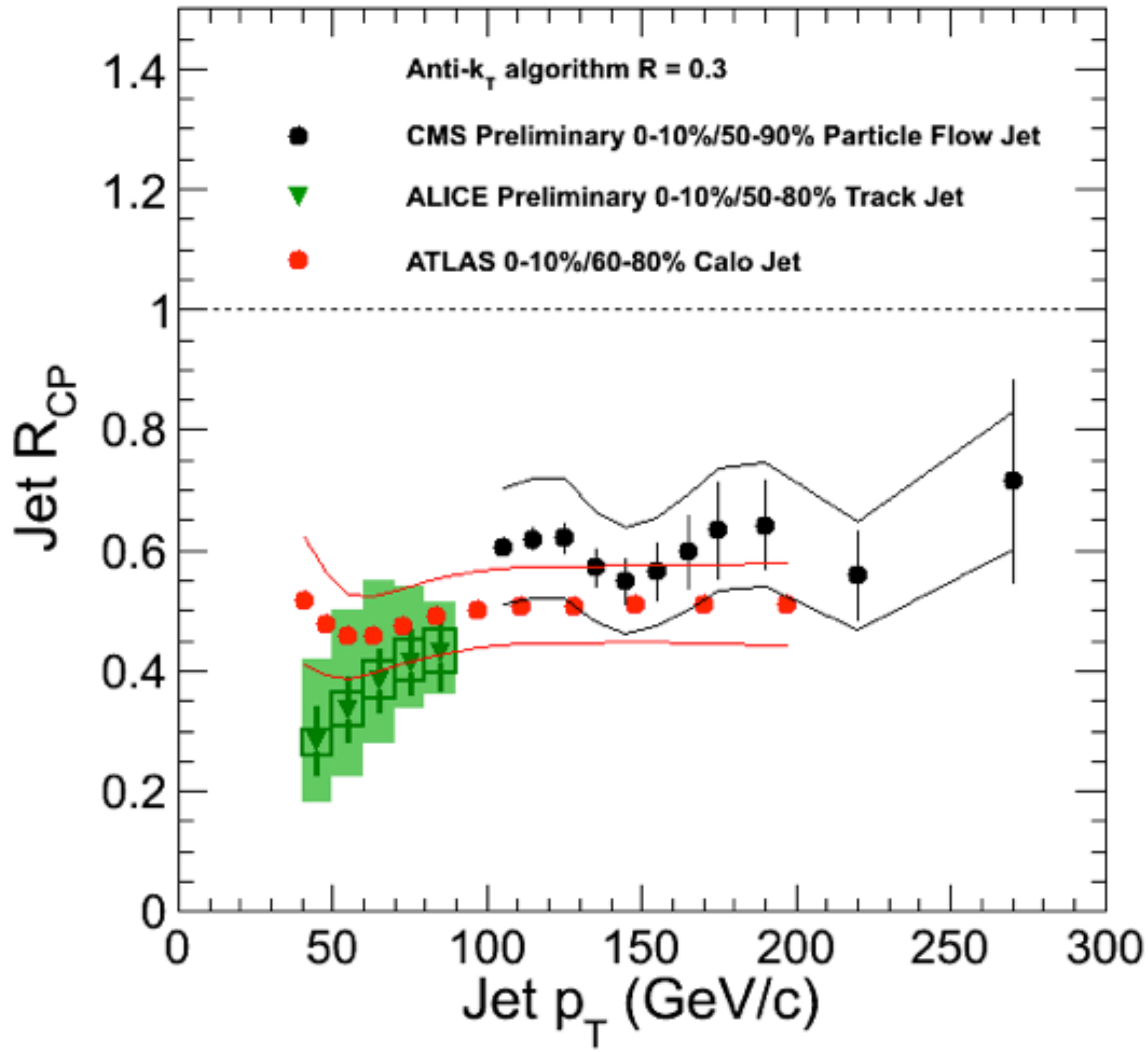
Jet R_{AA} measured by ATLAS, ALICE, CMS

Good agreement between experiments

Despite different methods:

ATLAS+CMS: hadron+EM jets

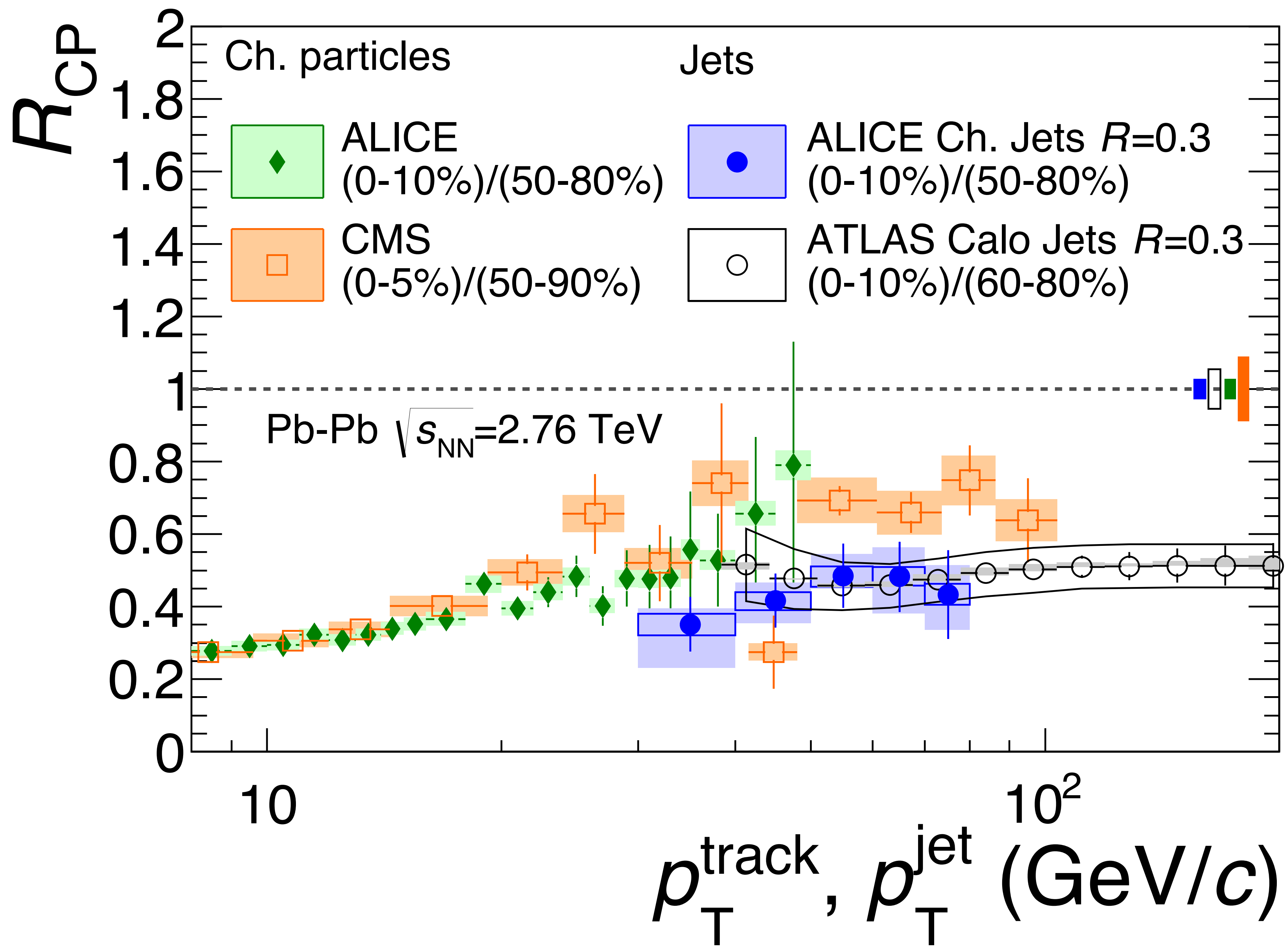
ALICE: charged track jets



$R_{AA} < 1$: 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

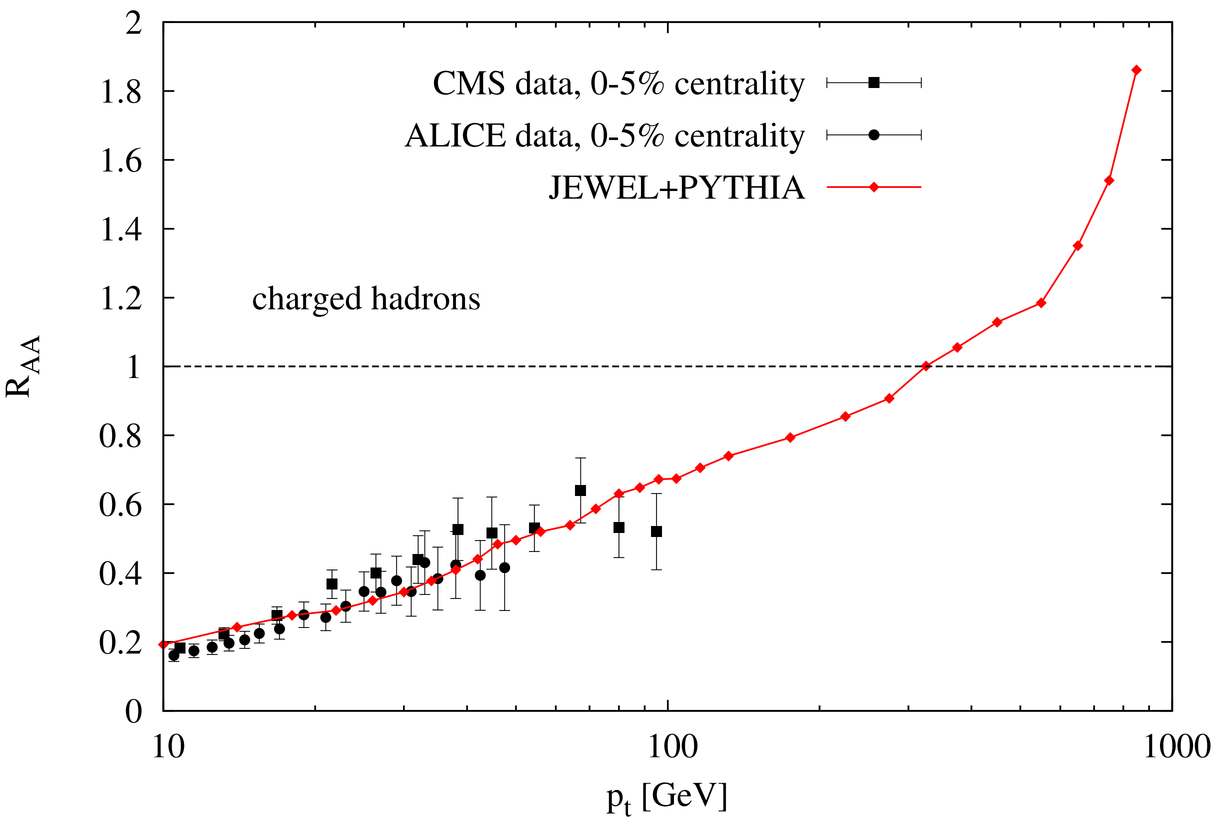
Comparing hadrons and jets

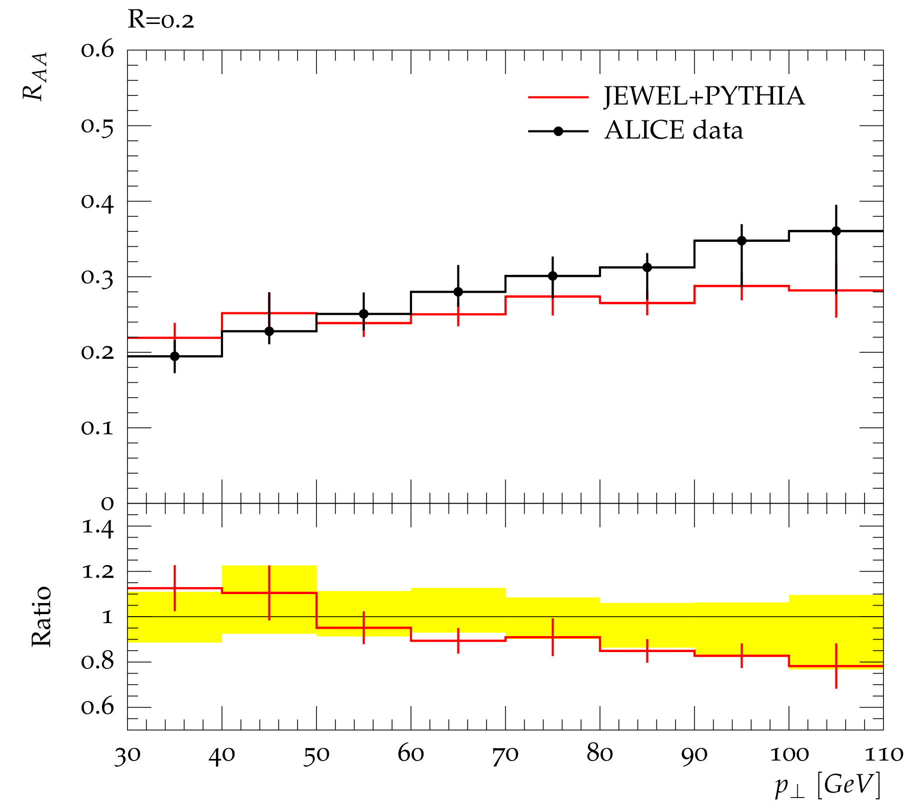


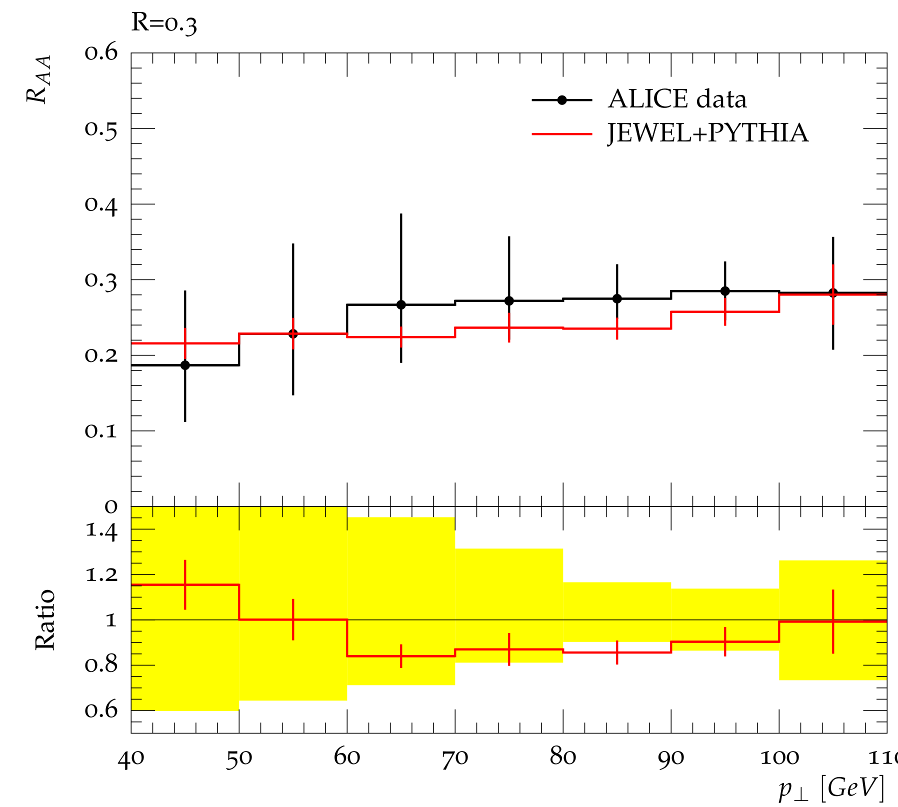
Suppression of hadron (leading fragment) and jet yield similar

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

Comparison to JEWEL energy loss MC



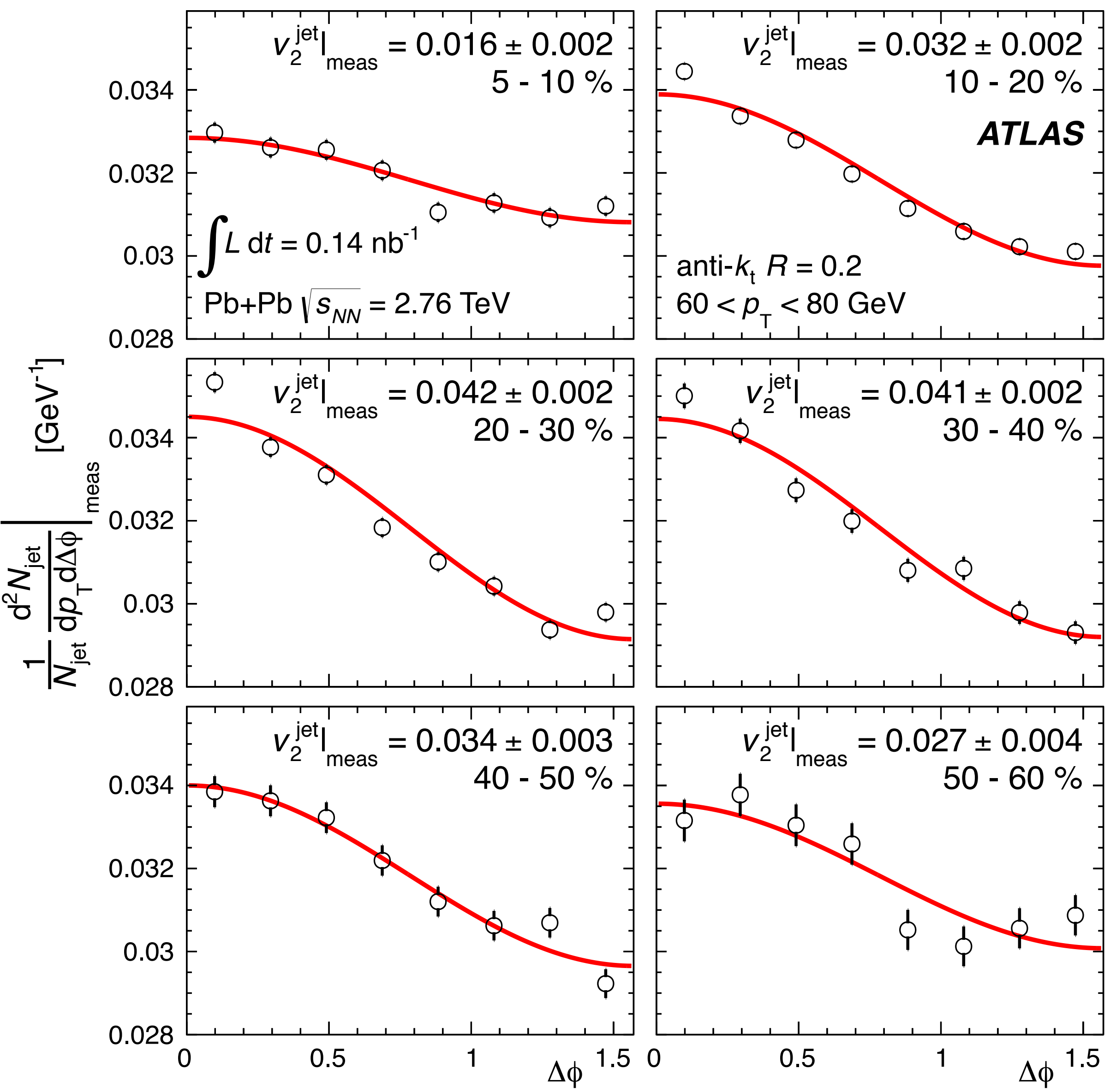


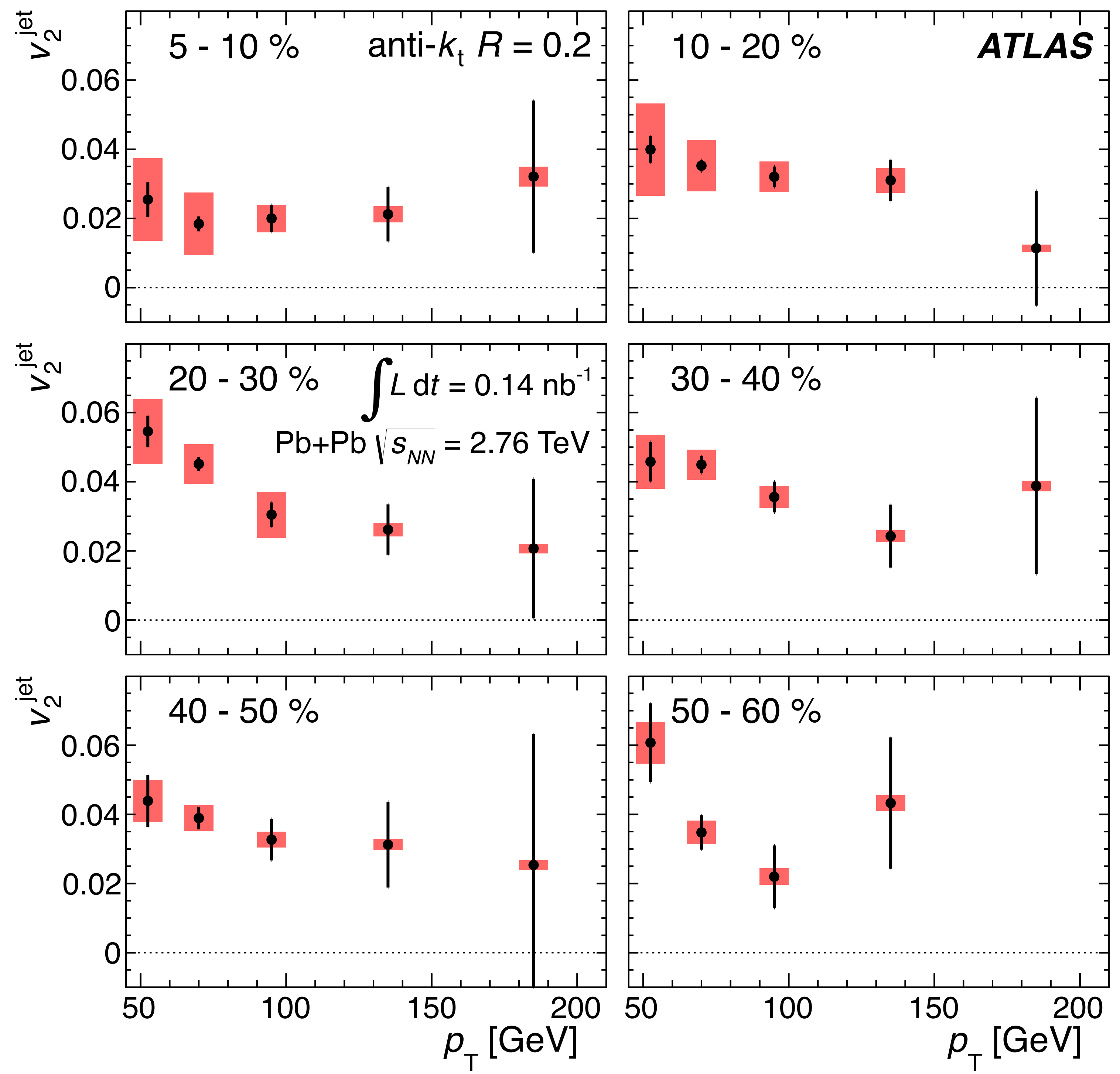


JEWEL shows the same feature:
jet R_{AA} ~ hadron R_{AA}

Path length dependence: v_2 of Jets

ATLAS, arXiv:1306.6469



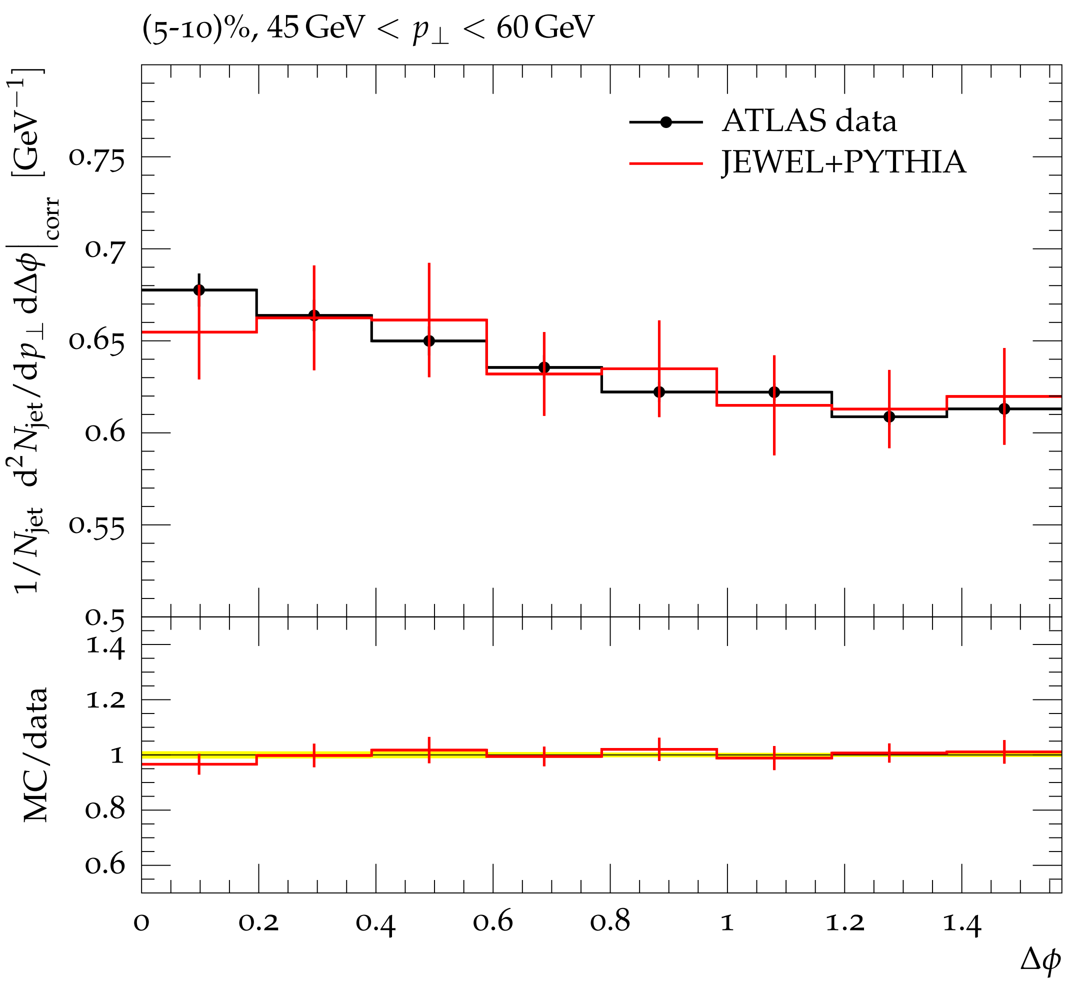


Significant azimuthal modulation of jet yield

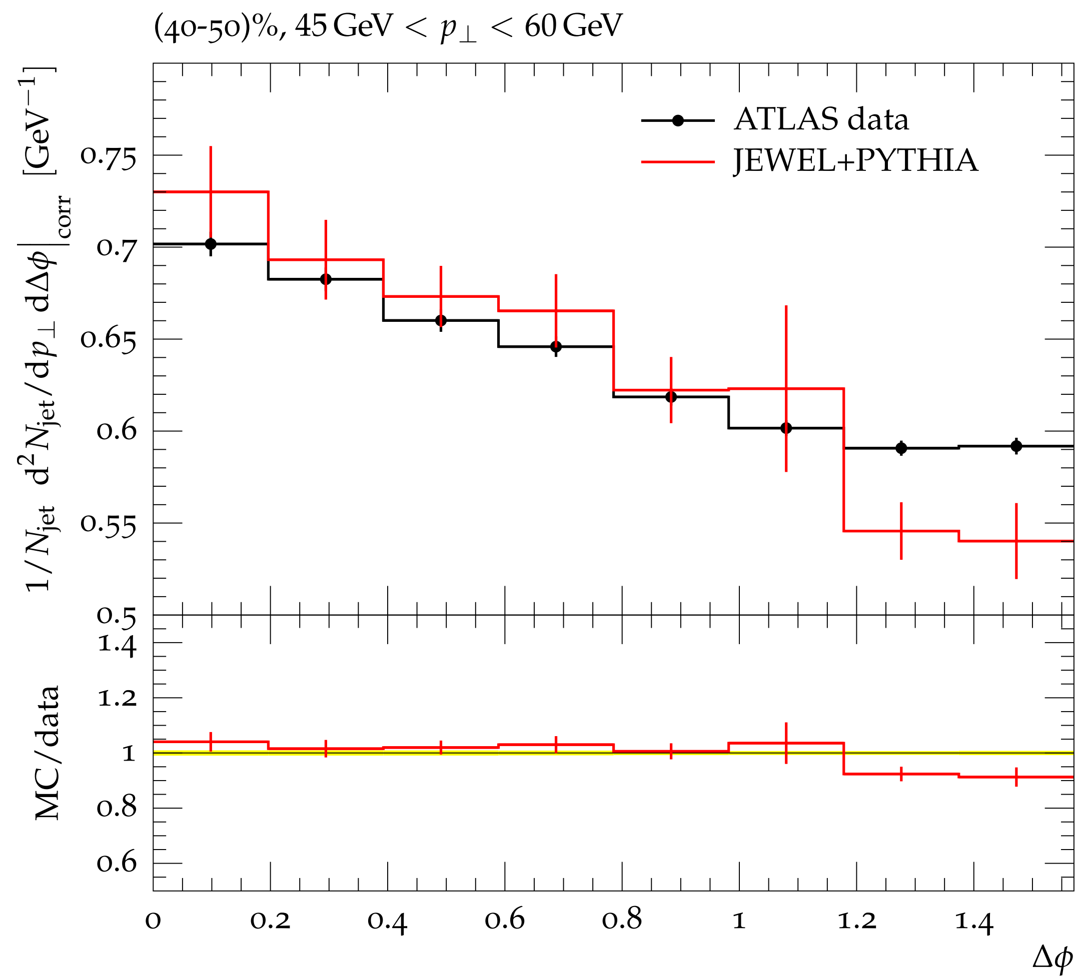
jet $v_2 \sim 0.03$ at high p_T

Comparing to JEWEL energy loss MC

5-10% centrality



40-50% centrality

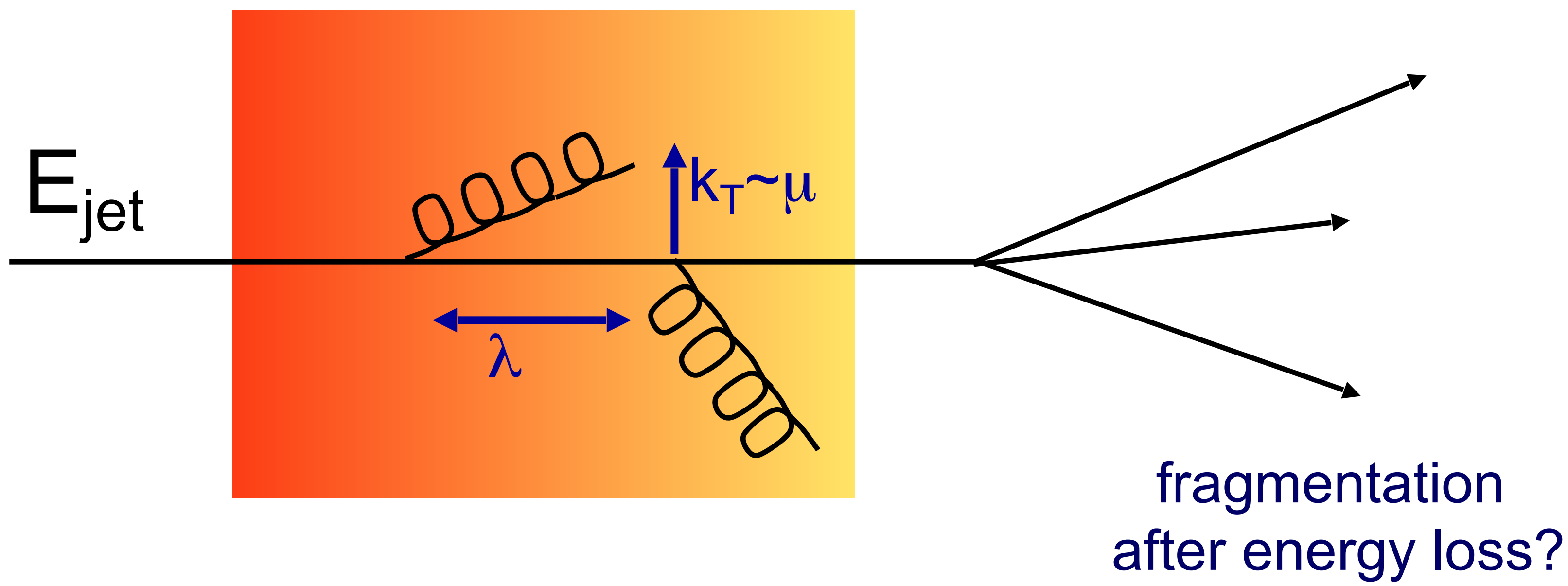


K. Zapp, arXiv:1312.5563

Good agreement between JEWEL and jet v_2 results

Geometry: Glauber overlap with Bjorken expansion

Generic expectations from energy loss



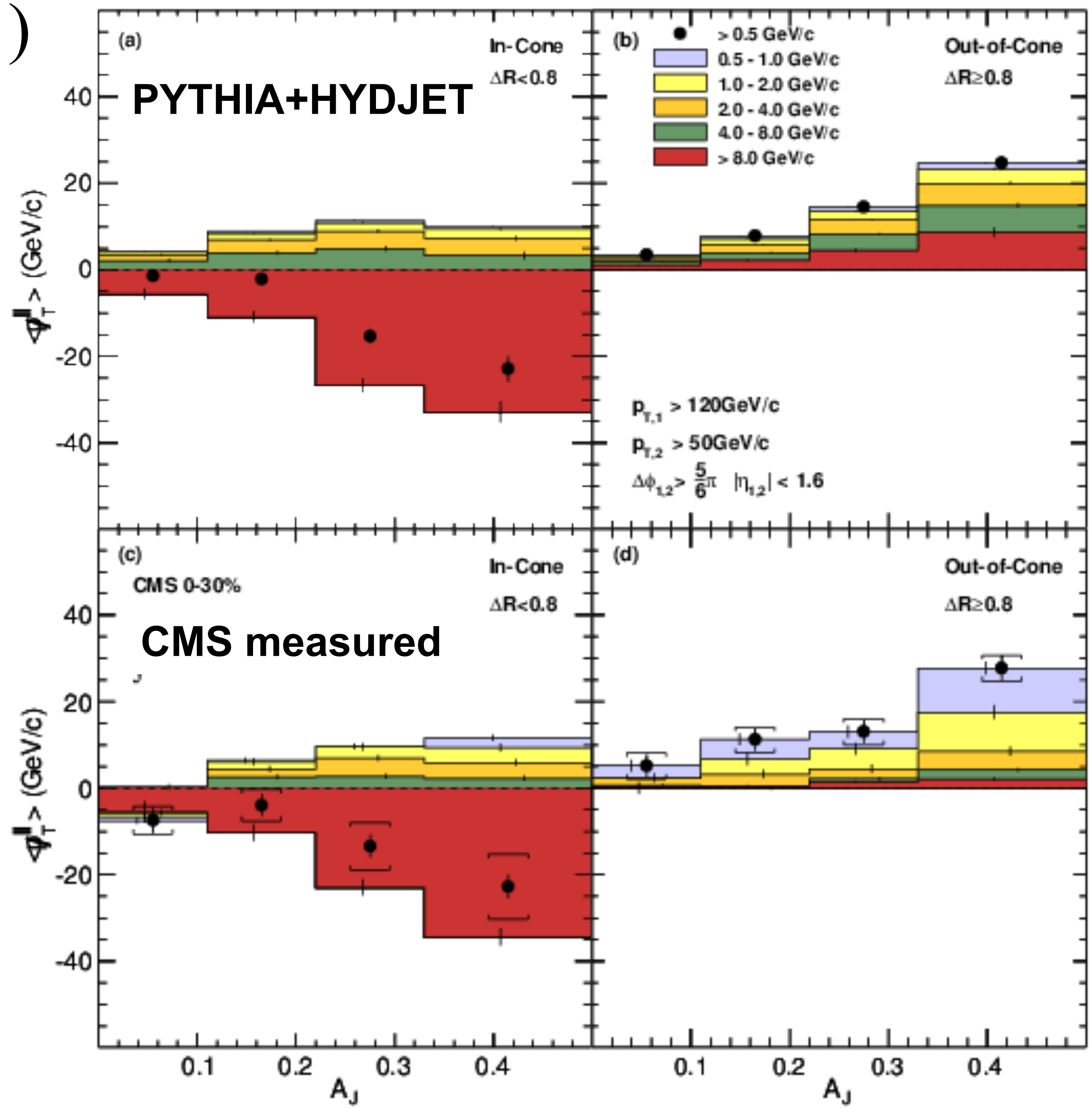
- Longitudinal modification:
  - out-of-cone ⇒ energy lost, suppression of yield, di-jet energy imbalance
  - in-cone ⇒ softening of fragmentation
- Transverse modification
  - out-of-cone ⇒ increase acoplanarity k_T
  - in-cone ⇒ broadening of jet-profile

Out-of-cone effects are large, so expect combination of all of the above

Looking outside the jet cone

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

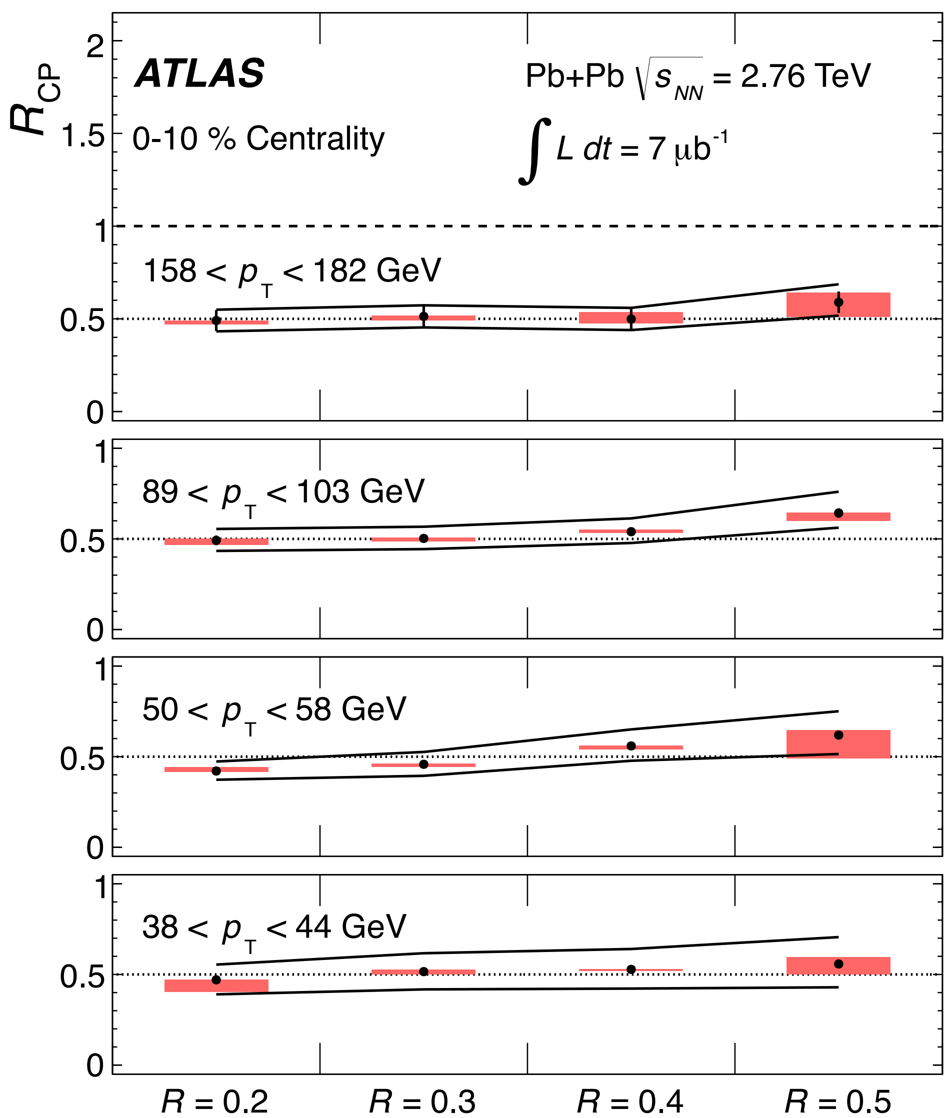
In Cone R<0.8 Out of Cone R>0.8



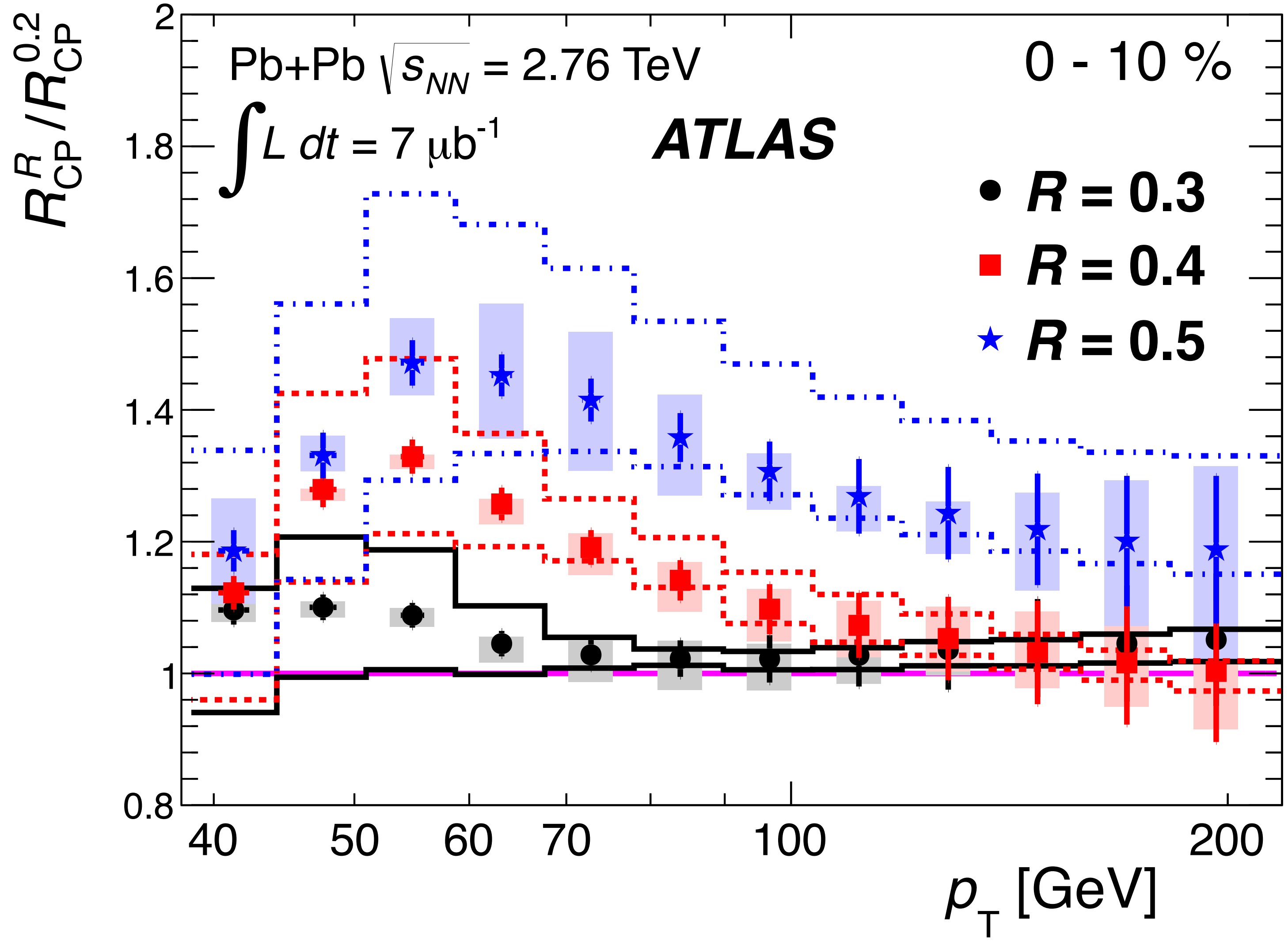
CMS, arXiv:1102.1957

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

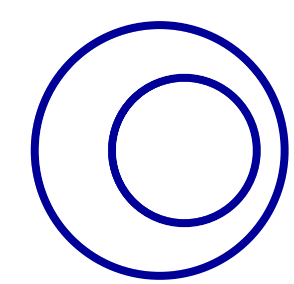
Jet broadening: R dependence of R_{AA}



Ratio of spectra with different *R*

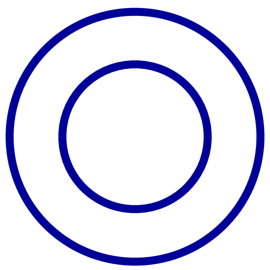


Larger jet cone: 'catch' more radiation → Jet broadening

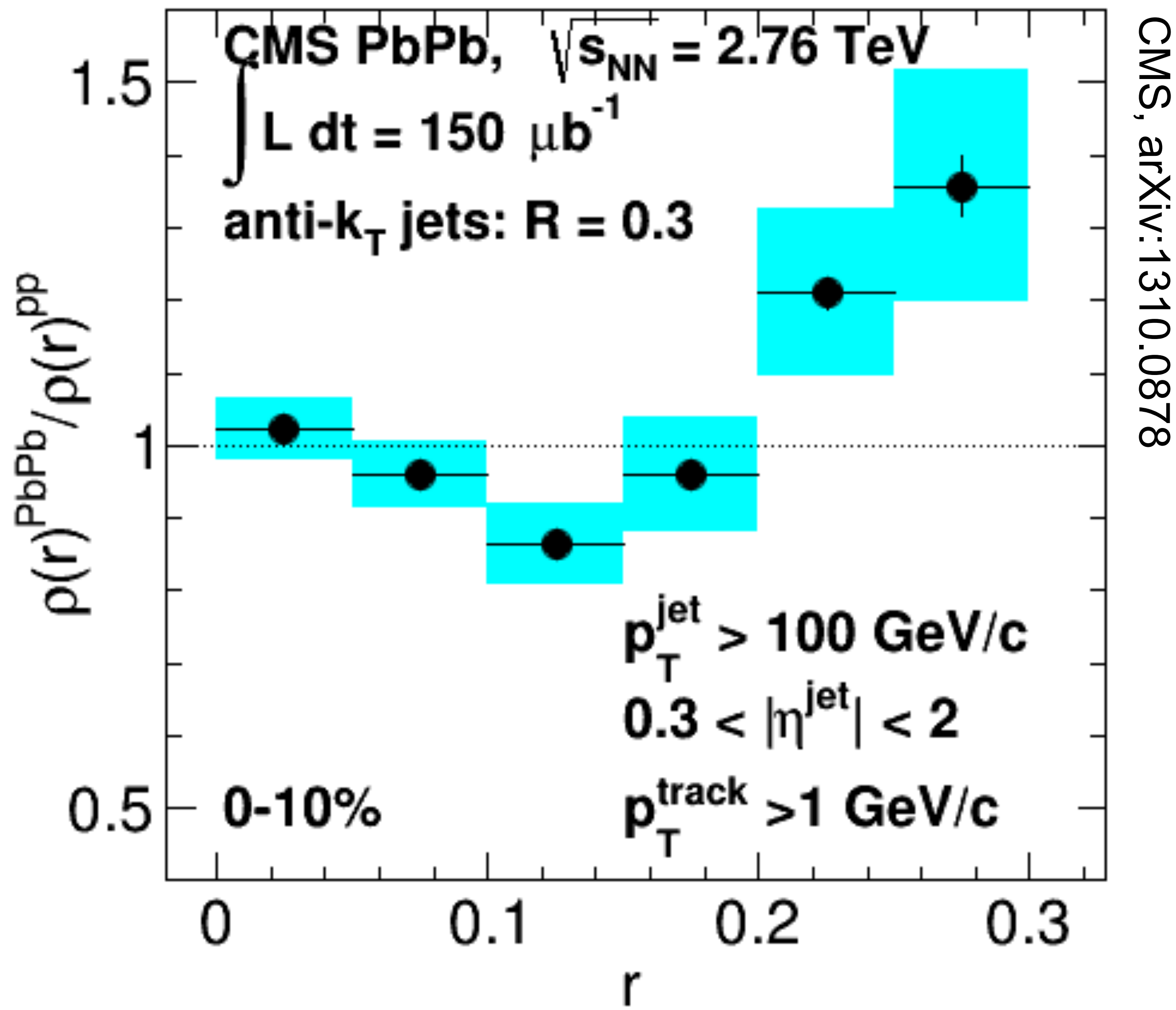


However, R = 0.5 still has R_{AA} < 1
– Hard to see/measure the radiated energy

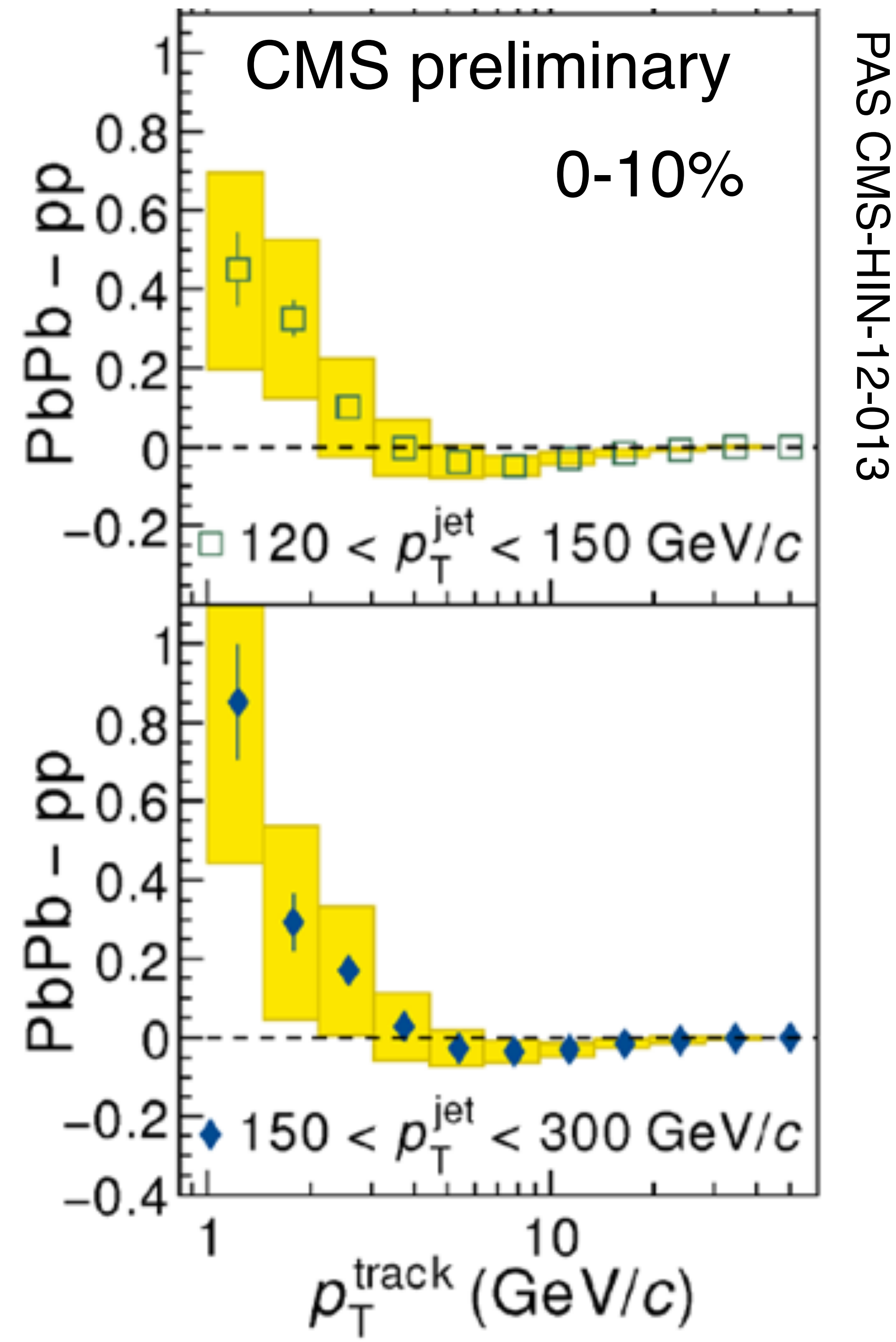
Changes in fragmentation



Transverse
fragment distributions



Longitudinal
fragment distributions

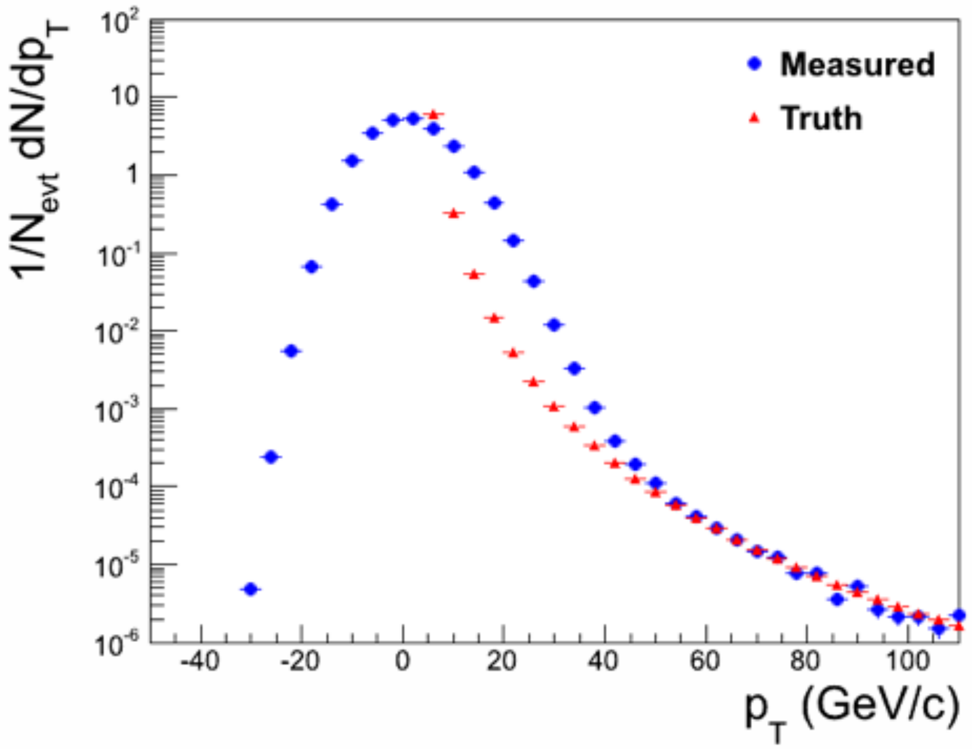


Enhancement at large R, low p_T

No modification at small R, large p_T: physics or auto-correlation?

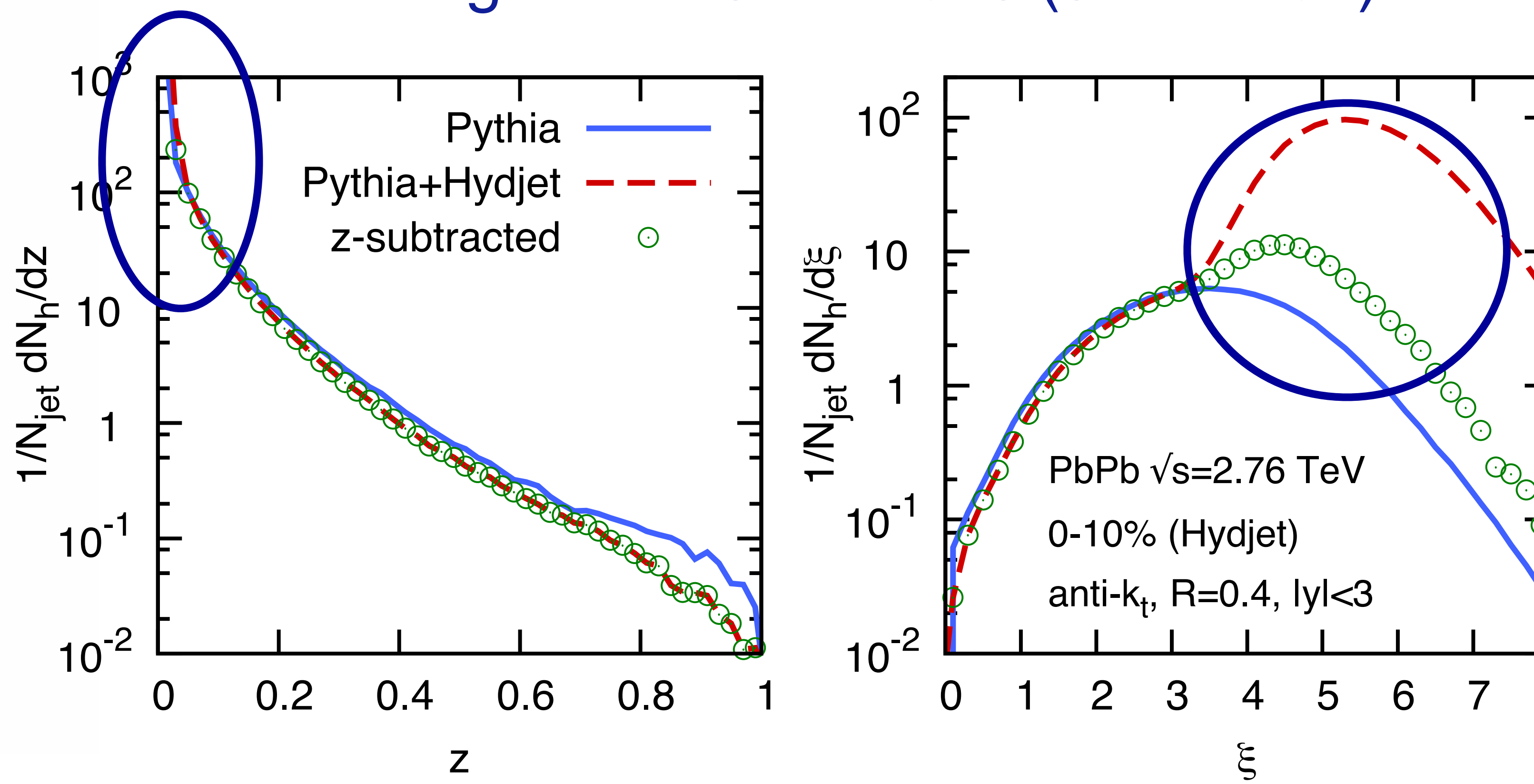
Again: background fluctuations

Toy model spectrum



Background fluctuations migrate yield to higher p_T

Fragment distributions (simulation)



Cacciari et al, arXiv:1209.6086

At fixed p_T: pick up above-average background contributions

$\xi \gtrsim 4 \Leftrightarrow p_T \lesssim 2$ GeV

Current measurements mostly $p_T > 2$ GeV

Jet Quenching Summary I

- So, jet R_{AA} is not close to 1
- Large out-of-cone radiation, low p_T, large angles
- NB: even the fragmentation measurements do not capture the 'initial energy'

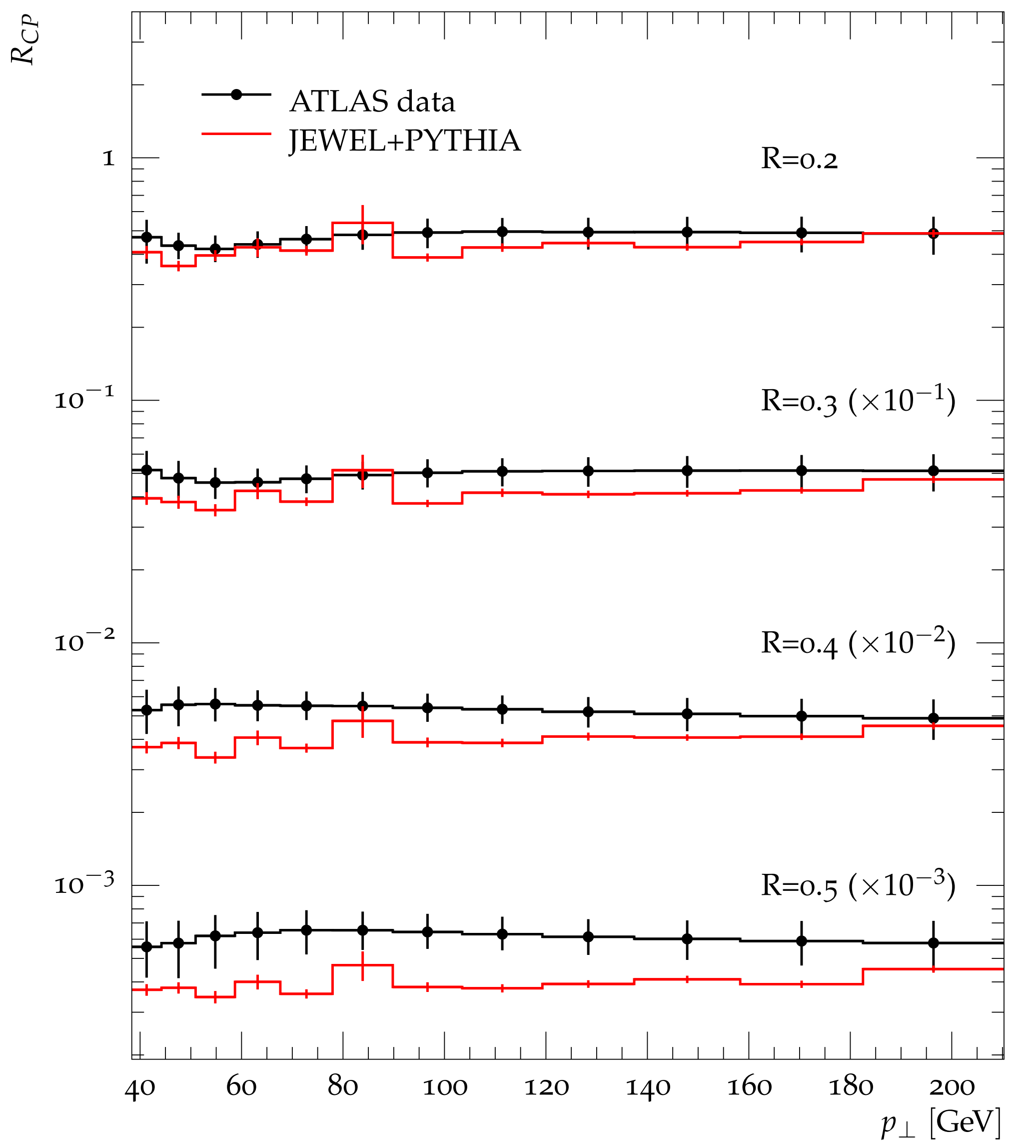
What is the (dominant) mechanism?
Several lines of investigation

- No angular ordering the the medium; large angle radiation allowed (Mehtar-Tani, Salgado, Tywoniuk)
  - Interplay of scales: medium density/mean free path vs opening angle of radiation
- Multiple interactions 'thermalise' the radiation (Renk, Wiedemann, Caselderrey-Solana)
- Large angle 'democratic' gluon splitting allowed in the medium (Blaizot, Iancu, Mehtar-Tani)
- Kinematics, (trigger-)biases also play a role
  - Thorsten Renk: effect of Angular Ordering is small in Pythia

Comparing to energy loss models

Jet observables: need explicit modelling of multi-particle final states

JEWEL: R_{CP} vs R



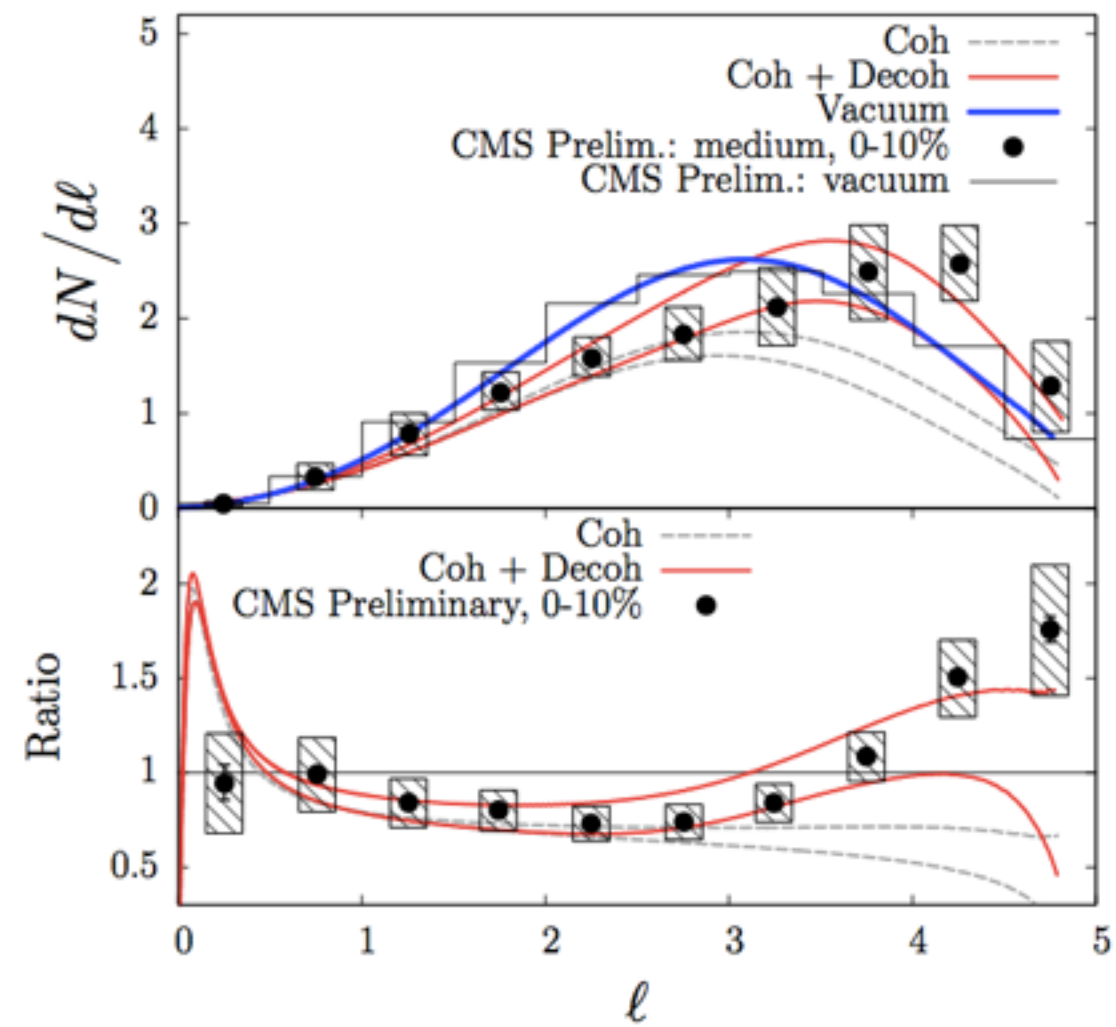
K. Zapp et al, arXiv:1212.1599

JEWEL gets the right suppression for R=0.2,

but not the increase with R

(Treatment of recoil partons?)

Mehtar-Tani, Tywoniuk, arXiv:1401.8293



Fragment distributions sensitive
to coherence effects
(NB: no geometry model yet)

Hadron trigger vs jet trigger

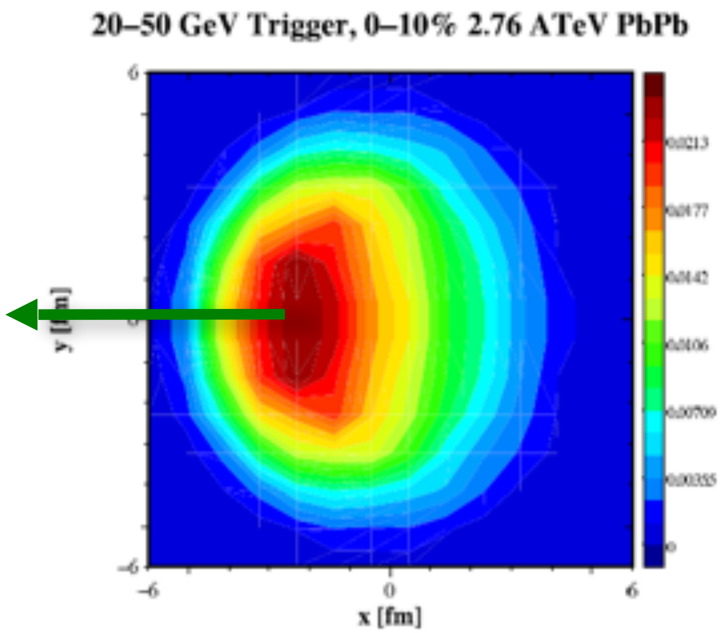
Are jets an unnecessary complication?

If hadron and jet R_{AA} are similar, why not use hadron observables?

Hadron trigger: strong "surface bias"

maximizes recoil path length

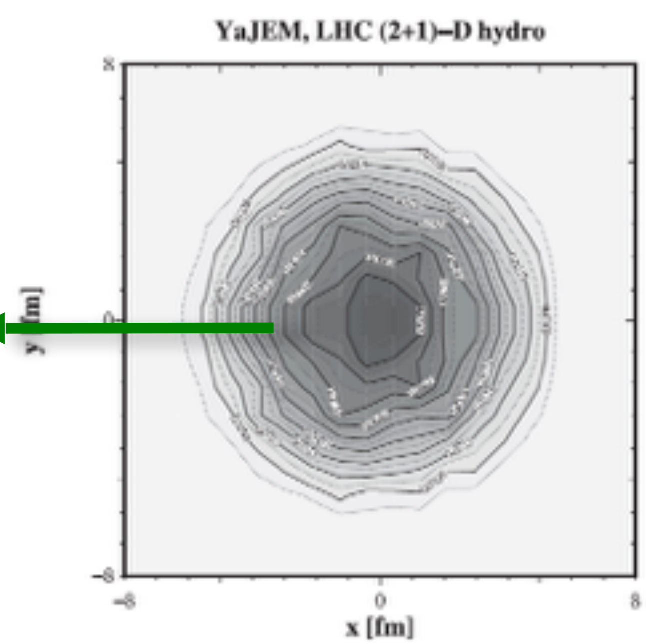
Hadron trigger



Full jet trigger: no geom. bias

partially cancelled by bkg fluctuations

Jet trigger



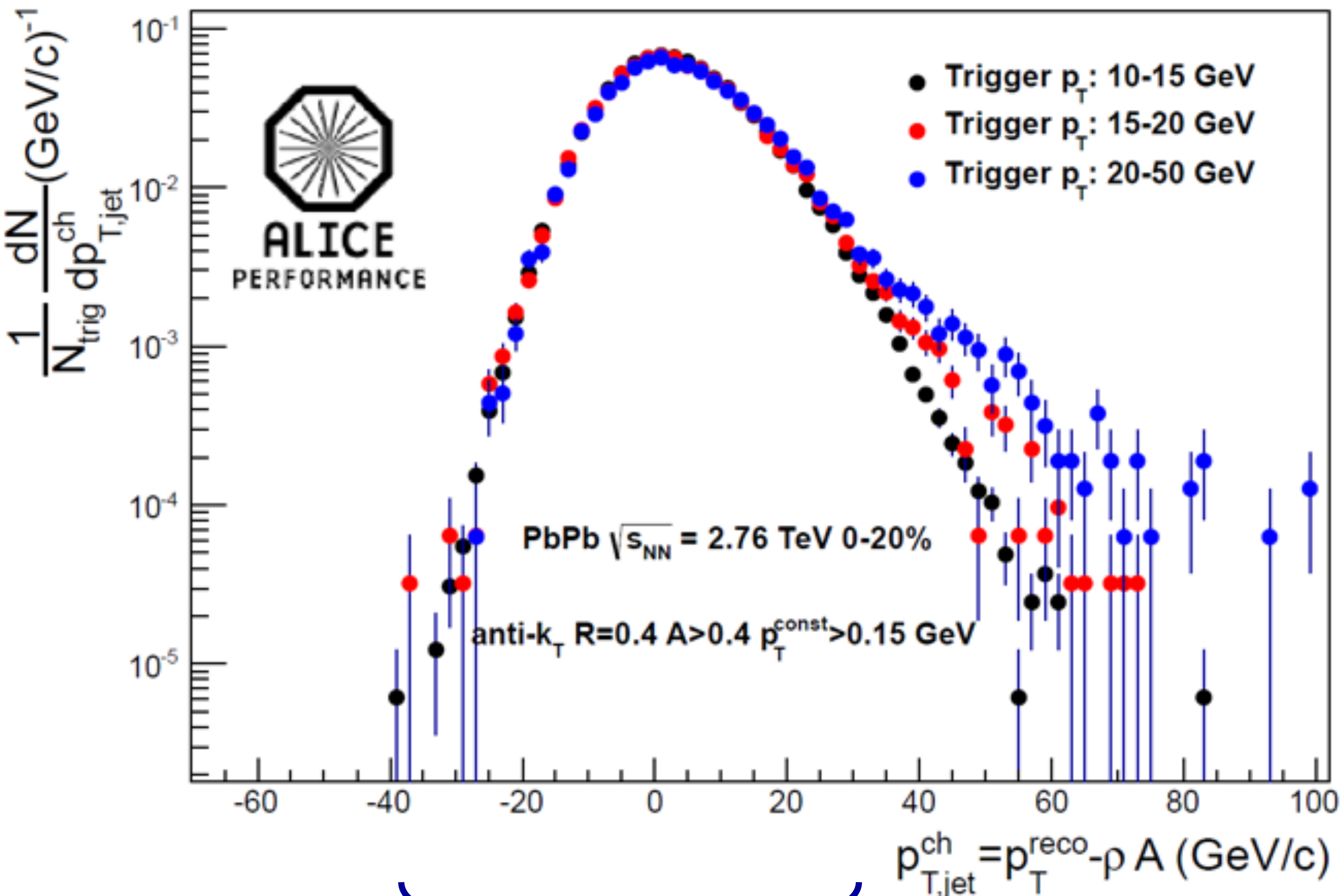
T.Renk, PRC85 064908

Biases are different! Can be exploited to constrain models

Hadron-recoil jet measurements

Hadron-triggered recoil jet distributions

G. de Barros et al., arXiv:1208.1518



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

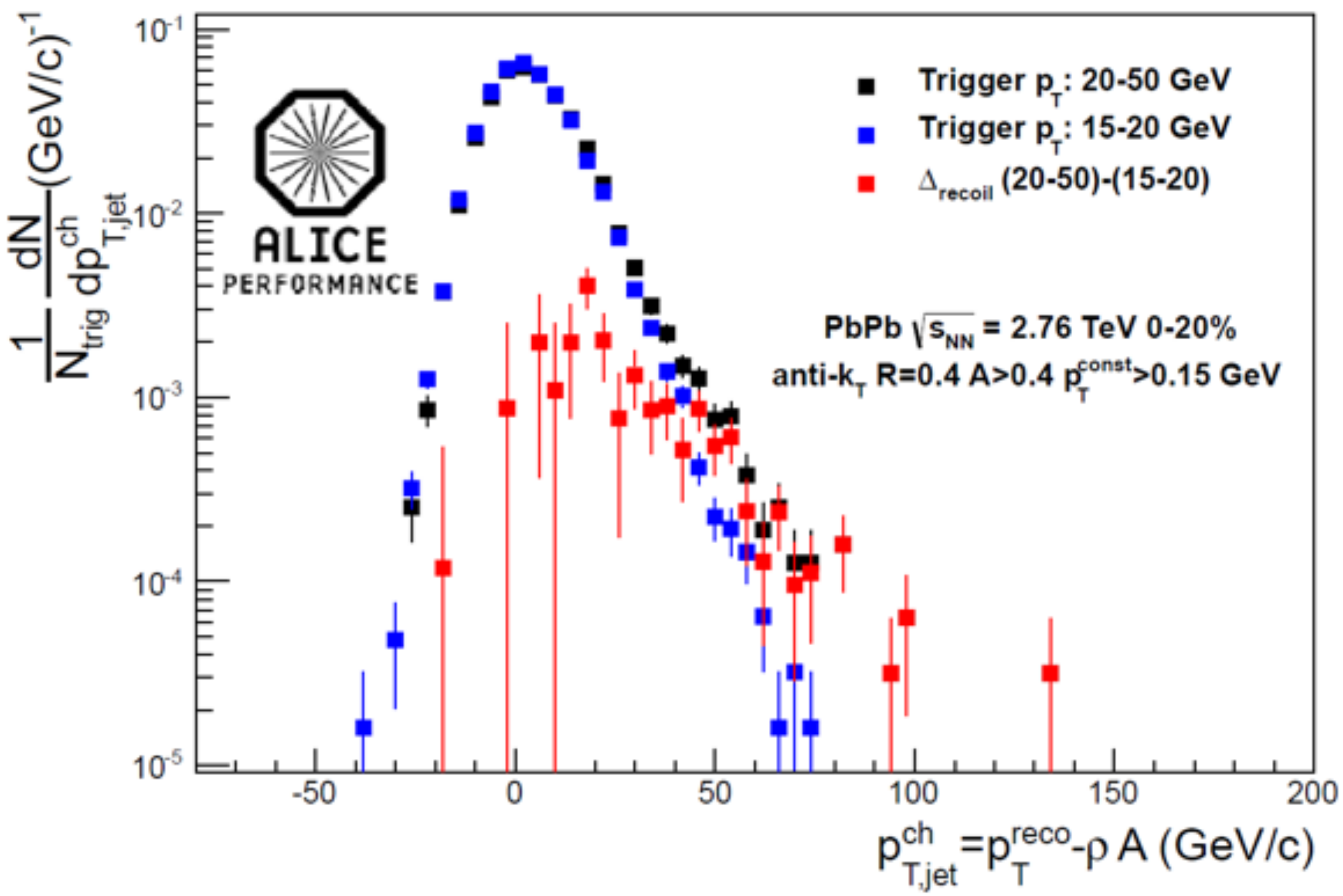
$p_{T,jet}$> 20 GeV/c:
Evolves with trigger p_T
Recoil jet spectrum

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

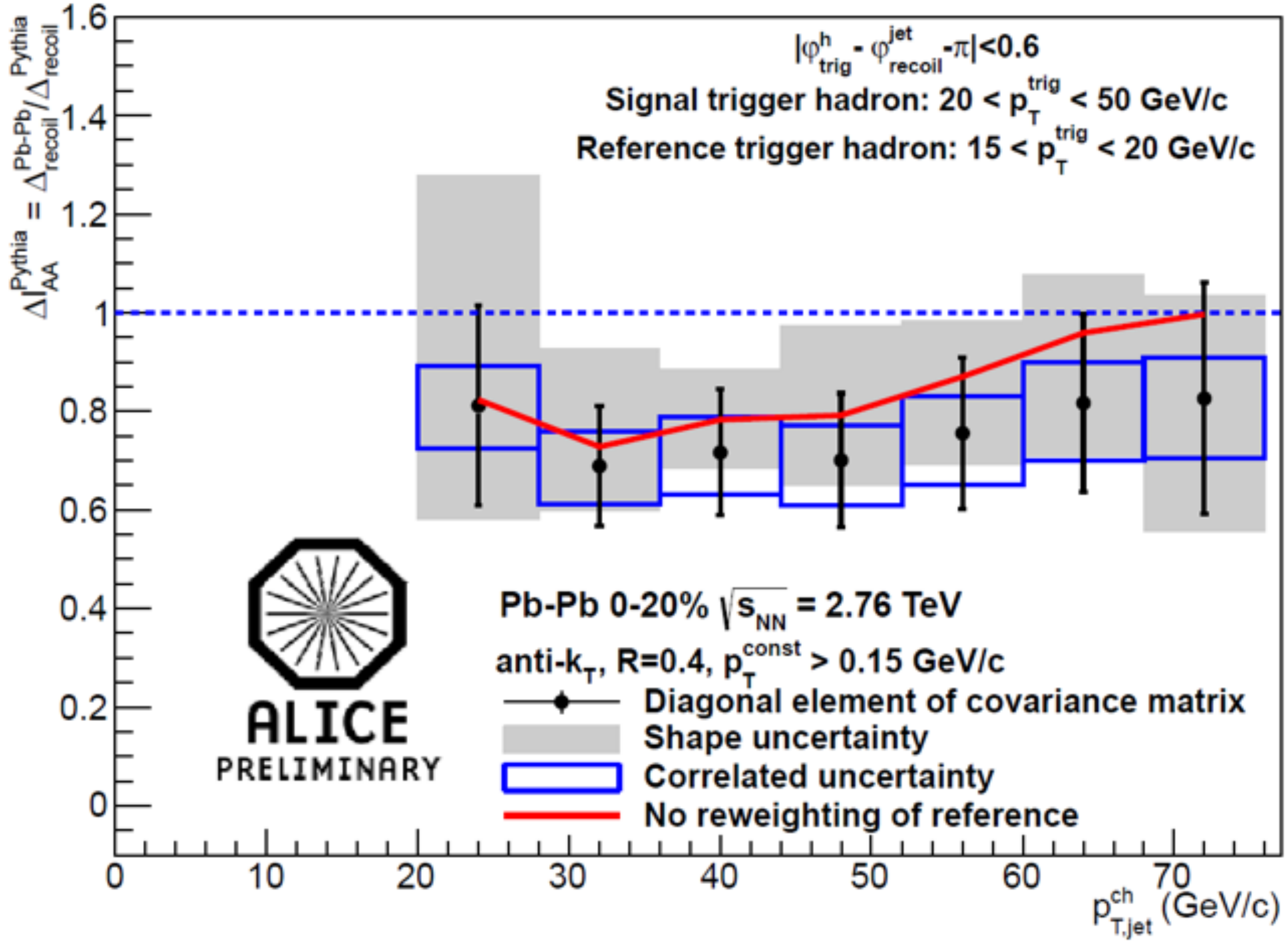
Ratio of Recoil Jet Yield ΔI_{AA}^{PYTHIA}

pp reference: PYTHIA (Perugia 2010)

R=0.4

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

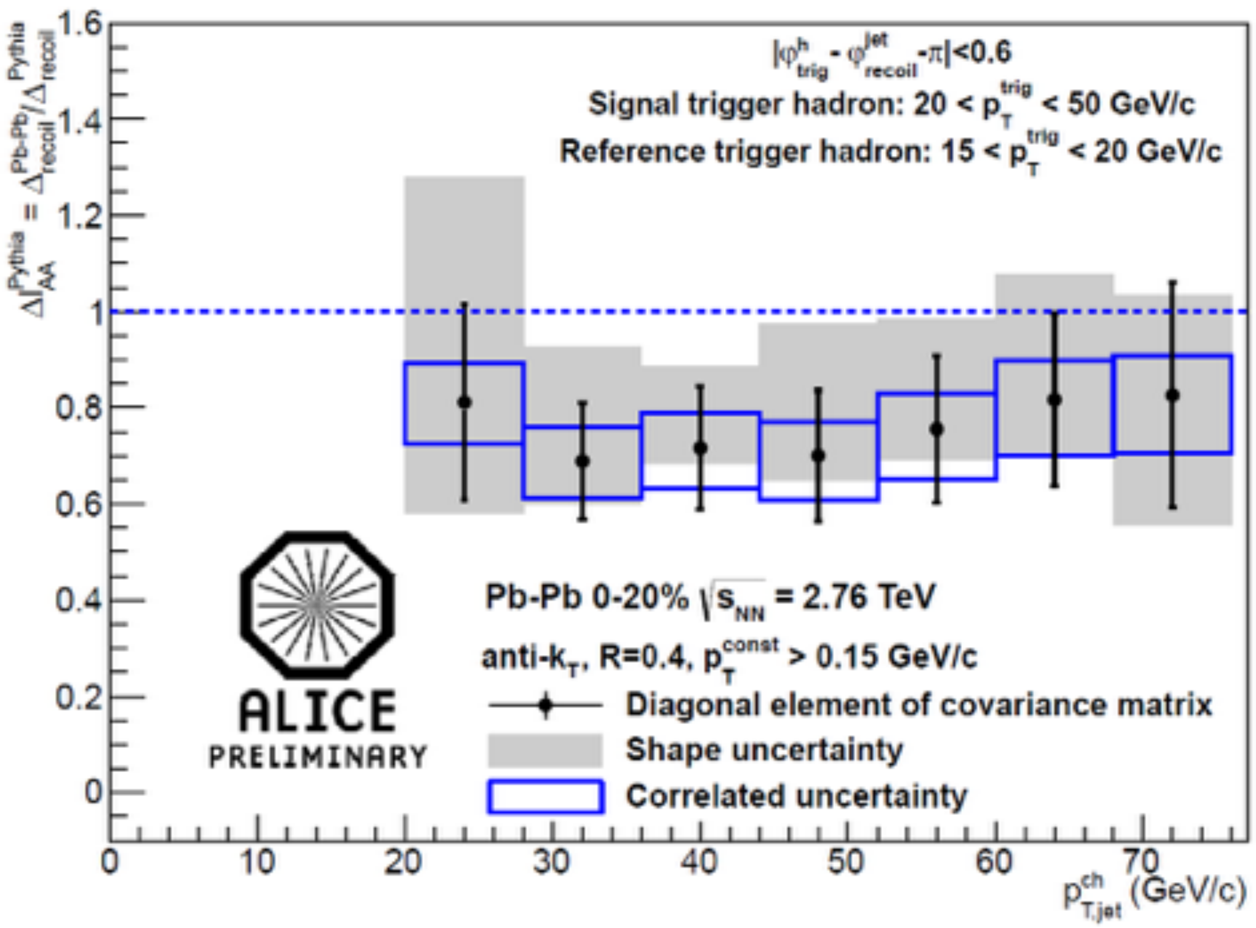
no additional cuts (fragmentation bias) on recoil jets



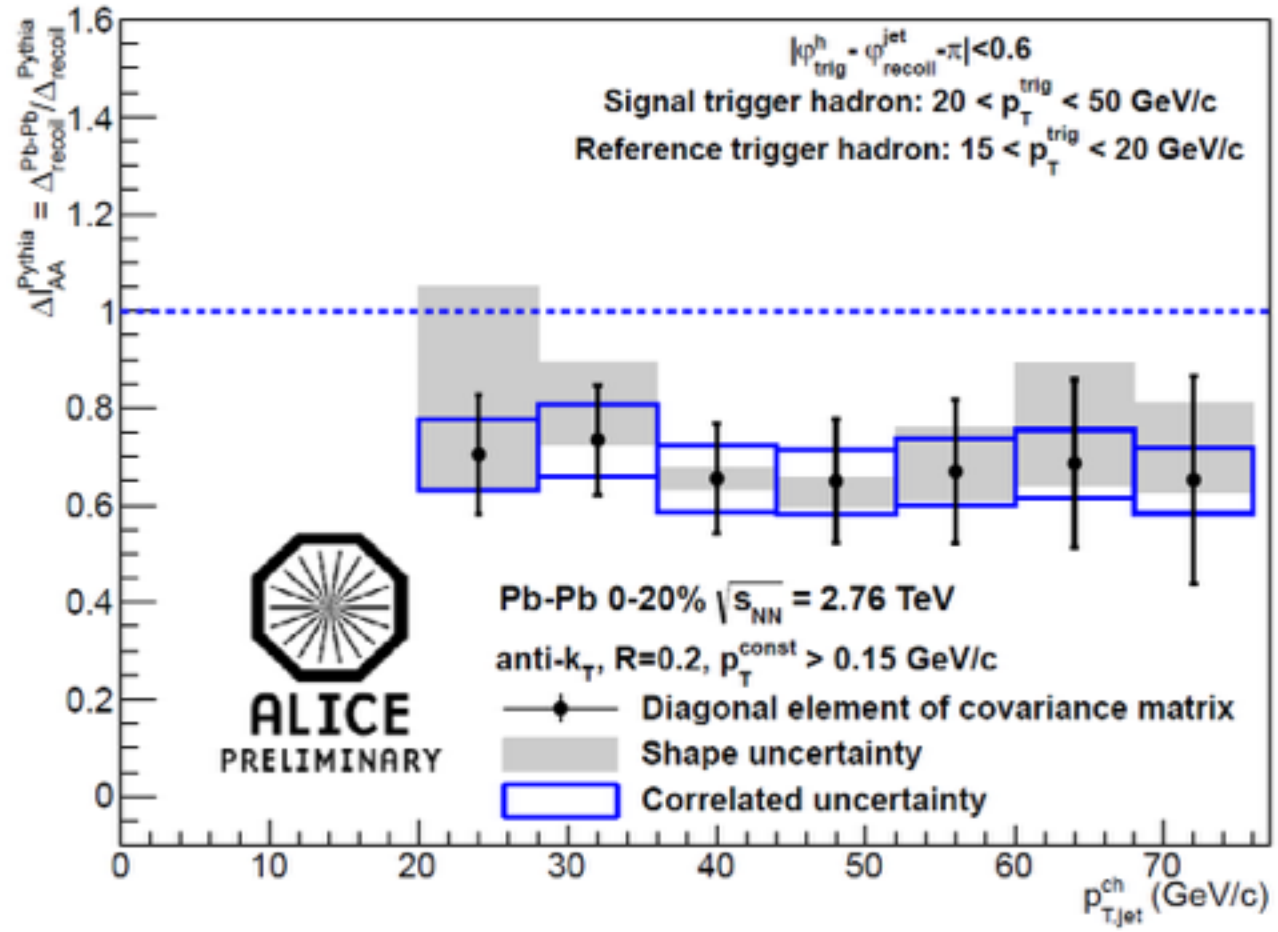
Recoil jet yield $\Delta I_{AA}^{PYTHIA} \approx 0.75$, approx. constant with jet p_T

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

R=0.4



R=0.2



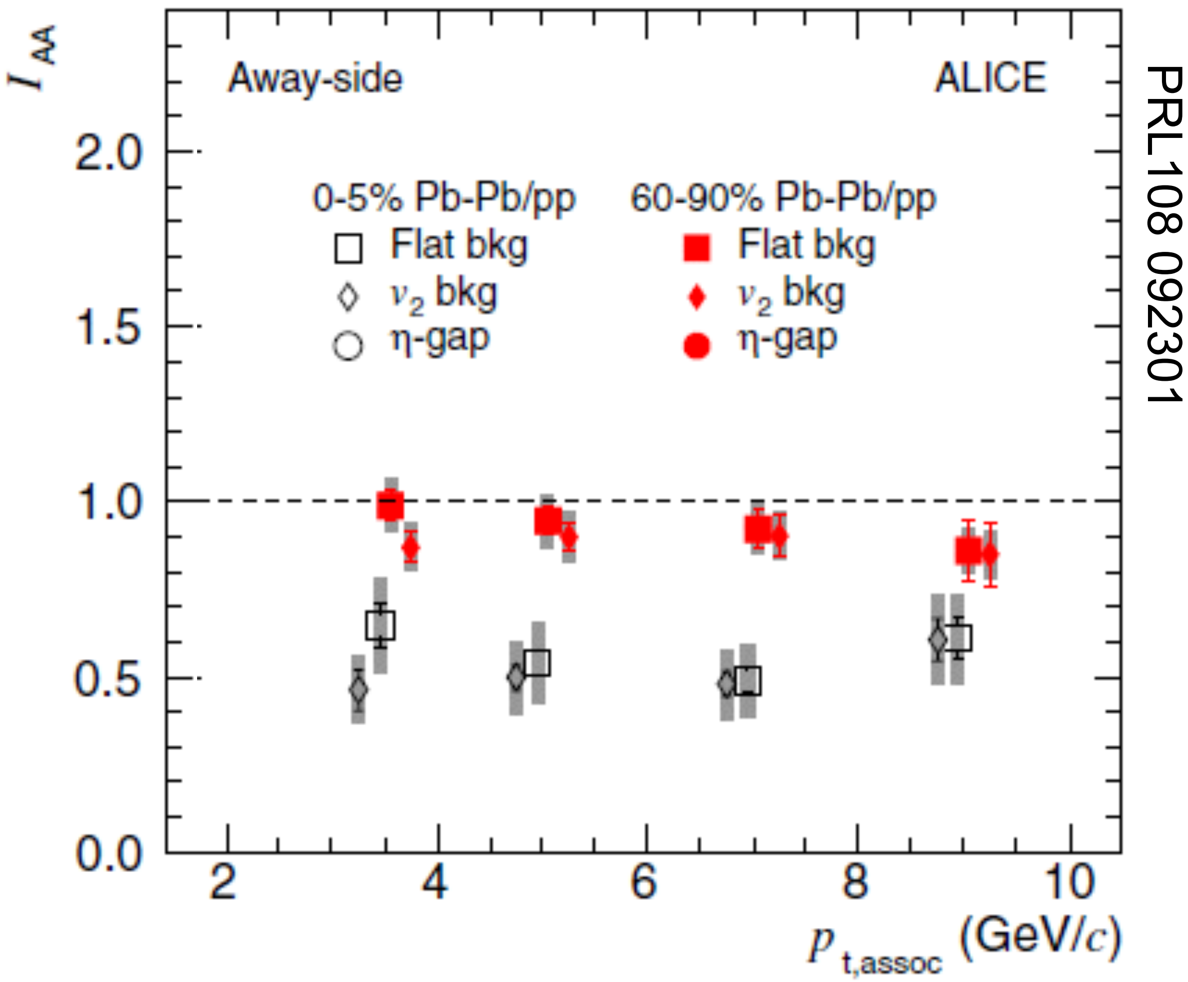
Similar ΔI_{AA}^{PYTHIA} for R=0.2 and R=0.4

No visible broadening within R=0.4

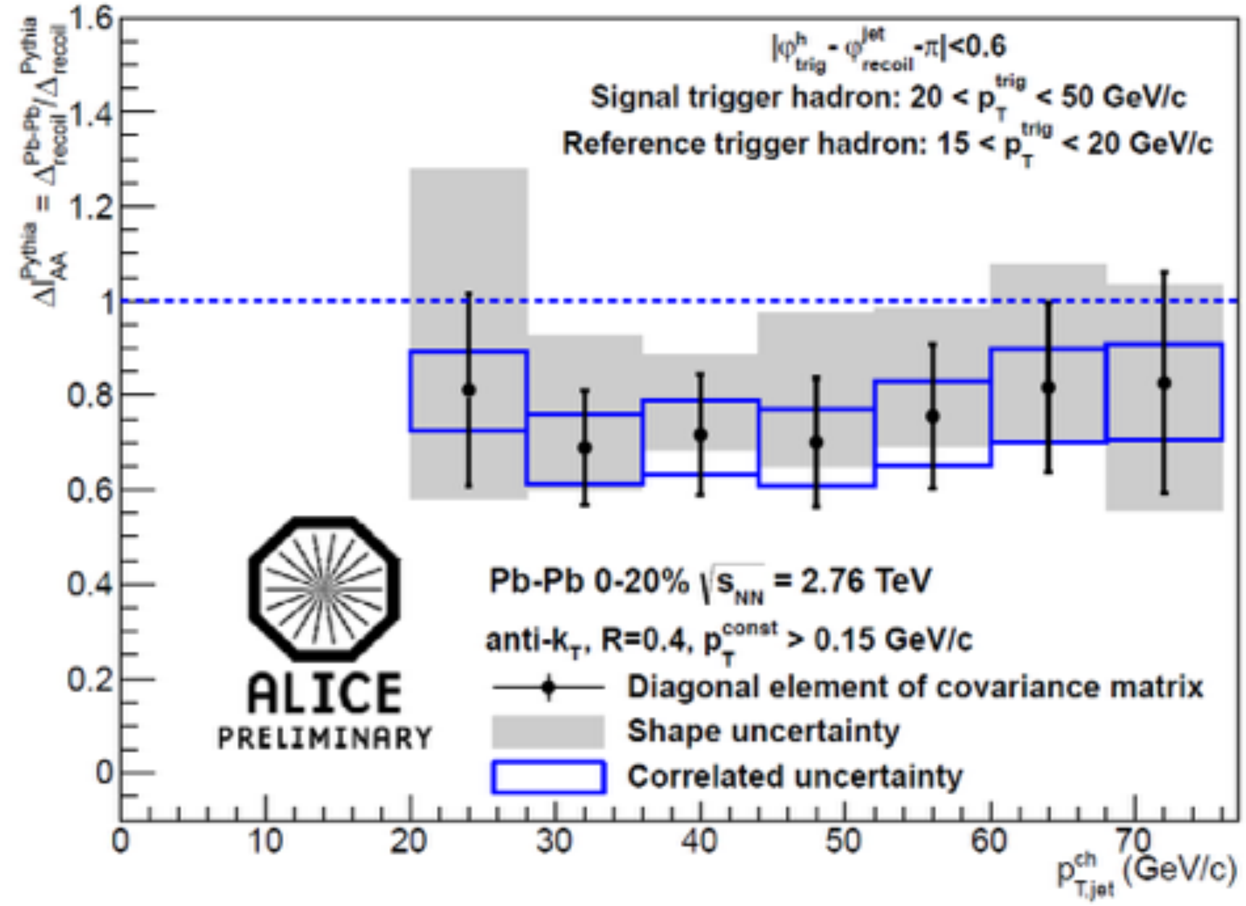
(within exp uncertainties)

Hadrons vs jets II: recoil

Hadrons



Jets



Hadron I_{AA} = 0.5-0.6

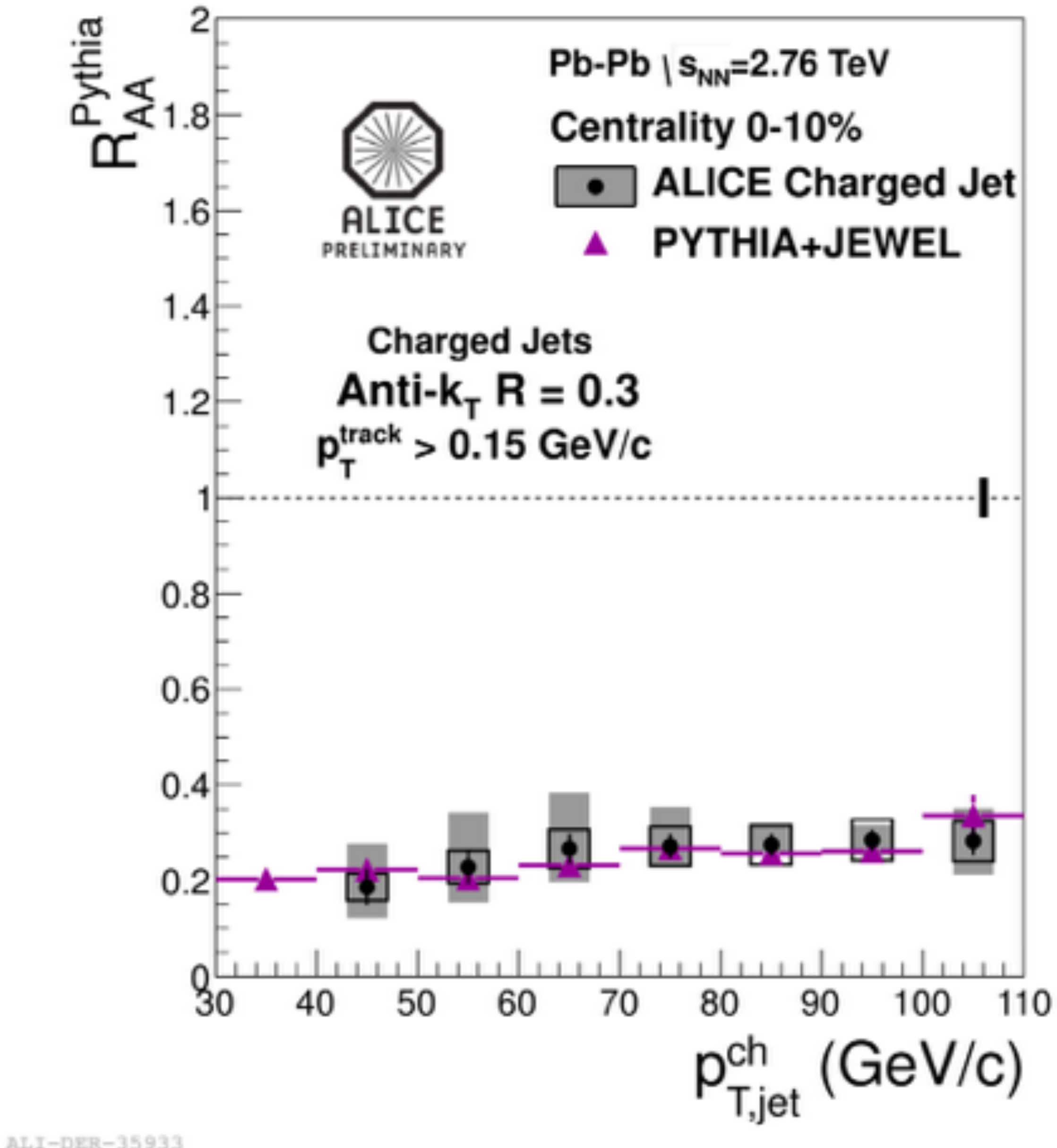
In approx. agreement with models; elastic E-loss would give larger I_{AA}

Jet I_{AA} = 0.7-0.8

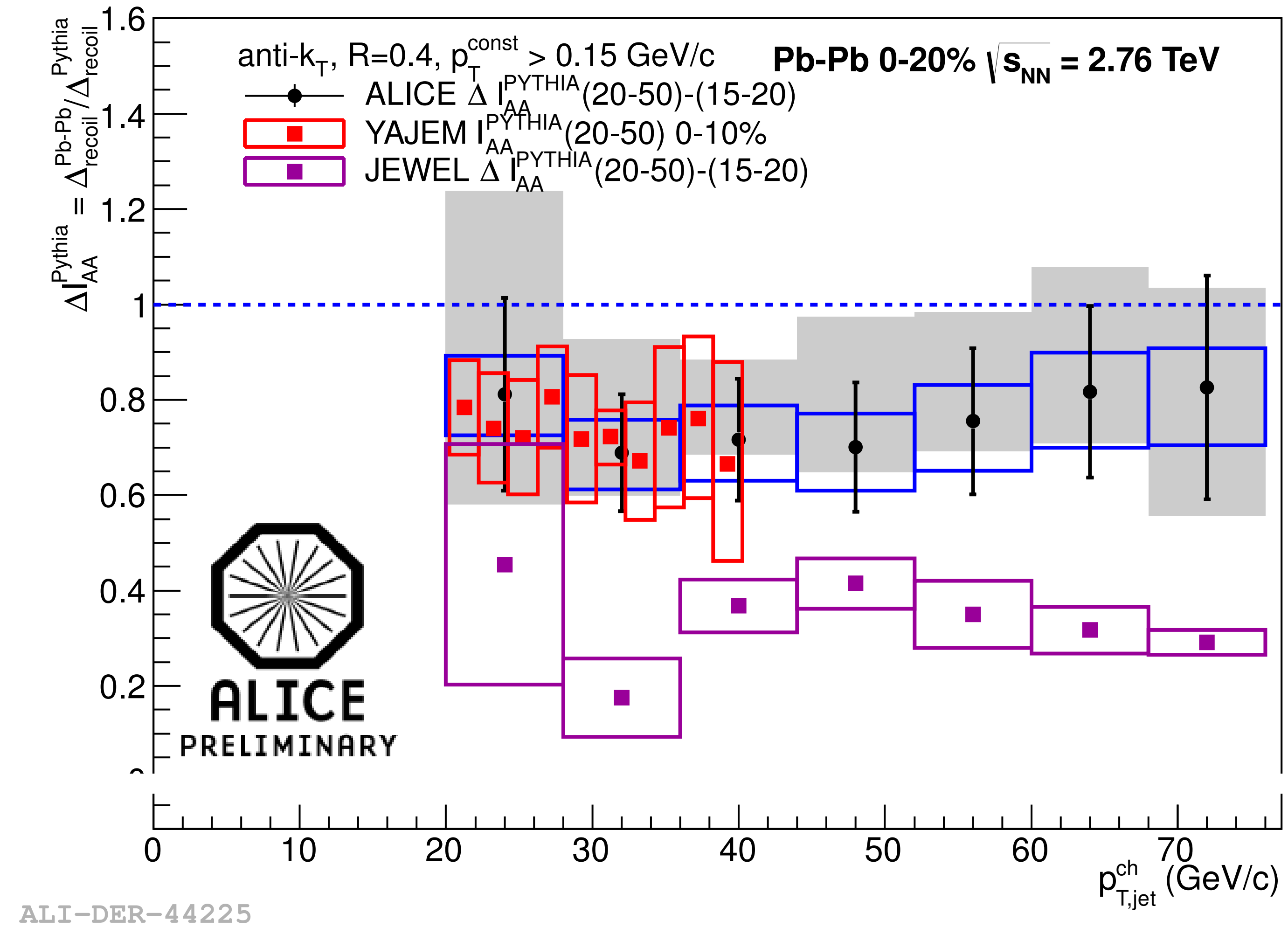
Jet I_{AA} > hadron I_{AA}
Not unreasonable

NB/caveat: very different momentum scales !

Model comparison I_{AA}



JEWEL: Zapp et al., EPJ C69, 617



JEWEL correctly describes inclusive jet R_{AA}

JEWEL ΔI_{AA}~0.4, below measured

YAJEM agrees with measurement

Difference in energy loss or geometry?

Summary

- Jets: a 'new' tool for parton energy loss measurements
  - Large out-of-cone radiation (R = 0.2-0.4)
    - Energy asymmetry
    - $R_{AA} < 1$, similar to hadrons
    - $I_{AA} < 1$
    - Radial shapes
  - Remaining jet has small modifications:
    - Longitudinal and transverse structure similar at small r, large z
    - Deviations at large r, low z
  - Most of the radiation is at low p_T
    - Scale set by medium temperature?
    - Democratic branchings?

Interplays of many effects: impossible to read simple conclusions off the plots

Need (detailed) calculations to draw conclusions

e.g. JEWEL and YaJEM energy loss MCs agree
with many of the observed effects

Does this constrain the energy loss mechanism(s)?

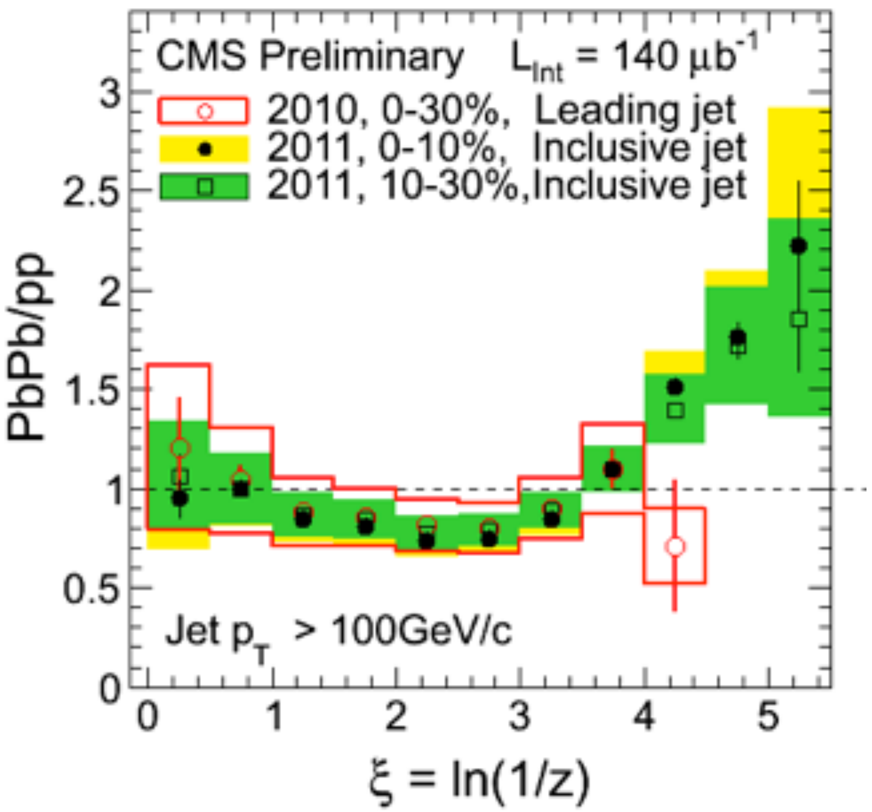
Ongoing work…

Extra slides

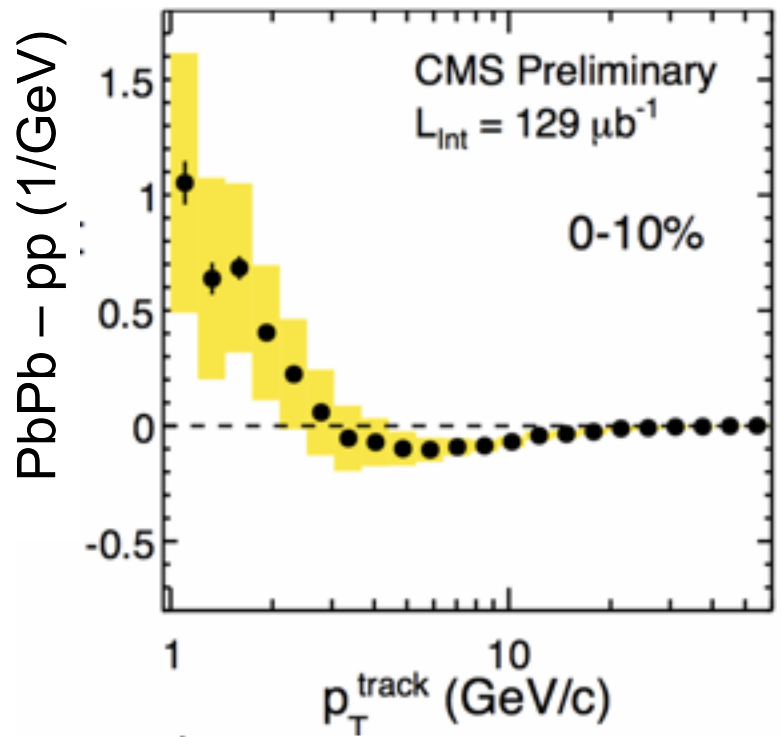
A consistent view of jet quenching

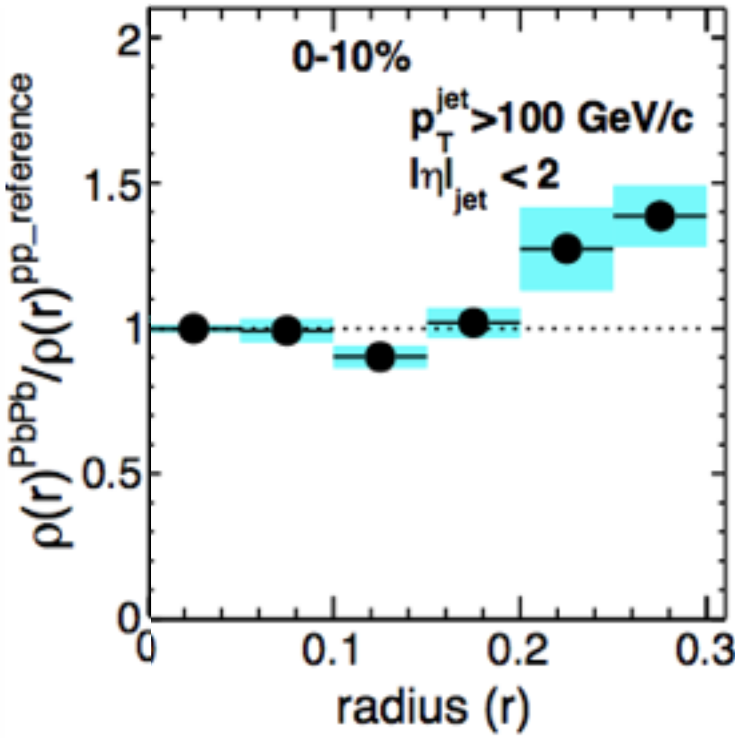
G. Roland@QM2012

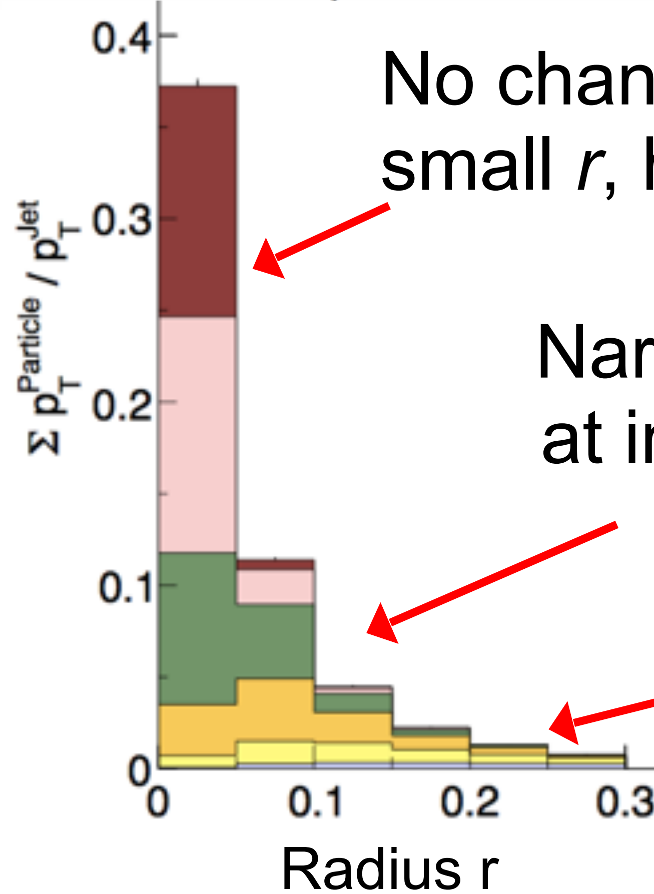
arXiv:1205.5872



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)

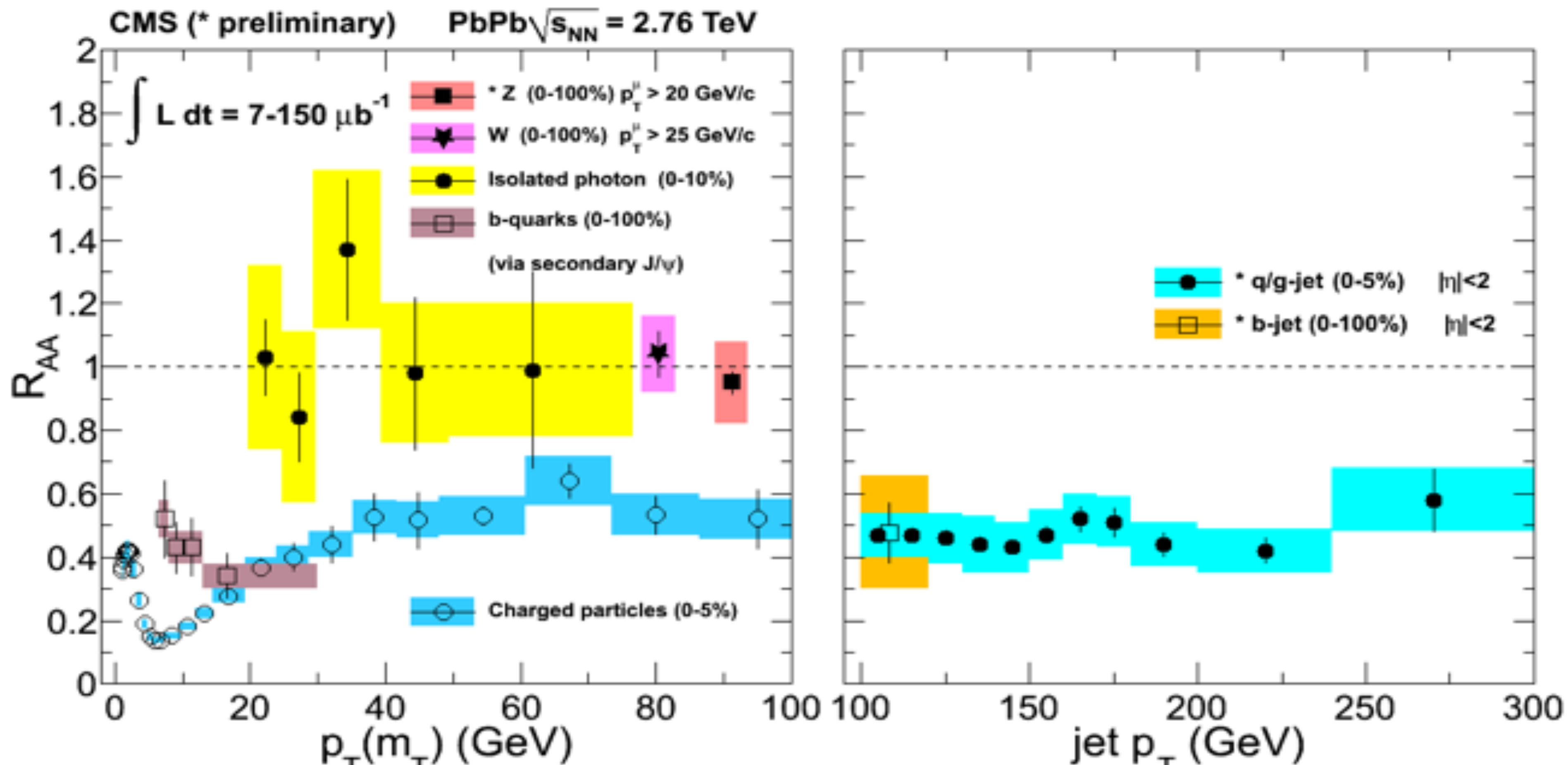
Consistent with 2010 result

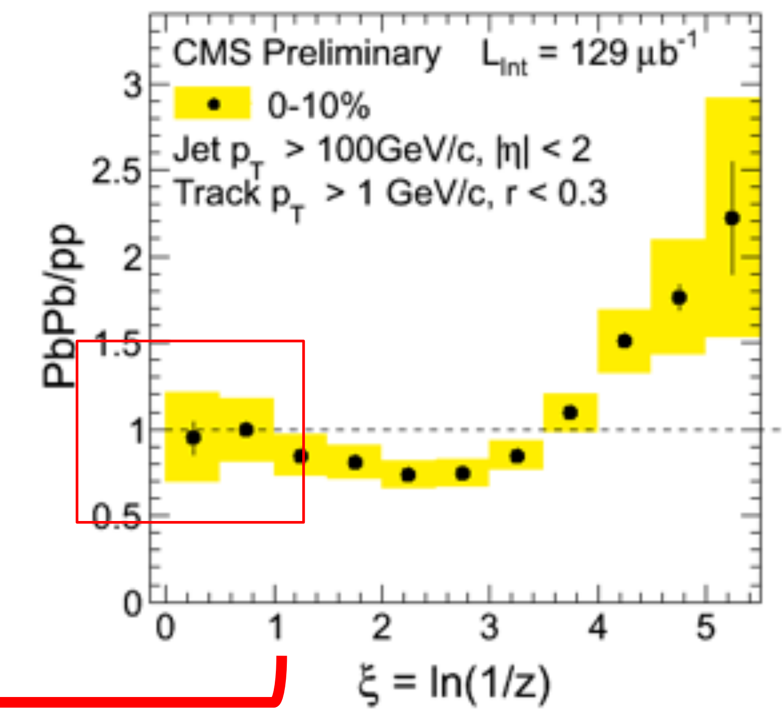
Recall (2010 vs 2011):

- 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

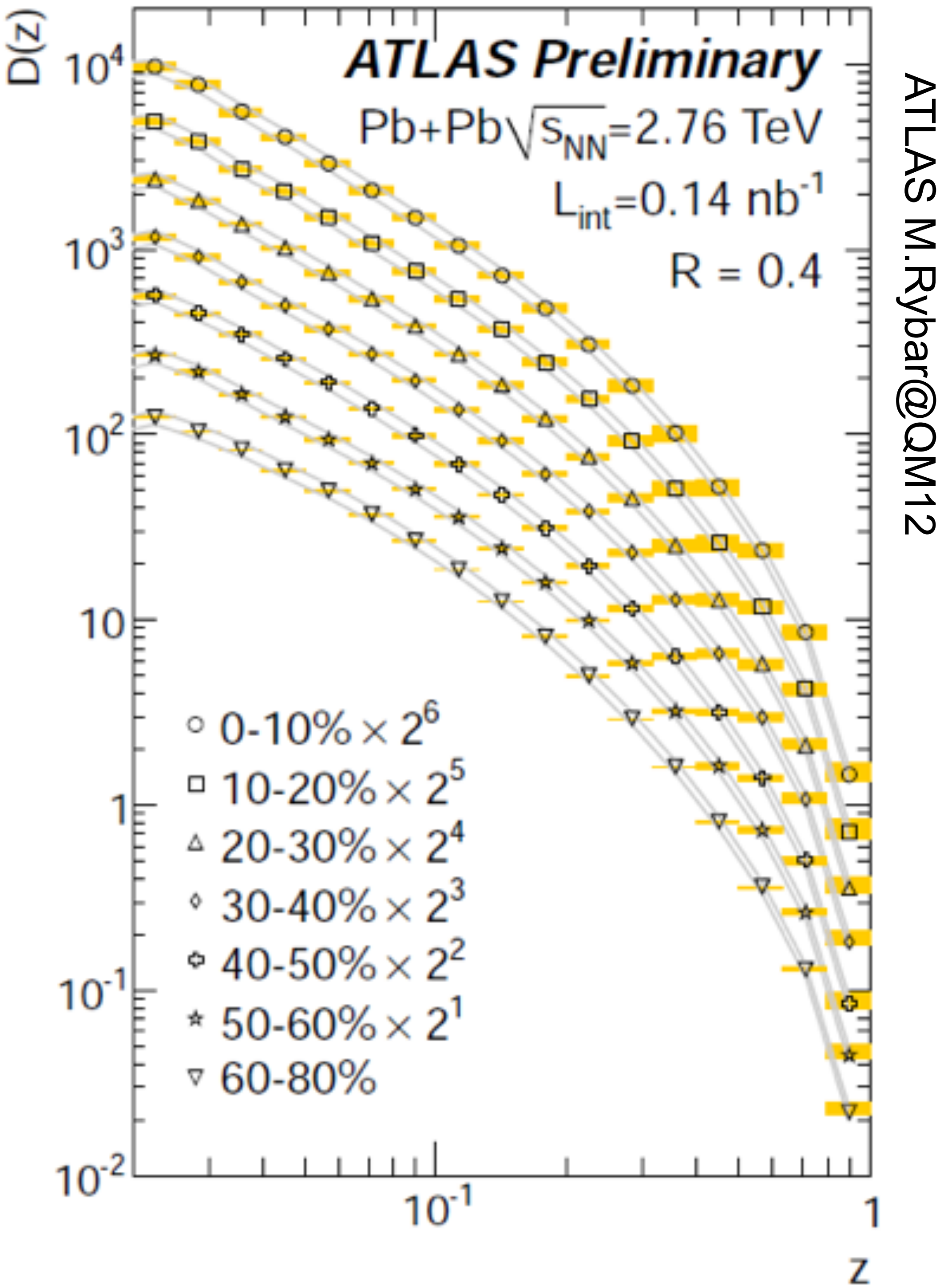
Charged particles from p_T =50-100 GeV:
z = p_T(track)/p_T(jet) = 0.4-0.6
→ ξ < 1

PbPb fragmentation function = pp for ξ <1

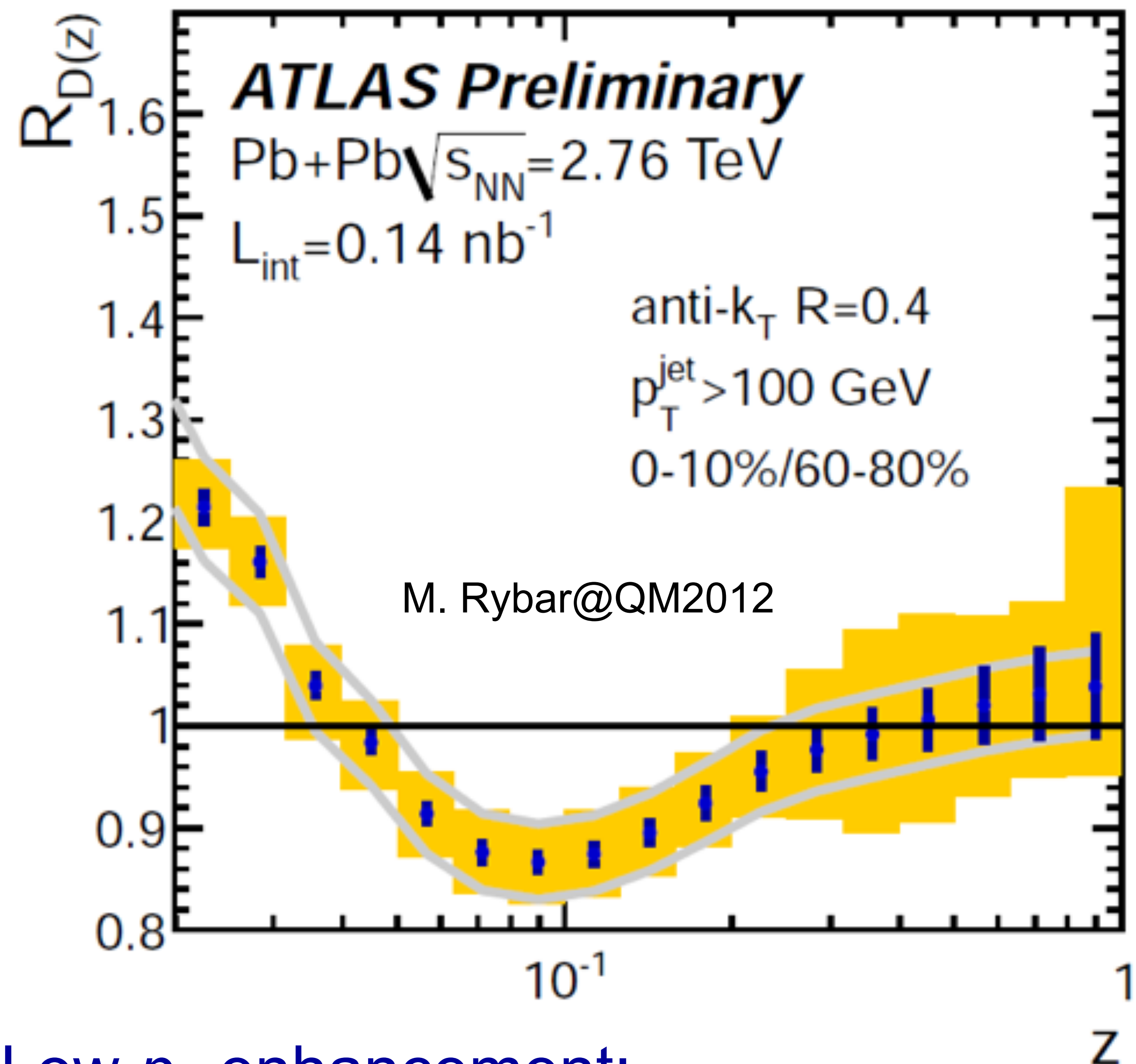
Consistent message from charged hadron R_{AA}, inclusive jet R_{AA} and fragmentation functions!

Jet fragment distributions

PbPb measurement



Ratio to pp



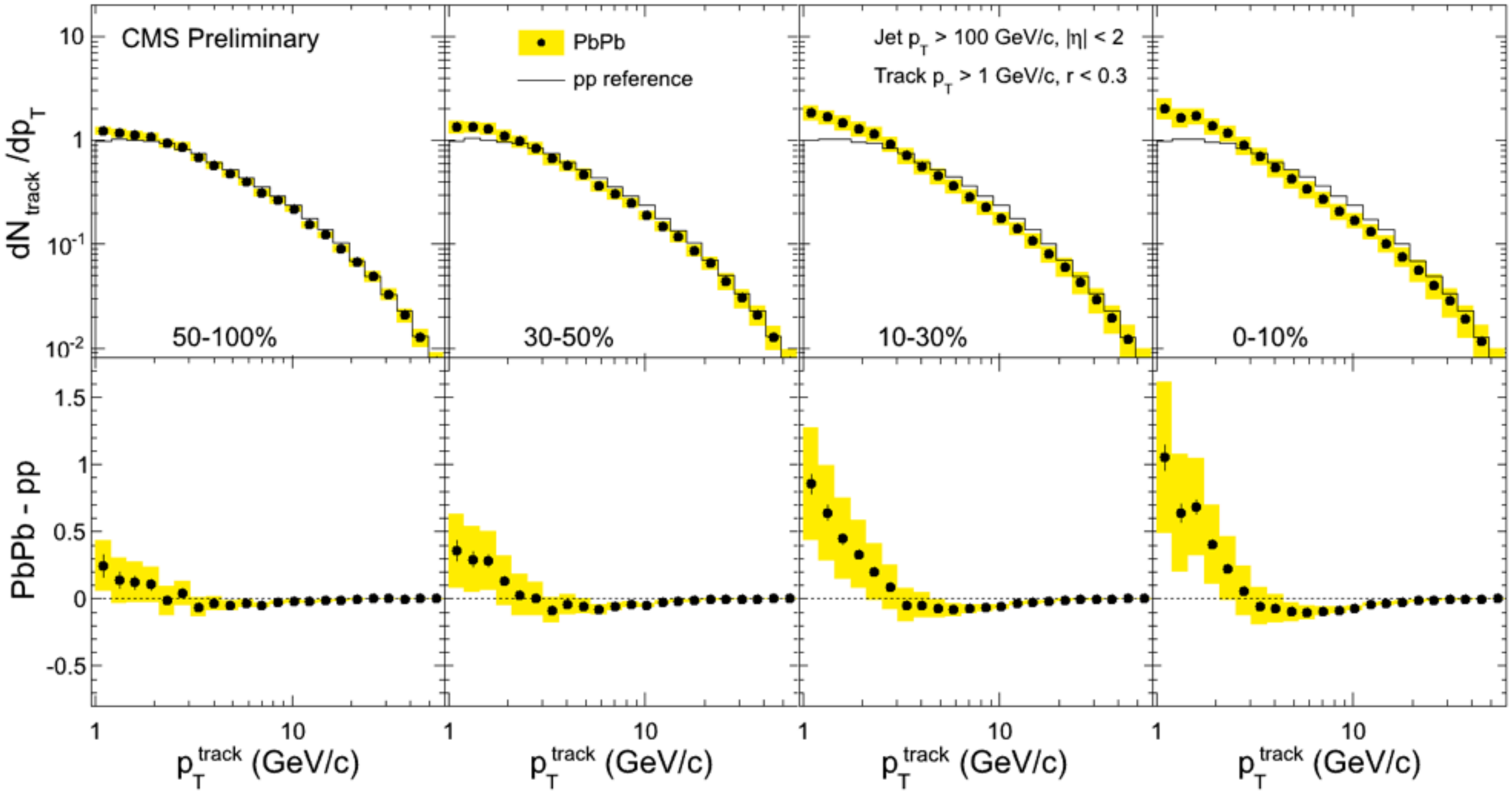
Low p_T enhancement: soft radiation

Intermediate z: depletion: E-loss

NB: z is wrt *observed* E_{jet} ≠ initial E_{parton}

Jet fragment distributions

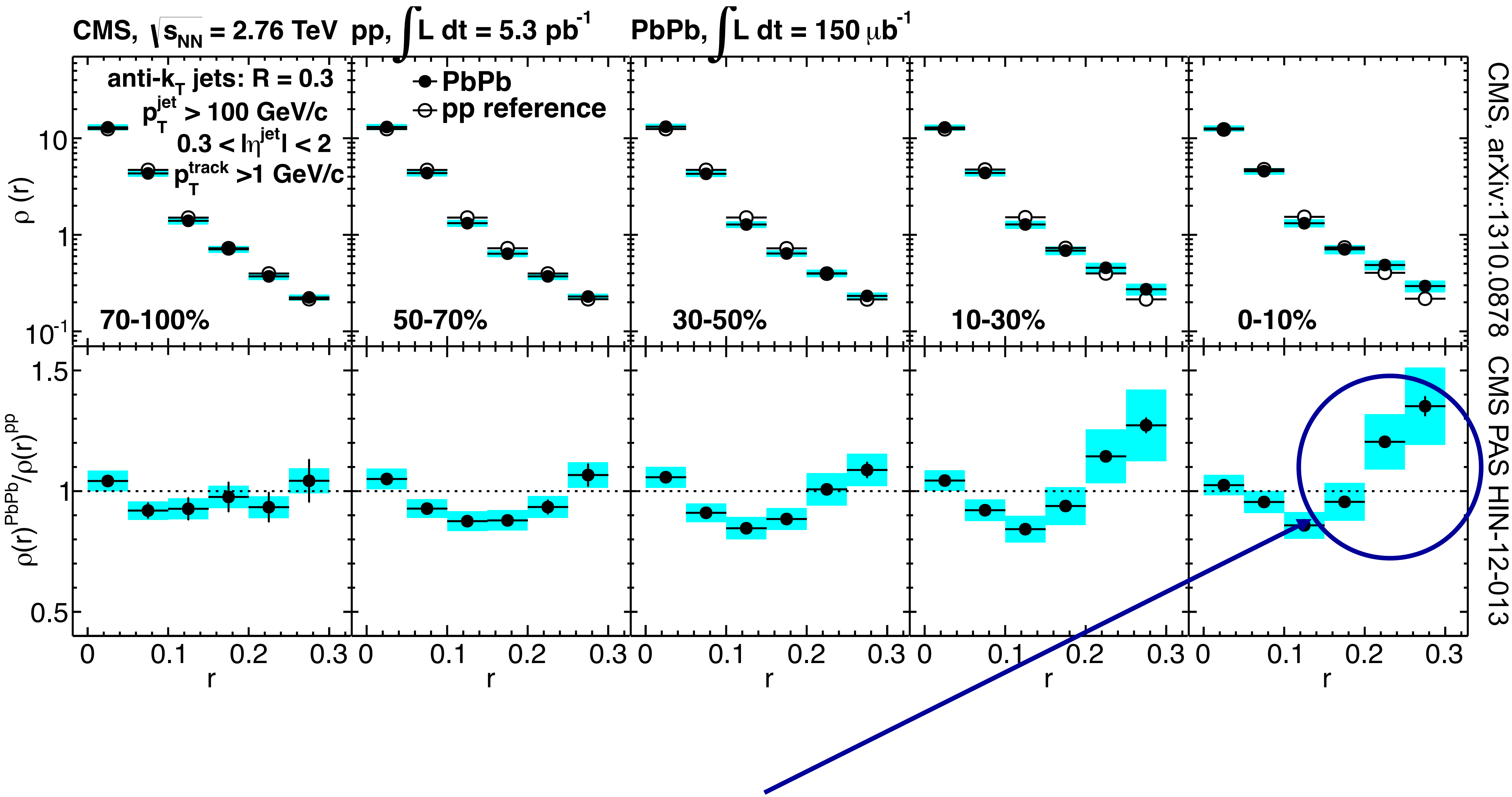
CMS, Frank Ma@QM12

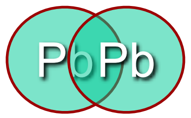


Low p_T enhancement: soft radiation

Intermediate z, p_T: depletion: E-loss

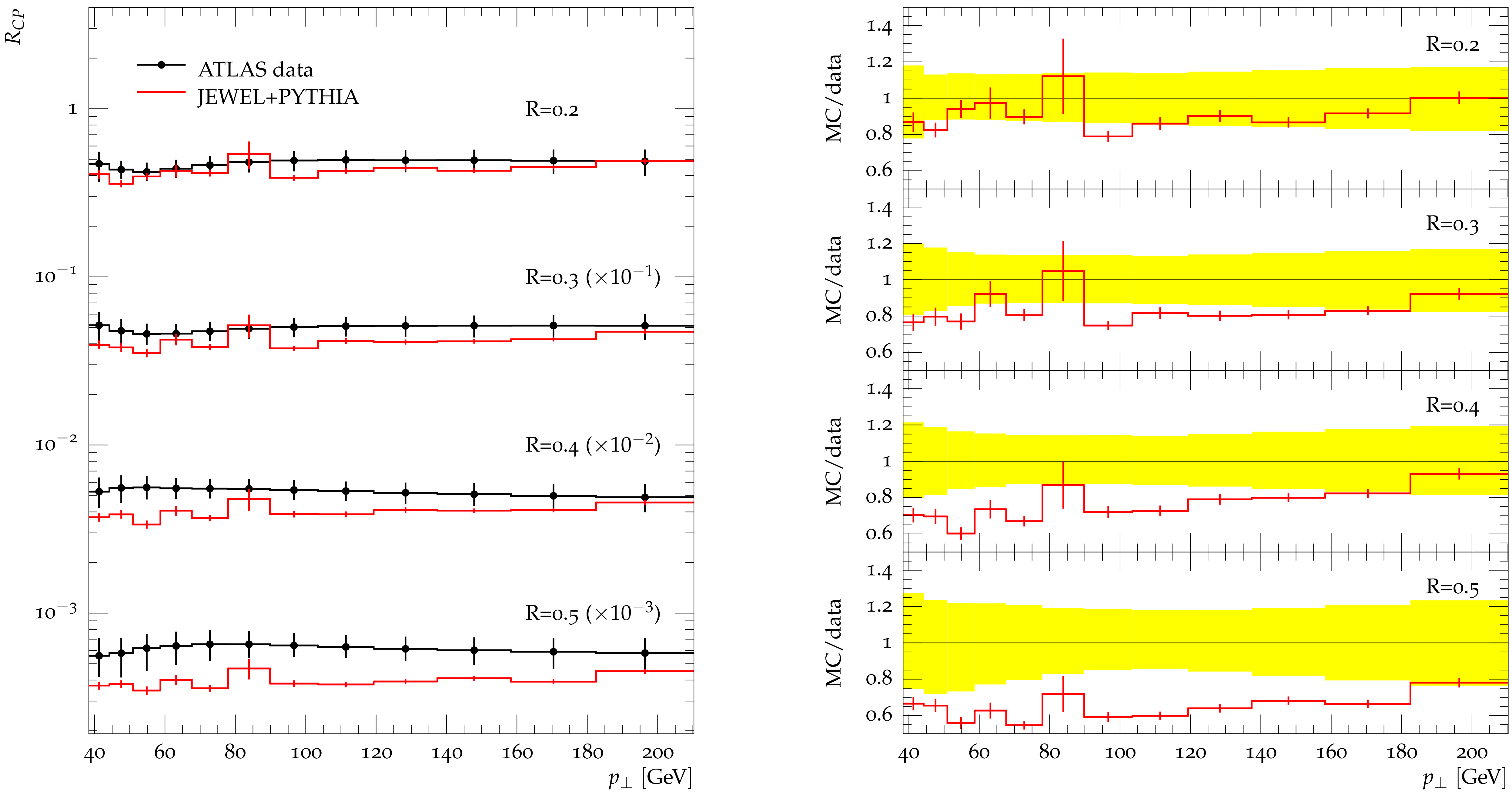
Jet broadening: transverse fragment distributions





Jet broadening: radiation at large angles

Comparing to JEWEL energy loss MC



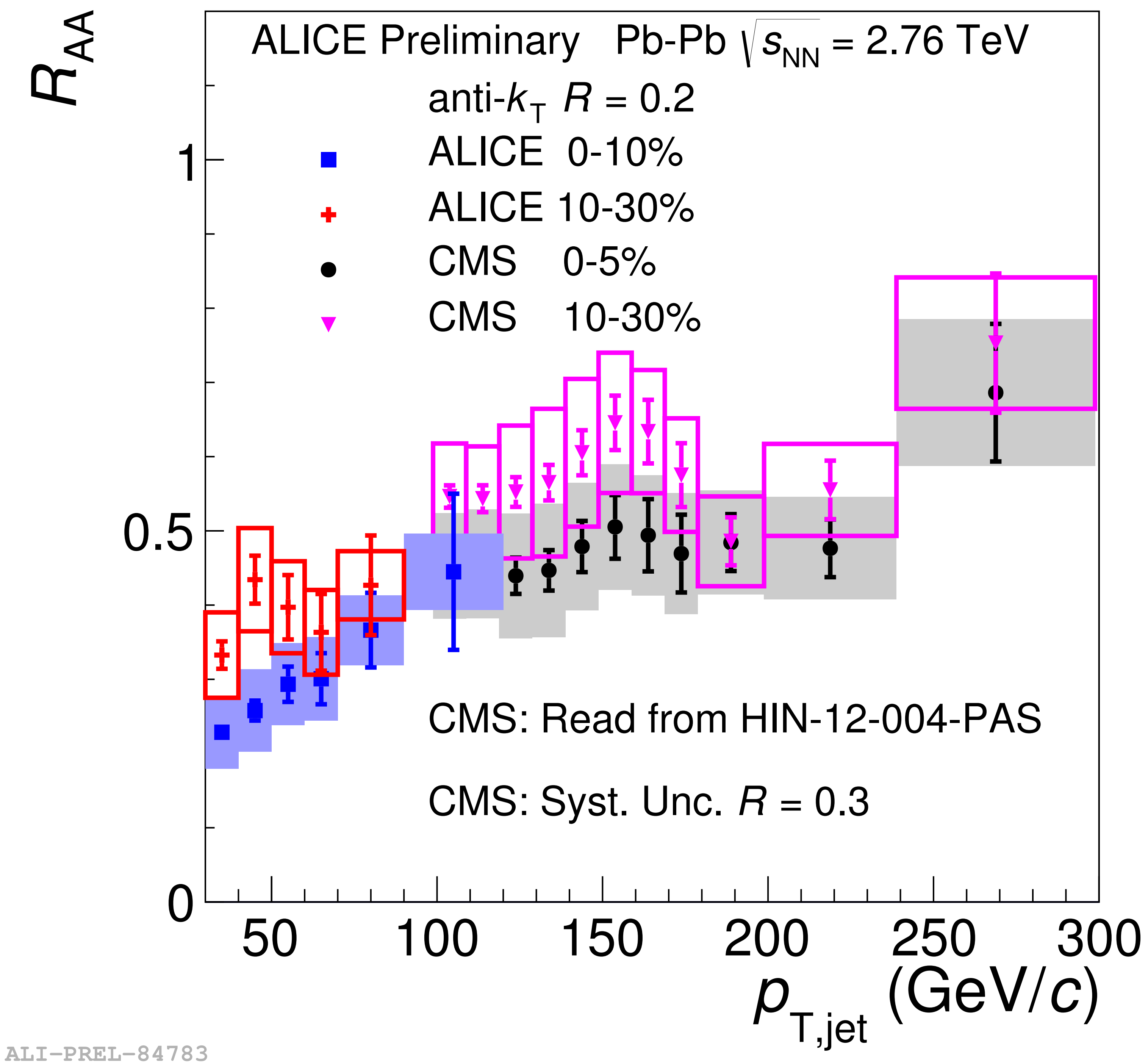
K. Zapp et al, arXiv:1212.1599

JEWEL gets the right suppression for R=0.2,

but not the increase with R

May be treatment of recoil patrons

Full jet comparison



Good agreement between experiments; hint of p_T dependence