Experimental Brainstorm*:
Opportunities and Challenges
in Jet Measurements

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Workshop on Opportunities and Challenges with Jets at LHC and Beyond
Institute of Particle Physics, Central China Normal University, Wuhan, June 9-12, 2018

***Brainstorm:**
- A moment in which one is suddenly unable to think clearly or act sensibly.
- A spontaneous group discussion to produce ideas and ways of solving problems.
- A sudden clever idea.

Brainstorming: the art of converting phantasy to reality …

Mini-Workshop on Jet Physics in ALICE at the LHC - Run II

Wuhan April, 14-16, 2015

Experimental Brainstorm:
What can be addressed using jet measurements ?

Andreas Morsch
CERN

Mini-Workshop on Jet Physics in ALICE at the LHC - Run II
Wuhan, April 14-15, 2015

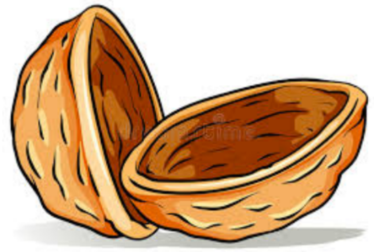
1

Brainstorming roles

- The Dreamer - me
- The Realists - physics coordination / conveners
- The Critics - everybody else

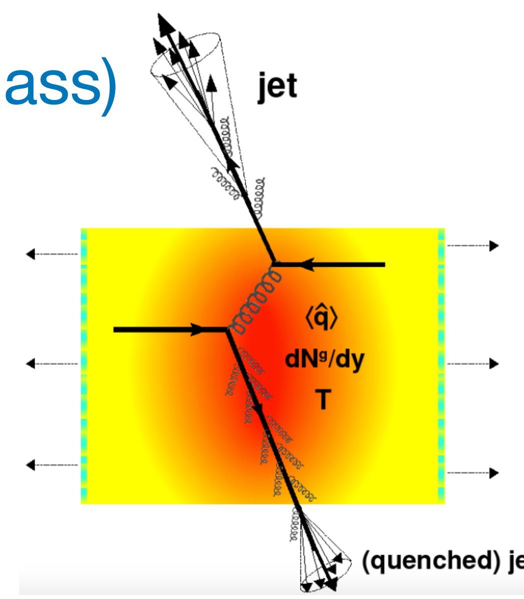
2

Actually, quite a few of the dreams of the last workshop became true …
… a good omen !?

Jets in AA in a 

Self generated probes of the medium …

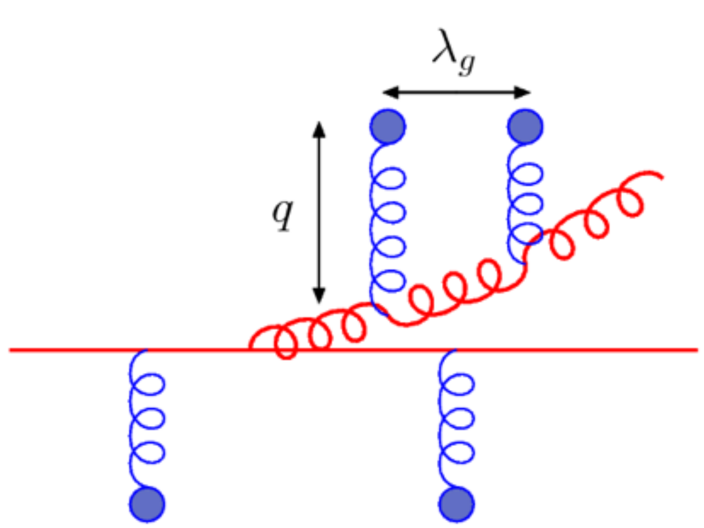
- High p_T partons produced at early stage (« 1 fm) of the collision
- Parton from initial scattering produced with large virtuality (related to jet mass)
- Loses virtuality in partonic shower
- Loose energy through
  - elastic scatterings
  - induced gluon radiation (dominant at high p_T)
- Jets probe medium on different scales (parton p_T - hadronisation scale)



Example BDMPS

$$\Delta E_{\rm rad} \sim \alpha_s C_R \hat{q} L^2 f(E,m) \qquad C_R = \begin{cases} 4/3 & quarks \\ 3 & gluons \end{cases}$$

$$\hat{q} = \frac{\langle p_T{}^2 \rangle}{\lambda} \text{ (transport parameter)}$$



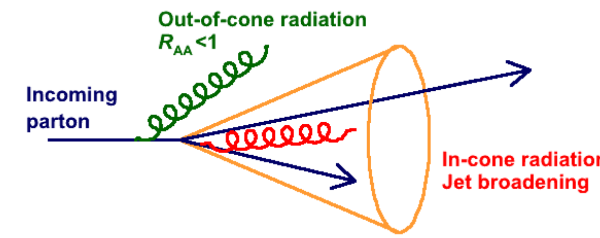
Rich phenomenology …

- Change of rate (R_{AA})
- Expect $\Delta E_{\rm gluon} > \Delta E_{\rm quarks} > \Delta E_{\rm heavy\ quarks}$ (dead cone effect)
- Change of longitudinal and transverse jet structure
- Path length dependence
- Back-reaction of the medium
- di-jet azimuthal de-correlation
- …

Jets Physics in A-A: The (very) early dreams

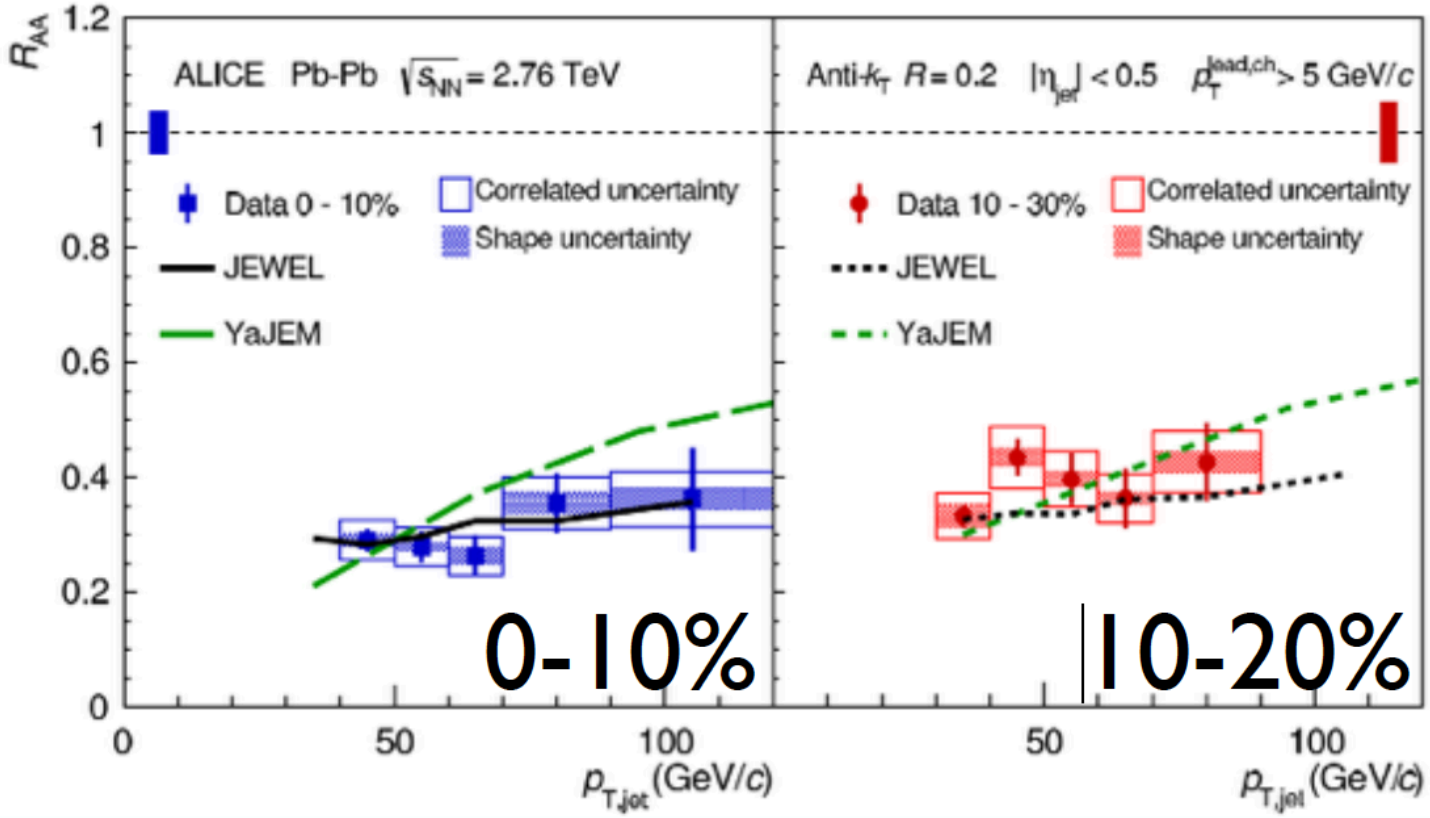
- **Dreamer:** Jets are robust objects, energy (including radiated) contained in jet cone: $R_{AA} \simeq 1$
  - relation to initial parton energy is the same in pp and Pb-Pb
  - details of energy loss can be studied by changes in longitudinal and transverse jet-structure
- **Spoiler:** possibly substantial out-of-cone radiation !!
- **Realist:** learn how to reconstruct jets above the large fluctuating background in heavy ion collisions and measure …

R_{AA} (Run1)

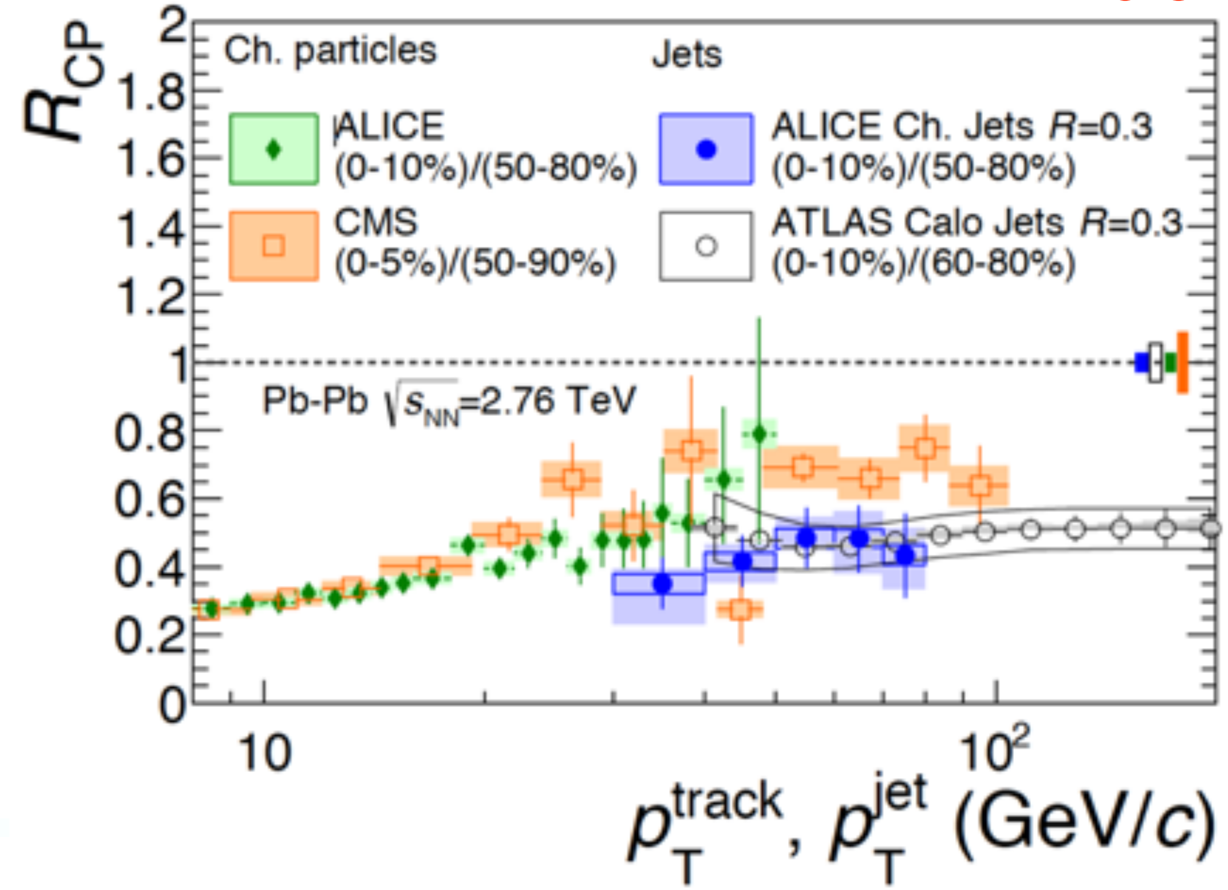


From Wuhan'15 Jet WS

R=0.2



R=0.3

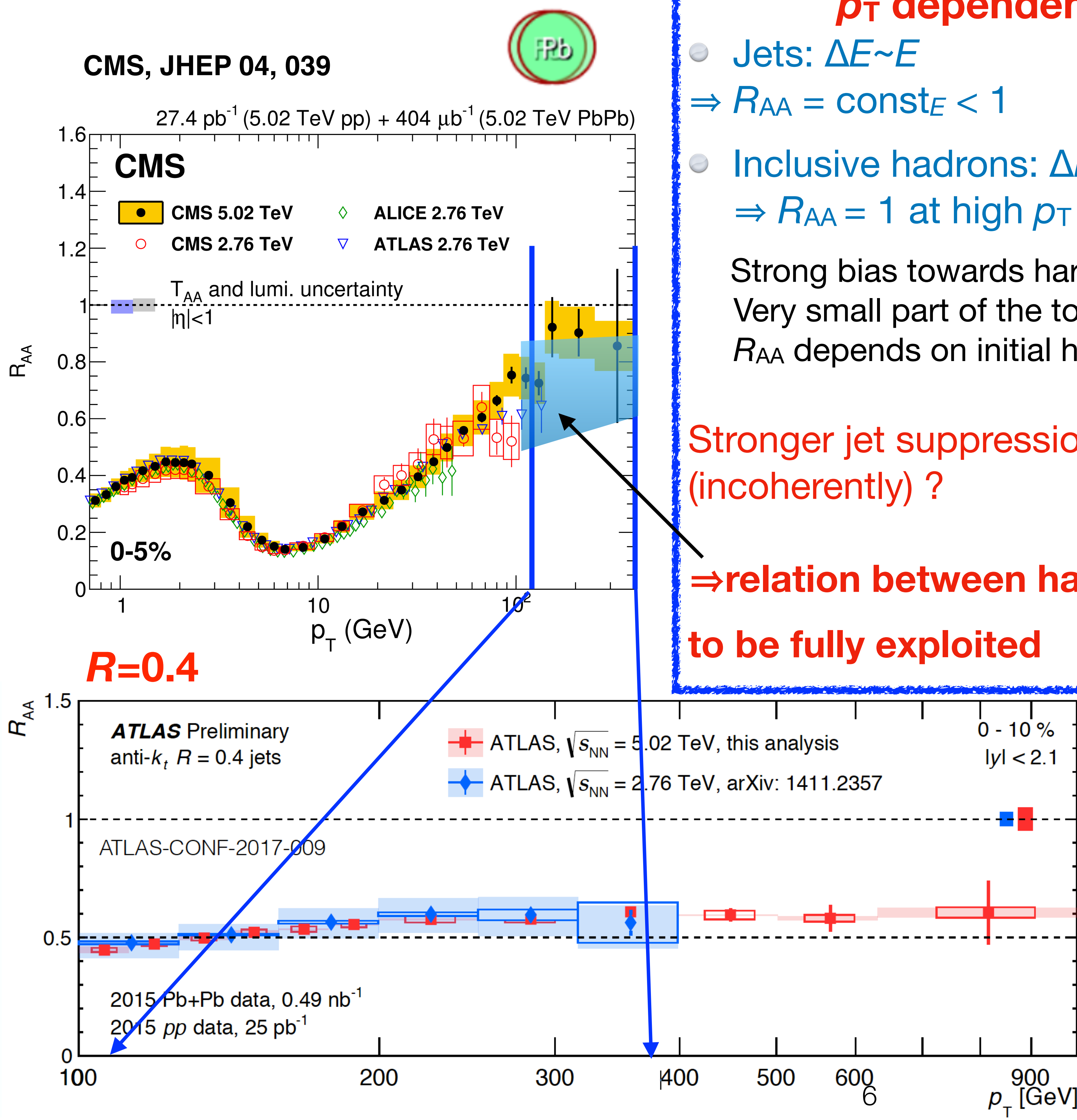


- Strong jet suppression: $R_{CP,Jet}$ = 0.3 - 0.45 slowly rising with $p_{T,jet}$
- For fixed p_T^{jet}, jets in Pb-Pb originate from larger parton p_T

- Jet suppression similar to inclusive hadron suppression at comparable parton p_T.
- Possible scenario:
  - Radiated energy mainly outside jet cone.
  - Leading particle p_T shifted in proportion to its contribution (z_L) to the jet energy

$$\Delta E_{leading} = z_L \, \Delta E_{part}$$

Inclusive Hadron and Jets R_{AA} (Run2)



p_T dependence of R_{AA} consistent with:

- Jets: $\Delta E \sim E$

$\Rightarrow R_{AA} = \text{const}_E < 1$

- Inclusive hadrons: $\Delta E = \text{const}_E$

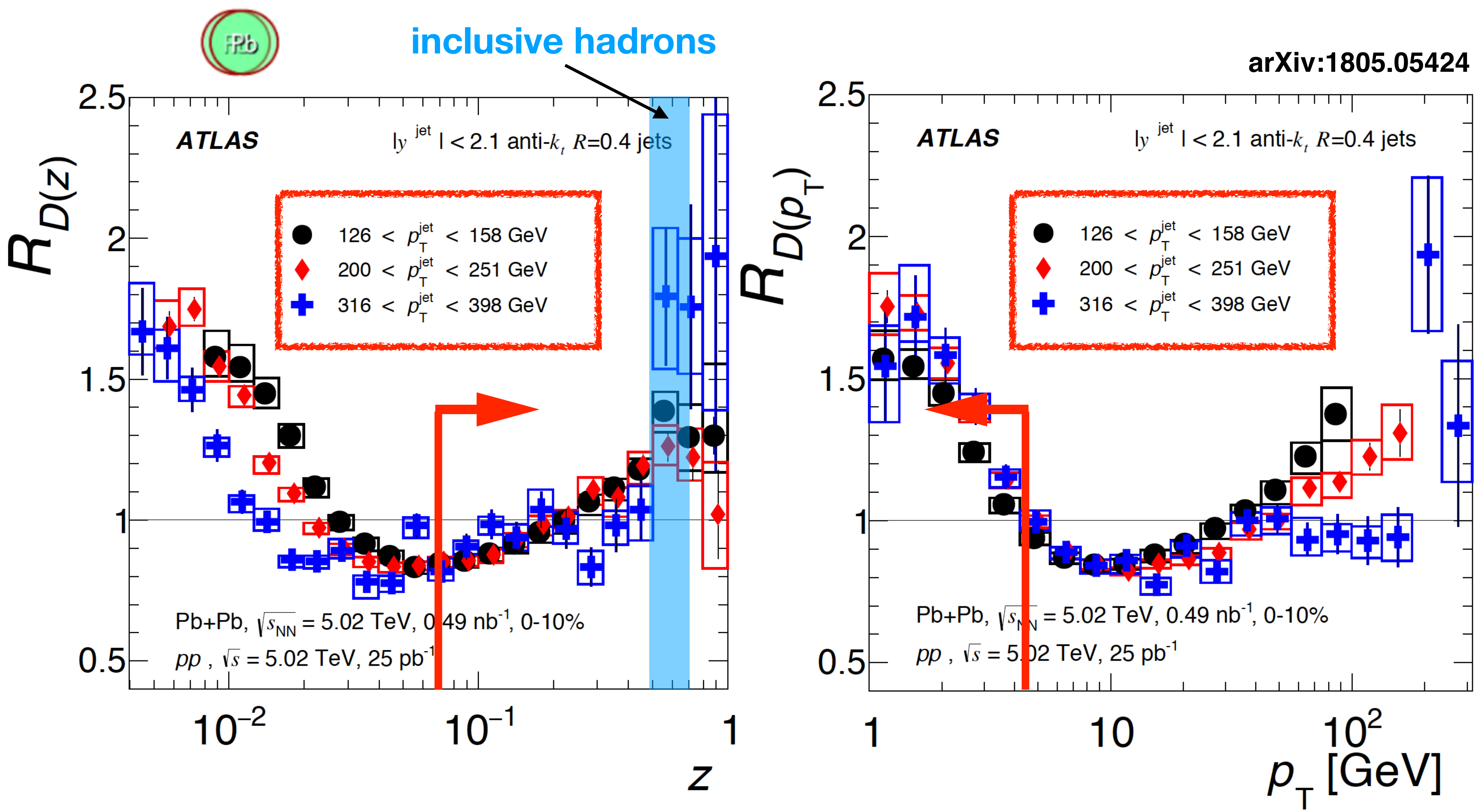
  $\Rightarrow R_{AA} = 1$ at high p_T

  Strong bias towards hard fragmenting jets (z ~ 0.6-0.7)
  Very small part of the total jet cross-section
  R_{AA} depends on initial hard partonic structure

Stronger jet suppression due to more partons losing energy (incoherently) ?

⇒relation between hard jet sub-structure and energy loss to be fully exploited

Consistent with Fragmentation Functions pp/PbPb ?



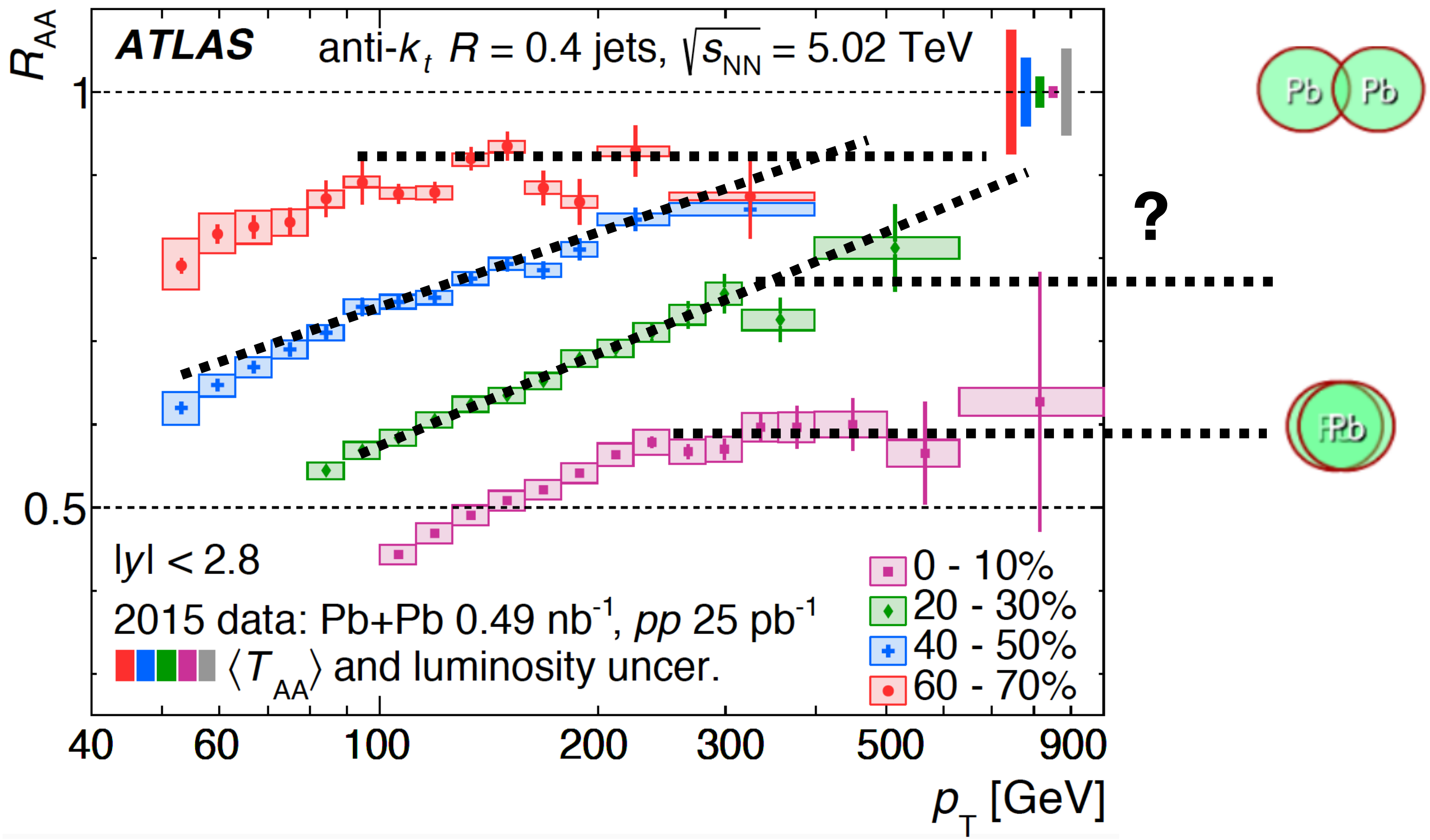
Scaling for high z

Invariant spectrum at low p_T

Parton p_T bias: PbPb > pp because of quenching!

Centrality Dependence

arXiv:1805.05635

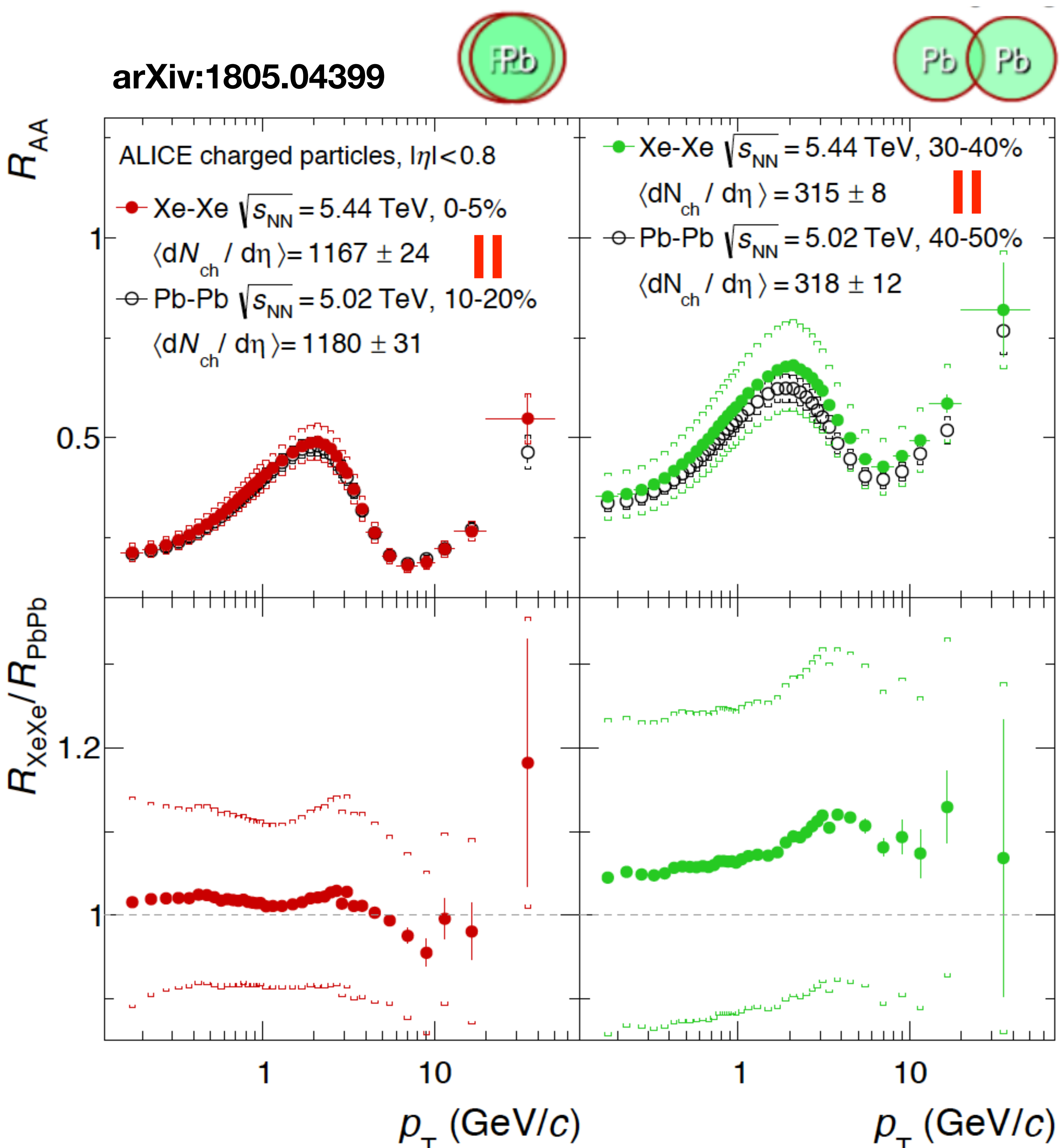


Flat R_{AA} up to which centrality ?
Change of shape in more peripheral collisions ?
System size dependence ?

Statistics !

Digression on System Size Dependence
R_{AA}: Pb-Pb vs Xe-Xe

arXiv:1805.04399



Central collisions:
Similar R_{AA} at the same multiplicity

Peripheral Collisions:
Larger differences

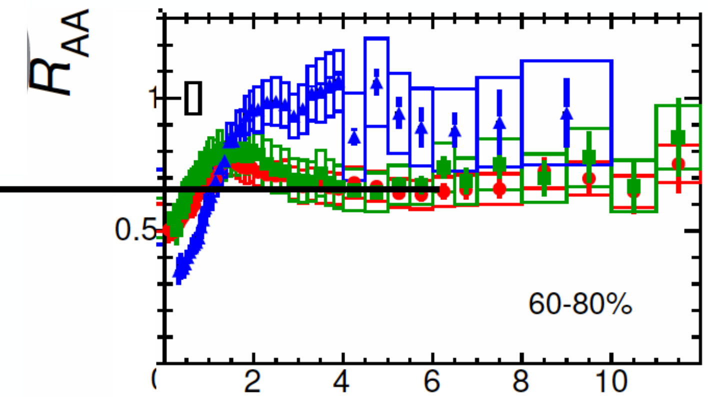
Constraints on path length dependence ?
Go to even smaller systems ?

Beware biases !

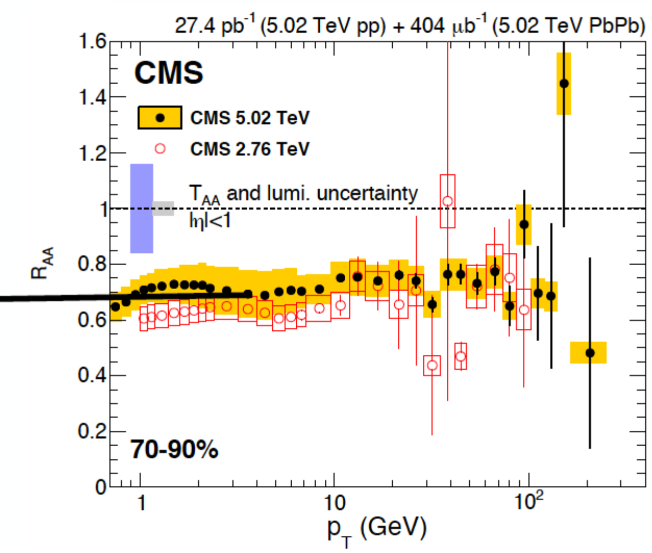
What is the smallest system exhibiting jet quenching ?

D. V. Perepelitsa, “*Hard Processes in Small Systems*”, Quark Matter 2017

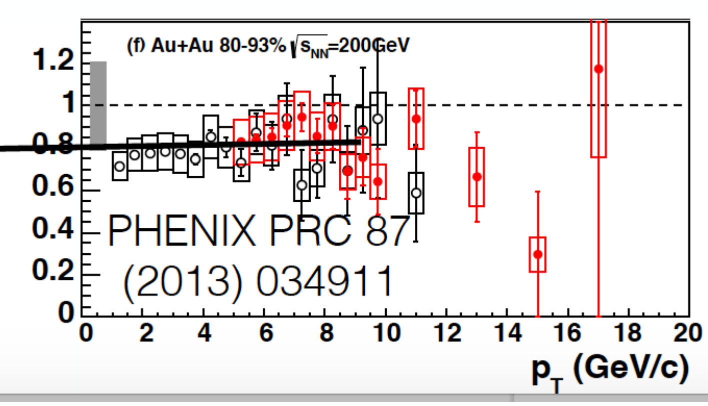
60-80% Pb+Pb, R_{AA} = 0.65
<N_{part}> = 23 (ATLAS similar)
<1% *p*+Pb (0-5% in Glauber-Gribov!)



70-90% Pb+Pb, R_{AA} = 0.7
$\boxed{<N_{part}> = 11}$
~20-30% *p*+Pb



80-93% Au+Au, R_{AA} = 0.8
$\boxed{<N_{part}> = 5}$
~50-70% *p*+Pb



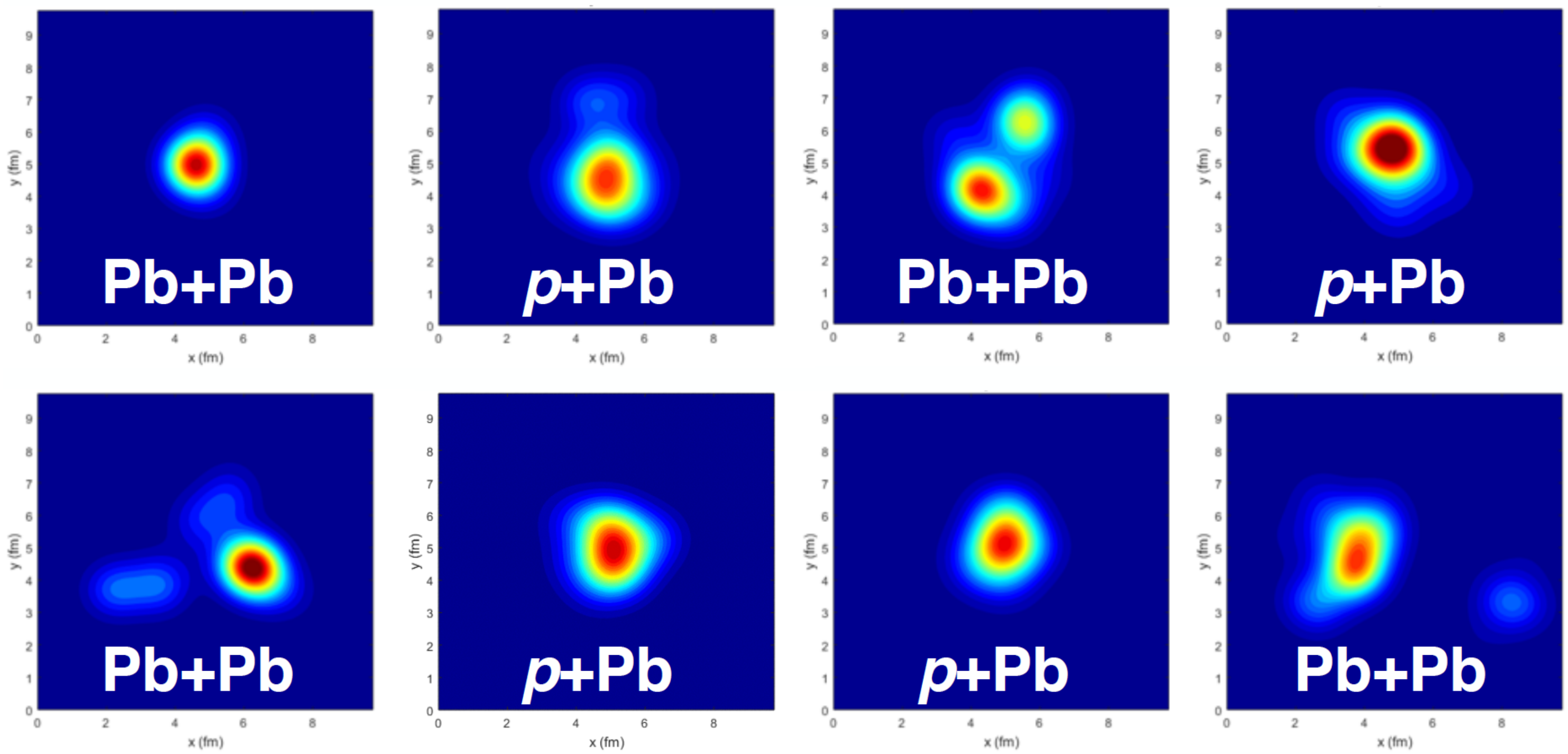
decreasing N_{part}

R_{AA} < 1; N_{part} in peripheral A-A similar to p-A

What is the smallest system exhibiting jet quenching ?

D. V. Perepelitsa, “*Hard Processes in Small Systems*”, QM 2017

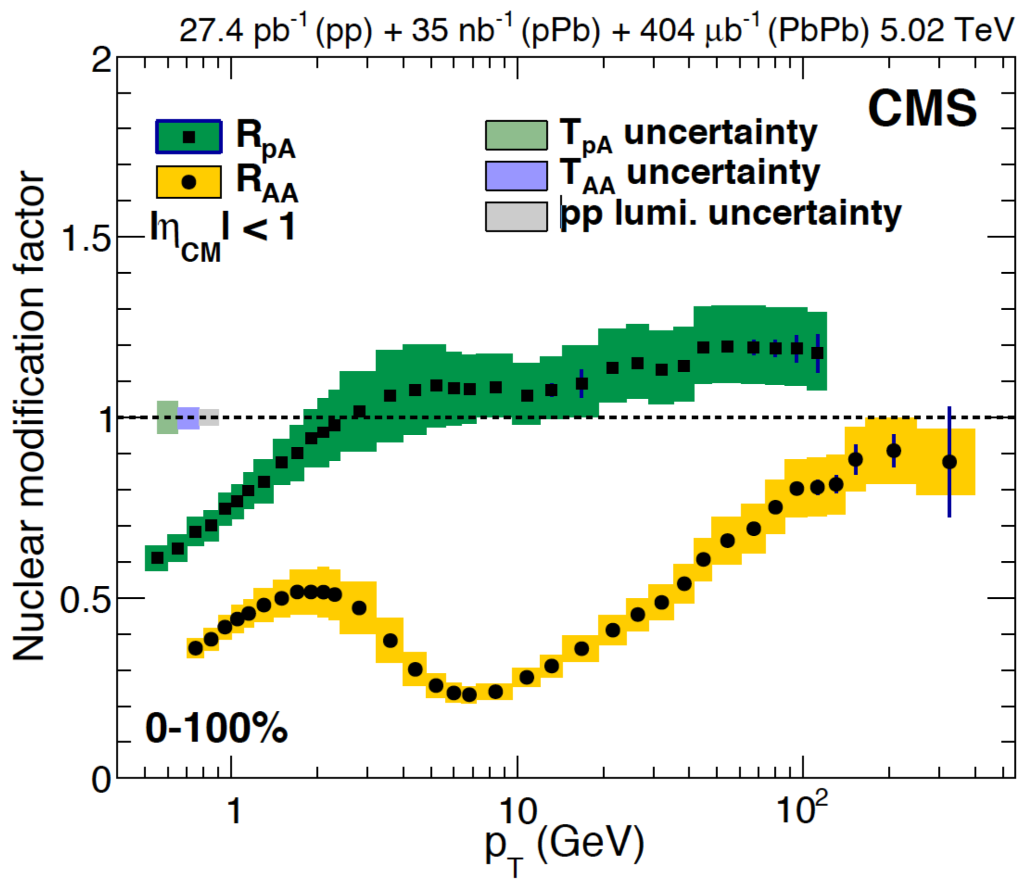
0-10% *p*+A or 70-90% A+A?

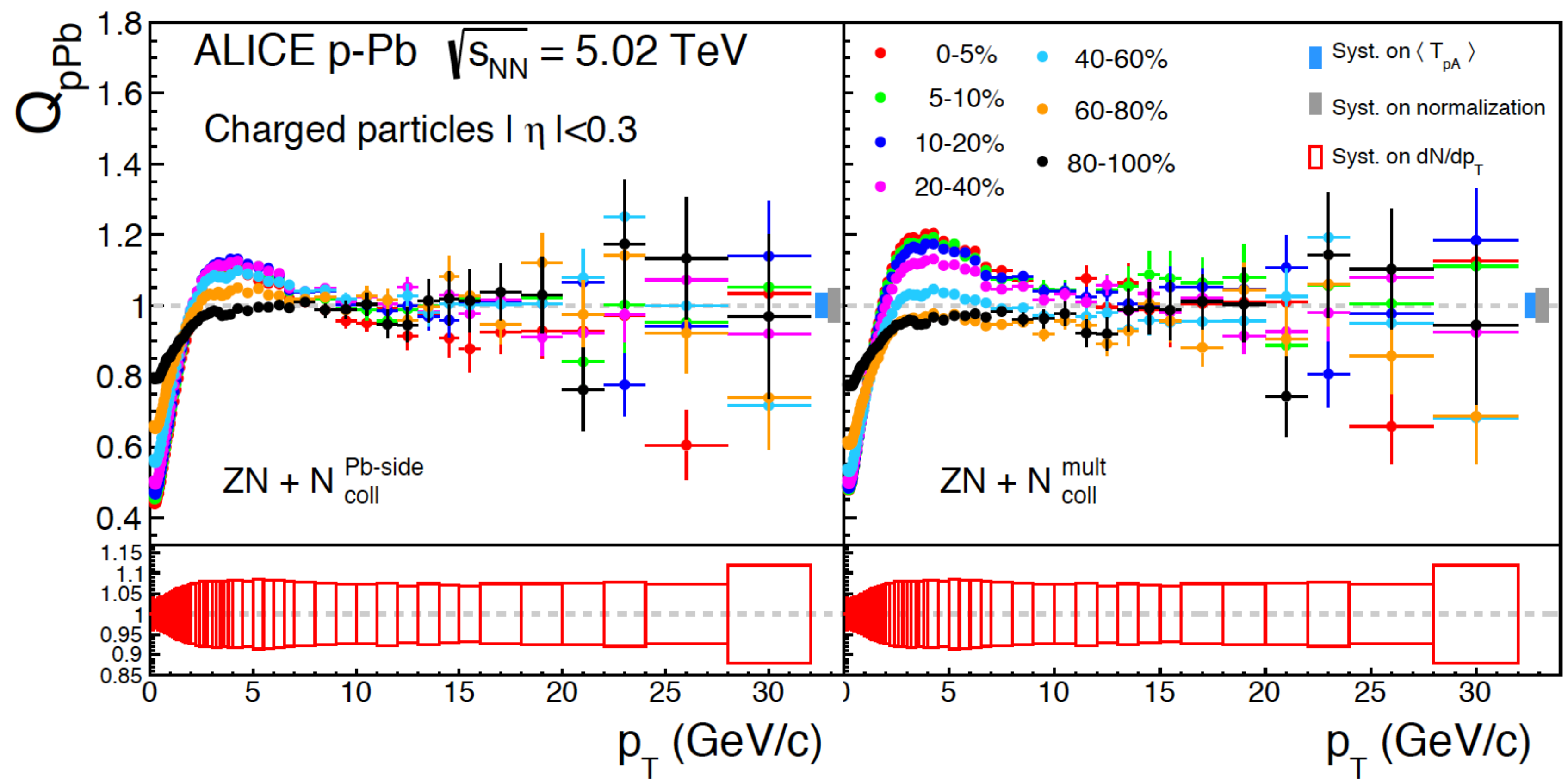


credit to R. Weller and P. Romatschke

Also similar initial geometry

R_{AA} in p-Pb



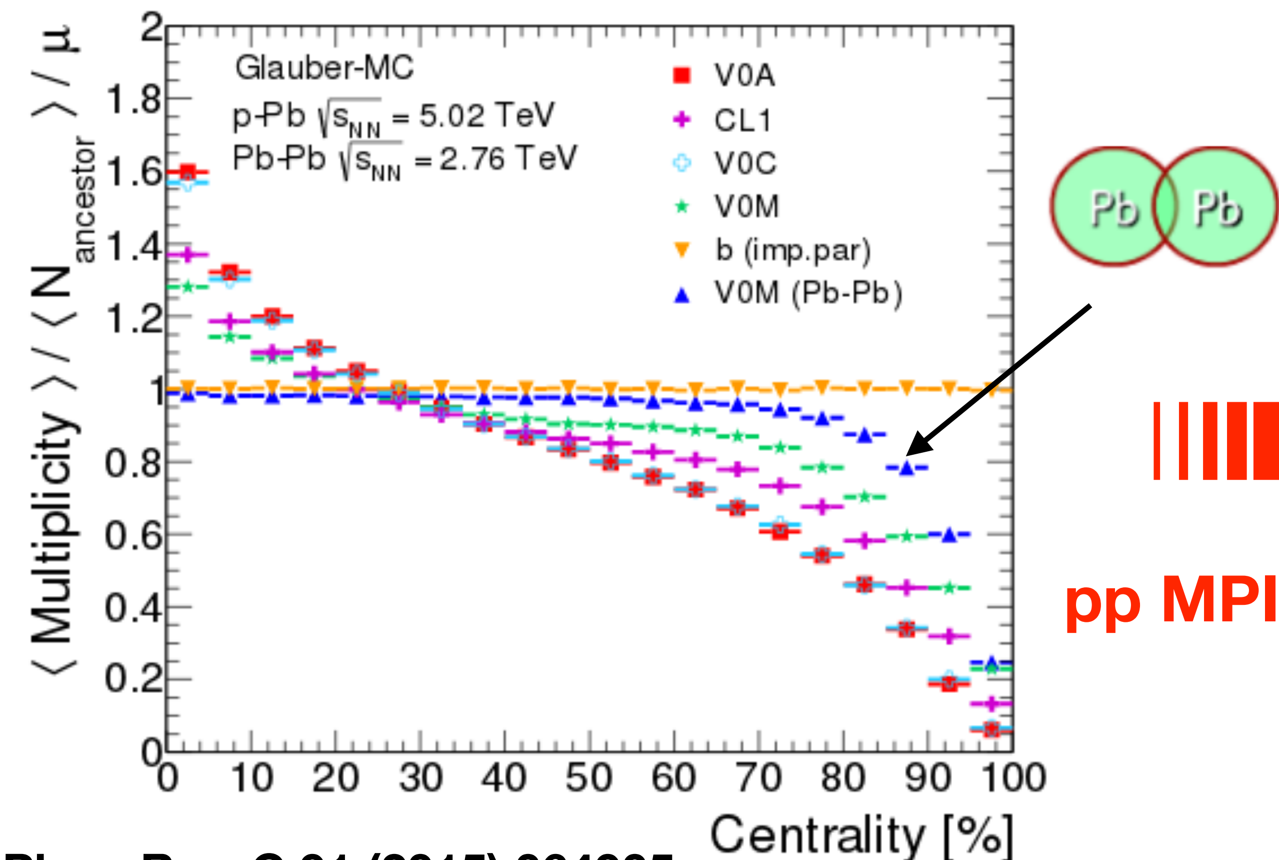


No significant modification at high p_T for N_{part} comparable to peripheral Pb-Pb.

Contradiction ?

Biases in Small Systems

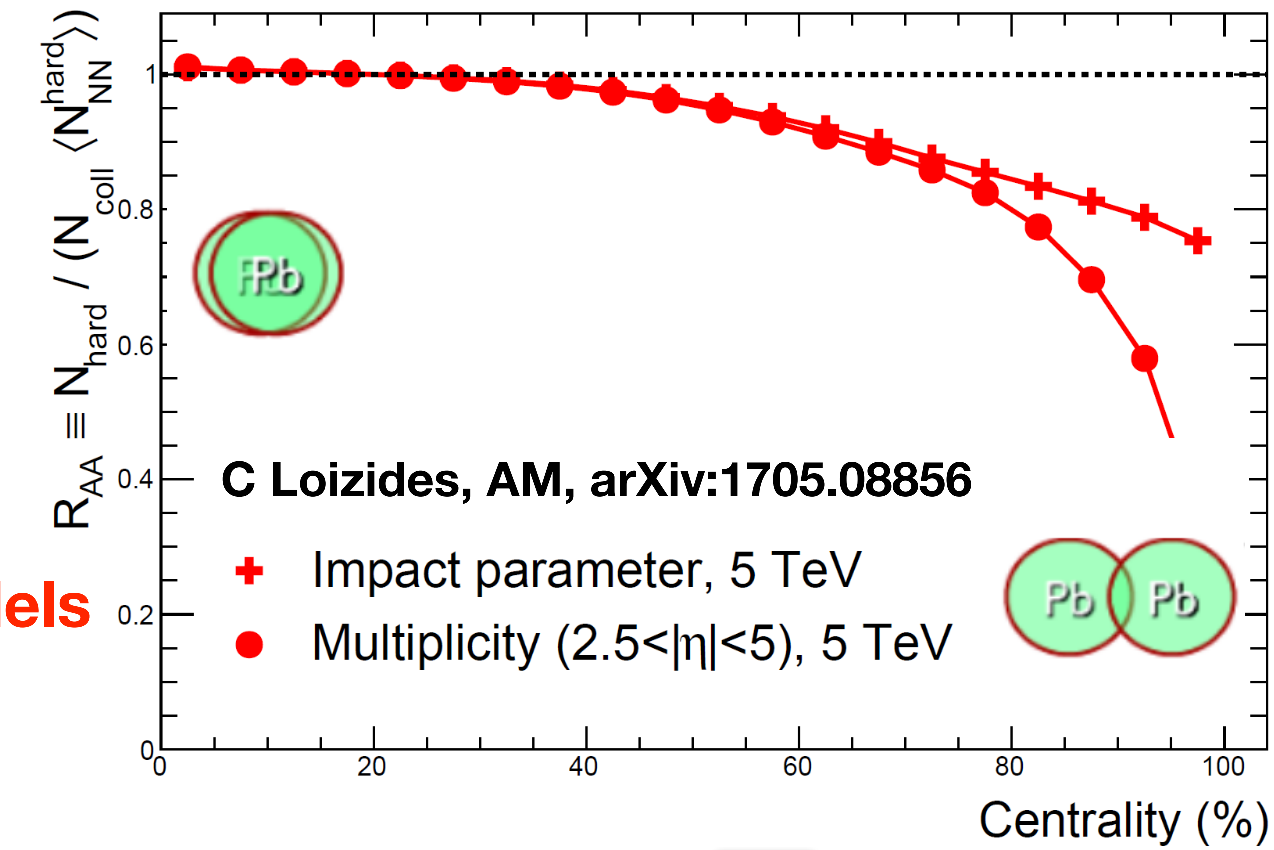
Bias on multiplicity / particle source quantified by standard Glauber-Fit to Multiplicity distribution

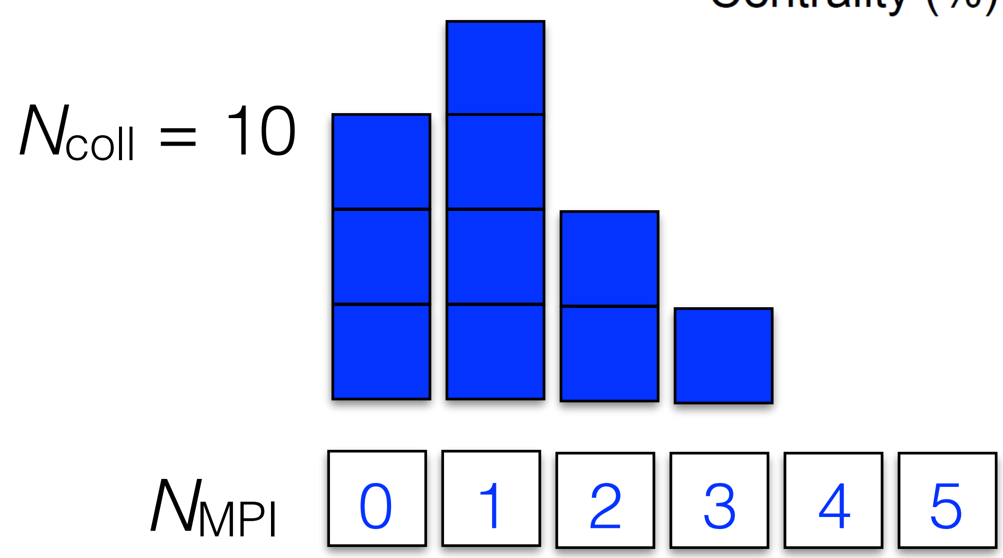


Phys. Rev. C 91 (2015) 064905

pp MPI Models

Bias on high-p_T R_{AA} quantified by incoherent superposition of pp

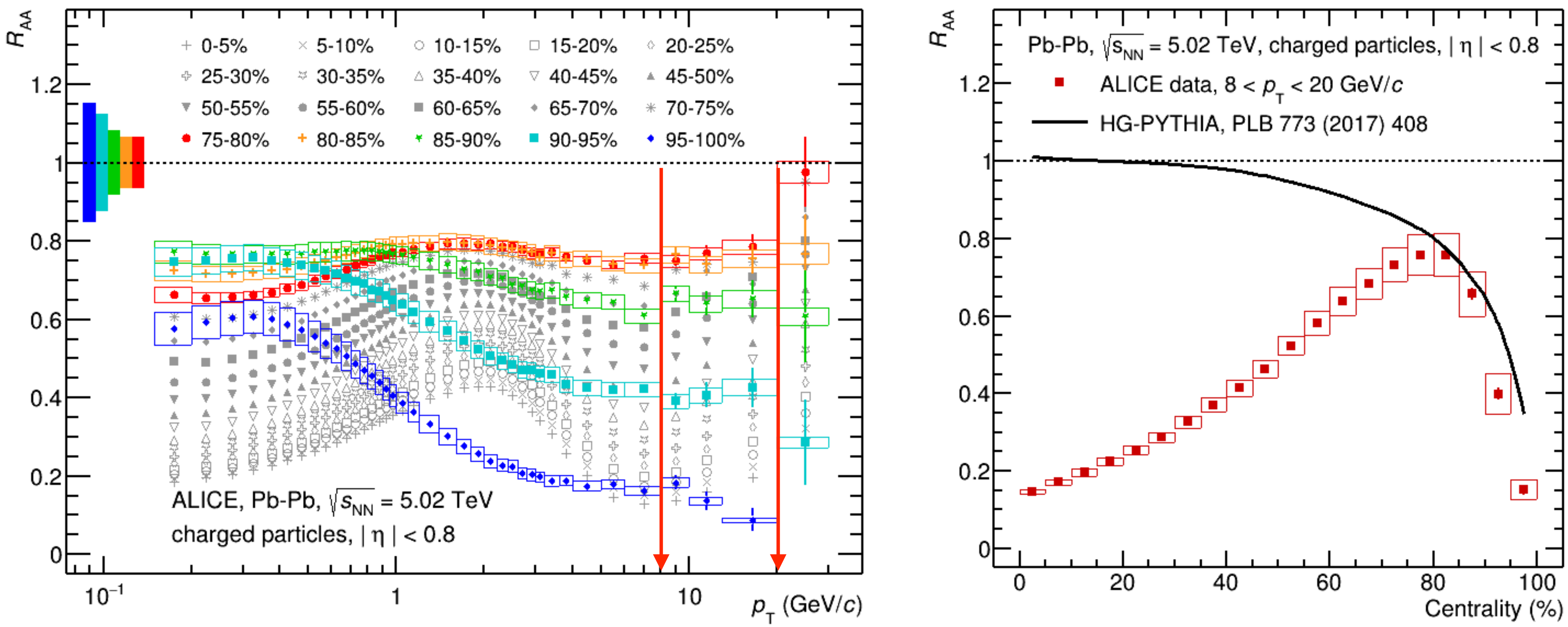




Biases can play a significant role in R_{AA} determination.
Can we observe the strong decrease of RAA for per. Pb-Pb ?

R_{AA} in very peripheral Pb-Pb collisions

arXiv:1805.05212

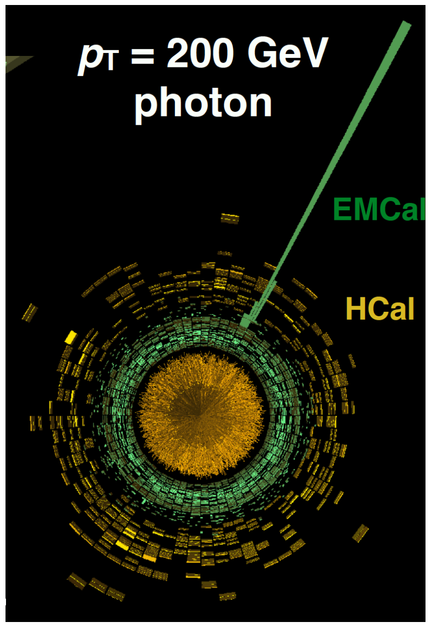


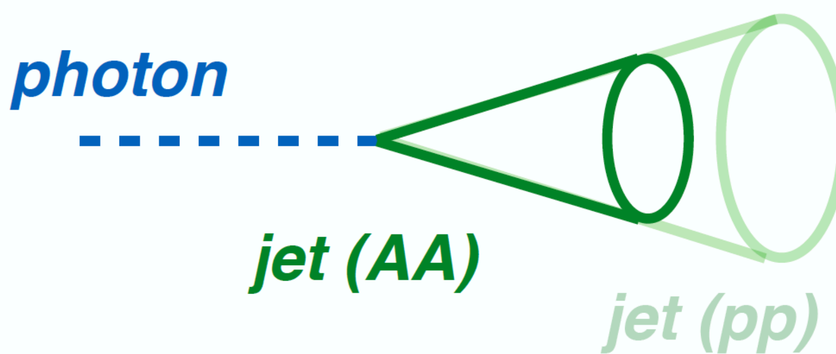
Centrality dependence of high p_T region

- R_{AA} never reaches unity (max 0.8)
- described by simple model based on HIJING Glauber MC and Pythia

Self-Normalised Observables:

Correlation Measurements





Photon+jet p_T-balance

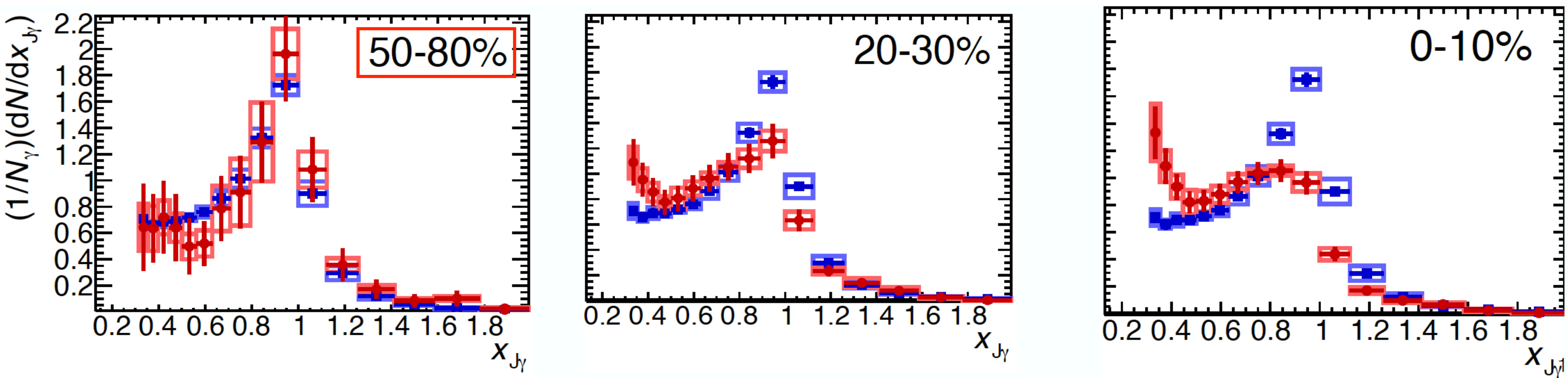
➡ $x_{J\gamma} = p_T^{jet} / p_T^{\gamma}$ (for $\Delta\phi > 7\pi/8$)

LO back-back configuration

pp (same each panel)

Pb+Pb p_T^{γ} = 100-158 GeV

Centrality

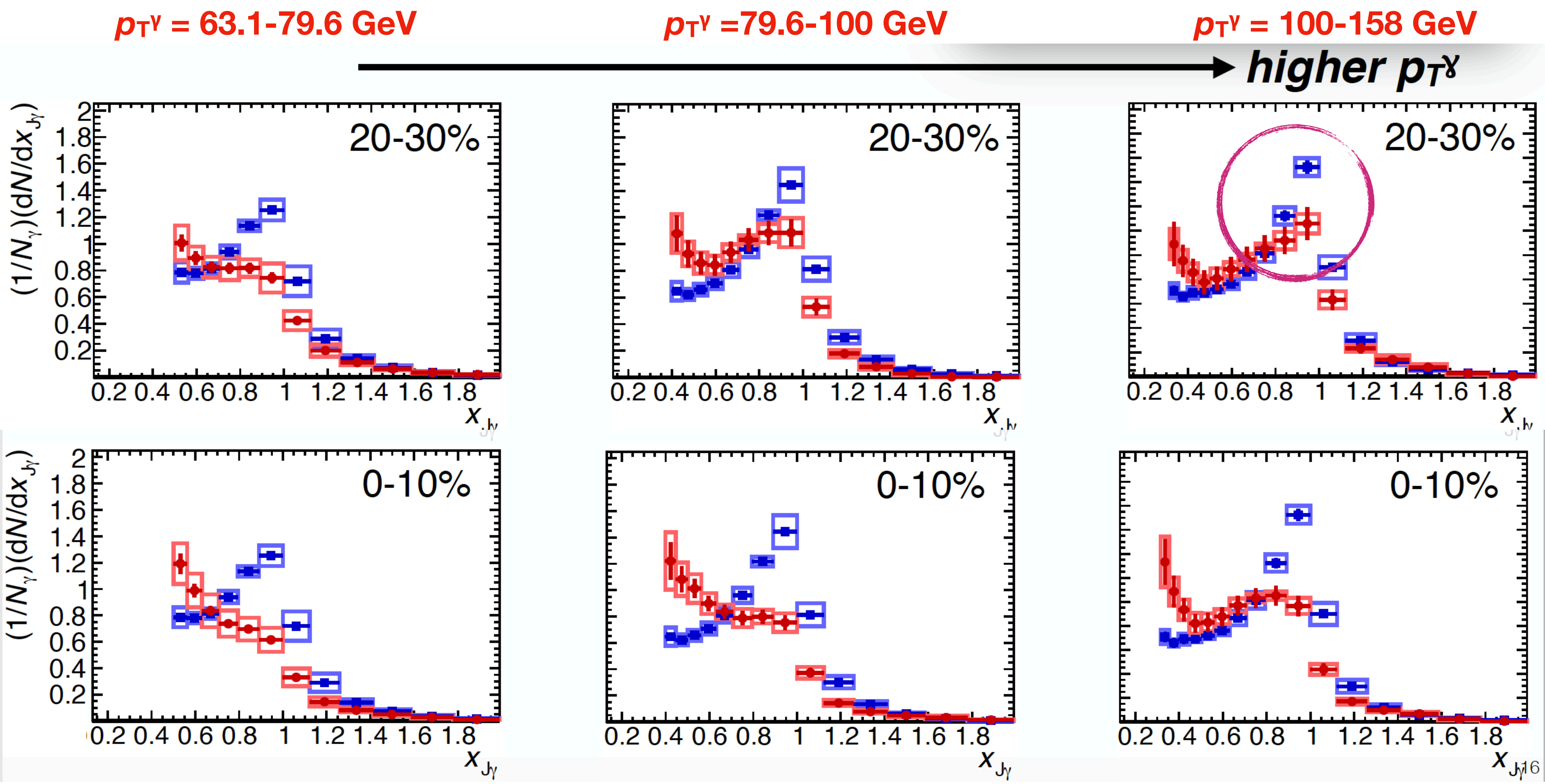


balance almost pp-like
despite $R_{AA} < 1$

Attention: production bias towards quark initiated jets

ATLAS-CONF-2018-009

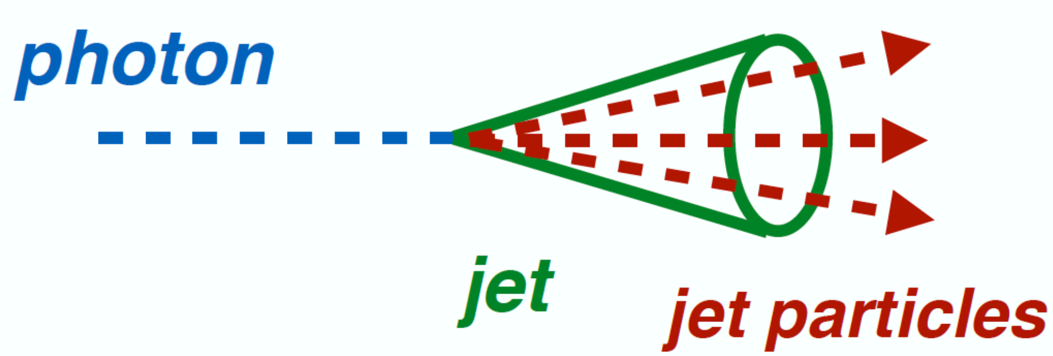
p_T Dependence



tendency to restore balance at high p_T

ATLAS-CONF-2018-009

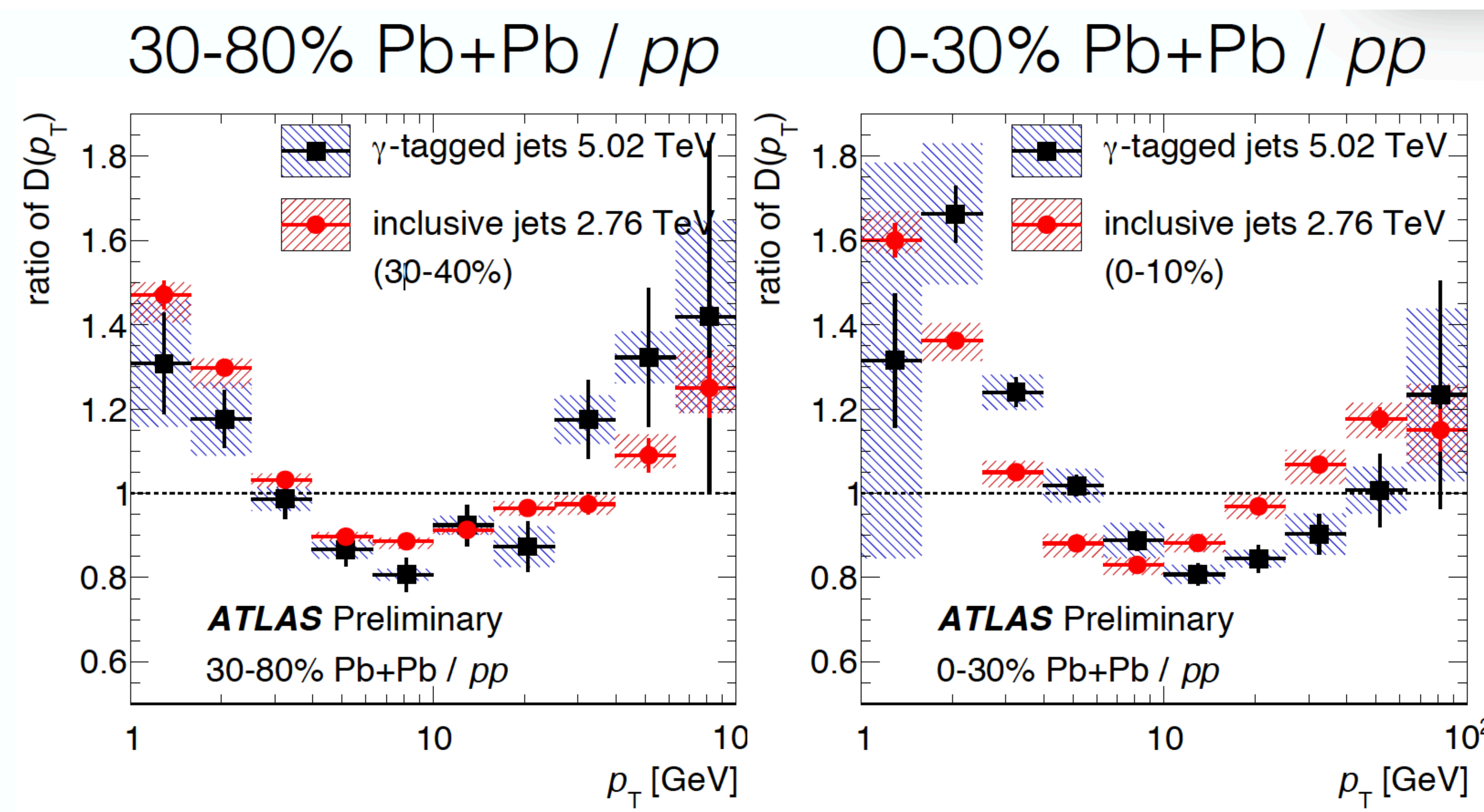
Photon tagged fragmentation function



Photon-tagged **frag. function**
(with respect to the **jet**)

➡ $D(p_T^h)$ or $D(z = p_T^h / p_T^{jet})$

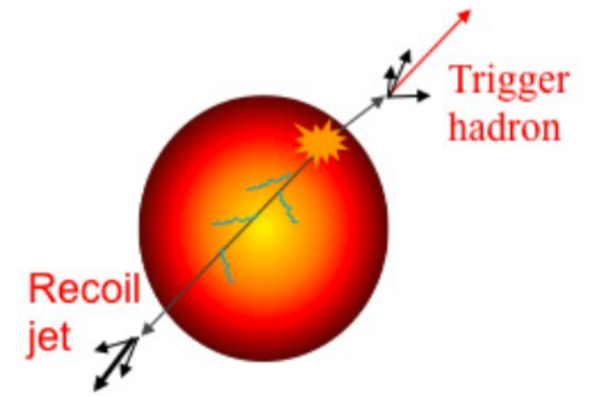
p_T^γ = 79.6-125 GeV
p_T^{jet} = 63.1-144 GeV



Stronger modification of photon tagged jets
despite production bias towards quark initiated jets !
Understand interplay between production and kinematic biases!

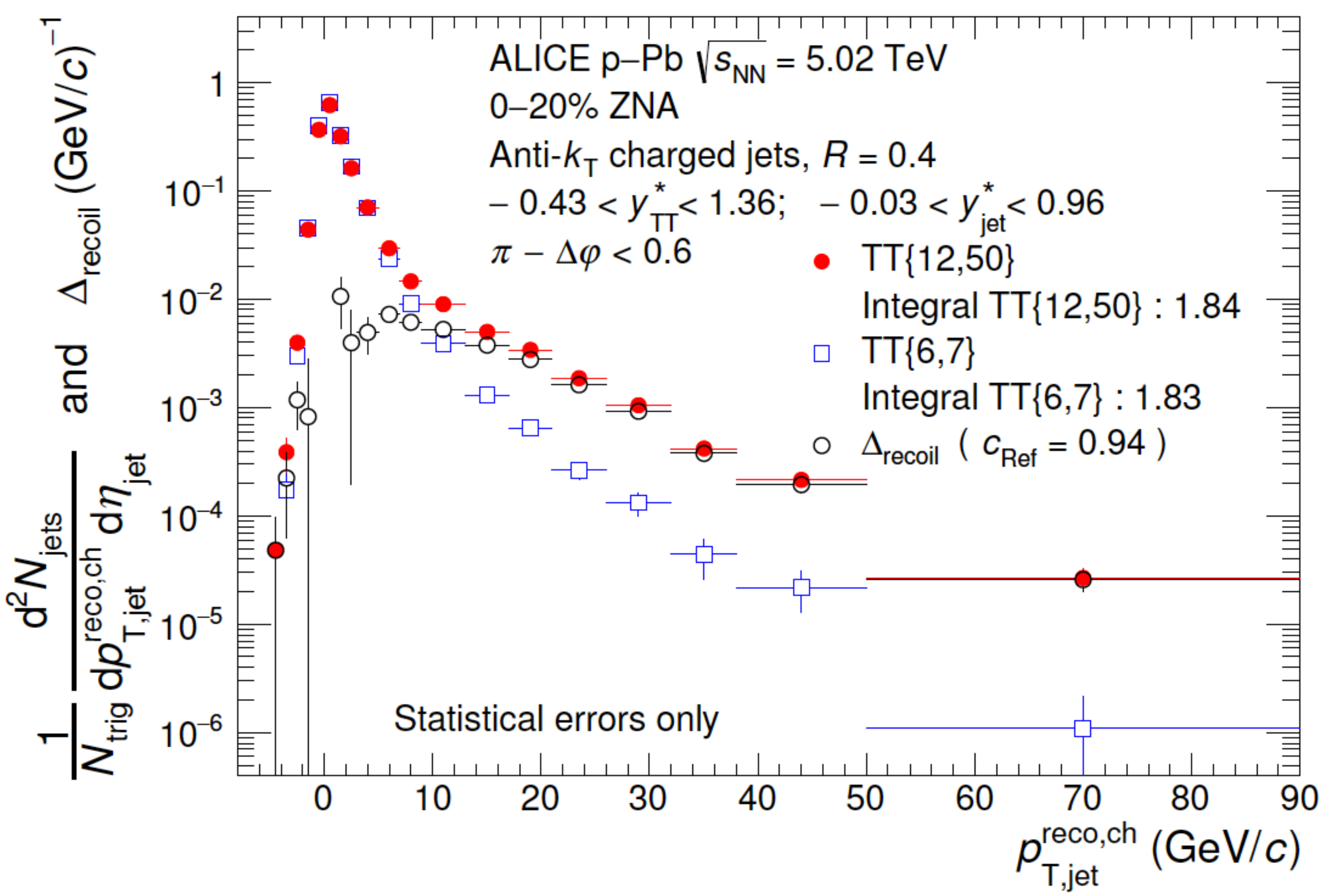
ATLAS-CONF-2017-074

h-Jet Correlations in p-Pb

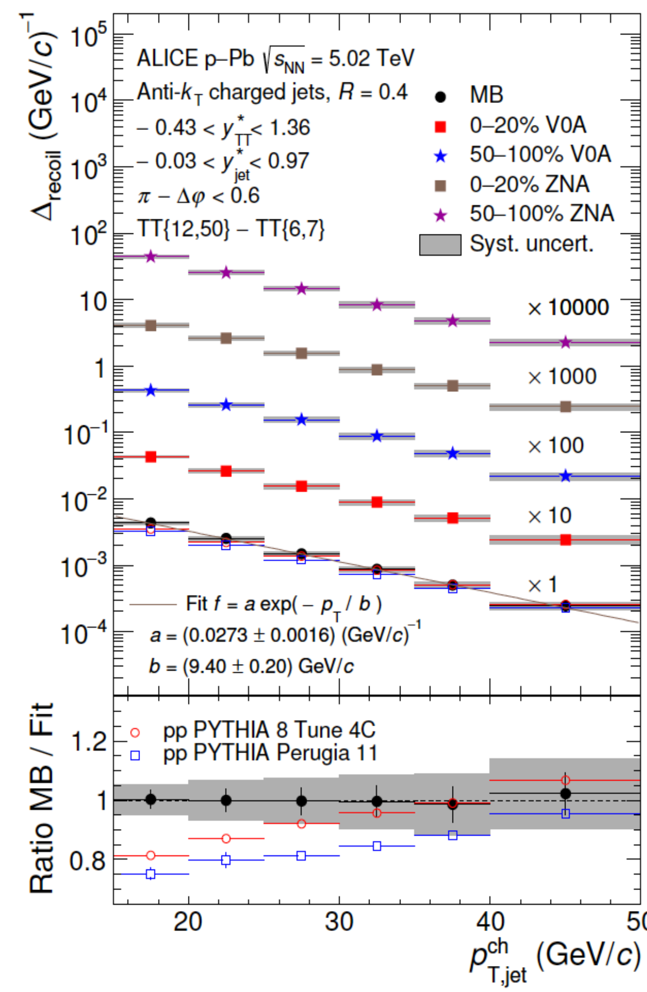


"per Trigger" Yields

Raw Spectrum



Corrected



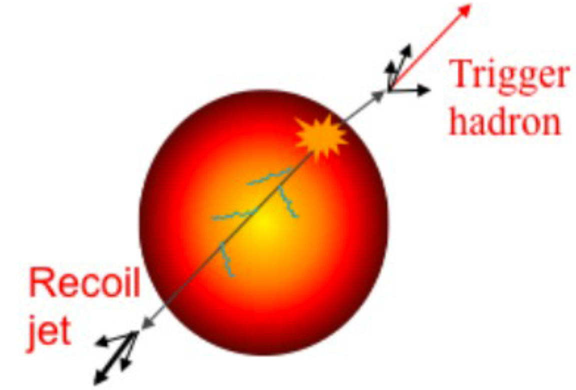
Remove uncorrelated BG:

$$\Delta_{recoil} = \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\eta}\bigg|_{p_{T,trig}\in TT\{12,50\}} - c_{Ref} \cdot \frac{1}{N_{trig}} \frac{d^2 N_{jet}}{dp^{ch}_{T,jet} d\eta}\bigg|_{p_{T,trig}\in TT\{6,7\}}$$

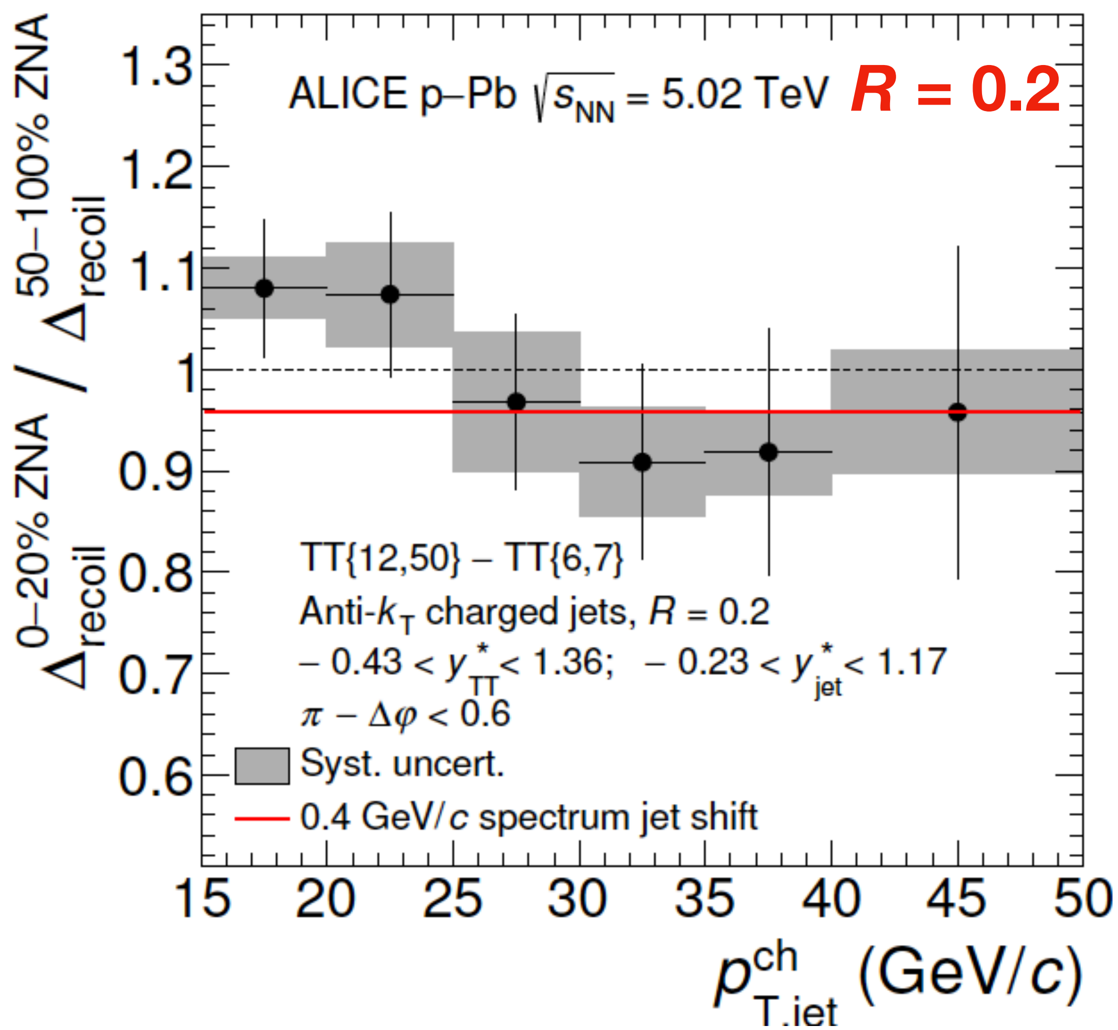
Per trigger yield does not require evaluation of N_{coll} (T_{pA})

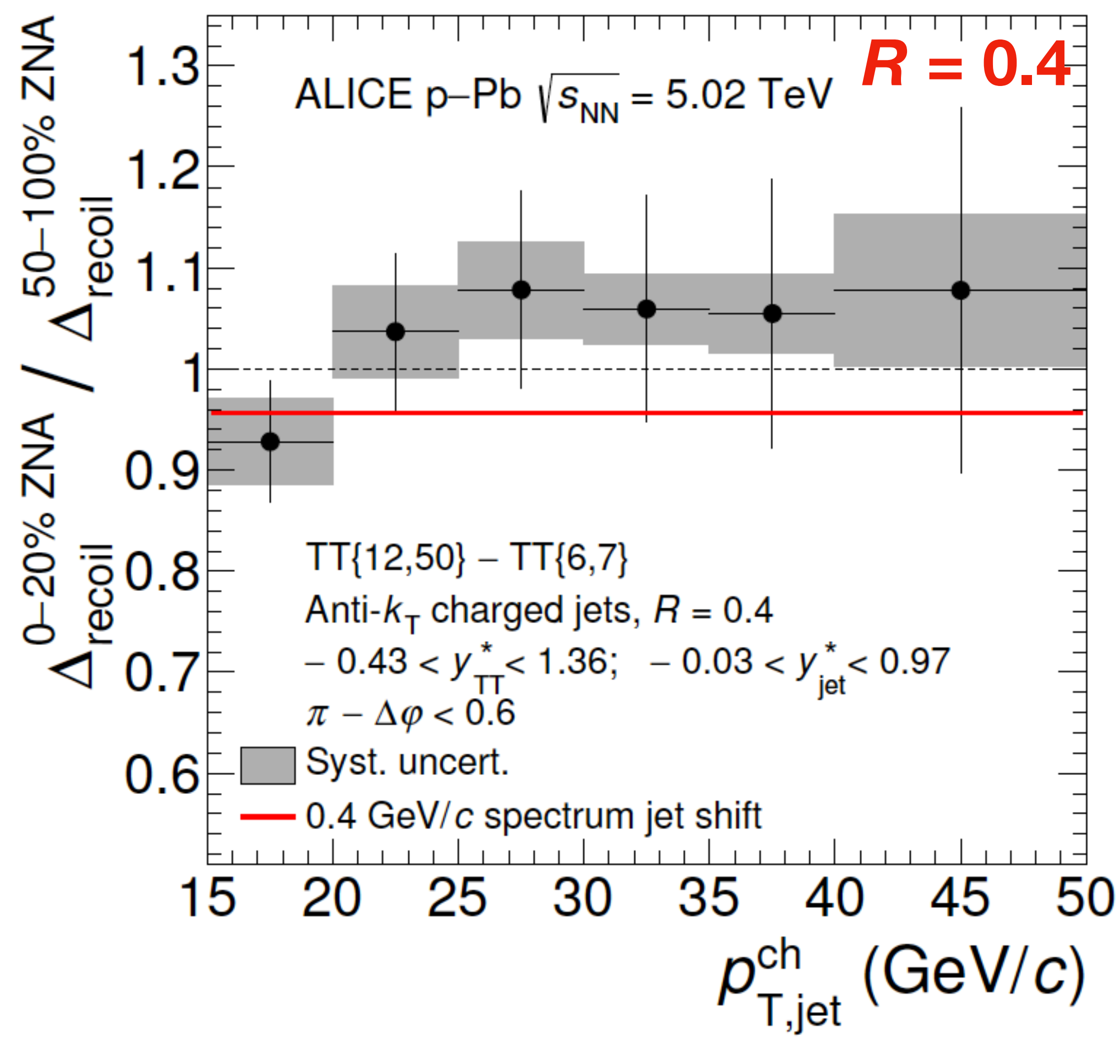
arXiv: 1712.05603

h-Jet Correlations in p-Pb



Central / Peripheral

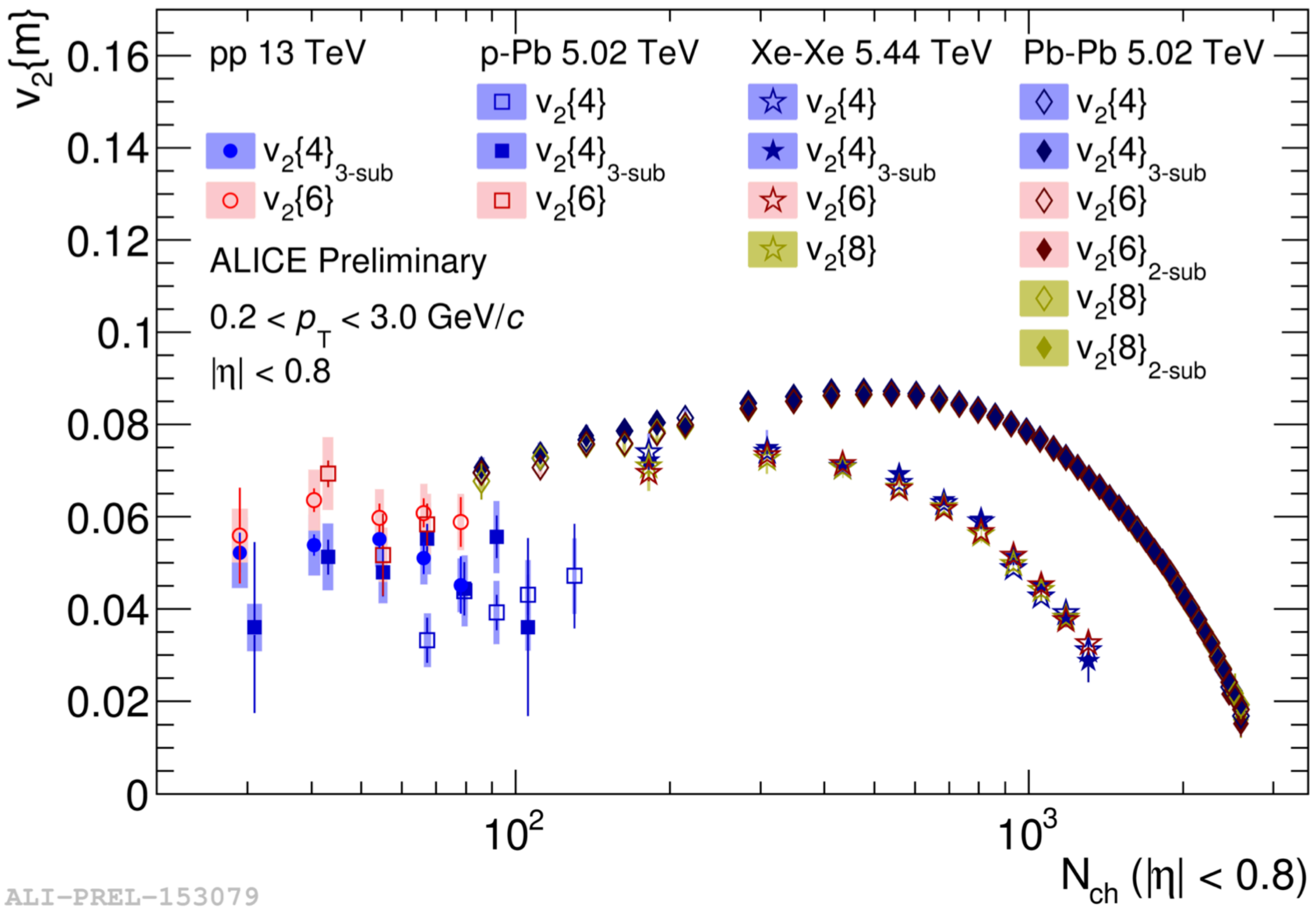


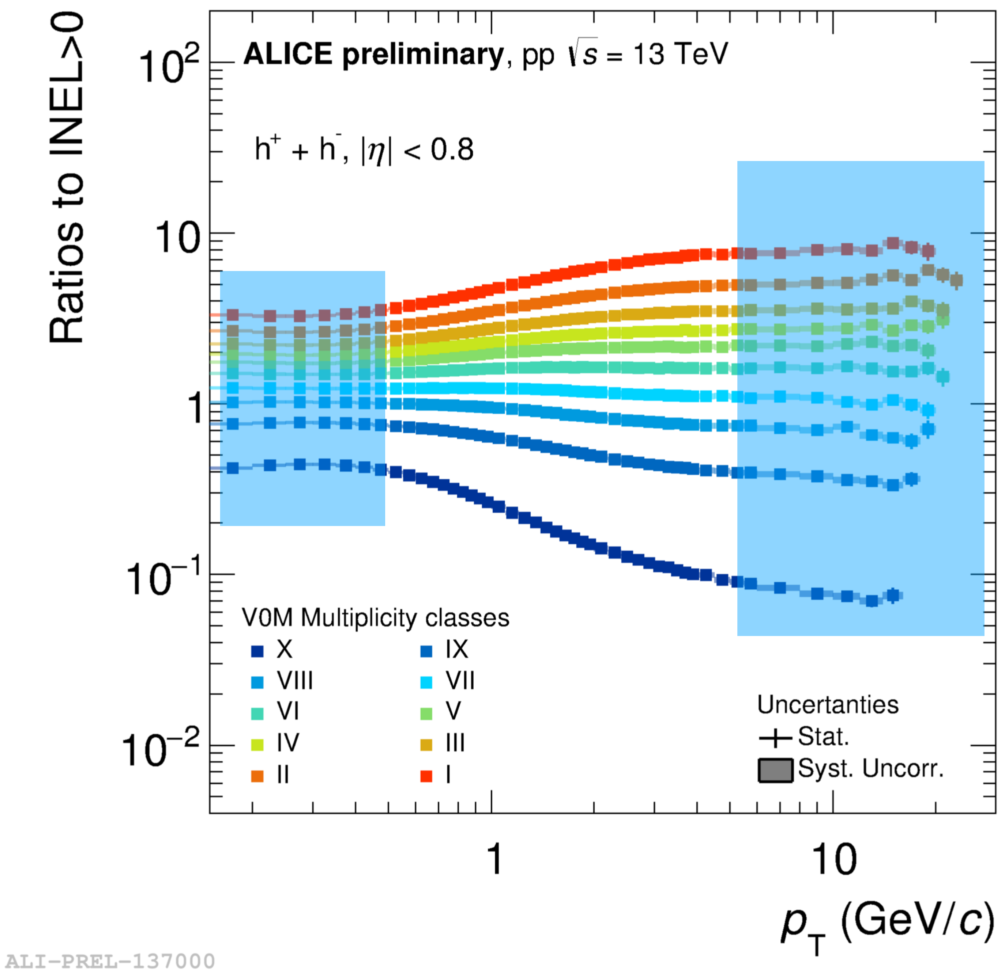


Ratio $\frac{\Delta_{recoil|0-20\%}}{\Delta_{recoil|50-100\%}}$ compatible with unity

arXiv: 1712.05603

What about pp ?





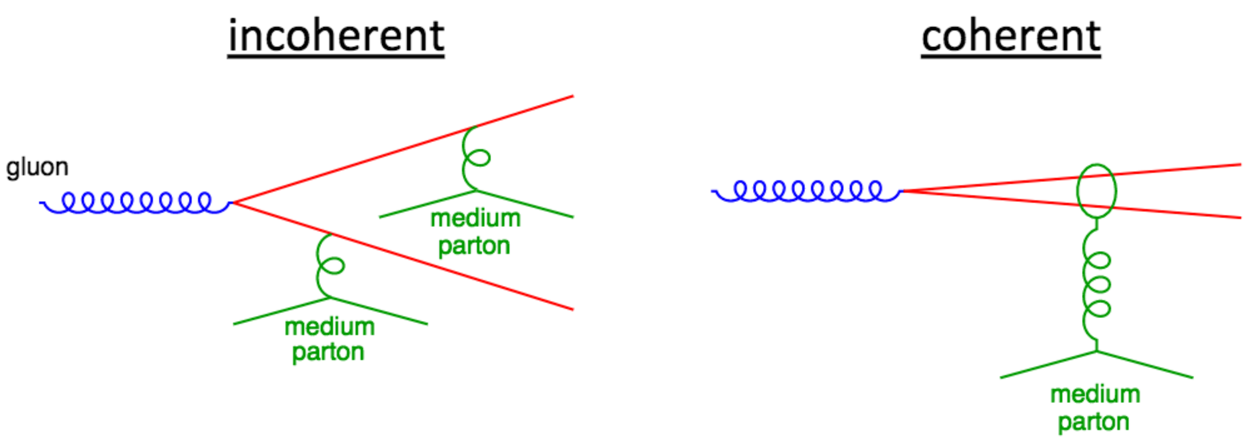
Collective behaviour is observed in multi-particle cumulants even in the smallest system p-Pb, pp.

- Expect also jet quenching effects.
- Quantitative not qualitative question

Challenge: sensitivity to measure jet quenching effects in small system ?

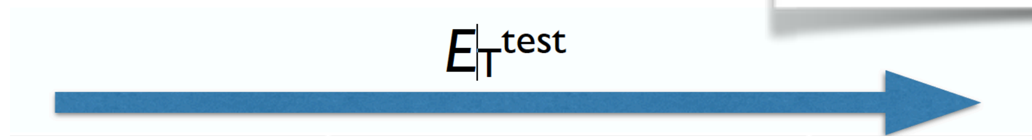
- p-Pb: N_{coll} determination difficult.
- h-jet correlations
- pp: MPI-like scaling at high p_T, but how to determine centrality
- γ (Z) production at high multiplicity

(In)Coherent Radiation after Run1

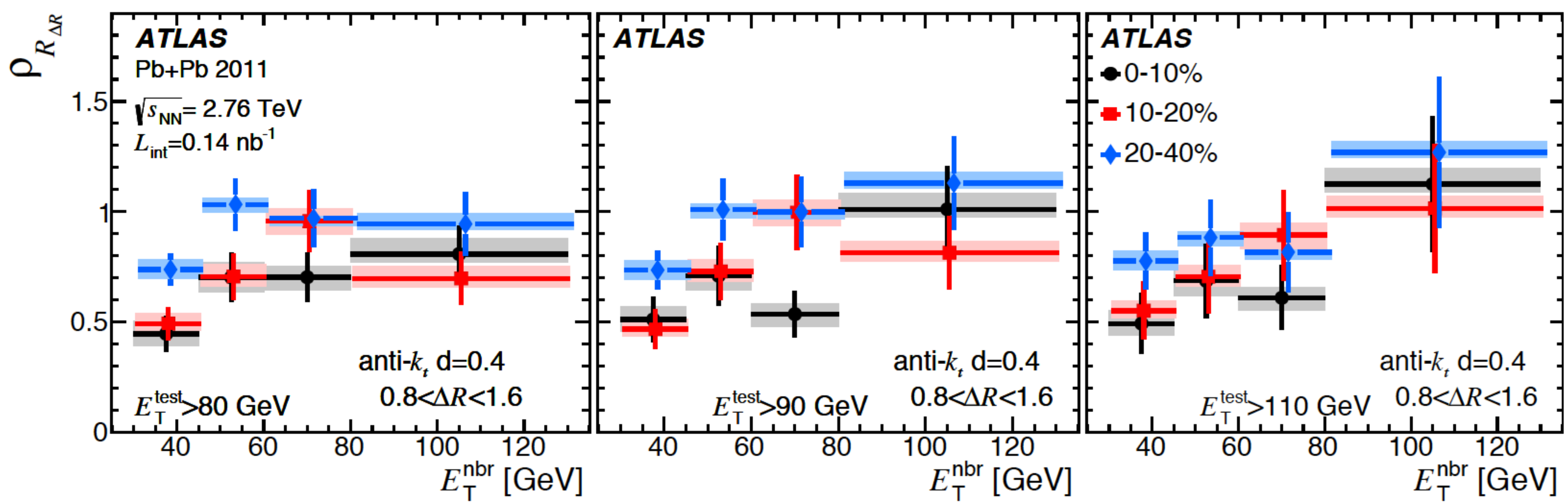


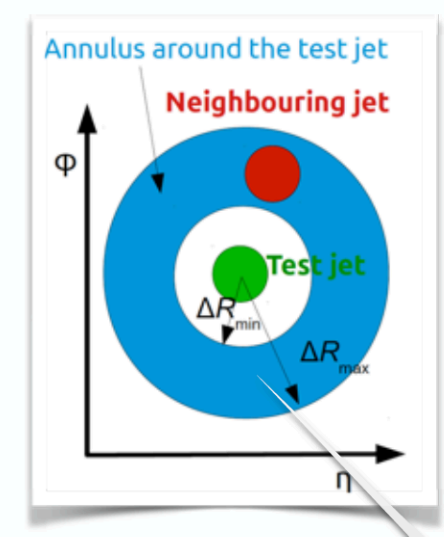
From Wuhan'15 Jet WS

- Neighbouring jets are selected with large angle and energy
  - formation essentially together with hard scattering
  - independent shower evolution expected
  - correlation only via common collision geometry
- Possible extensions
  - smaller angles
  - jets, sub-jets, single hadrons



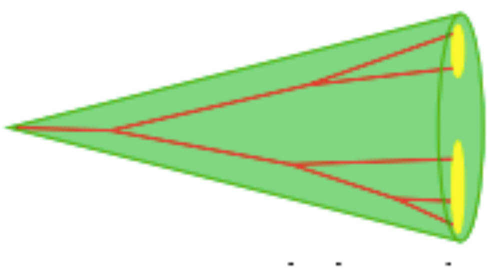
Incoherent at (very) large angles



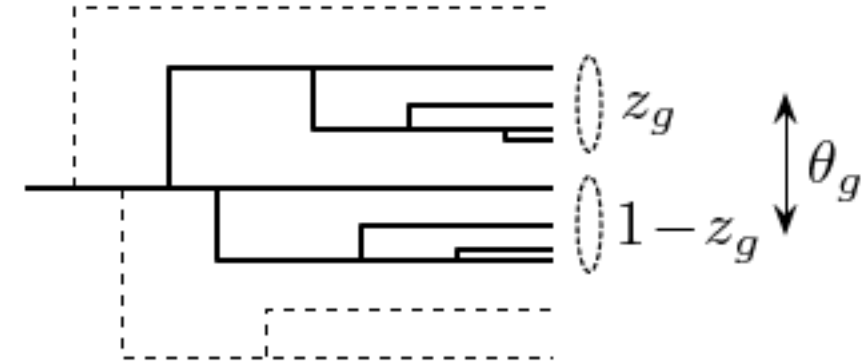


Look at sub-jets but how ?

Jet Substructure: undoing the clustering



$$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} \qquad z_g > 0.1$$

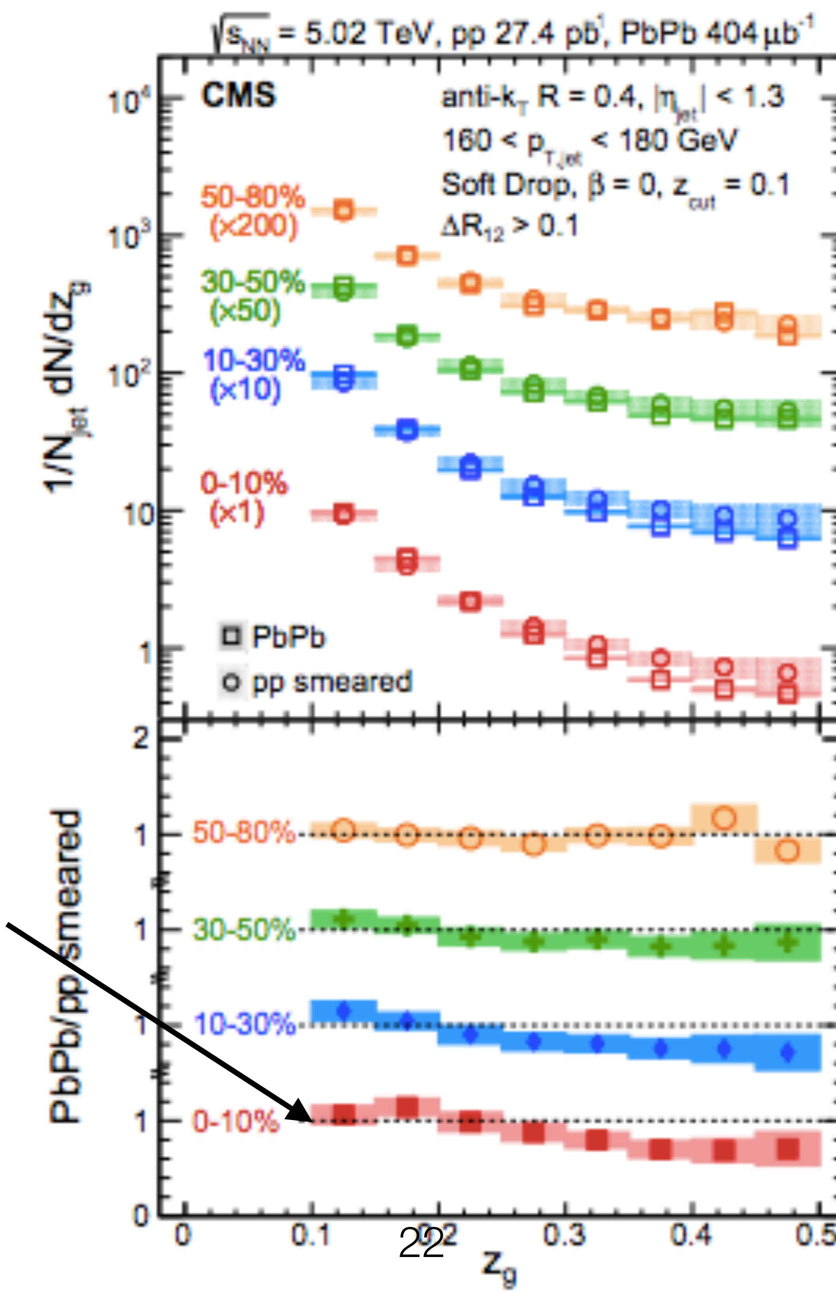


$$z > z_{\mathrm{cut}}\, \theta^{\beta}$$

Soft drop with β = 0
= mMDT with μ = 1

Normalised probability distribution

β=0
same z_{cut} for all angles

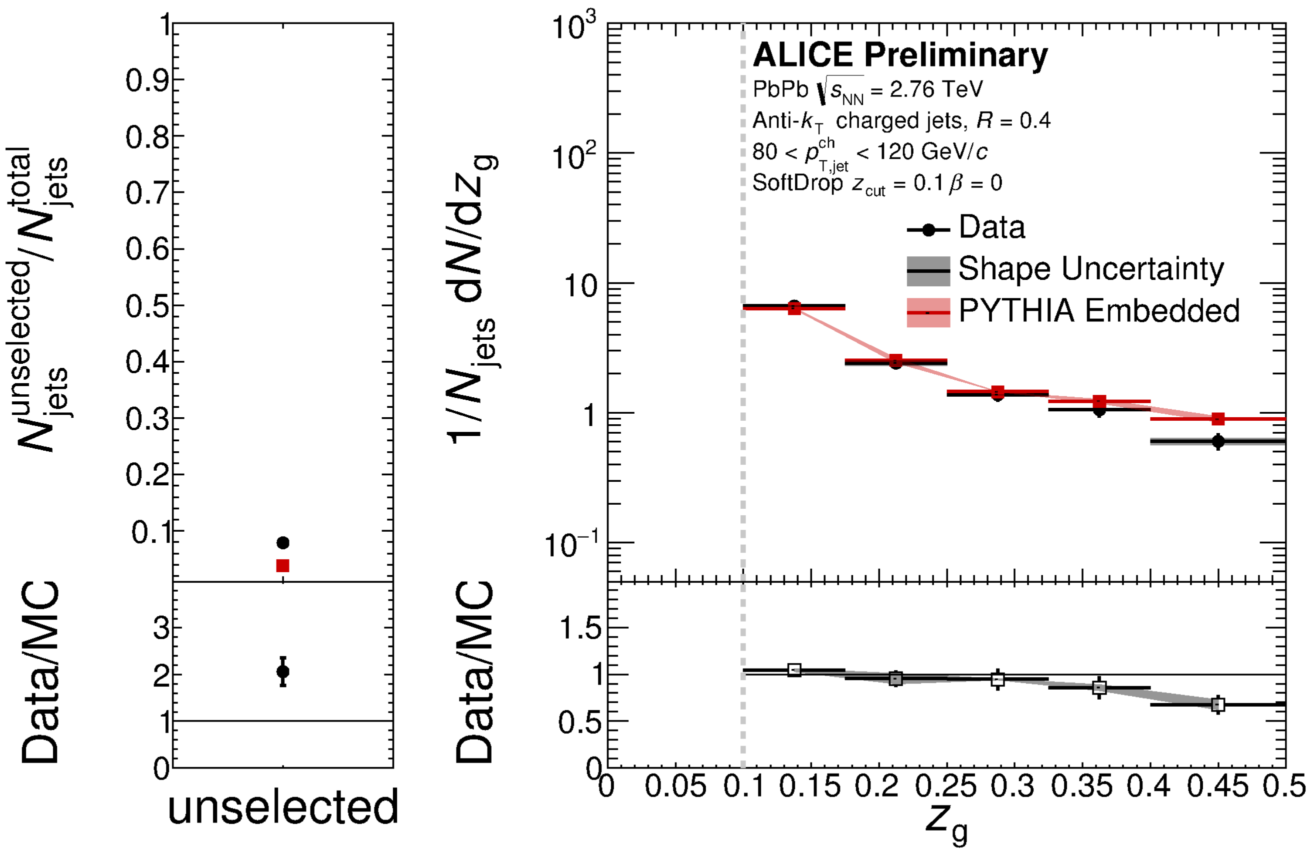


Increase in asymmetric splittings

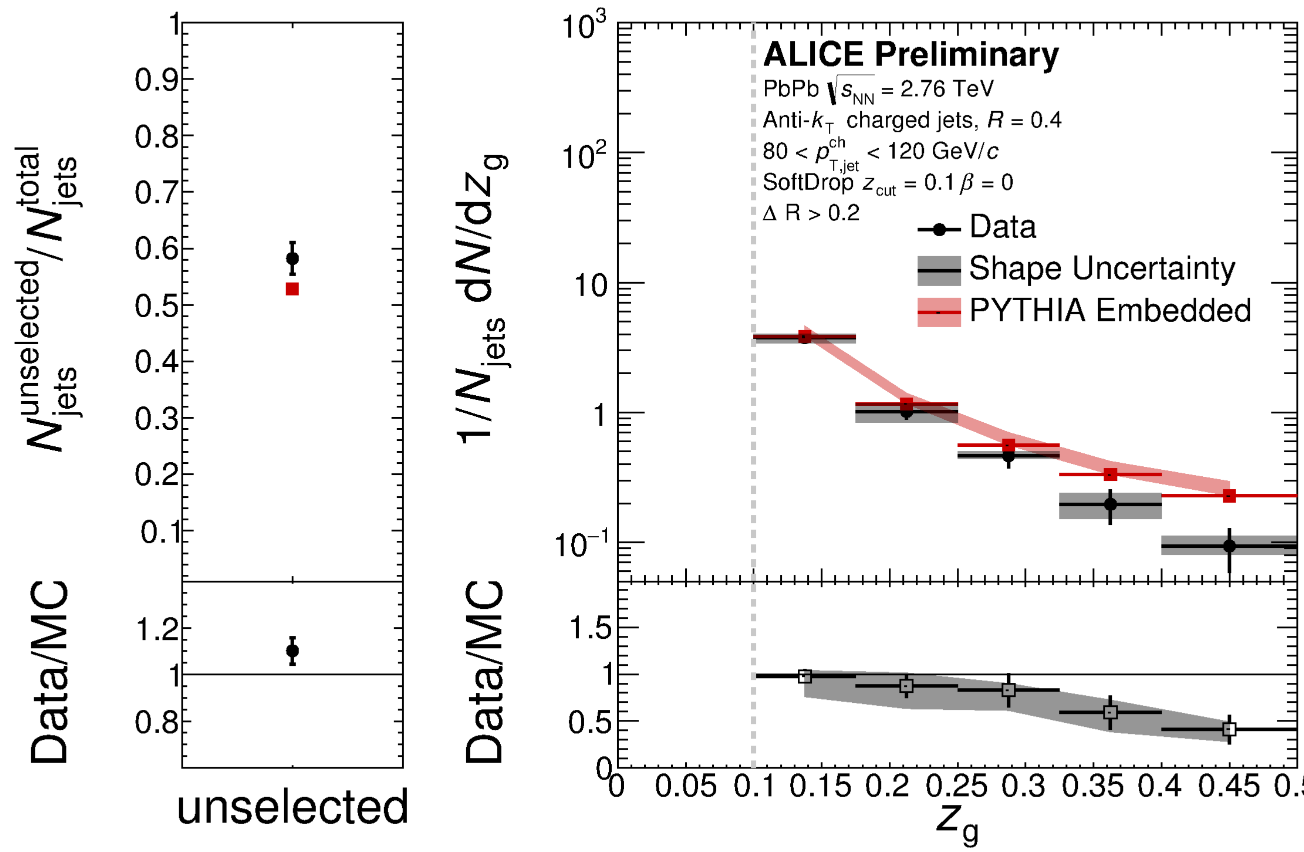
Reduction in (rare) symmetric splittings

Jet Substructure

z_g, all angles



z_g, $\Delta R > 0.2$



- Normalised to inclusive number of jets
- Suppression of symmetric splittings (large z_g)
- Consistent with independent energy loss of large angle splittings

Jet-by-Jet "shape" observable

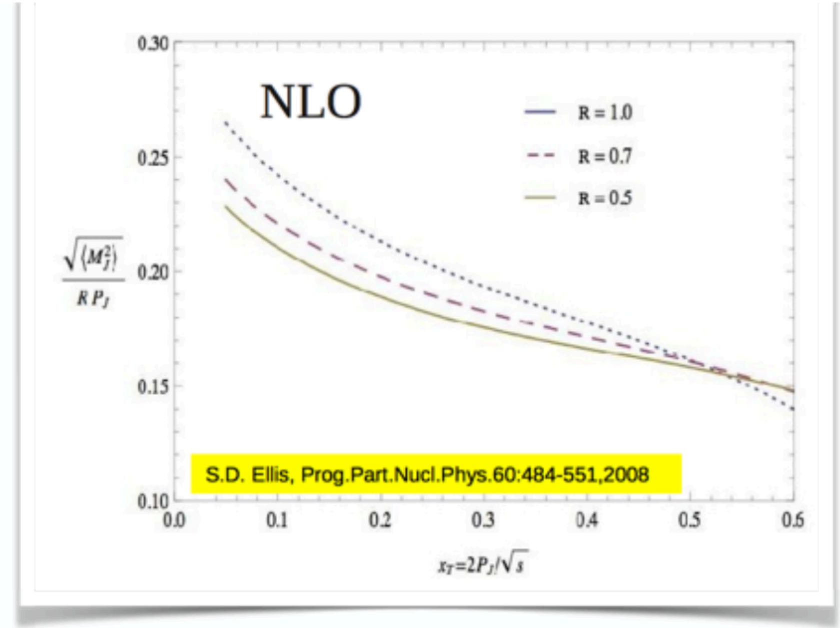
From Wuhan'15 Jet WS

- Global jet-by-jet "shape" observables

http://jets.physics.harvard.edu/qvg/

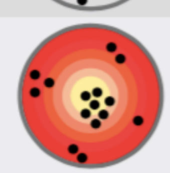
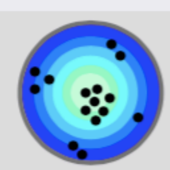
  - number of constituents
  - radial momentum $g = \frac{\sum_i \Delta R_i p_{\mathrm{T},i}}{\sum_i p_{\mathrm{T},i}}$
  - momentum spread $p_{\mathrm{T}}D = \frac{\sqrt{\sum_i p_{\mathrm{T},i}^2}}{\sum_i p_{\mathrm{T},i}}$
  - p_{T} of leading, sub-leading, … particle
  - 2dim geometric moments

Sensitivity can be increased by correlating several shapes



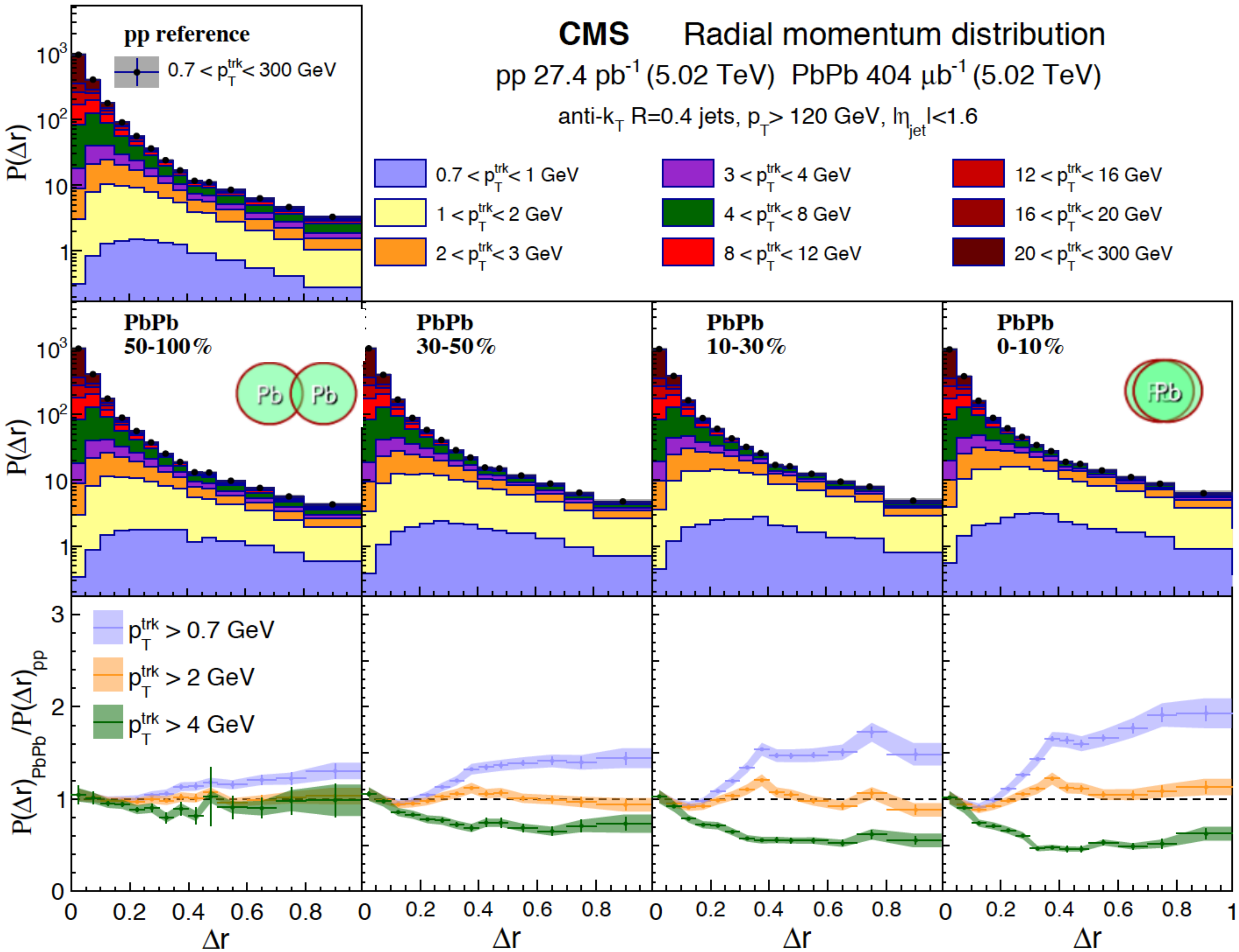
Sensitive to virtuality of initial parton

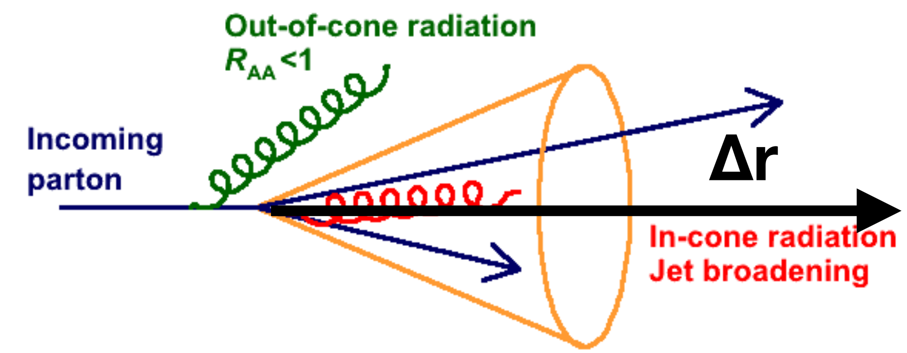
$$\langle M^2 \rangle \simeq \left. \begin{array}{l} \text{quarks: } 0.16 \\ \text{gluons: } 0.37 \end{array} \right\} \times \alpha_s p_{\mathrm{T}}^2 R^2$$

fragmentation function	$D(z) = \left\langle \sum_{i \in \text{jet}} \delta(z - p_{ti}/p_{t,\text{jet}}) \right\rangle_{\text{jets}}$	
differential jet shape	$\rho(r) = \frac{1}{p_\perp^{\text{jet}}} \sum_{\substack{k \text{ with} \\ \Delta R_{kJ} \in [r, r+\delta r]}} p_\perp^{(k)}$,	
girth ≡ broadening	$g = \frac{1}{p_\perp^{\text{jet}}} \sum_{k \in J} p_\perp^{(k)} \Delta R_{kJ}$,	
jet mass, groomed & ungroomed	$m^2 = \left(\sum_{i \in (\text{sub})\text{jet}} p_i^\mu \right)^2$	
z_g, ΔR_{12}	$z_g = \frac{\min(p_{\perp,1}, p_{\perp,2})}{p_{\perp,1} + p_{\perp,2}} > z_{\text{cut}} \left(\frac{\Delta R_{1,2}}{R_J} \right)^\beta$	

Radial distribution differential in p_T

arXiv:1803.00042





Sizeable modifications observed

Expect similar modifications for jet shape observables
+ larger sensitivity to event-by-event fluctuations.

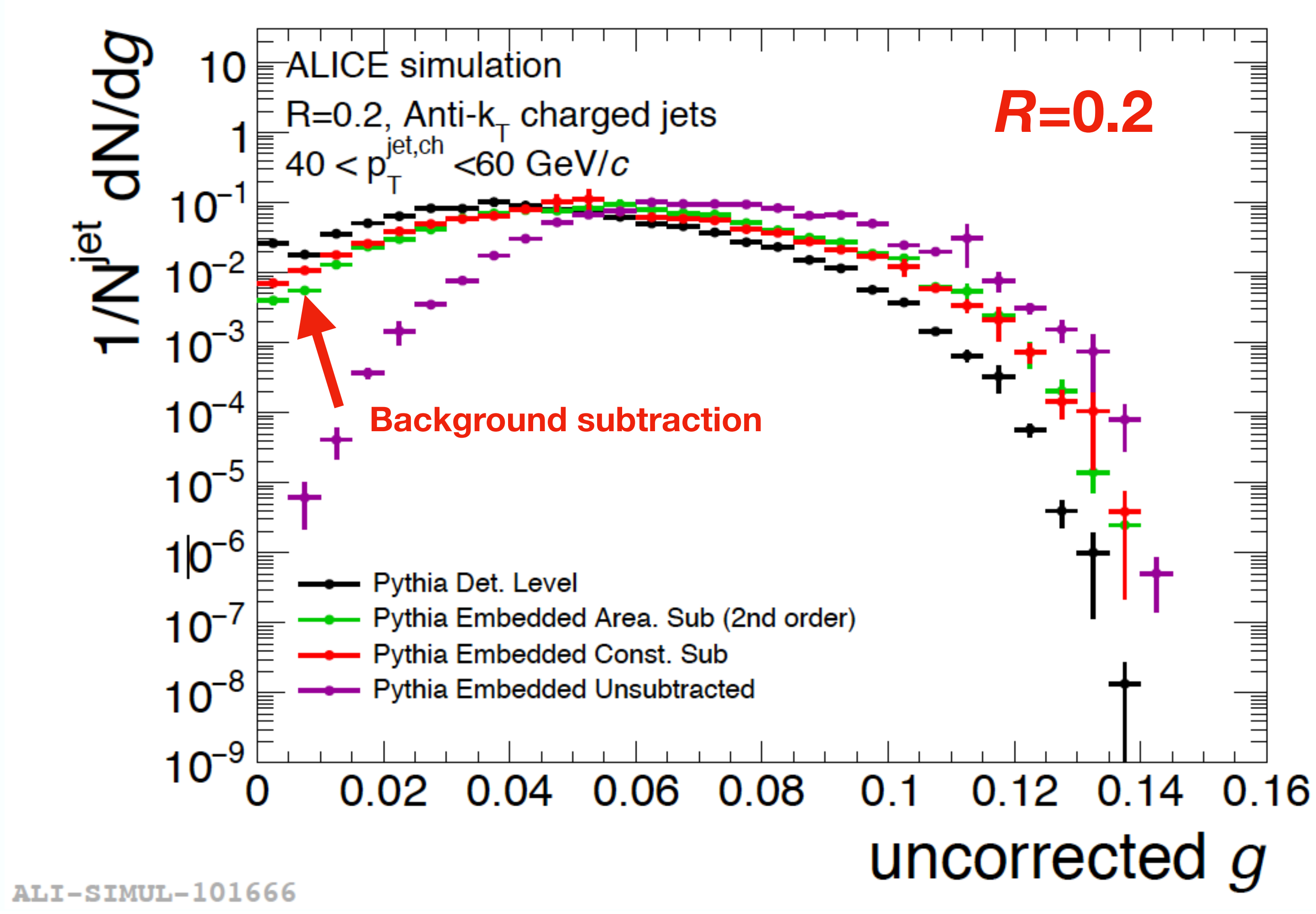
Jet Shape Corrections

The good news: We have learnt how to fully correct these observables

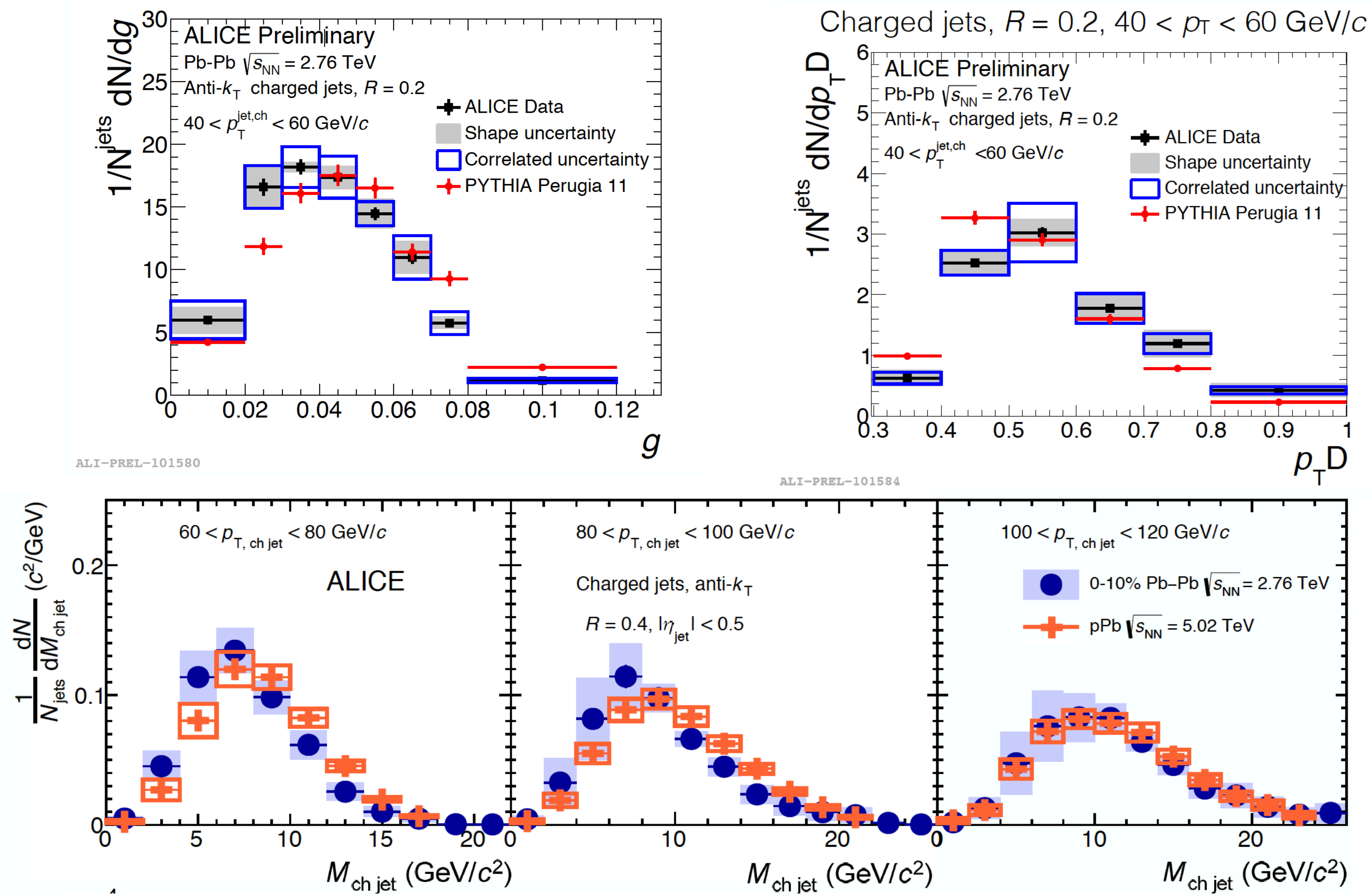
Average background removal for jet shapes based on recent techniques

- Derivatives (area based) subtraction [G Soyez et al, PRL 110 (2013) 16]
- Constituent subtraction [P Berta et al, JHEP 1406 (2014) 092]

+ 2D Bayesain Unfolding



Jet Shape Observables



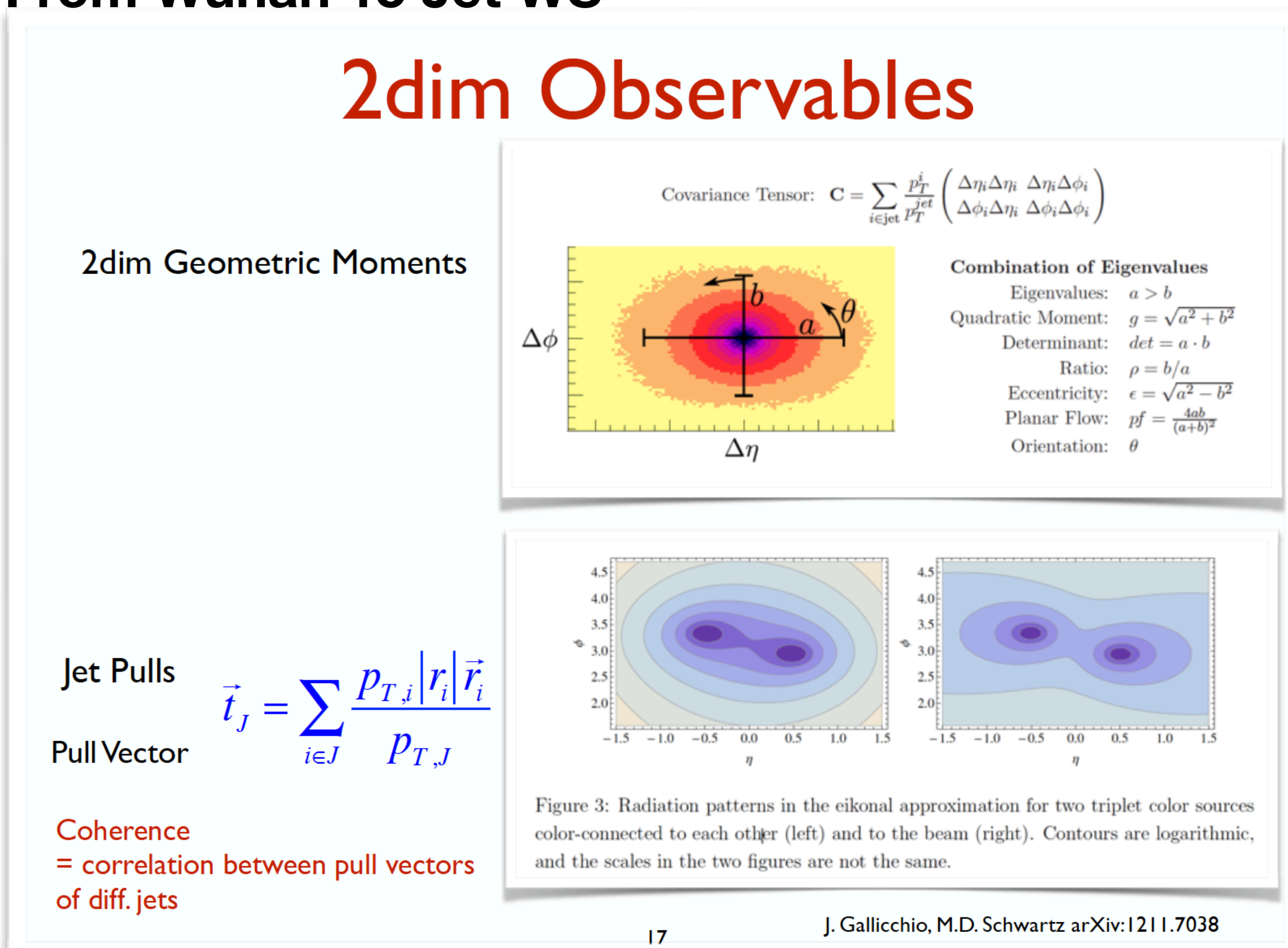
Very “mild” modifications, consistent with hardening of the jet core and small mass shift.

Challenges: go to larger *R*, design more sensitive shapes, or ..

Use apparent invariance of jet core as an advantage:

- Select (“engineer”) different hard configuration
- Study soft particle flow with respect to hard skeleton

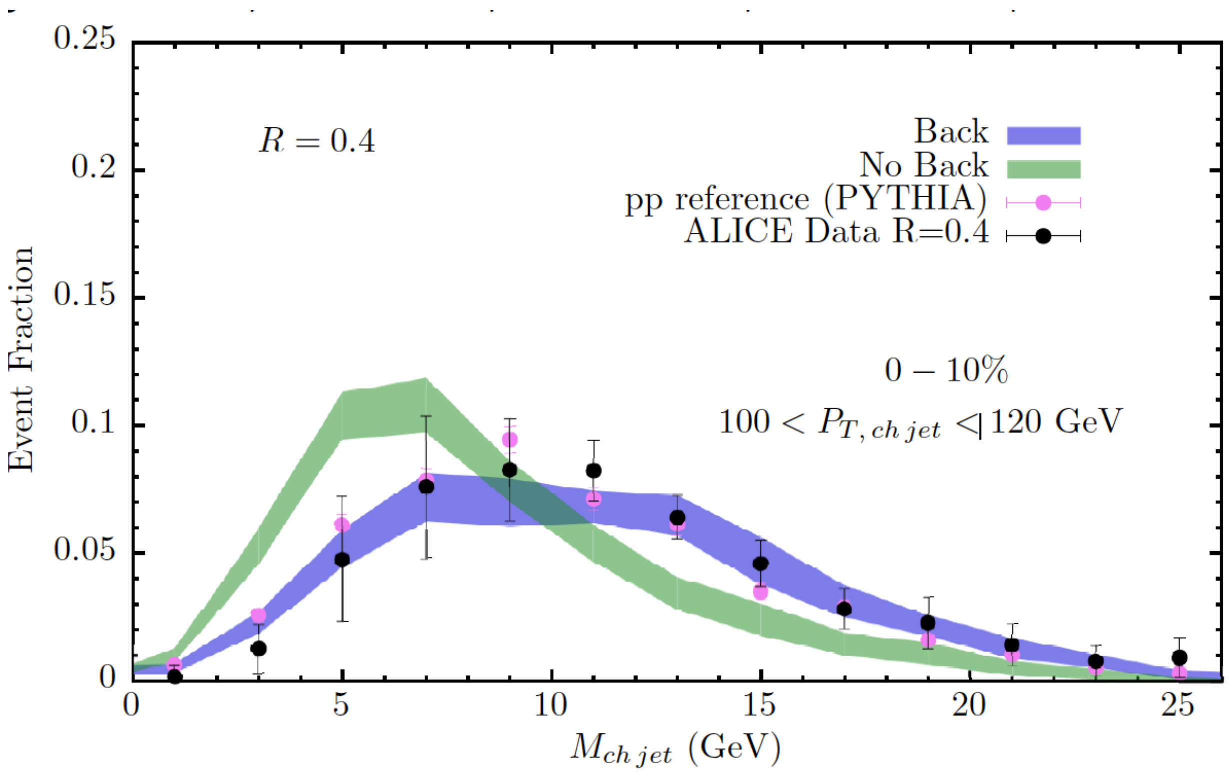
From Wuhan’15 Jet WS



Medium Response vs Modified Showers

Are we just unlucky ?

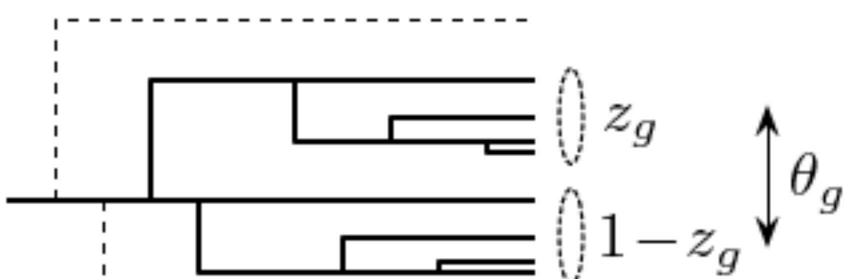
weak / strong coupling Hybrid
Casalderrey-Solana, Gulhan, Hulcher, Milhano, Pablos, Rajagopal, 2017



Mass sensitive to medium back-reaction
Two competing effects:

- stronger quenching of high mass jets
- angular broadening

Distinguish scenarios with groomed jet mass ?

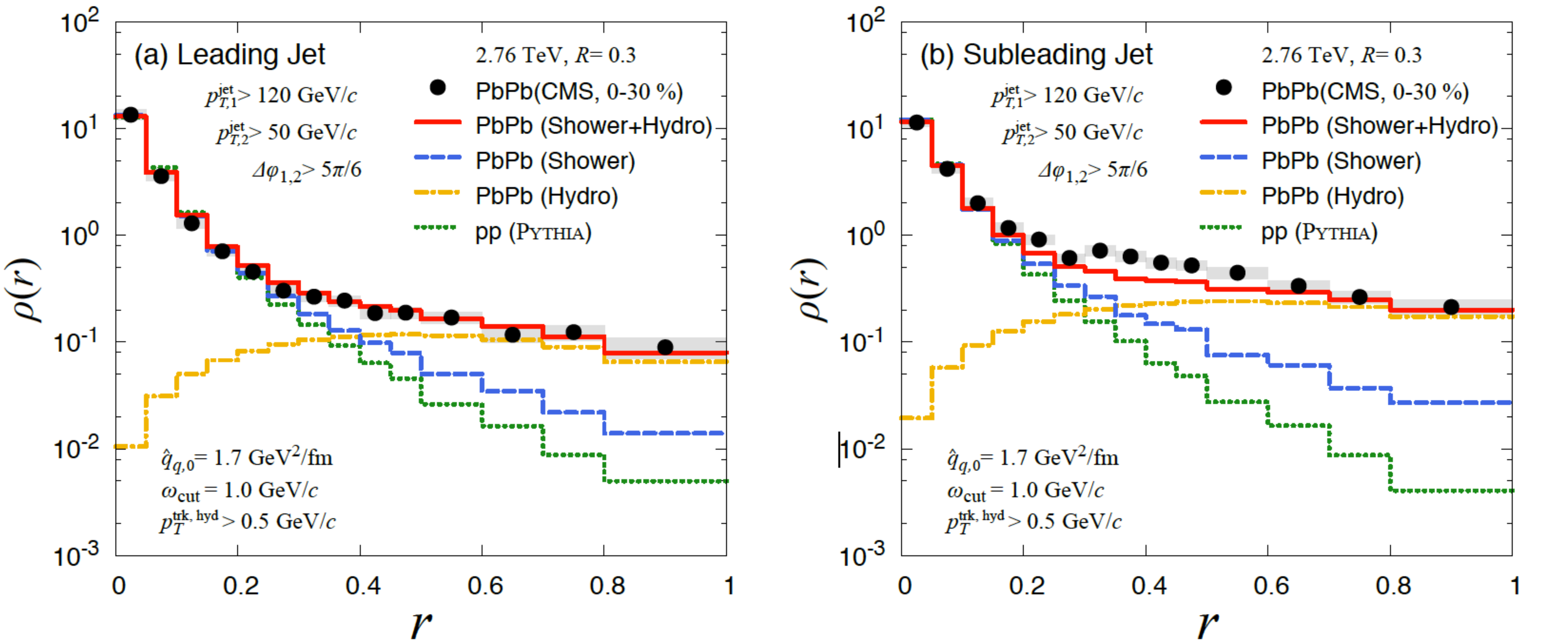


$$z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} > z_{cut} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}.$$

Two sets of soft drops (SD) conditions:

(SD1) z_{cut} = 0.1 β=0 (same cut for all angles)
(SD2) z_{cut} = 0.5 β=1.5 (harder cuts for large angles)

Medium Back-Reaction



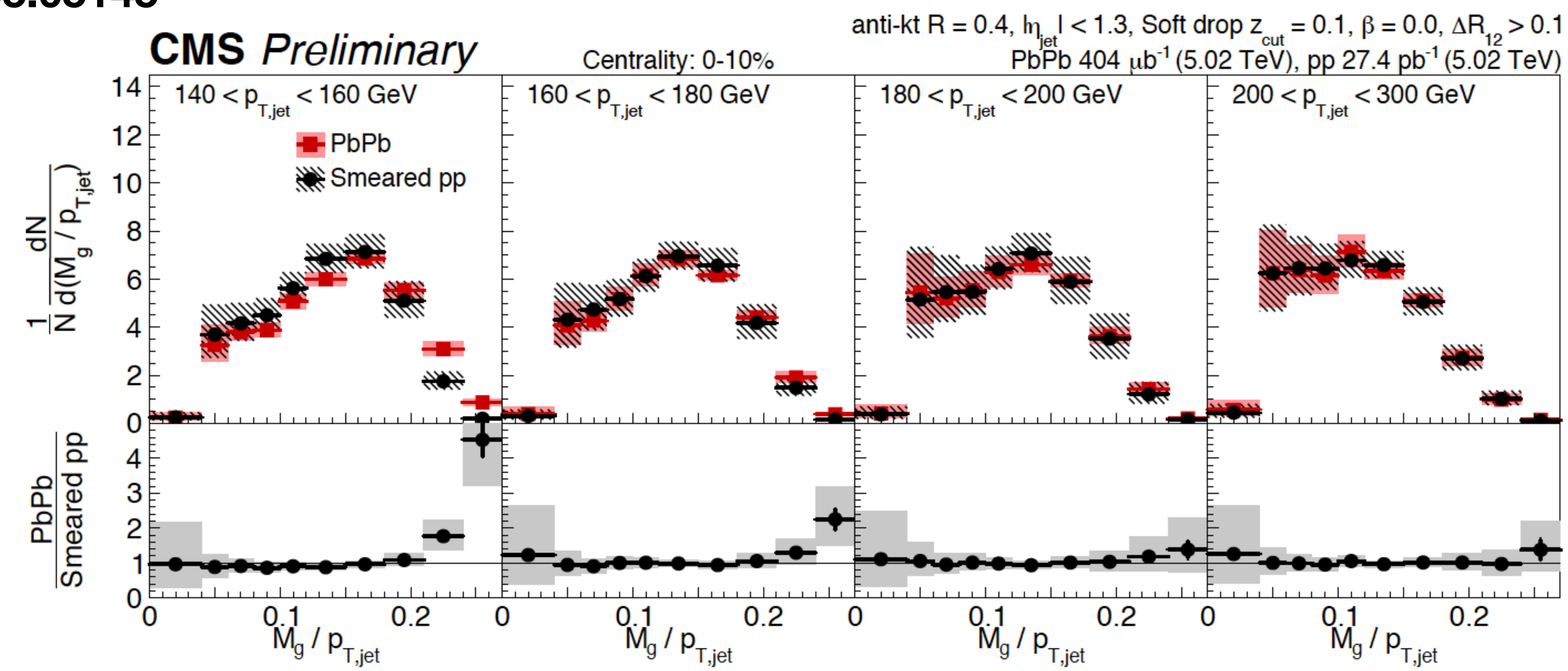
Hydro needed to describe tails

Y Tachibana, N-B Chang and G-Y Qin, arXiv: 1701.0795

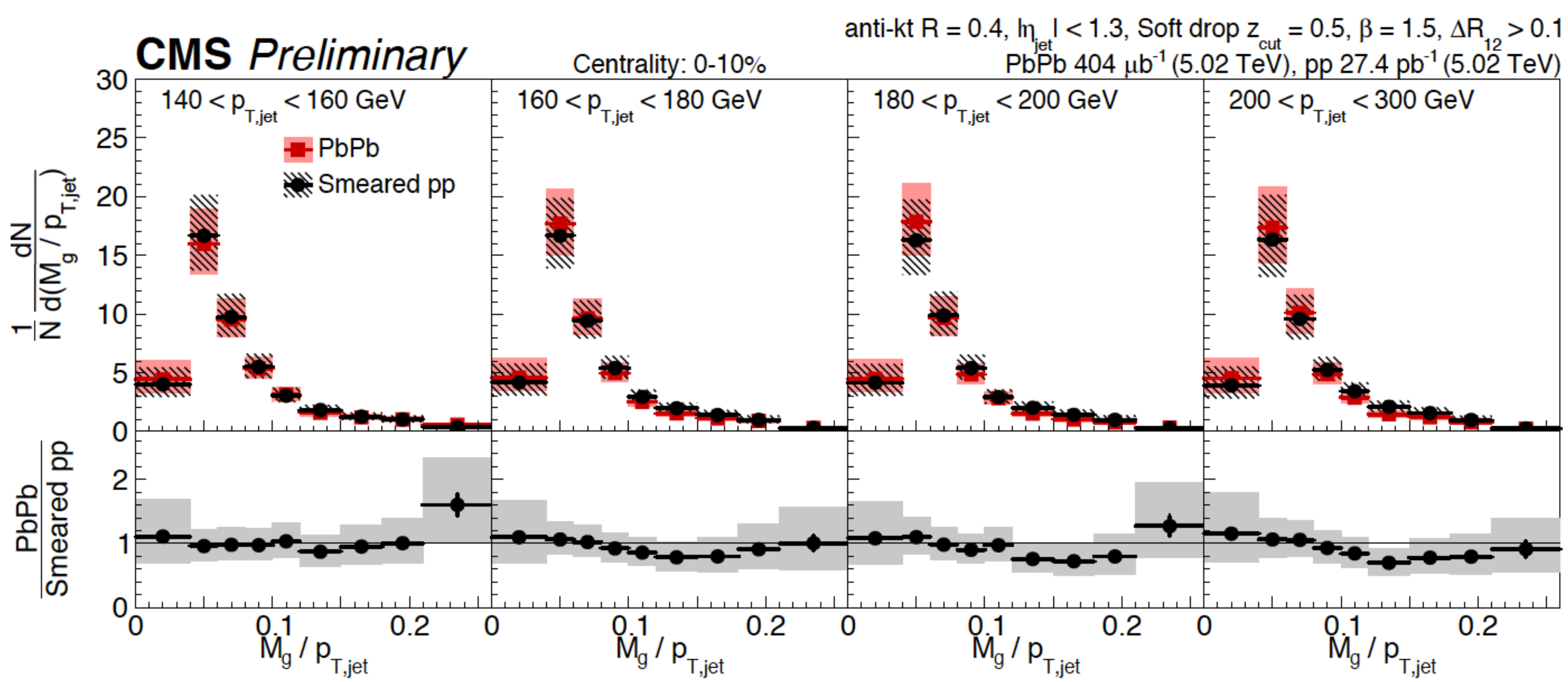
Groomed Jet Mass

arXiv:1805.05145

SD1

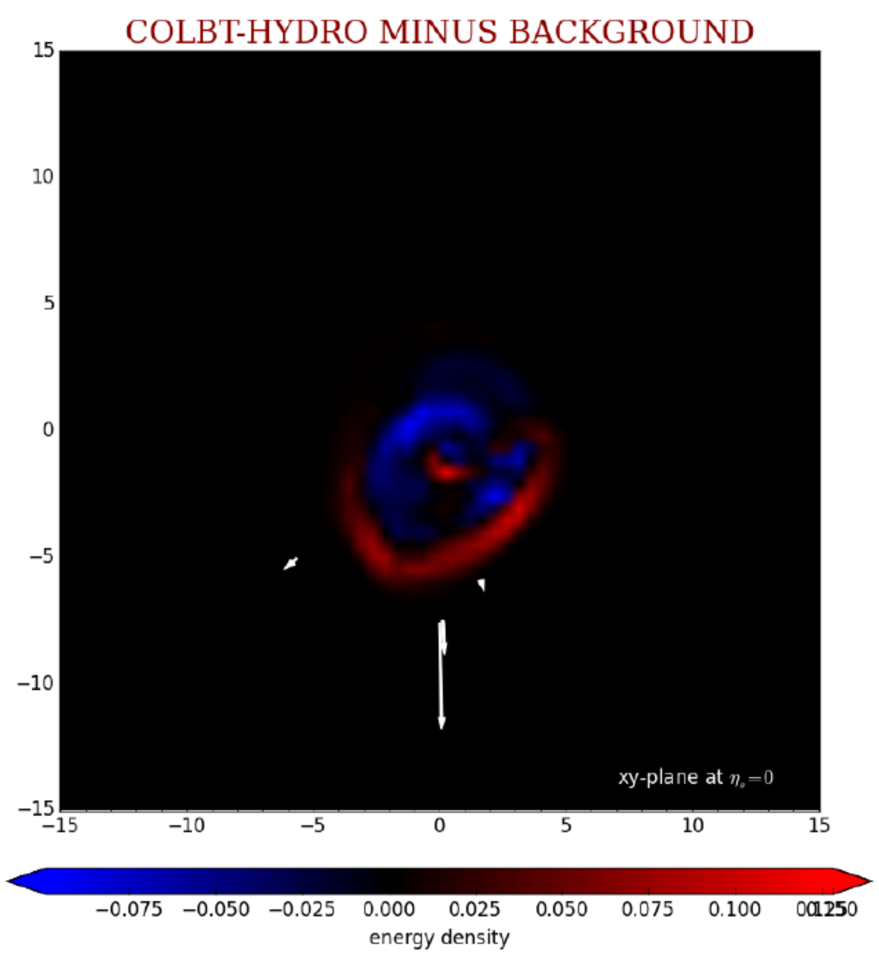


SD2

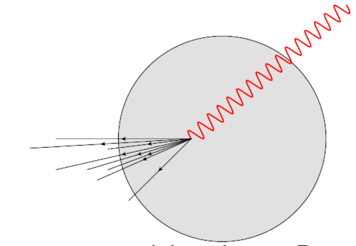


Medium Back-Reaction

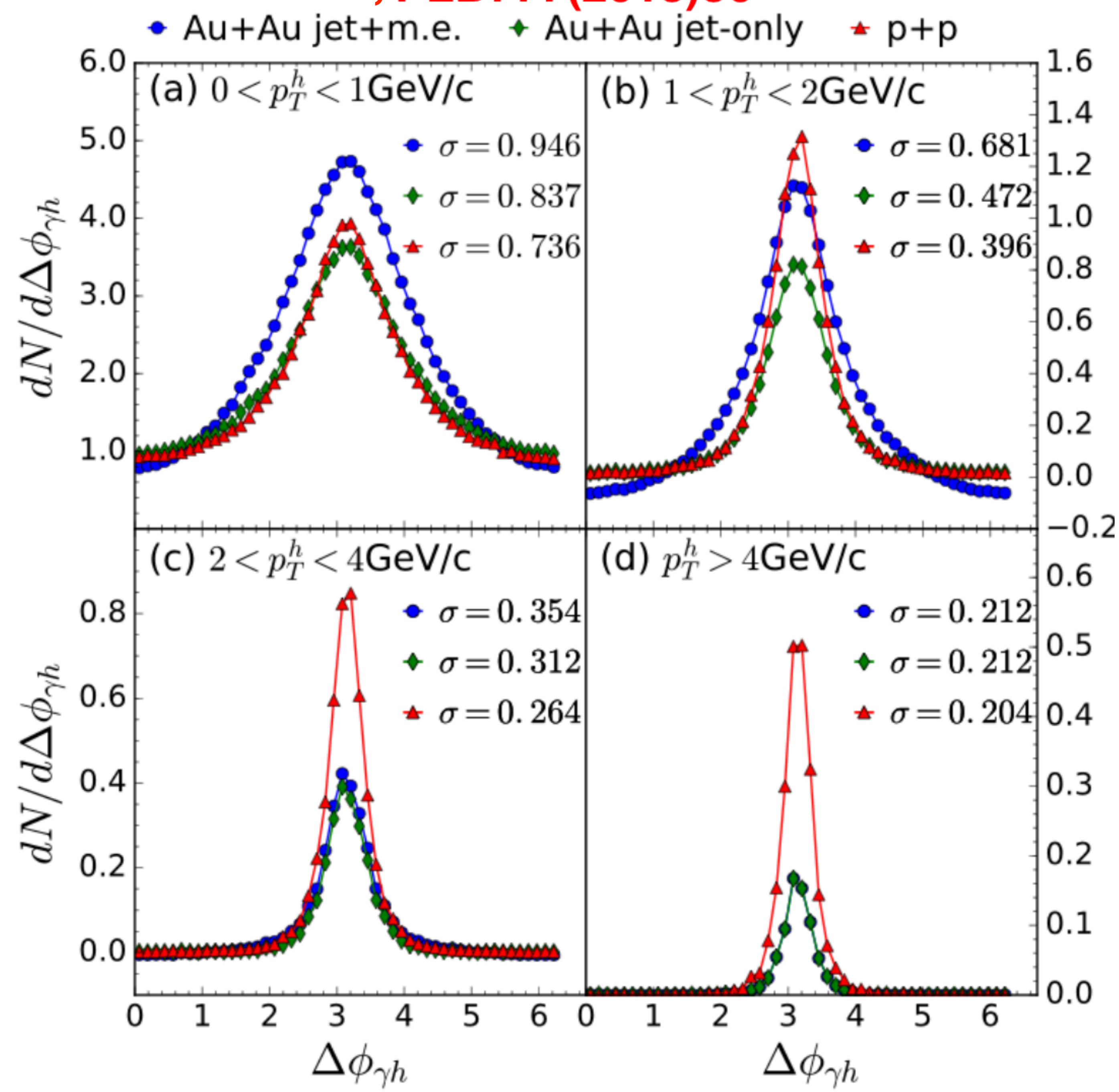
How to distinguish
medium response vs modified showers?



hadron-γ azimuthal correlations



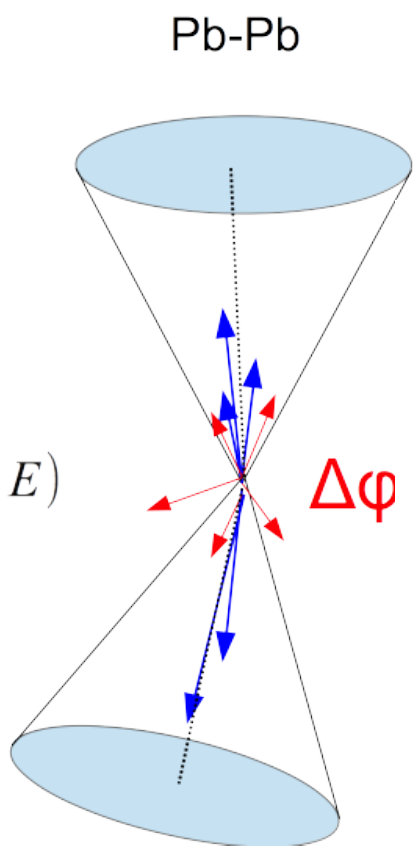
W Chen et al., PLB777(2018)86



Distinct features

- Increase of soft hadron production with increased width
- depletion in γ direction

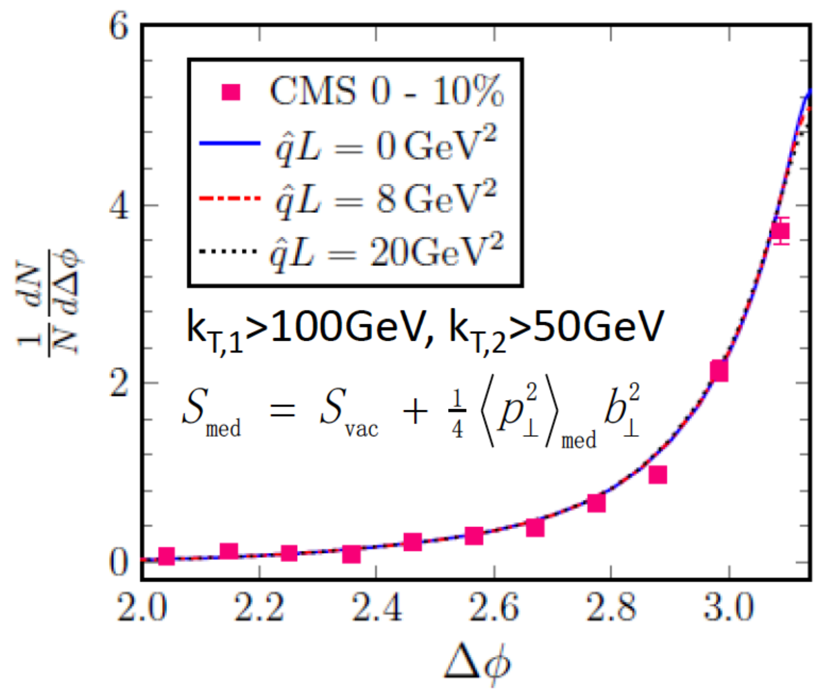
Di-Jet Azimuthal Correlations

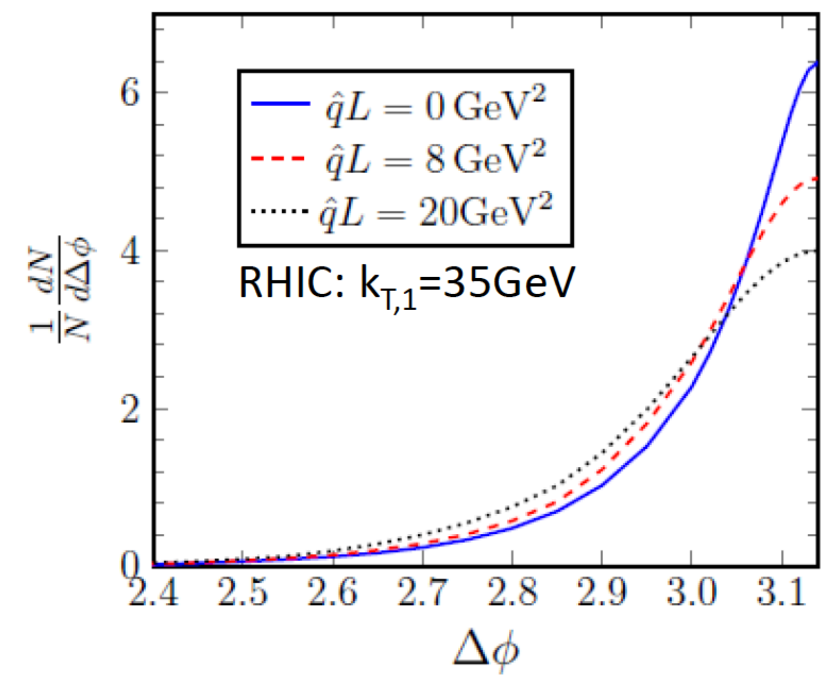


$$\langle \Delta q_T^2 \rangle = \int dy\, \hat{q}(y, E)$$

J. Casalderrey-Solana and XNW
arXix: 0705.1352 [hep-ph]

Mueller, Wu,Xiao,Yuan PLB763 (2016)



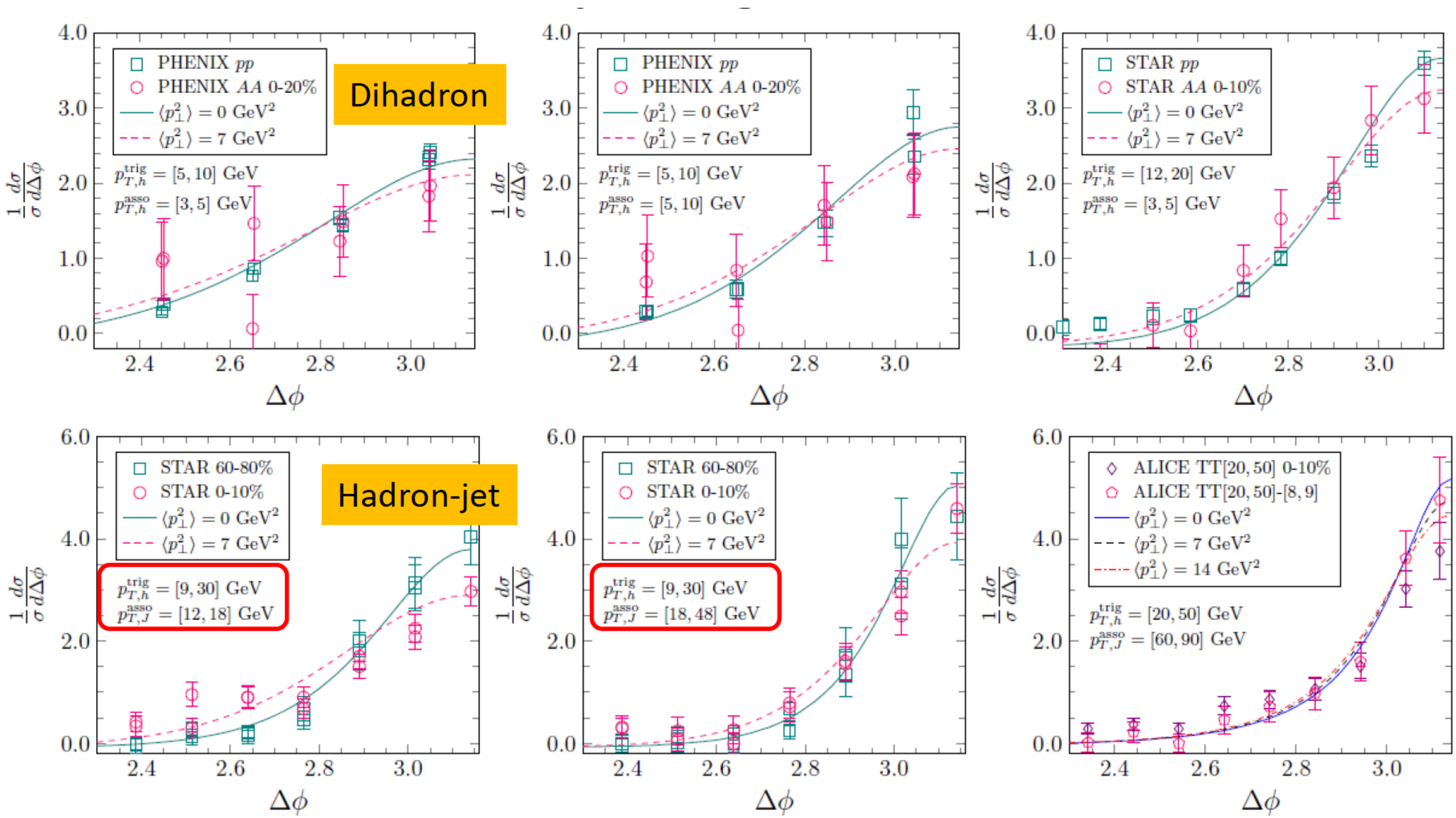


LHC: Sudakov broadening (ISR, FSR) dominates over medium-induced broadening

RHIC: The two effects are of comparable size

\+ possible (rare) large angle deflections
sensitive to quasi particle structure of the medium

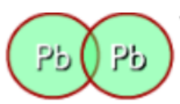
Di-Hadron and h-Jet Azimuthal Correlations

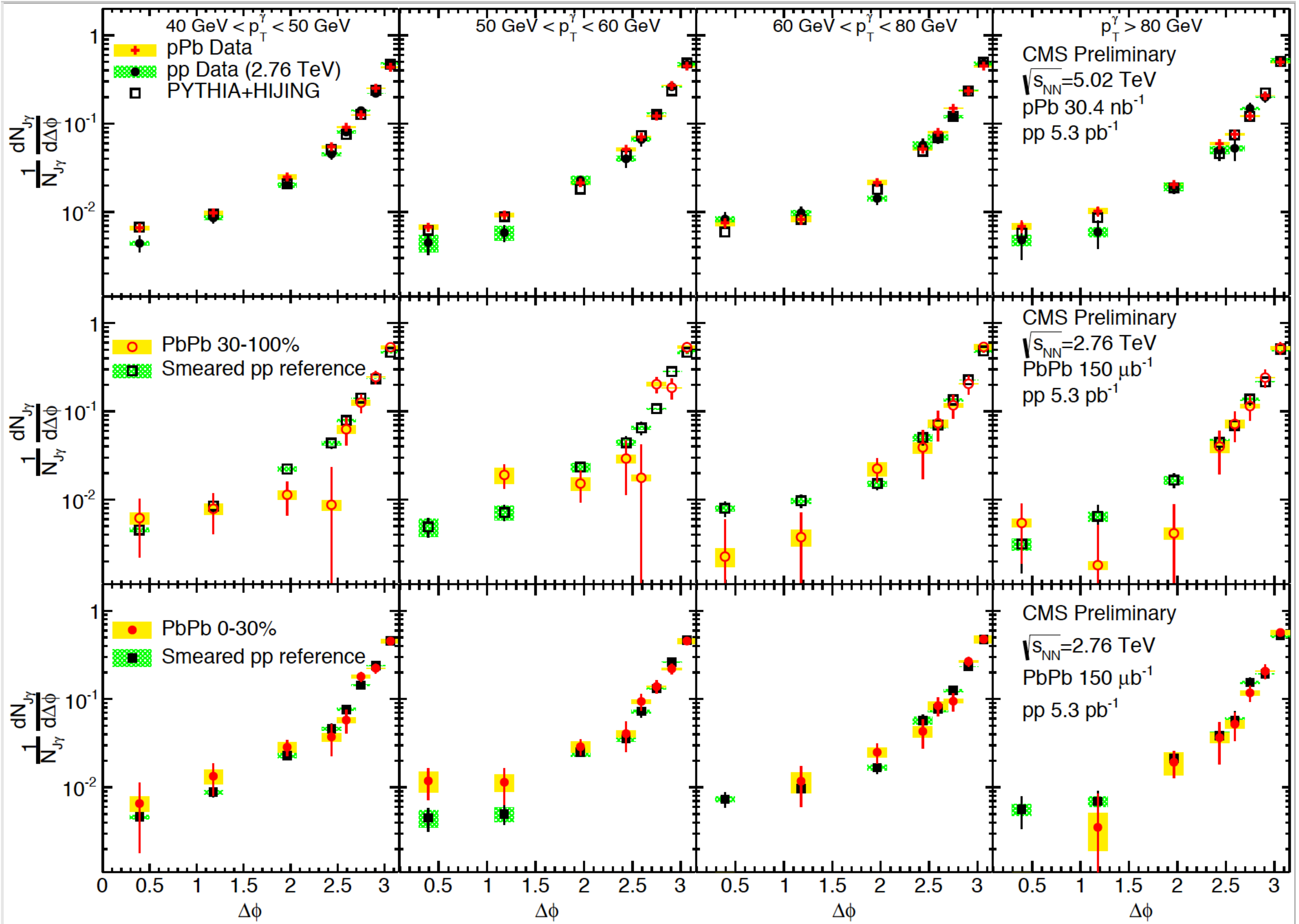


RHIC: at the edge of sensitivity

γ-Jet Δϕ-Correlations LHC

pp, pPb

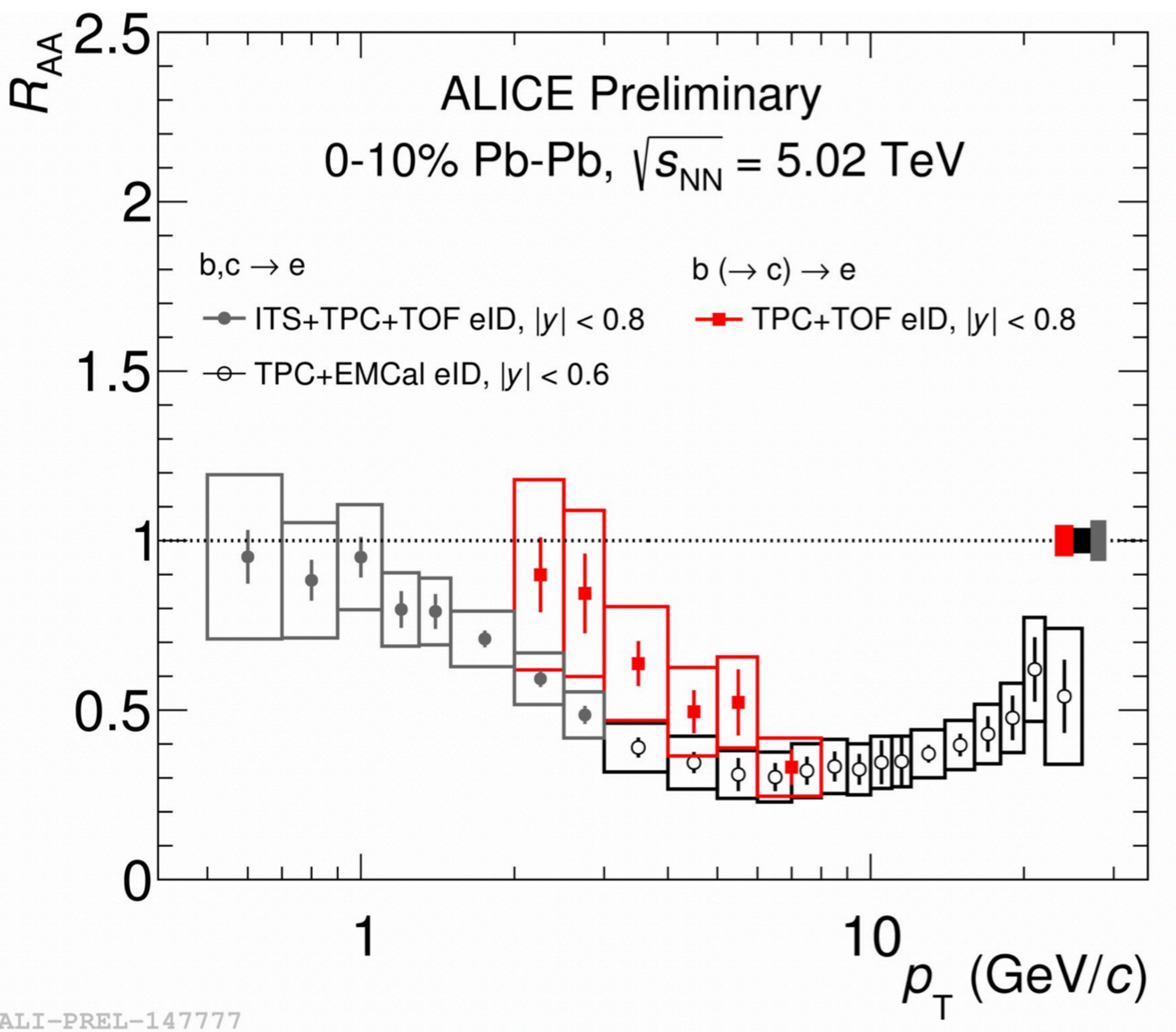


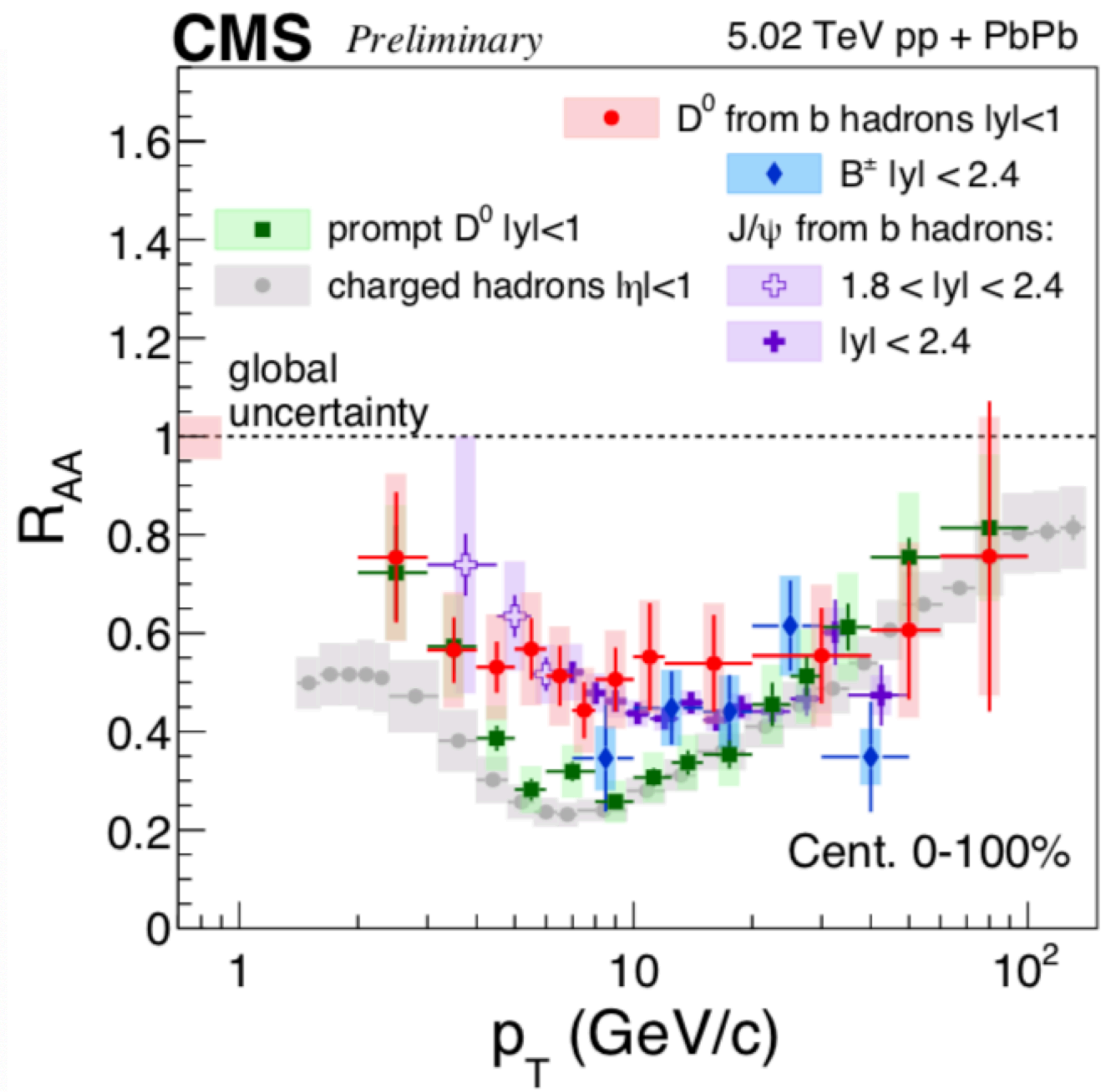


p_T^γ

No significant broadening observed.

Parton Mass Dependent Energy Loss



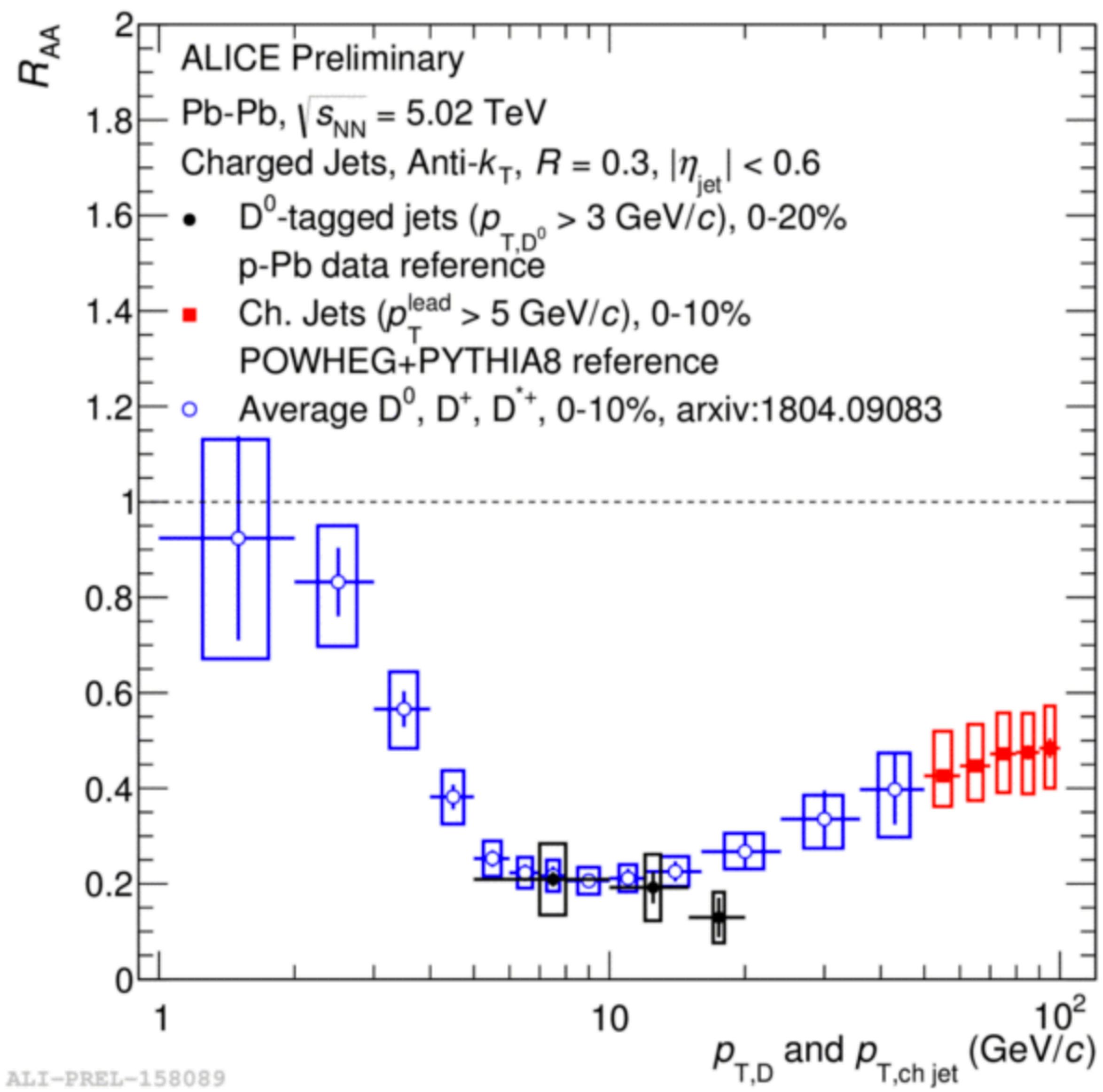


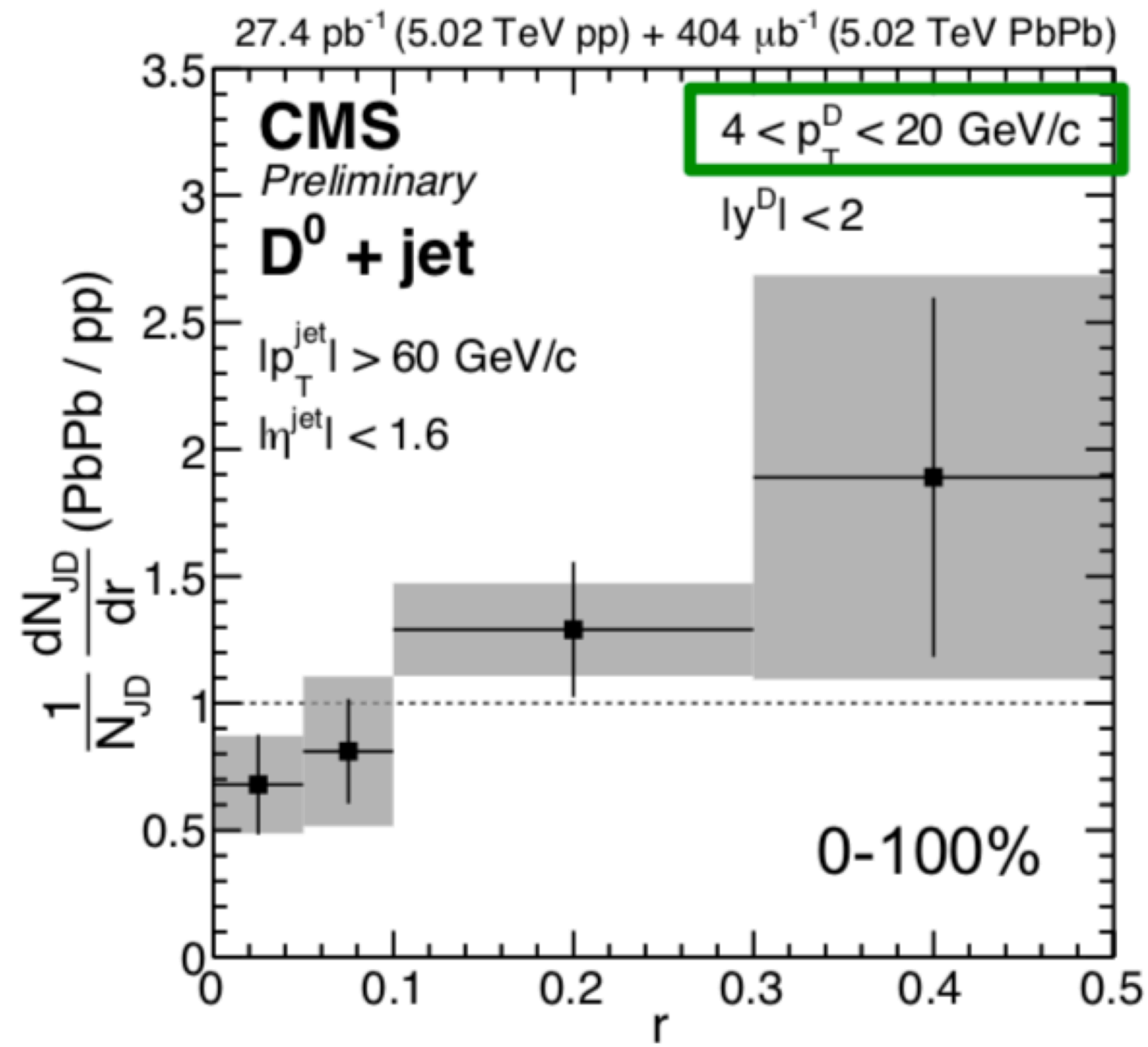
Low and intermediate p_T smaller suppression of

- electrons from b wrt b+c
- non-prompt J/Ψ and D from B wrt to direct production

High p_T similar suppression

Heavy Flavour Tagged Jets

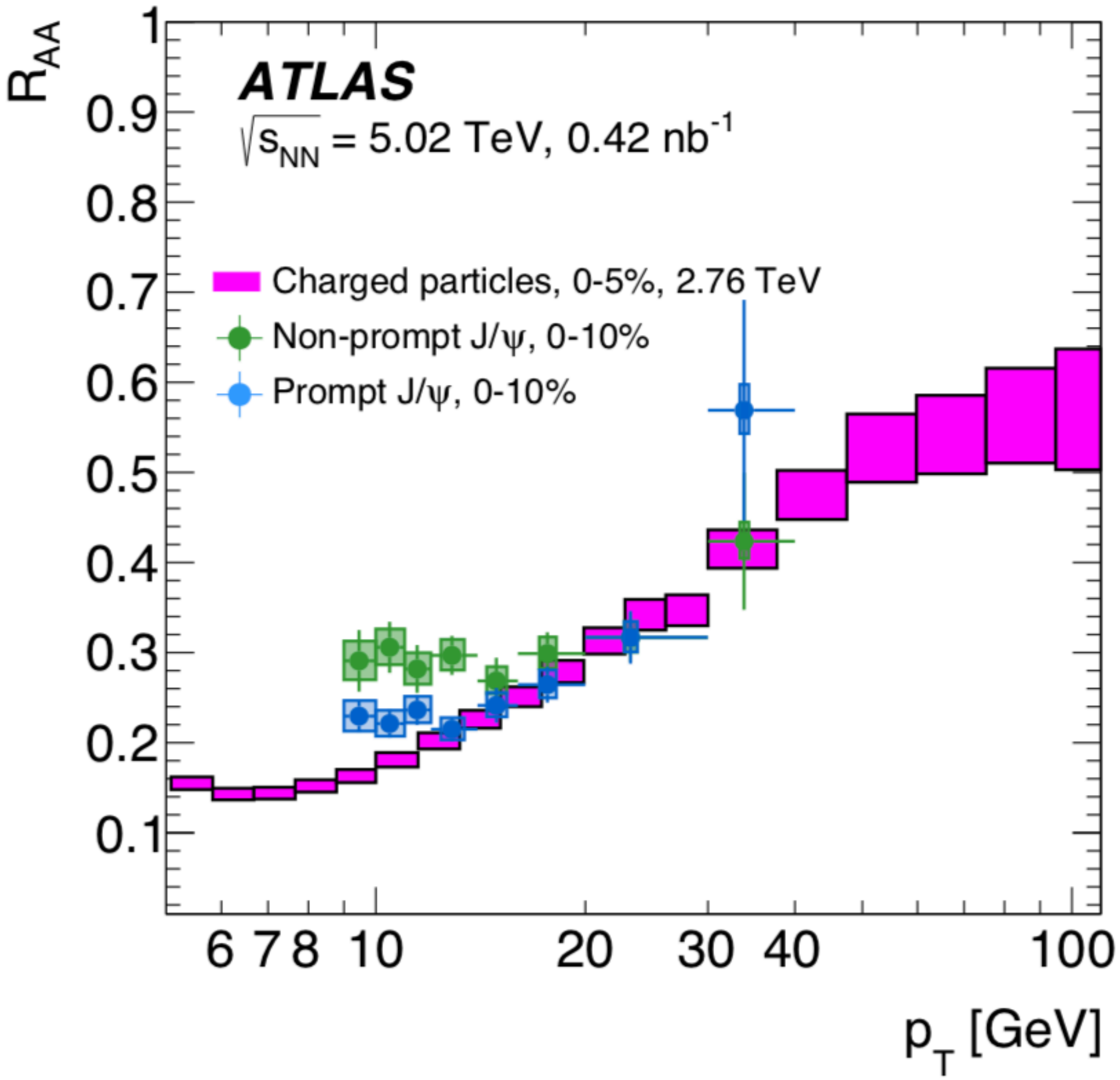




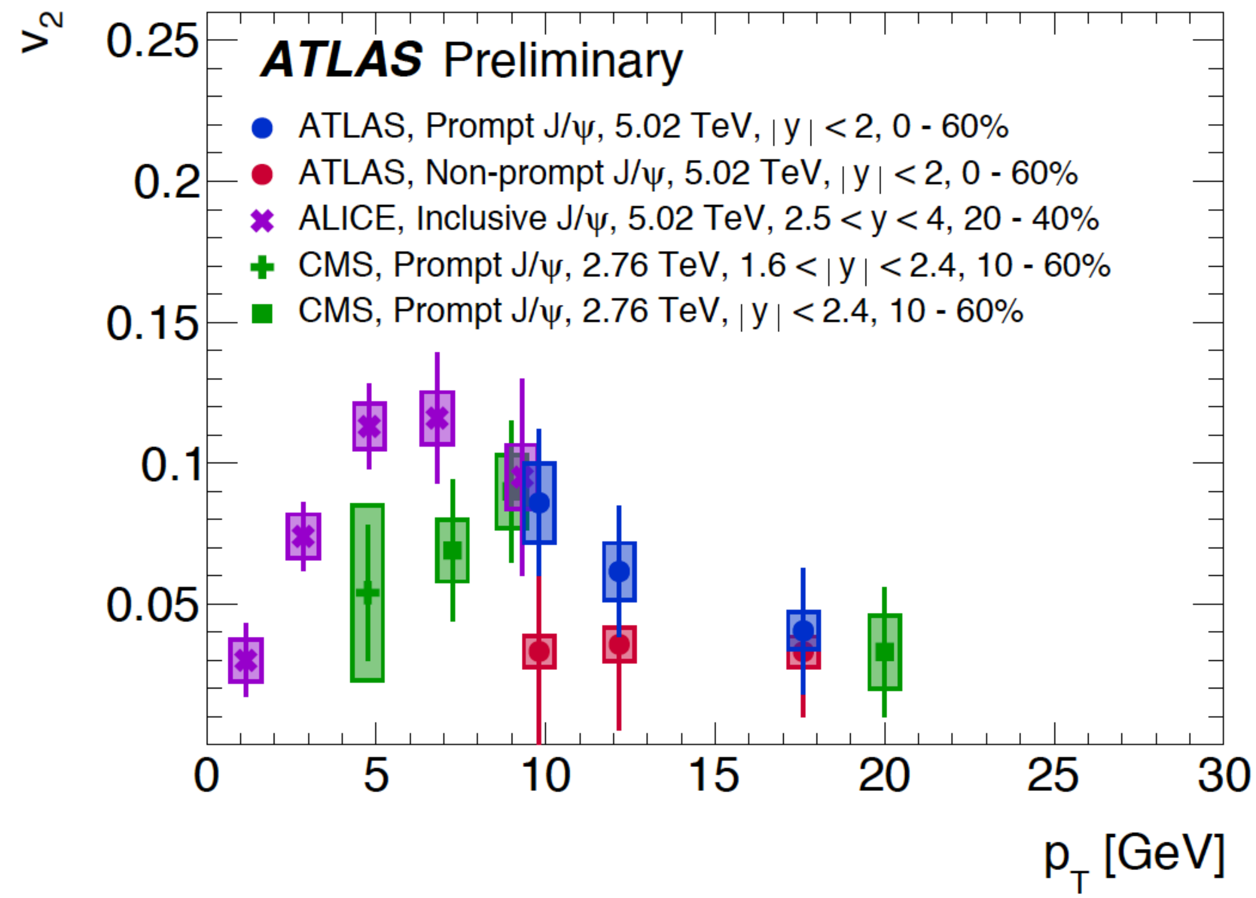
Similar R_{AA} for D-tagged Jets and charged jets

Hint of D^0 at low p_T appearing at large angles.

J/Ψ Suppression at High p_T



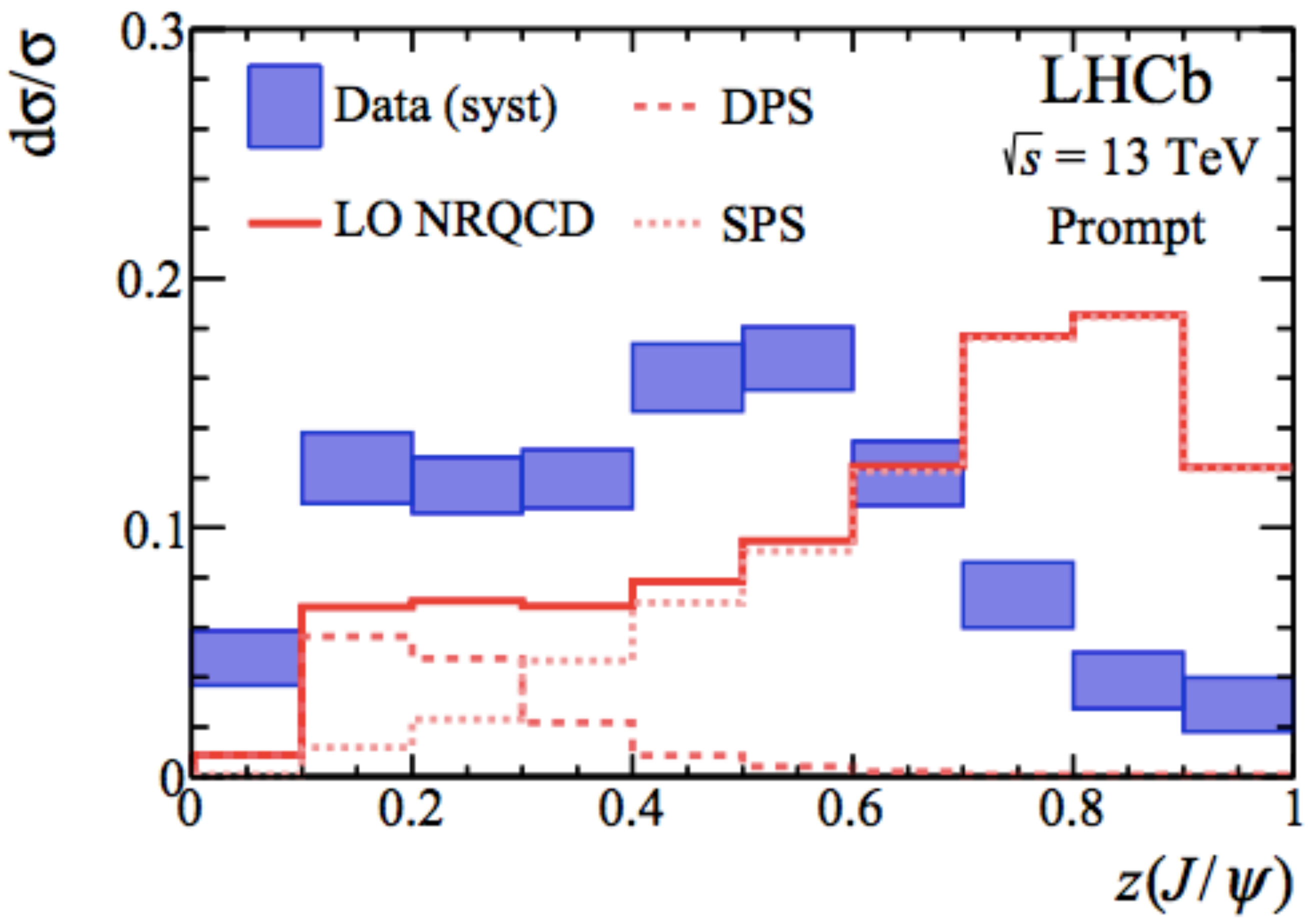
Prompt J/Ψ suppression similar to charged particles

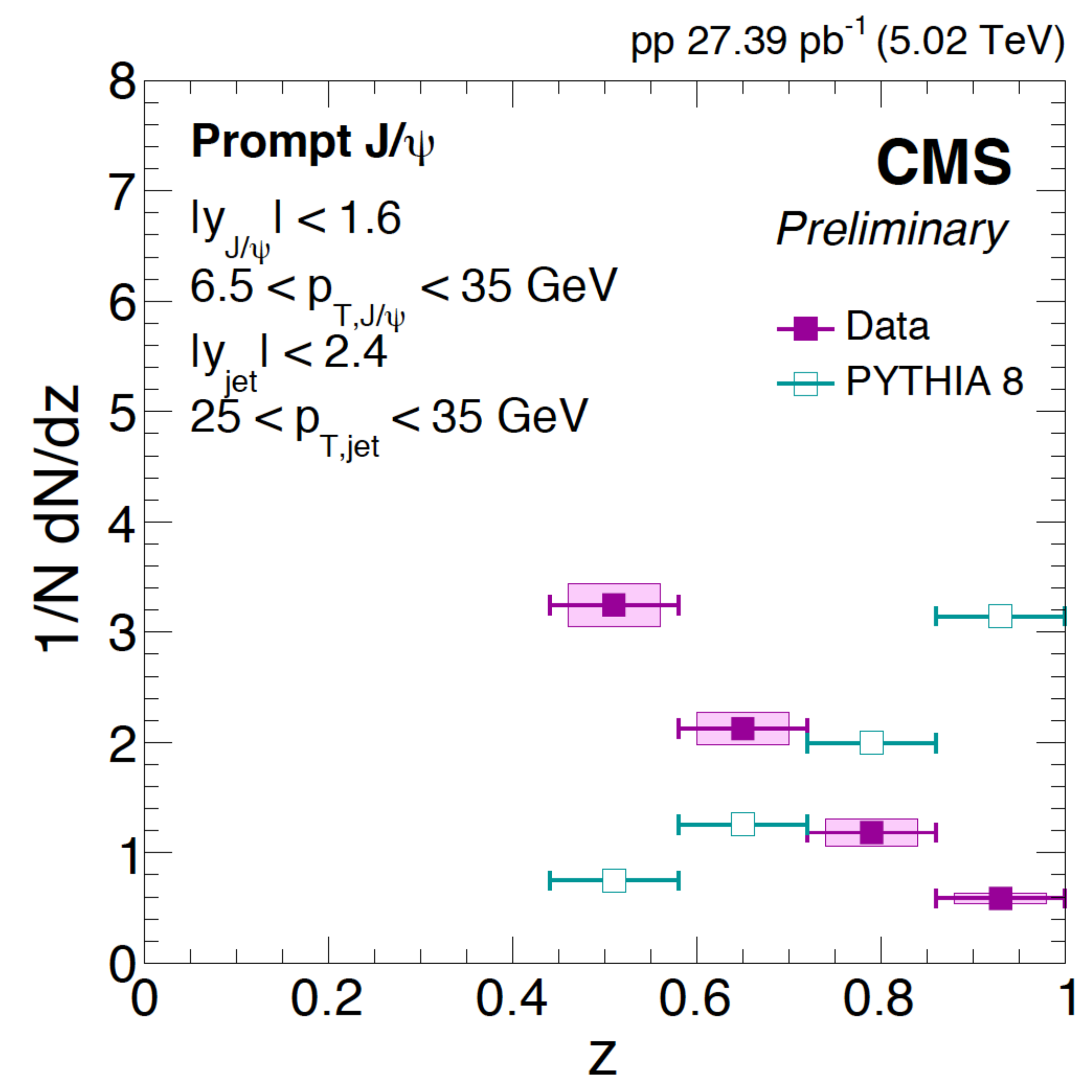


Finite v_2 at high p_T: path length dependence ?

Only a coincidence ?

J/Ψ in Jets





High p_T J/Ψ accompanied by sizeable amount of hadronic activity.
Not understood with standard event generator.
Consequences for high-p_T J/Ψ suppression ?

My brainstorm chart … add your sticky !

- Systematic study of R_{AA} up to highest possible p_T and as a function of centrality
  - Extend to unmeasured region in p_T for semi-peripheral collisions
  - Close the gap between inclusive jet and hadron suppression

- Un-biased measurements of system-size dependence of "jet quenching"
  - Constrain path length dependence
  - Quenching in small systems

- Jet shapes with increased cone-size
  - Jet shapes as tags for hard structure (jet shape engineering)
  - Particle flow in jet-cone as a function of hard structure (2-dim observables, planar flow)

- Azimuthal correlation studies (h-jet, γ-jet, …, jet-jet) with increase statistics

- γ-jet hadron correlations
  - find clear signal for medium back-reaction

- Quantitative similar R_{AA} at high p_T for all particles (including J/ψ)
  - only a strange coincidence ?
  - more differential studies needed