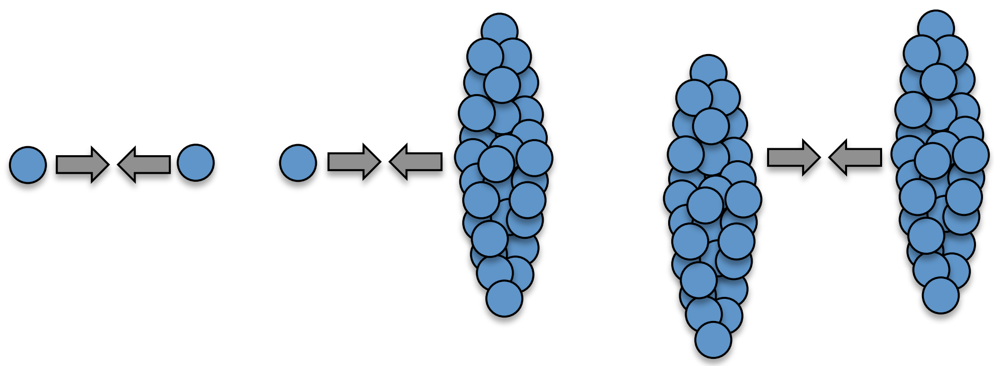
Jets in pp, pA and AA w/ CMS



Matt Nguyen

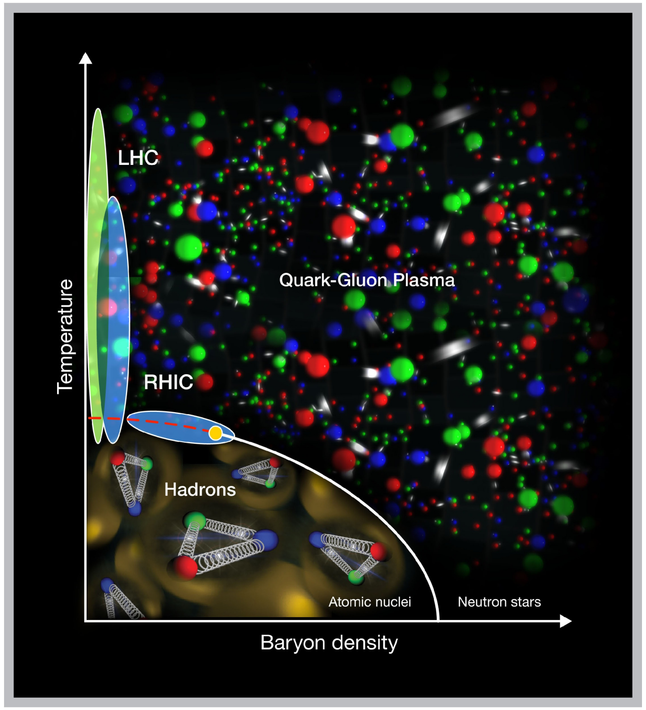
Low x, Bari

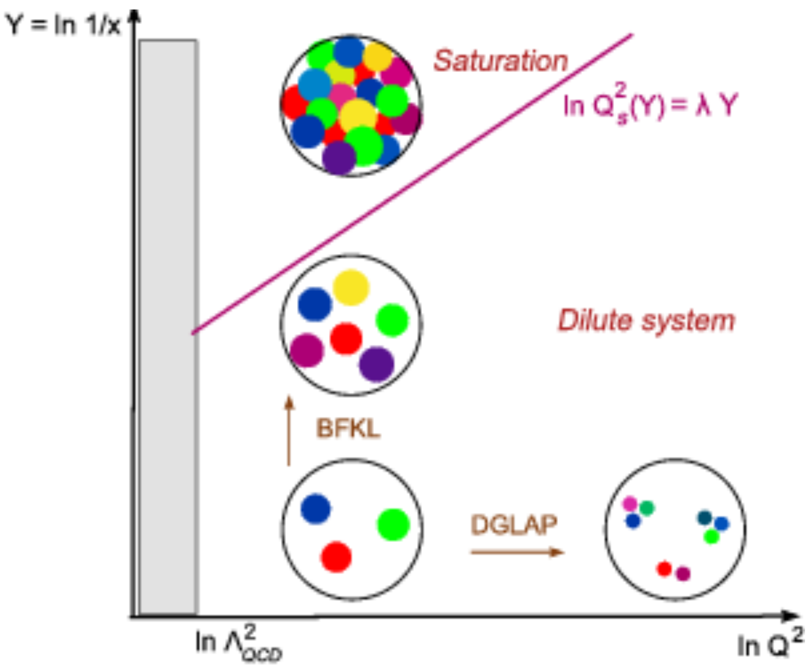
June 17th, 2017

Relativistic nuclear collisions

AA collisions create hot final state, EOS controlled by partonic d.o.f's

but also a dense initial state, where gluon saturation may be important





Aim is to disentangle various initial and final state effects by comparison of pp, pA & AA

The RHIC paradigm (ca. 2005)

The nuclear modification factor, R_{AA}, quantifies departure from *binary scaling*, i.e., expectation from pp in absence of nuclear effects

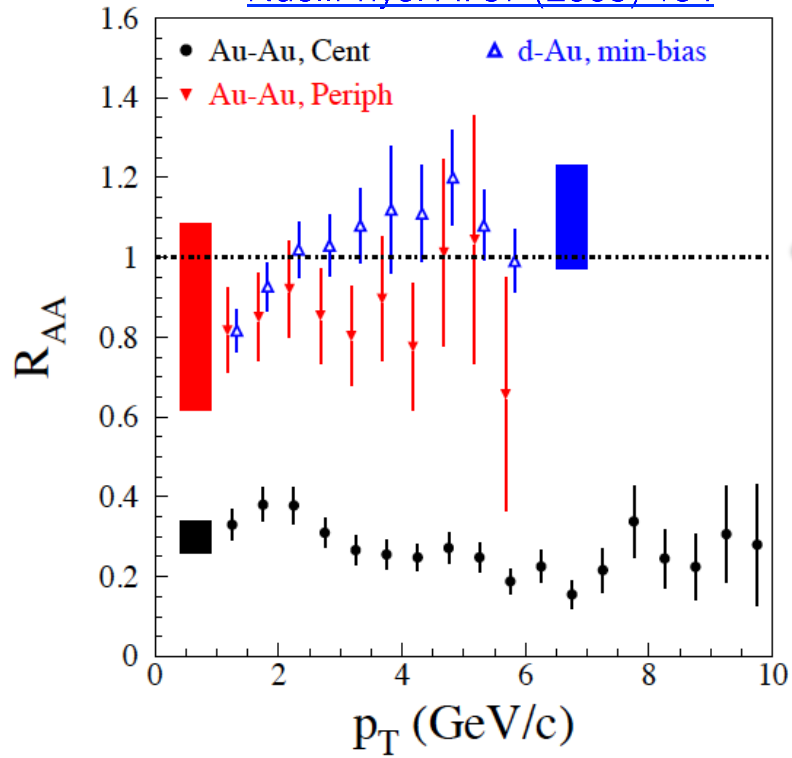
Yield in AA

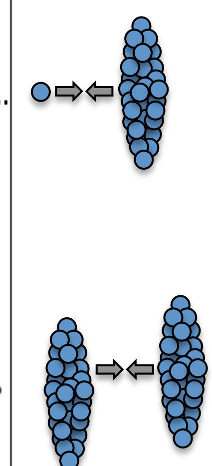
$$R_{\mathrm{AA}} = \frac{\mathrm{d}N^{\mathrm{AA}}/\mathrm{d}p_{\mathrm{T}}}{\langle N_{\mathrm{coll}}\rangle\, \mathrm{d}N^{\mathrm{pp}}/\mathrm{d}p_{\mathrm{T}}}$$

Expected yield in pp,
for no nuclear effects

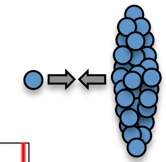
- R_{AA} near unity in pA interpreted as small "cold nuclear matter effects"
- Suppressed R_{AA} in AA interpreted as large "hot nuclear matter effects"

PHENIX "White paper", [Nucl.Phys. A757 (2005) 184]

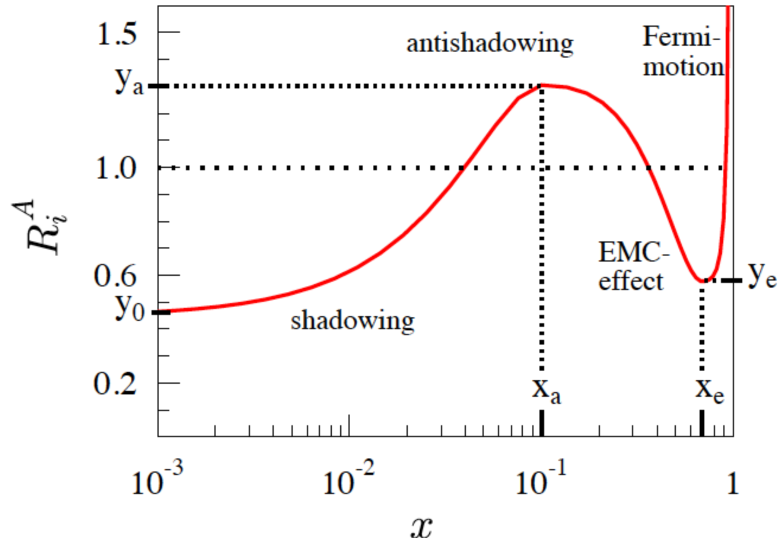


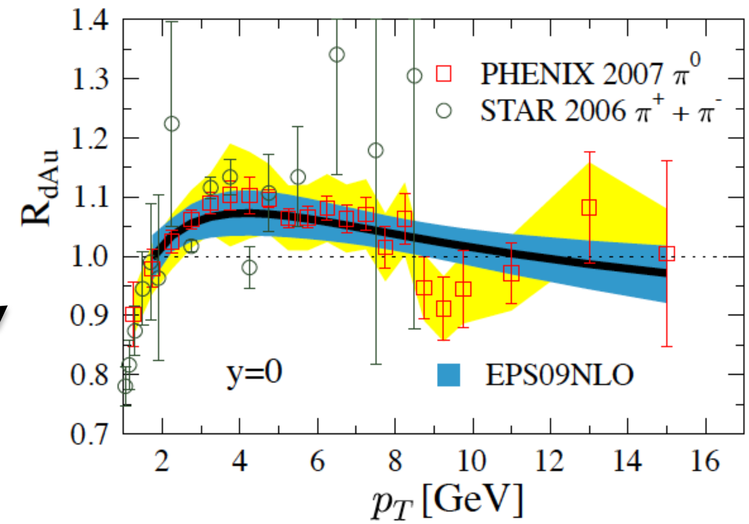


Initial state @ RHIC



- Several nuclear effects on PDFs known from DIS
- Moderate effects at mid-rapidity at RHIC energy
- Gluon distribution poorly constrained at any x
- Lack of clean inputs into nPDF fits at RHIC

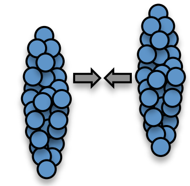




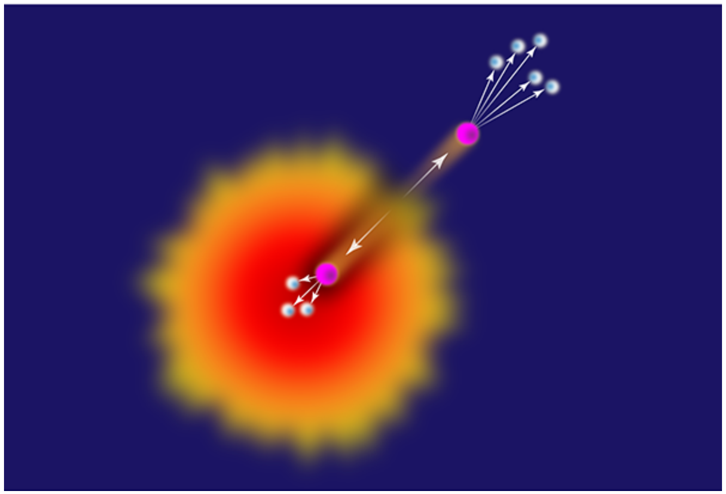
Neutral pion pA data from RHIC

"EPS09: a New Generation of NLO and LO Nuclear Parton Distribution Functions" Eskola et al., JHEP 0904 (2009) 065

Jet quenching @ RHIC

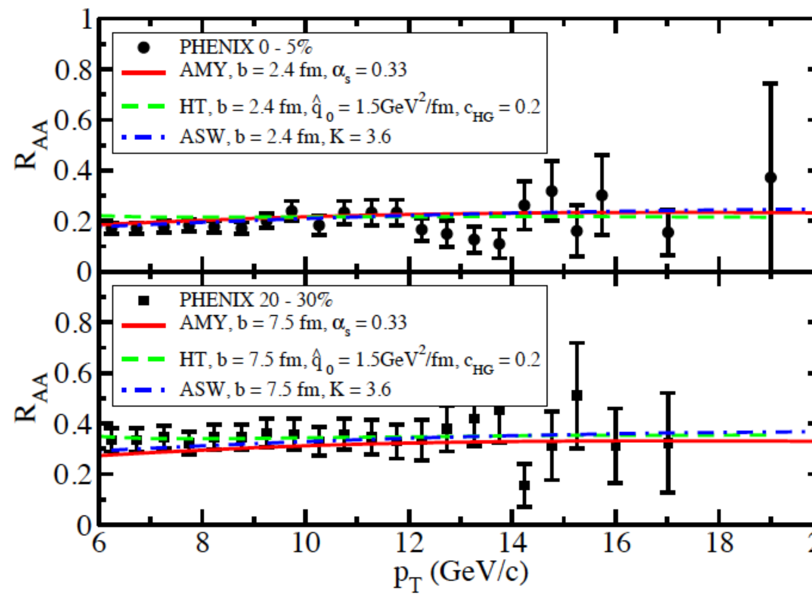


Embedding a hard scattering in a dense QCD medium



From C. Manuel, “The Stopping Power of Hot Nuclear Matter”

“Systematic Comparison of Jet Energy-Loss Schemes in a 3D hydrodynamic medium”
Bass et al., [J.Phys. G35 (2008) 104064]



Parton energy loss w/ pQCD:

$$d\sigma = \underbrace{f(x_a)\otimes f(x_b)}_{\text{(Nuclear) PDFS}} \otimes d\hat{\sigma} \otimes P(\Delta E) \otimes D(z)$$

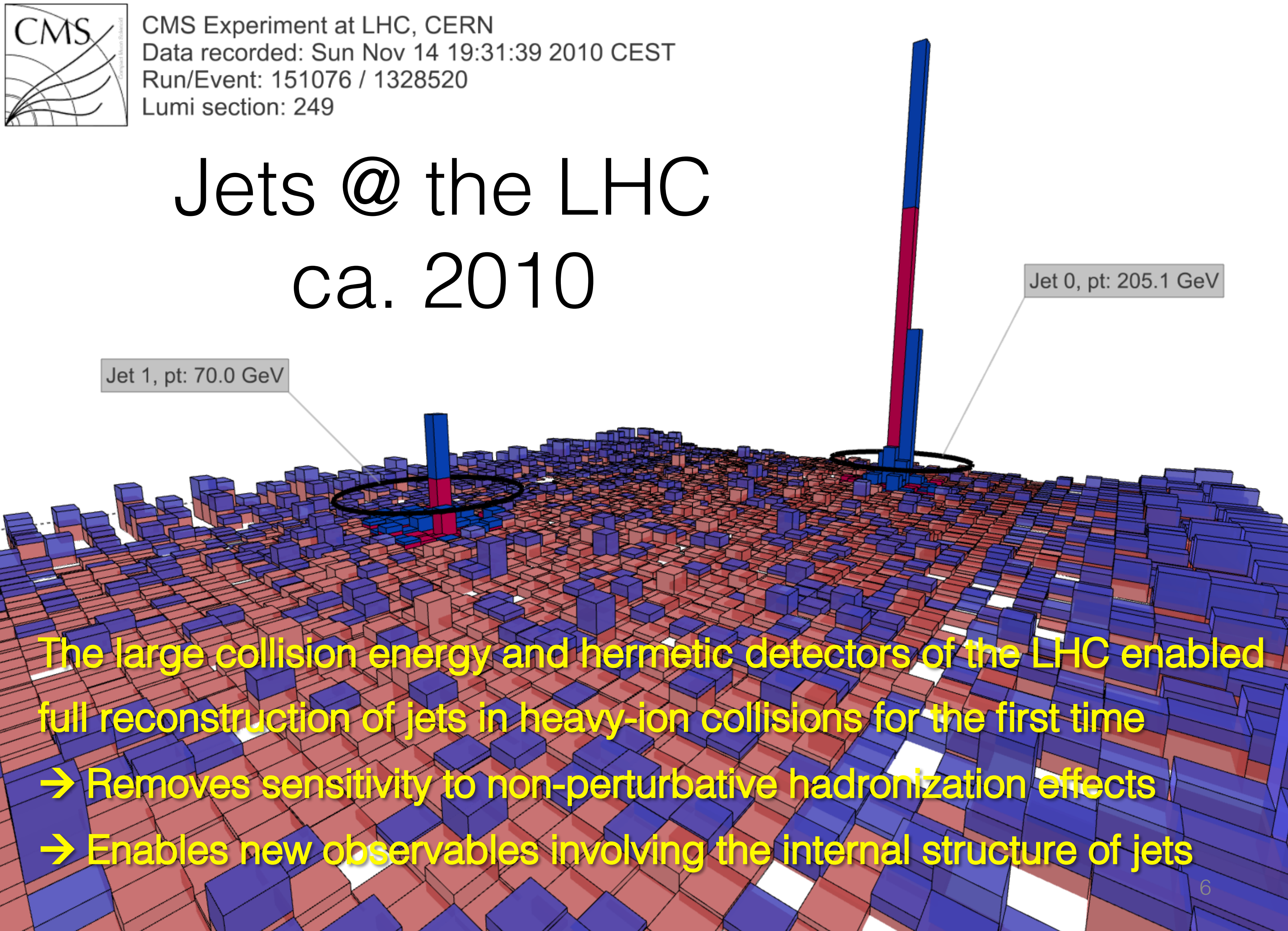
Vacuum pQCD

Insert energy loss model here!

Fragmentation

- Charged hadron R_{AA} well-described by pQCD models of energy loss
- Too successful? Models contain very different description of the dense medium, as well as very different kinematic limits and approximations

Jets @ the LHC ca. 2010

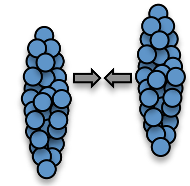


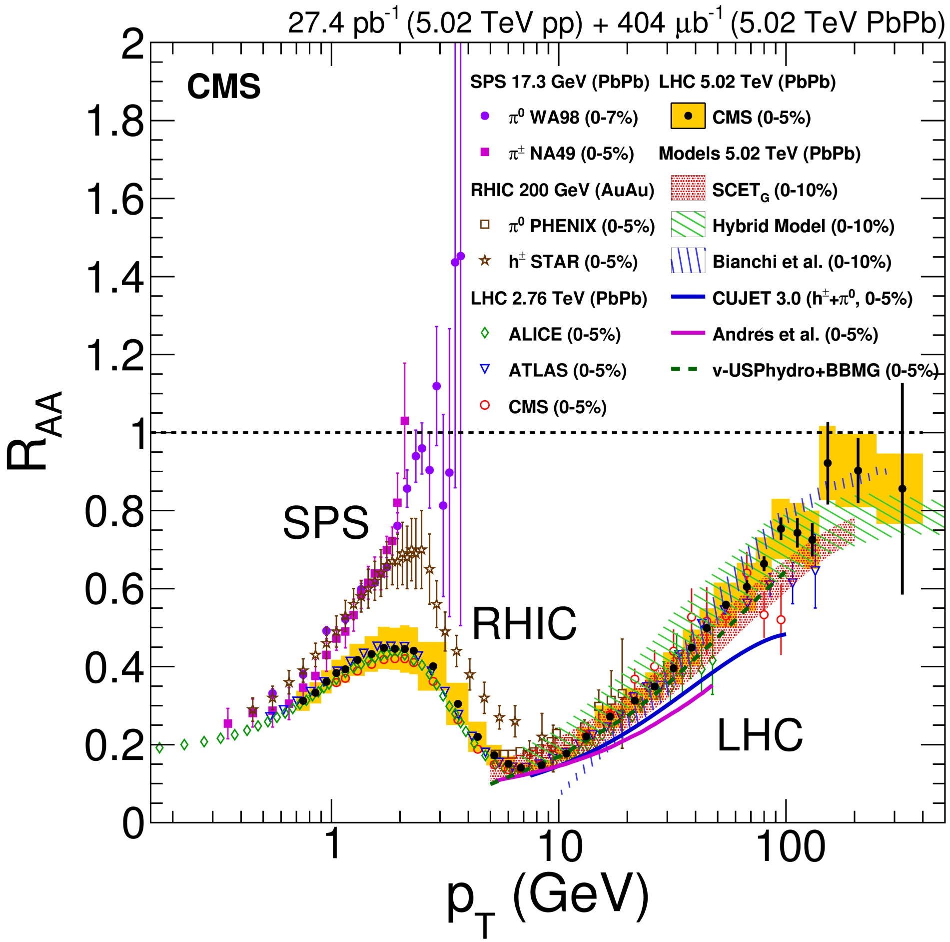
The large collision energy and hermetic detectors of the LHC enabled full reconstruction of jets in heavy-ion collisions for the first time

→ Removes sensitivity to non-perturbative hadronization effects

→ Enables new observables involving the internal structure of jets

Charged particle R_{AA}

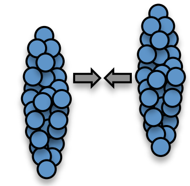




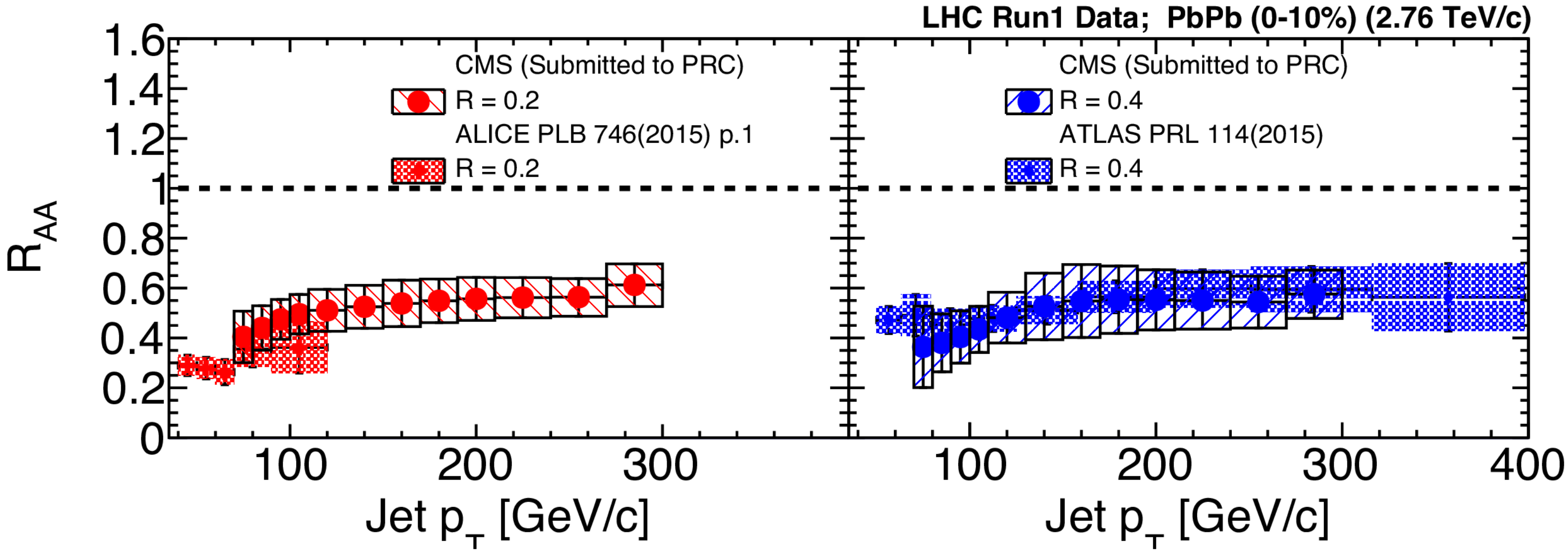
JHEP 1704 (2017) 039

- Extended to p_T > 100 GeV → adding discrimination power btwn models
- Whereas flat @ RHIC, now seen to slowly rise, nearly to unity

Jet R_{AA}

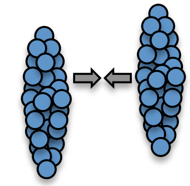


arXiv:1609.05383

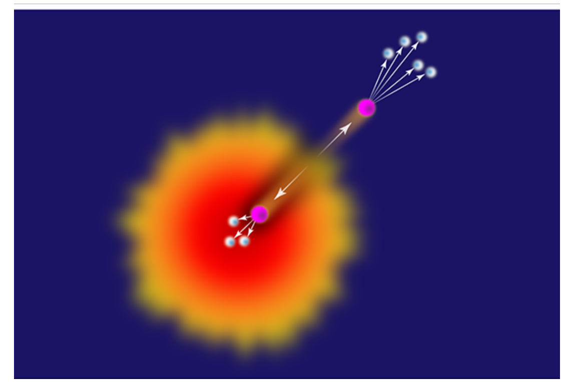


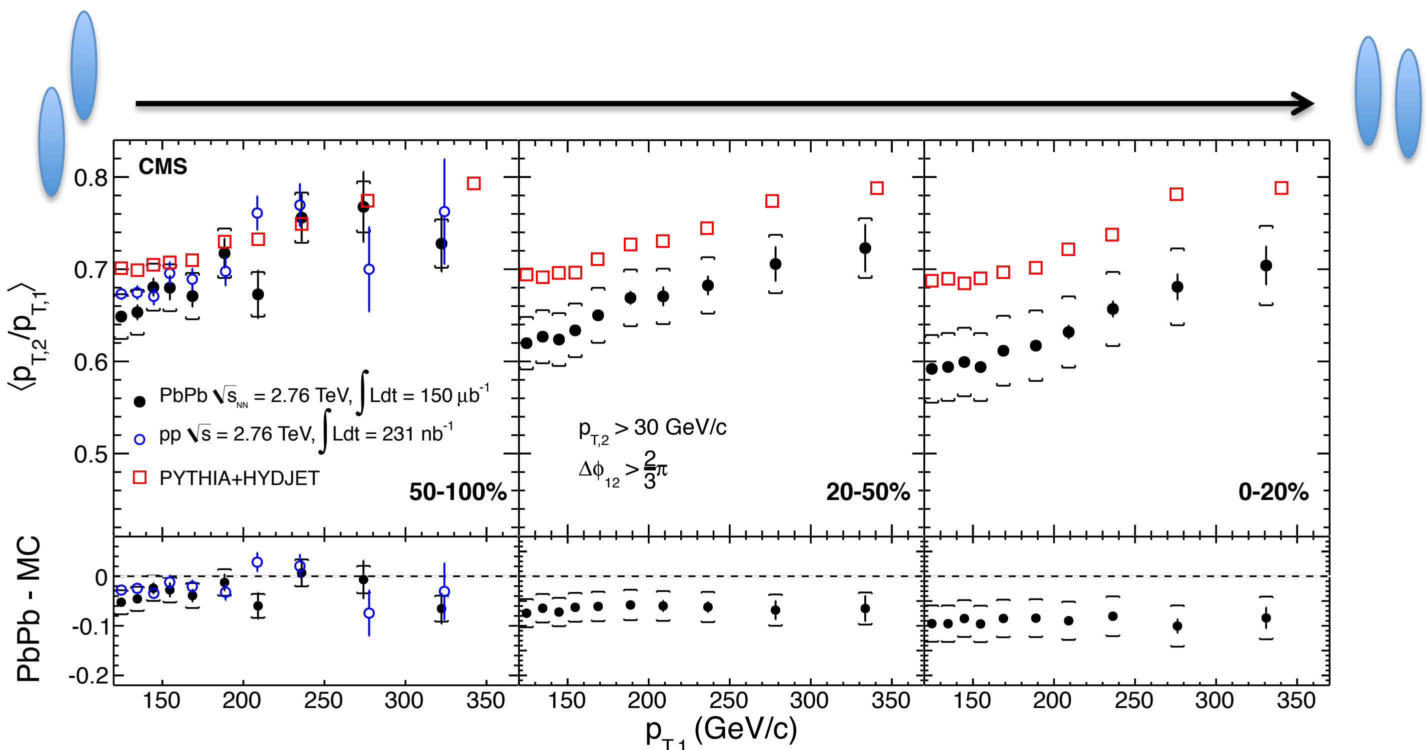
- R_{AA} for jets nearly flat out to the largest values of R_{AA} sampled!
- Quenching independent of cone size, up to R=0.4 (except @ low p_T)
  → quenched energy transferred to large angle (see also missing p_T)
- How to reconcile with charged hadrons? Is there an interplay between the jet fragmentation pattern and the parton energy loss?

Dijet imbalance



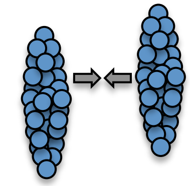
- Additional imbalance expected based on path-length difference btwn leading dijets
- Imbalance persists to largest p_T measured





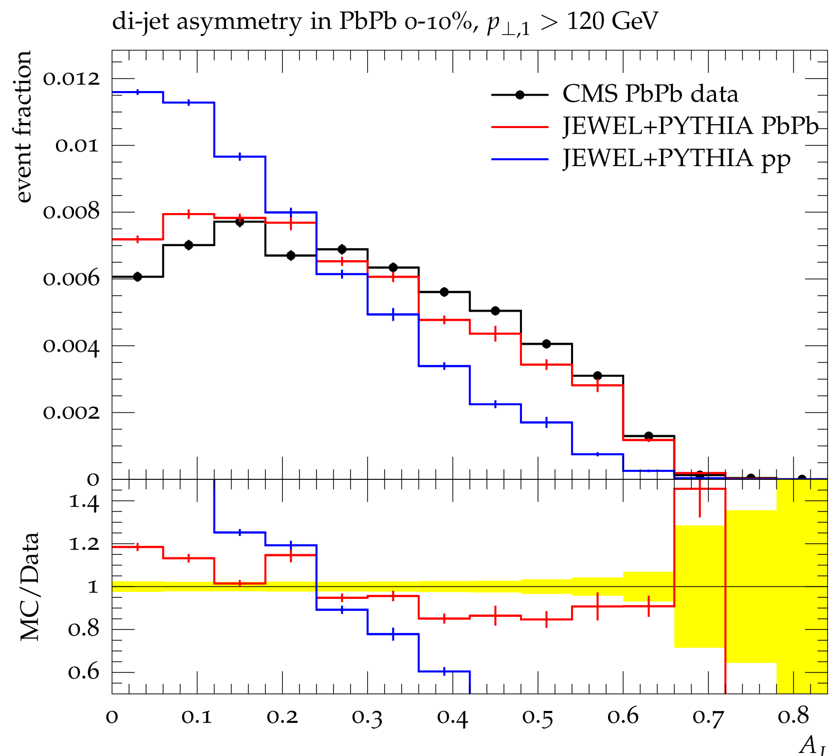
PLB 712 (2012) 176

Origin of dijet imbalance



- Surprisingly in JEWEL* imbalance not generated by path-length difference
- Rather driven by dependence of energy loss on jet fragmentation pattern

→ Softer fragmenting jets lose more energy



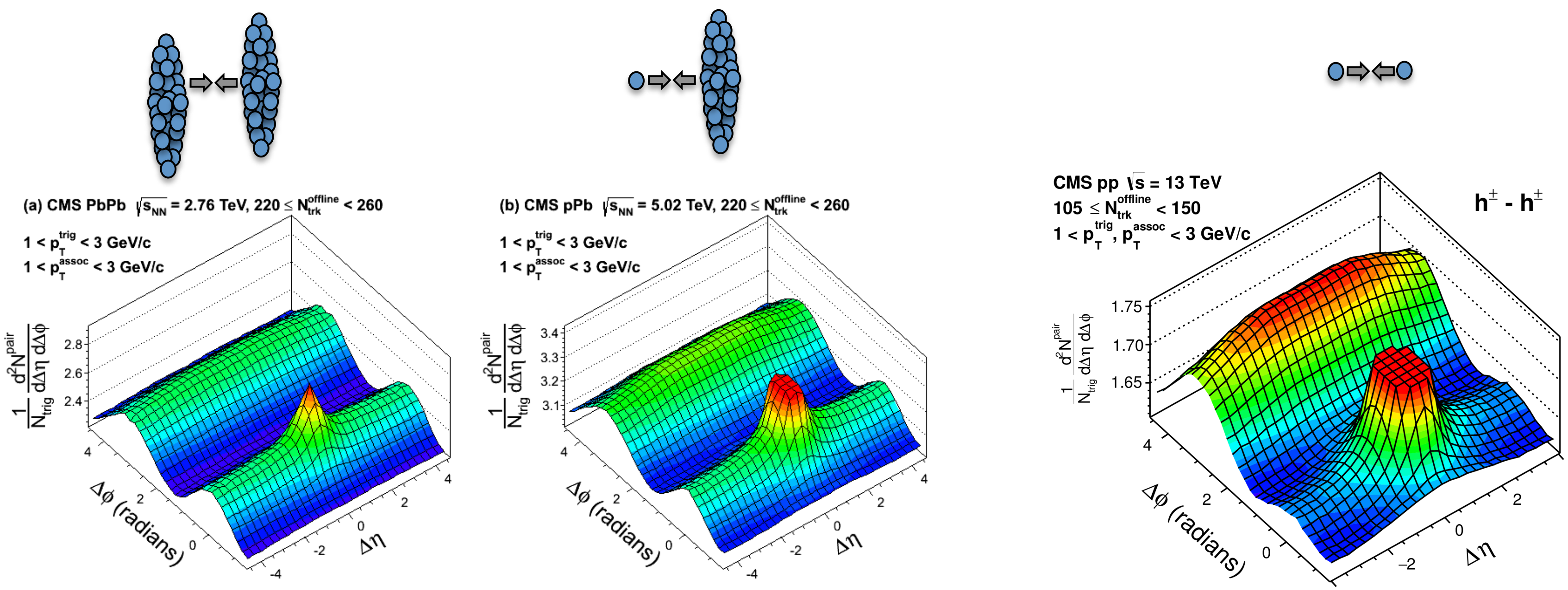
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

"Origins of the dijet asymmetry in heavy ion collisions",
Milhano & Zapp, EPJC 76 (2016) 288

*JEWEL: Pythia-based generator which incorporates energy loss into the parton shower

Collectivity in small systems

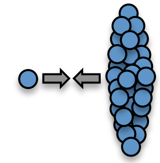
One ridge to bind them all?

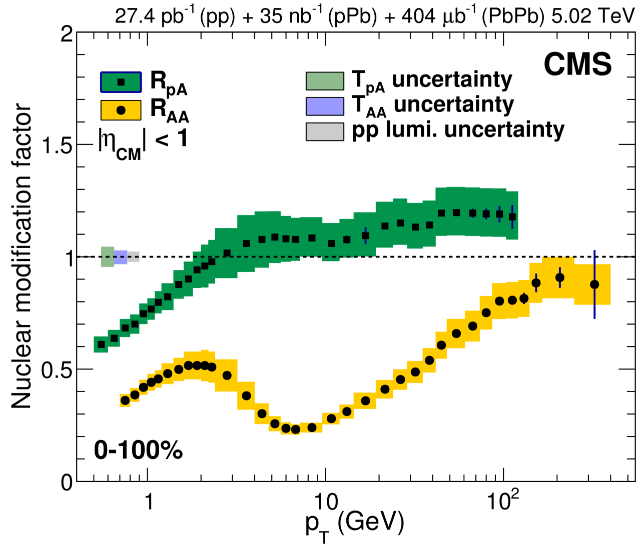


For details see talk by Damir, later today

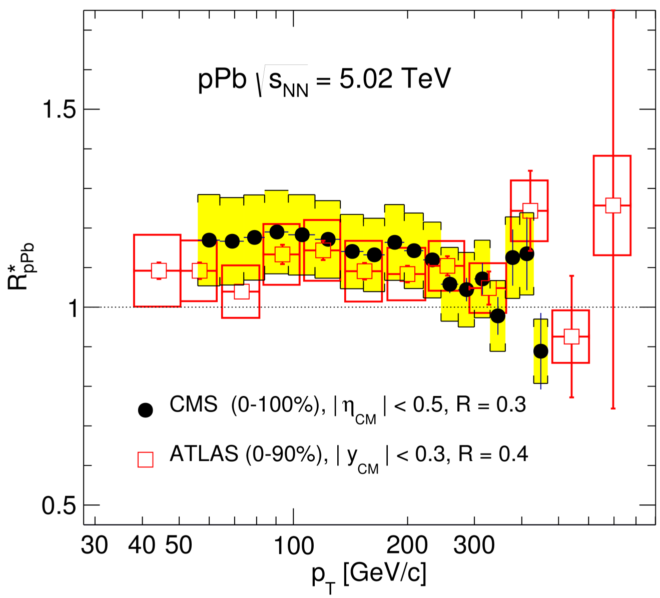
- Long-range correlations commonly understood to be a collective effect
- Shows up even in small systems given high enough multiplicity
- If a dense system is produced shouldn't jet quenching follow?

Spectra in pA





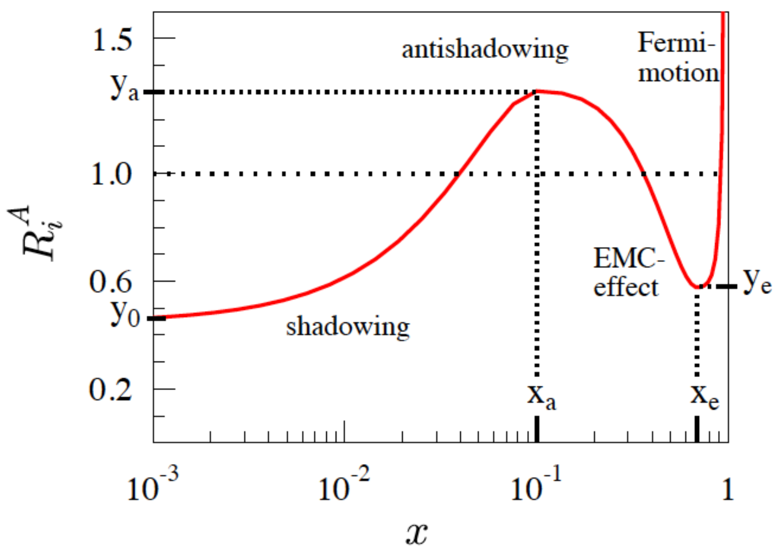
Charged hadrons



Jets

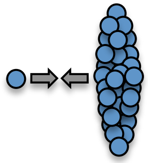
[EPJC 76 (2016) 372](https://doi.org/10.1140/epjc/s10052-016-4223-5)
JHEP 1704 (2017) 039

Large p_T @ LHC probes anti-shadowing peak around x=0.1

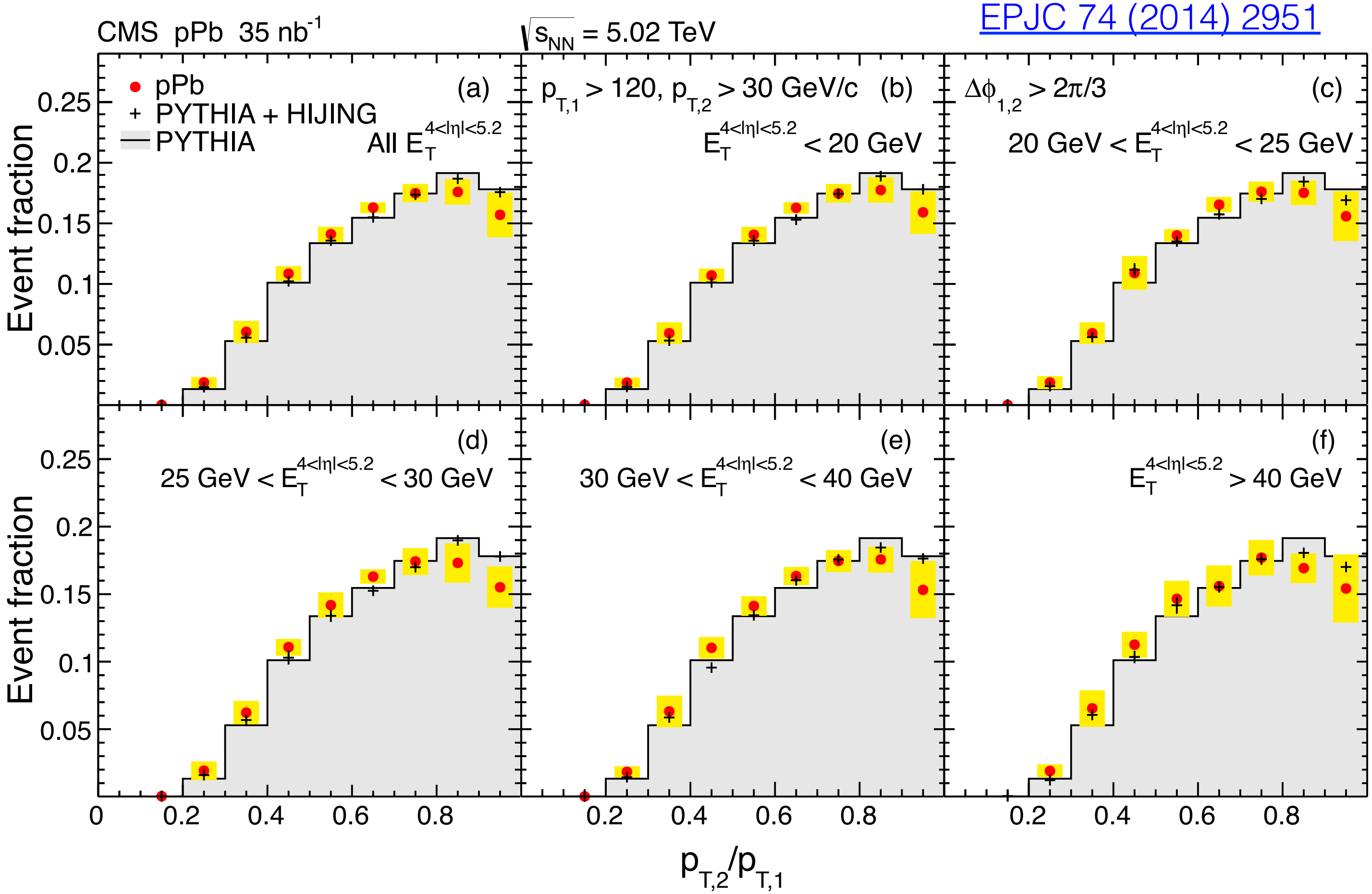


→ Expected nPDF effects are sufficient to explain pA data

Dijet imbalance in pA?

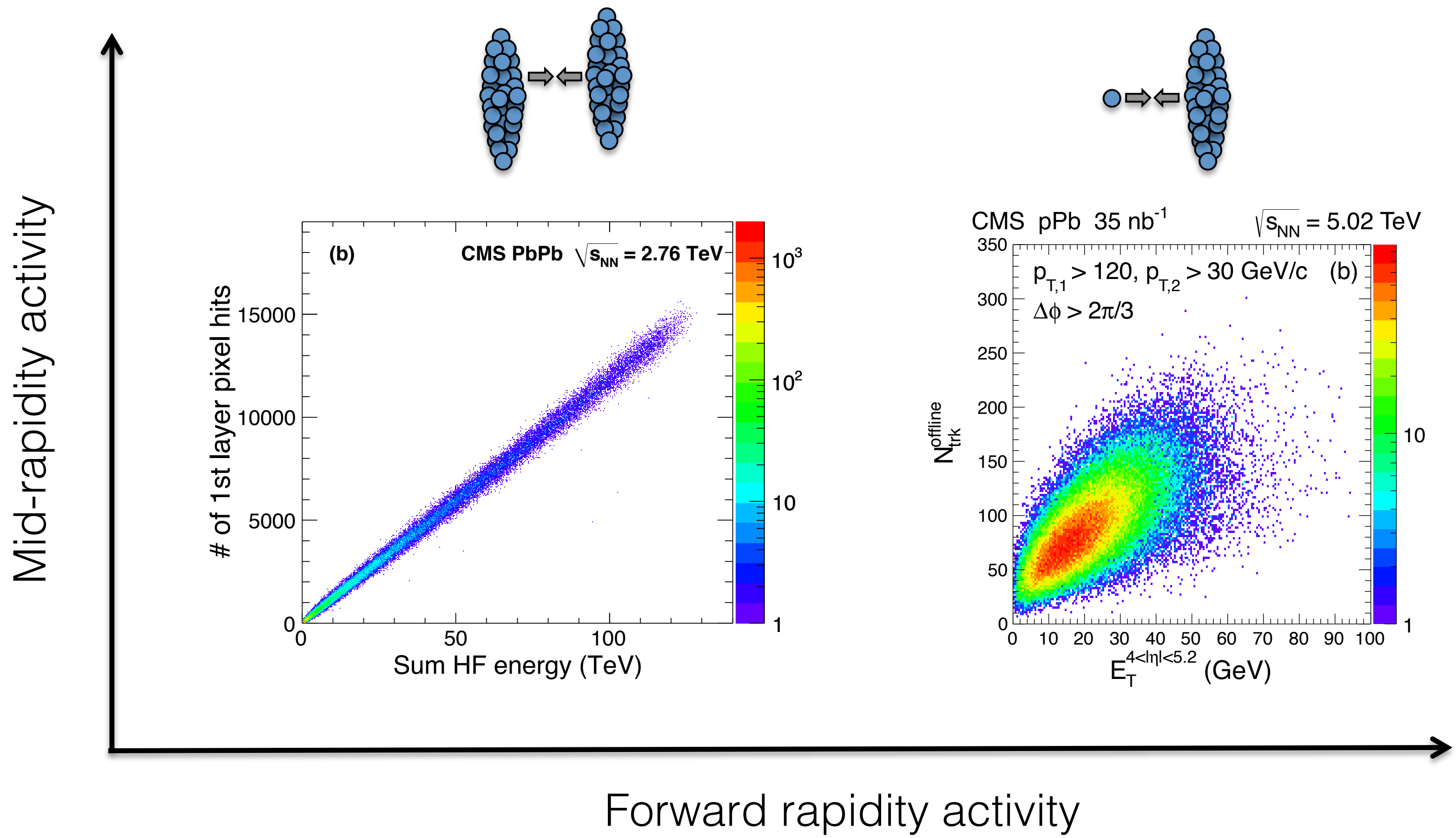


[EPJC 74 (2014) 2951](#)



- No anomalous imbalance observed in pA
- Independent of event activity at forward rapidity

Centrality in small systems



Activity decorrelated across event → hence also to impact parameter

Observed collective effects in pA & pp tied to mid-rapidity multiplicity

→ so far no way to tune multiplicity without biasing jet production

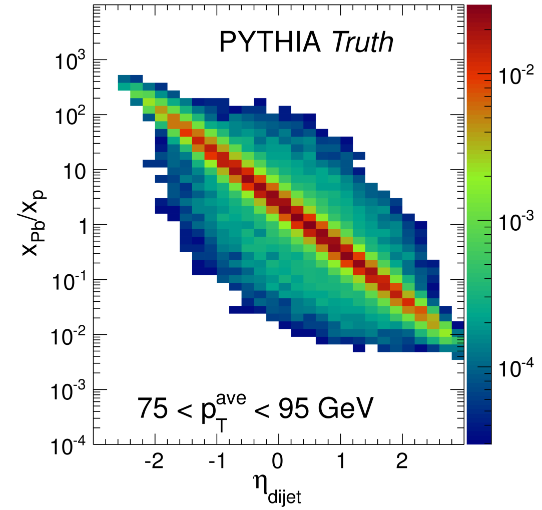
Dijet pseudorapidity

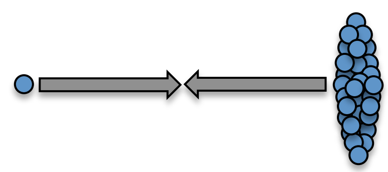
- Dijet η traces ratio of Bjorken x's

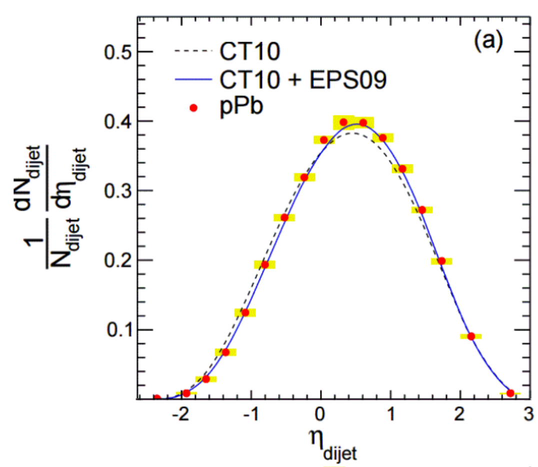
$$\eta_{\text{dijet}} = (\eta_1 + \eta_2)/2 \propto \log(x_p / x_A)$$

- Self-normalization reduces uncertainties
- LHC kinematics sample shadowing, anti-shadowing and EMC regimes
- Can also scan over Q with $\langle p_{T,\text{dijet}} \rangle$

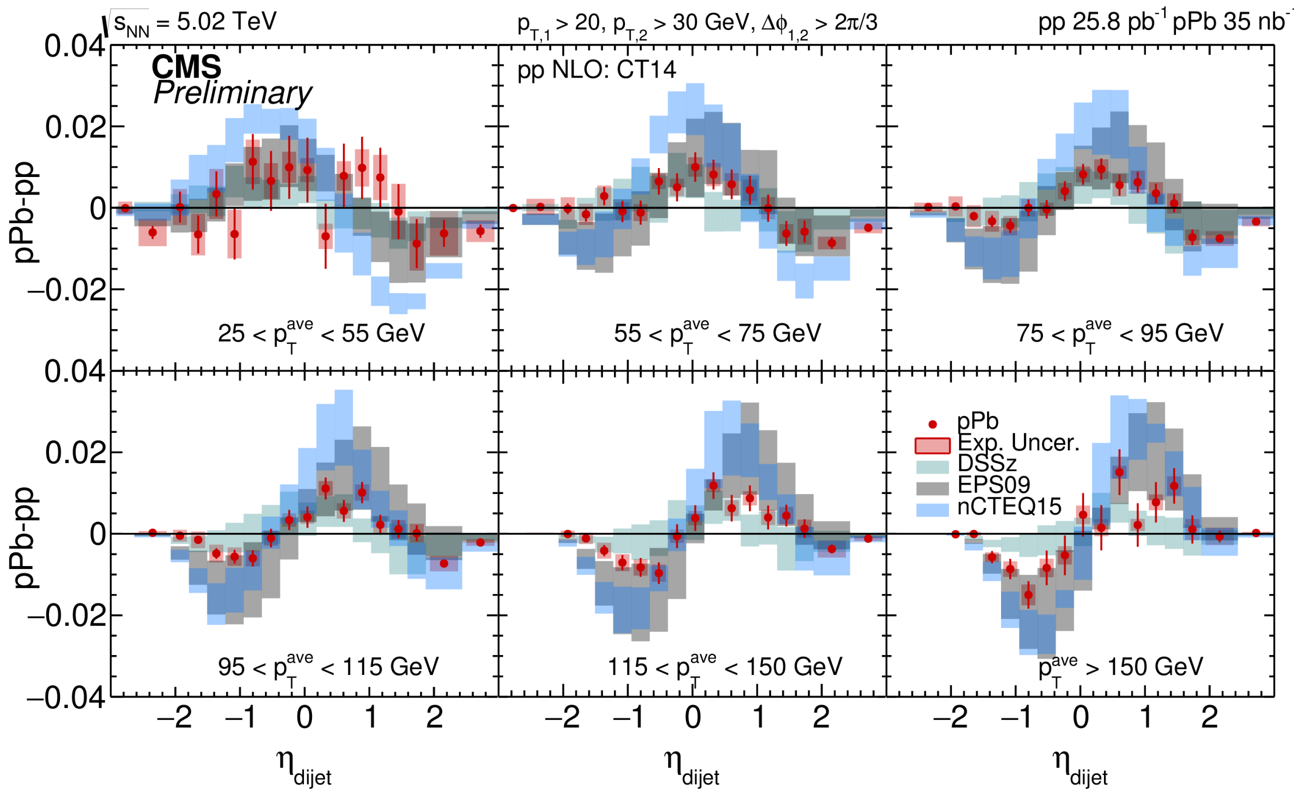
$$p_{T,\text{dijet}} = (p_{T,1} + p_{T,2})/2 \propto Q$$







Dijet η shift

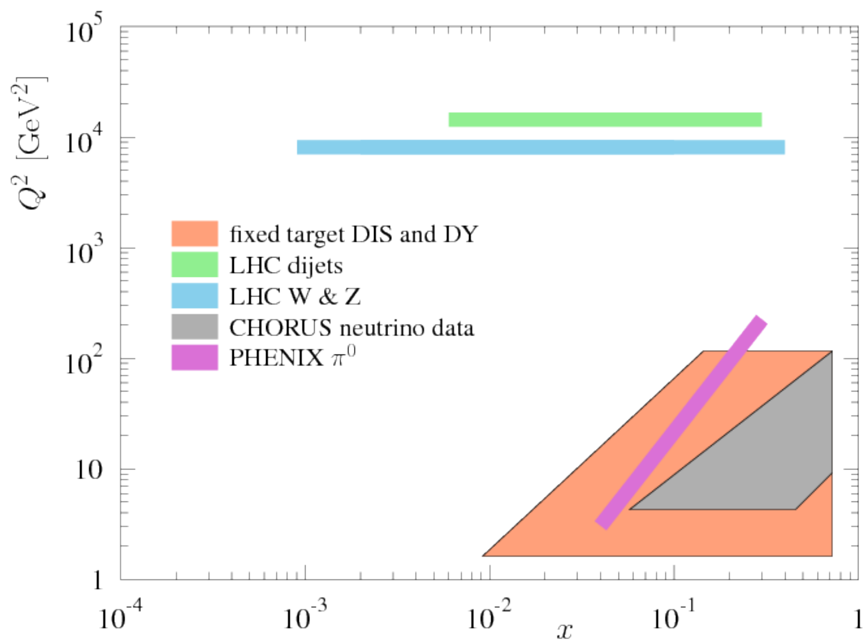


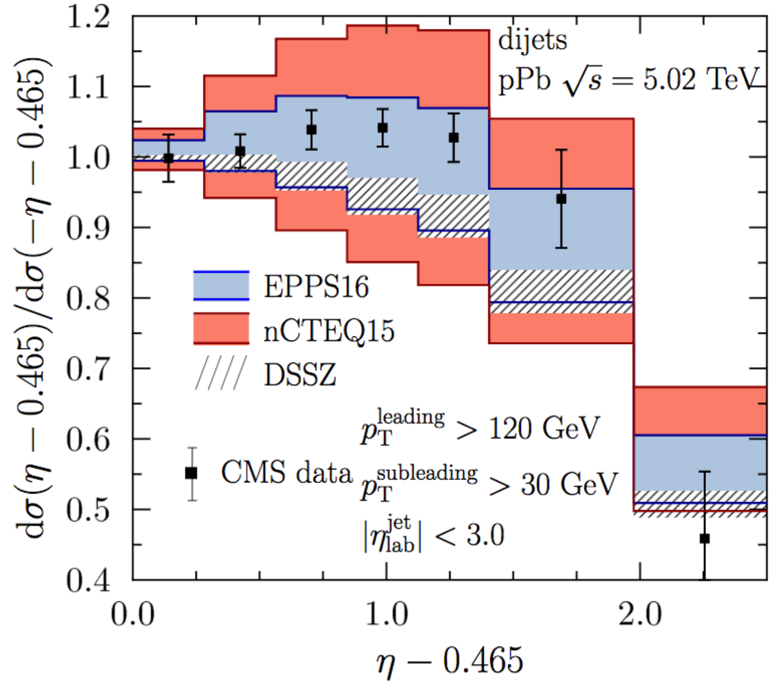
CMS-PAS-HIN-16-003

- Despite percent level deviations, significant nuclear effects observed
- Moreover, discriminates between various global fit analysis

Inclusion into nPDF fit

"EPPS16: Nuclear parton distributions with LHC data"
Eskola et al., [EPJC 77 (2017) 163]





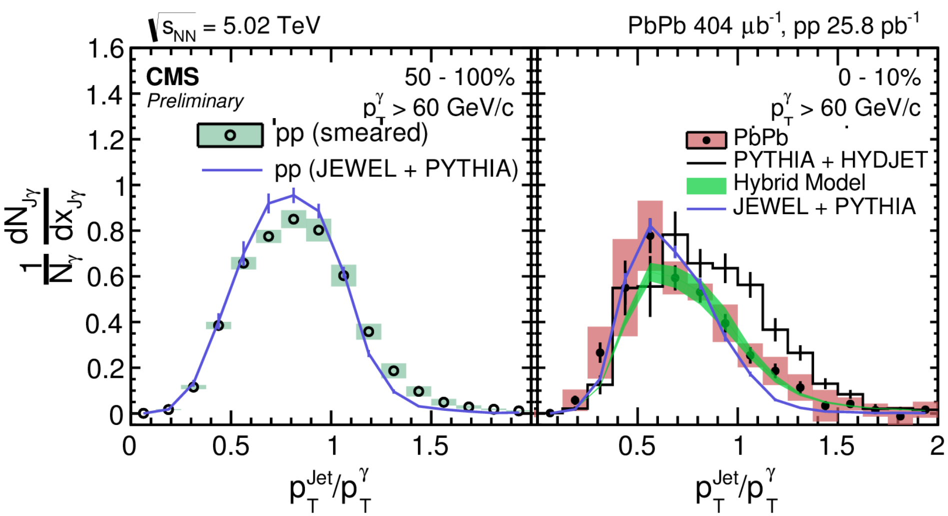
Gluon nuclear modification similar to quarks (from ν-nucleus DIS)

→ Supports collinear factorization and process independent nPDFs

Boson-jet correlations

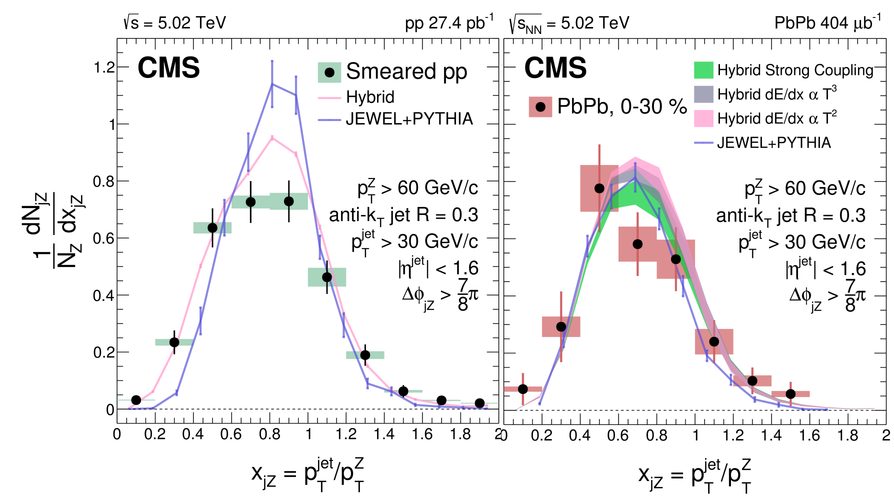
EW bosons do not interact strongly w/ the QGP
→ proxy for recoiling parton before energy loss

γ + jet



[CMS-PAS-HIN-16-002](CMS-PAS-HIN-16-002)

Z + jet



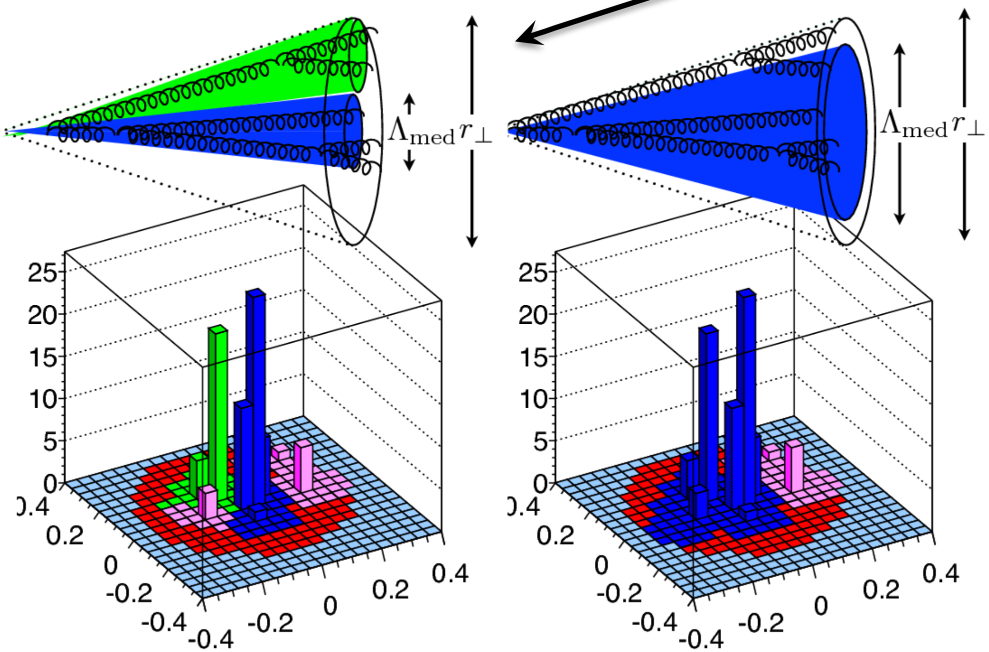
arXiv:1702.01060

- <u>Precision</u> quenching measurements for upcoming high luminosity data
- Requires advanced generators for vacuum physics (e.g., NLO + parton shower) as well as for parton energy loss models (exclusive final states, recoil, etc), possibly simultaneously.

The antenna problem

pQCD energy loss calculations consider successive gluon emissions, but not how color coherence of parton shower is modified by QGP

Test configuration: q-qbar antenna



For separation r_T larger than coherence length Λ_{med}, partons radiate independently

Otherwise acts as single emitter

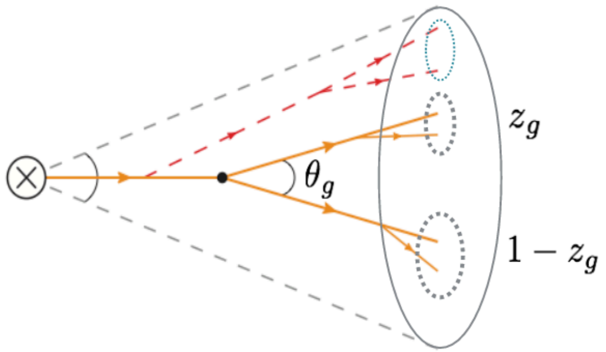
Λ_{med} inversely proportional to (scattering power * pathlength)^2

How can we access the antenna configuration experimentally?

"A new picture of jet quenching dictated by color coherence"
Casalderry-Solana, et al., PLB 725 (2013) 357

Substructure: a new frontier

- Methods developed to distinguish boosted objects from QCD jets
- Idea: Run jet clustering in reverse to isolate the hardest splittings



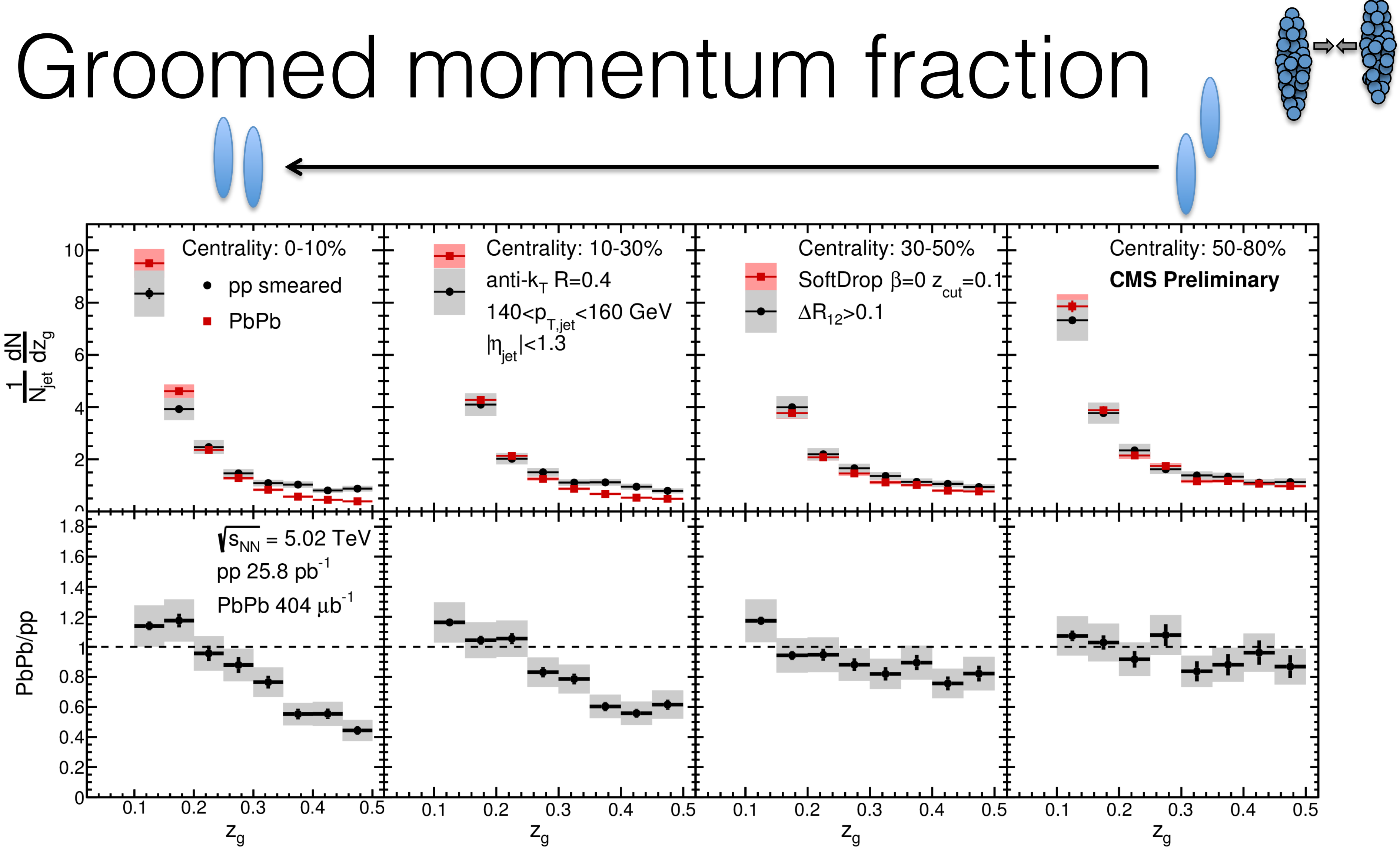
p_T fraction of subleading branch

$$z_g \equiv \frac{\min\left(p_{T,1}, p_{T,2}\right)}{p_{T,1} + p_{T,2}}$$

- Directly related to Altarelli-Parisi splitting for the vacuum case (pp)
- CMS measures down to minimum opening angle of $\theta_g = 0.1$
- Requires grooming*, a procedure to remove soft radiation and uncorrelated background

* CMS using "Soft-drop" Larkowski et al., [JHEP 1405 (2014) 146]

Groomed momentum fraction

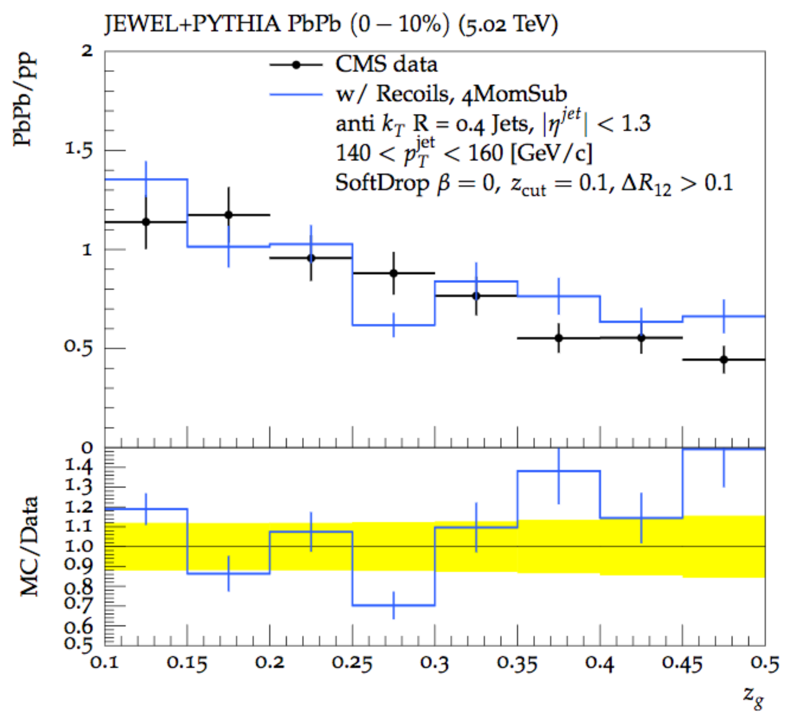


CMS-PAS-HIN-16-006

- Relatively fewer symmetric subjets w/ increasing centrality
- Effect disappears in peripheral & at high p_T (not shown)

Substructure outlook

A number of models reproduce the general trend observed in data
e.g., JEWEL: Nearby splitting promoted over min θ_g by jet-medium interaction



Complementary information being pursued: jet mass, n-subjettiness, etc.
Only the beginning! Expect to learn a lot about jet-medium interactions w/ substructure in the coming years

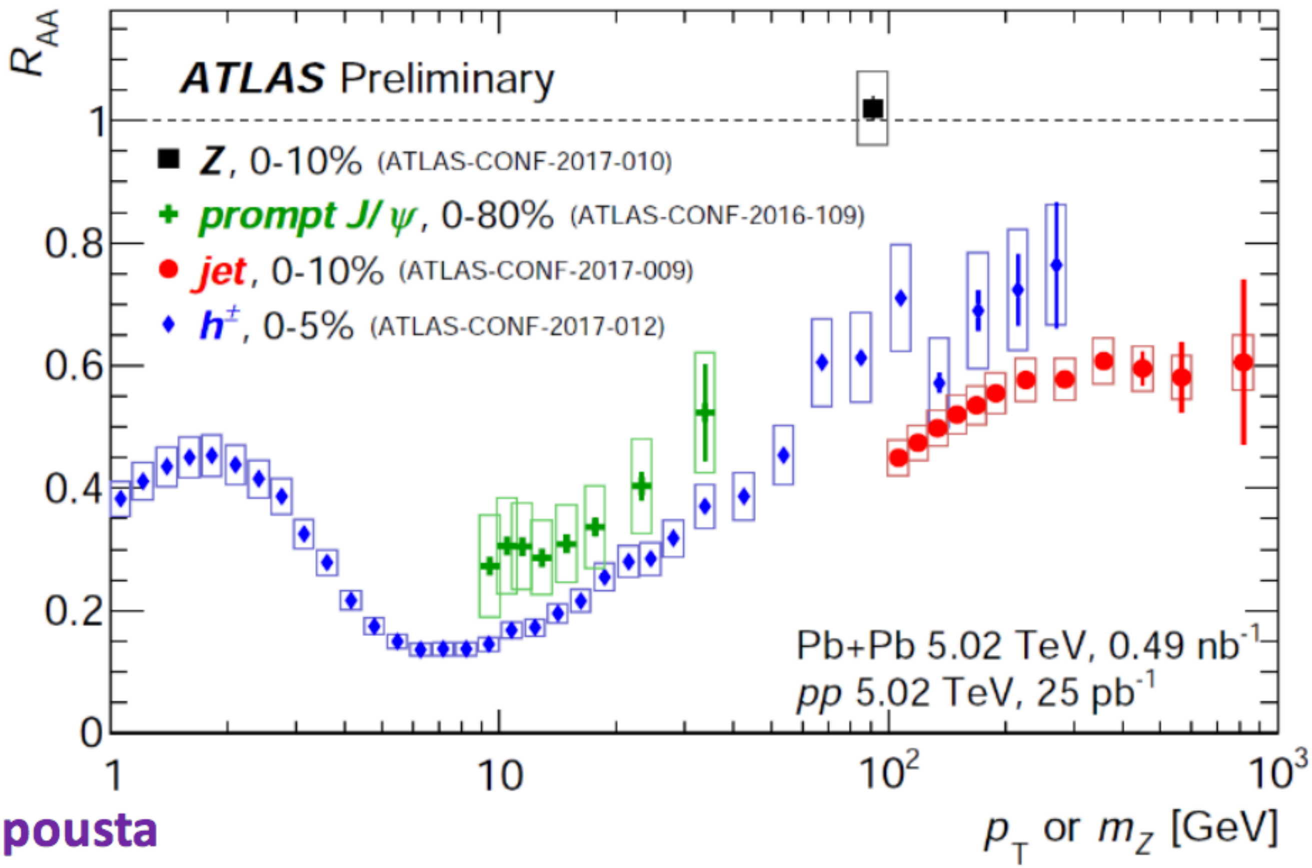
Conclusions

Jets in pA & AA are bringing new insight into the interaction of fast partons w/ dense QCD matter

- AA
  - o Strong final state effects (jet quenching) measured increasingly precisely
  - o New substructure observables providing a window into detailed dynamics of jet-medium interaction
- pA
  - o No evidence of strong final state effects, but so far difficult to isolate events with large final state effects
  - o Best constraints yet on the nuclear gluon distribution at large x

Backup

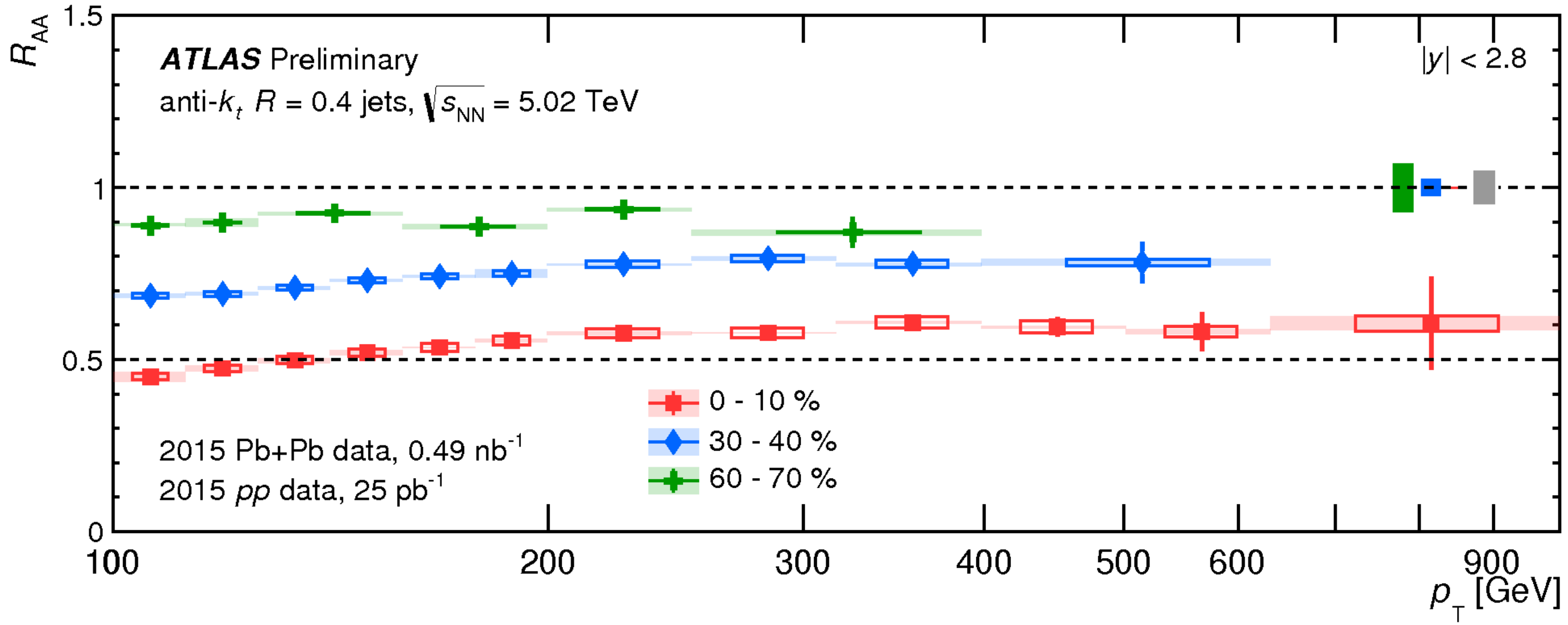
ATLAS R_{AA} compilation



rtin Spousta

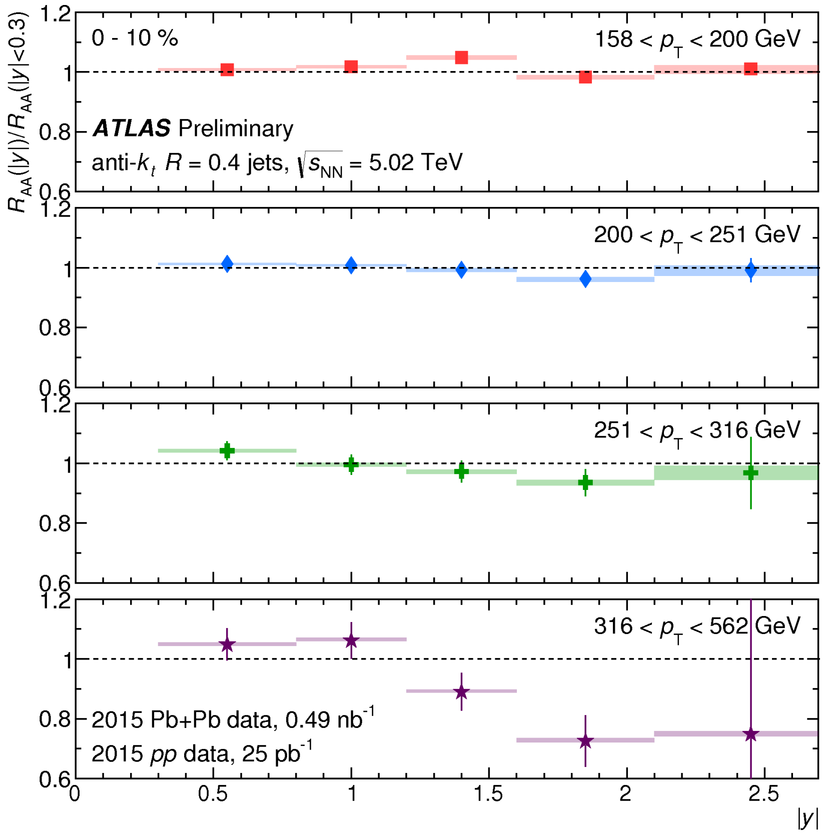
ATLAS Jet R_{AA} to 1 TeV

ATLAS-CONF-2017-009



ATLAS Jet R_{AA} vs. rapidity

ATLAS-CONF-2017-099



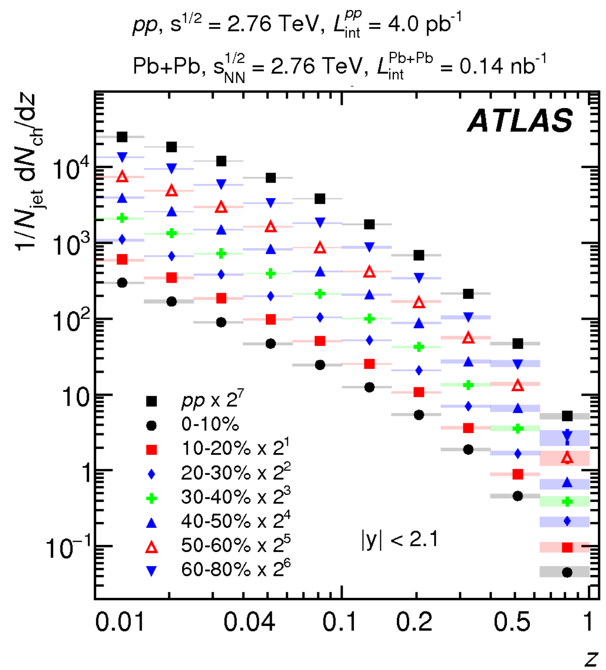
R_{AA} also flat vs. rapidity, except at largest p_T

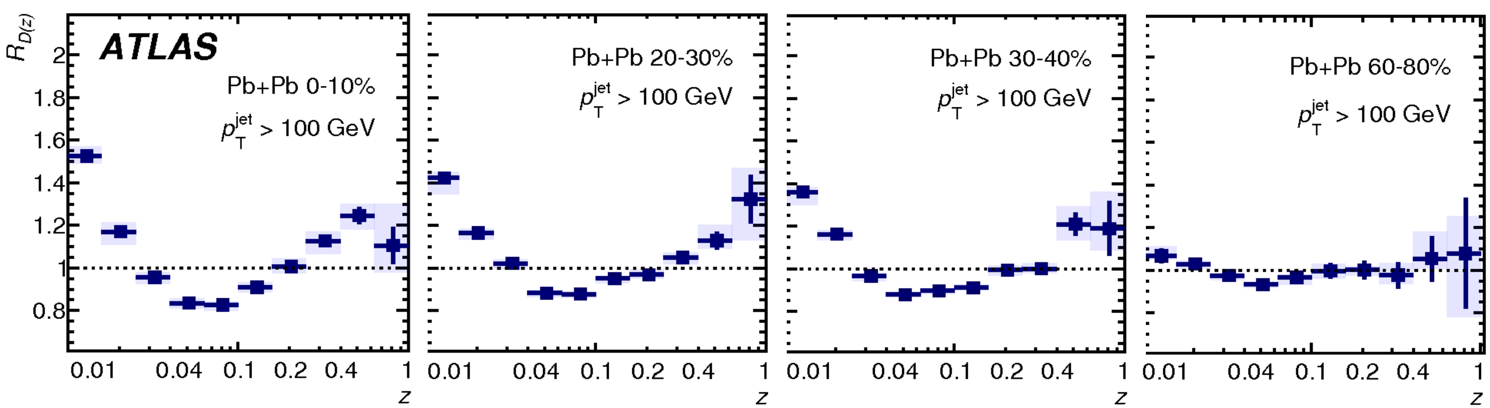
Some dependence expected based on steeping of spectral slope w/ increasing y

ATLAS Fragmentation Function

[arXiv:1702.00674](https://arxiv.org/abs/1702.00674)

- "Fragmentation function" measured wrt reconstructed jet
- Ratio of central PbPb to pp shows
  - Excess at low z
  - Depletion at intermediate z
  - Excess again at large z

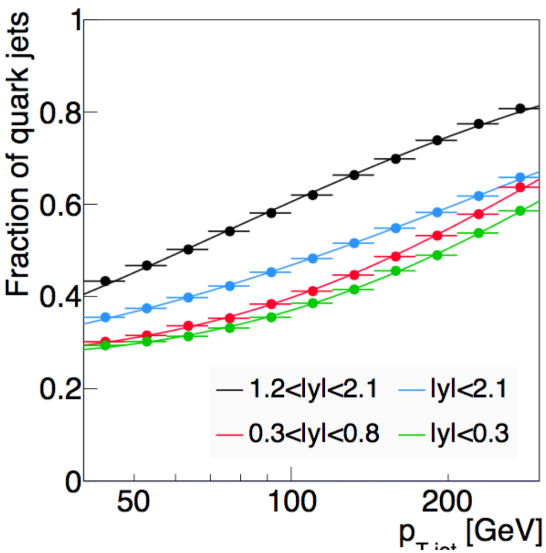




Quark vs. gluon energy loss

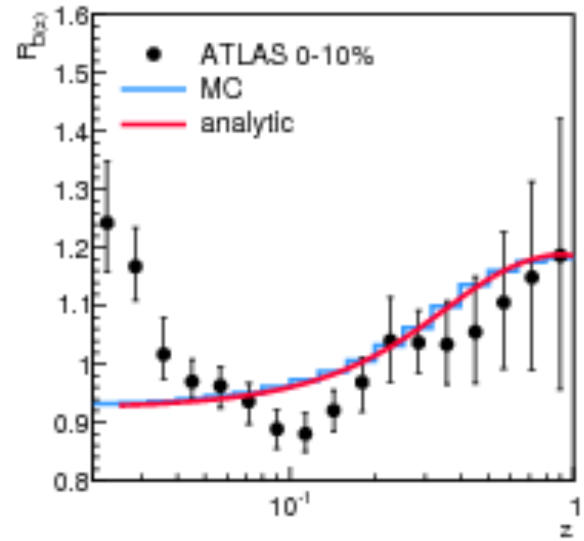
Quark vs. gluon fraction also changes with *y*

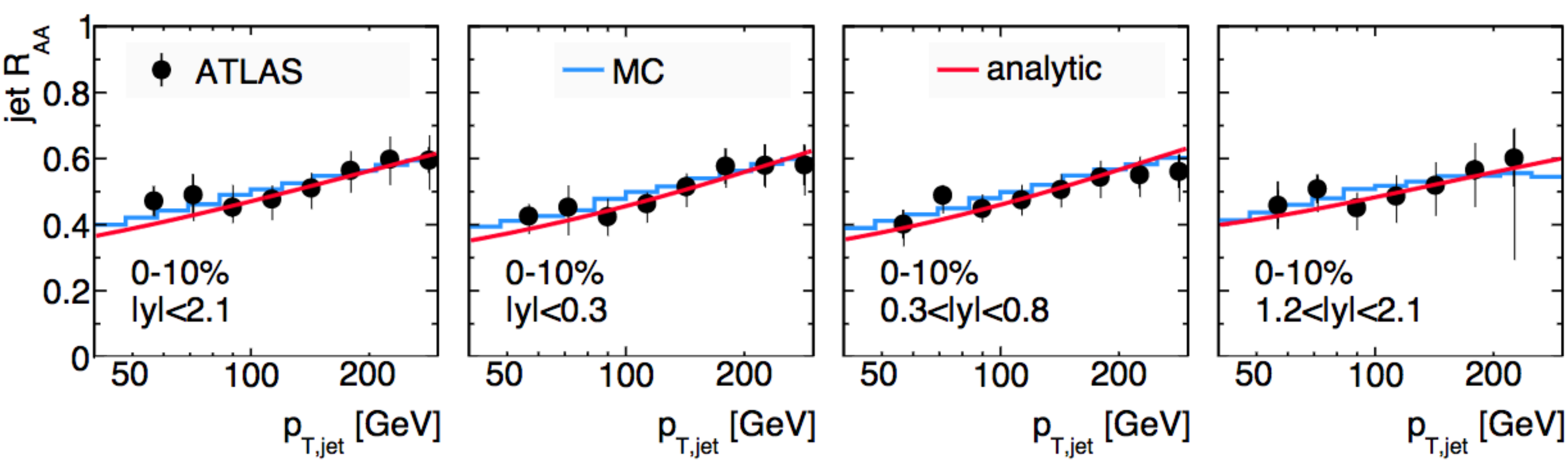
"Interpreting single jet measurements in Pb+Pb Collisions at the LHC"
Cole & Spousta EPJC 76 (2016) 50



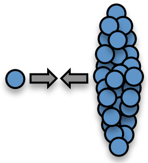
Naively, gluon/quark radiative energy loss: 9/4

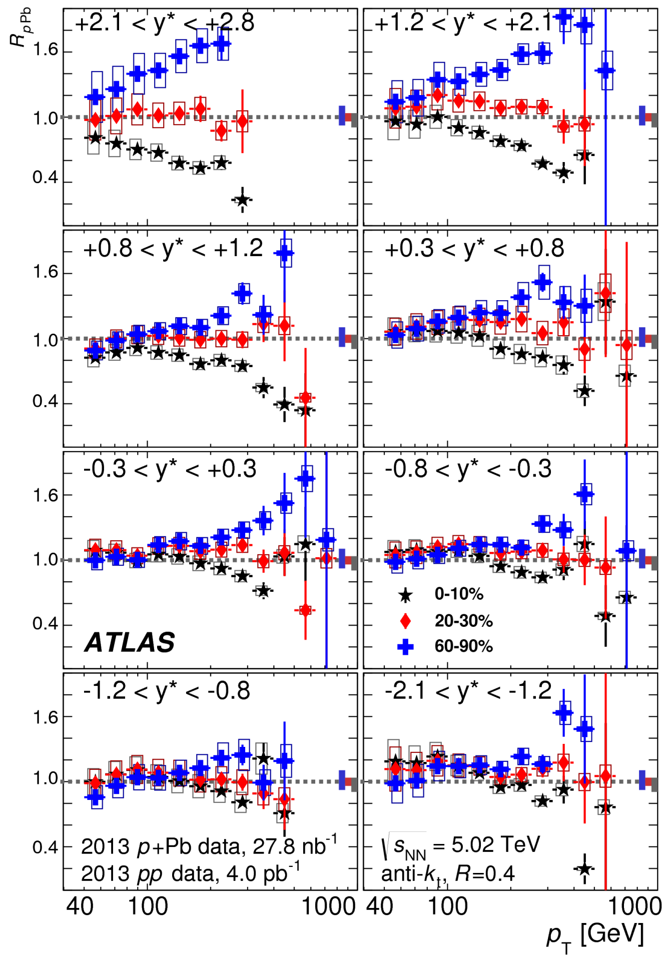
One model explains both high/medium *z* FF & jet R_{AA}, w/ <u>only</u> species dependent energy loss



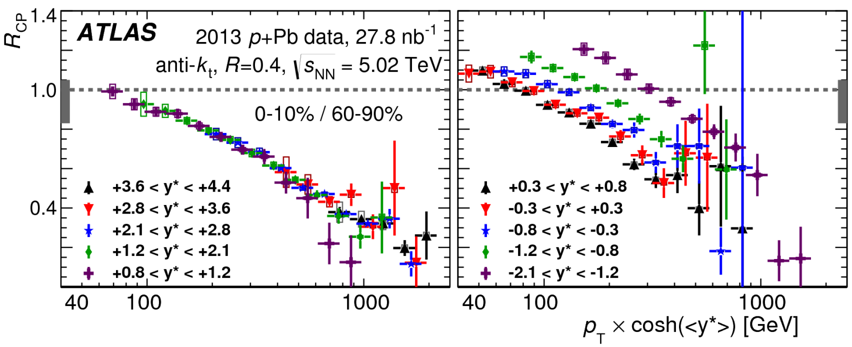


ATLAS RpA





Although "centrality"-integrated RpA ~ 1, slicing in forward activity causes splitting, particularly at forward (p-going) rapidity

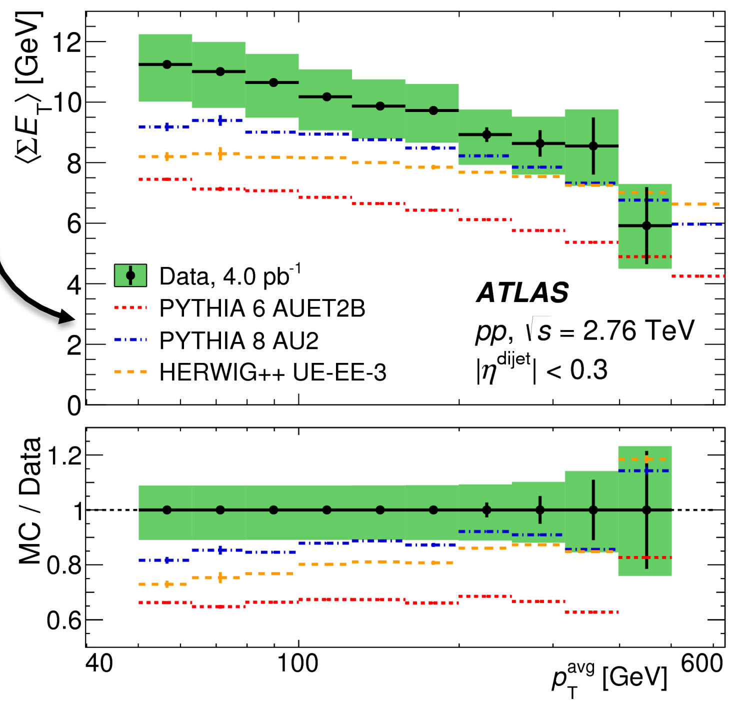


A scaling is observed with E ~ p_T * cosh y, which is ~ Bjorken *x* of the proton

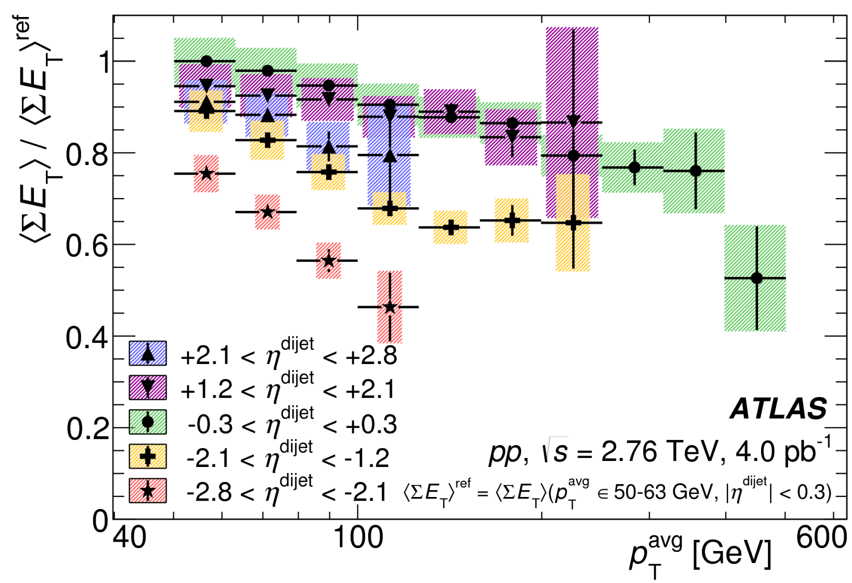
PLB 748 (2015) 392

Mid-forward correlation in pp

- In pp, anti-correlation btwn forward and central energy is observed
- as expected from energy conservation-type effects
- Under-predicted by standard MC generators



[PLB 756 (2016) 10](#)

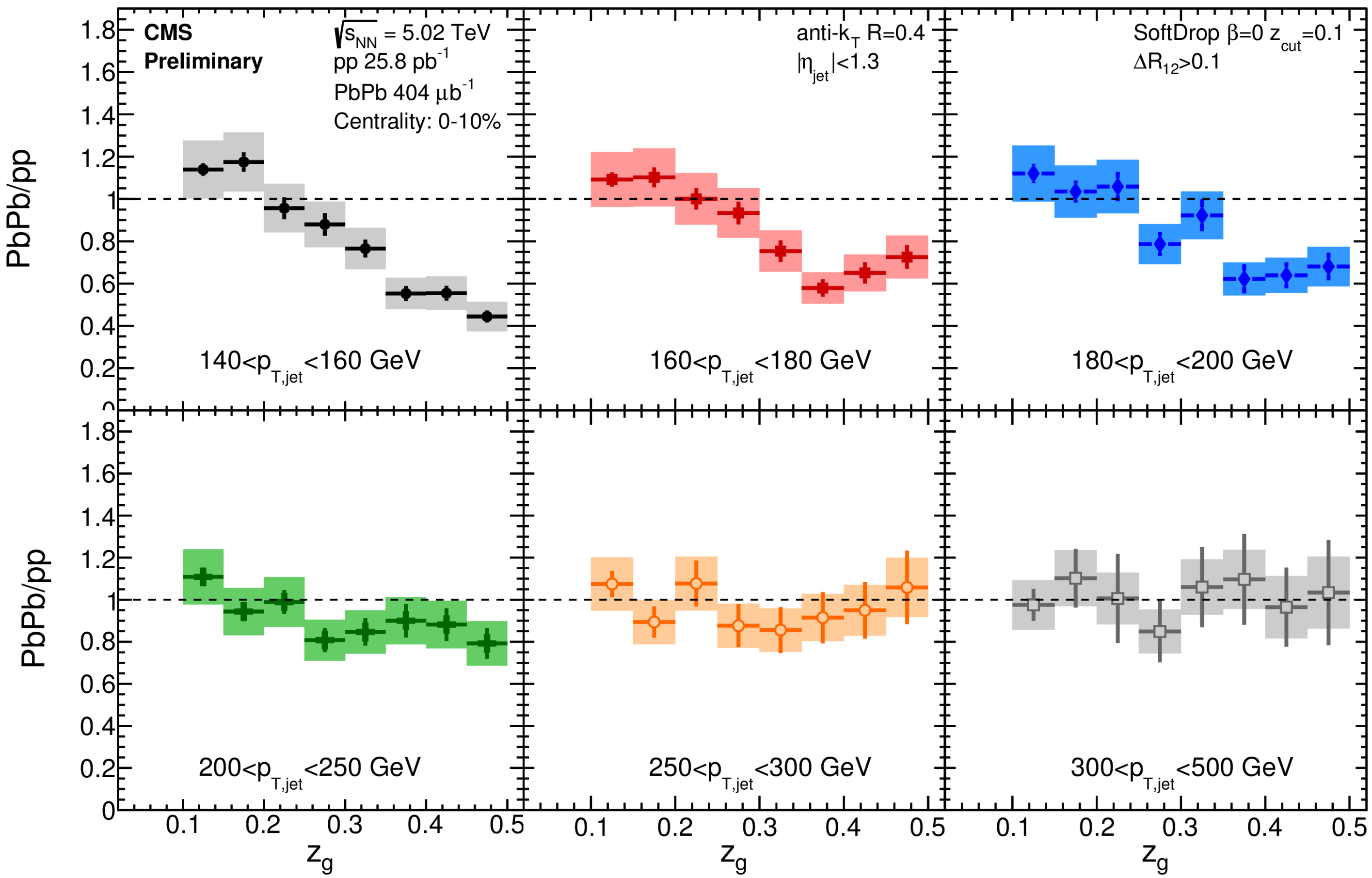


- However, correlation only between dijets and same-side forward energy
- NOT btwn "projectile"-side jet and forward "target" energy as seen in pPb
- One possibility: Due to proton size fluctuations, high x protons have a smaller cross-section for interacting with the nucleus → would explain EMC effect!

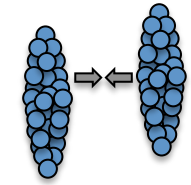
Alvioli et al., [PRC 93, 011902 (2016)](#)

p_T dependence of groomed momentum fraction

CMS-PAS-HIN-16-006

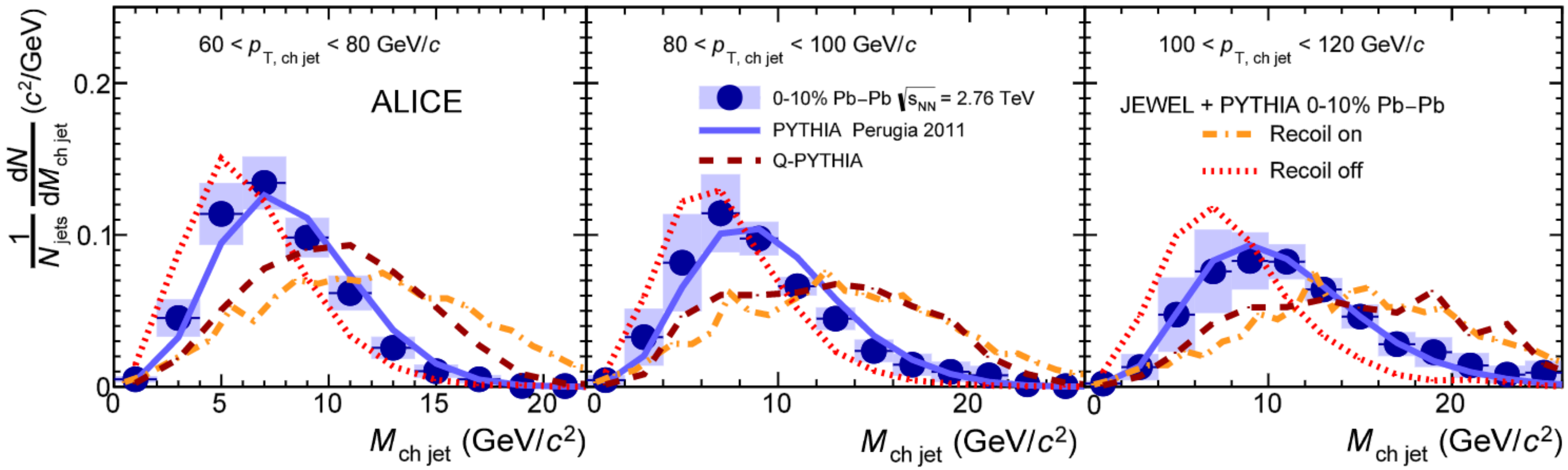


ALICE jet mass

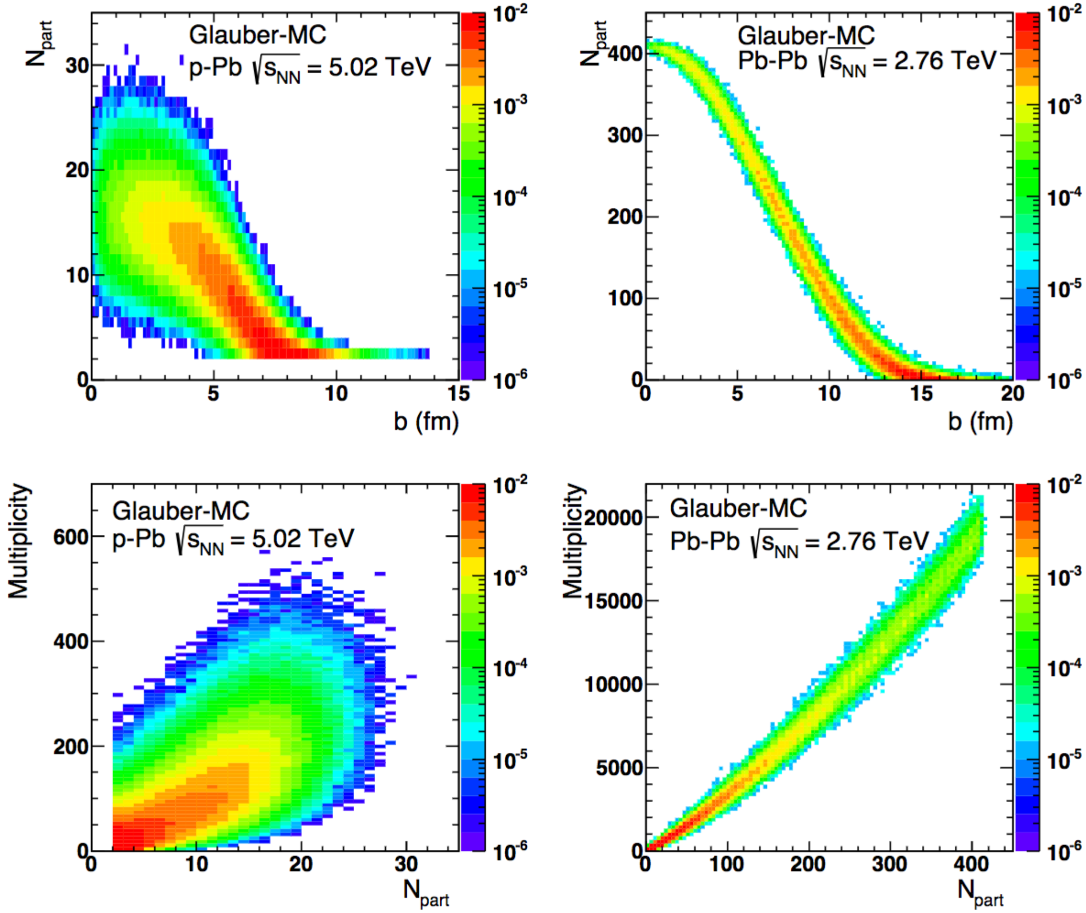


- Jet mass is sensitive to the initial virtuality of the iniating parton
- Jet quenching expected to induce add'l radiation, increasing mass

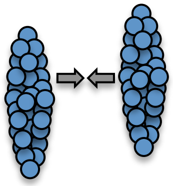
arXiv:1702.00804

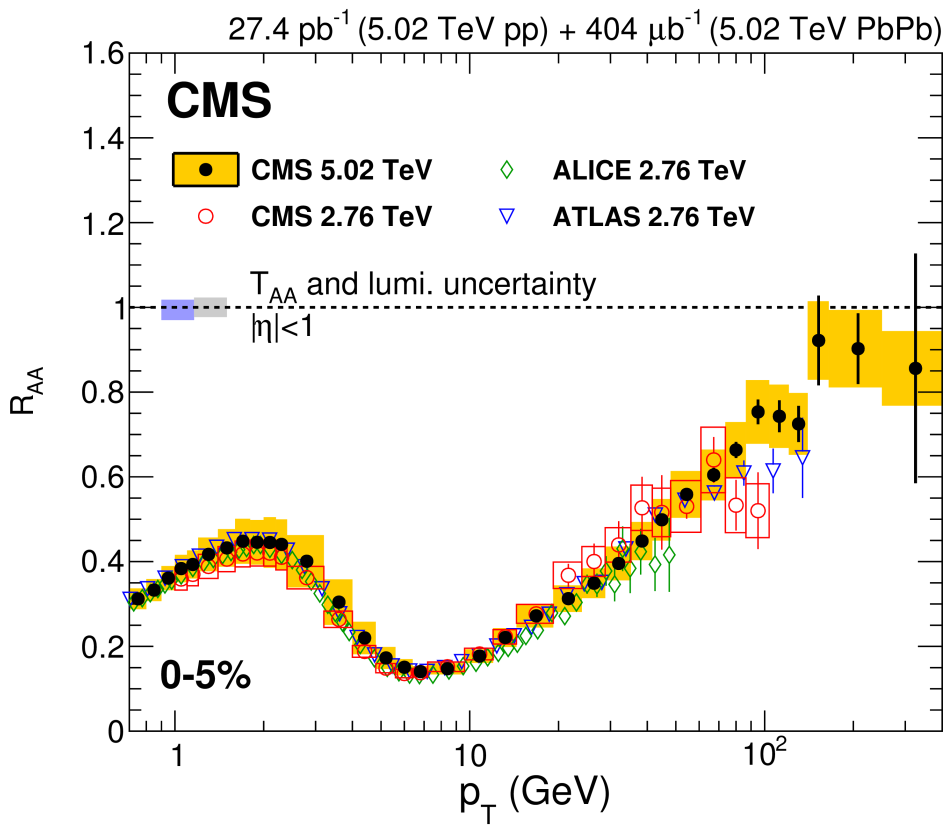


- Results consistent w/ Pythia … a model with no quenching!
- Q-Pythia which models quenching as enhanced parton splitting overestimates effect
- Jewel shows a strong sensitivity to how medium recoil is modeled suggesting a possible cancellation of effects


Glauber-MC
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
N_{part}
b (fm)
Glauber-MC
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
N_{part}
b (fm)
Glauber-MC
p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV
Multiplicity
N_{part}
Glauber-MC
Pb-Pb $\sqrt{s_{NN}}$ = 2.76 TeV
Multiplicity
N_{part}

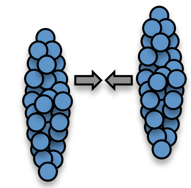
charged particle R_{AA} (alternate)

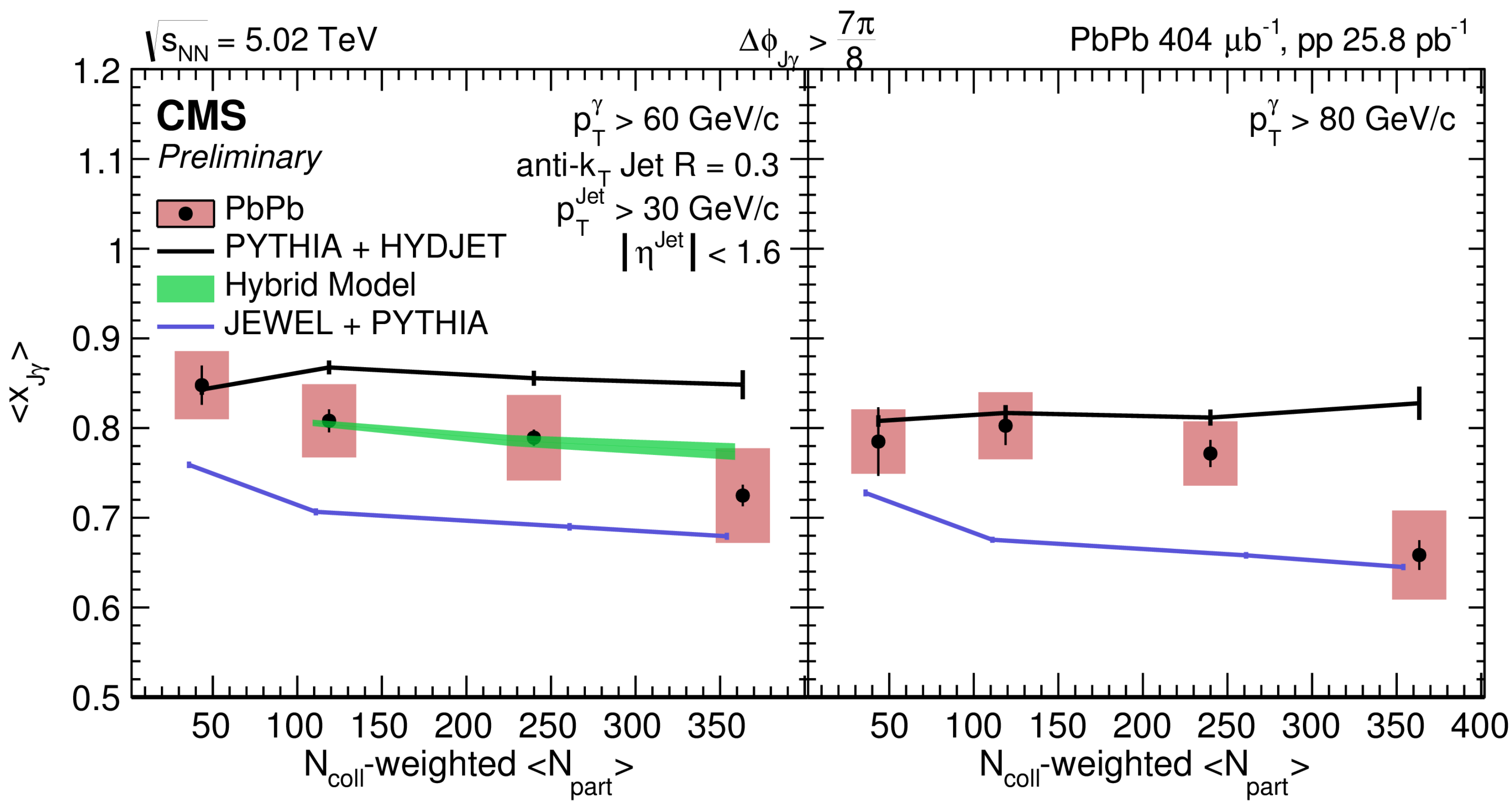




Reached extended to p_T > 100 GeV
Whearas flat @ RHIC, now seen to slowly rise, nearly to unity

Alternate CMS gamma-jet





ATLAS γ-jet

ATLAS-CONF-2016-110