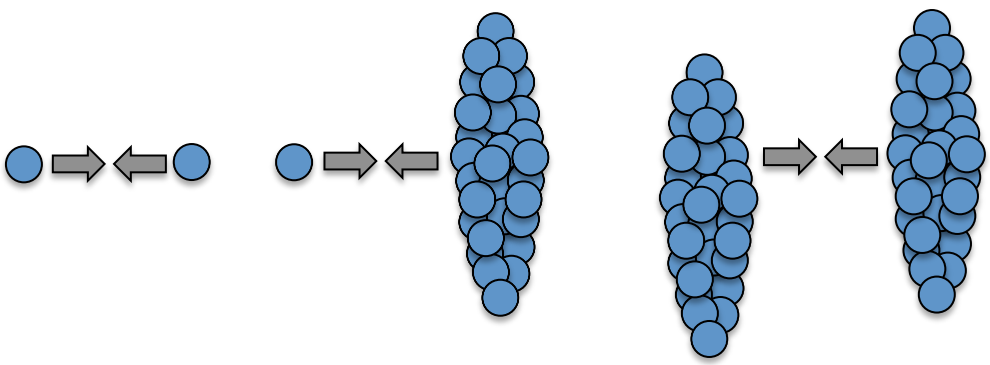
Jets & particle correlations in heavy-ion collisions



Matthew Nguyen

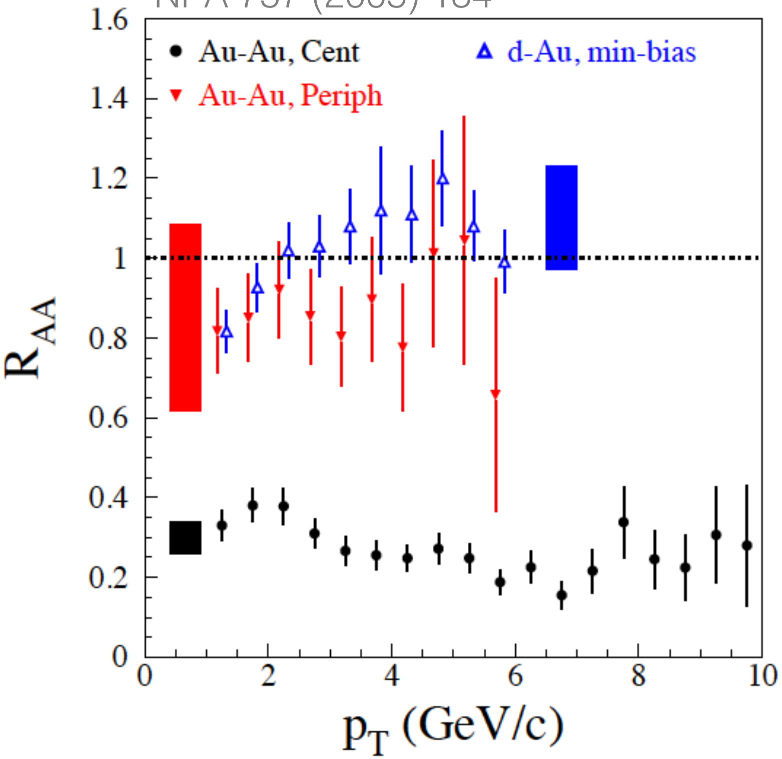
EPS-HEP, Venice

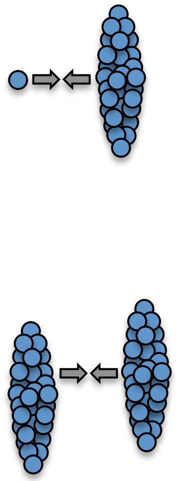
July 12^{th}, 2017

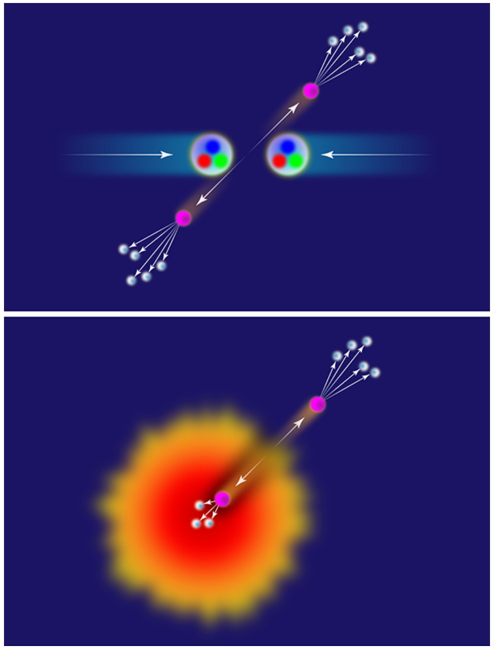
Jet quenching @ RHIC

ca. 2005

PHENIX “White paper”,
NPA 757 (2005) 184







C. Manuel, “The stopping power of hot nuclear matter”, PRL Viewpoint

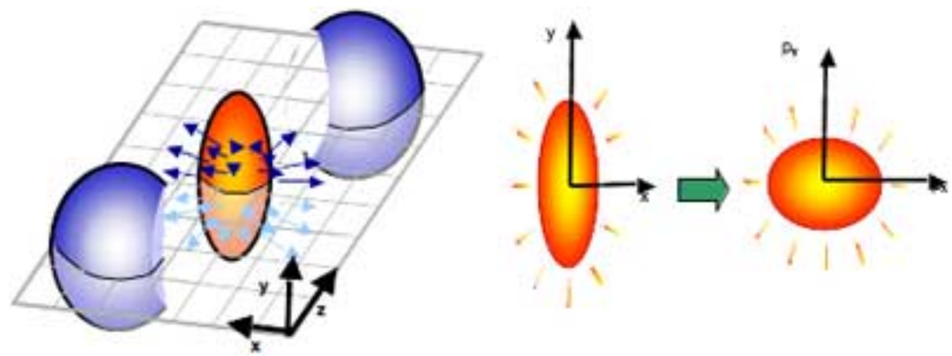
- High p_T hadron spectra in central AA suppressed by 5x
- No comparable suppression in peripheral AA or pA

→ Interpreted as parton energy loss in quark-gluon plasma

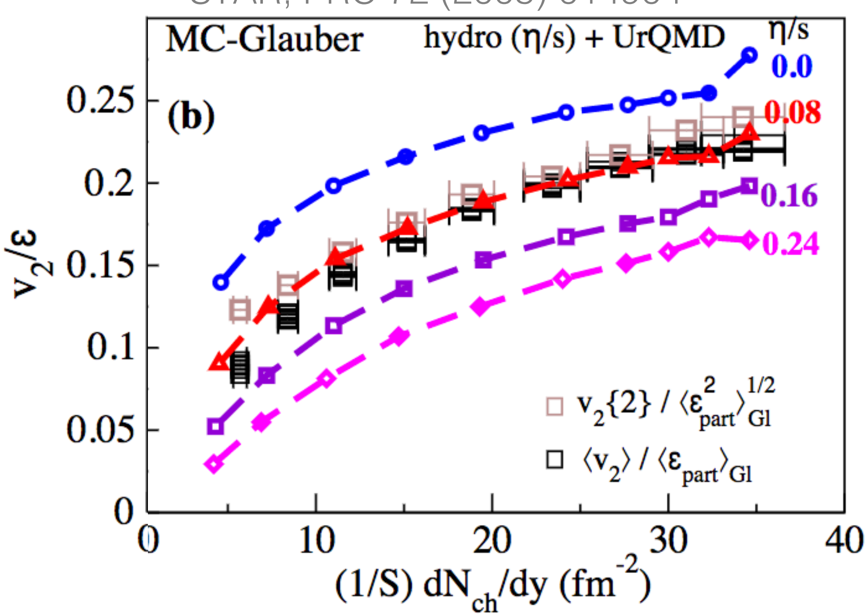
Collective flow @ RHIC

ca. 2005

- Collectivity measured with particle correlations
- Elliptic flow (v_2) measures how well initial asymmetry in non-central AA collisions propagates to final-state particles



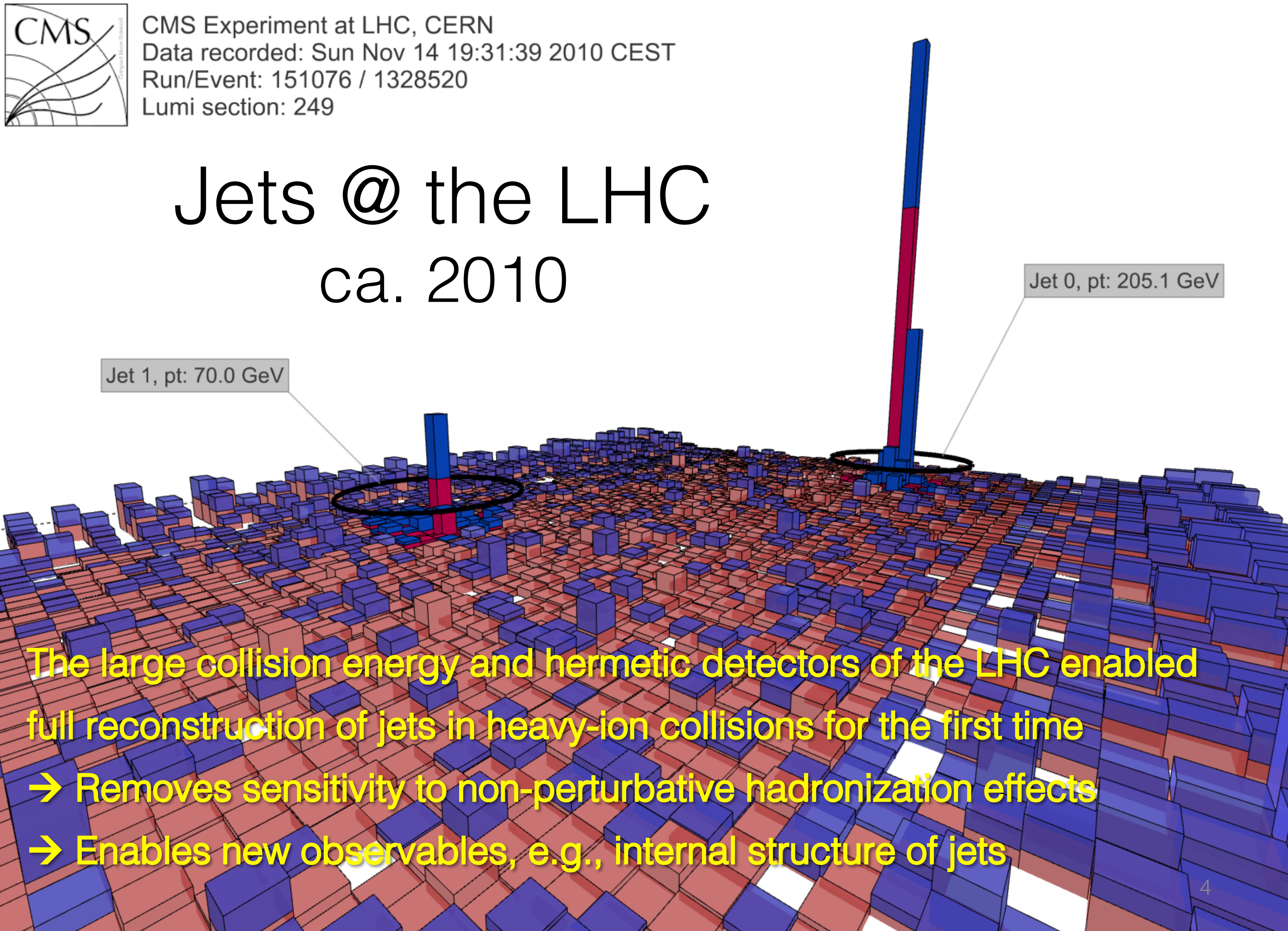
Heinz & Snellings
Ann.Rev.Nucl.Part.Sci. 63 (2013)123
STAR, PRC 72 (2005) 014904



- Flow measurements successfully described by hydrodynamics
- Surprisingly close to the ideal case, i.e., viscous corrections are small
- Shear viscosity / entropy density close to lower bound of 1/4π from AdS / CFT

Jets @ the LHC

ca. 2010

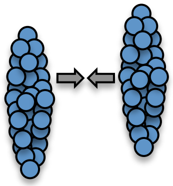


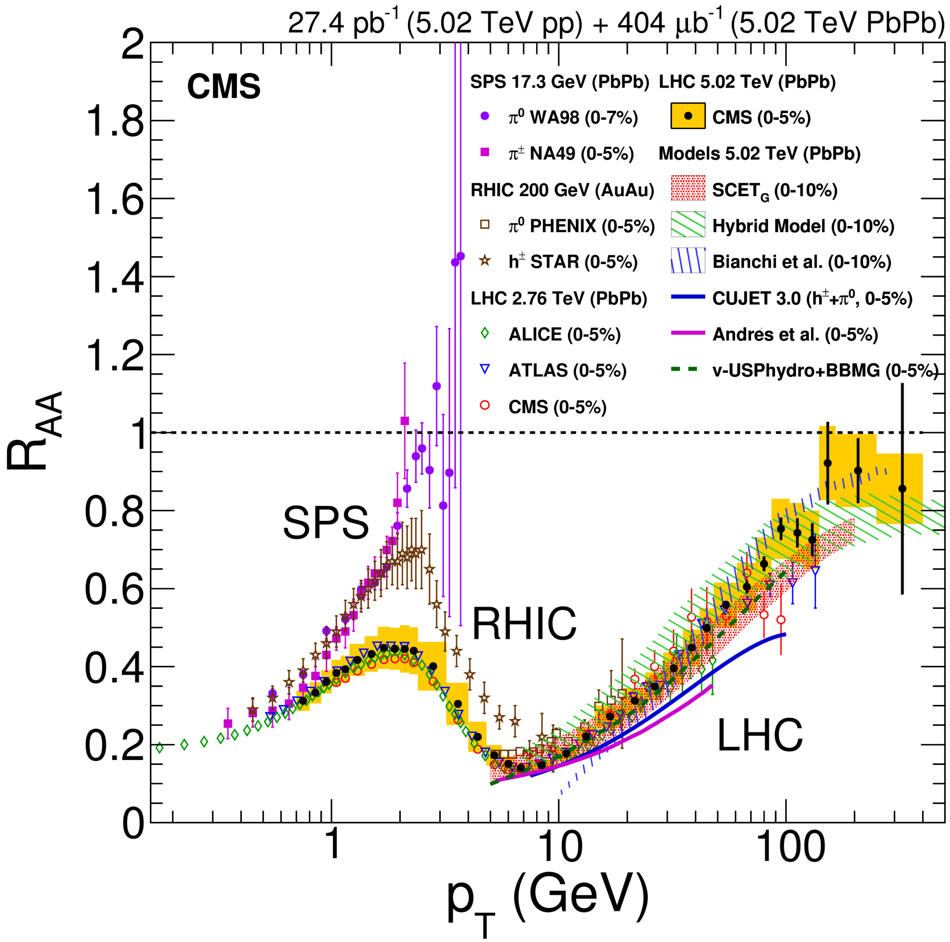
The large collision energy and hermetic detectors of the LHC enabled full reconstruction of jets in heavy-ion collisions for the first time

→ Removes sensitivity to non-perturbative hadronization effects

→ Enables new observables, e.g., internal structure of jets

Charged particle R_{AA}

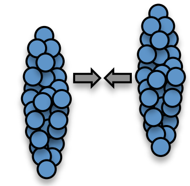




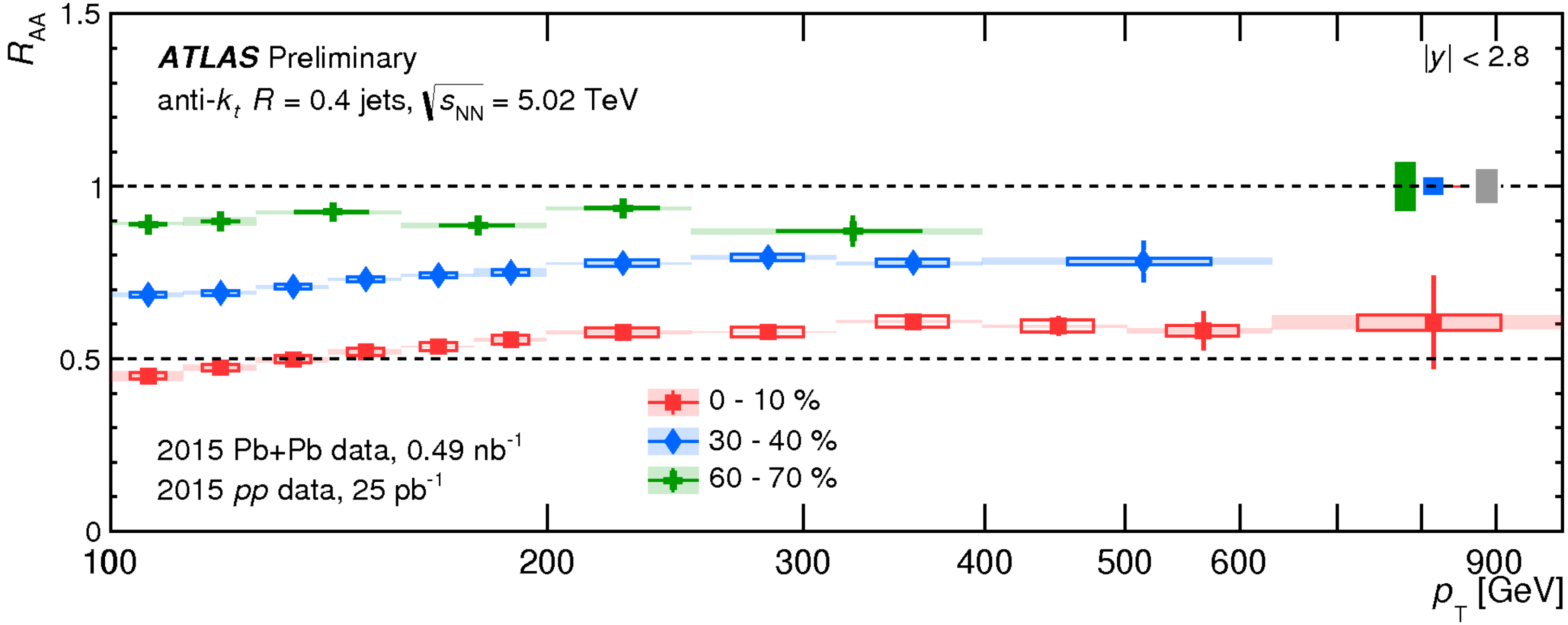
CMS, JHEP 1704 (2017) 039

- 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}

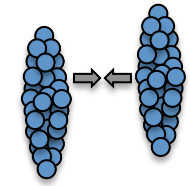


ATLAS-CONF-2017-009

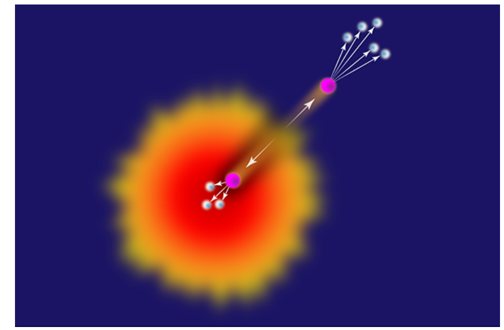


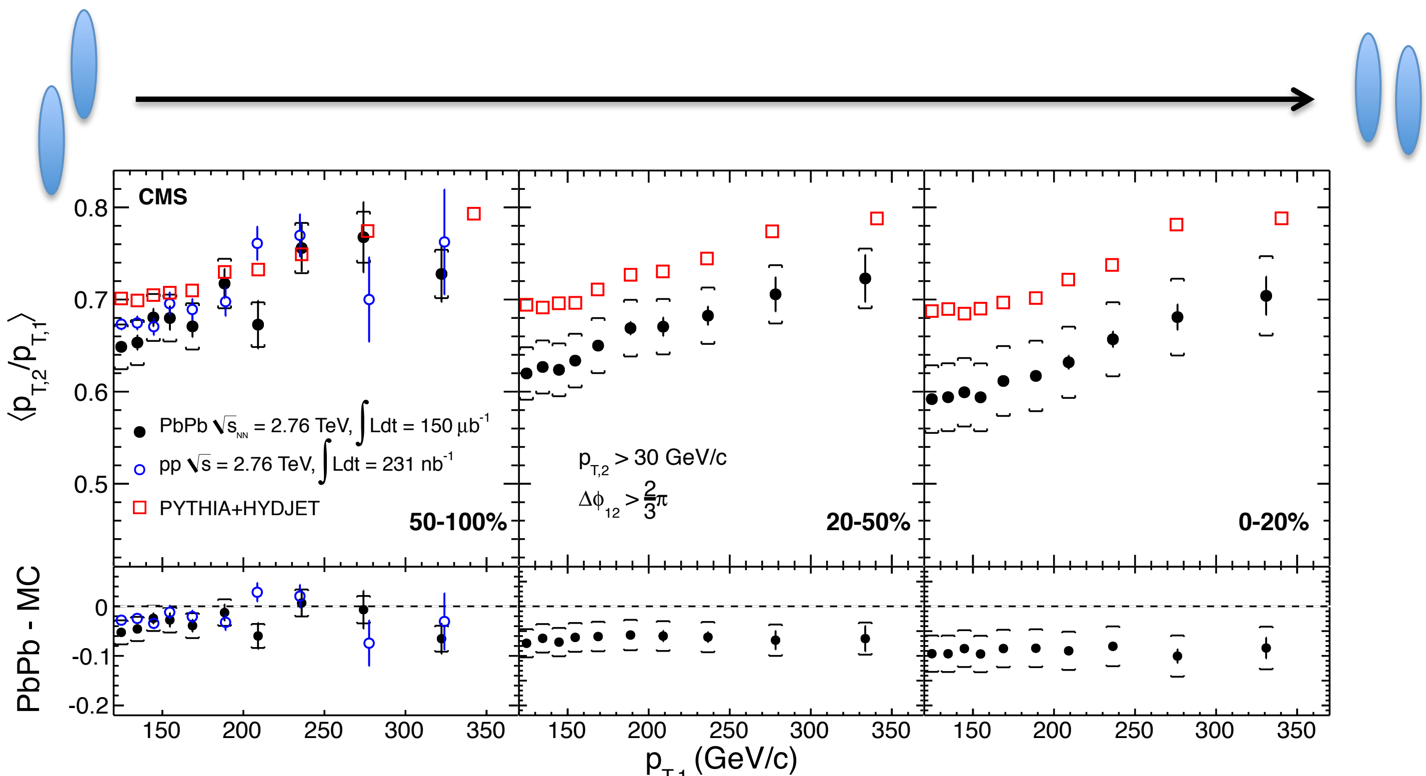
- R_{AA} for jets rises slowly, then remarkably flat out to ≈1 TeV !
- Quenching independent of cone size, up to R=0.4 (except @ low p_T)
  → quenched energy transferred to large angle (see also missing p_T)
- How to reconcile with charged hadrons? Is there an interplay between the jet fragmentation pattern and the parton energy loss?

Dijet imbalance



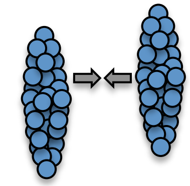
- Additional imbalance expected based on path-length difference between leading dijets
- Imbalance persists to largest p_T measured





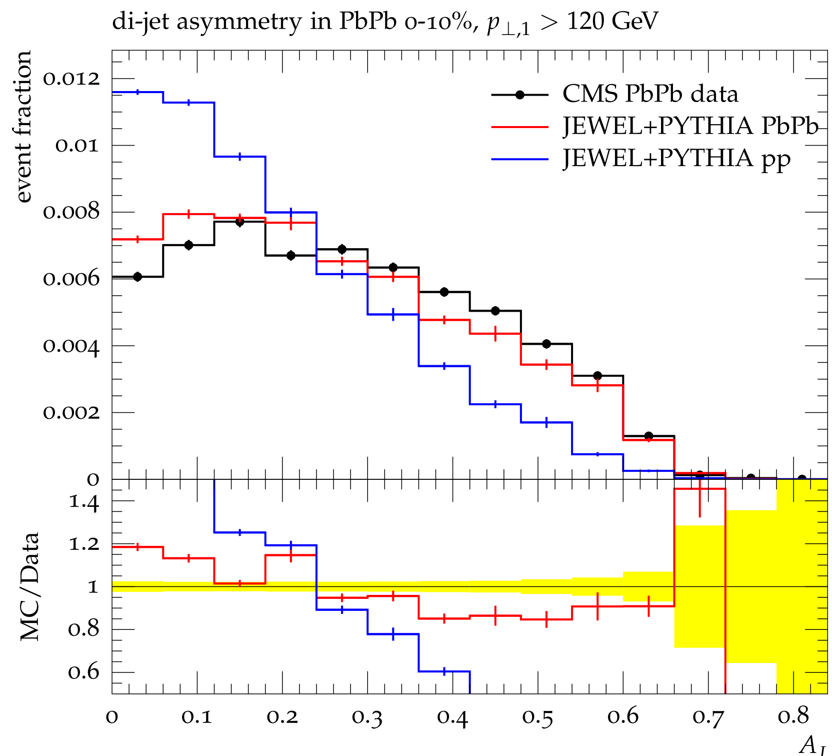
CMS, PLB 712 (2012) 176

Origin of dijet imbalance



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

→ For showers w/ more soft partons, more energy is pushed outside of the jet

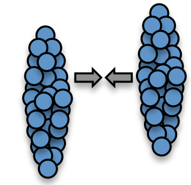


“Origins of the dijet asymmetry in heavy ion collisions”, Milhano & Zapp, EPJC 76 (2016) 288

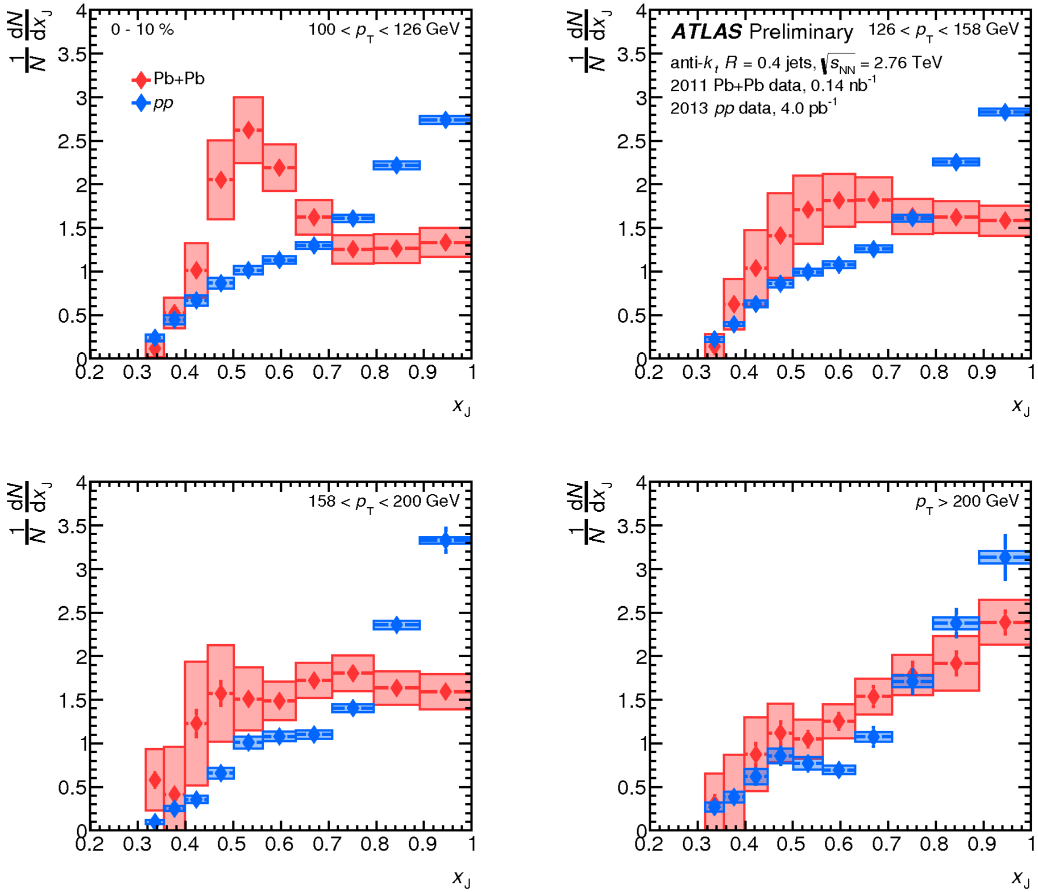
$$A_J \equiv \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

*JEWEL: PYTHIA-based generator that incorporates energy loss into parton shower model

Unfolded dijet p_T imbalance



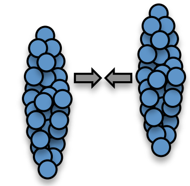
ATLAS, arXiv:1706.09363



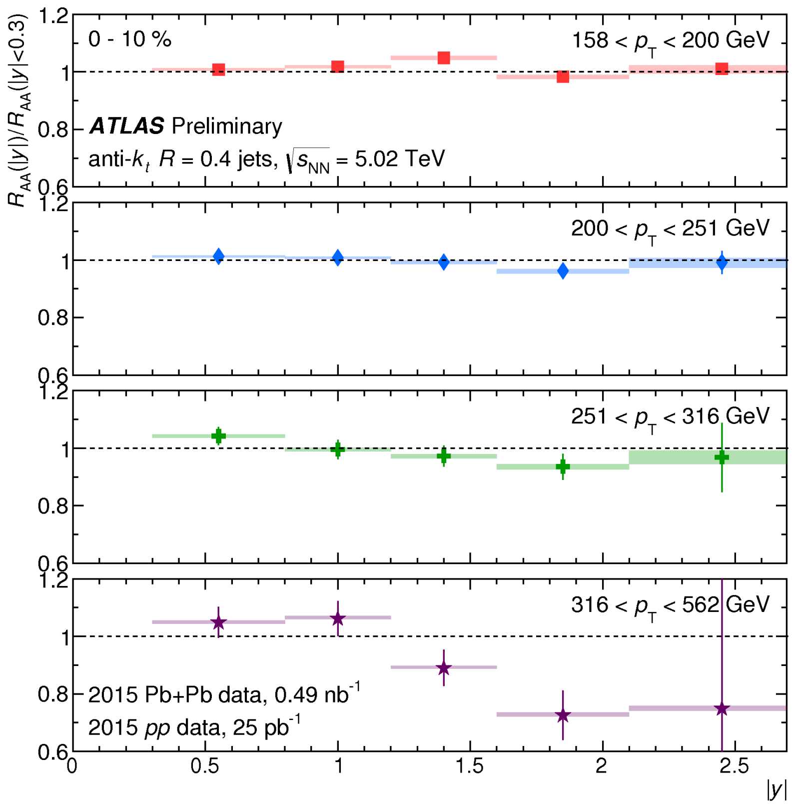
$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

- Dijet results recently unfolded for experimental effects
- Show a pronounced feature that diminishes with increasing p_T
- Not yet clear whether models will be able to reproduce this trend

Jet R_{AA} vs. rapidity



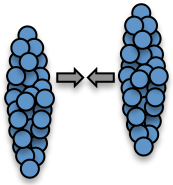
ATLAS-CONF-2017-009



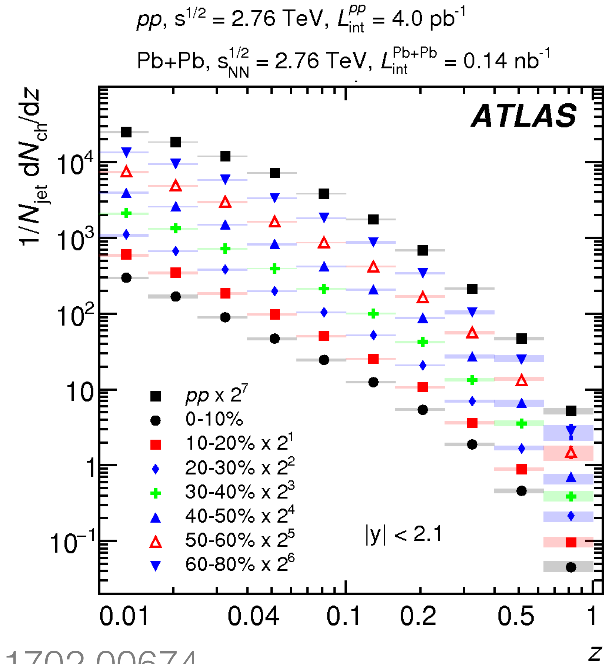
- R_{AA} flat vs. rapidity, except at largest p_T
- With increasing y expect:
  - Steeper spectral slope
  - Larger quark/gluon ratio

… which should push R_{AA} in opposite directions

Jet fragmentation



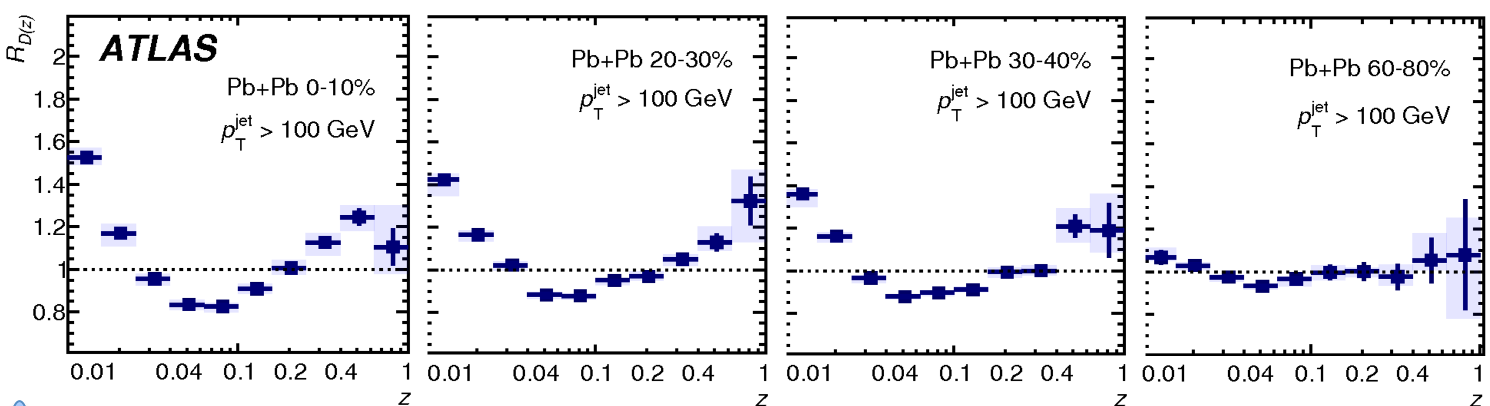
- Intra-jet fragmentation function: hadron w.r.t. reconstructed jet
- Ratio of central PbPb to pp shows
  - Excess at low z
  - Depletion at intermediate z
  - Excess again at large z

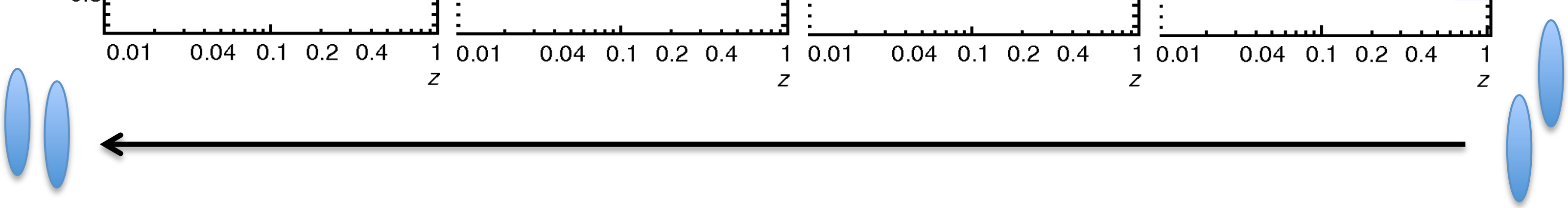


$$z = \frac{p_{\mathrm{T,hadron}}}{p_{\mathrm{T,jet}}}$$

ATLAS, arXiv:1702.00674

$\frac{\text{PbPb}}{\text{pp}}$

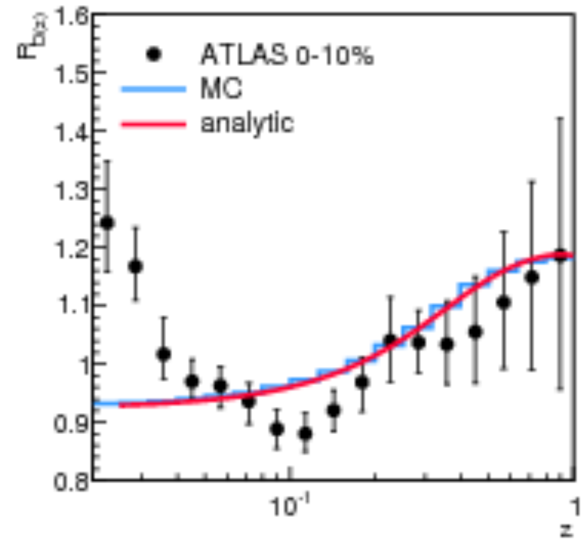


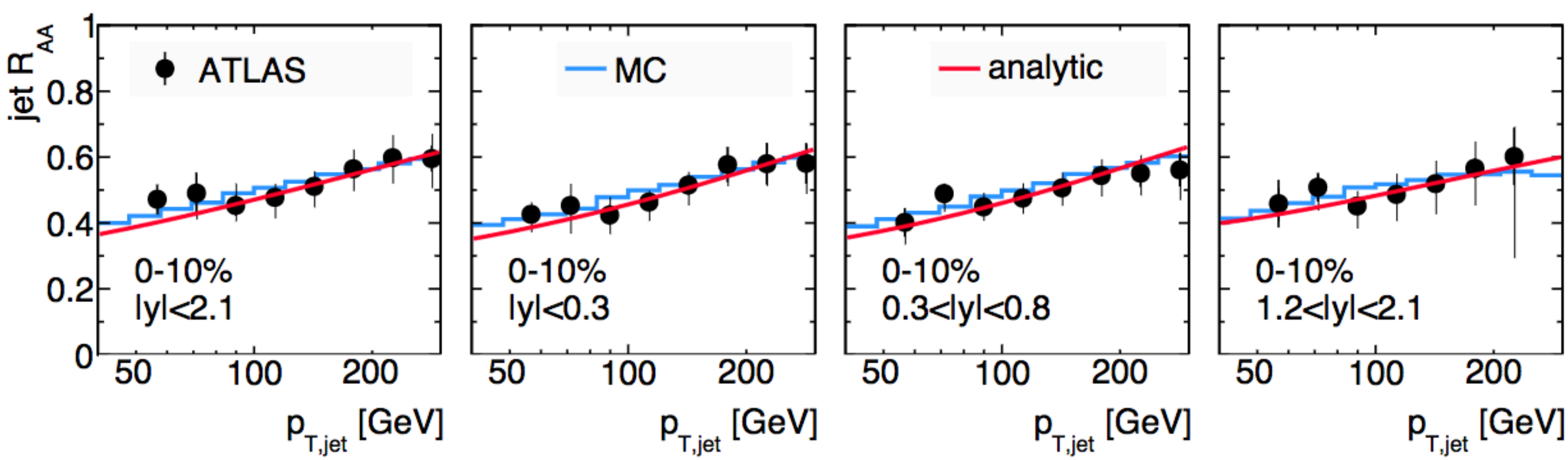


Quark vs. gluon energy loss

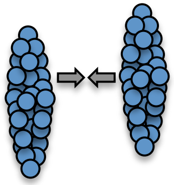
- Naively, gluon/quark radiative energy loss: 9/4
- One model explains both high & medium *z* fragmentation & jet R_{AA} vs. y, w/ <u>only</u> flavor dependence of energy loss
- In this picture, fragmentation dependent quenching related to the initiating parton, rather than subleading shower partons

Calculations by Cole & Spousta
EPJC 76 (2016) 50



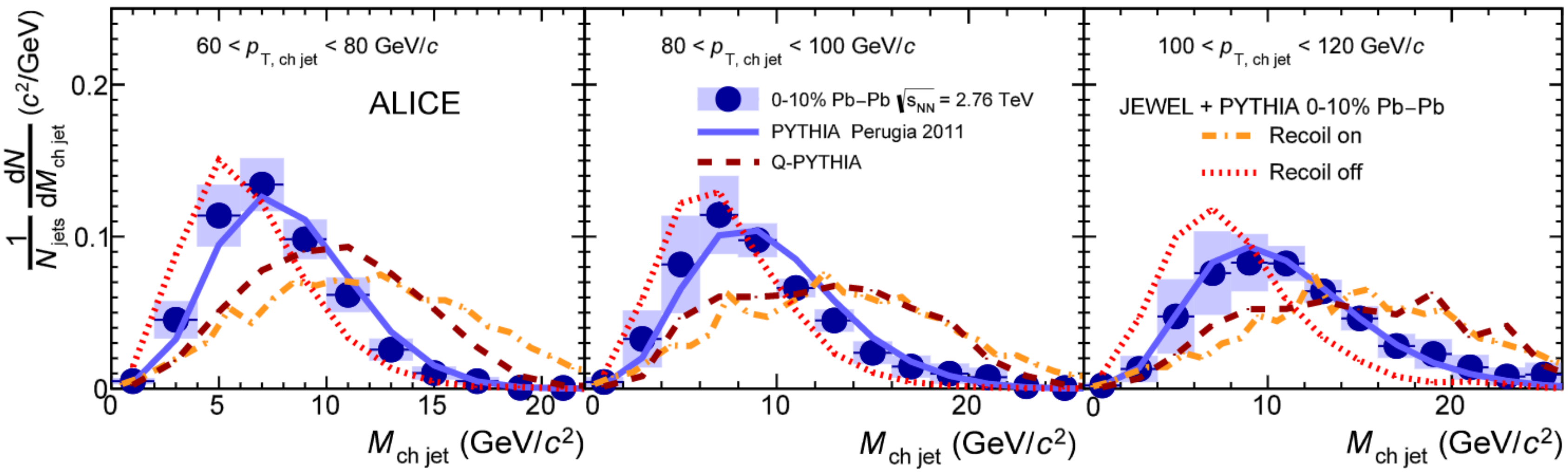


Jet mass



- Jet mass sensitive to the virtuality of the initiating parton
- Quenching expected to induce additional radiation, increasing mass

ALICE, arXiv:1702.00804



- Results consistent w/ PYTHIA… a model with no quenching!
  → Core of jet with R=0.4, may simply not be significantly modified
- Q-PYTHIA: quenching modeled as enhanced parton splitting, overestimates effect (update expected soon)
- JEWEL shows a strong sensitivity to how medium recoil is modeled

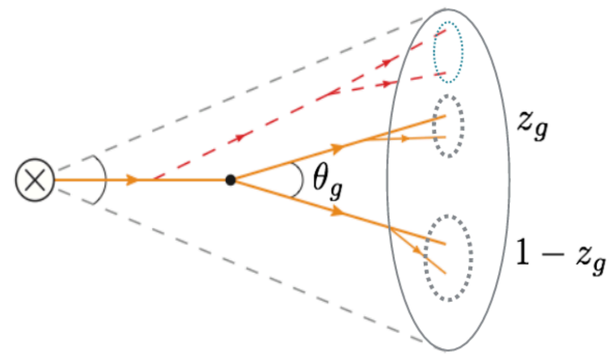
Discussion of jet background subtraction in JEWEL: Elayavalli & Zapp, arXiv:1707.01539

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:

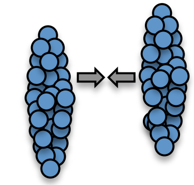
$$z_g \equiv \frac{\min\left(p_{T,1}, p_{T,2}\right)}{p_{T,1} + p_{T,2}}$$



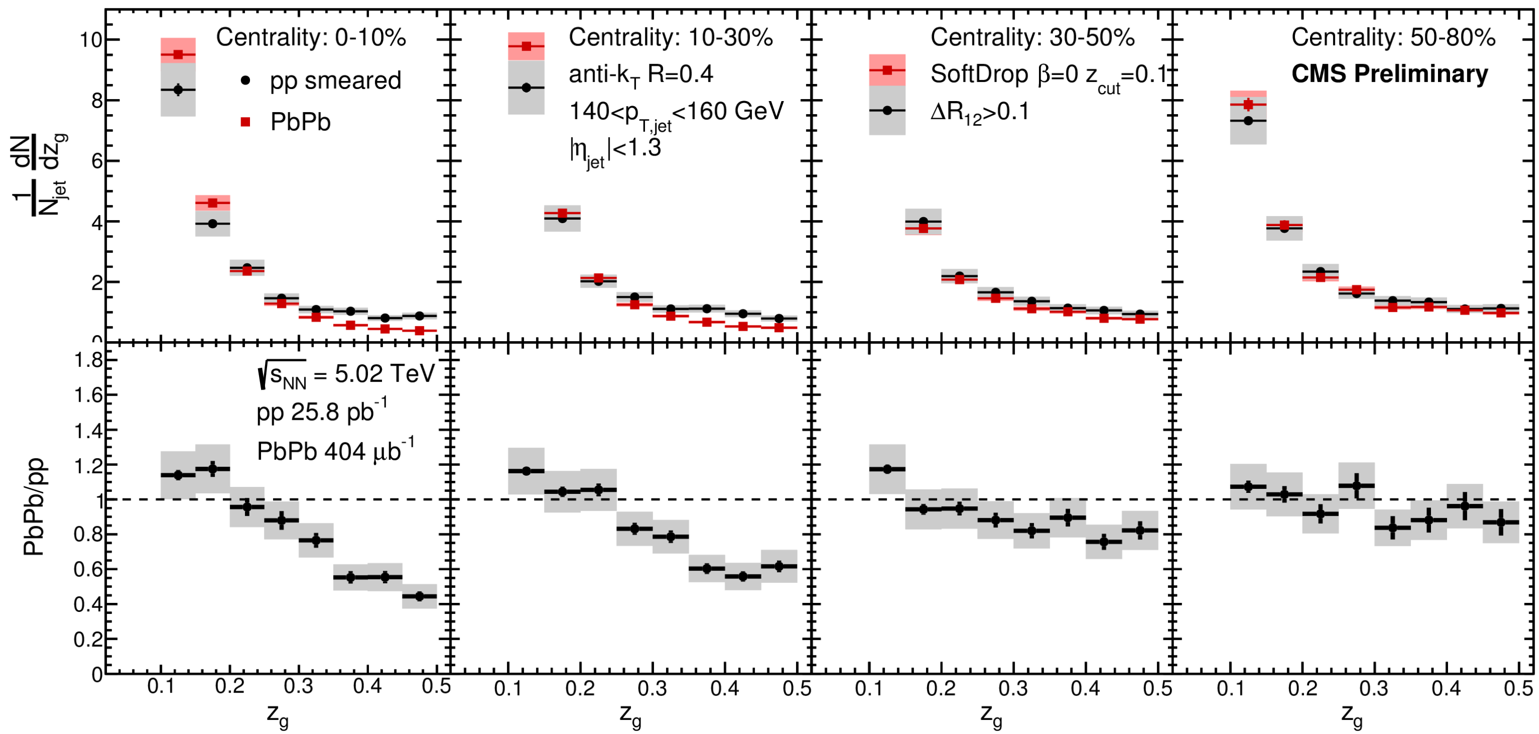
- For vacuum case (e.g., pp): directly related to Altarelli-Parisi splitting
- For quenching jets: sensitive to coherence between nearby partons
- CMS measures down to minimum opening angle of $\theta_g = 0.1$
- Requires grooming*, a procedure to remove soft radiation and uncorrelated background

* CMS using “Soft-drop” Larkowski et al., JHEP 1405 (2014) 146

Groomed momentum fraction

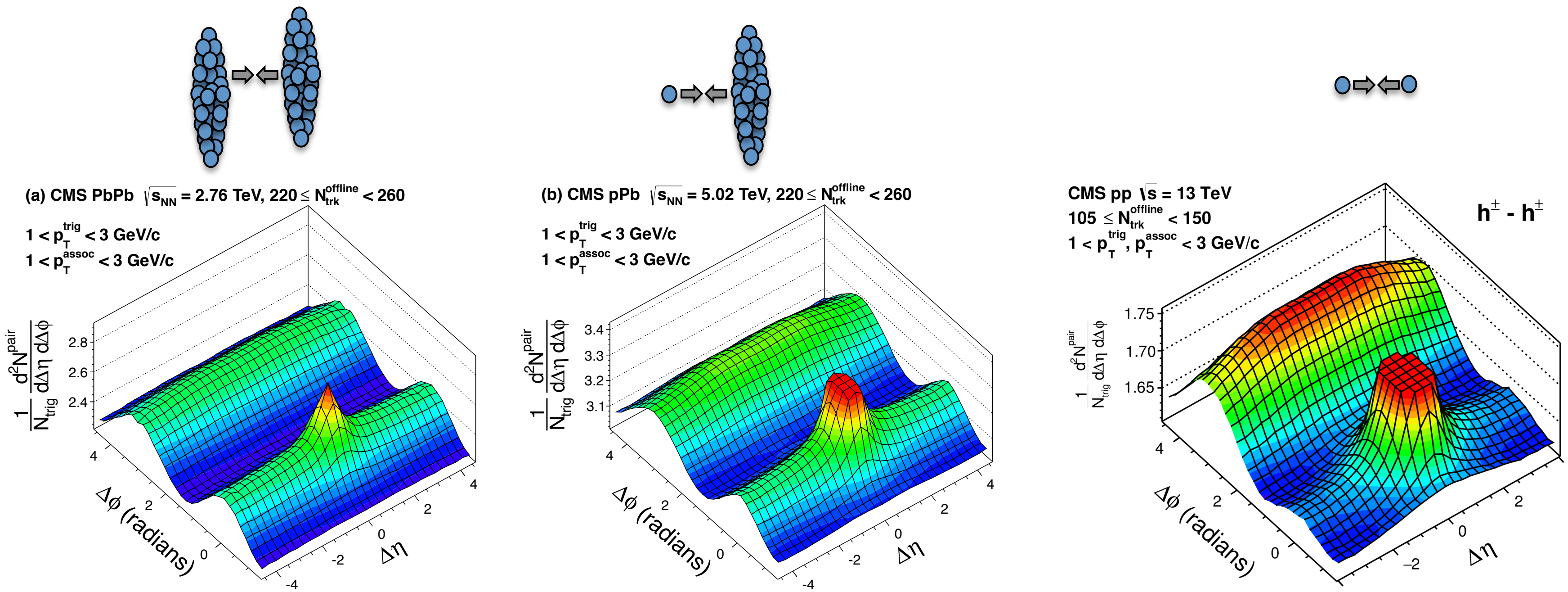


CMS-PAS-HIN-16-006



- Relatively fewer symmetric subjets w/ increasing centrality
- Effect disappears in peripheral & at high p_T (not shown)
- Several explanations on the market, premature to conclude this is coherence breaking at low p_T

Collectivity @ the LHC: small systems



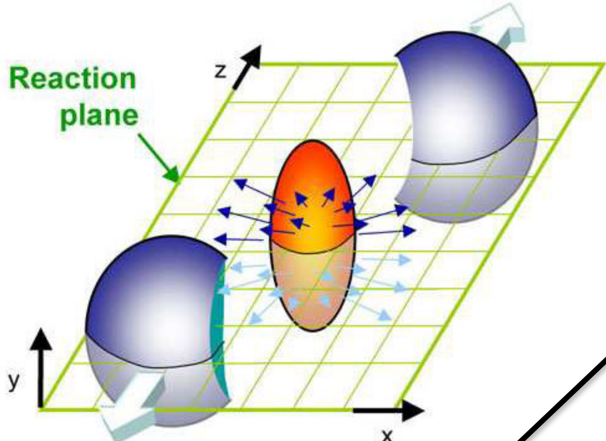
CMS, PLB 724 (2013) 213

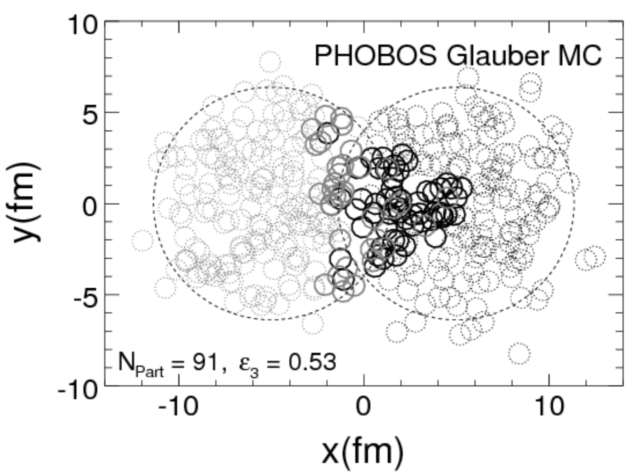
CMS, PLB 765 (2017) 193

- "Ridge" = long-range rapidity correlation → must arise @ early time
- Shows up even in small systems given high enough multiplicity

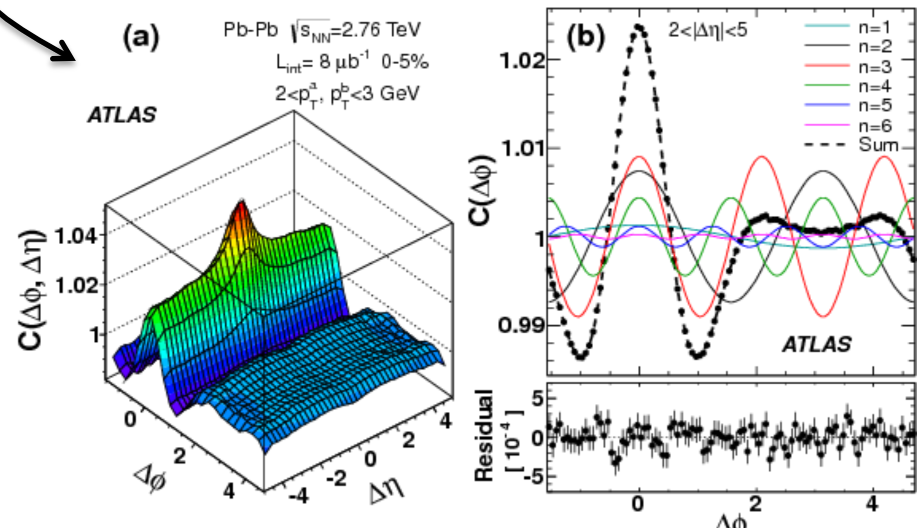
(De)composition of the ridge

- Flow coeff's v_n from Fourier analysis
- At the outset, large v_2 expected from almond shape of overlap region
- Later, fluctuations understood to generate higher order v_n terms, e.g., triangular flow (v_3)
- Ridge arises from coherent sum of v_n, i.e., corresponds to hydrodynamic flow

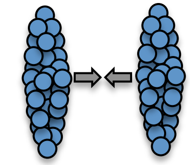


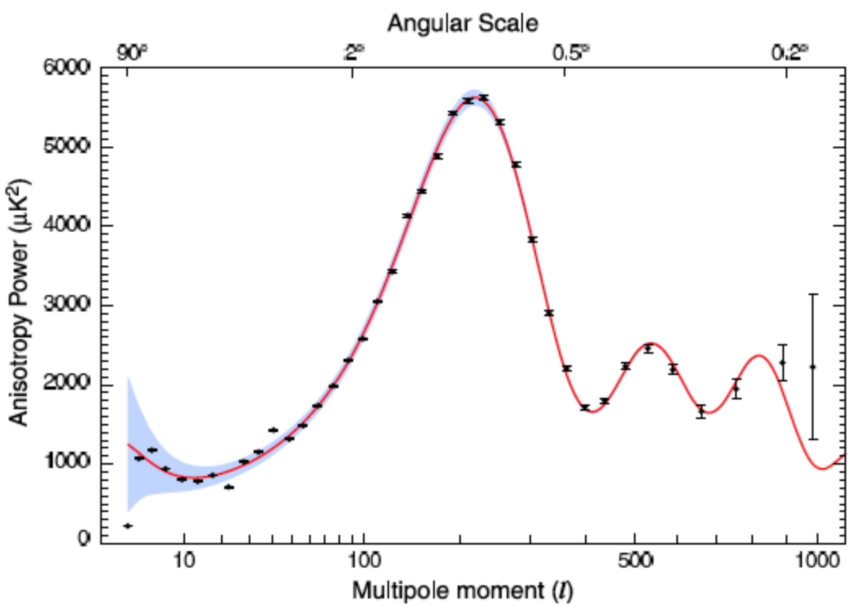


Alver & Roland, PRC 81 (2010) 054905



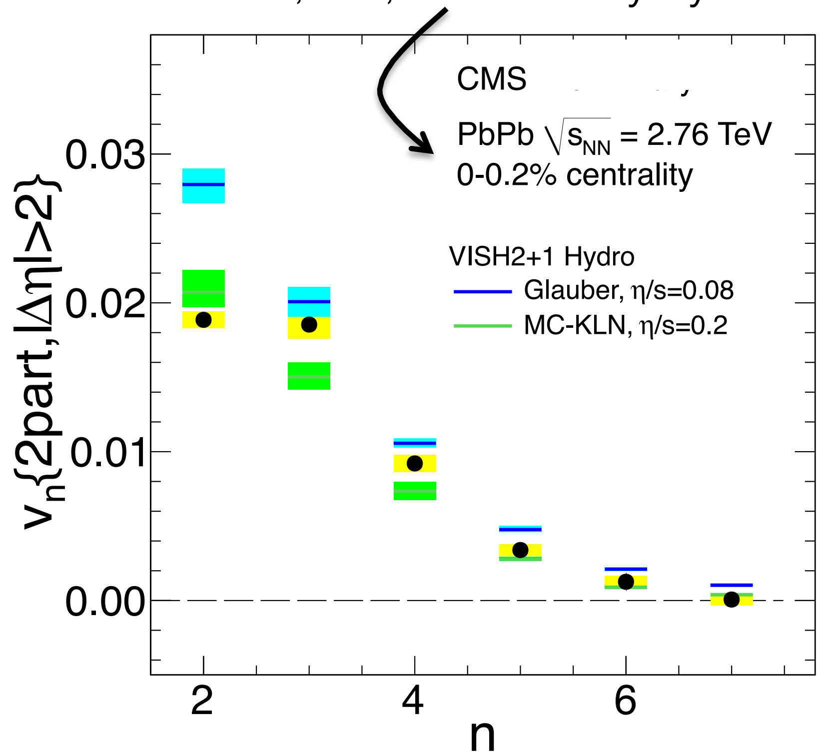
ATLAS, PRC 86 (2012) 014907

Mapping initial state fluctuations 



NASA/WMAP Science team

Ultra-central, i.e., azimuthally symmetric



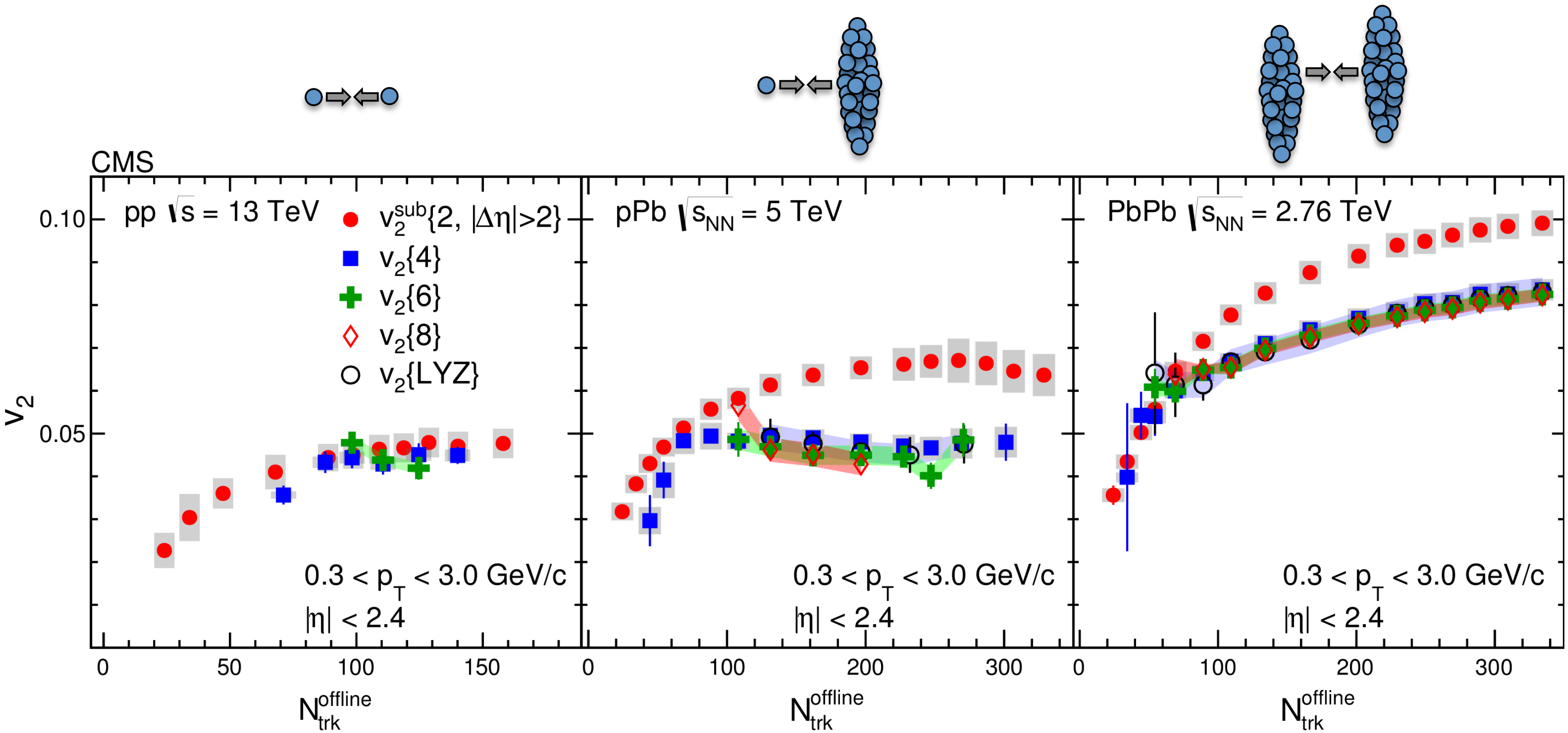
CMS, JHEP 02 (2014) 088

Power spectrum of the cosmic microwave background reflect fluctuations in the density of matter in the early universe before inflation

Fourier harmonics from long-range correlations reflect fluctuations of the initial state of dense QCD matter before hydrodynamic expansion

Multiparticle correlations

Two-particle correlations suffer from residual “non-flow” effects (e.g., from jets)
More robust (but statistically demanding) are correlations among many particles

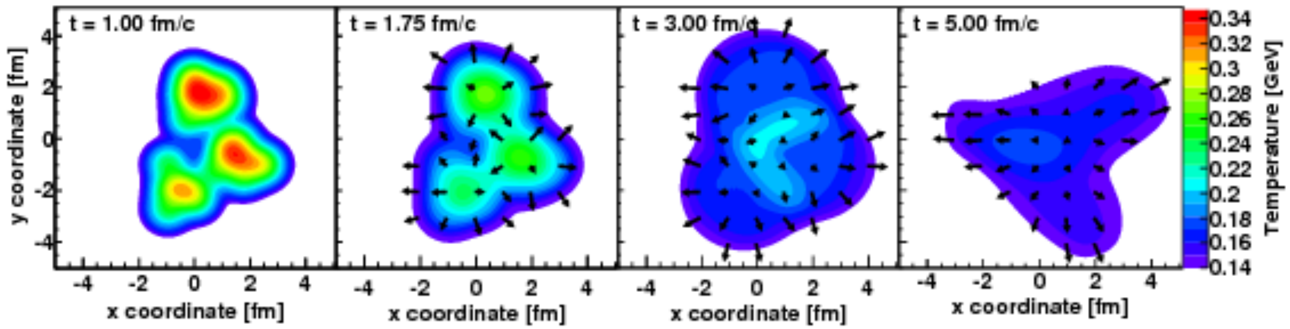


Common pattern emerges for all collision systems for multiplicity >~ 100
Collectivity apparently universal, seemingly arising from a fluctuations even at the scale of the proton

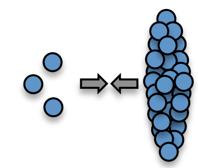
CMS, PLB 765 (2017) 193

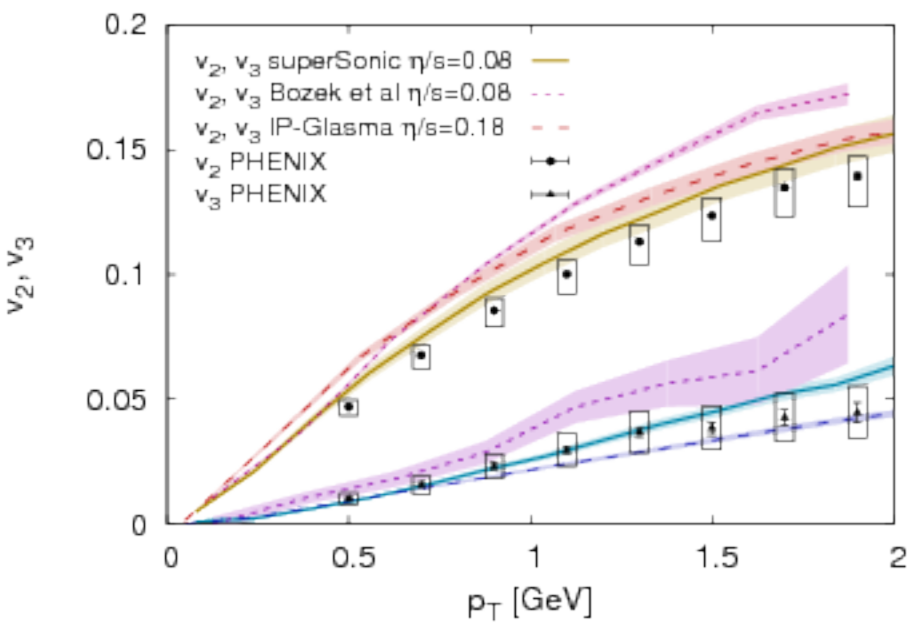
Manipulating geometry @ RHIC

Nagle et al., PRL 113 (2014), 112301



He3 + Au





PHENIX, PRL 115 (2015), 14230

- Helium 3 collided with gold to exploit intrinsic triangular geometry
- Hydrodynamics generally describes v_2 and v_3 in central He3+Au data
- However, relatively large sensitivity to initial state and pre-equilibrium dynamics

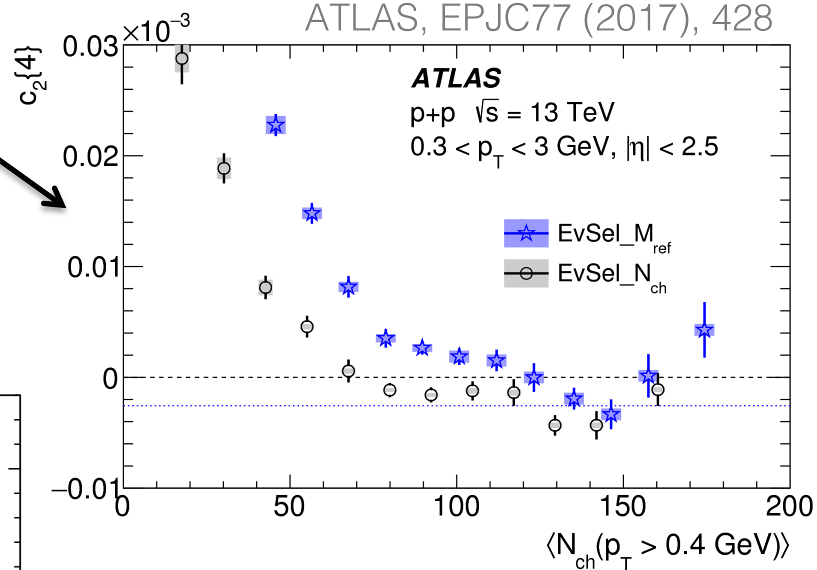
Flow & non-flow in pp

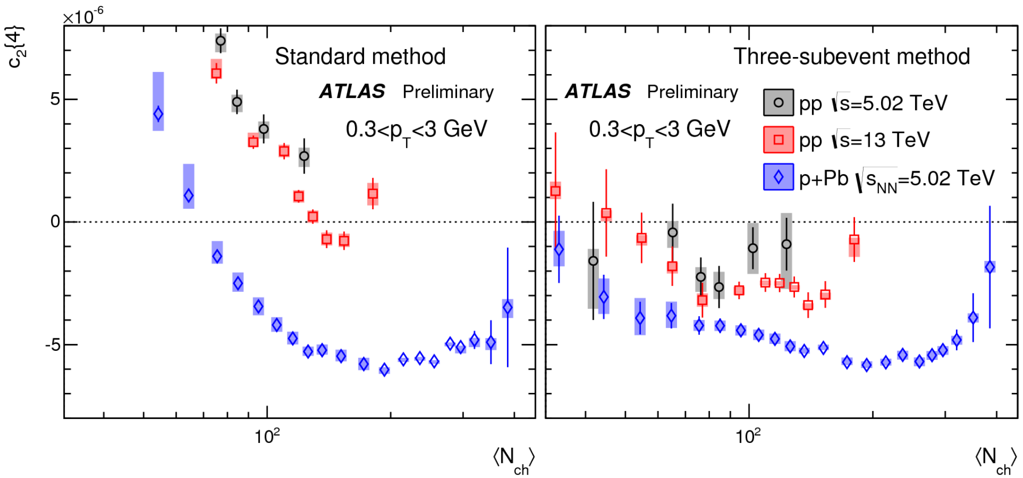
Flow extraction in pp is highly sensitive to event classification and residual non-flow

Collective flow signal only if $c_2\{4\} < 0$

$$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$$

ATLAS, EPJC77 (2017), 428



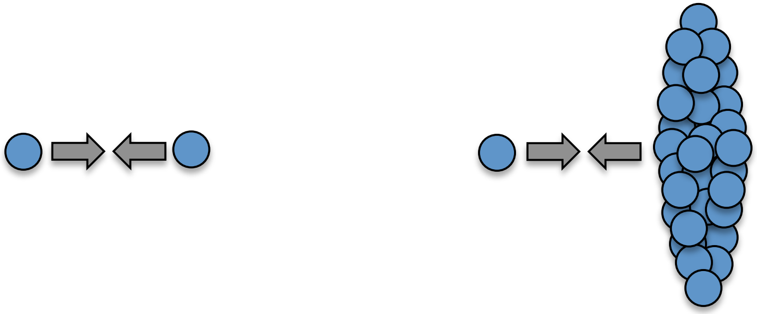


However, "sub-event" method, confirms positive flow signal

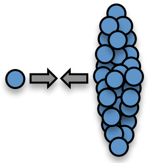
ATLAS-CONF-2017-002

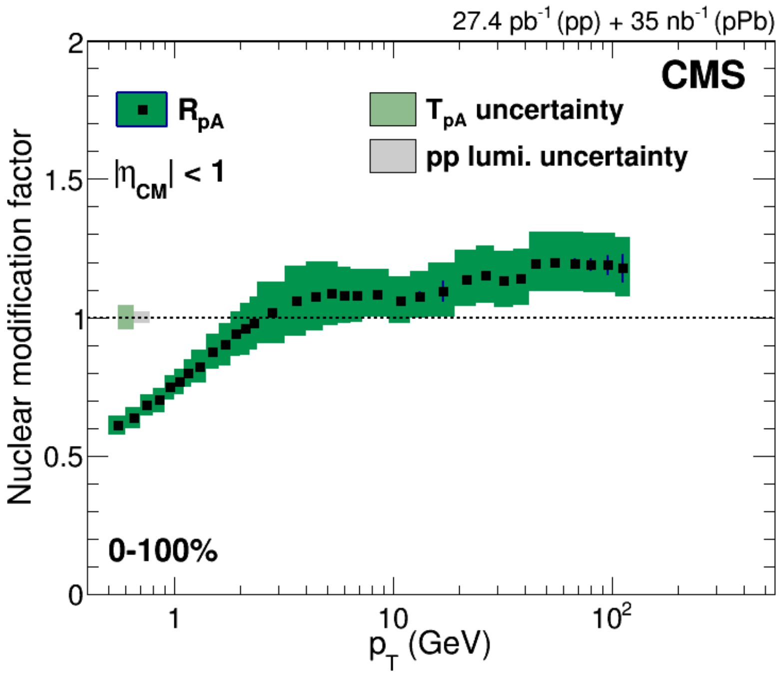
- Emerging consensus: High multiplicity pp collisions do exhibit collectivity
- Still debated:
  - Is hydrodynamics a valid description of small systems?
  - Can collectivity arise purely from initial state fluctuations?
- In any case, this is "new physics" emerging from high density QCD

If collective effects are observed in small systems, do jets also show effects from dense QCD?



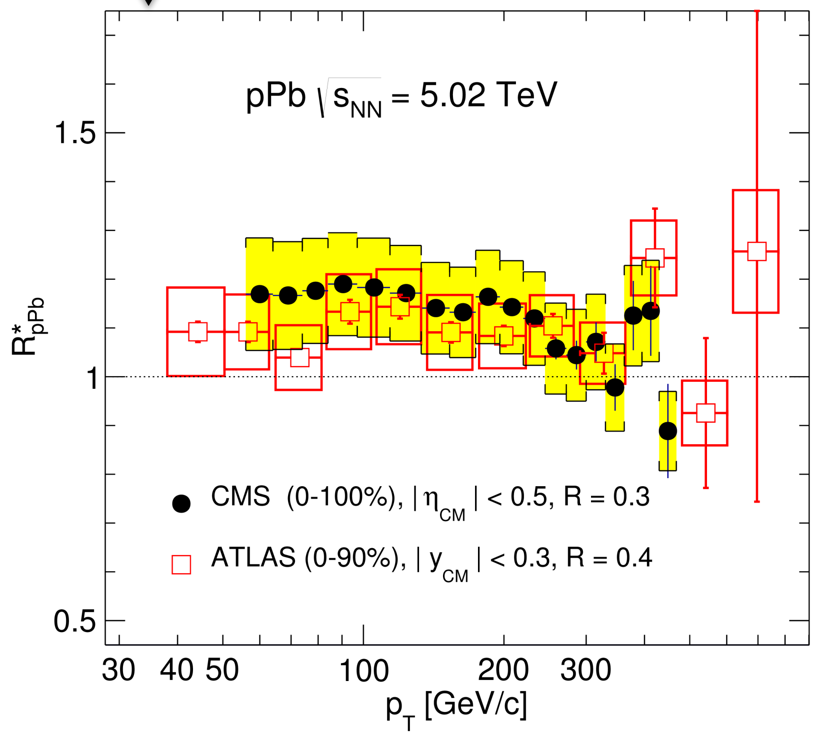
Hadron & jet R_{pA}





CMS, JHEP 04 (2017) 039

CMS, EPJC 76 (2016) 372



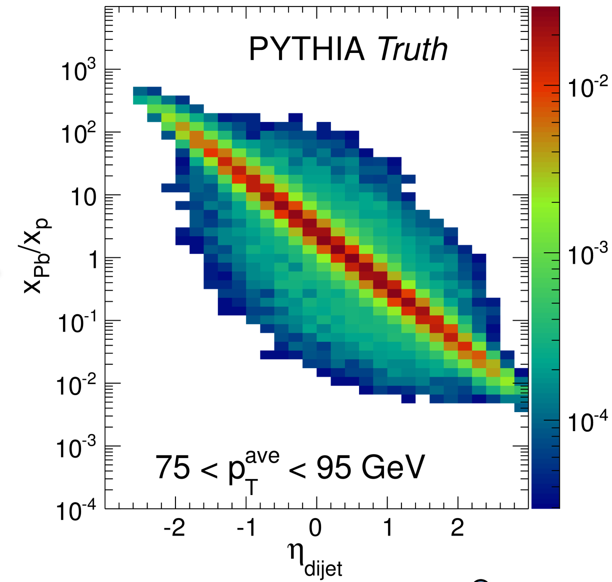
- No suppression as would be expected from jet quenching
- Rather, enhancement due to nuclear effects on the parton distributions
- How can these nPDF effects be measured with precision at the LHC?

Dijets in pA

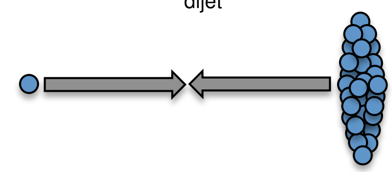
- Dijets correlated to parton kinematics, for leading order 2→2 scattering

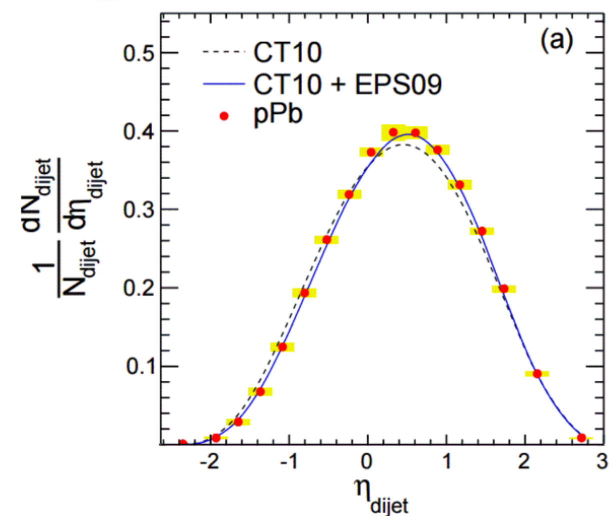
$$\eta_{\mathrm{dijet}} = (\eta_1 + \eta_2)/2 \propto \log(x_p / x_A)$$

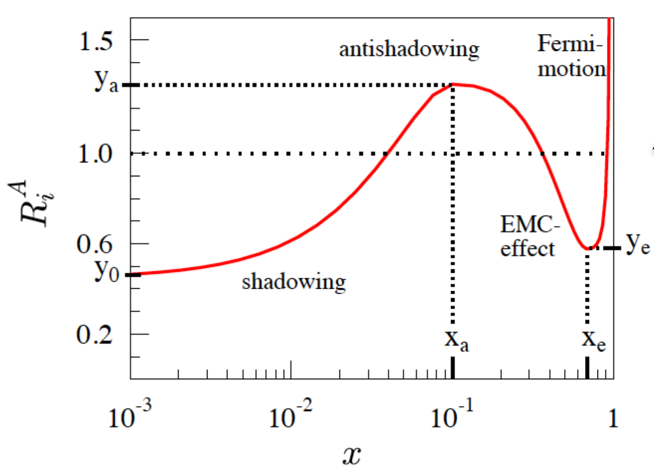
$$p_{\mathrm{T,dijet}} = (p_{\mathrm{T},1} + p_{\mathrm{T},2})/2 \propto Q$$



- Nuclear effects result in (tiny!) shift in η, but measurable w/ self-normalization
- Dijets @ LHC sample gluon shadowing, anti-shadowing and EMC regimes

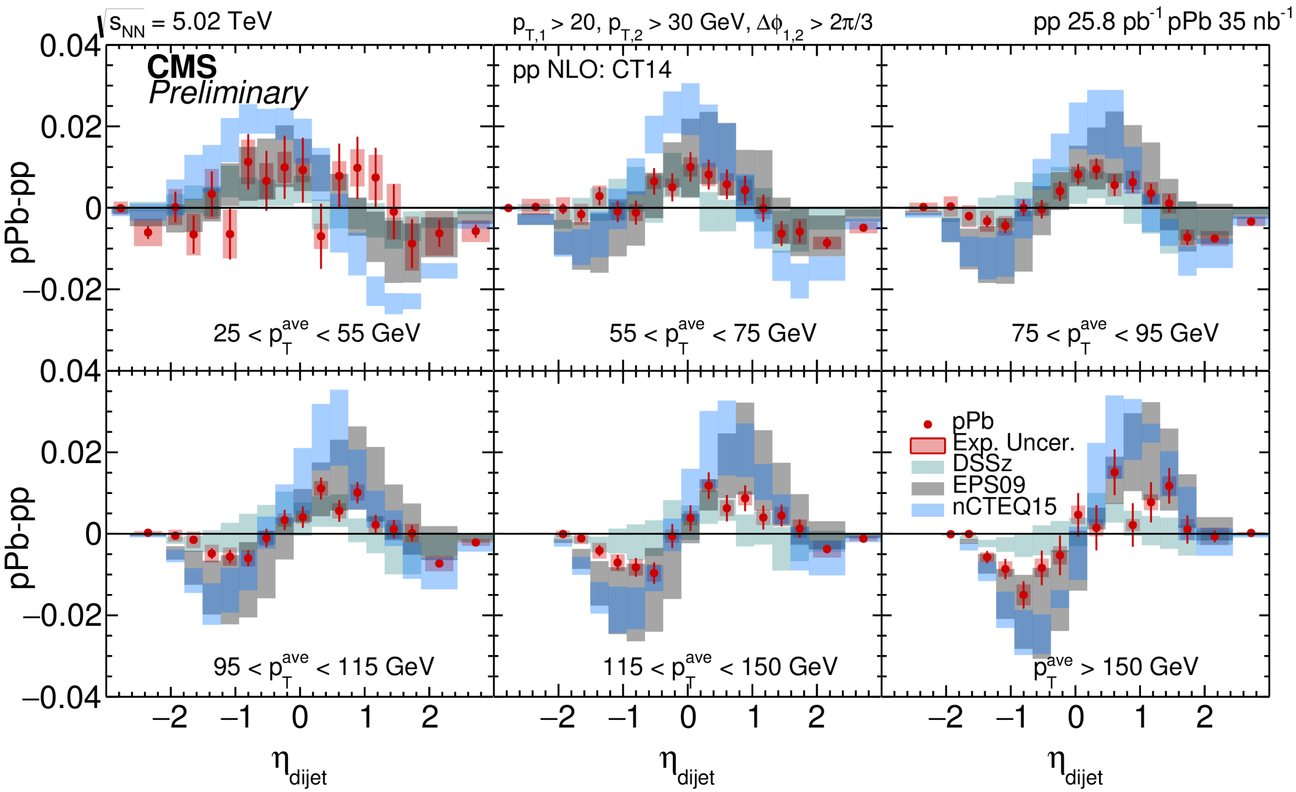






CMS, EPJC 74 (2014) 2951

Dijet η shift



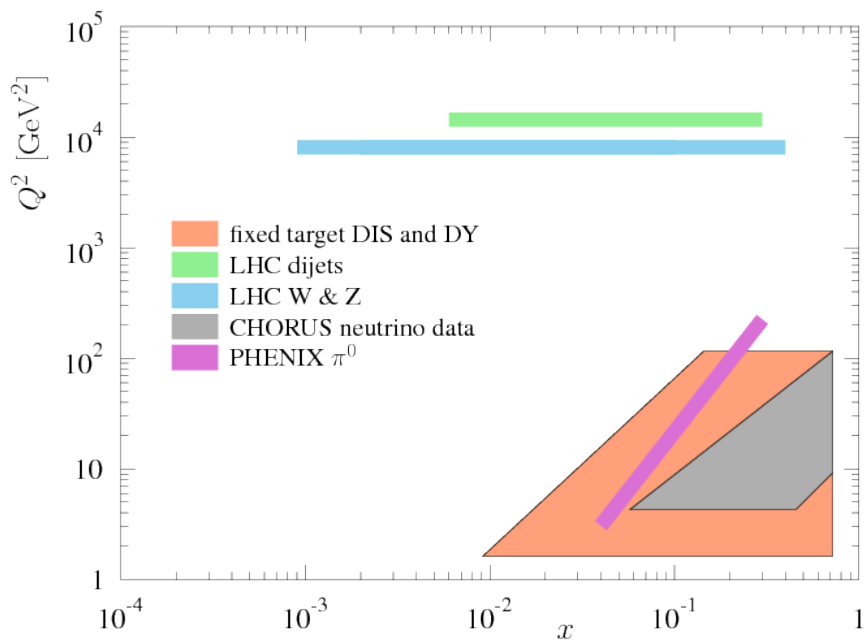
CMS-PAS-HIN-16-003

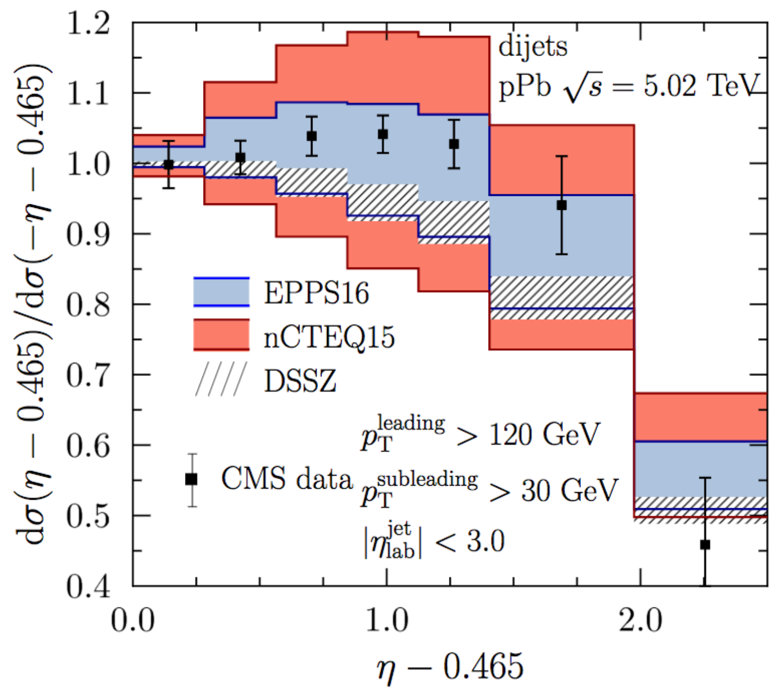
- Despite percent level deviations, significant nuclear effects observed
- Moreover, discrimination between various global fit analysis

Inclusion into nPDF fit

“EPPS16: Nuclear parton distributions with LHC data”

Eskola et al., EPJC 77 (2017) 163



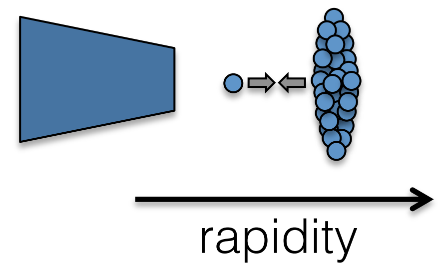


Gluon nuclear modification similar to quarks (from ν-nucleus DIS)

→ Supports collinear factorization and process independent nPDFs

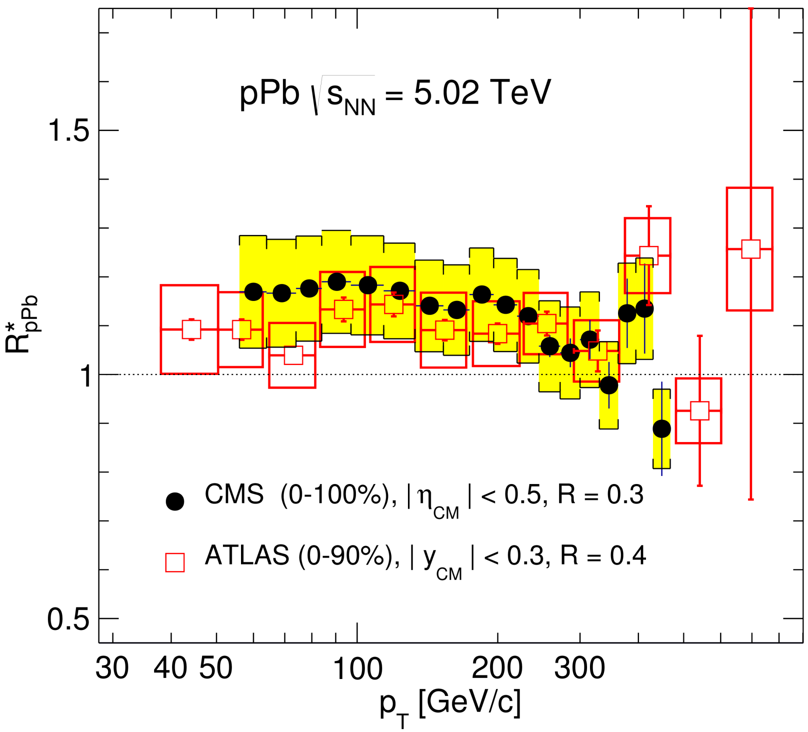
→ Best constraints so far on the high-x nuclear gluon distribution

Jets vs. event activity*

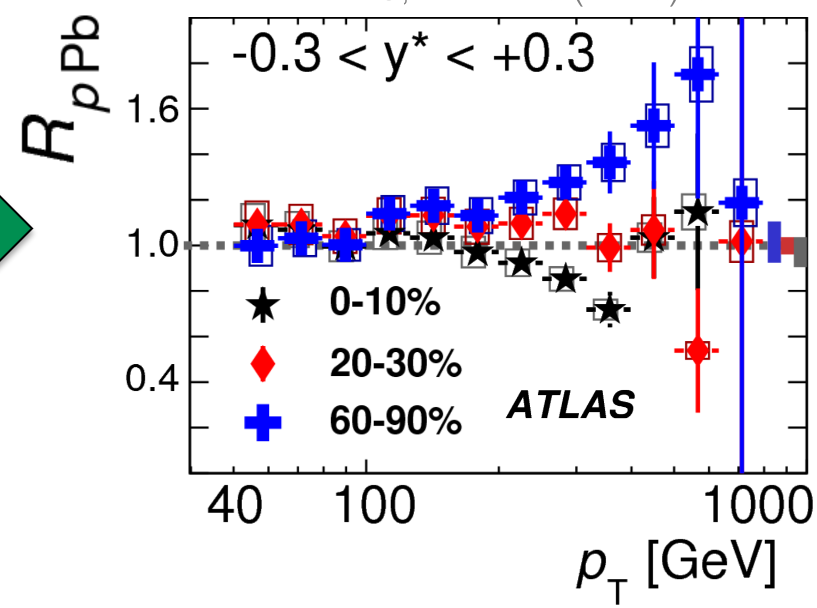


- Collectivity only clearly pronounced in light systems in high multiplicity events
- What about jets in high activity events?

*Activity measured with forward calorimeter on Pb-going side

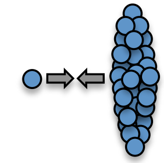


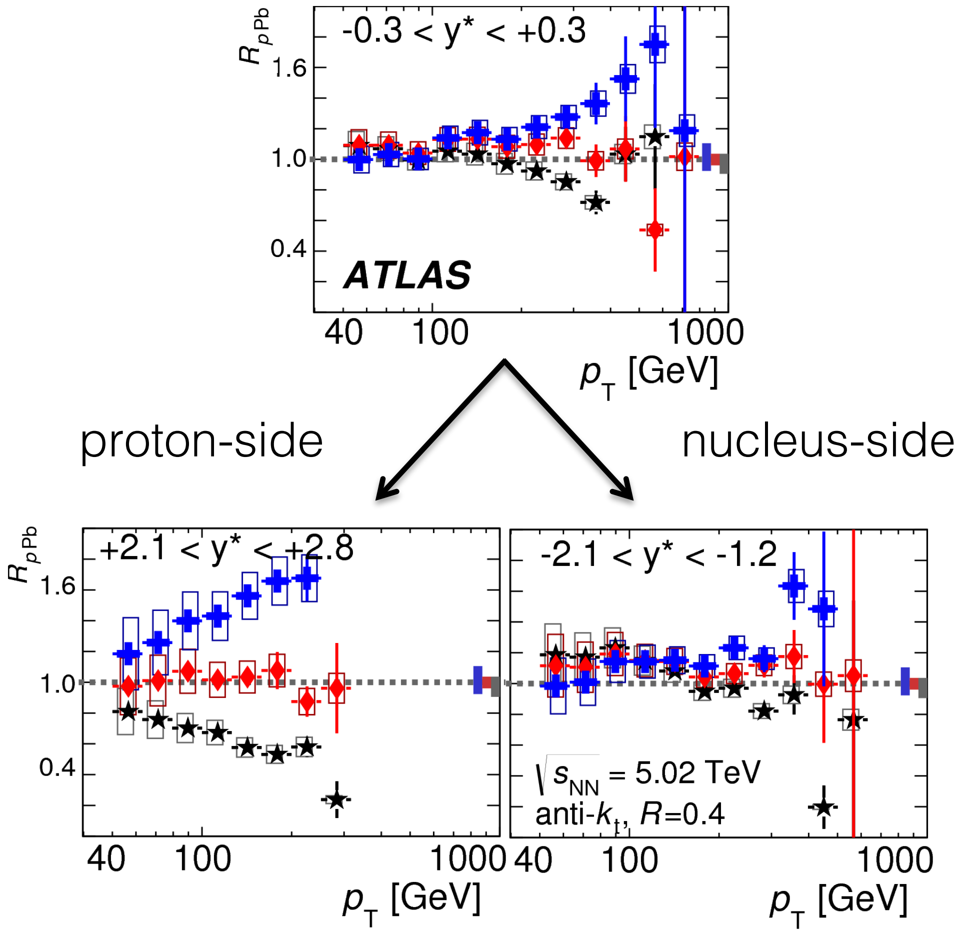
ATLAS, PLB 748 (2015) 392



- Suppression at high p_T in high activity pA
- Enhancement at high p_T in low activity pA!?

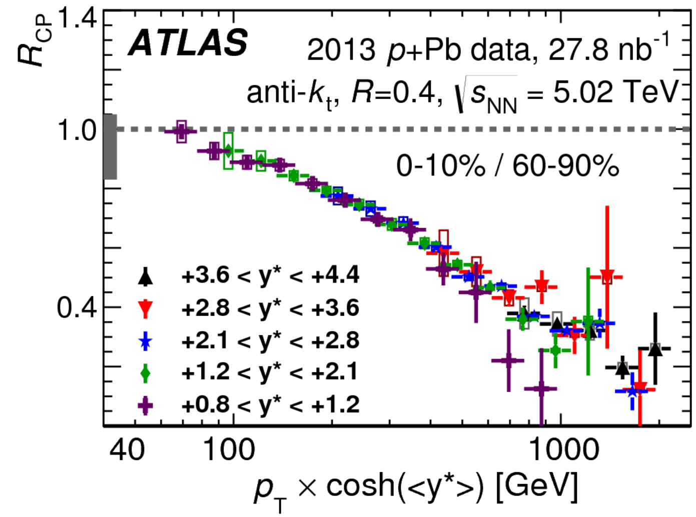
Projectile scaling of jets





- Effect stronger in proton-going direction
- Goes away on nucleus-going side

ATLAS, PLB 748 (2015) 392

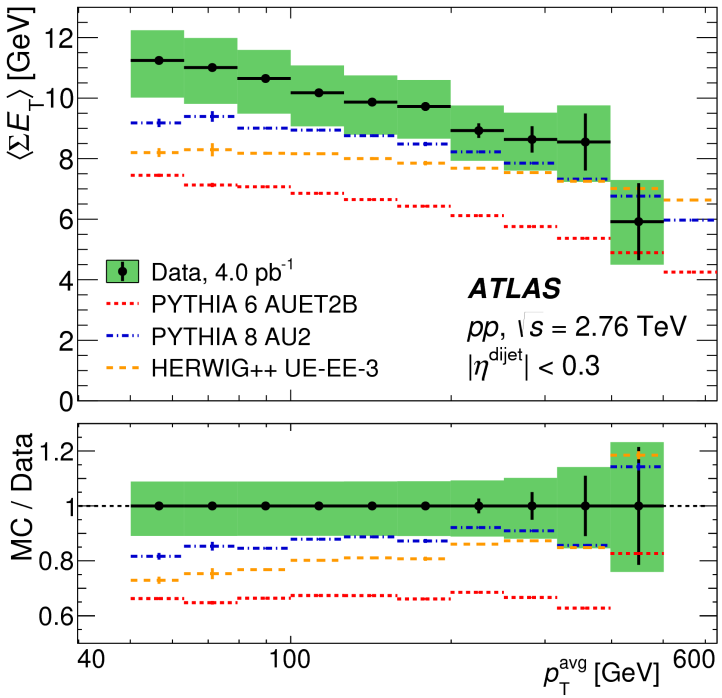


Scaling observed with E ≈ p_T x cosh y, which is ∝ Bjorken x from the proton

A possible explanation:
The more energy taken by jet, the less available at forward rapidity?

Dijet-forward energy correlation

- Dijets in pp: anti-correlation between jets and forward energy, as would be expected from momentum conservation
- Under-predicted by standard event generators



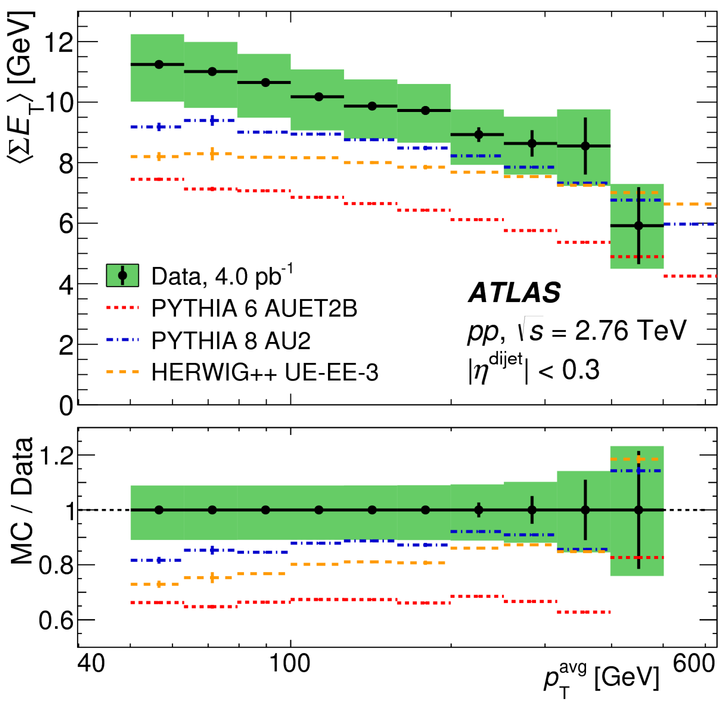
ATLAS, PLB 756 (2016) 10

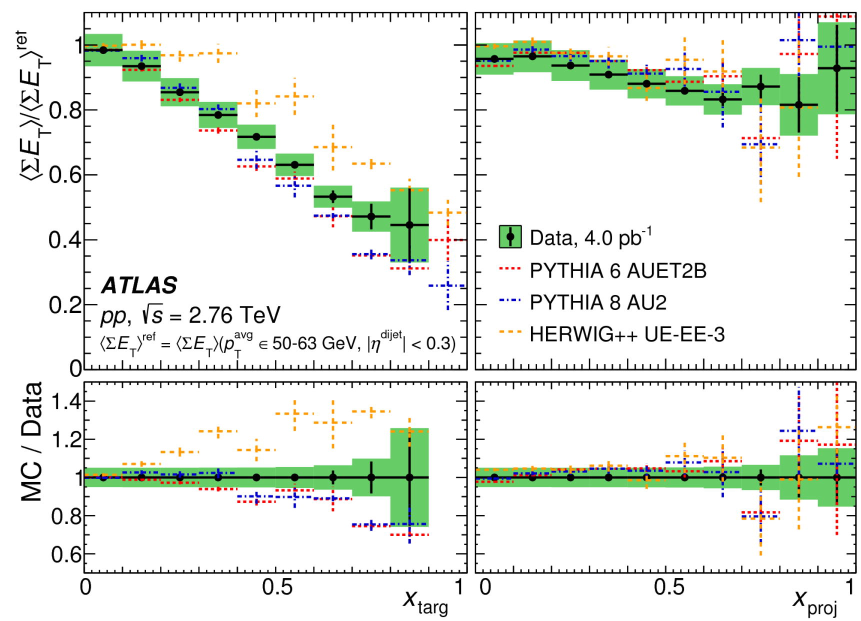
Dijet-forward energy correlation

- Dijets in pp: anti-correlation between jets and forward energy, as would be expected from momentum conservation
- Underpredicted by standard MC generators

$$x_{\mathrm{proj}} = p_{\mathrm{T}}^{\mathrm{avg}}(e^{+\eta_1} + e^{+\eta_2})/\sqrt{s},$$
$$x_{\mathrm{targ}} = p_{\mathrm{T}}^{\mathrm{avg}}(e^{-\eta_1} + e^{-\eta_2})/\sqrt{s}.$$

ATLAS, PLB 756 (2016) 10





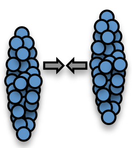
- However, correlation <u>only</u> between dijets and <u>same-side</u> forward energy
- NOT between "projectile"-side jet and opposite-side "target" energy as in pA
- One possibility: Due to proton size fluctuations, high x protons have a smaller cross-section for interacting with the nucleus (could explain the EMC effect)

Alvioli et al., PRC 93, 011902 (2016)

Conclusions

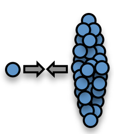
Jets and correlations in pp, pA & AA are bringing new insight into QCD in the high density regime

AA



- Measurements of jet quenching increasingly precise; internal structure of quenched jets sensitive to e-loss mechanism
- Successful description of collectivity in terms of hydrodynamics

pA



- No sign yet of jet quenching, but best constraints so far on the nuclear gluon distribution & novel effects related to "centrality"

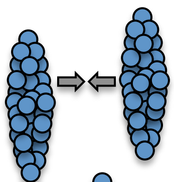
pp

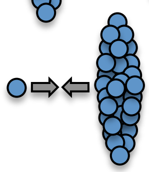
- Evidence indicating collectivity even in systems as small as pp, precise nature of fluctuating initial state still to be elucidated somewhat reductive

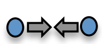
A parting thought:

In contrast to the high-energy physicist,

for the heavy-ion physicist,

 is the simple case,

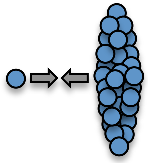
 is more complicated case, and for

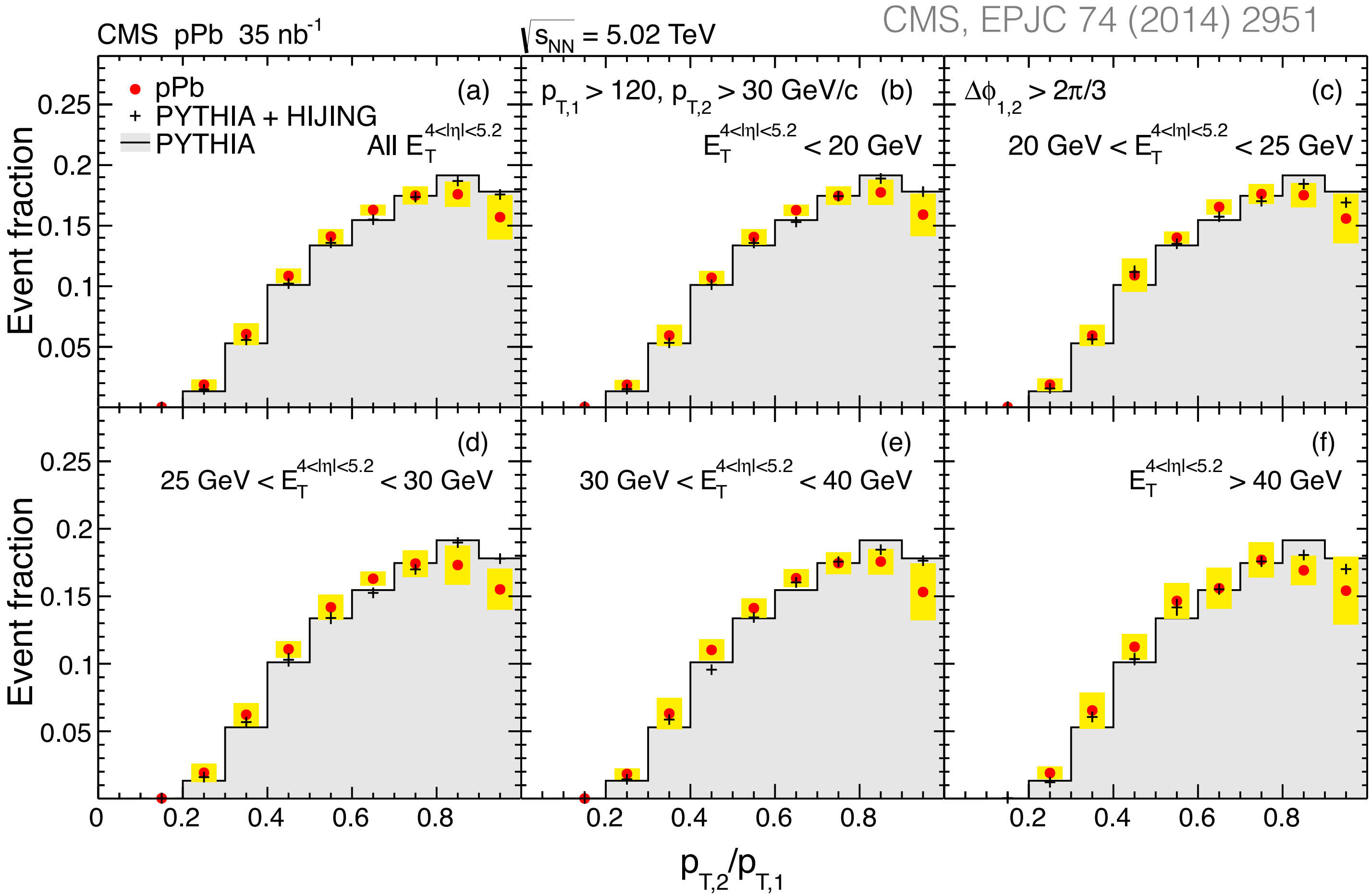
 we are only scratching the surface

Emergent QCD phenomena are a fertile area of progress in systems large & small!

Backup

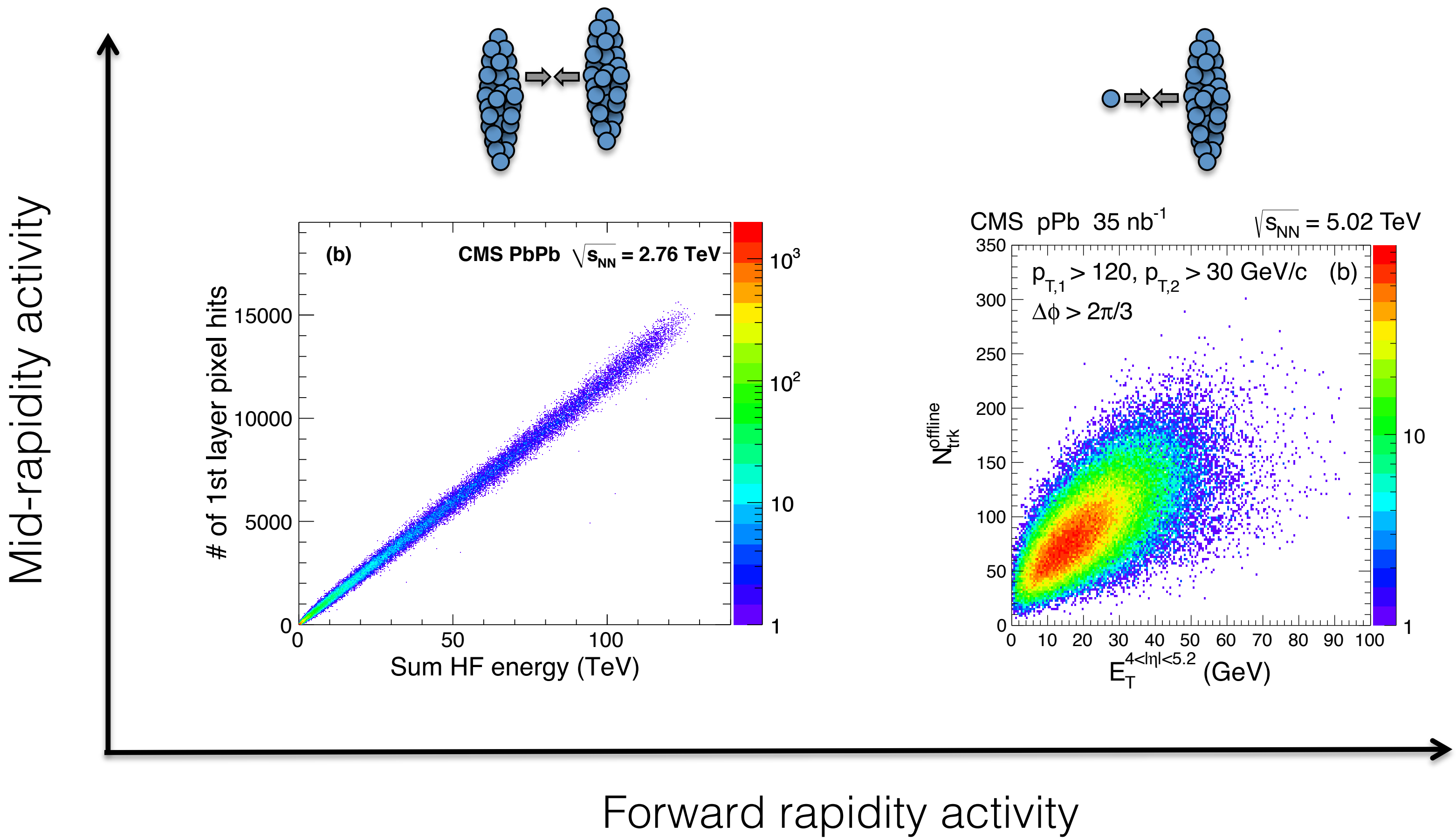
Dijet imbalance in pA?





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

Centrality in small systems

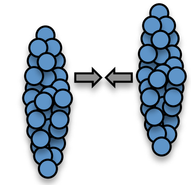


Activity decorrelated across event → hence also to impact parameter

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

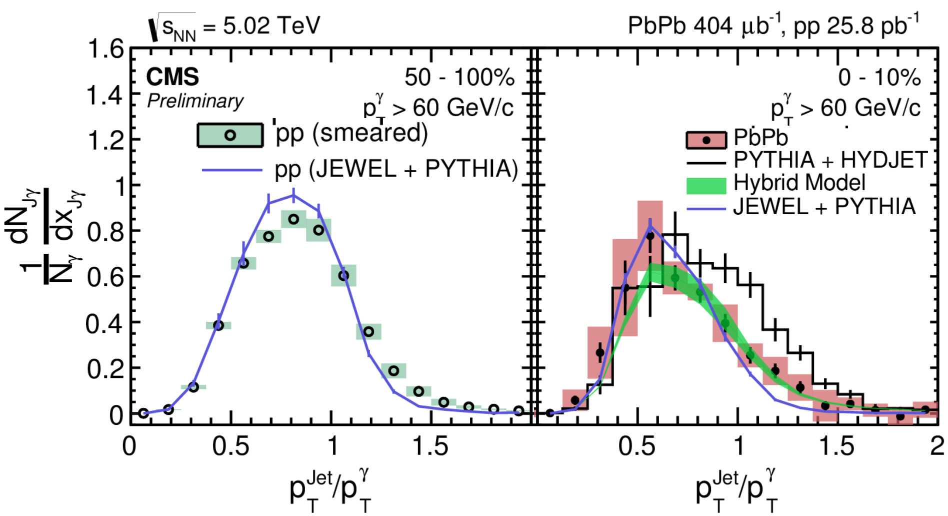
→ so far no way to tune multiplicity without biasing jet production

Boson-jet correlations



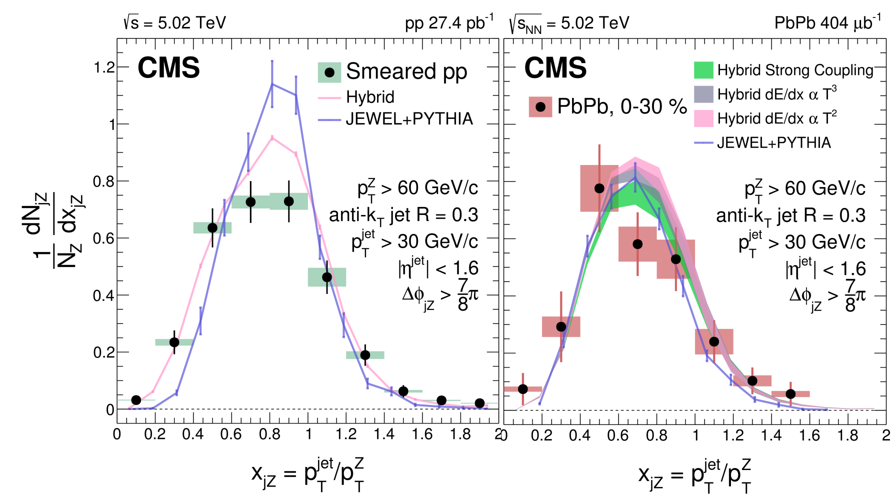
EW bosons do not interact strongly w/ the QGP
→ proxy for recoiling parton before energy loss

γ + jet



CMS-PAS-HIN-16-002

Z + jet



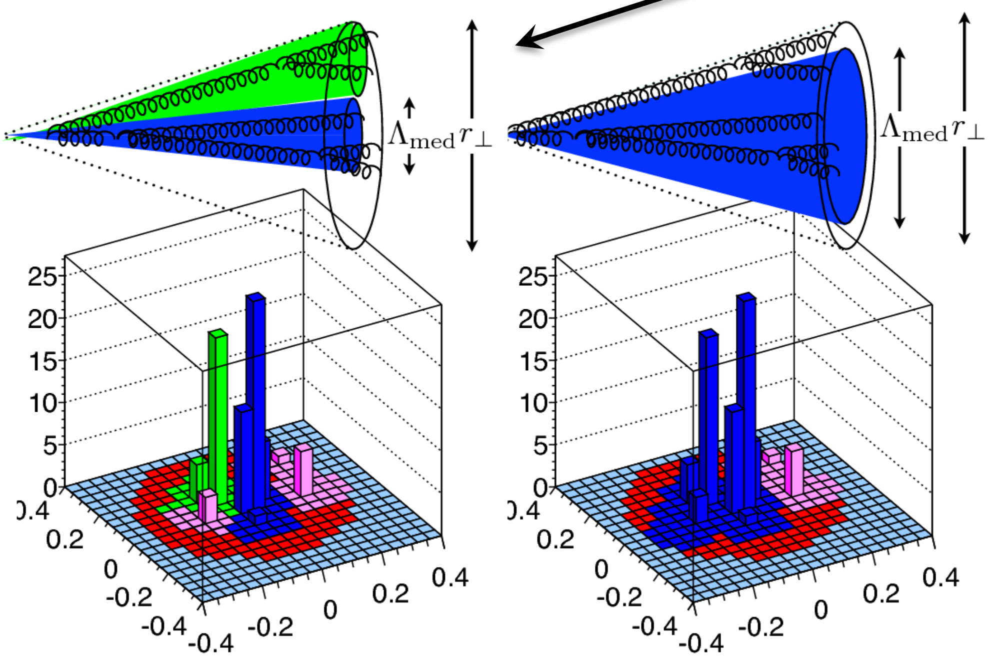
CMS, arXiv:1702.01060

- <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

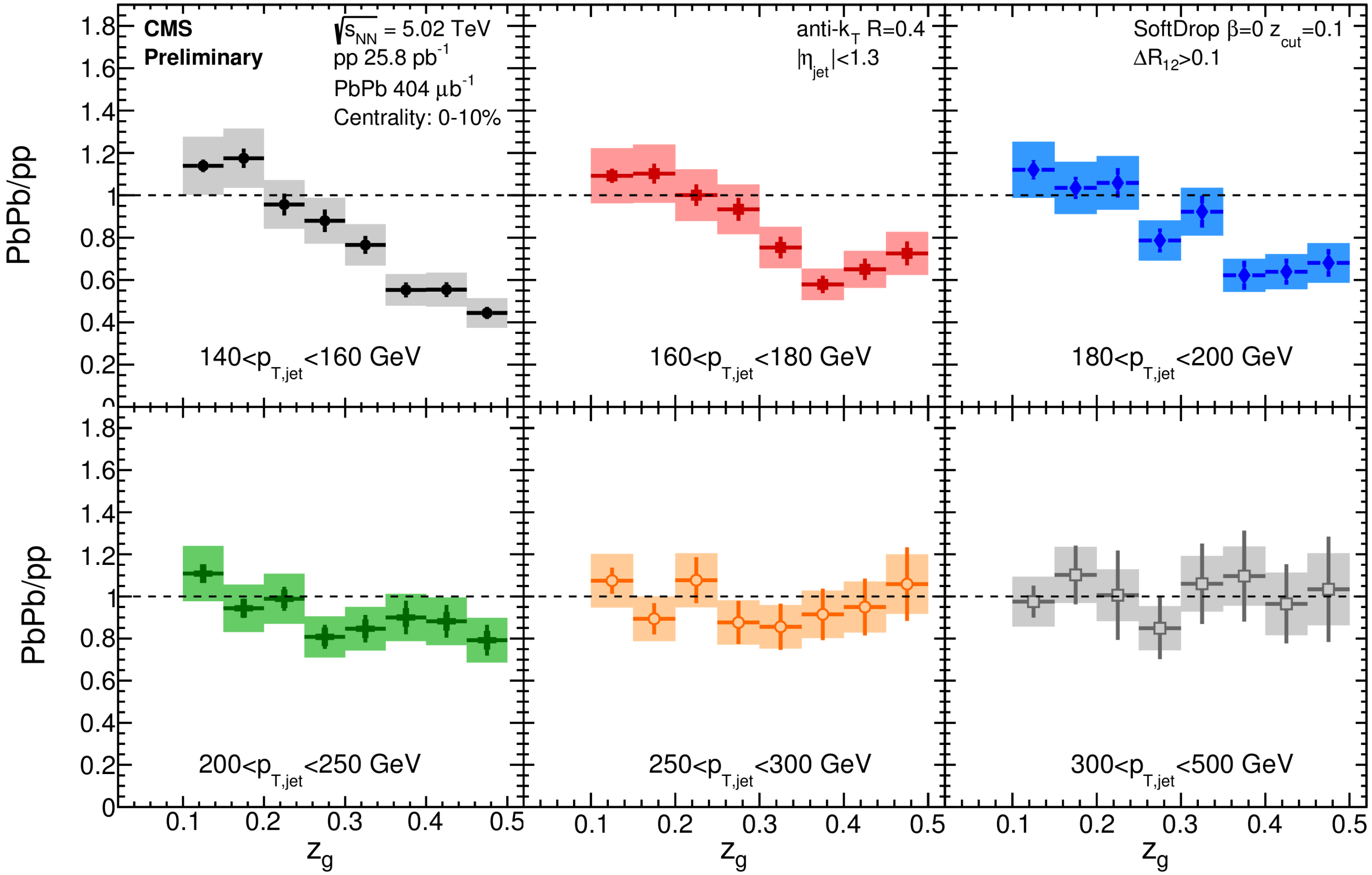
Λ_{med} inversely proportional to (scattering power * pathlength)^2

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

p_T dependence of groomed momentum fraction

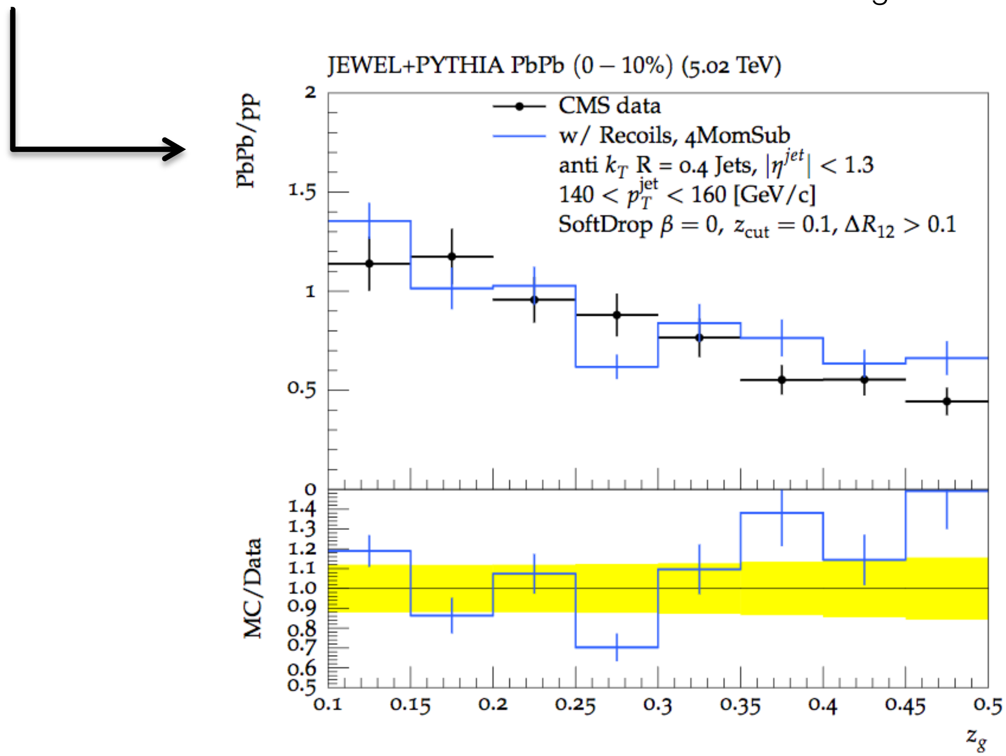
CMS-PAS-HIN-16-006



z_g interpretation

A number of models reproduce the general trend observed in data

e.g., JEWEL: Nearby splitting promoted over min z_g cut by jet-medium interaction



Complementary information being pursued: jet mass, n-subjettiness, etc.