Progress in Jet Tomography

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New Progress in HI Collisions
Wuhan, China
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Outline

"*Tomography*" — using internally generated probes to learn about the properties of the hot nuclear medium

1. Introductory material
2. Survey of jet tomography results

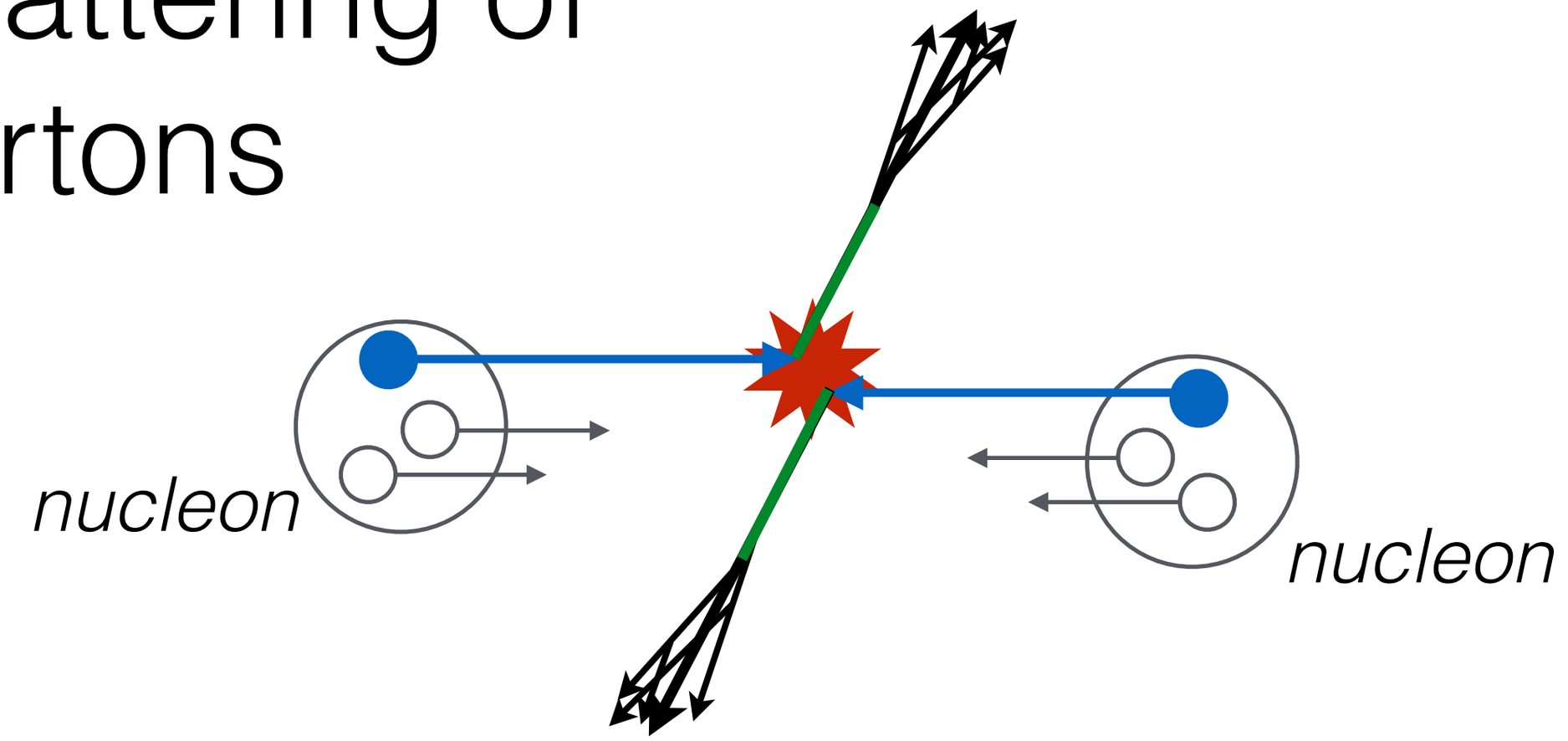
   ➡ selected topics, with an emphasis on new jet measurements presented at Quark Matter 2015

3. Future prospects at RHIC and the LHC

Jet tomography @ QM15

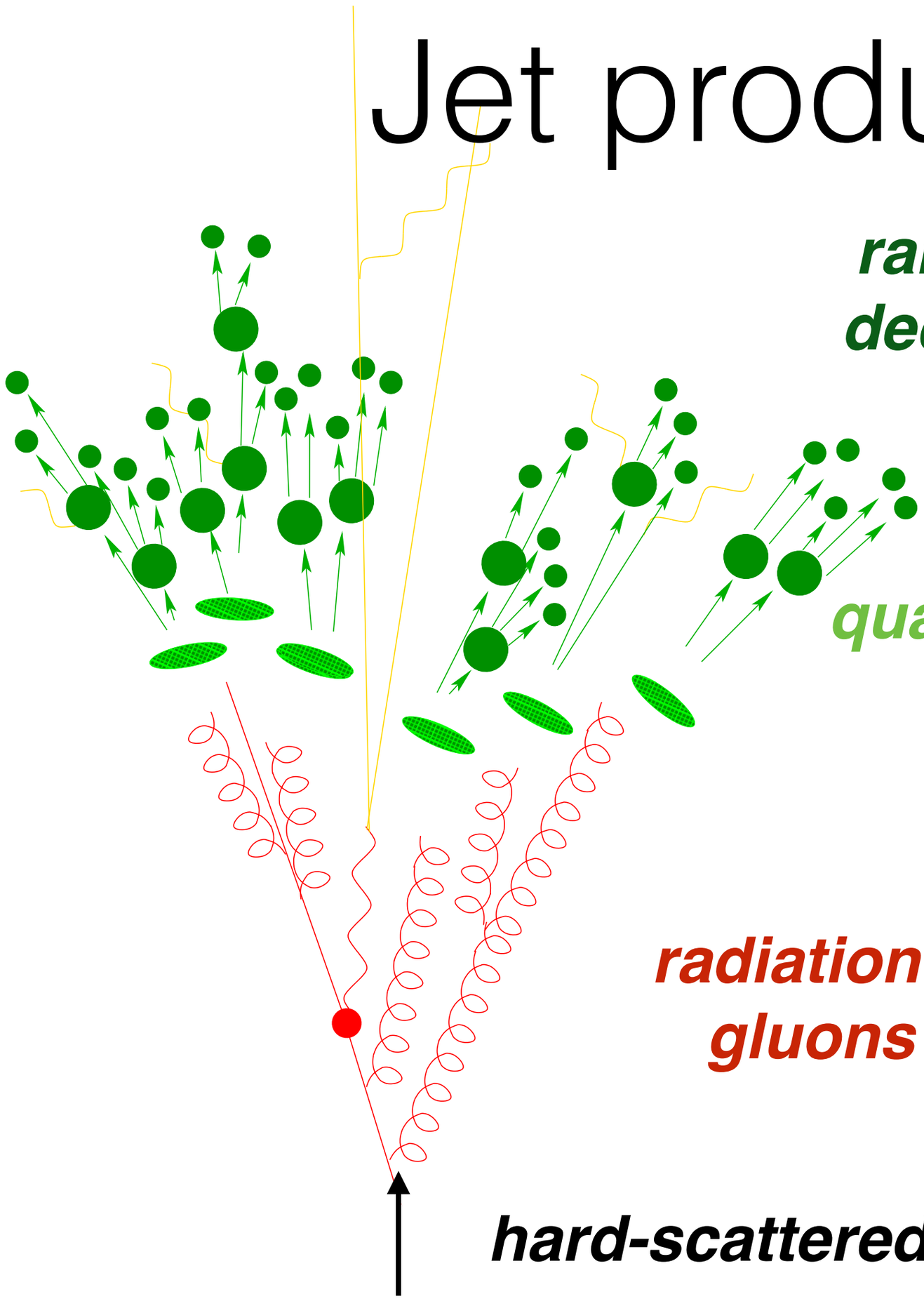
- ALICE jet shapes: L. Cunquiero Mendez, 28/09, 5:20pm
- ALICE jet v_2: R. Bertens, 29/09, 12:10pm
- ATLAS FF vs. η and p_T: T. Kosek, 29/09, 3:40pm
- ATLAS new dijet asymmetry: D. Perepelitsa, 29/09, 4pm
- ATLAS muon suppression and flow: S. Milov, 29/09, 12:10pm
- CMS jet-track flow: O. Evdokimova, C. McGinn, 28/09, 2:50pm and 3:10pm
- CMS D^0 suppression: J, Sun, 28/09, 15:50pm
- STAR recoil jet spectra: P. Jacobs, 29/09, 3pm
- PHENIX Cu+Au jet R_{AA}: A. Timilsina, 29/09, 3:20pm

Hard scattering of partons



- A **parton** (quark or gluon) from the nucleons in each nucleus can undergo a large-Q^2 **hard scattering**
  - ➡ the **scattered partons** fragment, hadronize and turn into experimentally detectable **jets**
  - ➡ initial spectrum calculable in pQCD / measurable in *pp* collisions

Jet production



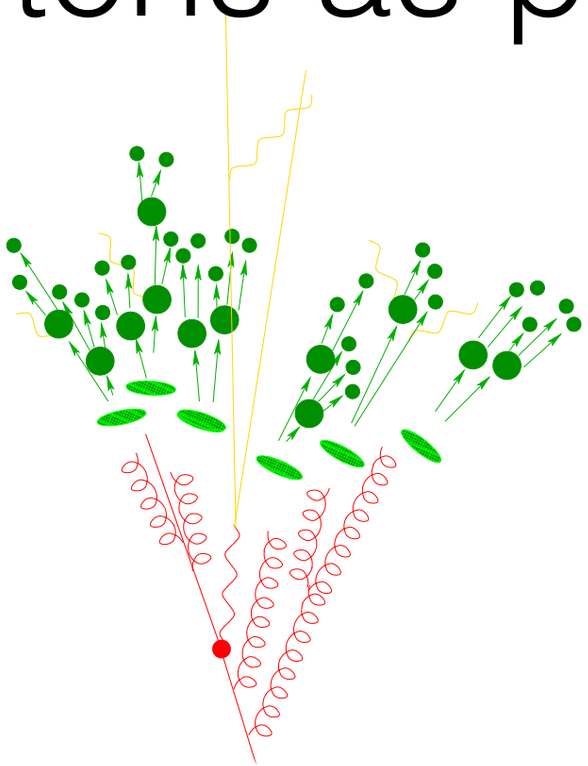
rare, short-lived particles decay into common, long-lived particles

quarks and gluons confined back into hadrons ("hadronization")

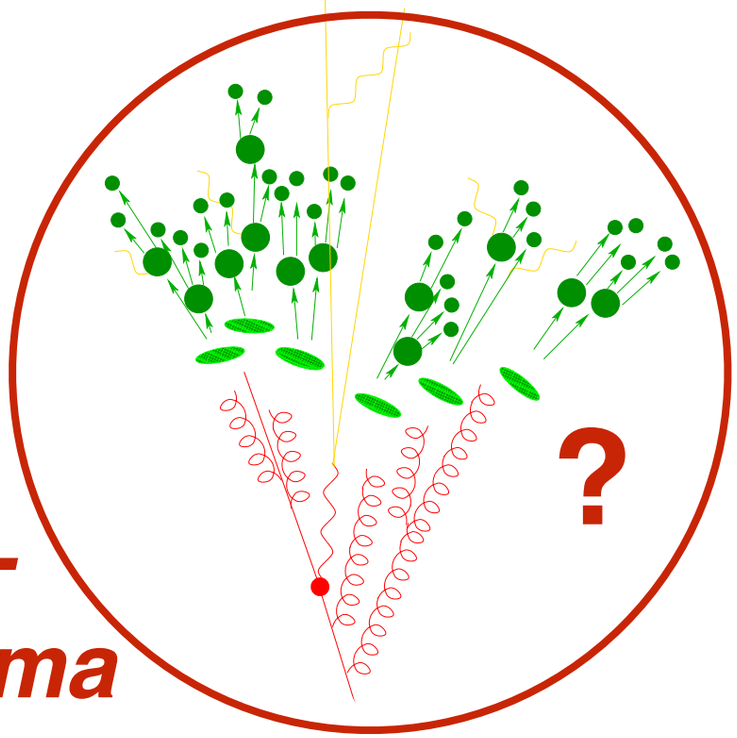
radiation of other quarks and gluons ("parton shower")

hard-scattered parton

Fast partons as probes of the medium



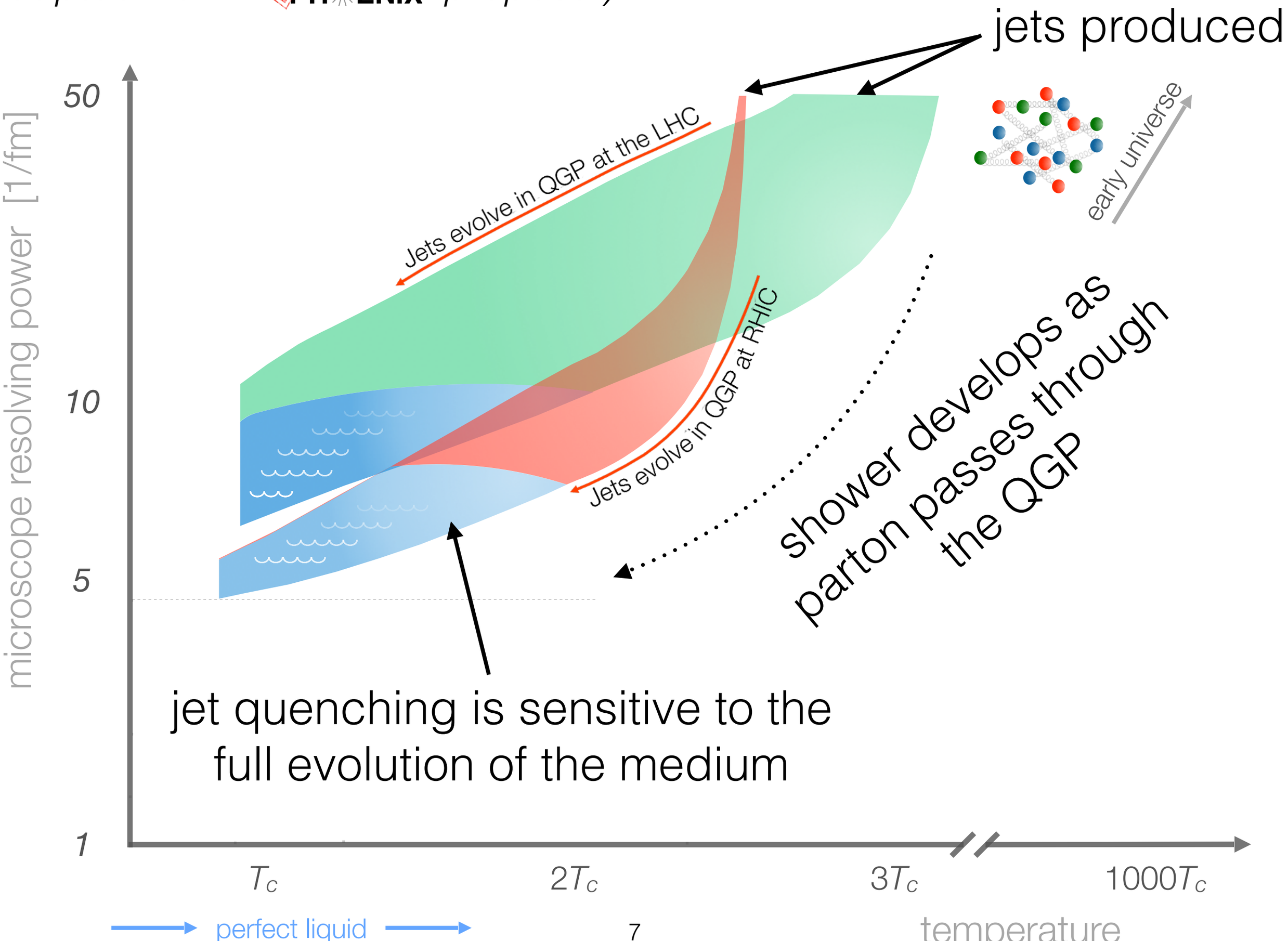
in vacuum



in quark-gluon plasma

- Hard scatterings happen <u>early</u> relative to medium formation time
- Shower develops as partons traverse the expanding, cooling plasma
  - ➡ interacts with the plasma over a <u>range of length scales and temperatures</u>
  - ➡ the jet is **quenched**, depositing some of its energy into the medium

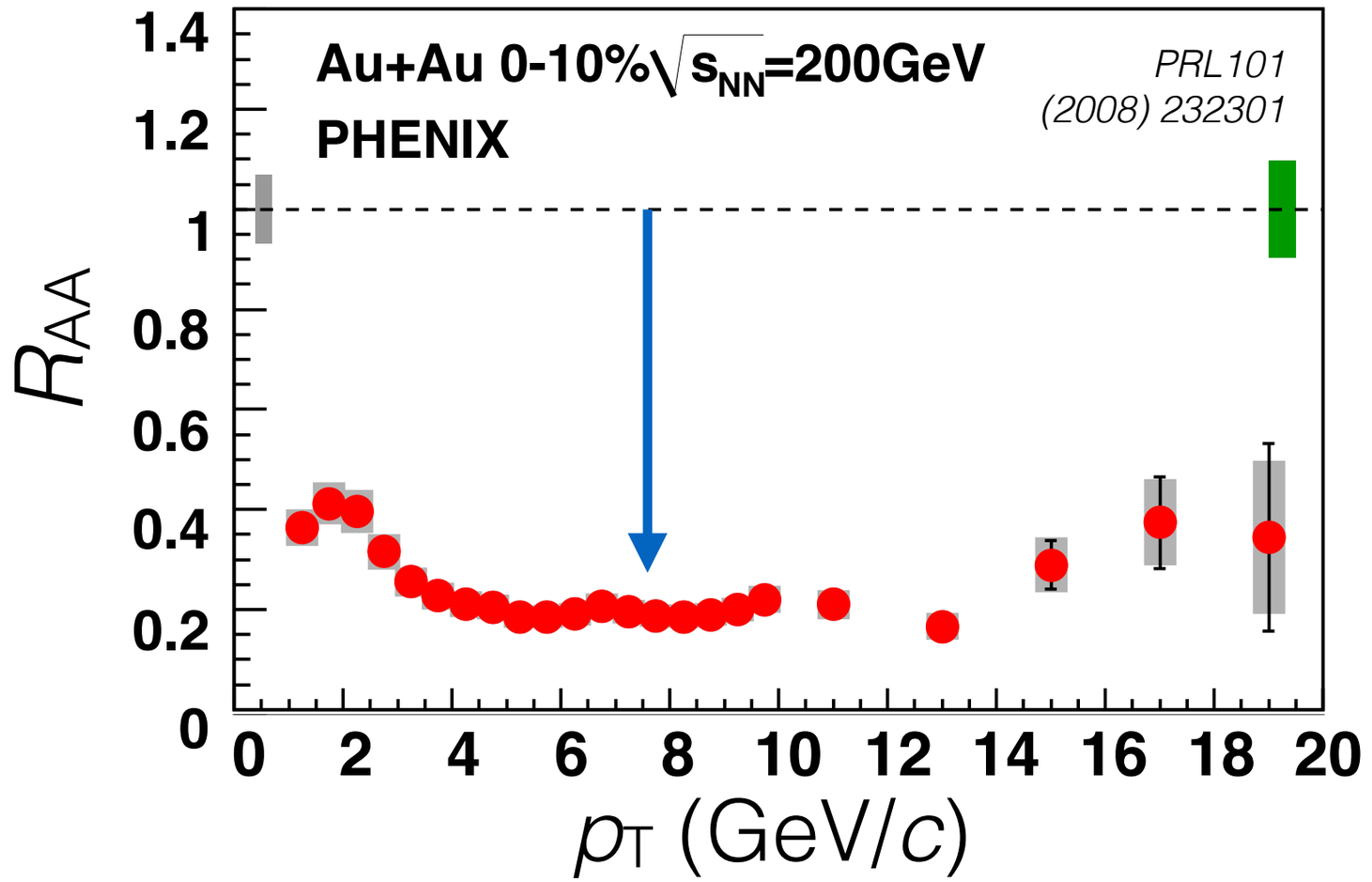
(adapted from PHENIX *proposal)*



“Jet” quenching at RHIC

RHIC measurements of inclusive **single particle** production in Au+Au

➡ Factor of five **suppression**!

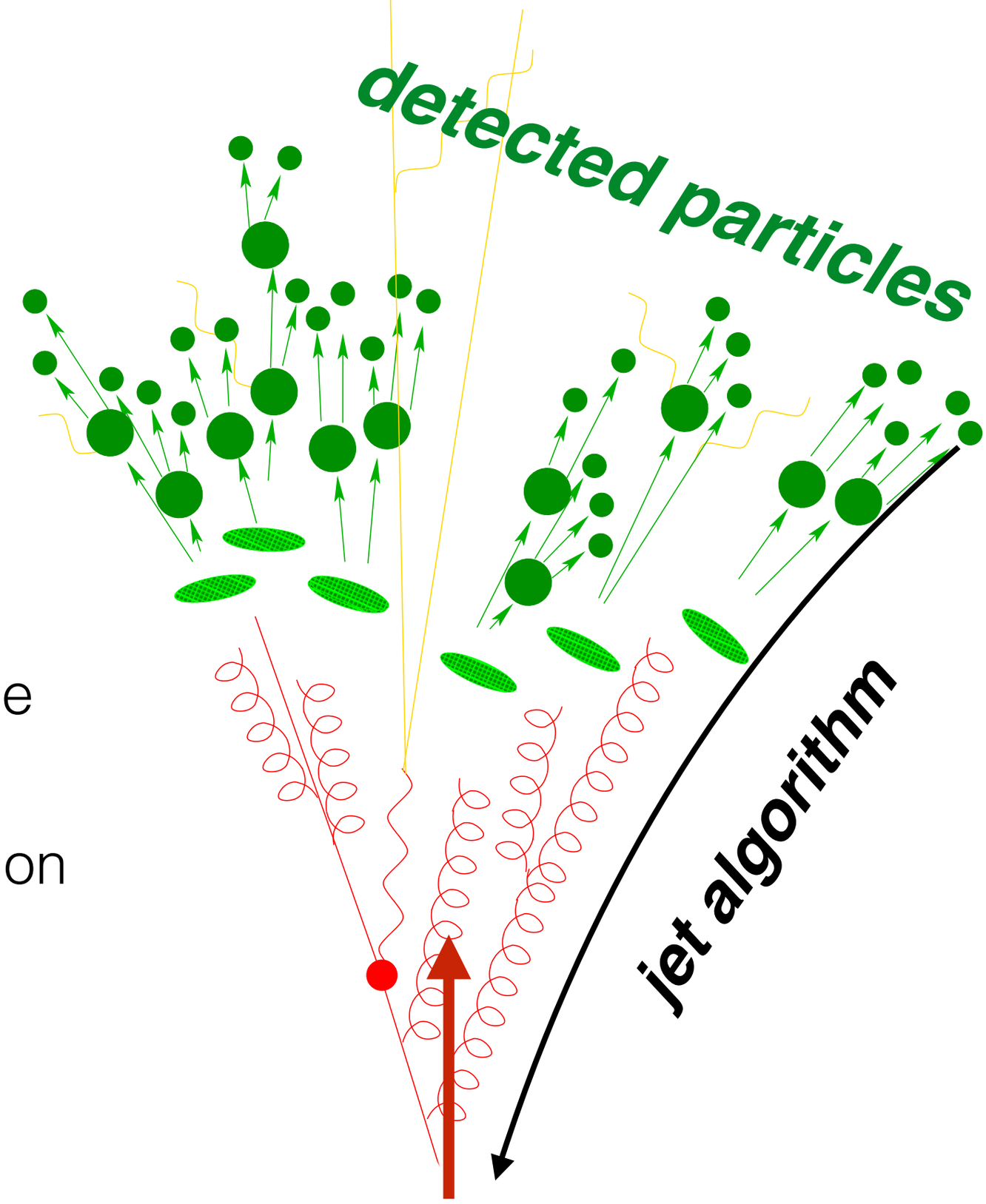


- Jet quenching inferred only “statistically”
- Information from the full jet may better encode what happened to the parton shower

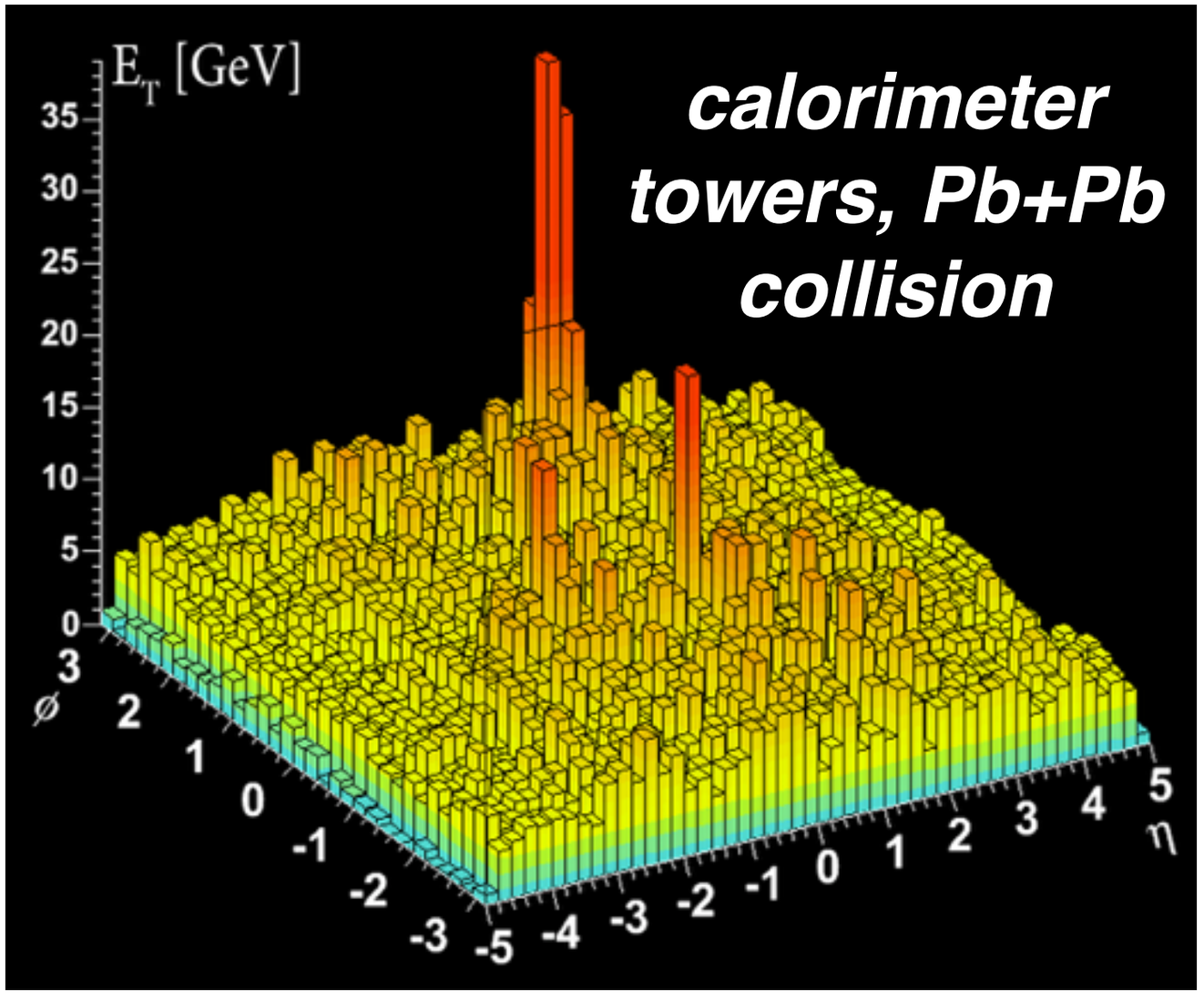
  ➡ since then, HI physics has learned from HEP…

Jet reconstruction in proton-proton collisions

- Jet "**reconstruction**" clusters nearby particles into a "jet"
  - ➡ "undoing" the branching in the parton shower
  - ➡ with some IRC-safe prescription (e.g. anti-k_T with cone size R)
- In a leading order picture, the resulting "jet" approximates the parton kinematics
  - ➡ successful tool in high-energy physics

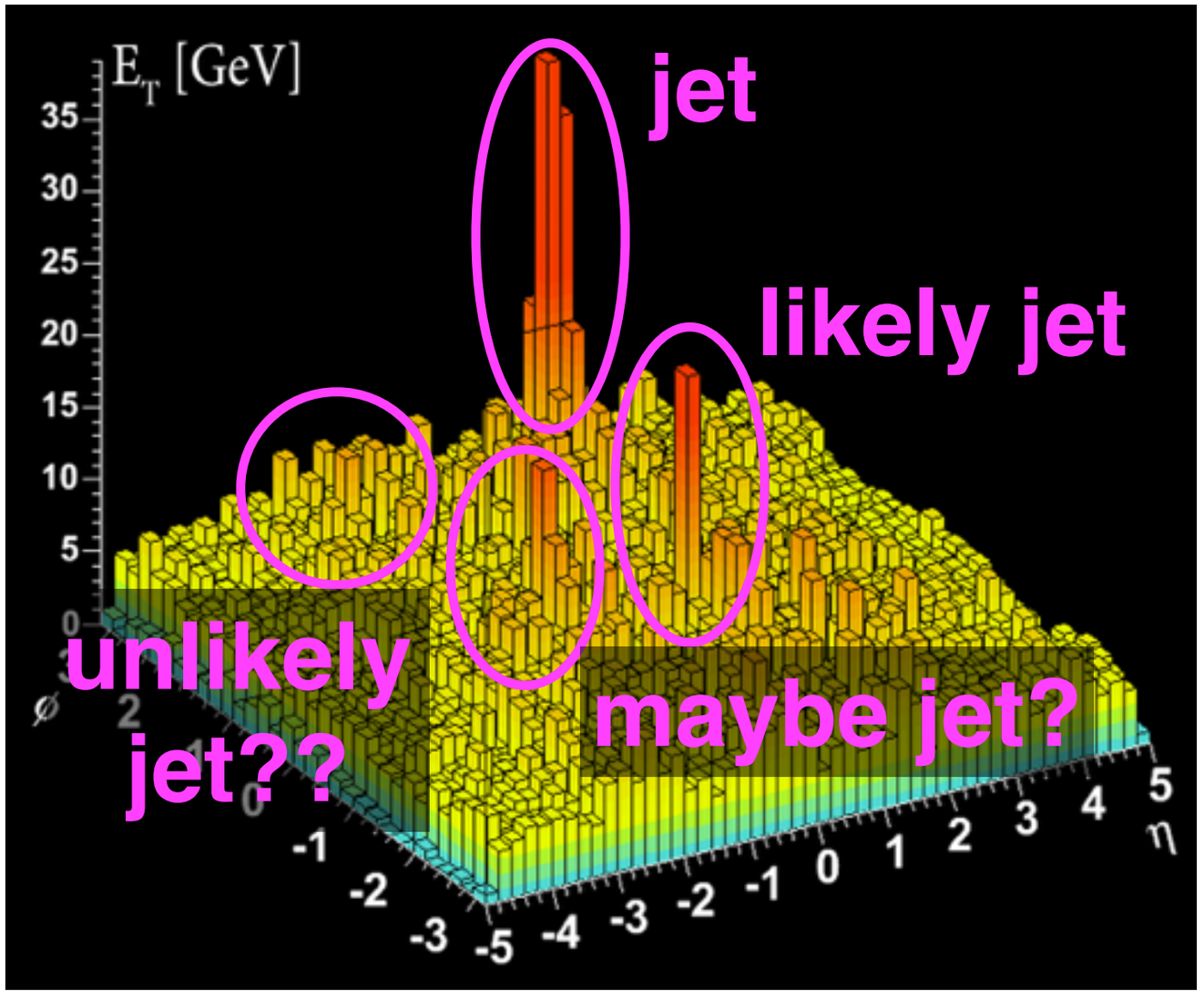


Jet reconstruction in HI collisions



- Heavy ion collisions feature a large, fluctuating background
  - ➡ difficult to identify jets & to measure their energy
  - ➡ only possible only after substantial technical effort

Jet reconstruction in HI collisions



- Heavy ion collisions feature a large, fluctuating background
  - ➡ difficult to identify jets & to measure their energy
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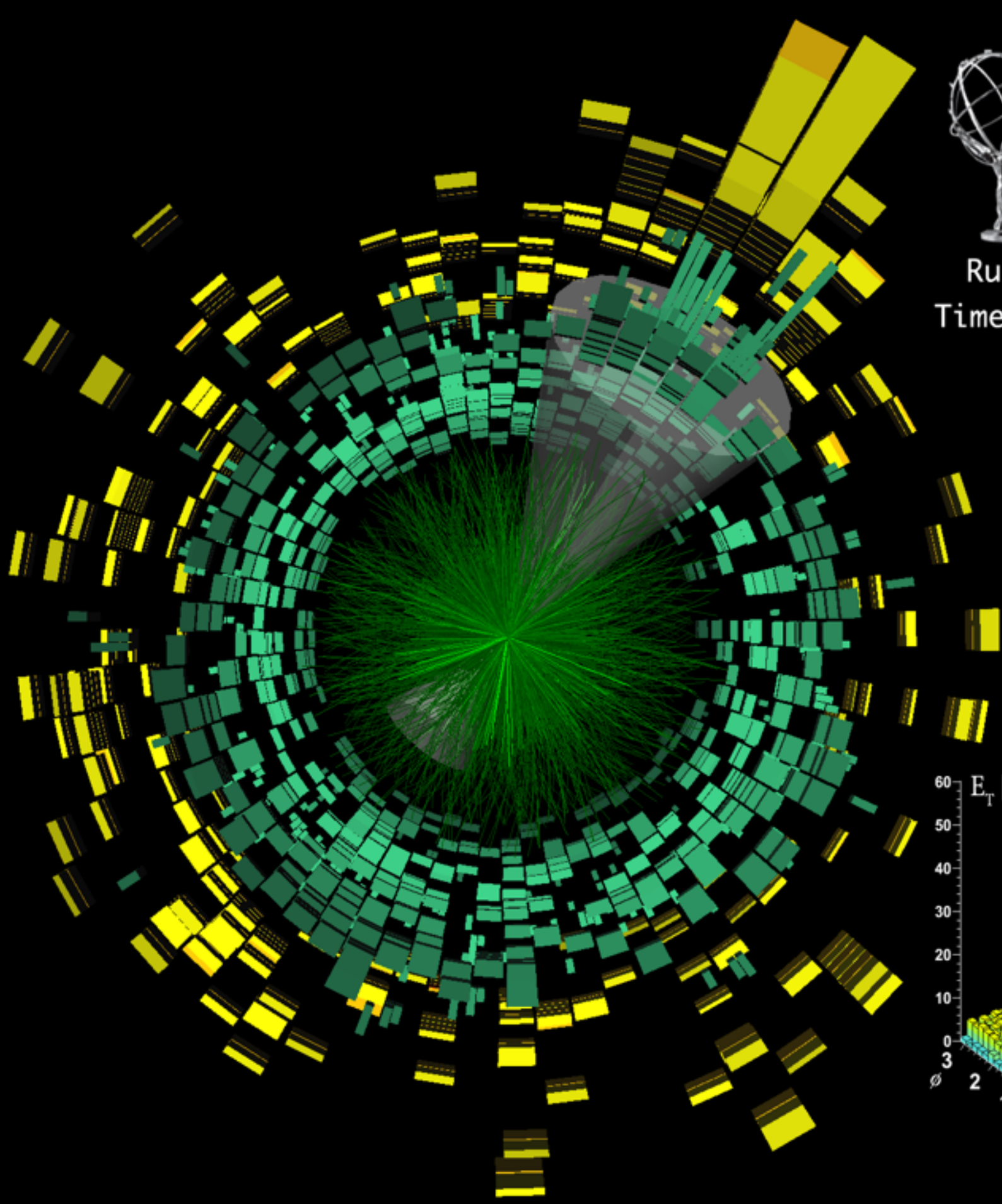
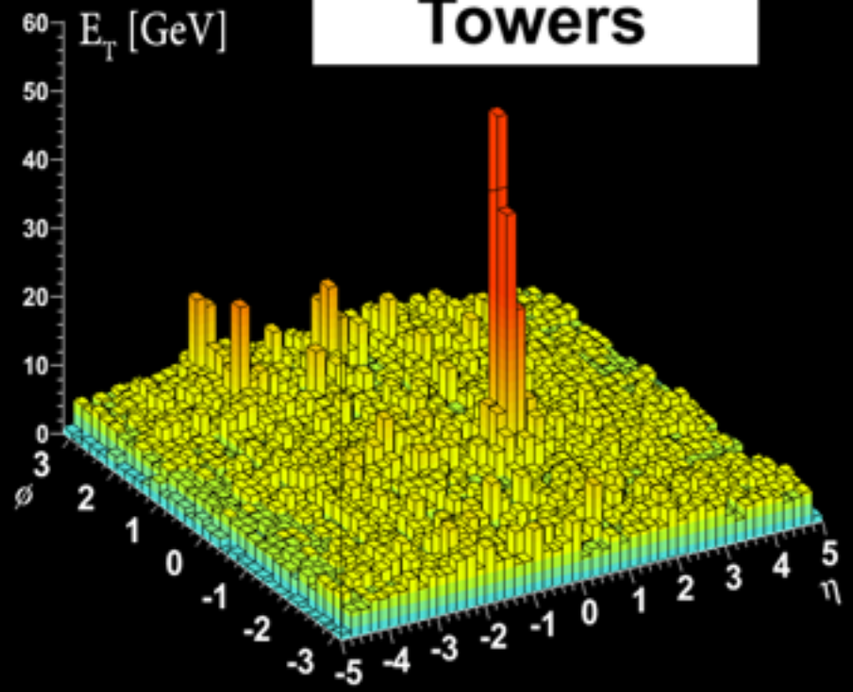
ATLAS
EXPERIMENT

Run 168795, Event 7578342

Time 2010-11-09 08:55:48 CET



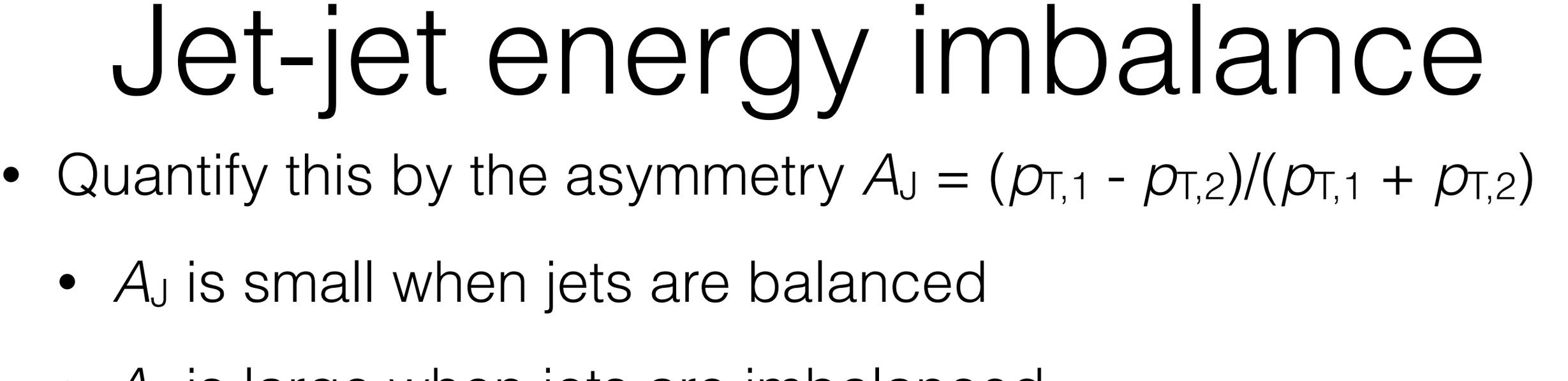


Jet-jet energy imbalance

- Quantify this by the asymmetry $A_J = (p_{T,1} - p_{T,2})/(p_{T,1} + p_{T,2})$
  - A_J is small when jets are balanced
  - A_J is large when jets are imbalanced

expectation w/o jet quenching

Pb+Pb collision data

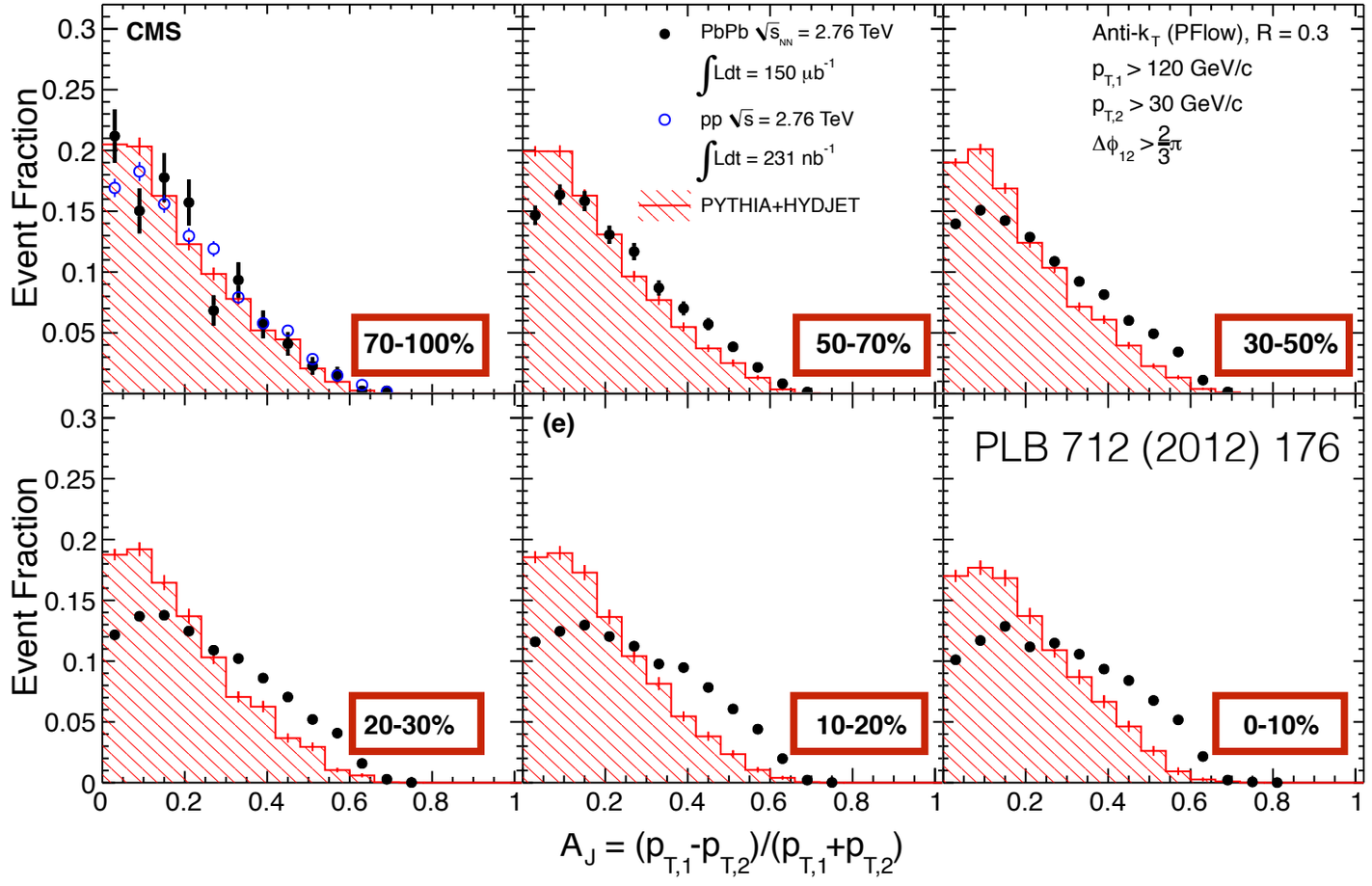


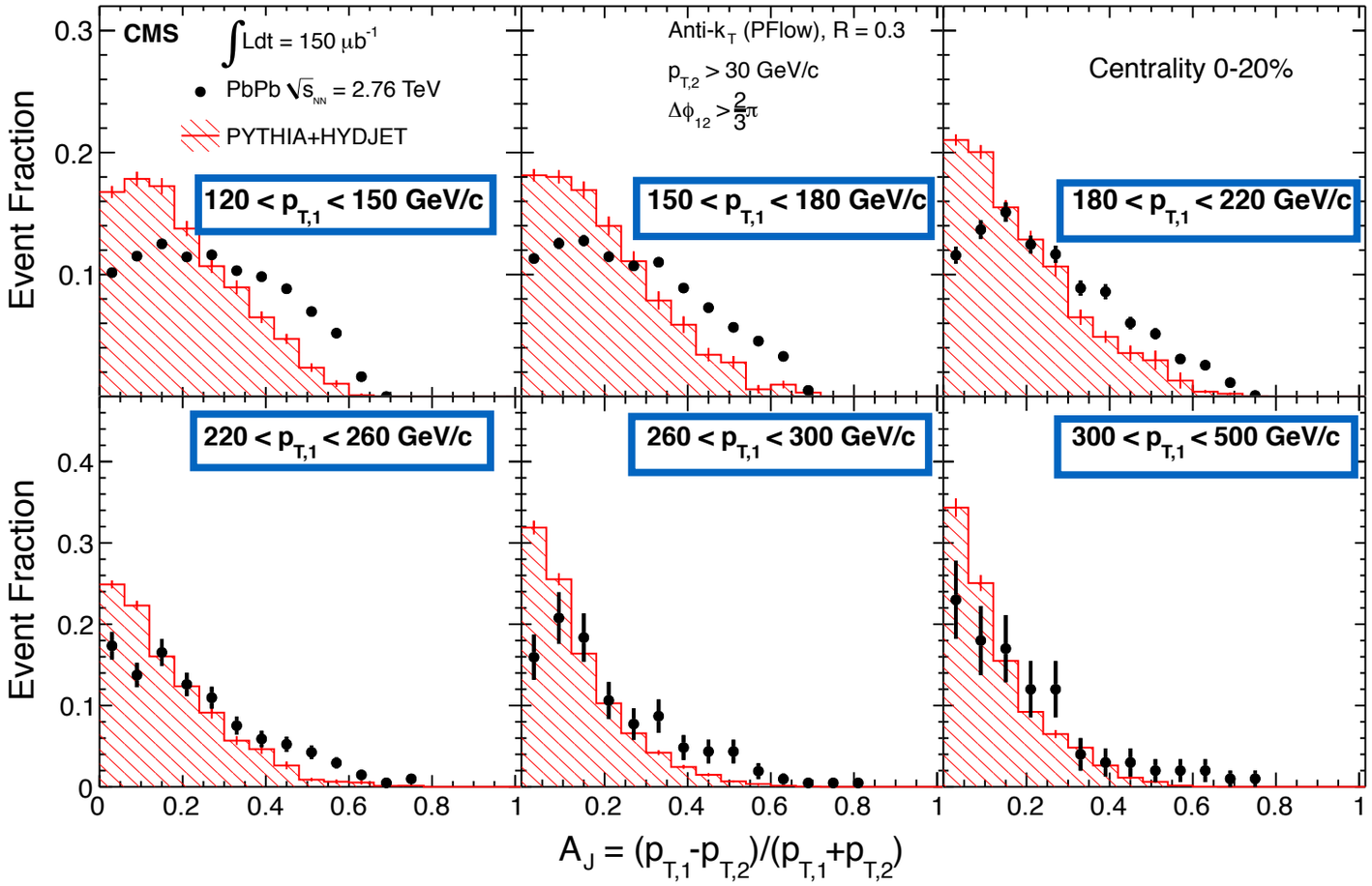
glancing ("peripheral") collisions

head on ("central") collisions

Further dijet asymmetries

- Updated measurement by CMS from higher-luminosity 2011 data

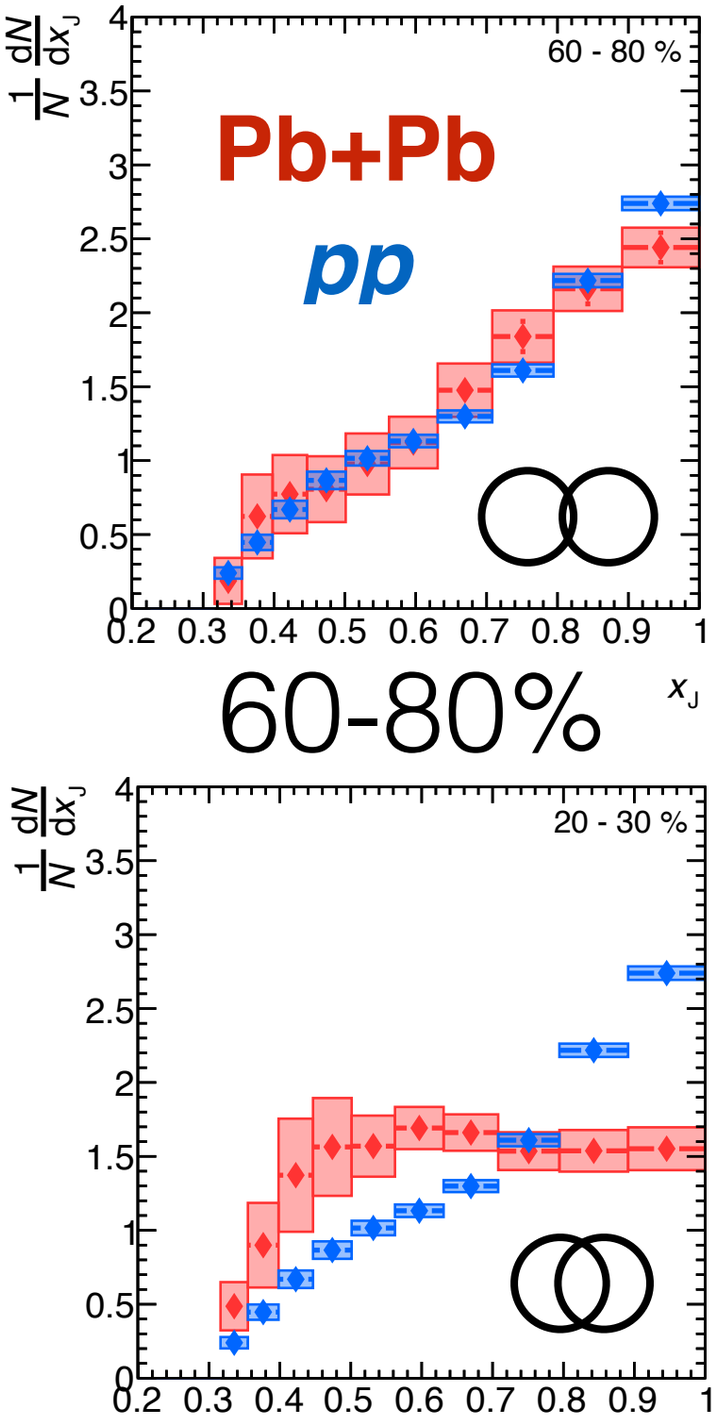


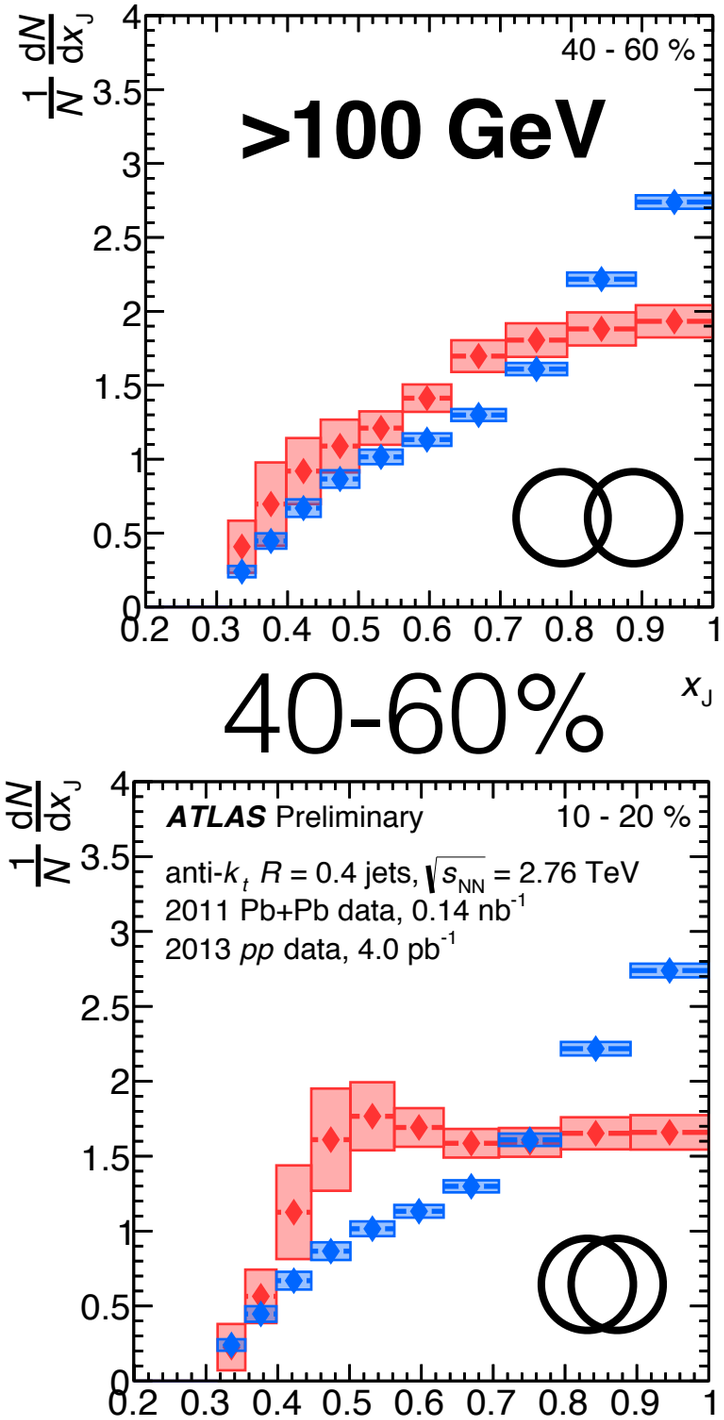


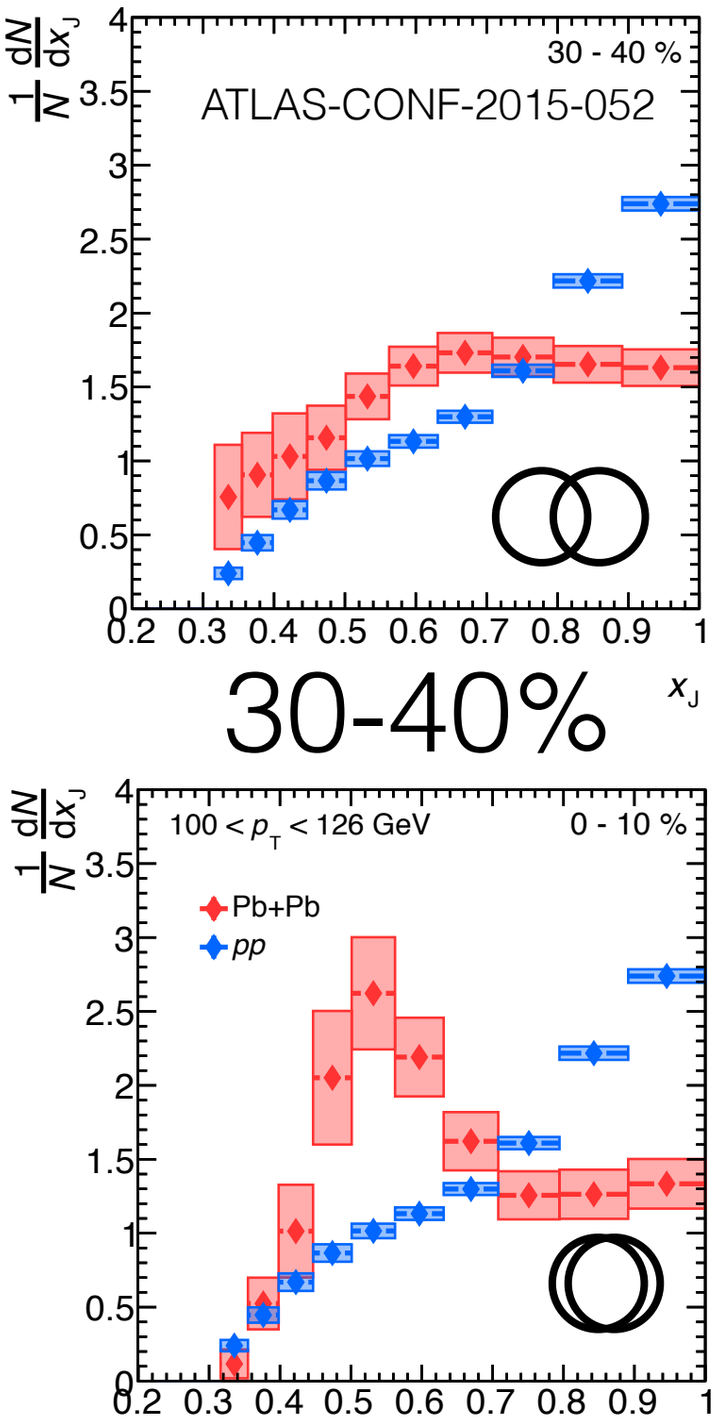
- Systematics of A_J vs. **centrality**
- and vs. **leading jet p_T**
- No correction for detector effects, direct comparison to models ambiguous…

New at QM15

Latest dijet asymmetry

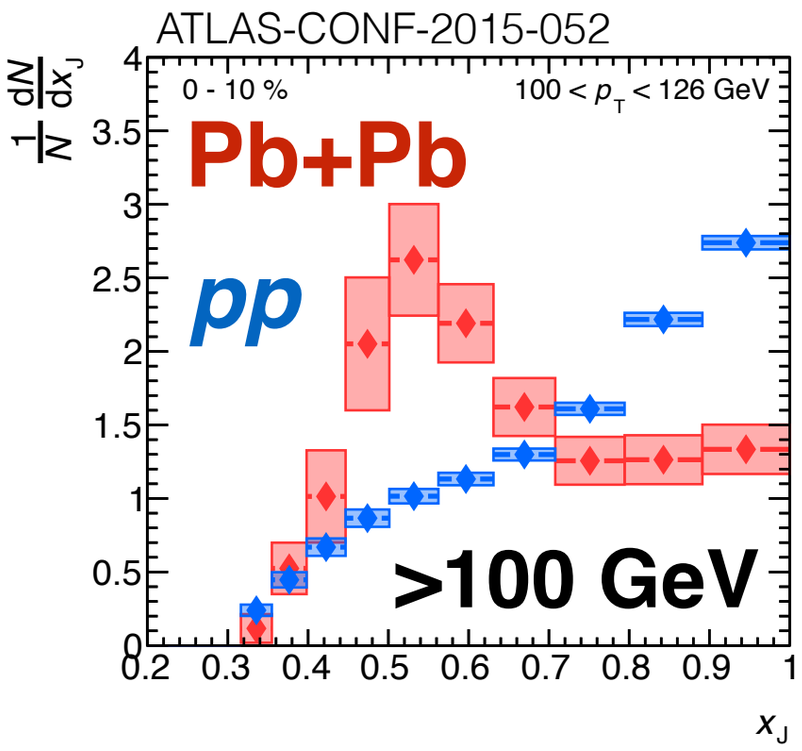


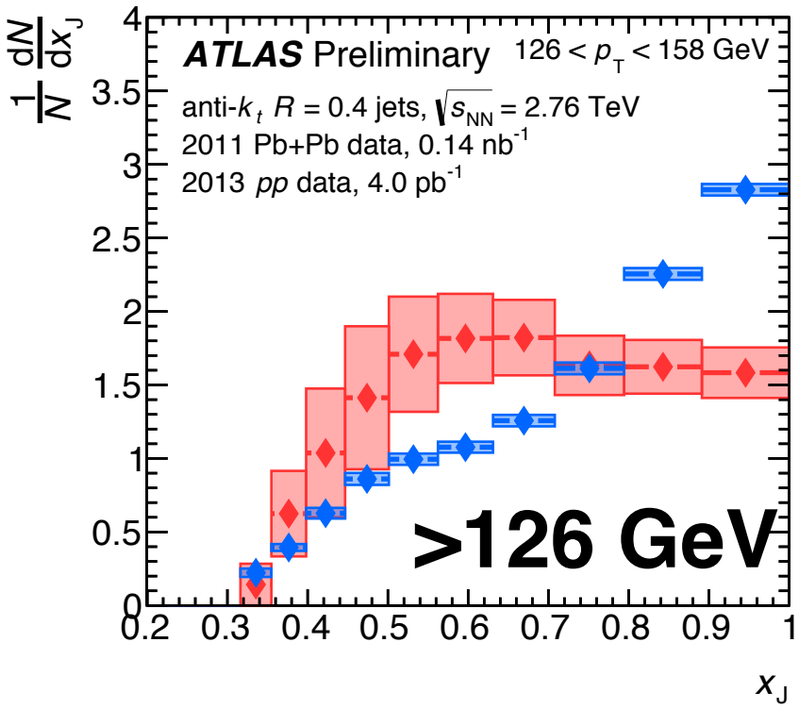


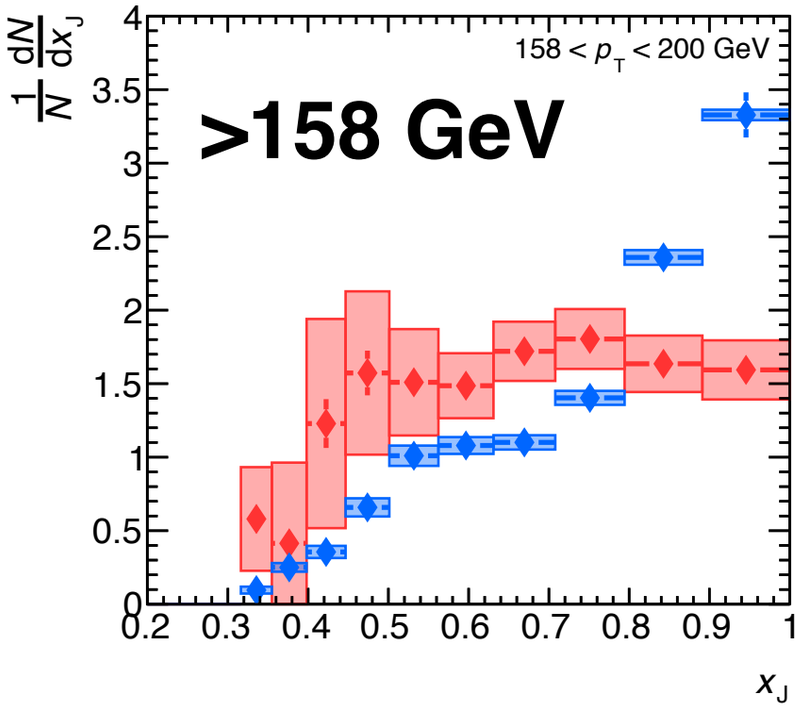


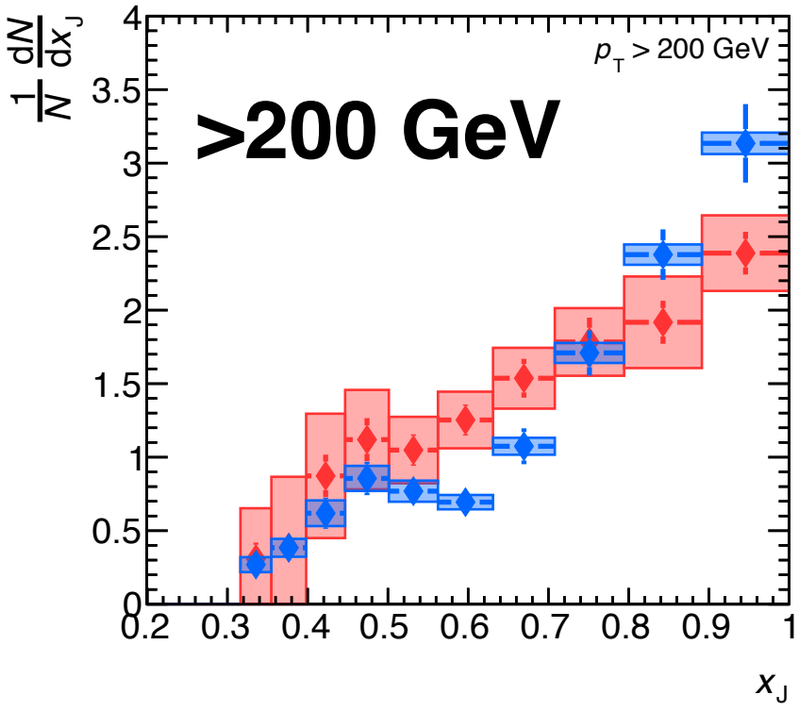
New at QM15

Latest dijet asymmetry









now fix centrality, consider **leading jet p_T**

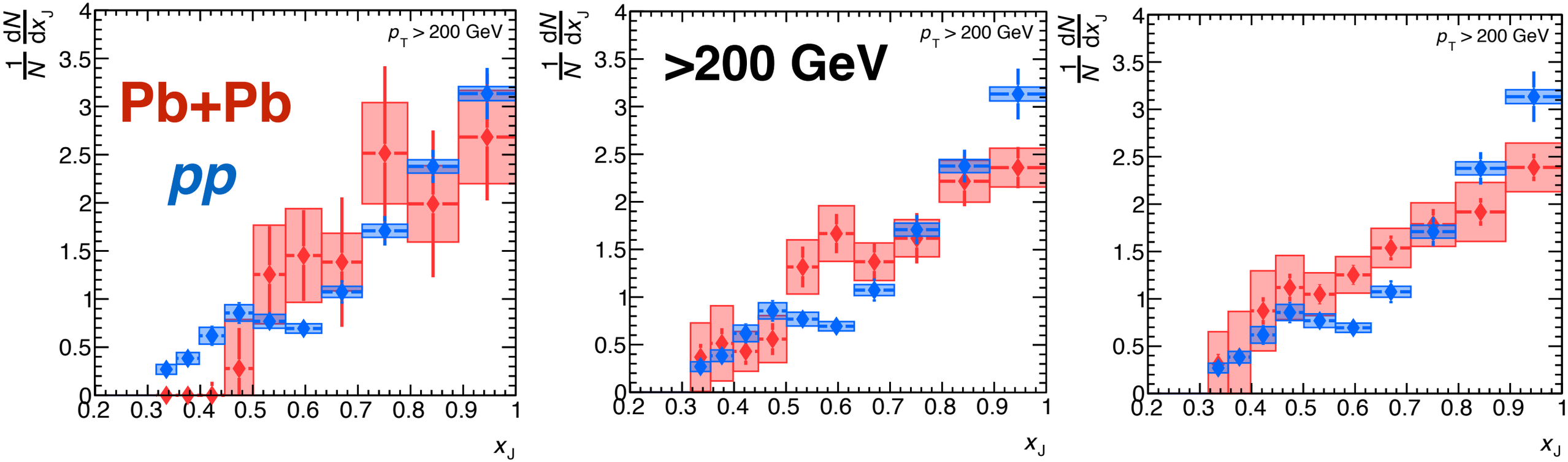
***pp*-like x_J** at high $p_{T,1}$!

fractional E-loss diff. between jets decreases w/ $p_{T,1}$?

New at QM15

Latest dijet asymmetry

ATLAS-CONF-2015-052

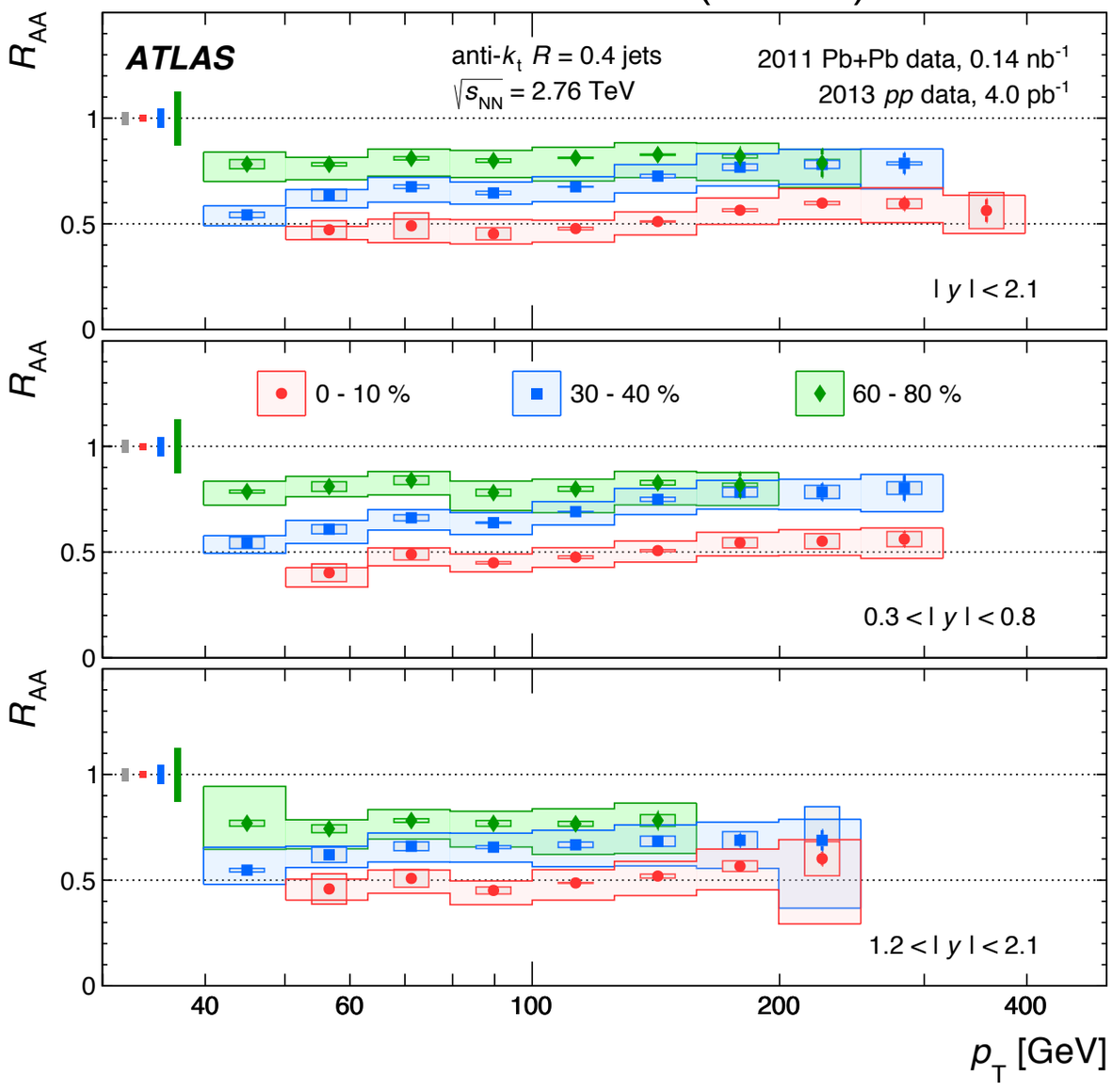


60-80% 20-30% 0-10%

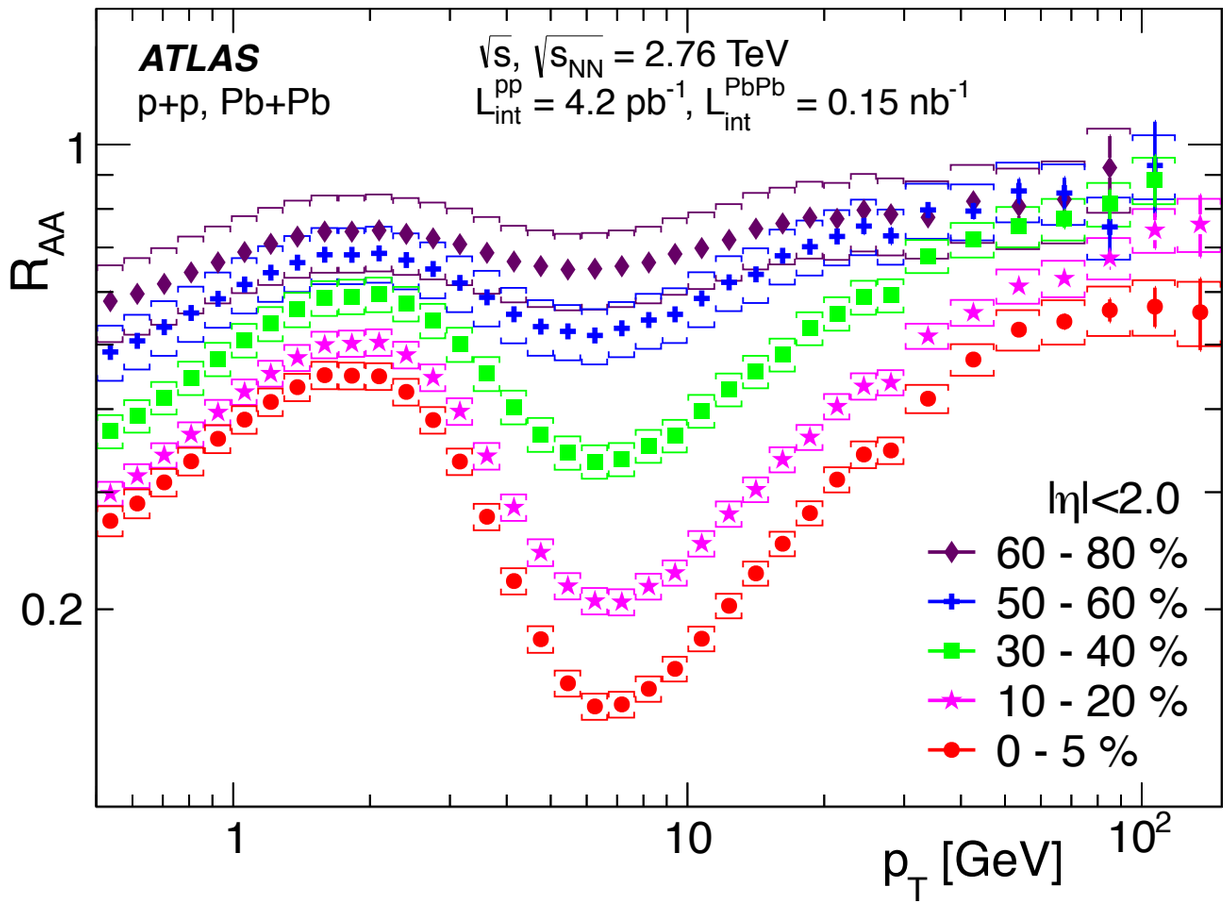
- Substantially **weaker centrality-dependence** for dijets with leading $p_{T,1}$ **> 200 GeV**

Inclusive suppression

PRL 114 (2015) 072302



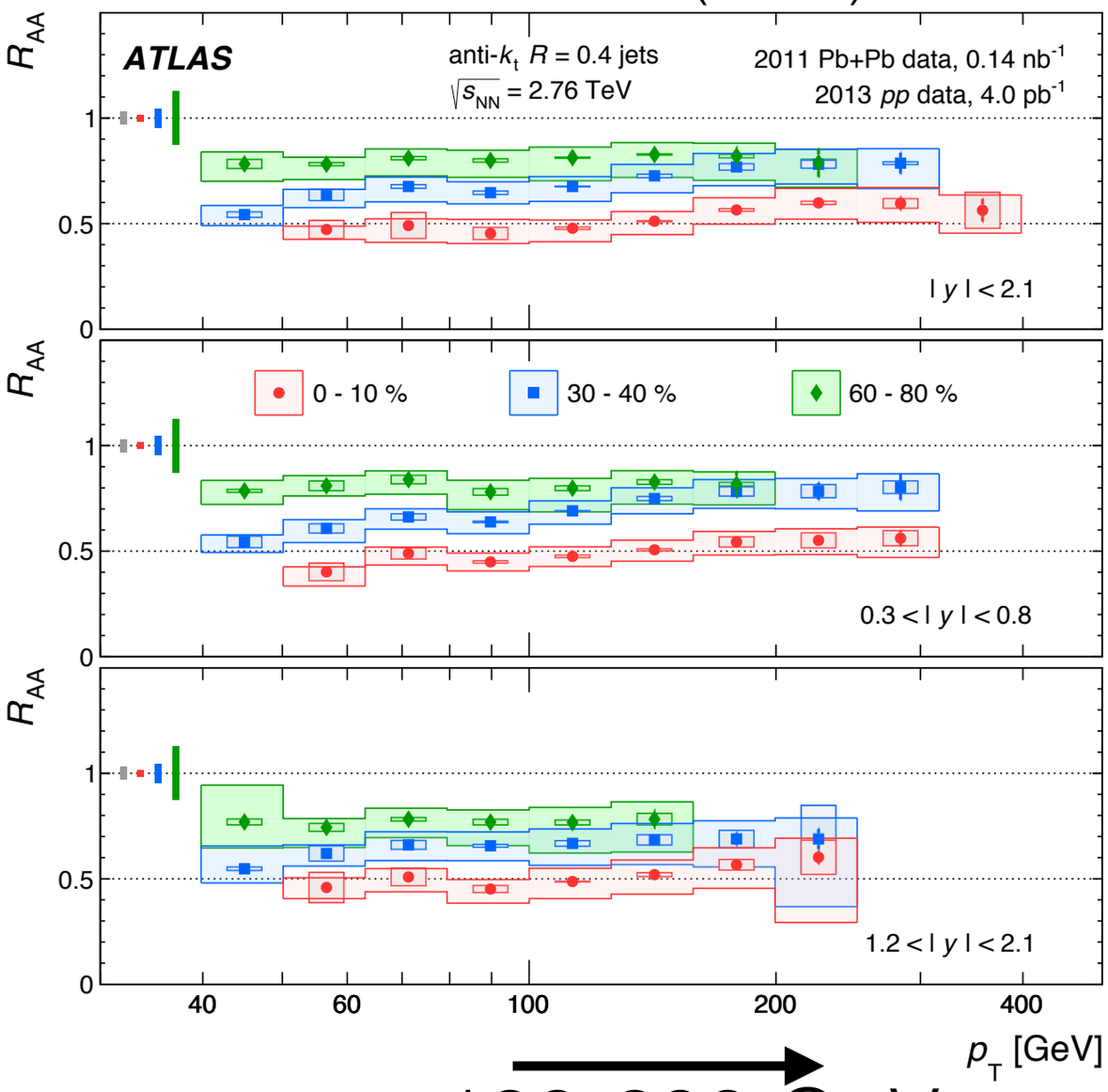
JHEP 09 (2015) 050



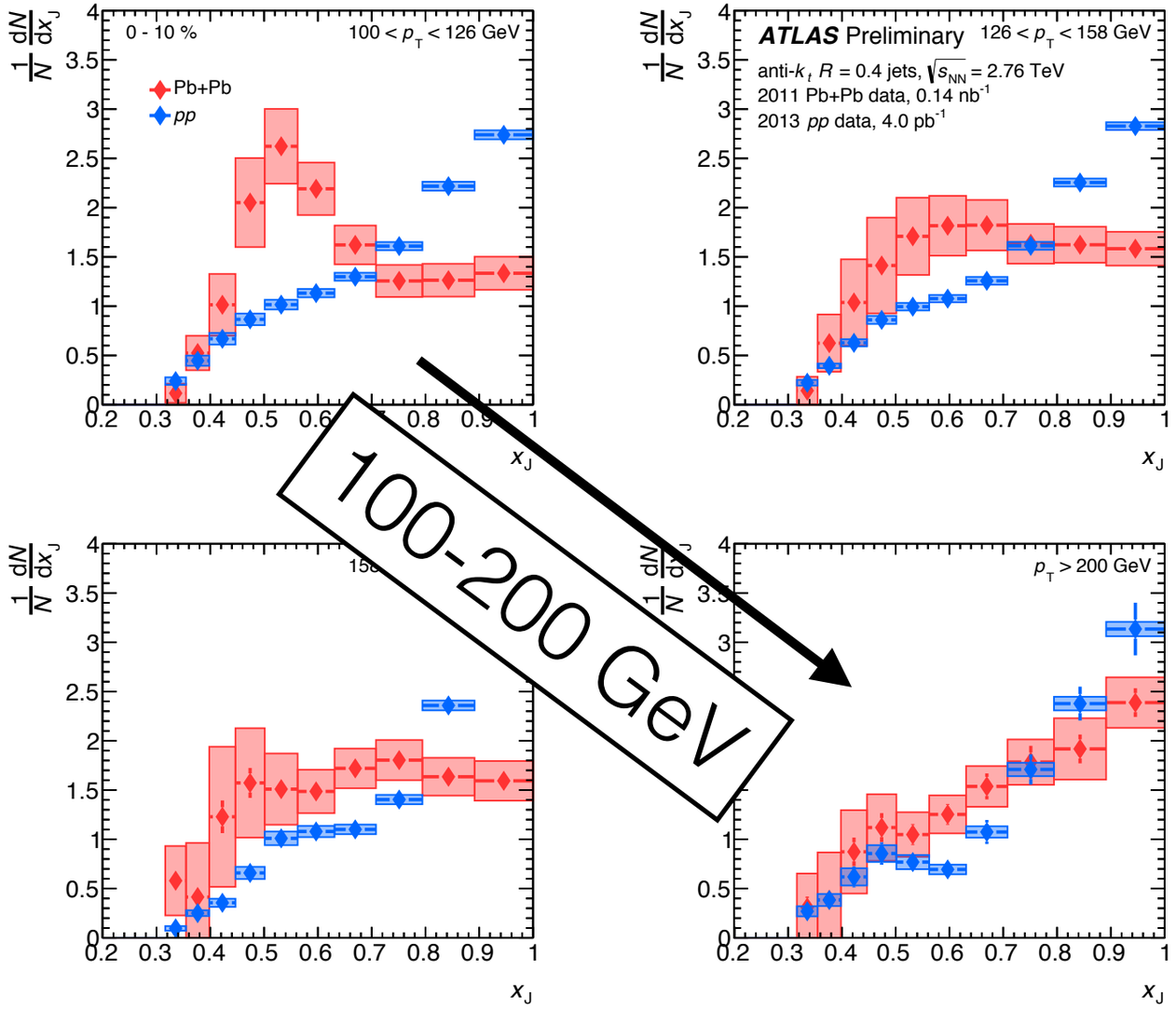
- Detailed measurements of R_{AA} vs. rapidity and centrality for jets and hadrons
- Run 1 “Legacy” measurements, for model benchmarking

p_T dependence: singles vs doubles?

PRL 114 (2015) 072302



100-200 GeV

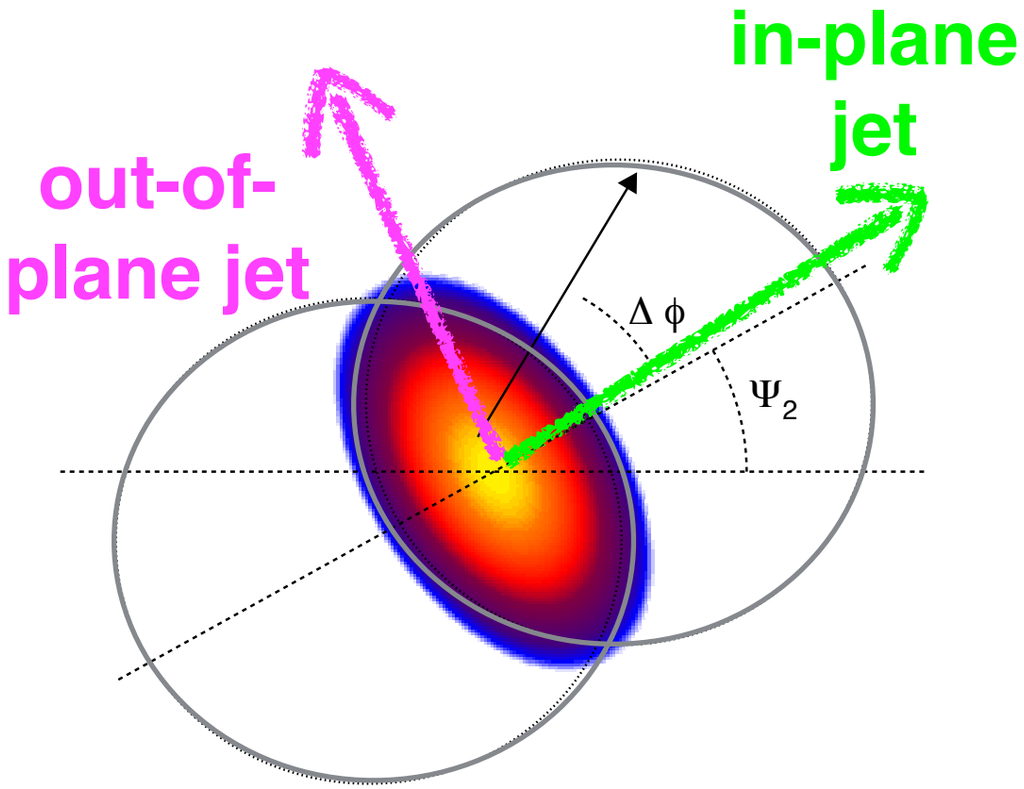


100-200 GeV

- R_{AA} only weakly dependent on p_T, but x_J evolves strongly between 100 GeV and 200 GeV

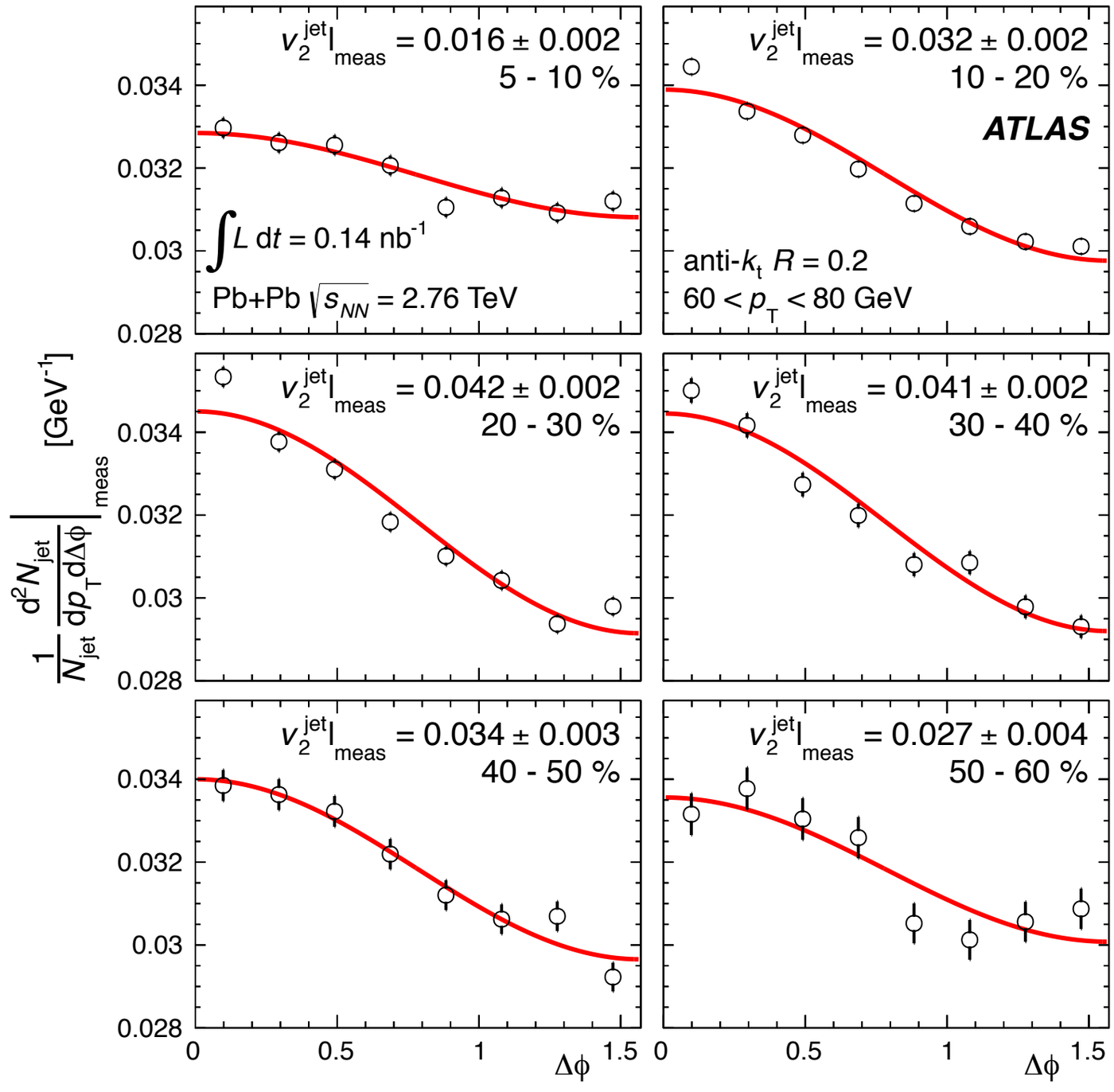
  ➡ Important to understand these two results together?

Reaction plane dependence



- "Almond"-shaped interaction region in non-central collisions
- Modulation of the jet yield vs. $\Delta\phi = \phi^{jet} - \Psi_2$

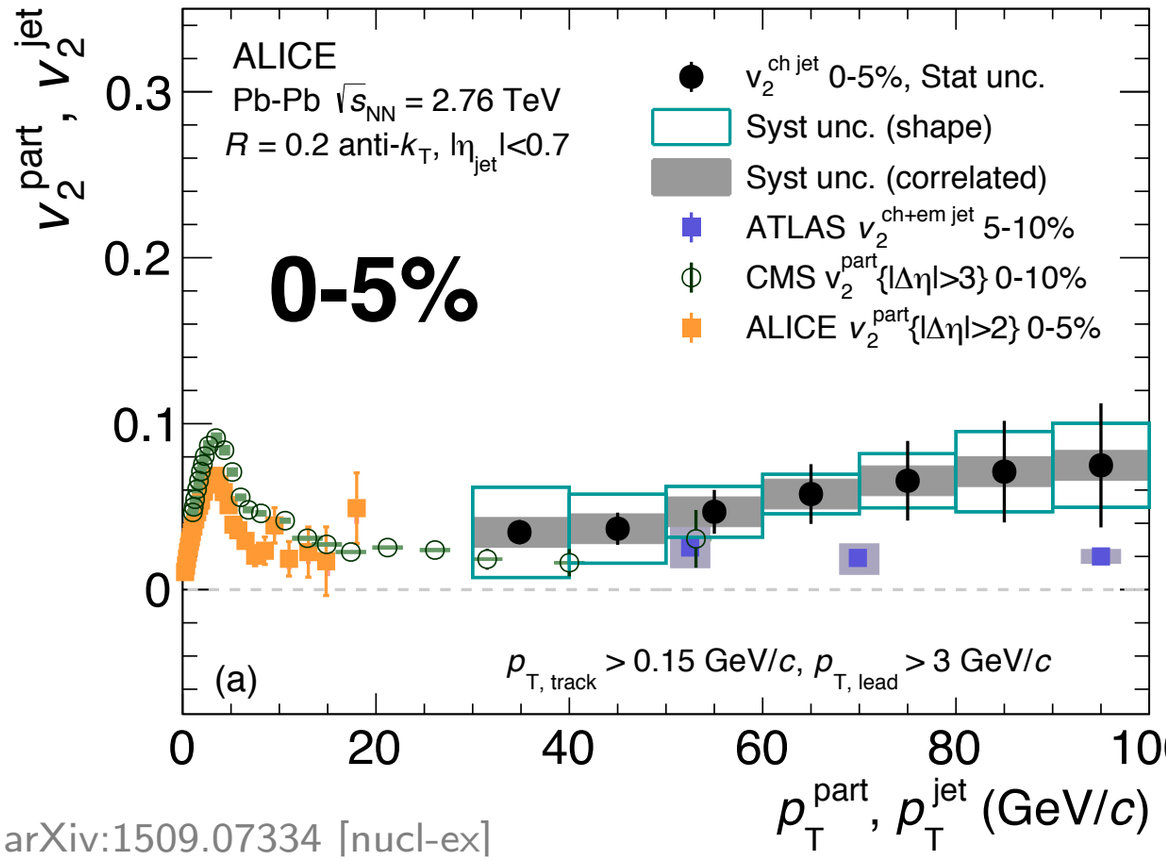
  ➡ path length dependence



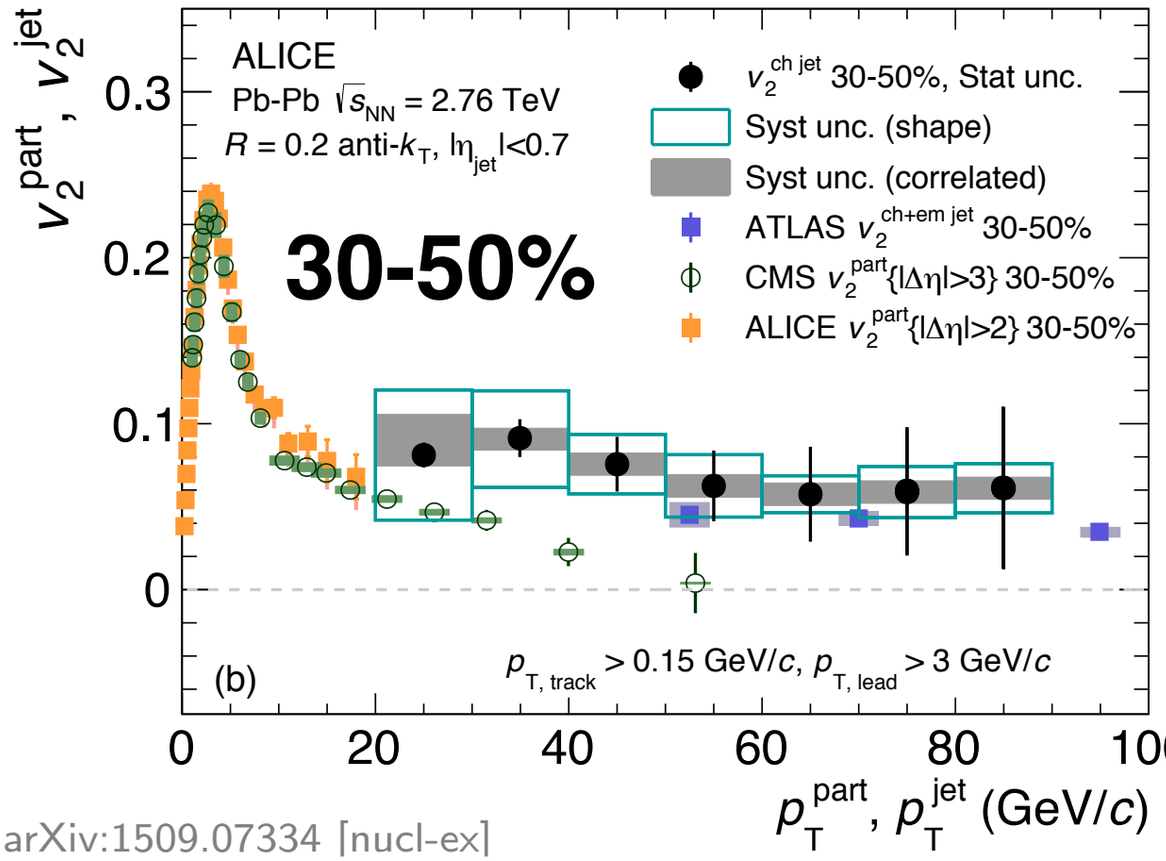
PRL 111 (2013)152301

New at QM15

Latest jet v_2



arXiv:1509.07334 [nucl-ex]

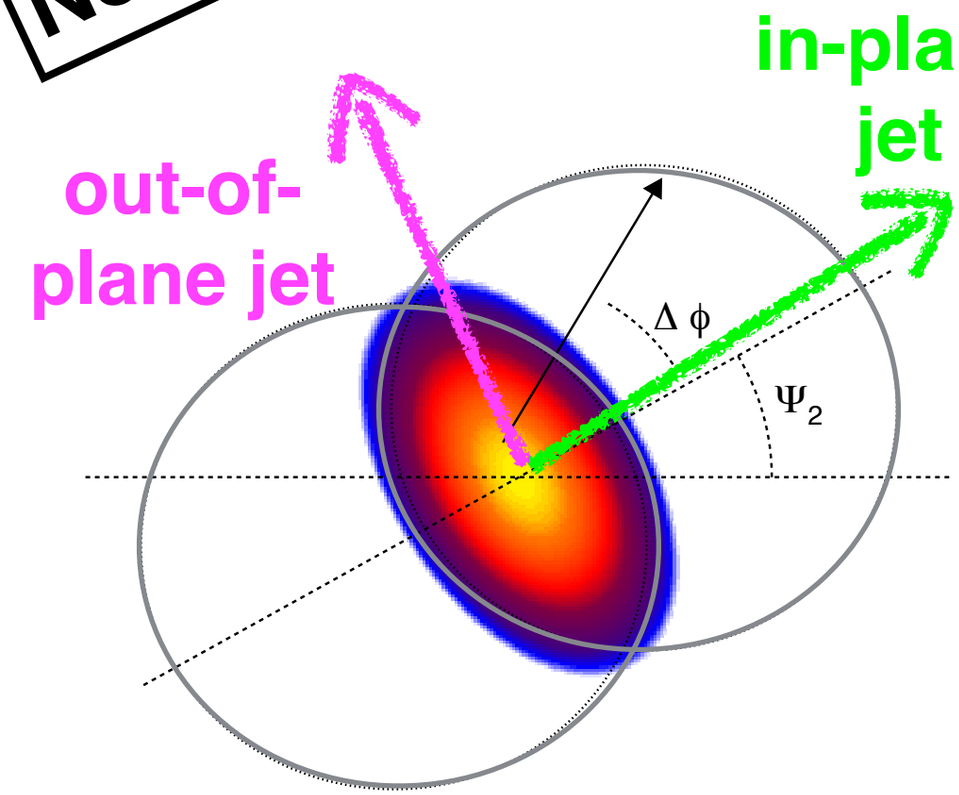


arXiv:1509.07334 [nucl-ex]

- New measurement by ALICE of **jet v_2**
  - ➡ in central and semi-central collisions
  - ➡ compared to early **ATLAS** results and **single particle** v_2
- Non-zero v2 in central events only 1.5σ significant…

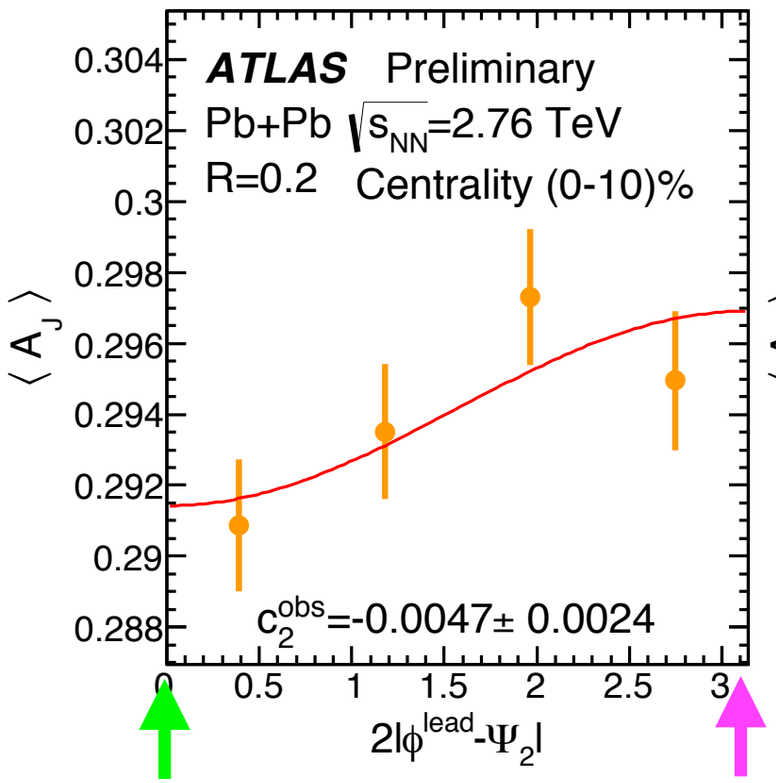
New at HP15

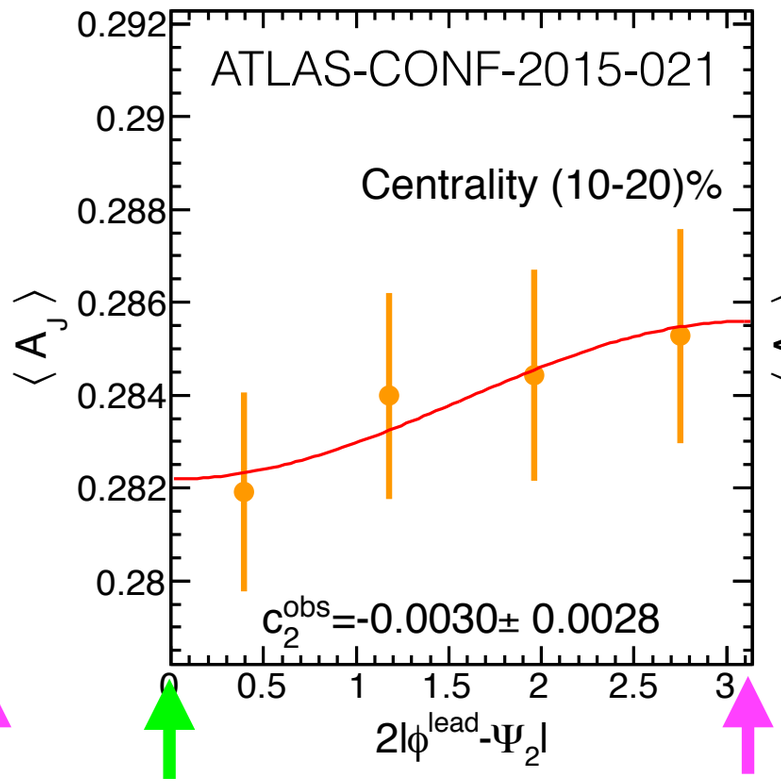
Dijets vs. reaction plane

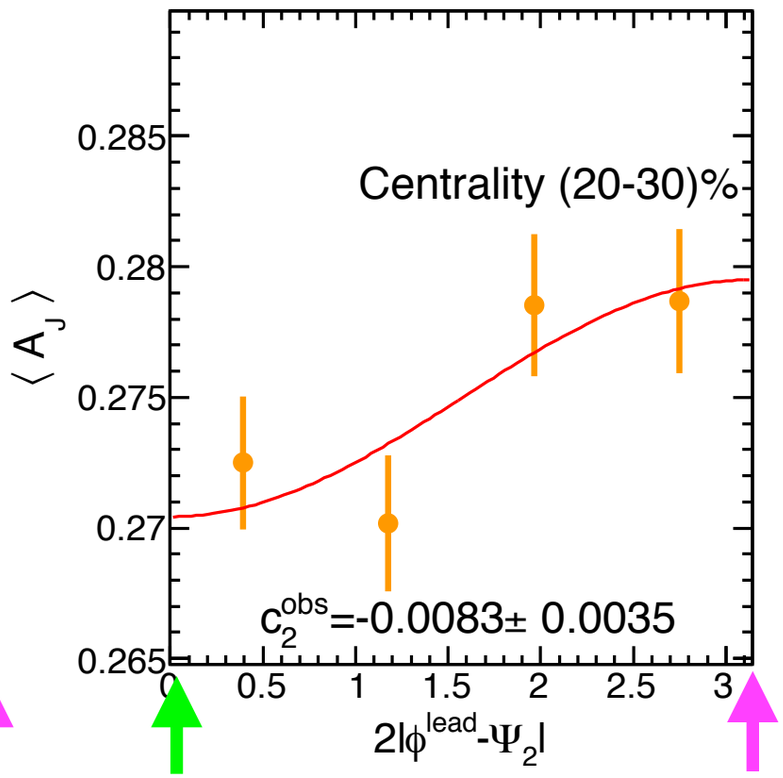


- Single jet suppression depends on **angle from reaction plane**
- How is dijet asymmetry affected?

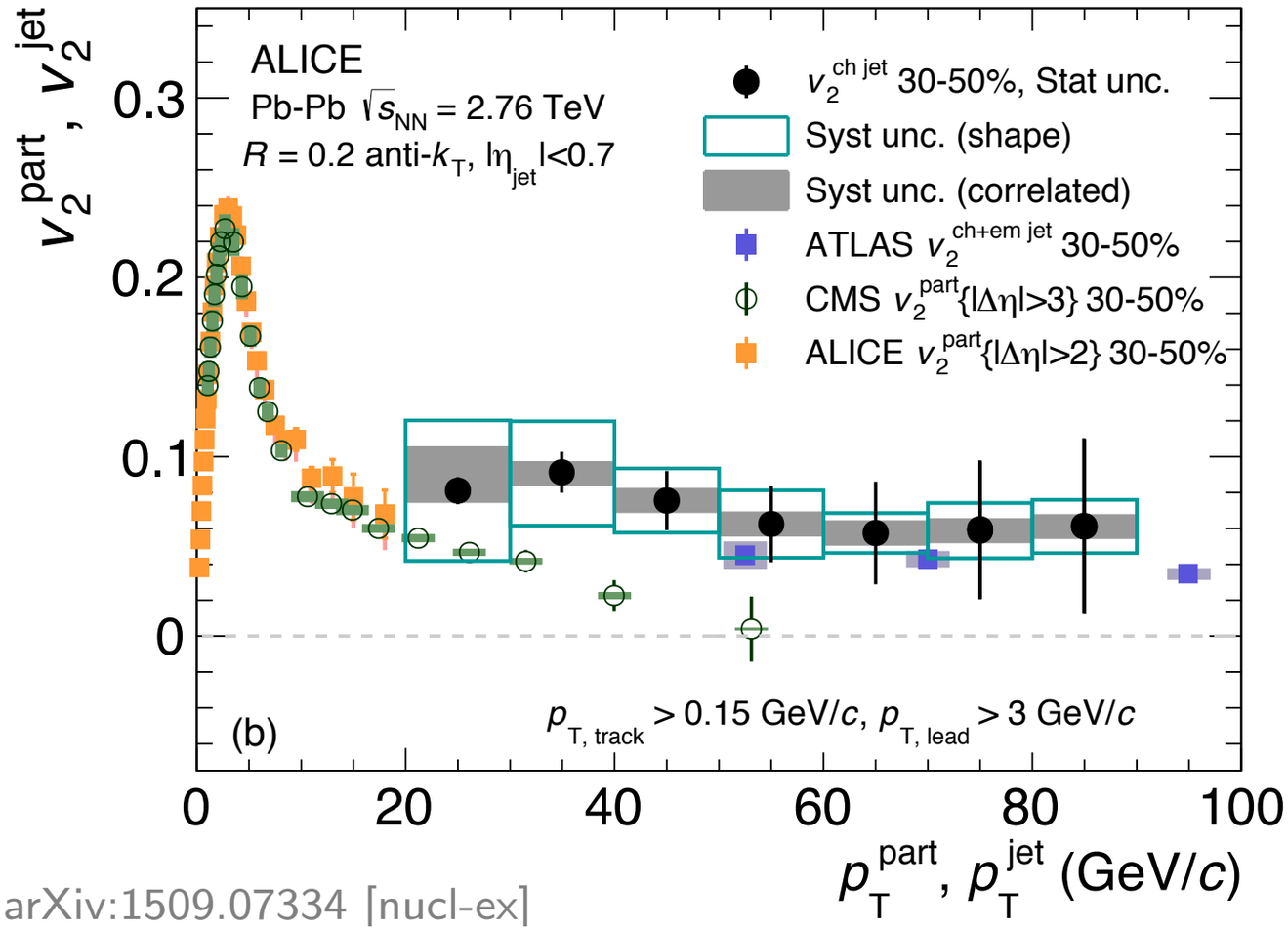
➡ for each centrality, **<A_J>** slightly **larger for out-of-plane** dijets







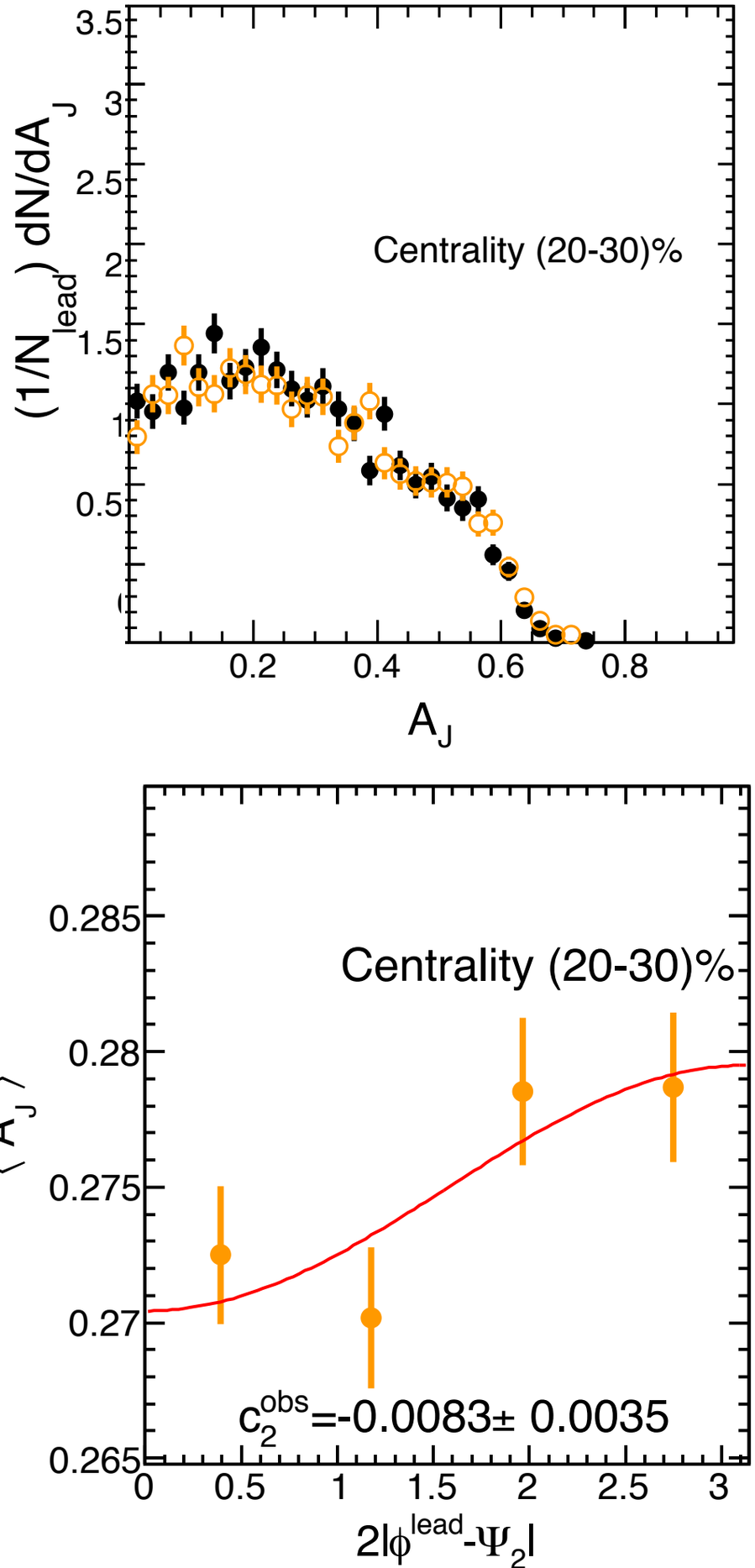
Reaction plane: singles vs doubles?



arXiv:1509.07334 [nucl-ex]

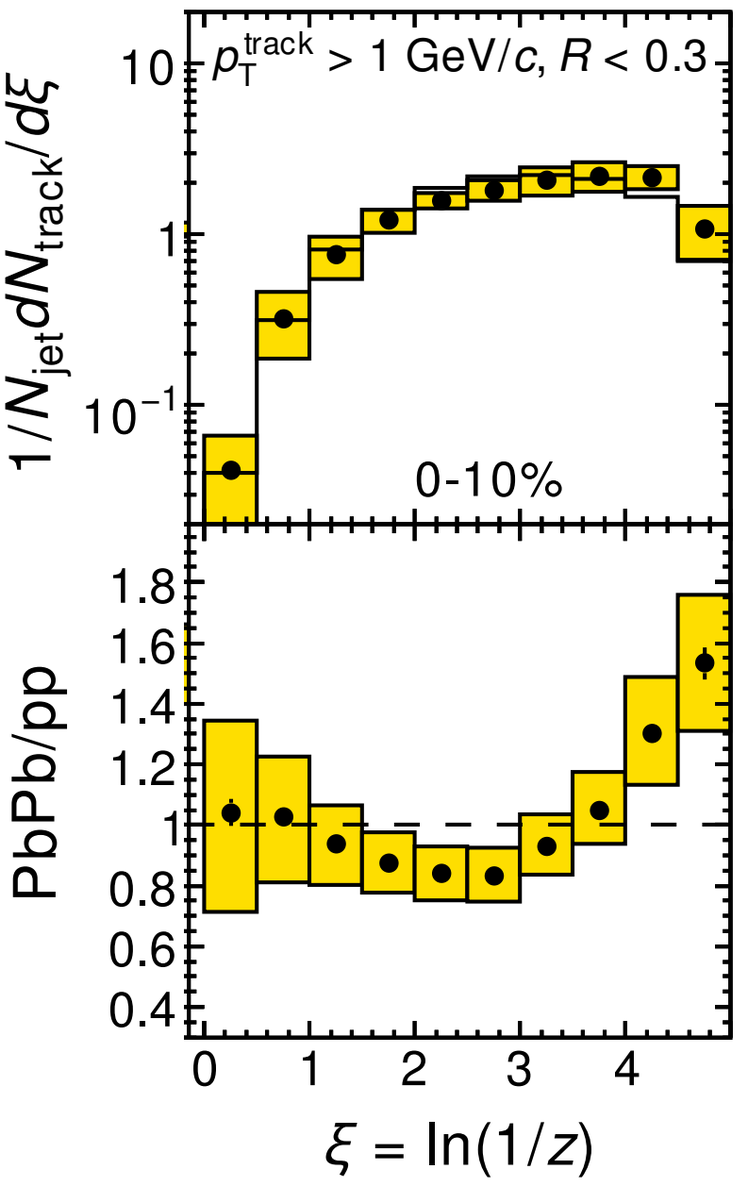
- Sizable v_2, but no change in mean asymmetry

  ➡ Important to understand these two results together?

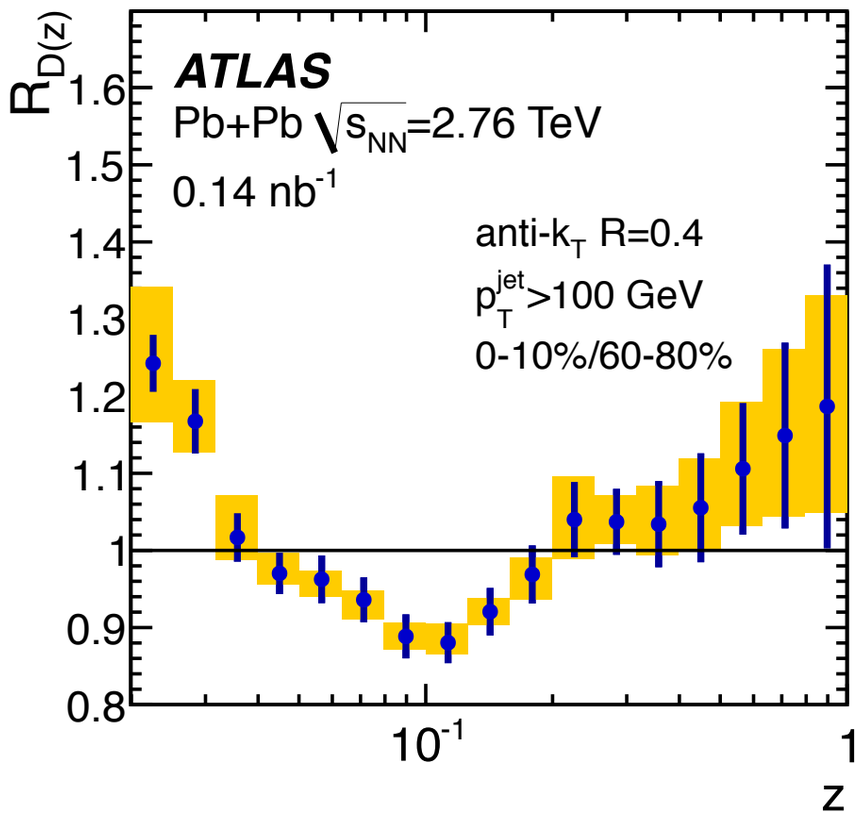


Modified jet structure

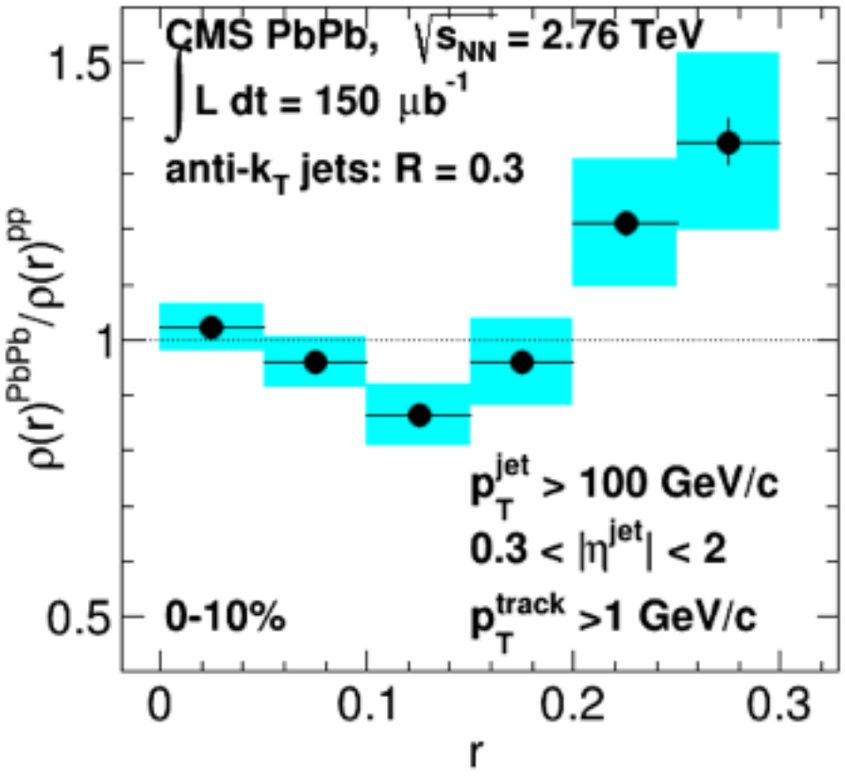
PRC 90 (2014) 024908



PLB 739 (2014) 320



PLB 730 (2014) 243



- Measurements of internal jet structure in Pb+Pb collisions
  - ➡ modified longitudinal momentum structure and radial structure

New at QM15

Fragmentation function vs. η

central ◯ →

mid-rapidity ↓ forward ↓

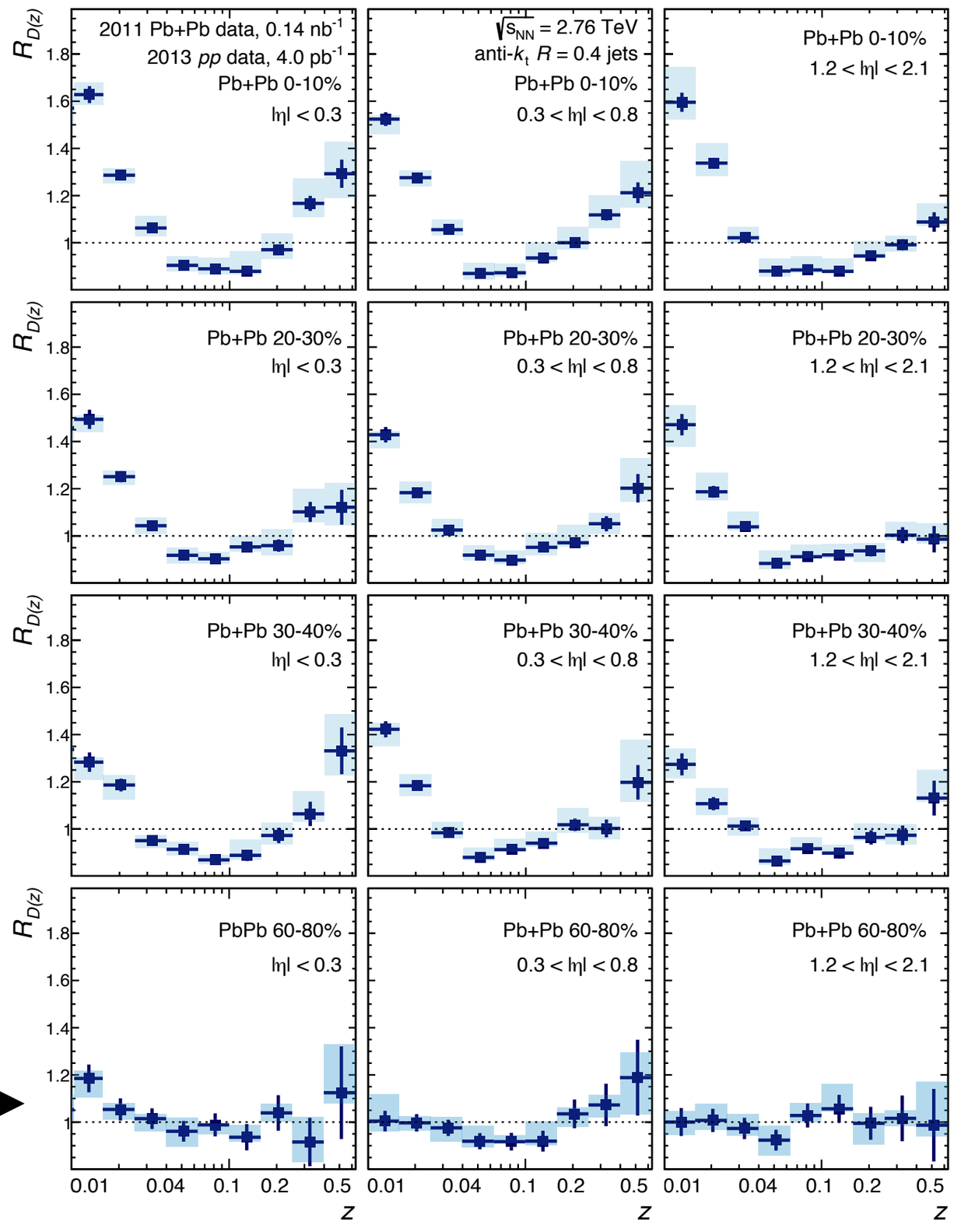
- $R_{D(z)} = D(z)^{\text{Pb+Pb}} / D(z)^{\text{pp}}$

  ➡ plotted here vs. z

- Modest η dependence at all centralities

  ➡ higher quark fraction at forward rapidities?

peripheral ◯◯ →

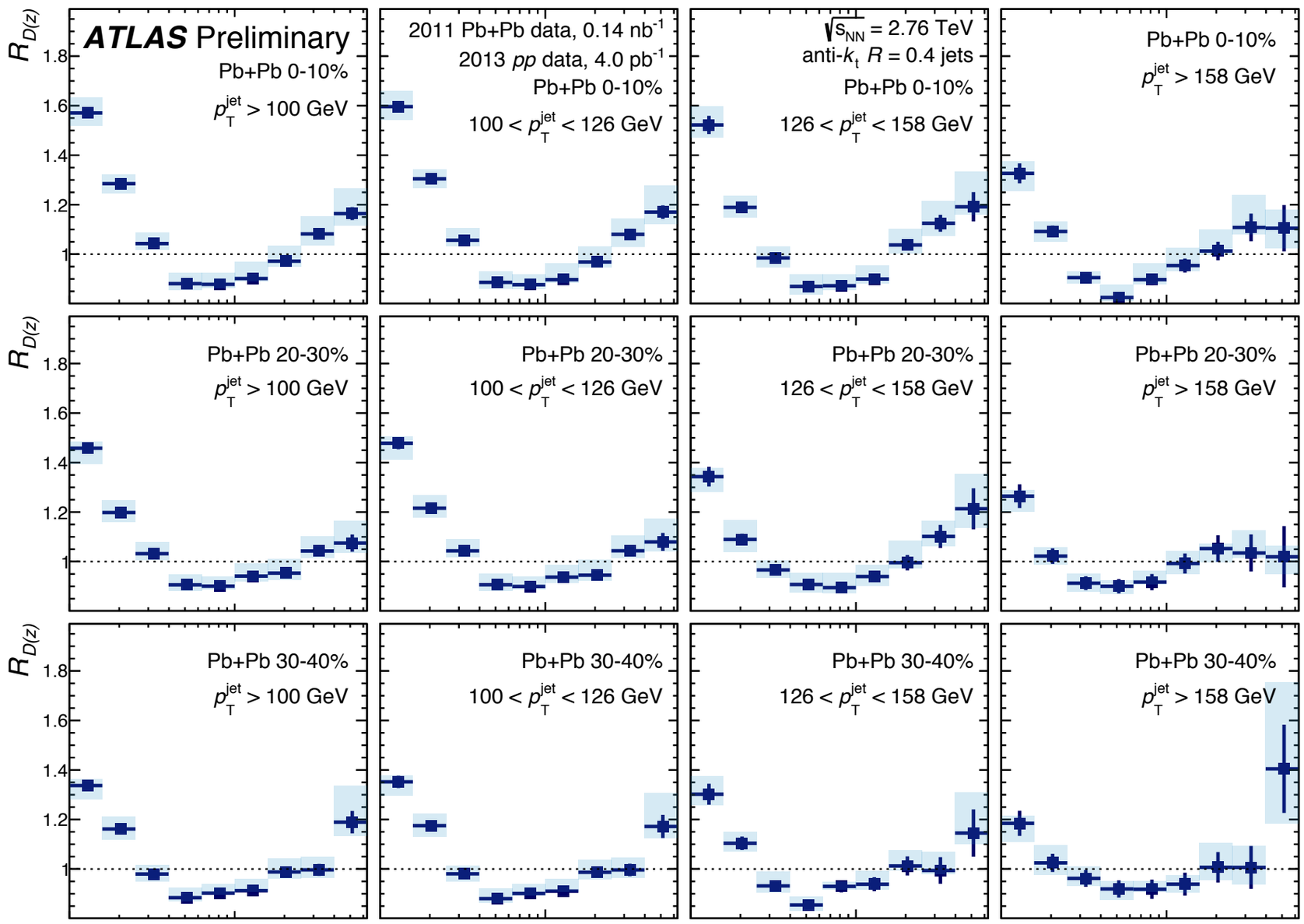


New at QM15

Fragmentation function vs. p_T

increasing p_T

central →

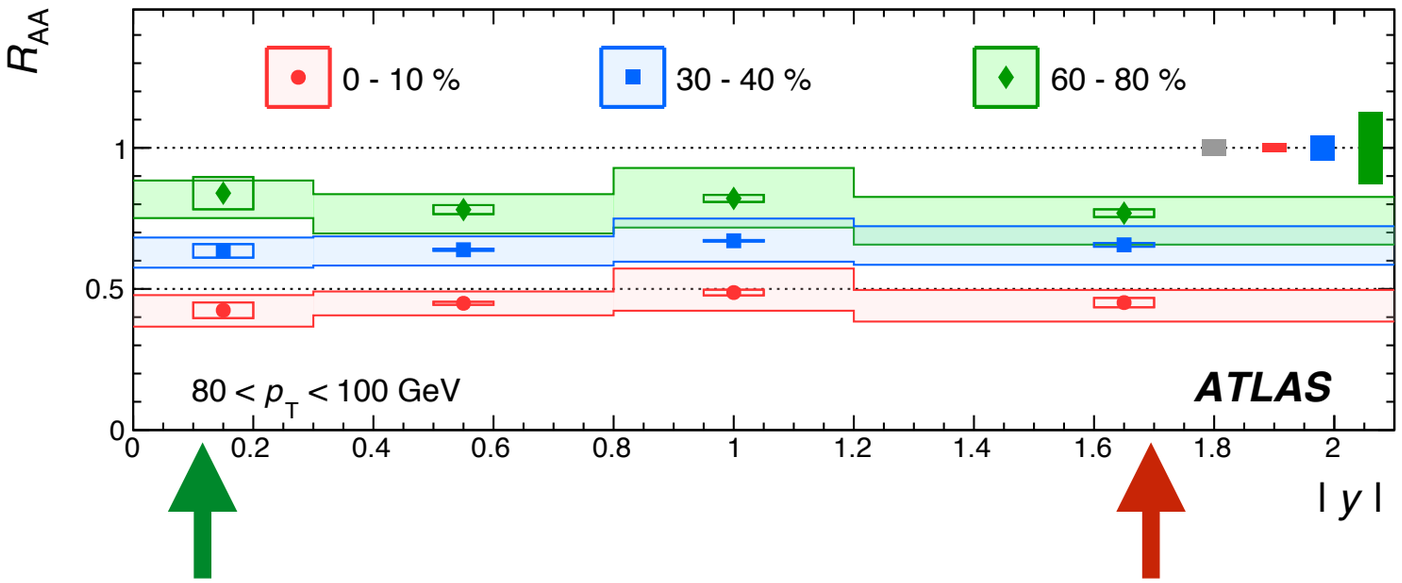


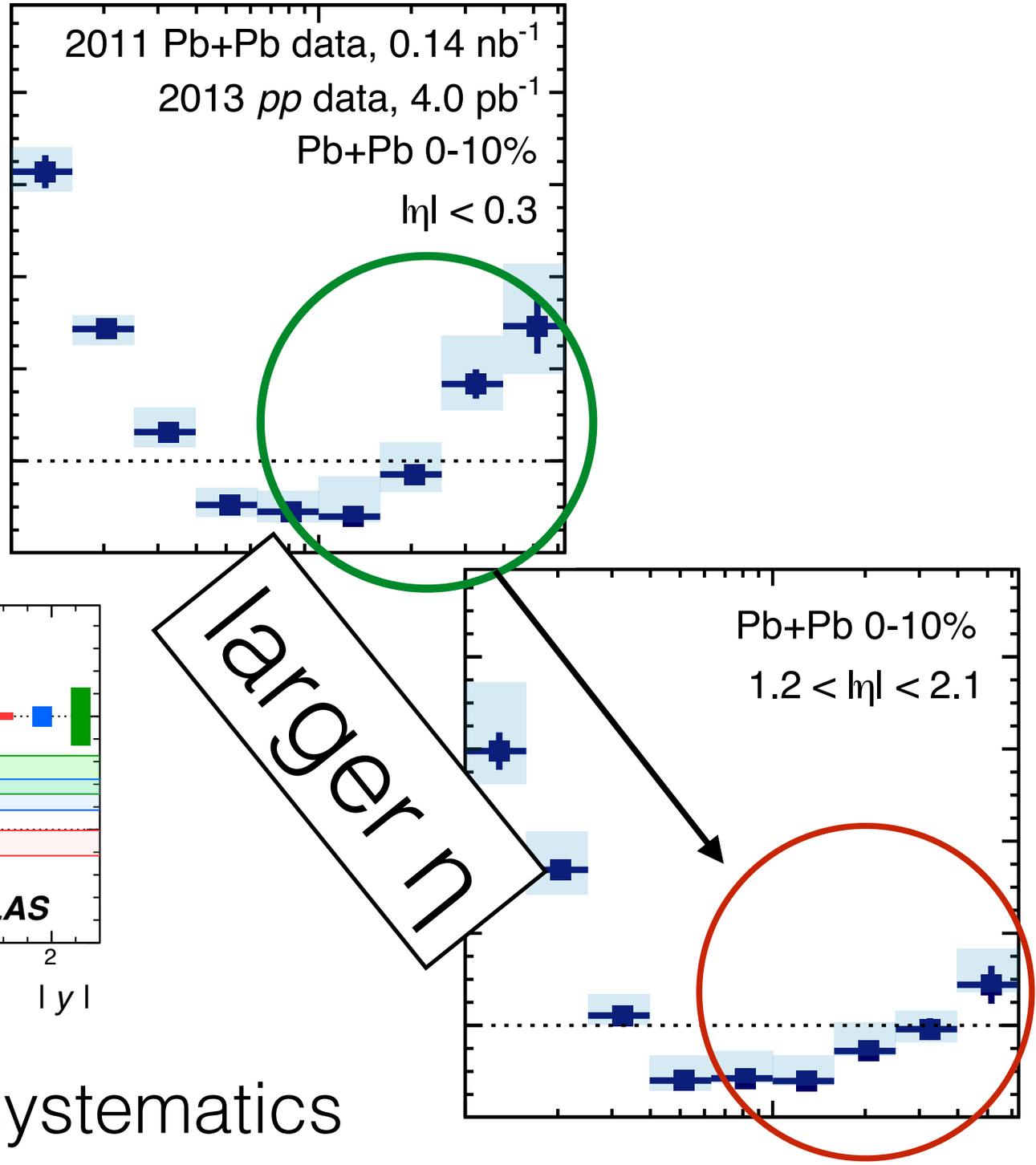
semi-central →

➡ Low and high-z excesses become systematically smaller with higher jet p_T…

η-dependence: suppression vs. modification?

PRL 114 (2015) 072302





- R_{AA} is η-independent within systematics
  - ➡ but fragmentation functions indicate a change in the level of jet modification at large η
  - ➡ Important to understand these two results together?

New at QM15

Jet shapes

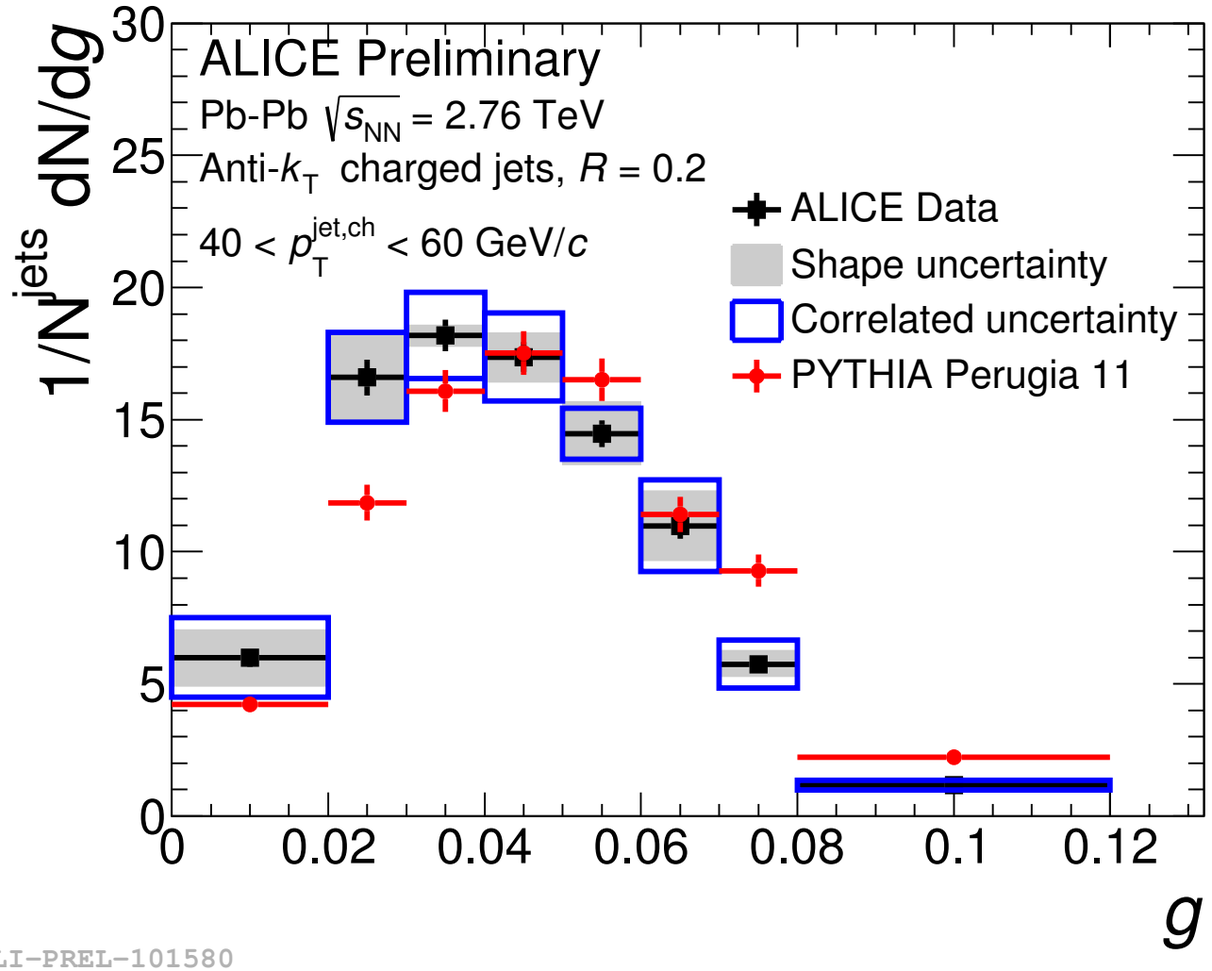
- New measurement by ALICE of modified jet shape variables in Pb+Pb

Radial moment *g*, from p_T-weighted hadron constituents *h*

$$g = \Sigma_h \, p_T^h \, \Delta R^{\text{jet-}h} \, / \, p_T^{\text{jet}}$$

Quenched jets somewhat more collimated than **reference**

➡ indicative of flavor-dependence (more *q* survive than *g*)?



ALI-PREL-101580

New at QM15

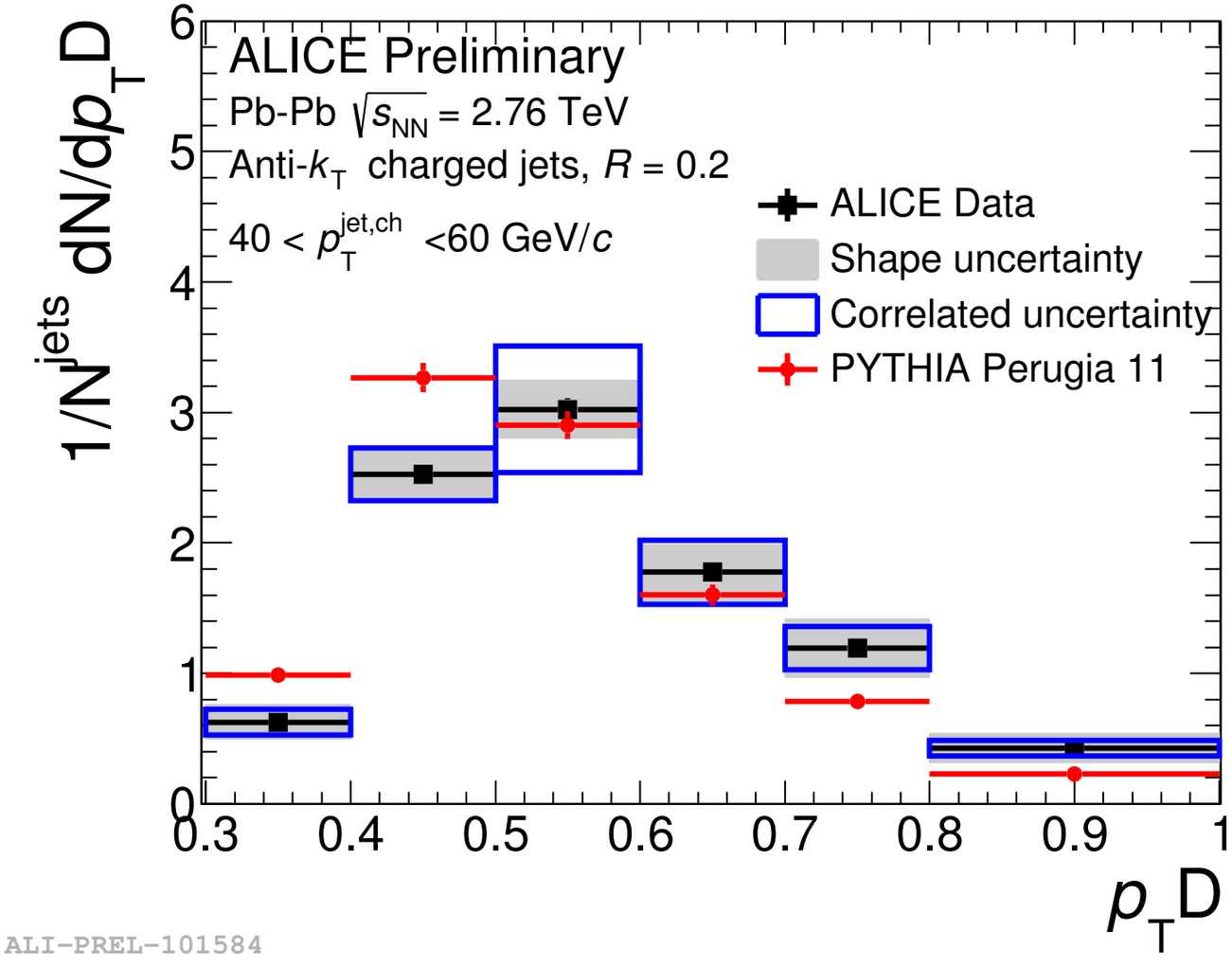
Jet shapes

Dispersion $p_T D$, from RMS p_T of hadron constituents h

$$p_T D = \sqrt{[\ \Sigma_h (p_T^h)^2\ ]} / \ p_T^{\text{jet}}$$

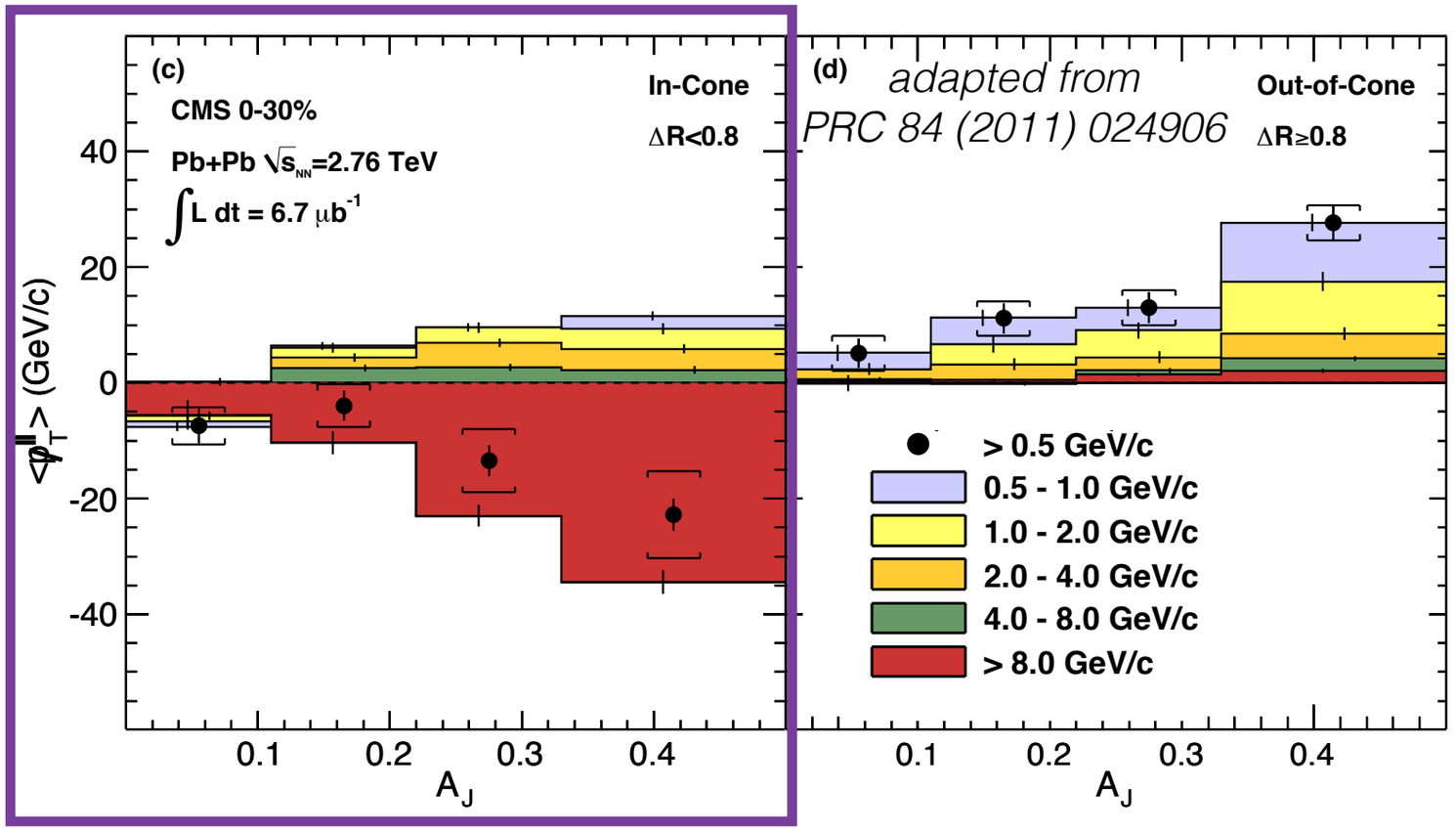
Quenched jets have harder fragmentation pattern than **reference**

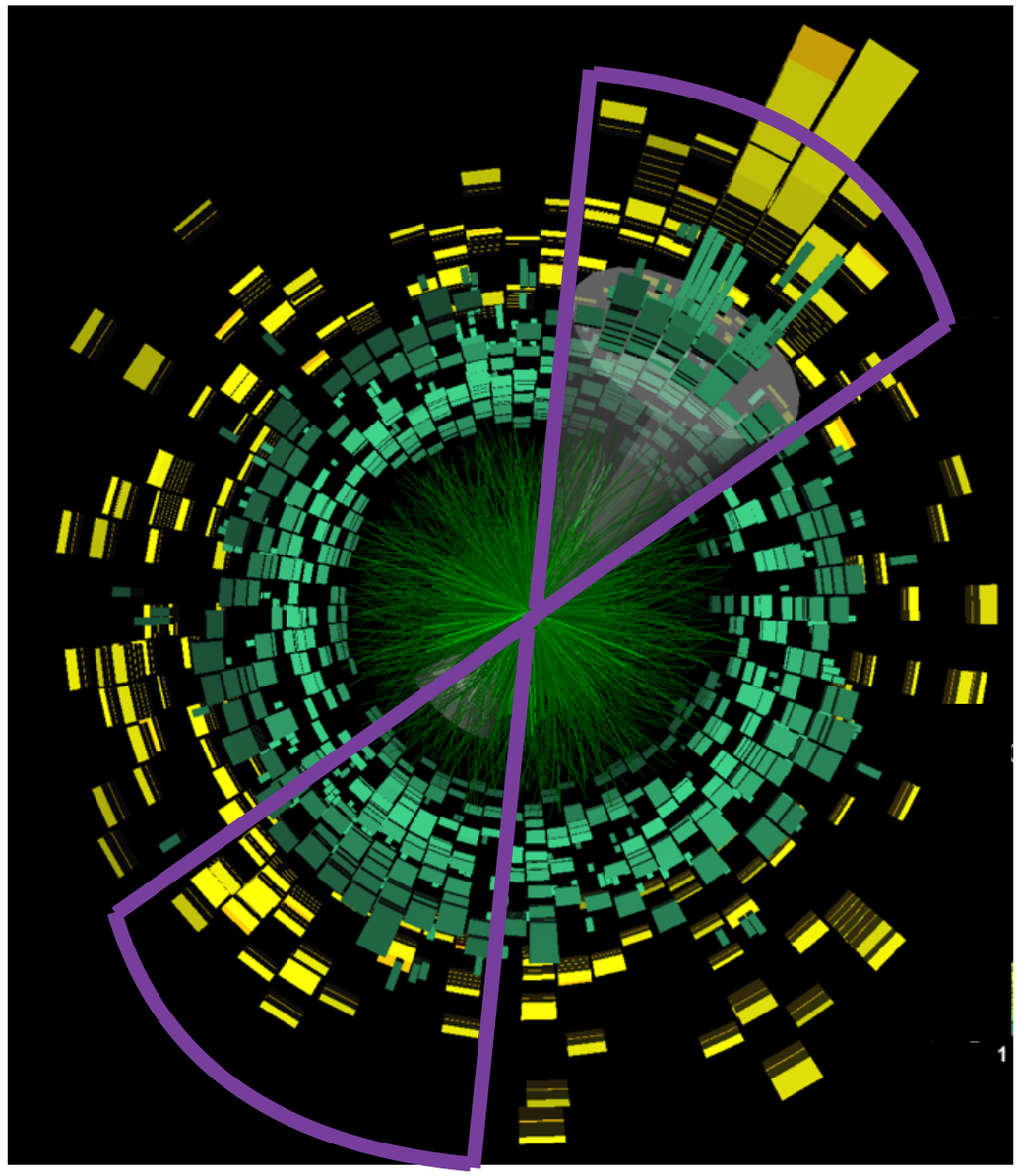
➡ indicative of flavor-dependence (more q survive than g)?



ALI-PREL-101584

Where does the energy go?



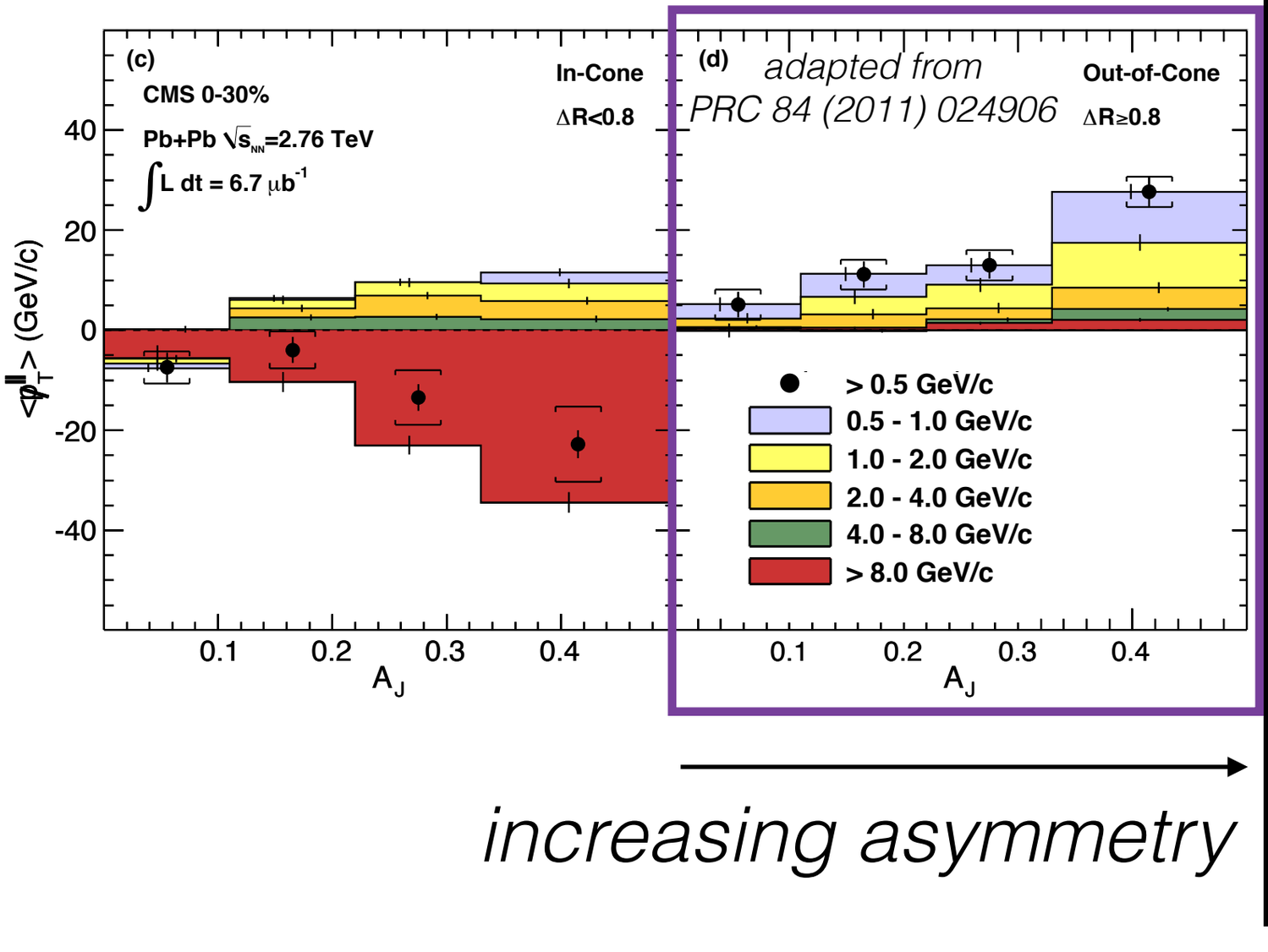


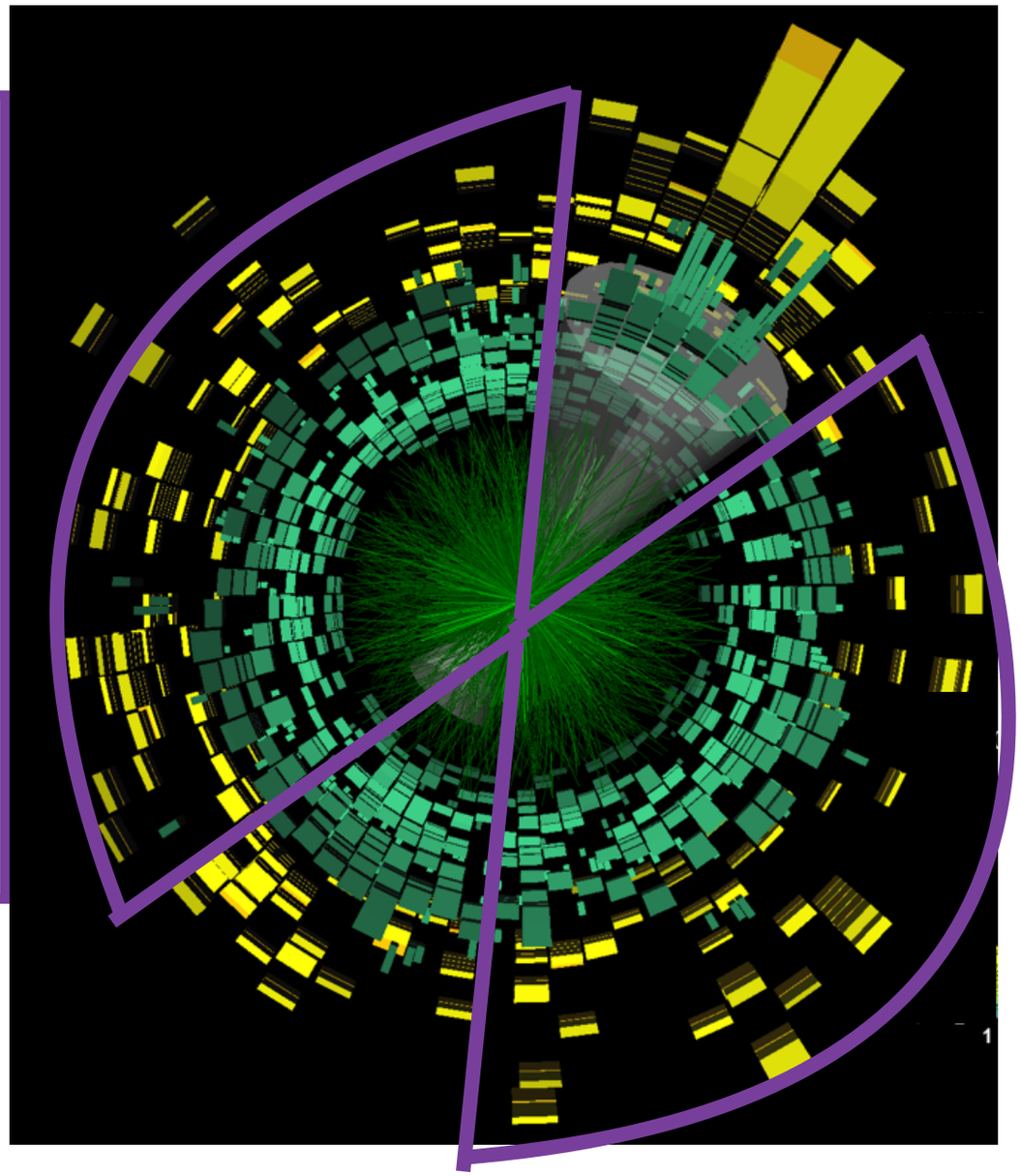
increasing asymmetry

- By <u>momentum conservation</u>, there should be no net momentum perpendicular to the incoming beams

  ➡ excess of high-energy particles **near the jets**

Where does the energy go?



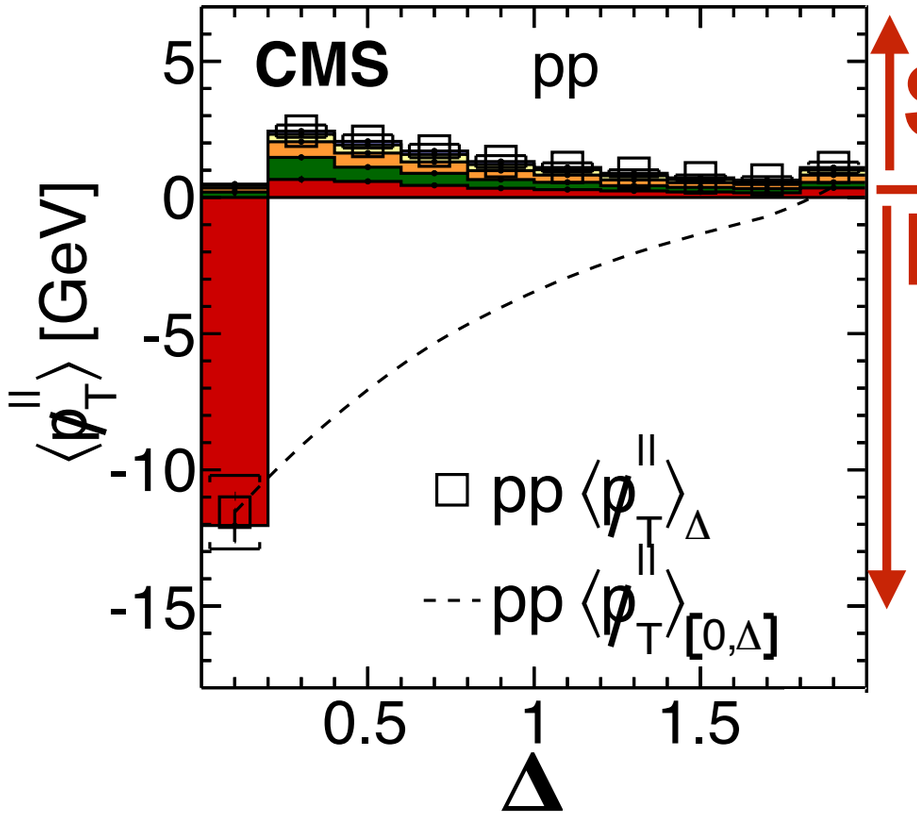


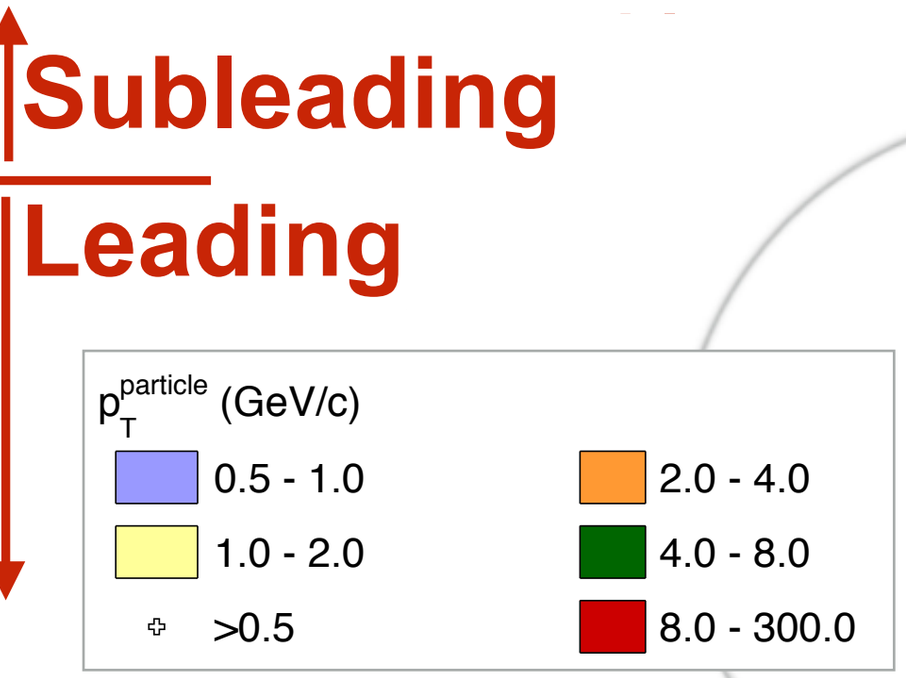
- Excess of low-energy particles **away from the jets**

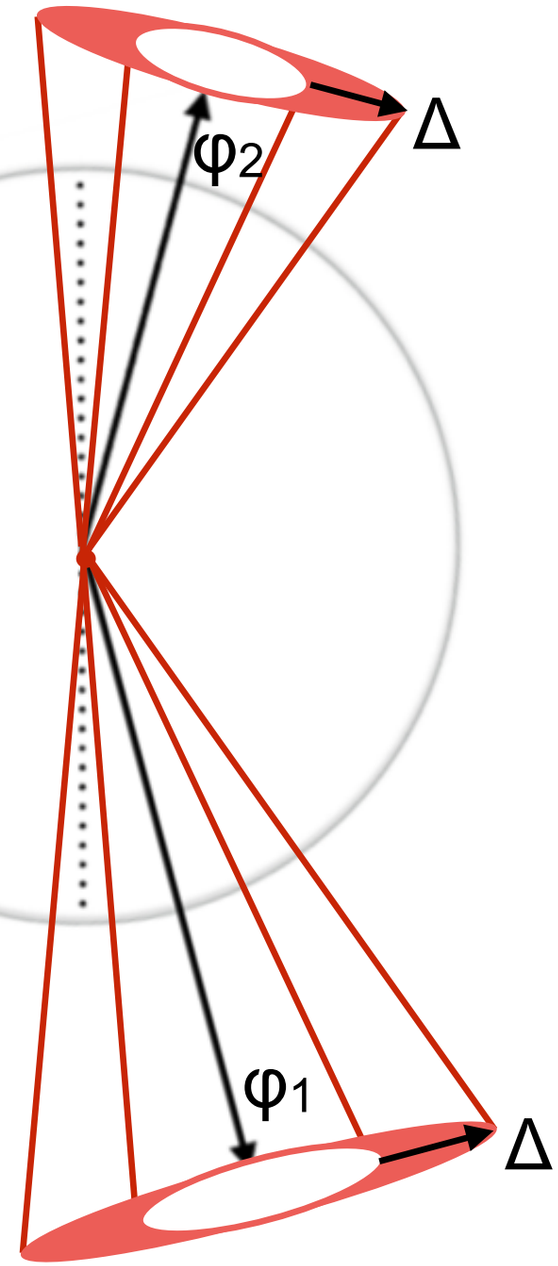
  ➡ the quenched energy is carried away by soft particles at large angles from the jets

New at QM15

Jet-track correlations



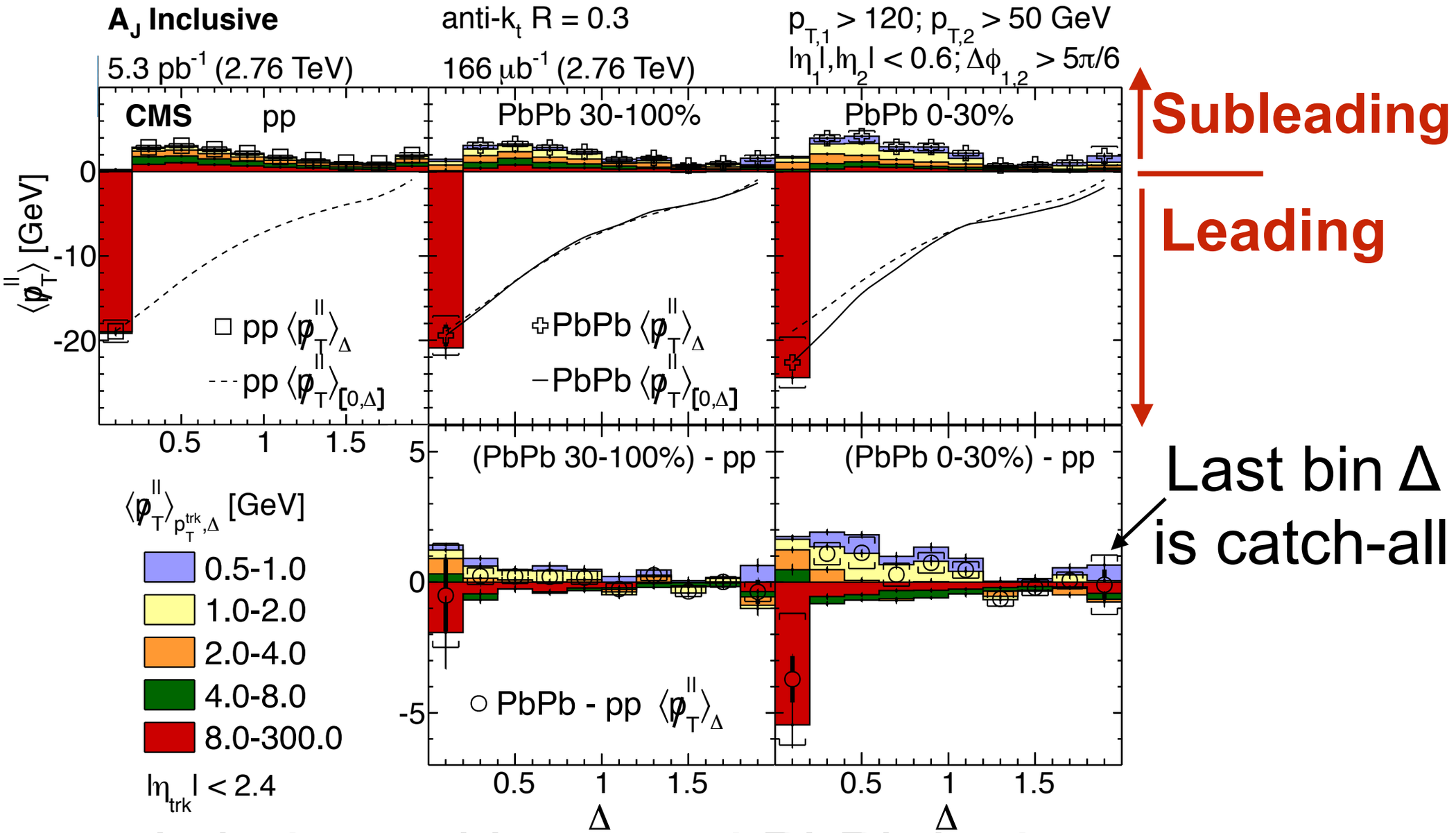




- CMS measurement of jet-jet p_T balance, as a function of angular distance Δ from dijet axis,
  - ➡ note: benchmarked here *in pp collisions*
  - ➡ deficit near jets, made up by excess at larger angles

New at QM15

Jet-track correlations



- More pronounced asymmetry at small Δ in Pb+Pb than in *pp*
  - ➡ made up by larger contribution of soft particles at large Δ

New at QM15

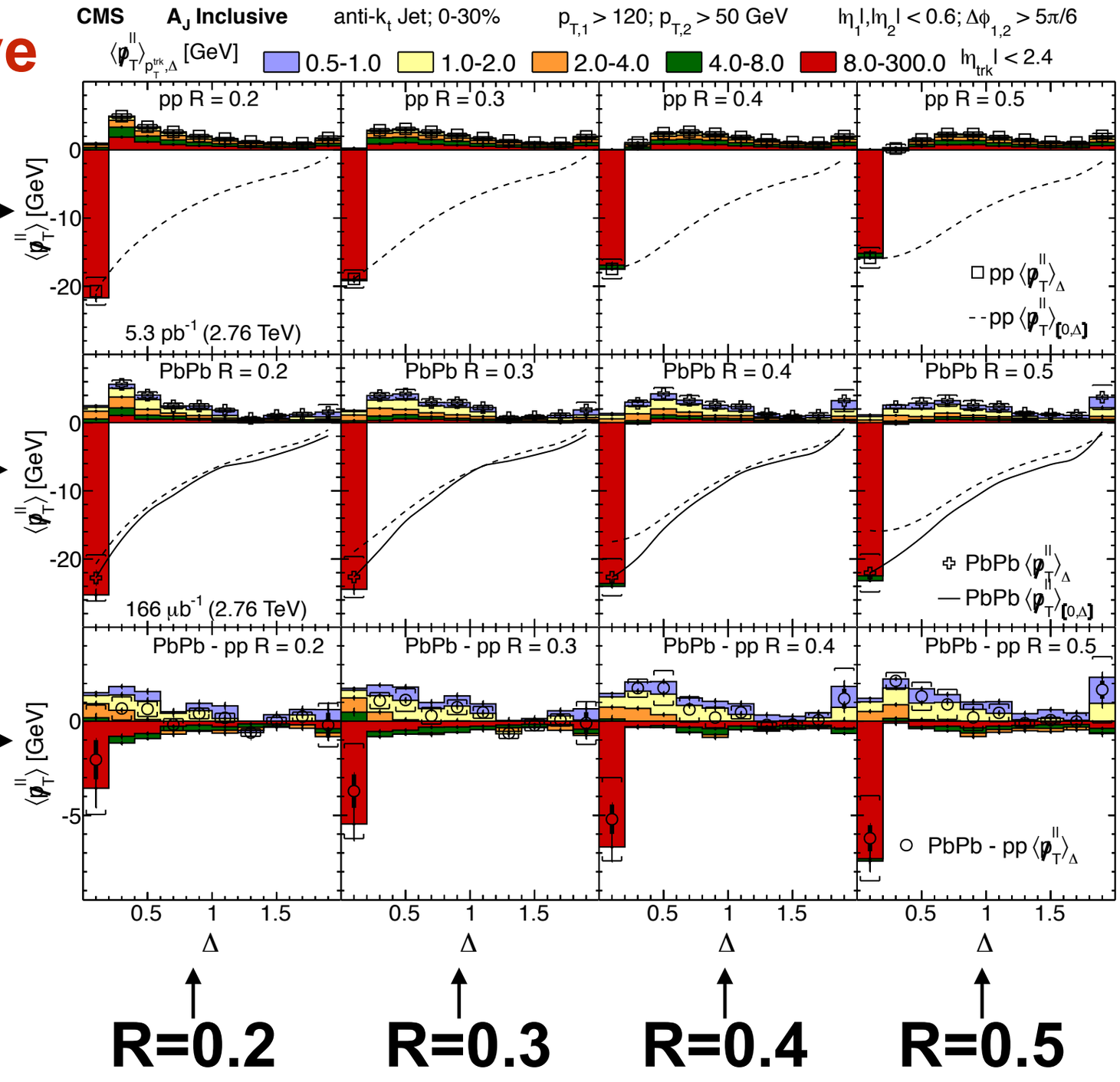
Jet-track correlations

A_J Inclusive

pp →

PbPb →
(0-30%)

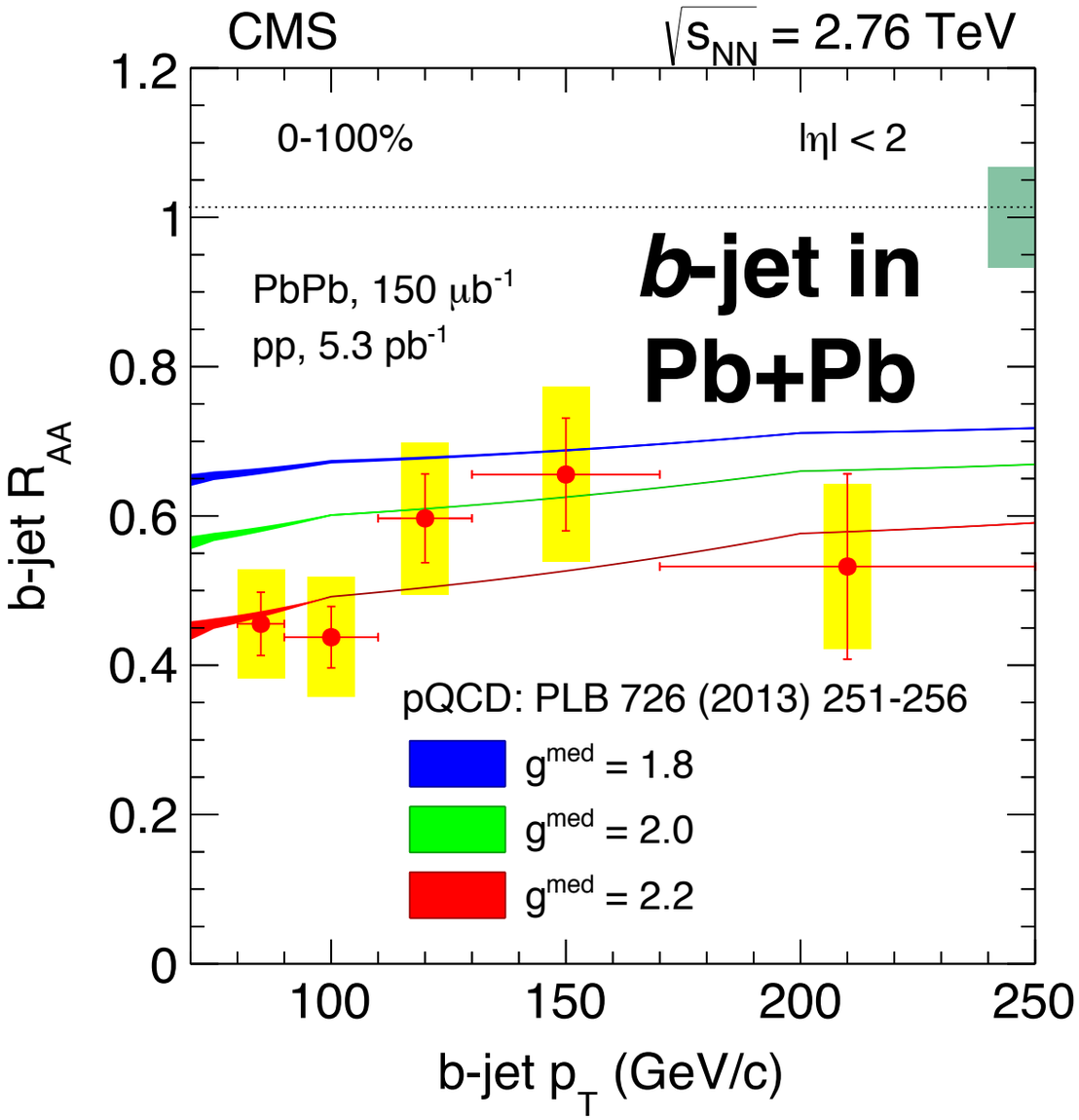
PbPb - pp →

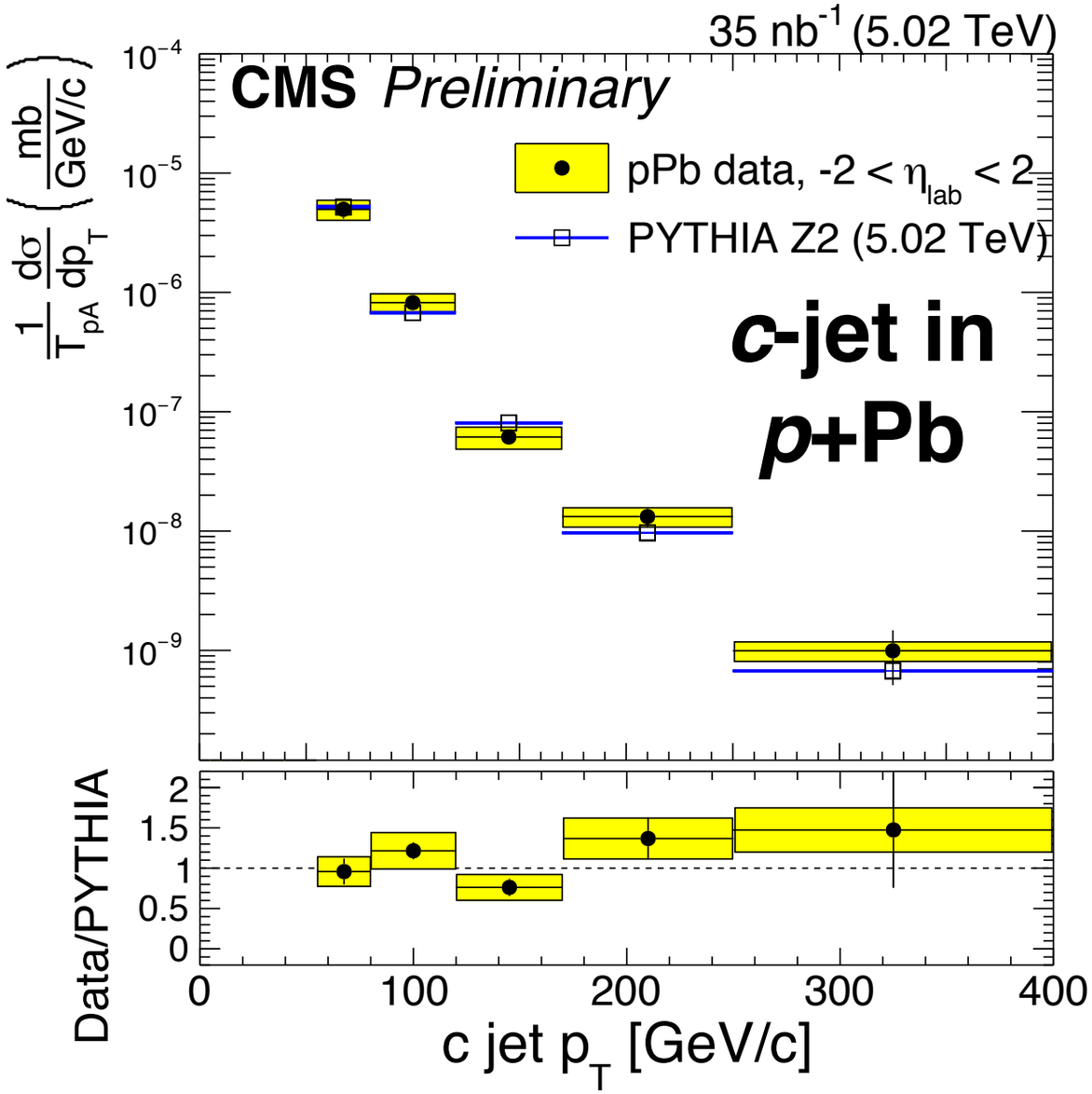


- Energy balance in Pb +Pb <u>modestly different than in *pp*</u>
- p_T composition of constituents changed

New at QM15

(Partial) progress in HF jets



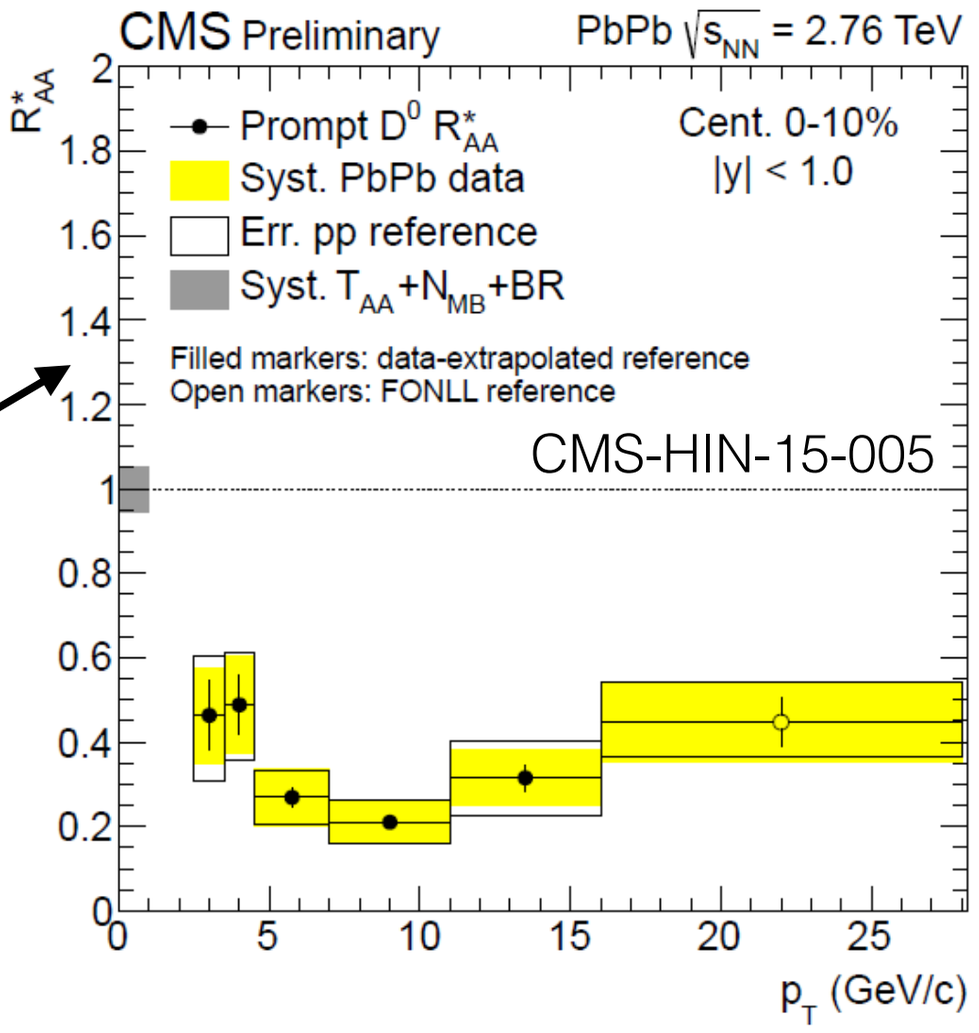


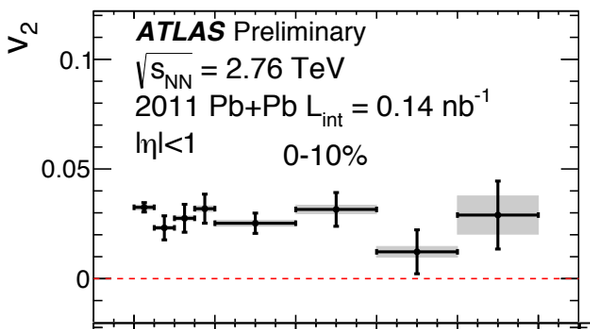
- During QM14, landmark CMS measurement of *b*-jet suppression
  - ➡ new this QM, *c*-jet R_{pPb}, but not yet a *c*-jet R_{AA}…

New at QM15

Other progress…

- Prompt D^0 suppression in Pb+Pb
- Jet suppression in Cu+Au
- Muon v_2 in Pb+Pb





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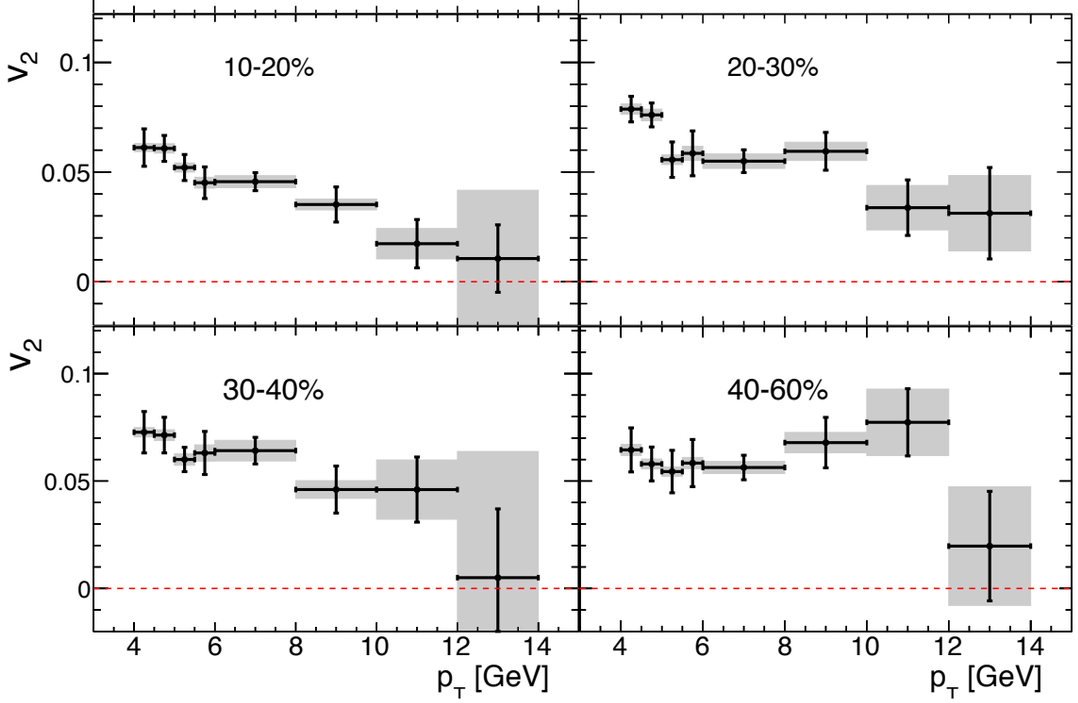
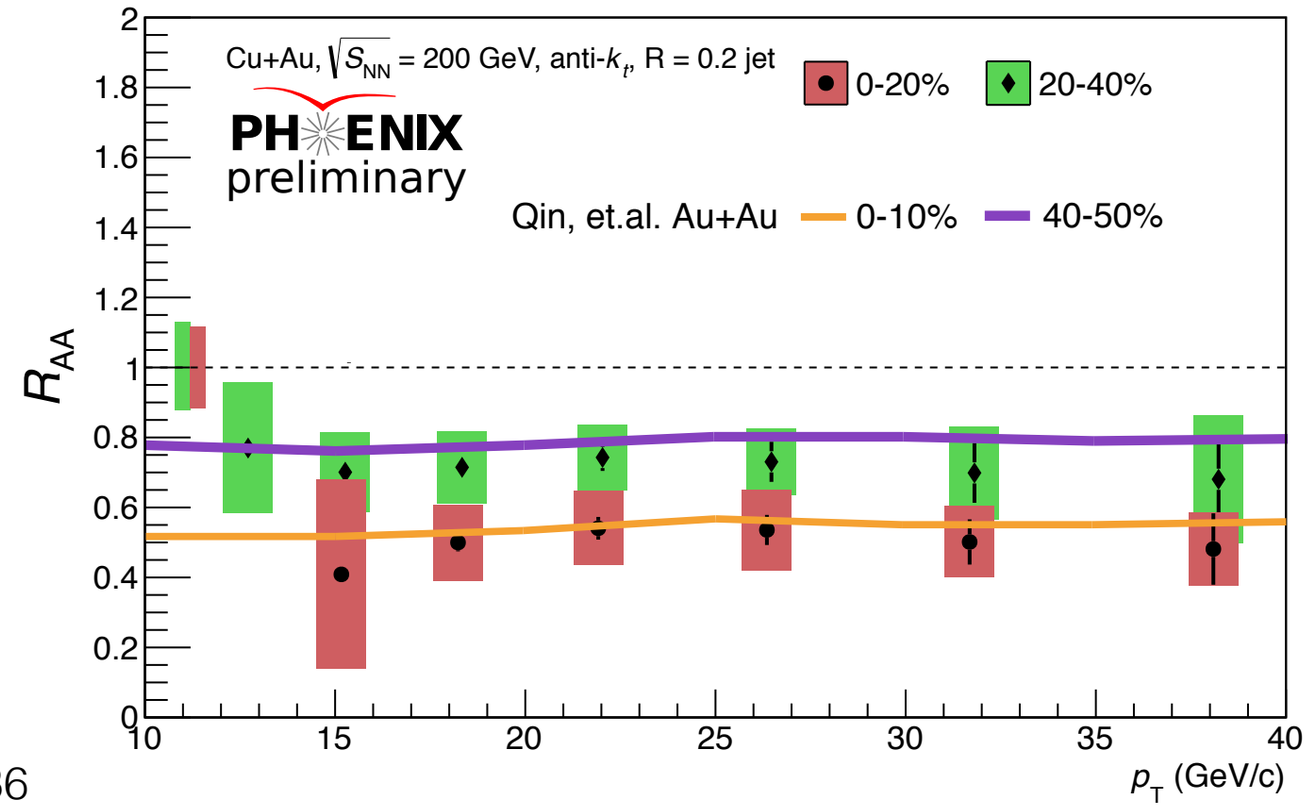
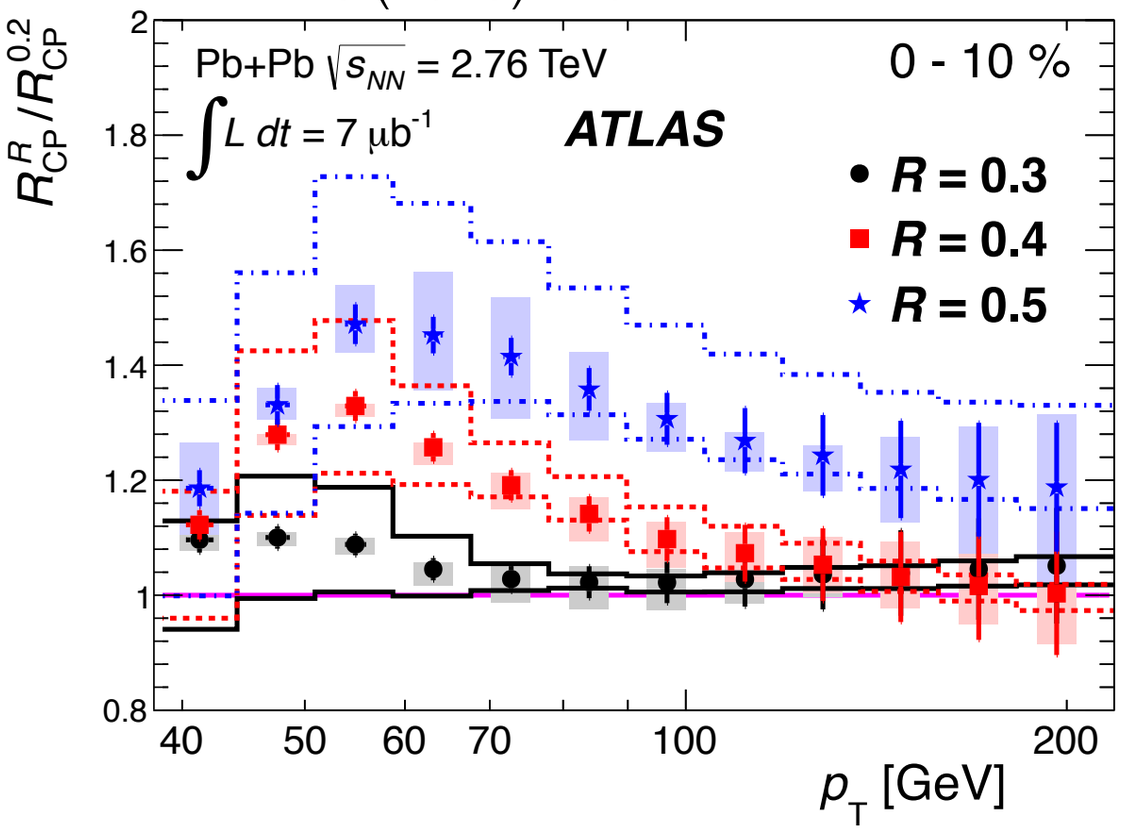




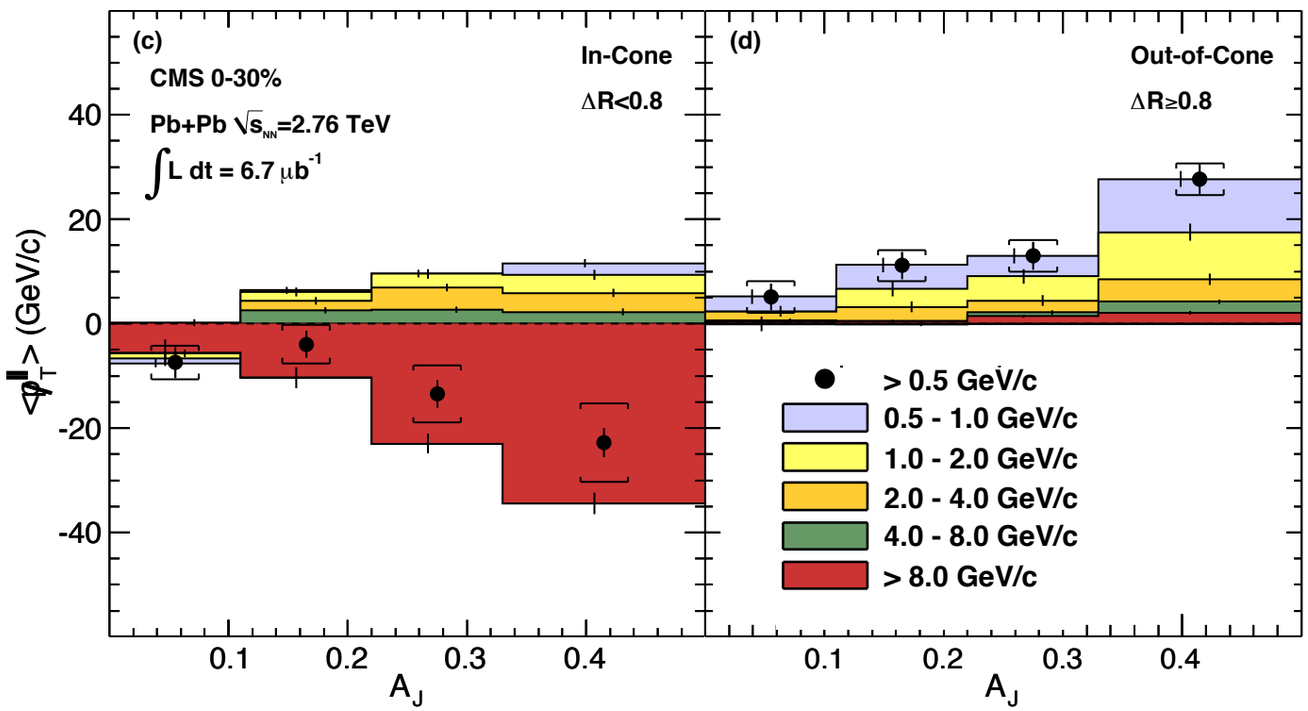
√s-dependence: LHC

PLB 719 (2013) 220



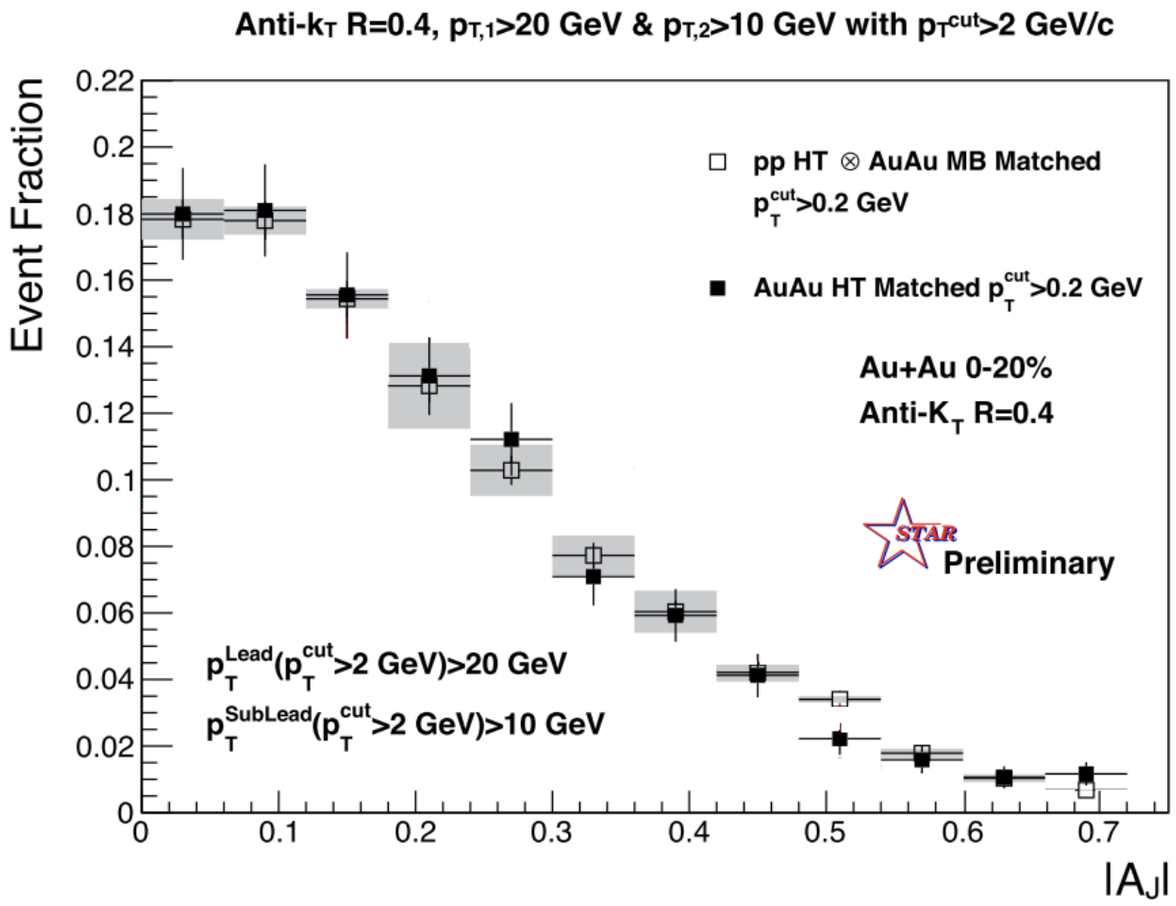
only modest cone size dependence

adapted from PRC 84 (2011) 024906

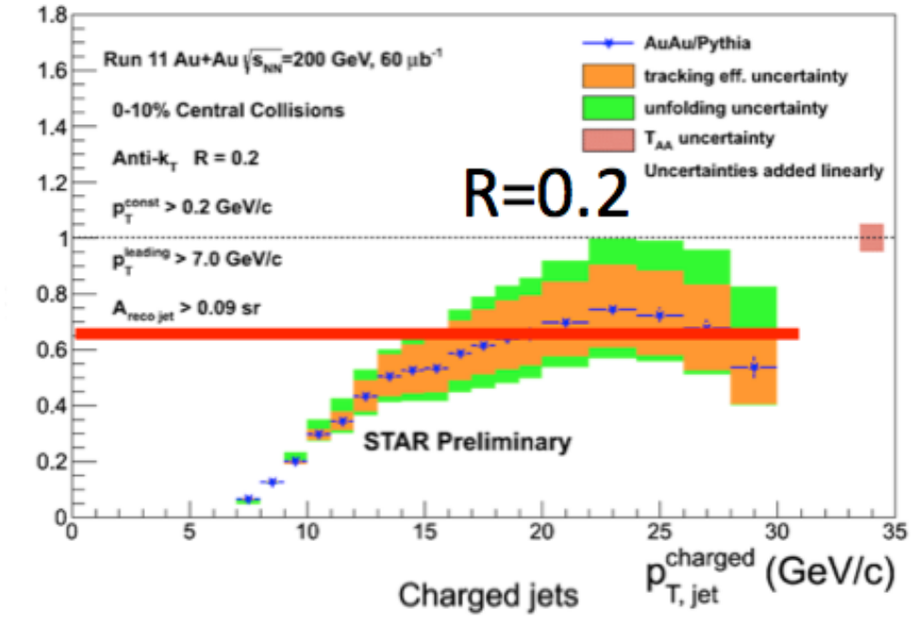


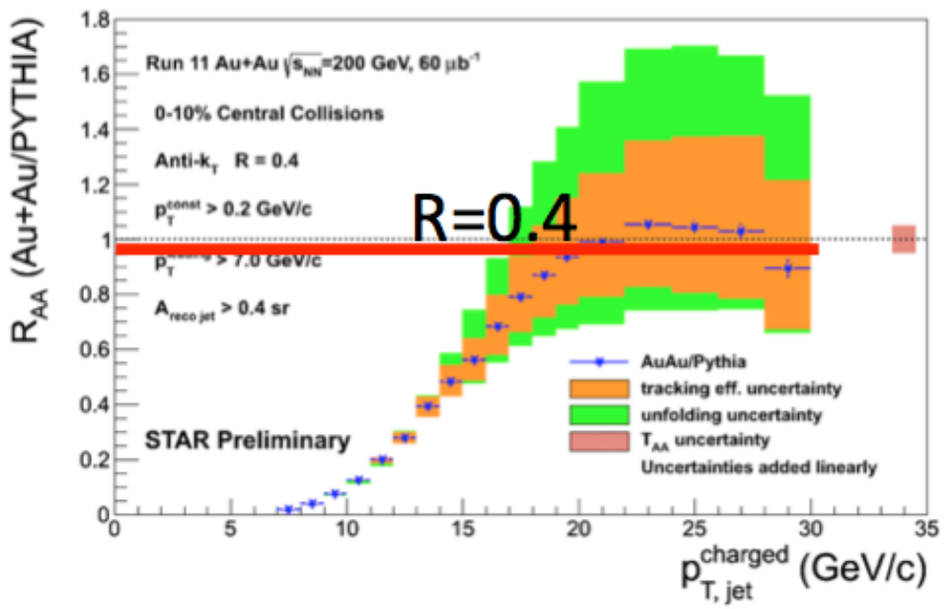
energy recovered only at large angles

√s-dependence: RHIC



Symmetric dijets recovered with low-p_T cut + large cone

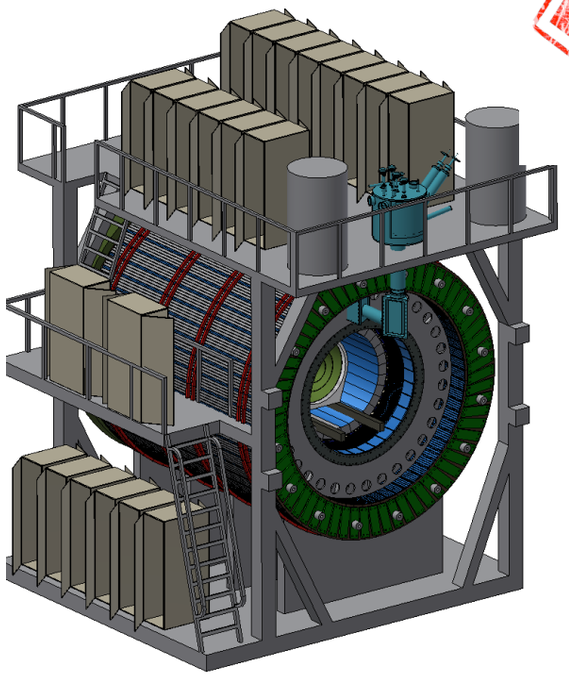


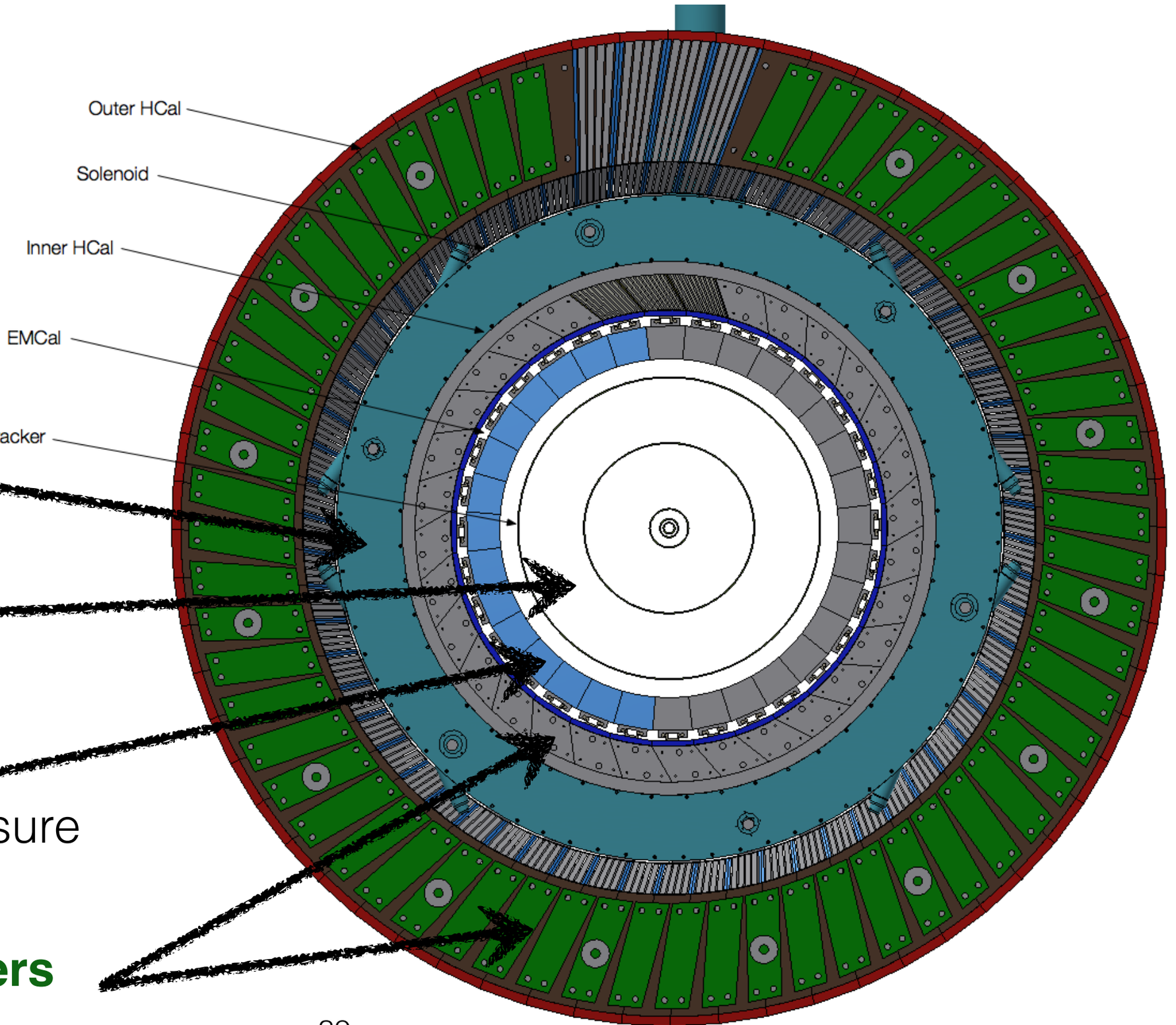


R_{AA} = 1 recovered by opening up the jet cone angle

➡ *strong <u>temperature dependence</u> of jet quenching?*

PHENIX Detector design





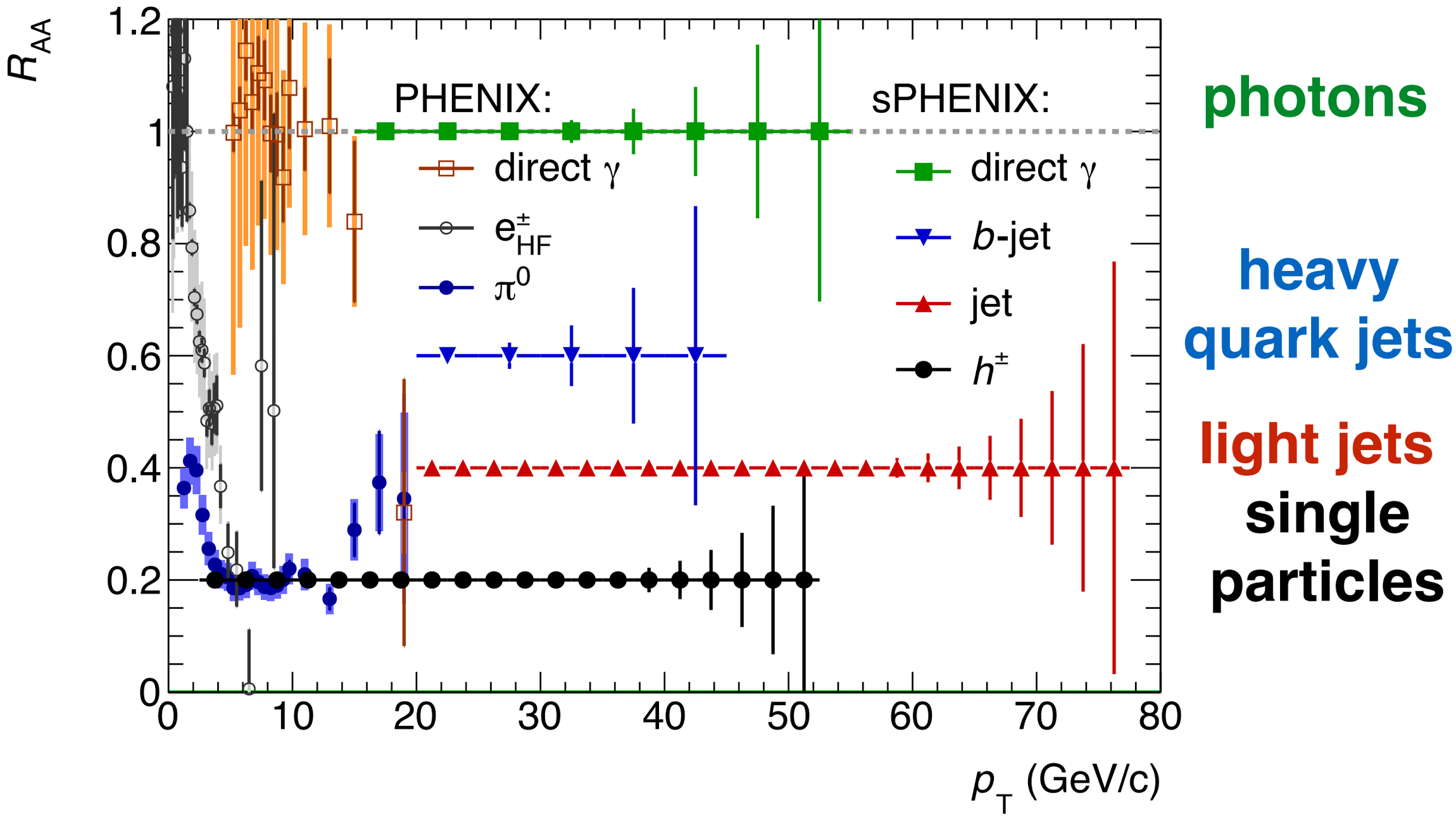
- 1.5 Tesla **magnet** from BaBar epxt.
- **silicon detectors** (to measure *charged particles)*
- **electromagnetic calorimeter** (to measure *photons* & *electrons)*
- **hadronic calorimeters** (to measure *jets*)

superconducting magnet leaving SLAC … arriving at BNL in 2015

Prototype of the **hadronic calorimeter**, undergoing beam tests in early 2014

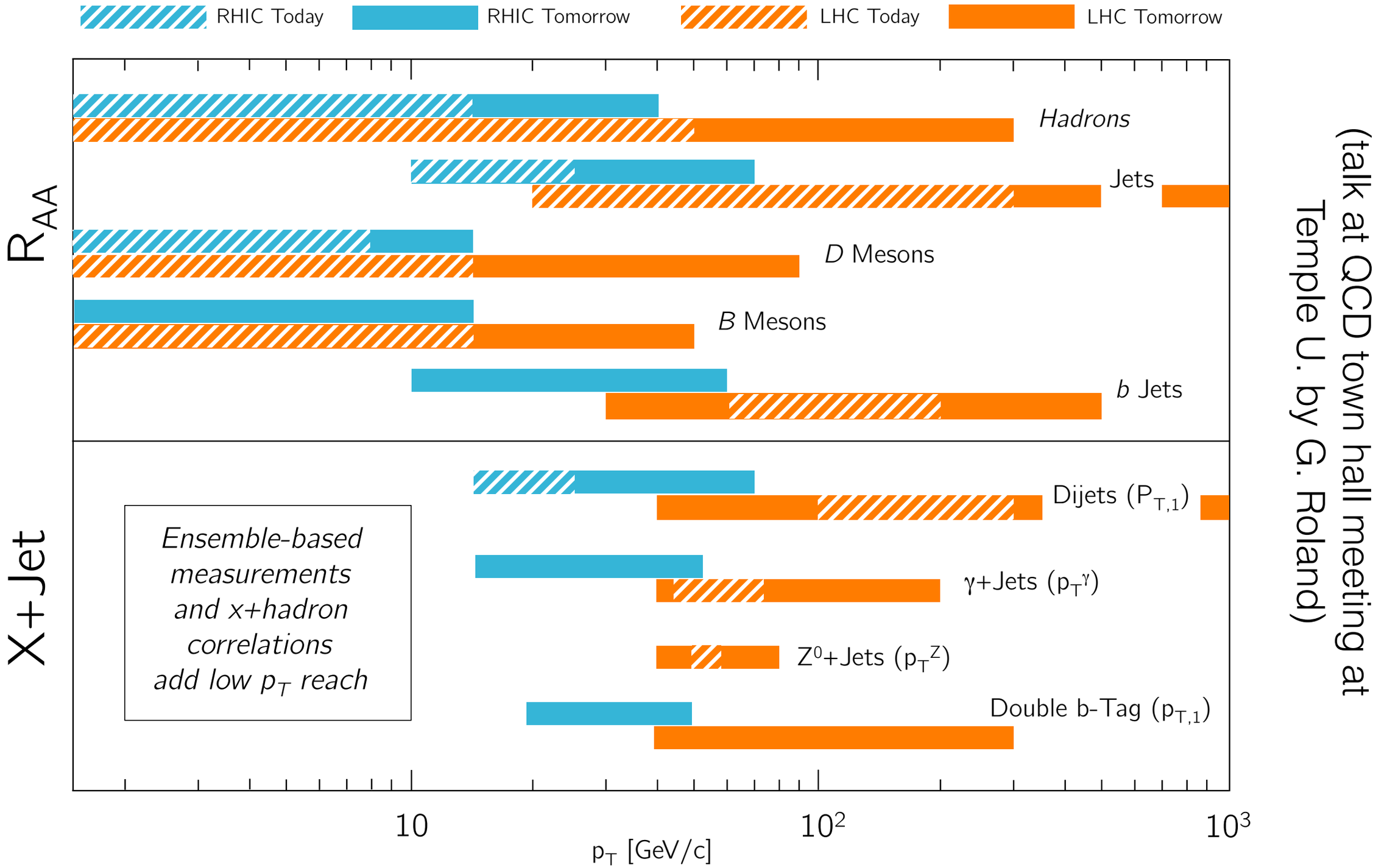
+ see J. Haggerty, QM15 talk

Jet tomography at RHIC



- Statistical projections after two years of sPHENIX running

Jet tomography in LHC Run 2



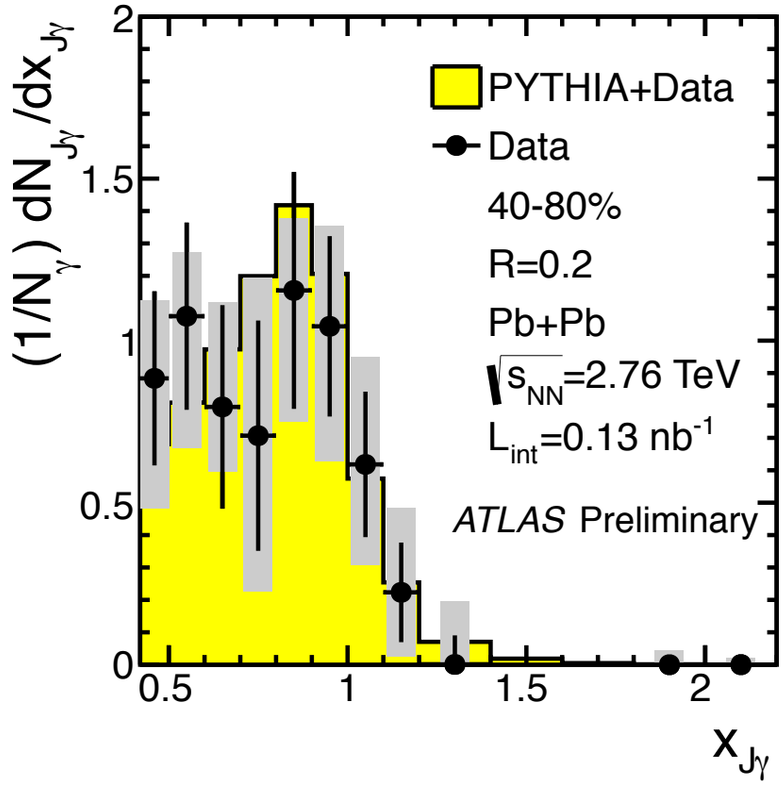
(talk at QCD town hall meeting at Temple U. by G. Roland)

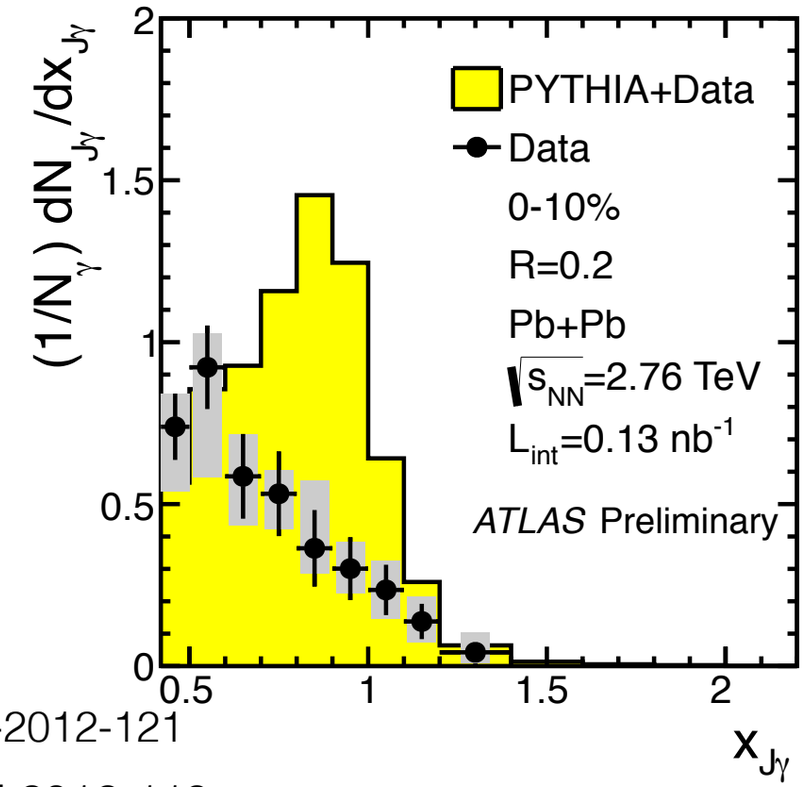
- Next month: 30x the hard probe rate in Run I
- Differential looks at Run I quantities + entirely new Run 2 observables

Peripheral

Central

γ-jet





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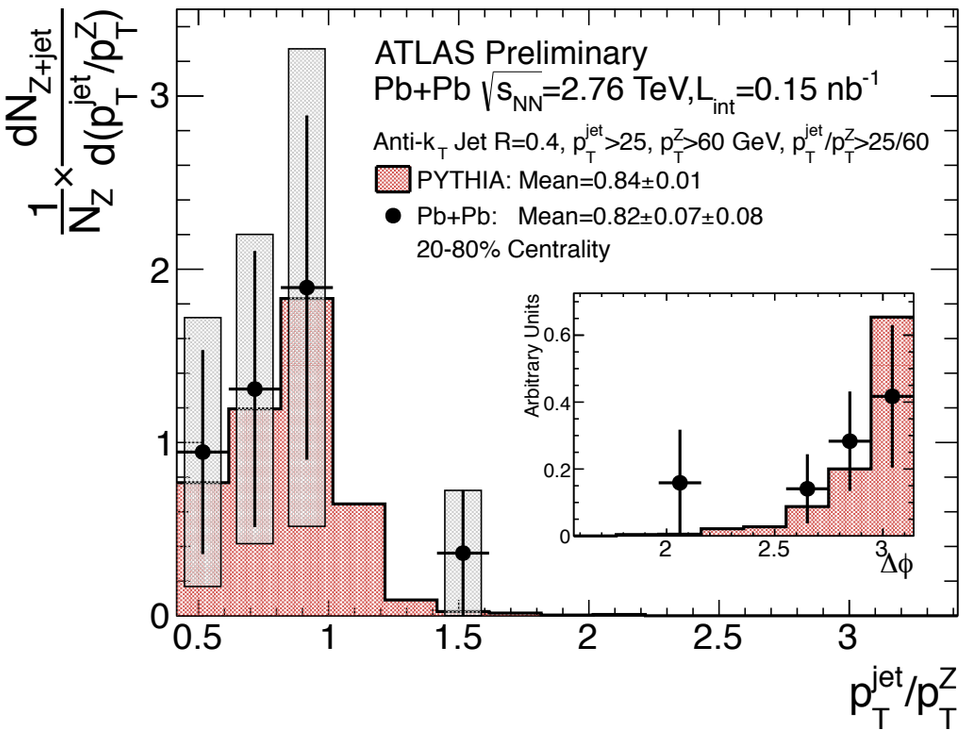
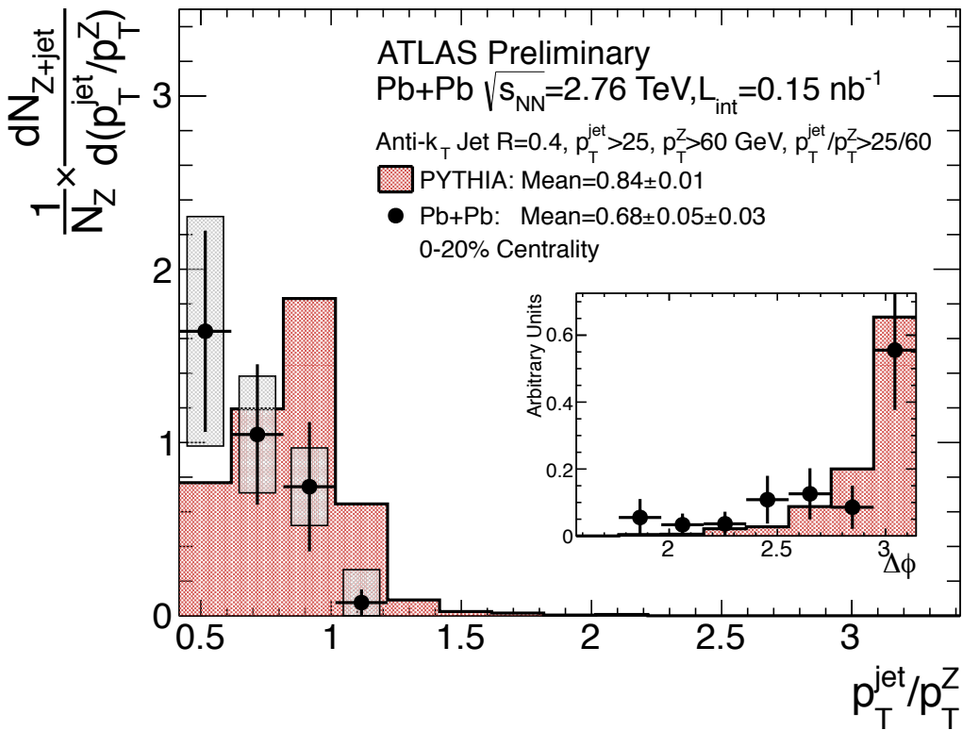
Z-jet





➡ No progress here… but wait until Run 2…

Outlook

- Many exciting developments in jet tomography:
  - ➡ jet-jet and multi-jet p_T correlations
  - ➡ differential probes of inclusive suppression
  - ➡ azimuthal dependence of jet yields and jet-jet balance
  - ➡ inventive probes of internal jet structure
  - ➡ progress in heavy flavor jet measurements
- Do we have a consistent picture of jet quenching?
- Looking forward to LHC Run 2 and future jet program at RHIC…