LHC Perspective

My Perspective

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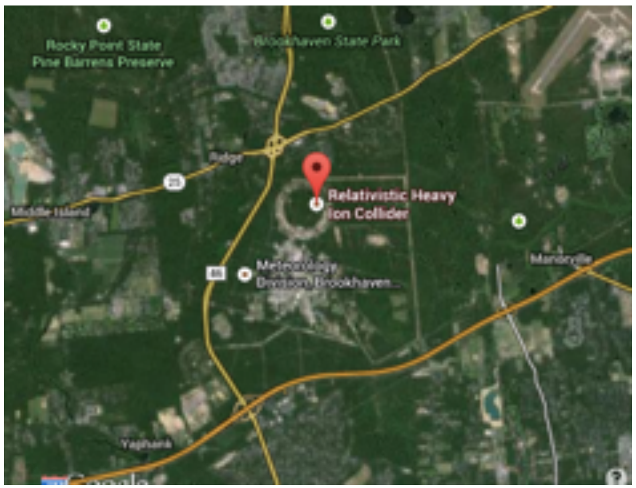
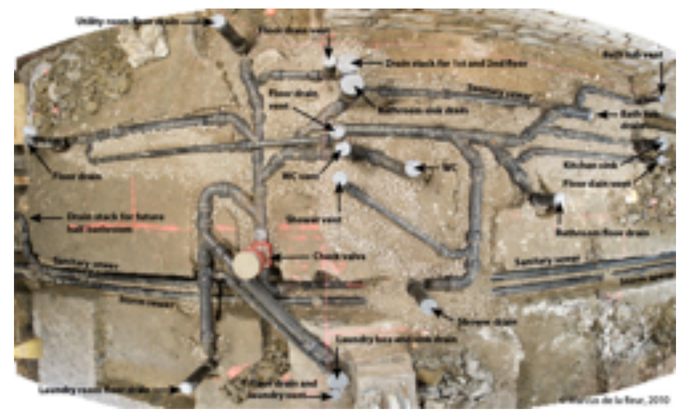
on current jet results at LHC, future LHC measurements and connections to jet physics at RHIC


Rocky Point State
Pine Barrens Preserve
Brookhaven State Park
Ridge
Middle Island
Relativistic Heavy
Ion Collider
Manorville
Yaphank



- Some basic considerations
- Results, Lessons, Future
  - Some prototypical LHC jet measurements
  - Technical/conceptual limitations
  - Future LHC plans (and some remarks on RHIC)
- Experiment/theory comparison

Some basic considerations

- Run 2 and 3+ energy/luminosity projections
- Recent technical developments and limits of event-by-event full jet reconstruction

Run 1 luminosities

year	system	$\sqrt{s_{NN}}$ (TeV)	L_{int}
2010	**Pb-Pb**	**2.76**	**~ 10 μb^{-1}**
2011	pp	2.76	~ 250 nb^{-1}
2011	**Pb-Pb**	**2.76**	**~ 150 μb^{-1}**
2013	p-Pb	5.02	~ 30 nb^{-1}
2013	pp	2.76	~ 5 pb^{-1}

Expectations for Run 2 ('15-'18)

- 2 PbPb runs @ 5 TeV
  - Lumi $5x10^{26}/cm^2s \rightarrow 5x10^{27}/cm^2s$ (0.15nb → 1-1.5/nb per run)
- 1 pPb run @ 9TeV

  10^9 events
  - Closer to rate limit: 30/nb → 100/nb
- pp reference running
  - Wide disparity in rate capability between ALICE vs ATLAS/CMS
  - run time determined by tolerance to pile-up

Expectations for Run 3+ ('20+)

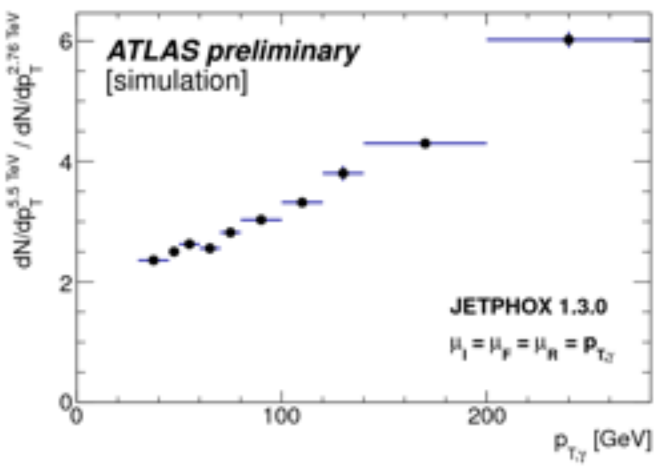
- Same collision energy as Run 2
- Total PbPb luminosity ~10/nb

Higher energy and luminosity increase jet statistics by factor of ~200 for Run 3

ATL-PHYS-PUB-2012-002
CMS PAS FTR-13-025

Run 3+

	2010–2011 2.76 TeV 160 μb^{-1}	HL-LHC 5.5 TeV 10 nb^{-1}
Jet p_T reach (GeV/c)	$\sim$ 300	$\sim$ 1000
Dijet ($p_{T,1} > 120$ GeV/c)	50k	$\sim$ 10M
b-jet ($p_T > 120$ GeV/c)	$\sim$ 500	$\sim$ 140k
Isolated γ ($p_T^\gamma > 60$ GeV/c)	$\sim$ 1.5k	$\sim$ 300k
Isolated γ ($p_T^\gamma > 120$ GeV/c)	–	$\sim$ 10k
W ($p_T^W > 50$ GeV/c)	$\sim$ 350	$\sim$ 70k
Z ($p_T^Z > 50$ GeV/c)	$\sim$ 35	$\sim$ 7k



For comparison:

First ATLAS jet paper used ~1600 dijet events

CMS γ+jet paper used ~1600 γ+jet events

Run 2: 1/5-1/3 of Run 3+

Jet reconstruction basics

- "Solved problem": Jet clustering using anti-k_T algorithm
  - Universally used in pp and AA collisions

- Correction of jet energy to particle level
- Subtraction of "underlying event" background
- Low-p_T limits of jet reconstruction

Jet reconstruction basics: Energy scale

- Correction of jet energy to particle level (CMS/ATLAS)
  - Multi-step procedure
  - Each step is **data-driven**
    - $Z \to ee$, dijet balance, γ-jet balance, 3-jet balance
  - HI uses same calibration/corrections as pp
- Quoted CMS/ATLAS uncertainties often similar/larger than MC-based uncertainties
- Significant challenge for RHIC jet program
  - pp statistics
  - “Particle-flow” vs calorimetric jet reconstruction

Jet reconstruction basics: UE subtraction

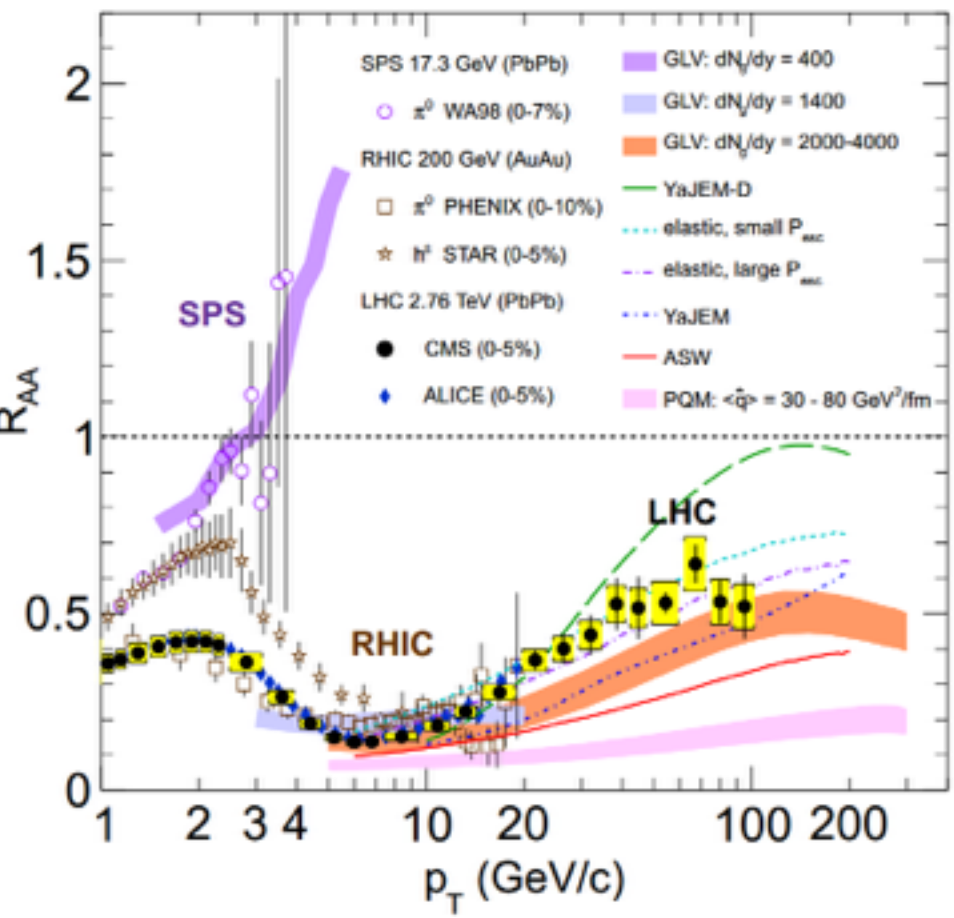
- HI Subtraction of non-jet-correlated in-cone energy
  - ATLAS/sPHENIX/STAR/ALICE
    - UE estimate based on ~local background
    - ATLAS/sPHENIX: include v_2 modulation
    - Correct final jet energy
  - CMS (old)
    - UE estimate based on local background (ϕ slice)
    - No ϕ modulation
    - Correct (pseudo-)tower energy before final clustering step
  - CMS (new)
    - UE estimate based on forward calorimeter energy
    - Include v_n modulation
    - Subtraction on jet constituents (PF candidates)

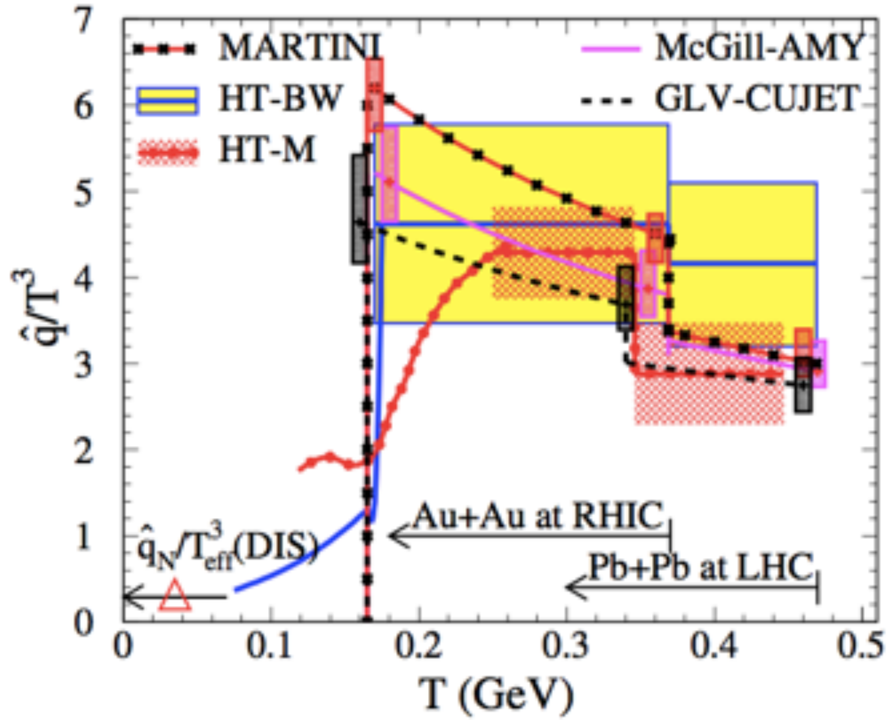
Jet reconstruction basics: Low-p_T limit

- Event-by-event (calorimetric) full-jet reco difficult at low-p_T
  - UE fluctuations
  - JES calibration
    - Calorimeter response
    - In-cone/out-of-cone transport
    - q/g differences
- Empirical observations for central PbPb@LHC
  - Tagged jets limit 25-30 GeV (dijets, γ-jets)
  - Single jet limit 40-50 GeV
  - Limits move ~ as sqrt(ρ) in PbPb
  - Factor 2 lower at RHIC?
- Transition to ensemble-based measurements at lower p_T
  - Background subtraction using side-bands, event-mixing, etc..

Results, Lessons, Future

- R_{AA}, dijet asymmetries
- γ-jet
- Jet structure and substructure
- Jet + medium

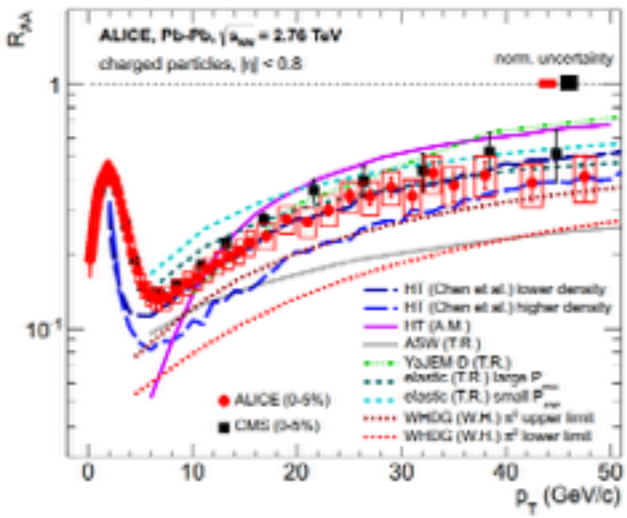


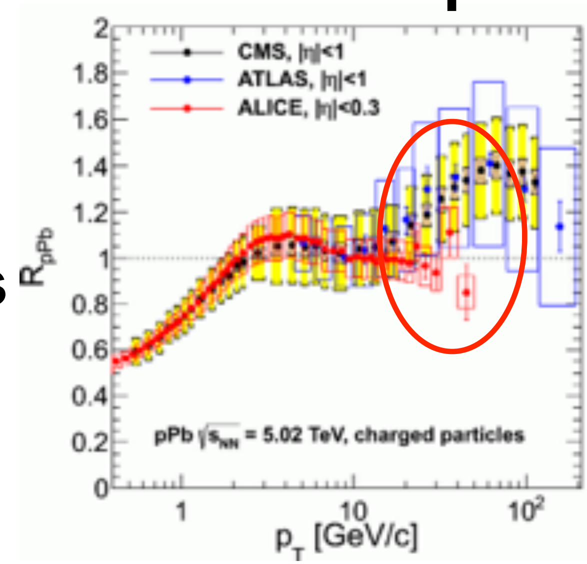


- JET collaboration extraction of qhat from hadron R_{AA} data
- Jet physics without jets?
  - Not quite: CMS high p_T R_{AA} impossible without jet trigger…
- Theoretical/experimental control?

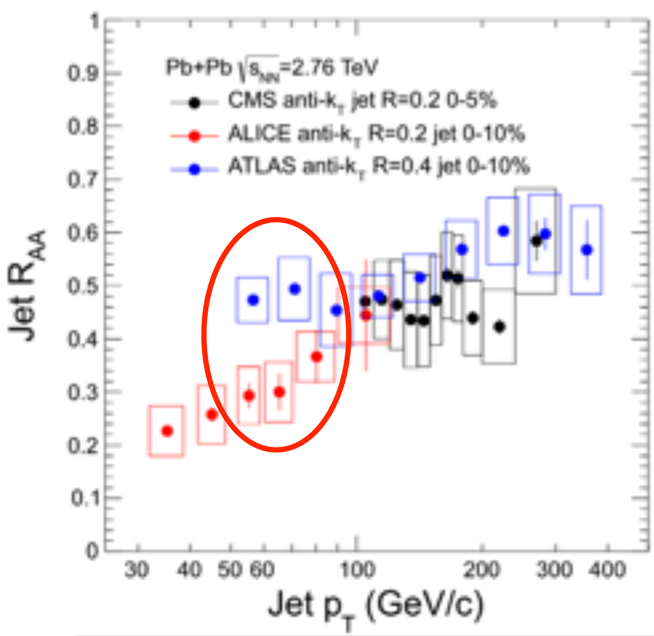
Experimental Challenges

PbPb **pPb**

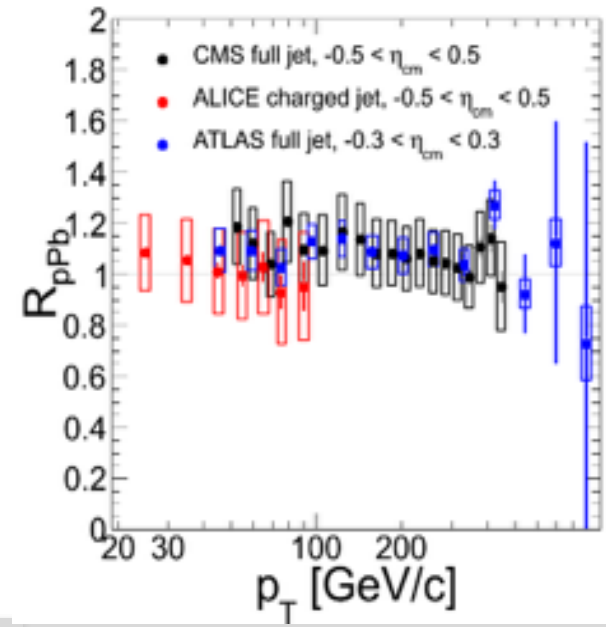


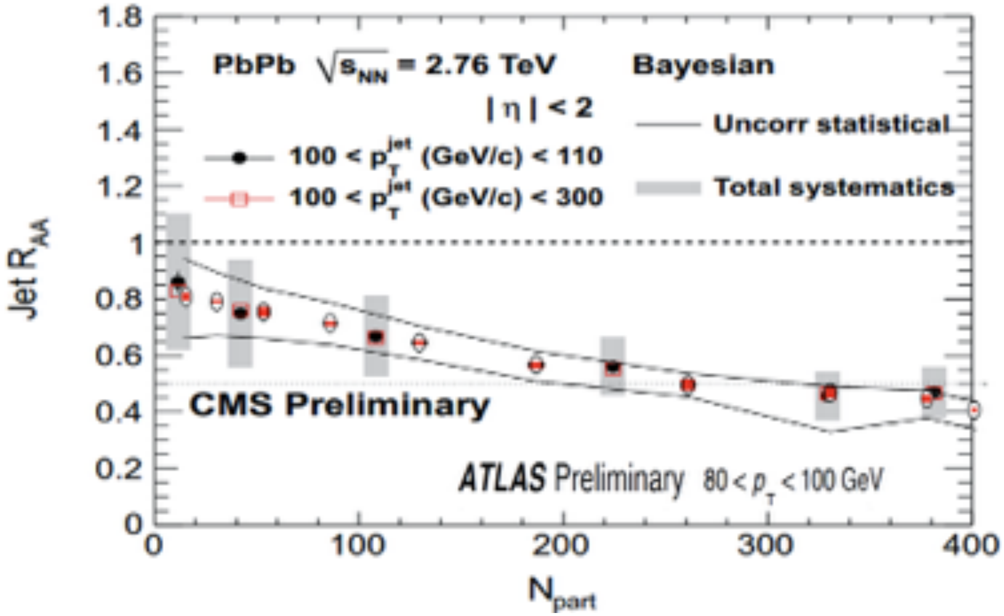


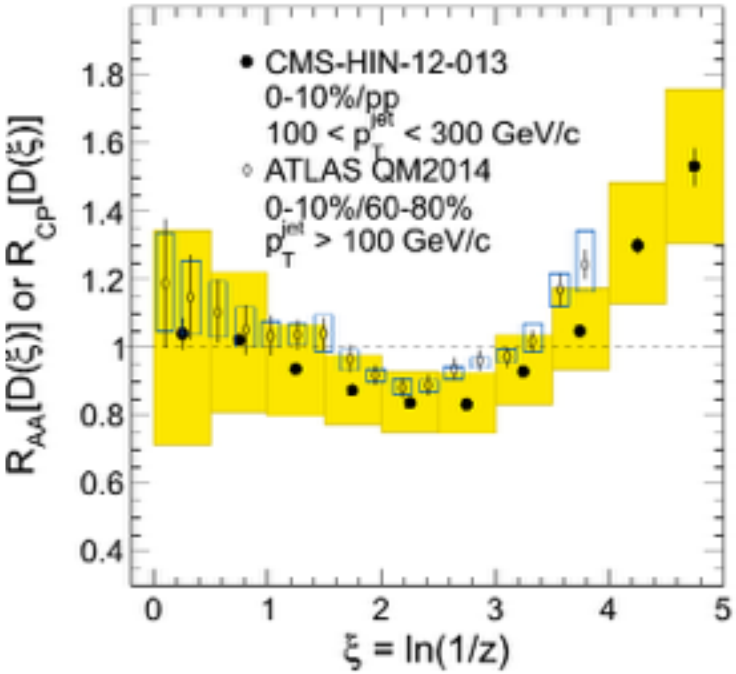
Charged particles



Jets



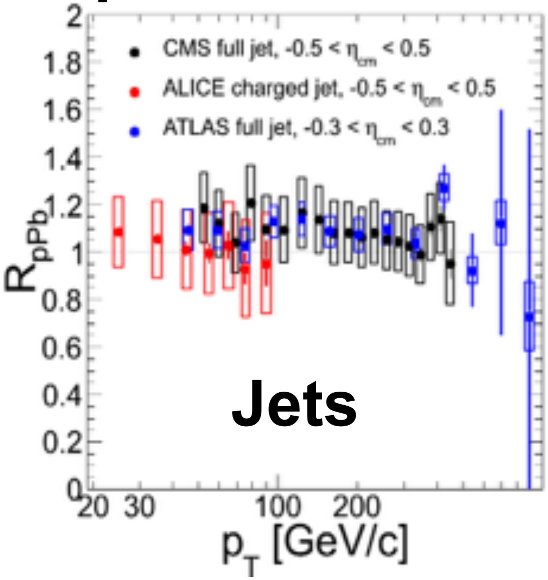


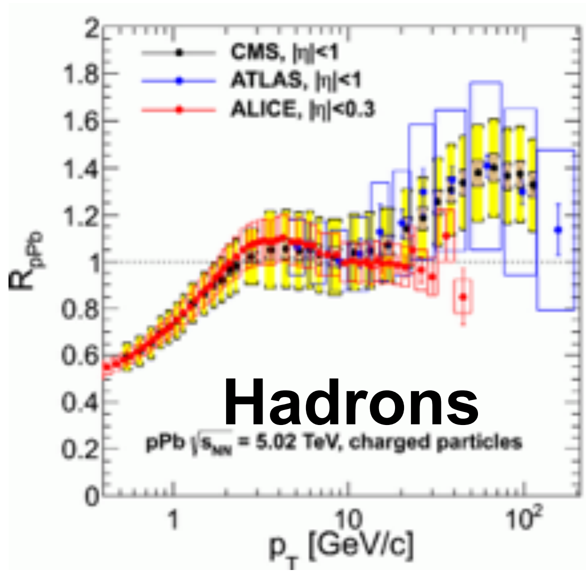


Generally, ATLAS/CMS excellent agreement at high p_T for jets

Theory Challenges

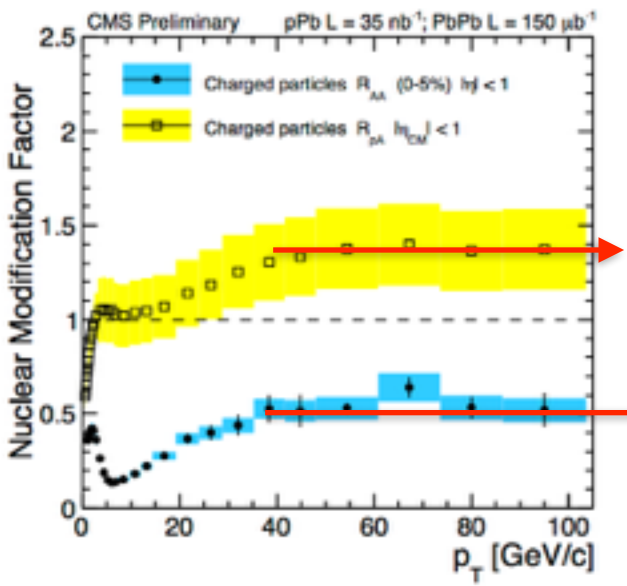
pPb

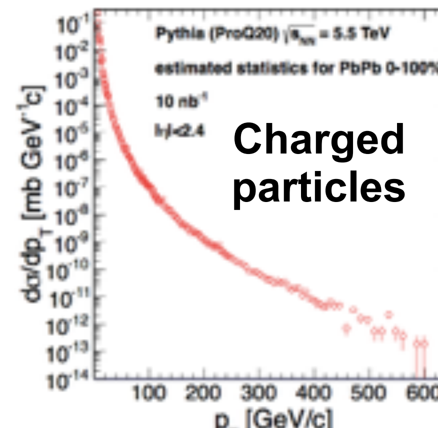




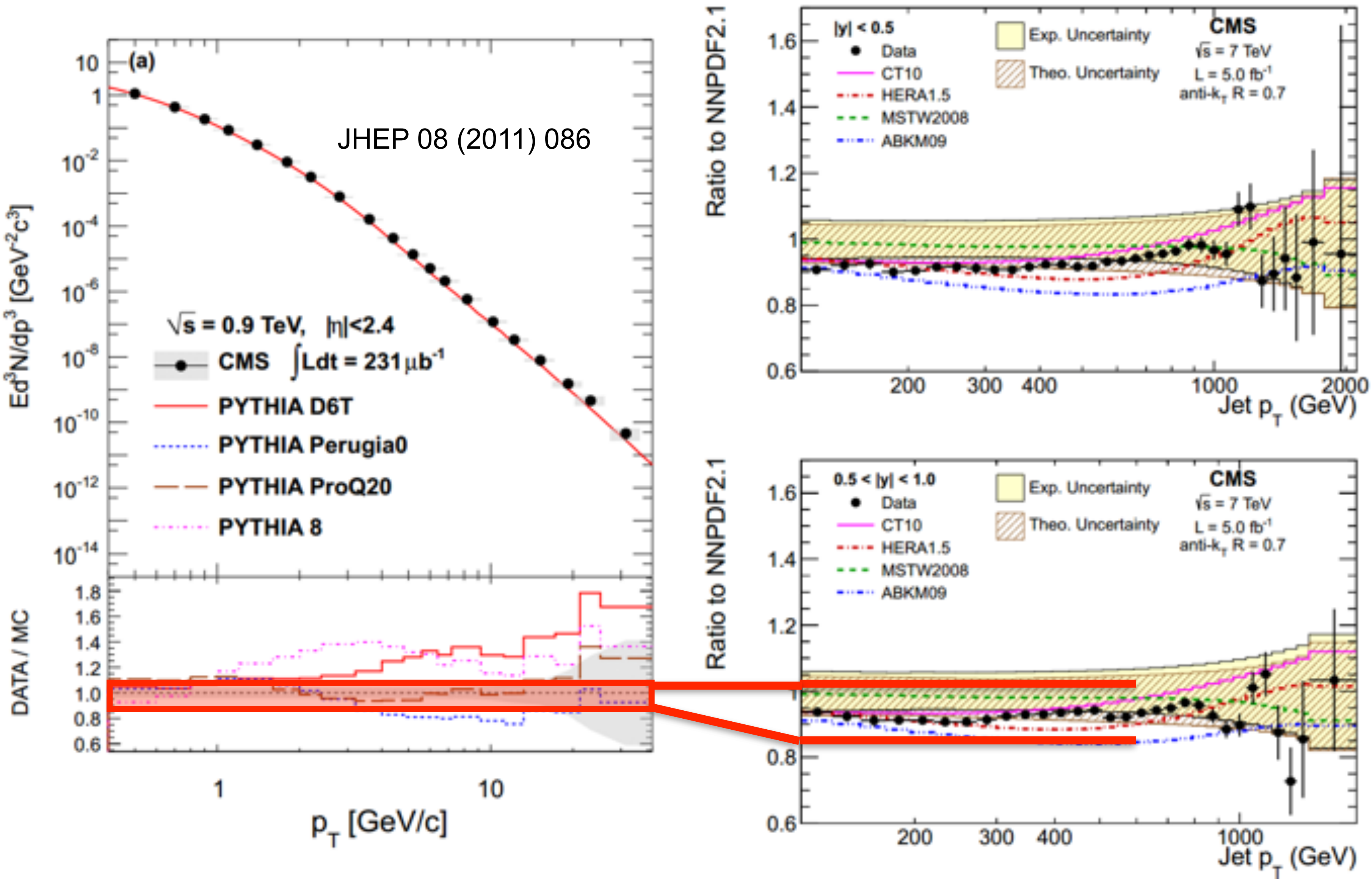
Modified jet fragmentation in pPb?

CMS Projection for Run 3+



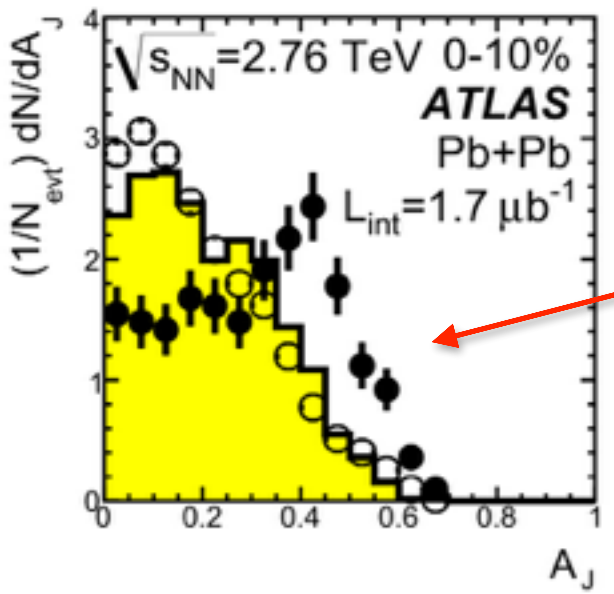


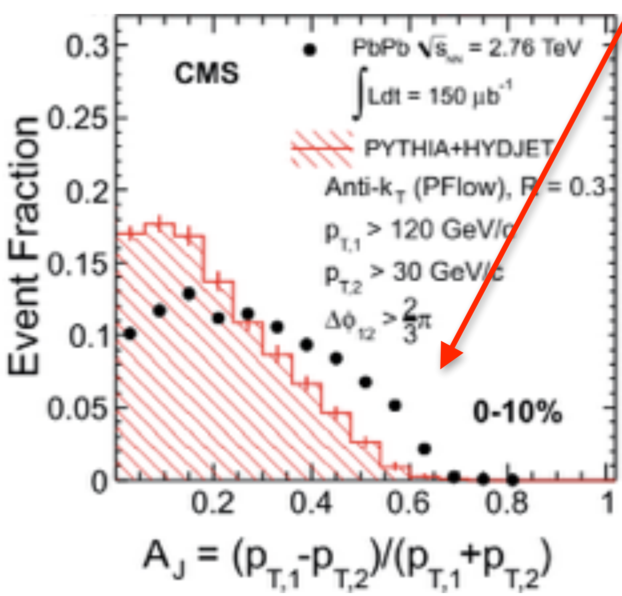
Natural explanation for flatness of charged particle RAA?

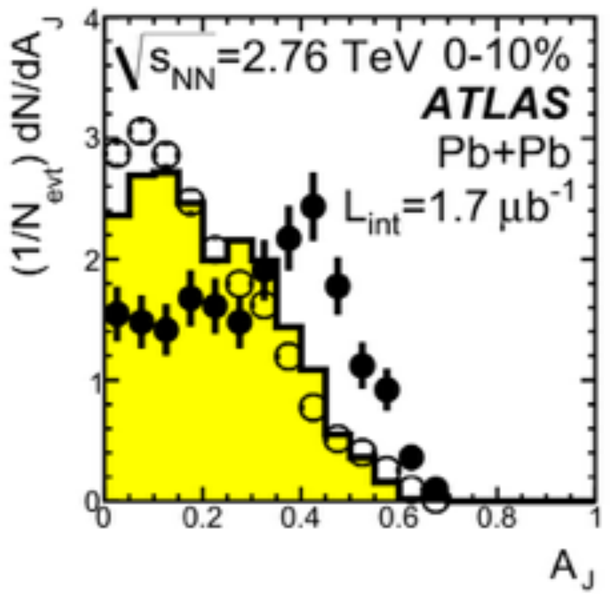


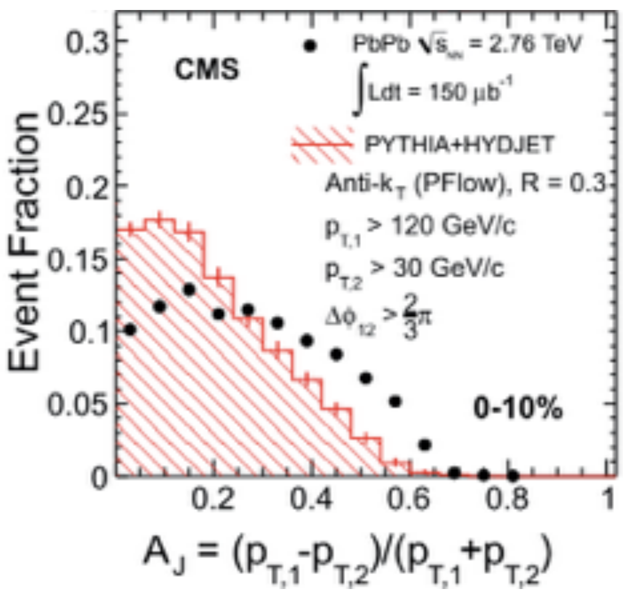
In pp, much better control over jet vs hadron spectra

Detailed understanding of A_J shape requires understanding of UE fluctuations, pp baseline, jet selection and jet resolution



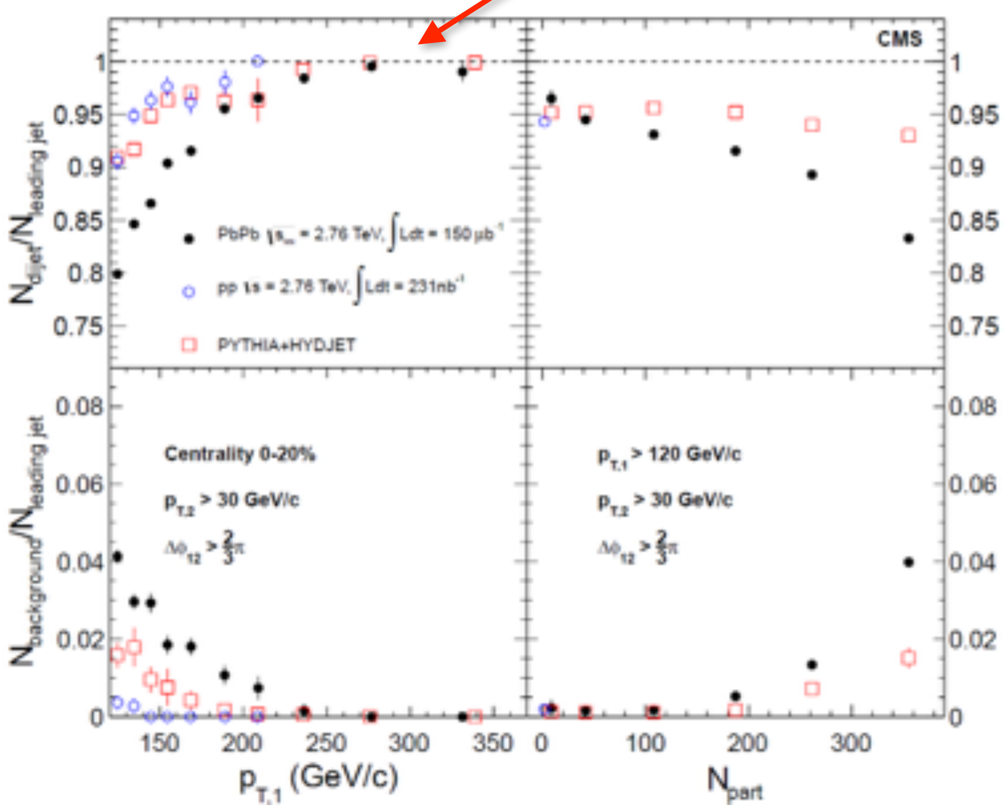


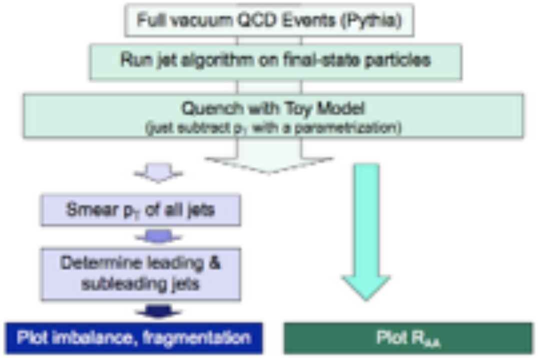




Additional information can be obtained from byproducts of the dijet analysis

(1-monojet rate)



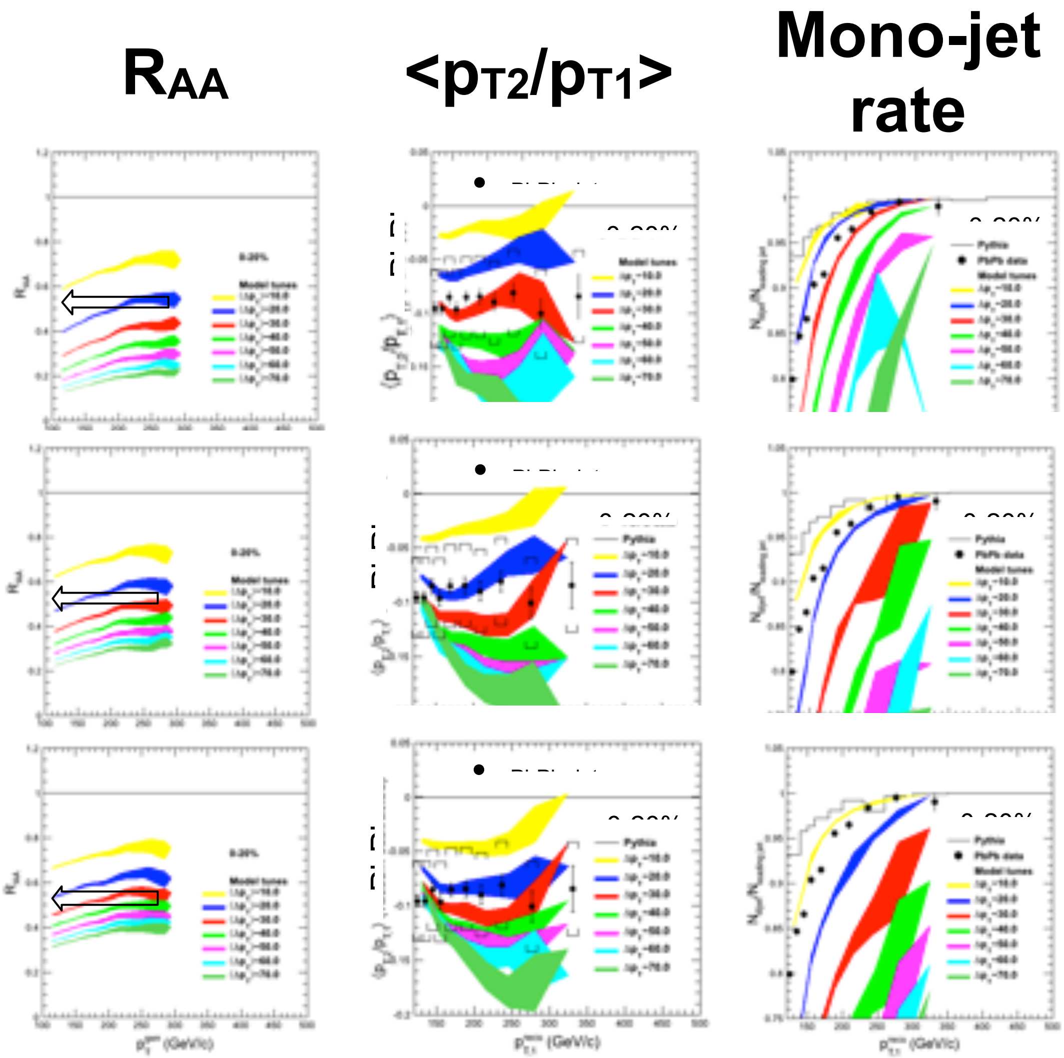


Toy model (Yetkin Yilmaz) based on Pythia

$\Delta p_T = f(p_T) \otimes g(L,\rho)$
using e.g.

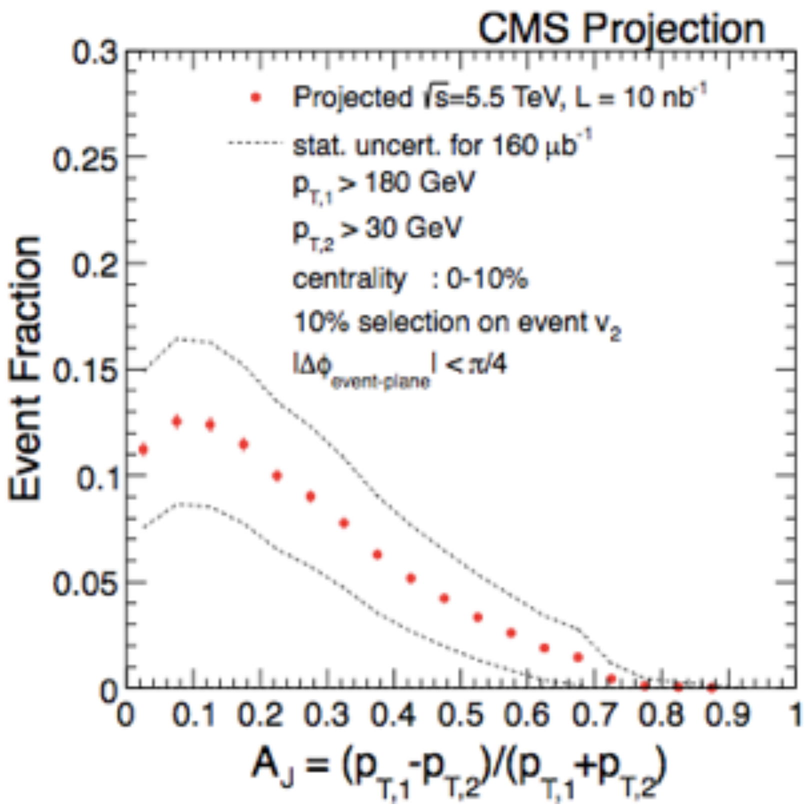
$f \propto$ const or $\log(p_T)$ or p_T and

$g \propto L$ or L^2 or L^3

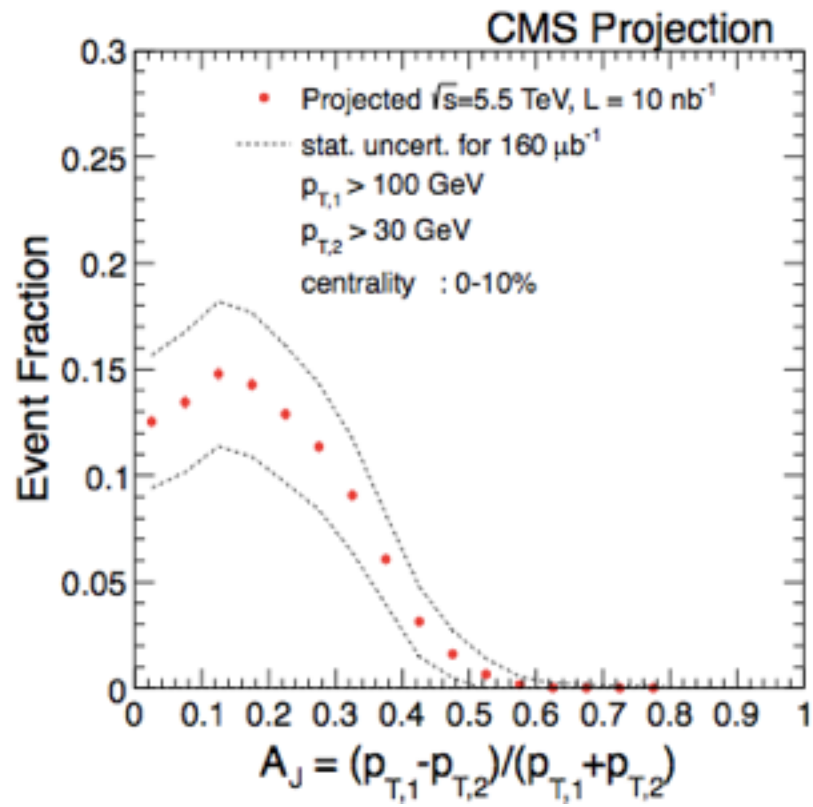


Combination of jet measurements provides constraints on parametric behavior of energy loss

New possibilities in Run 2 and 3

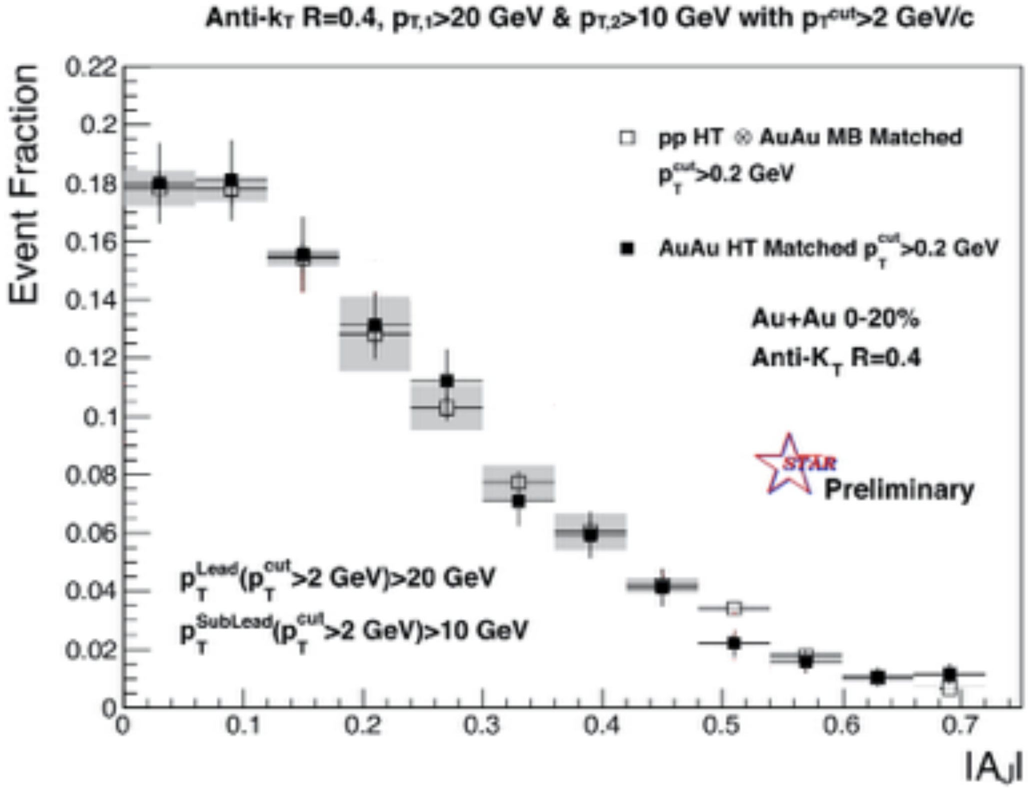


Dijets as a probe of initial geometry using event-shape engineering



Double b-tagged dijets

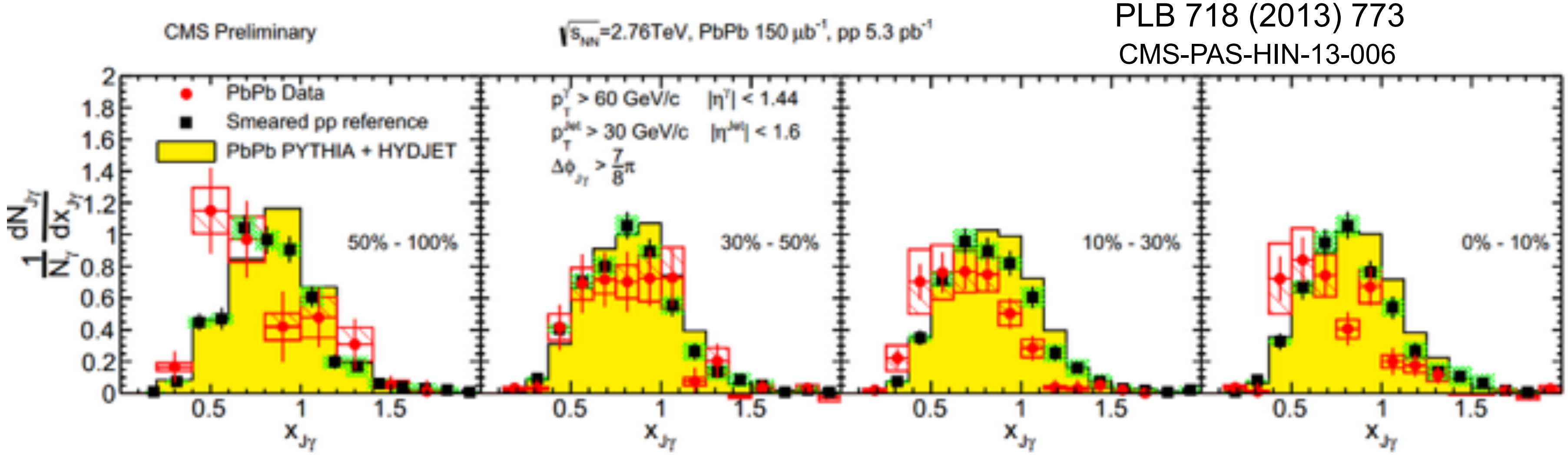
STAR QM'14



Dijet balance is recovered for R=0.4 jets when including low p_T particles

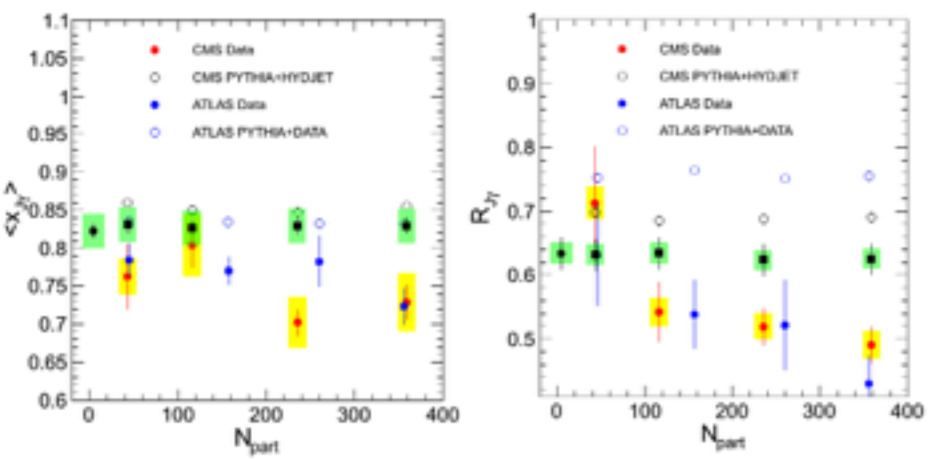
Compared to LHC:
Lower medium T and density, lower jet $p_{T,}$ different q/g mixture, explicit fragmentation bias (trigger/reco), stronger reconstruction biases

PLB 718 (2013) 773
CMS-PAS-HIN-13-006



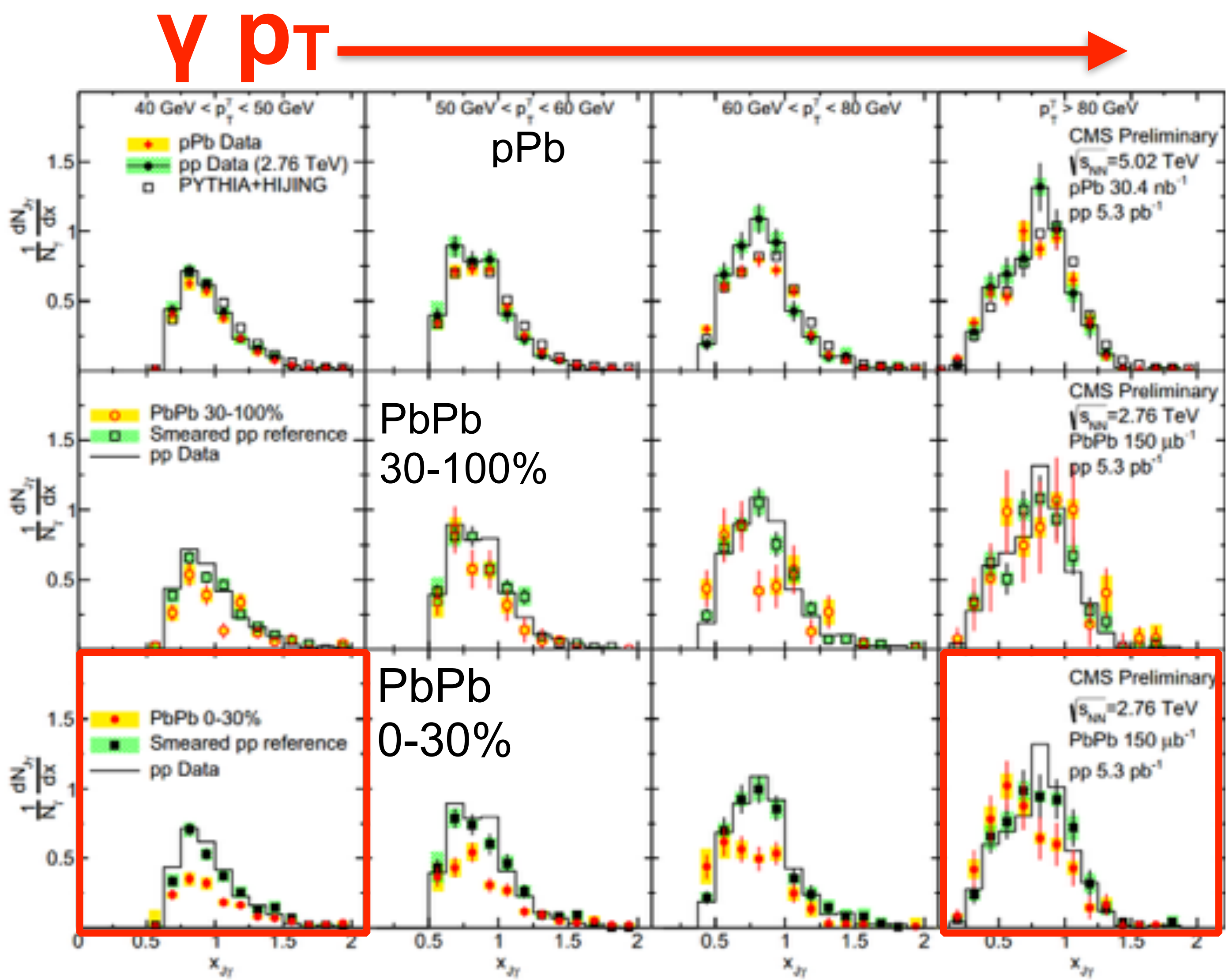
Isolated γ-jet correlations:

- γ tags initial jet energy, direction, flavor
- Reduced geometric (surface) and flow bias



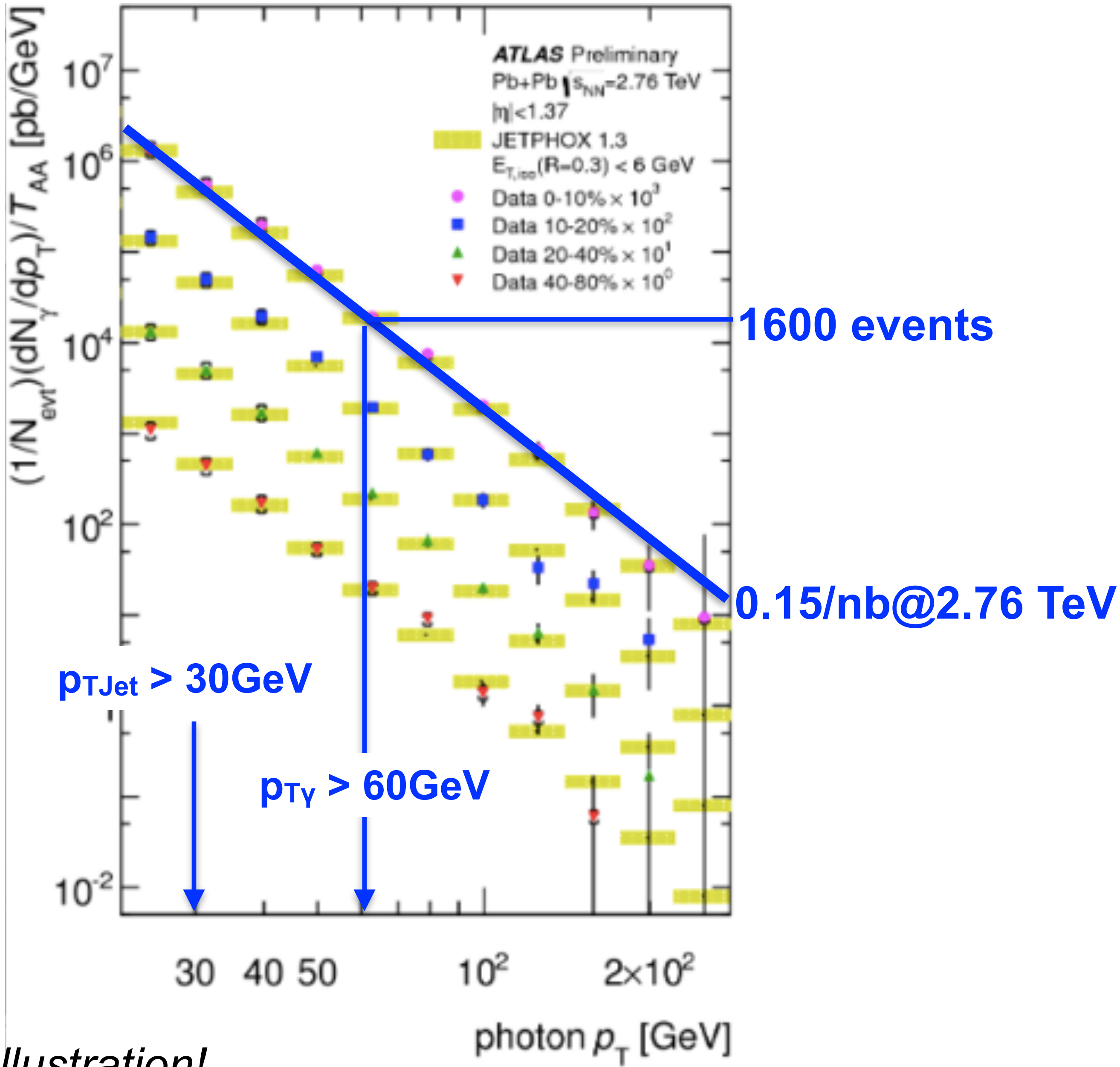
Semi-qualitative agreement between CMS and ATLAS

- Not the same measurement!

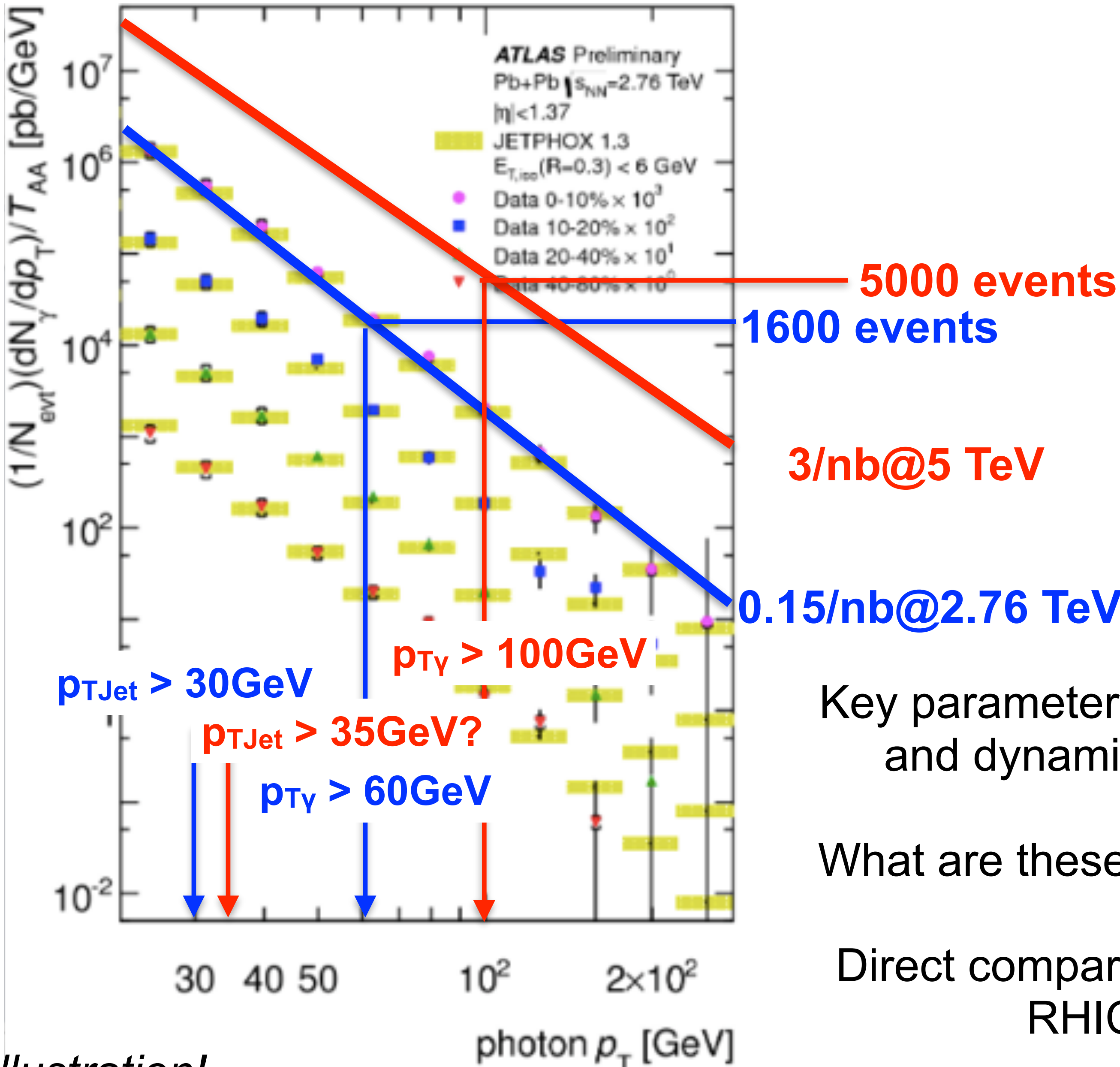


$p_{T,\gamma}$ <50 GeV: jets quenched below 30 GeV threshold

$p_{T,\gamma}$ <50 GeV: Jets shifted from high to low p_T



Illustration!



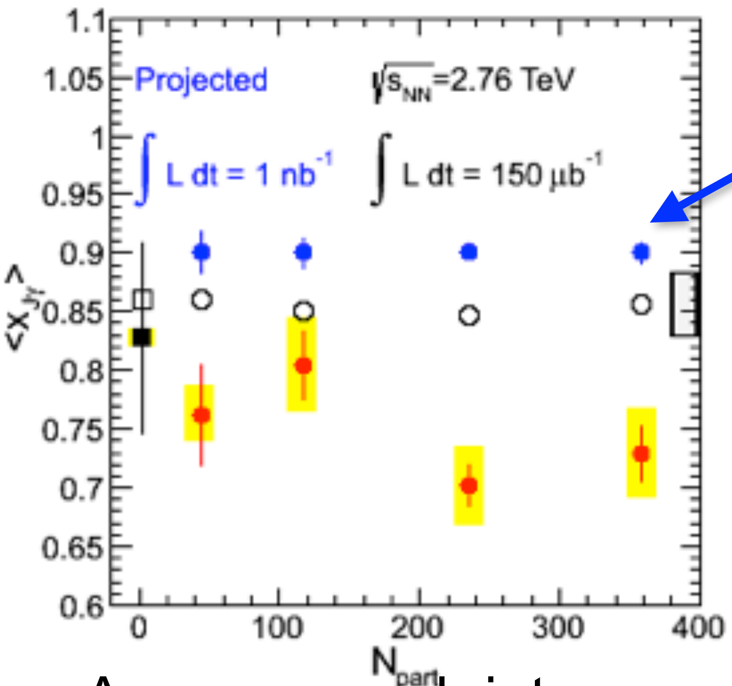
Illustration!

Key parameters are event statistics and dynamic range ("1/bias")

What are these numbers for RHIC?

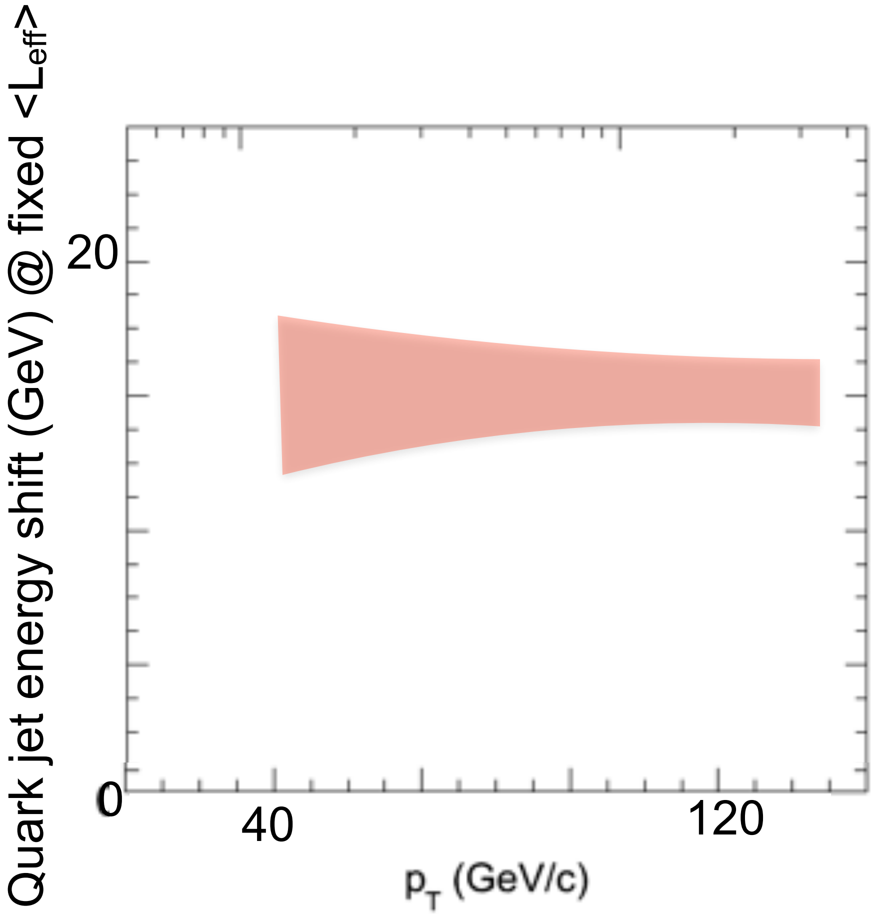
Direct comparison of quark jet ΔE RHIC vs LHC?

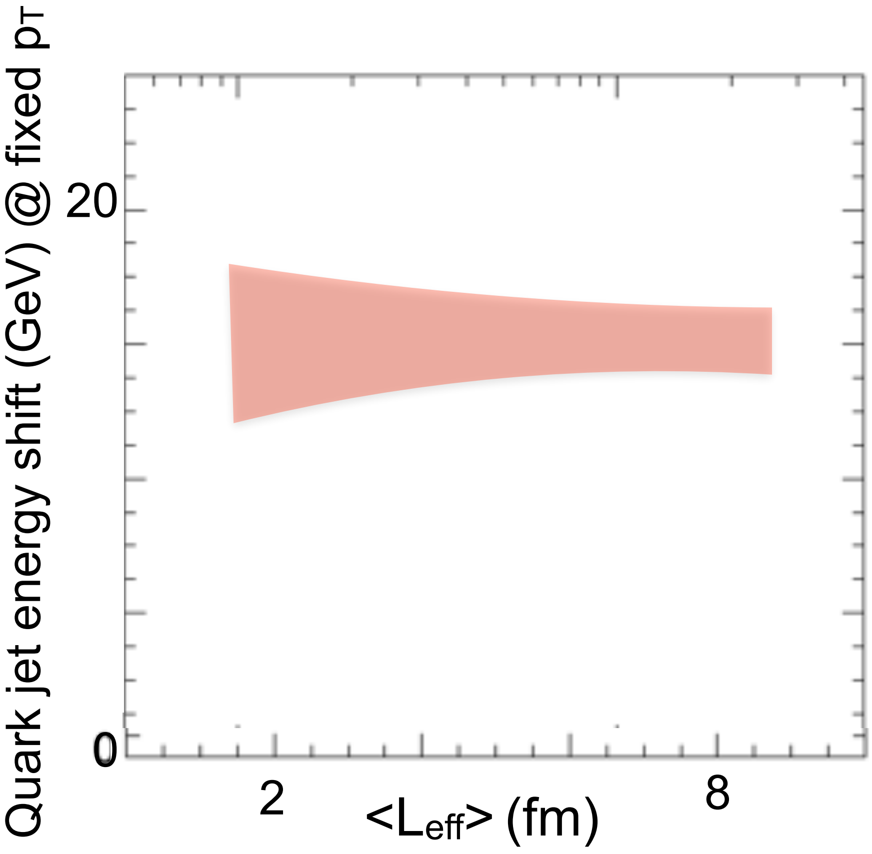
Precision jet physics using γ+jet in Run 2



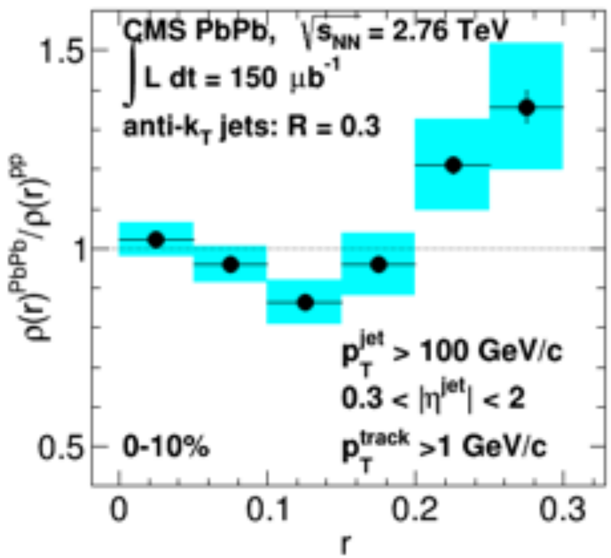
γ-jet in Run 2 projection (CMS)
Negligible statistical uncertainties for mid-peripheral to central events

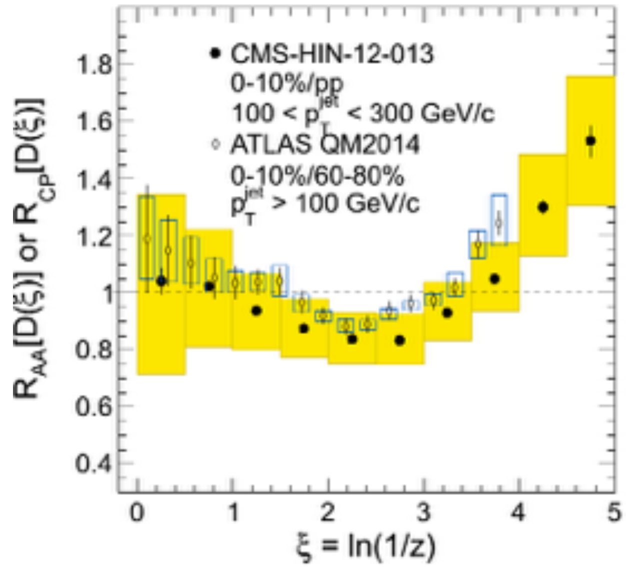
- Average quark-jet energy shift as a function of path length (**unbiased** at high photon p_T)
- Event-by-event measurement of jet energy loss
- Jet-hadron correlations (no flow bias of jet direction)
  - jet shapes, jet substructure, "missing p_T"
- Fragmentation functions wrt initial parton energy, without q/g uncertainty

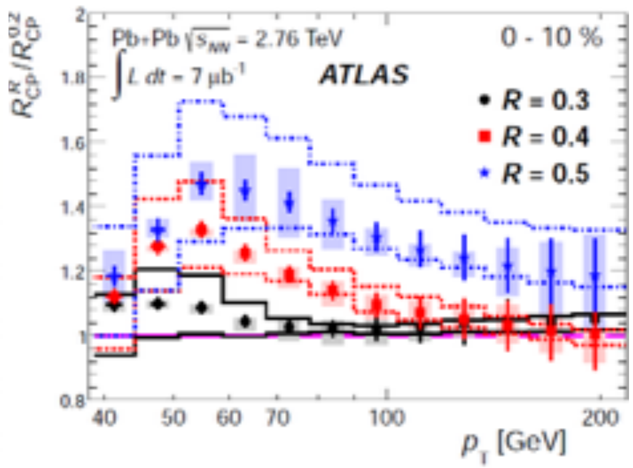


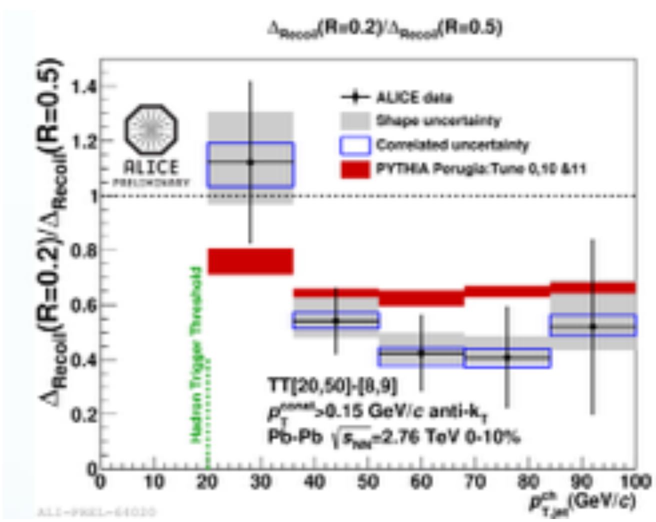


If experiment provides measurements like the cartoon above, will this improve determination of e.g. qhat?









Many studies of the in-cone modification of energy distribution relative to jet axis

Generally, broadening and softening of fragment distribution is seen

Redistributed energy is O(few GeV) compared to total “energy loss” of O(10GeV)

Future direction: Jet (sub-)structure

Major effort in LHC pp physics

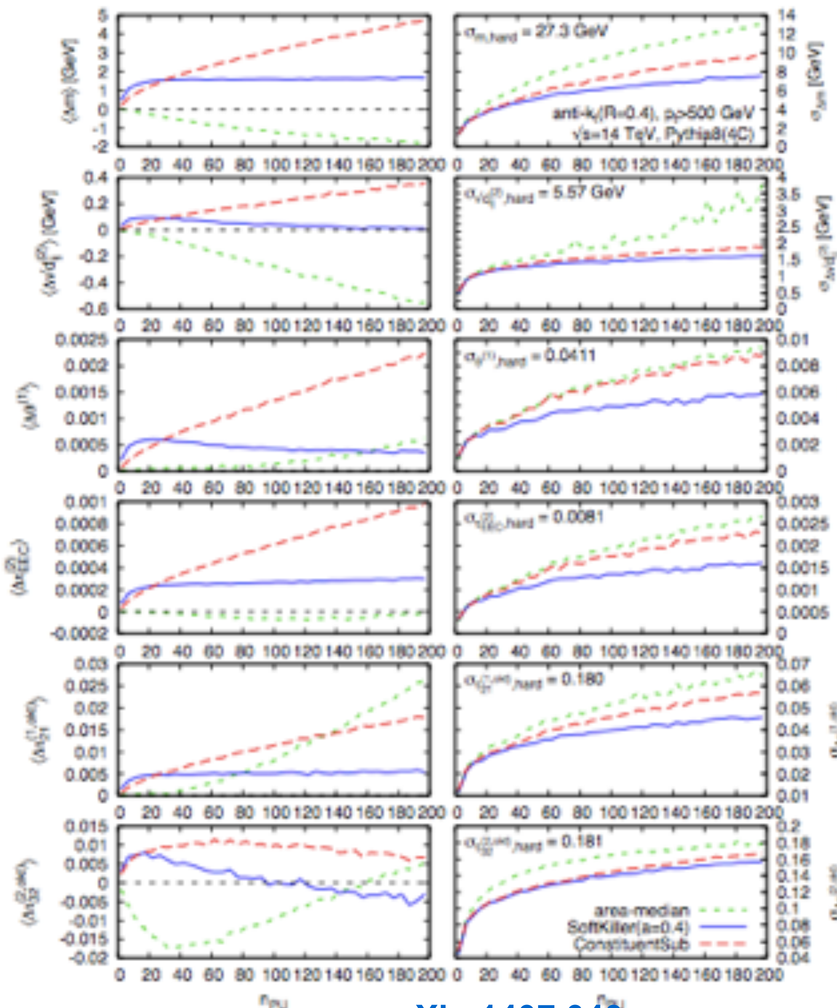
Key ingredient for precision physics using jet observables: q/g discrimination, boosted objects vs dijets

Key issue is **robustness vs pileup**

Jet shapes, jet mass, jet constituent correlations, N-subjettiness,…..

Obtain more detailed information on jet structure modification in HI collisions

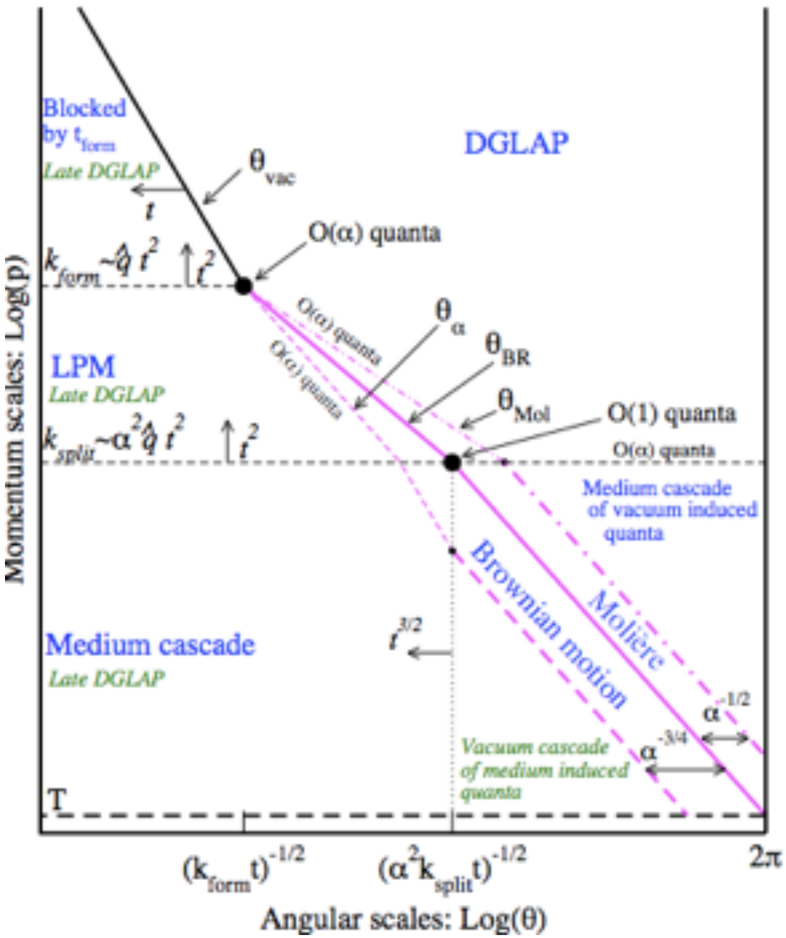
- Jet-by-jet observables
- Direct view of modified branching process?



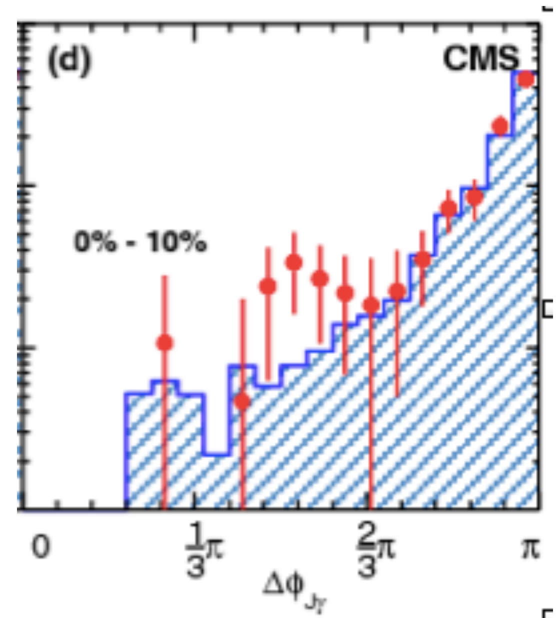
arXiv:1407.040

Cacciari, Salam, Soyez

Future direction: QGP Rutherford (Moliere?) scattering

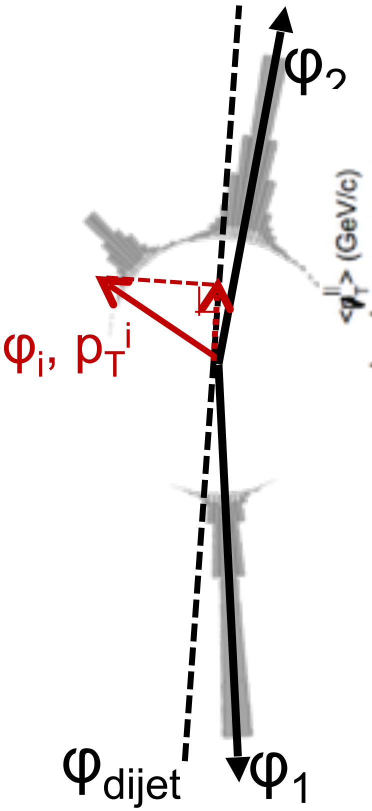


Kurkela, Wiedemann, arXiv:1407.0293

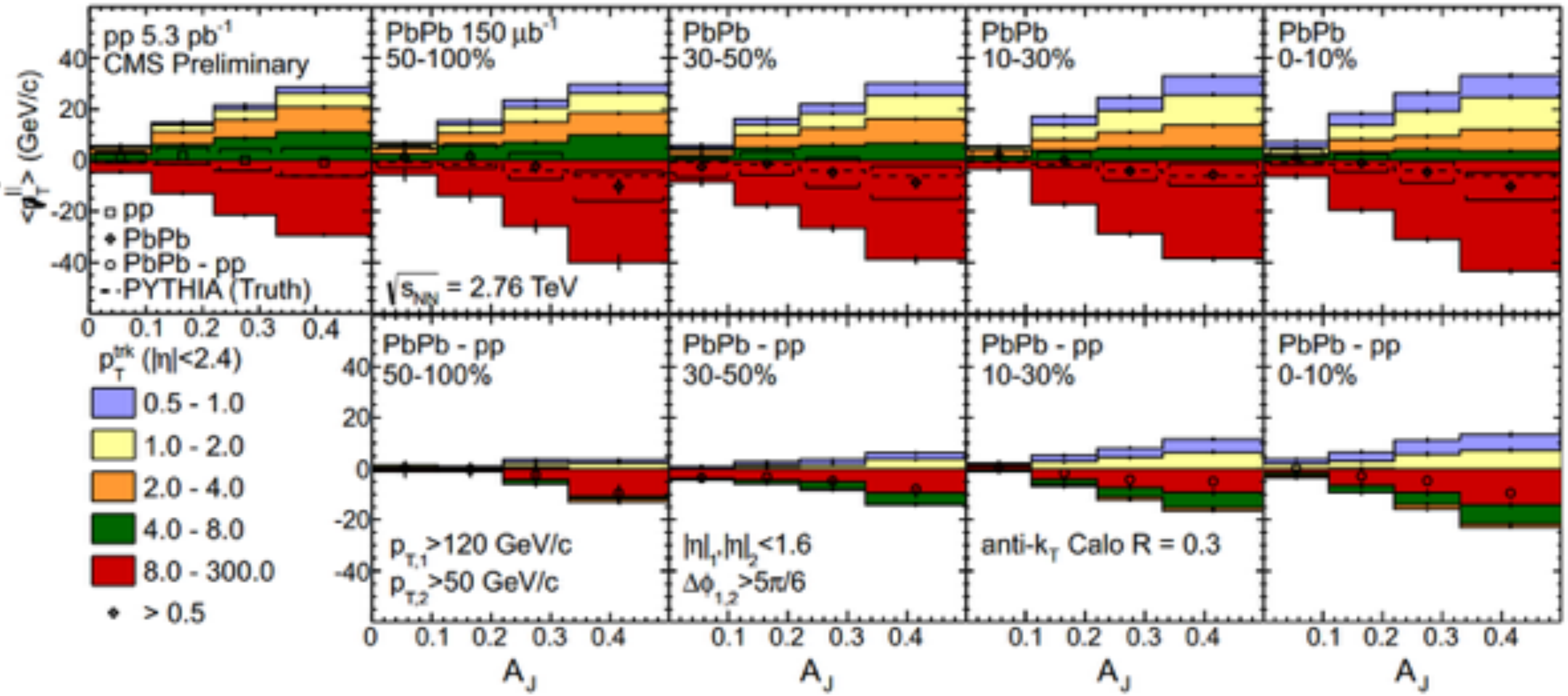


Probe short-length scale nature of the medium/quasiparticle nature (Rajagopal)

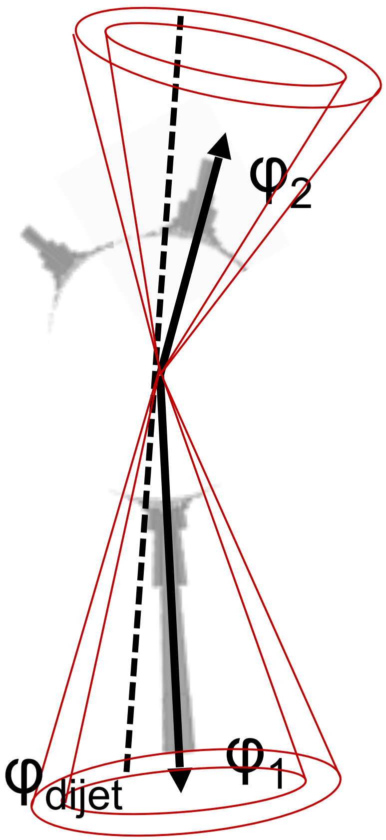
Where does the "lost" energy go?



CMS-PAS-HIN-14-010

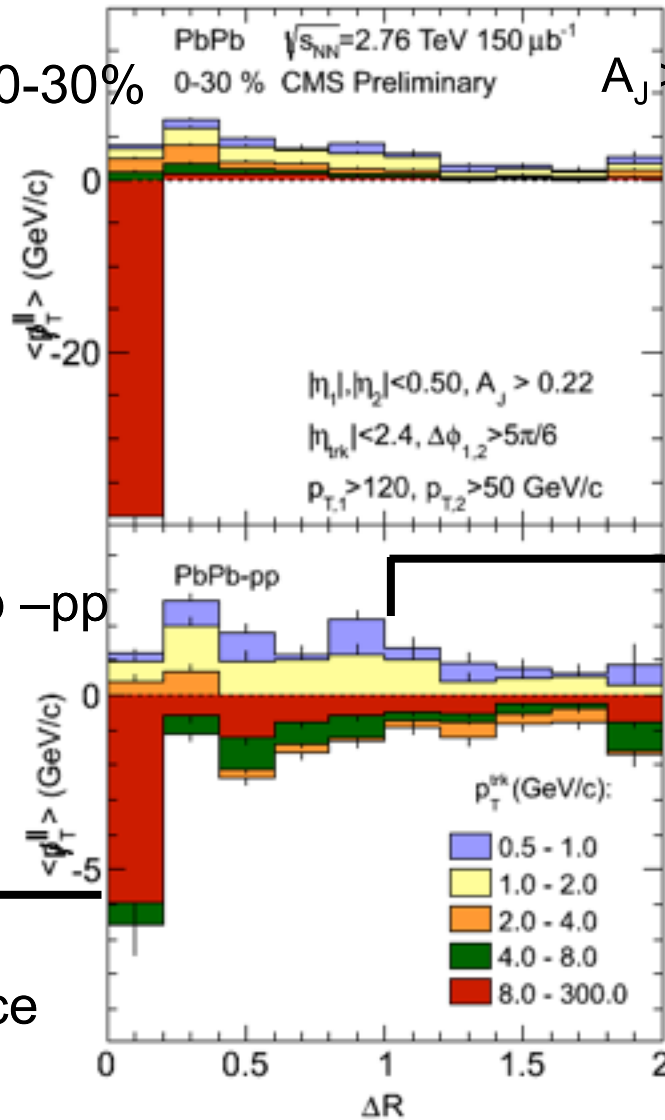


Energy difference between leading and sub-leading jet is recovered at low p_T



PbPb 0-30%

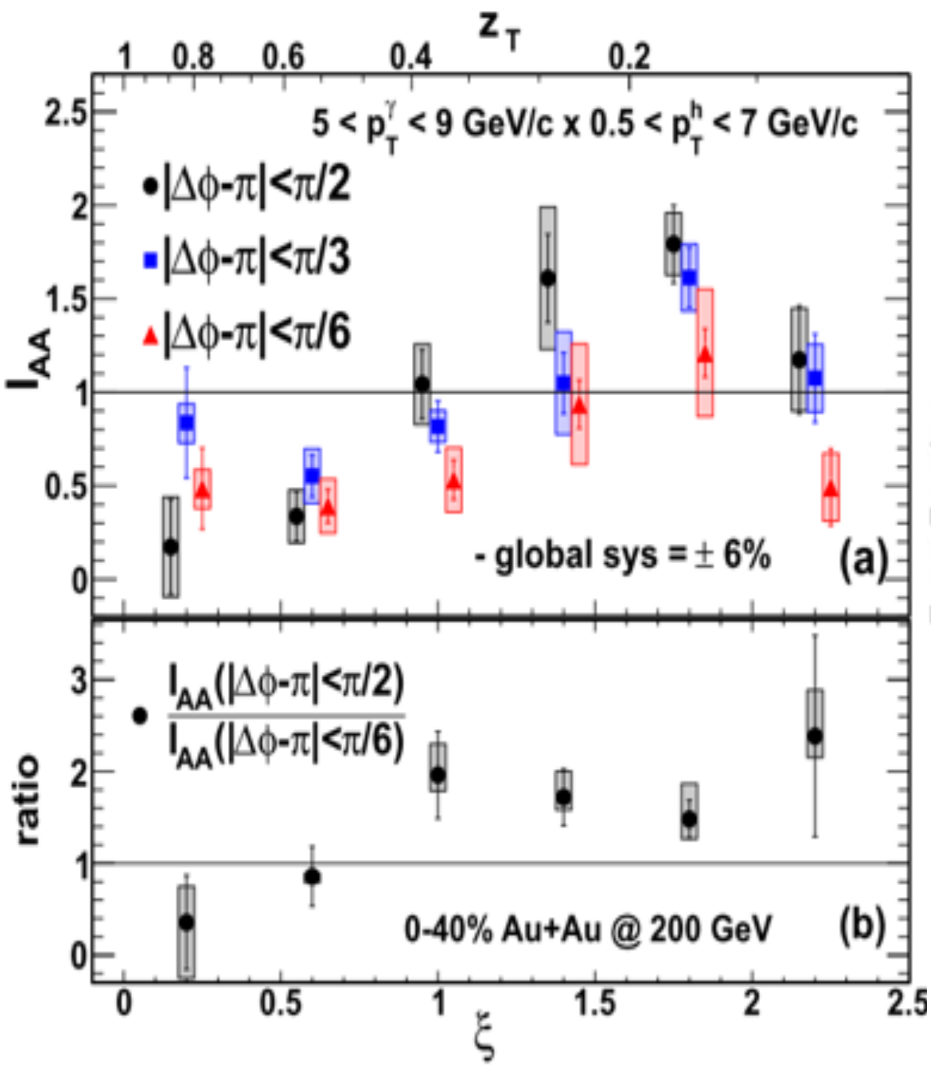
$A_J > 0.22$

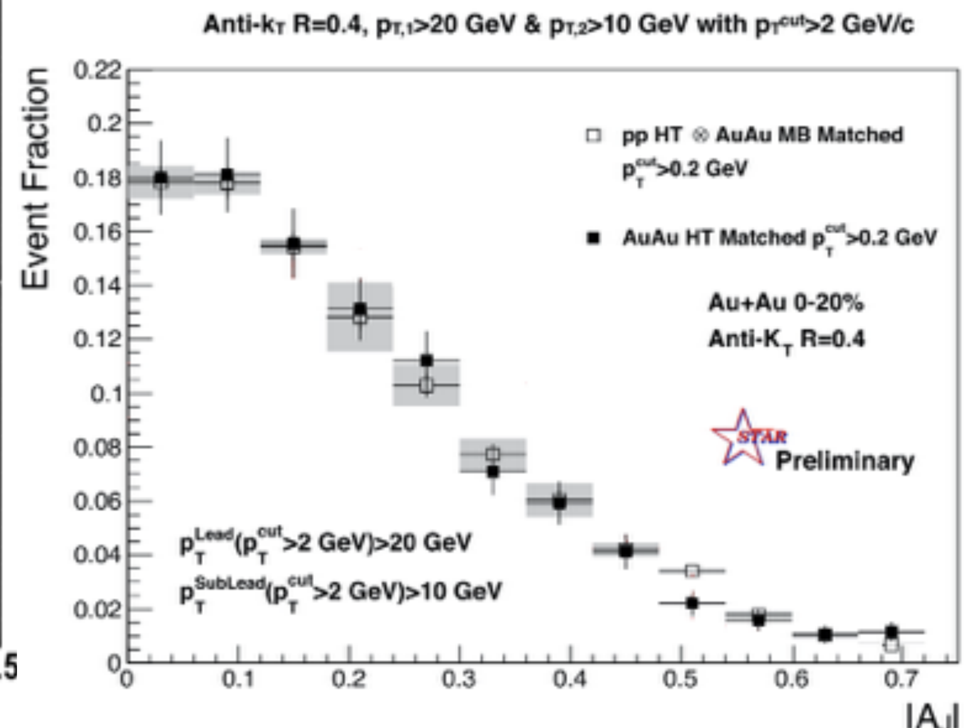


PbPb –pp

Enhancement of low p_T particles as a function of ΔR

Larger imbalance in PbPb

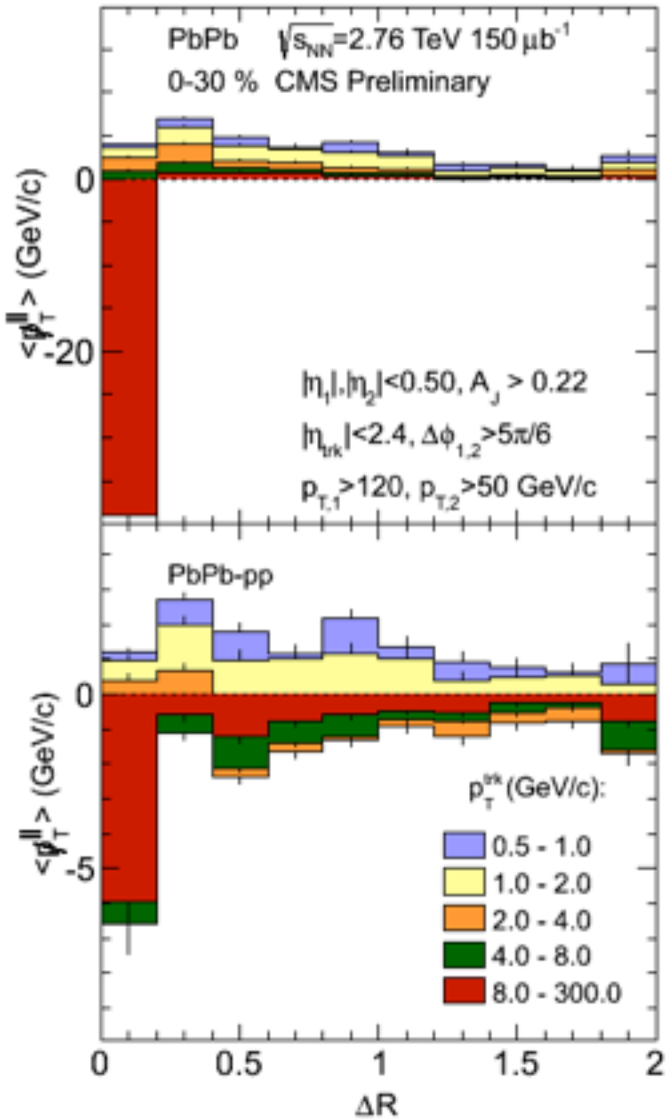




Qualitatively similar to PHENIX photon-hadron correlations…

…but different than STAR observation (for a very different event selection)

Energy redistribution to large angles and low p_T



Antenna people (… ased):
Greatest develo… …nce sliced
bread. Evide… …emocratic
branchin… …bulent flow

"ener… …o large angles requires only
si… …ematics → any model which
… …omentum flow between jet and
medium gets this"

Quantitative predictions?

Future direction in jet physics

Move jet data vs theory comparison from the era of analogies, metaphors and "qualitative agreement" to a quantitative basis, beyond "determining qhat"

Experiments:

- Many LHC run 2 results will have negligible statistical uncertainty and vastly extended kinematic range
- New/improved observables will **eliminate** many sources of systematic uncertainty/bias and "knobs" from theory comparison. For me, paradigmatic example is γ-jet measurement program
- Challenge: construct observables that have comparable meaning at LHC and RHIC to study T dependence (see e.g. STAR vs ATLAS/CMS dijet asymmetry)

Future direction in jet physics

Theory + experiment: “Lisbon accord”

- Comparison of data to full-event calculations including jet modification in medium as well as medium response

- Many models in various stages along the way: Jewel, Yajem, Q-Pythia, Pyquen/Hydjet, Martini, Hijing, JET collaboration MC

- Framework for fair theory/experiment comparison across many observables: Common hydro profile, common output forward, automated comparison to experiment data (RIVET)

- Theory/Experiment collaboration: Goal is not to “kill models”, but to learn what are meaningful questions to ask