

Jets and correlations in heavy-ion collisions

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**EUROPEAN PHYSICAL SOCIETY
CONFERENCE ON HIGH ENERGY PHYSICS**

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Challenges of heavy-ion physics

Exploration of the QCD phase diagram:

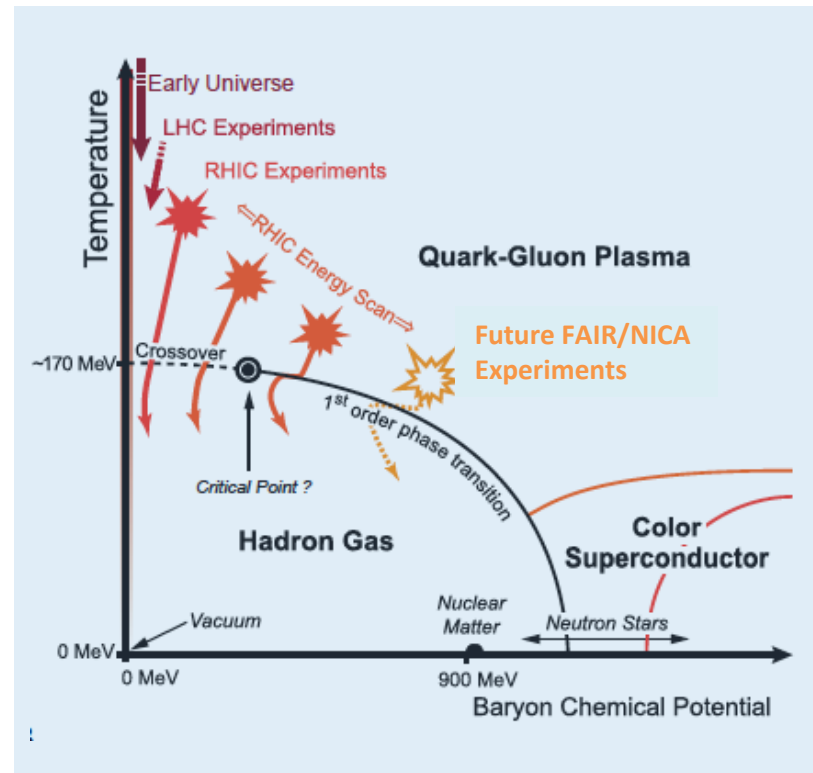
- nature of the phase transition and search for the critical point
- properties of the **quark-gluon plasma** at high temperature (RHIC/LHC) and large density (GSI FAIR/NICA)

Complementarity of LHC, RHIC and future FAIR/NICA heavy-ion programs.

Note: lifetime of QGP is very short
→ we need in-situ probes

Center of mass energies ($\sqrt{s_{NN}}$) for different accelerators:

GSI:	1-2 GeV
FAIR:	2 -6 (10 GeV)
NICA:	4 - 11 GeV
RHIC:	7- 200 GeV
LHC:	2.76, 5 TeV



Hard probes: tomography of nuclear matter

Jets, heavy quarks, quarkonia :

originate from initial hard scattering of partons which carry a color charge interact with nuclear matter

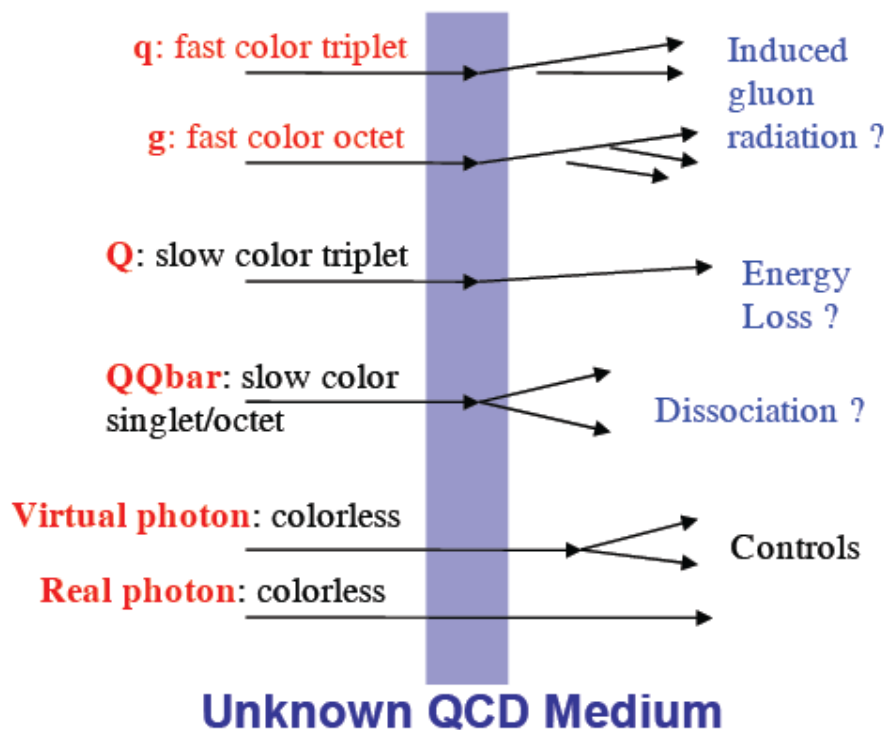
Photons, W and Z bosons:

do not carry a color charge provide information about initial state nuclear parton distribution functions

Jets: this talk
c, b, γ , W and Z next HI talk

Goal:

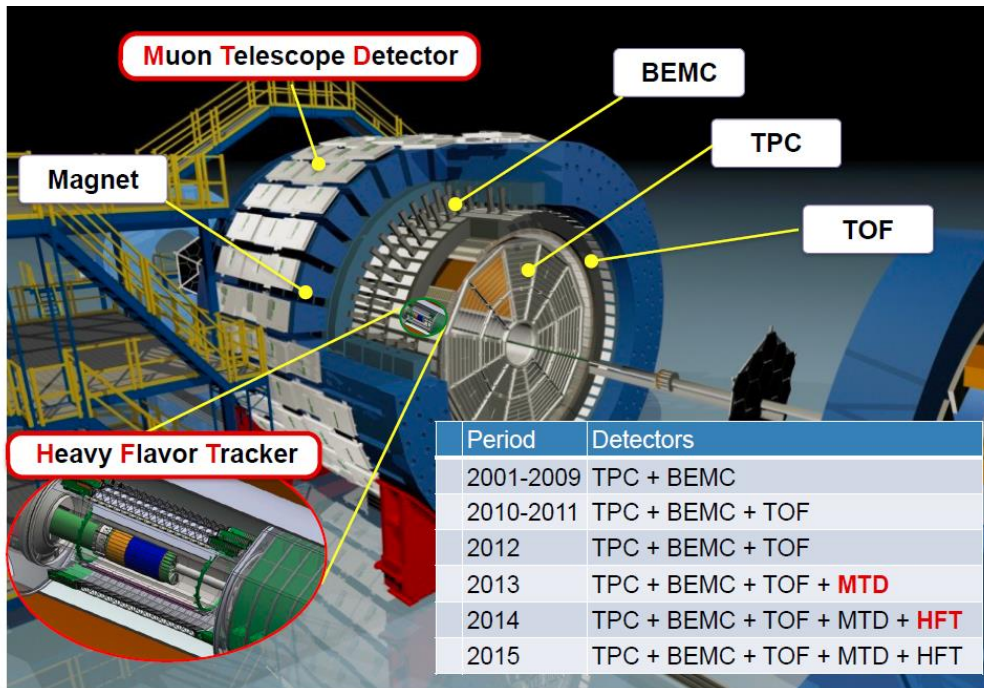
use in-medium parton energy loss to quantify medium properties



- energy loss different for gluons and light/heavy quarks (color factor, dead cone effect)
- parton interaction with medium not trivial: depends on strength of coupling, dynamics of fireball ...

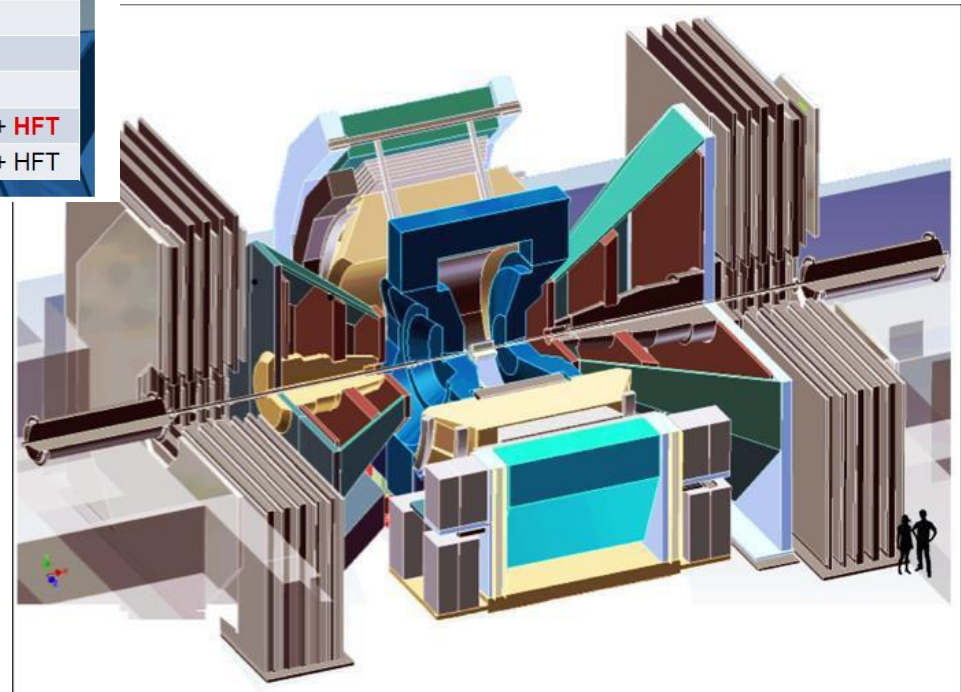
... challenge for theorists

Dedicated heavy-ion experiments at RHIC



PHENIX:

- **central arms:** electrons ($|\eta| < 0.35, \Delta\phi = \pi$)
tracking: DC, PC
PID: RICH, EMCal
- **forward arms:** muons ($-1.2 < |\eta| < 2.2, \Delta\phi = 2\pi$)
tracking: wire chamber

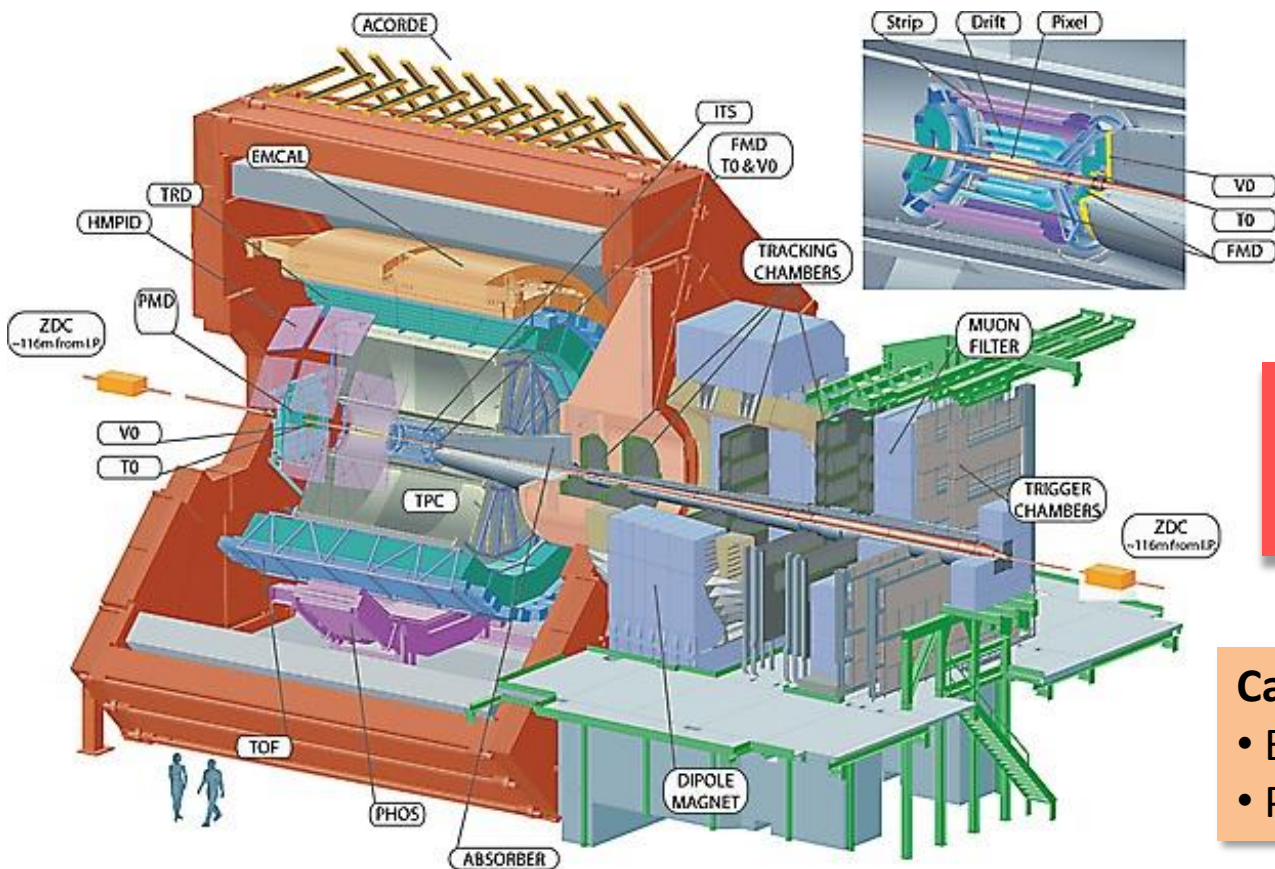


STAR:

- full azimuthal coverage
- excellent tracking and PID (TPC, TOF)
- electromagnetic calorimeter (BEMC)

NEW: Muon Telescope Detector,
Heavy Flavor Tracker → precision
measurements of heavy quarks

ALICE: dedicated HI experiment at the LHC



Forward Detectors

Large η
Interaction trigger
Event characterization

Muon Spectrometer

$-4 < |\eta| < -2.5$
 $p(\text{muons}) > 4\text{GeV}/c$

Calorimetry

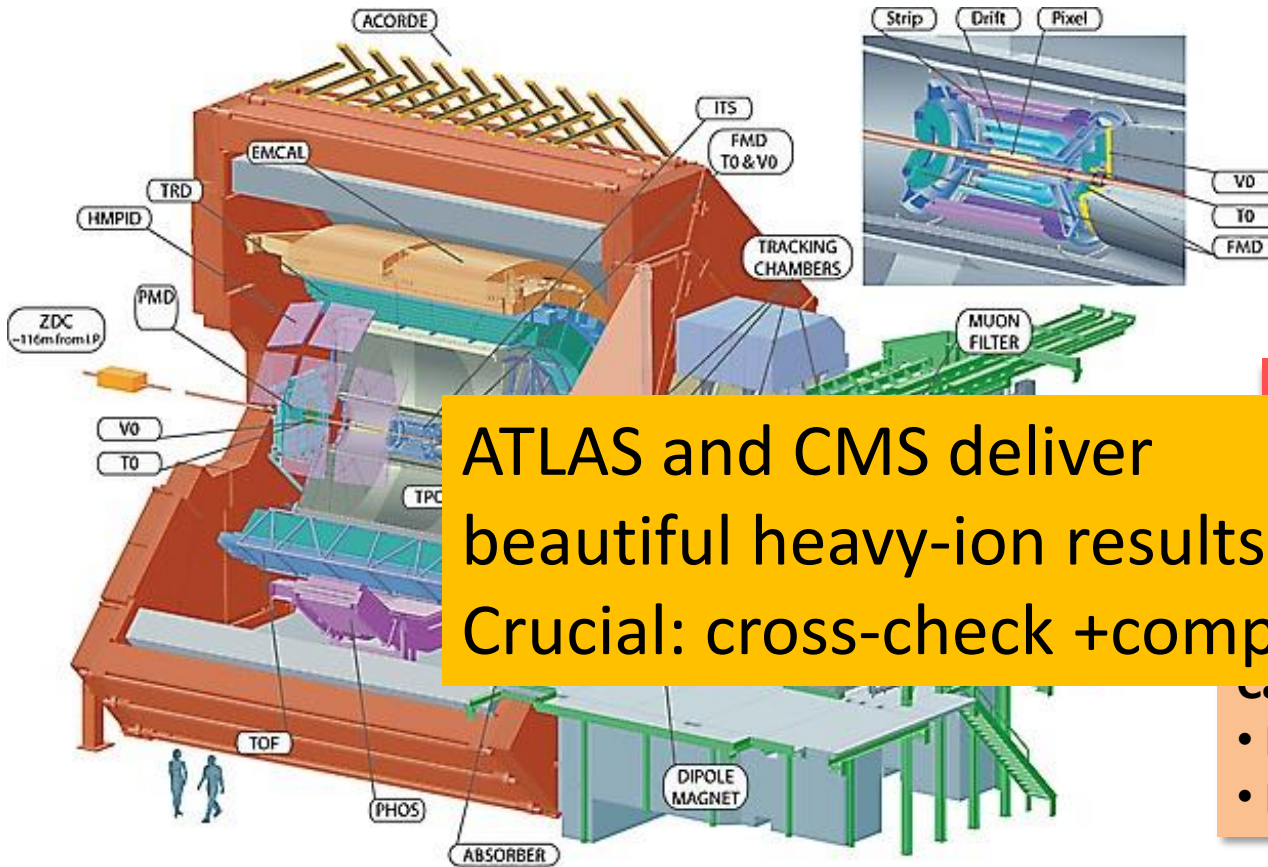
- EMCAL + DCAL (Run2)
- PHOS

Central Barrel ($|\eta| < 0.9$)

- hadrons, e and γ
- TPC: efficient tracking down to $\sim 100\text{ MeV}/c$
- ITS: excellent vertexing capability

**Excellent particle
identification capabilities!
Basically all known types.**

ALICE: dedicated HI experiment at the LHC



Forward Detectors
Large η
Interaction trigger
Event characterization

ATLAS and CMS deliver beautiful heavy-ion results as well!
Crucial: cross-check + complementarity!

Calorimetry

- EMCAL + DCAL (Run2)
- PHOS

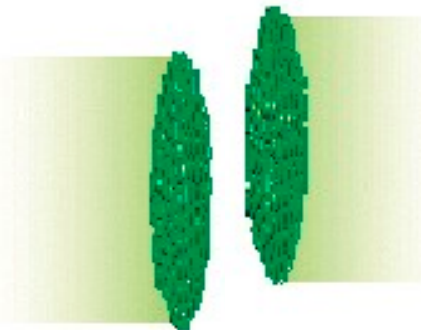
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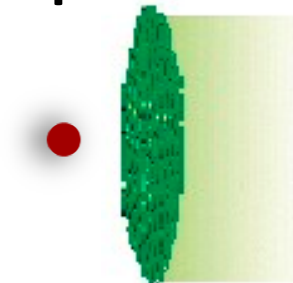
Excellent particle identification capabilities!
Basically all known types.

Some basic heavy-ion physics terminology ...

A + A



p + A



p + p



“hot/dense QCD matter”

final state effects

thermal and collective
particle production (flow)

“cold nuclear matter”

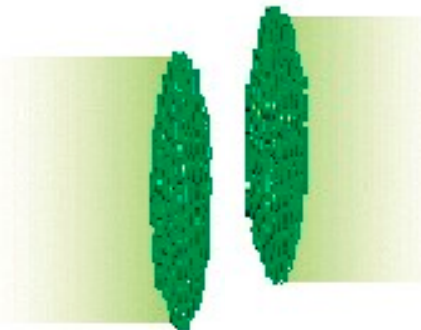
initial state effects

shadowing and gluon
saturation

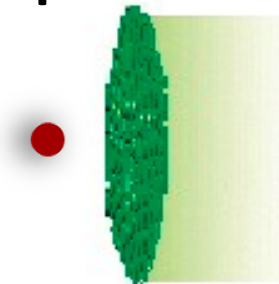
“vacuum”
reference

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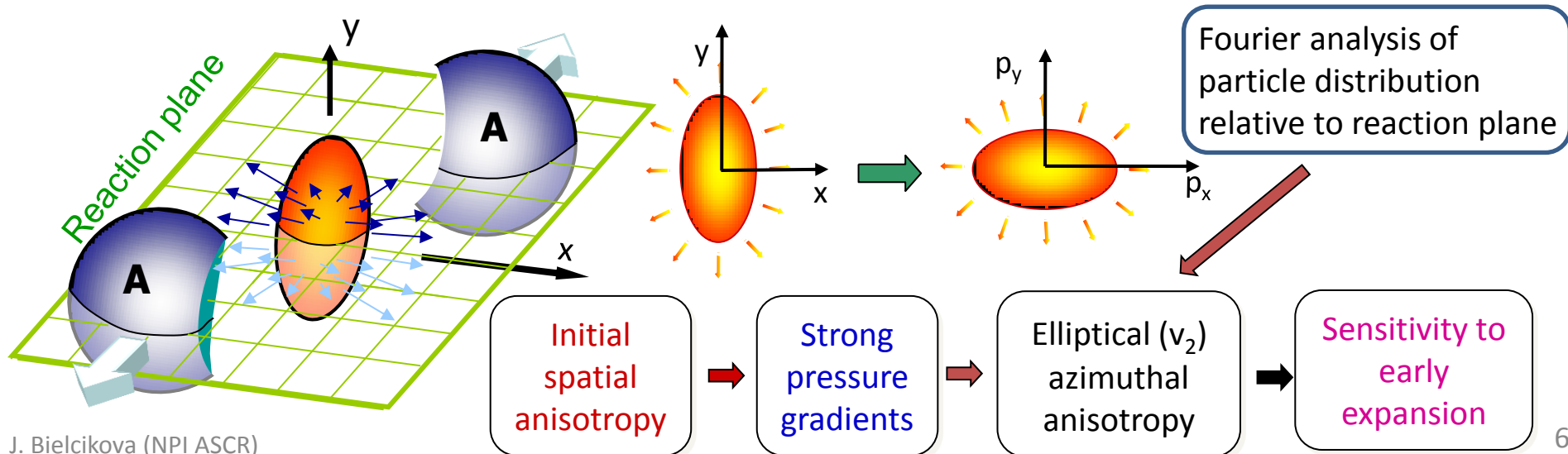
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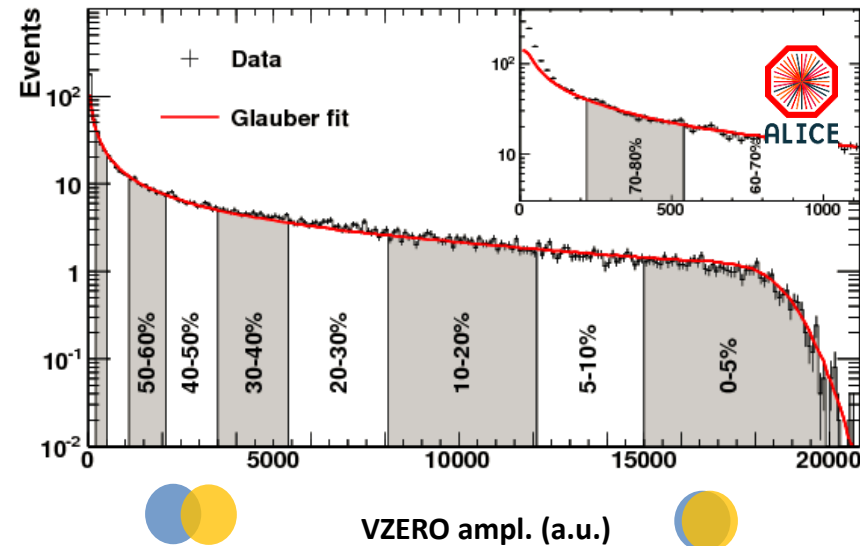
reference



Centrality and nuclear modification factor

Centrality in A+A:

- impact parameter cannot be directly measured and has to be estimated based on measured e.g. N_{ch} , E_T , ZDC ...
- centrality is typically expressed as a % fraction of total geometric cross section
- **Glauber model:** connects centrality to a number of binary collisions (N_{coll}) and participants (N_{part})

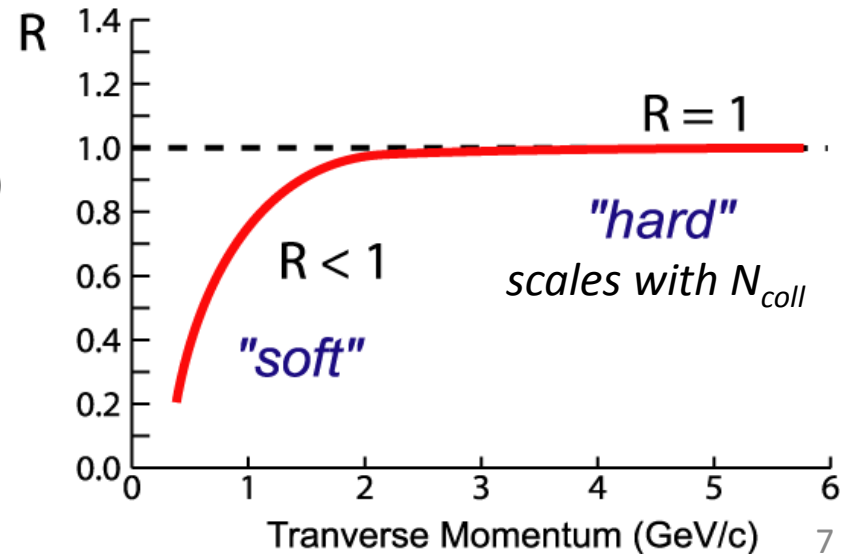


Nuclear modification factor:

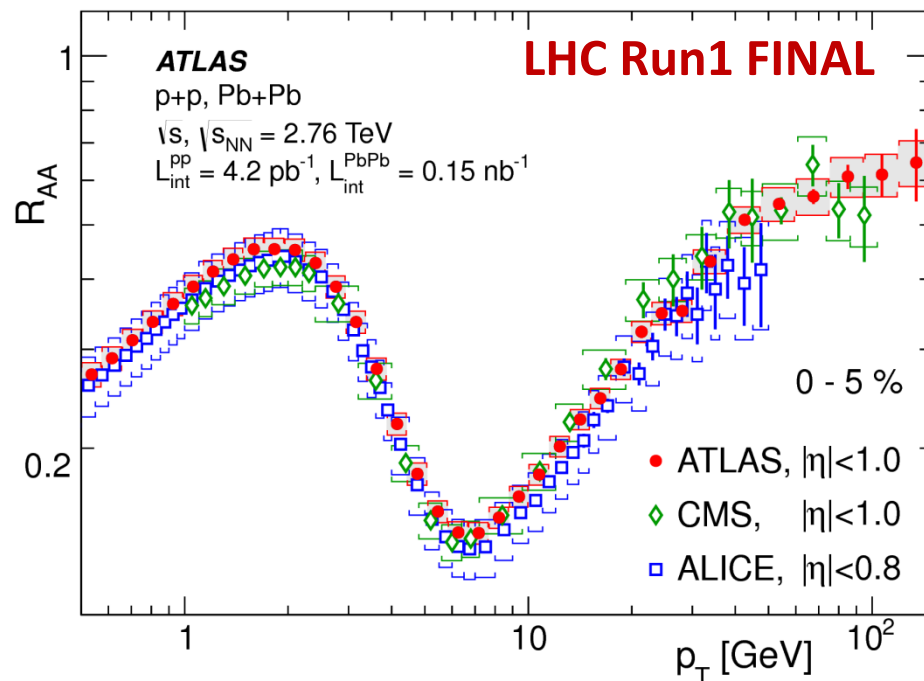
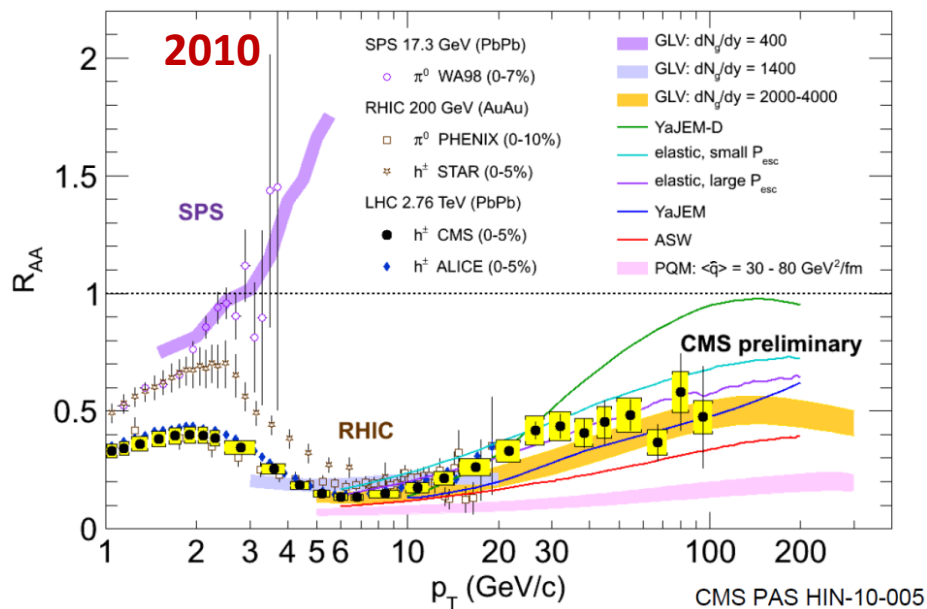
... the way to compare an observable in A+A collisions to the reference (p+p or peripheral A+A)

$$R_{AA}(p_T) = \frac{d^2 N^{AA} / dp_T d\eta}{T_{AA} d^2 \sigma^{NN} / dp_T d\eta}$$

$N_{coll} / \sigma_{inel}^{NN}$



Particle production in central Pb+Pb collisions



- suppression of charged hadron production: $R_{AA}(\text{LHC}) < R_{AA}(\text{RHIC})$
- minimum $R_{AA} \sim 0.14$ at $p_T = 6-7 \text{ GeV}/c$
- increase of R_{AA} with p_T but even at $p_T \sim 100 \text{ GeV}/c$ $R_{AA} < 1$
- although R_{AA} is known to be limited in sensitivity to models of quenching, these data excluded already some of them

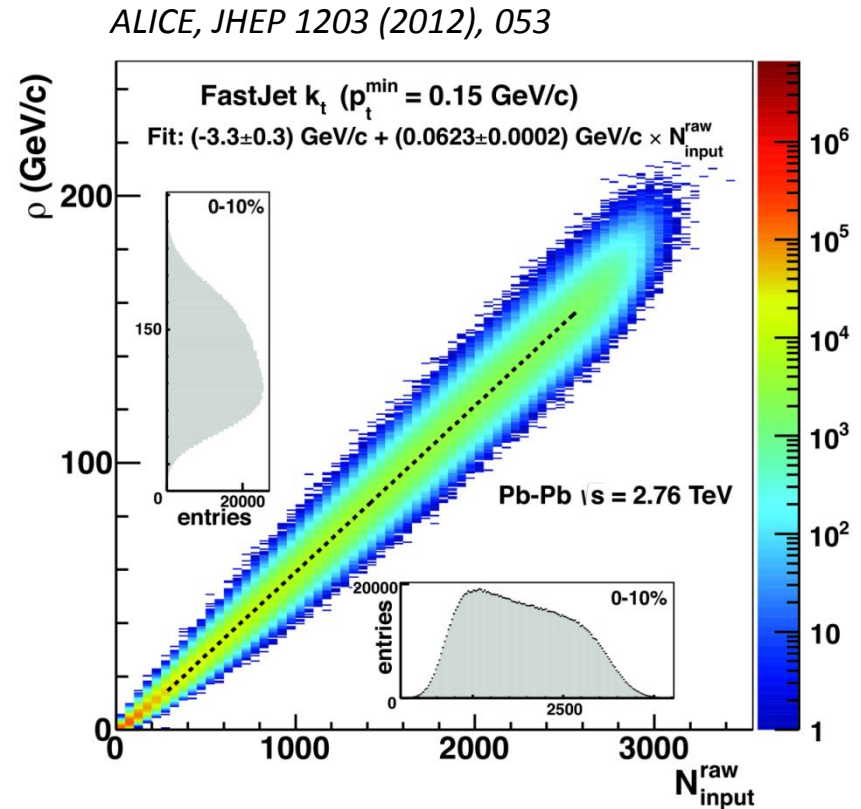
ATLAS: *arXiv:1504.04337*, ALICE: *PLB 720 (2013) 52*, CMS: *EPJ C72 (2012) 1945*

Jet tomography in heavy-ion collisions

- jet reconstruction is performed with a collinear and infrared safe anti-kt algorithm

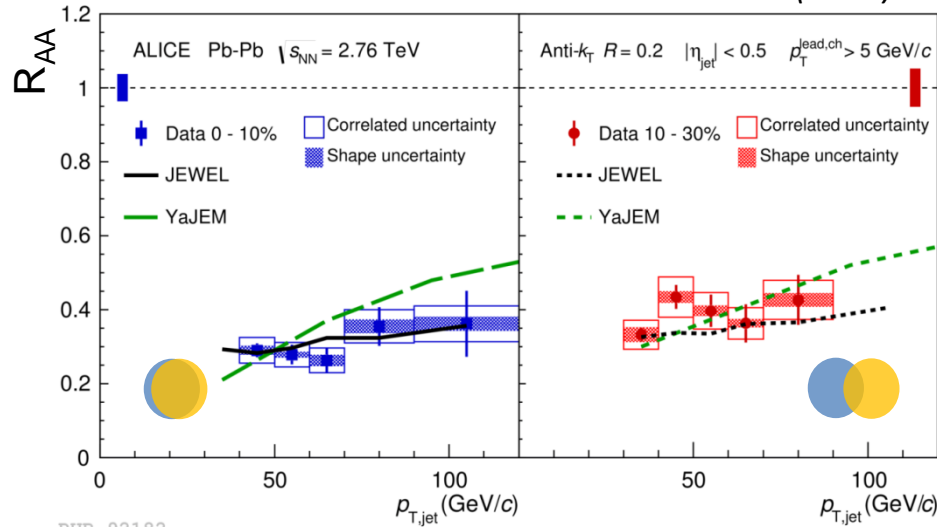
Challenge for experimentalists:

- large and fluctuating background:
 $\langle \rho \rangle \approx 180 \text{ GeV/c}$
in central Pb-Pb collisions @ 2.76 TeV
→ limits jet resolution parameter R
to modest values $R \sim 0.2-0.4$
- average background subtracted on jet-by-jet basis and fluctuations together with instrumental effects unfolded on statistical basis

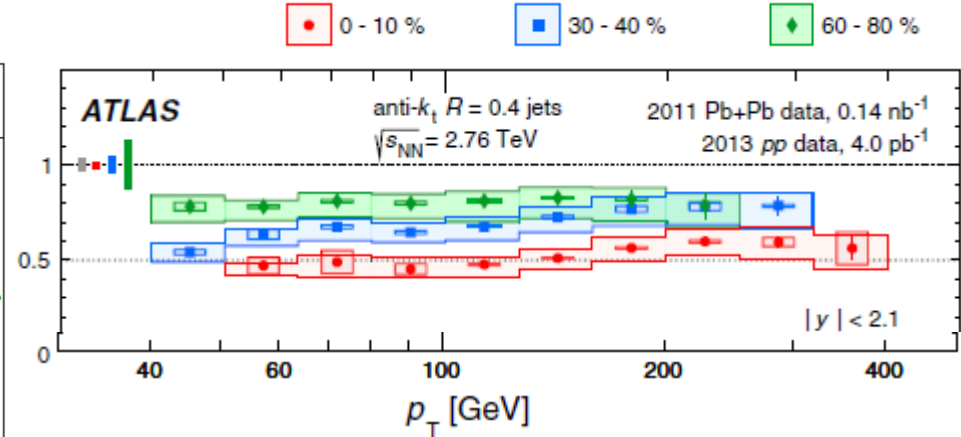


How much are jets modified?

ALICE: PLB 746 (2015) 1



-PUB-92182

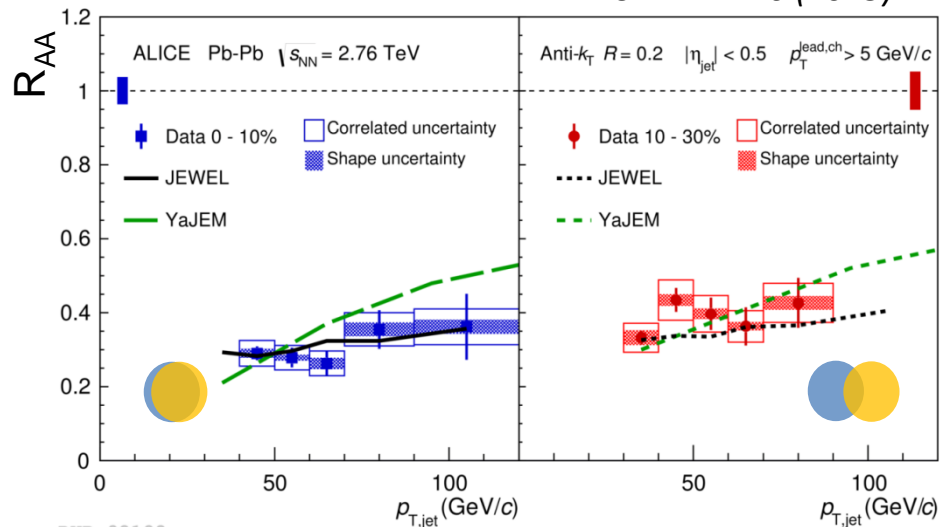


ATLAS: PRL 114 (2015) 072302

Inclusive jet production is suppressed in central Pb+Pb collisions ...

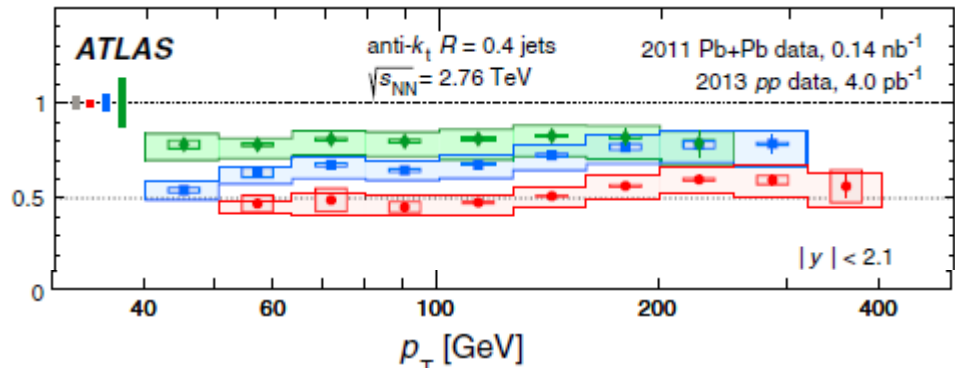
How much are jets modified?

ALICE: PLB 746 (2015) 1



-PUB-92182

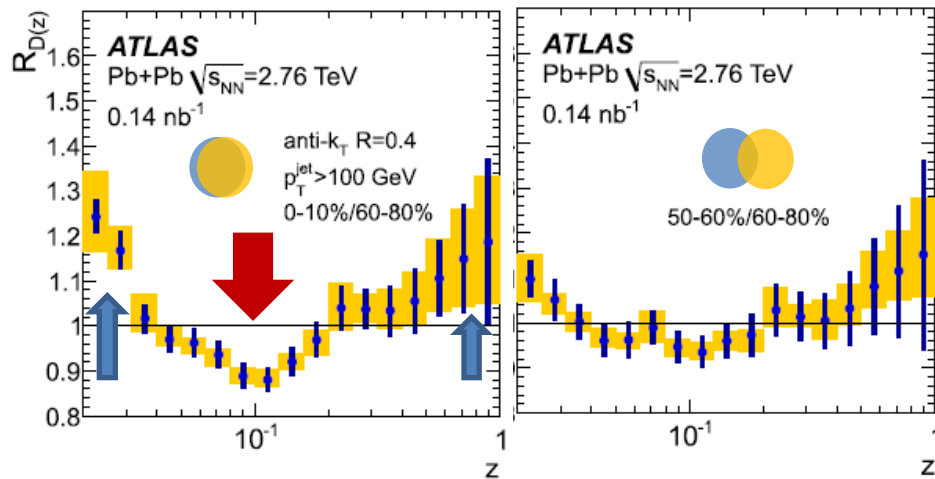
0 - 10% (red circle), 30 - 40% (blue square), 60 - 80% (green diamond)



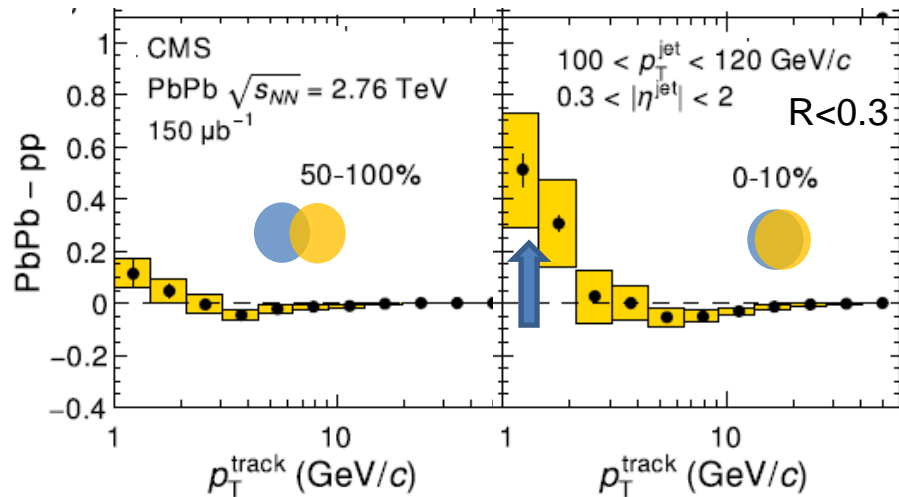
ATLAS: PRL 114 (2015) 072302

Inclusive jet production is suppressed in central Pb+Pb collisions ...

ATLAS: PLB 739 (2014) 320

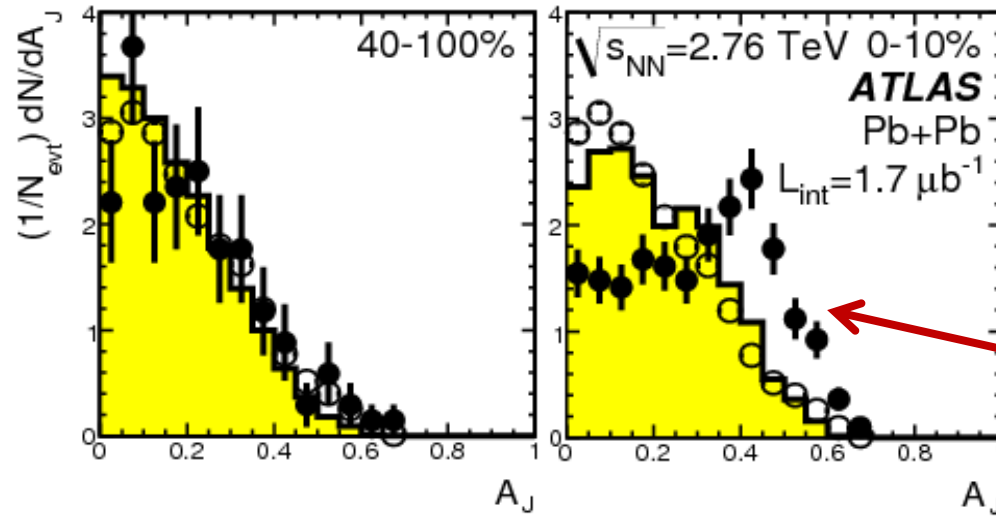


CMS: PRC 90 (2014) 024908



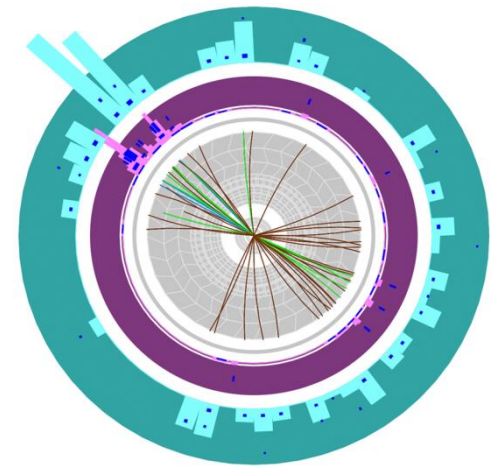
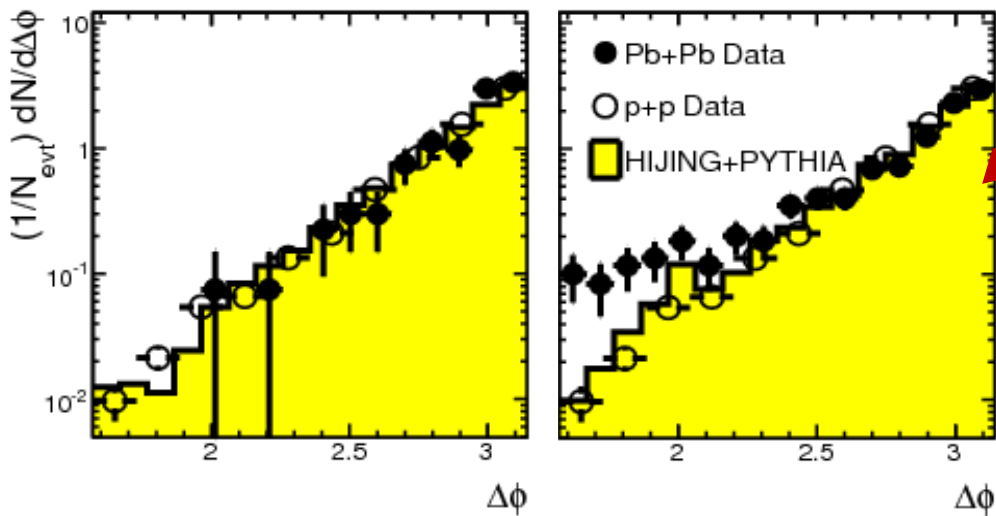
... and internal structure of jets is modified.

Dijet asymmetry in central Pb+Pb collisions



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

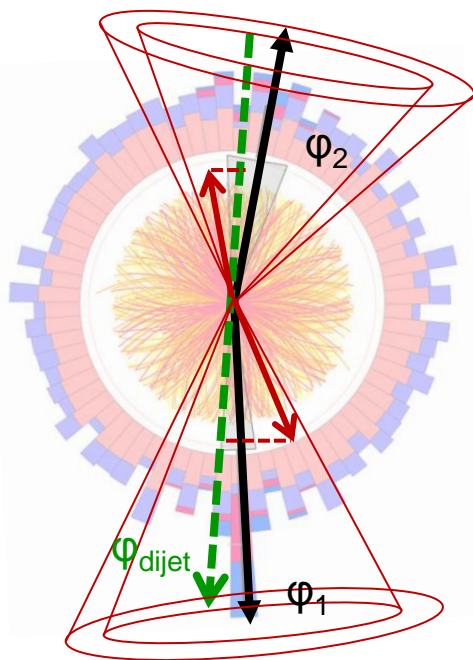
Dijet asymmetry observed in central Pb+Pb collisions, **without** angular decorrelation.



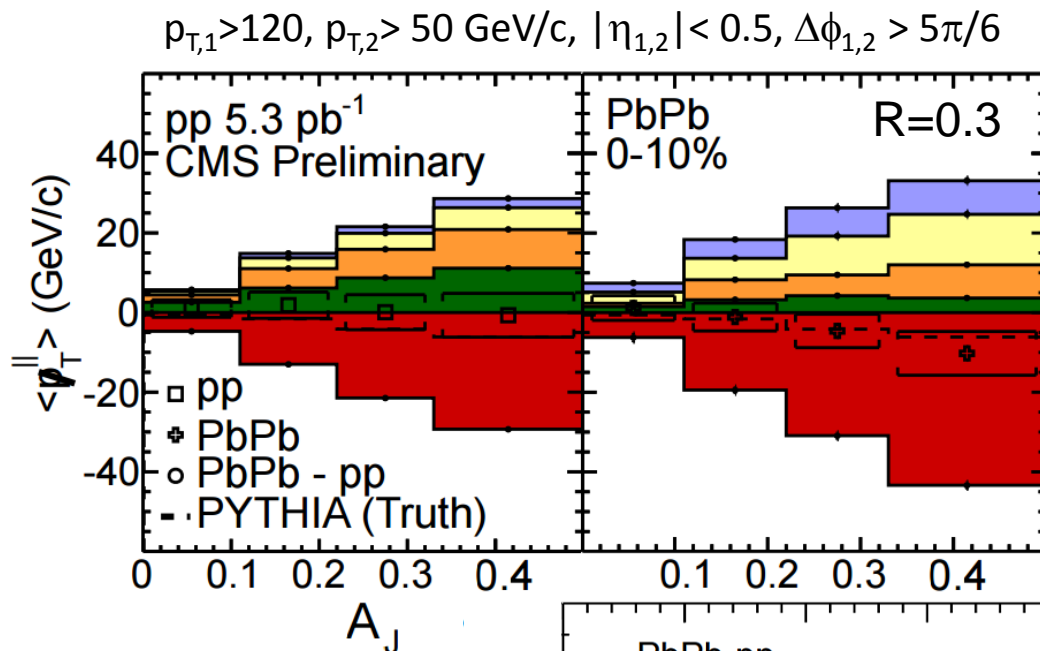
ATLAS: *PRL* 105 (2010) 252303

Where did the energy go? First studies in CMS paper: *PRC* 84 (2011) 024906

Where did the energy go?

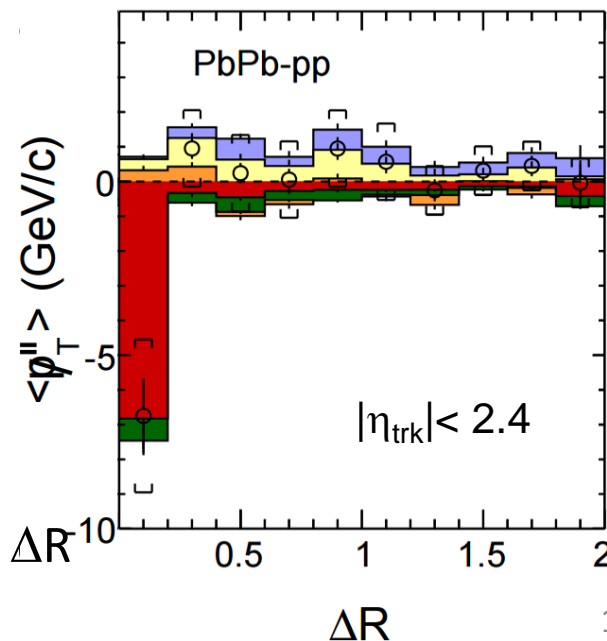
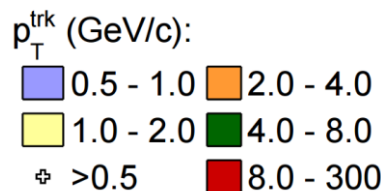


courtesy Y. J. Lee (CMS)



Missing p_T :

$$p_T^{\parallel} = \sum_i -p_T^i \cos(\phi_i - \phi_{\text{Dijet}})$$



- increases with A_J and is balanced by:
 - 2-8 GeV/c particles in pp
 - $p_T < 2$ GeV/c particles in 0-10% Pb+Pb
- high p_T imbalance at small ΔR compensated by low p_T particles in subleading jet direction extending to large ΔR

Path length effects on di-jet production

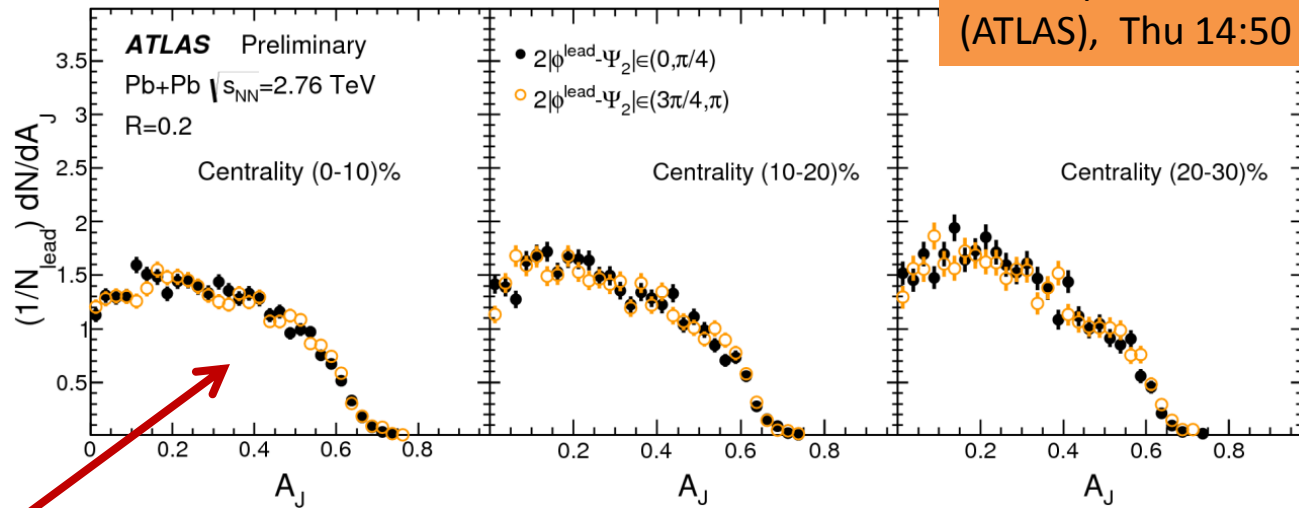
D. Perepelitsa
(ATLAS), Thu 14:50

- earlier study of jet production vs. event plane showed modest path length dependence ($v_2^{\text{jet}} \sim 2\text{-}5\%$)

ATLAS: *PRL* 111 (2013)152301

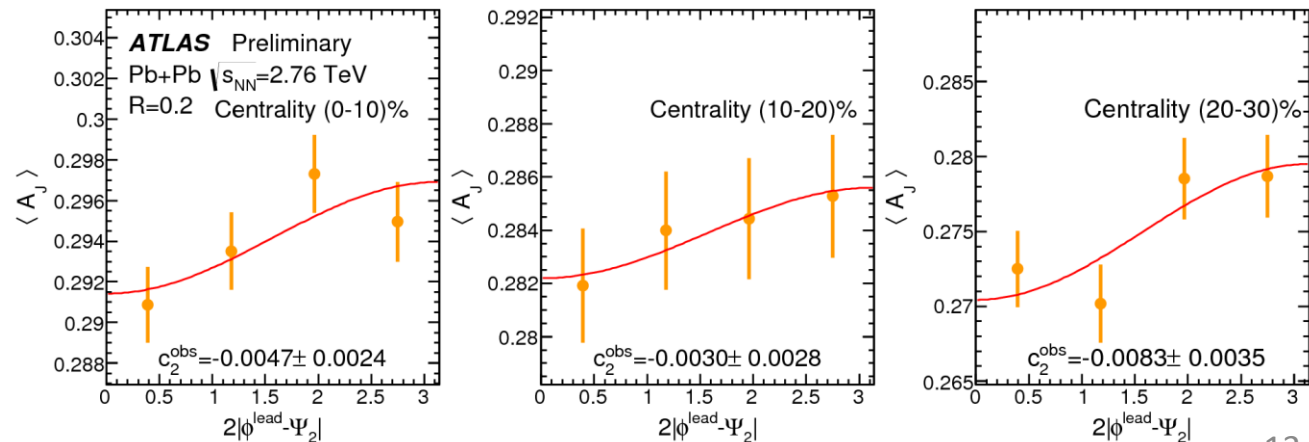
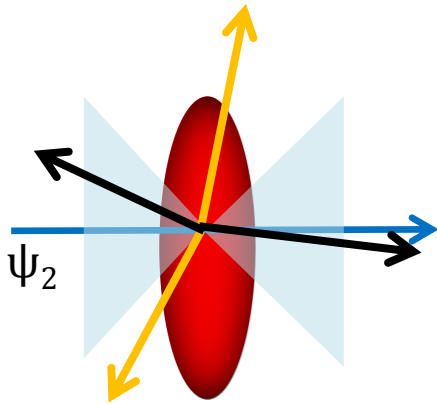
Study di-jet asymmetry A_J vs. event plane, extract its elliptical modulation c_2 .

ATLAS-CONF-2015-021



Calculate “elliptic” modulation c_2 :

$$\langle A_J \rangle(\varphi^{\text{lead}} - \psi_2) = A_{J,0} \left(1 + 2c_{2,obs} \cos \left(2(\varphi^{\text{lead}} - \psi_2) \right) \right)$$



Path length effects on di-jet production

D. Perepelitsa
(ATLAS), Thu 14:50

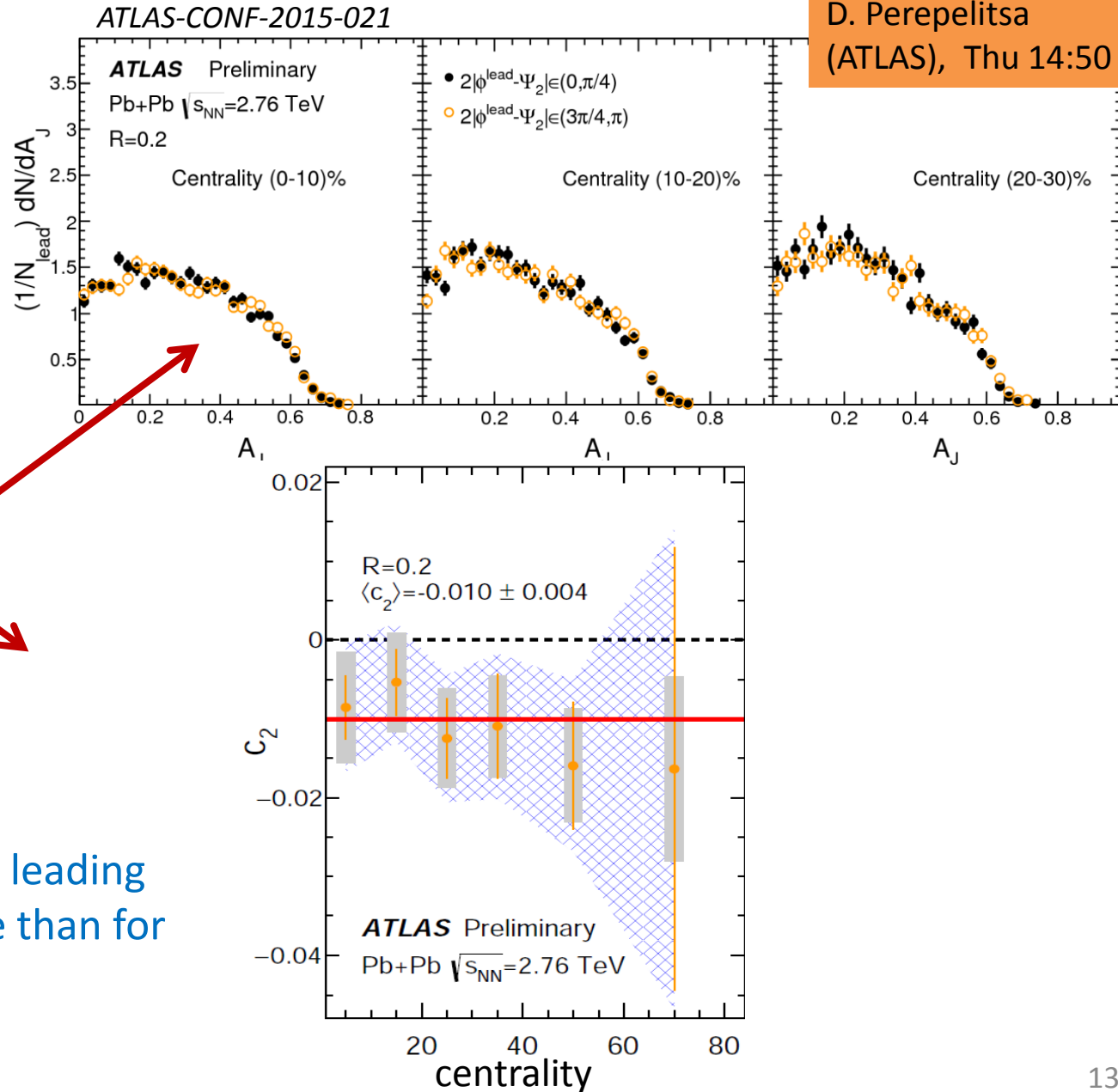
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ATLAS: *PRL* 111 (2013)152301

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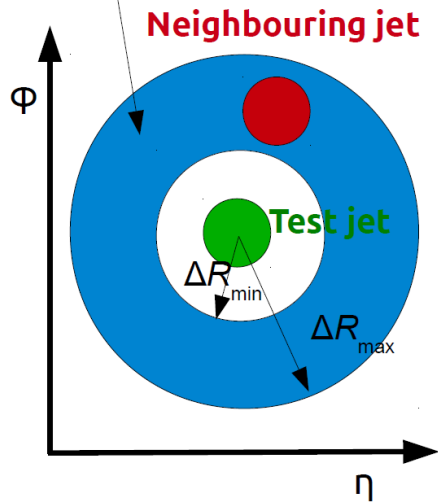
c_2 is small (<2%) and negative!

Data indicate larger A_J for leading jets oriented out-of-plane than for in-plane ones.



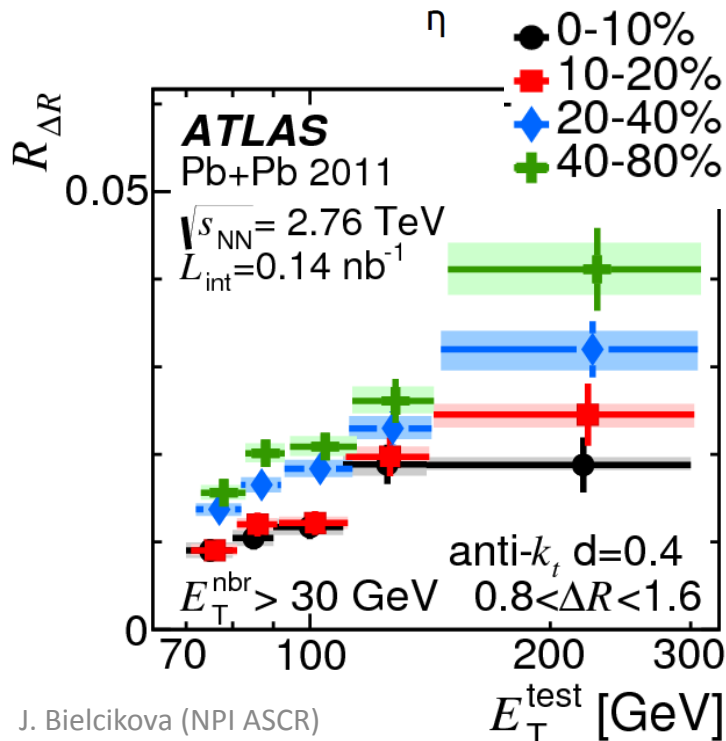
Neighbouring jet production in Pb-Pb collisions

Annulus around the test jet



Production of **neighbouring jets** quantified using a rate of jets accompanying a given **test jet**

$$R_{\Delta R} = \frac{1}{dN_{\text{jet}}^{\text{test}}/dE_T^{\text{test}}} \sum_{i=1}^{N_{\text{jet}}^{\text{test}}} \frac{dN_{\text{jet},i}^{\text{nbr}}}{dE_T^{\text{test}}} (E_T^{\text{test}}, E_{T,\text{min}}^{\text{nbr}}, \Delta R)$$



Similarly as for inclusive jets introduce **nuclear modification factor** $\rho_{R\Delta R}$

$$\rho_{R\Delta R} = R_{\Delta R}(\text{central})/R_{\Delta R}(\text{peripheral})$$

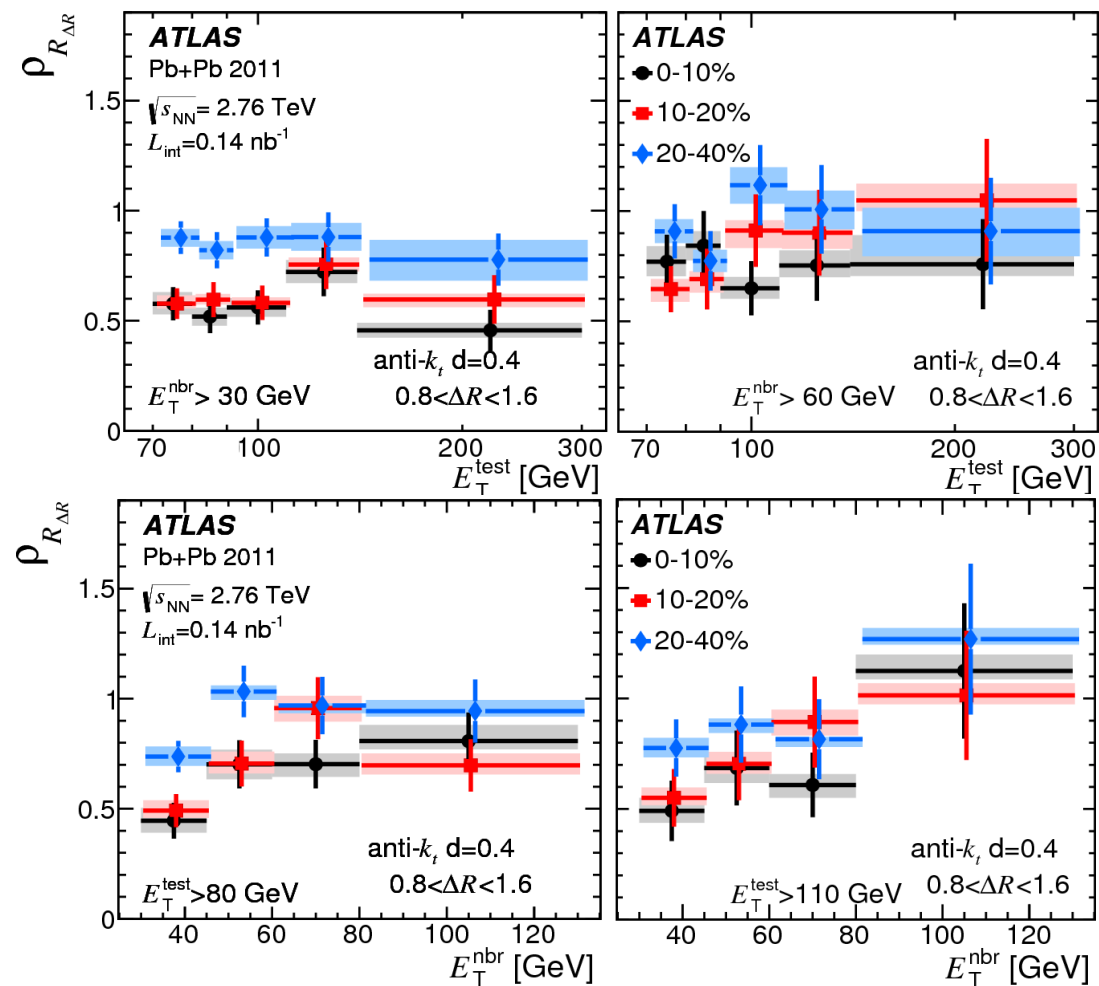
Study its dependence on:

- E_T of test jet
- E_T of neighbouring jet

D. Perepelitsa
(ATLAS), Thu 14:50

Neighbouring jet production in Pb-Pb collisions

ATLAS, arXiv:1506.08656



Suppression of neighbouring jet production in central Pb-Pb:

~ independent of test jet E_T
~ similar to inclusive jets

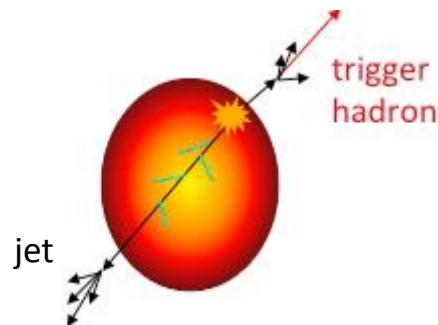
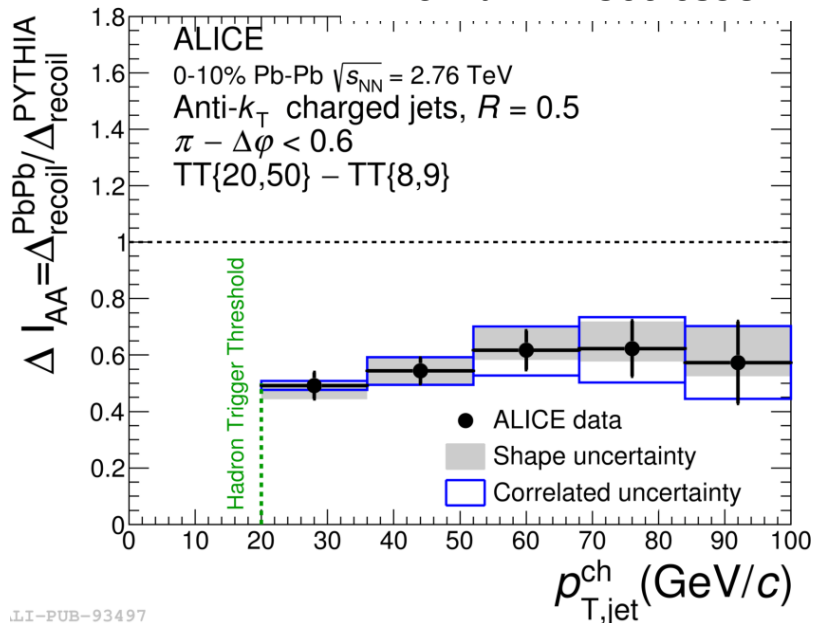
Nuclear modification factor for neighbouring jets approaches 1 when $E_T^{test} \approx E_T^{nbr}$.

Suggests similar quenching for jets with same observed E_T and path length.

D. Perepelitsa
(ATLAS), Thu 14:50

Semi-inclusive recoil jets in Pb-Pb

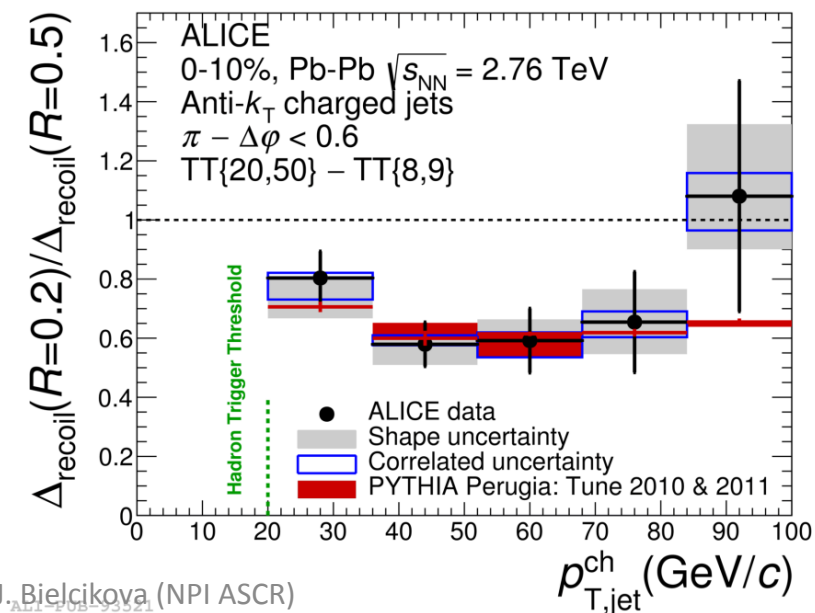
ALICE: arXiv:1506.03984



A unique observable: enables study of intra and inter-jet angular broadening + is directly comparable to analytic pQCD.

$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_T} \Big|_{p_{T,\text{trig}} \in \text{TT}_{\text{Sig}}} - \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_T} \Big|_{p_{T,\text{trig}} \in \text{TT}_{\text{Ref}}}$$

JHEP-93497



Recoil jet yields are suppressed ($\Delta_{I_{AA}}$): suppression is independent of R and slowly decreases with jet p_T

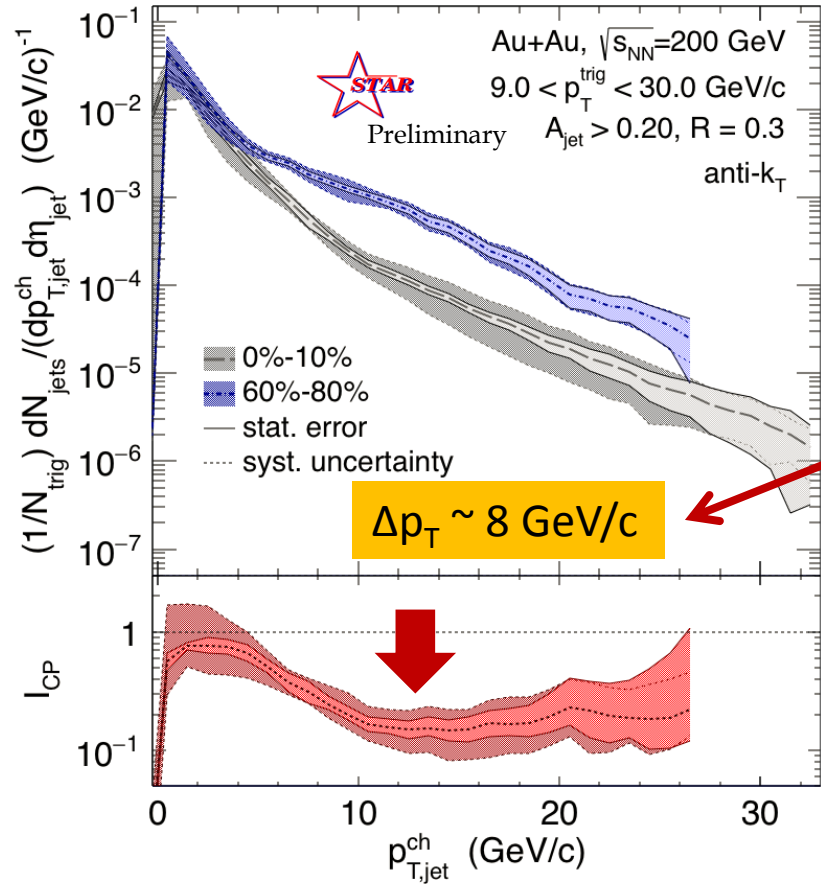
No evidence of intra-jet broadening:

Δ_{recoil} for R=0.2/0.5 similar in pp and central Pb-Pb collisions

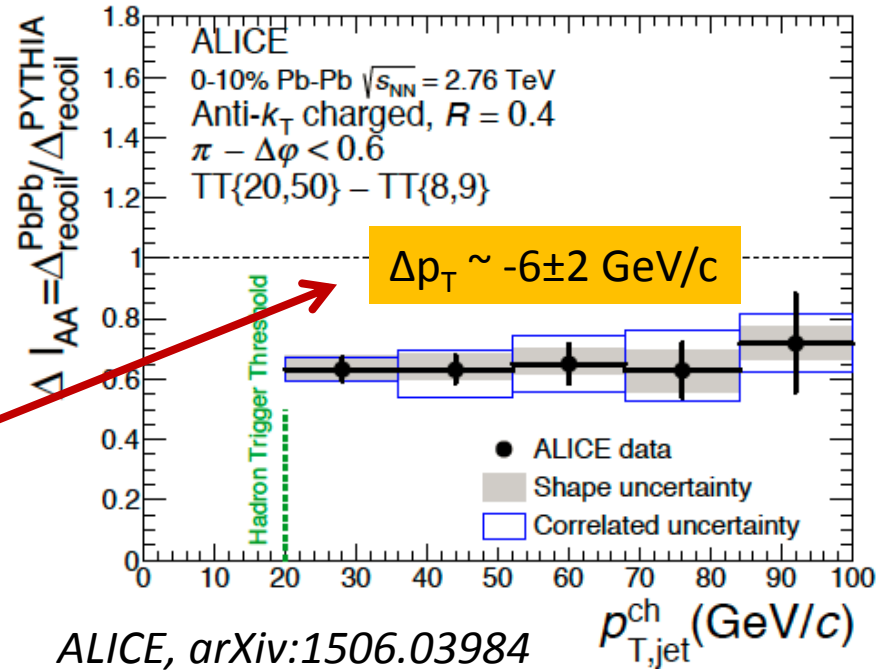
J. Otwinovski (ALICE)
Thu 15:40

Hadron-jet correlations at RHIC

STAR@RHIC 0.2 TeV



ALICE@ LHC 2.76 TeV



Larger suppression at RHIC compared to the LHC energy.

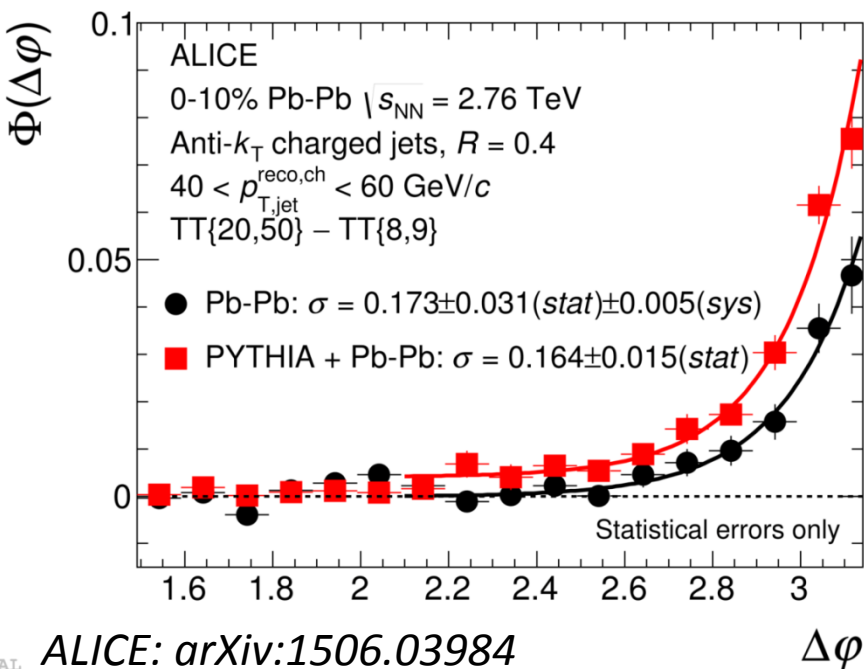
Nuclear modification factor “ I_{CP} ”:

- close to 1 at low p_T
- large suppression at $p_T > 10$ GeV/c: $I_{\text{CP}} \sim 0.2$

A word of caution: different kinematic selections, $\Delta\phi$ cut, ...

Acoplanarity?

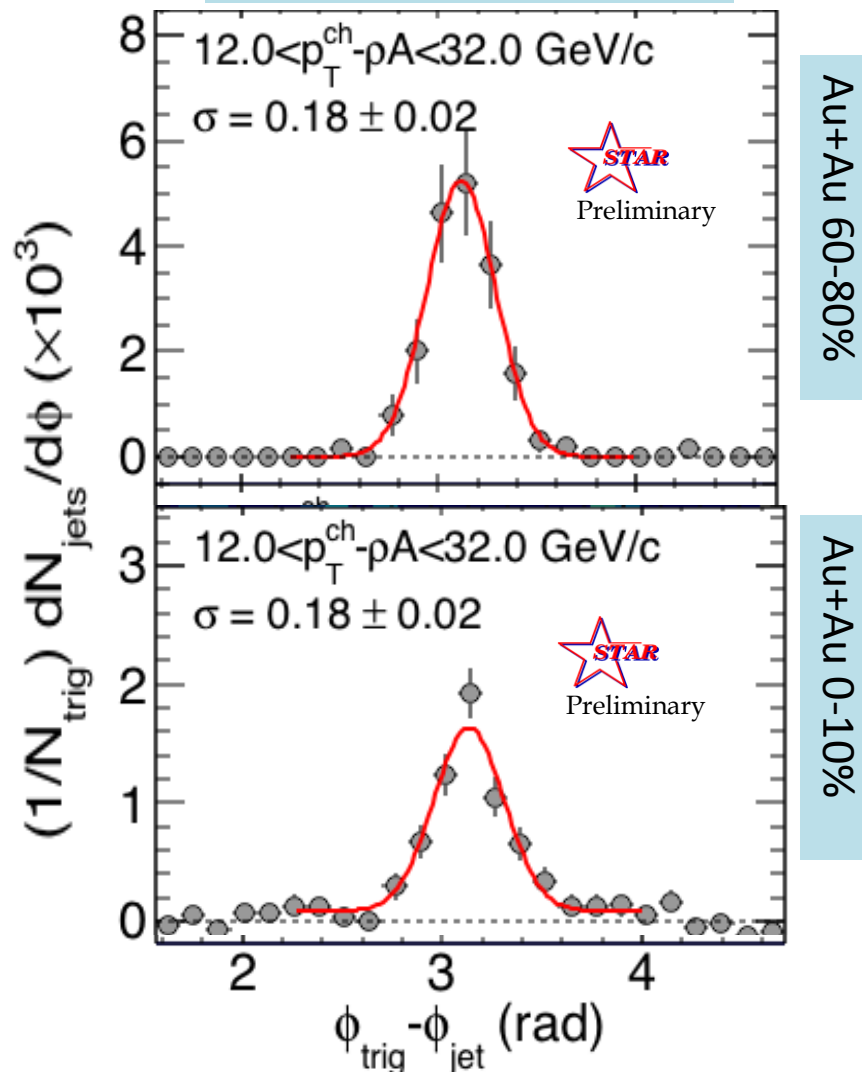
ALICE@ LHC 2.76 TeV



Width (σ) consistent in Pb+Pb with PYTHIA embedded data .

No evidence of medium-induced acoplanarity of recoil jets at the LHC.

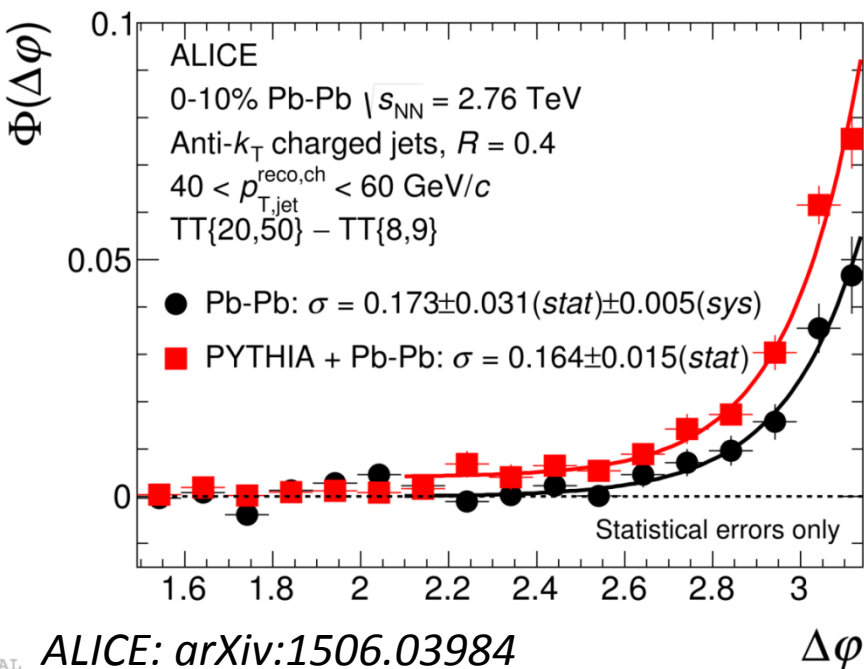
STAR@RHIC 0.2 TeV



High- p_T trigger: no broadening with centrality.

Acoplanarity?

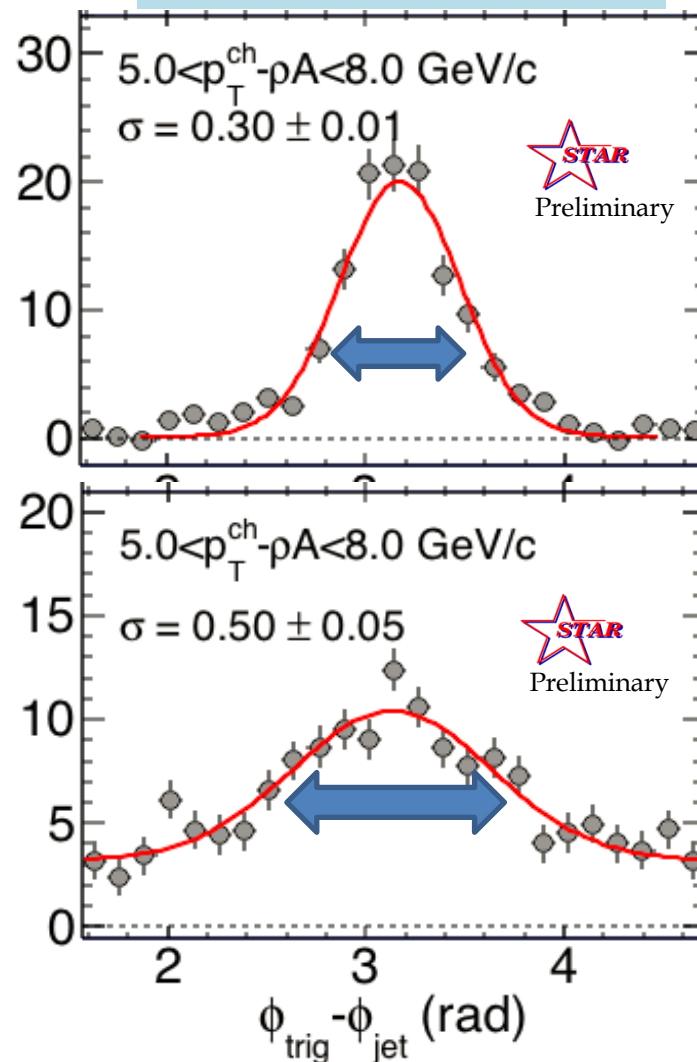
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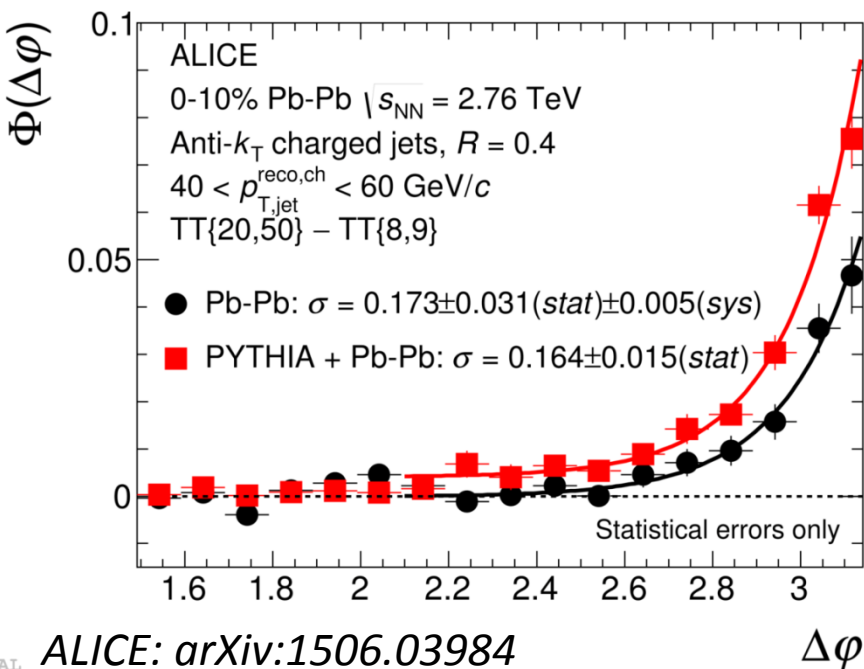
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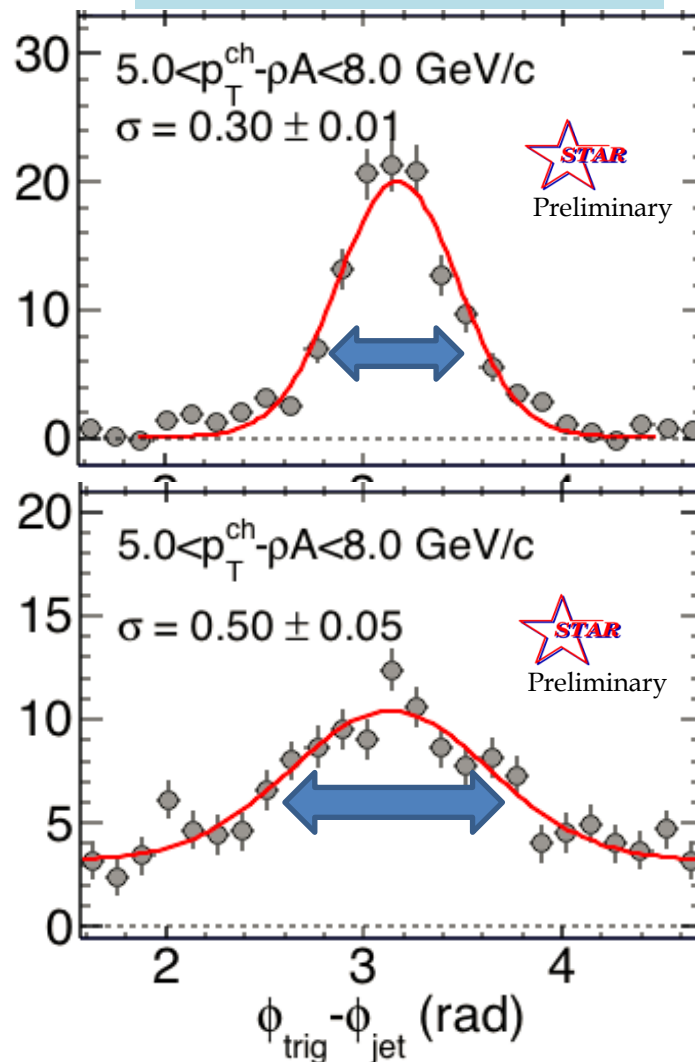
Low- p_T trigger: broadening with centrality

Acoplanarity?

ALICE@ LHC 2.76 TeV



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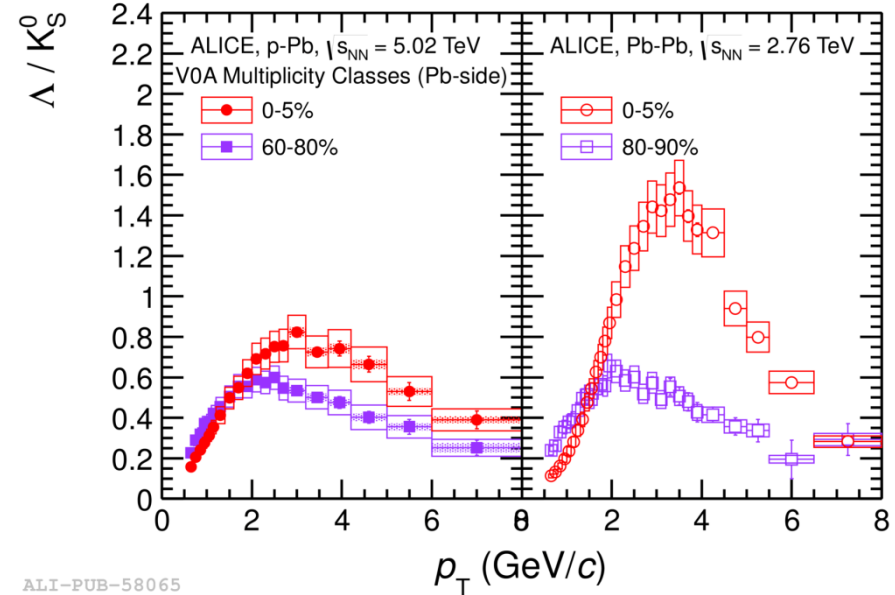
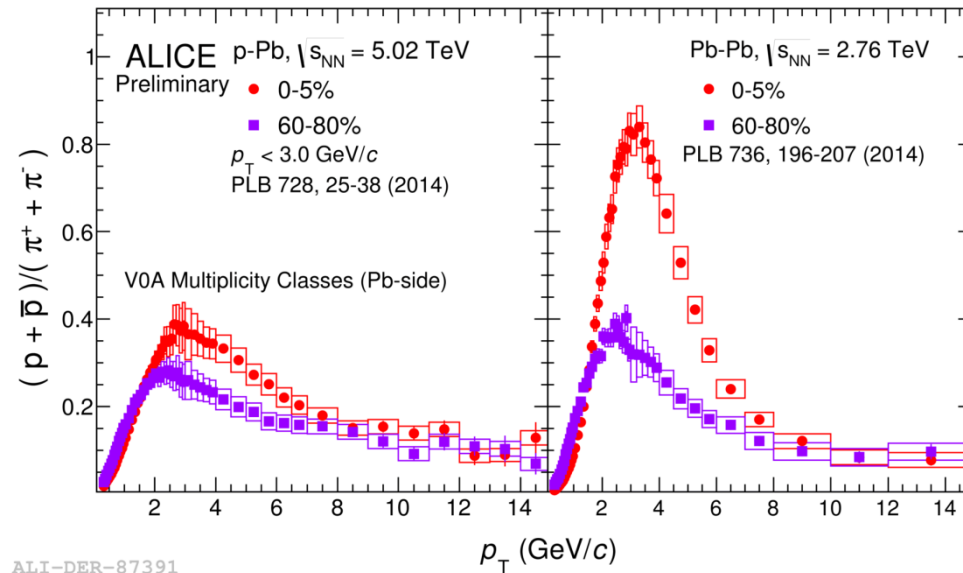
Future large-angle jet deflection studies may provide a direct probe of the nature of the quasi-particles in hot QCD matter.

Low- p_T trigger: broadening with centrality

Strange particle production in jets

Baryon/meson enhancement in p-Pb and Pb-Pb collisions relative to pp collisions

ALICE, PLB 728 (2014) 25, PLB 736 (2014) 196
arXiv: 1506.07287



High multiplicity p-Pb and Pb-Pb collisions have many similarities (see later) including also an enhanced p/π and Λ/K_s^0 ratio

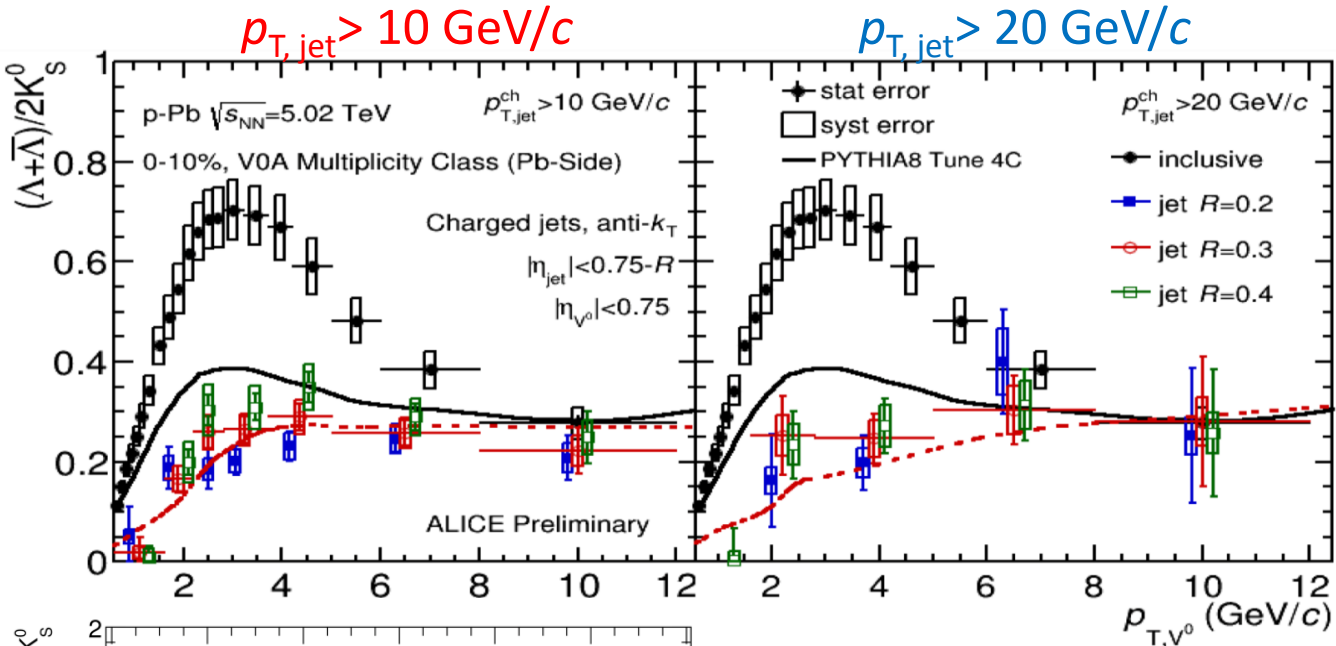
What is physics origin of this enhancement?

- radial flow
- coalescence/recombination vs fragmentation

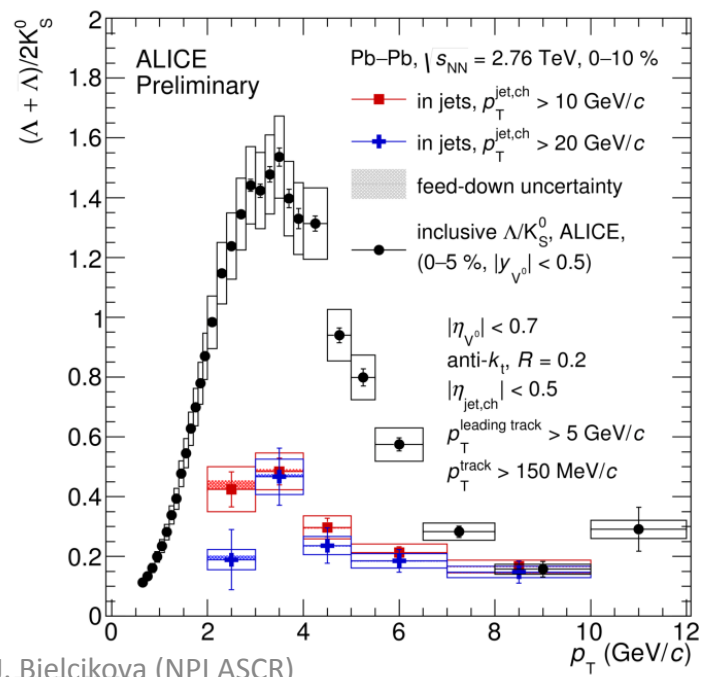
Measure B/M ratios in jets and compare to that in bulk ...

Strange particle production in jets

J. Otwinovski
(ALICE), Thu 15:40



V0s in PYTHIA
 - - - inclusive
 - - - in jets (R=0.3)

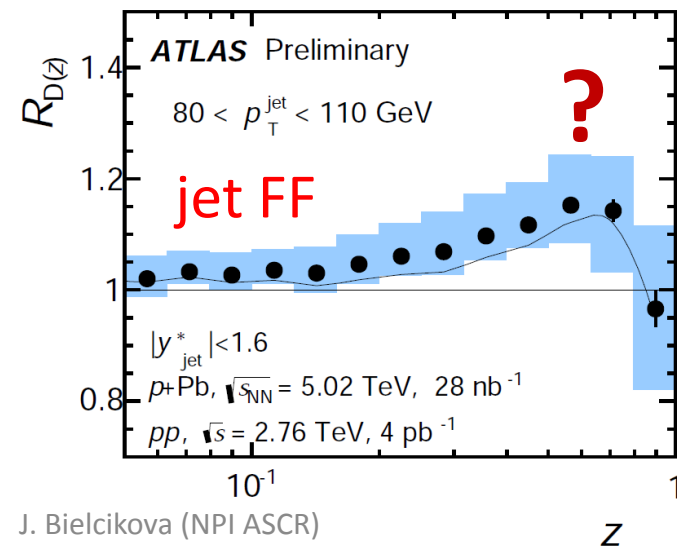
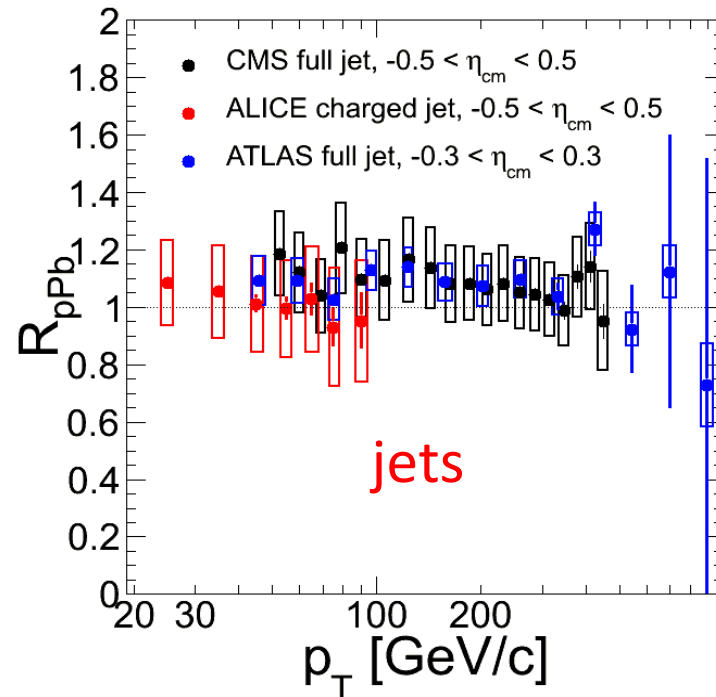
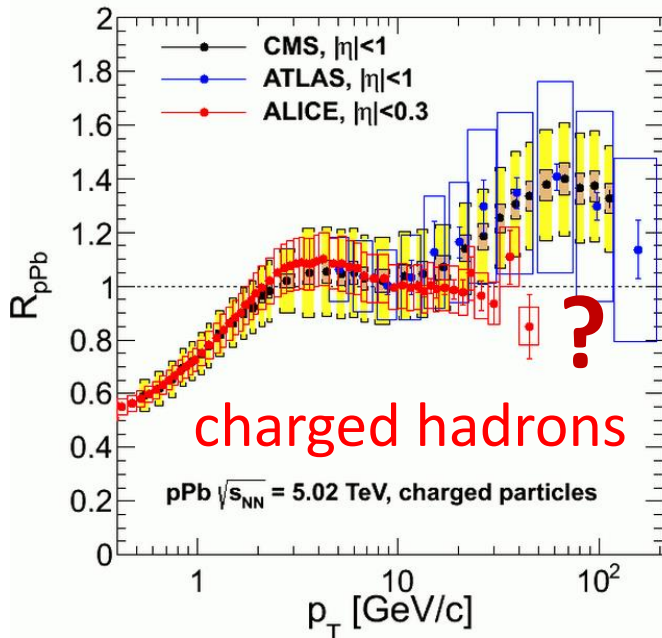


Λ/K_S^0 ratio in charged jets in p-Pb and Pb-Pb significantly lower than inclusive and pp

Jet composition is not influenced by the enhanced baryon/meson production in the bulk.

Cold nuclear matter effects on particle and jet production

Modification of particle and jet production in p-Pb collisions ?



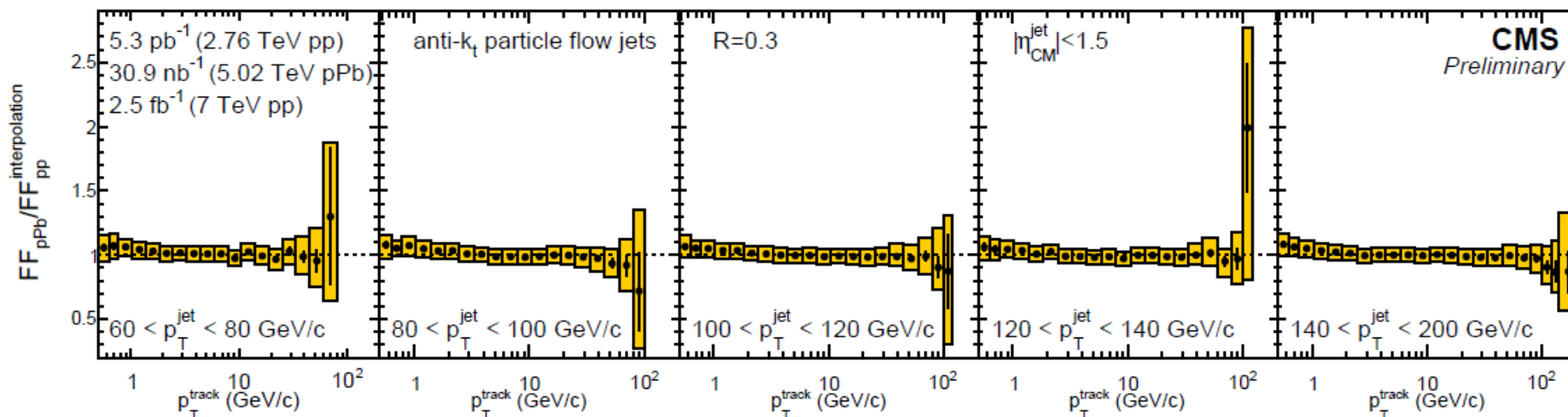
- single particle R_{pPb} : tension at high p_T between ALICE and ATLAS/CMS
- jet fragmentation: ATLAS observed modification in pPb

At the same time inclusive jet production is not modified in pPb, agreement across experiments.

Is it in the pp @ 5 TeV reference?

Note: no measured pp reference at 5 TeV exists, different interpolations used by individual experiments.

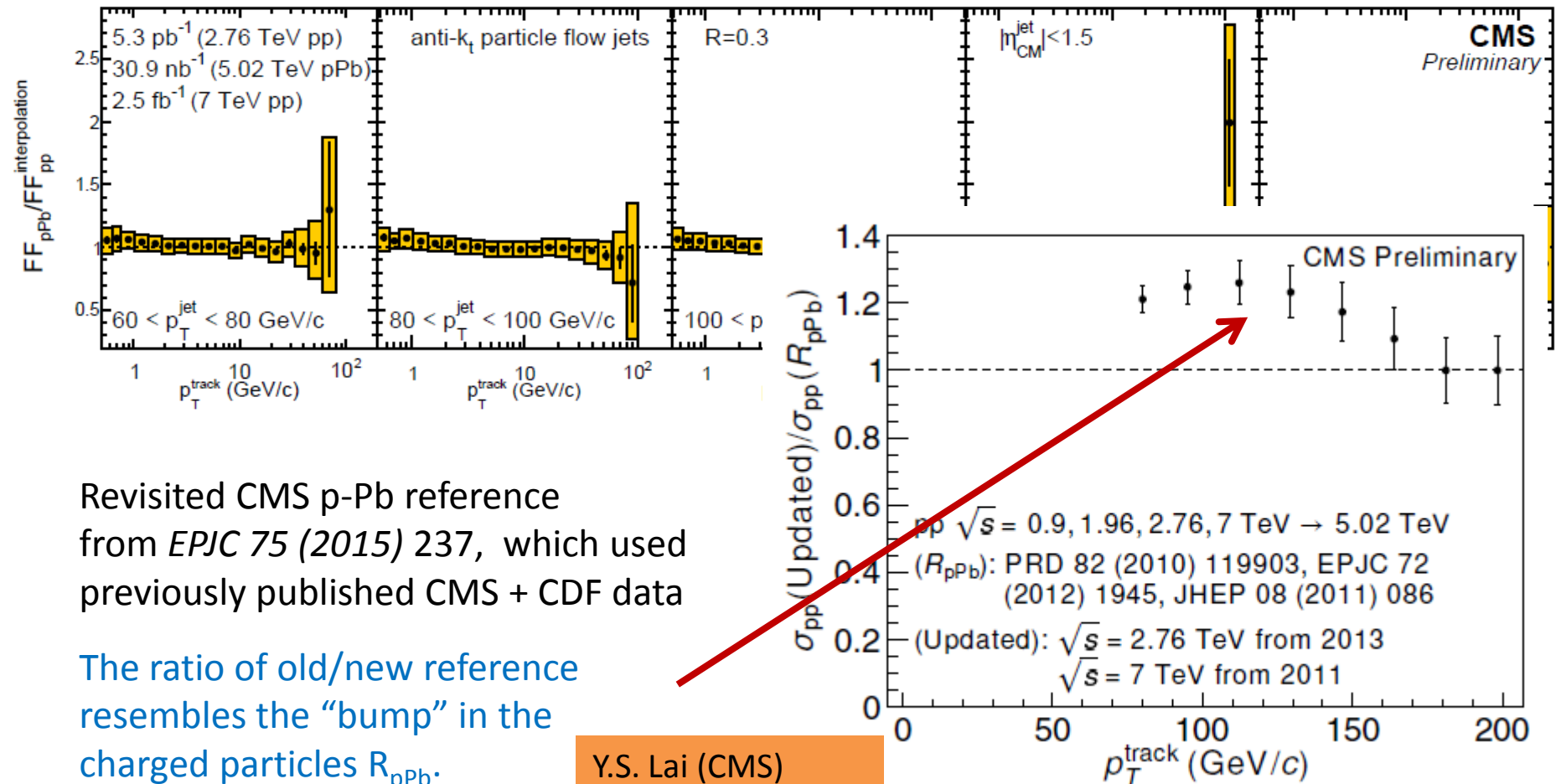
CMS does not observe modification of jet fragmentation in pPb collisions in contrast to ATLAS.



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Note: no measured pp reference at 5 TeV exists, different interpolations used by individual experiment.

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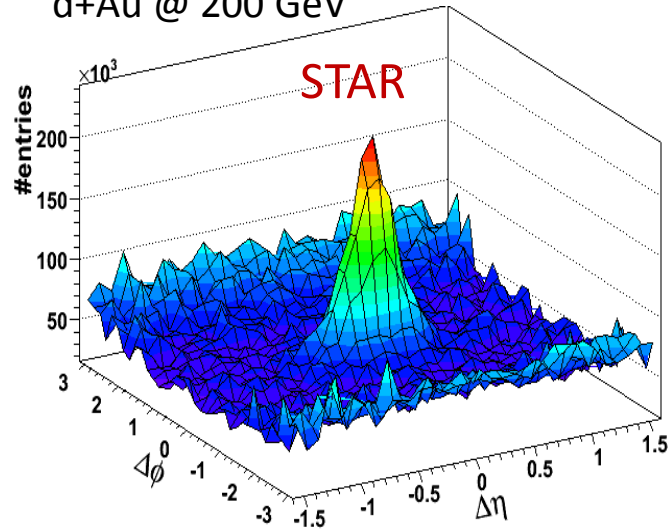


Y.S. Lai (CMS)
Hard Probes 2015

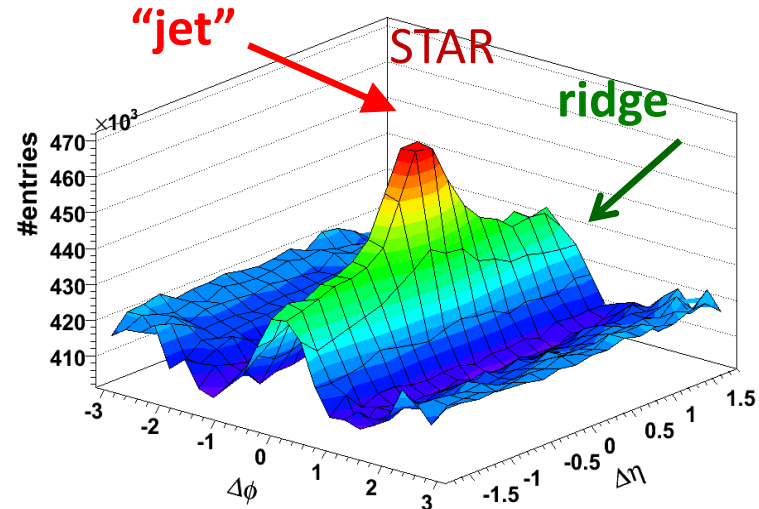
Ridge

The ridge phenomenon ...

d+Au @ 200 GeV

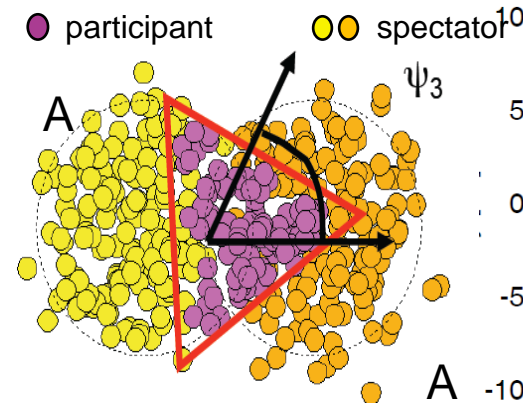


0-12% Au+Au @ 200 GeV



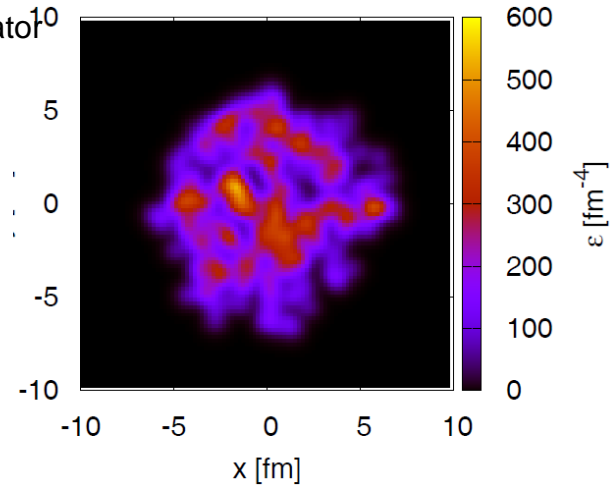
$p_T^{\text{trig}} = 3-4 \text{ GeV}/c, 2 \text{ GeV}/c < p_T^{\text{assoc}} < p_T^{\text{trig}}$

STAR: PRC80 (2009) 064912



Alver, Roland,
PRC81 (2010) 054905

$\tau = 0.4 \text{ fm}/c$



3+1D viscous hydrodynamics

Schenke, Jeon, Gale,
PRL 106 (2011) 042301

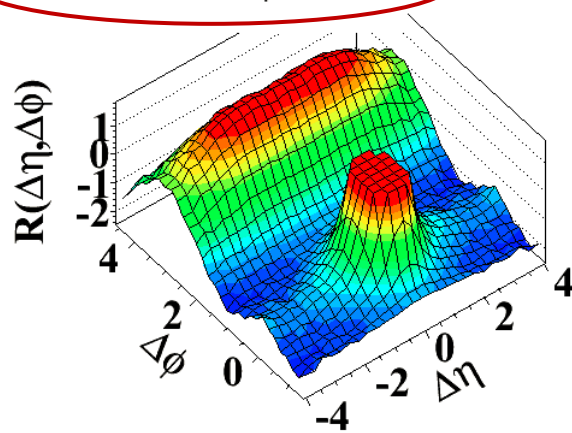
Additional near-side ($\Delta\phi$) correlation in pseudorapidity ($\Delta\eta$) observed in central Au+Au collisions at RHIC in 2004.

Many physics scenarios have been suggested. The near-side ridge probably originates from **initial state fluctuations**, which give a rise to a new „triangular flow“ (v_3).

Collectivity in small systems: the LHC ridges

High multiplicity pp @ 7 TeV

(d) $N > 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

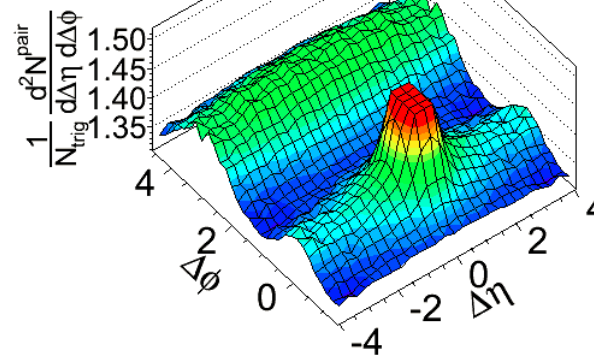


CMS, JHEP09 (2010) 091

pPb @ 5.02 TeV

CMS pPb $\sqrt{s} = 5.02 \text{ TeV}$, $N \geq 110$

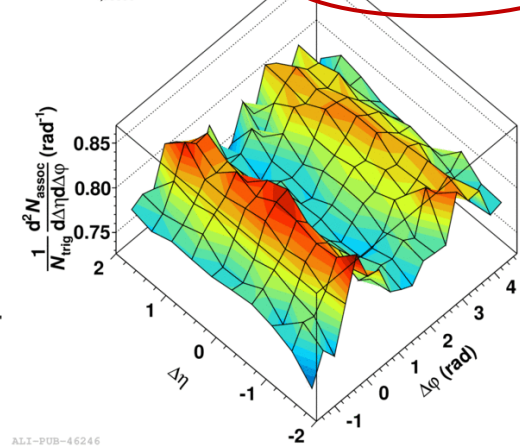
$1 < p_T^{\text{trig}} < 2 \text{ GeV}/c$
 $1 < p_T^{\text{assoc}} < 2 \text{ GeV}/c$



CMS, PLB 718 (2012) 795

$2 < p_{T,\text{trig}} < 4 \text{ GeV}/c$
 $1 < p_{T,\text{assoc}} < 2 \text{ GeV}/c$

p-Pb | $s_{NN} = 5.02 \text{ TeV}$
 (0-20%) - (60-100%)



ALI-PUB-46246

ALICE, PLB 719 (2013) 29

Similarity of the ridges in pp, pA and AA:

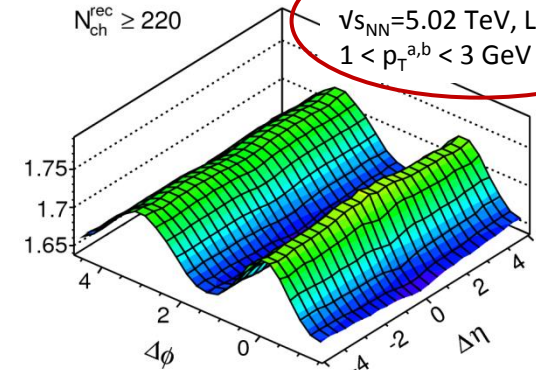
Common hydrodynamical origin?

But can hydrodynamical models be reliably applied in small systems?

Initial state effects (gluon saturation, extended color connections in longitudinal direction) or final-state parton-parton induced interactions?

$N_{\text{ch}}^{\text{rec}} \geq 220$

ATLAS p+Pb,
 $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, $L_{\text{int}} \approx 28 \text{ nb}^{-1}$
 $1 < p_T^{a,b} < 3 \text{ GeV}$



ATLAS, PRC 90 (2014) 044906

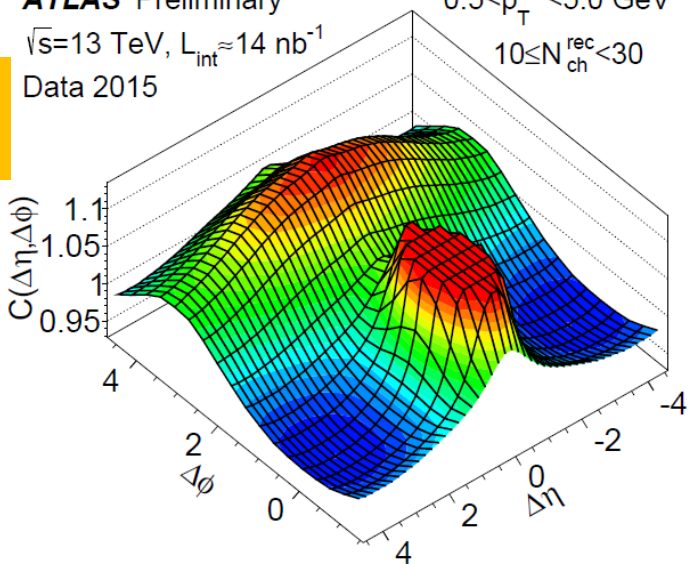
NEW!

Ridge persists in 13 TeV pp collisions

low multiplicity

ATLAS Preliminary
 $\sqrt{s}=13$ TeV, $L_{\text{int}} \approx 14$ nb $^{-1}$
Data 2015

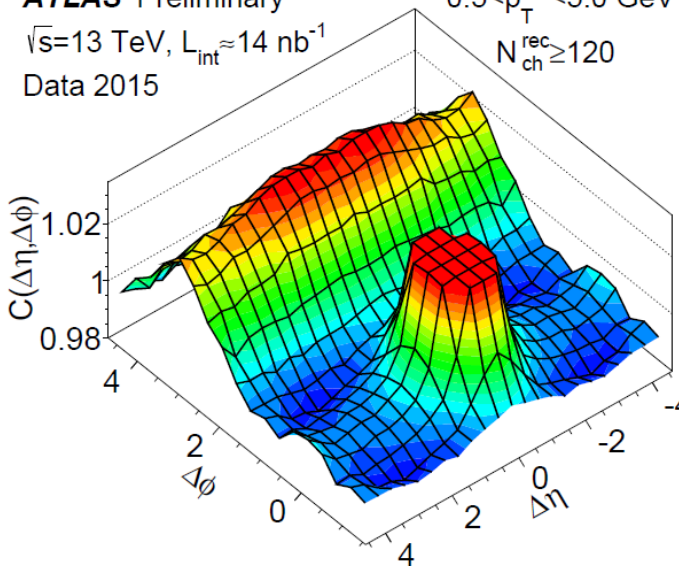
$0.5 < p_T^{a,b} < 5.0$ GeV
 $10 \leq N_{\text{ch}}^{\text{rec}} < 30$



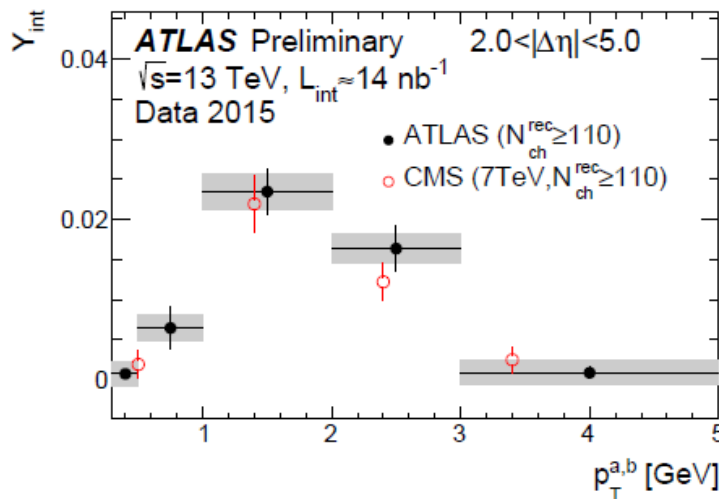
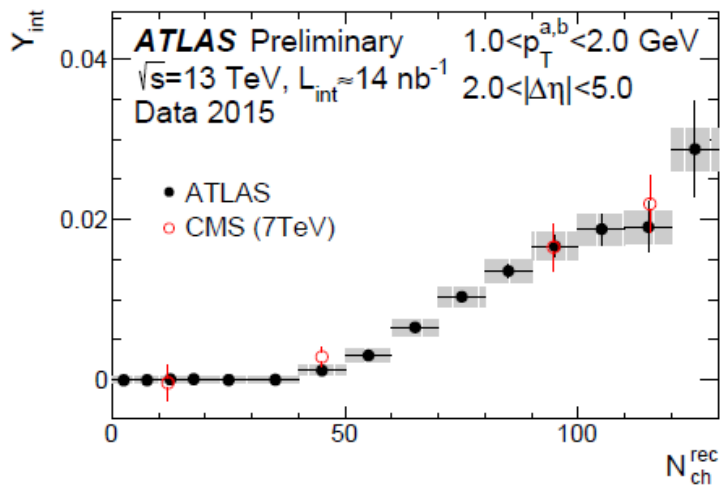
high multiplicity

ATLAS Preliminary
 $\sqrt{s}=13$ TeV, $L_{\text{int}} \approx 14$ nb $^{-1}$
Data 2015

$0.5 < p_T^{a,b} < 5.0$ GeV
 $N_{\text{ch}}^{\text{rec}} \geq 120$



M. Arratia
(ATLAS)
Fri 11:30



Very similar ridge properties at 7 and 13 TeV!
Looking forward to see the “ v_n ” study and more precision data!

NEW!

p-Pb ridge present at forward rapidity

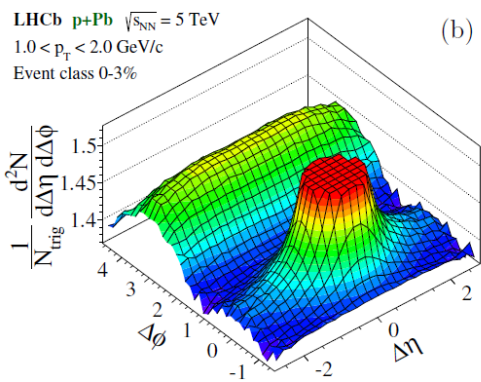
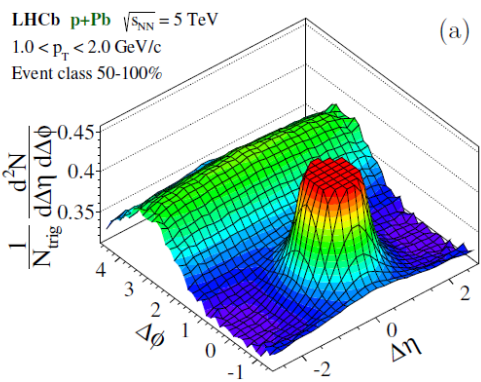
Correlations of charged particles in forward direction: $2 < \eta < 4.9$

M. Meissner (LHCb)
Thu 11:50

low multiplicity

high multiplicity

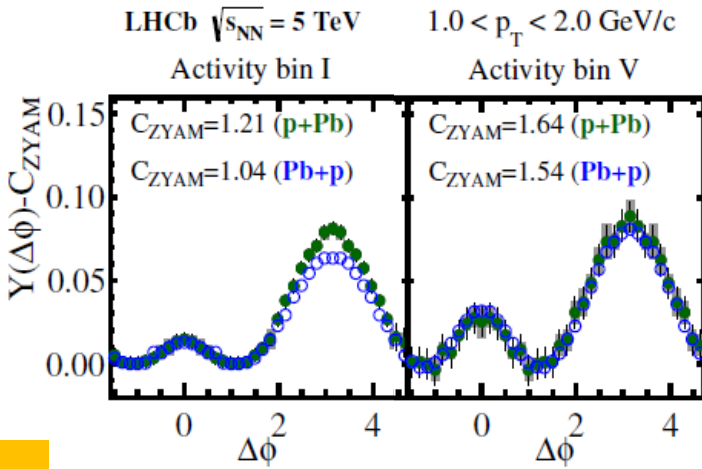
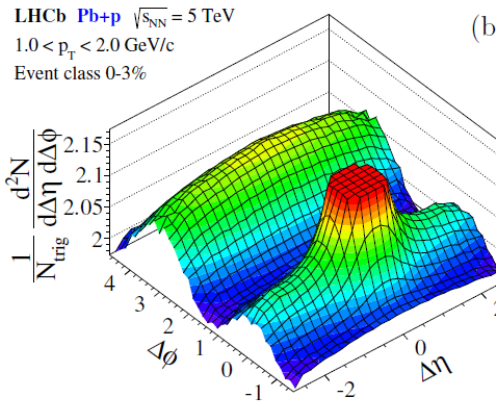
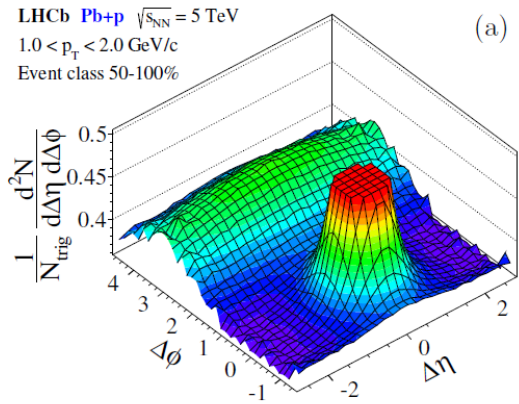
p+Pb



Ridge observed in high multiplicity p+Pb collisions in forward direction as well!

Ridge more pronounced in **Pb+p** than **p+Pb** hemisphere ...

Pb+p



The near-side ridges in both hemispheres are the same when evaluated in same absolute activity bins.

p-Pb ridges extend to large rapidities

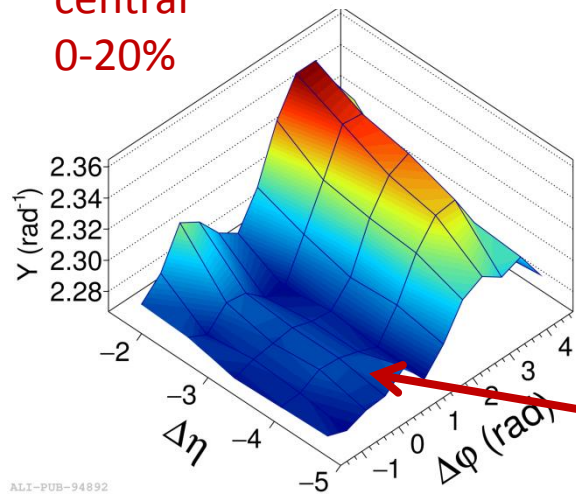
ALICE, p-Pb $\sqrt{s_{NN}}=5.02$ TeV, muon-tracklet correlations with $0.5 < p_T < 1$ GeV/c

J.F. Grosse-Oetringhaus (ALICE), Thu 16:50

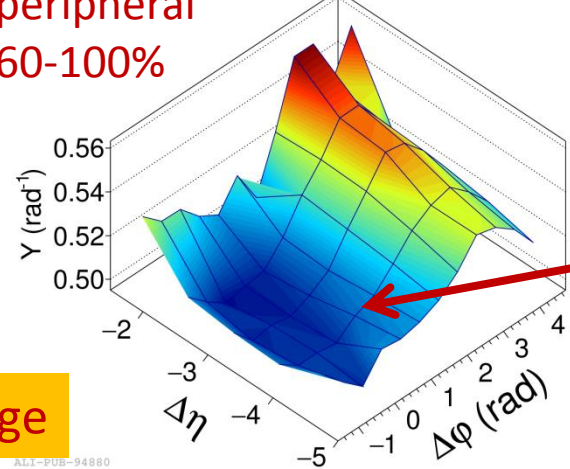
ALICE, arXiv: 1506.08032

central
0-20%

peripheral
60-100%



ridge

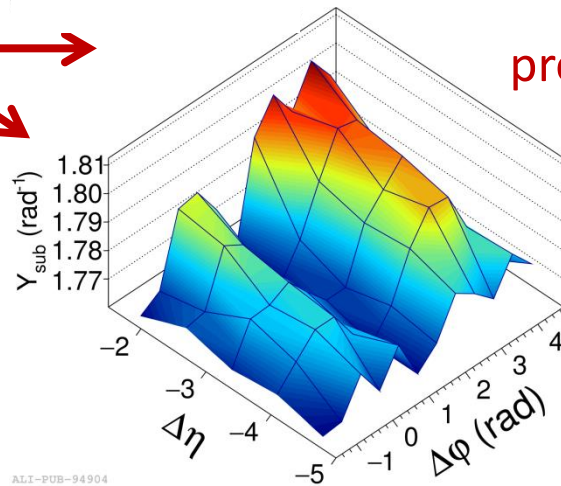


no ridge

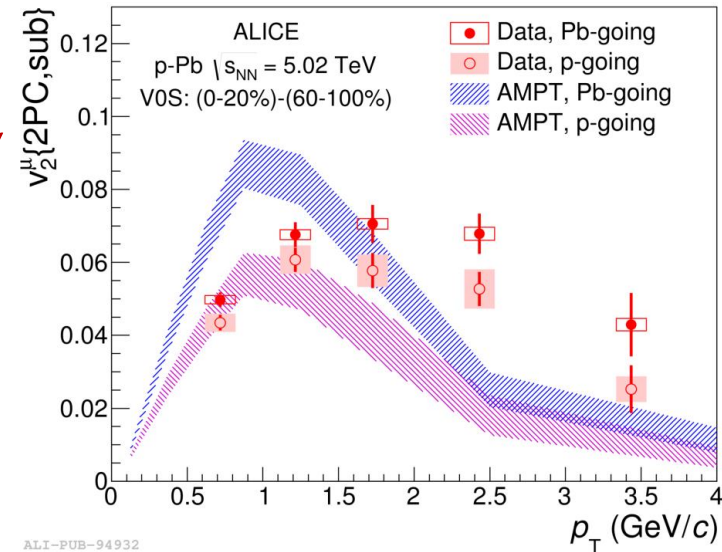
Double ridge extends over 10 units of rapidity.

(0-20%)- (60-100%)

2 ridges



project onto $\Delta\phi$, calculate " v_2 "



ALI-PUB-94932

ALI-PUB-94904

ALI-PUB-94880

ALI-PUB-94892

Evidence for collectivity in p-Pb?

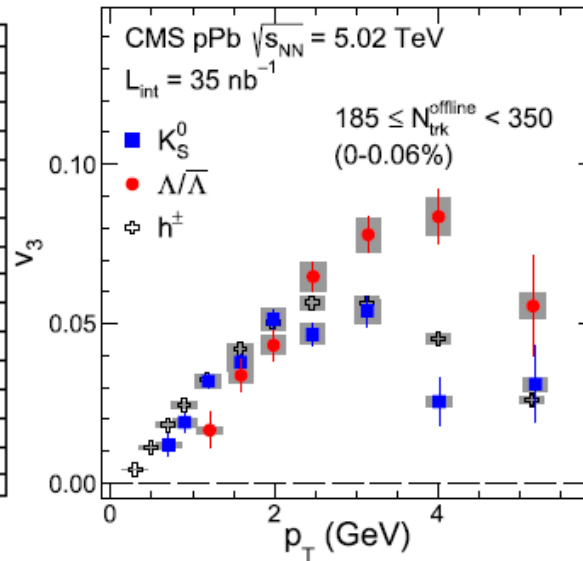
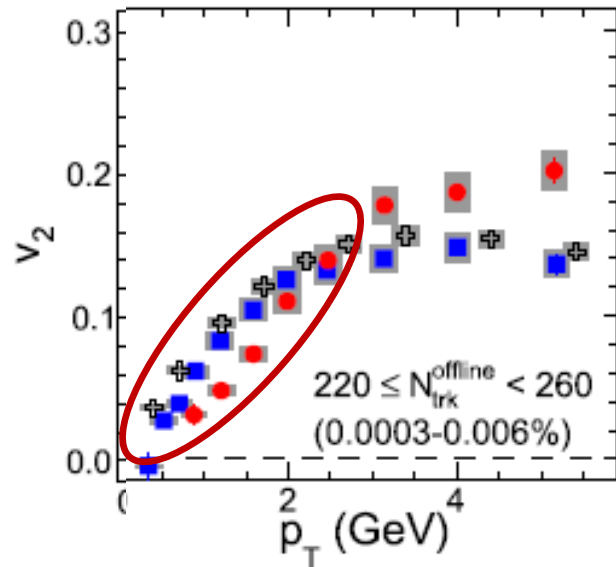
D. Devetak (CMS)
Thu 16:30

Mass ordering in v_2 resembling hydro picture observed earlier at low p_T in p, π and K by ALICE.

ALICE: PLB 726 (2013) 164

It is now confirmed by the CMS data for Λ and K_S^0 .

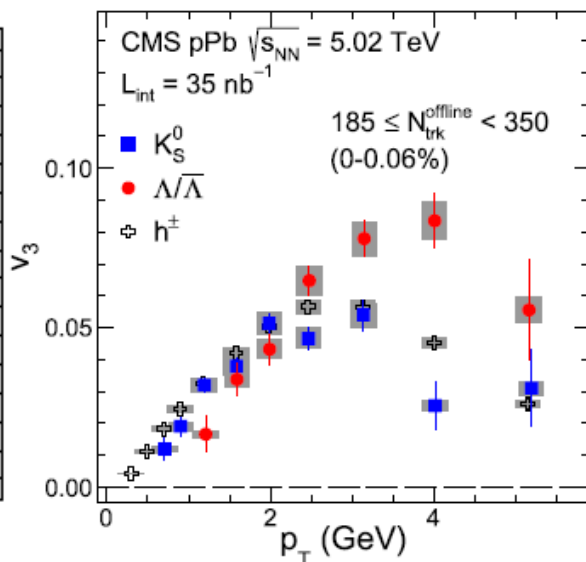
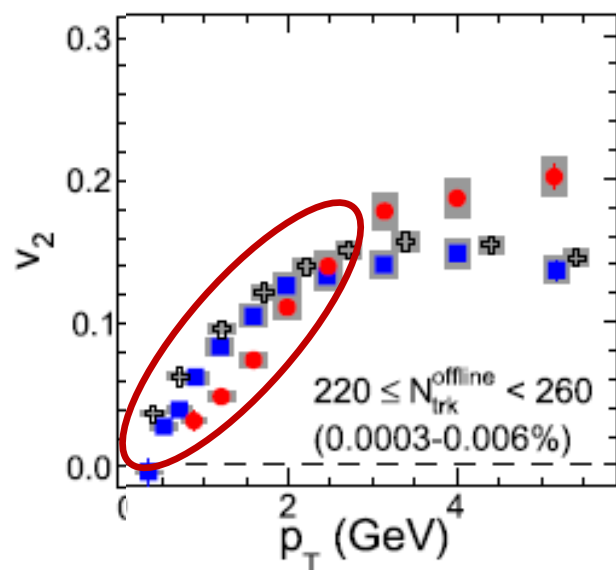
CMS, PLB 742 (2015) 200



Evidence for collectivity in p-Pb?

D. Devetak (CMS)
Thu 16:30

CMS, PLB 742 (2015) 200

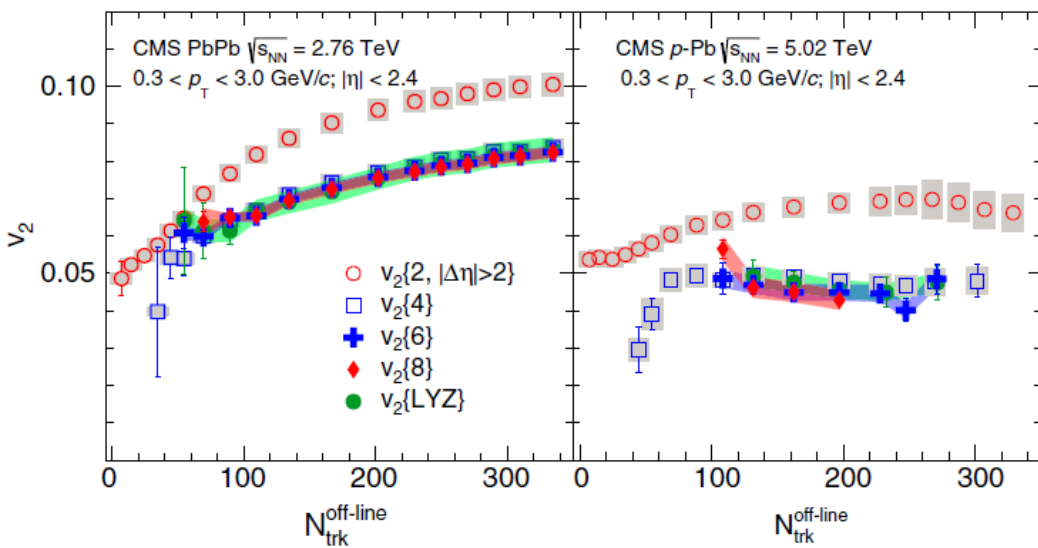


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ALICE: PLB 726 (2013) 164

It is now confirmed by the CMS data for Λ and K_S^0 .

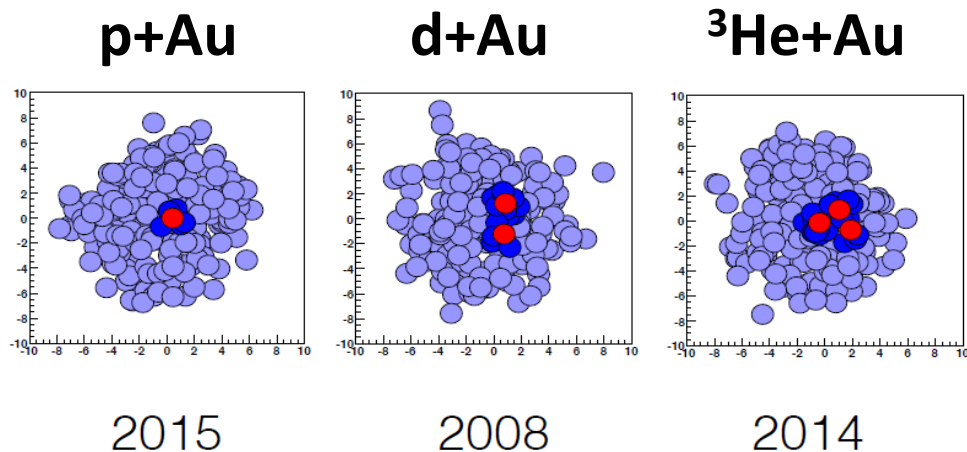
CMS, PRL 115 (2015) 012301



Multiparticle correlations (4-8) as well as Lee-Yang-Zero studies give consistent " v_2 " values. Proof of collectivity!

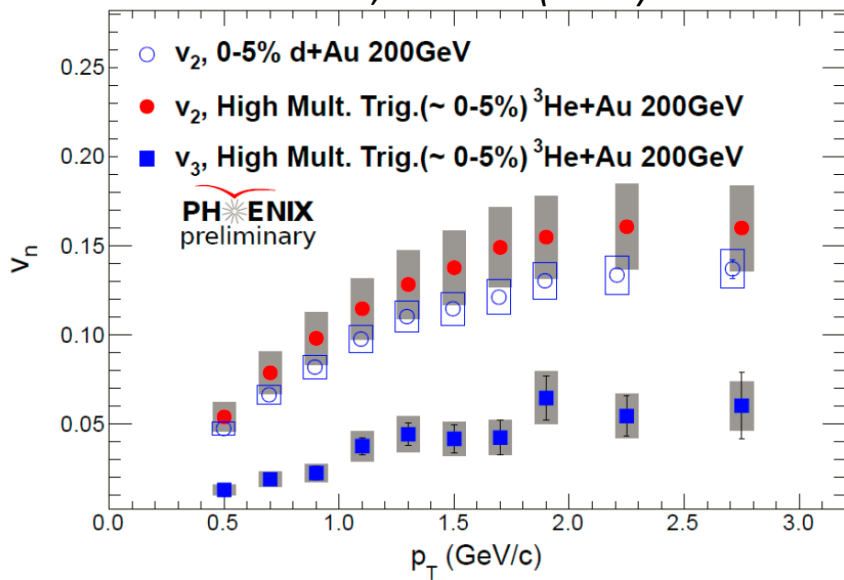
Can data from RHIC bring further insights?

Courtesy A. Sickles (PHENIX)

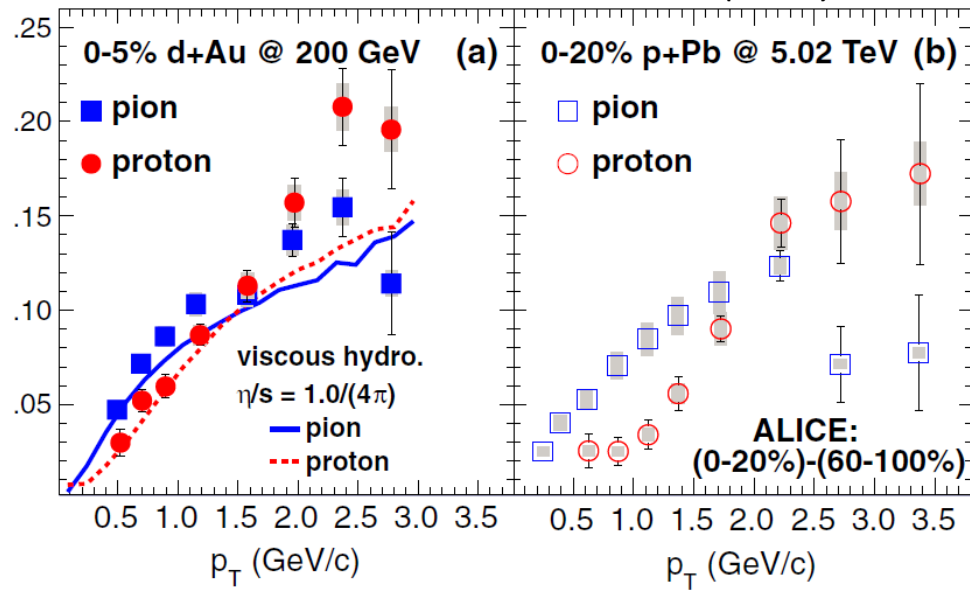


RHIC has unique capabilities to study variations in the initial state.

d+Au: PHENIX, *PRL* 111 (2013) 212301



PHENIX, *PRL* 114 (2015) 192301



Evidence for ridge in d+Au and ³He+Au collisions at 0.2 TeV at RHIC:
 non-zero v_2 , particle mass ordering

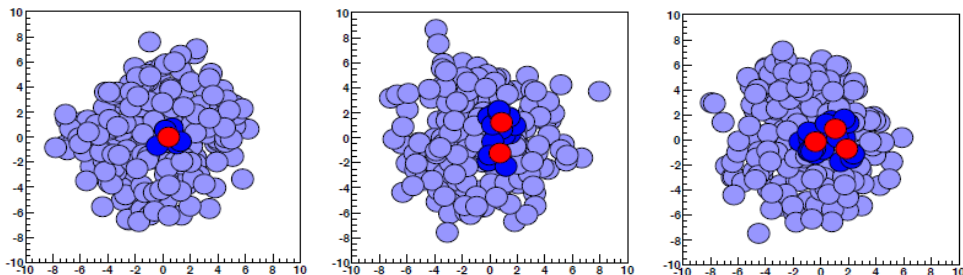
Can data from RHIC bring further insights?

Courtesy A. Sickles (PHENIX)

p+Au

d+Au

$^3\text{He}+\text{Au}$



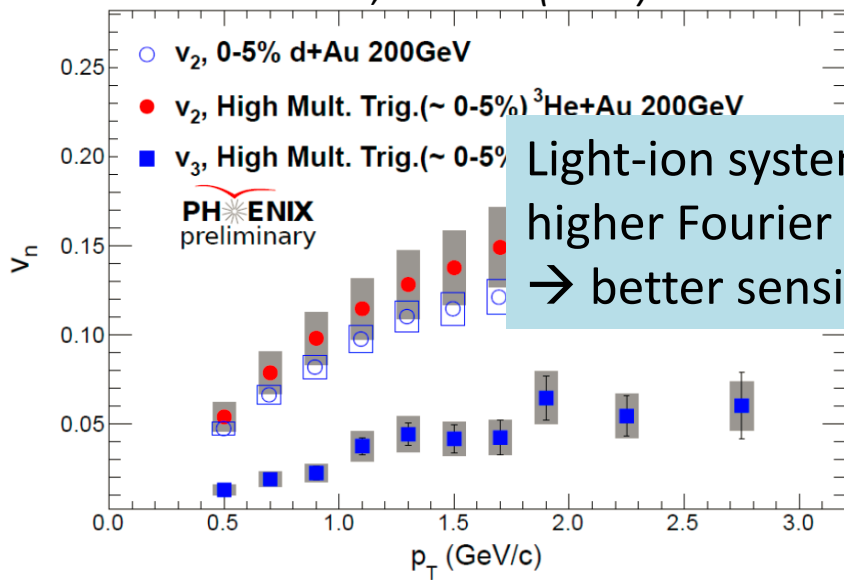
2015

2008

2014

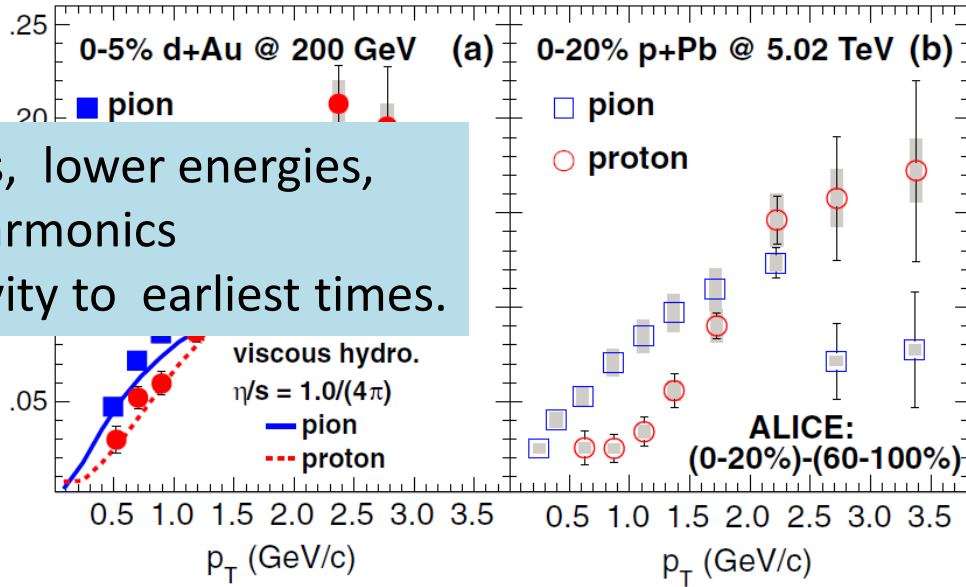
RHIC has unique capabilities to study variations in the initial state.

d+Au: PHENIX, *PRL* 111 (2013) 212301



Light-ion systems, lower energies, higher Fourier harmonics
 → better sensitivity to earliest times.

PHENIX, *PRL* 114 (2015) 192301



Evidence for ridge in d+Au and $^3\text{He}+\text{Au}$ collisions at 0.2 TeV at RHIC:
 non-zero v_2 , particle mass ordering

Summary

- wealth of new data on jets and correlations from Run 1 at the LHC as well as from RHIC experiments came since EPS-HEP 2013

(my apologies, it was not possible to show all of them today)

jets in A+A collisions: measurements of inclusive jet production are now accompanied with important information on several jet structure observables which should improve our understanding of the hot and dense matter

high-multiplicity p+p and p+Pb collisions: ridge phenomenon quantified in a great detail, but satisfactory theoretical understanding across collision systems and energies missing

 **for the EPS-HEP conference:** ridge measurements extended to pp @ 13 TeV and forward rapidities in p+Pb

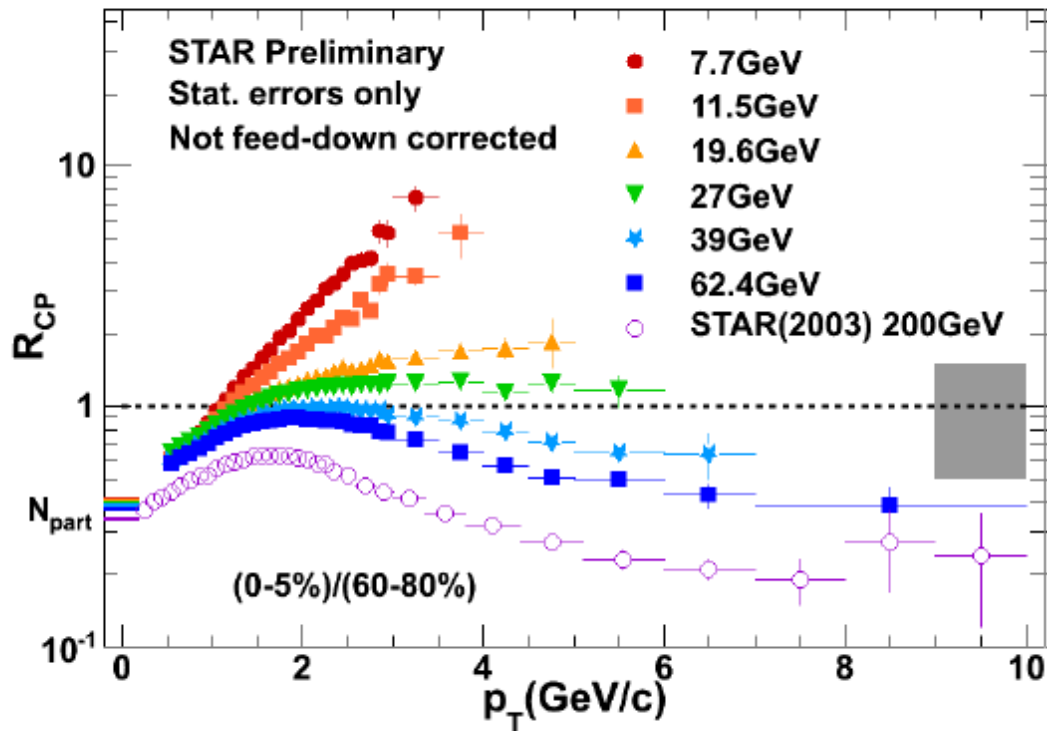
- looking forward to Run2 data at the LHC as well as high statistics runs at RHIC to pin down medium properties and possible collective effects in small collision systems !

THANK YOU!

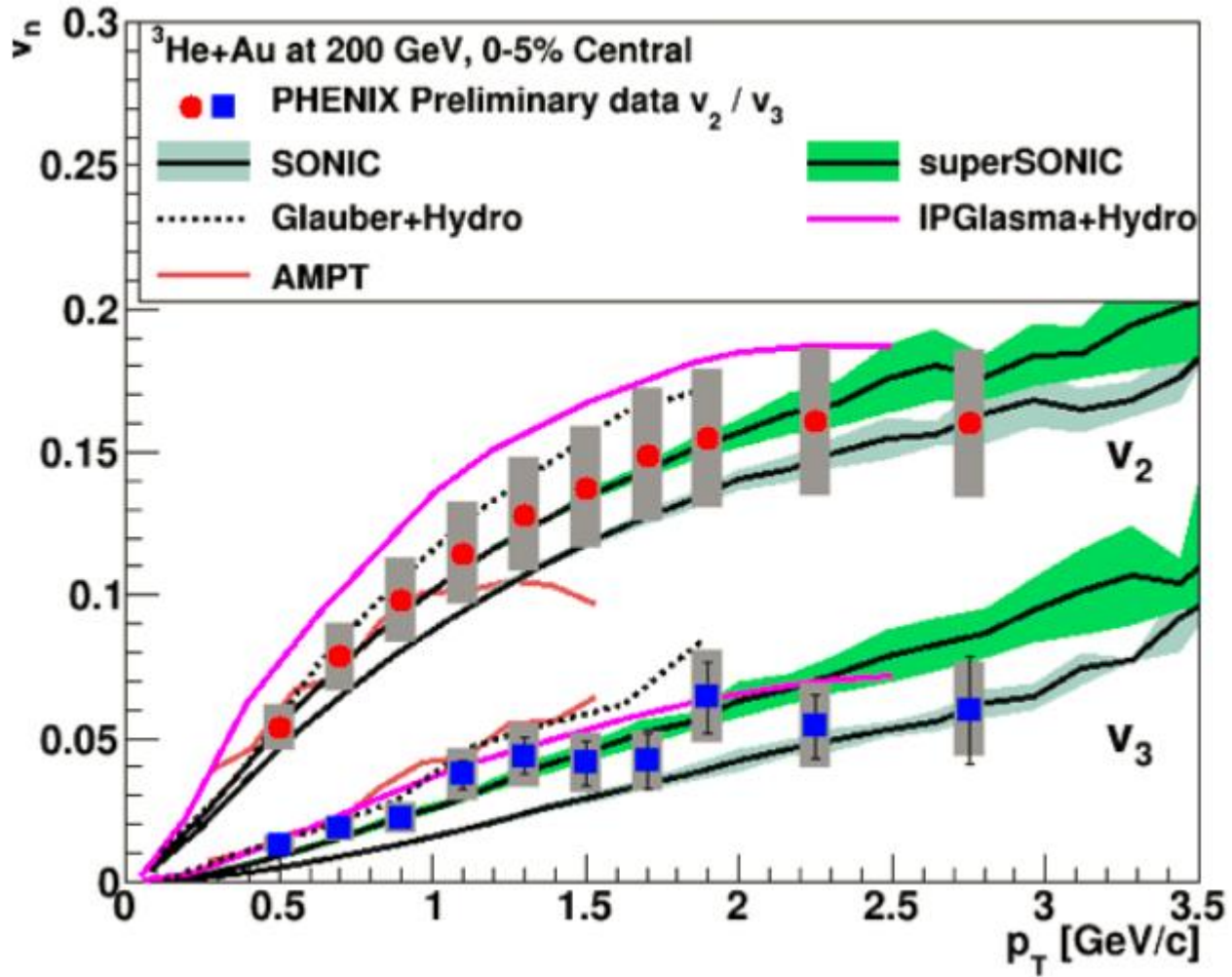
BACKUP slides

RHIC BES: charged particle R_{CP}

around $\sqrt{s_{NN}} = 27-39$ GeV turning point:
unquenched \rightarrow quenched particle production

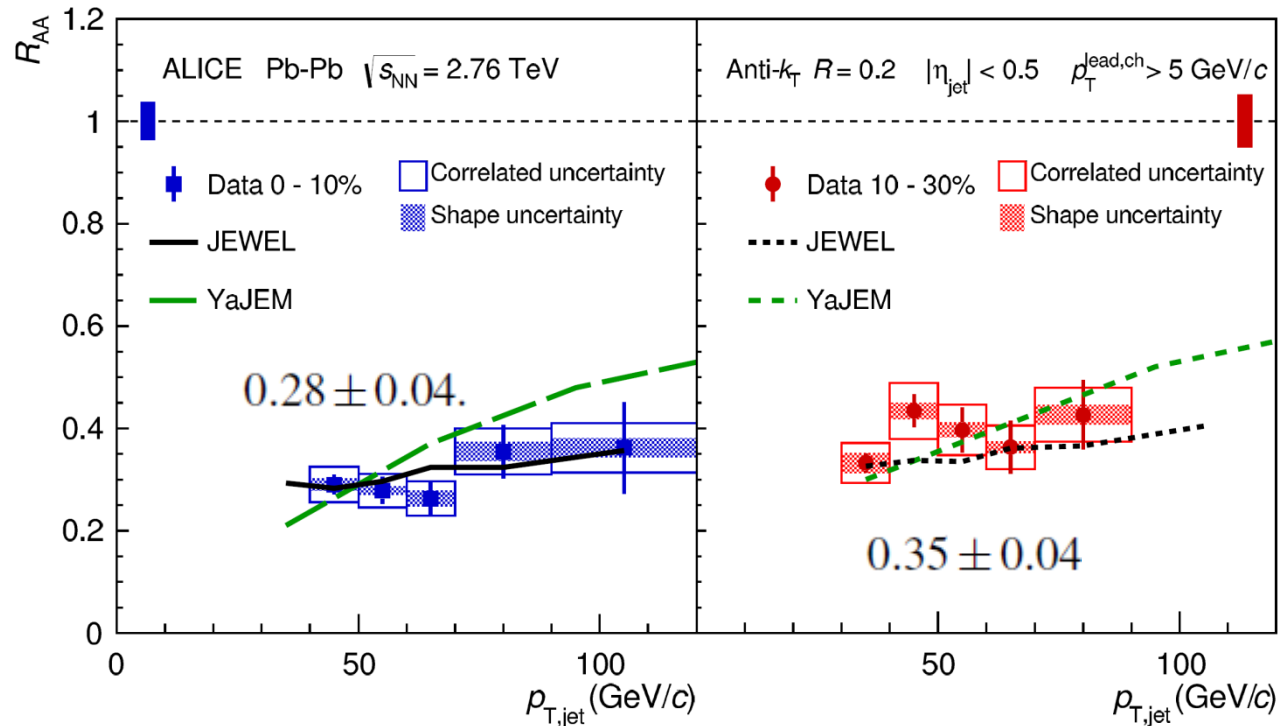


$^3\text{He}+\text{Au}$ vs models



Full jet suppression in Pb-Pb collisions

Phys.Lett. B746 (2015) 1, [arXiv:1502.01689](https://arxiv.org/abs/1502.01689)



JEWEL: K. Zapp, F. Kraus,
 U. Wiedemann
JHEP 1303 (2013) 080
Eur.Phys.J. C74 (2014) 2762

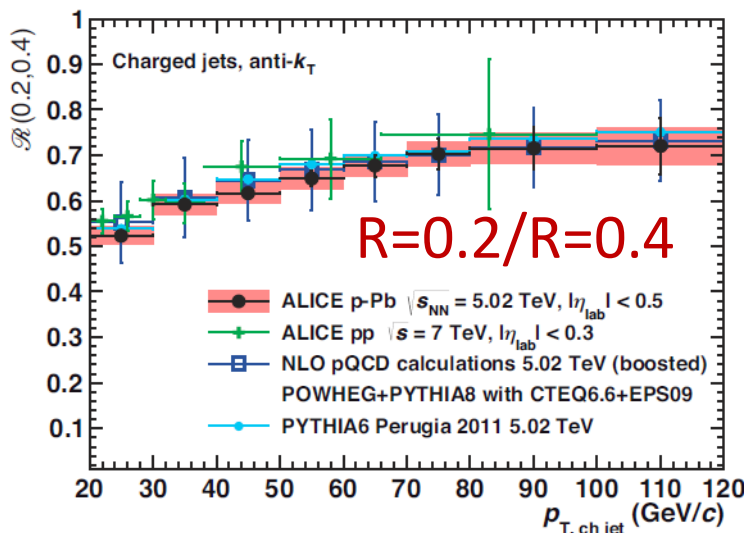
YaJEM: T. Renk,
PRC 78 (2008) 034908,
PRC 84 (2011) 067902

- well-established models: realistic collision geometry, initial state conditions, hadronization
- both use a fit to hadron R_{AA} to tune the free parameters within the model

Both models agree well with data, but YaJEM shows a slightly steeper increase with p_T

→ Jet R_{AA} vs event plane to pin down the path-length dependence of jet quenching
 and to differentiate models

ALICE: Charged jets in p-Pb arXiv:1503.00681

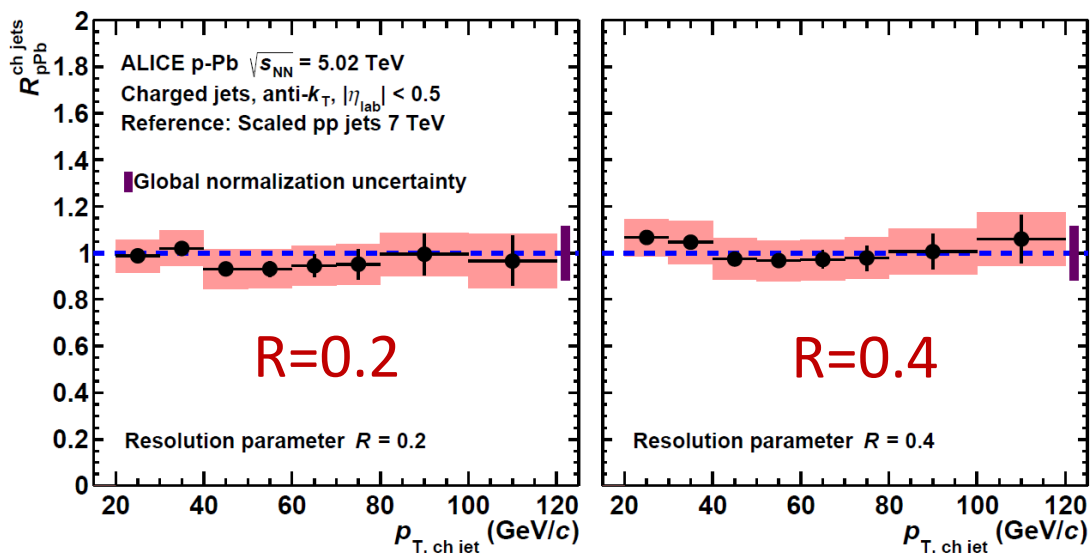


spectra:

agreement with boosted NLO pQCD (POWHEG+PYTHIA8) using nPDFs (CTEQ6.6+EPS09)

$\sigma(R=0.2)/\sigma(R=0.4)$:

jet energy redistribution?
No, p-Pb compatible with pp at 7 TeV, PYTHIA and POWHEG



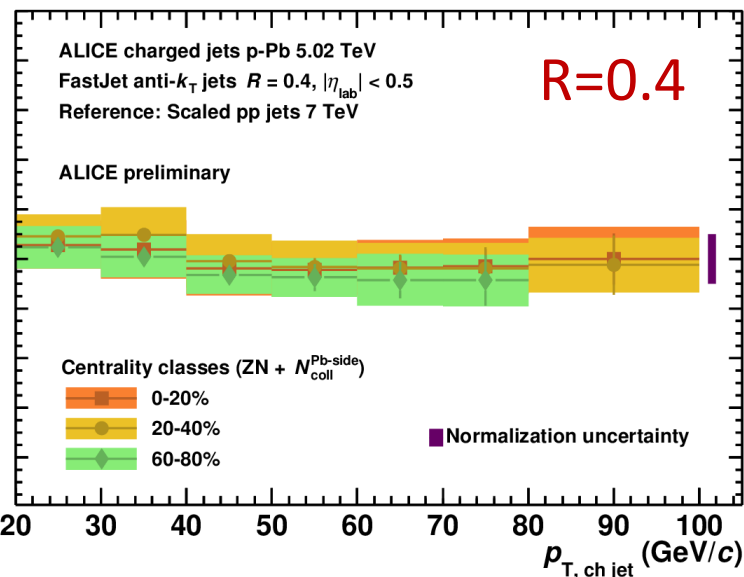
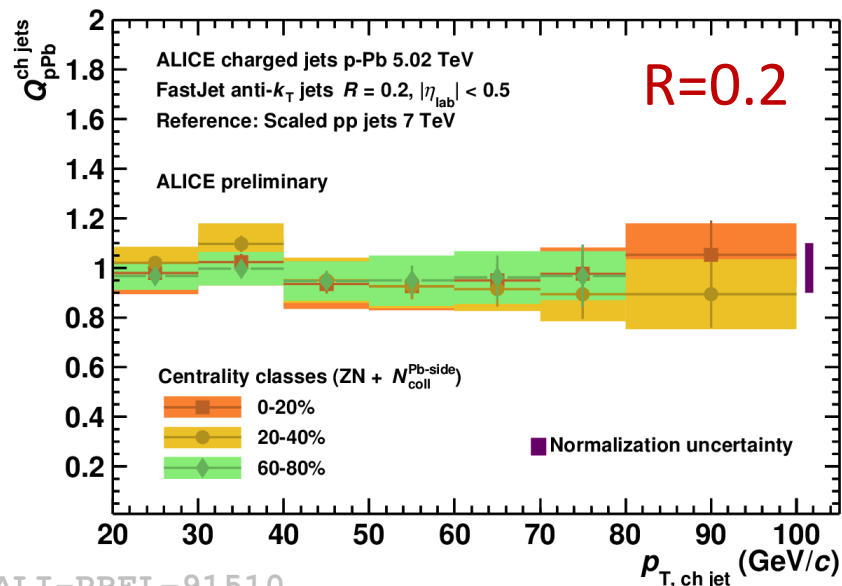
R_{pPb} :

within uncertainties no modification of charged jet spectra observed relative to pp

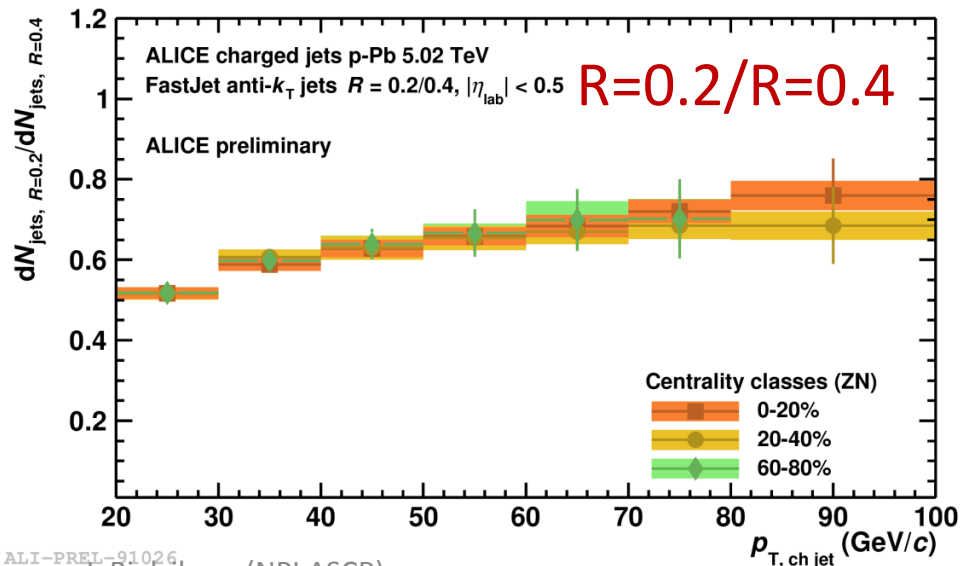
No indication of cold nuclear matter modification of jet production in MB data.

Multiplicity dependence of charged jets in p-Pb

N_{coll} from Pb-side estimator



ALICE-PREL-91510



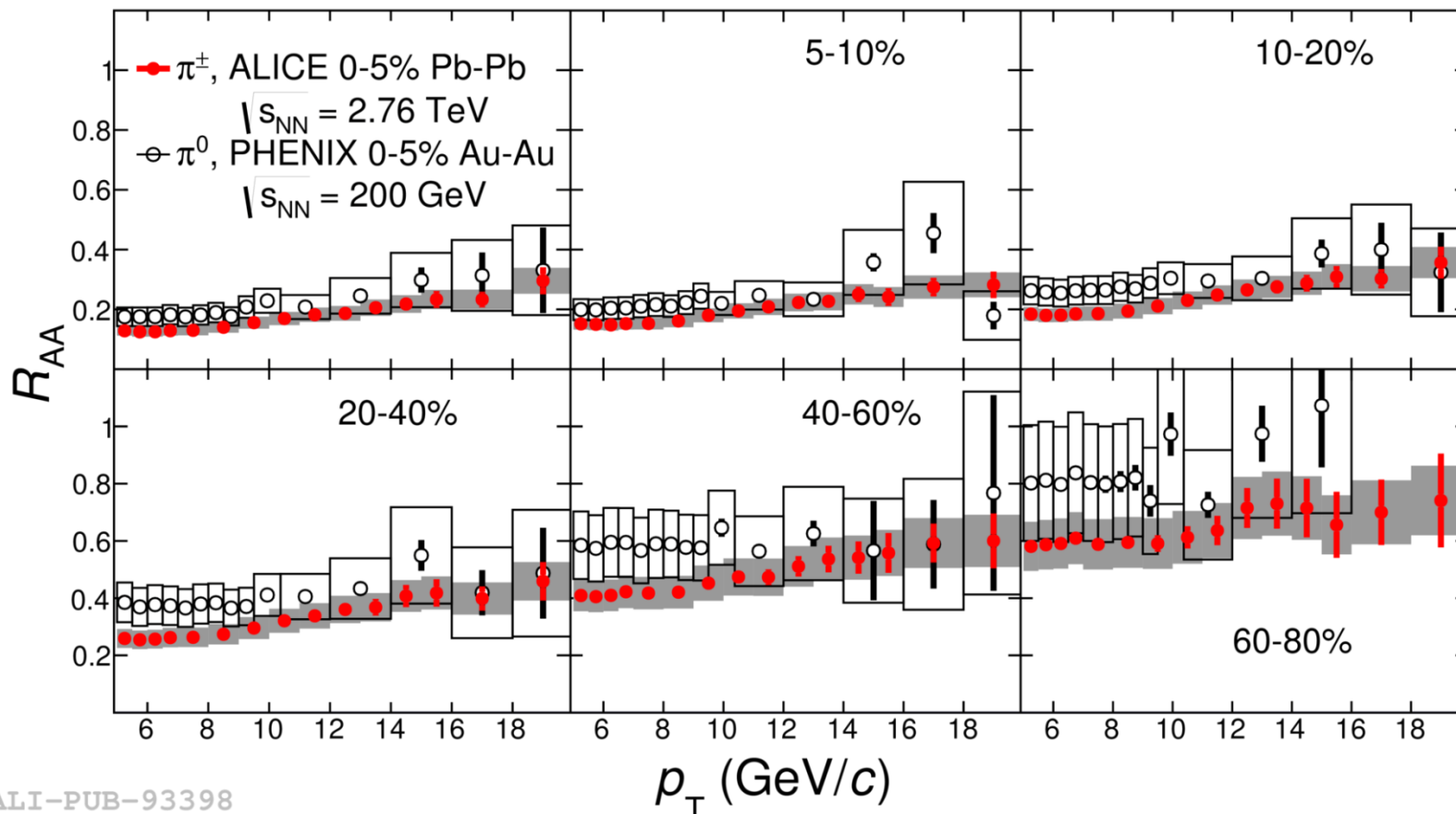
- centrality dependent charged jet Q_{pPb} measured up to 100 GeV/c: consistent with binary scaling
- no modification of jet radial structure

No significant multiplicity dependence or CNM effects observed.

ALICE-PREL-91026

Nuclear modification factor: RHIC vs LHC

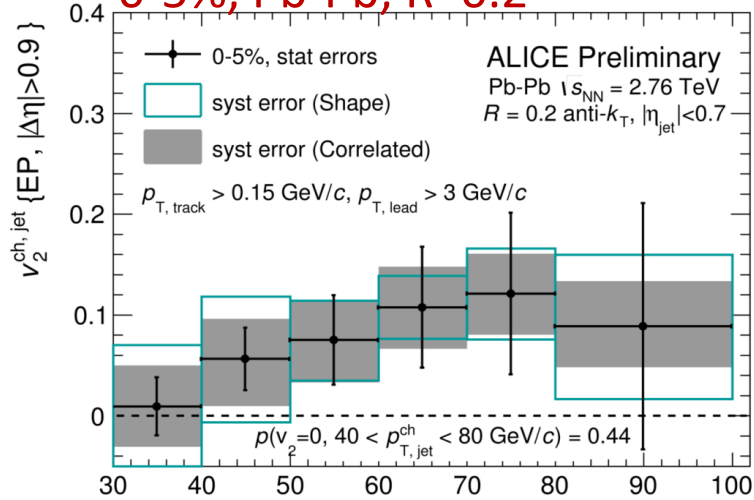
ALICE: arXiv-1506.07287



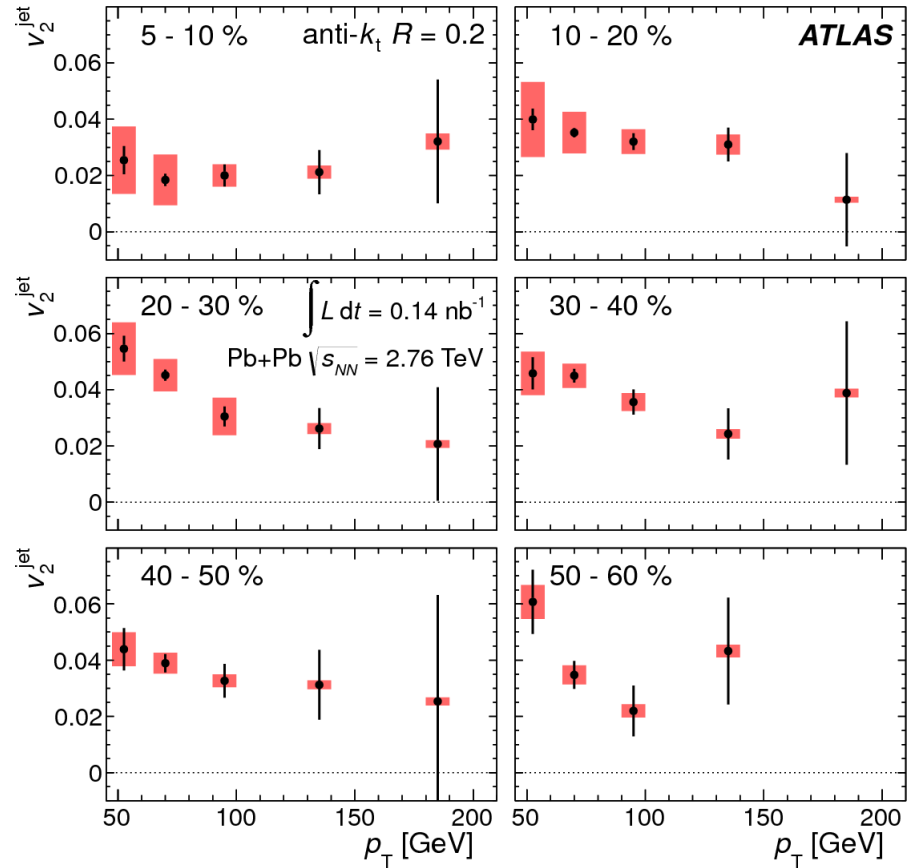
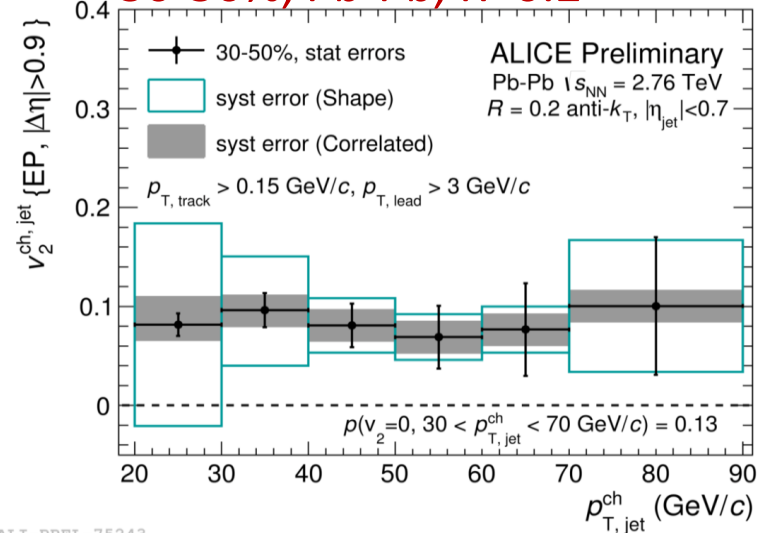
ALI-PUB-93398

Path length effects on jet production

0-5%, Pb-Pb, R=0.2



30-50%, Pb-Pb, R=0.2

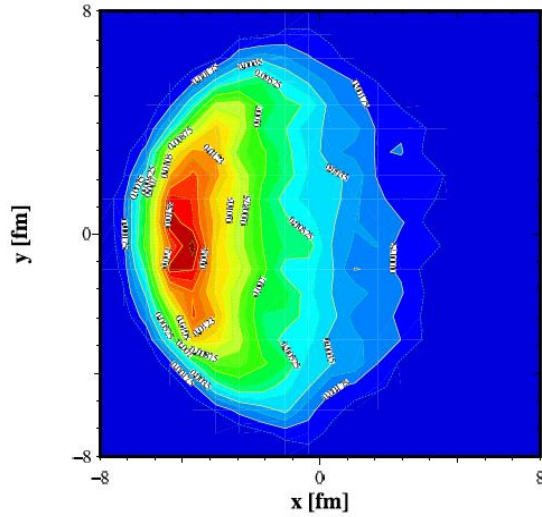


FINISH

Sensitivity of different observable

Renk, Eskola, PRC 75, 054910 (2007)

single h

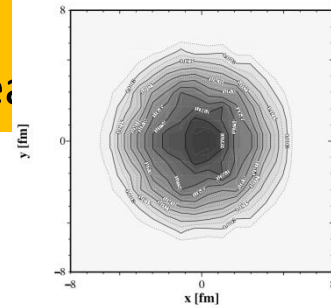


Surface bias dependence:

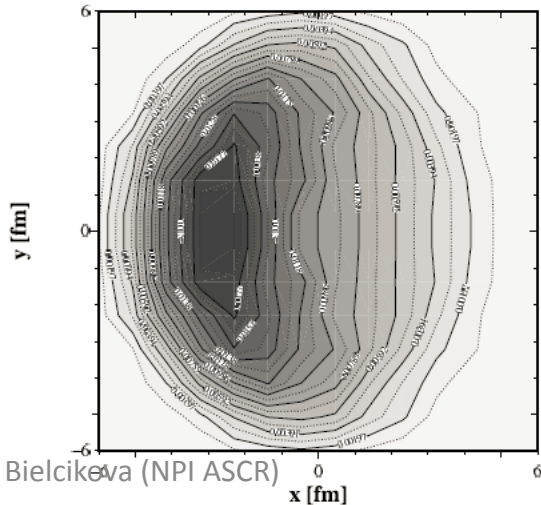
- single hadron and jet-hadron observables: strong surface bias
- di-hadron correlations: show less
- γ , Z- triggered: offer unbiased mea

LHC:
A_J Dijet Trigger
T. Renk, PRC 85, 064908 (2012)
RHIC
T. Renk, PRC 87, 024905 (2013)

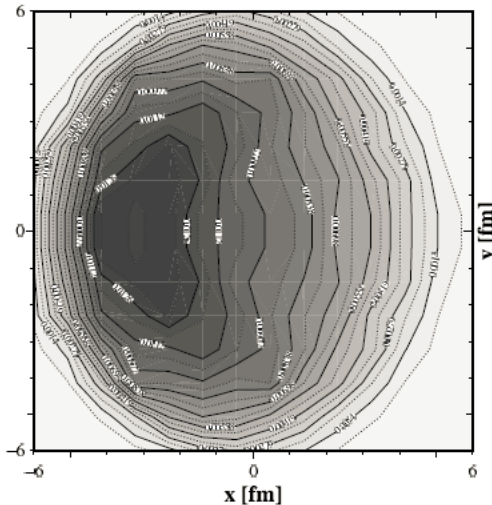
YaJEM, LHC 2+1d hydro



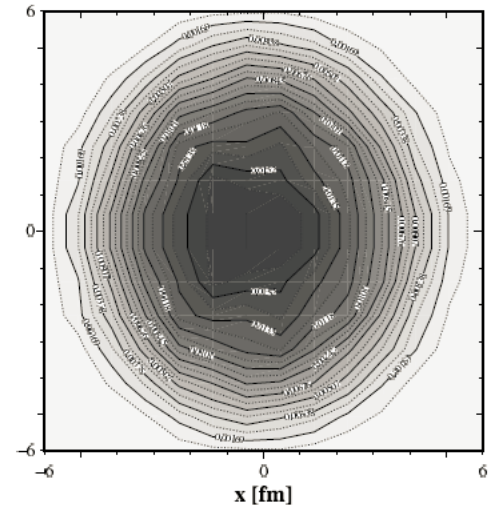
h - h



jet - h



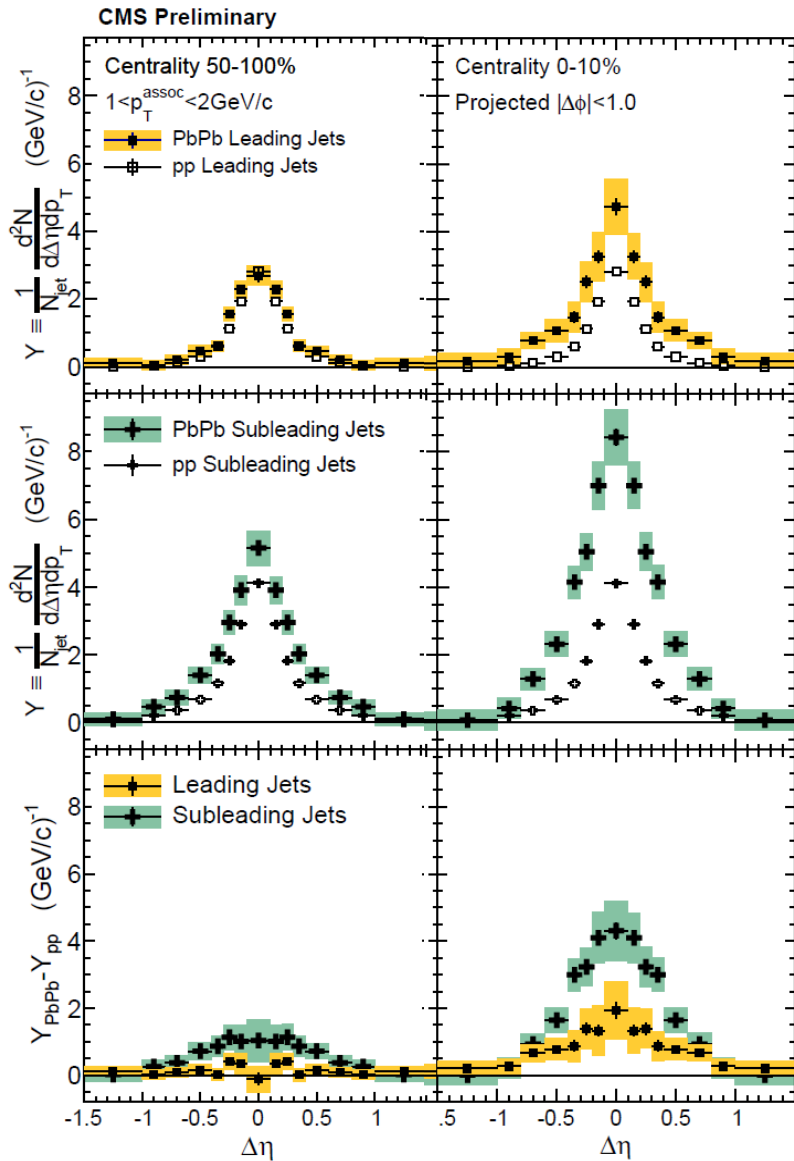
γ - h



T. Renk, YaJEM

J. Bielcikova (NPI ASCR)

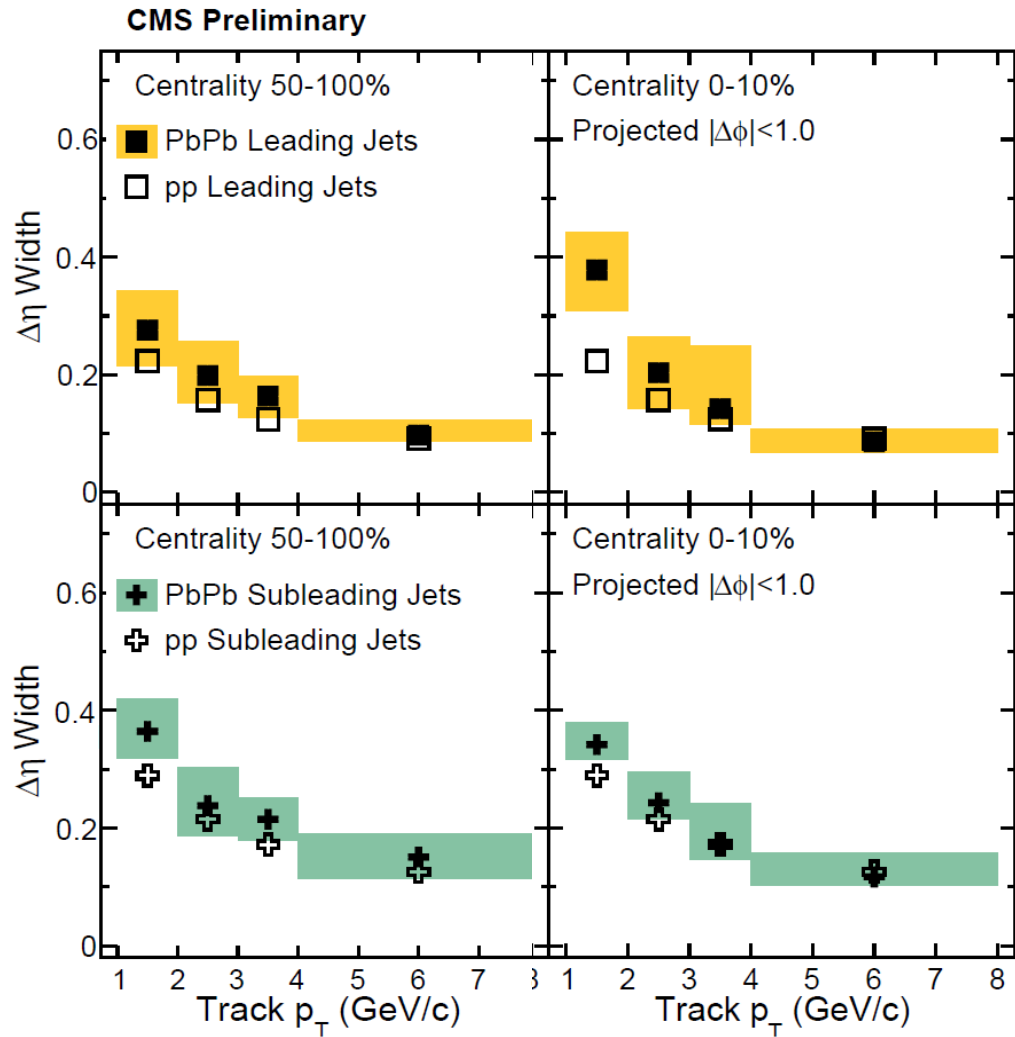
Jet-track correlations in Pb+Pb



J. Bielcikova (NPI ASCR)

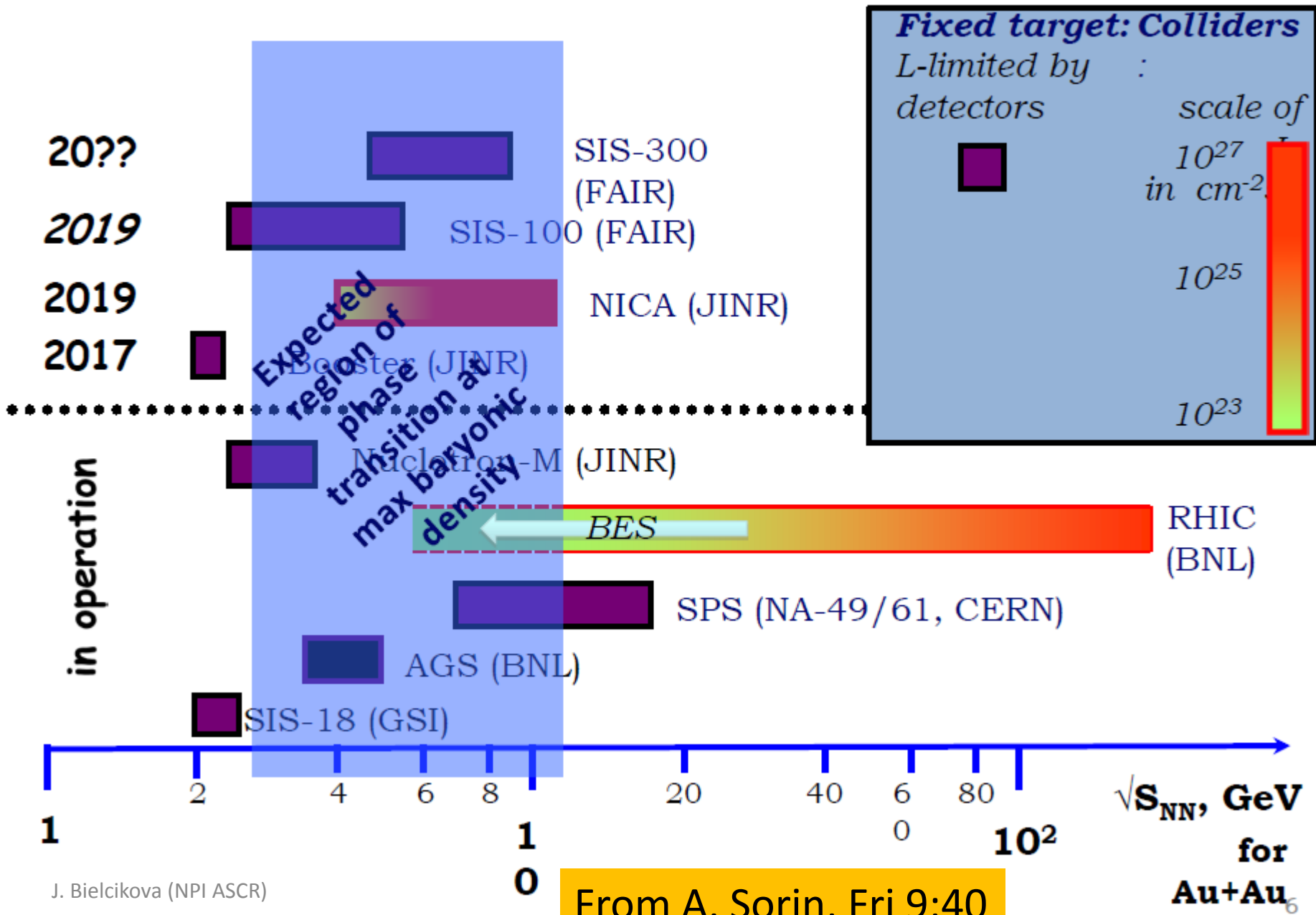
PbPb $166 \mu\text{b}^{-1}$ (2.76 TeV)

pp 5.3 pb^{-1} (2.76 TeV)



anti-kt $R=0.3$: $p_{T,1} > 120$, $p_{T,2} > 50 \text{ GeV}/c$,
 $|\eta_{\text{jet}}| < 1.6$, $\Delta\phi_{1,2} > 5\pi/6$

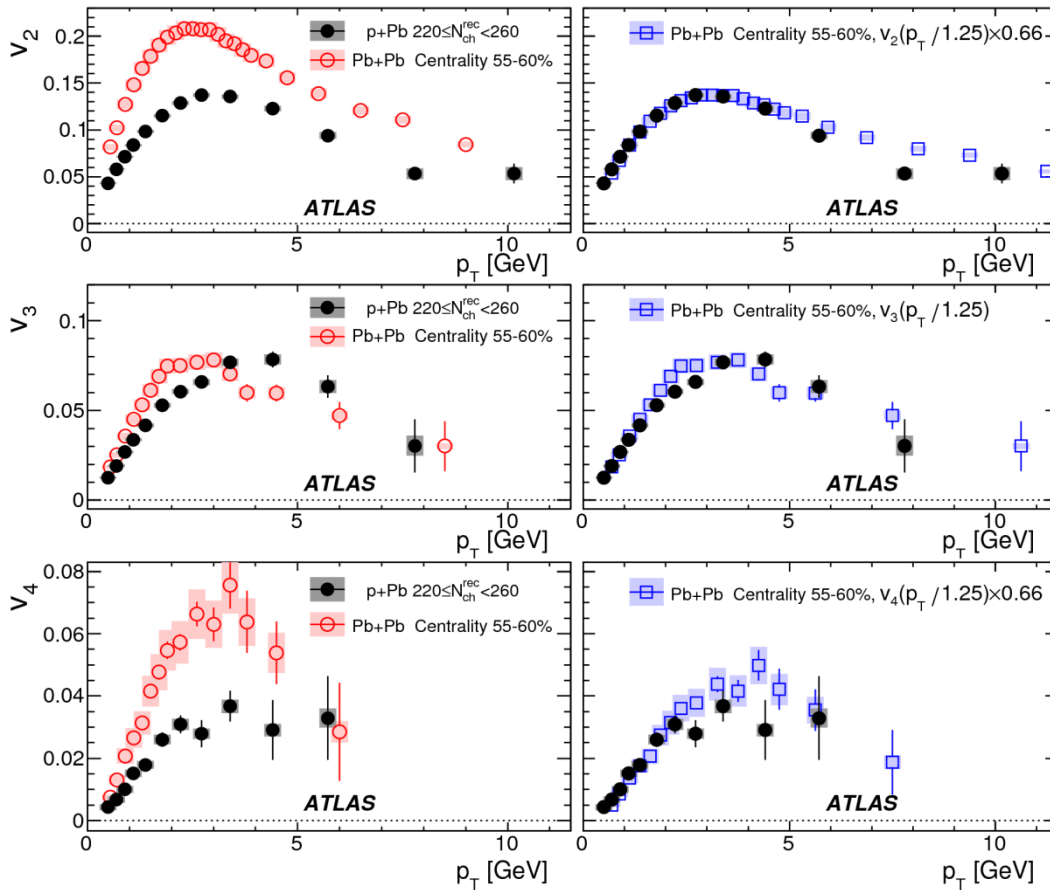
Present and future HI machines



Hunting the collectivity in pPb ...

$v_n(p_T)$

$v_n(p_T/1.25)$ in p-Pb scaled



ATLAS: PRC 90 (2014) 044906

Non-zero Fourier coefficients v_1 - v_4 measured in p-Pb collisions.

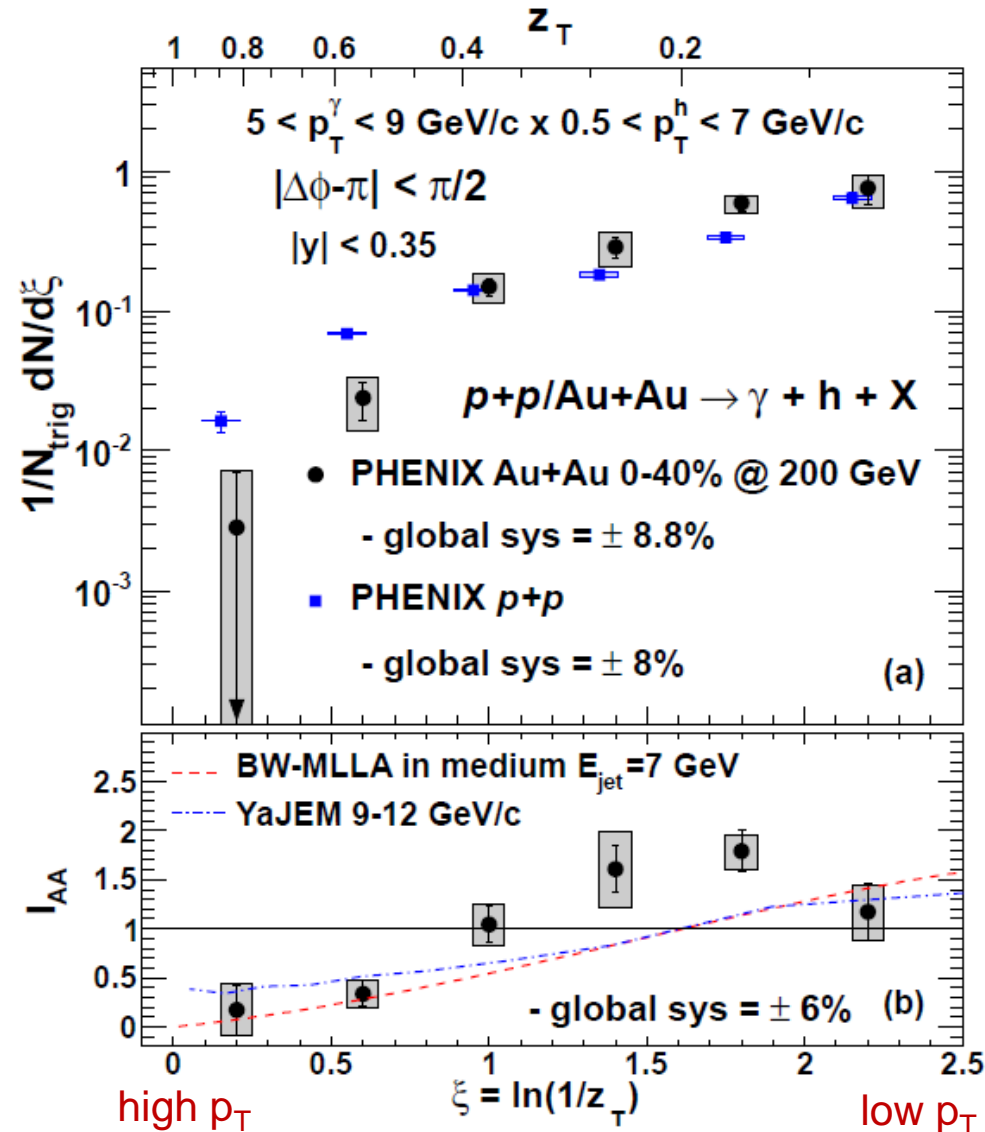
What is their relation to those measured in Pb-Pb?

Apply a scale factor $K = 1.25$ to account for the $\langle p_T \rangle$ difference in both systems

Basar, Teaney, arXiv:1312.6770

Similarity of the scaled $v_n(p_T/K)$ in p-Pb and v_n in Pb-Pb indicates a similar origin of the anisotropy in both systems.

γ -hadron correlations



- γ -jet a “golden probe” of parton energy loss in the medium
- produced in Compton scattering
- photons do not interact strongly
- precise measurement of the in-medium modification of fragmentation function

$$I_{AA} = \text{Yield}(A+A)/\text{Yield}(p+p)$$

The recoil jet is modified:
 softening of recoil jet in central Au+Au collisions at RHIC.

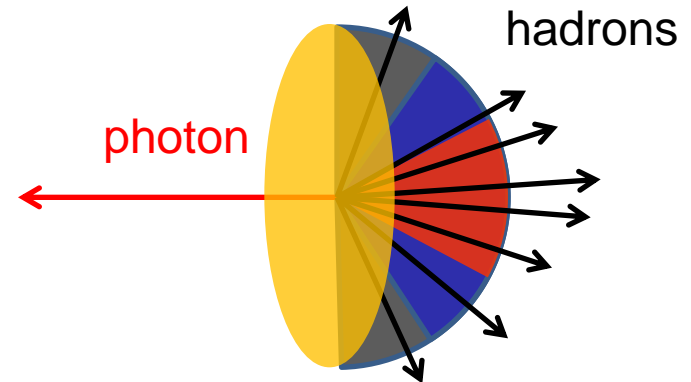
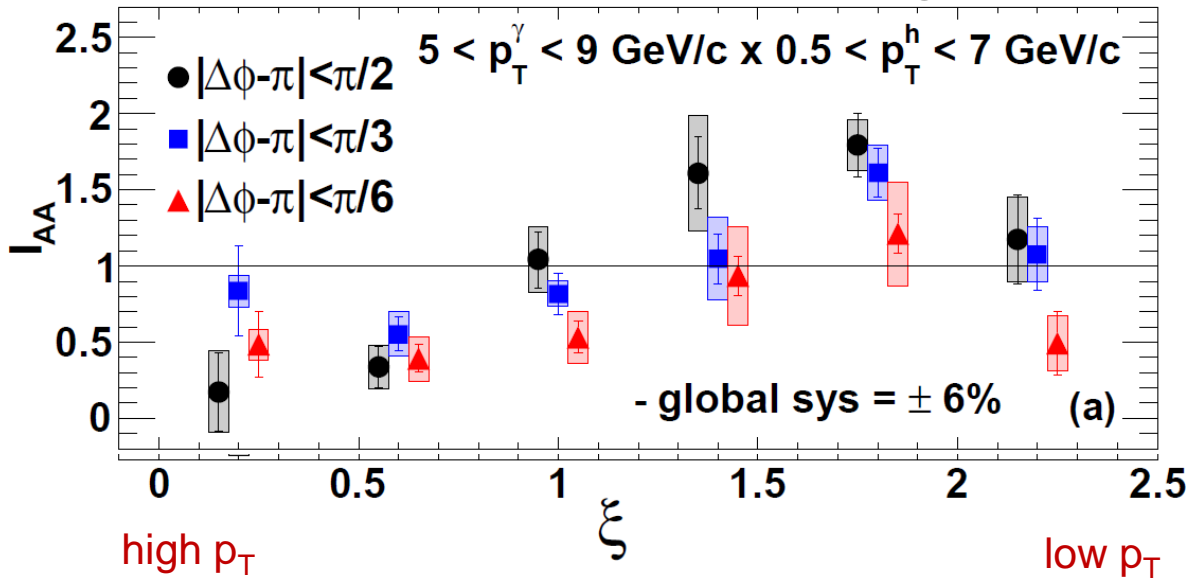
γ -hadron correlations

Where did the energy go?

Look into different cones away from the trigger photon!

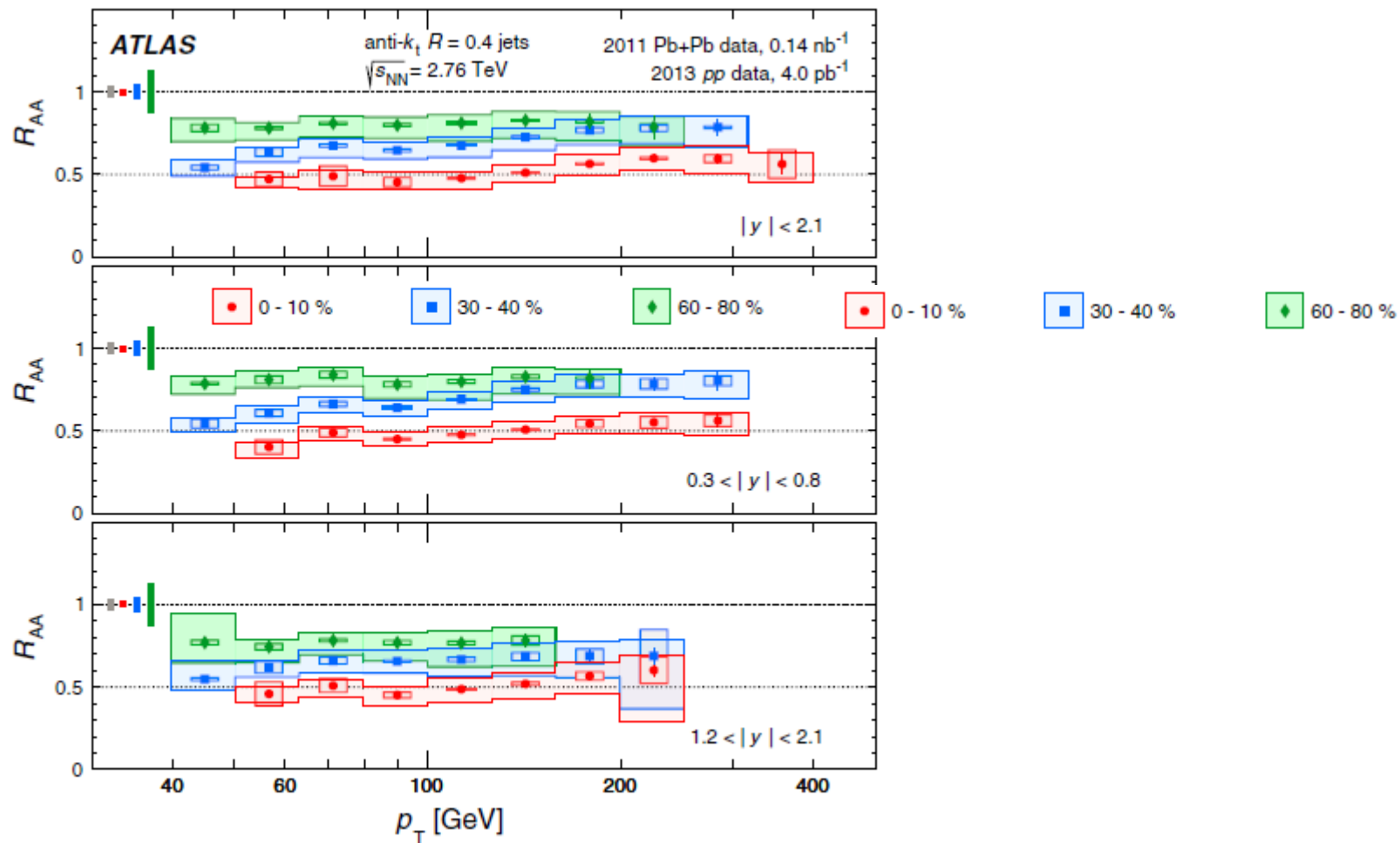
PHENIX: arXiv:1212.3323

0-40% Au+Au @ 200 GeV



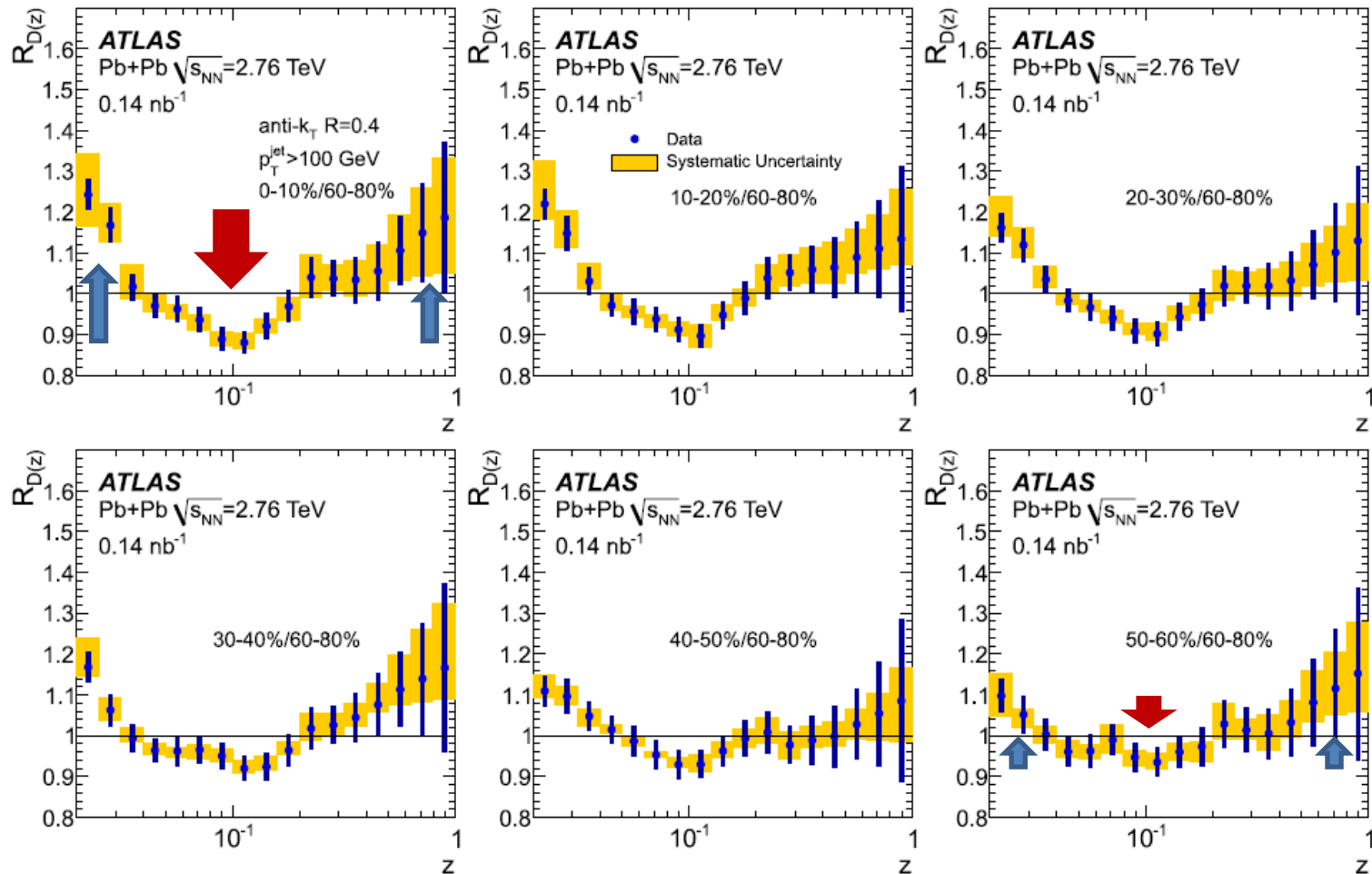
$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

Lost high- p_T hadrons emerge as multiple soft hadrons at large angles.



Modification of jet fragmentation in Pb-Pb

ATLAS: *PLB* 739 (2014) 320-342, CMS: *PRC* 90 (2014) 024908



enhancement for $z < 0.04$ → suppression at $z = 0.04-0.2$ → enhancement for $z > 0.2$

- most pronounced in central Pb-Pb collisions

Where did the energy go?

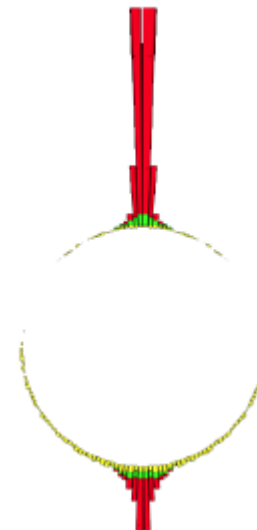
CMS, PRC 84 (2011) 024906

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

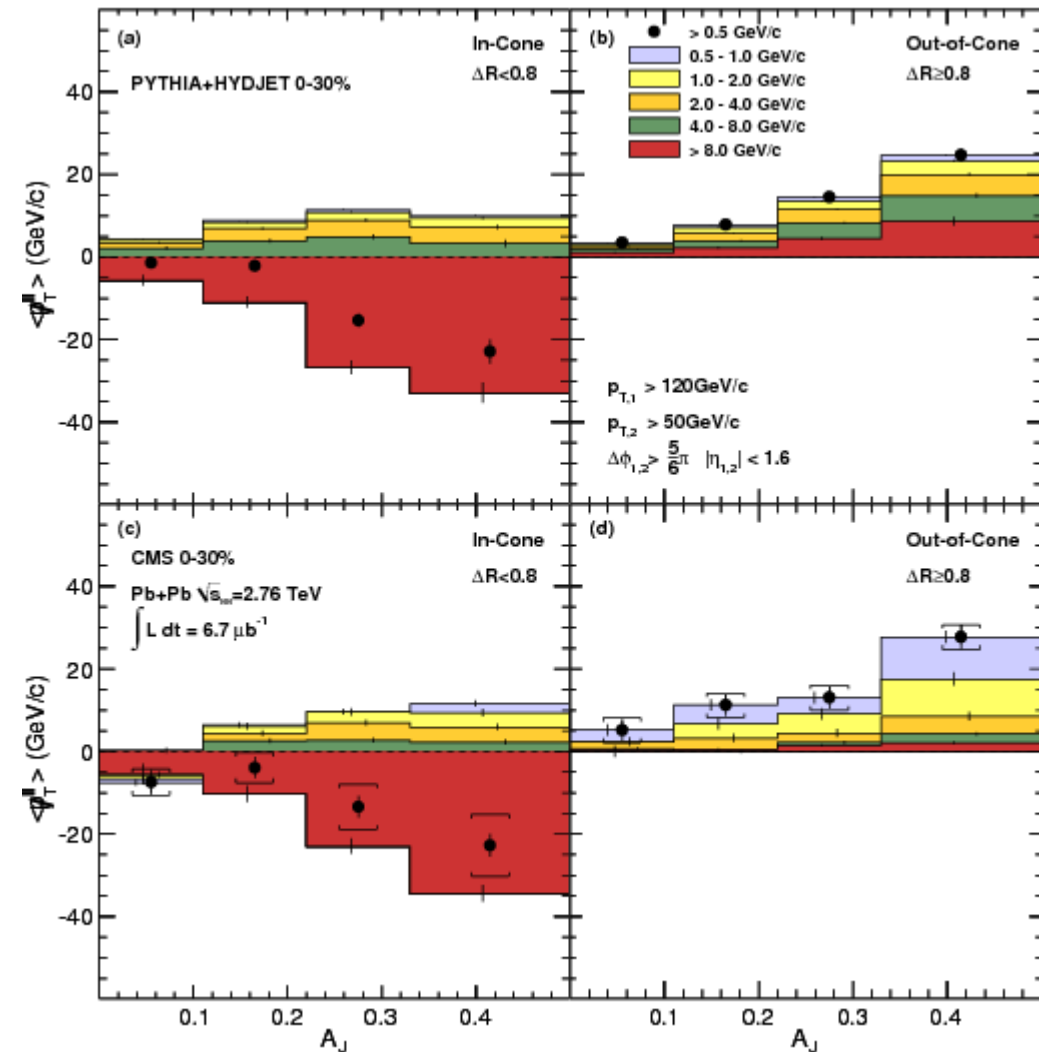
$$\cancel{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos(\phi_{\text{Track}} - \phi_{\text{Leading Jet}})$$

Jet asymmetry is balanced by soft particles at large angles.

Leading jet ($p_T > 120 \text{ GeV/c}$)



Subleading jet ($p_T > 30 \text{ GeV/c}$)



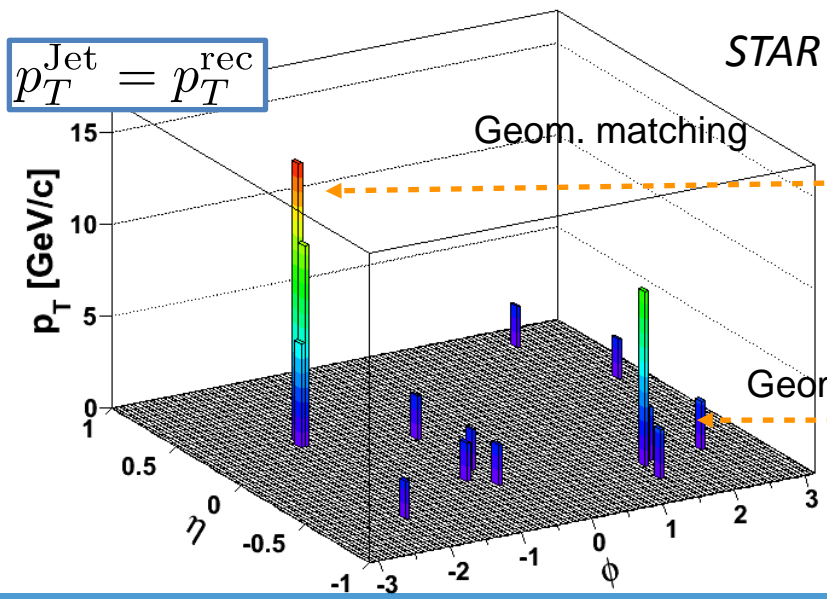
Does the picture change at RHIC energy?

2. Rerun jet-finding algorithm with low constituent p_T cut

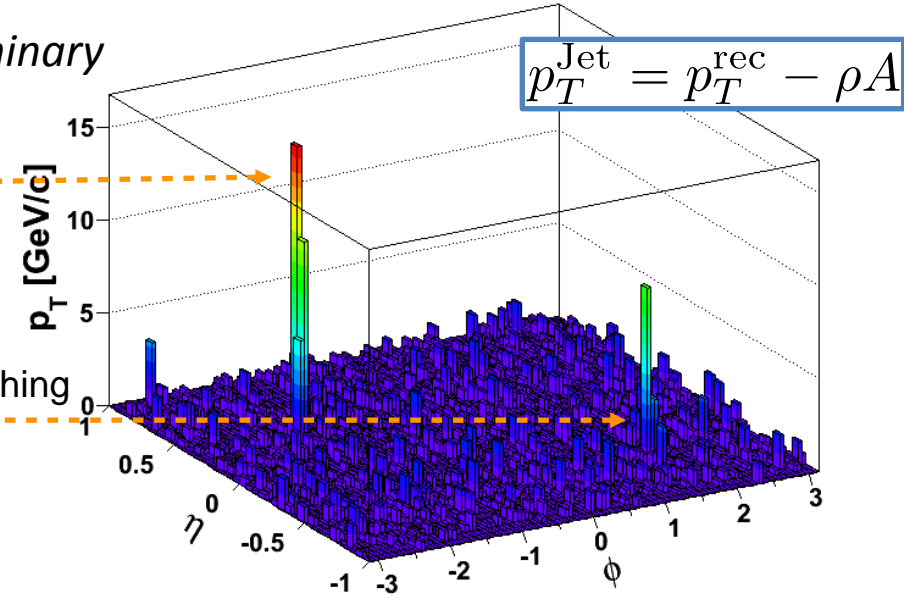
Constituent $p_T > 2 \text{ GeV}/c$



Constituent $p_T > 0.2 \text{ GeV}/c$



STAR preliminary



1. Run jet-finding algorithm and find di-jets

Anti-kt R=0.4
 $p_{T}^{\text{leading}} > 20 \text{ GeV}/c$, $p_{T}^{\text{subleading}} > 10 \text{ GeV}/c$
 $|\Delta\phi| < 0.4$
J. B. K. (NSI ASCR)

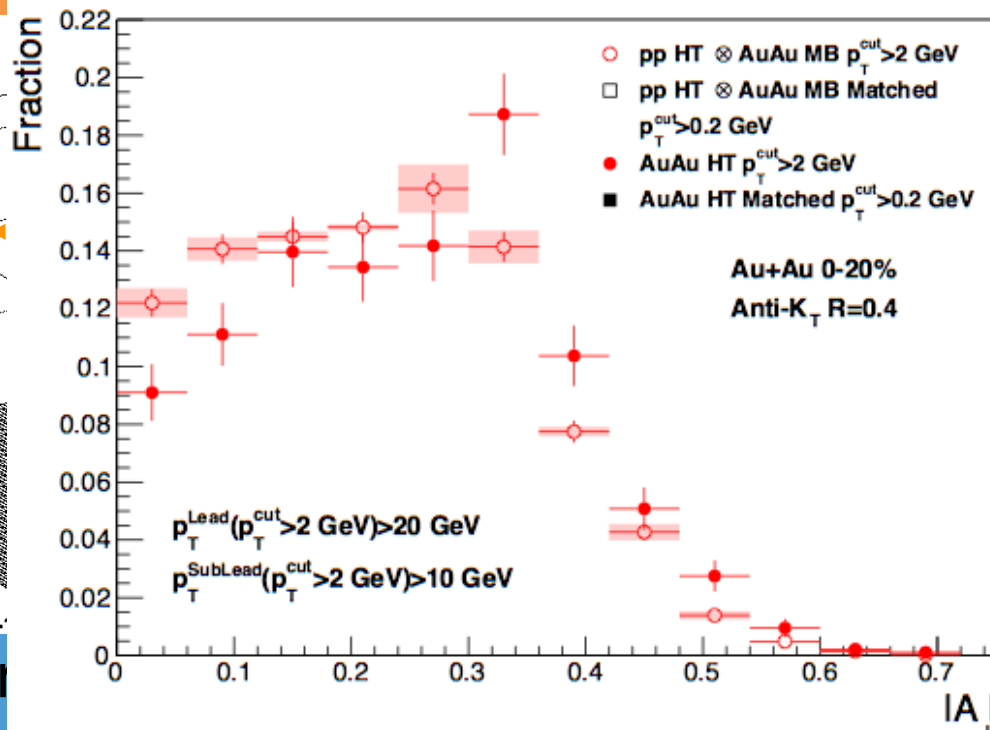
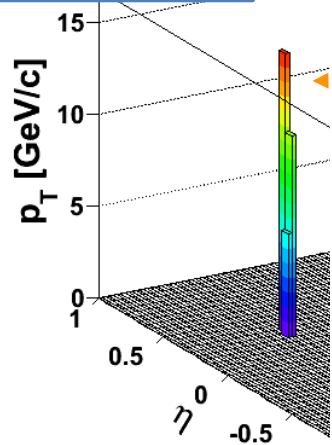
3. Do jet matching and calculate “matched” $|A_J|$ with constituent $p_{T,\text{cut}} > 0.2 \text{ GeV}/c$

A_J measurement at RHIC energy

2. Rerun jet-finding algorithm with low constituent p_T cut

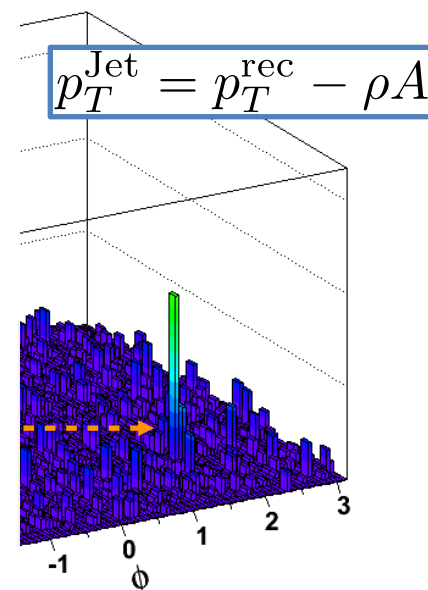
Constituent $p_T > 0.2$ GeV/c

$$p_T^{\text{Jet}} = p_T^{\text{rec}}$$



Constituent $p_T > 0.2$ GeV/c

$$p_T^{\text{Jet}} = p_T^{\text{rec}} - \rho A$$



1. Run jet-finding algorithm and find di-jets

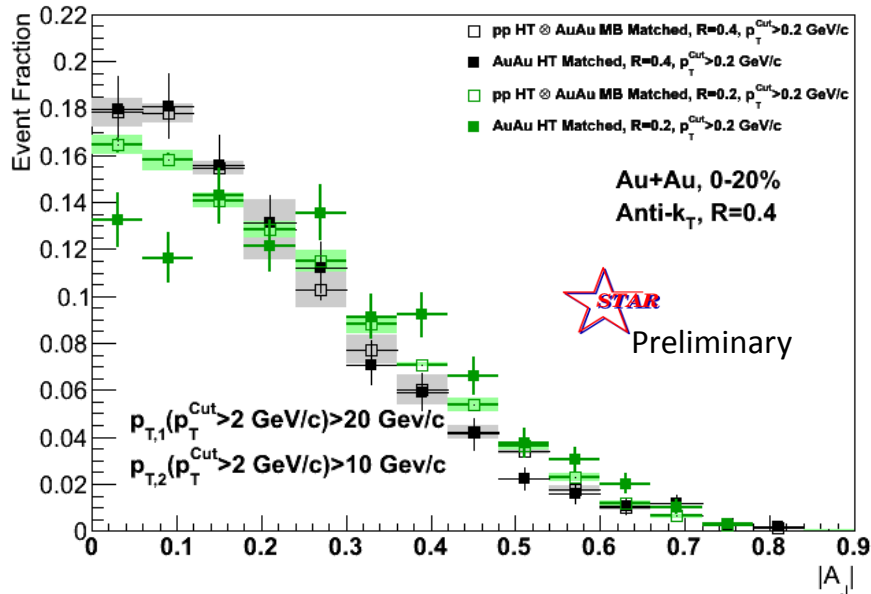
Anti-kt R=0.4

$p_T^{\text{leading}} > 20$ GeV/c, $p_T^{\text{subleading}} > 10$ GeV/c

$|\Delta\phi| < 0.4$

3. Do jet matching and calculate “matched” $|A_J|$ with constituent $p_{T,\text{cut}} > 0.2$ GeV/c

A_j measurement at RHIC energy



Study softening

$R=0.2$

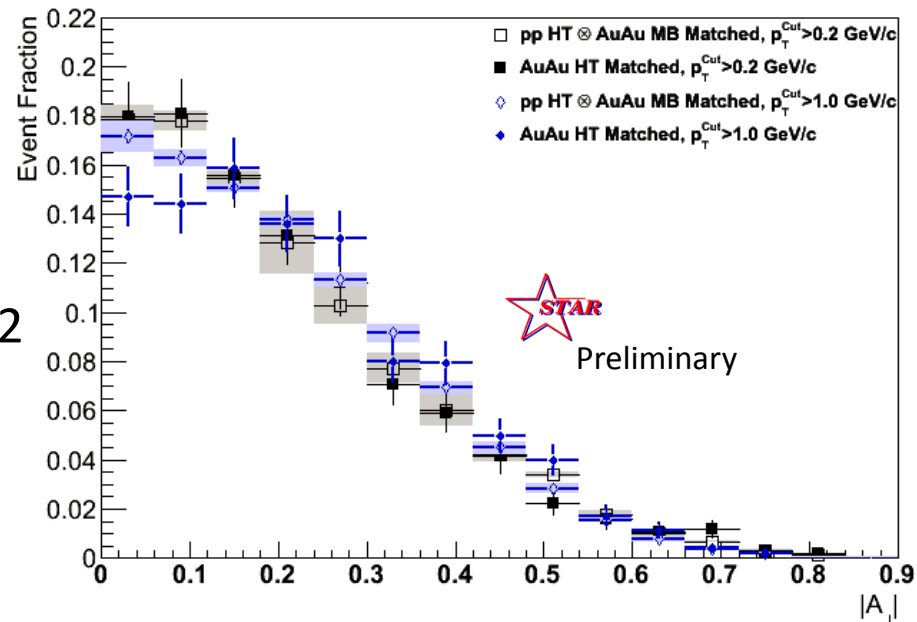
$p_T^{cut} > 0.2 \text{ GeV/c}$

Study broadening

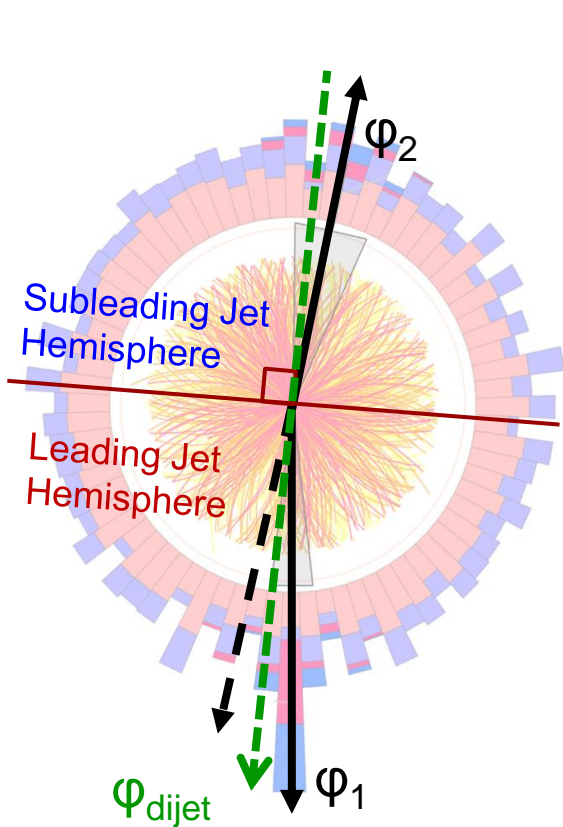
$R=0.4$

$p_T^{cut} > 1 \text{ GeV/c}$

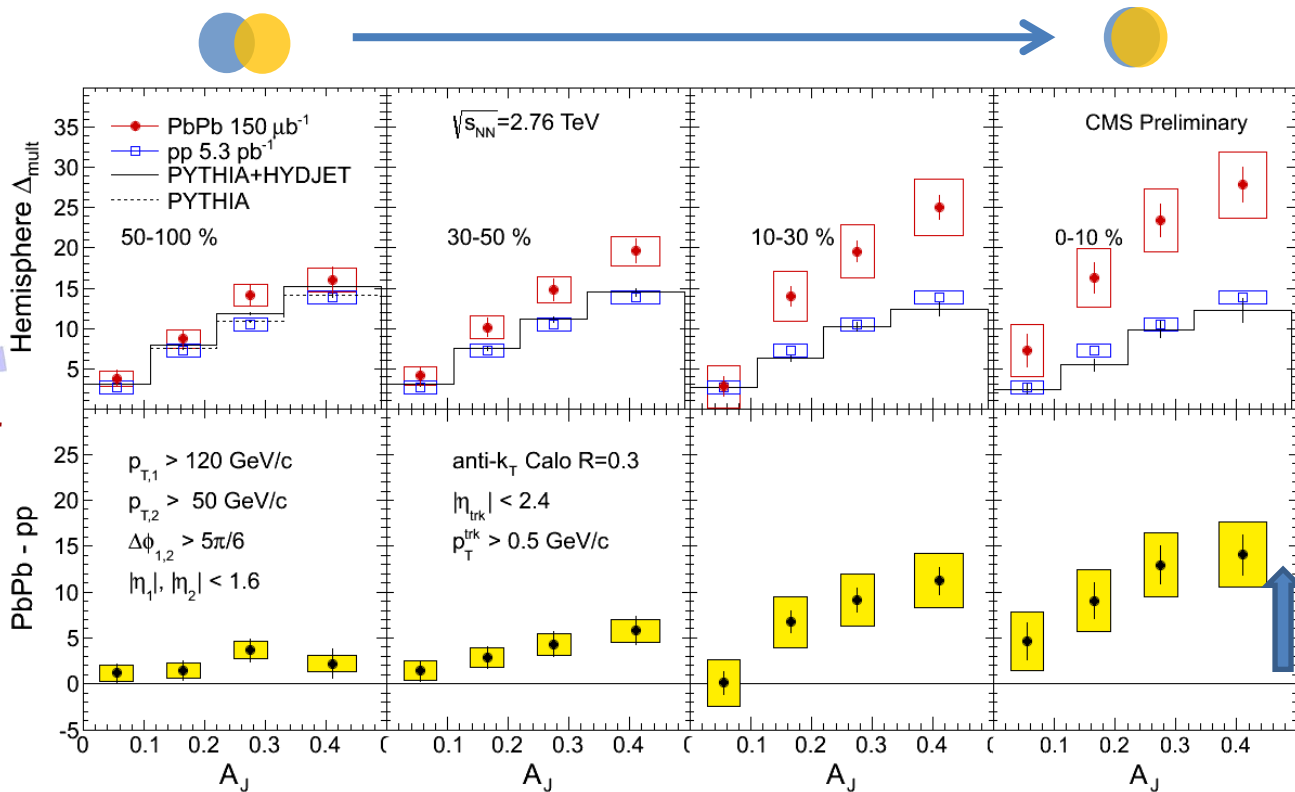
- Lost energy reemerges in low p_T particles
- Decreasing $p_T = 2 \rightarrow 1 \rightarrow 0.2 \text{ GeV/c}$ dijet is regaining balance
- For the same $R=0.4$ and jet p_T selection, balance can not be restored within $R=0.2$
 \rightarrow broadening
- $p_T^{cut} = 1 \text{ GeV/c}$ not sufficient to restore balance \rightarrow signs of jet softening between 1 and 2 GeV/c



How many particles carry the missing energy?



courtesy Y. J. Lee (CMS)



- Δ_{mult} increases with centrality
- for large A_j and central Pb-Pb collisions there are **about 14 extra particles with $p_T > 0.5 \text{ GeV}/c$ in the subleading jet hemisphere**

hemisphere N_{ch} difference:

$$\Delta_{\text{mult}} = N_{\text{ch}}^{\text{subleading}} - N_{\text{ch}}^{\text{leading}}$$

J. Bielcikova (NPI ASCR)