Jets and correlations in heavy-ion collisions

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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

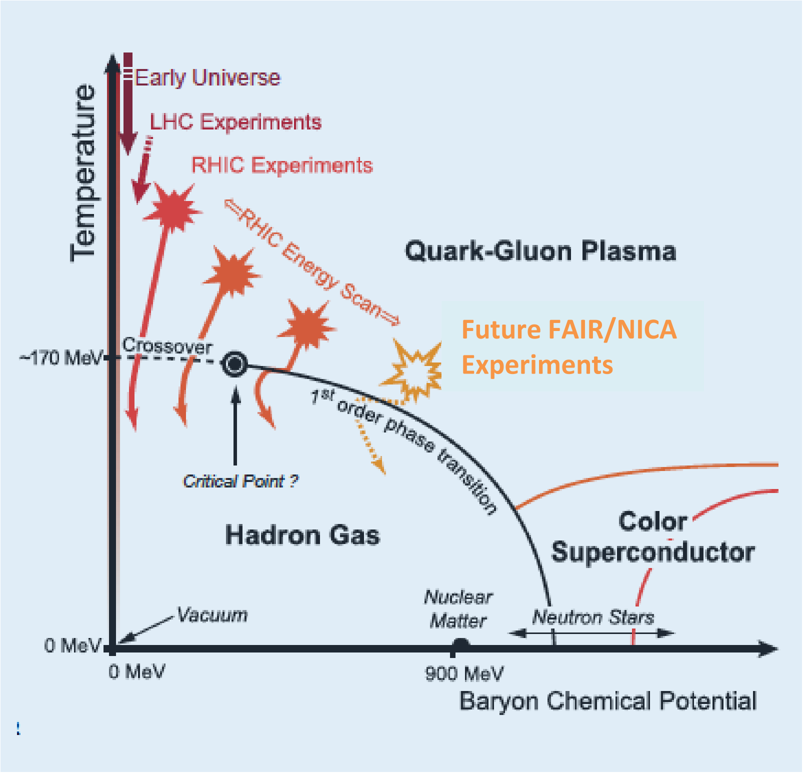
- properties of the quark-gluon plasma at high temperature (RHIC/LHC) and large density (GSI FAIR/NICA)

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 :

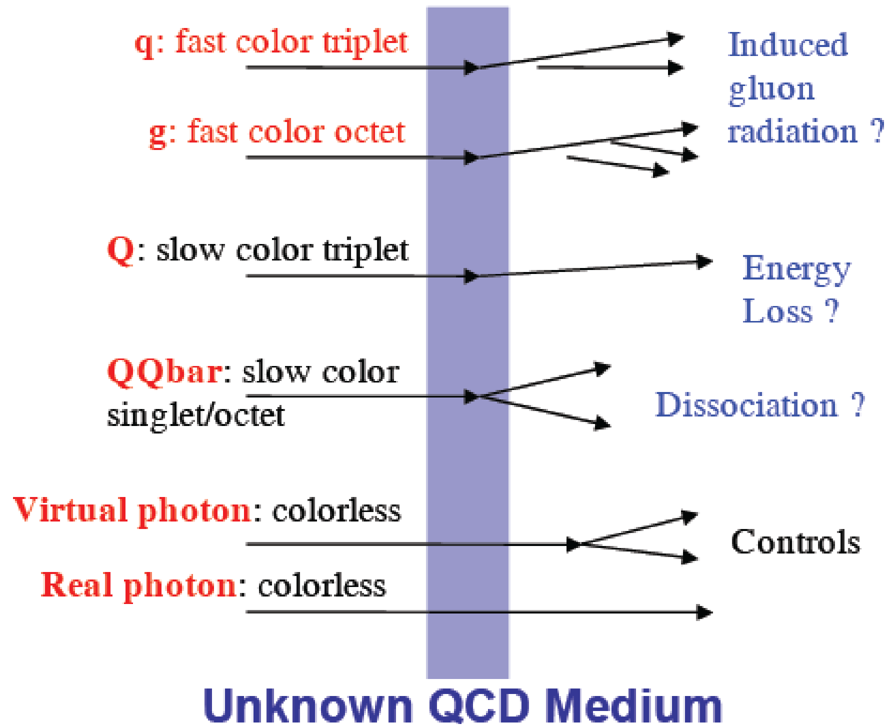
originate from initial hard scattering of partons which carry a color charge interact with nuclear matter

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

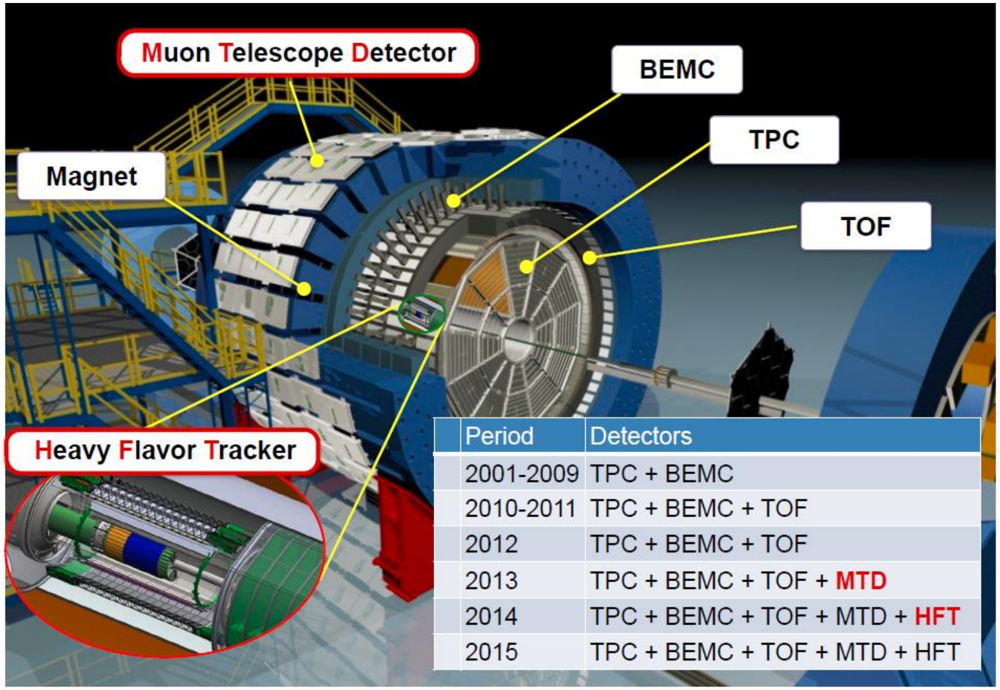
Goal:
use in-medium parton energy loss to quantify medium properties



- 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

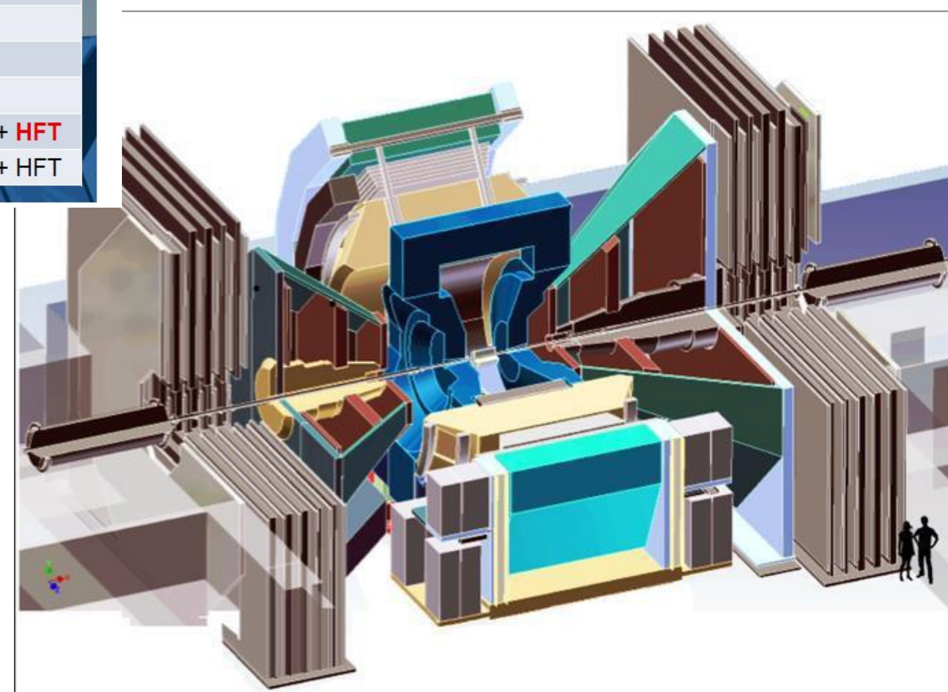
Dedicated heavy-ion experiments at RHIC



Period	Detectors
2001-2009	TPC + BEMC
2010-2011	TPC + BEMC + TOF
2012	TPC + BEMC + TOF
2013	TPC + BEMC + TOF + **MTD**
2014	TPC + BEMC + TOF + MTD + **HFT**
2015	TPC + BEMC + TOF + MTD + HFT

PHENIX:

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

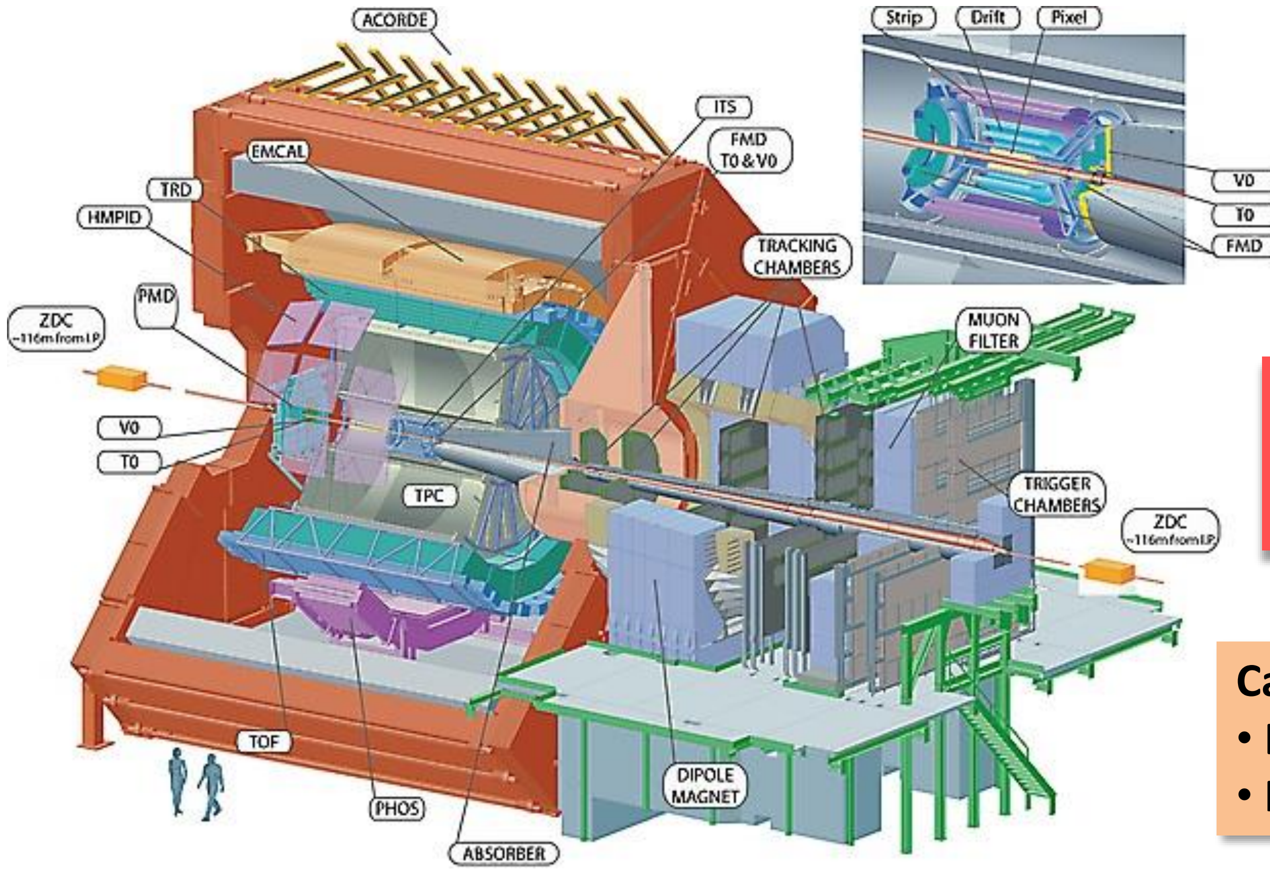


STAR:

- 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

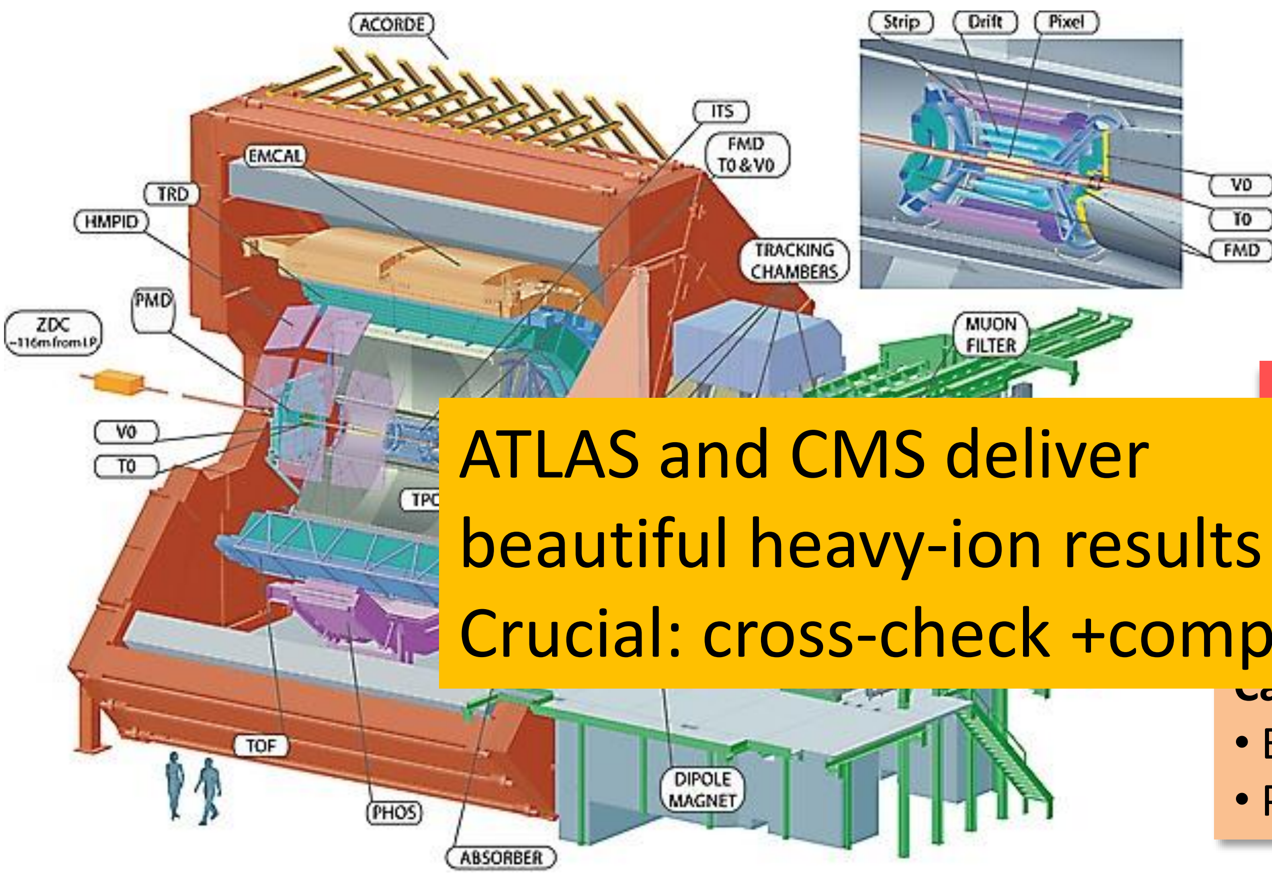
Muon Spectrometer
$-4 < |\eta| < -2.5$
p(muons) > 4GeV/c

Calorimetry
- EMCAL + DCAL (Run2)
- PHOS

Central Barrel ($|\eta|<0.9$)
- hadrons, e and γ
- TPC: efficient tracking down to ~ 100 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!

- EMCAL + DCAL (Run2)
- PHOS

Central Barrel ($|\eta|<0.9$)
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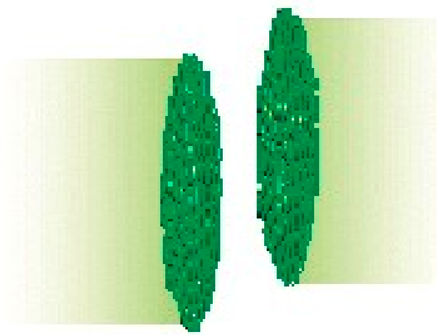
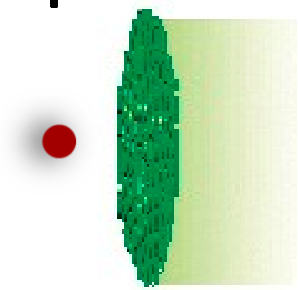
Some basic heavy-ion physics terminology …

A + A



"hot/dense QCD matter"
final state effects
thermal and collective particle production (flow)

p + A



"cold nuclear matter"
initial state effects
shadowing and gluon saturation

p + p

"vacuum"
reference

Some basic heavy-ion physics terminology …

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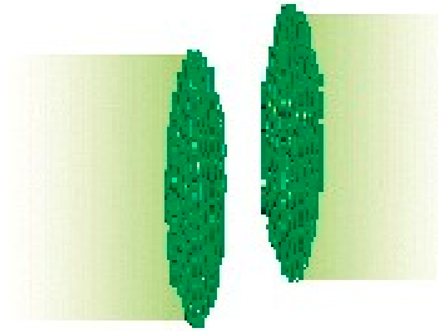

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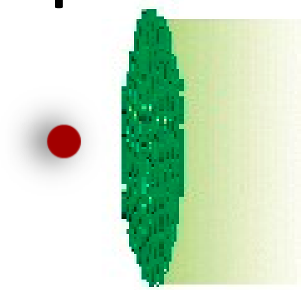

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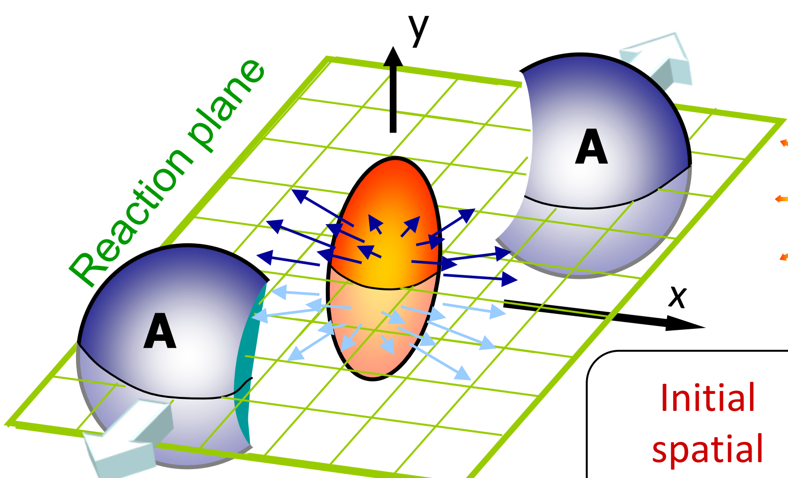
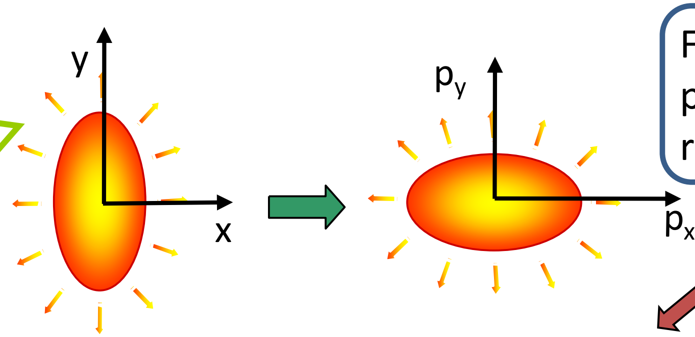




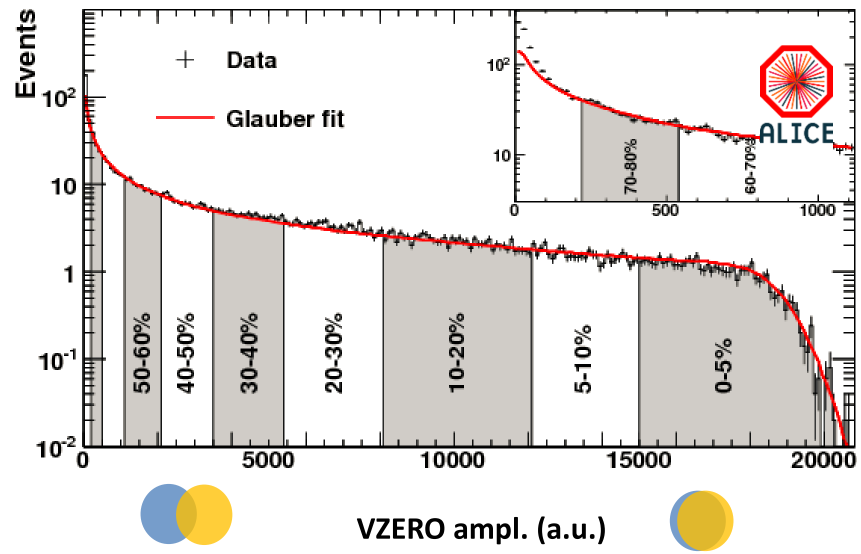
Fourier analysis of particle distribution relative to reaction plane

Initial spatial anisotropy → Strong pressure gradients → Elliptical (v_2) azimuthal anisotropy → Sensitivity to early expansion

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})

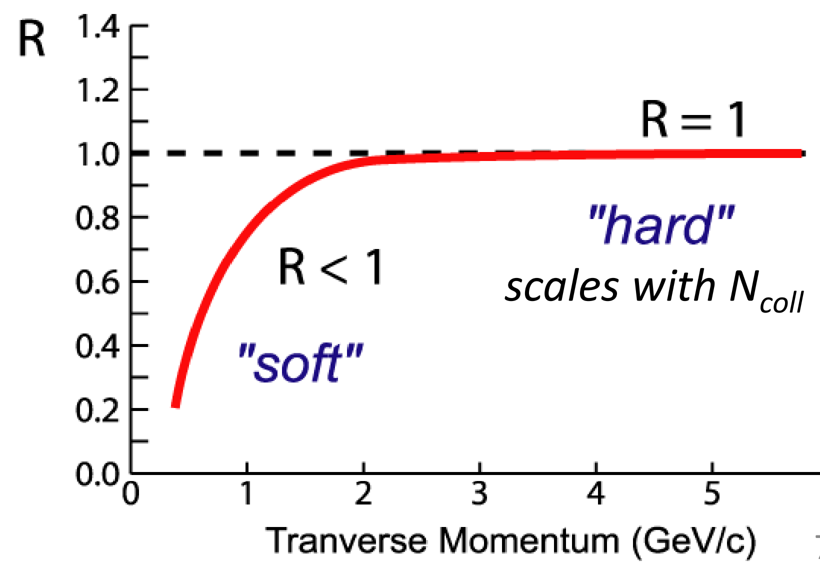


Nuclear modification factor:

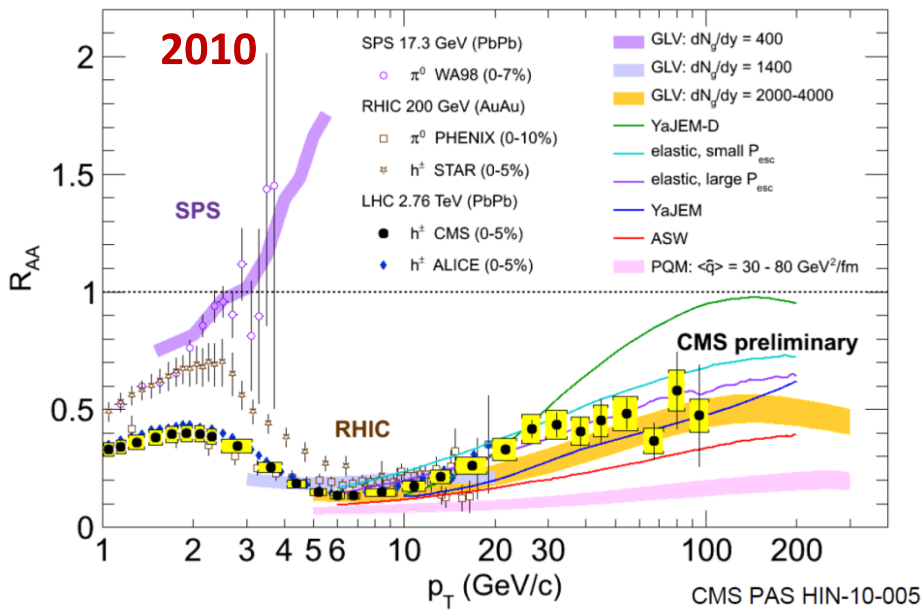
… the way to compare an observable in A+A collisions to the reference (p+p or peripheral A+A)

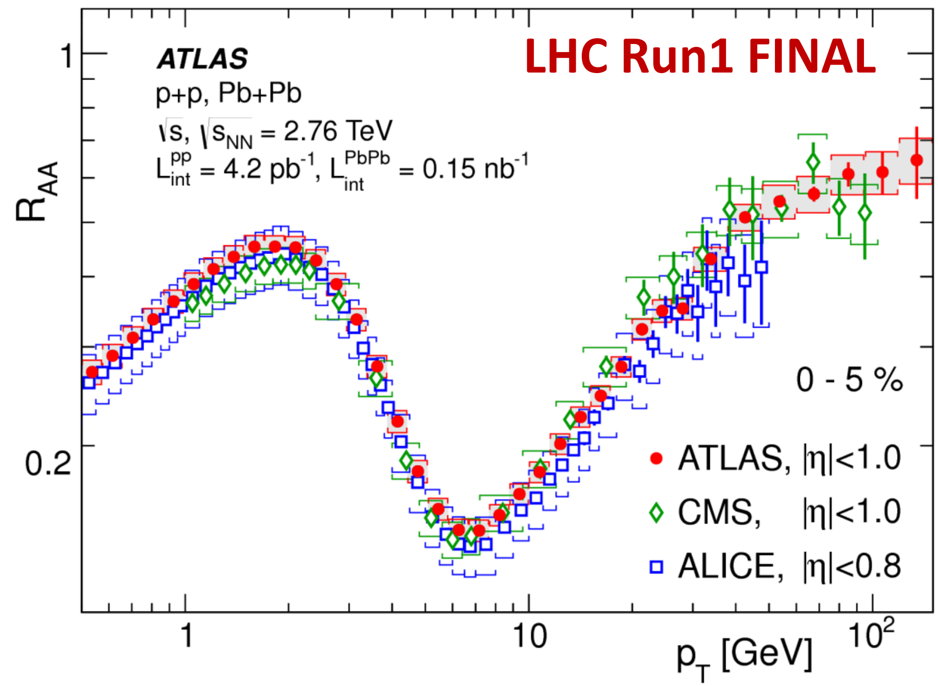
$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA}\, d^2\sigma^{NN}/dp_T d\eta}$$

T_{AA}: $N_{coll}/\sigma_{inel}^{NN}$



Particle production in central Pb+Pb collisions





- suppression of charged hadron production: R_{AA}(LHC)< R_{AA}(RHIC)
- minimum R_{AA} ~ 0.14 at p_T = 6-7 GeV/c
- increase of R_{AA} with p_T but even at p_T ~ 100 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:

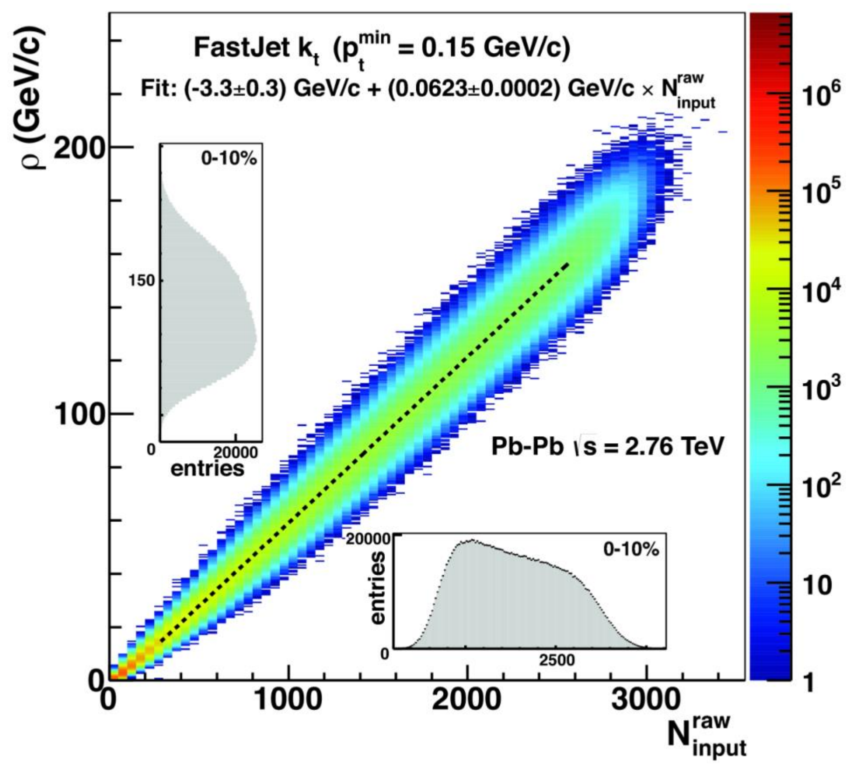
  $<\rho> \approx 180$ GeV/c

  in central Pb-Pb collisions @ 2.76 TeV

→ limits jet resolution parameter R to modest values R ~ 0.2-0.4

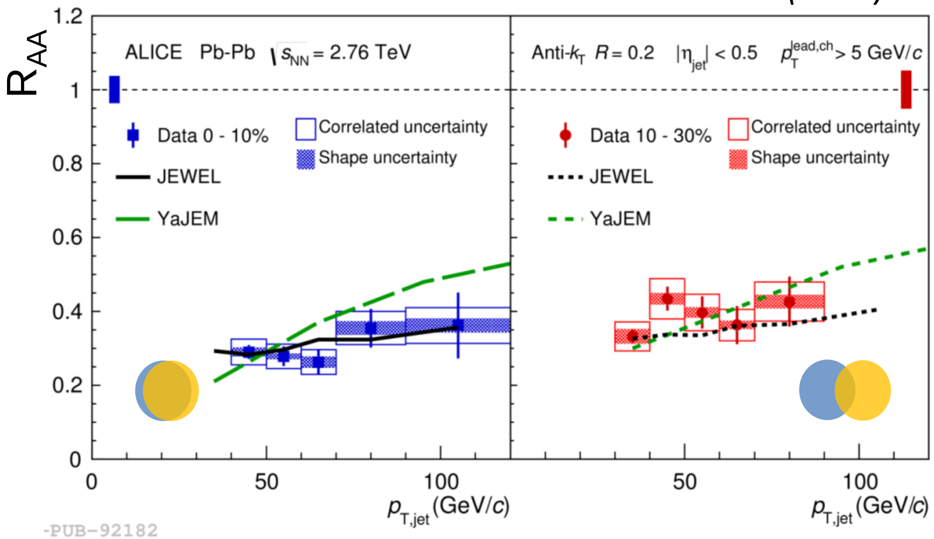
- average background subtracted on jet-by-jet basis and fluctuations together with instrumental effects unfolded on statistical basis

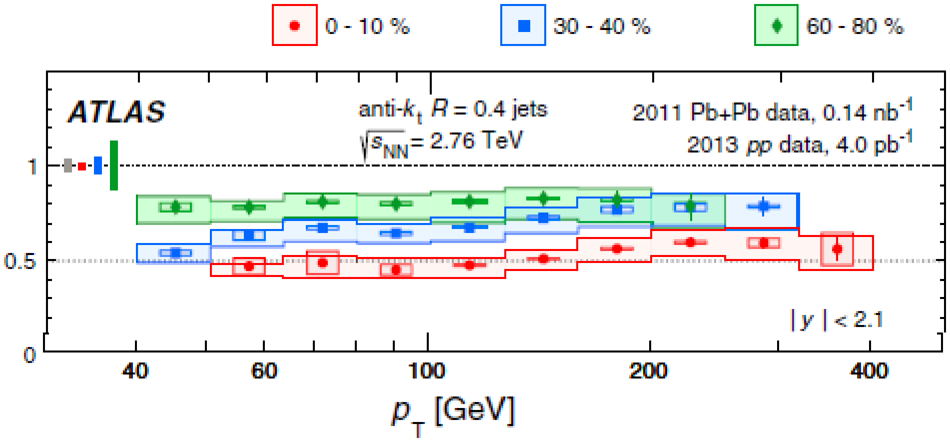
ALICE, JHEP 1203 (2012), 053



How much are jets modified?

ALICE: *PLB 746 (2015) 1*





ATLAS: *PRL 114 (2015) 072302*

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

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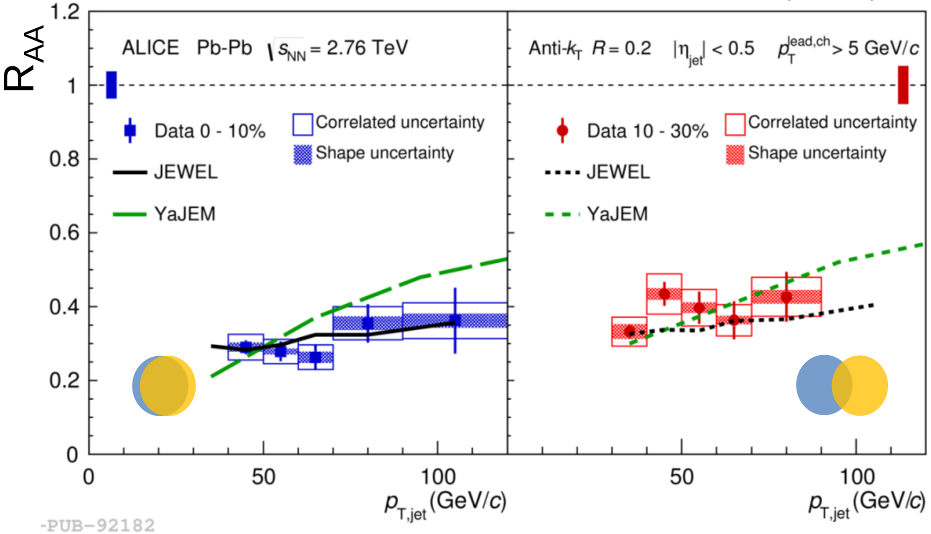
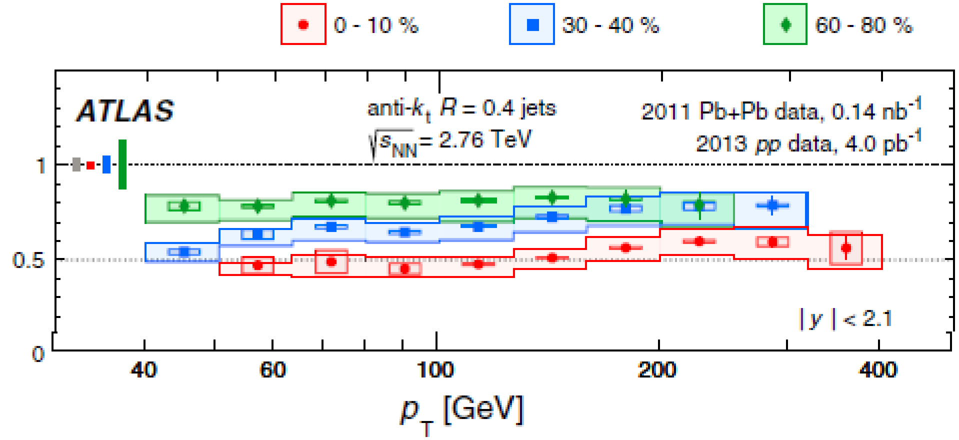
ALICE: *PLB 746 (2015) 1*

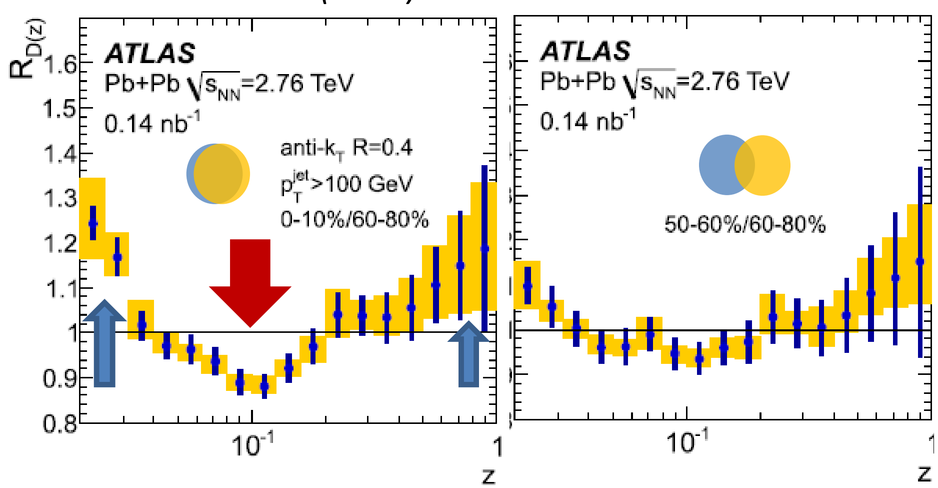




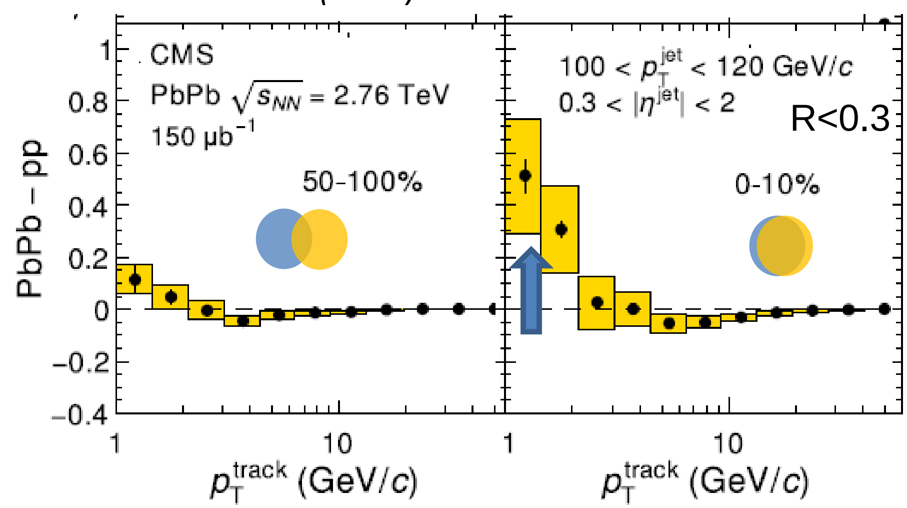
ATLAS: *PRL 114 (2015) 072302*

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

ATLAS: *PLB 739 (2014) 320*

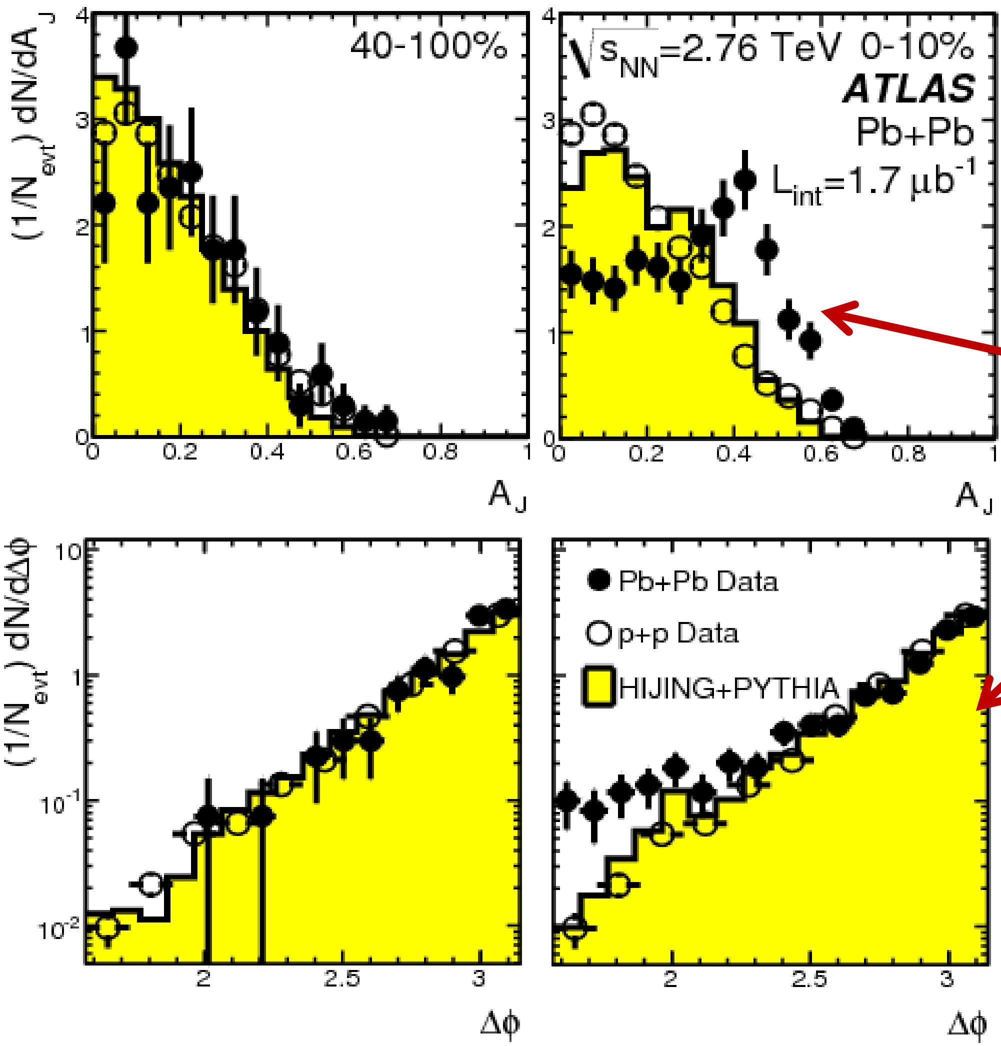


CMS: *PRC 90 (2014) 024908*



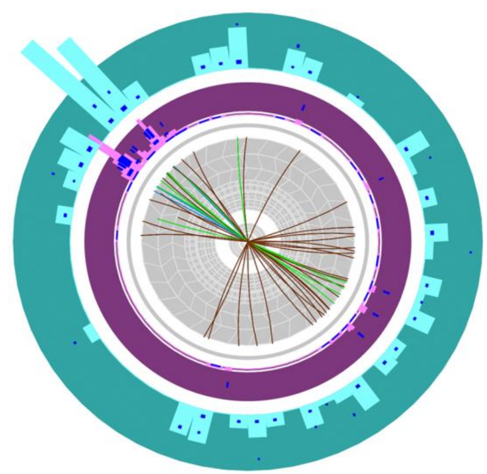
… and internal structure of jets is modified.

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.

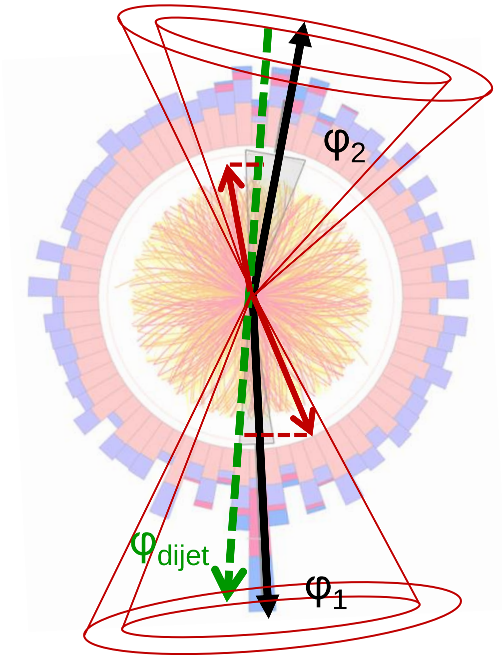


ATLAS: *PRL 105 (2010) 252303*

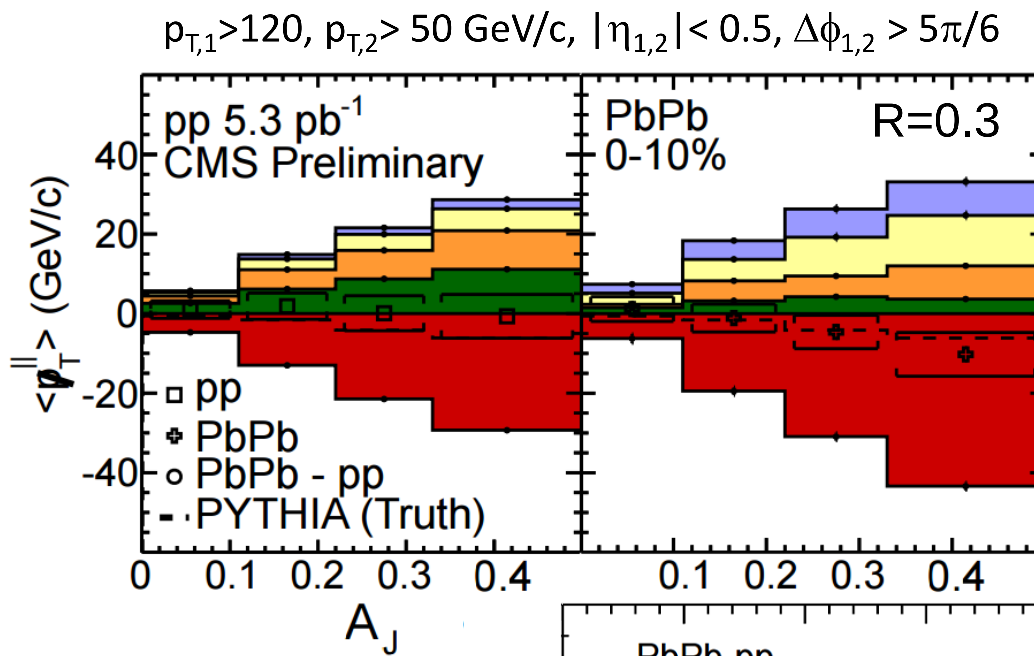
Where did the energy go? First studies in CMS paper: PRC 84 (2011) 024906

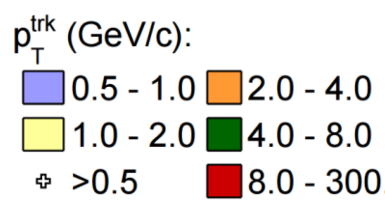
Where did the energy go?

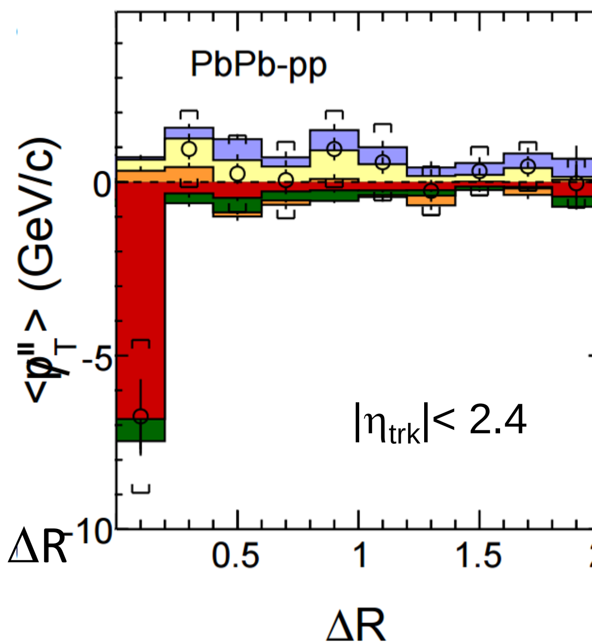
Y.S. Lai (CMS)
Thu 15:15



courtesy Y. J. Lee (CMS)







Missing p_T:

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{Dijet}\right)$$

- 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

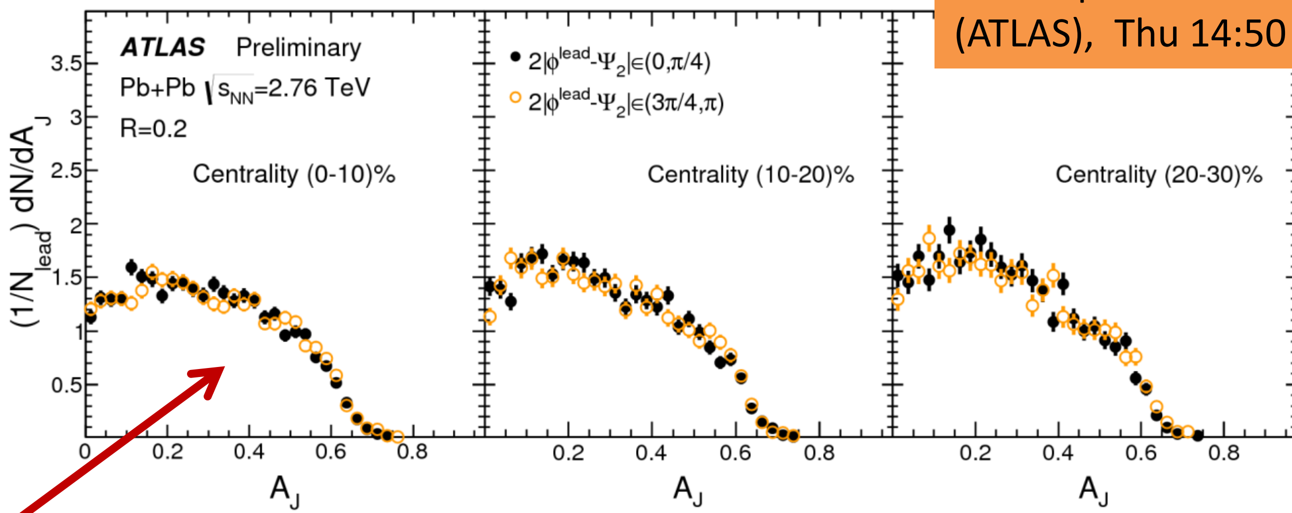
Path length effects on di-jet production

D. Perepelitsa (ATLAS), Thu 14:50

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

ATLAS: *PRL 111 (2013)152301*

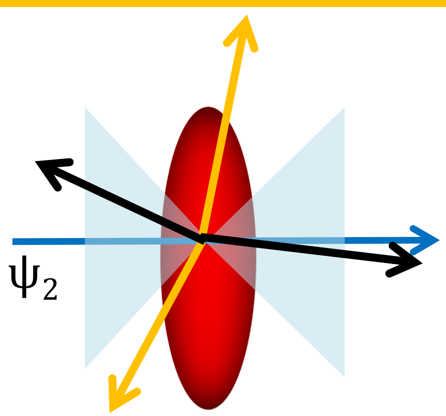
ATLAS-CONF-2015-021

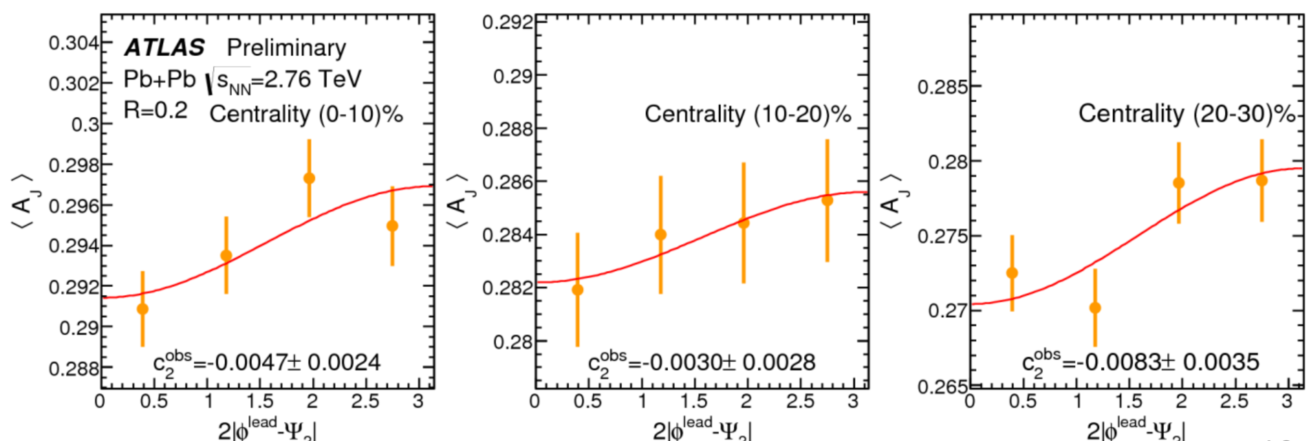


Study di-jet asymmetry A_J vs. event plane, extract its elliptical modulation c_2.

Calculate "elliptic" modulation c_2:

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





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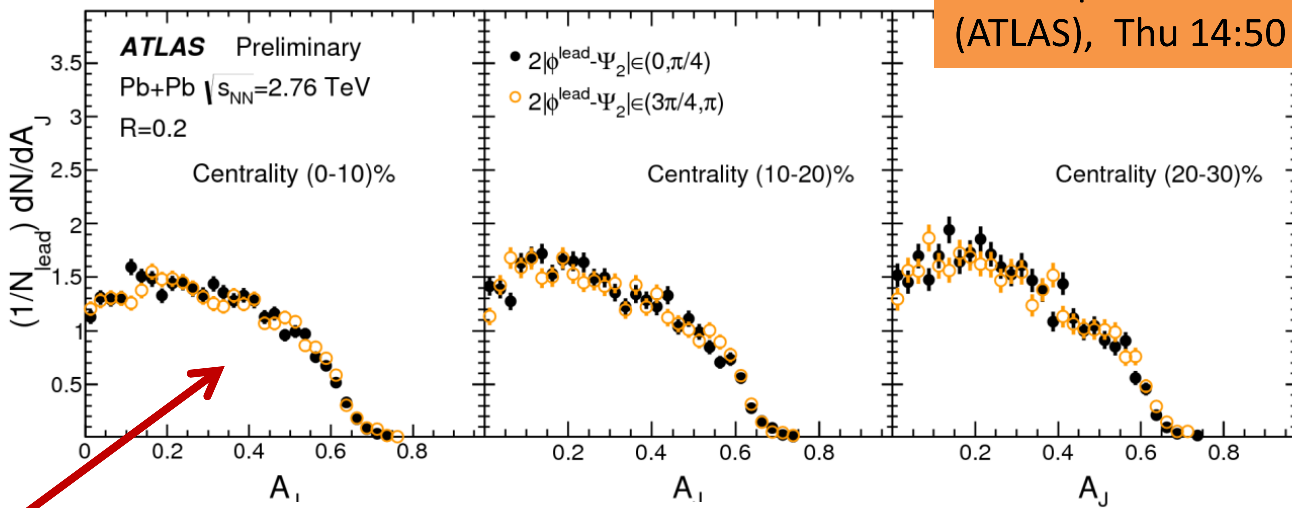
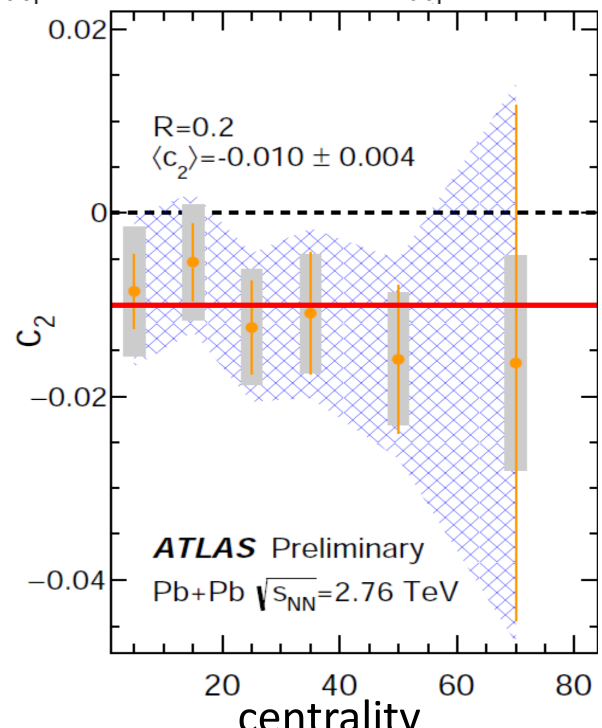
ATLAS-CONF-2015-021

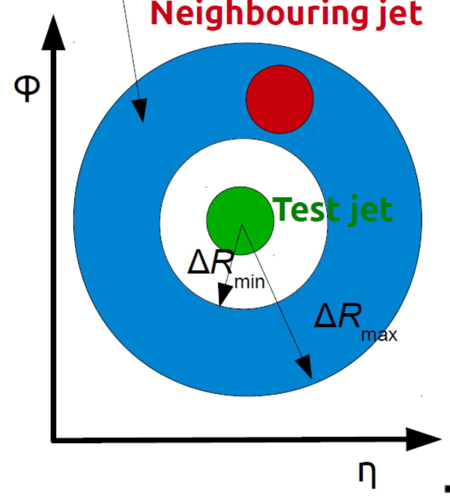




c_2 is small (<2%) and negative!

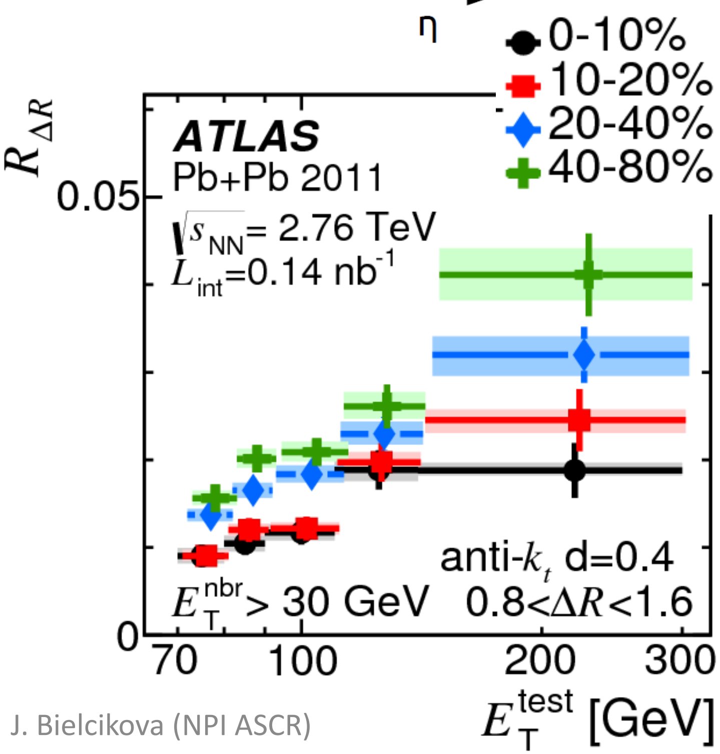
Data indicate larger A_J for leading jets oriented out-of-plane than for in-plane ones.

Neighbouring jet production in Pb-Pb collisions



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

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



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

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

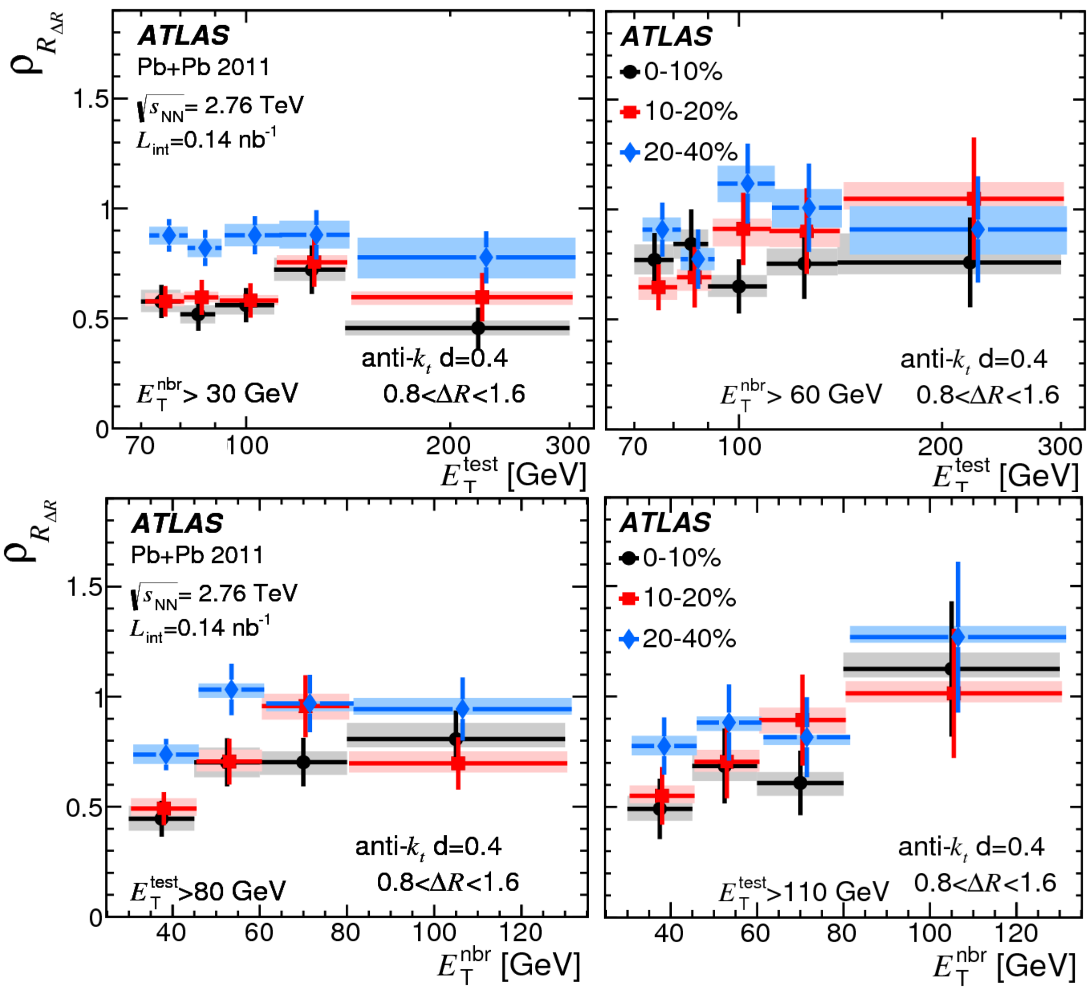
Study its dependence on:

- 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

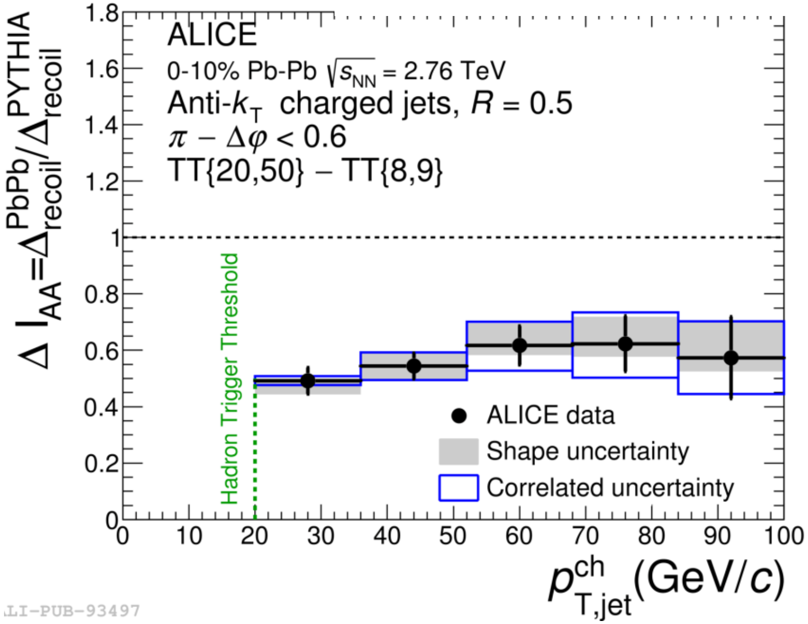
Nuclear modification factor for neighbouring jets approaches 1 when $E_T^{test} \approx E_T^{nbr}$.

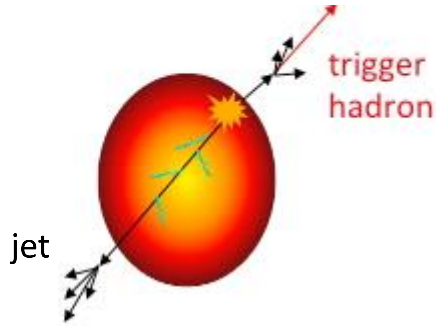
Suggests similar quenching for jets with same observed E_T and path length.

D. Perepelitsa (ATLAS), Thu 14:50

Semi-inclusive recoil jets in Pb-Pb

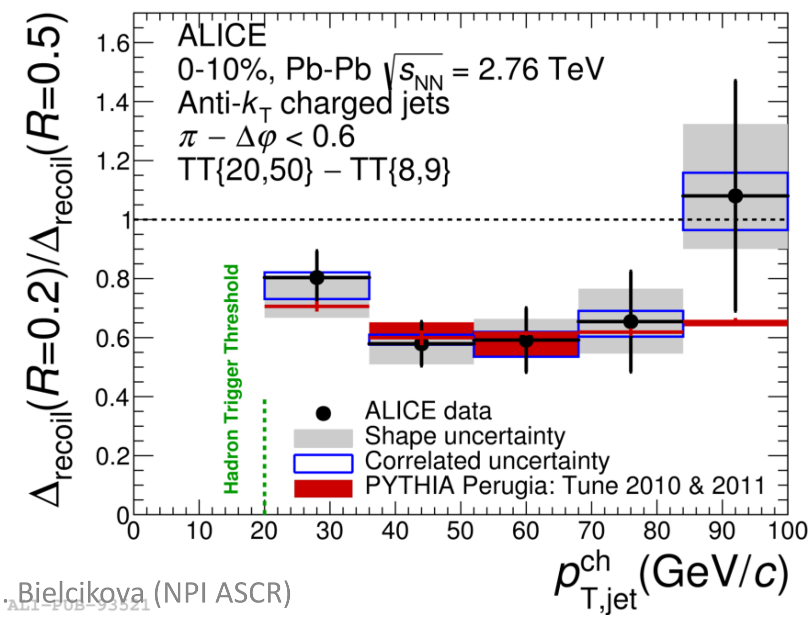
ALICE: arXiv:1506.03984





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

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



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

No evidence of intra-jet broadening:

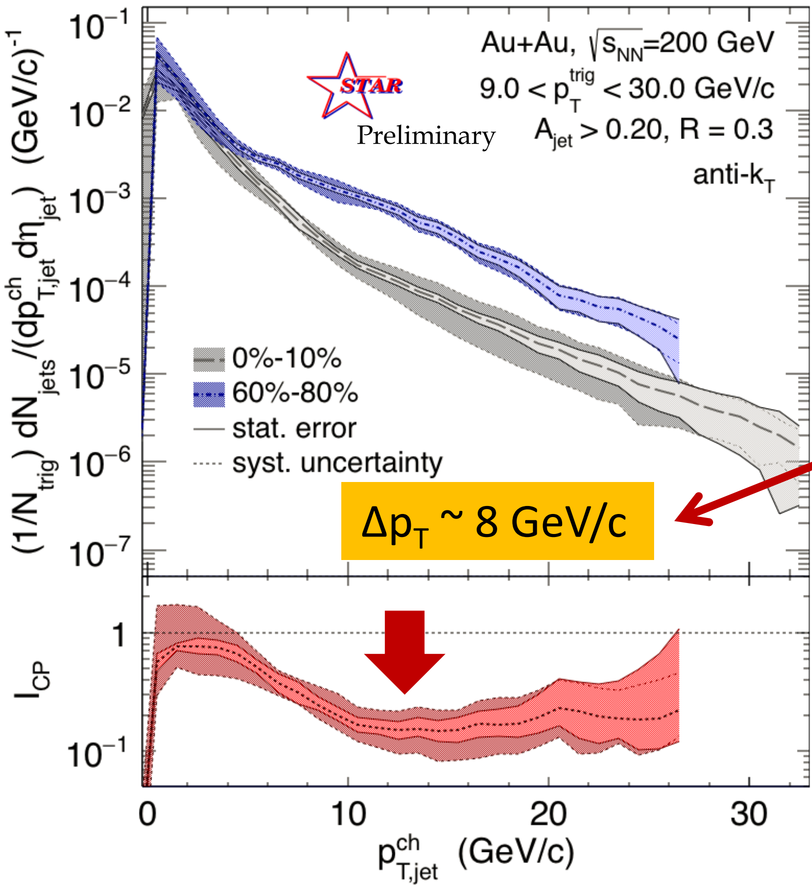
Δ_{recoil} for R=0.2/0.5 similar in pp and central Pb-Pb collisions

J. Otwinovski (ALICE)
Thu 15:40

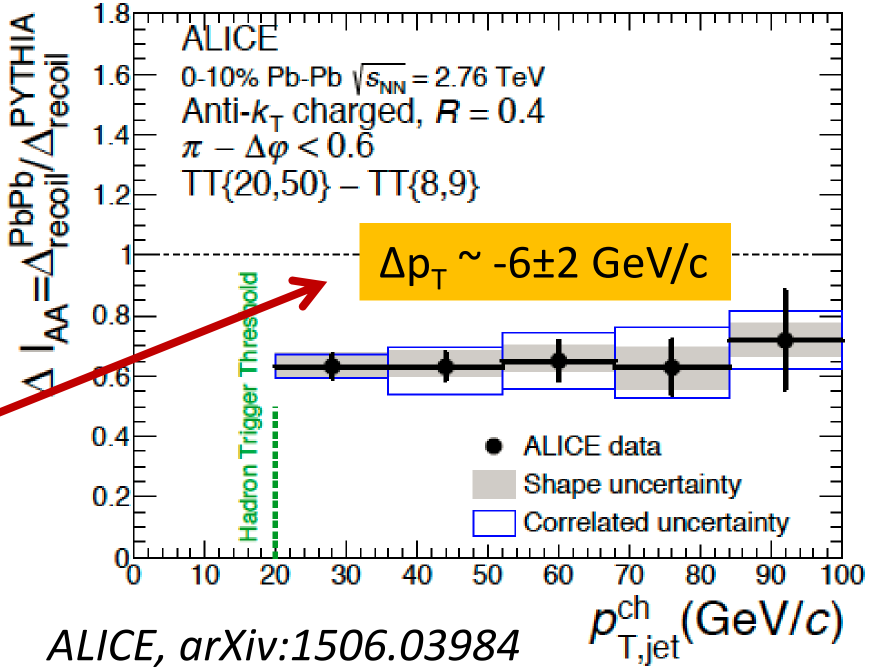
Hadron-jet correlations at RHIC

J. Rusnak (STAR)
Thu 14:30

STAR@RHIC 0.2 TeV



ALICE@ LHC 2.76 TeV



ALICE, arXiv:1506.03984

Larger suppression at RHIC compared to the LHC energy.

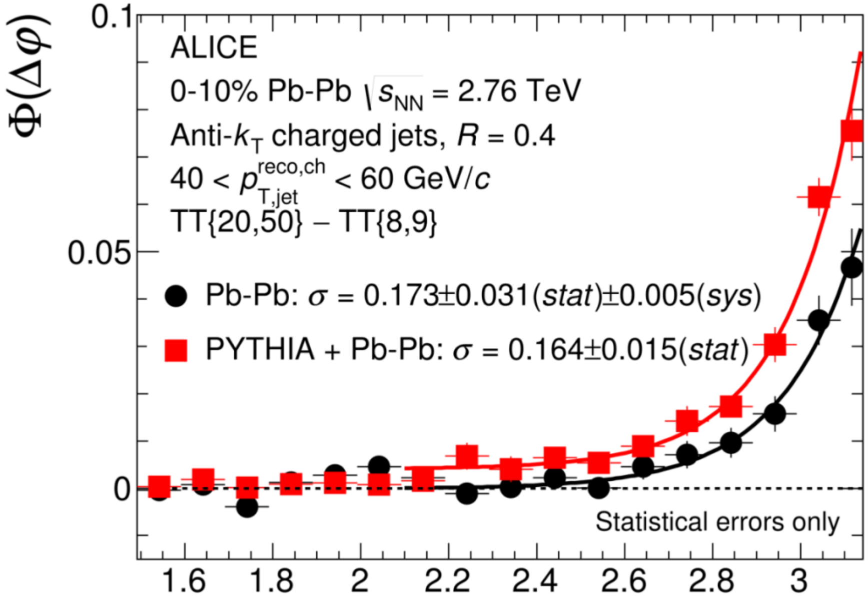
Nuclear modification factor "I_{CP}":

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

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

Acoplanarity?

ALICE@ LHC 2.76 TeV

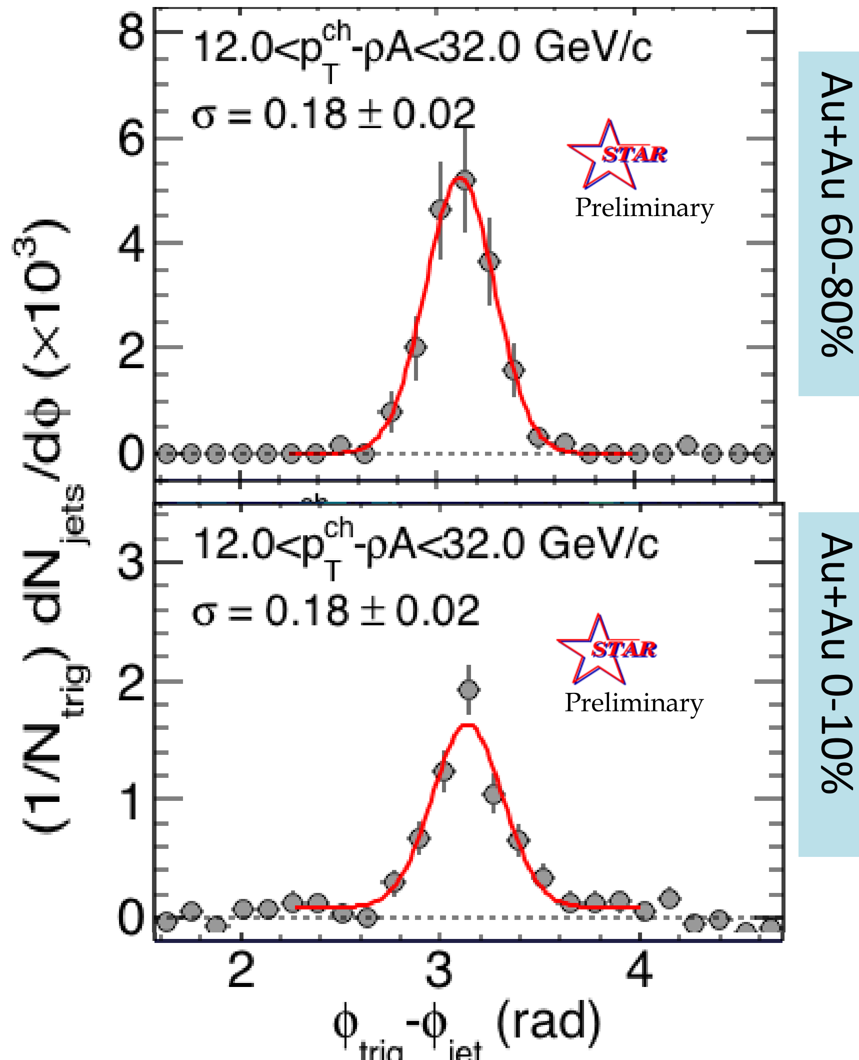


ALICE: arXiv:1506.03984

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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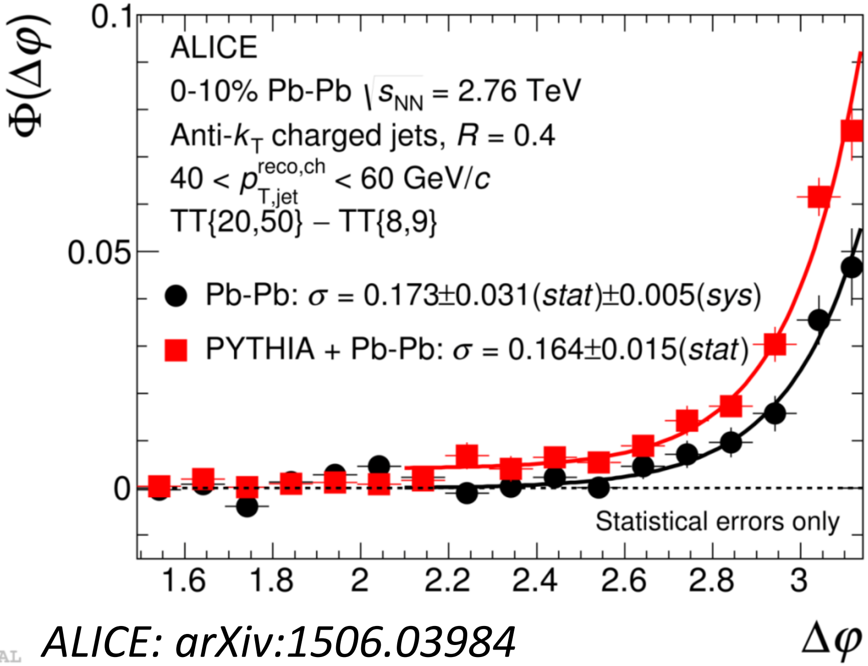

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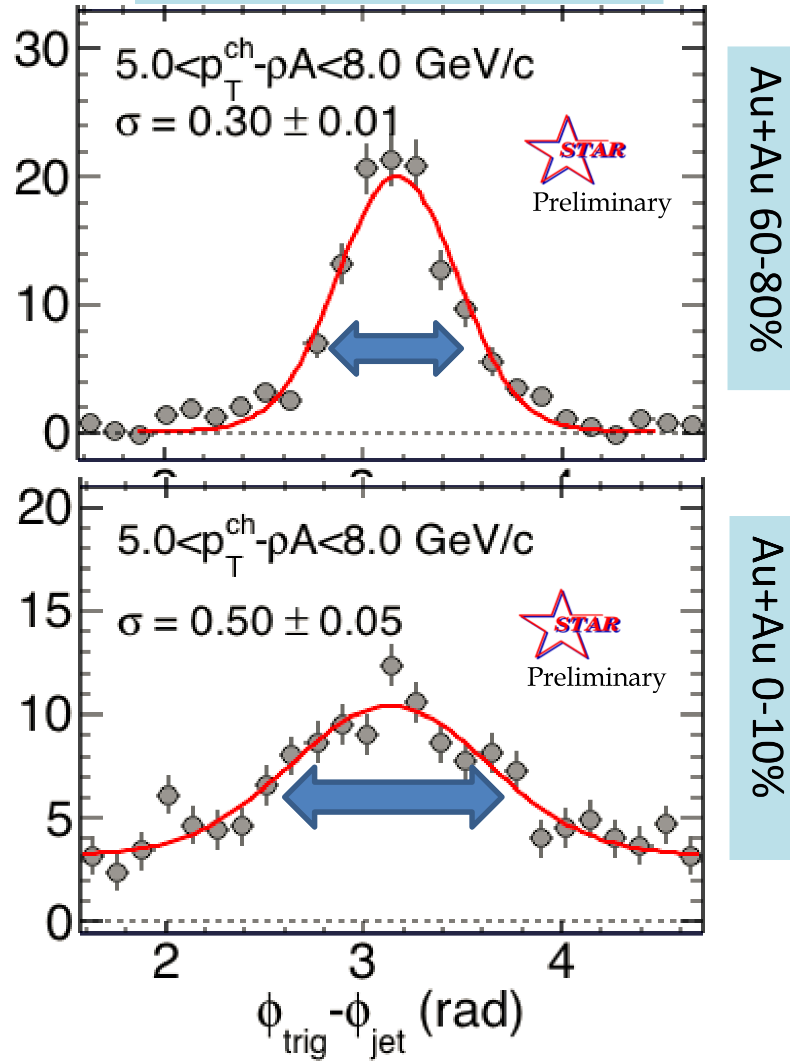
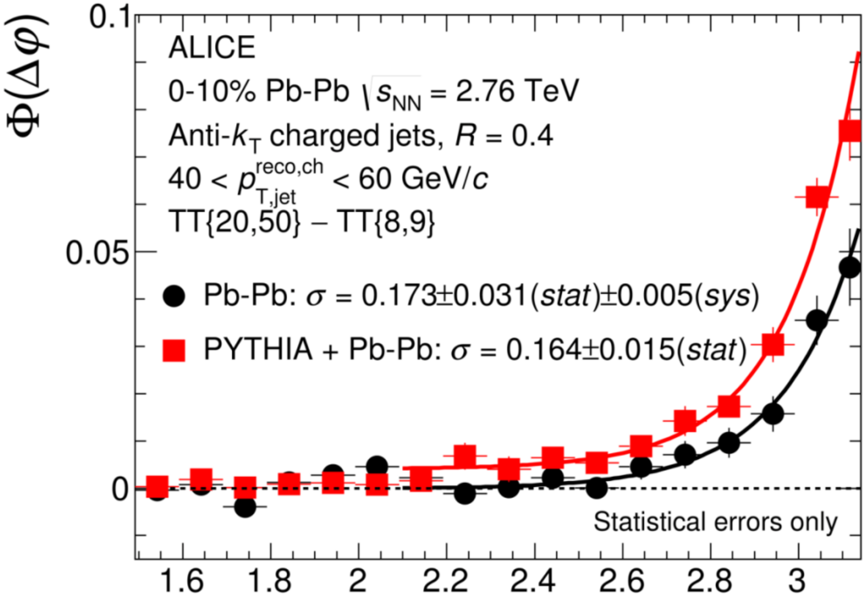


Low-p_T trigger: broadening with centrality

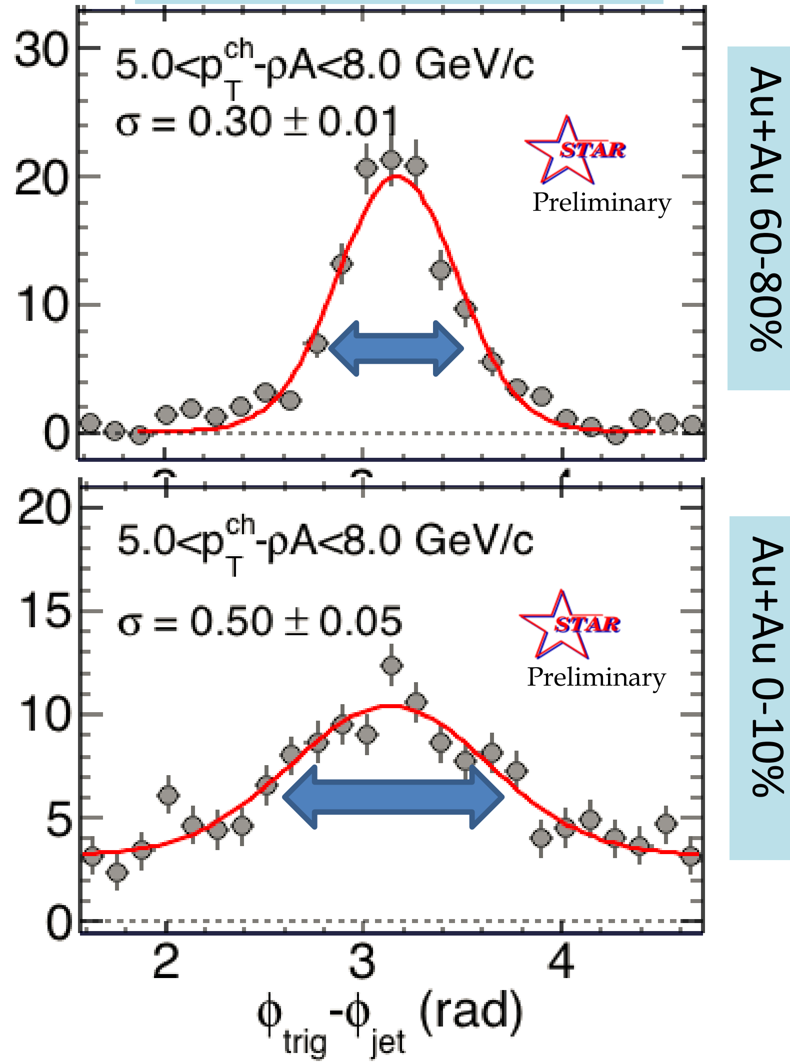
Acoplanarity?

ALICE@ LHC 2.76 TeV

STAR@RHIC 0.2 TeV



ALICE: arXiv:1506.03984



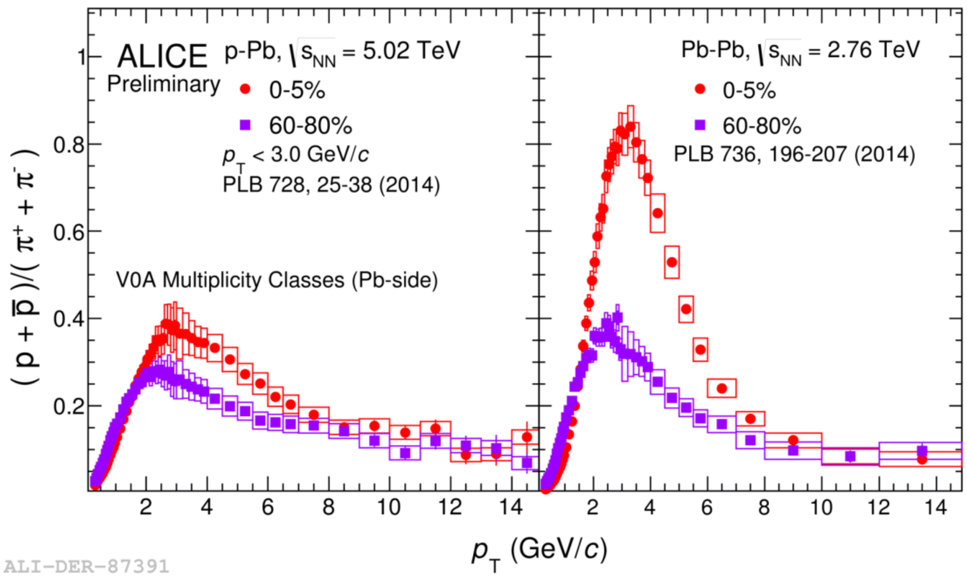
Future large-angle jet deflection studies may provide a direct probe of the nature of the quasi-particles in hot QCD matter.

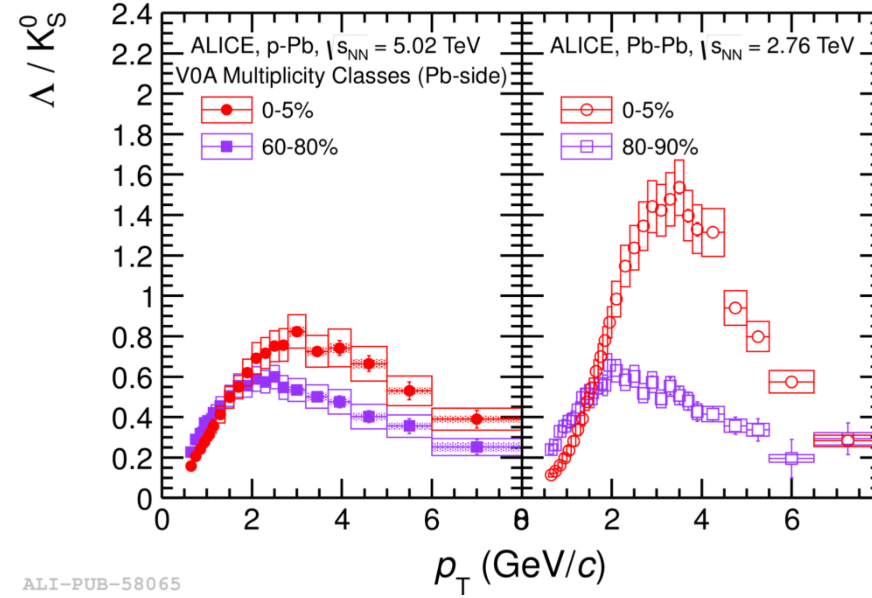
Low-p_T trigger: broadening with centrality

Strange particle production in jets

Baryon/meson enhancement in p-Pb and Pb-Pb 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^0_S ratio

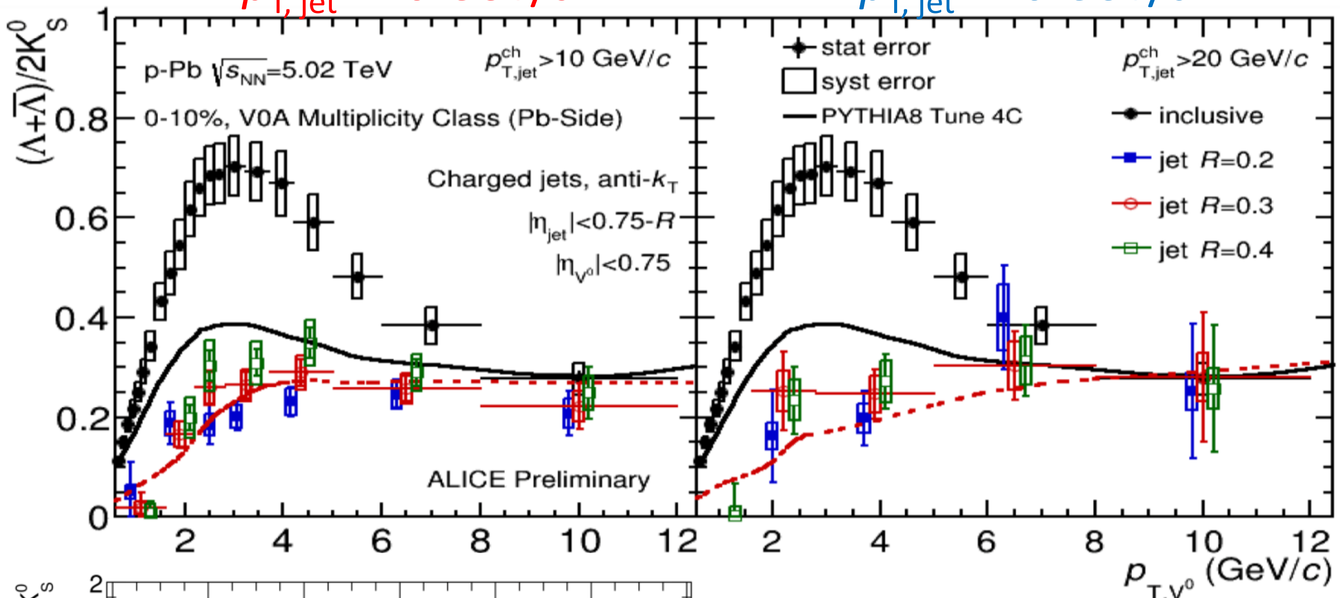
What is physics origin of this enhancement?

- radial flow
- coalescence/recombination vs fragmentation

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

Strange particle production in jets

$p_{T,\,jet}$> 10 GeV/c $p_{T,\,jet}$> 20 GeV/c

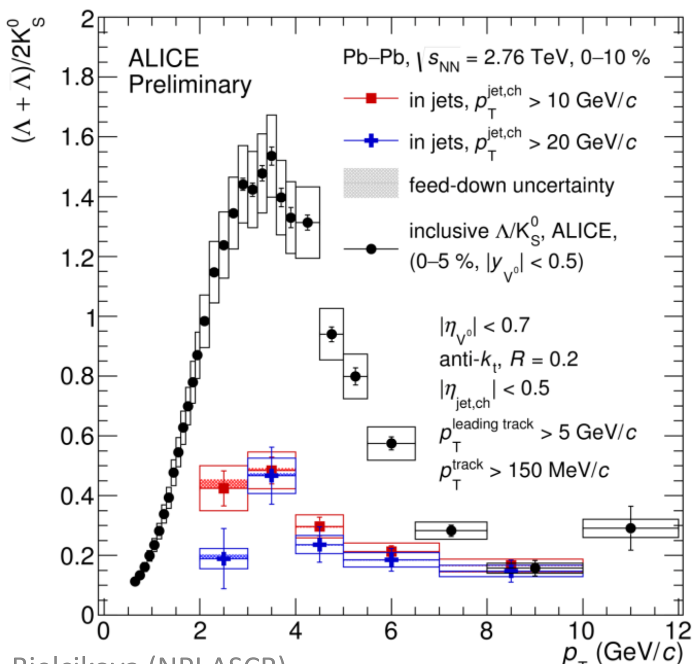


J. Otwinovski (ALICE), Thu 15:40

V0s in PYTHIA

----- inclusive

----- in jets (R=0.3)

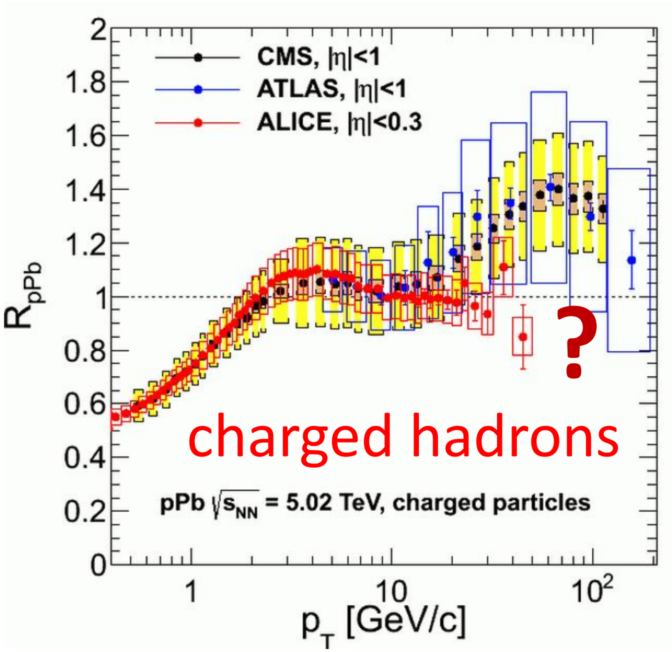


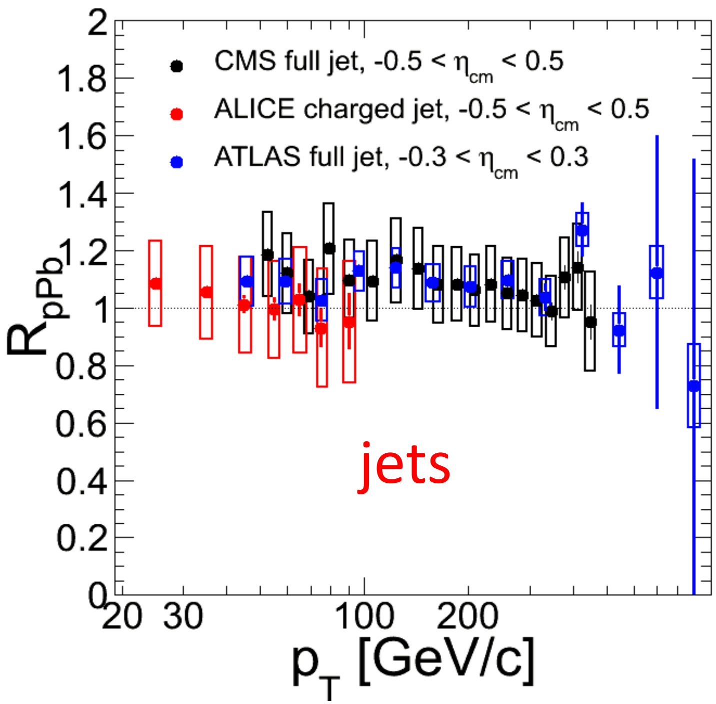
Λ/K^0_S ratio in charged jets in p-Pb and Pb-Pb significantly lower than inclusive and pp

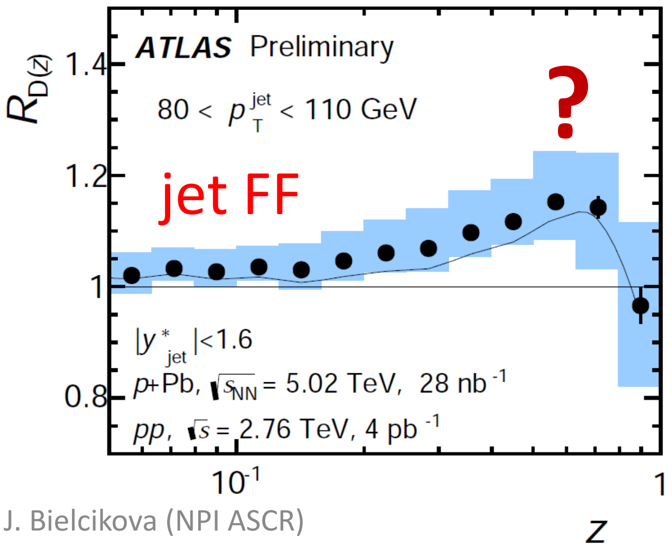
Jet composition is not influenced by the enhanced baryon/meson production in the bulk.

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

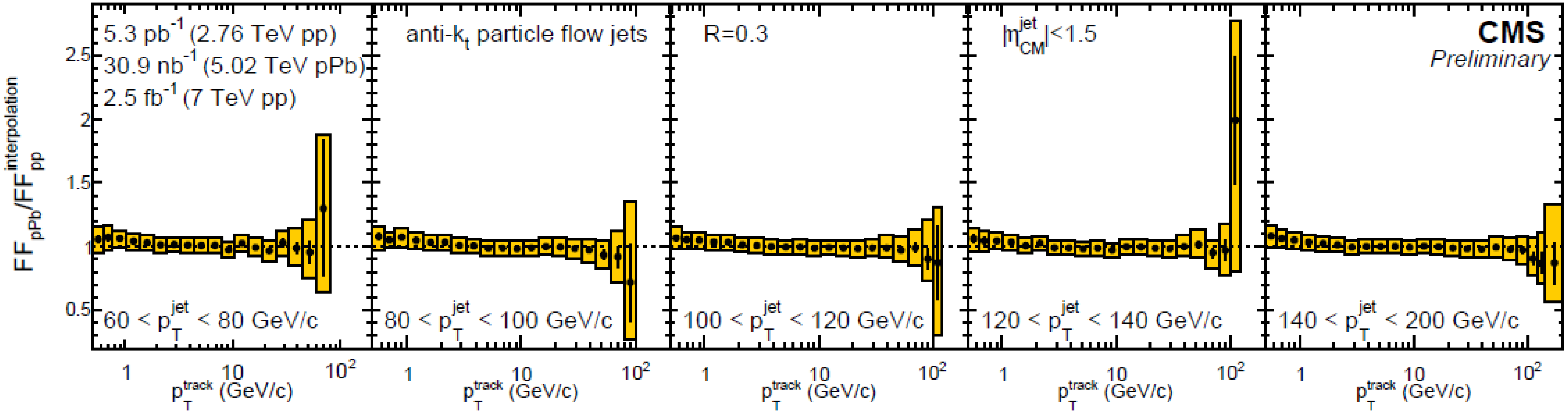
At the same time inclusive jet production is not modified in pPb, agreement across experiments.

Is it in the pp @ 5 TeV reference?

Y.S. Lai (CMS)
Thu 15:15

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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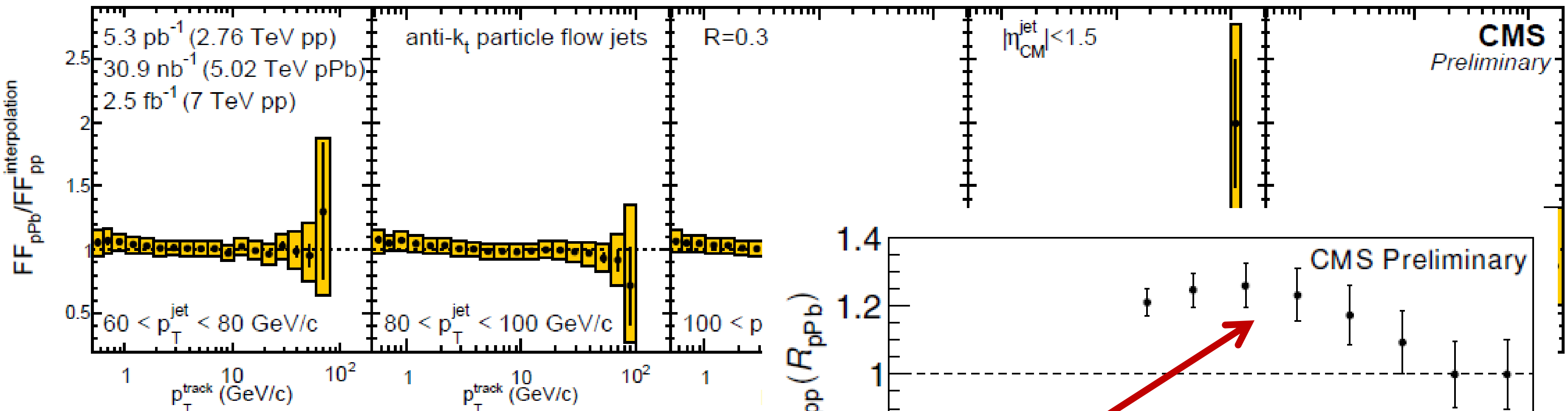
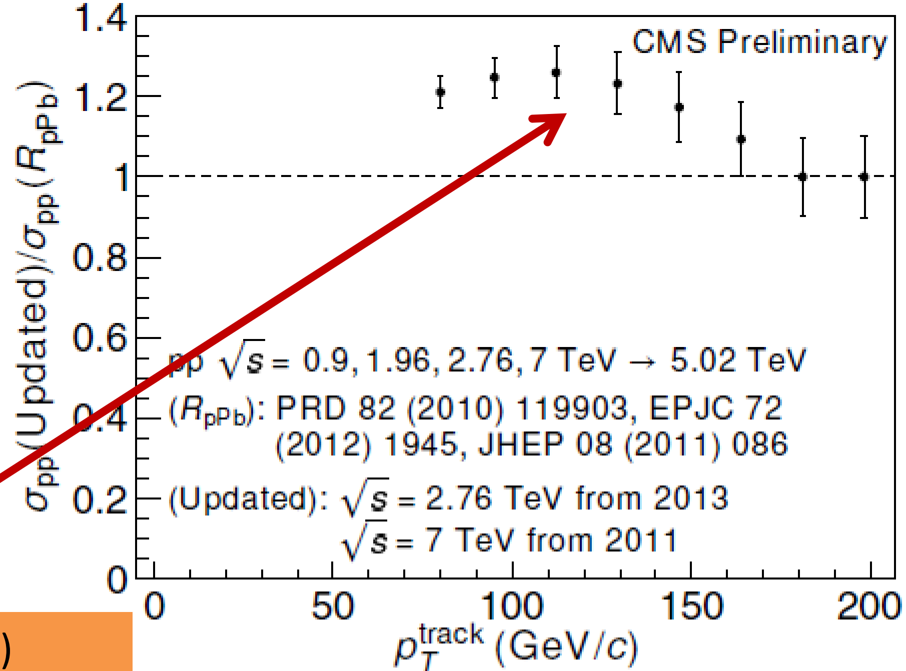




Revisited CMS p-Pb reference from *EPJC 75 (2015)* 237, which used previously published CMS + CDF data

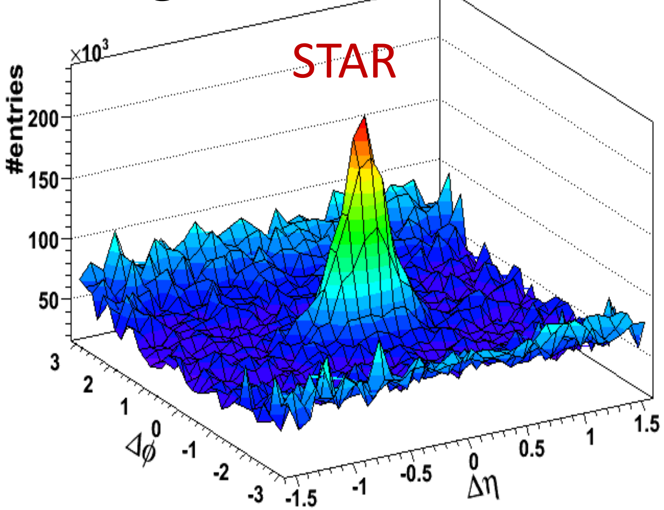
The ratio of old/new reference resembles the "bump" in the charged particles R_{pPb}.

Y.S. Lai (CMS)
Hard Probes 2015

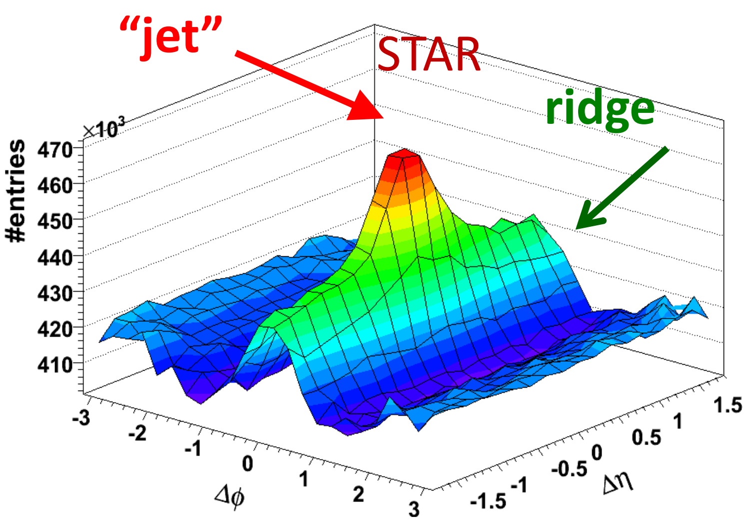
Ridge

The ridge phenomenon …

d+Au @ 200 GeV

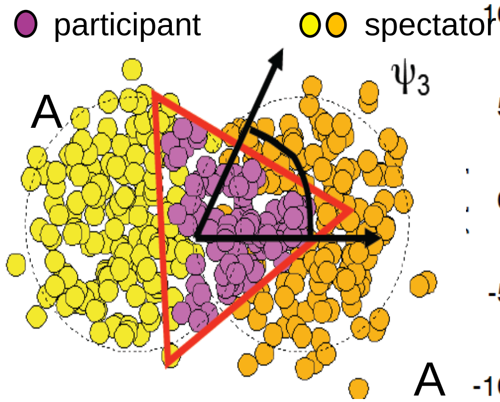


0-12% Au+Au @ 200 GeV

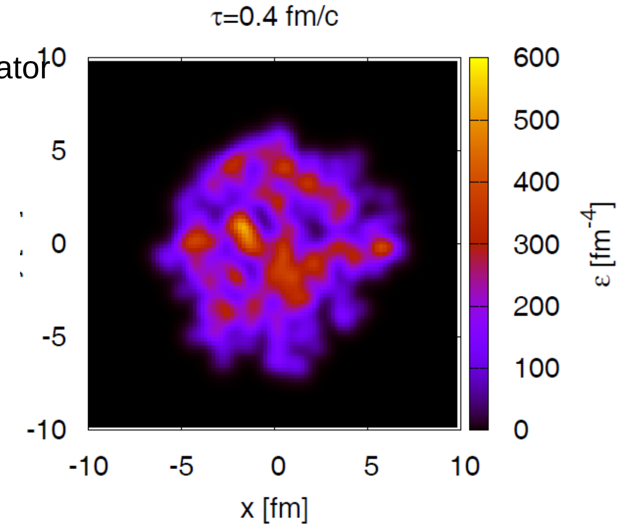


p_T^{trig}=3-4 GeV/c, 2 GeV/c $< p_T^{assoc} < p_T^{trig}$

STAR: *PRC80 (2009) 064912*



Alver, Roland,
PRC81 (2010) 054905



3+1D viscous hydrodynamics

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

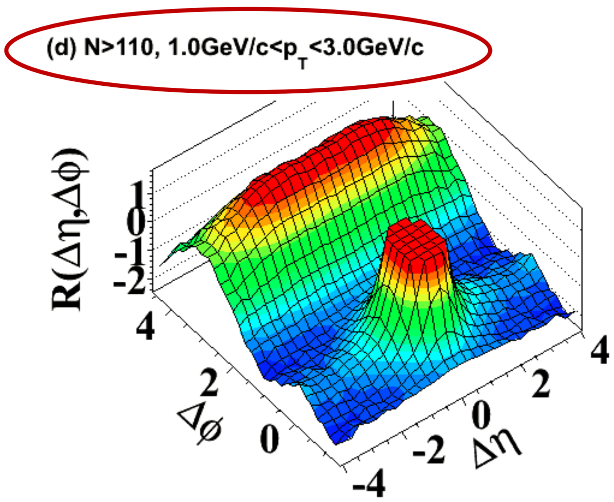
Additional near-side ($\Delta\phi$) correlation in pseudorapidity ($\Delta\eta$) observed in central Au+Au collisions at RHIC in 2004.

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).

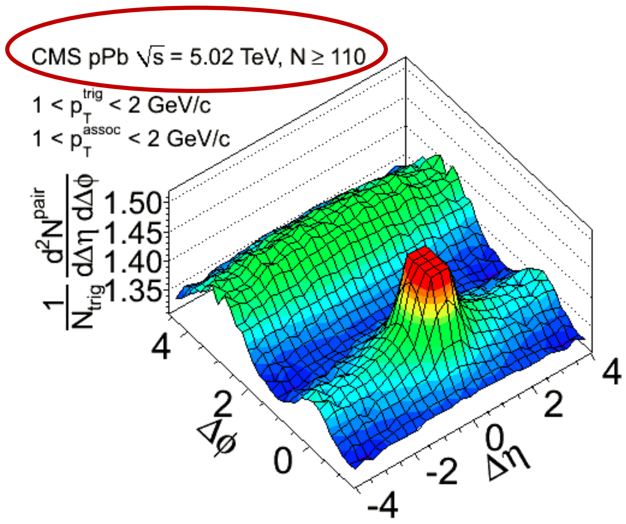
Collectivity in small systems: the LHC ridges

High multiplicity pp @ 7 TeV

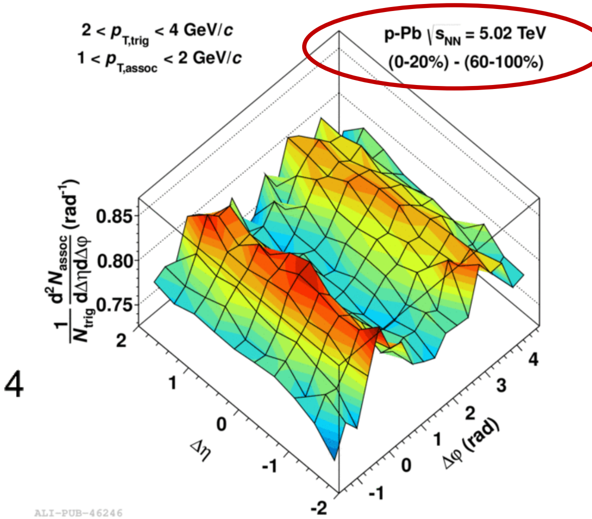
pPb @ 5.02 TeV



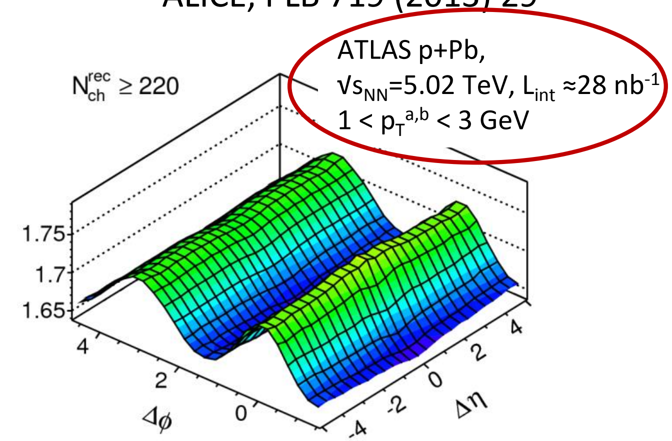
CMS, JHEP09 (2010) 091



CMS, PLB 718 (2012) 795



ALICE, PLB 719 (2013) 29



ATLAS, PRC 90 (2014) 044906

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?

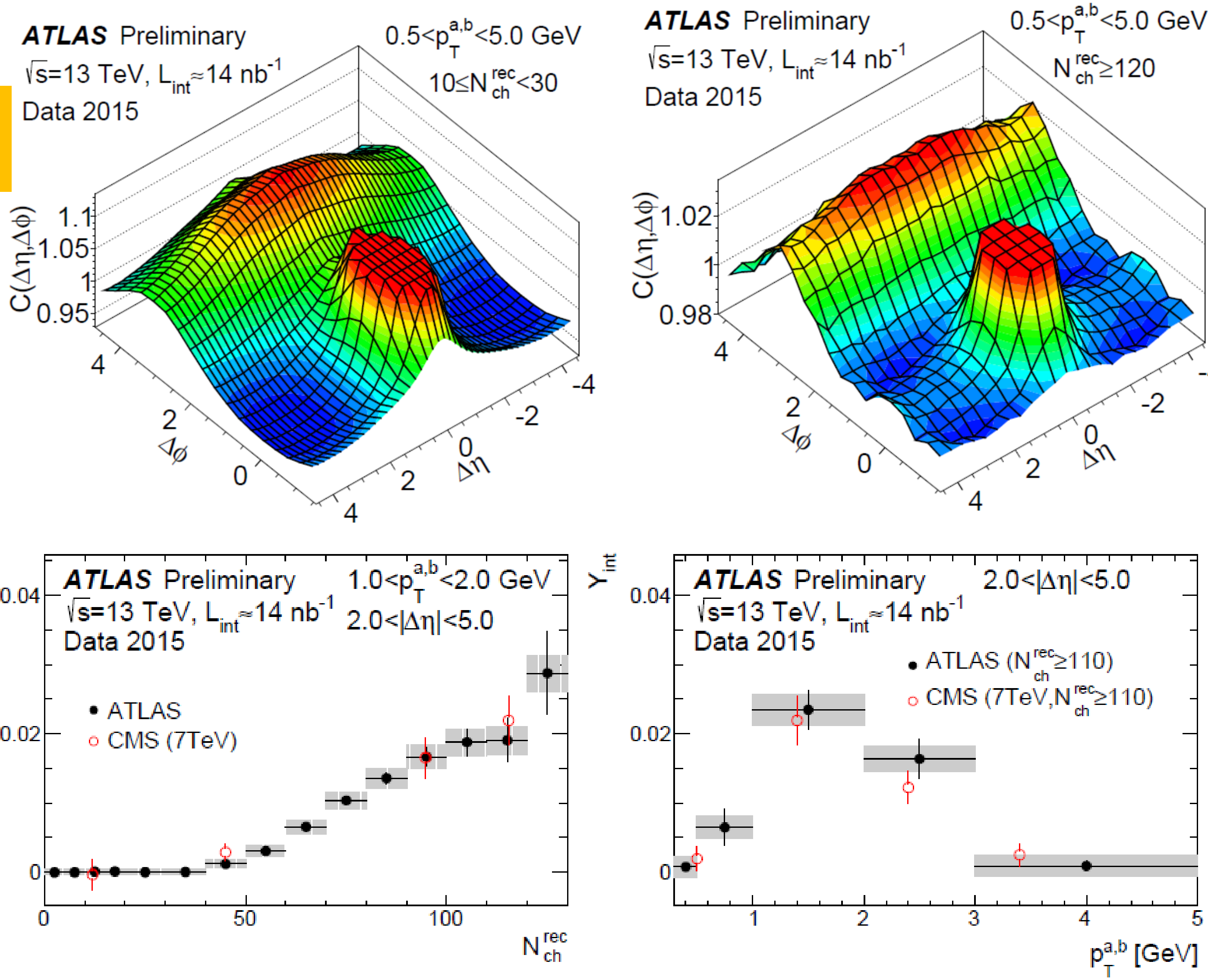
Ridge persists in 13 TeV pp collisions

NEW!

low multiplicity

high multiplicity

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

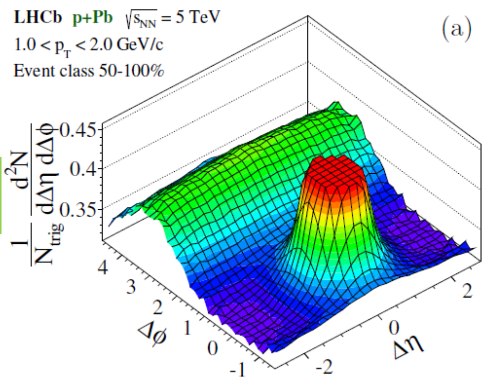
Correlations of charged particles in forward direction: 2< η < 4.9

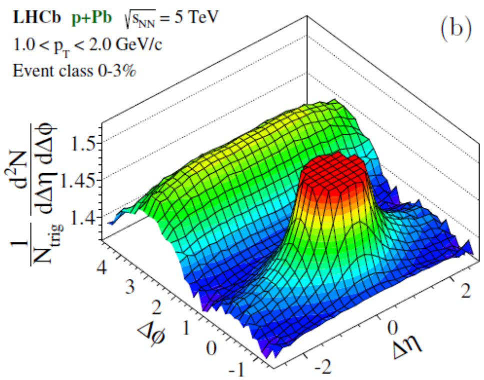
M. Meissner (LHCb)
Thu 11:50

low multiplicity

high multiplicity

p+Pb

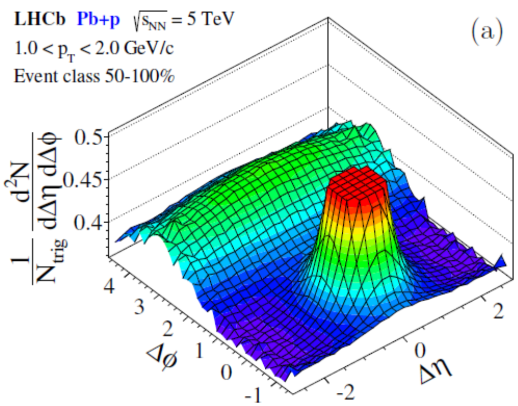


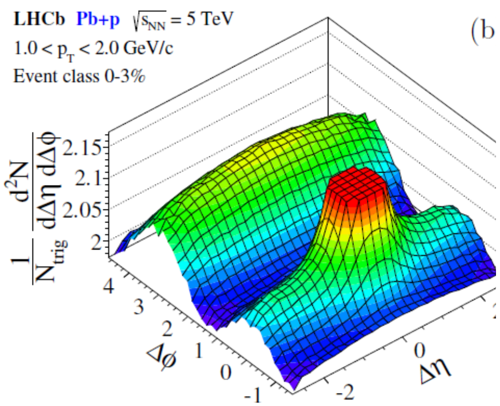


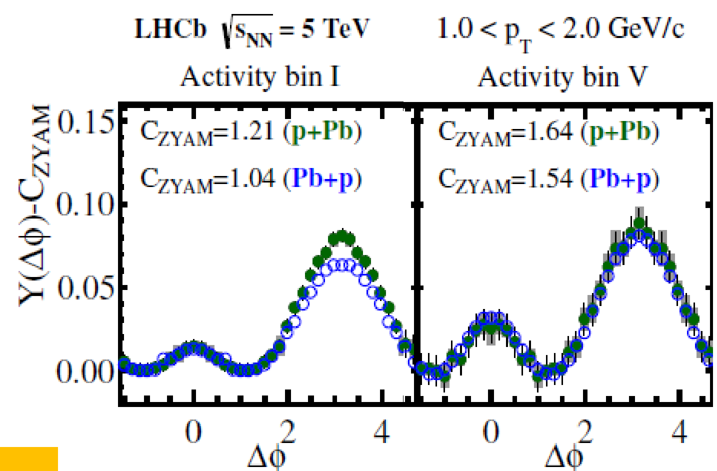
Ridge observed in high multiplicity p+Pb collisions in forward direction as well!

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.

LHCB-CONF-2015-004

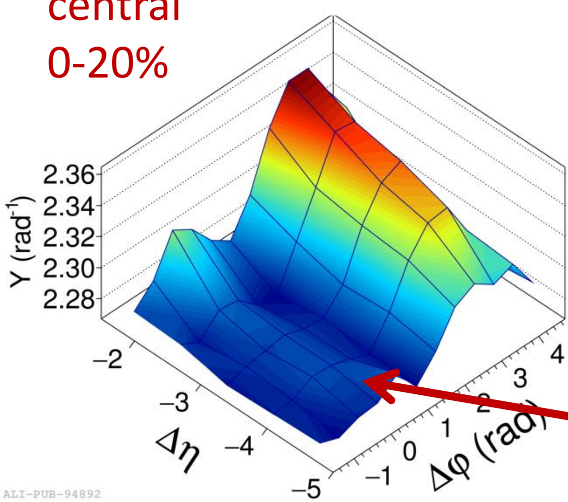
p-Pb ridges extend to large rapidities

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*

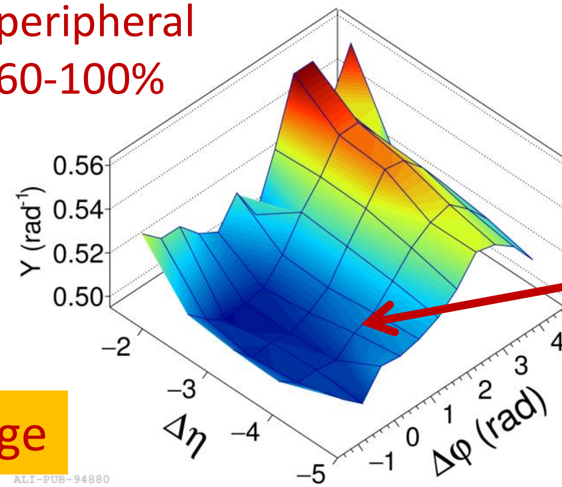
central
0-20%



ridge

−

peripheral
60-100%



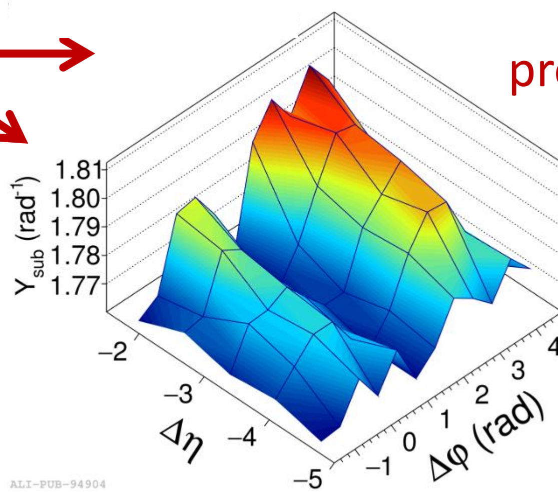
no ridge

Double ridge extends over 10 units of rapidity.

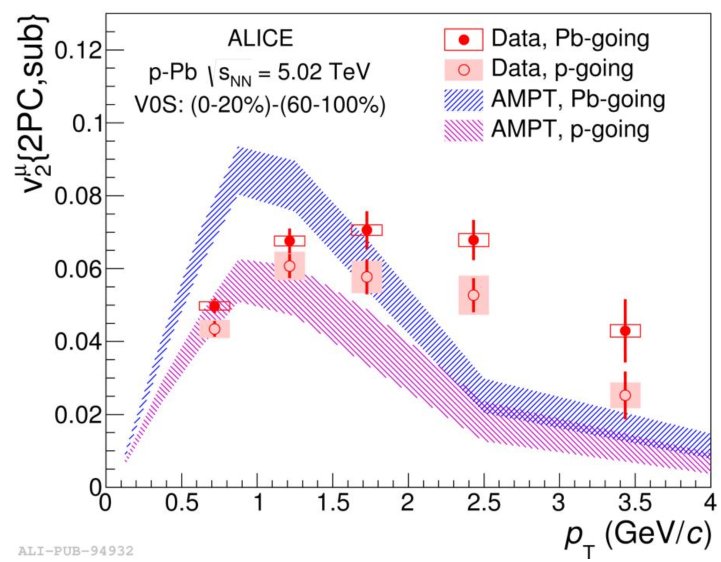
(0-20%)- (60-100%)

2 ridges

=



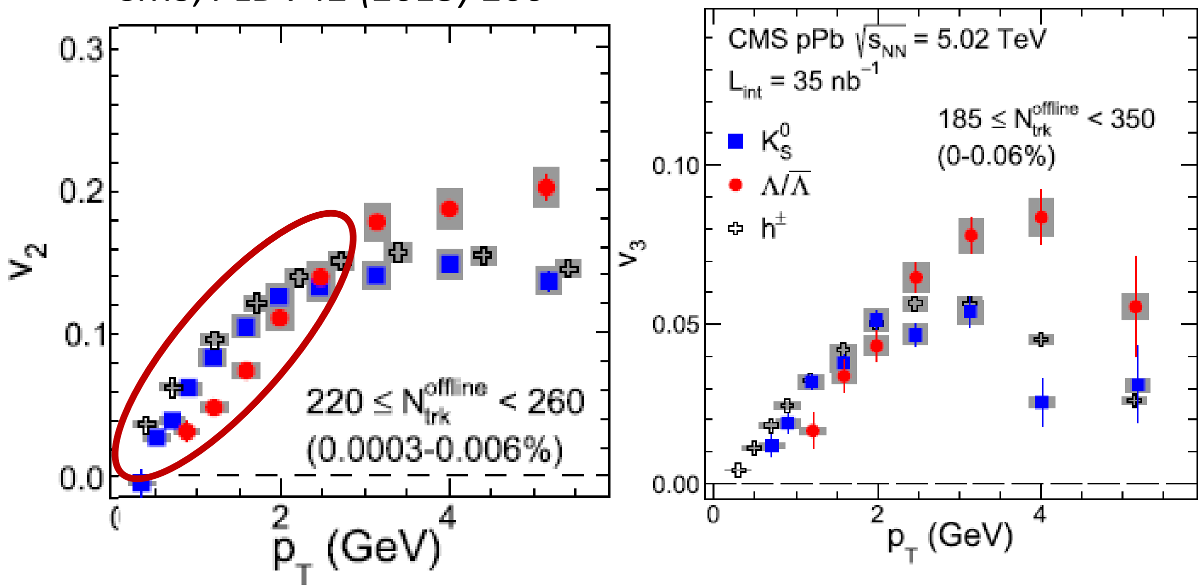
project onto Δϕ, calculate "v_2"



Evidence for collectivity in p-Pb?

D. Devetak (CMS)
Thu 16:30

CMS, *PLB 742 (2015) 200*



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

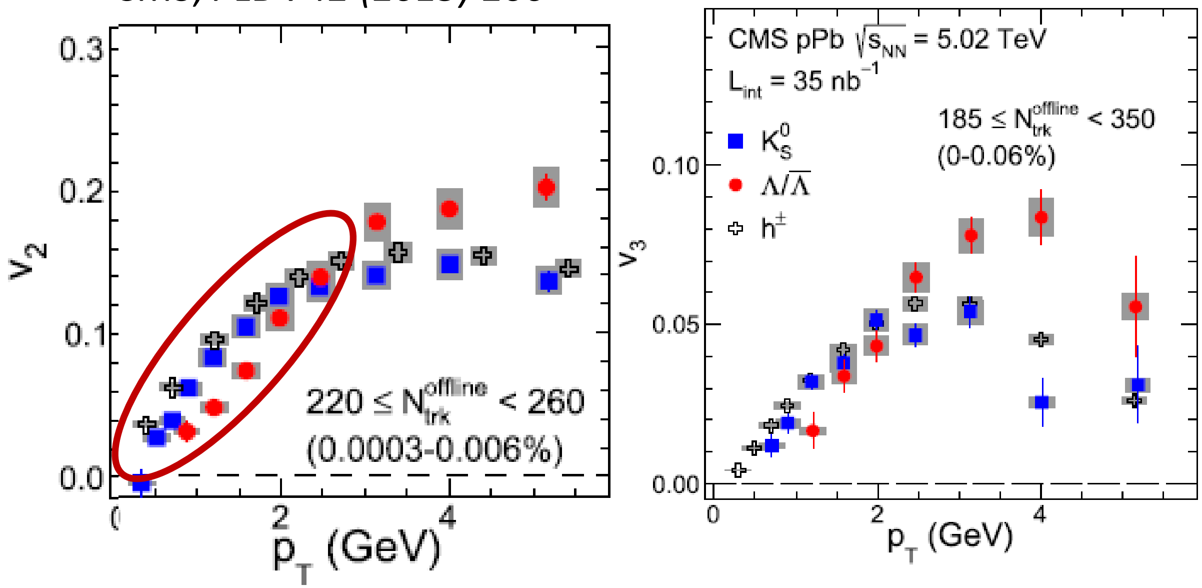
ALICE: PLB 726 (2013) 164

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

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

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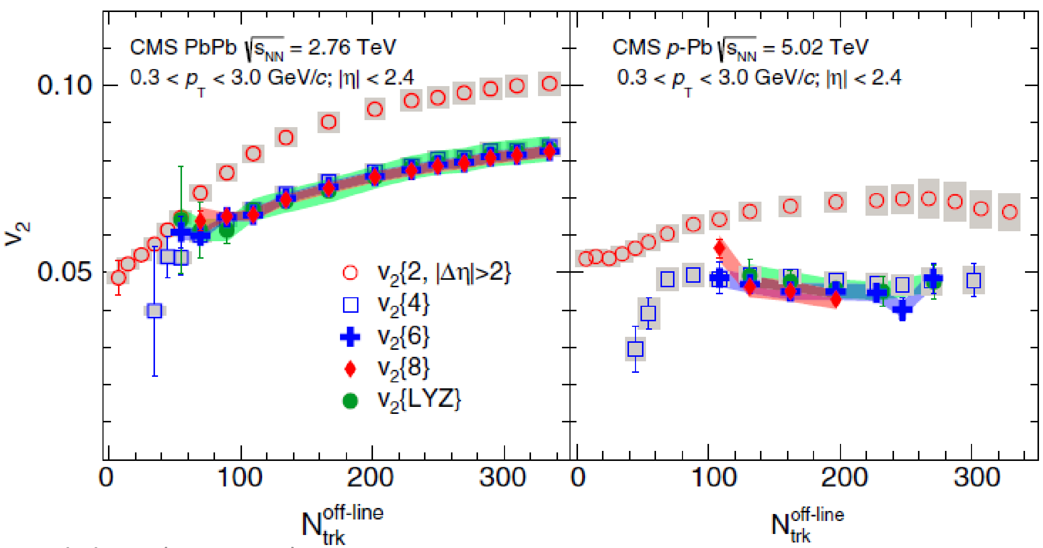
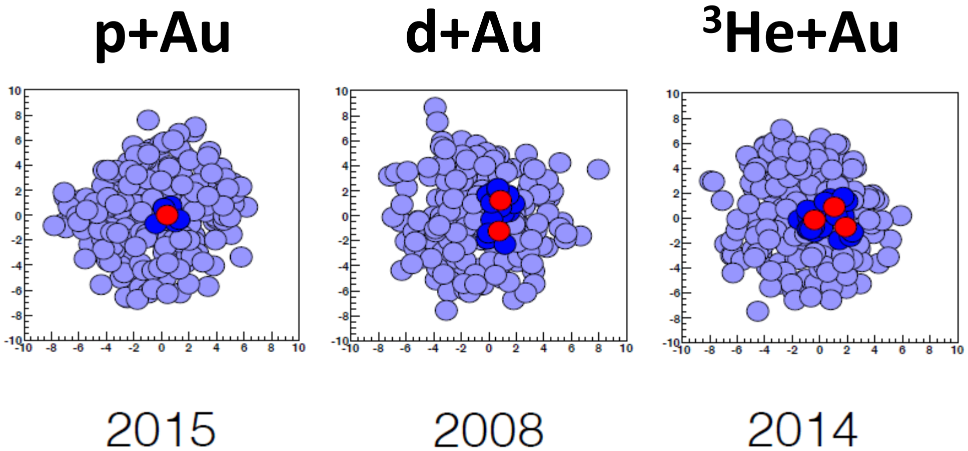
CMS, *PRL 115 (2015) 012301*



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

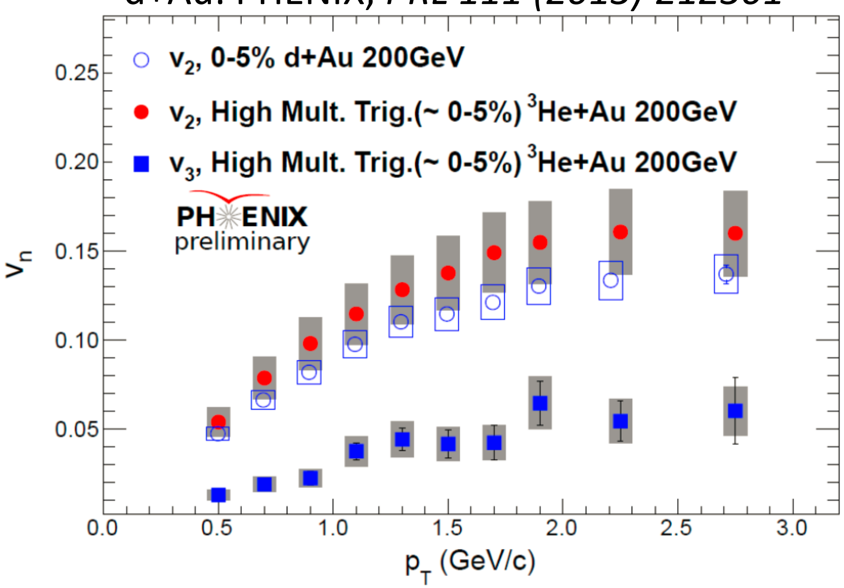
Can data from RHIC bring further insights?

Courtesy A. Sickles (PHENIX)

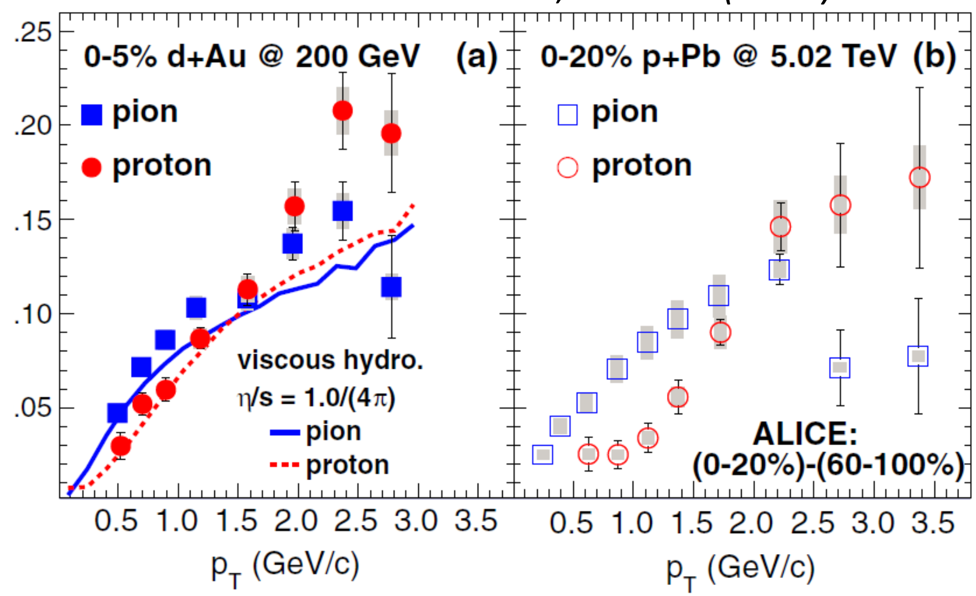


RHIC has unique capabilities to study variations in the initial state.

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



PHENIX, *PRL 114 (2015) 192301*

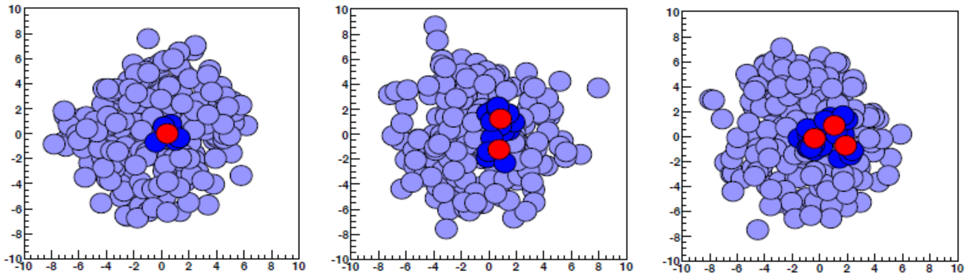


Evidence for ridge in d+Au and ^{3}He+Au collisions at 0.2 TeV at RHIC:
non-zero v_2, particle mass ordering

Can data from RHIC bring further insights?

Courtesy A. Sickles (PHENIX)

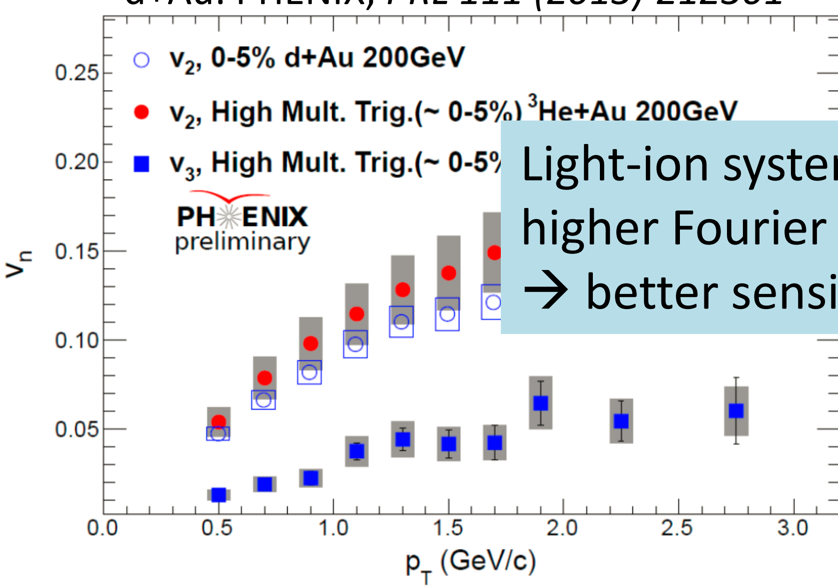
p+Au **d+Au** **^{3}He+Au**



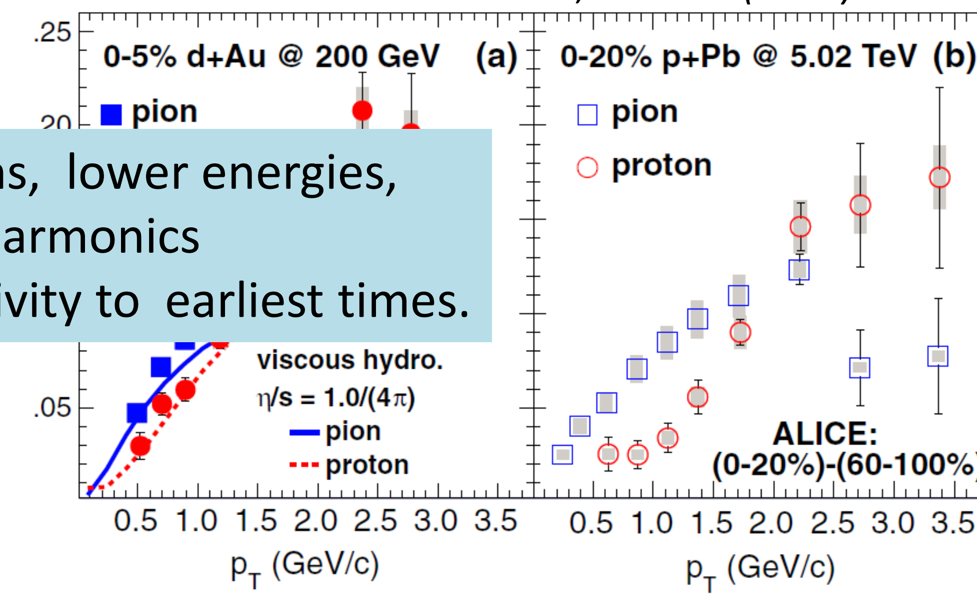
2015 2008 2014

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

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



PHENIX, *PRL 114 (2015) 192301*



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

Evidence for ridge in d+Au and ^{3}He+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

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

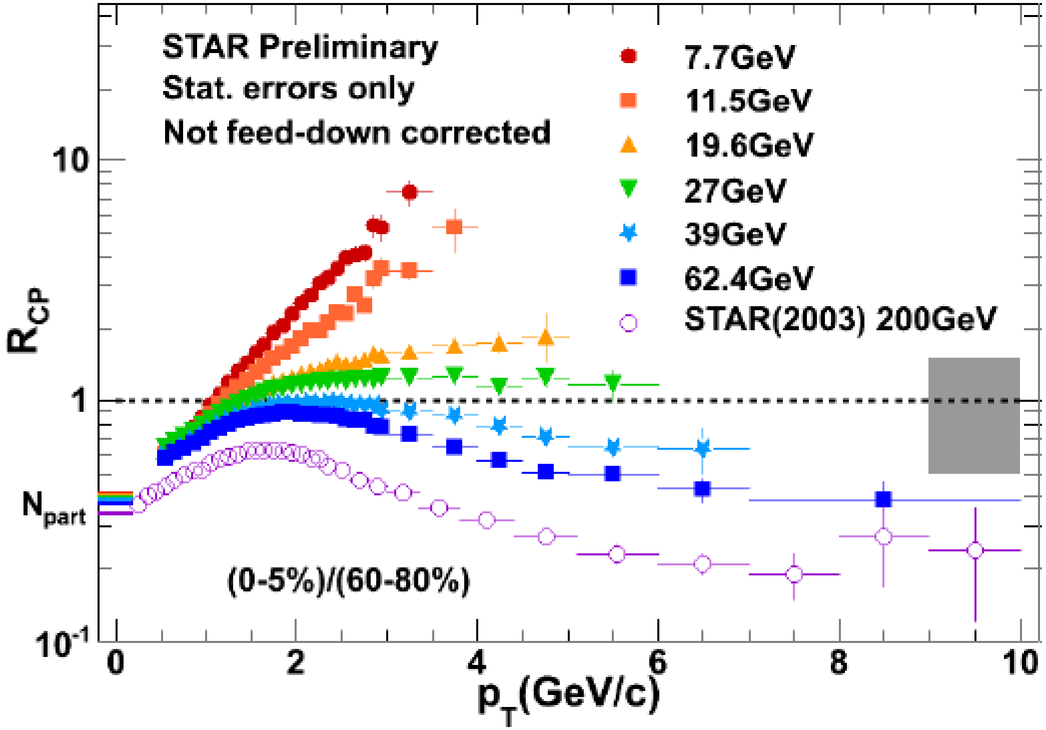
- looking forward to Run2 data at the LHC as well as high statistics runs at RHIC to pin down medium properties and possible collective effects in small collision systems !

THANK YOU!

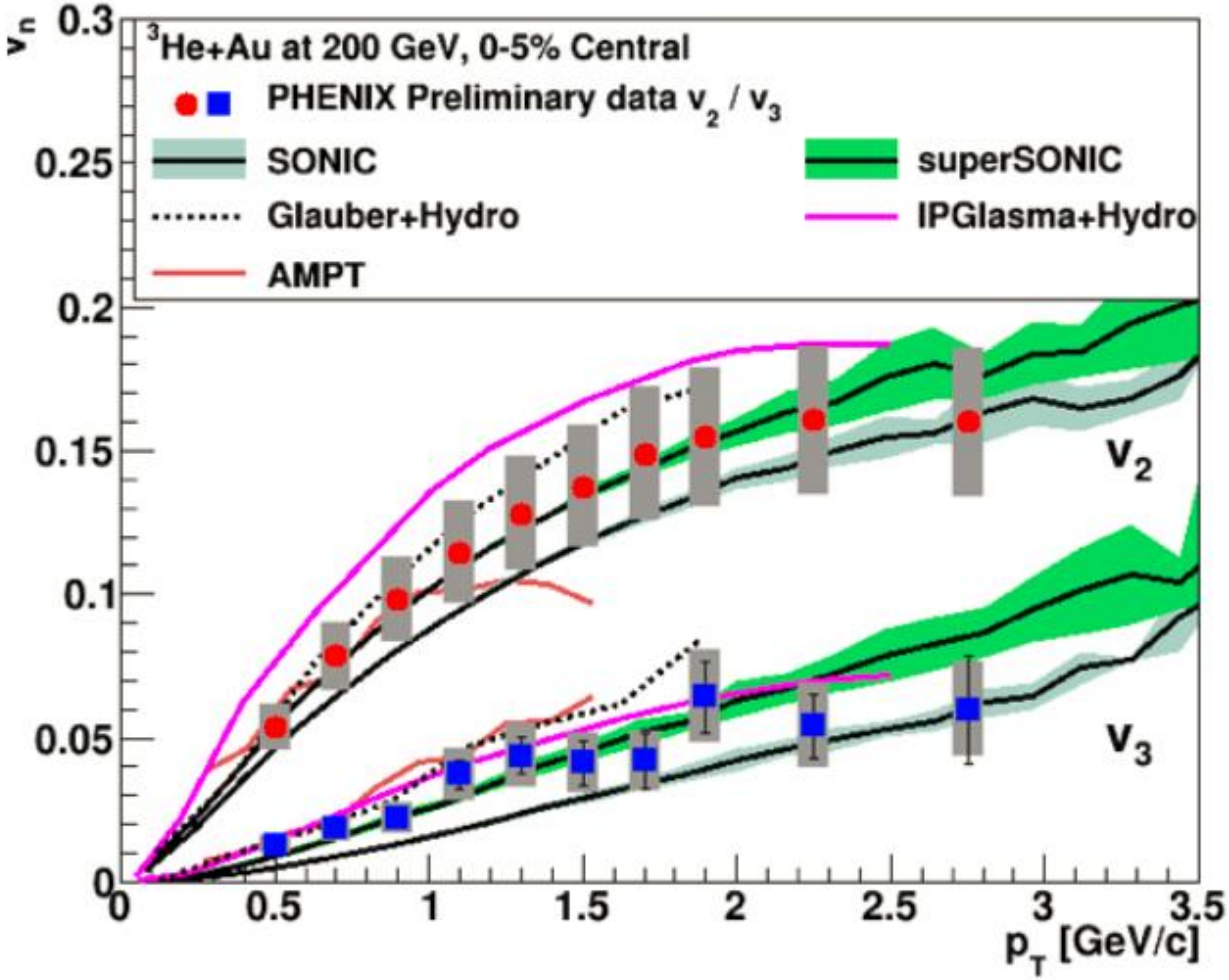
BACKUP slides

RHIC BES: charged particle R_{CP}

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

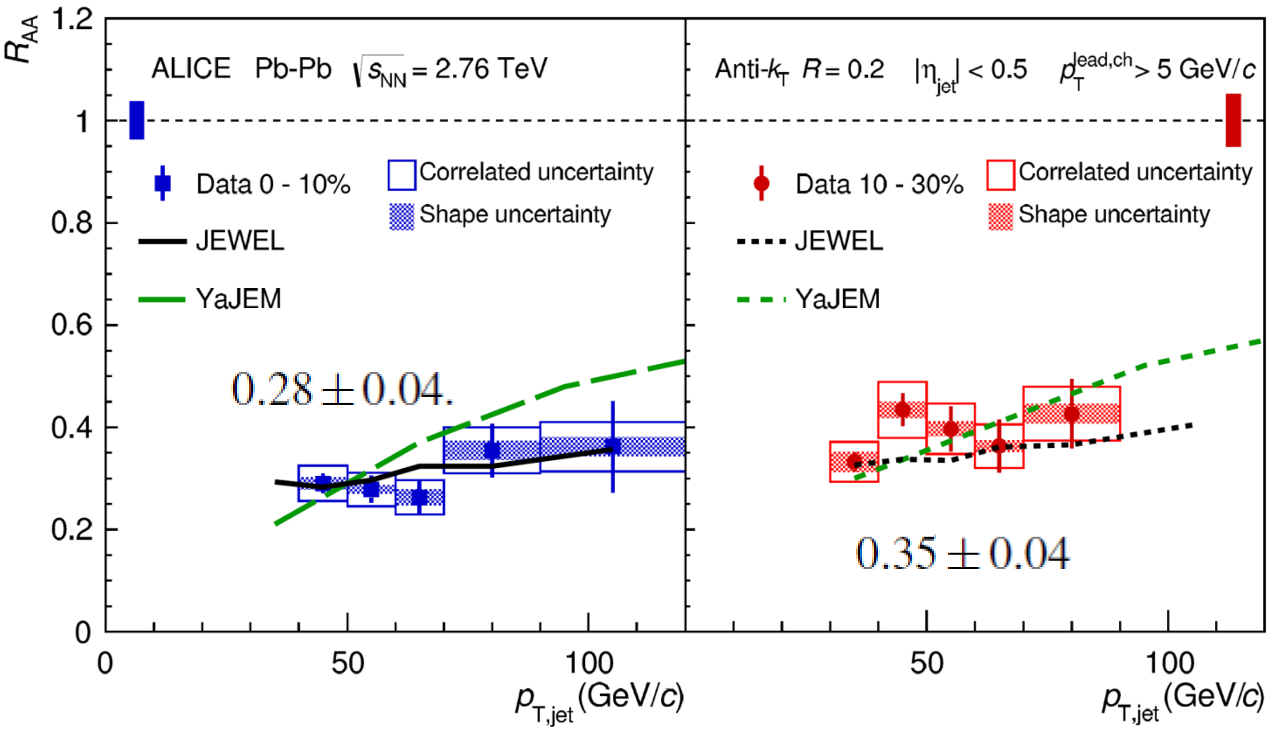


^{3}He+Au vs models



Full jet suppression in Pb-Pb collisions

Phys.Lett. B746 (2015) 1, [arXiv:1502.01689]



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

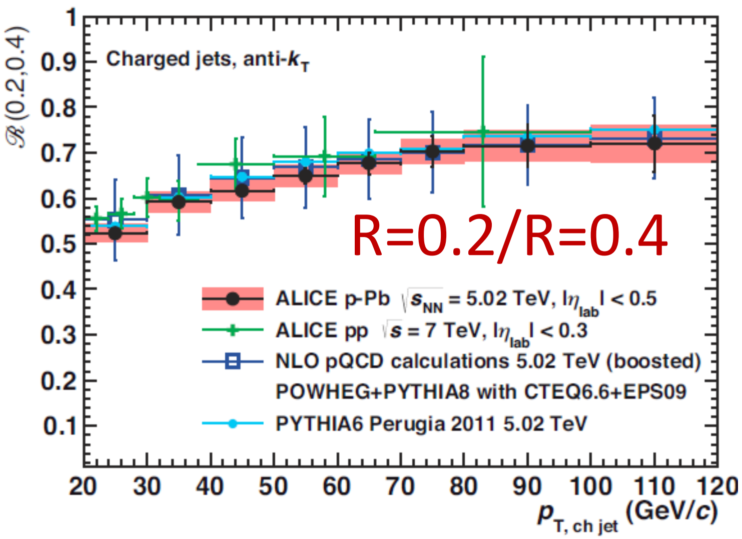
YaJEM: T. Renk,
PRC 78 (2008) 034908,
PRC 84 (2011) 067902

- 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

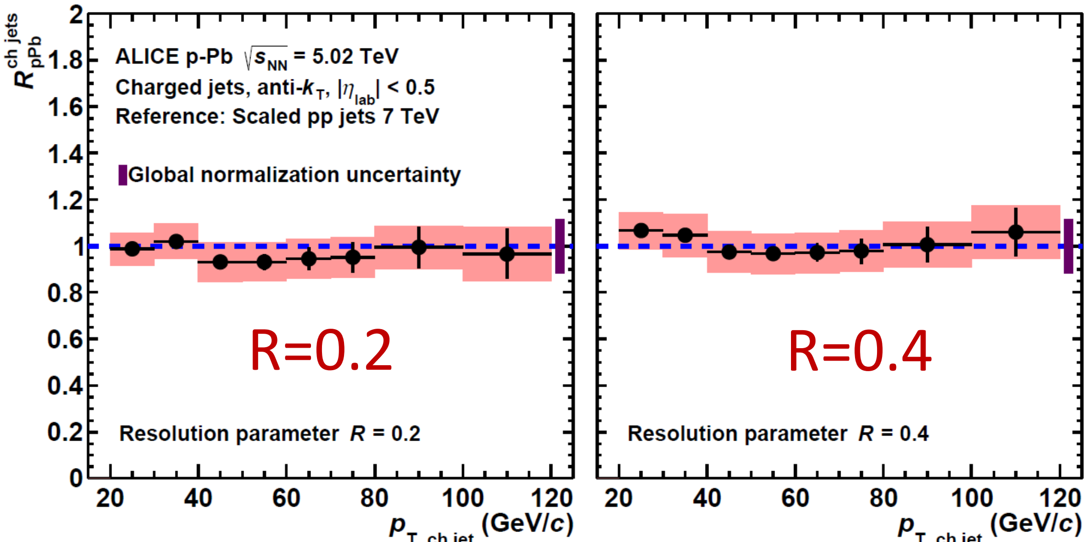
→ Jet R_{AA} vs event plane to pin down the path-length dependence of jet quenching and to differentiate models

ALICE: Charged jets in p-Pb *arXiv:1503.00681*



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

σ(R=0.2)/σ(R=0.4):
jet energy redistribution? No, p-Pb compatible with pp at 7 TeV, PYTHIA and POWHEG

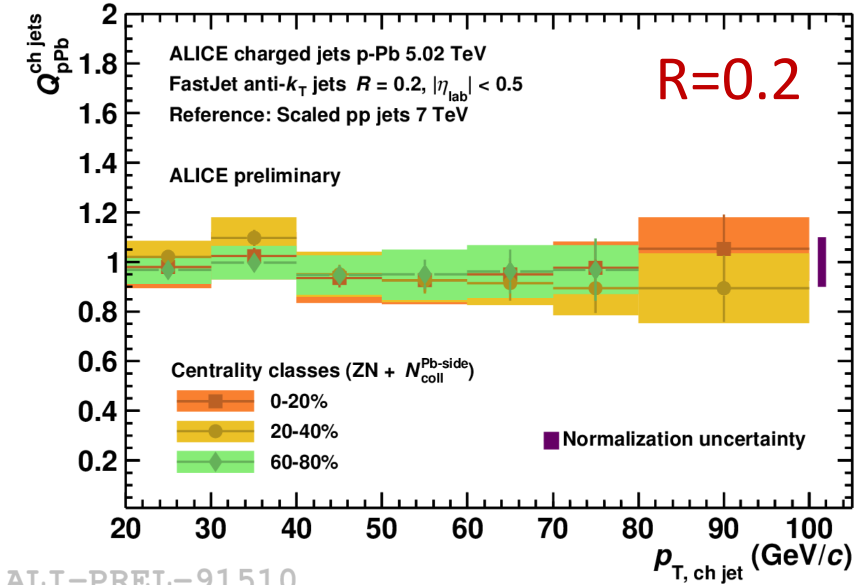


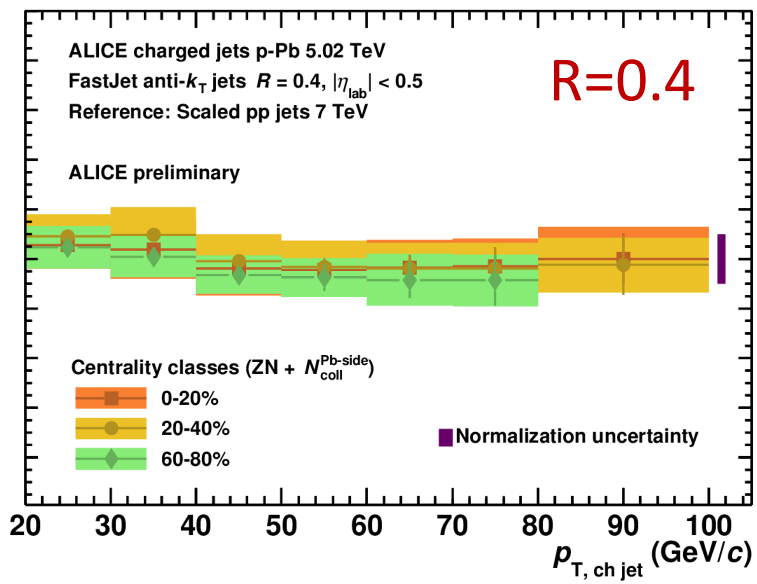
R_{pPb}:
within uncertainties no modification of charged jet spectra observed relative to pp

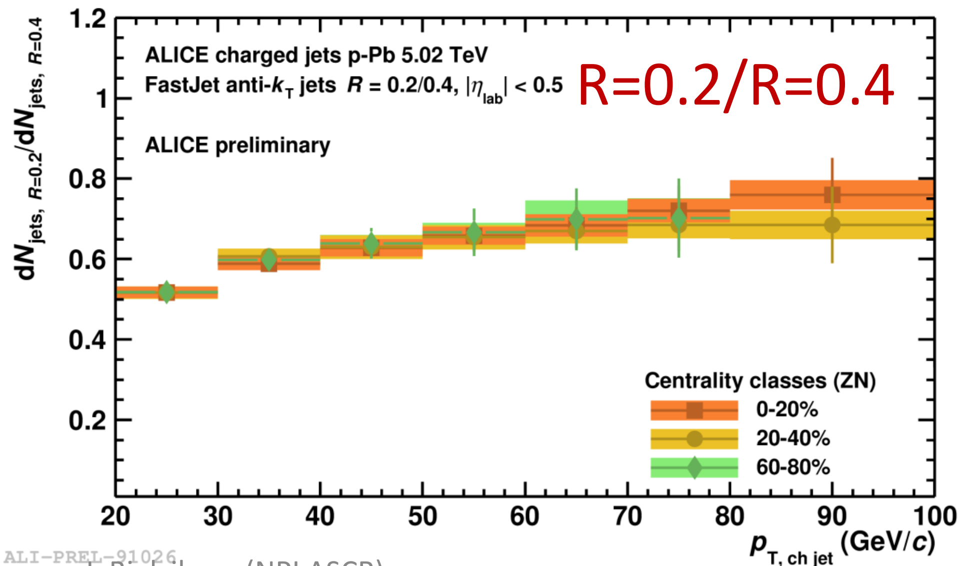
No indication of cold nuclear matter modification of jet production in MB data.

Multiplicity dependence of charged jets in p-Pb

N_{coll} from Pb-side estimator







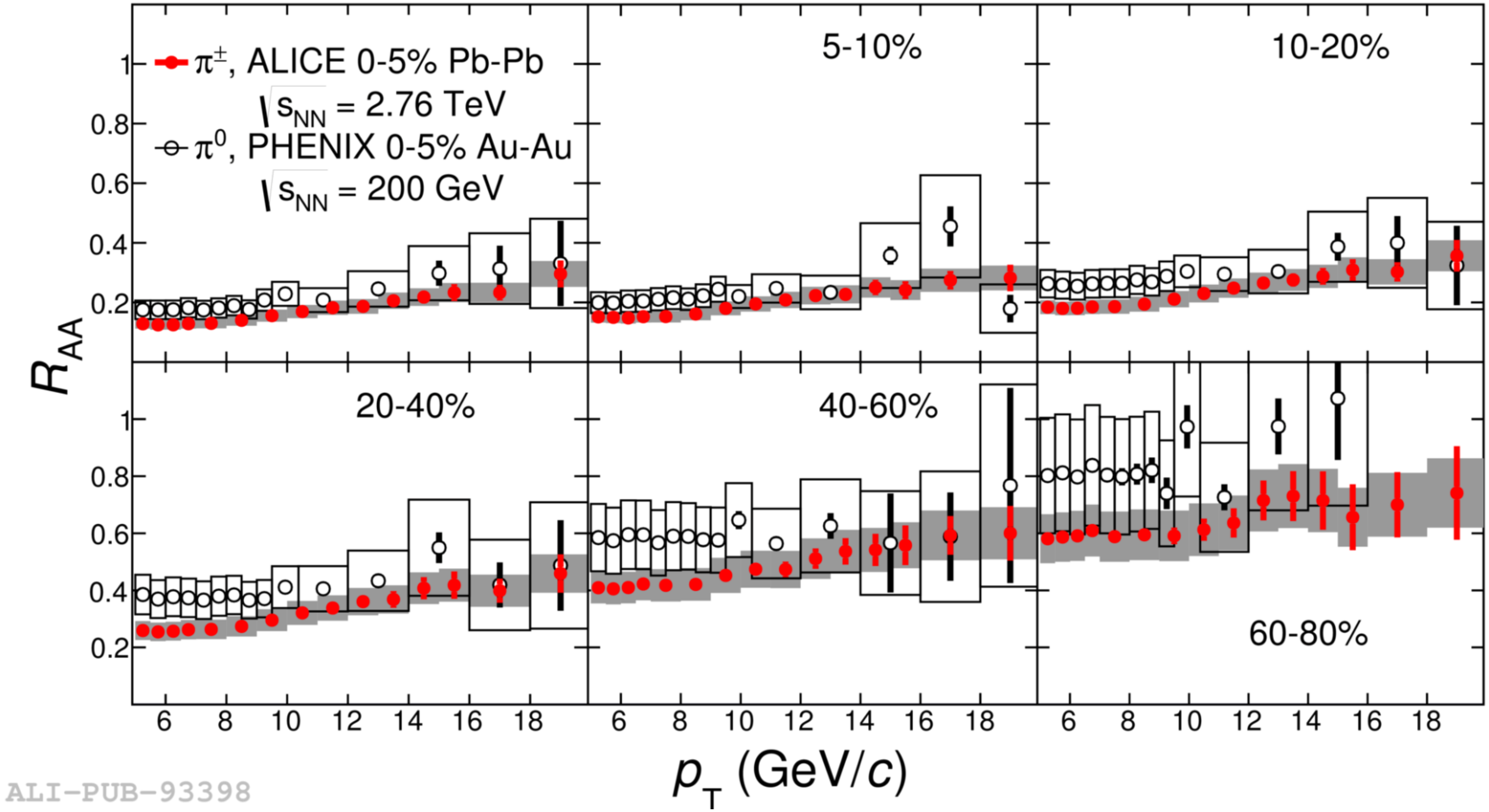
- centrality dependent charged jet Q_{pPb} measured up to 100 GeV/*c:* consistent with binary scaling

- no modification of jet radial structure

No significant multiplicity dependence or CNM effects observed.

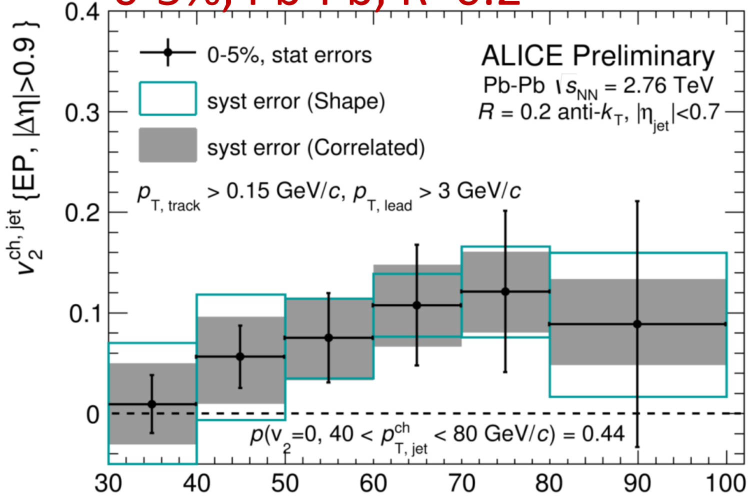
Nuclear modification factor: RHIC vs LHC

ALICE: arXiV-1506.07287

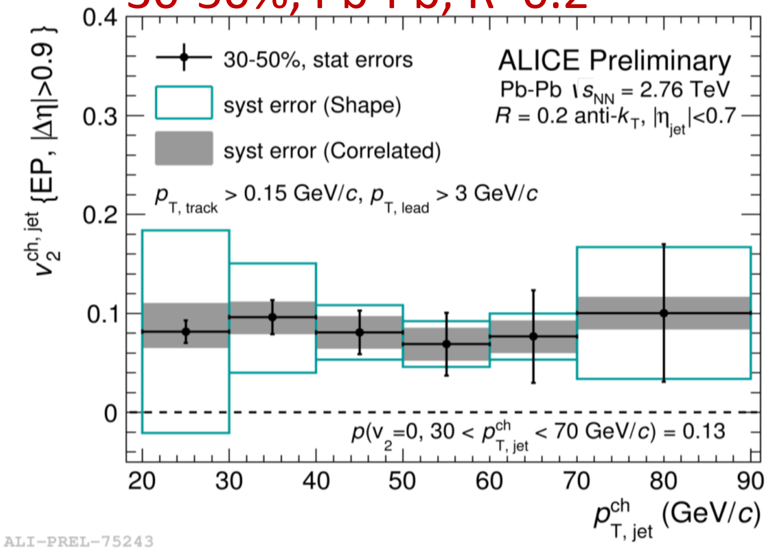


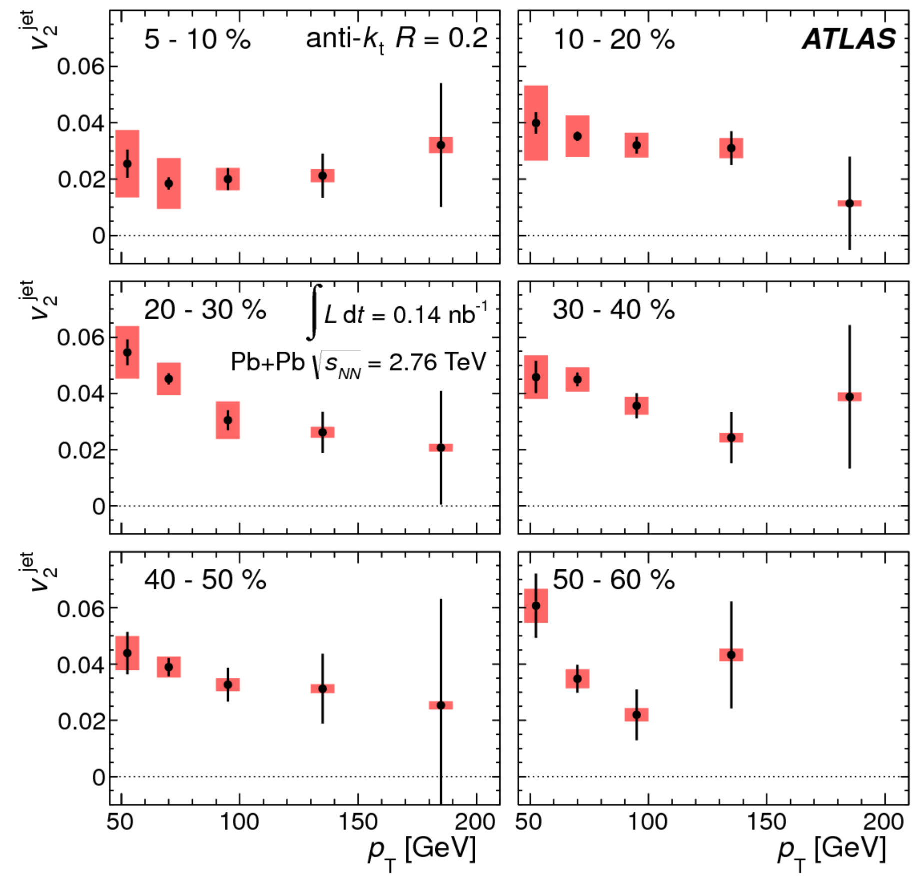
Path length effects on jet production

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



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





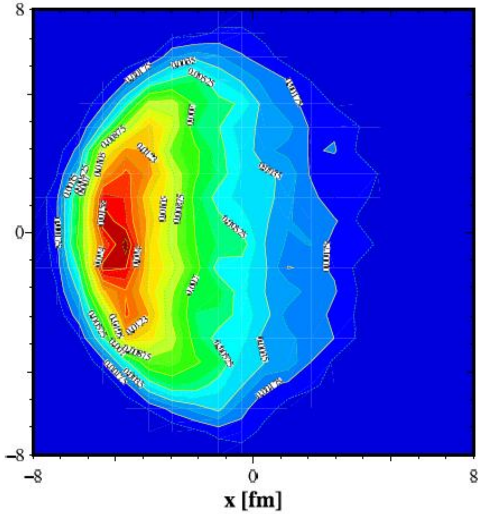
FINISH

Sensitivity of different observables

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

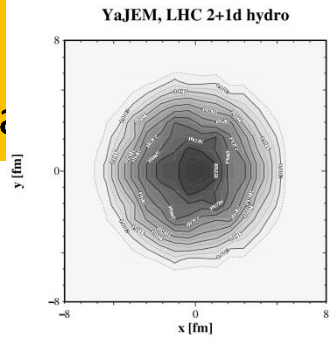
Renk, Eskola, PRC 75, 054910 (2007)

single h



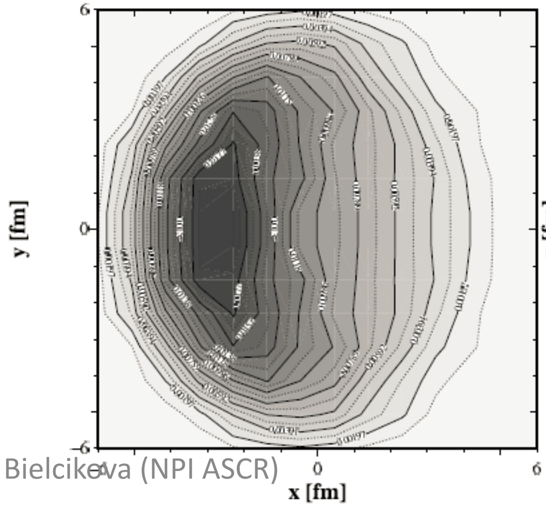
Surface bias dependence:

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

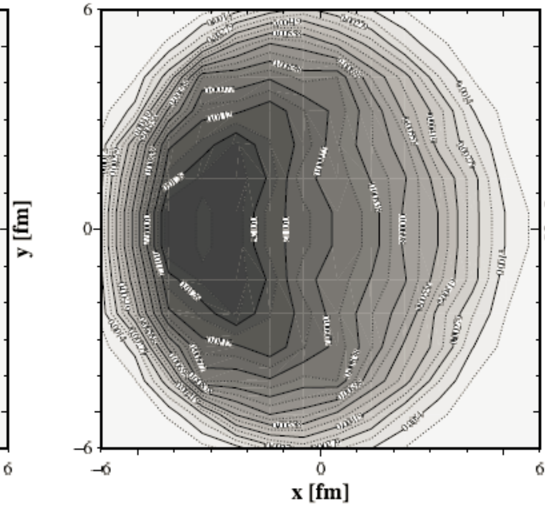


T. Renk, YaJEM

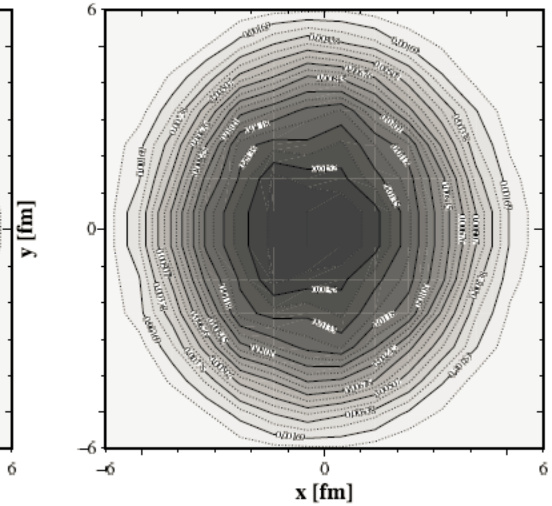
h - h



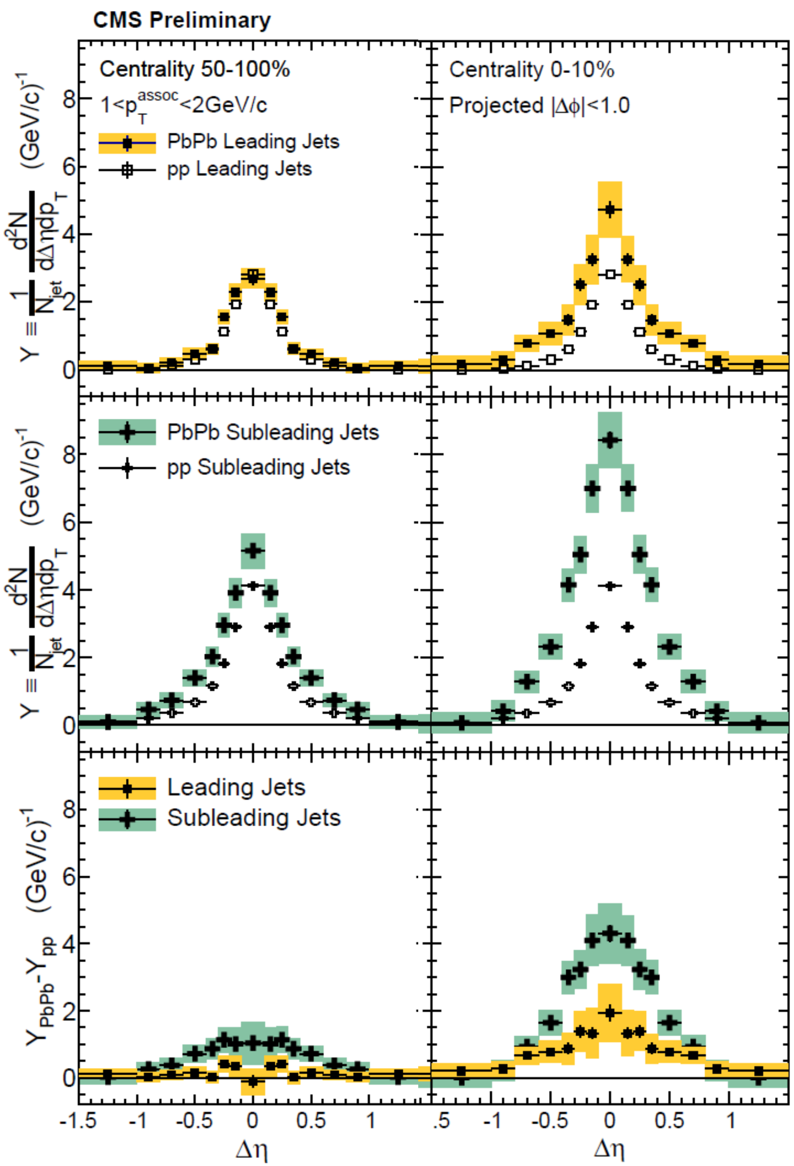
jet - h

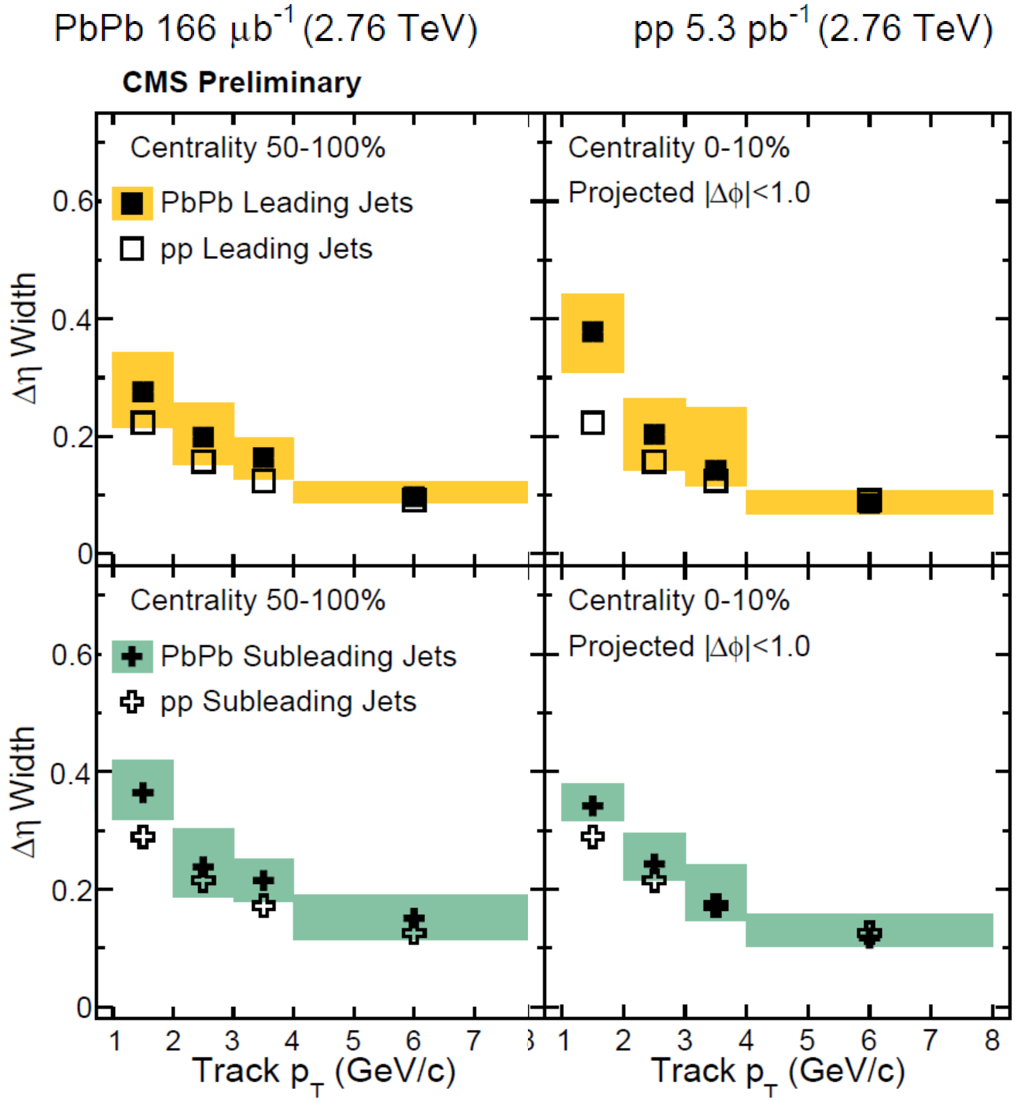


γ - h



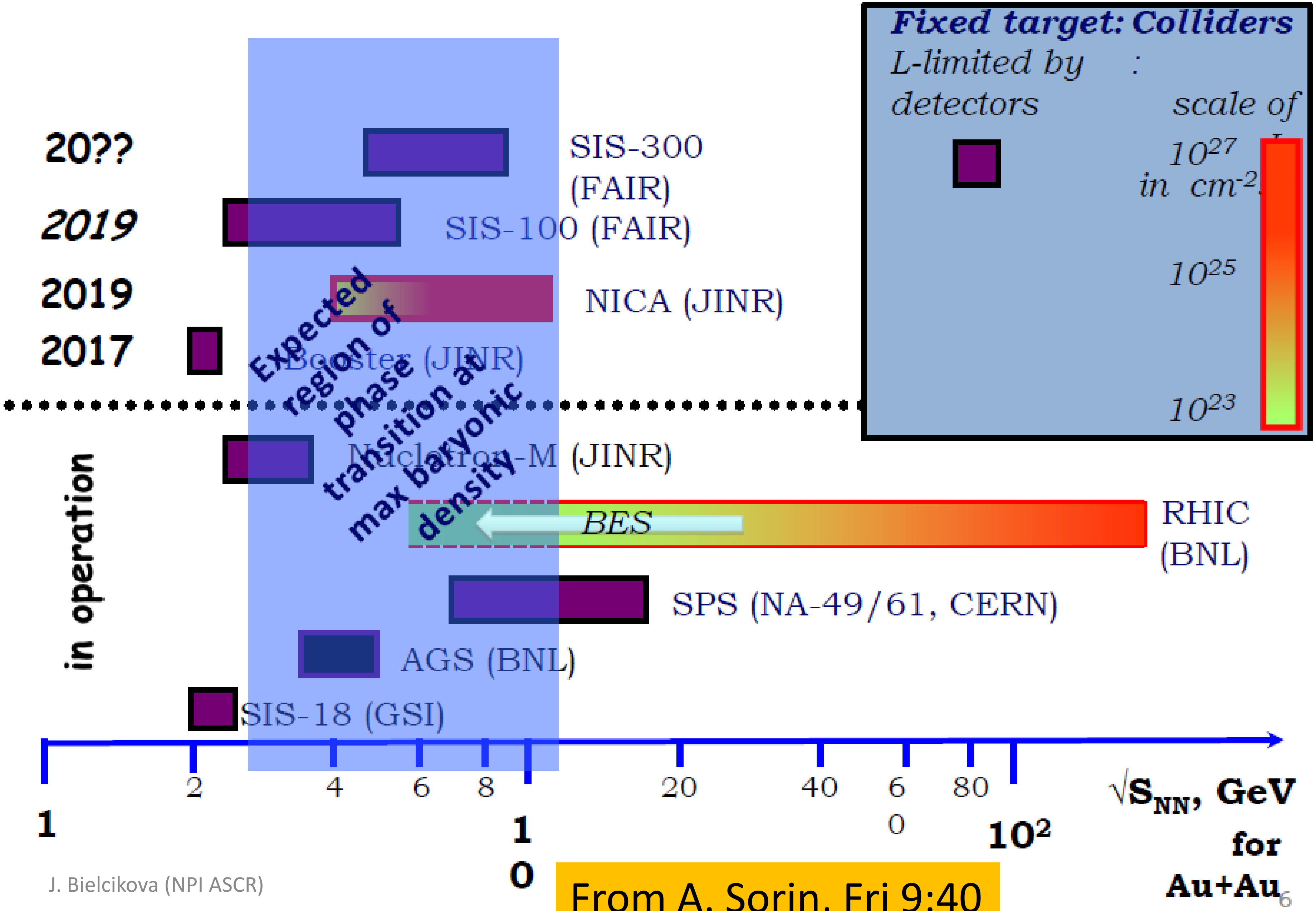
Jet-track correlations in Pb+Pb





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

Present and future HI machines

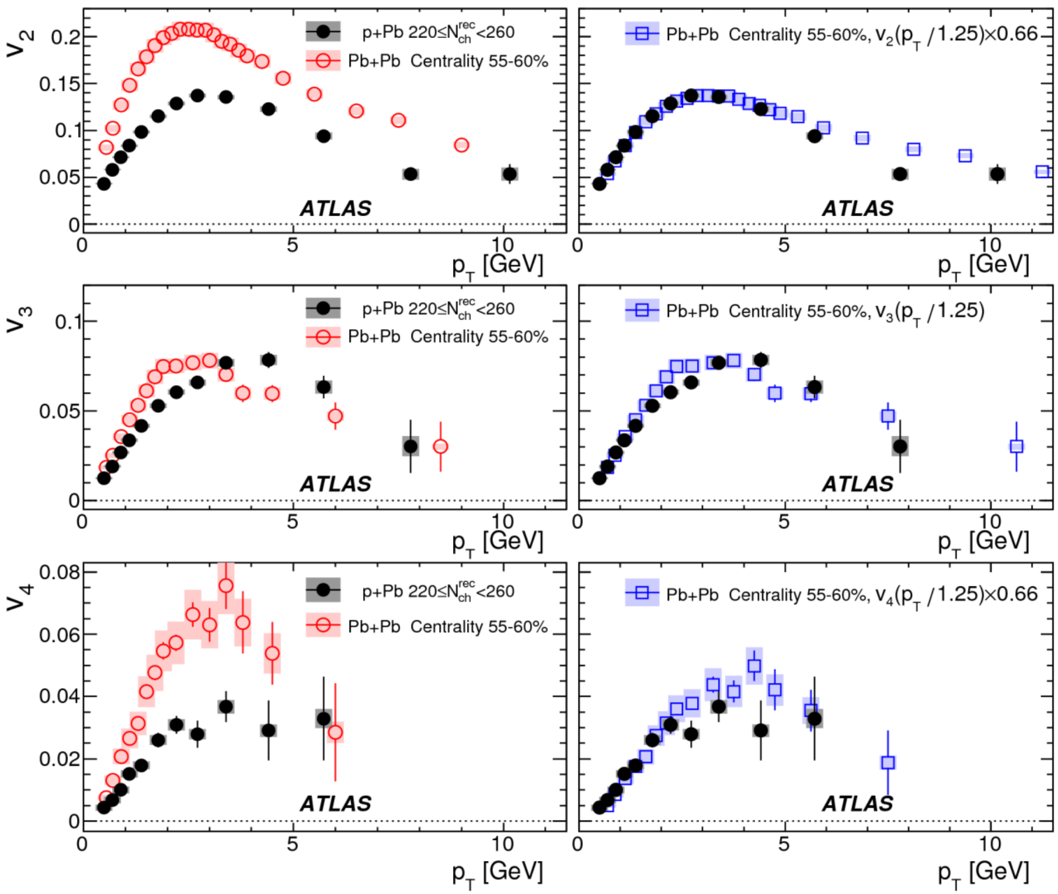


From A. Sorin, Fri 9:40

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.

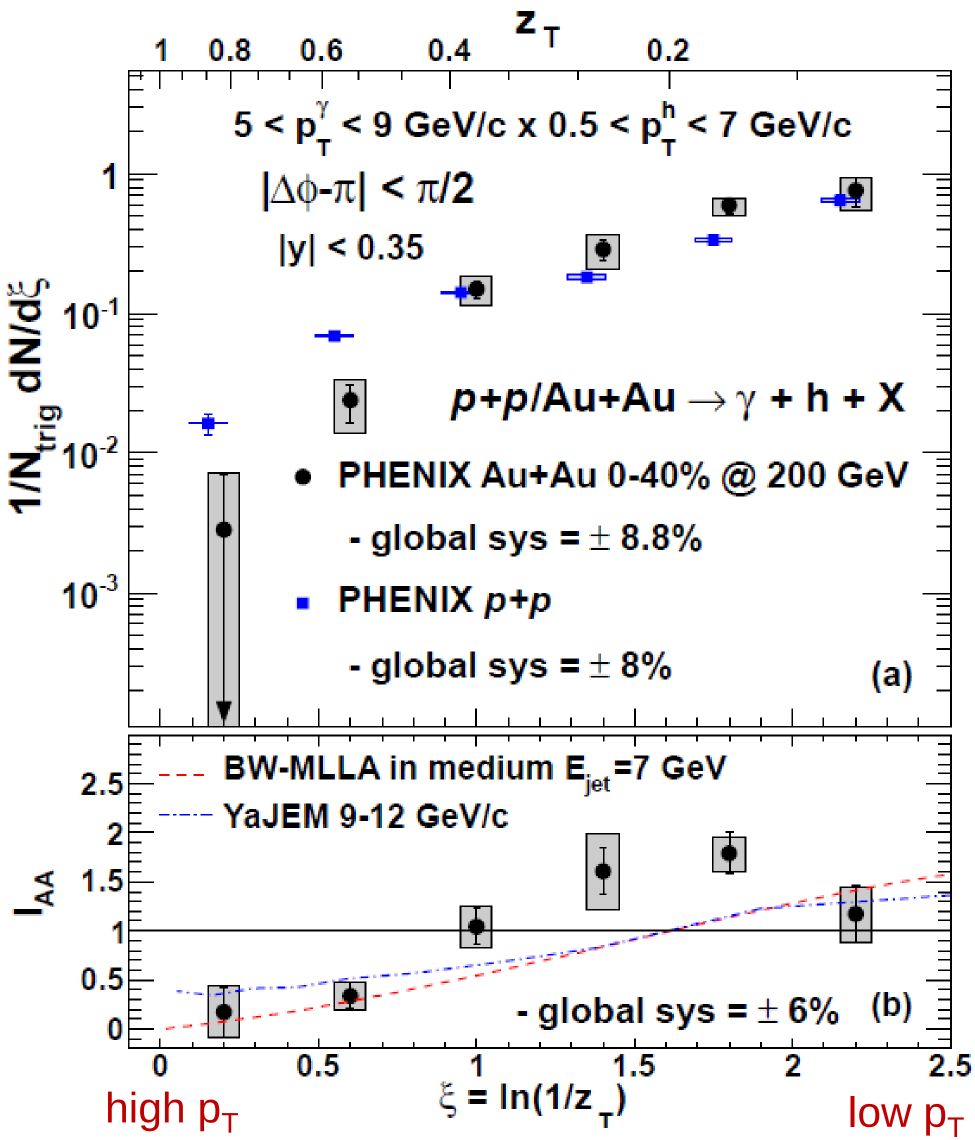
What is their relation to those measured in Pb-Pb?

Apply a scale factor *K* = 1.25 to account for the <p_T> 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



PHENIX: arXiv:1212.3323

- γ-jet a "golden probe" of parton energy loss in the medium
- produced in Compton scattering

$q+g \rightarrow q+\gamma$

- photons do not interact strongly
- precise measurement of the in-medium modification of fragmentation function

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

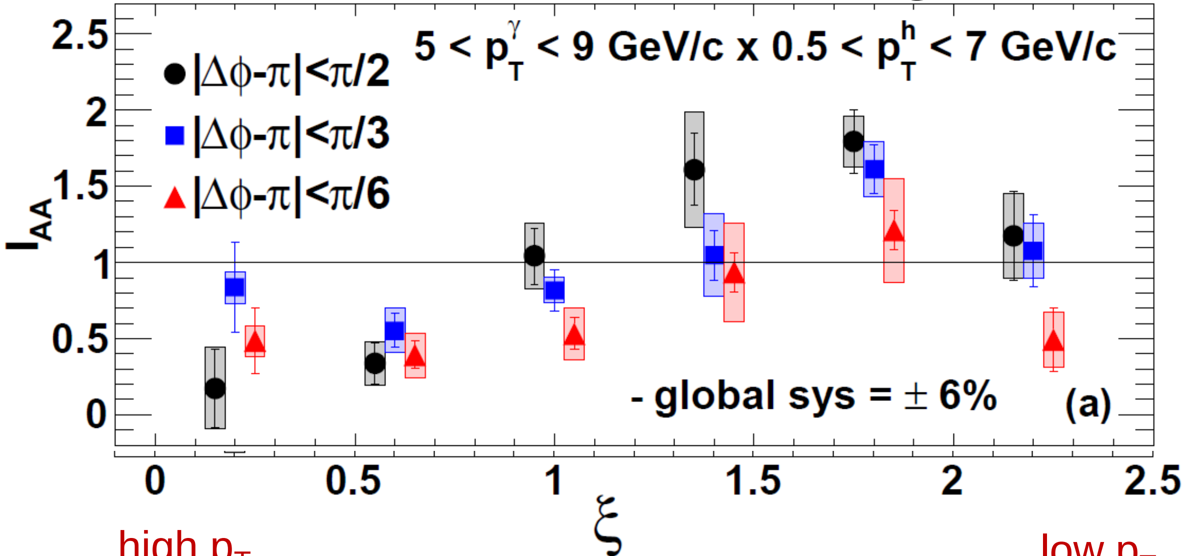
The recoil jet is modified:
softening of recoil jet in central Au+Au collisions at RHIC.

γ-hadron correlations

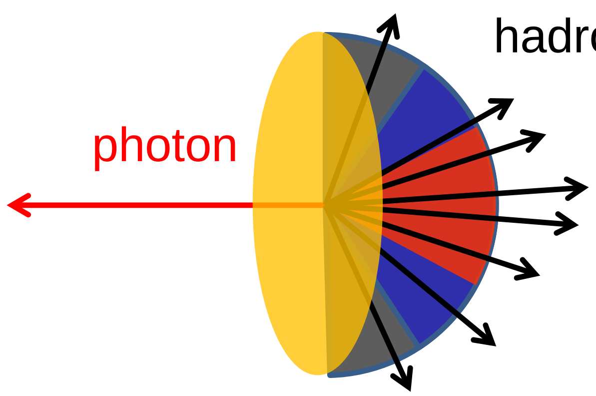
Where did the energy go?

Look into different cones away from the trigger photon!

PHENIX: arXiv:1212.3323

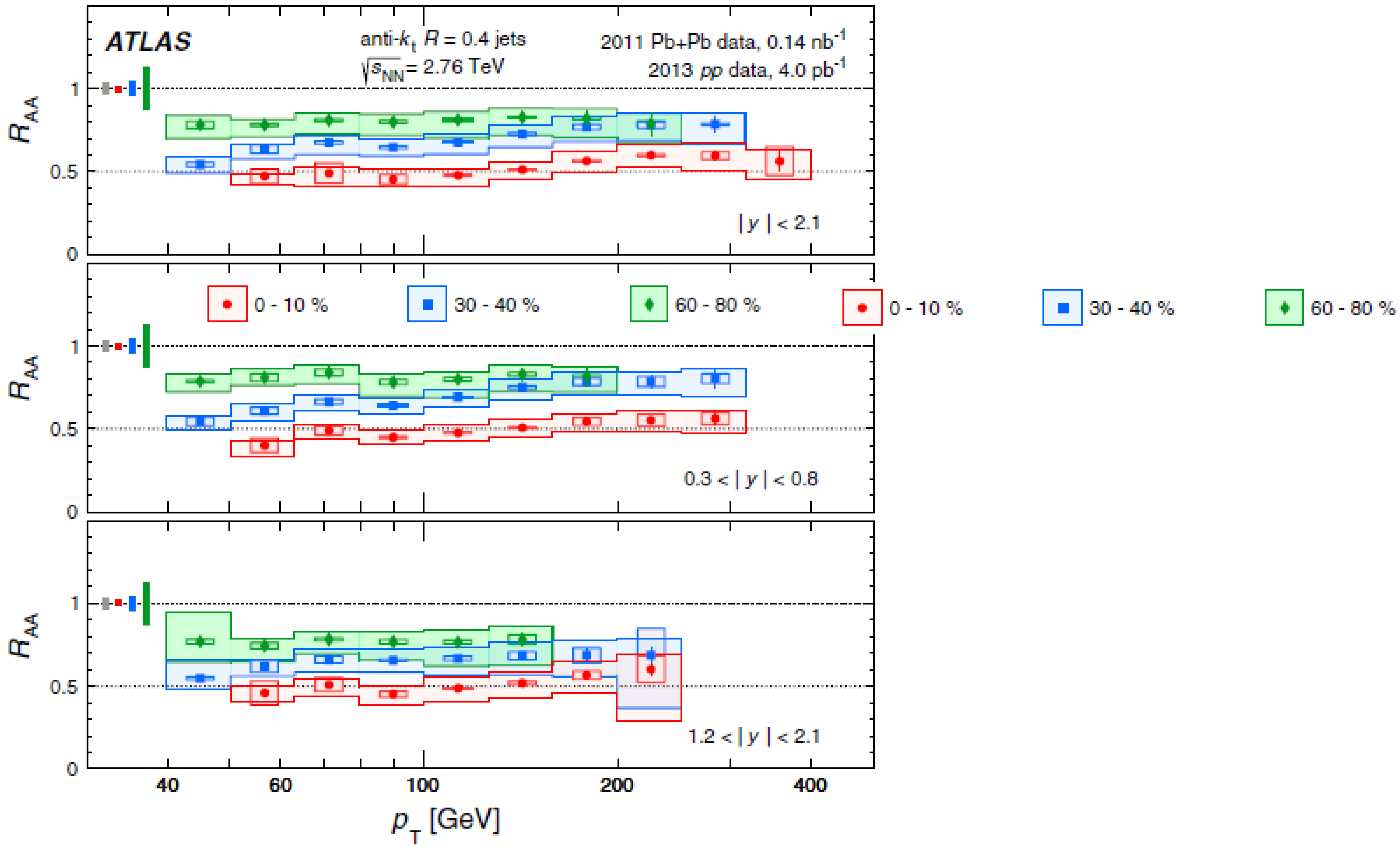


high p_T low p_T



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

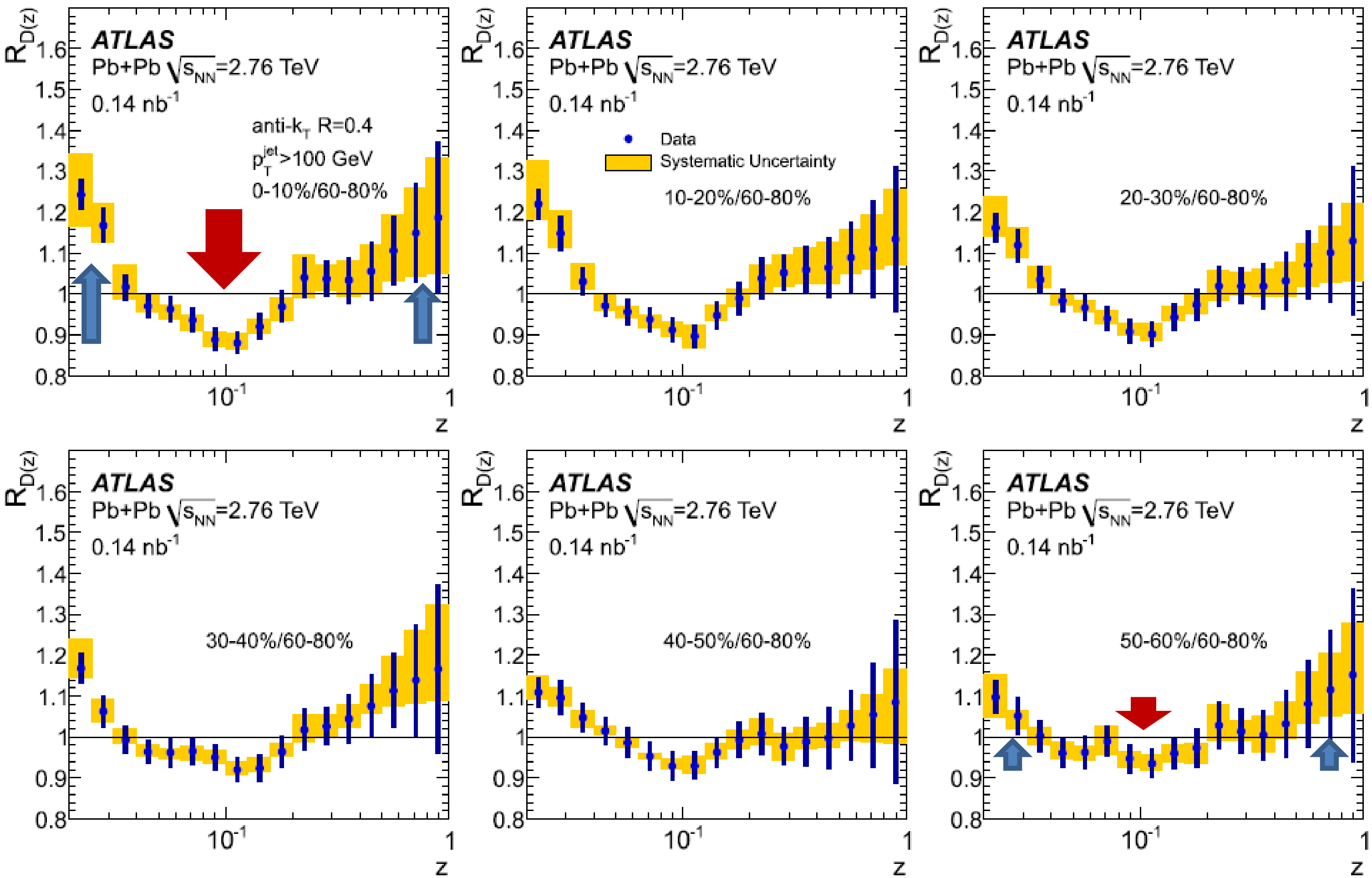
Lost high-p_T hadrons emerge as multiple soft hadrons at large angles.



ATLAS
anti-k_t R = 0.4 jets
$\sqrt{s_{NN}}$ = 2.76 TeV
2011 Pb+Pb data, 0.14 nb^{-1}
2013 pp data, 4.0 pb^{-1}
| y | < 2.1
0.3 < | y | < 0.8
1.2 < | y | < 2.1
0 - 10 %
30 - 40 %
60 - 80 %
R_{AA}
p_T [GeV]

Modification of jet fragmentation in Pb-Pb

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

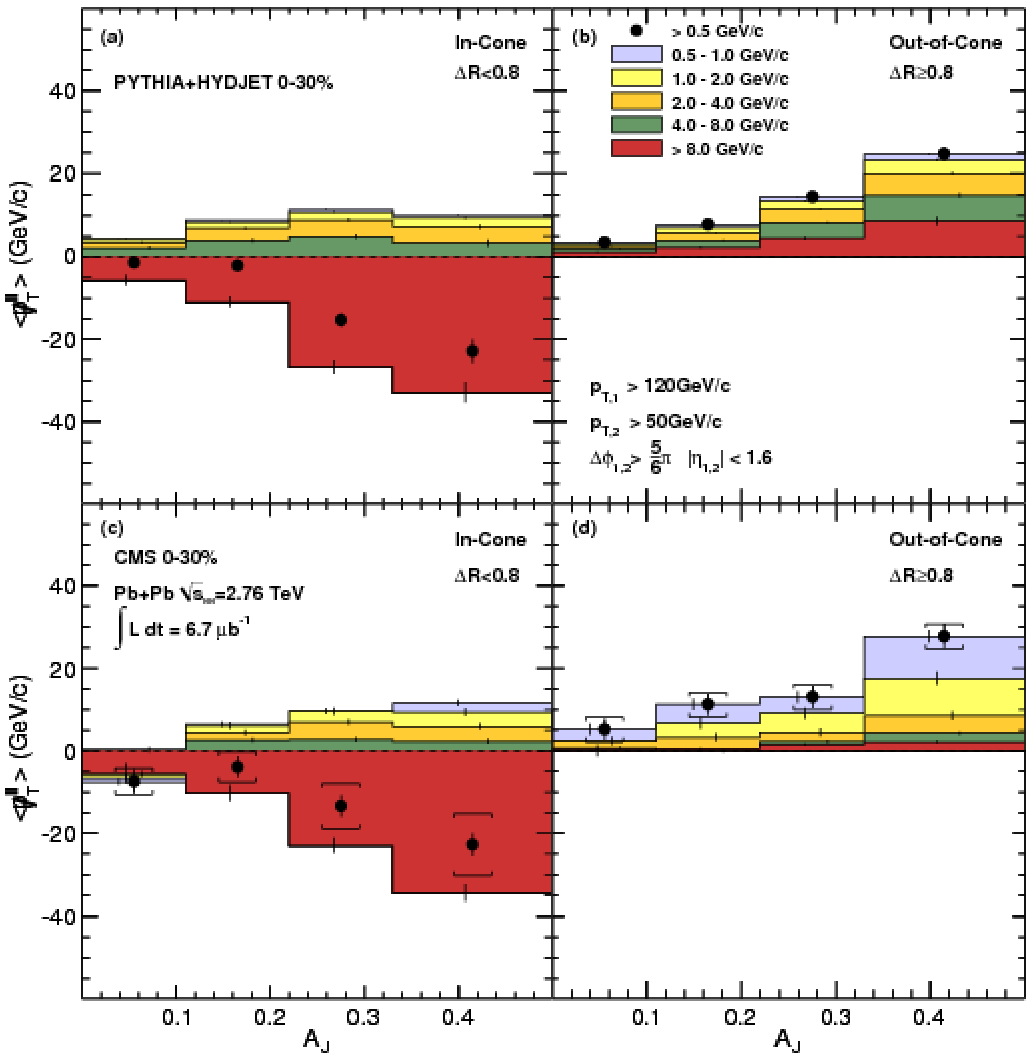


enhancement for z<0.04 → suppression at z = 0.04-0.2 → enhancement for z>0.2

- most pronounced in central Pb-Pb collisions

Where did the energy go?

CMS, PRC 84 (2011) 024906

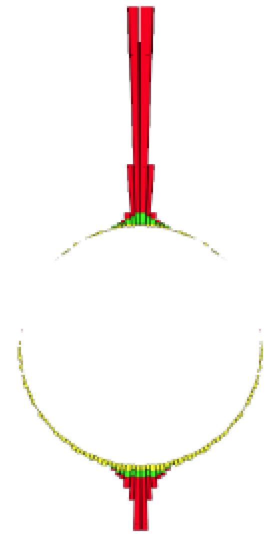


$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$$

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

Jet asymmetry is balanced by soft particles at large angles.

Leading jet (p_T>120GeV/c)



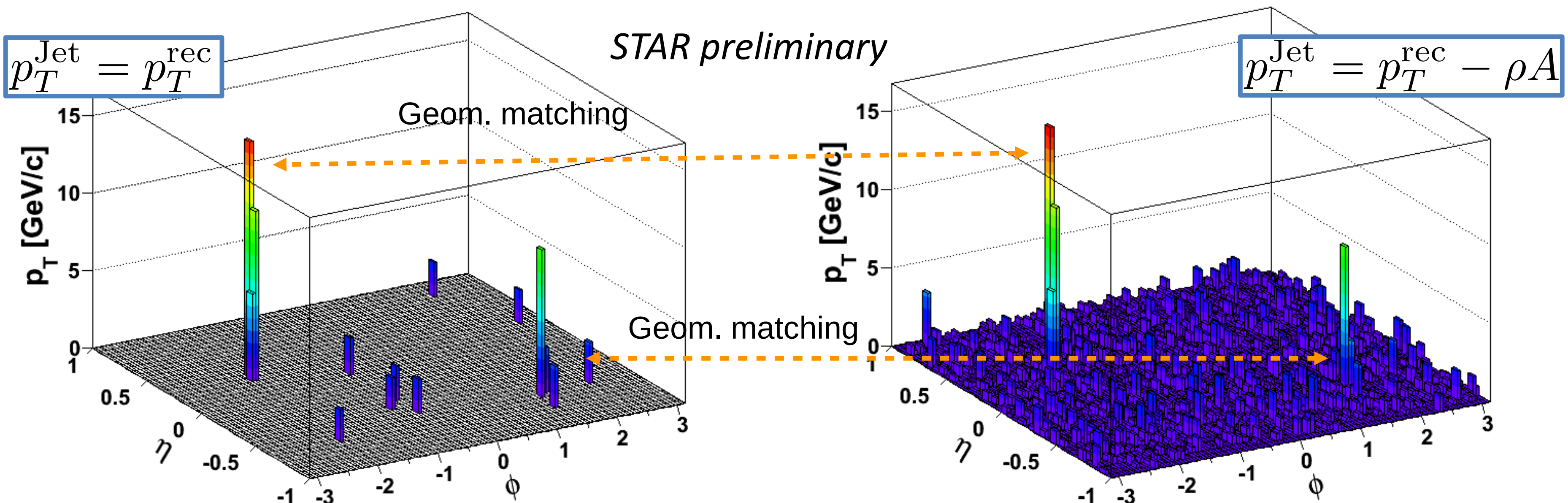
Subleading jet (p_T>30GeV/c)

Does the picture change at RHIC energy?

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

Constituent p_T > 2 GeV/*c*

Constituent p_T > 0.2 GeV/*c*



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

Anti-kt R=0.4

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

$|\Delta\phi-\pi|<0.4$

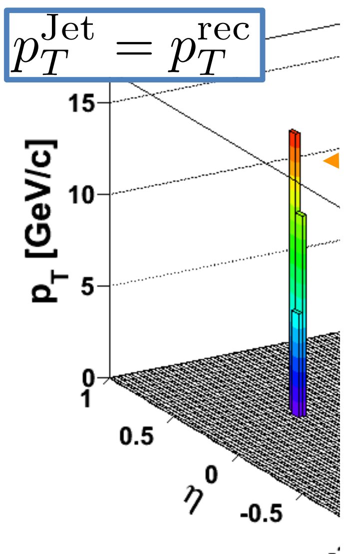
3. Do jet matching and calculate "matched" $|A_J|$ with constituent $p_{T,cut}$>0.2 GeV/c

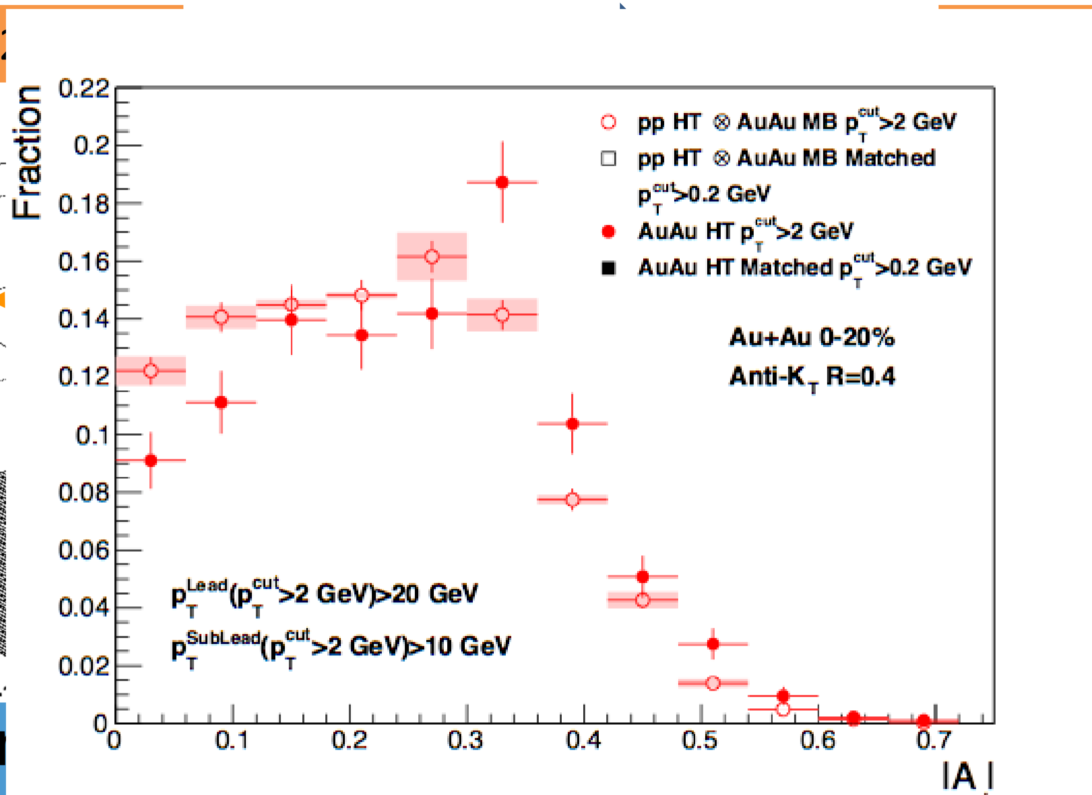
A_J measurement at RHIC energy

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

Constituent p_T > 2

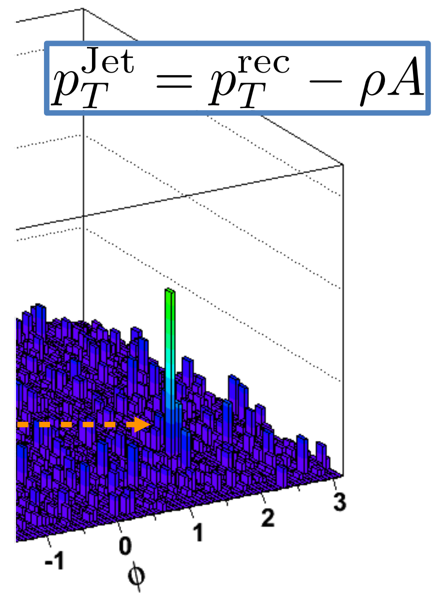
$p_T^{\rm Jet} = p_T^{\rm rec}$





uent p_T > 0.2 GeV/*c*

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



1. Run jet-fi… and find di-jets

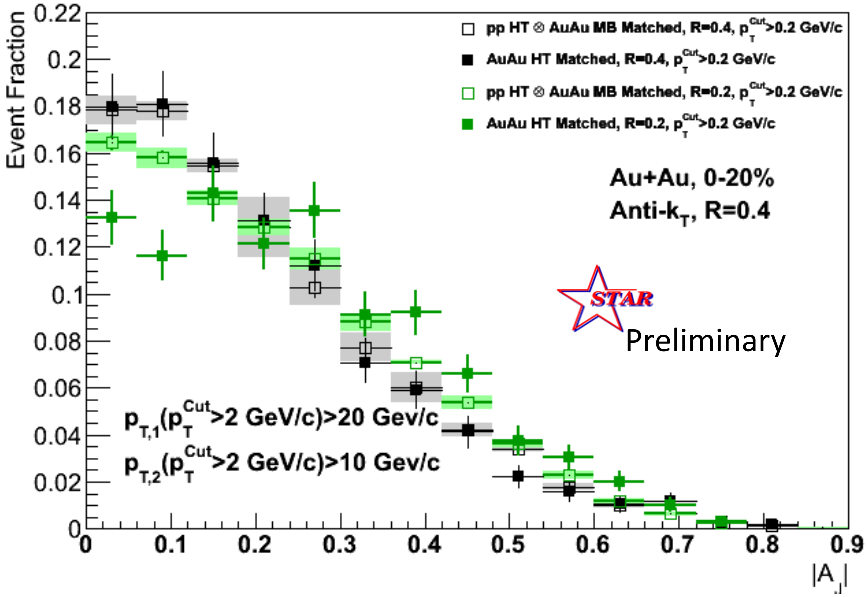
Anti-kt R=0.4

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

$|\Delta\phi-\pi|$<0.4

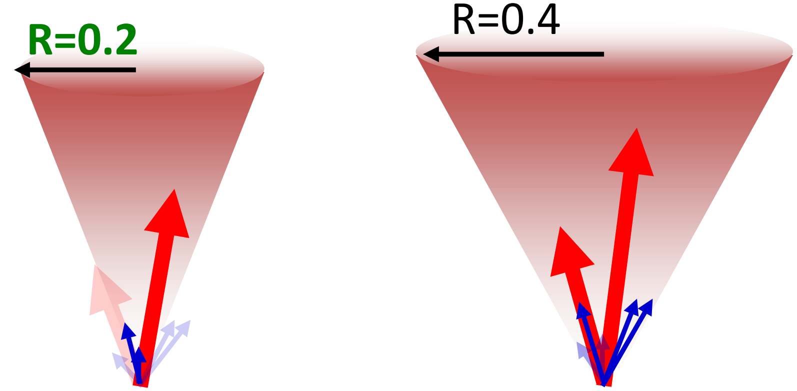
3. Do jet matching and calculate "matched" $|A_J|$ with constituent $p_{T,cut}$>0.2 GeV/c

A_J measurement at RHIC energy



Study softening

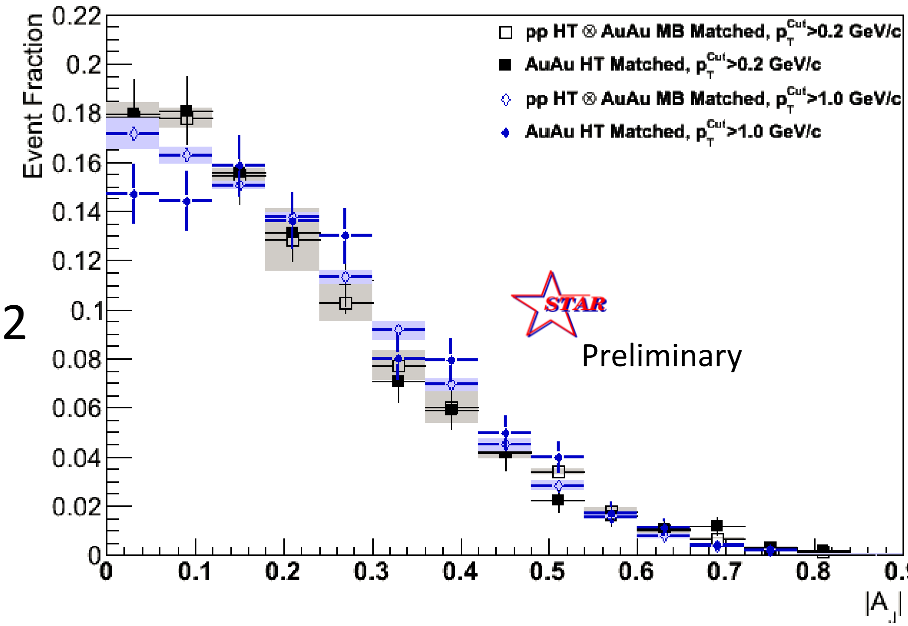
Study broadening



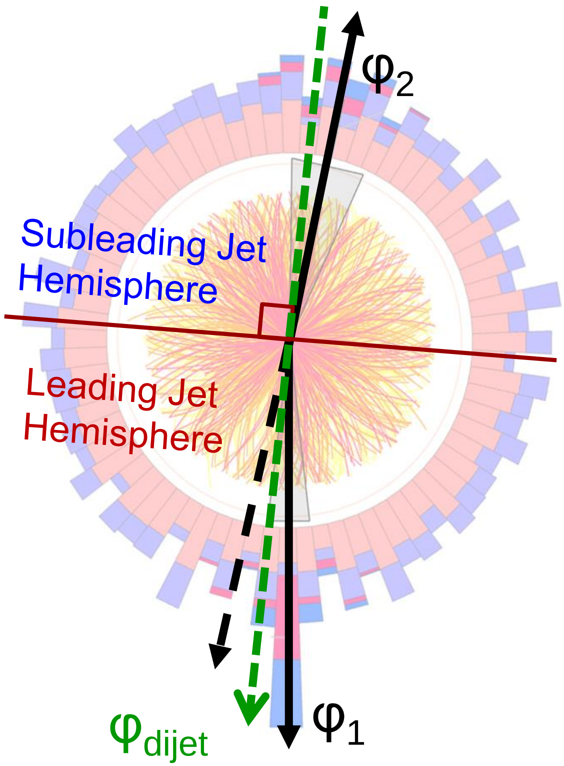
p_T^{Cut} > 0.2 GeV/*c*

p_T^{Cut} > 1 GeV/*c*

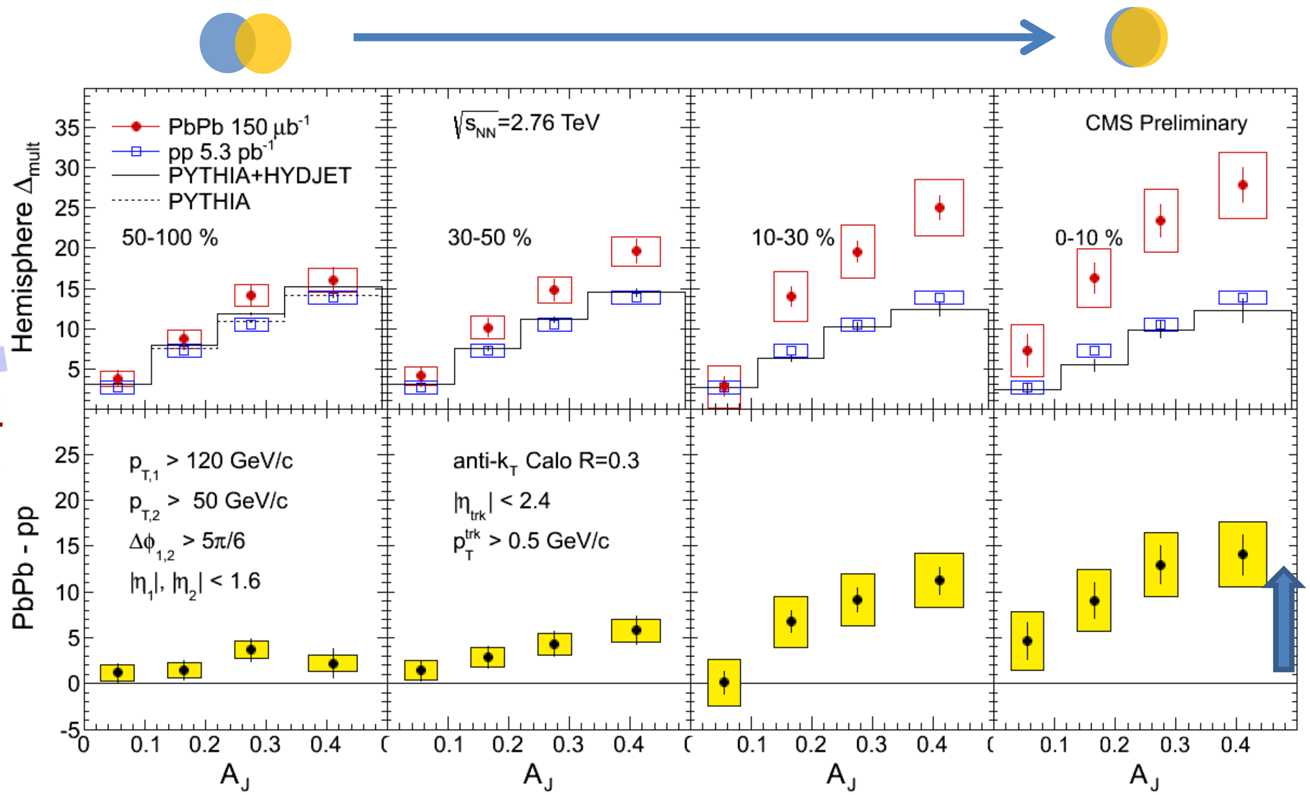
- Lost energy remerges in low p_T particles
- Decreasing p_T = 2 → 1 → 0.2 GeV/*c* dijet is regaining balance
- For the same R=0.4 and jet p_T selection, balance can not be restored within R=0.2
  → broadening
- p_T^{cut} = 1 GeV/*c* not sufficient to restore balance → signs of jet softening between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

hemisphere N_{ch} difference:
$\Delta_{mult} = N_{ch}^{subleading} - N_{ch}^{leading}$

Y.S. Lai (CMS)
Thu 15:15