Lecture 4: Intermediate p_T, pp and p+Pb

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Helmholtz School Manigod
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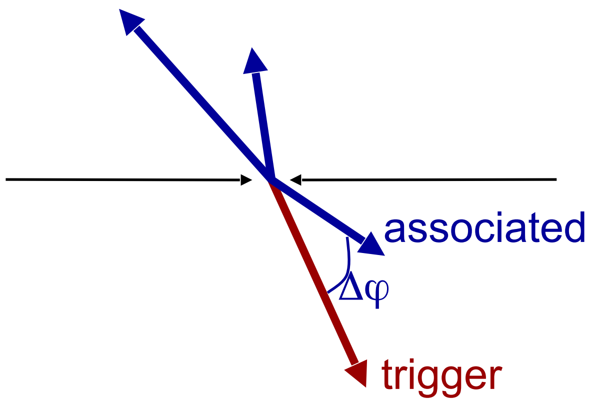
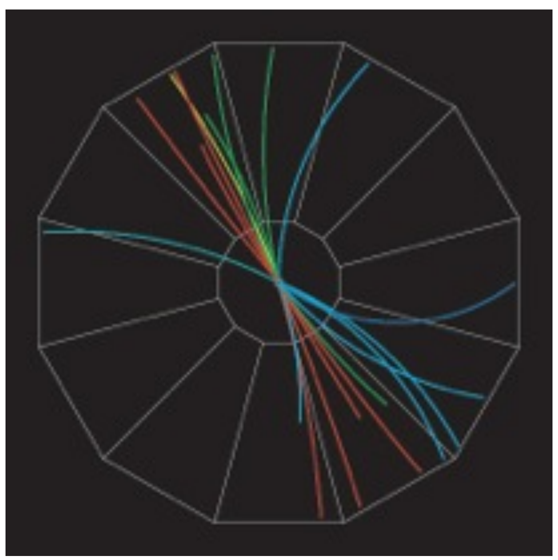
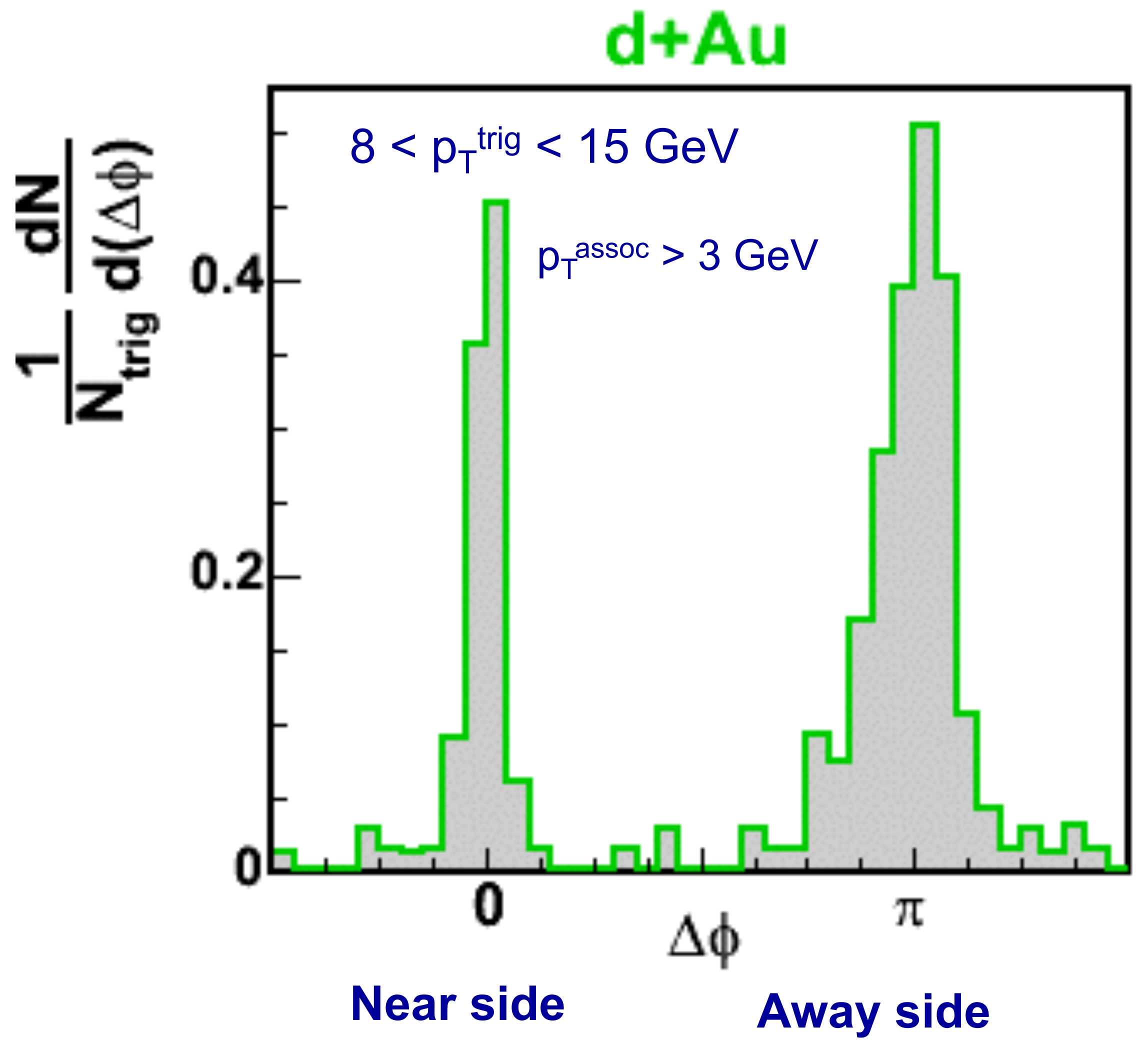
Universiteit Utrecht

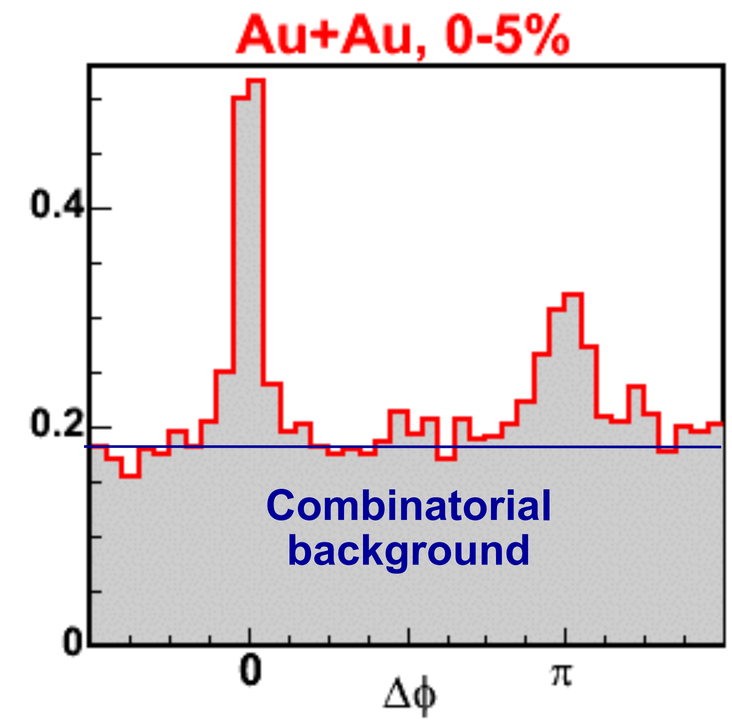
NIKHEF

Reminder: di-hadron correlations



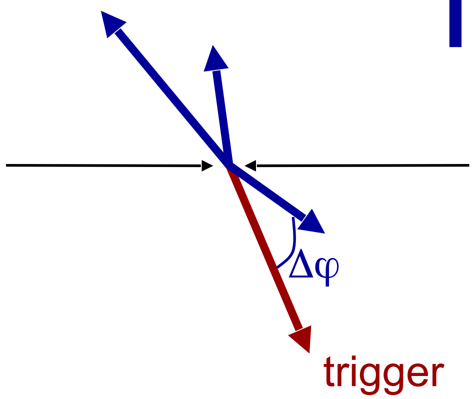


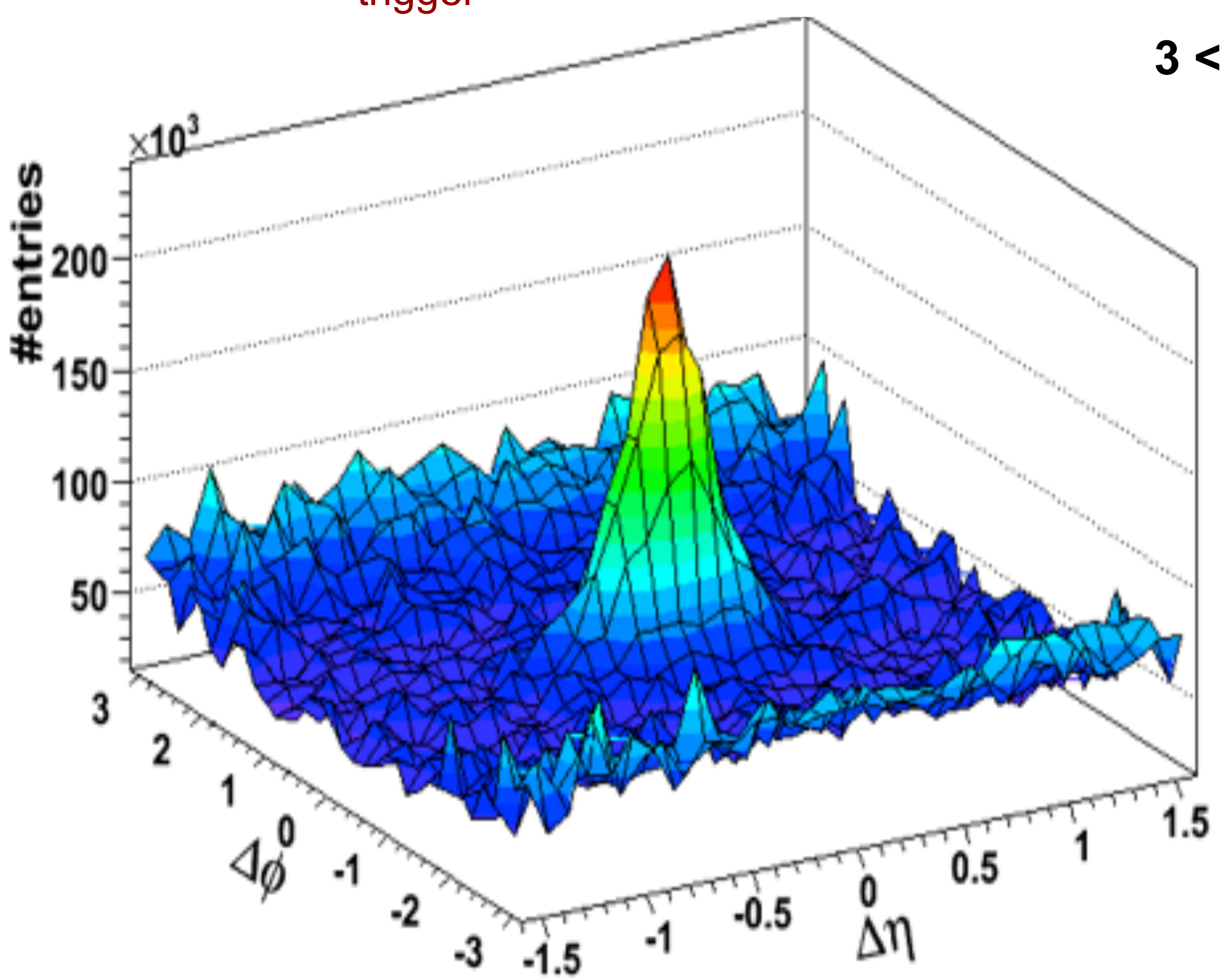


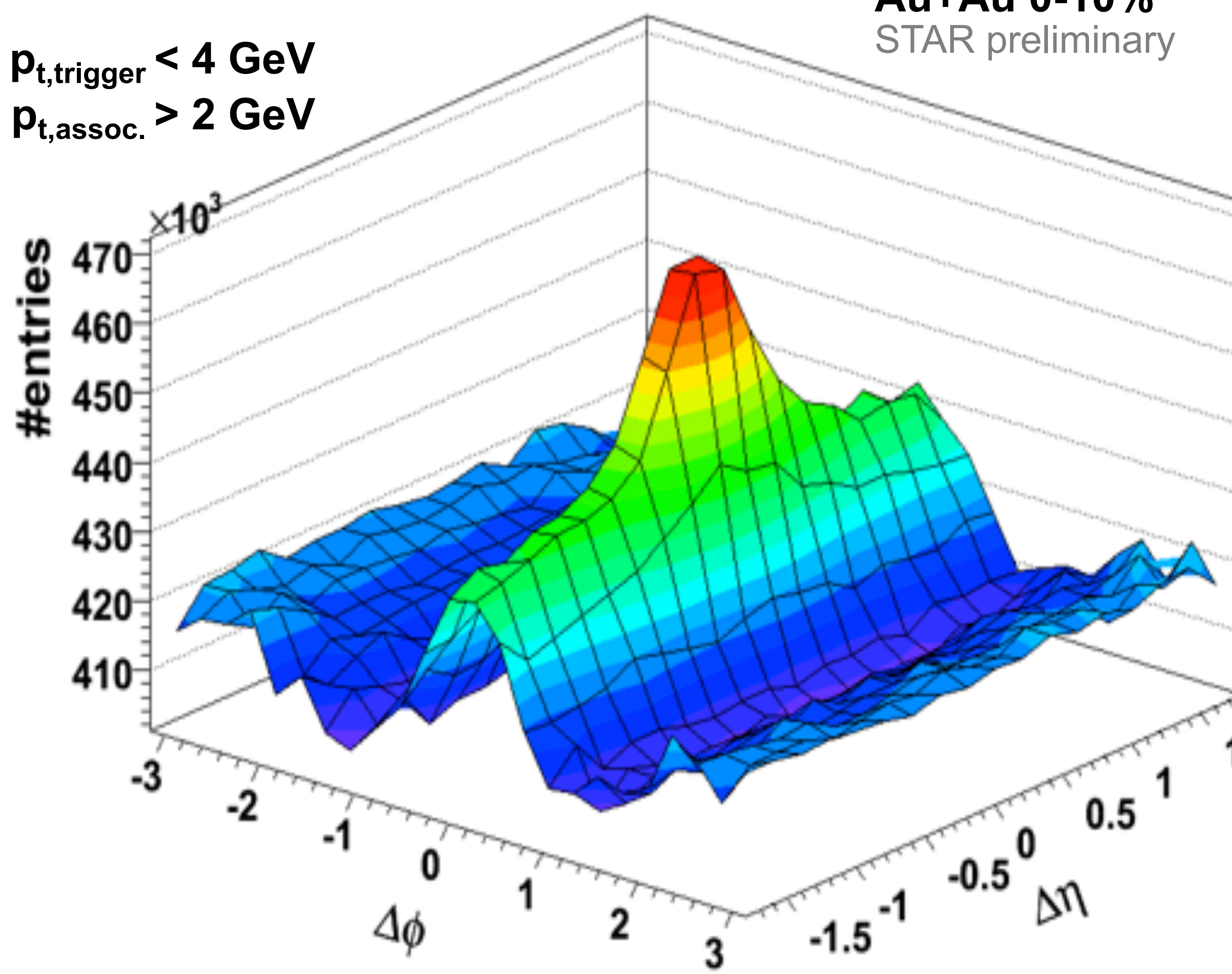


Use di-hadron correlations to probe the jet-structure in p+p, d+Au and Au+Au

Near-side ridge in AA – Flow







d+Au: 'jet'-peak,
symmetric in ϕ, η

Au+Au: extra correlation strength
at large $\Delta\eta$ → 'Ridge'

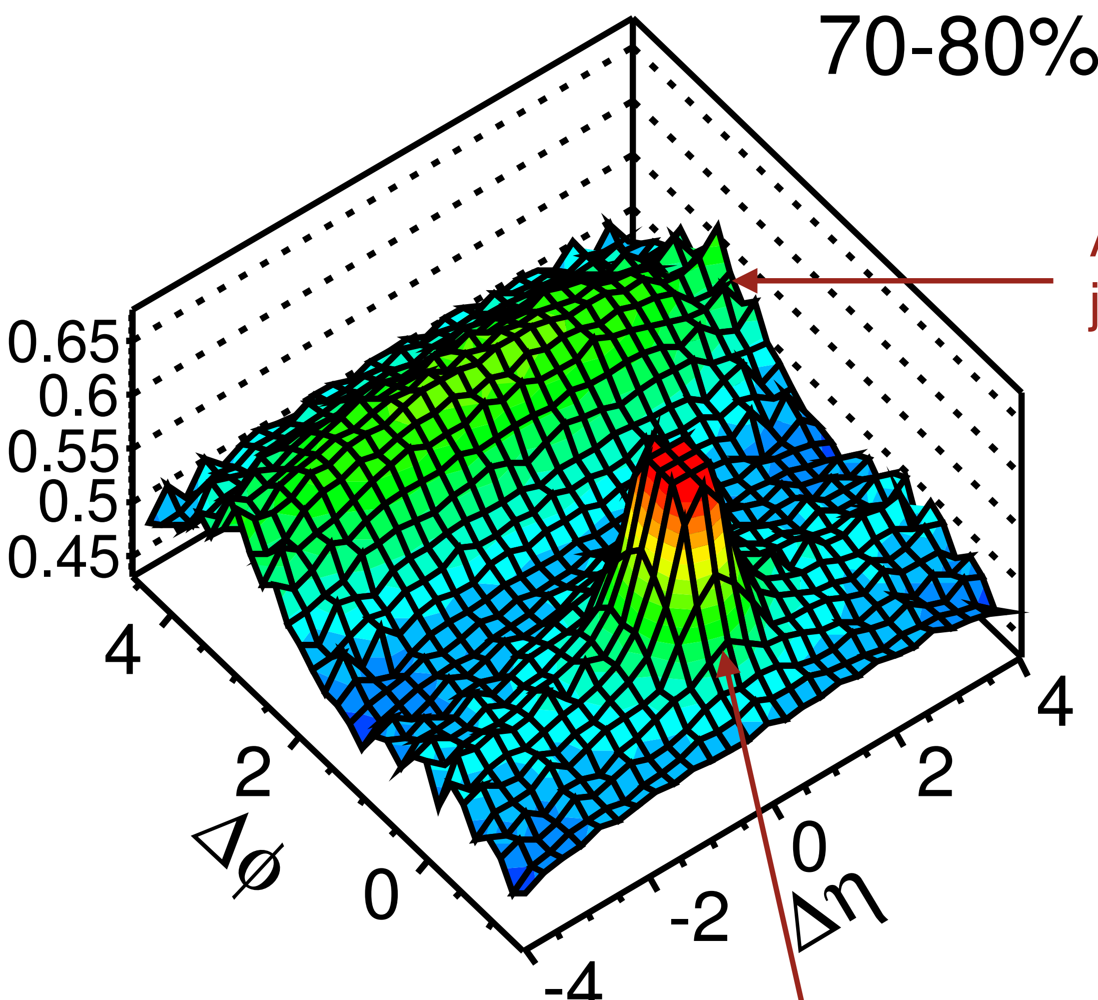
First seen at RHIC – Unexplained for a while
Most likely: flow, v_3

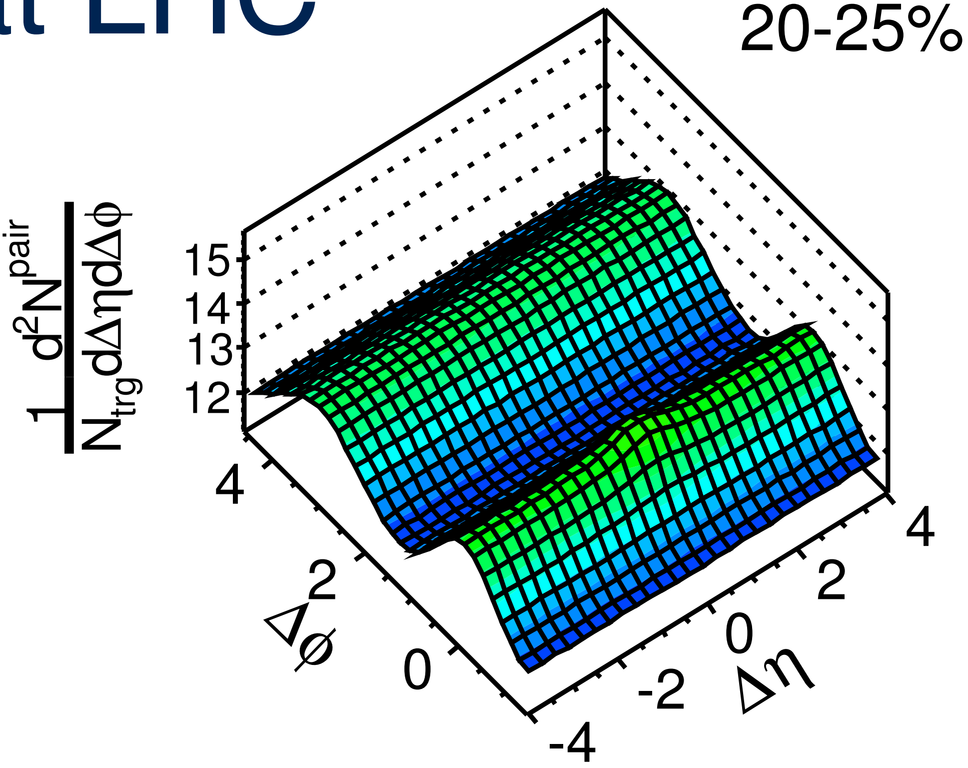
PbPb ridge at LHC

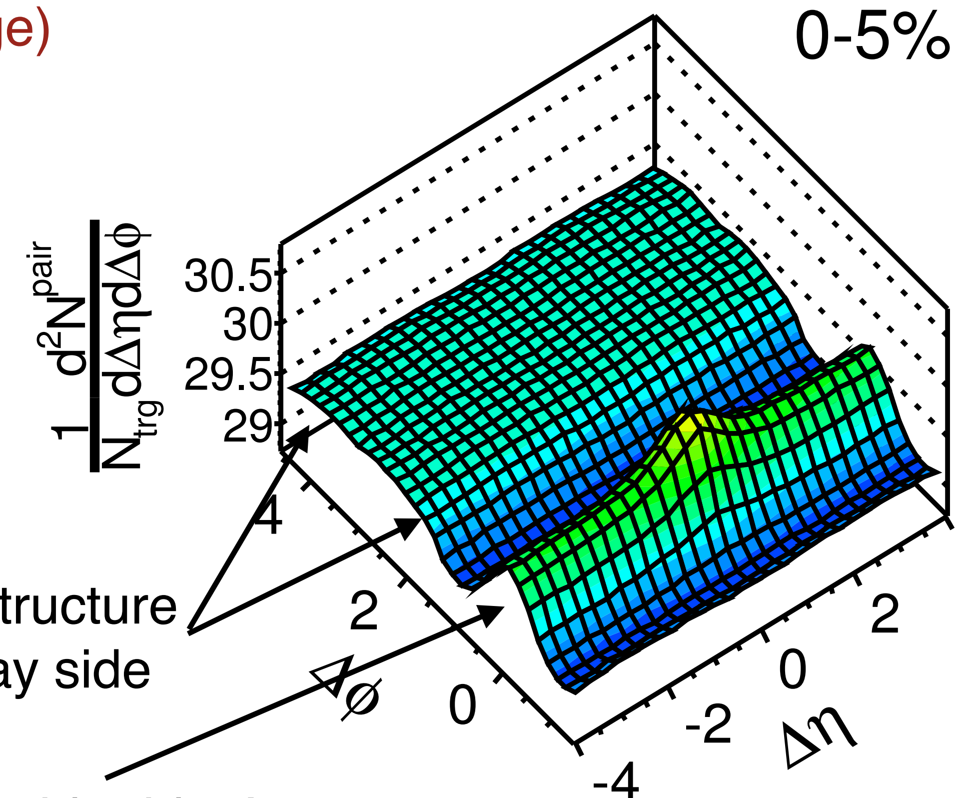
CMS, PbPb $\sqrt{s}$ = 2.76 TeV

$1.0 < p_{T,assoc} < 1.5$ GeV

$3.0 < p_{T,trig} < 3.5$ GeV



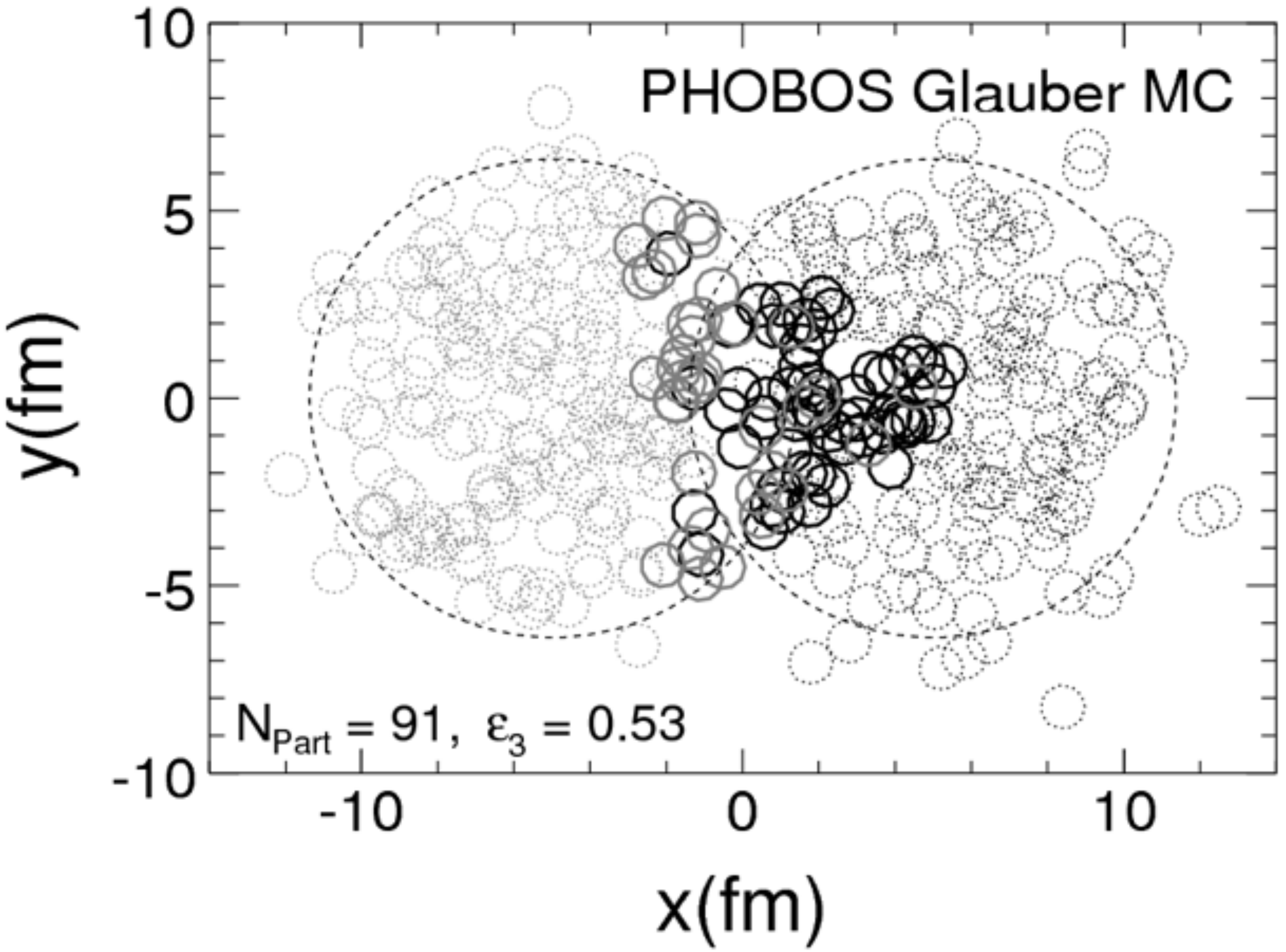




CMS, arXiv:1201.3158

Very long range correlation: Δη ~ 4

v_3, triangular flow

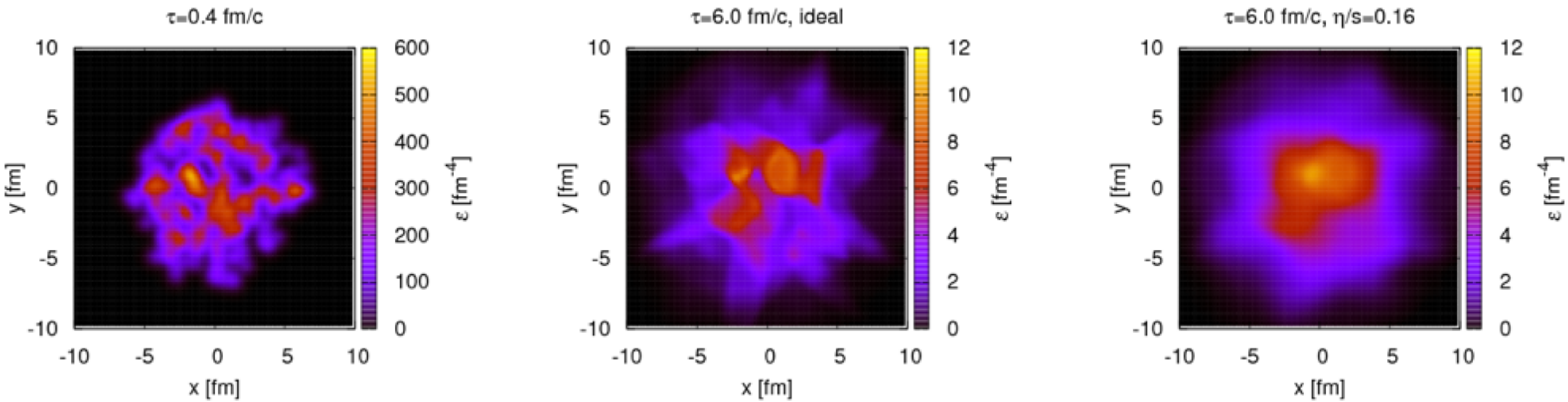


Alver and Roland, PRC81, 054905

Participant fluctuations lead to triangular component of initial state anisotropy

v_3 in Hydro

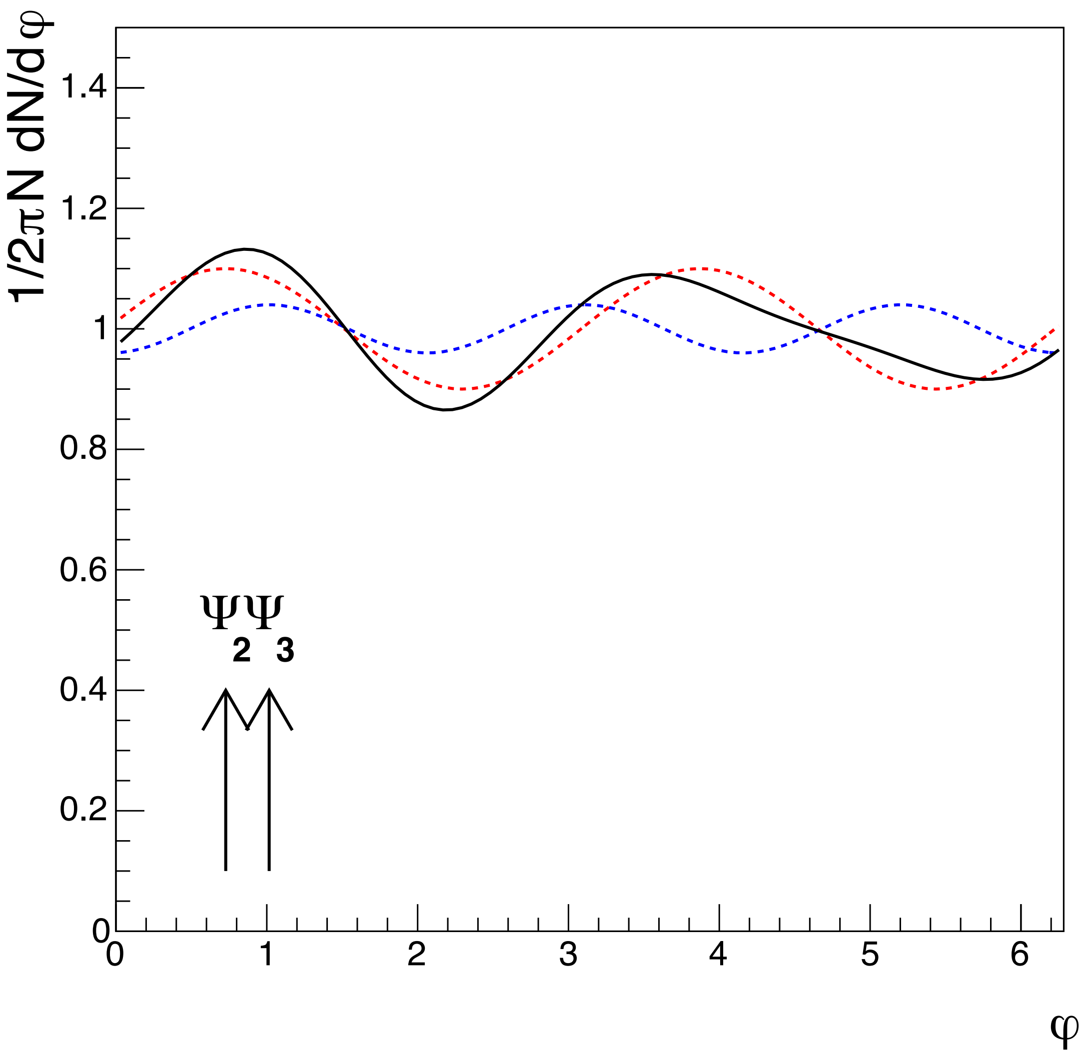
Schenke, Jeon, Gale, PRL 106, 042301



Evolution of initial state spatial anisotropy preserved in expansion
Exact size depends on viscosity

How does flow enter in $\Delta\varphi$ distributions?

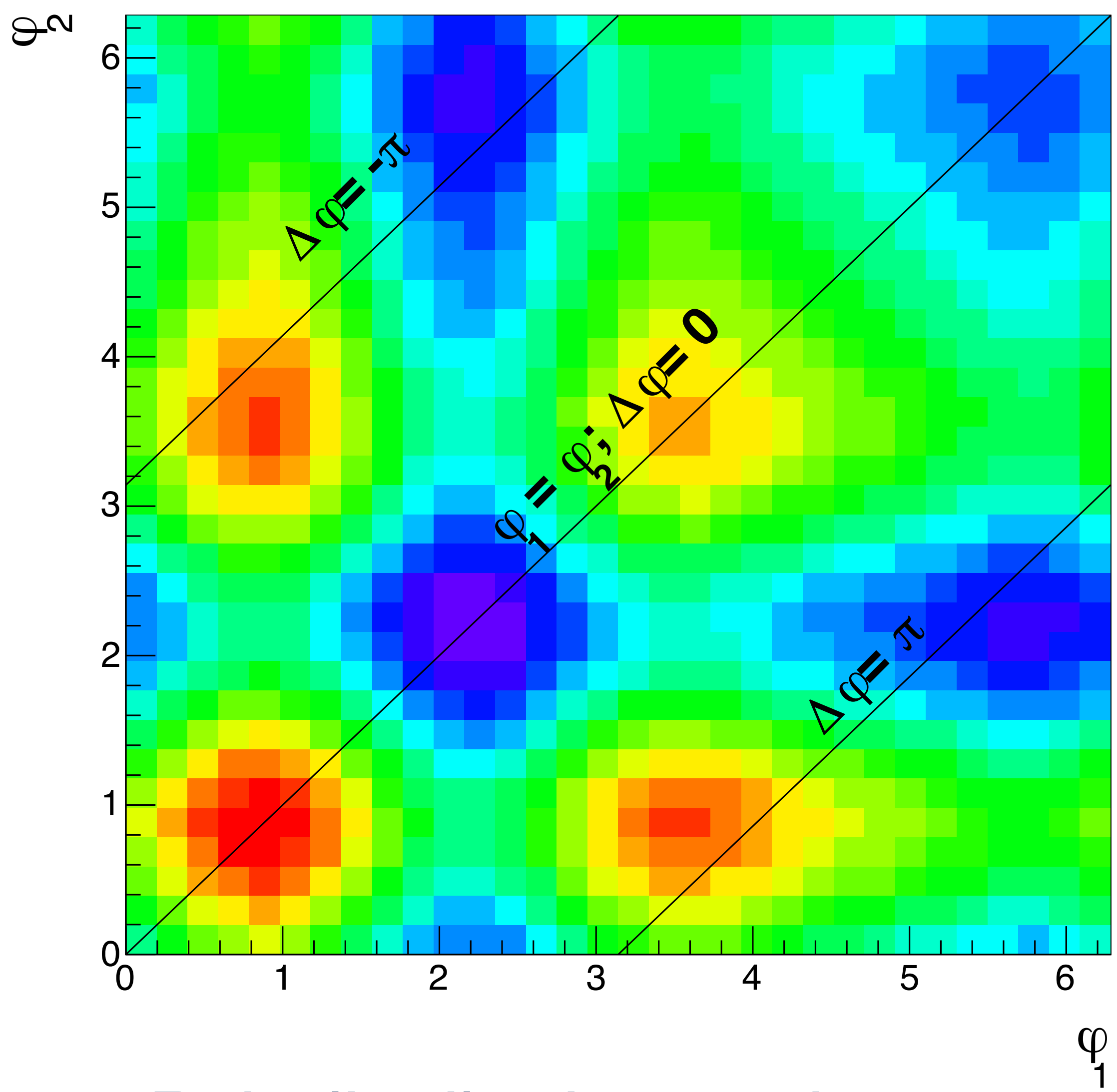
Azimuthal distribution, single event



Event plane angle changes from event to event

Ψ_2 and Ψ_3 mostly independent

Pair distribution

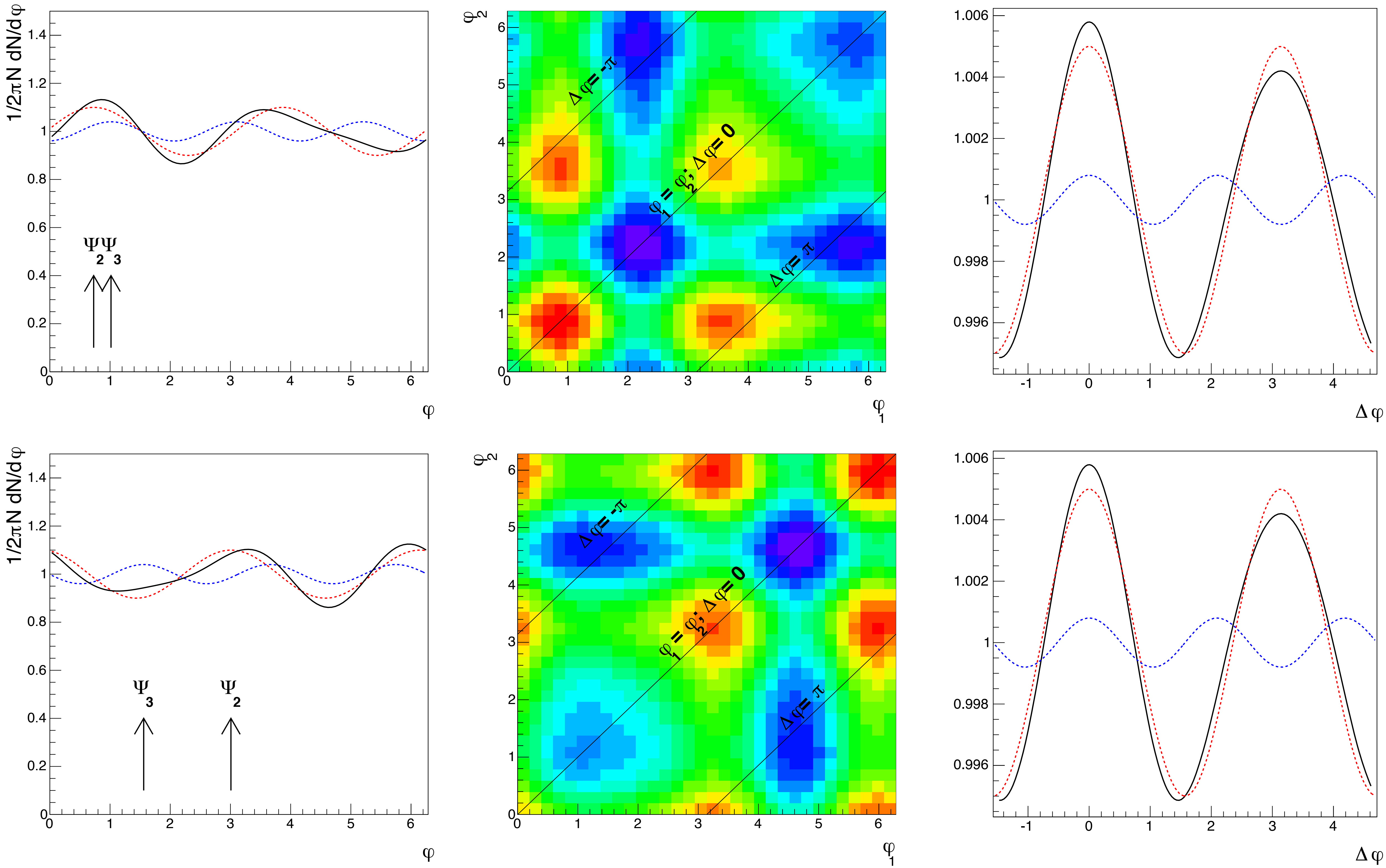


Pair distribution peaks around

$\Delta\varphi = 0, \pi$ for v_2

$\Delta\varphi = 0, 2/3\ \pi, 4/3\ \pi$ for v_3

More examples



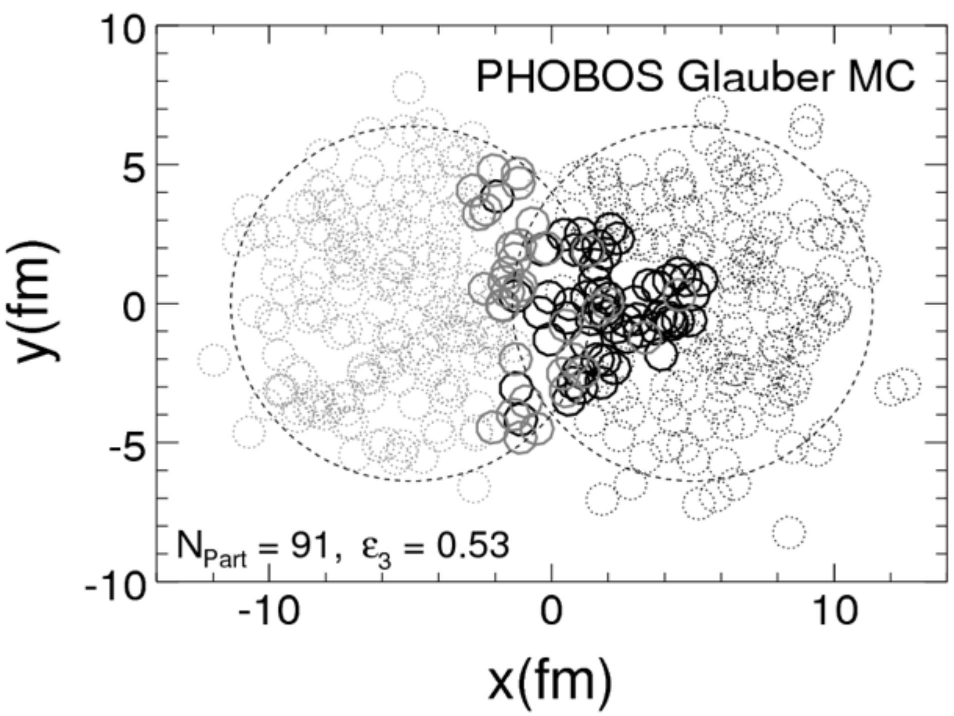
Conditions for forming a ridge

- Long range correlation in η
  - In case of flow: initial state + Bjorken expansion
- Trigger and associated subject to same effect
  - Flow (+path length dep E-loss): both are correlated to event plane(s)
  - Others have suggested radial flow: implies that both trigger and associated feel a radial push
  - Other alternatives: coherent emission of some sort (CGC? Di-jet color flow/ropes)

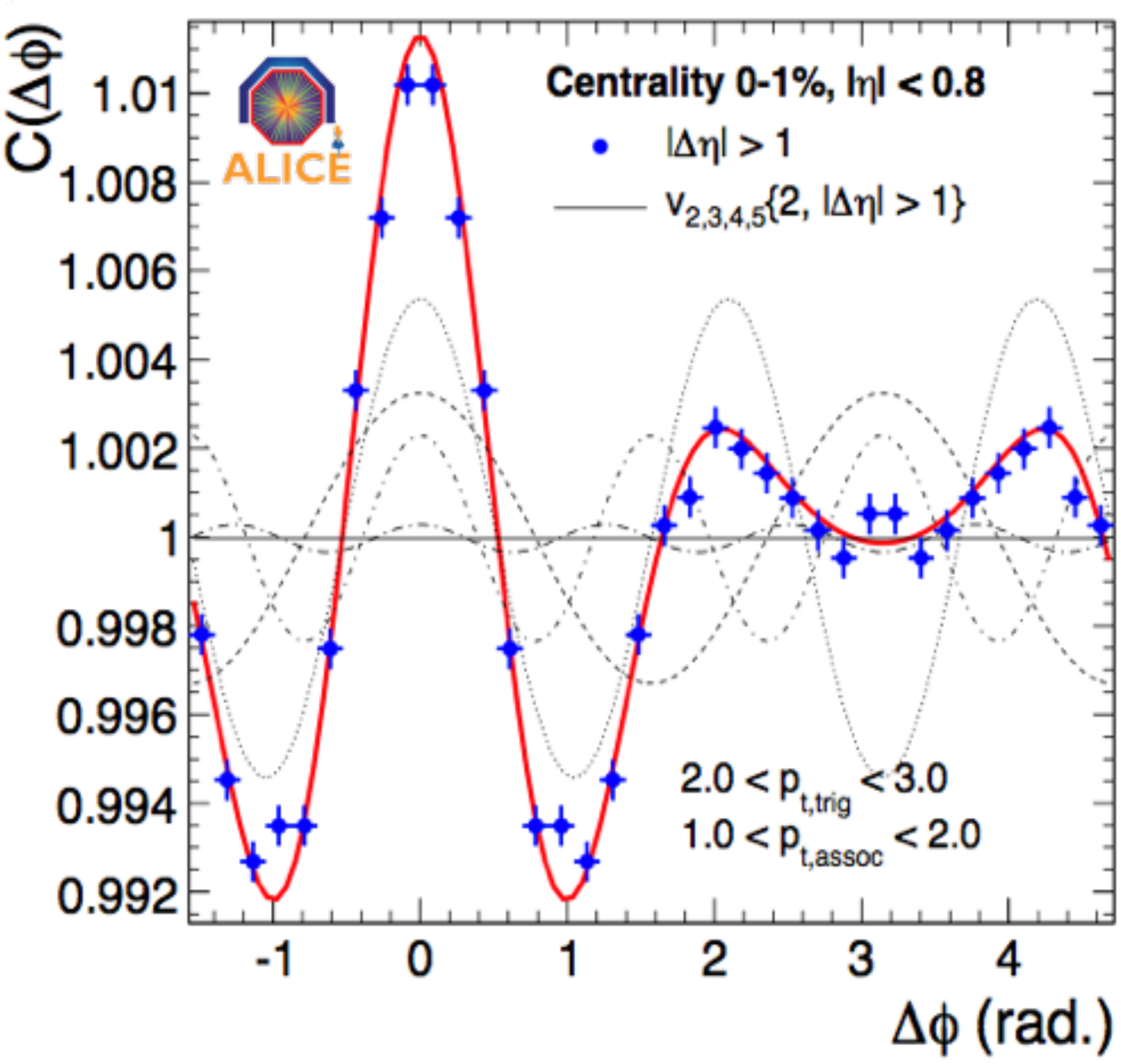
Di-hadron correlations and flow at low p_T

Low p_T <~ 3 GeV: di-hadron correlations dominated by flow

Important contributions from v_3, v_4



Alver and Roland, PRC81, 054905

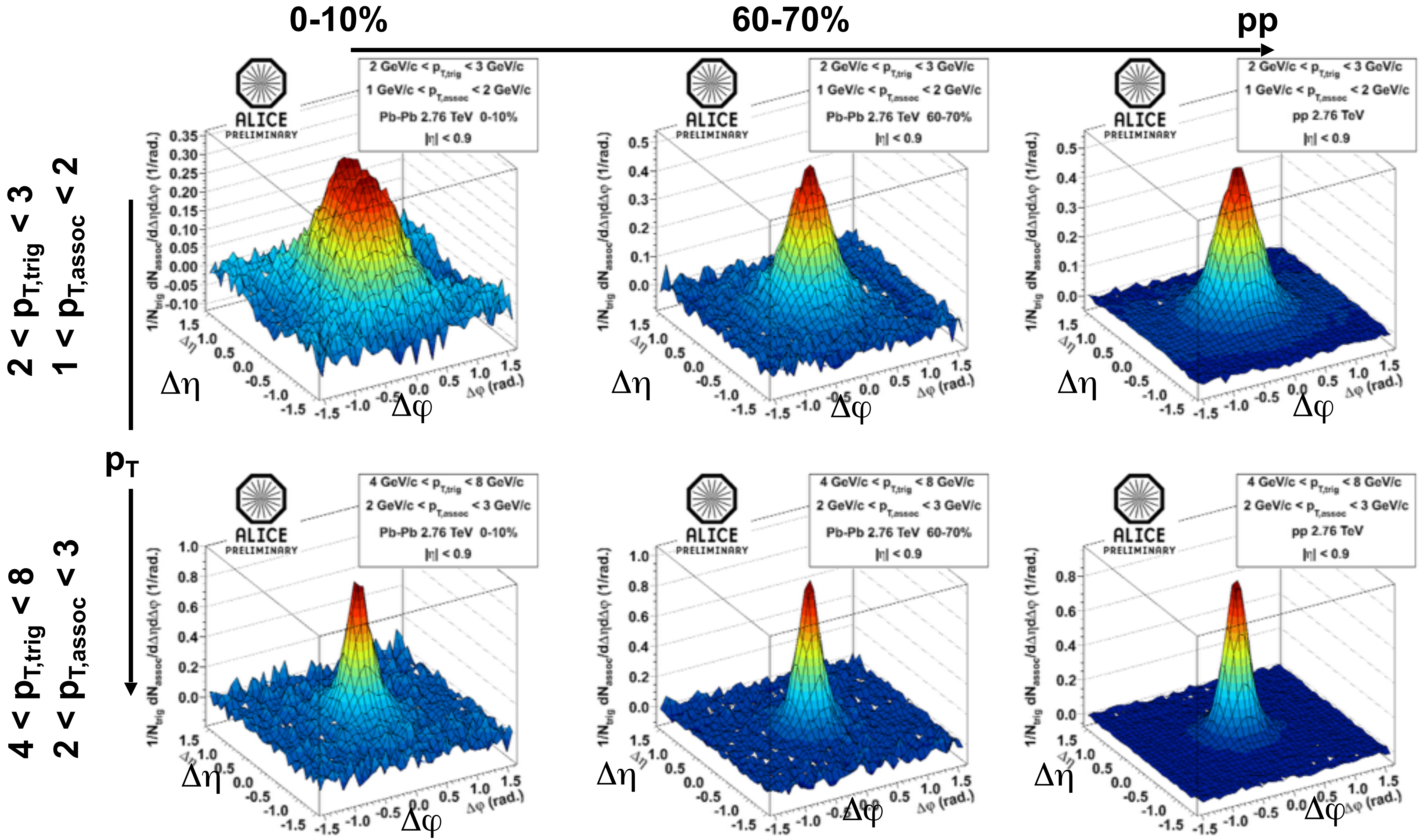


ALICE, PRL 107, 032301

Also NB: v_1 can mimick jet (near or away-side)

Going to lower p_T

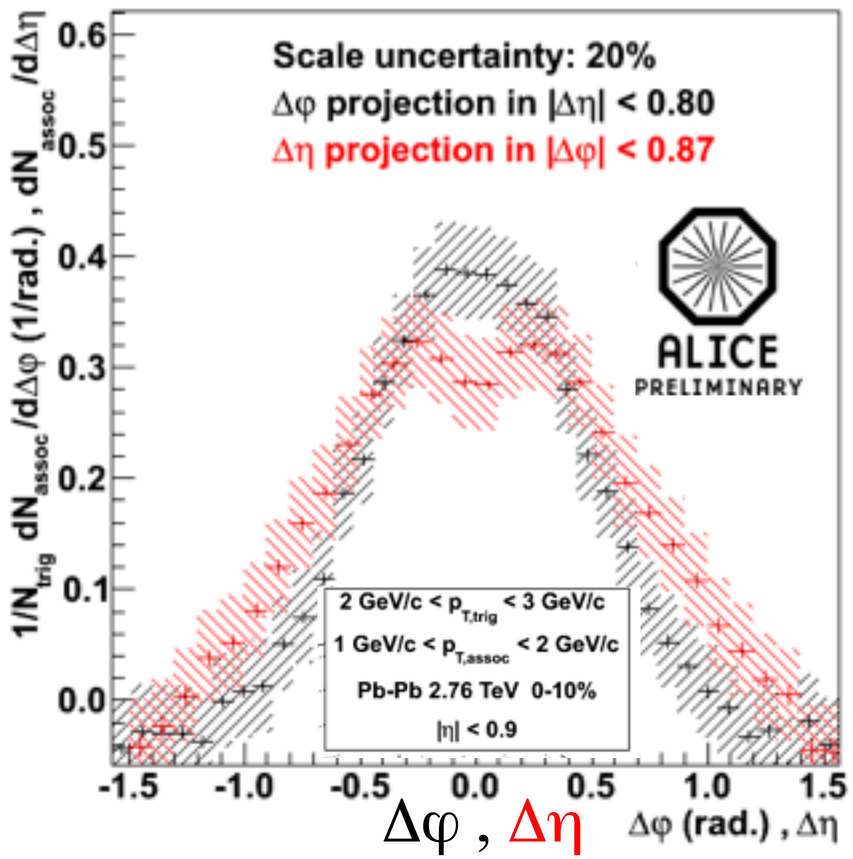
Low p_T di-hadron shapes at LHC



Departure from Gaussian

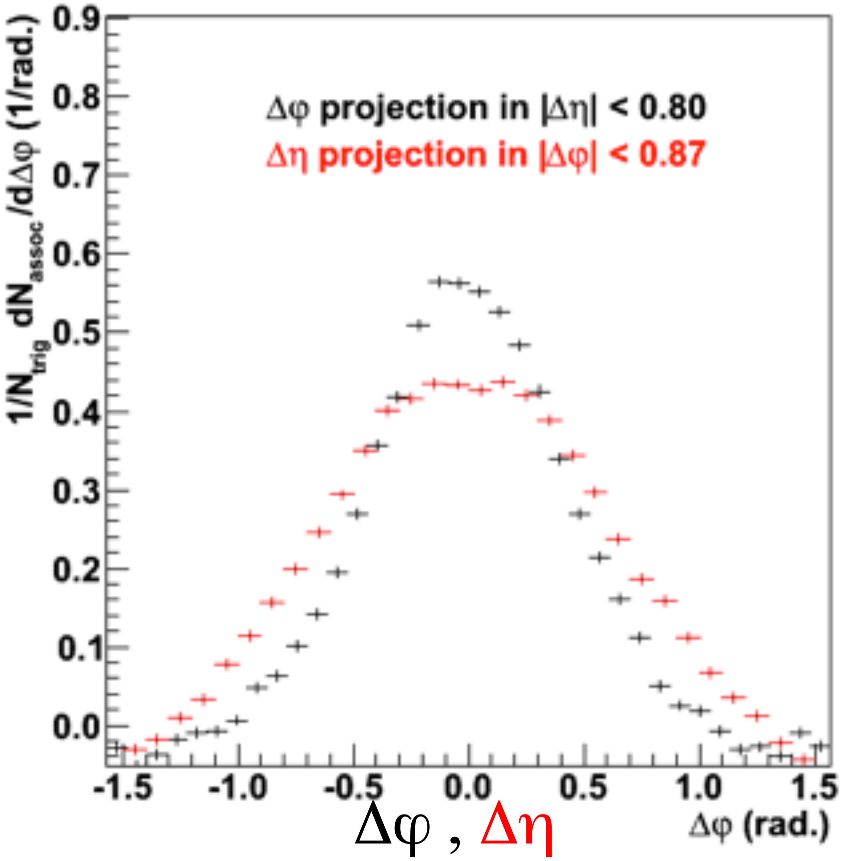
- The lowest p_T bin shows a structure with a flat top in $\Delta\eta$
- This feature is reproduced by AMPT

Data



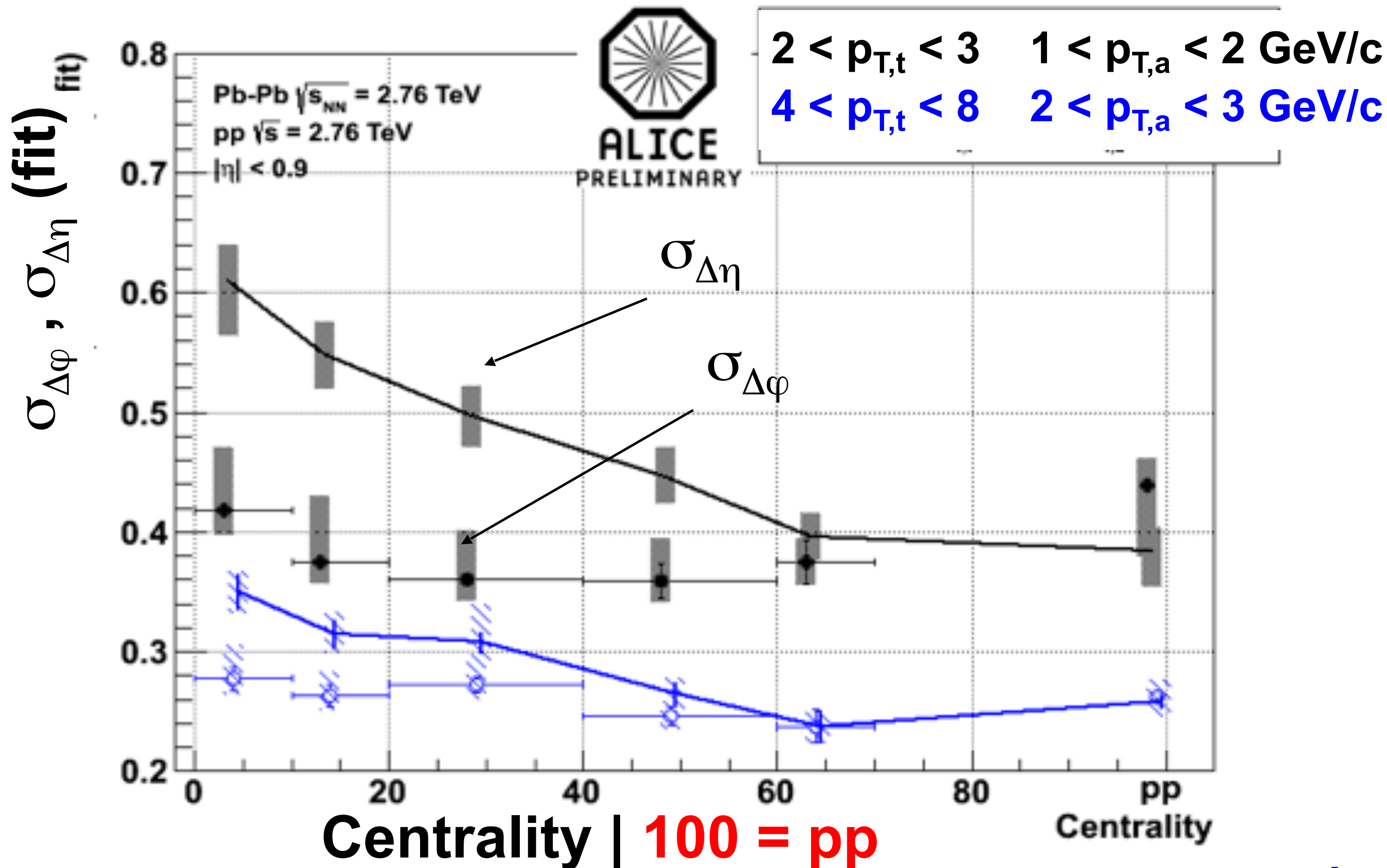
0-10%
$2 < p_{T,t} < 3$ GeV/c
$1 < p_{T,a} < 2$ GeV/c

AMPT

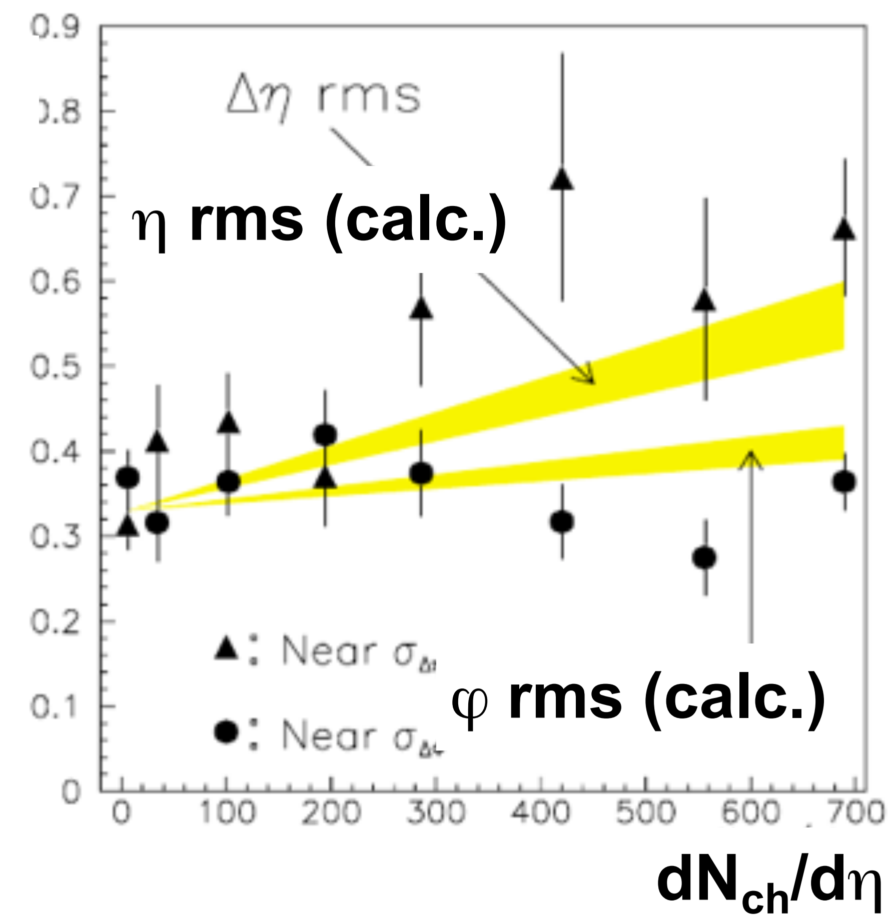


- Qualitative and quantitative agreement of peak shapes with AMPT compatible with hypothesis of interplay of jets with the flowing bulk

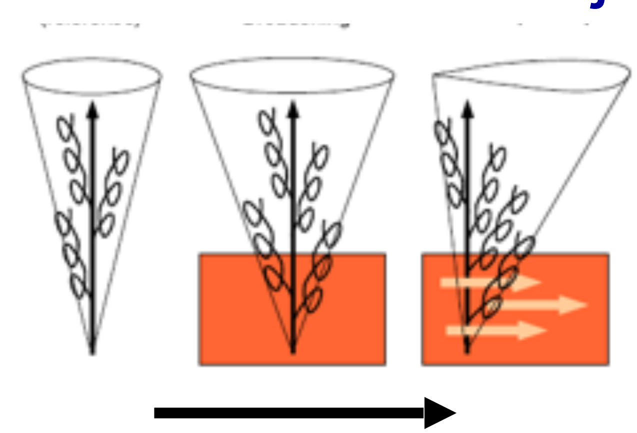
Peak Deformation



Calculation + STAR prel:



Longitudinal flow deforms jet shape

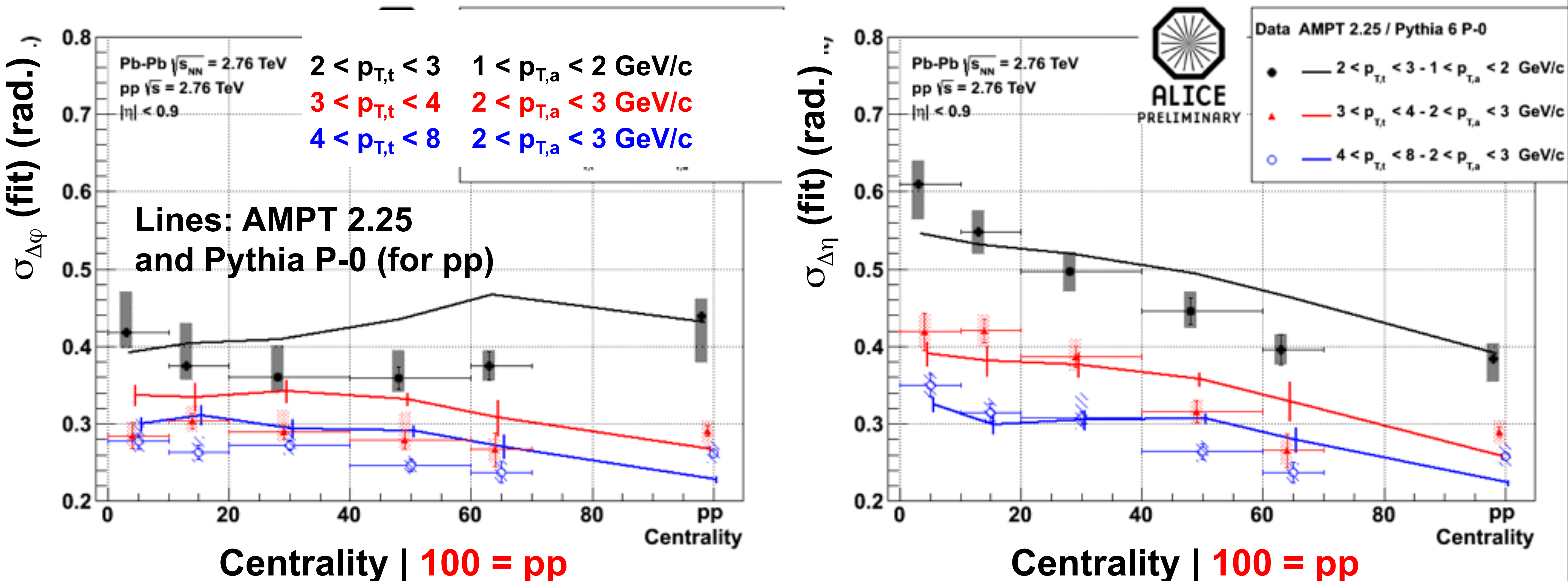


Armesto, Salgado, Wiedemann
PRL 93,242301 (2004)

Significant increase of $\sigma_{\Delta\eta}$ towards central events

– $\sigma_{\Delta\eta} > \sigma_{\Delta\varphi}$ (eccentricity ~ 0.2)

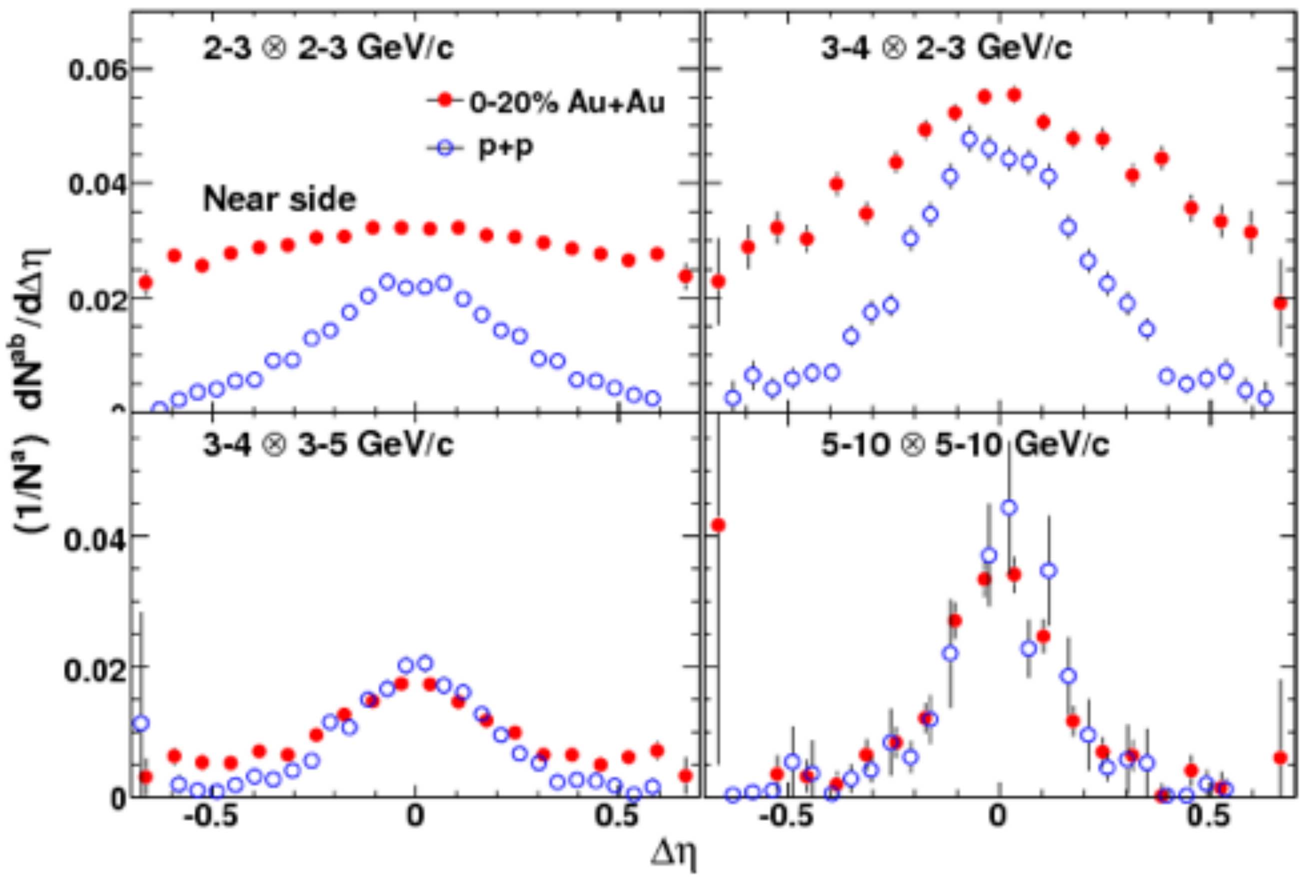
AMPT Comparison



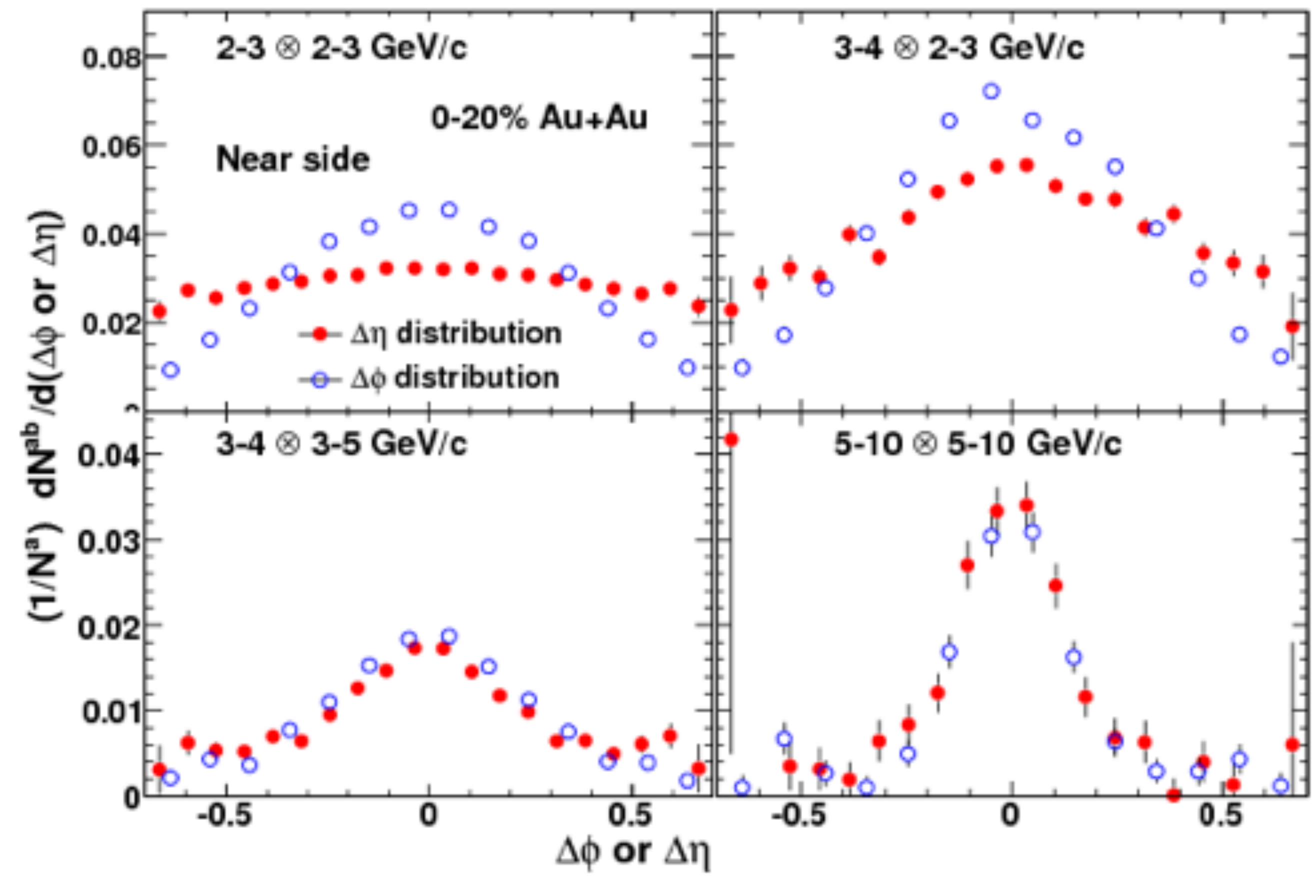
- AMPT (A MultiPhase Transport Code) describes collective effects (e.g. v_2, v_3, v_4) in HI collisions at LHC
  - Here version with string melting (2.25) is shown
- RMS of the near-side peak reasonably described by AMPT
  - Detailed mechanism not known; Interplay of jet and flow ?

Low p_T di-hadrons at RHIC

Au+Au vs p+p



Δη vs Δφ



Low p_t: jet-like peak broadened in $\Delta\eta$

High p_t: jet-like peak similar to p+p reference + ridge

Qualitatively similar to results at LHC

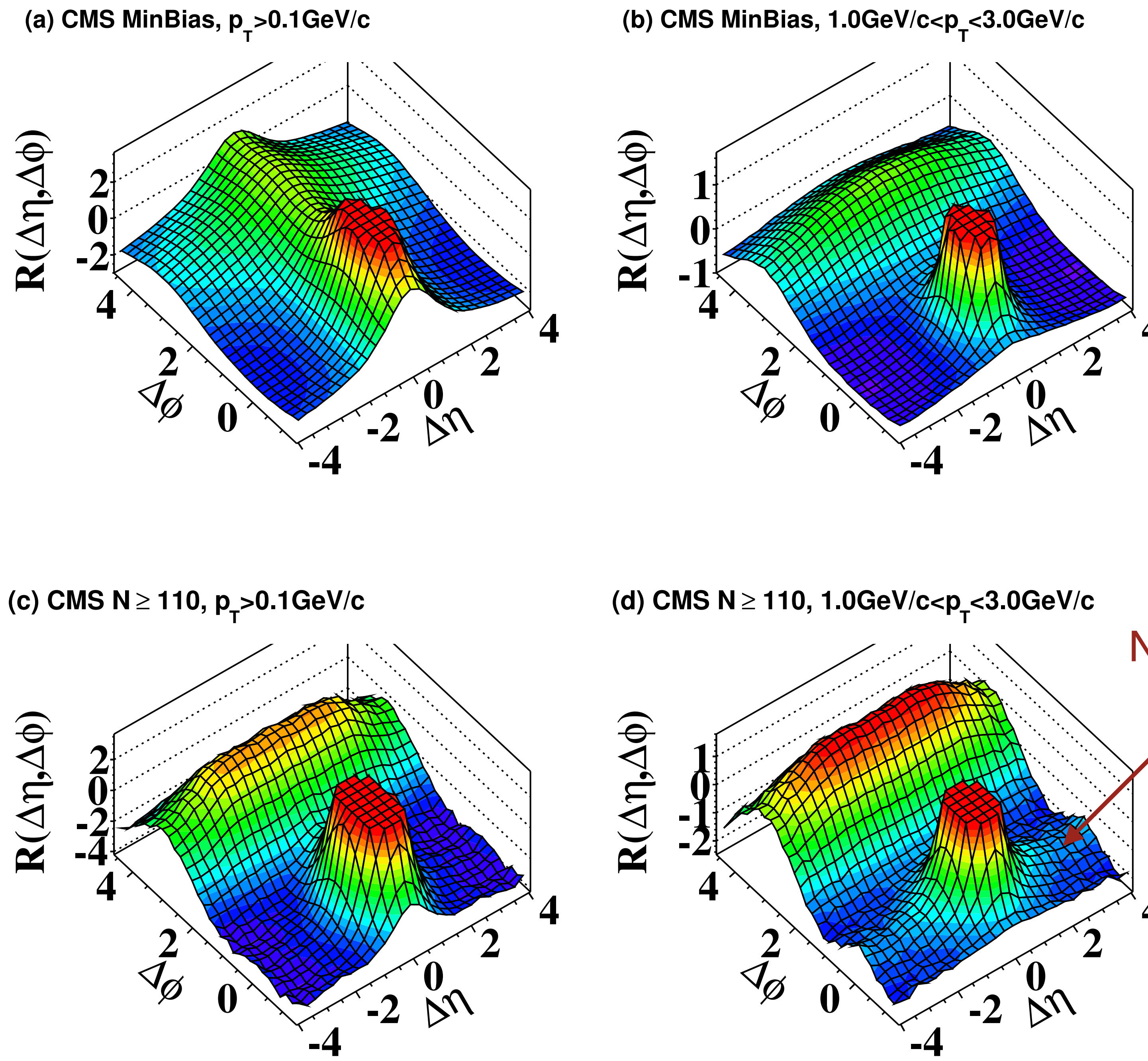
Ridge in pp

Low $p_T > 0.1$ GeV/c | $1.0 < p_T < 3.0$ GeV/c

CMS, arXiv:1009.4112

Min bias

Large mult



Near side ridge in pp

Long range in η

Near side ridge seen in pp, small effect, only high multiplicity corrections

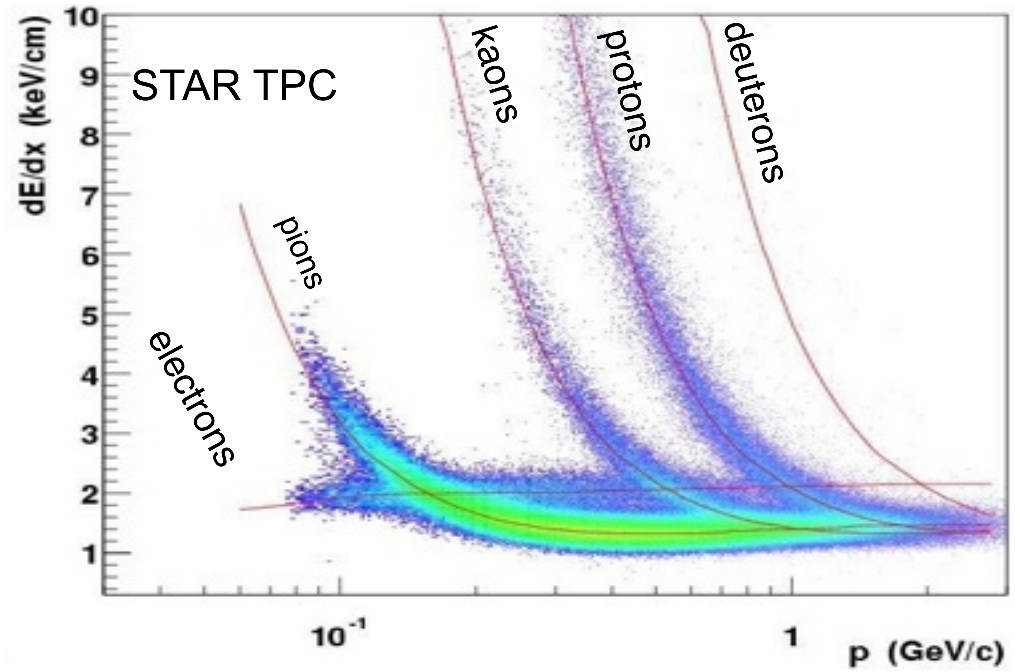
What is this? Some form of directed radiation (color connections, three-jet events?) or a collective effect?

Intermediate p_T: identified particles

Charged hadron identification

Other techniques identify π, K, p by measuring mass (velocity)

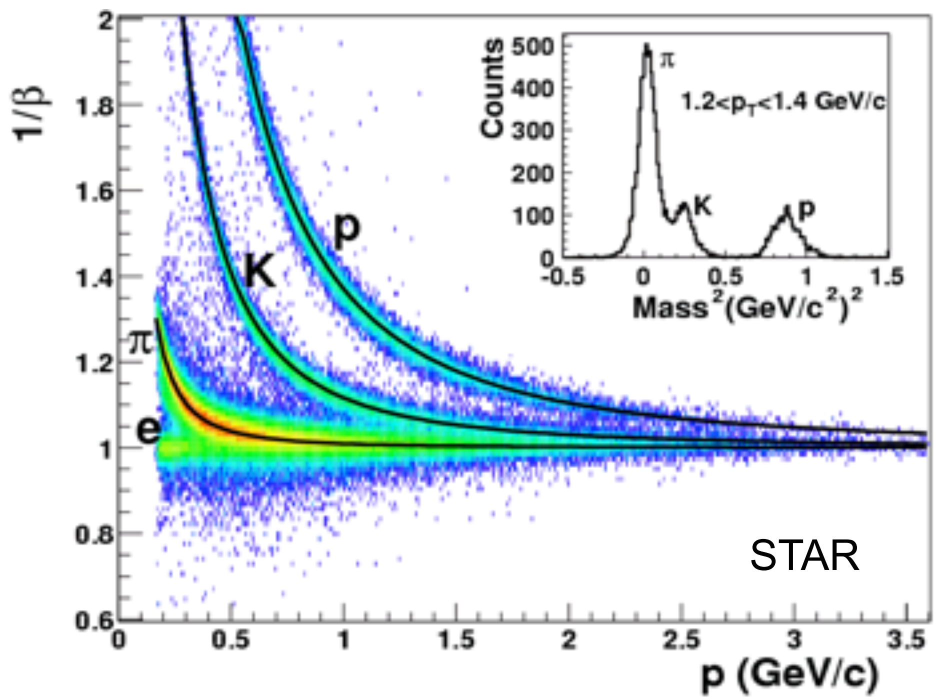
Specific energy loss *dE/dx*



Depends on βγ

Mostly at low p_T < 1 GeV

Time-of-flight (TOF)

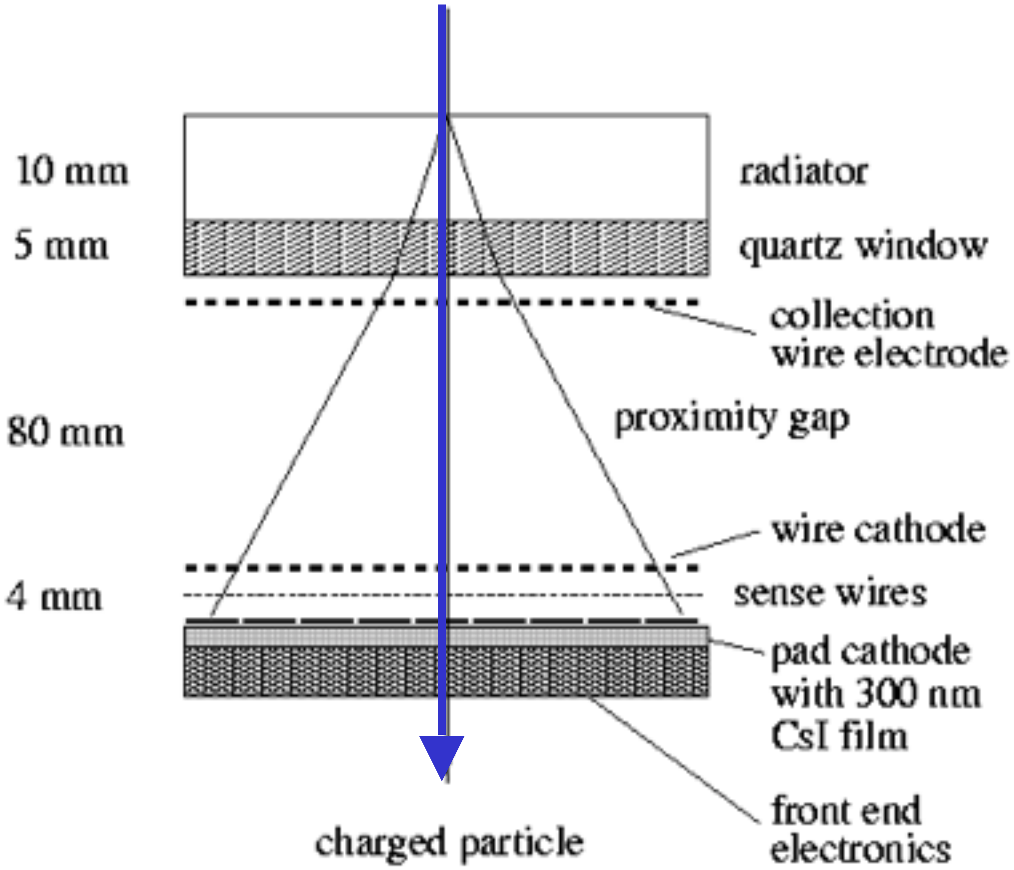


Depends on β

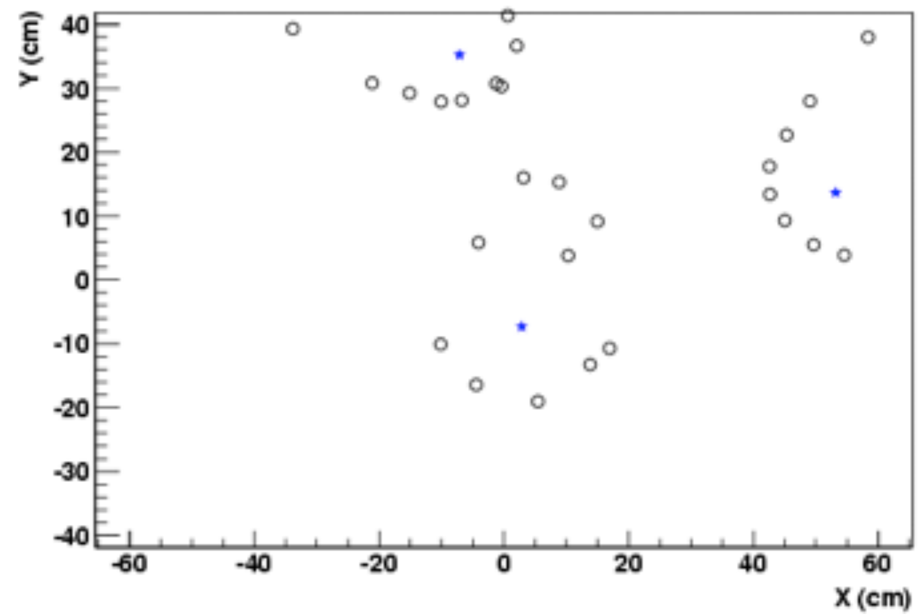
< 100 ps resolution, PID up to few GeV

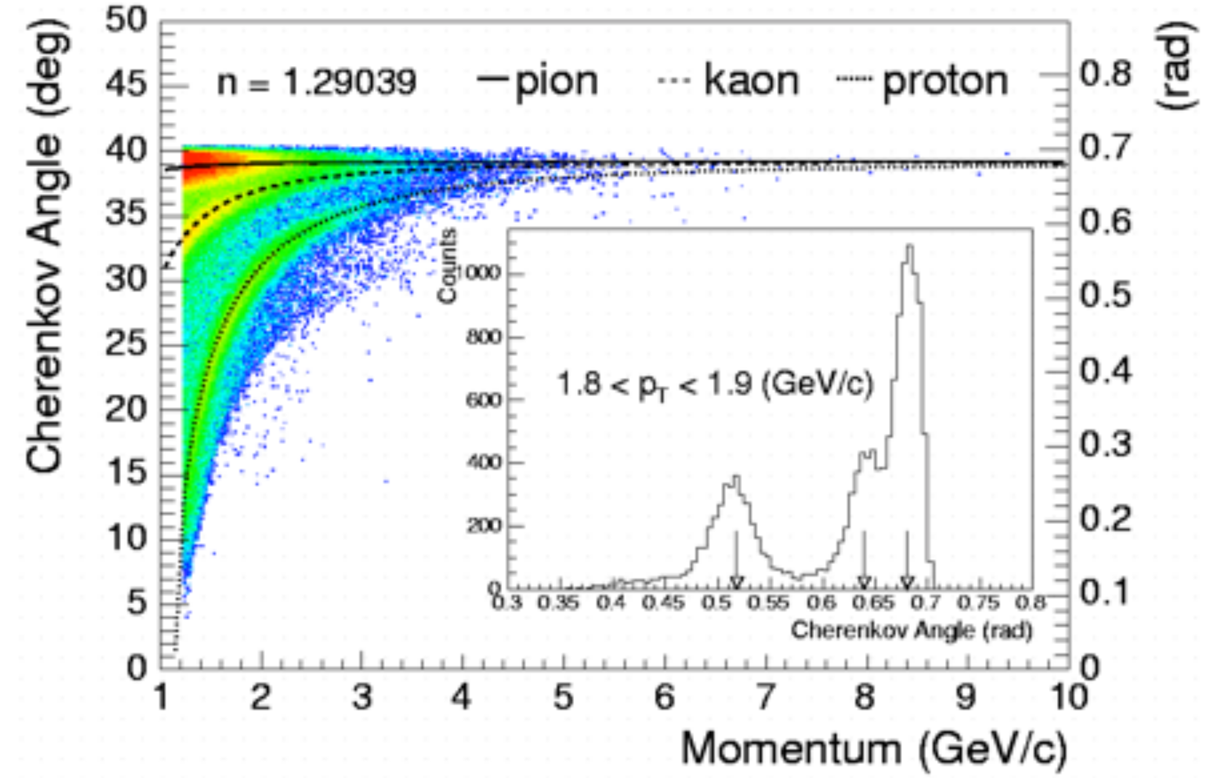
TPC-*dE/dx* and TOF are basic features of most Heavy-Ion detectors (PHENIX, STAR, ALICE)

Ring Imaging Cherenkov (RICH)



Ring reconstruction





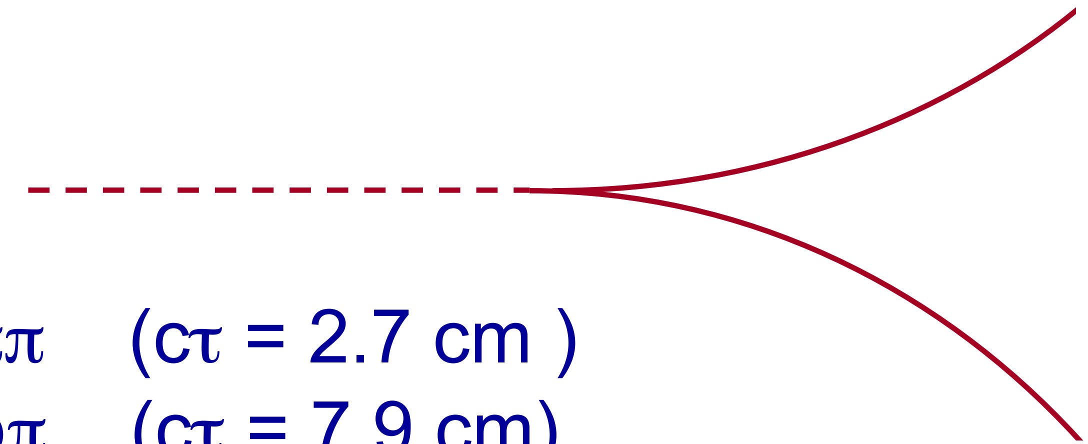
Cherenkov angle depends on index of refraction → tunable

Advantage: RICH can be optimised for large momentum
Not so easy with high track densities

PID: weak decays in tracker

'topological reconstruction'

With a tracker, reconstruct weak decays:

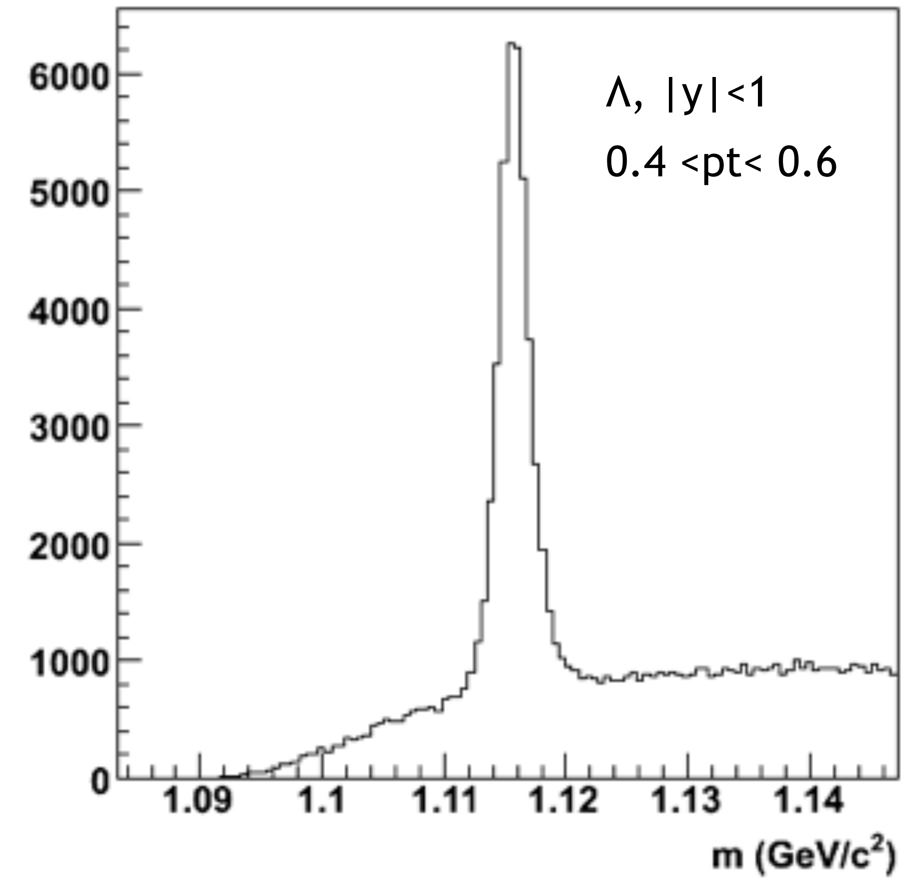


$K^0 \rightarrow \pi\pi$ ($c\tau$ = 2.7 cm)

$\Lambda^0 \rightarrow p\pi$ ($c\tau$ = 7.9 cm)

$D^0 \rightarrow K\pi$ ($c\tau$ = 124 μm)

$D^+ \rightarrow K\pi\pi$ ($c\tau$ = 315 μm)



And also:

τ -> hadrons

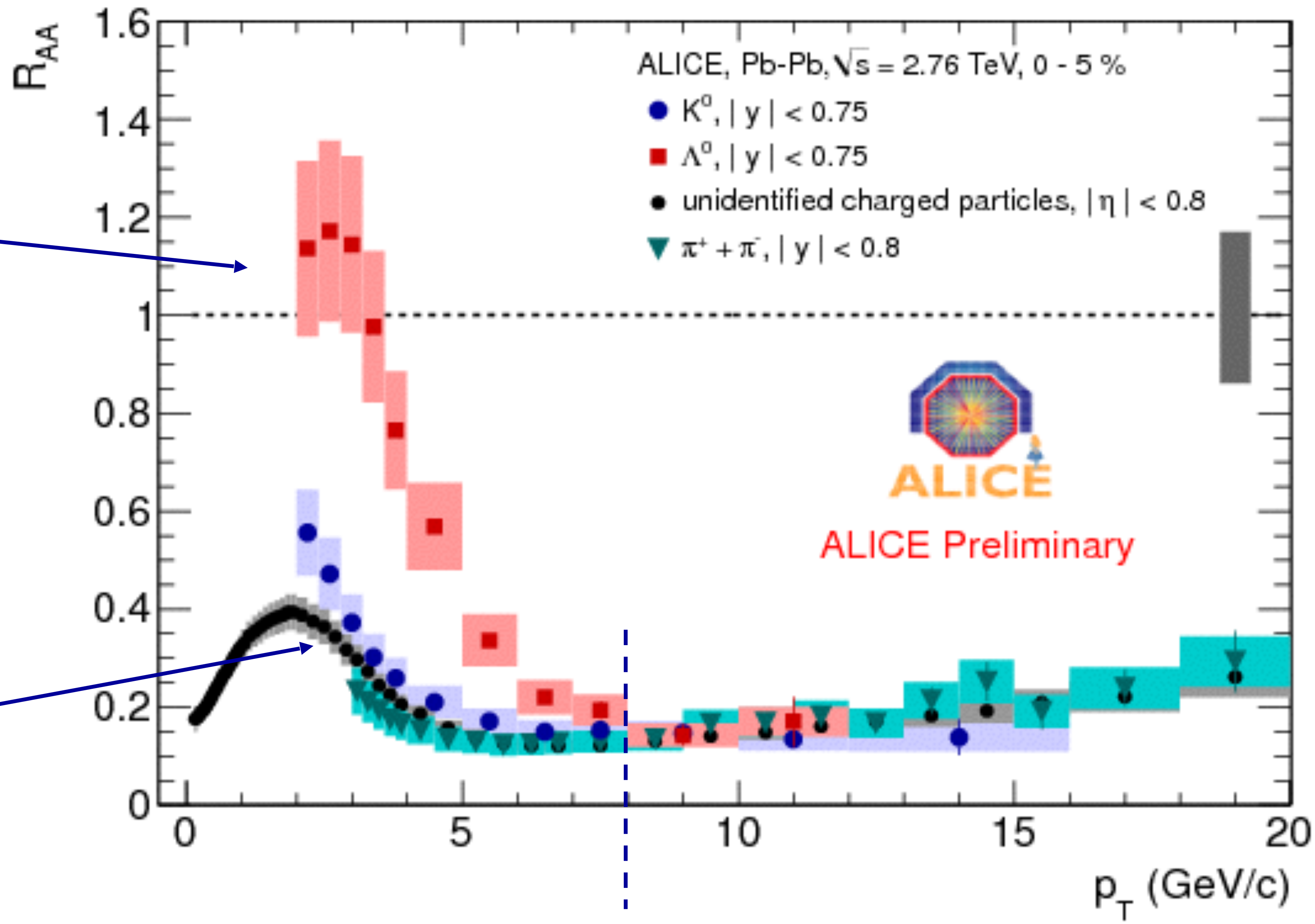
t -> Wb ->…

Advantages: can be done with tracking detectors; momentum range not limited

Identified hadron R_{AA} (strangeness)

Λ: R_{AA}~1 at p_T~3 GeV/*c*
Smaller suppression,
Λ/K enhanced at low p_T

Kaon, pion R_{AA}
similar

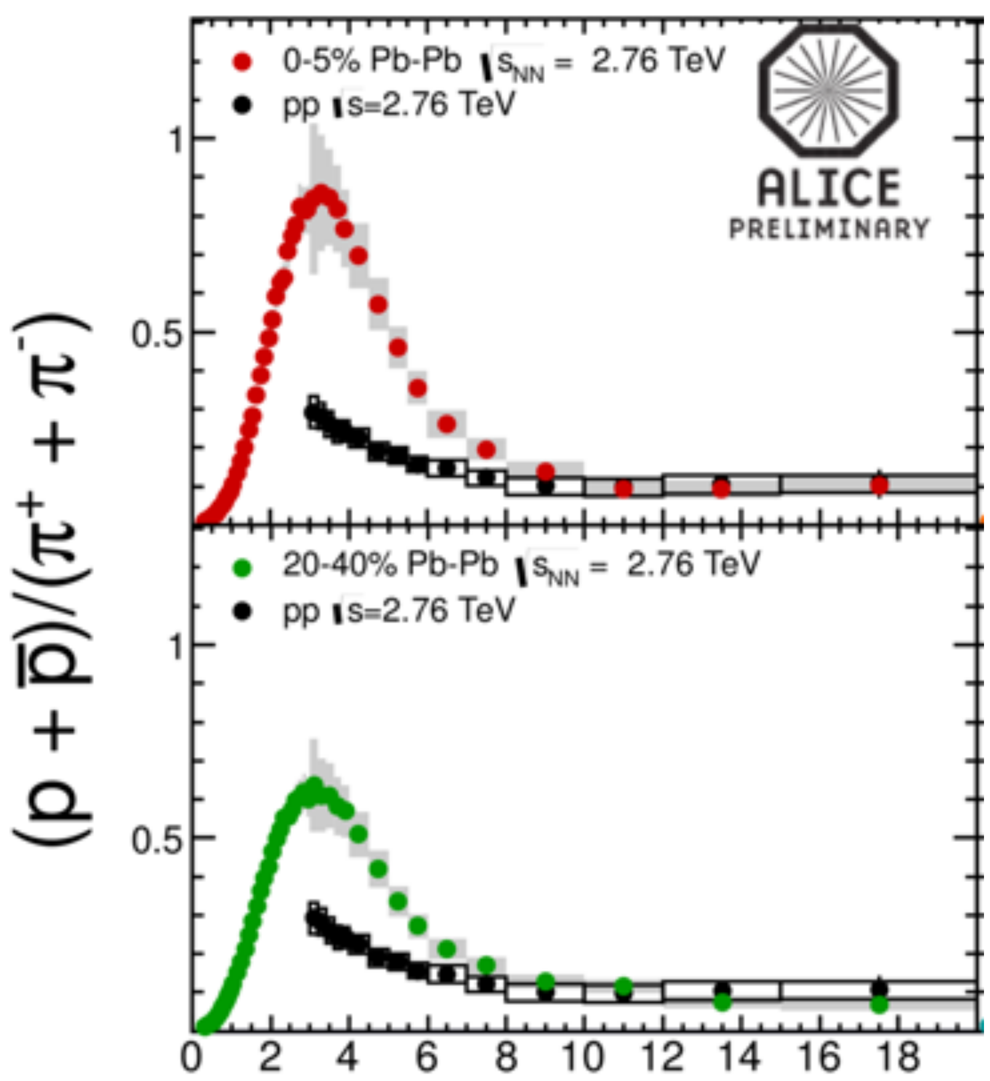


$p_T \geq$ ~8 GeV/*c*:
All hadrons similar

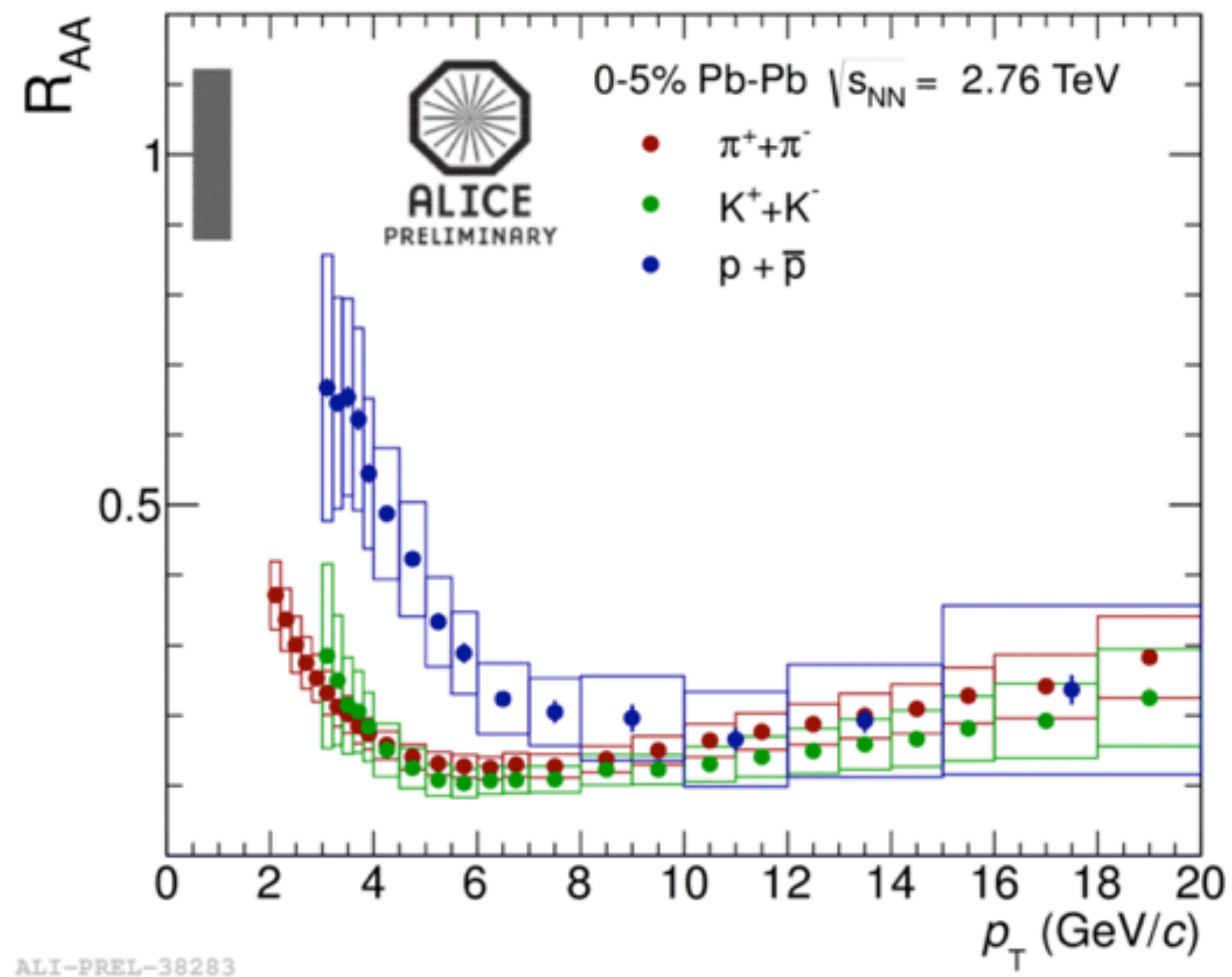
partonic energy loss + pp-like fragmentation?

Identified hadron R_{AA}

M. Ivanov, A. Ortiz@QM2012



M. Ivanov, A. Ortiz@QM2012



Low-intermediate p_T (1-6 GeV):
Large baryon/meson ratio

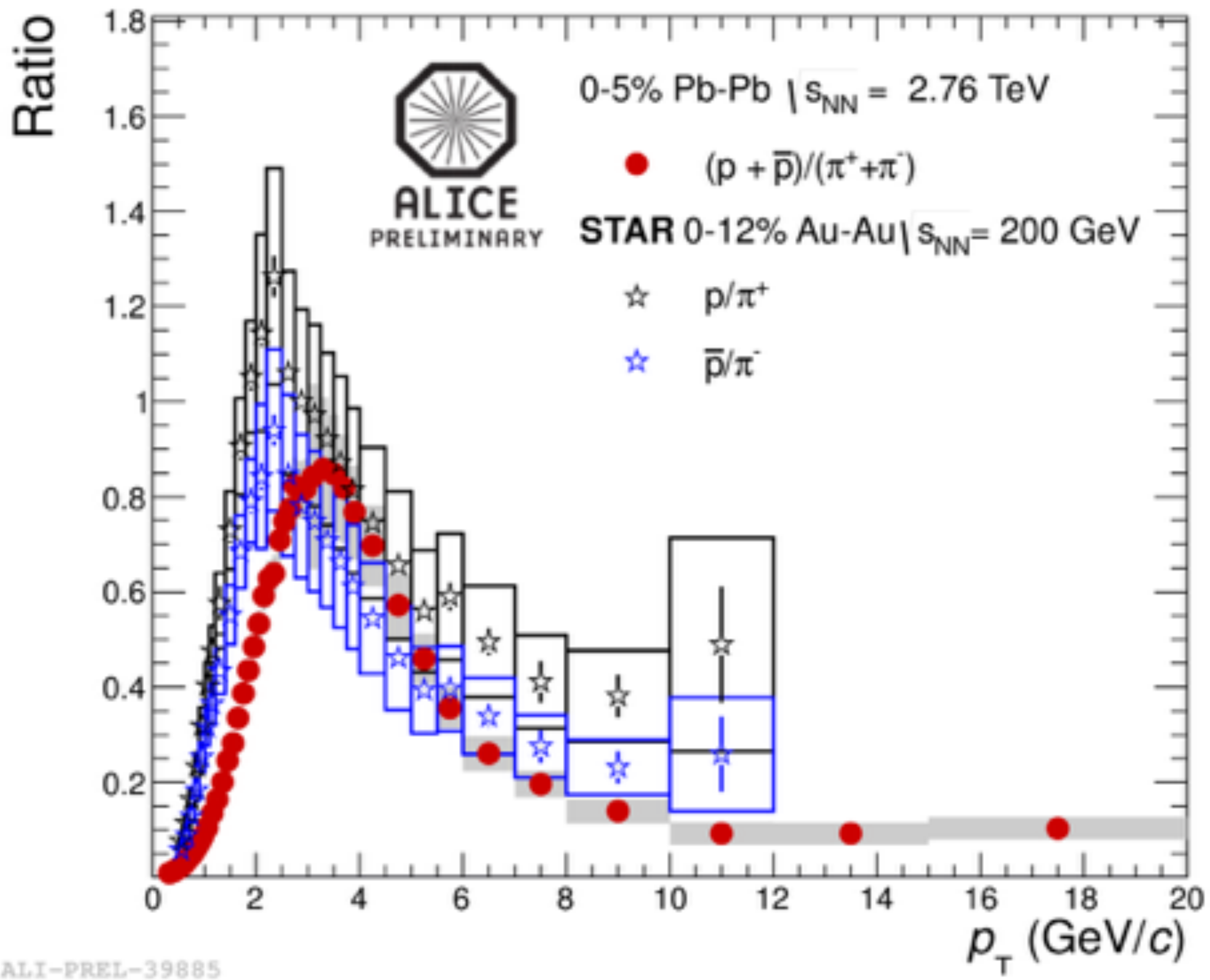
Probably due to:
1)radial flow
2)parton recombination

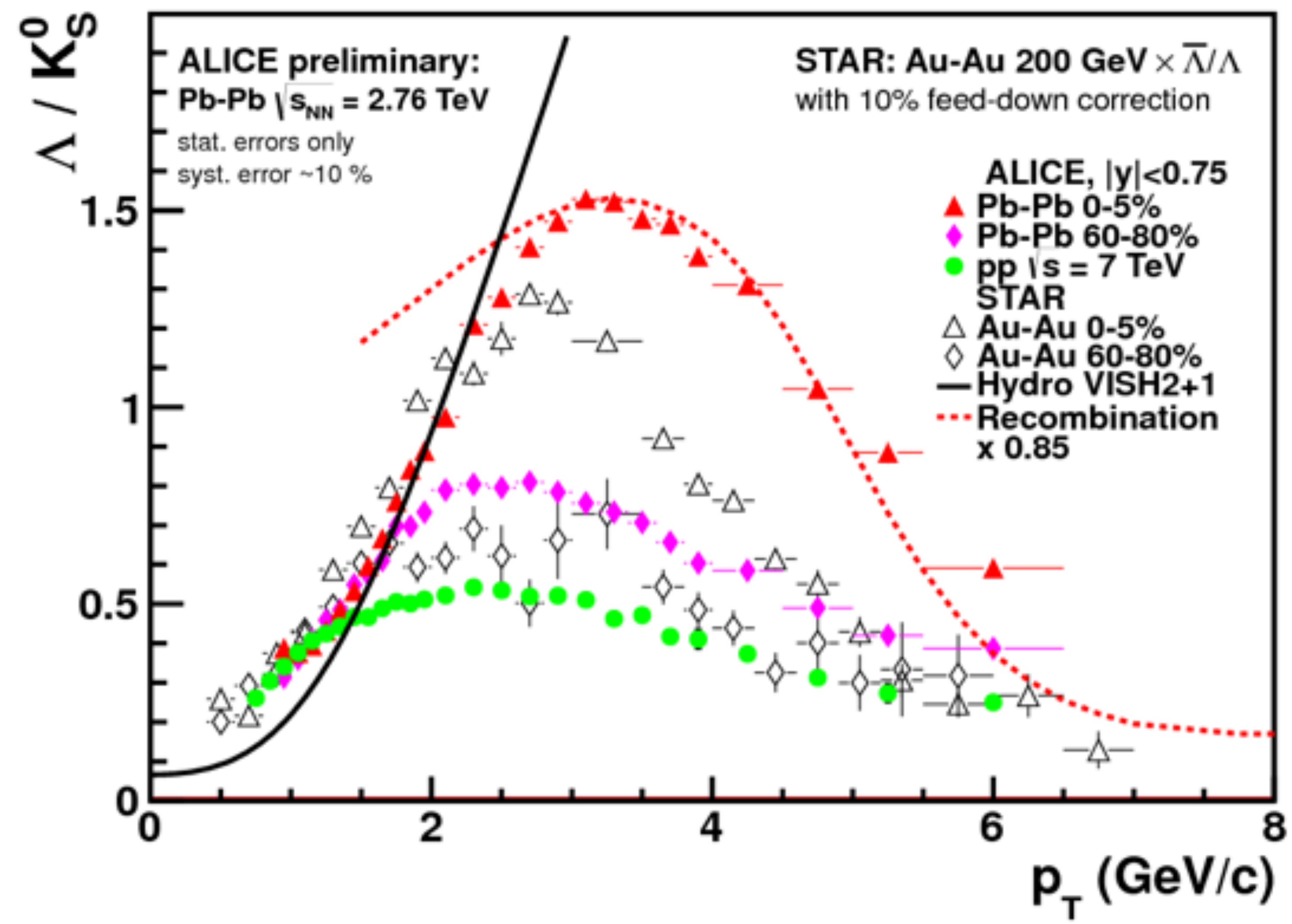
Baryon, meson R_{AA} similar at p_T > 8 GeV

As expected from ***parton*** energy loss

Spectra at intermediate p_T

Schukraft et al, arXiv:1202.3233

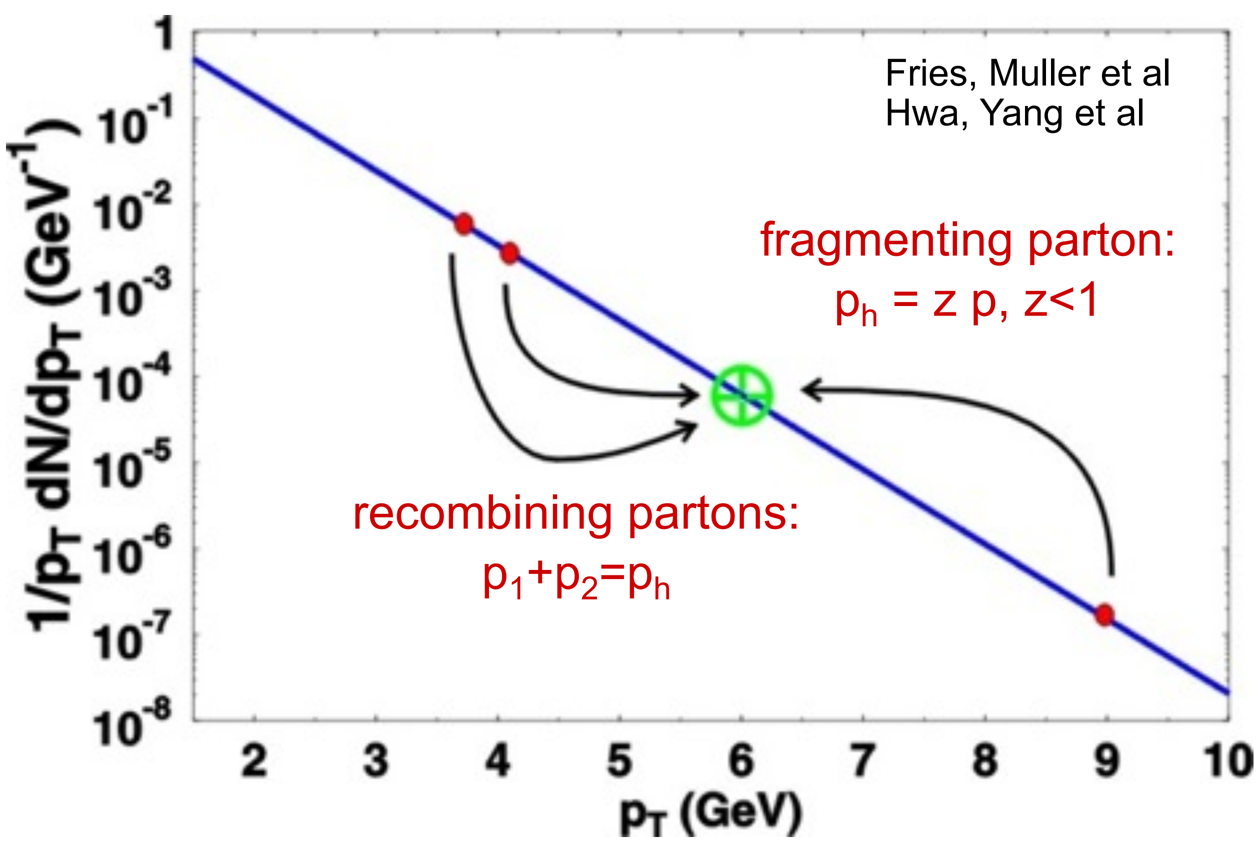




Low-intermediate p_T (1-6 GeV):
Large baryon/meson ratio

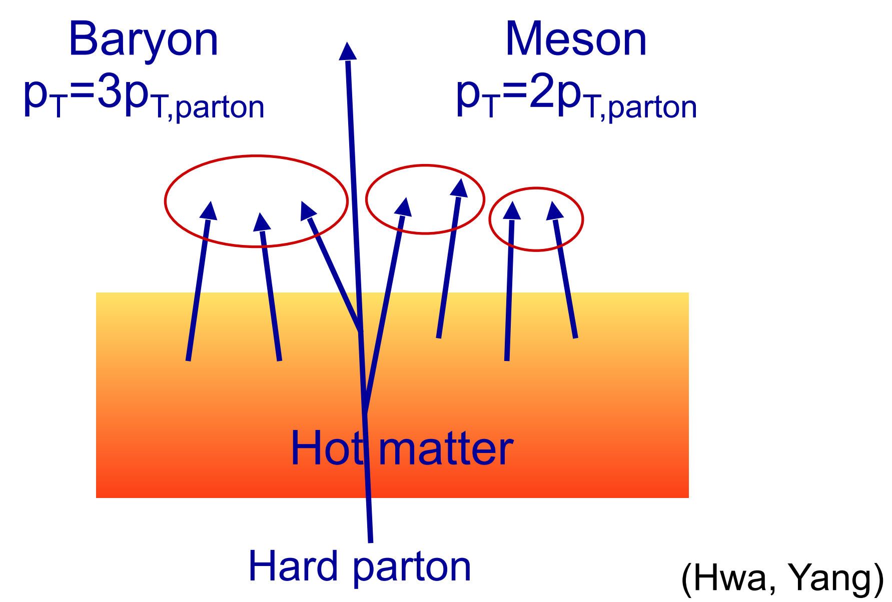
Probably due to:
1) radial flow
2) parton recombination

Hadronisation by recombination

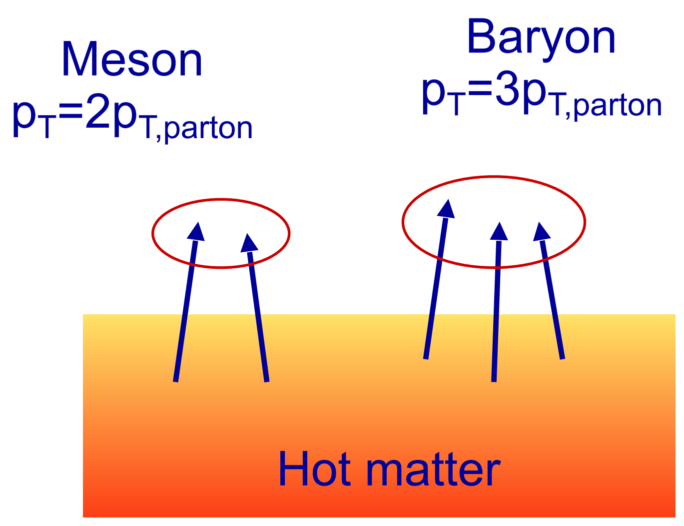


Recombination of thermal ('bulk') partons produces baryons at larger p_T

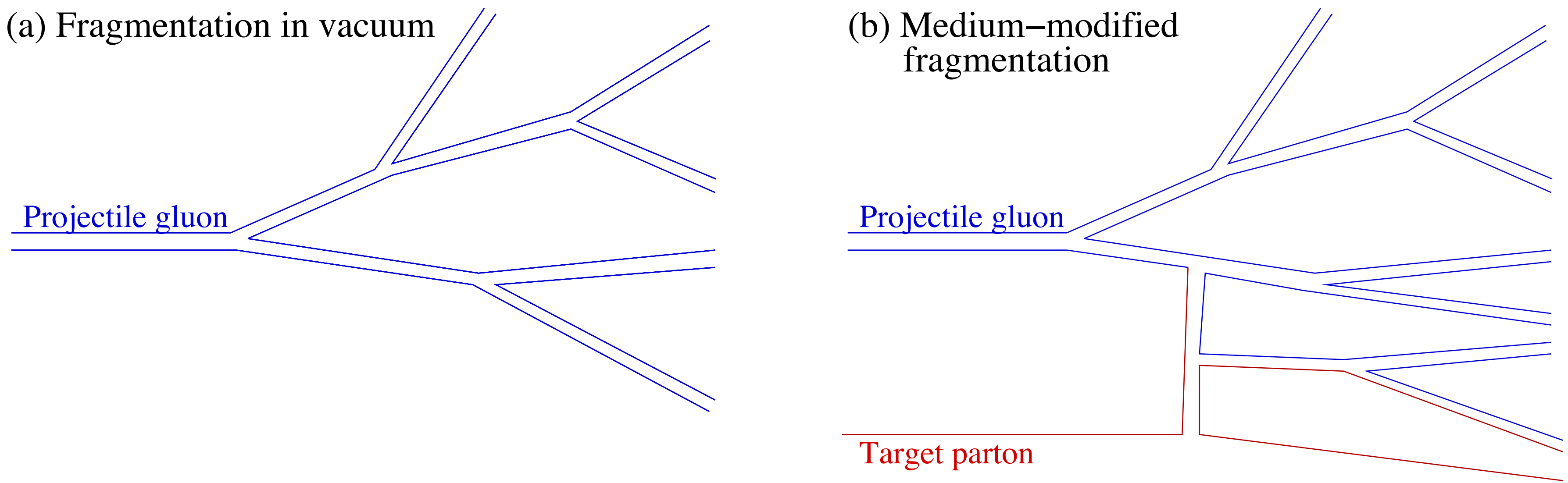
'Shower-thermal' recombination

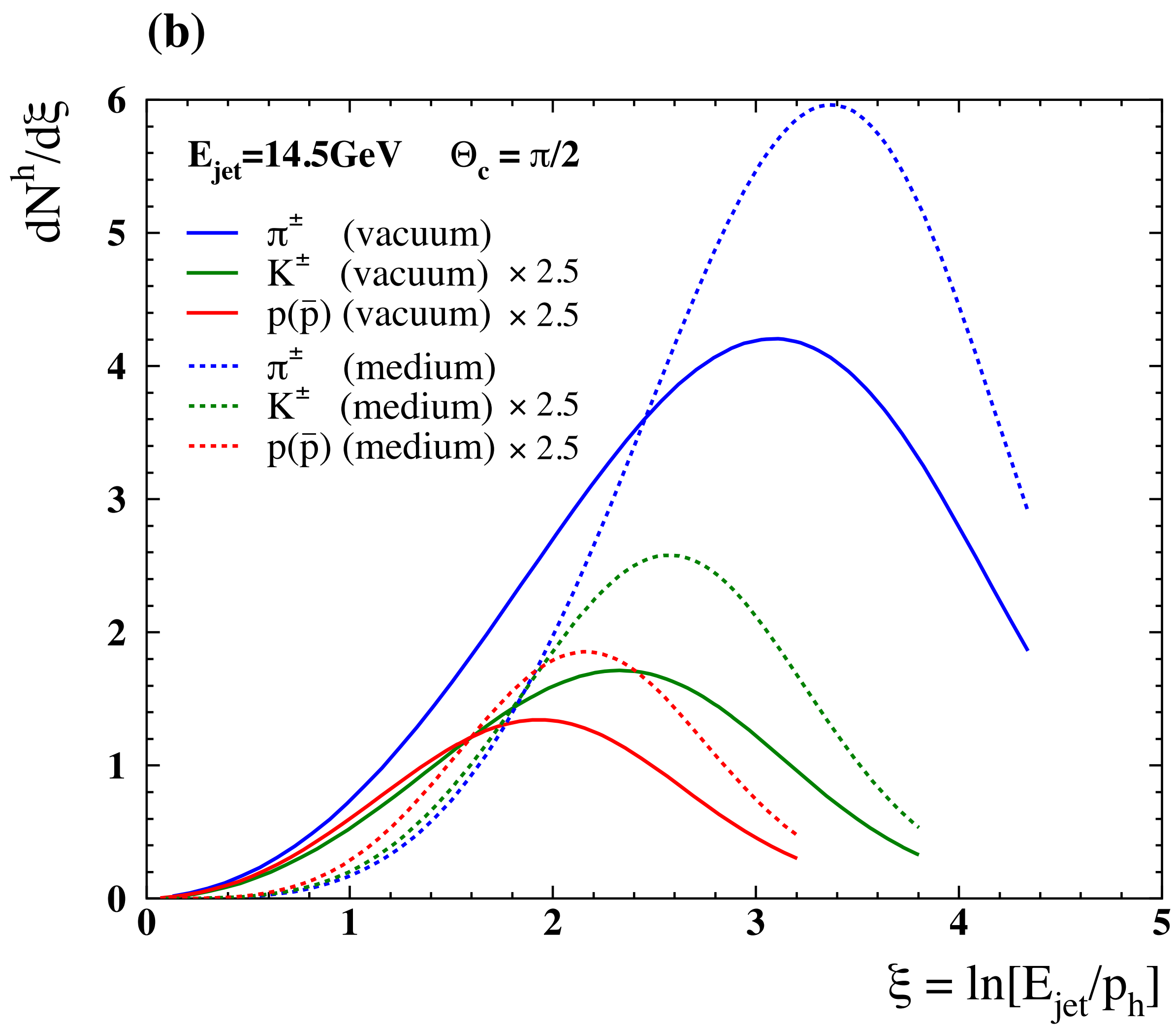


Expect large baryon/meson ratio associated with high-p_T trigger



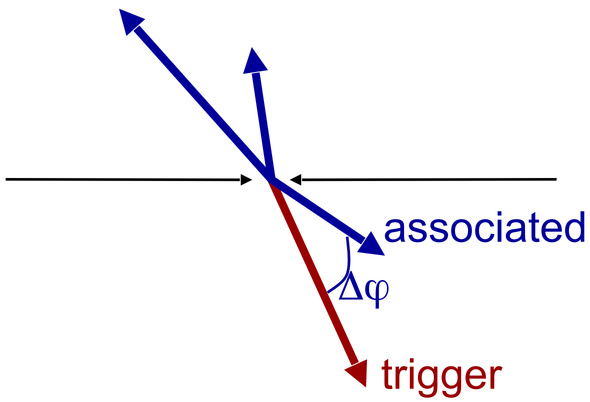
Change of color flow may also affect hydrochemistry





Sapeta, Wiedemann, arXiv:0707.3494
(also: Milhano, Caselderrey-Solana)

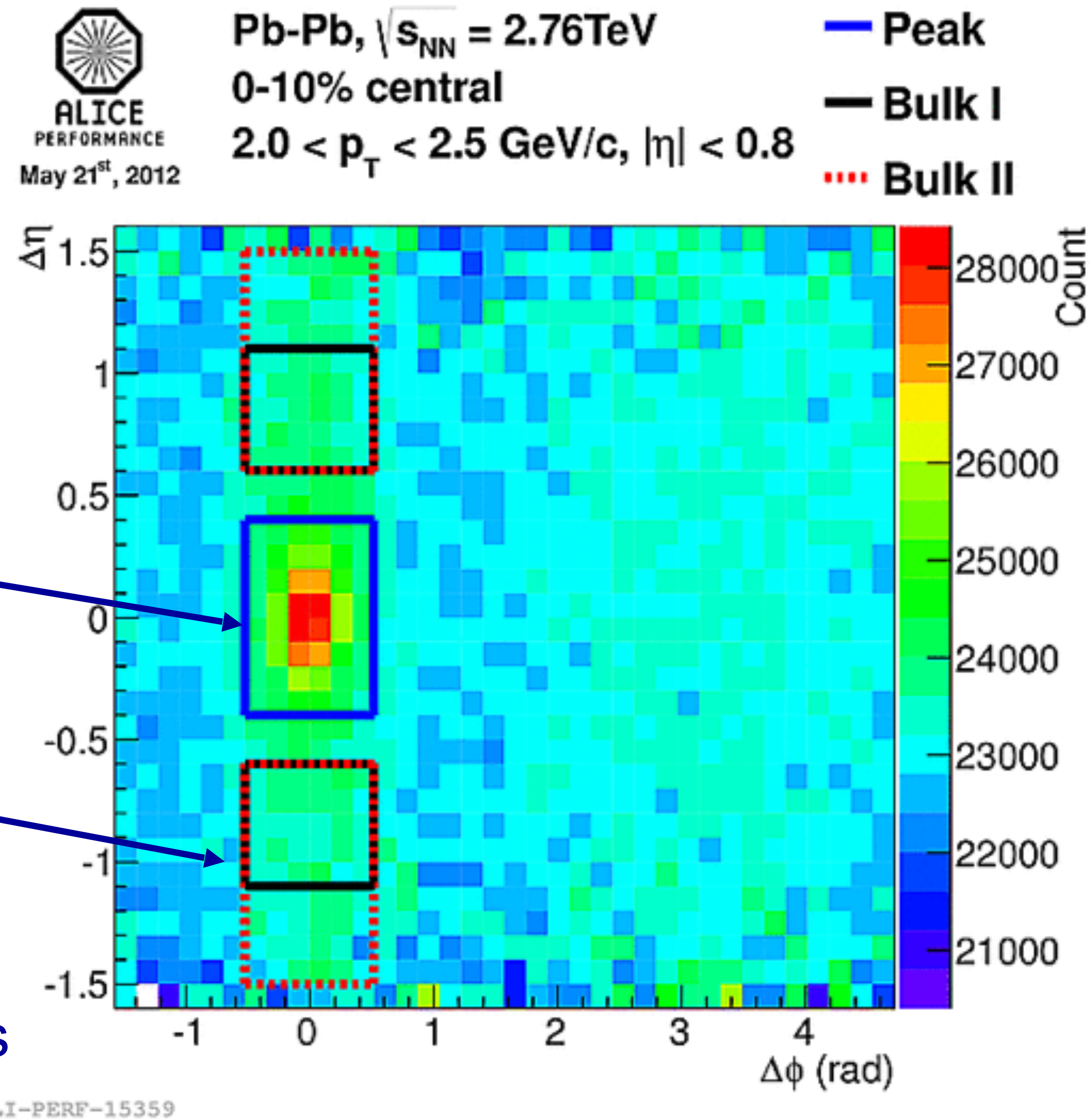
Di-hadrons: p/π in jets



$5 < p_T^{trig} < 10$ GeV

Jet peak

Background/Bulk region
(v_2, v_3 peak here)



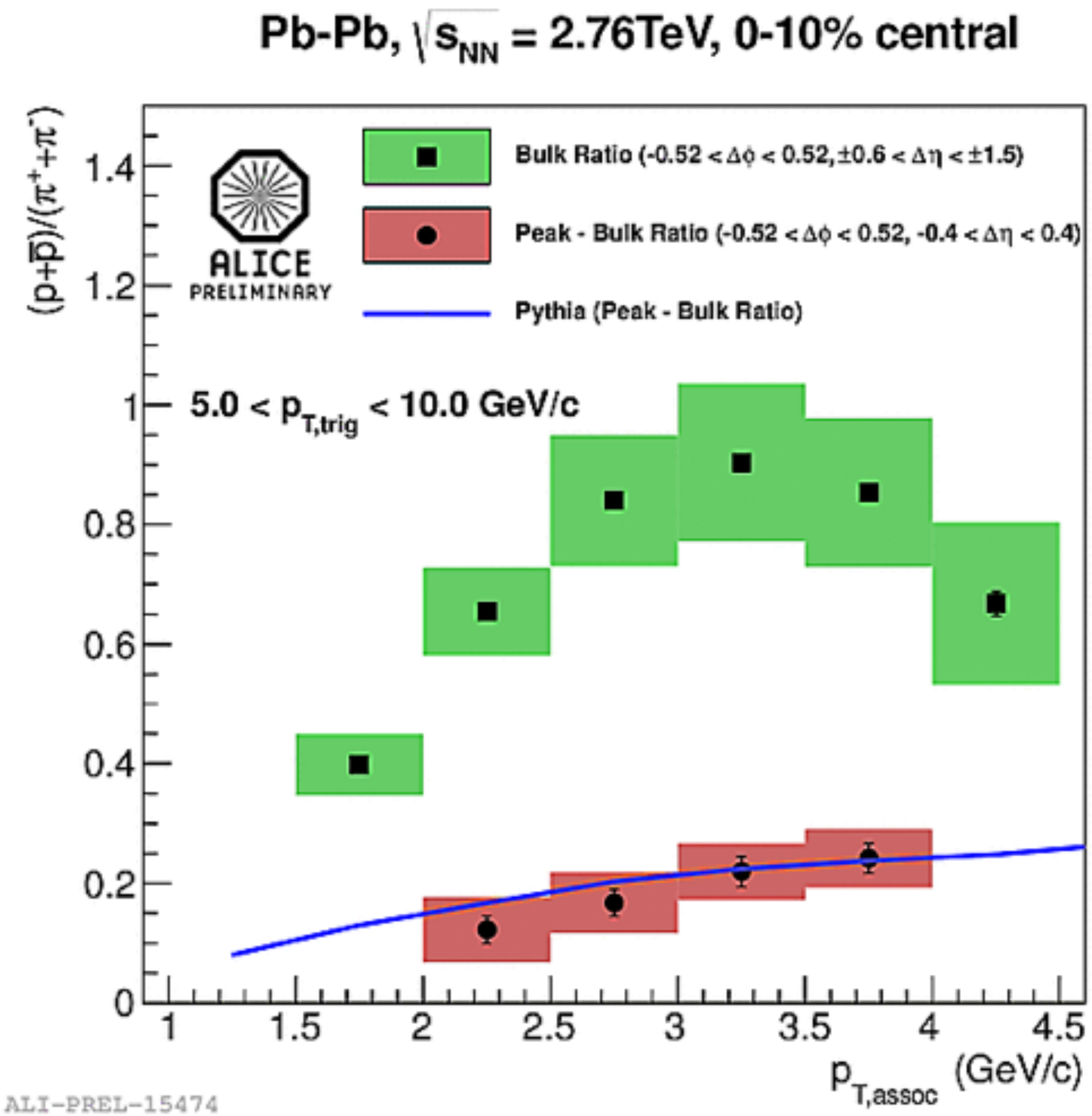
Use TOF+dE/dx to identify particles

p/π bulk vs jets

p/π ratio in Bulk region agrees with inclusive

p/π ratio in jet* agrees with Pythia

*after background subtraction



ALICE, M. Veldhoen, HP

No effect of shower-thermal recombination and/or modified color flow observed in the associated yield in jets

p+Pb and Color Glass Condensate

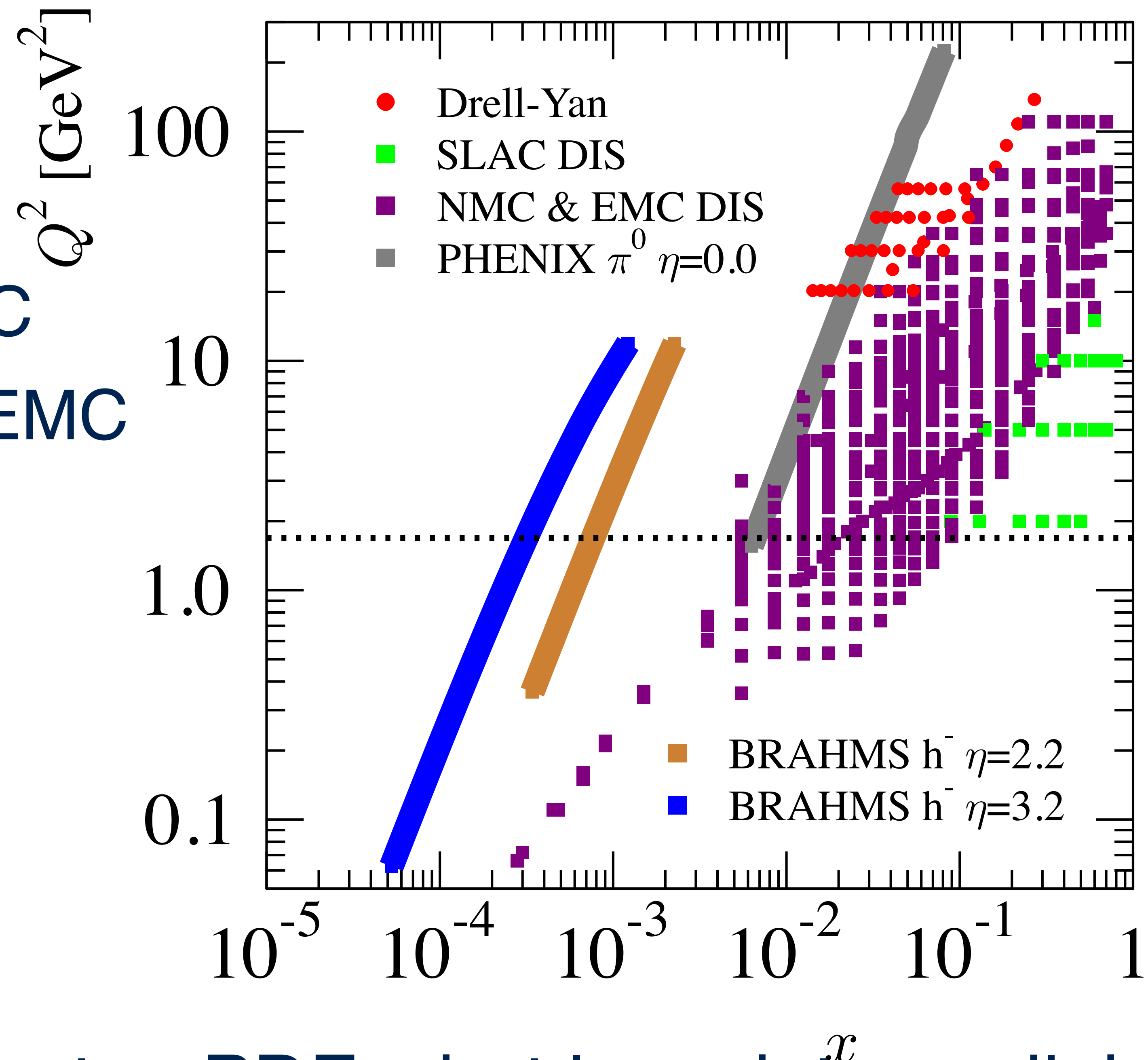
p+Pb and 'cold nuclear matter effects'

- Initial state effects: change of proton wave function in nucleus
  - 'Shadowing': nuclear PDFs
  - Saturation of gluon density at low x; Color Glass Condensate
- Final state
  - (Hadronic) Energy Loss in Cold Nuclear Matter

Initial state effects: nPDFs — data

Experimental data:

- DIS with electrons: SLAC
- DIS with muons: NMC, EMC
- Drell-Yan in p+A
- p0 production in p+A

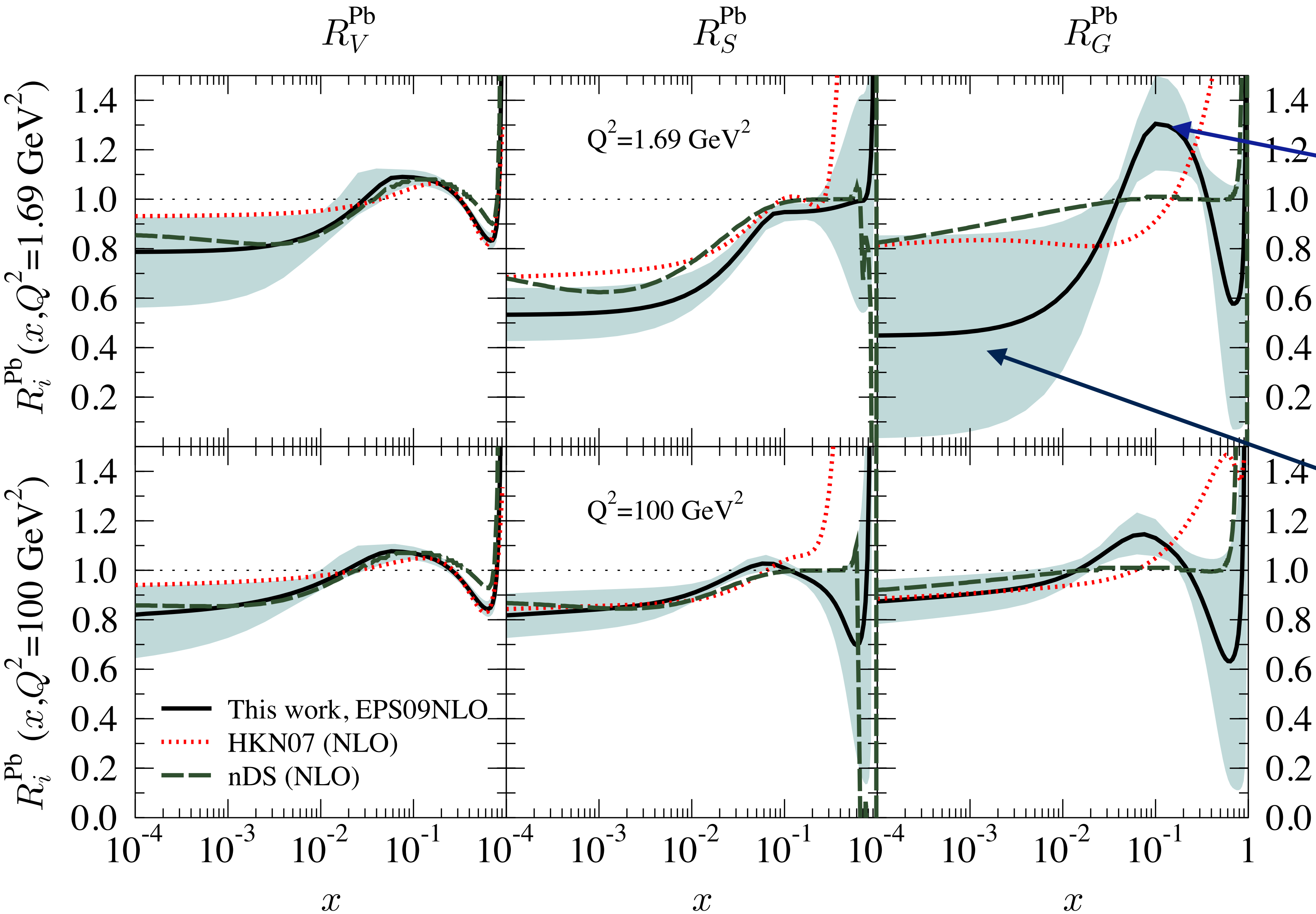


Eskola, Paukkunen, Salgado, arXiv:0902.4154

Similar procedure like proton PDFs, but less data available in particular: no data for x < 10^{-2}

Initial state effects: nPDFs

nPDF results shown as ratio to proton



Enhancement at intermediate x: ‘anti-shadowing’

Low-x suppression: shadowing

Valence quarks
u-u + d-d

Sea quarks
u+u + d+d

Gluons

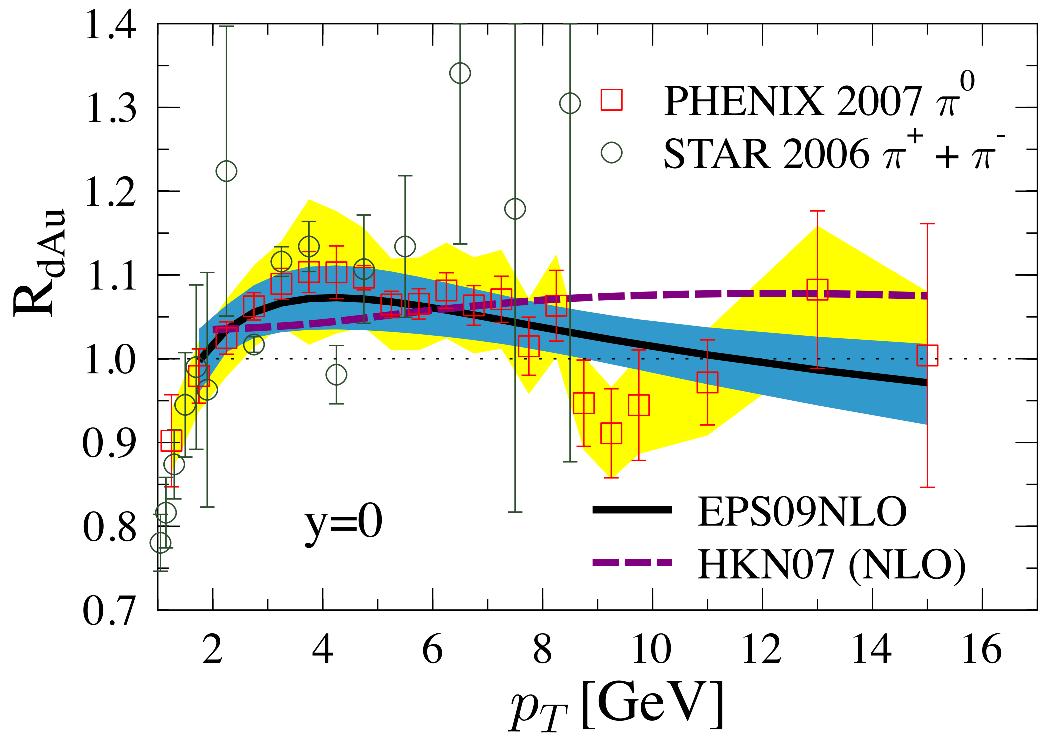
Significant effects in gluons at low Q^2

No experimental information for small x (large uncertainty)

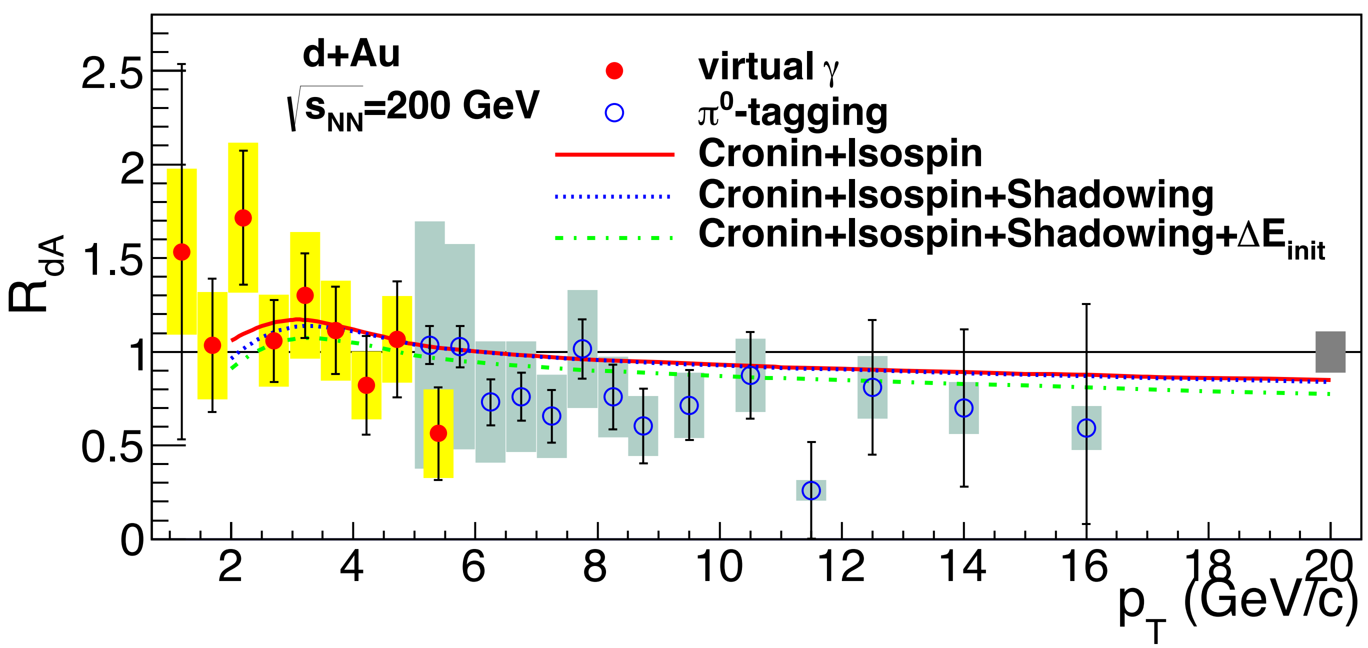
Sea quarks ‘follow’ gluons

Effects of shadowing/anti-shadowing

π^0 spectra at RHIC



Direct γ at RHIC



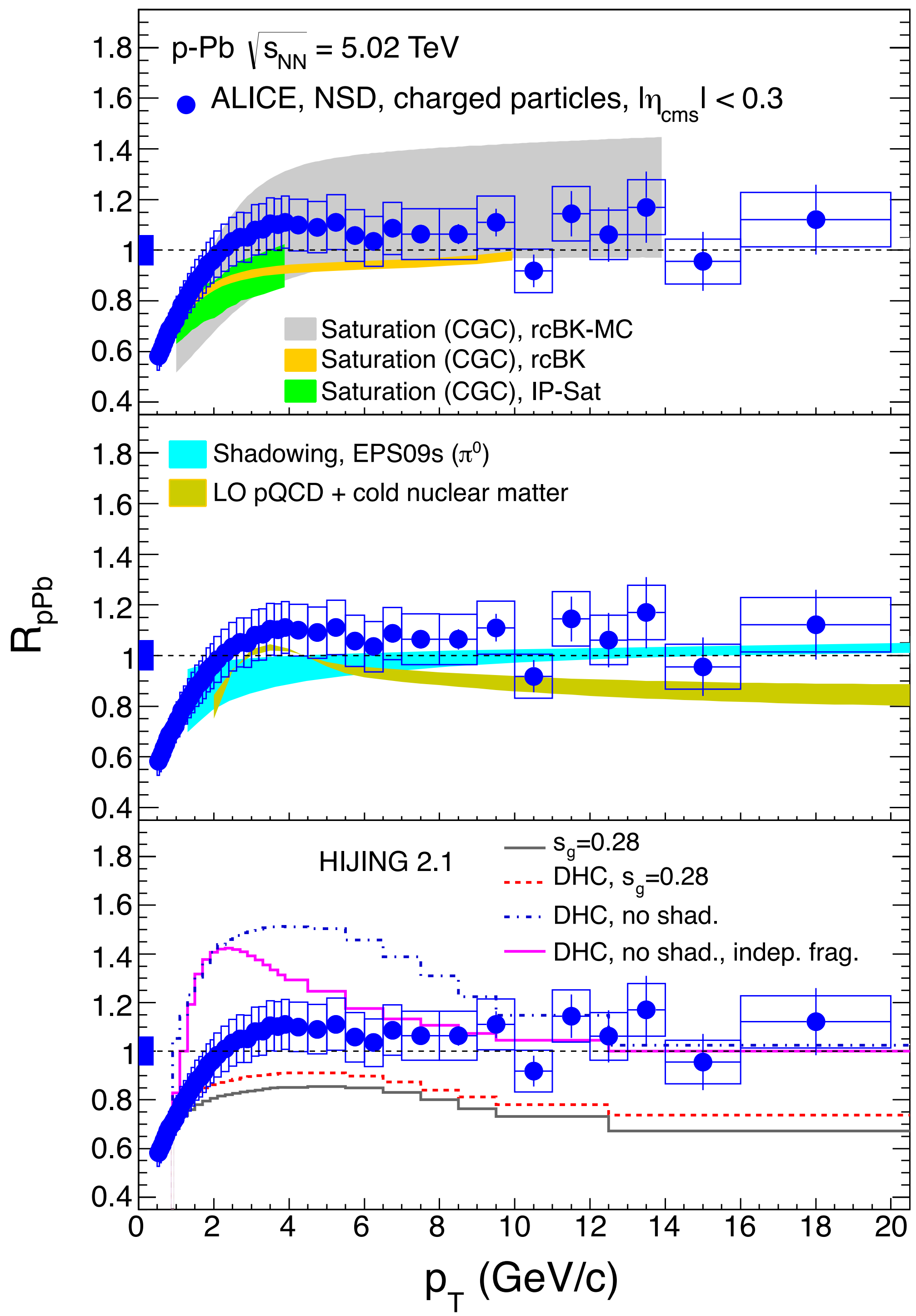
PHENIX, arXiv:1208.1234

$R_{dAu} > 1$ at intermediate p_T could be anti-shadowing; shadowing at higher p_T

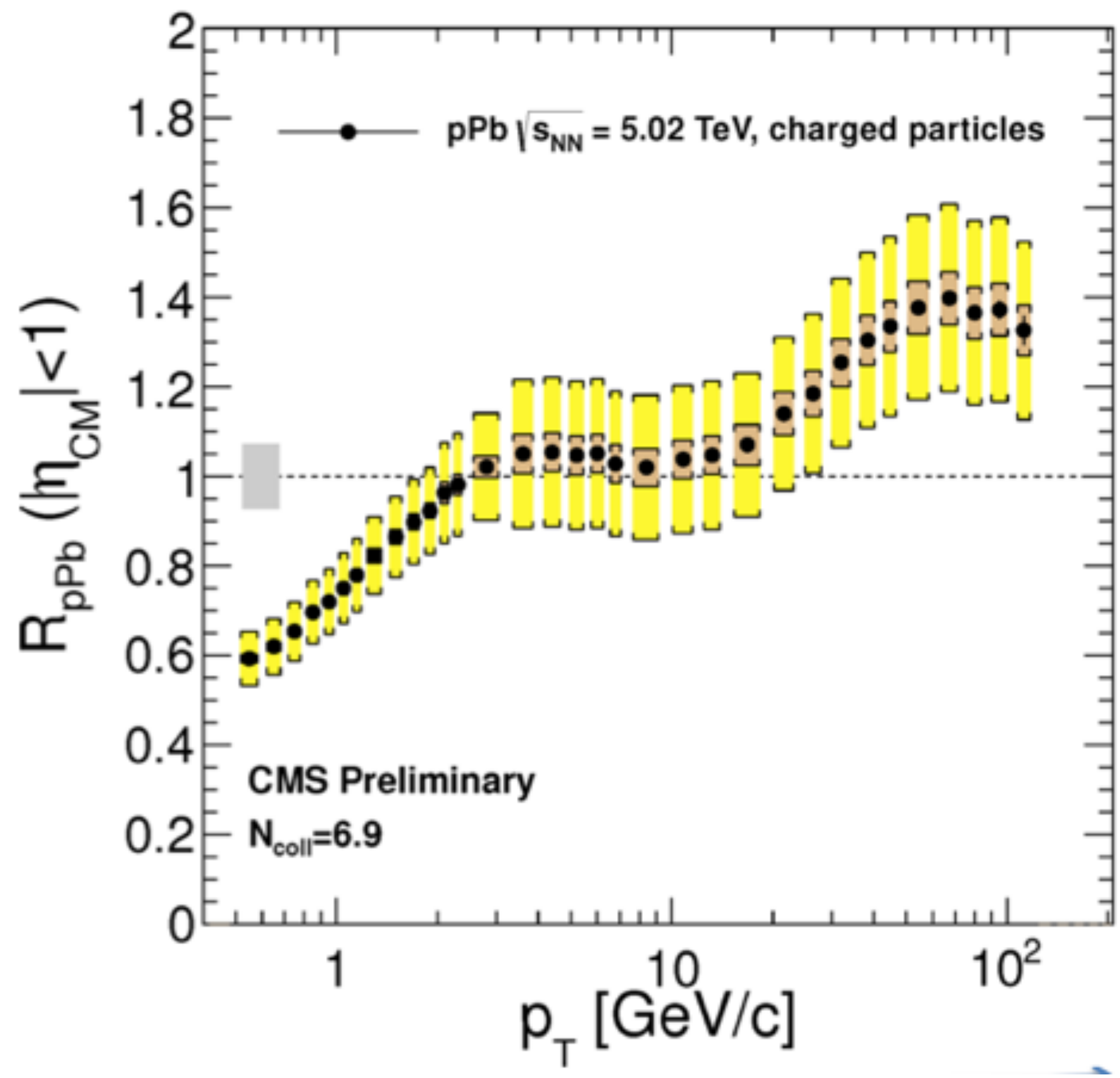
Photons: largest effect: isospin

Shadowing (EKS98) has only small impact at mid-rap, higher p_T

Hadron R_{pPb} at LHC



ALICE, arXiv:1210.4520



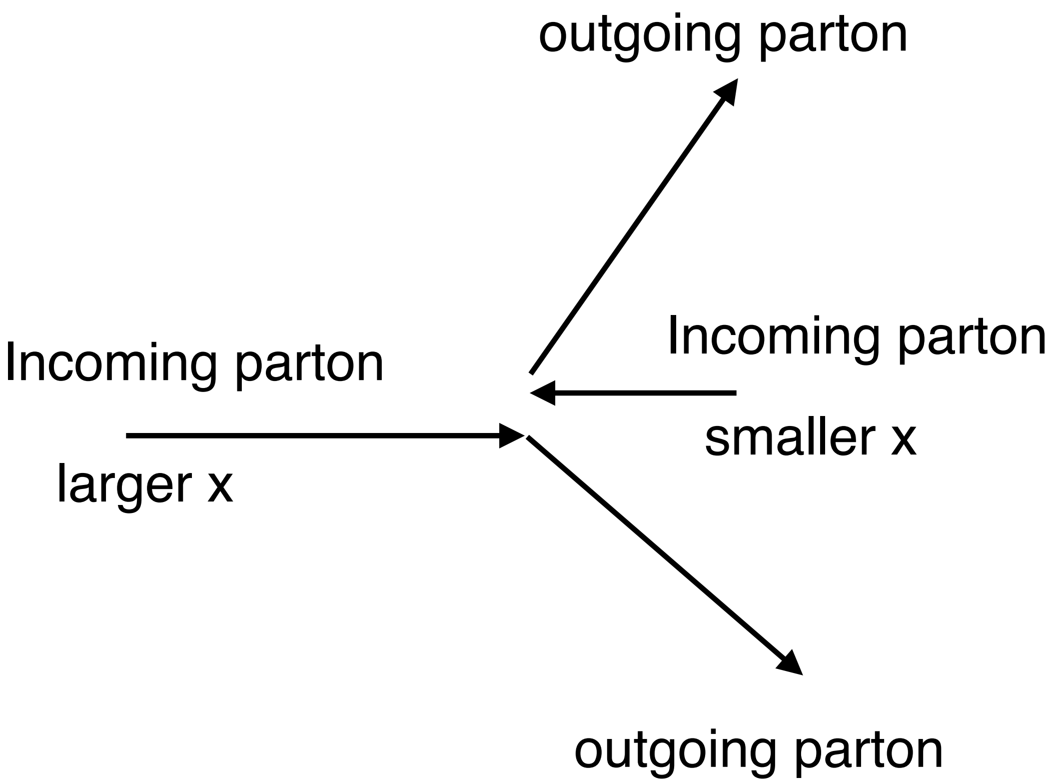
No nuclear modification in p+Pb for hadrons p_T >~ 3 GeV

Agrees with nuclear PDFs

CMS: enhancement at $p_T > 30$ GeV

No obvious physics interpretation…

Changing x-ranges in di-hadrons

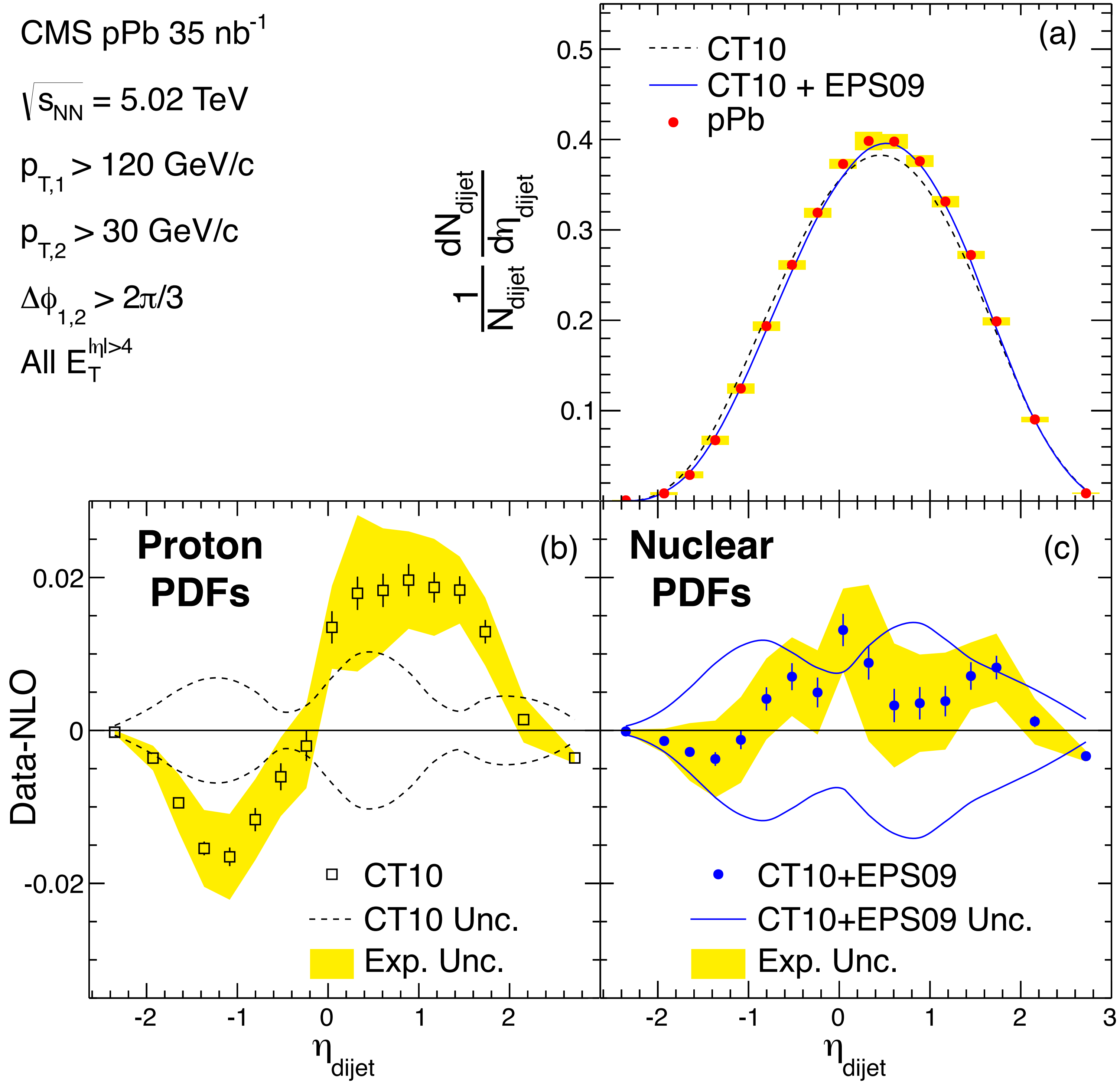


When both outgoing partons are at positive η,
asymmetric collision: large x + small x parton

η dependence of production in pp sensitive to x dependence of PDFs

Varying *x* in p+Pb: di-jets

$\eta_{dijet} = (\eta_1 + \eta_2)/2$

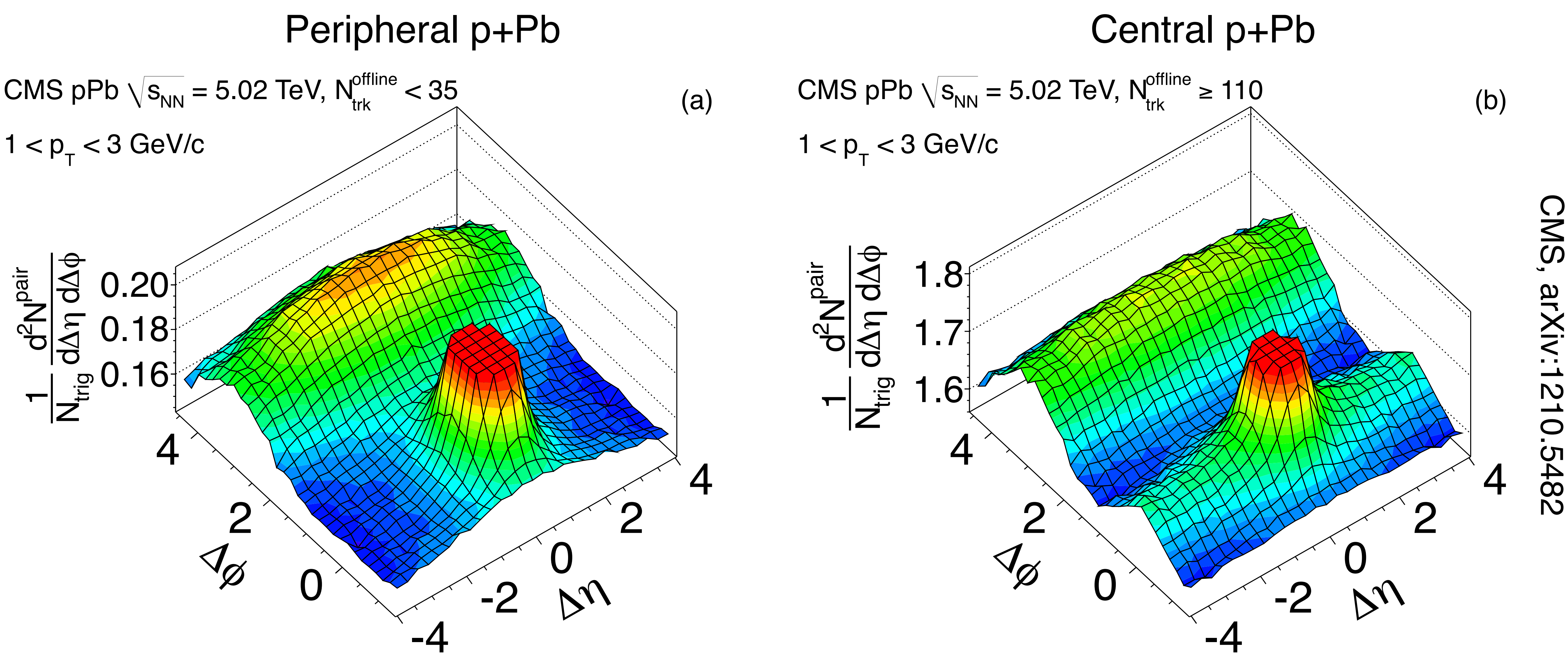


Distribution peaked at forward η: anti-shadowing

NB: asymmetric beam energies: mid-rapidity is at η~1

Di-hadrons in p+A

Ridge in p+Pb



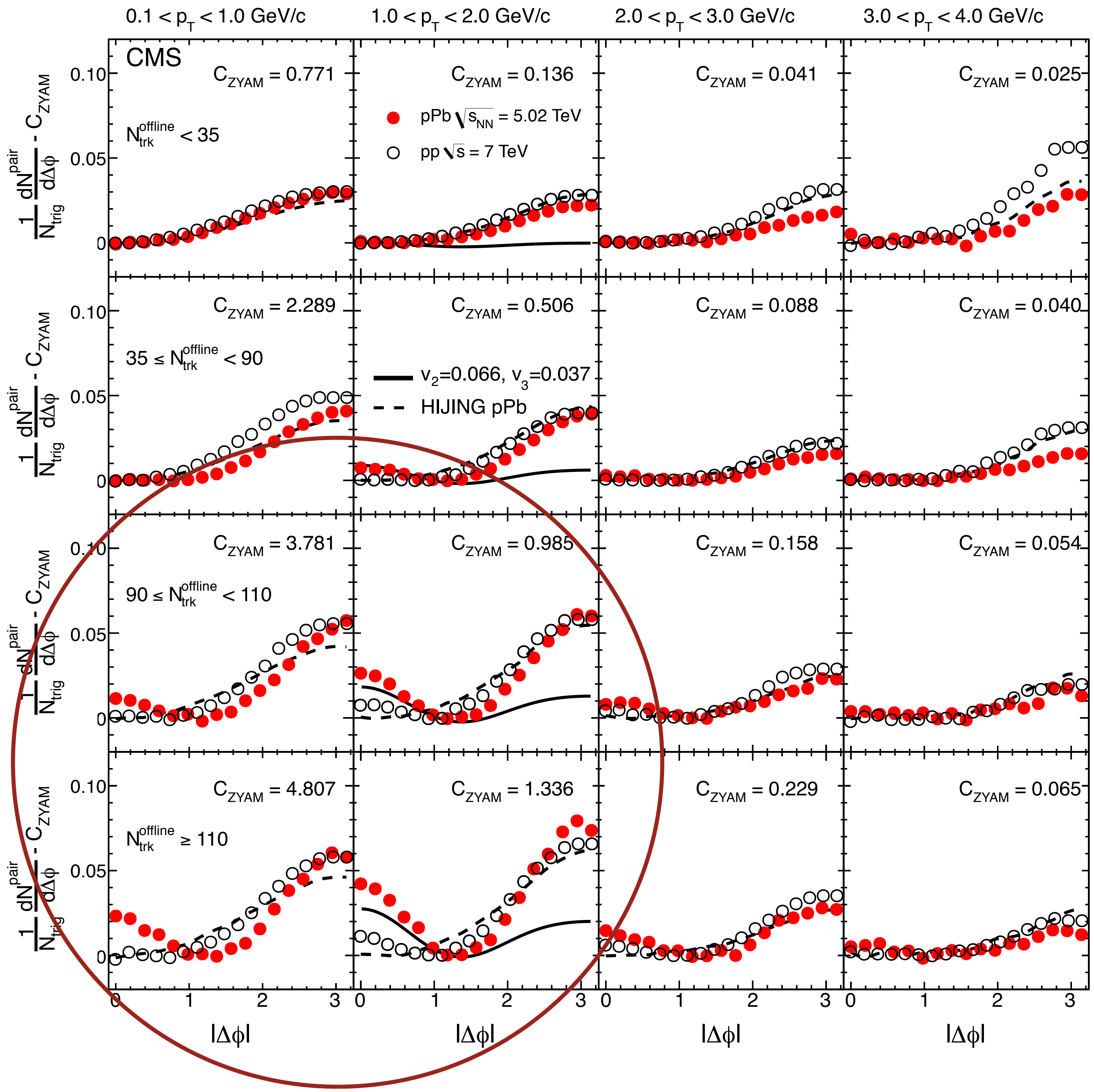
Near-side ridge visible in central p+Pb events

What is this?

A more quantitative look at the ridge

p_T

2 < Δη <4

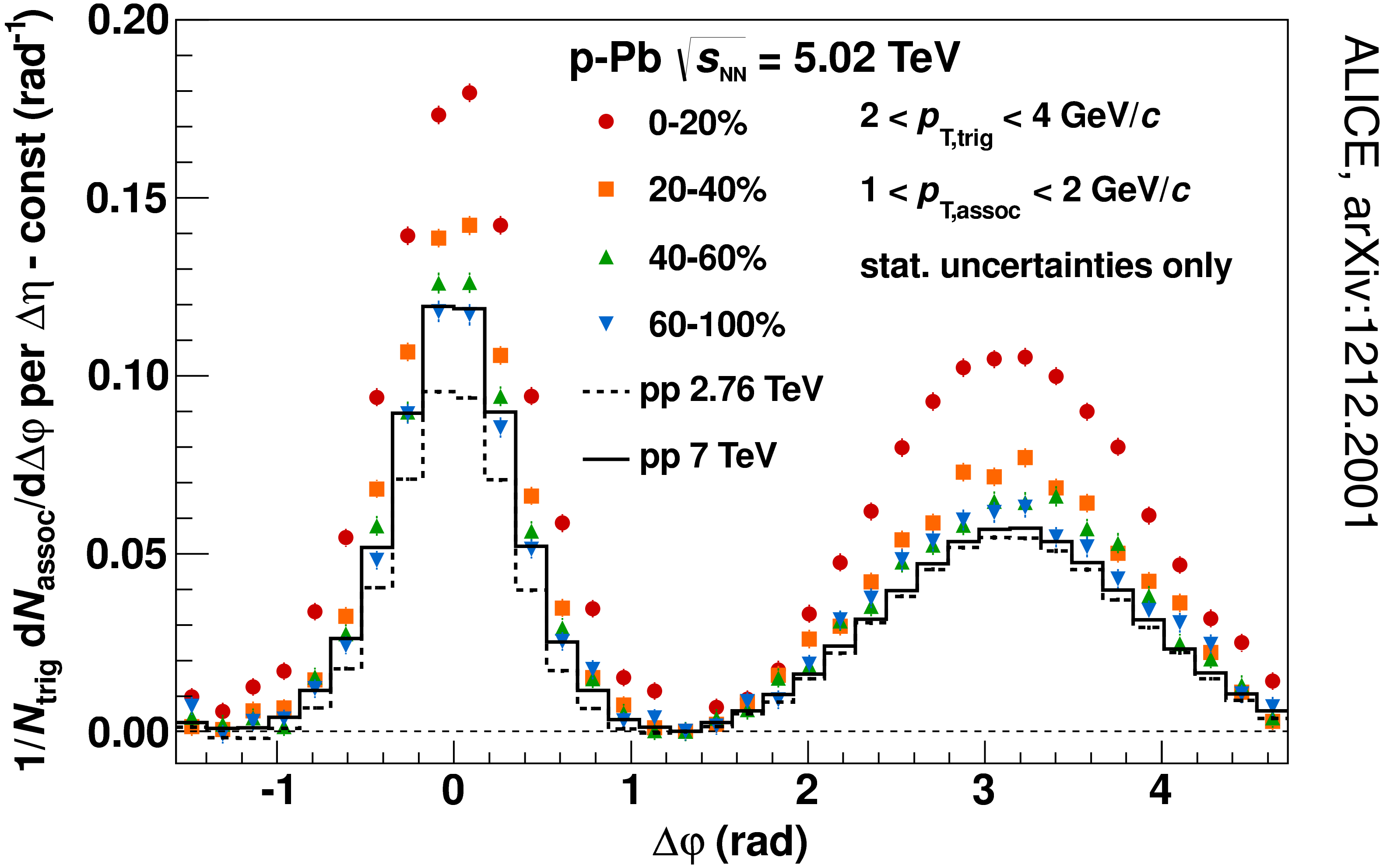


Centrality/multiplicity

Effect largest at low p_T, high multiplicity

Fourier coefficient $v_2 \sim 0.066$

Is there an away-side ridge?

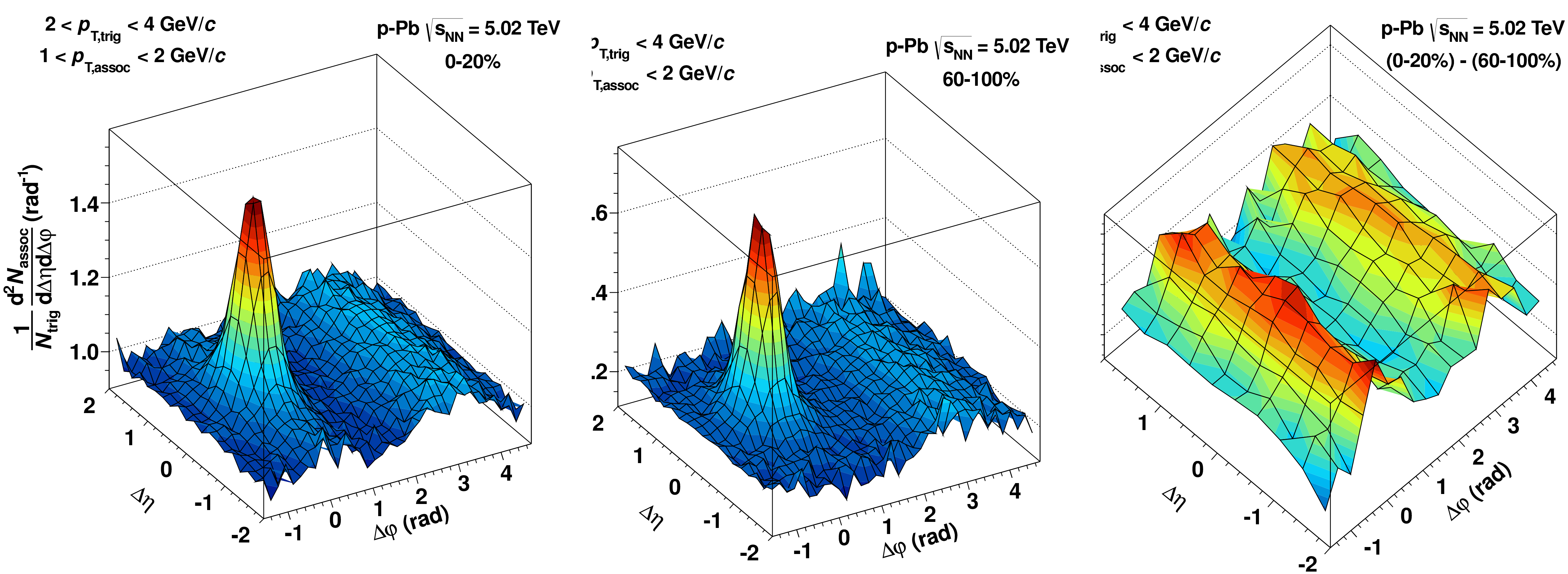


Away-side yield also increases with centrality

Not expected for di-jets, excess yield could be a ridge-effect

Extracting the double-ridge/flow

Central - Peripheral = Double ridge



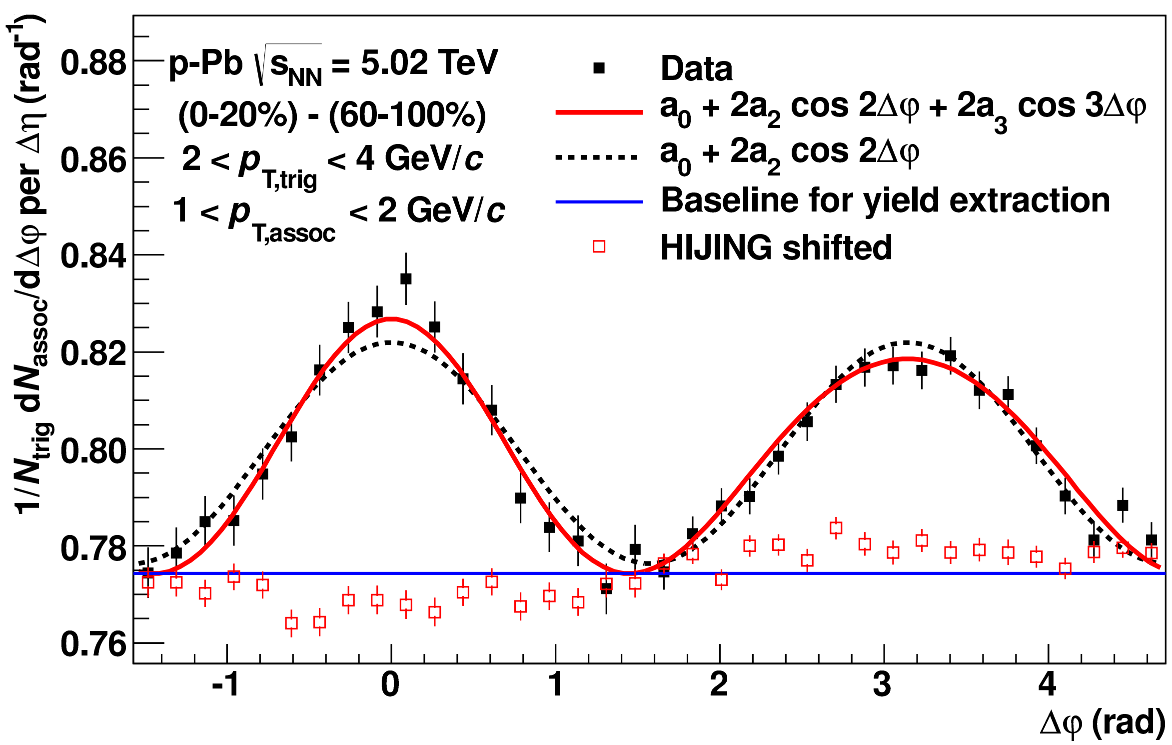
ALICE, arXiv:1212.2001

Hypothesis: associated jet yields (recoil) are the same in central and peripheral p+Pb

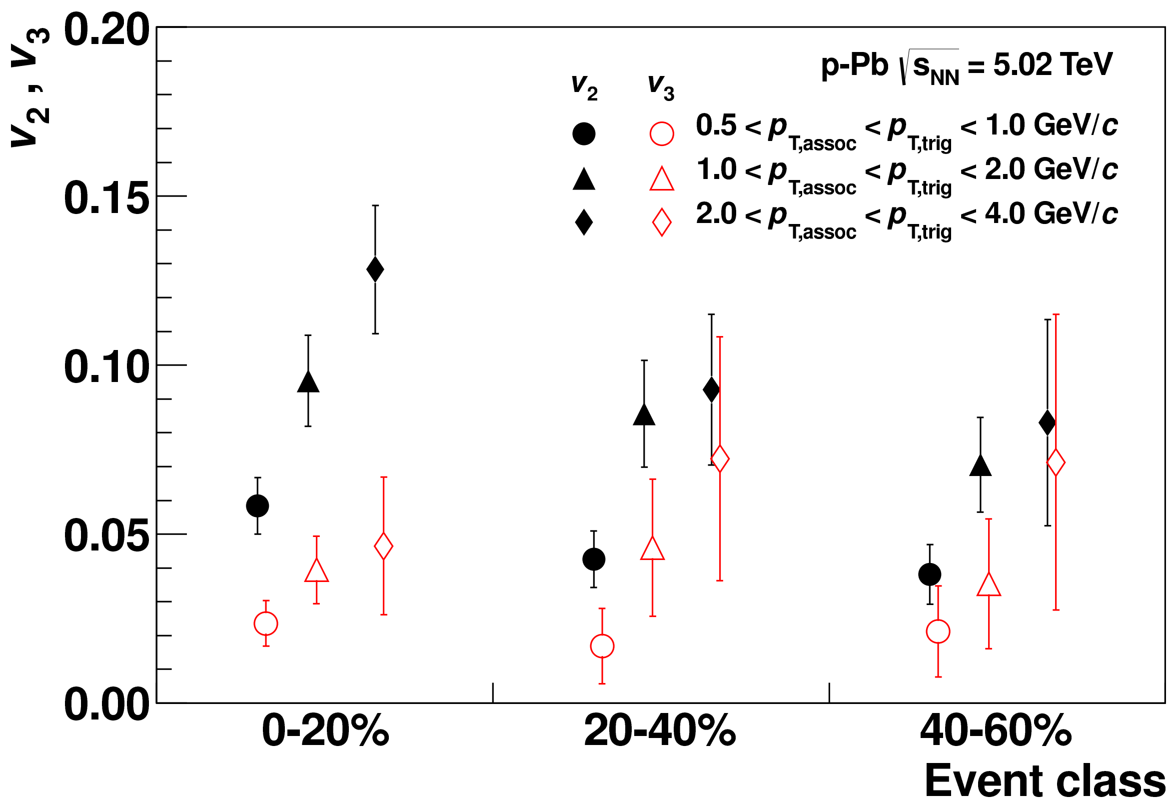
Use peripheral to subtract jet contribution from central

Result: 'v₂' in p+Pb

Example $\Delta\varphi$ projection



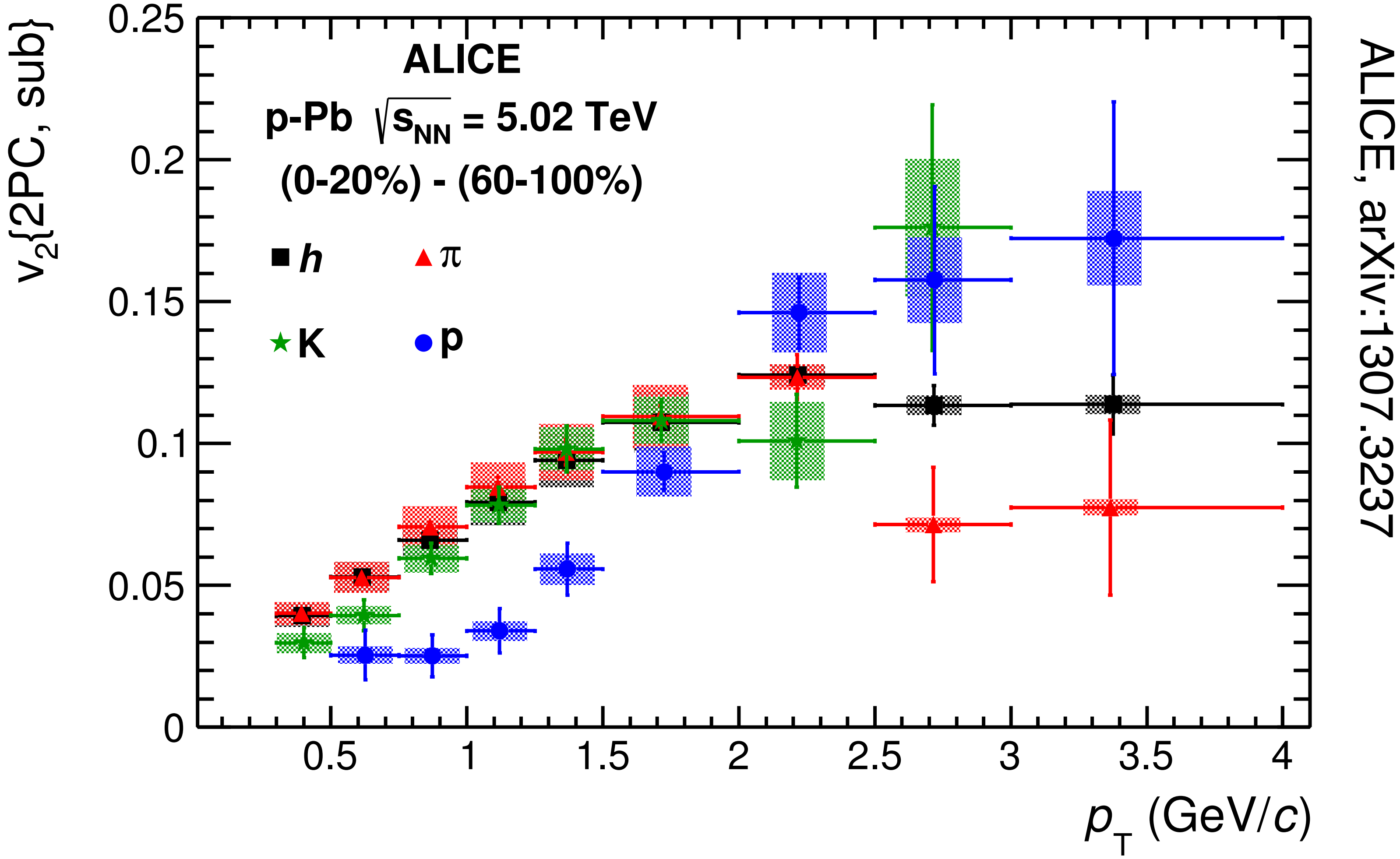
It's really symmetric in $\Delta\varphi$



v_2 values: increase with p_T (as for PbPb) and centrality

Mass dependence of double ridge

Same procedure: subtract peripheral from central and fit Δϕ distribution



Different p_T dependence for protons and light hadrons, suggestive of flow (common velocity)

Summary

- Intermediate p_T (2-6 GeV) in A+A
  - Baryon enhancement in single particle spectra (radial flow and/or coalescence)
  - Di-hadrons: interplay between flow and jets
  - Di-hadrons: no baryon enhancement in associated particle production
- p+Pb
  - Nuclear effects in PDFs: shadowing at low x, anti-shadowing
  - Nuclear effects at mid-rapidity at LHC are small (R_{pPb}; puzzling result from CMS)
  - Probe x-dependence by η-dependence: asymmetry in di-jets due to (anti-)shadowing
  - Di-hadrons: double ridge. Can it be flow?

Extra slides

Integrated vs differential

- Inclusive hadron suppression R_{AA}
  - Overall magnitude + p_T dependence: limited dynamical information
  - Only useful when the energy loss mechanism is understood
- Di-hadrons; I_{AA}
  - Two 'degrees of freedom'
  - Adds constraints when compared to R_{AA}; mostly geometry?
- Low p_T, shape info
  - More differential, but also more difficult to model