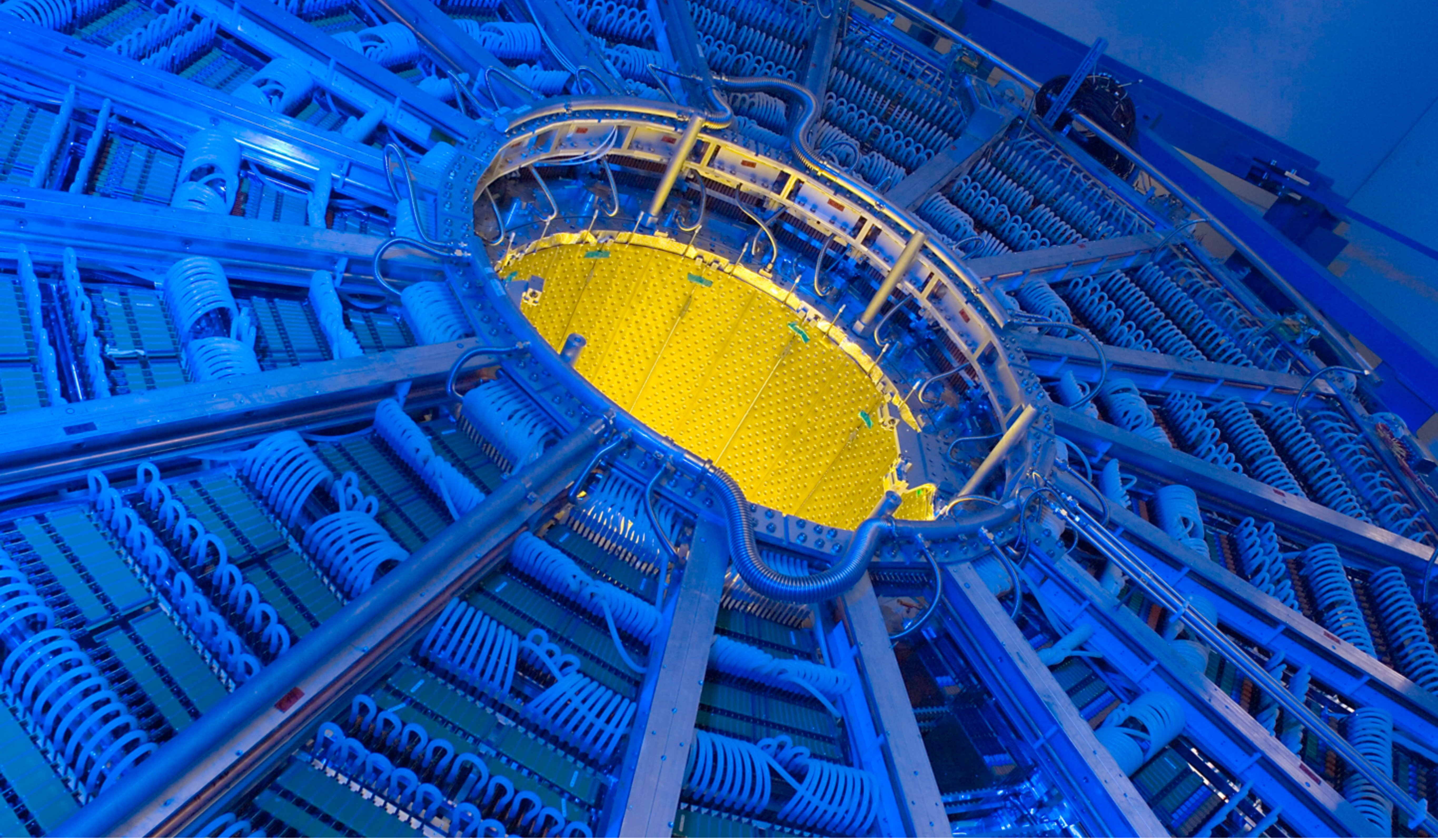


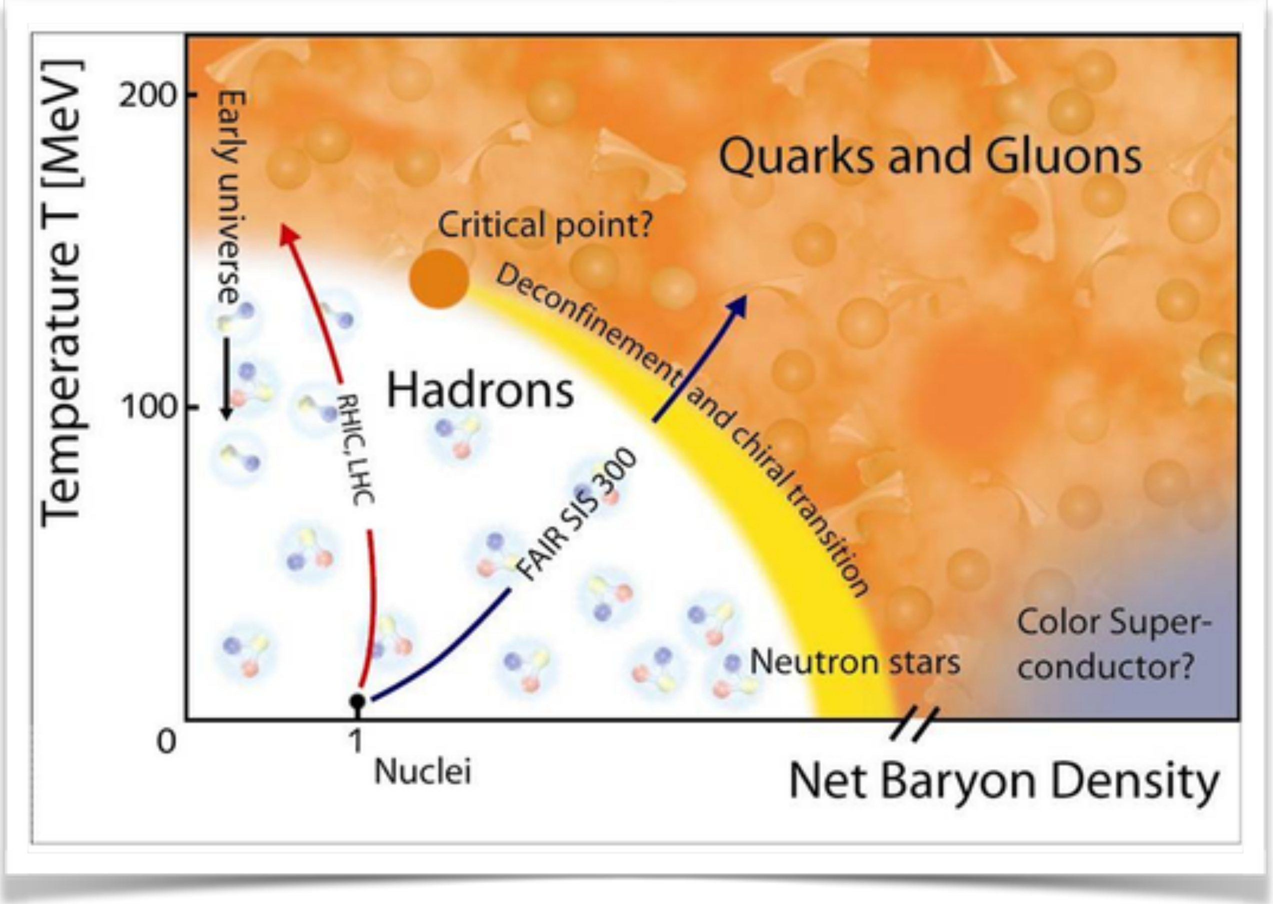
Two-particle correlation measurements in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Michele Floris (CERN)
for the ALICE Collaboration

MPI@LHC 2015

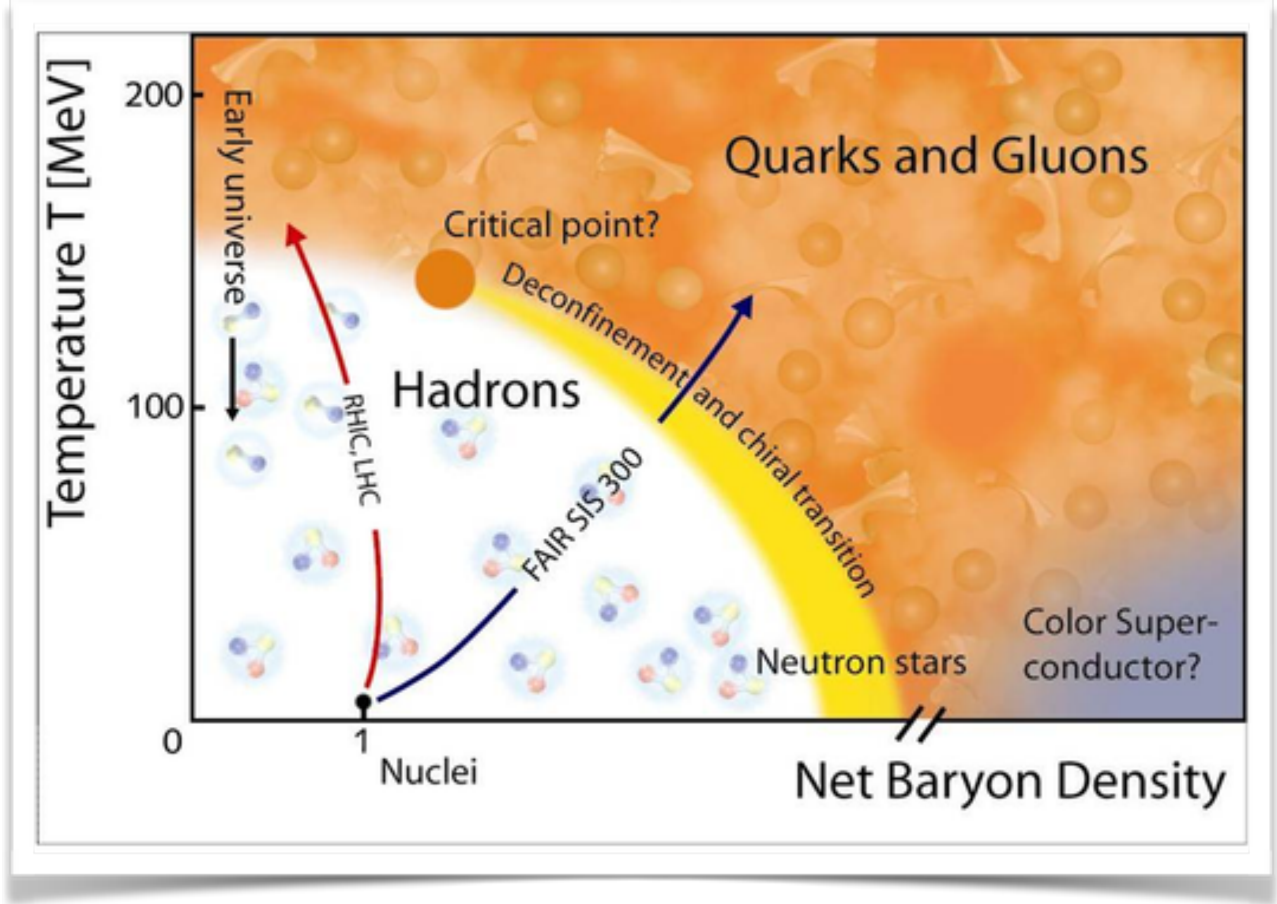
Setting the stage: Collectivity in AA

- **Working hypothesis**: a **thermalized** (and deconfined) **medium** is created in AA collisions
- It **expands and cools** down under the effect of pressure gradients

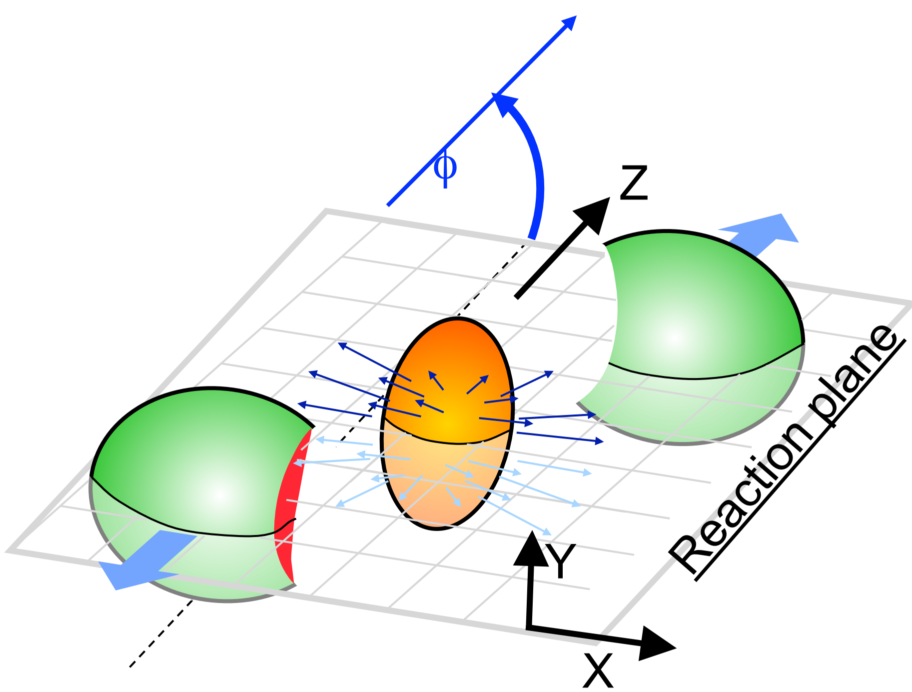


Setting the stage: Collectivity in AA

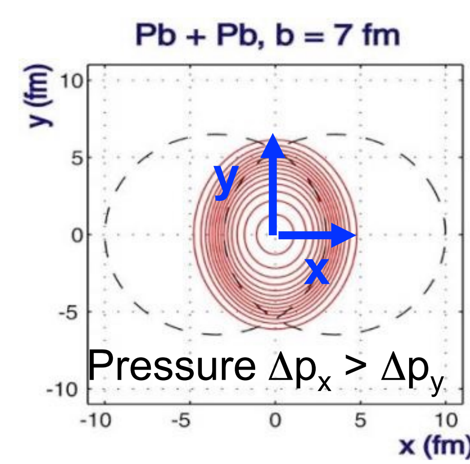
- **Working hypothesis**: a **thermalized** (and deconfined) **medium** is created in AA collisions
- It **expands and cools** down under the effect of pressure gradients
- Leads to **asymmetry in momentum space**
- **Anisotropic flow:** can be studied with **2-particle** correlations



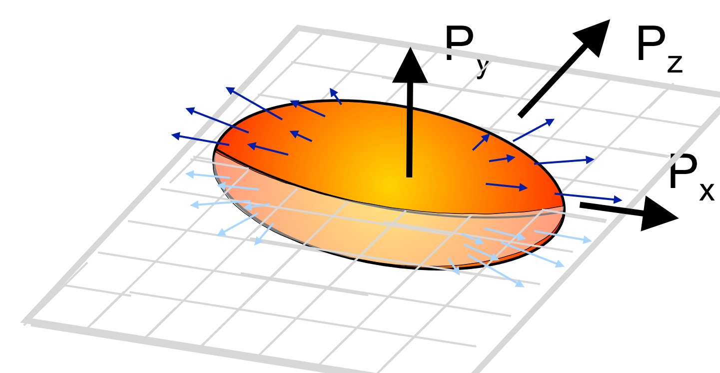
Spatial deformation



Azimuthal (ϕ) pressure gradients

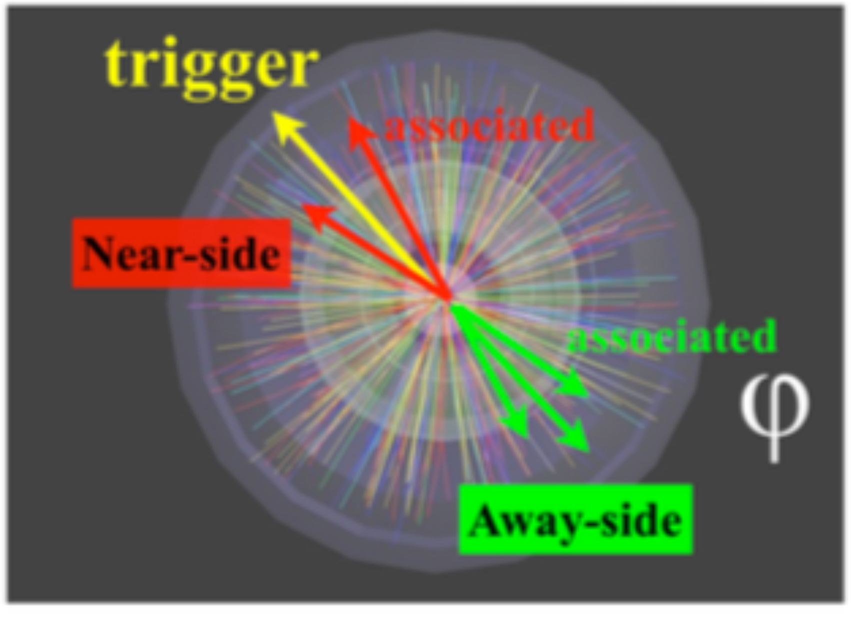


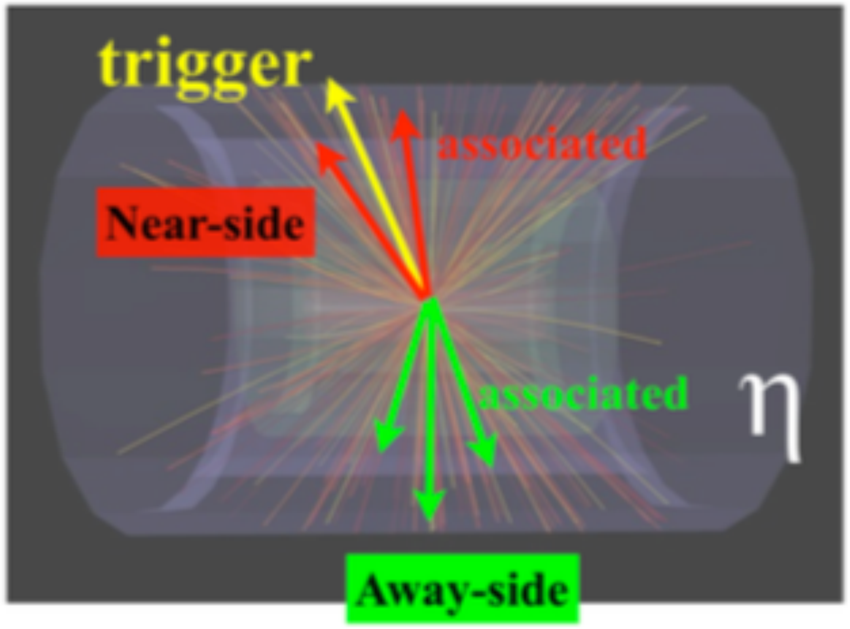
Anisotropic particle density

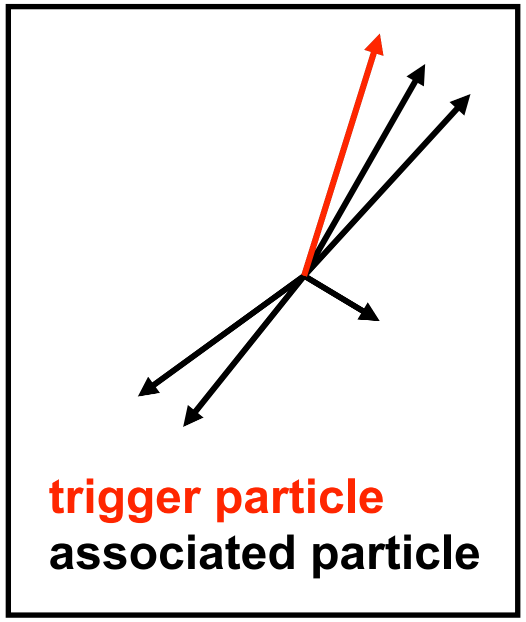


$$\frac{dN}{d\varphi} \propto 1 + 2v_1\cos[\varphi - \Psi_1] + 2v_2\cos[2(\varphi - \Psi_2)] + 2v_3\cos[3(\varphi - \Psi_3)] + \ldots$$

Abridged anatomy of 2PC

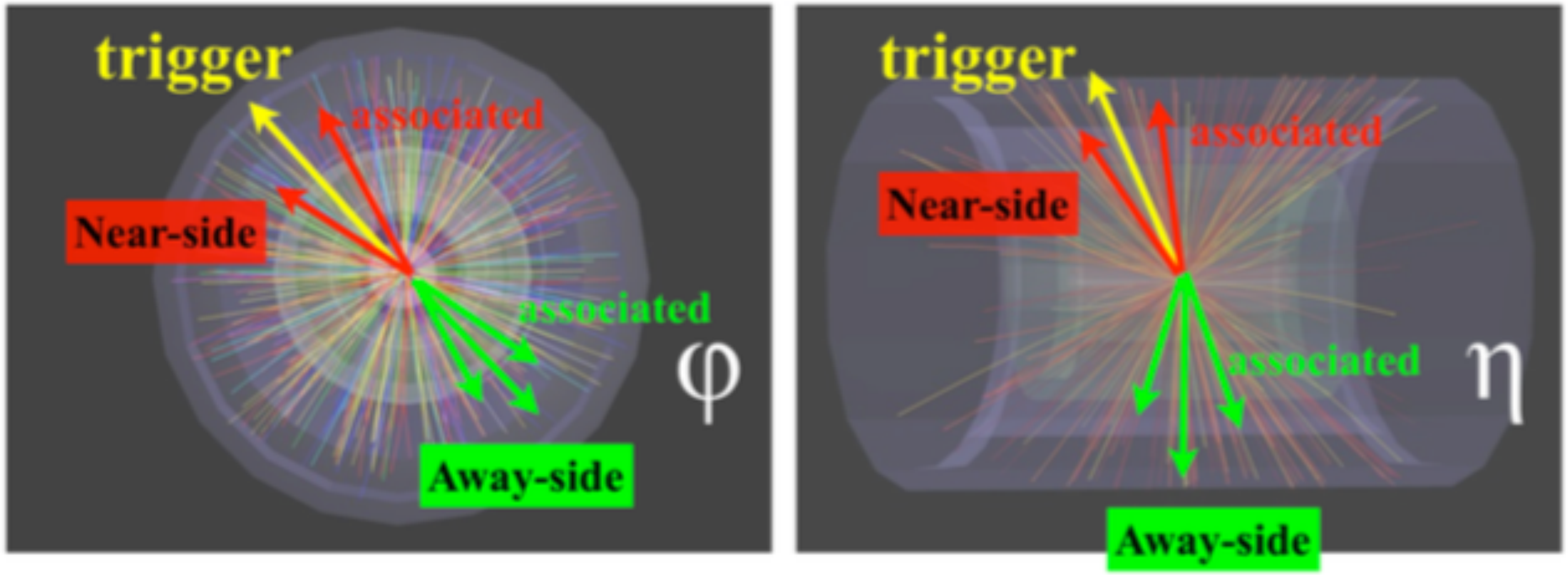


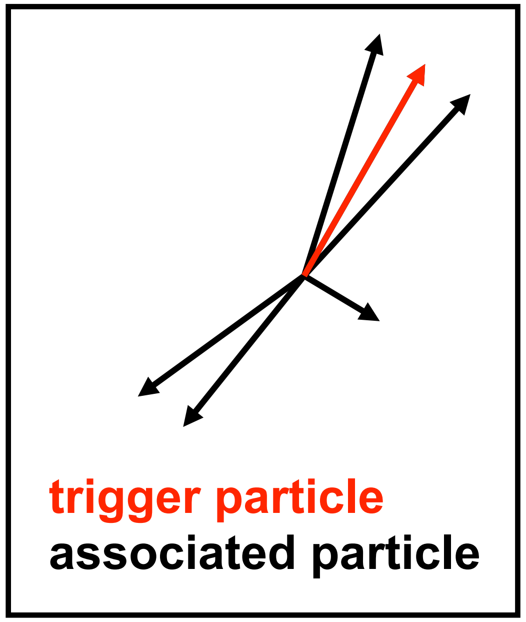




CMS, JHEP, 2010 (9) 091

Abridged anatomy of 2PC





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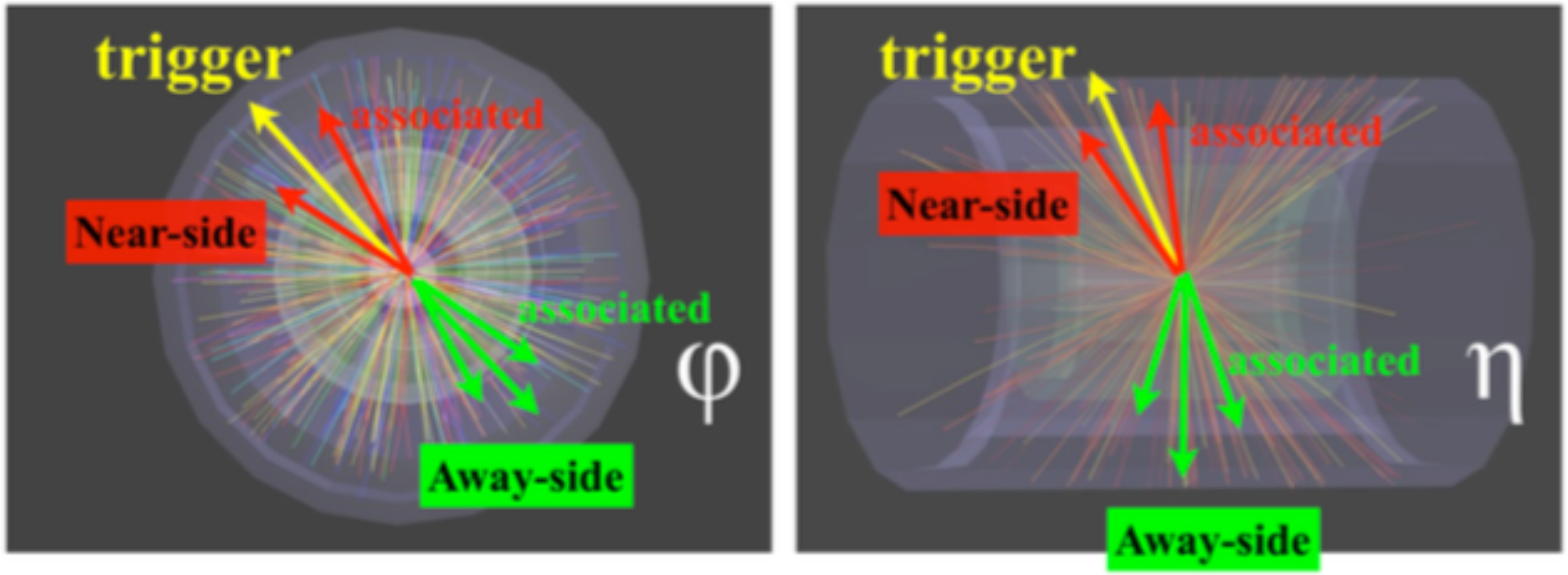

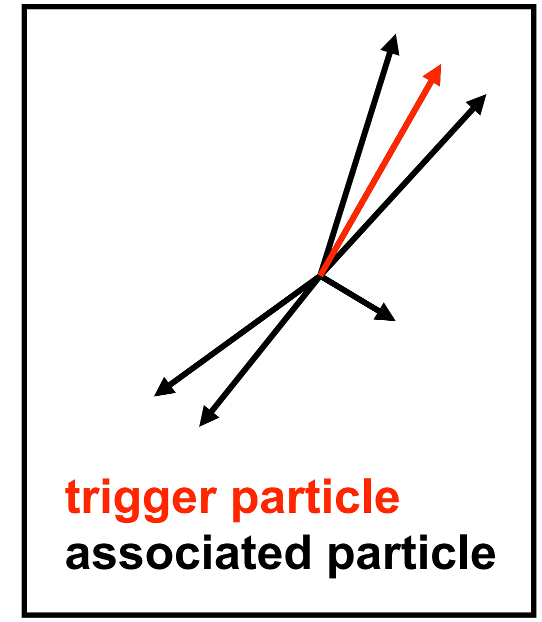

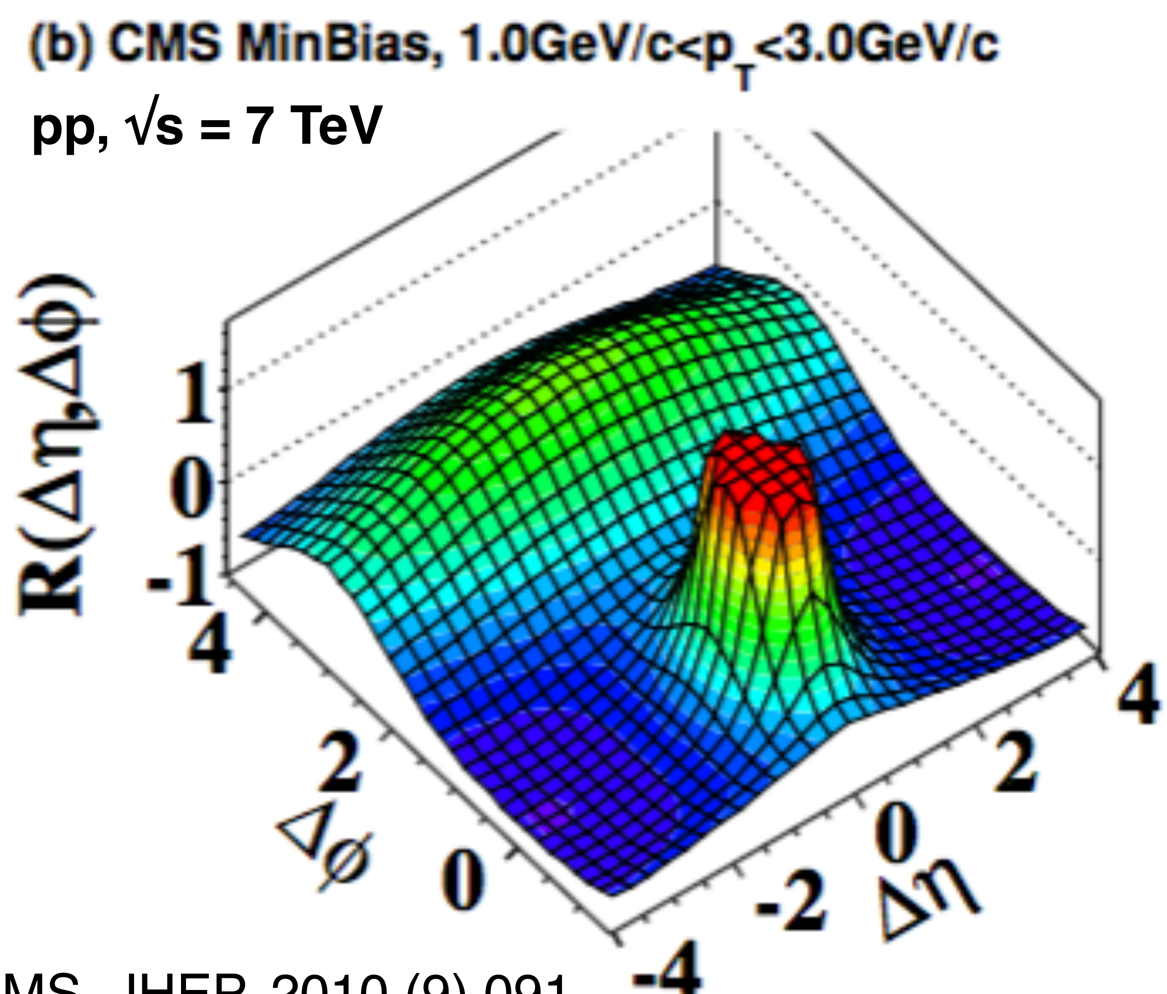

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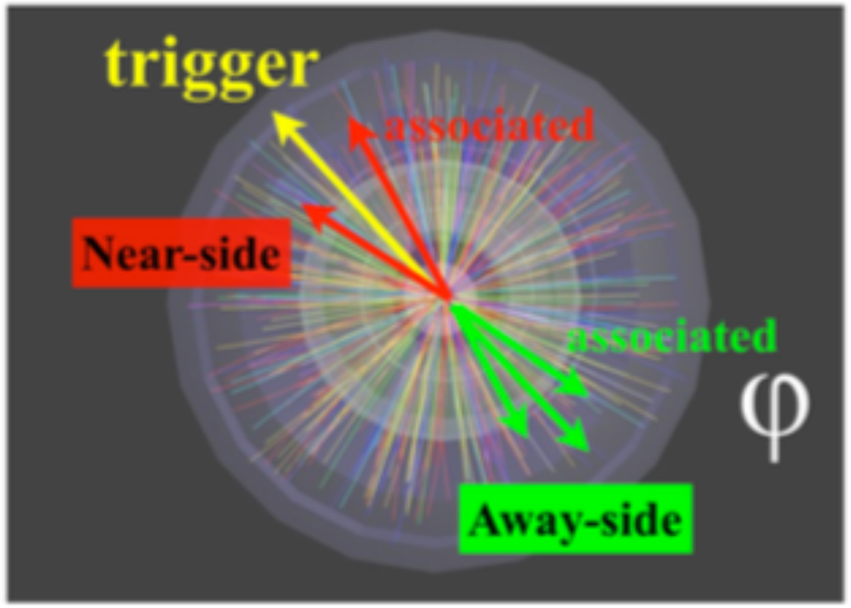
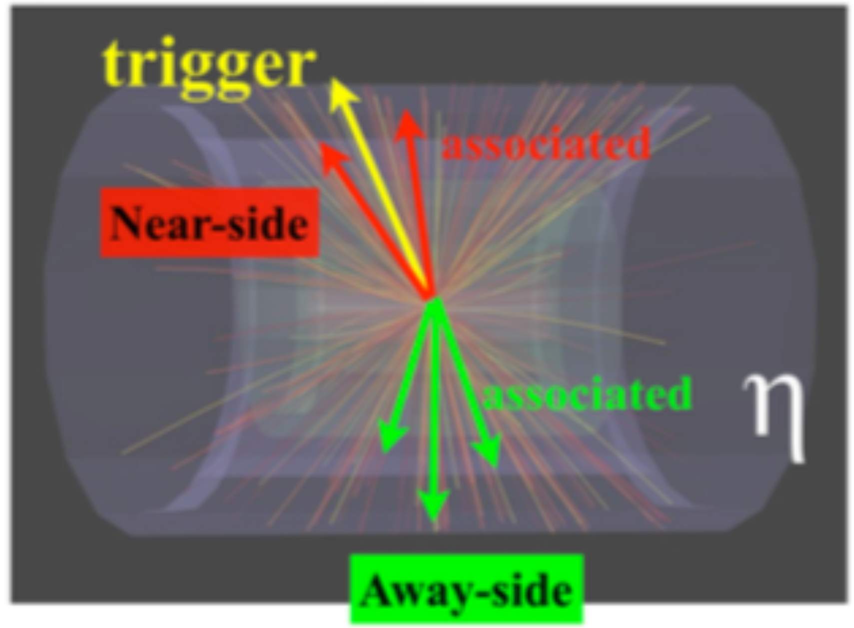
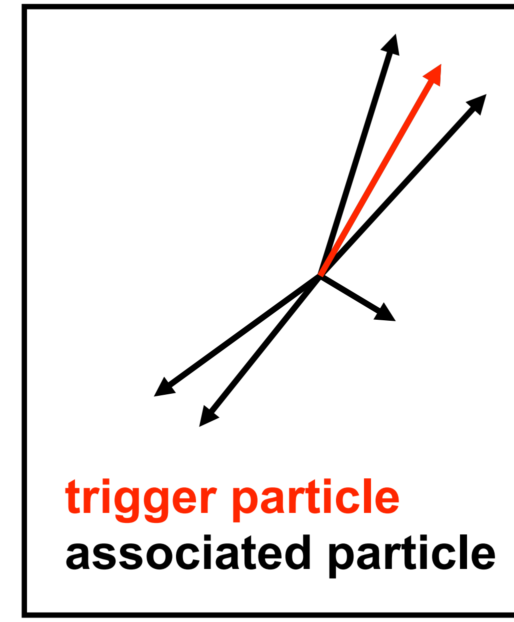
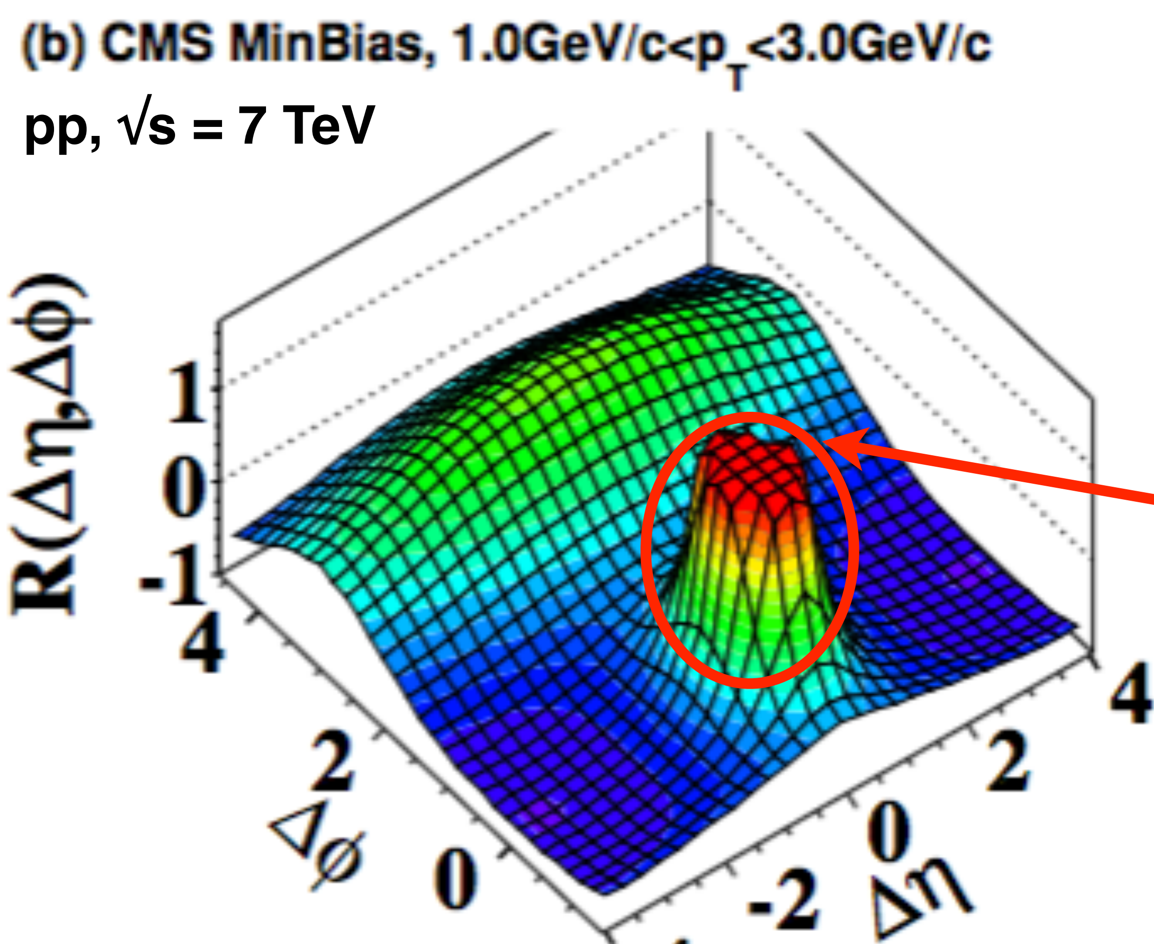




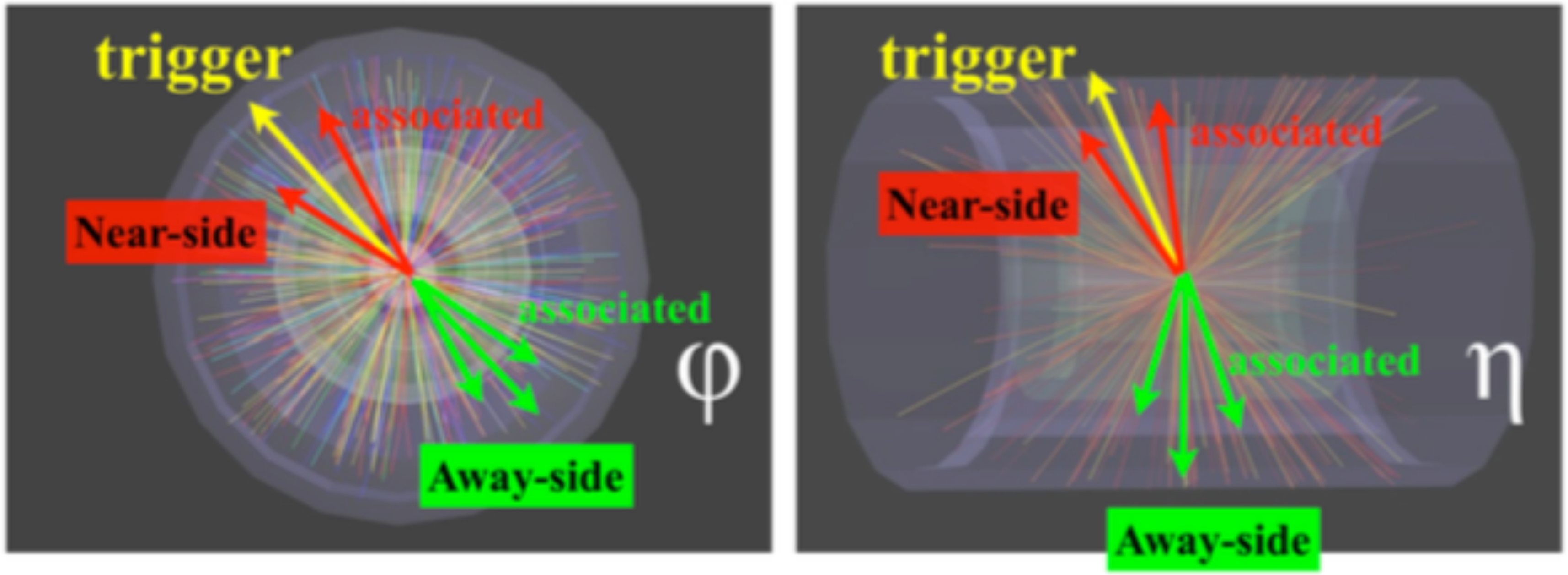


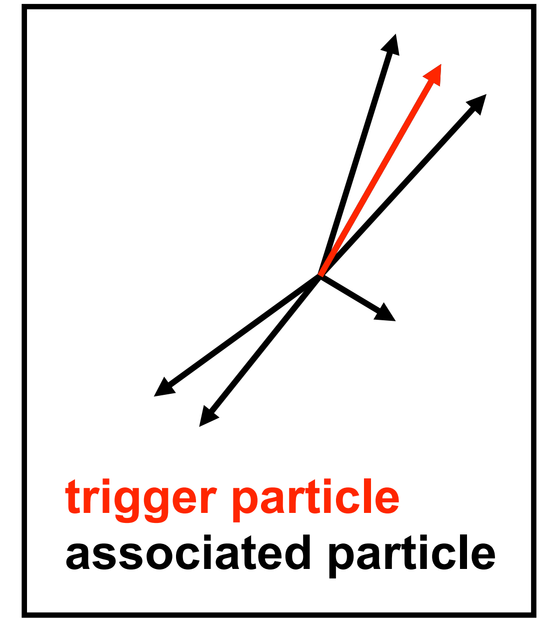


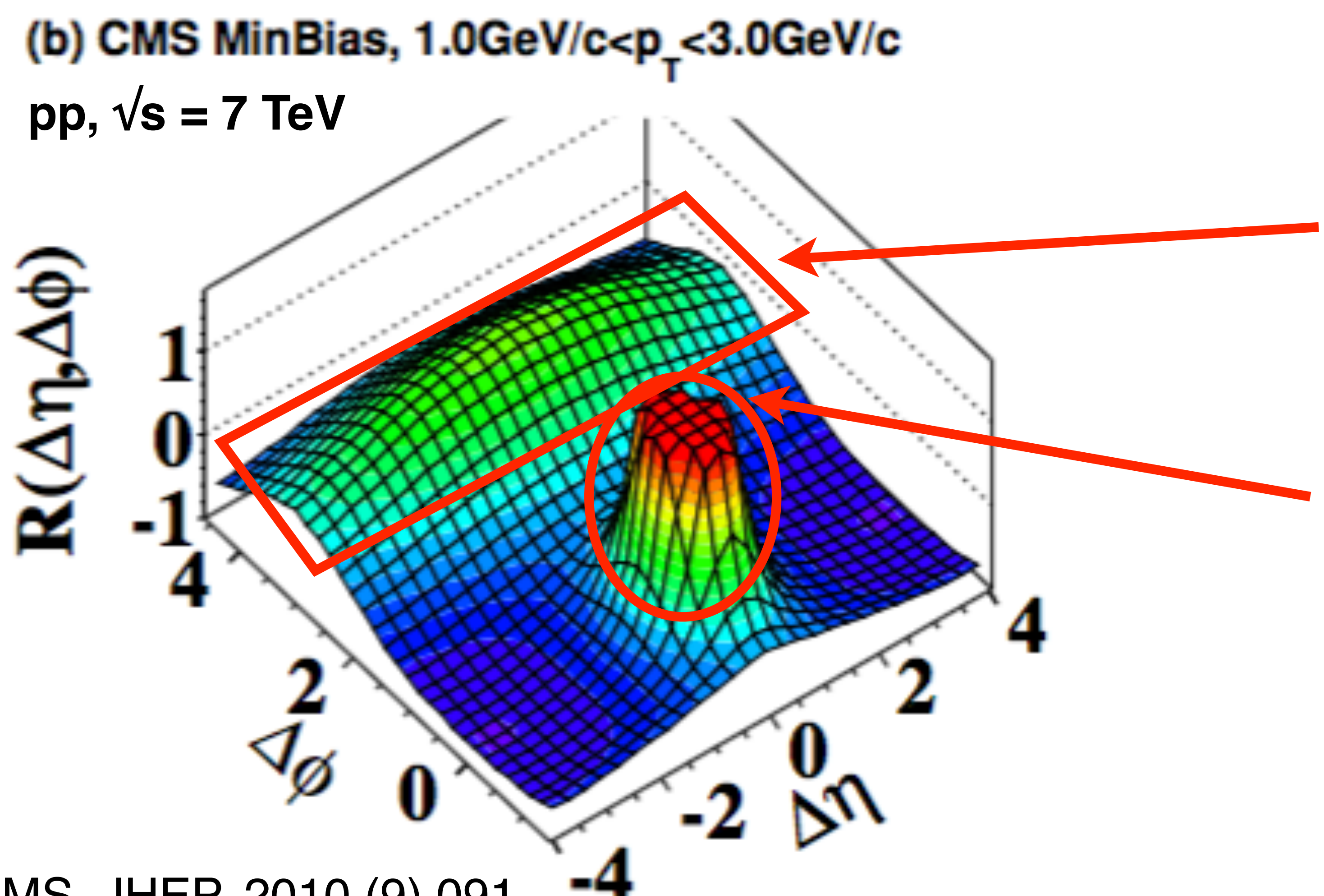
Near-side jet
($\Delta\phi \sim 0$, $\Delta\eta \sim 0$)

CMS, JHEP, 2010 (9) 091

Abridged anatomy of 2PC





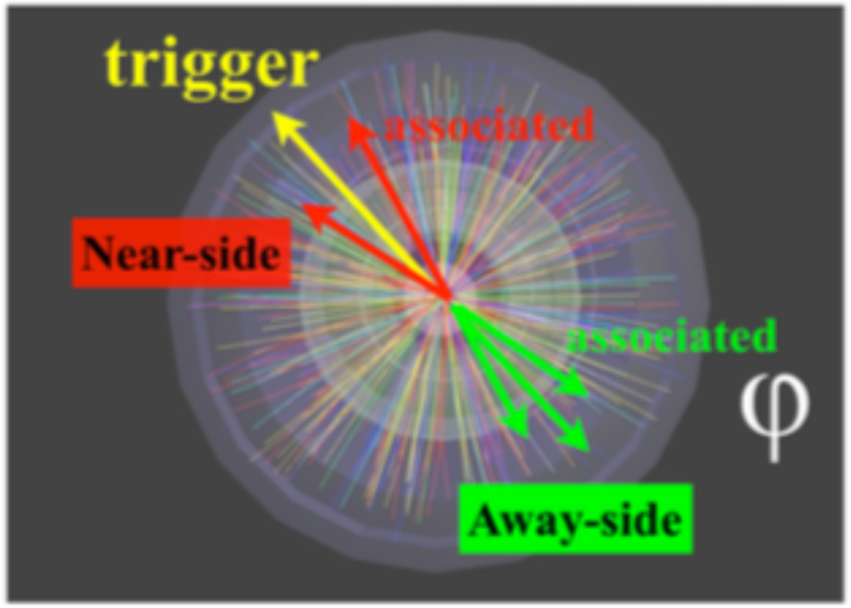


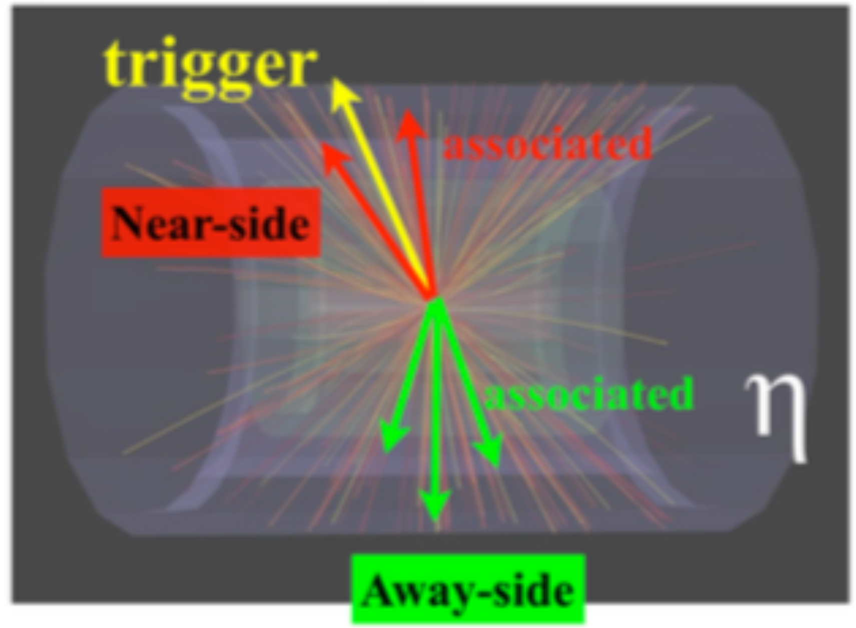
Recoil (away-side) jet
(Δϕ ~ π, elongated in Δη)

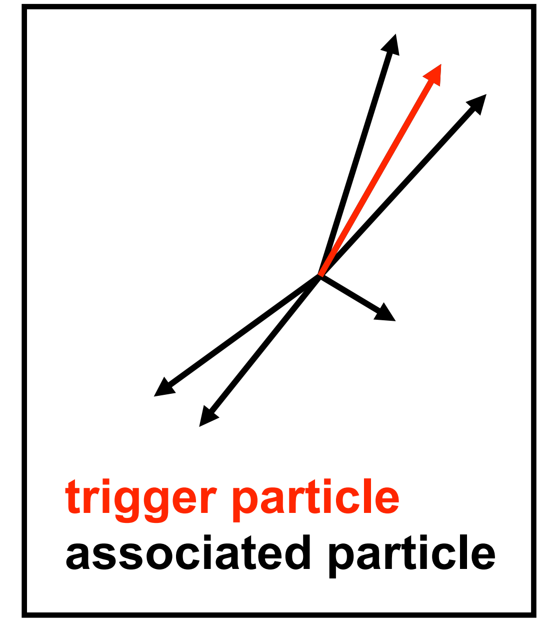
Near-side jet
(Δϕ ~ 0, Δη ~ 0)

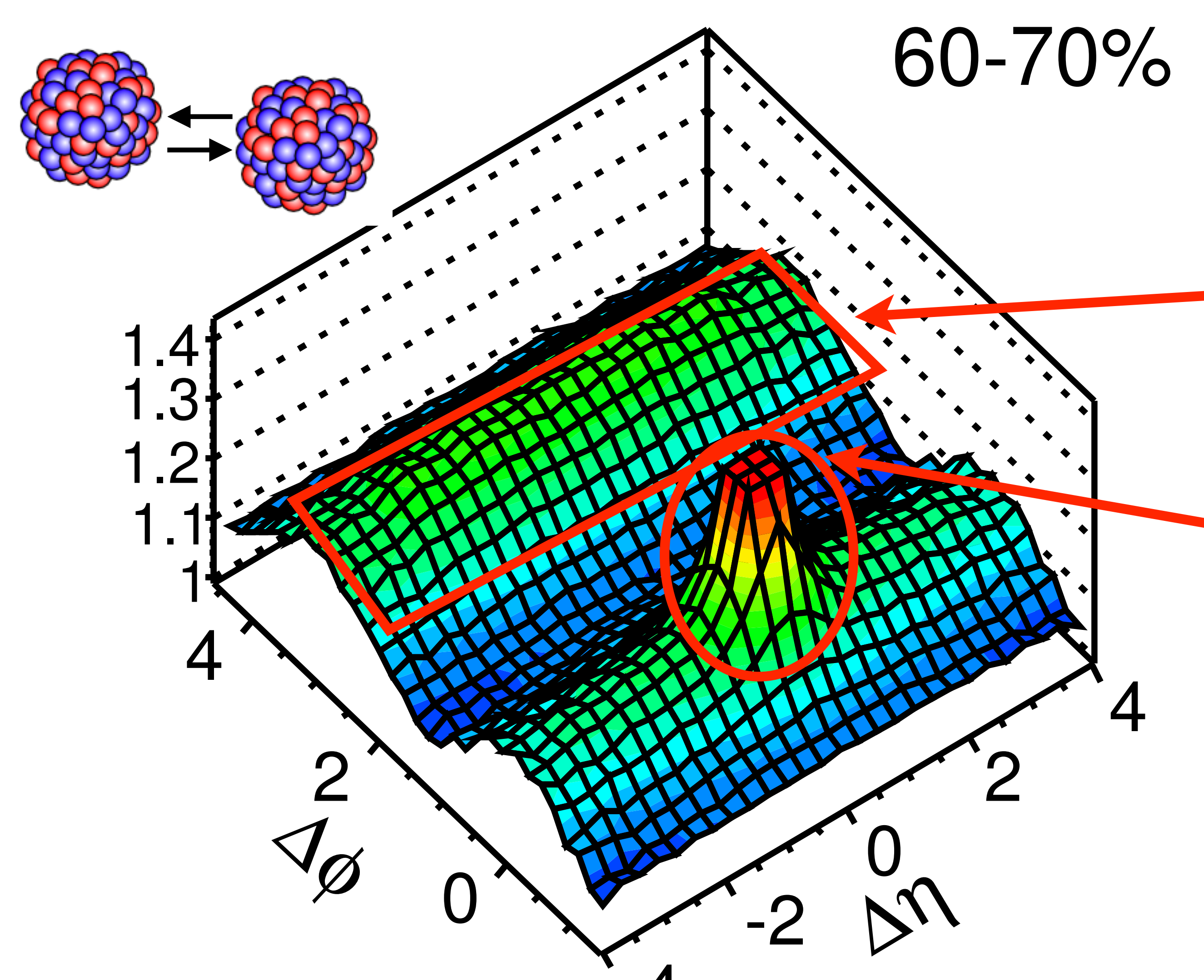
CMS, JHEP, 2010 (9) 091

Abridged anatomy of 2PC









CMS, EPJC 72 (2012) 2012

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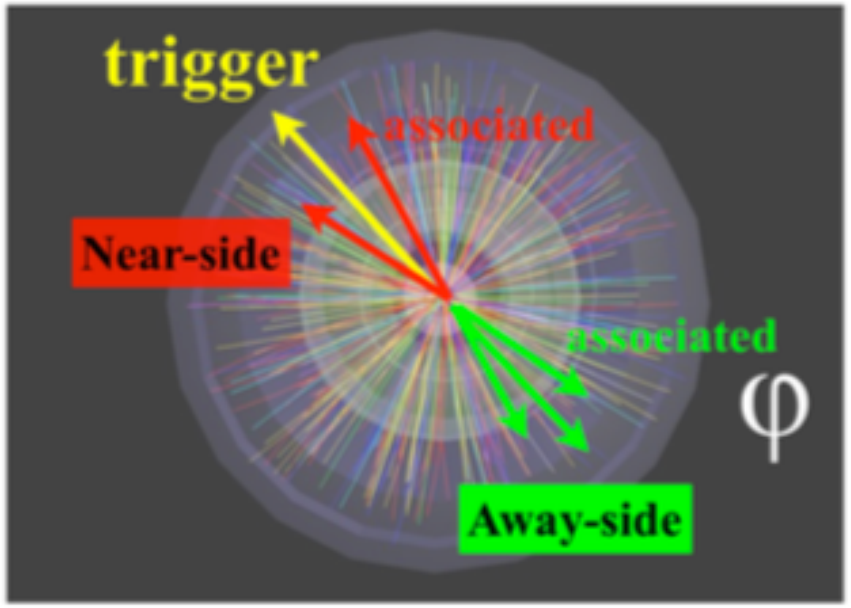
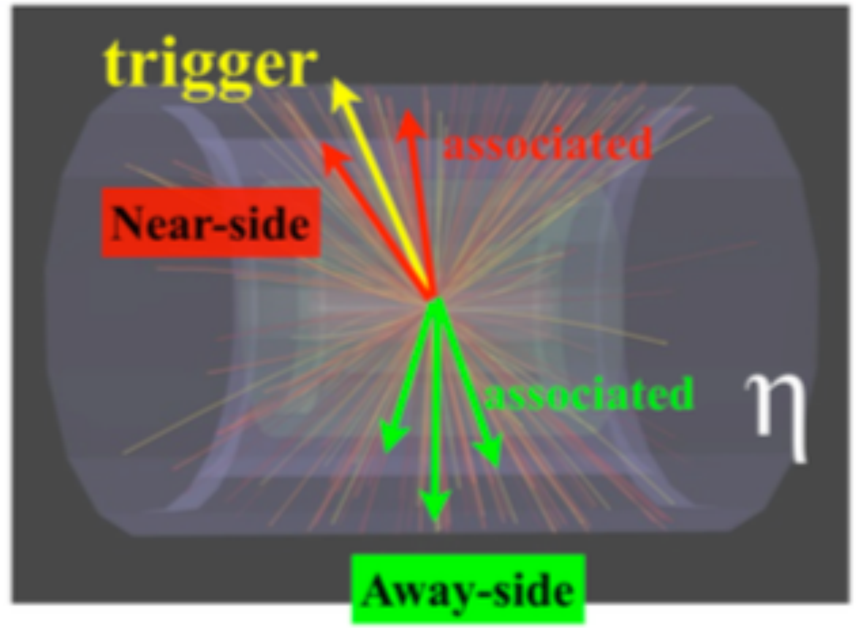
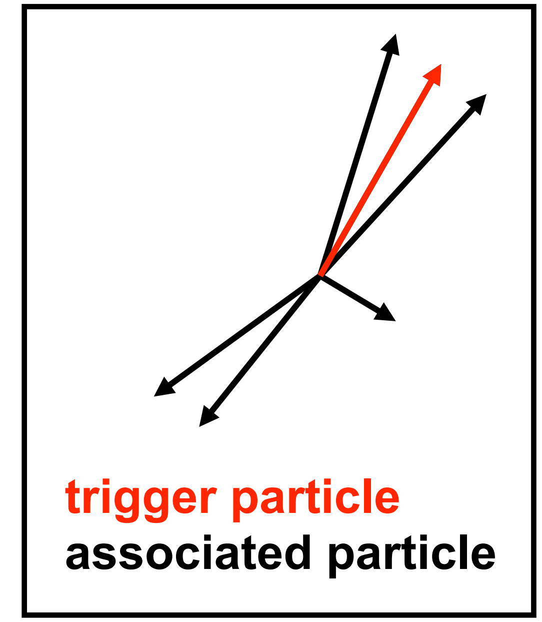
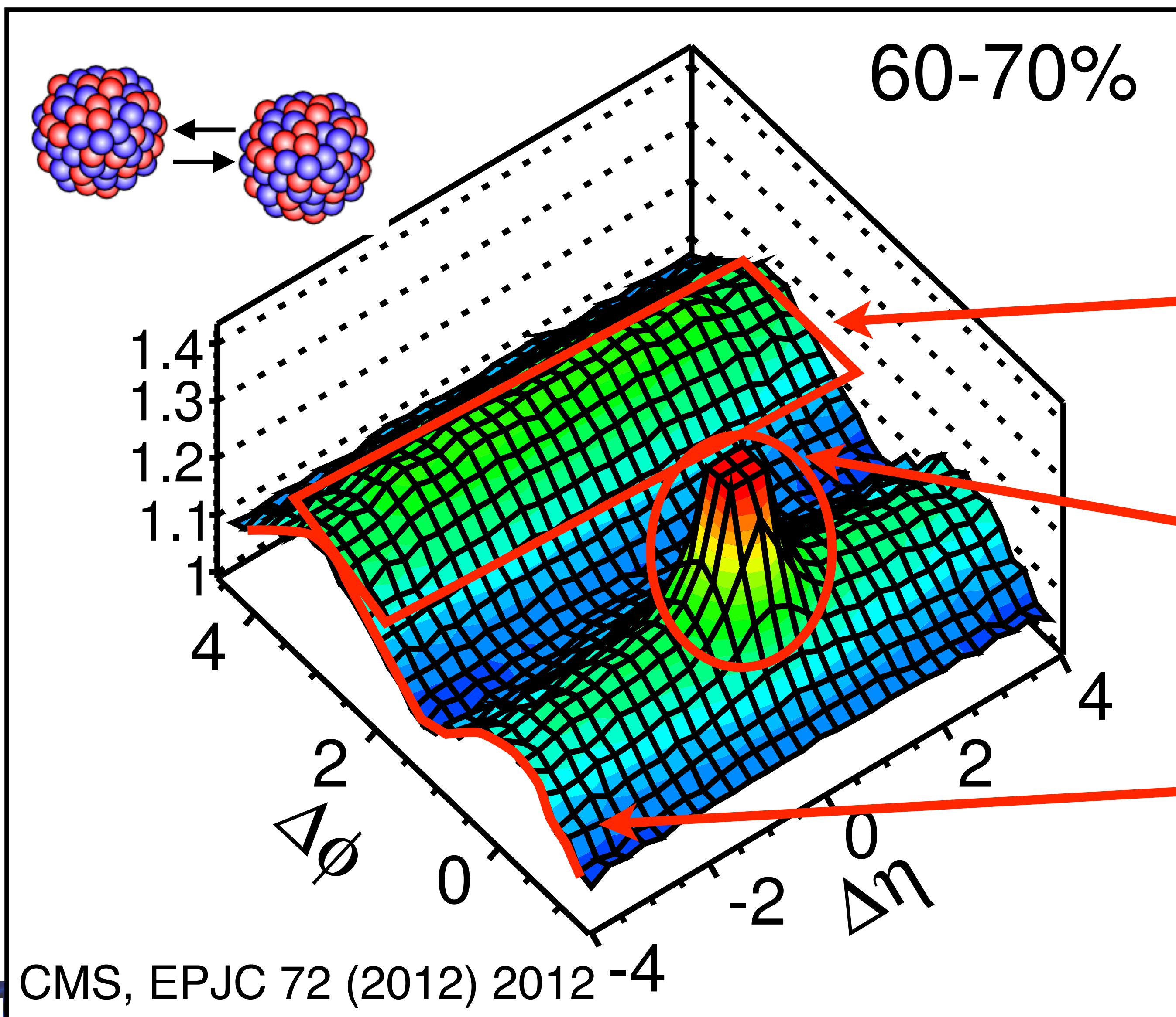
Abridged anatomy of 2PC









Recoil (away-side) jet
($\Delta\phi \sim \pi$, elongated in $\Delta\eta$)

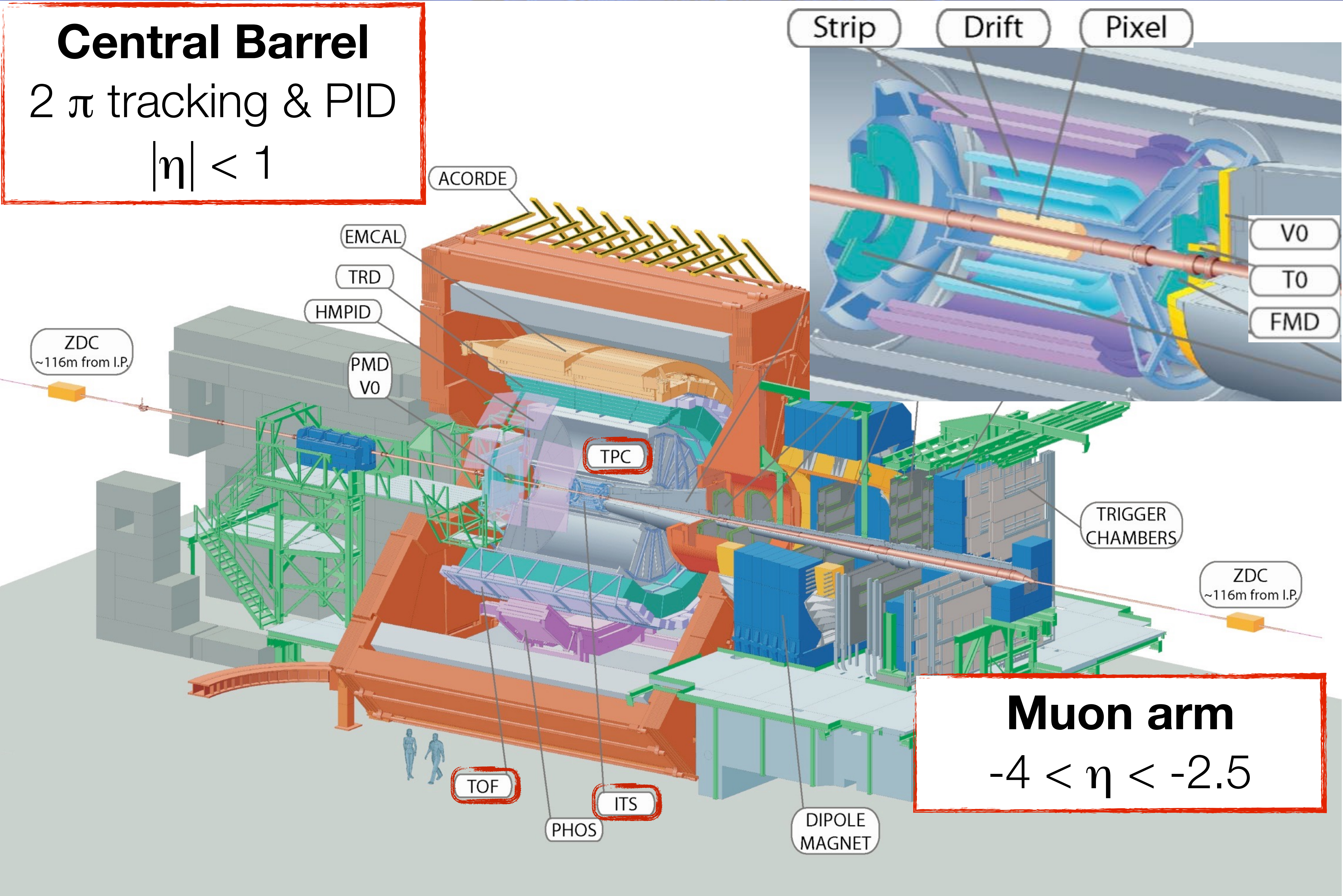
Near-side jet
($\Delta\phi \sim 0$, $\Delta\eta \sim 0$)

Azimuthal modulation (v_n)

Central Barrel

2 π tracking & PID

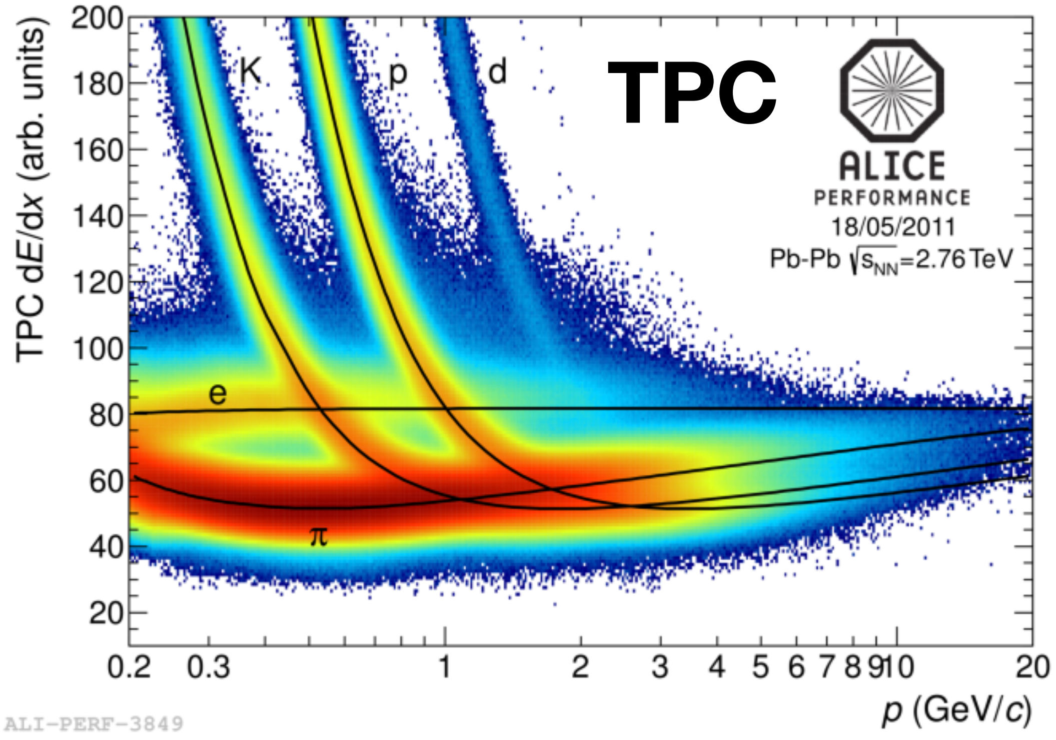
$|\eta| < 1$

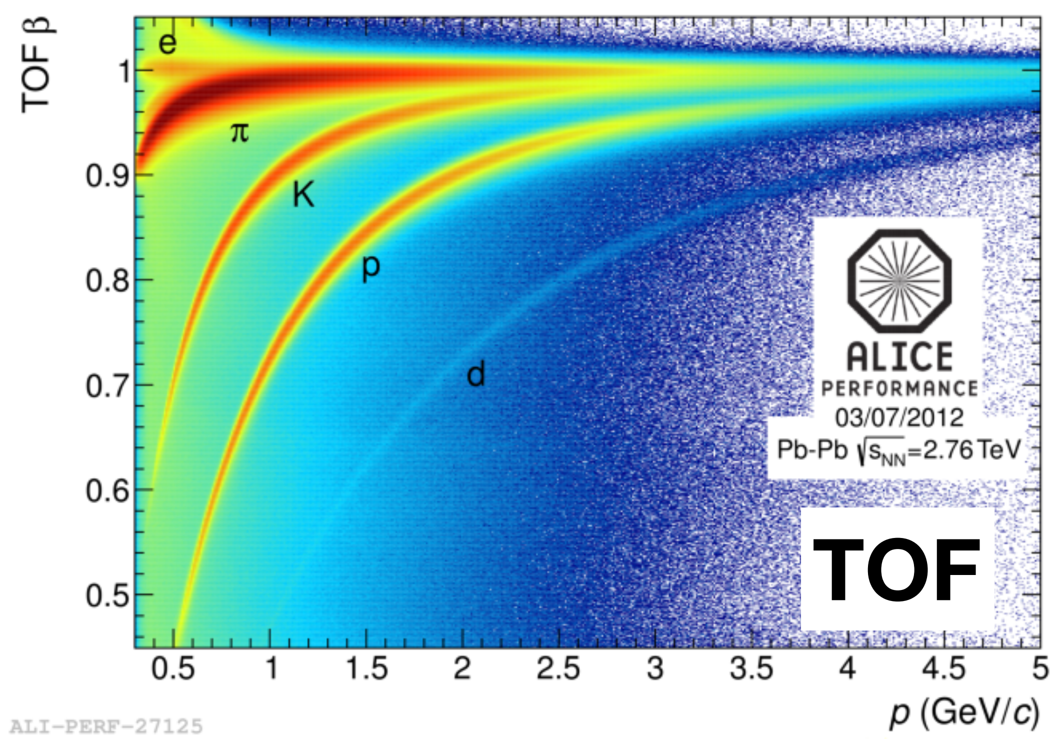


Muon arm

$-4 < \eta < -2.5$

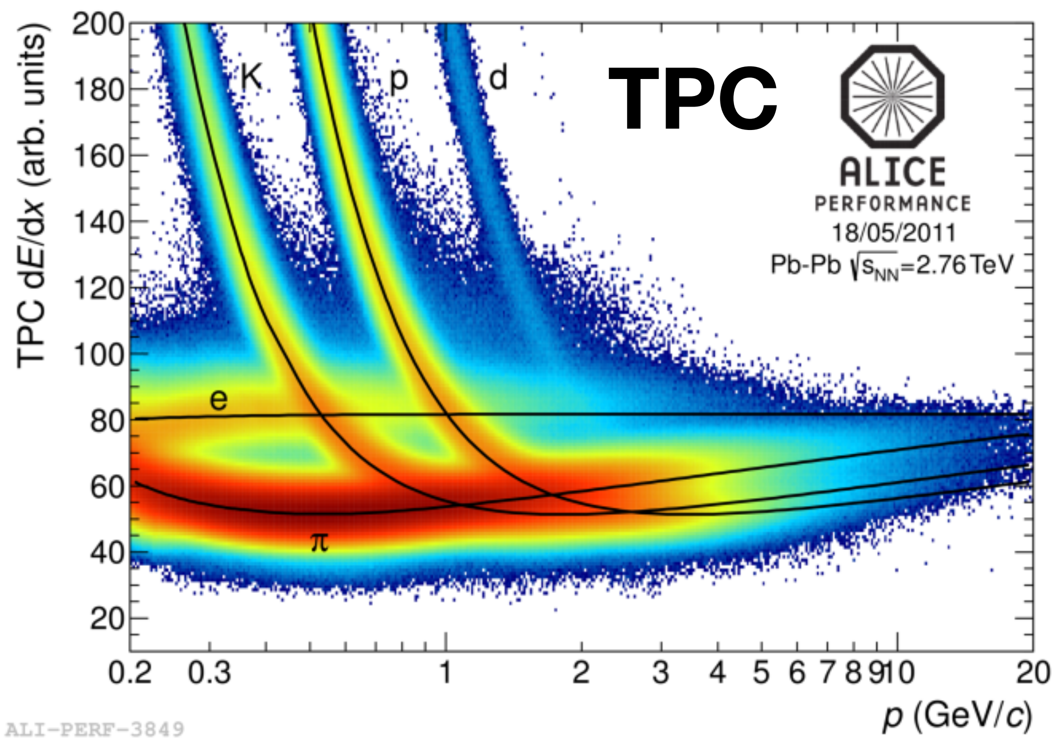
Particle identification

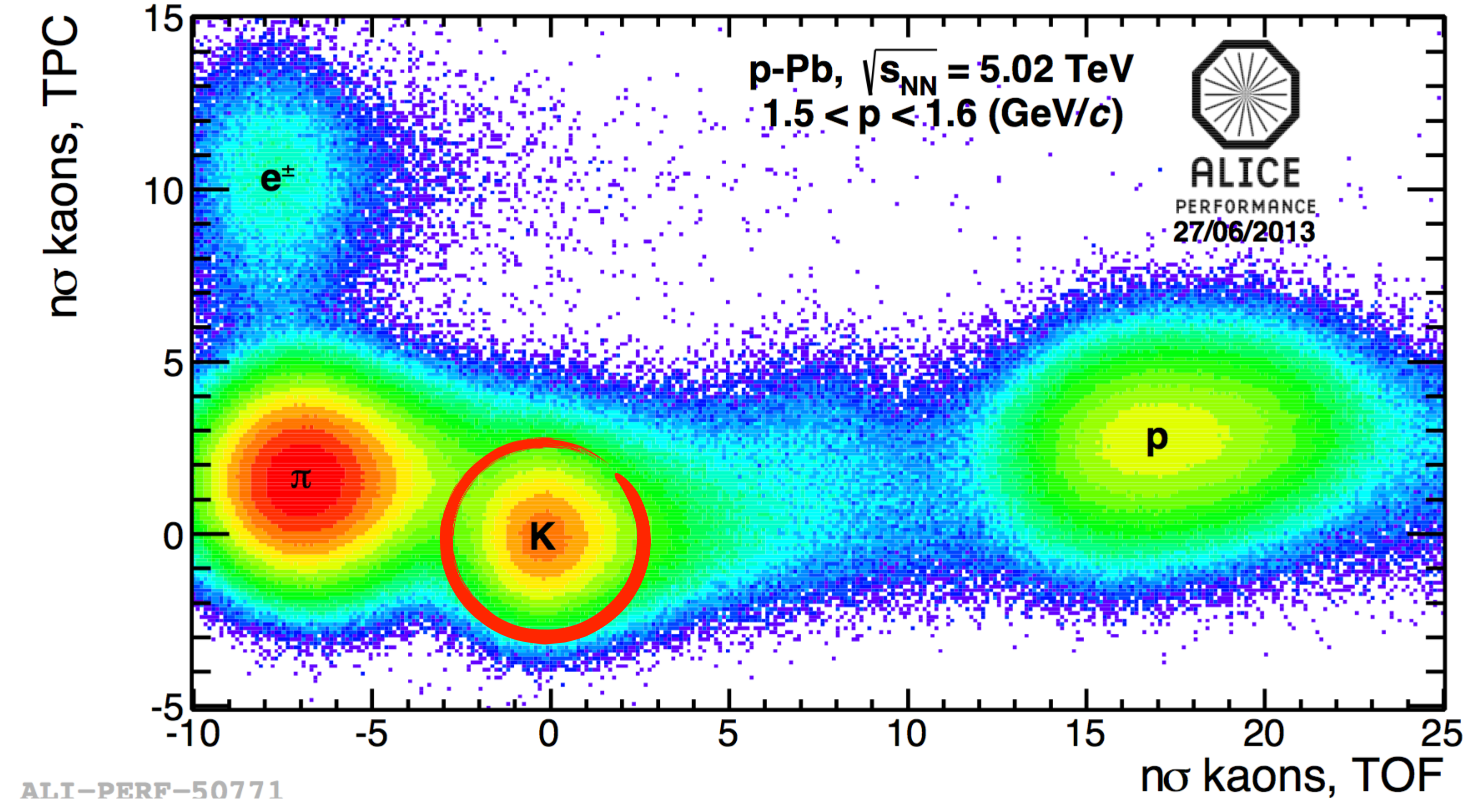


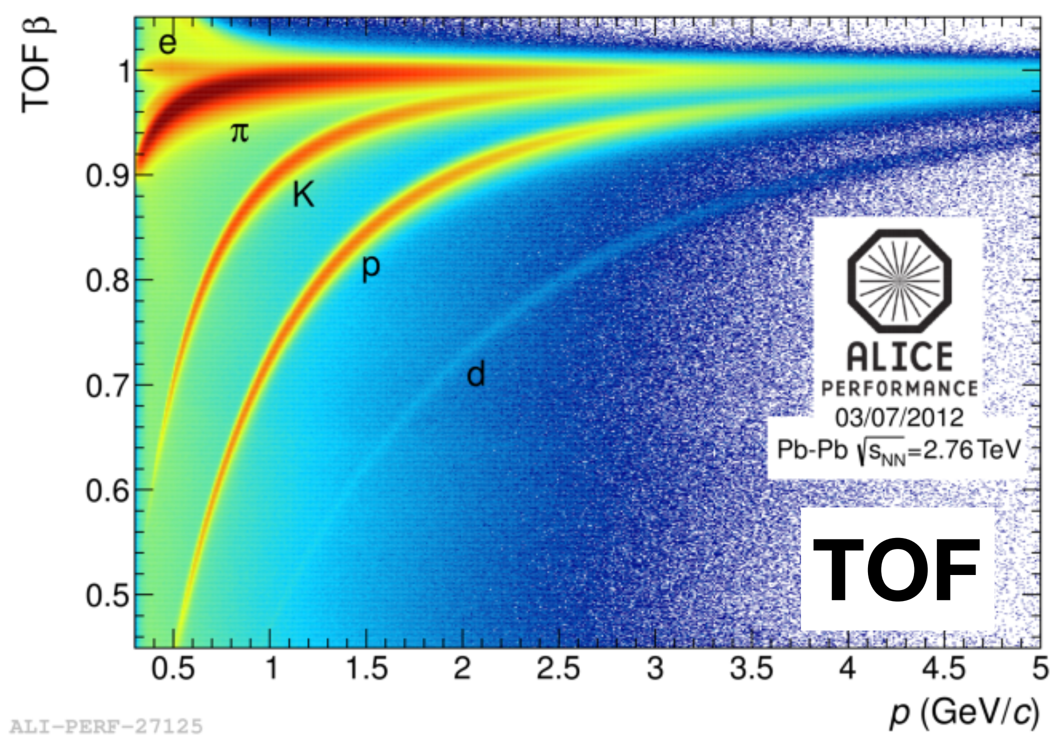


ALICE provides **extensive PID** capabilities, **several techniques** (d*E*/dx, time-of-flight, Cherenkov…)

Particle identification





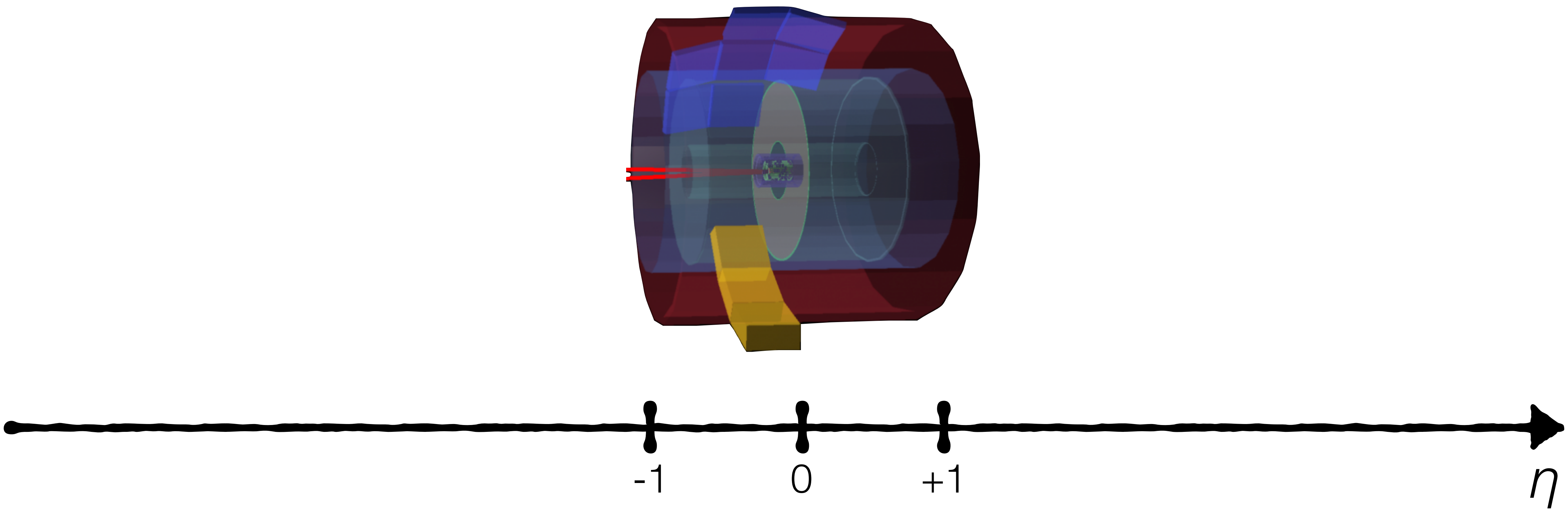


ALICE provides **extensive PID** capabilities, **several techniques** (dE/dx, time-of-flight, Cherenkov…)

This talk: PID based on **combined TPC/TOF** information

What correlates with what?

ITS, TPC & TOF



Central Barrel:

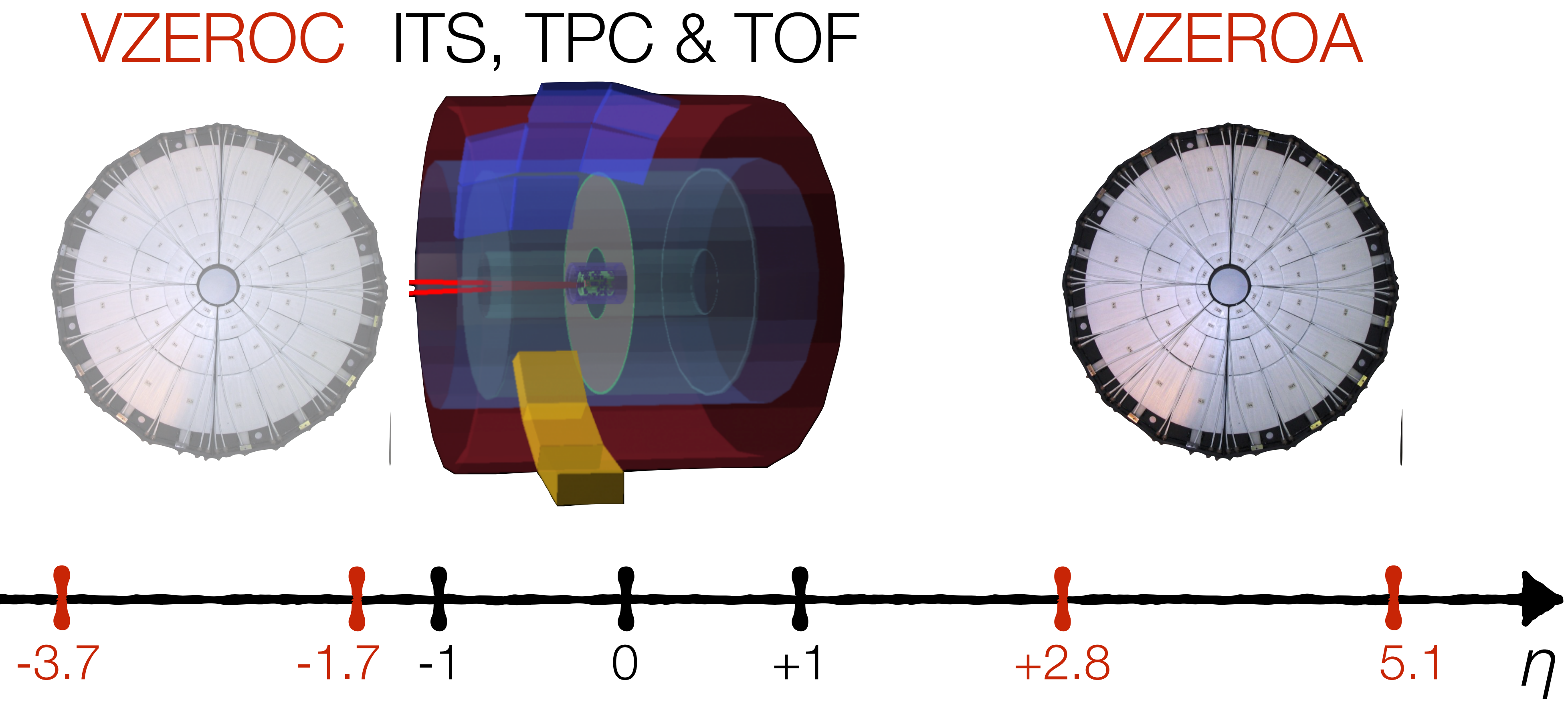
tracks and PID in $|\eta| \lesssim 0.8$

tracklets in $|\eta| \lesssim 1.0$

2012 pilot run (1.7 M MB events)
2013 run (10^8 MB events, $50\mu b^{-1}$)

NB: in the following: $\eta = \eta_{lab}$

What correlates with what?



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VZERO: used for event activity classes

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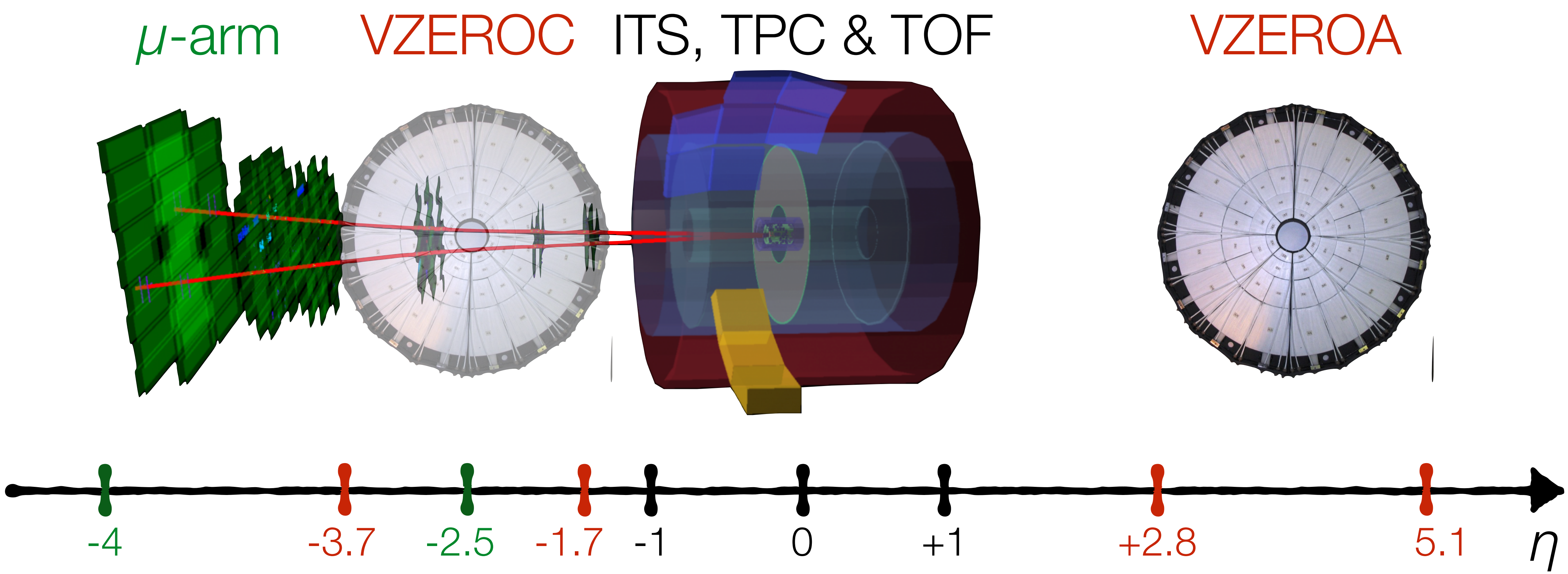

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(MB + 5-6 nb^{-1} triggered events)

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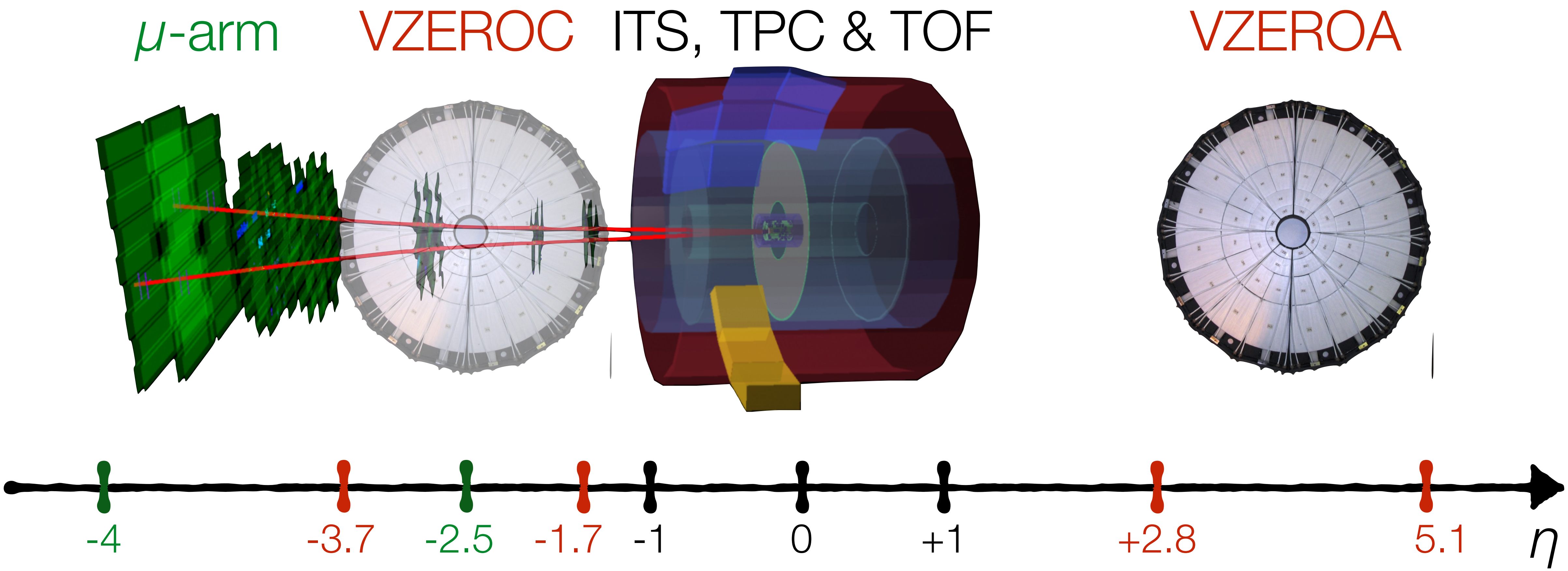

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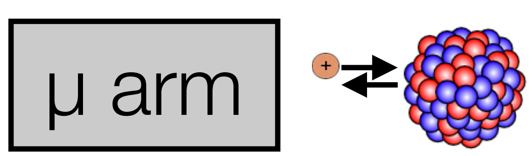
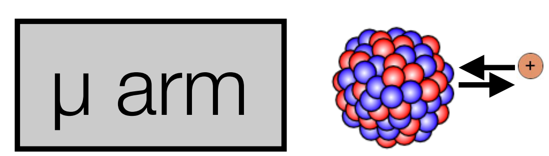
2013 run
(MB + 5-6 nb^{-1} triggered events)

Two configurations

Pb-p: Pb-going



p-Pb: p-going



NB: in the following: $\eta = \eta_{lab}$

Associated yield per trigger particle

$$\frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{assoc}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi} = \frac{S(\Delta\eta, \Delta\varphi)}{B(\Delta\eta, \Delta\varphi)}$$

Associated yield per trigger particle

$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{assoc}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)} \quad S(\Delta\eta,\Delta\varphi) = 1/N_{\mathrm{trig}}\ \mathrm{d}^2N_{\mathrm{same}}/\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi$$

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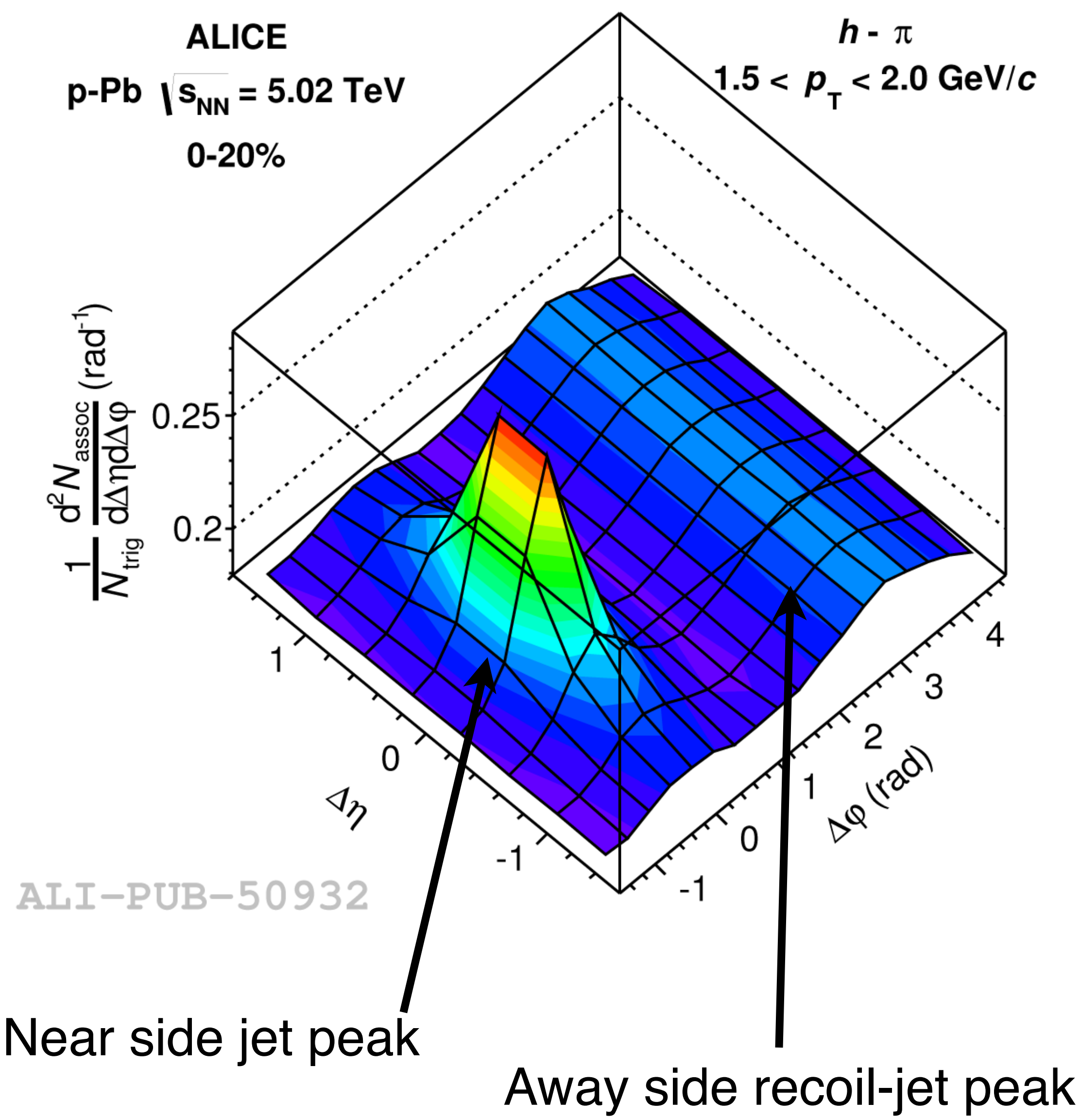

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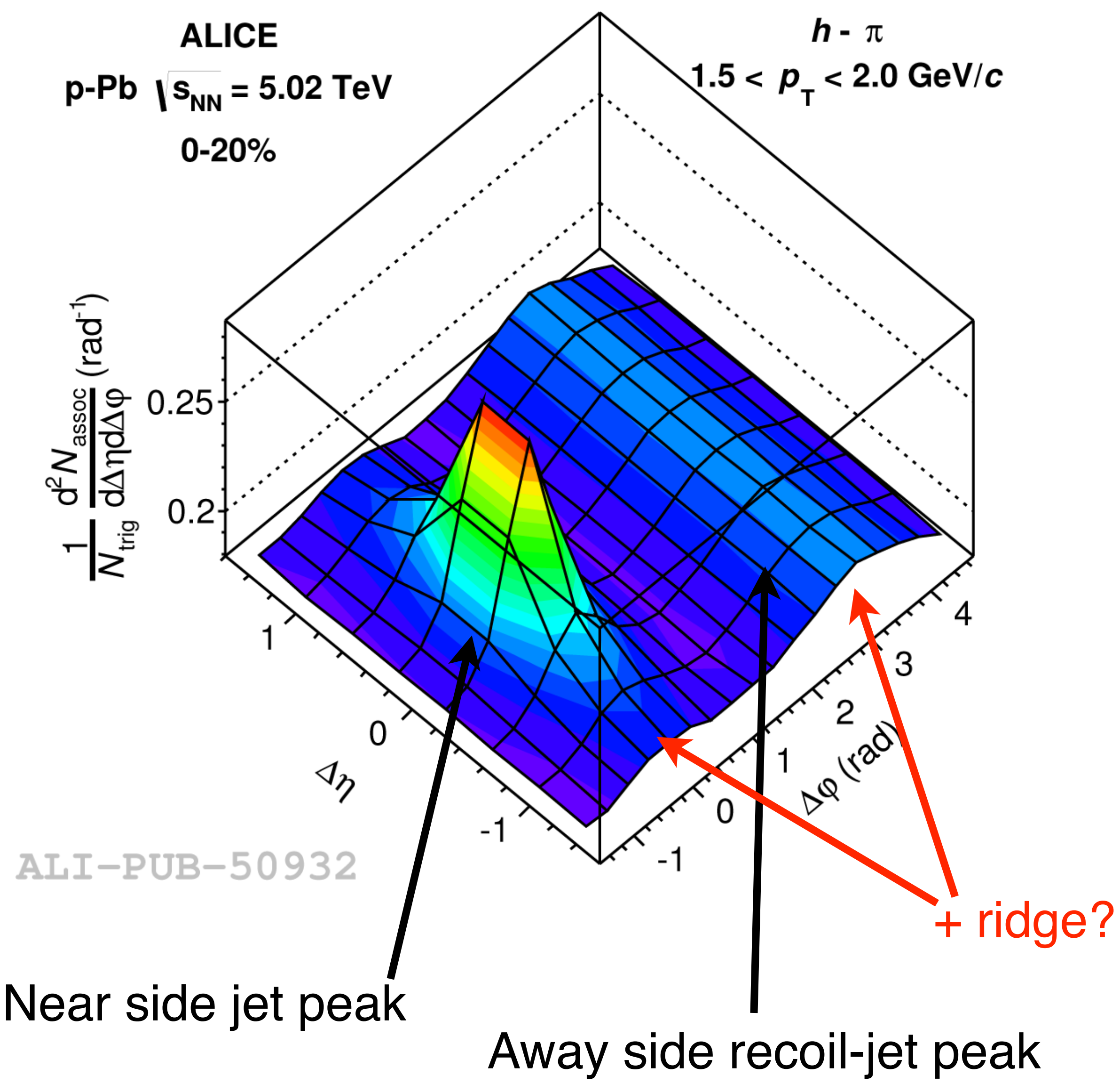

Associated yield per trigger particle

$$\frac{1}{N_{trig}}\frac{d^2N_{assoc}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

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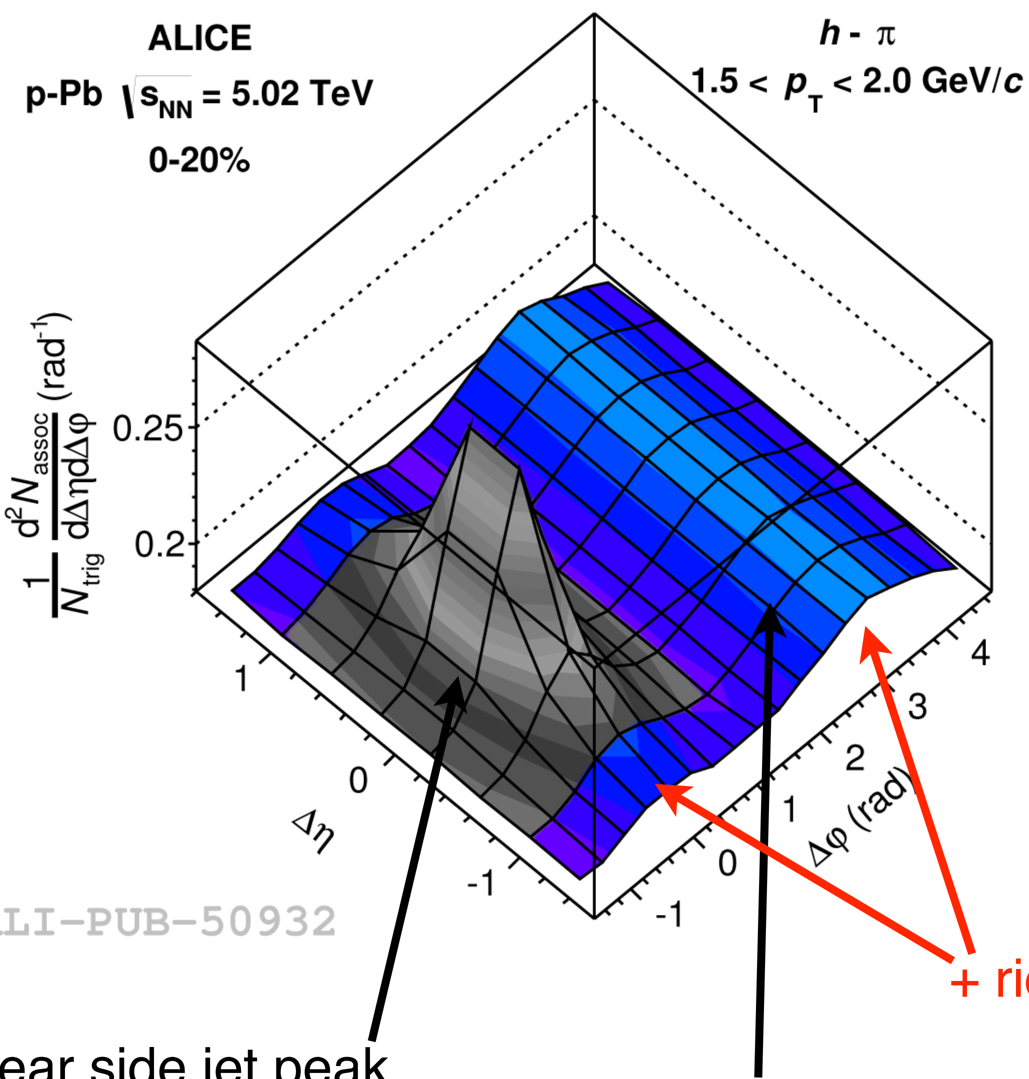
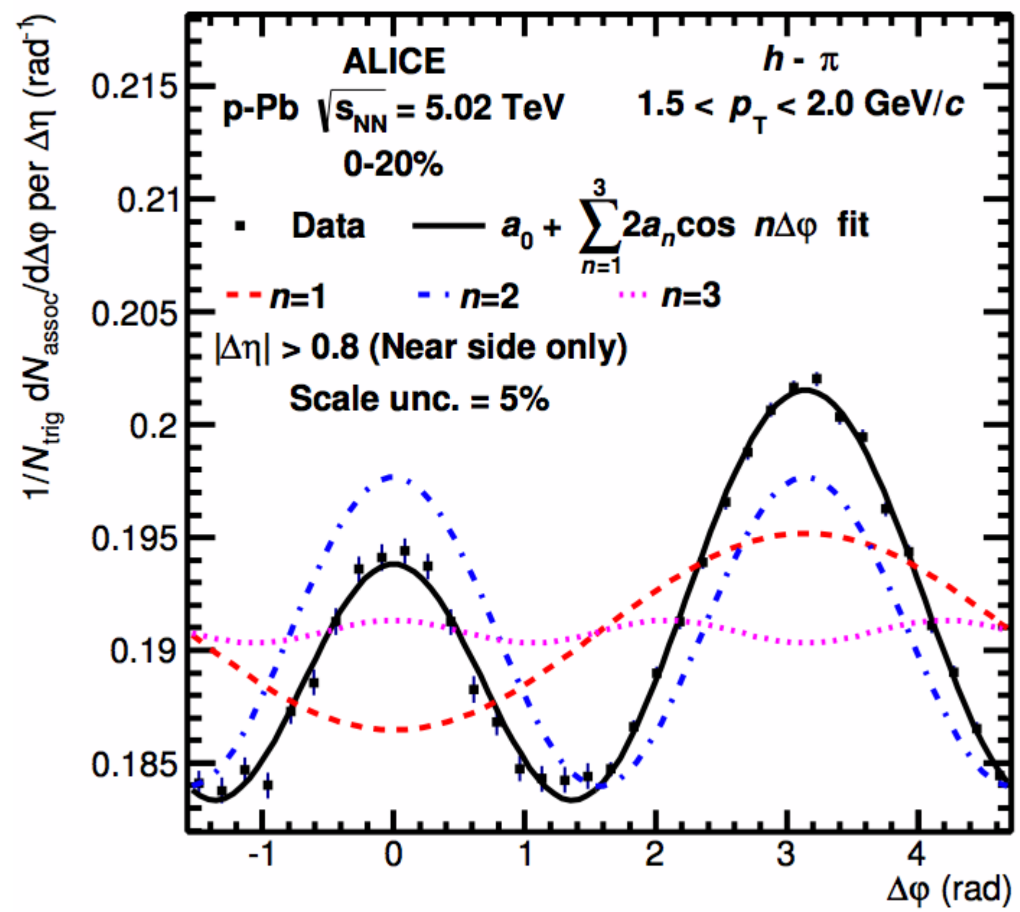


Jet peak in the near side excluded (|Δη|<0.8)



Good fit with 3 components:

- first component large due to recoil jet
- a_2 given by jet+ridge
- a_3 much smaller than the other components

Associated yield per trigger particle

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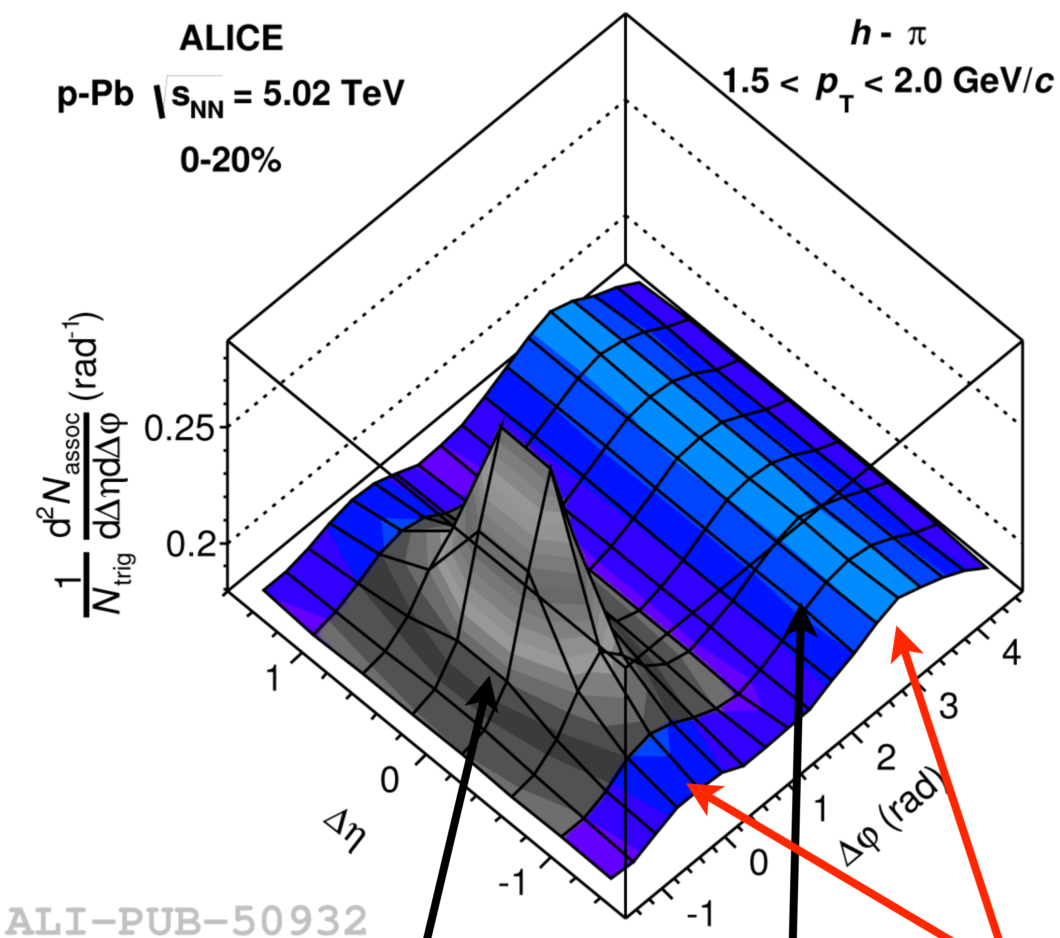
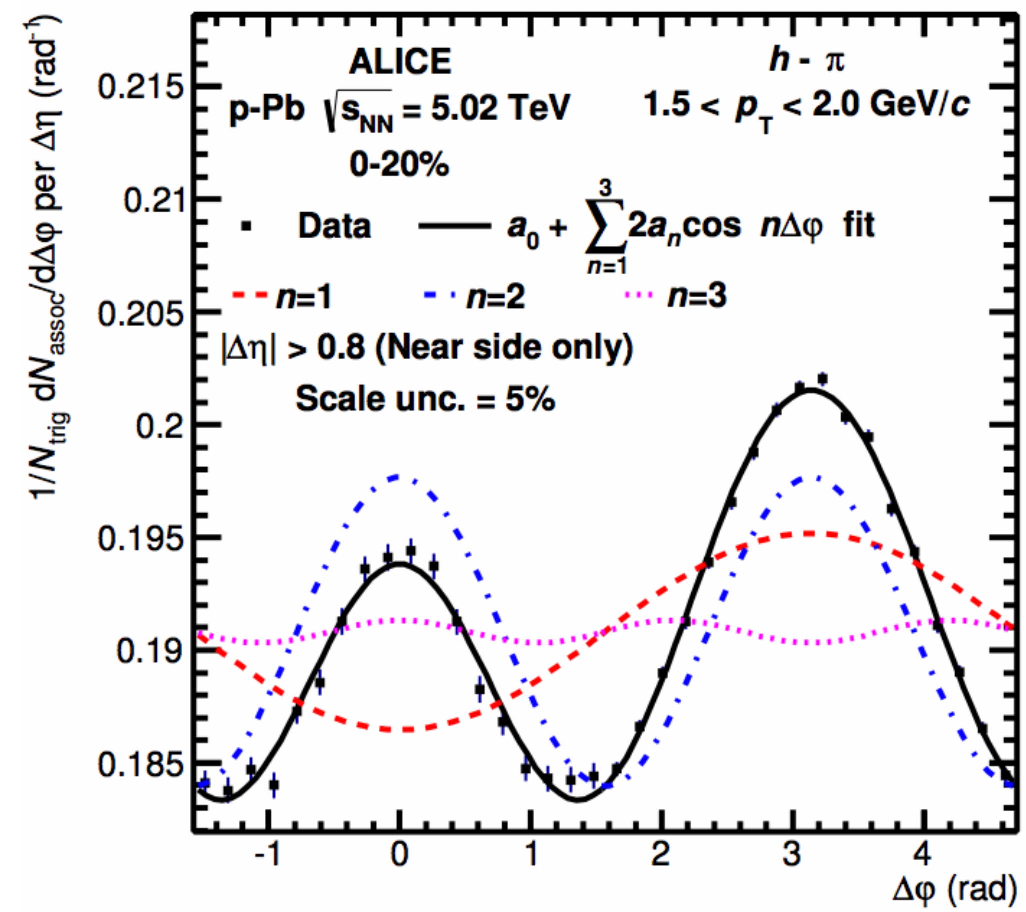


Near side jet peak

Away side recoil-jet peak

+ ridge?

Jet peak in the near side excluded (|Δη|<0.8)



Good fit with 3 components:

- first component large due to recoil jet
- a_2 given by jet+ridge
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How to get rid of the jet contribution?

Suppressing jets: the subtraction procedure

Jet contribution **reduced** assuming:

- Mostly **jet** contribution (i.e. no significant ridge) in **low multiplicity** events

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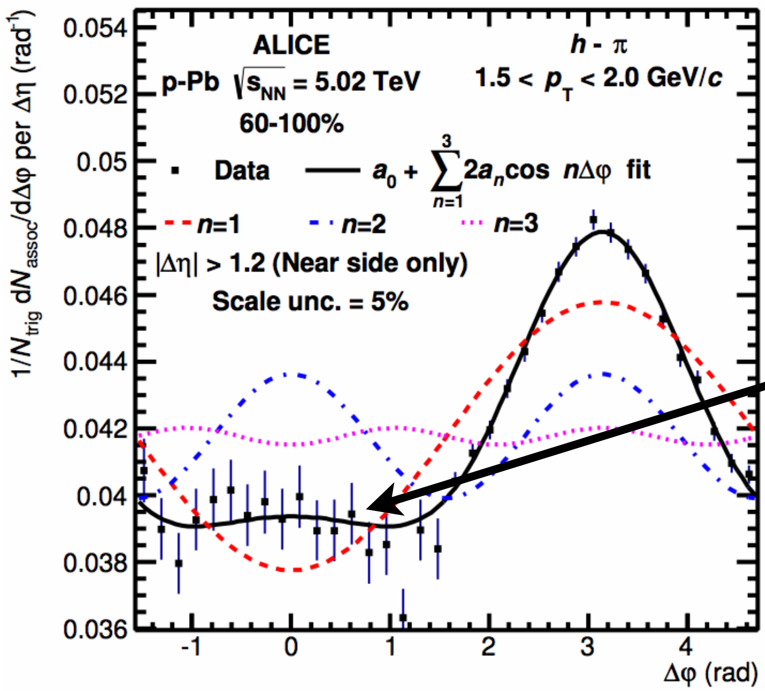

low mult.

No significant ridge in 60-100%

Jet contribution **reduced** assuming:

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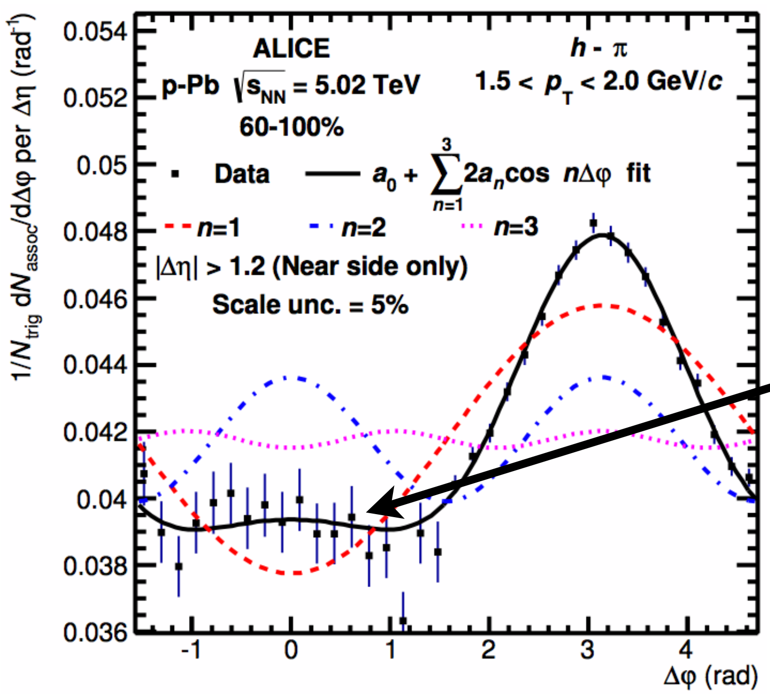

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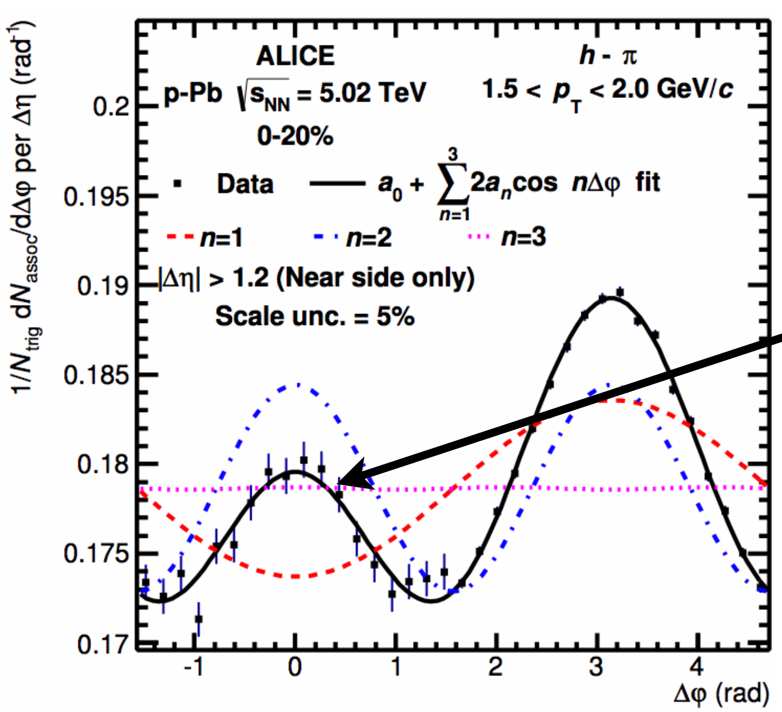


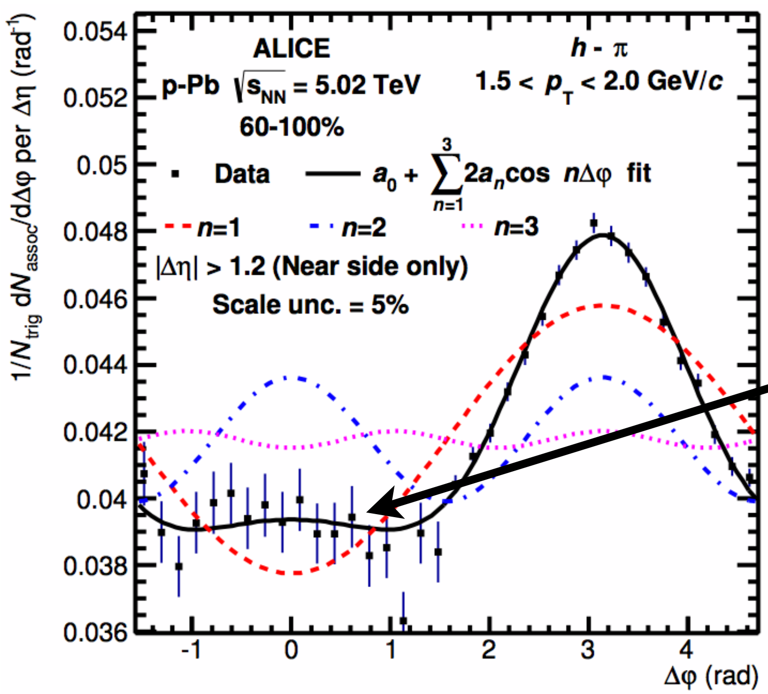
high mult.

Not the case for 0-20%

Suppressing jets: the subtraction procedure

Jet contribution **reduced** assuming:

- Mostly **jet** contribution (i.e. no significant ridge) in **low multiplicity** events
- **No** significant **medium effect** in the energy loss / jet fragmentation



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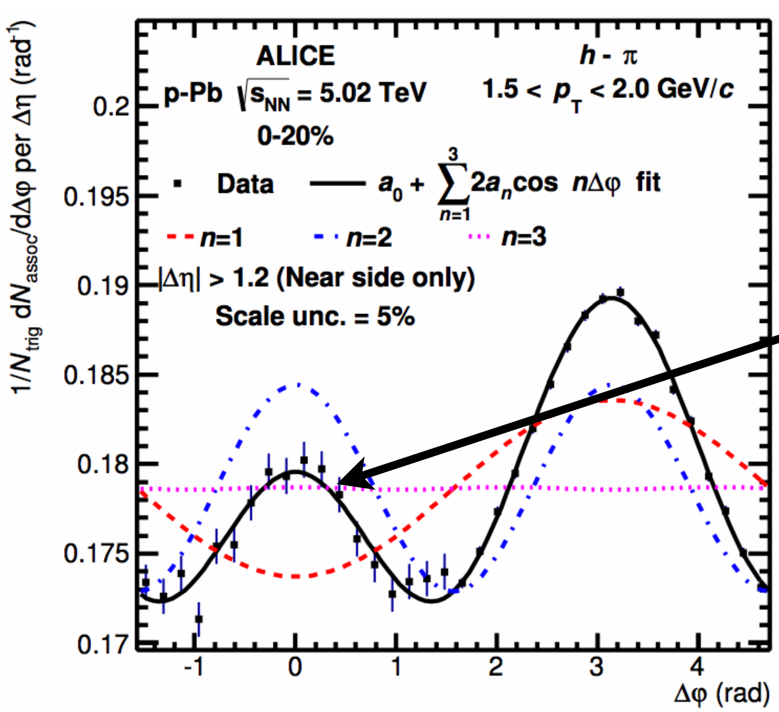
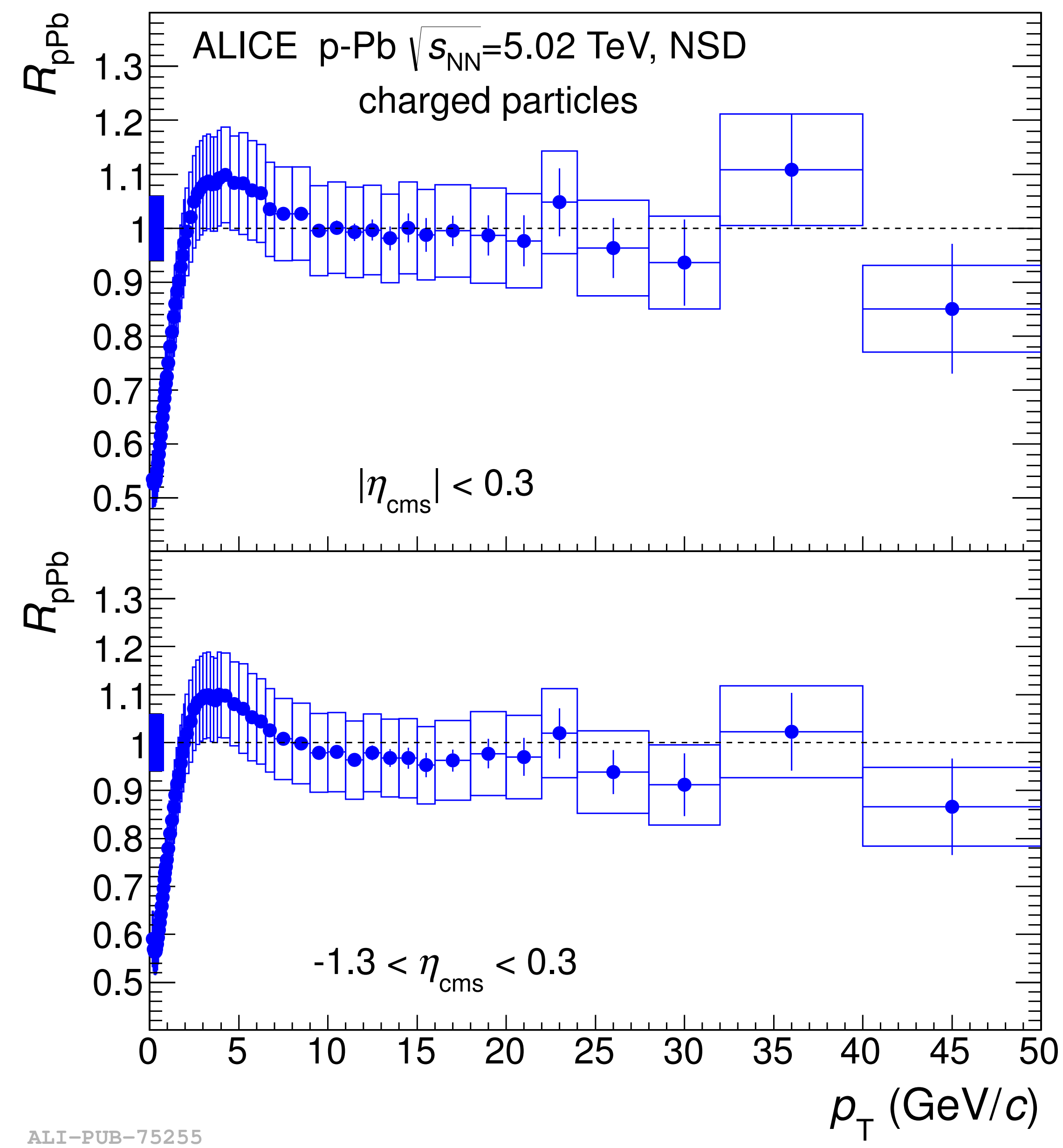


high mult.

Not the case for 0-20%

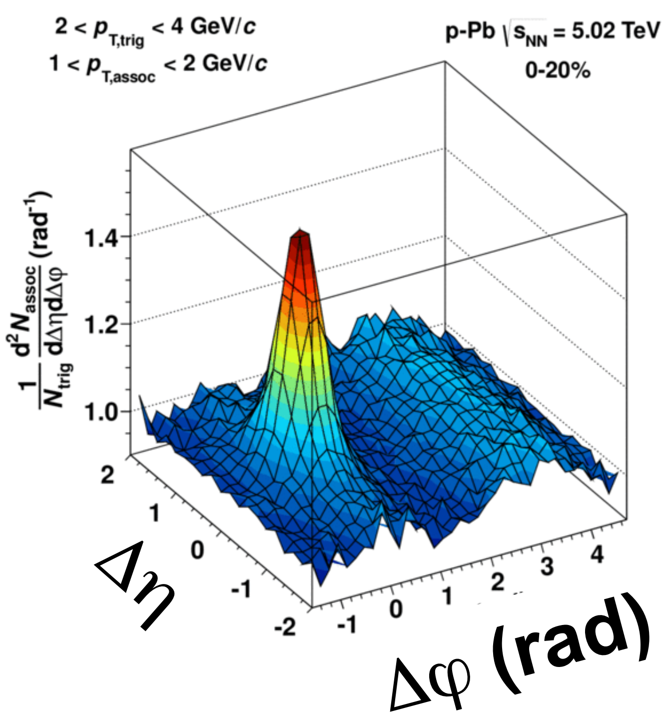


ALICE, EPJC 74 (2014) 3054
ALICE, PLB 741 (2015) 38–50

The Double Ridge

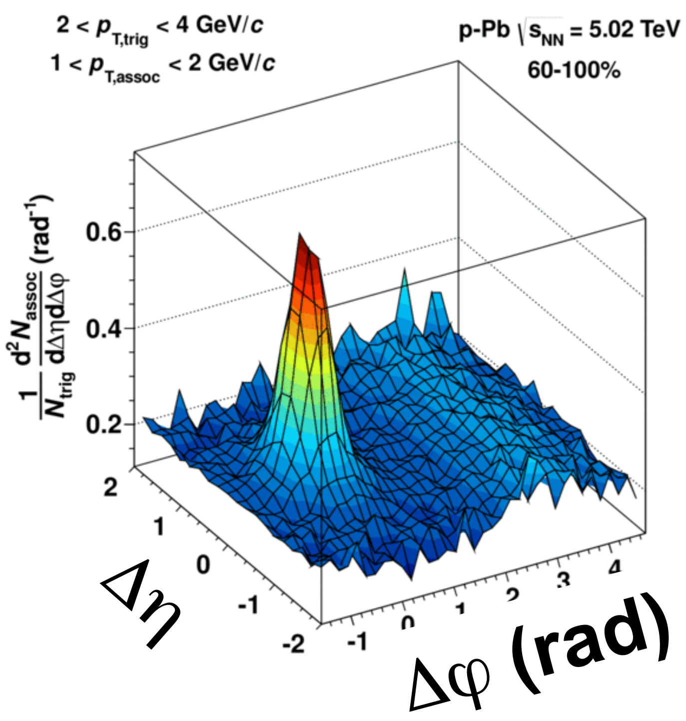
ALICE, PLB719 (2013) 29

0-20%



−

60-100%



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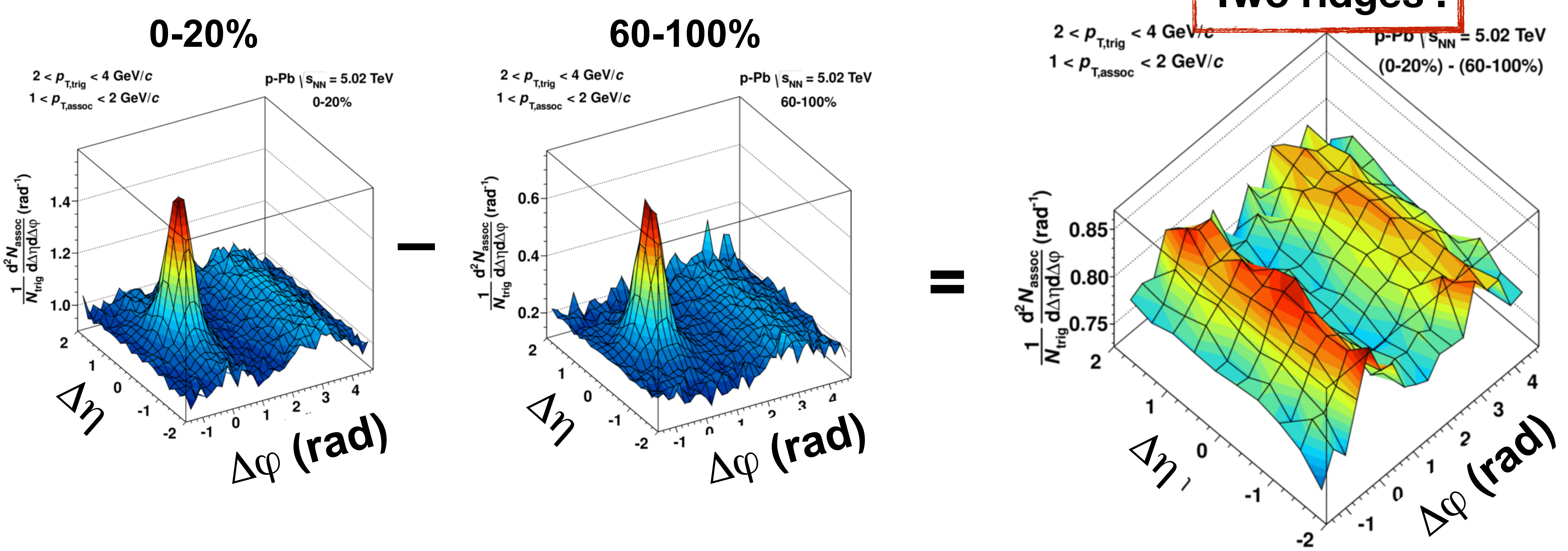
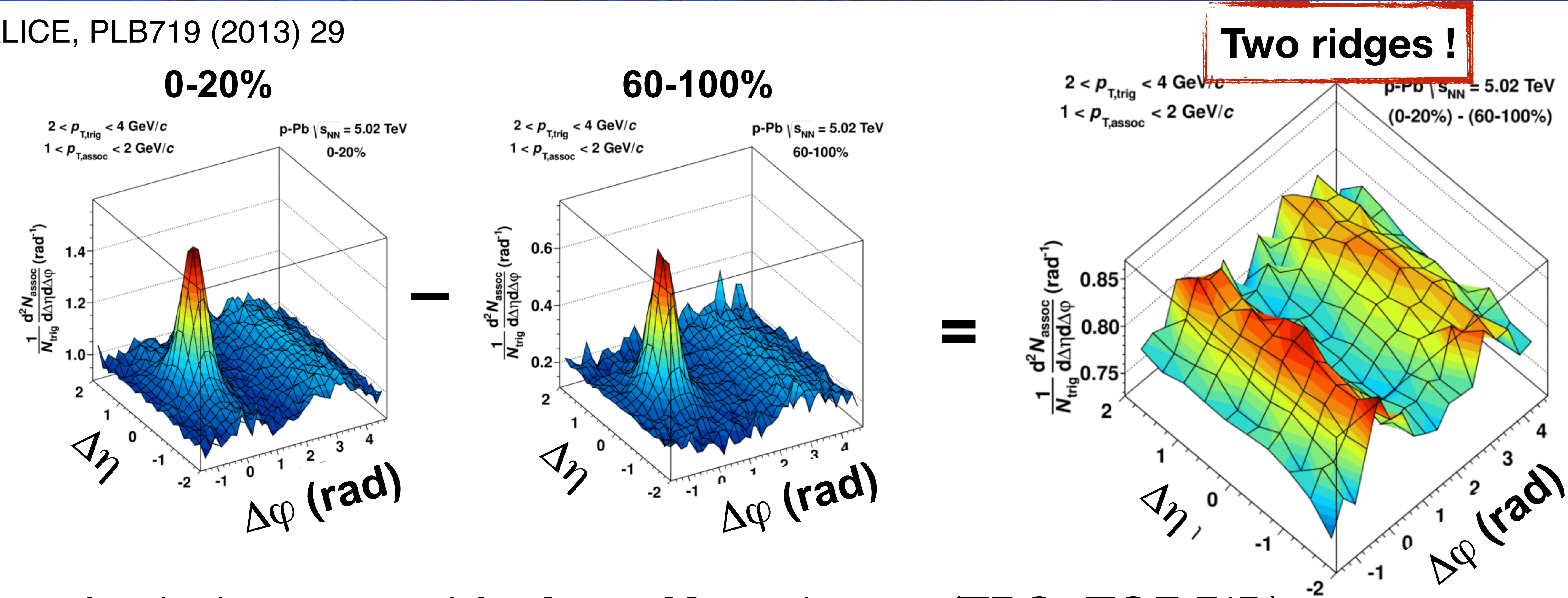
The Double Ridge

ALICE, PLB719 (2013) 29



The Double Ridge

ALICE, PLB719 (2013) 29

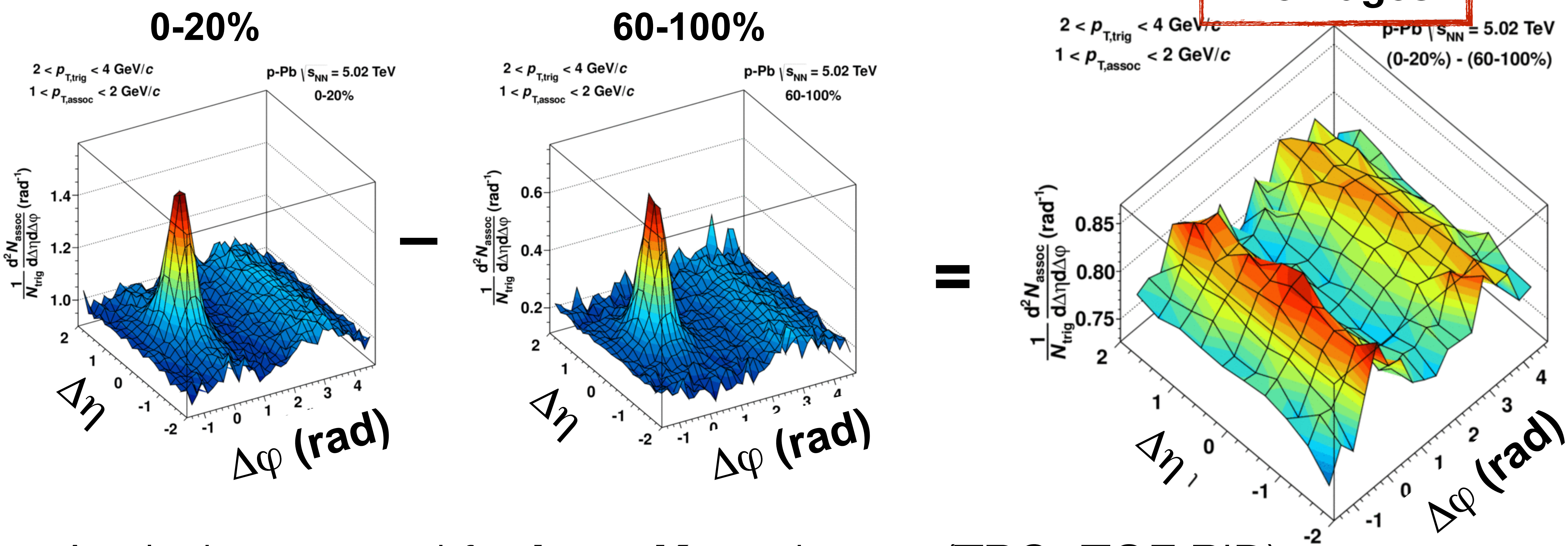


Analysis repeated for **h, π, K, p** triggers (TPC+TOF PID)

The Double Ridge

ALICE, PLB719 (2013) 29

Two ridges !



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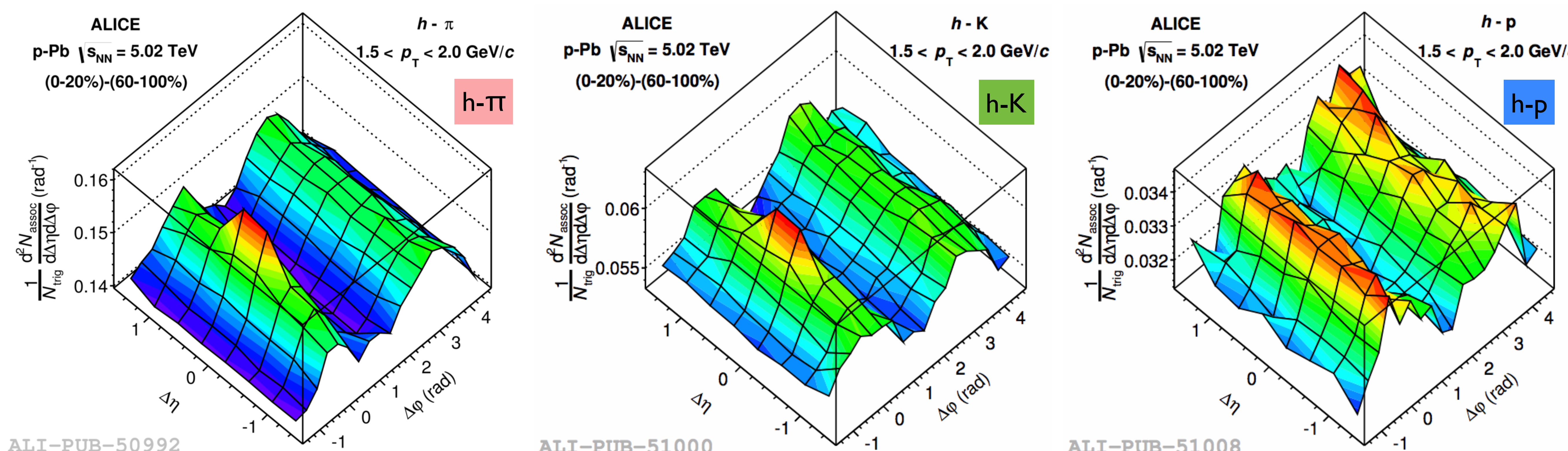


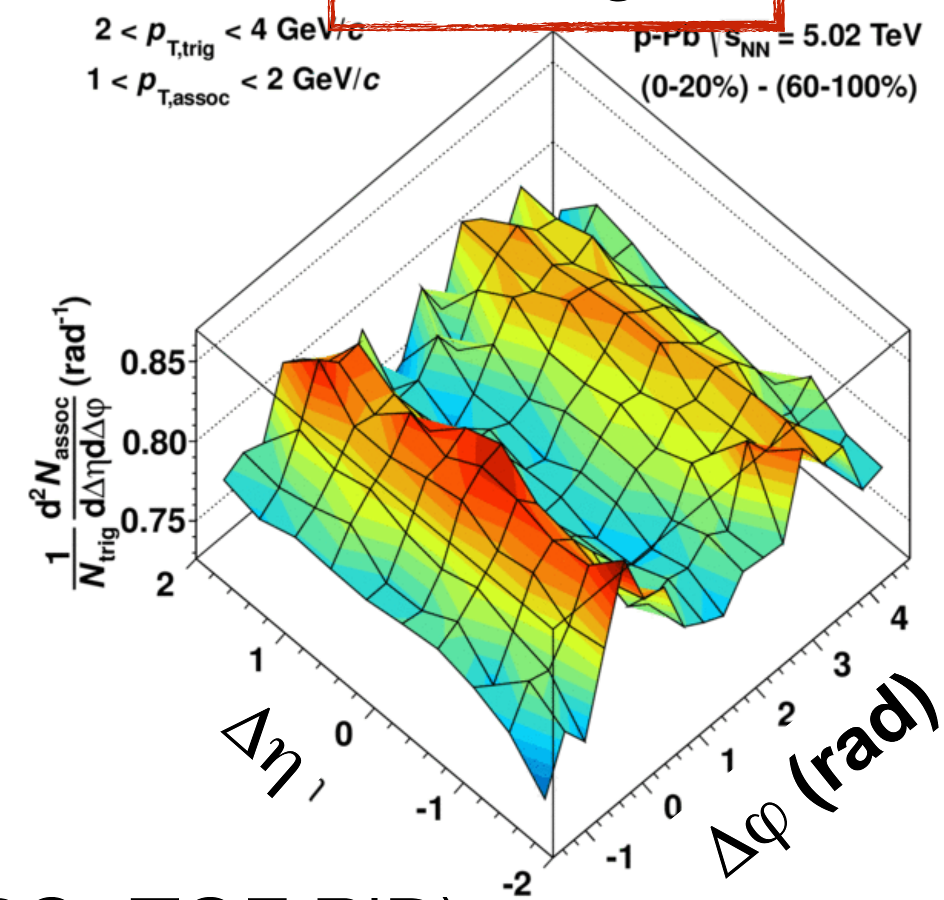
The Double Ridge

ALICE, PLB719 (2013) 29

Residual of jet, particularly important for π

- Most likely event **selection bias** on jet fragmentation
- **Excluded** on the **near** side (|Δη|>0.8)
- **Systematic** on the **away** side taken into account

Two ridges !



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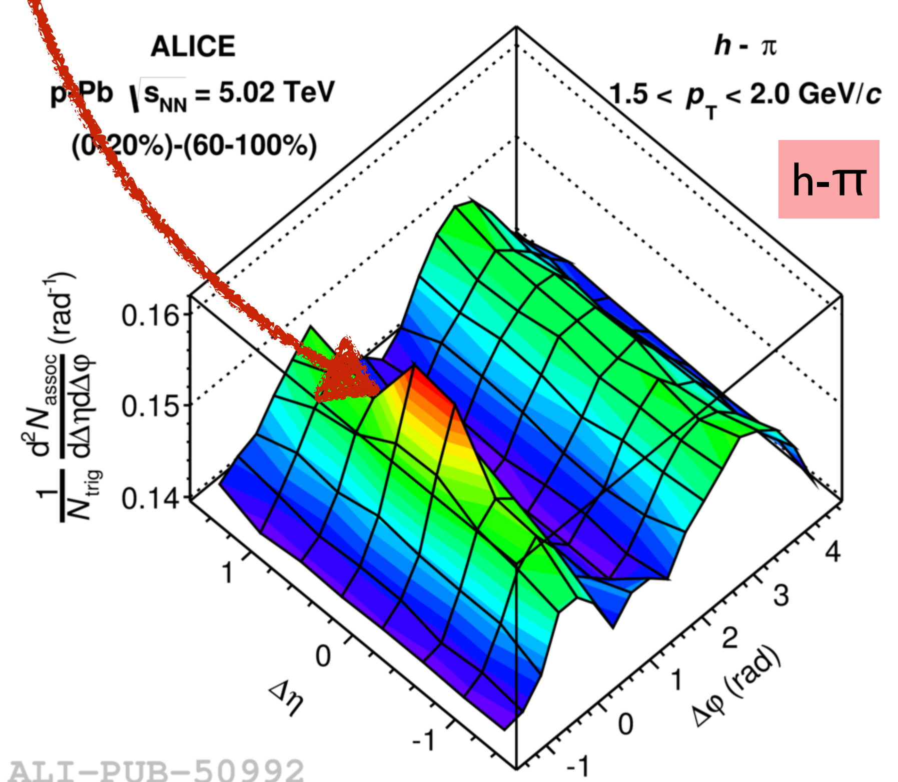
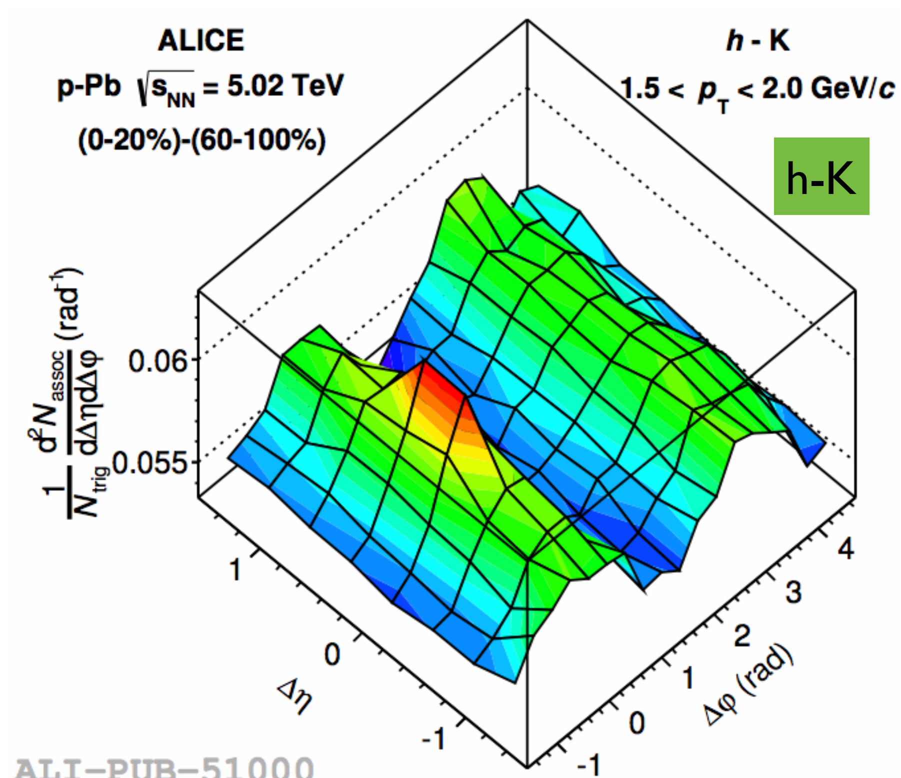
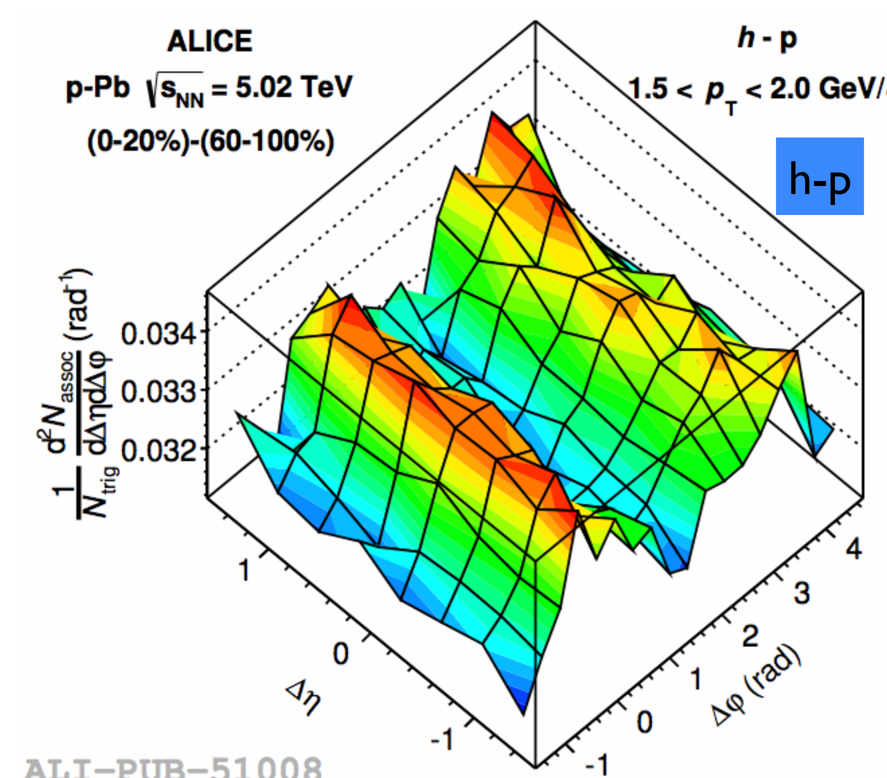
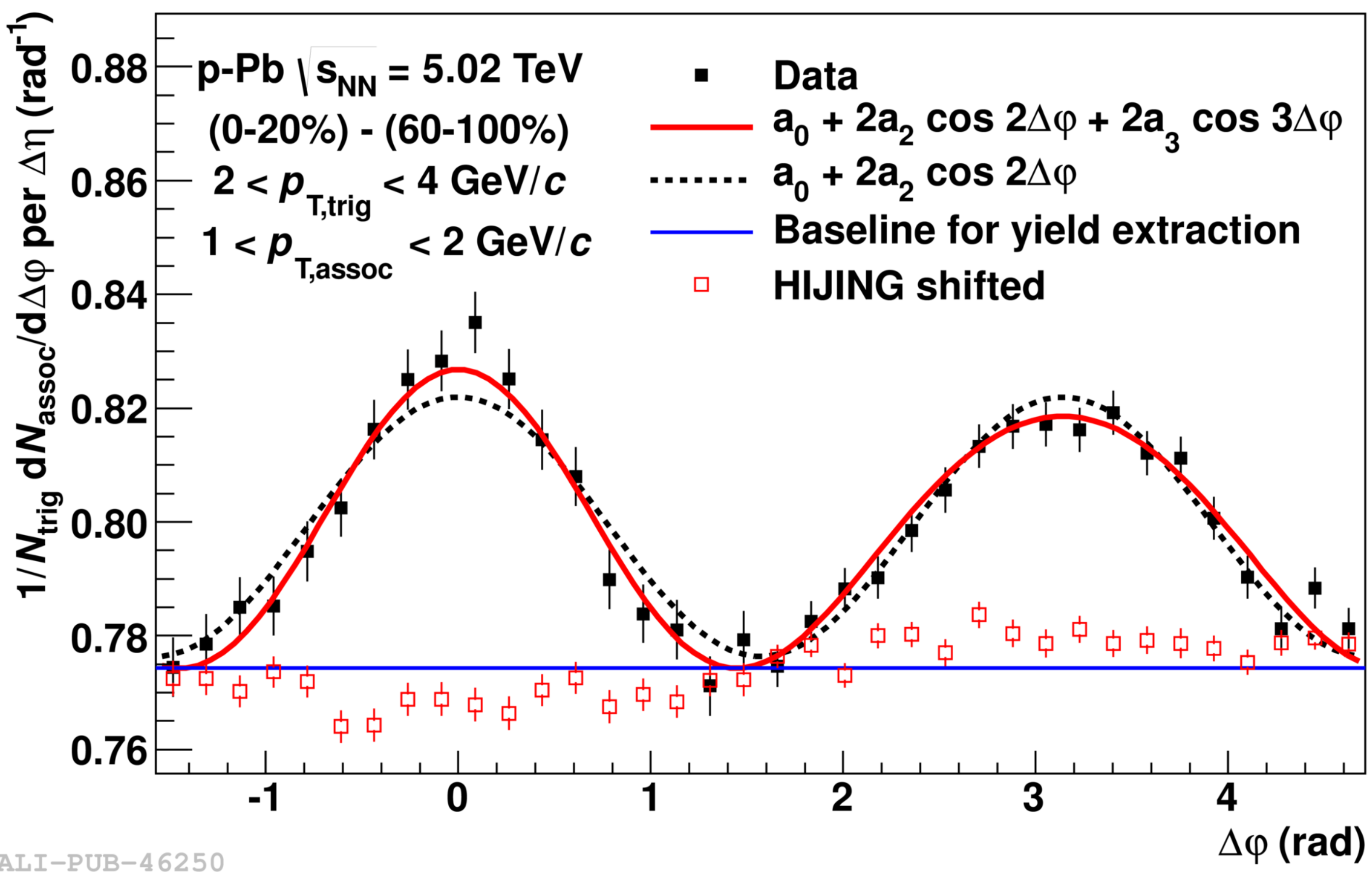






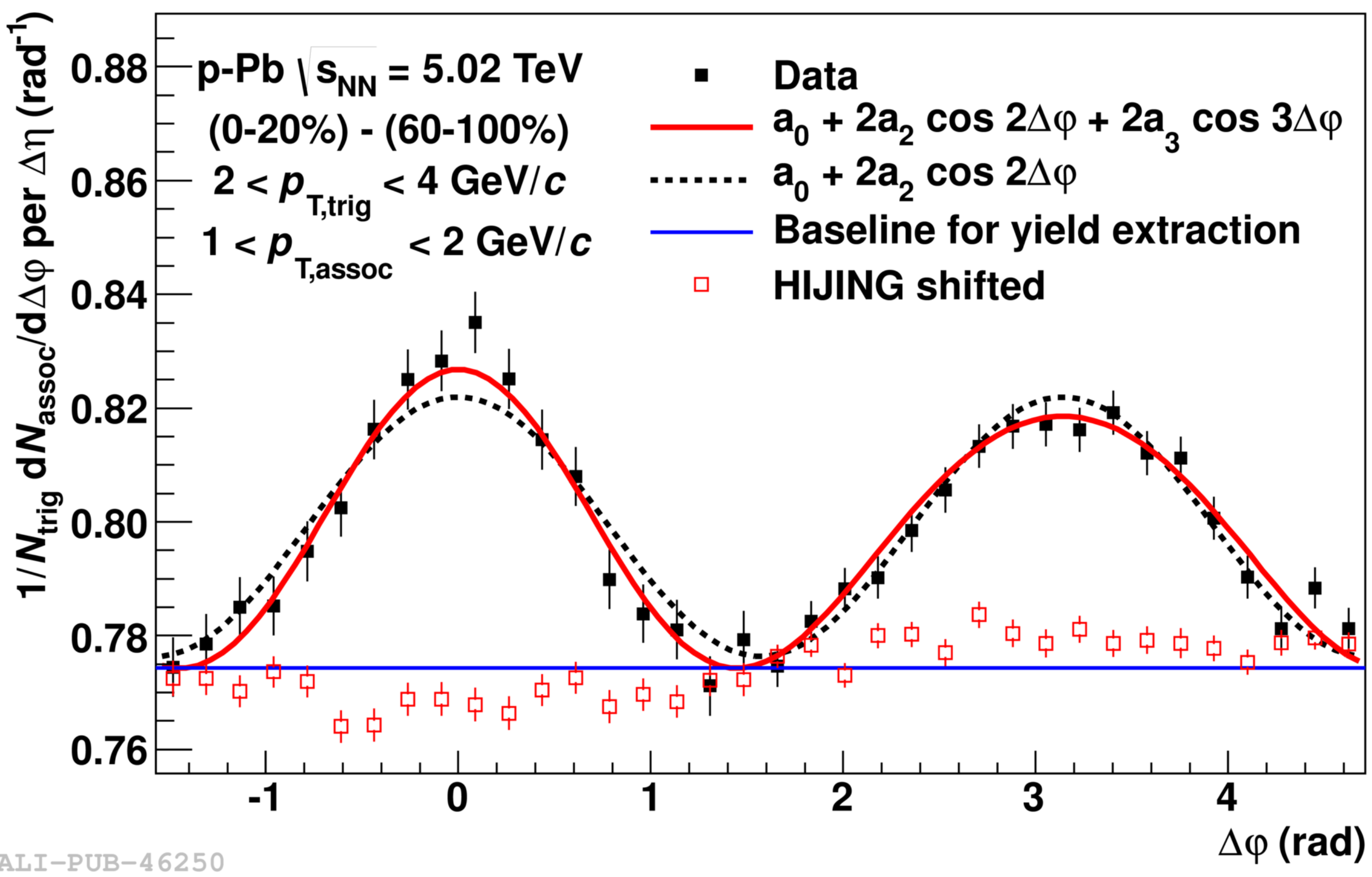
Extracting the v_n coefficients



$$\frac{1}{N_{\text{trig}}}\frac{dN_{\text{assoc}}}{d\Delta\varphi} = a_0 + 2a_1\cos\Delta\varphi + 2a_2\cos 2\Delta\varphi + 2a_3\cos 3\Delta\varphi.$$

ALICE, PLB 719, 29-41 (2013)

Extracting the v_n coefficients



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2PC modulation:

$$V_{n\Delta}\{2\mathrm{PC},\mathrm{sub}\} = a_n/(a_0+b)$$

ALICE, PLB 719, 29-41 (2013)

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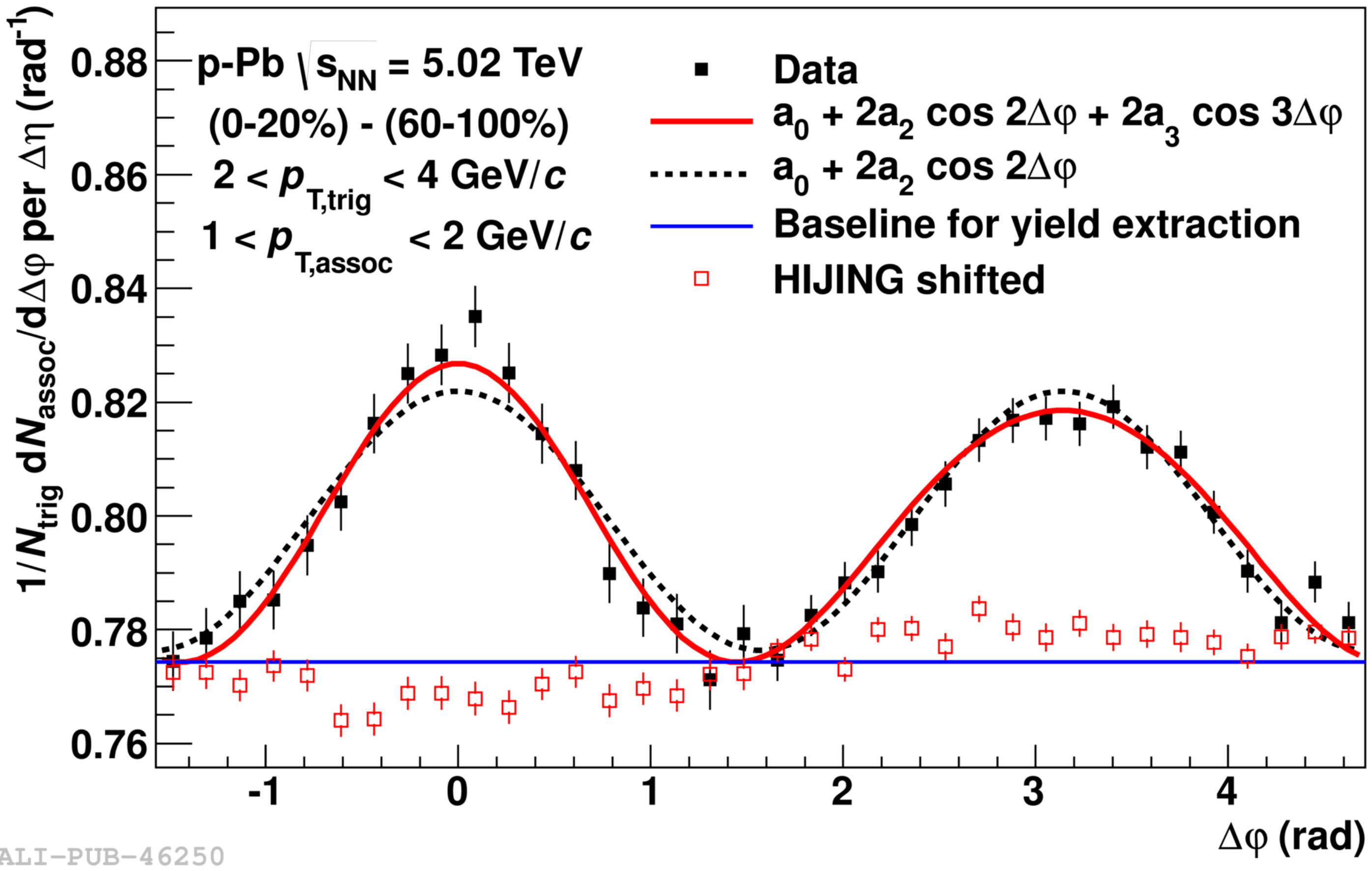

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2PC modulation:

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Subtraction removes part of baseline: to be restored!

ALICE, PLB 719, 29-41 (2013)

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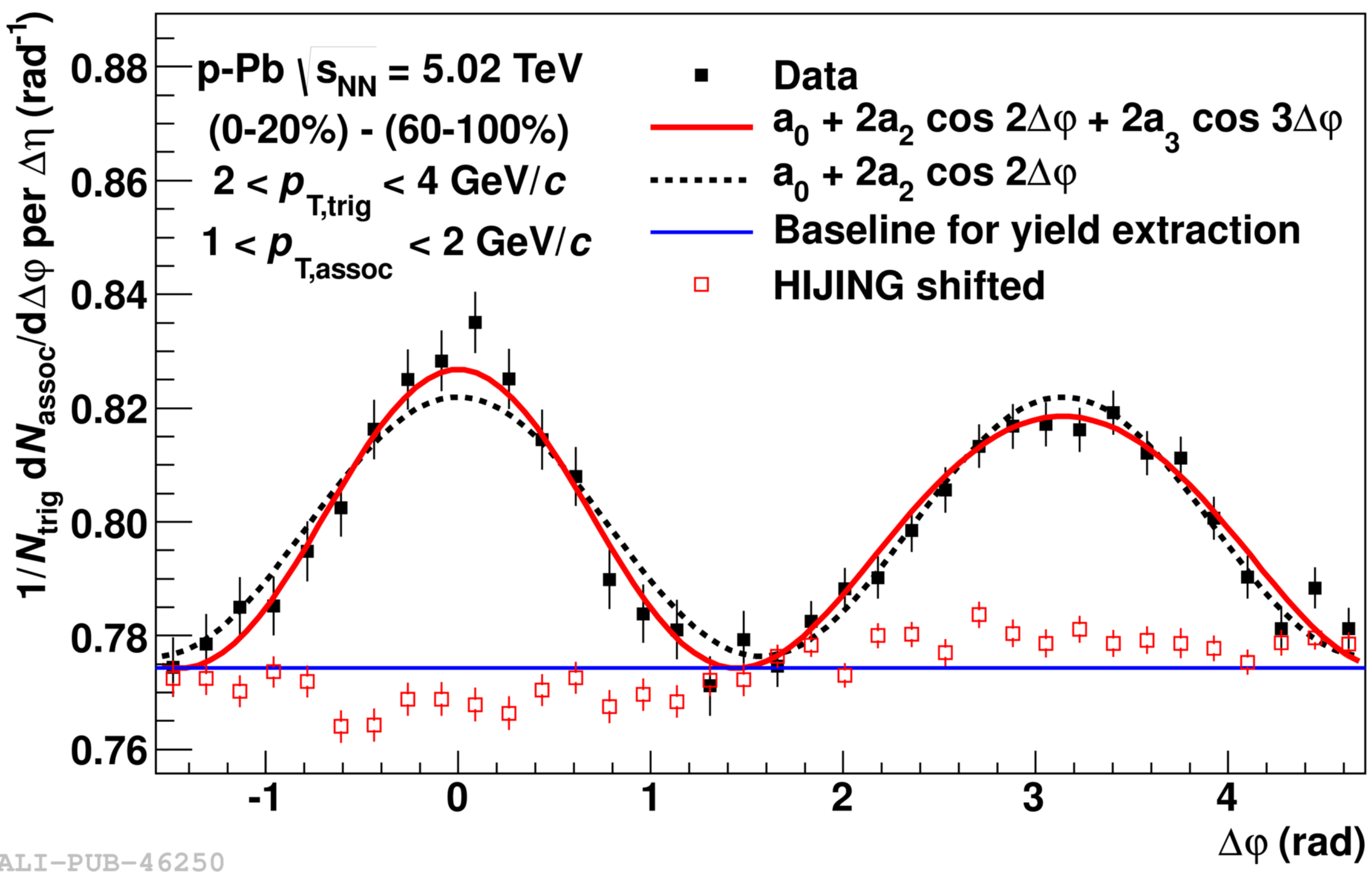

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ALICE, PLB 719, 29-41 (2013)

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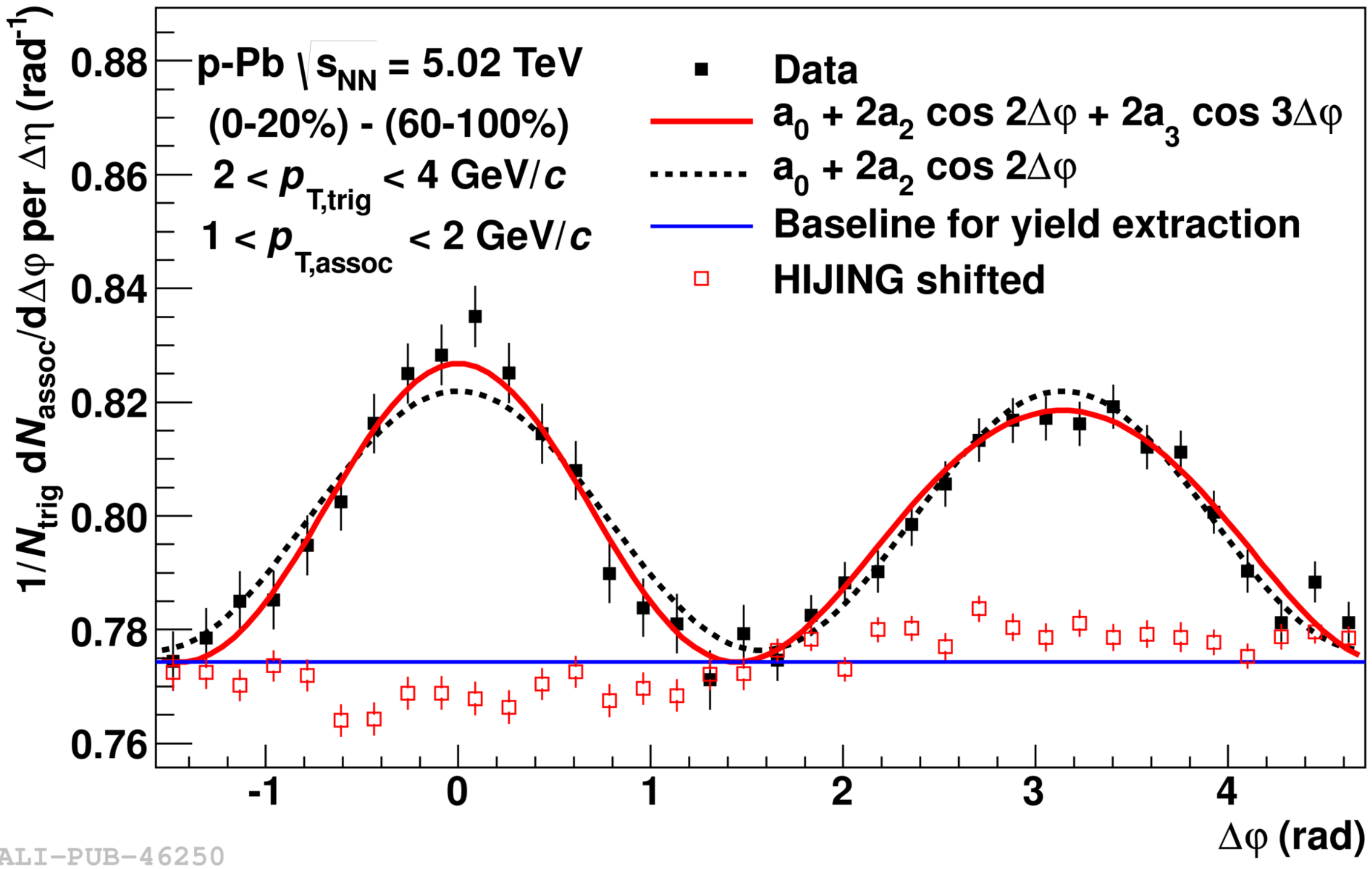

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2PC modulation:

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Subtraction removes part of baseline: to be restored!

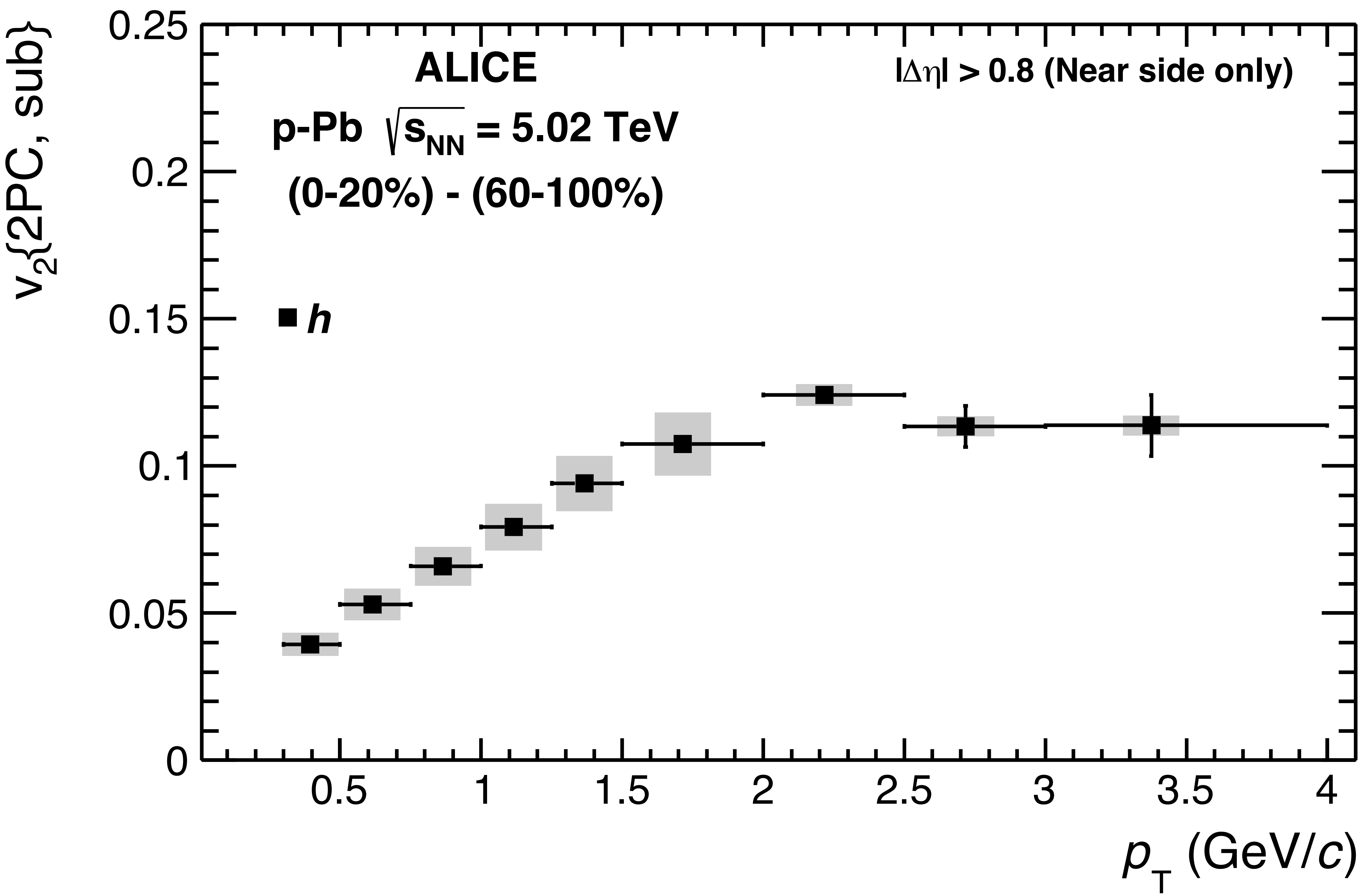
Single particle modulation can be extracted as:

$$v_n^h\{2\mathrm{PC}\} = \sqrt{V_{n\Delta}^{h-h}}$$ (symmetric trigger and associate particles)

$$v_n^i\{2\mathrm{PC}\} = V_{n\Delta}^{h-i}/\sqrt{V_{n\Delta}^{h-h}}$$ (different particle species)

ALICE, PLB 719, 29-41 (2013)

v_2 of h, π, K, p in high-multiplicity p-Pb



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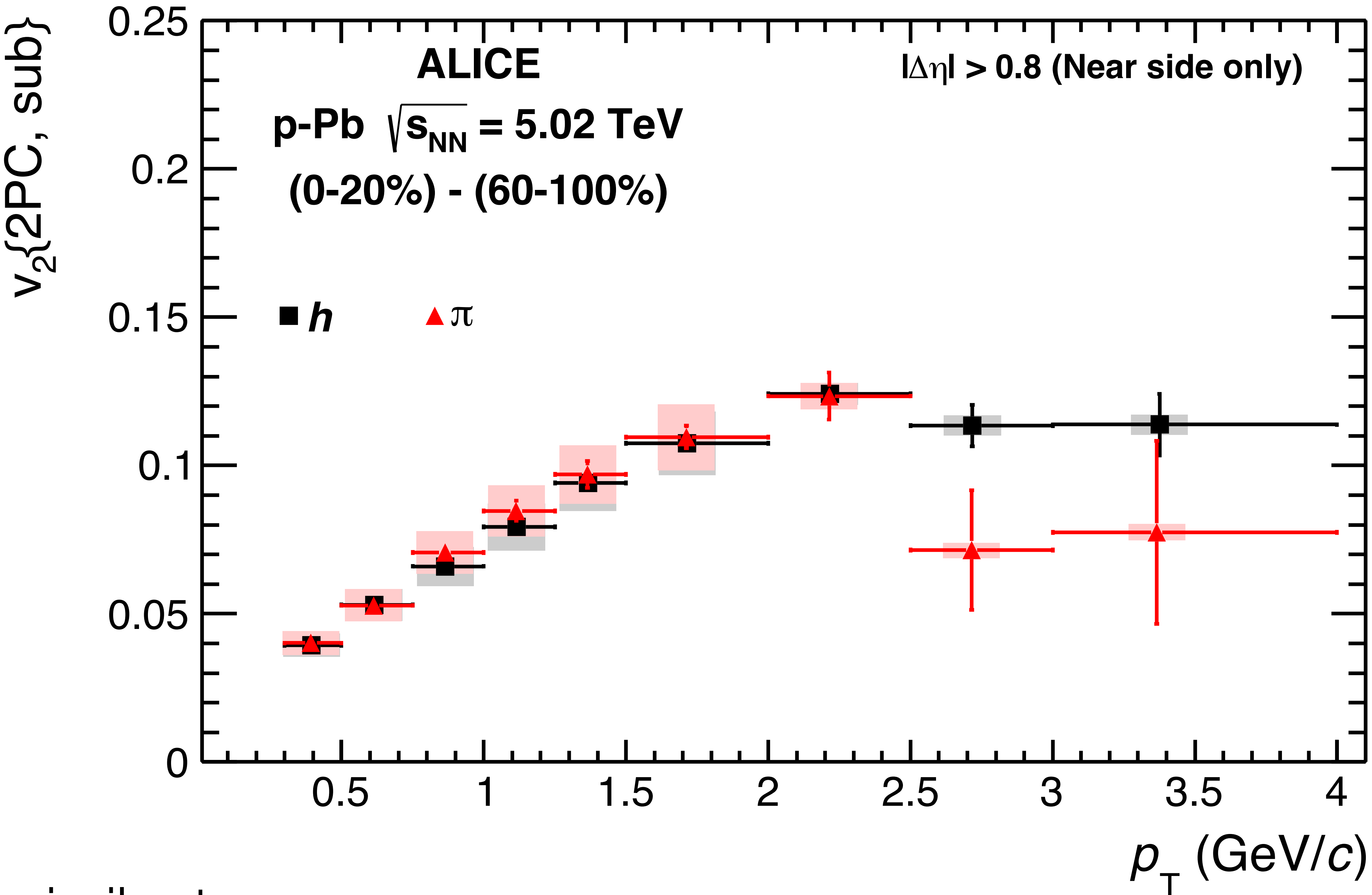
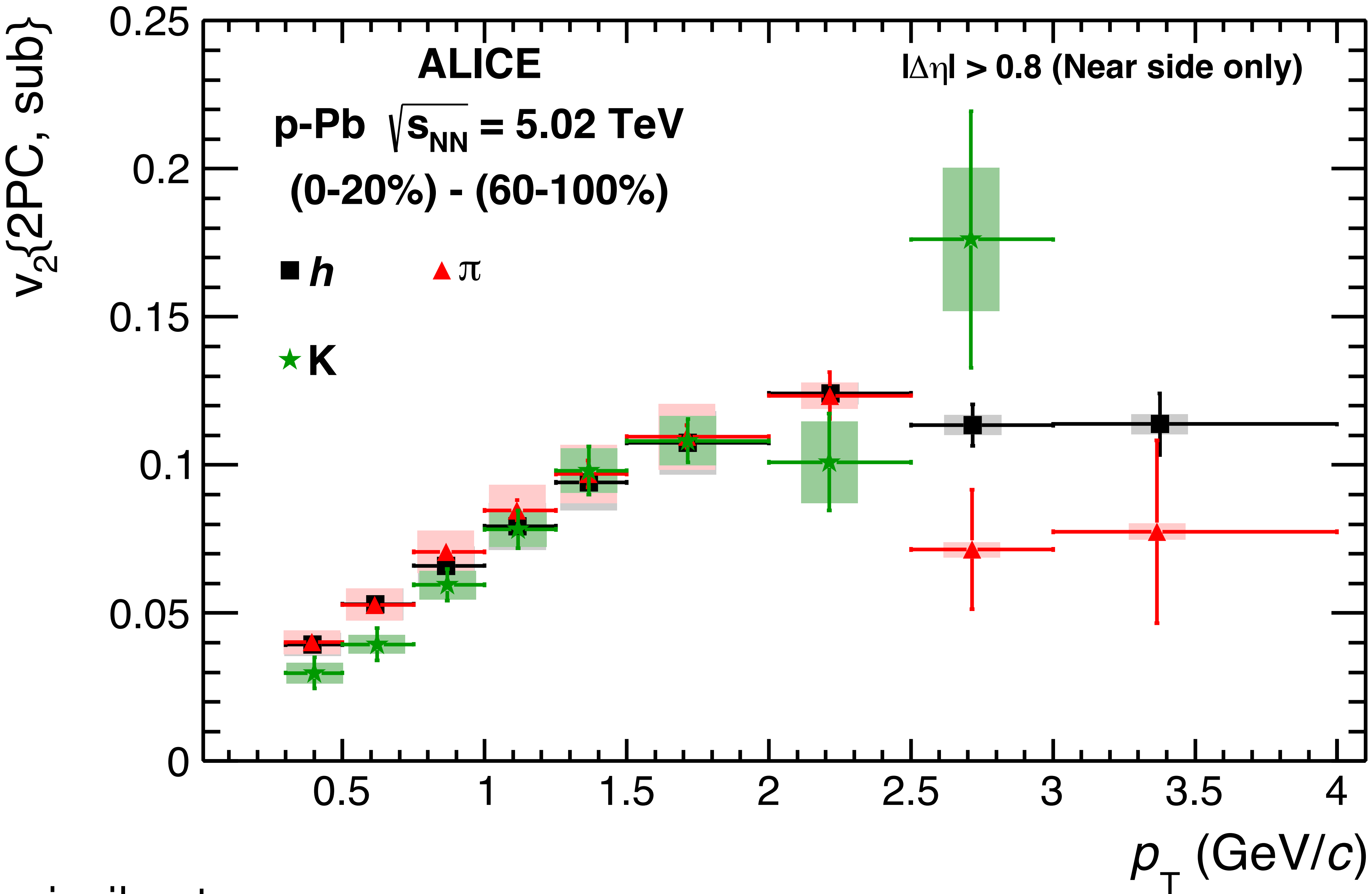


$v_{2,\pi}$ similar to $v_{2,h}$

v_2 of h, π, K, p in high-multiplicity p-Pb



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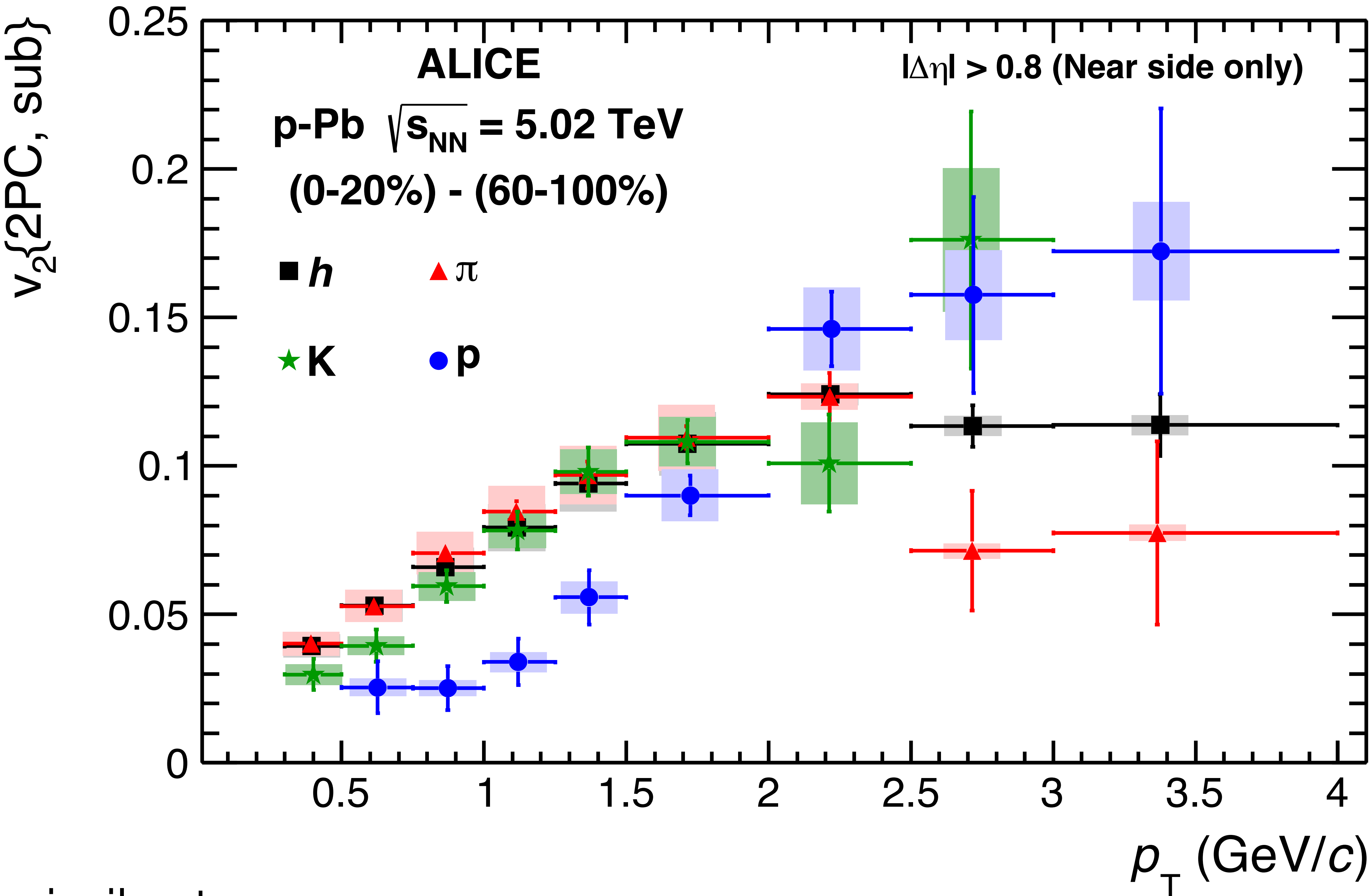
Hint of $\boldsymbol{v_{2,K}}$ smaller than $v_{2,\pi}$ at low p_T

v_2 of h, π, K, p in high-multiplicity p-Pb

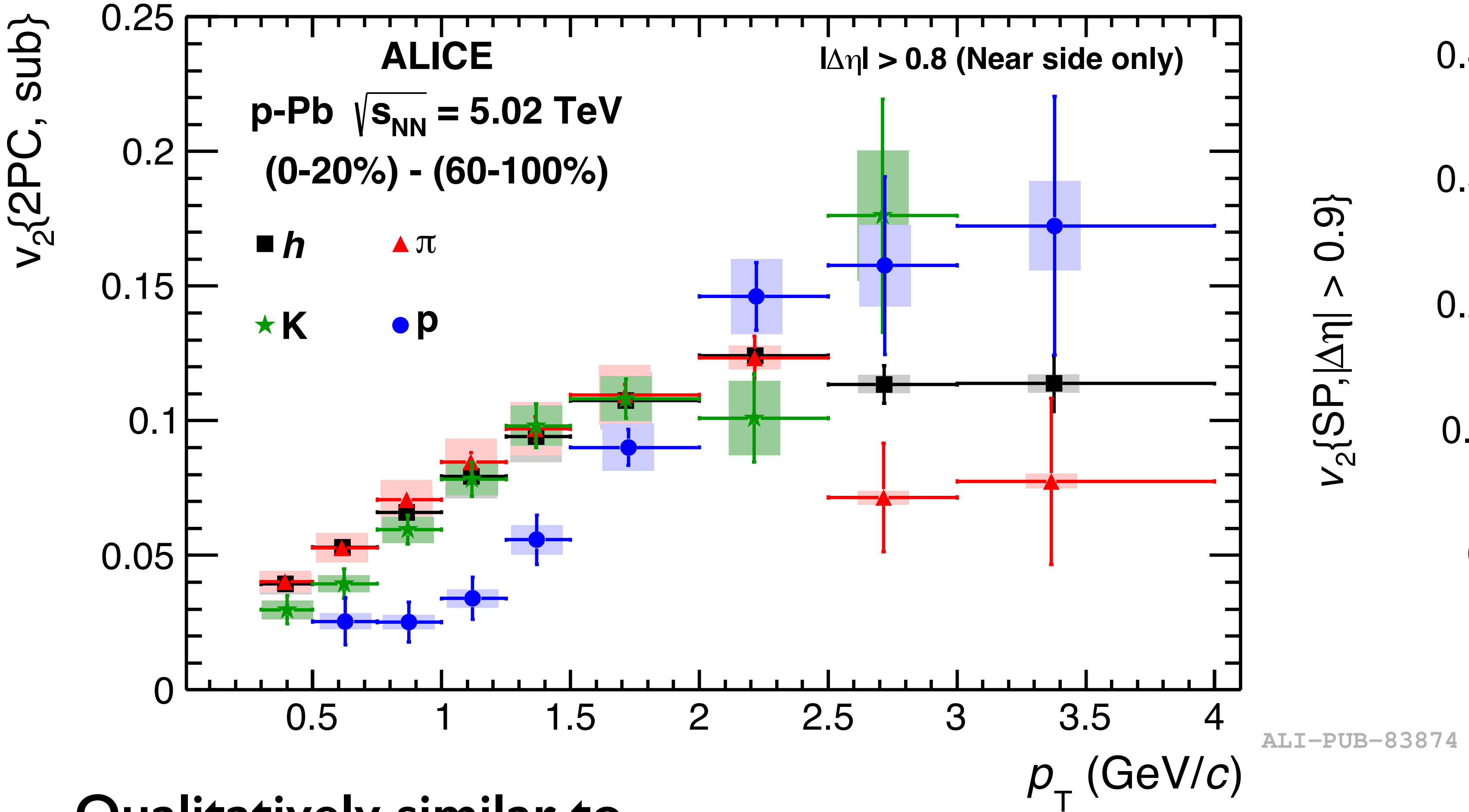


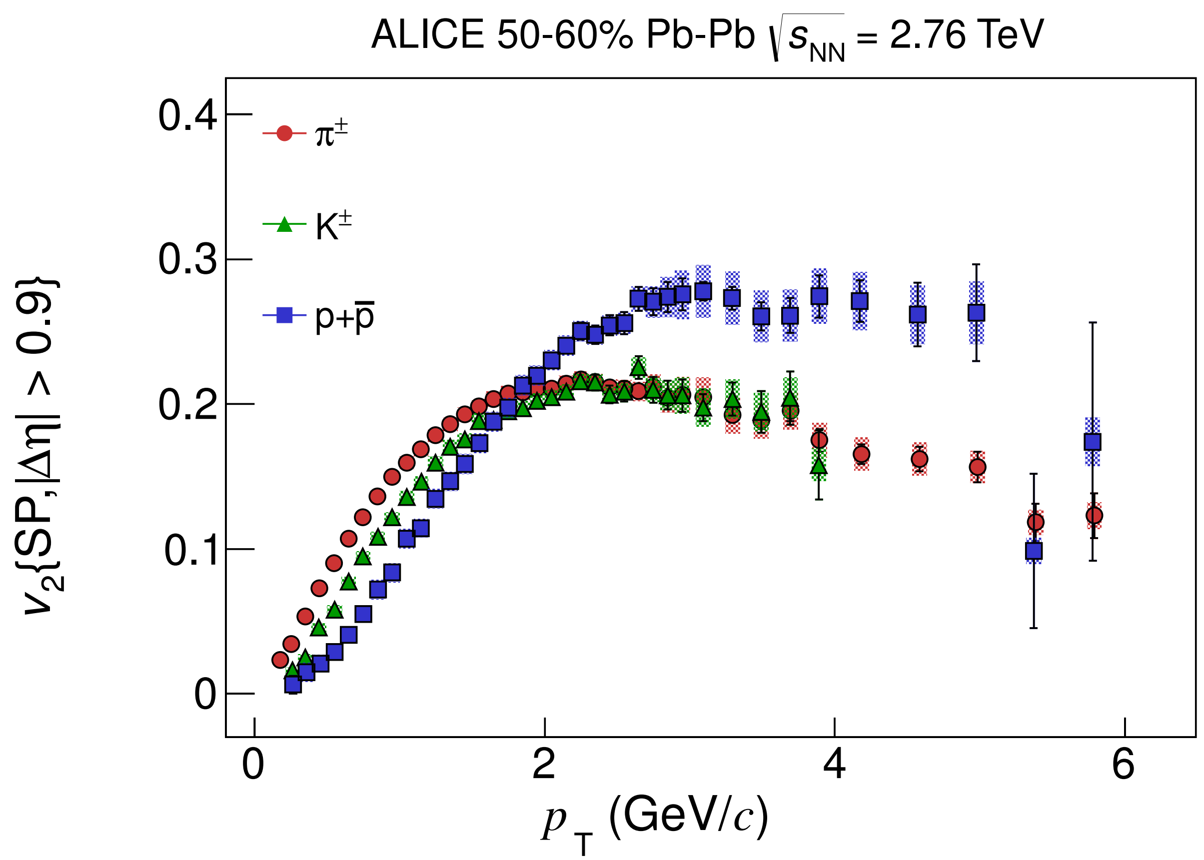
$\boldsymbol{v_{2,\pi}}$ similar to $\boldsymbol{v_{2,h}}$

Hint of $\boldsymbol{v_{2,K}}$ smaller than $v_{2,\pi}$ at low p_T

$v_{2,p}$ smaller than $v_{2,\pi}$ below 2 GeV/c and larger above crossing at about 2 GeV/c

ALICE, PLB 726 164-177 (2013)

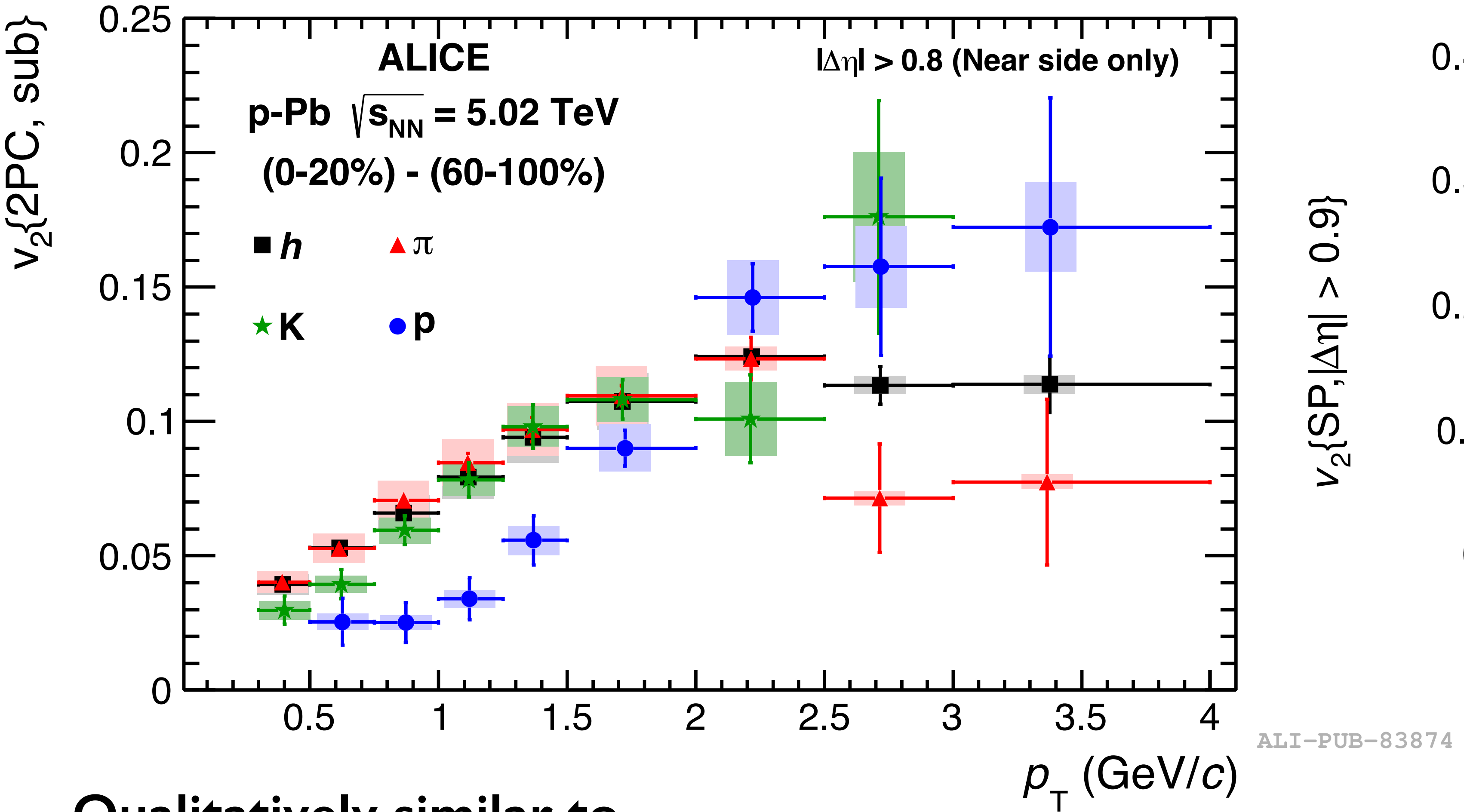


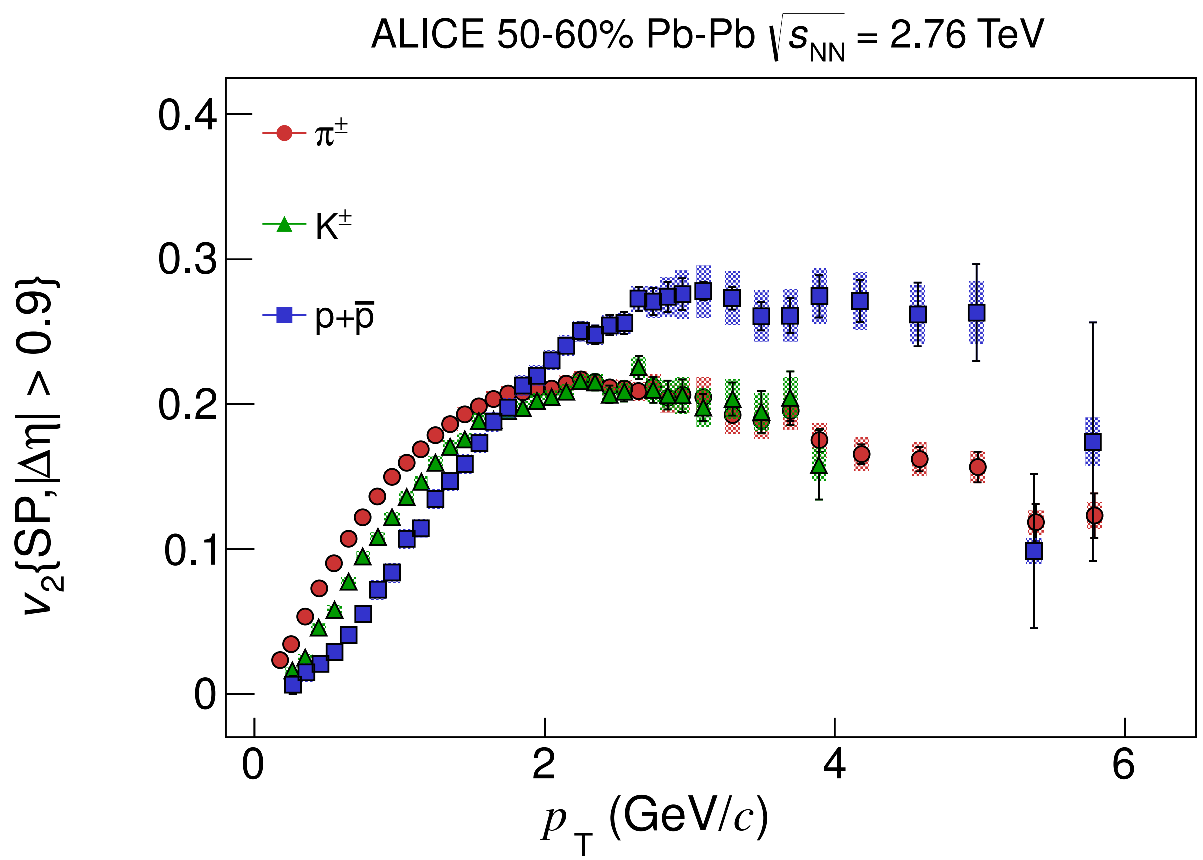


ALICE, JHEP 06 (2015) 190
arXiv:1405.4632 [nucl-ex]

Qualitatively similar to Pb-Pb collisions

v_2 of π, K, p in high-multiplicity p-Pb





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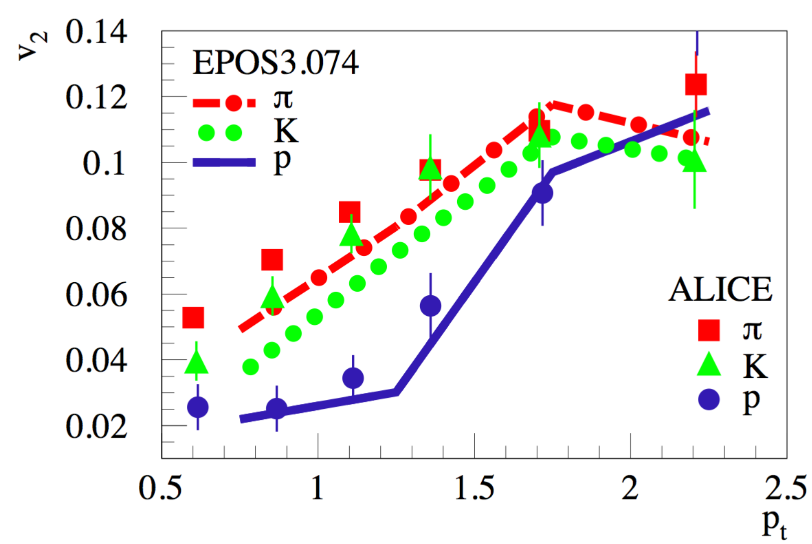
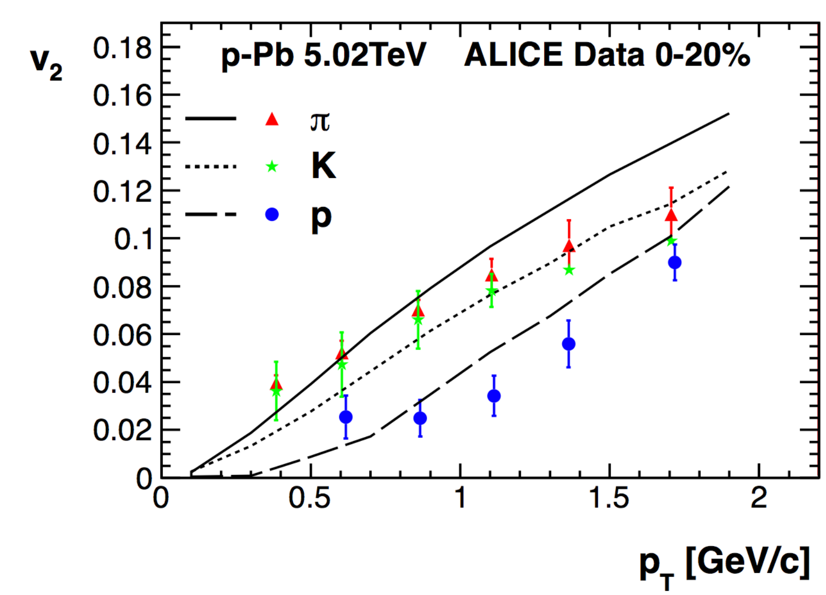
Qualitatively similar to Pb-Pb collisions

… and consistent with hydro predictions

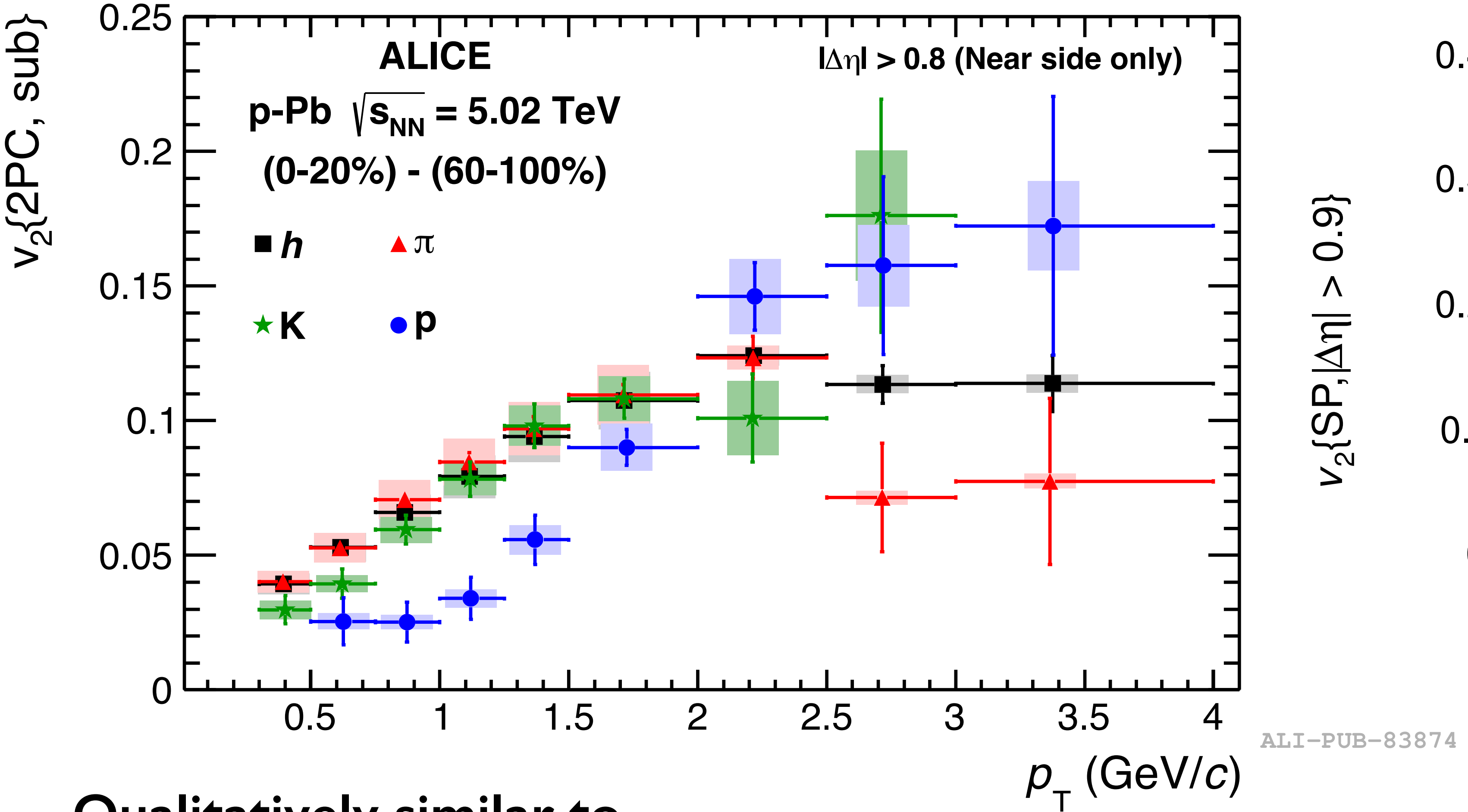


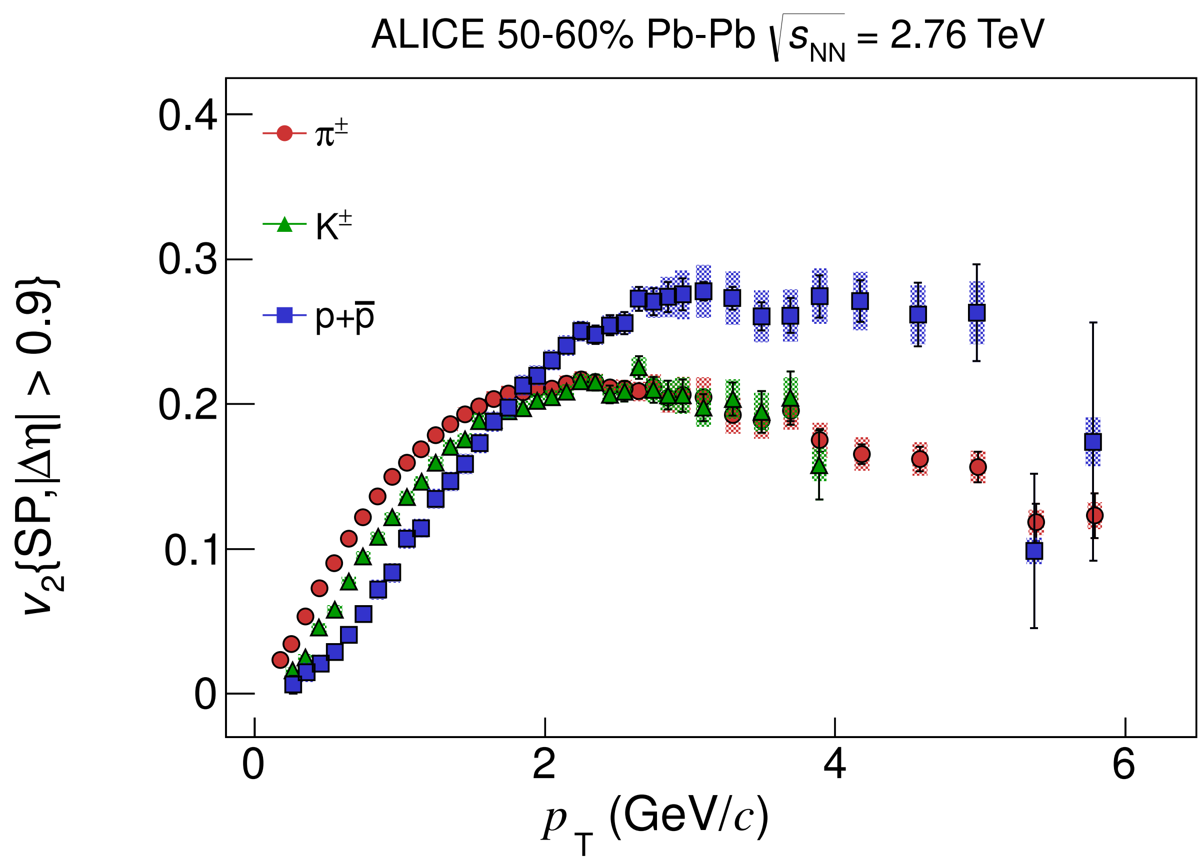
K. Werner et al, PRL 112, 232301
arXiv:1307.4379 [nucl-th]



P. Bozek, et al,
PRL 111, 172303 (2013)

v_2 of π, K, p in high-multiplicity p-Pb





ALICE, JHEP 06 (2015) 190
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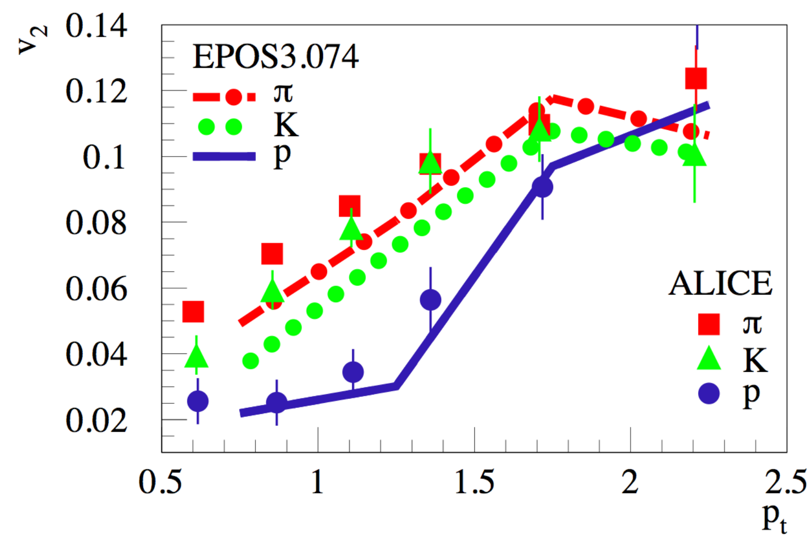
Qualitatively similar to Pb-Pb collisions

… and consistent with hydro predictions

Double ridge structure also in Color Glass Condensate (CGC) model

See, e.g. K. Dusling et al, PRD87 (2013) 094034.



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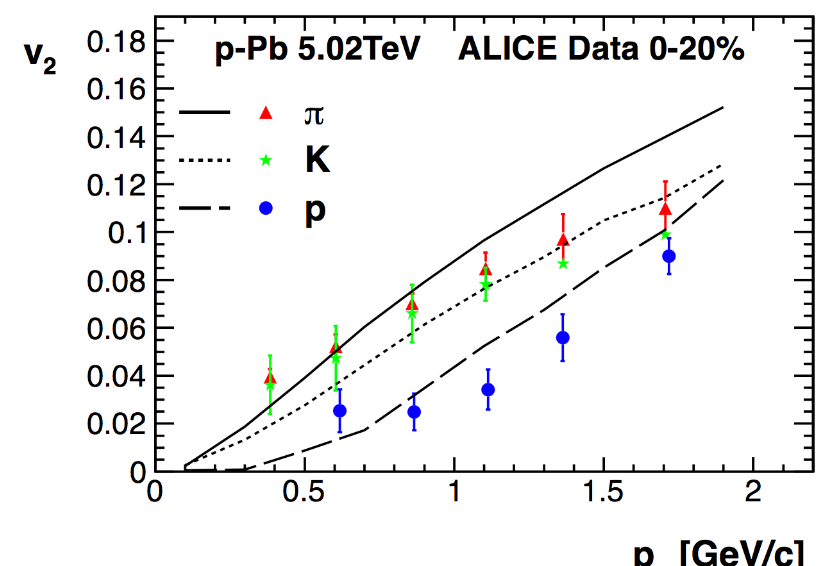
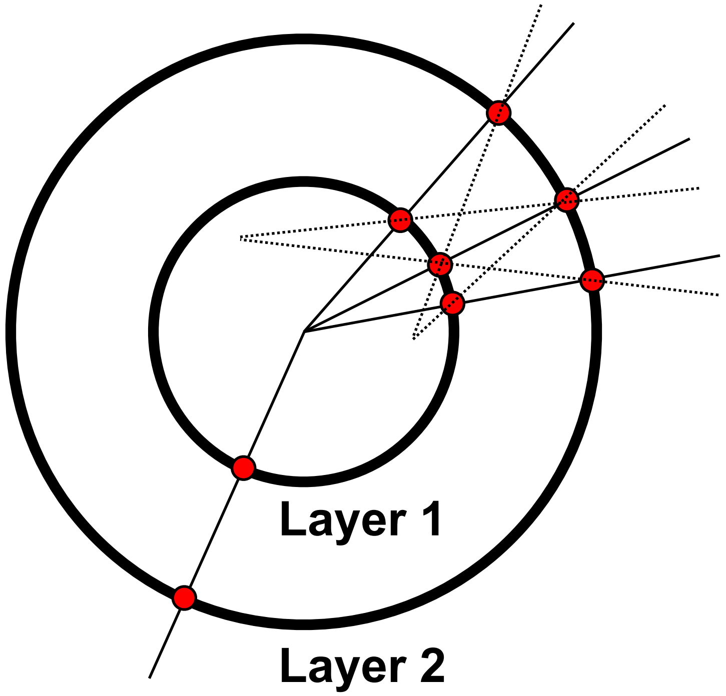


P. Bozek, et al, PRL 111, 172303 (2013)

Forward-Central Correlations

- **Hadrons** at mid rapidity **($|\eta| < 1.0$)** and forward inclusive muons **($-4 < \eta < -2.5$)**
- **Tracklets**
  - Straight line using first two layers of ITS
  - $\langle p_T \rangle \sim 0.75$ GeV/c
  - Cross-checked with reconstructed tracks (lower statistics)



arXiv:1506.08032

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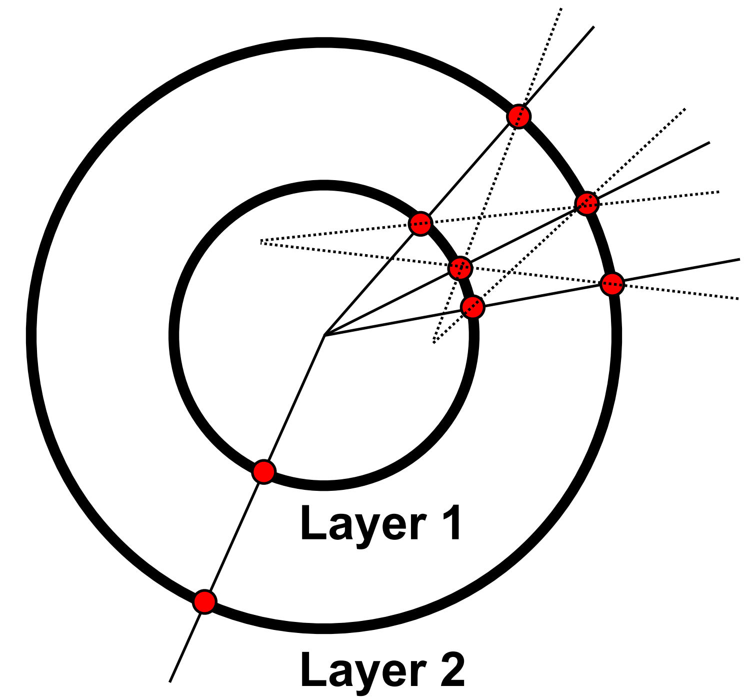
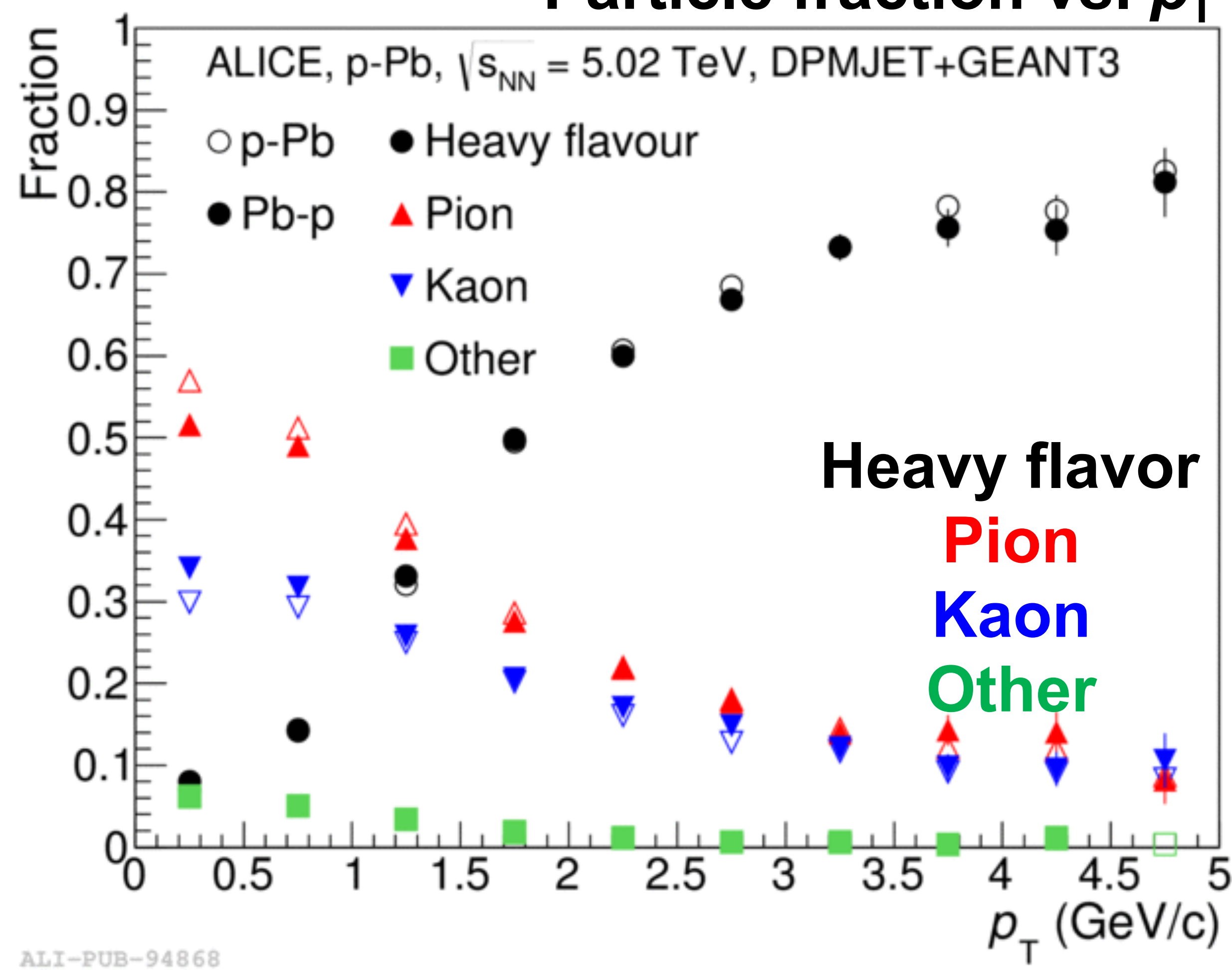
- Inclusive **muons**
  - **Composition** varies as a function of p_T
  - Higher p_T: dominated by **heavy flavor**



Particle fraction vs. p_T



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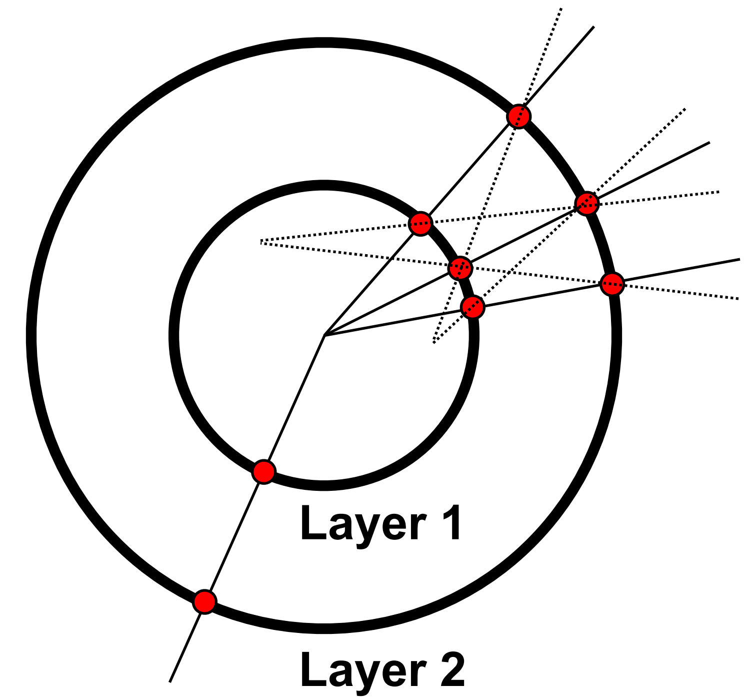
  - Higher p_T: dominated by **heavy flavor**
- Sample split into **multiplicity classes** (V0, 2.8 < η < 3.9 and -3.7 < η < -2.7)
  - Symmetric for both beam configurations
  - 0-20% = high mult; 60-100% low mult



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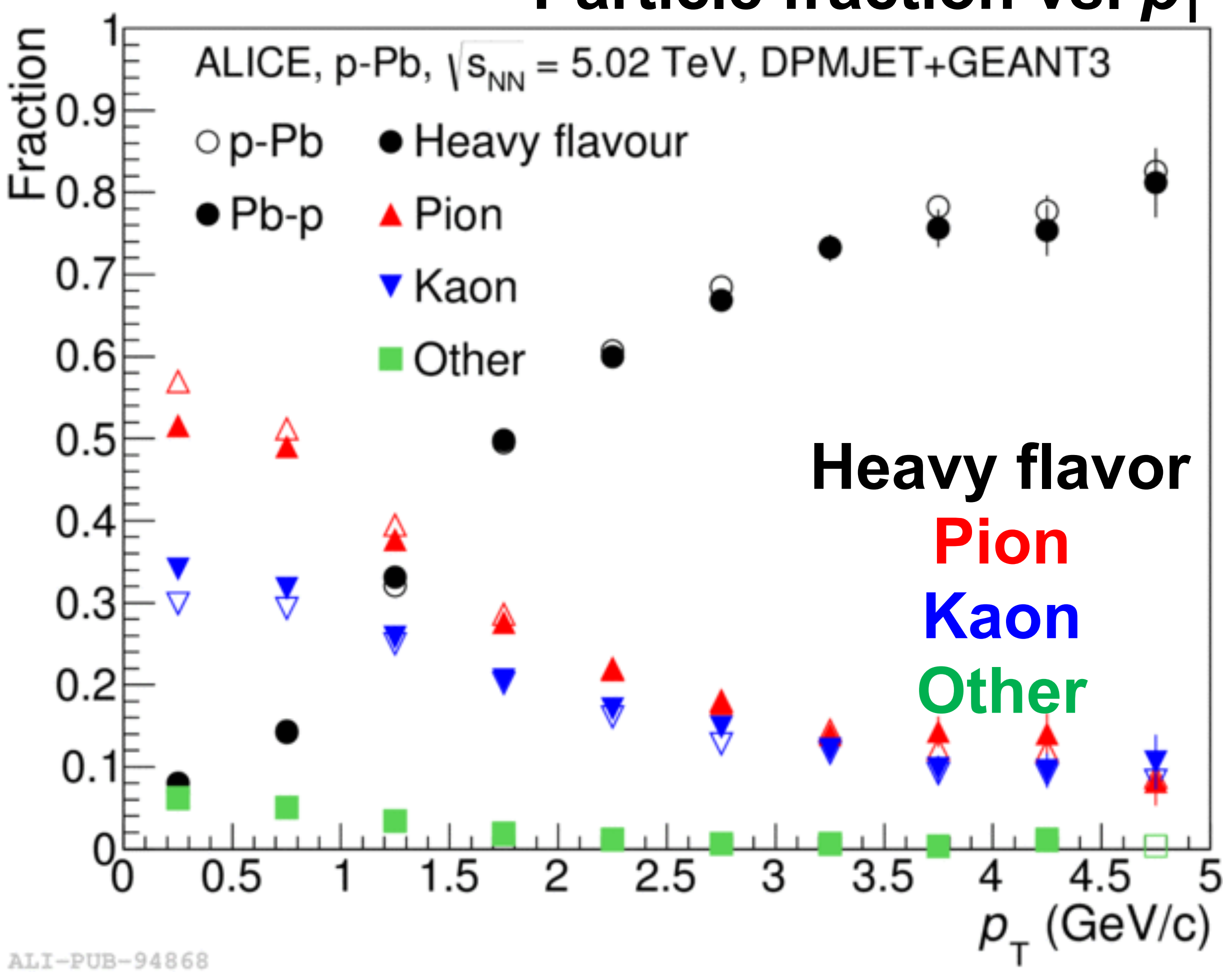


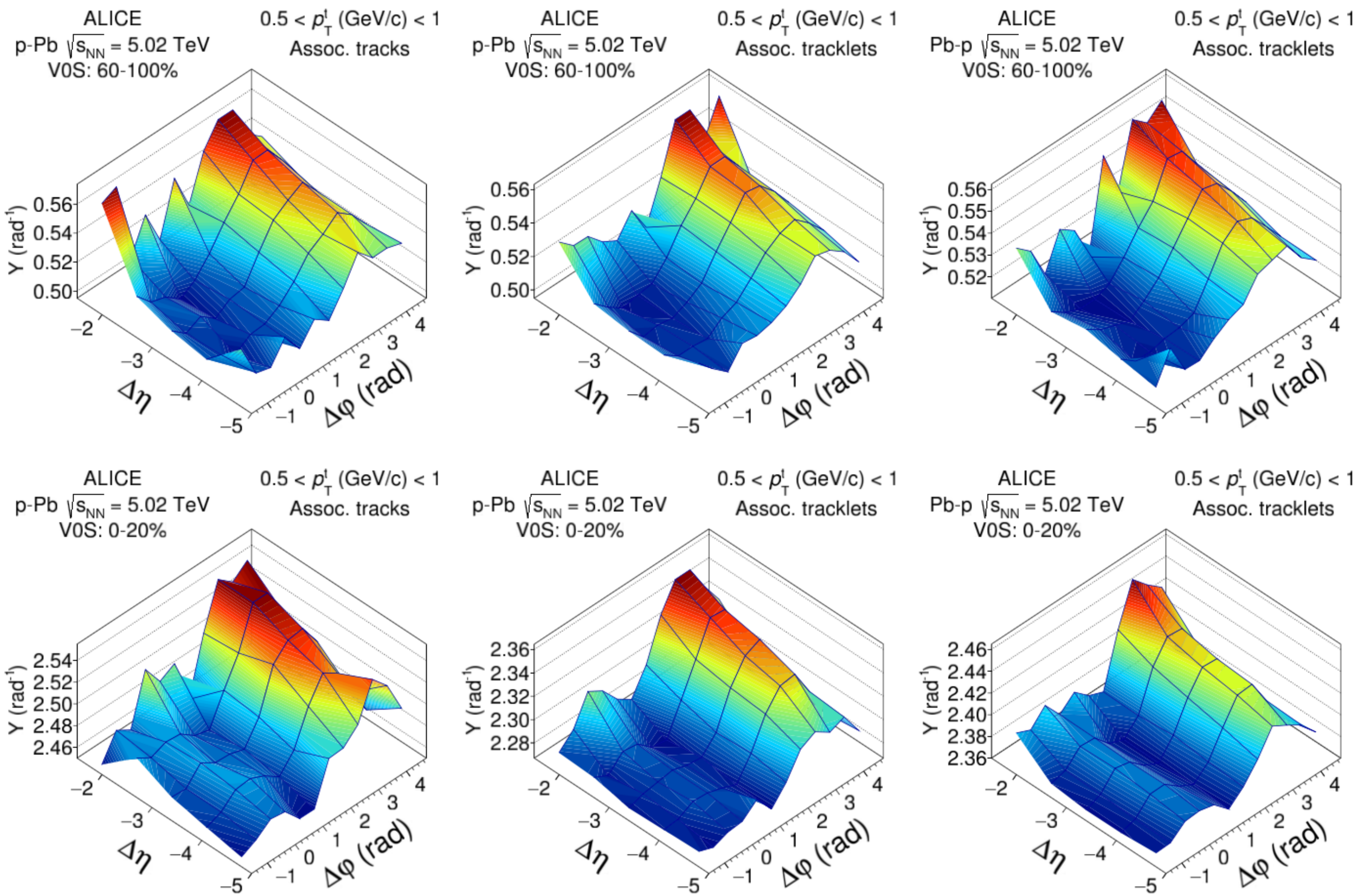
arXiv:1506.08032

Associated yield per trigger particle

μ-track (p-Pb) | μ-tracklet (p-Pb) | μ-tracklet (Pb-p)

low mult.

high mult.



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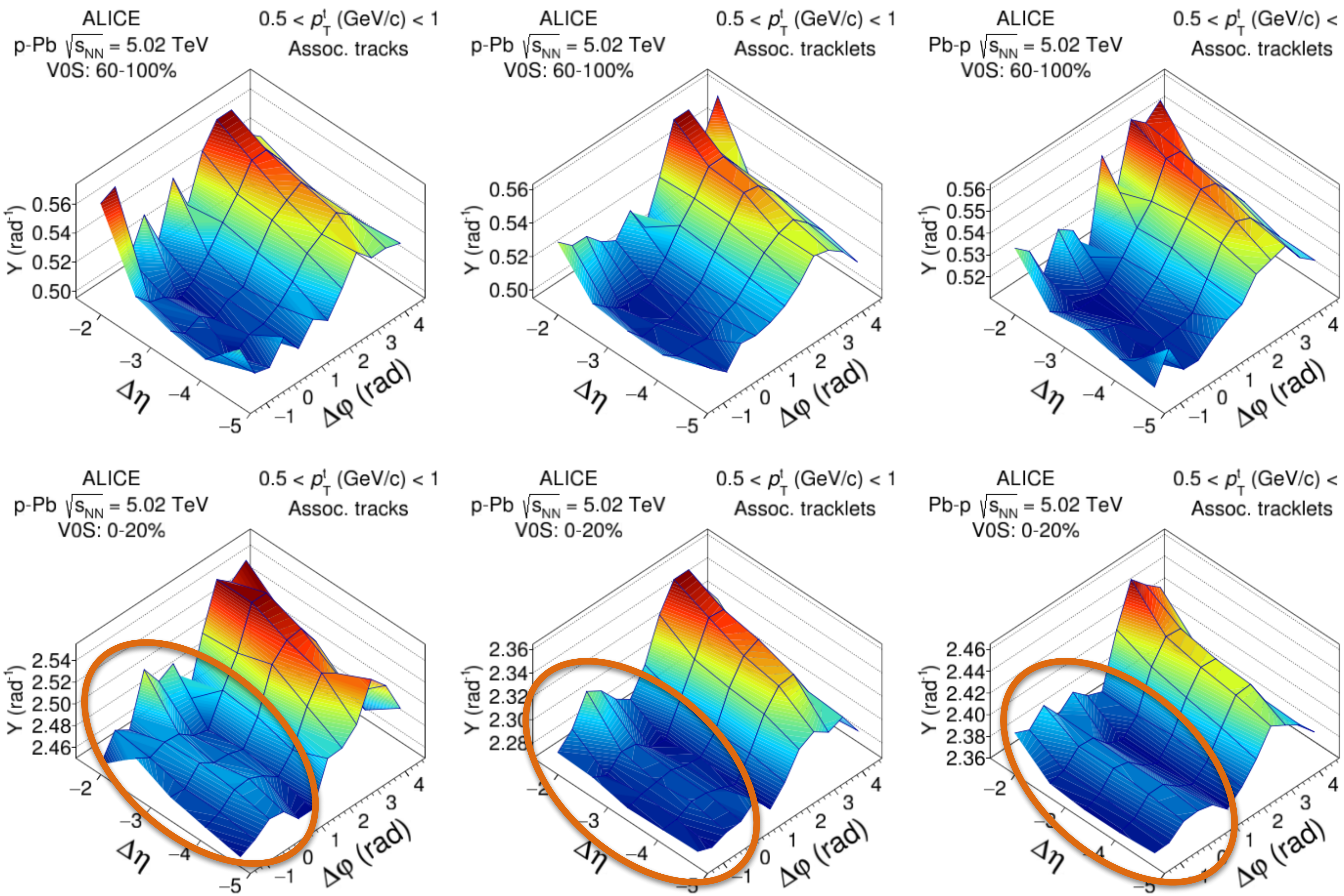
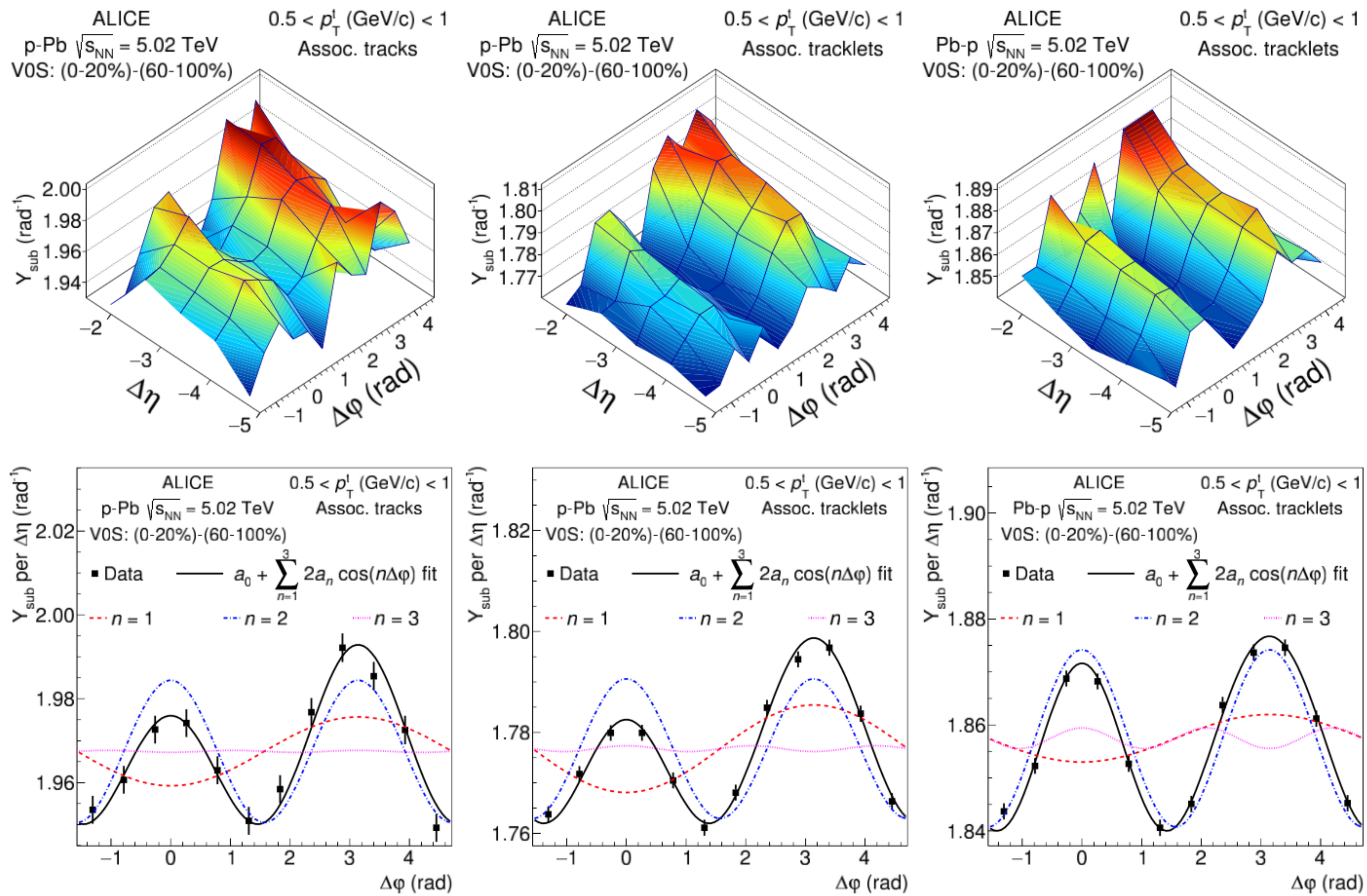


Associated yield per trigger particle

μ-track (p-Pb) | μ-tracklet (p-Pb) | μ-tracklet (Pb-p)

High-low mult.



Validation of the tracklet analysis

$$v_n^{\mu}\{2\mathrm{PC},\mathrm{sub}\} = V_{n\Delta}\{2\mathrm{PC},\mathrm{sub}\}/\sqrt{V_{n\Delta}^{c}\{2\mathrm{PC},\mathrm{sub}\}}$$

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v_n of muons measured in the muon arm

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v_n of muons measured in the muon arm

Measured in the central barrel (track-track or tracklet-tracklet)

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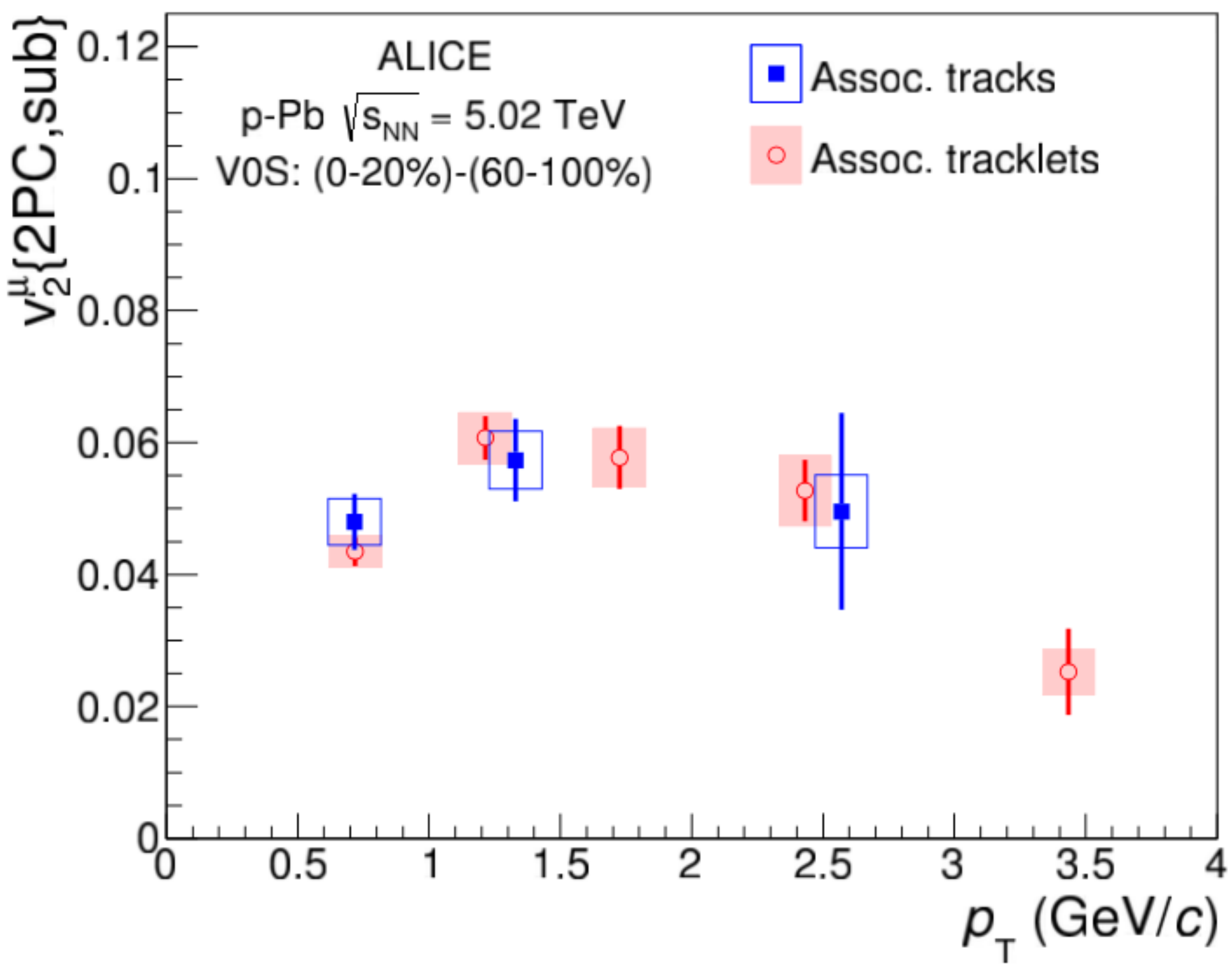
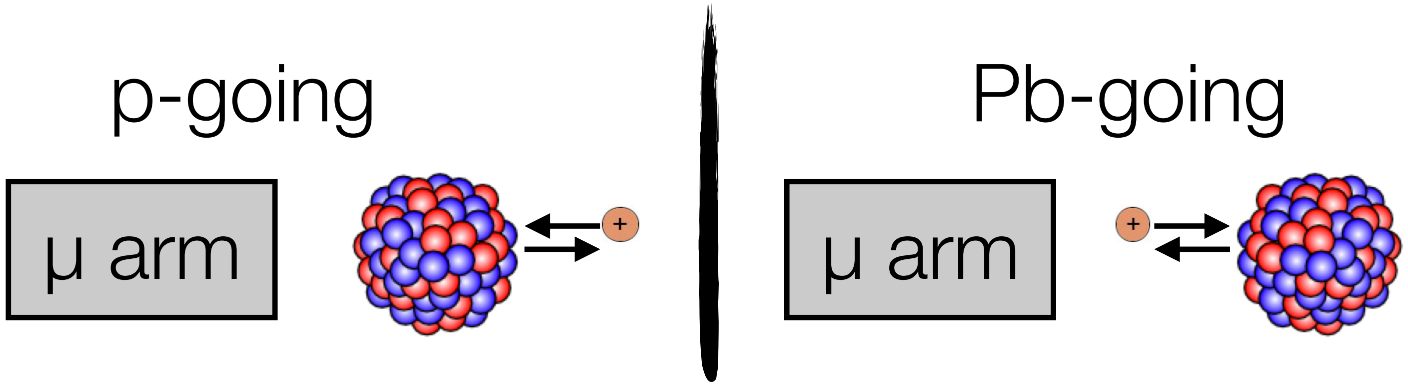
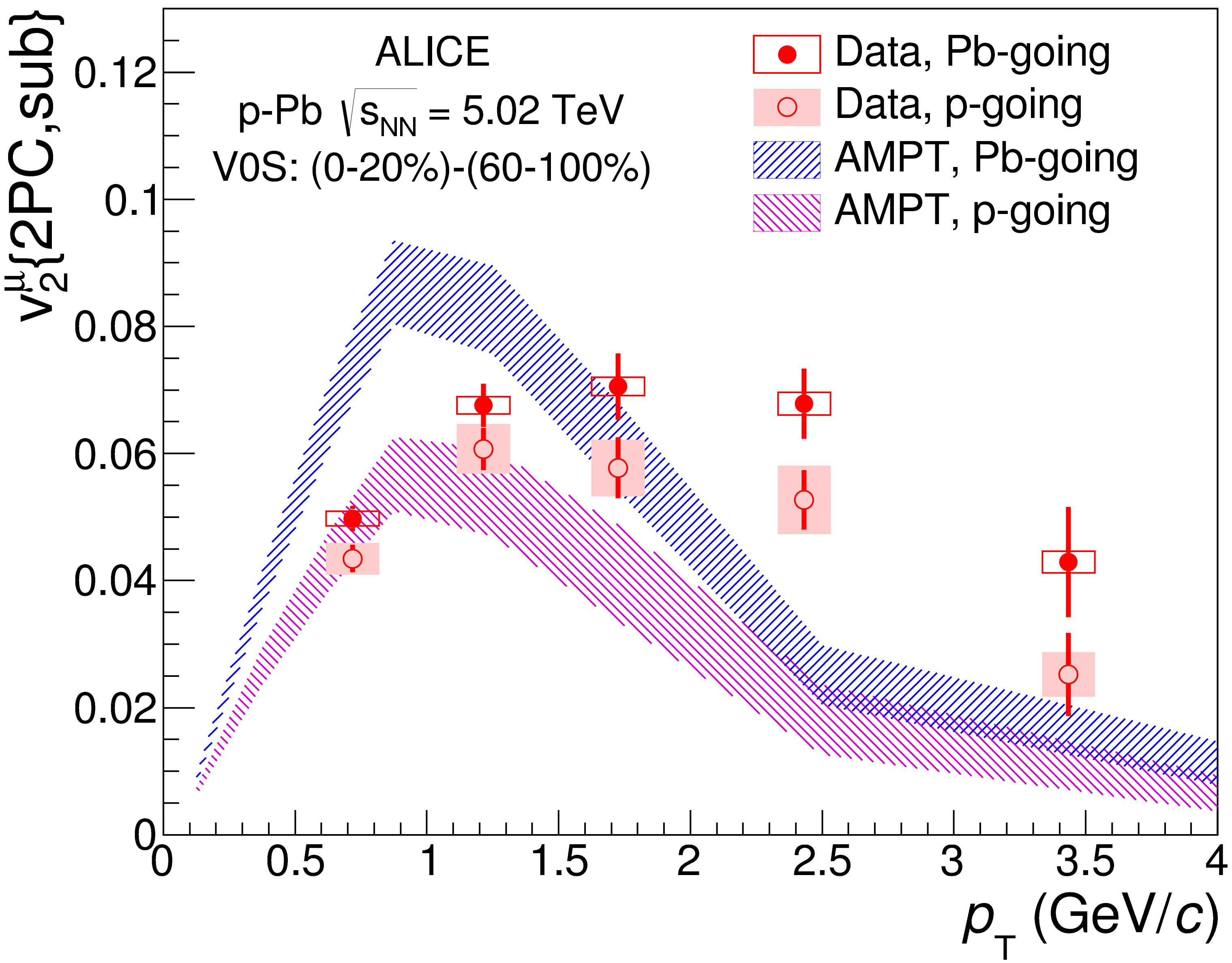


Good agreement between the two analyses, tracklet analysis works!

Forward-μ – hadron correlations



Similar p_T dependence in p-going and Pb-going directions



~(16±6)% higher in the Pb-going direction

arXiv:1506.08032 [nucl-ex]

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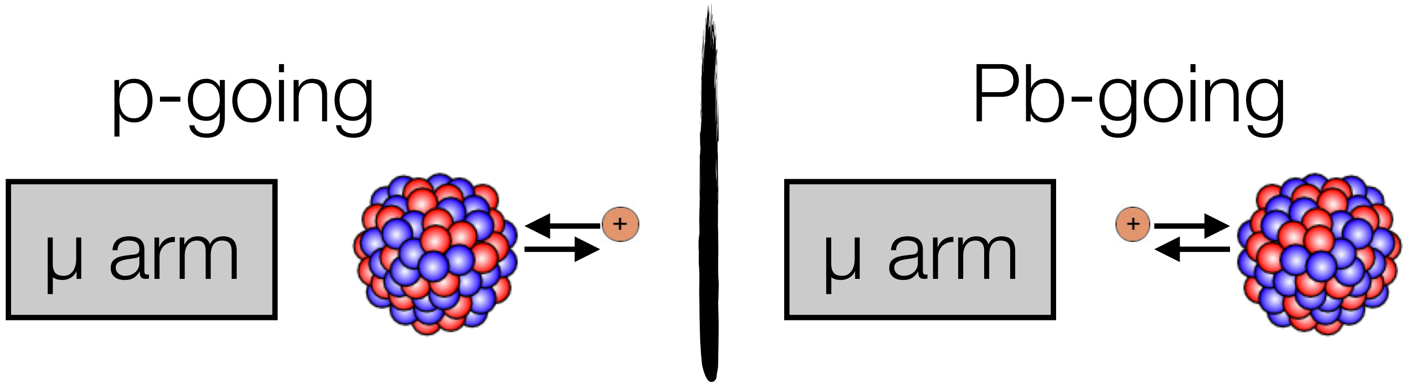

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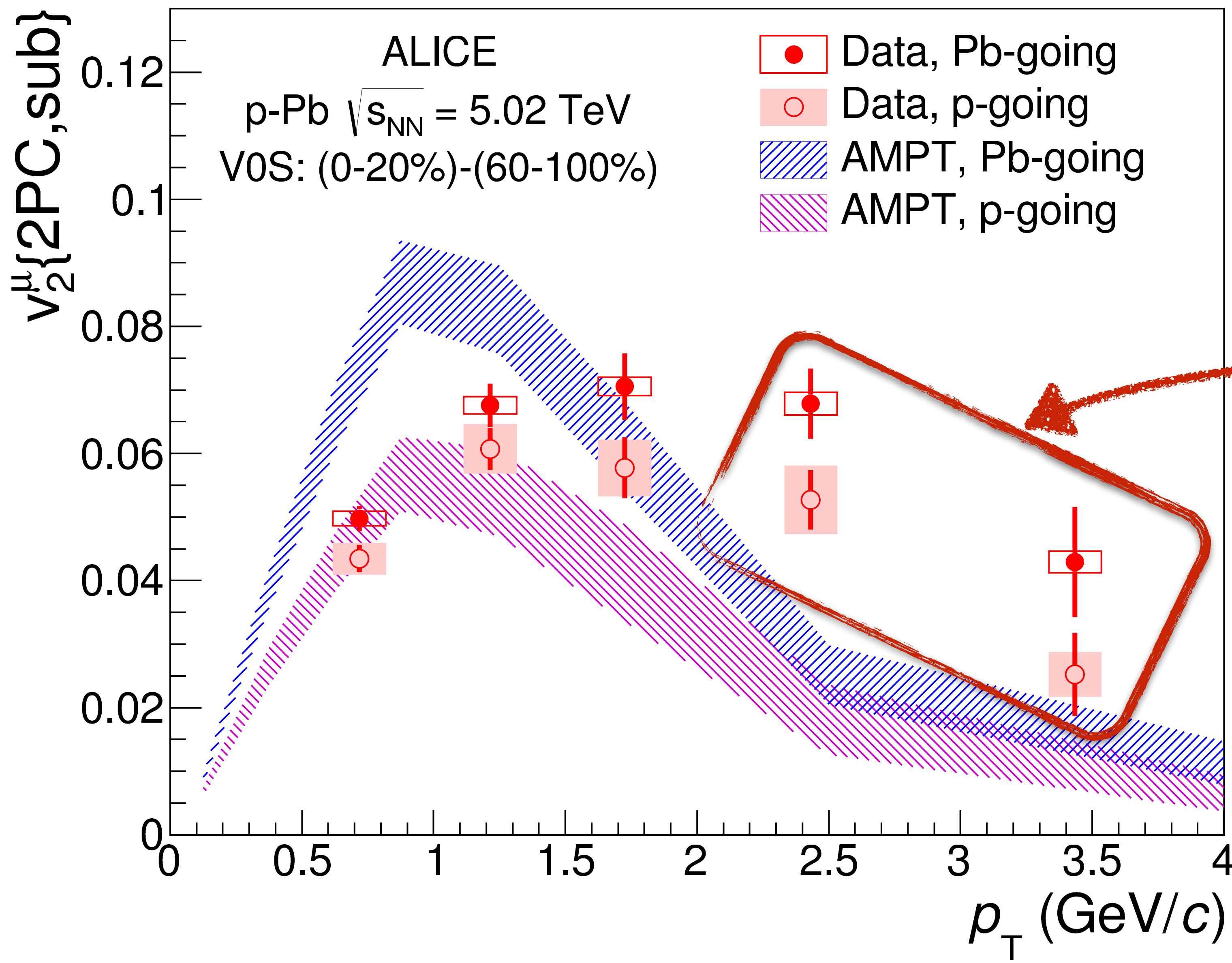

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μ ← HF dominate!

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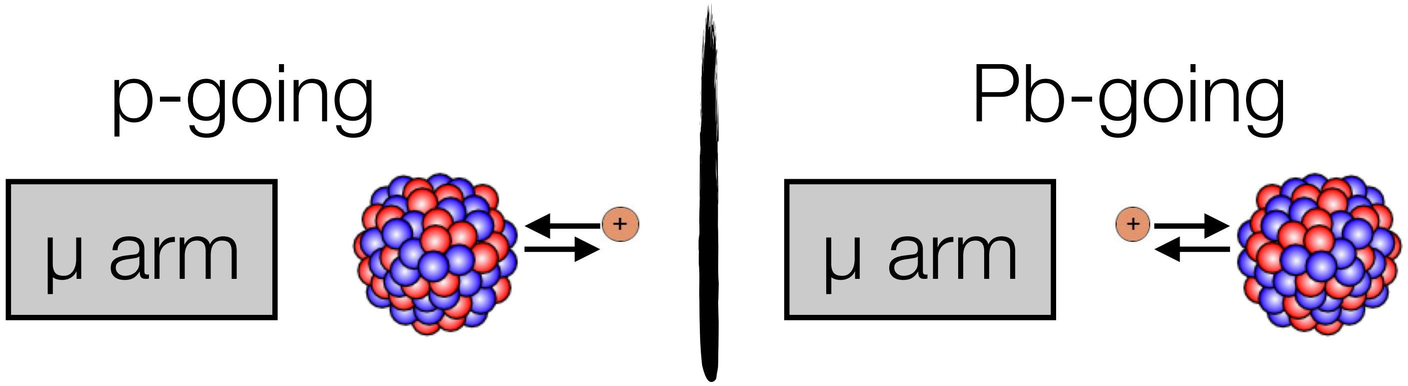

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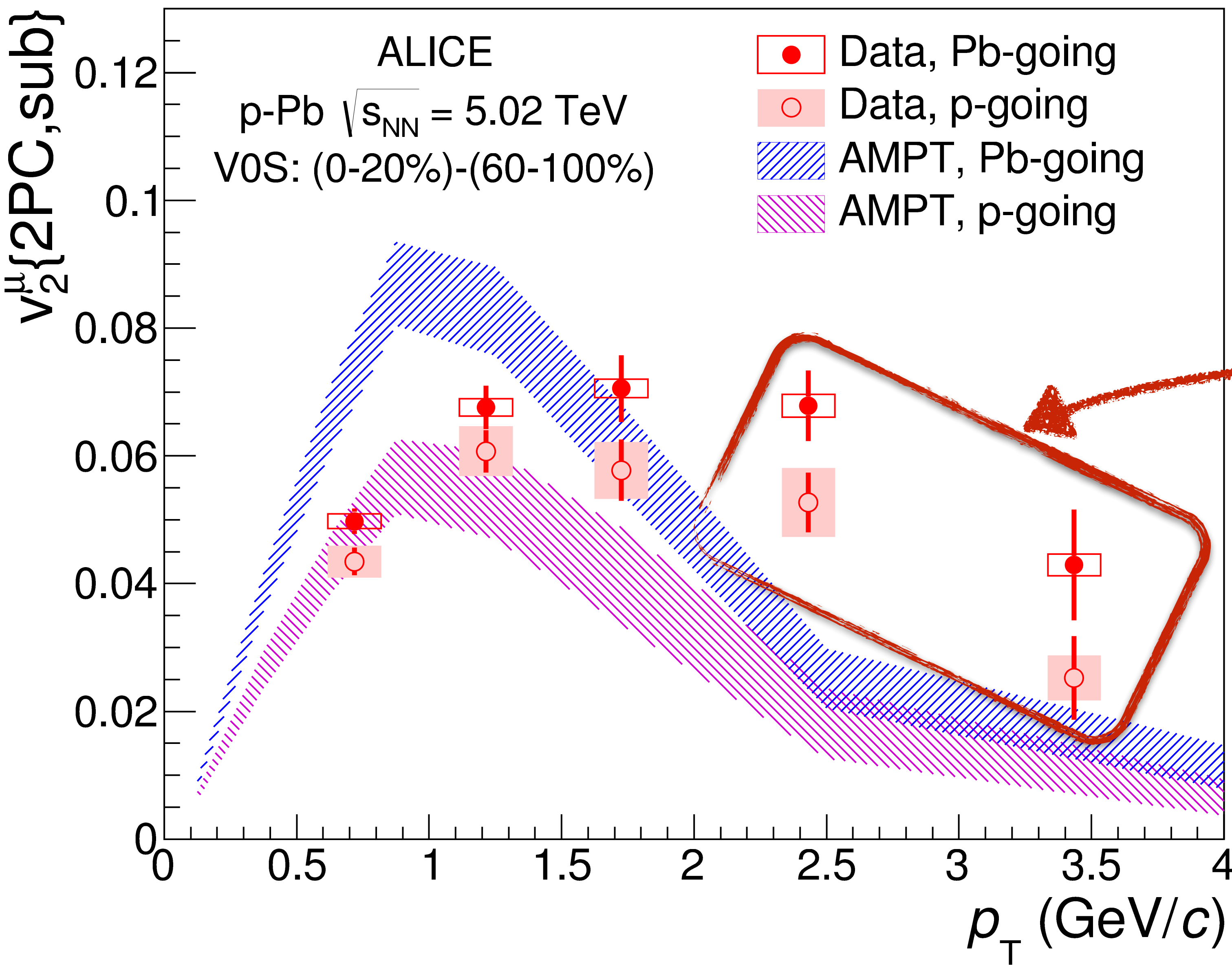

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~(16±6)% higher in the Pb-going direction

μ ← HF dominate!

Possible scenarios:

v_2 > 0 for HF decay muons? (no HF v_2 in AMPT)

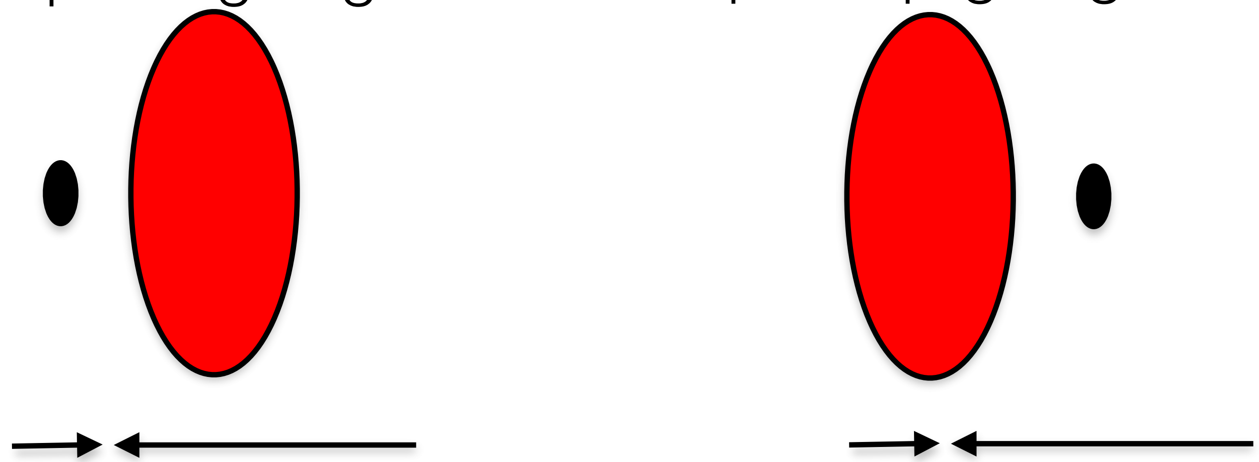
Different parent particle composition?

Origin of the double ridge(s)?

Saturation effects

Pb-p: Pb going side

p-Pb: p-going side



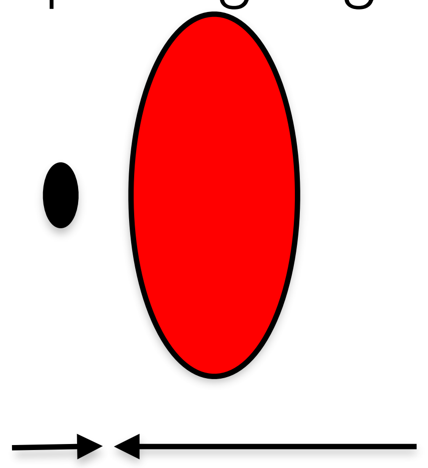
Large-x gluons in the Pb
CGC effects suppressed

Low-x gluons in the Pb
CGC effects enhanced

(naive expectation, no actual prediction yet)

Origin of the double ridge(s)?

Saturation effects



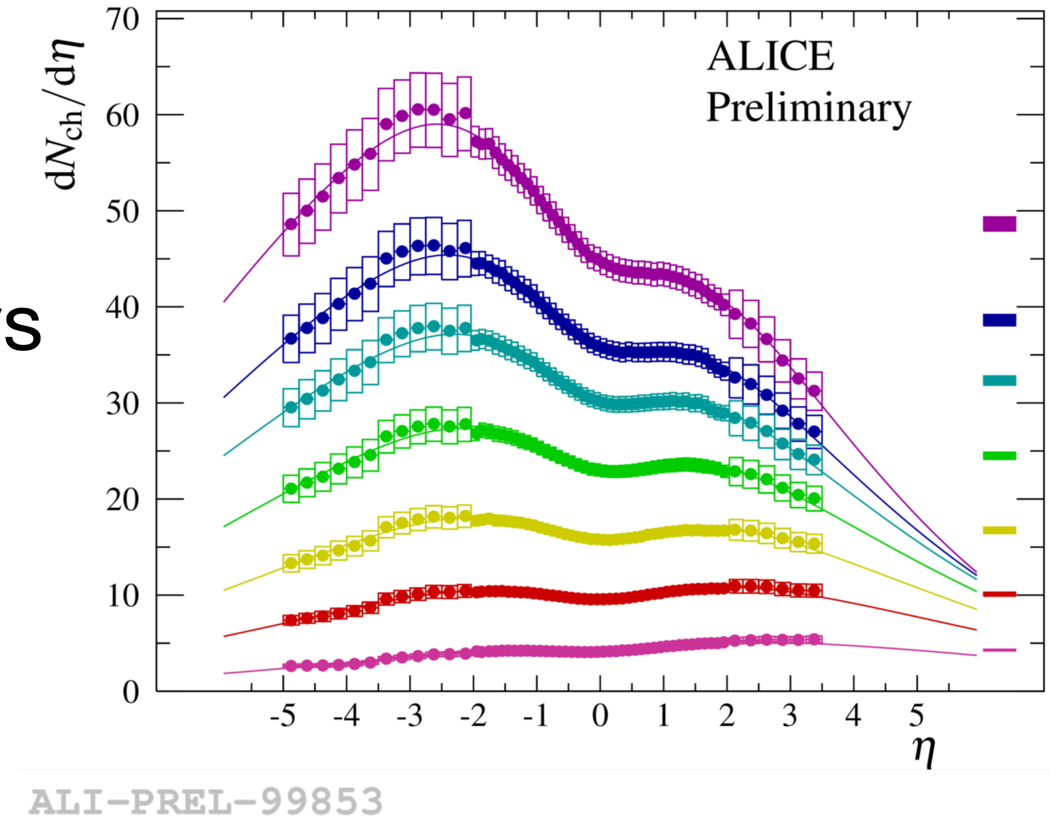
Large-x gluons in the Pb
CGC effects suppressed

Low-x gluons in the Pb
CGC effects enhanced

(naive expectation, no actual prediction yet)

vs

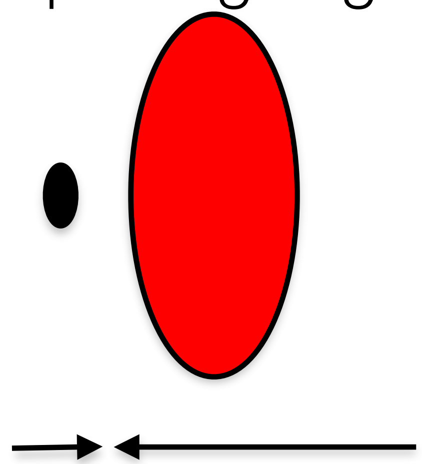
density effects (hydro?)



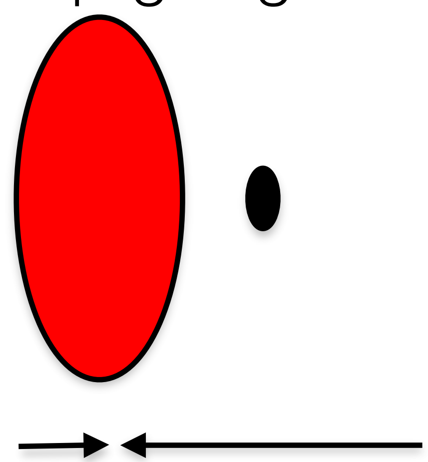
Origin of the double ridge(s)?

Saturation effects

Pb-p: Pb going side



p-Pb: p-going side



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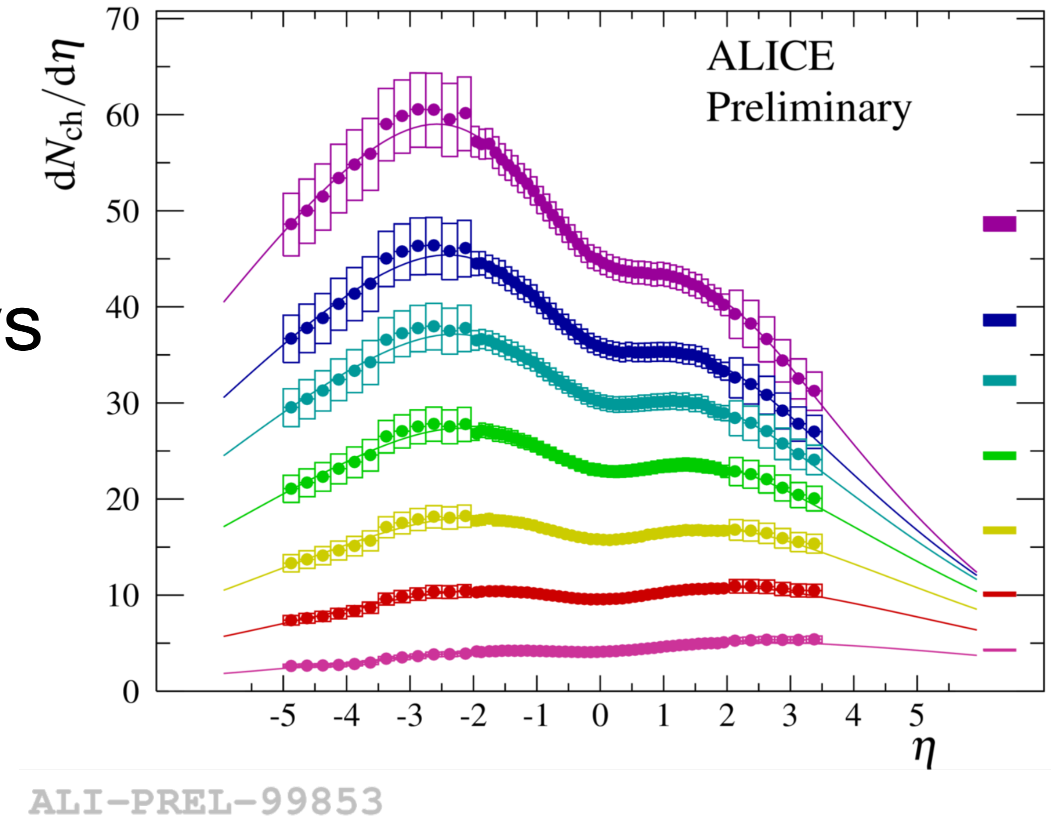


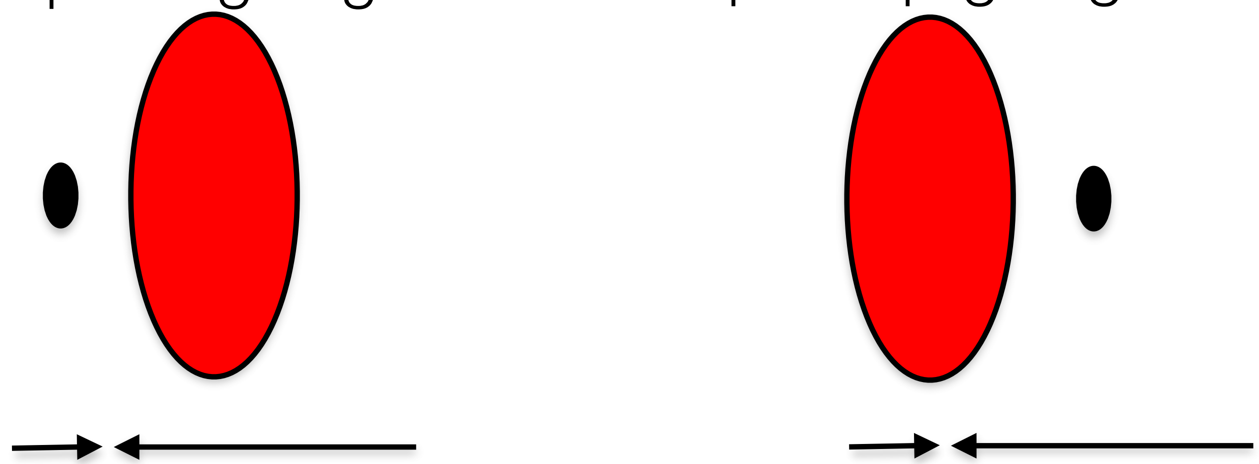
Forward rapidity measurements favor density effects

Origin of the double ridge(s)?

Saturation effects

Pb-p: Pb going side

p-Pb: p-going side



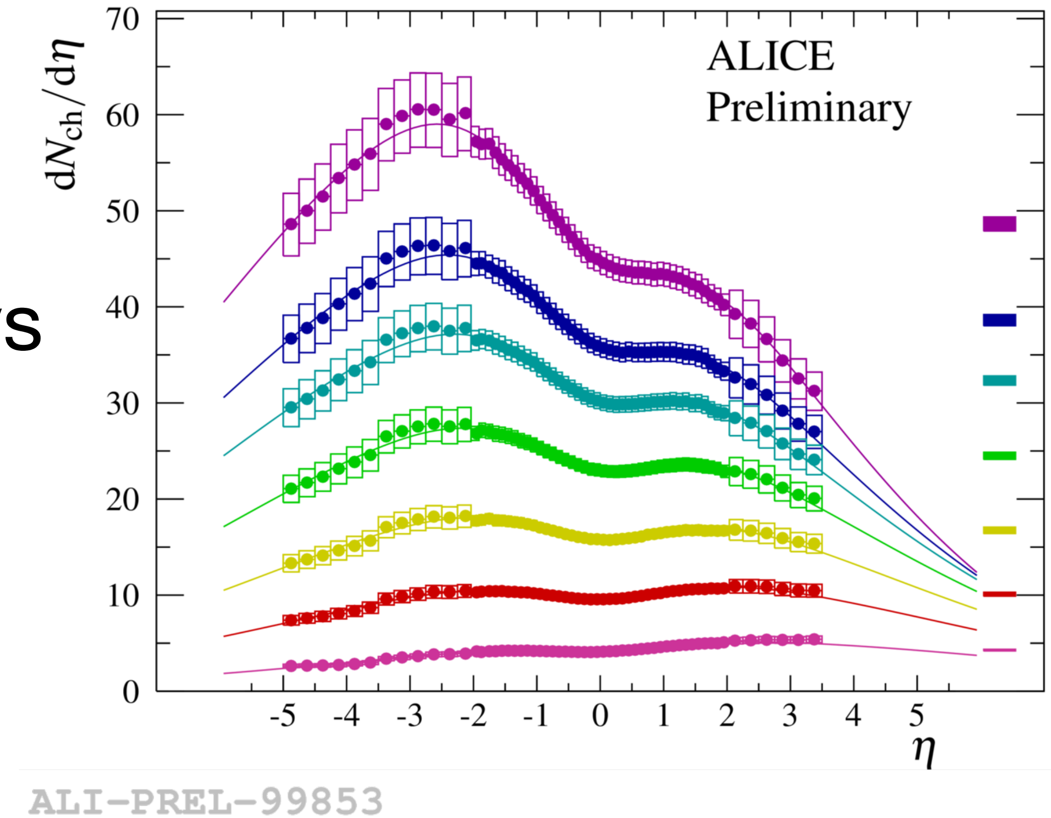
Large-x gluons in the Pb
CGC effects suppressed

Low-x gluons in the Pb
CGC effects enhanced

(naive expectation, no actual prediction yet)

vs

density effects (hydro?)



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Other ideas on the market for small systems ridges:

- Color connections in the longitudinal direction

  [B. Arbuzov, E. Boos, and V. Savrin, Eur.Phys.J. C71 (2011) 1730]

- Multiparton interactions

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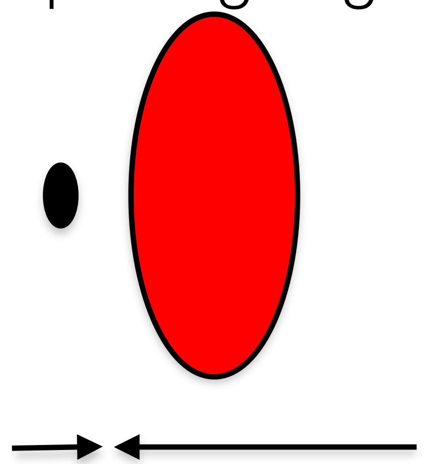

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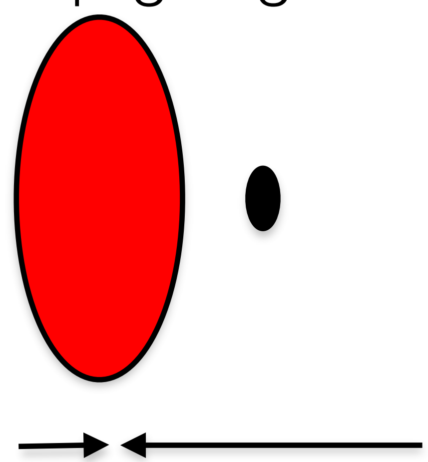

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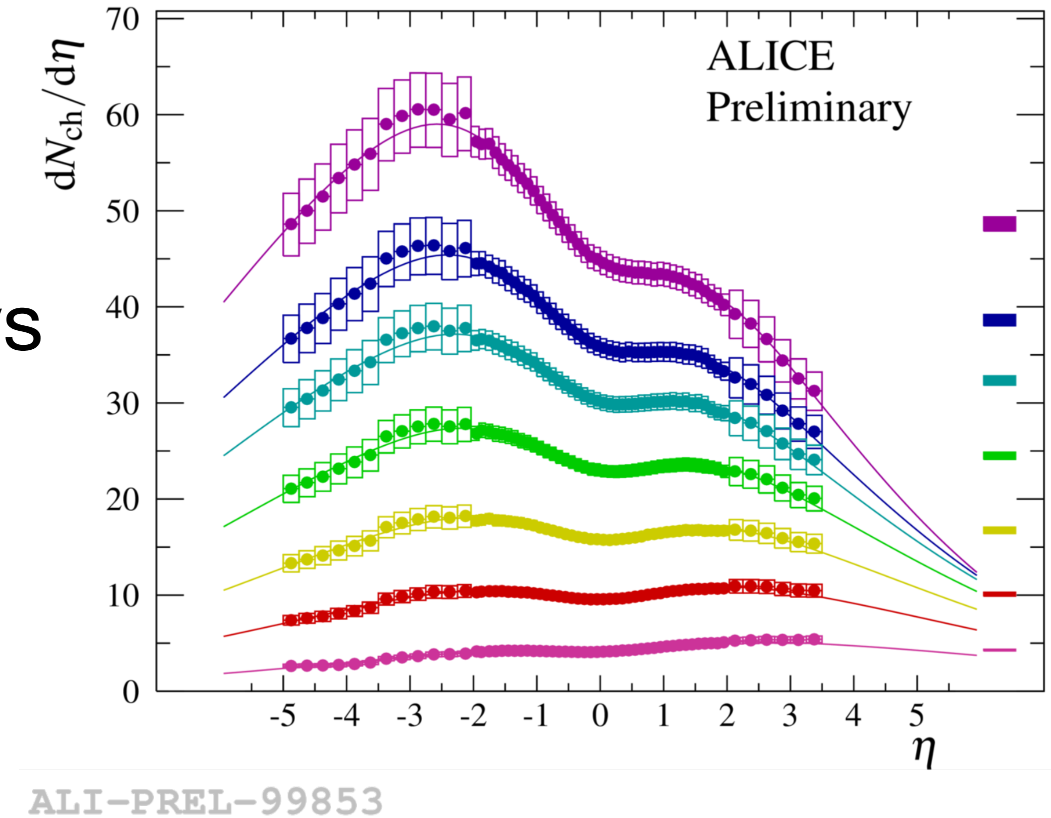

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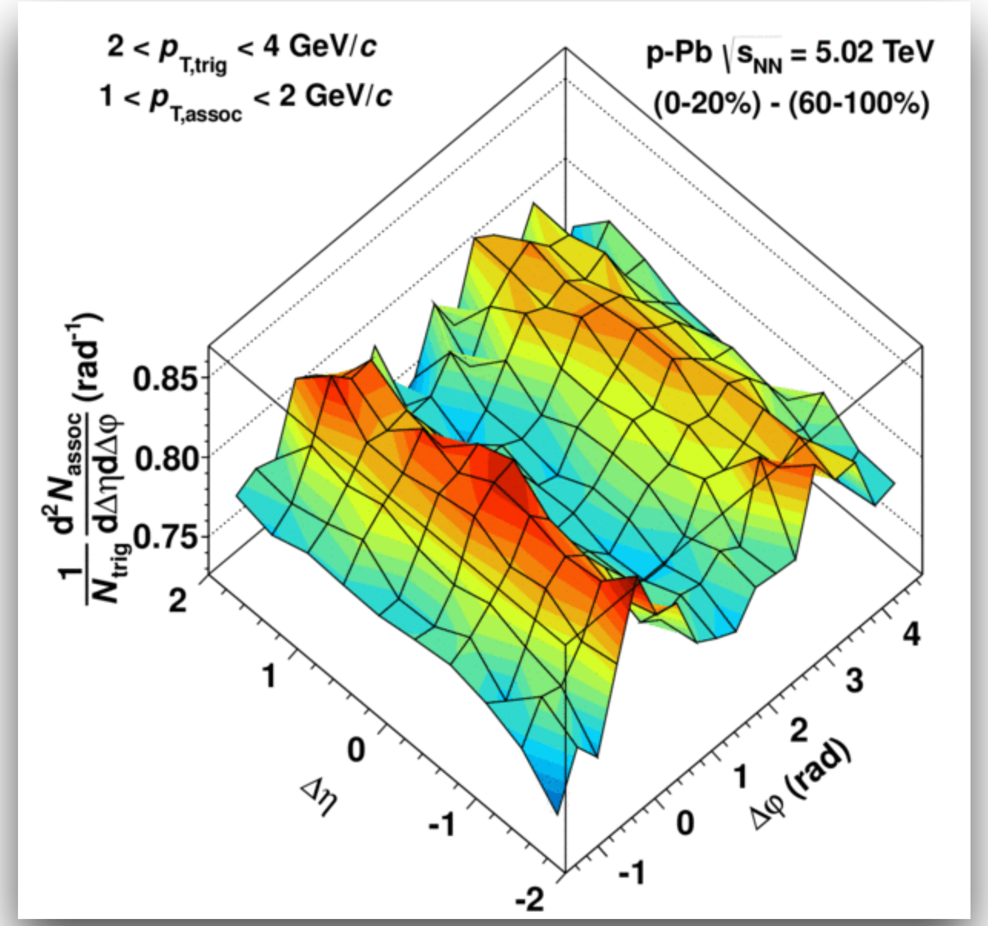
Open question!

Summary

- A "**double ridge**" is seen in **high multiplicity p-Pb** at $\sqrt{s_{NN}}$ = 5.02 TeV collisions, once jet correlations are subtracted
- **ALICE** fully characterized the "double ridge" in p-Pb collisions
  - Identified particles show a clear **mass ordering**, similar to Pb-Pb collisions
  - Ridge extends to **forward rapidities** ($|\eta|$~5)
  - v_2 **stronger in the Pb-going** directions at forward rapidities
  - Hint of **heavy flavor** "flow"?
- **Current observations** consistent with hydrodynamic interpretation
  - Many alternatives in the market
- What is the **underlying physics** driving ridges in pp, pA, AA?



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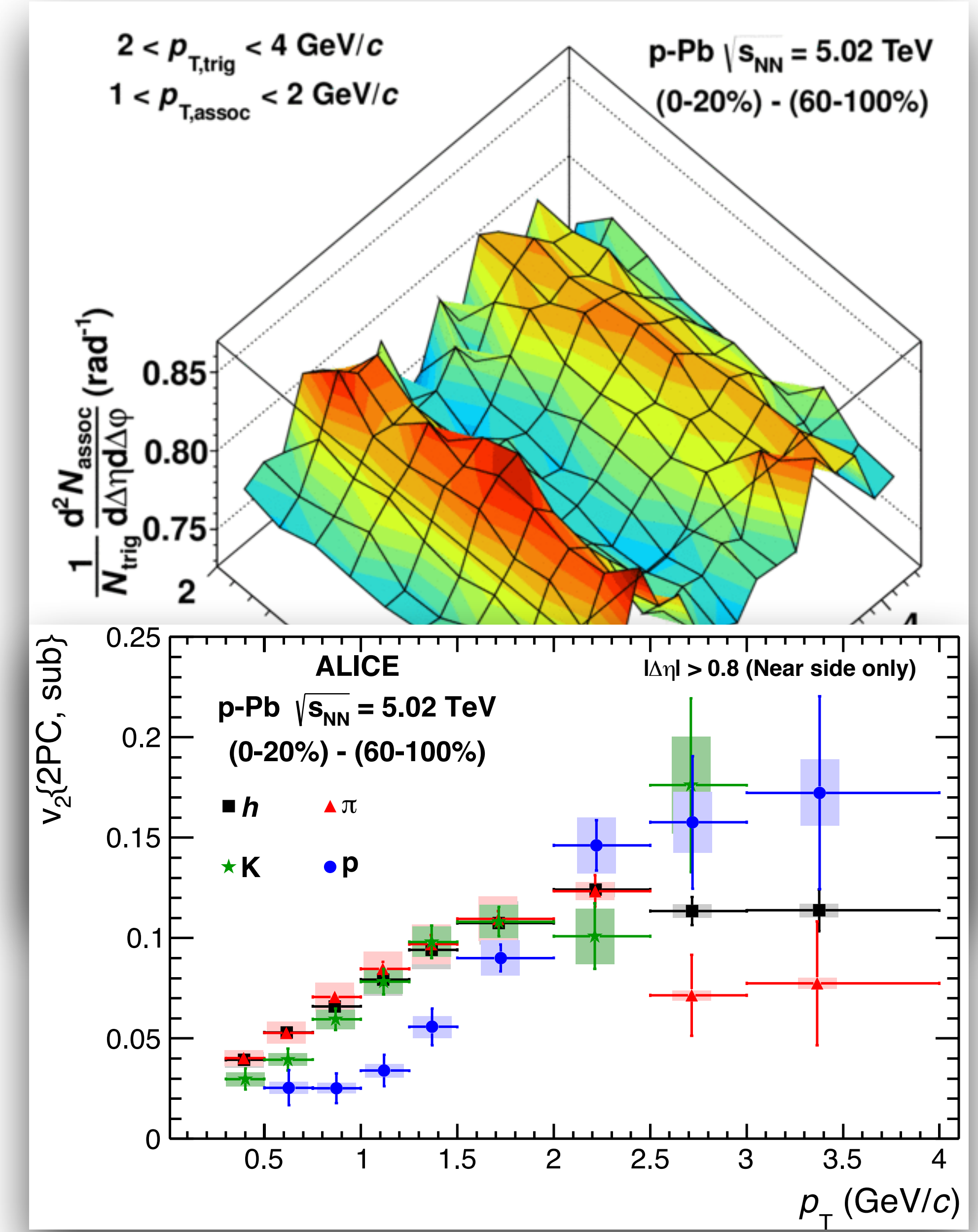

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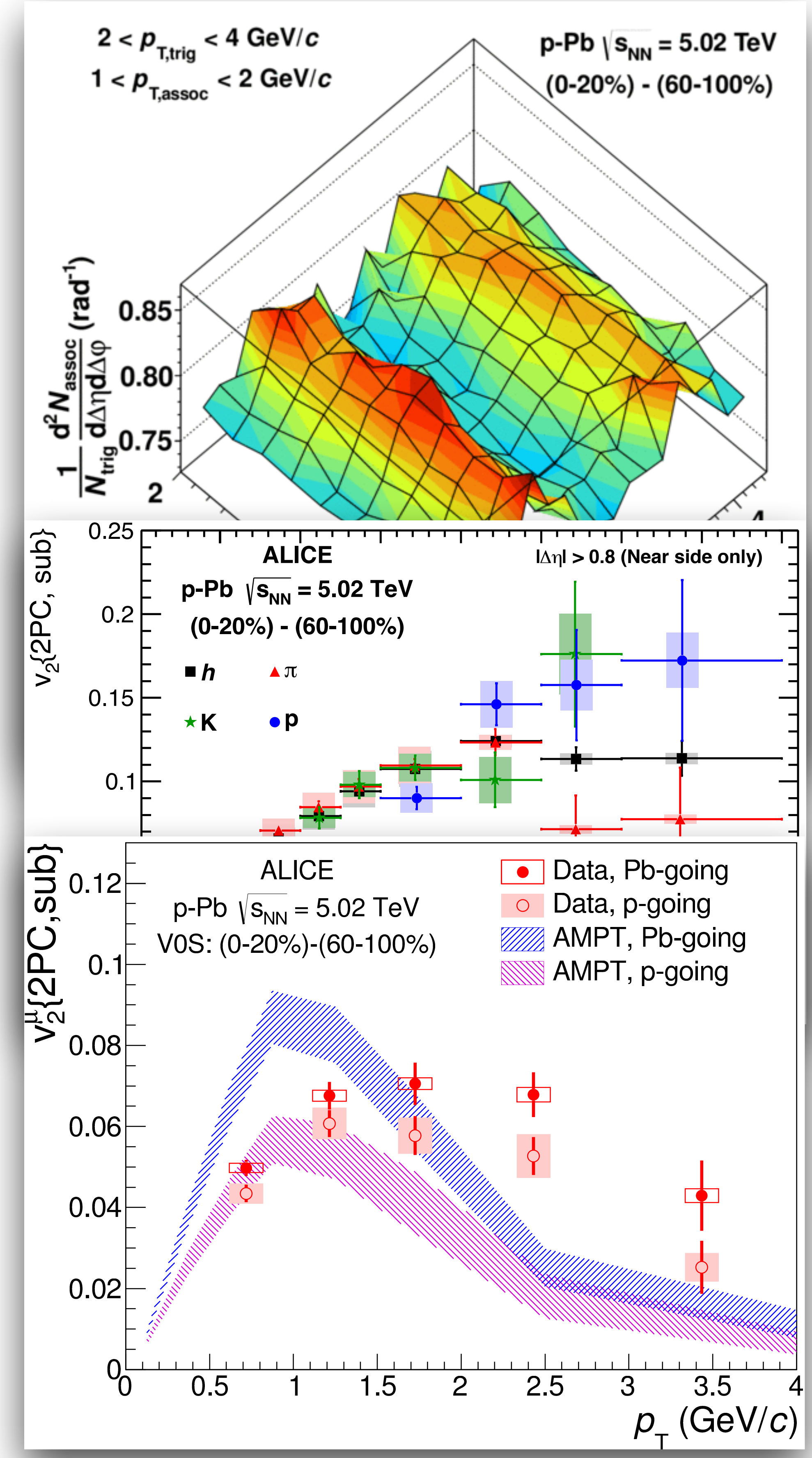
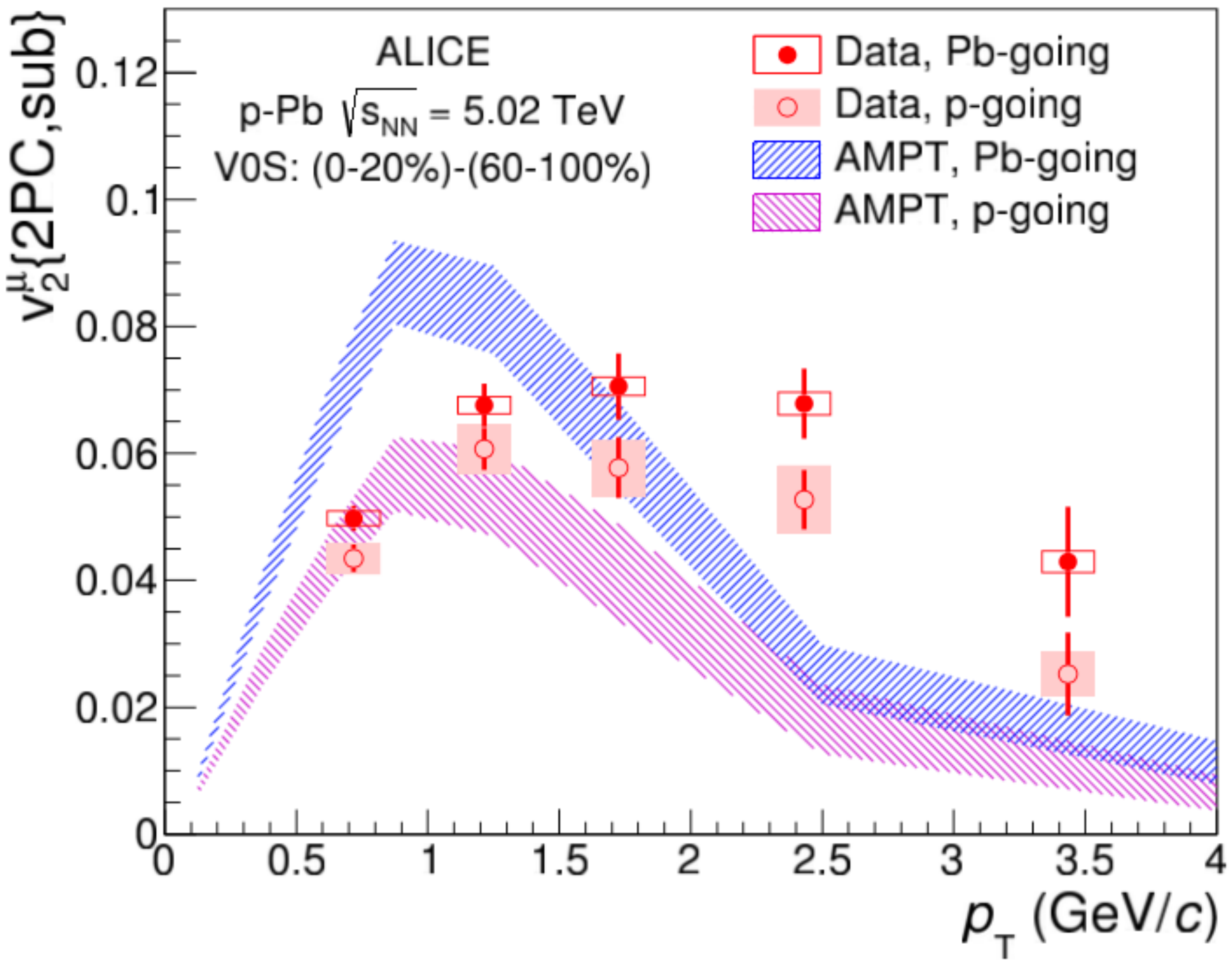


Backup

v2 in Pb-going and p-going direction



Paper submitted to PLB
arXiv:1506.08032 [nucl-ex]

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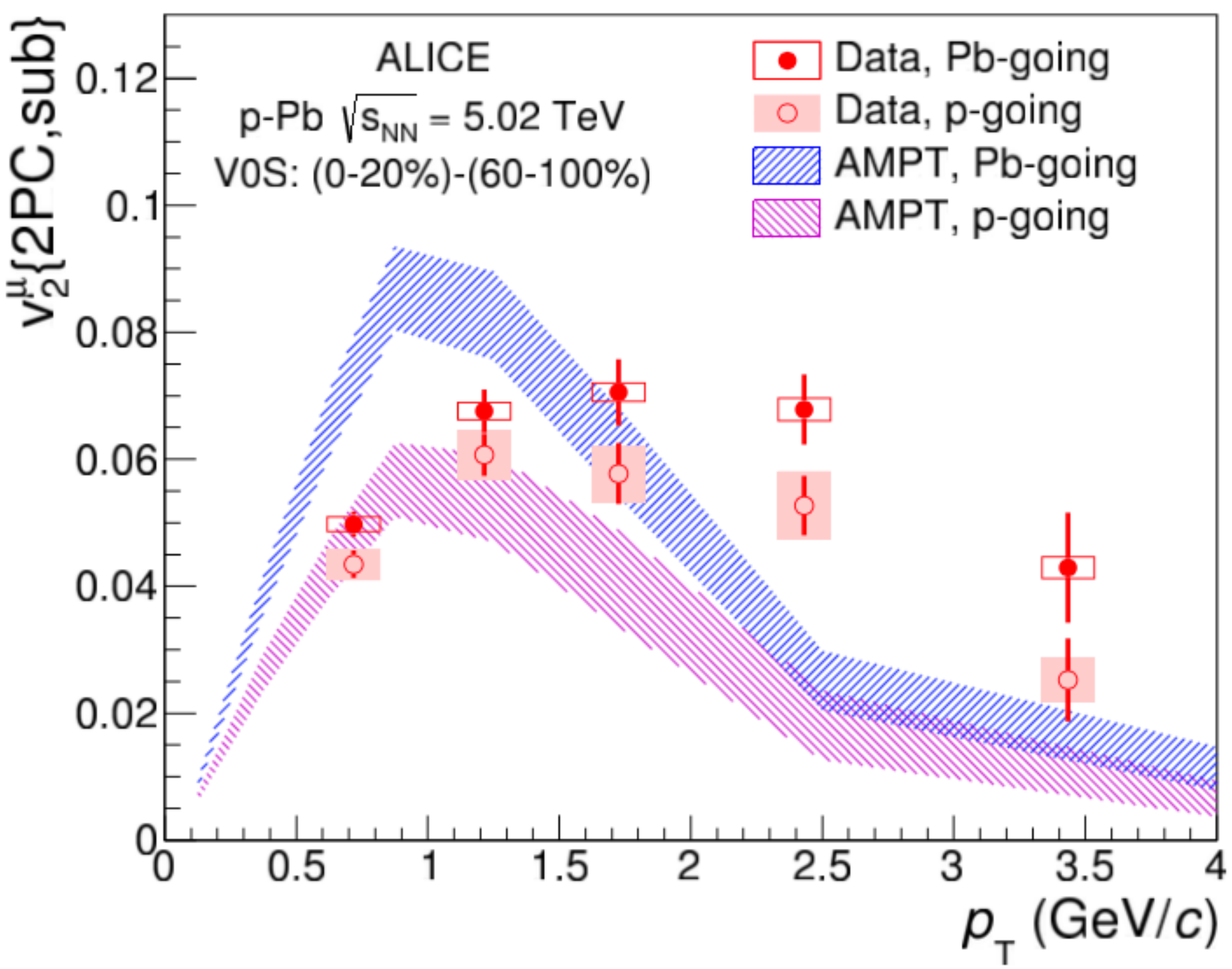

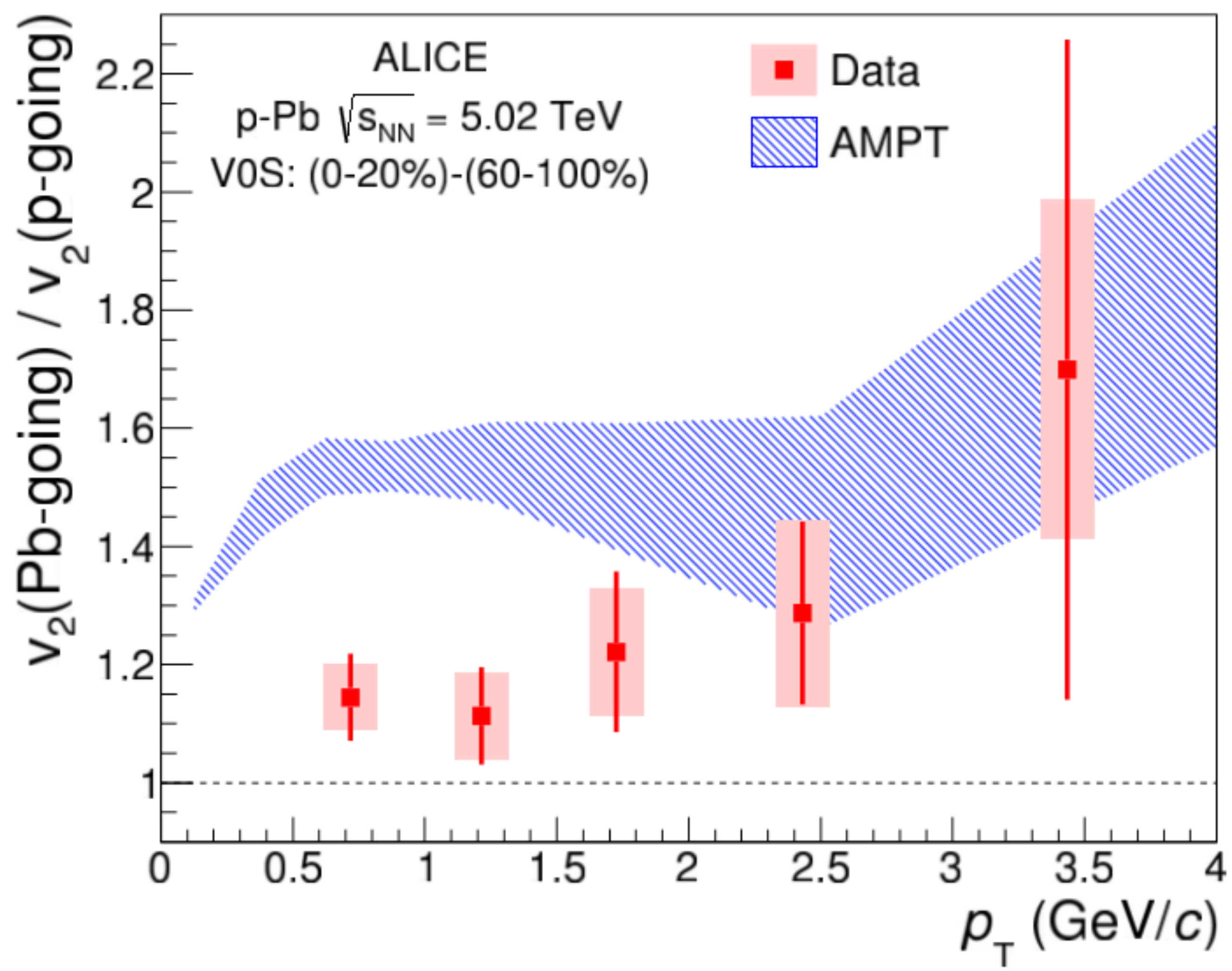

Constant fit: 1.16±0.06 with χ^2/NDF =0.5

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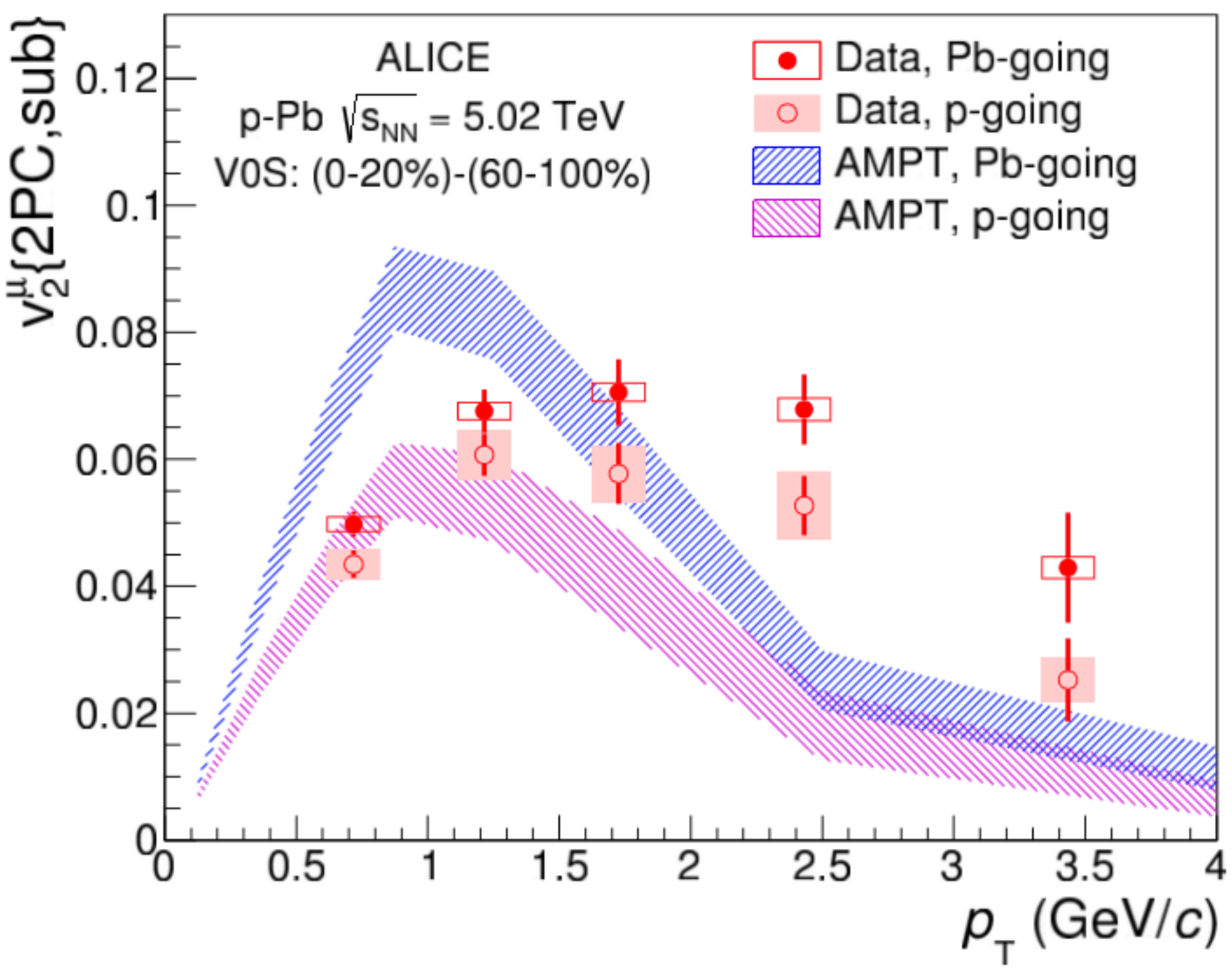

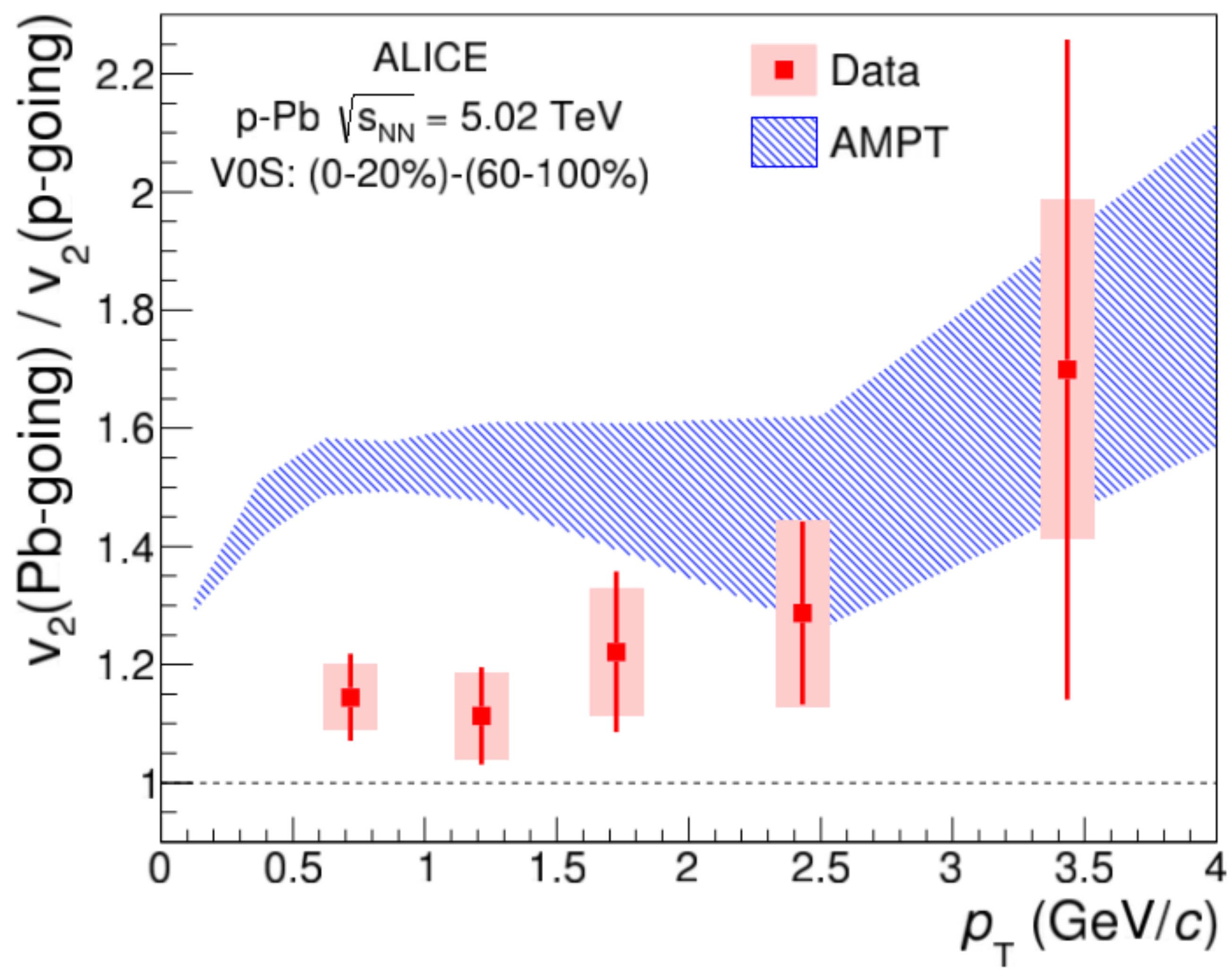

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Double ridge extends up to very large Δη

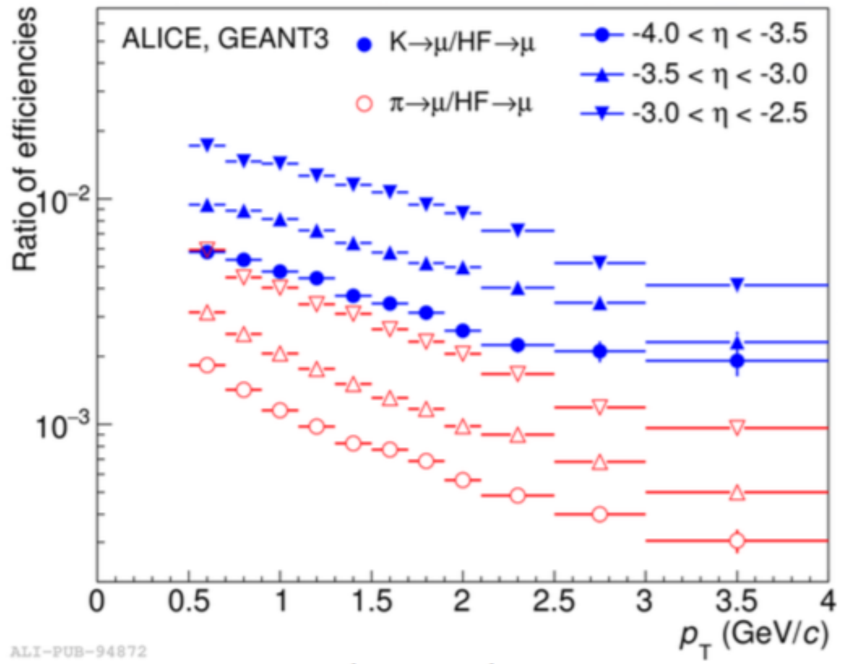
Asymmetry between the two sides observed (no CGC prediction yet)

Forward-central correlations sensitive to HF muon v_2

Paper submitted to PLB
arXiv:1506.08032 [nucl-ex]

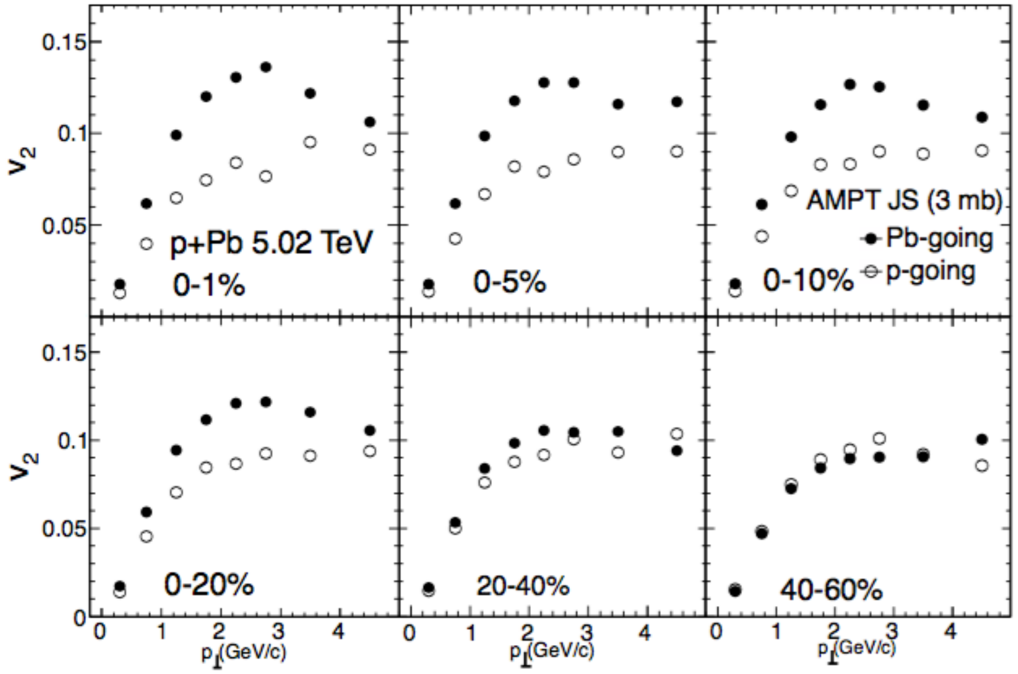
- Measured $v_2^{\mu}\{2PC,sub\}$ is for decay muons measured in FMS
  - in order to account for the effects of the absorber, future model calculations should use the efficiencies provided

arXiv:1506.08032

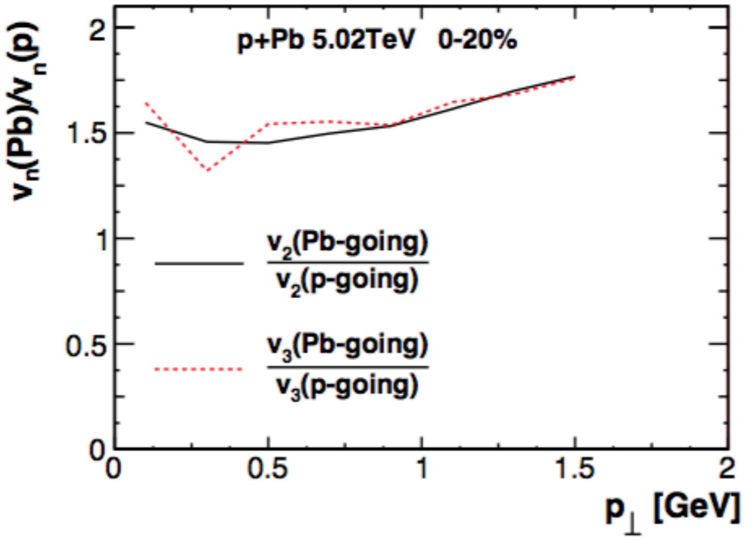


- Published model predictions cannot yet be directly compared to data

3+1D hydrodynamics



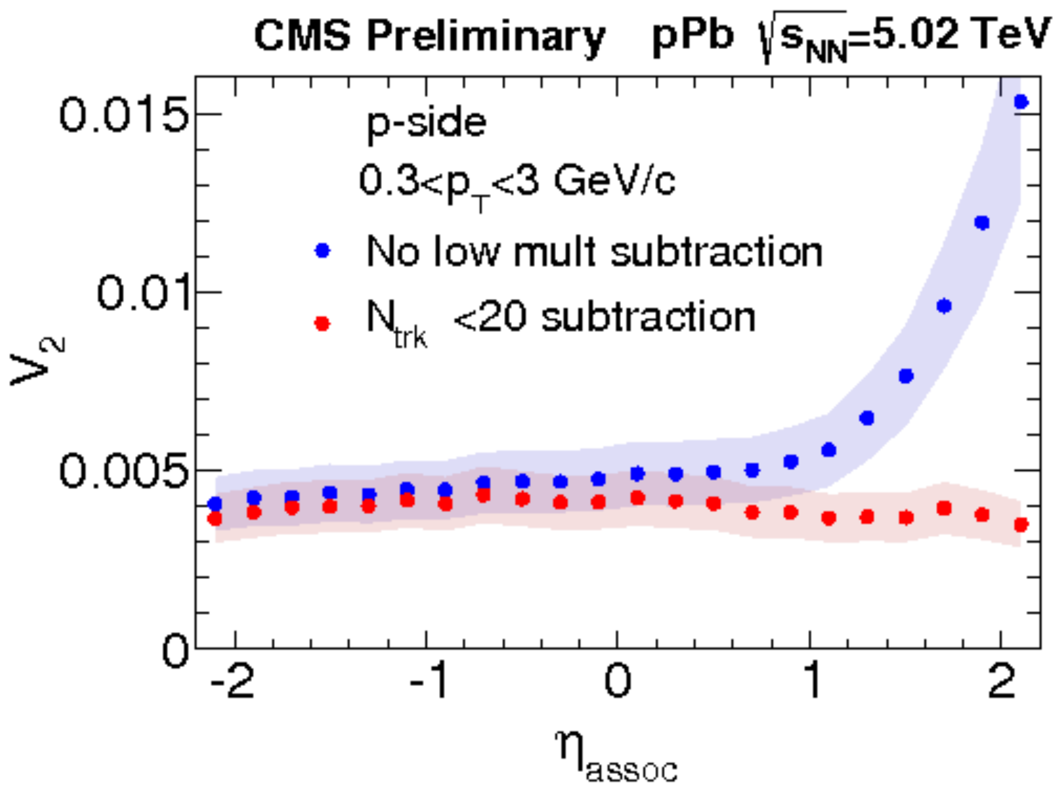
AMPT

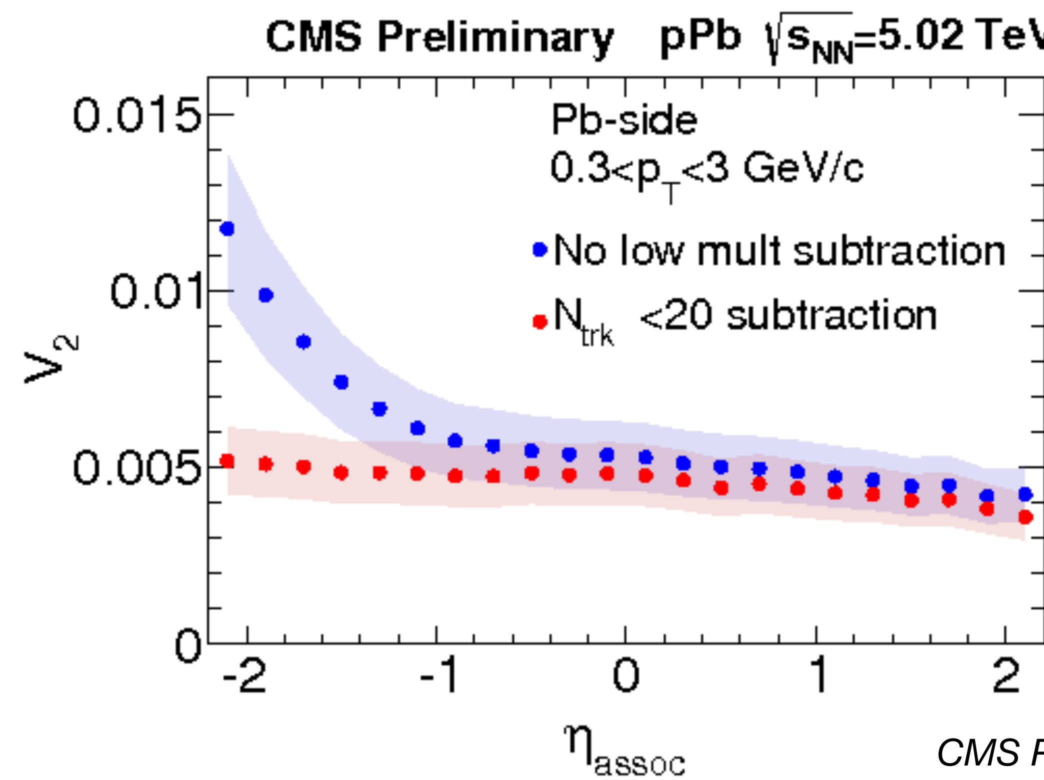


arXiv: 1503.03655

Forward-central correlations in p-Pb

For further understanding of the production mechanism of the ridges,
η-dependence of the long-range correlation structures needs to be investigated.





CMS PAS HIN-14-008

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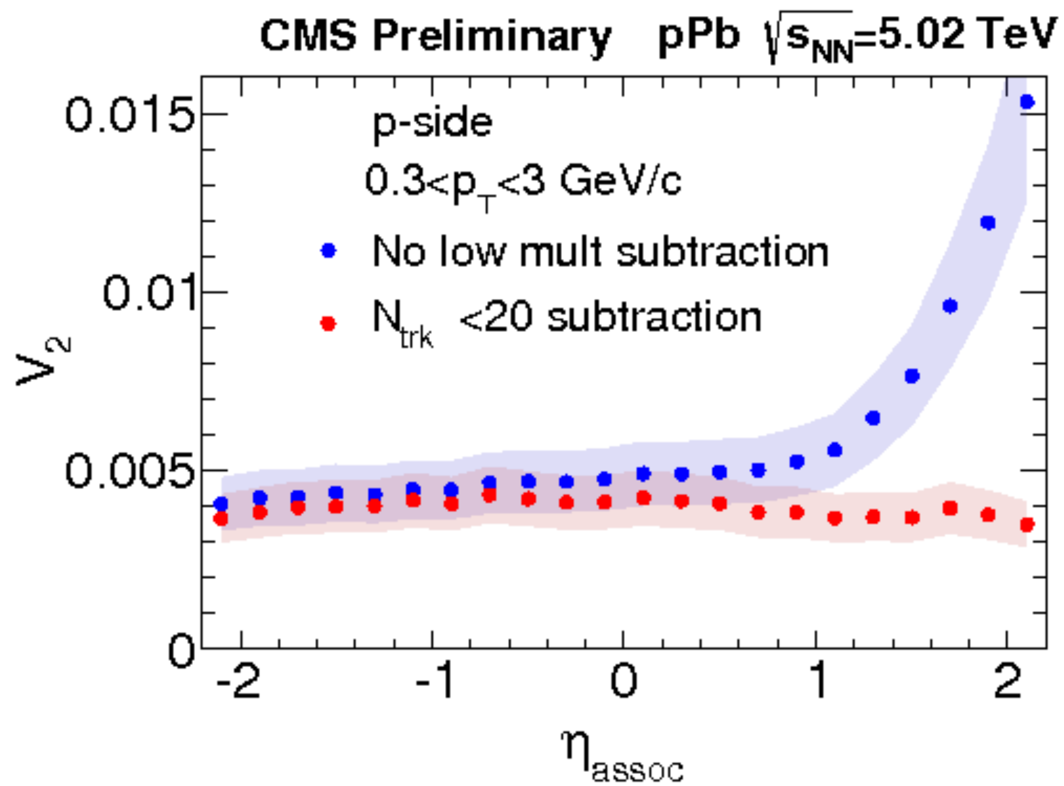

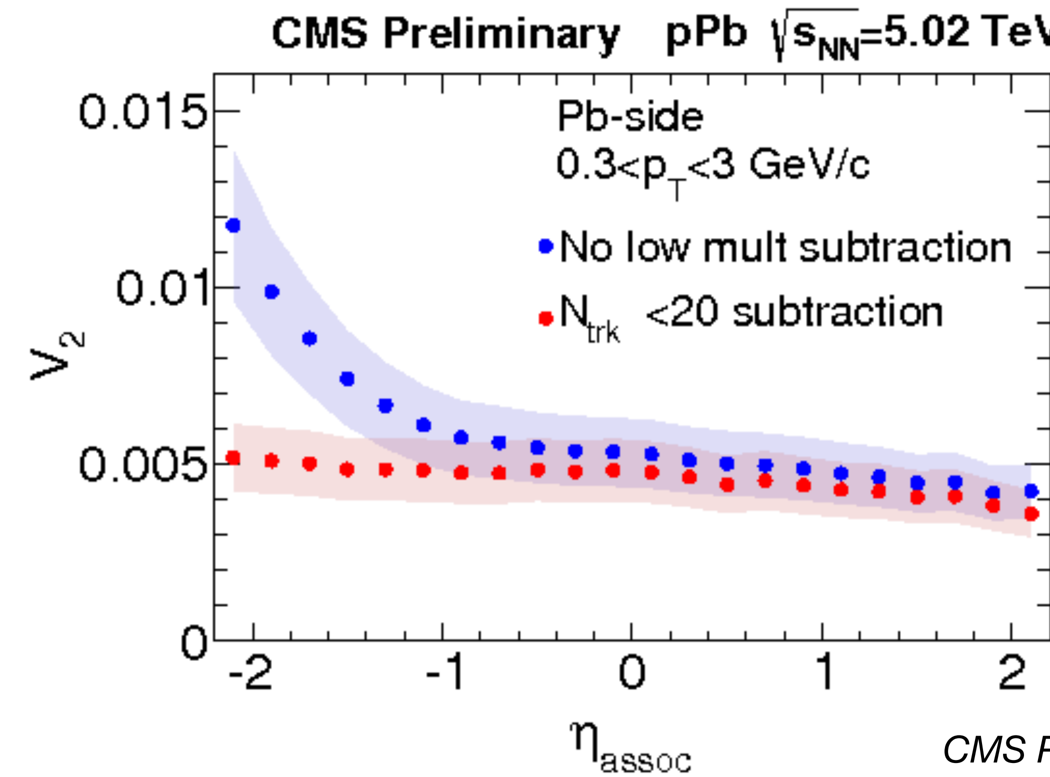

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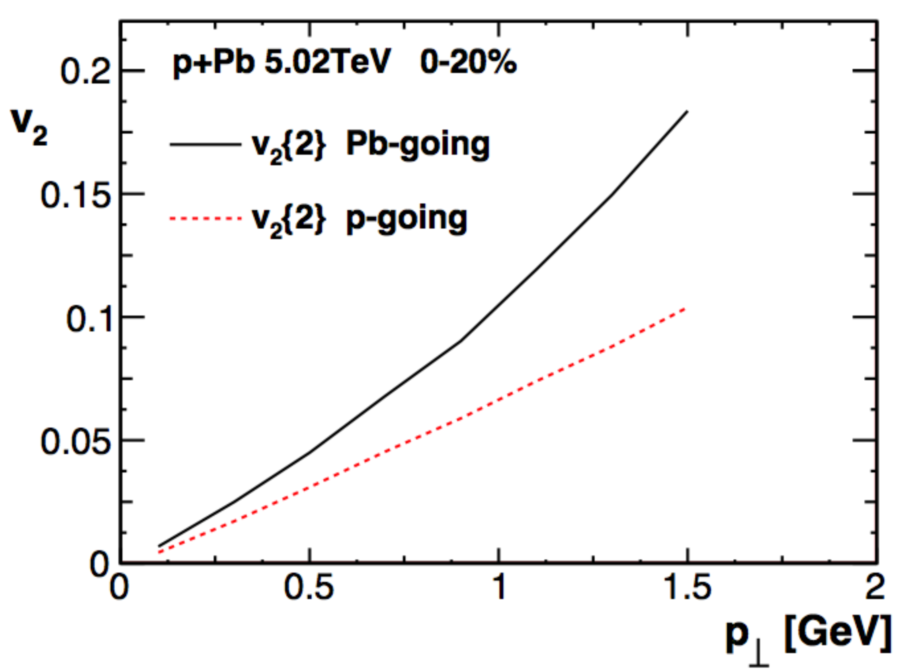


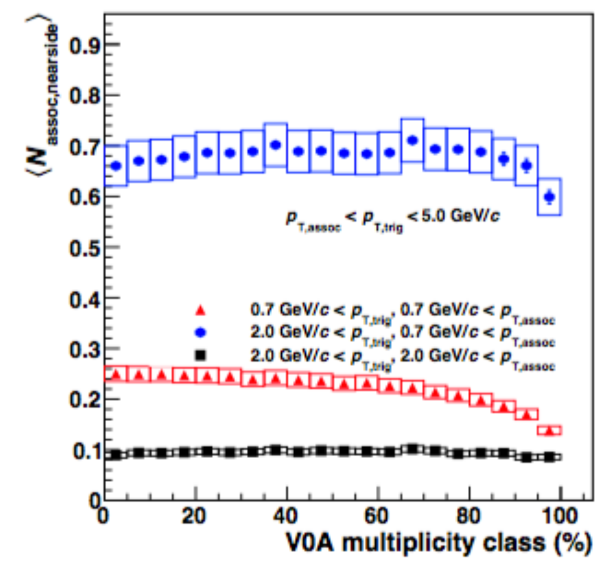
v_2 calculations at 2.5 < |η| < 4 from 3+1D viscous *hydrodynamical model*

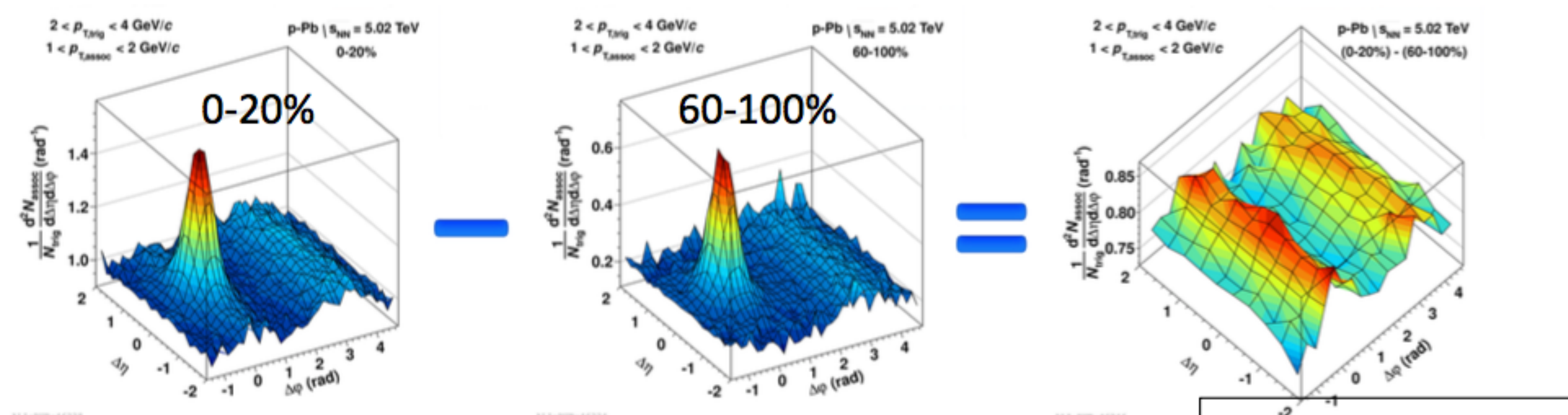
Piotr Bozek, Adam Bzdak, Guo-Liang Ma, arXiv:1503.03655

Double Ridge in pPb

- Nearside peak yields are mostly independent of multiplicity
- For the same trigger/associated p_T we select the same jet population regardless of multiplicity
- Justification for subtracting low-multiplicity correlations from high-multiplicity correlations to isolate ridge structure
- Remaining yield on the awayside after subtraction of jet structures → a symmetric “double” ridge

ALICE PLB 741 (2015)





ALICE PLB 719:29 (2013)

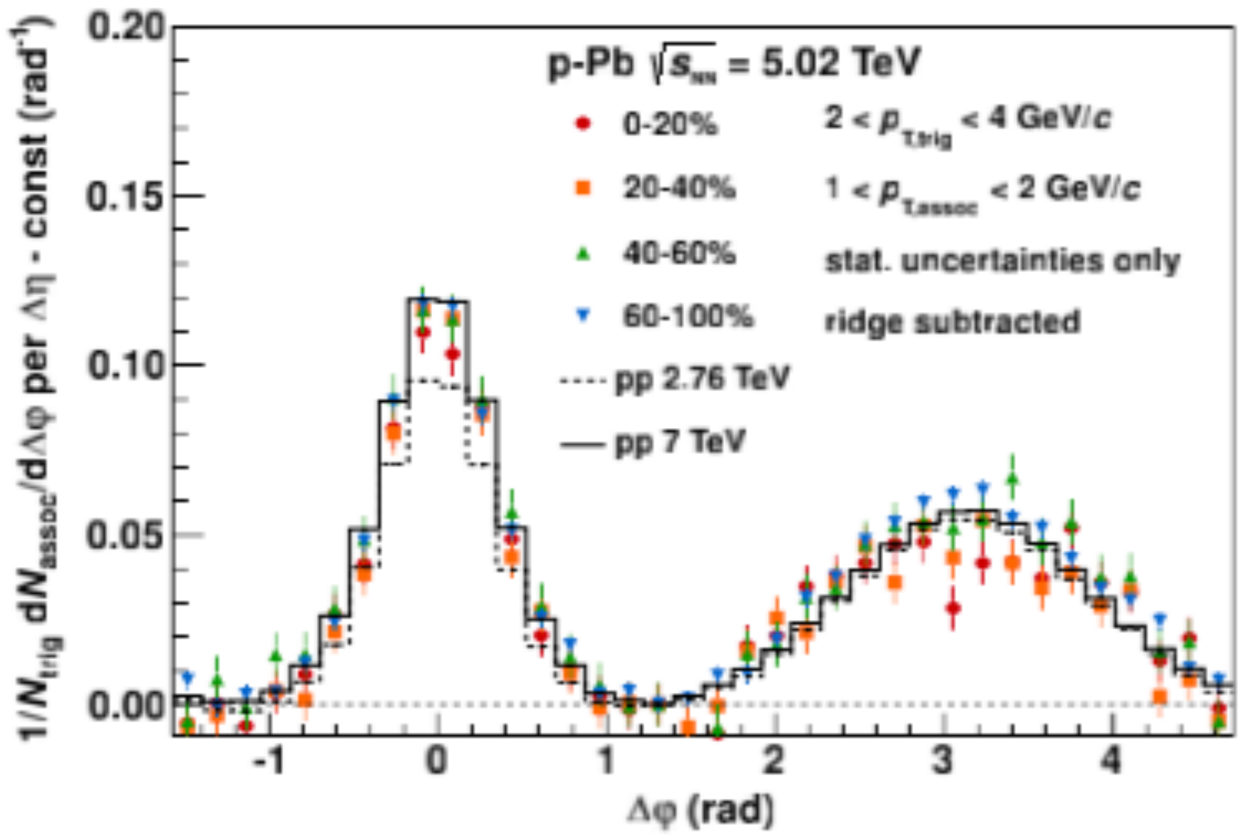


Fig. 5: Associated yield per trigger particle as a function of $\Delta\varphi$ averaged over $|\Delta\eta| < 1.8$ for pairs of charged particles with $2 < p_{T,trig} < 4$ GeV/c and $1 < p_{T,assoc} < 2$ GeV/c in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for different event classes, compared to pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. For the event classes 0–20%, 20–40% and 40–60% the long-range contribution on the near-side $1.2 < |\Delta\eta| < 1.8$ and $|\Delta\varphi| < \pi/2$ has been subtracted from both the near side and the away side as described in the text. Subsequently, the yield between the peaks (determined at $\Delta\varphi \approx 1.3$) has been subtracted in each case. Only statistical uncertainties are shown; systematic uncertainties are less than 0.01 (absolute) per bin.