Observation of the double ridge at forward and backward rapidity in p-Pb collisions

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on behalf of the ALICE collaboration

04 August 2015
CERN LHC seminar

Outline:

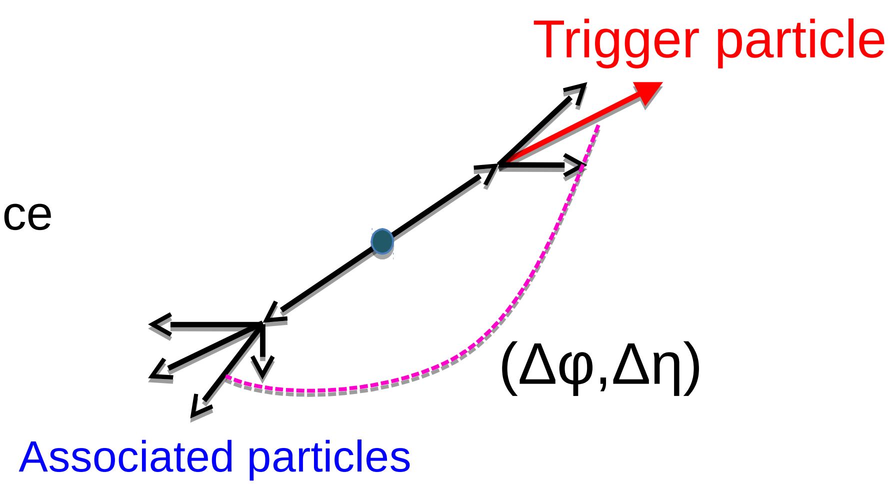
Part1 : Two-particle correlations and hydrodynamic flow in PbPb

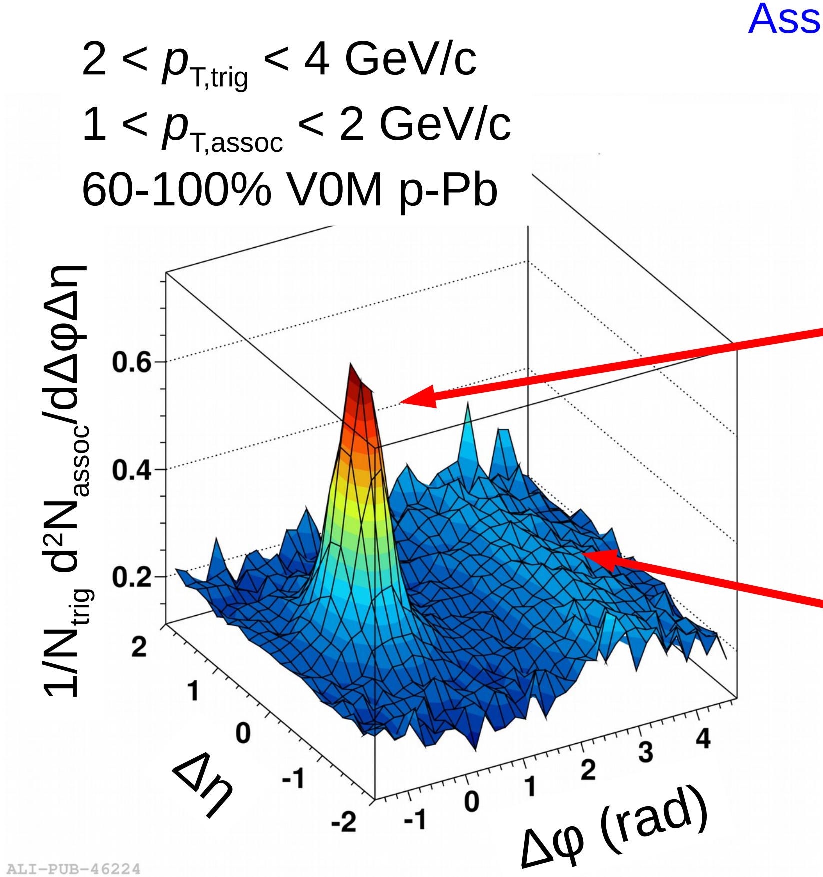
Part2: Two-particle correlations and v_n in pPb

Part3: New ALICE paper arXiv:1506.08032 and related results

3 Two-particle angular correlations

Associated particle per-trigger yield:
count “associated” particles in given pT range
relative to “trigger” particles in given pT range
vs azimuthal angle and pseudo-rapidity difference



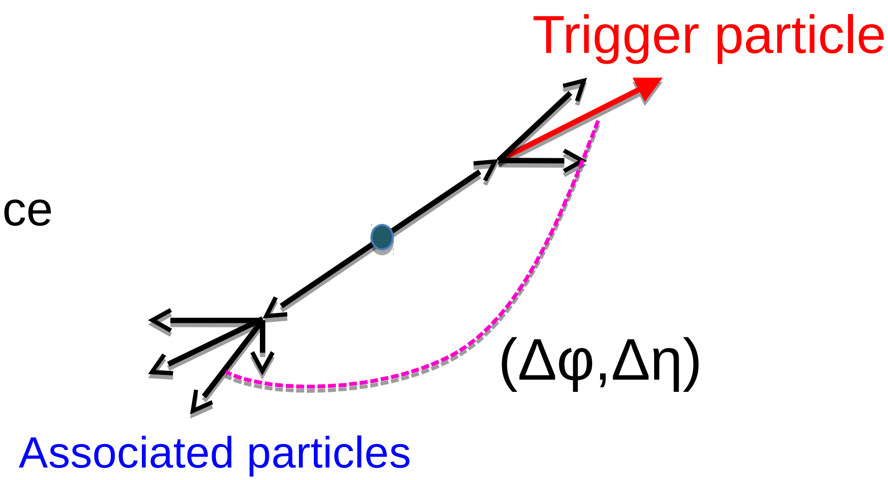


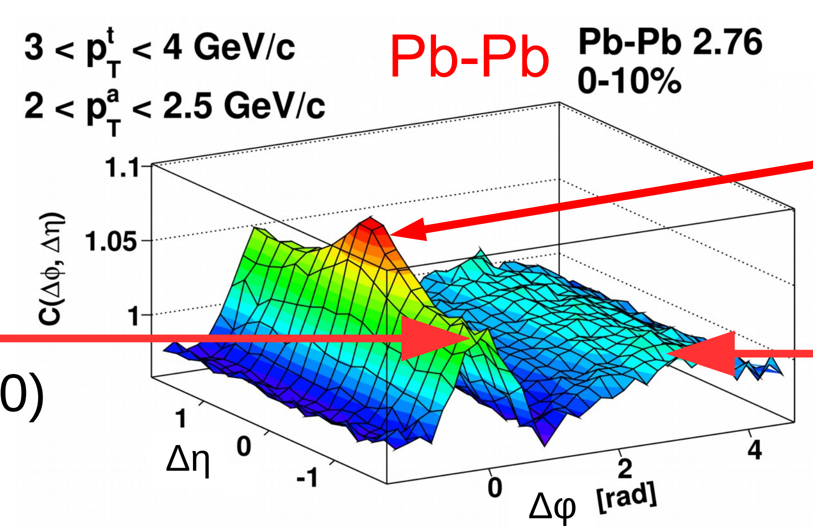
Near-side jet
+ resonances
(Δφ ~ 0, Δη ~ 0)

Away-side jet
+ mom. conversation
(Δφ ~ π, along Δη)

4 In Pb-Pb, there are additional structures

Associated particle per-trigger yield:
count "associated" particles in given pT range
relative to "trigger" particles in given pT range
vs azimuthal angle and pseudo-rapidity difference





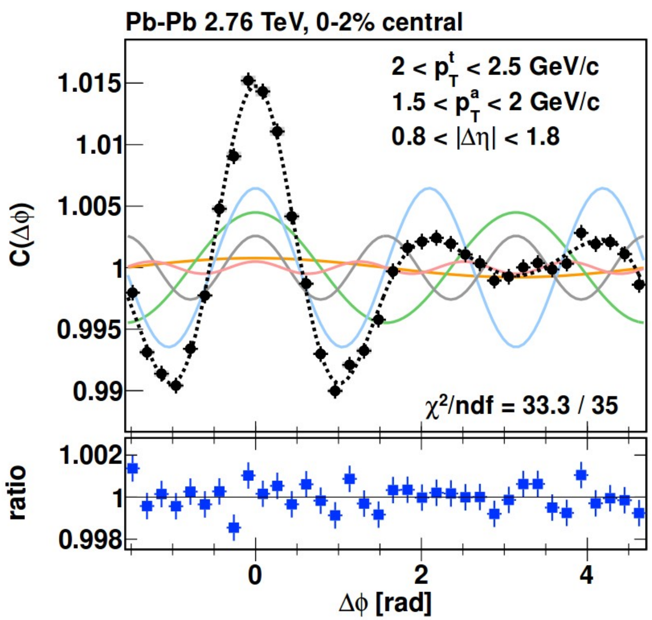
Near-side jet
+ resonances
(Δφ ~ 0, Δη ~ 0)

Near-side
ridge (Δφ ~ 0)

Broad away-side
(Δφ ~ π, along Δη)

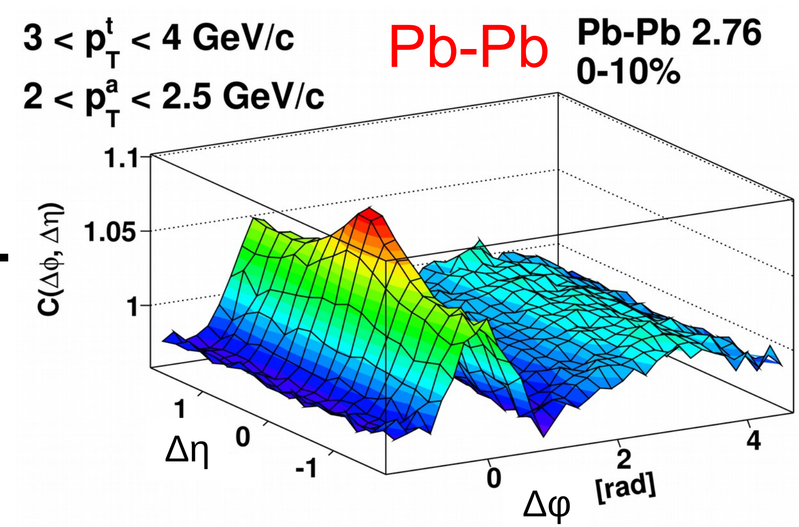
ALICE, PLB 708 (2012) 249

5 Analysis of ridge in Pb-Pb



Project on Δφ

(w/o jet peak, eg. |Δη|>0.8)



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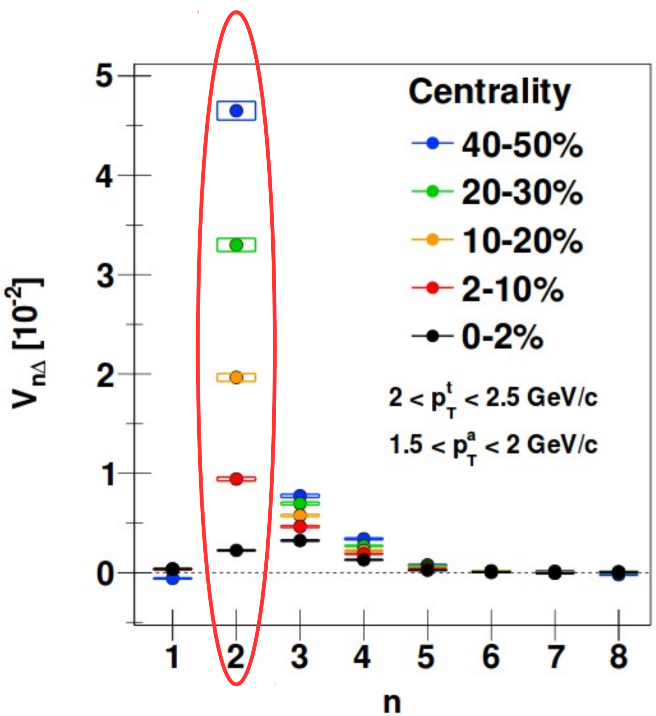
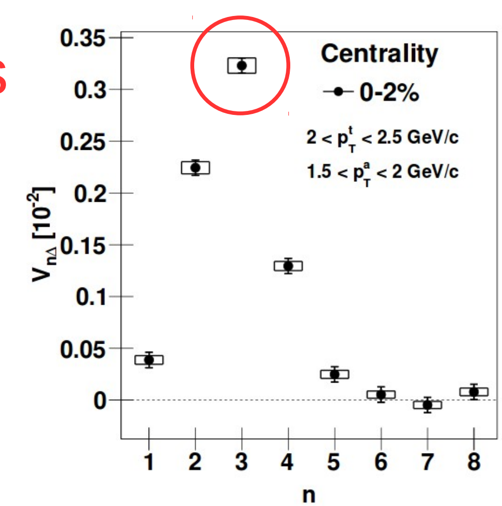
Get $V_{n\Delta}$ (Fourier coefficients of 2-particle distribution)



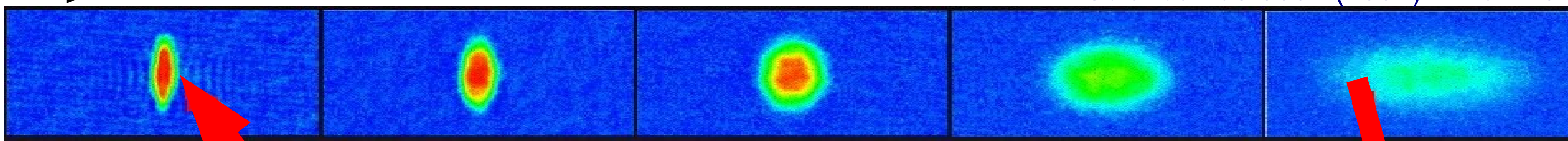
2[nd] order dominant except for 0-2% central collisions



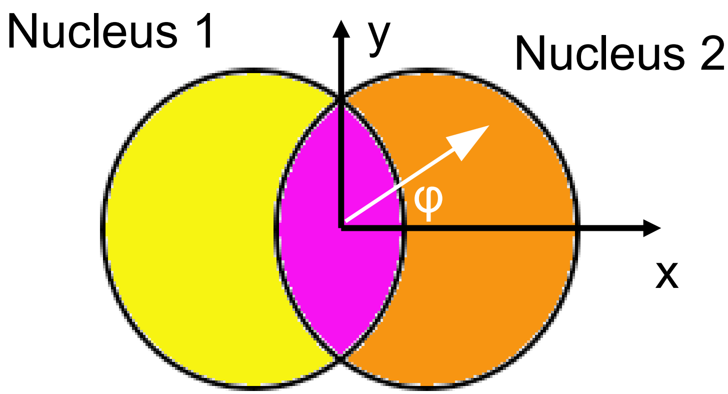
6 Initial spatial and final momentum anisotropy

Time →

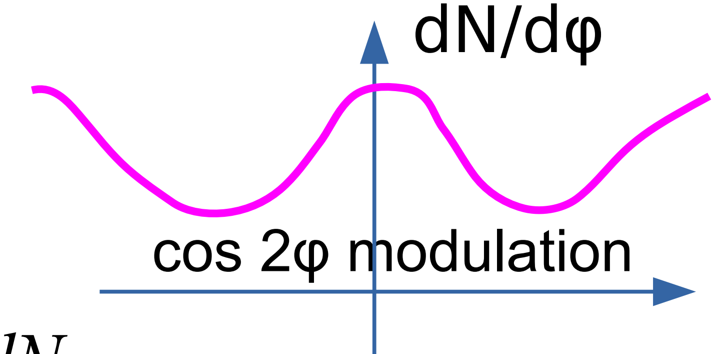
Science 298 5601 (2002) 2179-2182



(process is self quenching)



(ψ_R=0 , ie. along x)



$$\frac{dN}{d\varphi} \sim 1 + 2 v_2 \cos[2(\varphi - \psi_R)] + \ldots$$

Expect $v_2 \propto \varepsilon \frac{\mathrm{d}N/\mathrm{d}y}{S}$

Initial spatial anisotropy: Eccentricity

$$\epsilon_{std} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

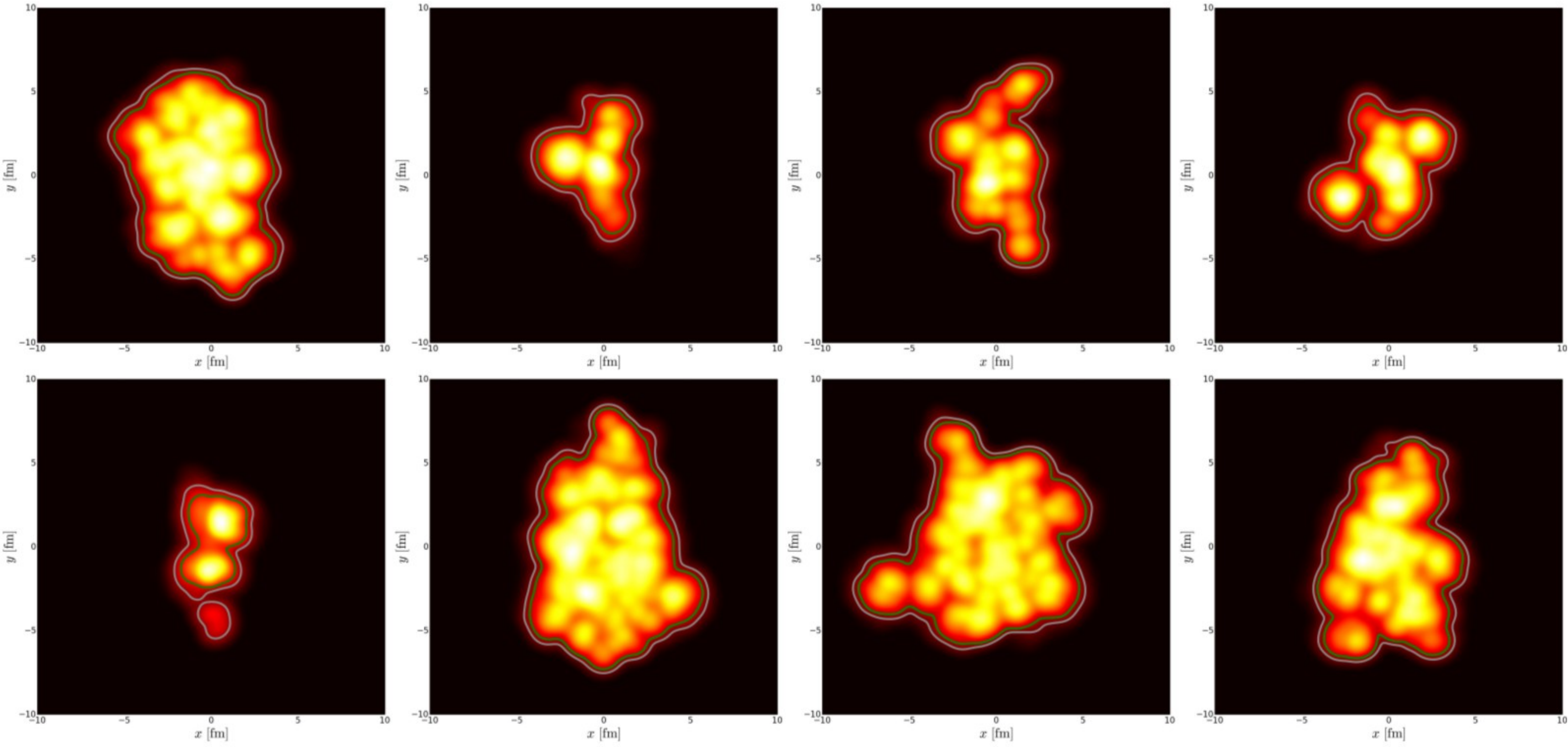
→ If interactions present early (induces long-range Δη correlations)

Momentum space anisotropy: Elliptic flow

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

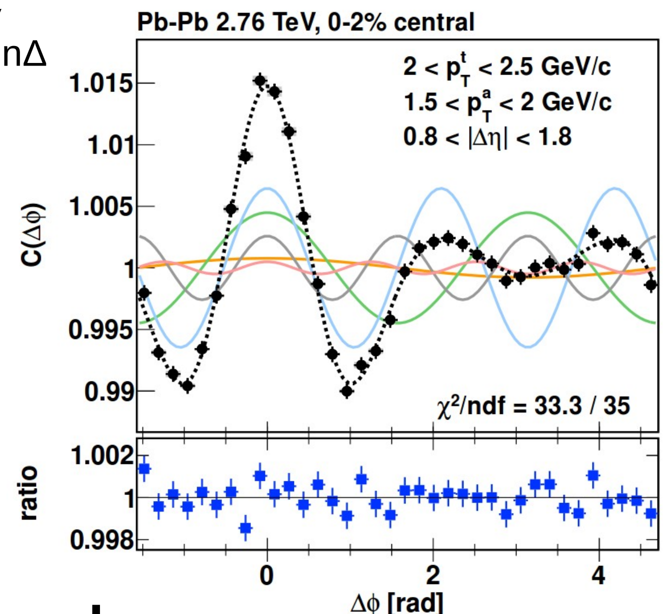
7 Initial spatial and final momentum anisotropy

Initial spatial anisotropy not smooth, contains other higher harmonics / symmetry planes.



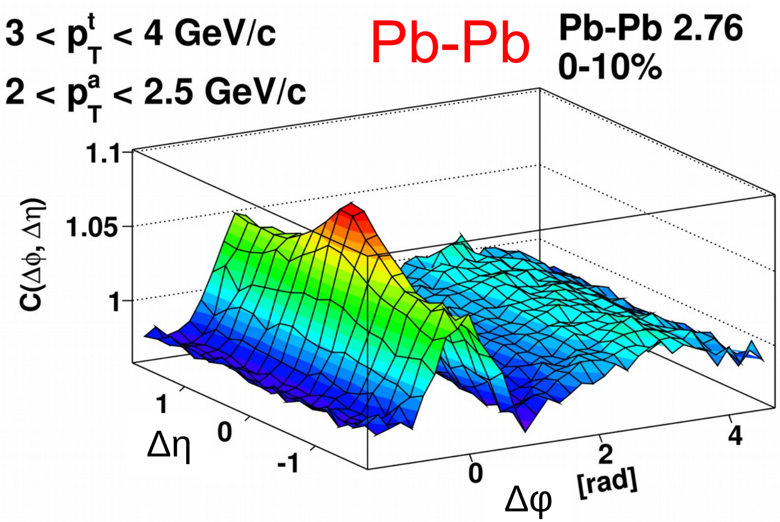
Temperature profiles in transverse plane from hydrodynamical calculation (H. Niemi)

8 Analysis of ridge in Pb-Pb



Project on Δφ

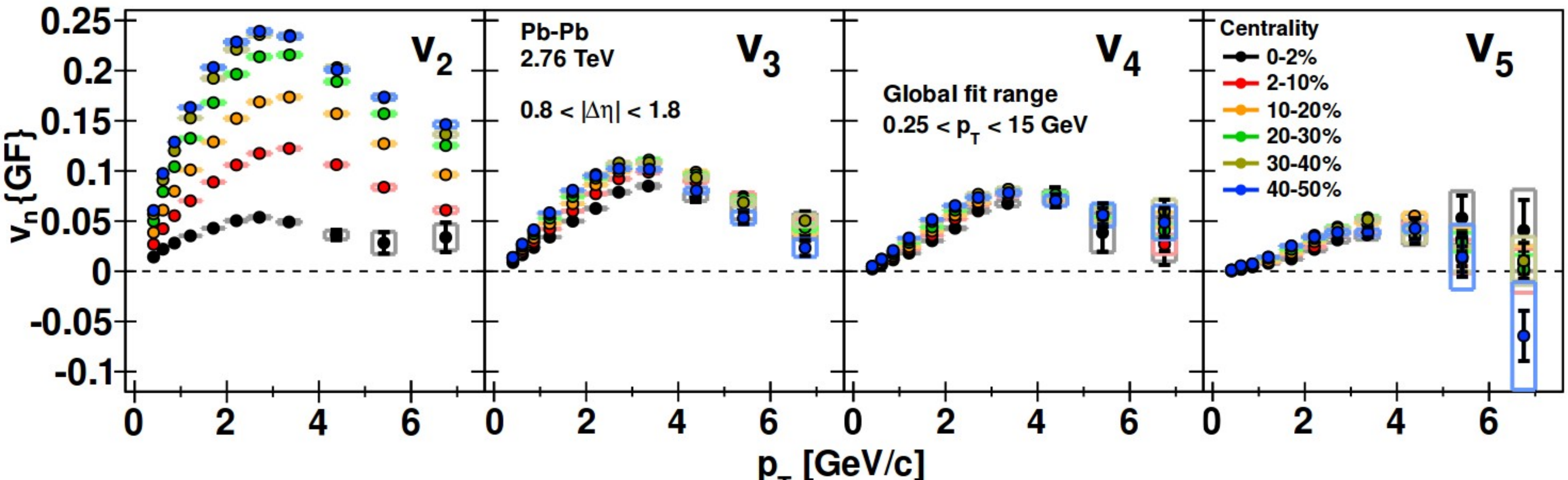
(w/o jet peak, eg. |Δη|>0.8)



ALICE, PLB 708 (2012) 249

Extract $v_n(p_T)$ using factorization ansatz(*) from global fit

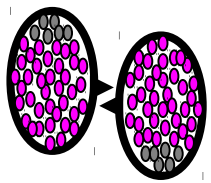
$$V_{n\Delta}(p_T^t, p_T^a) = v_n(p_T^t)v_n^a(p_T)$$



(*) factorization only approximate, see arXiv:1503.01692

Hydrodynamical model calculations

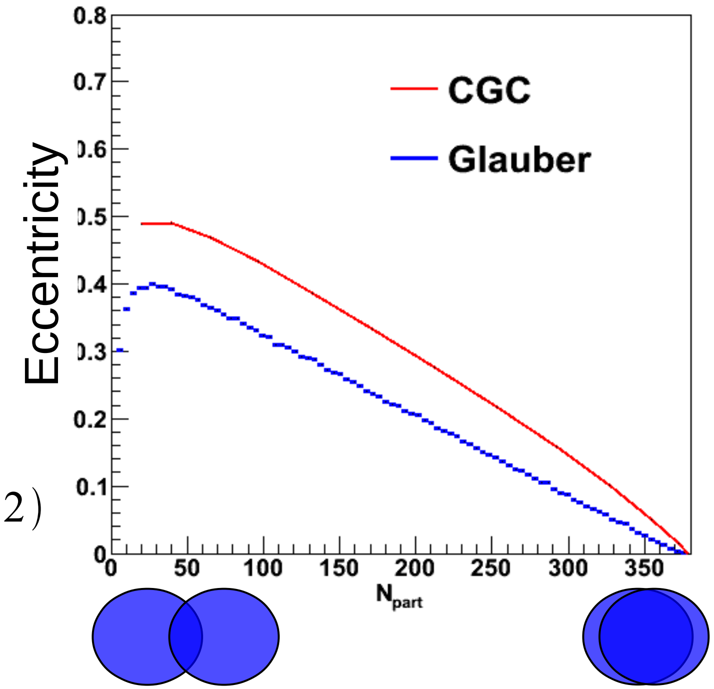
Glauber IC



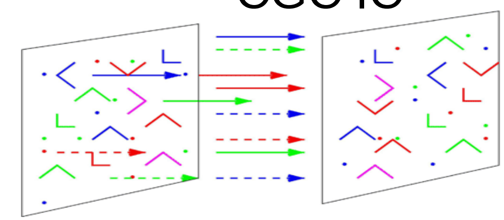
Glauber IC
Two-component model

$$\frac{dN}{d\eta}=\frac{dN}{d\eta}^{pp}\left((1-x)N_{coll}+x\,N_{part}/2\right)$$

PRC 70 021902 (2004)



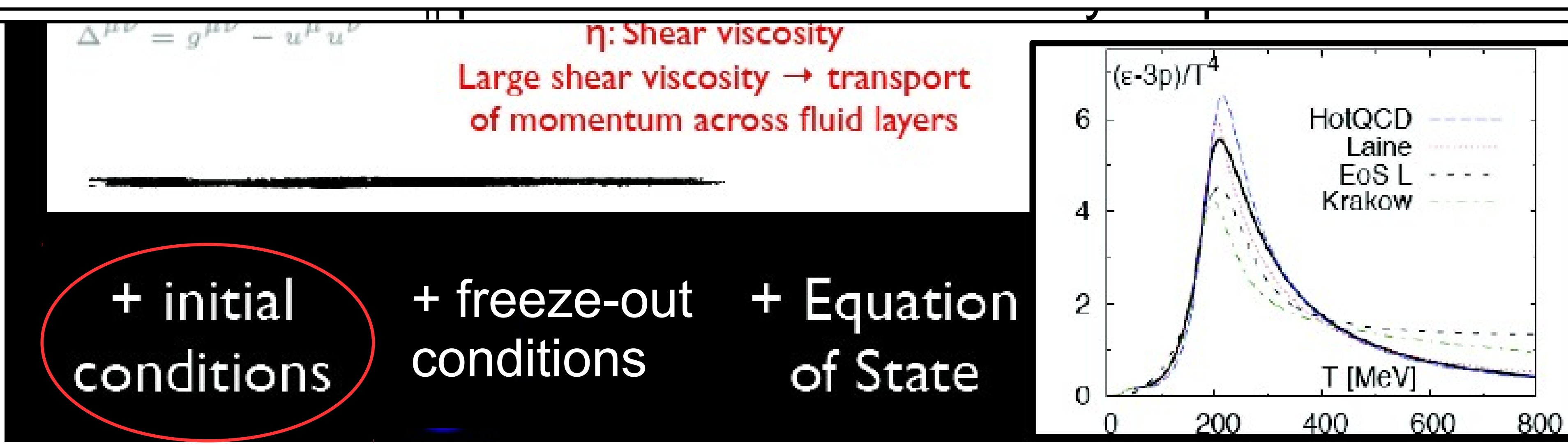
CGC IC



CGC IC
Color glass condensate

$$\frac{dN}{d\eta}\propto N_{part}^{\alpha}\sqrt{s}^{\lambda}$$

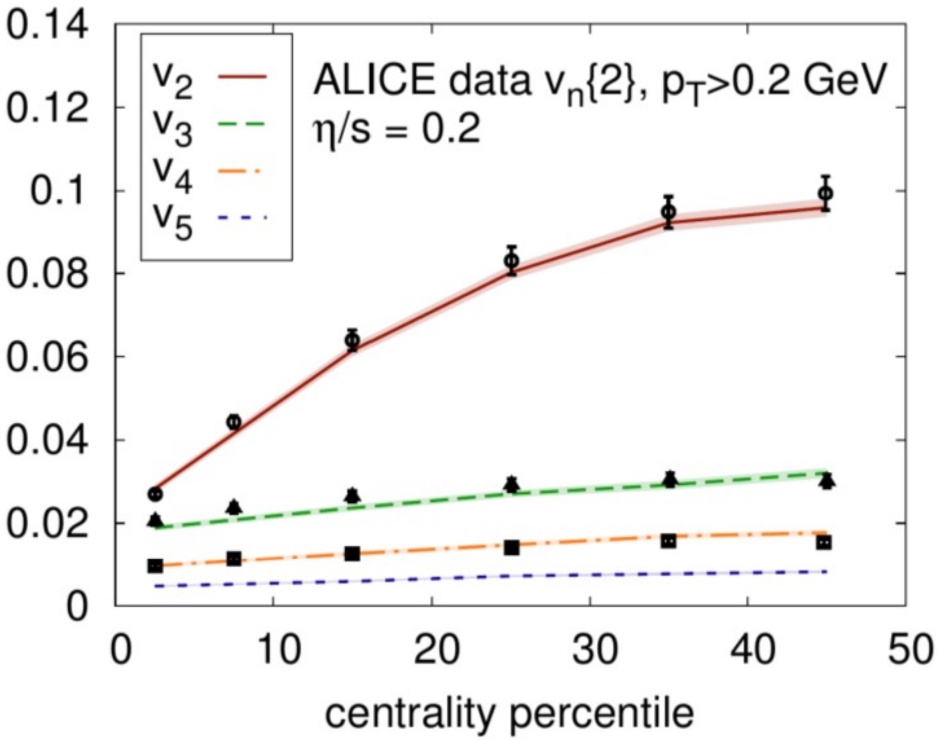
PRL 94 022002 (2005)



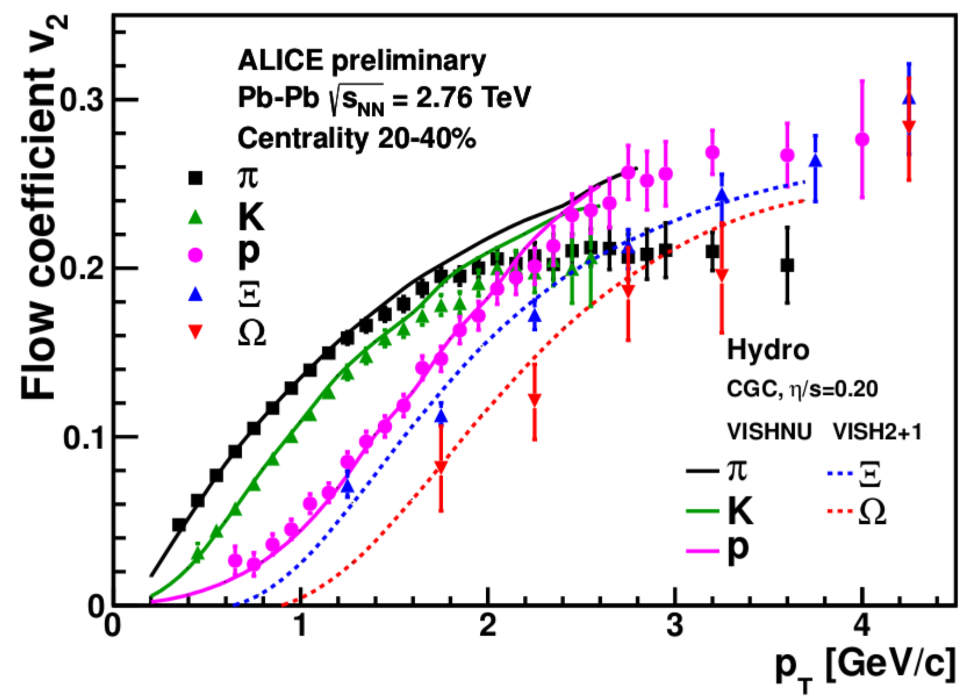
Today even second order calculations (full Israel-Stewart) calculations are done.

10 Comparison with data (examples)

Schenke et al., PRL 110 (2013) 012302



arXiv:1202.3233



Higher harmonics provide constraints to initial conditions: IP-GLASMA + viscous hydro

Viscous hydrodynamics (plus hadronic afterburner) quantitatively describes identified v_2 spectra

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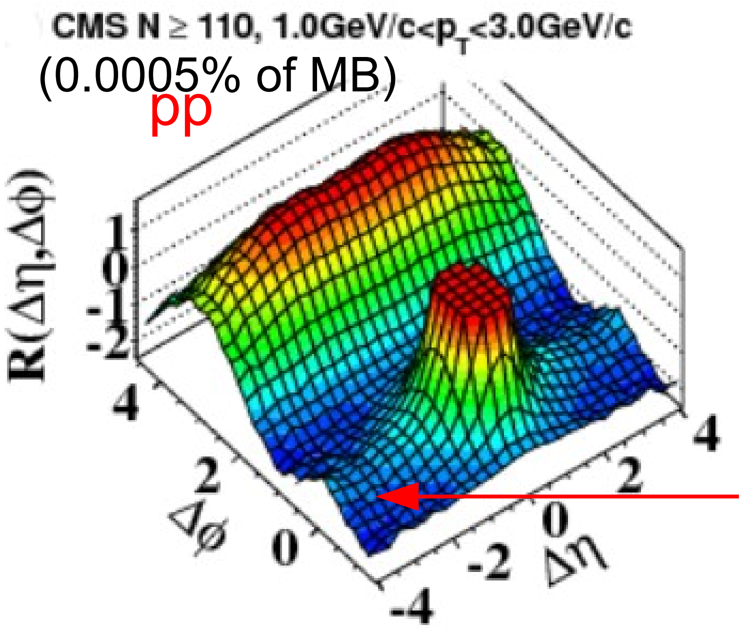
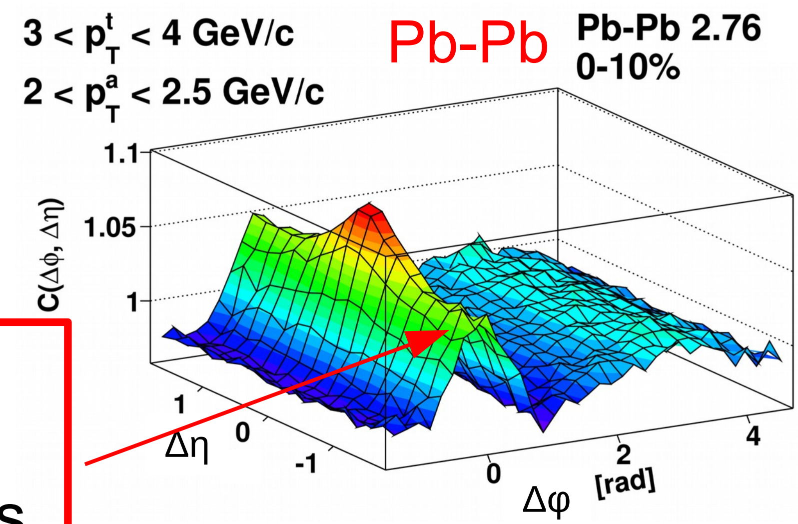
Part3: New ALICE paper arXiv:1506.08032 and related results

12 NS ridge structures in angular correlations

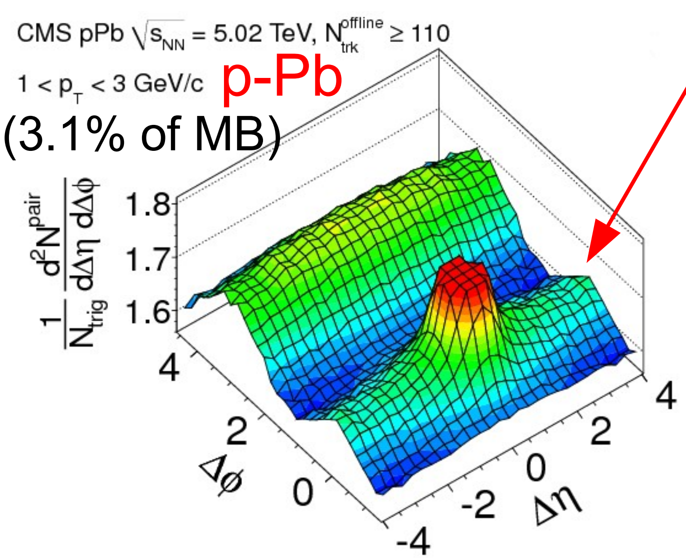


CMS, JHEP 1009 (2010) 91

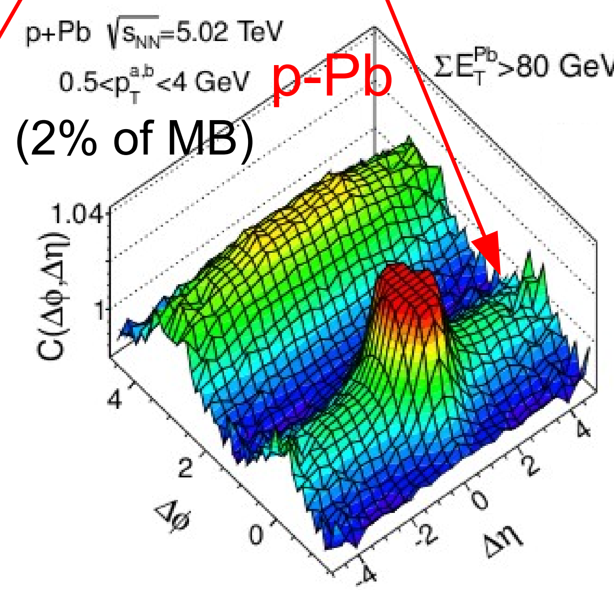
Near-side (NS) ridges in high multiplicity events at LHC energies



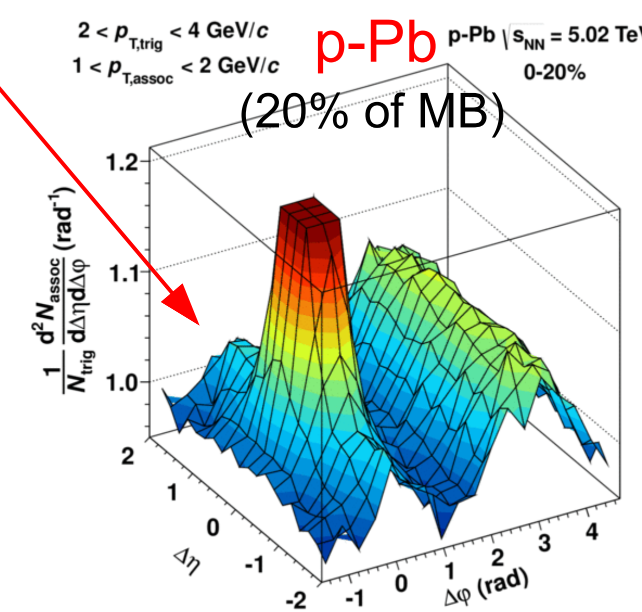
ALICE, PLB 708 (2012) 249



CMS, PLB 718 (2012) 795



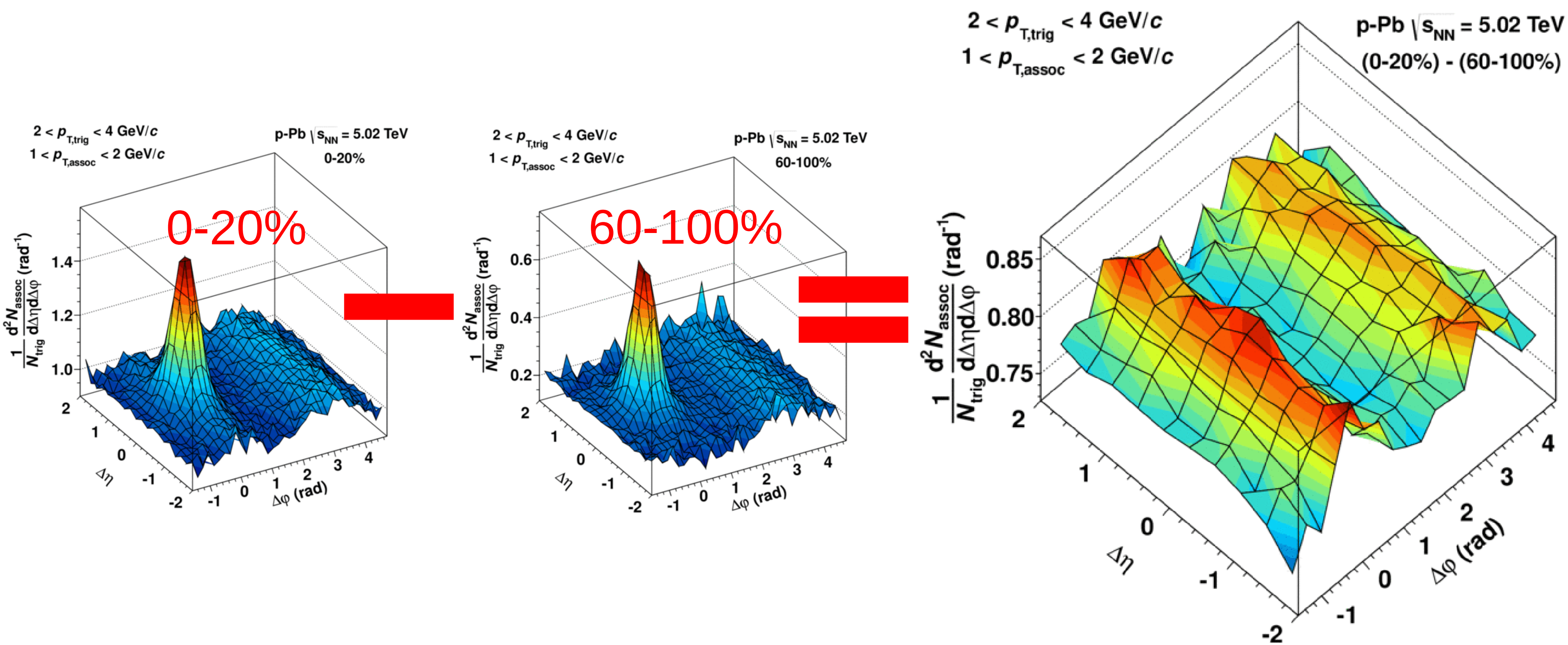
ATLAS, PRL 110 (2013) 182302



ALICE, PLB 719 (2013) 29

13 Observation of double ridge

ALICE, PLB 719 (2013) 29

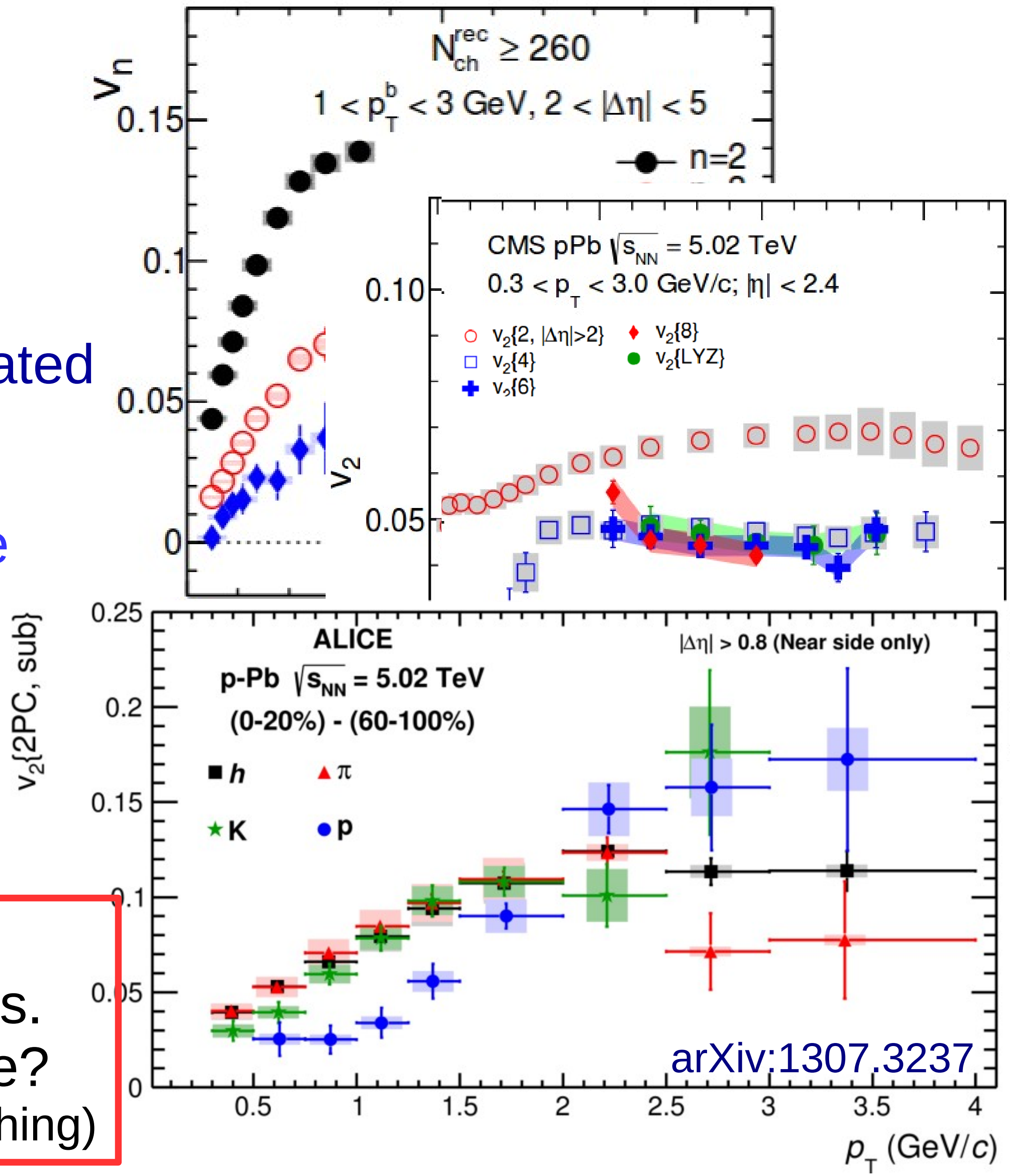


- Extract double ridge structure by subtracting the jet-like correlations from 60-100% low multiplicity class
  - Checked that correlations in 60-100% are similar to pp (at 2.76 and 7 TeV)

14 Analysis of double ridge

- v_n coefficients
  - Significant for n=2 to 5
  - Substantial to even high p_T
- Multi-particle correlations
  - At least 8 particles correlated
  - $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Particle species dependence
  - Cross of v_2(proton) with v_2(pion) at about 2 GeV/c for p_T<2 GeV/c

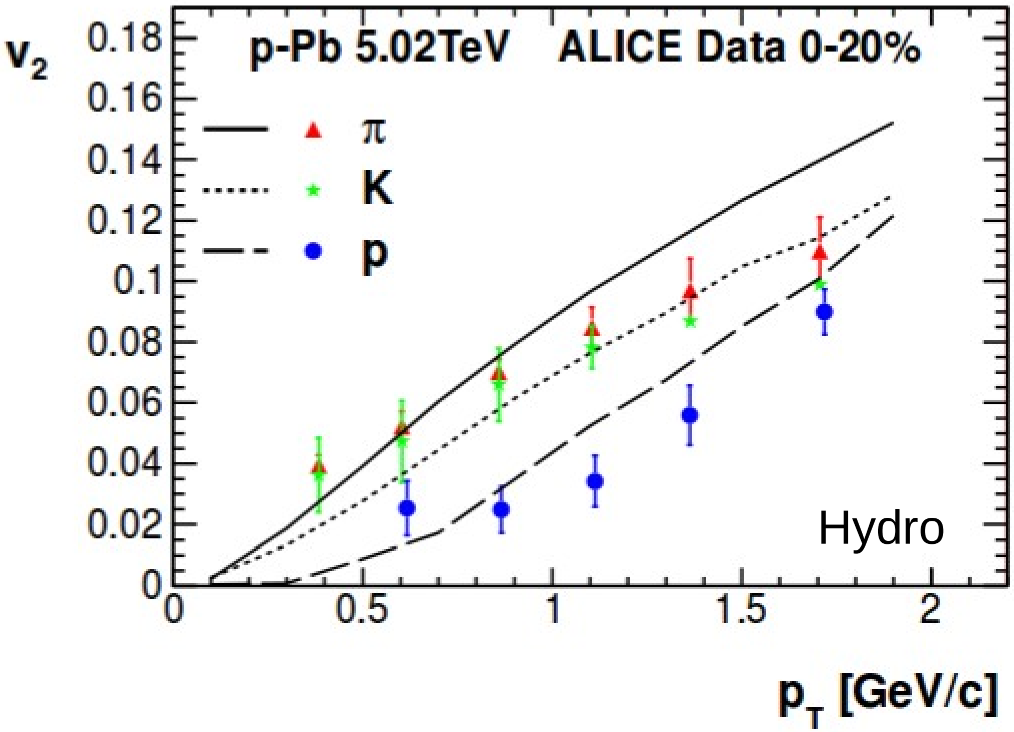
arXiv:1409.1792



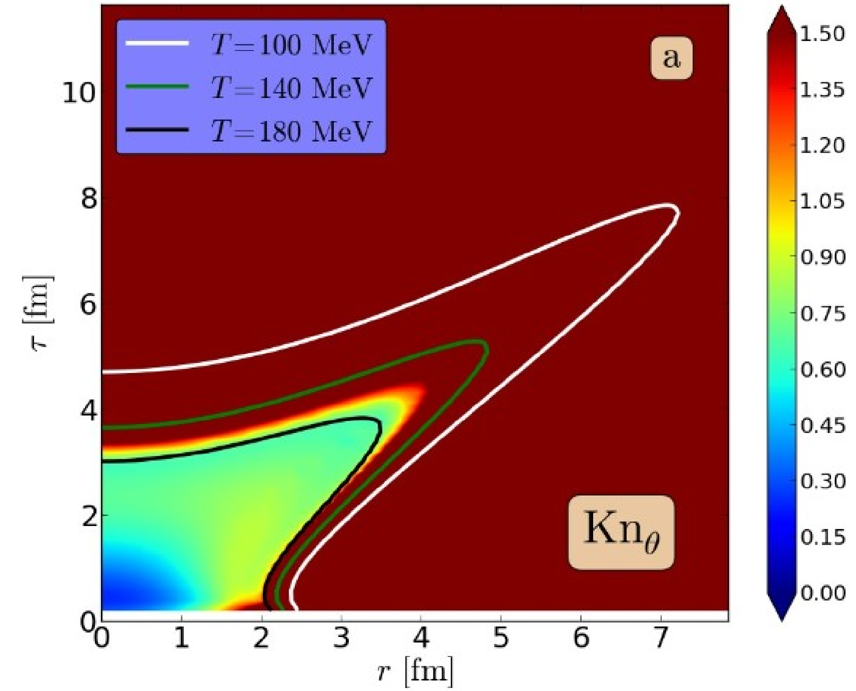
Features qualitatively similar
to those seen in Pb-Pb collisions.
Suggests same physics at place?
(Note: no direct evidence of jet quenching)

15 Interpretation: Hydrodynamics

arXiv:1307.5060



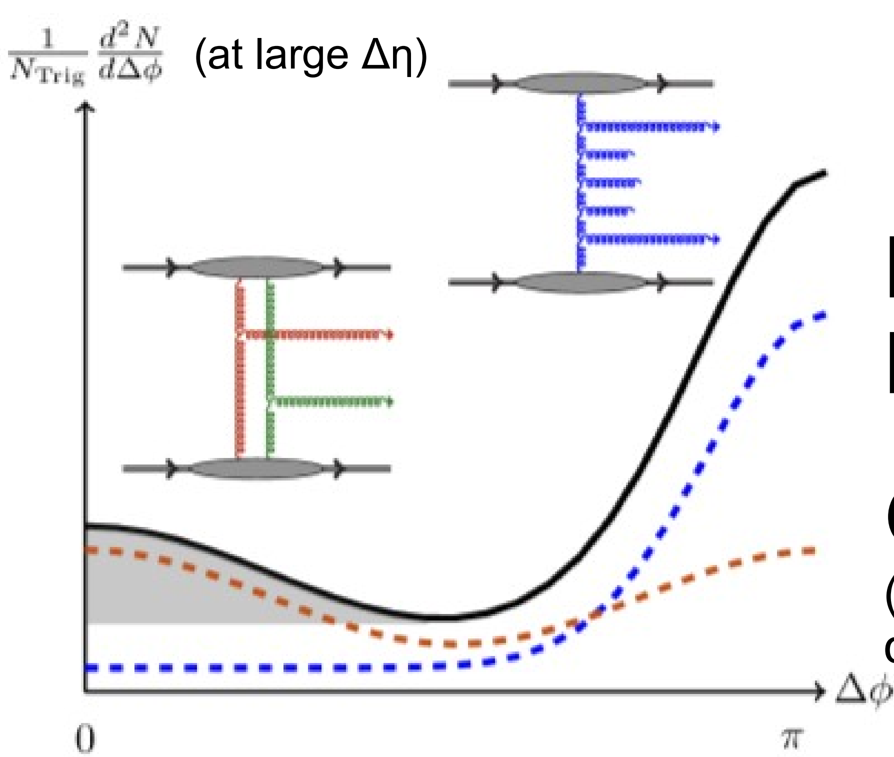
arXiv:1404.7327



- Formation of mini-QGP with hydrodynamical evolution
  - Obvious conclusion, since features in data similar to Pb-Pb
- Debate if hydro can be applied, and gives with meaningful parameters (eg. η/s~0.08 smaller than in PbPb)?
- Macro- and microscopic length/time scales separable?

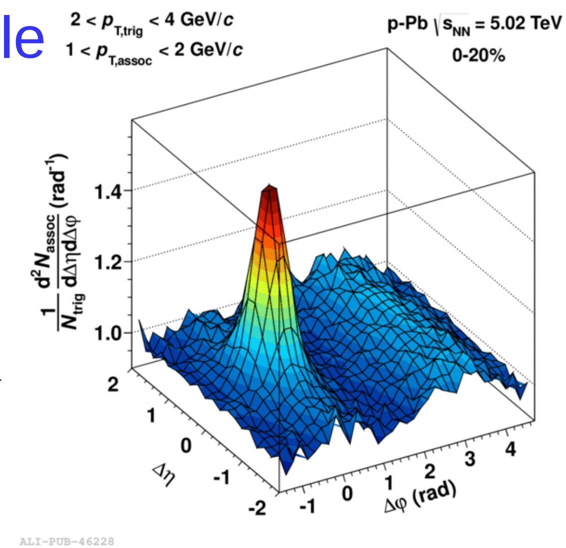
16 Interpretation: Glasma graphs in initial state

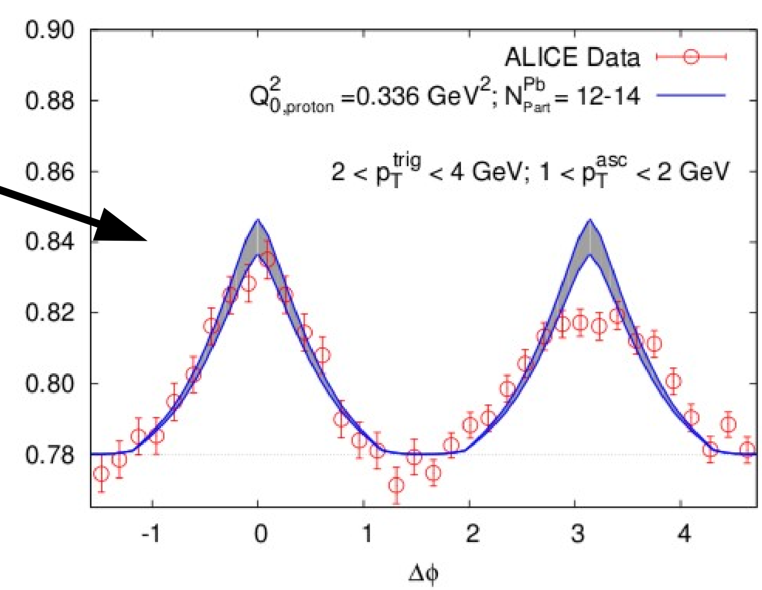
- Two symmetric ridges predicted by CGC glasma graphs found to describe the ridge yields and shape
  - Already applied at RHIC and in 7 TeV pp
- However, not obvious how to explain multi-particle cumulants and PID dependence



BFKL-Minijets

Glasma
(enhanced by α_s^{-8} for $k_T < Q_s$)





Dusling and Venugopalan, PRD 87 (2013) 094034

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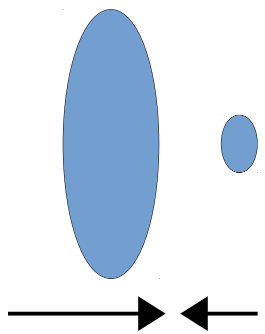
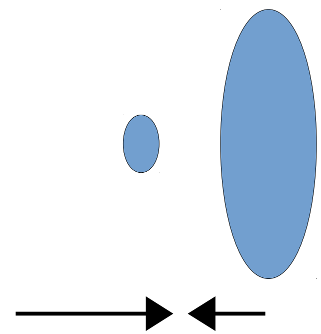
Part3: New ALICE paper arXiv:1506.08032 and related results

18 Saturation vs multiplicity effect?

Pb-going side



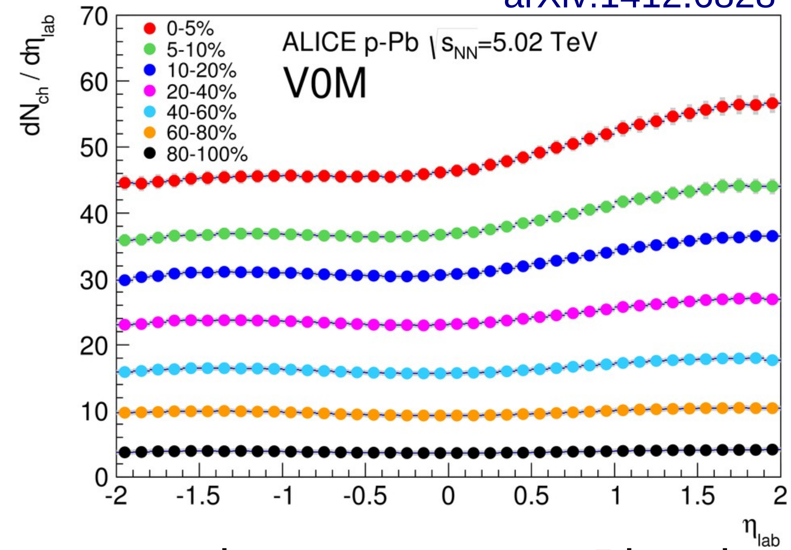
p-going side



Large-x gluons in Pb
Small-x effects suppressed

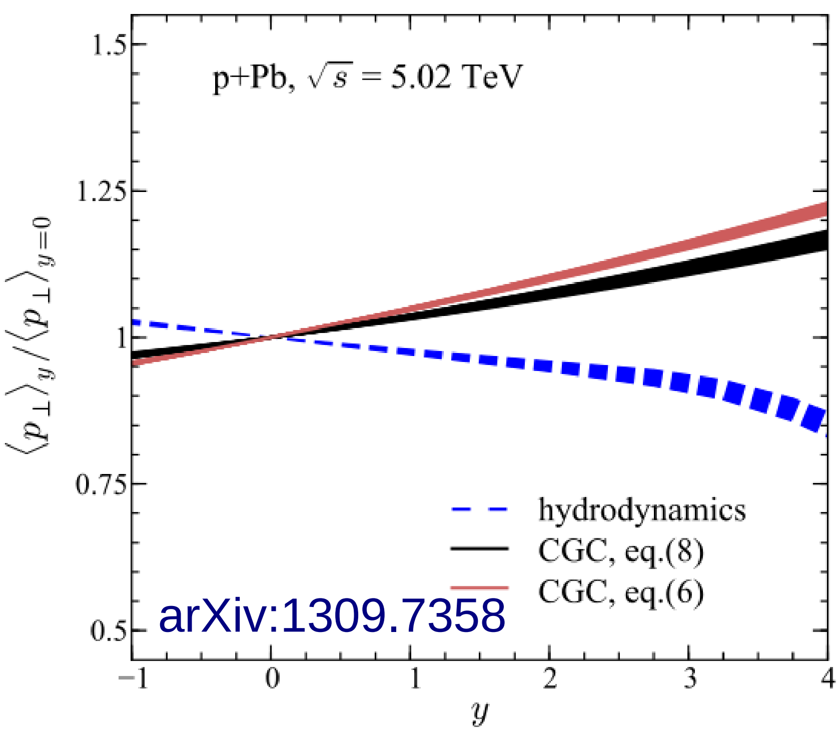
Small-x gluons in Pb
Small-x effects enhanced

arXiv:1412.6828



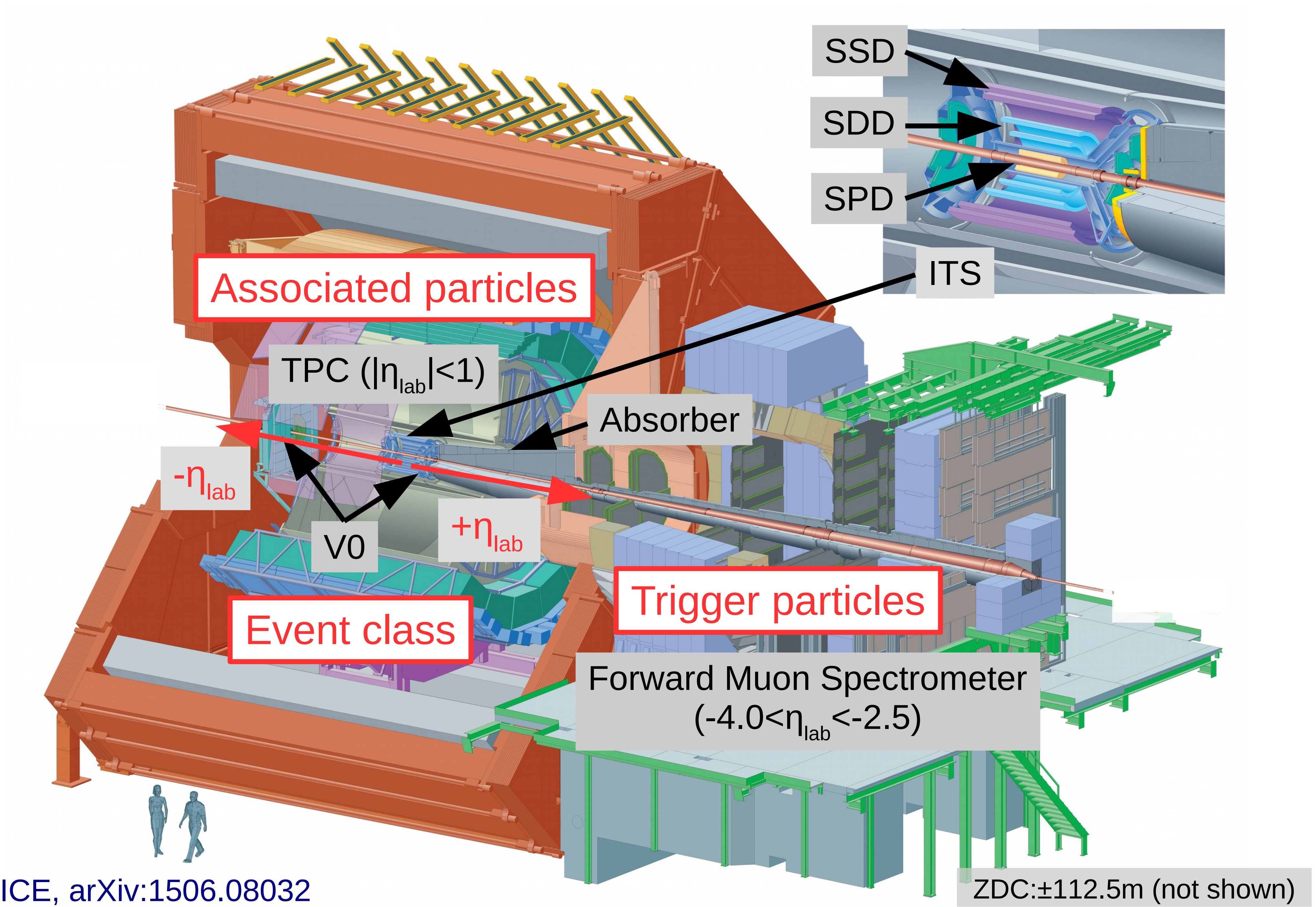
p-going Pb-going

$$v_2 \propto \varepsilon \frac{dN/dy}{S}$$



No explicit calculations for long range correlations exist at LHC. But generally expect that the effects should be enhanced with increasing rapidity of the pair, increasing centrality and decreasing p_T (see arXiv:1209.0336)

19 ALICE systems used in the analysis

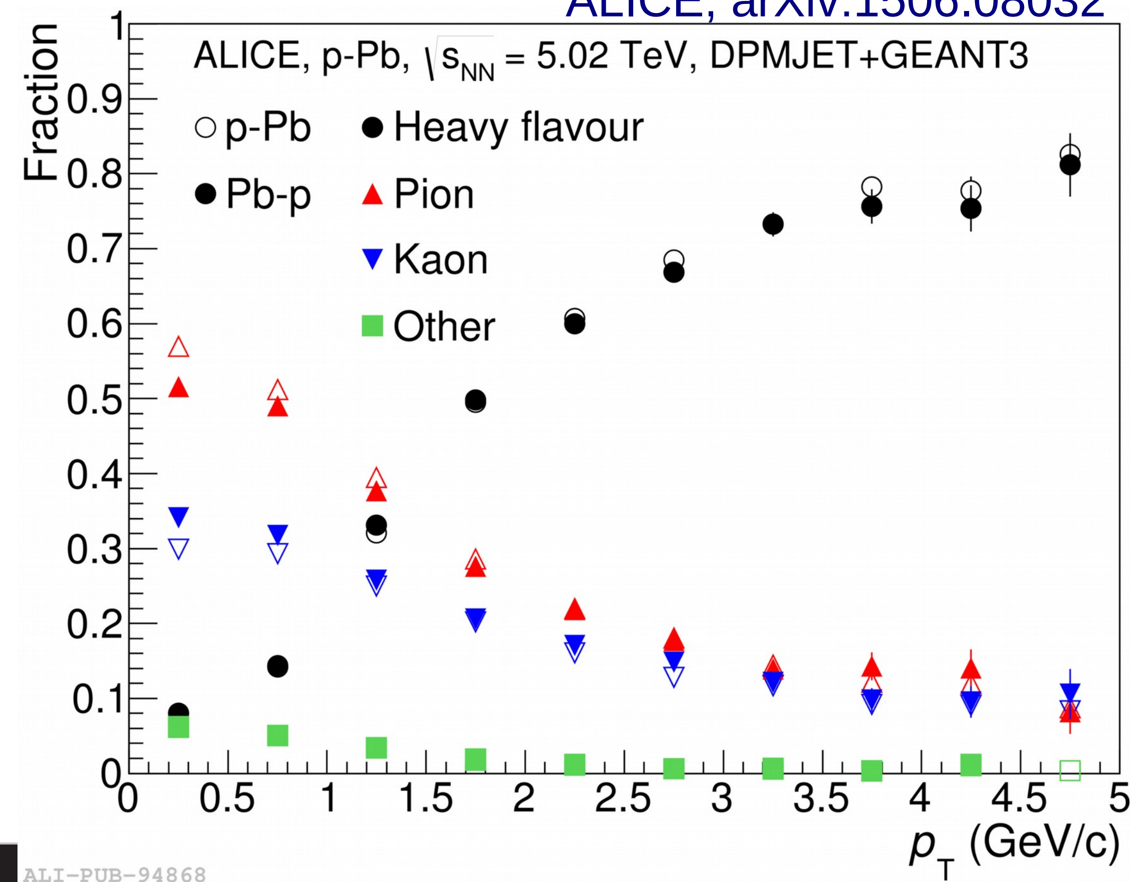


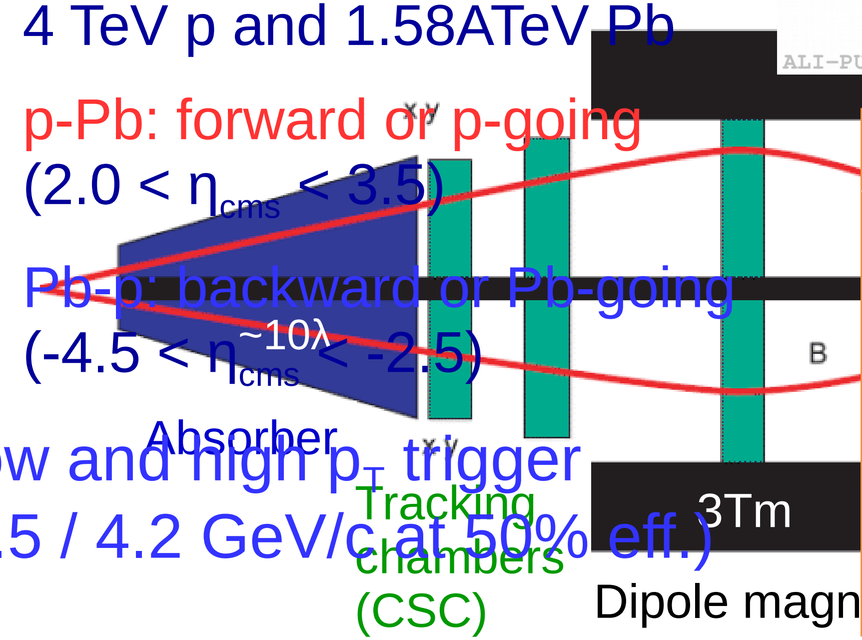
ALICE, arXiv:1506.08032

20 Trigger particles

ALICE, arXiv:1506.08032

- Inclusive muons in single arm spectrometer ($-4.0<\eta_{lab}<-2.5$)
  - Composition changes as a function of p_T
  - Dominated by decays from heavy flavor above 2 GeV/c
- Effect of beam configuration
  - $\sqrt{s_{NN}}$=5.02 TeV with 4 TeV p and 1.58ATeV Pb
  - p-Pb: forward or p-going ($2.0 < \eta_{cms} < 3.5$)
  - Pb-p: backward or Pb-going ($-4.5 < \eta_{cms} < -2.5$)
- Low and high p_T trigger (0.5 / 4.2 GeV/c at 50% eff.)



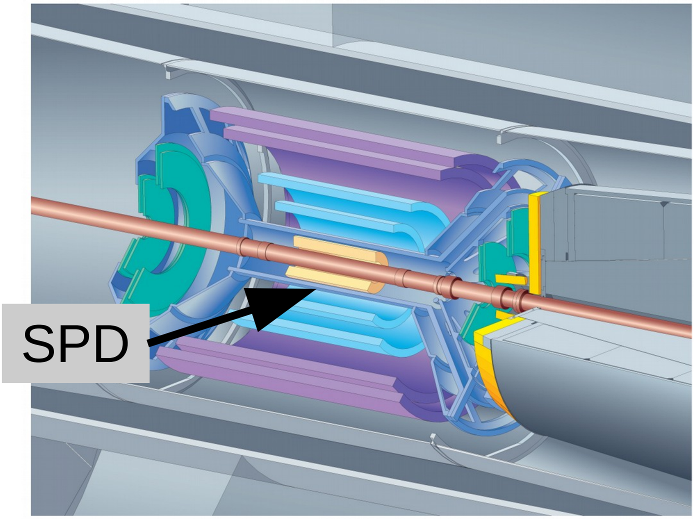


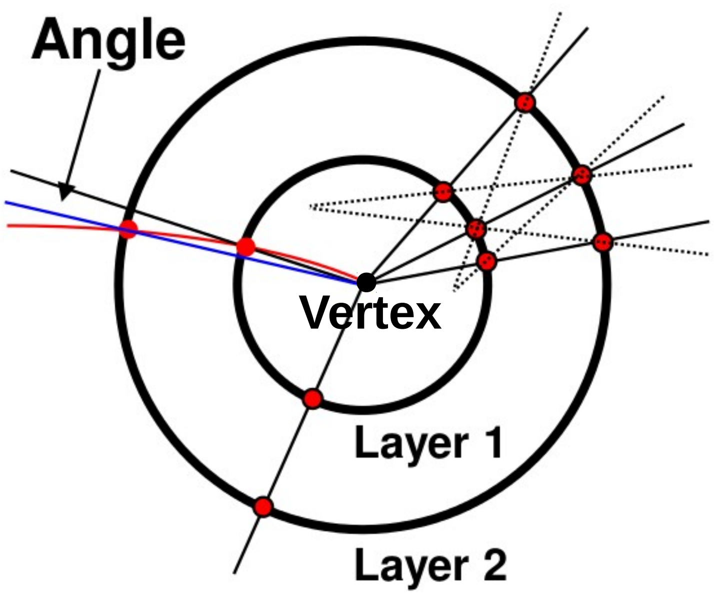
	p-Pb	Pb-p
Muon high-p_T trigger	5.0 nb^{-1}	5.8 nb^{-1}
Muon low-p_T trigger	0.28 nb^{-1}	0.26 nb^{-1}
Fraction of TPC readout in μ-low-p_T	25%	10%

21 Associated particles

ALICE, arXiv:1506.08032

- Charged particles at mid-rapidity ($|\eta|<1$)
- Tracklets
  - Pair of hits on SPD layers 1 and 2 compatible with a straight line from vertex
  - Selection uses azimuthal and polar angle differences of the hits
  - Use harder cut than usual ($\Delta\varphi$<5mrad)
    - Mean p_T about 0.75 GeV/c from MC
  - First used by PHOBOS (see arXiv:hep-ex/0007036)
- Reconstructed tracks using TPC+ITS
  - Cross-check of tracklet-based analysis in p-Pb collisions
  - With limited statistical precision due to low fraction of events with central barrel in read-out

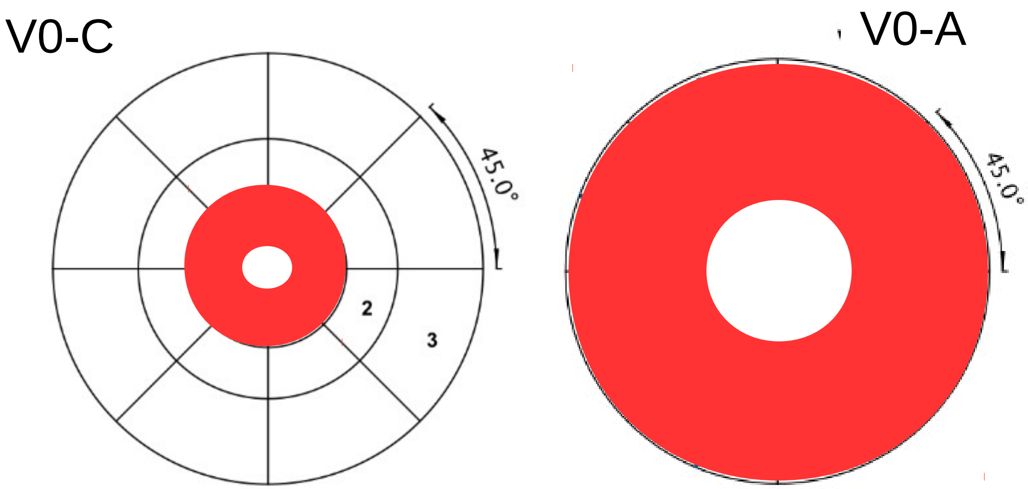




22 Event class definition

ALICE, arXiv:1506.08032

- Attempt comparison between two beam configurations
  → Requires event class def. with symmetric acceptance
- V0 detector acceptance
  - V0-A: $2.8<\eta_{lab}<5.1$
  - V0-C: $-3.7<\eta_{lab}<-1.7$
- Select two rings on each side with approximate symmetric coverage: V0S estimator
  - $2.8<\eta_{lab}<3.9$ from V0-A
  - $-3.7<\eta_{lab}<-2.7$ from V0-C
- Focus on 0-20%: roughly $2*\langle dN_{ch}/d\eta\rangle_{minbias}$



Event class	$\langle dN_{ch}/d\eta \rangle \|_{\|\eta\|<0.5}$ $p_T > 0\,\mathrm{GeV}/c$
0–20%	35.8 ± 0.8
20–40%	23.2 ± 0.5
40–60%	15.8 ± 0.4
60–100%	6.8 ± 0.2

23 Associated yield per trigger

ALICE, arXiv:1506.08032

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

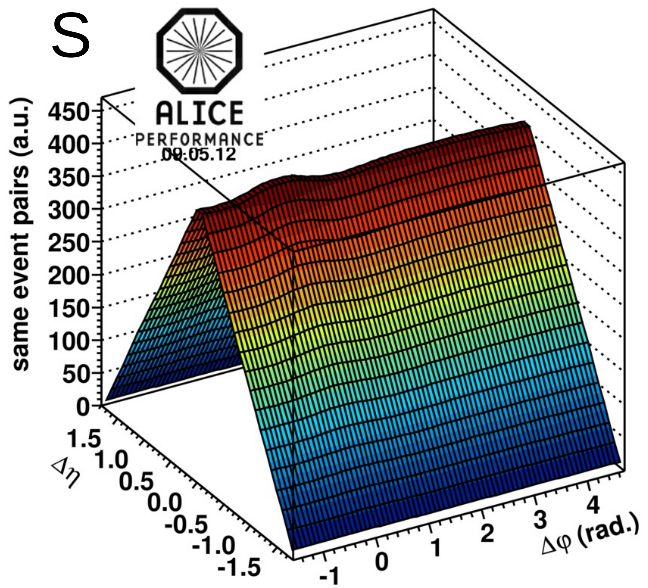
$$S(\Delta\varphi, \Delta\eta) = \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{same}}}{\mathrm{d}\Delta\varphi \mathrm{d}\Delta\eta}$$

(definition as ratio of sums to be multiplicity independent)

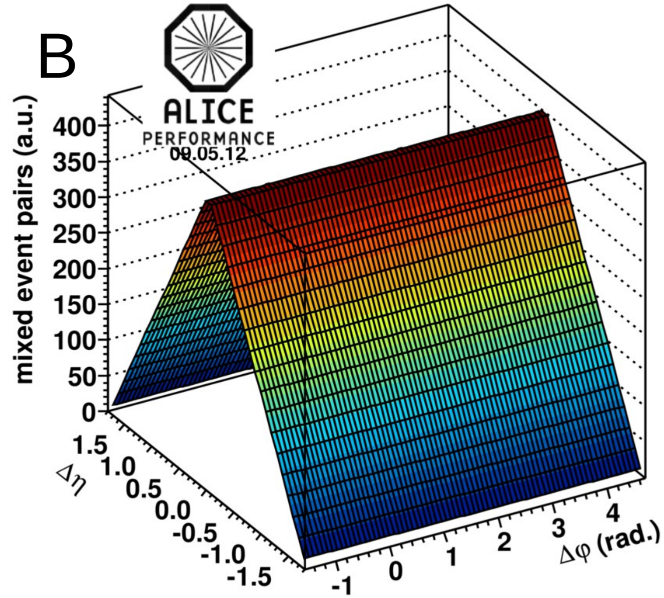
$$B(\Delta\varphi, \Delta\eta) = \alpha \frac{\mathrm{d}^2 N_{\mathrm{mixed}}}{\mathrm{d}\Delta\varphi \mathrm{d}\Delta\eta}$$

(α normalizes B in region of maximum pair acceptance)

Note: Unlike other analyses by default in this analysis we do not use single-particle efficiency corrections, ie aim only at relative modulations (v_2)



ALI-PERF-15347



24 $Y \equiv \frac{1}{N_{\rm trig}} \frac{{\rm d}^2 N_{\rm assoc}}{{\rm d}\Delta\varphi {\rm d}\Delta\eta}$ $0.5 < p_{\rm T}^{\rm trig} < 1 {\rm GeV}/c$

ALICE, arXiv:1506.08032

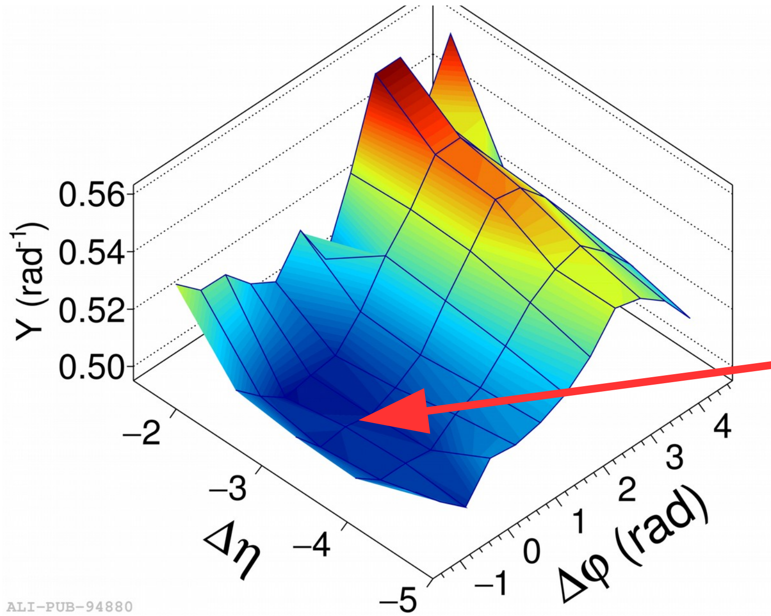
Forward-going (p-Pb)

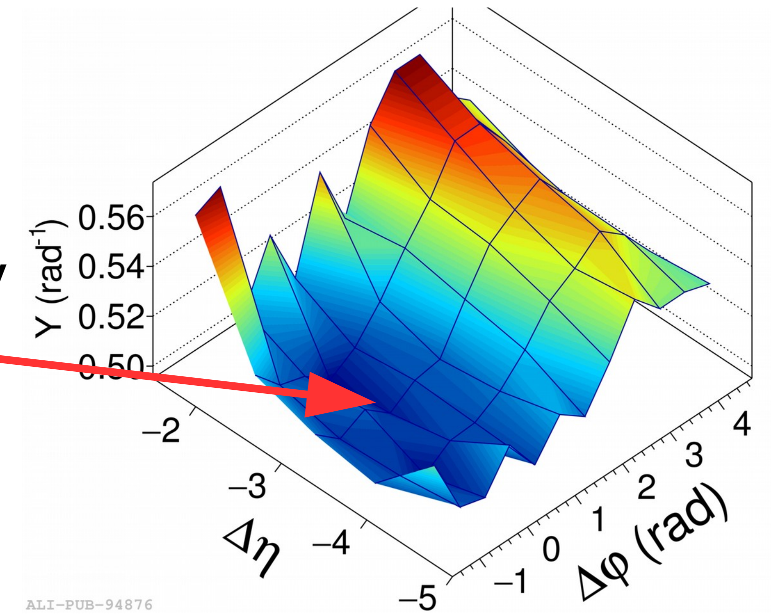
Assoc. tracklets

Assoc. tracks

60-100% V0S

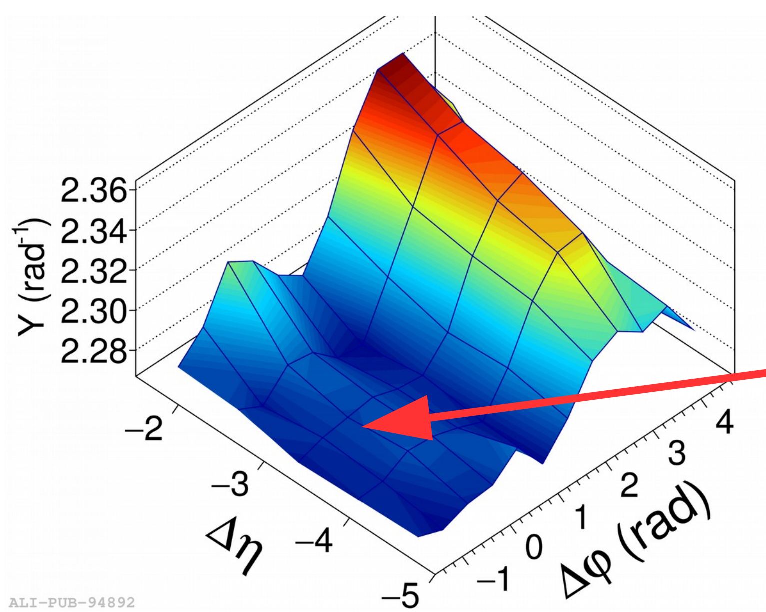
No ridge for
low multiplicity

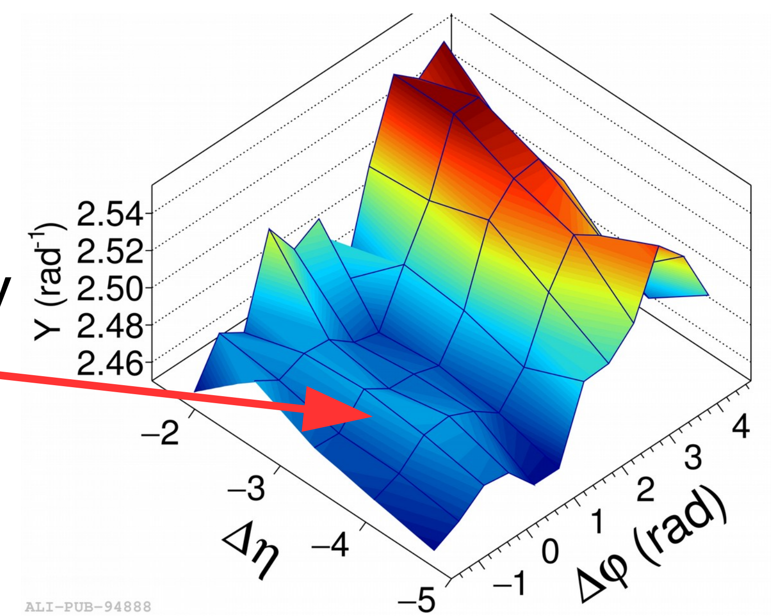




0-20% V0S

NS ridge for
high multiplicity





$$Y \equiv \frac{1}{N_{\mathrm{trig}}} \frac{\mathrm{d}^2 N_{\mathrm{assoc}}}{\mathrm{d}\Delta\varphi \mathrm{d}\Delta\eta} \quad 0.5 < p_{\mathrm{T}}^{\mathrm{trig}} < 1\mathrm{GeV}/c$$

ALICE, arXiv:1506.08032

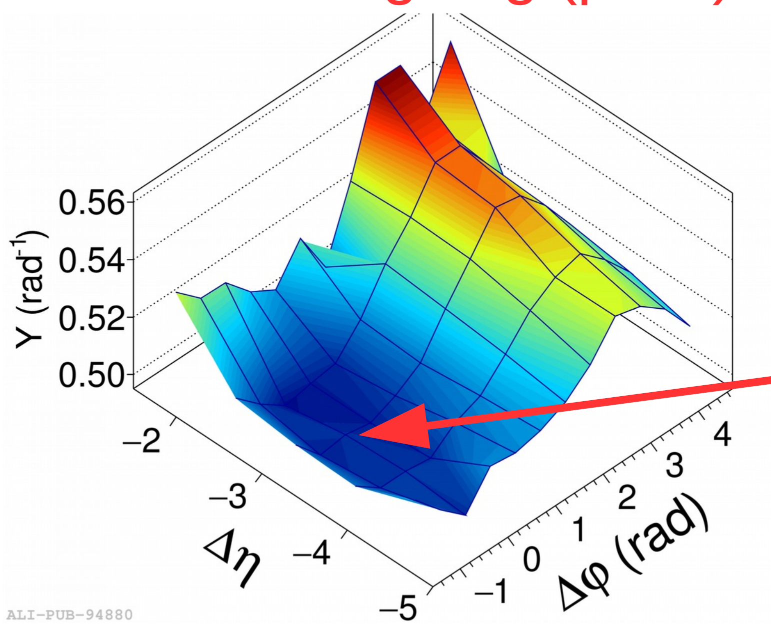
Associated tracklets

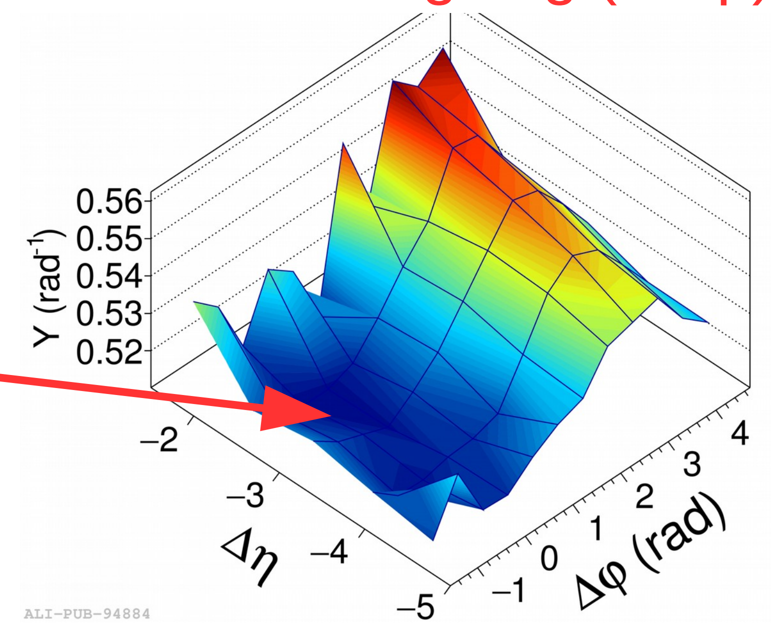
Forward-going (p-Pb)

Backward-going (Pb-p)

60-100% V0S

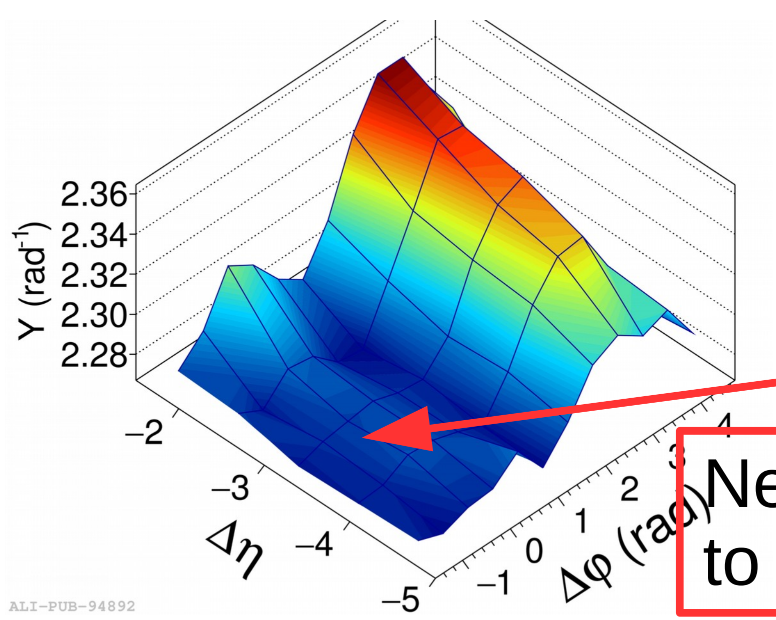
No ridge for low multiplicity

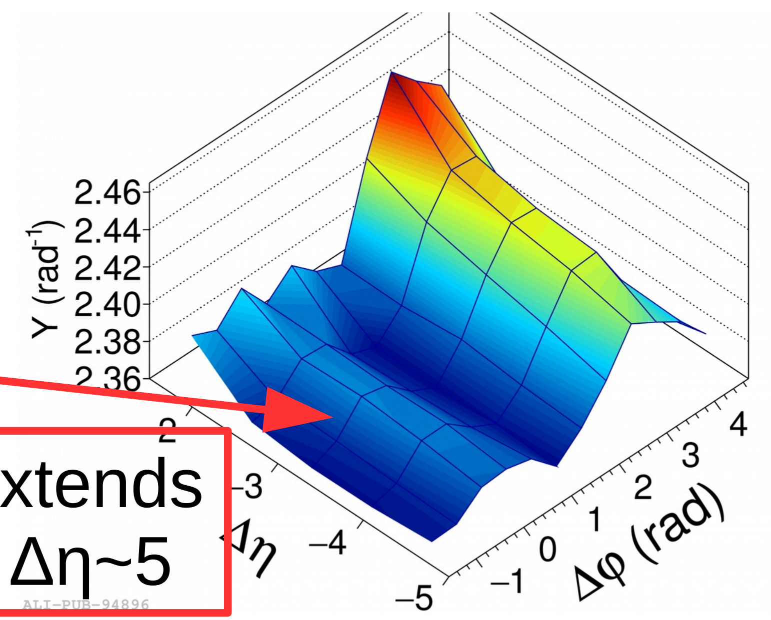




0-20% V0S

NS ridge for high multiplicity





Near-side ridge extends to η~±4 and over Δη~5

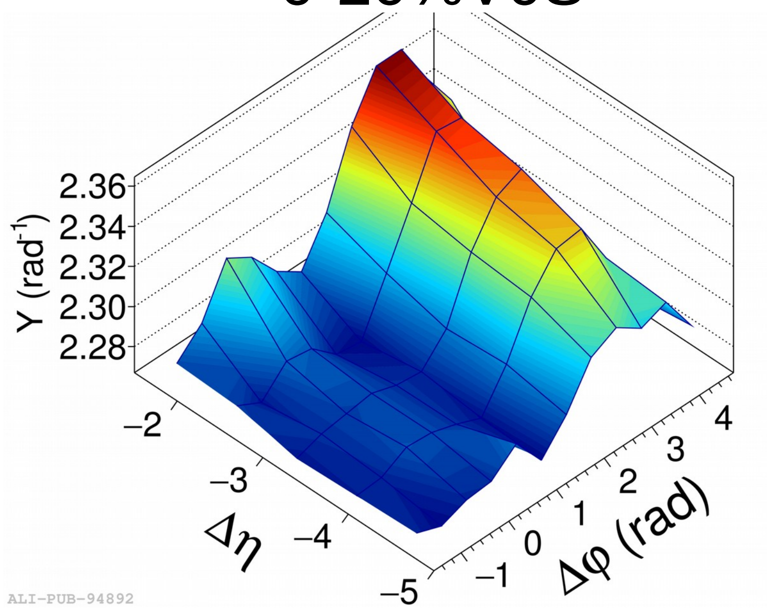
26 Subtraction method

ALICE, arXiv:1506.08032

To isolate long range correlations,
subtract low multiplicity from high multiplicity correlations

$Y_{\mathrm{sub}} \equiv$

0-20%V0S



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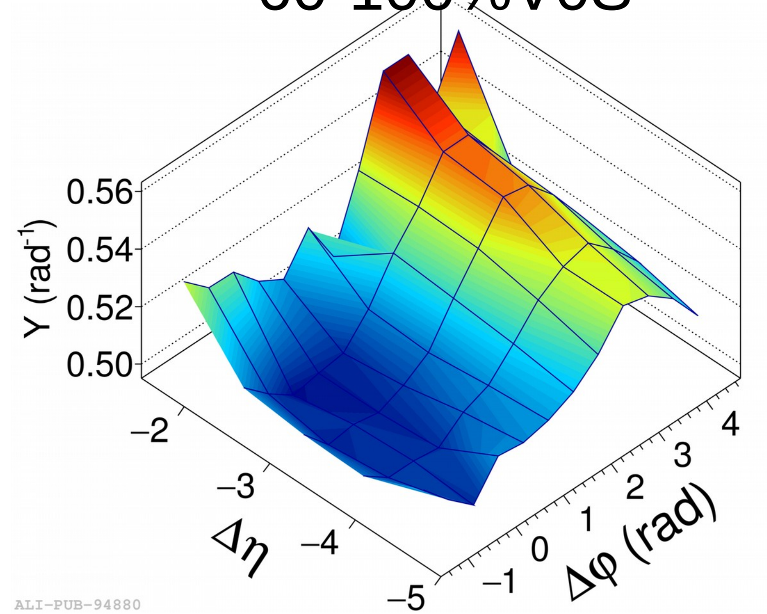
60-100%V0S



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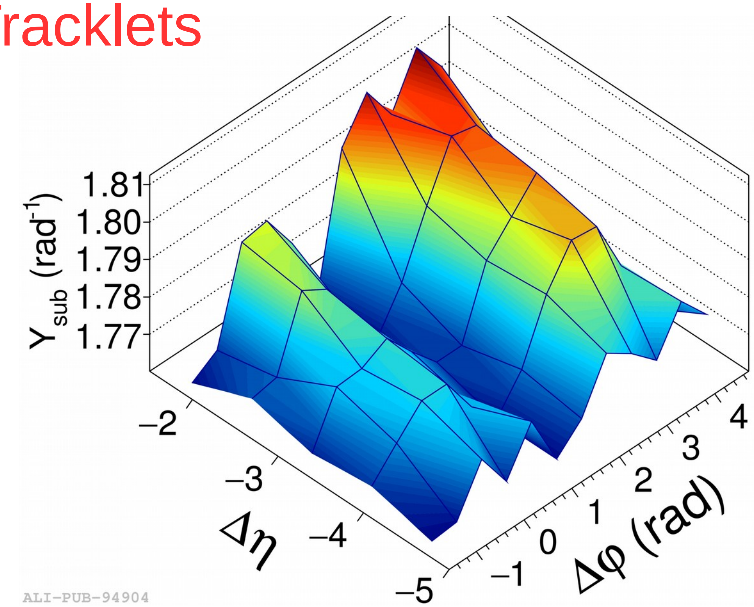
(first done in arXiv:1212.2001)

27 Subtracted correlations

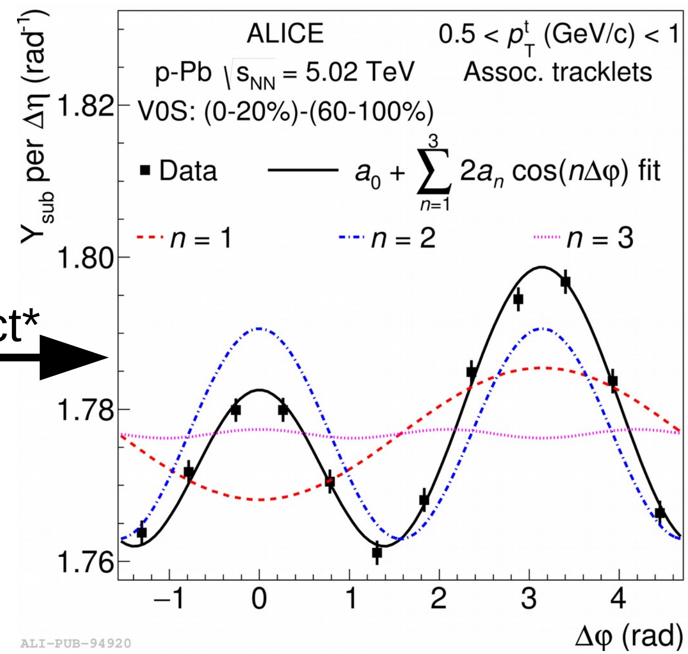
ALICE, arXiv:1506.08032

(0-20%)-(60-100%)V0S

Forward-going
Tracklets

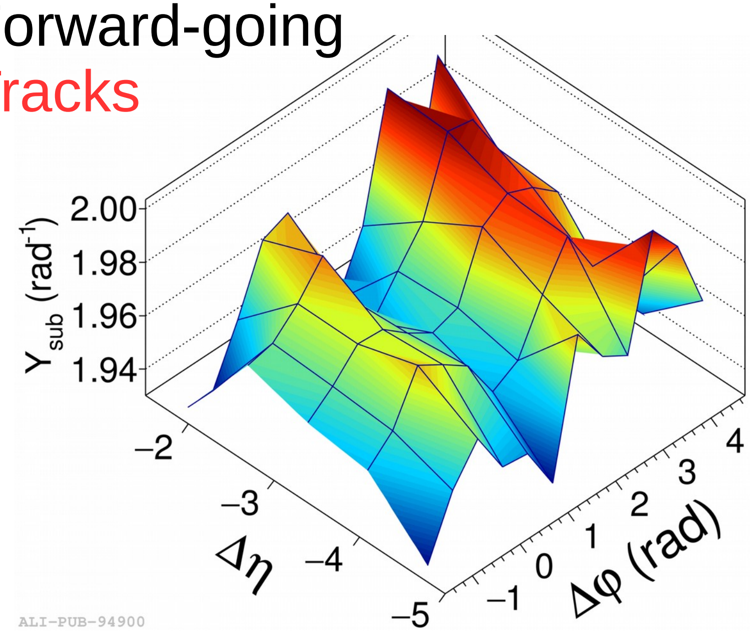


Project*

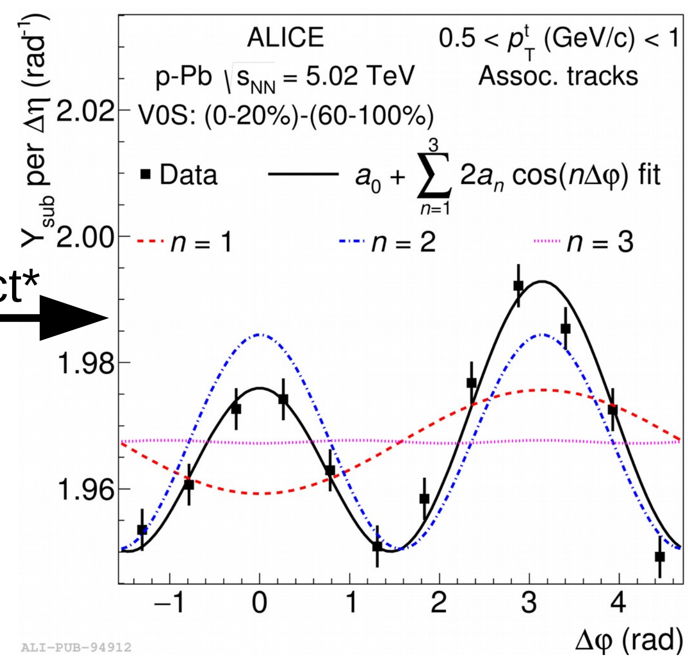


Double ridge

Forward-going
Tracks



Project*



n=1
n=2
n=3

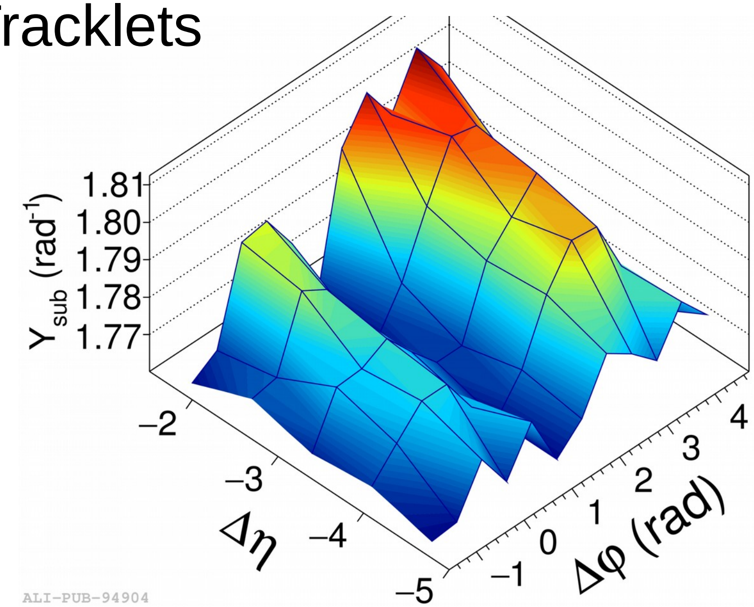
(*) done with a pol1 fit

28 Subtracted correlations

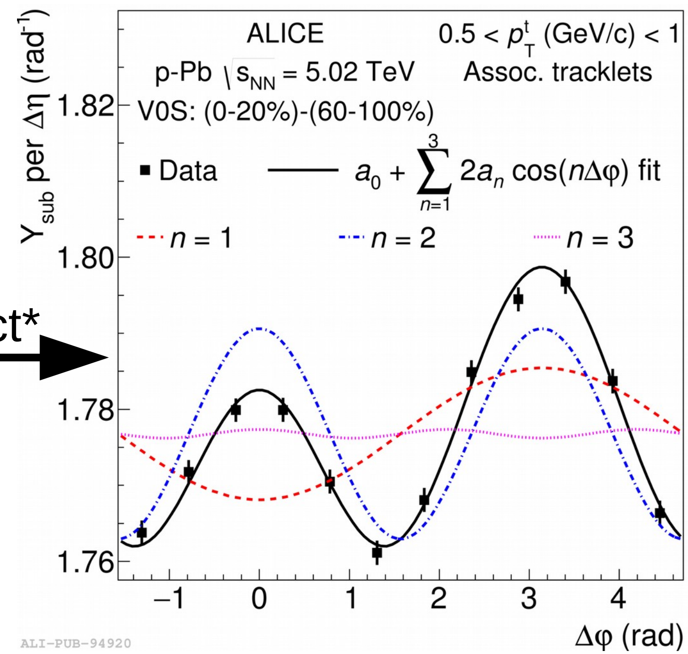
ALICE, arXiv:1506.08032

(0-20%)-(60-100%)V0S

Forward-going
Tracklets

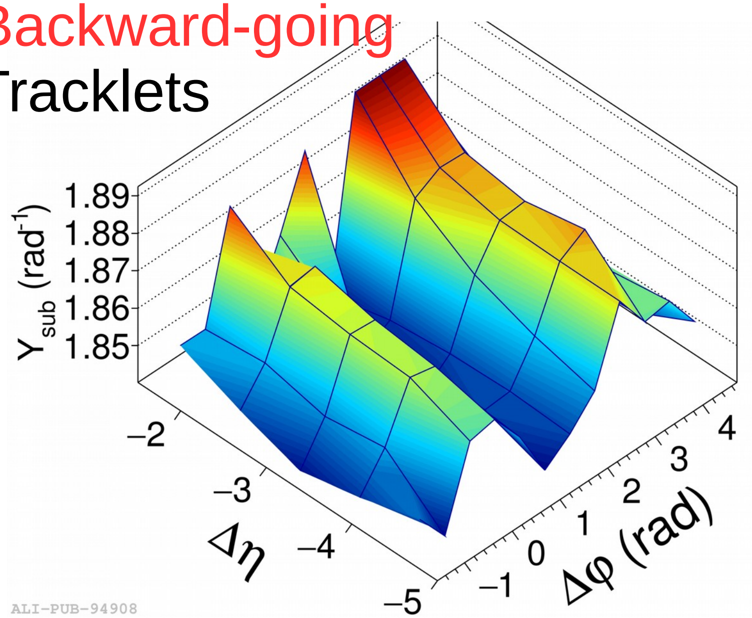


Project*

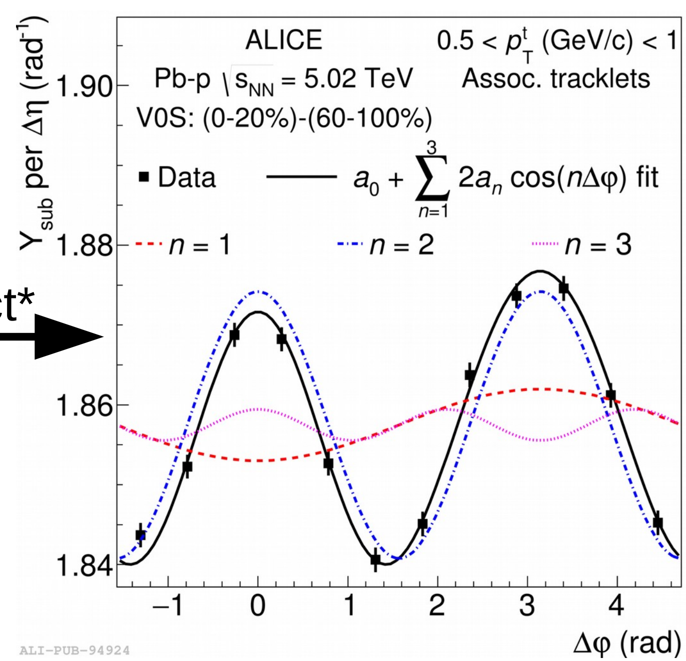


Double ridge in both directions

Backward-going
Tracklets



Project*



Second order dominates!

n=1
n=2
n=3

(*) done with a pol1 fit

29 Extraction of muon v_2

ALICE, arXiv:1506.08032

- Relative modulation

$$V_{2\Delta}^{\mu,c}(\mathrm{2PC},\mathrm{sub}) = \frac{a_2}{a_0 + b}$$

Baseline in low mult. class

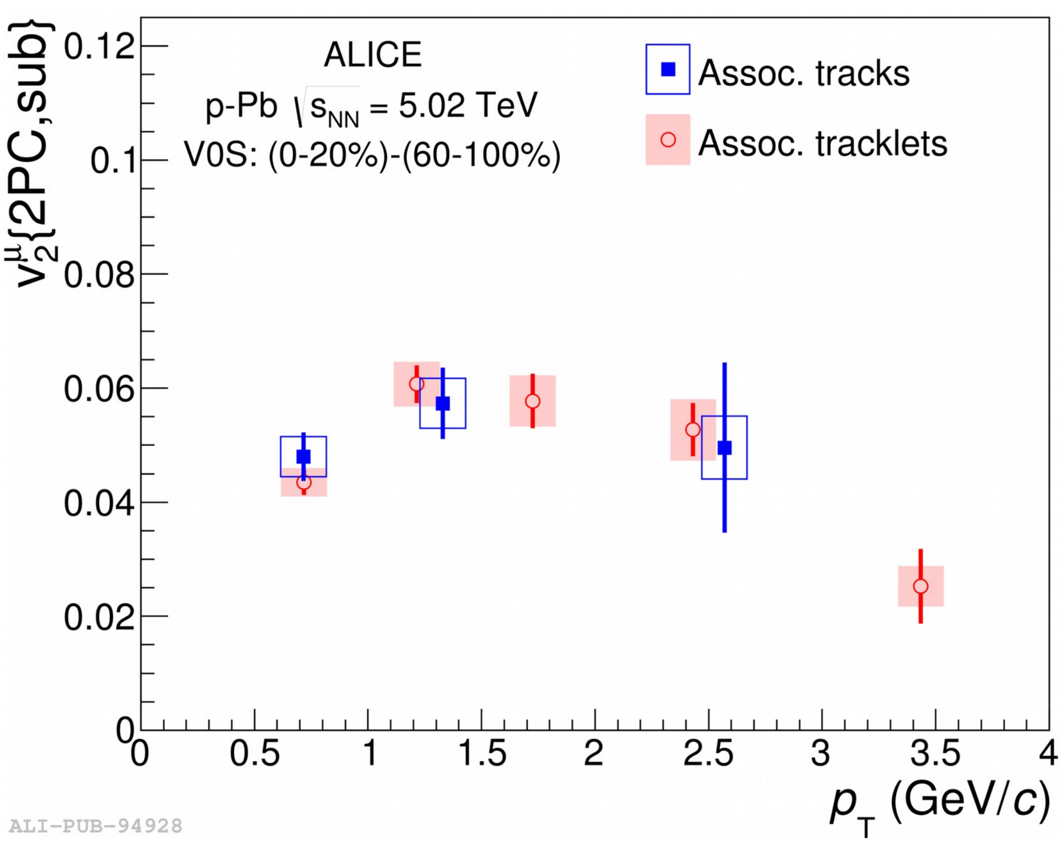
- Assume factorization

$$v_2^{\mu}(\mathrm{2PC},\mathrm{sub}) = V_{2\Delta}^{\mu,c} / \sqrt{V_{2\Delta}^{c,c}}$$

Measured in central barrel from track-track or tracklet-tracklet correlations

  - At mid-rapidity found to hold to better than 5% (CMS, arXiv:1503.01692)

- Good agreement using either associated tracklets or tracks
  - Probes factorization
  - Verified independence of results for single track efficiency/acceptance



Systematic uncertainties

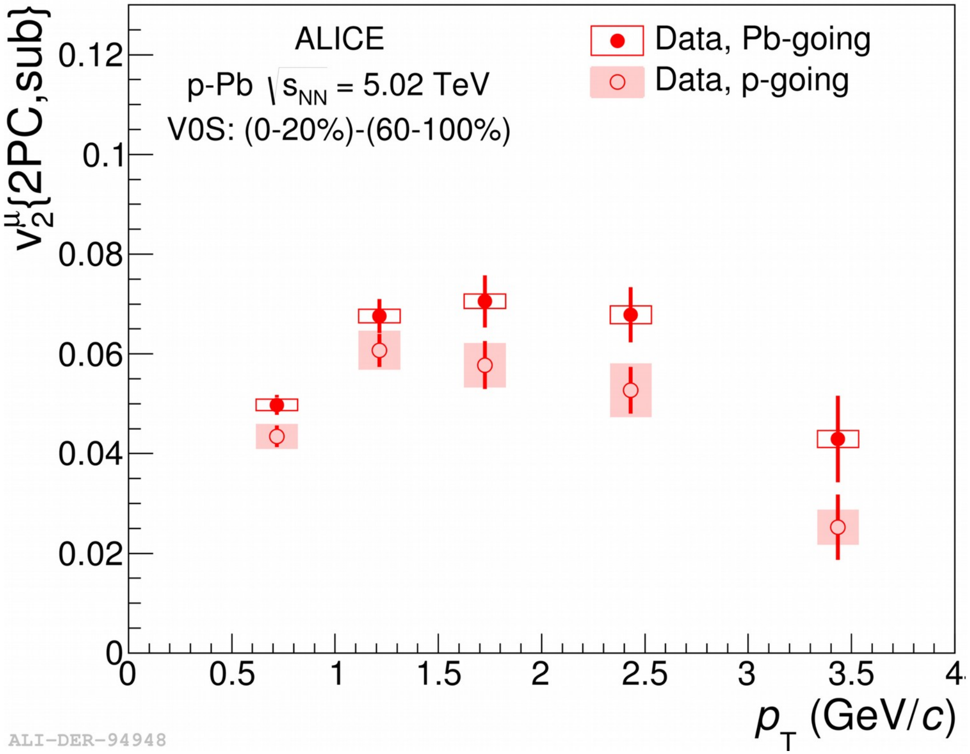
ALICE, arXiv:1506.08032

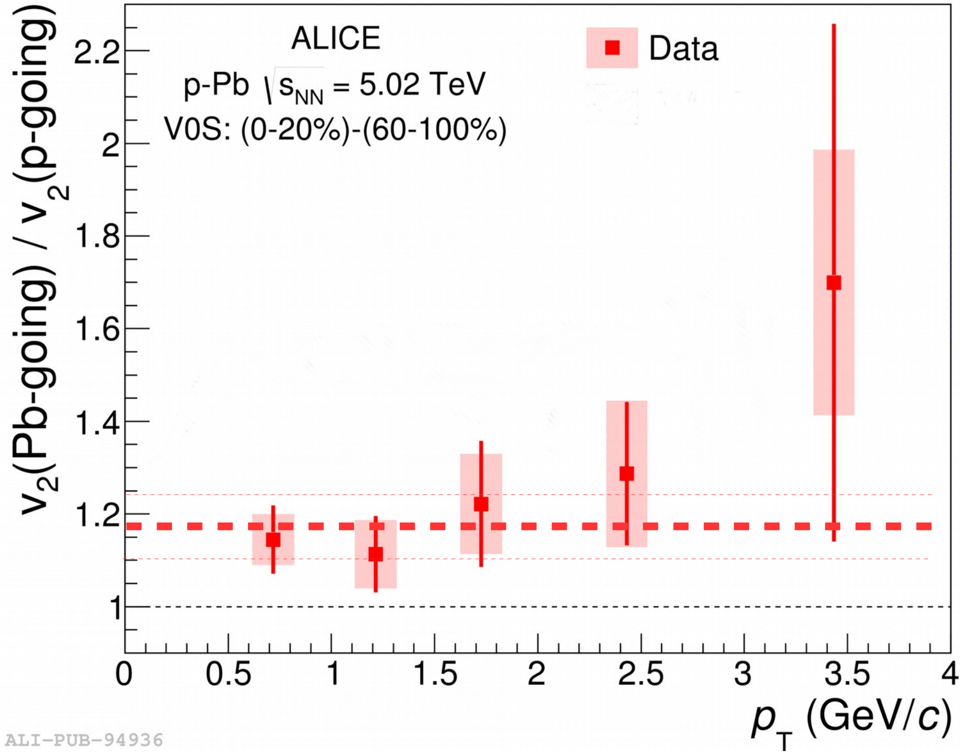
Systematic effect	Assoc. tracks p–Pb	Assoc. tracklets p–Pb	Assoc. tracklets Pb–p	Assoc. tracklets Ratio
Acceptance (z_{vtx} dependence)	3–4%	0–5%	0–3%	0–1%
Remaining jet after subtraction	4–10%	5–14%	1–2%	3–15%
Remaining ridge in low-multiplicity class	1–4%	1–6%	0–2%	2–8%
Calculation of v_2	0–1%	0–1%	1%	0–2%
Resolution correction	1%	0–1%	0–1%	0–2%
Sum (added in quadrature)	7–11%	6–14%	2–4%	5–17%

- Acceptance
  - Varied z vertex requirement from ±7 to ±5cm
- Remaining jet after subtraction
  - Vary Δη cut from 1.2 to 0.8
  - Scale 60-100% by factor (f) determined from the ratio of away-side yields in high over low multiplicity after sub-traction of 2nd order component
- Remaining ridge in low mult
  - Use 70-100% instead of 60-100% V0S for the subtraction
- Calculation of v_2
  - Vary fit and extraction of b
  - Use weighted average for projection instead of pol1 fit
- Resolution correction
  - From MC using 50% variation of the input v_2 at low and high p_T

31 Final results

ALICE, arXiv:1506.08032



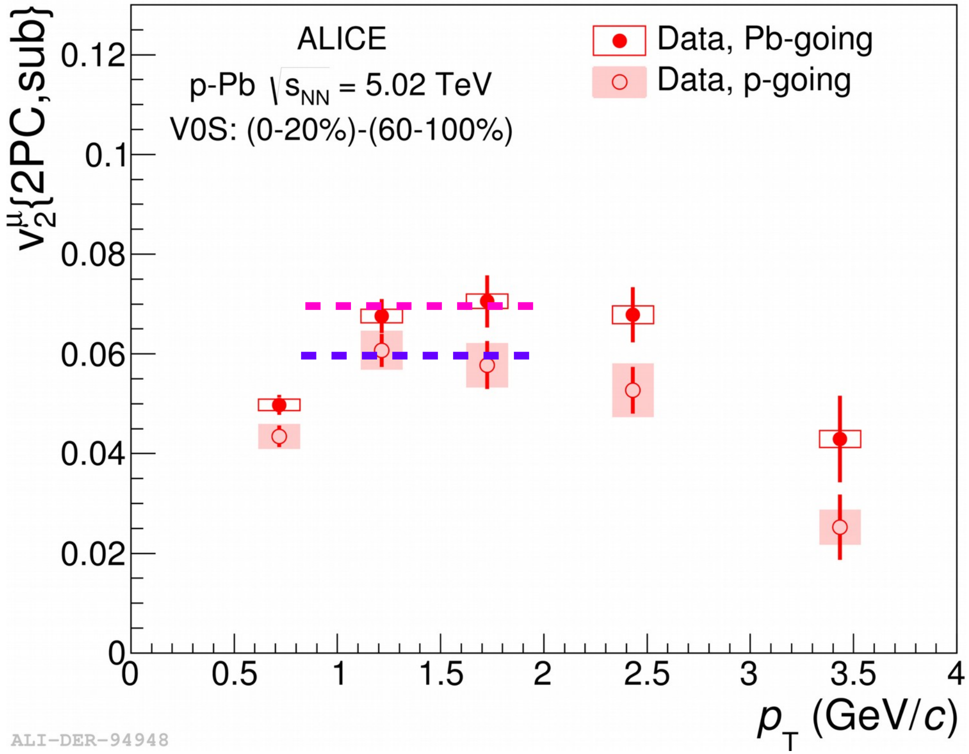


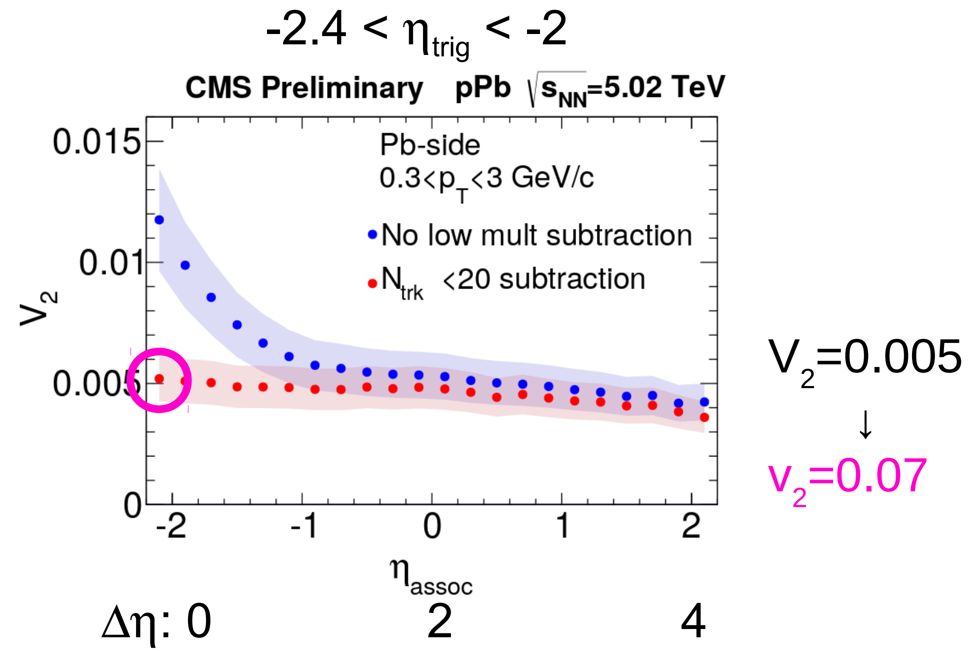
- Sizable inclusive muon v_2
- Pb-going larger than p-going
- Results within 25% when changing from V0S to ZN (zero-degree neutron energy)

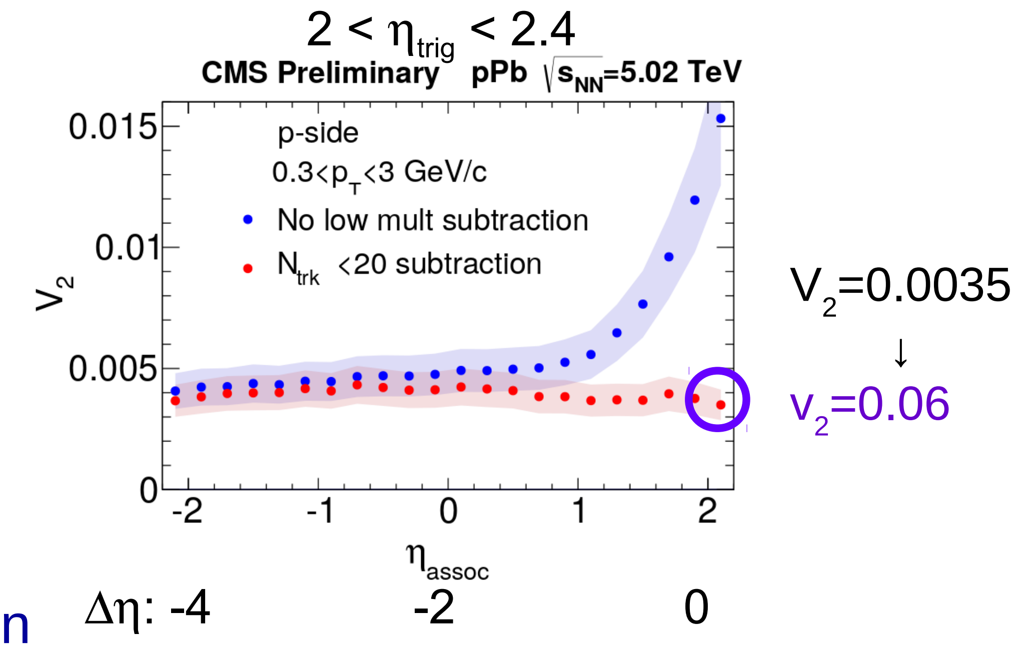
- Ratio (asymmetry) rather independent of p_T
- Constant fit (adding stat. + sys. uncertainty in quadrature)
  - 1.16 ± 0.06 with $\chi^2/NDF = 0.4$
- Similar asymmetry for ZN

32 Comparison to prel. CMS

CMS-HIN-14-000





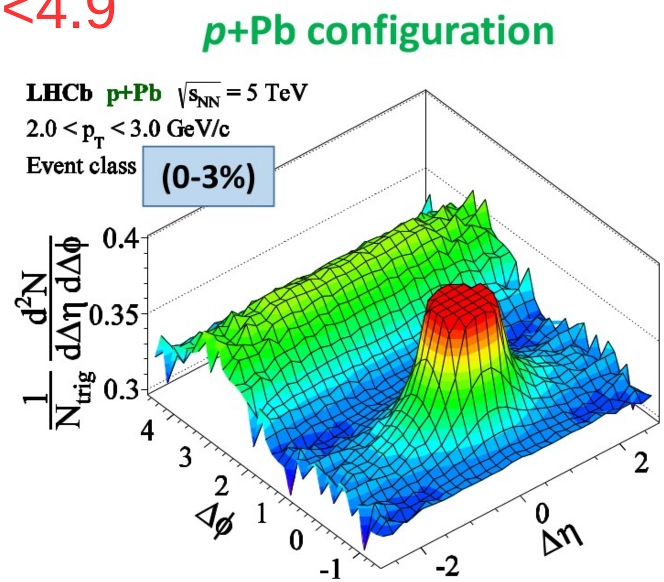


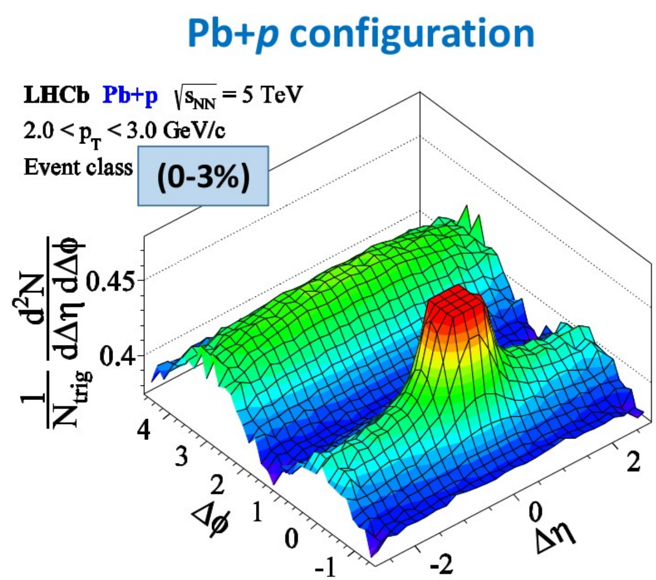
- Resulting coefficients
  - of similar magnitude
  - with same asymmetry
- Not apples-to-apples comparison
  - Muons vs charged particles
  - Kinematic ranges + event selection

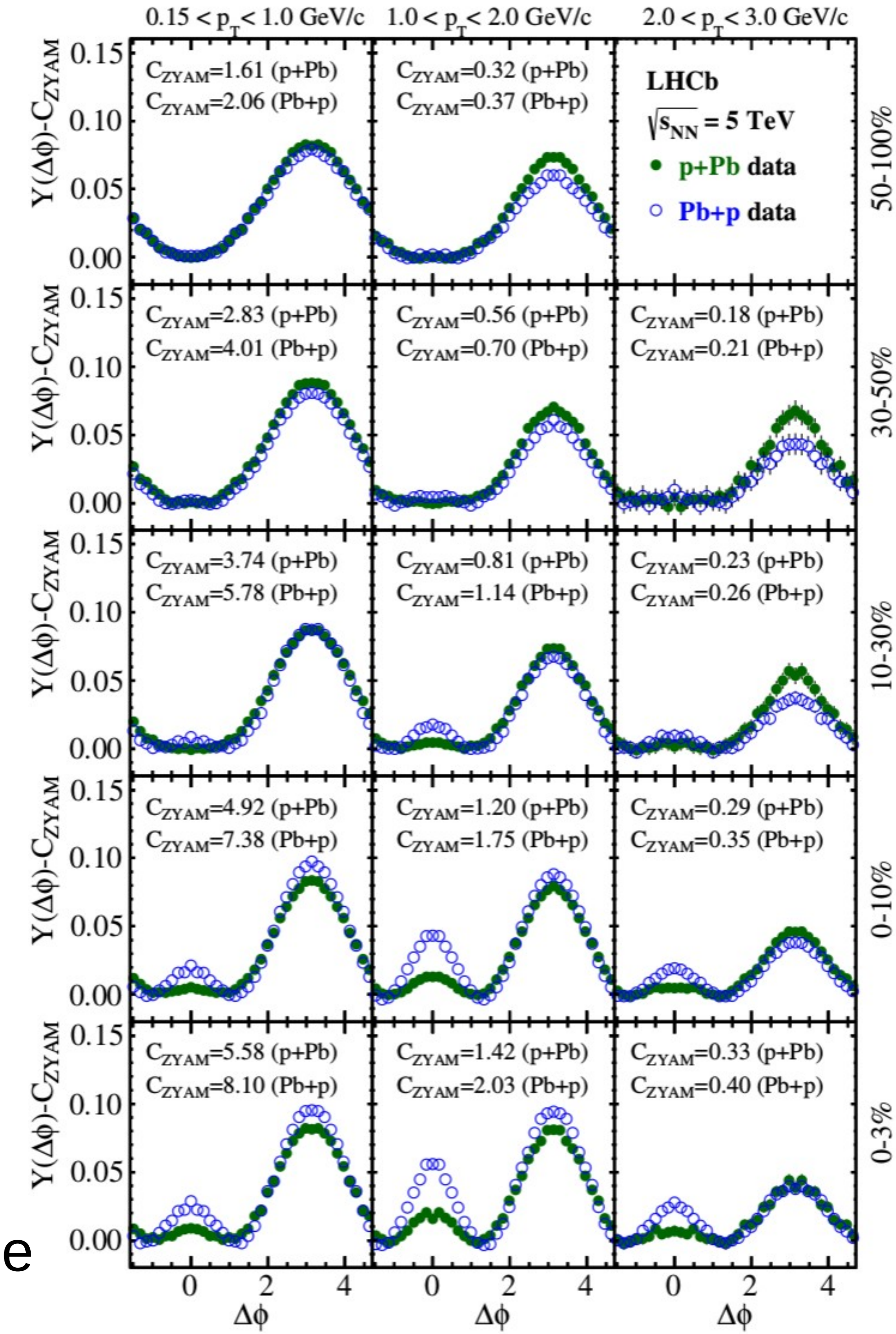
33 LHCb prel. result

LHCb-CONF-2015-004

$2<\eta_{lab}<4.9$



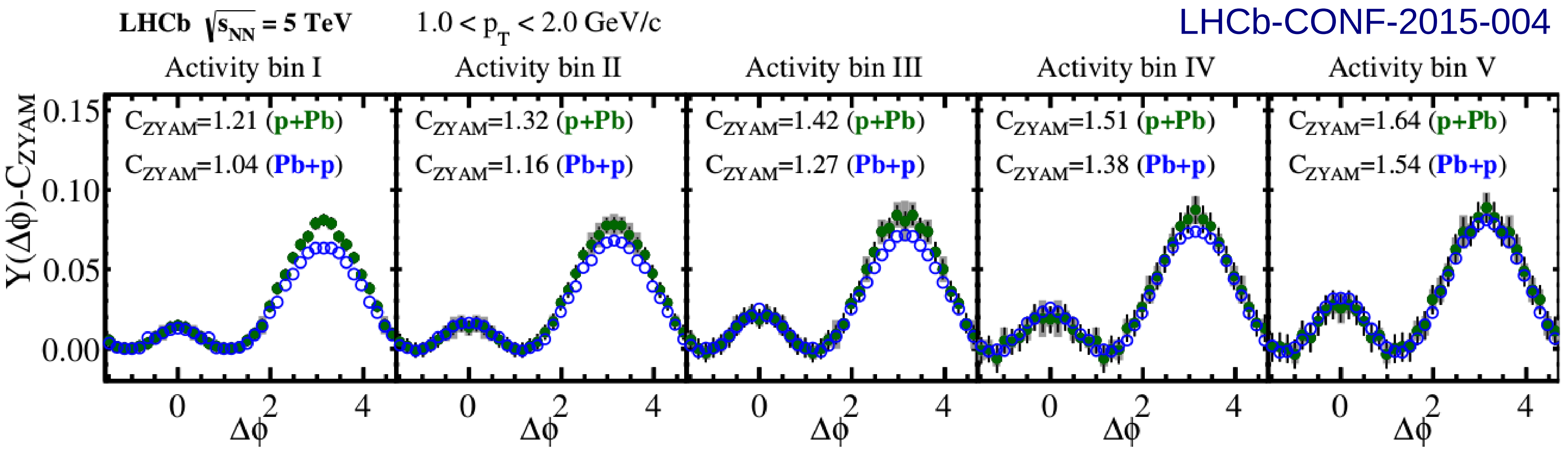




NS ridge is stronger in Pb-going case

Saturation vs multiplicity effect?

LHCb-CONF-2015-004

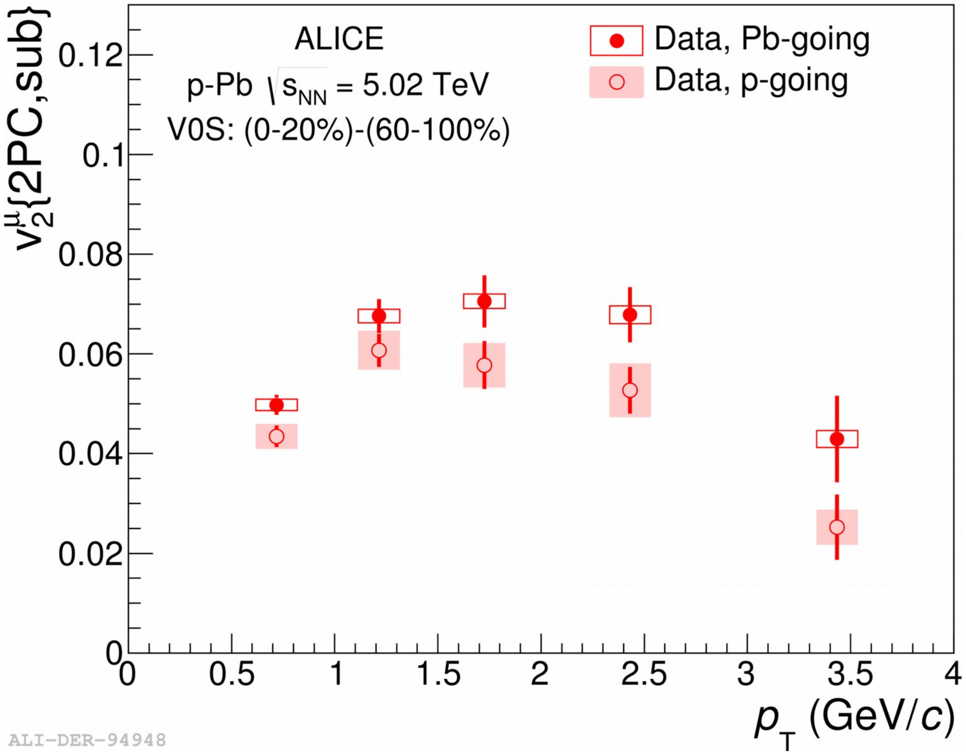


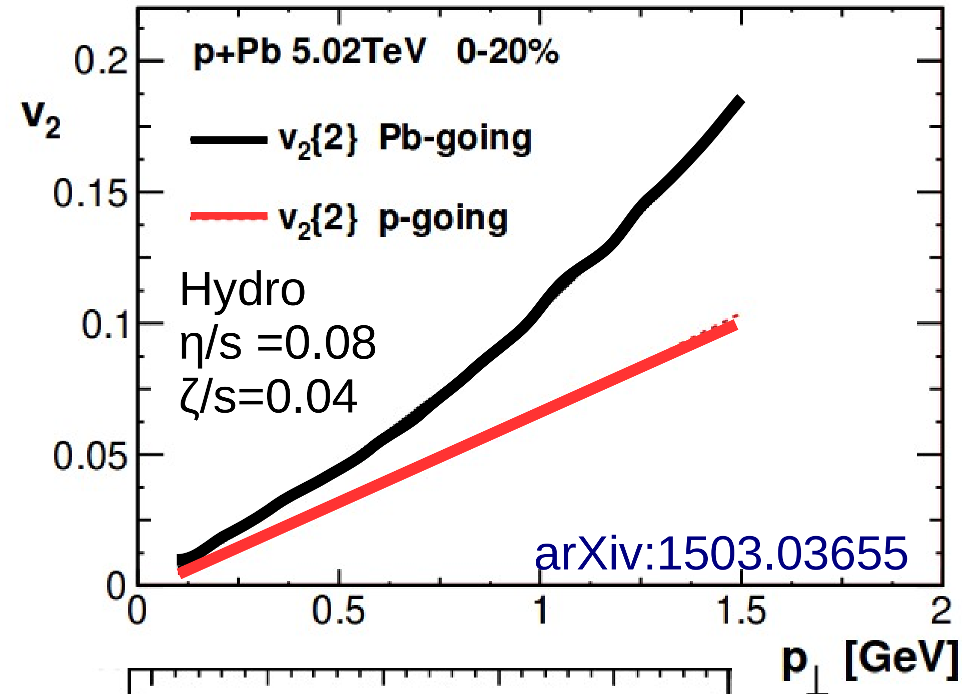
- v_2 (or NS rigde yields) larger on Pb-going than on p-going side
- For same multiplicity (in 2<η<4.9) LHCb finds the same NS rigde yields
- Suggests that multiplicity (density) matters

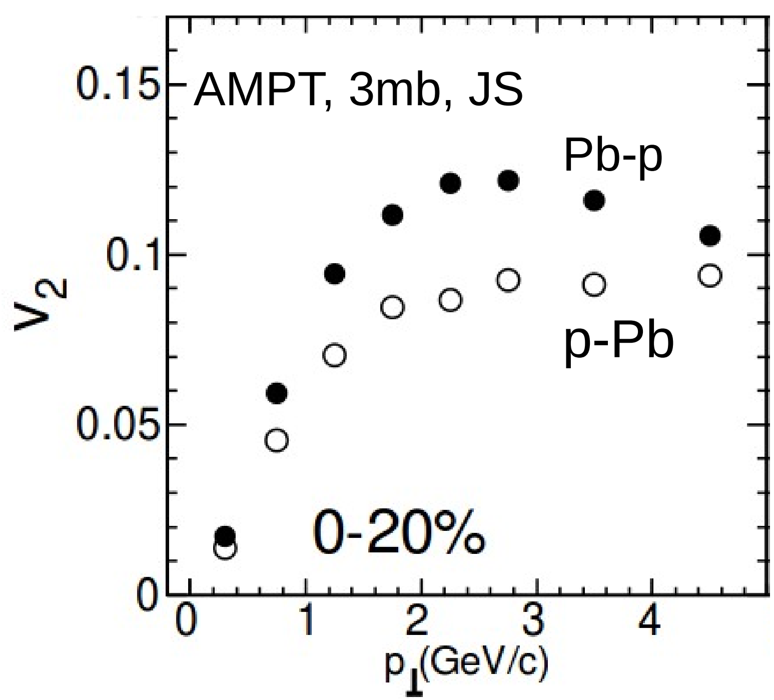
Common absolute activity bins	$\mathcal{N}_{\text{VELO}}^{\text{hit}}$-range in Pb+$p$
Bin I	2200 – 2400
Bin II	2400 – 2600
Bin III	2600 – 2800
Bin IV	2800 – 3000
Bin V	3000 – 3500

(p-Pb activity scaled by ~0.77 for backward VELO acceptance)

35 Predictions from Hydro and AMPT

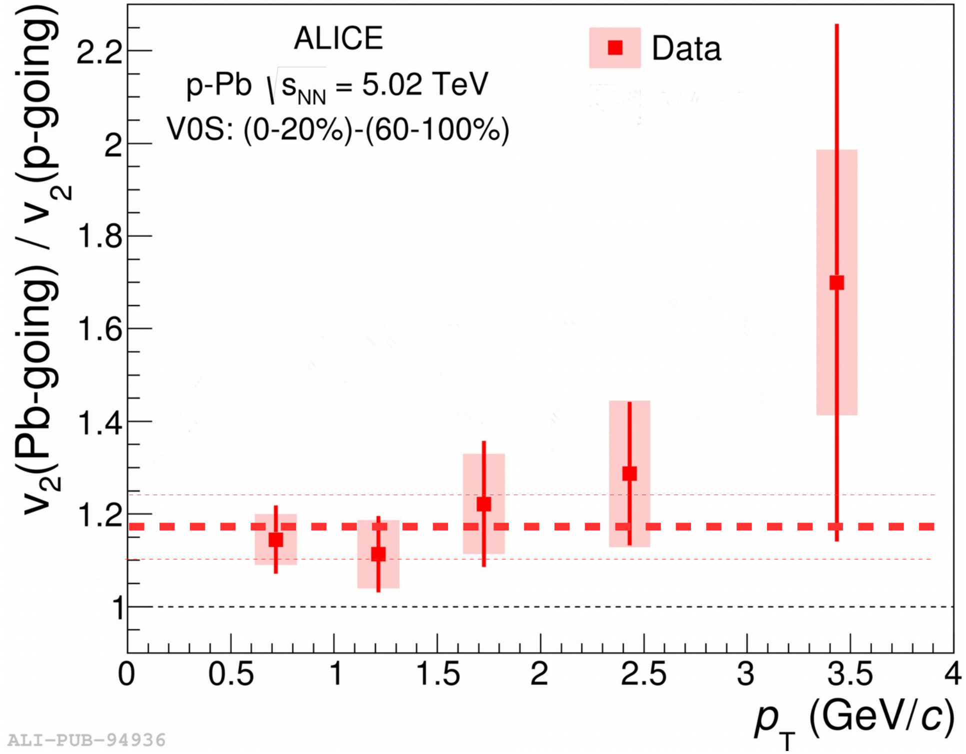


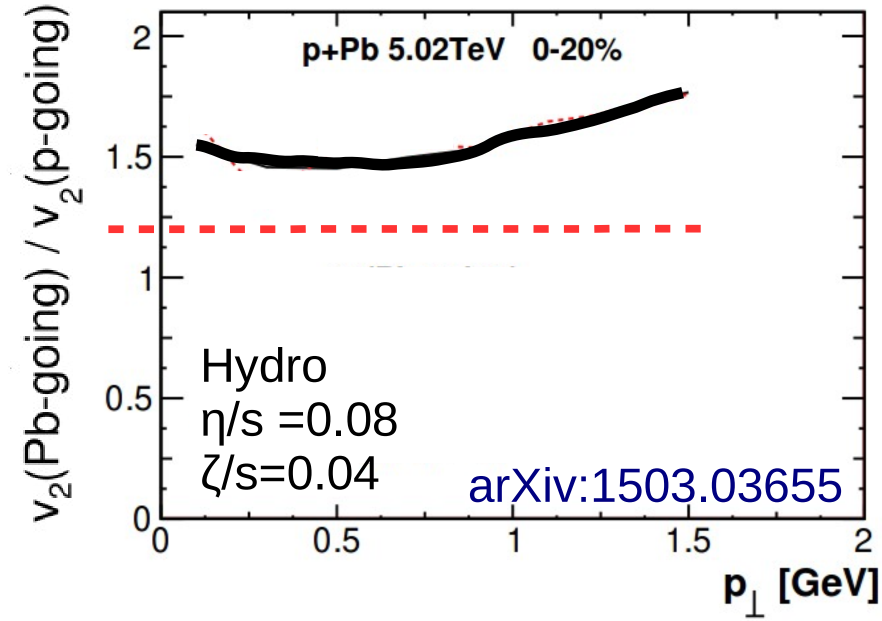


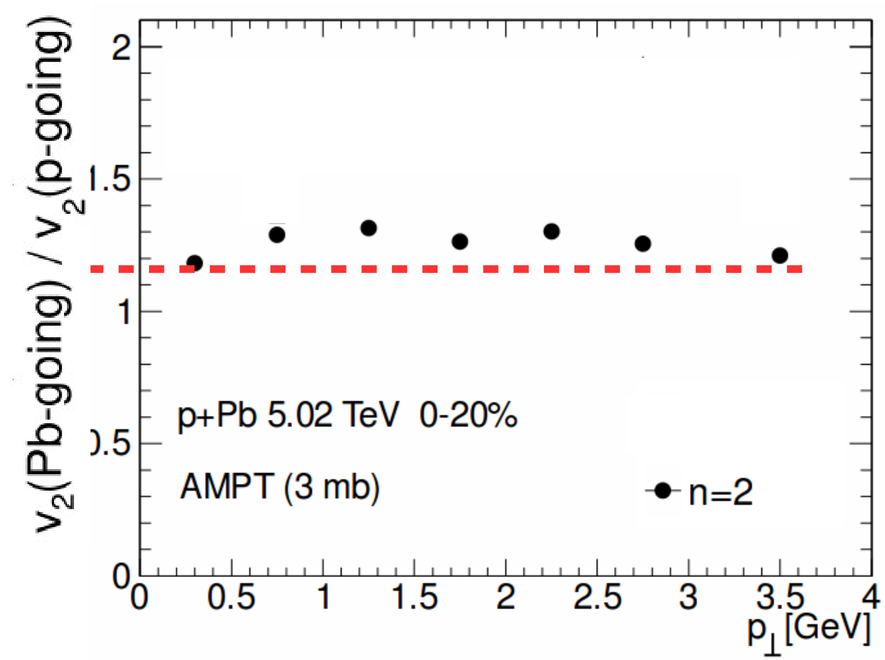


- Trend comparable but larger predicted v_2 than in data

36 Predictions from Hydro and AMPT





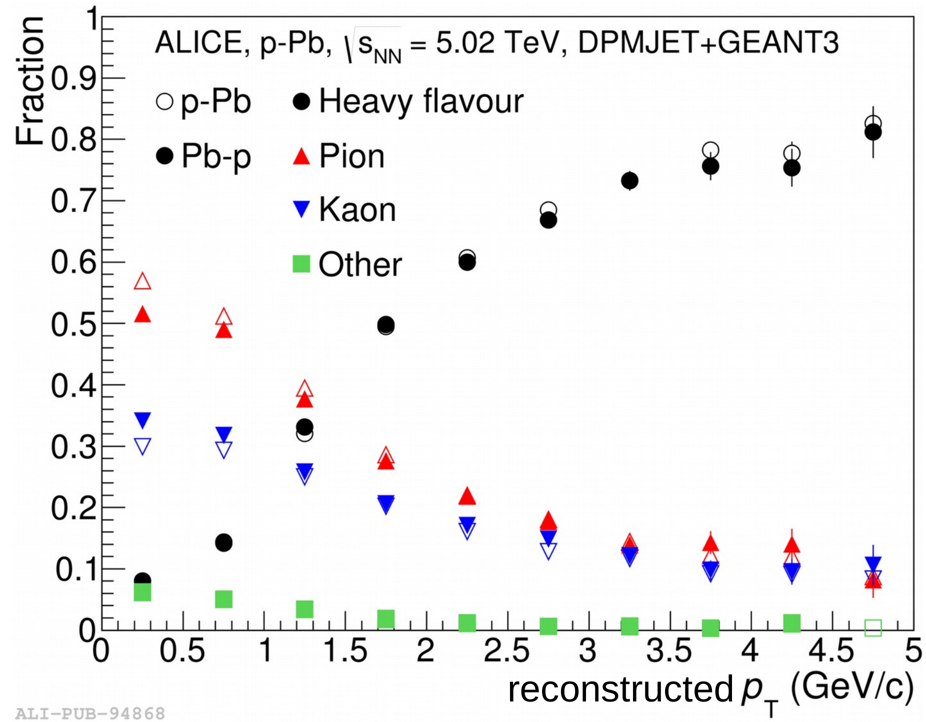


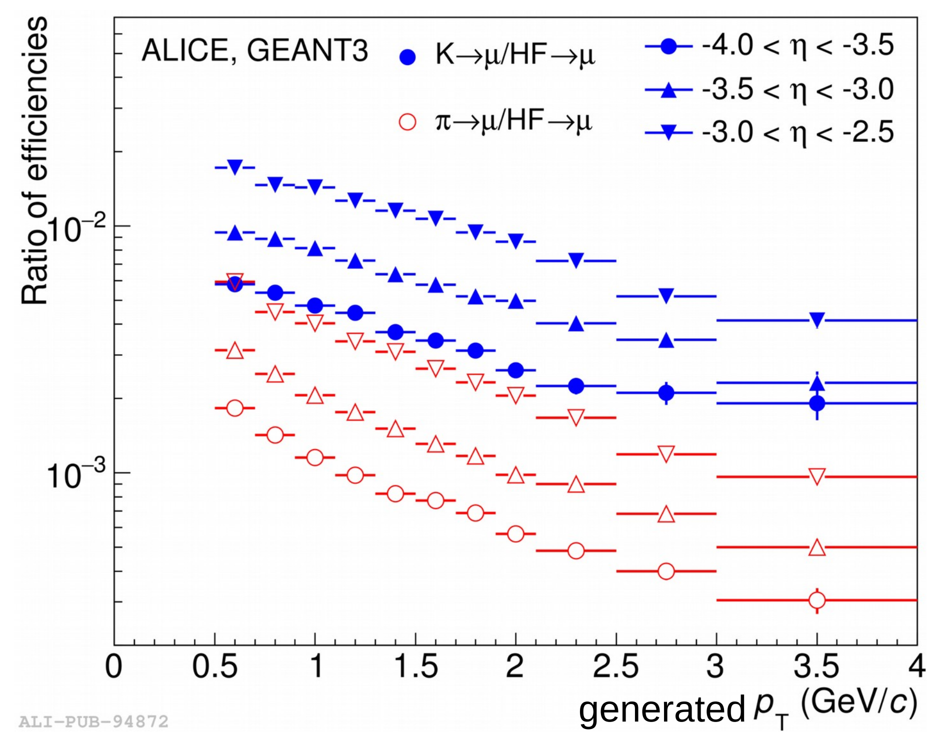
- Trend comparable but larger predicted v_2 than in data
  - Also larger ratio than in data
- Not apples-to-apples comparison
  - Muons vs charged particles
  - Event selection
  - Non-flow

37 Model comparison

ALICE, arXiv:1506.08032

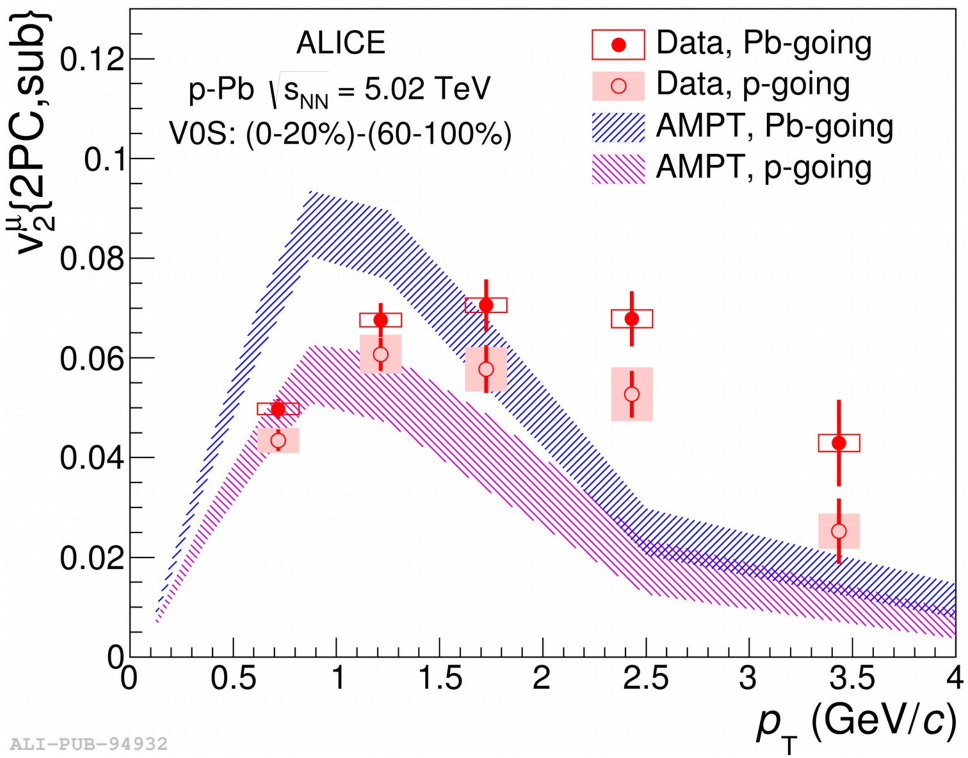
- Measurement of v_2 for inclusive muons
  - Composition of parent distribution strongly affected by absorber
  - Not straight-forward to unfold
- Instead, provide relative efficiencies as weights to be used in calculation
- Recipe:
  - Decay particles to muons (eg. with pythia decayer)
  - Apply weights to muons from pions or kaons
  - Keep muons from HF decays (weight = 1)





38 Comparison with AMPT

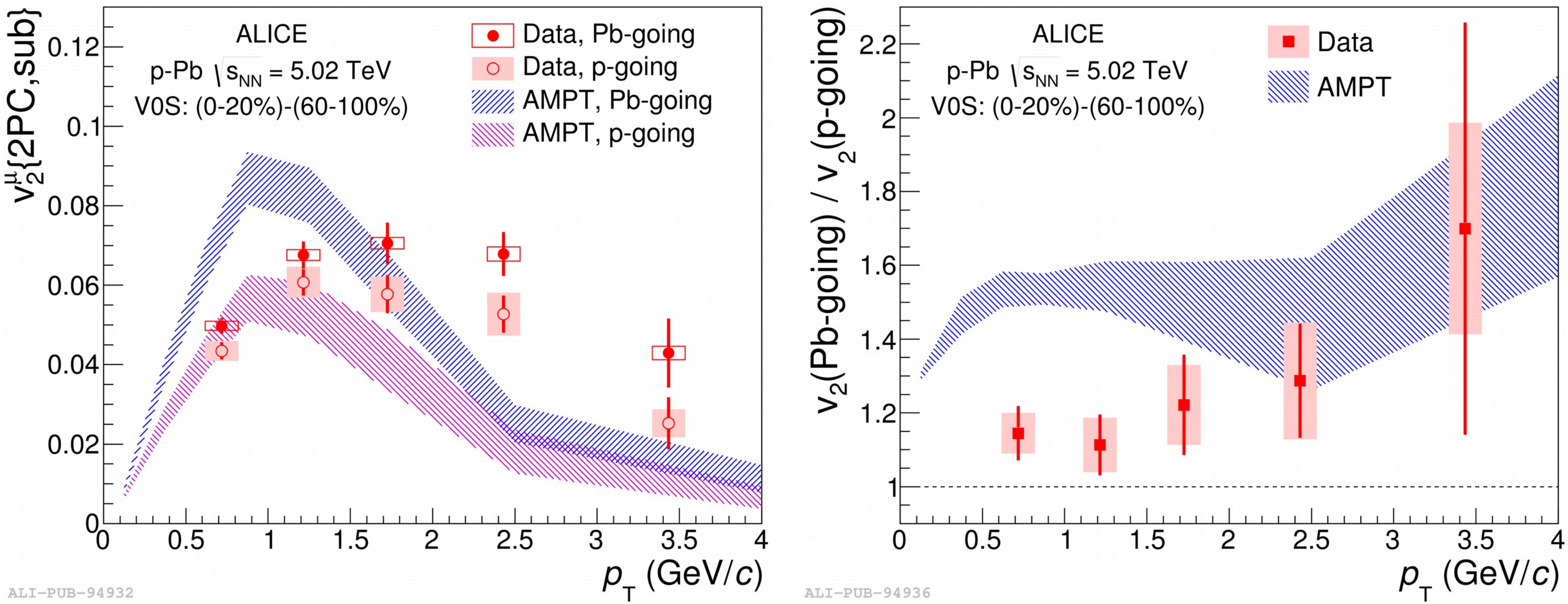
ALICE, arXiv:1506.08032



- AMPT (σ=3mb) at generator level, decay particles to muons, apply rel. efficiencies
- Mimic every aspect of the analysis as closely as possible
  - Event selection
  - Subtraction method
    - AMPT shows larger sensitivity than data to low-multiplicity class scaling (up to f=2)
- Find HF muon v_2 to be 0 in AMPT (using 5M events with HF muon in acceptance for each beam direction)
  - Set it to 0 in the final results to reduce statistical fluctuations

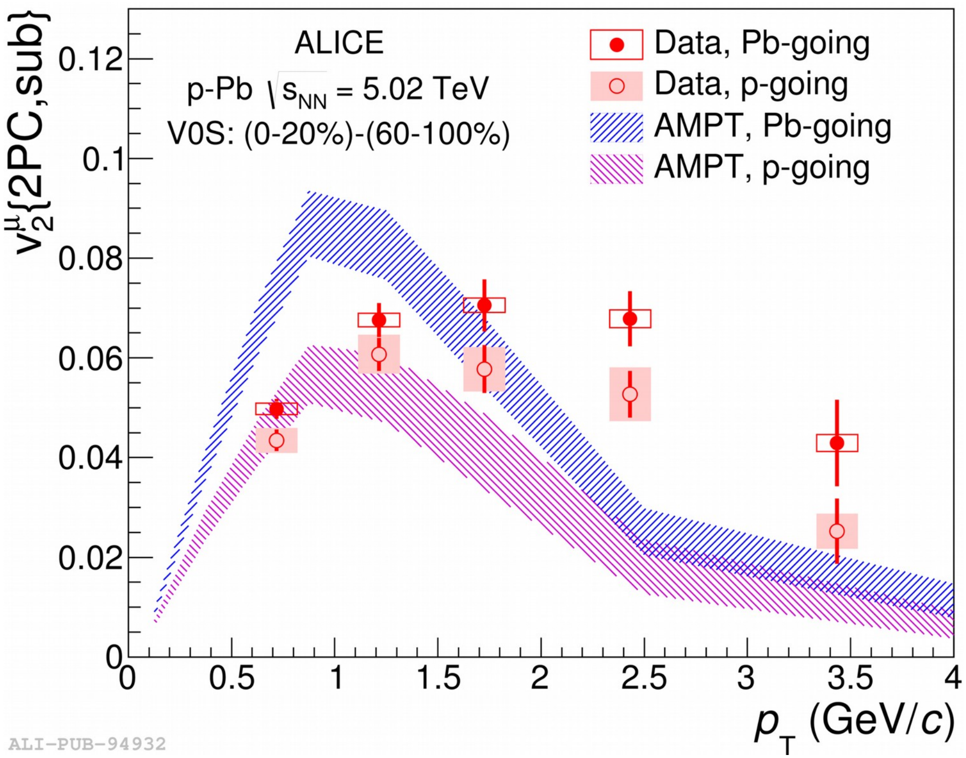
39 Comparison with AMPT

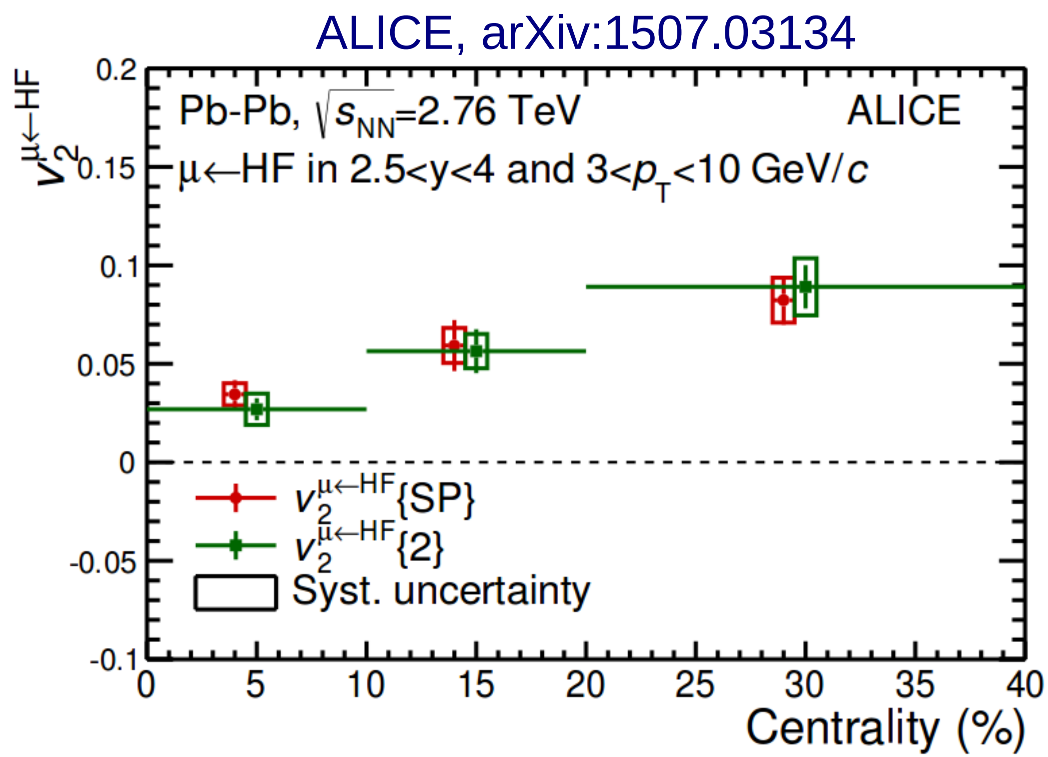
ALICE, arXiv:1506.08032



- At low p_T (<1.5 GeV/c), the calculation roughly describes the p-going, but overpredicts the Pb-going case
- At higher p_T, different trends for both beam directions
- Possible scenario
  - Drastically different relative parent composition in AMPT vs data

Comparison with Pb-Pb





- At low p_T (<1.5 GeV/c), the calculation roughly describes the p-going, but overpredicts the Pb-going case
- At higher p_T, different trends for both beam directions
- Possible scenario
  - Drastically different relative parent composition in AMPT vs data
  - Finite value of v_2 for muons from HF decay (observed in Pb-Pb)

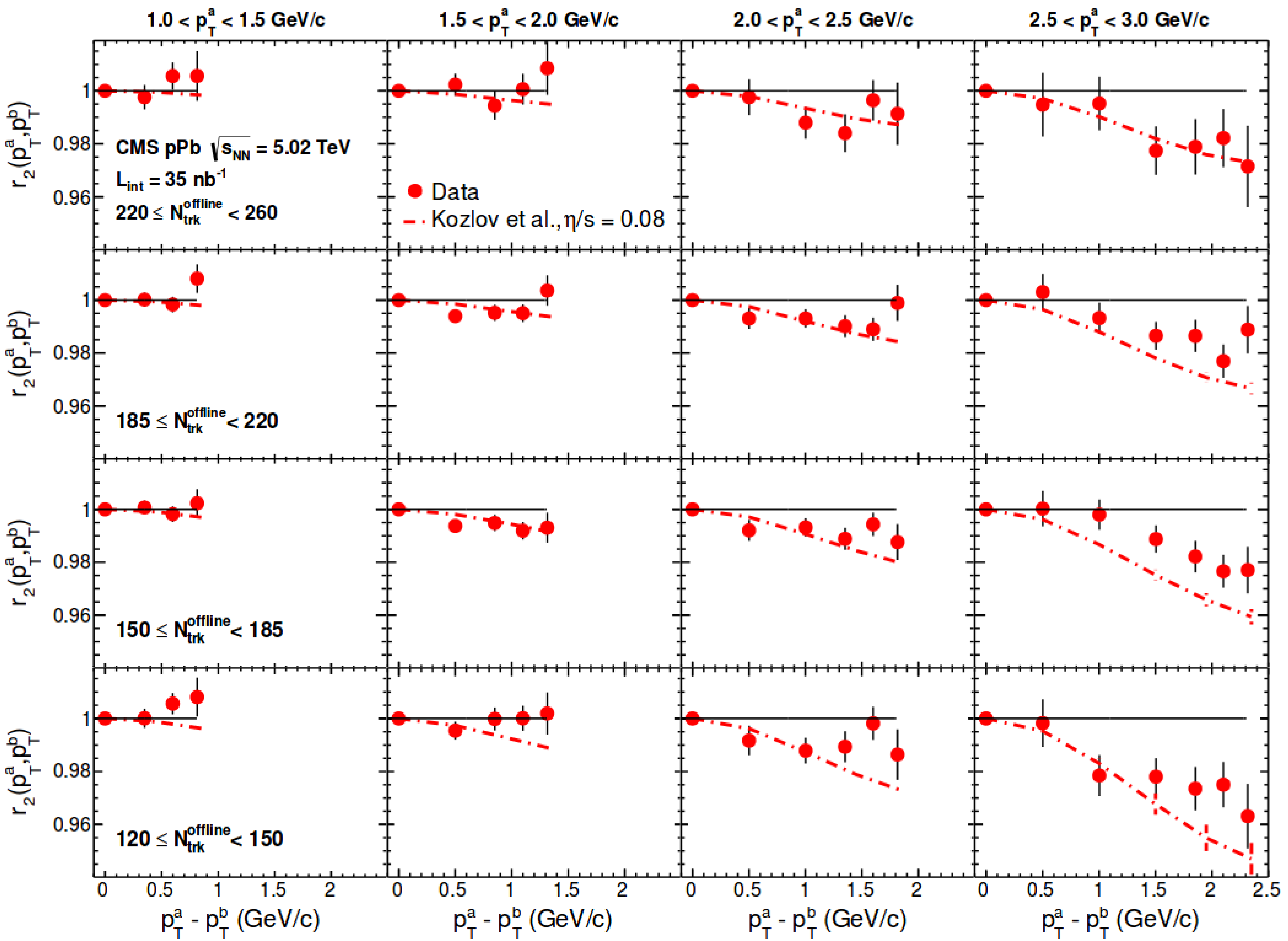
41 Summary

- Two-particle correlation analyses from p-Pb collisions show features, remarkably similar to those from Pb-Pb
  - And there usually attributed to collectivity and hydrodynamic flow
- New ALICE paper (ALICE, arXiv:1506.08032) explores two-particle correlations more forward and backward in rapidity than before
  - Double ridge observed in inclusive muon-hadron correlations
  - Consistent with expectations from hydrodynamics: v_2 on Pb-side is larger (~16%) than on p-side
  - Above 2 GeV/c, the measurement is sensitive to v_2 of muons from HF decays, which might be non-zero (as in Pb-Pb)
- The data further constrains hydrodynamic (and other) models
  - A finite v_2 from HF (if interpreted as in Pb-Pb) would indicate significant interactions of the HQ with the created system

42 Extra

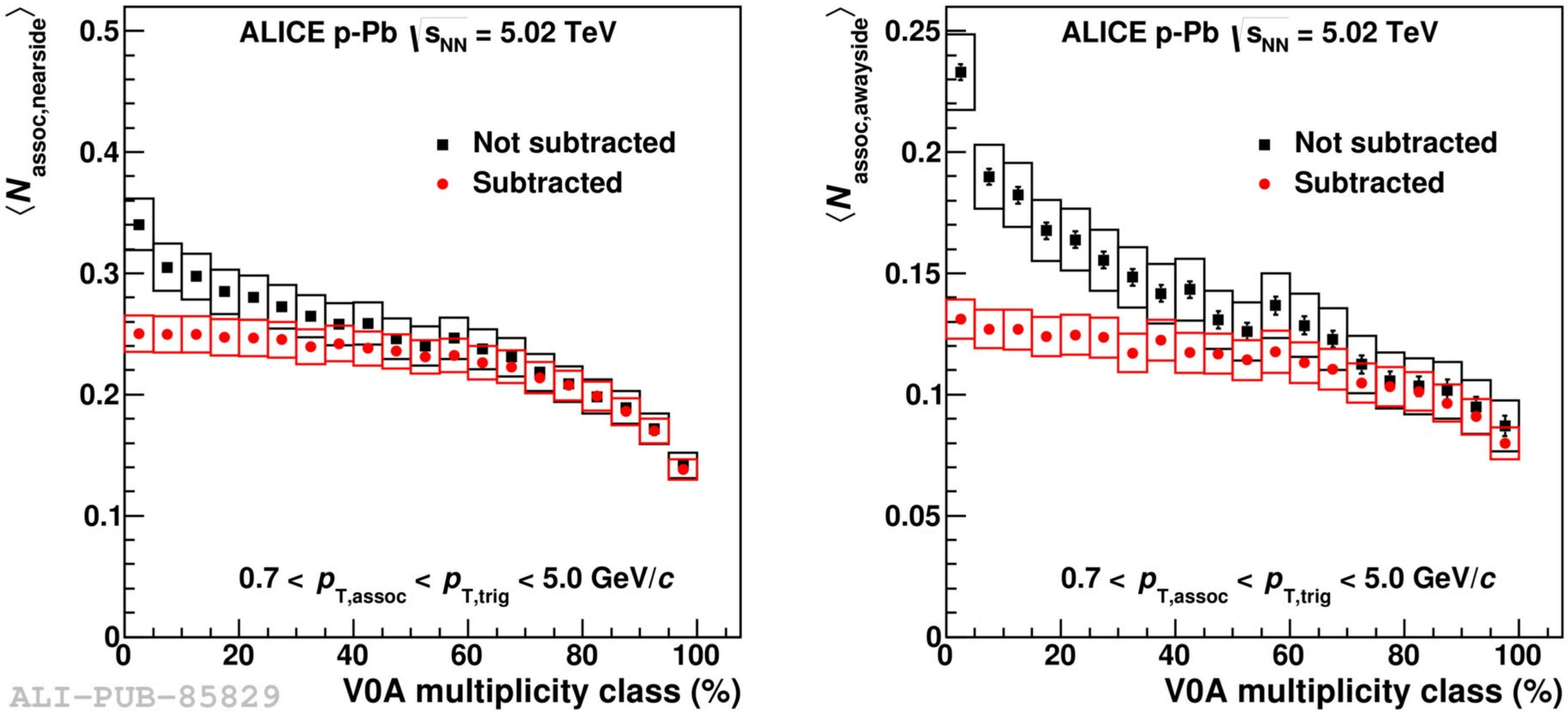
43 Factorization of v_2 in p-Pb

CMS, arXiv:1503.01692



Associated yields

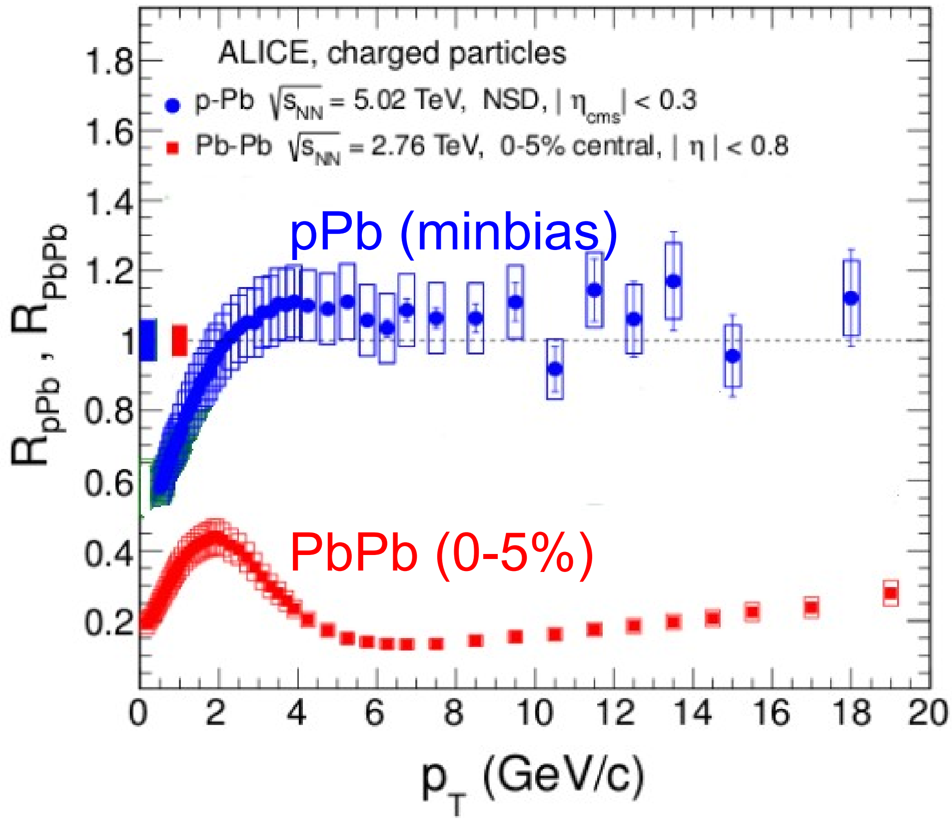
ALICE, arXiv:1406.5463



Associated yields after long range subtraction
are smaller for lower multiplicity classes

45 Charged particle R_{pPb}

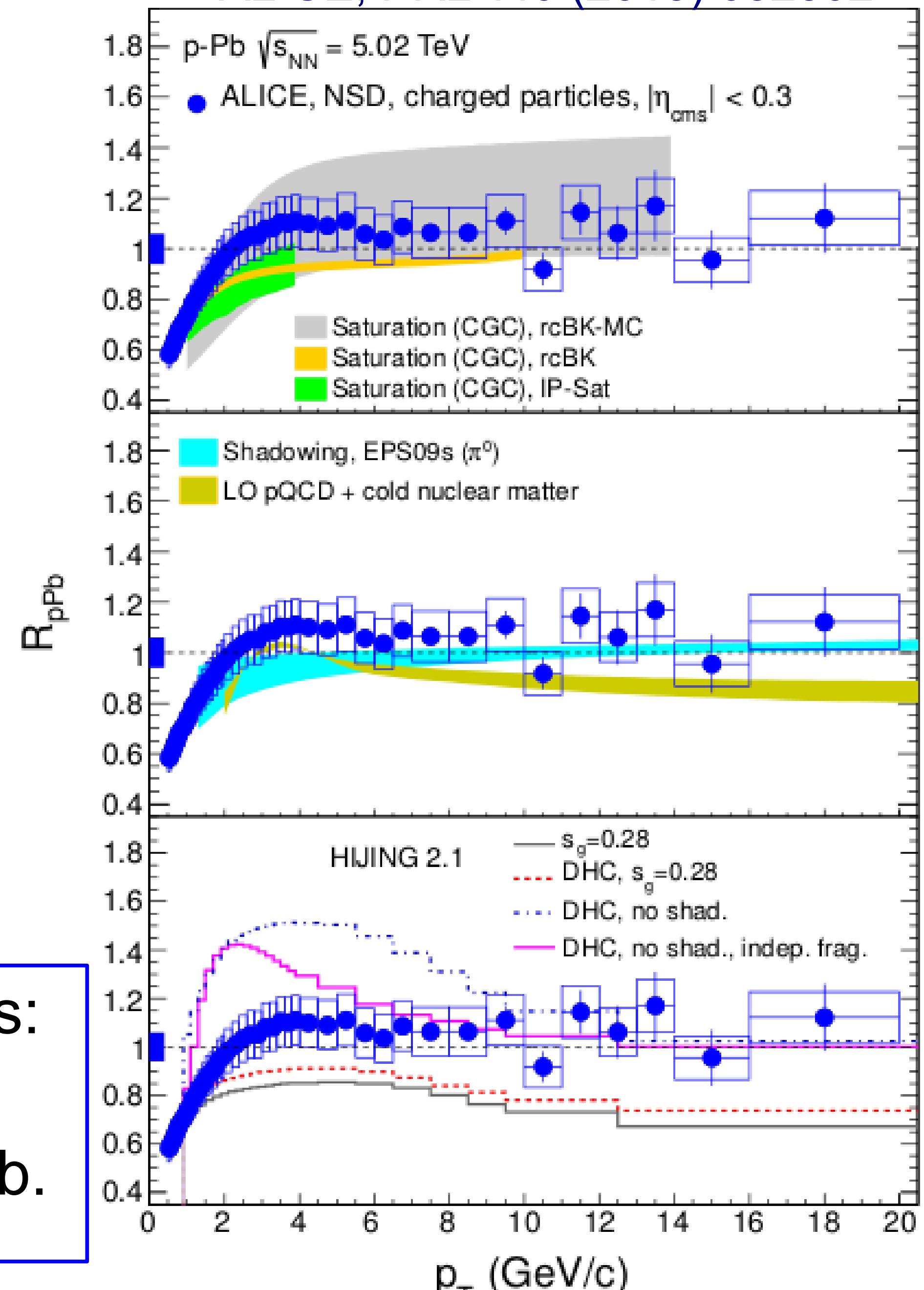
$$R_{AB} = \frac{dN_{AB}/dp_T}{\langle N_{coll} \rangle dN_{pp}/dp_T}$$



No surprises at high p_T in first results:

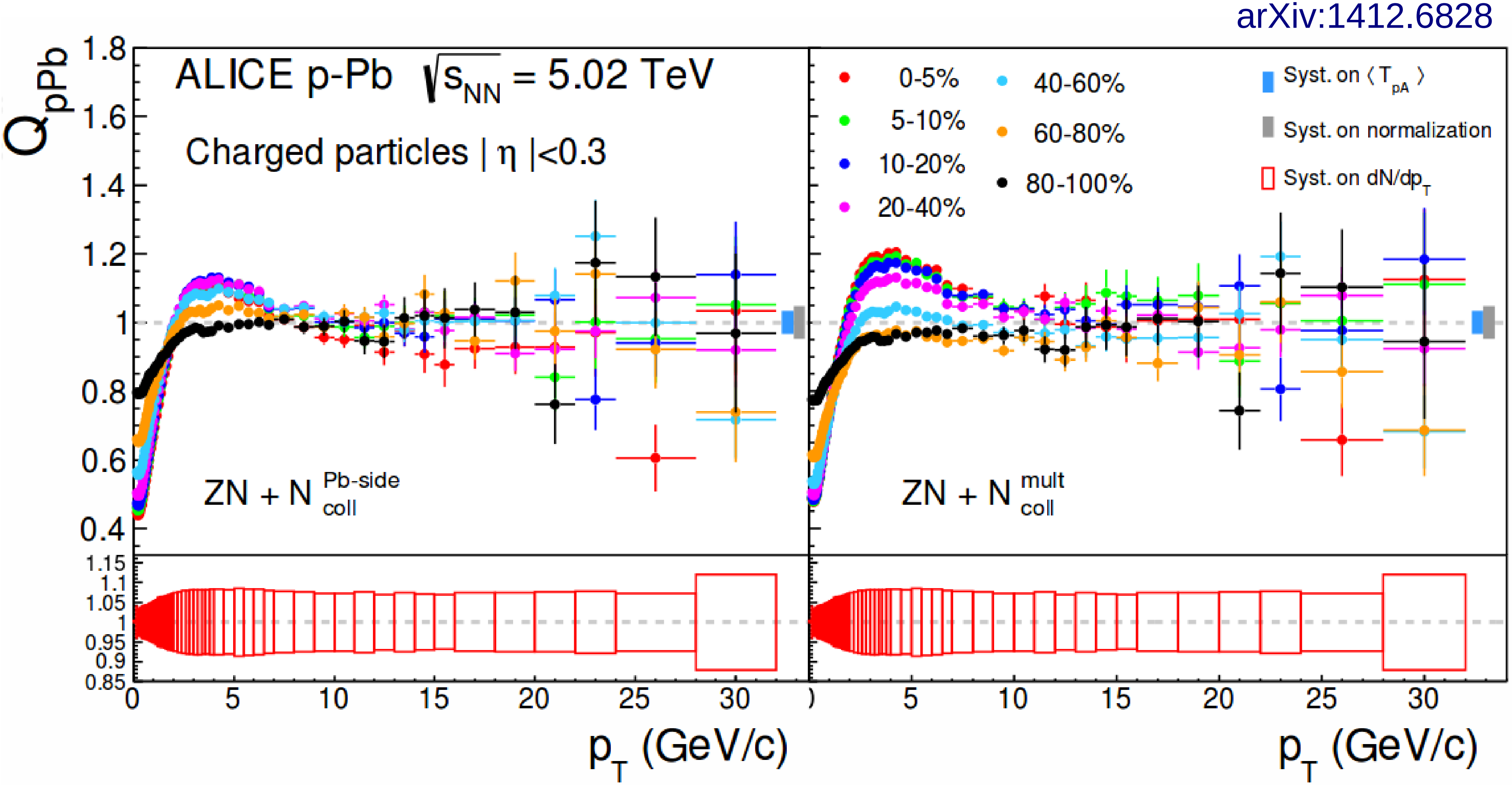
Supports existence of strong final state effects (at mid-rapidity) in PbPb.

ALICE, PRL 110 (2013) 082302



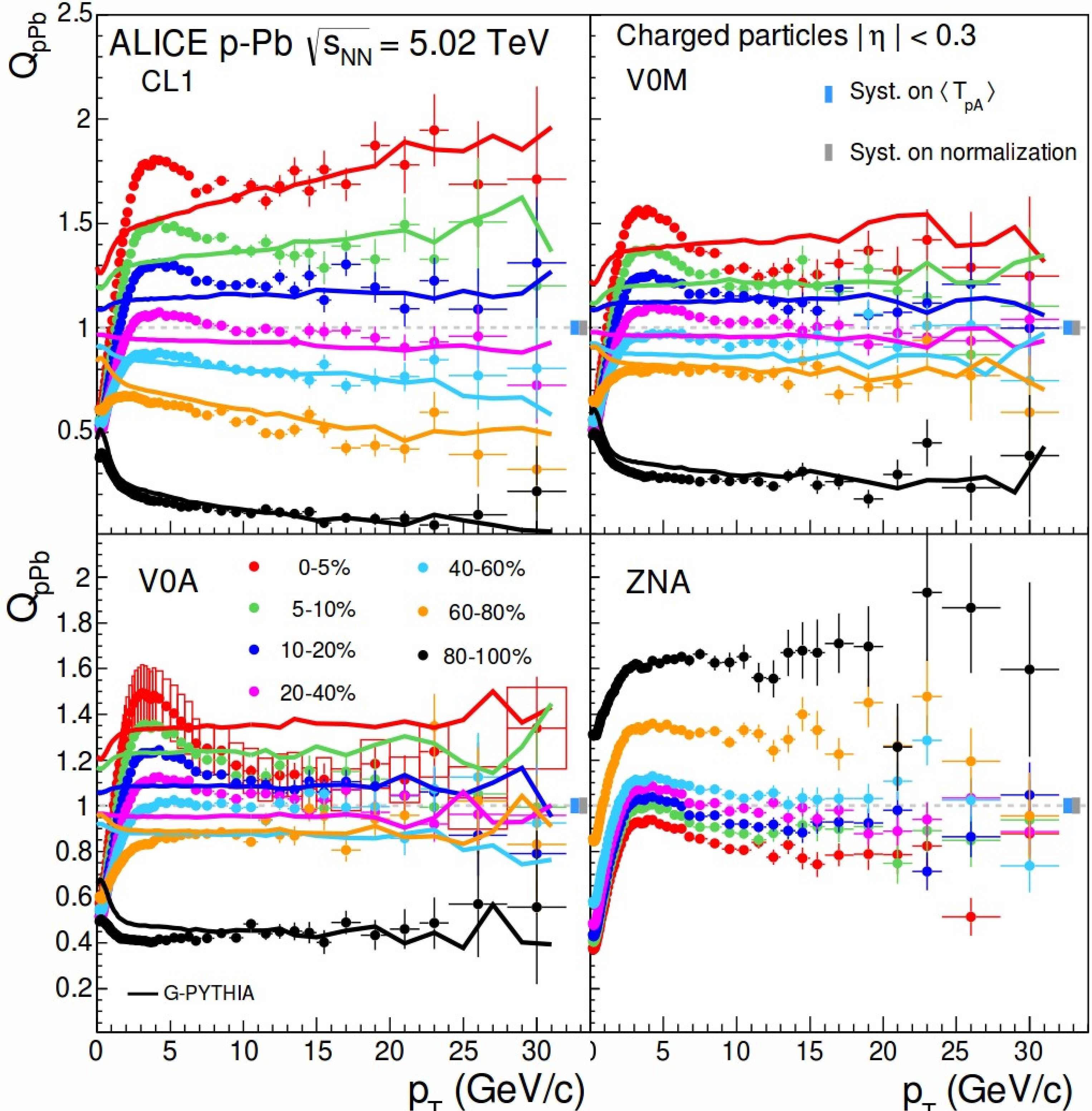
 QpPb

arXiv:1412.6828

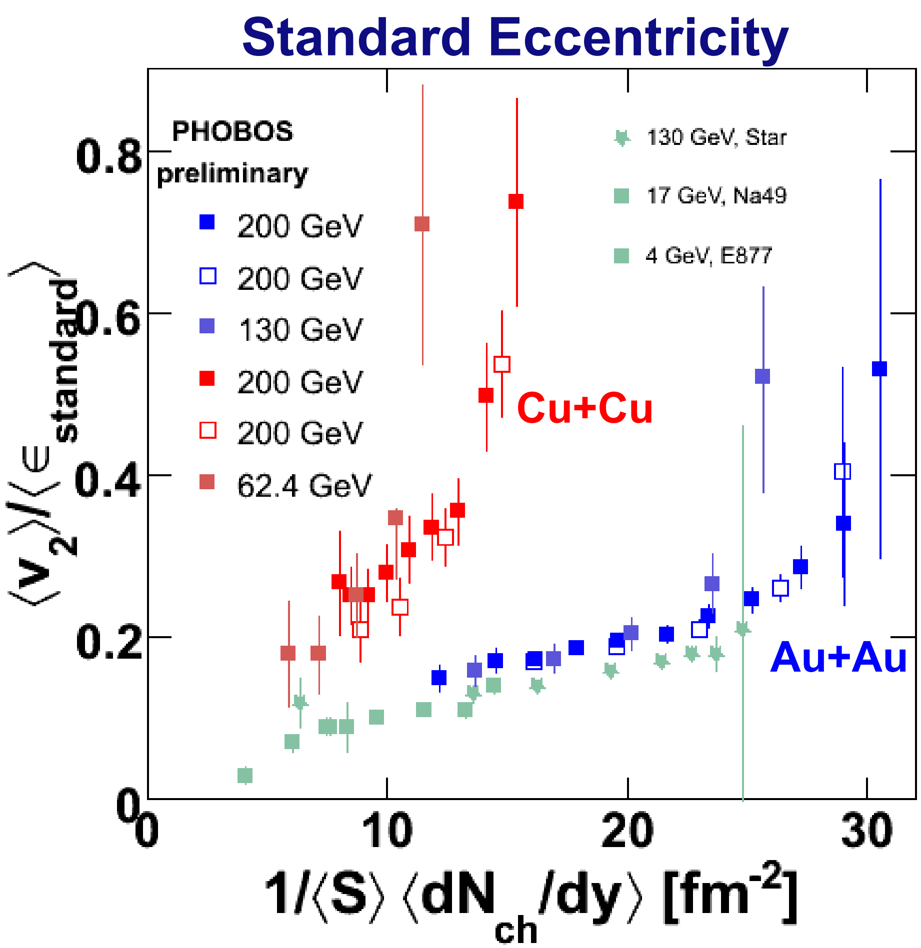


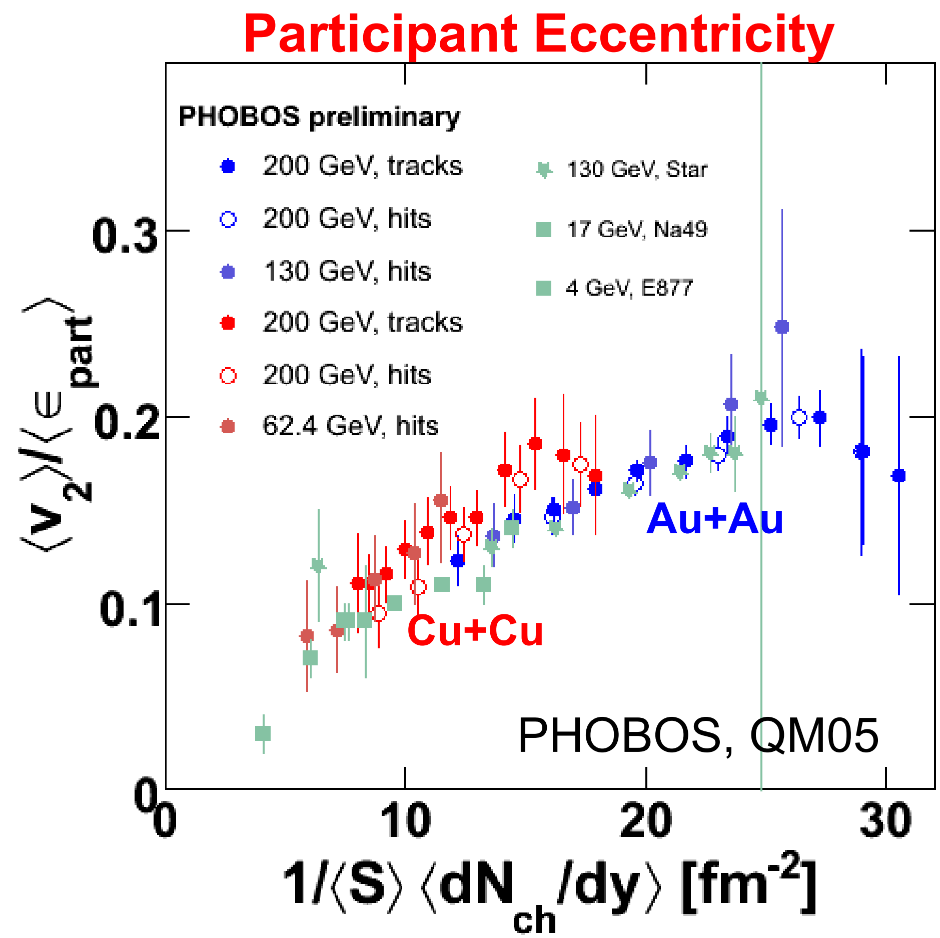
47 QpPb

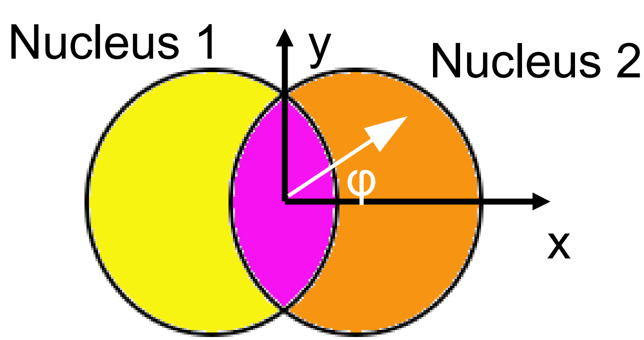
arXiv:1412.6828

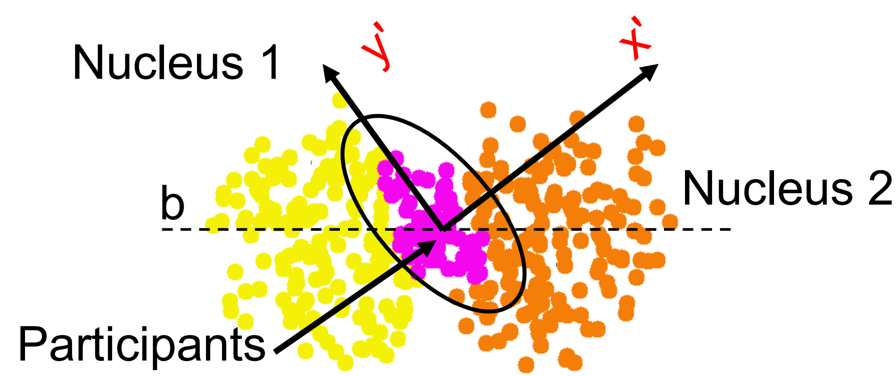


48 Importance of initial state fluctuations









49 Measuring the v_2 coefficient

$$v_2 = \langle \cos(2\varphi - 2\Psi_R) \rangle$$

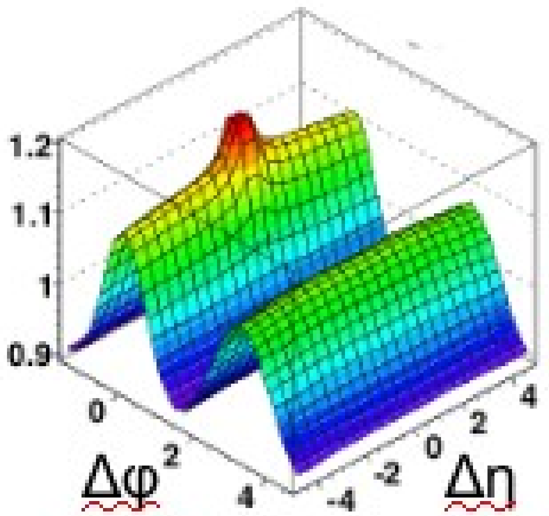
Needs to deal with unknown reaction plane angle:
Either use angular differences or measure it

Two-particle correlations

$$v\{2\} = \sqrt{\langle \cos(2\varphi_1 - 2\varphi_2) \rangle}$$

Can suppress "non-flow" by employing cuts in |Δη|

$$v \gg 1/\sqrt{M}$$



Estimate ψ_R using two sub-events.
Then correlate particles of interest,
and correct for event plane resolution:

$$\tan(2\psi_A) = \frac{\langle \sin(2\phi) \rangle_A}{\langle \cos(2\phi) \rangle_A}$$

$$v_2^{obs} = \langle \cos(2\phi - 2\psi_A) \rangle_B$$

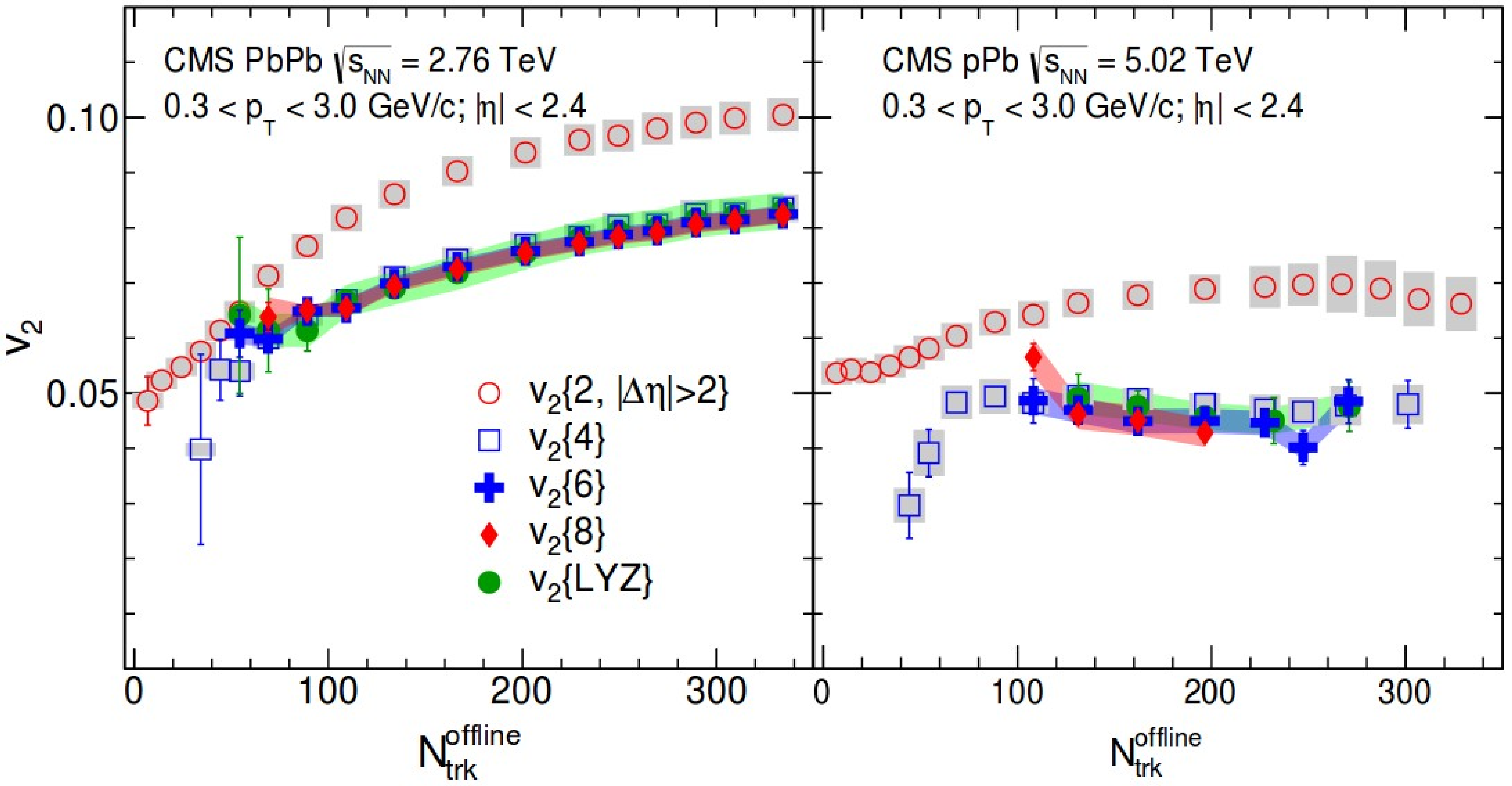
$$v_2 = \frac{\langle v_2^{obs} \rangle_{events}}{\sqrt{\langle \cos(2\psi_A - 2\psi_B) \rangle_{events}}}$$

Powerful method:
Measure cumulants and report multi-particle correlation results where lower correlations have been subtracted, eg. $V_2\{4\}$
(see arXiv:1010.0233)

Poskanzer, Voloshin, nucl-ex/9805001

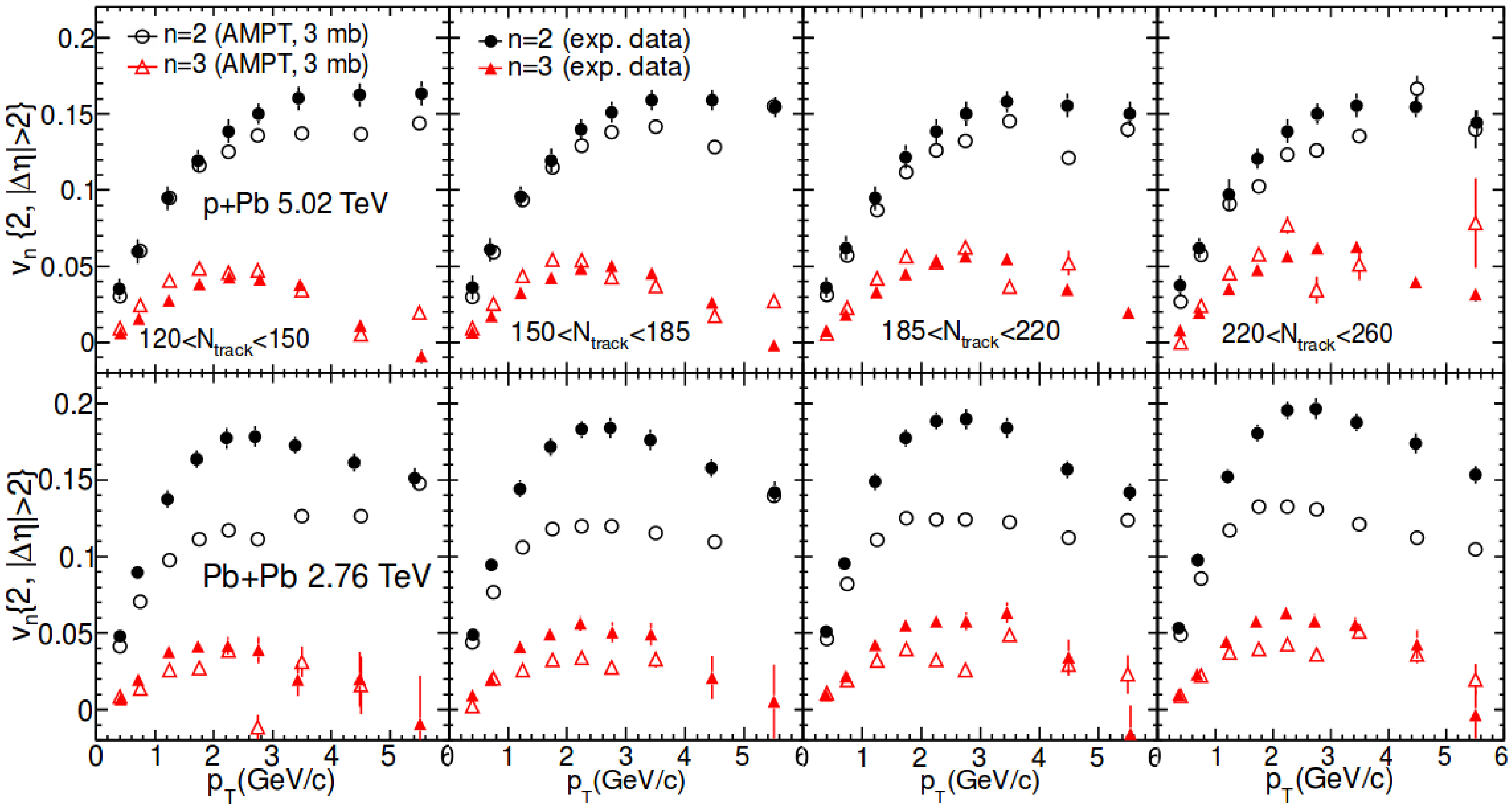
50 Multi-particle correlations

CMS, arXiv:1502.05382



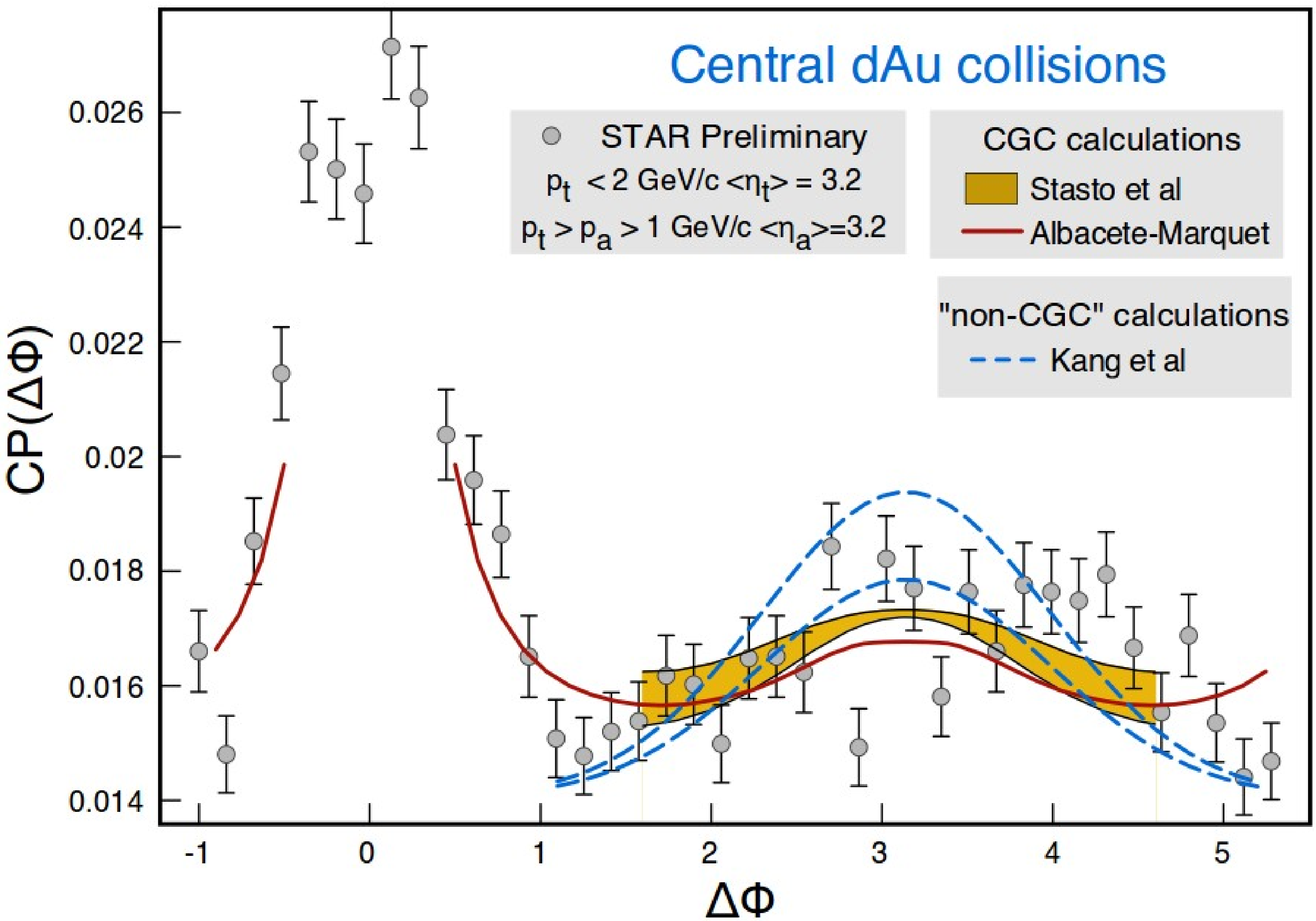
51 AMPT describes data quite well (example)

arXiv:1406.2804



52 Decorrelation induced by IS

arXiv:1209.0336



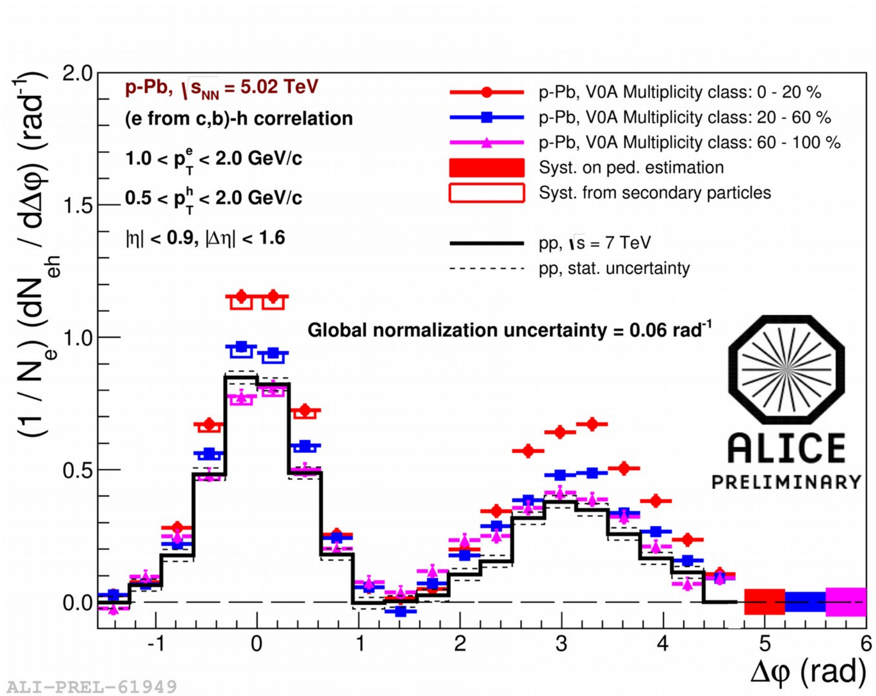
It should serve as the reference to generate precise quantitativepredictions for p+Pb collisons at the LHC. So far, qualitative expectations indicate that analogous suppression of azimuthal correlations should be observed in at the LHC. Generically the strength of the decorrelation is expected to be stronger with:

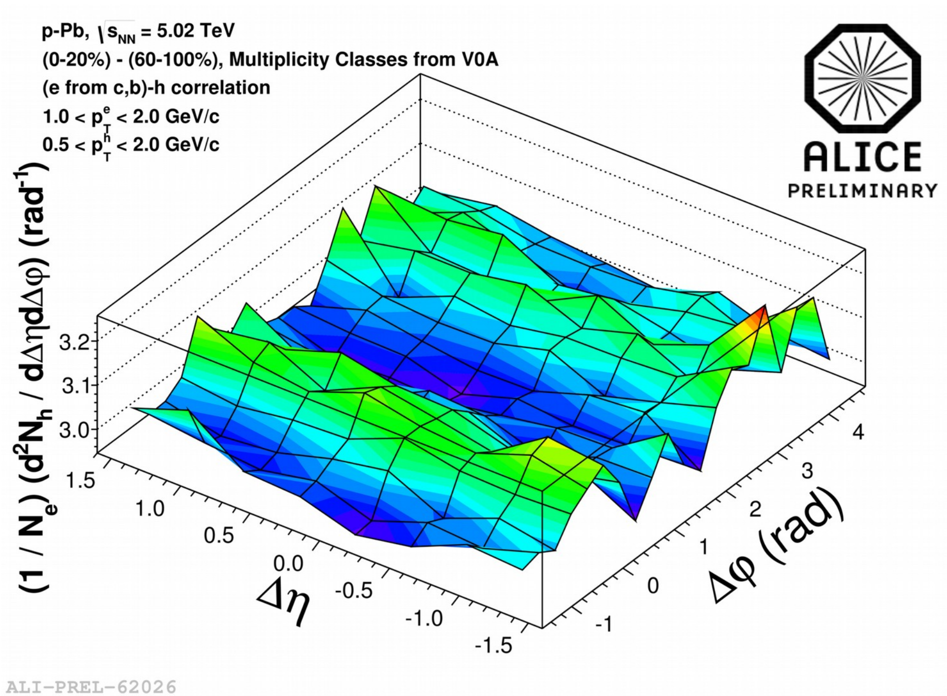
I) increasing rapidity of the produced pair;

ii) increasing collision centrality and

iii) decreasing transverse momentum of the trigger and associated particle.

53 Heavy-flavor electron ridge





At mid-rapidity, double ridge for electrons from HF decays observed