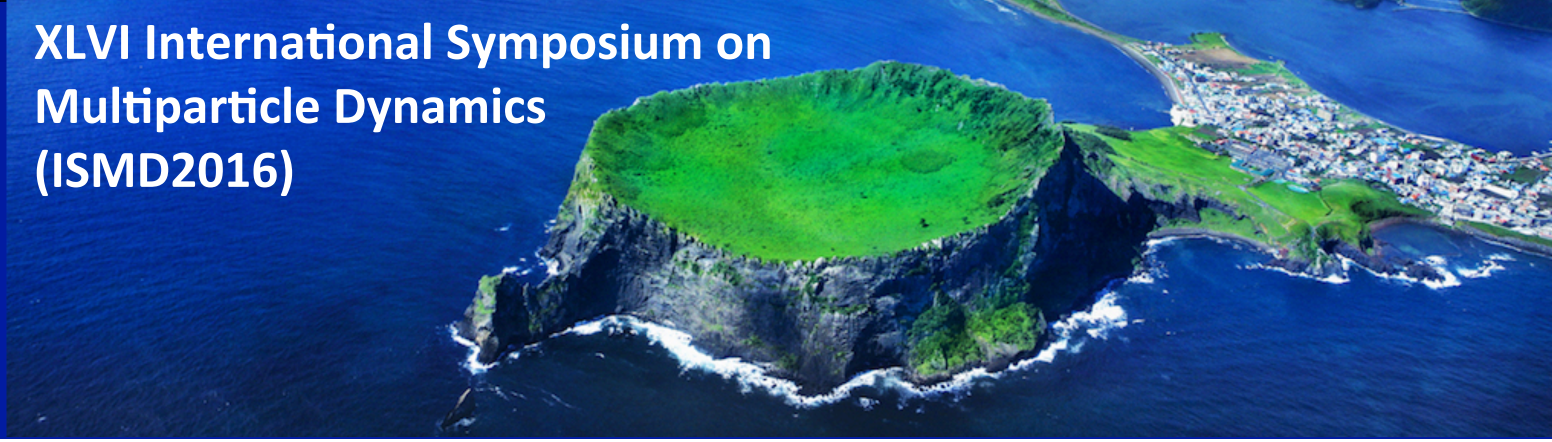


Correlations, multiplicity distributions, and the ridge in pp and p-Pb collisions

Alice Ohlson (CERN)
for the ALICE Collaboration

29 August 2016

ALICE

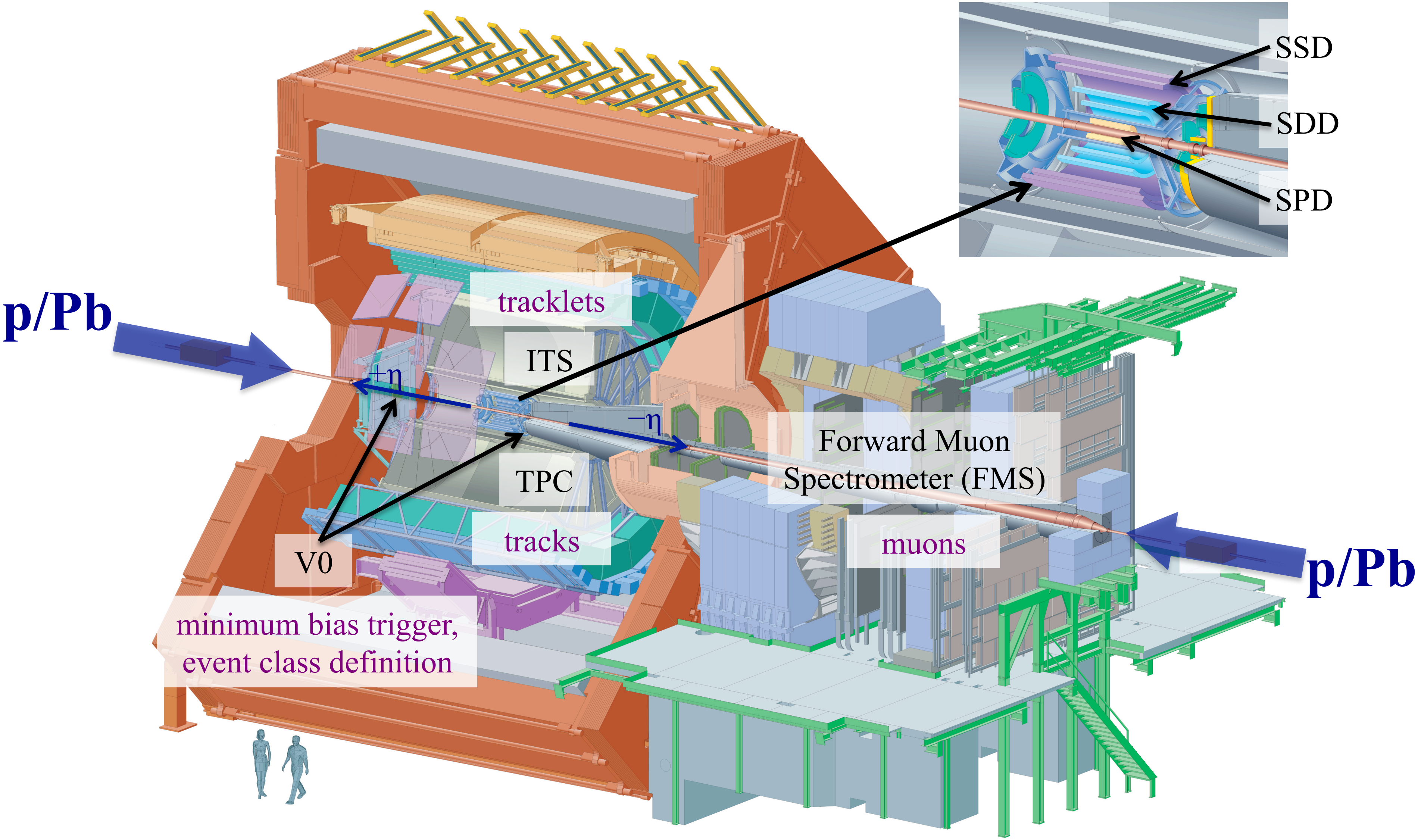
CERN

Introduction

- Our goal: characterizing the global properties of collisions in nuclear systems, from pp to p-A to A-A
  - Small systems provide a baseline for studies of nucleus-nucleus collisions (and also some surprises!)

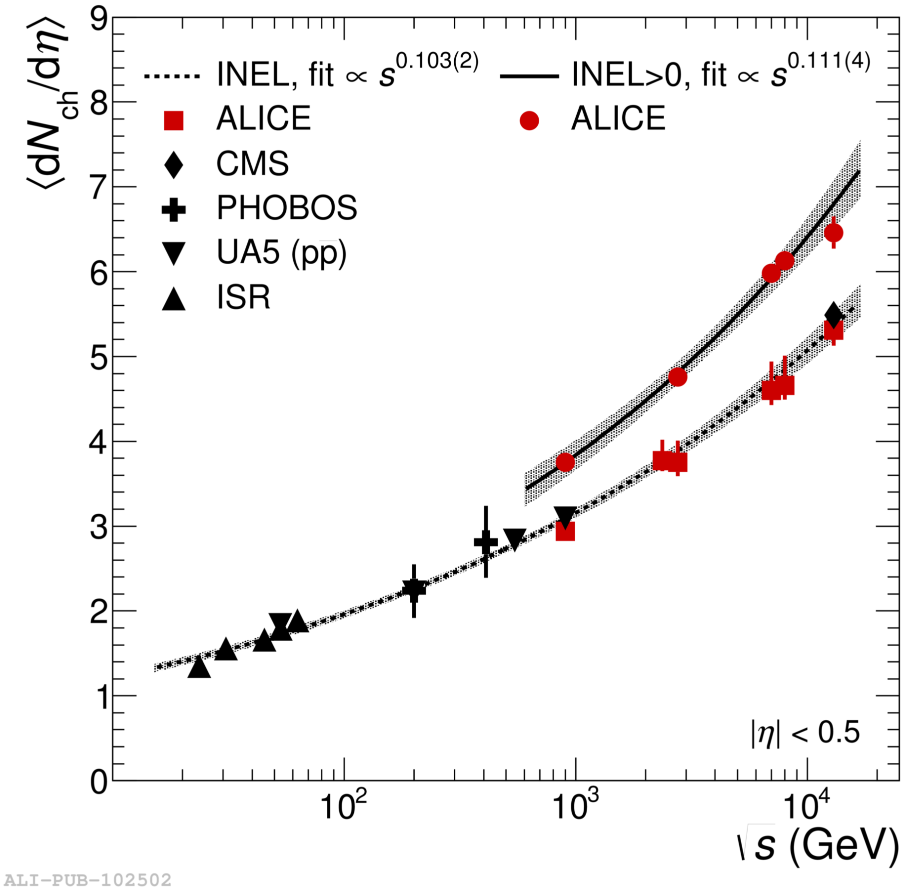
- Global characteristics of events → dominated by non-perturbative regime, useful for tuning models
  - Multiplicity distributions in pp
- Initial state of nuclear collisions / Cold nuclear matter effects
  - Multiplicity measurements in p-Pb
  - Two-particle correlations in p-Pb

ALICE Detector



$\langle dN_{ch}/d\eta \rangle$ versus $\sqrt{s}$

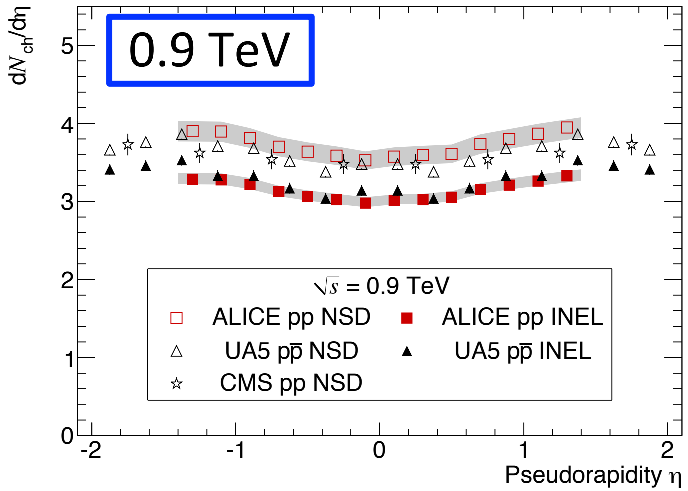
- $\langle dN_{ch}/d\eta \rangle$ measured across three orders of magnitude in center-of-mass energy, up to $\sqrt{s}$ = 13TeV
- Event classes:
  - INEL: inelastic events
  - INEL>0: inelastic events with at least one charged particle within $|\eta| < 1$
  - NSD: non-single-diffractive
- Efficiency of the trigger and event selection for each class is estimated using Monte Carlo models (including DPMJET, PHOJET, STARLIGHT, etc.)

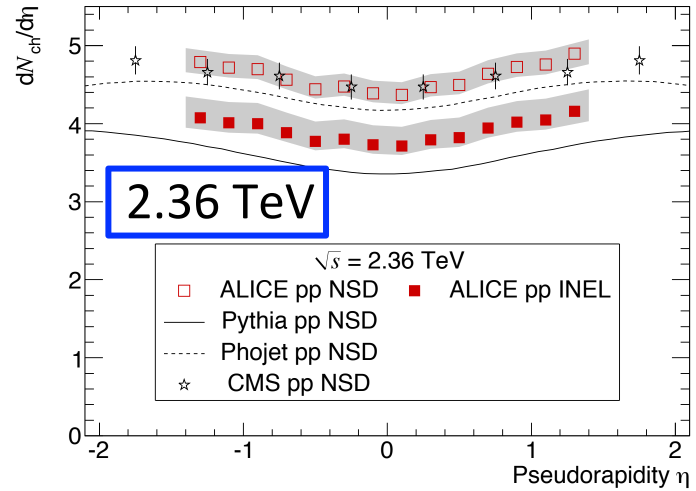


PLB 753 (2016) 319

- Power law scaling is observed for INEL and INEL>0 event classes

$<dN_{ch}/d\eta>$ versus η

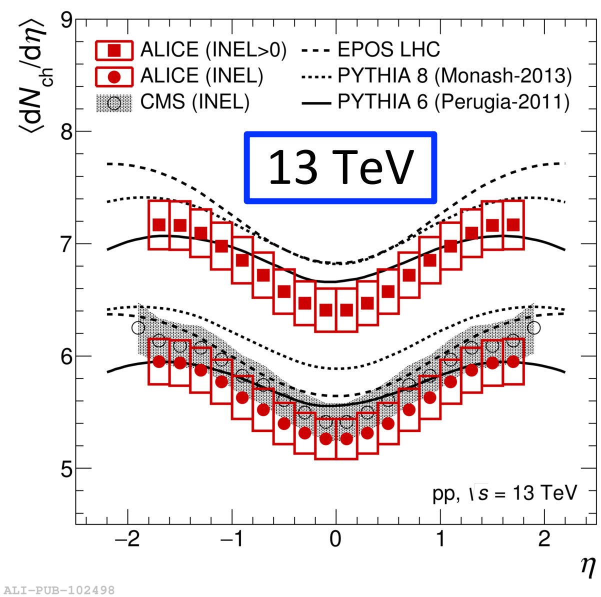




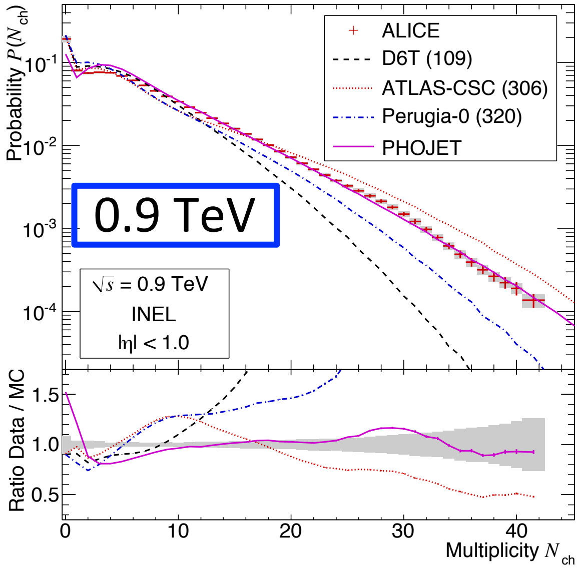
EPJC 68 (2010) 89

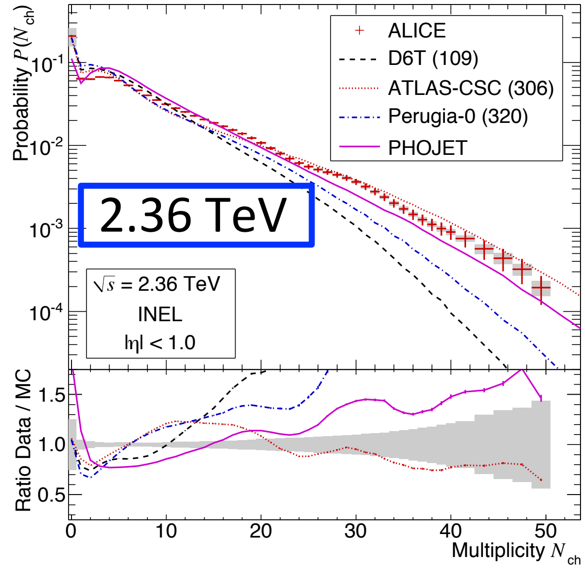
PLB 753 (2016) 319

- Multiplicity measured versus pseudorapidity shows characteristic shape at $\sqrt{s}$ = 0.9, 2.36, 13 TeV
- Results compared with Pythia 6, Pythia 8, Phojet, EPOS LHC
- Best agreement with Pythia 6 at $\sqrt{s}$ = 13 TeV



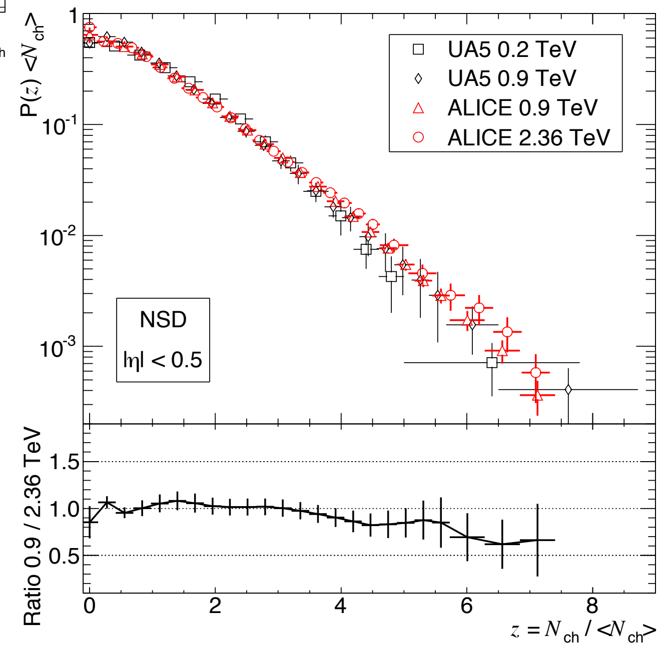
Multiplicity distributions





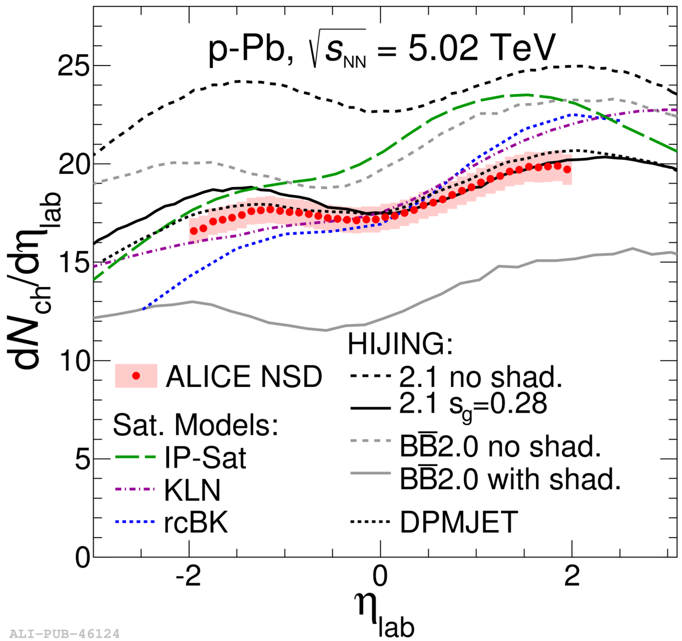
EPJC 68 (2010) 89

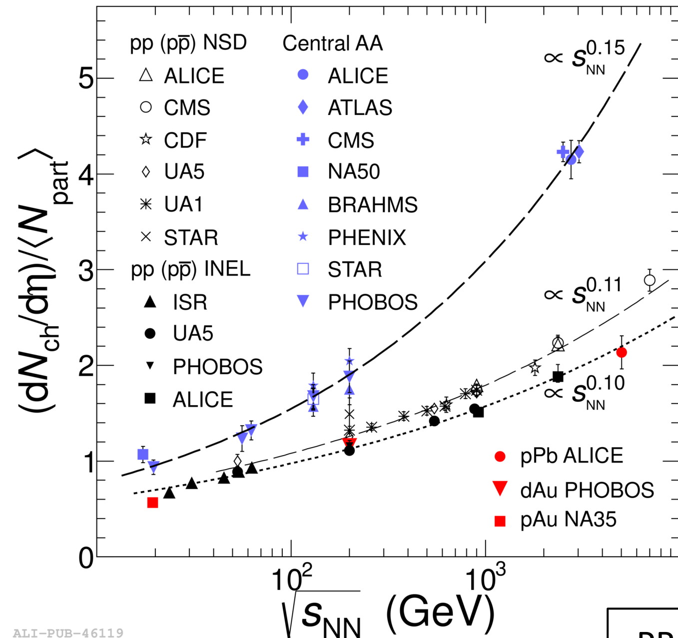
- Results compared to Phojet and 3 Pythia tunes
- Best agreement with Phojet at √s = 0.9 TeV and Pythia ATLAS-CSC tune at √s = 2.36 TeV
- KNO scaling: $z = N_{ch}/\langle N_{ch}\rangle$
  - scaling holds up to $z \sim 4$



$\langle dN_{ch}/d\eta \rangle$ in p-Pb collisions

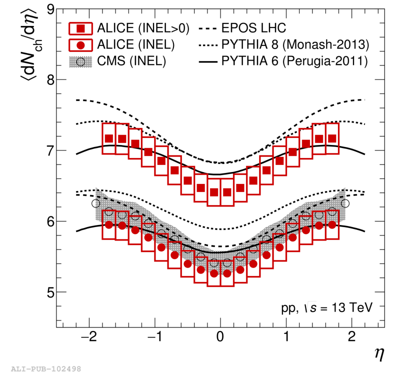
- p-Pb collisions: sensitive to initial state nuclear effects
- Asymmetric system (center of mass shifted in lab frame $\Delta y_{NN} = 0.465$)
- Data compared with saturation models, HIJING, DPMJET
- For comparison with pp, p-Au, d-Au results at different $\sqrt{s}$, $\langle dN_{ch}/d\eta \rangle$ is scaled by $\langle N_{part} \rangle$
- Results are consistent with extrapolated results from pp collisions at lower $\sqrt{s}$

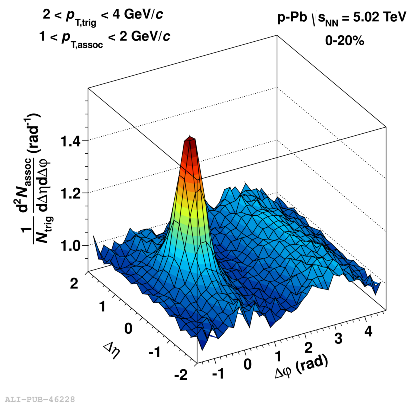




PRL 110 (2013) 032301

From single particle measurements ...

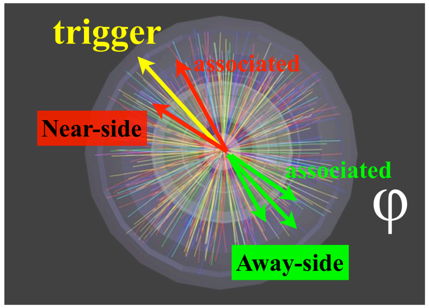


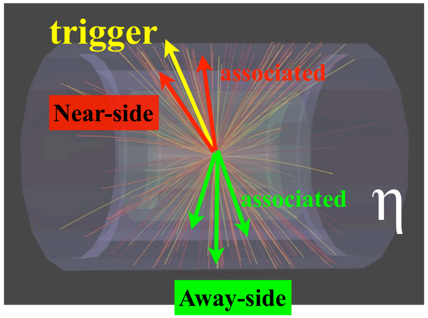


... to two-particle correlations

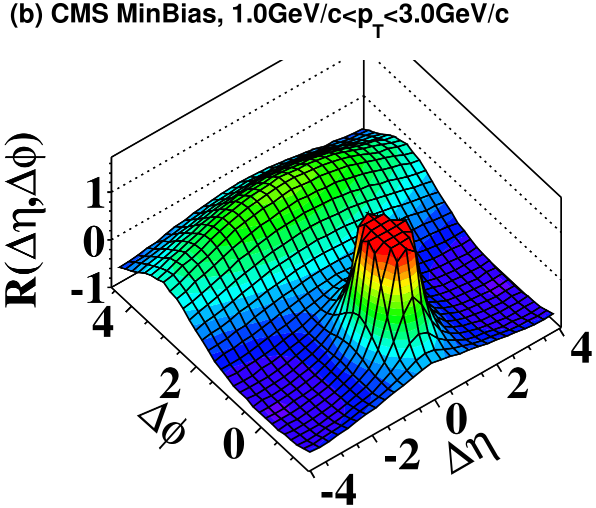
Two-particle correlations (2PC)

- Measurements of correlations in $(\Delta\varphi,\Delta\eta)$





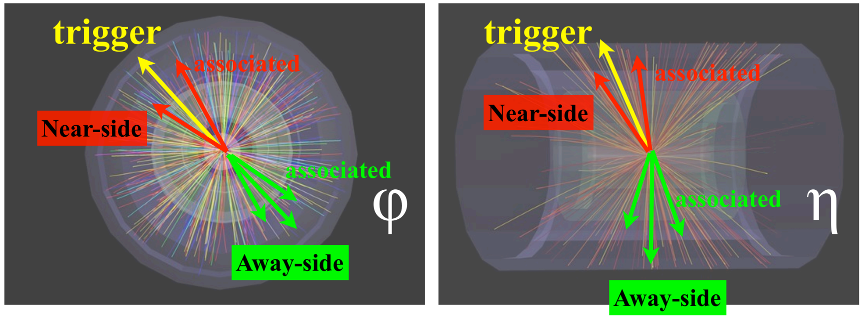
pp



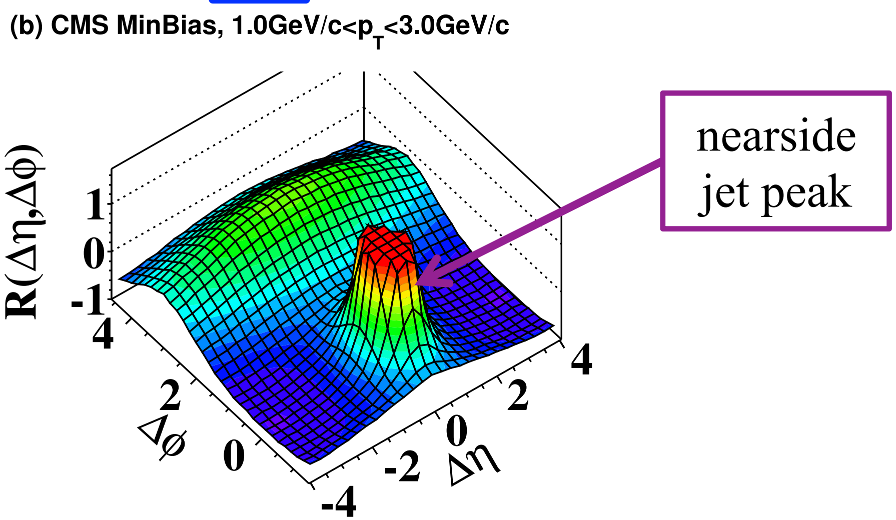
CMS JHEP 1009 (2010) 091

Two-particle correlations (2PC)

- Measurements of correlations in ($\Delta\varphi$,$\Delta\eta$)



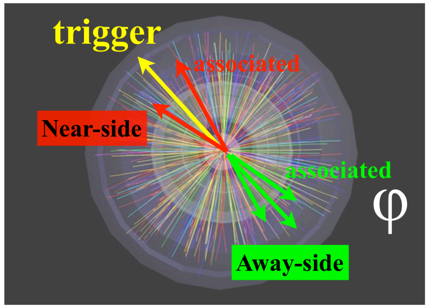
pp

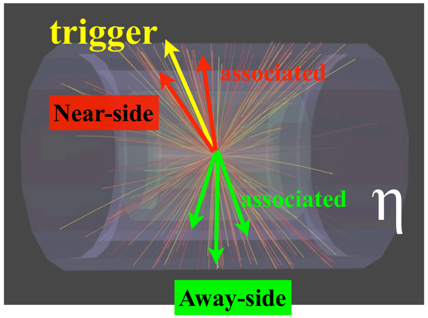


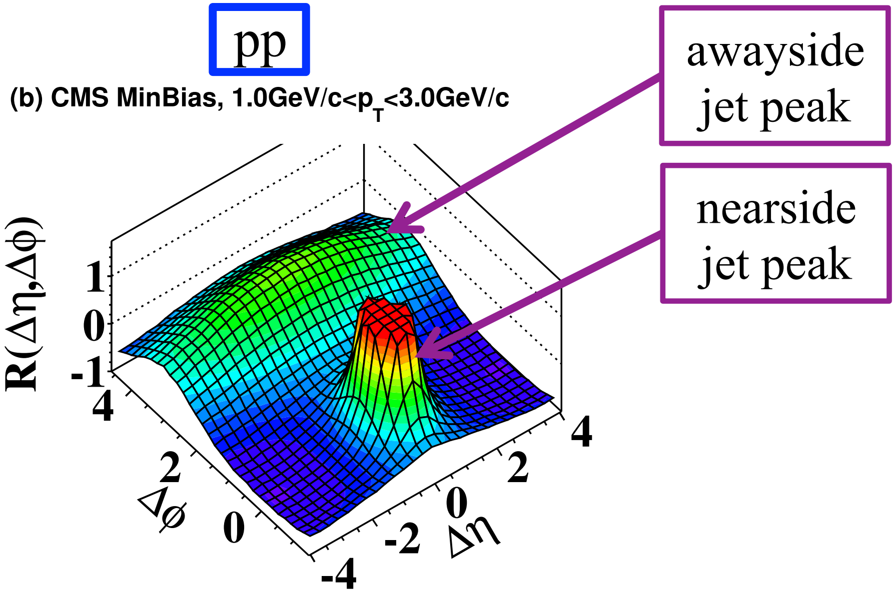
CMS JHEP 1009 (2010) 091

Two-particle correlations (2PC)

- Measurements of correlations in (Δφ,Δη)







CMS JHEP 1009 (2010) 091

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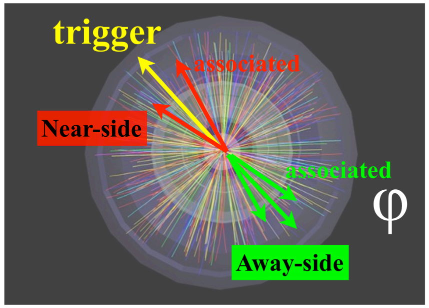
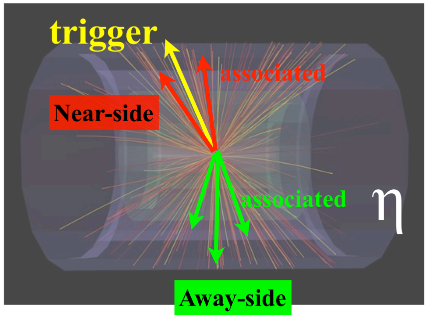
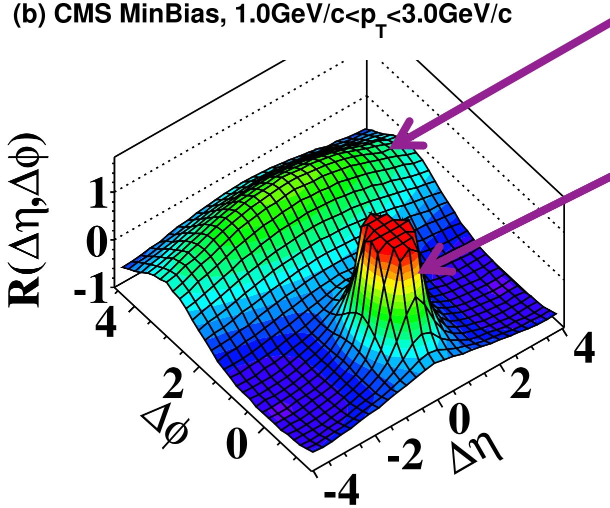




pp

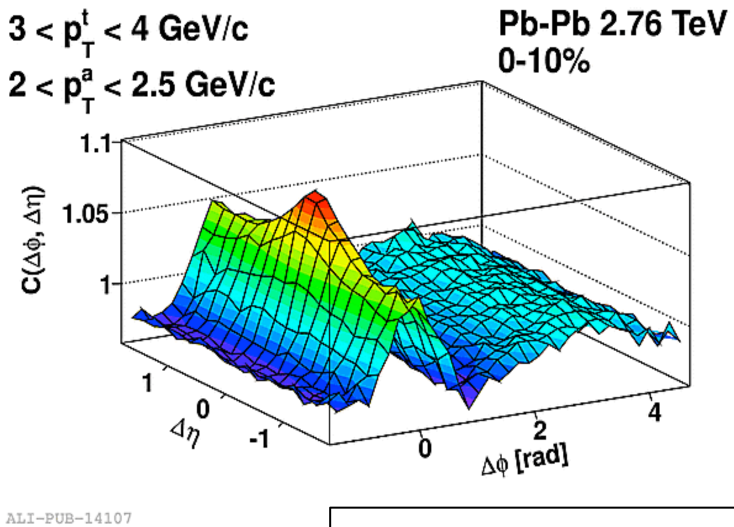


awayside jet peak

nearside jet peak

CMS JHEP 1009 (2010) 091

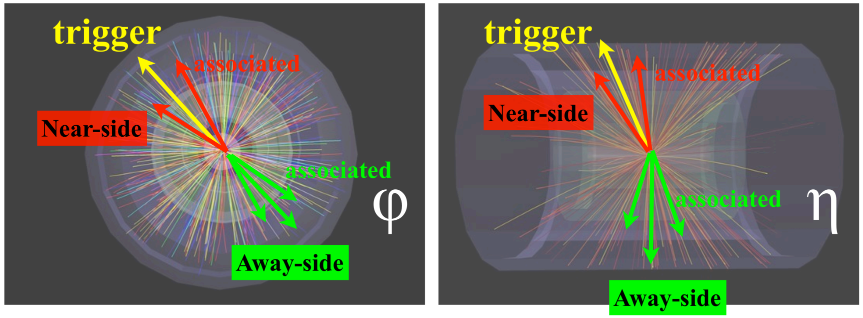
Pb-Pb



ALICE PLB 708 (2012) 249

Two-particle correlations (2PC)

- Measurements of correlations in $(\Delta\varphi, \Delta\eta)$



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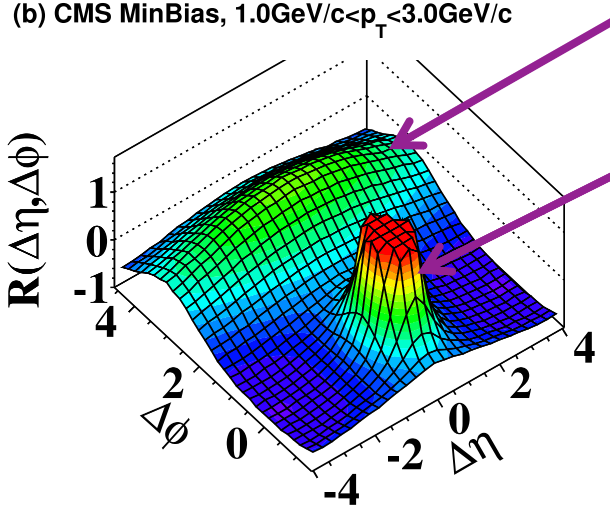
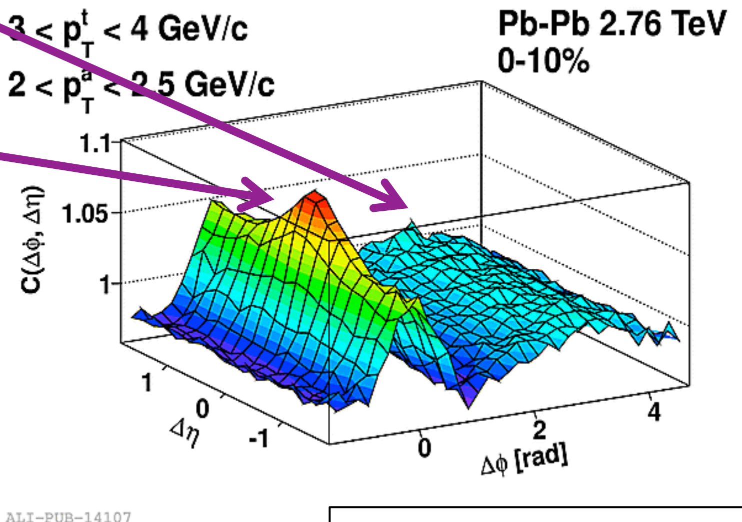


awayside jet peaks

nearside jet peaks

Pb-Pb



CMS JHEP 1009 (2010) 091

ALICE PLB 708 (2012) 249

Two-particle correlations (2PC)

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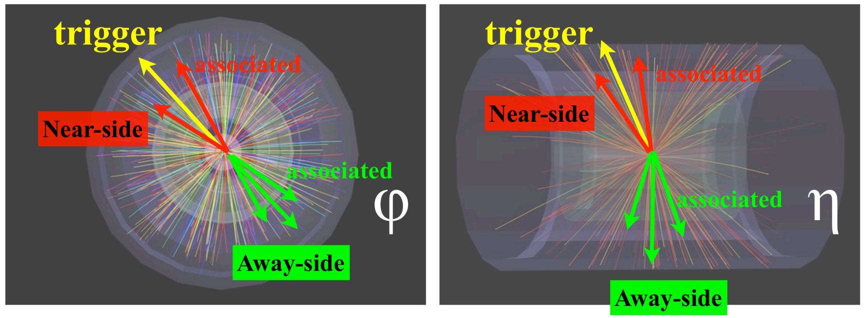
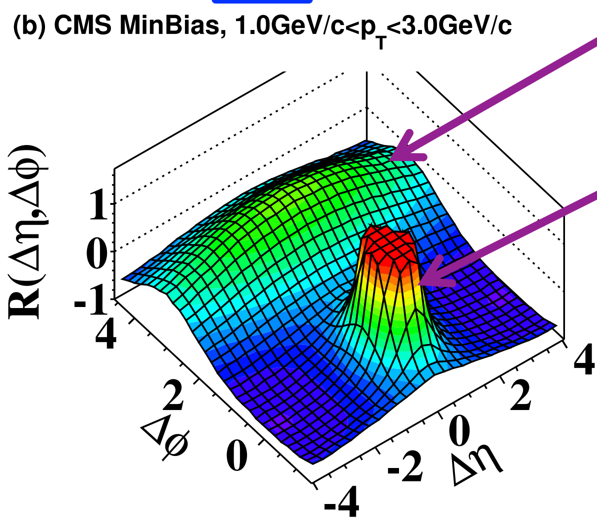


pp

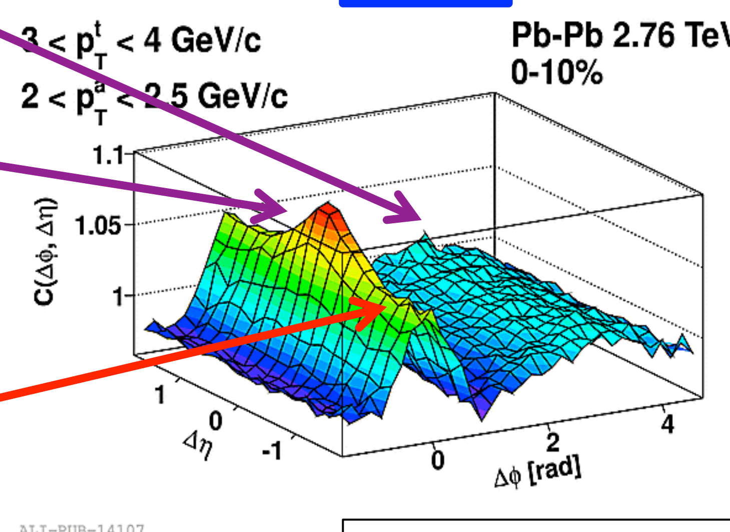


awayside jet peaks

nearside jet peaks

long-range structure in $\Delta\eta$ = “ridge”

Pb-Pb



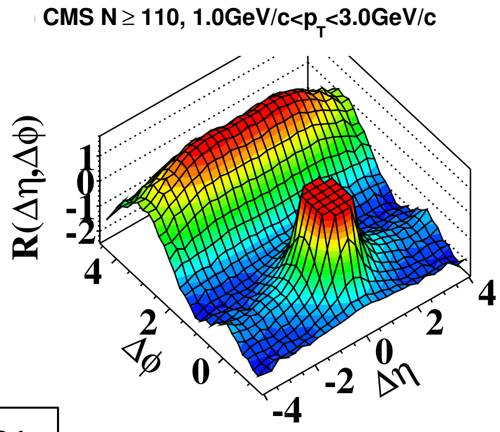
CMS JHEP 1009 (2010) 091

ALICE PLB 708 (2012) 249

Ridges in high multiplicity collisions

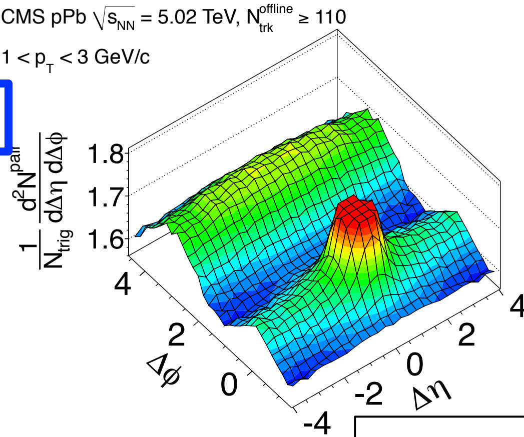
- The nearside ridge was observed in high multiplicity pp and p-Pb collisions
  → reminiscent of structures seen in Pb-Pb collisions where it is attributed to flow

pp



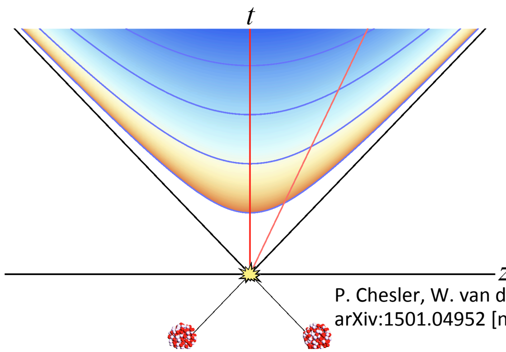
CMS JHEP 1009 (2010) 091

p-Pb



CMS PLB 718 (2013) 795

- What could cause long-range correlations in η?
  - correlations in the initial state?
  - collective behavior of the system at later times in the evolution?
- What does the presence of the ridge in small systems tell us about ridges in heavy ion collisions?

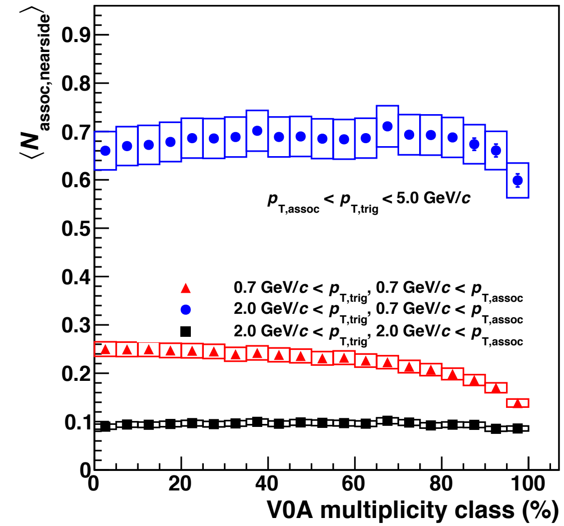


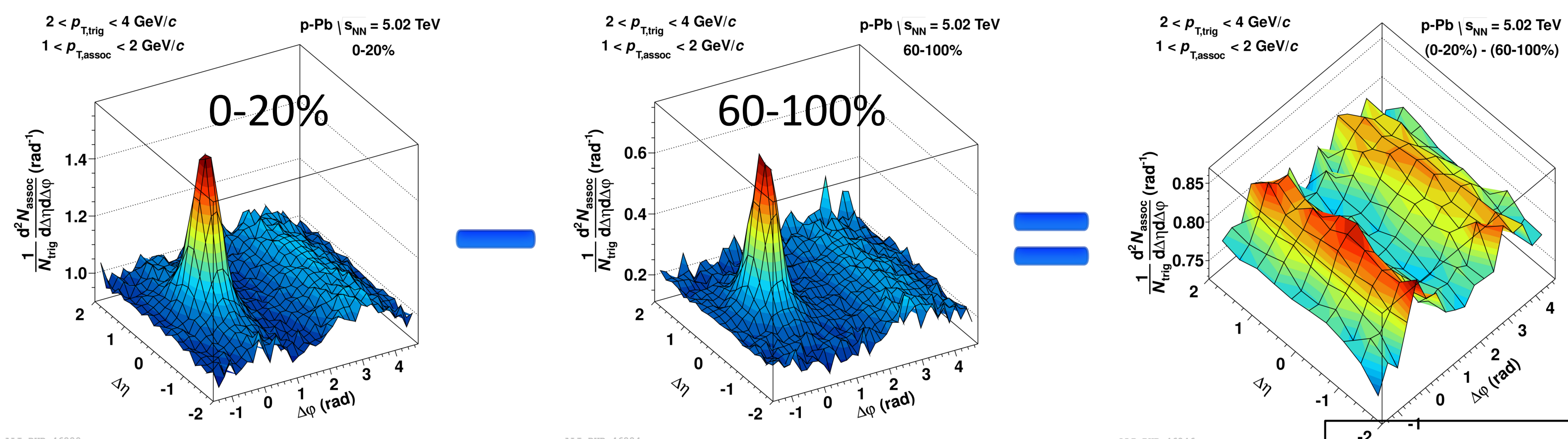
P. Chesler, W. van der Schee, arXiv:1501.04952 [nucl-th]

Double Ridge in p-Pb

- 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

PLB 741 (2015) 38

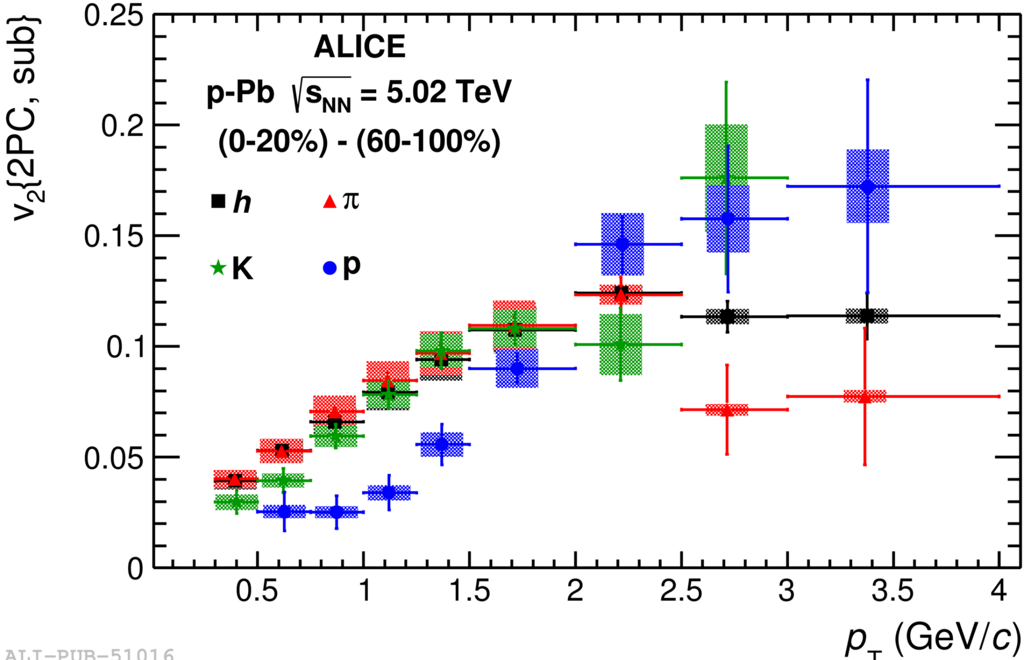




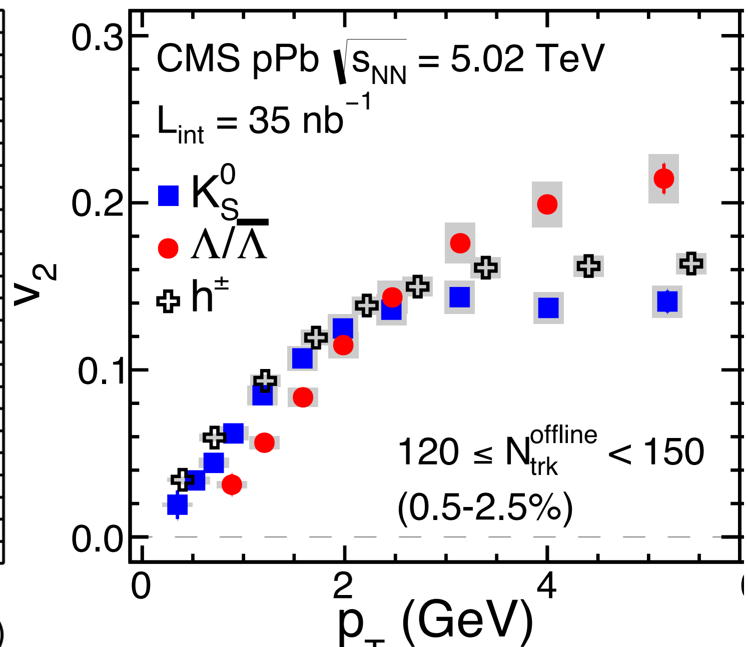
PLB 719 (2013) 29

v_2 in p-Pb

- Extract v_2 by fitting subtracted distributions with Fourier series (ALICE, ATLAS)
- Or obtain v_2 from harmonic decomposition with η gap (|Δη| > 2) (CMS)



ALICE PLB 726 (2013) 164



CMS PLB 742 (2015) 200

- Similar mass ordering is observed for v_2 in p-Pb and for v_2 in Pb-Pb, for π, K, p, K_S^0, Λ

Collectivity in p-Pb?

- Non-zero $v_2\{4\}$, $v_2\{6\}$, $v_2\{8\}$, $v_2\{LYZ\}$
- Non-zero Fourier coefficients measured up to $n = 5$
- Ridges observed at $\sqrt{s_{NN}} = 200$ GeV
- Ridges observed in ^{3}He+Au

CMS PRL 115 (2015) 012301

ATLAS PRC 90 (2014) 044906

PHENIX PRL 114 (2015) 192301

PHENIX PRL 115 (2015) 142301

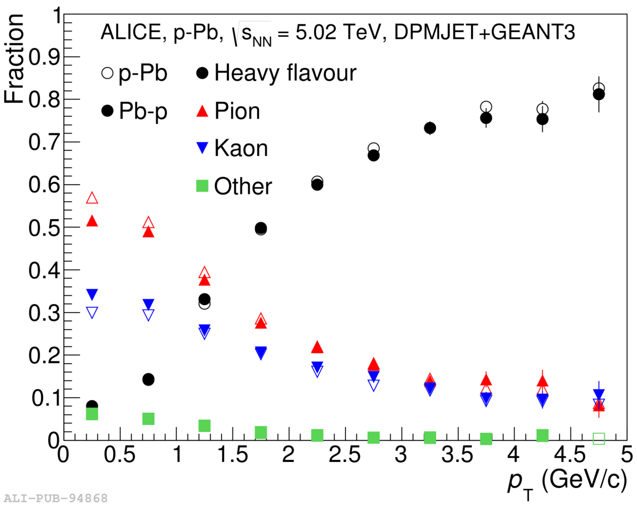
- Possible explanations for the ridges in small systems:
  - hydrodynamics
  - gluon saturation (CGC)
  - extended color connections forming along the longitudinal direction
  - final state parton-parton interactions

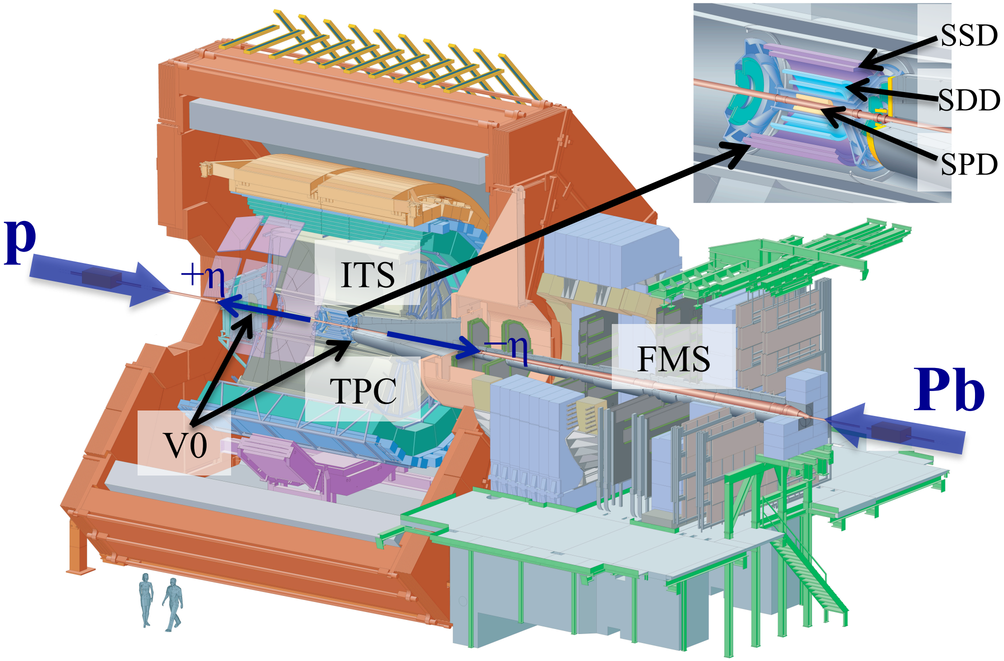
Study η dependence of the (double) ridge
to gain insight into the origins of long-range structures in p-Pb collisions

→ **muon-hadron correlations in ALICE**

μ-track(let) correlations

- Trigger particles measured in the Forward Muon Spectrometer (FMS): $-4 < \eta < -2.5$
  - Composition of parent particles of reconstructed muons varies as a function of p_T
- Associated particles reconstructed in the central barrel: $|\eta| < 1$
  - ITS+TPC tracks: $0.5 < p_T < 4$ GeV/c
  - SPD tracklet: mean $p_T \approx 0.75$ GeV/c (p_T is correlated with differences of azimuthal and polar angles of hits in the SPD layers)





PLB 753 (2016) 126

Associated Yield per Trigger Muon

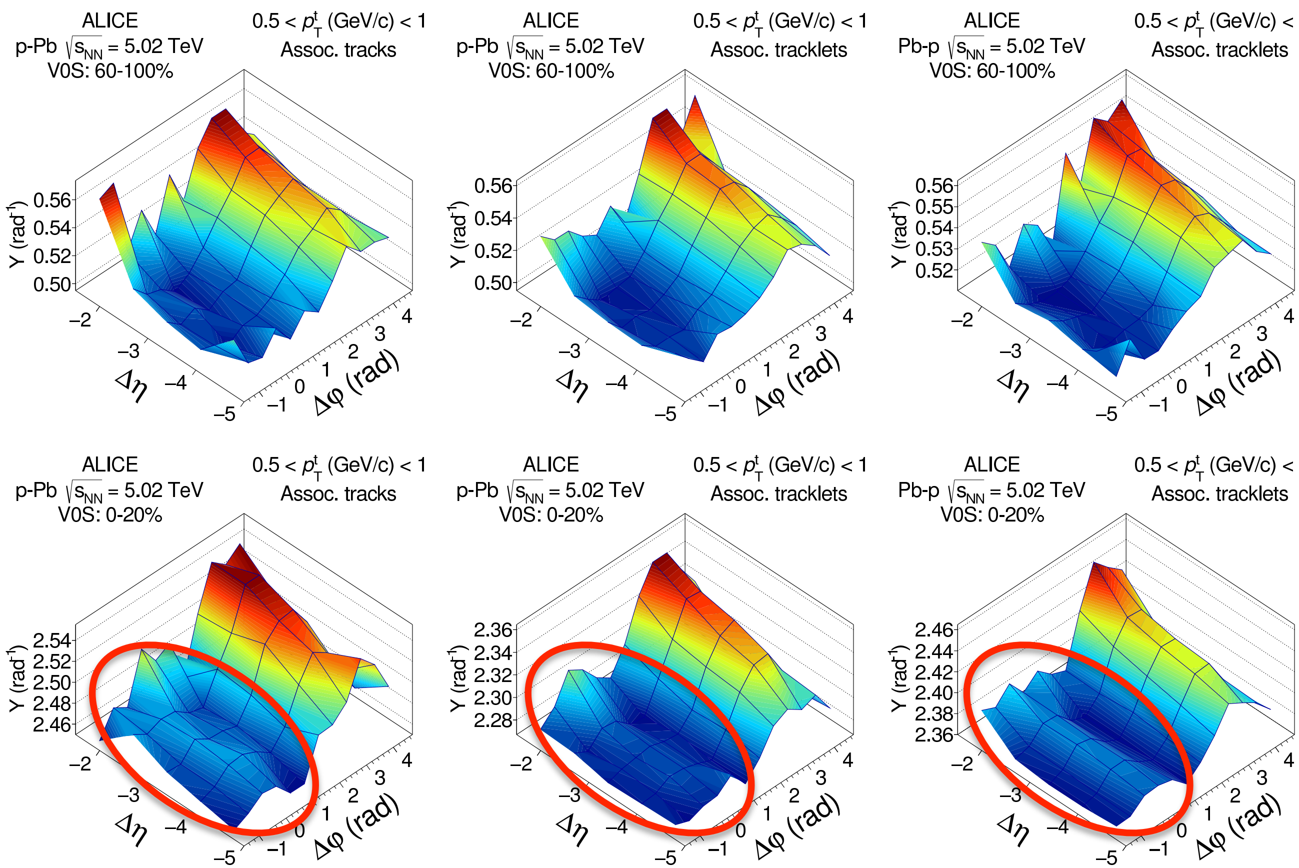
PLB 753 (2016) 126

$$Y = \frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\varphi d\Delta\eta}$$

	muon-track p-going trigger	muon-tracklet p-going trigger	muon-tracklet Pb-going trigger

60-100%

0-20%



Structure observed around $\Delta\varphi$=0 at large $\Delta\eta$ – nearside ridge in high-multiplicity events

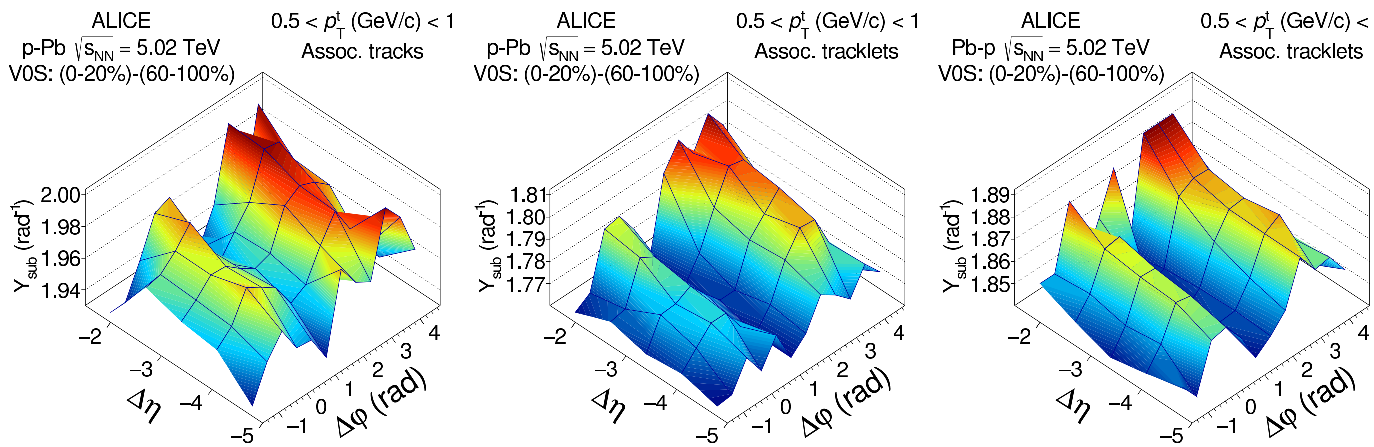
Long-range correlations

ALICE

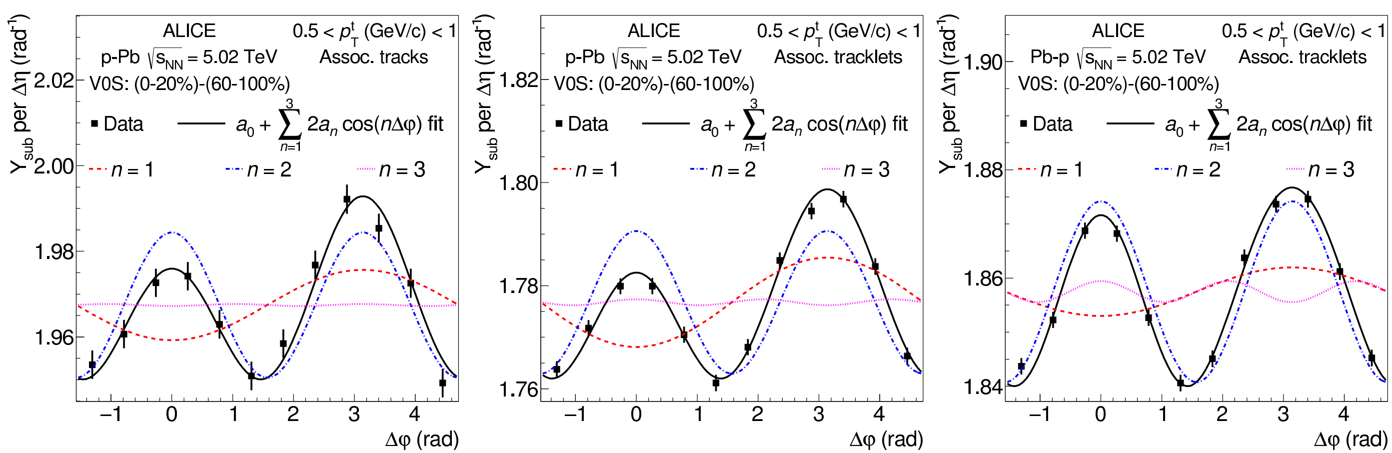
- Subtract low-multiplicity correlations from high-multiplicity correlations to remove jet components and isolate long-range structures
- Project onto Δφ and fit to extract Fourier coefficients a_n

PLB 753 (2016) 126

subtracted
(0-20%) – (60-100%)



Δφ projections



Muon v_2\{2PC,sub\}

- $V_{2\Delta}$ measured by scaling a_n to the appropriate baseline

  $V_{2\Delta}\{2PC,sub\} = a_2/(a_0+b)$ where b is the baseline in the low-multiplicity event class

- $V_{2\Delta} = v_2^{trig} v_2^{assoc}$ if factorization is valid

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

v_2 of muons

measured in muon-tracklet correlations or muon-track correlations

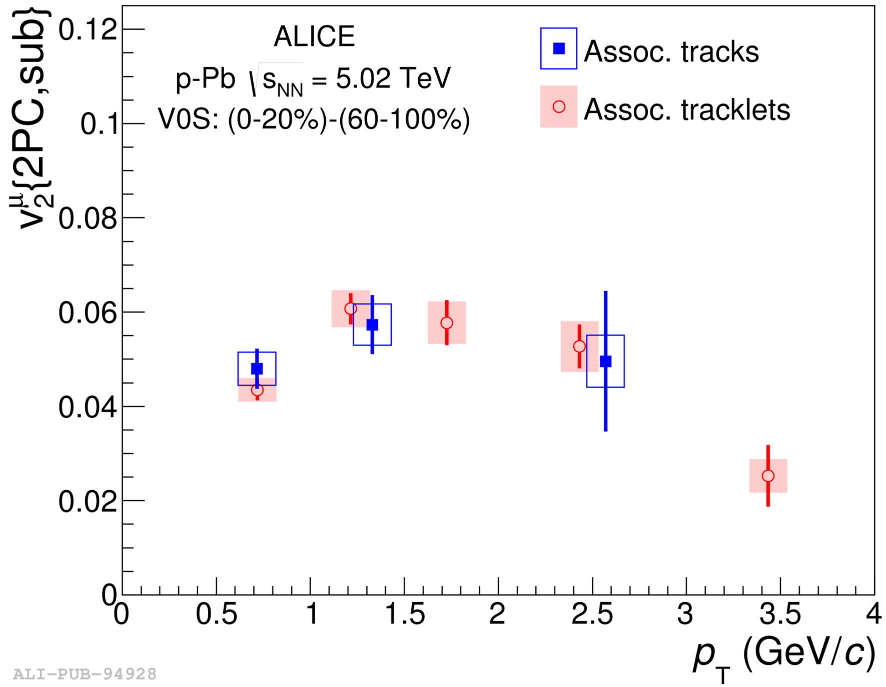
measured in tracklet-tracklet correlations or track-track correlations

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%

Results: Tracklet vs. track comparison

PLB 753 (2016) 126

$v_2^{\mu}\{2PC,sub\}$ in the p-going direction

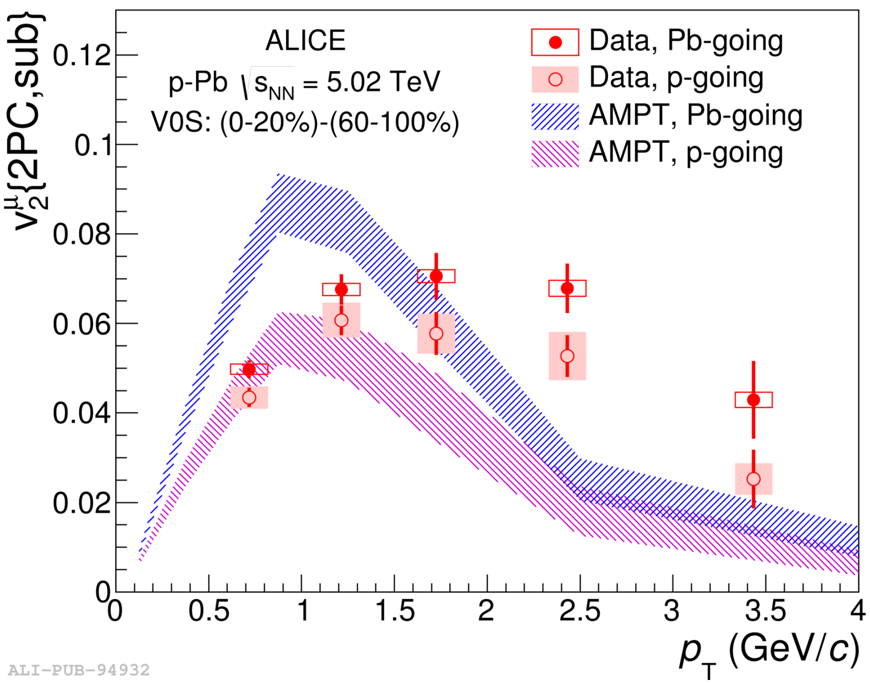


- Agreement between track and tracklet results demonstrates that factorization of trigger and associate v_2 is valid
  - measured trigger muon v_2 is the same even though associated track and tracklet p_T distributions are different

Results: $v_2^{\mu}\{2pc,sub\}$

PLB 753 (2016) 126

$v_2^{\mu}\{2PC,sub\}$ in the p-going and Pb-going directions



- Data compared to calculations from AMPT with Pythia decayer
  - qualitatively similar trends at low p_T
  - quantitatively different p_T and η dependence between data and model, especially at high p_T
- High p_T (> 2 GeV/c) muon production dominated by heavy flavor decays
  - Possible scenarios at p_T > 2 GeV/c:
    - HF muons have $v_2 \neq 0$
    - different composition of the parent distribution and their v_2

Results: Ratio in p- and Pb-going directions

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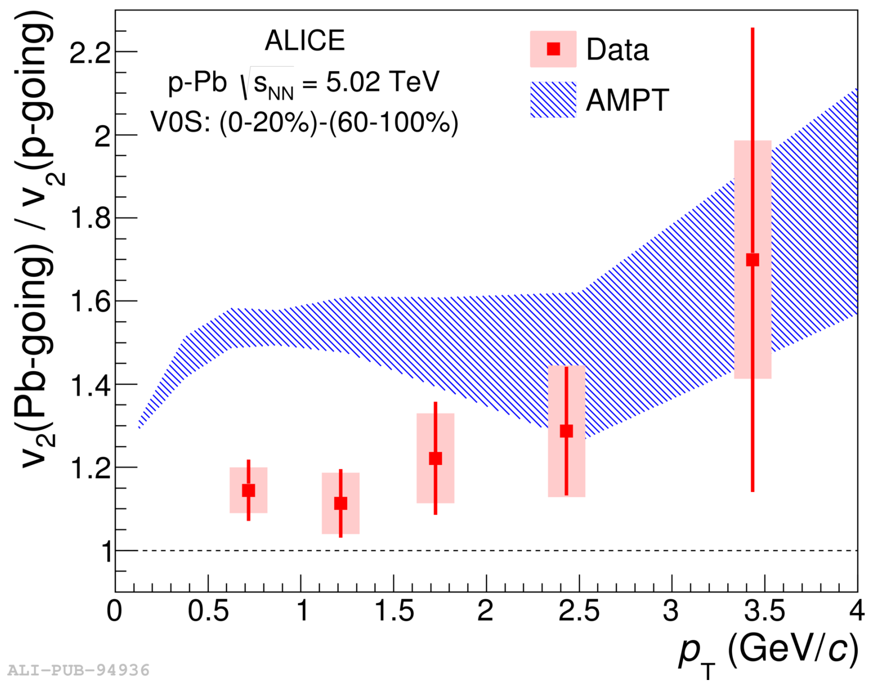
Ratio of $v_2^{\mu}\{2PC,sub\}$ in the Pb-going and p-going directions



- Ratio is independent of p_T within statistical and systematic uncertainties
- Constant fit to the ratio:

  1.16 ± 0.06 with $\chi^2/NDF = 0.5$
- Ratios of observed quantities in the Pb-going and p-going directions should be sensitive to the initial state conditions

P. Bozek, A. Bzdak, V. Skokov, PLB 728 (2014) 662

Model Comparisons

- 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

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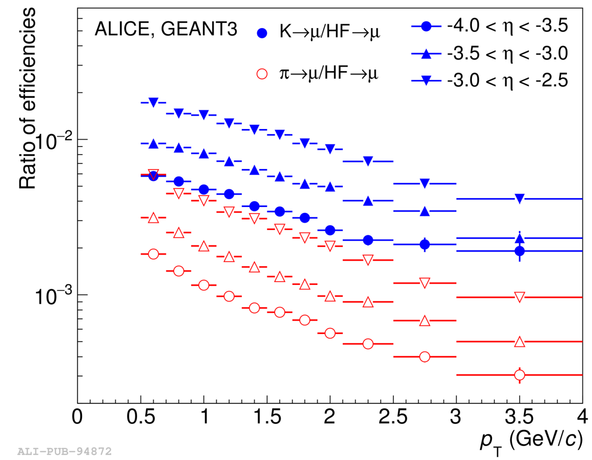
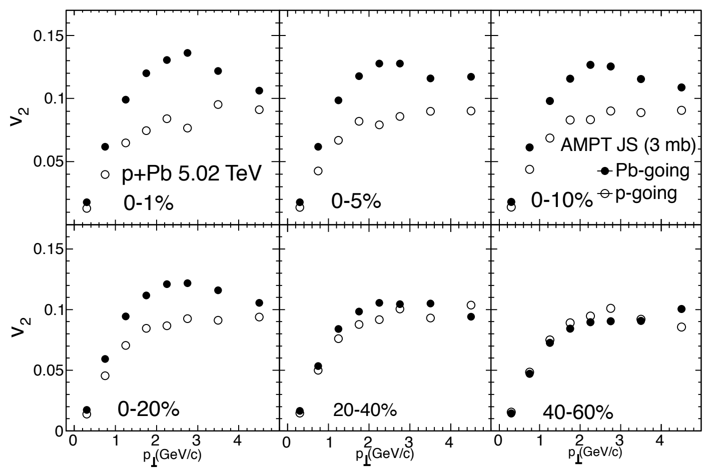
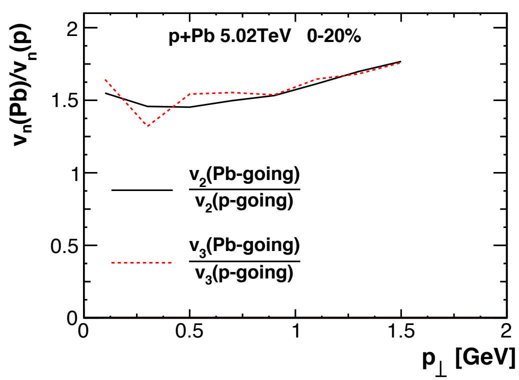


- Published model predictions cannot yet be directly compared to data

3+1D hydrodynamics



AMPT



P. Bozek, A. Bzdak, G.-L. Ma, arXiv: 1503.03655

Conclusions

- Global properties of nuclear collisions: pseudorapidity density has been measured in pp at $\sqrt{s}$ = 0.9, 2.36, 13 TeV and p-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
  - power law scaling across wide range in center-of-mass energy
  - multiplicity distributions and pseudorapidity dependence used to tune models
- Two-particle correlations in small systems show features reminiscent of nucleus-nucleus collisions
  - Double ridge structure in p-Pb shows mass ordering similar to Pb-Pb
- $v_2\{2PC,sub\}$ has been measured for muons at forward rapidities in p-Pb
  - $v_2^{\mu}\{2PC,sub\}$ has similar p_T dependence in both directions
  - $v_2^{\mu}\{2PC,sub\}$ in the Pb-going direction is $(16 \pm 6)\%$ higher than in the p-going direction
  - Results are compared to AMPT model calculations, p_T dependence is similar, particularly at low p_T

- Future measurements and model comparisons will allow us to gain understanding of the production mechanisms of multiplicities and long-range correlations in small systems

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