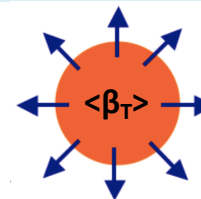


Recent results on collectivity in small systems from ALICE

Zhanna Khabanova

on behalf of the ALICE Collaboration



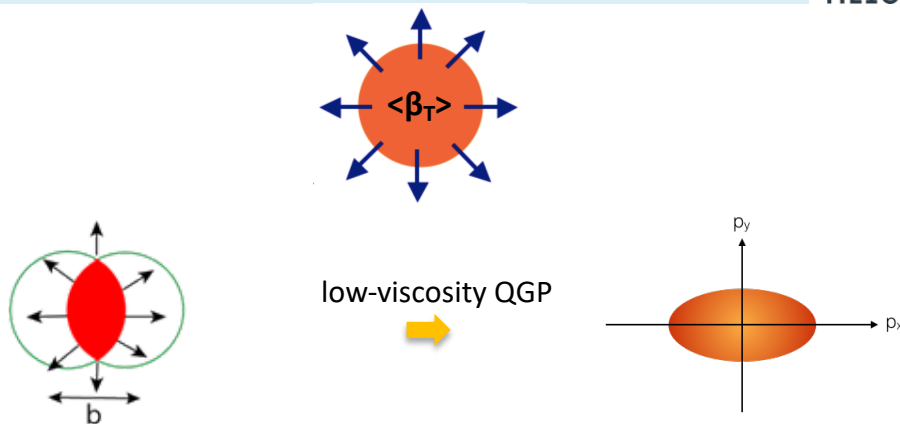
Heavy-ion collisions

- study properties of quark-gluon plasma (QGP)
- QGP evolution is described by hydrodynamics
- **radial flow:** characterised by collective average transverse velocity $\langle \beta_T \rangle$

Collectivity in heavy-ion collisions

Heavy-ion collisions

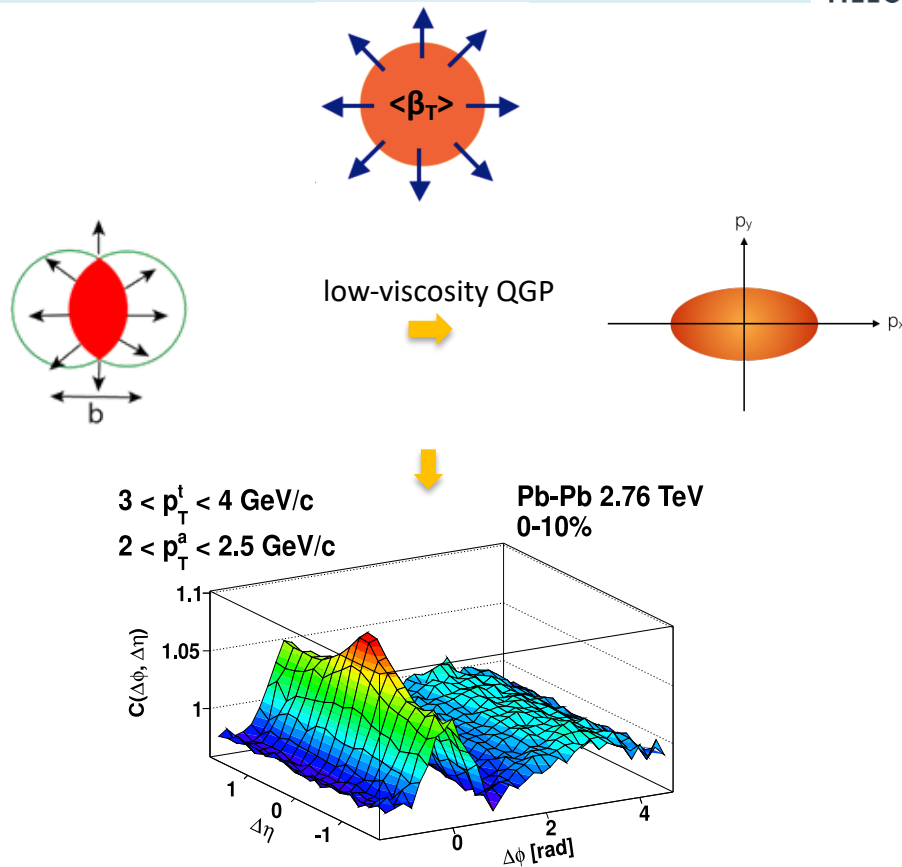
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Collectivity in heavy-ion collisions

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ALI-PUB-14107

ALICE Coll. PLB 708 (2012) 249

Small systems (old picture)

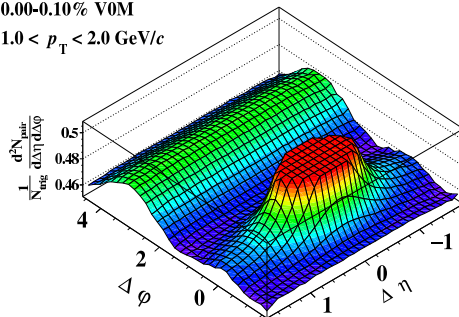
- p-A and pp collisions
- medium-free reference to disentangle cold nuclear matter effects from QGP

Small systems: change of paradigm

Small systems (old picture)

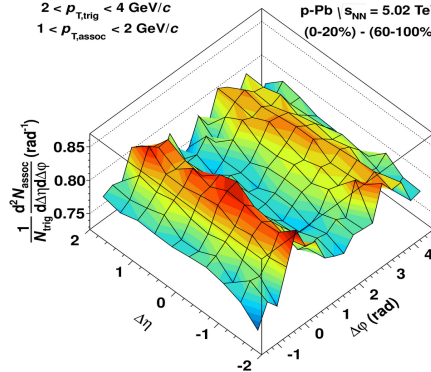
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ALICE Preliminary, pp $\sqrt{s} = 13$ TeV
0.00-0.10% V0M
 $1.0 < p_T < 2.0$ GeV/c



ALI-PREL-319153

$2 < p_{T,\text{trig}} < 4$ GeV/c
 $1 < p_{T,\text{assoc}} < 2$ GeV/c
p-Pb | $s_{NN} = 5.02$ TeV
(0-20%) - (60-100%)



ALICE Coll. PLB 719 (2013) 29-41



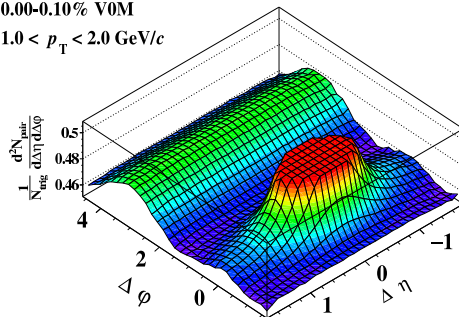
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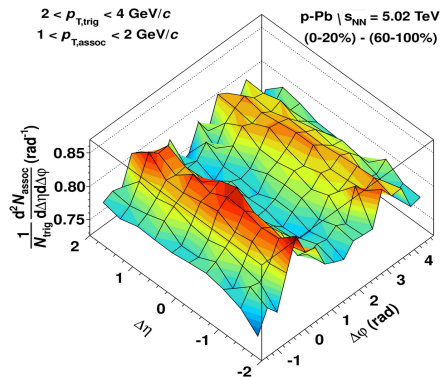
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ALICE Coll. PLB 719 (2013) 29-41



**change of
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Small systems (new picture)

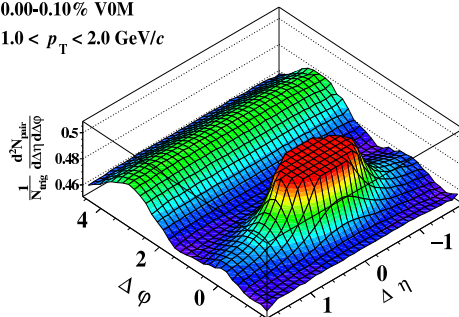
- are these observations a manifestation of collectivity? ("long-range multi-particle correlations")
- what is the origin of collectivity in small systems?
- down to which multiplicity do we see it?

Small systems: change of paradigm

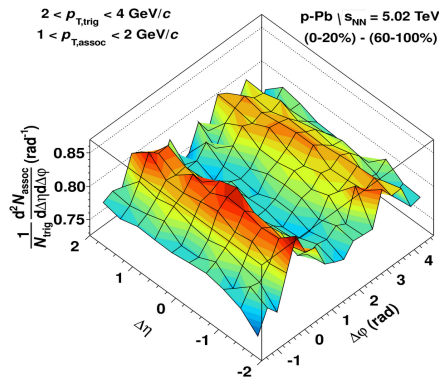
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ALICE Coll. PLB 719 (2013) 29-41

change of
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Small systems (new picture)

- are these observations a manifestation of collectivity? ("long-range multi-particle correlations")
- what is the origin of collectivity in small systems?
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initial state (IS): initial momentum correlations

- at nucleonic level (Glauber model)
- at sub-nucleonic level (CGC-based IP-Glasma model)

final state (FS): final state correlations

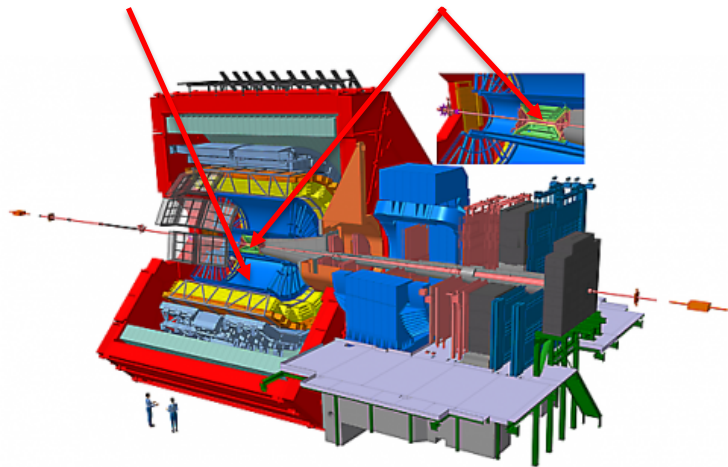
- at macroscopic level -> driven by pressure gradients (MUSIC, EPOS-LHC)
- at microscopic level -> due to other mechanisms such as string recombination (color reconnection in PYTHIA8, rope hadronization in DIPSY, cluster hadronization in HERWIG7)

both: hybrid models (IP-Glasma+MUSIC+UrQMD, AMPT)

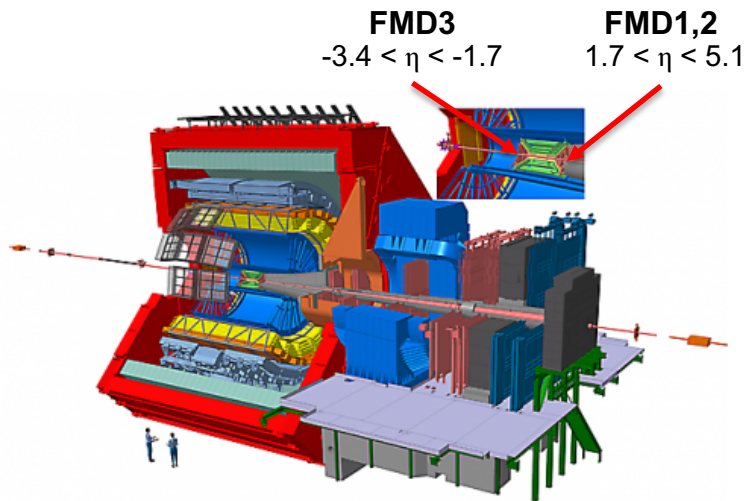
provide more measurements to constrain models

Results: long-range angular correlations in p-Pb and pp collisions using FMD

TPC $-0.9 < \eta < 0.9$ ITS



Results: long-range angular correlations in p-Pb and pp collisions using FMD

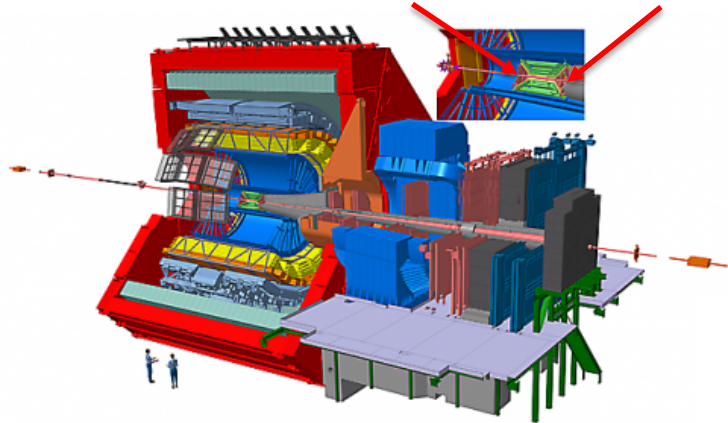


- ALICE Forward Multiplicity Detector (FMD)
- allows measurement up to $\Delta\eta \sim 8$
- unique measurement at the LHC

Results: long-range angular correlations in p-Pb and pp collisions using FMD

FMD3
 $-3.4 < \eta < -1.7$

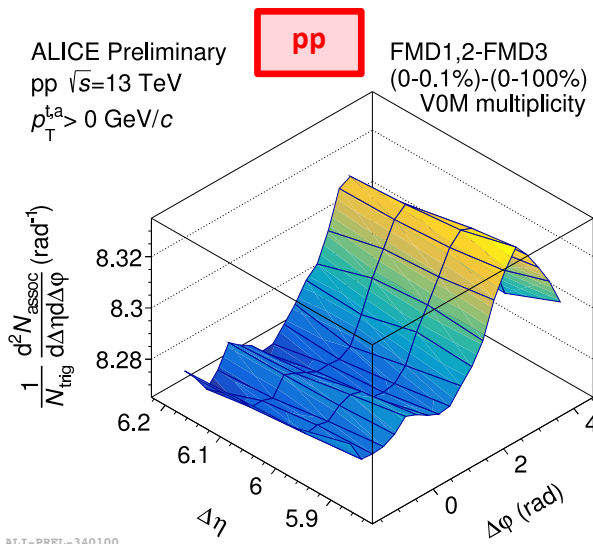
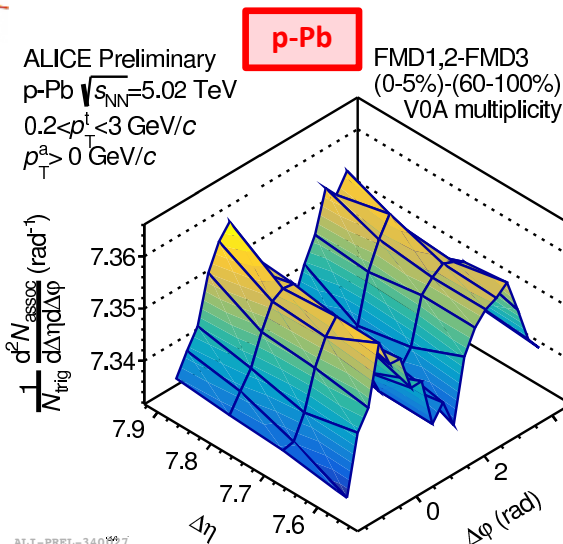
FMD1,2
 $1.7 < \eta < 5.1$



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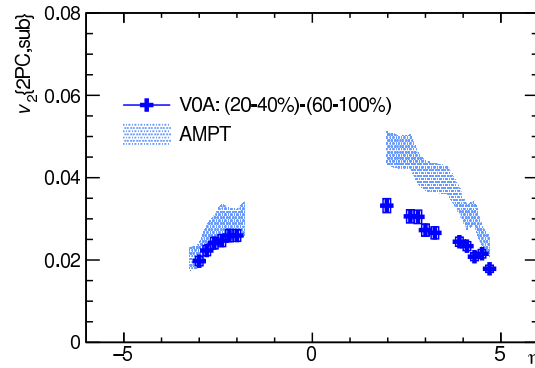
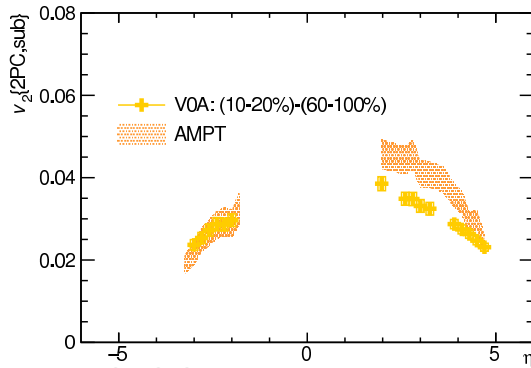
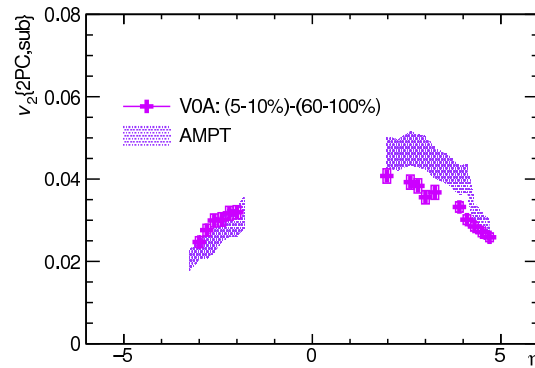
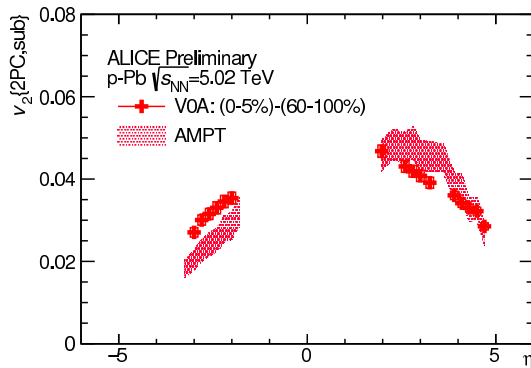
- ridge extends up to:

- $\Delta\eta \sim 8$ in p-Pb
- $\Delta\eta \sim 6$ in pp



Results: $v_2(\eta)$ in p-Pb collisions for charged particles using FMD

p-Pb



ALI-DER-340203

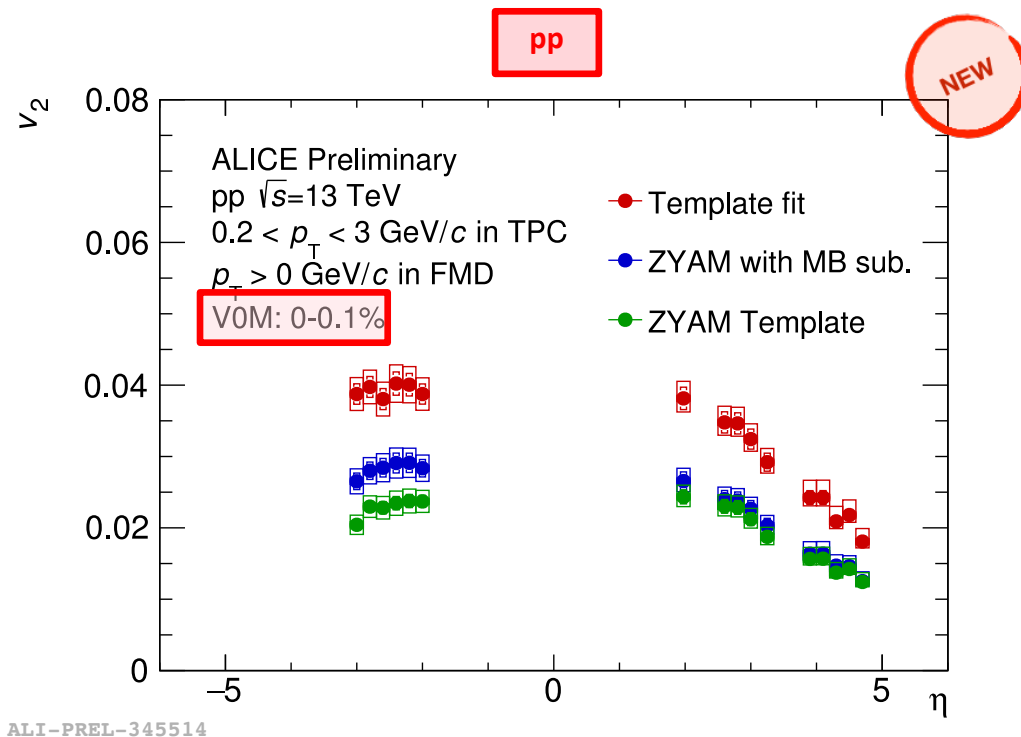
AMPT: Phys.Rev.C 65 (2002) 034904

- data in p-Pb compared with predictions from AMPT with string melting
- $v_2(\eta)^*$ is asymmetric similar to the trend of charged particle multiplicity
- AMPT successfully reproduces asymmetry of $v_2(\eta)$, but not the multiplicity dependence

* η in the laboratory system

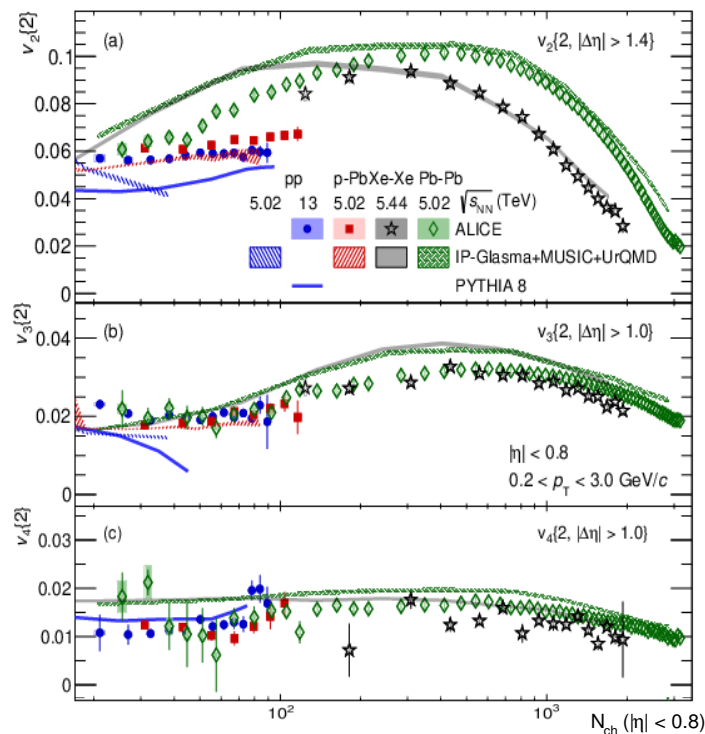
Results: $v_2(\eta)$ in pp collisions for charged particles using FMD

- new result of $v_2(\eta)$ in high-multiplicity pp collisions
- three curves correspond to the results with different non-flow subtraction methods



Results: multiplicity and system size dependence of $v_n\{m\}$ for charged particles

ALICE Coll. Phys. Rev. Lett. 123, 142301



IP-Glasma + hydrodynamics + UrQMD: PLB 772 (2017) 681

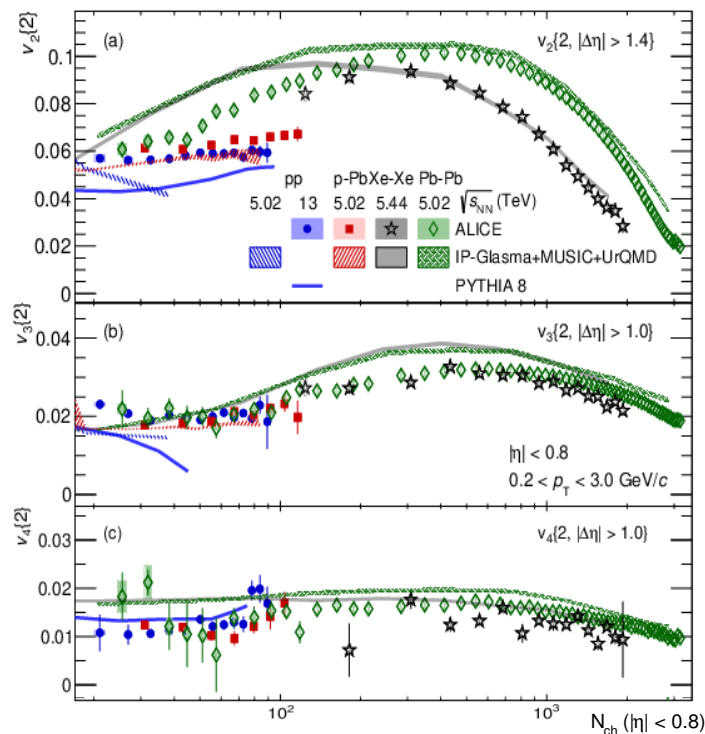
PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

Results: multiplicity and system size dependence of $v_n\{m\}$ for charged particles

collectivity: “**long-range** multi-particle correlations”

- $v_n\{2\}_{\text{sub}}$: long-range correlations shared by two particles

ALICE Coll. Phys. Rev. Lett. 123, 142301



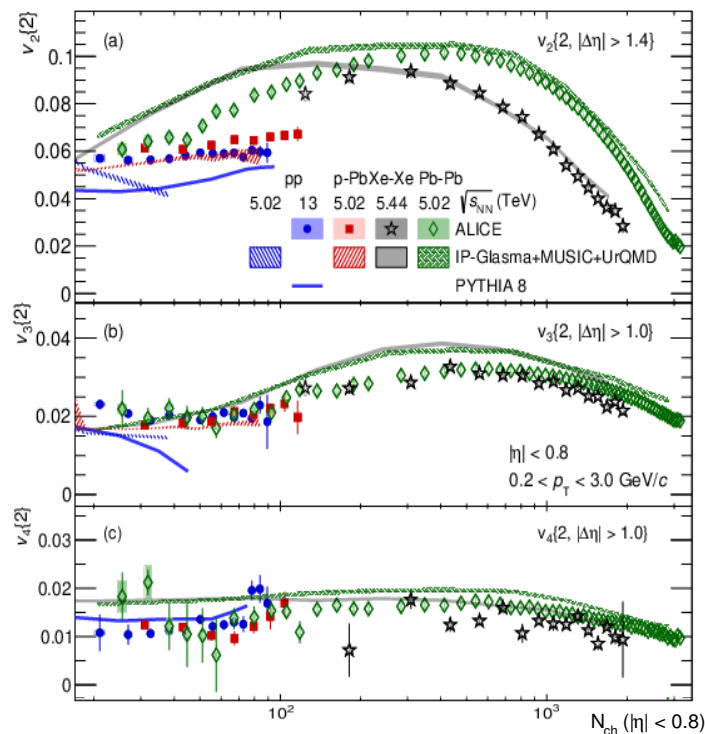
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- $v_n\{2\}$ in small systems are compatible with large systems at low N_{ch}

ALICE Coll. Phys. Rev. Lett. 123, 142301



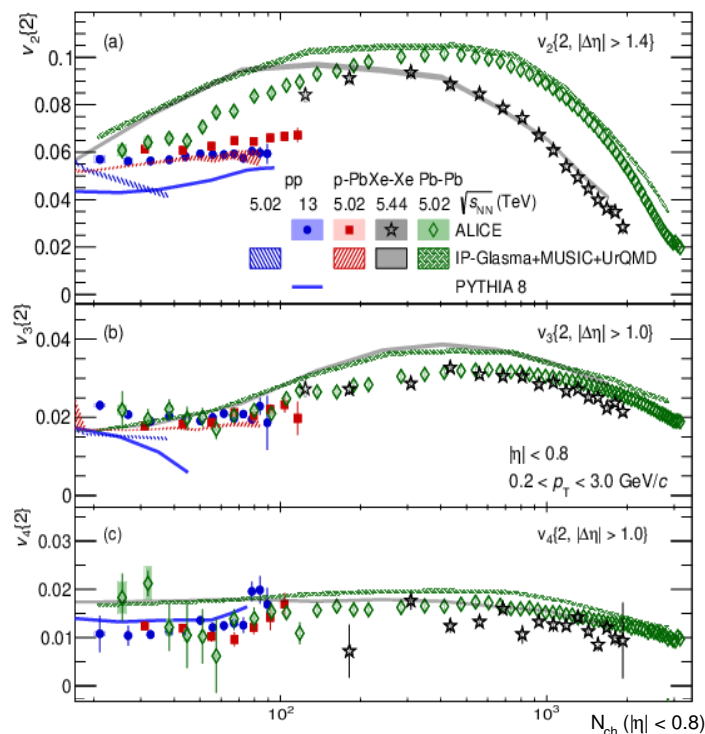
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PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

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collectivity: “**long-range** multi-particle correlations”

- $v_n\{2\}_{\text{sub}}$: long-range correlations shared by two particles
- $v_n\{2\}$ in small systems are compatible with large systems at low N_{ch}
- pp data can not be described solely by non-flow (PYTHIA8)
- hydro with IS (IP-Glasma+MUSIC+UrQMD) reproduces data quite well in Pb-Pb and Xe-Xe (except $v_2\{2\}$ at low N_{ch}) and qualitatively in p-Pb, but not in pp collisions

ALICE Coll. Phys. Rev. Lett. 123, 142301



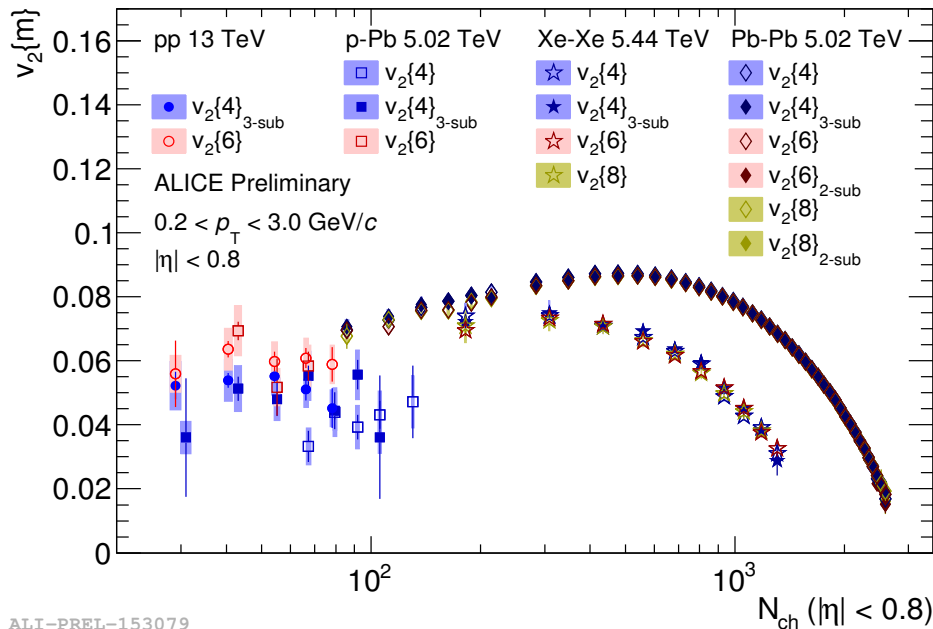
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PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

Results: multiplicity and system size dependence of $v_n\{m\}$ for charged particles

collectivity: “**long-range multi-particle** correlations”

- $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\}$: genuine long-range multi-particle correlations persist down to very low multiplicities
- hard to conclude if origin of correlations is the same as in heavy-ion collisions based only on v_n measurements

ALICE Coll. Phys. Rev. Lett. 123, 142301



Results: balance function of identified particles in pp collisions at $\sqrt{s} = 5.02$ TeV

$$B(\Delta\eta, \Delta\phi) = \frac{1}{2} [C_{+,-} + C_{-,+} - C_{+,+} - C_{-,-}]$$

$$C(\Delta\eta, \Delta\phi) = \frac{1}{N_{trig}} \frac{d^2 N_{assoc}}{d\Delta\eta d\Delta\phi} = \frac{S}{f}$$

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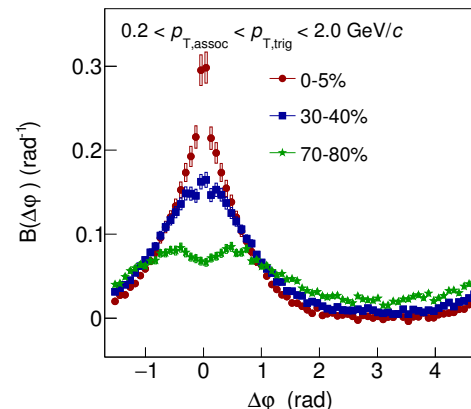
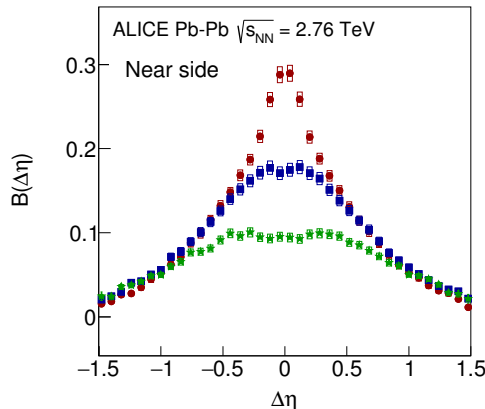
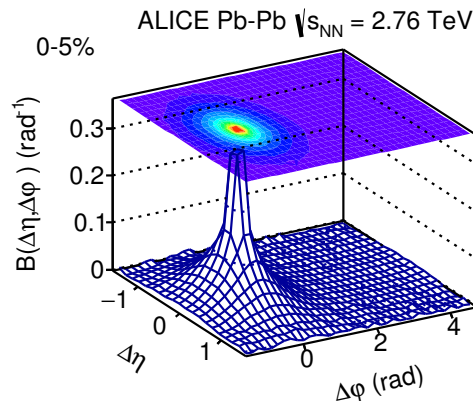
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ALICE Coll. Eur. Phys. J. C 76 (2016) 86



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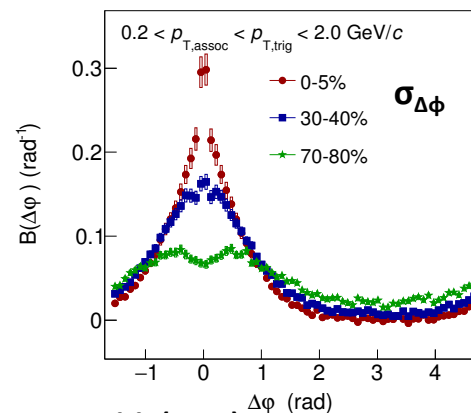
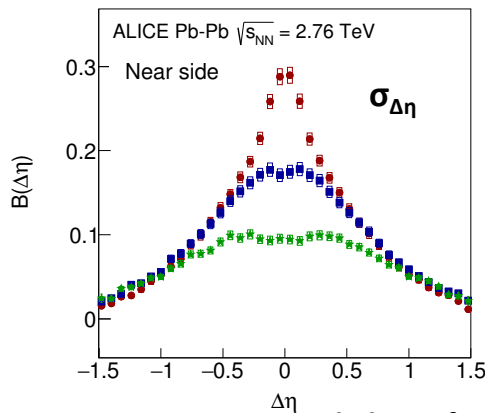
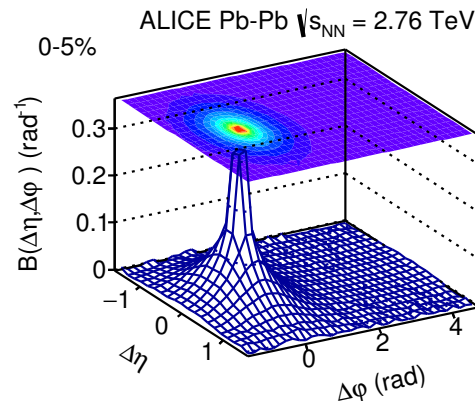
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ALICE Coll. Eur. Phys. J. C 76 (2016) 86



balance function width (RMS)

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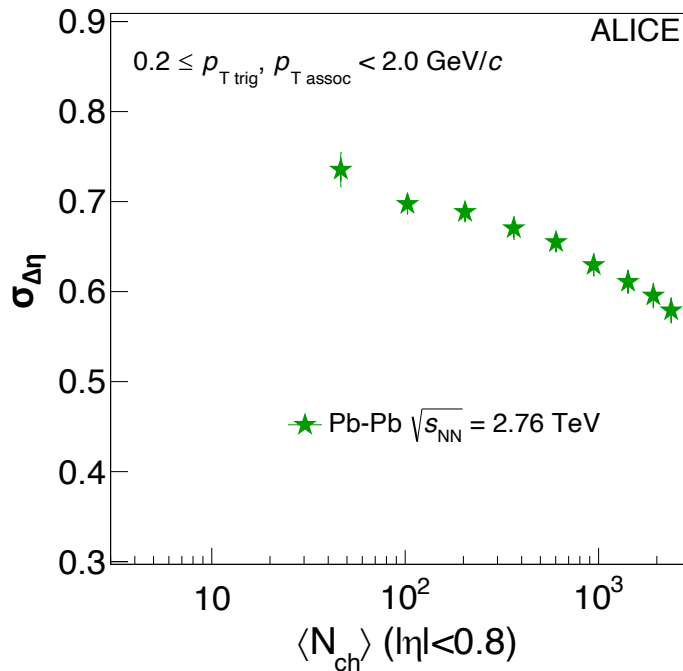
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ALICE Coll. Eur. Phys. J. C 76 (2016) 86



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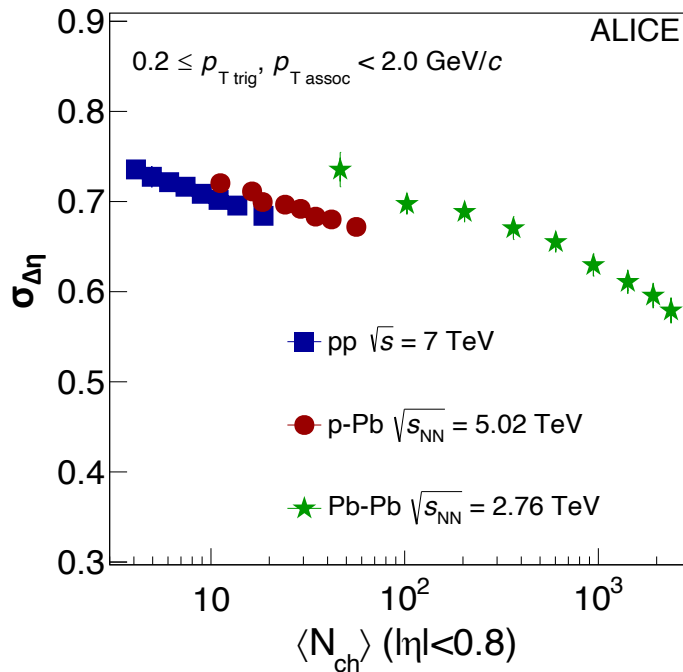
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ALICE Coll. Eur. Phys. J. C 76 (2016) 86



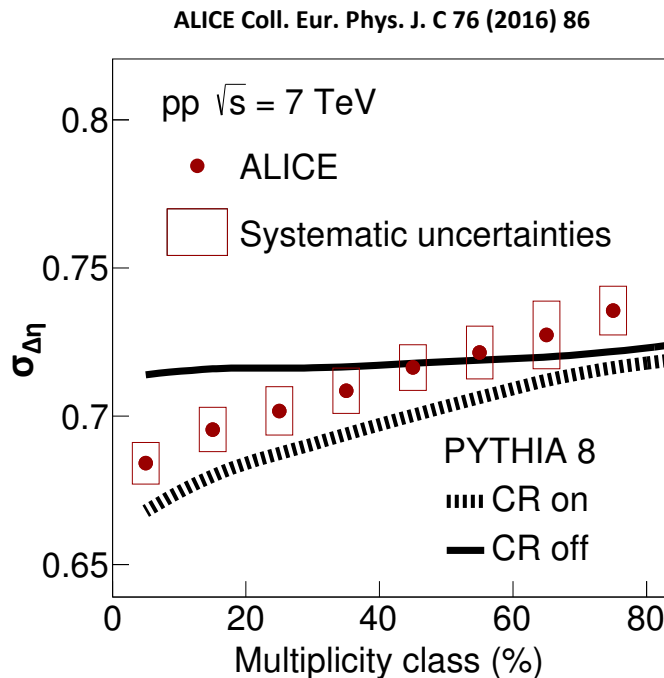
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- balance function reflects the charge-dependent part of angular correlations -> anisotropic flow effects are removed
- balance function width narrowing with increasing multiplicity attributed to the radial flow effect in heavy-ion collisions
- similar trend observed in smaller systems for charged particles
- PYTHIA8 with color reconnection qualitatively describes pp data
- identified hadrons: narrowing should be more pronounced for heavier particles if driven by collective phenomena in small systems



PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

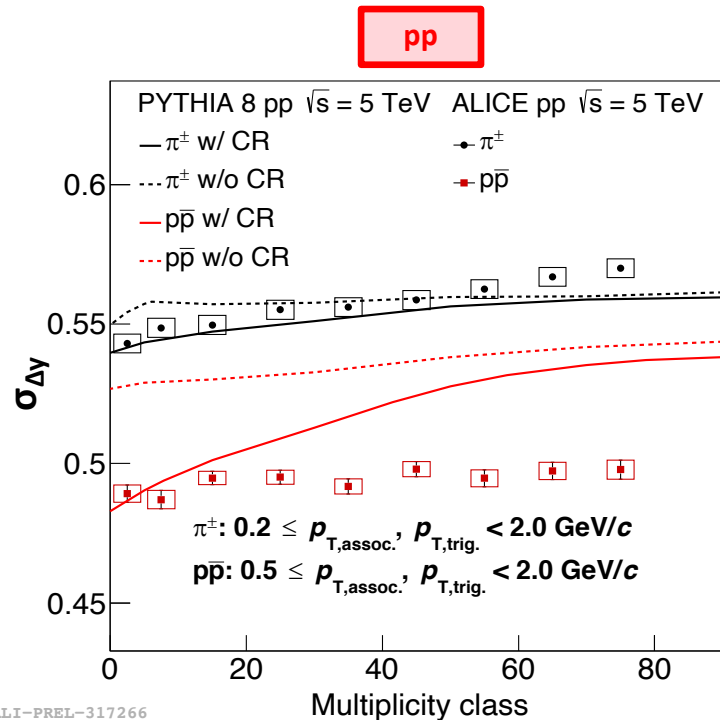
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- protons show almost flat dependence, but narrowing can not be excluded within the current uncertainties
- balance function width results for identified hadrons in pp collisions disfavor color reconnection mechanism implemented in PYTHIA8



PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

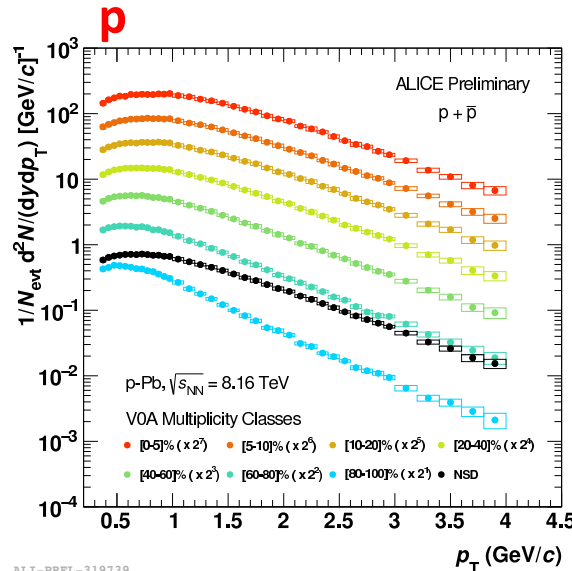
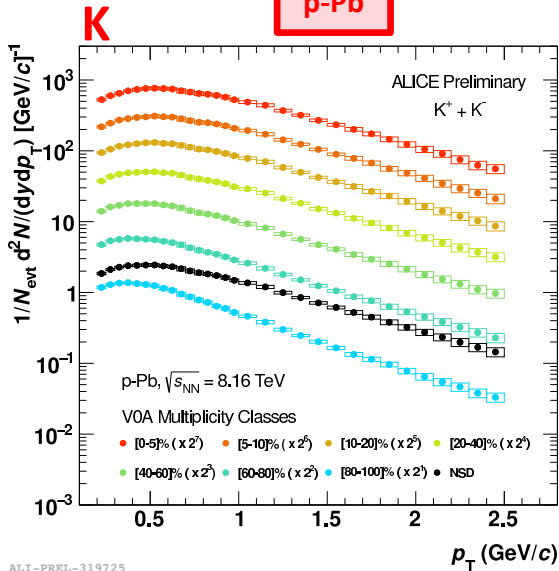
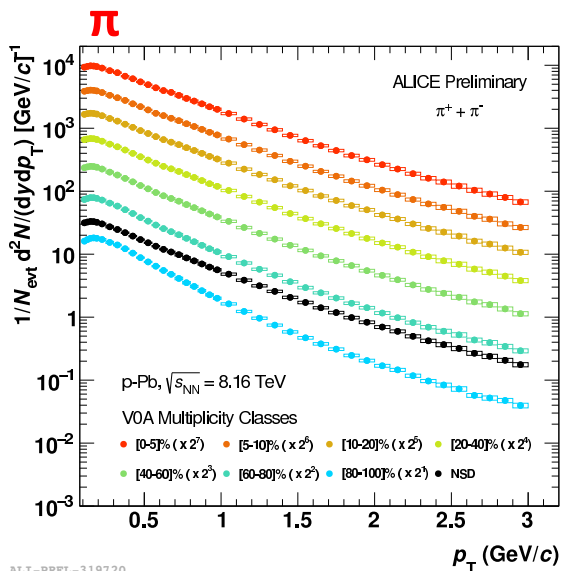
Results: p_T spectra of light-flavor hadrons in p-Pb collisions at $\sqrt{s} = 8.16$ TeV

- qualitatively similar behavior as in Pb-Pb driven by radial flow
- hardening of p_T spectra at higher multiplicity
- flattening at low p_T : stronger for heavier particles

pp at 13 TeV: ALICE Coll. CERN-EP-2020-024, CERN-EP-2019-168

pp at 7 TeV: ALICE Coll. Phys. Rev. C 99, 024906

p-Pb at 5.02 TeV: ALICE Coll. Phys. Lett. B 728 (2014) 25-38

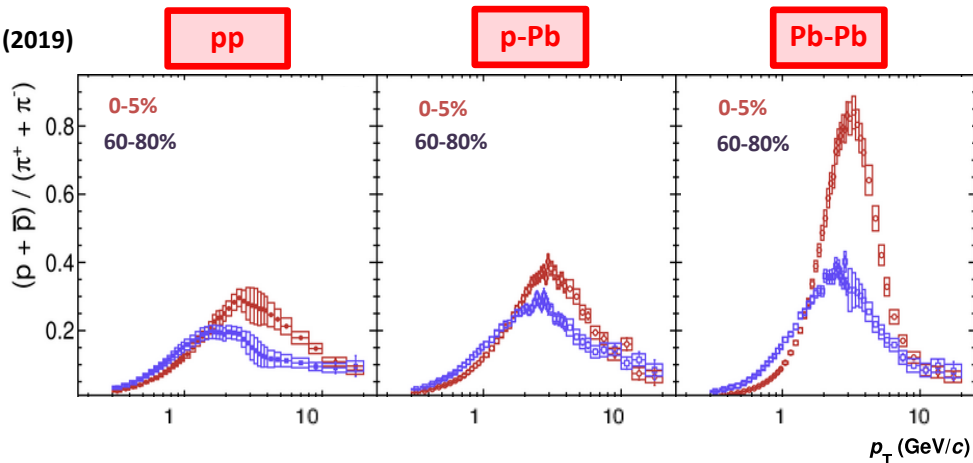


highest multiplicity

lowest multiplicity

Results: system size dependence of light-flavor particle yield ratios

ALICE Coll. Phys. Rev. C99, 024906 (2019)

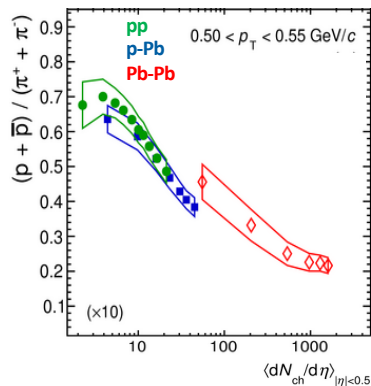
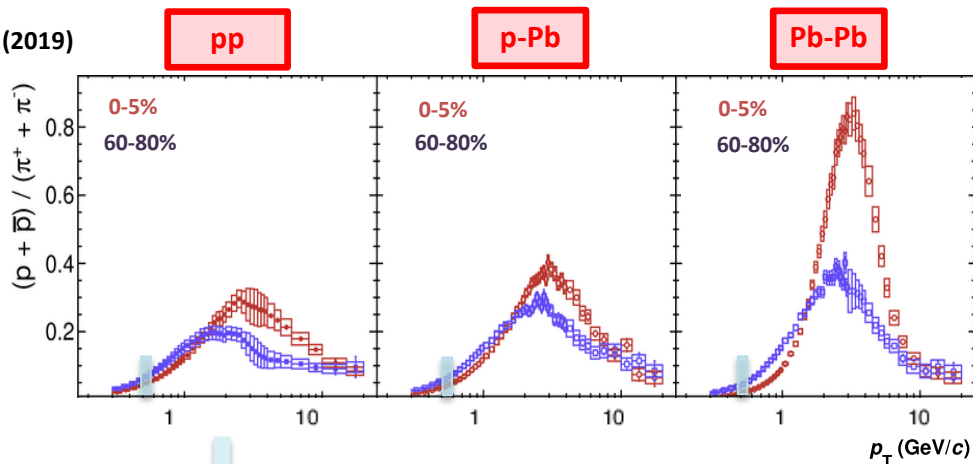


- enhancement at intermediate p_T
- consistent with radial flow, but also with quark coalescence at hadronization
- striking similarity in the trend across all systems

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ALICE Coll. Phys. Rev. C99, 024906 (2019)

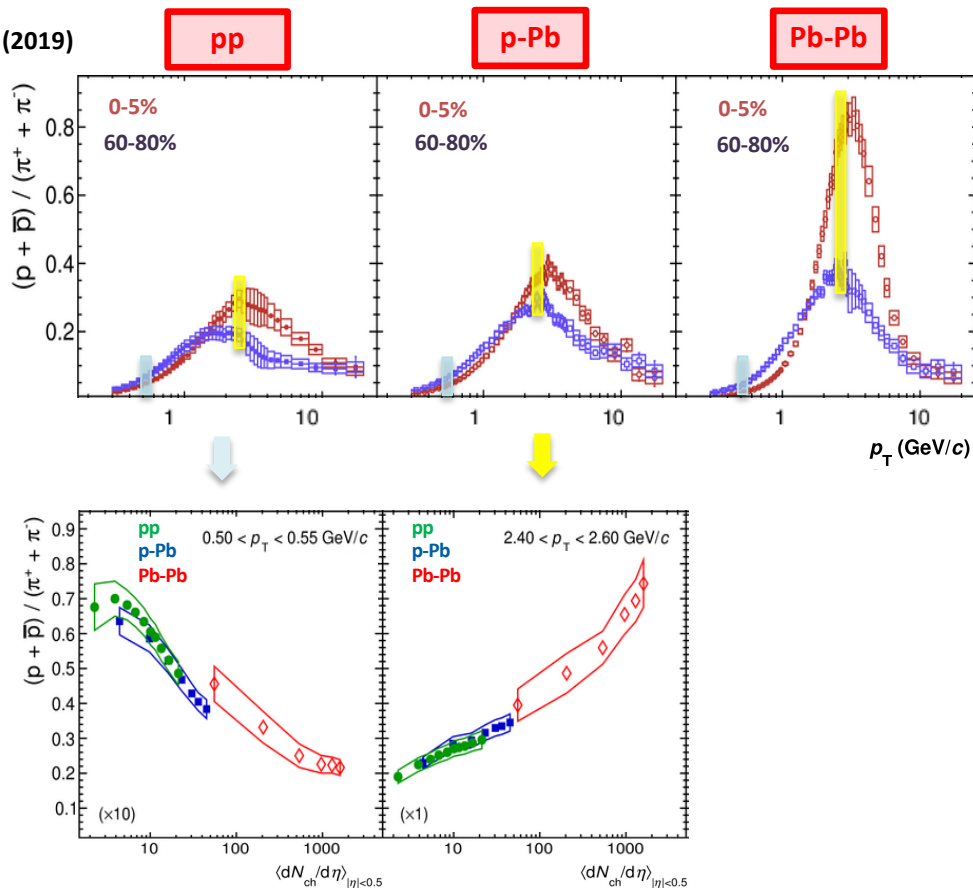
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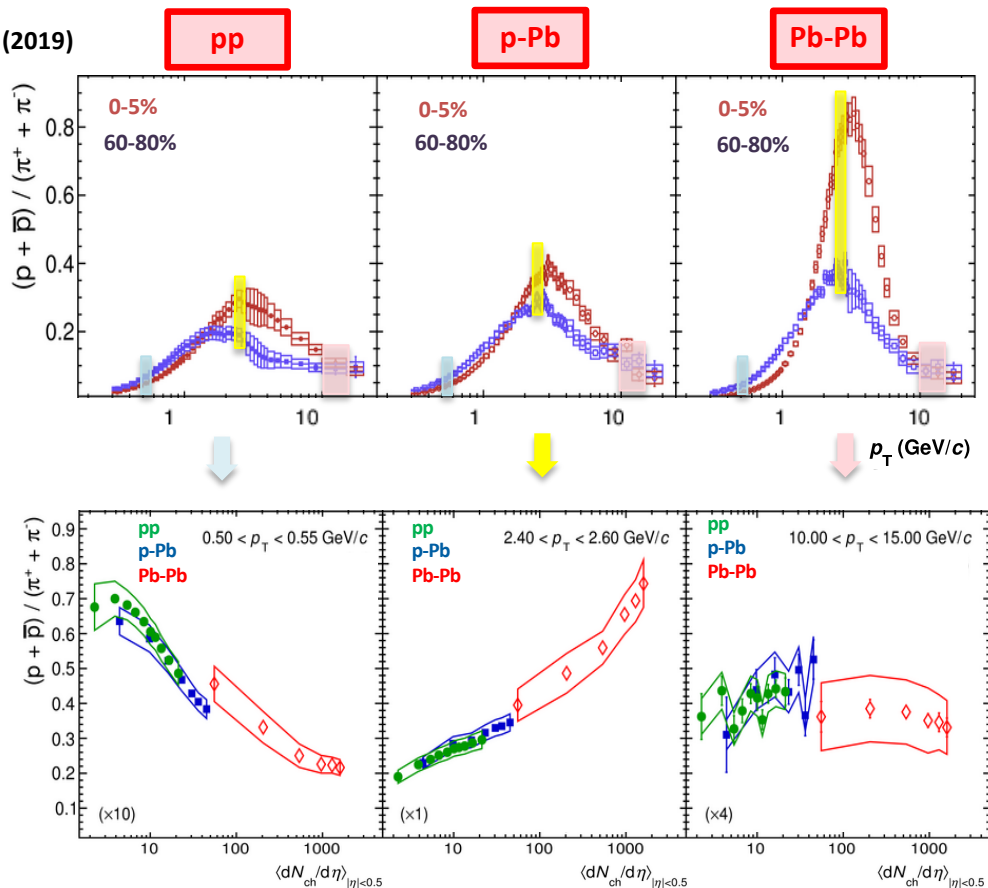
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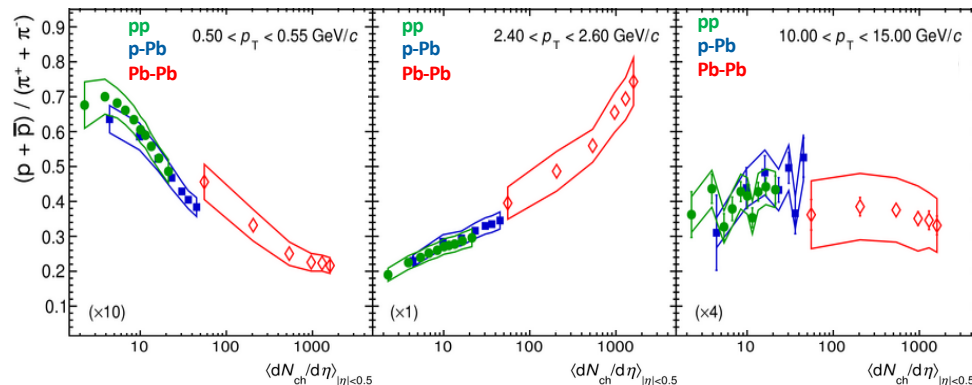
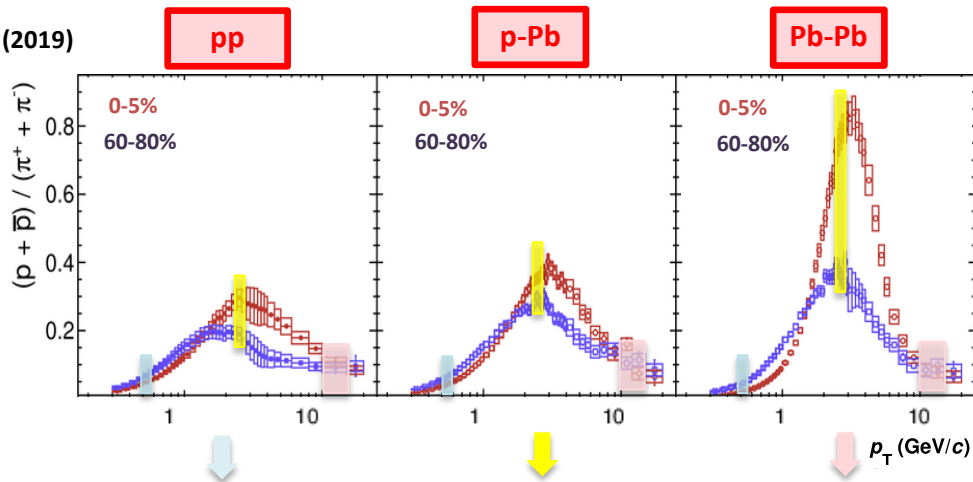
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ALICE Coll. Phys. Rev. C99, 024906 (2019)



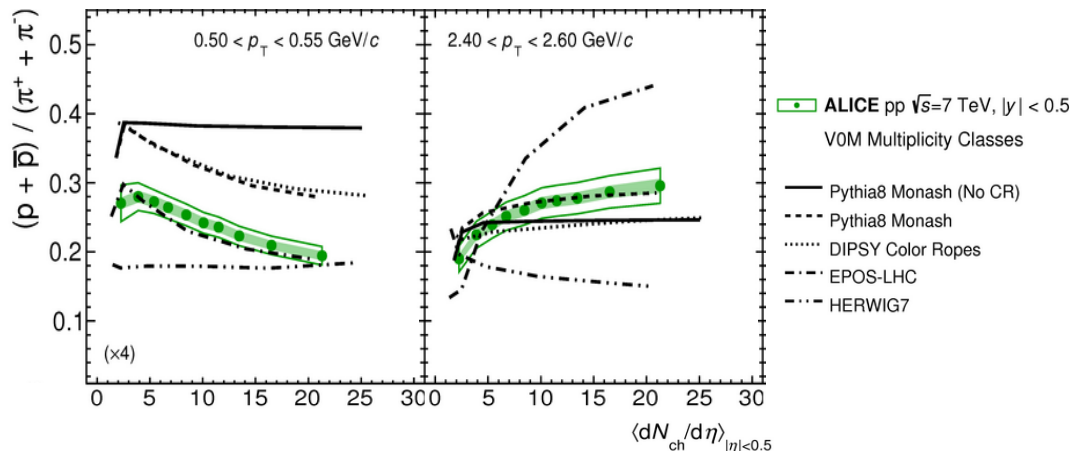
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- consistent with radial flow, but also with quark coalescence at hadronization
- striking similarity in the trend across all systems
- smooth multiplicity evolution from pp to Pb-Pb \rightarrow common mechanism driving multiplicity dependence
- further support for collective effects in small systems

Results: system size dependence of light-flavor particle yield ratios

ALICE Coll. Phys. Rev. C99, 024906 (2019)

pp

- PYTHIA8 is successful in describing the qualitative features only if CR is enabled
- HERWIG7 is not able to reproduce the trend
- DIPSY is able to get the qualitative trend but not the absolute values
- EPOS-LHC is successful in reproducing data at low p_T , but overestimates the intermediate p_T



PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

DIPSY: JHEP 0701:012,2007, JHEP 08 (2011) 103

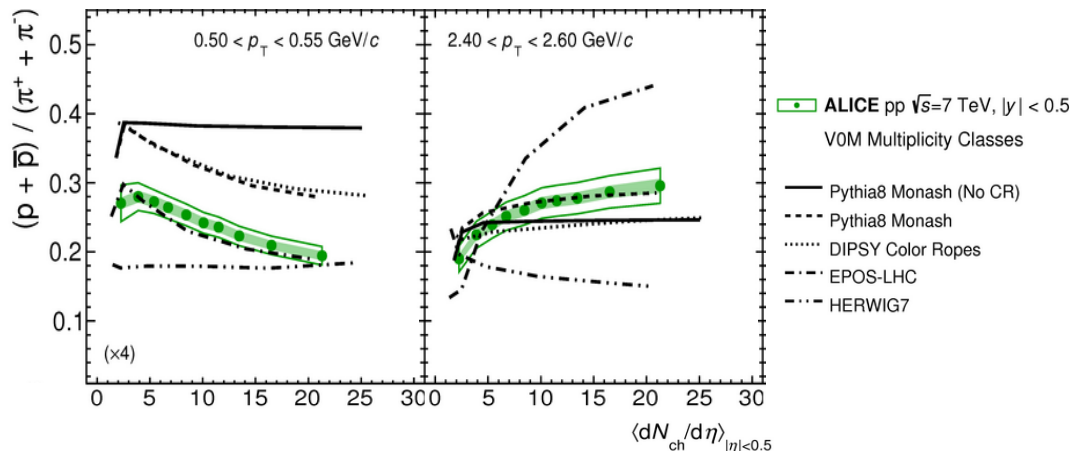
EPOS-LHC: Phys. Rev. C 92, 034906 (2015)

HERWIG7: Eur.Phys.J.C 76 (2016) 4, 196

Results: system size dependence of light-flavor particle yield ratios

ALICE Coll. Phys. Rev. C99, 024906 (2019)

pp



PYTHIA8 Monash: Eur.Phys.J.C 74 (2014) 8, 3024

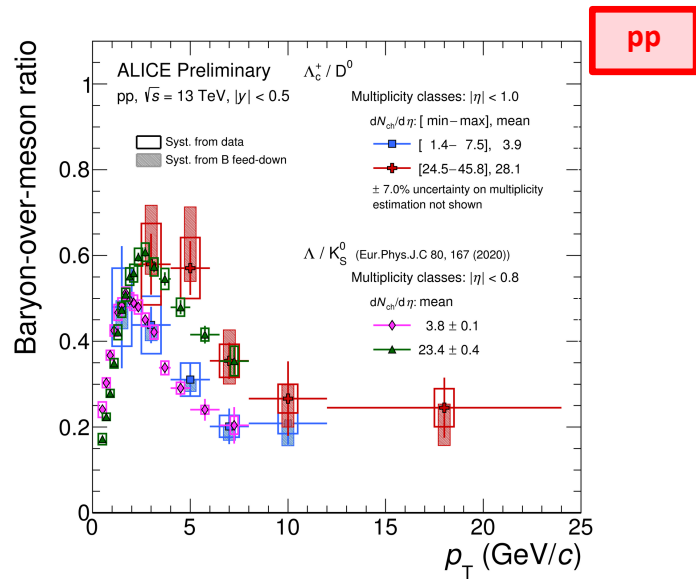
DIPSY: JHEP 0701:012,2007, JHEP 08 (2011) 103

EPOS-LHC: Phys. Rev. C 92, 034906 (2015)

HERWIG7: Eur.Phys.J.C 76 (2016) 4, 196

➔ L. Bianchi: Soft probes (May 27, 14:00)

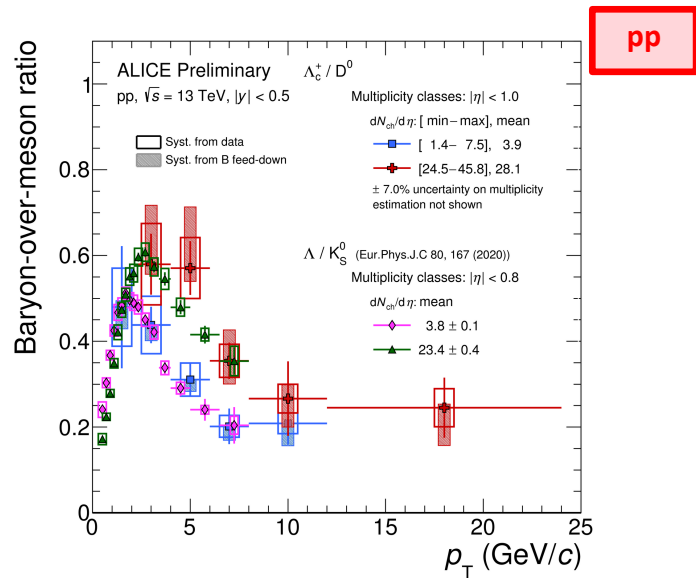
Results: heavy-flavor particle yield ratios



ALI-PREL-348097

- similar trend in LF and HF sectors

Results: heavy-flavor particle yield ratios



ALI-PREL-348097

- similar trend in LF and HF sectors

➔ **G.M. Innocenti: Heavy flavor and quarkonia (May 27, 13:30)**

➔ **V. Zaccaro: Soft QCD (May 26, 18:00)**

➔ **A. Harlanderova: Recent results on hard and rare probes from ALICE (May 25, 15:36)**

- similar behavior attributed to collectivity in heavy-ion collisions is seen in many observables in small systems down to very low multiplicities
- most of the times existing models do not fully reproduce the data in small systems
- understanding the origin of collectivity in small collision systems remains a challenging task

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THANK YOU FOR YOUR ATTENTION!

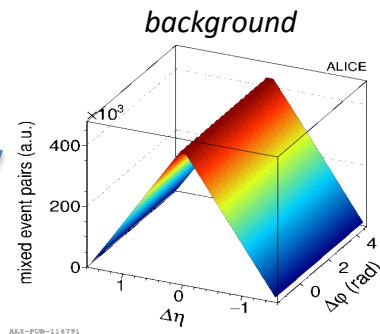
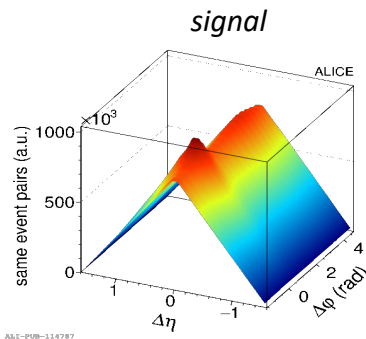
Angular correlations: per-trigger yield extraction

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

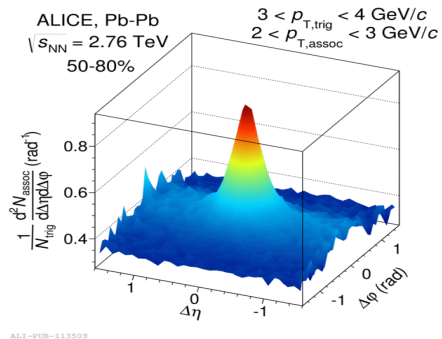
$$S = \frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{assoc, same}}}{d\Delta\eta d\Delta\varphi}$$

$$f = \alpha \frac{d^2 N_{\text{assoc, mixed}}}{d\Delta\eta d\Delta\varphi}$$

- trigger particle: $\mathbf{p}_{\text{T, trig}}$
- associated particle: $\mathbf{p}_{\text{T, ass}}$
- the associated per-trigger yield as a function of $\Delta\varphi, \Delta\eta$
- $\Delta\varphi = \varphi_{\text{trig}} - \varphi_{\text{assoc}}, \Delta\eta = \eta_{\text{trig}} - \eta_{\text{assoc}}$

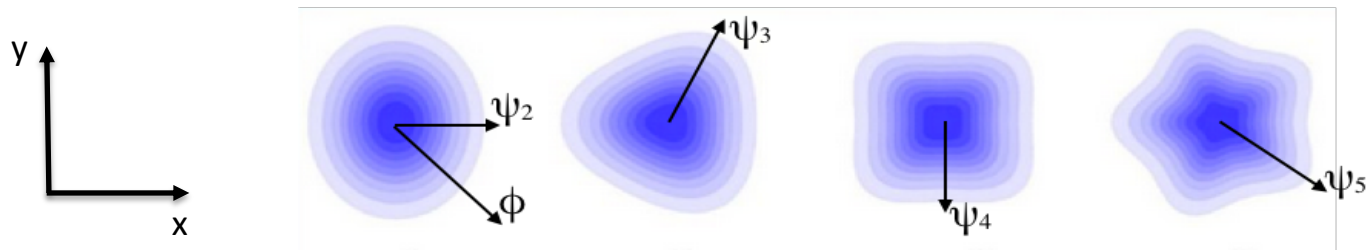


=



- a key feature related to collectivity in A-A: the “near-side ridge” - an enhanced structure on the near side

Anisotropic flow coefficients



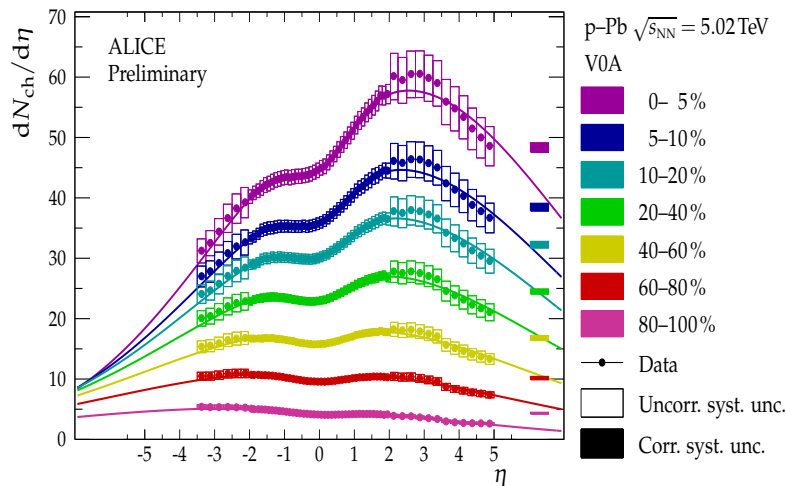
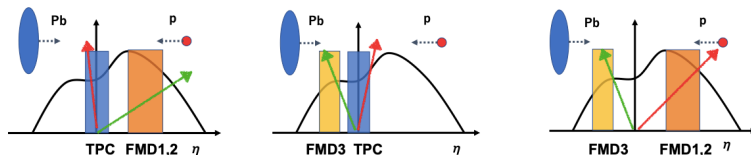
$$\frac{dN}{d\varphi} = \frac{1}{2\pi} (1 + 2v_1 \cos(\varphi - \psi_1) + 2v_2 \cos(2(\varphi - \psi_2)) + 2v_3 \cos(3(\varphi - \psi_3)) + 2v_4 \cos(4(\varphi - \psi_4)) + \dots)$$

$$v_n = \langle \cos[n(\varphi - \psi_n)] \rangle$$

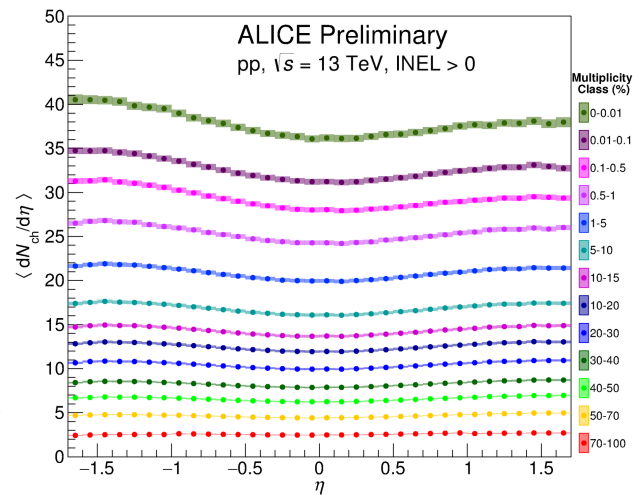


azimuthal correlations

Multiplicity dependence of pseudorapidity density distributions in p-Pb and pp collisions



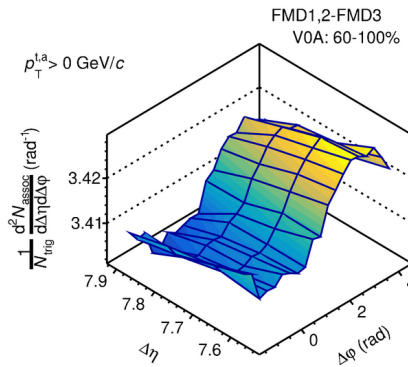
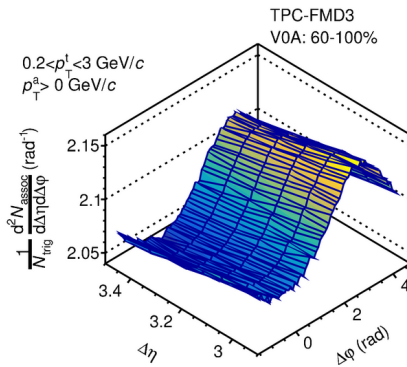
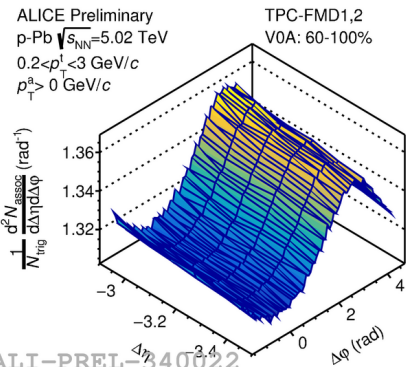
ALI-PREL-118244



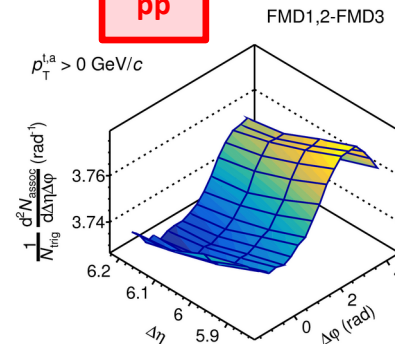
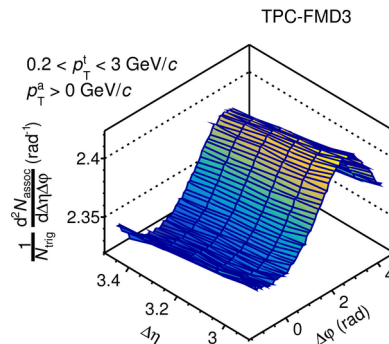
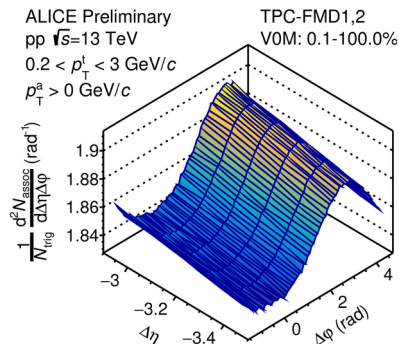
ALI-PREL-141031

Long-range angular correlations in peripheral p-Pb and MB pp collisions using FMD

- no significant ridge structure is observed in peripheral events in p-Pb (MB in pp) where non-flow is assumed to be the dominant effect



p-Pb

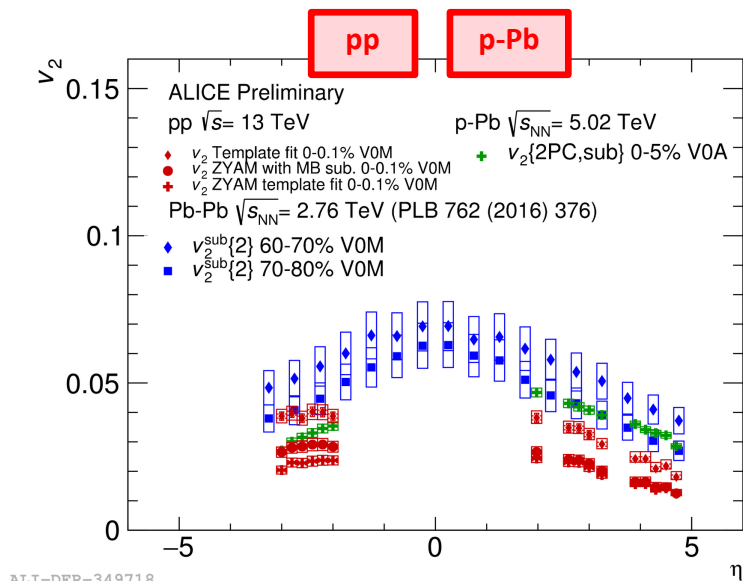


pp

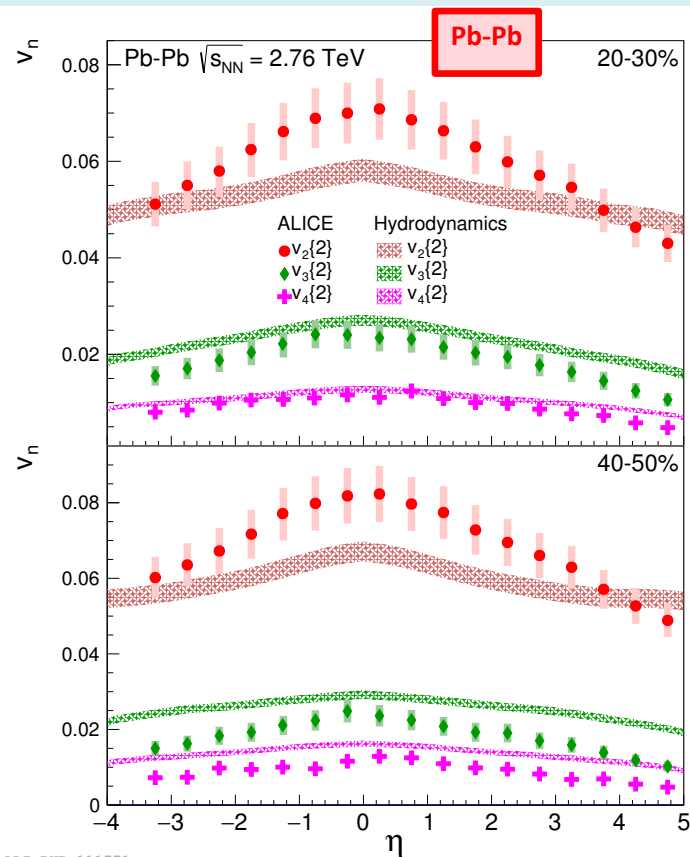
ALI-PREL-345479

$v_2(\eta)$ in Pb-Pb, p-Pb and pp collisions for charged particles using FMD

- values of $v_2(\eta)$ are comparable between p-Pb and Pb-Pb at the same multiplicity at forward η



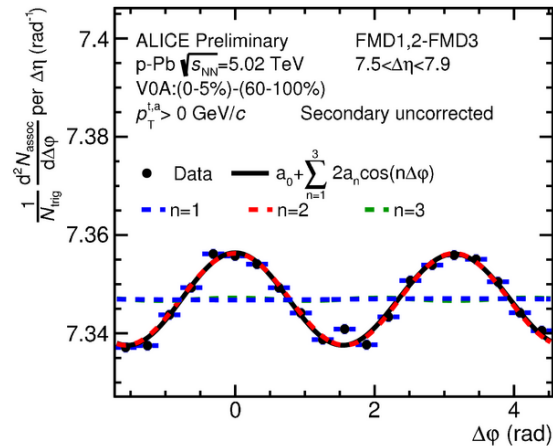
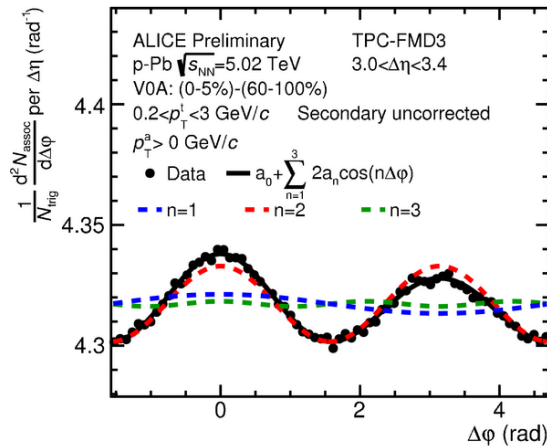
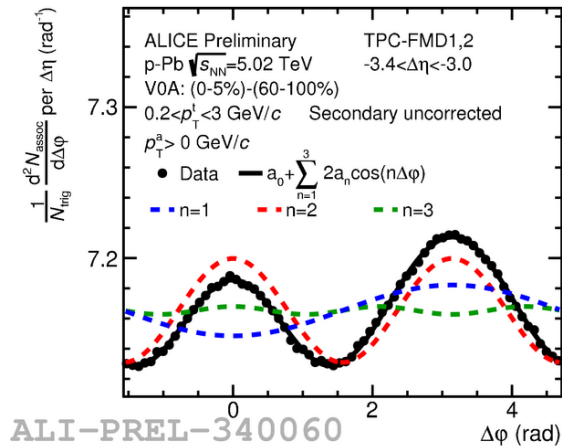
ALI-DER-349718



ALI-PUB-111771

ALICE Coll. Phys.Lett.B 762 (2016) 376-388

$v_2(\eta)$ extraction in p-Pb collisions for charged particles using FMD



$$\frac{1}{N_{trig}} \frac{dN_{asso}}{d\Delta\phi} = a_0 + 2\sum a_i \cos(n\Delta\phi)$$

$$V_2\{2PC, sub\} = \frac{a_2}{a_0 + b}, \quad b = \text{baseline of 2PC in the peripheral events}$$

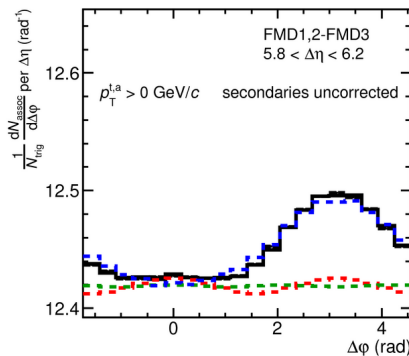
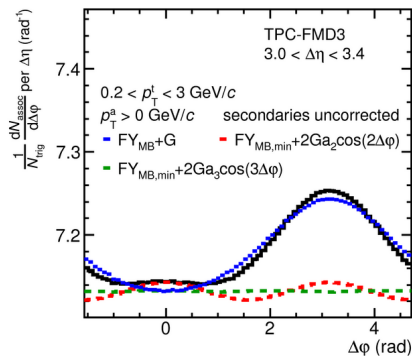
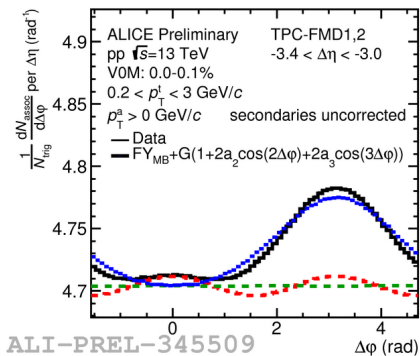
$$V_2\{2PC, sub\} = v_2^{trig} v_2^{assoc}$$

$$v_{2,\eta_A}\{2PC, sub\} = \sqrt{\frac{V_{2,\Delta\eta=\eta_A-\eta_B}\{2PC, sub\} V_{2,\Delta\eta=\eta_A-\eta_C}\{2PC, sub\}}{V_{2,\Delta\eta=\eta_B-\eta_C}\{2PC, sub\}}}$$

$$v_{n,FMD1,2} = \sqrt{\frac{V_n(\eta_{TPC}, \eta_{FMD1,2}) V_n(\eta_{FMD1,2}, \eta_{FMD3})}{V_n(\eta_{TPC}, \eta_{FMD3})}}$$

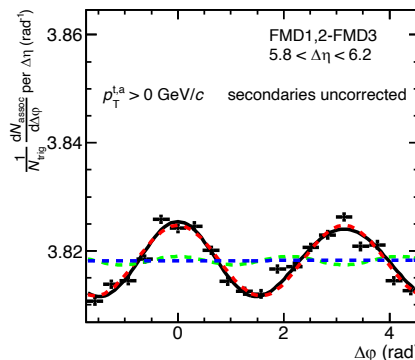
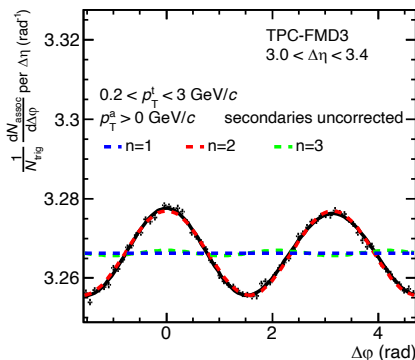
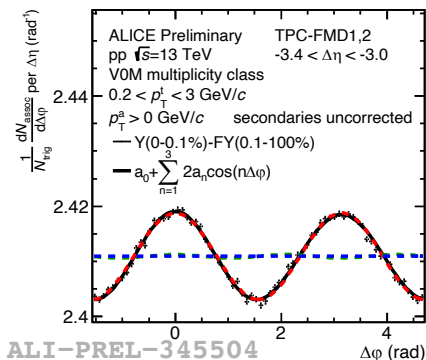
$v_2(\eta)$ extraction in pp collisions for charged particles using FMD

- Template fit method (ATLAS)



$$Y^{\text{templ}}(\Delta\phi) = Y^{\text{ridge}}(\Delta\phi) + F Y^{\text{periph}}(\Delta\phi)$$

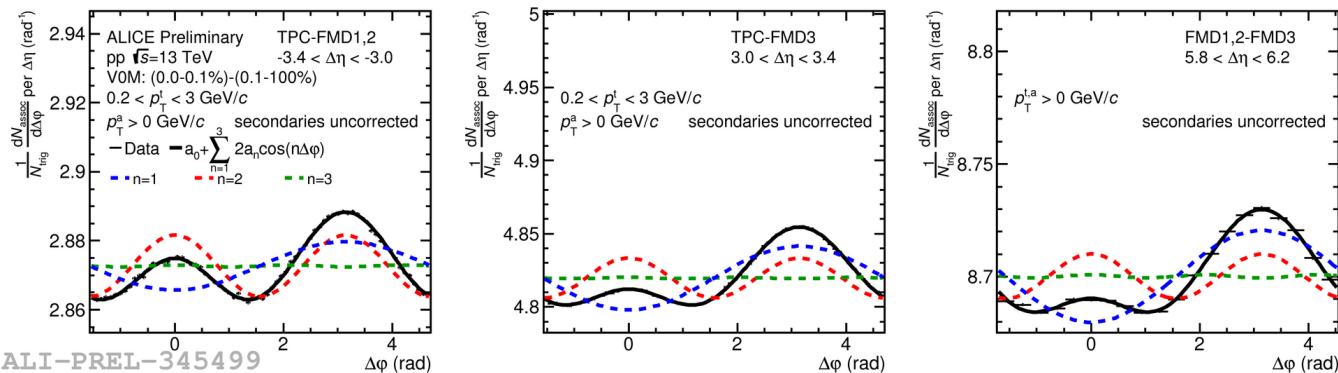
$$Y^{\text{ridge}}(\Delta\phi) = G \left(1 + \sum_{n=2}^{\infty} 2v_{n,n} \cos(n\Delta\phi) \right)$$



- residual non-flow is smaller compared to ZYAM with MB subtraction

$v_2(\eta)$ extraction in pp collisions for charged particles using FMD

- ZYAM with low multiplicity (MB) subtraction

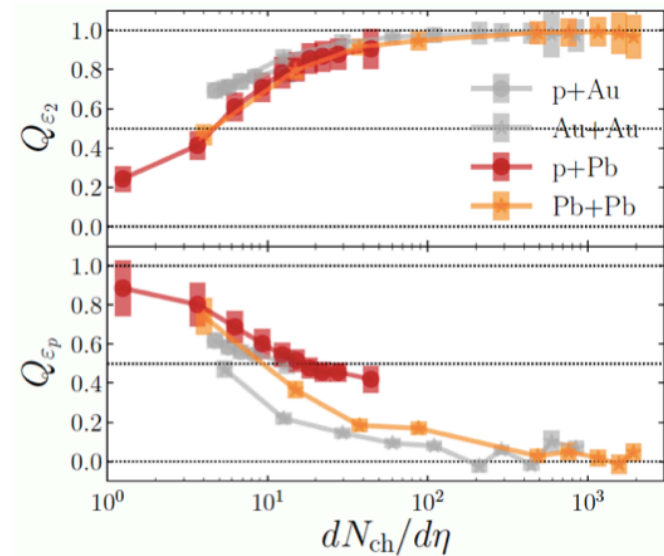
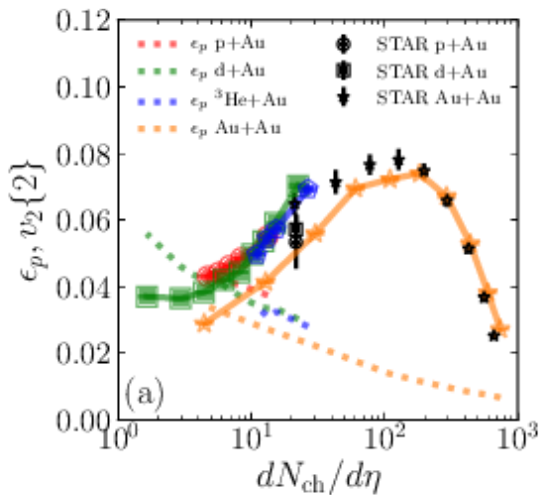


- Alternative template fit (template ZYAM)

$$Y^{\text{periph}}(\Delta\phi) = Y^{\text{periph}}(\Delta\phi) - Y^{\text{periph}}(0)$$

Contribution of initial state effects in models

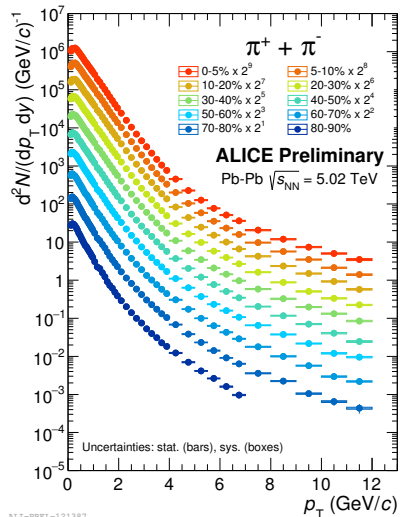
Phys.Lett.B 803 (2020) 135322



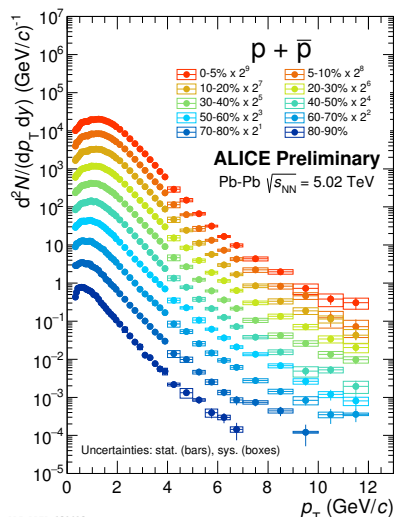
- Initial momentum anisotropy (gluon momentum flow) dominant in small systems
- Initial spatial anisotropy (sub-nucleon fluctuations) dominant in large systems

p_T spectra and mean p_T in Pb-Pb, p-Pb and pp collisions

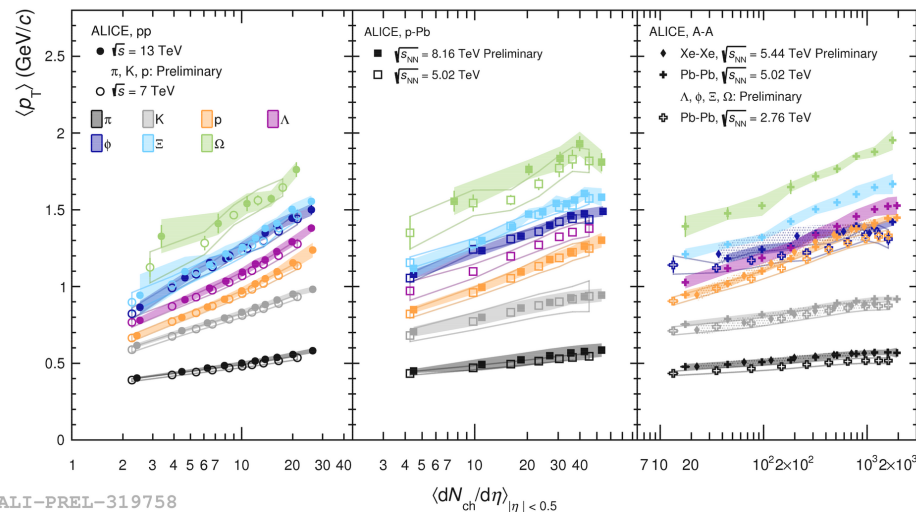
multiplicity



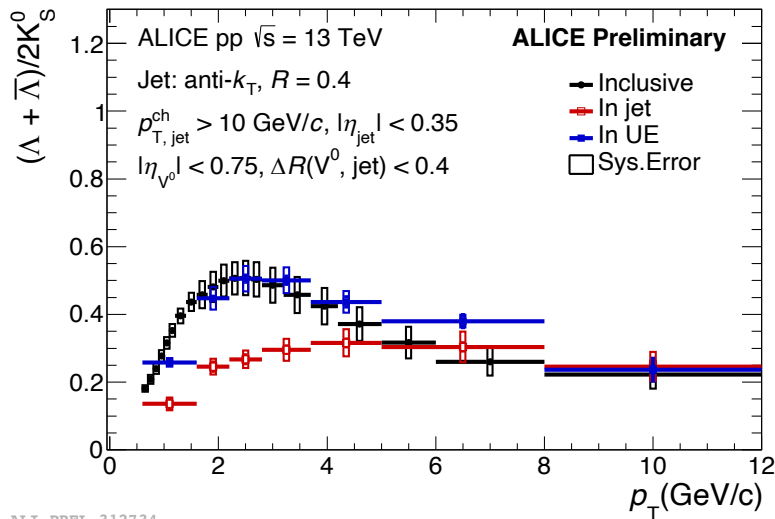
ALI-PREL-121387



ALI-PREL-121419

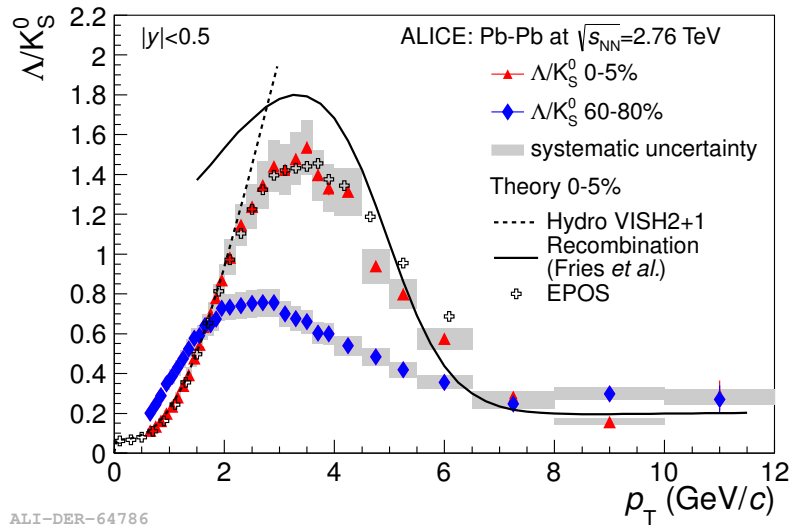


Light-flavor particle yield ratios



ALI-PREL-312734

ALICE Collaboration, Phys. Rev. Lett. 111 (2013) 222301



ALI-DER-64786

- Feature of the bulk (not arising from jets)
- EPOS reproduces the data reasonably well
- Recombination model describes the data at intermediate p_T but overestimates it at low p_T