Charge dependent two-particle correlation with one identified hadron relative to the reaction plane

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for the ALICE Collaboration

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GSI

EMMI

H-QM Helmholtz Research School
Quark Matter Studies

ALICE

Symmetry violation in QCD

- Local Parity violation in strong interactions:

  allowed in theory, but not observed

  T. D. Lee, Phys. Rev. D8, 1226 (1973).
  T. D. Lee and G. C. Wick, Phys. Rev. D9, 2291 (1974).
  P. D. Morley and I. A. Schmidt, Z. Phys. C26, 627 (1985)

- A possible signal in heavy-ion collisions:

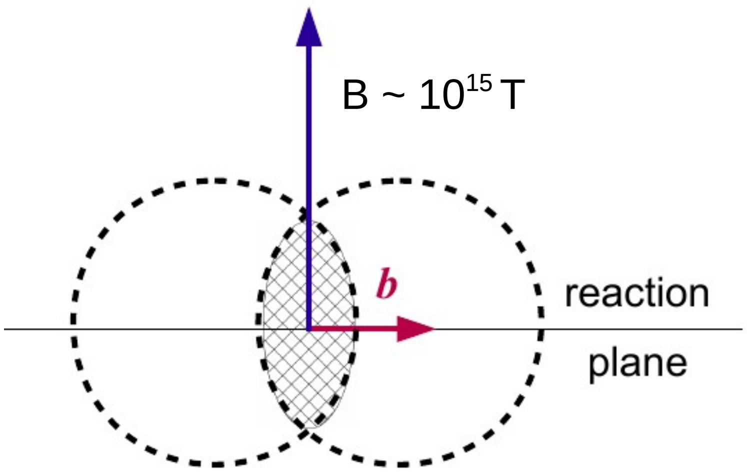
  The chiral magnetic effect (CME):

  Magnetic field and parity odd effects lead to charge separation

  D. E. Kharzeev, Phys. Rev. B633, 260-264 (2006).

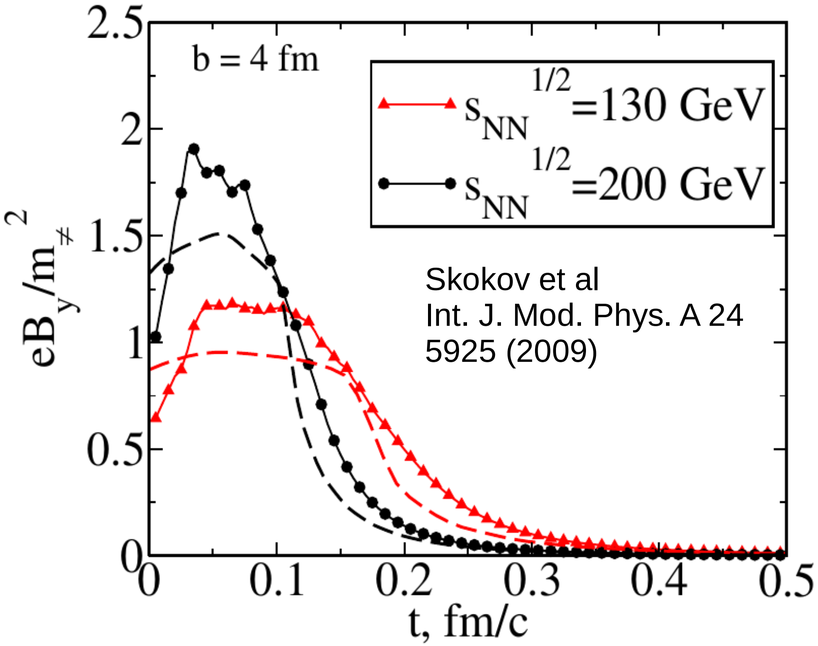
Magnetic field in heavy-ion collisions

- Generated by moving ions
- Field lines perpendicular to reaction plane (RP)



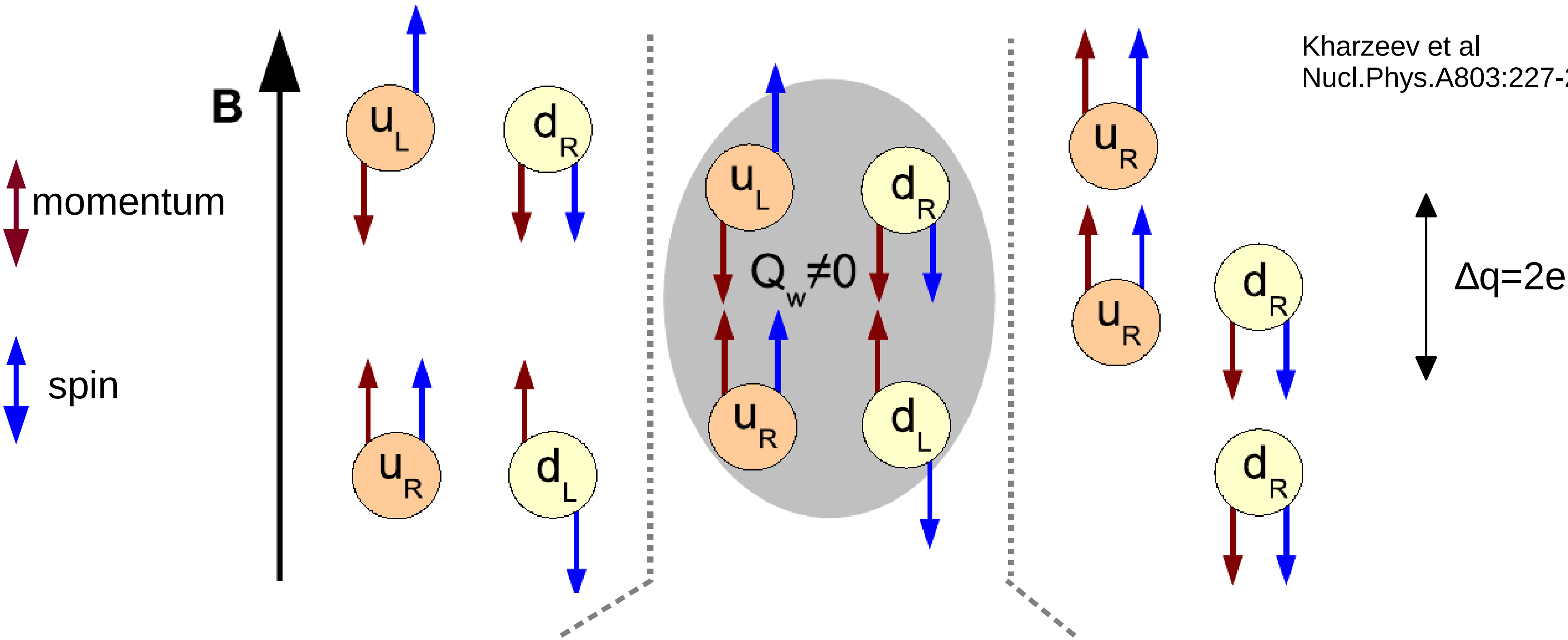
I. Selyuzhenkov
WPCF 2011

Time evolution of the magnetic field



Skokov et al
Int. J. Mod. Phys. A 24
5925 (2009)

Local parity violation and charge separation



Kharzeev et al
Nucl.Phys.A803:227-253,2008

Spin aignment (anti) parallel to direction of B

Interaction of quarks with Q_w=-1 region reverses momentum of left-handed up/down quark

Momentum change leads to charge separation

Charge dependent correlations : experimental probe of CME

CME gives rise to P-odd sine terms in the Fourier decomposition of azimuthal spectrum wrt reaction plane (Ψ_{RP})

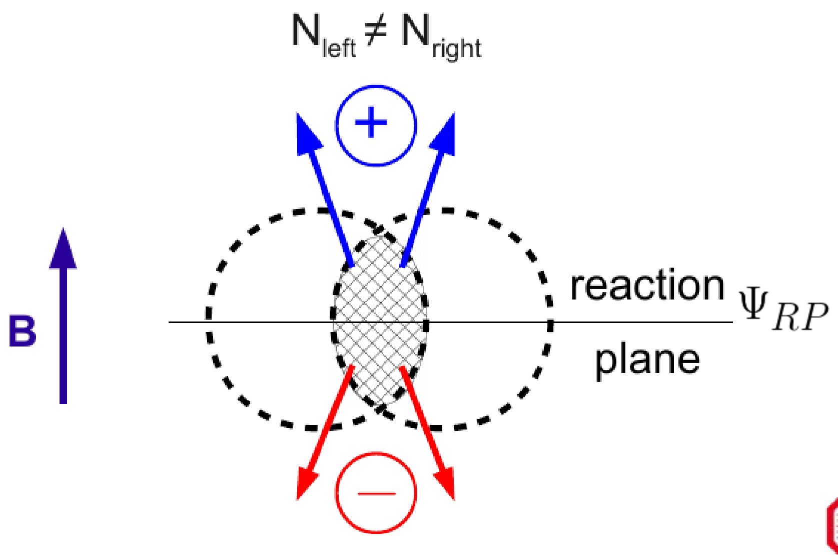
$$\frac{dN}{d\varphi_\alpha} \sim 1 + 2\sum_n [v_{n,\alpha} \cos n\Delta\varphi_\alpha + a_{n,\alpha} \sin n\Delta\varphi_\alpha]$$

$$\Delta\varphi_\alpha = \varphi_\alpha - \Psi_{RP} \qquad \alpha = +/-$$

Main contribution by n=1

Parity odd term is zero on average

$$\langle a_\alpha \rangle = \langle \sin \Delta\varphi_\alpha \rangle = 0$$



Charge dependent correlations : experimental probe of CME

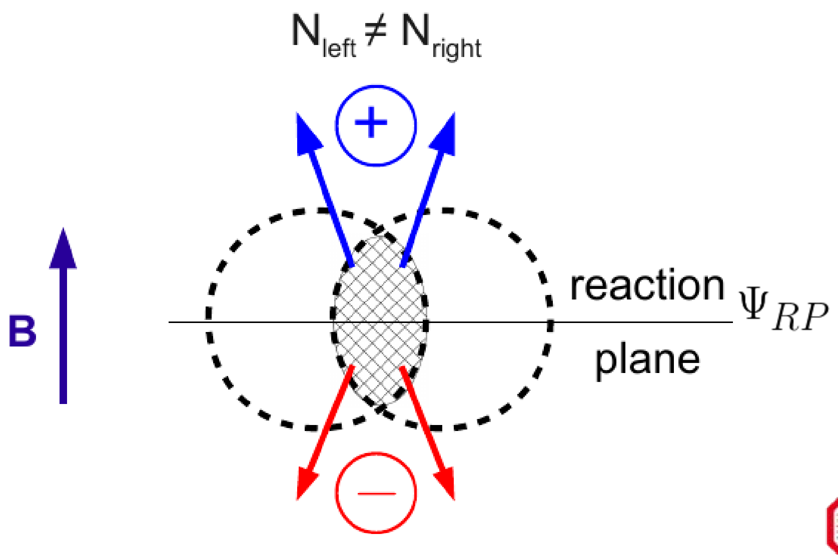
Measure two particle correlations wrt
reaction plane.

$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle = \langle \cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta \rangle - \langle \sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta \rangle$$
$$= [\langle v_{1,\alpha} v_{1,\beta} \rangle + Bg^{(in)}] - [\langle a_\alpha a_\beta \rangle + Bg^{(out)}]$$

Voloshin
Phys.Rev. C70 (2004)

Backgrounds uncorrelated with reaction plane are canceled.

Remaining background:
reaction plane dependent correlations not from CME



Measurements at RHIC and LHC with charged hadrons

Centrality and beam energy dependence

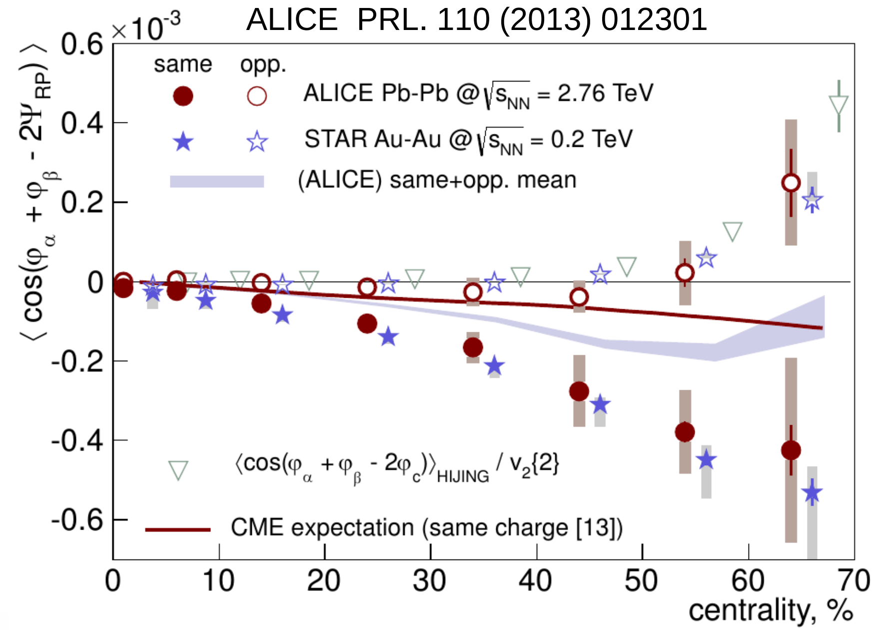
$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle \propto -\langle a_\alpha a_\beta \rangle$$

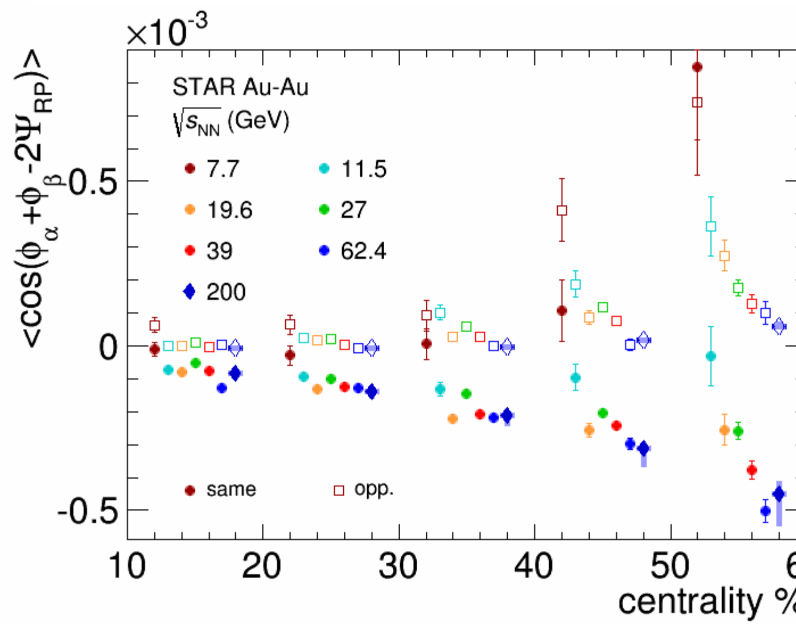
Expected for CME:

- Same sign < 0
- Opposite sign = (-1)*same sign

Data:

- Same sign < 0
- Opposite sign ~ 0
  signal possibly inhibited by medium
- Signal grows from central to peripheral
- Significant difference between same and opposite sign correlations at RHIC and LHC down sqrt(s_{NN}) ~ 10 GeV



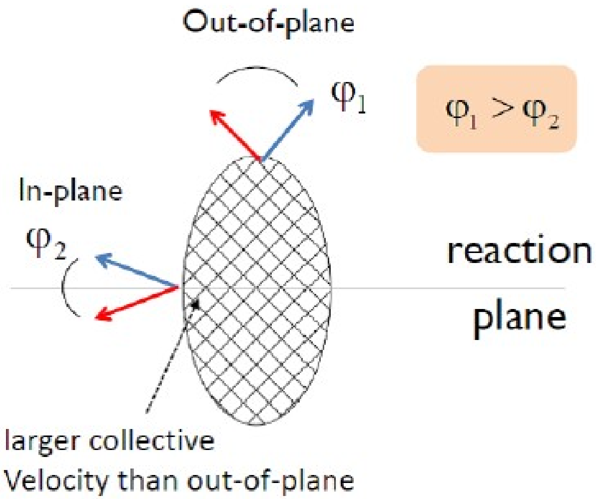


Derived from:
STAR
PRL. 113 (2014) 052302
PRL. 103 (2009) 2A51601

Main sources of background correlations

$$\langle\cos(\varphi_\alpha+\varphi_\beta-2\Psi_{RP})\rangle = \langle\cos\Delta\varphi_\alpha\cos\Delta\varphi_\beta\rangle-\langle\sin\Delta\varphi_\alpha\sin\Delta\varphi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle+Bg^{(in)}]-[\langle a_\alpha a_\beta\rangle + Bg^{(out)}]$$

- Local charge conservation (LCC)
  - Local pair production modulated by anisotropic flow



Yasuto Hori
CERN-THESIS-2013-021

- Flow fluctuations
  - Dipole flow (rapidity even directed flow, v_1)

Teaney and Yan PR C83:064904,2011

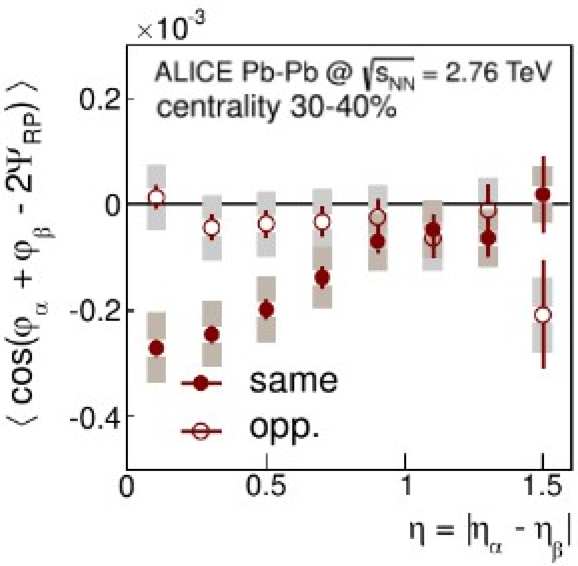
More insight from:

- Differential measurement vs.
  pair pseudo-rapidity and transverse momentum
- Realistic modeling of background correlations (and CME signal)

Background studies

Differential:

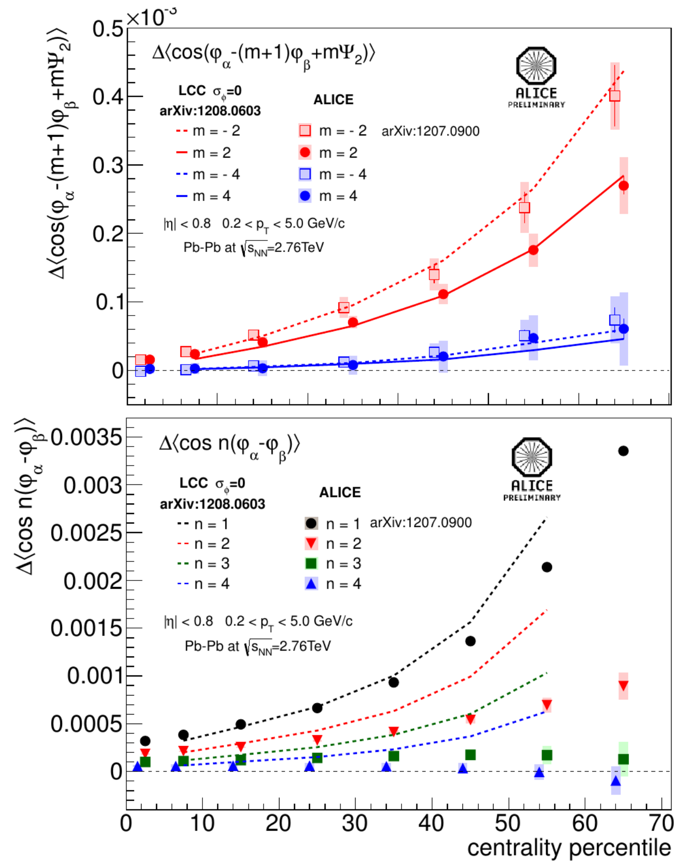
$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle \quad \text{vs } \Delta\eta$$



ALICE
PRL 110 (2013) 012301

Signal width similar to expected hadronic width of $\Delta\eta \sim 1$

Model comparison:



ALICE
Nucl.Phys. A904-905 (2013) 475c-478c

Local charge conservation (LCC) may have a significant contribution to the charge dependent part of the correlation.
LCC can reproduce only a subset of measurement

Correlations with identified hadrons

- Correlations with different species and charges provide a way to further constrain background contributions from LCC and flow

$$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle, \qquad \alpha, \beta = h^\pm, \pi^\pm, K^\pm, p(\bar{p}), \ldots$$

- New result: charge dependent two-particle correlation with one identified hadron (pion, kaon,or proton) relative to the reaction plane as a function of transverse momentum of the identified particle

$$\boxed{\langle \cos(\varphi_\alpha(p_\mathrm{T}) + \varphi_\beta - 2\Psi_2) \rangle, \qquad \alpha = h^\pm, \pi^\pm, K^\pm, p(\bar{p}), \quad \beta = h^\pm}$$

ALICE experiment

<u>Data:</u>

$\sqrt{s_{NN}}$= 2.76 GeV/c

2010 Minimum Bias data

12 x 10^6 events

<u>Kinematic cuts:</u>

$|\eta|$<0.8

0.2 < p_T < 5.0 GeV/c

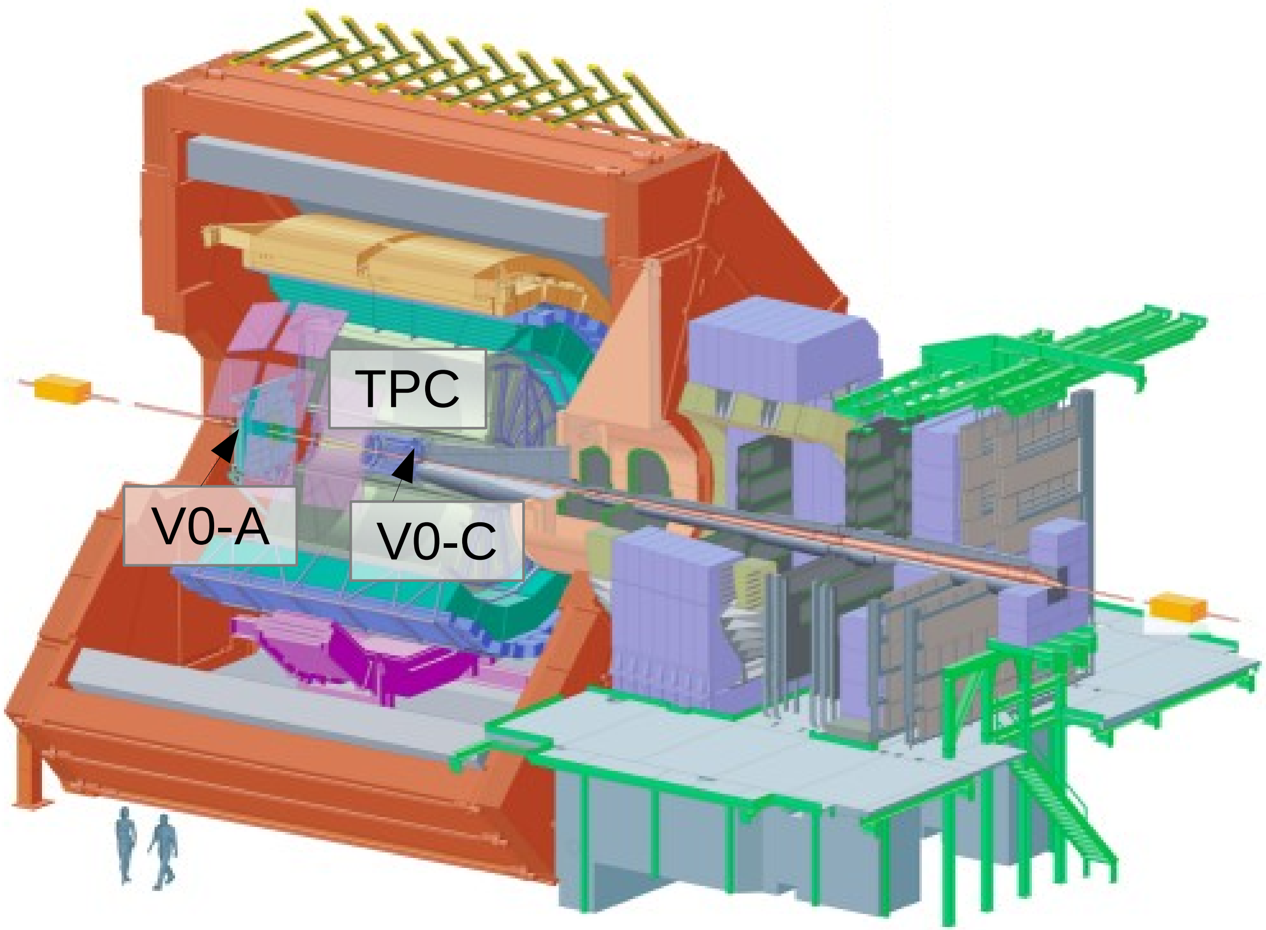
<u>Particle identification:</u>

Time projection chamber (TPC)

Time-of-flight detector (TOF)

<u>Event plane estimation:</u>

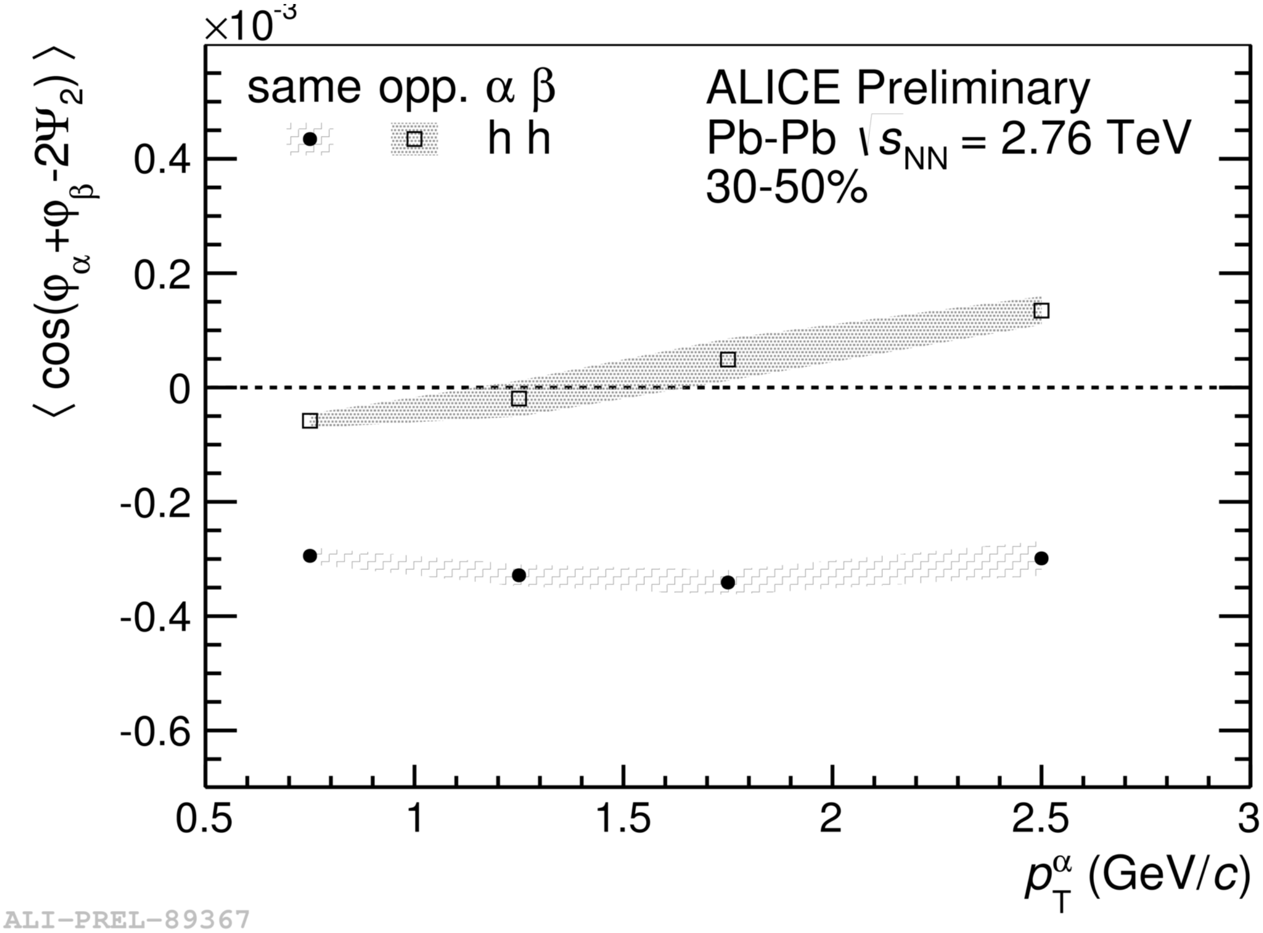
V0-A and V0-C



Results

Two hadron correlation wrt event plane

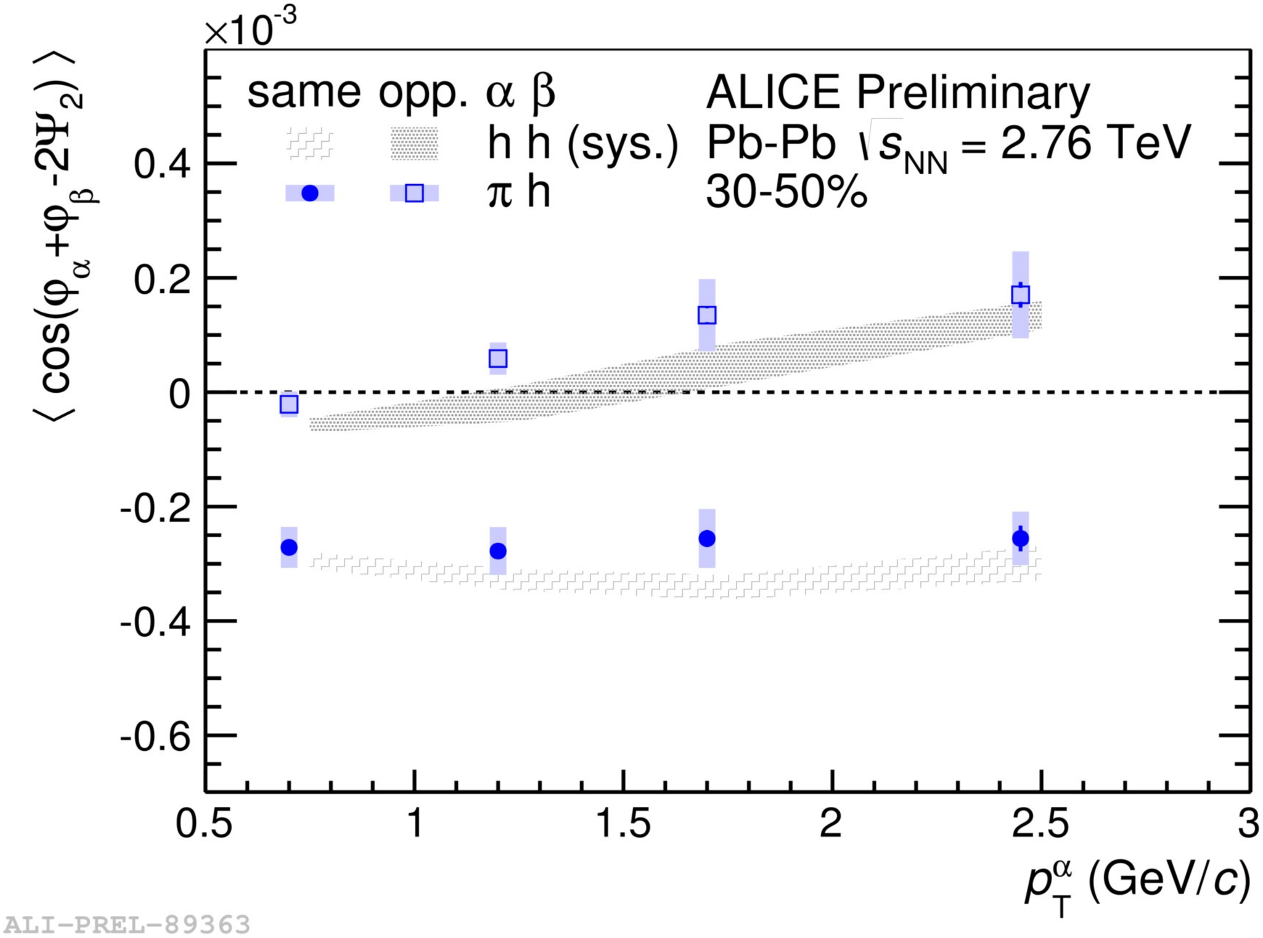
$$\langle \cos(\varphi_\alpha(p_\mathrm{T}) + \varphi_\beta - 2\Psi_2)\rangle, \qquad \alpha, \beta = h^\pm$$



- Opposite sign correlations close to zero with slight upward trend
- Same sign correlation negative and no significant p_T -dependence

Pion-hadron correlation

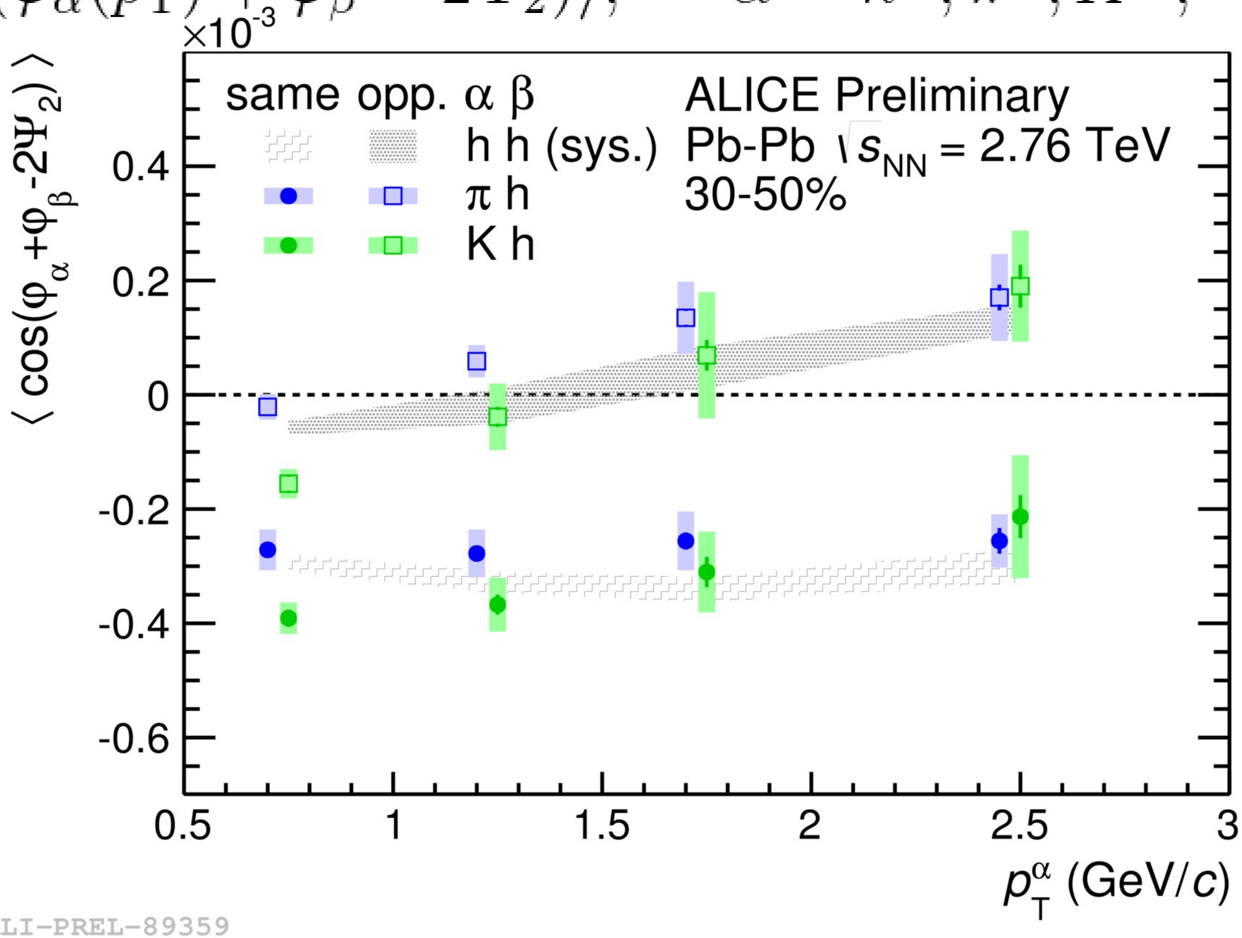
$$\langle \cos(\varphi_\alpha(p_\mathrm{T}) + \varphi_\beta - 2\Psi_2)\rangle, \qquad \alpha = h^\pm, \pi^\pm, \quad \beta = h^\pm$$



- Pion-hadron correlation slightly above the hadron-hadron measurement

Kaon-hadron correlation

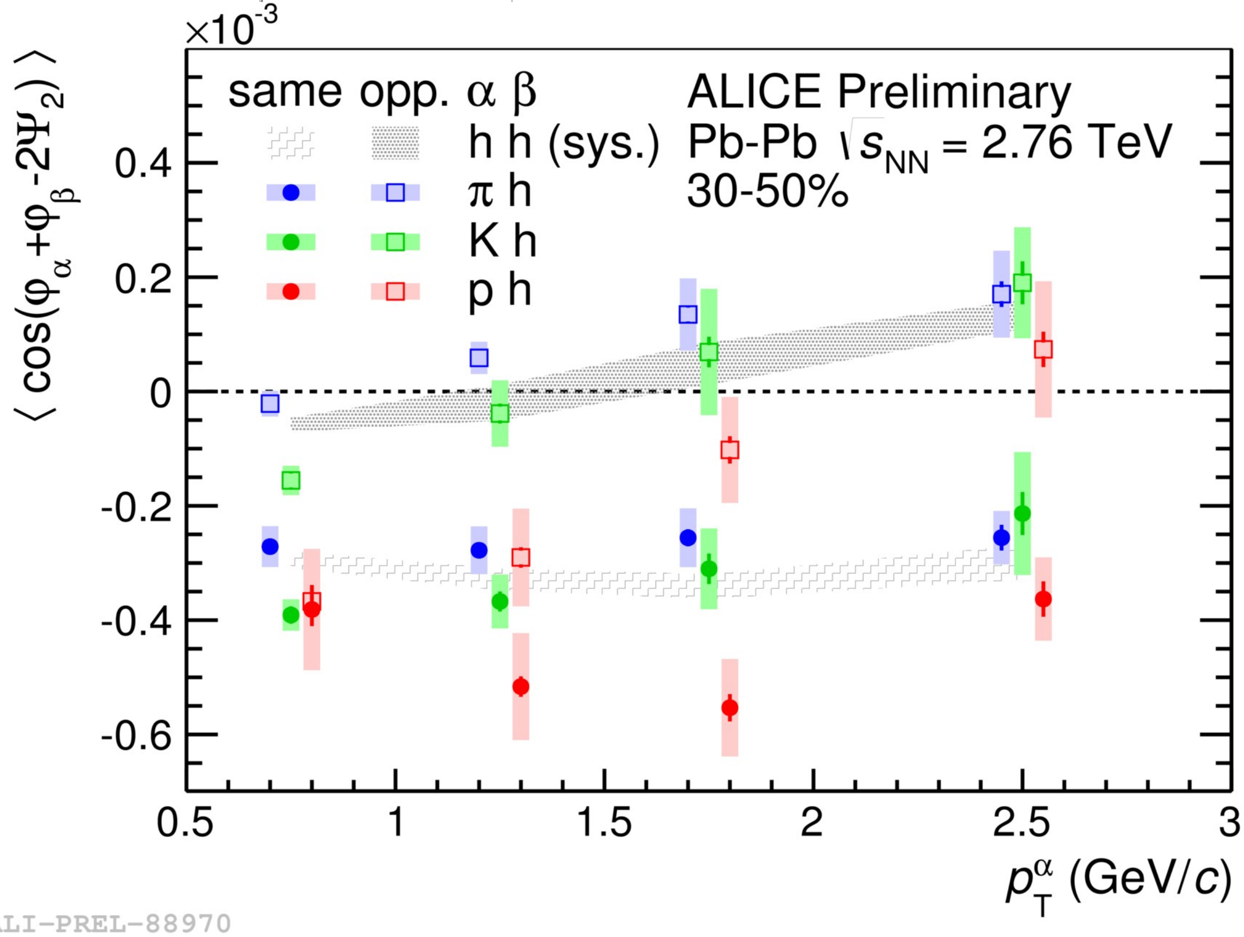
$$\langle \cos(\varphi_\alpha(p_\mathrm{T}) + \varphi_\beta - 2\Psi_2) \rangle, \qquad \alpha = h^\pm, \pi^\pm, K^\pm, \quad \beta = h^\pm$$



- Kaon-hadron correlation significantly stronger than pion-hadron correlation at low p_T. Difference smaller towards higher p_T

Proton-hadron correlation

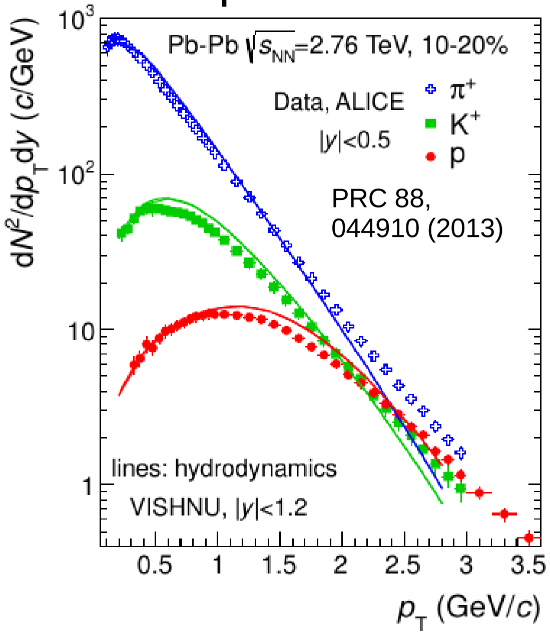
$$\langle \cos(\varphi_\alpha(p_T) + \varphi_\beta - 2\Psi_2) \rangle, \qquad \alpha = h^\pm, \pi^\pm, K^\pm, p(\bar{p}), \quad \beta = h^\pm$$



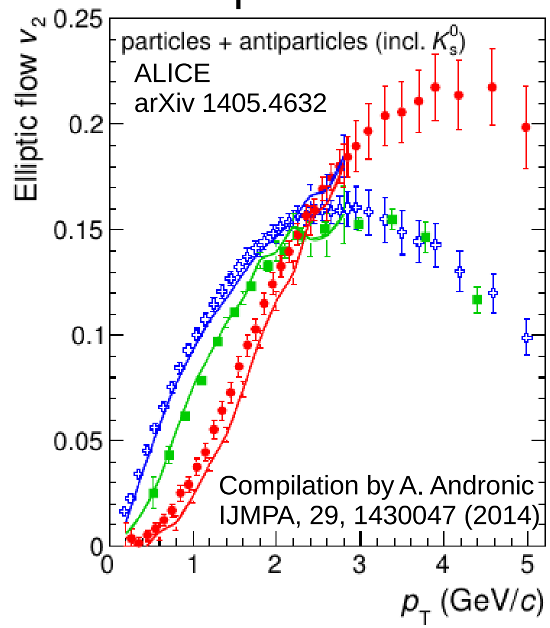
- Proton-hadron correlations are even stronger than kaon-hadron
- Difference in opposite sign correlation for different species decreases towards higher p_T

Modeling background contributions

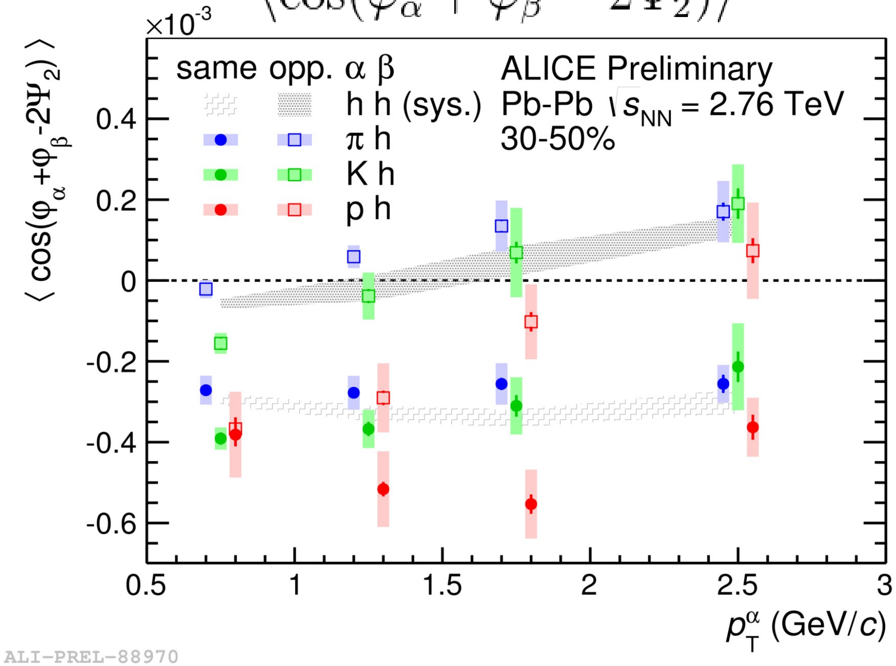
Spectra



Elliptic flow



$\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_2) \rangle$



Quantify contribution from local charge conservation with a model
(e.g. Monte-Carlo Blast Wave model or hydrodynamics)
with parameters tuned to measurements of:

- identified particle spectra
- identified particle elliptic flow

Compare to data

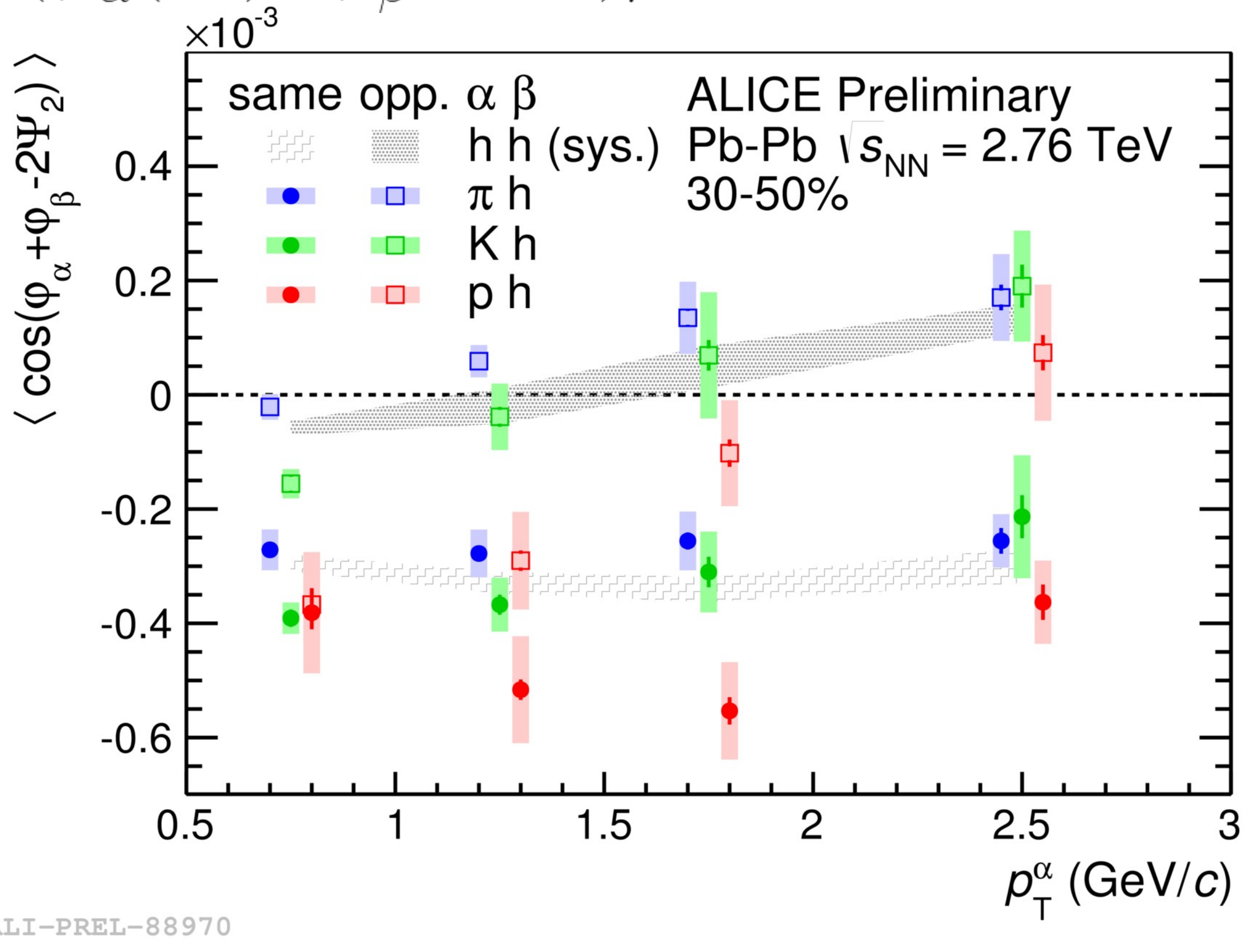
Summary & outlook

- Charge dependent two-particle correlation with one identified hadron (pion, kaon,or proton) relative to the reaction plane has been measured in Pb-Pb collisions as a function of transverse momentum
- Charge correlation shows particle species dependence
- These results may have an important implication for understanding background sources in the CME search such as
  - Local charge conservation
  - Flow fluctuations
- Model comparisons are required to disentangle the physics sources contributing to the measurement

Backup

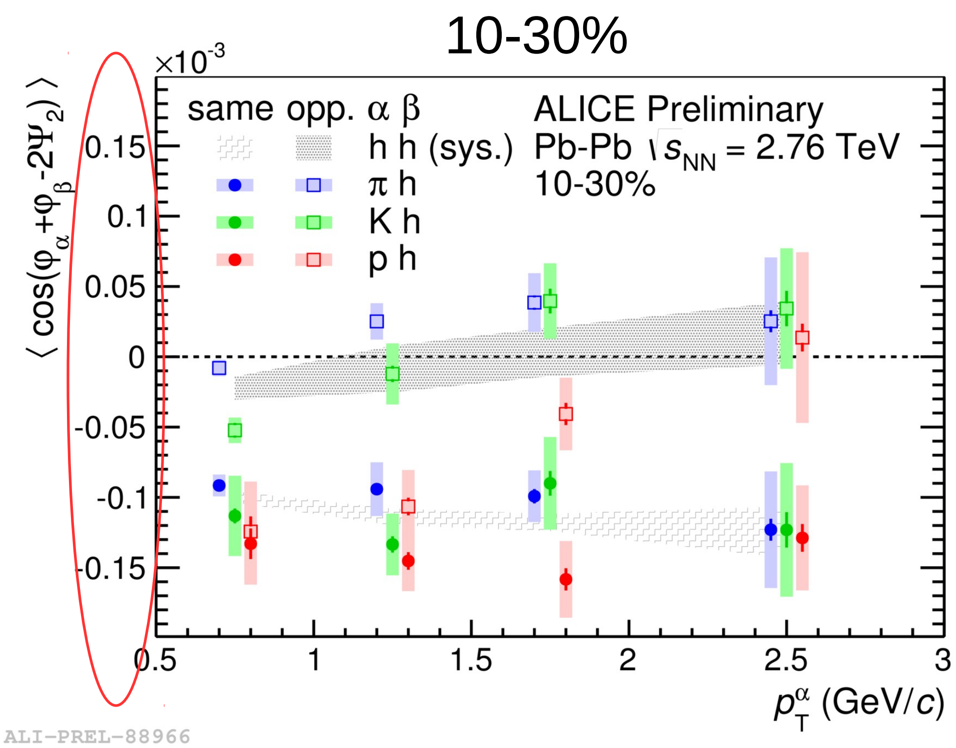
All identified particle correlations

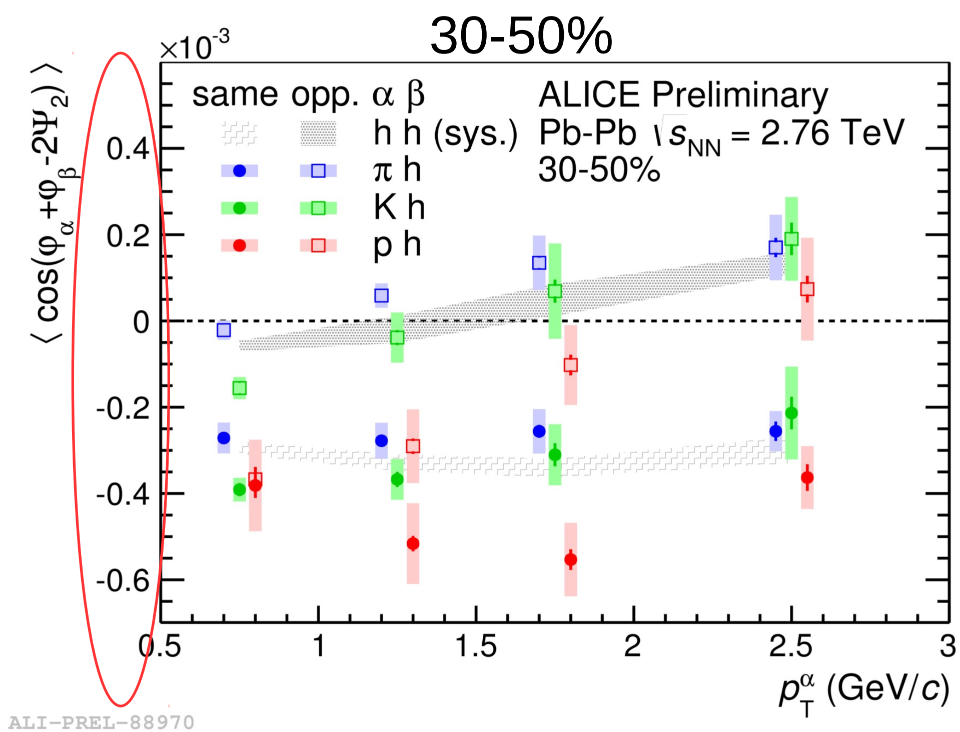
$$\langle\cos(\varphi^s_\alpha(p_\mathrm{T})+\varphi^h_\beta-2\Psi_2)\rangle,\qquad s=h^\pm,\pi^\pm,K^\pm,p(\bar{p})$$



- Opposite sign correlation value and slope increases from pions to kaons to protons
- Same sign correlation, while ~flat, also increases in the same order

Centrality dependence

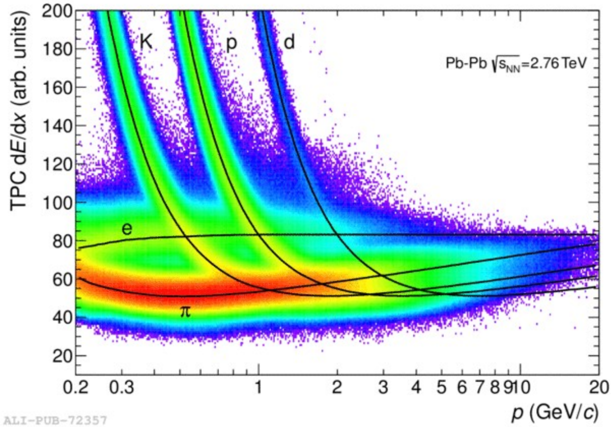




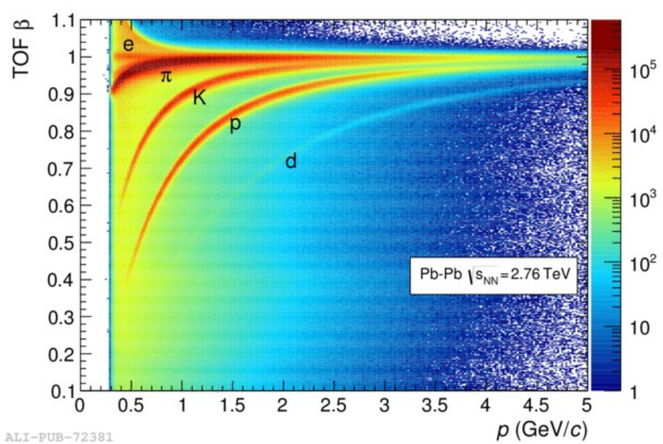
- Correlations stronger in 30-50% compared to 10-30%
- Same features of the measured correlation observed in 10-30% and 30-50% centrality range

Particle identification in ALICE

Energy loss dE/dx in the TPC vs *p*



Speed measurement vs *p*



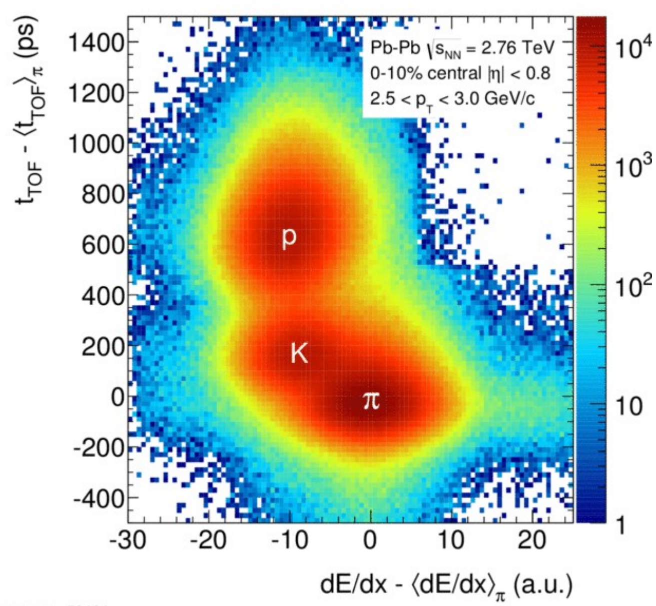
Figures:
ArXiv: 1402.4476

Particle selection with Bayesian probilities using TPC and TOF.

Bayesian weights $w(i|s) = \frac{r(s|i)C_i}{\sum_{k=e,\mu,\pi,\ldots} r(s|k)C_k}$

C_i A priory probability for a particle of type *i*.

$r(s|i)$ Conditional probability to get signal *s* for particle *i.*



Event plane estimation

$$\langle \cos(\varphi_\alpha+\varphi_\beta-2\Psi_{RP})\rangle = \frac{\langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{EP})\rangle}{R}$$

Ψ_{EP} is reconstructed for V0-A/C (forward multiplicity detector with 32 sectors on each side of the interaction point)

$$\Psi_{EP} = \arctan 2(q_y, q_x)$$

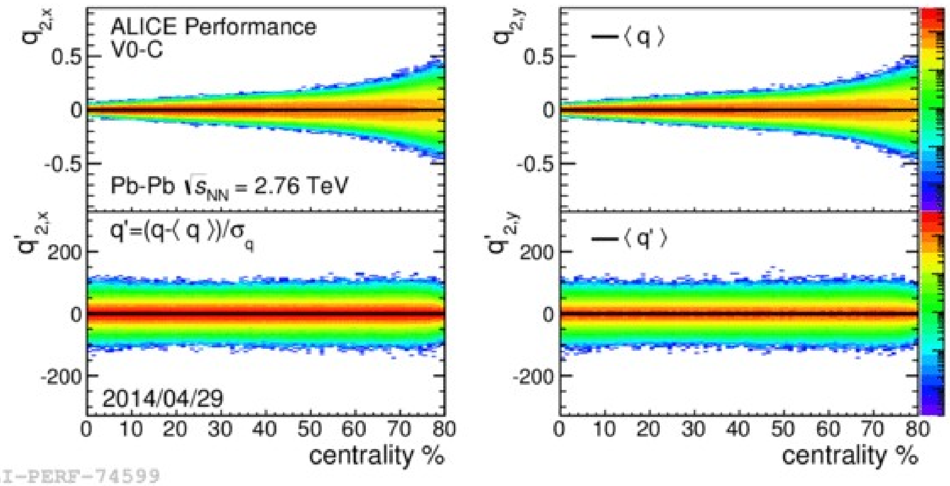
$$(q_x, q_y) = \frac{\sum_{i=0}^{32} M_i(\cos\varphi_i, sin\varphi_i)}{\sum_{i=0}^{32} M_i}$$

Corrected for detector non-uniformity

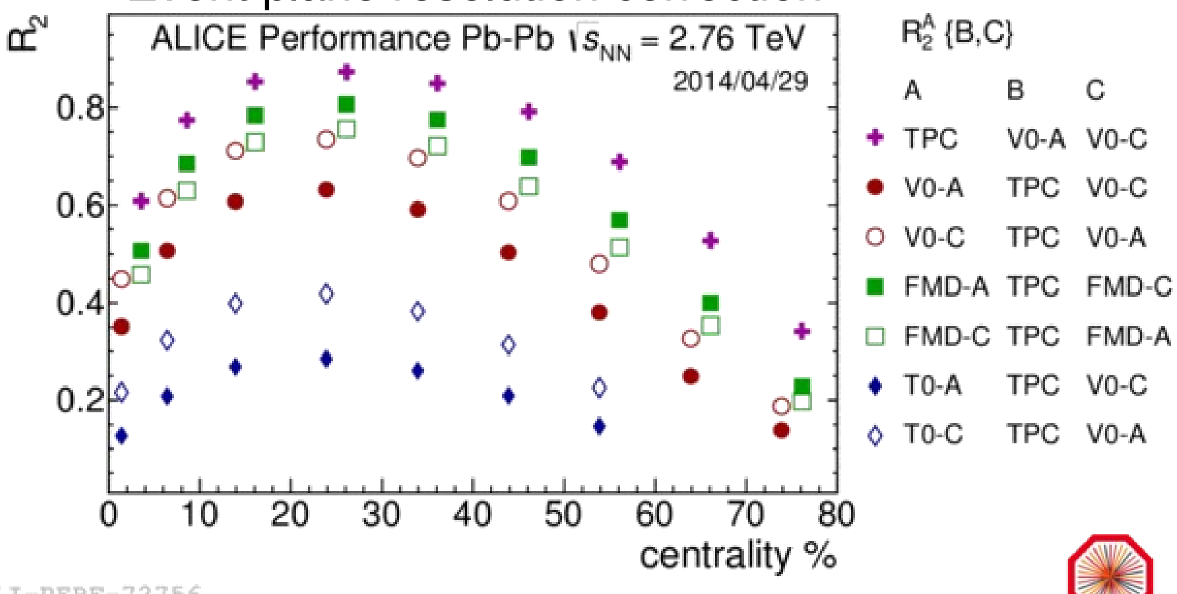
R extracted with 3-subevent method:

$$R_A^2 = \frac{cos(\Psi_A - \Psi_B)\cos(\Psi_A - \Psi_C)}{\cos(\Psi_B - \Psi_C)}$$

Recentering and with equalization of the V0-C q-vector measurement



Event plane resolution correction



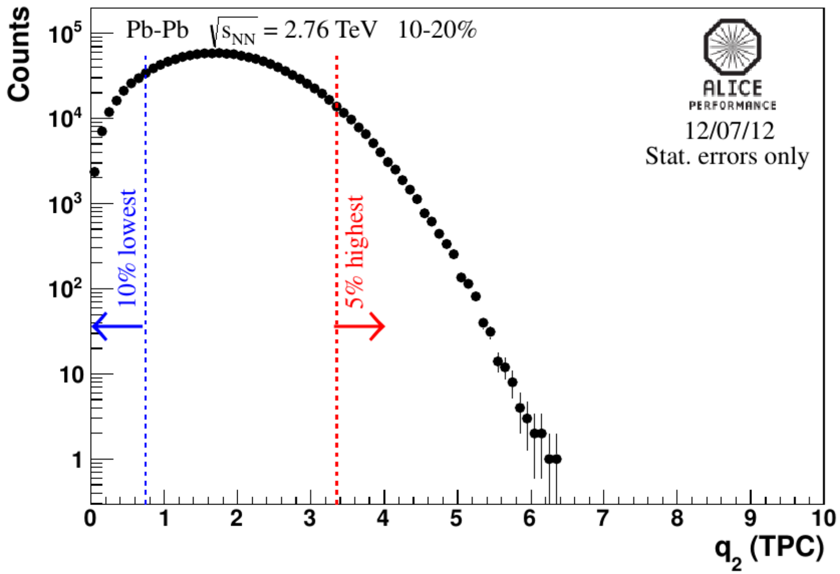
Controlling background with event shape engineering

To understand background effects related to v_2:

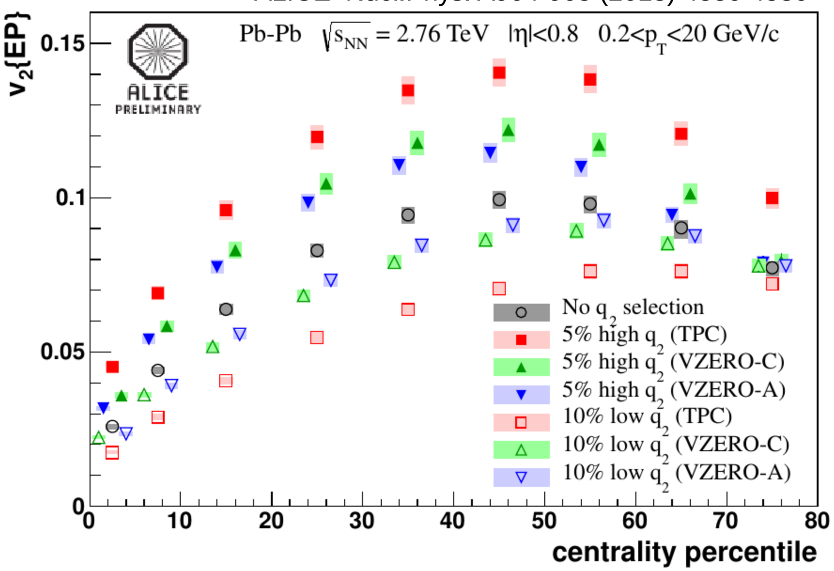
at fixed centrality (and magnetic field) vary the magnitude of flow

$$Q_{2,x} = \sum_i^M \cos(2\phi_i), \quad Q_{2,y} = \sum_i^M \sin(2\phi_i), \qquad q_2 = Q_2/\sqrt{M}$$

Select events with large (small) q-vector for events with strong (small) anisotropic flow



ALICE Nucl.Phys. A904-905 (2013) 455c-458c



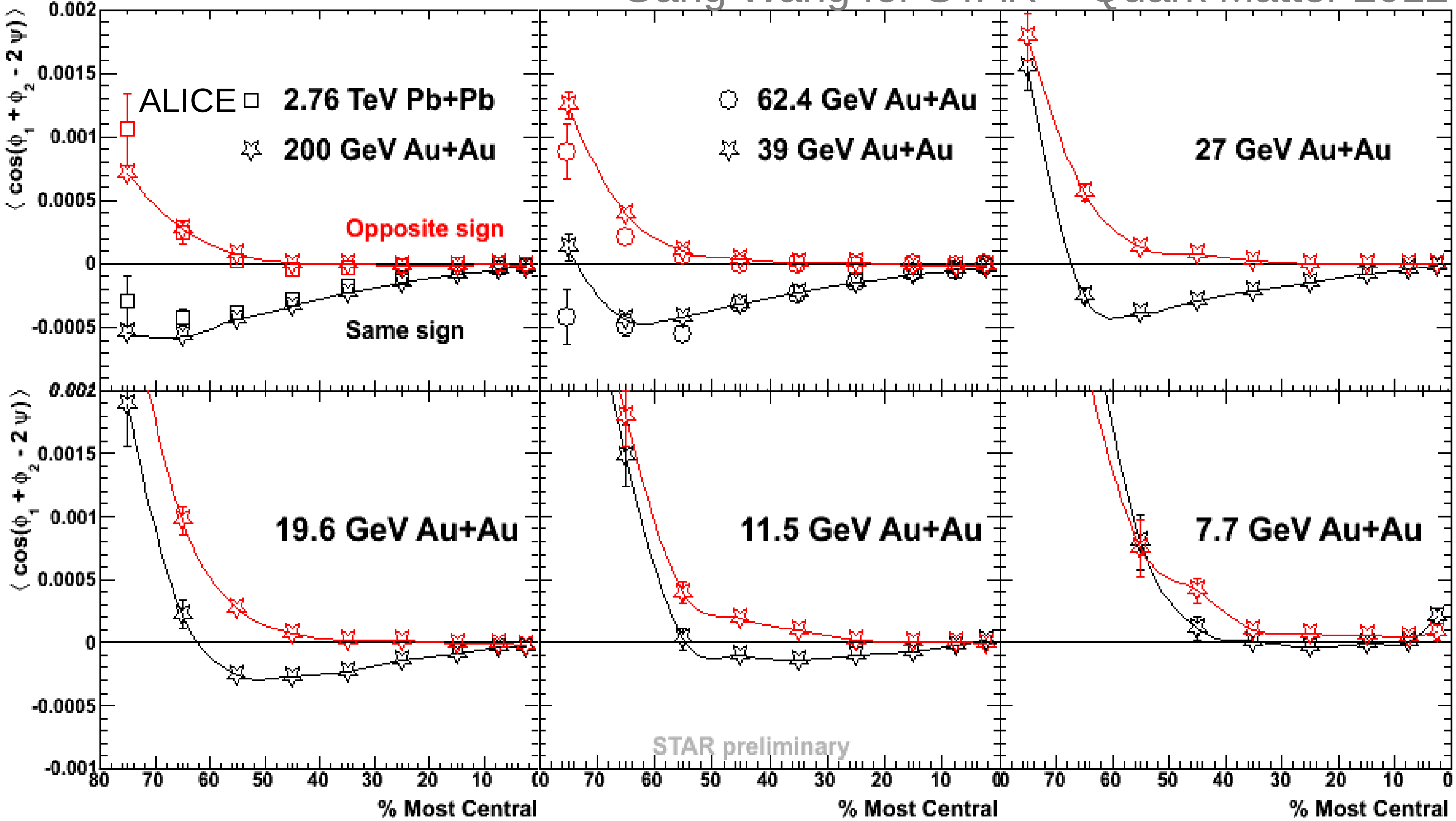
Central, small B + strong/small flow

Semi-central, strong B + strong/small flow

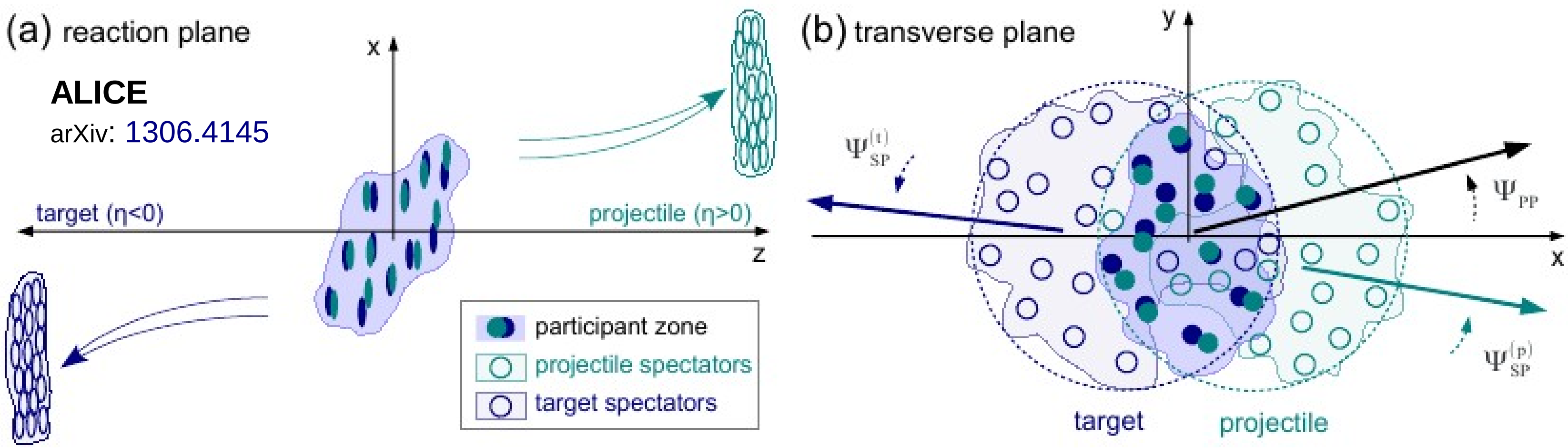
Different regimes

- Collision systems: Pb-Pb, U-U, Cu-Cu, pp, p-Pb
- Collision energy: Energy scan including sub-deconfinement

Gang Wang for STAR - Quark Matter 2012

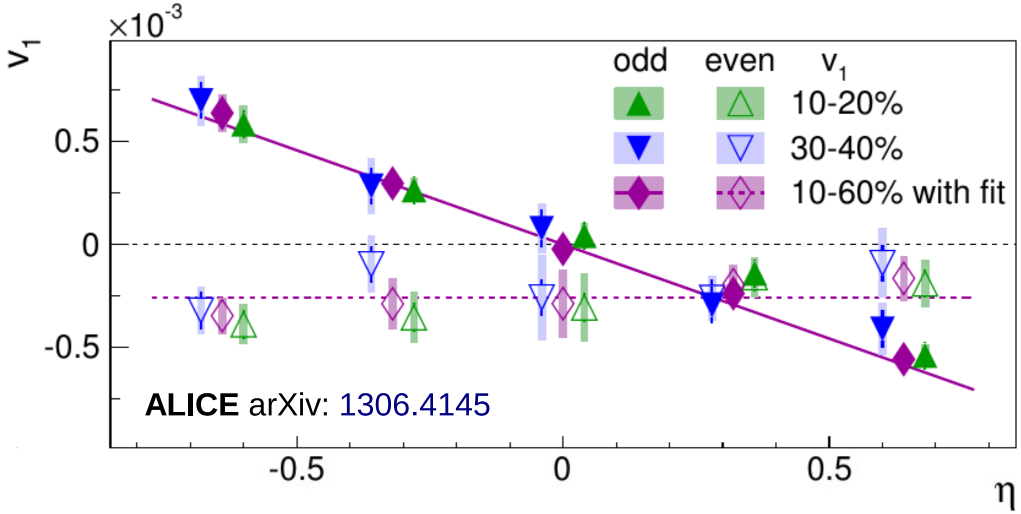


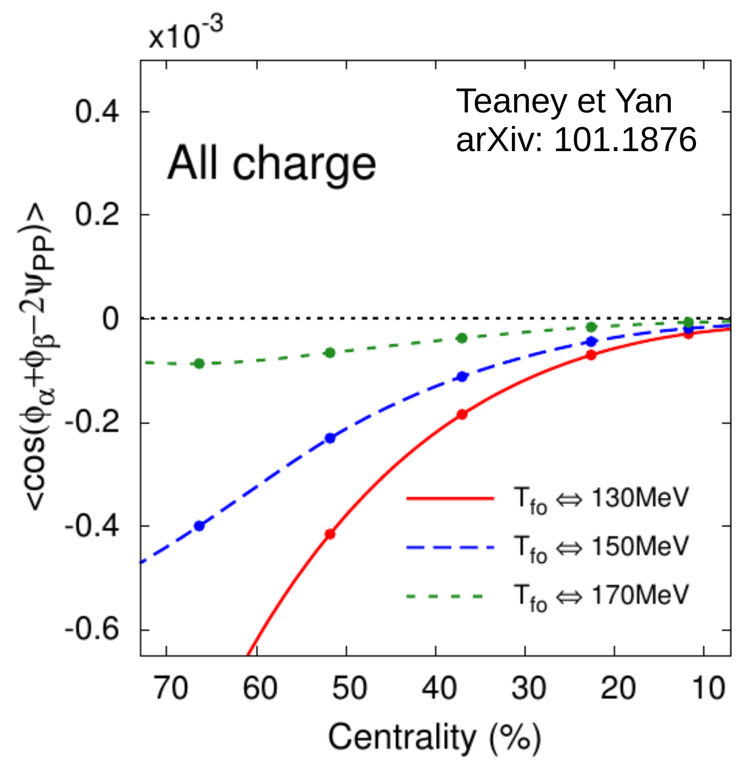
Directed flow fluctuation



$$v_1^{\mathrm{odd}}\{\Psi_{\mathrm{SP}}\} = \left[v_1\{\Psi_{\mathrm{SP}}^{\mathrm{p}}\} + v_1\{\Psi_{\mathrm{SP}}^{\mathrm{t}}\}\right]/2$$

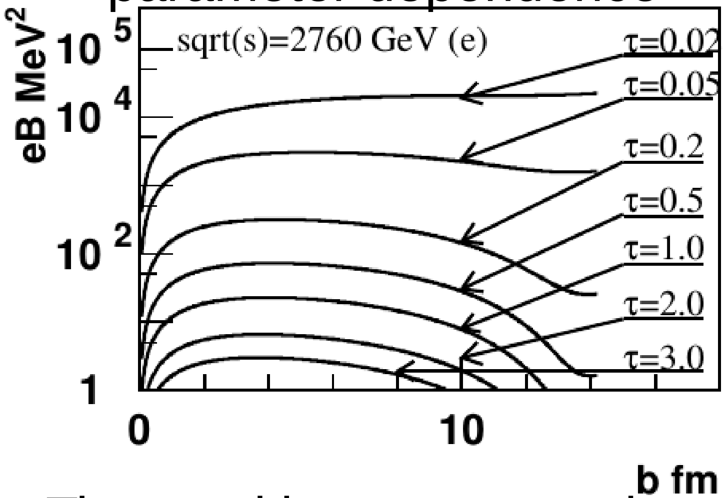
$$v_1^{\mathrm{even}}\{\Psi_{\mathrm{SP}}\} = \left[v_1\{\Psi_{\mathrm{SP}}^{\mathrm{p}}\} - v_1\{\Psi_{\mathrm{SP}}^{\mathrm{t}}\}\right]/2$$



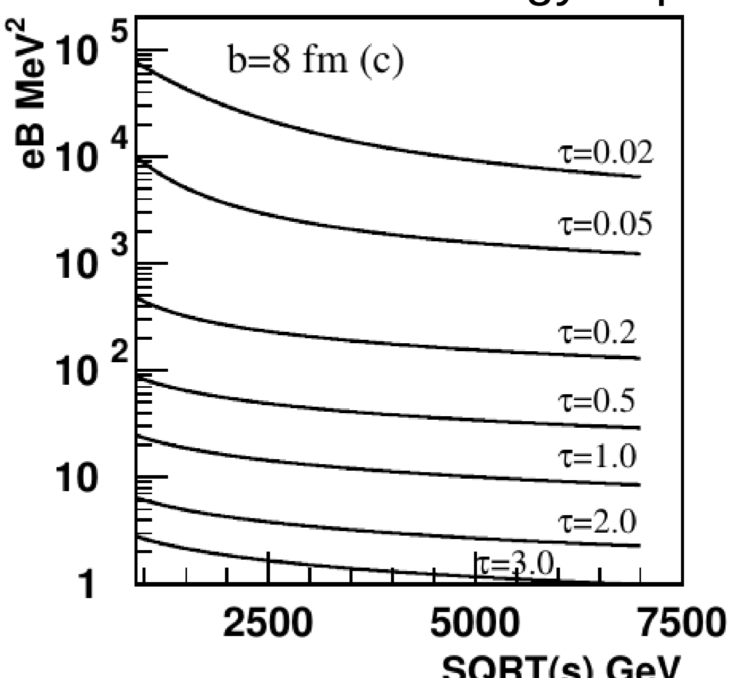


Magnetic field in HIC

Time and impact parameter dependence

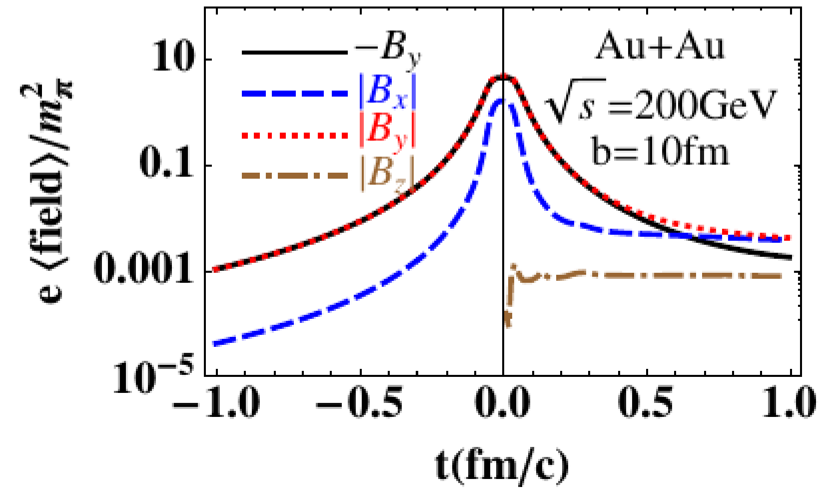


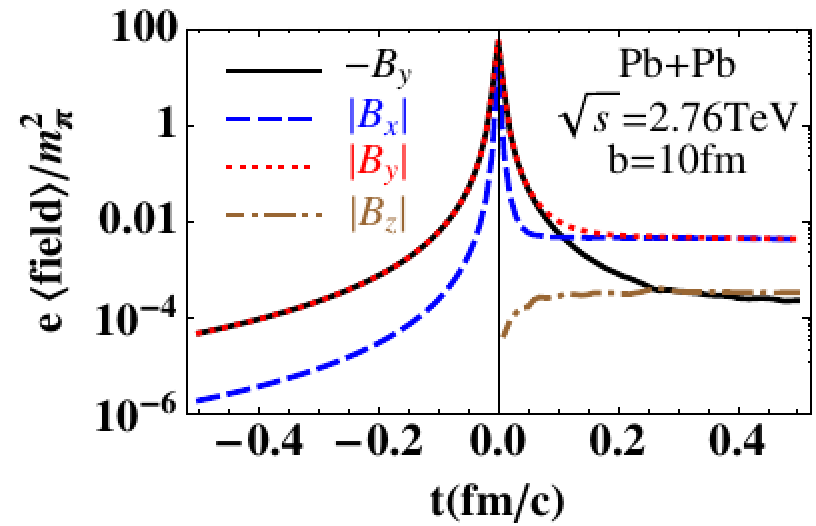
Time and beam energy dependence



Yang Zhong, Chunbin Yang, Xu Cai, Shengqin Feng
Advance In High Energy Physics, 2014 (2014)

Time and beam energy dependence





Wei-Tian Deng, Xu-Guang Huang
Phys. Rev. C 85, 044907 (2012)