NATIONAL SCIENCE CENTRE
POLAND

ALICE
A JOURNEY OF DISCOVERY

Soft QGP probes in ALICE:
a personal overview of recent correlation results in pp, p-Pb, and Pb-Pb

Łukasz Graczykowski
for the ALICE Collaboration

Faculty of Physics
Warsaw University of Technology

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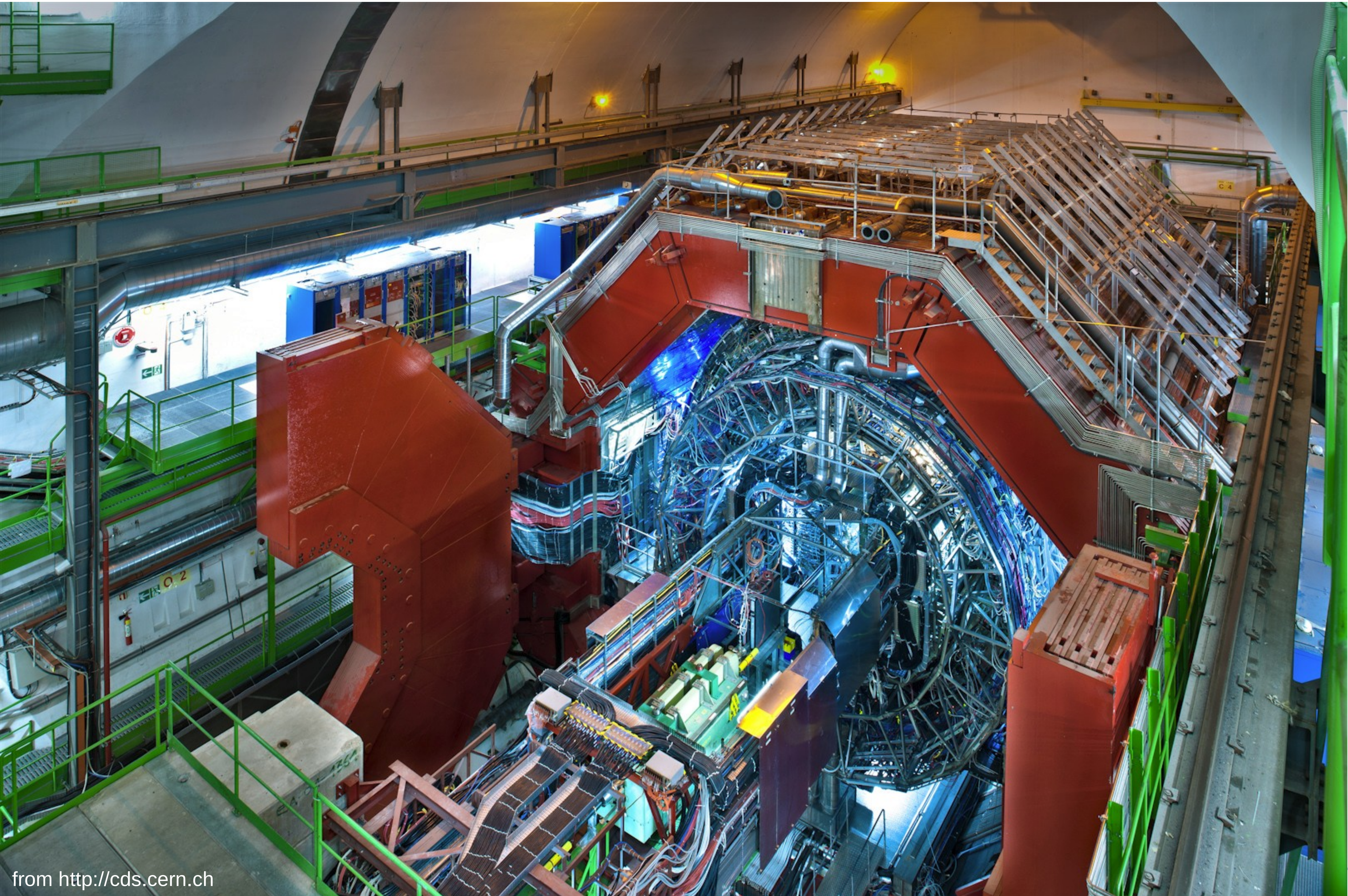
Outline

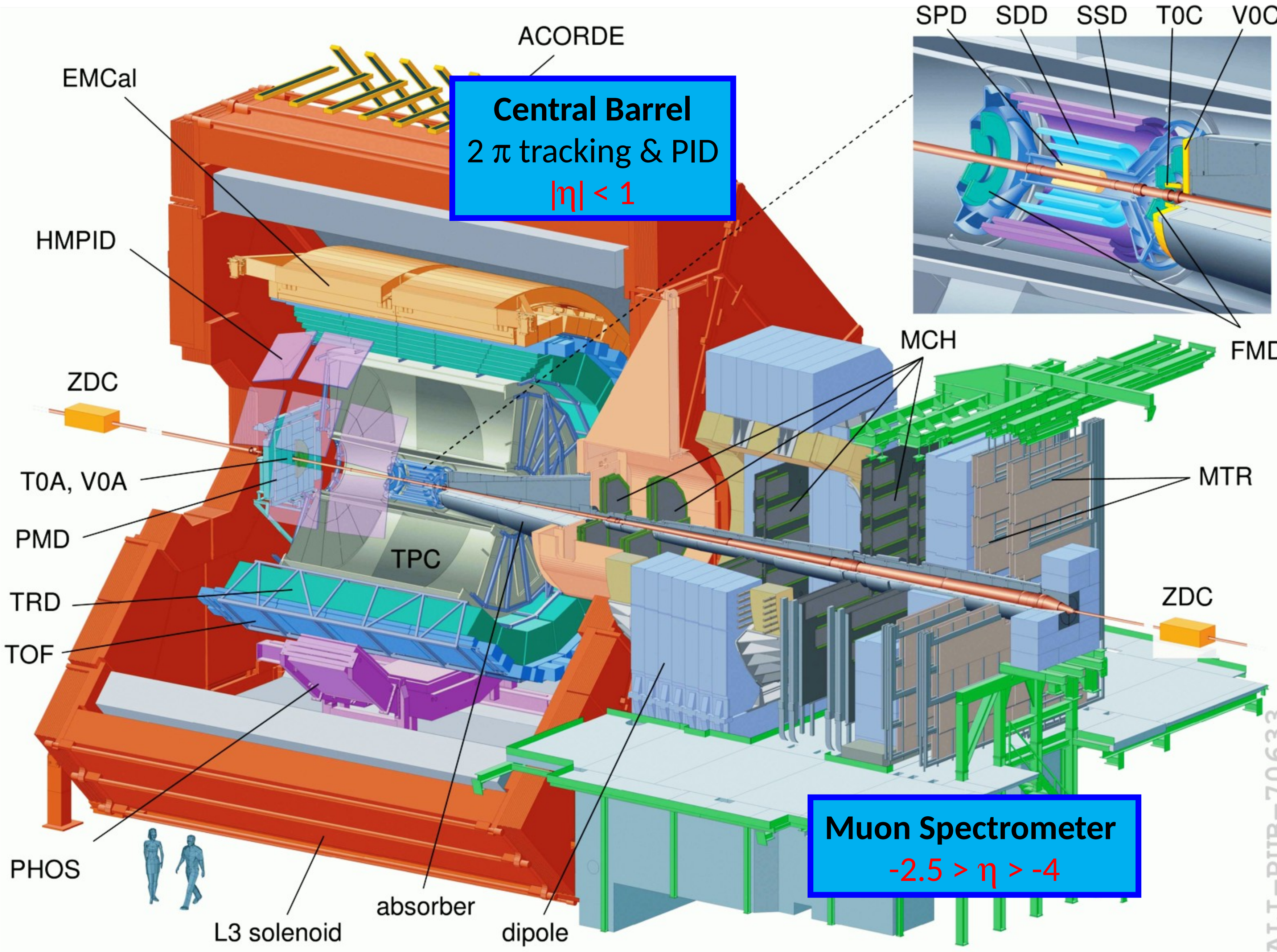
- **Angular correlations:**
  - the Ridge and Double Ridge
  - forward-central correlations in p-Pb
  - angular correlations with PID in pp
- **Femtoscopic measurements:**
  - 3D pion femtoscopy in p-Pb
  - K^0_s-$K^{\pm}$ femtoscopy in Pb-Pb
  - 1D pion, kaon, proton femtoscopy in Pb-Pb
- **First results from Pb-Pb LHC run II at $\sqrt{s}$ = 5.02 TeV**

ALICE experiment



from http://cds.cern.ch

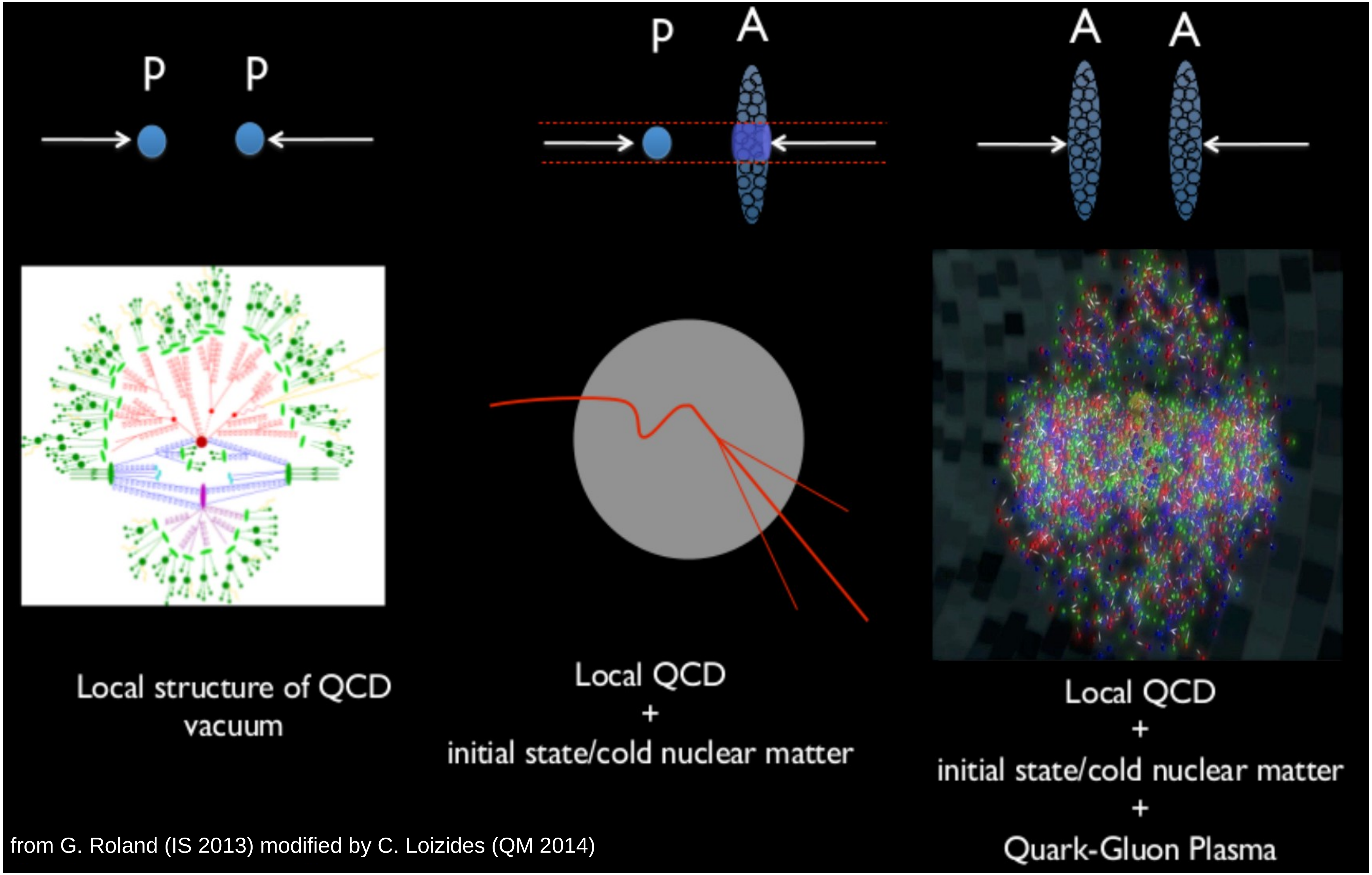
ALICE experiment



Central Barrel
2π tracking & PID
$|\eta| < 1$

Muon Spectrometer
$-2.5 > \eta > -4$

Different collision systems – different physics



The Ridge and Double Ridge

ΔηΔφ angular correlations

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

triggered

or

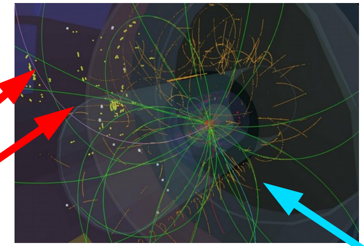
$$S(\Delta\eta,\Delta\varphi)=\frac{d^2N^{signal}}{d\Delta\eta\Delta\varphi}$$

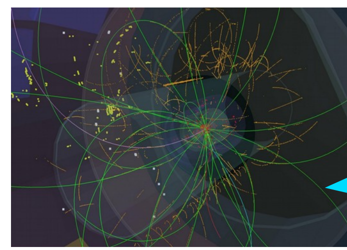
untriggered

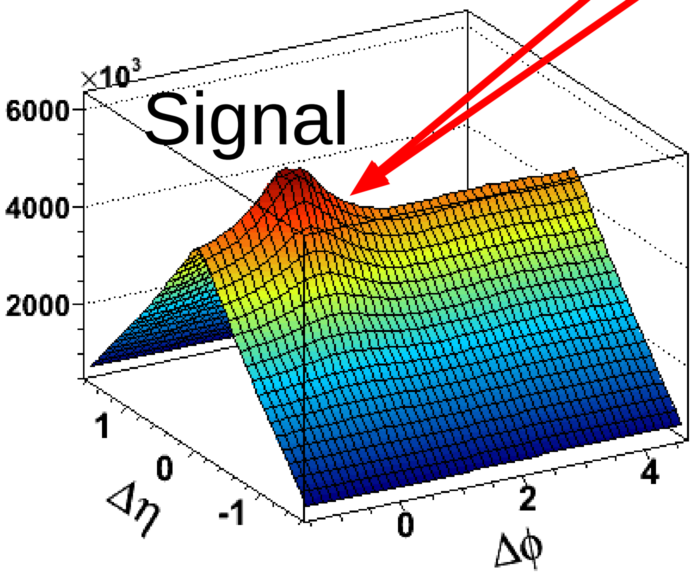
$$B(\Delta\eta,\Delta\varphi) = \alpha\,\mathrm{d}^2N_{\mathrm{mixed}}/\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi$$

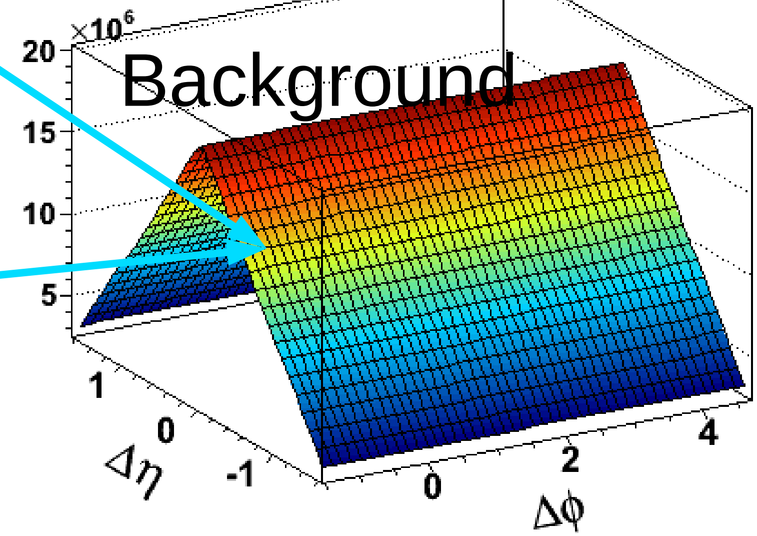
or

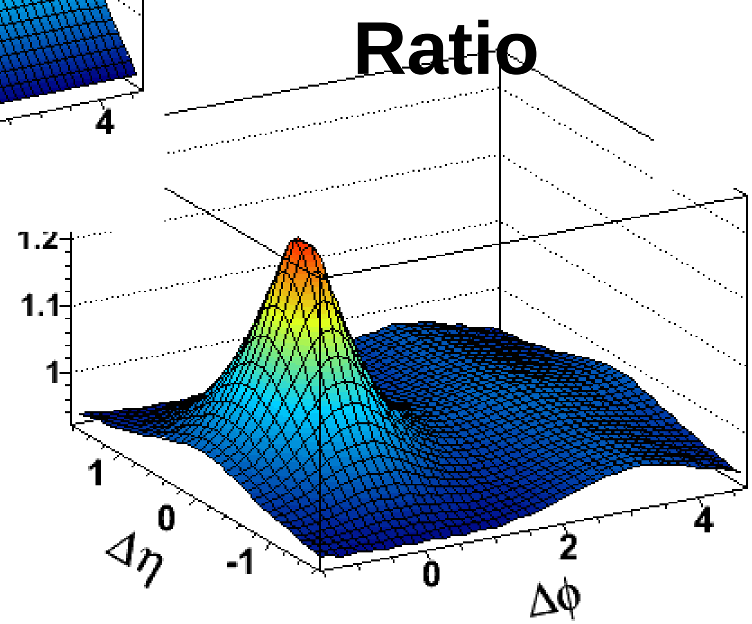
$$B(\Delta\eta,\Delta\varphi)=\frac{d^2N^{mixed}}{d\Delta\eta\Delta\varphi}$$











Same event pairs

Mixed event pairs

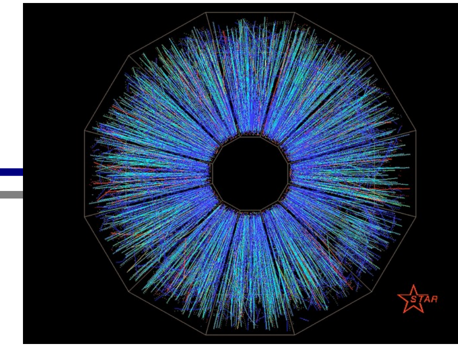
$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{assoc}}}{\mathrm{d}\Delta\eta\,\mathrm{d}\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

or

$$C(\Delta\eta,\Delta\varphi)=\frac{N^{mixed}_{pairs}}{N^{signal}_{pairs}}\frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

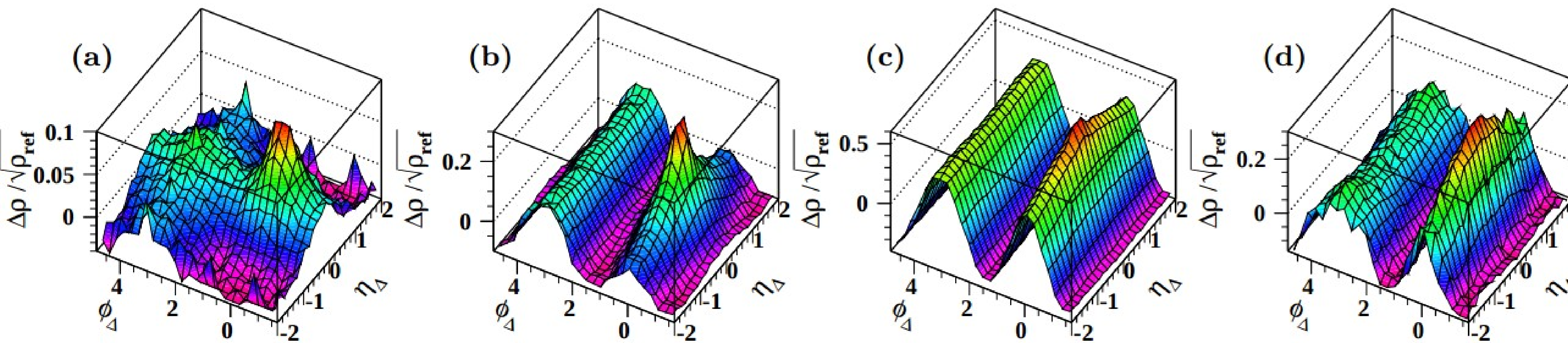
$$\Delta\eta=\eta_1-\eta_2$$
$$\Delta\varphi=\varphi_1-\varphi_2$$

The Ridge in heavy-ions

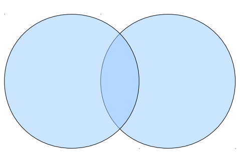


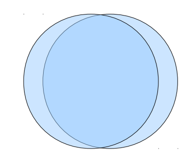
Au-Au
at √s=200 GeV

centrality



STAR: 10.1103/PhysRevC.86.064902





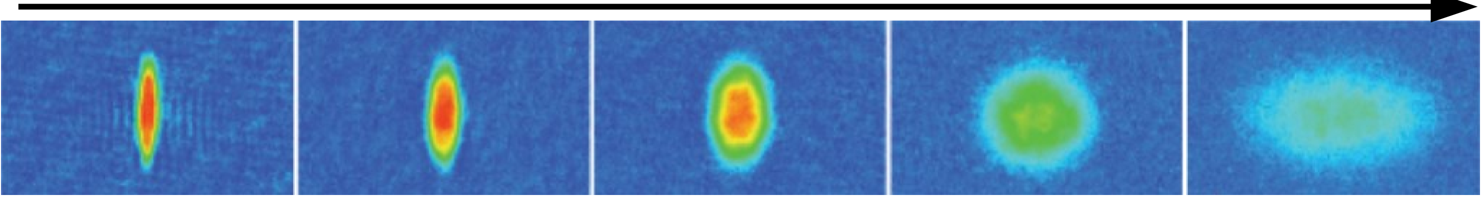
Similar to pp

Strong contribution of flow

100 μs

2000 μs

time

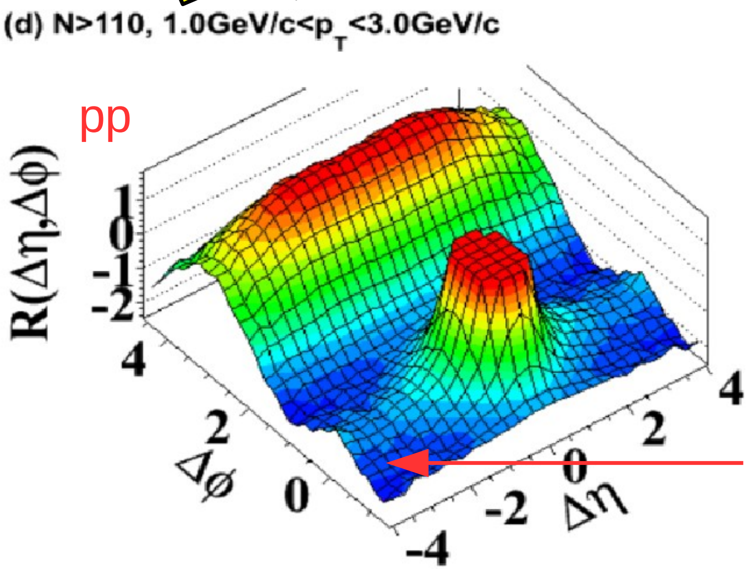


Elliptic flow in trapped atoms (cold Fermi gas) T~0.1 neV

O'Hara *et al.* Phys.Rev. A66 (2002) 041401

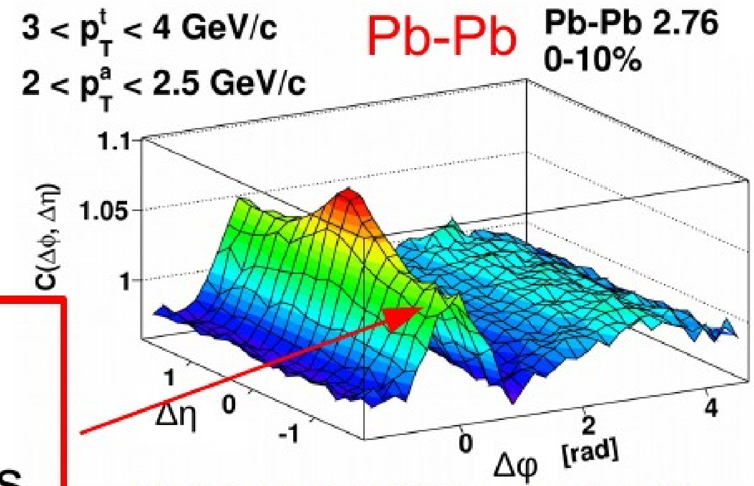
First LHC discovery

The Ridge at the LHC

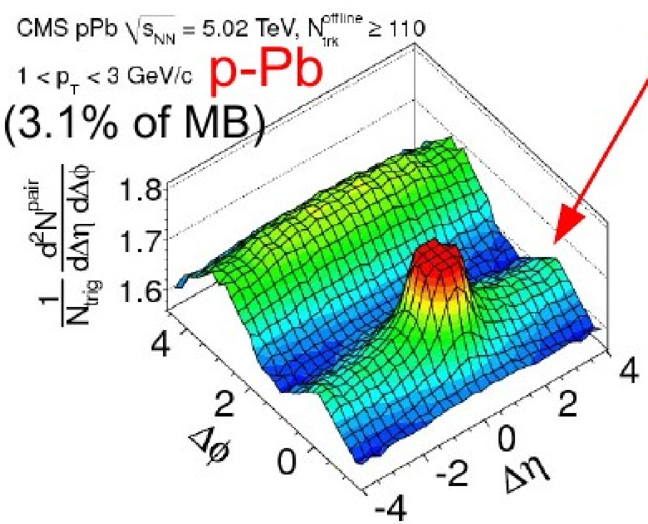


CMS, JHEP 1009 (2010) 91

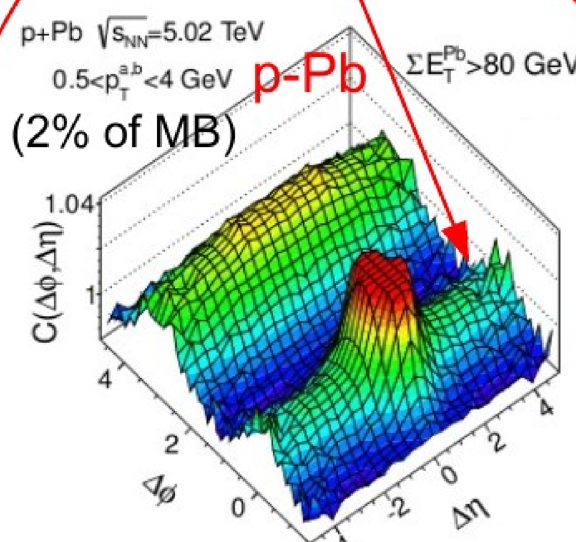
Near-side (NS) ridges in high multiplicity events at LHC energies



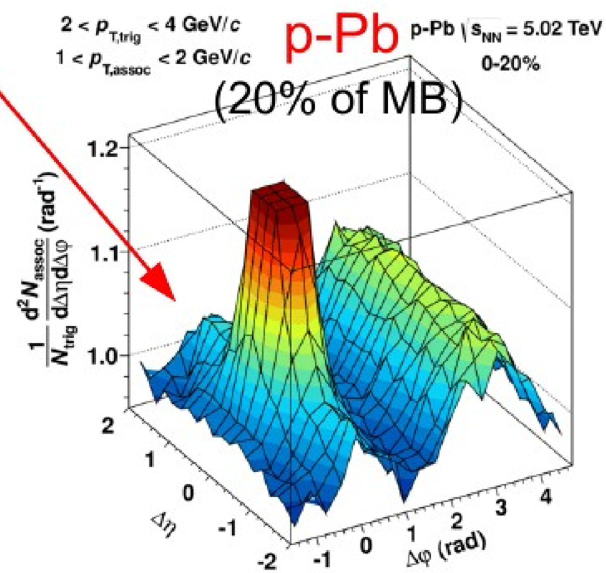
ALICE, PLB 708 (2012) 249



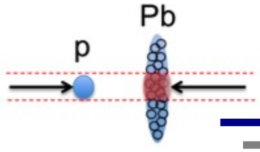
CMS, PLB 718 (2012) 795



ATLAS, PRL 110 (2013) 182302



ALICE, PLB 719 (2013) 29



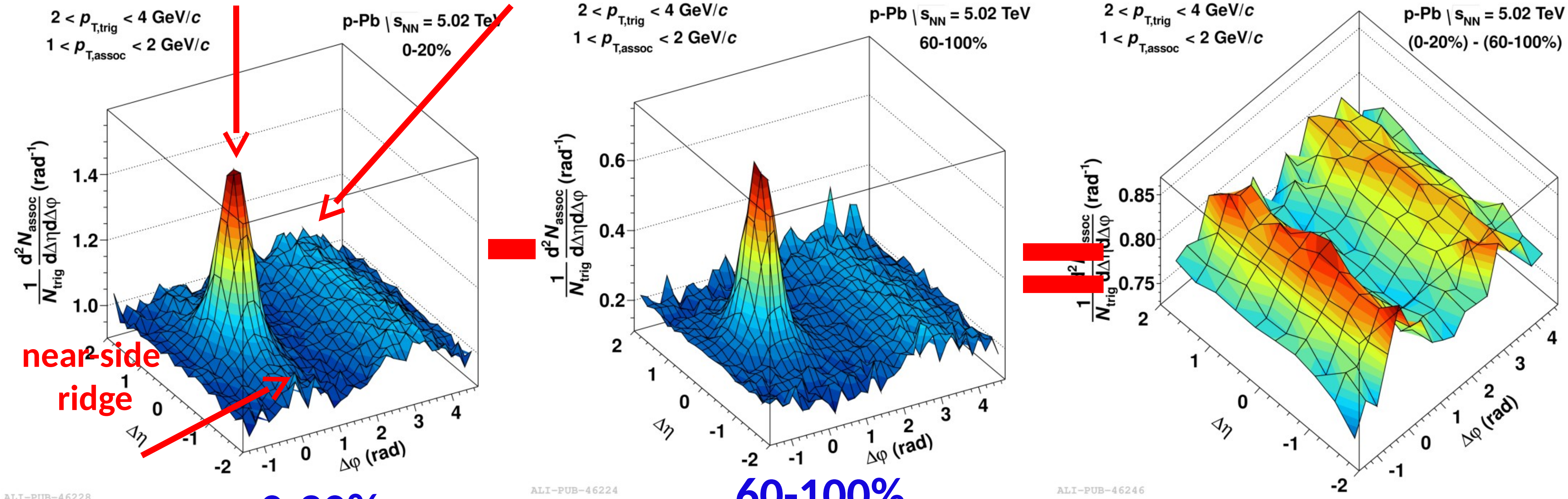
p-Pb: Double Ridge

E. Kryshen
LHCP 2015

Phys. Lett. B 719 (2013) 29
ALICE: arXiv:1212.2001

near-side jet correlations

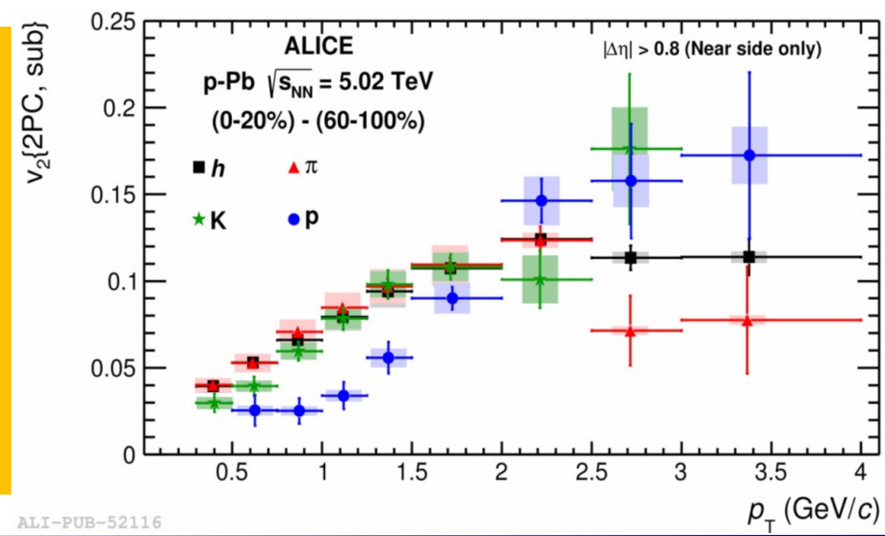
away-side jet correlations

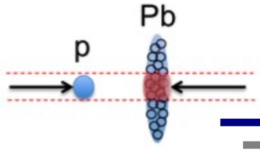


0-20%

60-100%

- Subtraction of jet correlations reveals **double ridge structure**
- Clear indication for **mass ordering** in p-Pb
- Resembles Pb-Pb
- **Collective flow?**





p-Pb: Double Ridge

E. Kryshen
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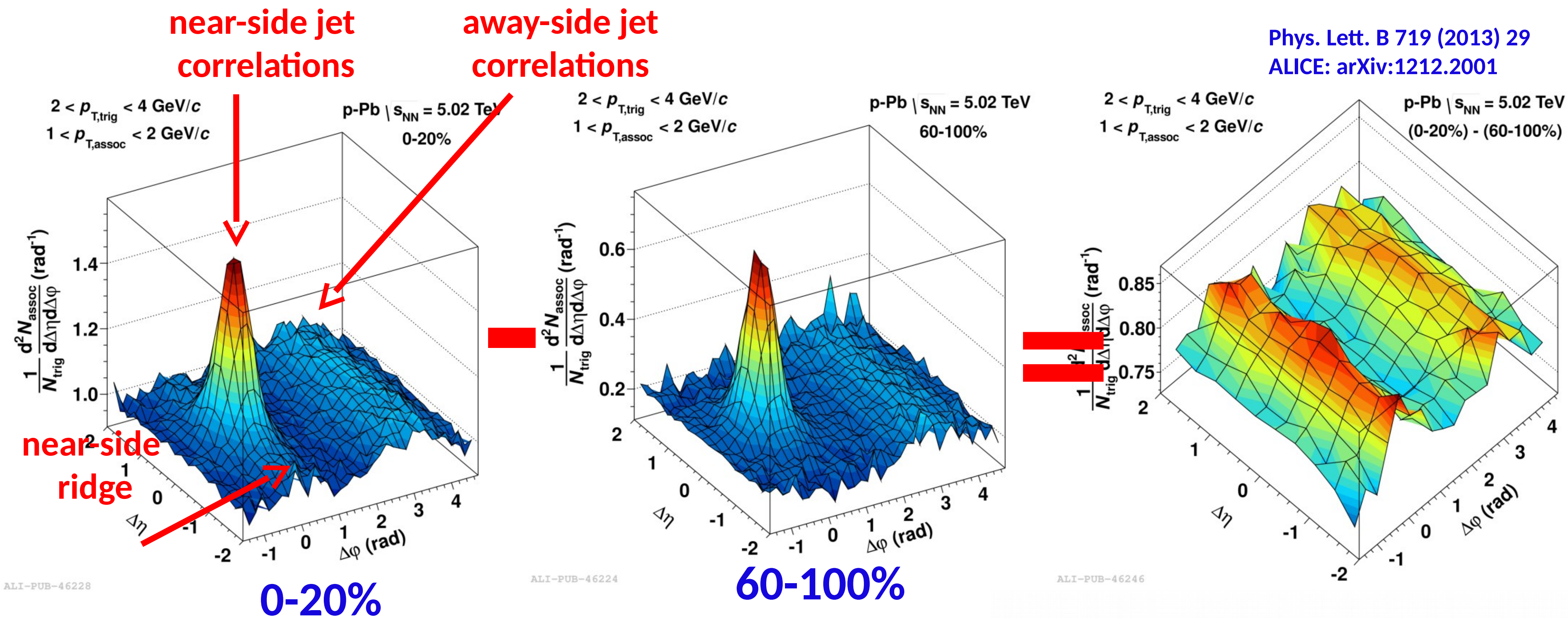
Phys. Lett. B 719 (2013) 29
ALICE: arXiv:1212.2001



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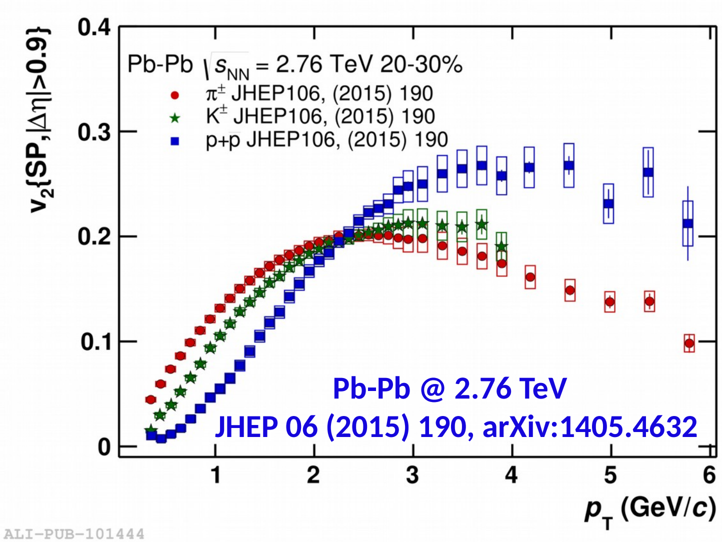
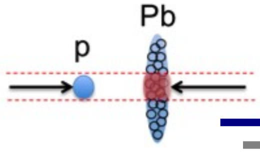
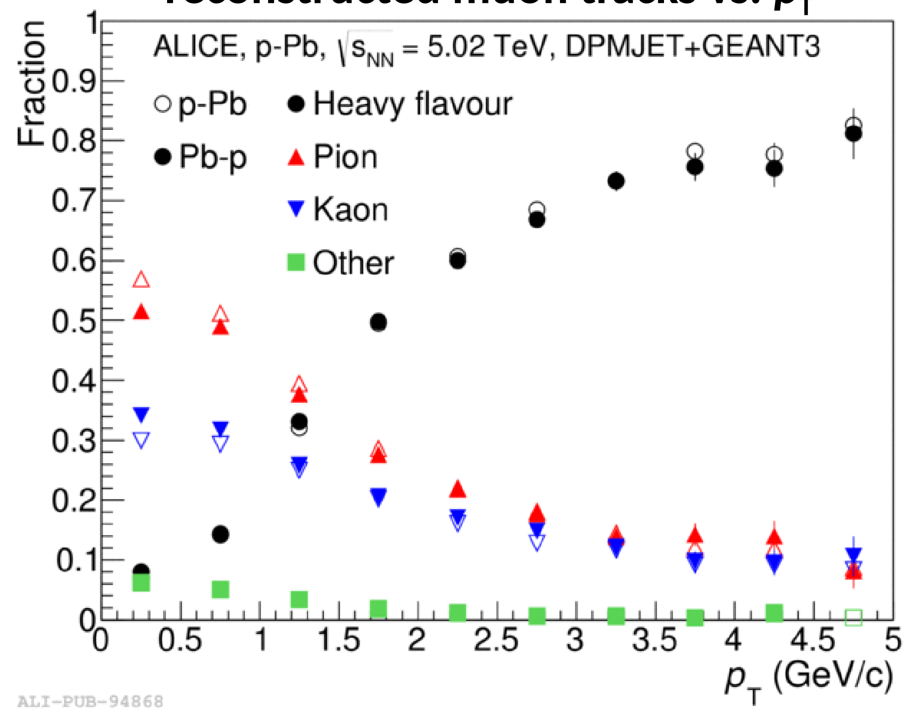




p-Pb: forward-central correlations

- **Tracklets** at mid rapidity ($|\eta| < 1.0$)
- **Forward muons** ($-4<\eta<-2.5$)
  - Composition varies as a function of p_T
  - Higher p_T: dominated by heavy flavour
- **Two beam configurations:**
  - **p-Pb:** muons in p-going direction
  - **Pb-p:** muons in Pb-going direction

Parent particle composition of reconstructed muon tracks vs. p_T



- Event sample split into multiplicity classes defined as a sum of multiplicities in V0 rings approximately symmetric in η:
  - V0A: $2.8 < \eta < 3.9$
  - V0C: $-3.7 < \eta < -2.7$

ALICE: arXiv:1506.08032

E. Kryshen
LHCP 2015

p-Pb: forward-central correlations

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

$$0.5 < p_{\mathrm{T}}^{\mathrm{trig}} < 1\mathrm{GeV}/c$$

p-going direction

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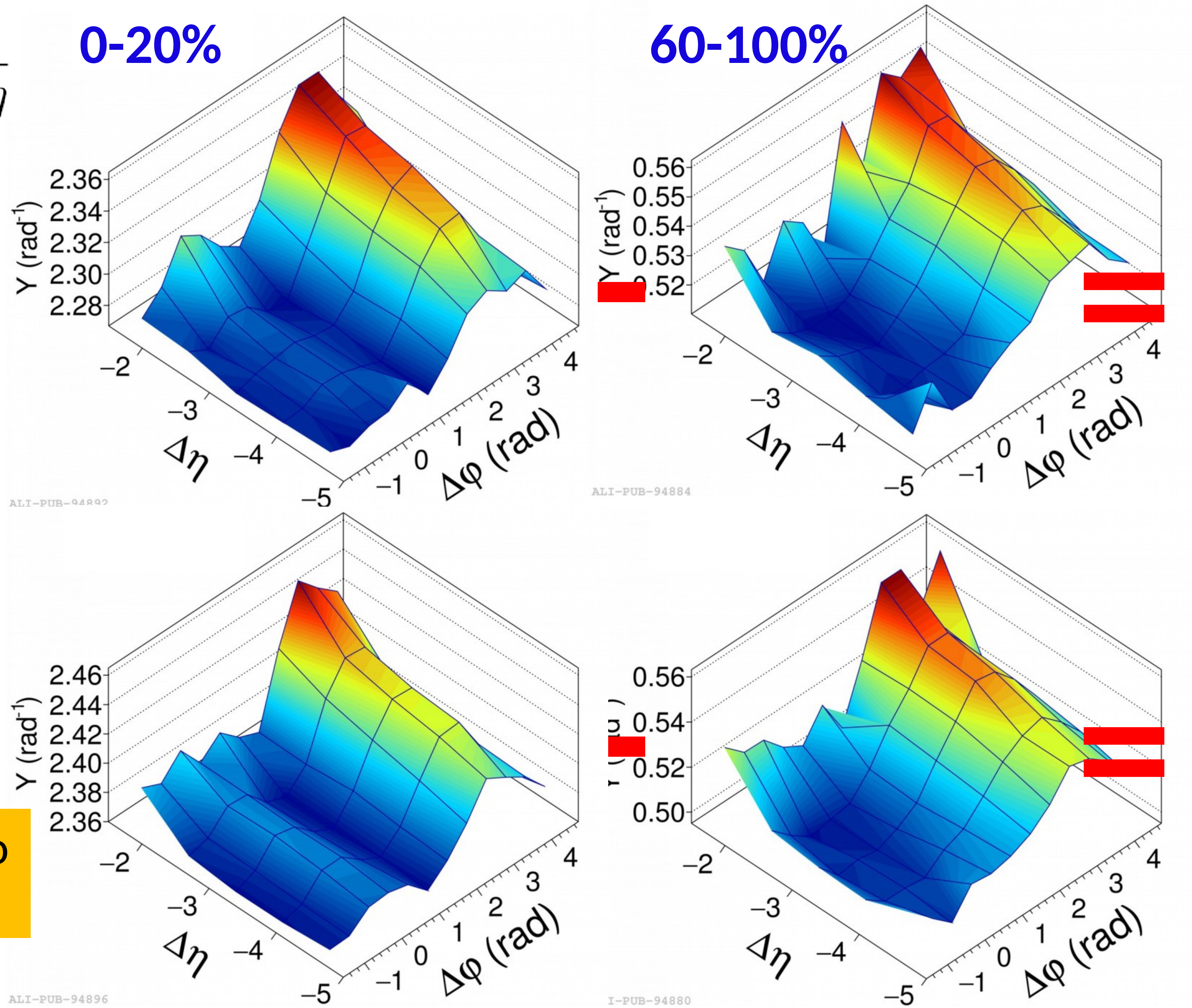
Pb-going direction

Ridge extends up to **$|\Delta\eta|=5$** and **$|\eta|\sim 4$**

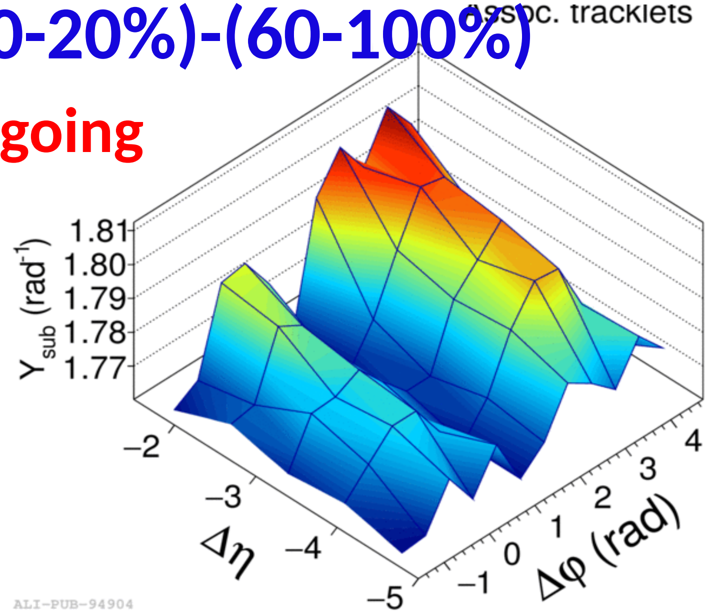
ALICE: arXiv:1506.08032

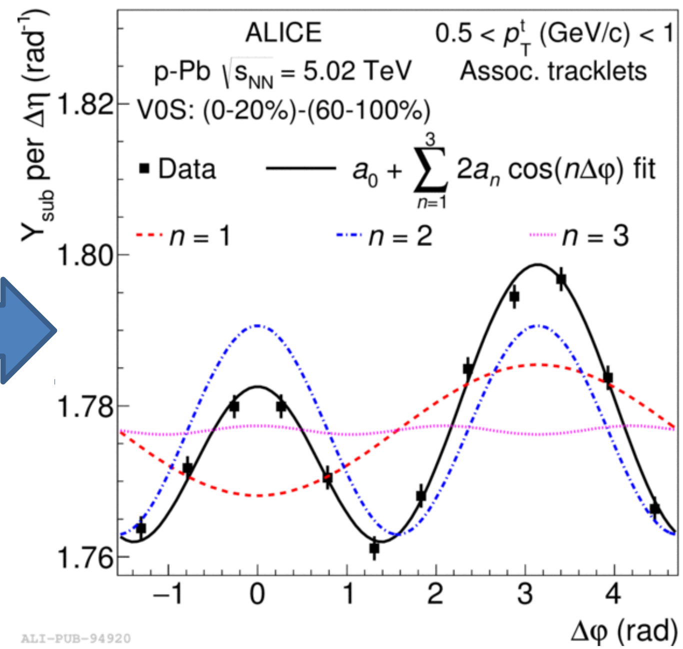


p-Pb: forward-central correlations

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

p-going





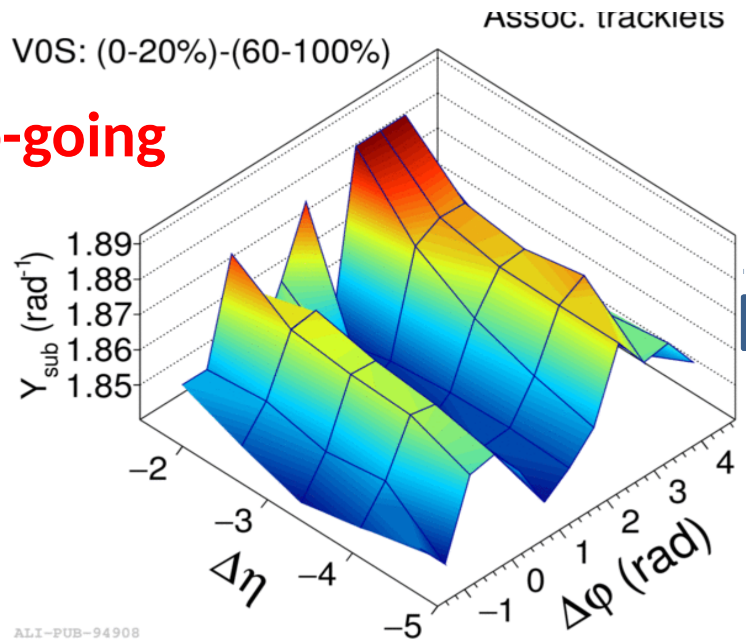
Double ridge in both directions

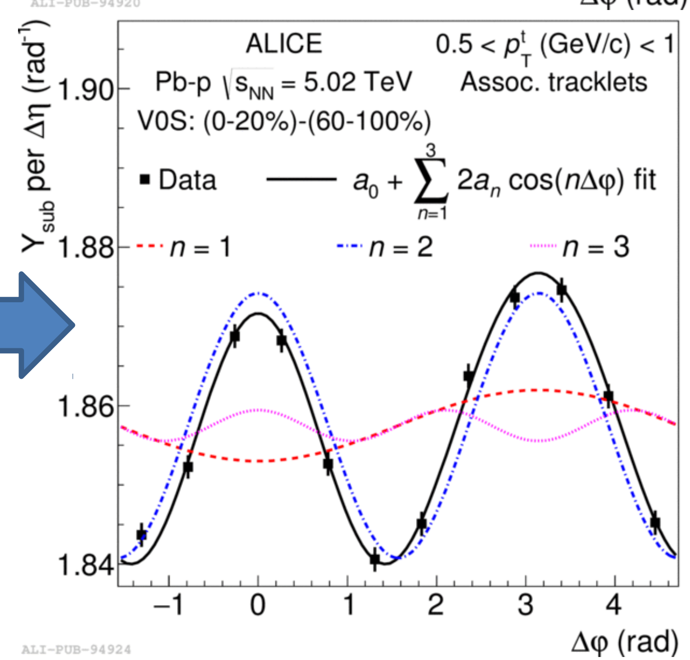
n = 1

n = 2

n = 3

Pb-going





2nd coefficient dominates

ALICE: arXiv:1506.08032

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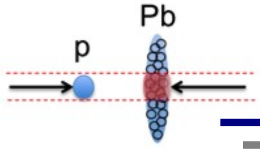
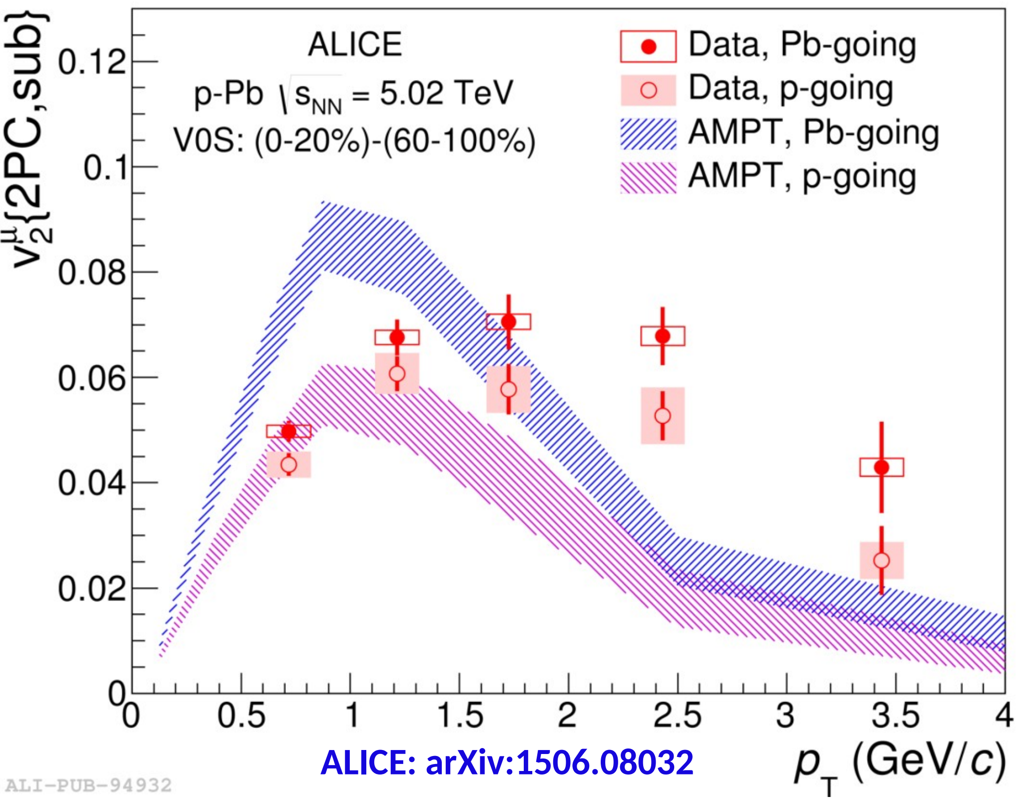
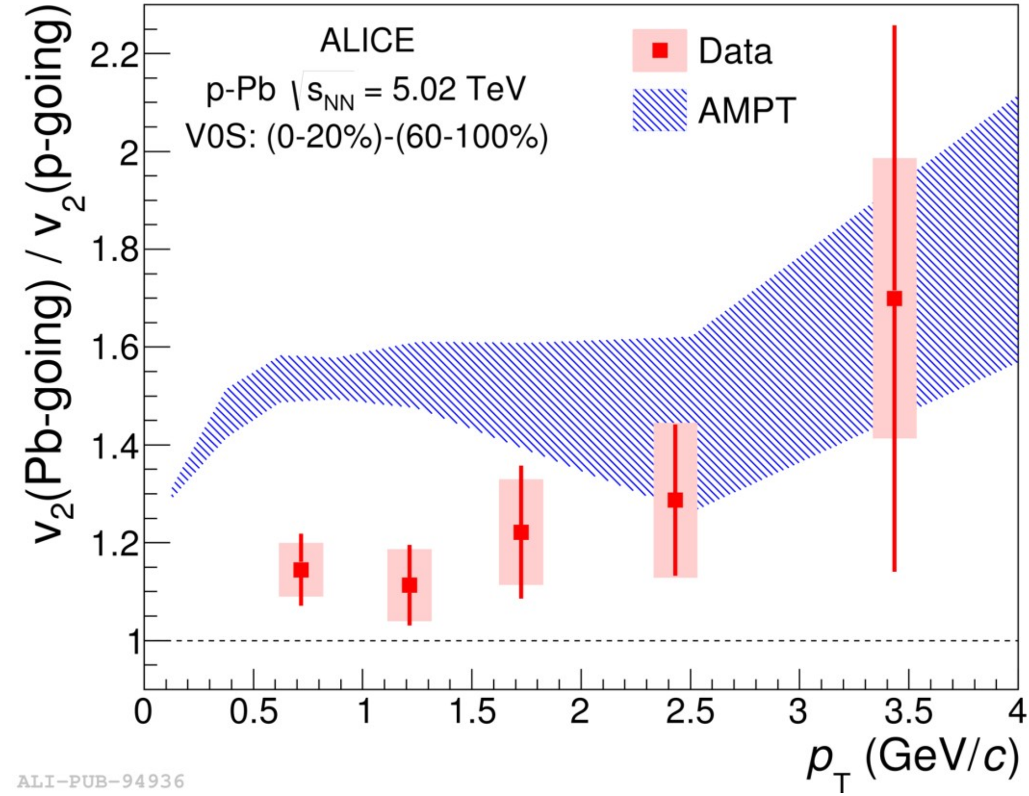


p-Pb: v_2 in p and Pb-going directions



ALICE: arXiv:1506.08032



v_2(Pb-going) > v_2(p-going) as qualitatively expected in hydro
Phys. Lett. B 748 (2015) 301-305, arXiv:1503.03655

Quantitatively different p_T dependence in AMPT

Possible scenarios at p_T > 2 GeV/c (dominated by heavy flavour muons):

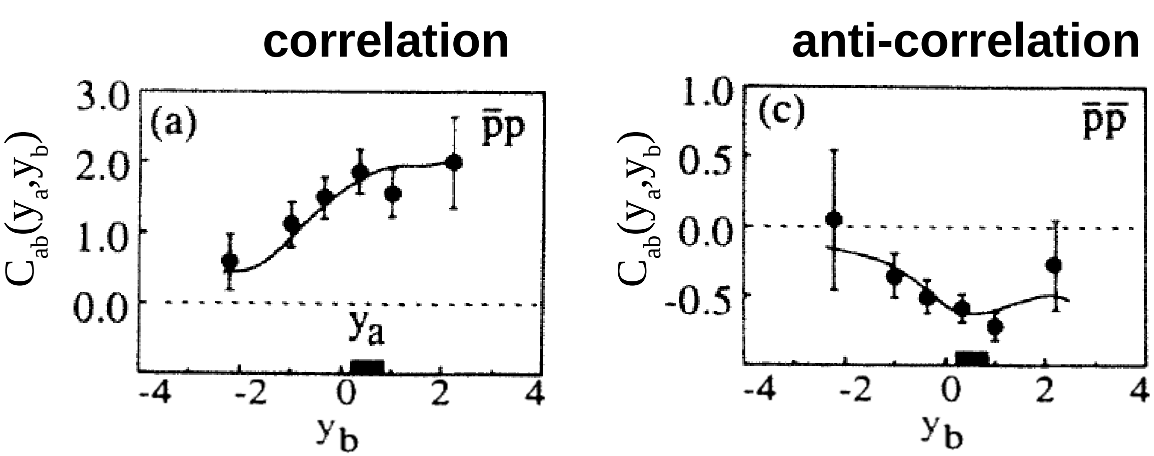
- v_2 (heavy flavour) > 0
- Different composition of the parent distribution and their v_2

E. Kryshen
LHCP 2015

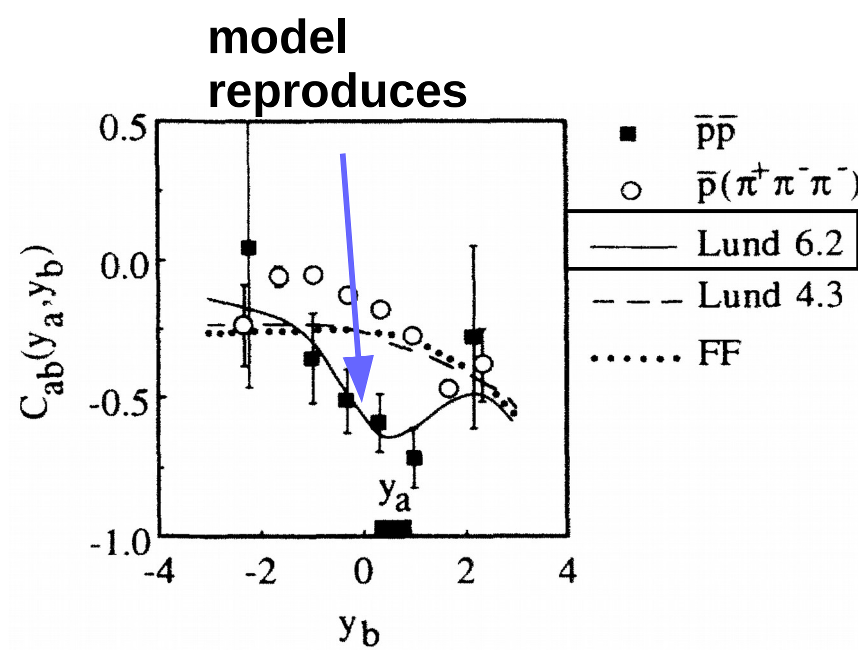
Study of angular correlations with PID in pp: a mystery of baryons

Rapidity correlations in e^+e^- at $\sqrt{s}$ = 29 GeV

We are not likely to find two baryons or two antibaryons at the same phase space.



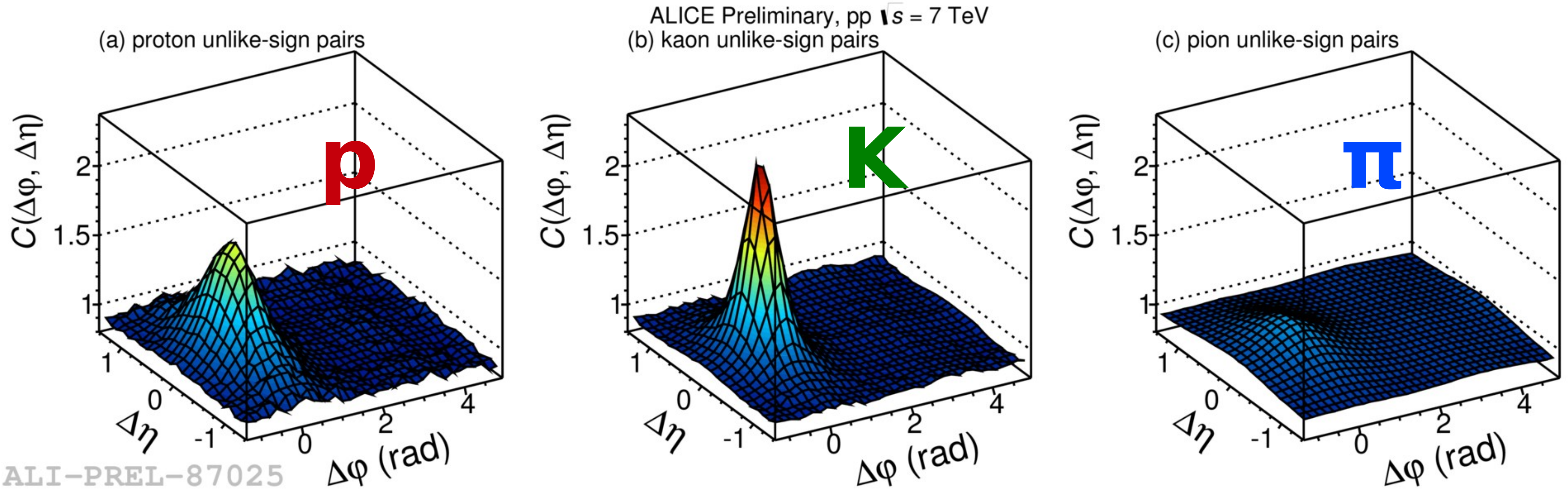
Study of baryon correlations in e+e− annihilation at 29-GeV
TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140



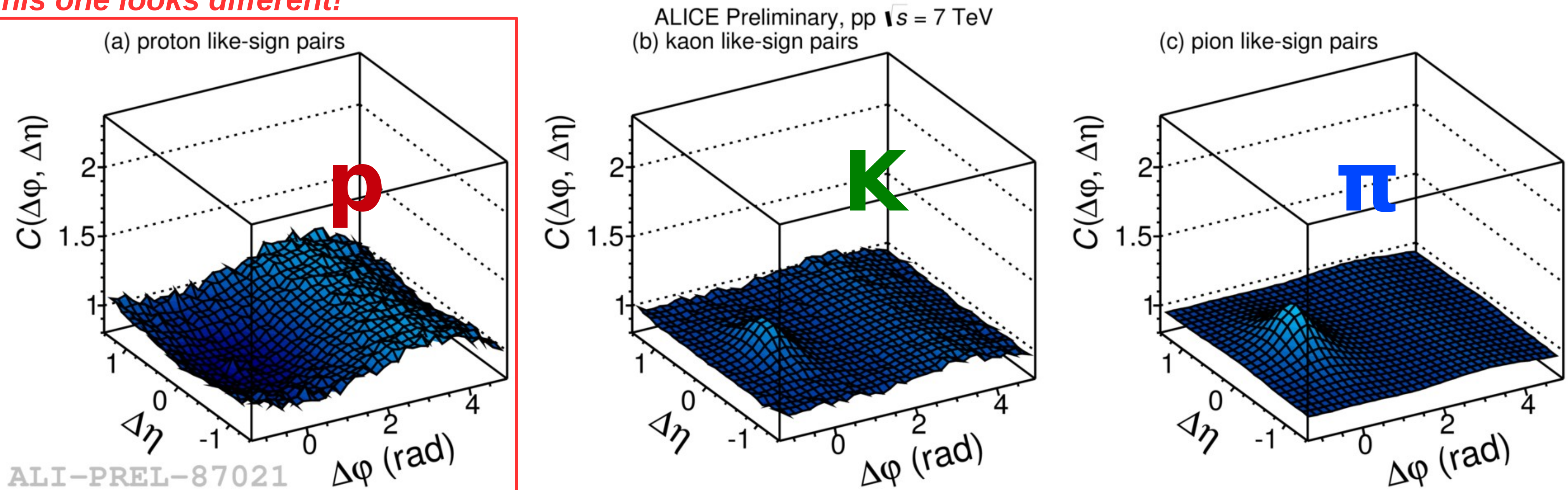
- **Lund 6.2 model for e^+e^- agrees** with observations seen in data
- **Not enough energy** to produce baryon pairs in a **single fragmentation**
- How does it look like in proton-proton collisions at 7 TeV?

17

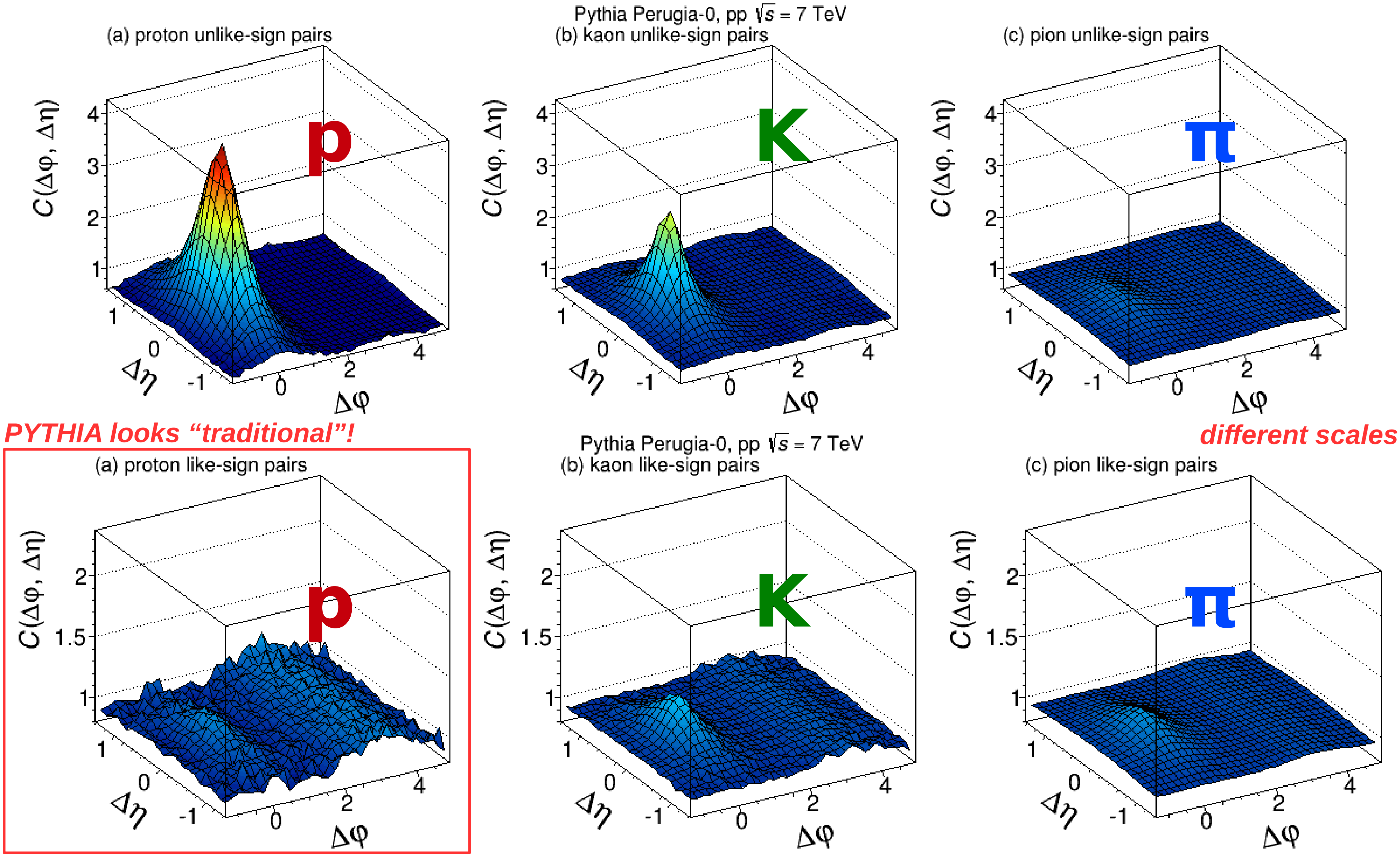
pp: ΔηΔφ of identified particles in ALICE



This one looks different!



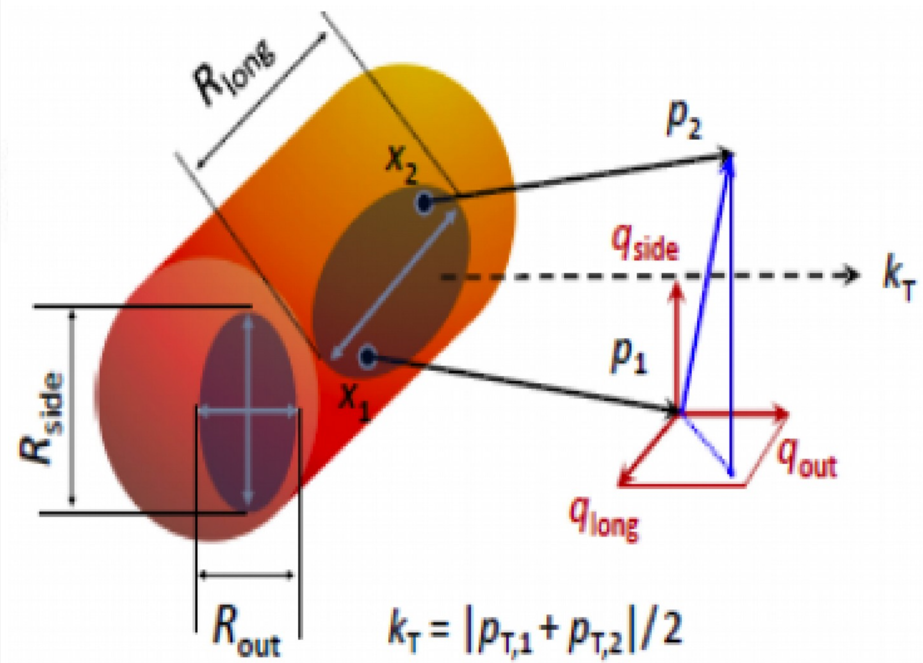
pp: PYTHIA 6.4 Perugia-0

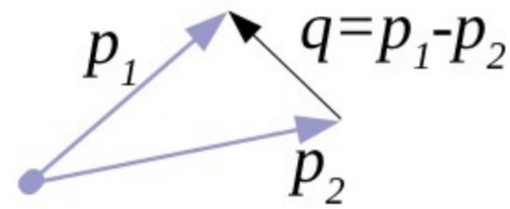


- At 29 GeV the explanation was there is **not enough energy** to produce baryon pairs. At the LHC there must exist **additional fundamental mechanism forbidding fragmentation into two baryons**

Recent femtoscopic measurements

Femtoscopy technique





The Koonin-Pratt formula
(S.E. Koonin, PLB70 (1977) 43; S.Pratt et al., PRC42 (1990) 2646)

$$C(\vec{q}) = \int S(\boldsymbol{r}) |\Psi(\vec{q}, \boldsymbol{r})|^2 d^4 r$$

$$S(\boldsymbol{r}) \sim \exp\left(\frac{-r_{out}^2}{4R_o^2} - \frac{r_{side}^2}{4R_s^2} - \frac{r_{long}^2}{4R_l^2}\right)$$

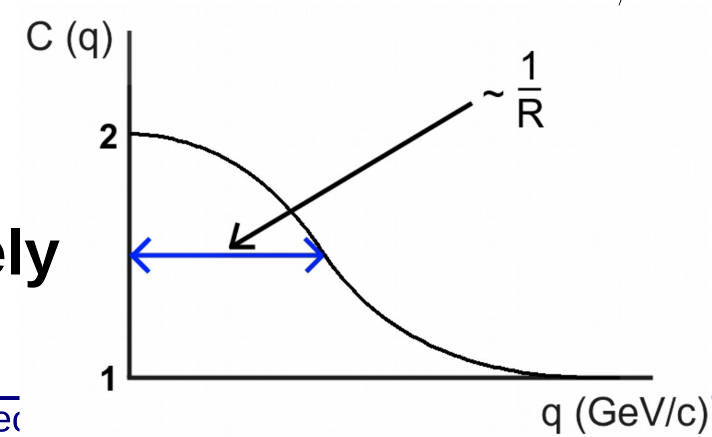
$$|\Psi(\vec{q}, \boldsymbol{r})|^2 = 1 + \cos(\vec{q}\,\vec{r})$$

$$C = 1 + \lambda \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)$$

with Coulomb – Bowler-Sinyukov formula:

$$C = (1-\lambda) + \lambda K \left(1 + \exp\left(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2\right)\right)$$

- The size ***R*** is a **variance of single-particle emission function** (emission probability distr.)
- The **width** of the correlation function is **inversely proportional to *R***



Size of the emission source and collectivity in ultra-relativistic p-Pb collisions

Piotr Bożek[a,b], Wojciech Broniowski[c,b]

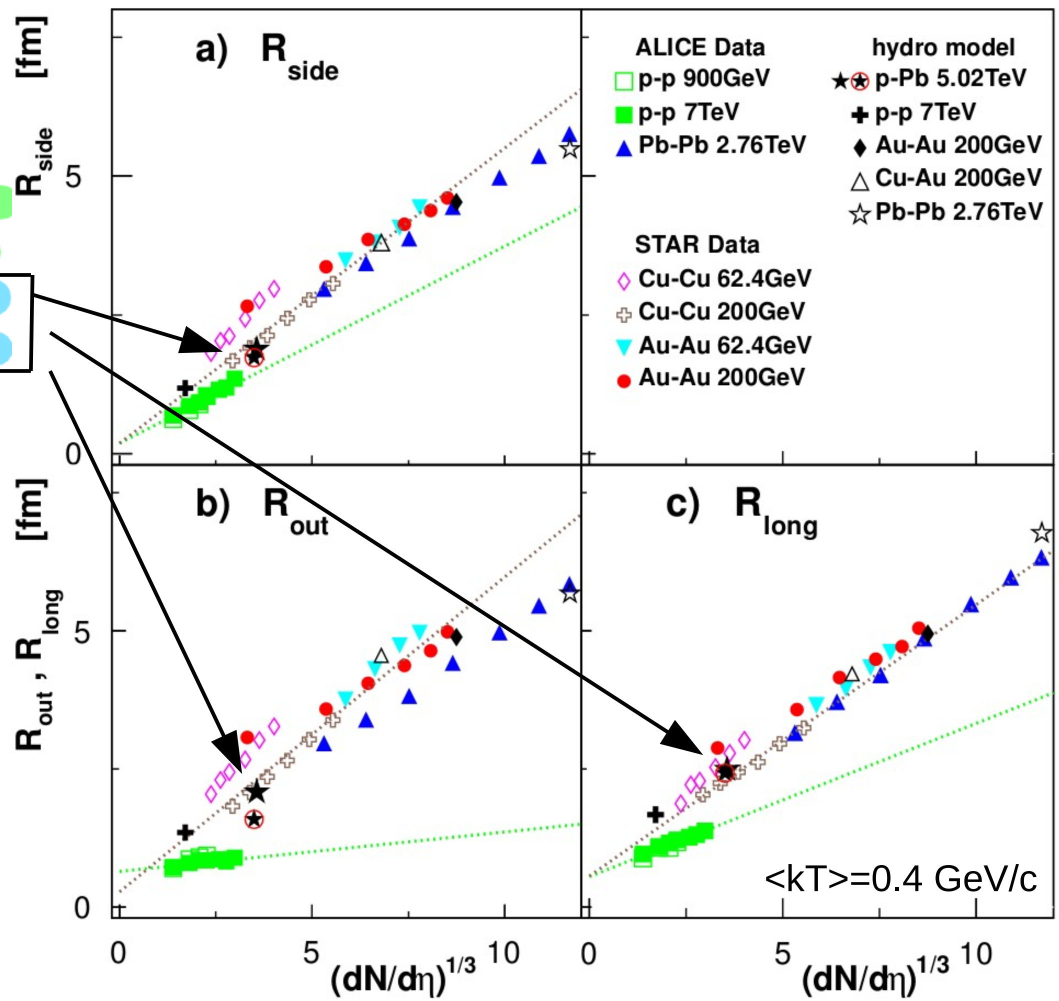
Phys. Lett. B720 (2013) 250
arXiv:1301.3314

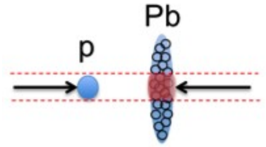
Abstract

The interferometric radii in the system formed in ultra-relativistic proton-lead collisions are investigated in a framework based on event-by-event 3+1 dimensional viscous hydrodynamics. We argue that the most central p-Pb collisions undergoing collective expansion behave similarly to the peripheral nucleus-nucleus collisions. The interferometric observables can serve as signatures of the formation of an extended fireball.

To conclude, we state again the importance of the experimental femtoscopic measurements for the p-A system, which will help to determine the nature of its dynamics. The proximity to the A-A scaling line of Fig. 1 will place the system in the collective evolution mode, on the other hand, if it turns out to be close to the p-p line, elementary dynamics will be vivid. Our simple hydrodynamic calculation for the most central p-Pb system gives radii consistent with the A-A scaling. We should note, however, that in a more realistic treatment we expect some deviations due to remnants from the elementary p-p collisions, as modeled for instance in the core-corona picture. We also note that if a large size fireball is found, it could be used in quenching models to be compared with the R_{AA} data.

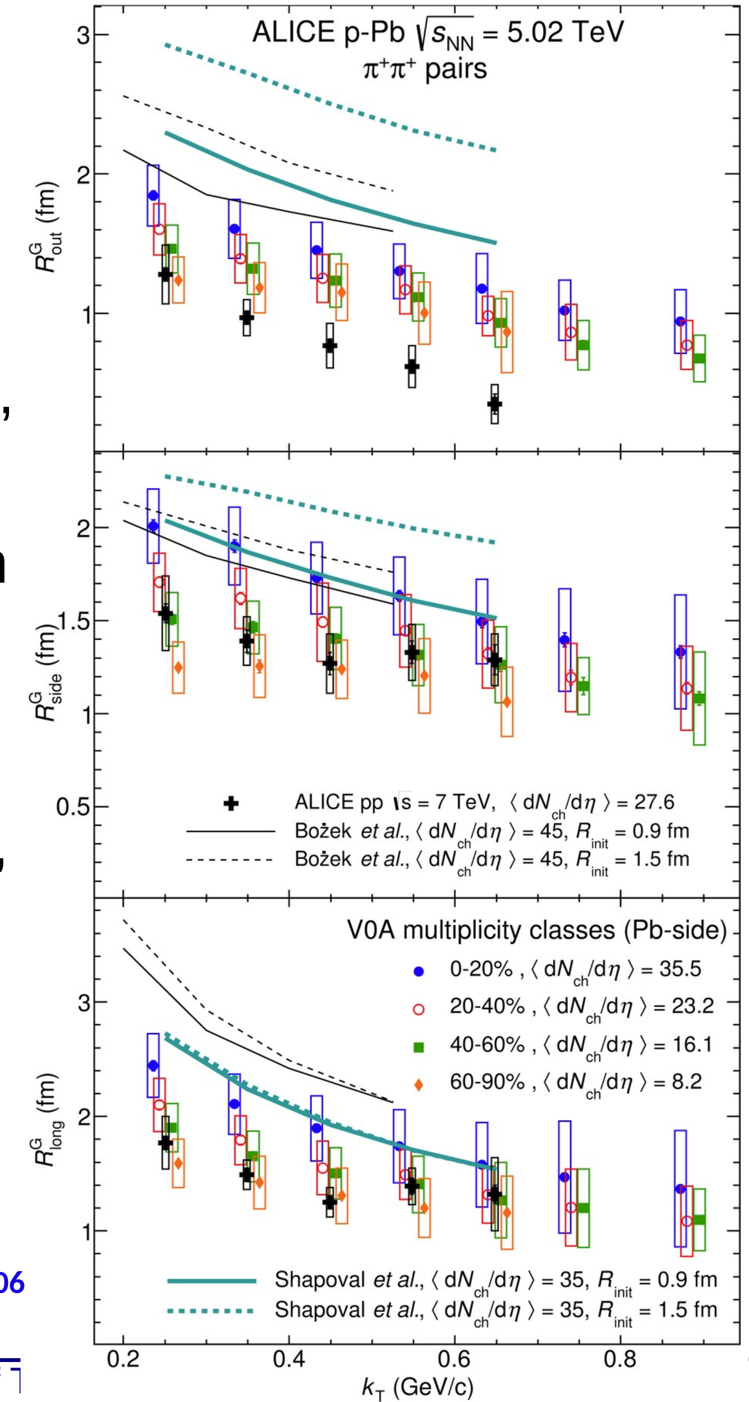
- Hydro predictions for p-Pb consistent with Pb-Pb scaling?



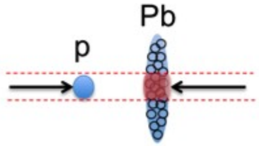


p-Pb: Comparison with hydro calculations

- Two calculations assuming the existence of a collectively expanding system.
- Initial transverse size assumptions: R_{init} = 0.9 fm and R_{init} = 1.5 fm.
- Scenarios with lower initial size closer to the data, but still above.
- Slope of the k_T dependence comparable between all calculations and data:
  - R_{out} predictions universally higher,
  - R_{side} predictions in good agreement with data,
  - R_{long} – calculations from Bożek *et al.* higher ~30%, Shapoval *et al.* only slightly higher.



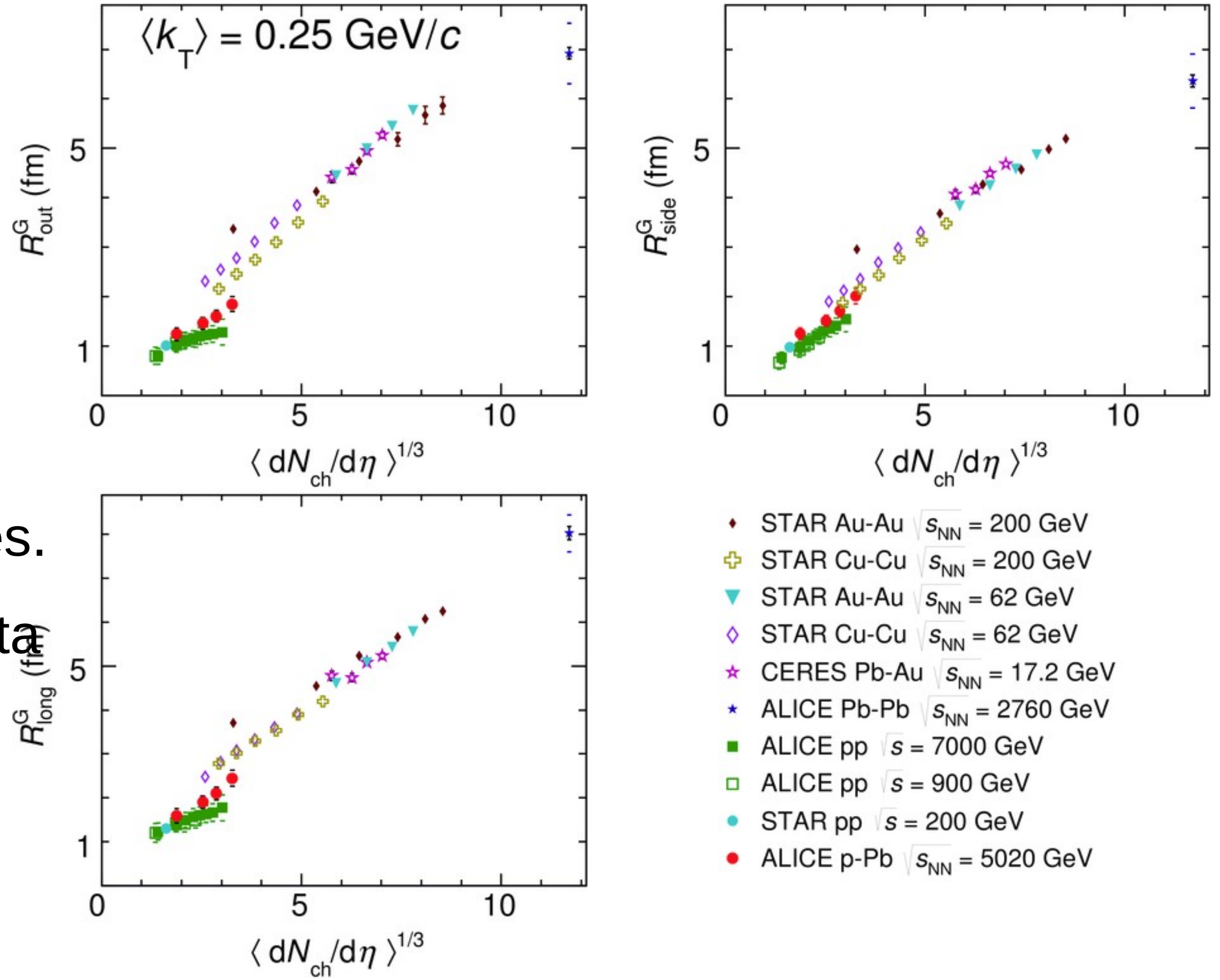
Phys.Rev.C 91 (2015) 034906
ALICE: arXiv:1502.00559



p-Pb: Comparison with world data

- Femtoscopic radii scale approximately with cube root of multiplicity.
- Scaling for pp is clearly different compared to heavy ions.
- Radii from p-Pb collisions agree with pp for low multiplicities and start to diverge at higher multiplicities.
- Interpretation of the p-Pb data is still an open question.
- For details see: arXiv:1502.00559 [nucl-ex]

ALICE Collaboration
Phys. Rev. C 91 (2015), 034906

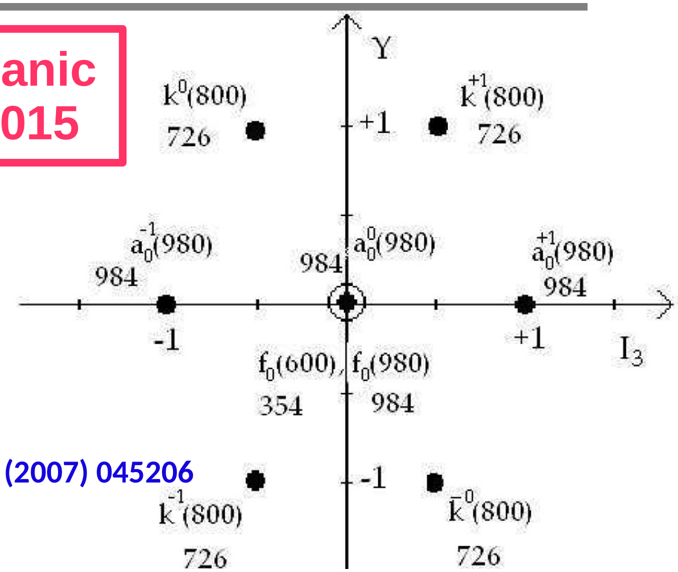


Phys.Rev.C 91 (2015) 034906
ALICE: arXiv:1502.00559

Pb-Pb: K^0_s-$K^\pm$ analysis

T. Hummanic WPCF 2015

- **Pair-wise interactions:**
  - No Coulomb
  - No Quantum Statistics
  - Only Strong FSI through $a_0(980)$ resonance
- **K^0_s-$K^\pm$ has never been published before**



Phys.Rev.C 75 (2007) 045206

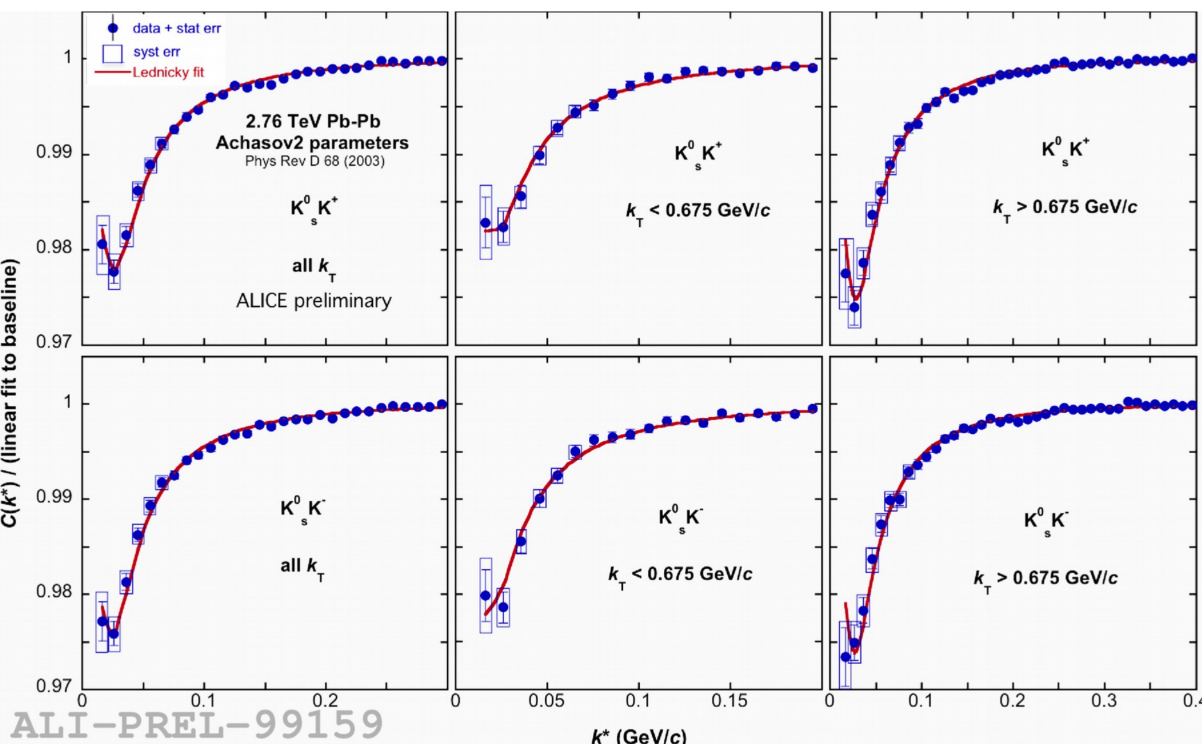
Figure 3: Schematic graph of the fundamental tetraquark nonet. The theoretical masses (in MeV), predicted according to Equation (22), are reported below each resonance.

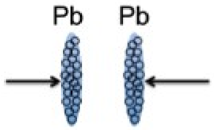
What could be learned?

- Extract R using only the $a_0(980)$ FSI
- Since

$$|K^0_S\rangle = \frac{1}{\sqrt{2}}\left(|K^0\rangle + |\overline{K^0}\rangle\right) \rightarrow \left.\begin{array}{l} K^0_S K^+ \rightarrow \overline{K^0}\, K^+ \\ K^0_S K^- \rightarrow K^0 K^- \end{array}\right\} \text{only these pairs pass through the } a_0(980)$$

  are there any differences in the source parameters?
- Study properties of the $a_0(980)$ resonance
  - Decay decoupling parameters and mass
  - $a_0(980)$ is a **tetraquark candidate**

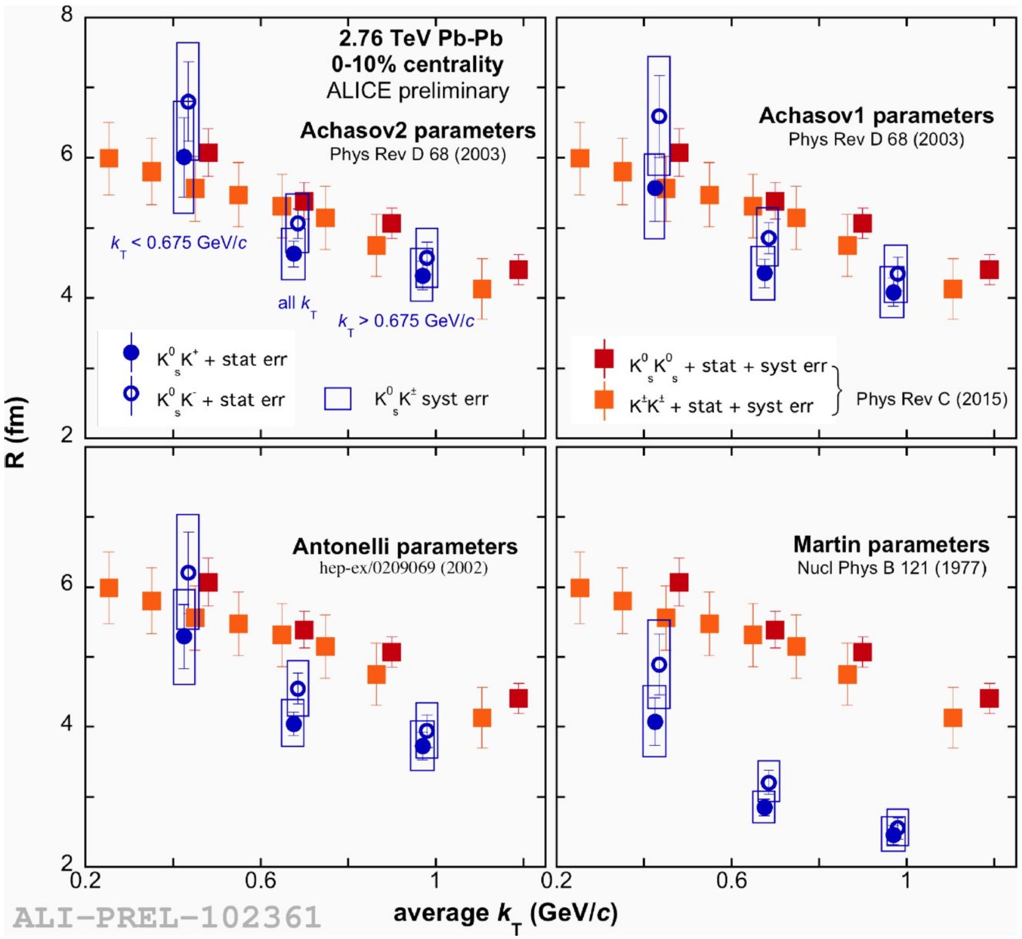


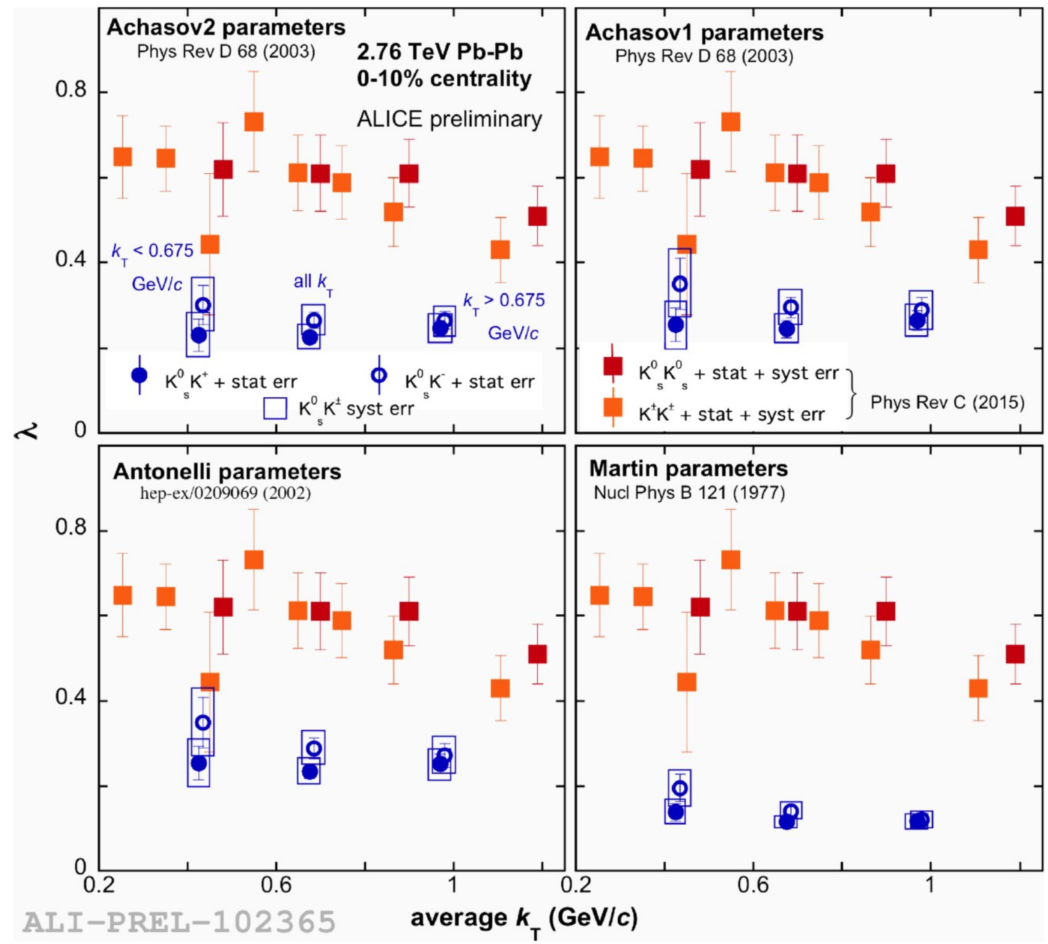


Pb-Pb: K^0_s-$K^\pm$ analysis

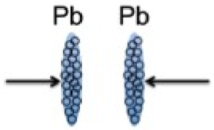
T. Hummanic
WPCF 2015

Results for R and λ for separate $K^0_sK^+$ and $K^0_sK^-$





A slight tendency for $R(K^0_sK^-) > R(K^0_sK^+)$ is seen, but the difference is not significant, i.e. within the error bars

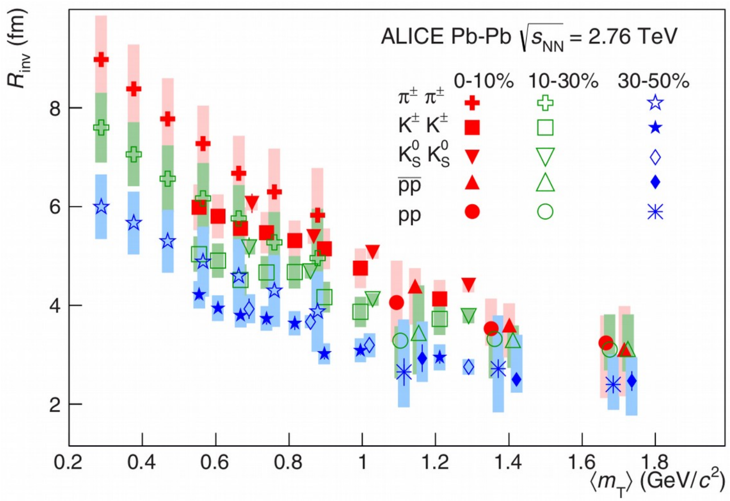


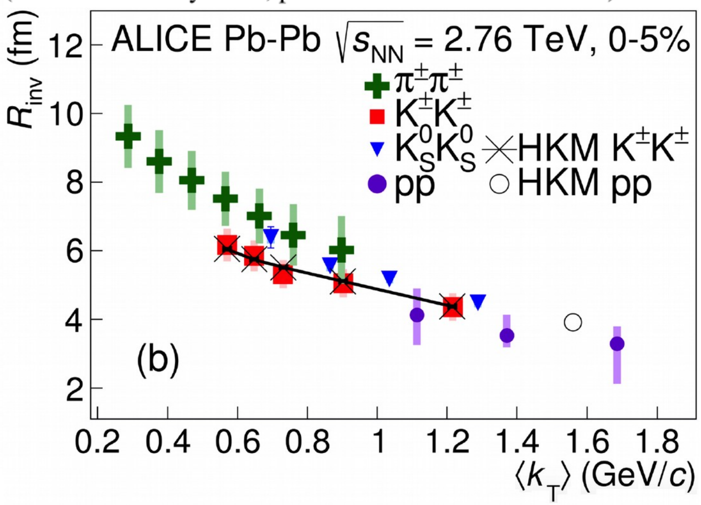
Pb-Pb: pion, kaon, proton correlations

PHYSICAL REVIEW C **92**, 054908 (2015)

One-dimensional pion, kaon, and proton femtoscopy in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

J. Adam *et al.**
(ALICE Collaboration)
(Received 30 July 2015; published 19 November 2015)





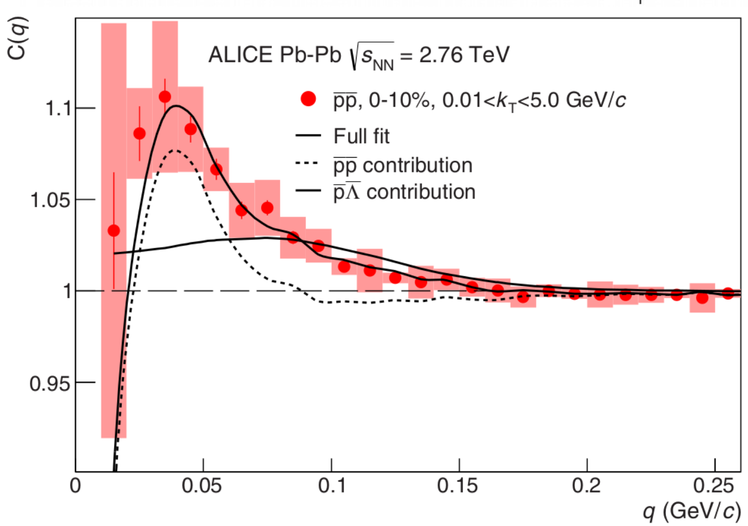


FIG. 6. (Color online) Example correlation function with fit for $\bar{p}\bar{p}$ for centrality 0–10% and $\langle k_T \rangle = 1.0$ GeV/c. Statistical (thin lines) and systematic (boxes) uncertainties are shown. The main source of systematic uncertainty is the variation of two-track cuts.

The experimental correlation function of pp and $\bar{p}\bar{p}$ systems were fitted with [45]

$$C_{\text{meas}}(q_{\text{pp}}) = 1 + \lambda_{\text{pp}}[C_{\text{pp}}(q_{\text{pp}}; R) - 1] + \lambda_{\text{p}\Lambda}[C_{\text{p}\Lambda}(q_{\text{pp}}; R) - 1], \tag{10}$$

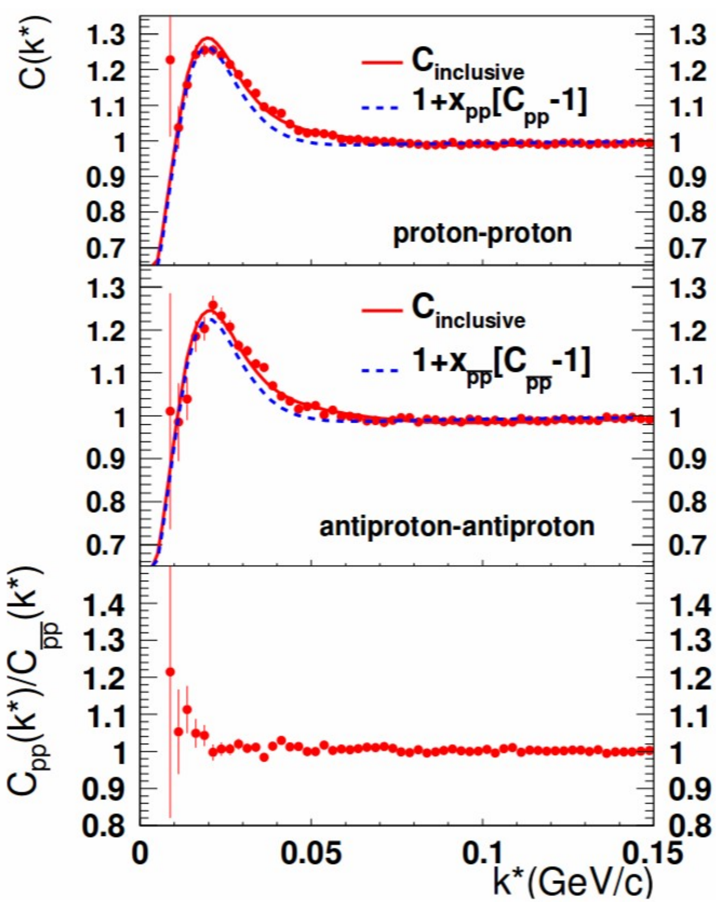
where λ_{pp} is the fraction of correlated pp pairs where both particles are primary, and $\lambda_{\text{p}\Lambda}$ is the fraction of correlated pp pairs where one particle is primary and the other is a daughter of Λ decay. The theoretical proton-proton correlation function was calculated as

$$C(q_{\text{pp}}) = \frac{1}{4}\left[\frac{\int S(\mathbf{r}^*)\frac{1}{2}\left|\Psi^S_{-\mathbf{q}_{\text{pp}}}(\mathbf{r}^*) + \Psi^S_{+\mathbf{q}_{\text{pp}}}(\mathbf{r}^*)\right|^2}{\int S(\mathbf{r}^*)}\right] + \frac{3}{4}\left[\frac{\int S(\mathbf{r}^*)\frac{1}{2}\left|\Psi^T_{-\mathbf{q}_{\text{pp}}}(\mathbf{r}^*) - \Psi^T_{+\mathbf{q}_{\text{pp}}}(\mathbf{r}^*)\right|^2}{\int S(\mathbf{r}^*)}\right]. \tag{11}$$

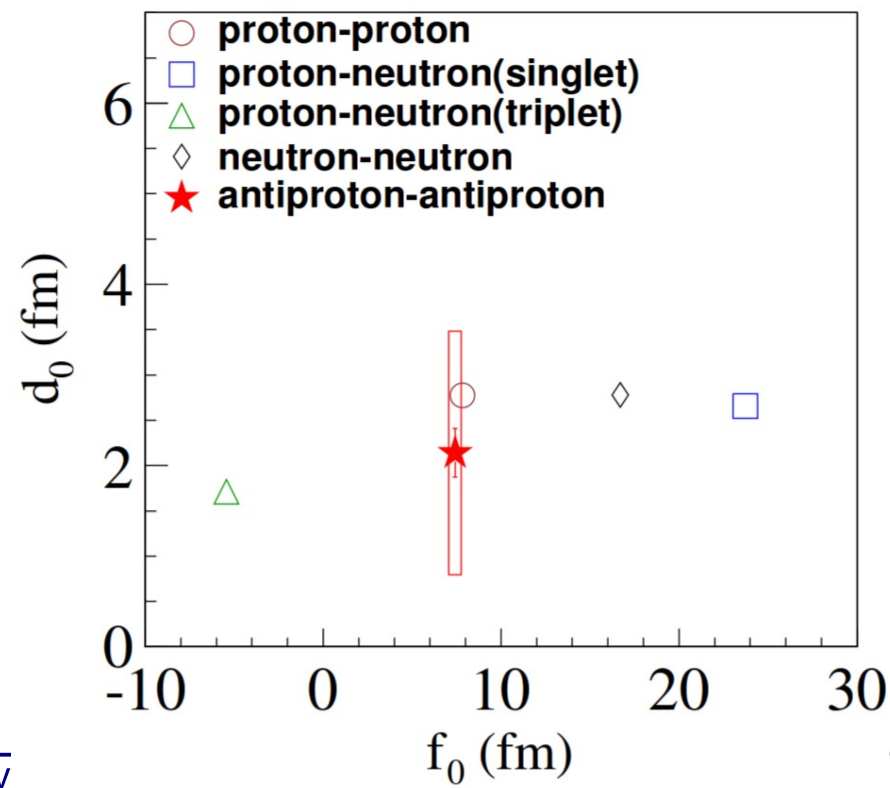
- Radii decrease with m_T → radial flow
- $R_\pi > R_K$ due to pion Lorentz factor
- R_p compatible with R_K at same m_T
- Radii for kaons show good agreement with HKM predictions for $K^{\pm}K^{\pm}$ (Nucl.Phys.A929 (2014))

Au-Au: pp and $\bar{p}\bar{p}$ correlations – STAR

Figure 4 presents the first measurement of the antiproton-antiproton interaction, together with prior measurements for nucleon-nucleon interactions. Within errors, the f_0 and d_0 for the antiproton-antiproton interaction are consistent with their antiparticle counterparts – the ones for the proton-proton interaction. Our measurements provide parameterization input for describing the



STAR Collaboration
Nature 527,345-348 (2015)



Are (anti)baryons important? YES

LETTER **BASE experiment** OPEN

doi:10.1038/nature14861

nature

High-precision comparison of the antiproton-to-proton charge-to-mass ratio

S. Ulmer[1],
Y. Matsud

Invariance
formation[1]
model of
fundament
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Search for potential CPT symmetry breaking

LETTER **STAR**

doi:10.1038/nature15724

Measurement of interaction between antiprotons

The STAR Collaboration*

One of the primary goals of nuclear physics is to understand t
force between nucleons, which is a necessary step for understandi
the structure of nuclei and how nuclei interact with each oth
Rutherford discovered the atomic nucleus in 1911, and the lar
body of knowledge about the nuclear force that has since be
acquired was derived from studies made on nucleons or nucl
Although antinuclei up to antihelium-4 have been discovere
and their masses measured, little is known directly about t
nuclear force between antinucleons. Here, we study antiprot
pair correlations among data collected by the STAR experimer
at the Relativistic Heavy Ion Collider (RHIC)[3], where gold io
are collided with a centre-of-mass energy of 200 gigaelectronvo
per nucleon pair. Antiprotons are abundantly produced in su
collisions, thus making it feasible to study details of the antiproto
antiproton interaction. By applying a technique similar to Hanbu
Brown and Twiss intensity interferometry[4], we show that the for
between two antiprotons is attractive. In addition, we repo
two key parameters that characterize the corresponding stro
interaction: the scattering length and the effective range of t
interaction. Our measured parameters are consistent within erro
with the corresponding values for proton–proton interactions. O
results provide direct information on the interaction between tw
antiprotons, one of the simplest systems of antinucleons, and
are fundamental to understanding the structure of more-compl

nature physics **ALICE** LETTERS
PUBLISHED ONLINE: 17 AUGUST 2015 | DOI: 10.1038/NPHYS3432

OPEN

Precision measurement of the mass difference between light nuclei and anti-nuclei

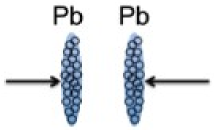
ALICE Collaboration†

The measurement of the mass differences for systems bound by the strong force has reached a very high precision with protons and anti-protons[1,2]. The extension of such measurement from (anti-)baryons to (anti-)nuclei allows one to probe any difference in the interactions between nucleons and anti-nucleons encoded in the (anti-)nuclei masses. This force is a remnant of the underlying strong interaction among quarks and gluons and can be described by effective theories[3], but cannot yet be directly derived from quantum chromodynamics. Here we report a measurement of the difference between the ratios of the mass and charge of deuterons (d) and anti-deuterons ($\overline{d}$), and ^{3}He and $^3\overline{He}$ nuclei carried out with the ALICE (A Large Ion Collider Experiment)[4] detector in Pb-Pb collisions at a centre-of-mass energy per nucleon pair of 2.76 TeV. Our direct measurement of the mass-over-charge differences confirms

and specific energy loss (dE/dx) measurements, and the TOF (tim
of flight)[23] detector to measure the time t_{TOF} needed by each track
to traverse the detector. The combined ITS and TPC information i
used to determine the track length (L) and the rigidity (p/z, where
is the momentum and z the electric charge in units of the elementar
charge e) of the charged particles in the solenoidal 0.5 T magnetic
field of the ALICE central barrel (pseudo-rapidity $|\eta|<0.8$). On
the basis of these measurements, we can extract the squared mass
over-charge ratio $\mu^2_{TOF}\equiv(m/z)^2_{TOF}=(p/z)^2[(t_{TOF}/L)^2-1/c^2]$. The
choice of this variable is motivated by the fact that μ^2 is directly
proportional to the square of the time of flight, allowing to bette
preserve its Gaussian behaviour.

The high precision of the TOF detector, which determines the
arrival time of the particle with a resolution of 80 ps (ref. 20), allow
us to measure a clear signal for (anti-)protons, (anti-)deuterons and

First results from LHC run II



Pb-Pb: charged-particle multiplicity density

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

ALICE: arXiv:1512.06104

CERN-PH-EP-2015-324
14 December 2015

Centrality dependence of the charged-particle multiplicity density at mid-rapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

ALICE Collaboration*

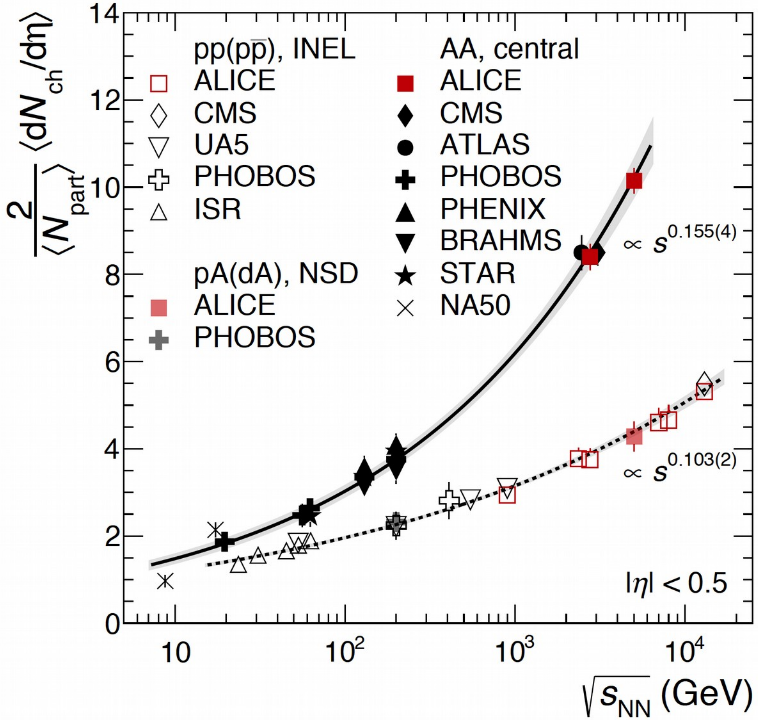


Fig. 1: Values of $\frac{2}{\langle N_{\mathrm{part}}\rangle}\langle dN_{\mathrm{ch}}/d\eta\rangle$ for central Pb–Pb [4–7] and Au–Au [8–12] collisions (see text) as a function of $\sqrt{s_{\mathrm{NN}}}$. Measurements for inelastic pp collisions and p$\bar{\mathrm{p}}$ collisions as a function of $\sqrt{s}$ are also shown [26–28] along with those from non-single diffractive p–A and d–A collisions [29, 30]. The s-dependence, proportional to $s_{\mathrm{NN}}^{0.155}$ for AA collisions is indicated by a solid line: similarly a dashed line shows an $s_{\mathrm{NN}}^{0.103}$ dependence in pp collisions. The shaded bands show the uncertainties on the extracted power-law dependencies. The central Pb–Pb measurements from CMS and ATLAS at 2.76 TeV have been shifted horizontally for clarity.

- Mean $\langle dN_{ch}/d\eta\rangle = 1943 \pm 54$ for $|\eta|<0.5$
- 20% increase of $\langle dN_{ch}/d\eta\rangle$ wrt. 2.76 TeV data, in agreement with power law dependence
- Centrality dependence calculated with Glauber model increased by 1.2 wrt. 2.76 TeV data
- MC models without retuning compared to data, EKRT seems to agree best

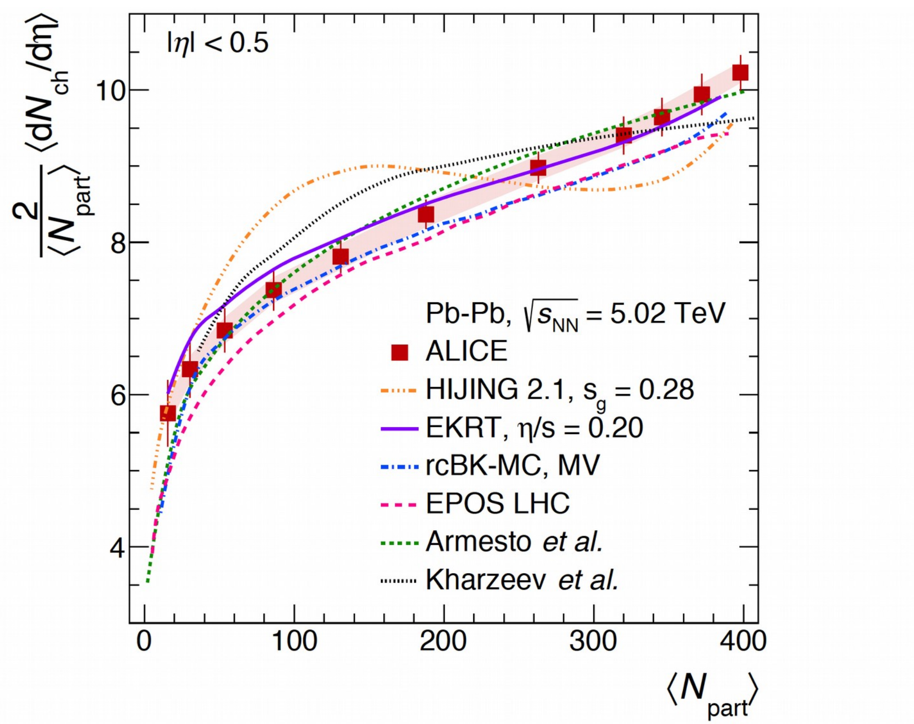


Fig. 3: The $\frac{2}{\langle N_{\mathrm{part}}\rangle}\langle dN_{\mathrm{ch}}/d\eta\rangle$ for Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV in the centrality range 0-80%, as function of $\langle N_{\mathrm{part}}\rangle$ in each centrality class, compared to model predictions [31–39].

Summary

- Angular correlations:
  - **Double ridge** structure measured in p-Pb, extends to large rapidities with v_2 larger in the Pb-going direction (muon-hadron correlations)
  - **Mass ordering of v_2 in p-Pb**, consistent with hydro predictions → **signature of collectivity?**
  - Surprising **anticorrelation structure for proton pairs** in pp collisions resembling e^+e^- results at much lower energies → suggesting a **fundamental mechanism forbidding production of two baryons in a single fragmentation**
- Femtoscopic measurements:
  - 3D pion femtoscopy measured in p-Pb collisions → source size similar to pp at low multiplicity, multiplicity scaling of p-Pb radii different from pp and resembling Pb-Pb, data compared to hydro predictions favor lower initial size, **interpretation still an open question**
  - **First time K^0_s-$K^{\pm}$ femtoscopy measured** → $a_0(980)$ FSI gives excellent representation of the signal, a_0 a tetraquark state?
  - 1D pion, kaon, proton femtoscopy measured in Pb-Pb → clear **m_T scaling observed**, **pp and $\overline{p}p$ correlations measured for the first time** (before STAR Nature paper)
- **Correlations of baryons reveal interesting features** and baryons in general seem to be of great importance (recent Nature publications)
- **First results from LHC run II, Pb-Pb collisions at $\sqrt{s}$ = 5.02 TeV**, more to come – stay tuned!

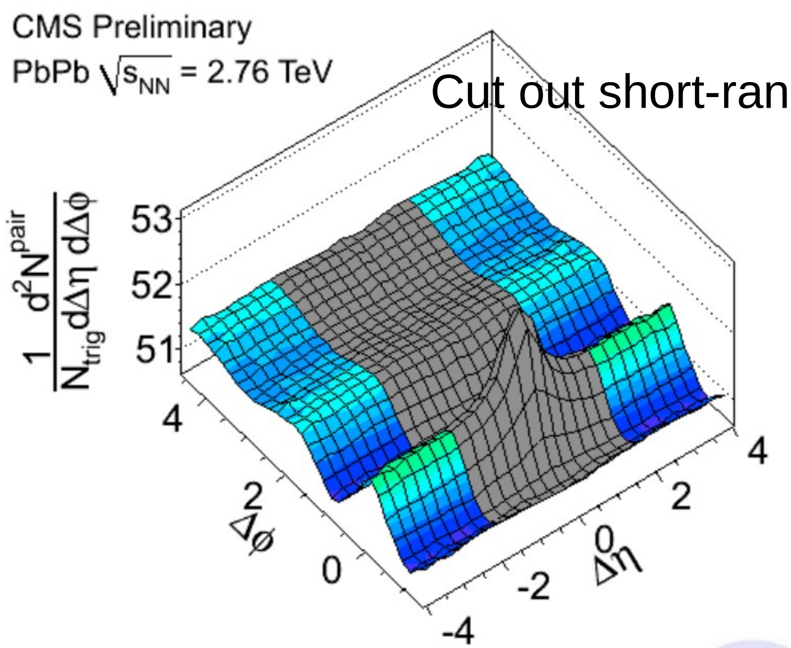
THANK YOU!

lgraczyk@cern.ch, lgraczyk@if.pw.edu.pl

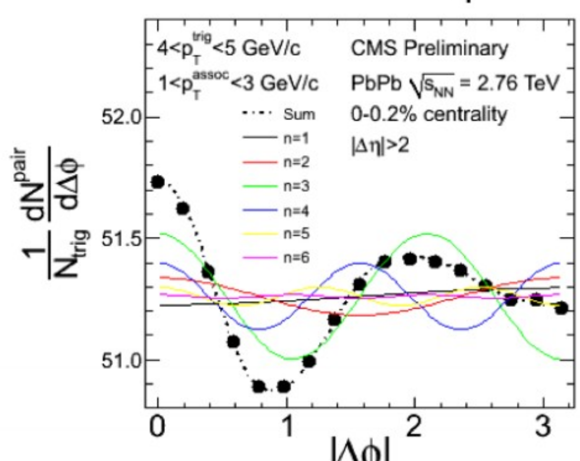
Collective effects: flow

Fourier decomposition:

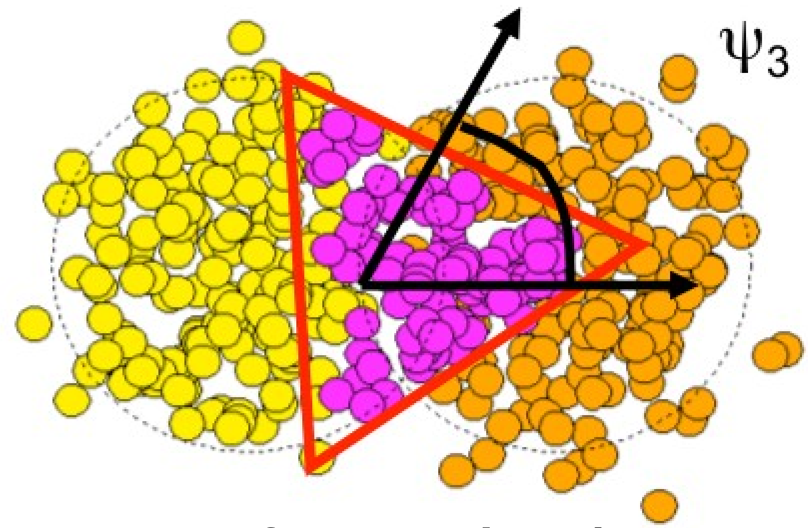
$$\frac{1}{N_{trig}}\frac{dN^{pair}}{d\Delta\Phi}=\frac{N_{assoc}}{2\pi}\left\{1+\sum_{n=1}^{\infty}2V_{n\Delta}\cos(n\Delta\Phi)\right\}$$



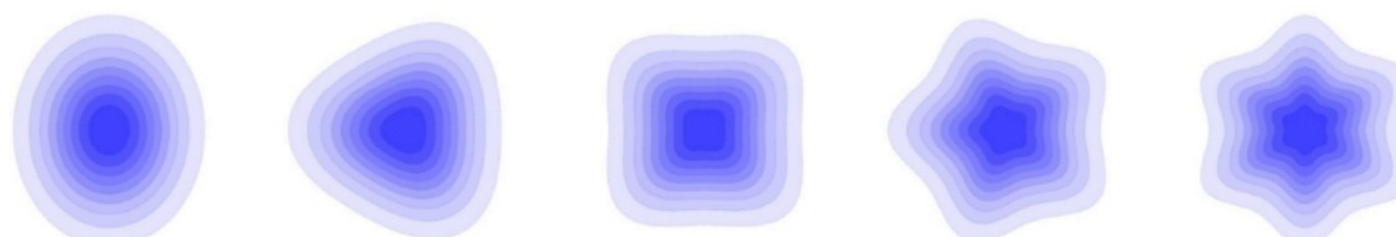
Cut out short-range



<u>Precise measurements at the LHC:</u>
higher harmonics due to
fluctuations of initial conditions

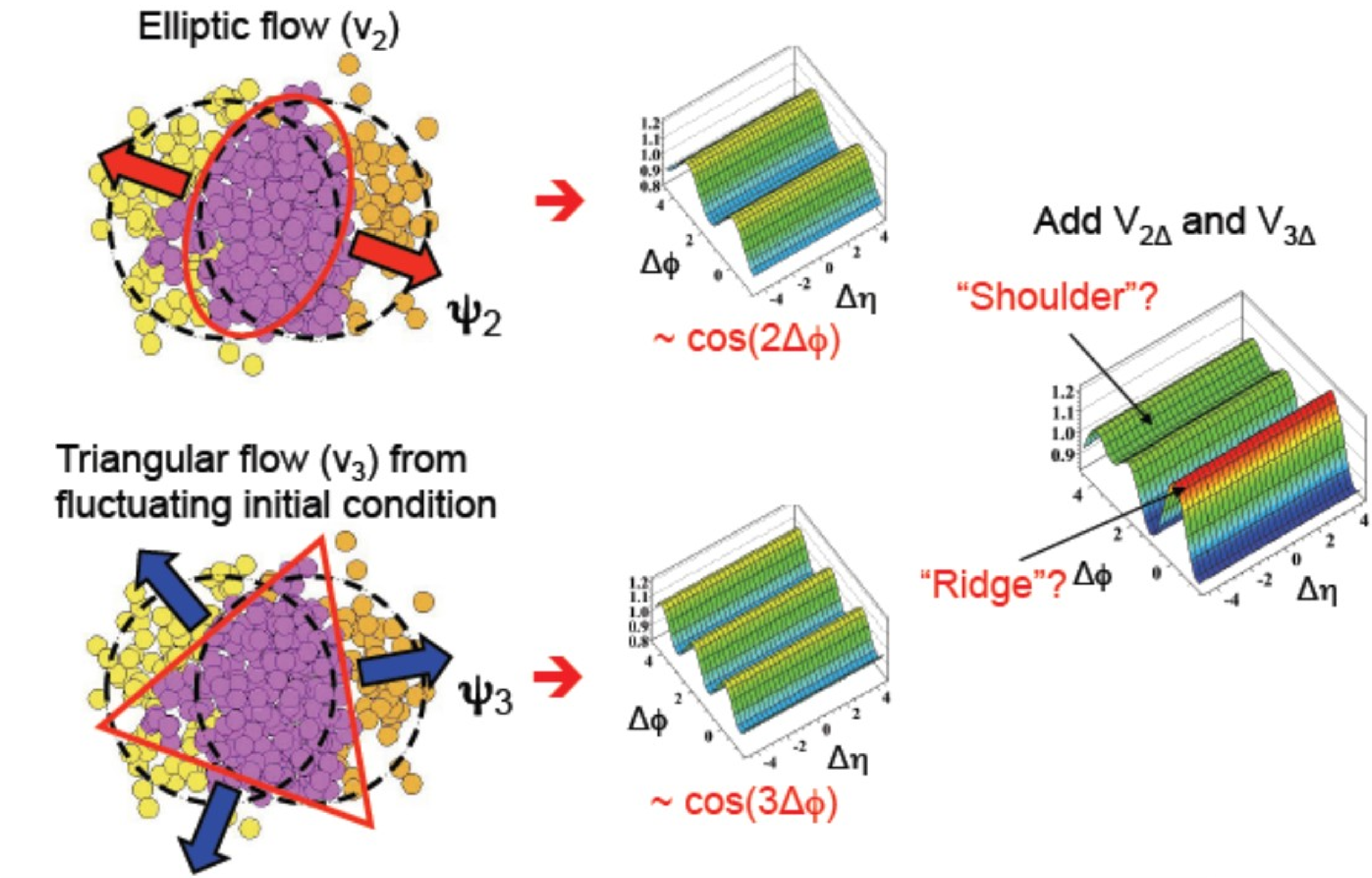


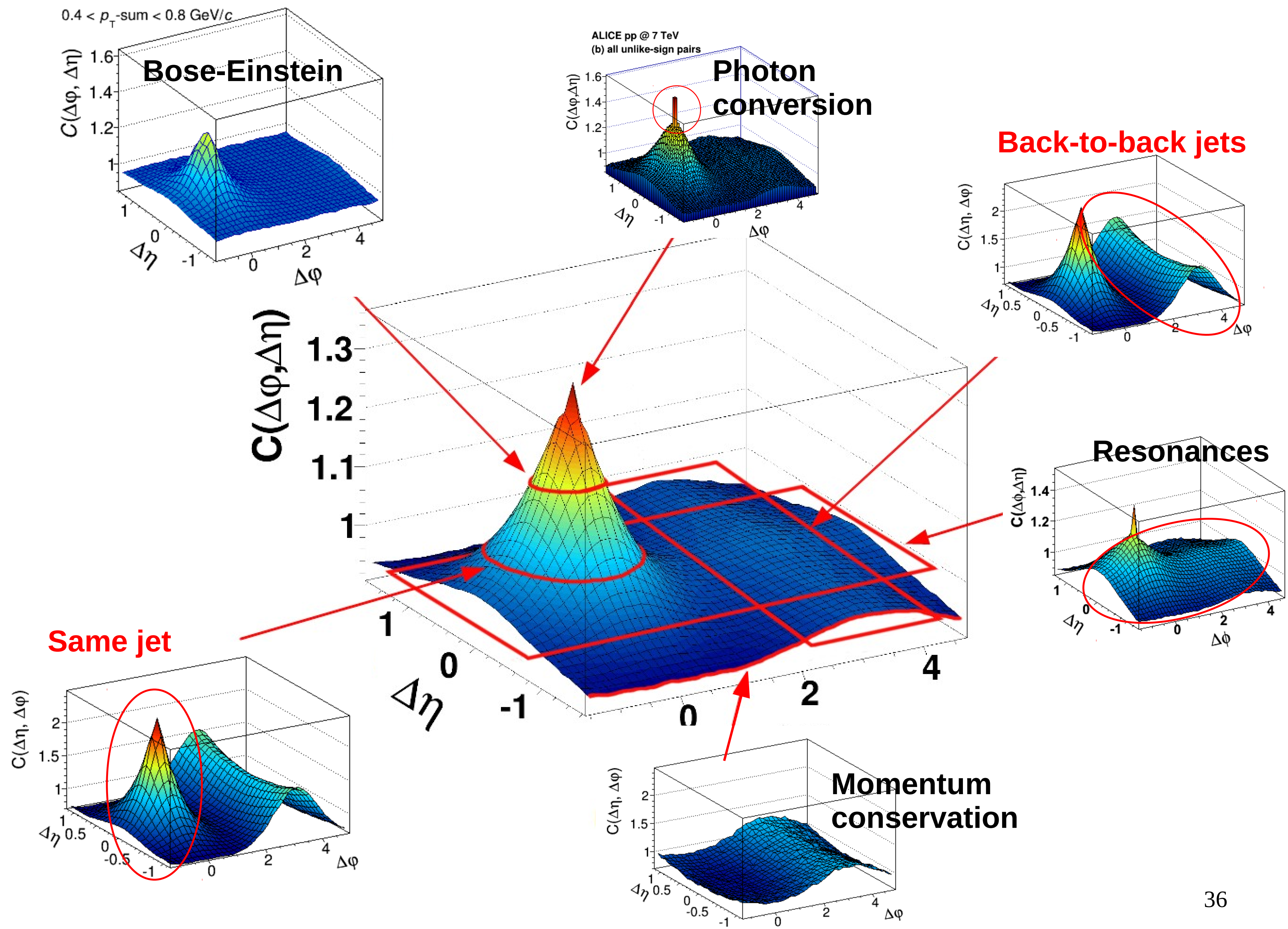
<u>Pre-LHC</u>: **fancy explanations**
- Double ridge?
- Mach cones?



n = 2 n = 3 n = 4 n = 5 n = 6

Collective effects: flow




Bose-Einstein
0.4 < p_T-sum < 0.8 GeV/c
Photon conversion
ALICE pp @ 7 TeV
(b) all unlike-sign pairs
Back-to-back jets
Resonances
Same jet
Momentum conservation
C(Δφ,Δη)
Δη
Δφ
36

Properties of quark jets

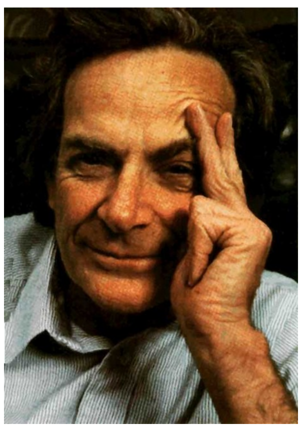
The story starts with **Richard Feynman**... Field-Feynman hadronization model

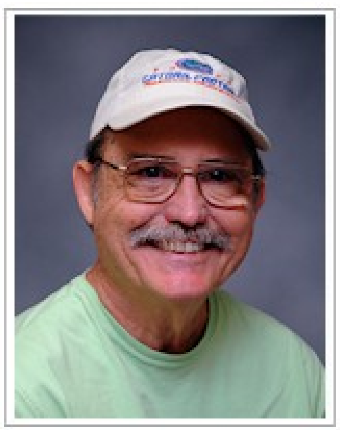
Nuclear Physics B136 (1978) 1–76

A PARAMETRIZATION OF THE PROPERTIES OF QUARK JETS *

R.D. FIELD and R.P. FEYNMAN
California Institute of Technology, Pasadena, California 91125, USA

Received 11 October 1977





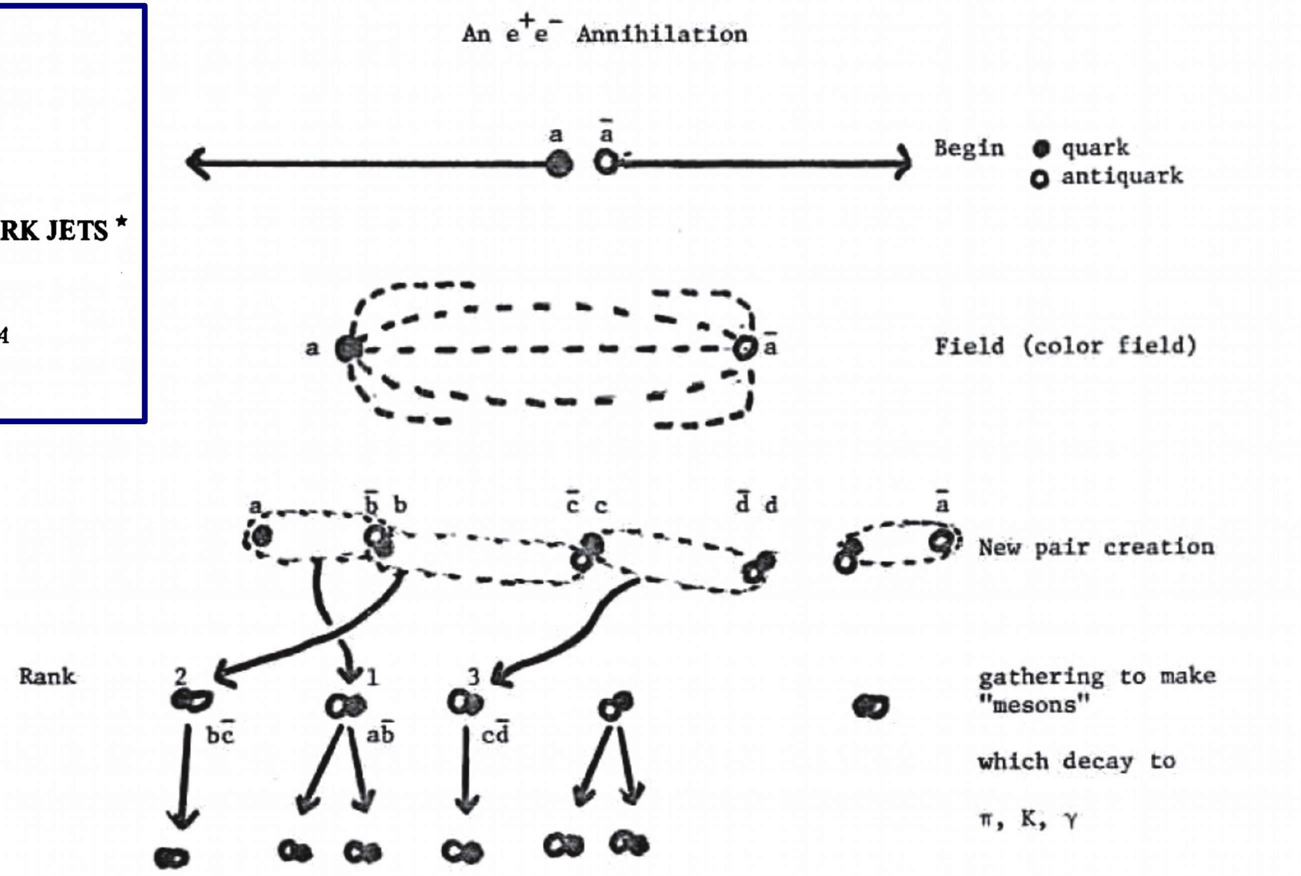


Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

from R.D. Field, International Journal of Modern Physics A, Vol. 30, No. 1 (2015) 1530005

Properties of quark jets

Two primary hadrons with the same
- baryon number
- (or) charge
- (or) strangeness

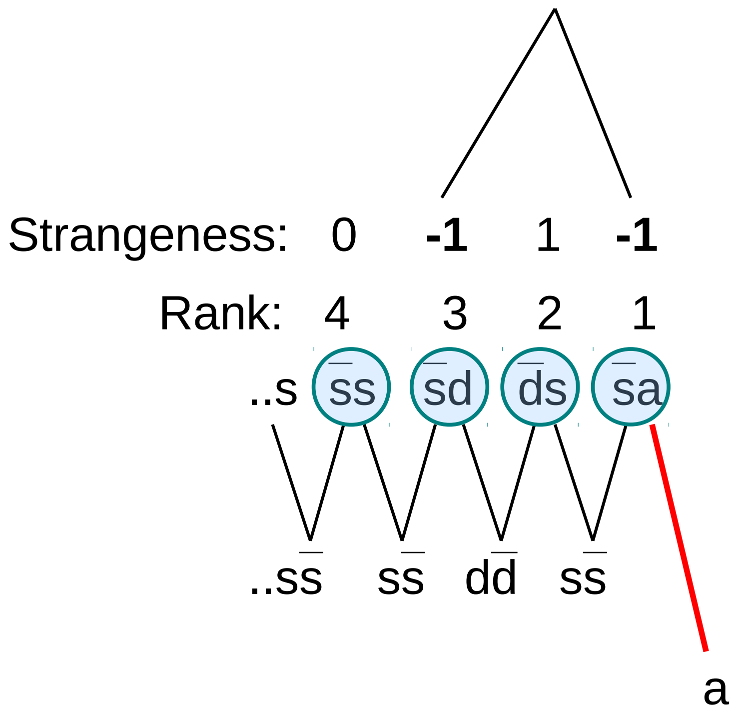
are **separated** by at least two steps is rank.

We are not likely to find two baryons/strange particles or two antibaryons/anti-strange particles at the same rapidity*.

Modern models (like Lund string mode used in PYTHIA) are derived from FF model.

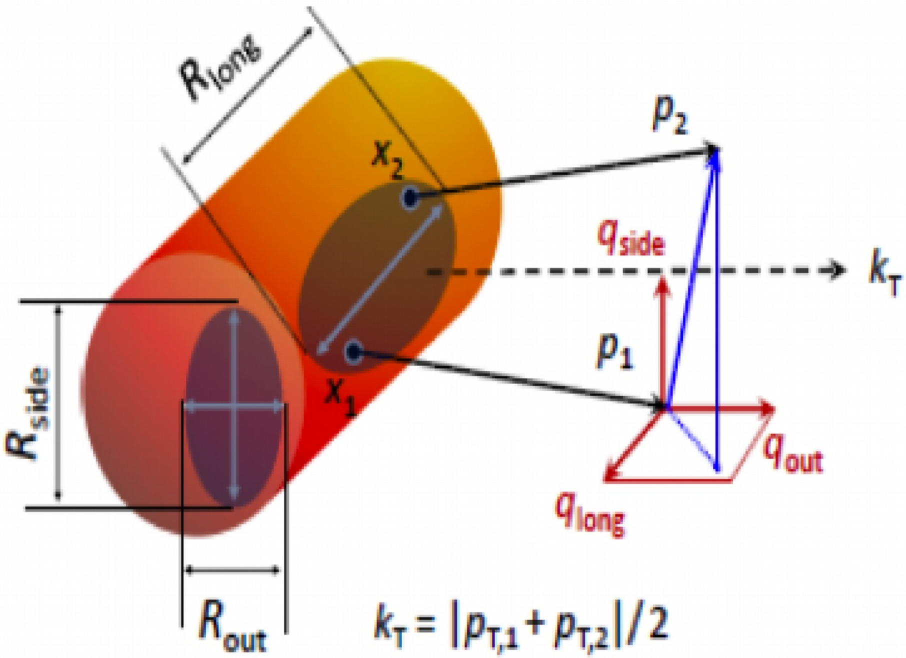
Example

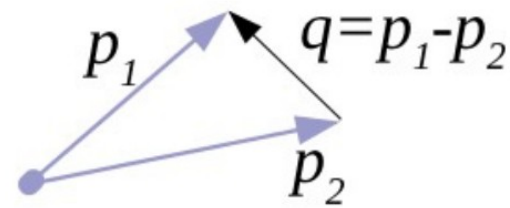
The same strangeness:
3 – 1 = 2 steps in rank



*) Provided that the order of particles in rapidity closely reflects their order in rank

Femtoscopy technique





The Koonin-Pratt formula
(S.E. Koonin, PLB70 (1977) 43; S.Pratt et al., PRC42 (1990) 2646)

$$C(\vec{q}) = \int S(\boldsymbol{r}) |\Psi(\vec{q}, \boldsymbol{r})|^2 d^4 r$$

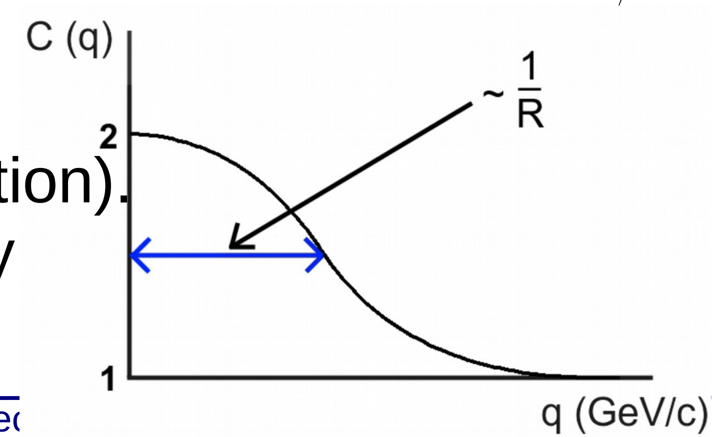
$$S(\boldsymbol{r}) \sim \exp\left(\frac{-r_{out}^2}{4R_o^2} - \frac{r_{side}^2}{4R_s^2} - \frac{r_{long}^2}{4R_l^2} \right)$$

$$|\Psi(\vec{q}, \boldsymbol{r})|^2 = 1 + \cos(\vec{q}\,\vec{r})$$

$$C = 1 + \lambda \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2)$$

with Coulomb – Bowler-Sinyukov formula:

$$C = (1-\lambda) + \lambda K \left(1 + \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2)\right)$$



- The size *R* is a **variance of single-particle emission function** (emission probabilit distribution).
- The width of the correlation function is inversely proportional to *R*.

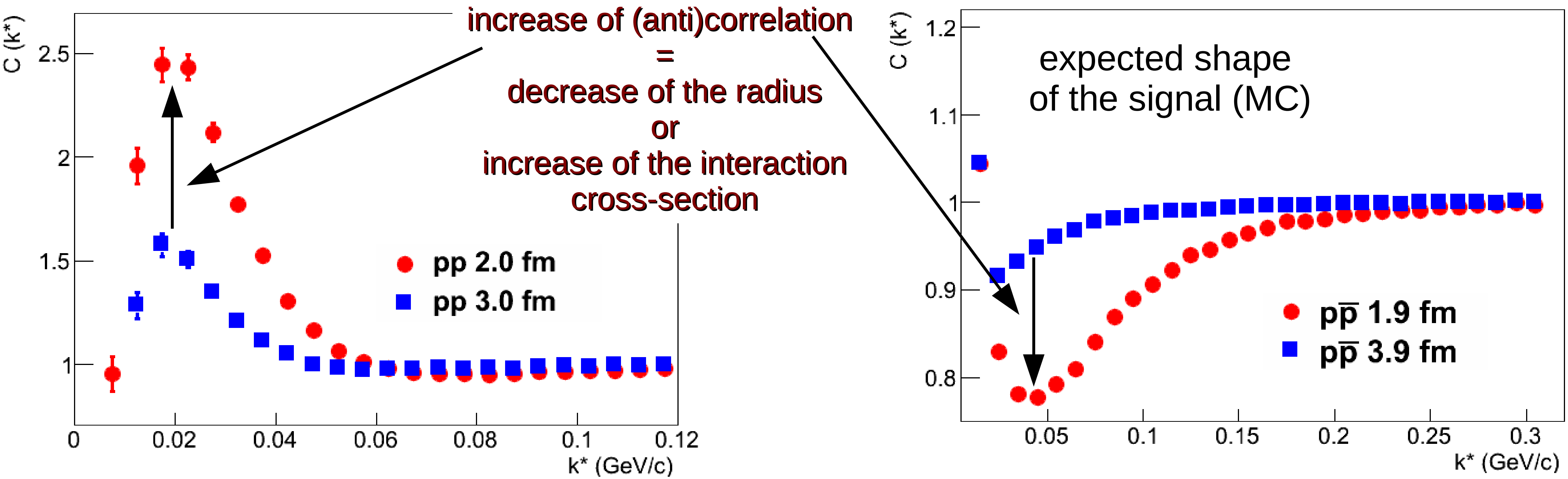
Baryon femtoscopy

$$C(\vec{q}) = \int S(\vec{r})\,|\Psi(\vec{q},\vec{r})|^2\, d^4 r$$

measured correlation

two-particle emission function
(radius – width of the function)

cross-section



- For protons, cross-sections known, only radius can change.
- For others ($p\bar{\Lambda}$, $\Lambda\Lambda$, $\Lambda\bar{\Lambda}$), the radius and the cross-section not known (or known with large uncertainties) → only one can be a free parameter; cross-sections can be obtained with constraints from pp analysis.
- Test of CPT symmetry (precise measurements of $\overline{bb}$ pairs wrt. to bb)

A. Kisiel
Quark Matter 2015

Baryon production in HIC

- Comparable number of baryons and anti-baryons at RHIC and LHC, low-p_T PID (STAR, ALICE)
- Yields lower than chemical model calculations
  - Proton (and Lambda) yield in Pb-Pb at LHC below thermal model expectations (extrapolated from RHIC)
  - Models: annihilation in "rescattering" phase influences yields – (codes which include "hadronic rescattering": UrQMD, EPOS)
  - Steinheimer, Aichelin, Bleicher; Phys.Rev.Lett. 110 (2013) 4, 042501
  - Werner et al.; Phys.Rev. C85 (2012) 064907
  - Karpenko, Sinyukov, Werner; Phys.Rev. C87 (2013) 2, 024914
  - But … annihilation cross-sections only measured for $p\bar{p}$, $\bar{p}n$, and $\bar{p}d$
  - Annihilation **is** the source of the femtoscopic correlation observed for many $B\bar{B}$ pairs – must be observed if this explanation is correct.