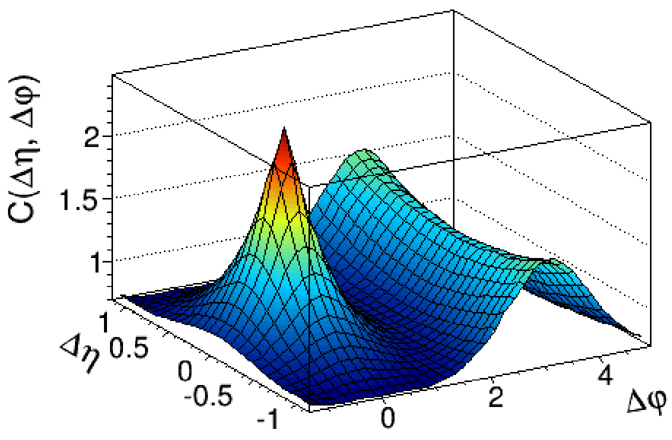
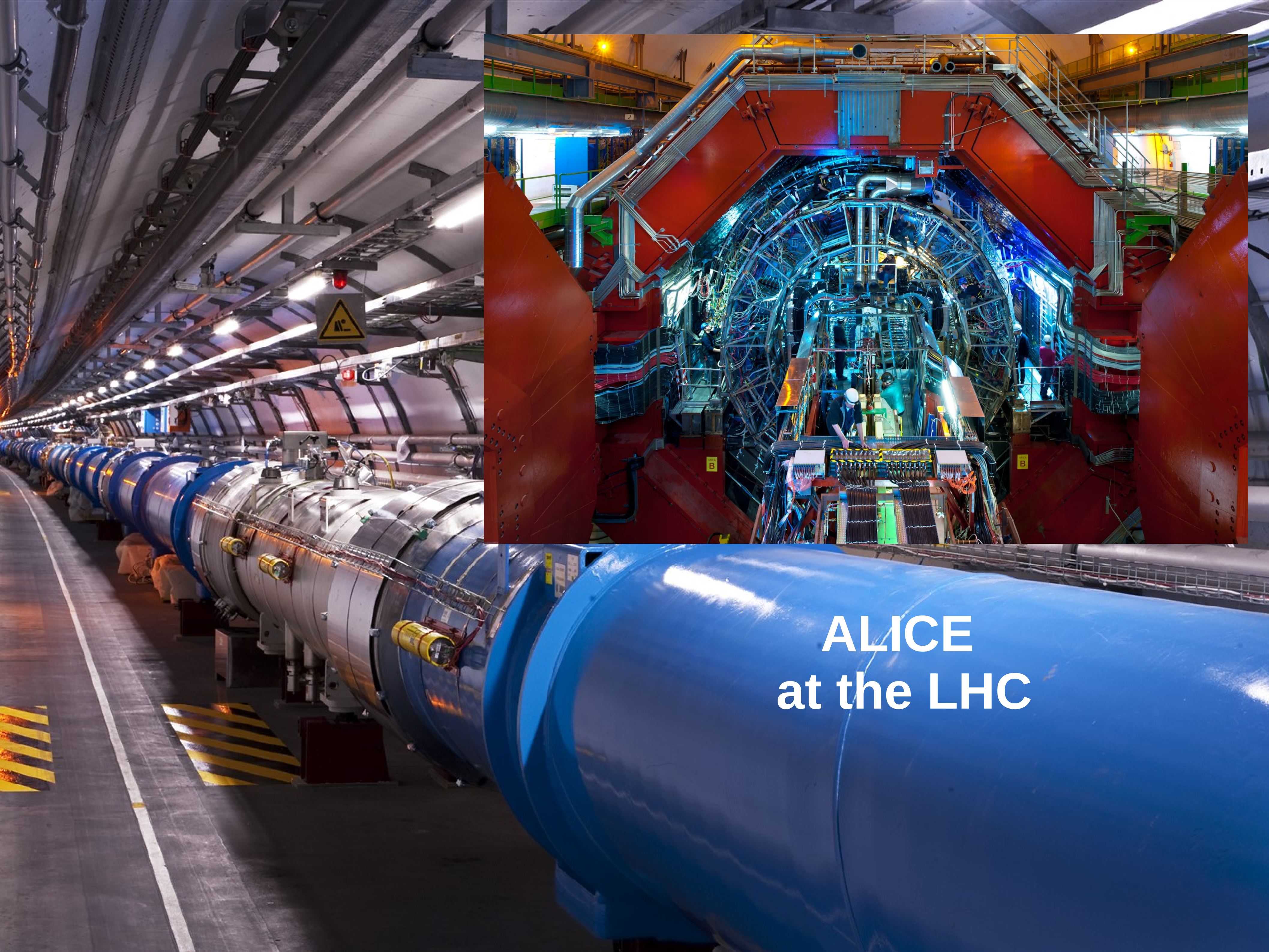
Correlations in ALICE: research activities of the Warsaw University of Technology group

Małgorzata Janik



Faculty of Physics
Warsaw University of Technology

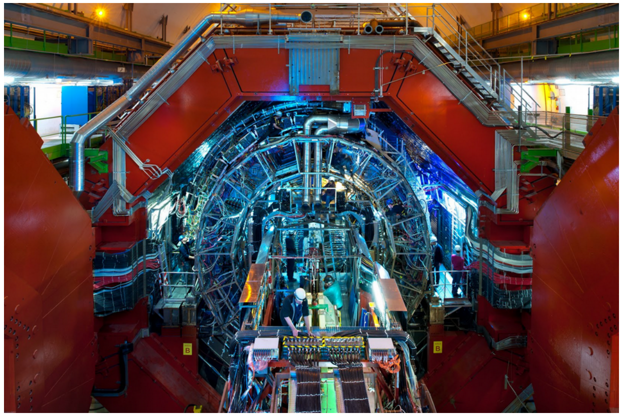
NICA Days
7.11.2017



ALICE at the LHC

WUT group in ALICE

- **Team Leader: Adam Kisiel**
- Members (staff): A. Kisiel, Ł. Graczykowski, M. Janik, J. Pluta, H. Zbroszczyk, J. Oleniacz, J. Myrcha, T. Trzciński, P. Rokita
- **ALICE group specializes in particle correlations and femtoscopy**
- **Femtoscopy Physics Analysis Group**
  - Convenors: **Łukasz Graczykowski (WUT)**, Tom Humanic
- **Correlations Physics Analysis Group**
  - Convenors: **Małgorzata Janik (WUT)**, Alice Ohlson
- **Visualization & Machine learning**
  - Julian Myrcha, Tomasz Trzciński, Przemysław Rokita



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Nica Days 2017

Baryon-(anti-)baryon interaction measurement with femtoscopy, A. Kisiel

Non-identical particle femtoscopy in STAR, M. Szymański

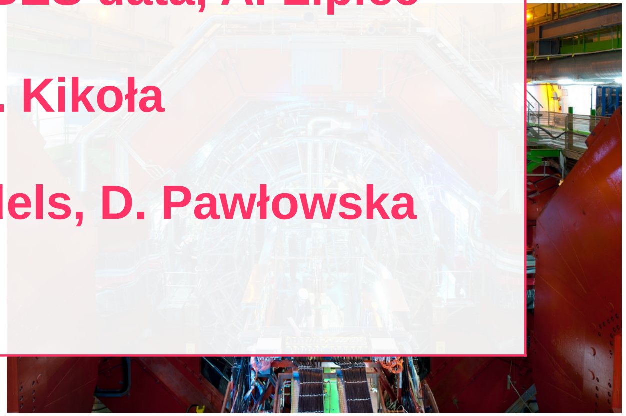
Femtoscopic measurements at MPD, D. Wielanek

Measurements of angular correlation function in the STAR BES data, A. Lipiec

The STAR group at the Warsaw University of Technology, D. Kikoła

Femtoscopic measurements in the frame of theoretical models, D. Pawłowska

Proton femtoscopy, S. Siejka (just after me)



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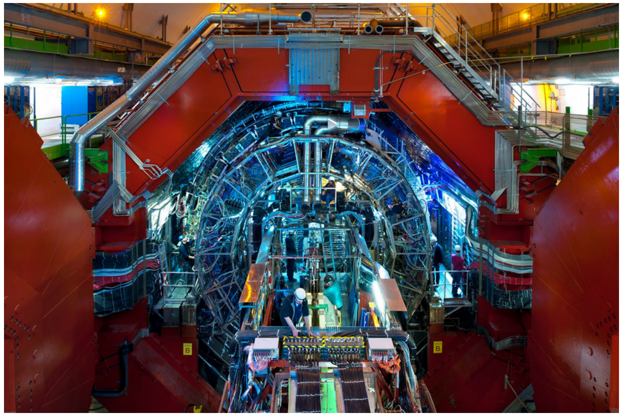
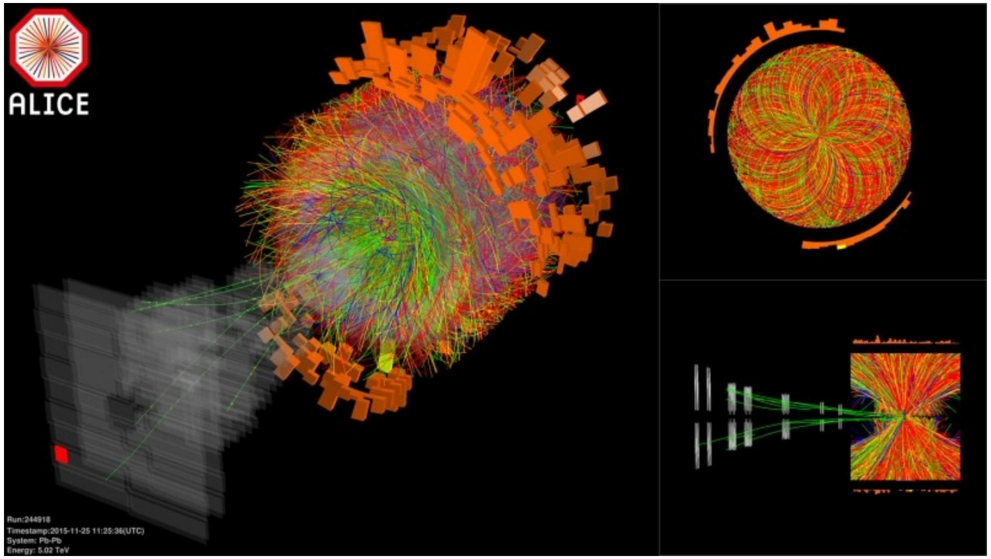
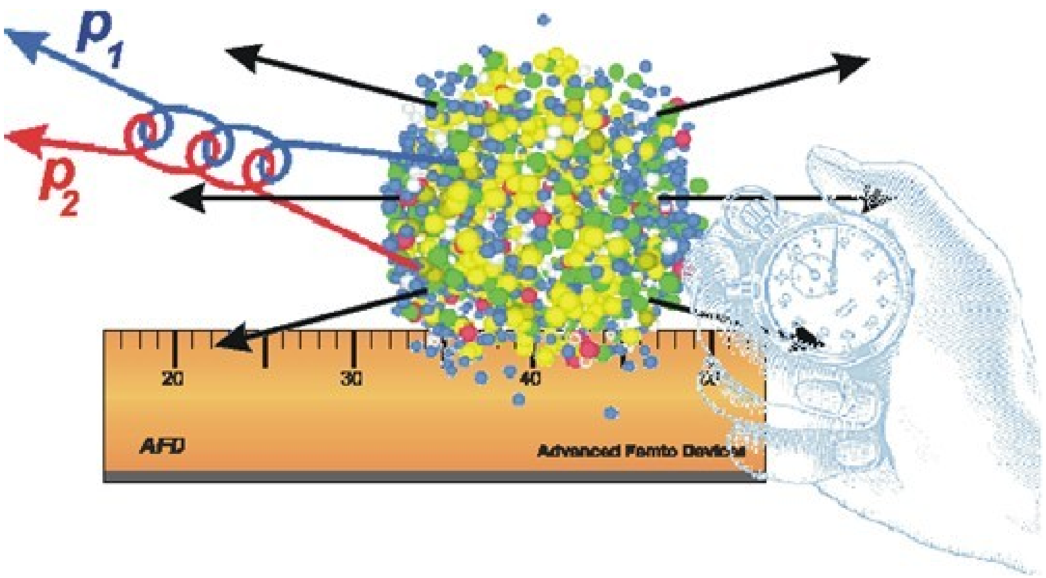


Femtoscopy technique





- **Femtoscopy** – measures space-time characteristics of the source using particle correlations in <u>momentum space</u>
- Main sources of correlations:
  - Quantum statistics (QS)
    - bosons (i.e. pions) – Bose-Einstein QS
    - fermions (i.e. protons) – Fermi-Dirac QS
  - Final-state interactions (FSI)
    - strong interaction
    - Coulomb repulsion or attraction

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

In the experiment:

$$C(q)=A(q)/B(q)$$

$A(q)$ - signal distribution (“same” events)

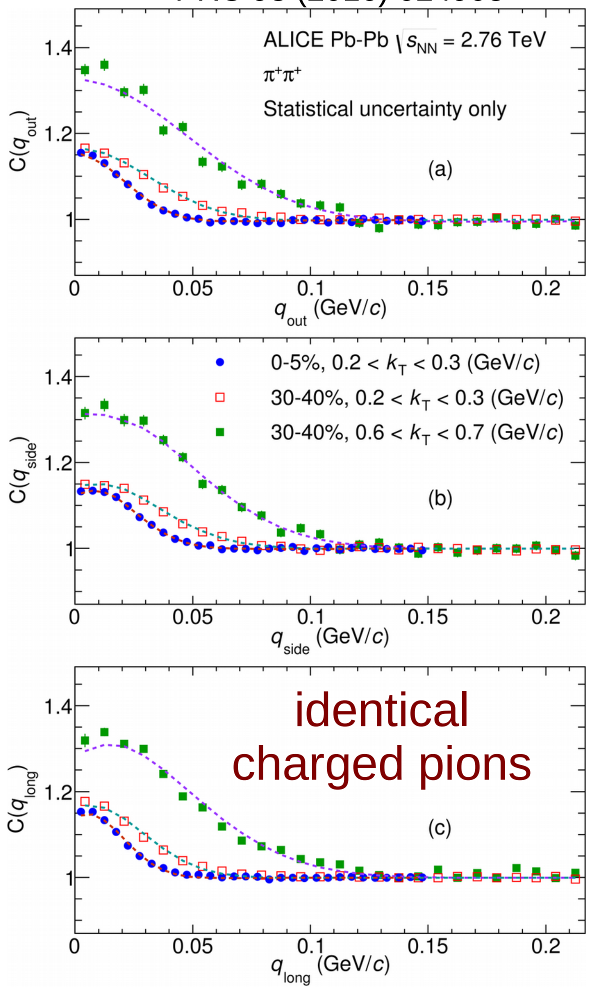
$B(q)$ - background distribution (“mixed” events)

$$q=p_1-p_2$$

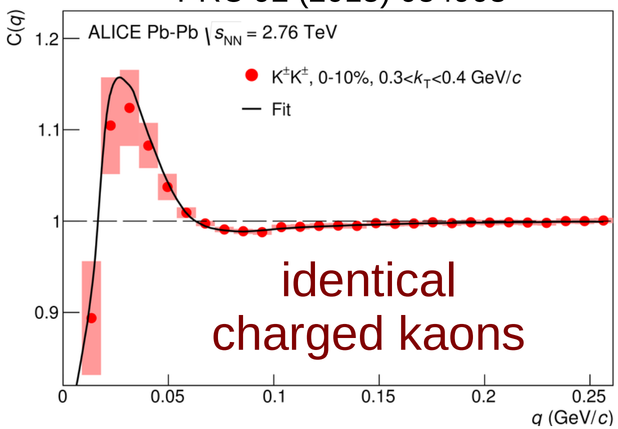
How does it look like?

The correlation functions have various shapes, depending on the pair type (interactions involved), collision system and energy, pair transverse momentum, etc.

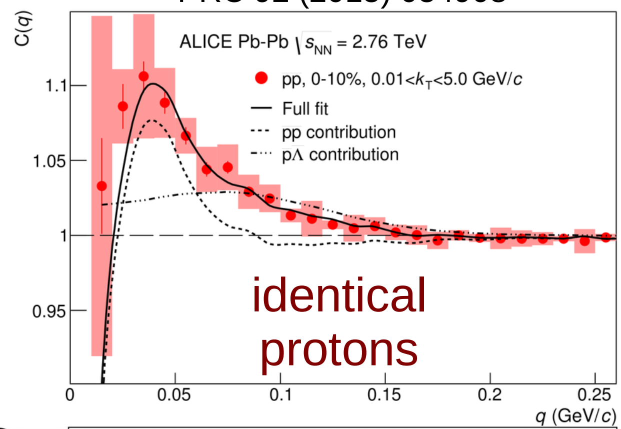
PRC 93 (2016) 024905

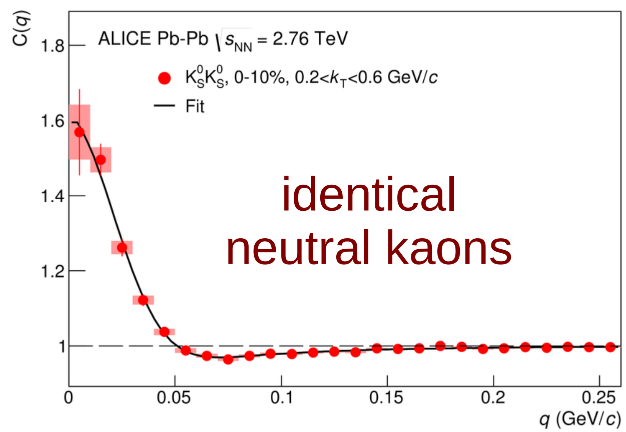


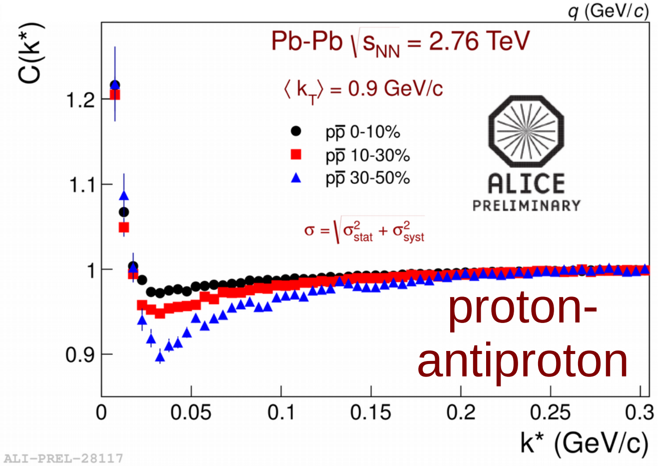
PRC 92 (2015) 054908



PRC 92 (2015) 054908



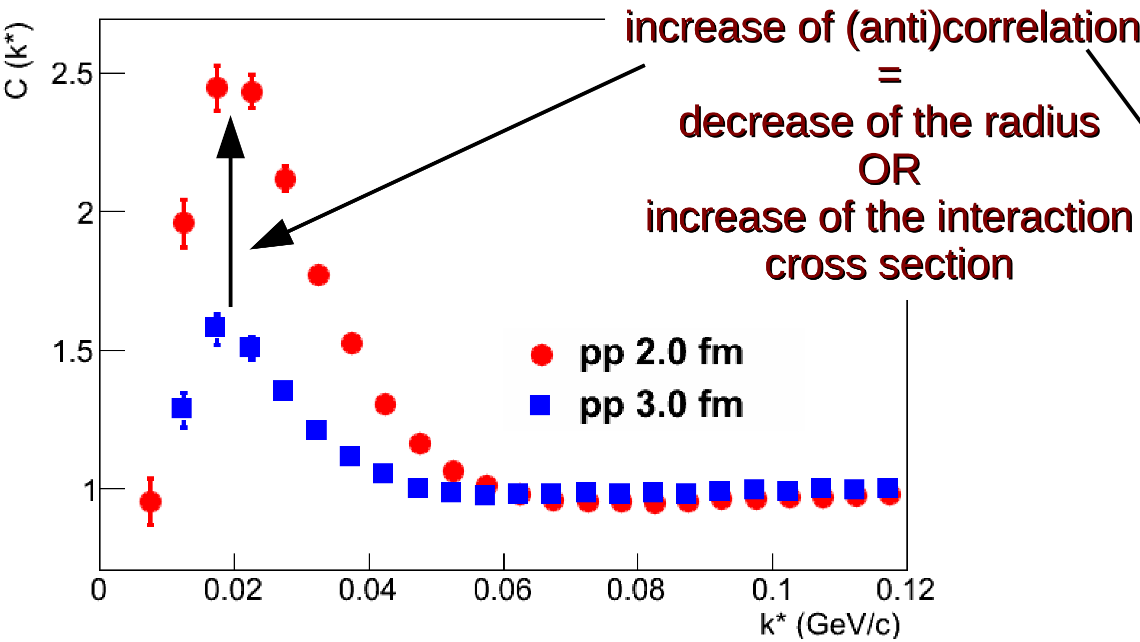


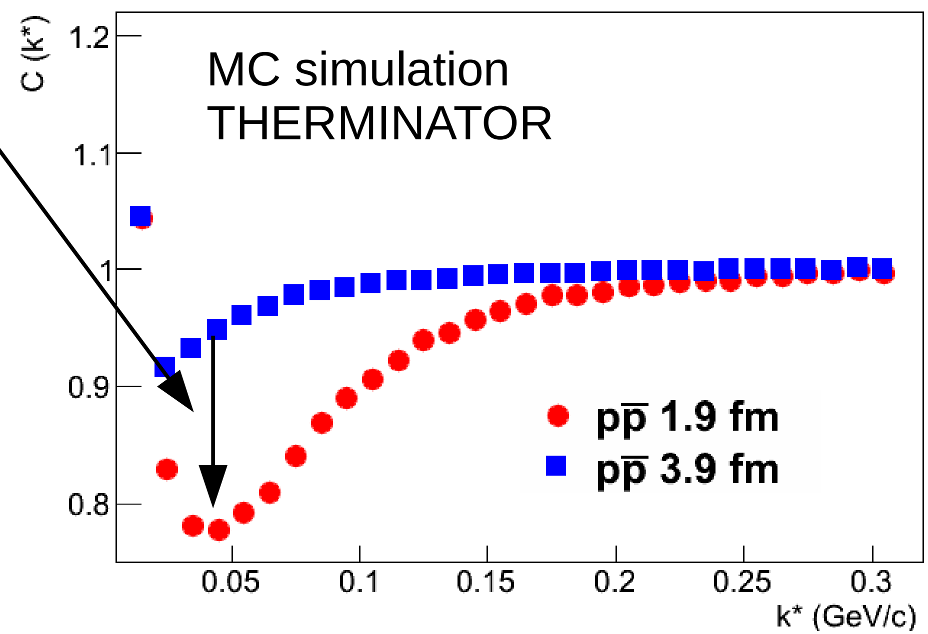


Going beyond the system size

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

- $C(q)$: measured correlation
- $S(r)$: emission function (source size/shape)
- $|\Psi(q,r)|^2$: pair wave function (includes cross section)





Correlation from Strong Interaction

$$C(q)=\int S(r)|\Psi(q,r)|^2 d^4 r \qquad q=2\cdot k^*$$

- $C(q)$: measured correlation
- $S(r)$: emission function (source size/shape)
- $|\Psi(q,r)|^2$: **pair wave function (includes cross section)**

$$\Psi=\exp(-ik^*r)+f\frac{\exp(ik^*r)}{r}$$ s-wave scattering approximation

$$f^{-1}(k^*)=\frac{1}{f_0}+\frac{1}{2}d_0 k^{*2}-ik^*$$ effective range approximation

- If only Strong Final State Interaction (FSI) the result of integration:

$$C(k^*)=1+\sum_S \rho_S\left[\frac{1}{2}\left|\frac{f^S(k^*)}{R}\right|^2\left(1-\frac{d_0^S}{2\sqrt{\pi}R}\right)+\frac{2\Re f^S(k^*)}{\sqrt{\pi}R}F_1(2k^*R)-\frac{\Im f^S(k^*)}{R}F_2(2k^*R)\right]$$

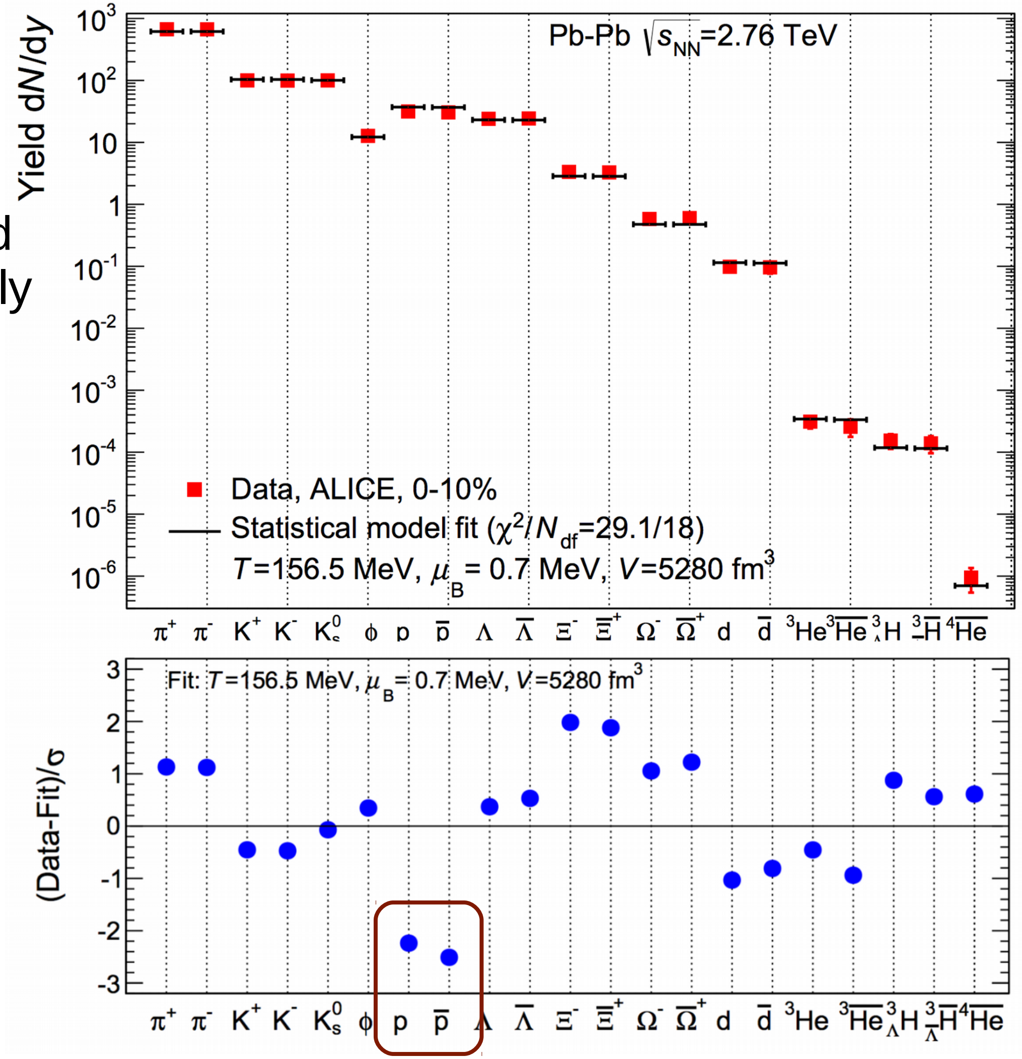
Lednicky, Lyuboshitz, Sov. J. Nucl. Phys., 35, 770 (1982)

where ρ_S are the spin fractions

- The correlation function is finally characterized by **three parameters**:
  - **radius** R, **scattering length** f_0, and **effective radius** d_0
  - **Cross section** σ (at low k^*) **is simply:** $\sigma=4\pi|f|^2$

What are the potential applications?

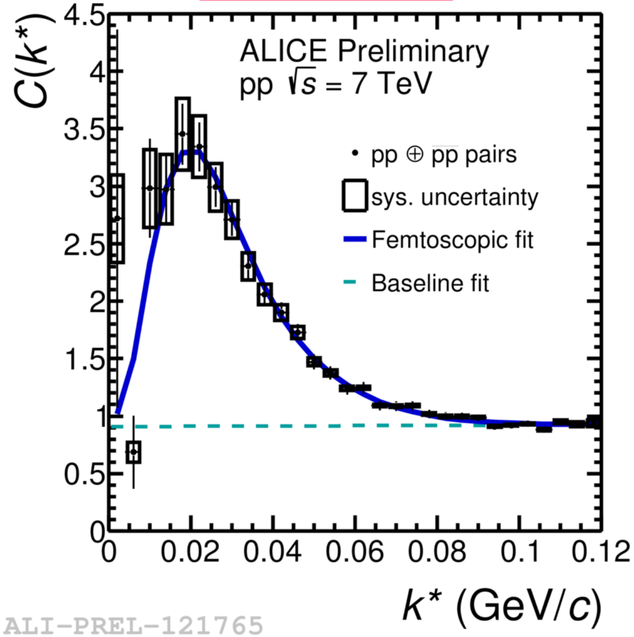
- Input to models with re-scattering phase (eg. UrQMD):
  PRC 89 (2014) 054916
  - annihilation cross sections only measured for $p\bar{p}$, $\bar{p}n$, and $\bar{p}d$ pairs – UrQMD currently **guesses it for other systems** from $p\bar{p}$ pairs
  - should help us to answer the question on deviations of baryon yields from thermal model expectations
- Structure of baryons/search for CPT violation
  STAR, Nature 527, 345-348 (2015)
- Search for H-dibaryon
  ALICE, PLB 752 (2016) 267-277
- Hypernuclear structure theory
  Nucl.Phys. A914 (2013) 377-386
- Neutron star equation of state
  Nucl.Phys. A804 (2008) 309-321



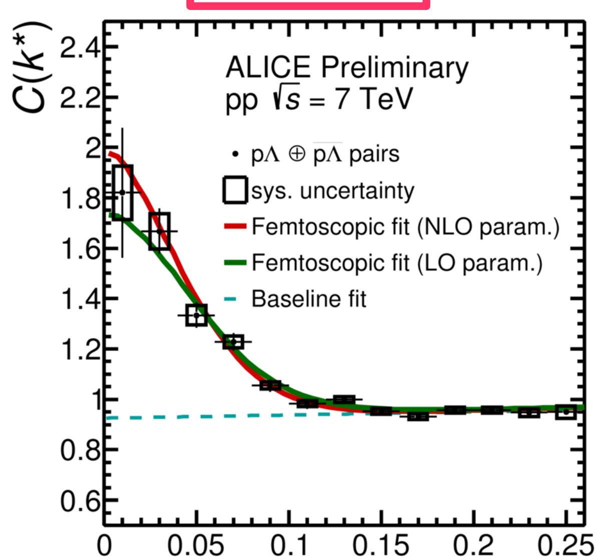
A. Andronic, SQM 2016

Baryon-baryon correlations

pp+$\overline{\text{pp}}$



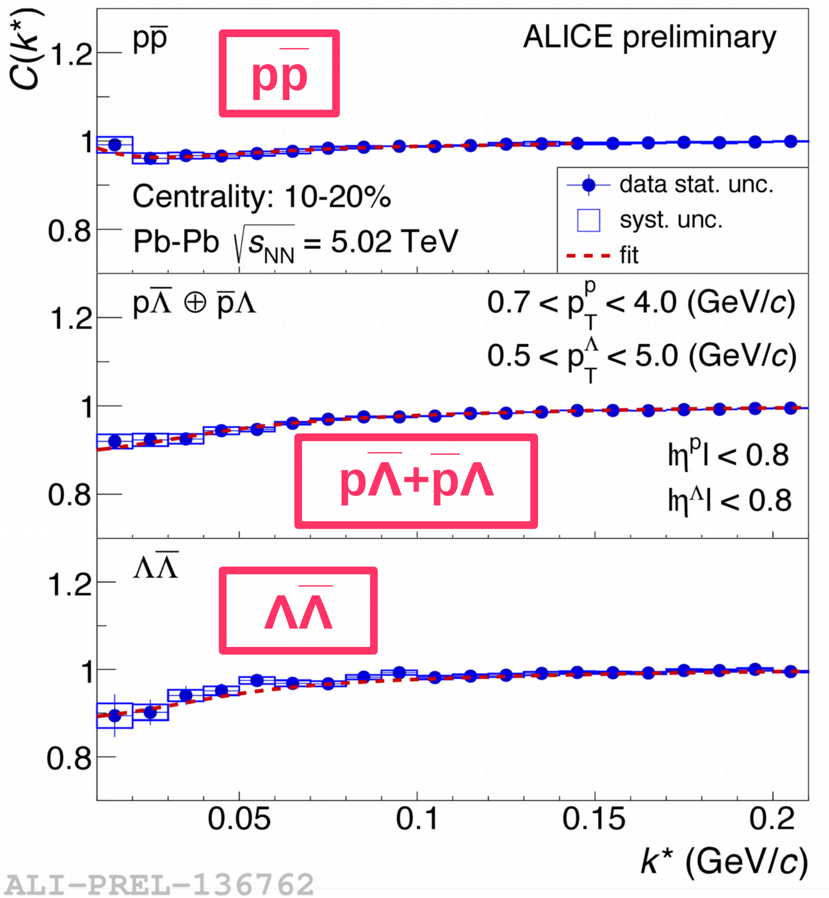
pΛ+$\overline{\text{p}\Lambda}$

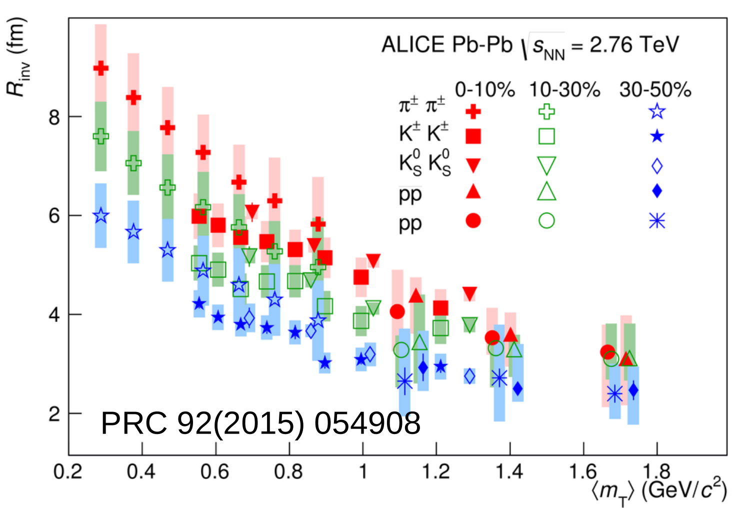


Oliver Arnold
QM 2017 poster
http://cern.ch/go/bTS8

- Except for pairs like proton-proton or proton-neutron, cross sections for other baryons practically not known
  - eg. only ~30 points for proton-lambda interaction measurements exist
- ALICE can constrain cross sections for these systems at low relative momentum *k**
- Assuming LO and NLO scattering parameter predictions in the fit (from Nucl. Phys. A915, 24-58)
- Preliminary results of simultaneous fit to proton-proton and proton-lambda correlation functions:
  - extracted source size: $R = 1.31 \pm 0.02 \quad fm$
  - NLO predictions seems to be slightly more accurate, however we still lack statistics
  - we hope to have more accurate results after analysing 13 TeV LHC Run2 data

Baryon-antibaryon correlations



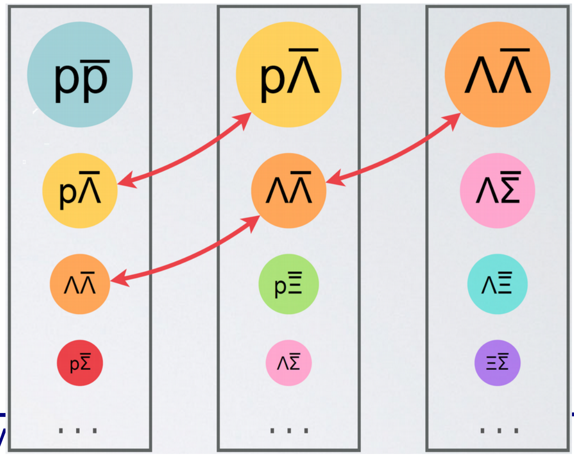


Explanation of the fitting procedure:

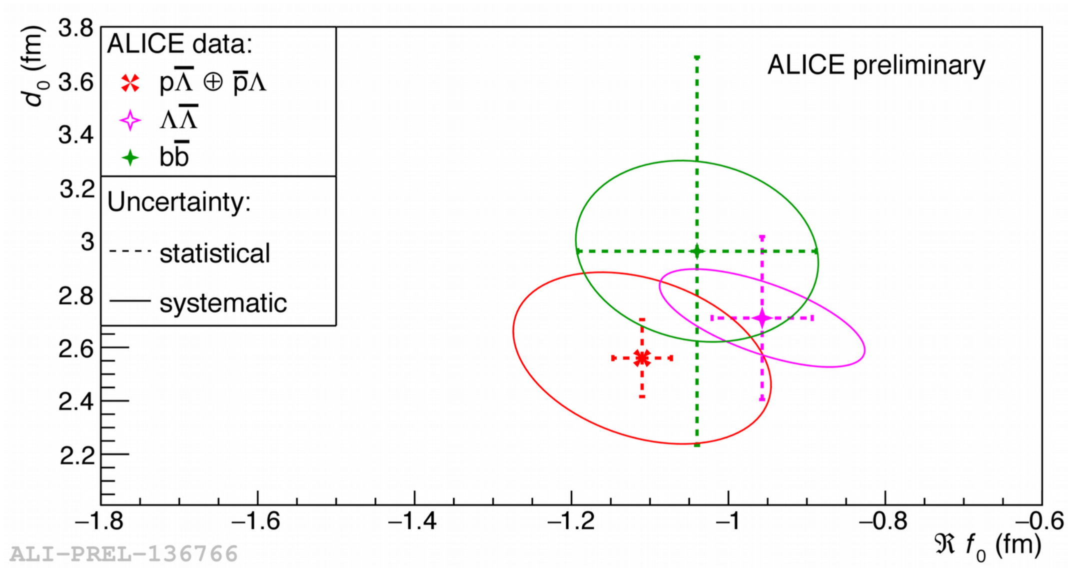
- χ^2 is calculated from a "global" fit to all functions: 2 data sets, 3 pair combinations, 6 centrality bins (**total 36 functions**)
- simultaneous fit accounts for parameters **shared** between different systems (such as $\Lambda\bar{\Lambda}$ scattering length)
- **radii scale with multiplicity** for a given system

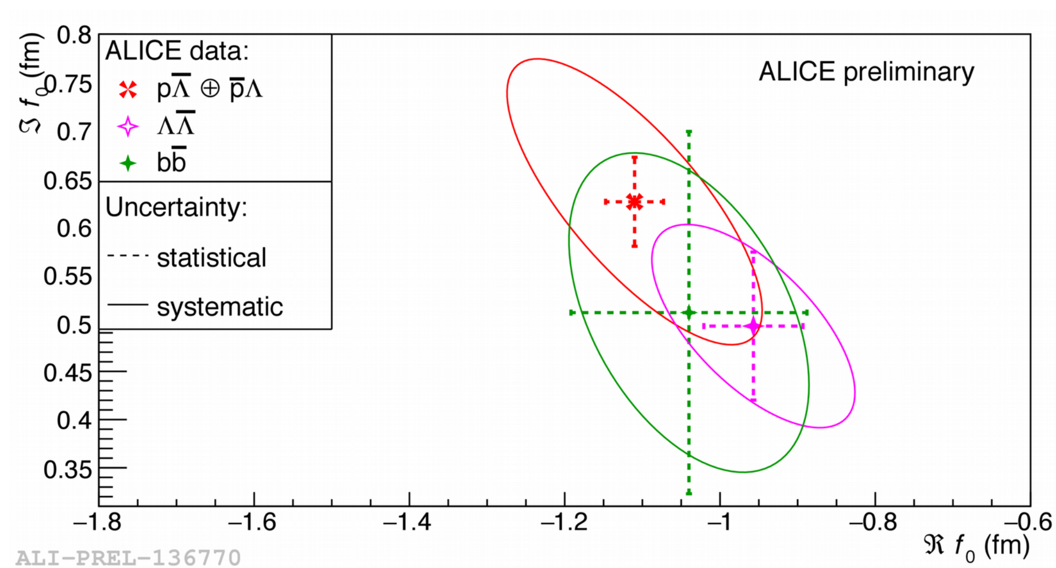
$$R_{inv} = a \cdot \sqrt[3]{N_{ch}} + b$$

- for different system we assume **radii scaling with m_T**
- Fractions of **residual pairs** taken from AMPT



Baryon-antibaryon correlations





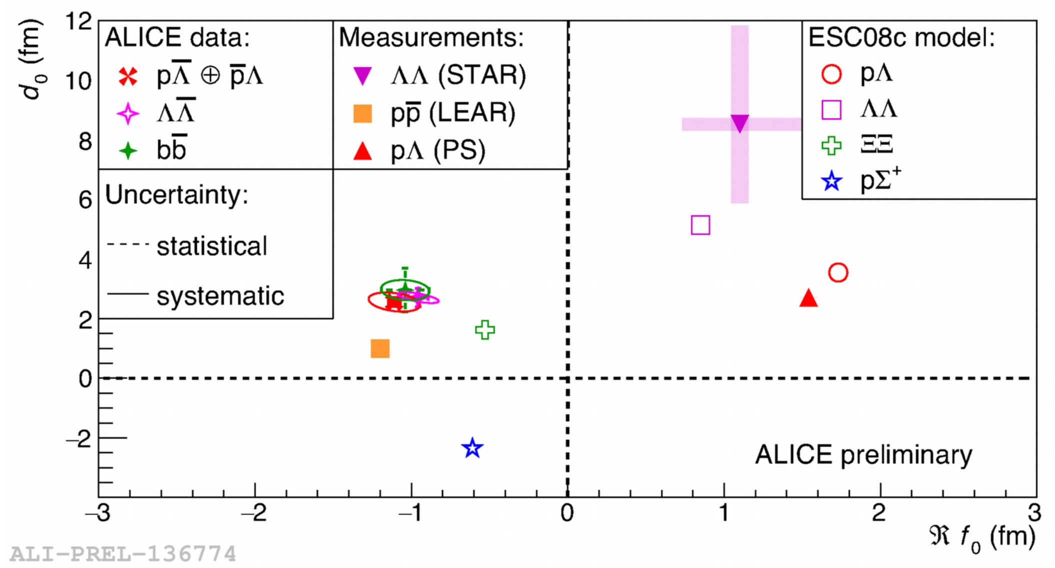
Conclusions from fitting:

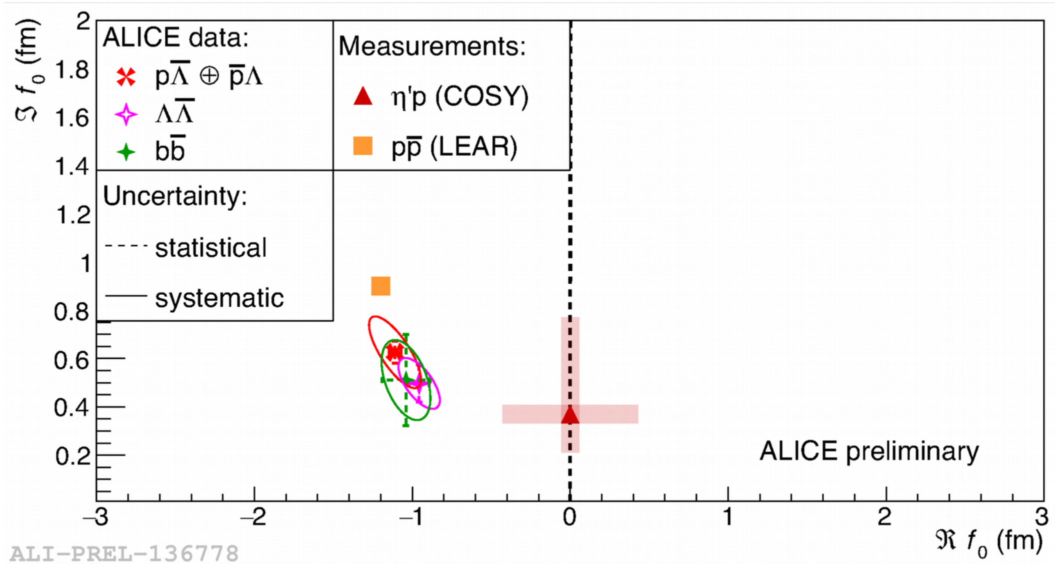
- Interaction parameters are measurable
- Scattering parameters for **all baryon-antibaryon pairs are similar to each other** (UrQMD assumption is valid)
- We observe a **negative real part of scattering length** → repulsive strong interaction or creation of a bound state (existence of baryon-antibaryon bound states?)
- Significant **positive imaginary part of scattering length** – presence of a non-elastic channel – annihilation

Next steps:

- Try to look for baryon-antibaryon bound states

Baryon-antibaryon correlations





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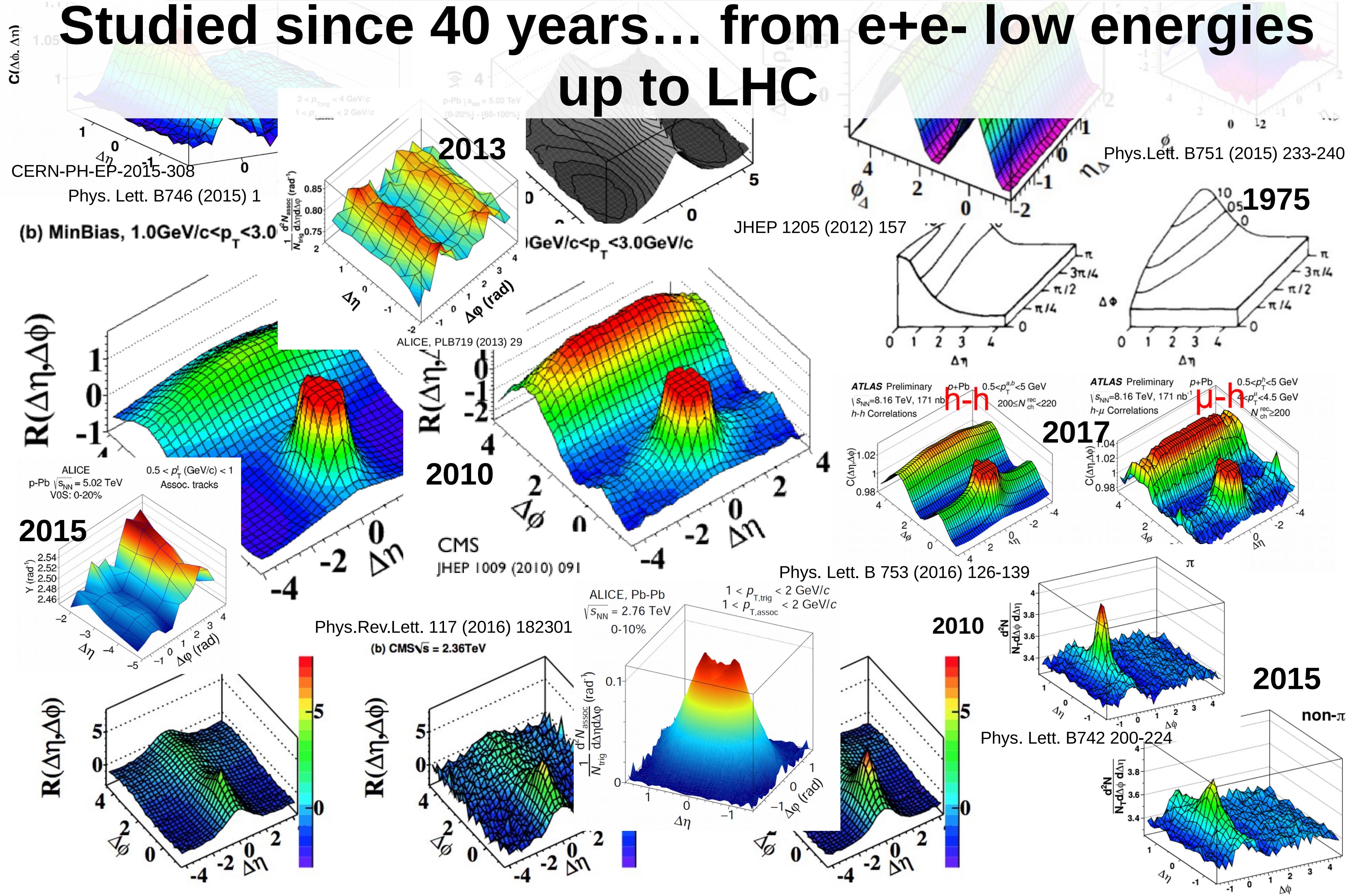
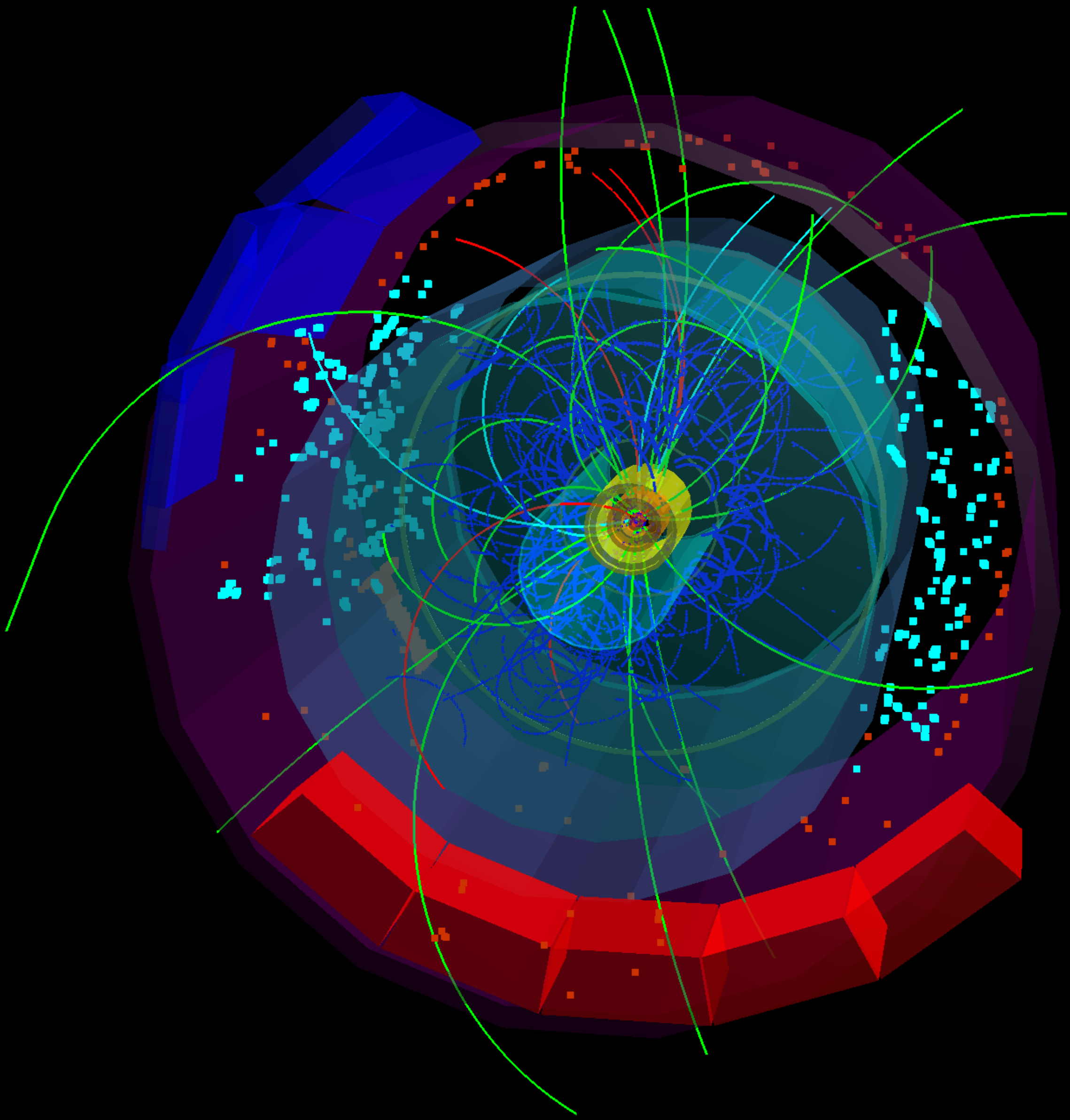
Angular correlations

Studied since 40 years… from e+e- low energies up to LHC



Two-particle ΔηΔφ angular correlations



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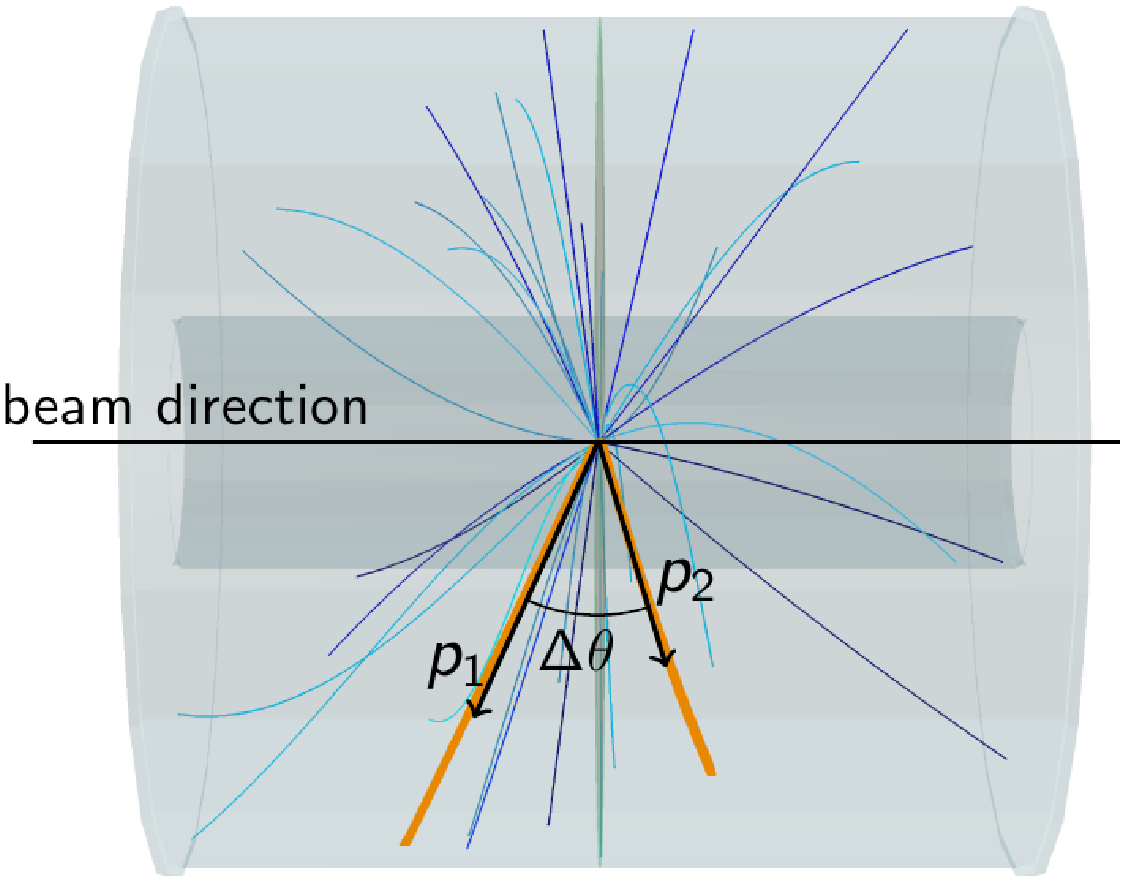
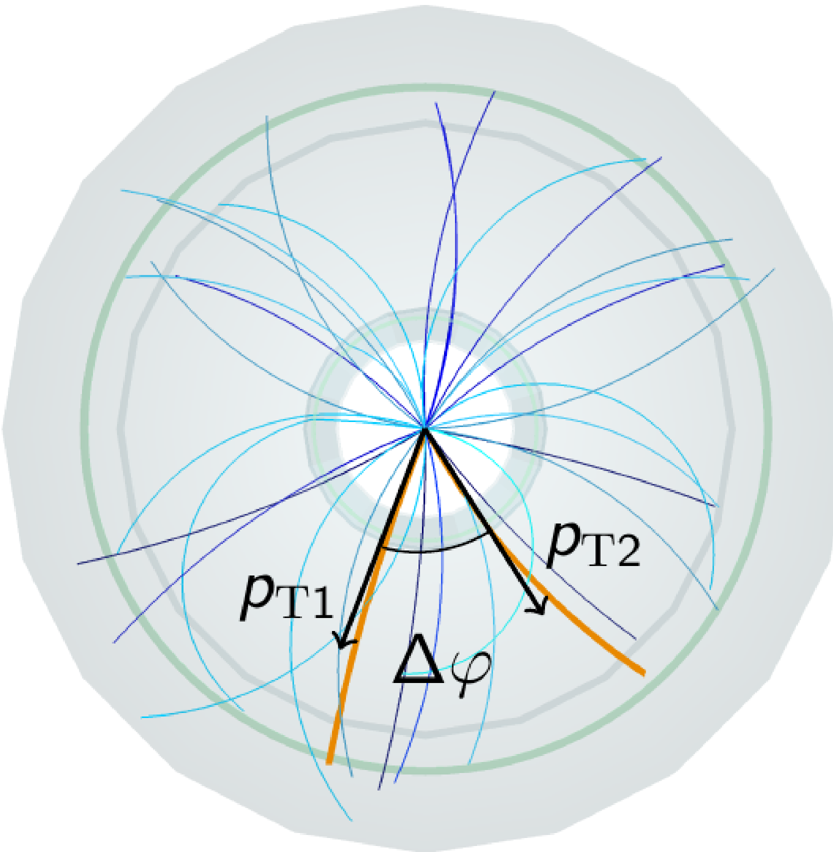




p - particle momentum;

θ - polar angle;

η - pseudorapidity:

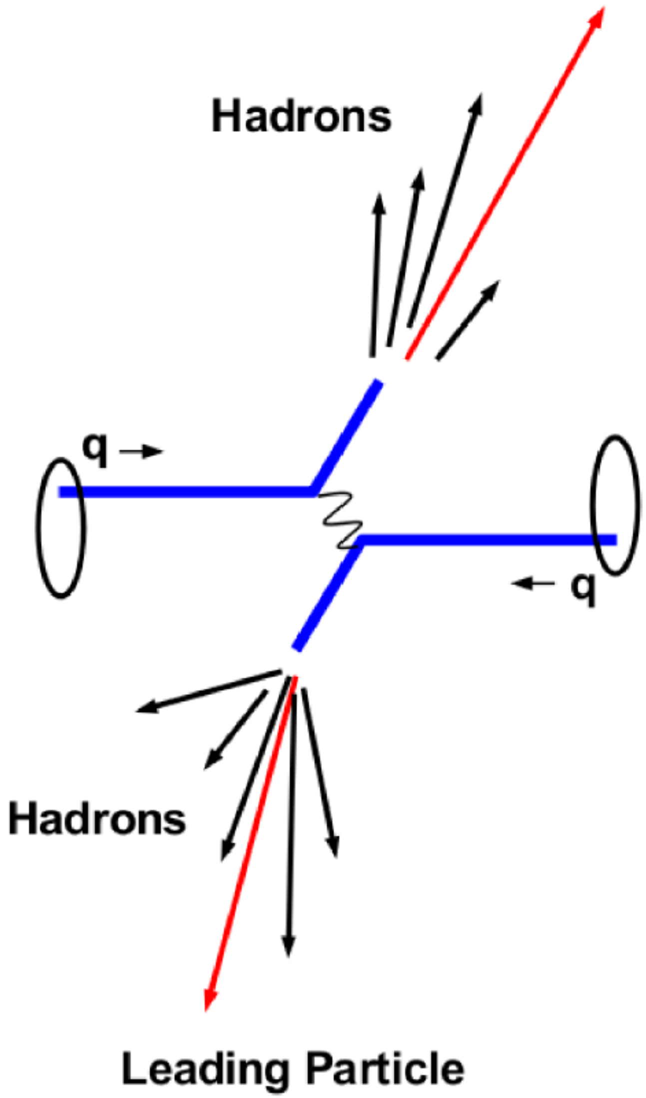
$$\eta = -\ln\left|\mathrm{tg}\frac{\theta}{2}\right|$$

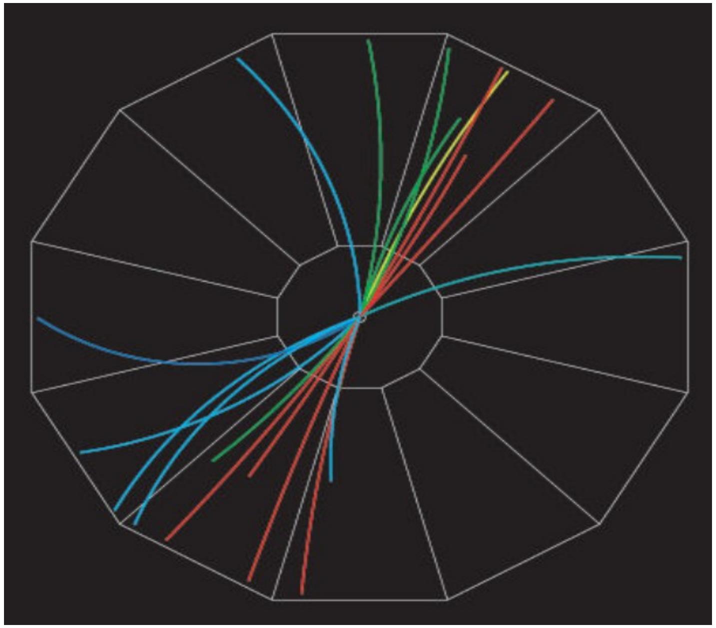
p_T - transverse momentum;

φ - azimuthal angle;

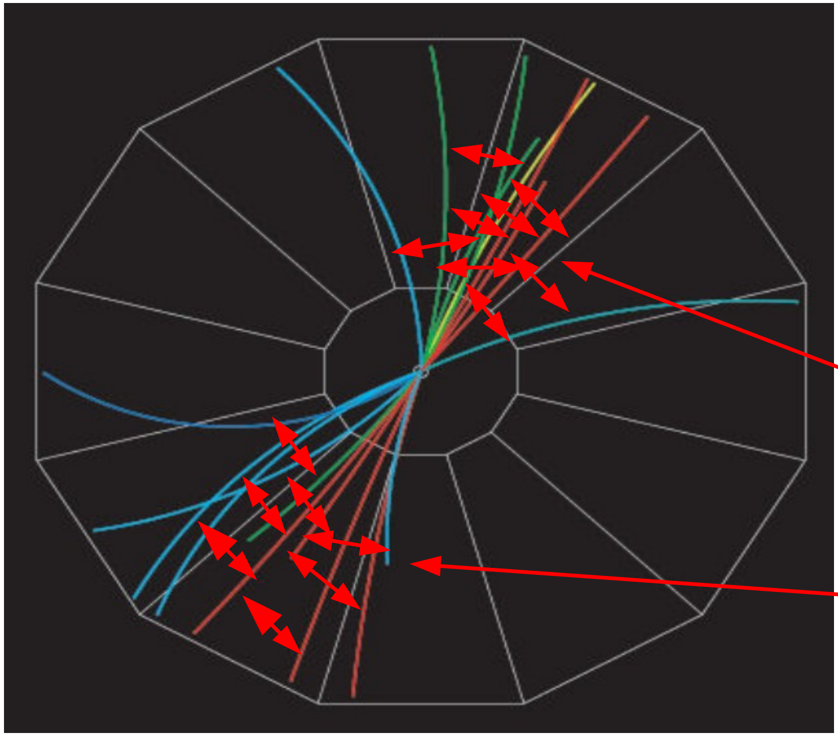
Fig. A. Zaborowska

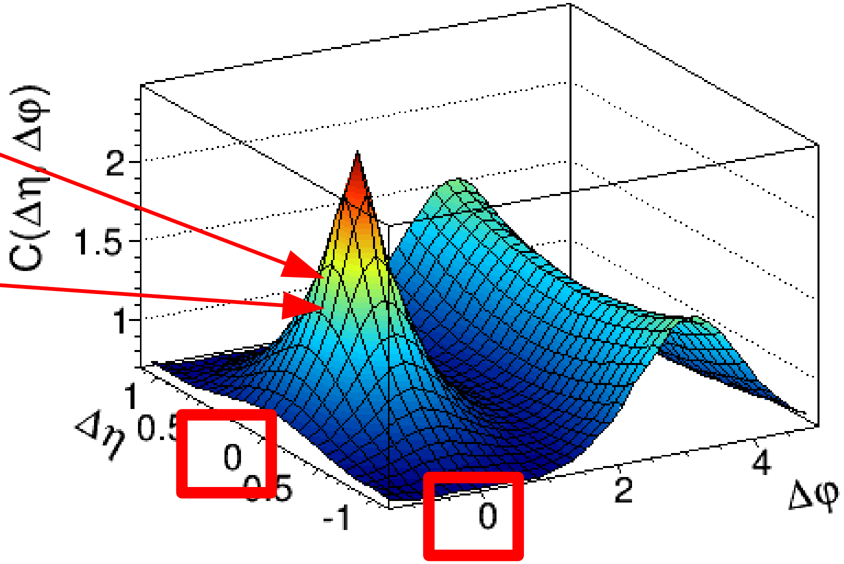
Creation of jets





How does it work?





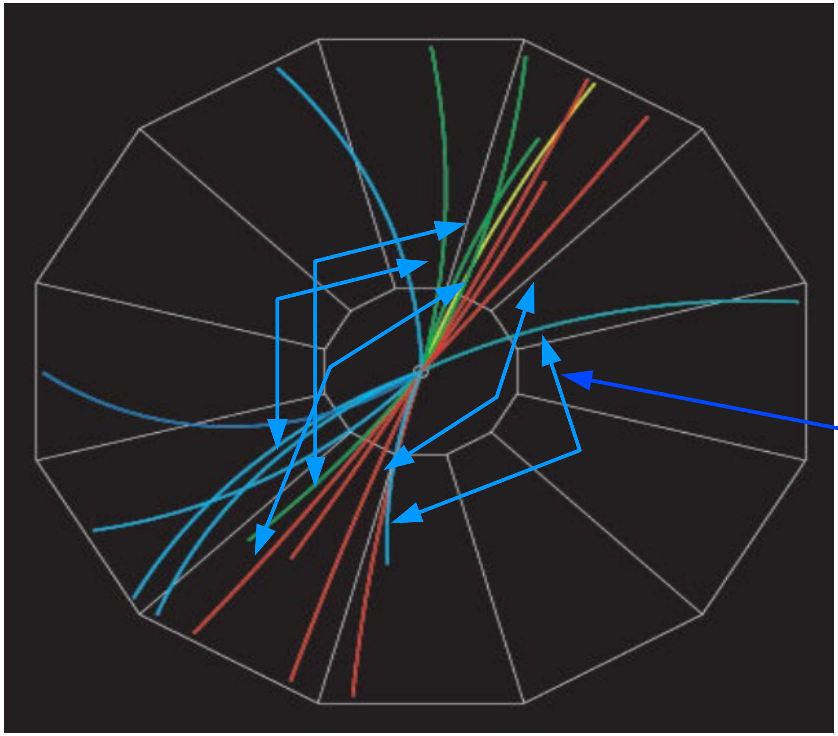
Near-side peak

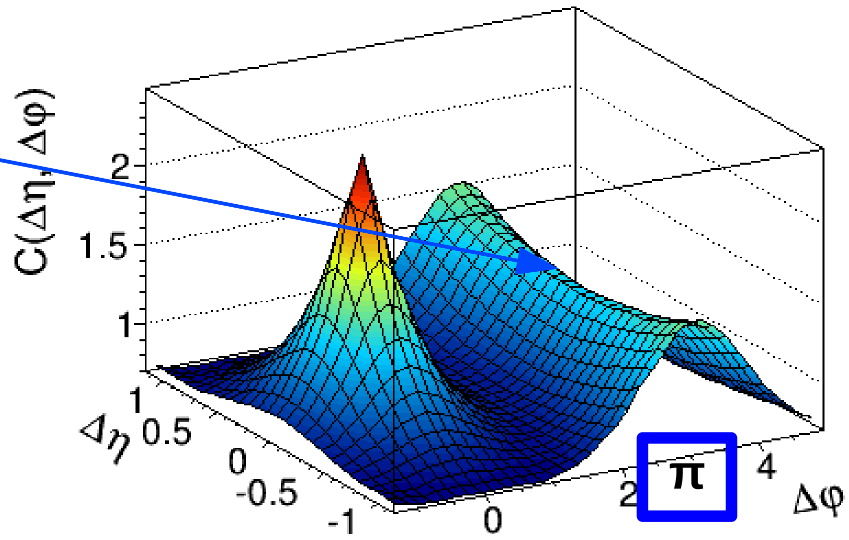
For particles from the same jet (red):

- Δφ ~ 0

- Δη ~ 0

How does it work?

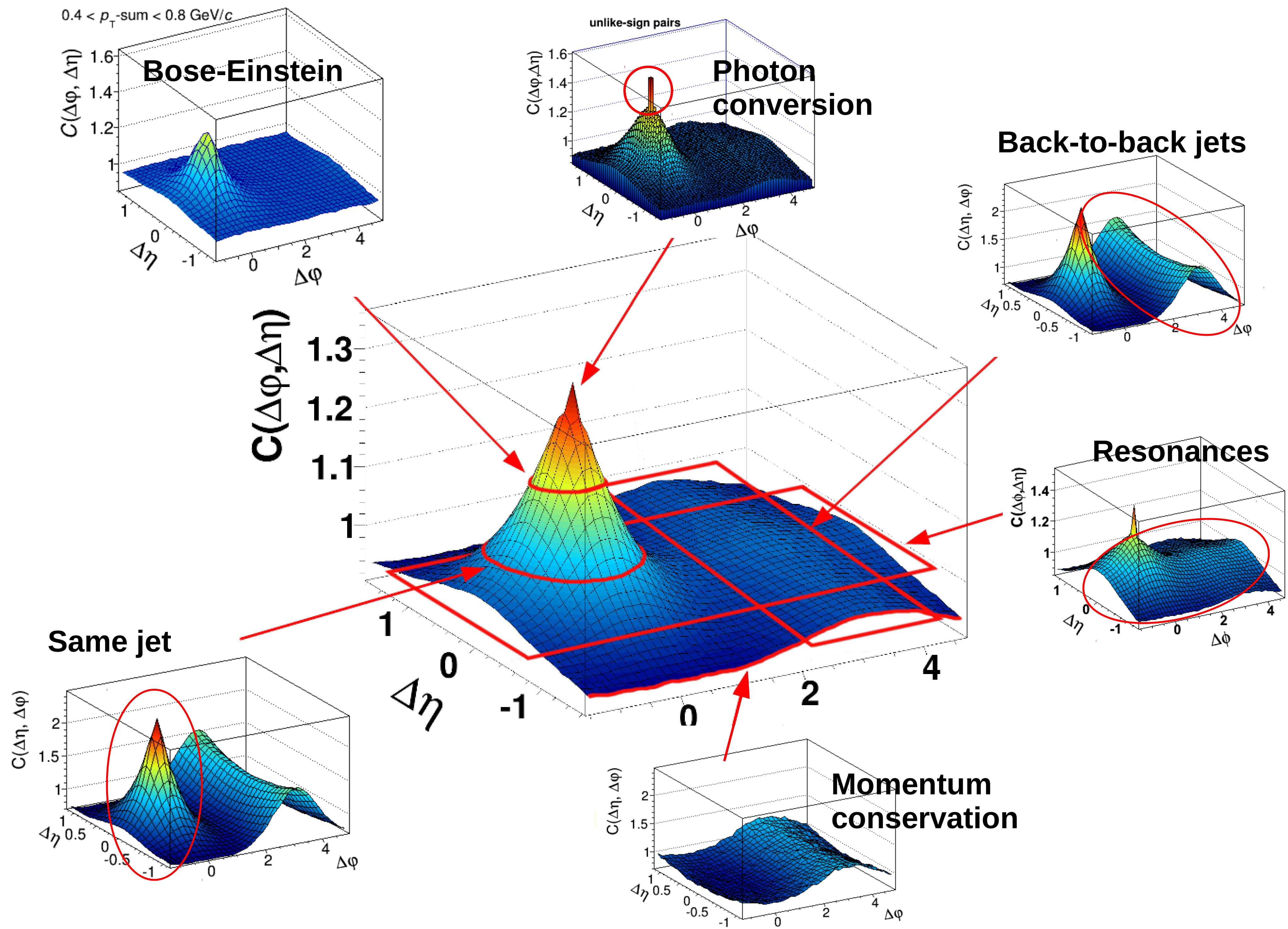




For particles from from back-to-back jets (blue):

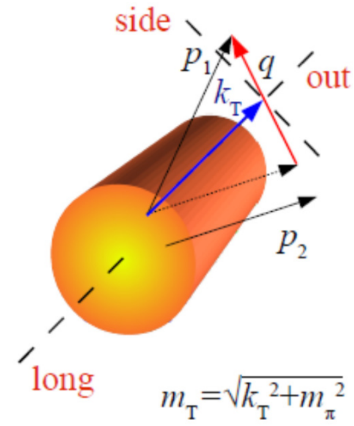
Away-side ridge

- **$\Delta\varphi \sim \pi$**
- **$\Delta\eta$ ~ const, if avaraged over many events**

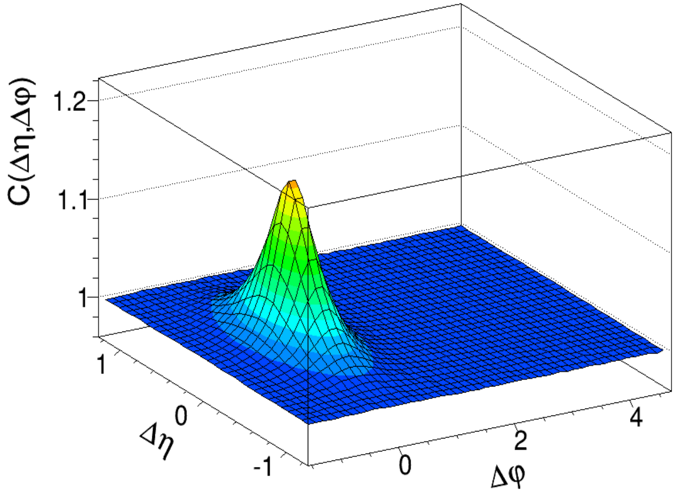


0.4 < p_T-sum < 0.8 GeV/c
Bose-Einstein
unlike-sign pairs
Photon conversion
Back-to-back jets
Resonances
Same jet
Momentum conservation
C(Δφ,Δη)
Δη
Δφ

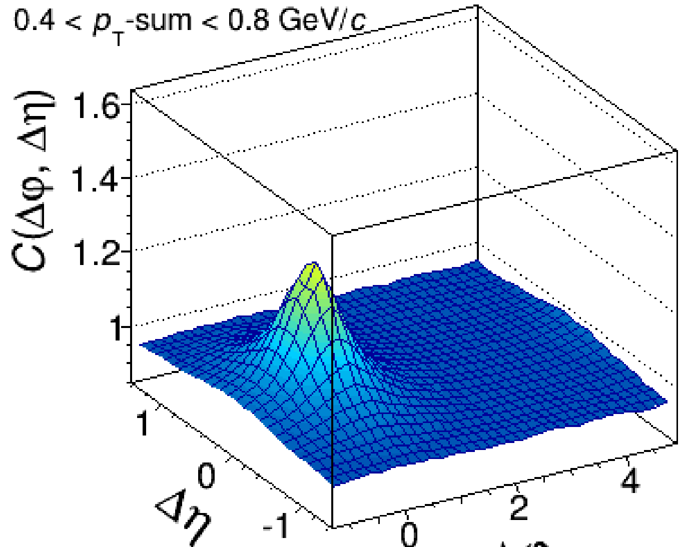
How does it work?



Bose-Einstein Correlations



EPOS p-Pb



ALICE

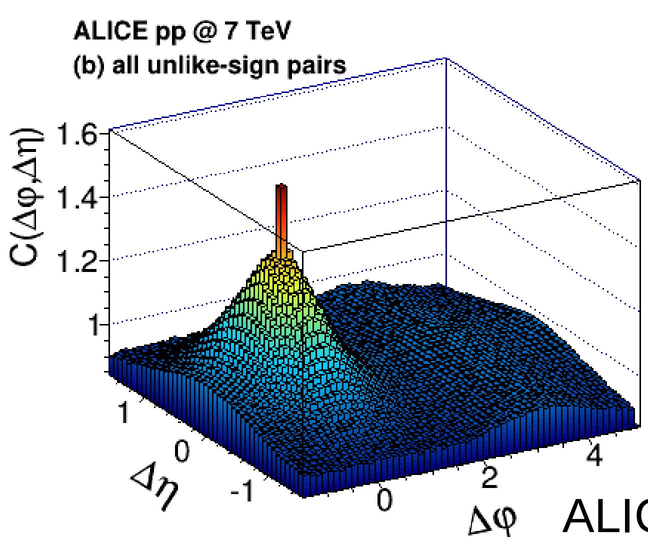
Bose–Einstein Correlations of identical-pion pairs result in an enhancement at low relative momentum.

$$q_{out} \sim p_{T,1} - p_{T,2}$$

$$q_{side} \sim (p_{T,1} + p_{T,2}) \Delta\phi$$

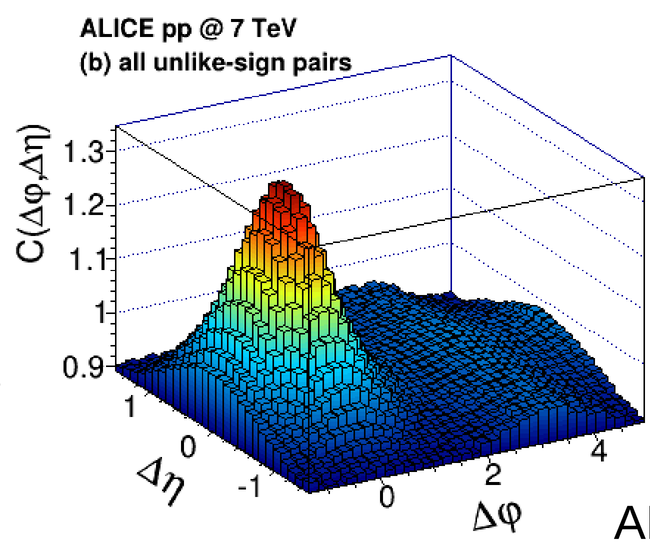
$$q_{long} \sim (p_{T,1} + p_{T,2}) \Delta\eta$$

Photon conversion

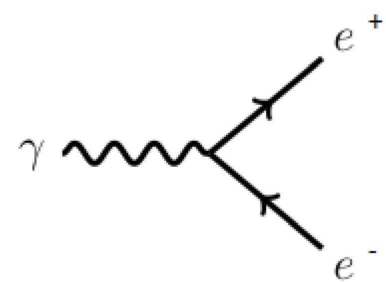


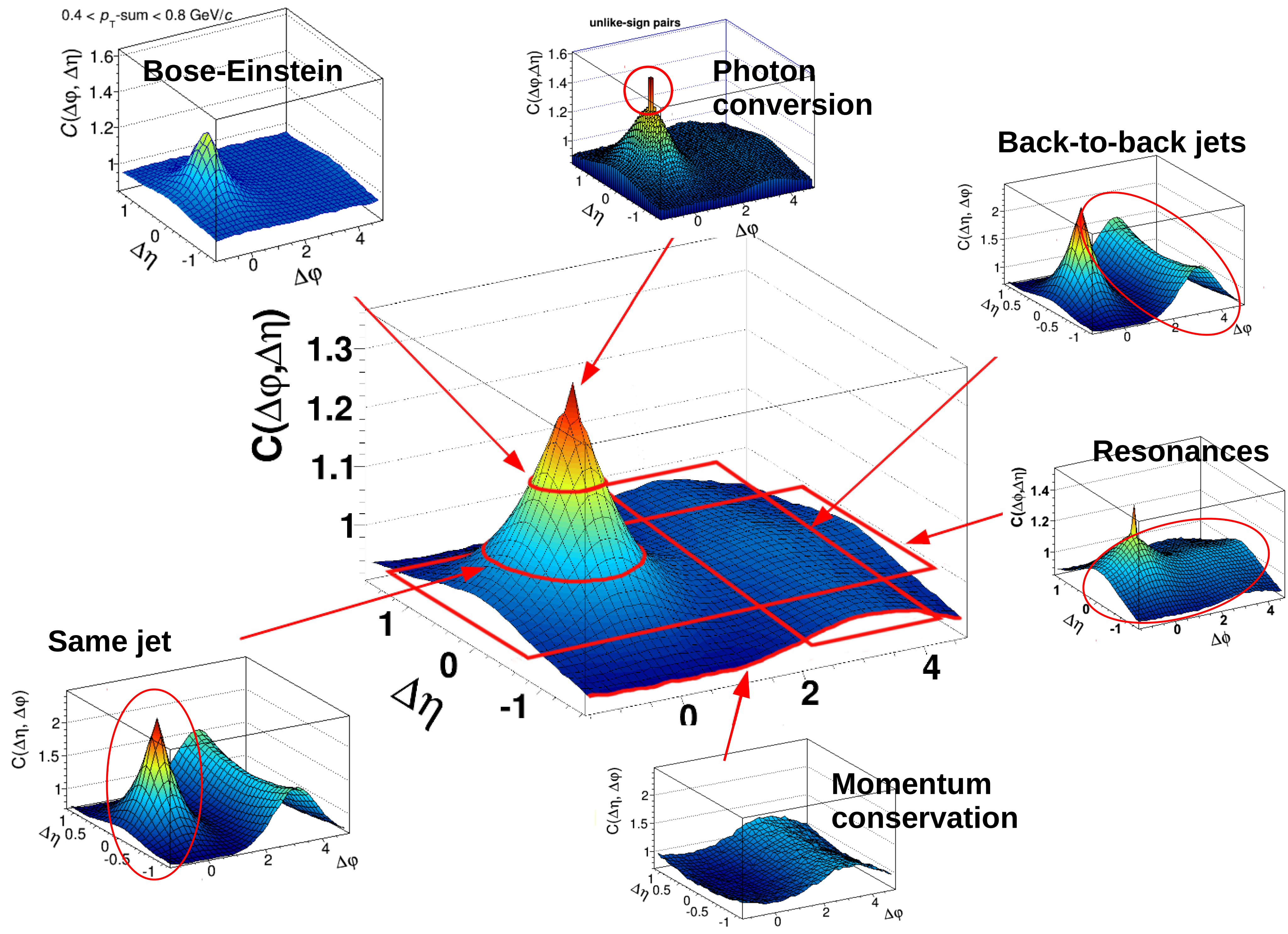
ALICE

Electron rejection



ALICE





0.4 < p_T-sum < 0.8 GeV/c
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C(Δφ,Δη)
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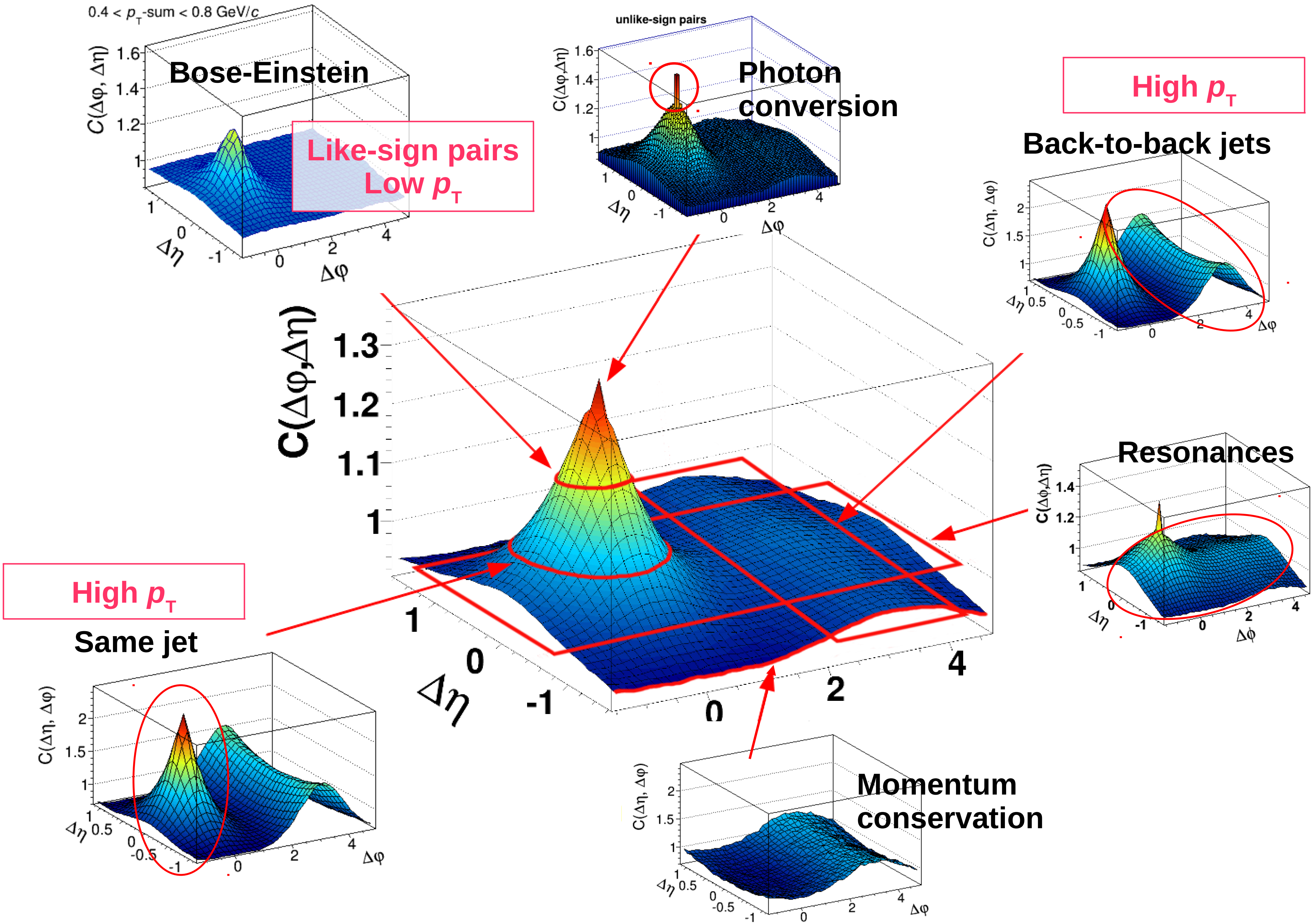


0.4 < p_T-sum < 0.8 GeV/c
Bose-Einstein
Like-sign pairs
Low p_T
unlike-sign pairs
Photon conversion
High p_T
Back-to-back jets
Resonances
High p_T
Same jet
Momentum conservation
C(Δφ,Δη)
Δη
Δφ

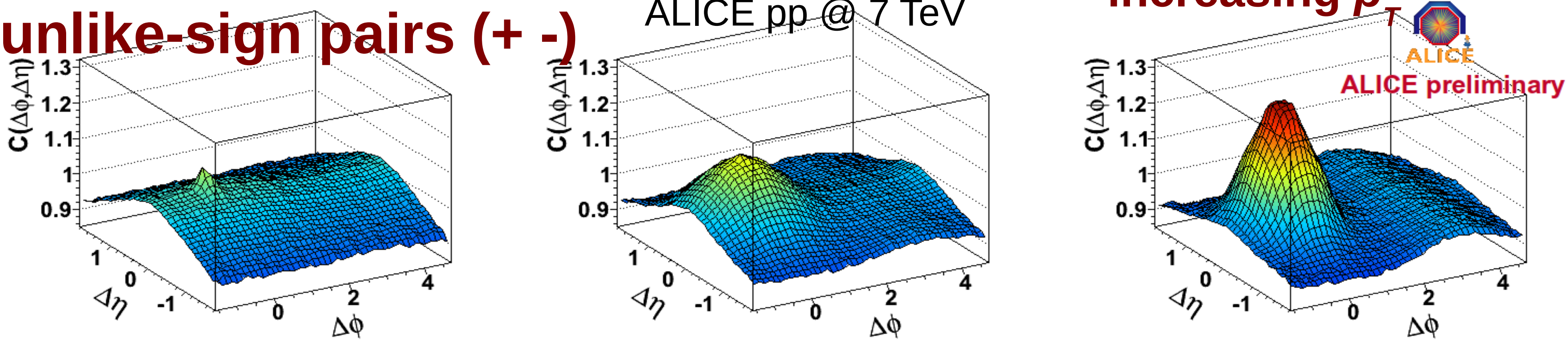
$\Delta\eta\Delta\varphi$ angular correlations

No Bose-Einstein correlations for unlike-sign pairs

Correlations coming from "minijets" increase with increasing p_T

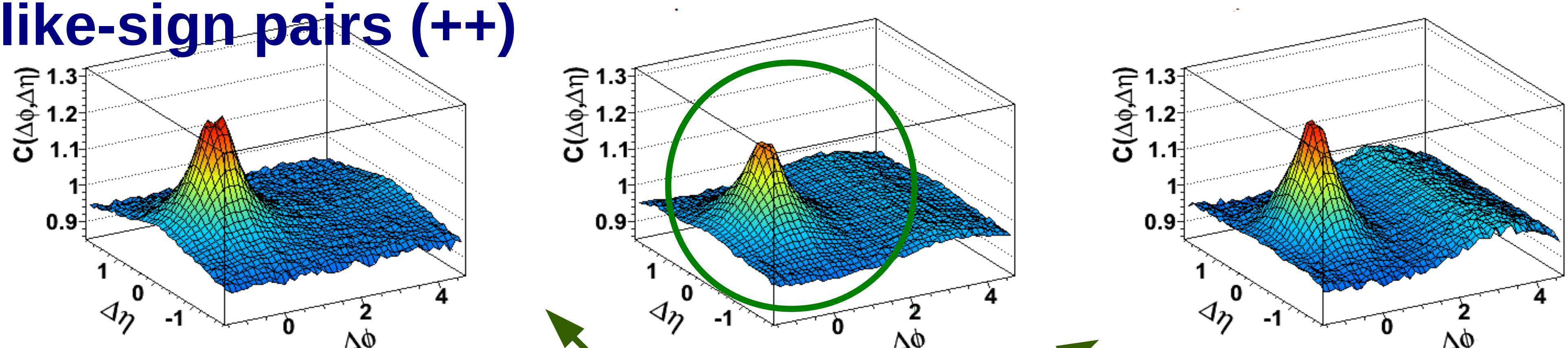
unlike-sign pairs (+ -)

ALICE pp @ 7 TeV



$0 < p_{Tsum} < 0.75\, GeV/c$ $0.75 < p_{Tsum} < 1.5\, GeV/c$ $1.5 < p_{Tsum} < 2.55\, GeV/c$

like-sign pairs (++)



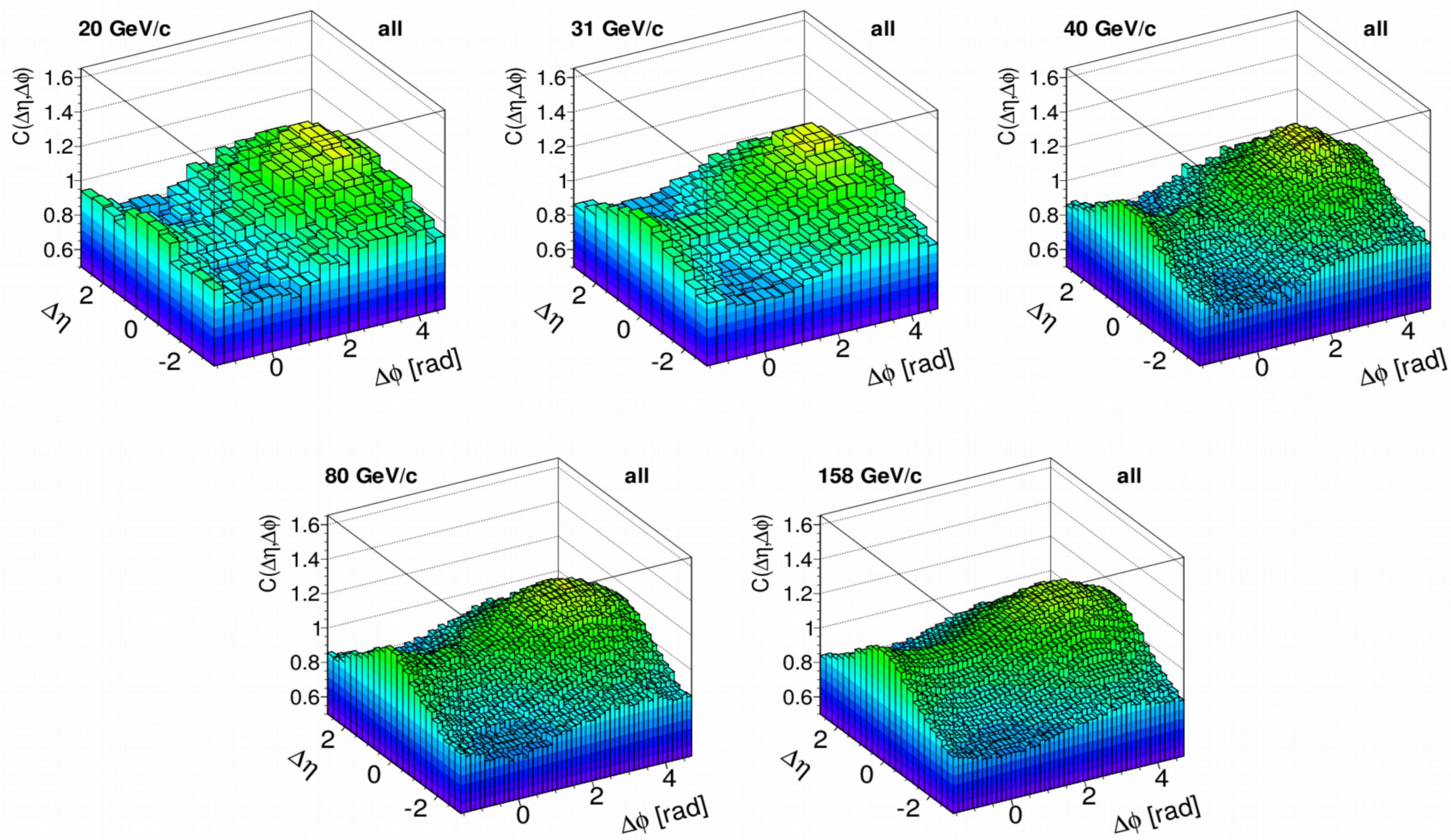
Bose-Einstein correlations decrease with increasing p_T

smaller

$$p_{Tsum} = |\vec{p}_{T1}| + |\vec{p}_{T2}|$$

Correlations coming from "minijets" increase with increasing p_T also for like-sign pairs

Low energy pp results from SPS: NA61



Eur. Phys. J. C77, 59 (**2017**)

The results show structures which can be connected to phenomena such as resonance decays, momentum conservation and Bose-Einstein correlations.

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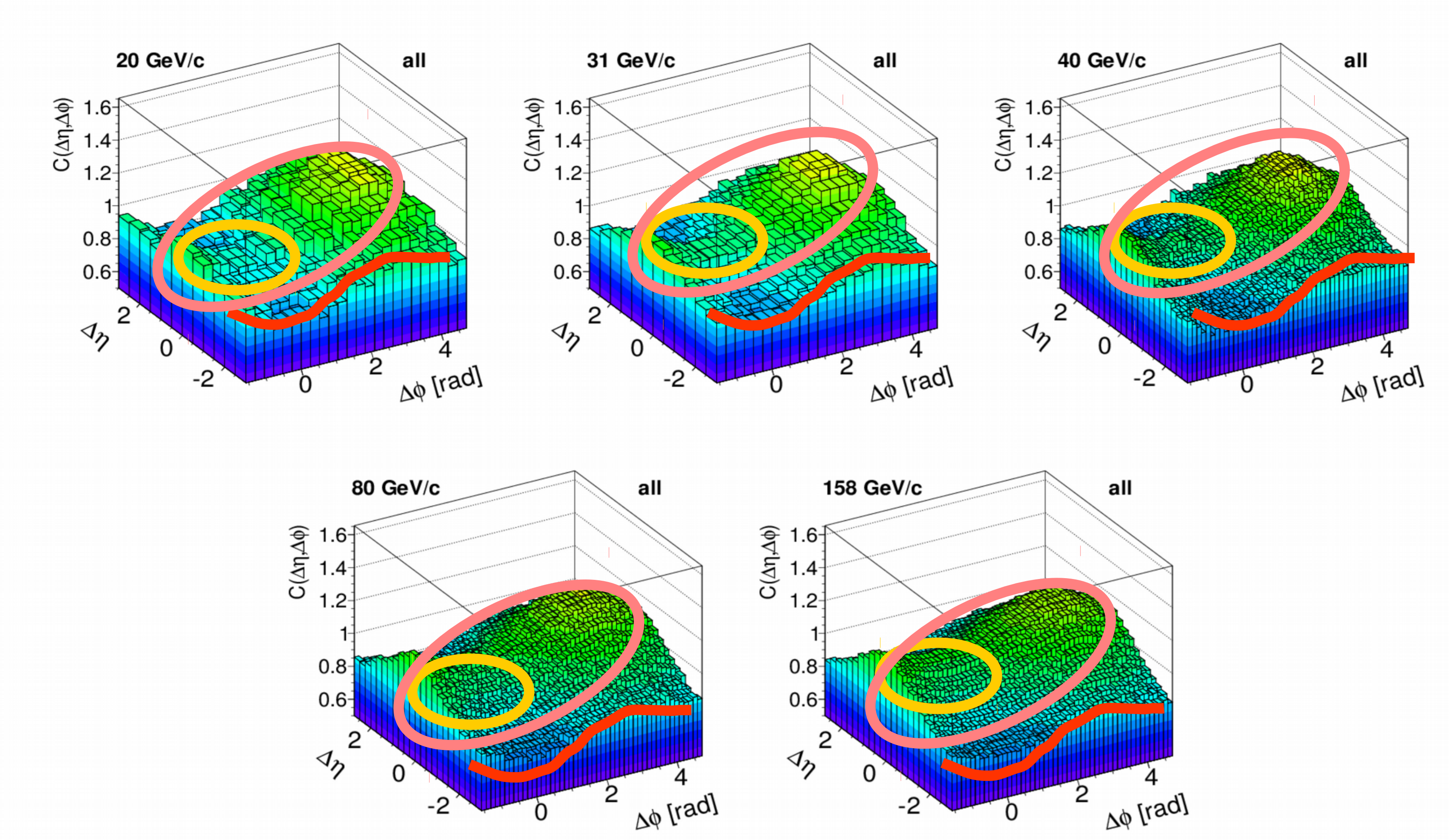

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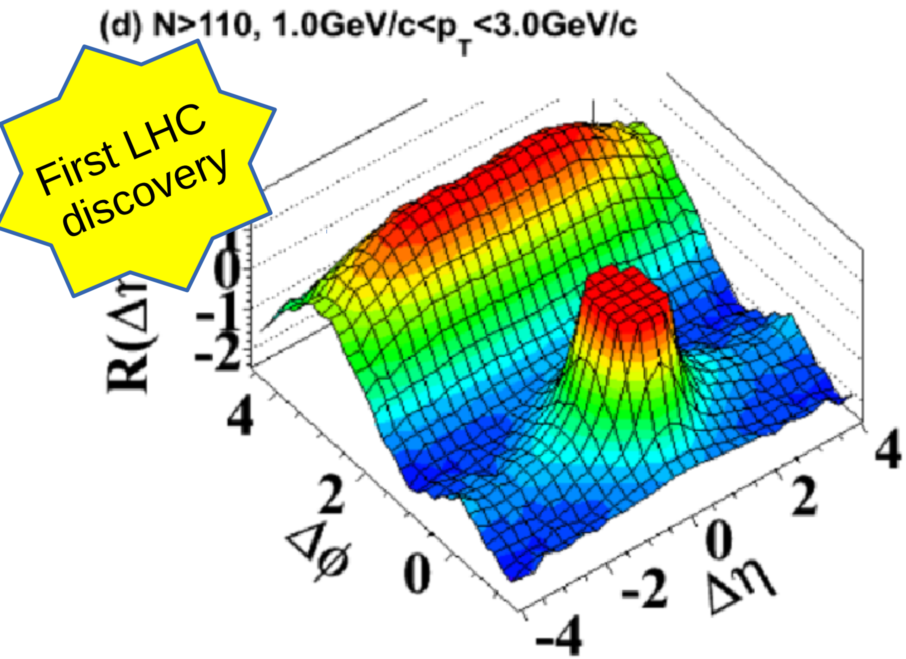
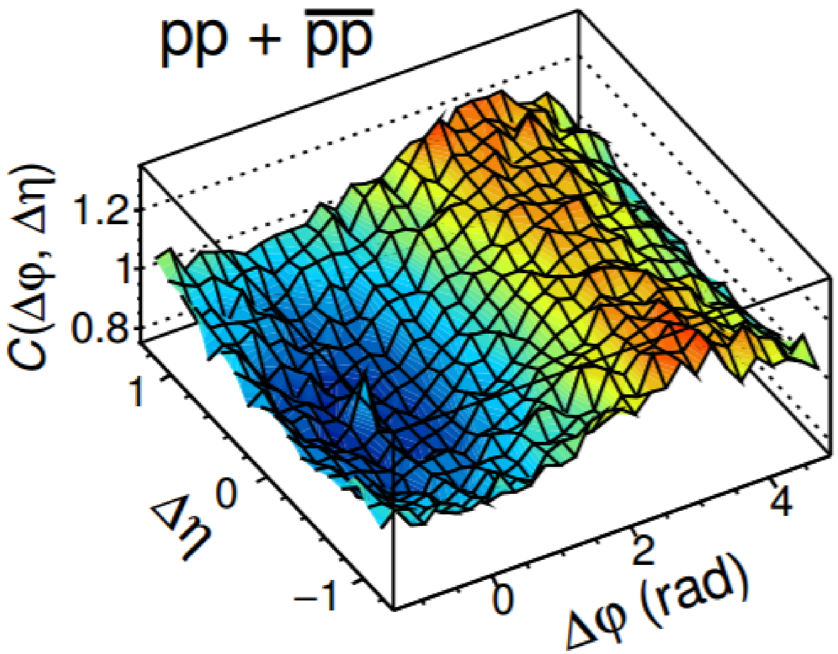
The results show structures which can be connected to phenomena such as resonance decays, momentum conservation and Bose-Einstein correlations.

Can we learn something more?

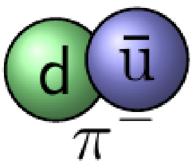


CMS Collaboration, 2010

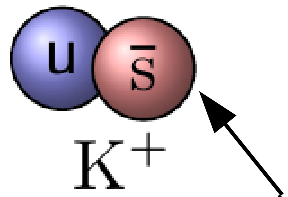


One step further: ΔηΔφ of identified particles!

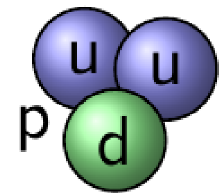
Unexplored phenomena **conservation laws** and their influence on **particle production mechanisms –** study via correlation functions for particles with **different quark content**



Pion:
- Charge



Kaon:
- Charge
- Strange quark



Proton:
- Charge
- Baryon

particles	conservation laws momentum	charge	strangeness	baryon number
pions	✓	✓		
kaons	✓	✓	✓	
protons	✓	✓		✓

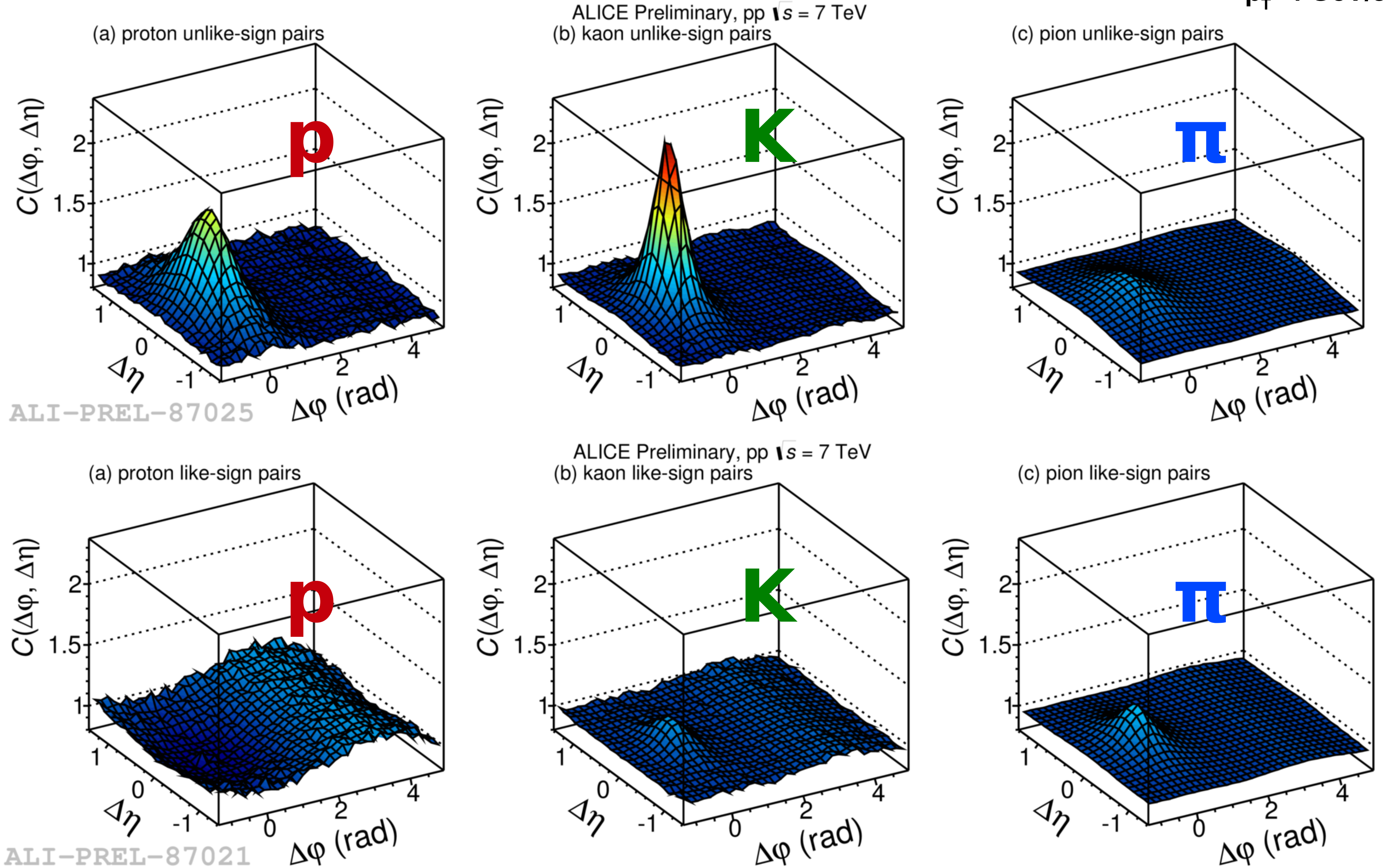
Useful to perform analysis in a more refined way:
- **charge dependence**
- **identified particles**

Eur.Phys.J. C77 (2017) 569

ΔηΔφ of identified particles in pp collisions

arXiv:1612.08975

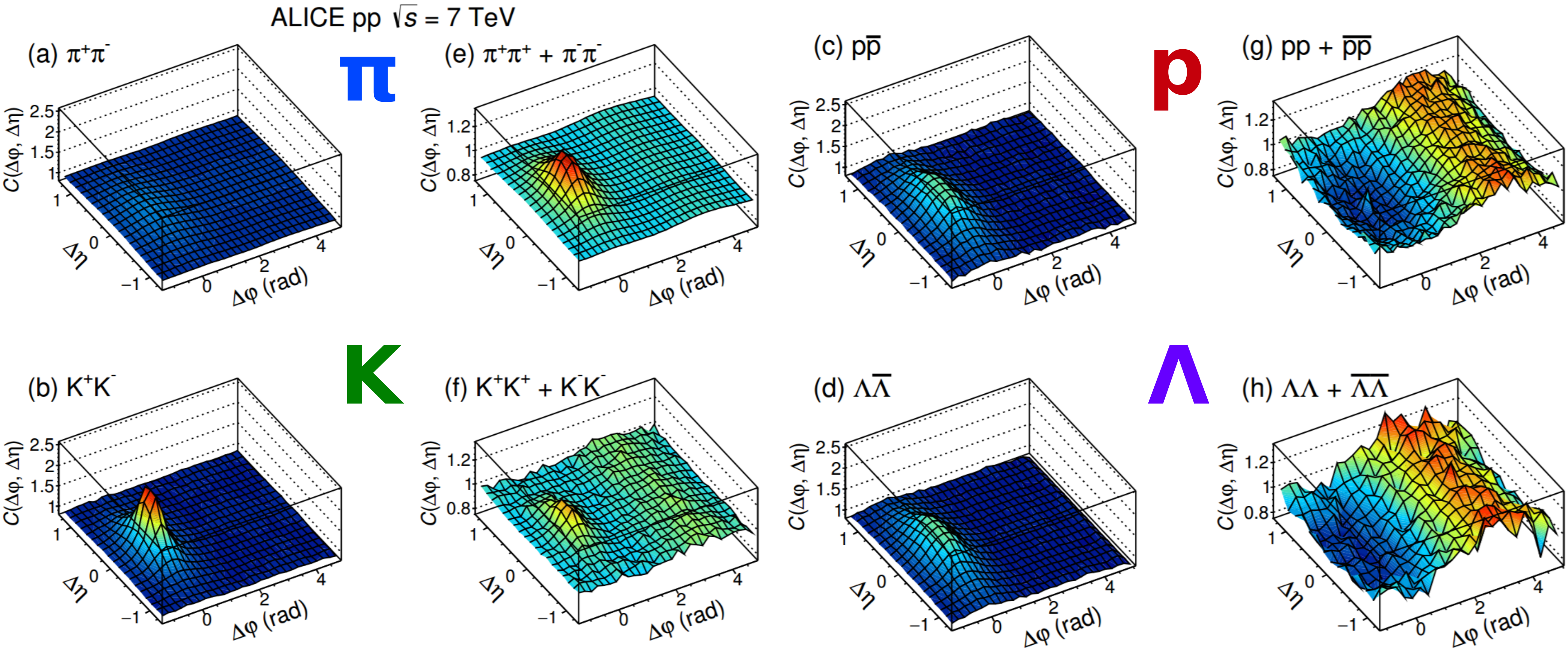
p_T<4 GeV/c



ΔηΔφ of identified particles in pp collisions

Eur.Phys.J. C77 (2017) 569

p_T<2.5 GeV/*c*



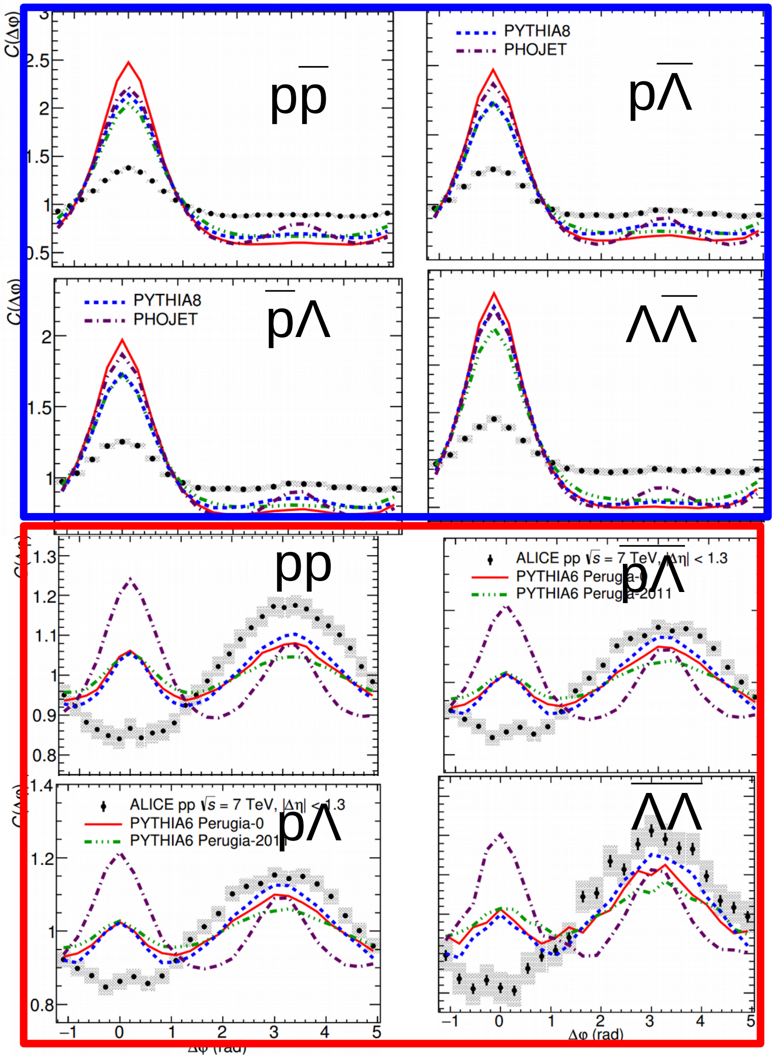
Baryon correlations

Eur.Phys.J. C77 (2017) 569

Not reproduced by MC models:
- **Pythia6**
- **Pythia8**
- **Phojet**
- **EPOS**
- **Herwig**

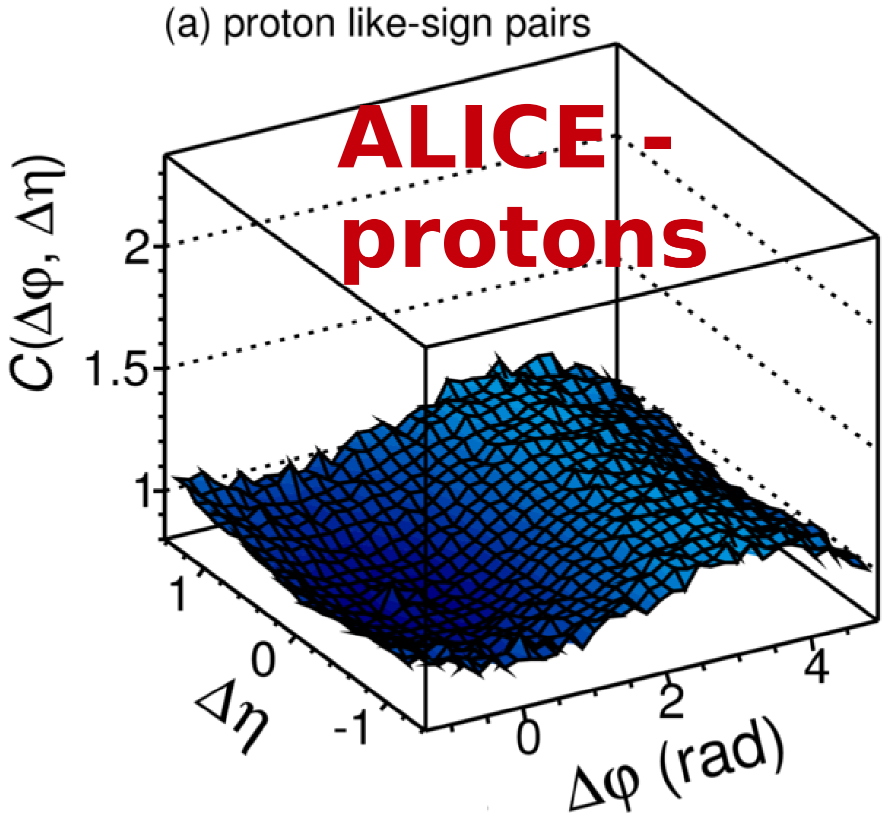
- **No plausible explanation**

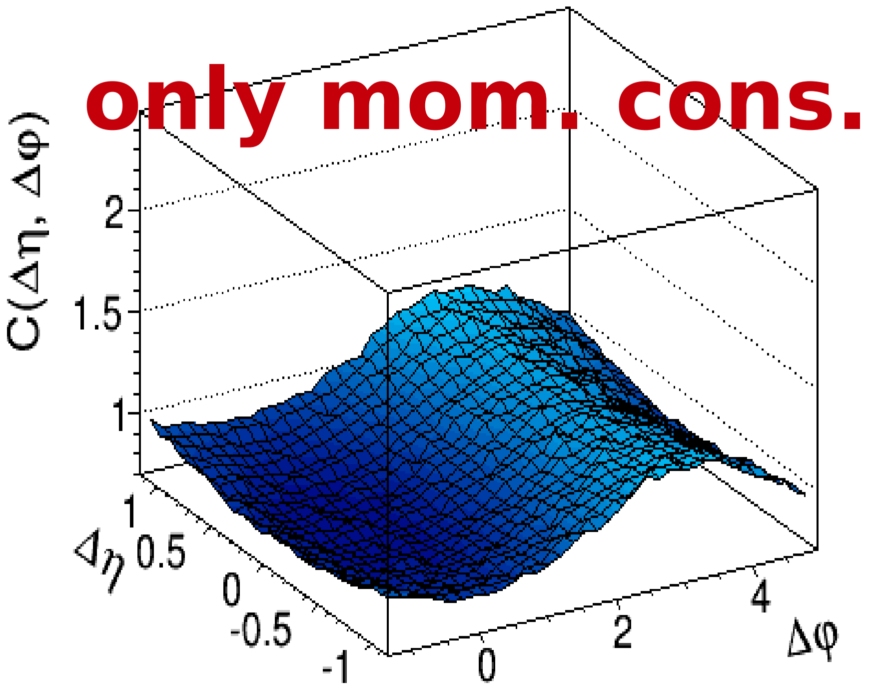
baryon-antibaryon correlation



(anti)baryon-(anti)baryon anticorrelation!

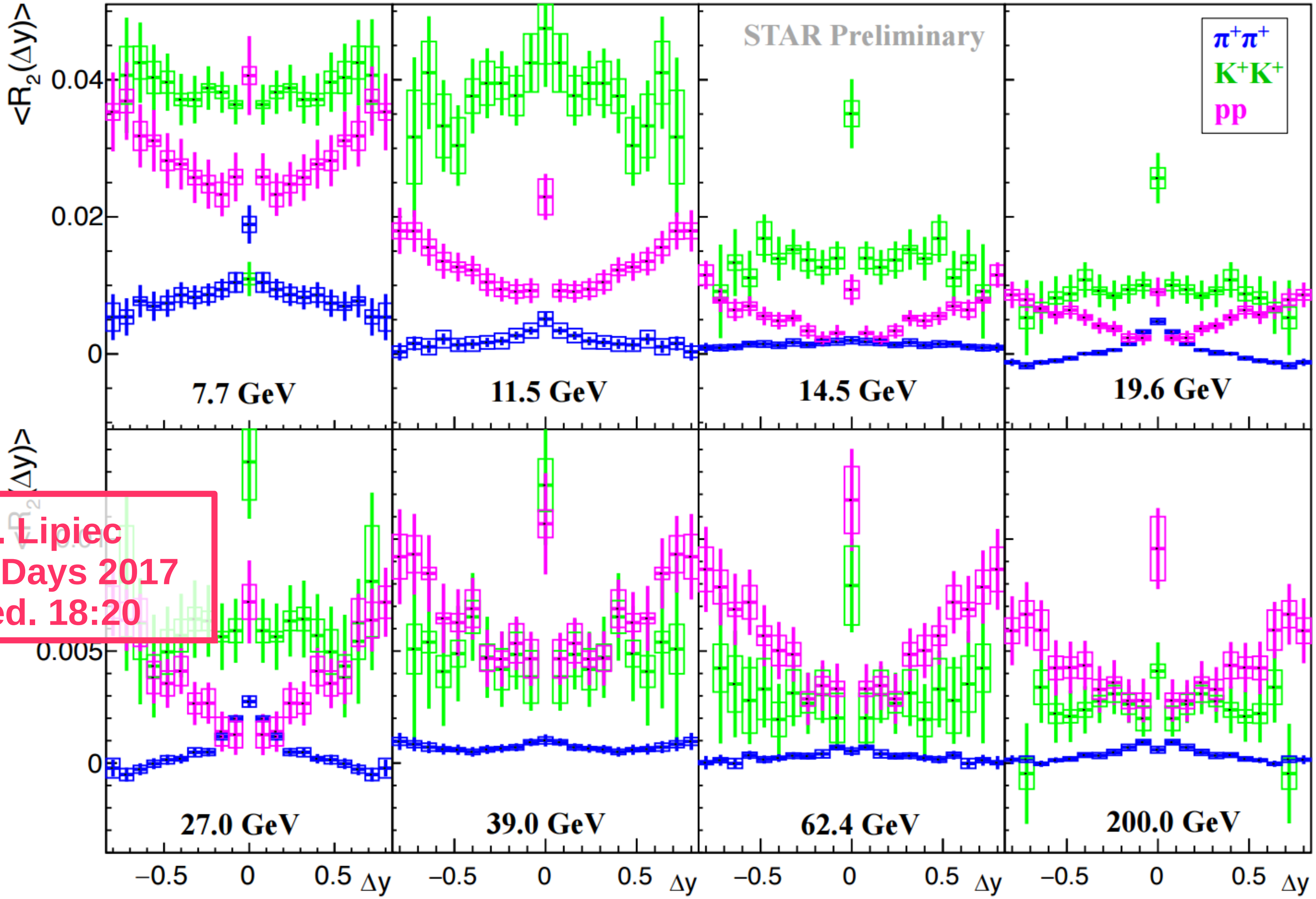
ΔηΔφ of identified particles of pp collisions





$\pi^+\pi^+$, K^+K^+ and pp, 0-5% centrality

SRC was not subtracted



A. Lipiec
Nica Days 2017
Wed. 18:20

Minima in $\langle R_2\rangle$ of protons around $\Delta y=0$ at all beam energies

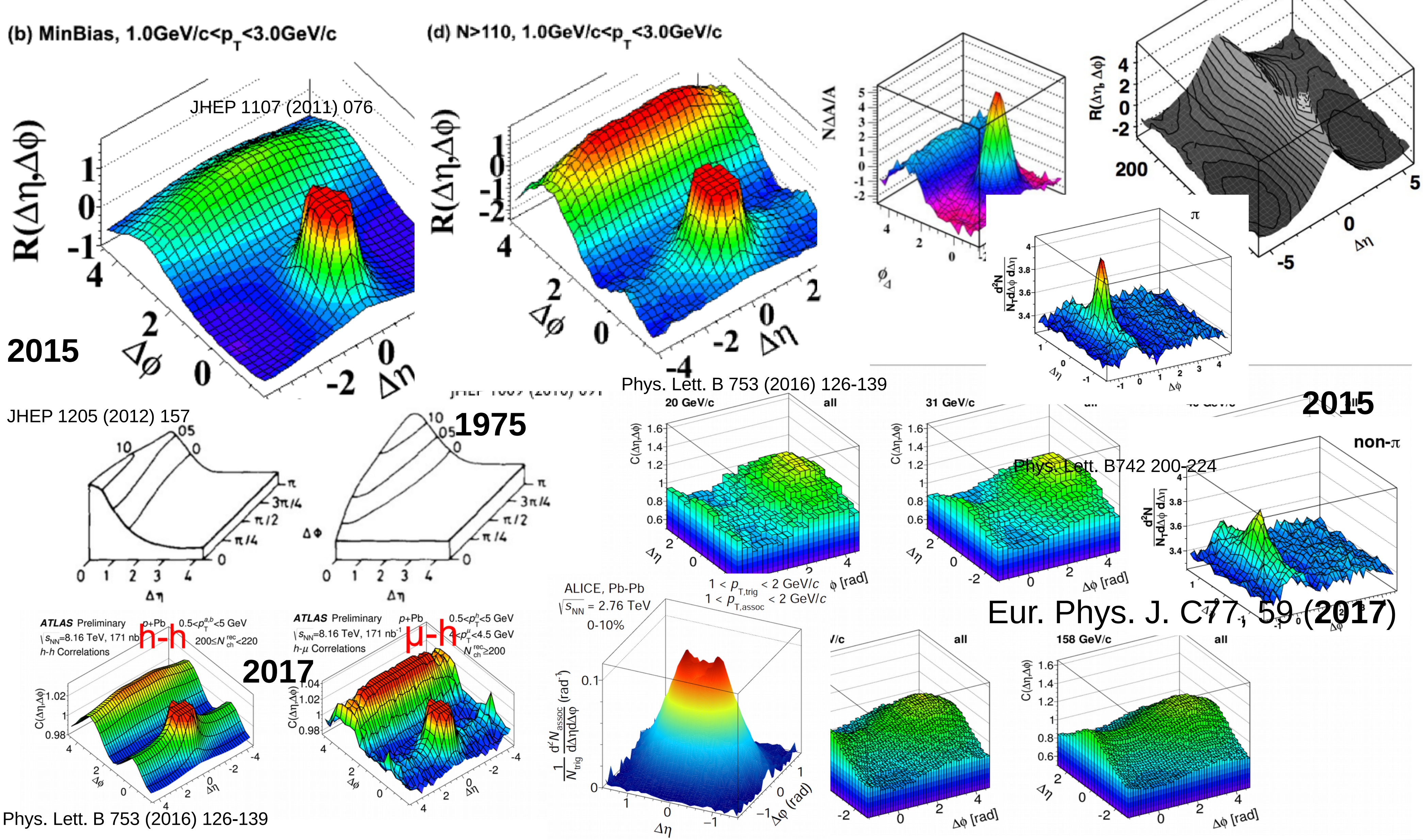
Point at $\Delta y=0$ reflects combination of SRC and the removal of track merging effects

S. Jowzaee, Quark Matter 2017

9

Angular correlations summary

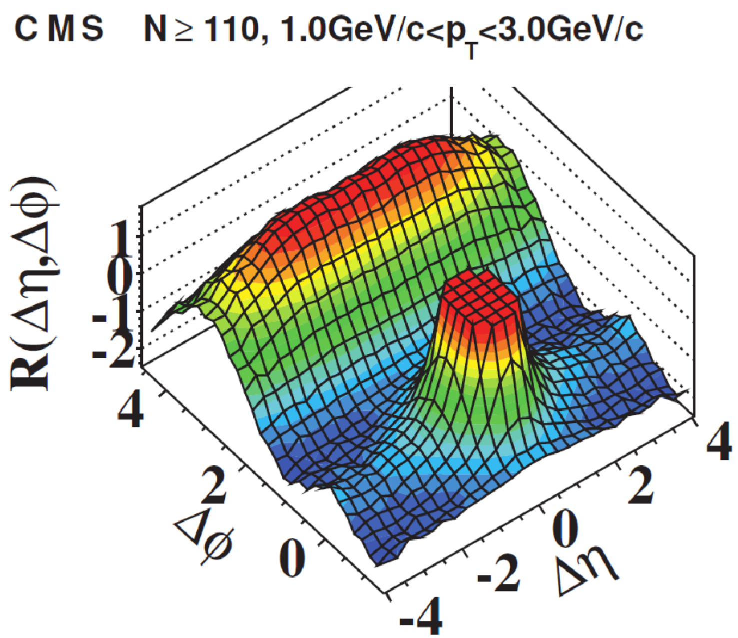
- **Allow to study wide range of physics phenomena**

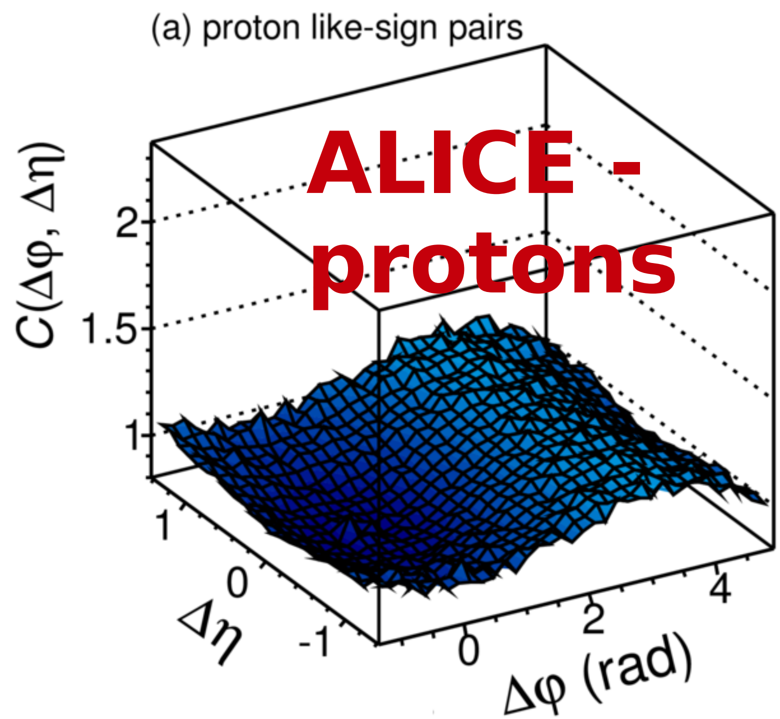


Angular correlations summary

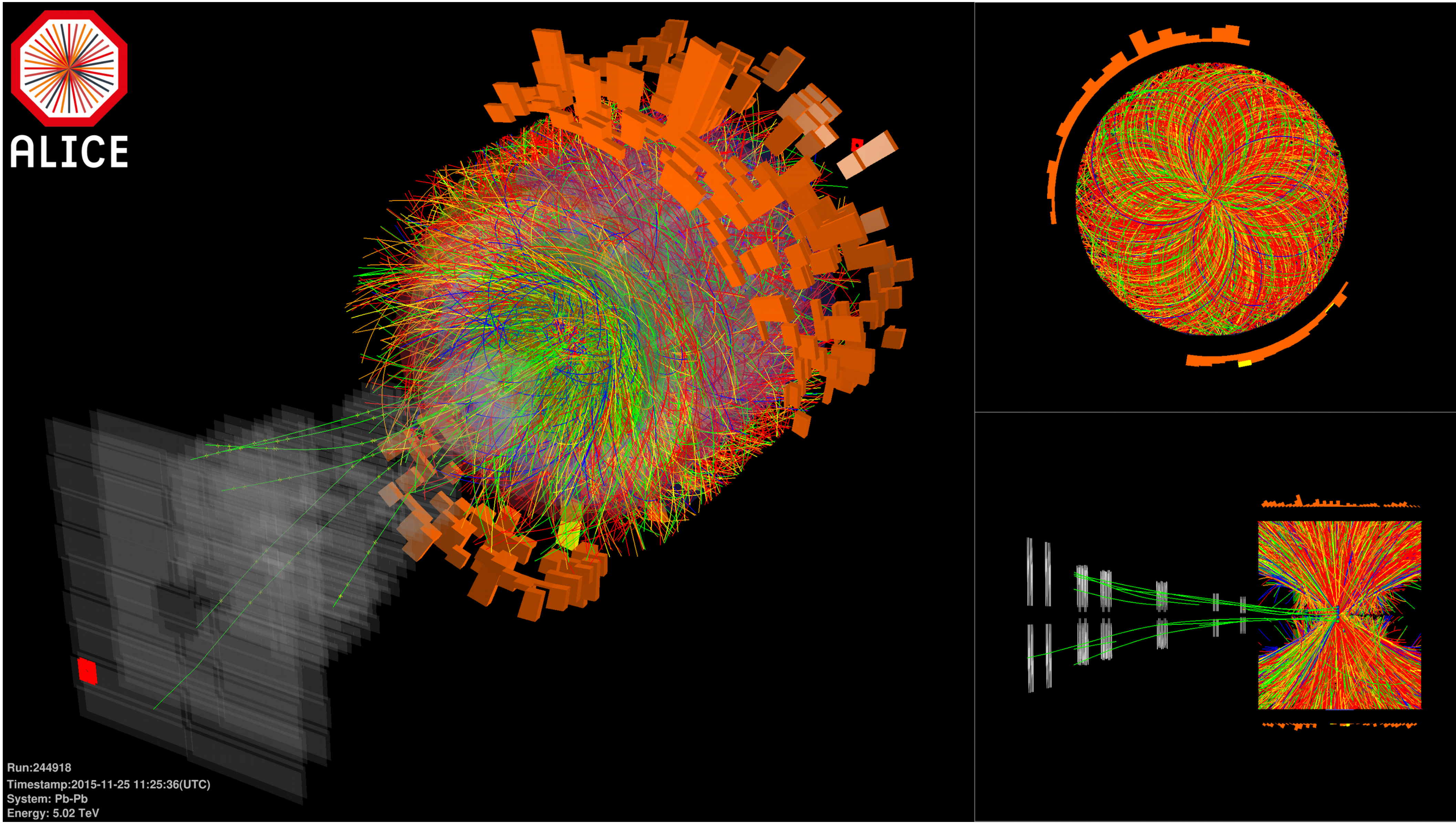
- **Allow to study wide range of physics phenomena**
- **Still new mysteries to solve**

Ridges





ALICE Event Display

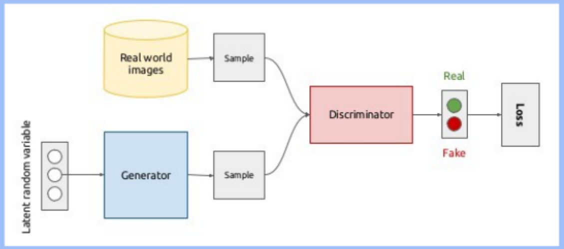


Data Quality Monitoring with Machine Learning

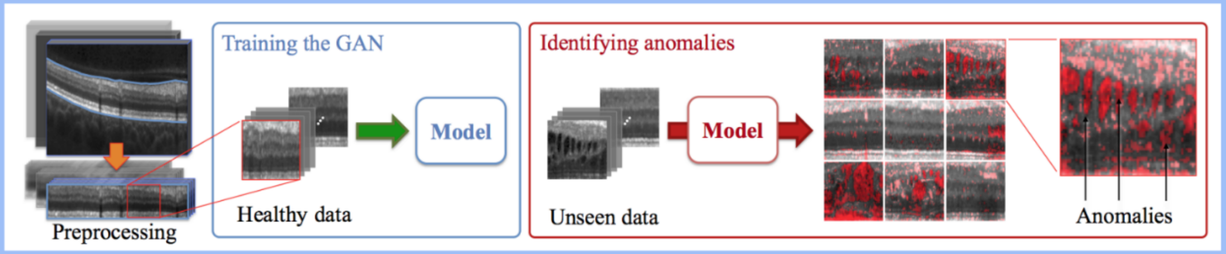
T. Trzciński
Nica Days 2017
Wed. 15:00

Using Generative Adversarial Networks (GANs) for anomaly detection

- GANs are used to synthetically generate data (e.g. images) that look **authentic.**



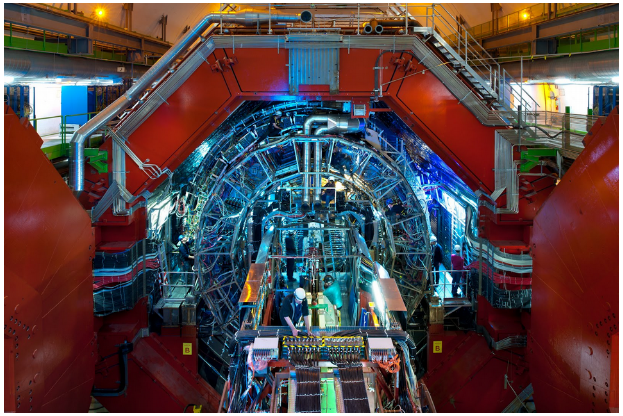
- In ALICE, a GAN model trained on **correct data** can be used to **simulate correct detector outputs.**
- When real data comes to the detector, it can be compared to GAN-generated data points and **differences** can be interpreted as **anomalies.**
- Other applications include data compression and detector aging modeling



Similar Anomaly Detection mechanism proposed for anomaly detection in medical images.
Source: Unsupervised Anomaly Detection with Generative Adversarial Networks to Guide Marker Discovery

WUT group in ALICE

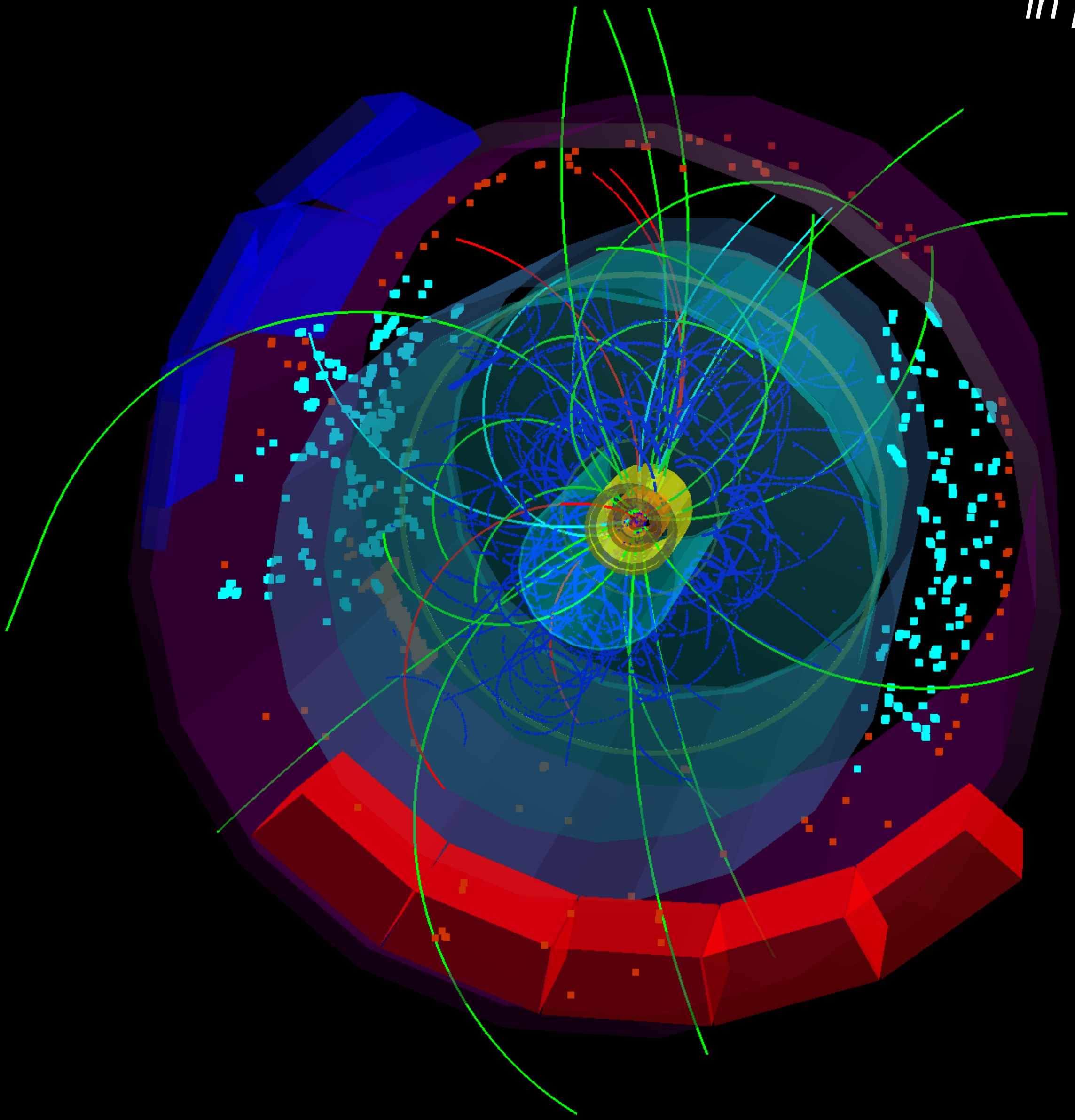
- **Team Leader: Adam Kisiel**
- Members (staff): A. Kisiel, Ł. Graczykowski, M. Janik, J. Pluta, H. Zbroszczyk, J. Oleniacz, J. Myrcha, T. Trzciński, P. Rokita
- **ALICE group specializes in particle correlations and femtoscopy**
- **Femtoscopy Physics Analysis Group**
  - Convenors: **Łukasz Graczykowski (WUT)**, Tom Humanic
- **Correlations Physics Analysis Group**
  - Convenors: **Małgorzata Janik (WUT)**, Alice Ohlson
- **Visualization & Machine learning**
  - Julian Myrcha, Tomasz Trzciński, Przemysław Rokita



The End

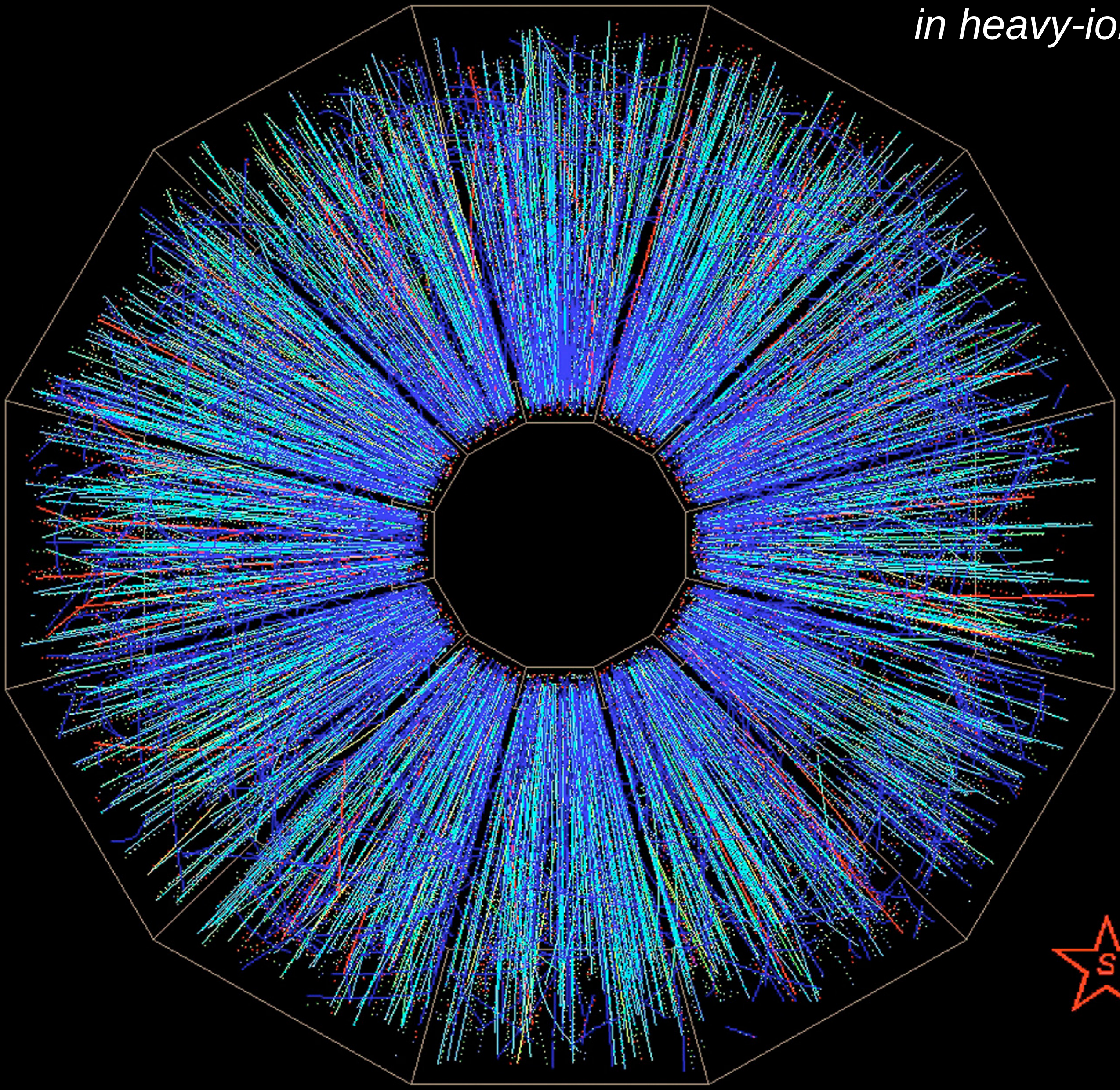
ΔηΔφ angular correlations

in pp collisions



ΔηΔφ angular correlations

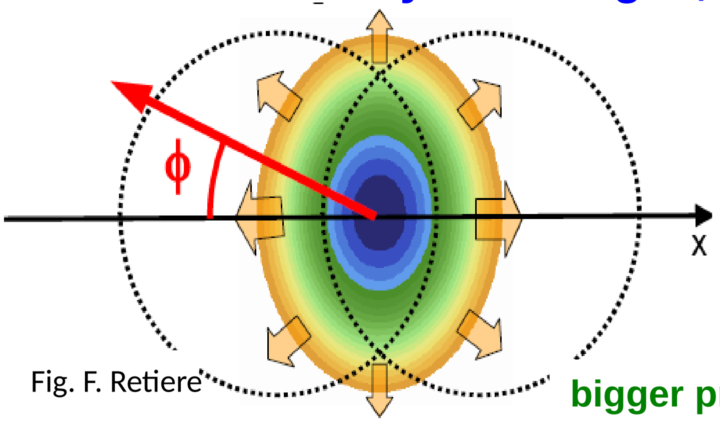
in heavy-ion collisions



Elliptic flow

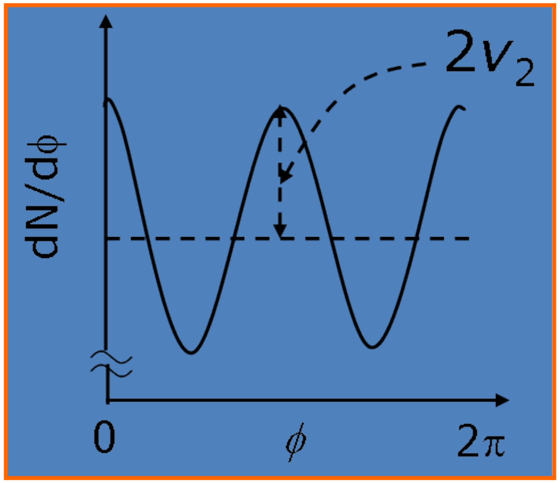
The initial spatial anisotropy leads to the momentum anistotropy, which leads to larger flow in the plane of the minor-axis of the ellipse.

The collimated production of particles along the reaction plane produces a near- and away-side ridges, of the cosine shape in deltaphi.

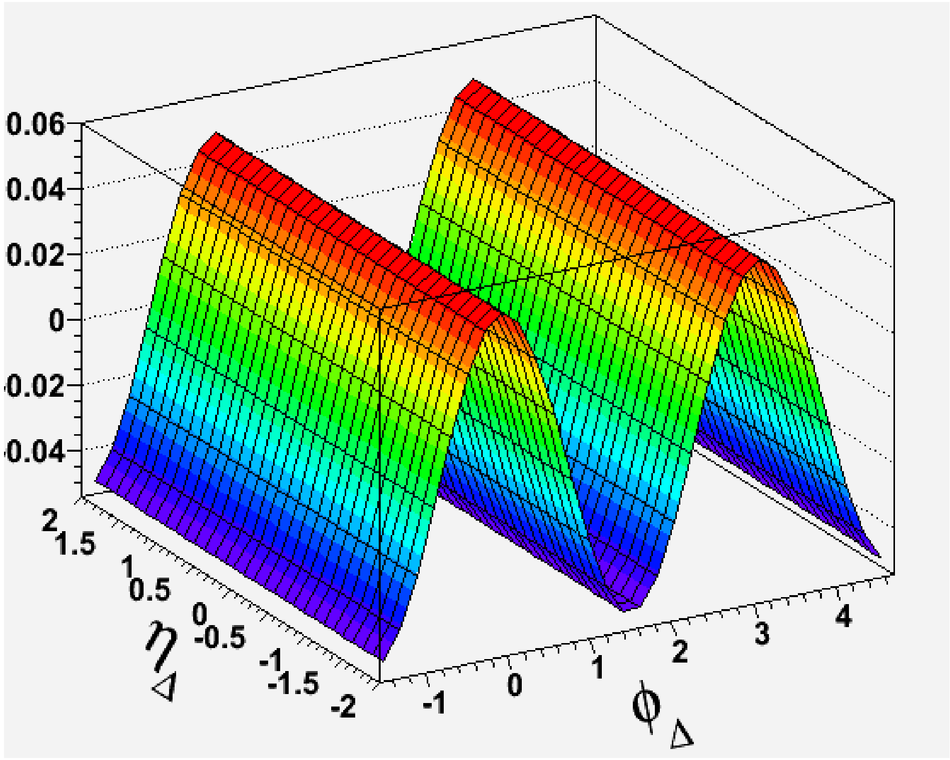


Reaction plane

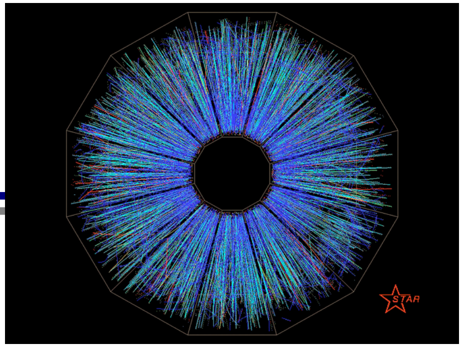
bigger pressure gradients in-plane than out-of-plane



$$v_2 = \langle \cos 2\phi \rangle$$

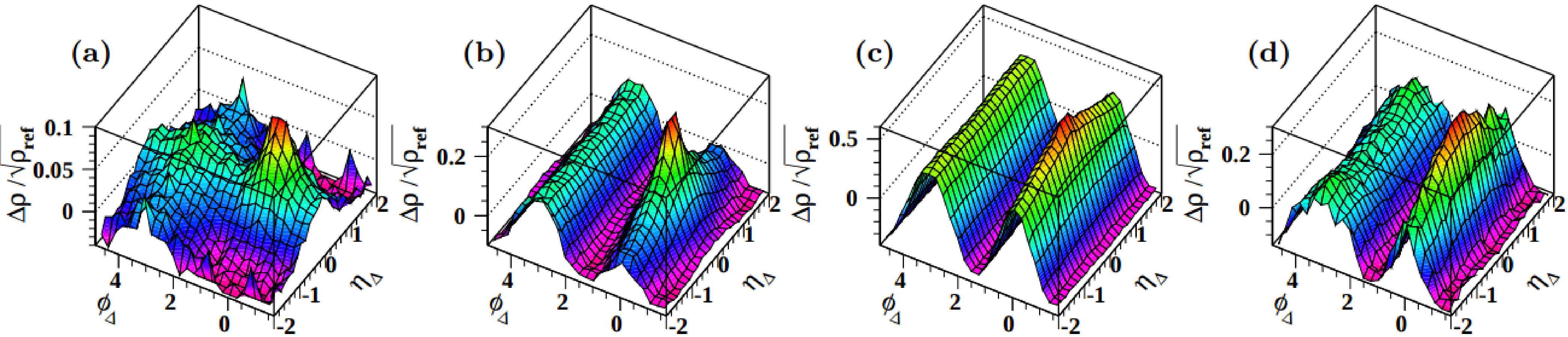


Angular correlations in Au-Au

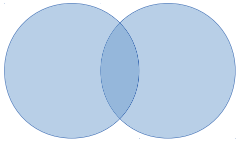


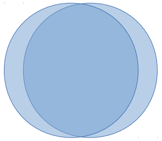
Heavy-ions

centrality



STAR: 10.1103/PhysRevC.86.064902



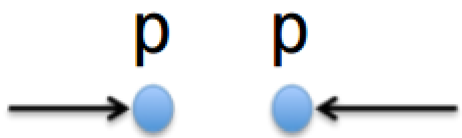


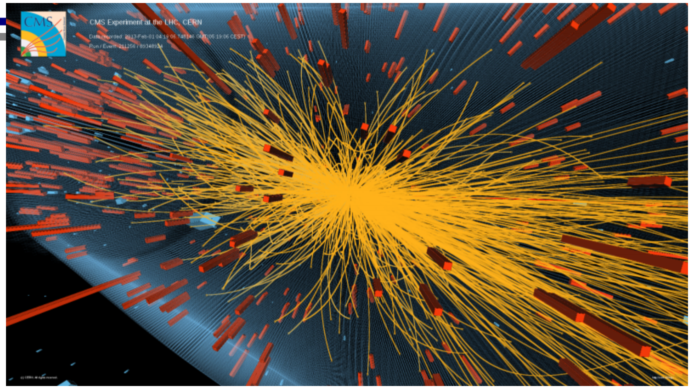
Similar to pp

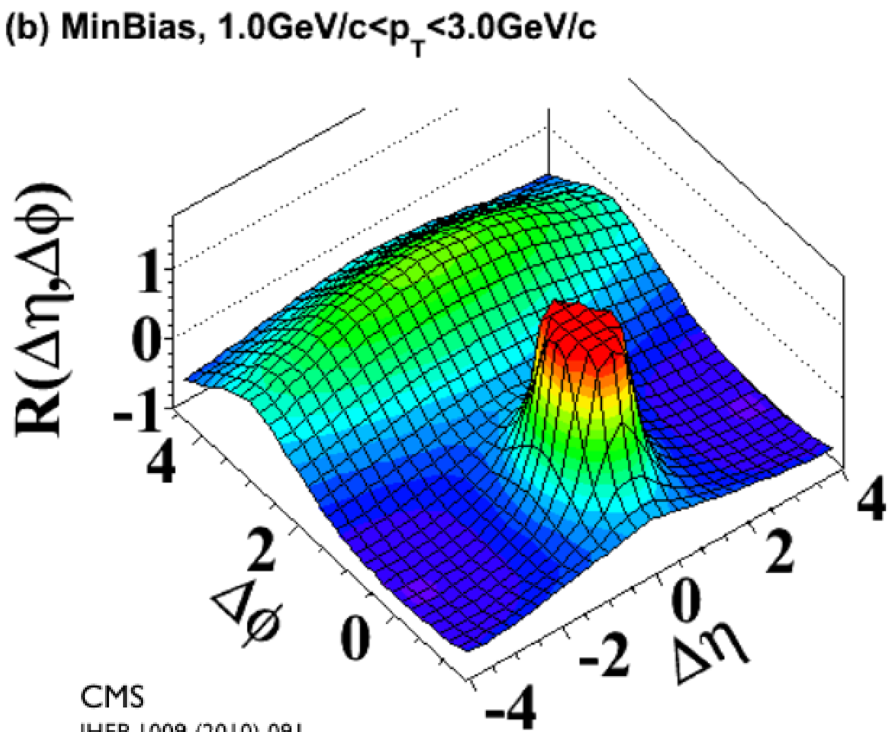
Strong contribution of flow

The Ridge: CMS 2010

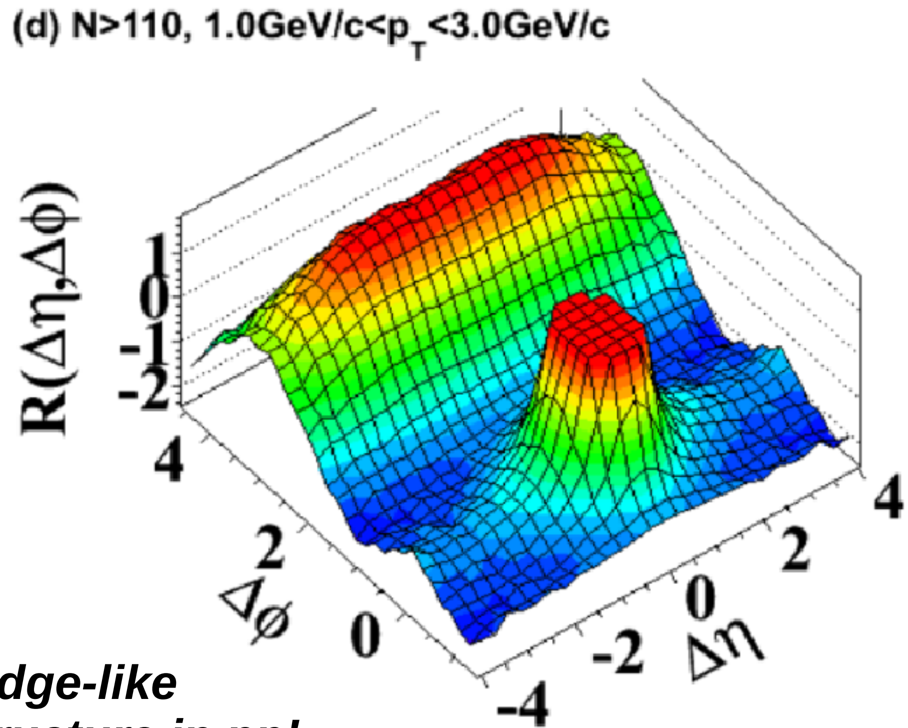
First LHC discovery





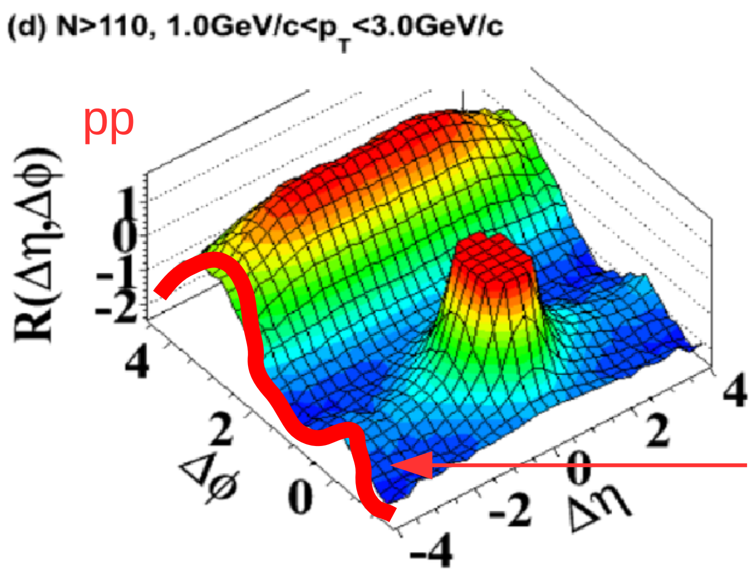


CMS
JHEP 1009 (2010) 091



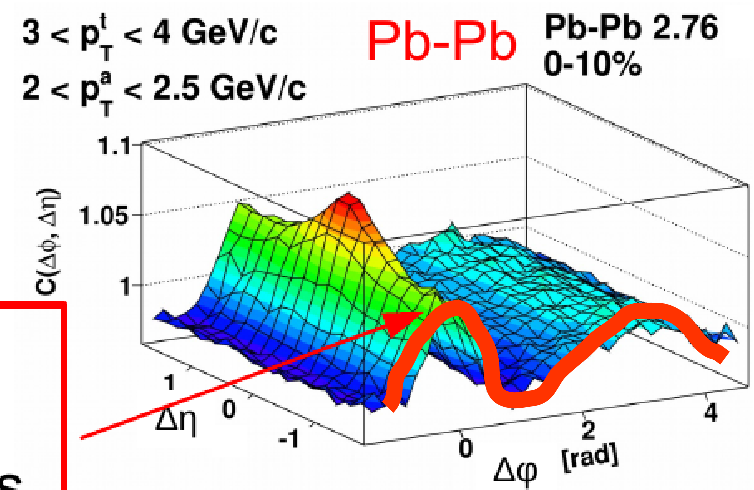
Ridge-like structure in pp!

The Ridge

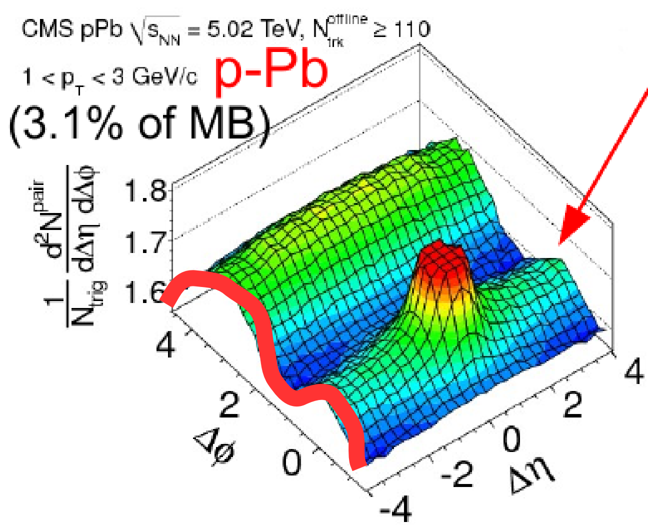


CMS, JHEP 1009 (2010) 91

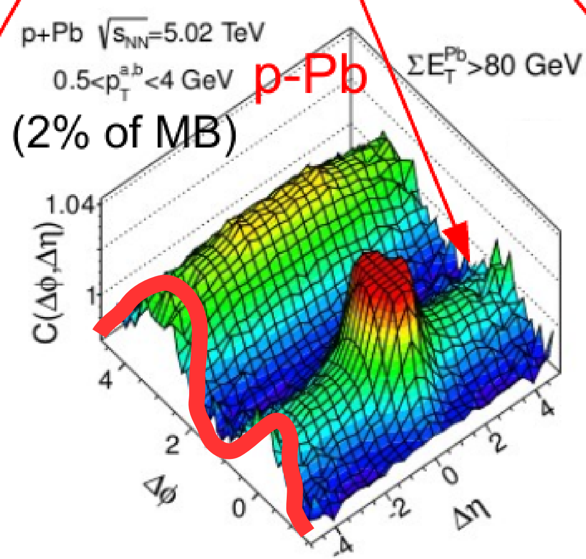
Near-side (NS) ridges in high multiplicity events at LHC energies



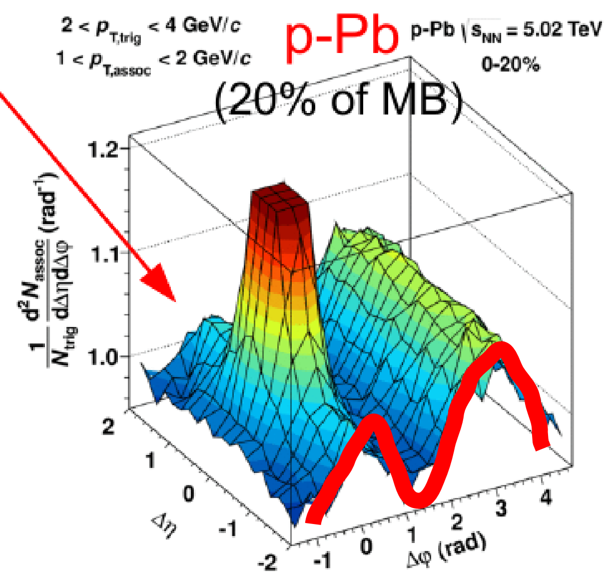
ALICE, PLB 708 (2012) 249



CMS, PLB 718 (2012) 795

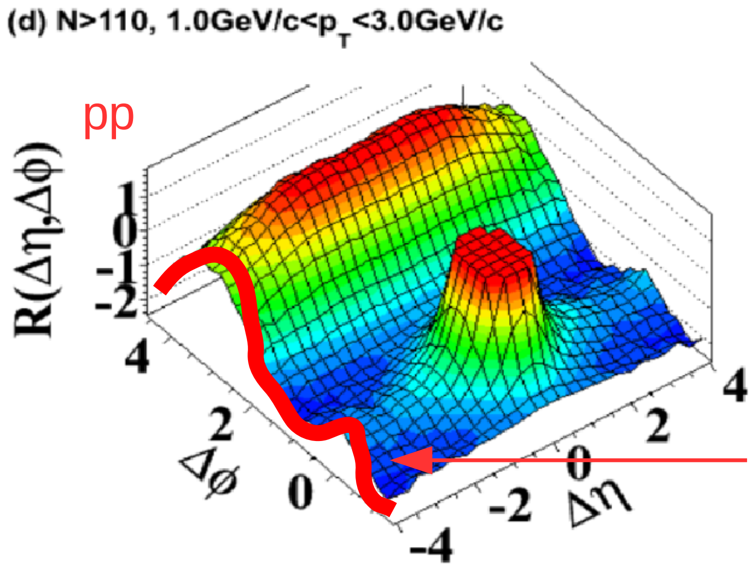


ATLAS, PRL 110 (2013) 182302

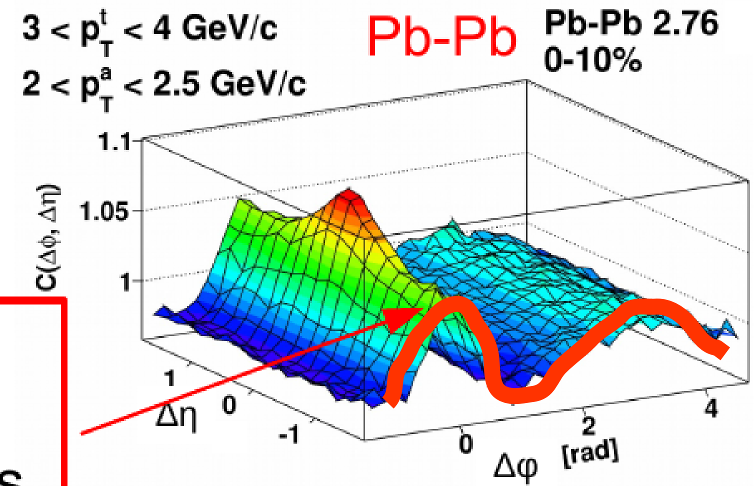


ALICE, PLB 719 (2013) 29

The Ridge



CMS, JHEP 1009 (2010) 91



ALICE, PLB 708 (2012) 249

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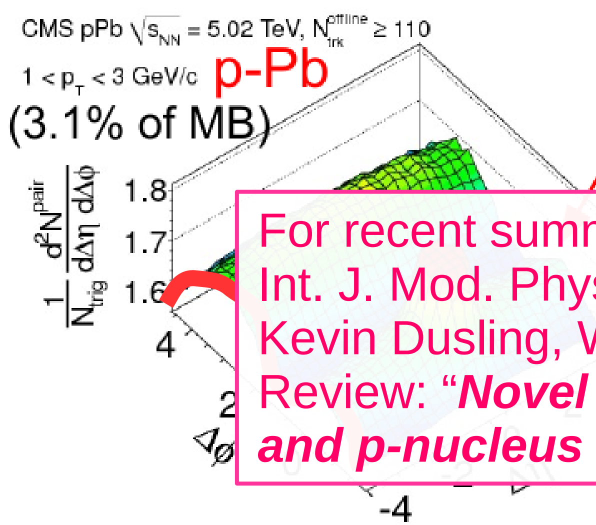
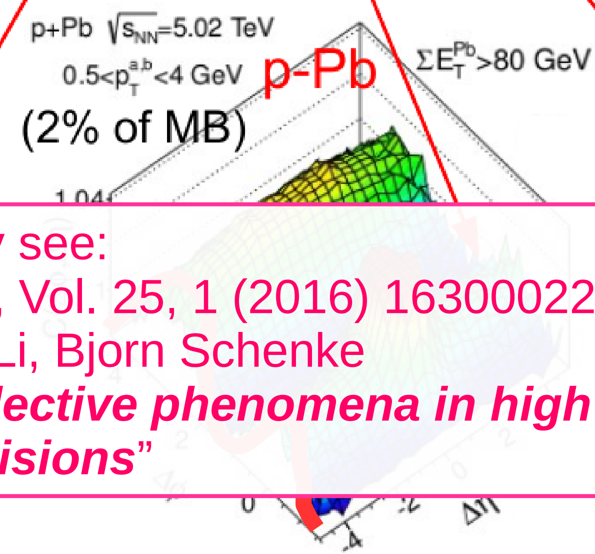
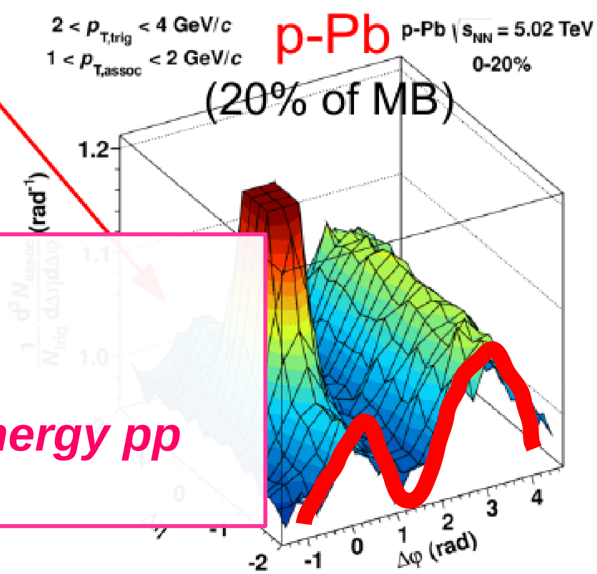


CMS, PLB 718 (2012) 795



ATLAS, PRL 110 (2013) 182302

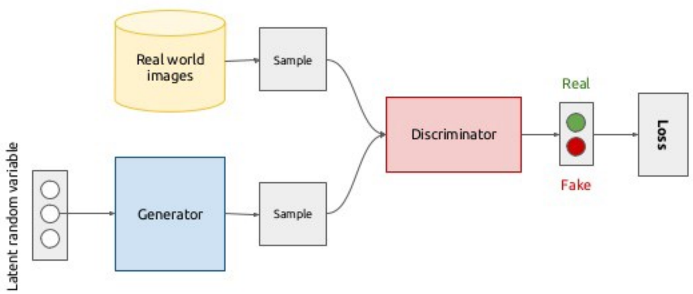


ALICE, PLB 719 (2013) 29

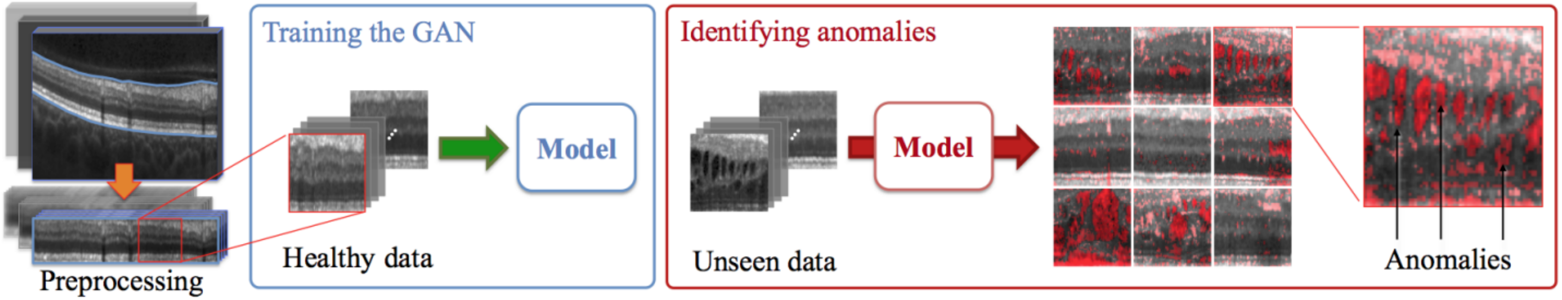
For recent summary see:
Int. J. Mod. Phys. E, Vol. 25, 1 (2016) 16300022
Kevin Dusling, Wei Li, Bjorn Schenke
Review: "***Novel collective phenomena in high energy pp and p-nucleus collisions***"

Generative Adversarial Networks for Simulation

- GANs are used to synthetically generate data (e.g. images) that look **authentic.**

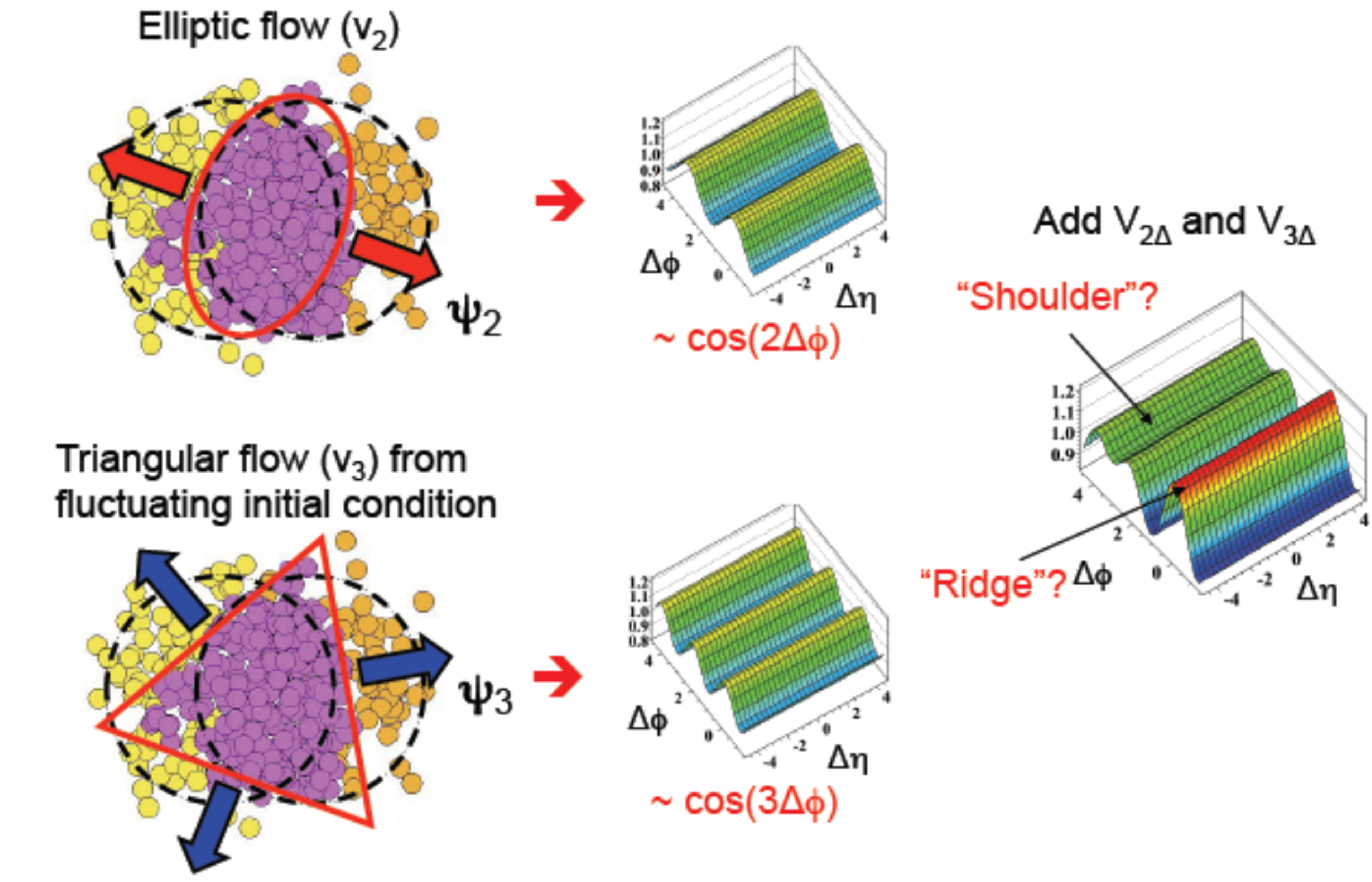


- In ALICE, a GAN model trained on **correct data** can be used to **simulate correct detector outputs.**
- When real data comes to the detector, it can be compared to GAN-generated data points and **differences** can be interpreted as **anomalies.**
- Other applications include data compression and detector aging modeling



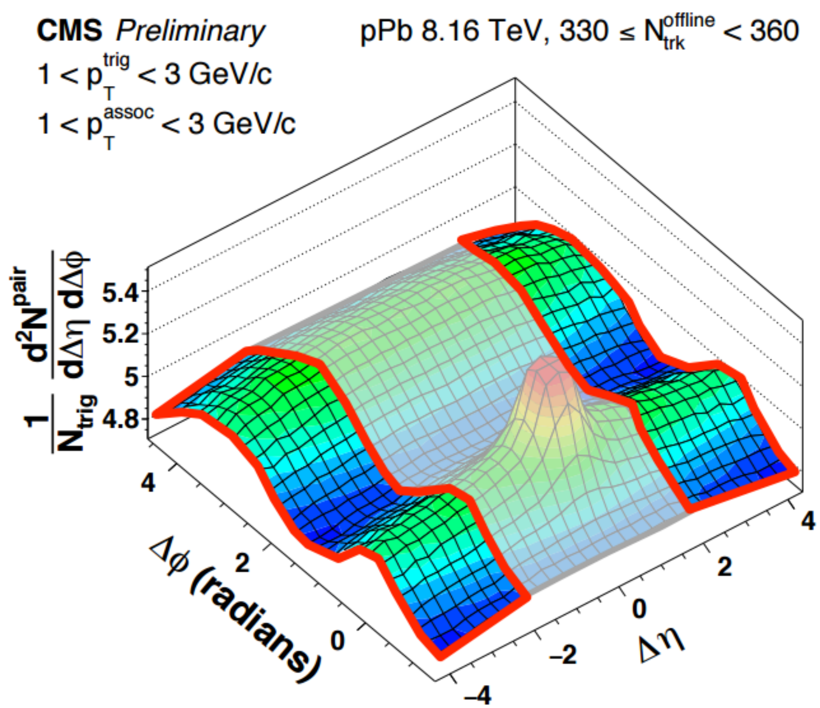
Similar Anomaly Detection mechanism proposed for anomaly detection in medical images.
Source: Unsupervised Anomaly Detection with Generative Adversarial Networks to Guide Marker Discovery

Collective effects: flow

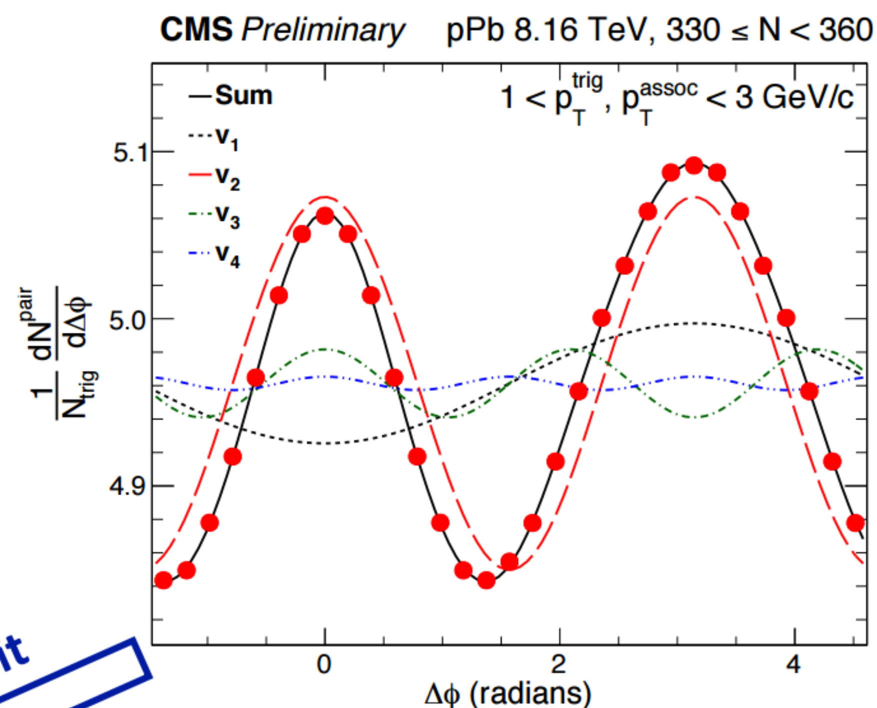


Collective effects: flow

2D correlation function

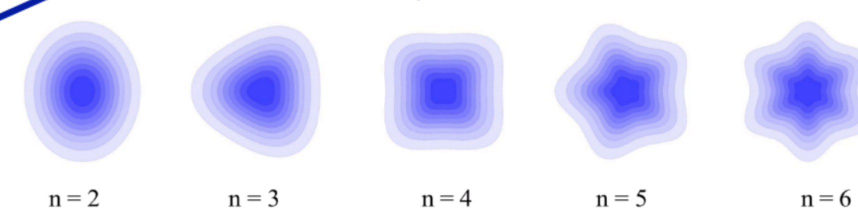


1D correlation function



Projection on ΔΦ

Fourier fit



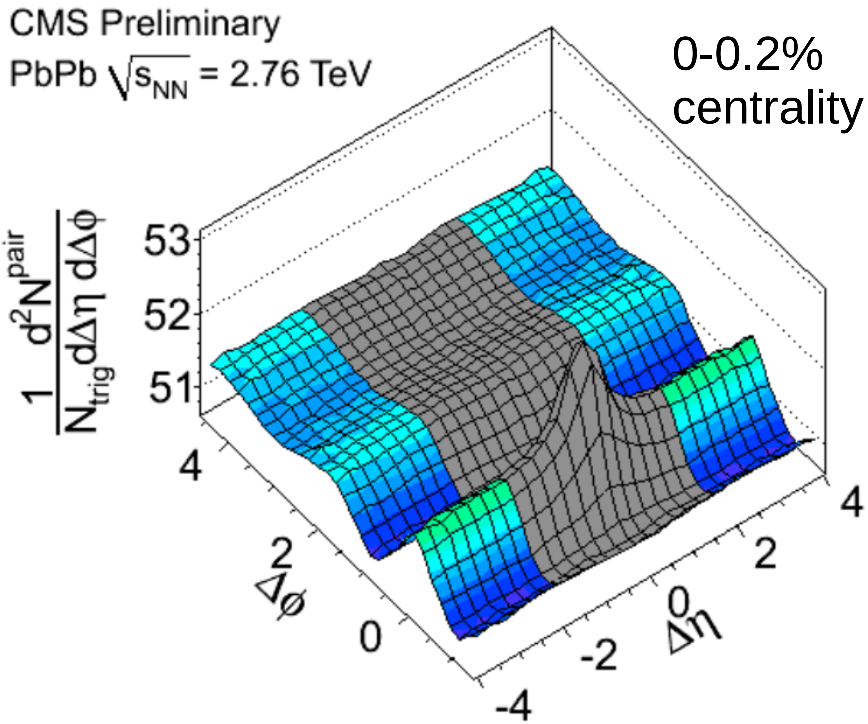
$$\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}\left[1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

$$v_n = \sqrt{V_{n\Delta}}$$

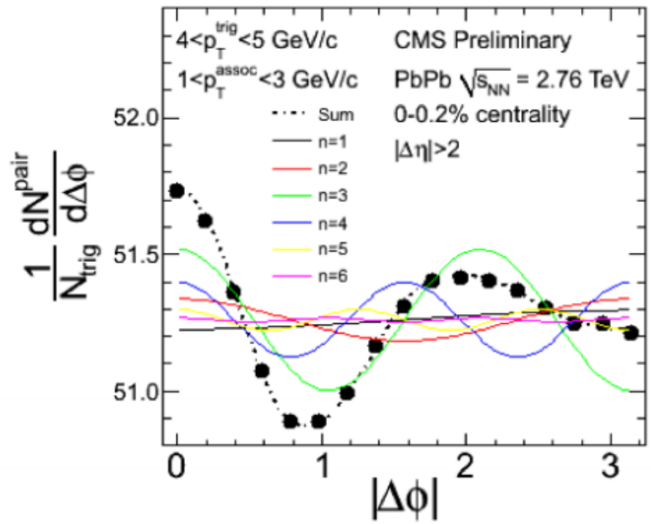
Extract single particle v_n

Collective effects: flow

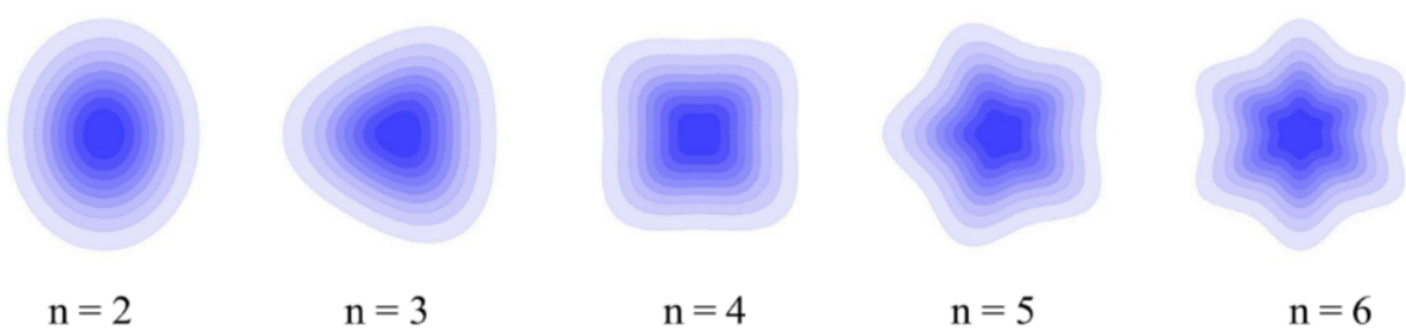
➢ 2D correlation function



➢ 1D correlation function



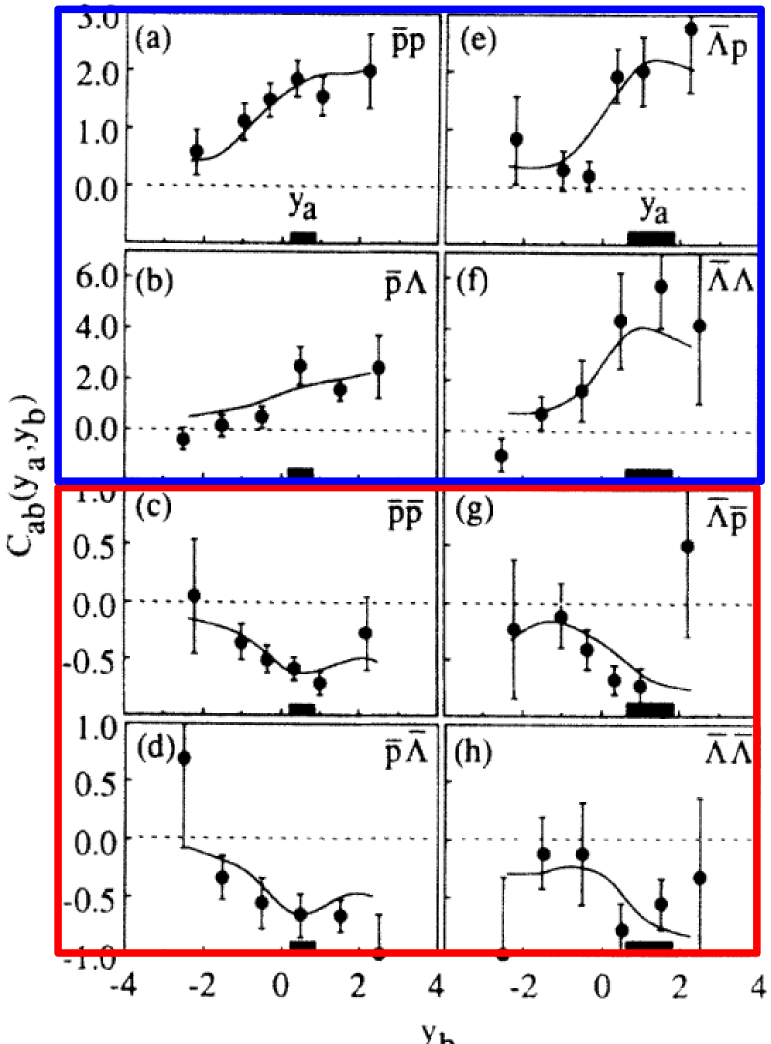
At LHC, the large acceptance of the experiments, together with the high particle density (as a collective effect, the flow signal increases strongly with multiplicity) **made the observation and interpretation straightforward and unambiguous.** J. Schukraft



Baryon correlations

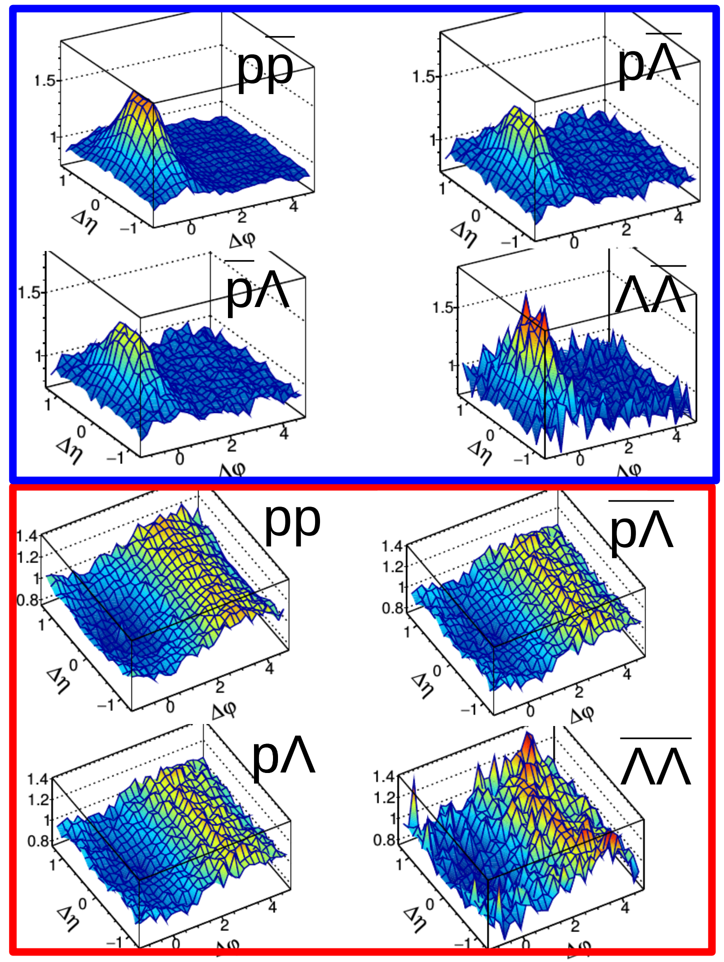
Study of baryon correlations in **e^+e^-** annihilation at **$\sqrt{s}$=29 GeV**
TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140

baryon-antibaryon
correlation **in e+e-**



antibaryon-antibaryon
anticorrelation!

baryon-antibaryon
correlation **in ALICE**



(anti)baryon-(anti)baryon
anticorrelation!

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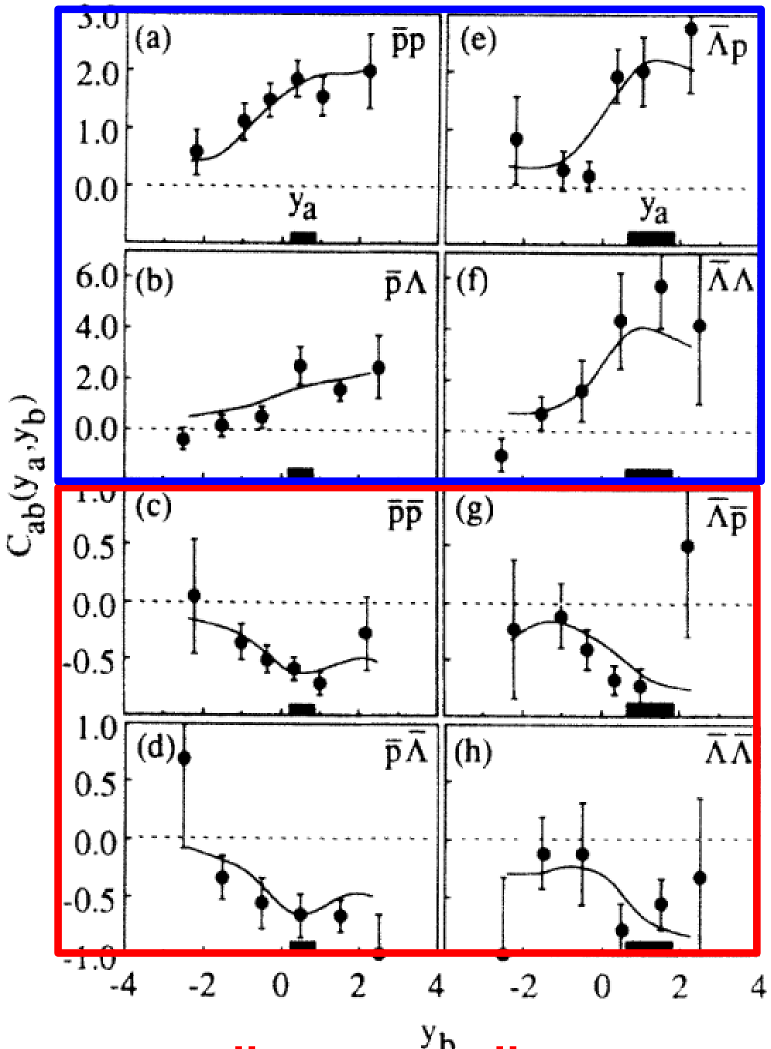
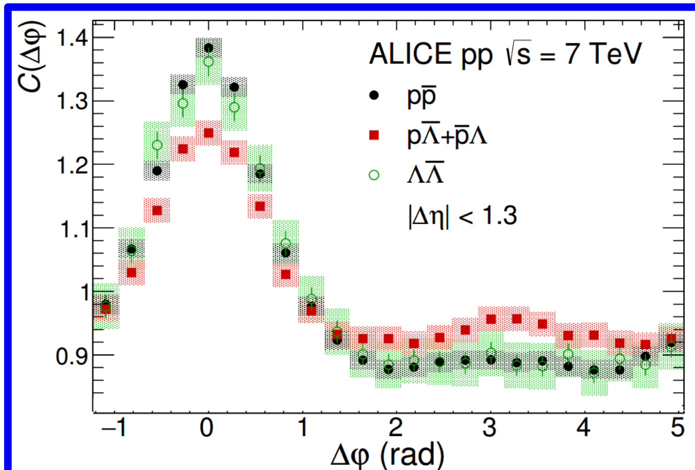
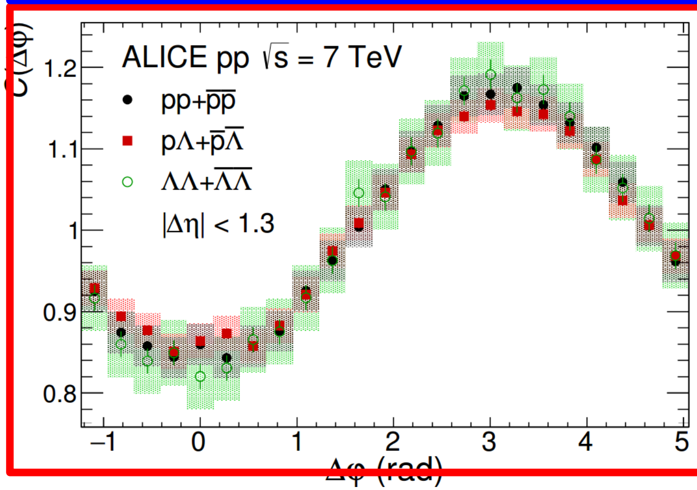
baryon-antibaryon
correlation **in e+e-**



antibaryon-antibaryon
anticorrelation!

baryon-antibaryon
correlation **in ALICE**

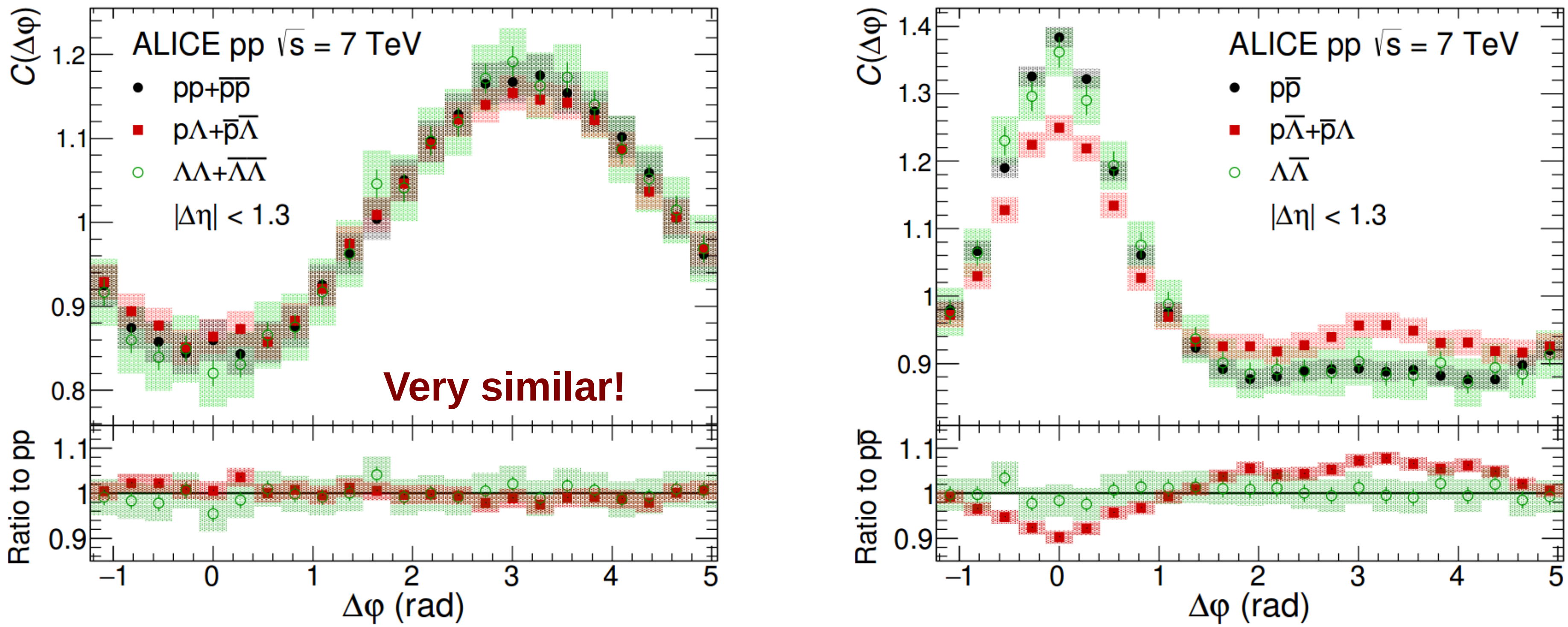




(anti)baryon-(anti)baryon
anticorrelation!

ALICE data

arXiv:1612.08975



Possible explanations:

- **Fermi-Dirac Quantum Statistics? NO (non-identical particles)**
- **Coulomb repulsion? NO (uncharged particles)**
- **Strong Final-State Interactions? NO**

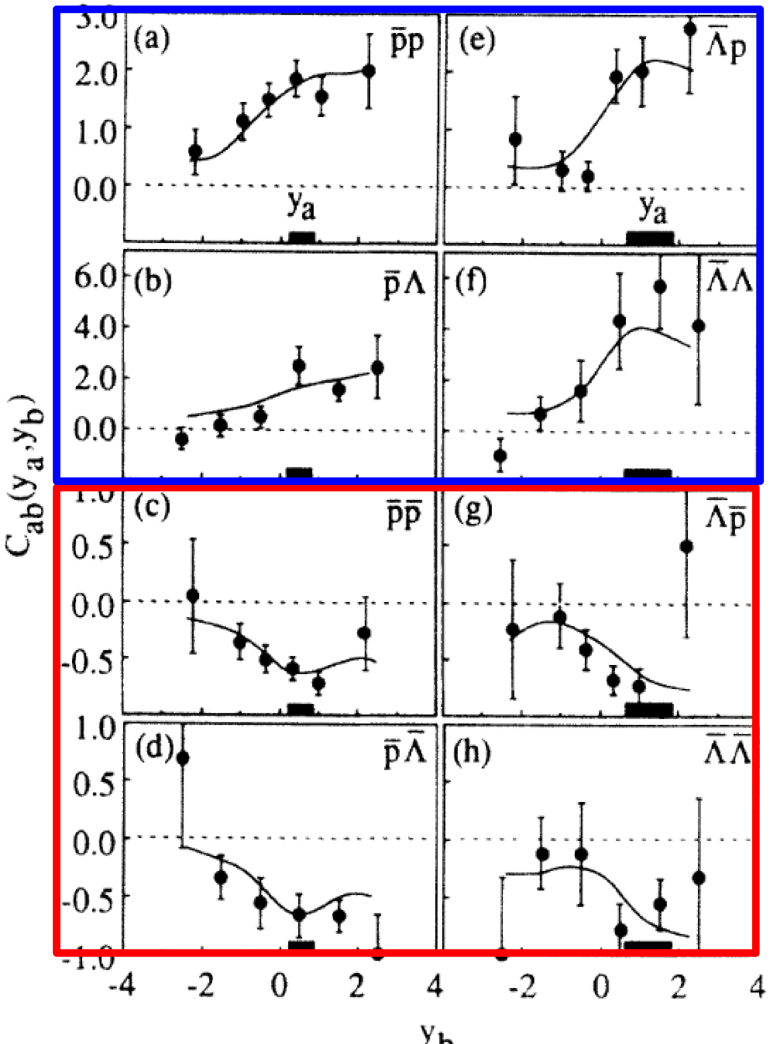
Hypothesis from e^+e^- studies:

- **Depletion is a manifestation of "local" baryon number conservation**
- **Production of 2 baryons in a single mini-jet would be suppressed if the initial parton energy is small when compared to the energy required to produce 4 baryons in total (2 in the same mini-jet + 2 anti-particles) – fine at 29 GeV, but why at 7 TeV?!**

Baryon correlations

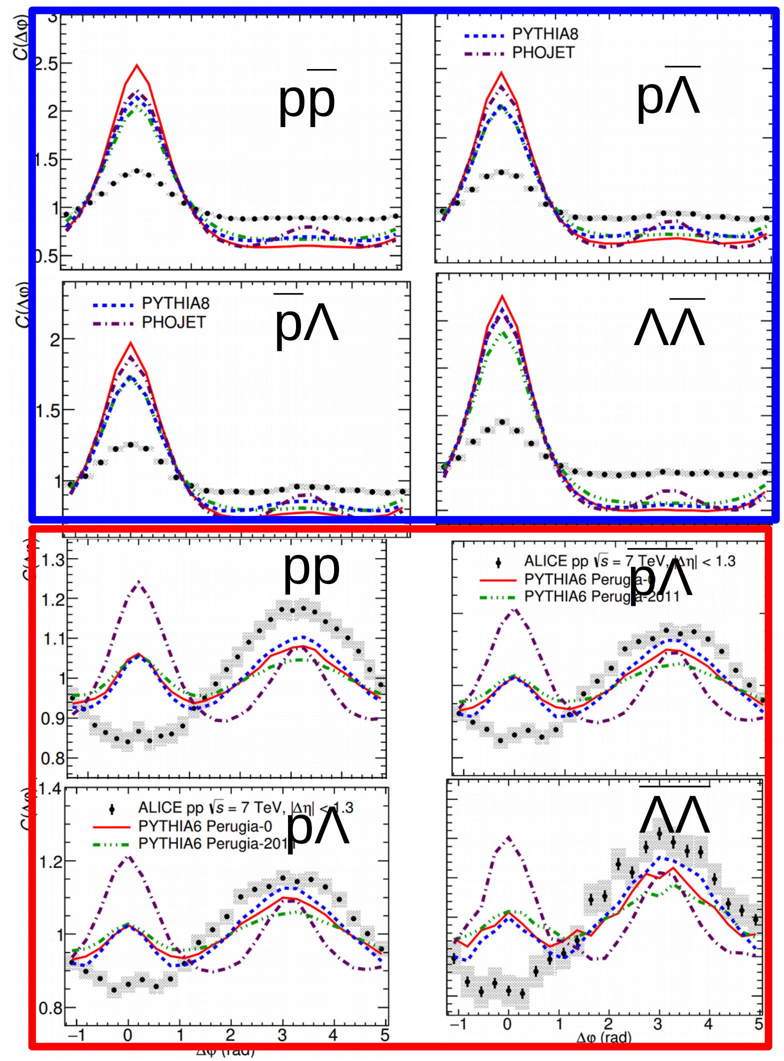
Study of baryon correlations in e⁺e⁻ annihilation at √s=29 GeV
TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140

baryon-antibaryon
correlation



antibaryon-antibaryon
anticorrelation!

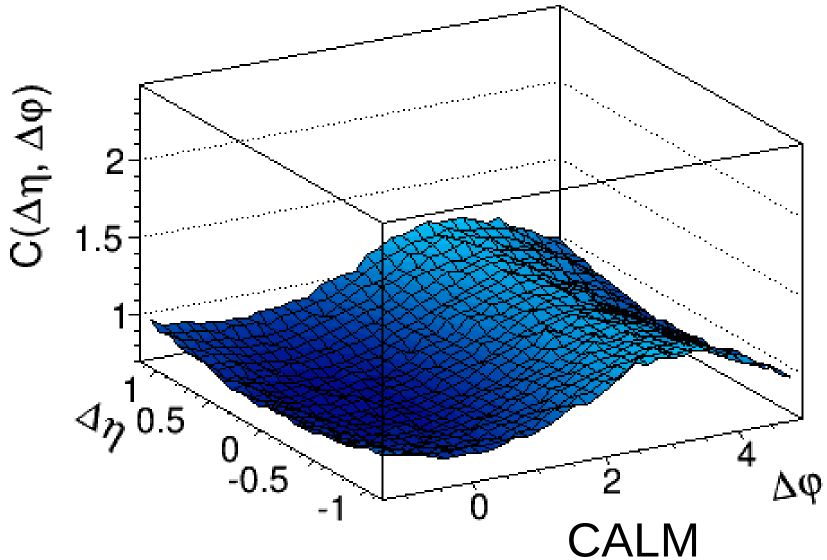
baryon-antibaryon
correlation

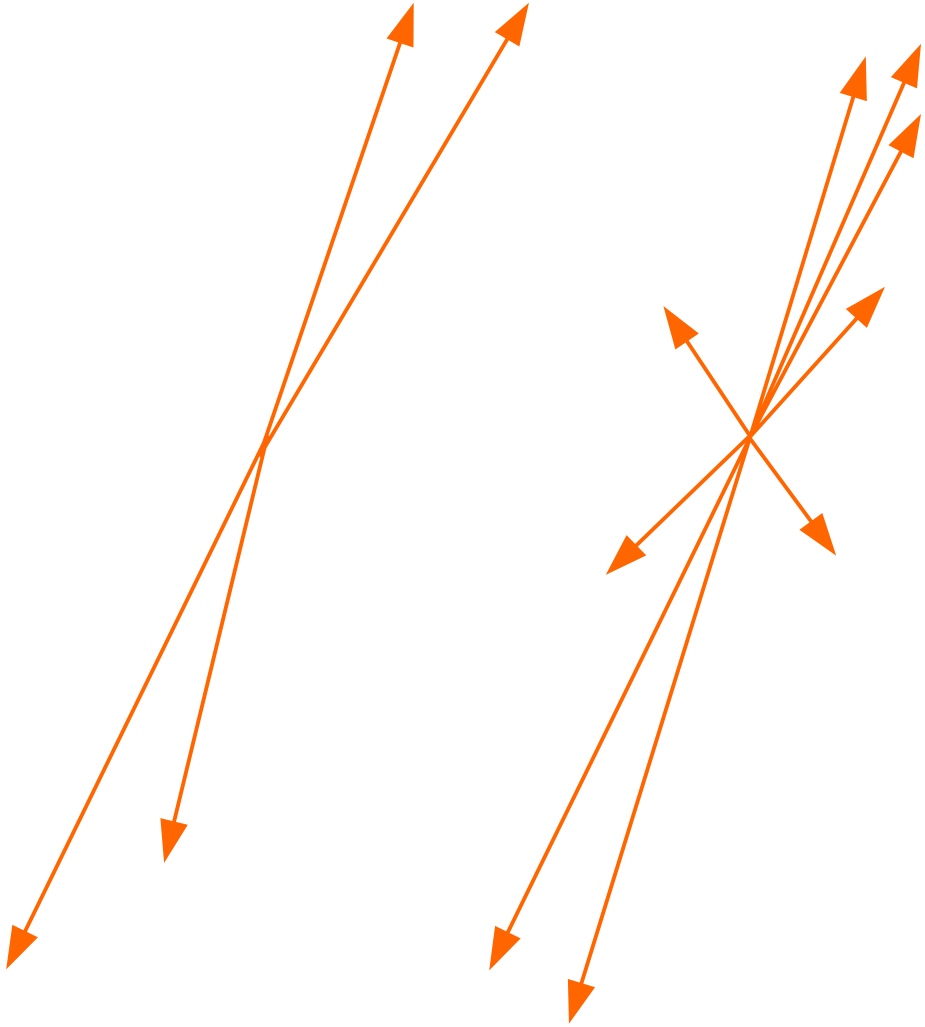


(anti)baryon-(anti)baryon
anticorrelation!

How does it work?

Momentum conservation



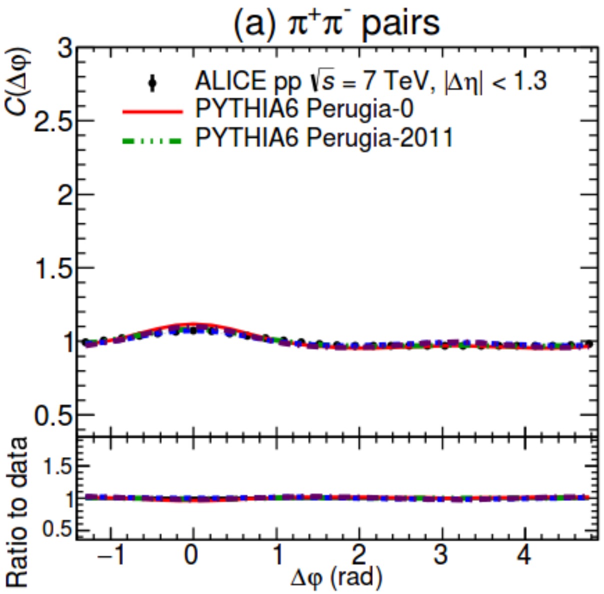


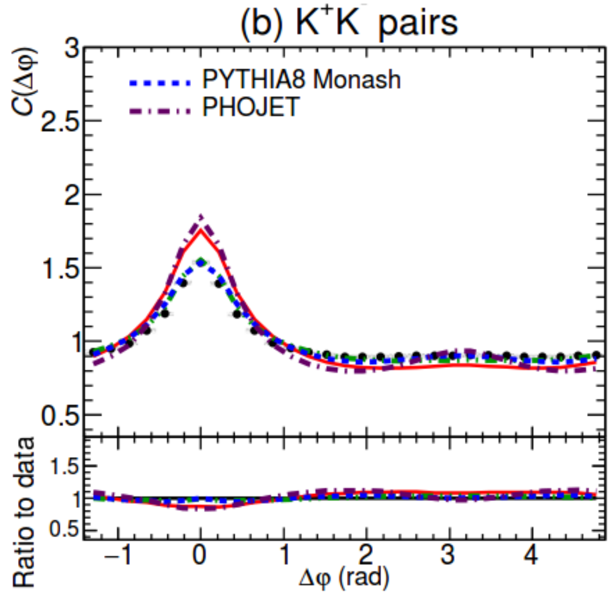
Events with angular momentum conserved only

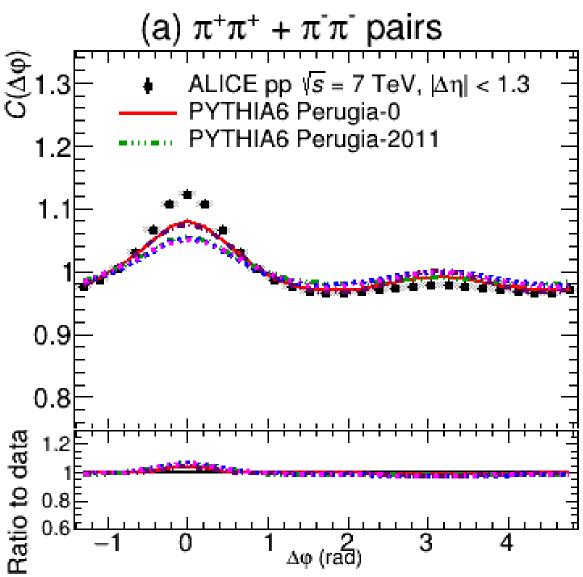
CALM – toy MC that allows to study the effects of different sources of correlations in a well-controlled way

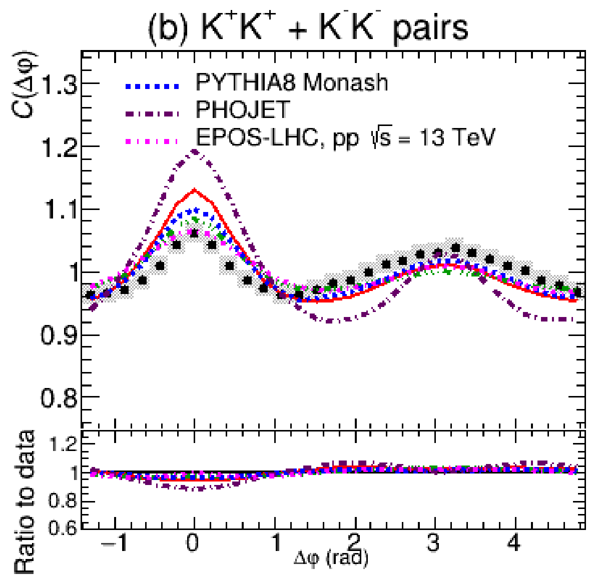
Comparison to MC models

arXiv:1612.08975









- PYTHIA and PHOJET were successfully used to describe non-femtoscopic background in HBT correlations for pions and kaons
- The models reproduce reasonably well the angular correlations for mesons as well
- The models fails to reproduce the results for baryons – apparently they produce 2 baryons close in the phase space
- **These results argue against the hypothesis that the combination of energy and baryon-number conservation is enough to explain the anti-correlation, since both local conservation laws are implemented in all studied models**

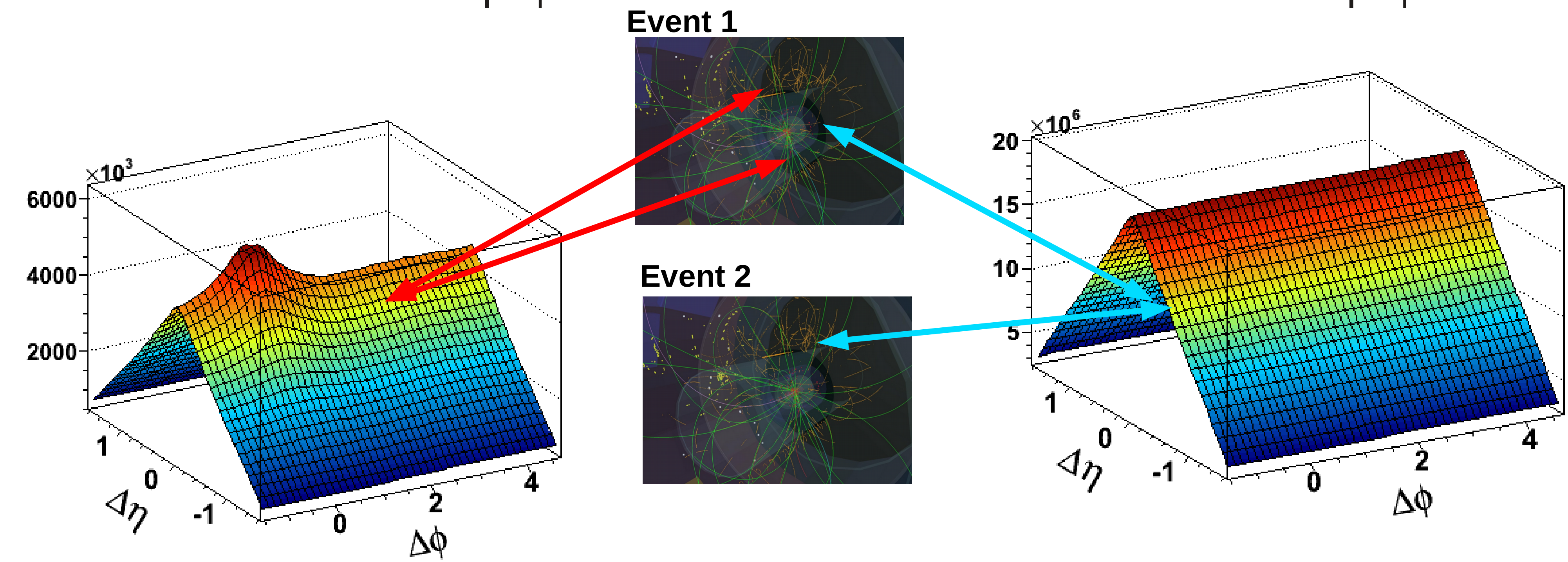
ΔηΔφ Experimental Correlation Function

Signal distribution

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

Background distribution

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



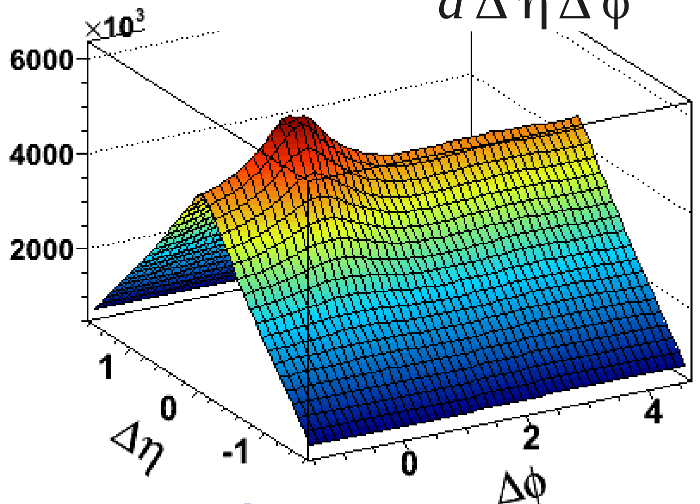
Same event pairs

Mixed event pairs

ΔηΔφ Experimental Correlation Function

Signal distribution

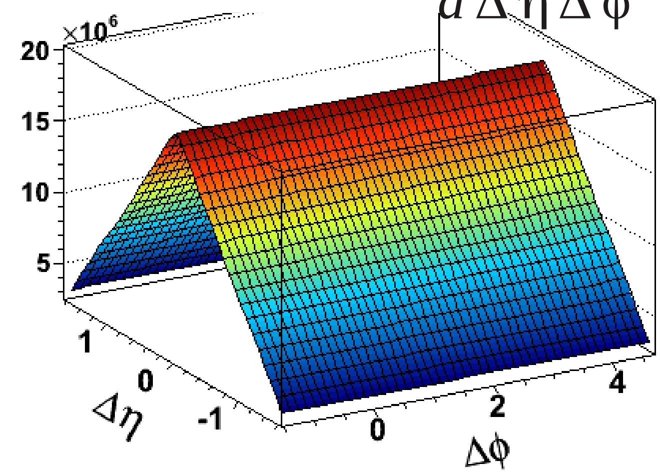
$$S(\Delta\eta,\Delta\phi)=\frac{d^2N^{signal}}{d\Delta\eta\Delta\phi}$$



Same event pairs

Background distribution

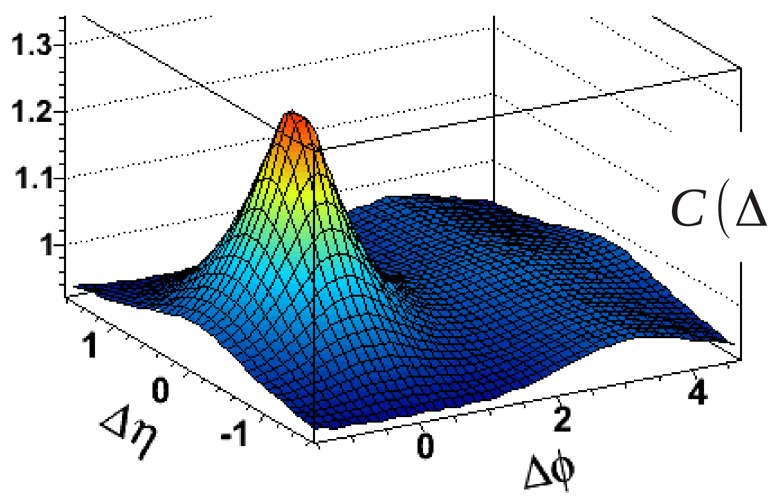
$$B(\Delta\eta,\Delta\phi)=\frac{d^2N^{mixed}}{d\Delta\eta\Delta\phi}$$



Mixed event pairs

Ratio signal/background

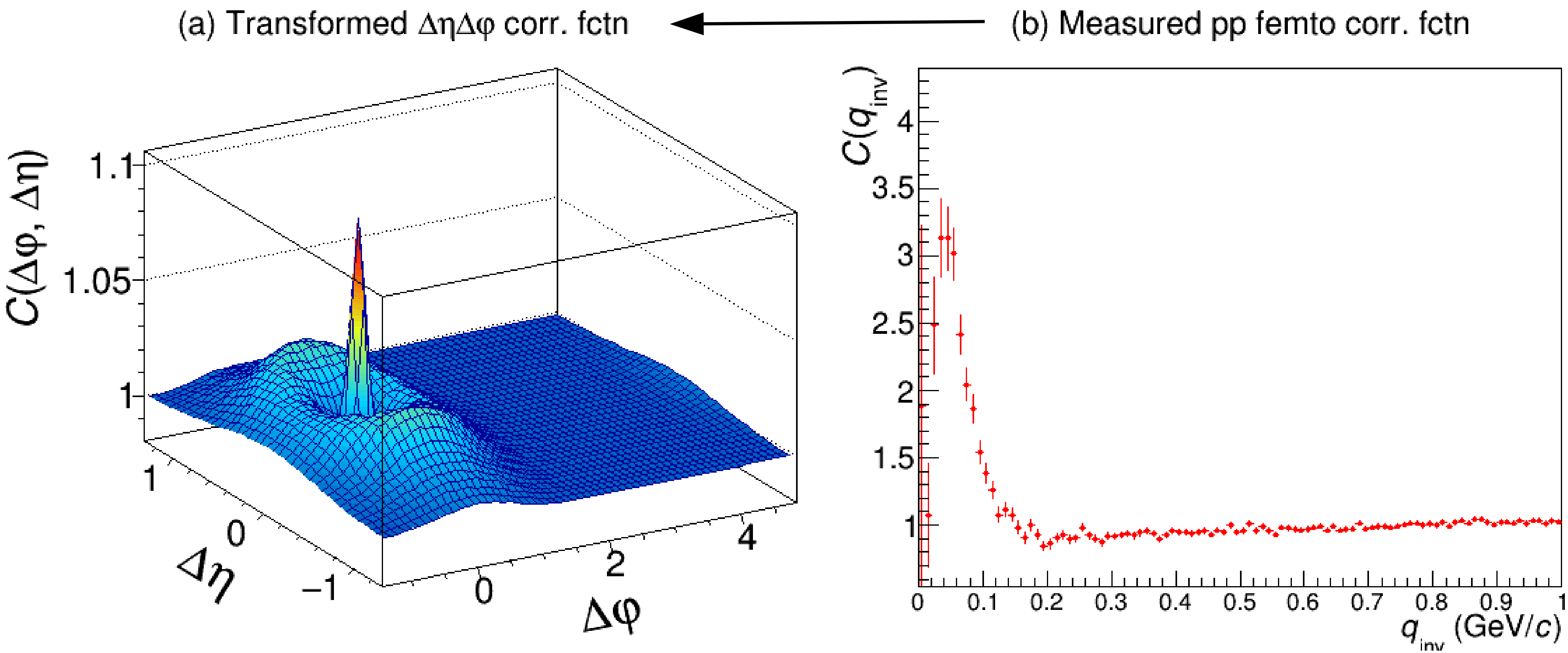
$$\Delta\eta=\eta_1-\eta_2$$
$$\Delta\phi=\phi_1-\phi_2$$



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

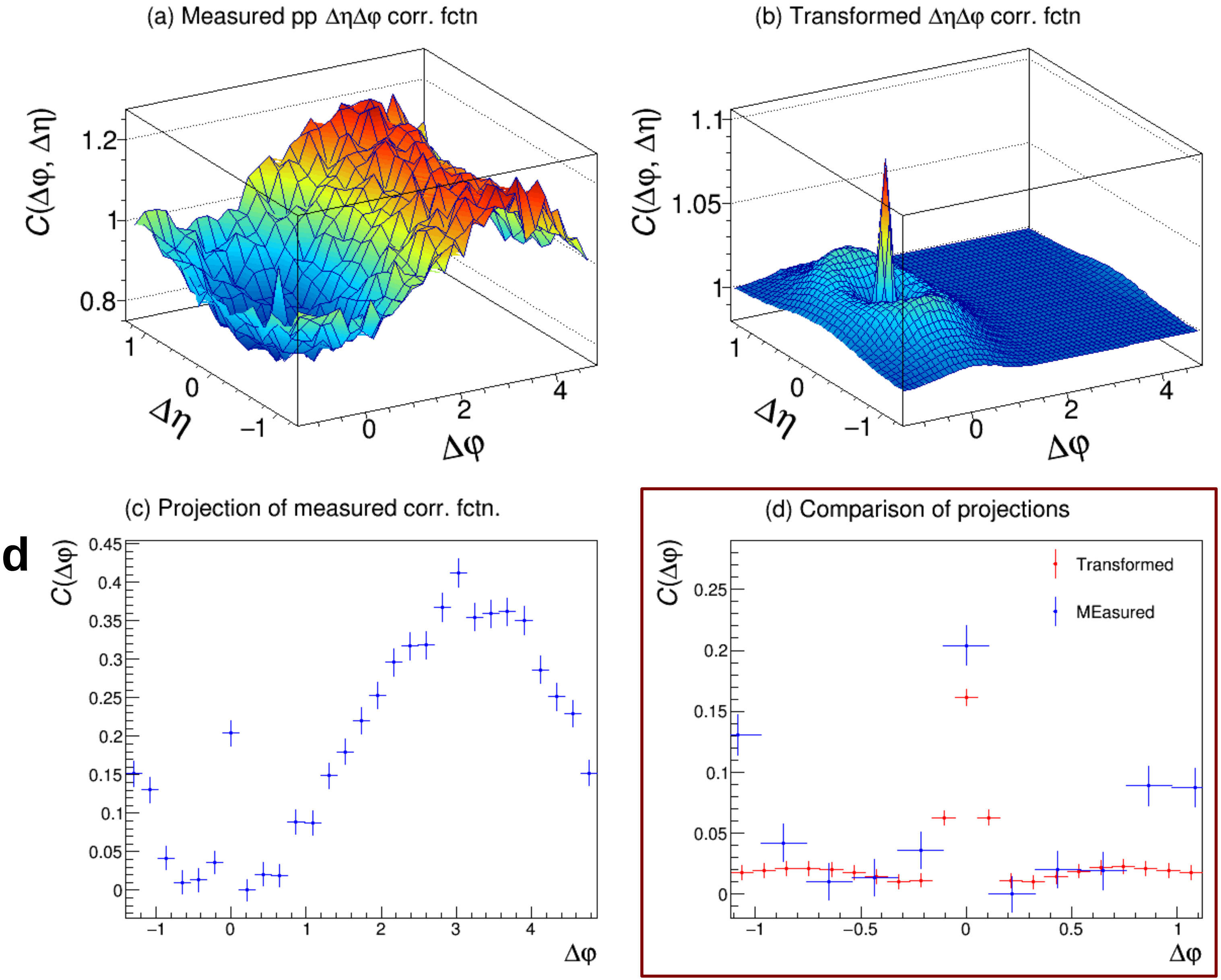
Protons – femtoscopic correlations

- Direct transformation from $C(q_{inv})$ to $C(\Delta\eta\Delta\varphi)$ **not possible**
- One can employ a simple **Monte Carlo procedure:**
  - generate random η and φ from uniform distributions (for 2 particles: η_1, η_2, φ_1, φ_2)
  - generate random p_T from measured p_T distribution (for 2 particles: p_{T1}, p_{T2})
  - calculate q_{inv} from generated η_1, η_2, φ_1, φ_2, p_{T1} and p_{T2}
  - take the value of measured femtoscopic correlation function at given q_{inv} and apply it as weight while filling the numerator of ΔηΔφ



Protons – femtoscopic correlations

- **Results:**
- Femto correlation produces spike at $(\Delta\eta,\Delta\varphi)=(0,0)$
- Comparison of two peaks: 1-bin wide projection on $\Delta\varphi$ (subtract minimum)
- **Both the height and the width of two peaks comparable**



Rapidity correlations in e^+e^- collisions

A Parametrization of the Properties of Quark Jets
R.D. Field, R.P. Feynman (Caltech). Nov 1977. 131 pp.
Published in Nucl.Phys. B136 (1978) 1

<u>From mechanism of jet production</u>:
Two primary hadrons with the same **baryon number** (or **charge** or **strangeness**) **are separated** by at least two steps in rank ("rapidity").

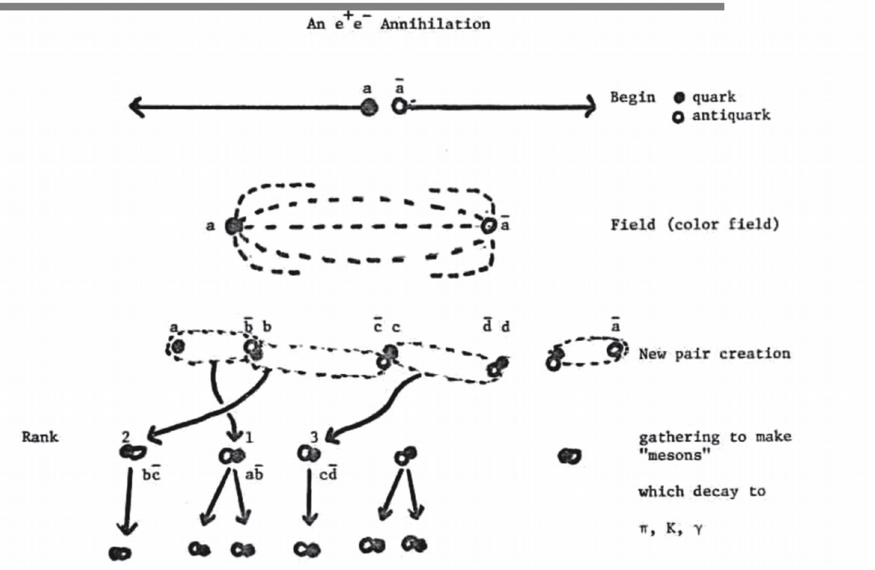
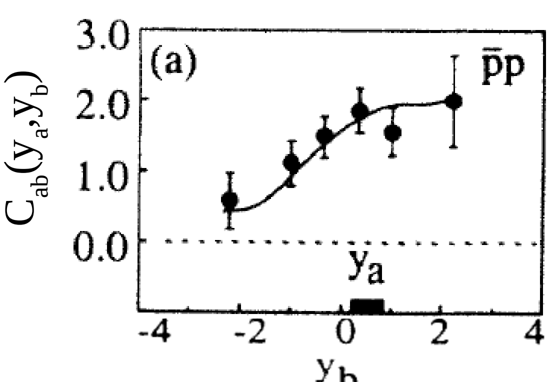


Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

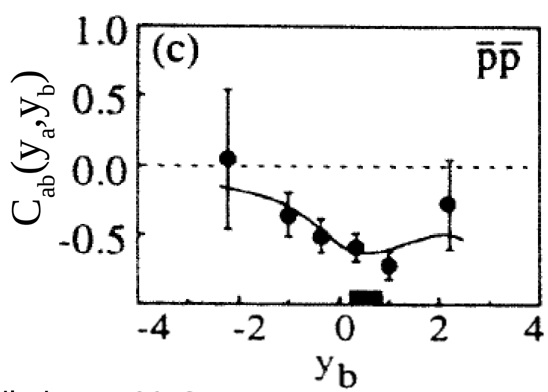
We are not likely to find two baryons or two antibaryons at the same rapidity

- **Models for e^+e^- agree** with observations seen in data.

correlation



anti-correlation

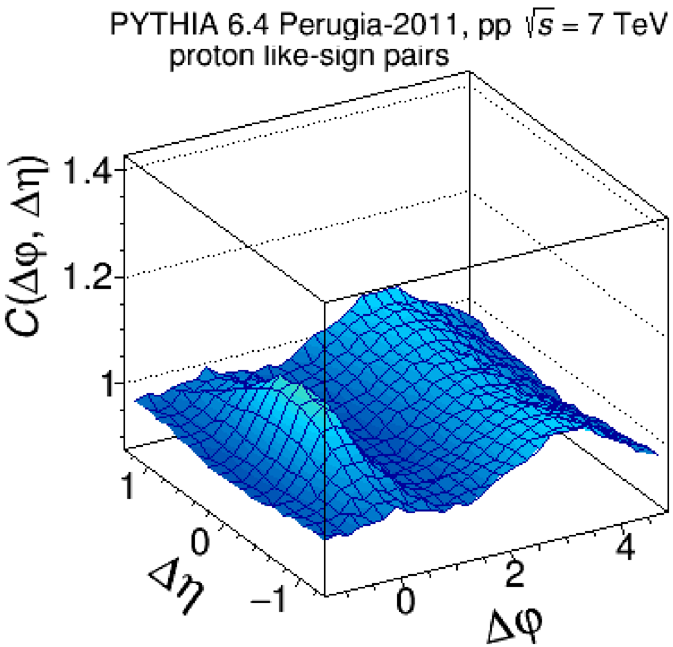


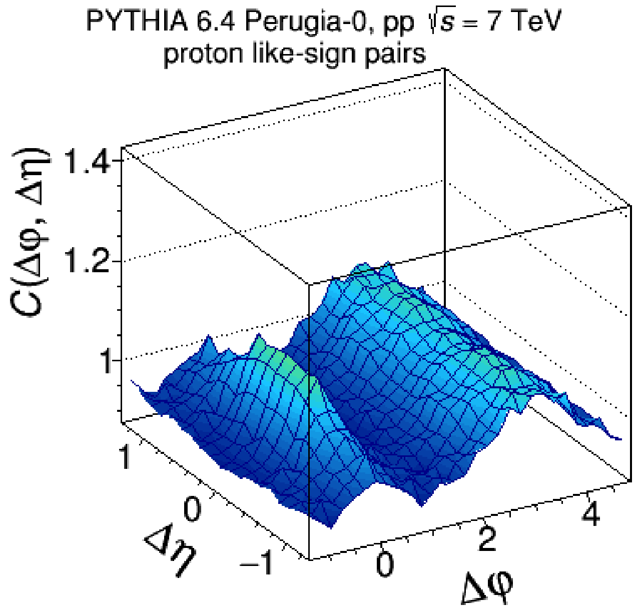
Lund model reproduces

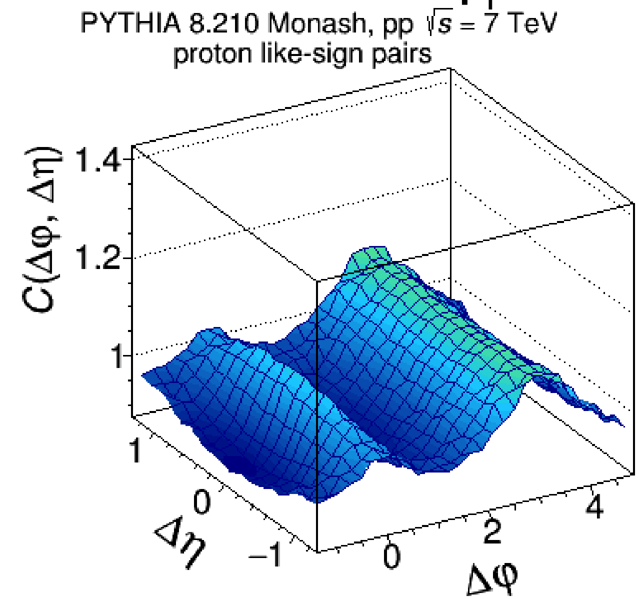
Study of baryon correlations in e+e− annihilation at 29-GeV
TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140

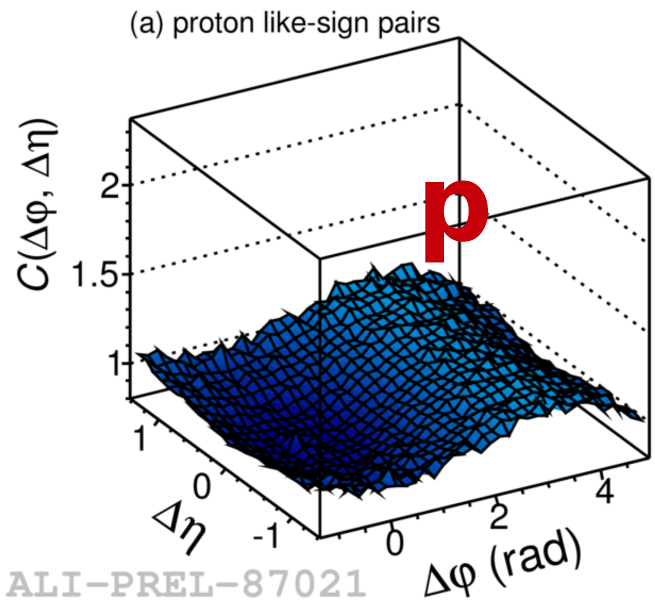
ΔηΔφ of identified particles in pp collisions

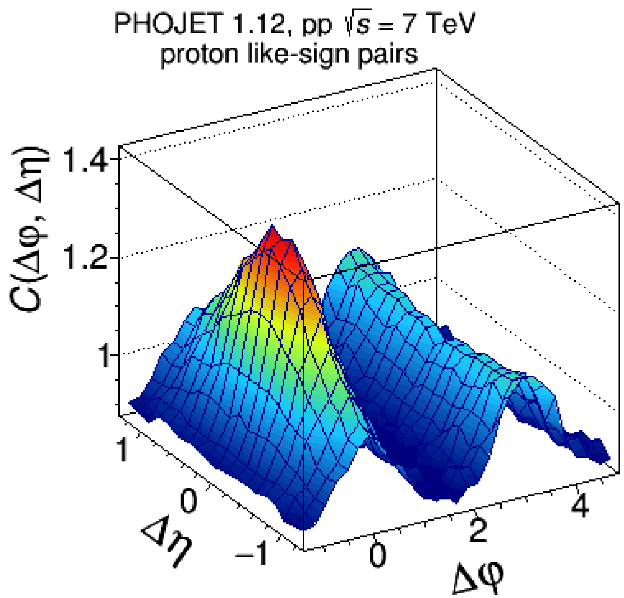
p_T<4 GeV/*c*











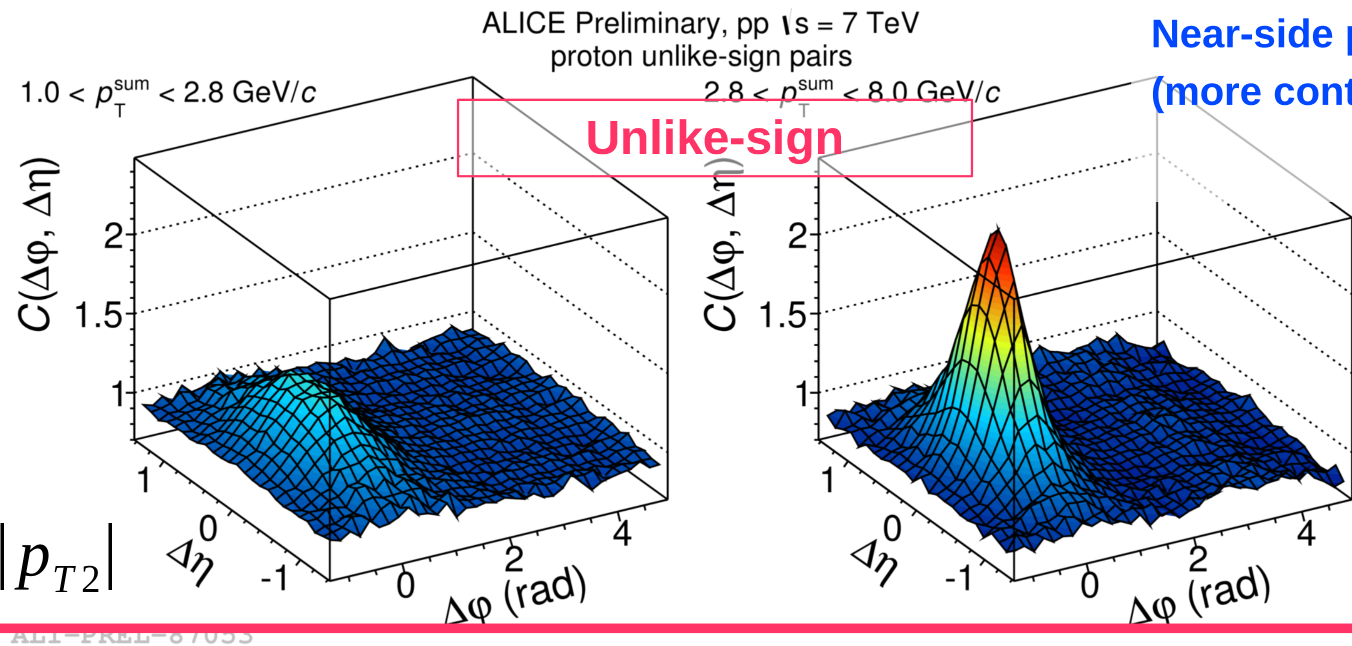
None of common MC models reproduces ALICE data!

Protons

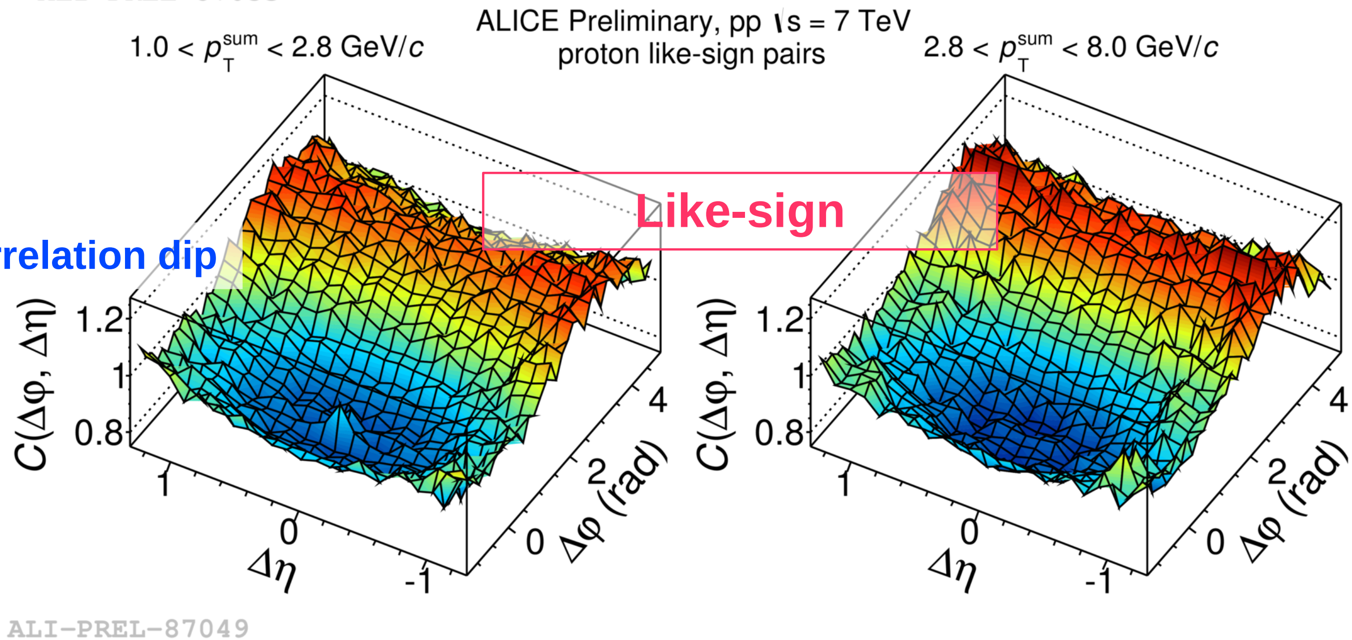
$p_{Tsum} = |\vec{p}_{T1}| + |\vec{p}_{T2}|$

Near-side peak grows with p_T (more contribution from jets)

$p_T^{sum} = |p_{T1}| + |p_{T2}|$



p_T growth



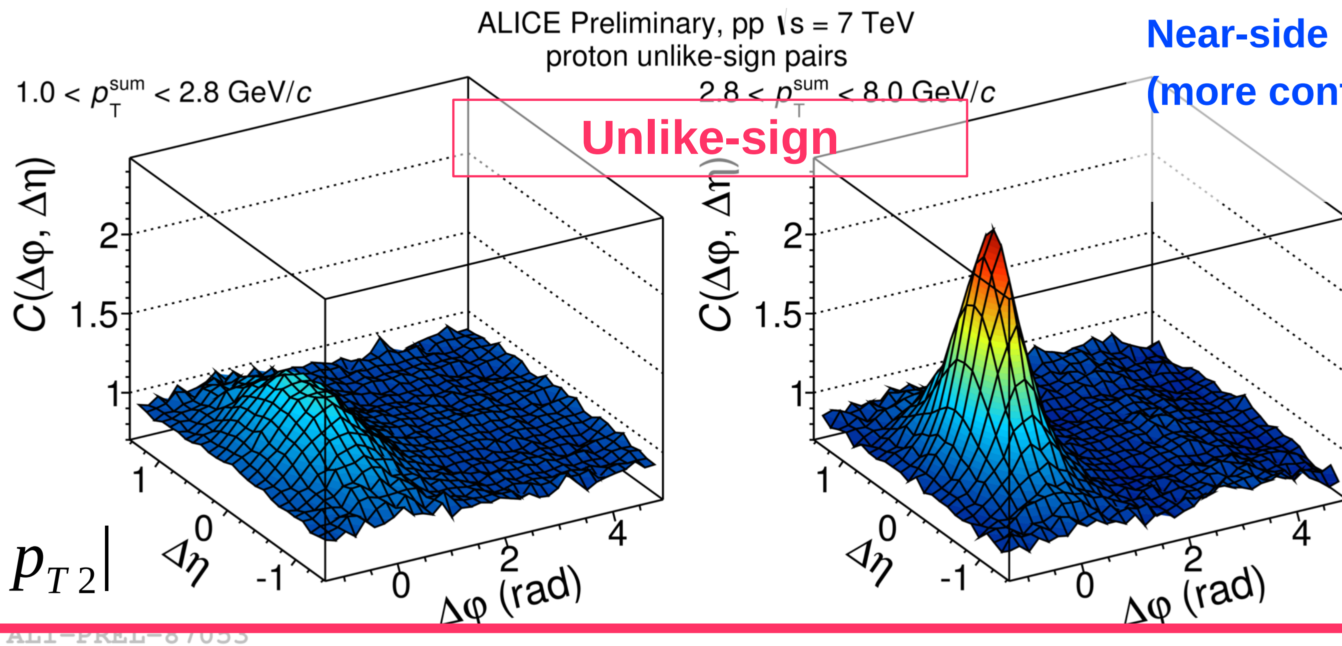
Anticorrelation dip

Small peak disappears for high p_T-sum

Shape of the dip does not change

Protons

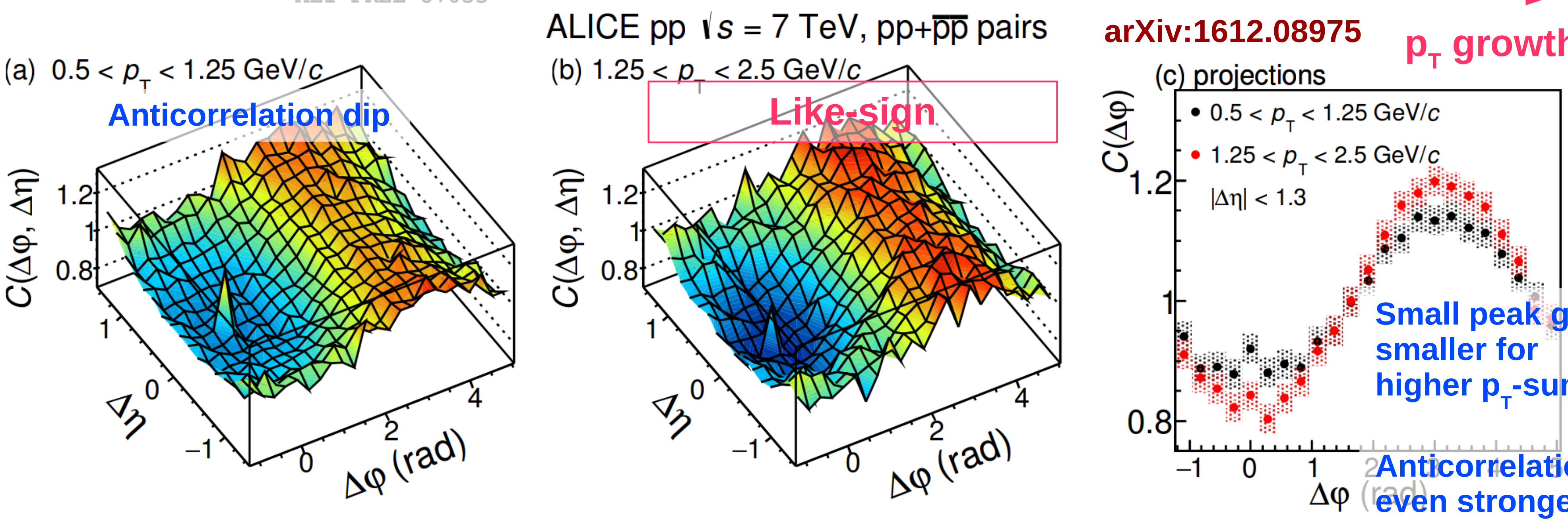
Near-side peak grows with p_T (more contribution from jets)



$$p_T^{sum} = |p_{T1}| + |p_{T2}|$$

p_T growth

arXiv:1612.08975



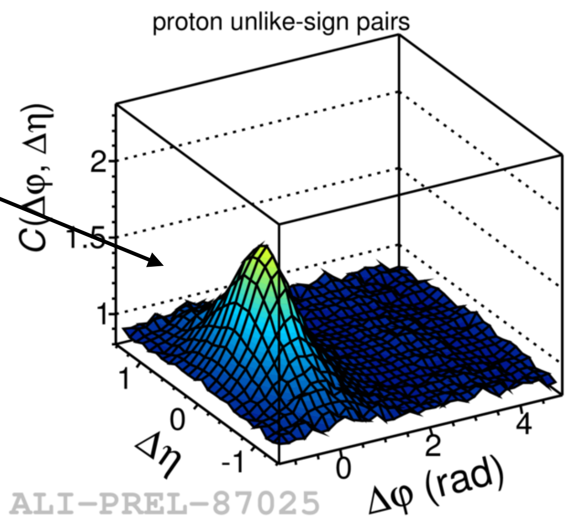
Small peak gets smaller for higher p_T-sum

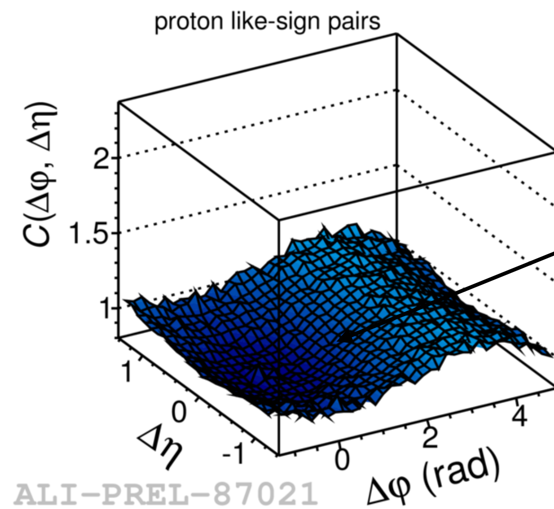
Anticorrelation even stronger

Two-particle rapidity correlations in e⁺e⁻ collisions

correlation

ALICE



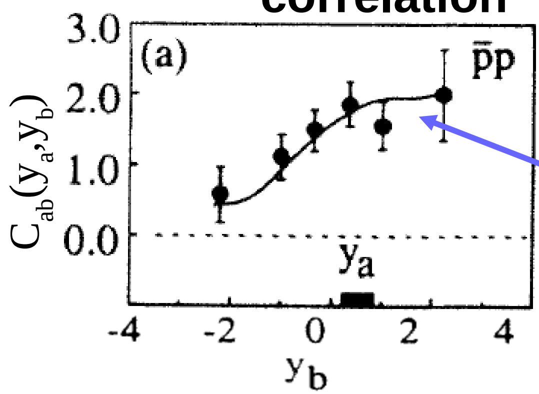


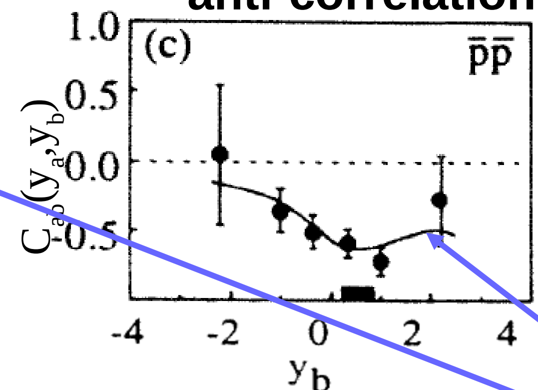
anti-correlation

correlation

anti-correlation

e⁺e⁻





TPC/Two Gamma Collaboration (H. Aihara et al.), Phys.Rev.Lett. 57 (**1986**) 3140

Much more unlike-sign baryons close together in the phase-space than like-sign baryons.

Models (Lund 6.2) **for e⁺e⁻ agree** with observations seen in data.