Faculty of Physics

WARSAW UNIVERSITY OF TECHNOLOGY

Studying baryon production using two-particle angular correlations

Małgorzata Janik

9/09/2019

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MYSTERY OF BARYON CORRELATIONS

Małgorzata Janik

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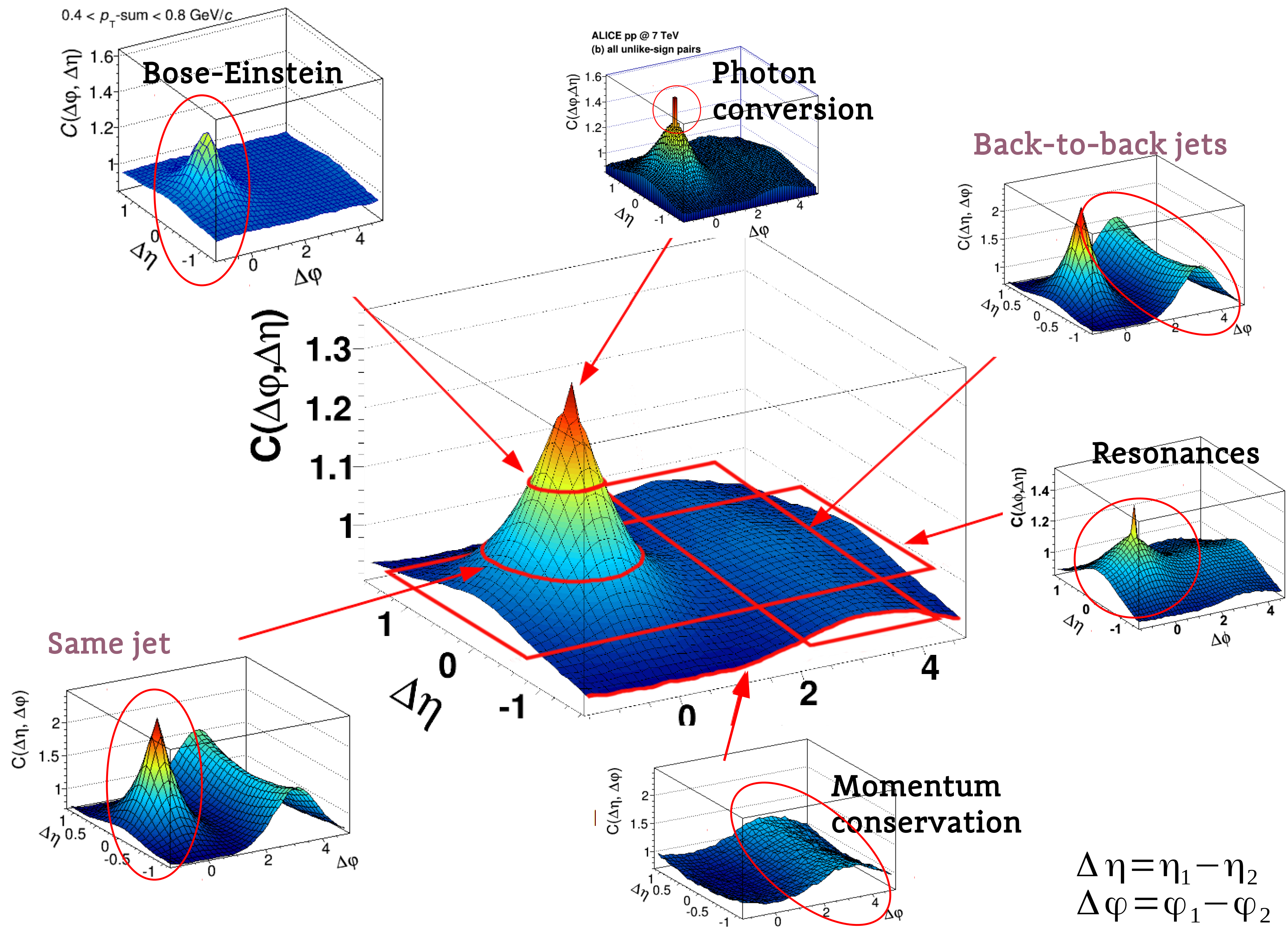
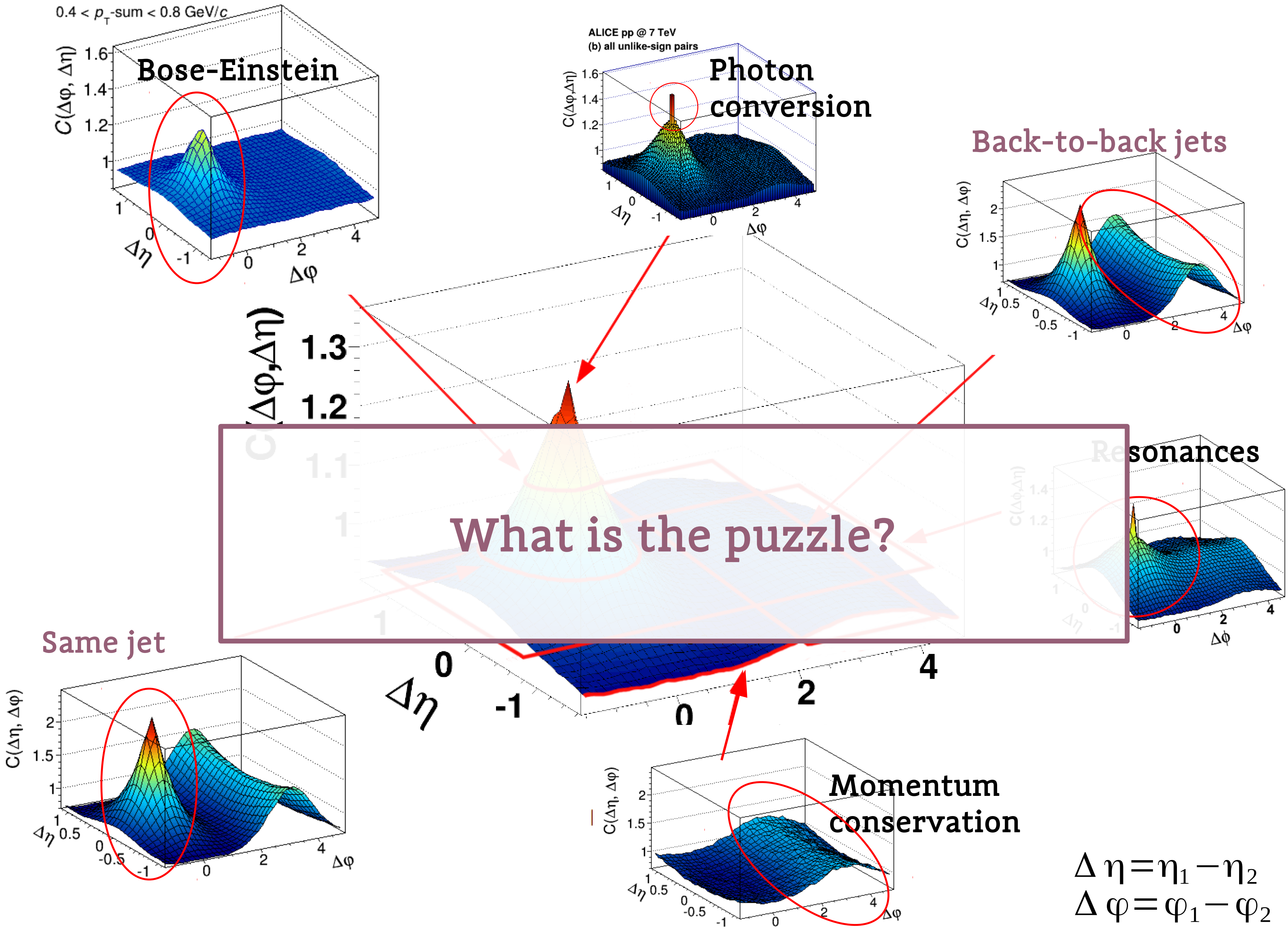

0.4 < p_T-sum < 0.8 GeV/c
Bose-Einstein
ALICE pp @ 7 TeV
(b) all unlike-sign pairs
Photon conversion
Back-to-back jets
Resonances
Same jet
Momentum conservation
$\Delta\eta = \eta_1 - \eta_2$
$\Delta\varphi = \varphi_1 - \varphi_2$



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

Data sample & analysis

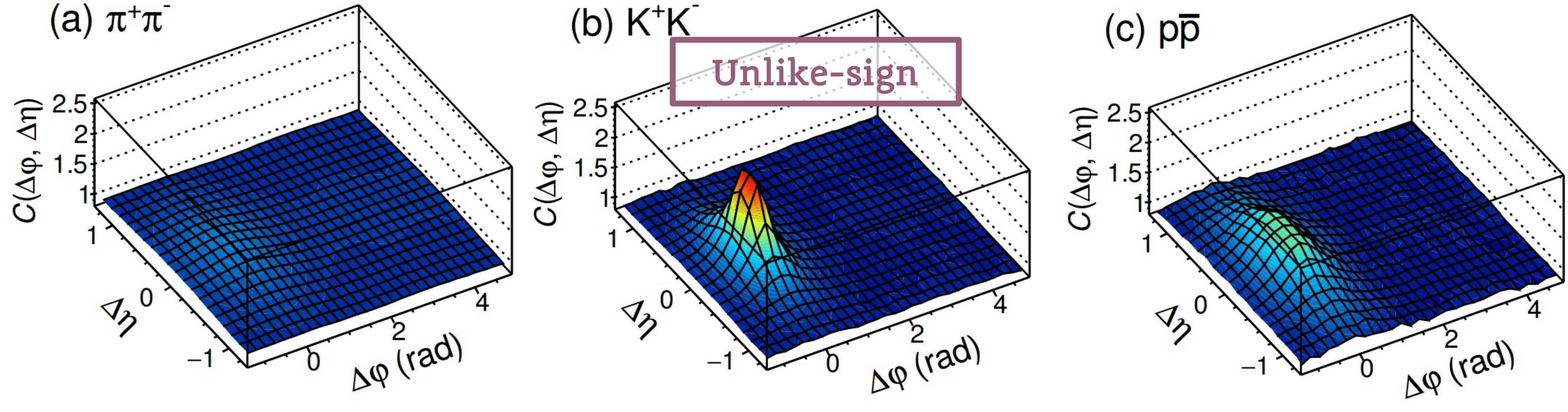
- Let's take "vanilla events" = no QGP, no high multiplicities
  - And see how different particles are distributed in momentum space

- First seen in ~200 million **minimum bias pp** collisions at 7 TeV collected by ALICE in 2010
  - But also other energies, systems, kinematic regimes....

- Kinematic cuts:
  - $0.2 < p_T < 2.5$ (4.0) GeV/*c* *for pions*
  - $0.3 < p_T < 2.5$ (4.0) *GeV/c for kaons*
  - $0.5 < p_T < 2.5$ (4.0) *GeV/c for protons*
  - $0.7 < p_T < 2.5$ (4.0) *GeV/c for lambdas*
  - $|\eta| < 0.8$

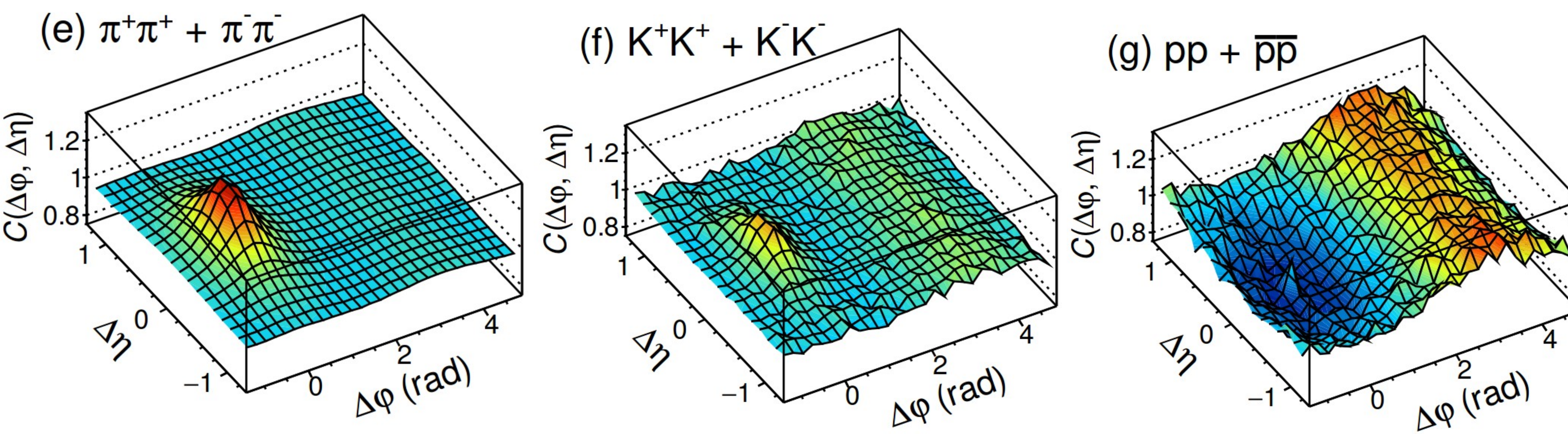
98-99% purity

ΔηΔφ of identified particles



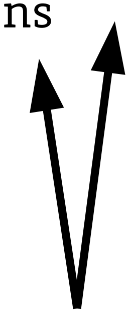
Eur.Phys.J. C77 (2017) 8, 569

Like-sign



What does it mean?

Strong near side peak:
- probability of producing two particles close in phase space is higher than in other directions



Possible reasons:
- (mini)jet collimation
- resonances
- quantum statistics
- FSI (strong, Coulomb)
- conservation laws (charge, strangeness, baryon number)

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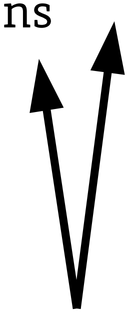

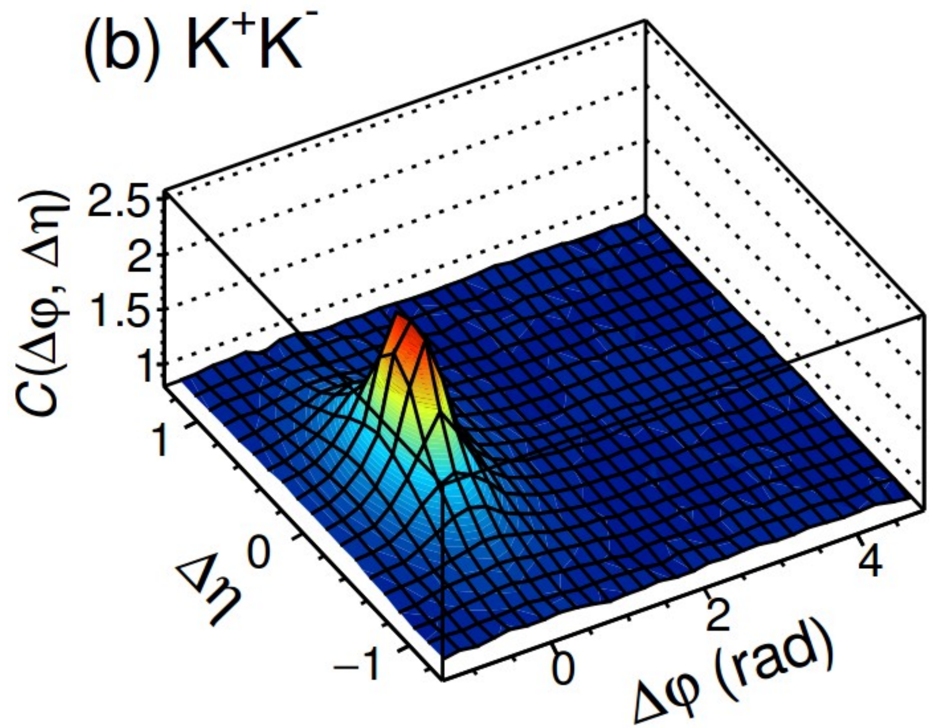

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- **(mini)jet collimation**
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- ~~quantum statistics~~
- **FSI** (~~strong~~, **Coulomb**)
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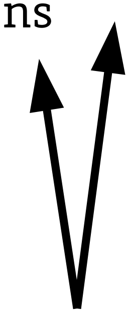

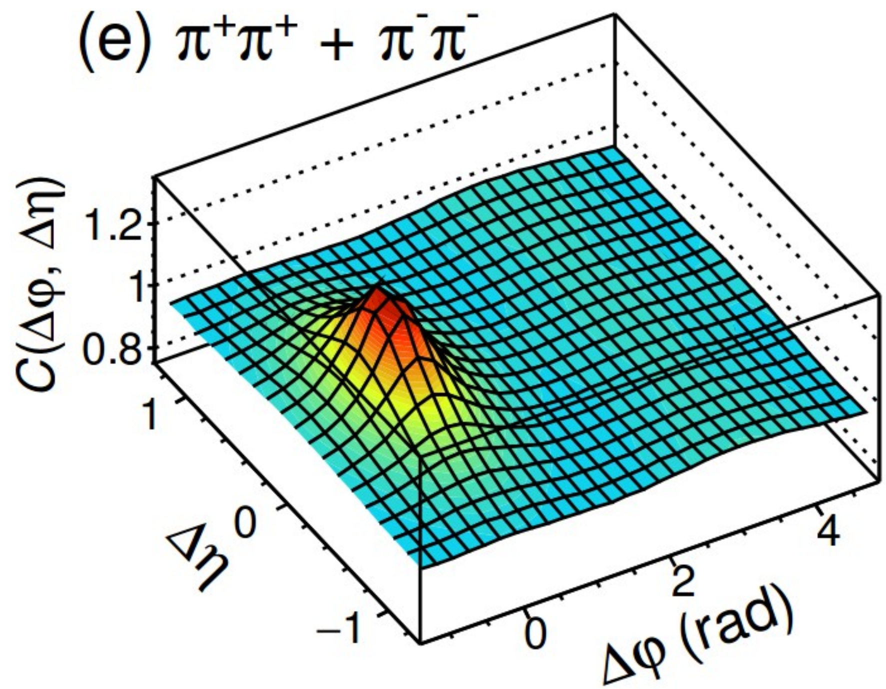

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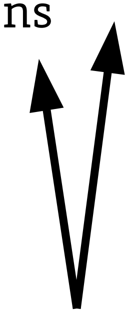

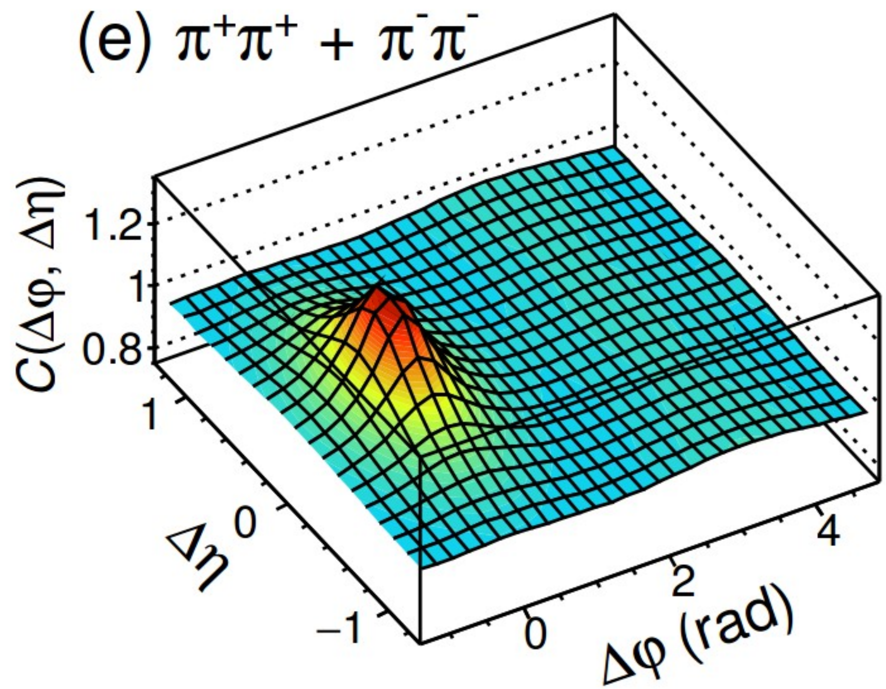

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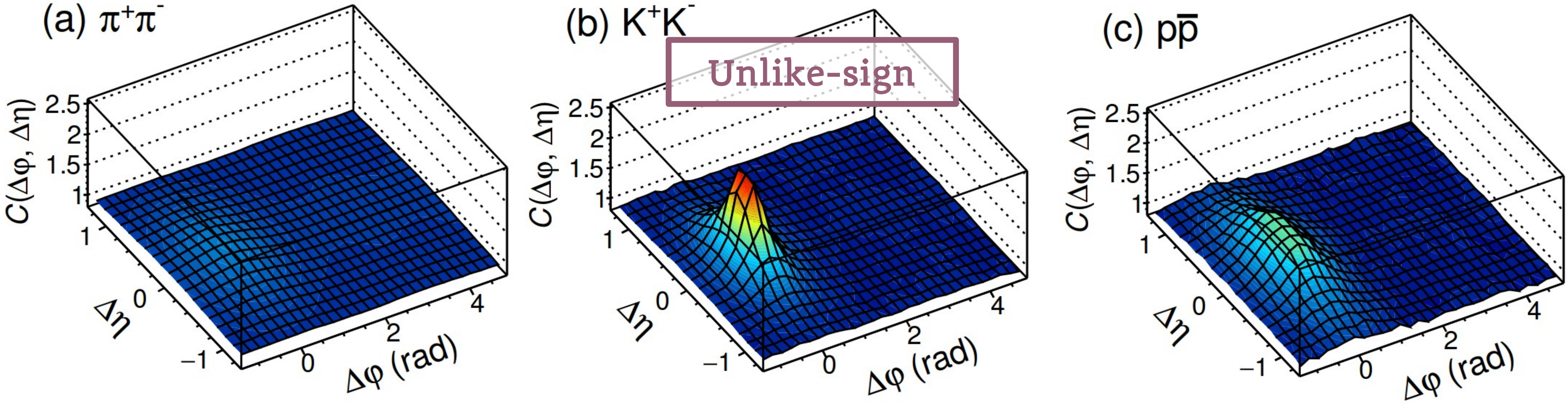
could introduce negative correlations

ΔηΔφ of identified particles

Unlike-sign



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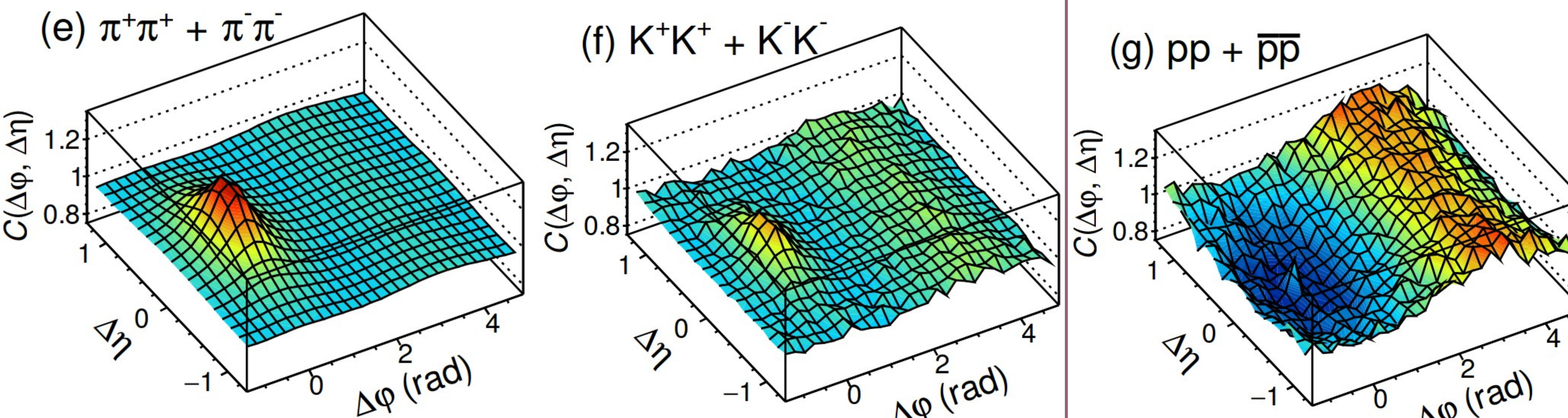
Like-sign

This one looks different!



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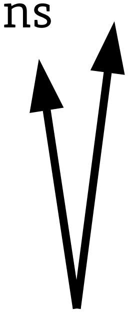

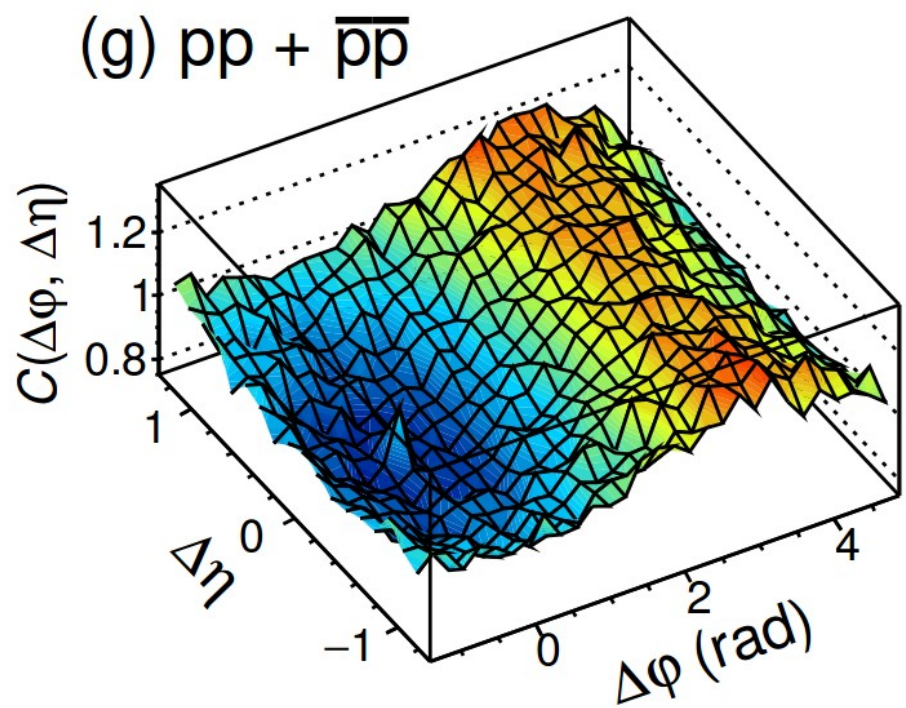

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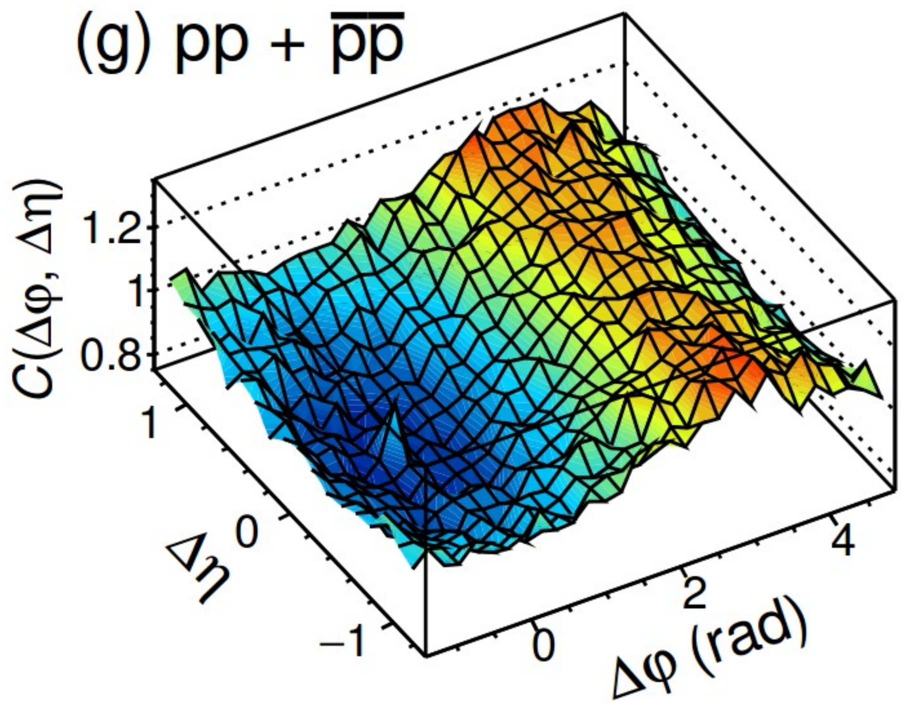
Anti-correlation in (0,0):
- probability of producing two particles close in phase space is **lower** than in other directions



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ΛΛ and pΛ correlation functions

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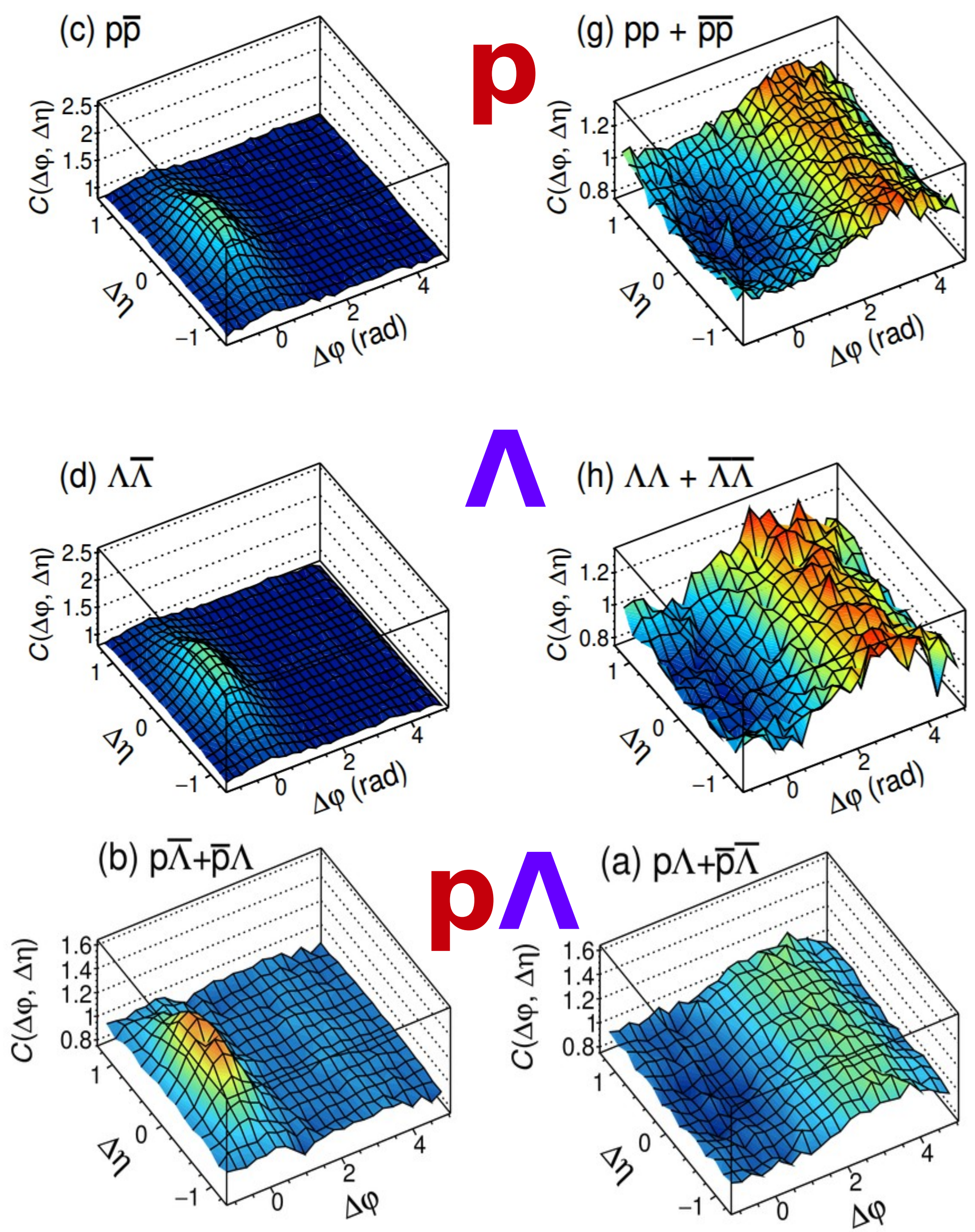
- Useful to check if effect persists for other baryons than protons – is this a common effect for all baryons?
- Correlation functions were calculated for **ΛΛ and pΛ** pairs
- Λ baryons are neutral → no Coulomb repulsion
- p and Λ are not identical → no effect from Fermi-Dirac statistics
- **All observations from pp can be extended to ΛΛ and pΛ**

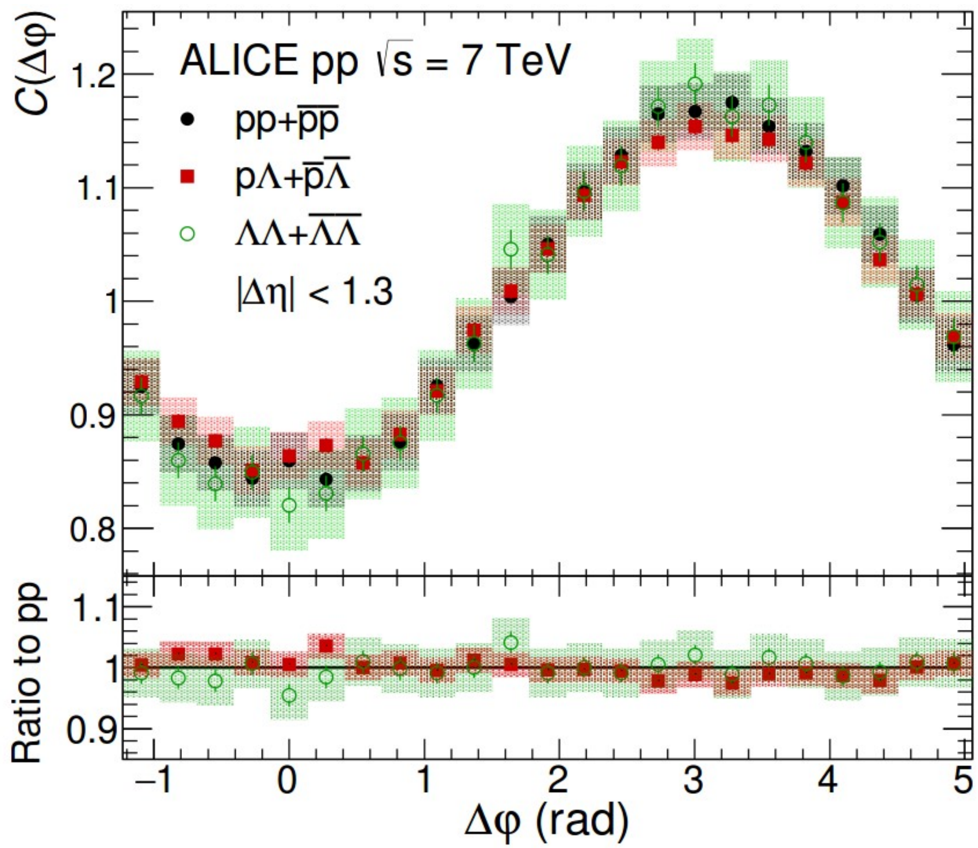


Do we understand anti-correlation?

Anti-correlation in (0,0):
- probability of producing two particles close in phase space is **lower** than in other directions

Possible reasons (pΛ):
- (mini)jet collimation
- ~~resonances~~
- ~~quantum statistics~~
- FSI (strong, ~~Coulomb~~)
- conservation laws (~~charge~~, ~~strangeness~~, baryon number)

The same, just **projection**



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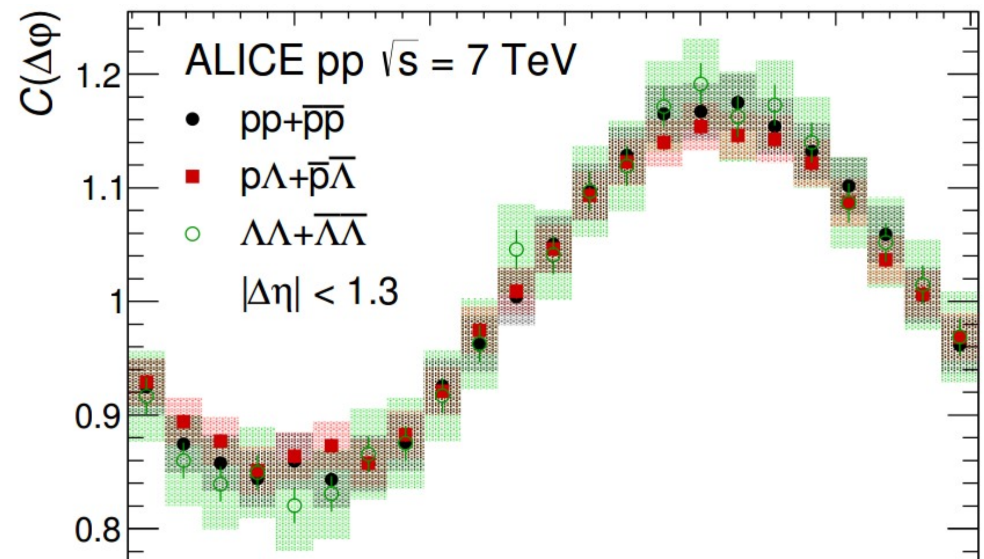

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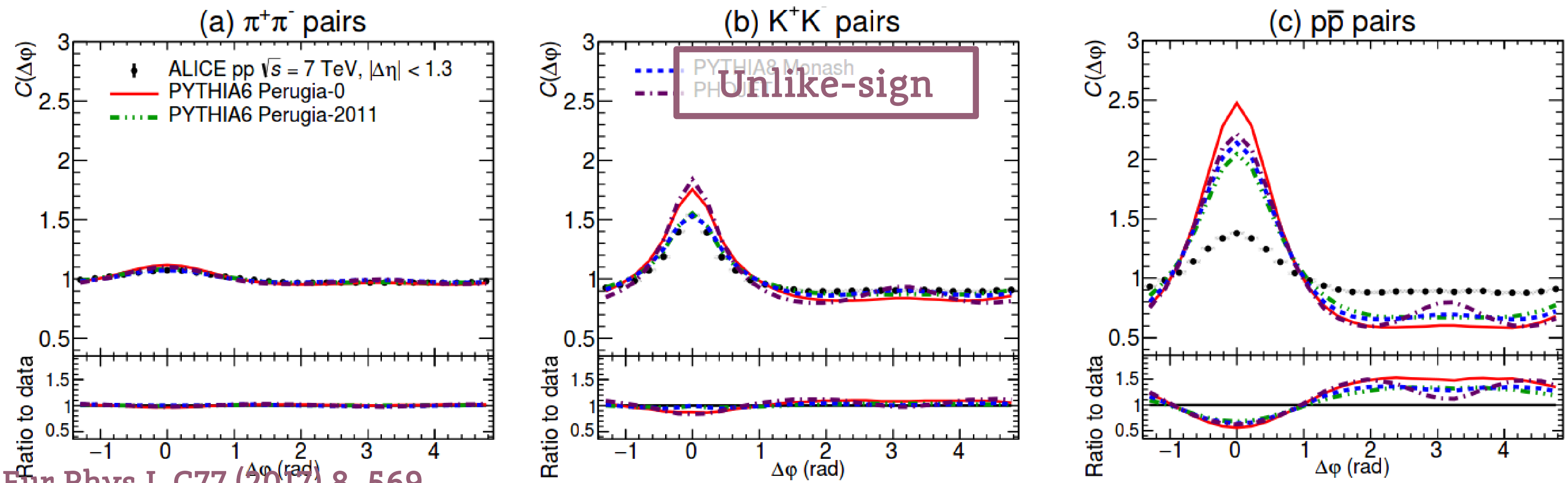
Can this be just a manifestation of baryon number conservation?

Producing many (**at least 4**, to get pp correlation function) **baryons** (heavy particles) **in similar direction may be just too improbable due to energy constraints**...

MC models do not reproduce

Unlike-sign



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Like-sign

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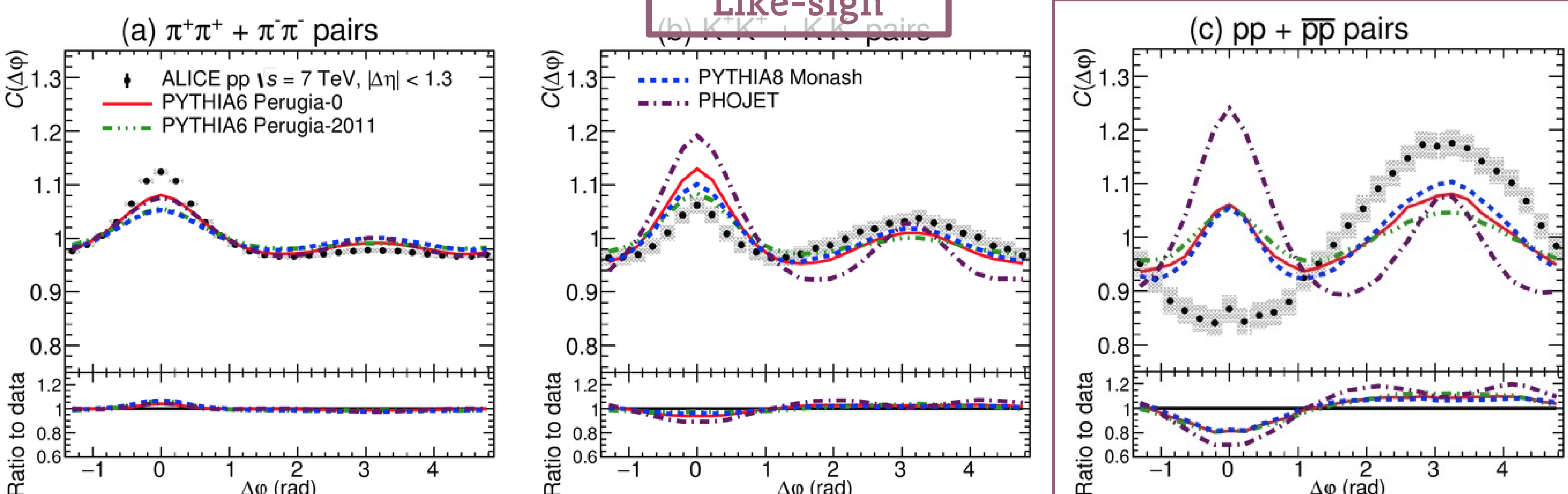

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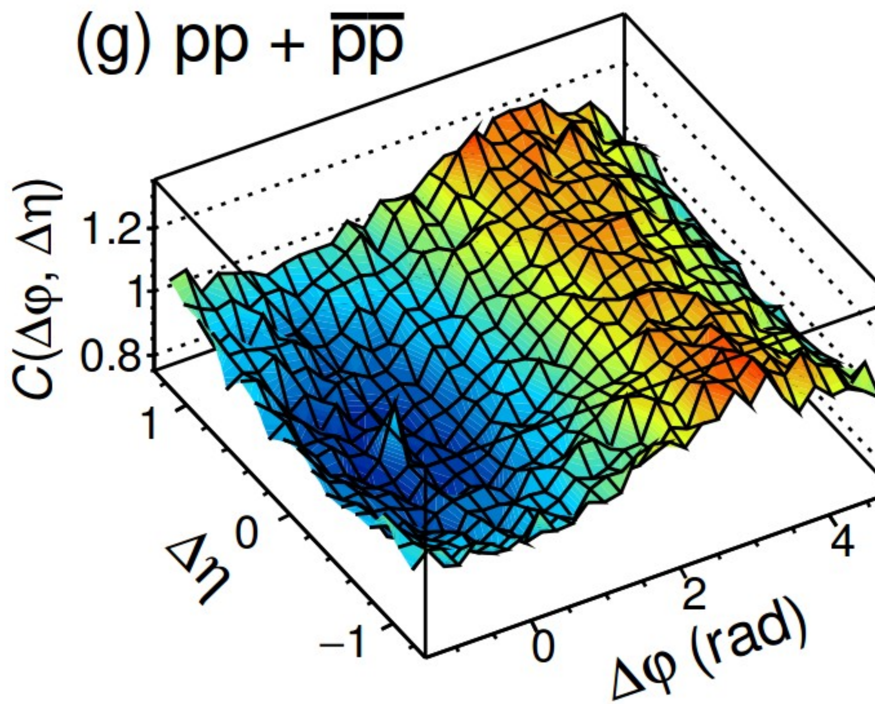

Possible reasons:
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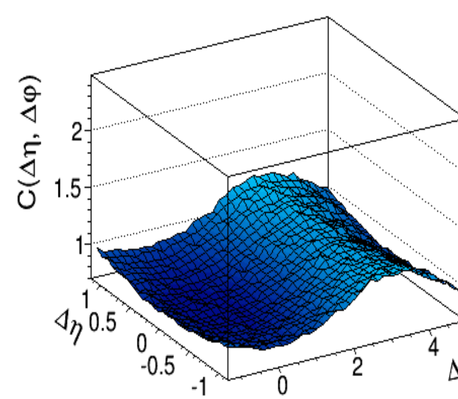
- conservation laws (charge, ~~strangeness~~, baryon number)

+ momentum conservation
(but this is there for all possible pairs)



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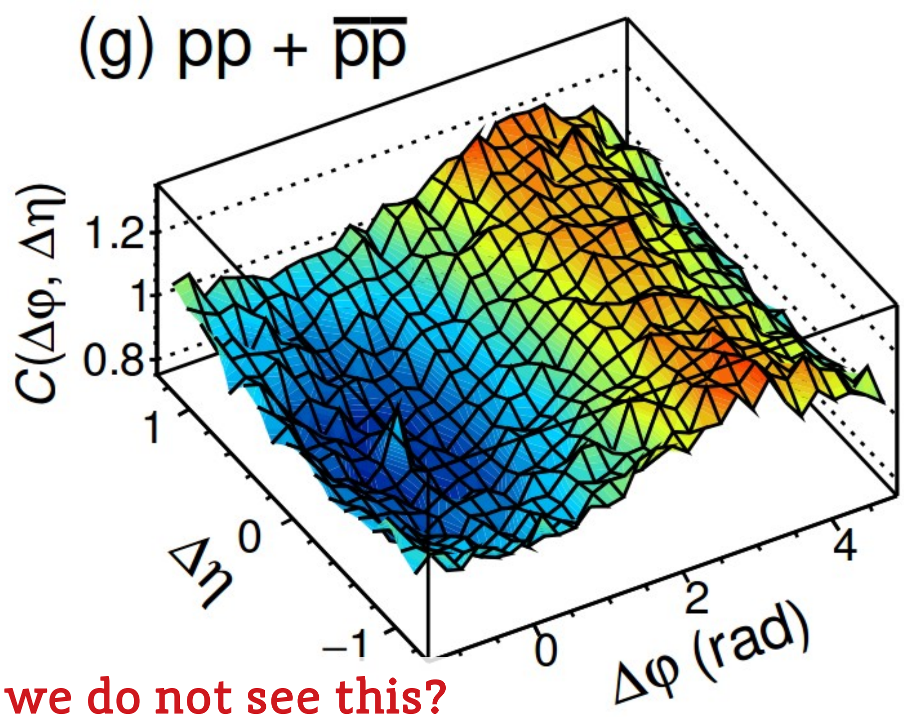

Possible reasons:
- (mini)jet collimation
- ~~resonances~~
- quantum statistics
- FSI (strong, Coulomb)
- conservation laws (charge, ~~strangeness, baryon~~ number) +momentum cons.
- ANY OTHER REASONS? → no ideas so far

Why we do not see this?
DIFFERENT PHYSICS FOR BARYONS?
Special rules for baryon production?

List of different questions

- More differential p_T bins?
- How does it look like for different systems? (p-A, A-A)
- How does it look like for different multiplicities?
- How does it look like for different energies?

Δφ correlation of baryons

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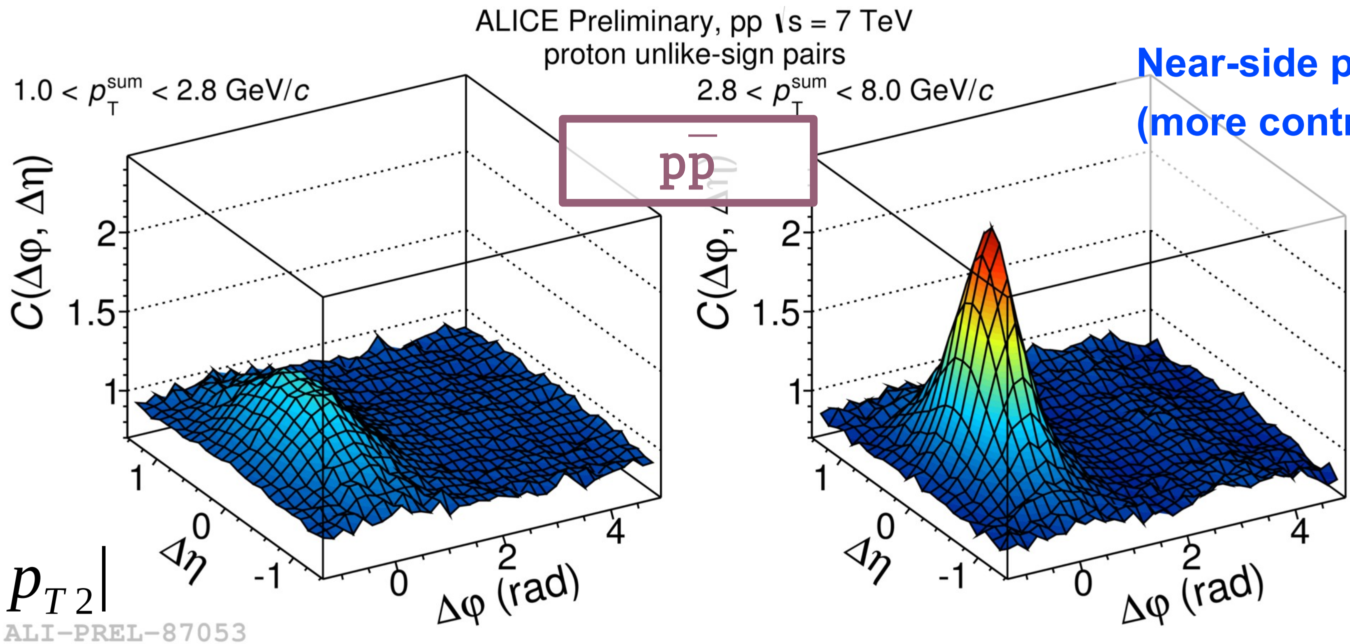
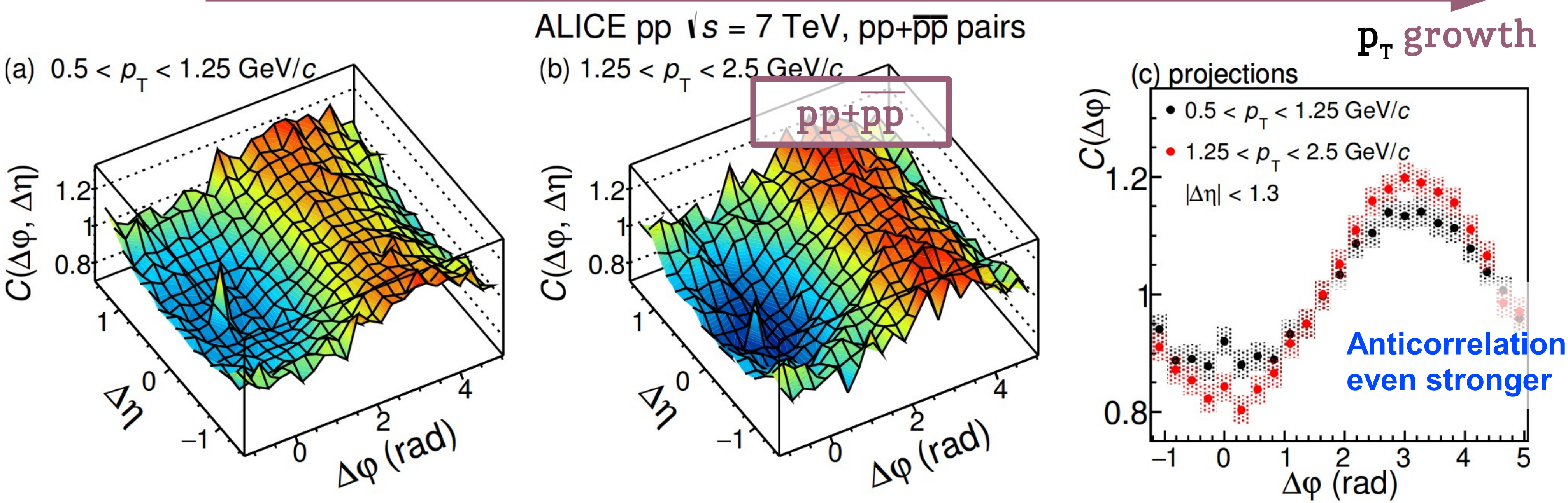


Near-side peak grows with p_T (more contribution from jets)

$$p_T^{\text{sum}} = |p_{T\,1}| + |p_{T\,2}|$$

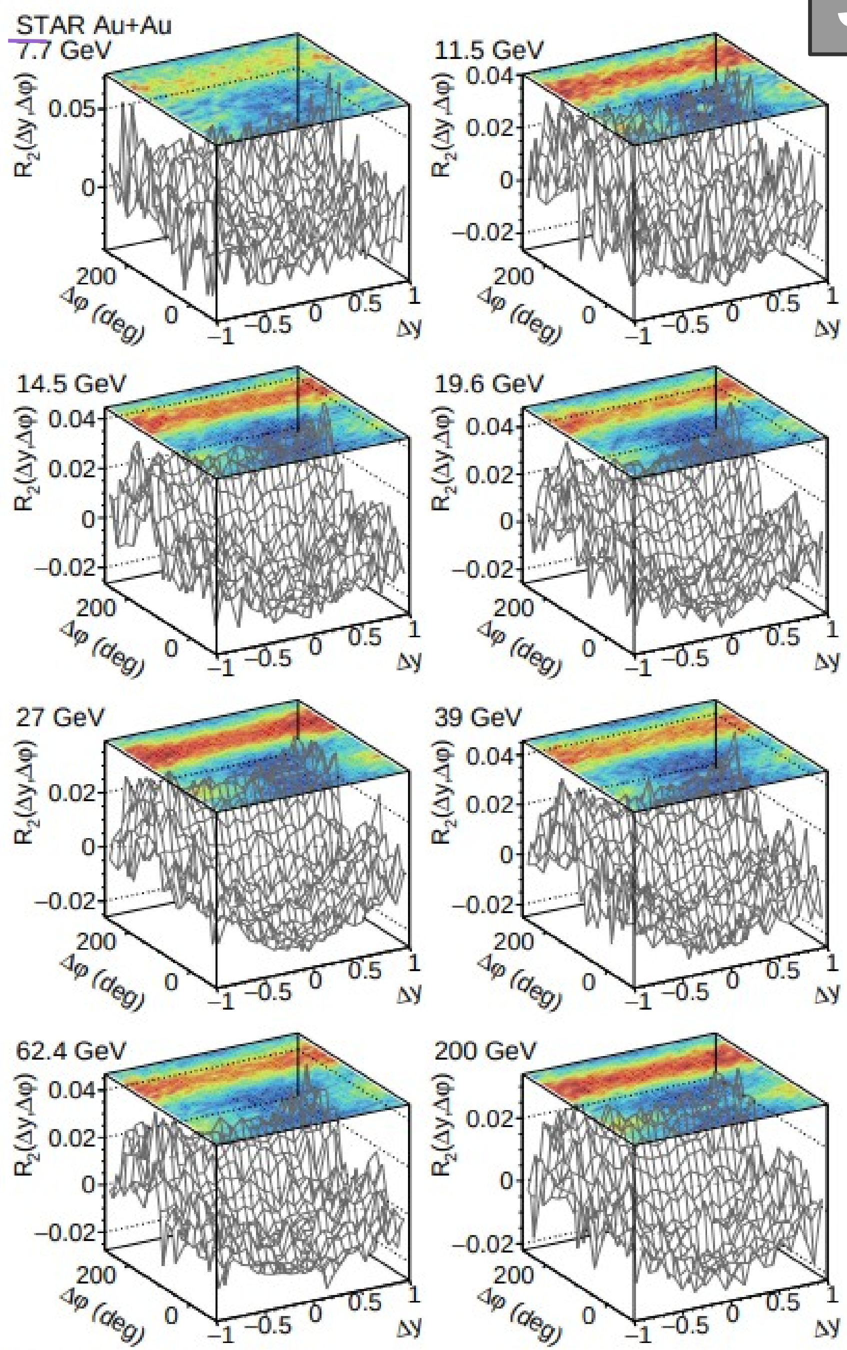
p_T growth



Anticorrelation even stronger

Energy dependence of correlation function

30-40%



(a) Like-sign protons

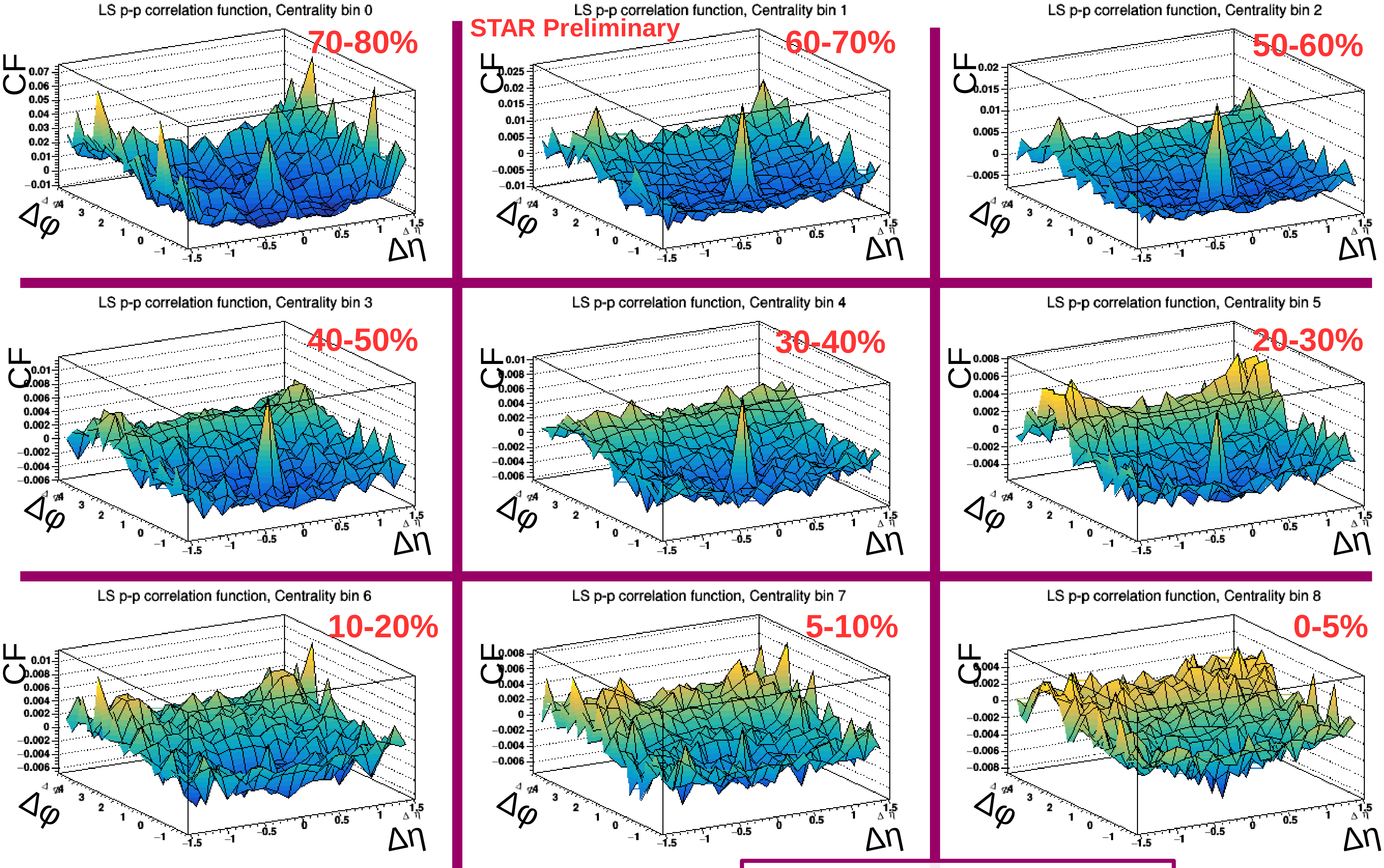
Au+Au collision energy

STAR Collaboration

arXiv:1906.09204

Jun 2019

pp + $\overline{pp}$ correlations, Au-Au @ 19.6 GeV



Qualitative description:

- → **Anti-correlated on the near-side**
- → **Sharp peak at (Δη;Δφ) ≈ (0;0)**
- → **Visible away-side ridge**

STAR Collaboration
Preliminary

Rapidity correlations in e^+e^-

A Parametrization of the Properties of Quark Jets
R.D. Field, R.P. Feynman (Caltech)
Nucl.Phys. B136 (1978) 131

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

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

R. Feynman
"Quark Jets"
8th ISMD 1977

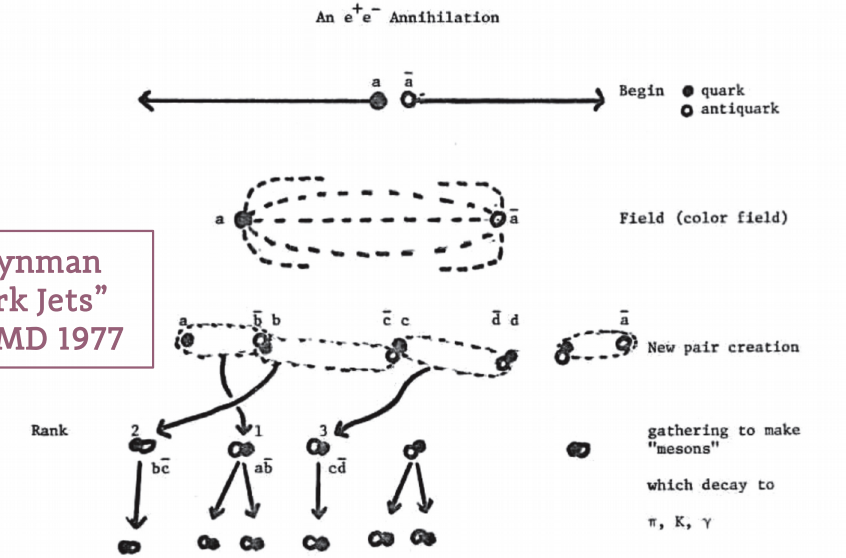
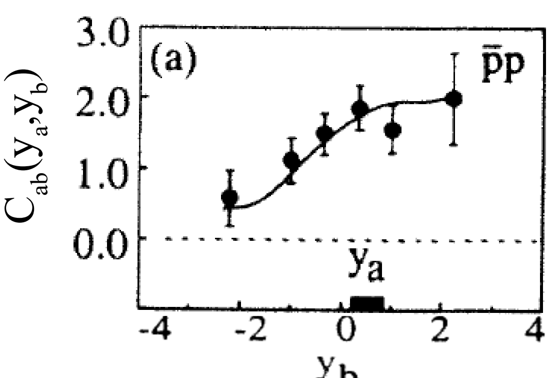


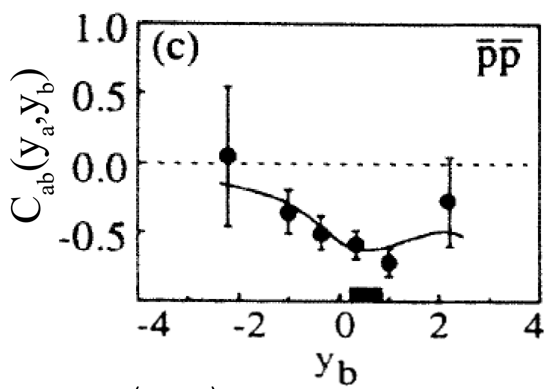
Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

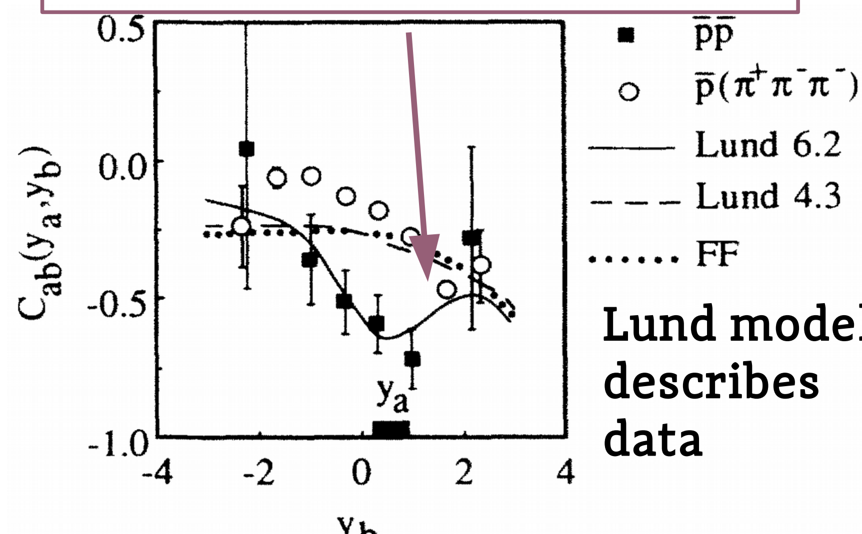
Models for e^+e^- agree with observations seen in data

correlation



anti-correlation





Lund model describes data

TPC/Two Gamma Collaboration, Phys.Rev.Lett. 57 (1986) 3140

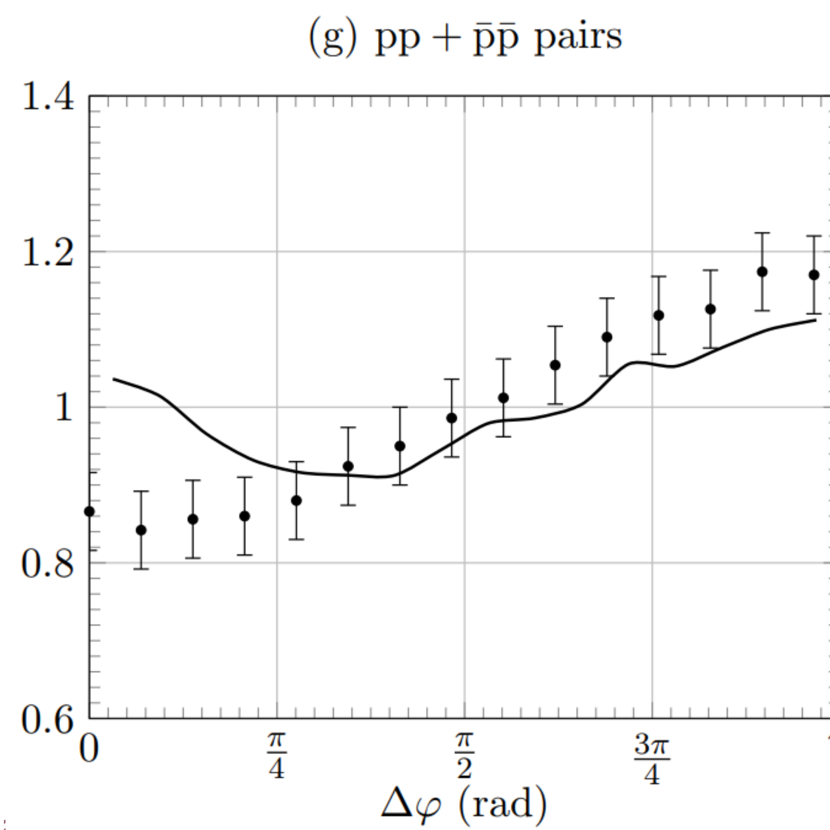
Pythia QM Plenary

- Torbjorn Sjostrand presentation
  - "PYTHIA: baryons too strongly correlated in minijets!"
  - "**Need new framework for baryon production.**"
  - "Further experimental input crucial!"

Collective Effects:
the viewpoint of HEP MC codes

Torbjörn Sjöstrand
Department of Astronomy and Theoretical Physics
Lund University
Sölvegatan 14A, SE-223 62 Lund, Sweden

Quark Matter 2018, Venice, 13–19 May 2018



The **real problem is baryon production**. [...] so it is clear we still lack some fundamental insight on baryon production, at least in the string context.

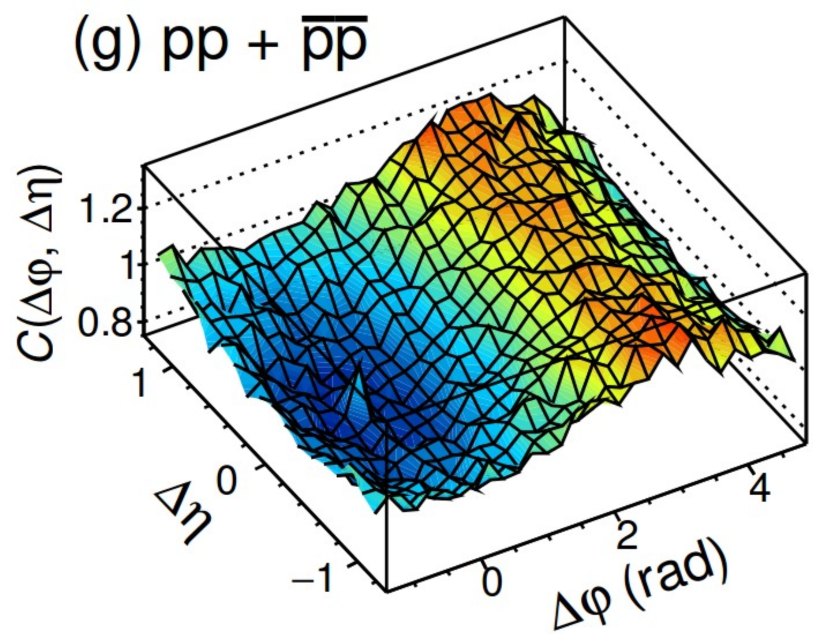
Nucl.Phys. A982 (2019) 43-49

Outlook

- **Wealth of results will be released soon by ALICE**
- Other small systems: results from pp at 13 TeV and p-Pb collisions
  - The same structures visible, no significant changes in respect to 7 TeV
- Heavy-ion collisions
  - Anti-correlation visible, sitting on top of the significant flow modulation
- Measure Xi and Omega baryons
  - Both p-Xi (sharing only one quark) and p-Omega (not sharing any quarks between particles in the pair) show significant anti-correlation
- Measure high p_T baryons
  - The anti-correlation effect does not disappear if we study higher p_T particles (above 2.5 GeV/c).

Summary

- We do not understand mechanism of production of one of the most common particles in the Universe: protons
- Effect observed in minimum bias pp 7 TeV “vanilla” events
  - but persists for other systems, multiplicities, momentum ranges
- Common for all baryons
- We need new baryon production framework!
  - Can influence other analyses measuring baryons as well?
- More data available soon!



THANK YOU!

Faculty of Physics

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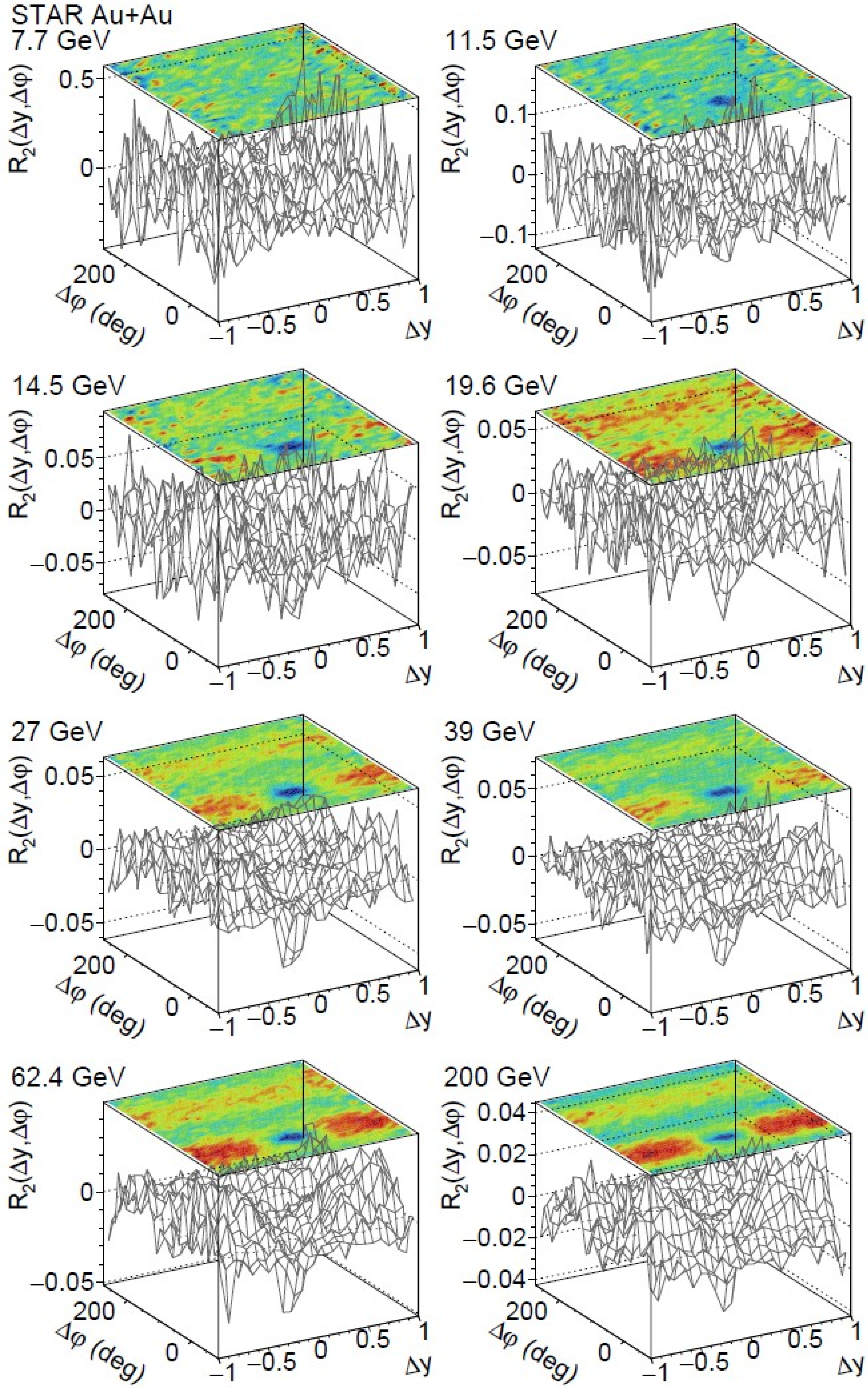
Backup

Proton-antiproton: anti-correlation (effect of annihilation)



Results from AMPT

https://arxiv.org/abs/1808.10641

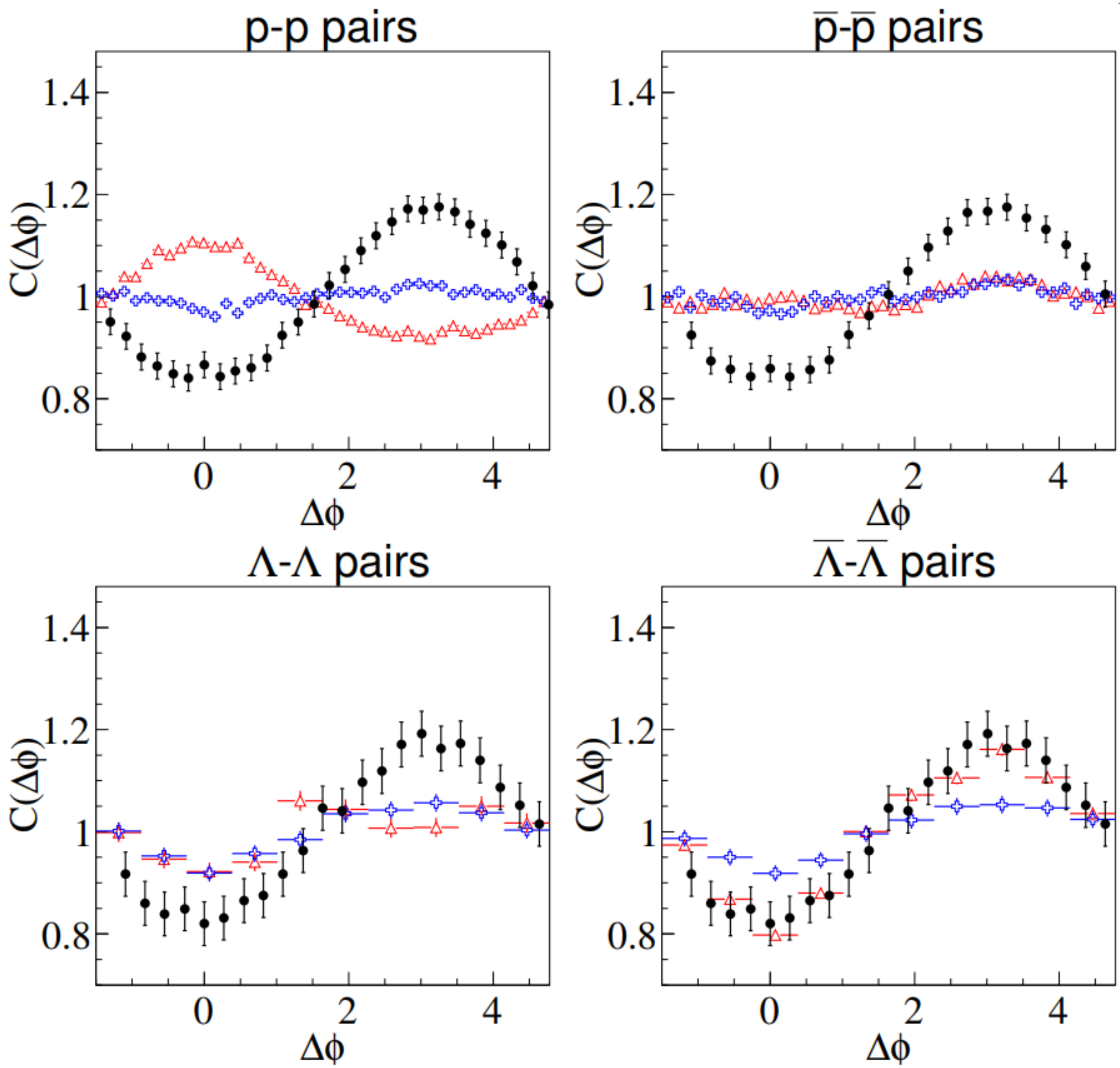
- New coalescence model introduced in AMPT

  (blue – new, red - old)

- Now baryons and anti-baryons give the same results

- Qualitatively model can reproduce our result (especially for lower p_T)

- Coalescence and string melting in low multiplicity pp collisions???



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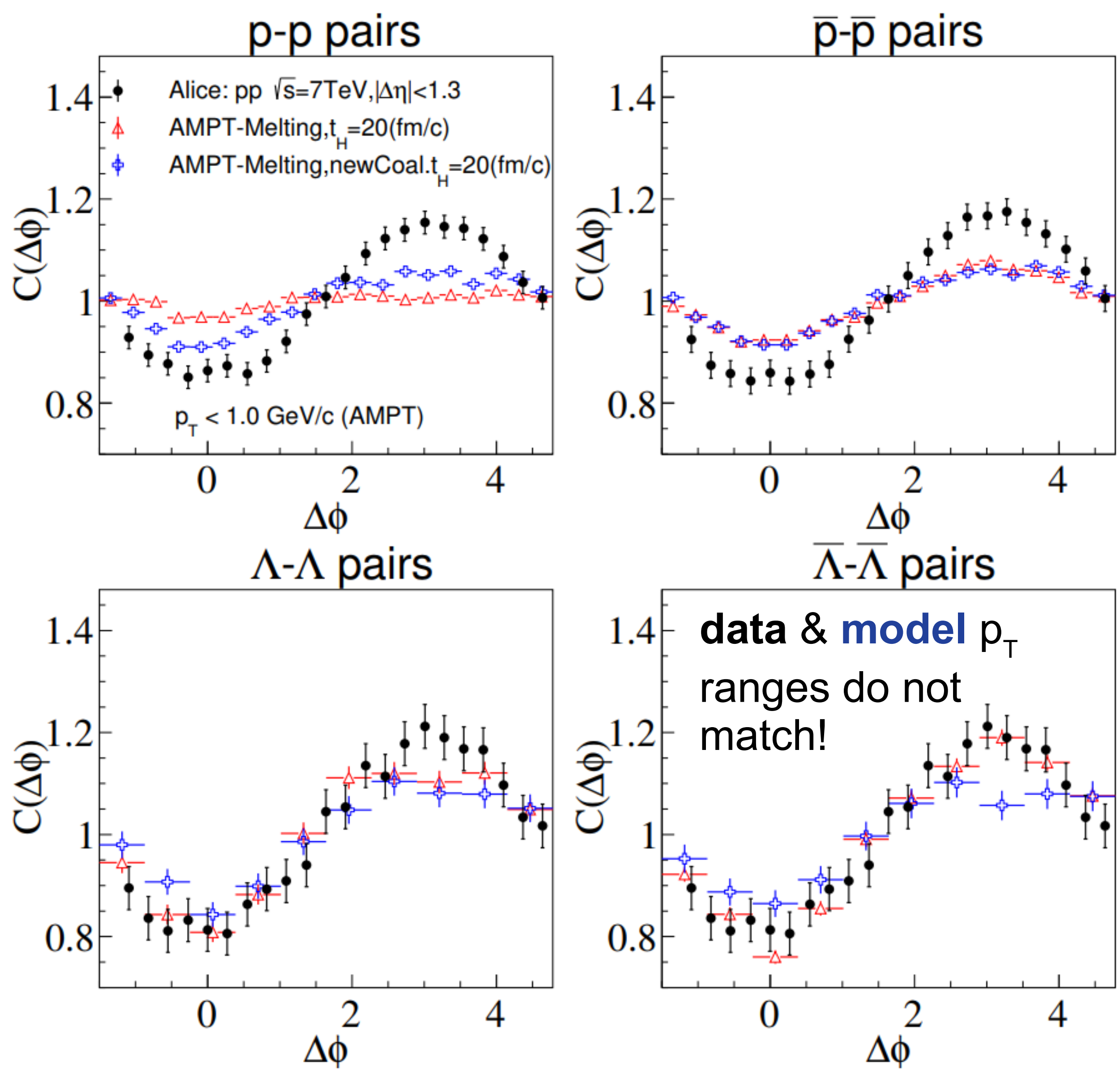
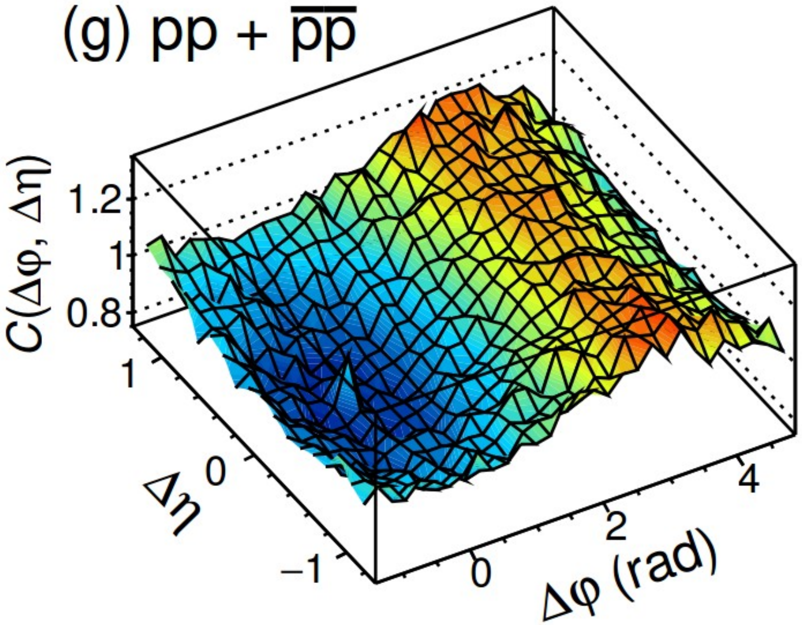


Małgorzata Janik (WUT)

https://arxiv.org/pdf/1904.08603.pdf

Reminder

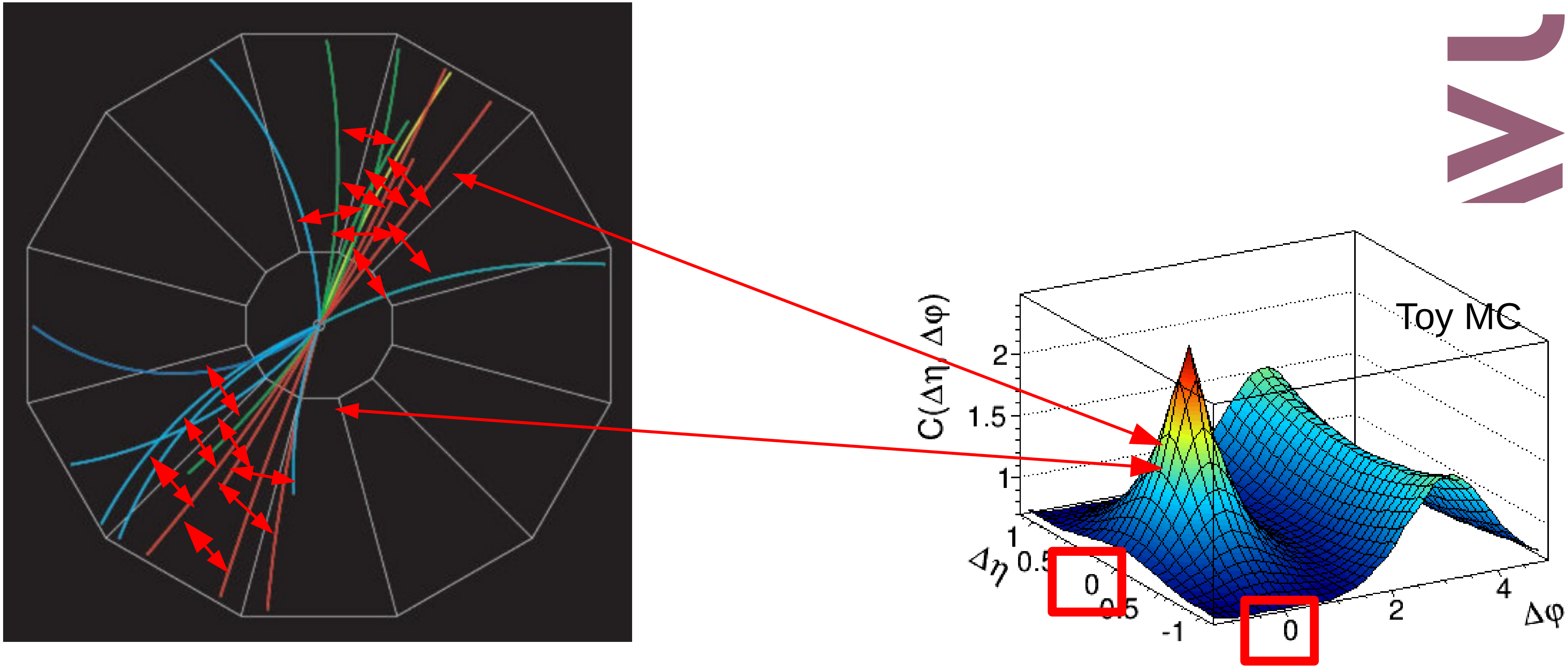


1) ALICE paper
Eur. Phys. J. C77 (2017) 569
https://arxiv.org/abs/1612.08975

2) SQM Proceedings (short write-up with most relevant results and ideas)
https://aliceinfo.cern.ch/node/29210

3) CERN LHC Seminar
https://indico.cern.ch/event/632396/ (video recording available)

How does it work?

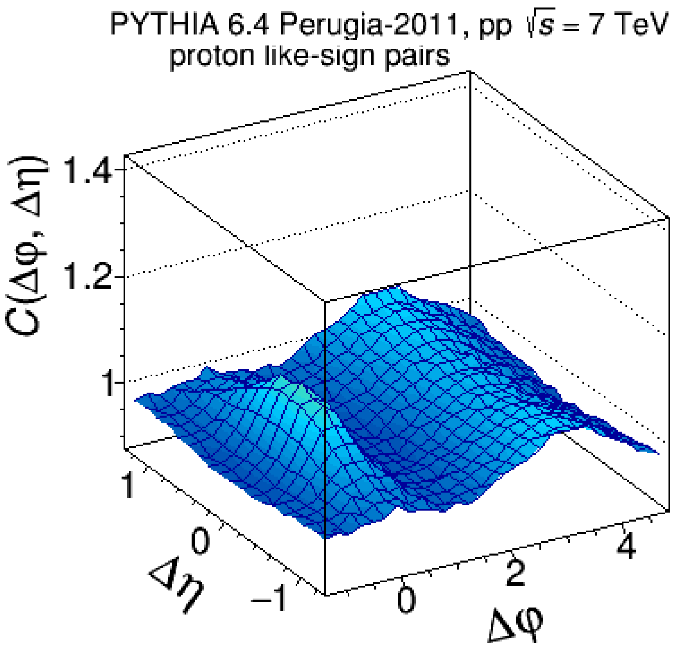


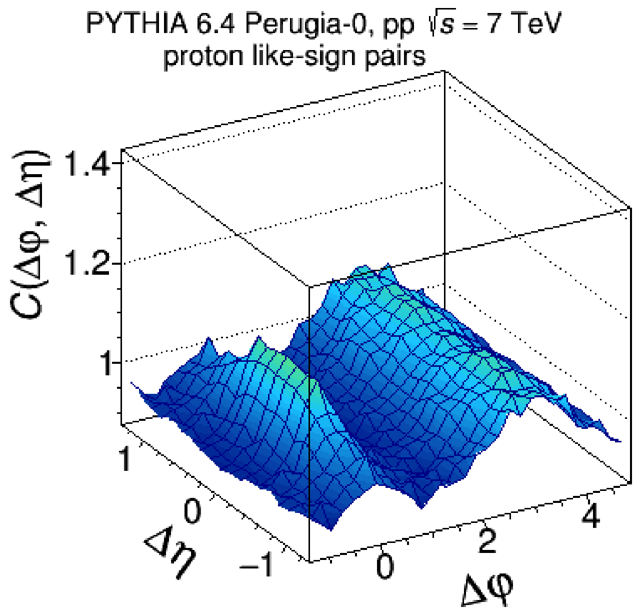
Near-side peak

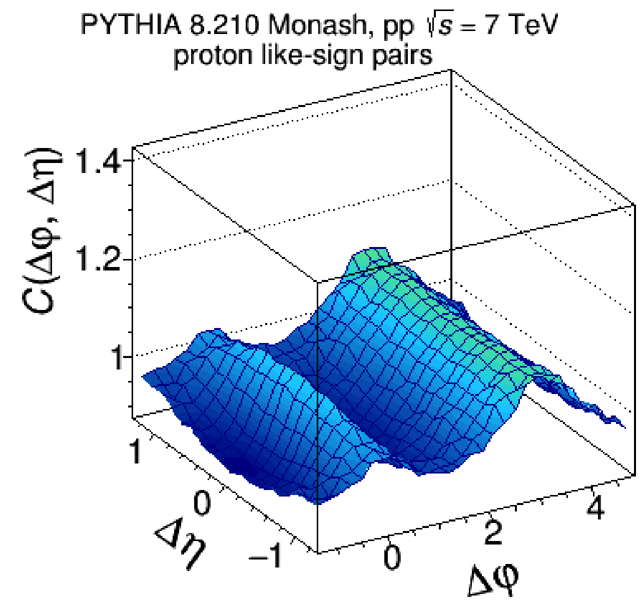
For particles from the same jet (red):

- centered at Δφ = Δη = 0

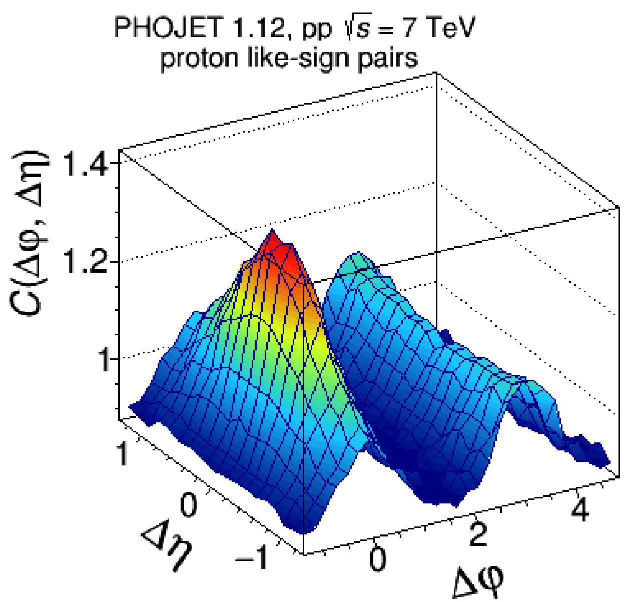
MC models do not reproduce







None of common MC models reproduces ALICE data!



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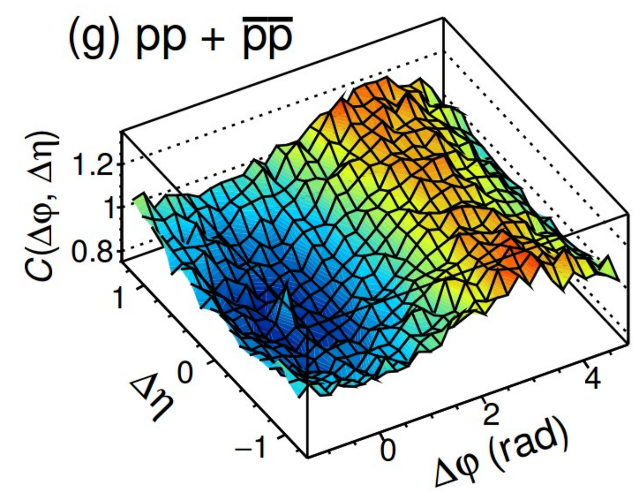
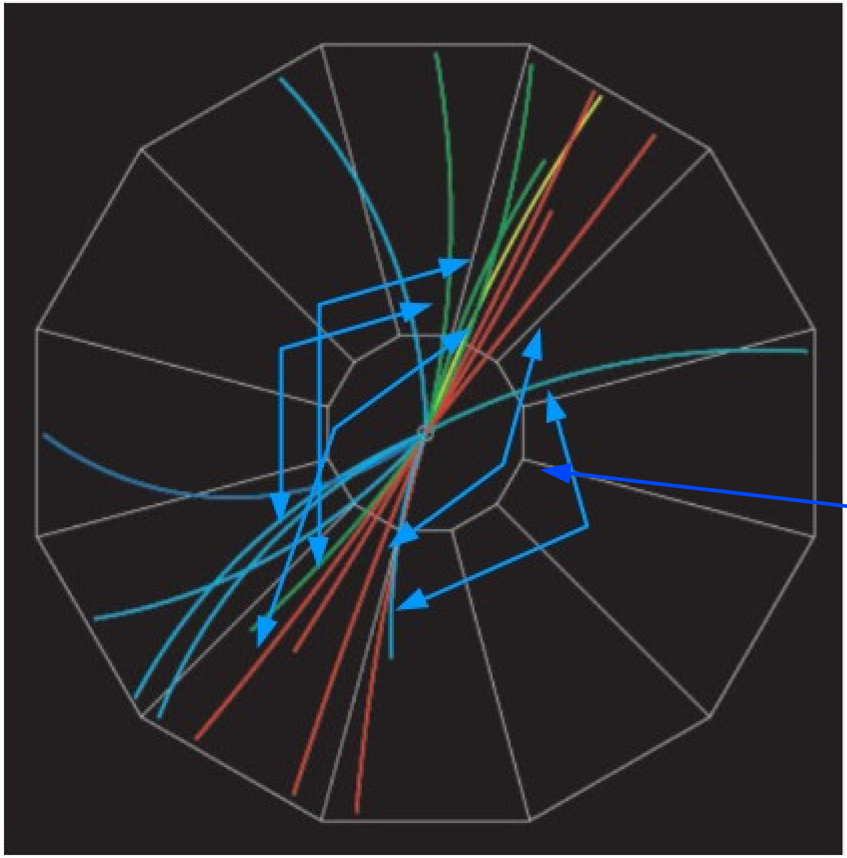
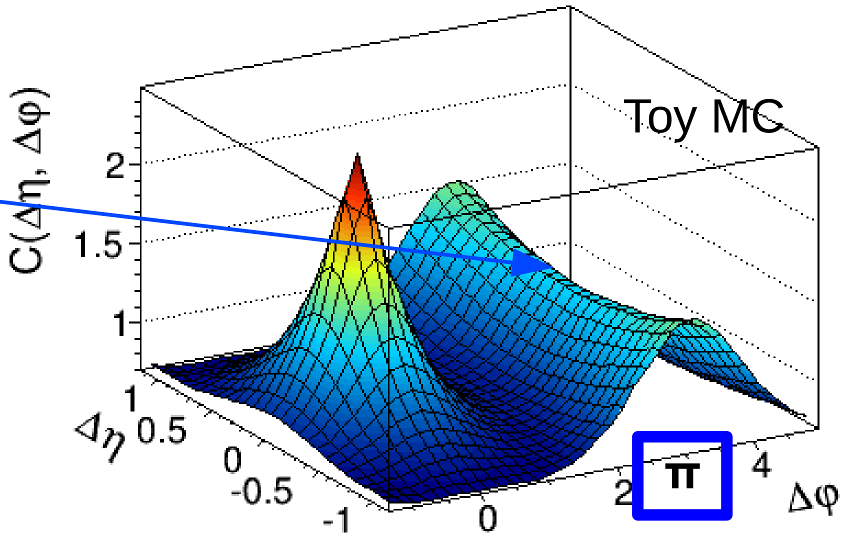


How does it work?



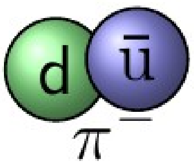


For particles from from back-to-back jets (blue): *Away-side ridge*

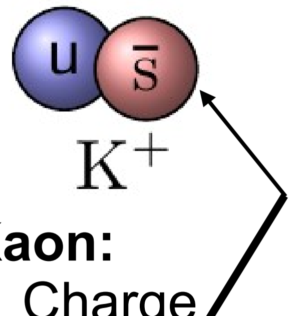
- **centered at $\Delta\varphi = \pi$**
- **dN/Δη ~ const, if averaged over many events**

One step further: identified particles!

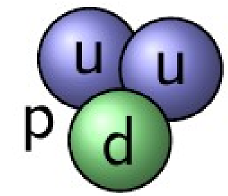
Unexplored phenomena: **conservation laws** and their influence on **particle production mechanisms –** study via correlation functions for particles with **different quark content**



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 differential way:

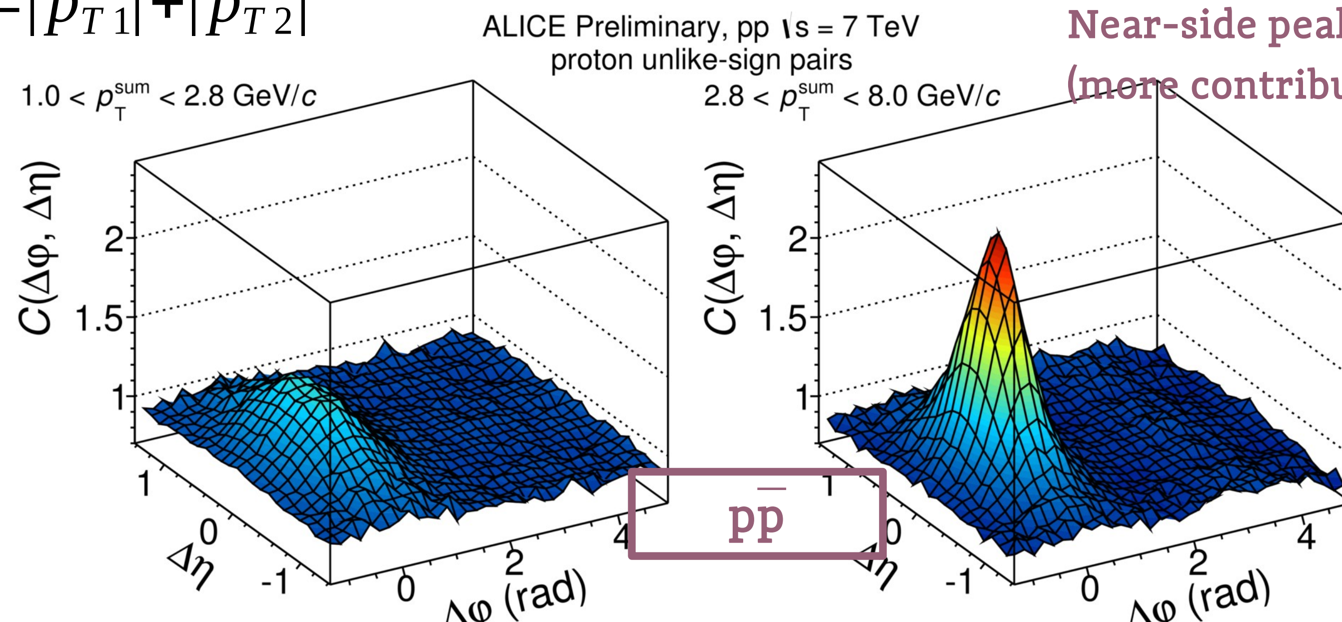
- **charge dependence**

  for unlike-sign pairs quantum numbers conserved: stronger correlation
  for like-sign pairs new particles need to be produced: weaker correlations

- **identified particles**

$\Delta\eta\Delta\varphi$ of protons vs p_T

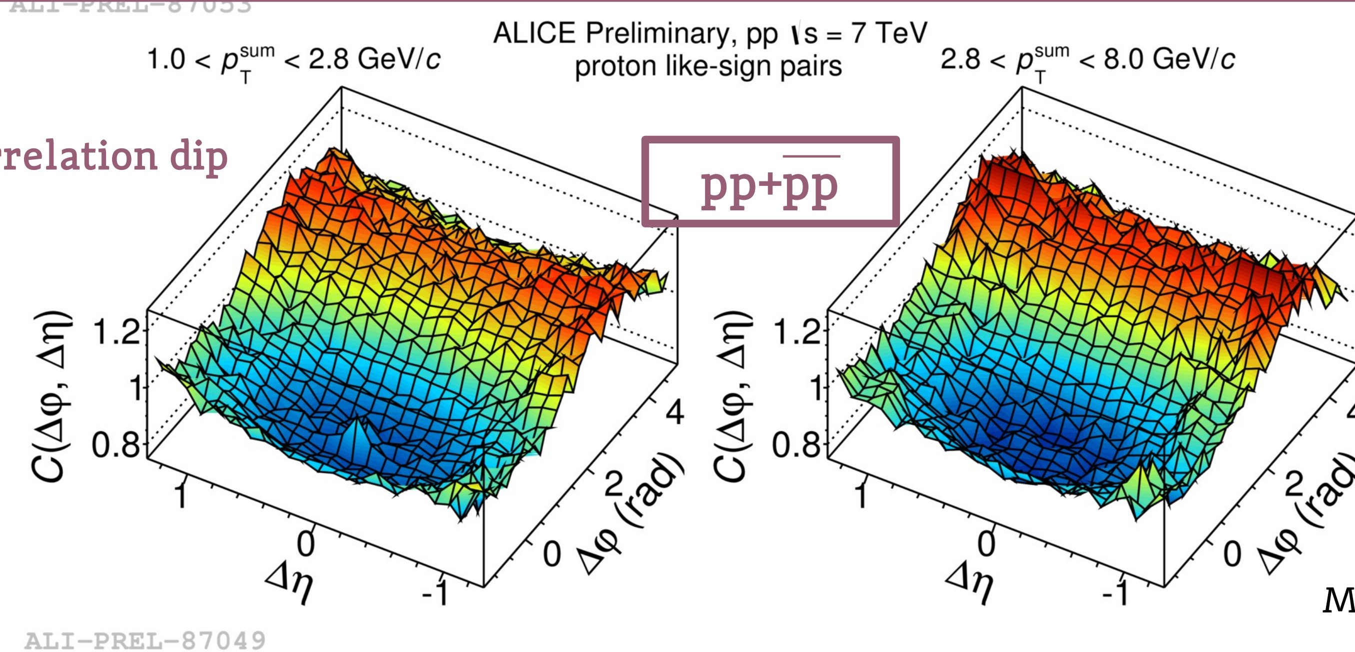
$$p_T^{sum} = |p_{T\,1}| + |p_{T\,2}|$$



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

p_T growth

Anticorrelation dip



Small peak disappears for high p_T-sum

Shape of the dip does not change

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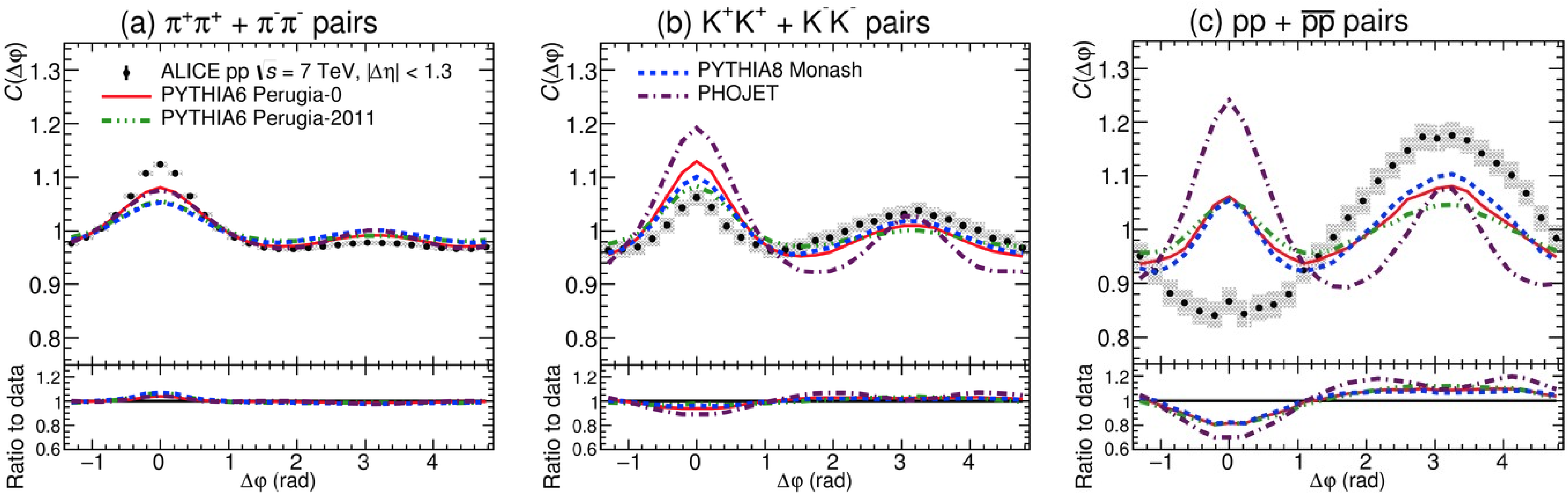
Comparison to MC models: like-sign

arXiv:1612.08975



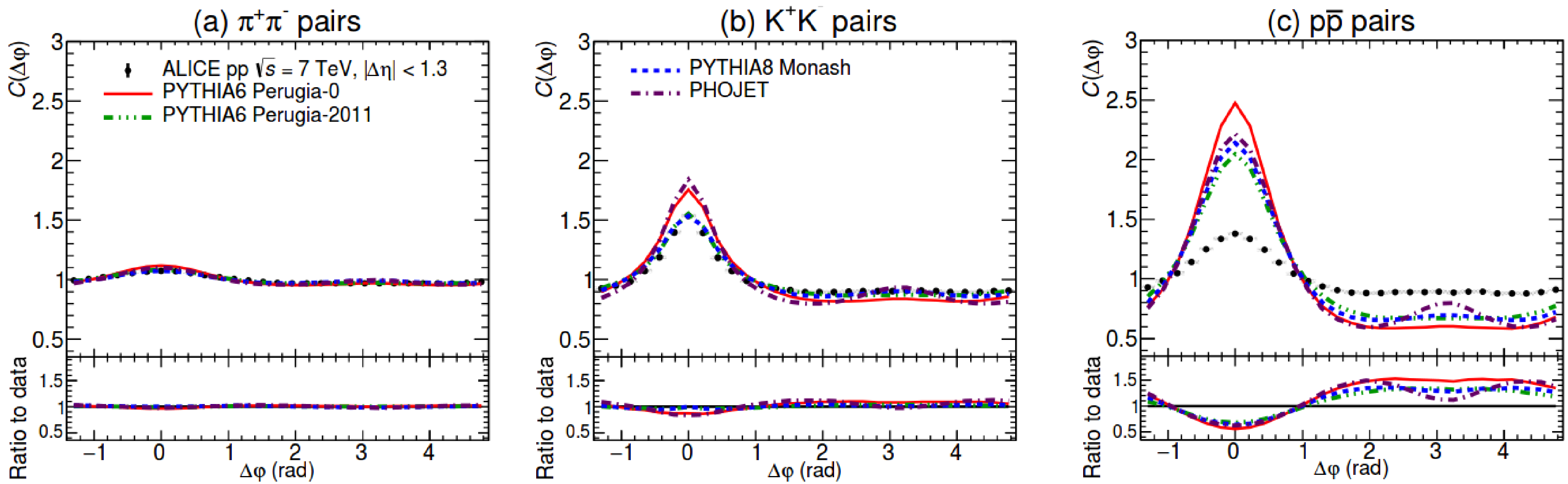
- The models reproduce reasonably well the angular correlations for mesons

- The models fail to reproduce the results for baryons – they are able to produce 2 baryons close in the phase space

- **Energy and local baryon-number conservation laws are implemented in all studied models - not enough to explain the anti-correlation observed in experimental data**

Comparison to MC models: unlike-sign

arXiv:1612.08975

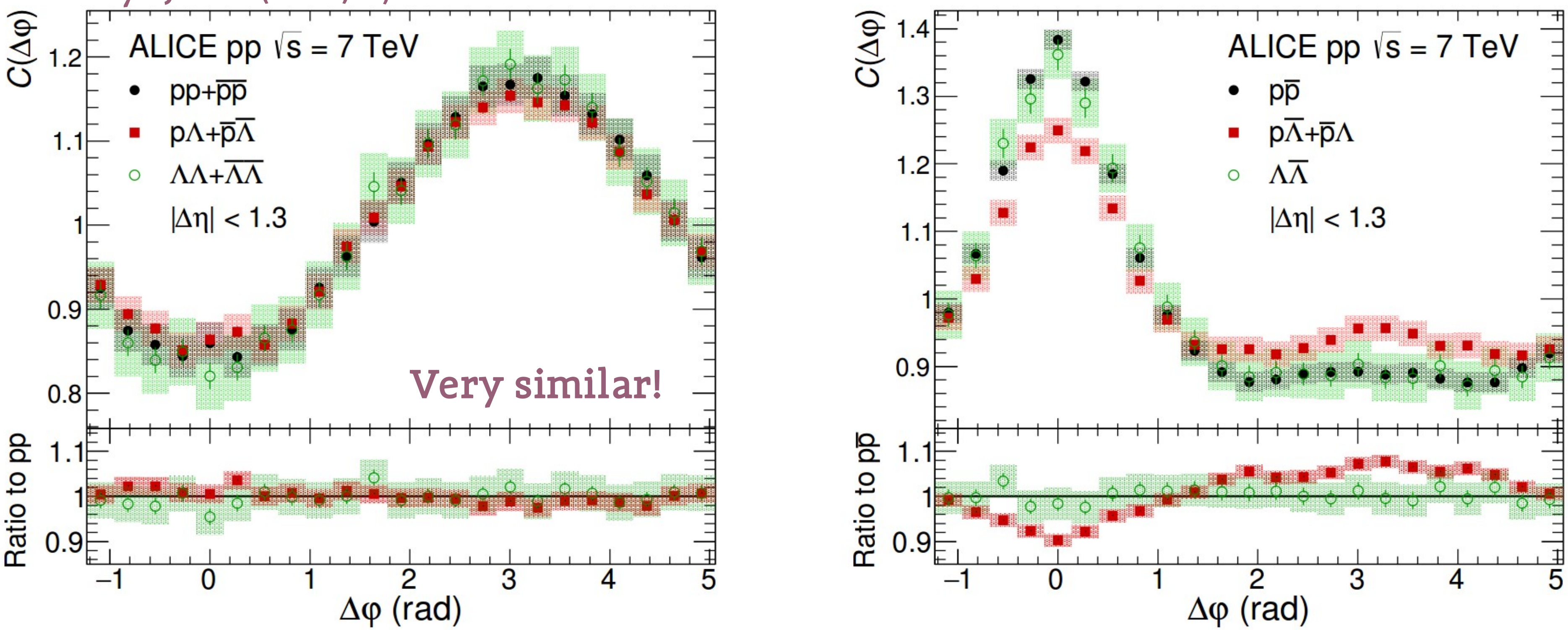


- The models reproduce reasonably well the angular correlations for mesons
- The models fail to reproduce the results for baryons – they are able to produce 2 baryons close in the phase space, also baryon-antibaryon pairs have 2 x the magnitude for MC
- **Energy and local baryon-number conservation laws are implemented in all studied models - not enough to explain the anti-correlation observed in experimental data**

ΔηΔφ of baryons

Małgorzata Janik, ŁG

Eur.Phys.J. C77 (2017) 8, 569



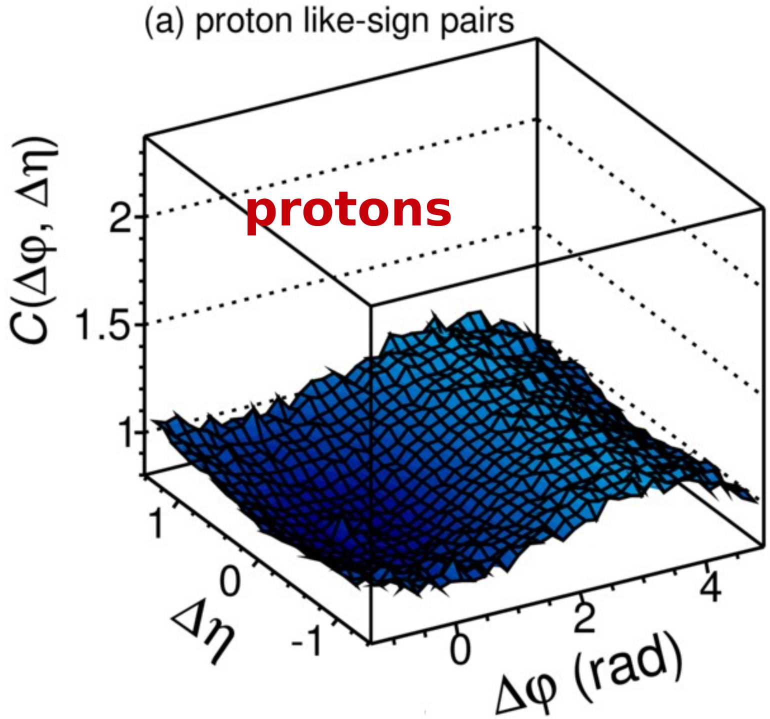
- Projections show how similar are baryon-baryons pairs to each other
- Similarity between pairs, to a lesser extent, is also observed in the baryon-antibaryon case

Possible explanations:

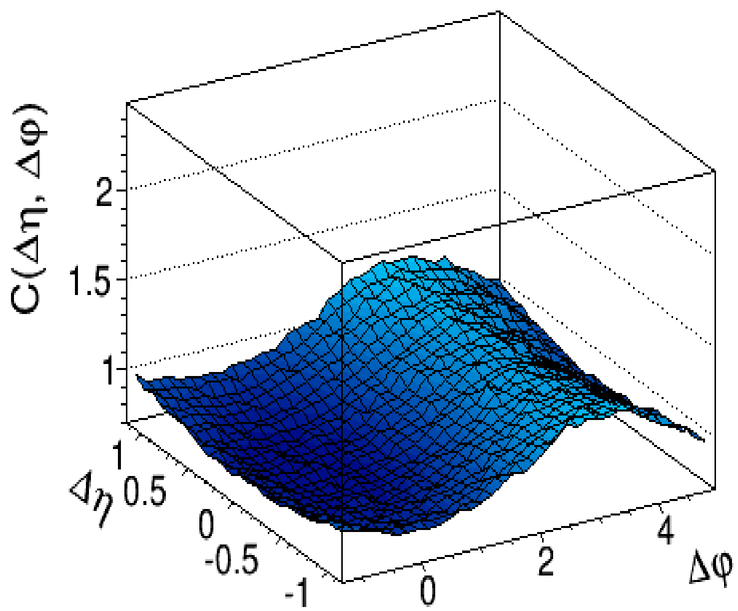
- Fermi-Dirac Quantum Statistics? **NO (non-identical particles)**
- Coulomb repulsion? **NO (uncharged particles)**
- Strong Final-State Interactions?**NO (checked)**

Toy Monte Carlo
CALM – ConservAtion Laws Model

ALICE exp data



MC only mom. cons.



Toy Monte Carlo Events
with momentum conservation only

Strong suppression of any other effects?
What is the underlying mechanism?

ΔηΔφ of baryons

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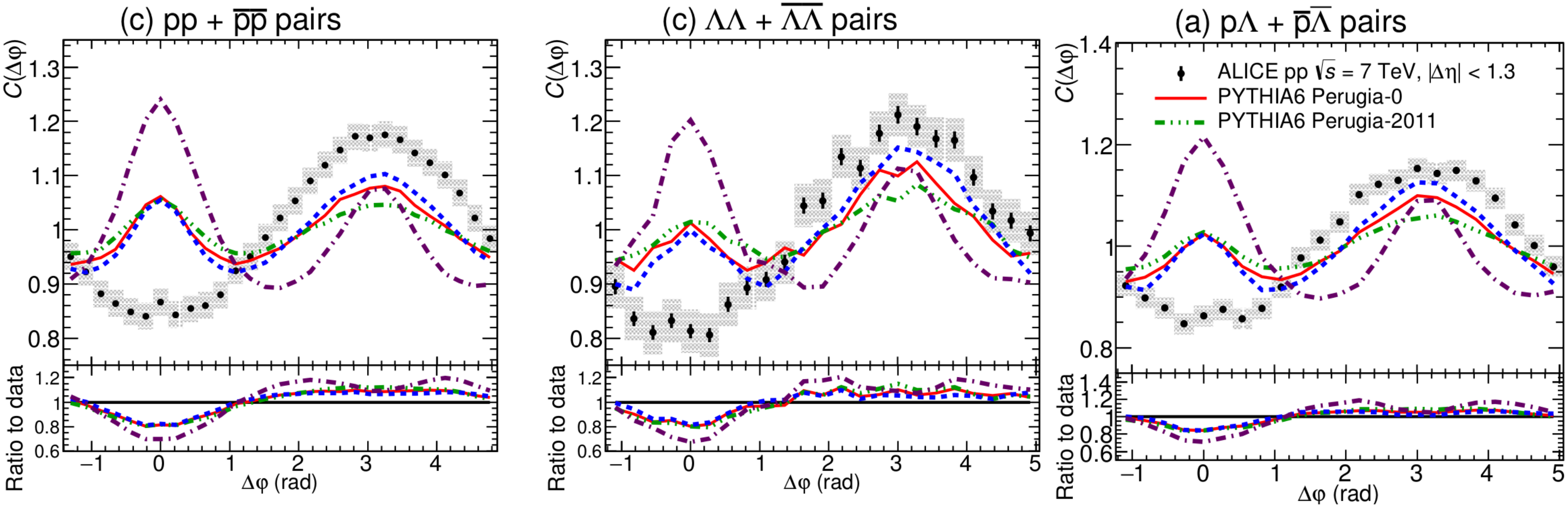


- None of studied MC models (PYTHIA, PHOJET, EPOS, HERWIG) agrees with the data even qualitatively

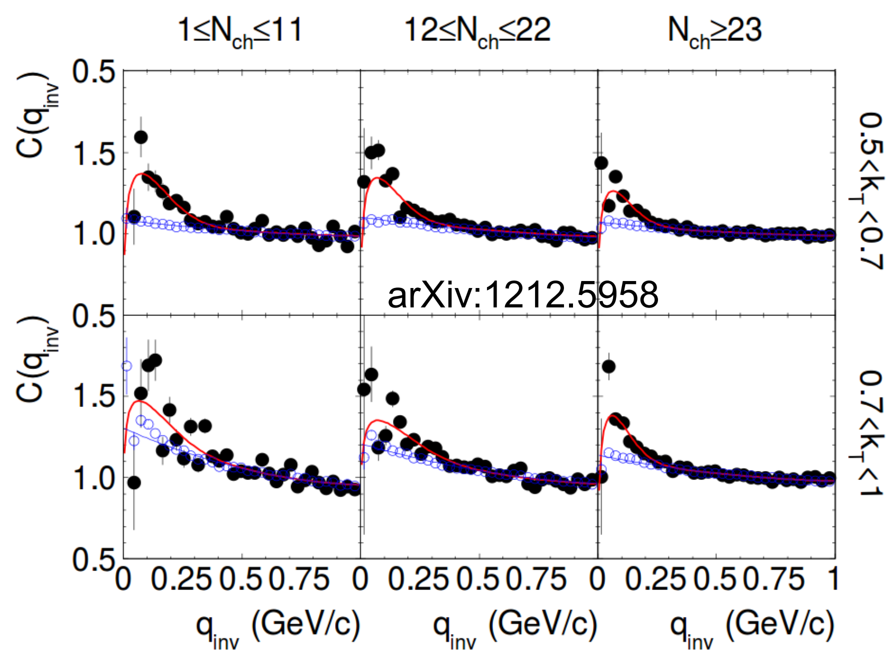
The same effect in other analyses?

Femtoscopy

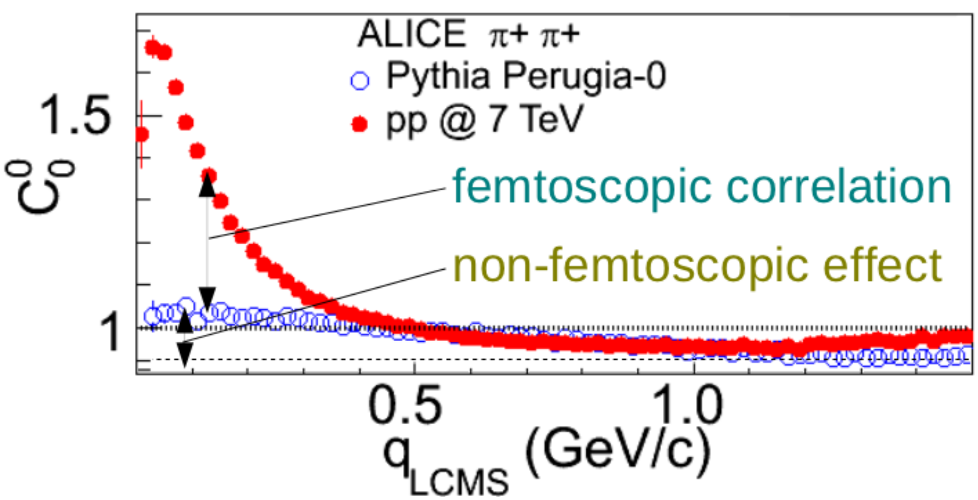
Non-femtoscopic correlations

- Non-femtoscopic correlations visible in small systems for **pions** and **kaons**:
  - Grow with increasing k_T
  - Grow with decreasing multiplicity
  - **Significant source of systematics in the fitting procedure**
- So far only **<u>hypothesis</u> of (mini-)jet origin**
- **How do baryon correlations look like in pp?**

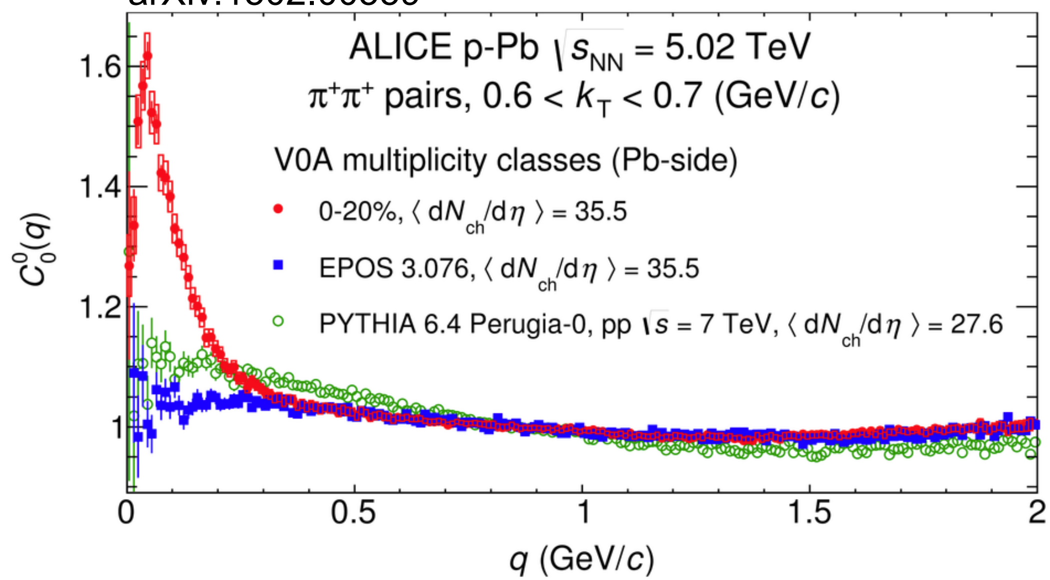
$$k_T = |p_{T1} + p_{T2}|/2$$



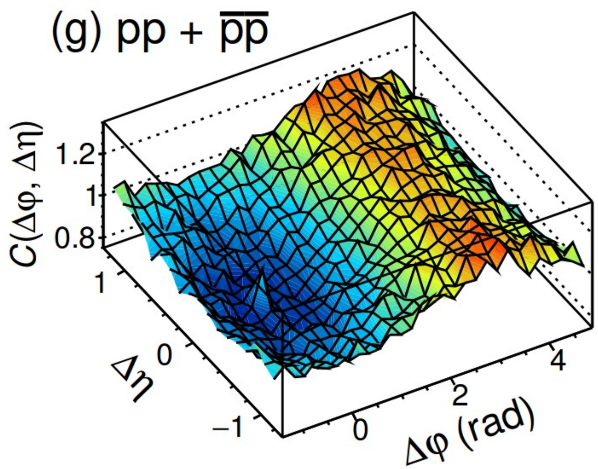
arXiv:1101.3665

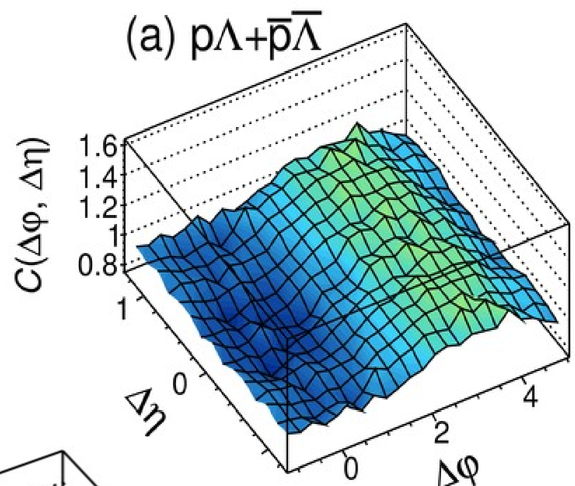


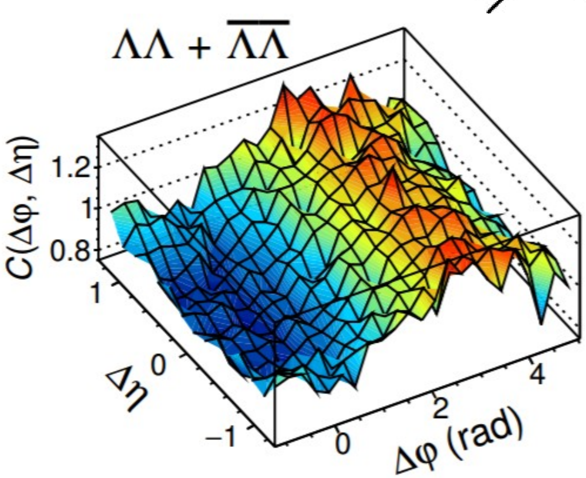
arXiv:1502.00559

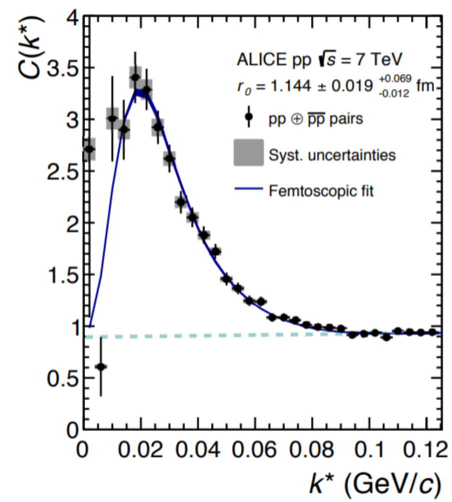


Comparison of angular and femto corr. fun.

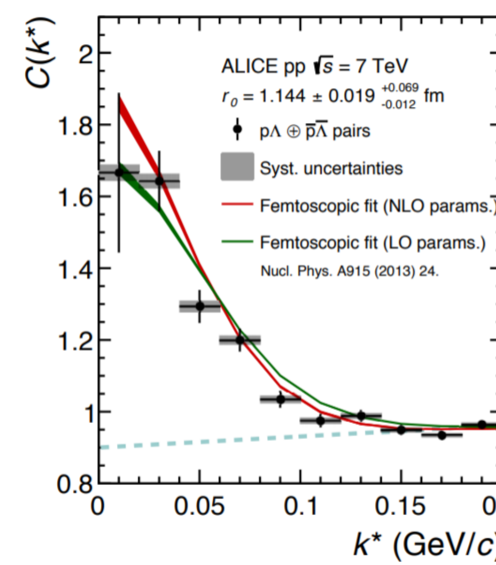


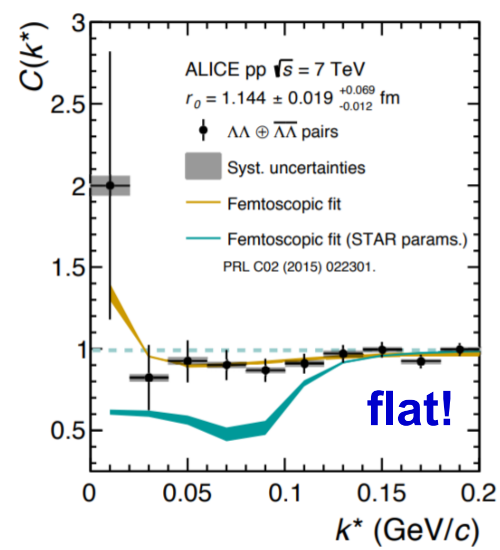






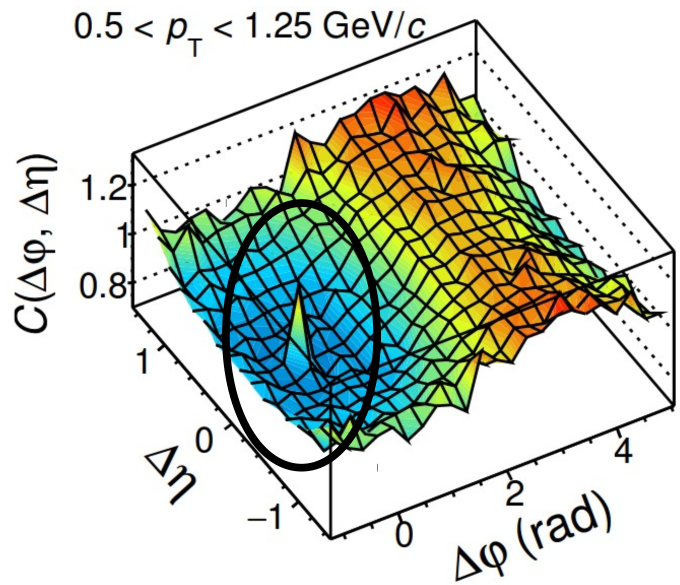
Non-femto NOT PRESENT for all bb systems





Non-femto STRONG for all b$\overline{b}$ systems

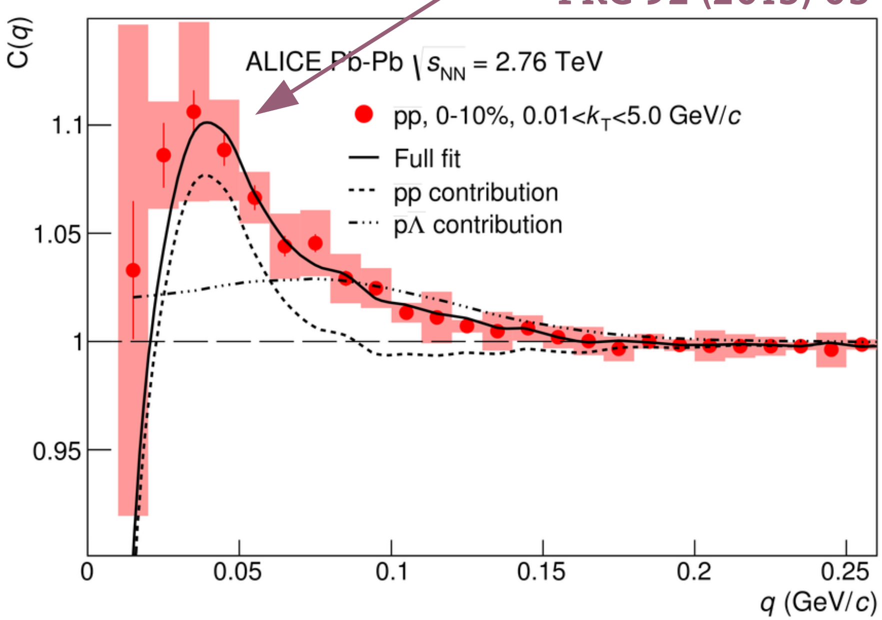
Possible origin of the small peak



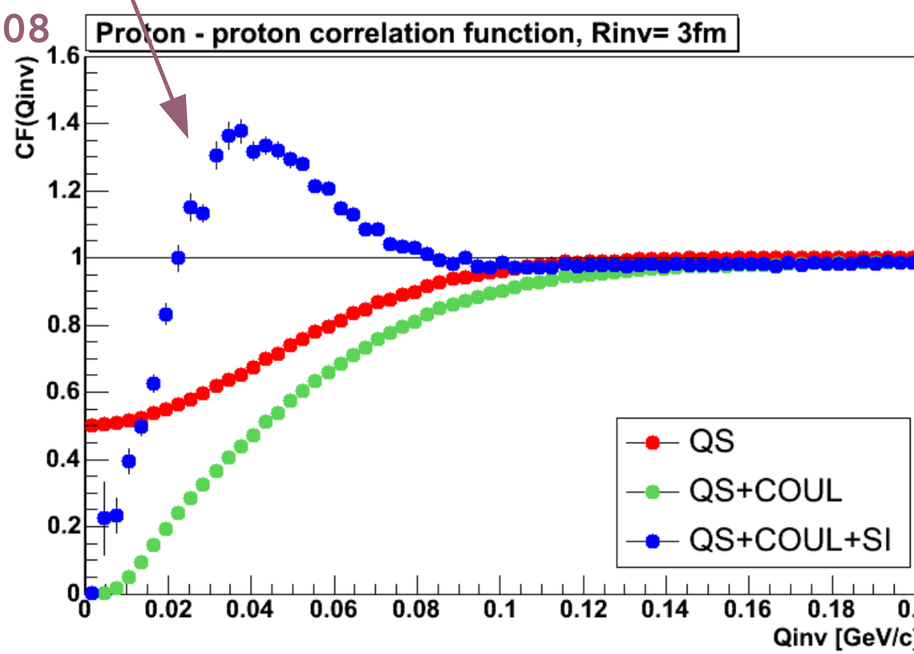
Femto correlations of protons

Possible origin of the small peak: QS(Fermi-Dirac) +Coulomb+Strong

- Visible in femtoscopic correlation function
- Dominant effect around q_{inv} = 0.04 GeV/c
- **Strong interaction** the only source of positive correlation for baryons



PRC 92 (2015) 054908



Femto correlations of protons

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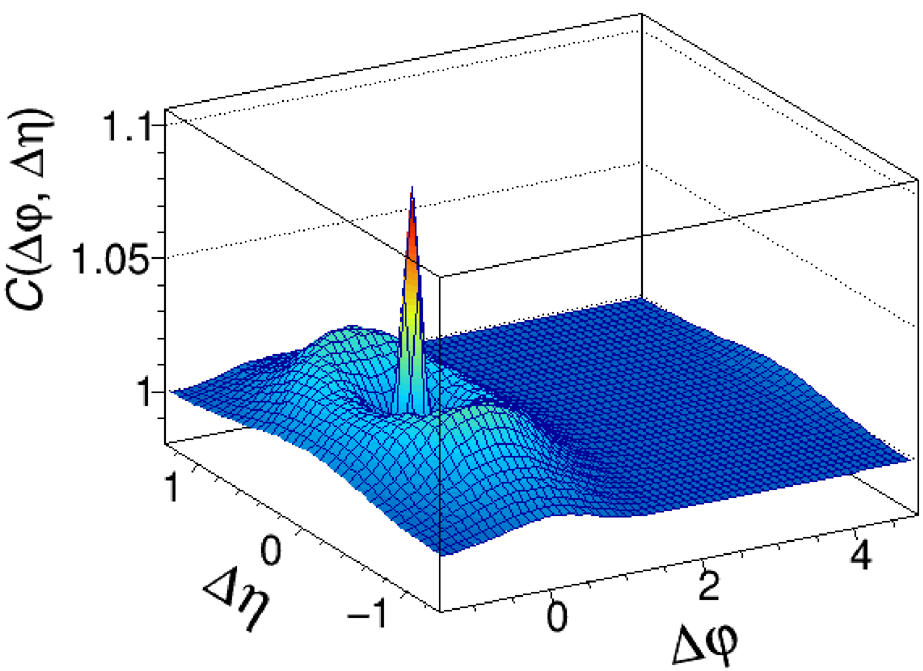
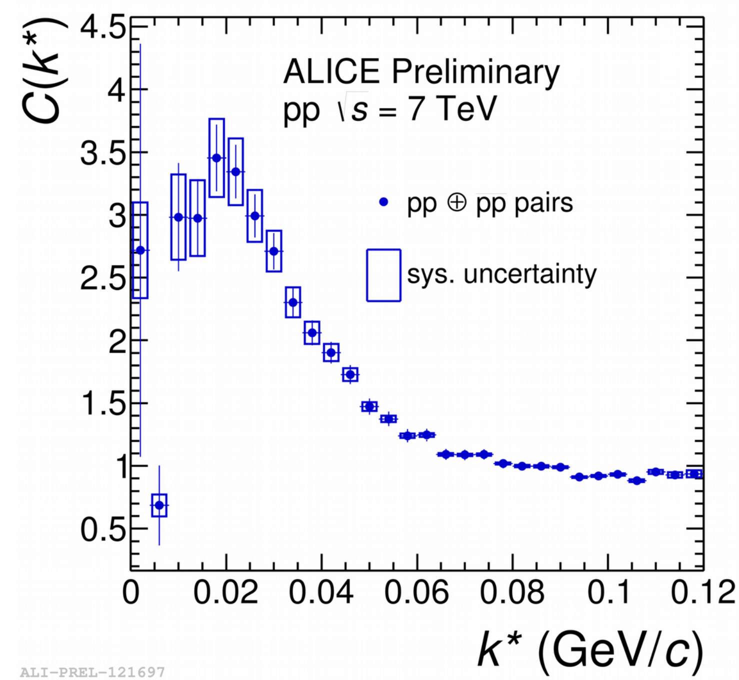
- **Direct transformation from** C(q_{inv}) **to** C(ΔηΔφ) **not possible**
- **One can use a simple Monte Carlo procedure:**
  - generate random η and φ values from uniform distributions (for 2 particles: η_1, η_2, φ_1, φ_2)
  - generate random p_T value from measured p_T distribution (for 2 particles: p_{T1}, p_{T2})
  - calculate q_{inv} from generated η_1, η_2, φ_1, φ_2, p_{T1} and p_{T2} (the longest step)
  - randomly select q_{inv} and take a corresponding value from measured femtoscopic correlation and apply it as a weight while filling the numerator of ΔηΔφ correlation

Transformed ← **Measured**





Femto correlations of protons

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Results:

- Femto correlation produces spike at (Δη,Δφ)=(0,0)
- Comparison of two peaks: 1-bin wide projection on Δφ (subtract minimum)
- **Both the height and the width of two peaks comparable**
- **Strong interaction does not cause the wide depletion**