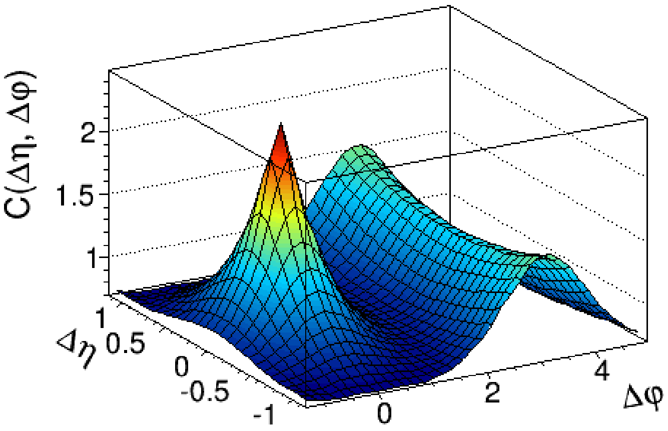
NATIONAL SCIENCE CENTRE

# Two-particle angular correlations

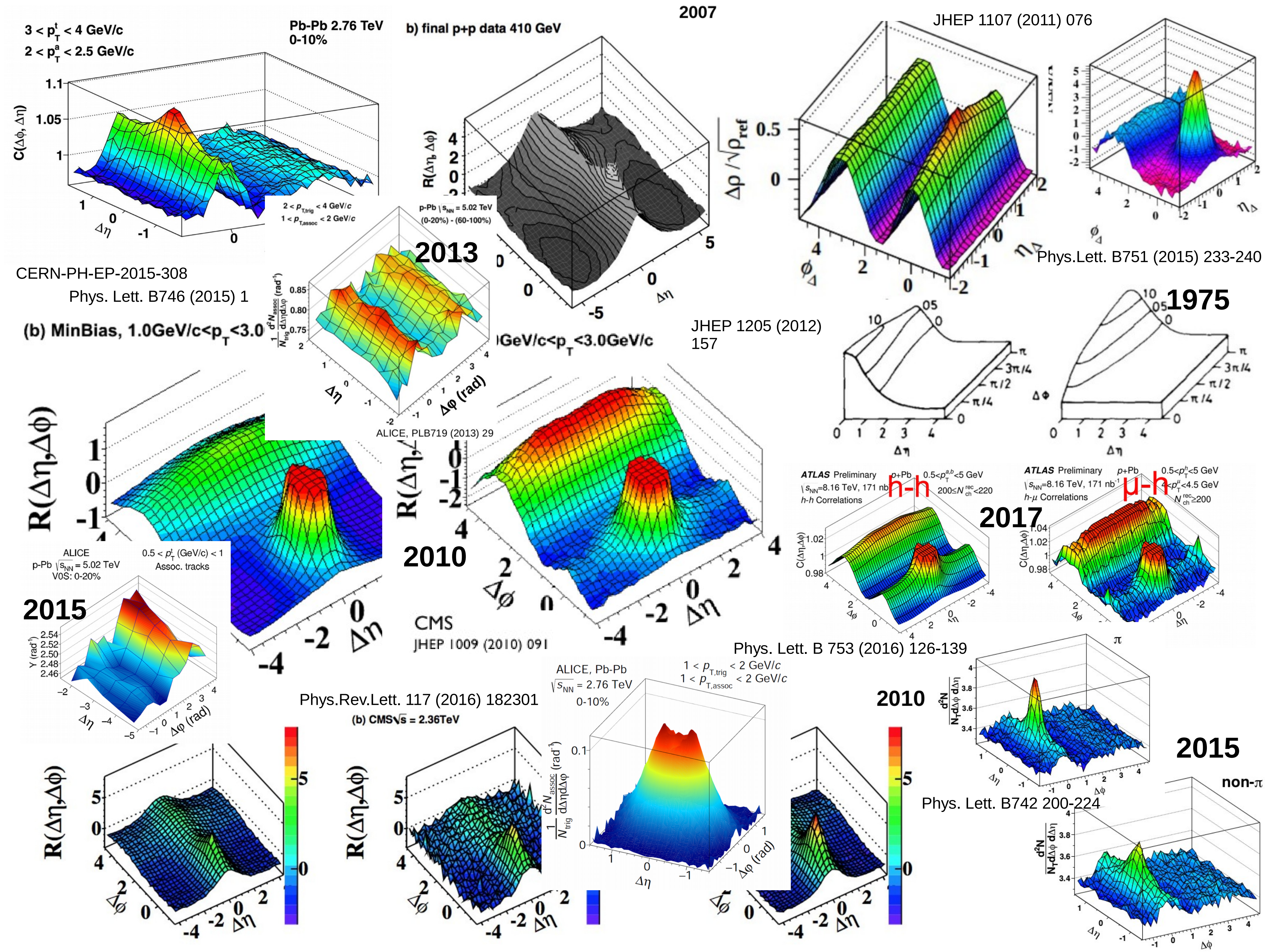

Małgorzata Janik



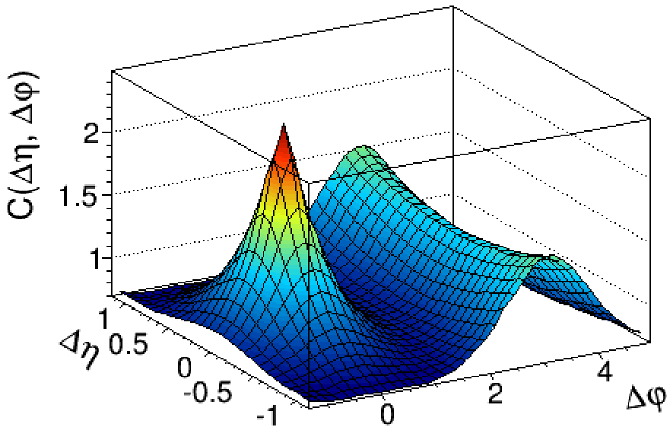
Faculty of Physics
Warsaw University
of Technology


Oslo Winter School
2-7.01.2018

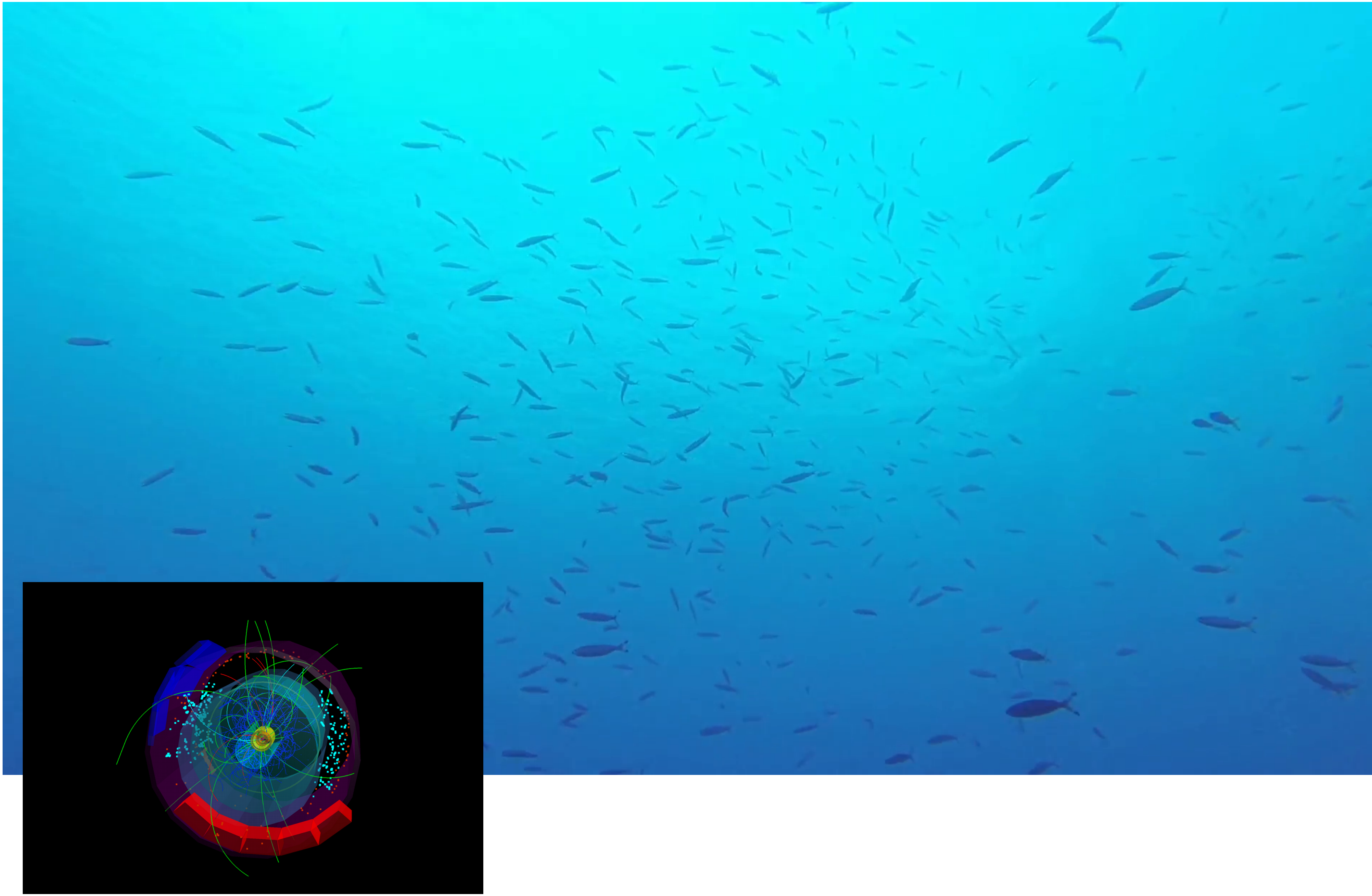


2007
JHEP 1107 (2011) 076
Pb-Pb 2.76 TeV
0-10%
b) final p+p data 410 GeV
CERN-PH-EP-2015-308
Phys. Lett. B746 (2015) 1
2013
p-Pb √sNN = 5.02 TeV
(0-20%) - (60-100%)
ALICE, PLB719 (2013) 29
Phys.Lett. B751 (2015) 233-240
1975
JHEP 1205 (2012) 157
(b) MinBias, 1.0GeV/c<pT<3.0GeV/c
2010
CMS
JHEP 1009 (2010) 091
ATLAS Preliminary
h-h
μ-h
h-h Correlations
h-μ Correlations
2017
ALICE
p-Pb √sNN = 5.02 TeV
V0S: 0-20%
Assoc. tracks
2015
Phys. Lett. B 753 (2016) 126-139
ALICE, Pb-Pb
√sNN = 2.76 TeV
0-10%
Phys.Rev.Lett. 117 (2016) 182301
(b) CMS√s = 2.36TeV
2010
Phys. Lett. B742 200-224
2015
π
non-π

# How does it work?

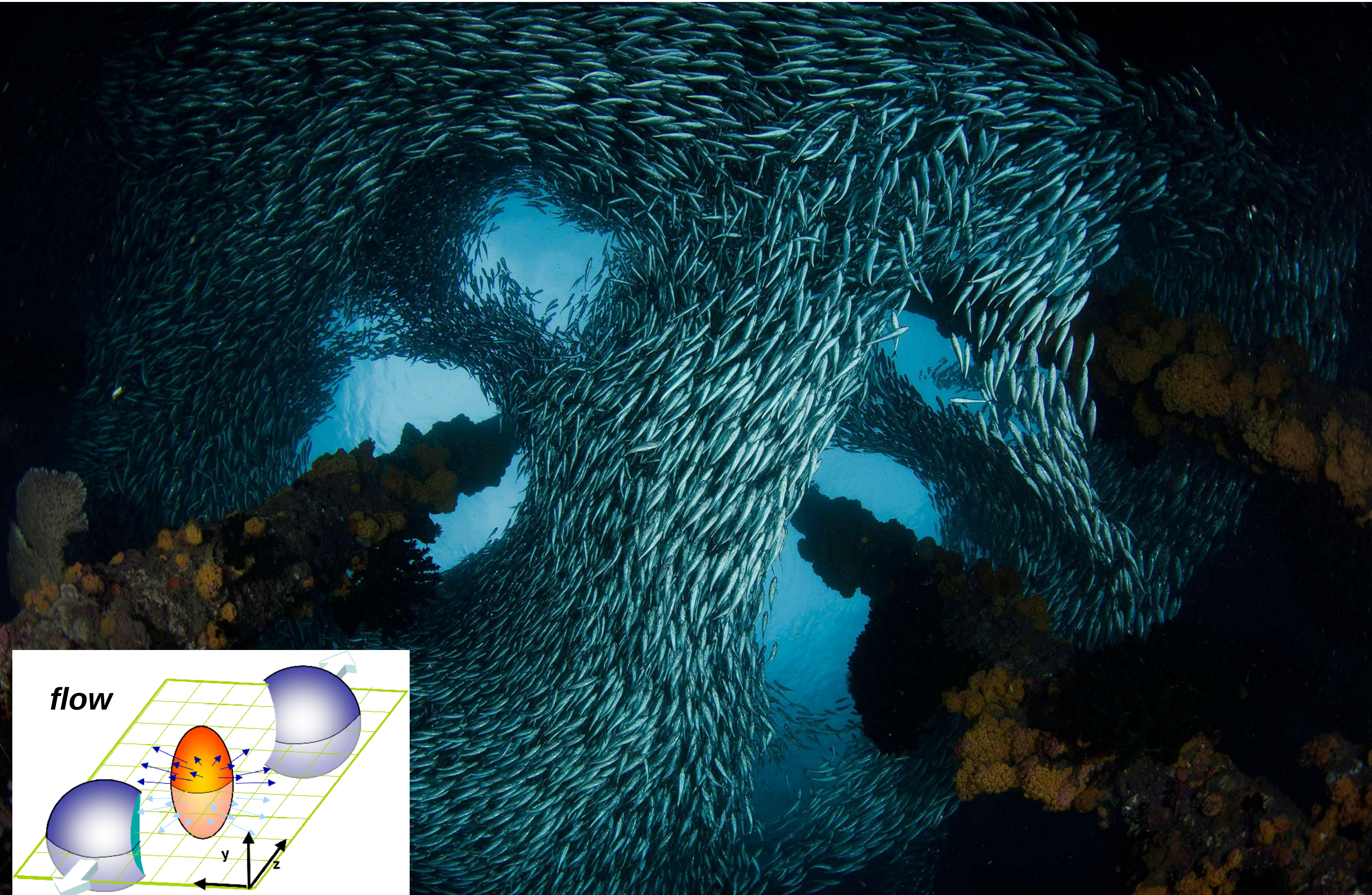


# Correlations

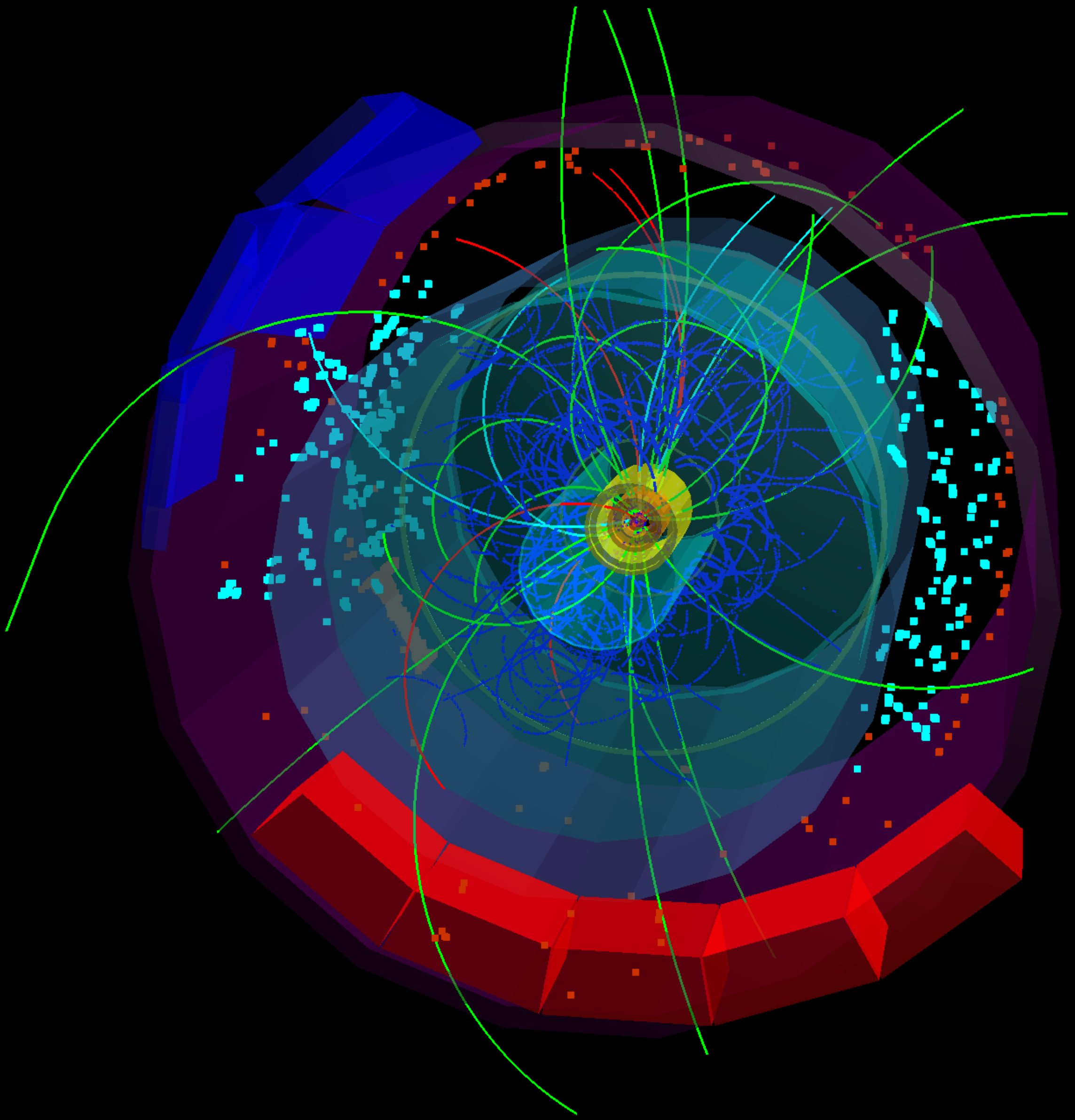


# Correlations

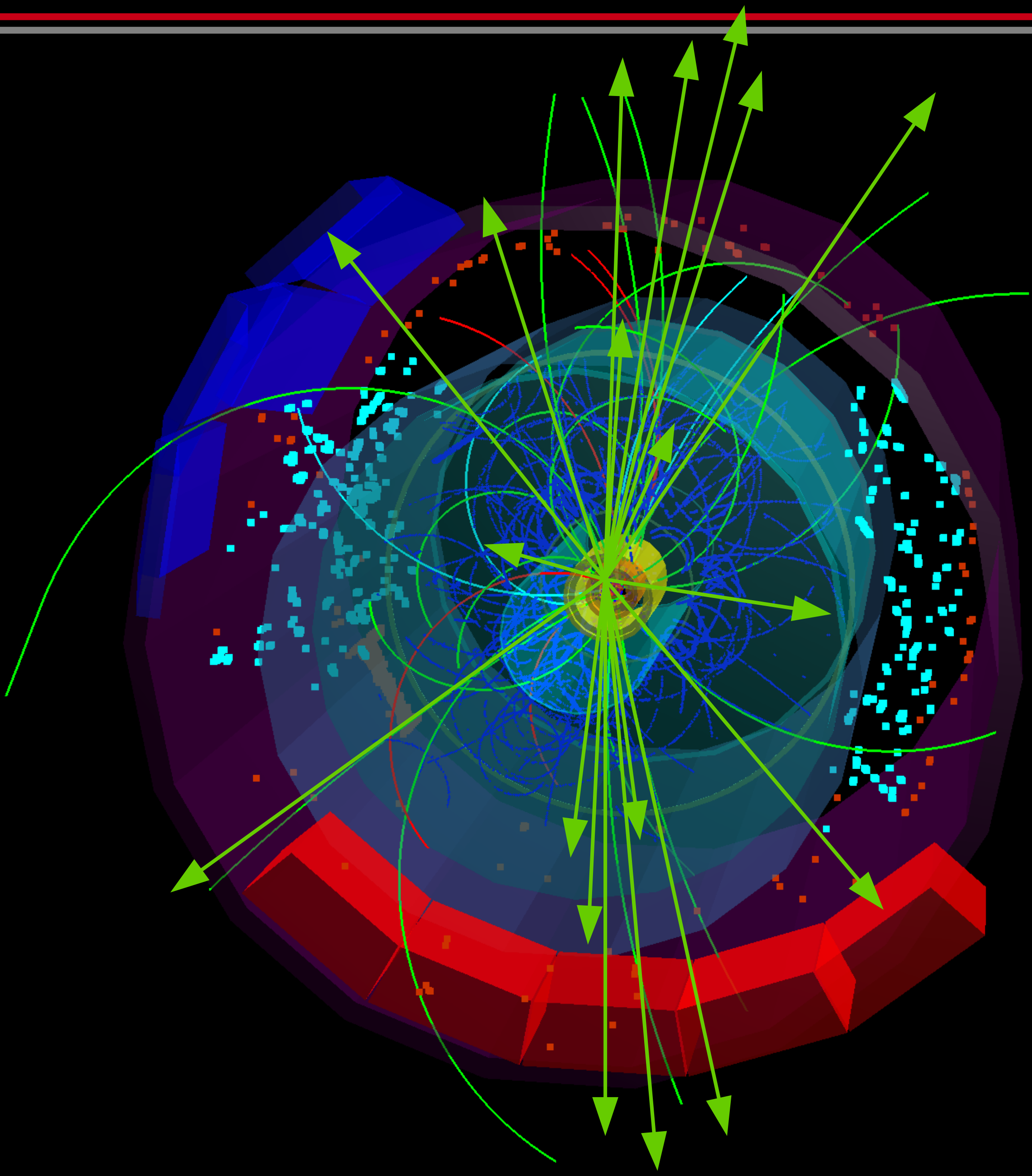
# Correlations



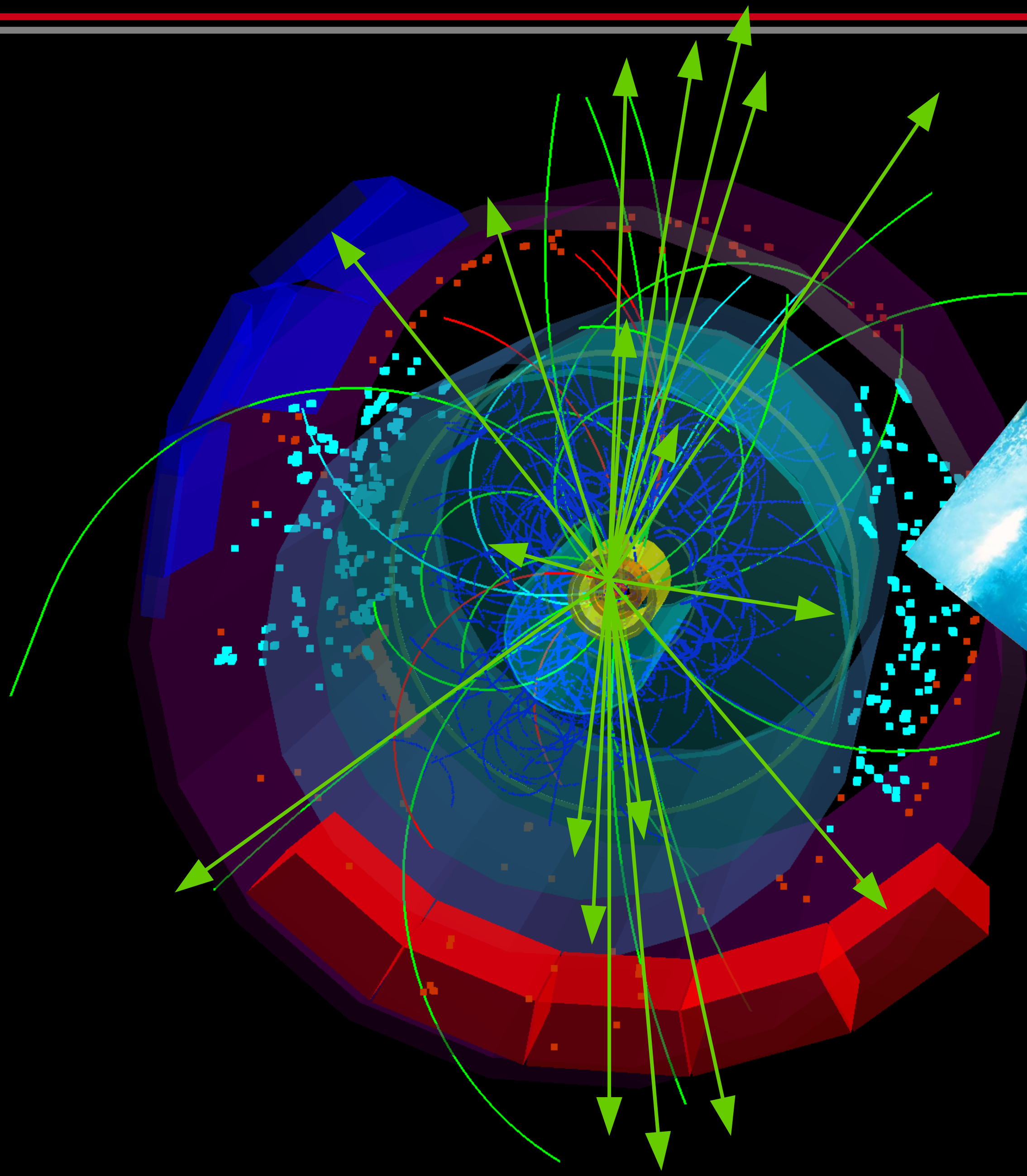
# Two-particle ΔηΔφ angular correlations

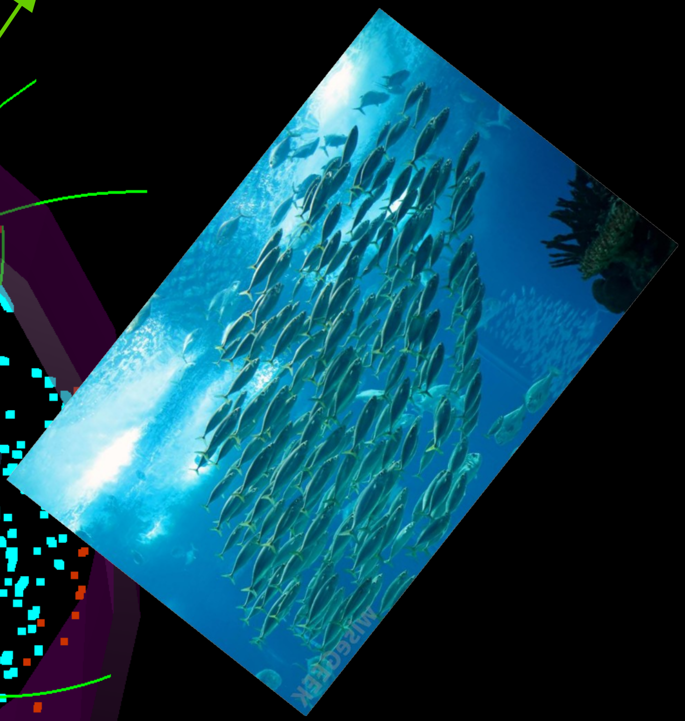


# Two-particle ΔηΔφ angular correlations

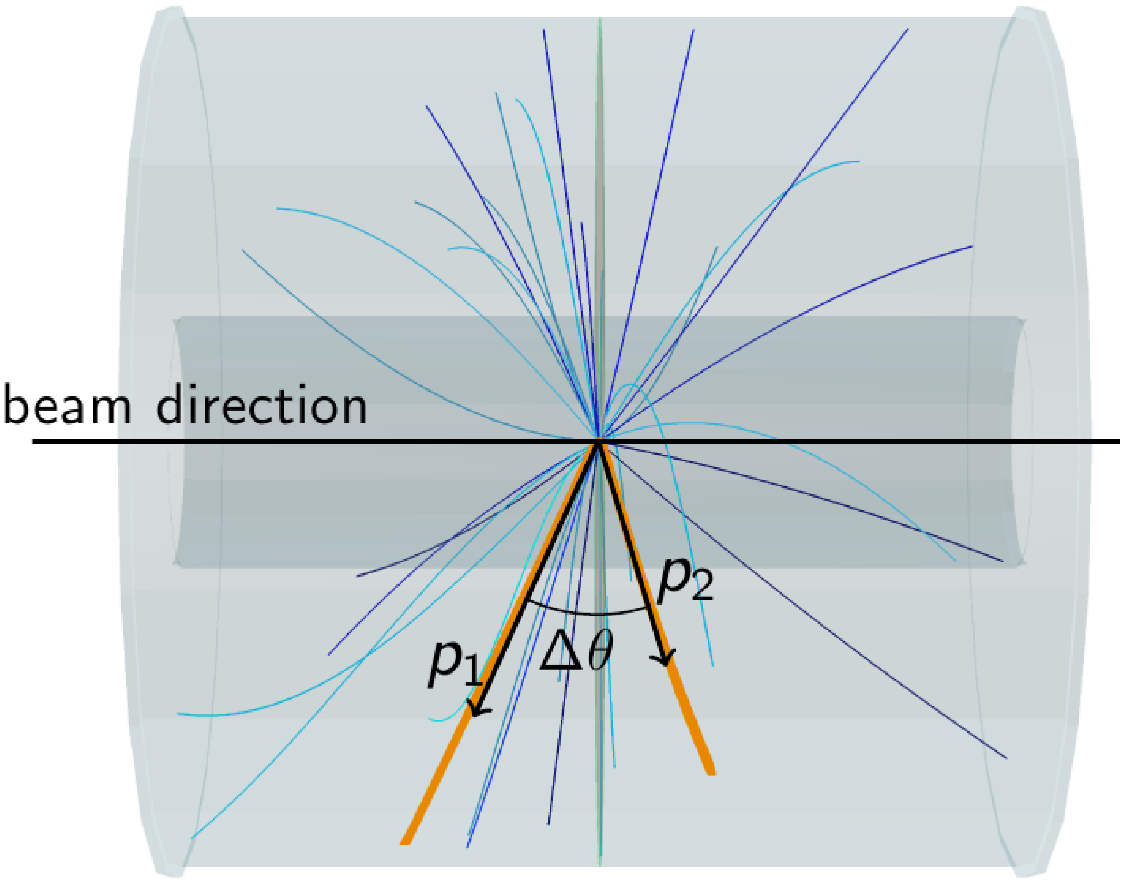


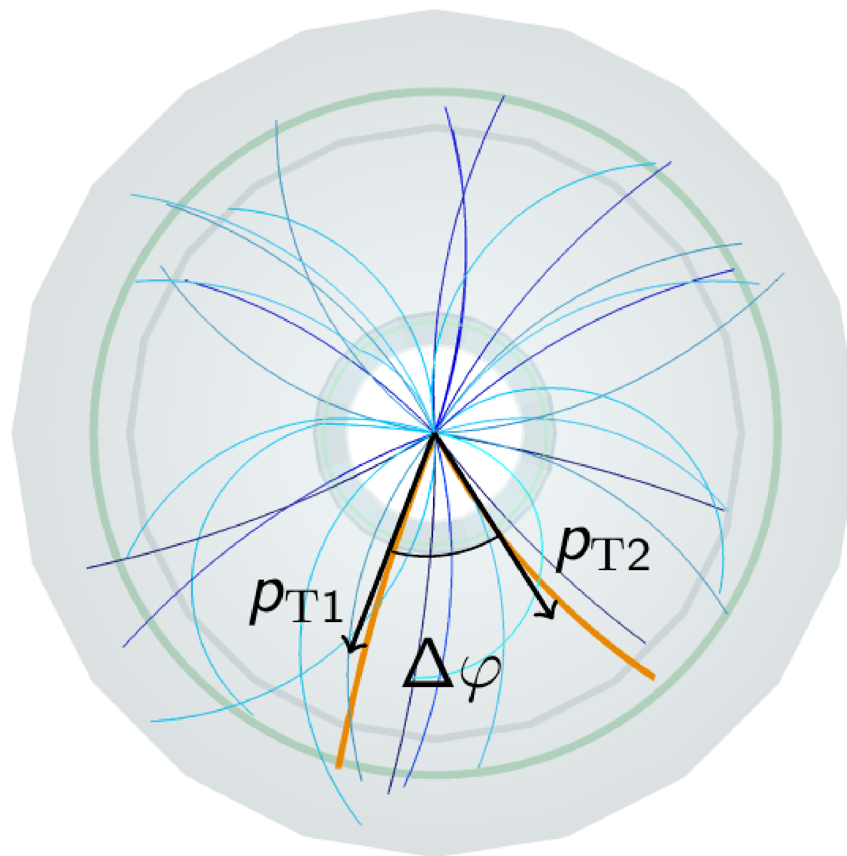
# Two-particle ΔηΔφ angular correlations





# Two-particle ΔηΔφ angular correlations




$p$ - particle momentum;

$\theta$ - polar angle;

$\eta$ - pseudorapidity:

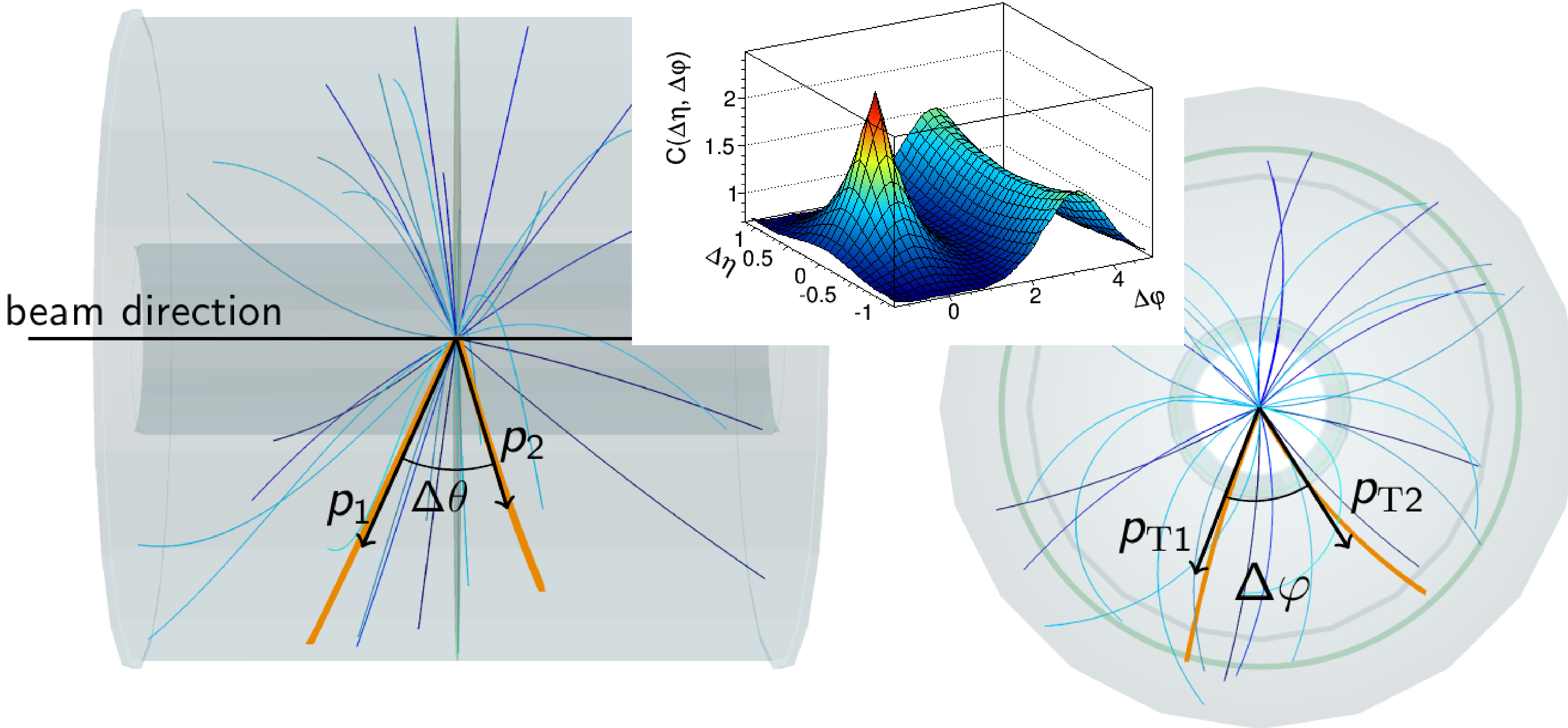
$$\eta = -\ln\left(tg\,\frac{\theta}{2}\right)$$

$p_T$ - transverse momentum;

$\varphi$ - azimuthal angle;

Fig. A. Zaborowska

# Two-particle ΔηΔφ angular correlations

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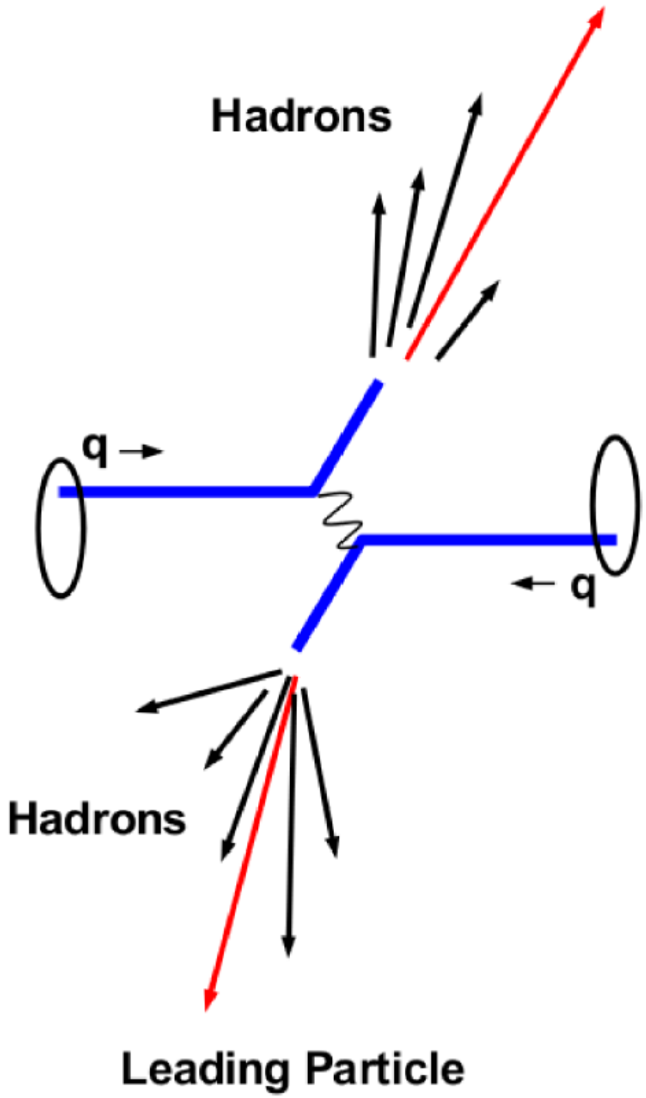
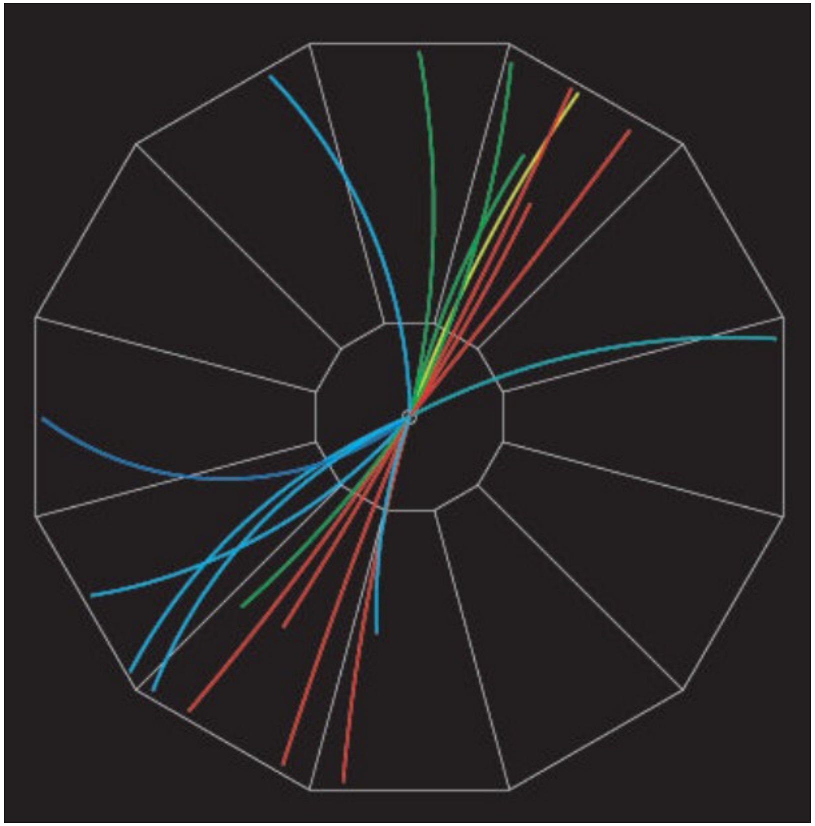
$\varphi$ - azimuthal angle;

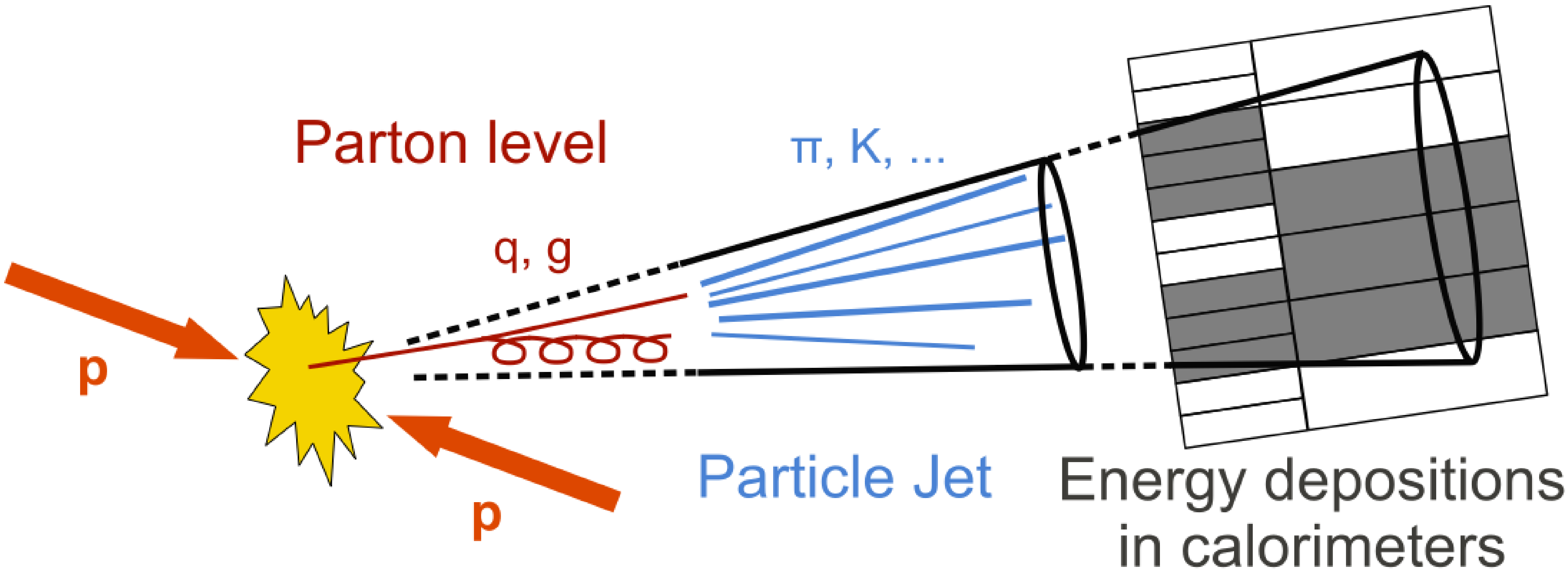
Fig. A. Zaborowska

# Production of jets



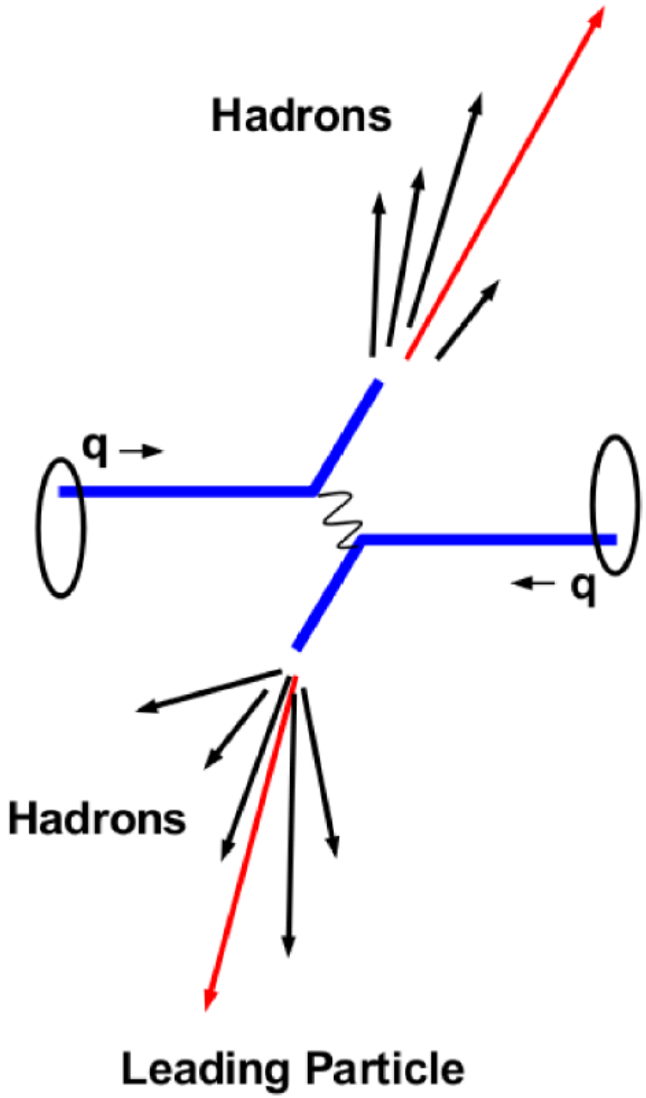



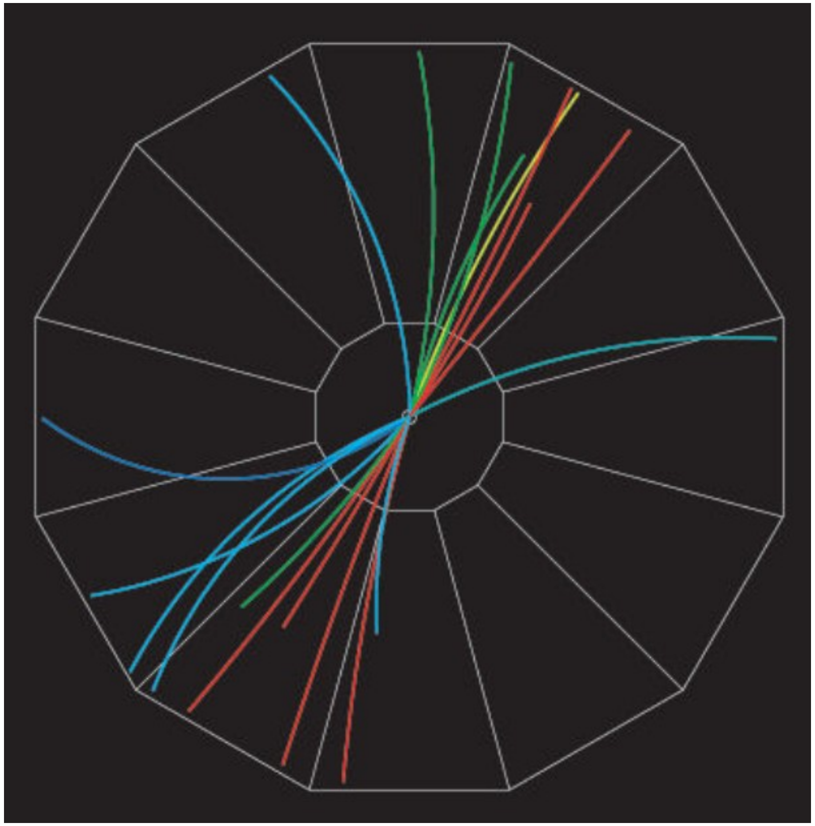
# Jets – collimated spray of hadrons



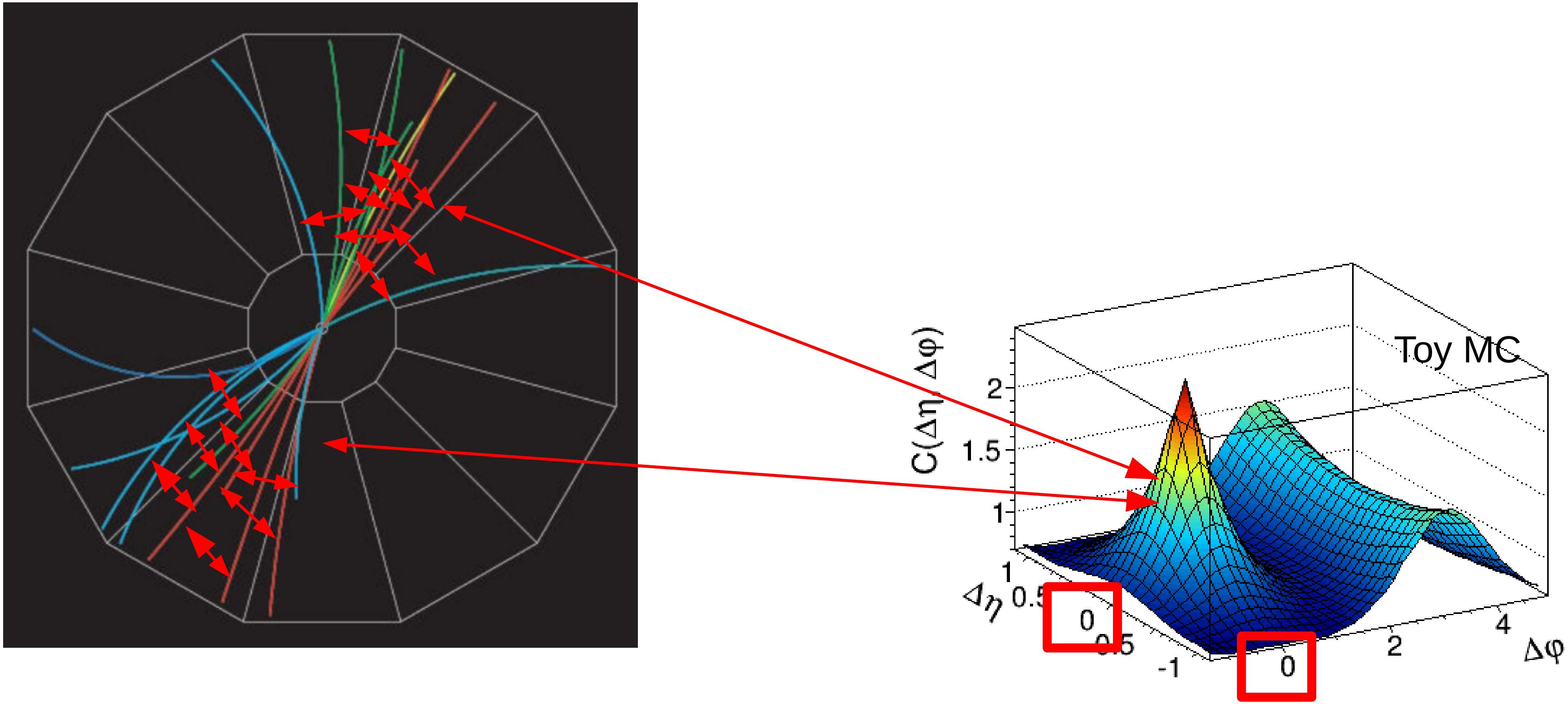

- experimental signatures of quarks and gluons produced in high-energy processes
- quarks and gluons cannot exist freely due to color-confinement
- instead, they come together to form colour-neutral hadrons, in a process that leads to production of **collimated spray of hadrons** called **a jet.**

# Production of jets



# How does it work?

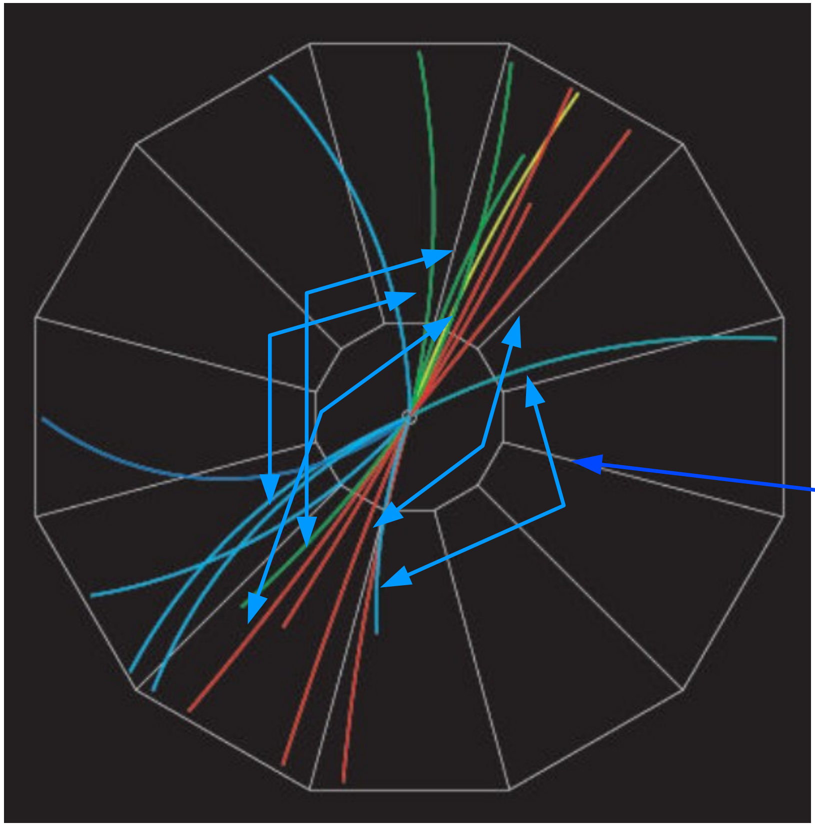


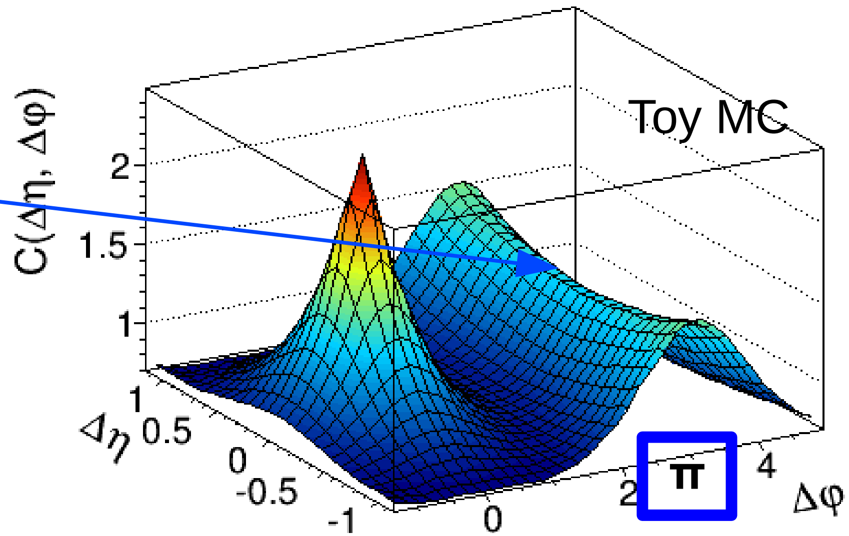

*Near-side peak*

For particles from the same jet (red):

**- centered at Δφ = Δη = 0**

# How does it work?



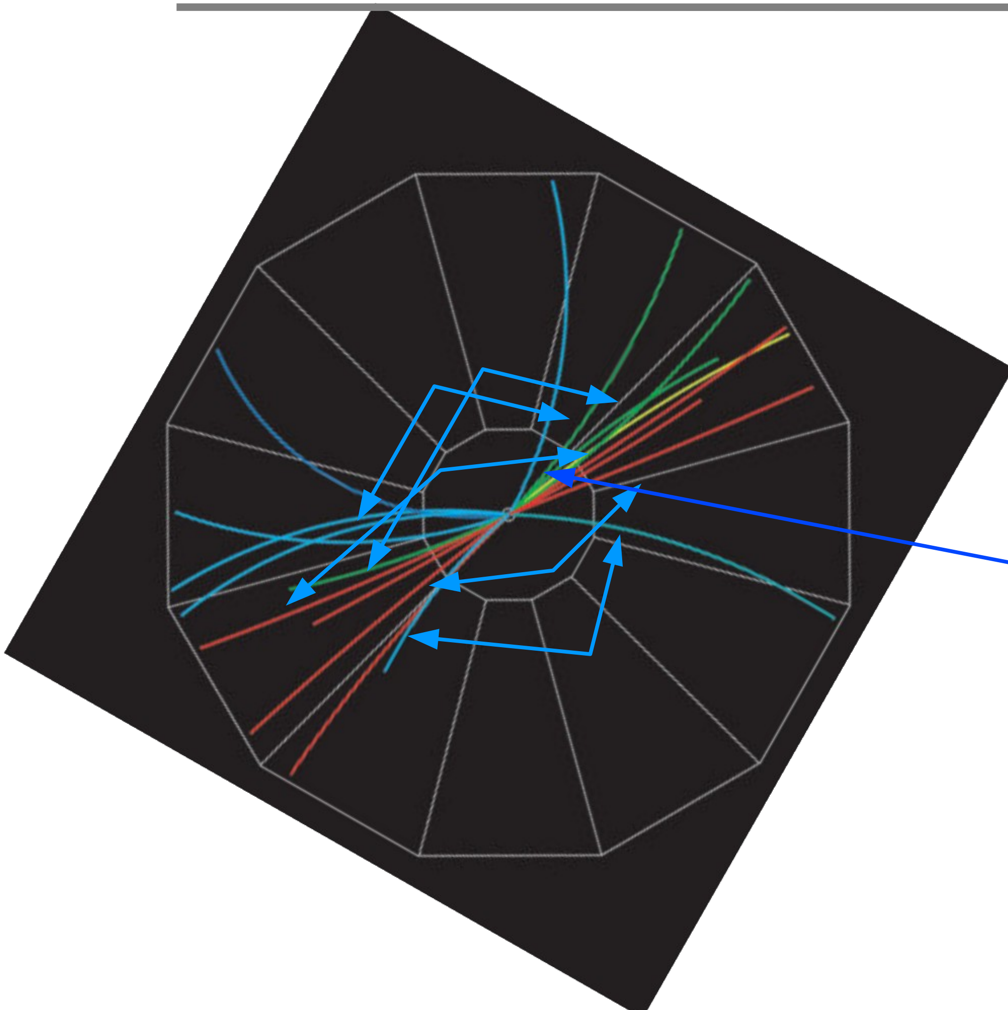


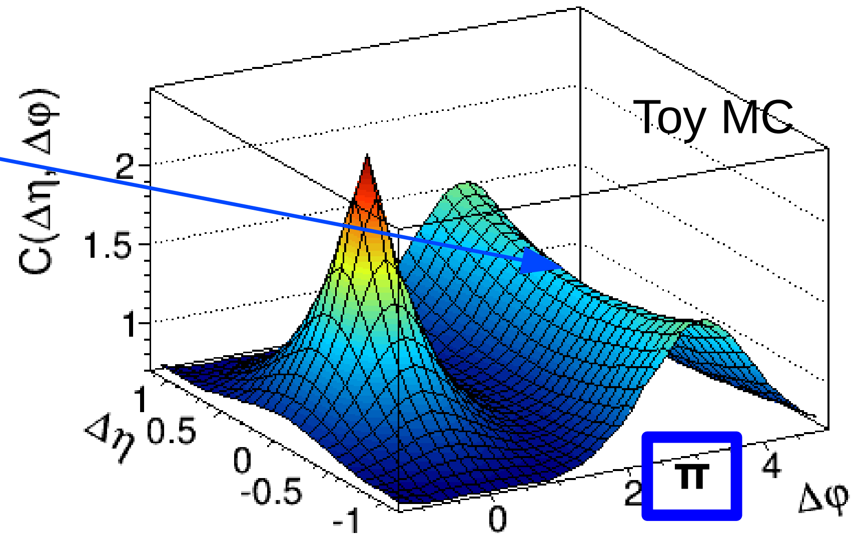

For particles from from back-to-back jets (blue): *Away-side ridge*

## - centered at $\Delta\varphi = \pi$

- **dN/Δη ~ const, if averaged over many events**

# How does it work?

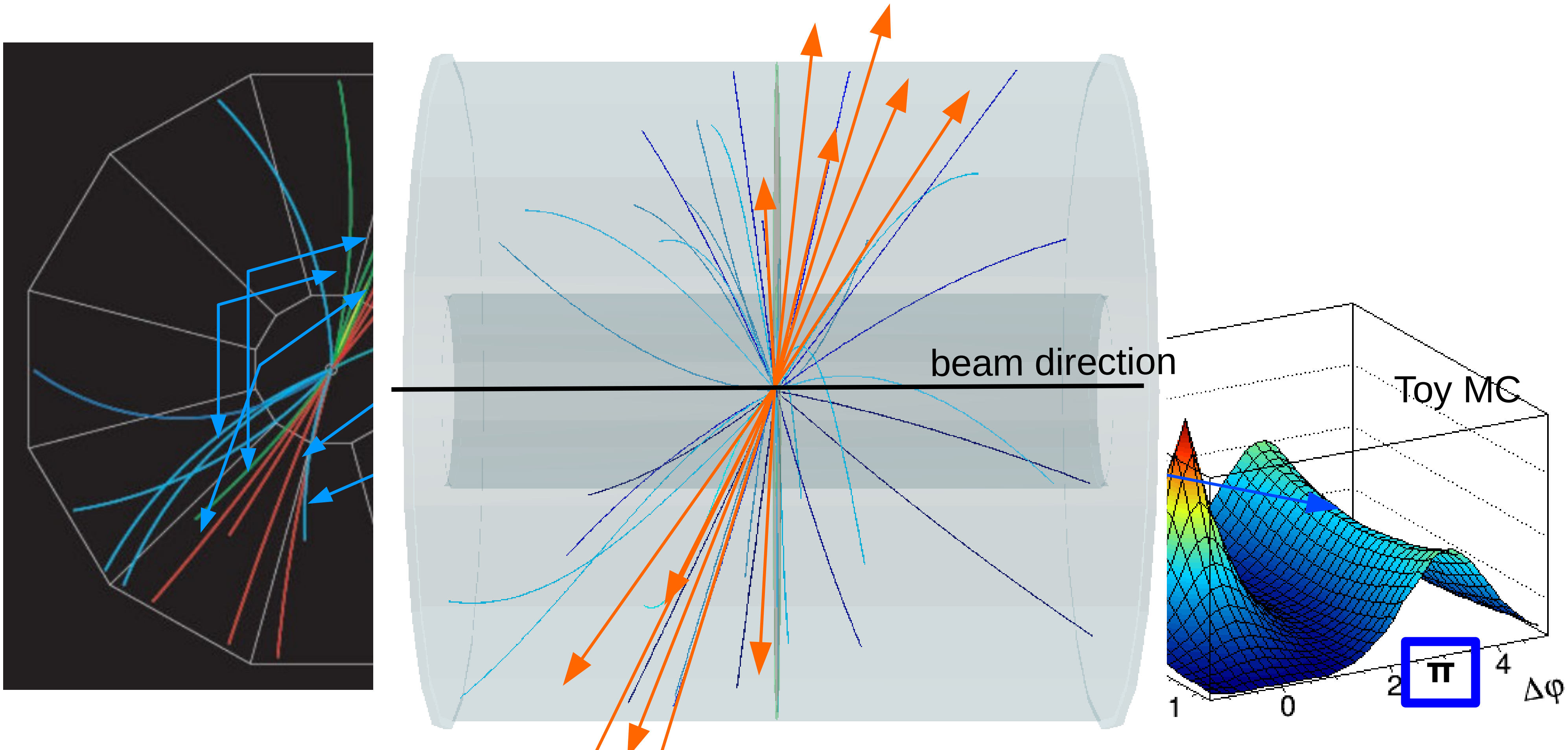





For particles from from back-to-back jets (blue):

- **centered at Δφ = π**
- **dN/Δη ~ const, if averaged over many events**

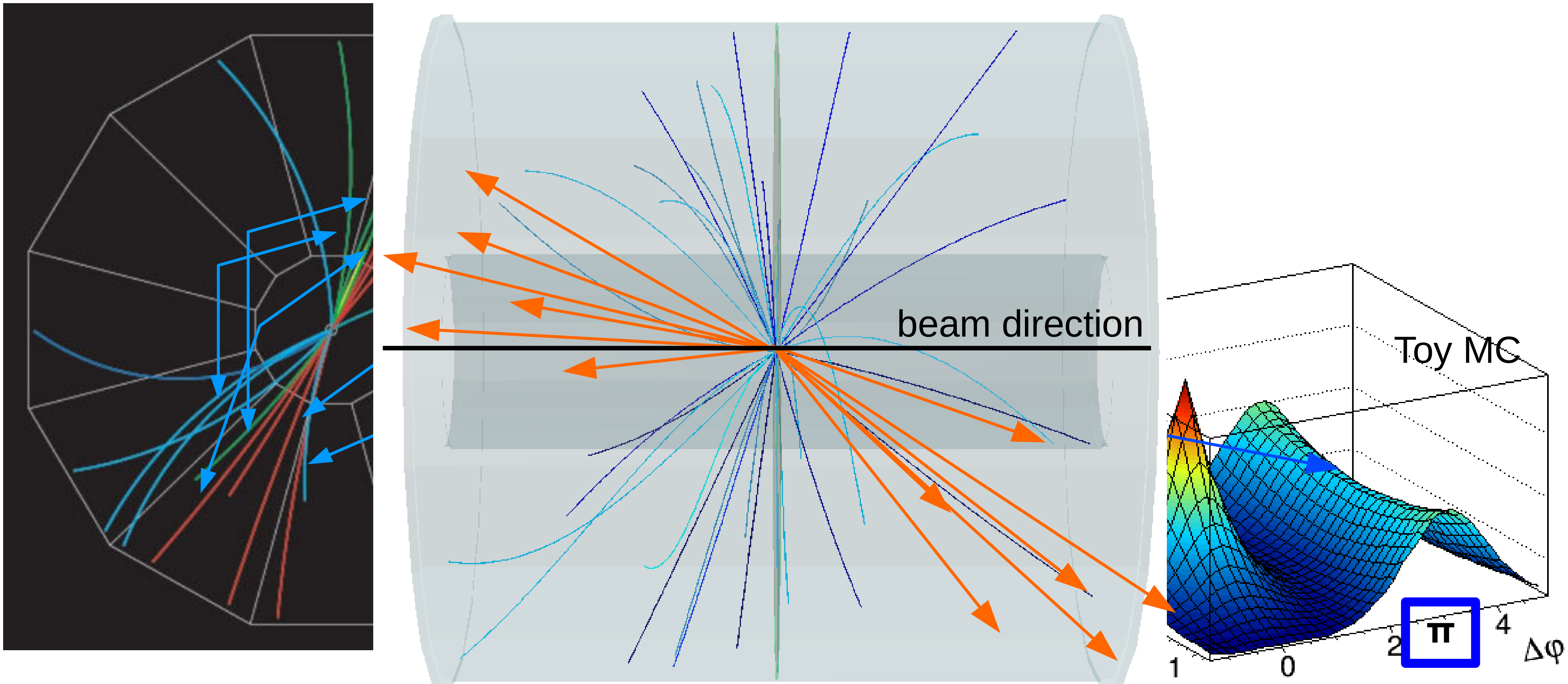
# How does it work?




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

- **centered at Δφ = π**
- **dN/Δη ~ const, if averaged over many events**

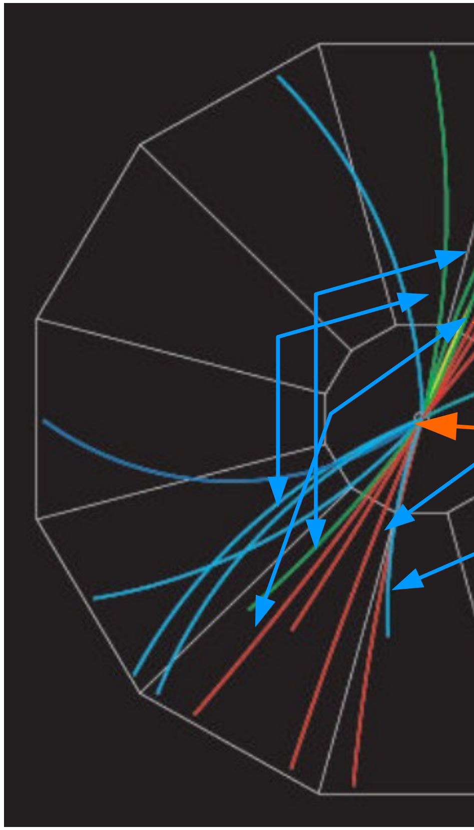
# How does it work?

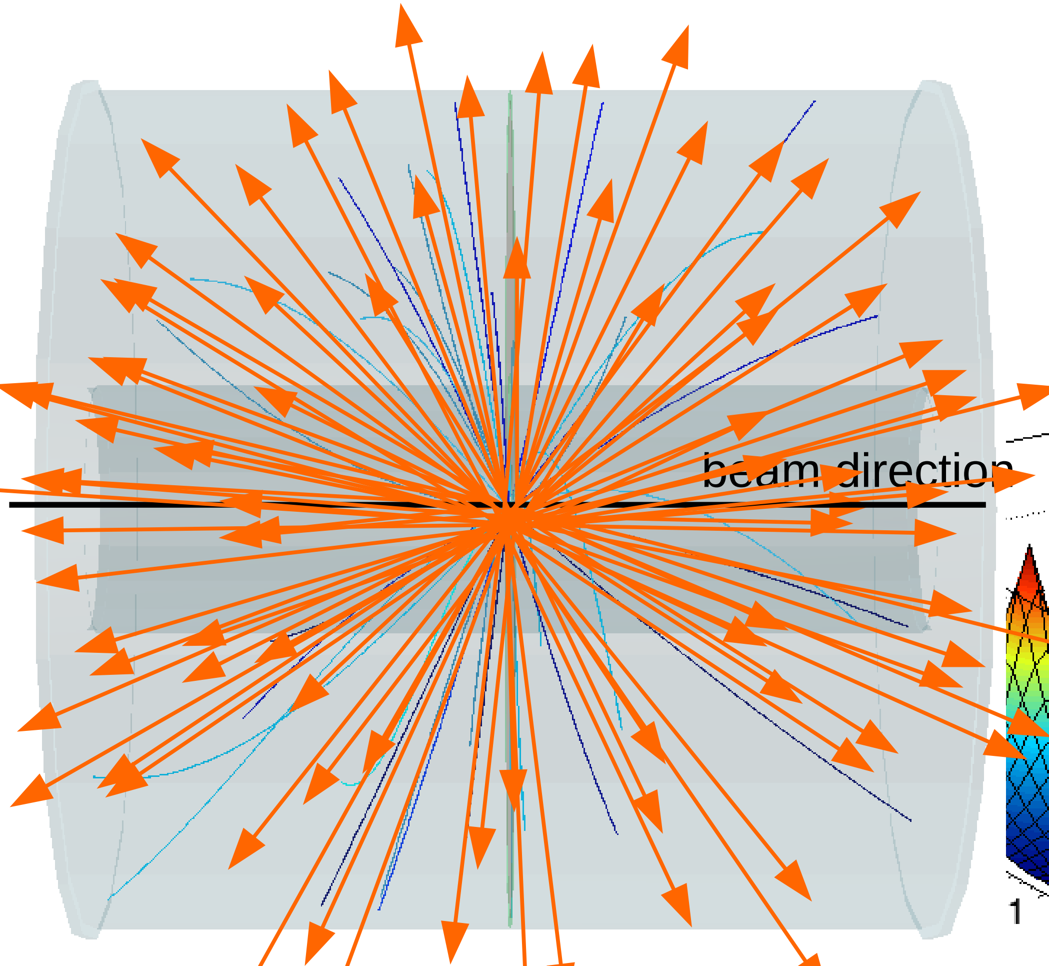


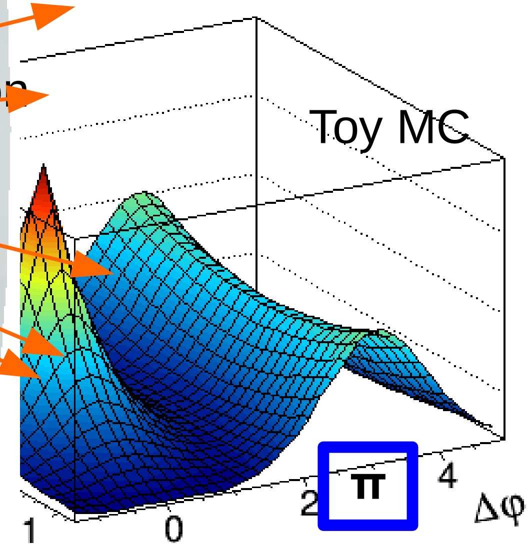

For particles from  from back-to-back jets (blue):

- **centered at Δφ = π**
- **dN/Δη ~ const, if averaged over many events**

# How does it work?

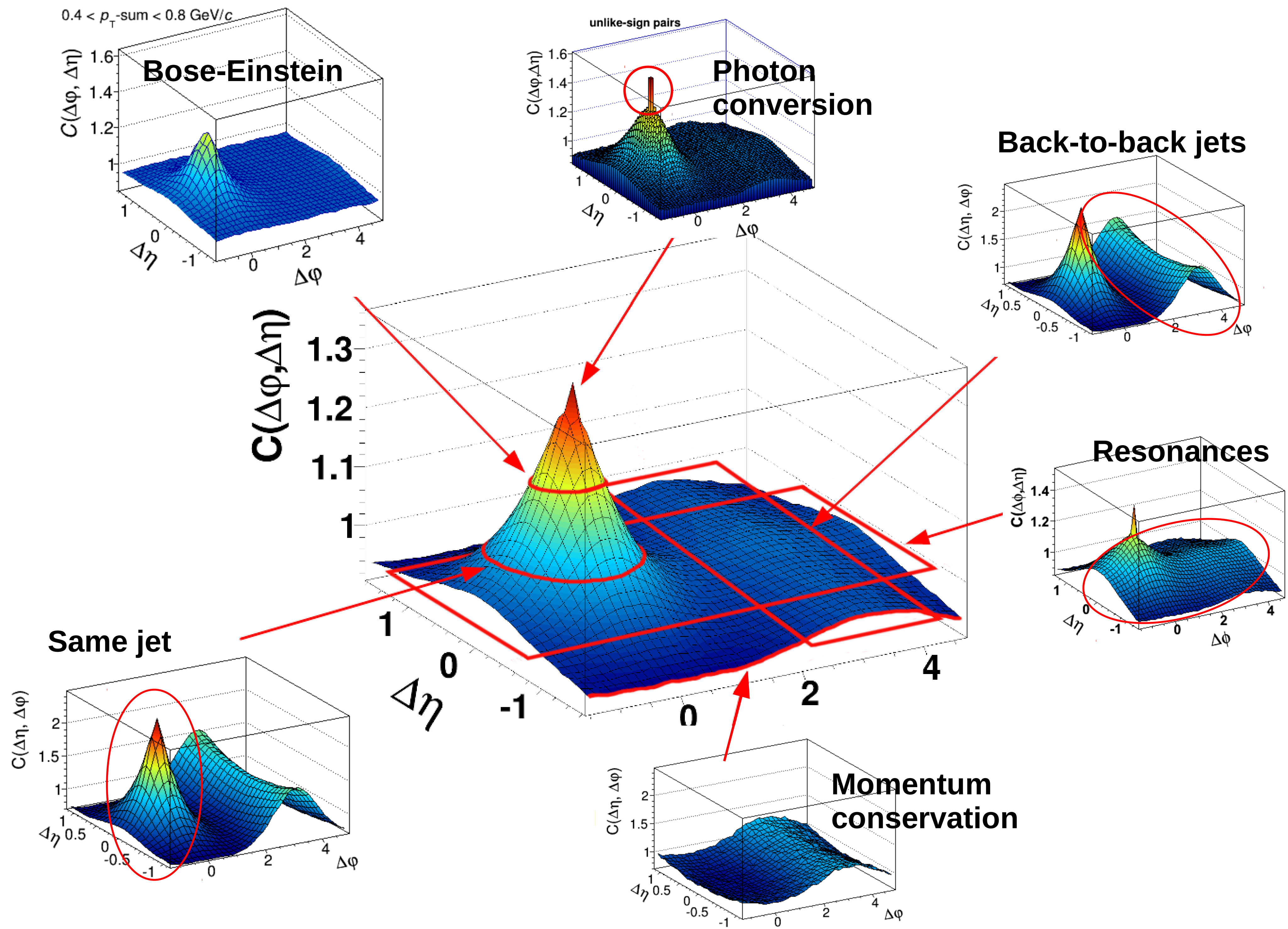




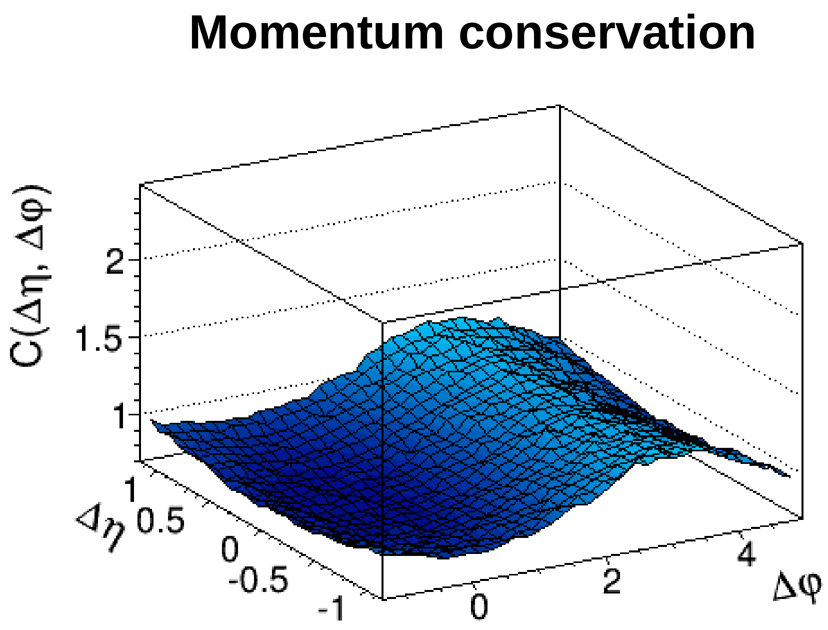




For particles from  from back-to-back jets (blue):

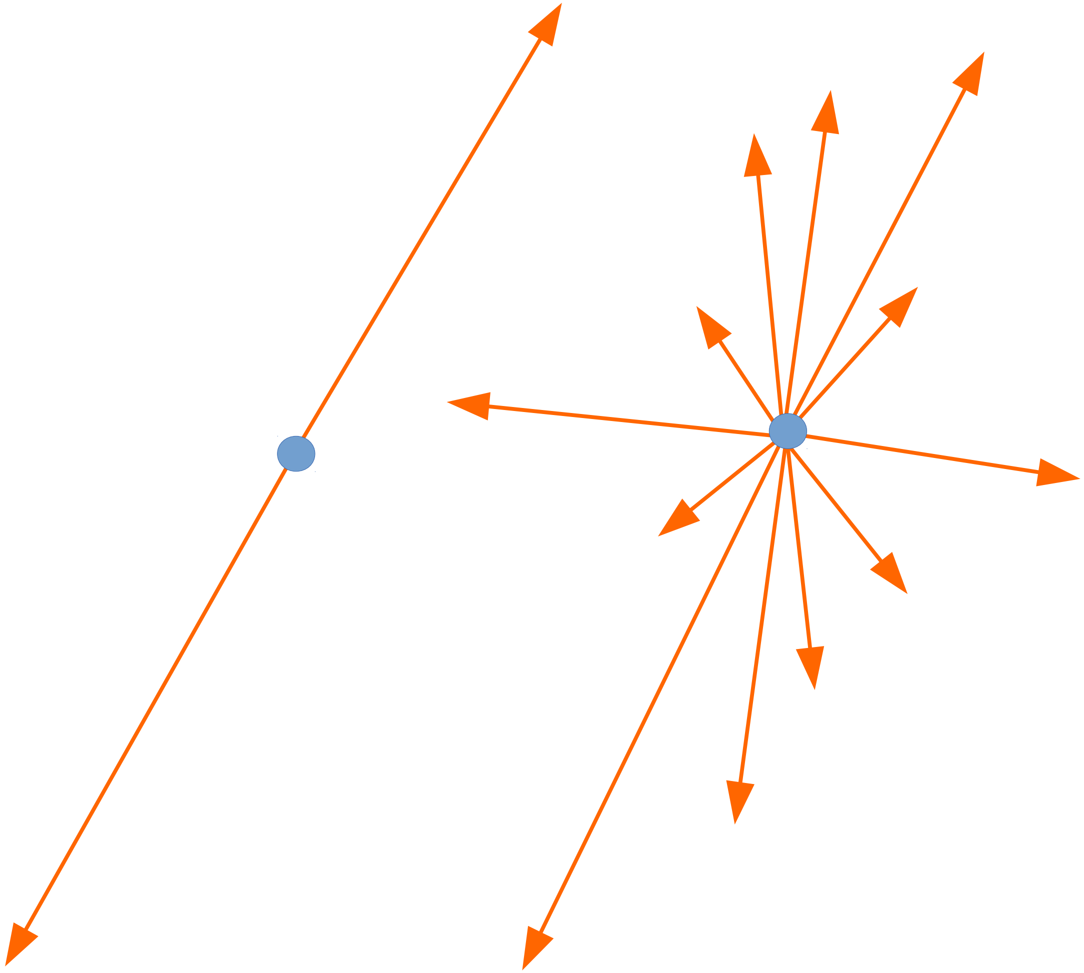
- **centered at $\Delta\varphi = \pi$**
- **dN/$\Delta\eta$ ~ const, if averaged over many events**


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

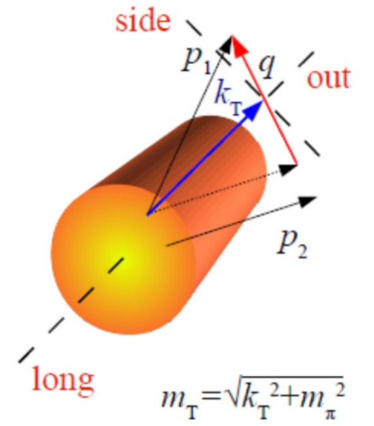
# Momentum Conservation



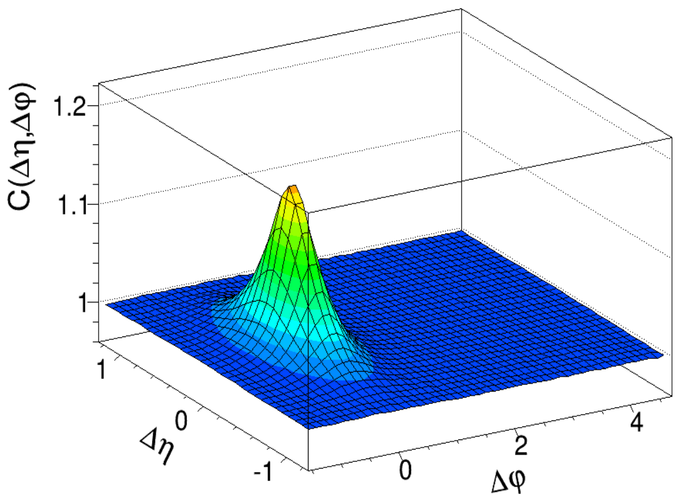

Events with angular
momentum conserved only



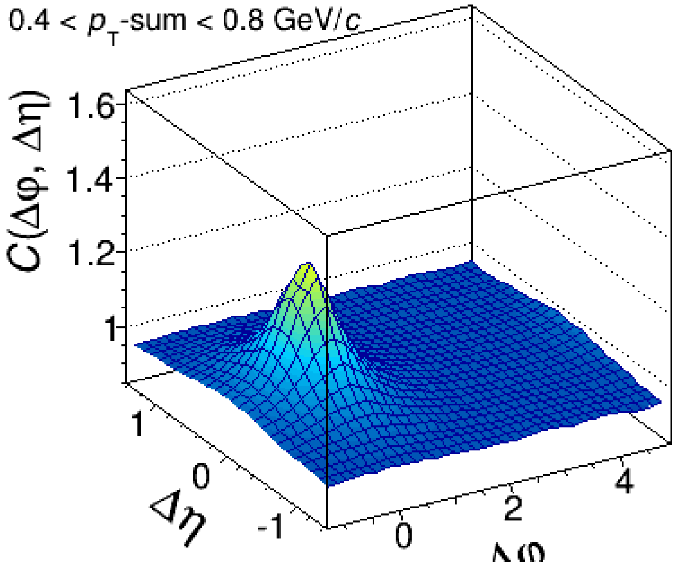
# Bose-Einstein Correlations




**Bose-Einstein Correlations**

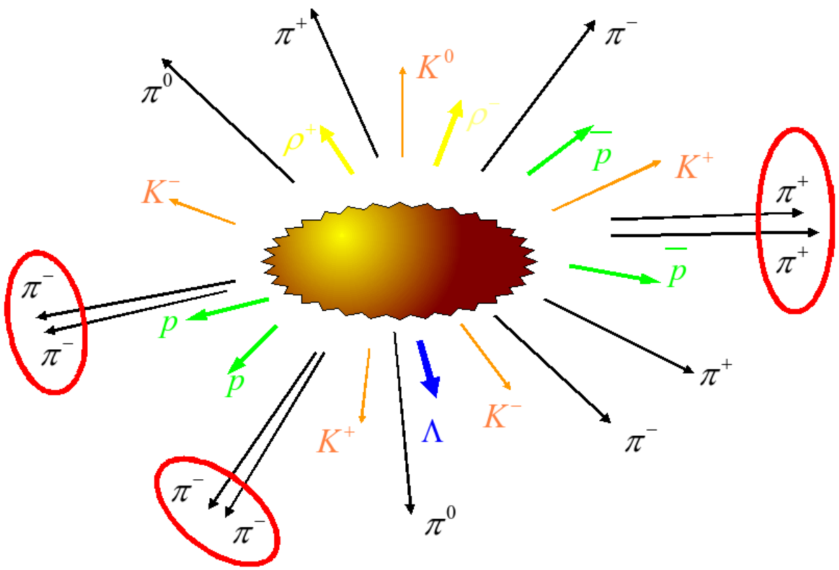



EPOS p-Pb

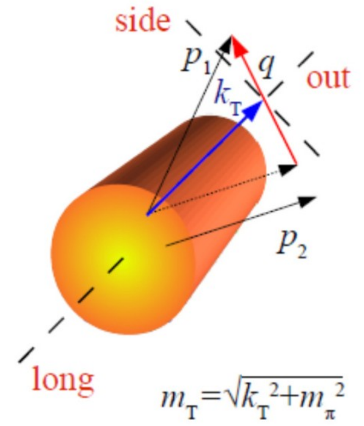



ALICE

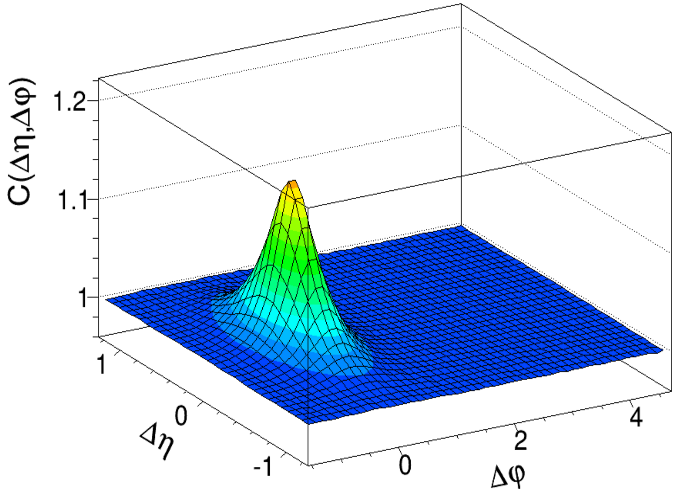
Bose–Einstein Correlations of identical-pion pairs result in an enhancement at low relative momentum.



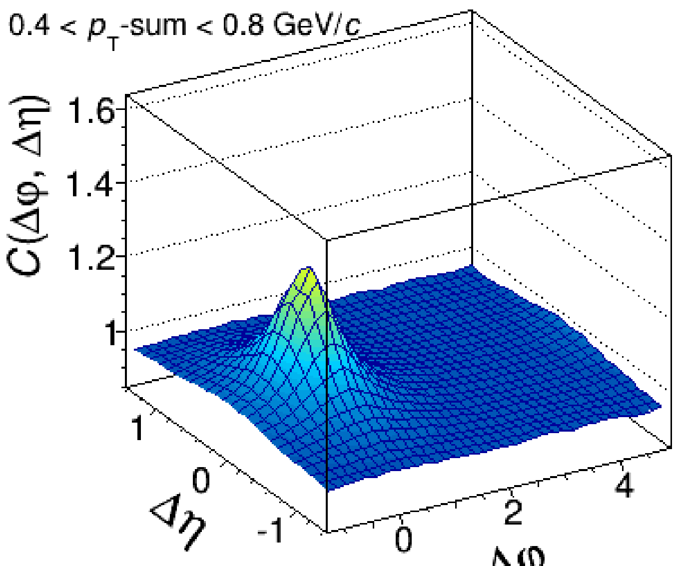
# Photon conversion




## Bose-Einstein Correlations



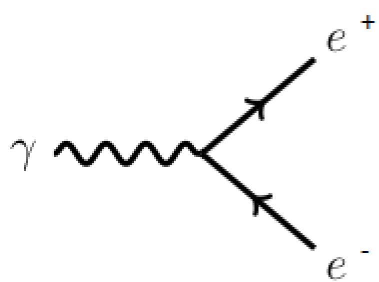

EPOS p-Pb

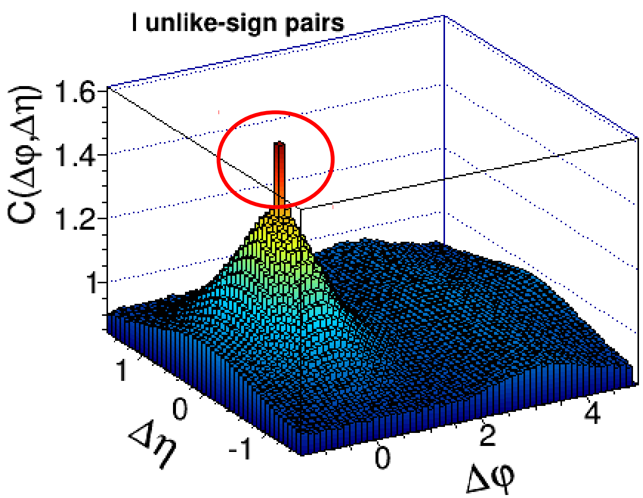


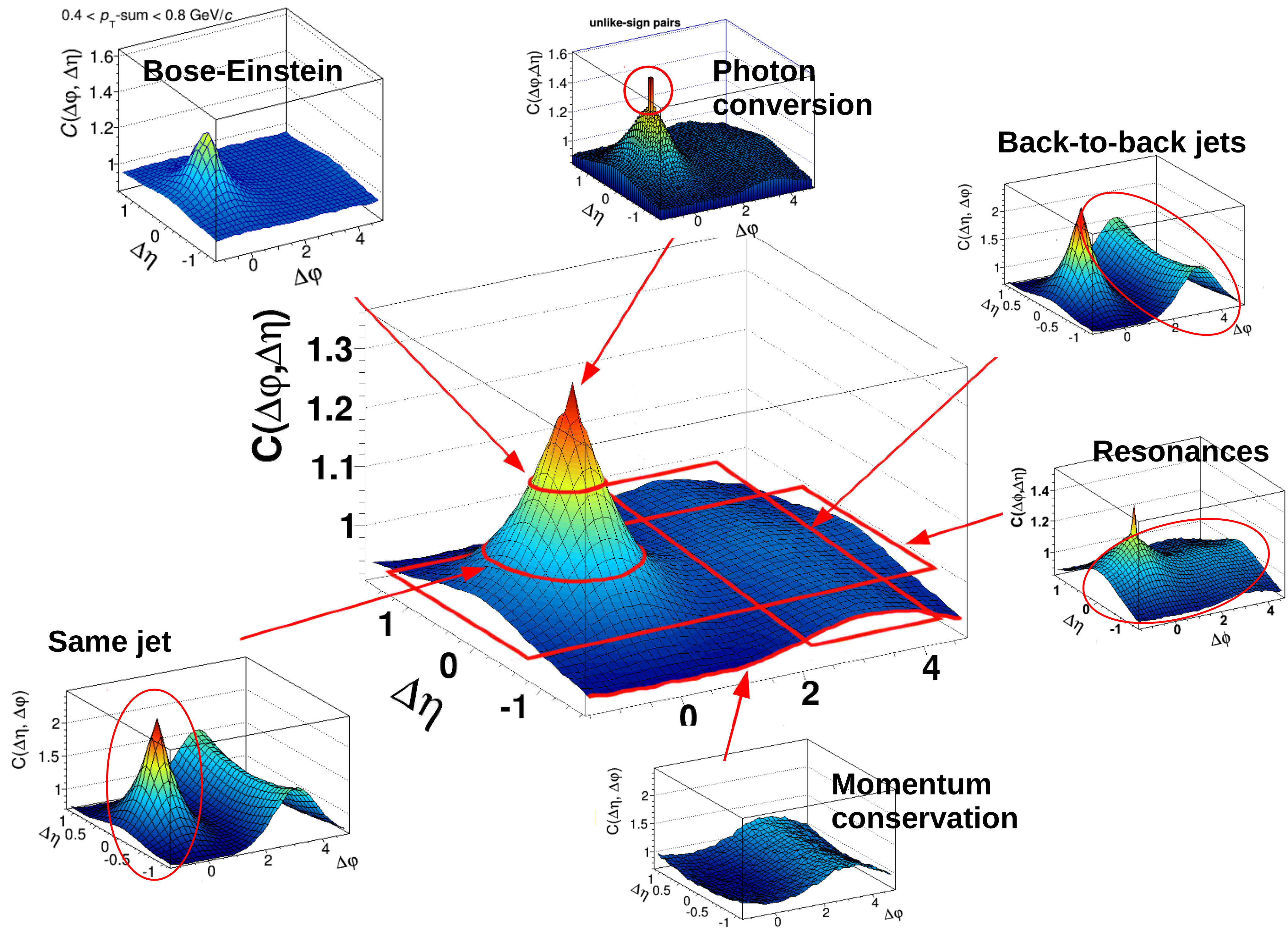

ALICE

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

## Photon conversion



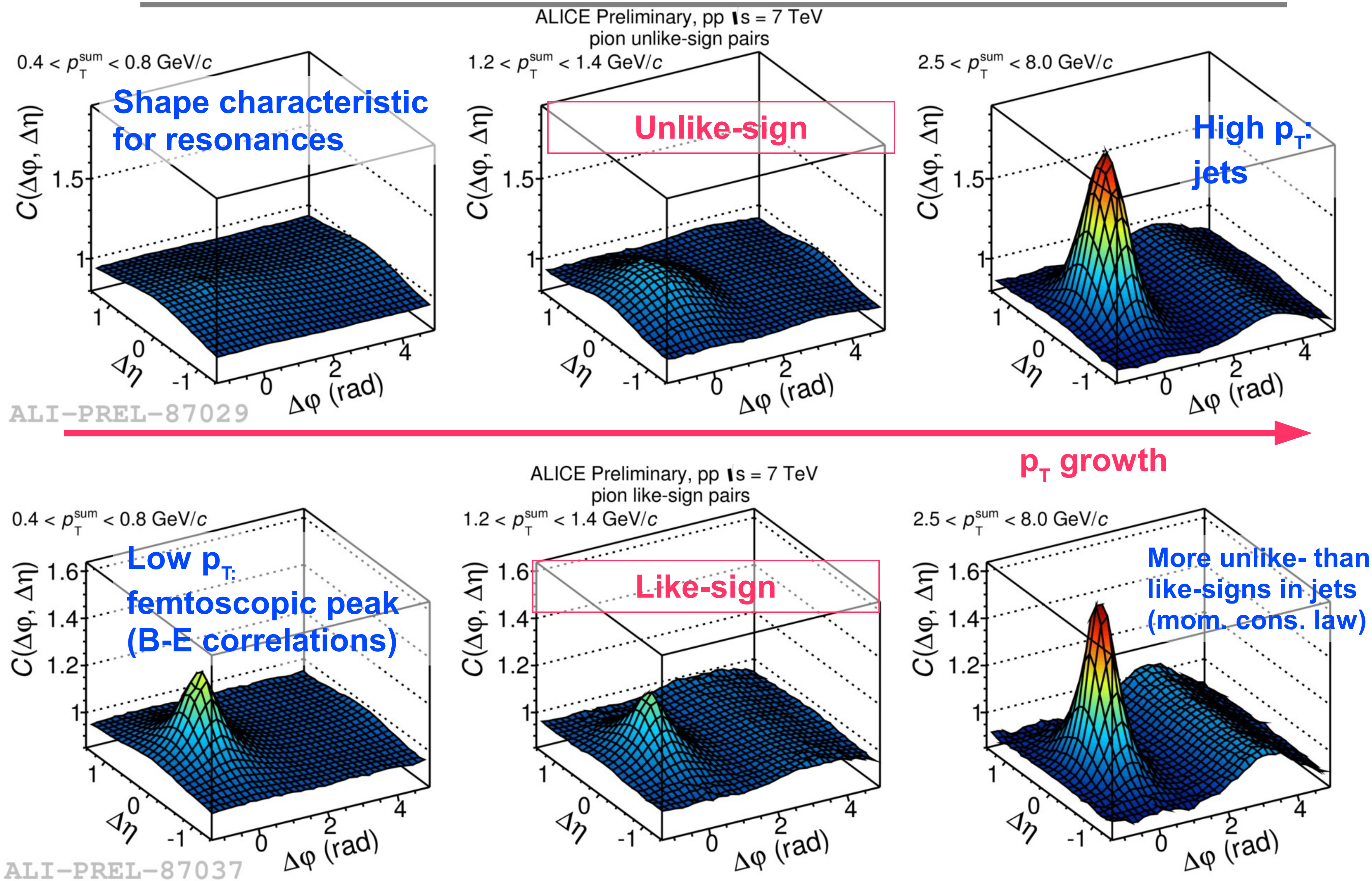



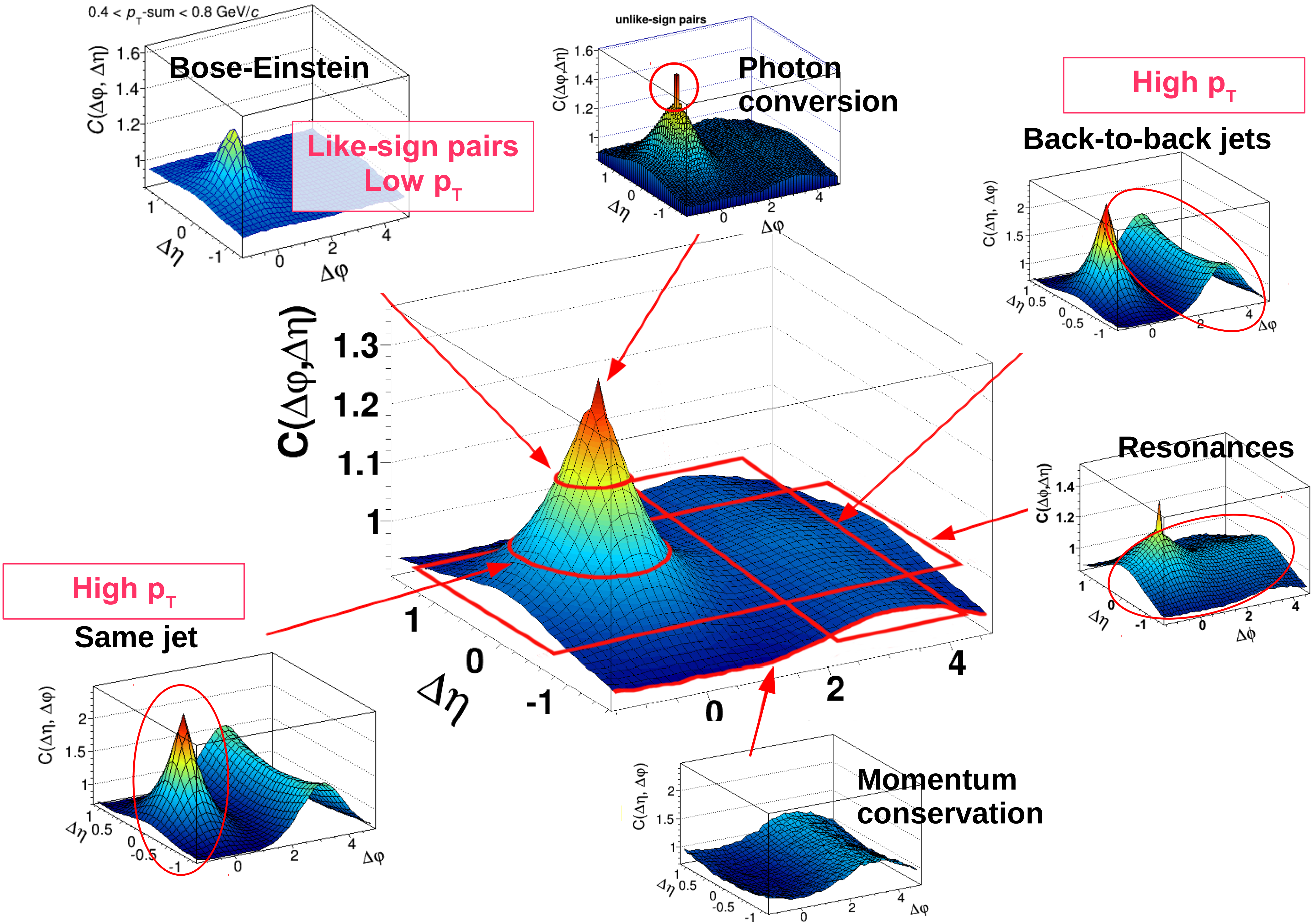


Bose-Einstein
0.4 < $p_T$-sum < 0.8 GeV/$c$
Photon conversion
unlike-sign pairs
Back-to-back jets
Resonances
Same jet
Momentum conservation
C(Δφ,Δη)
Δη
Δφ

# Pions

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

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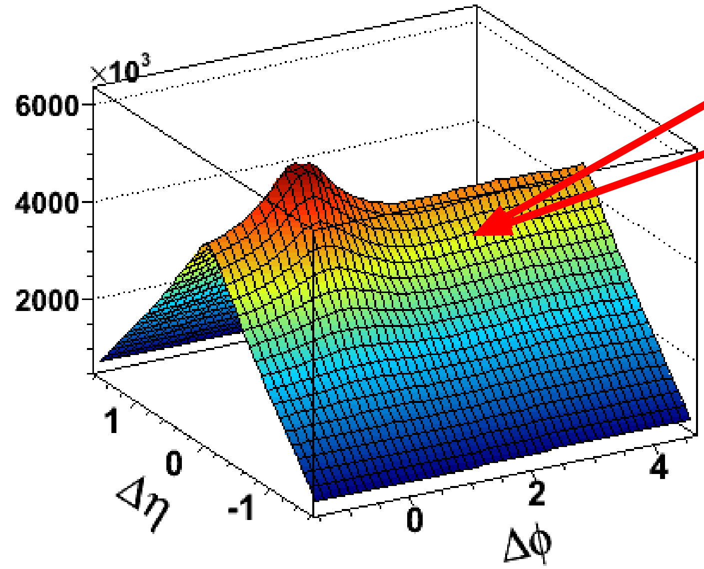
C(Δφ,Δη)
Δη
Δφ

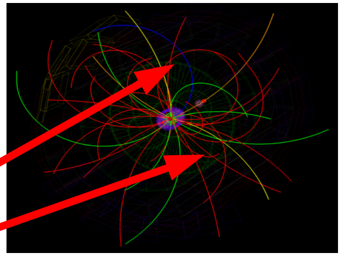
# ΔηΔφ Experimental Correlation Function

Signal distribution

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




Event 1



**Same event pairs**

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

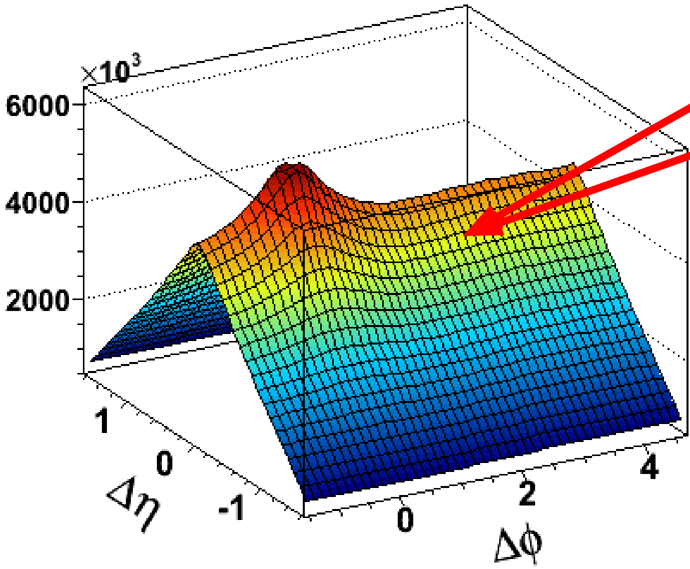
# ΔηΔφ Experimental Correlation Function

## Signal distribution

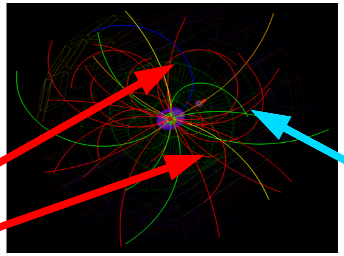
$$S(\Delta\eta,\Delta\varphi)=\frac{d^2 N^{signal}}{d\Delta\eta\Delta\varphi}$$

## Uncorrelated reference

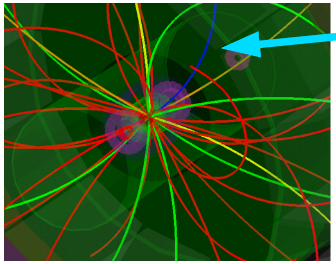
$$B(\Delta\eta,\Delta\varphi)=\frac{d^2 N^{mixed}}{d\Delta\eta\Delta\varphi}$$

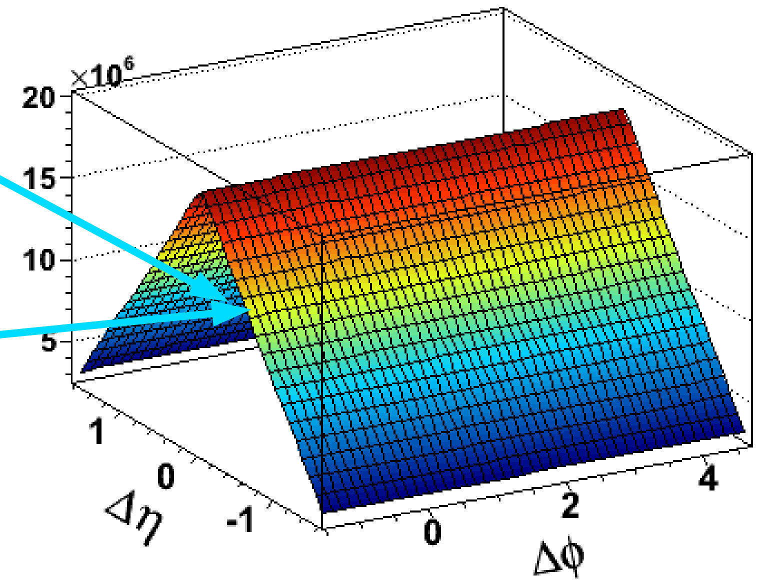



Event 1



Event 2






**Same event pairs**

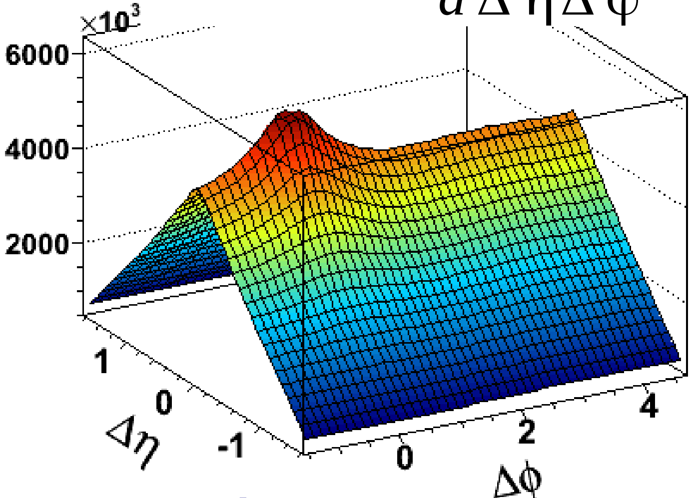
**Mixed event pairs**

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

# ΔηΔφ Experimental Correlation Function

## Signal distribution

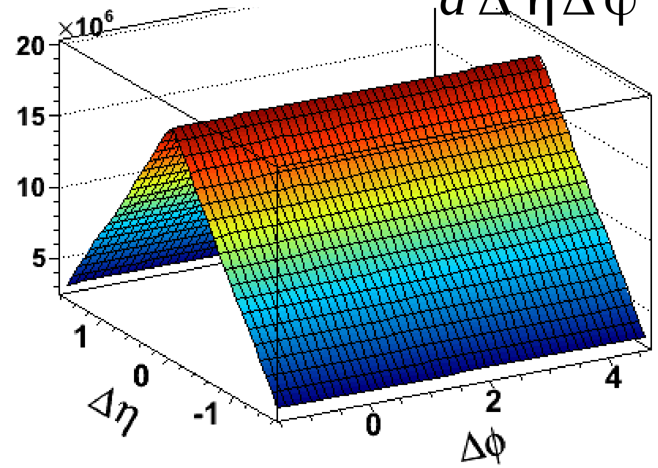
$$S(\Delta\eta,\Delta\varphi)=\frac{d^2N^{signal}}{d\Delta\eta\Delta\varphi}$$




**Same event pairs**

## Uncorrelated reference

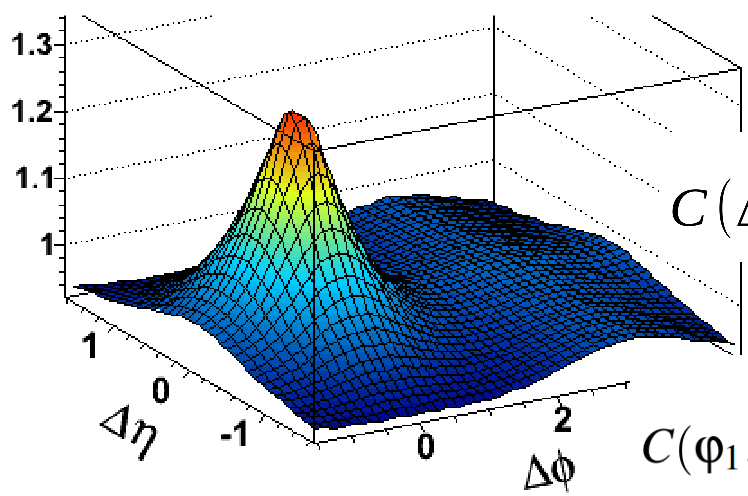
$$B(\Delta\eta,\Delta\varphi)=\frac{d^2N^{mixed}}{d\Delta\eta\Delta\varphi}$$




**Mixed event pairs**

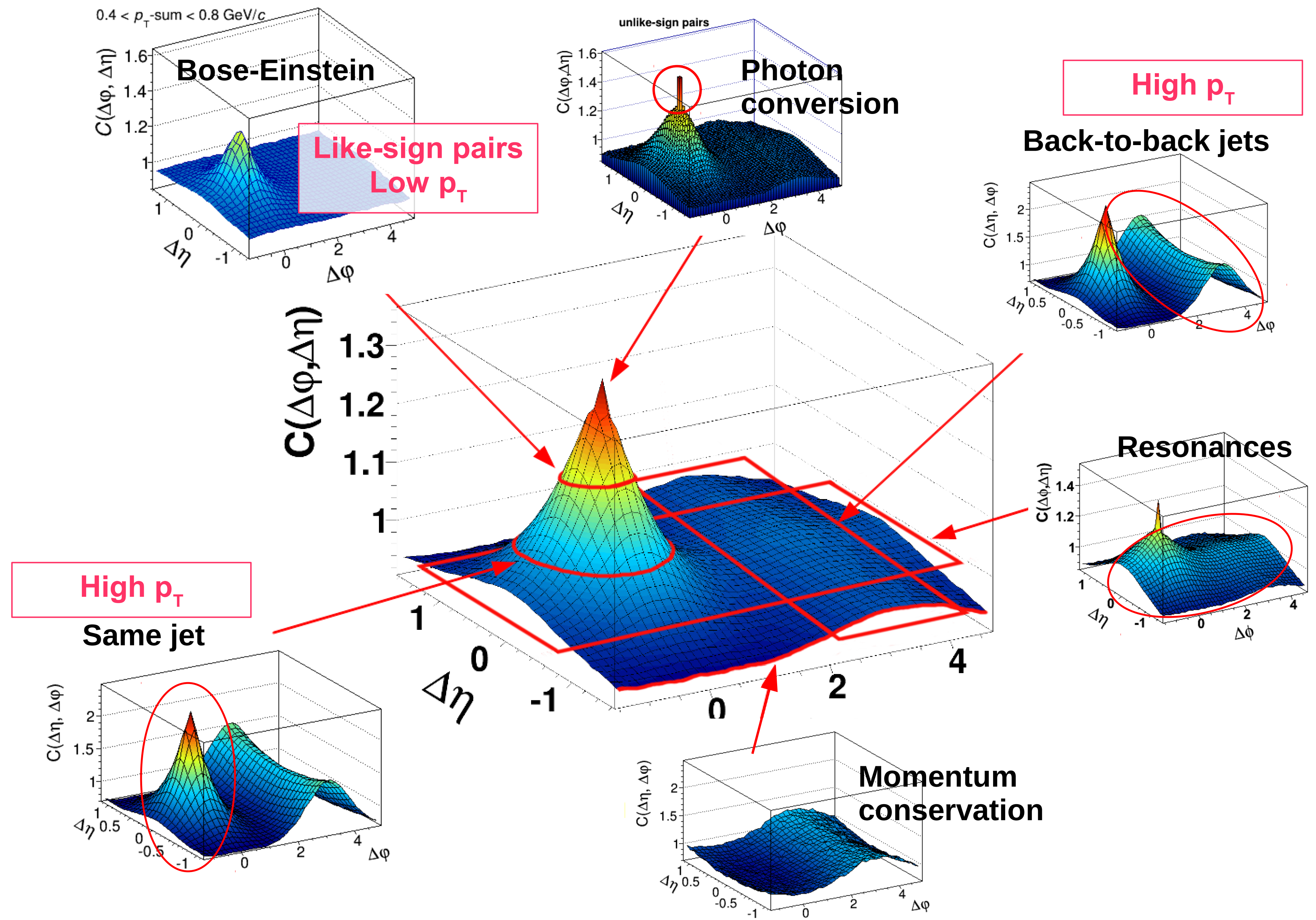
## Correlation function

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




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

$$C(\varphi_1,\eta_1,\varphi_2,\eta_2)=\frac{P_{12}(\varphi_1,\eta_1,\varphi_2,\eta_2)}{P_1(\varphi_1,\eta_1)P_2(\varphi_2,\eta_2)}$$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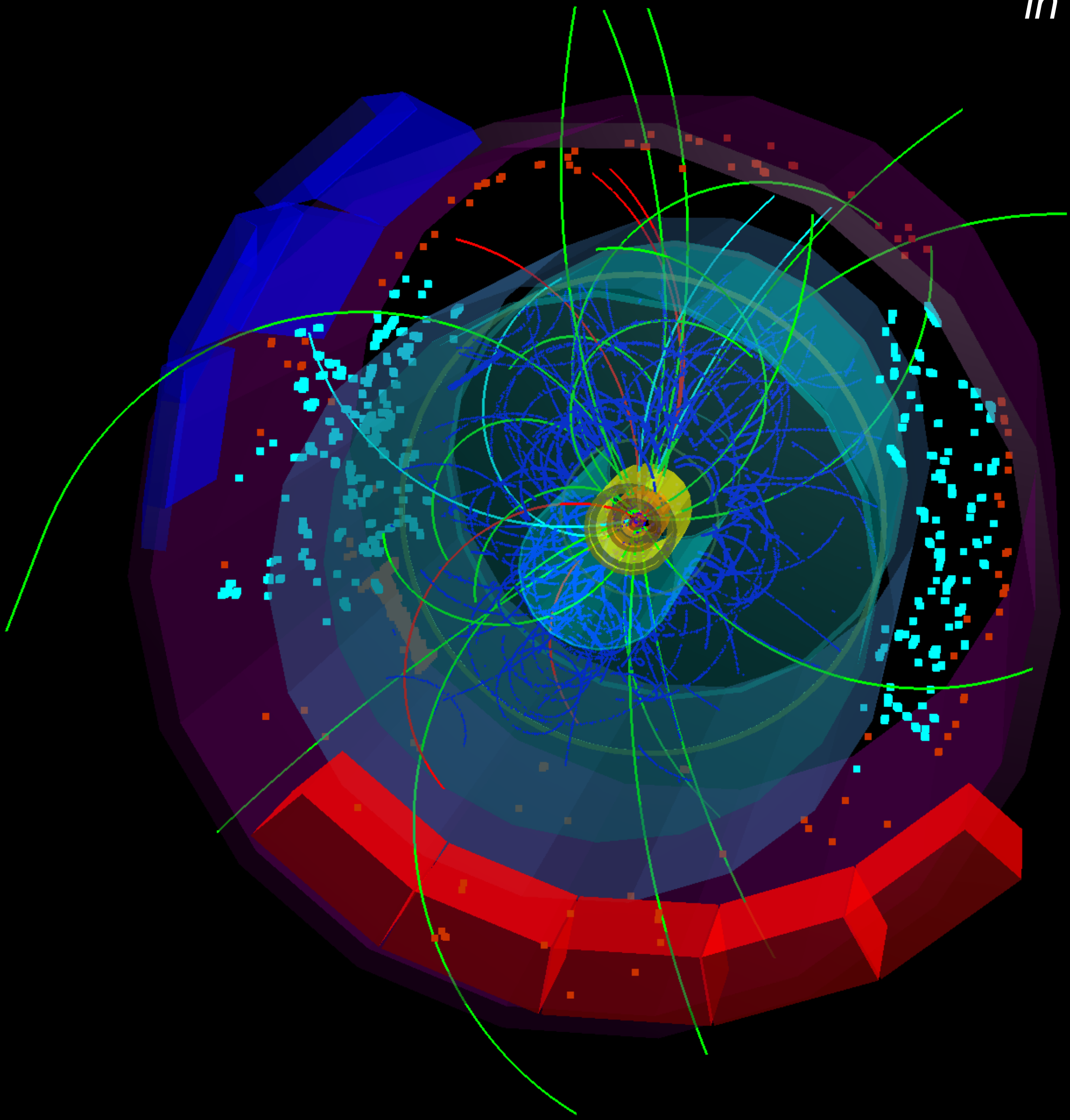
Momentum conservation
$C(\Delta\varphi,\Delta\eta)$
$\Delta\eta$
$\Delta\varphi$

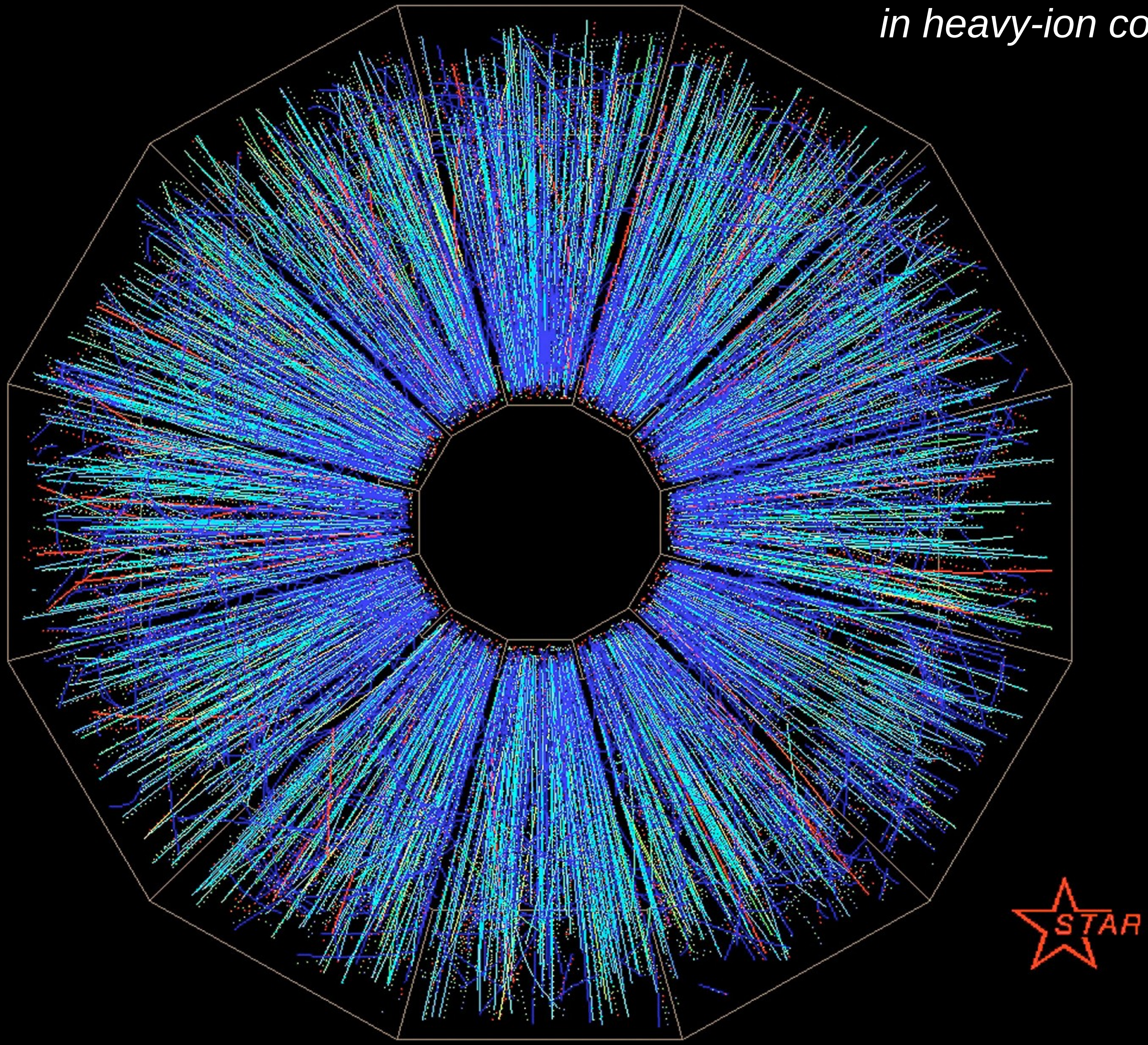
# ΔηΔφ angular correlations

*in pp collisions*



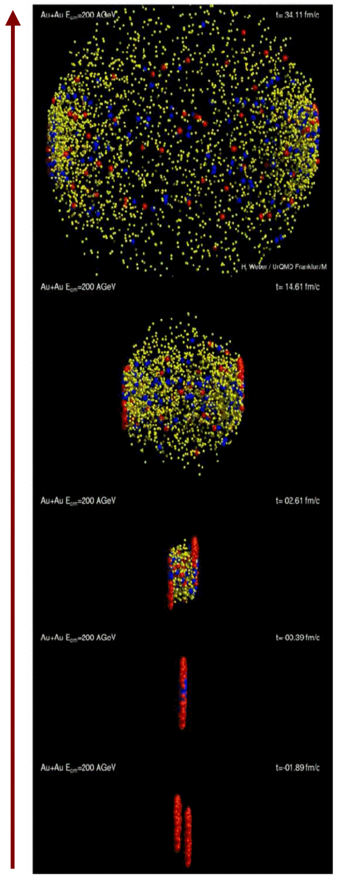
# ΔηΔφ angular correlations

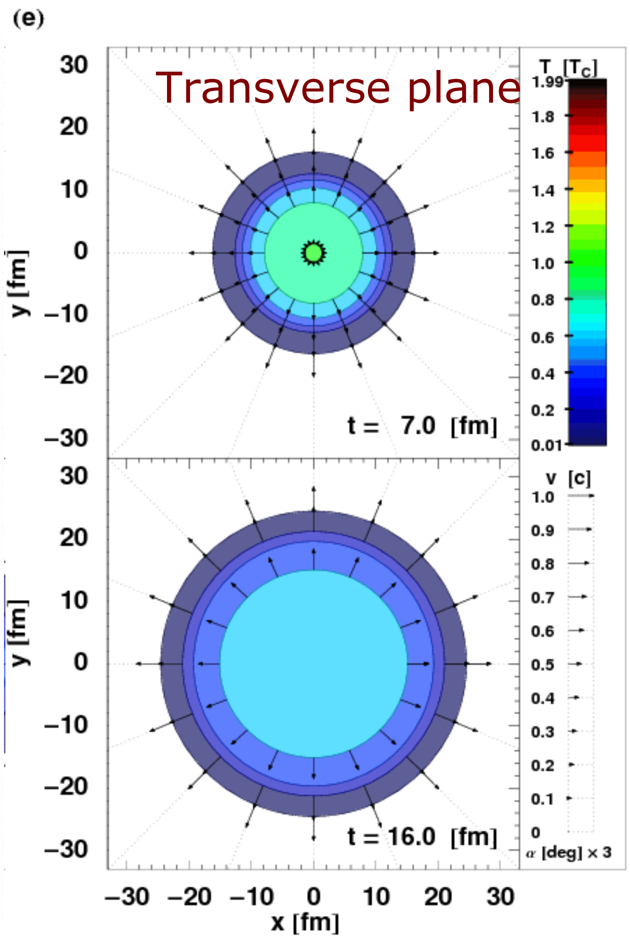
*in heavy-ion collisions*



# *How we can use it?*
# *Flow*

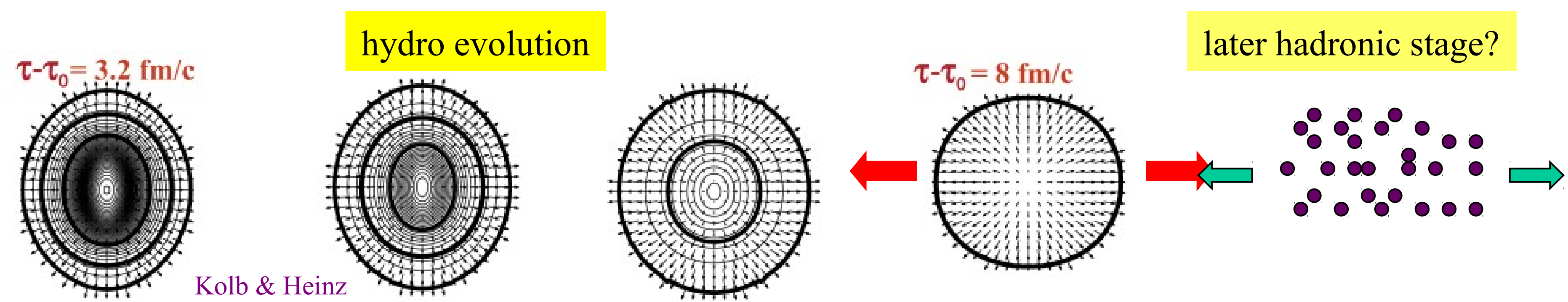
# Heavy Ion collision evolution





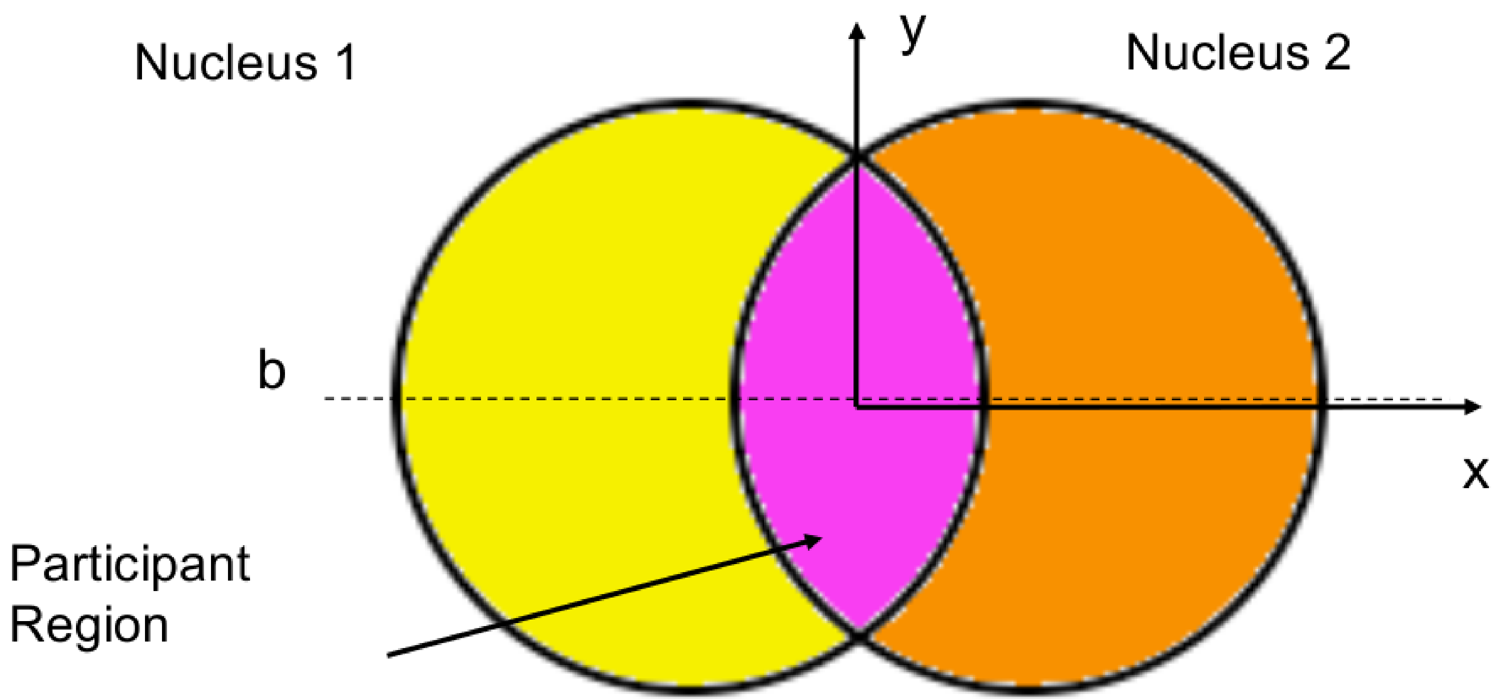

- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

M. Chojnacki, W. Florkowski, PRC 74 (2006) 034905



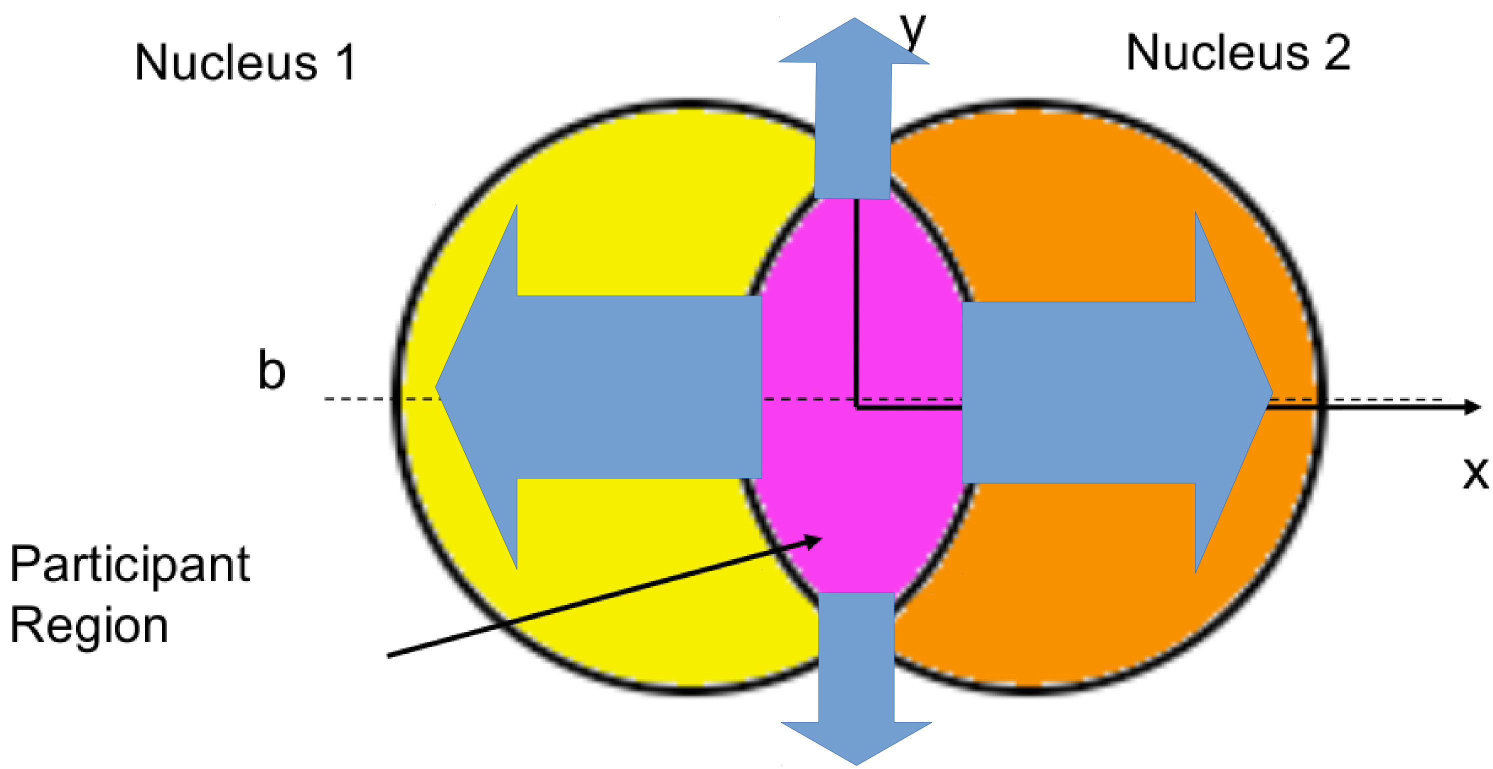
# Collective effects: flow

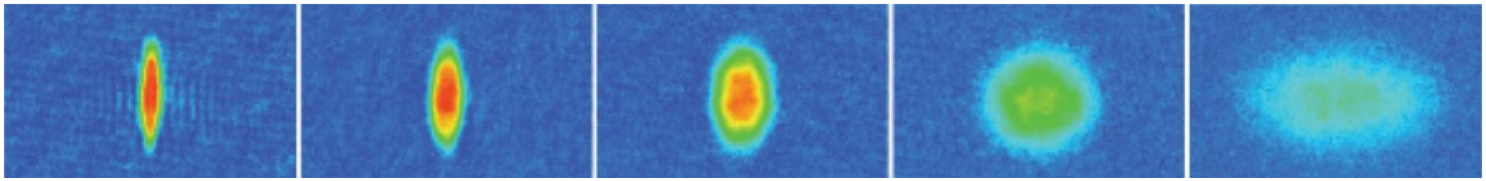
***Flow:***
***Textbook signature of QGP***



# Collective effects: flow

***Flow:***
***Textbook signature of QGP***



# Non-central collisions = elliptic flow

Elliptic flow is a sensitive probe of early dynamics – used as a primary evidence for hydrodynamics-like flows at RHIC.

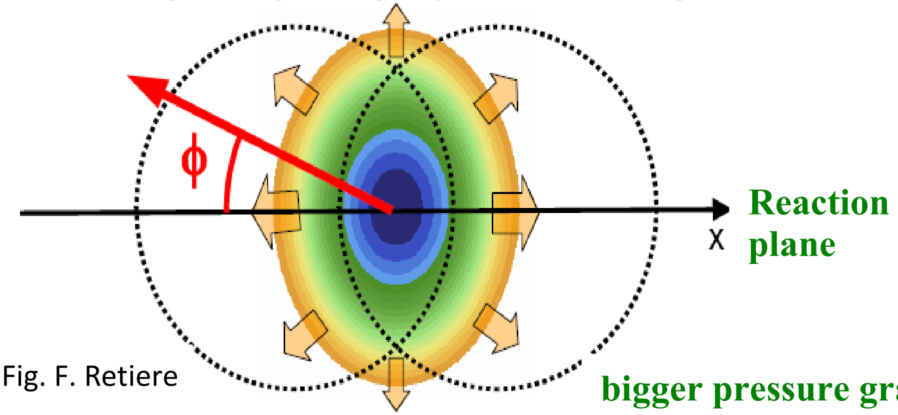
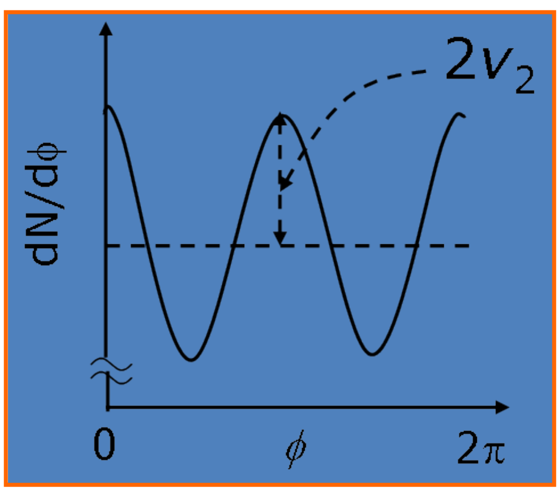
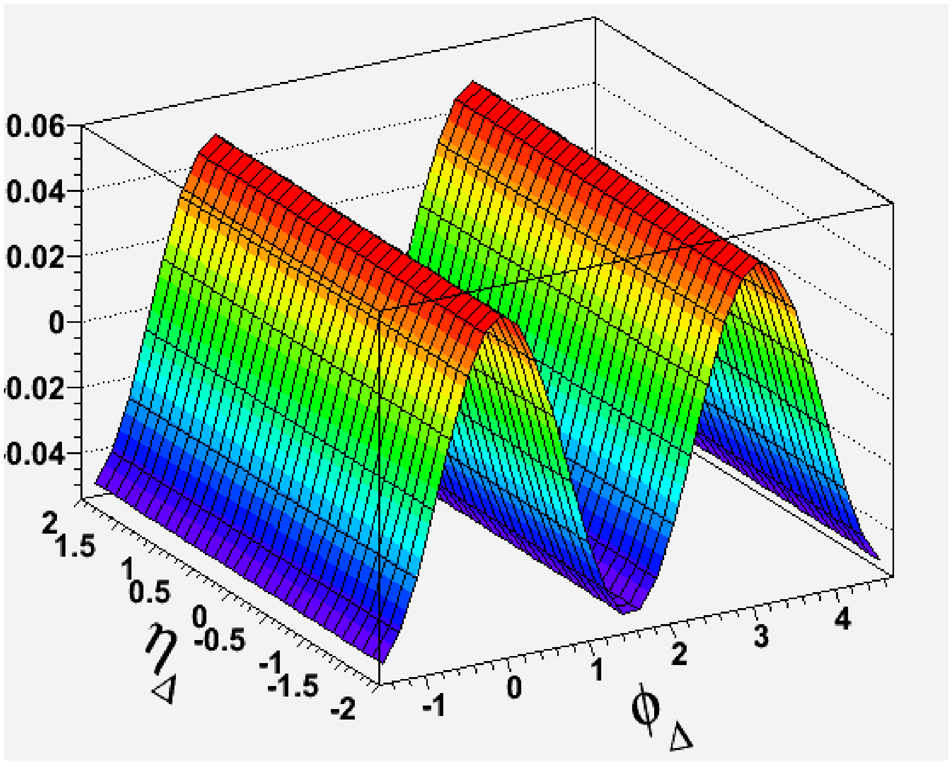



Fig. F. Retiere

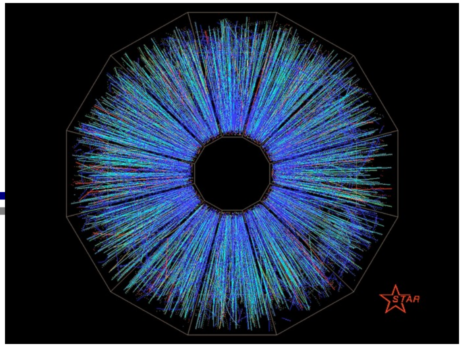
bigger pressure gradients in-plane than out-of-plane




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

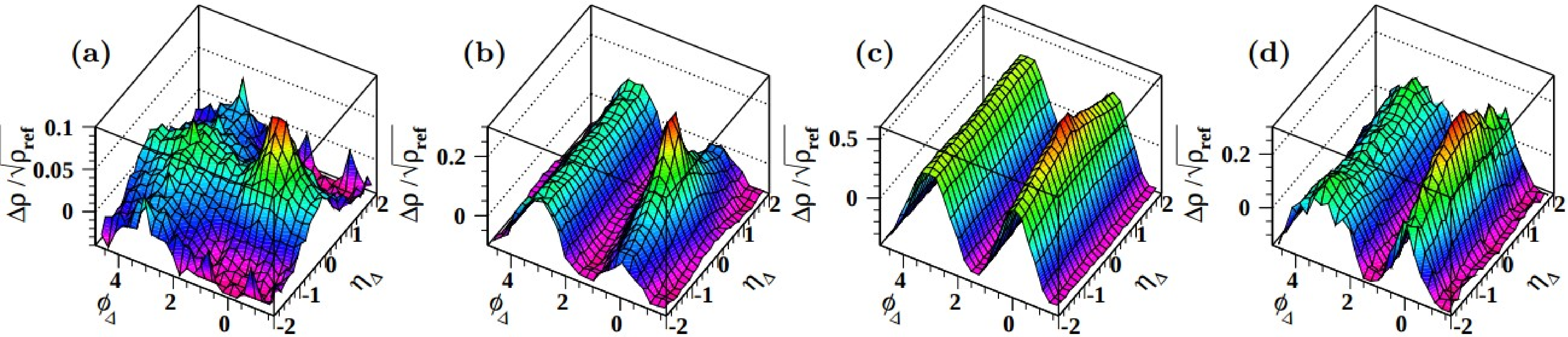


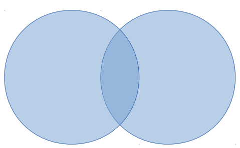
# Angular correlations in Au-Au



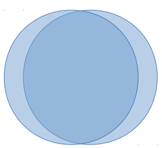
*Heavy-ions*

*centrality*



STAR: 10.1103/PhysRevC.86.064902

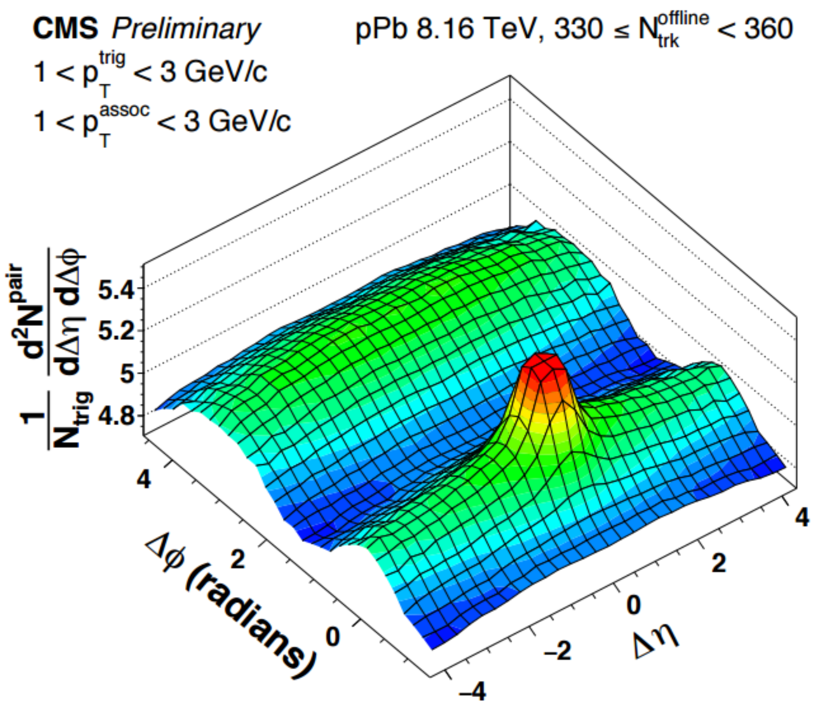


*Similar to pp*

*Strong contribution of flow*

# Collective effects: flow

## ➢ 2D correlation function



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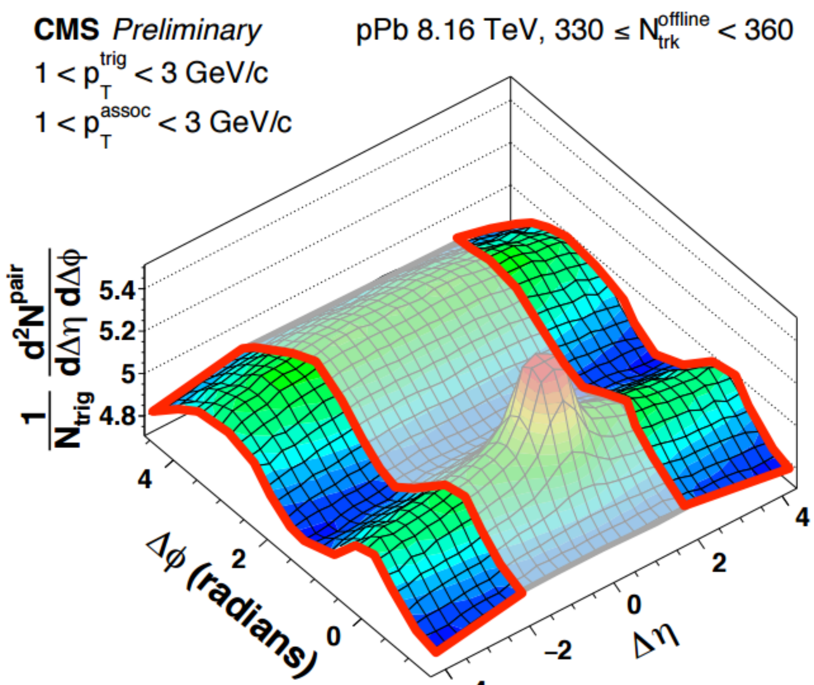
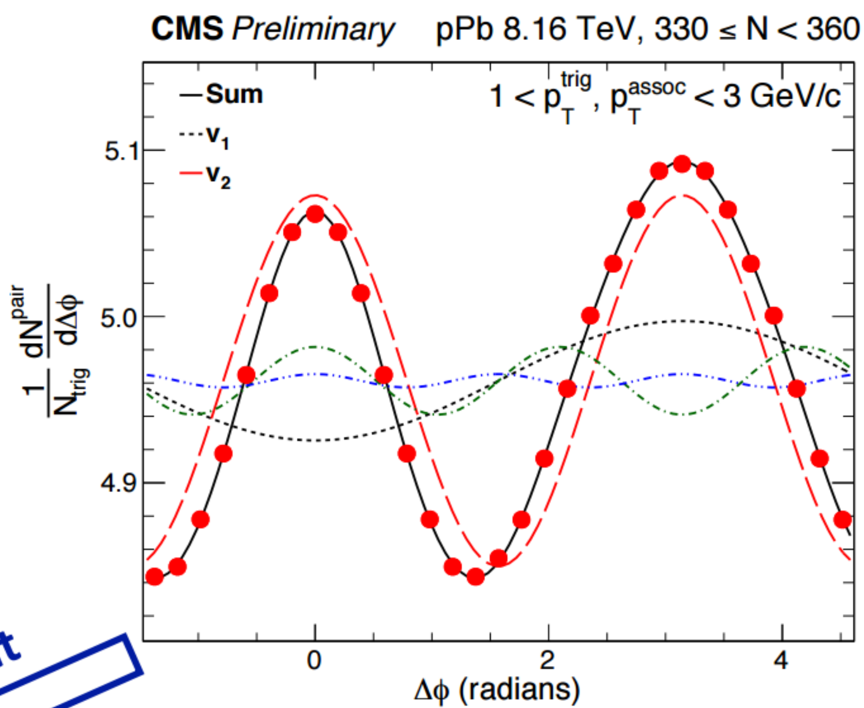



## ➢ 1D correlation function




Projection on ΔΦ

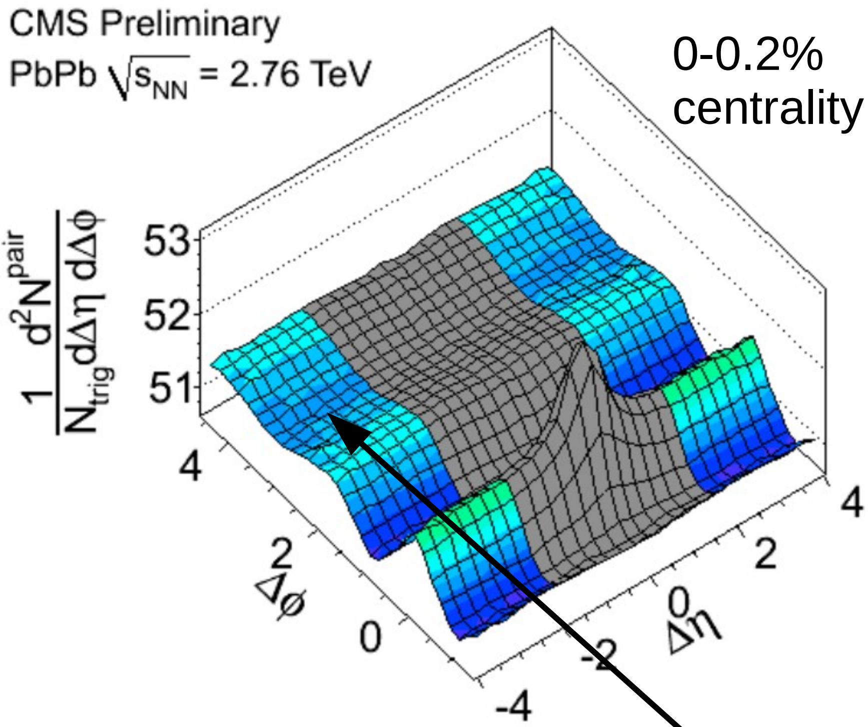
Fourier fit

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

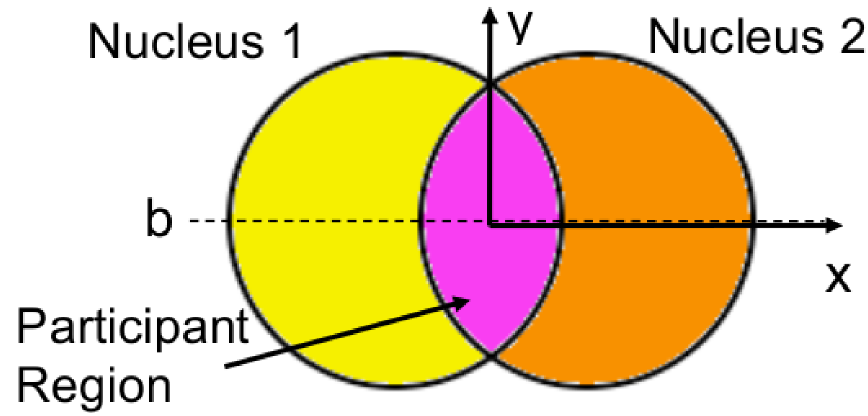
$$v_2 = \langle \cos 2\phi \rangle$$

# Collective effects: flow

## ➢ 2D correlation function




## ➢ 1D correlation function

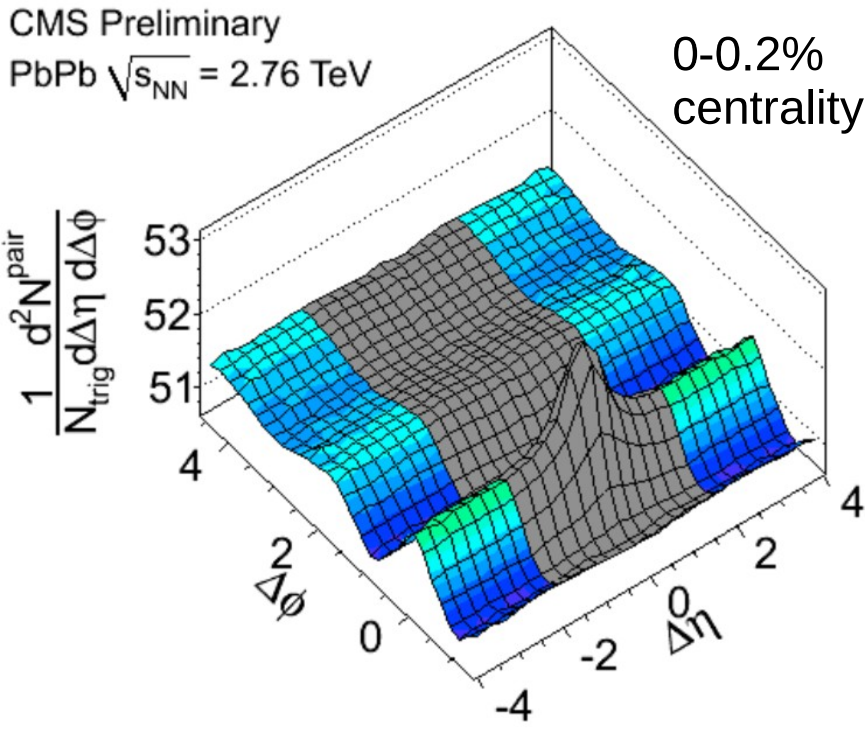



<u>Before 2011:</u>
To many only v1, v2 seemed important

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

# Collective effects: flow

## ➢ 2D correlation function

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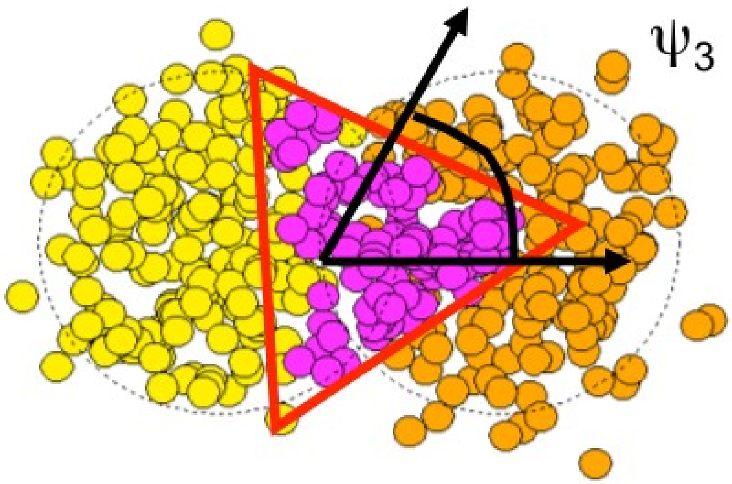
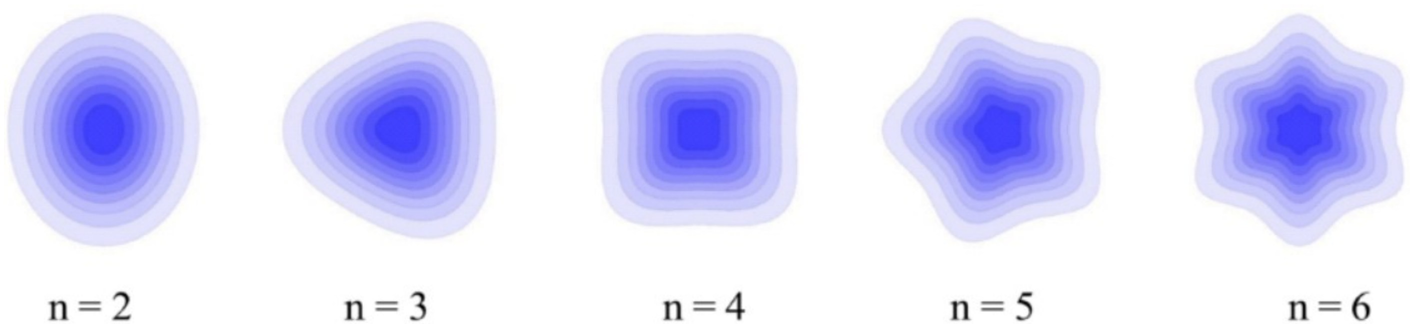



**At LHC**, the large acceptance of the experiments, together with the high particle density (as a collective effect, the flow signal increases strongly with multiplicity) **made the observation and interpretation straightforward and unambiguous.**

J. Schukraft



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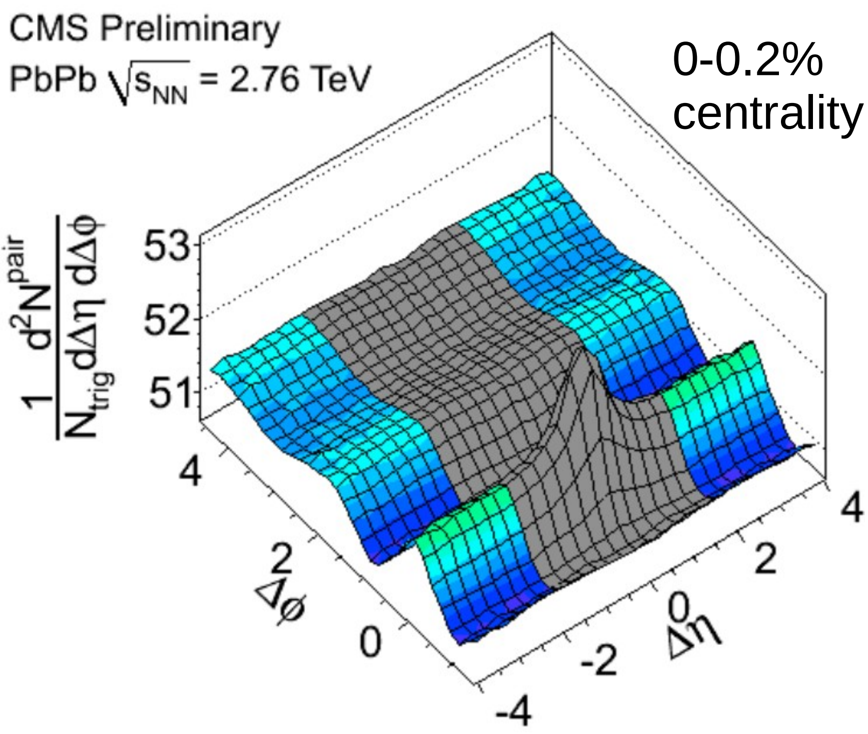
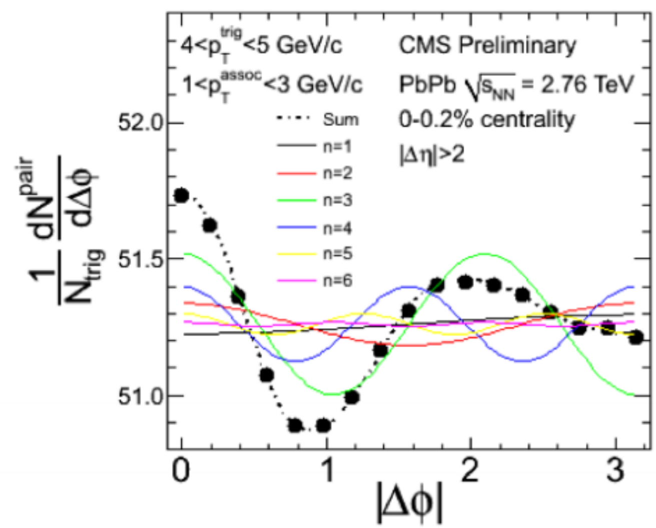



## ➢ 1D correlation function

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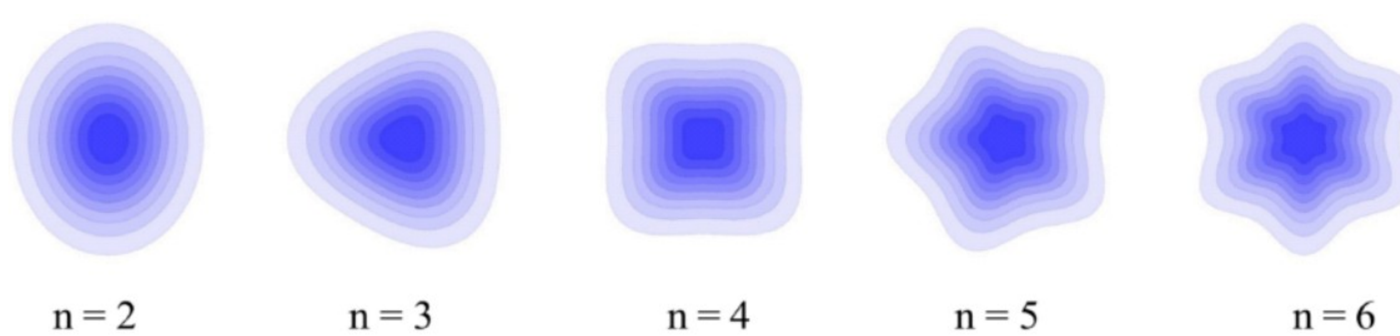
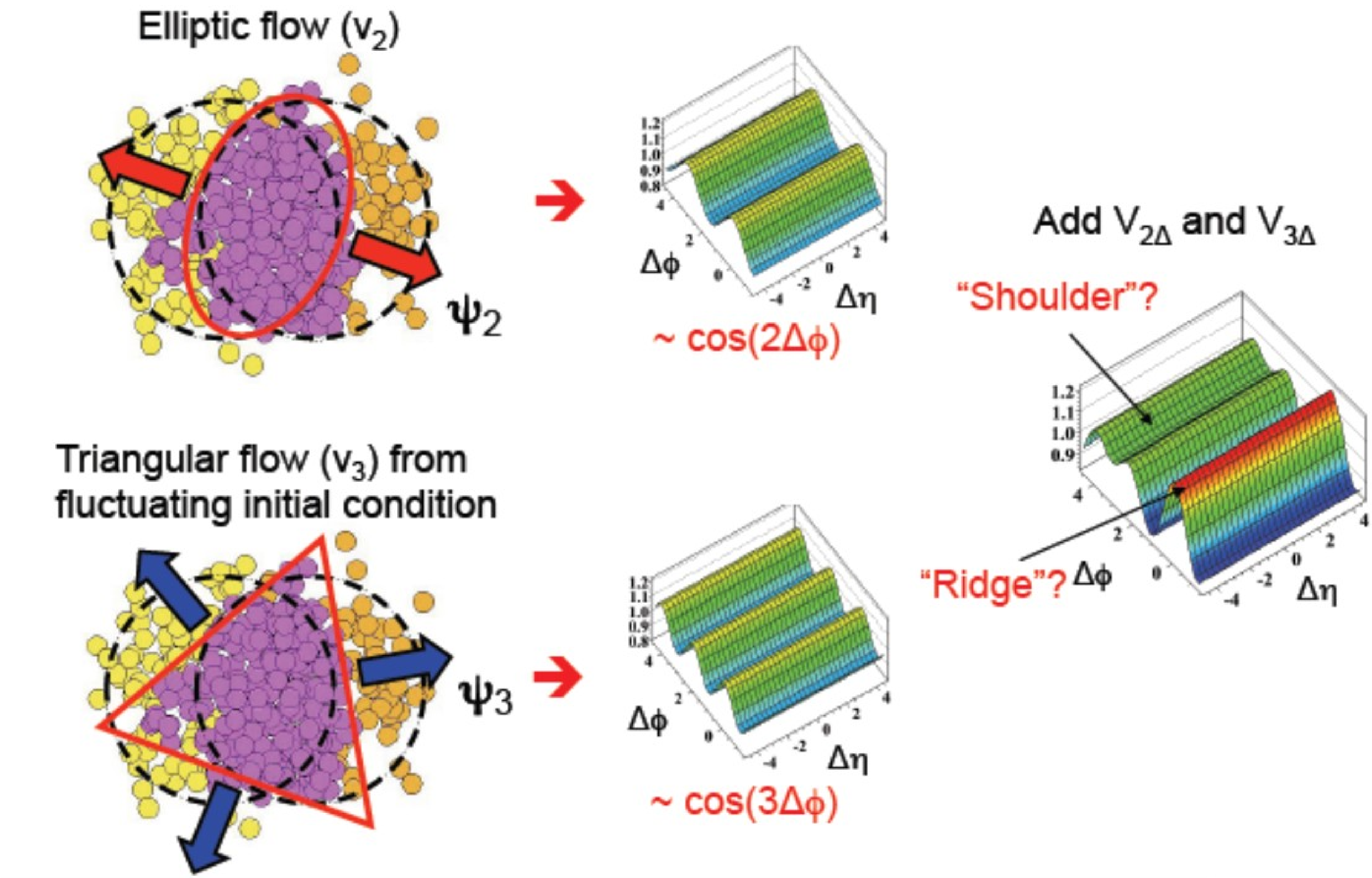
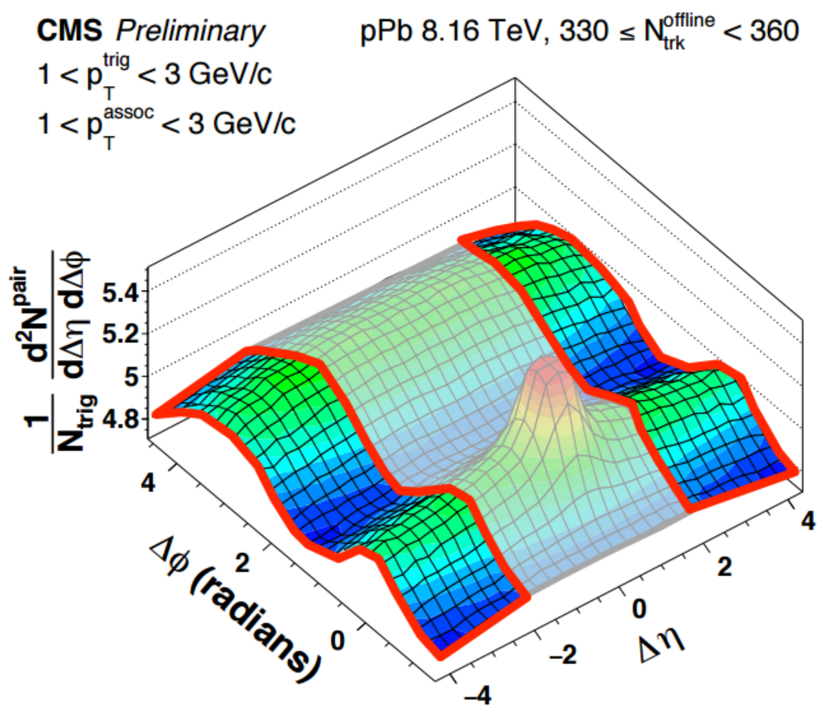


# Collective effects: flow



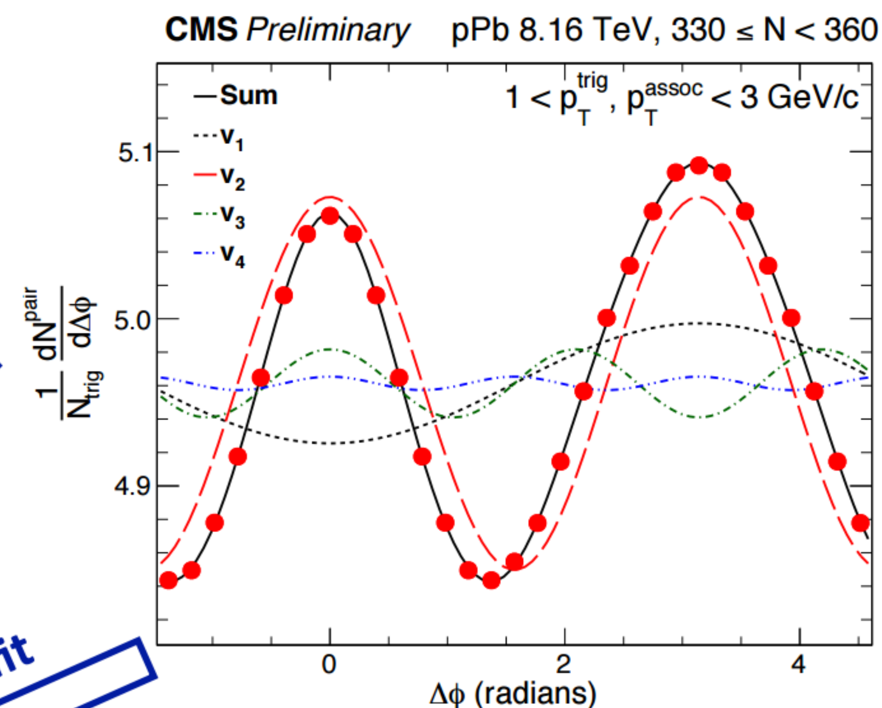
# Collective effects: flow

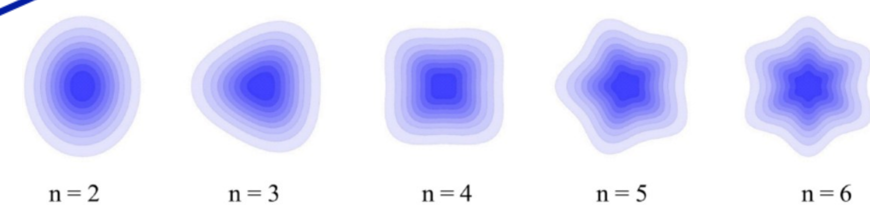
## ➢ 2D correlation function




**Projection on ΔΦ**

## ➢ 1D correlation function




**Fourier fit**

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

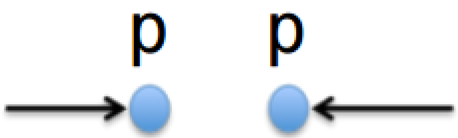
$$v_n = \sqrt{V_{n\Delta}}$$

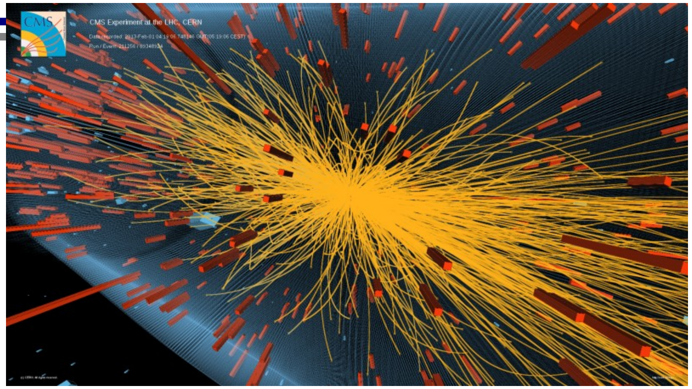
**Extract single particle $v_n$**

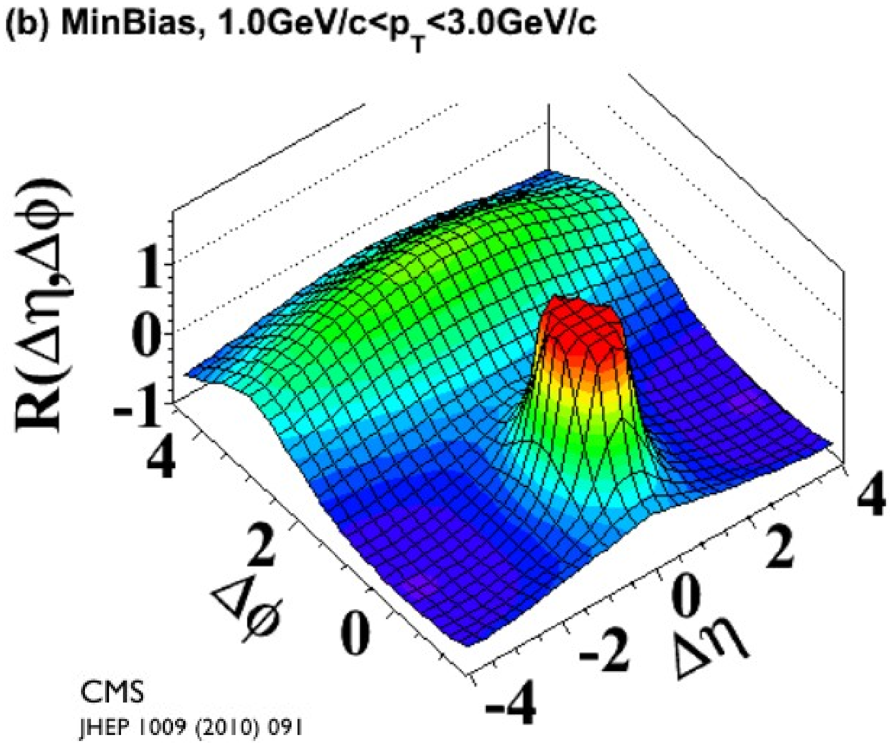
# The Ridge: CMS 2010

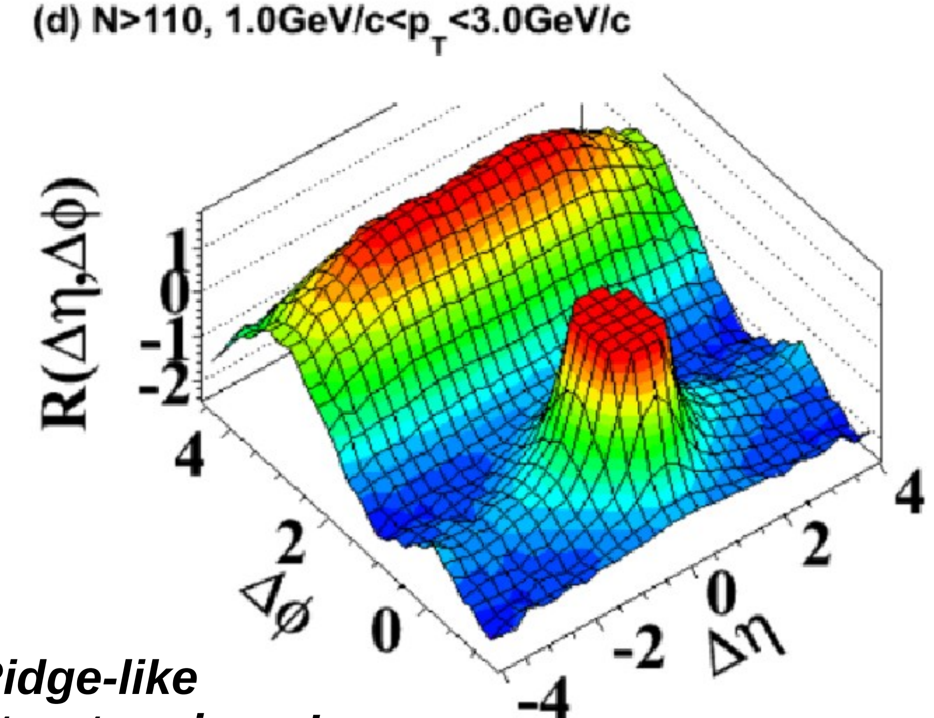
# The Ridge: CMS 2010

First LHC discovery



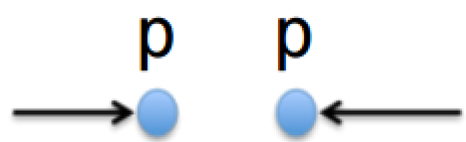


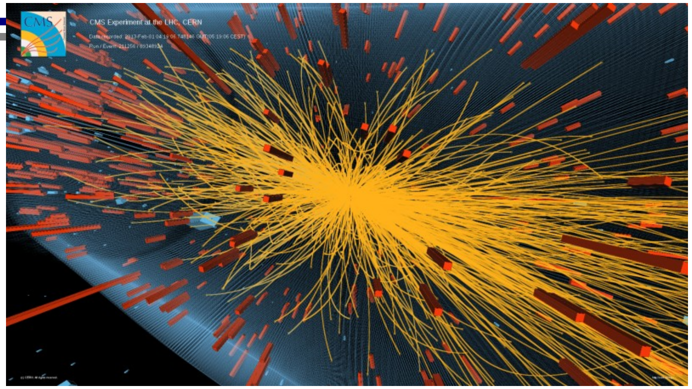




***Ridge-like structure in pp!***

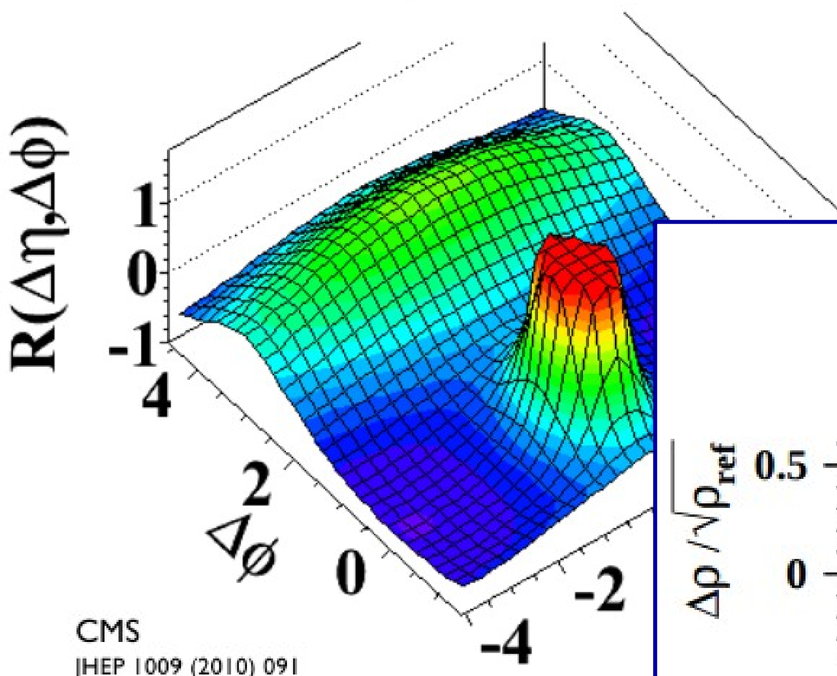
# The Ridge: CMS 2010

First LHC discovery

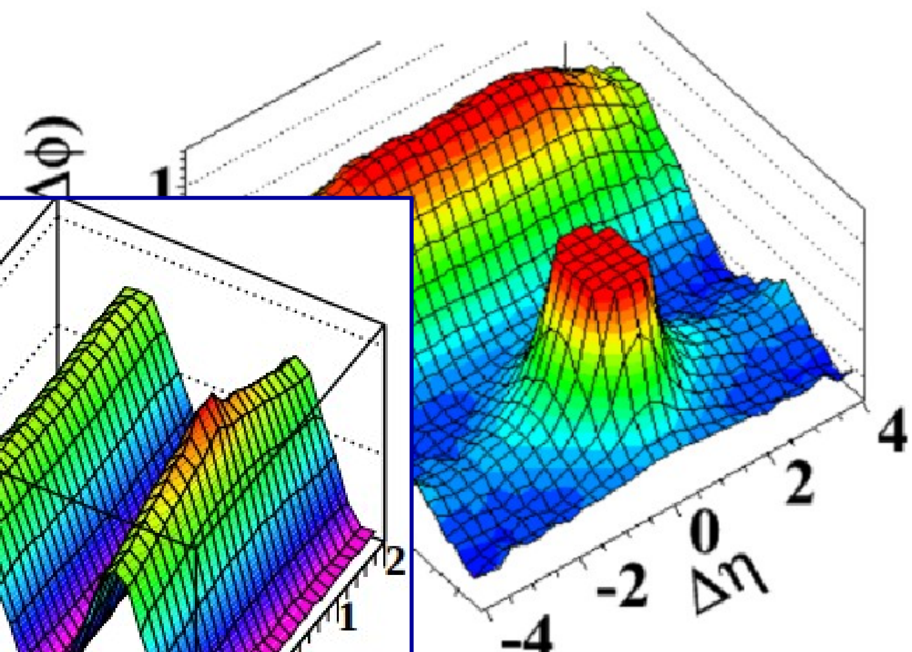


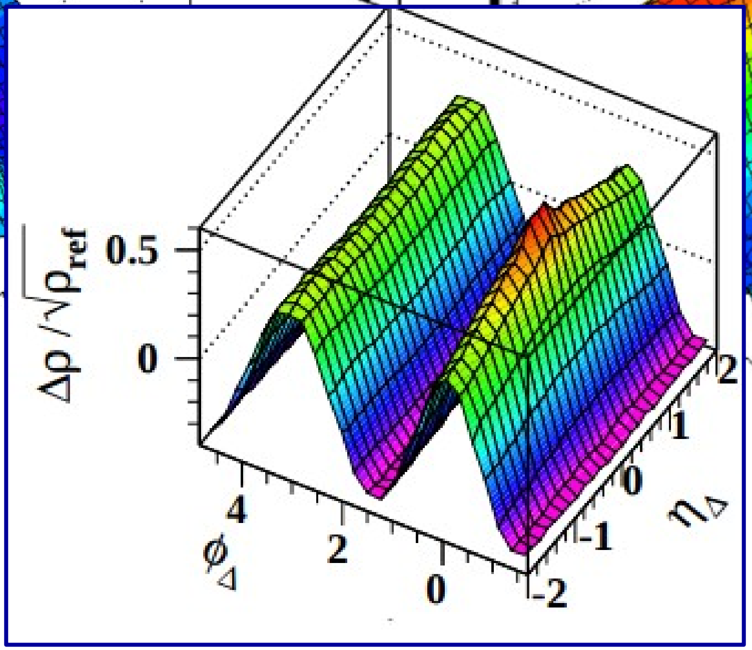



(b) MinBias, 1.0GeV/c<p$_T$<3.0GeV/c




(d) N>110, 1.0GeV/c<p$_T$<3.0GeV/c

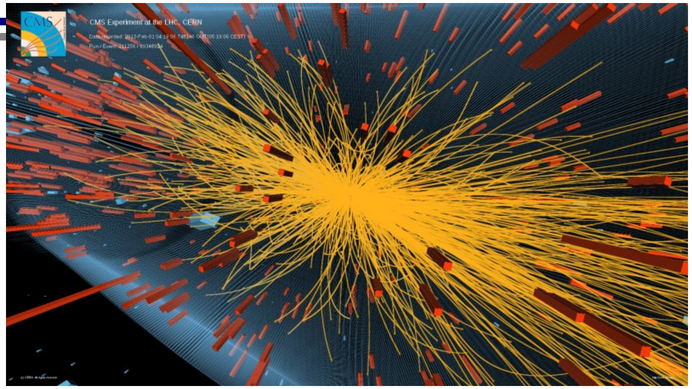



***Heavy ions: well understood as flow.***

# The Ridge: CMS 2010

First LHC discovery

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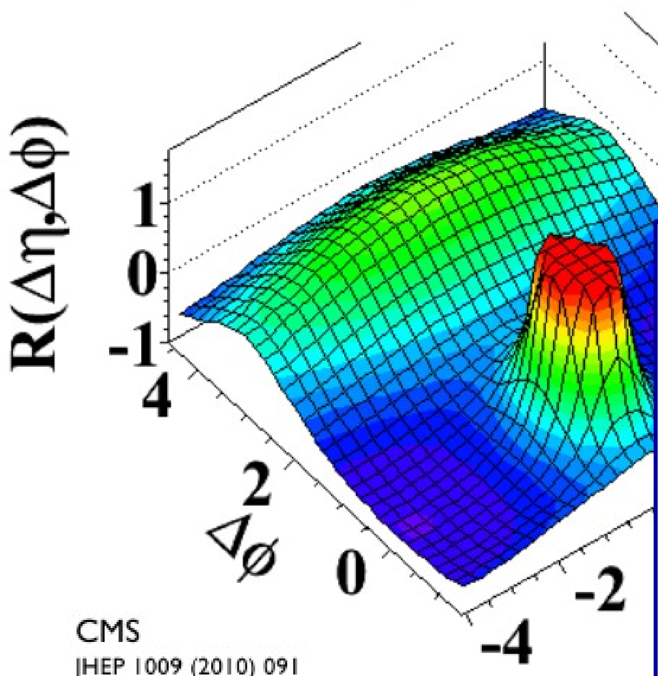


CMS
JHEP 1009 (2010) 091

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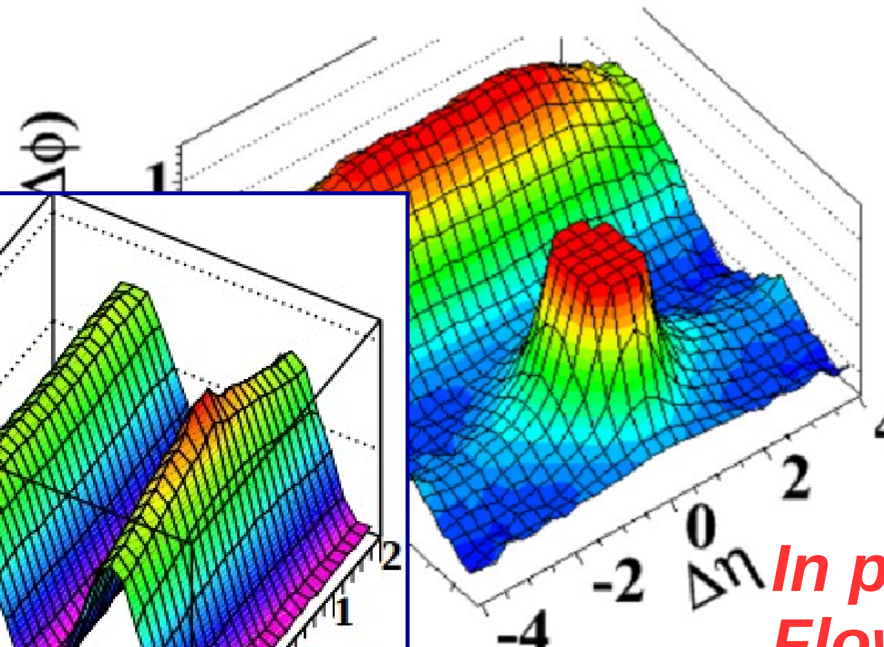
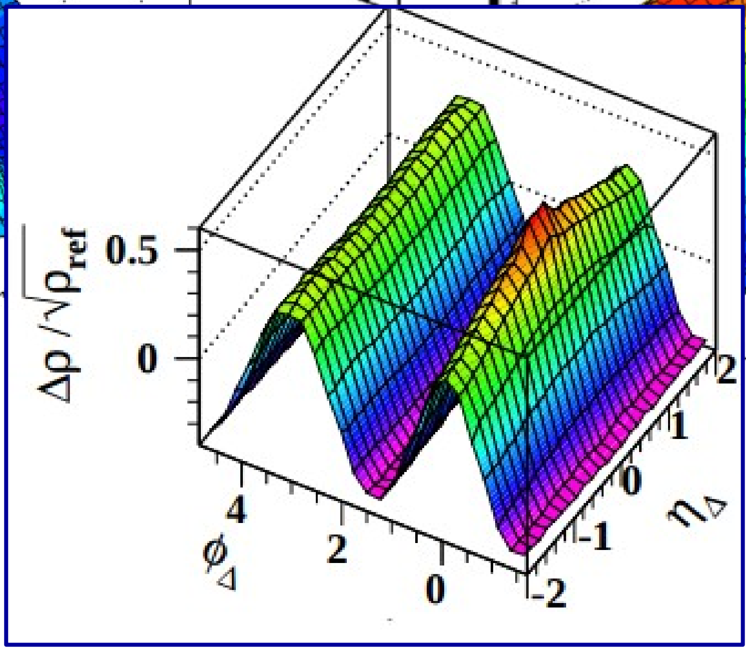
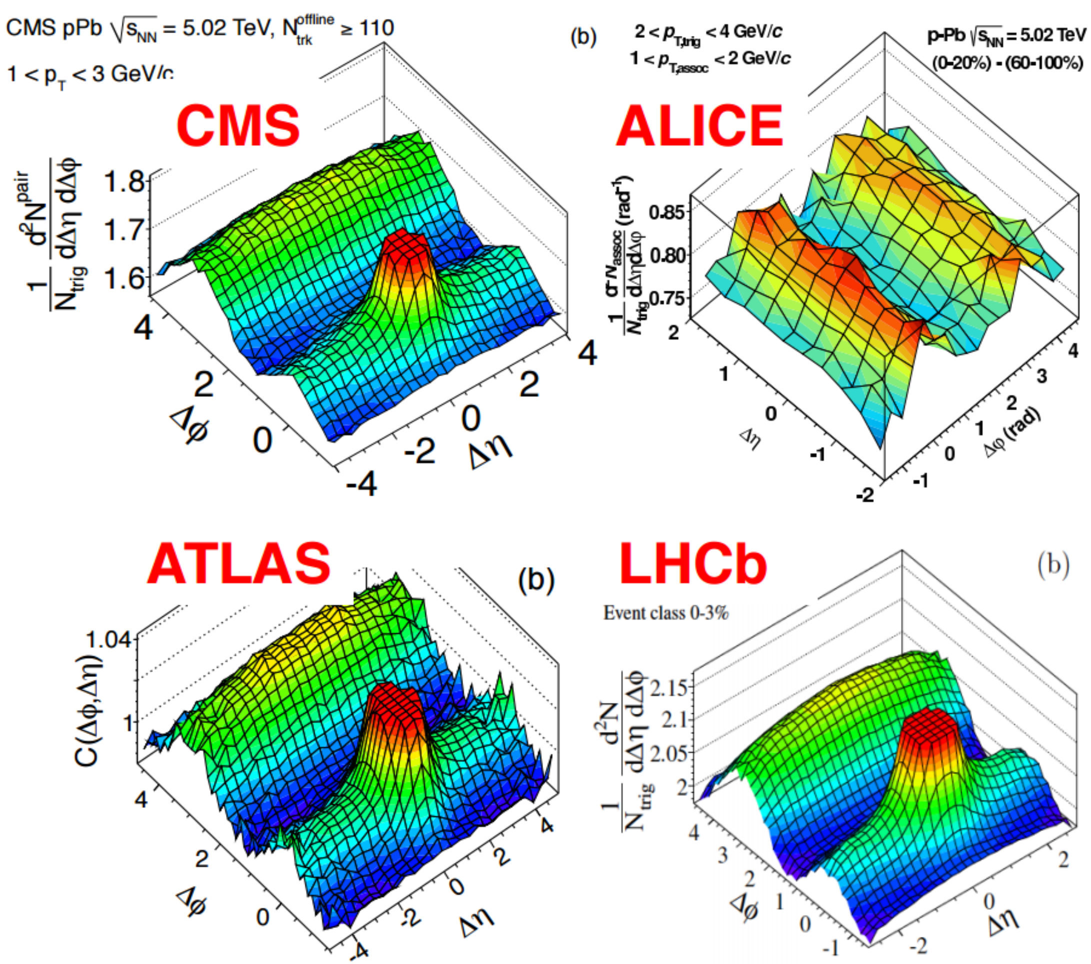


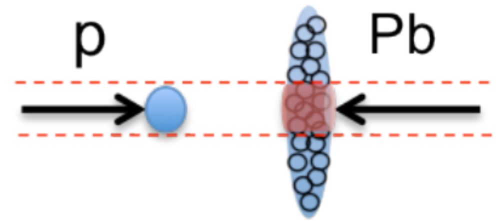




**In pp? Flow?!**

***Heavy ions: well understood as flow.***

# More Ridges

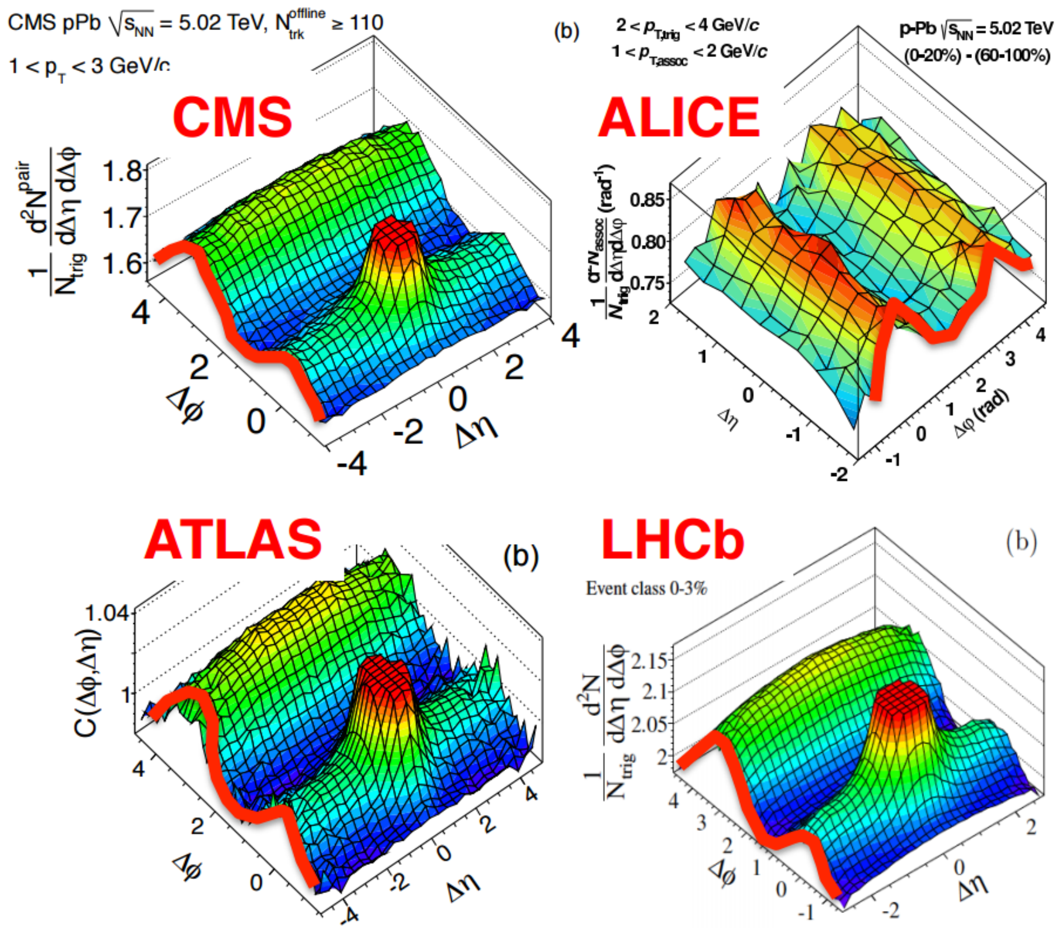


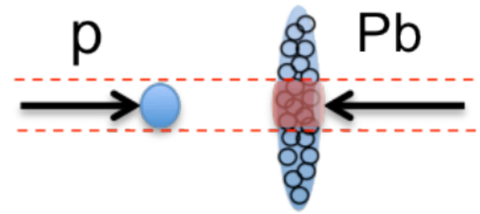




in 2012

**Collective phenomena and QGP fluid in small systems (L ~ 1fm)?!**

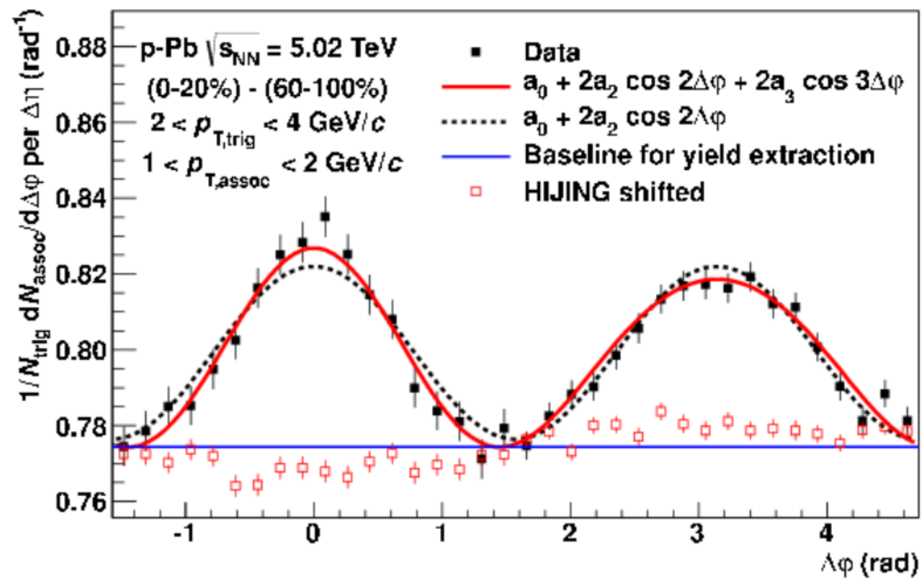
# More Ridges



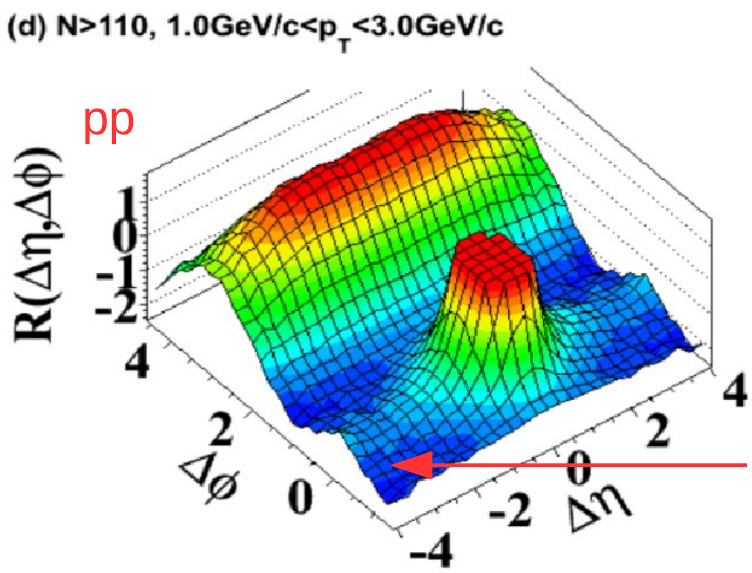

in 2012

"Flow" analysis



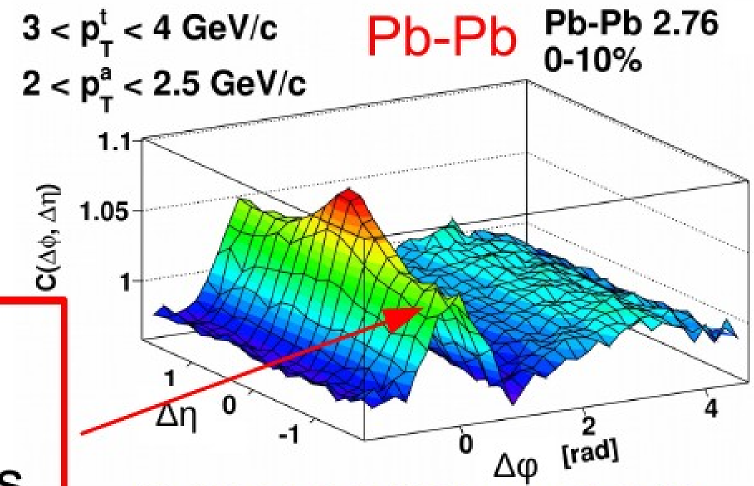

**Collective phenomena and QGP fluid in small systems (L ~ 1fm)?!**

# The Ridge

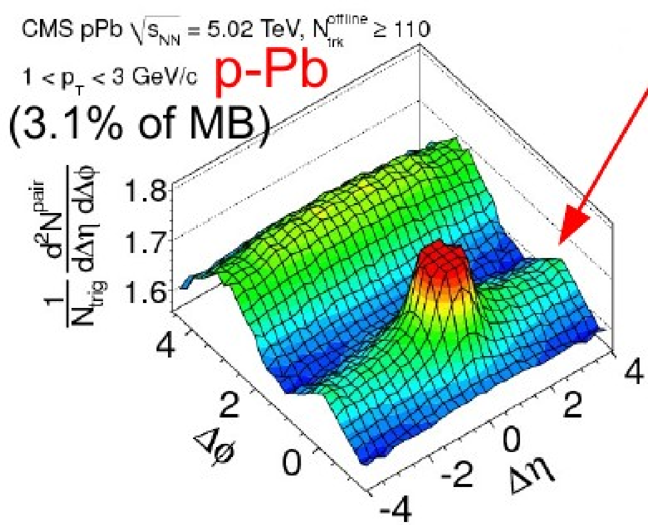



CMS, JHEP 1009 (2010) 91

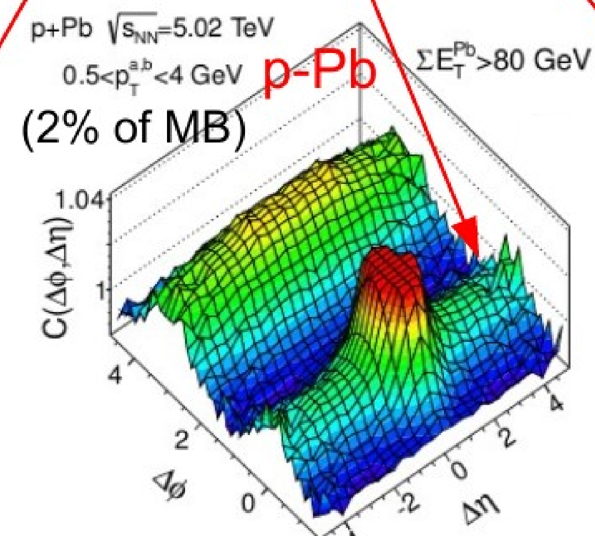
Near-side (NS) ridges in high multiplicity events at LHC energies



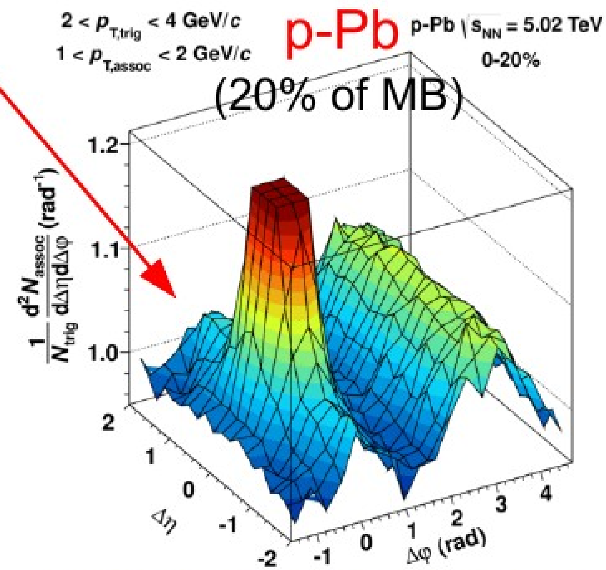

ALICE, PLB 708 (2012) 249




CMS, PLB 718 (2012) 795

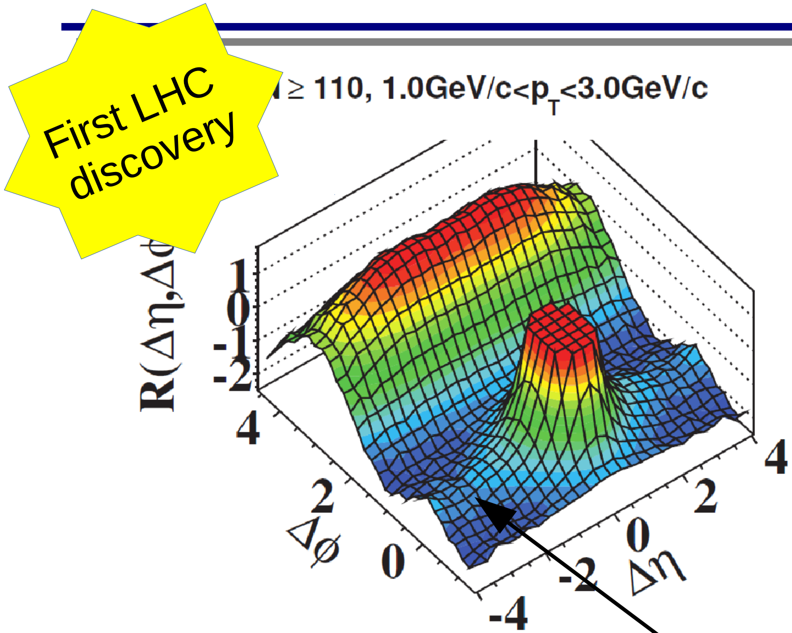



ATLAS, PRL 110 (2013) 182302

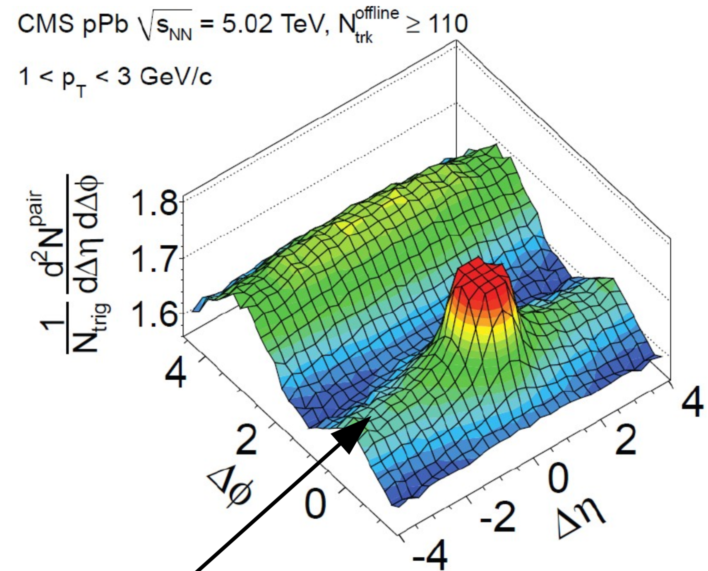



ALICE, PLB 719 (2013) 29

# The Ridges




pp




p-Pb

**The Ridge**

The first discovery made at LHC was announced in Sept. 2010 on a subject which was as unlikely as it was unfamiliar to most in the packed audience: The CMS experiment had found a **mysterious 'long range rapidity correlation' in a tiny subset of extremely high multiplicity pp collisions** at 7 TeV. While in the meantime far eclipsed by the discovery of 'a Higgs-like particle', this 'near side ridge' **is arguably still the most unexpected LHC discovery** to date and **spawned a large variety of different explanations, from mildly speculative to outright weird.**

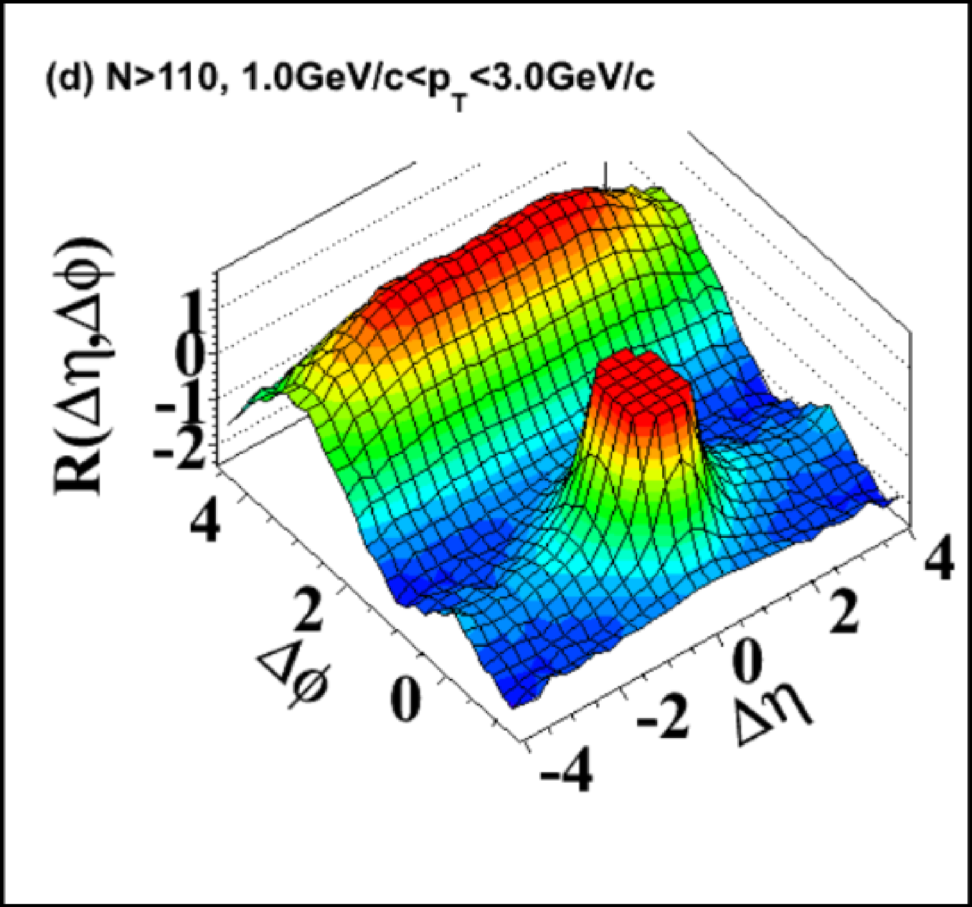
Phys.Scripta T158 (2013) 014003
Heavy ion physics at the Large Hadron Collider: what is new? What is next?
J. Schukraft

Paper titles:
„...Building bridges with **ridges**"
„Observation of a '**Ridge**' correlation structure ..."
„**Ridge** from Strings"
„On the onset of **the ridge** structure"

# The Ridge

High multiplicity (N>110)

~100 citations within a year




Interpretation:

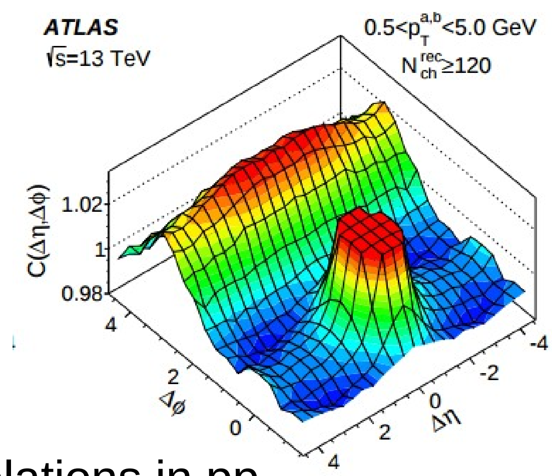
Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections
Jet-remnant connections + medium
Glasma correlations
Quantum entanglement
Angular momentum conservation
Angular momentum conservation + medium
Hydrodynamic flow

?

Multiplicity in these events is dominated by jet contribution.

Gunther Roland International Conference on the Initial Stages of High-Energy Nuclear Collisions Illa da Toxa September 2013

# The Ridge

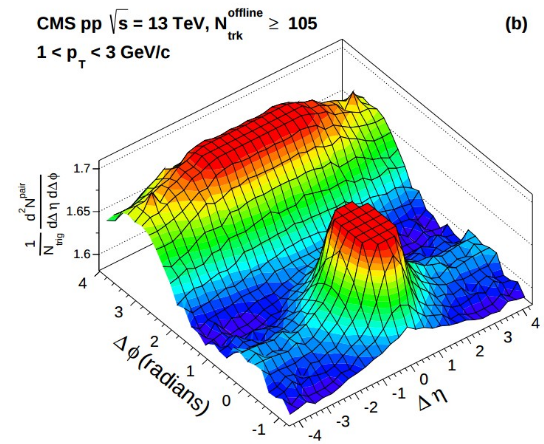



First ATLAS heavy-ion paper of 13 TeV

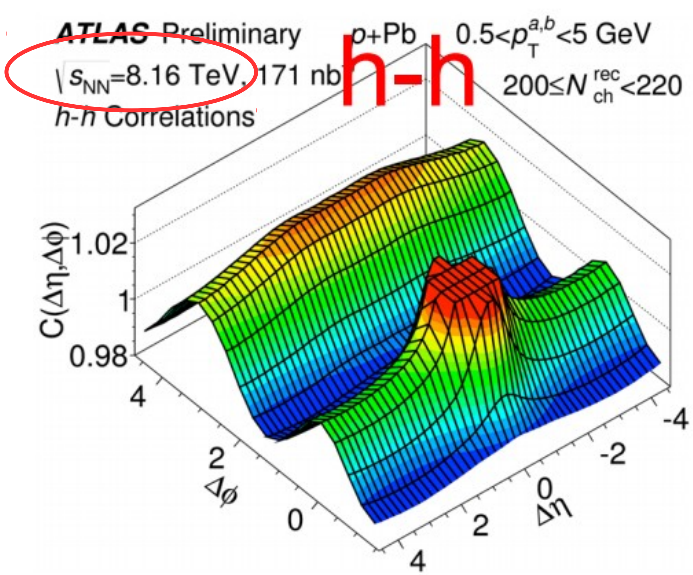
Observation of long-range elliptic anisotropies in sqrt{s}=13 and 2.76 TeV pp collisions with the ATLAS detector
**Phys. Rev. Lett. 116, 172301 (2016)**

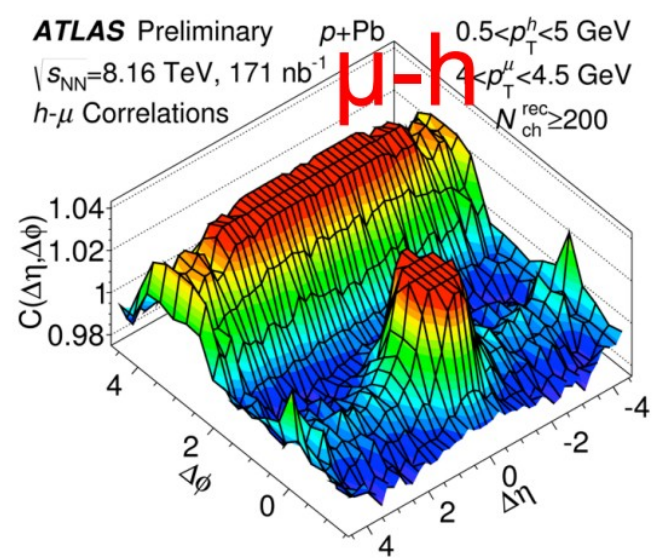
Second CMS paper of 13 TeV

Measurement of long-range near-side two-particle angular correlations in pp collisions at sqrt(s)= 13 TeV **PRL 116 (2016) 172302**




ATLAS QM2017



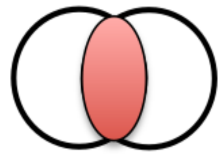



Collective flow from AA, pA to pp

— *Toward a unified paradigm*

# Summary and outlook

Scenario #1



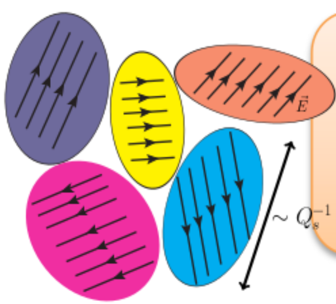
Hydrodynamics

Parton transport, escape

**Initial** spatial $\varepsilon_s$ + **final** interactions

0 $\tau$

Scenario #2




**Initial** momenta $\varepsilon_p$ by **initial** interactions

CGC Glasma

Color-field domains, etc.

**Wei Li**

Quark Matter 2017

Chicago, February 6 – 11

# Summary and outlook

Clear evidence of *long-range*, *collective* phenomena **universal** in all **high-multiplicity** hadronic collisions

| Initial spatial $\varepsilon_s$ + final interactions | OR | Initial momentum $\varepsilon_p$ via initial interactions |
|---|---|---|

In AA, consistent with "hydro-like" **– "perfect fluid"**

**QCD fluid in pp/pA?** Connection to **initial geometry** is the key to be established – "New" flow observables!

- *Unique probes of subnucleonic fluctuations!*

Open issue: collectivity ever turning off at low $N_{trk}$?

**Wei Li**
Quark Matter 2017
Chicago, February 6 – 11

# Summary and outlook

Clear evidence of *long-range*, *collective* phenomena **universal** in all **high-multiplicity** hadronic collisions

Initial spatial $\varepsilon_s$ + final interactions OR Initial momentum $\varepsilon_p$ via initial interactions

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➢ *Unique probes of subnucleonic fluctuations!*

Open

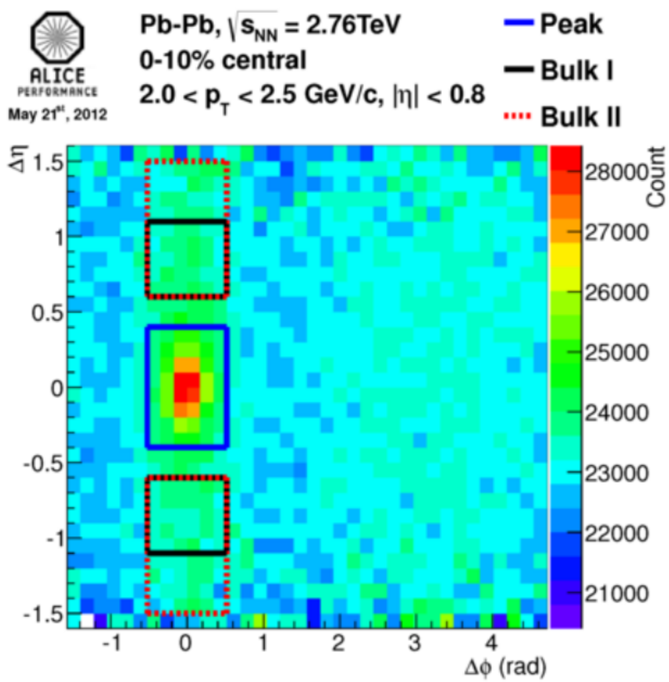
1 June 2016 - EMMI Seminar
Raju Venugopalan
"***The gift that keeps giving: surprises from ridges in p+p, p/d/He+A and A+A collisions***"

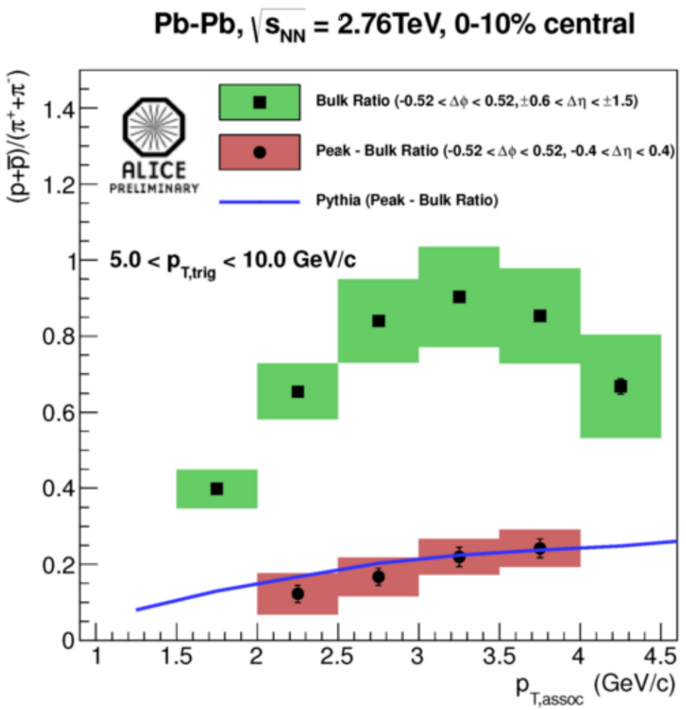
Int. J. Mod. Phys. E, Vol. 25, 1 (2016) 16300022
Kevin Dusling, Wei Li, Bjorn Schenke
Review: "***Novel collective phenomena in high energy pp and p-nucleus collisions***"

# *Can we learn something more?*
# *Selection of particles*

# p/π ratio

Nucl Phys A, Volumes 910–911, August 2013, Pages 306-309

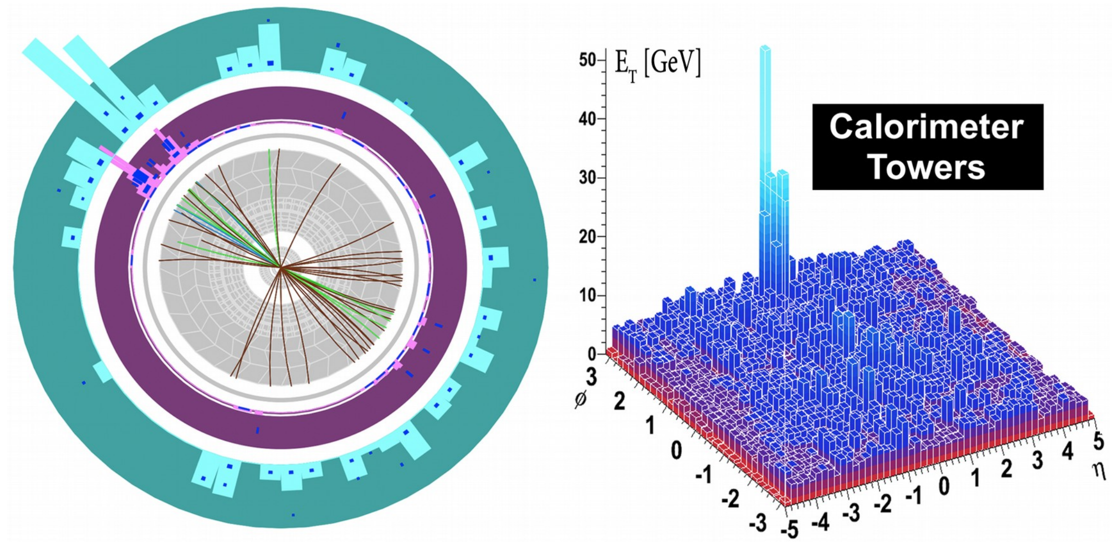


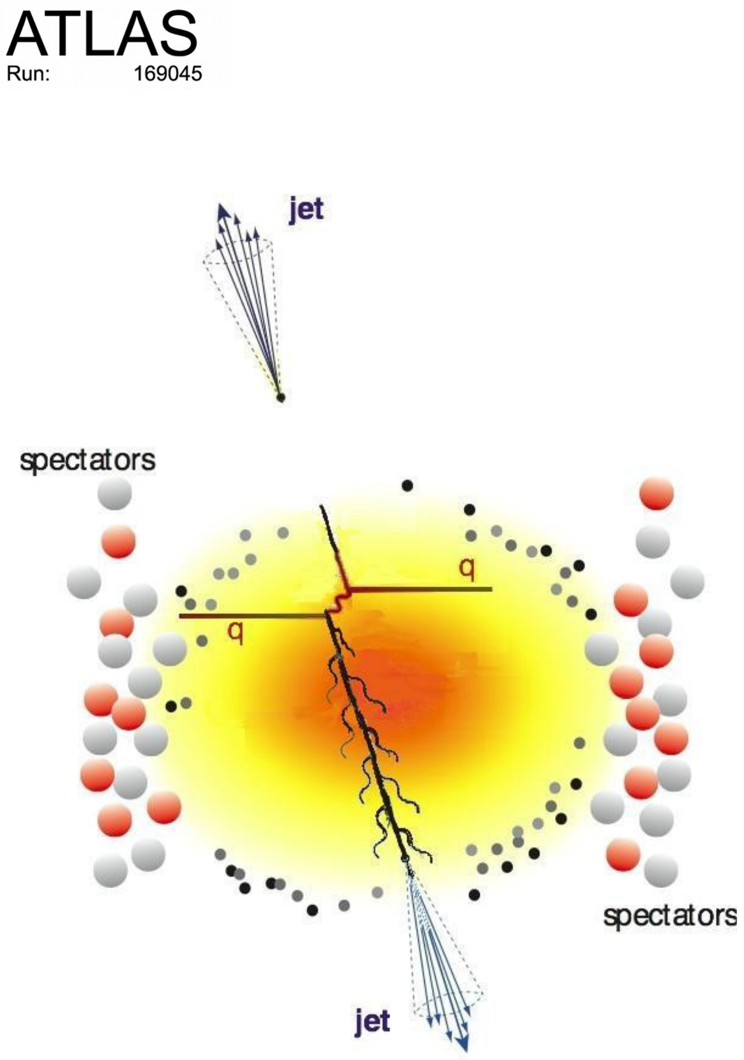




- A very clear increase of the p/π ratio is observed in the bulk of central Pb–Pb collisions compared to the PYTHIA reference.
- The p/π ratio in the yield associated with a high-pT trigger particle is compatible with the PYTHIA reference, suggesting that particle production is unmodified by the presence of the medium. One possible explanation is that fragmentation of energetic partons occurs outside the medium.

## *How we can use it?*
## *Jet quenching*

# Parton Energy Loss (jet quenching)




**Interaction of gluons, light and heavy quarks inside the medium**
**→ energy loss, suppression**

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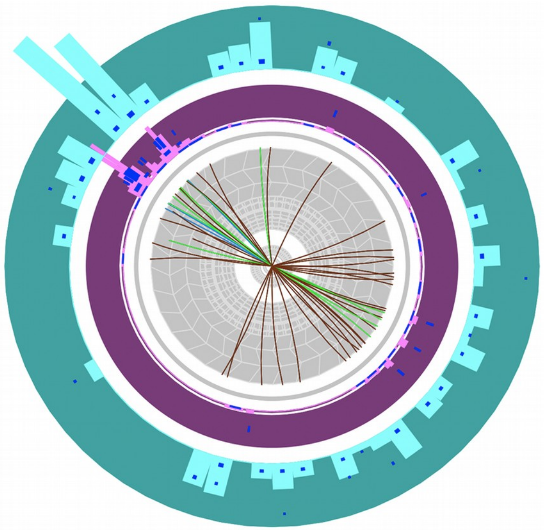
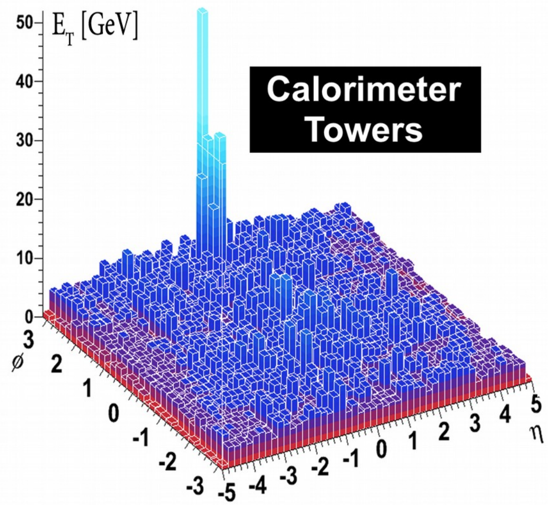
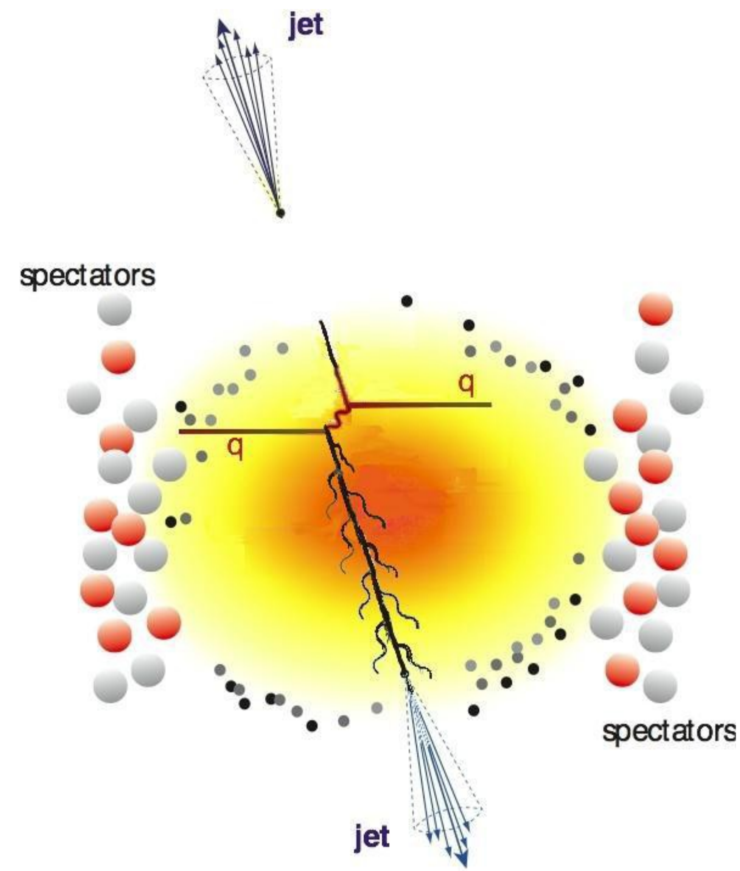





ATLAS
Run: 169045

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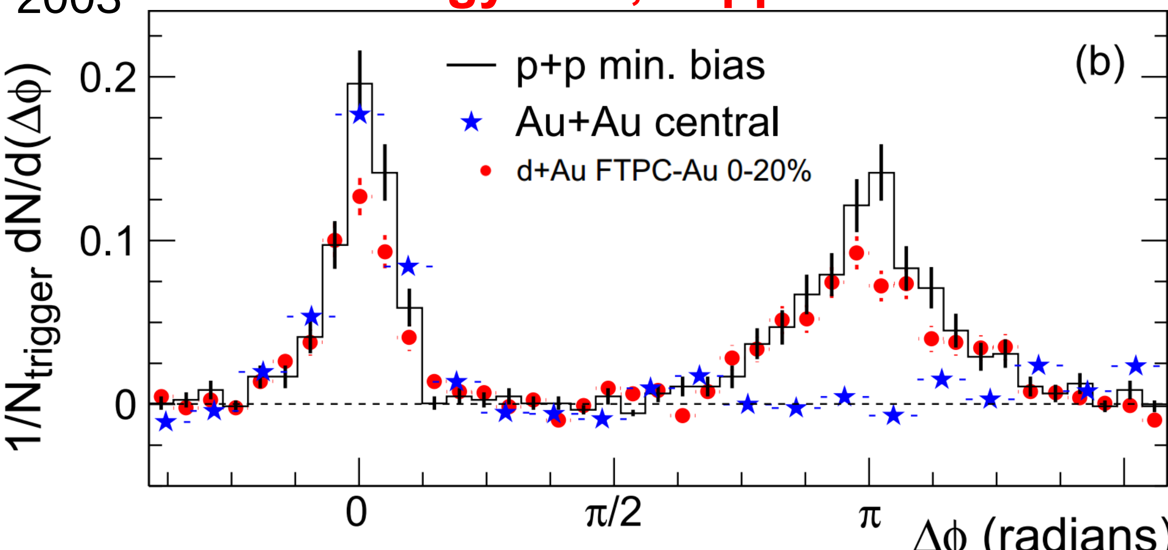

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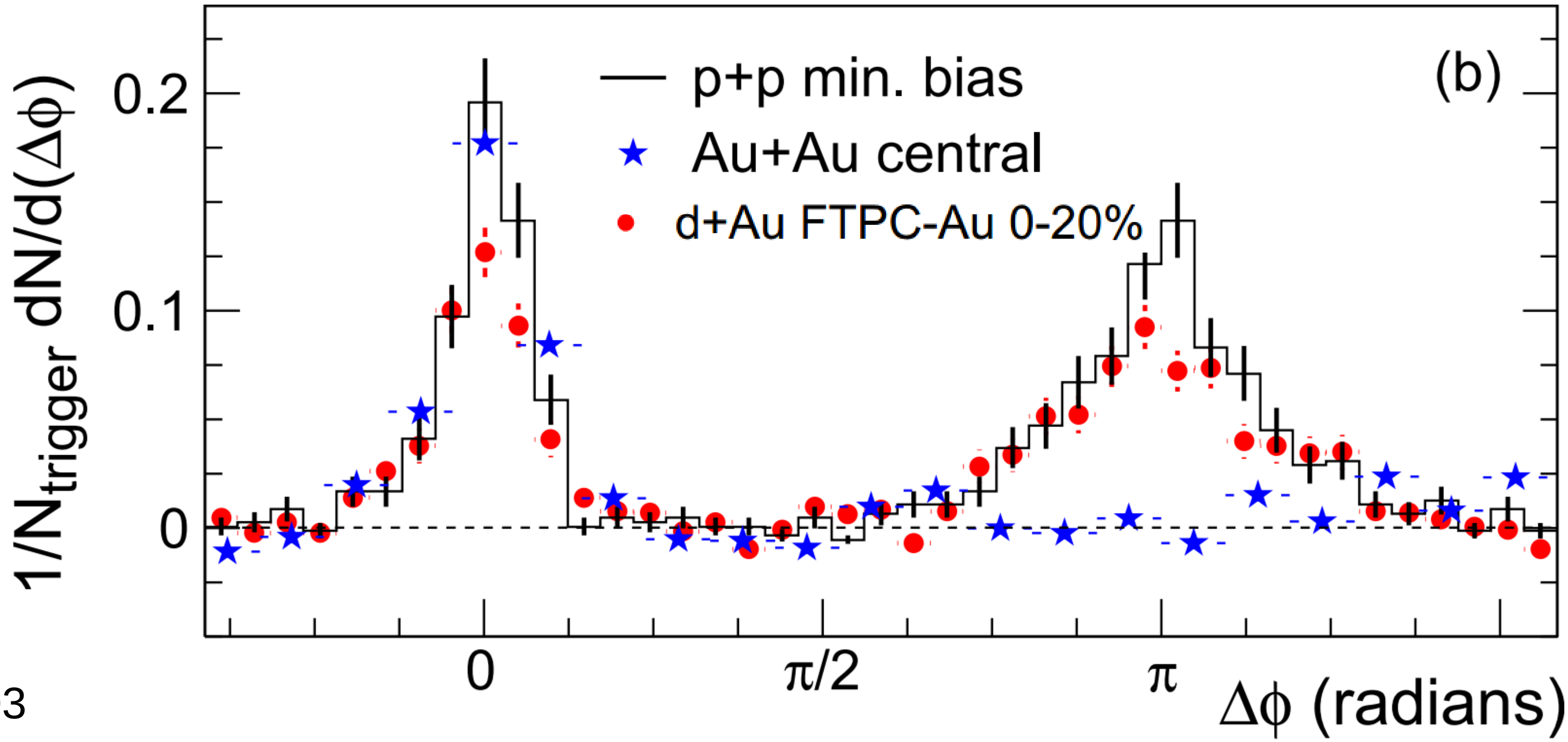


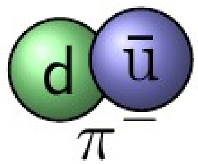

2003

**Interaction of gluons, light and heavy quarks inside the medium**
**→ energy loss, suppression**

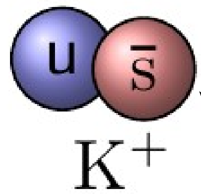
## *Can we learn something more?*

# One step further: ΔηΔφ of identified particles!

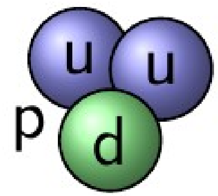
**Conservation laws** and their influence on **particle production mechanisms – **study via correlation functions for particles with **different quark content**




**Pion:**
- Charge




**Kaon:**
- Charge
- Strange quark




**Proton:**
- Charge
- Baryon

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

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

# Particle production mechanisms

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").

**We are not likely to find two strange particles / baryons at the same rapidity**

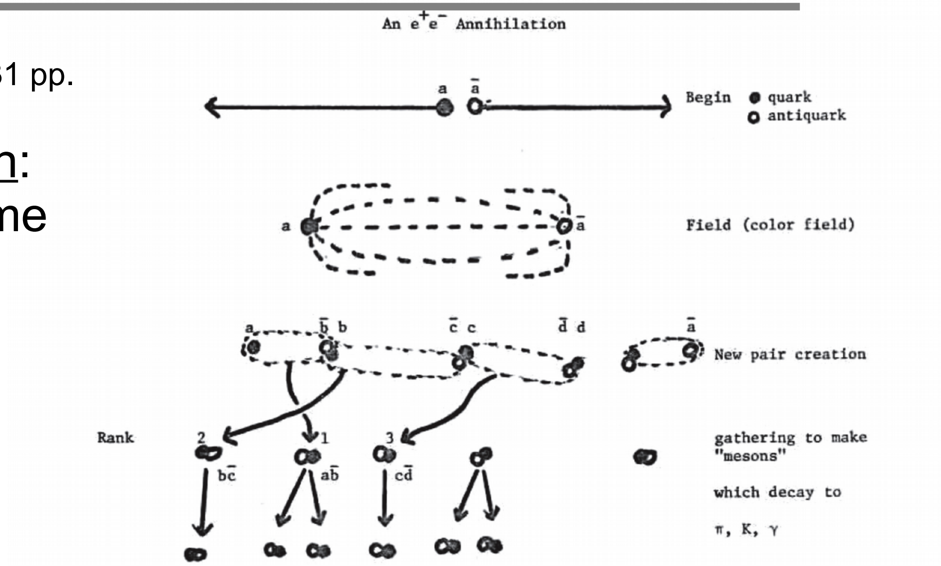



Fig. 10. Transparency from a talk Feynmen gave on our model for how quarks fragment into hadrons at the International Symposium on Multiparticle Dynamics (ISMD), Kaysersberg, France, June 12, 1977.

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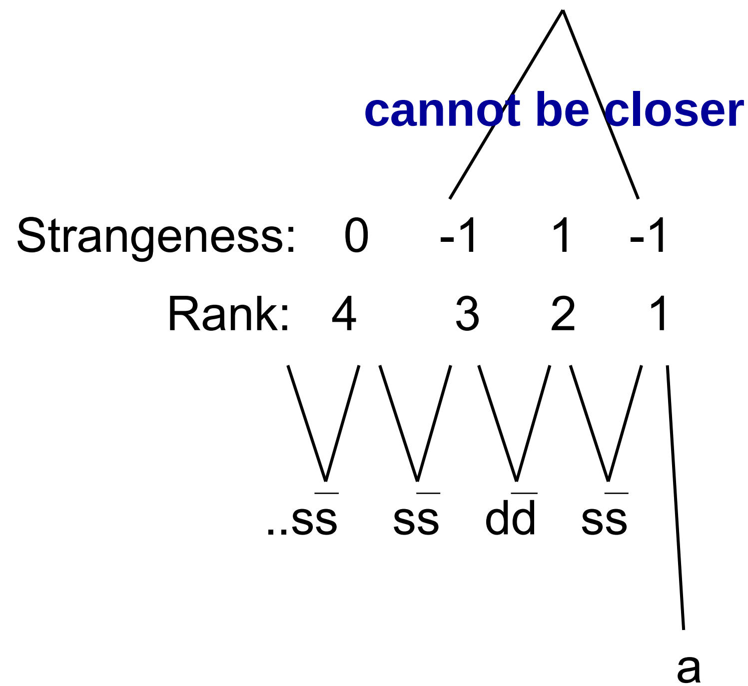
The same strangeness:
3 – 1 = 2 steps in rank



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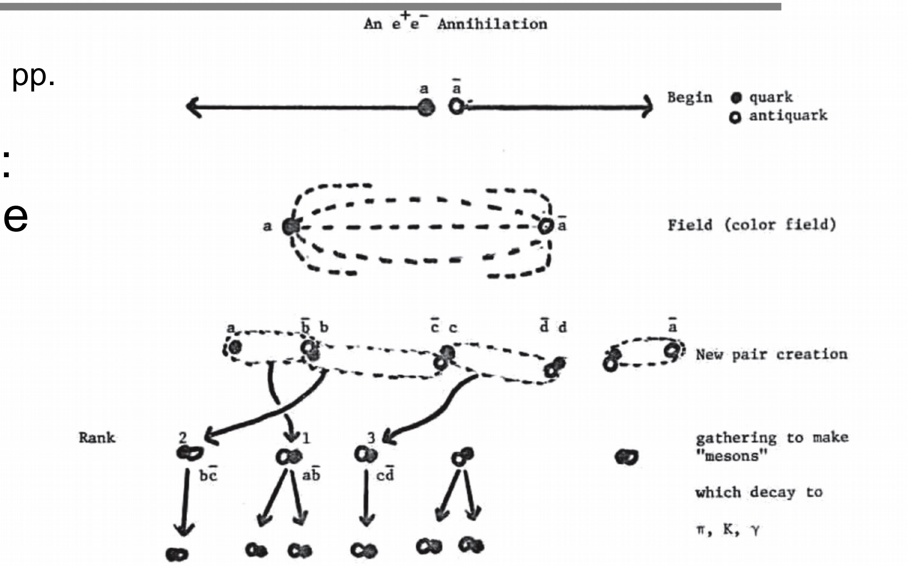


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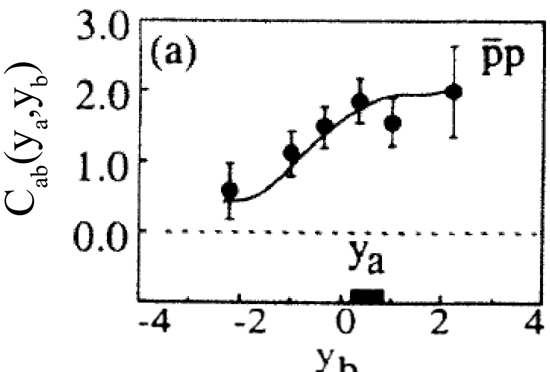
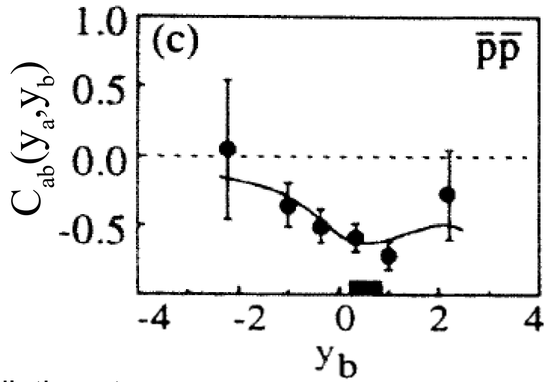
**We are not likely to find two strange particles / baryons at the same rapidity**

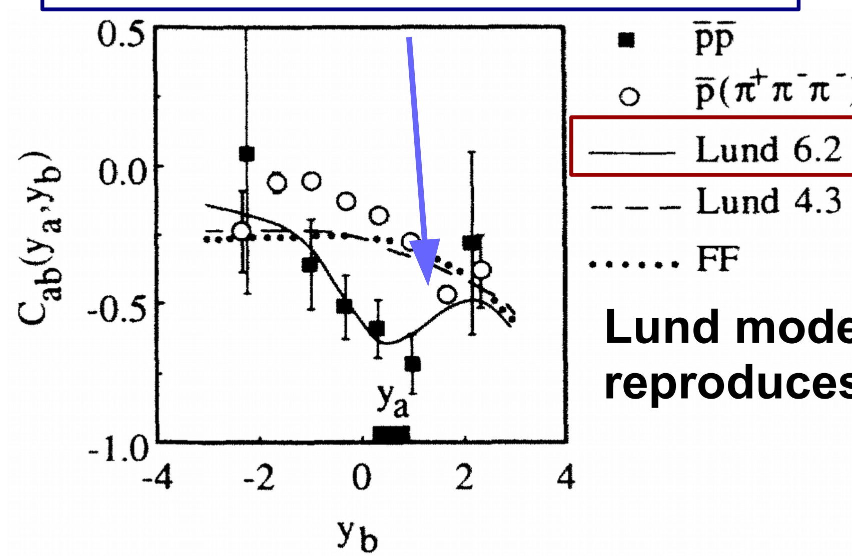
- **Models for $e^+e^-$ agree** with observations seen in data.

**correlation**




**anti-correlation**

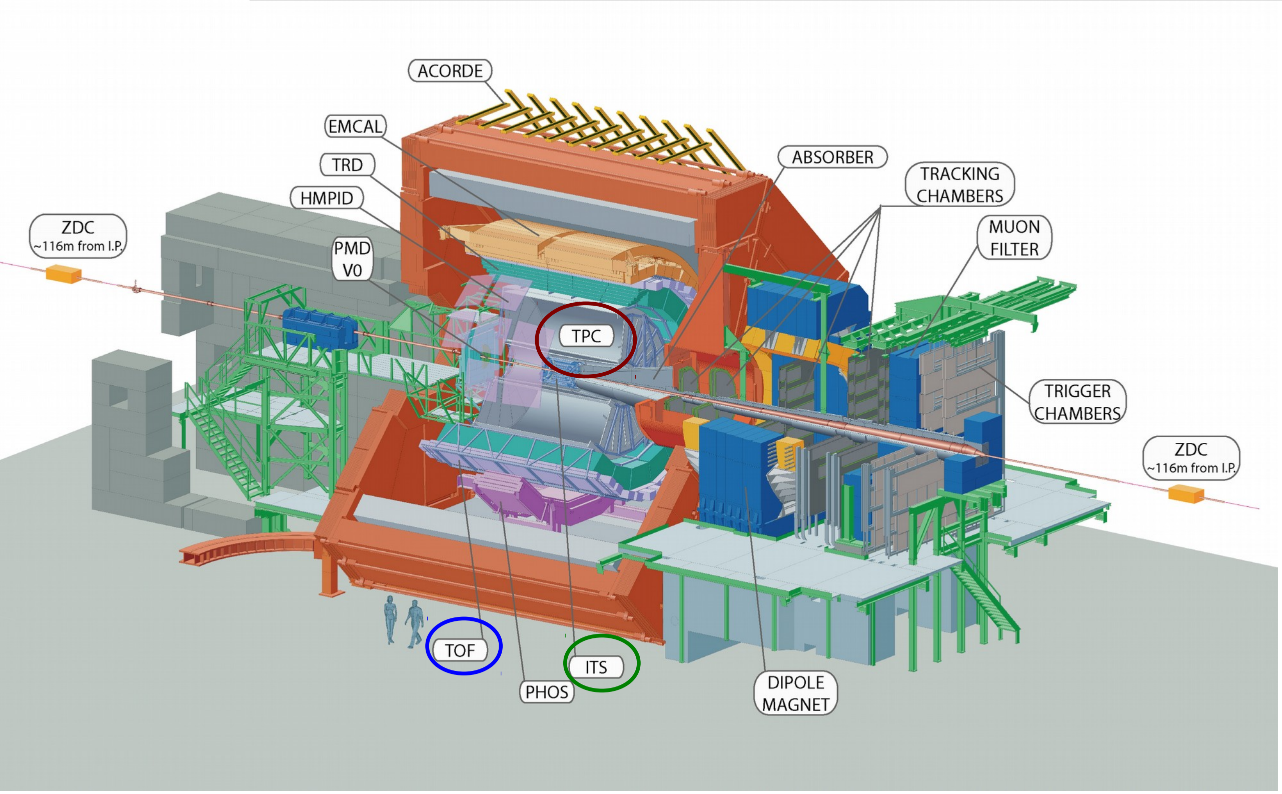



**Lund model reproduces**

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

# Data sample & analysis

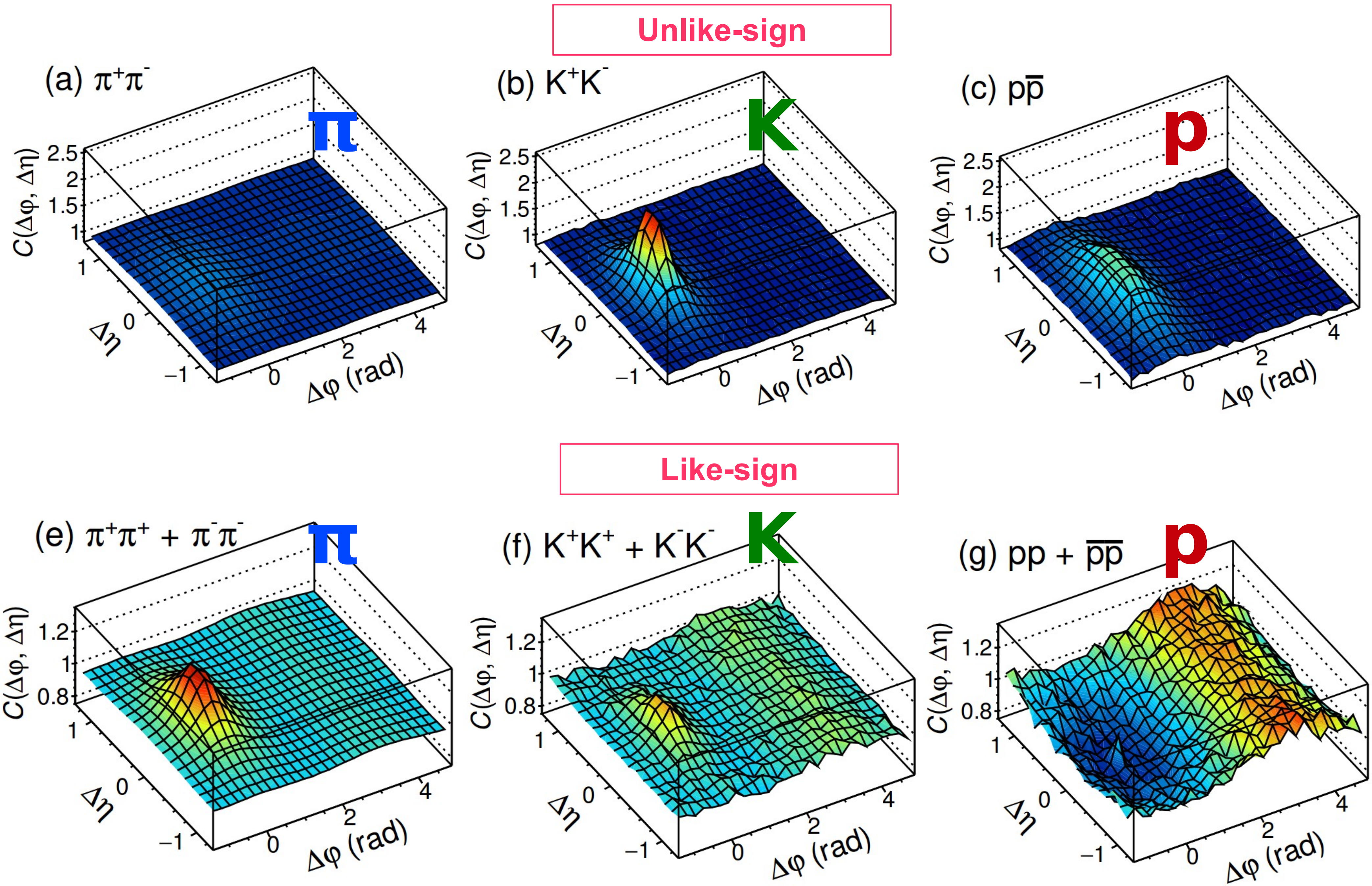



- ~200 million minimum bias pp collisions at 7 TeV registered by ALICE in 2010
- Tracking:
  - Inner Tracking System (ITS)
  - Time Projection Chamber (TPC)
- Particle identification:
  - TPC
  - Time-of-Flight (TOF)
- Recent paper **arXiv:1612.08975**
- Preliminary results

- 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*
  - $|\eta| < 0.8$

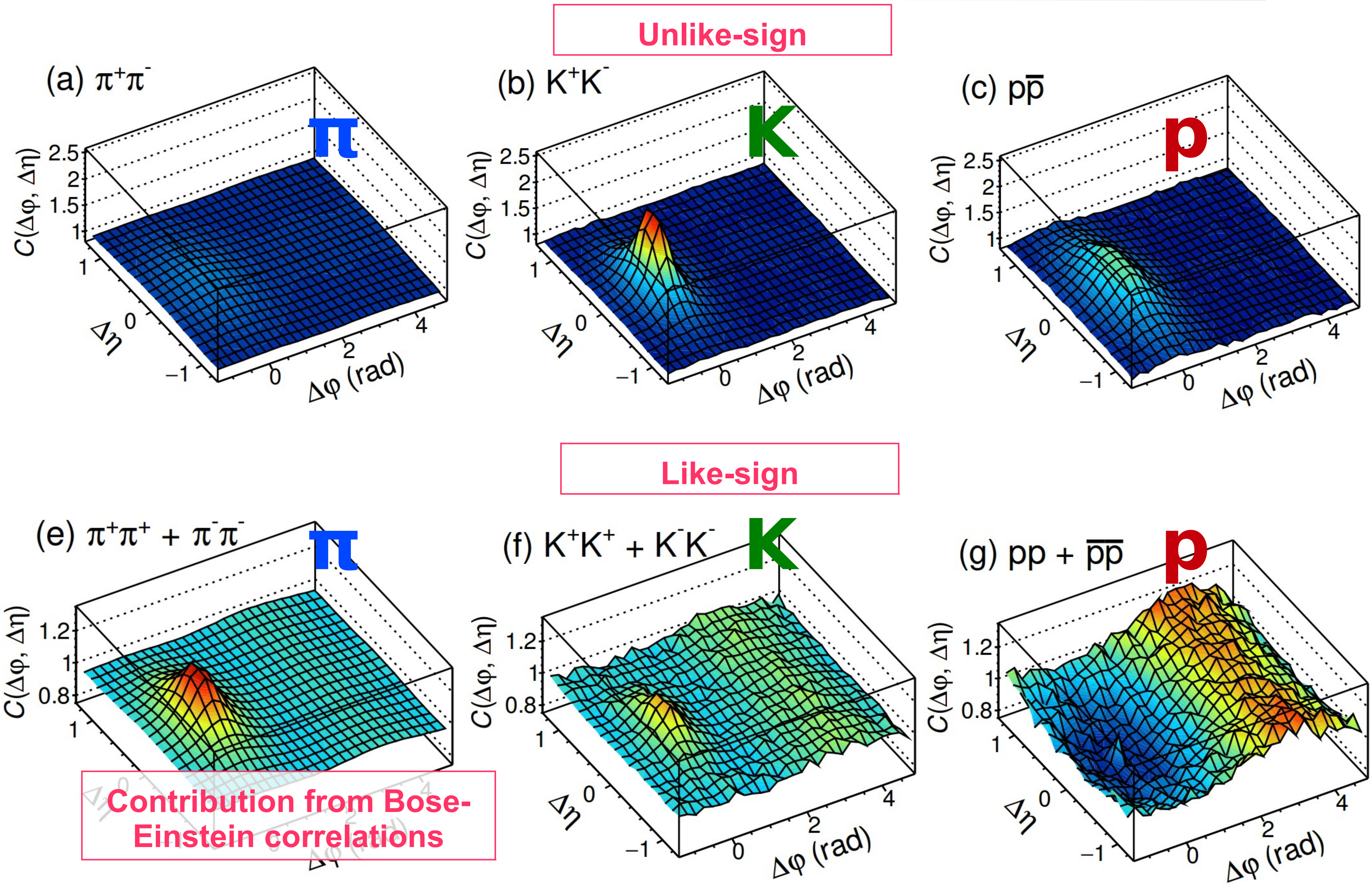
# ΔηΔφ of identified particles

arXiv:1612.08975



# ($\Delta\eta$,$\Delta\varphi$) of identified particles

arXiv:1612.08975



# (Δη,Δφ) of identified particles

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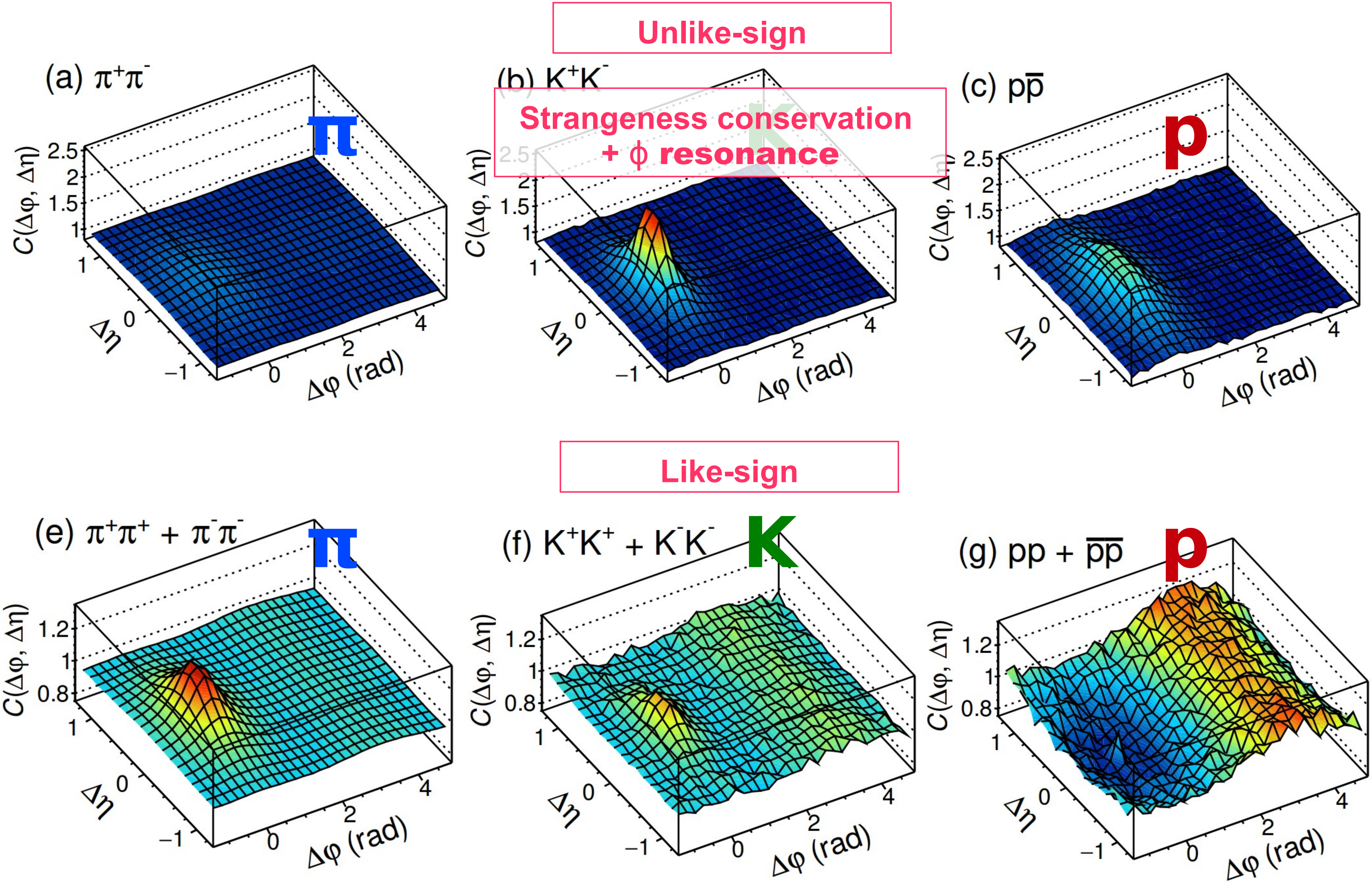

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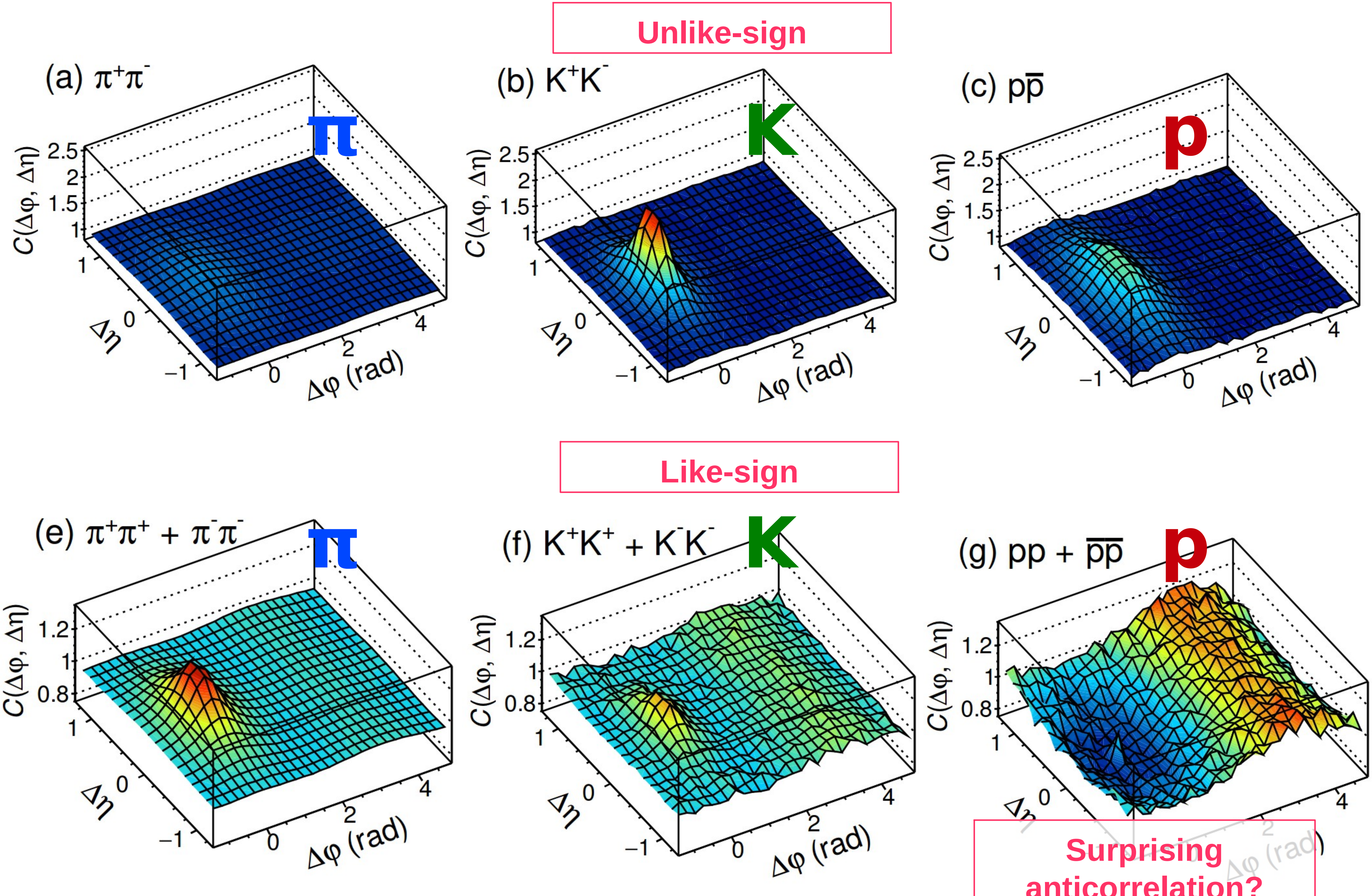

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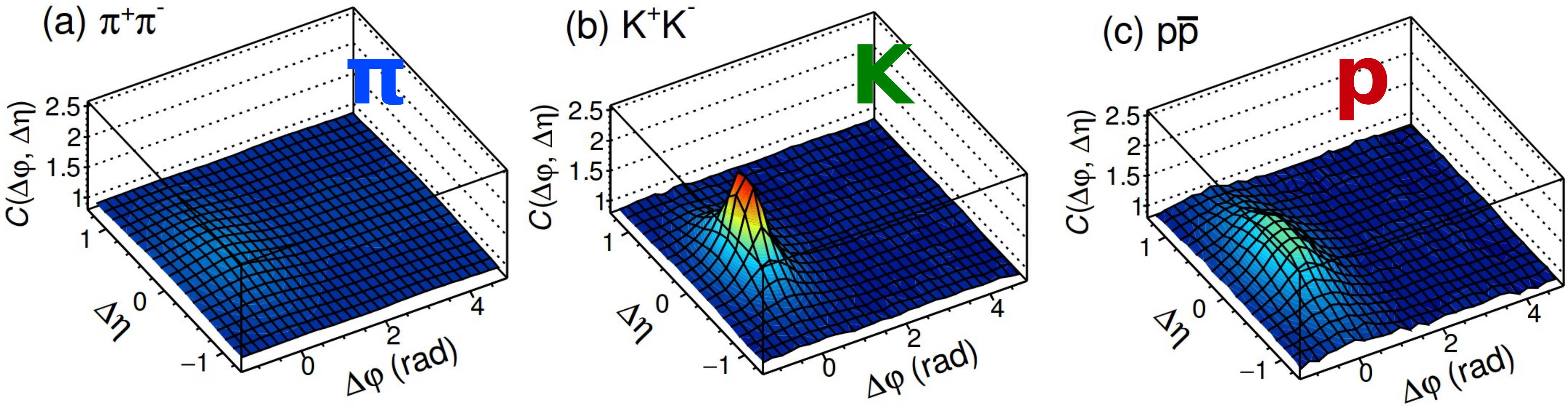
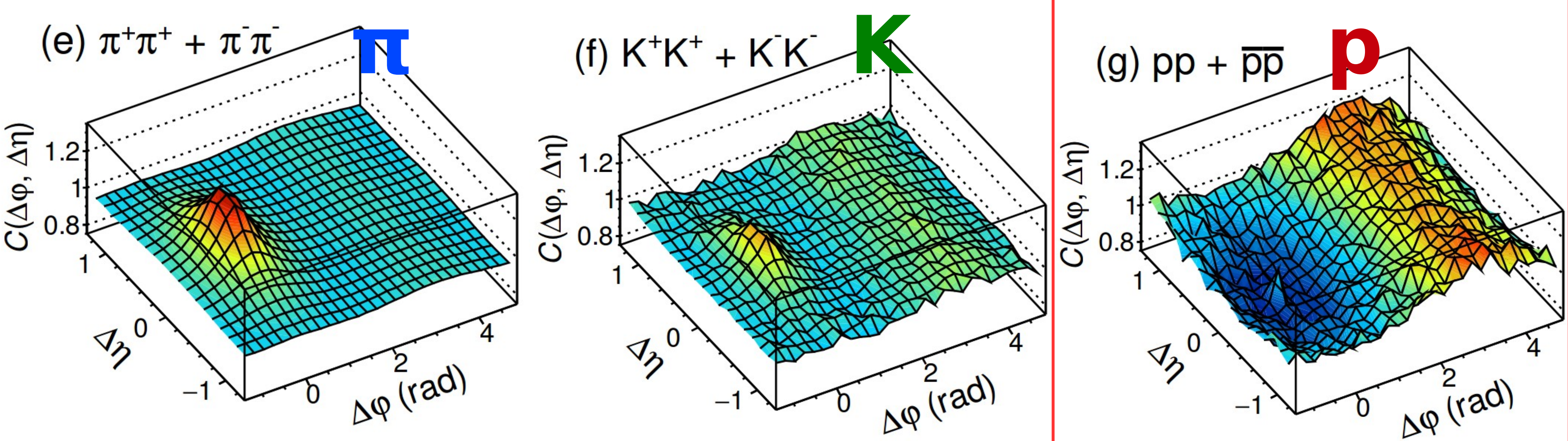
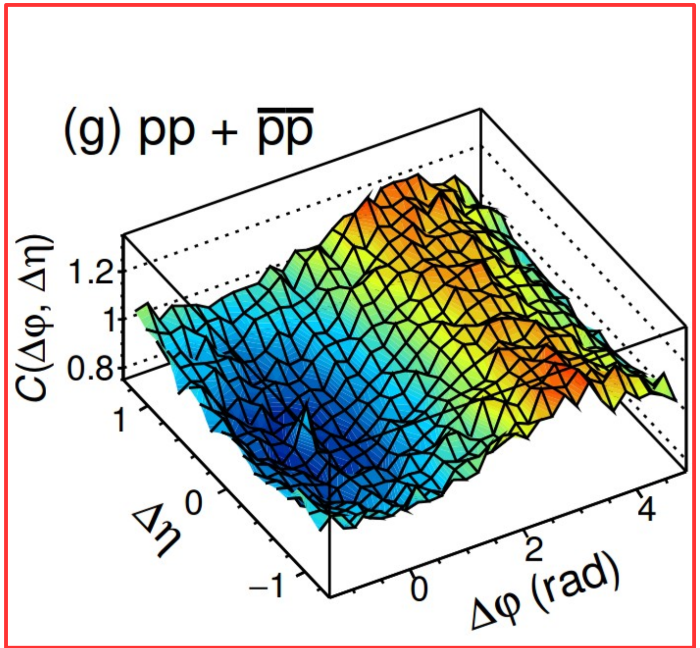



*Let's compare with models!*



# ΔηΔφ of identified particles in pp collisions



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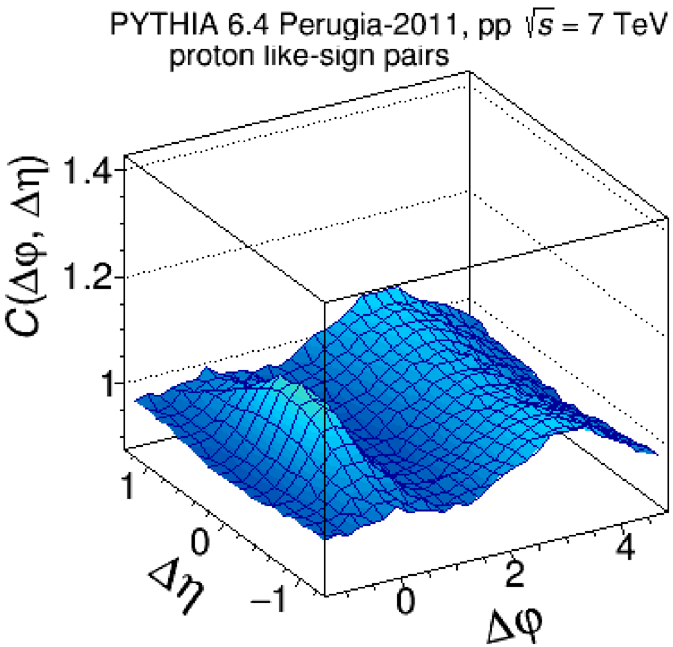


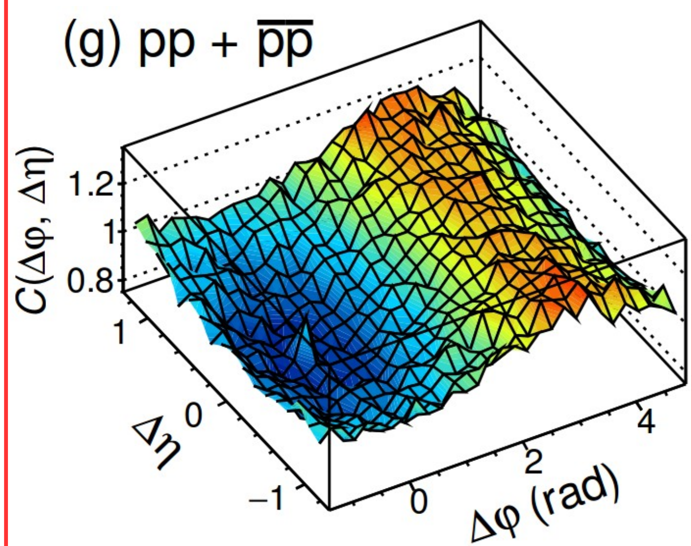

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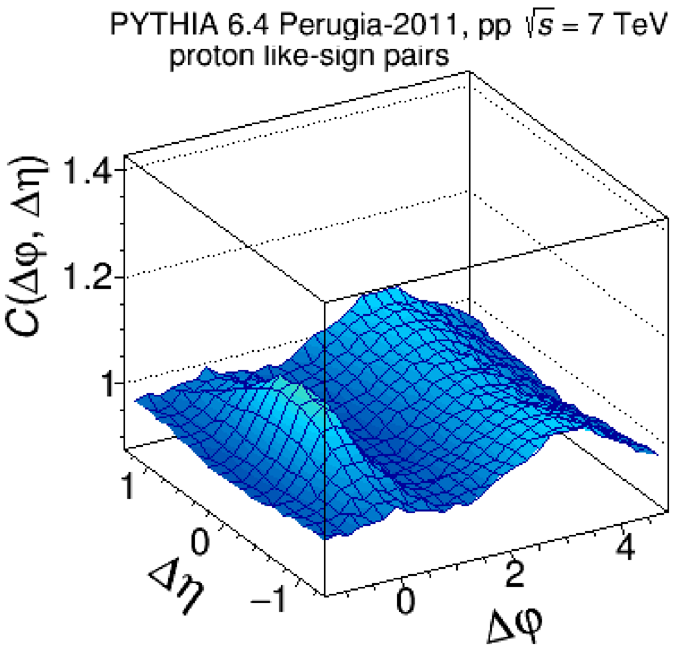


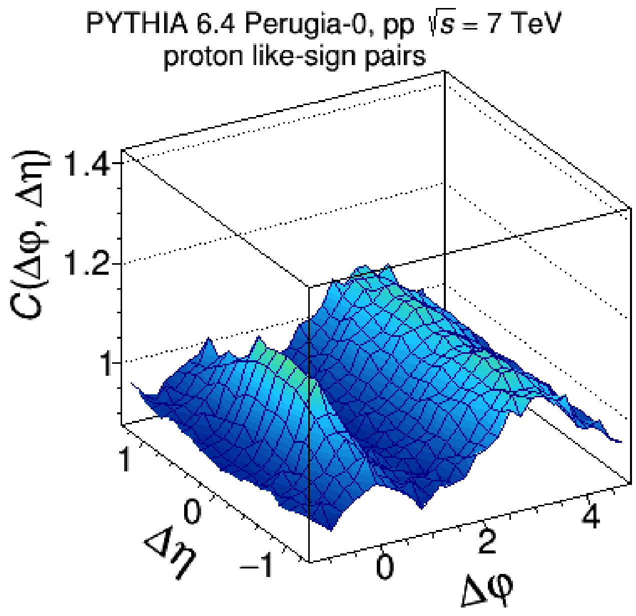


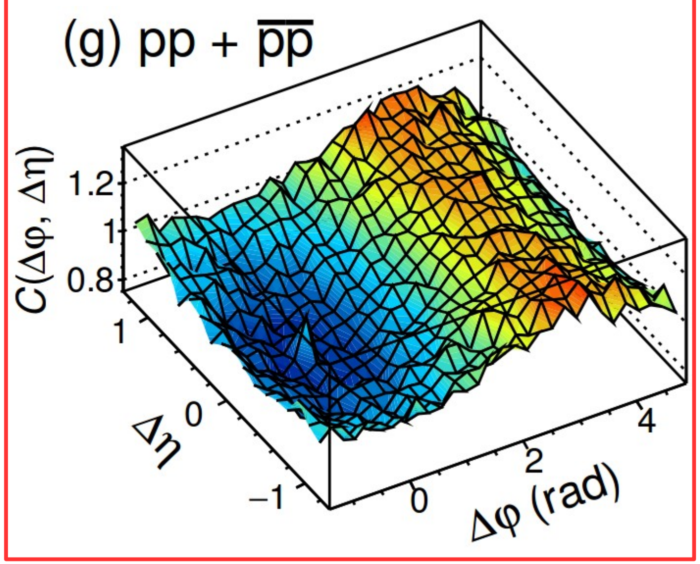

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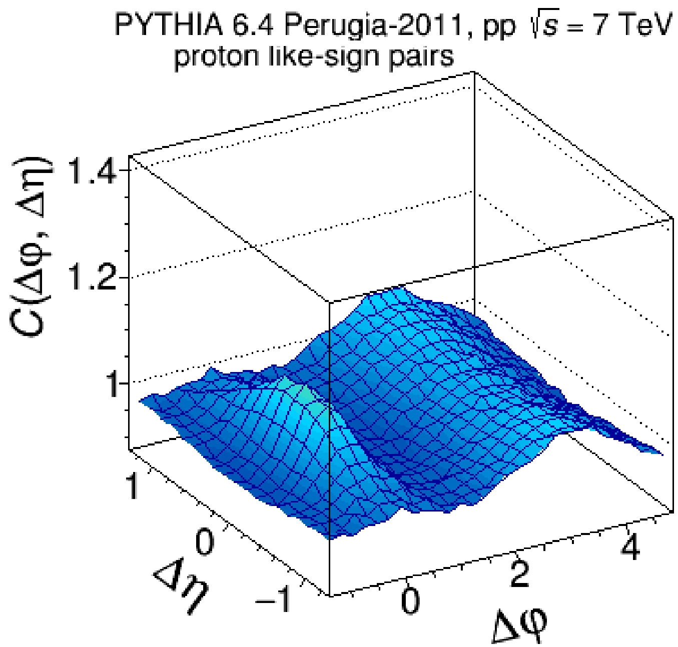


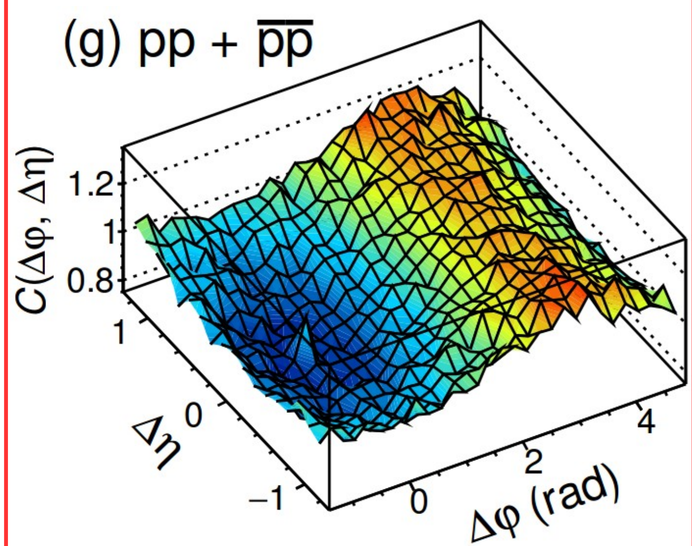

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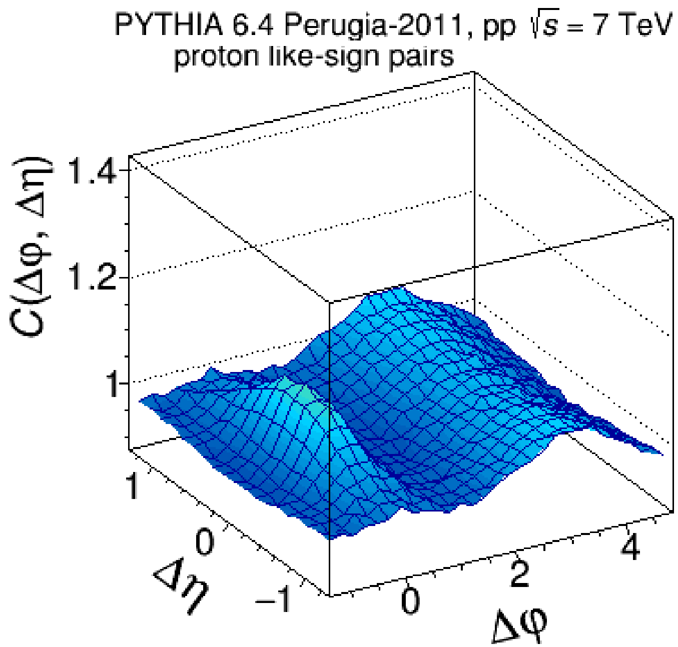
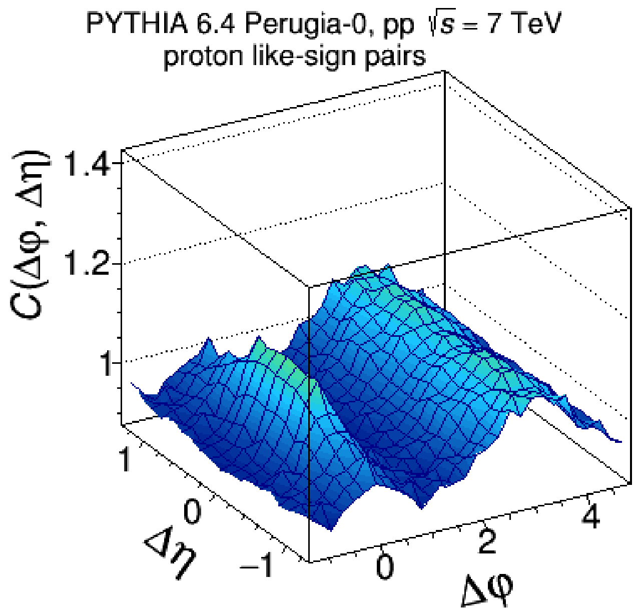
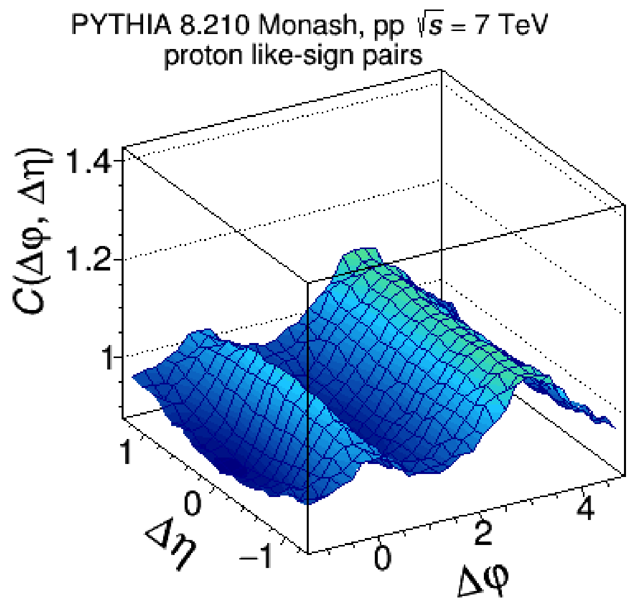
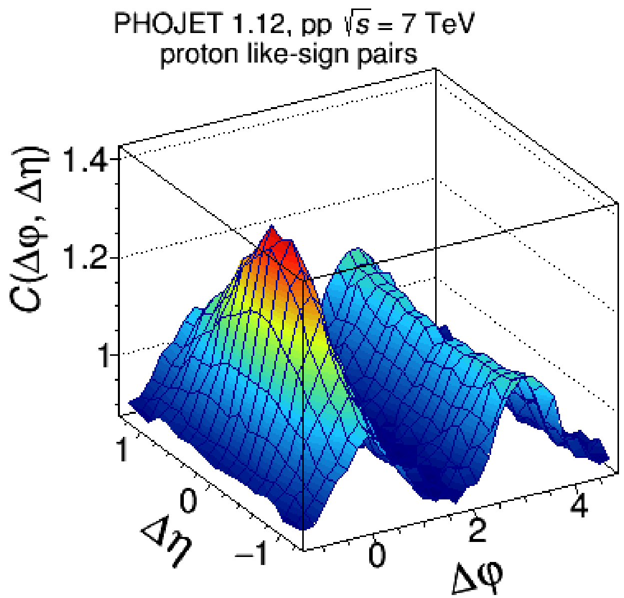
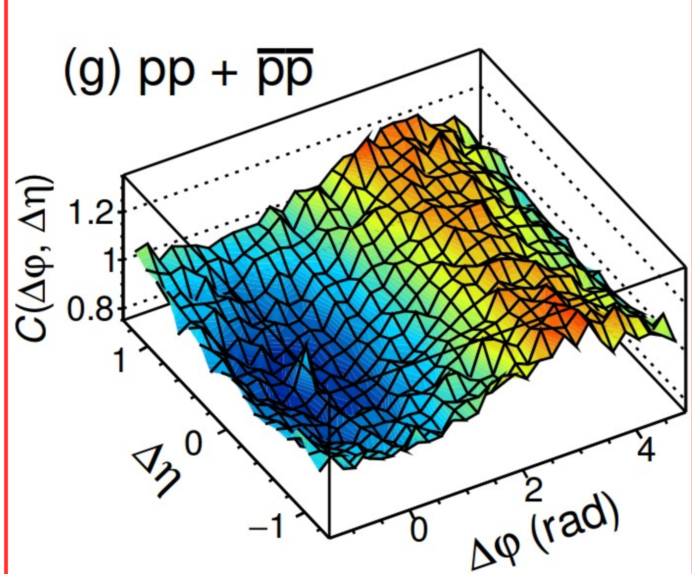


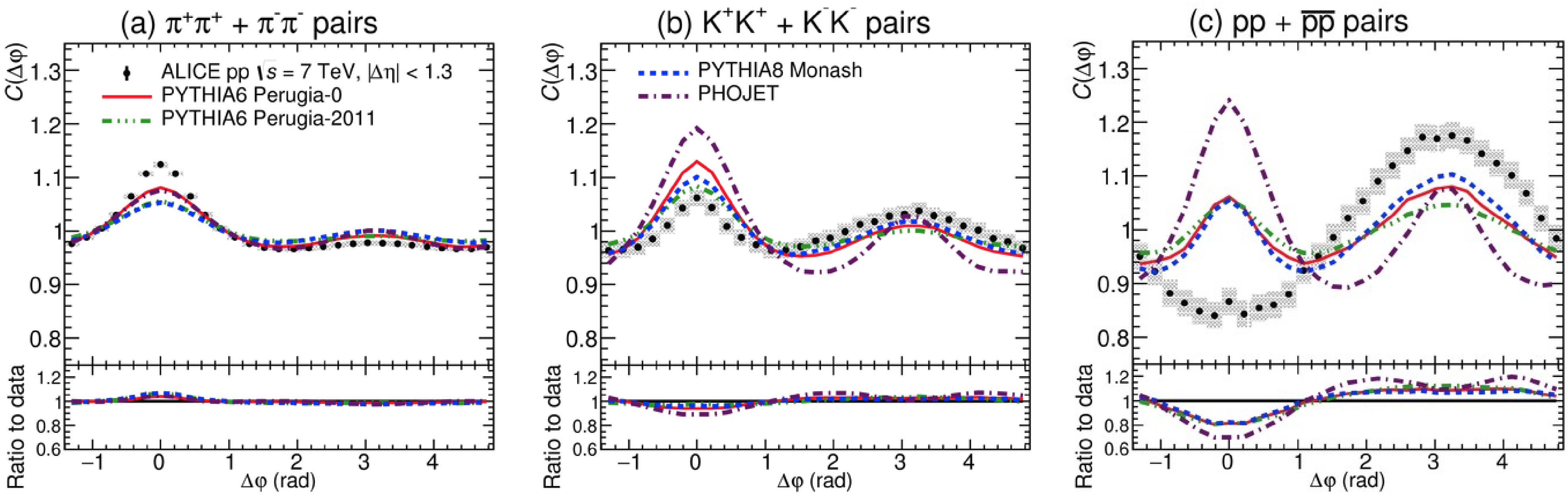

*None of common MC models reproduces ALICE data!*



# 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 – 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**

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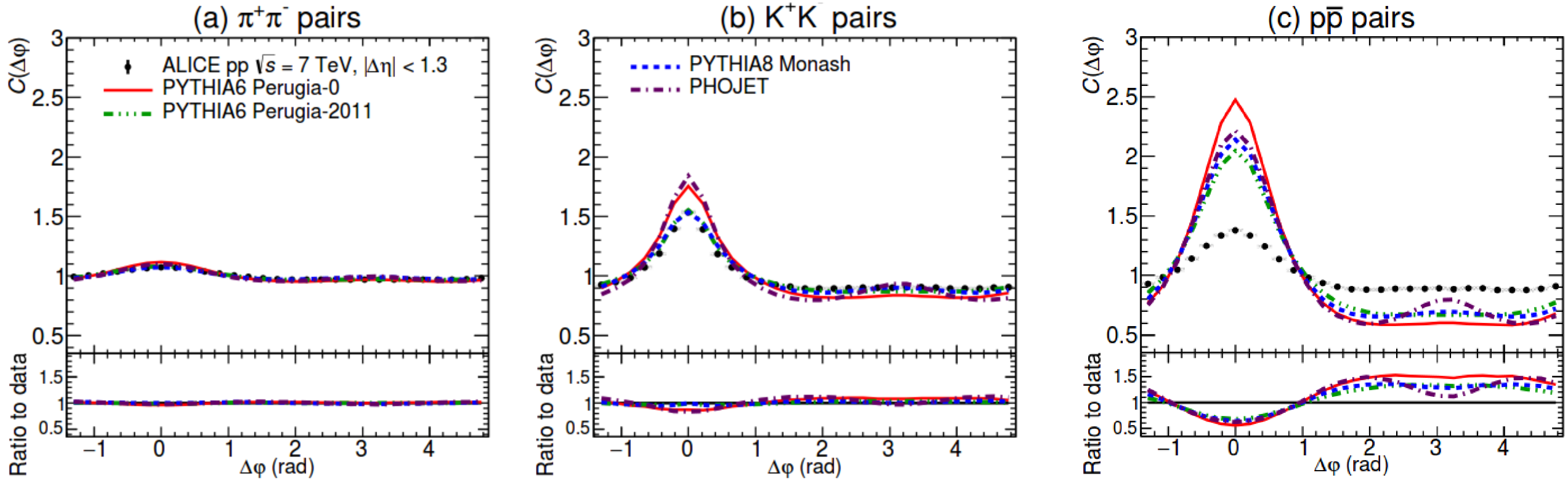



• The models reproduce reasonably well the angular correlations for mesons

• The models fail to reproduce the results for baryons – apparently they produce 2 baryons close in the phase space, also baryon-antibaryon pairs have 2 x the magnitude for MC

• **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**

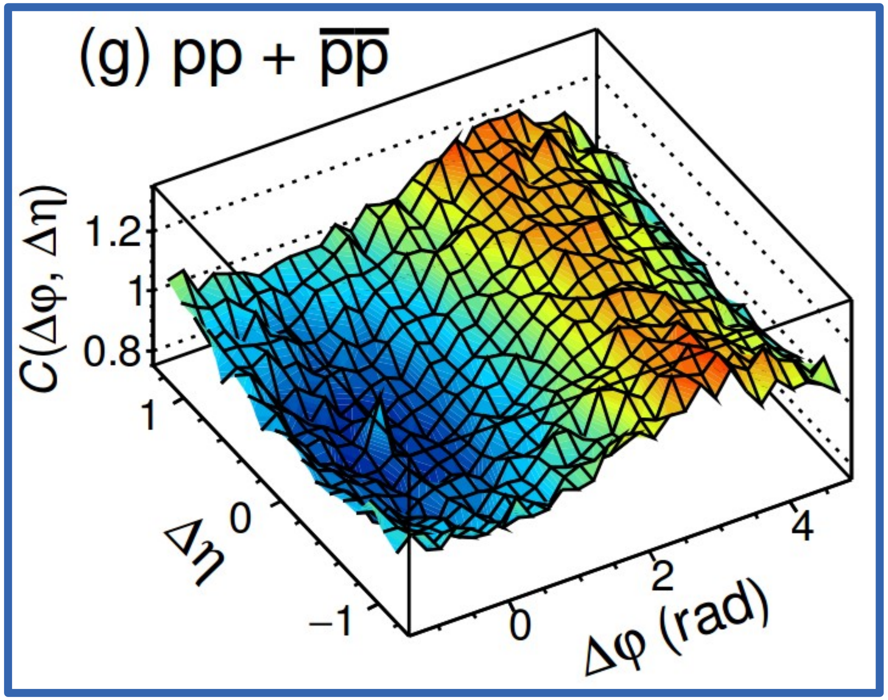
# Possible explanations

## Not likely (checked with MC):

- Depletion is a simple manifestation of **"local" baryon number conservation and energy 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?!**

## Other possible explanations:

- Too small pT range?
- Coulomb repulsion?
- Other baryons?
- Fermi-Dirac Quantum Statistics?



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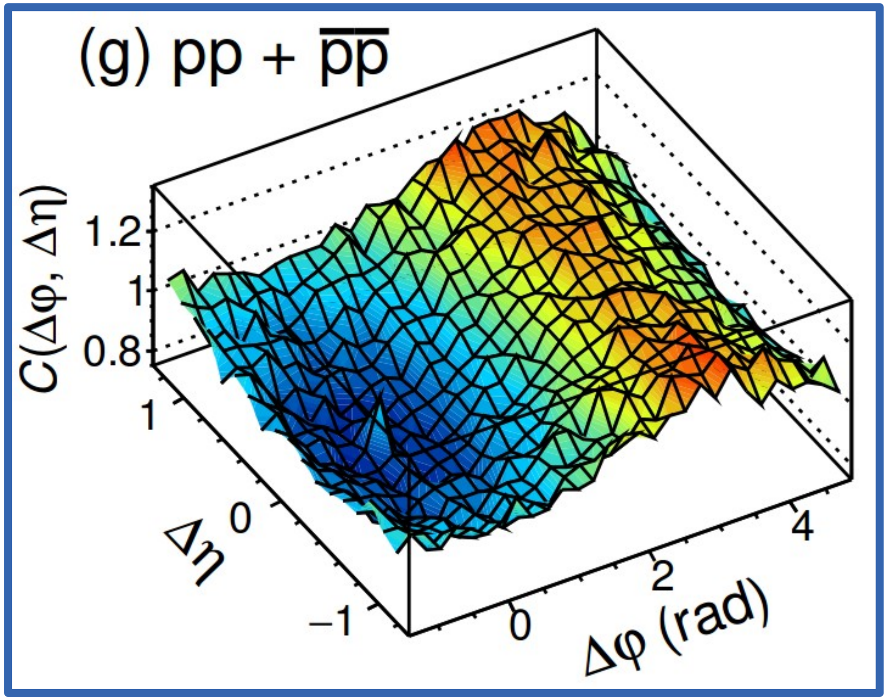
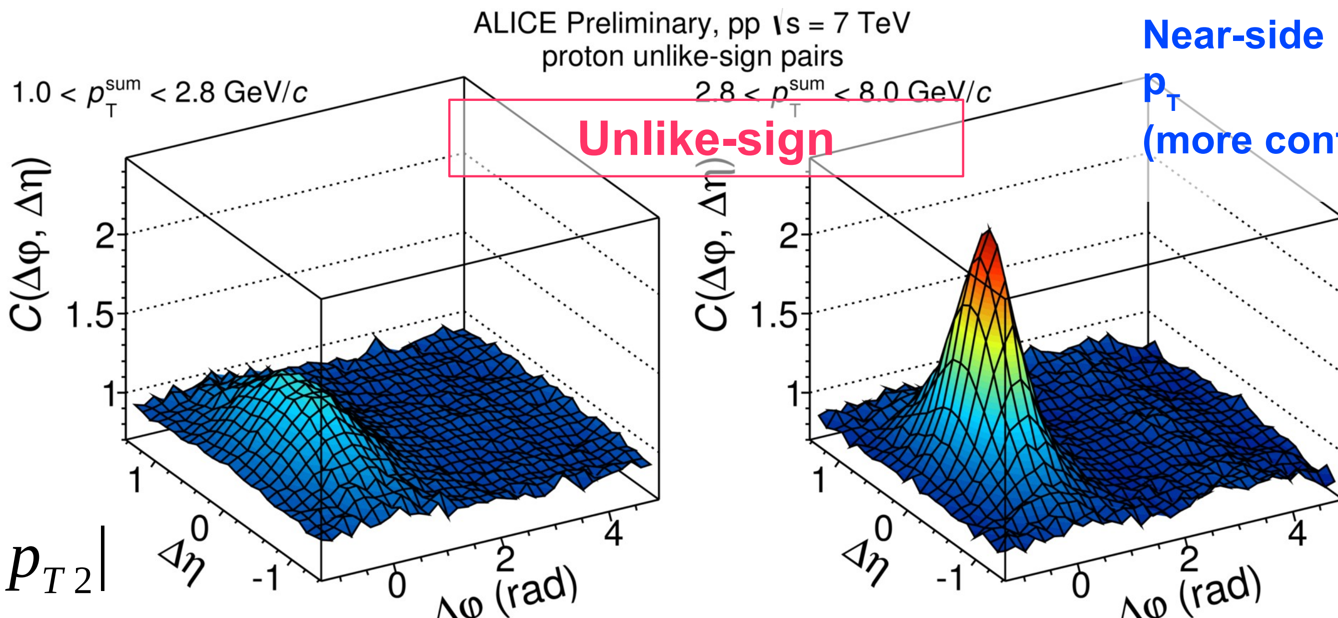


# Protons

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

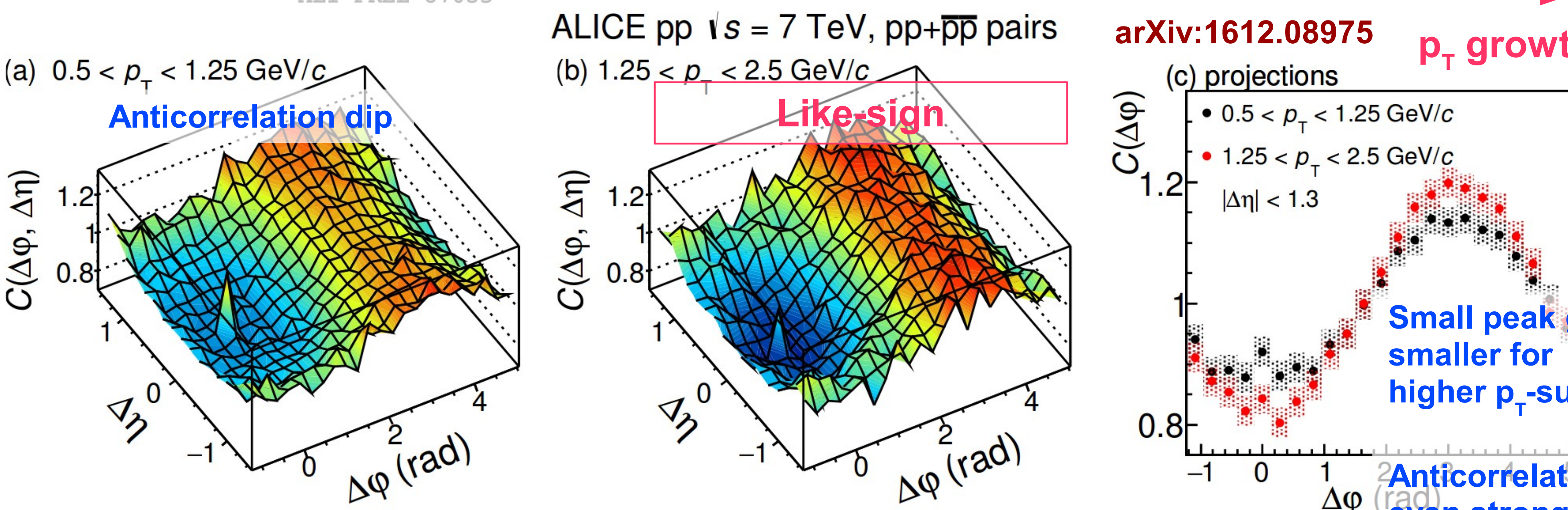



Near-side peak grows with $p_T$ (more contribution from jets)

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

$p_T$ growth

arXiv:1612.08975




Anticorrelation dip

Small peak gets smaller for higher $p_T$-sum

Anticorrelation even stronger

# Protons

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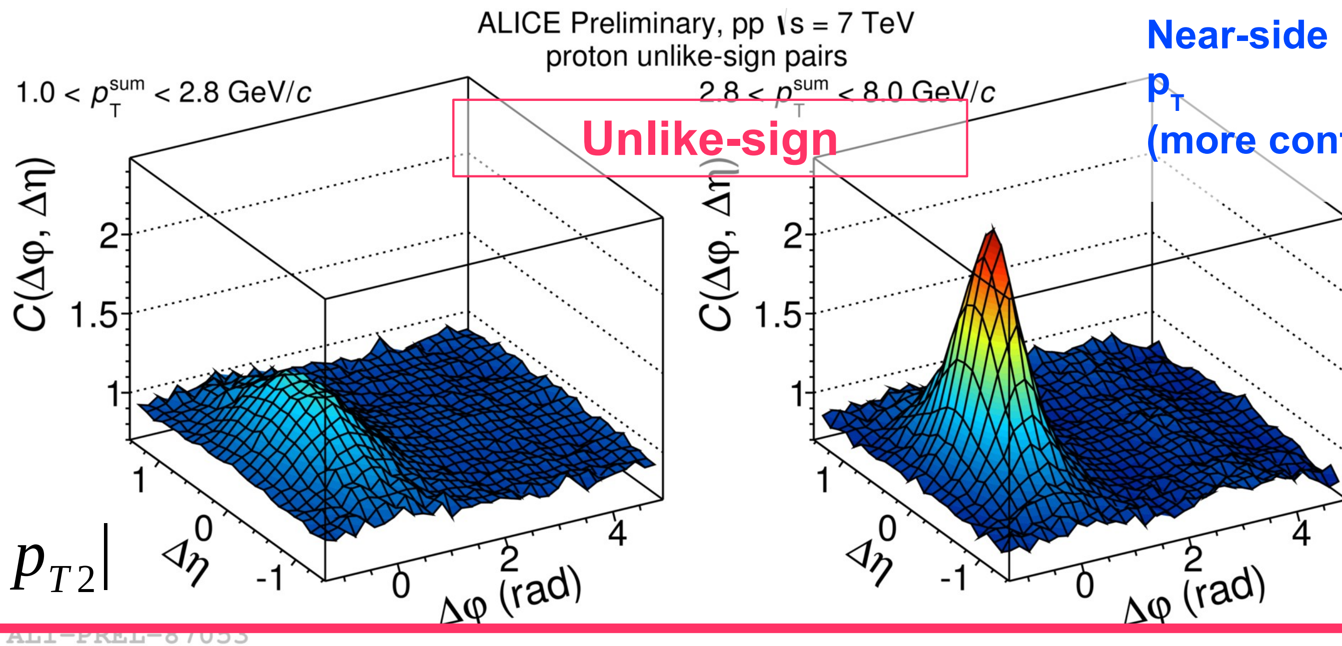
Unlike-sign

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$p_T$ growth

Like-sign

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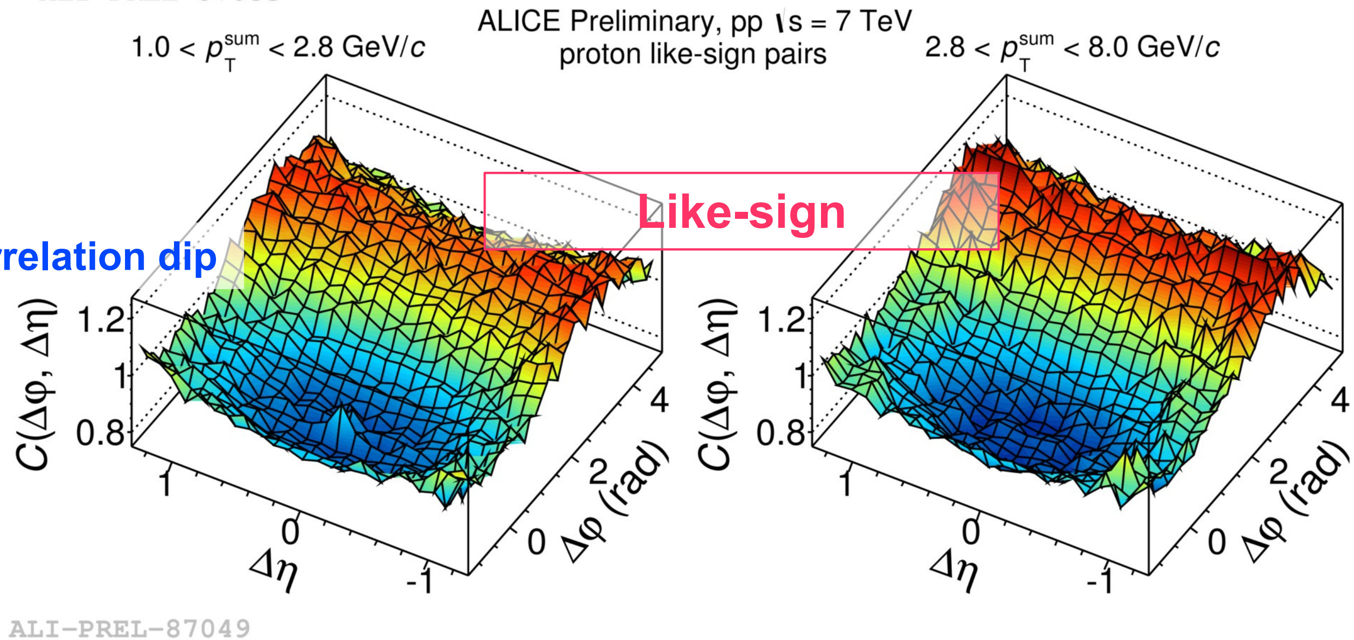


Small peak disappears for high $p_T$-sum

Shape of the dip does not change

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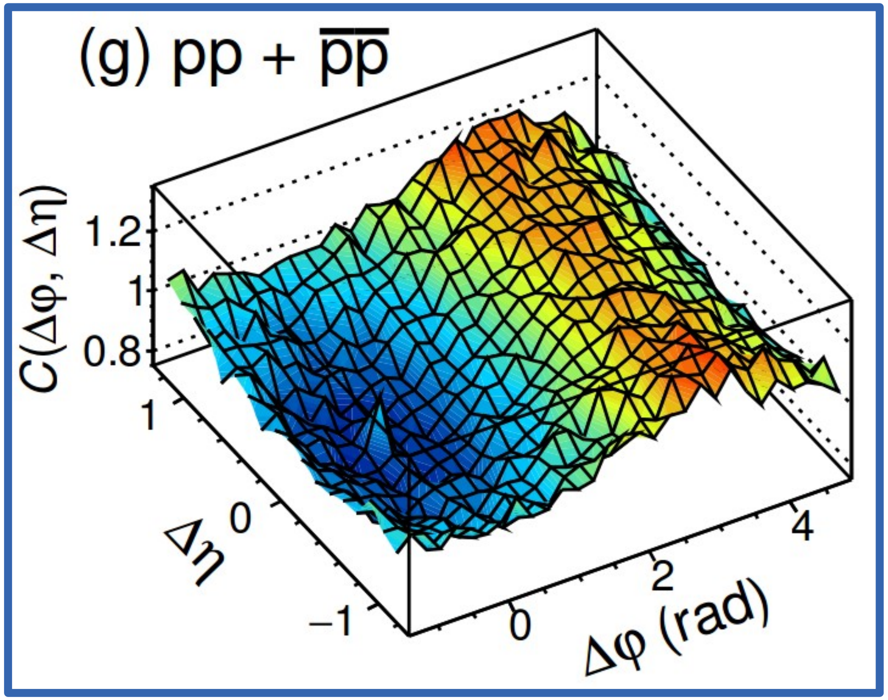
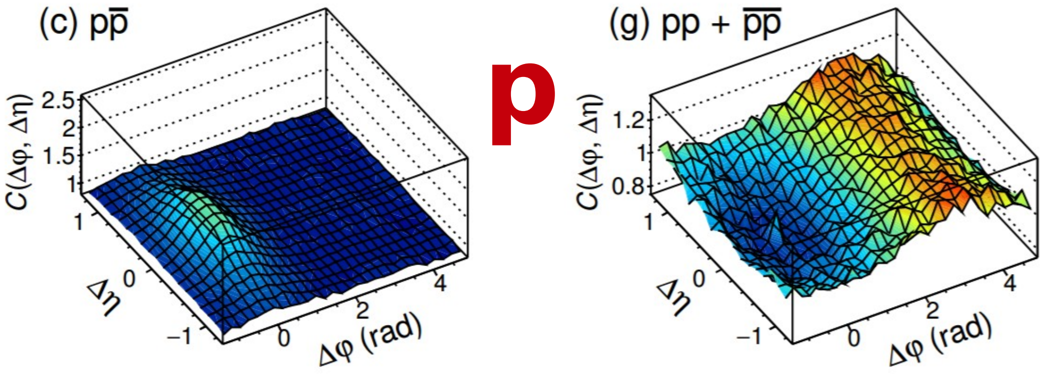


# Other baryons?

- Useful to check if effect persists for other baryons than protons – is this a common effect for all baryons?



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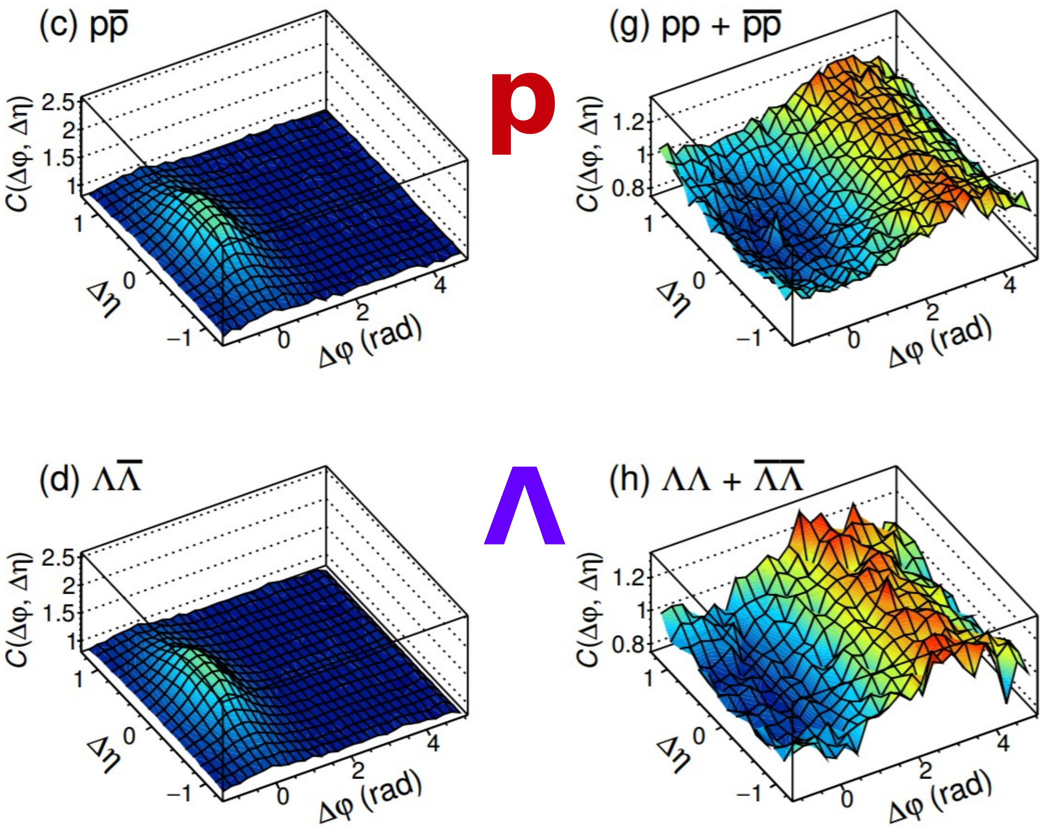
- Correlation functions were calculated for lambda hiperons

- **All observations from pp can be extended to ΛΛ**

- Since Λ baryons are neutral, we are sure that effects of Coulomb repulsion plays marginal role



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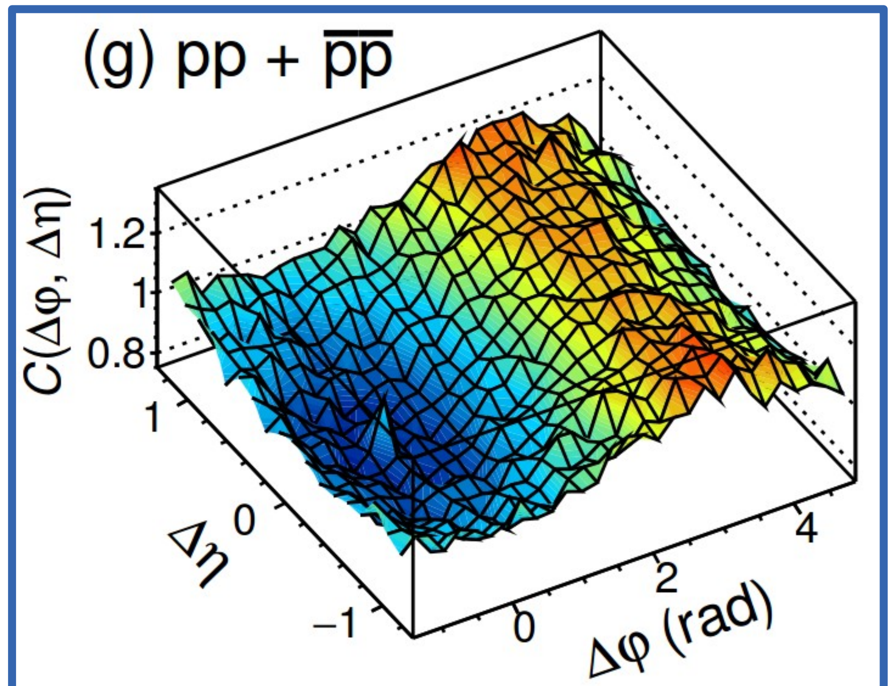
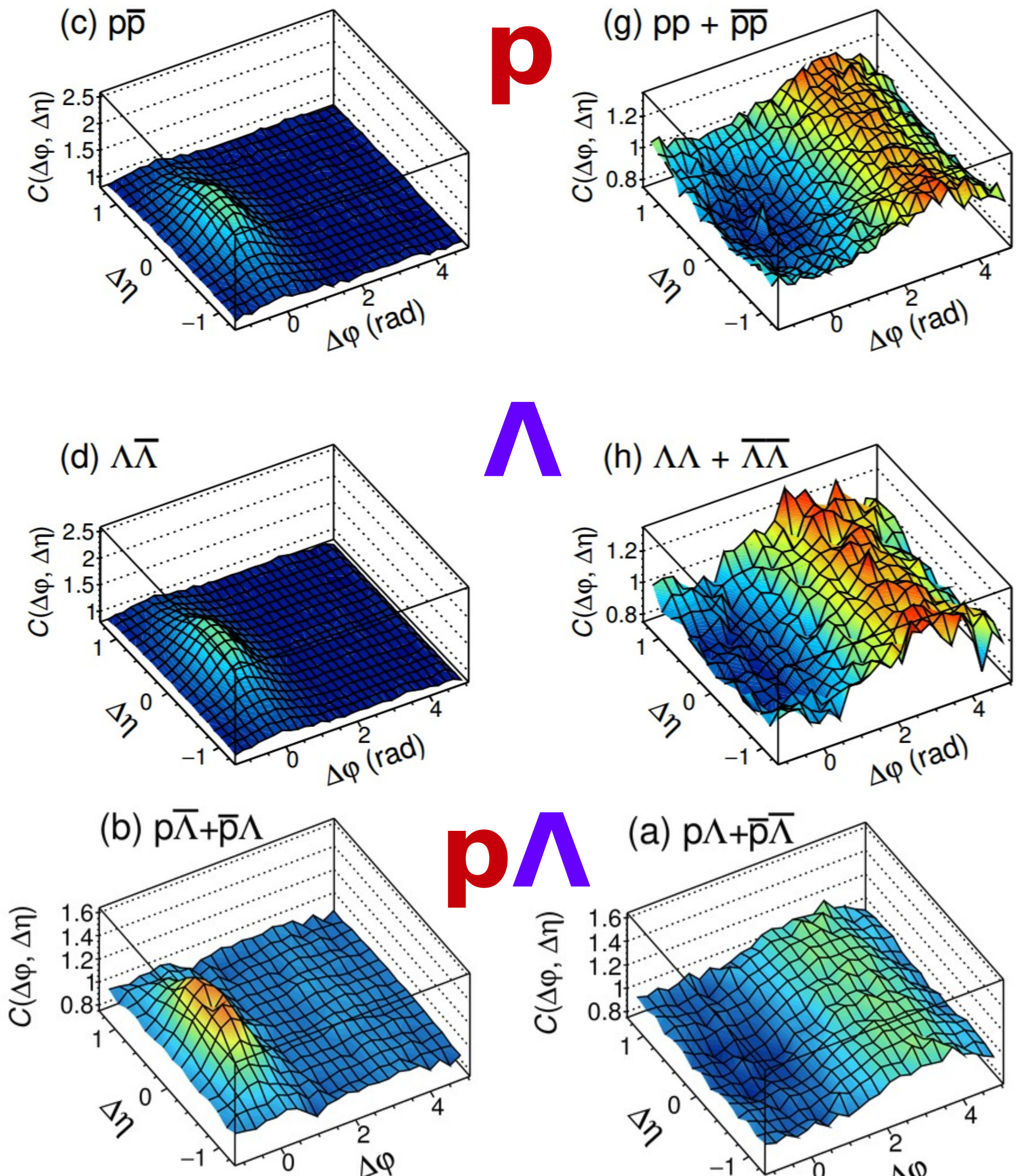


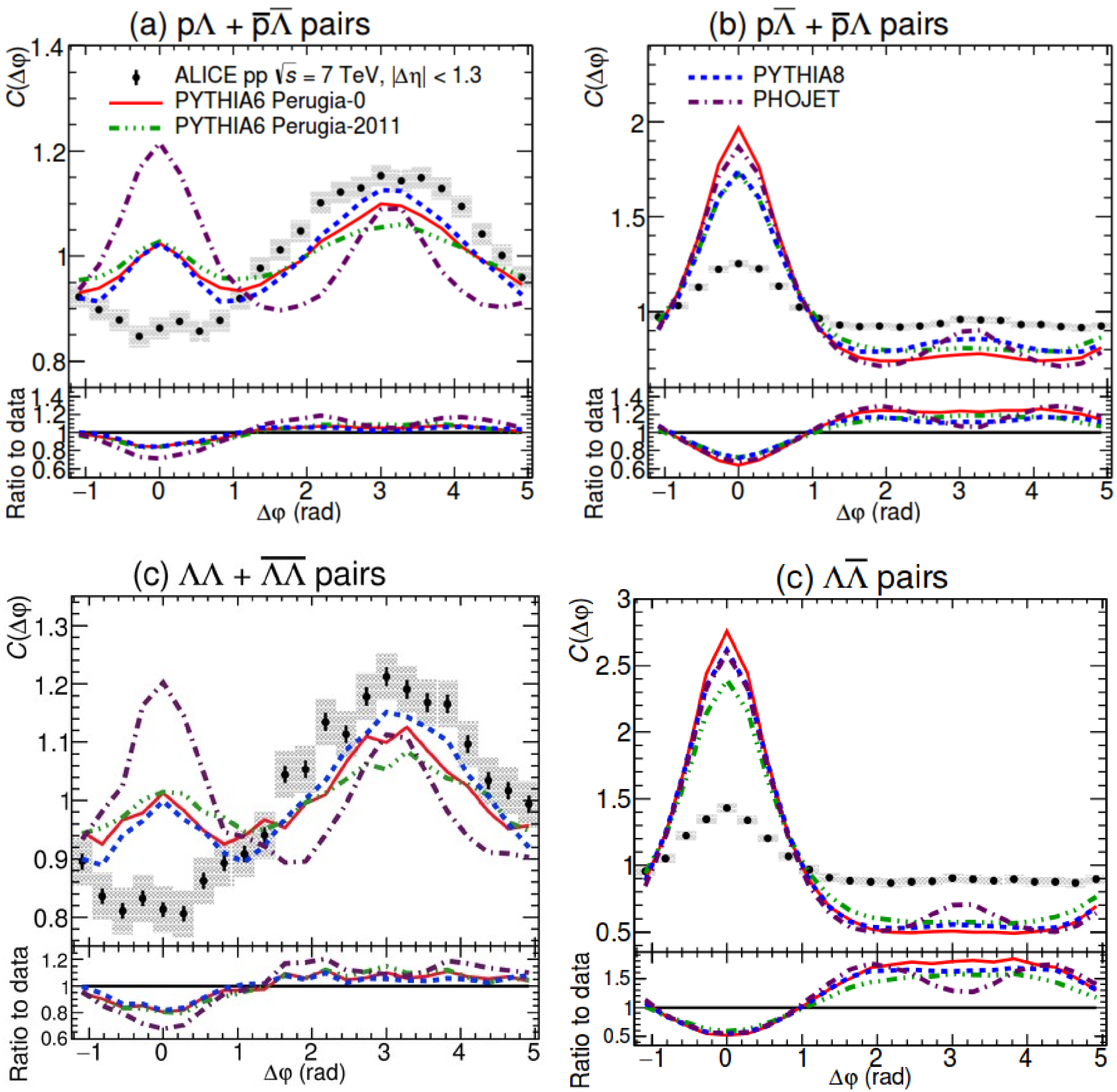
# pΛ correlation functions

- Useful to check if effect persists for other baryons than protons – is this a common effect for all baryons?
- Correlation functions were calculated for non-identical proton-lambda pairs
- **All observations from pp and ΛΛ can be extended to pΛ**
- Since p and Λ are not identical particles, we are sure that effects of Fermi-Dirac quantum statistics play marginal role



# Comparison to MC models

arXiv:1612.08975




- **The models fail to reproduce the results for baryons for all pair combinations**

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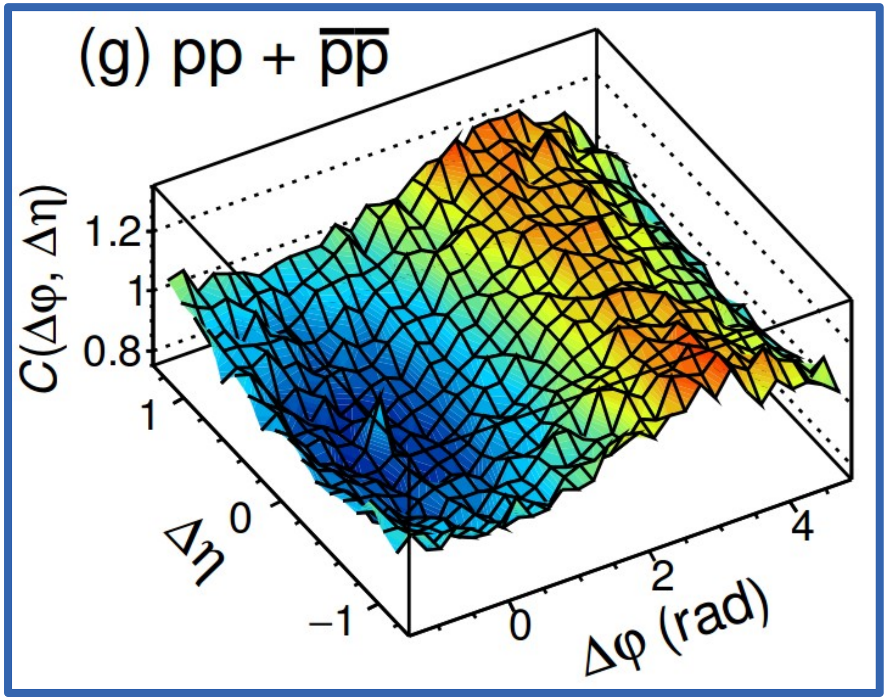
## Not likely (checked with MC):

- Depletion is a simple manifestation of **"local" baryon number conservation and energy 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?!**

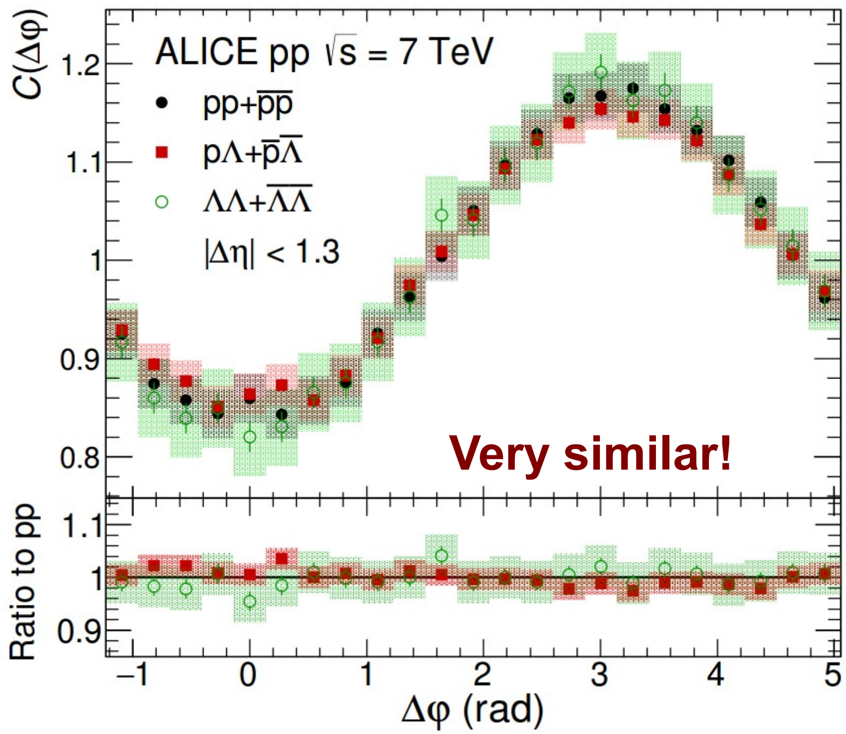
## Other possible explanations:

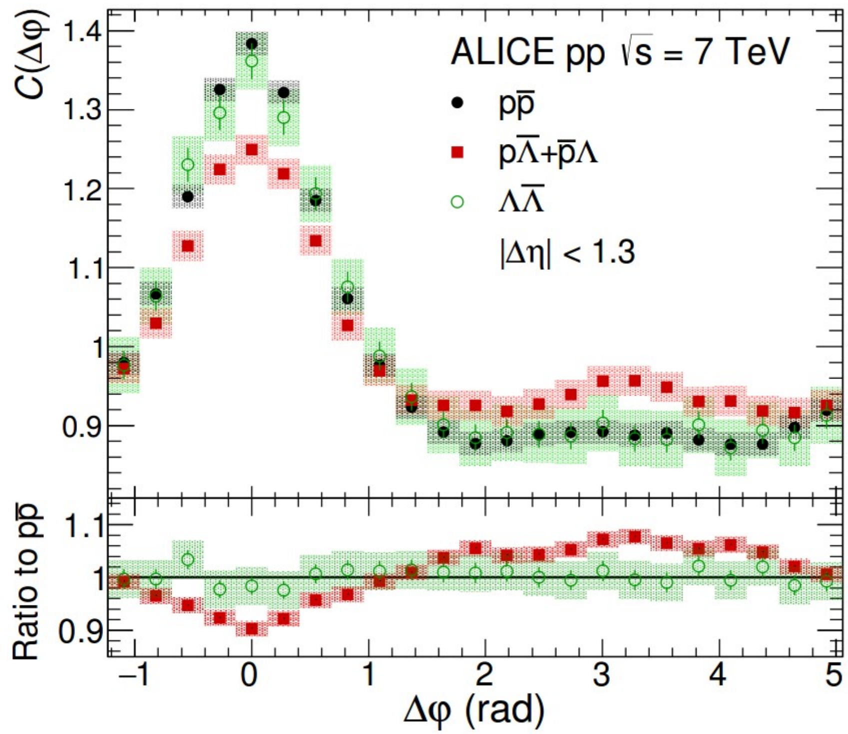
- ~~Too small pT range?~~
- ~~Coulomb repulsion?~~
- ~~Other baryons?~~
- ~~Fermi-Dirac Quantum Statistics?~~
- ???



# Comparison between pairs

arXiv:1612.08975

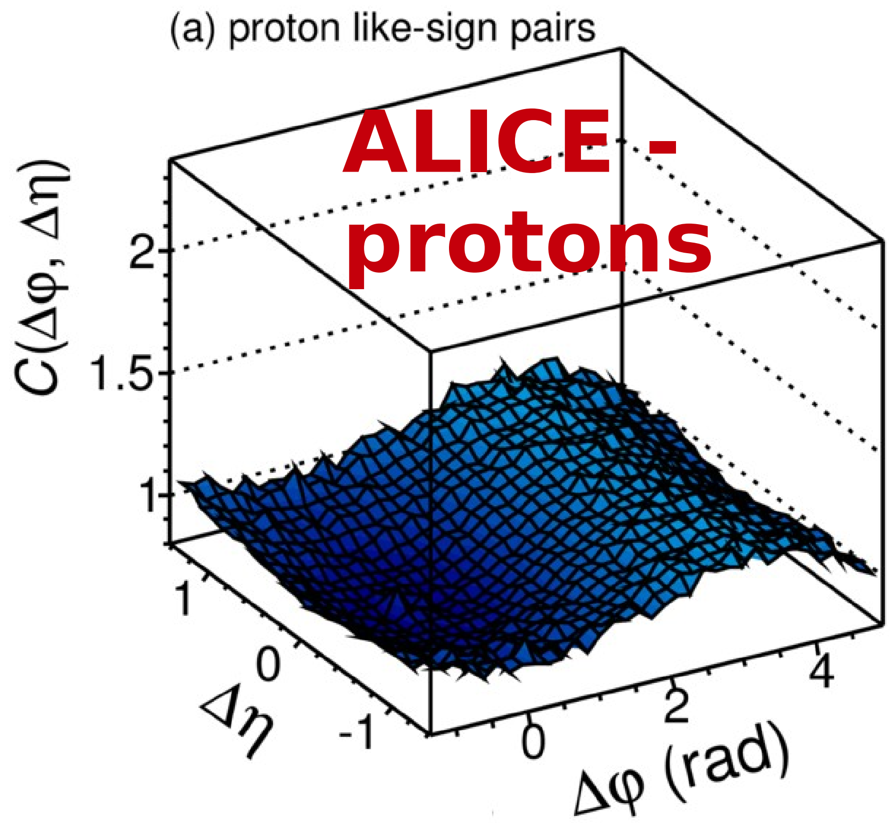


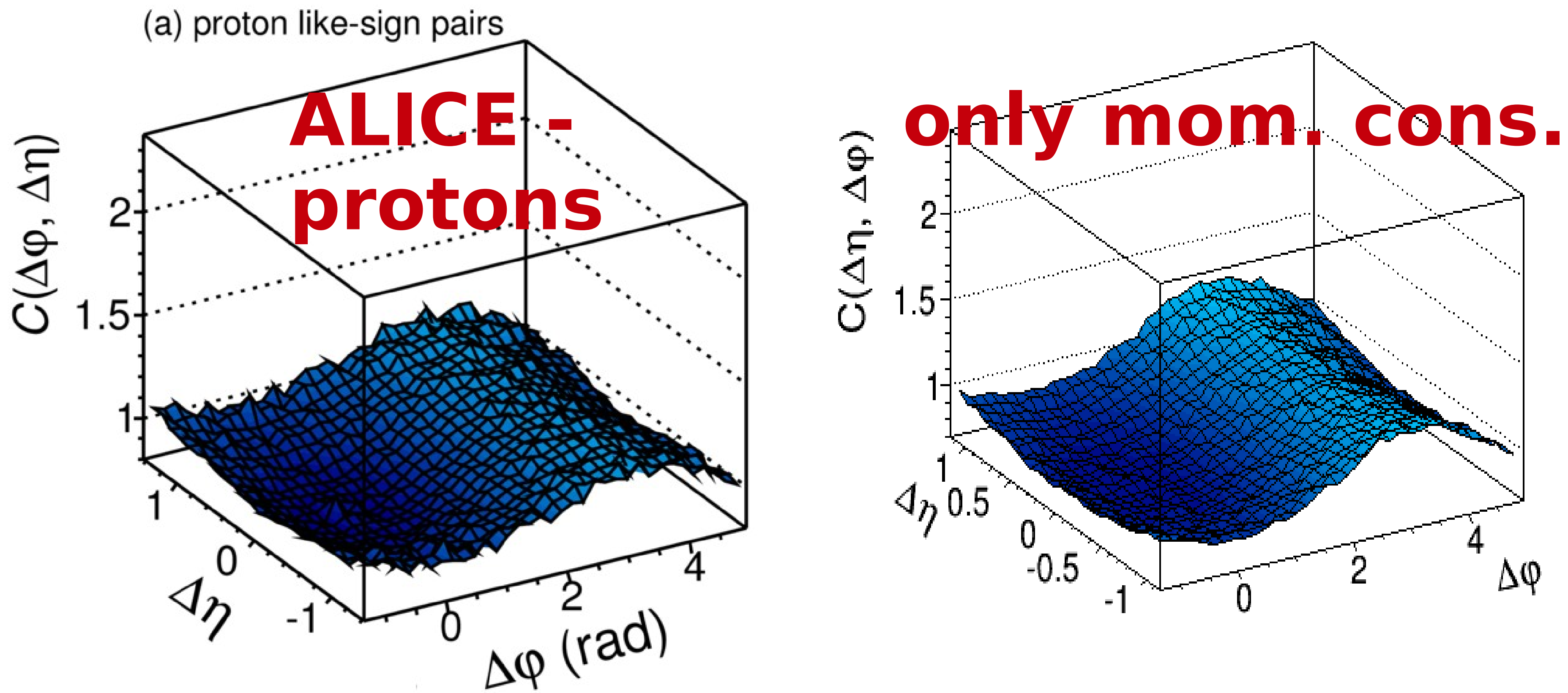

**The shape of the correlation function for all studied baryon–baryon pairs is similar, regardless of particles' electric charge.**

**The depression is a characteristic attribute connected solely to the baryonic nature of a particle.**

# ΔηΔφ of identified particles of pp collisions

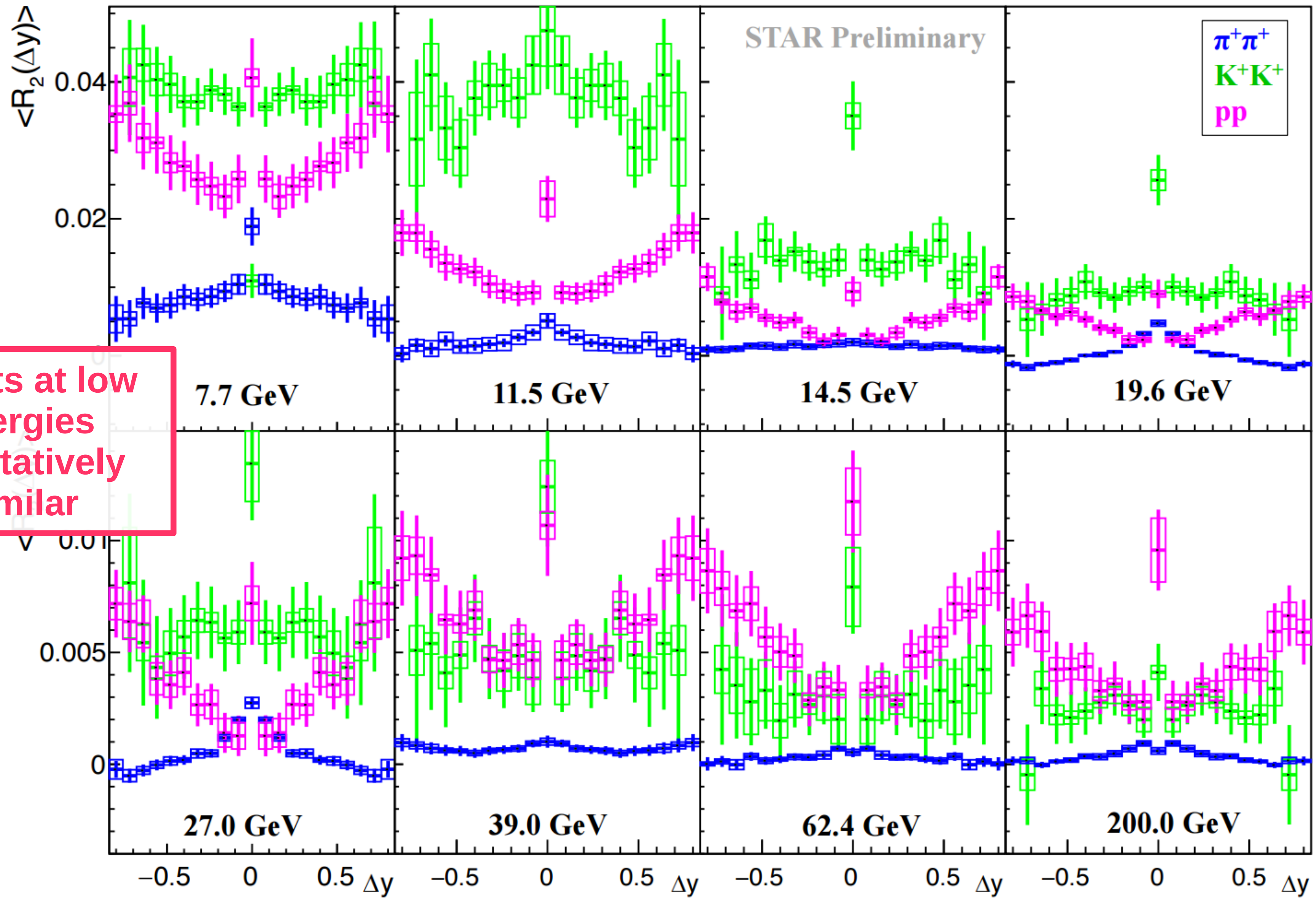


# ΔηΔφ of identified particles of pp collisions



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

**SRC was not subtracted**




Effects at low energies qualitatively similar

**Minima in $<R_2>$ of protons around $\Delta y=0$ at all beam energies**

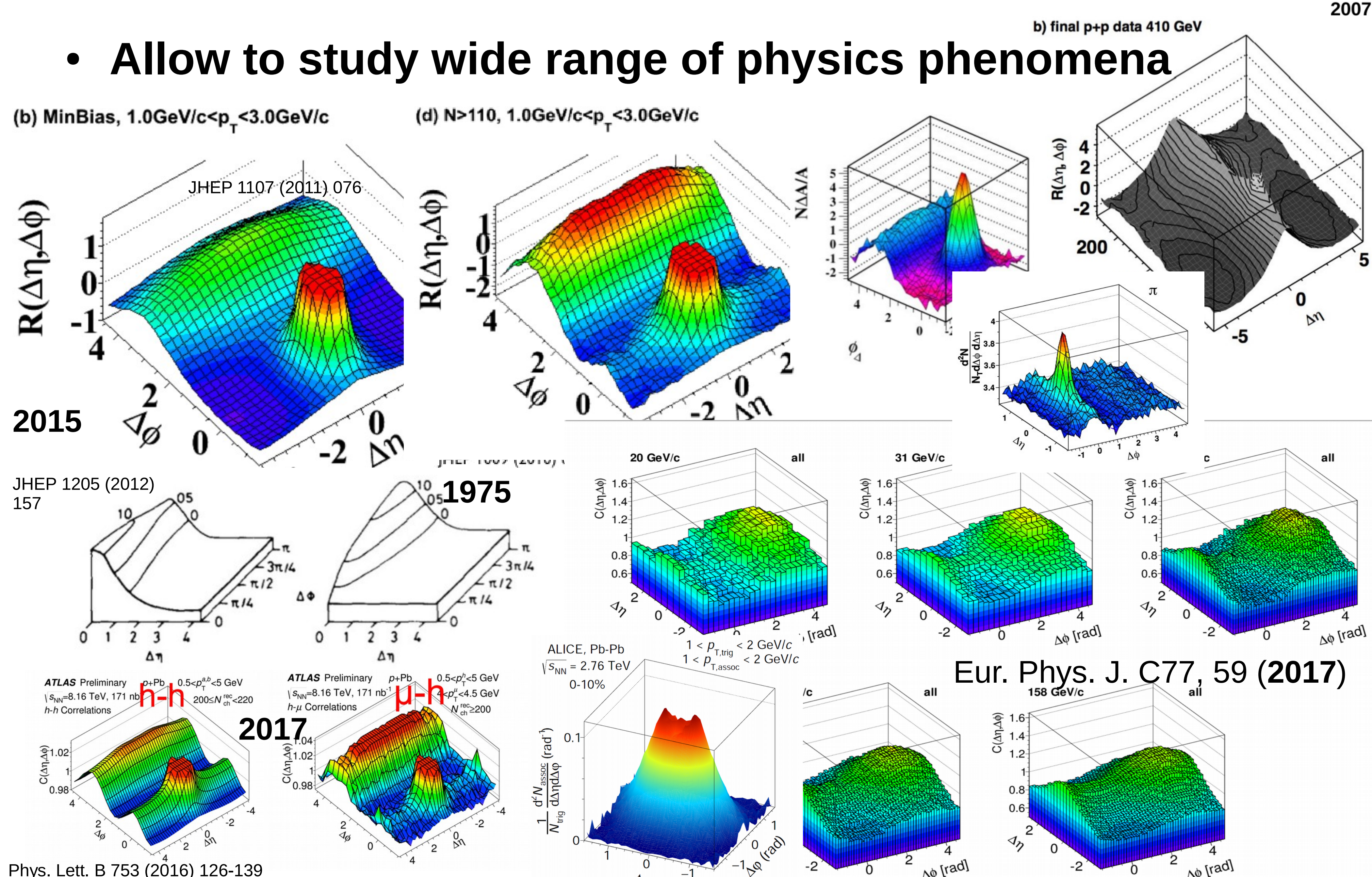
Point at $\Delta y=0$ reflects combination of SRC and the removal of track merging effects

S. Jowzaee, Quark Matter 2017

9

# Summary

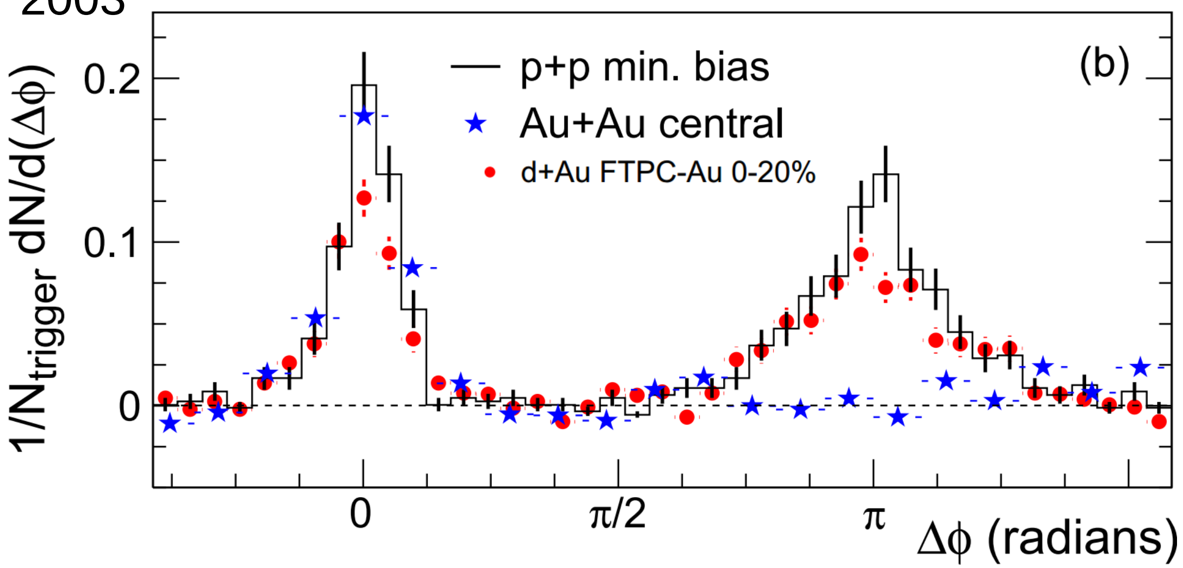
- **Allow to study wide range of physics phenomena**

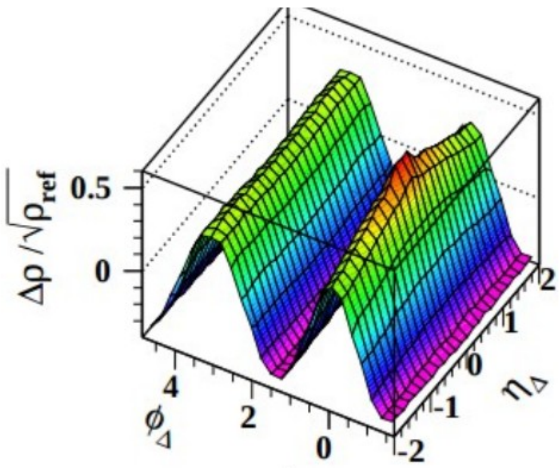


# Summary

- **Allow to study wide range of physics phenomena**
- **Helped to establish current understanding of HI physics**

2003



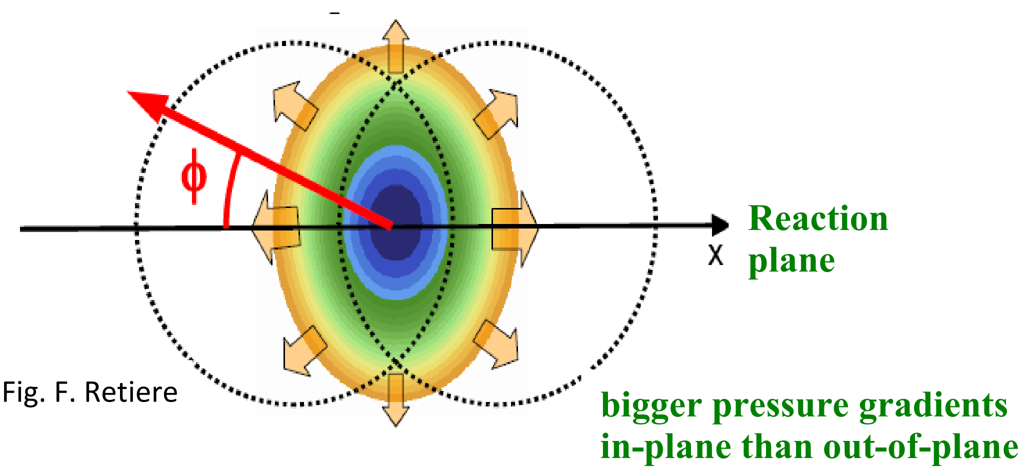
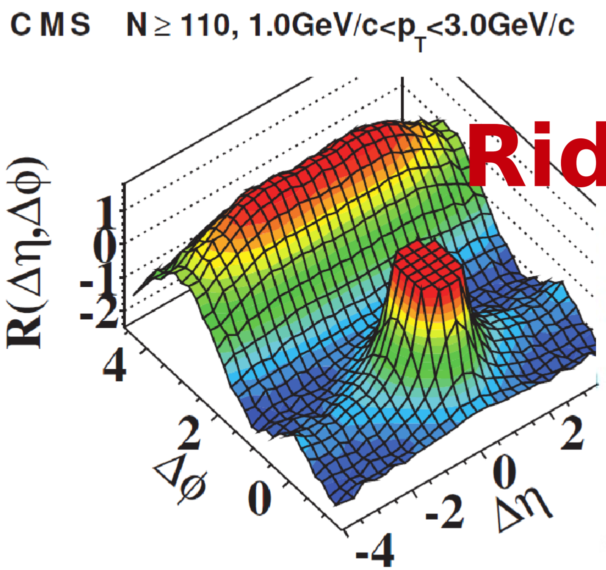
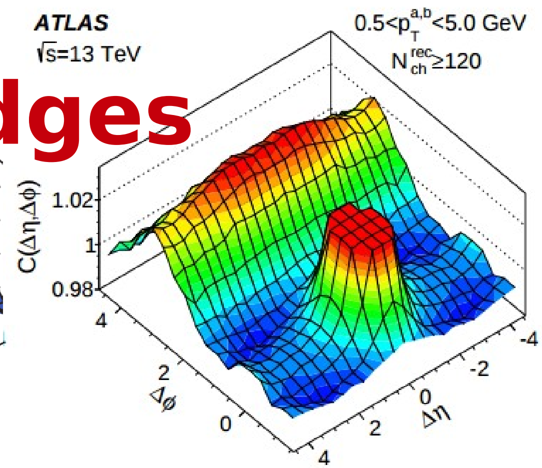



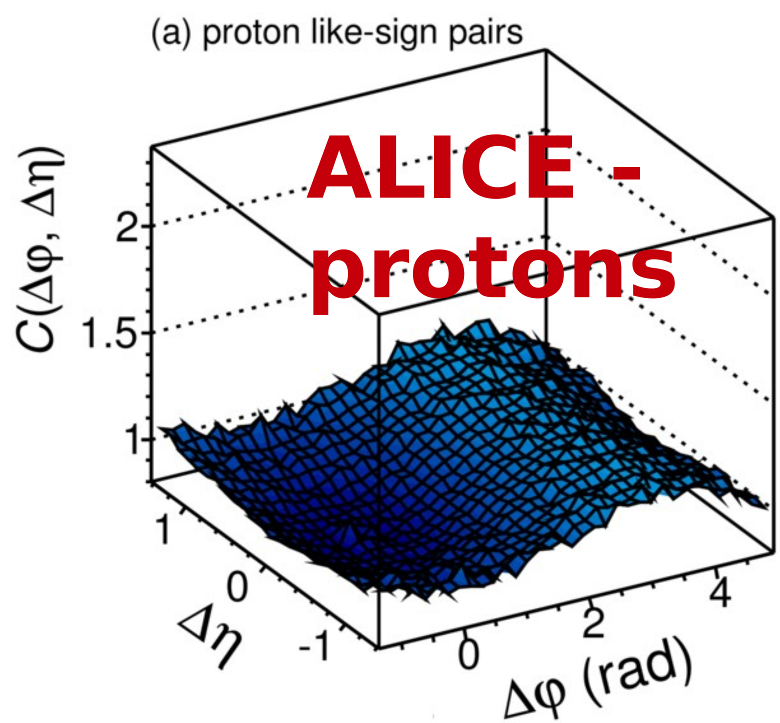

Fig. F. Retiere

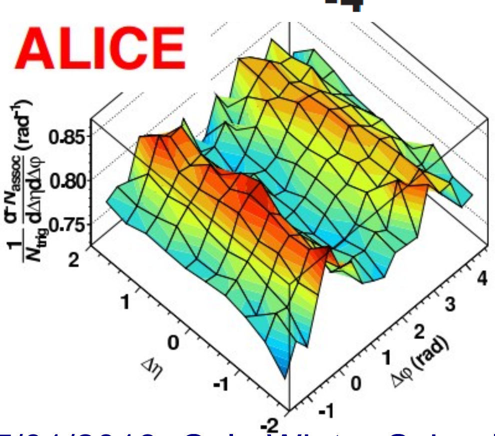
# Summary

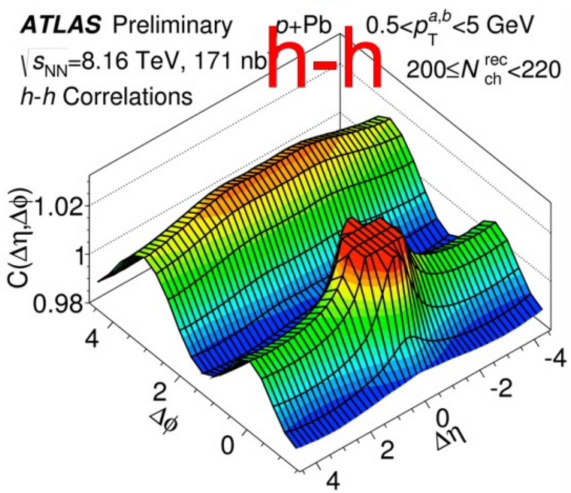
- **Allow to study wide range of physics phenomena**
- **Helped to establish current understanding of HI physics**
- **Still new mysteries to solve**



# *Backup*

# *How we can use it?*
# *Background for femtoscopy*

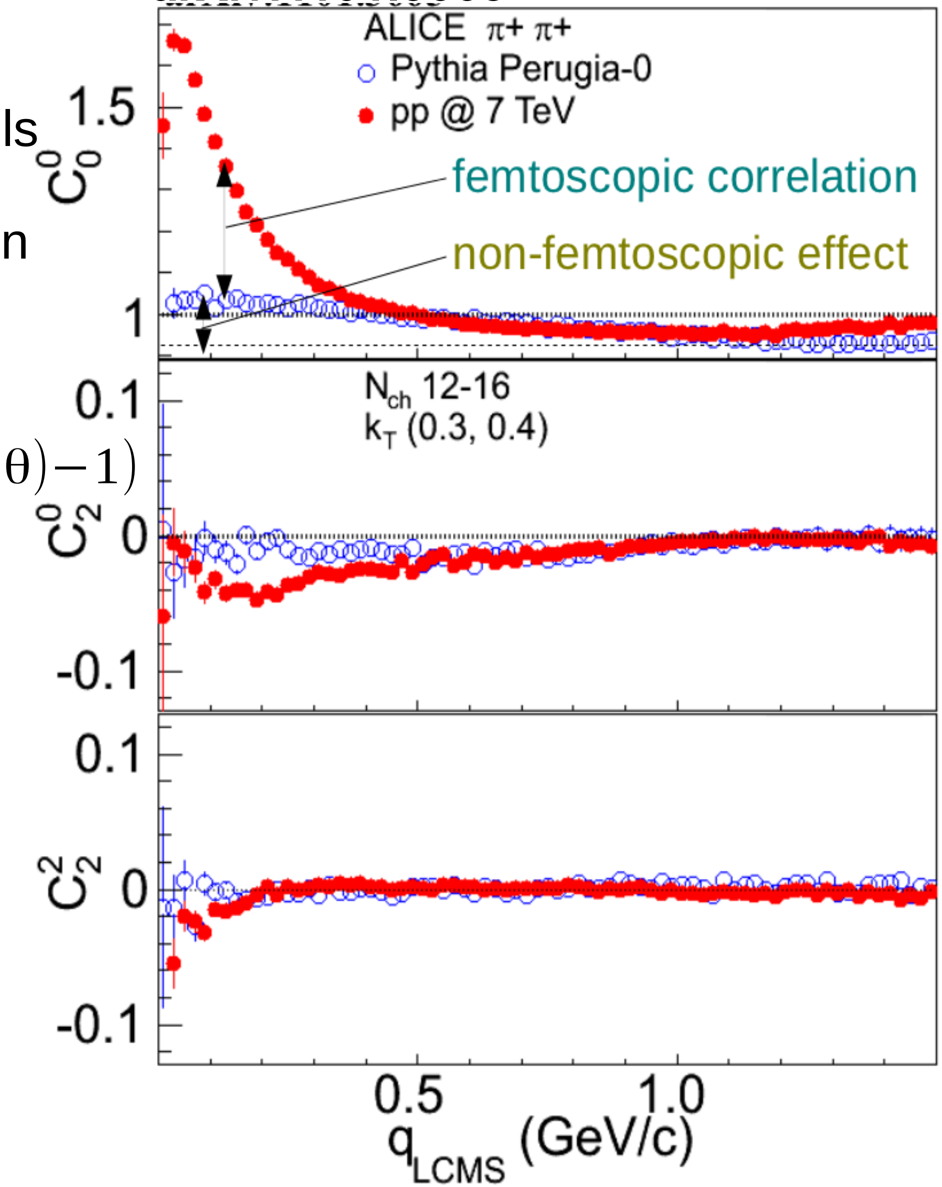
# Baseline of the CF

- Non-flat baseline is clearly seen in the experimental data.
- The baseline is described well by the MC models (in this case *Pythia Perugia-0*) – the correlation grows with increasing $k_T$. Parameterization taken from the MC (data-driven functional form):

$$B(\vec{q}) = A_h \exp(-|\vec{q}|^2 A_w^2) + B_h \exp\left(\frac{-(|\vec{q}| - B_m)^2}{2 B_w^2}\right)(3\cos^2(\theta) - 1)$$

- Two competitive explanations (minijets, hydro): Akkelin, Sinyukov **arXiv:1106.5120**.

**arXiv:1101.3665**



# Baseline of the CF

- Non-flat baseline is clearly seen in the experimental data.
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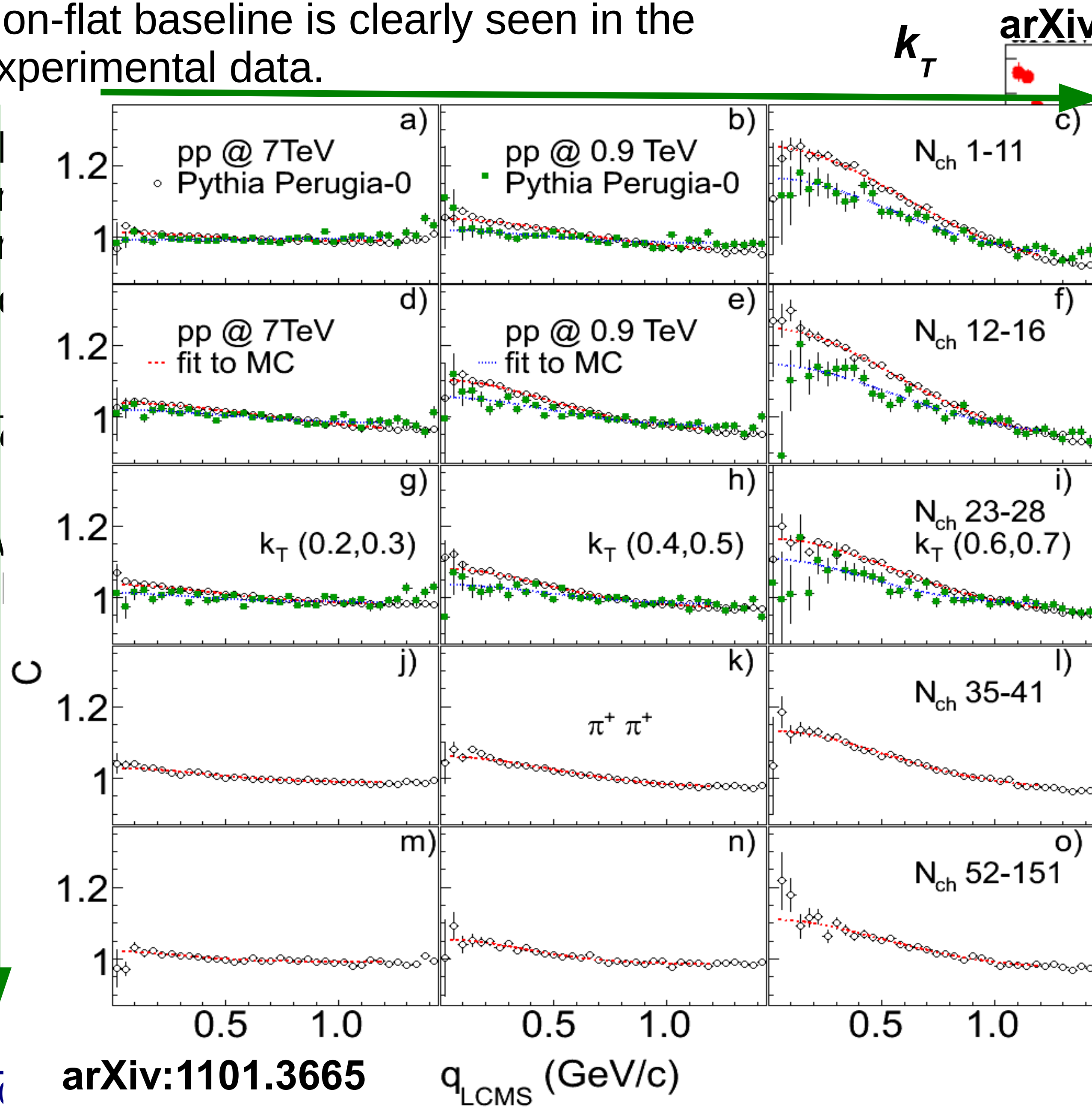
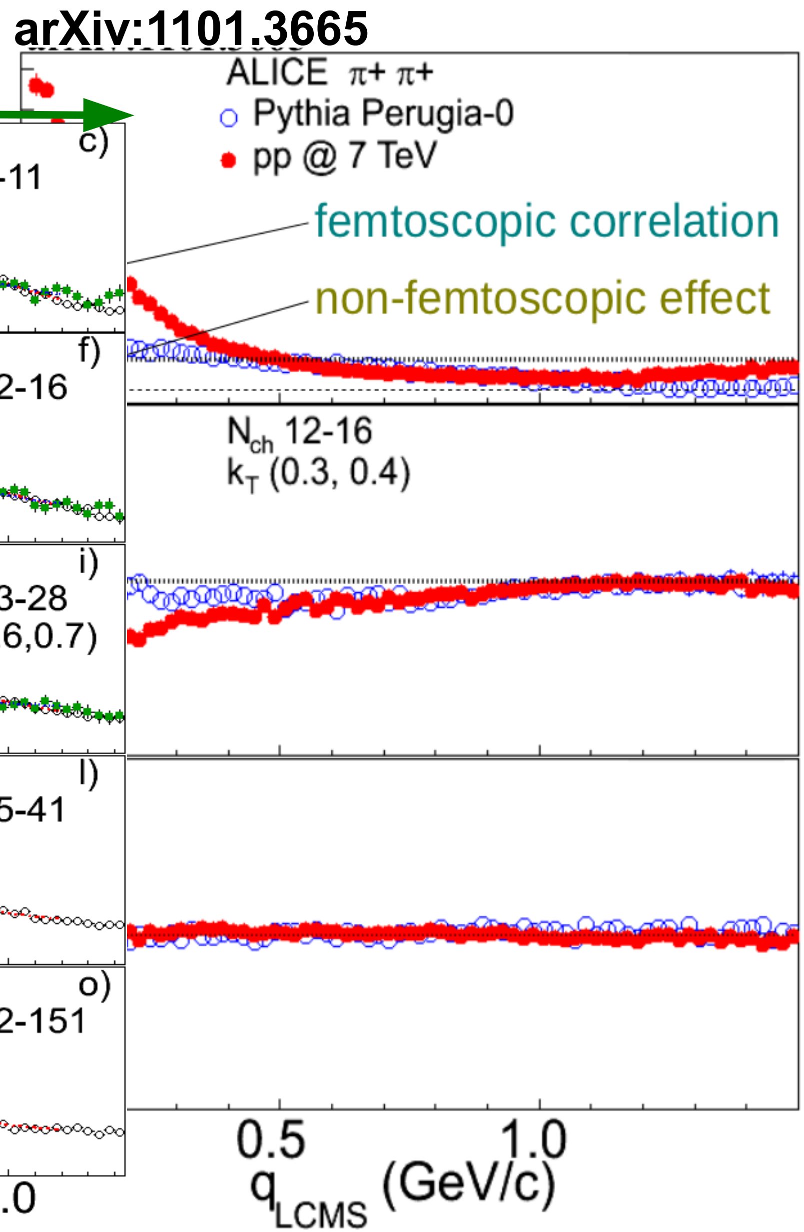
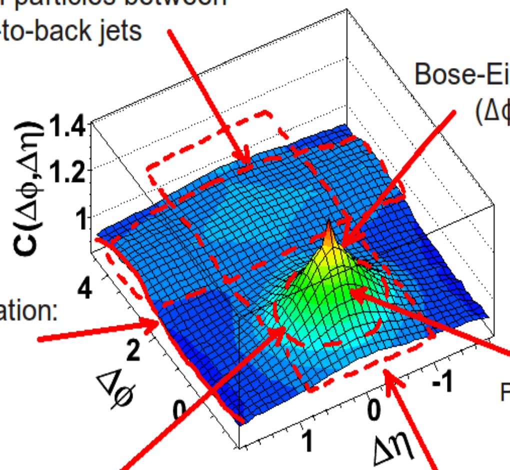


# $\Delta\eta\Delta\varphi$ angular correlations




- Minijets are usually studied using two-particle correlations in $\Delta\eta\Delta\varphi$ coordinates.
- To test the "minijet" origin hypothesis of the non-femtoscopic background we employed the $\Delta\eta\Delta\varphi$ un-triggered angular correlations
- There is a direct connection between $\Delta\eta$, $\Delta\varphi$ and the $q_{inv}$ momentum components:

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

- The femtoscopic effect is located in the so-called near-side peak of the correlation function.
- It is expected to be seen only for like-sign charge pairs, but not for unlike-sign pairs, where only minijets and resonances contribute.

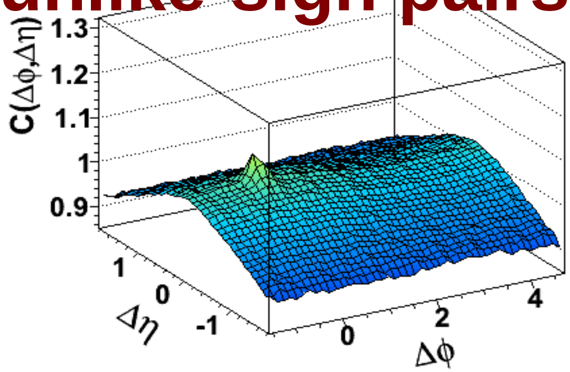
# $\Delta\eta\Delta\varphi$ angular correlations

**No Bose-Einstein correlations for unlike-sign pairs**

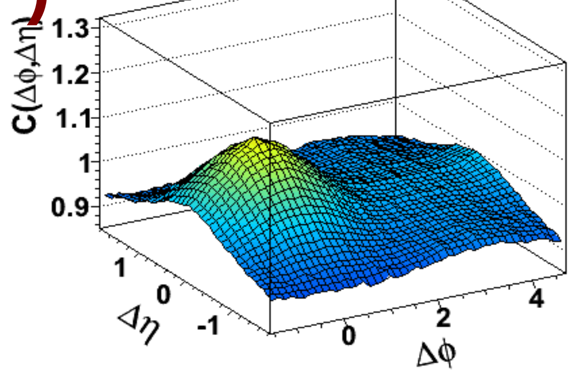
**Correlations coming from "minijets" increase with increasing $p_T$**

ALICE pp @ 7 TeV

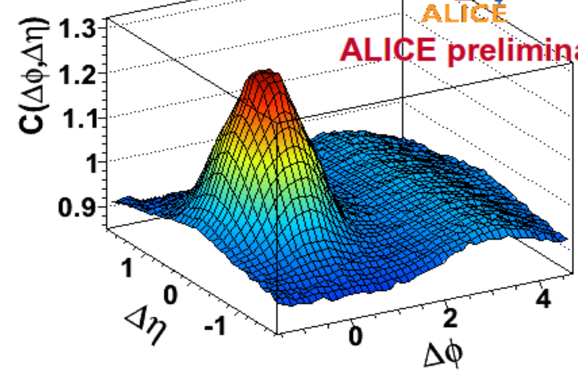
## unlike-sign pairs (+ -)




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

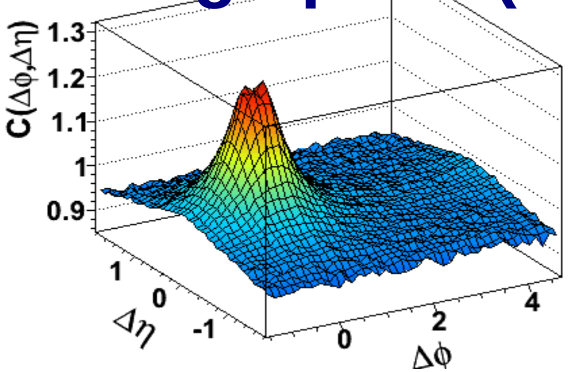


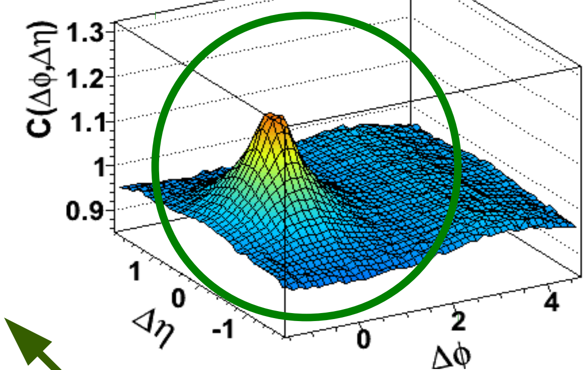

$0.75 < p_{Tsum} < 1.5\, GeV/c$

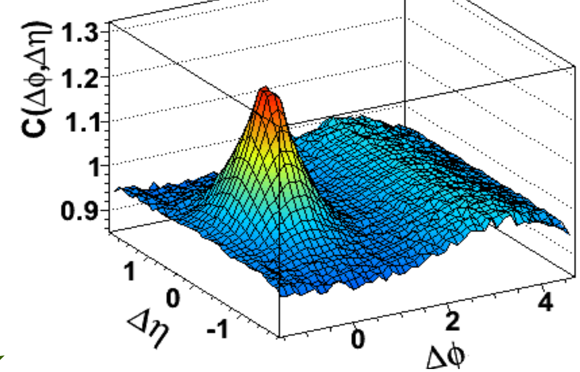



$1.5 < p_{Tsum} < 2.55\, GeV/c$

## like-sign pairs (++)




**Bose-Einsein correlations decrease with increasing $p_T$**

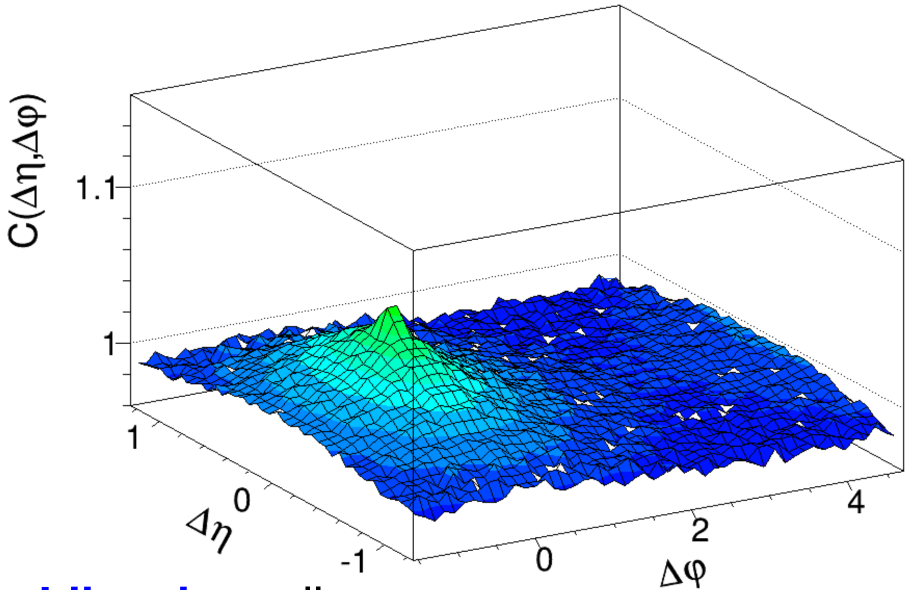
**smaller**

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

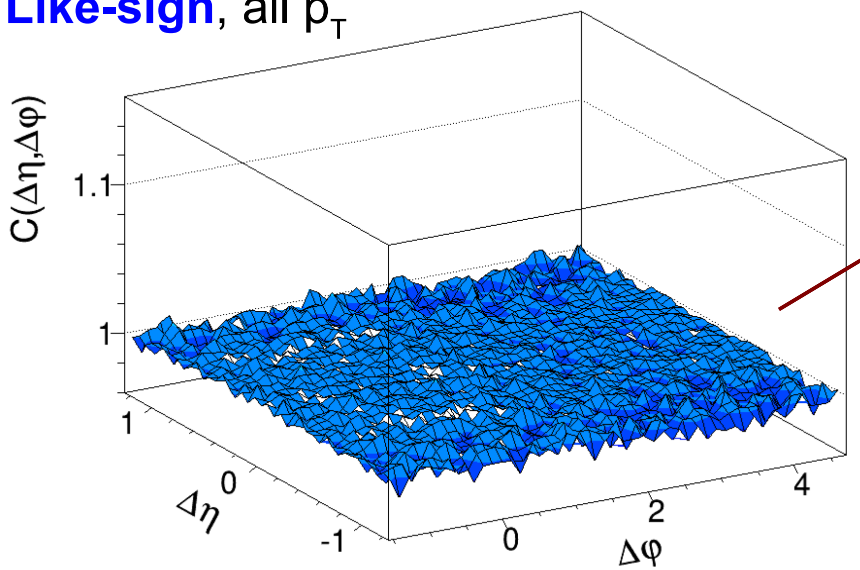
**Correlations coming from "minijets" increase with increasing $p_T$ also for like-sign pairs**

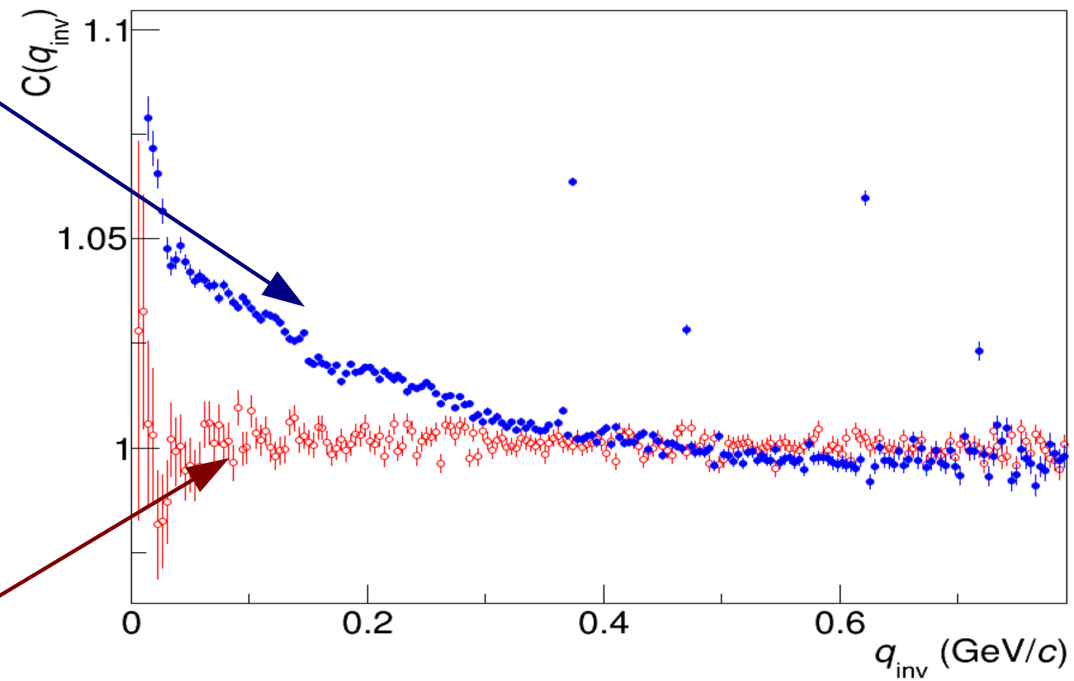
# Therminator, background, *balanced* *like-* vs *unlike-sign*

**Unlike-sign**, all $p_T$




**Like-sign**, all $p_T$



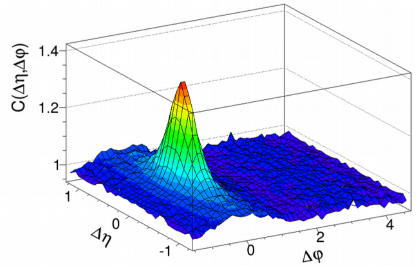




No structures in $\Delta\eta\Delta\varphi$ – no structures in $q_{inv}$

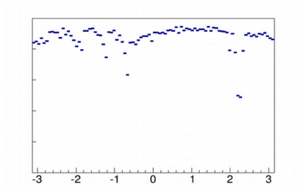
Resonances visible for unlike-sign

# Transformation from $\Delta\eta\Delta\varphi$ to $q_{inv}$

We used the following **Monte Carlo procedure**:

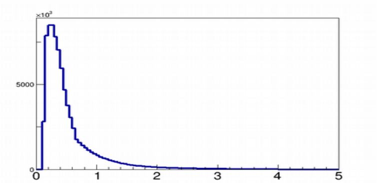



- Generate two random numbers ($\Delta\eta$,$\Delta\varphi$) with probability according to $\Delta\eta\Delta\varphi$ distribution (separately for numerator and denominator)



- Generate random $\varphi_1$, $\eta_1$ from single particle distributions
- Calculate $\varphi_2$, $\eta_2$ of the second particle using $\Delta\eta$ and $\Delta\varphi$

$$\phi_2 = \phi_1 - \Delta\phi$$



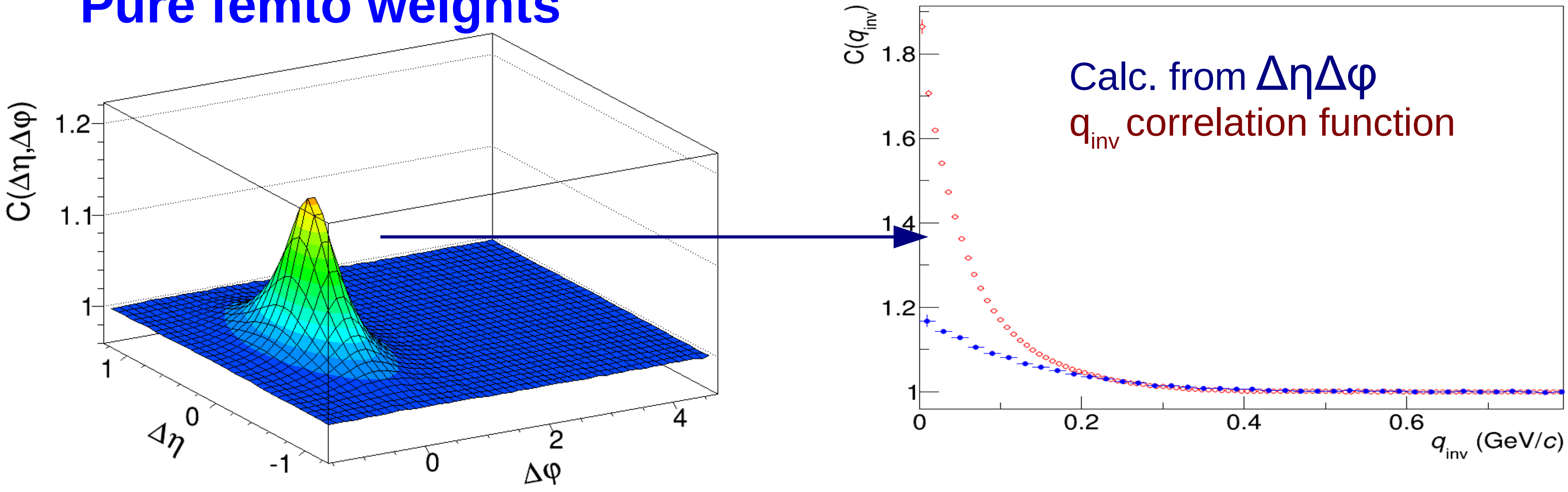
- Generate random $p_T$ for those two particles from single particle $p_T$ distribution
- Calculate $p_x$, $p_y$ and $p_z$ using $p_T$, $\varphi$ and $\eta$
- Calculate $q_{inv}$ from $p_x$, $p_y$, $p_z$

$$p_x = p_T \cos(\phi)$$
$$p_y = p_T \sin(\phi)$$
$$p_z = p_T \sinh(\eta)$$

$$q_{inv} = \sqrt{\left(\Delta E^2 - \left(\Delta p_x^2 + \Delta p_y^2 + \Delta p_z^2\right)\right)}$$

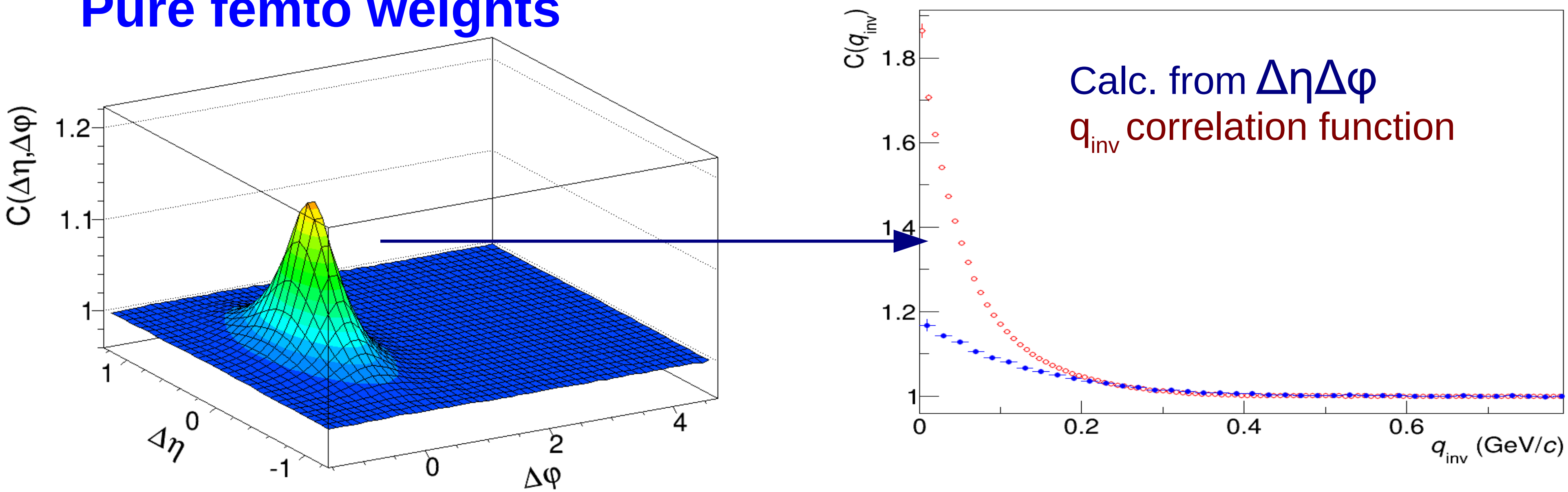
# EPOS 3, transformation of $\Delta\eta\Delta\varphi$ to $q_{inv}$

## Pure femto weights

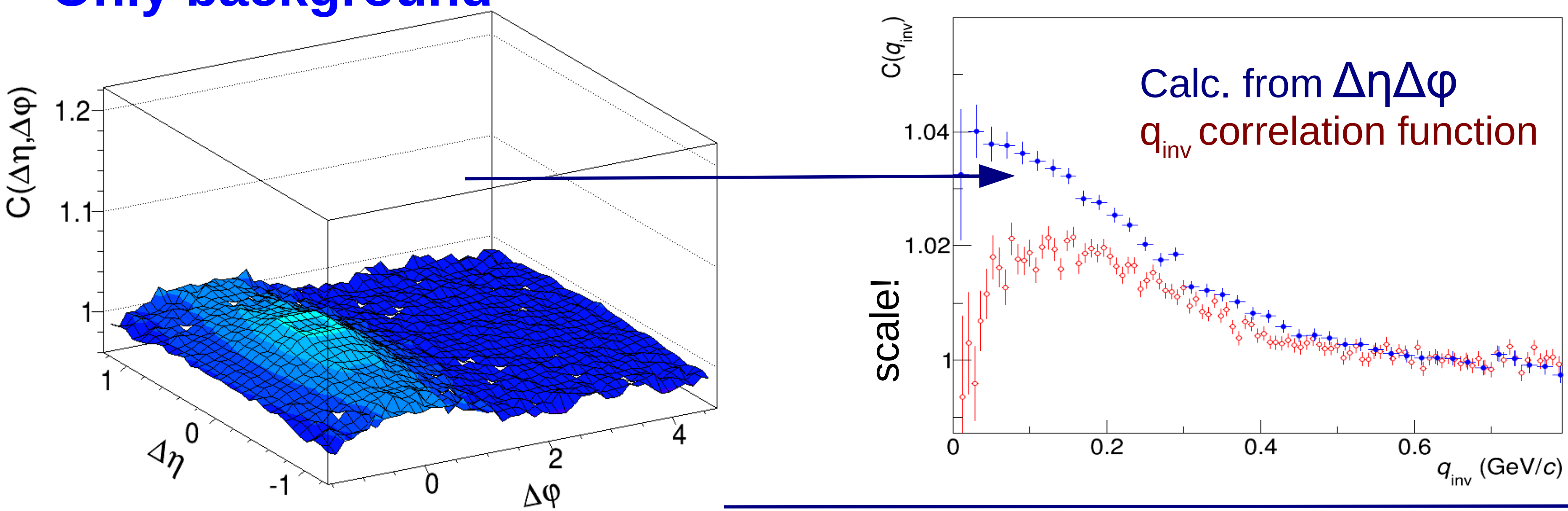


# EPOS 3, transformation of ΔηΔφ to $q_{inv}$

## Pure femto weights

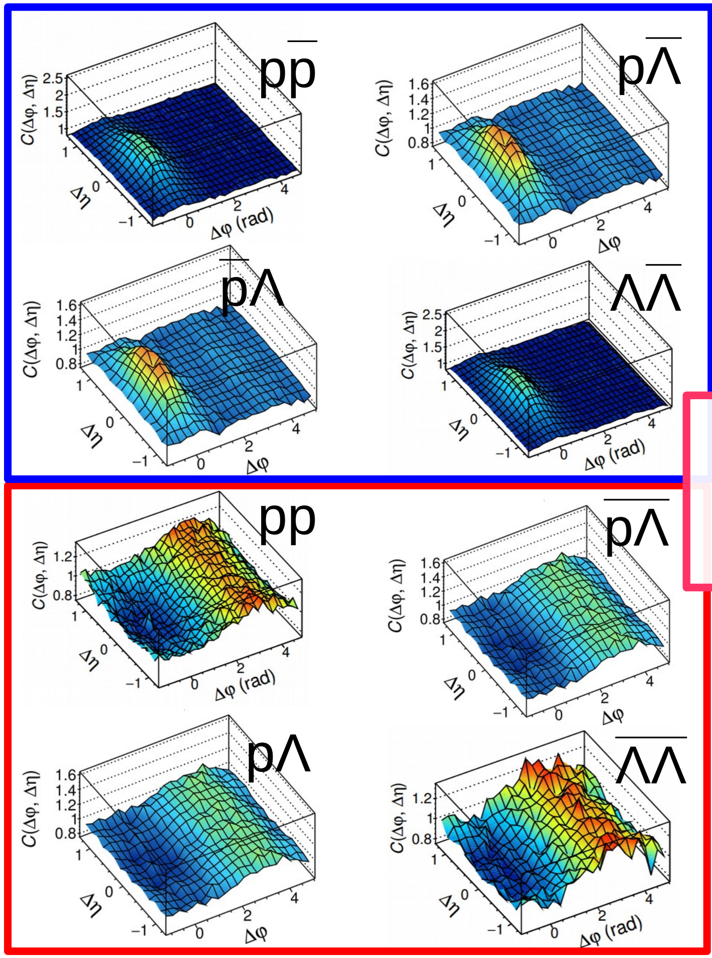



## Only background



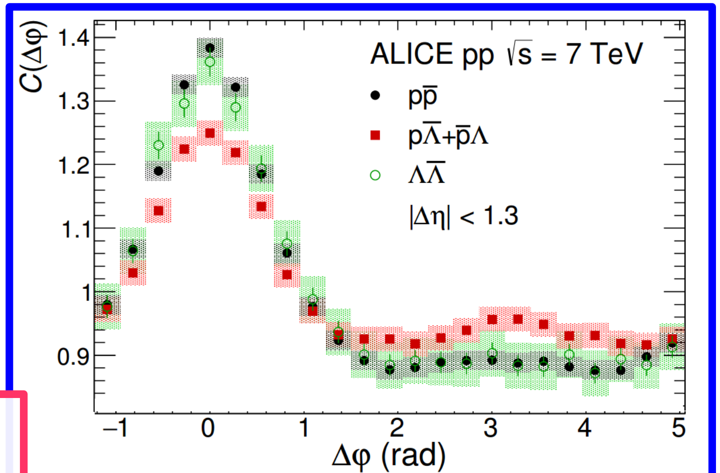
# ΔηΔφ of identified particles of pp collisions

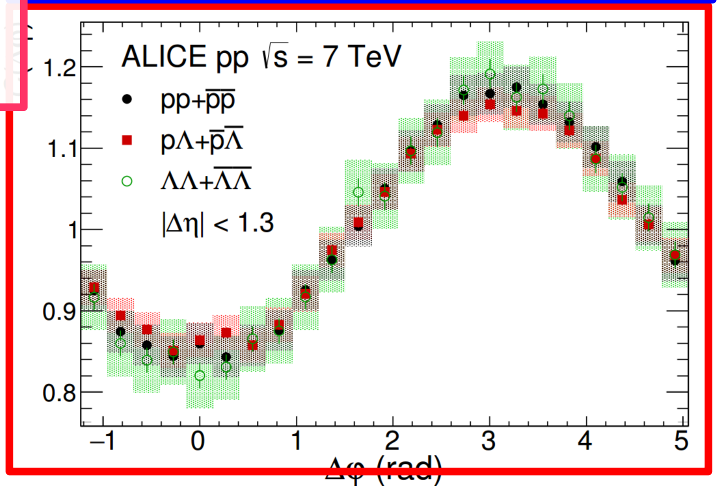
**baryon-antibaryon**
correlation




**common behaviour for all baryons**

**baryon-antibaryon**
correlation



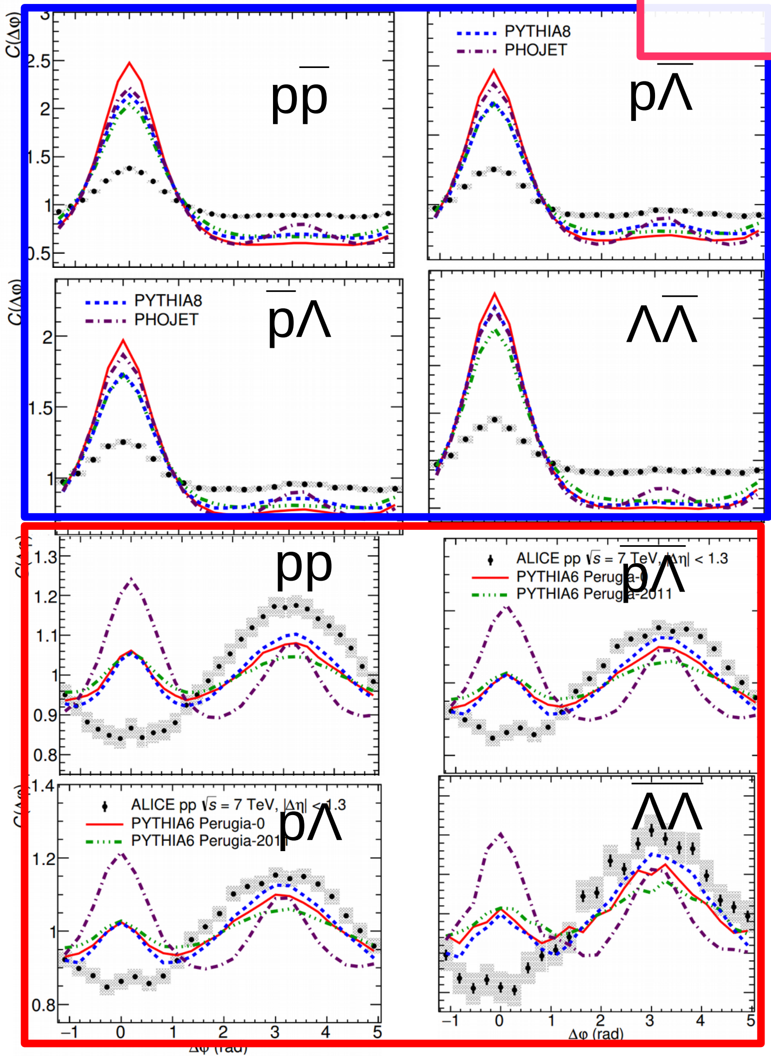

**(anti)baryon-(anti)baryon**
anticorrelation!

**(anti)baryon-(anti)baryon**
anticorrelation!

# ΔηΔφ of identified particles of pp collisions

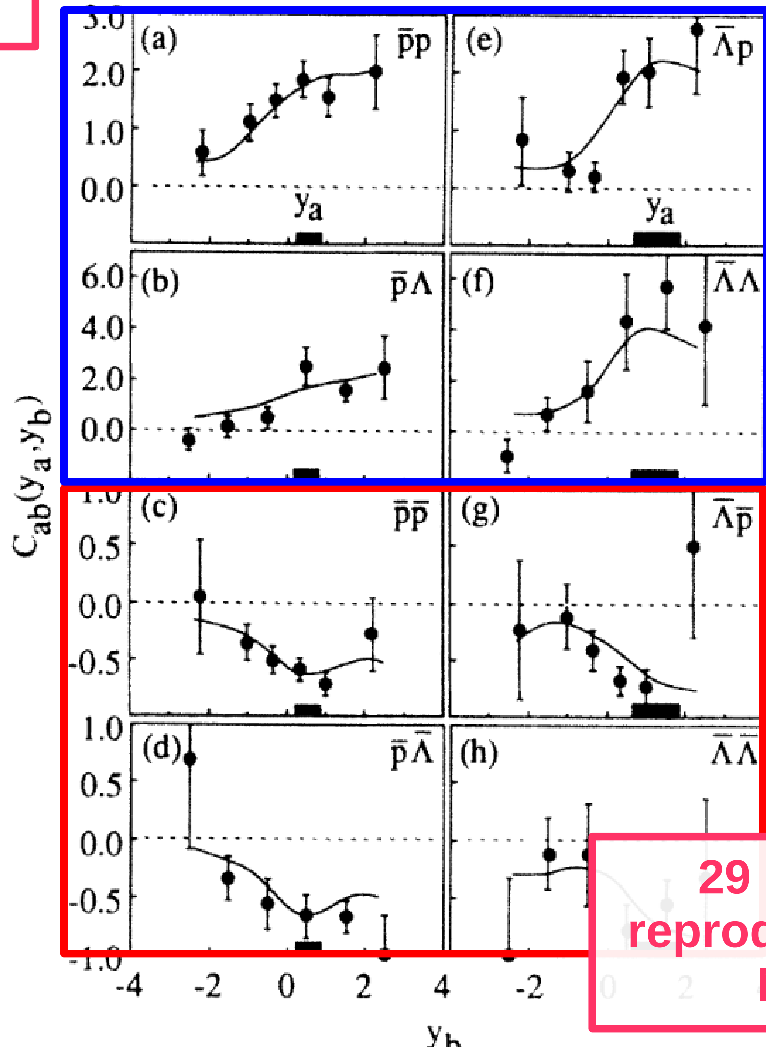
baryon-antibaryon
correlation

7 TeV :
not reproduced by MC




(anti)baryon-(anti)baryon
anticorrelation!

baryon-antibaryon
correlation

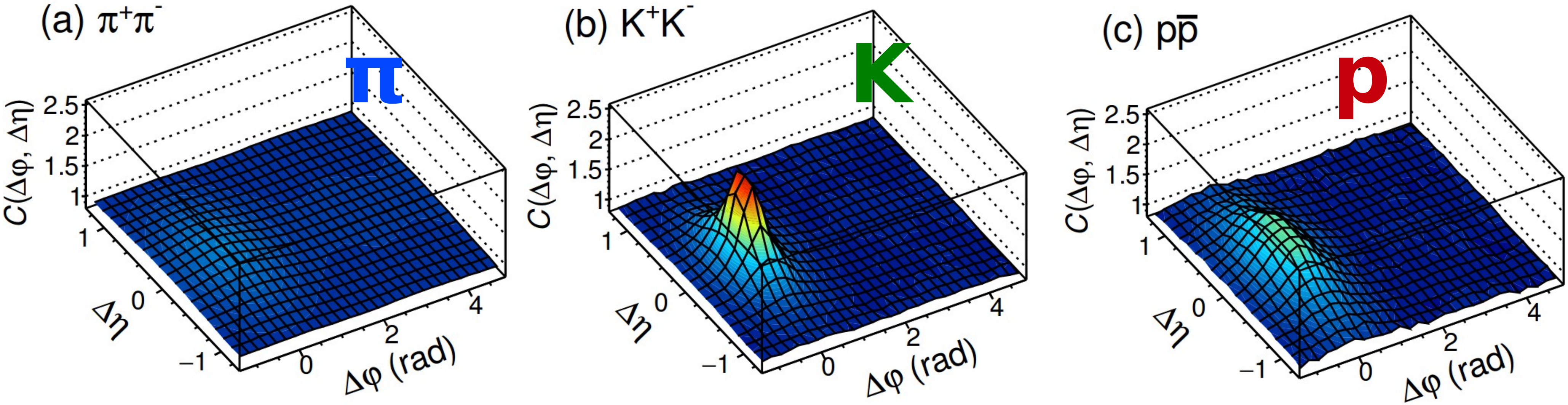



29 GeV :
reproduced by MC

antibaryon-antibaryon
anticorrelation!

# Unlike-sign pairs

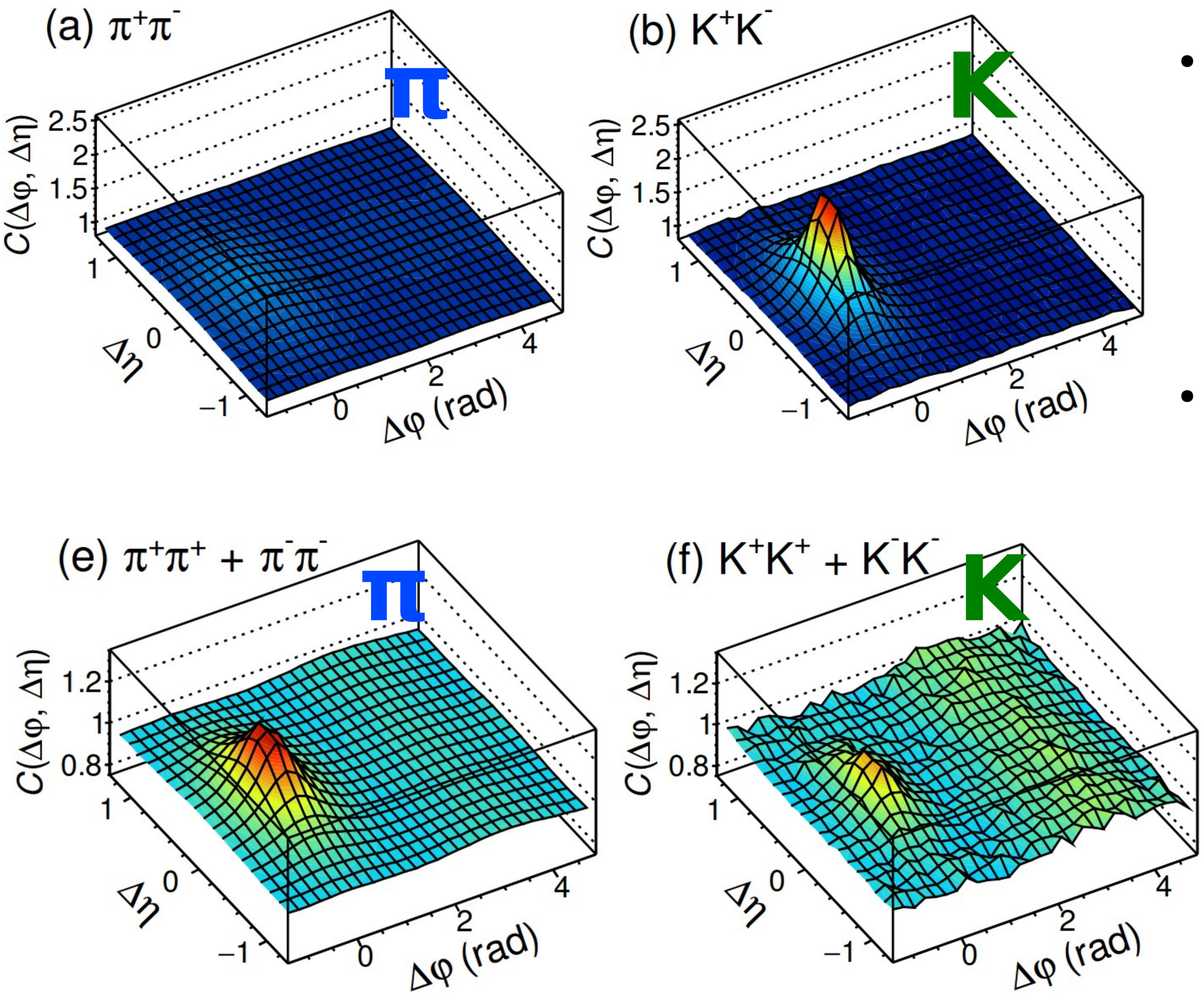
arXiv:1612.08975




- For unlike-sign particles the **least energetically expensive** is always to **produce the particle-antiparticle pair → strong near-side peak**
- The **strength of the correlation** ~ **'price' of the alternative solution**.
The larger the difference in 'prices' between basic and alternative solutions, the stronger the correlation.
  - for **pions** the alternative solution is just another opposite-charge particle,
  - for **protons** another antibaryon (charged, or neutral plus additional charged particle),
  - for **kaons** another strange particle, so at least a lambda + another baryon.

# Unlike vs. Like-sign pairs

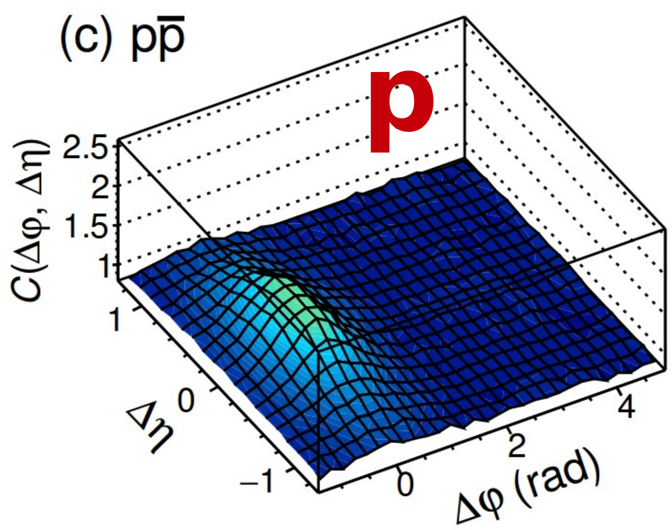
arXiv:1612.08975

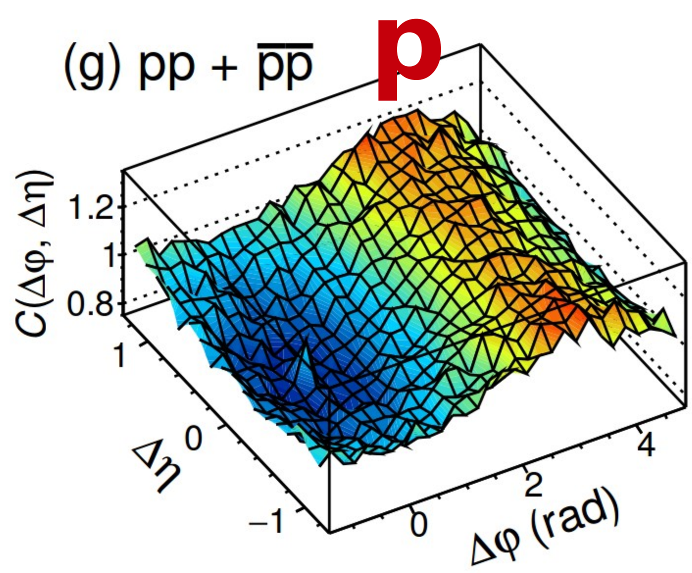



- For like-sign particles **producing two identical particles is not the cheapest** energetically like for particle – antiparticle case
- **Masses of the particles play significant role**
  - still for **kaons** and **pions** we can see the prominent near-side peak in the correlation function (due to the minijets, femtoscopic correlations)

# Unlike vs. Like-sign pairs

arXiv:1612.08975



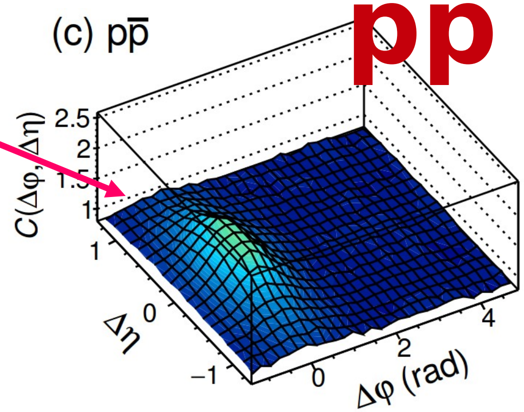



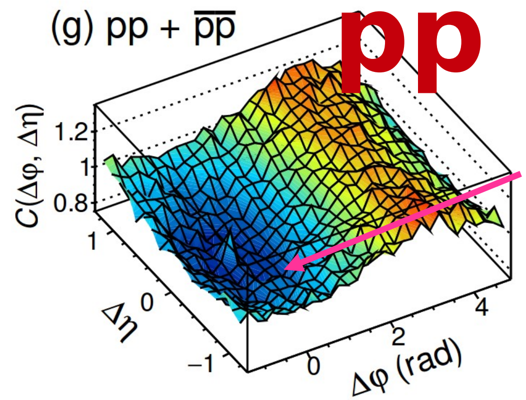

- **Masses of the particles play significant role**
  - for **protons** a large dip near the ($\Delta\eta$, $\Delta\varphi$) = (0,0) is present: by producing two very heavy identical particles going in roughly the same direction we would have to produce also two baryons (two antiprotons), so another two heavy particles. The price of such solution is very high.

# 7 TeV pp vs. 29 GeV $e^+e^-$ collisions

ALICE

correlation



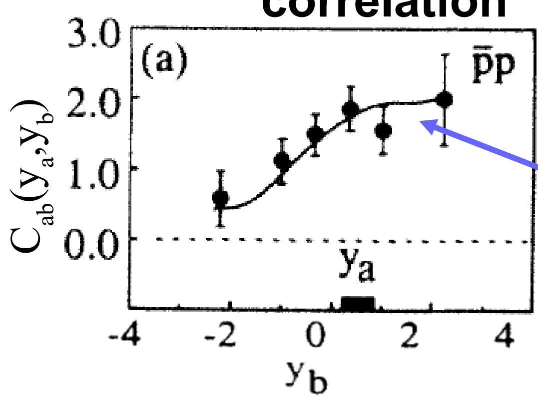




anti-correlation

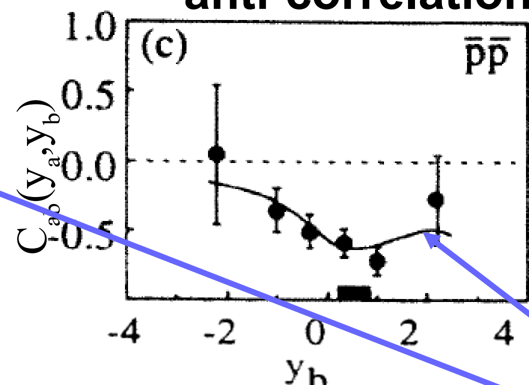
Much more unlike-sign baryons close together in the phase-space than like-sign baryons.

$e^+e^-$

correlation




anti-correlation




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

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