NATIONAL SCIENCE CENTRE

Angular correlations as an experimental tool to probe hadron collisions

Małgorzata Janik

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Warsaw University
of Technology

EMMI Seminar
15.04.2017

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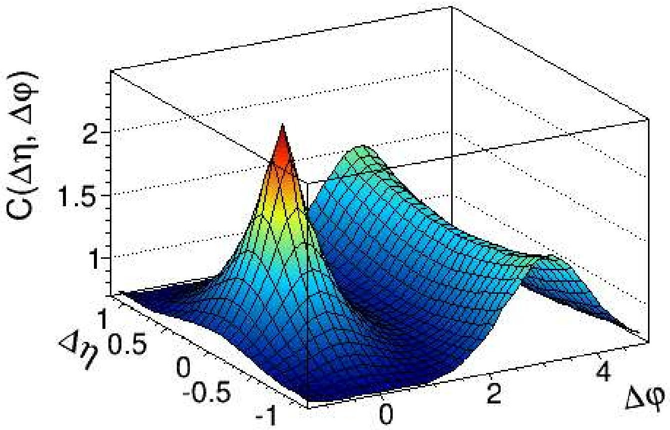

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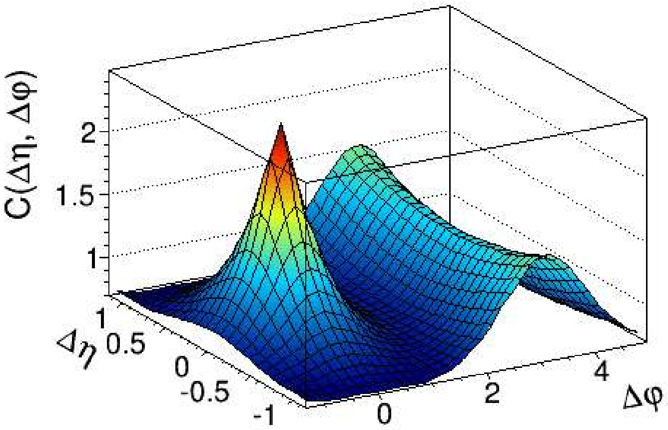
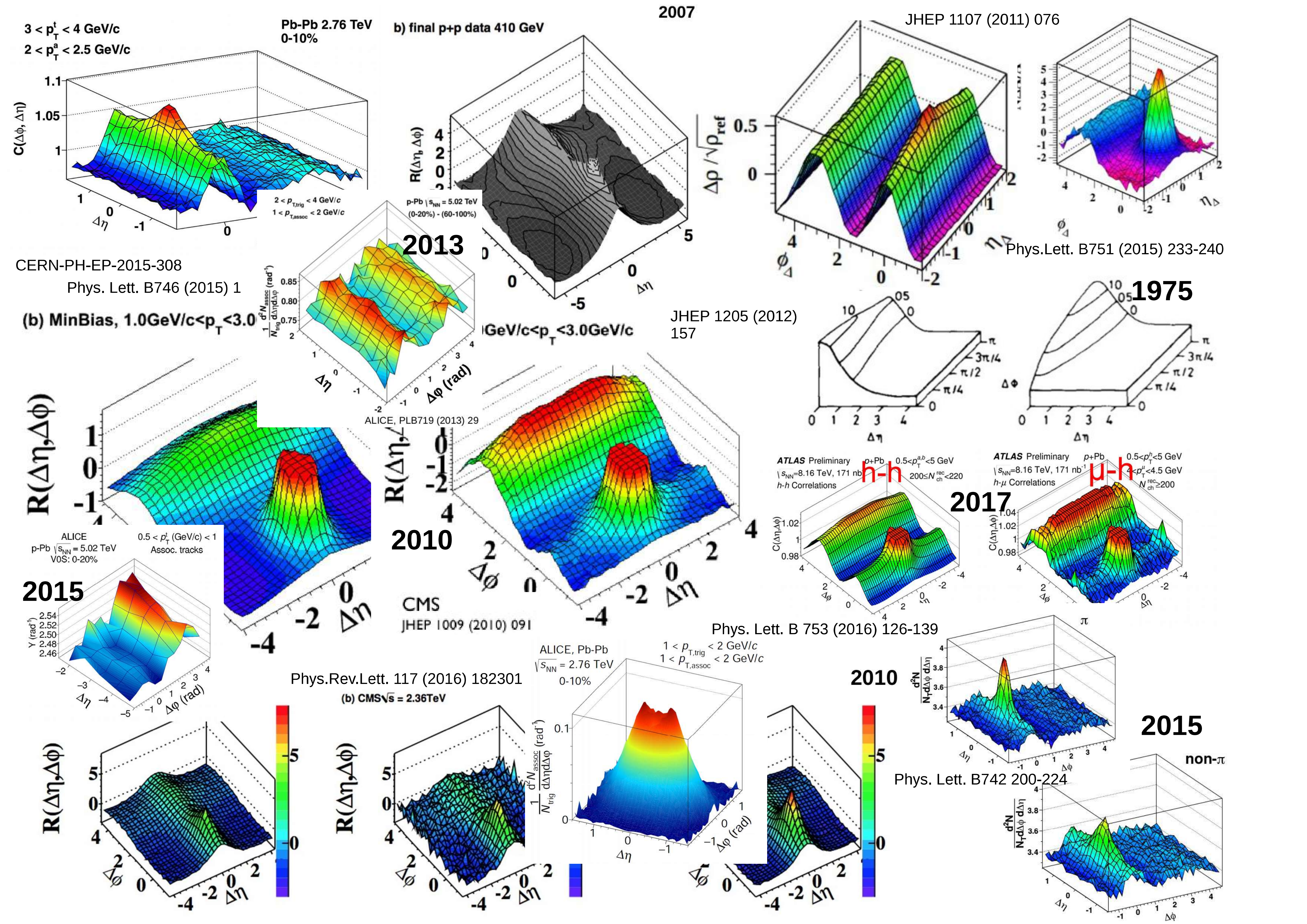
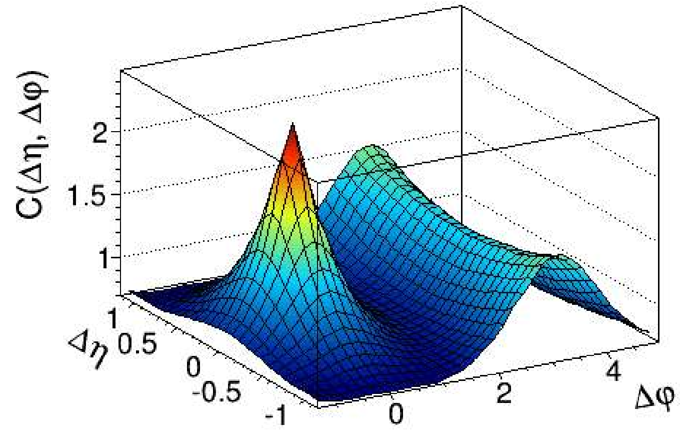
How does it work?



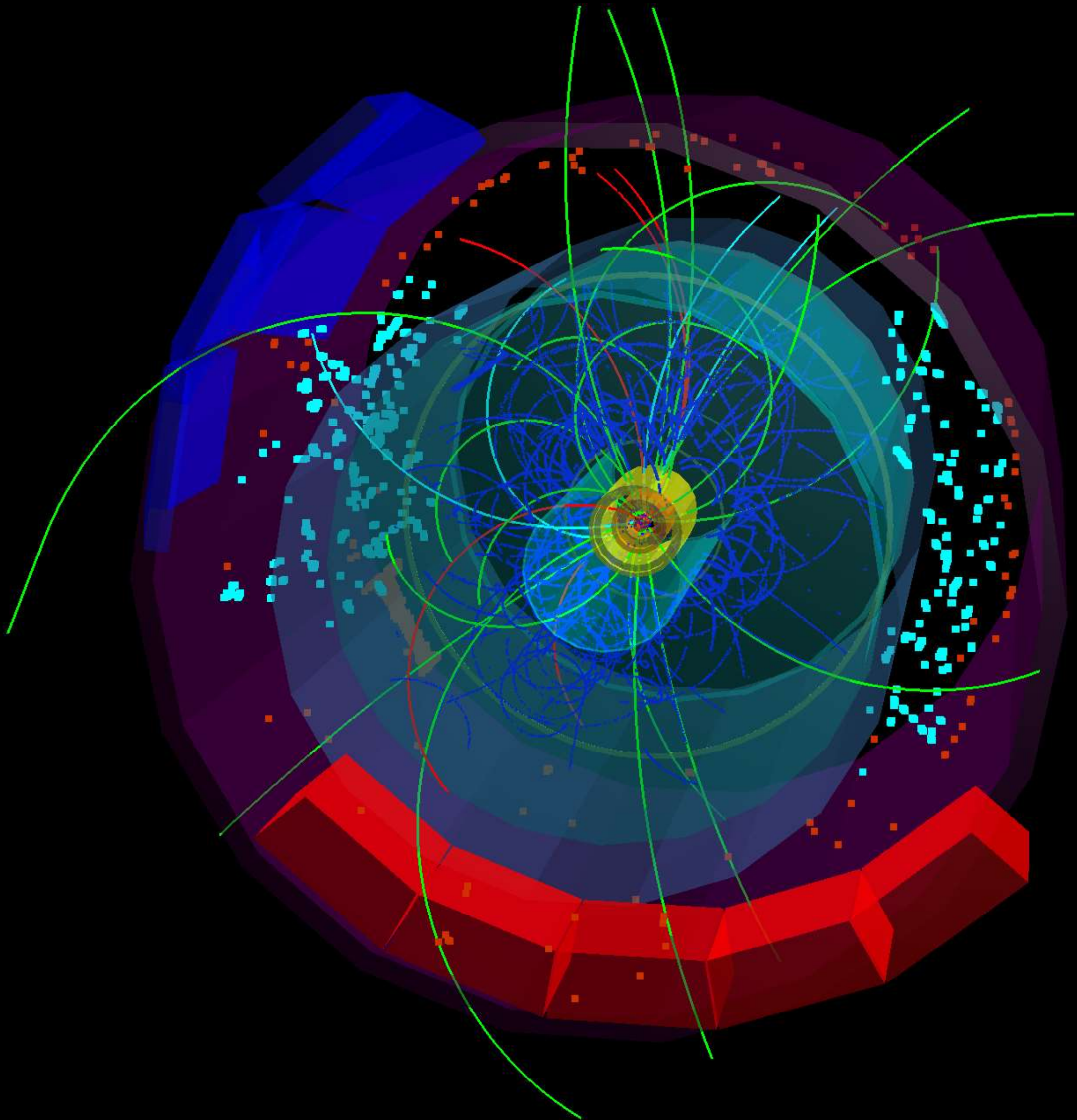


2007
JHEP 1107 (2011) 076
Phys.Lett. B751 (2015) 233-240
1975
JHEP 1205 (2012) 157
2013
ALICE, PLB719 (2013) 29
CERN-PH-EP-2015-308
Phys. Lett. B746 (2015) 1
(b) MinBias, 1.0GeV/c<p$_T$<3.0GeV/c
b) final p+p data 410 GeV
Pb-Pb 2.76 TeV 0-10%
2010
CMS
JHEP 1009 (2010) 091
2015
2017
ATLAS Preliminary
h-h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

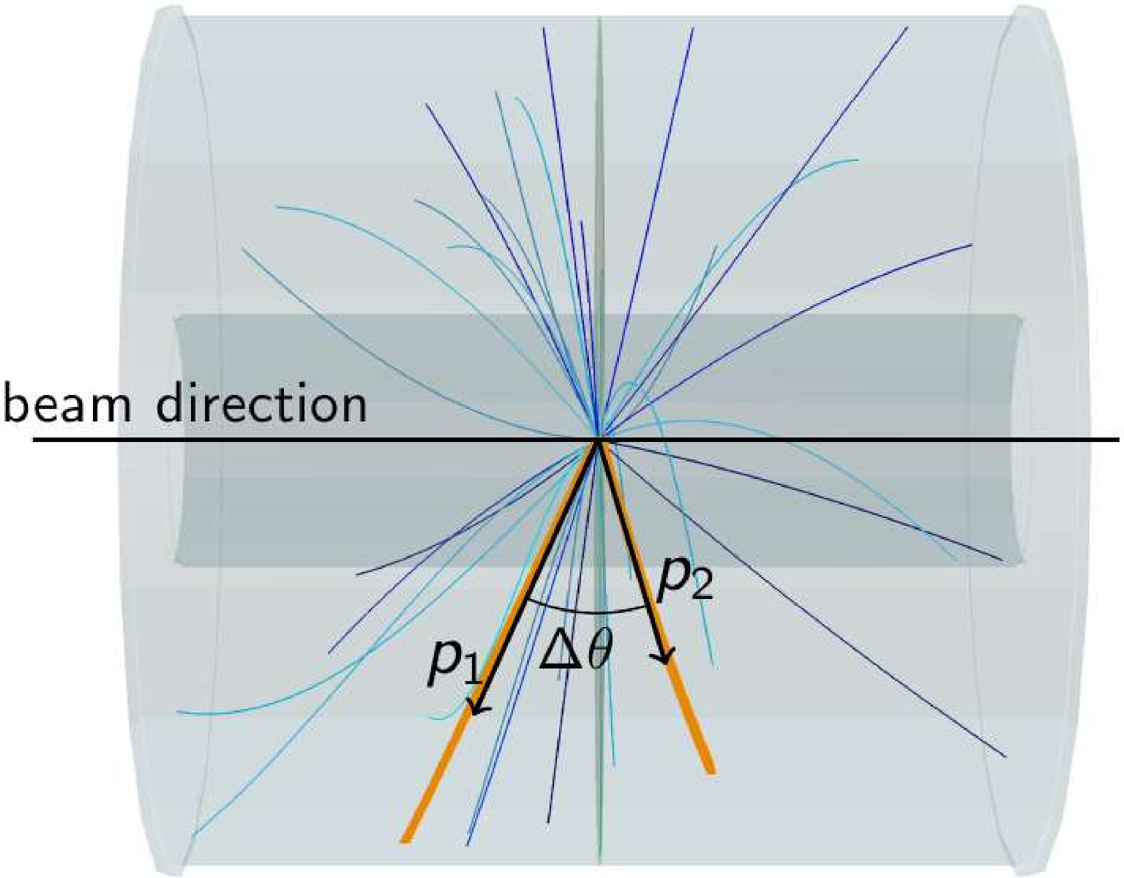
How does it work?

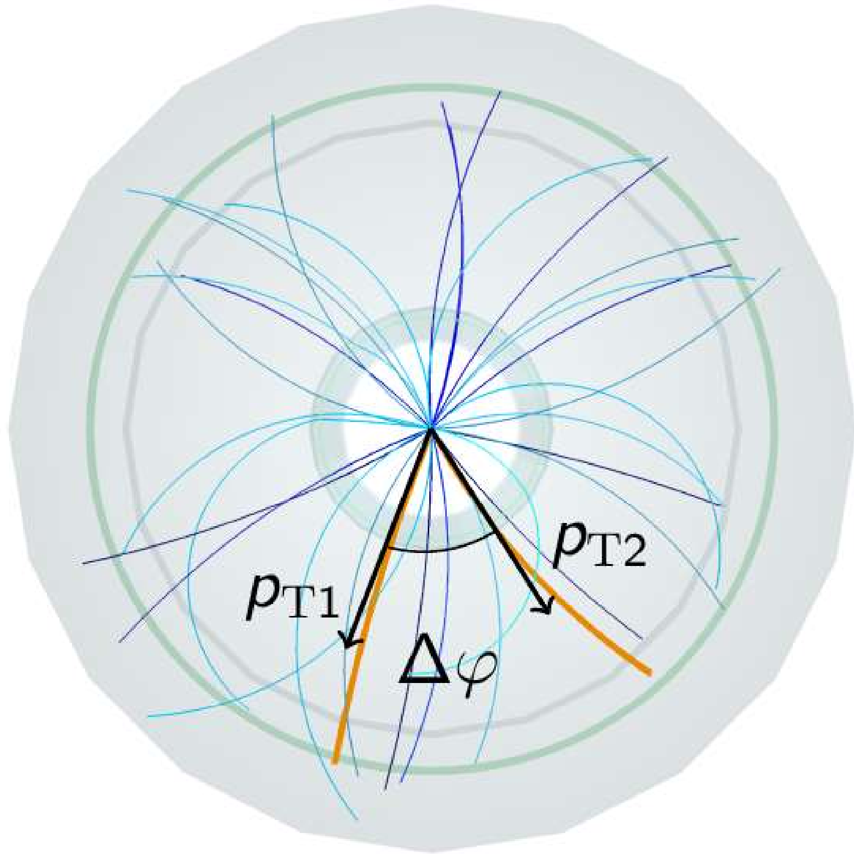


Two-particle ΔηΔφ angular correlations



Two-particle ΔηΔφ angular correlations





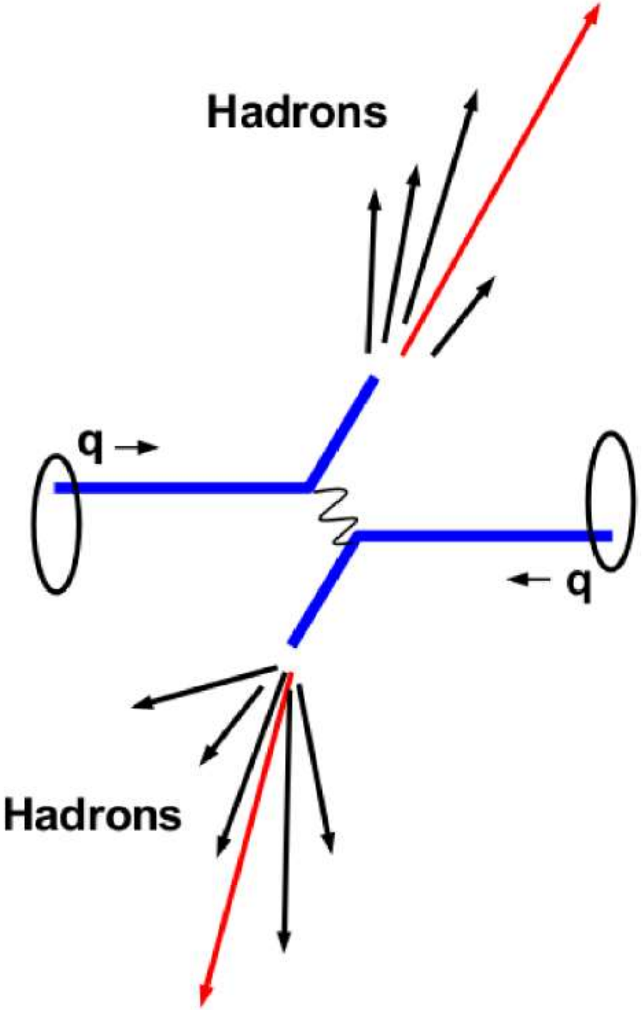
p - particle momentum;
θ - polar angle;
η - pseudorapidity:

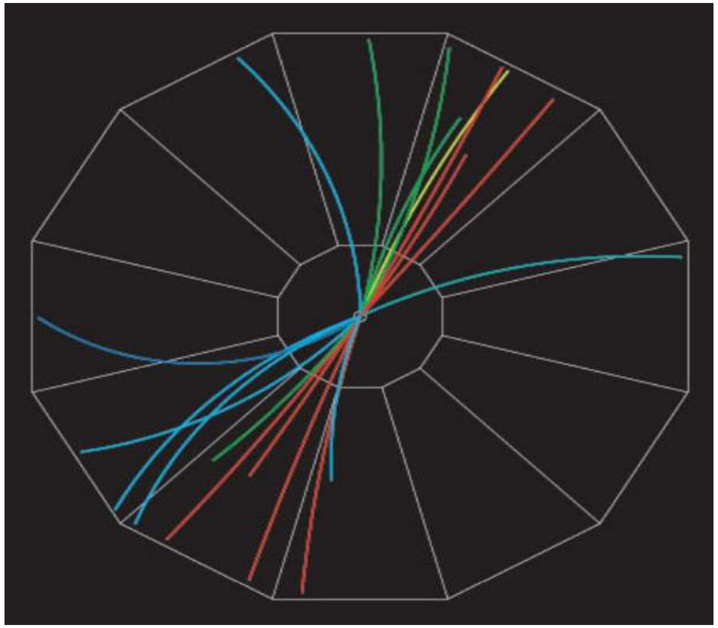
$$\eta = -\ln\left|\mathrm{tg}\frac{\theta}{2}\right|$$

p_{T} - transverse momentum;
φ - azimuthal angle;

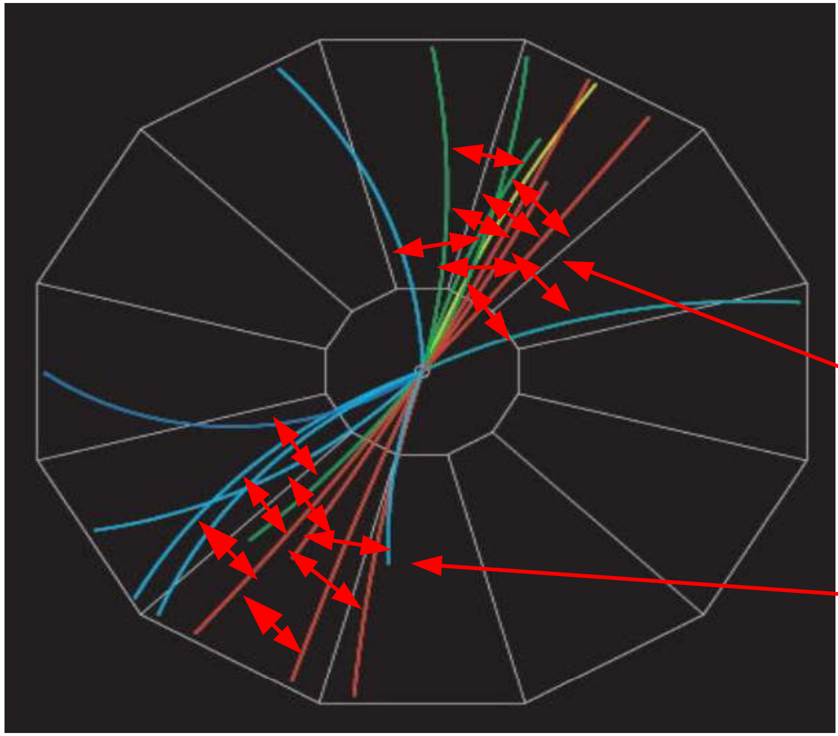
Fig. A. Zaborowska

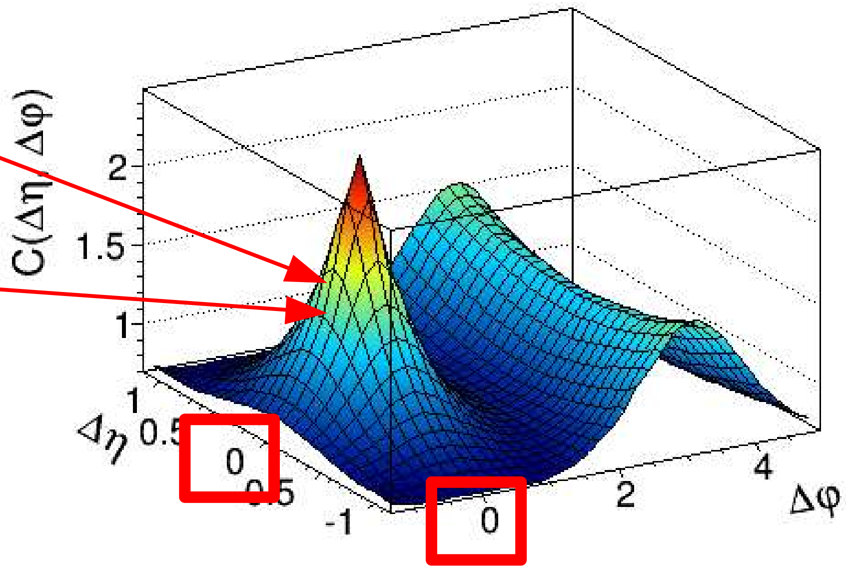
Creation of jets





How does it work?





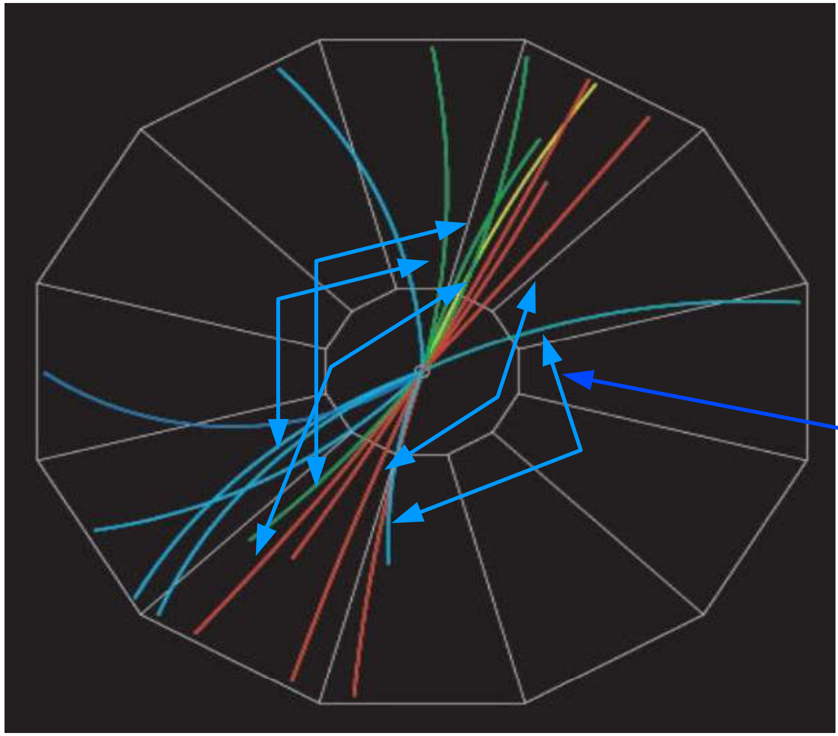
Near-side peak

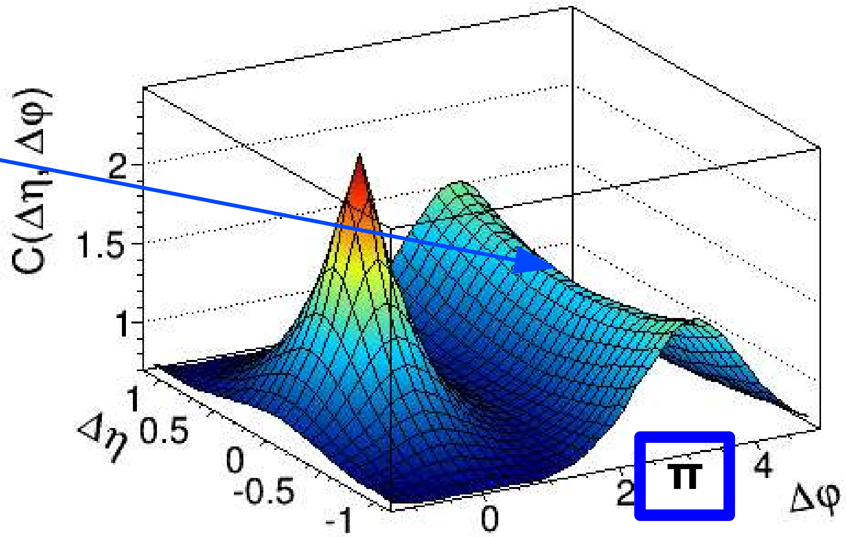
For particles from the same jet (red):

- Δφ ~ 0

- Δη ~ 0

How does it work?

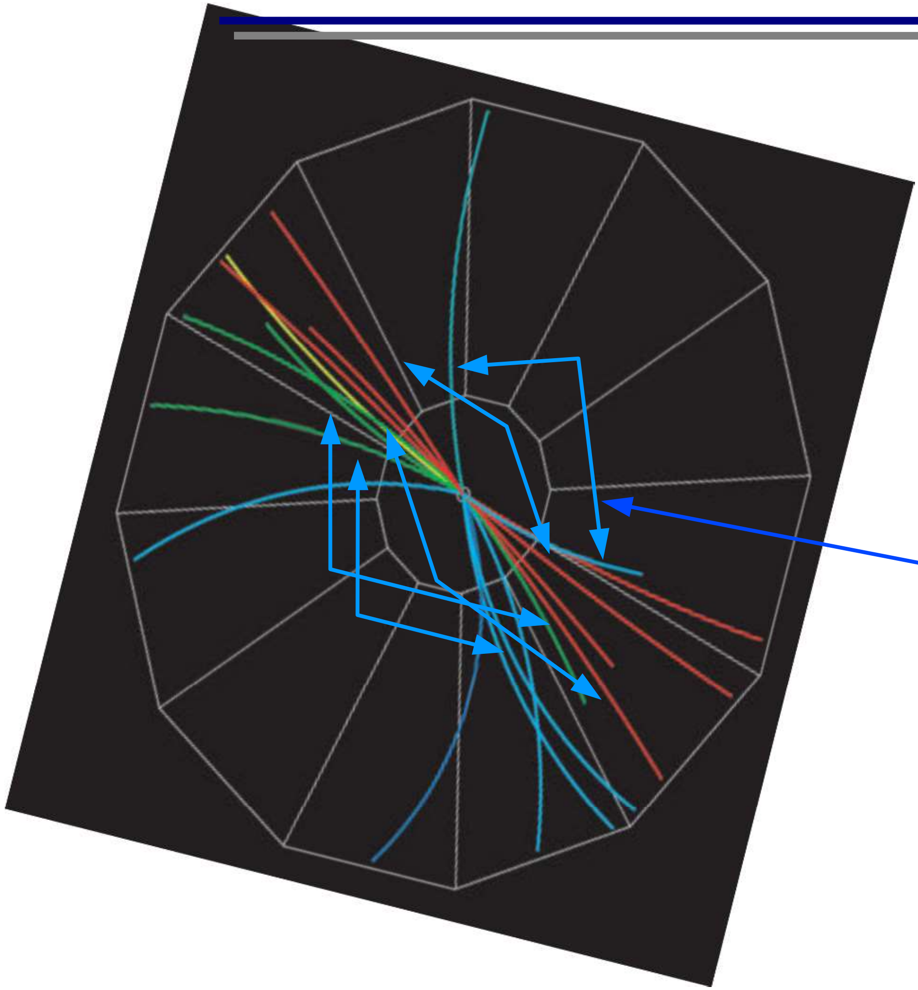


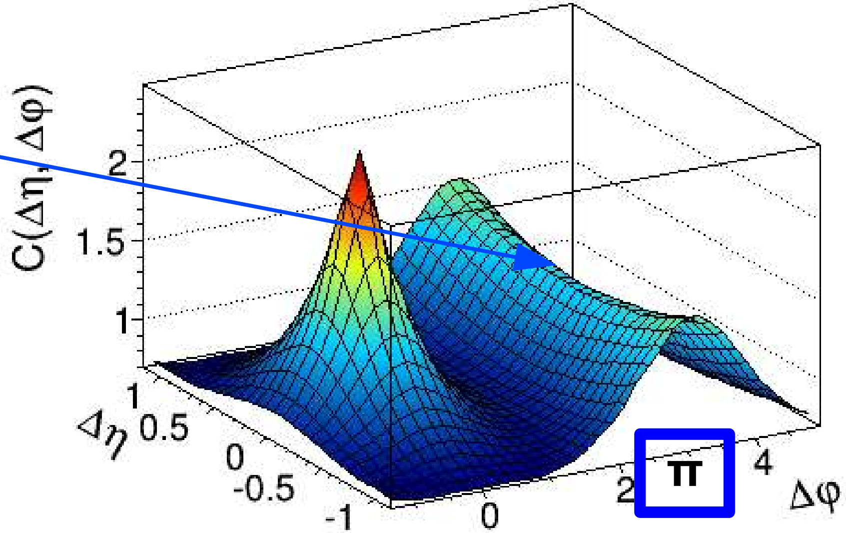


For particles from from back-to-back jets (blue): *Away-side ridge*

- **Δφ ~ π**
- **Δη ~ const, if avaraged over many events**

How does it work?





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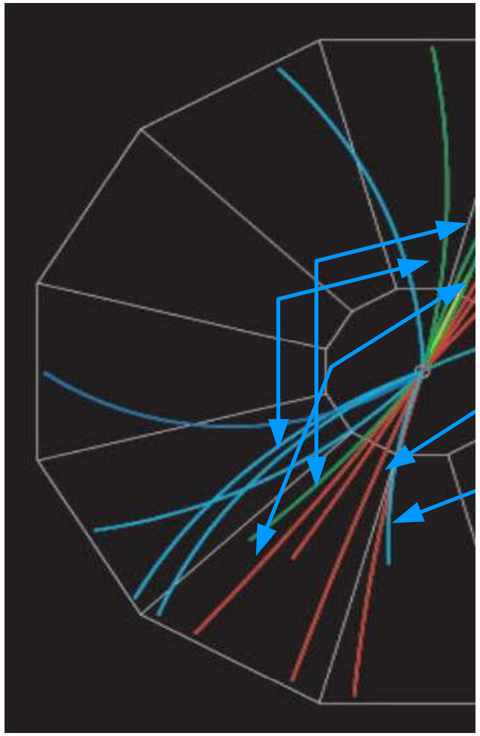
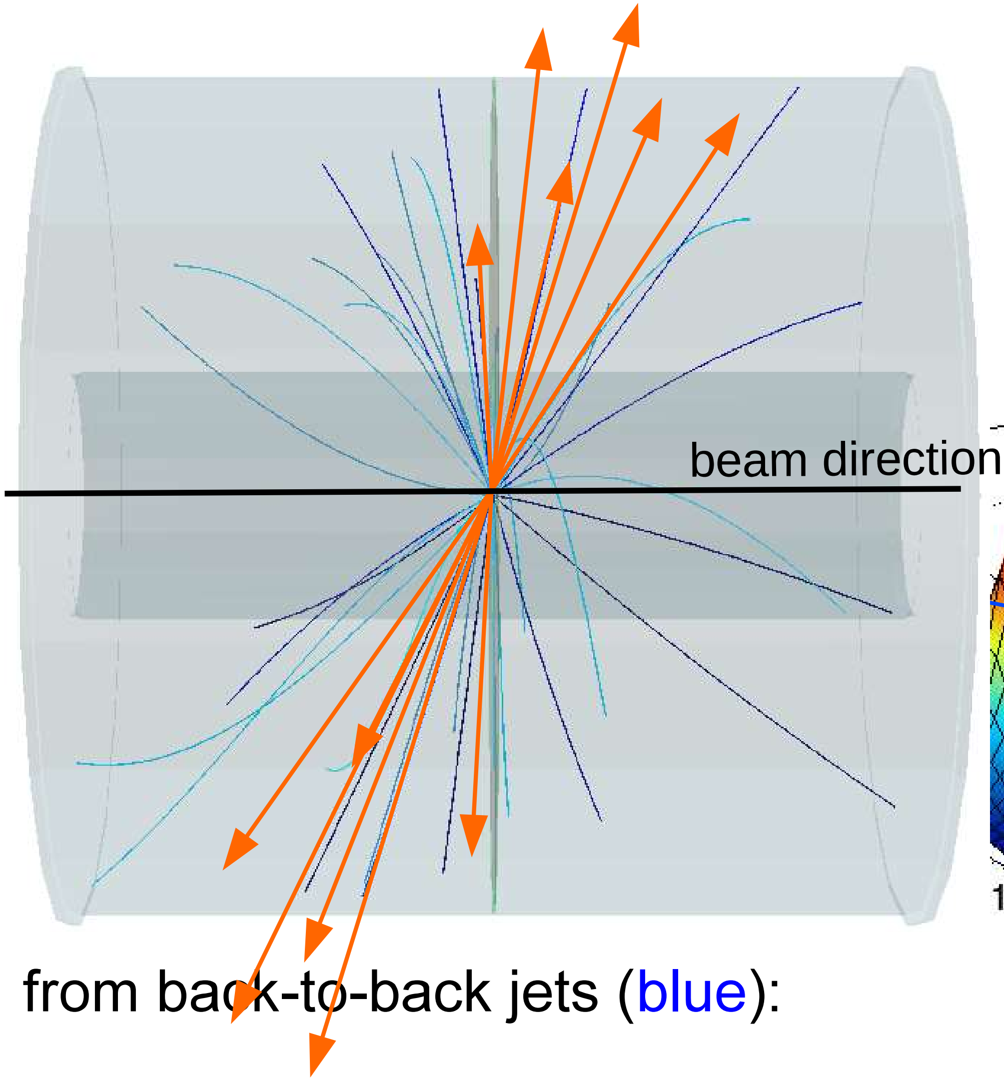
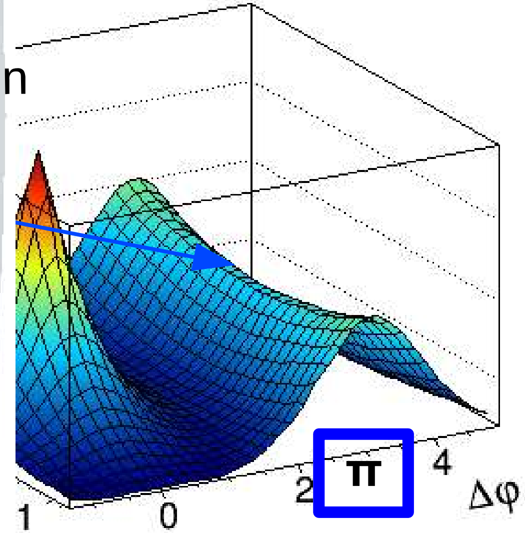
- **Δη ~ const, if avaraged over many events**

How does it work?



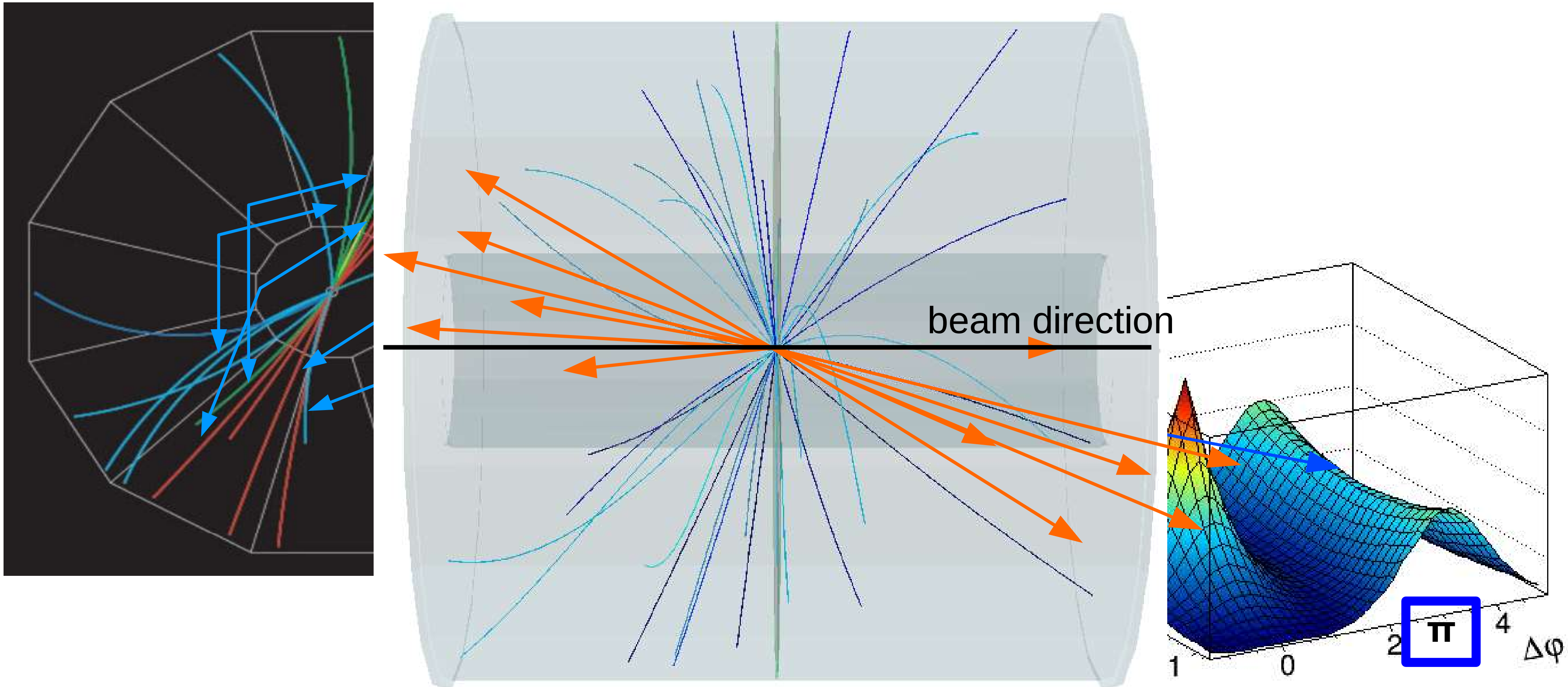




For particles from from back-to-back jets (blue):

- **Δφ ~ π**
- **Δη ~ const, if avaraged over many events**

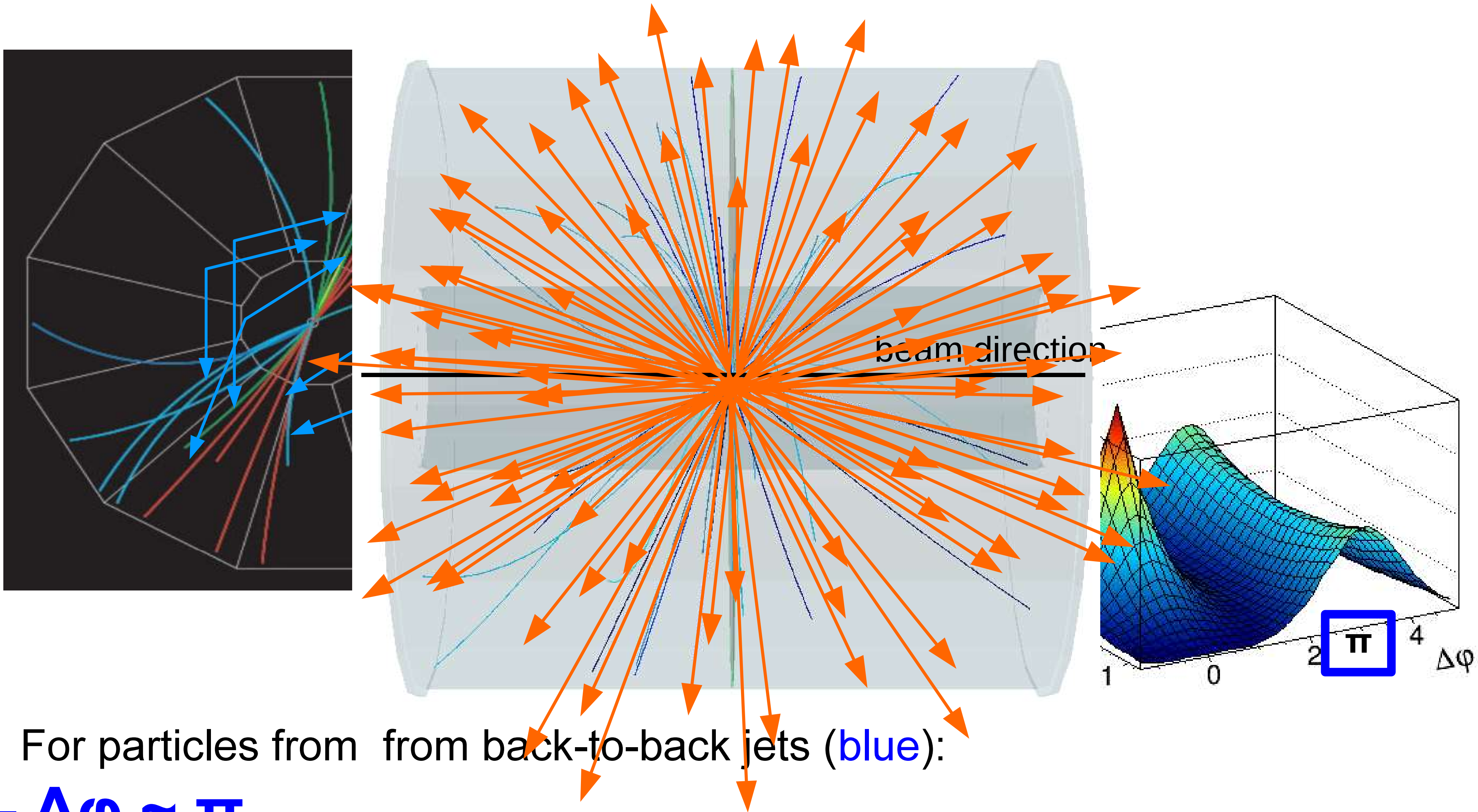
How does it work?



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

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

How does it work?



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

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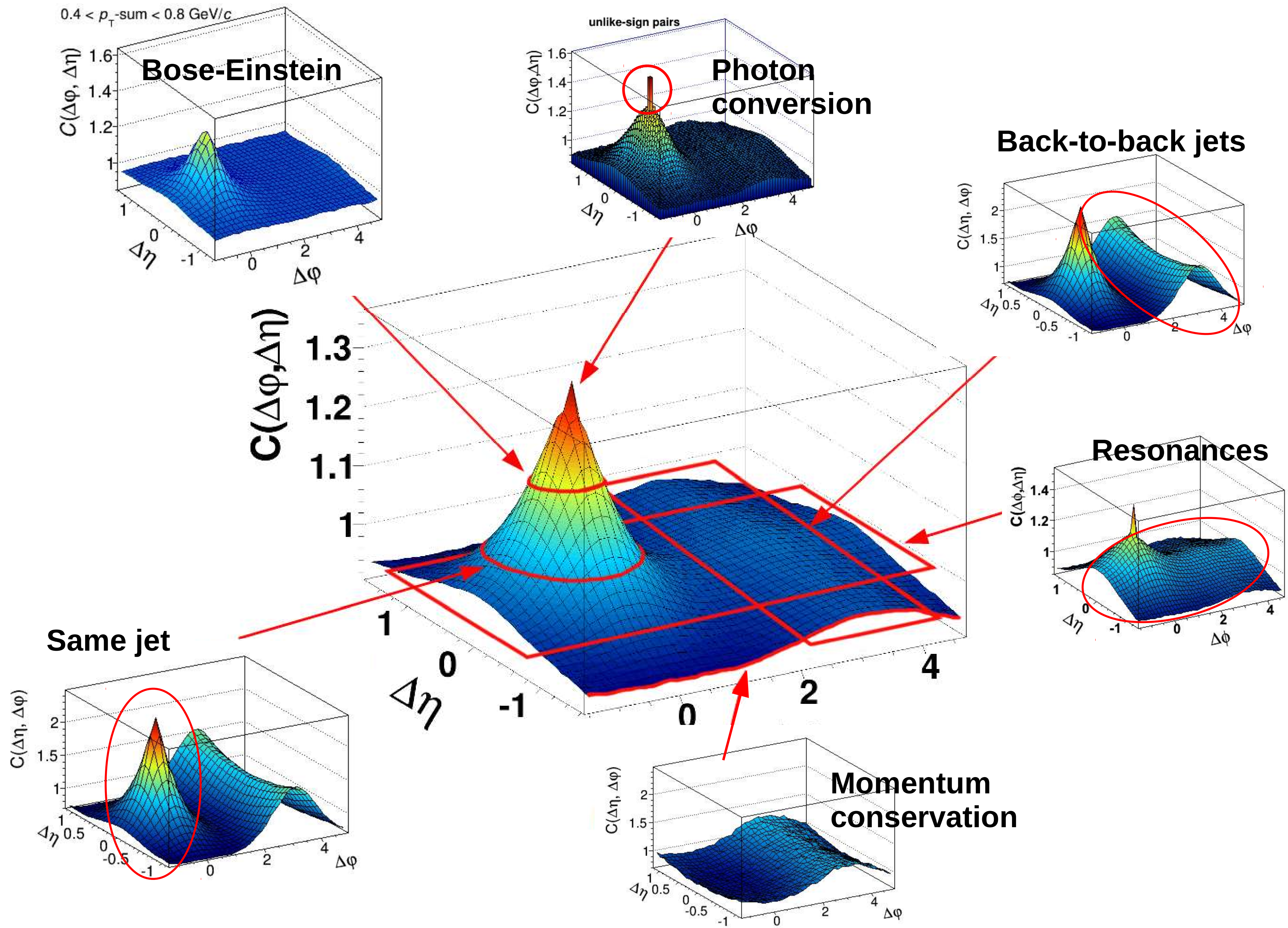
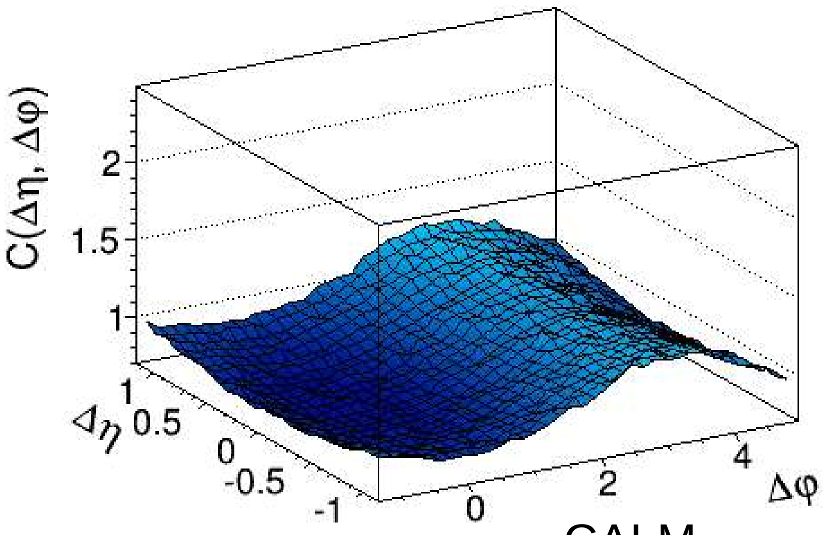
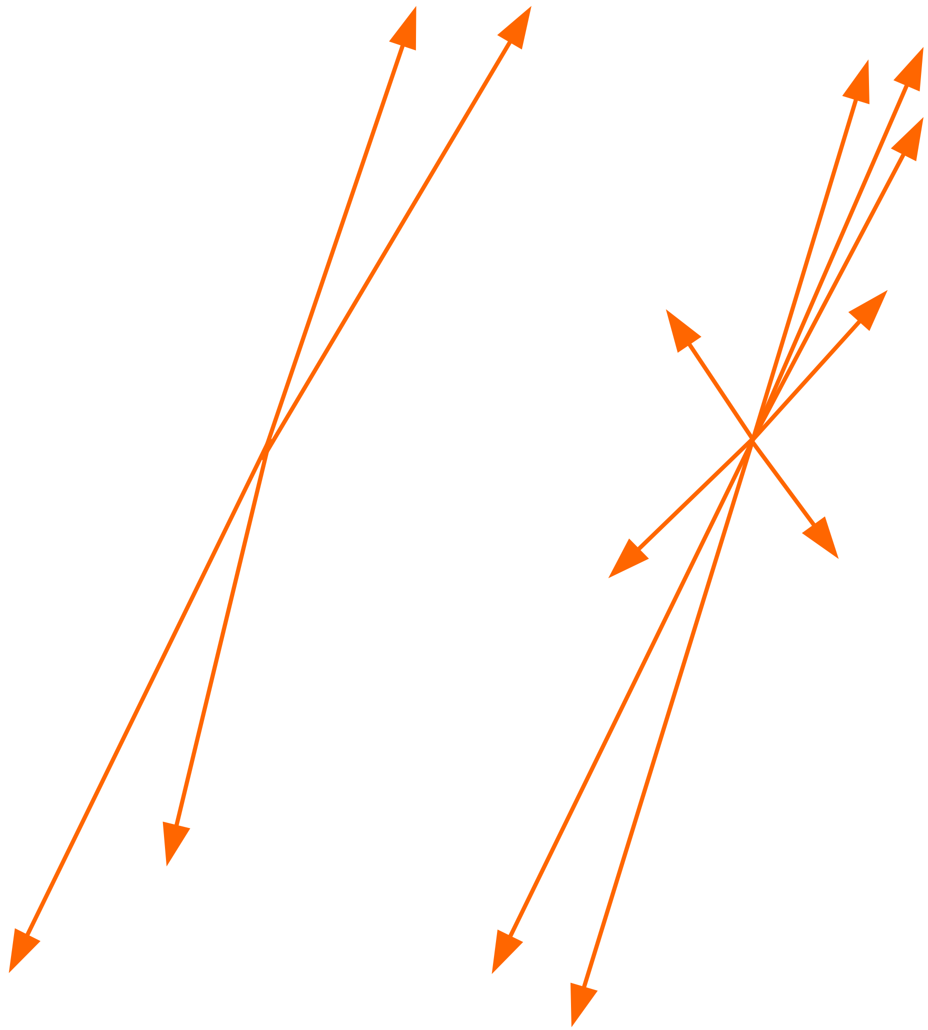

Bose-Einstein
0.4 < p_T-sum < 0.8 GeV/c
Photon conversion
unlike-sign pairs
Back-to-back jets
Resonances
Same jet
Momentum conservation
C(Δφ,Δη)
Δη
Δφ

How does it work?

Momentum conservation



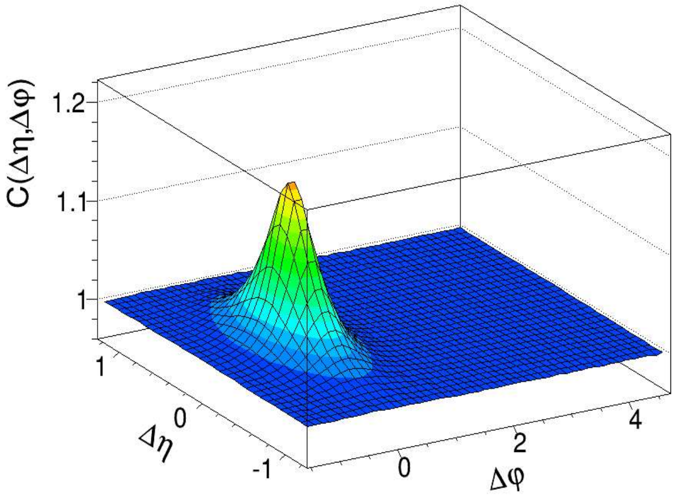
CALM



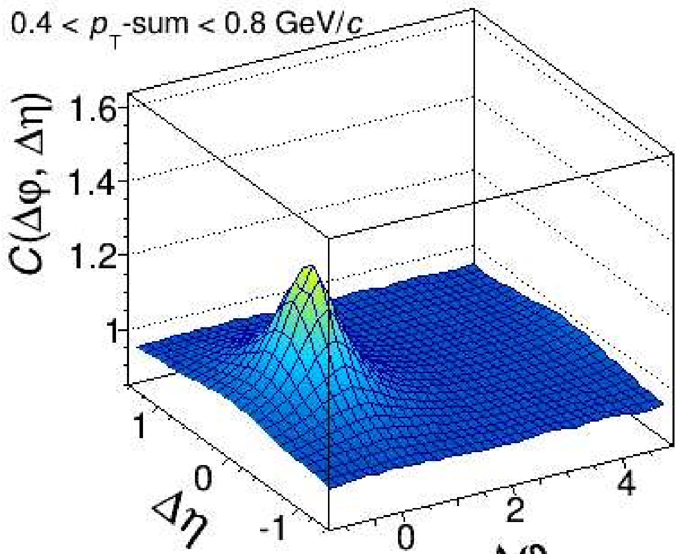
Events with angular momentum conserved only

How does it work?

Bose-Einstein Correlations



EPOS p-Pb



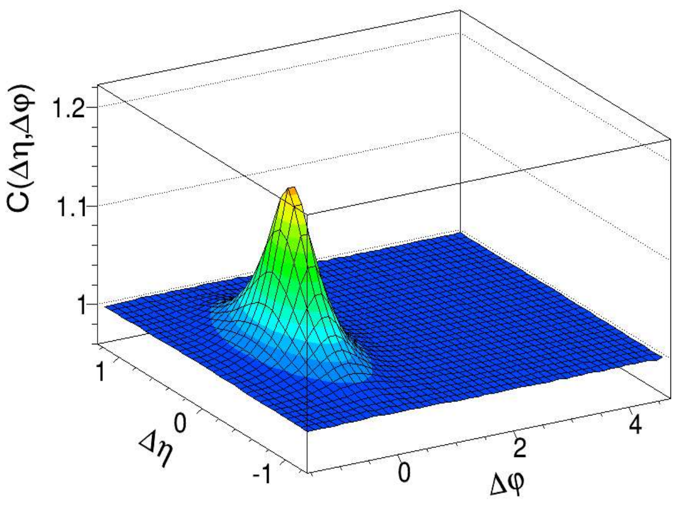
ALICE

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

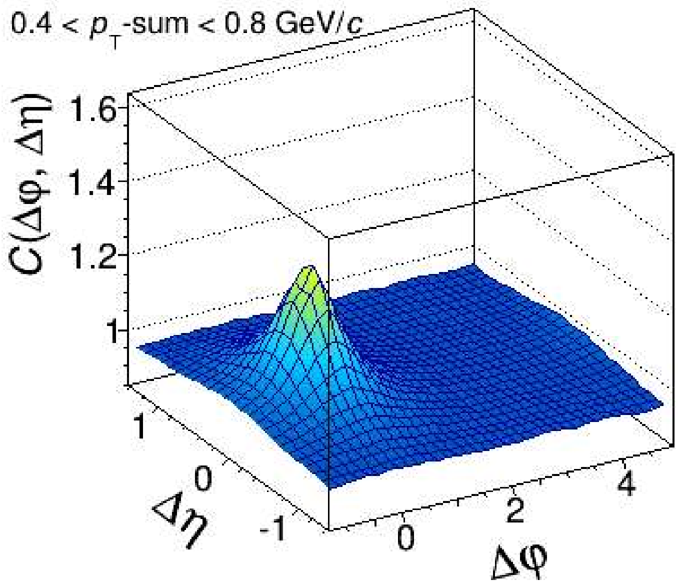
This was first observed in collisions by Goldhaber, Goldhaber, Lee, and Pais more than 50 years ago.

How does it work?

Bose-Einstein Correlations

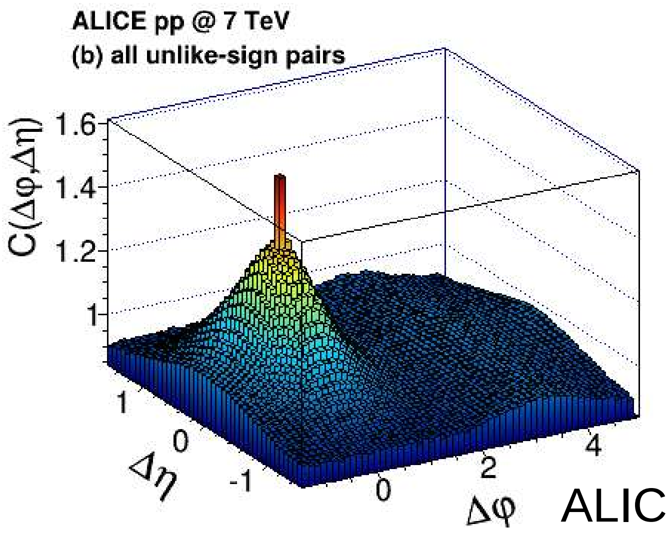


EPOS p-Pb



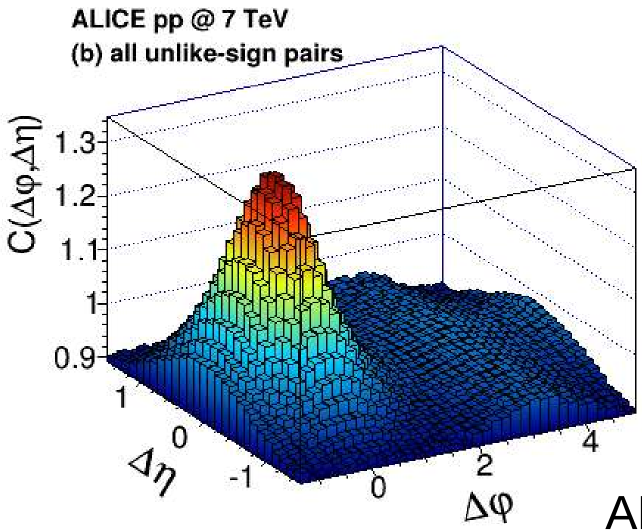
ALICE

Photon conversion

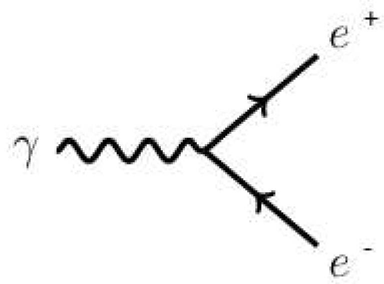


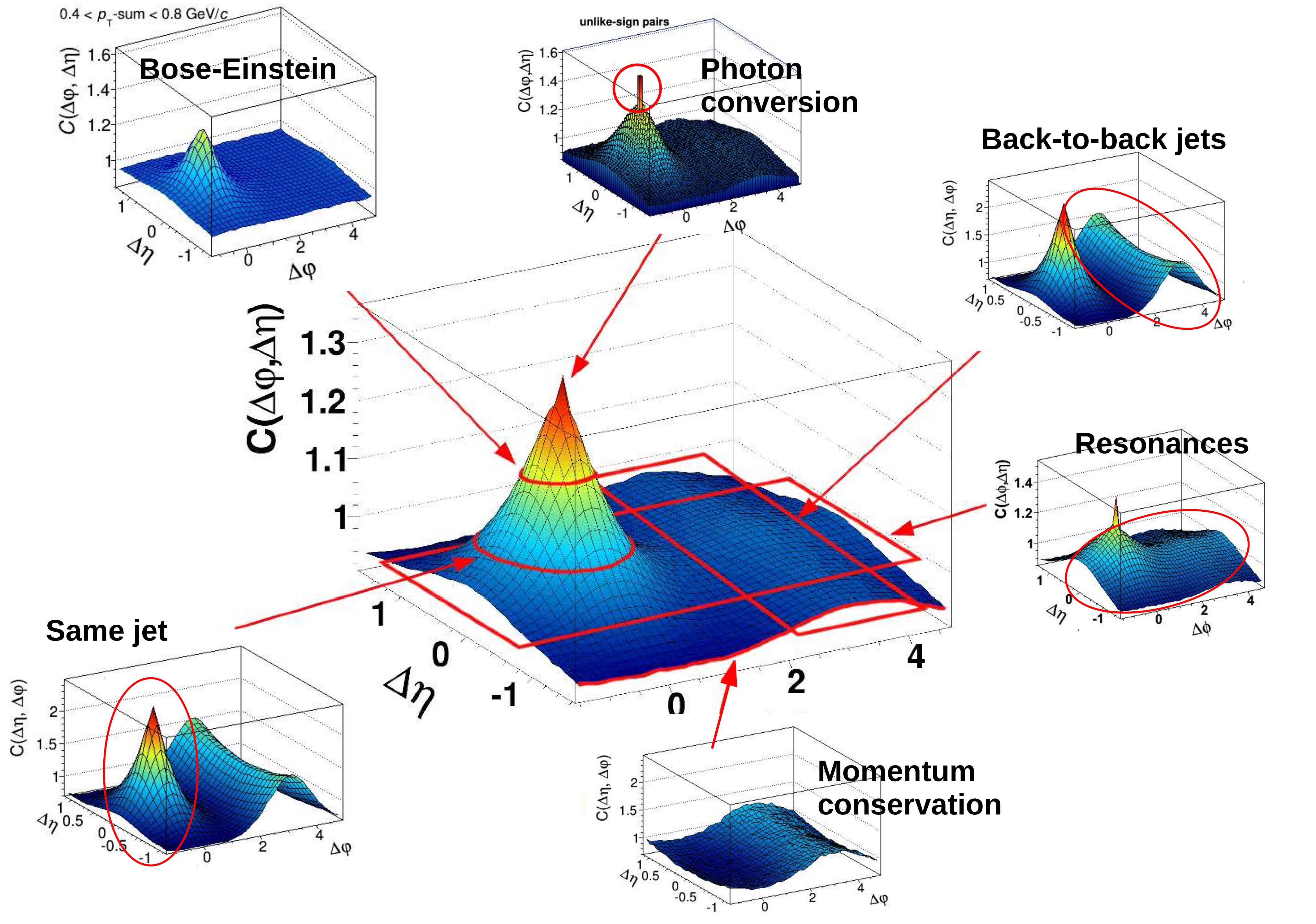
ALICE

→ *Electron rejection*

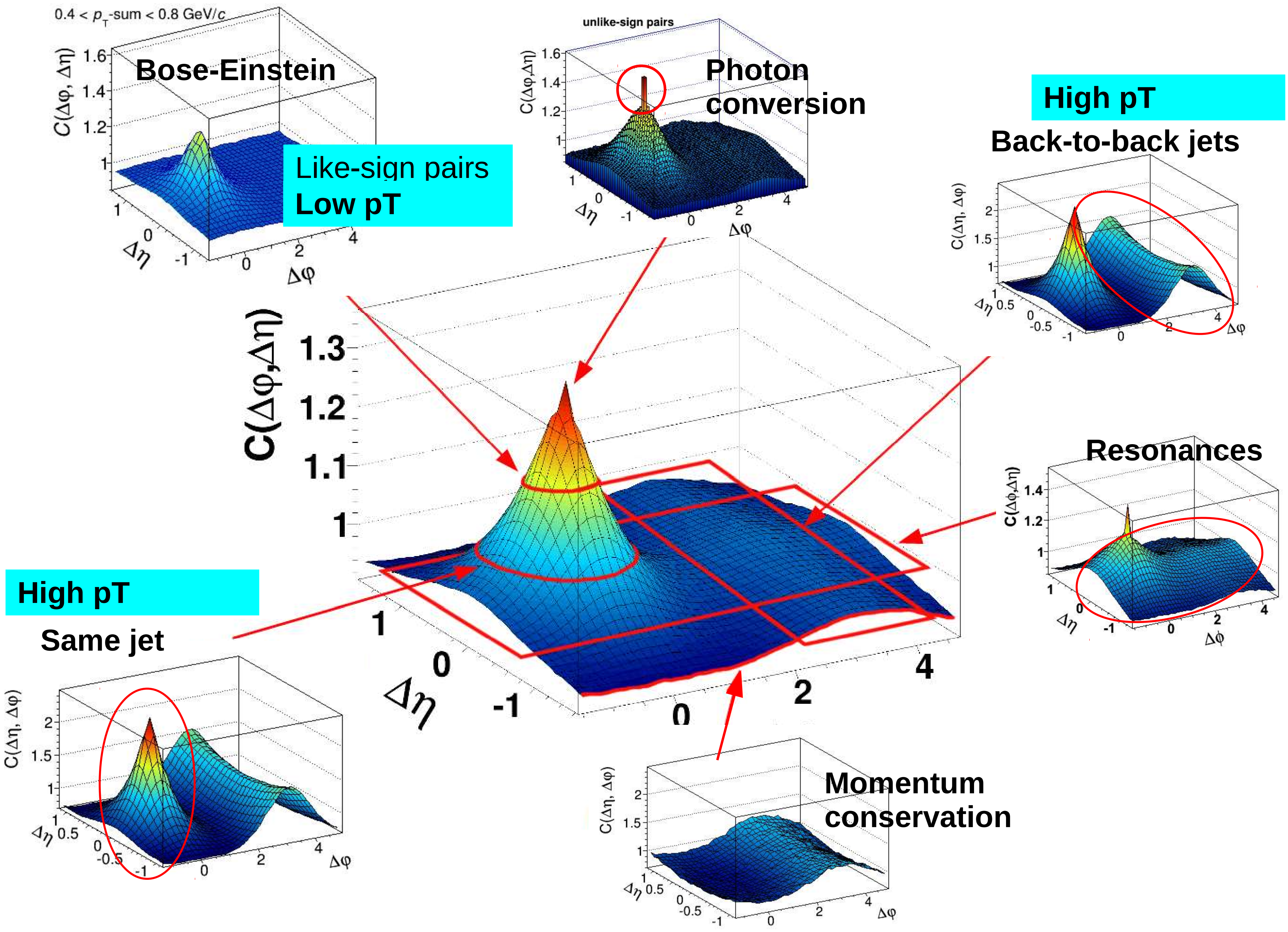


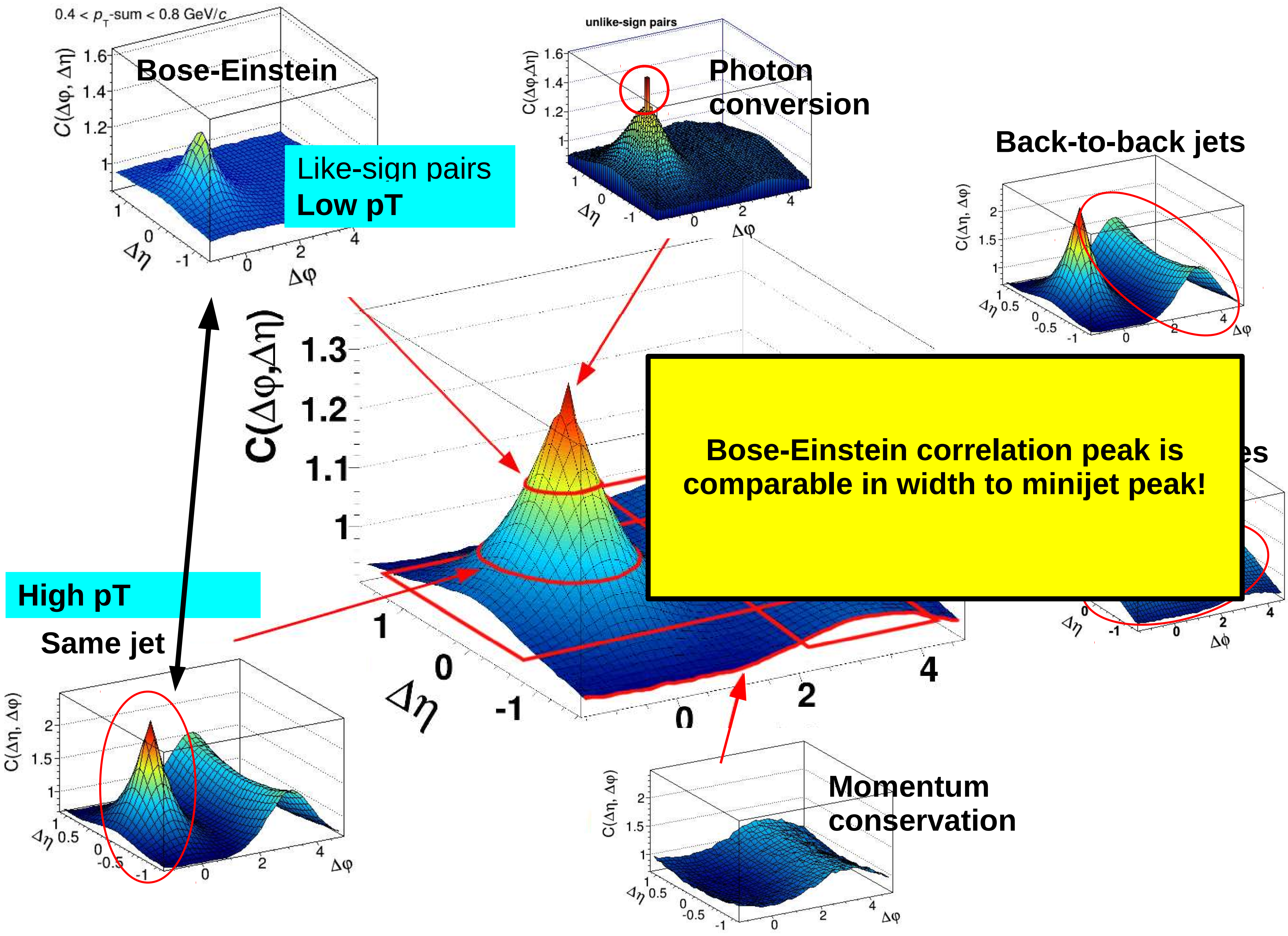
ALICE





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


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


0.4 < p_T-sum < 0.8 GeV/c
Bose-Einstein
Like-sign pairs
Low pT
unlike-sign pairs
Photon conversion
Back-to-back jets
Bose-Einstein correlation peak is comparable in width to minijet peak!
High pT
Same jet
Momentum conservation

How we can use it?
Background for femtoscopy

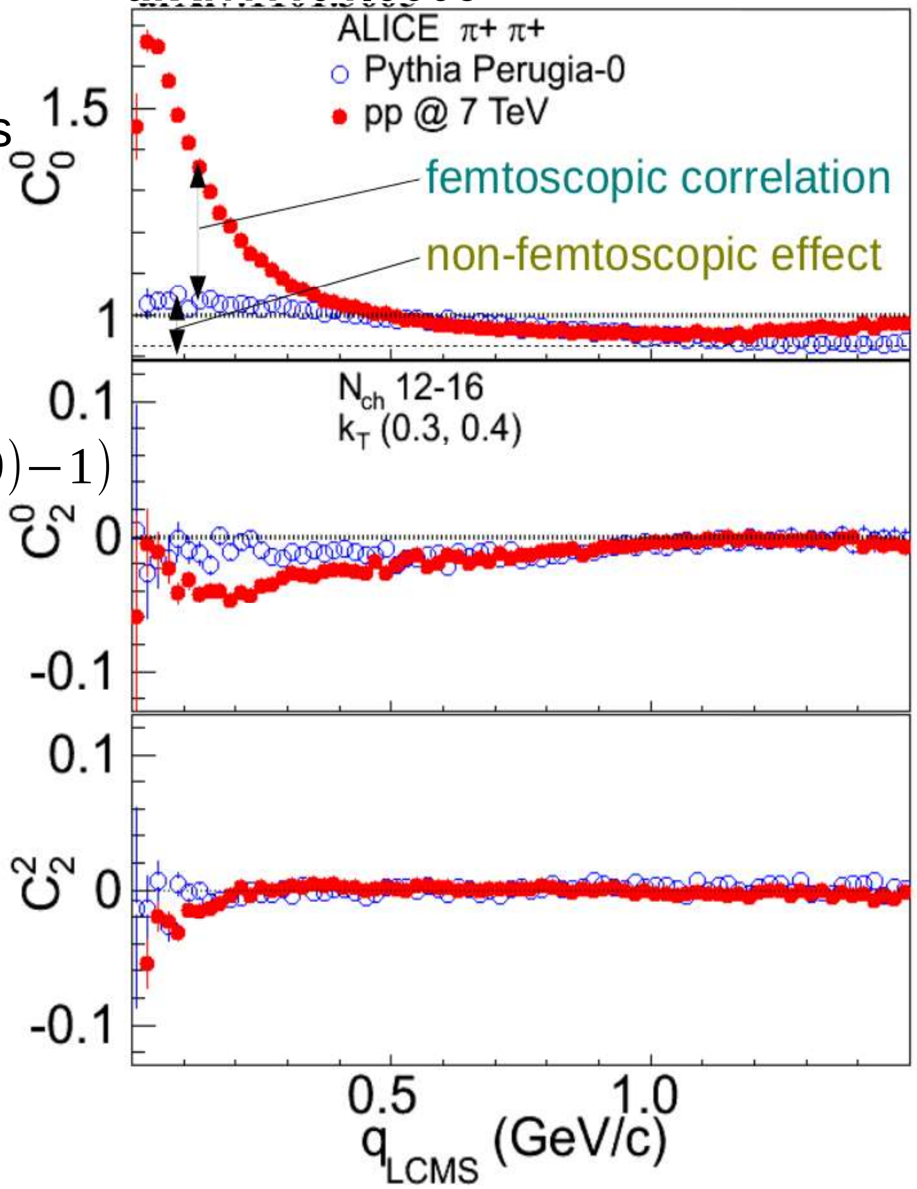
Baseline of the CF

- 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

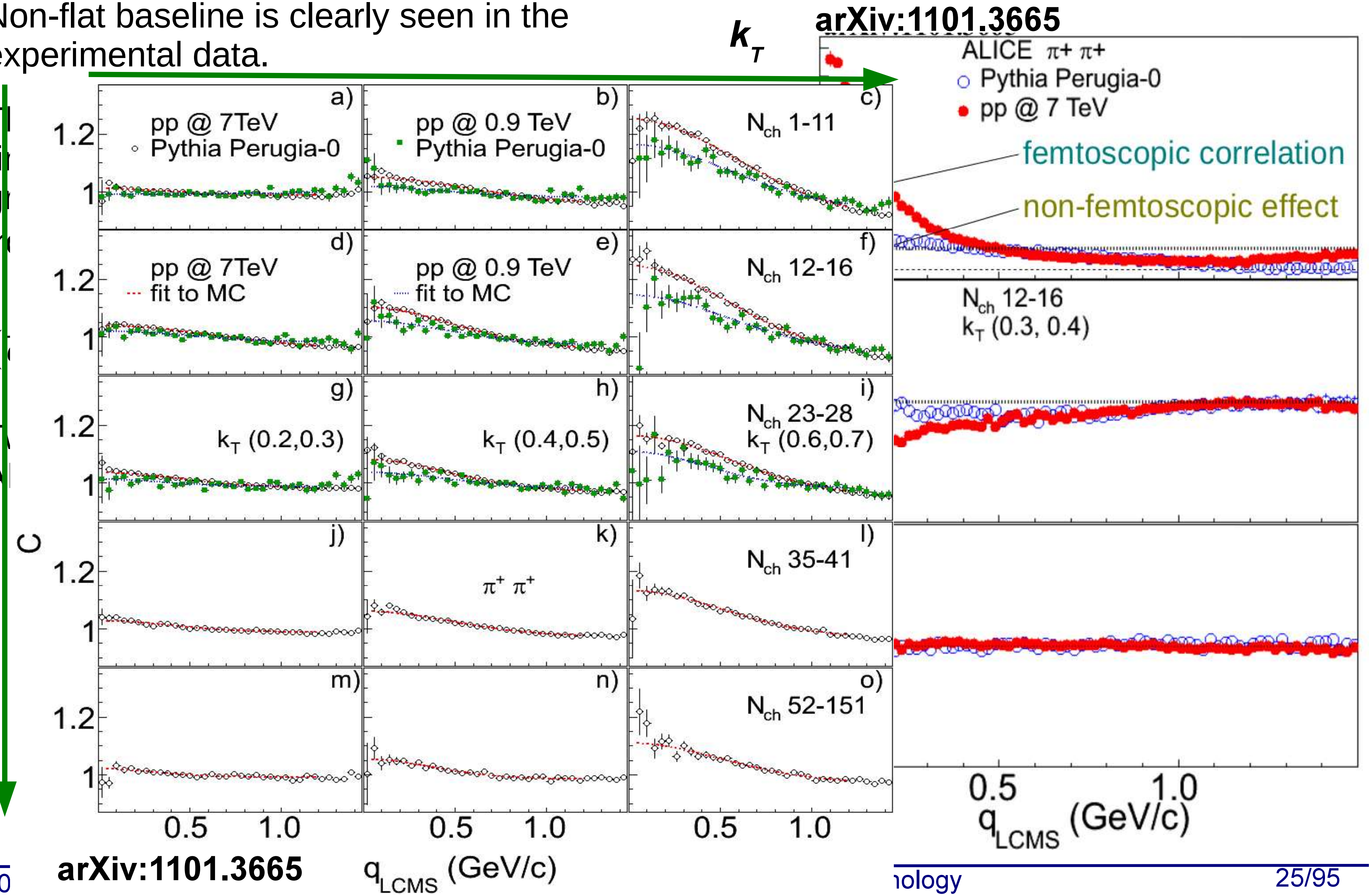


Baseline of the CF

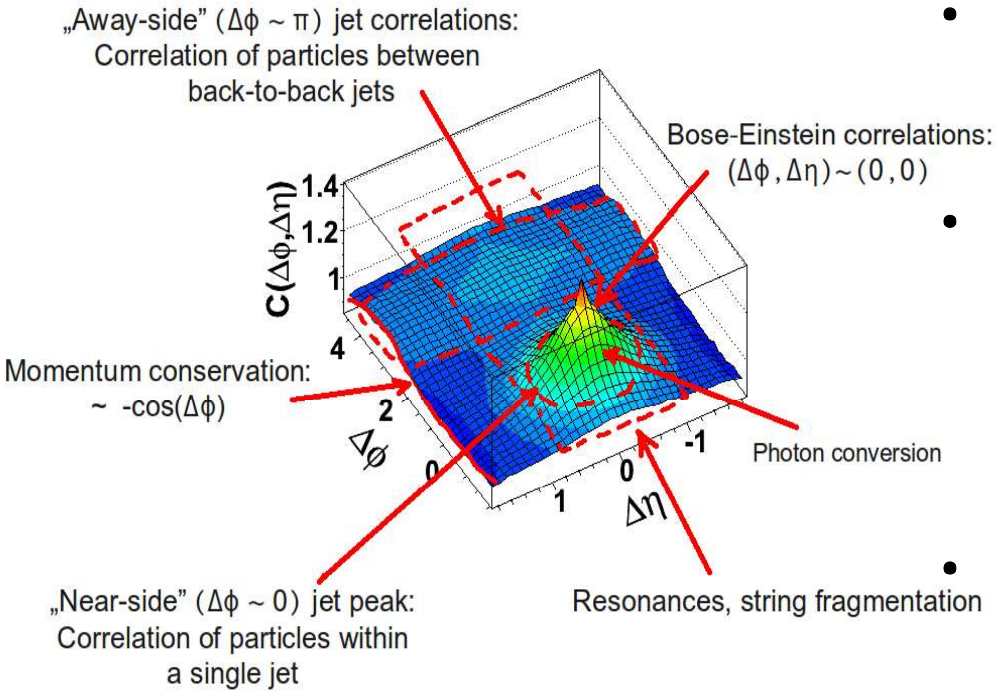
- Non-flat baseline is clearly seen in the experimental data.
- Tl (i g fr

$B($

- T A



ΔηΔφ angular correlations



- Minijets are usually studied using two-particle correlations in *ΔηΔφ* coordinates.
- To test the "minijet" origin hypothesis of the non-femtoscopic background we employed the *ΔηΔφ* un-triggered angular correlations
- There is a direct connection between *Δη*, *Δφ* 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.

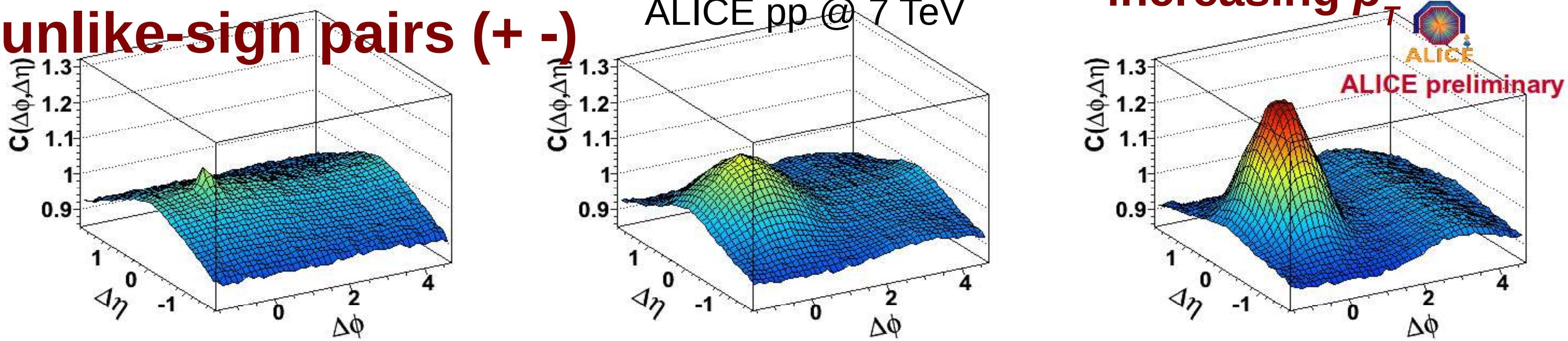
ΔηΔφ angular correlations

No Bose-Einstein correlations for unlike-sign pairs

Correlations coming from "minijets" increase with increasing p_T

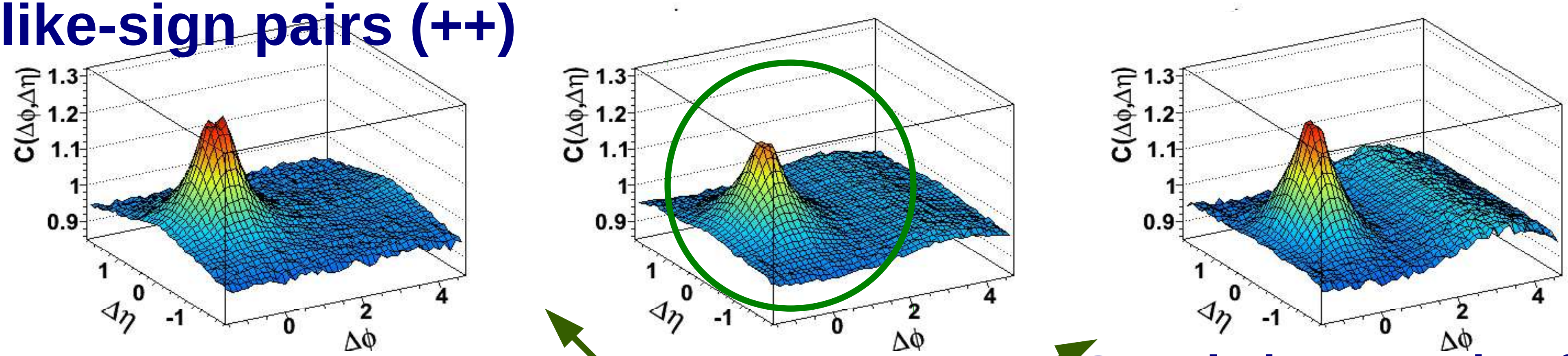
ALICE pp @ 7 TeV

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

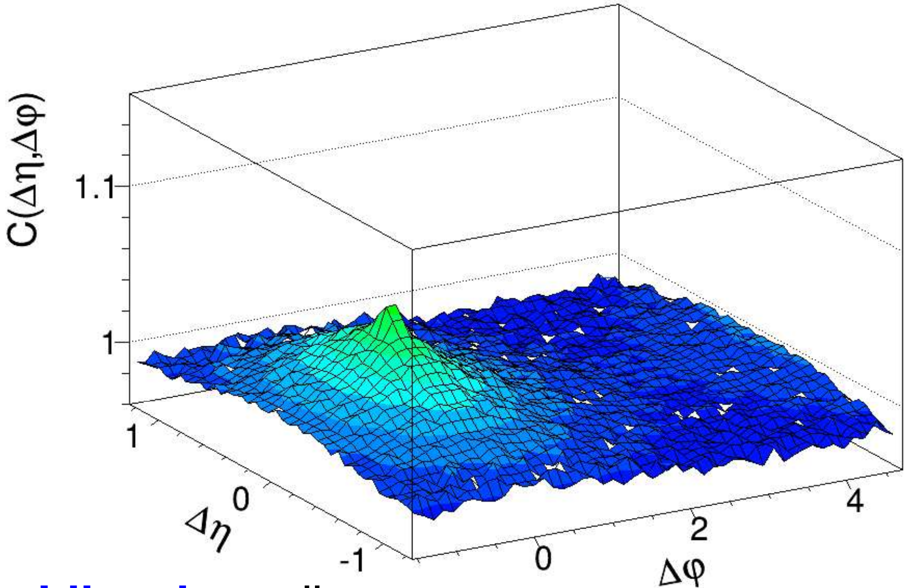
smaller

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

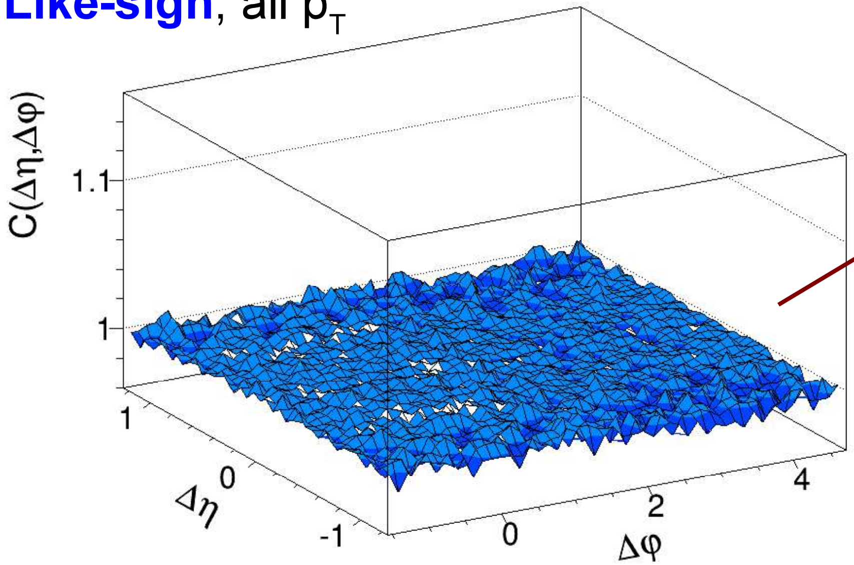
Correlations coming from "minijets" increase with increasing p_T also for like-sign pairs

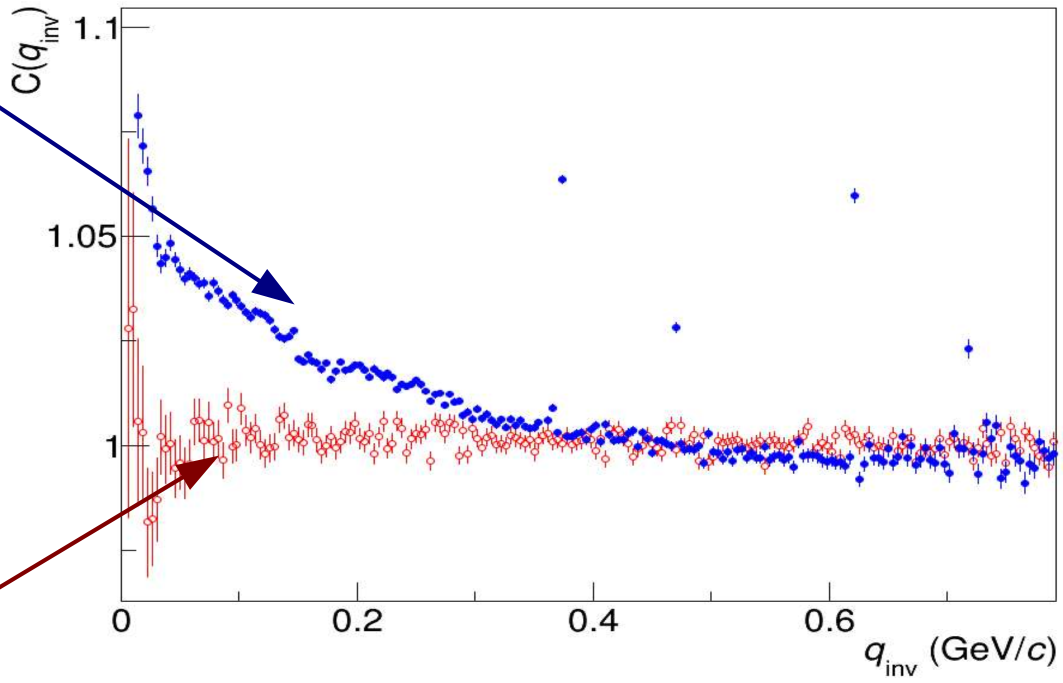
Therminator, background, *balanced*
like- vs *unlike-sign*

Unlike-sign, all p_T



Like-sign, all p_T



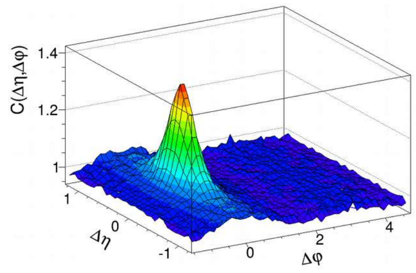


No structures in ΔηΔφ – no structures in q_{inv}

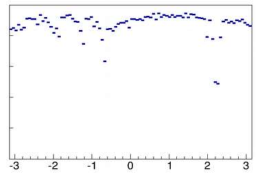
Resonances visible for unlike-sign

Transformation from ΔηΔφ to q_{inv}

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

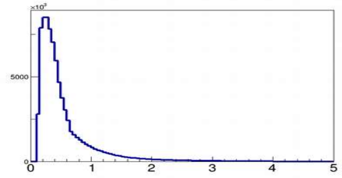


- Generate two random numbers (Δη,Δφ) with probability according to ΔηΔφ distribution (separately for numerator and denominator)



- Generate random φ_1, η_1 from single particle distributions
- Calculate φ_2, η_2 of the second particle using Δη and Δφ

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



- 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, φ and η

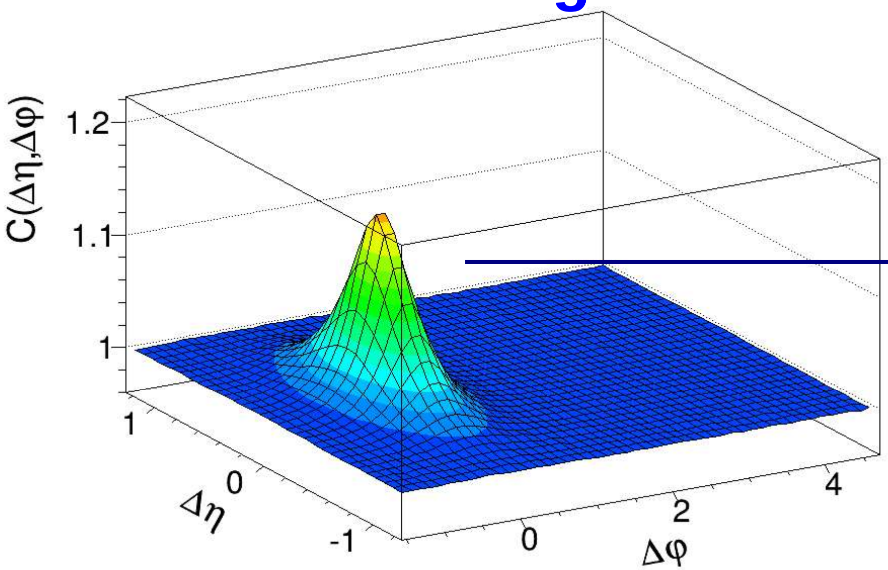
$$p_x = p_T \cos(\phi)$$
$$p_y = p_T \sin(\phi)$$
$$p_z = p_T \sinh(\eta)$$

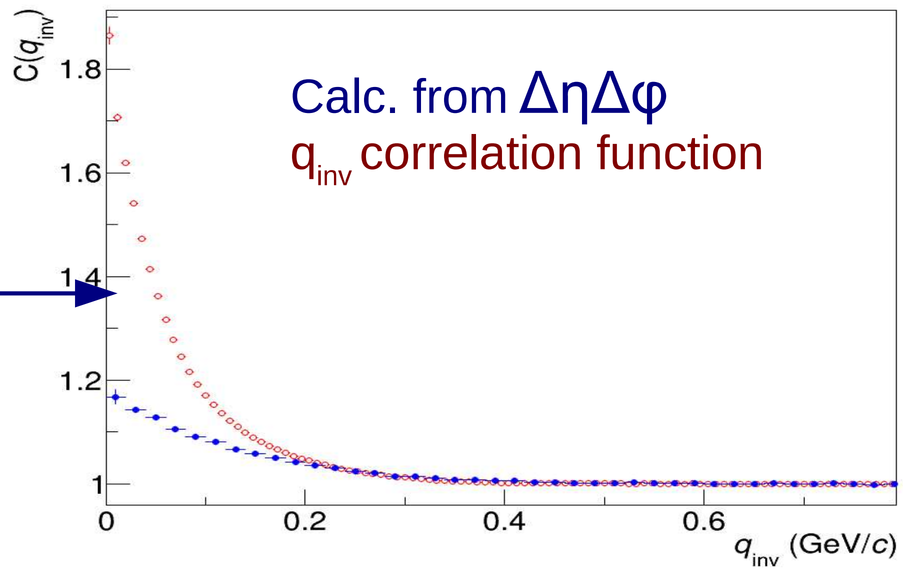
- Calculate q_{inv} from p_x, p_y, p_z

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

EPOS 3, transformation of ΔηΔφ to q_{inv}

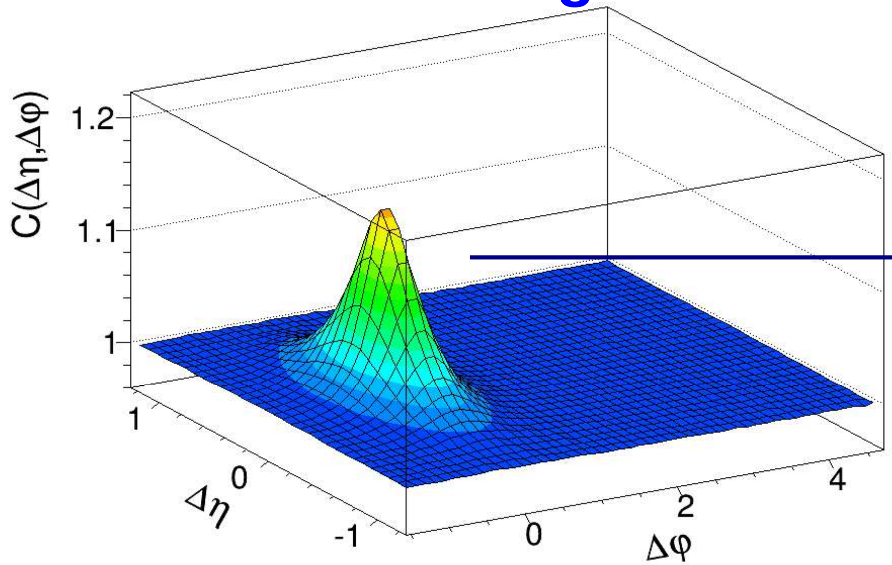
Pure femto weights

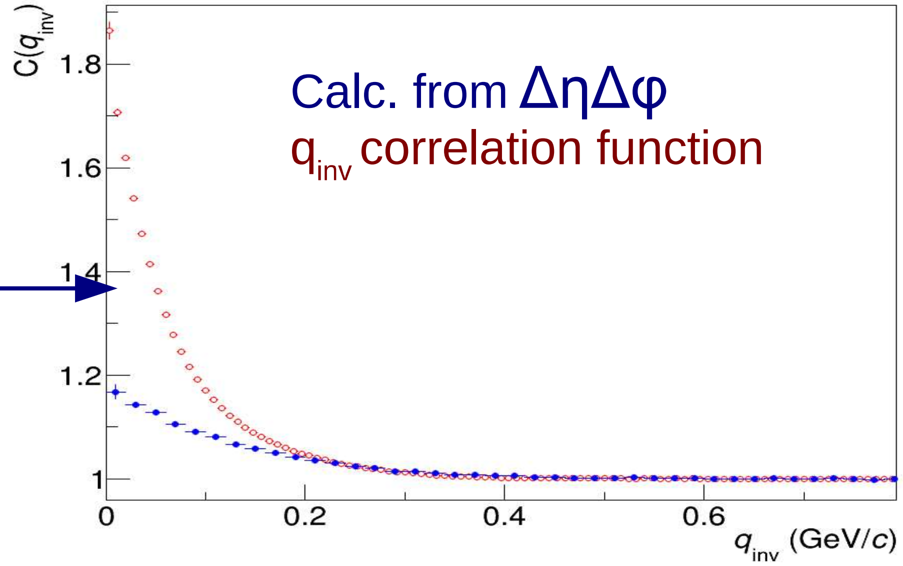




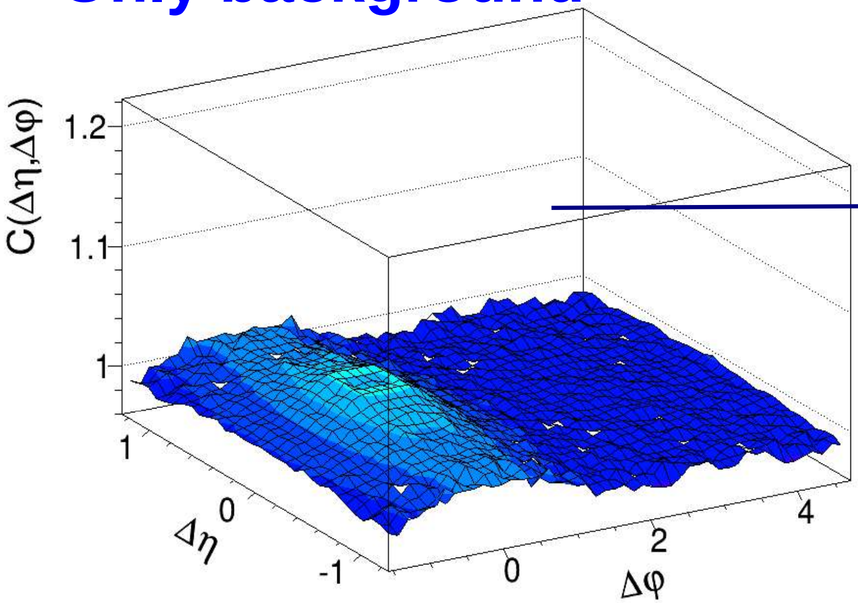
EPOS 3, transformation of ΔηΔφ to q_{inv}

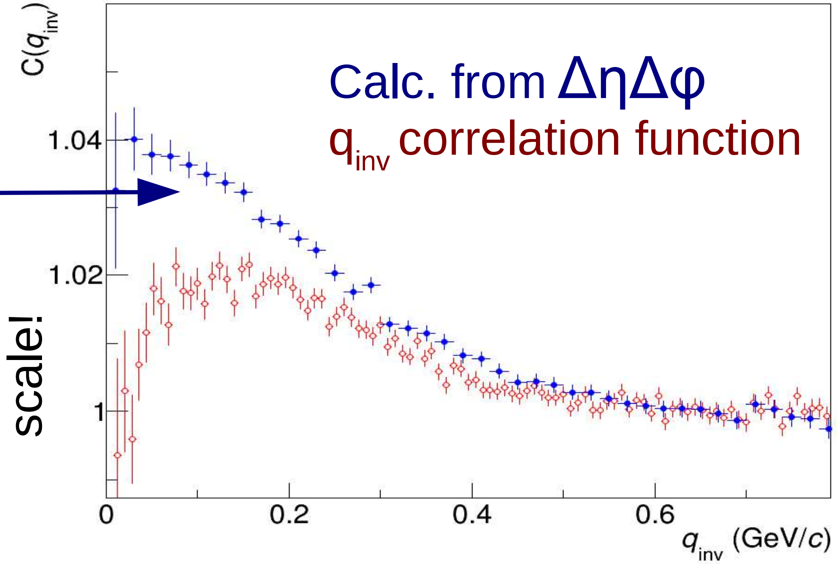
Pure femto weights





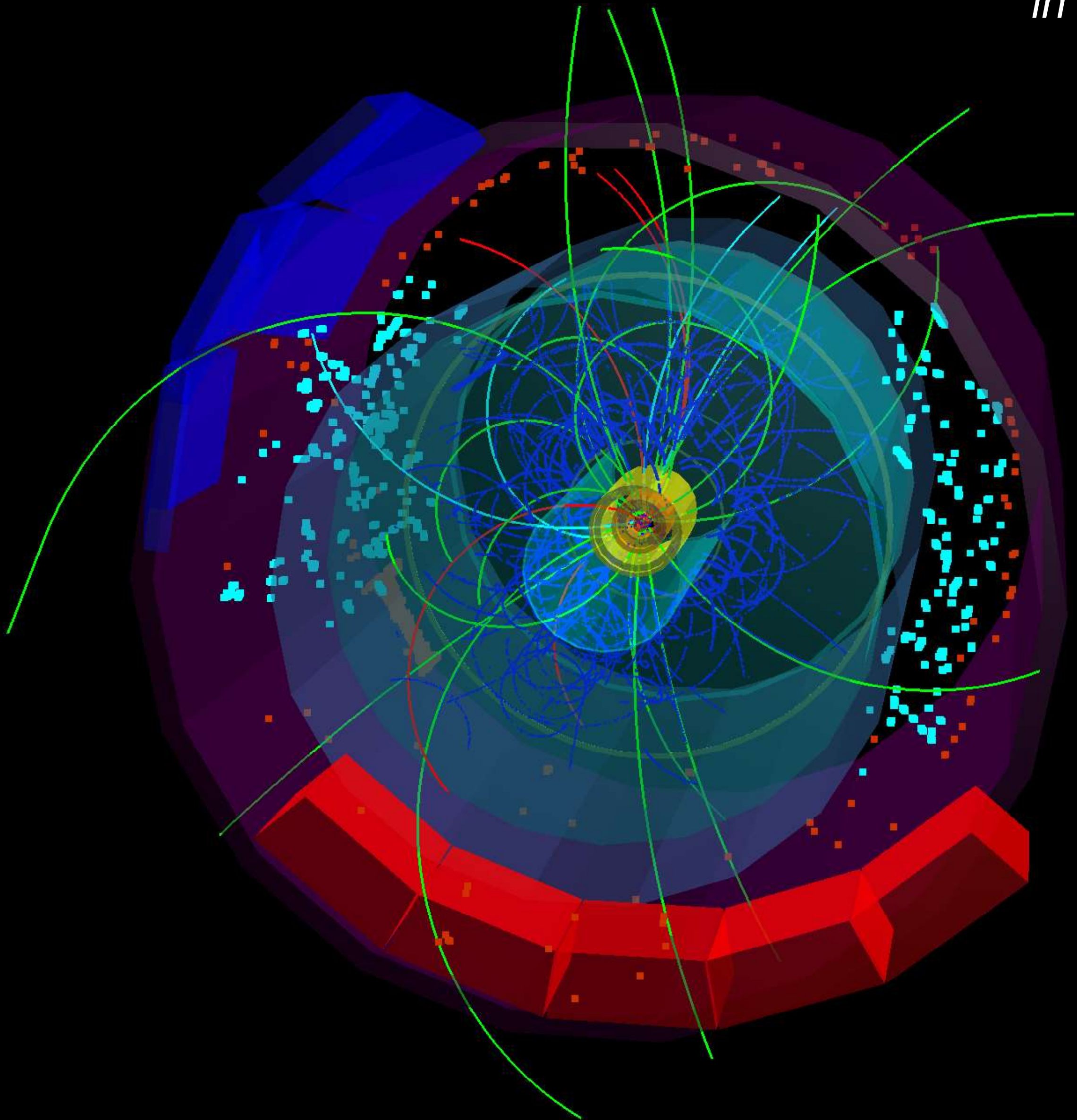
Only background





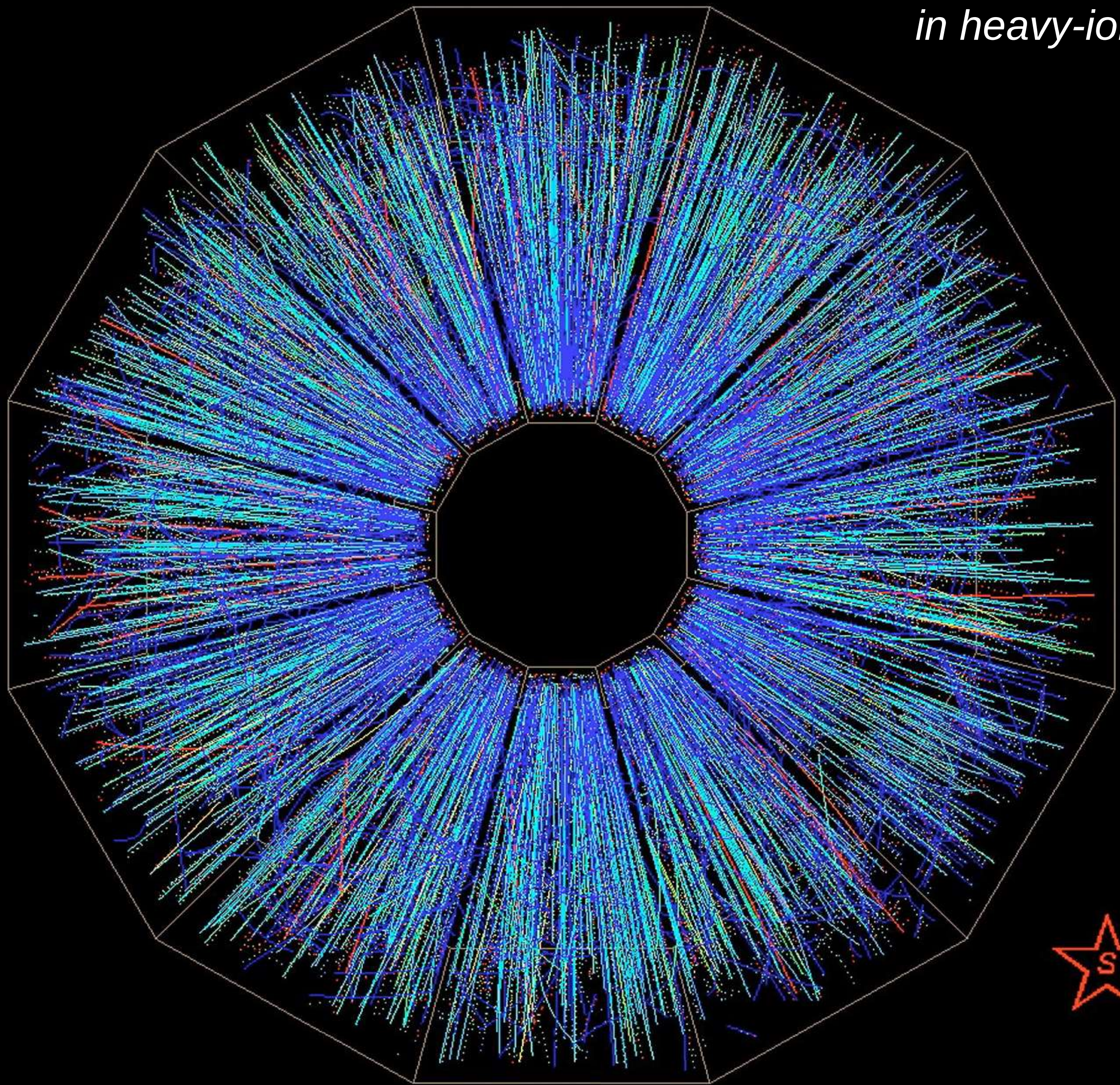
ΔηΔφ angular correlations

in pp collisions

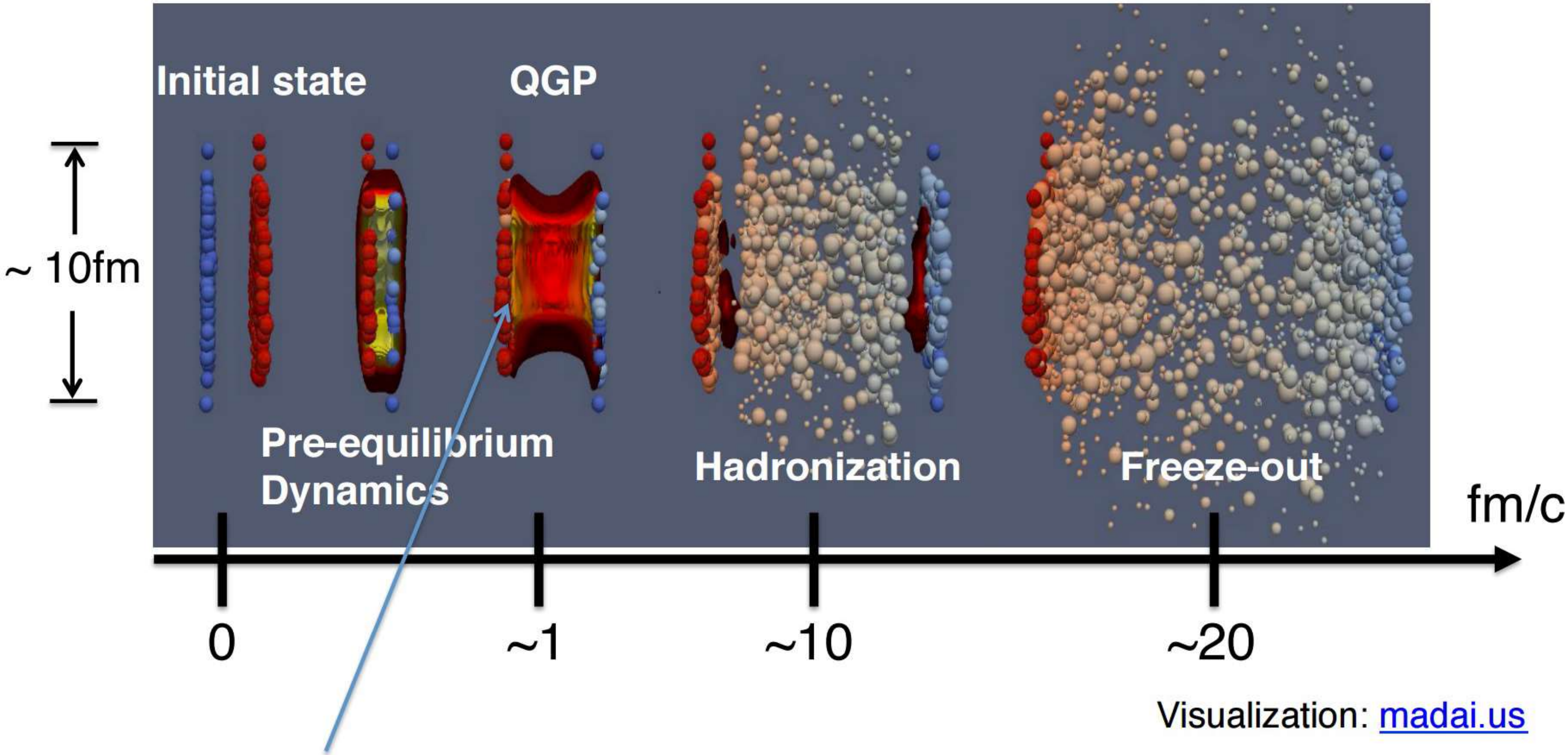


ΔηΔφ angular correlations

in heavy-ion collisions



Standard paradigm of heavy-ion collision

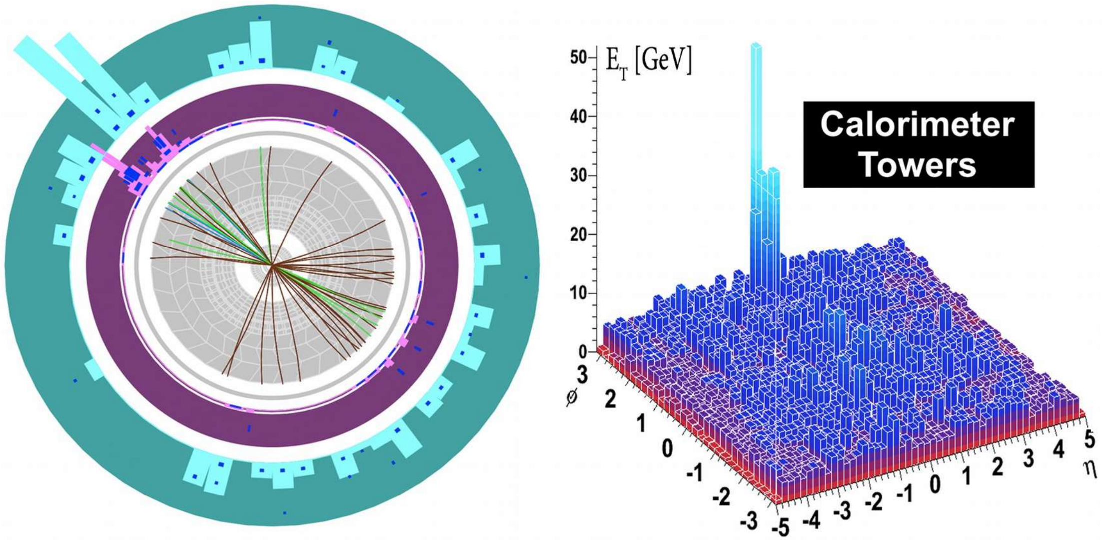


Visualization: madai.us

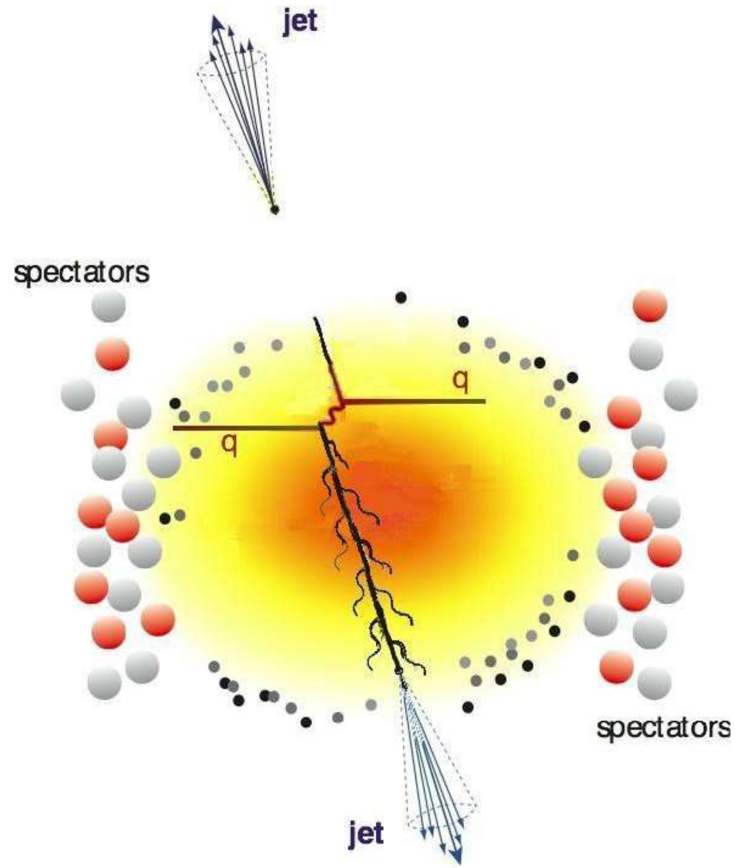
Discovery of a high temperature, thermalized medium with quark and gluon degree of freedom

How we can use it?
Jet quenching

Parton Energy Loss (jet quenching)

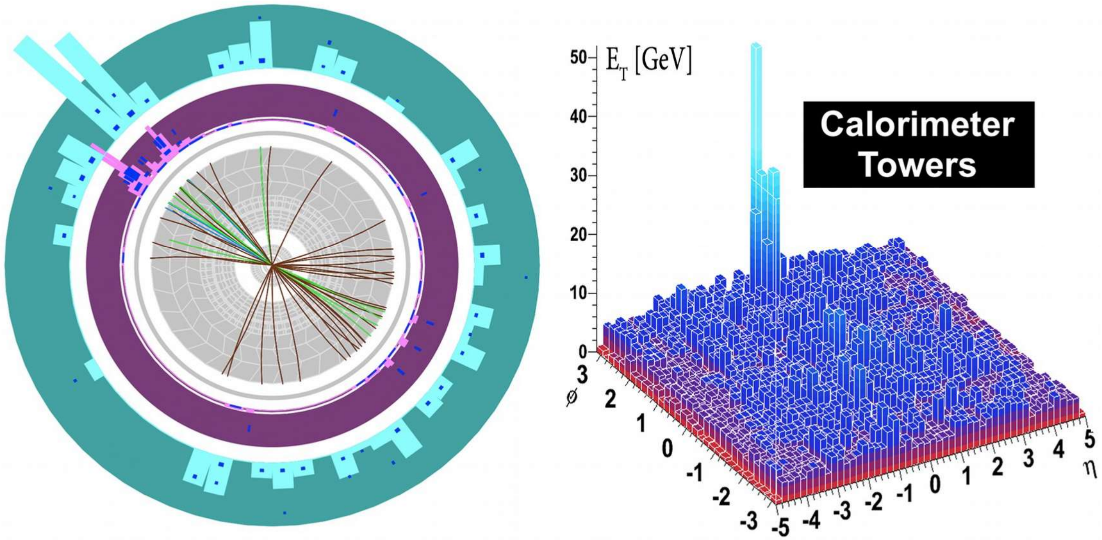


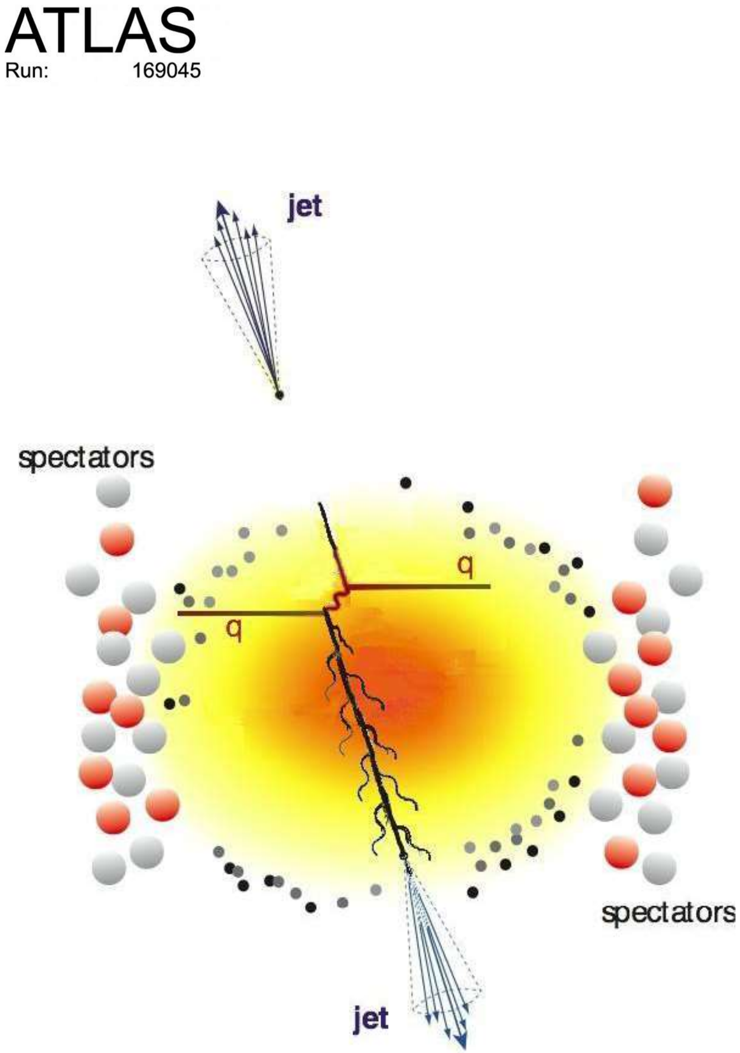
ATLAS
Run: 169045



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

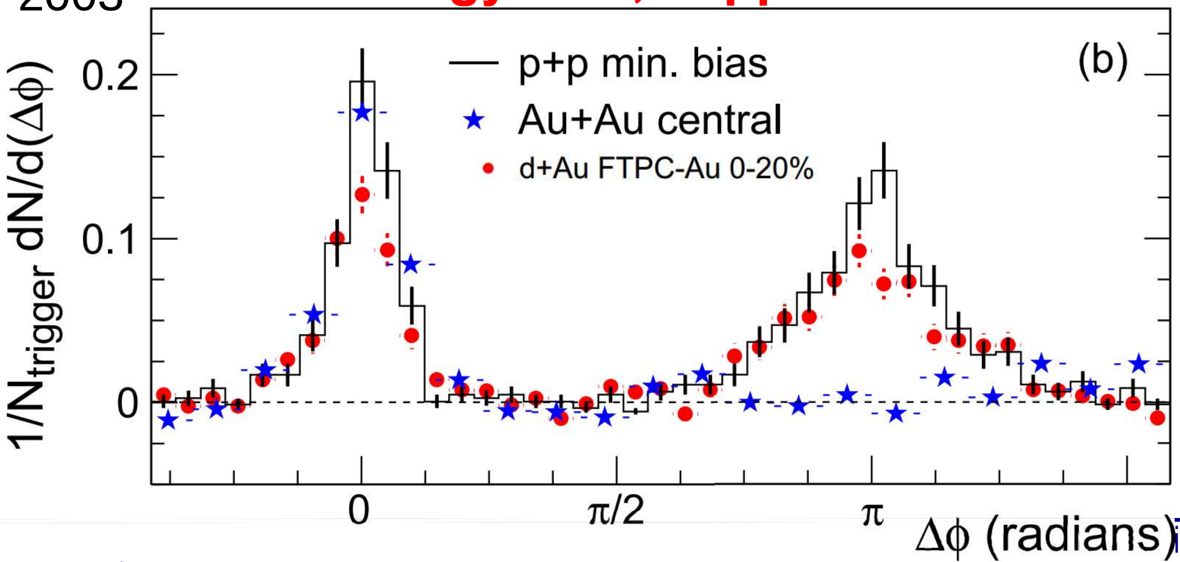
Parton Energy Loss (jet quenching)





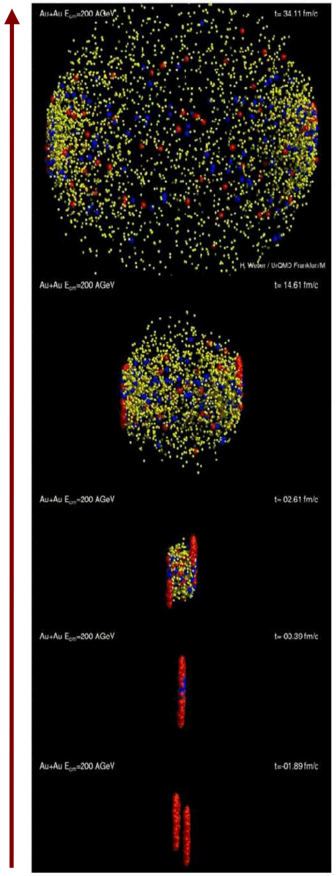
Interaction of gluons, light and heavy quarks inside the medium
→ energy loss, suppression

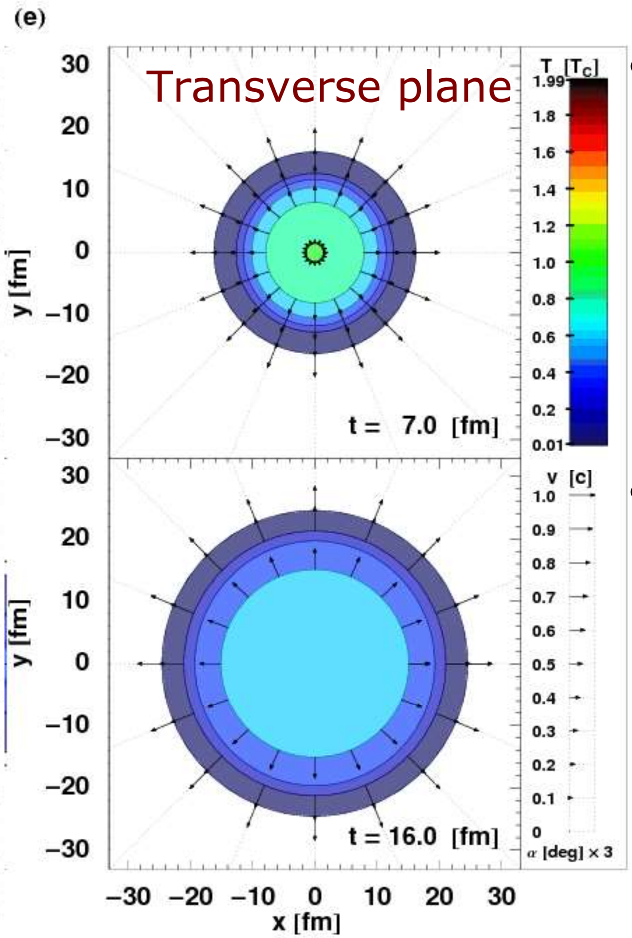
2003



How we can use it?
Flow

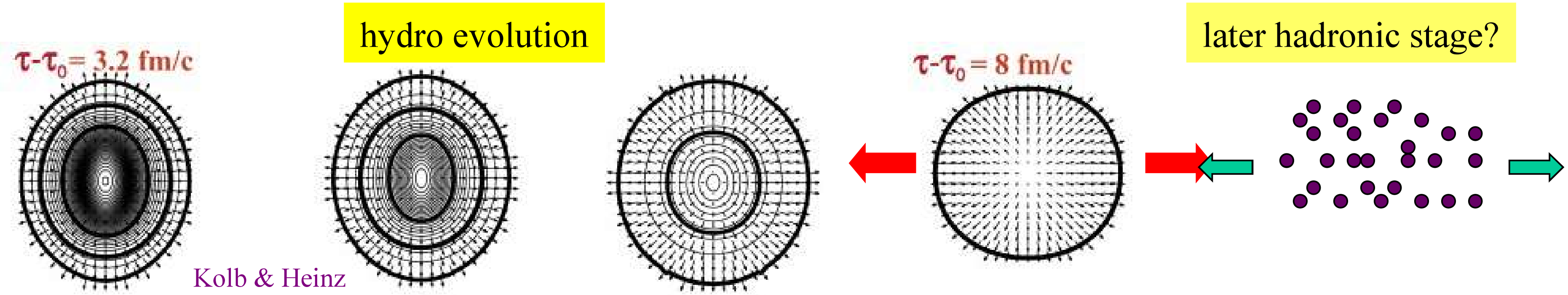
Heavy Ion collision evolution





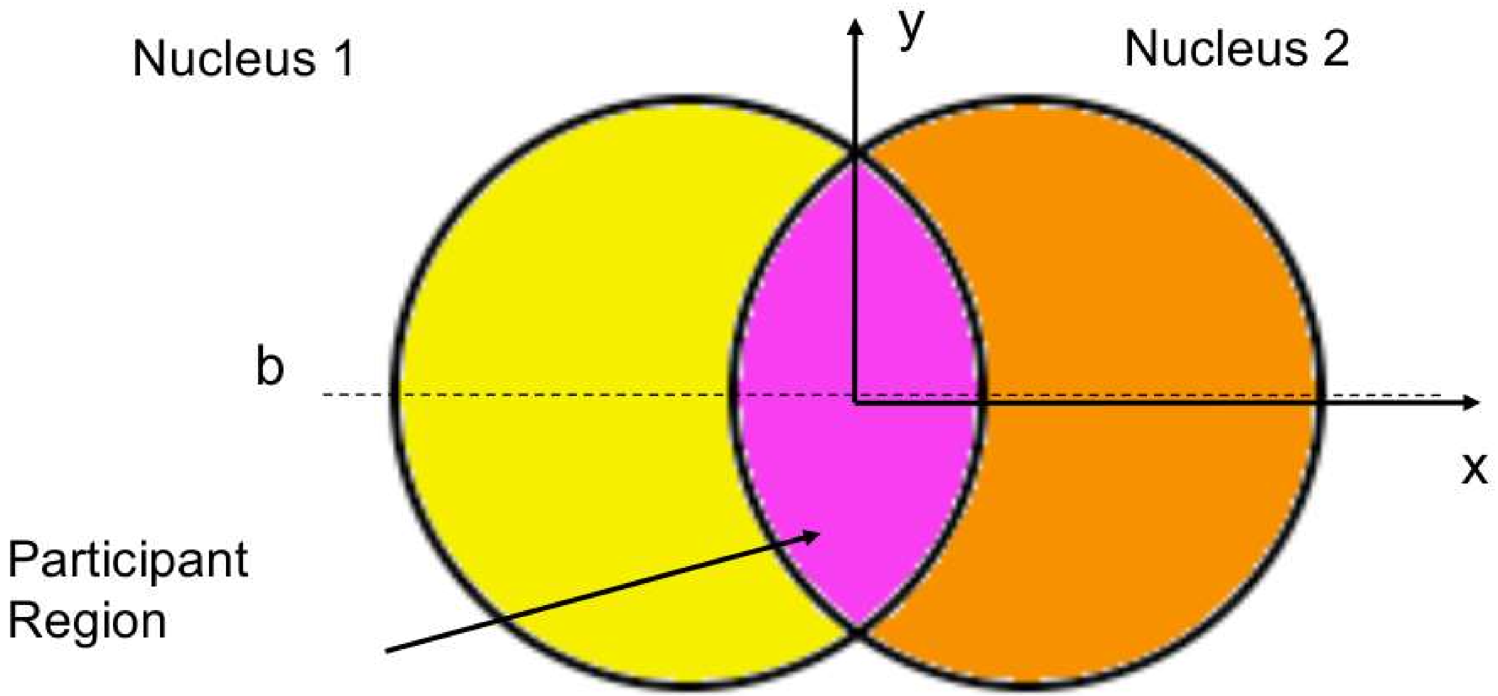
- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion
- Radial flow dominates, with elliptic flow as azimuthal modification

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



Collective effects: flow

Flow:
Textbook signature of QGP



Collective effects: flow

Flow:
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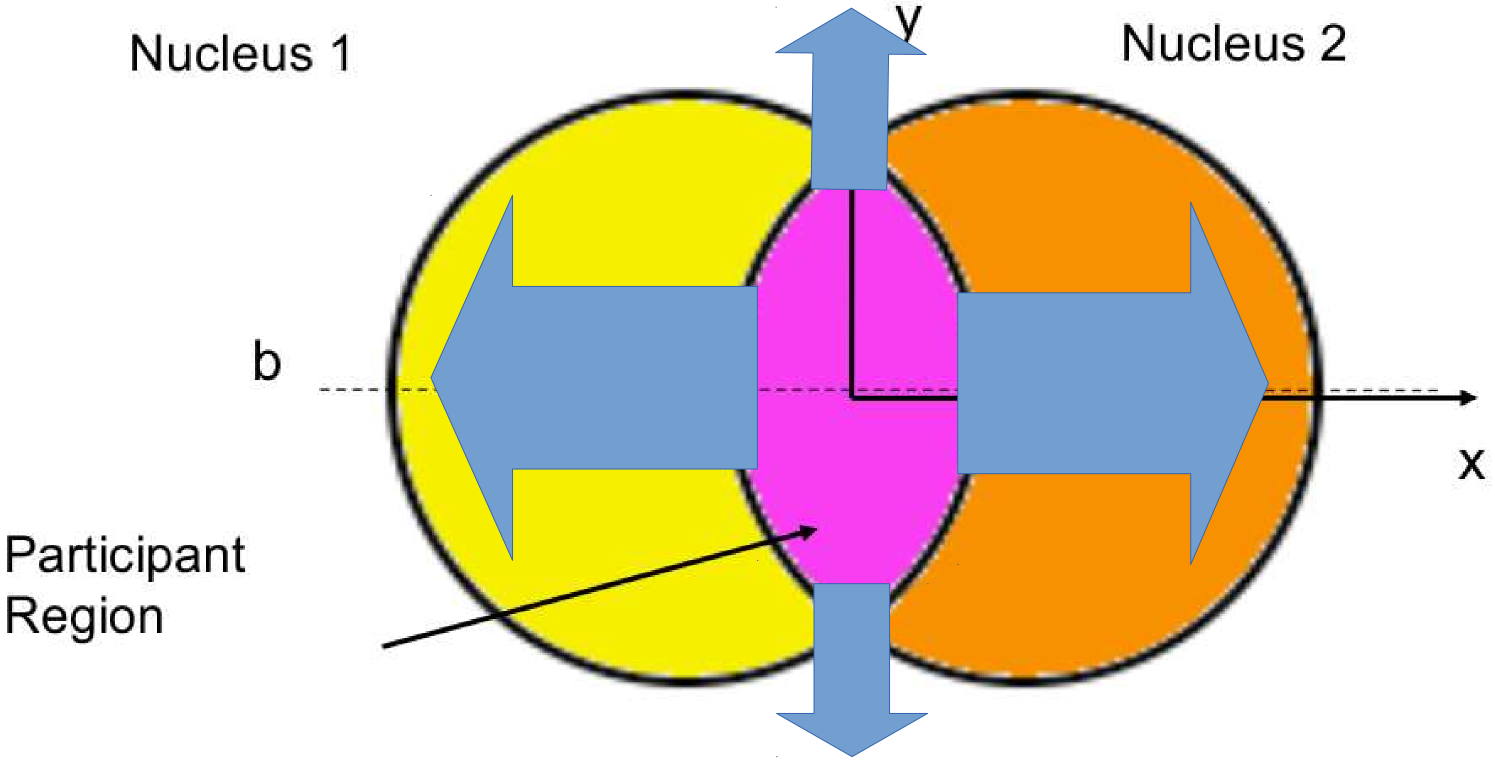
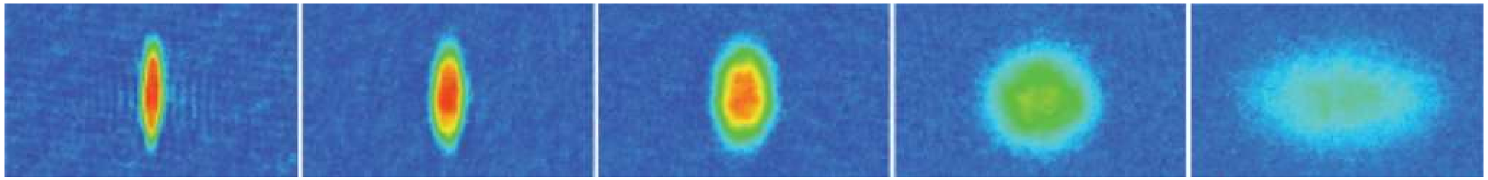
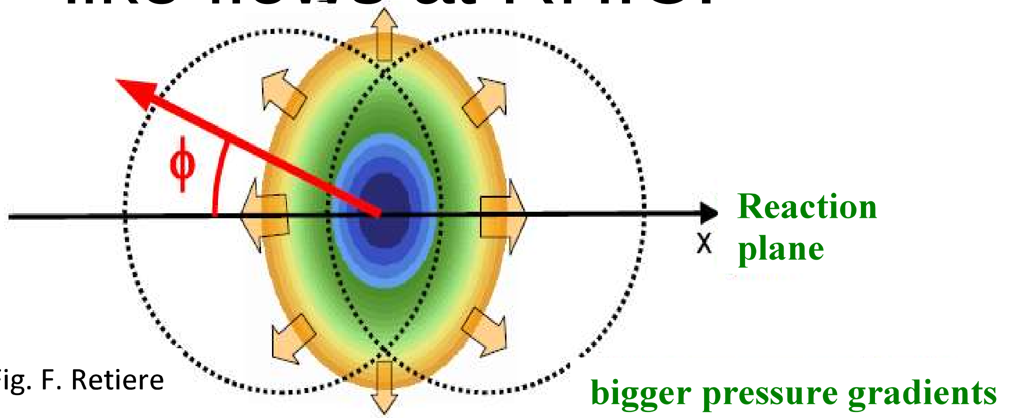
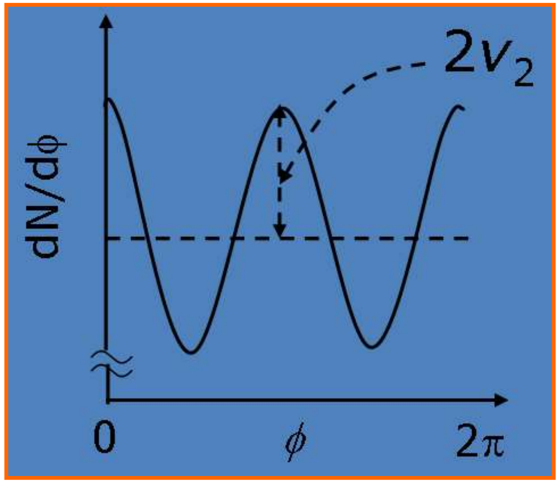




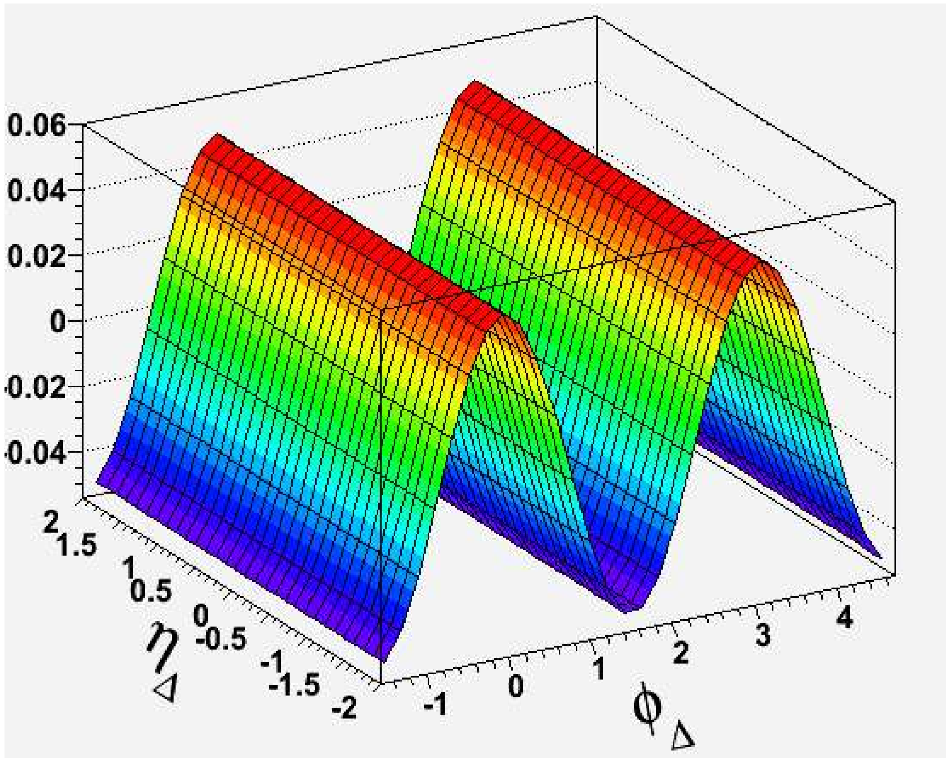
Non-central collisions = elliptic flow

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

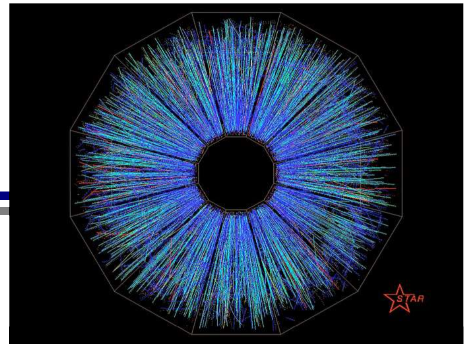




$$v_2 = \langle \cos 2\phi \rangle$$

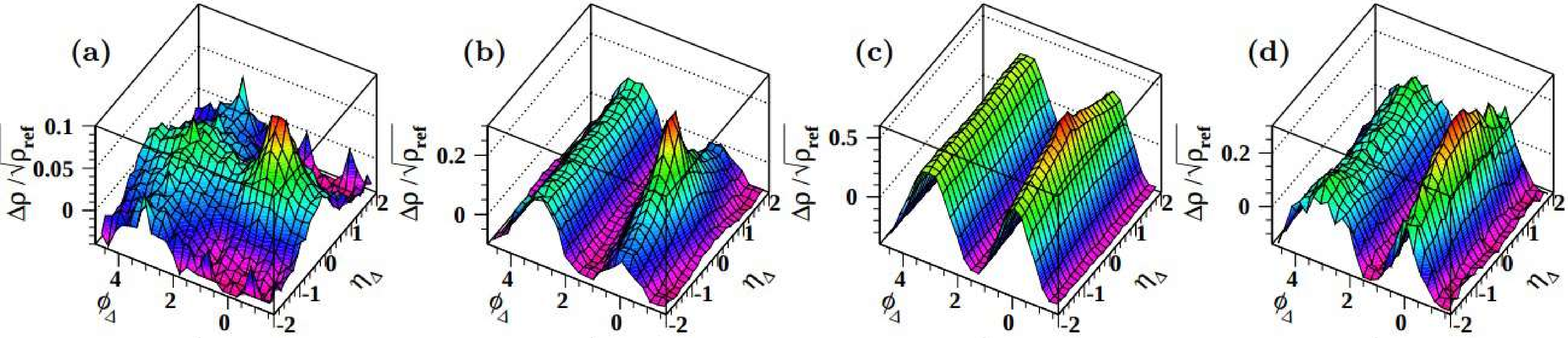


Angular correlations in Au-Au

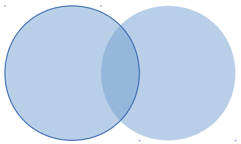


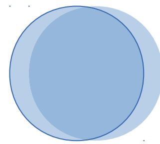
Heavy-ions

centrality



STAR: 10.1103/PhysRevC.86.064902



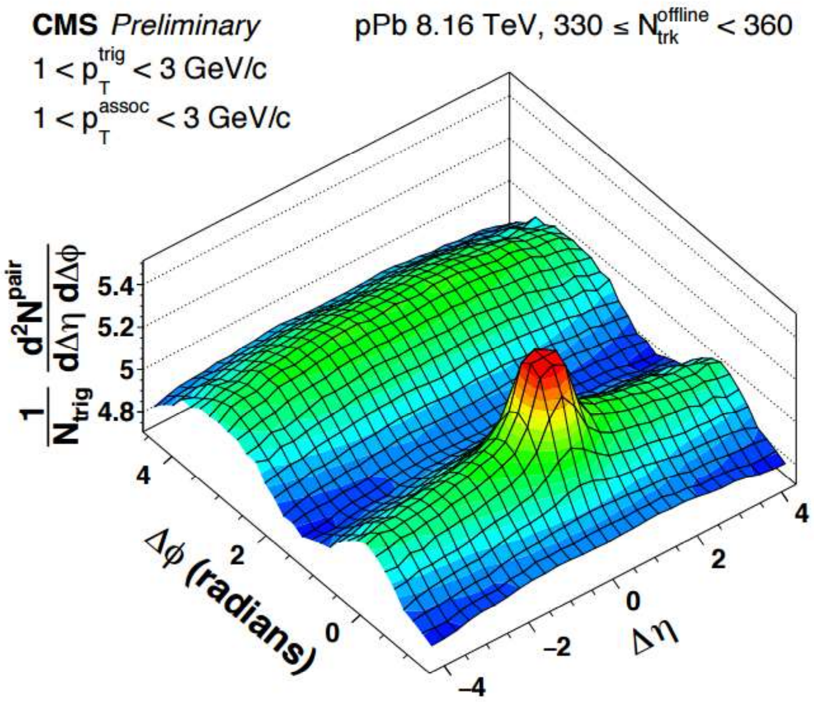


Similar to pp

Strong contribution of flow

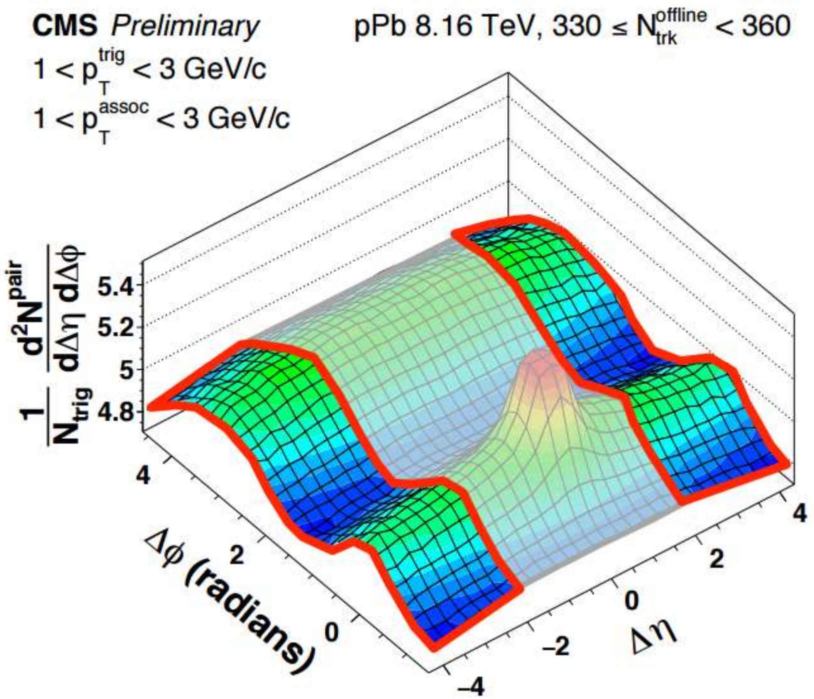
Collective effects: flow

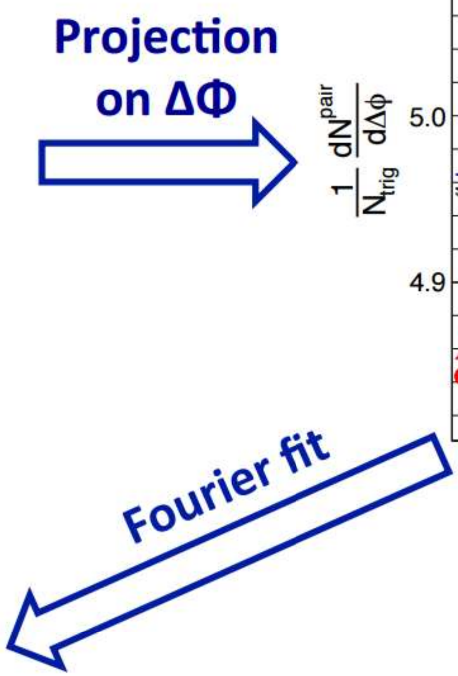
- **2D correlation function**

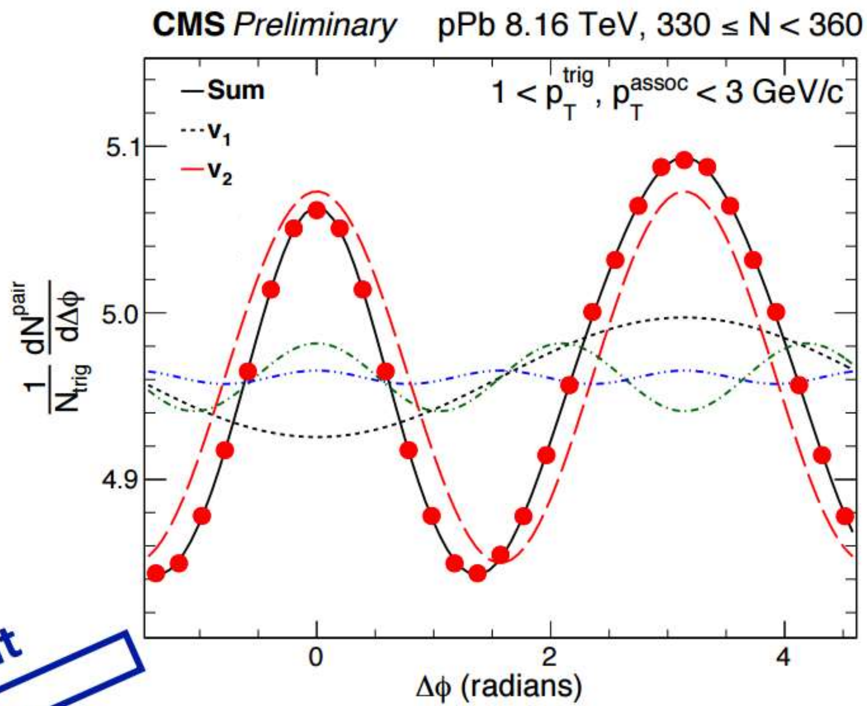


Collective effects: flow

- 2D correlation function
- 1D correlation function





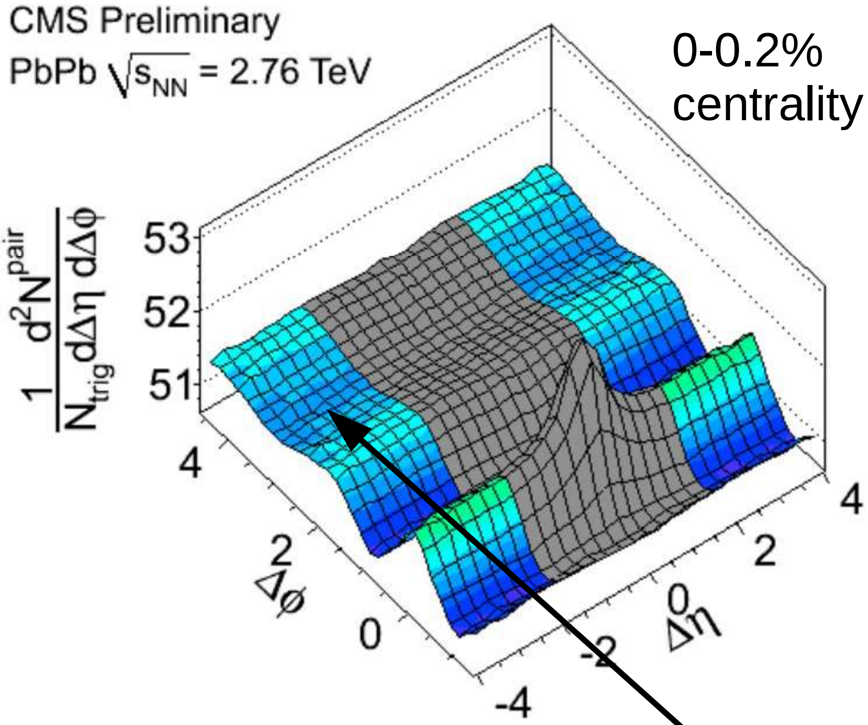


$$\frac{1}{N_{\text{trig}}}\frac{\mathrm{d}N^{\text{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\text{assoc}}}{2\pi}\left[1 + \sum_n 2V_{n\Delta}\cos(n\Delta\phi)\right]$$

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

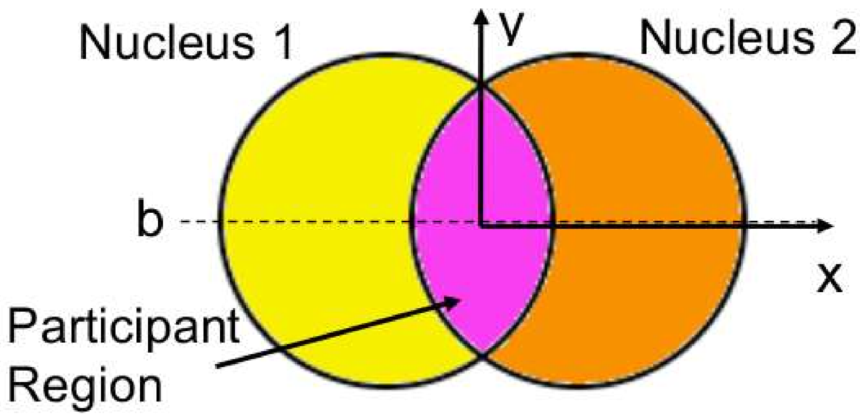
Collective effects: flow

➢ 2D correlation function



0-0.2% centrality

➢ 1D correlation function

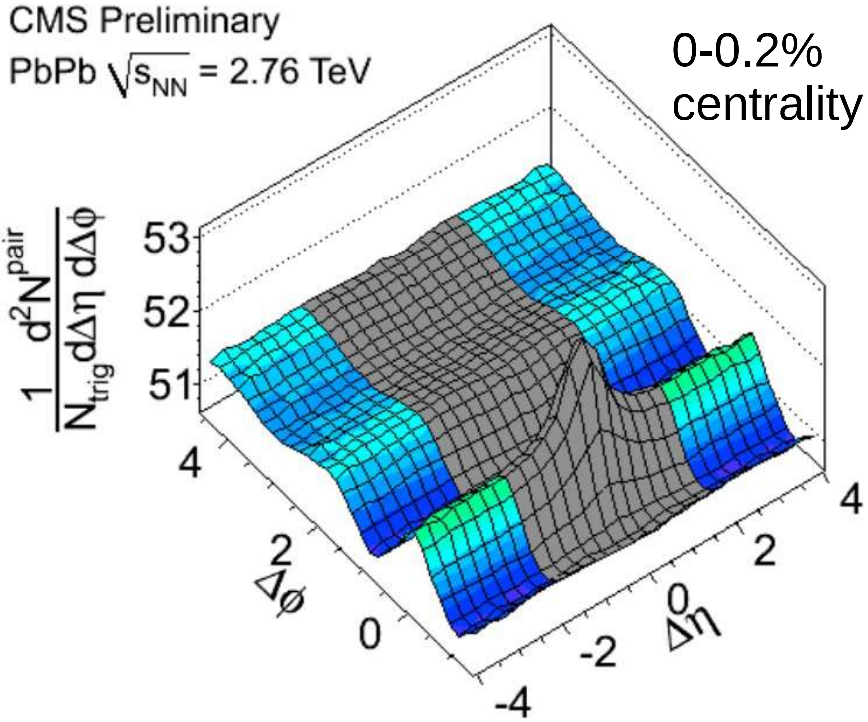


<u>Before 2011:</u>
To many only v1, v2 seemed important

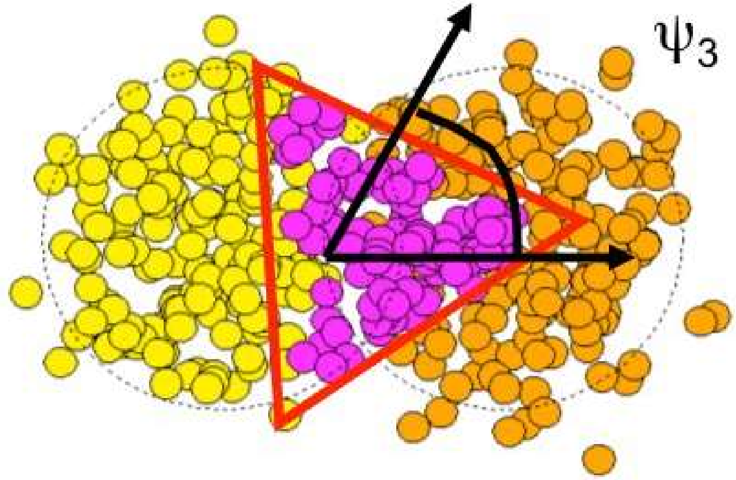
<u>Pre-LHC</u>: **fancy explanations**
- Double ridge?
- Mach cones?

Collective effects: flow

➢ **2D correlation function**

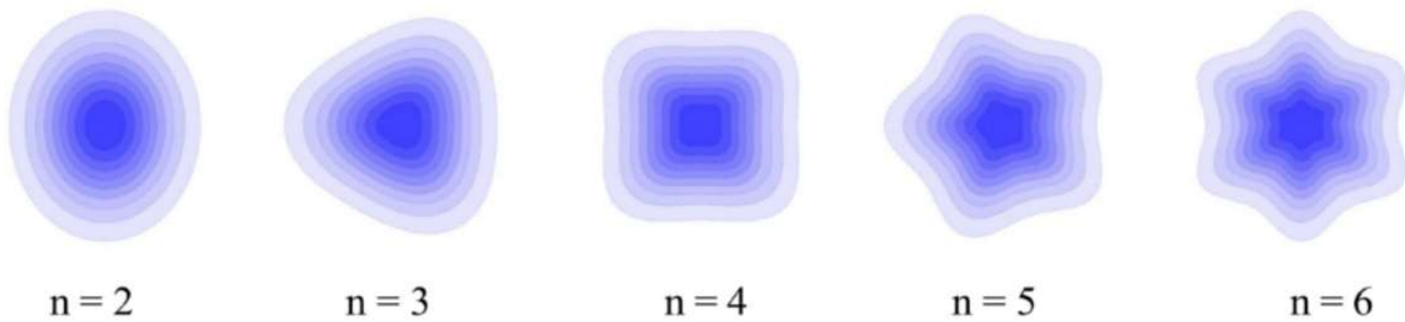


➢ **1D correlation function**



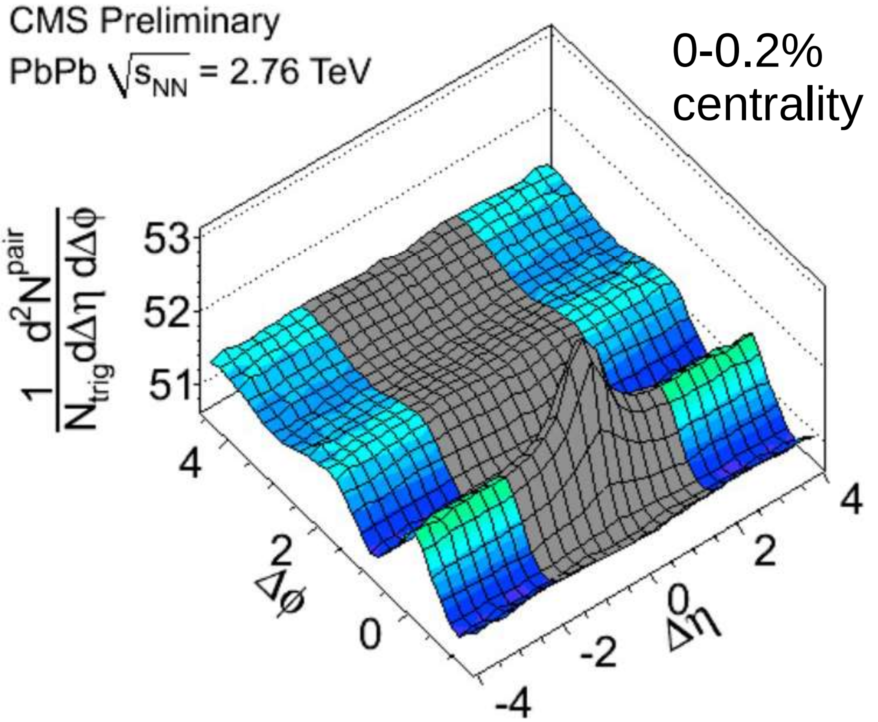
At LHC, the large acceptance of the experiments, together with the high particle density (as a collective effect, the flow signal increases strongly with multiplicity) **made the observation and interpretation straightforward and unambiguous.**

J. Schukraft

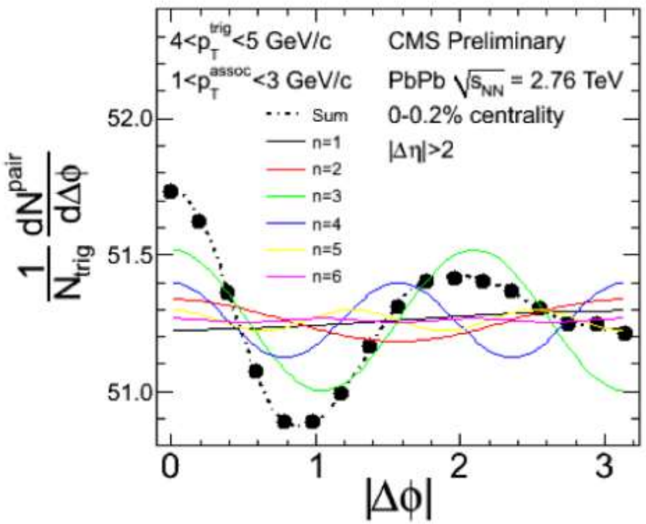


Collective effects: flow

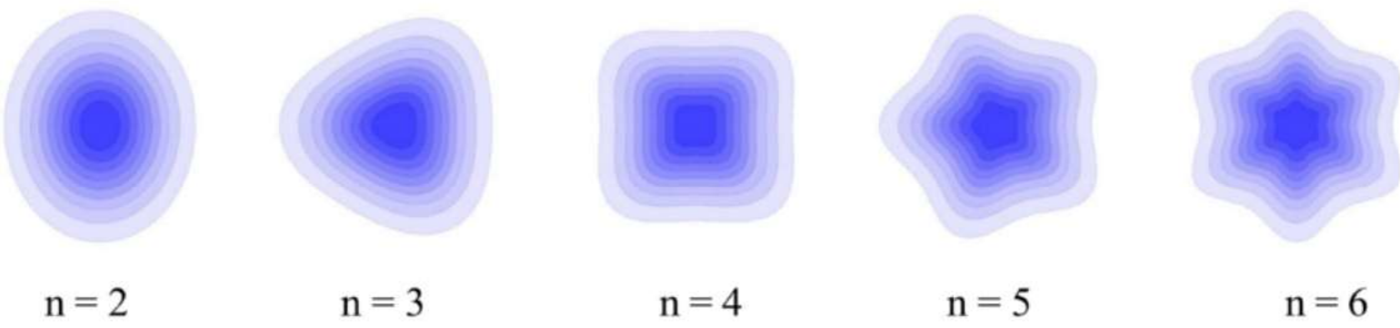
➢ 2D correlation function



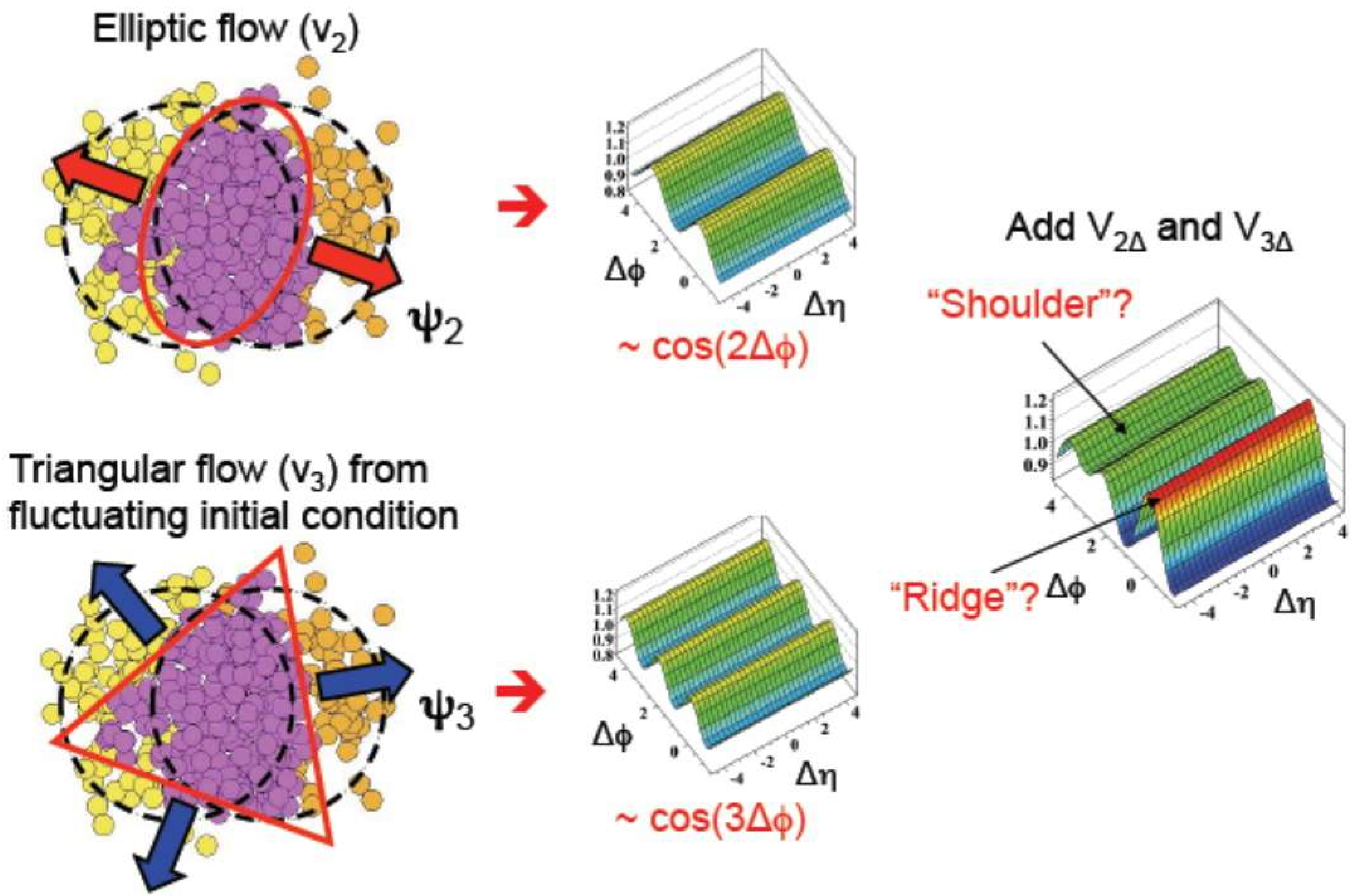
➢ 1D correlation function



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

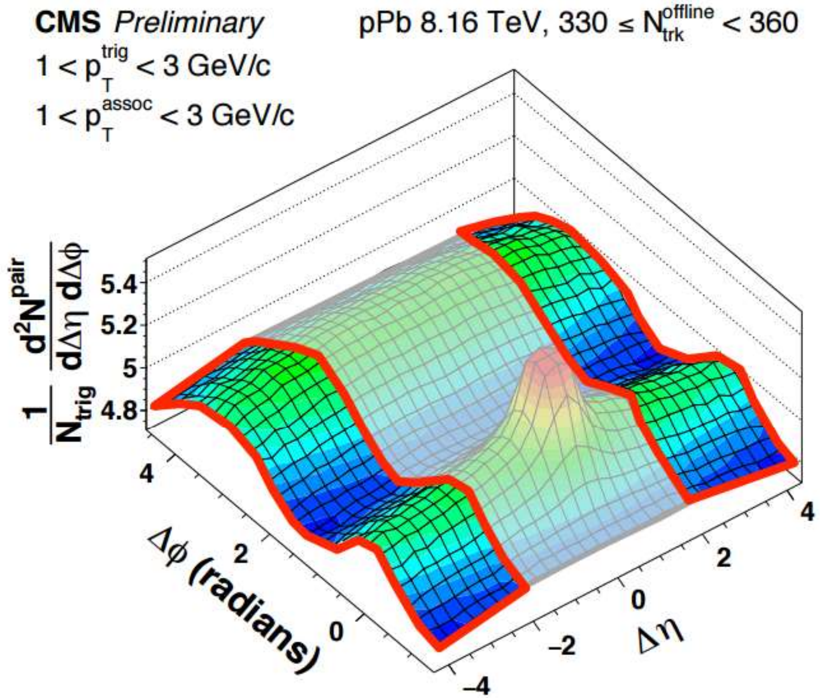


Collective effects: flow



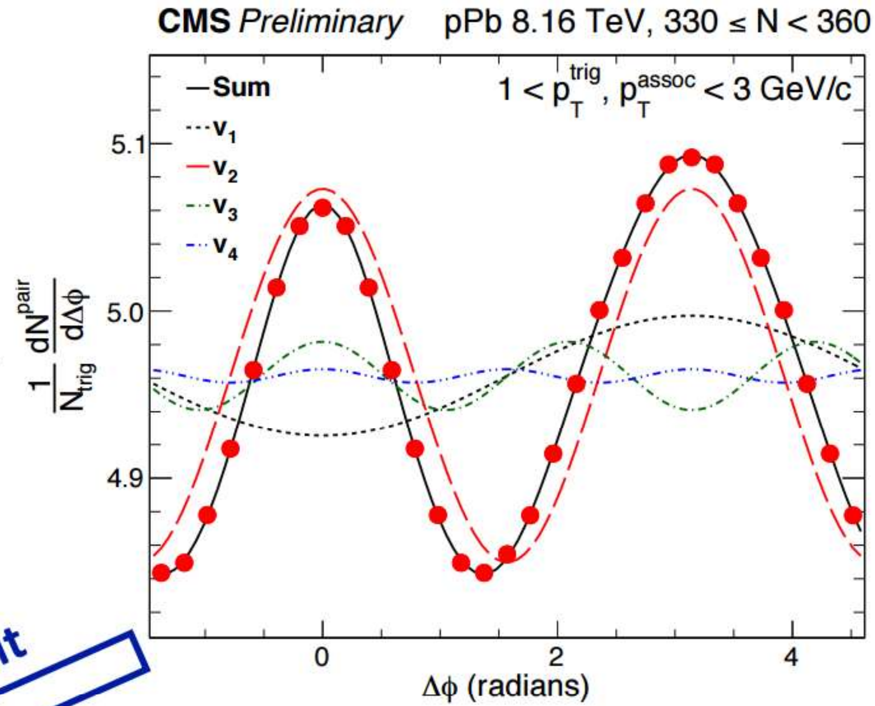
Collective effects: flow

➢ 2D correlation function

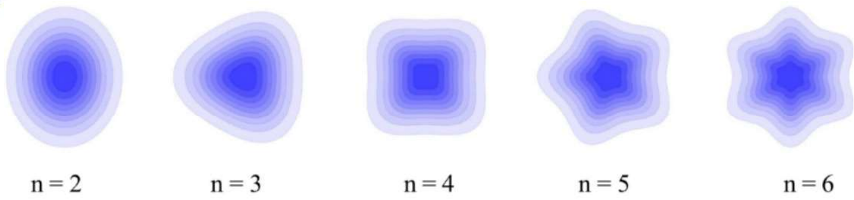


Projection on ΔΦ ⇒

➢ 1D correlation function



Fourier fit



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

⇒

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

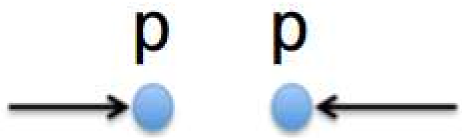
Extract single particle v_n

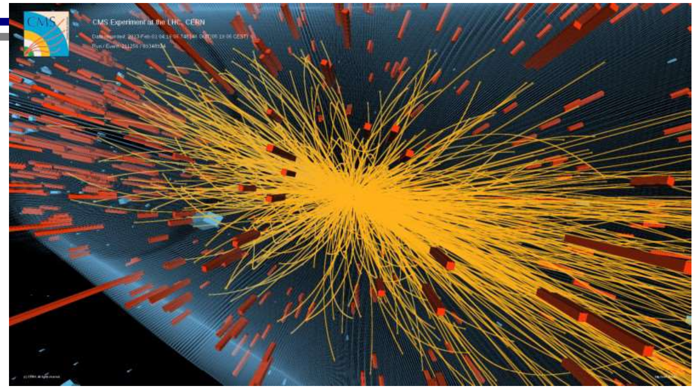
The Ridge

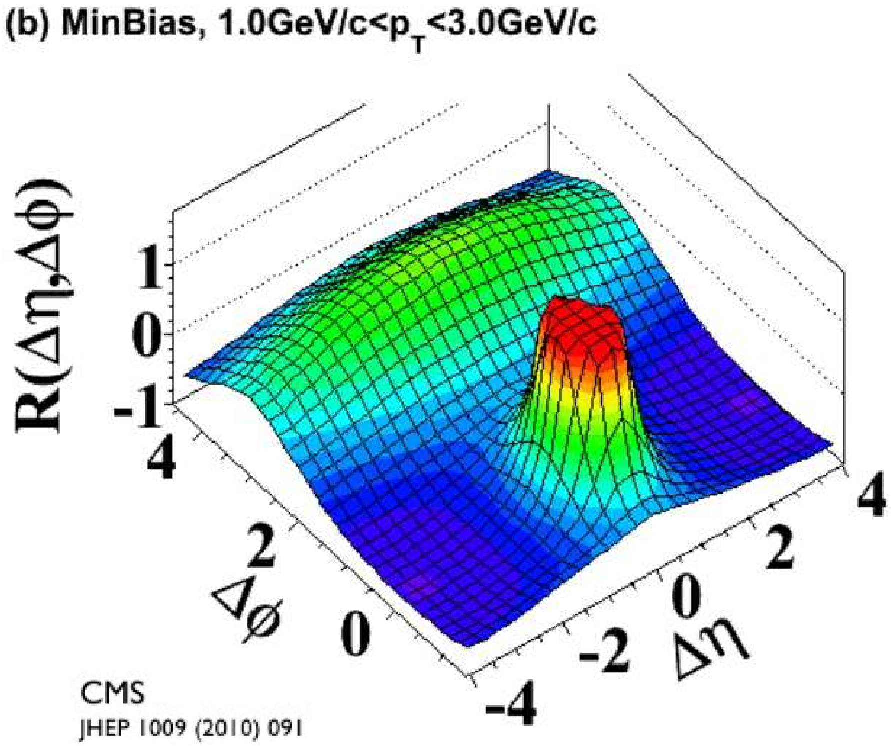
The Ridge: CMS 2010

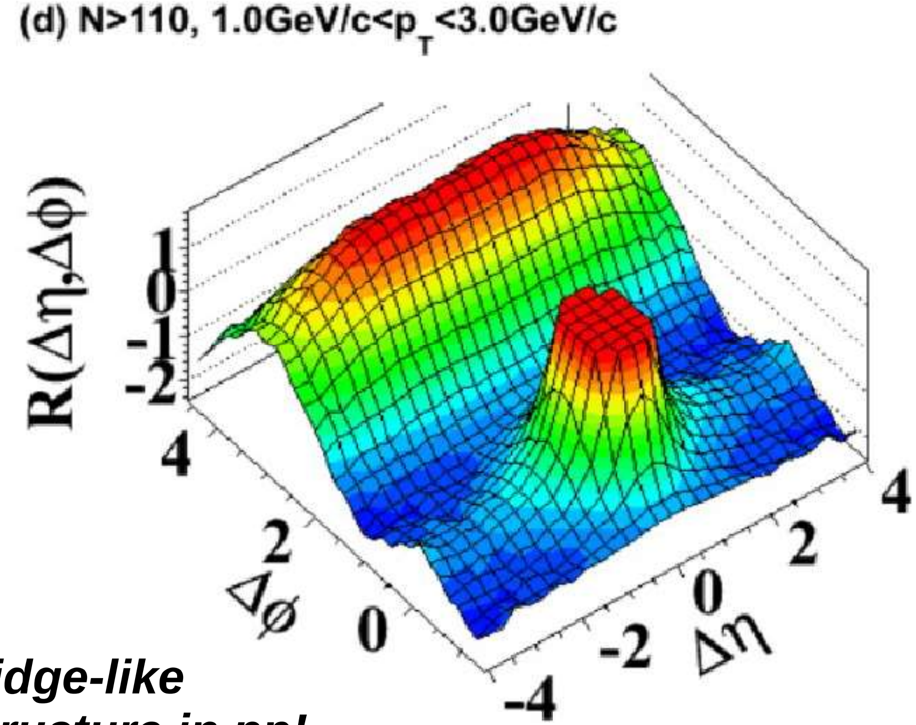
The Ridge: CMS 2010

First LHC discovery





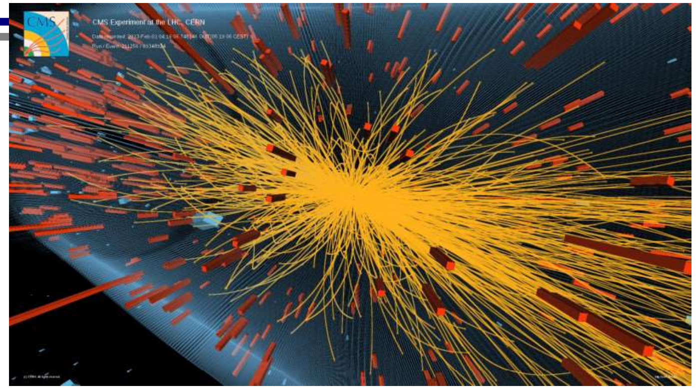


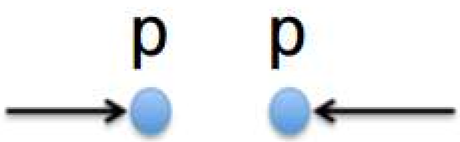


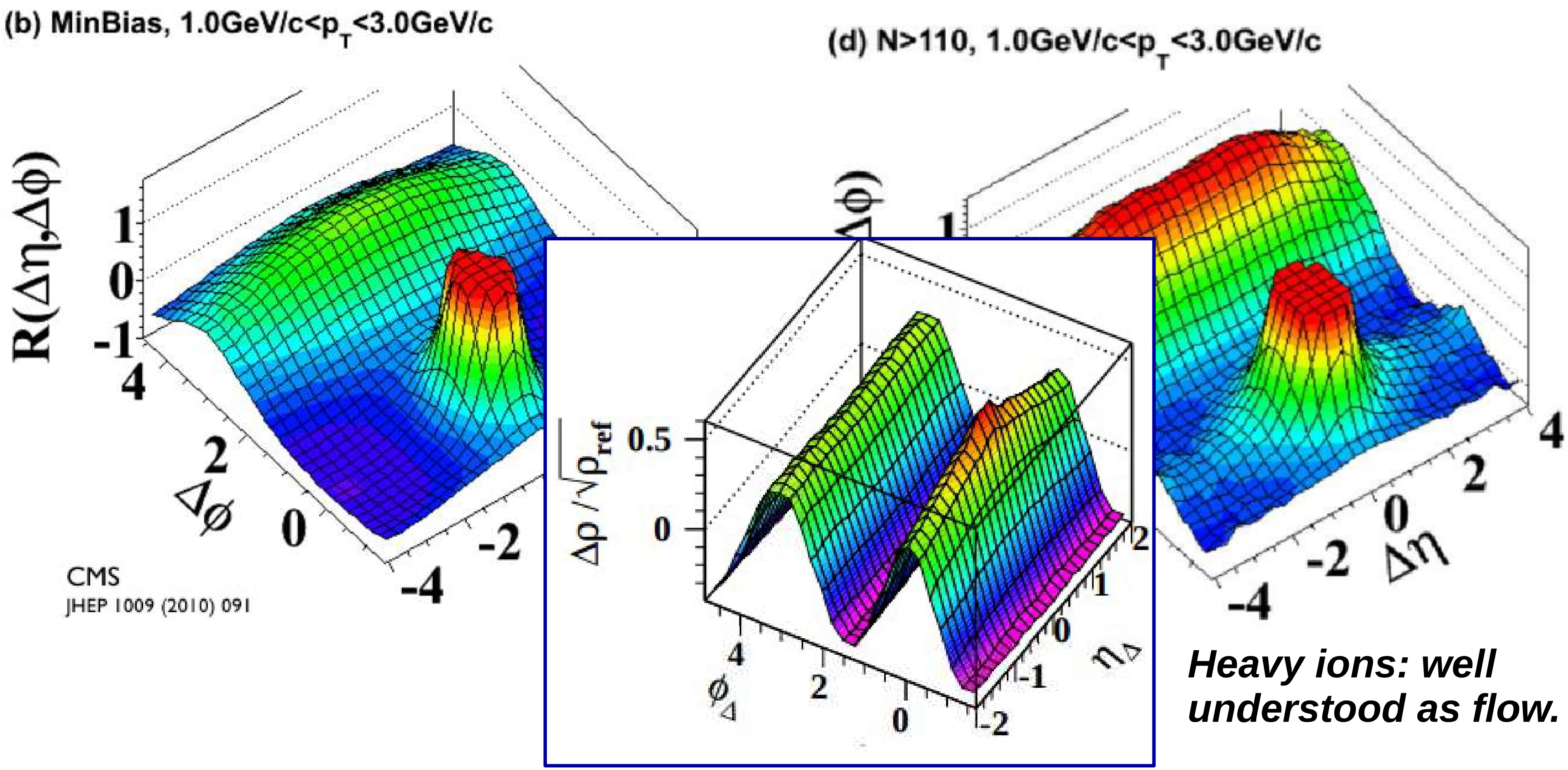
Ridge-like structure in pp!

The Ridge: CMS 2010

First LHC discovery



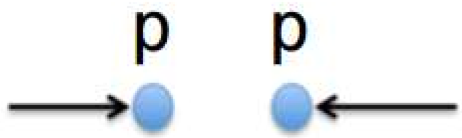


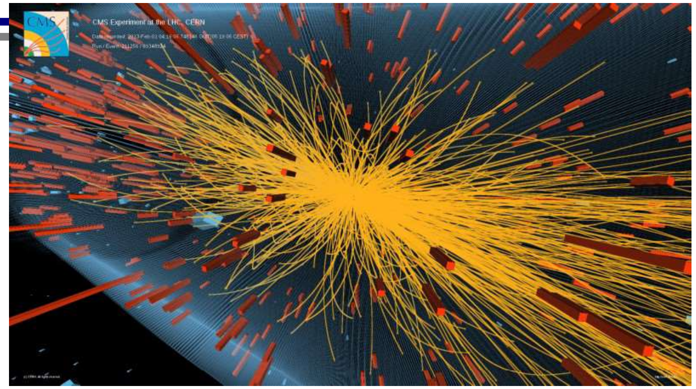


Heavy ions: well understood as flow.

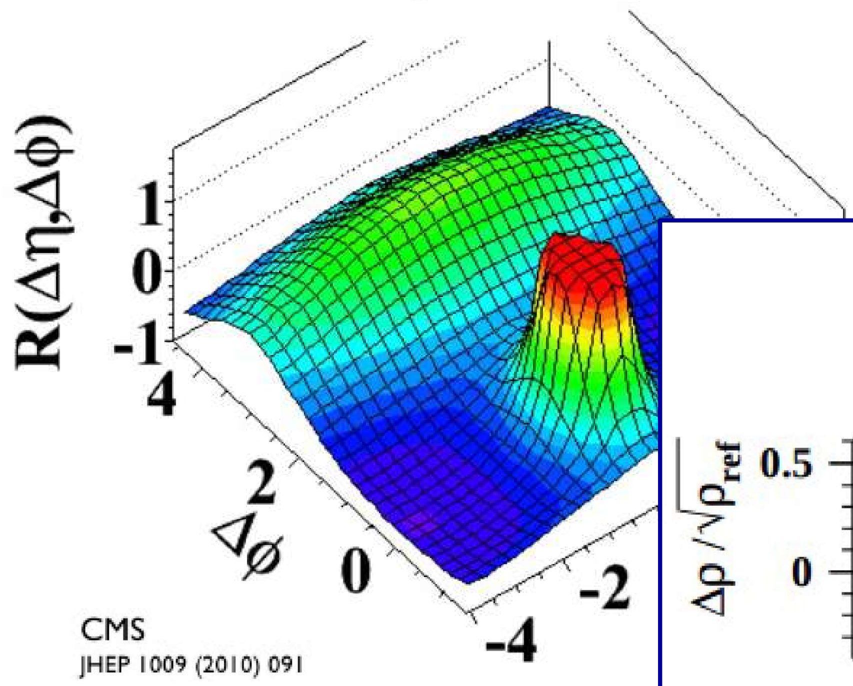
The Ridge: CMS 2010

First LHC discovery

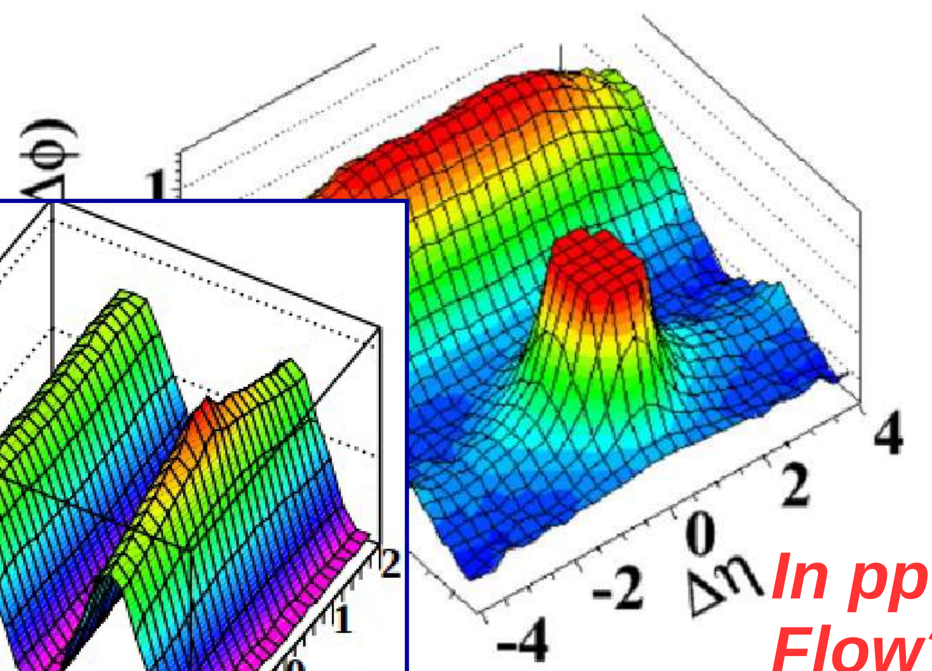


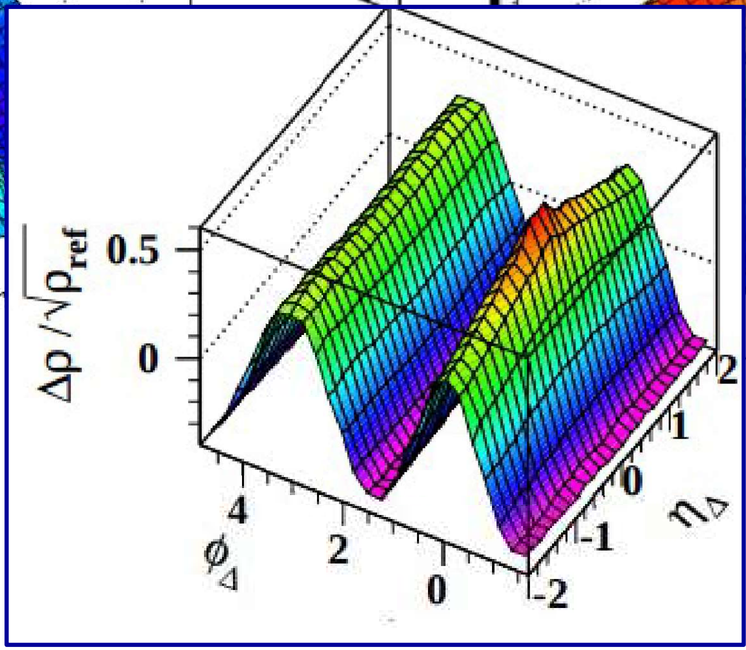


(b) MinBias, 1.0GeV/c<p_T<3.0GeV/c



(d) N>110, 1.0GeV/c<p_T<3.0GeV/c

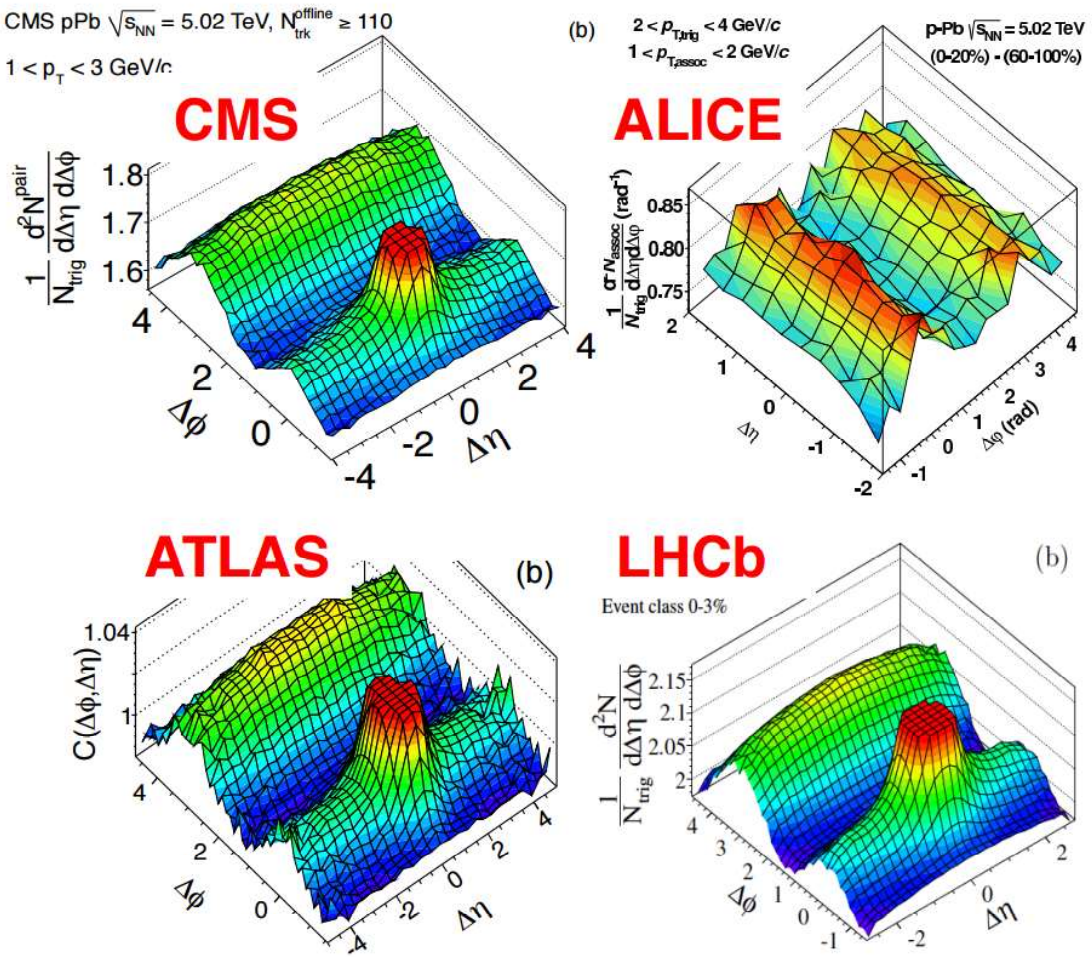


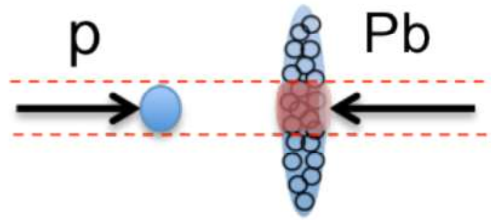


In pp? Flow?!

Heavy ions: well understood as flow.

More Ridges

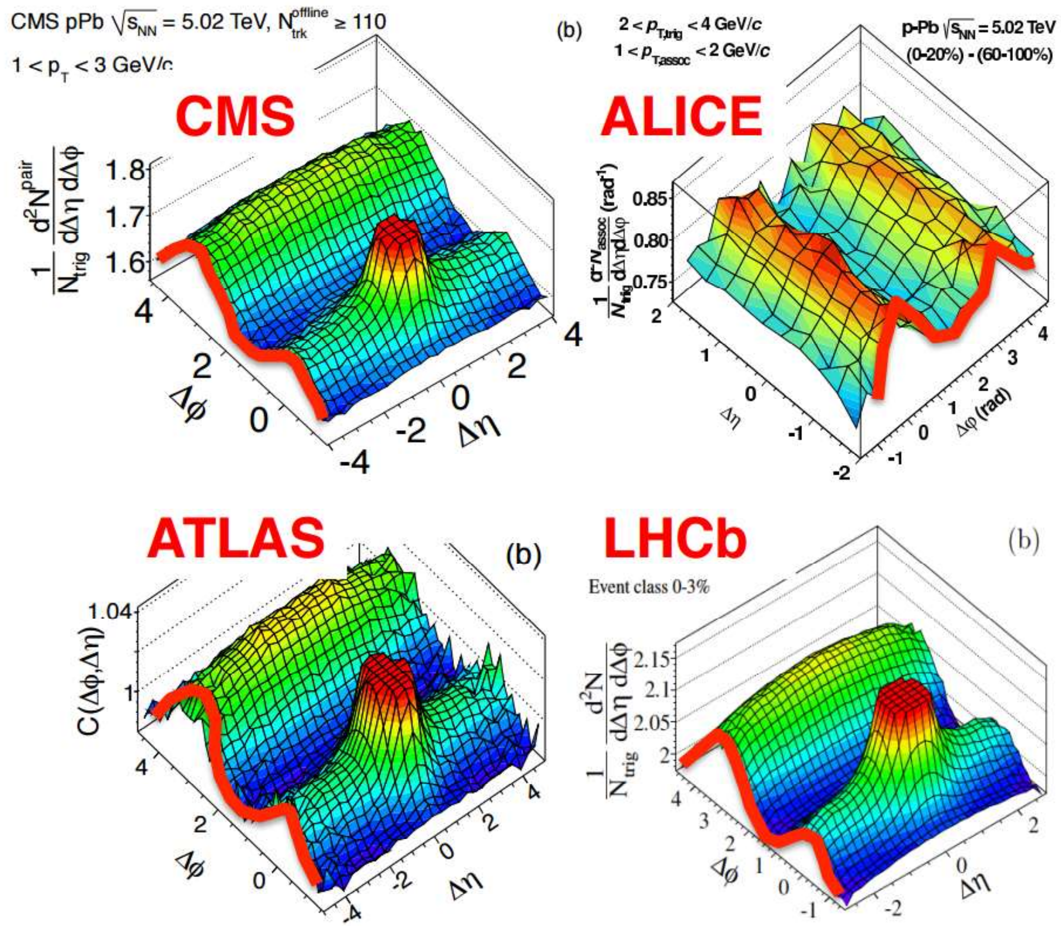


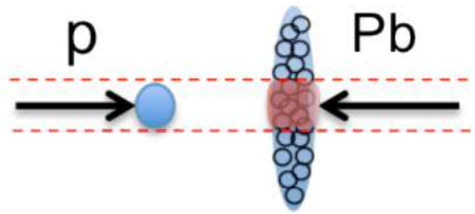


in 2012

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

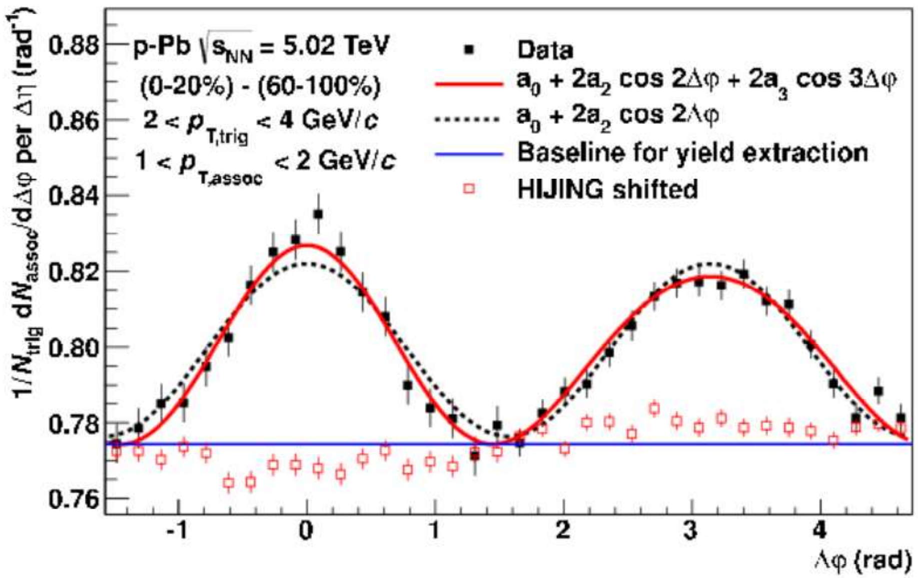
More Ridges





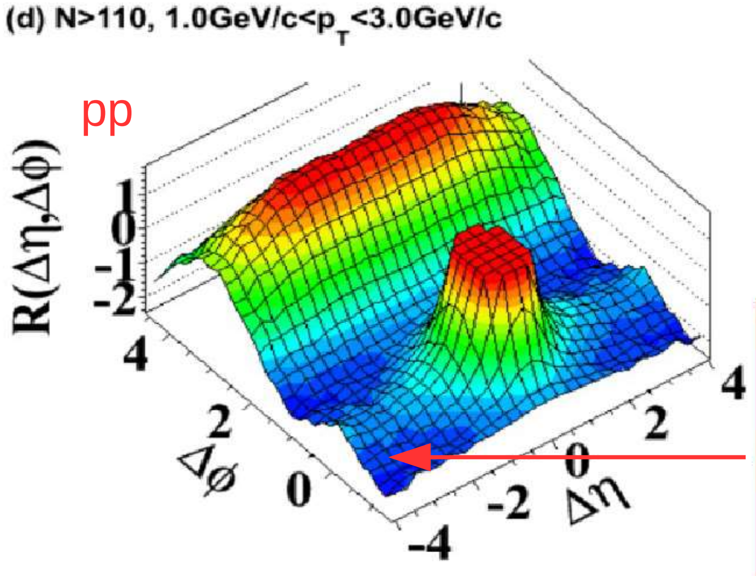
in 2012

"Flow" analysis



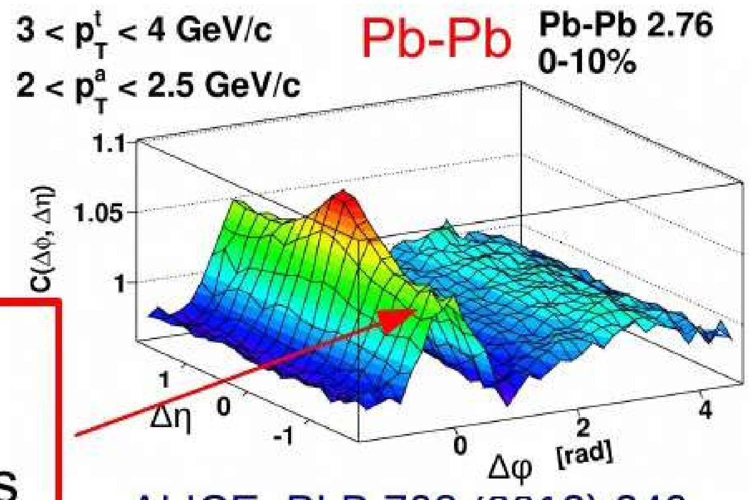
Collective phenomena and QGP fluid in small systems (L ~ 1fm)?!

The Ridge

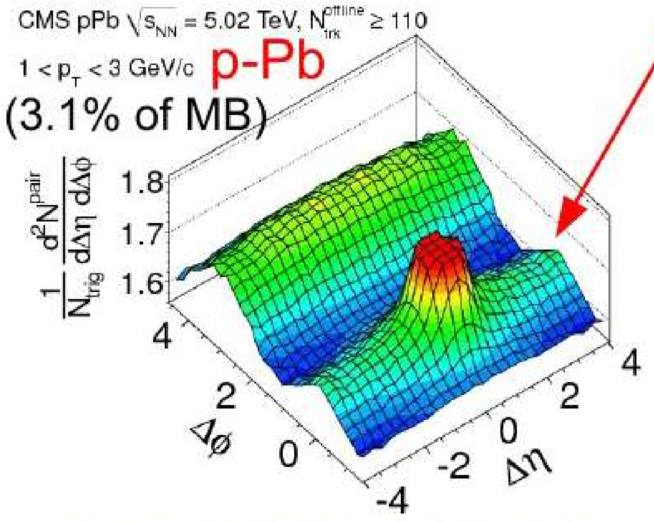


CMS, JHEP 1009 (2010) 91

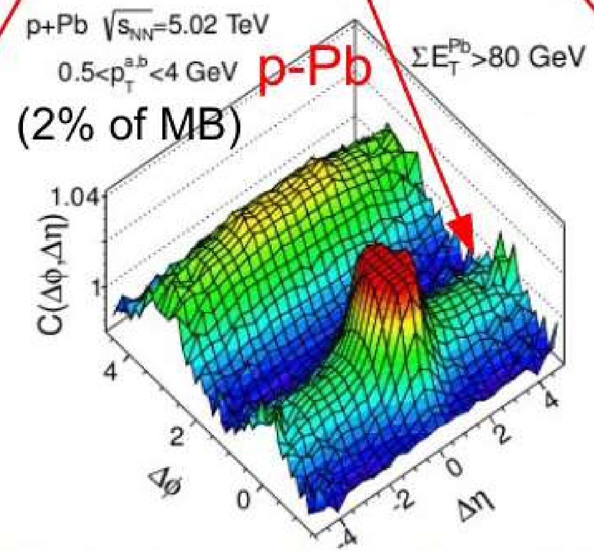
Near-side (NS) ridges in high multiplicity events at LHC energies



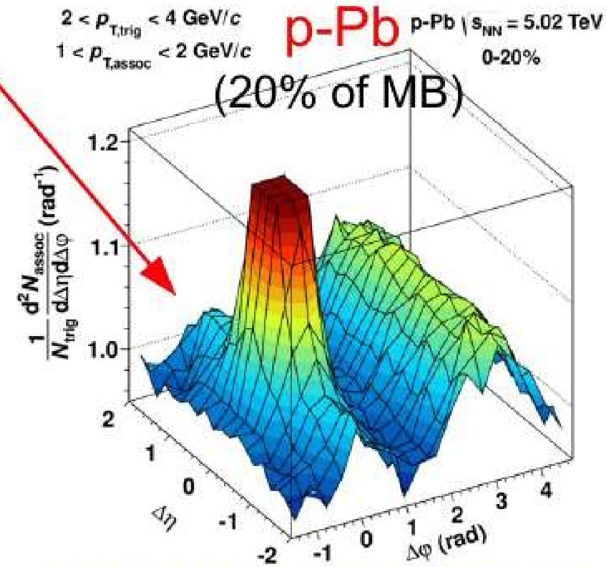
ALICE, PLB 708 (2012) 249



CMS, PLB 718 (2012) 795

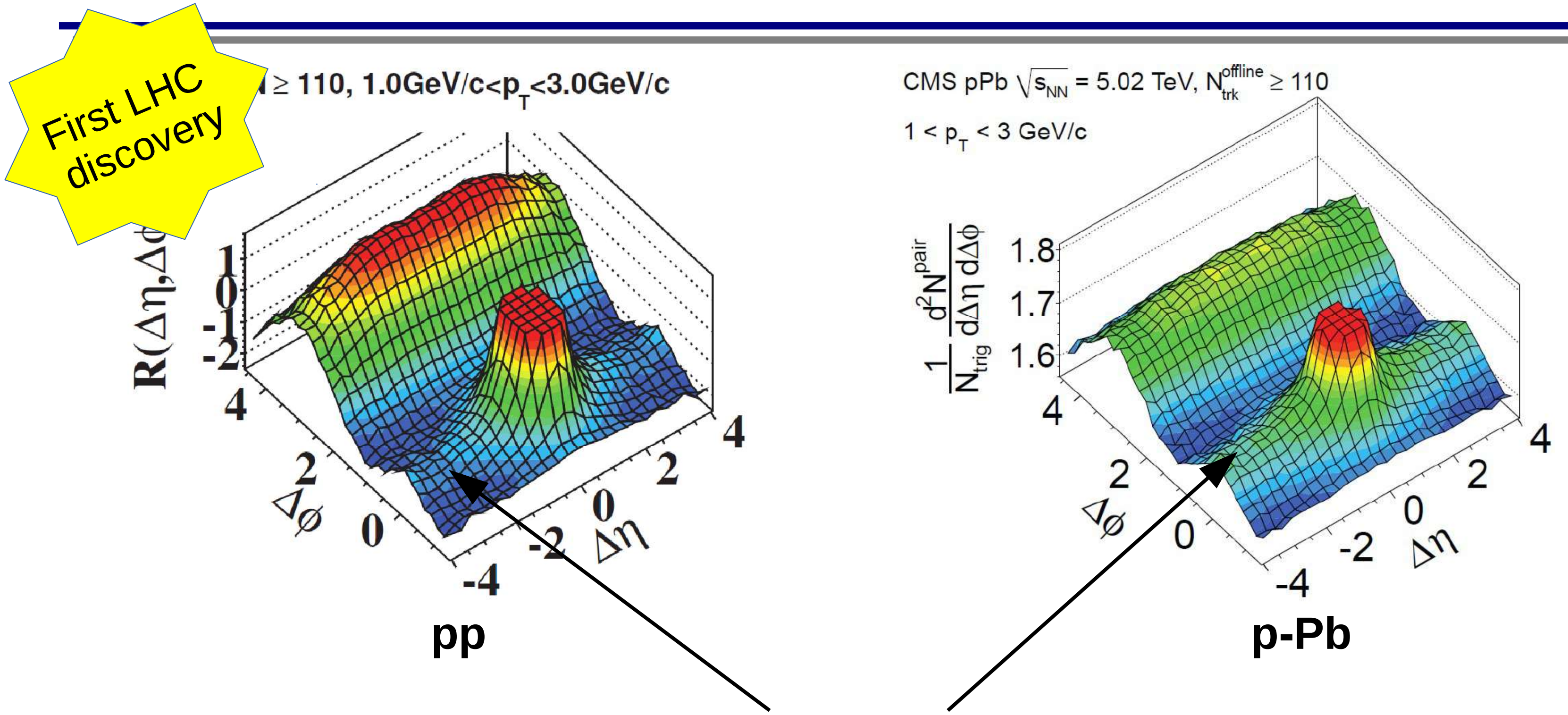


ATLAS, PRL 110 (2013) 182302



ALICE, PLB 719 (2013) 29

The Ridges



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 ..."

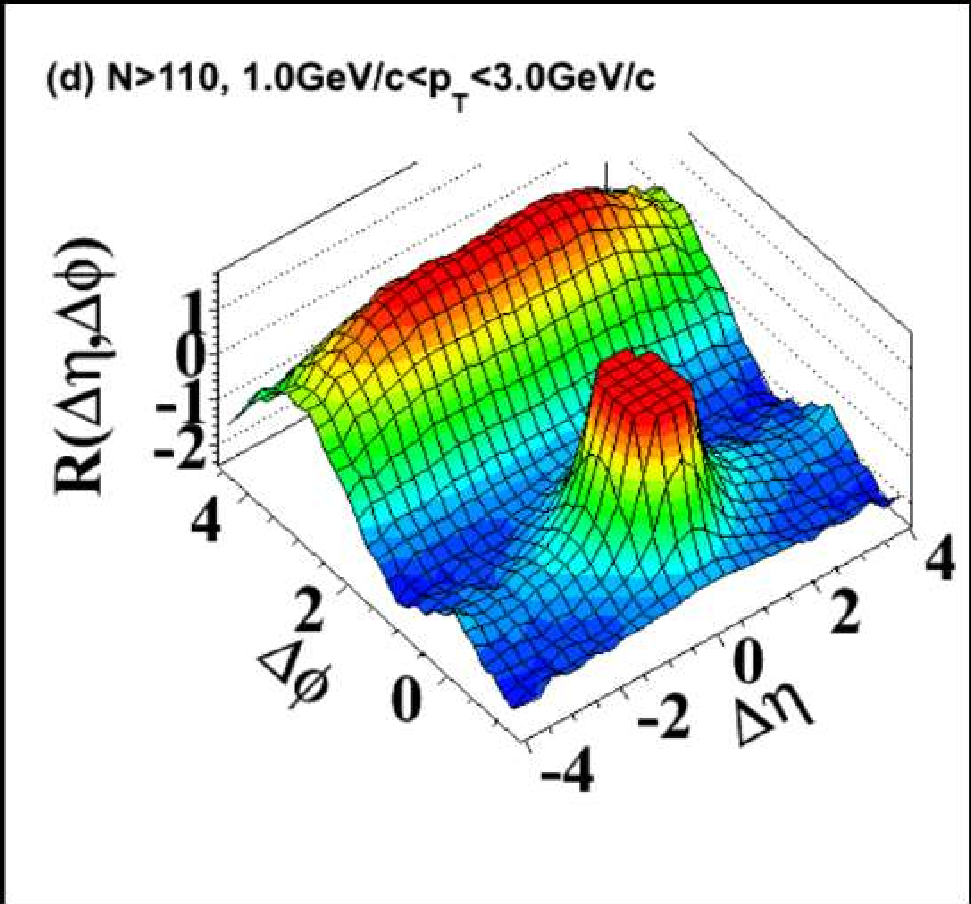
„**Ridge** from Strings"

„On the onset of **the ridge** structure"

The Ridge

High multiplicity (N>110)

~100 citations within a year



Interpretation:

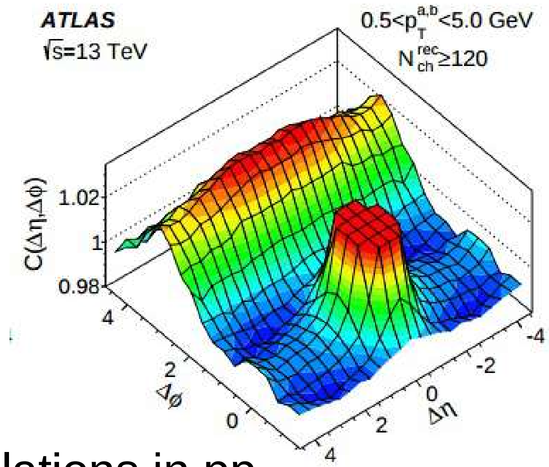
Multi-jet correlations
Jet-Jet color connections
Jet-proton remnant color connections
Jet-remnant connections + medium
Glasma correlations
Quantum entanglement
Angular momentum conservation
Angular momentum conservation + medium
Hydrodynamic flow

?

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

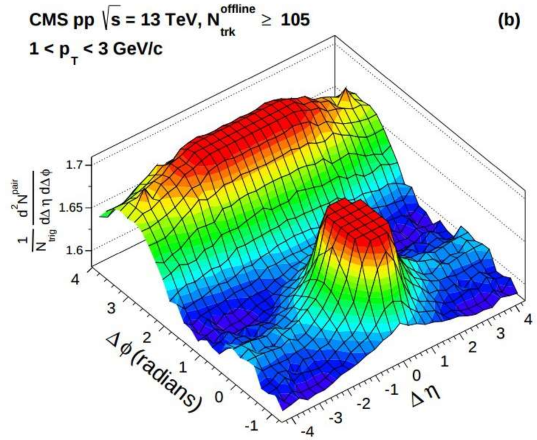
Observation of long-range elliptic anisotropies in sqrt{s}=13 and 2.76 TeV pp collisions with the ATLAS detector

Phys. Rev. Lett. 116, 172301 (2016)

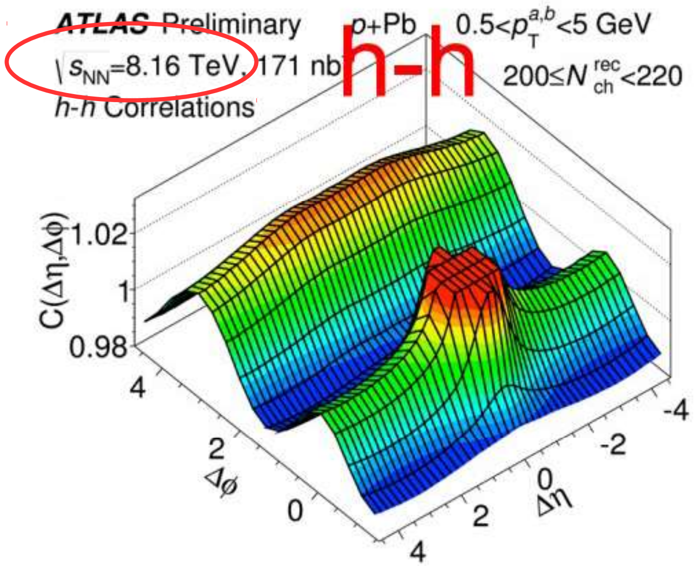
Second CMS paper of 13 TeV

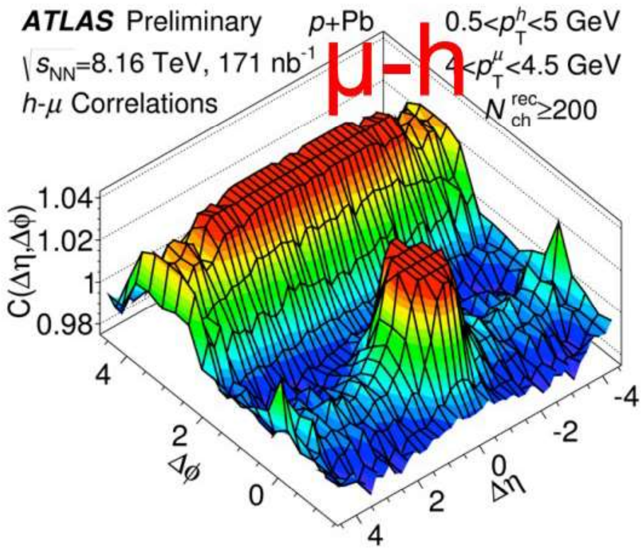
Measurement of long-range near-side two-particle angular correlations in pp collisions at sqrt(s)= 13 TeV

PRL 116 (2016) 172302

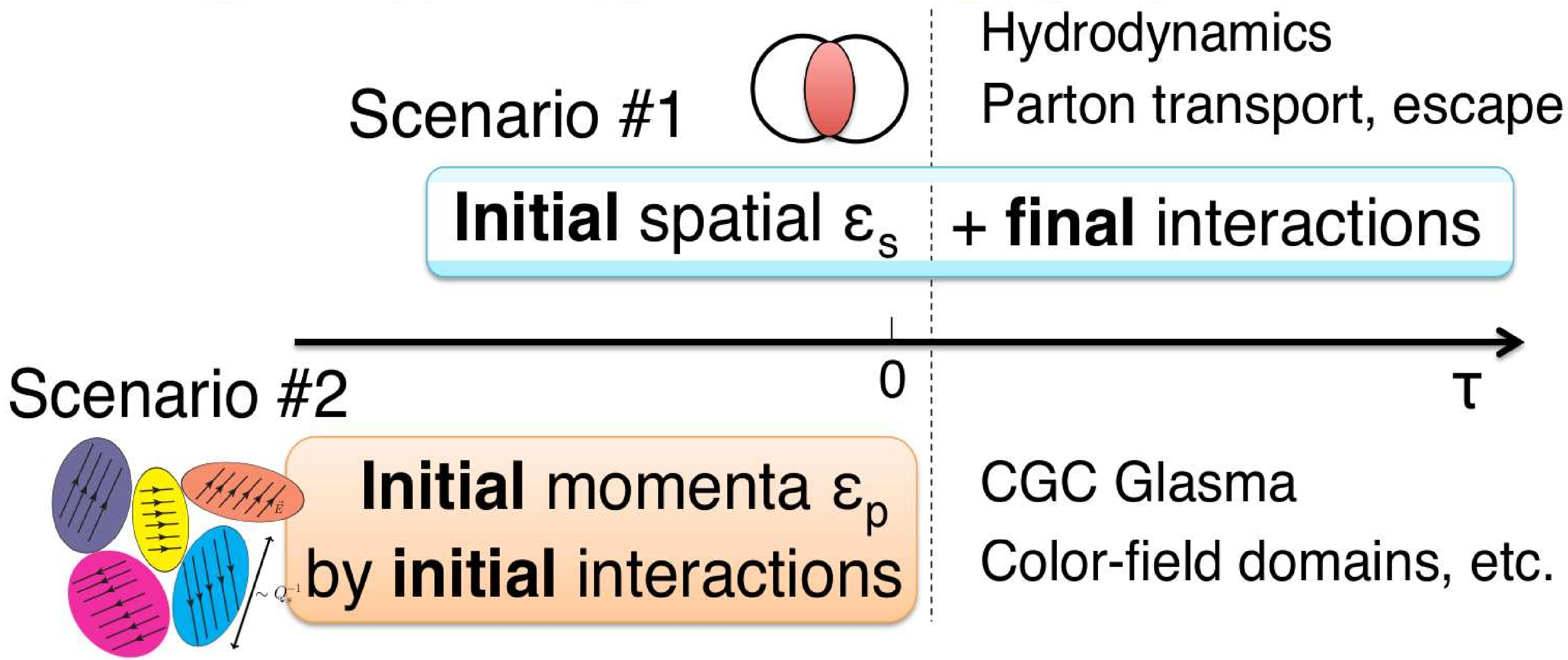


ATLAS QM2017





Summary and outlook



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 ε_s + final interactions	OR	Initial momentum ε_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

Quark Matter 2017

Summary and outlook

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

Initial spatial ε_s + final interactions OR Initial momentum ε_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

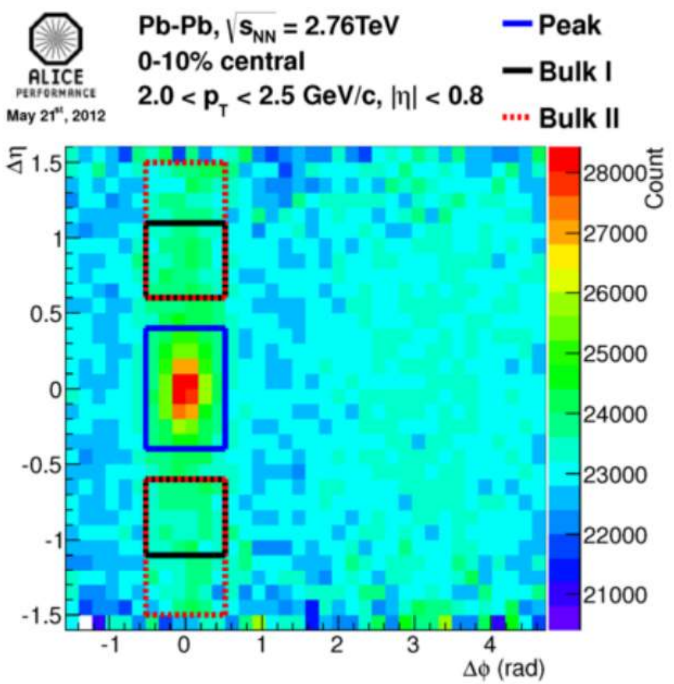
1 June 2016 - EMMI Seminar
Raju Venugopalan
"***The gift that keeps giving: surprises from ridges in p+p, p/d/He+A and A+A collisions***"

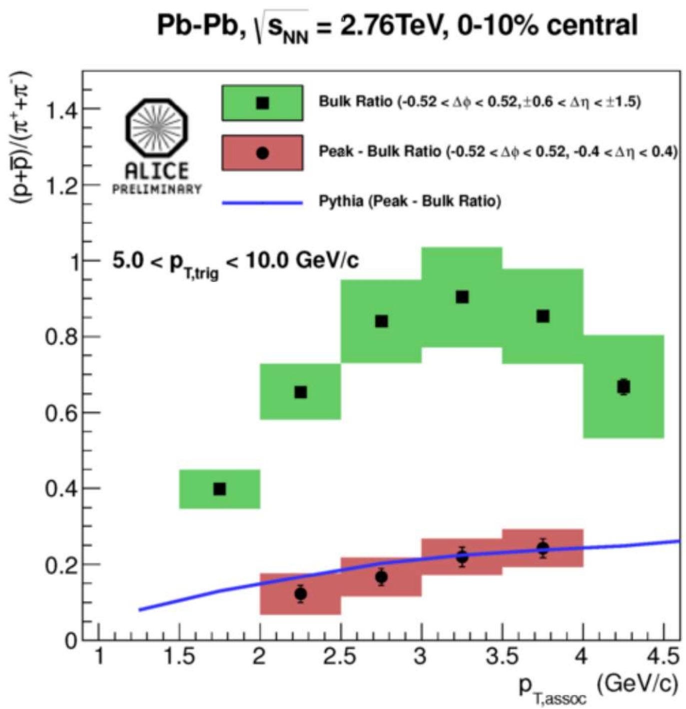
Int. J. Mod. Phys. E, Vol. 25, 1 (2016) 16300022
Kevin Dusling, Wei Li, Bjorn Schenke
Review: "***Novel collective phenomena in high energy pp and p-nucleus collisions***"

Can we learn something more?
Selection of particles

p/π ratio

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



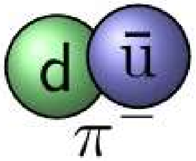


- A very clear increase of the p/π ratio is observed in the bulk of central Pb–Pb collisions compared to the PYTHIA reference.
- The p/π ratio in the yield associated with a high-pT trigger particle is compatible with the PYTHIA reference, suggesting that particle production is unmodified by the presence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

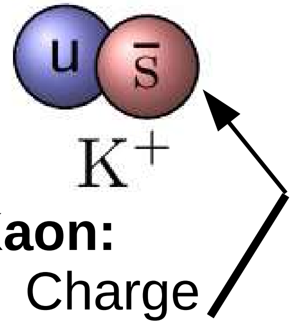
Can we learn something more?

One step further: ΔηΔφ of identified particles!

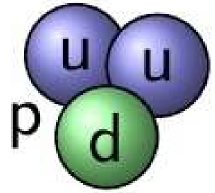
Unexplored phenomena **conservation laws** and their influence on **particle production mechanisms –** study via correlation functions for particles with **different quark content**



Pion:
- Charge



Kaon:
- Charge
- Strange quark



Proton:
- Charge
- Baryon

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

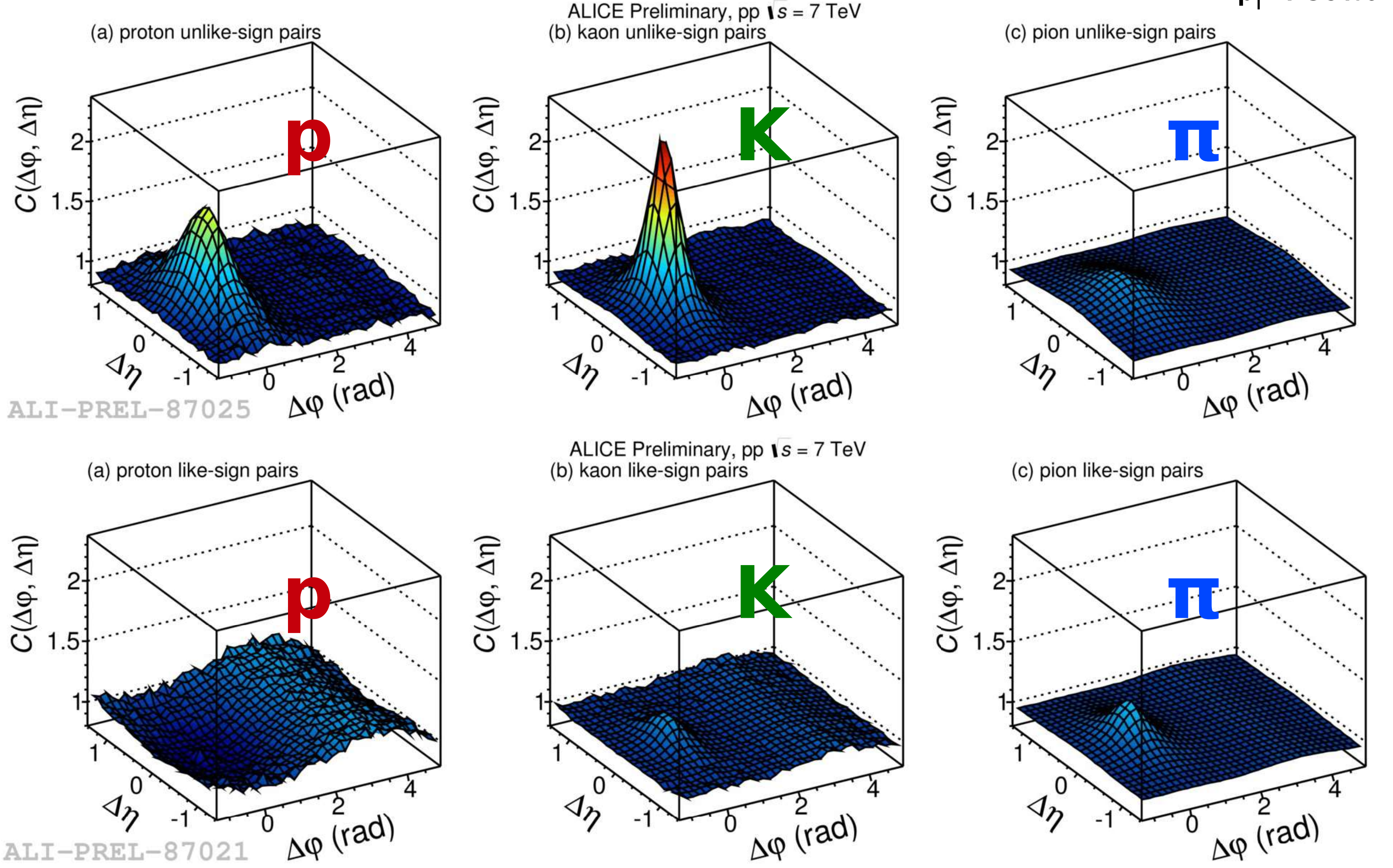
Useful to perform analysis in a more refined way:

- **charge dependence**
- **identified particles**

ΔηΔφ of identified particles in pp collisions

arXiv:1612.08975

p_T<4 GeV/*c*



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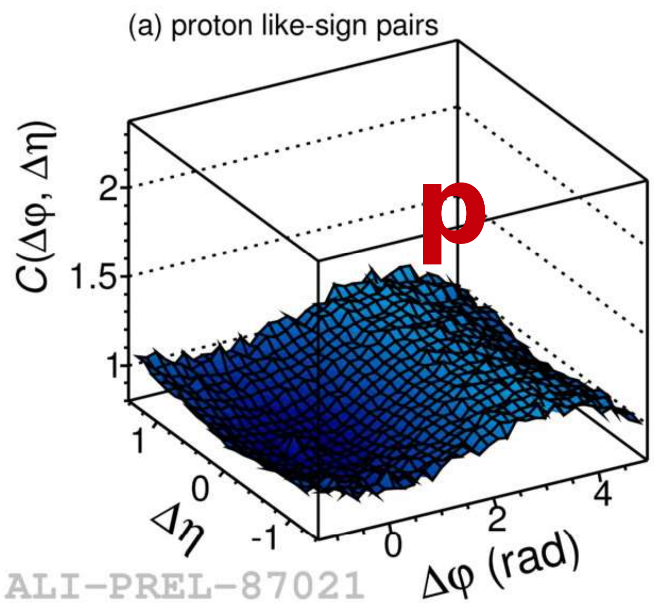

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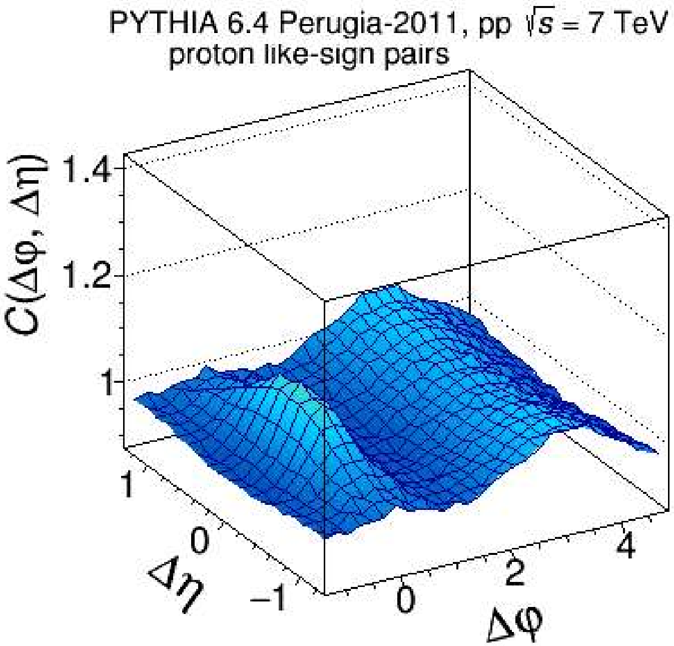

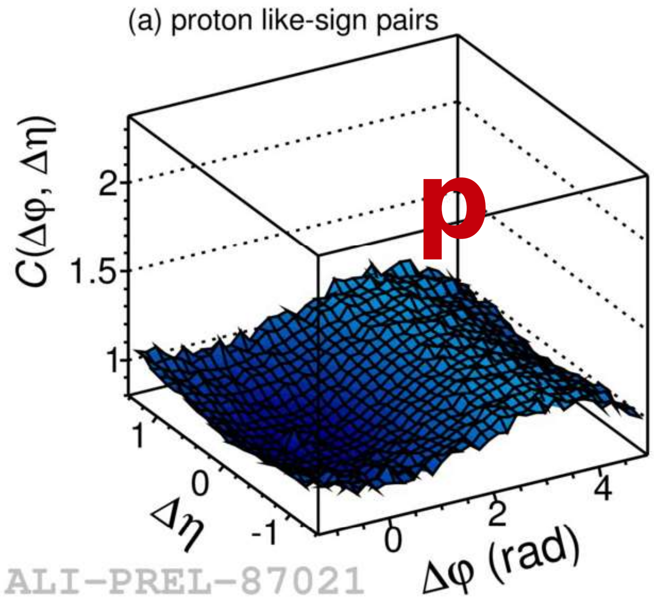

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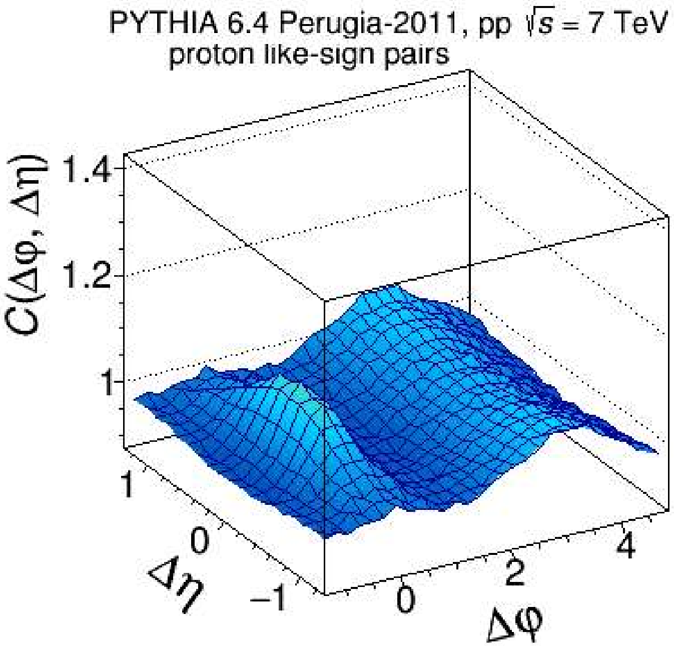
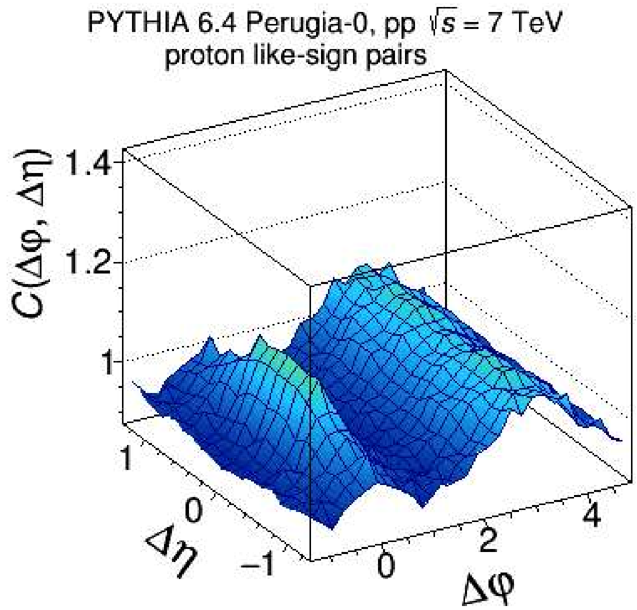
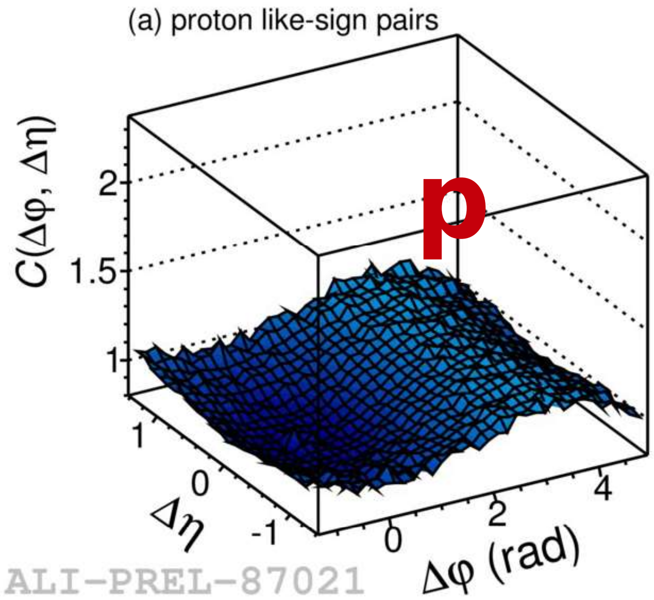
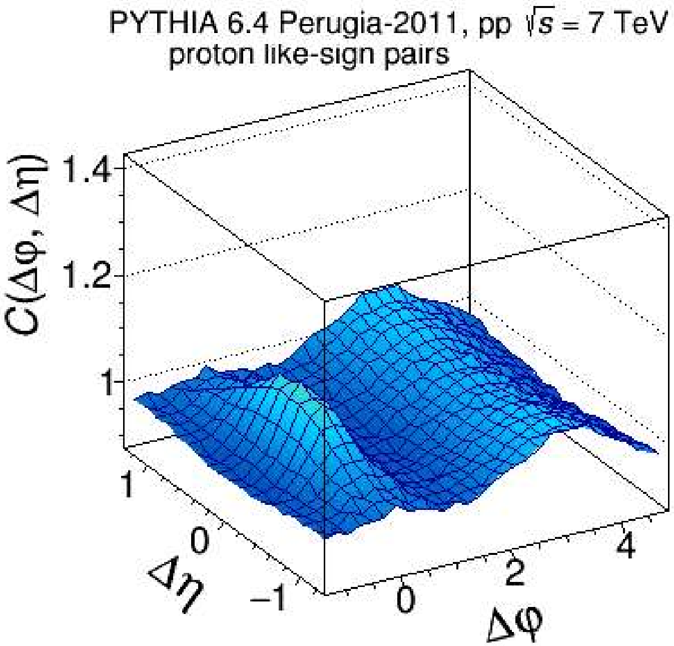


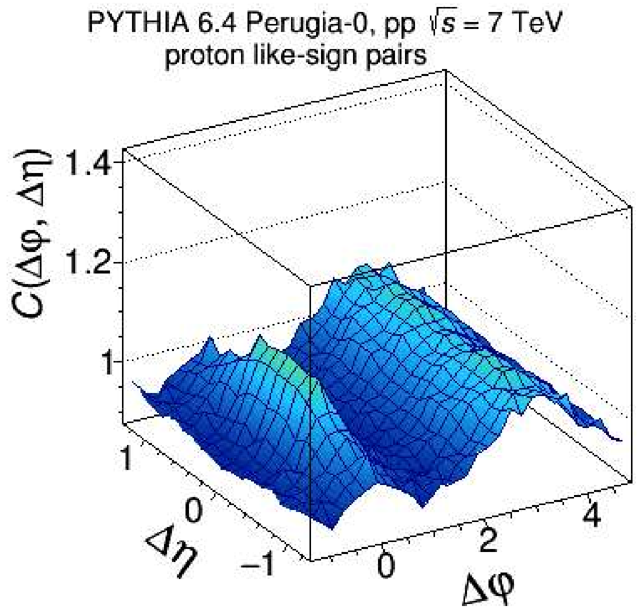


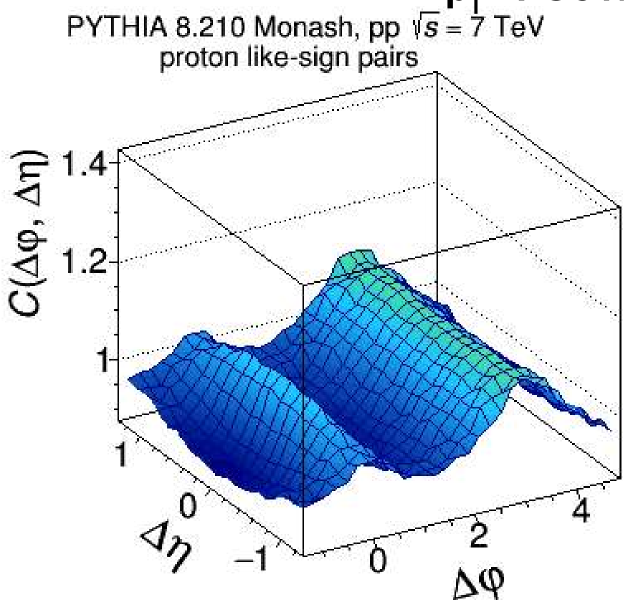


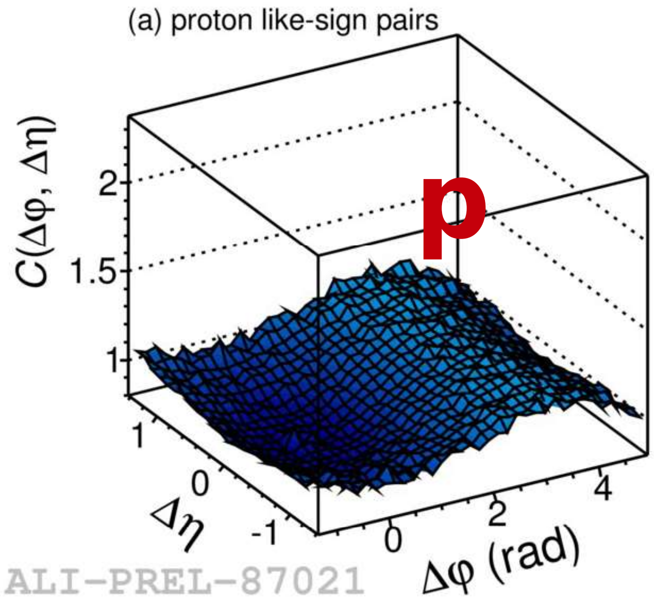
ΔηΔφ of identified particles in pp collisions

p_T<4 GeV/c









ΔηΔφ of identified particles in pp collisions

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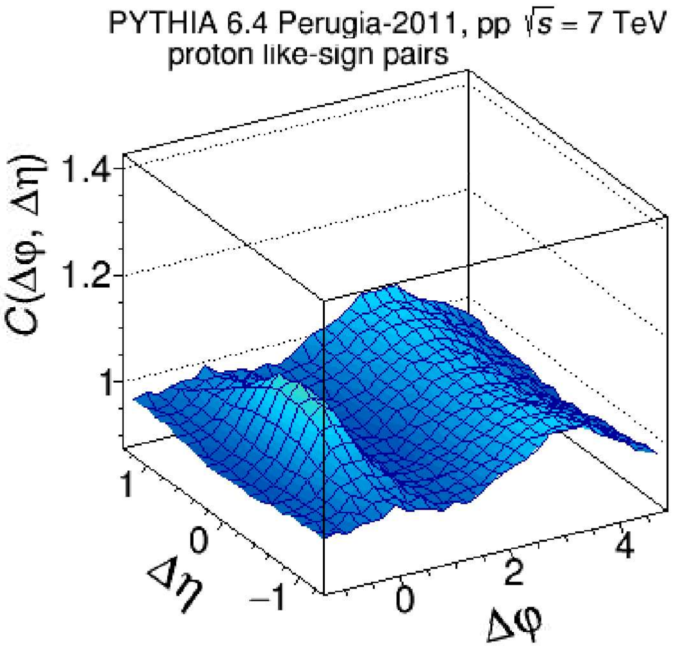
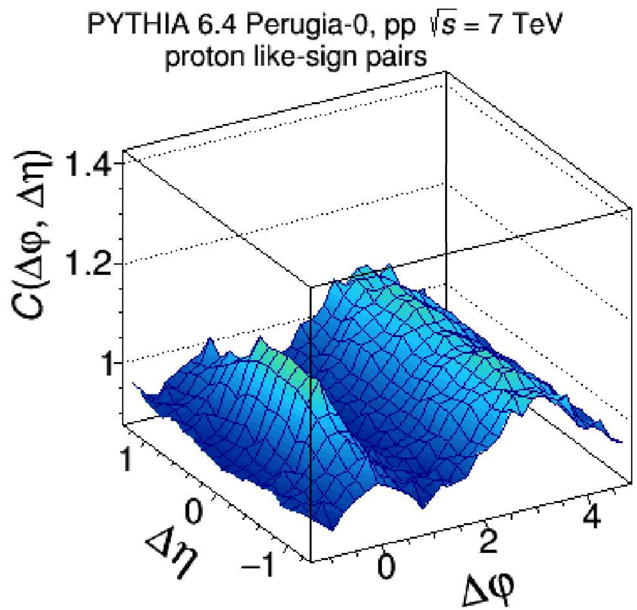
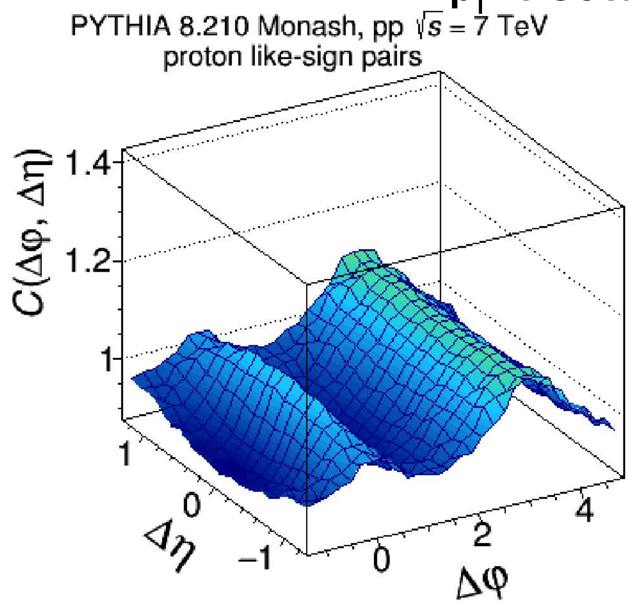
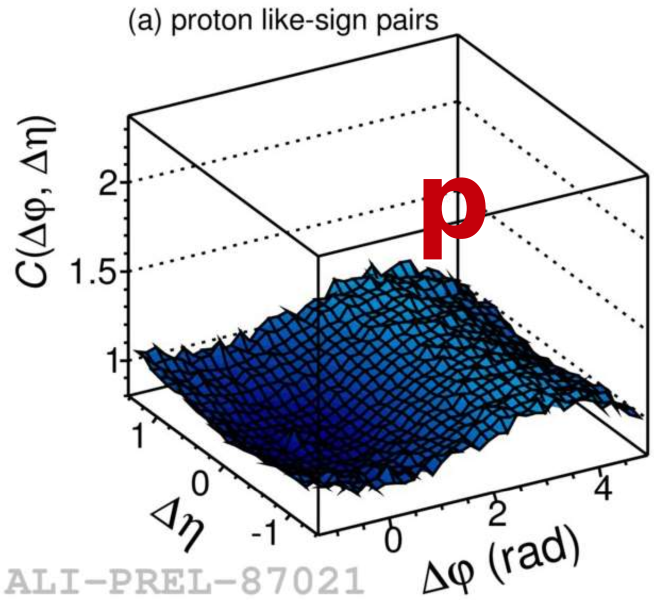
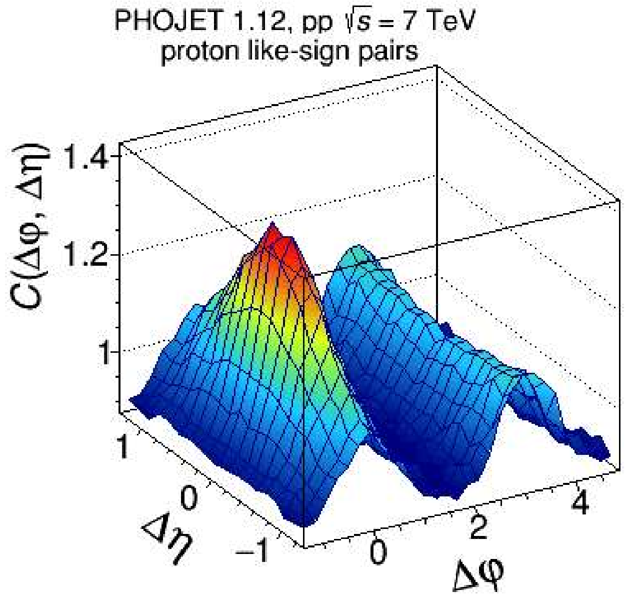






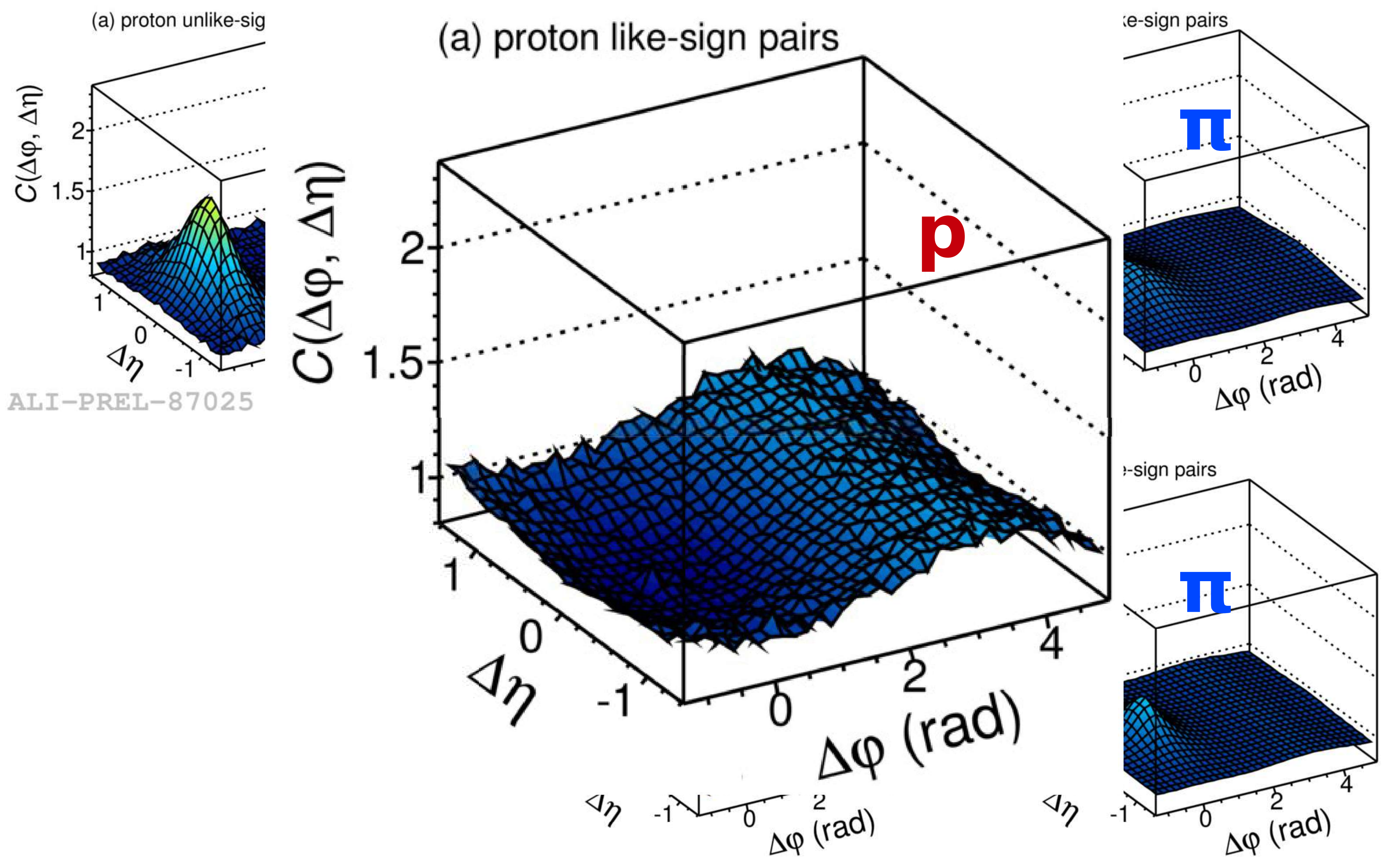




None of common MC models reproduces ALICE data!

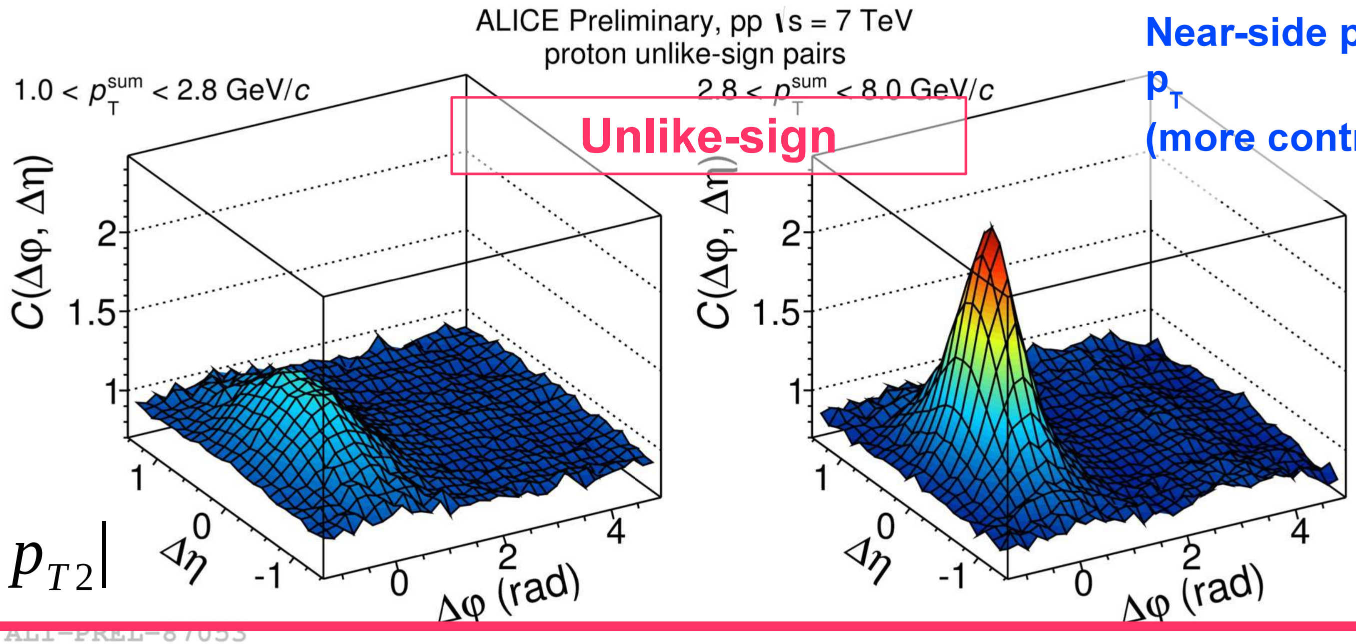
ΔηΔφ of identified particles of pp collisions

p_T<4 GeV/c



Protons

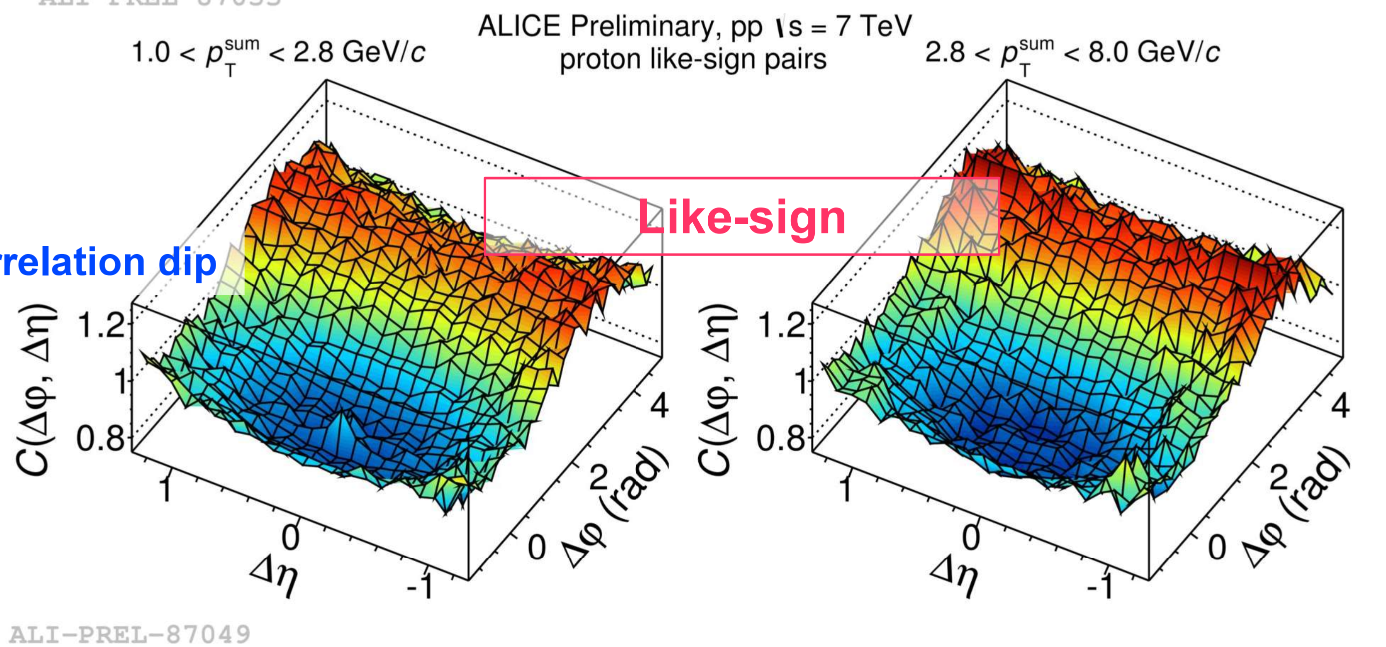
$$p_{Tsum} = |\vec{p}_{T1}| + |\vec{p}_{T2}|$$



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

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

p_T growth

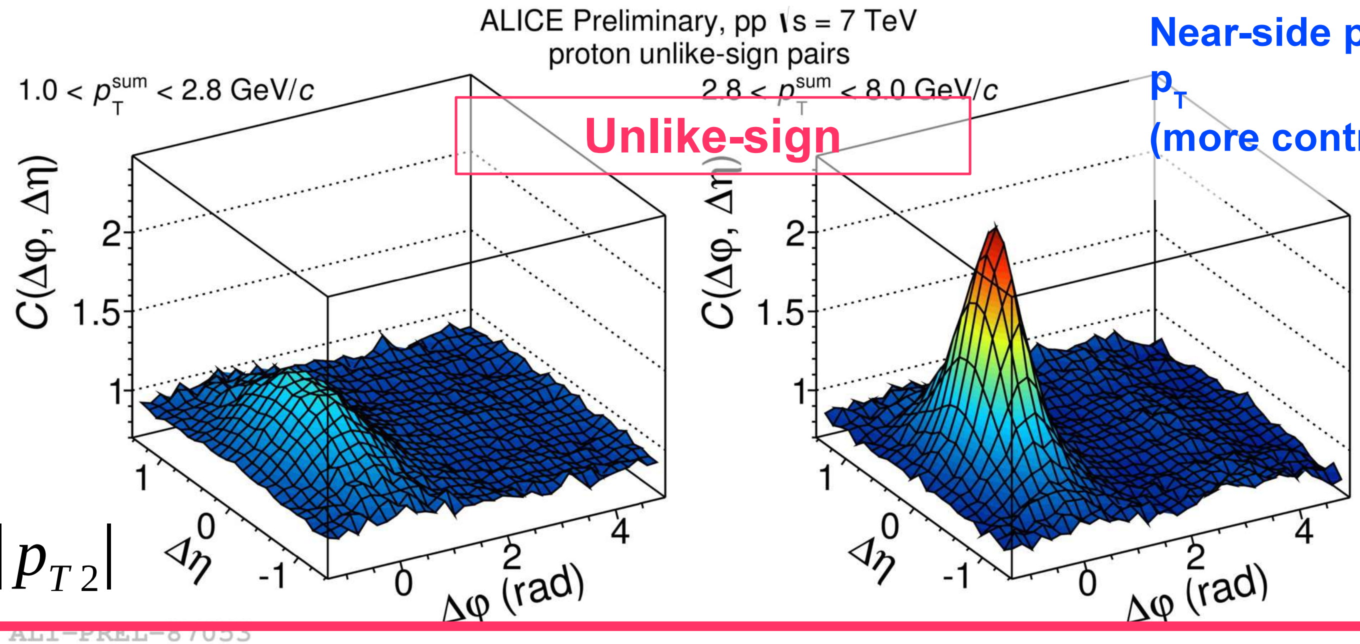


Anticorrelation dip

Small peak disappears for high p_T-sum

Shape of the dip does not change

Protons



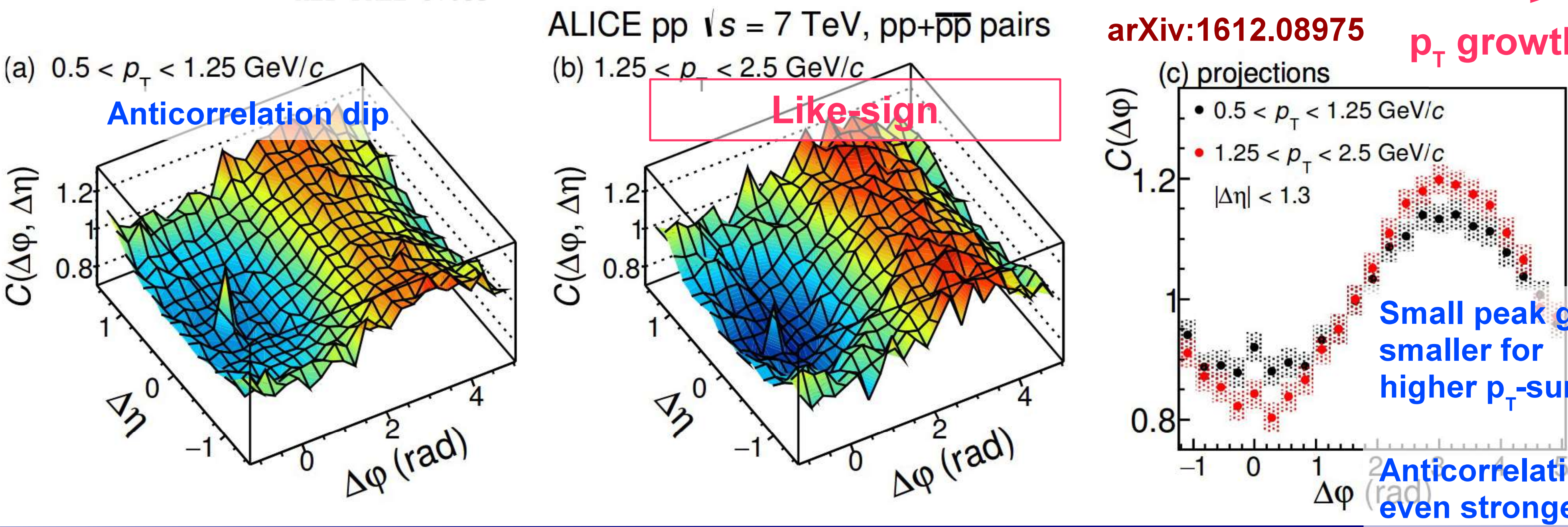
Unlike-sign

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

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

p_T growth

arXiv:1612.08975



Like-sign

Anticorrelation dip

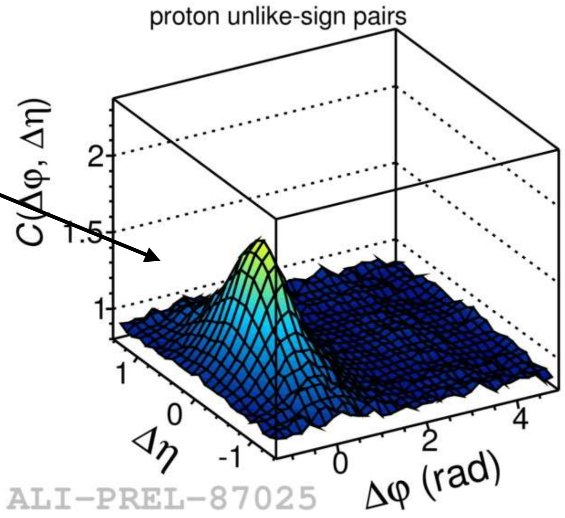
Small peak gets smaller for higher p_T-sum

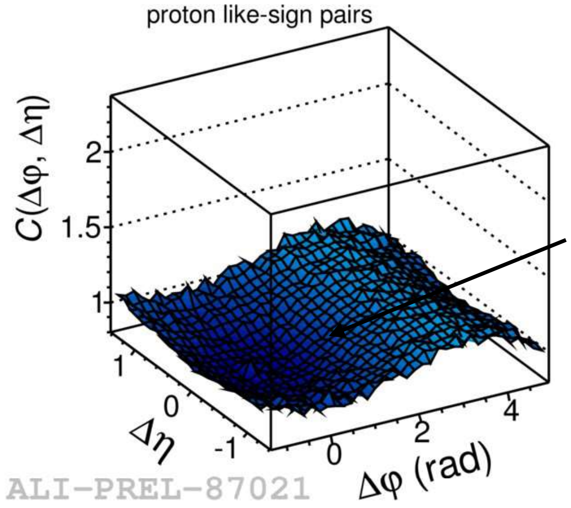
Anticorrelation even stronger

Two-particle rapidity correlations in e^+e^- collisions

ALICE

correlation

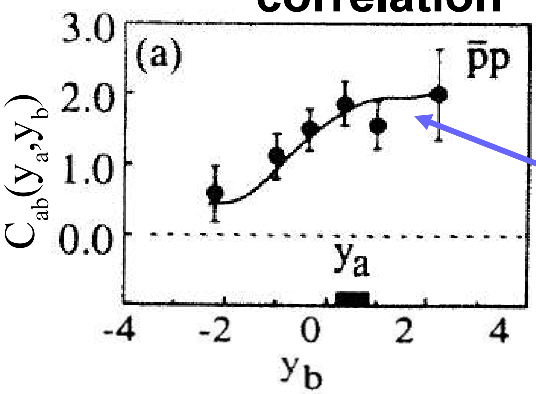




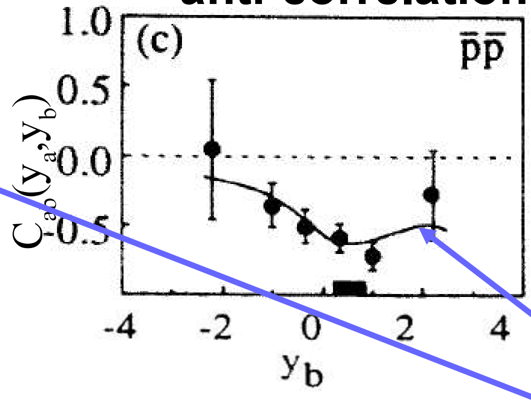
anti-correlation

e^+e^-

correlation



anti-correlation



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

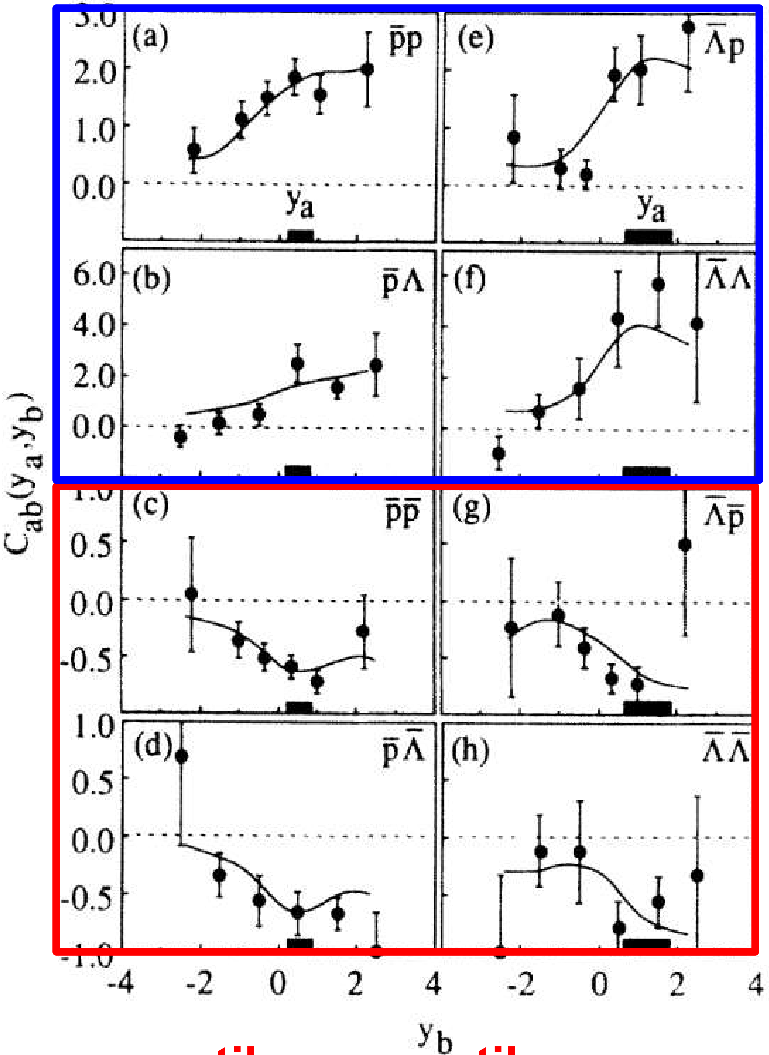
Much more unlike-sign baryons close together in the phase-space than like-sign baryons.

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

Rapidity correlations in e^+e^- collisions

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

baryon-antibaryon
correlation



antibaryon-antibaryon
anticorrelation!

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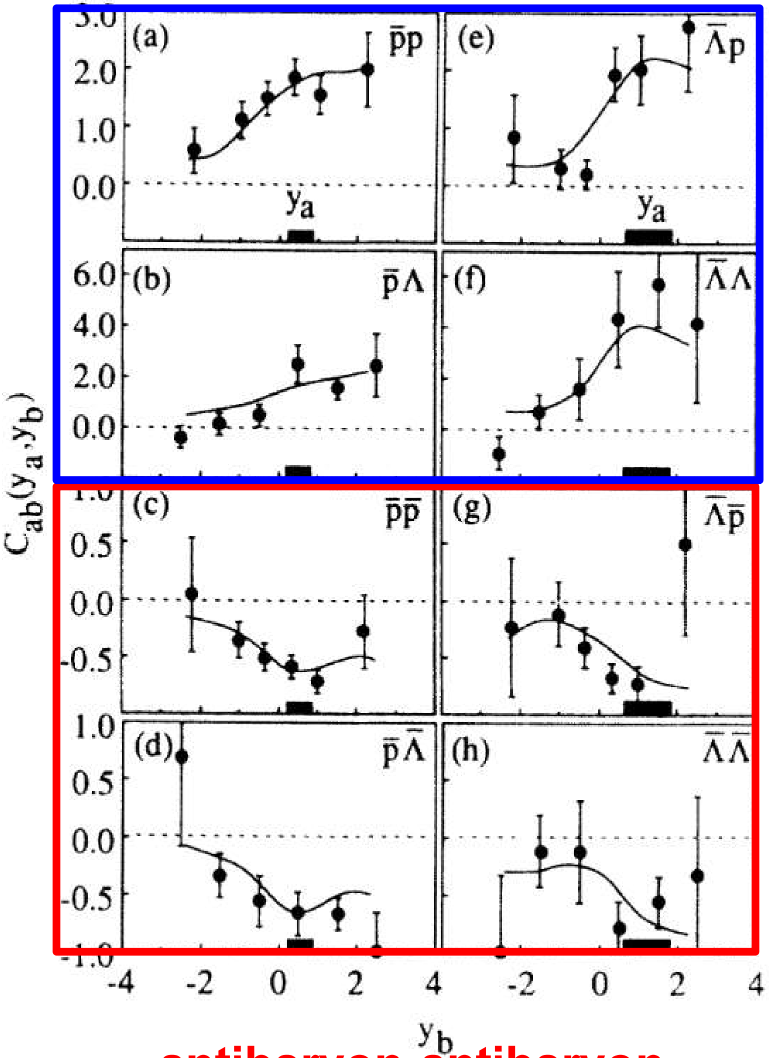
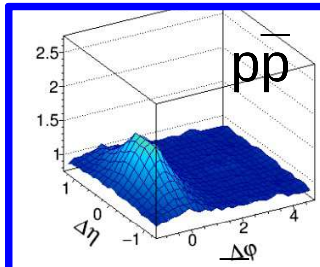
baryon-antibaryon
no anticorrelation



antibaryon-antibaryon
anticorrelation!

baryon-antibaryon
no anticorrelation

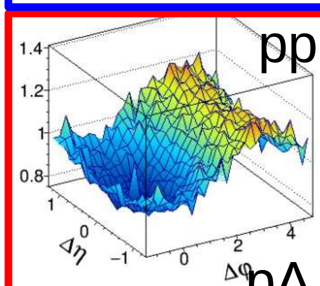


$p\bar{p}$ $p\bar{\Lambda}$

?

$\bar{p}\Lambda$ $\Lambda\bar{\Lambda}$

? ?



pp $\overline{p\Lambda}$

?

$p\Lambda$ $\overline{\Lambda\Lambda}$

? ?

(anti)baryon-(anti)baryon
anticorrelation!

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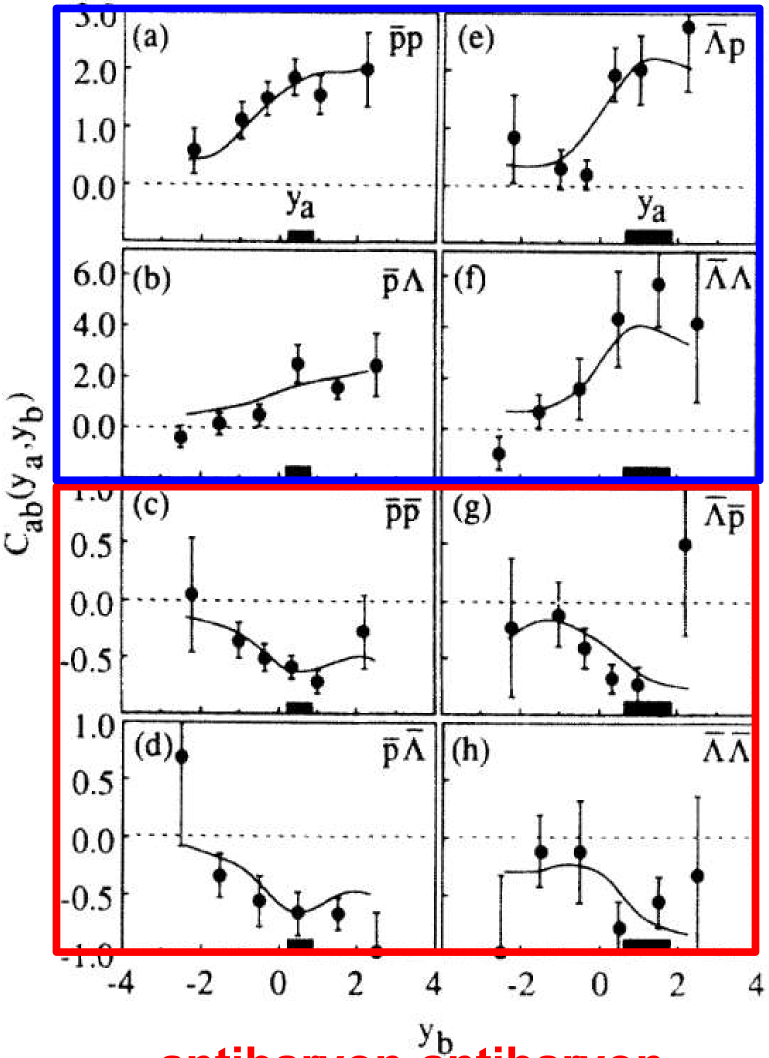
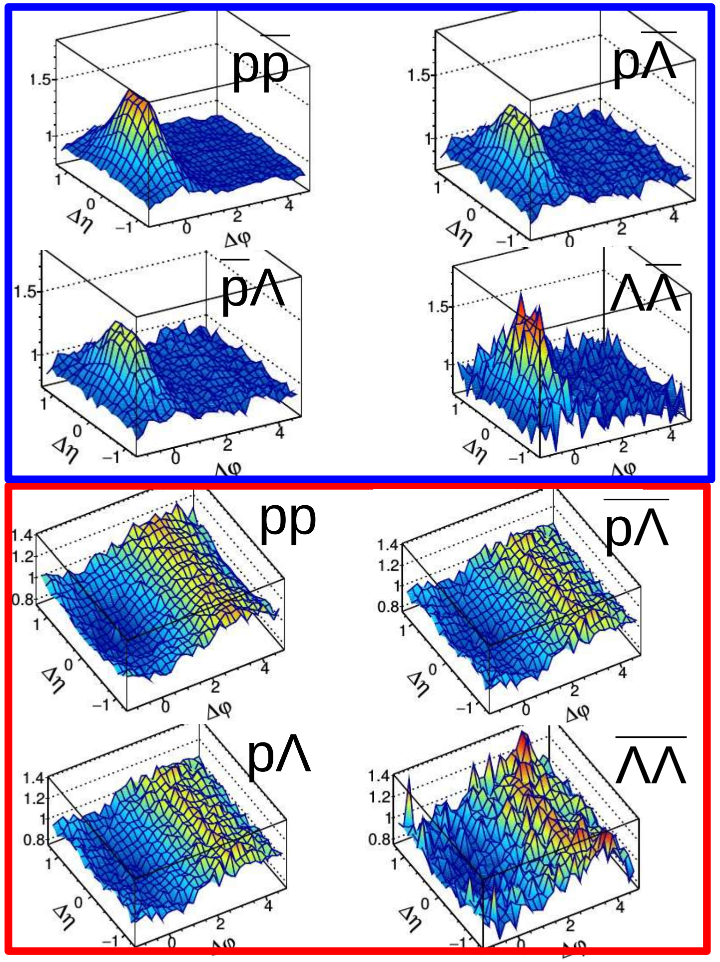


antibaryon-antibaryon
anticorrelation!

baryon-antibaryon
correlation



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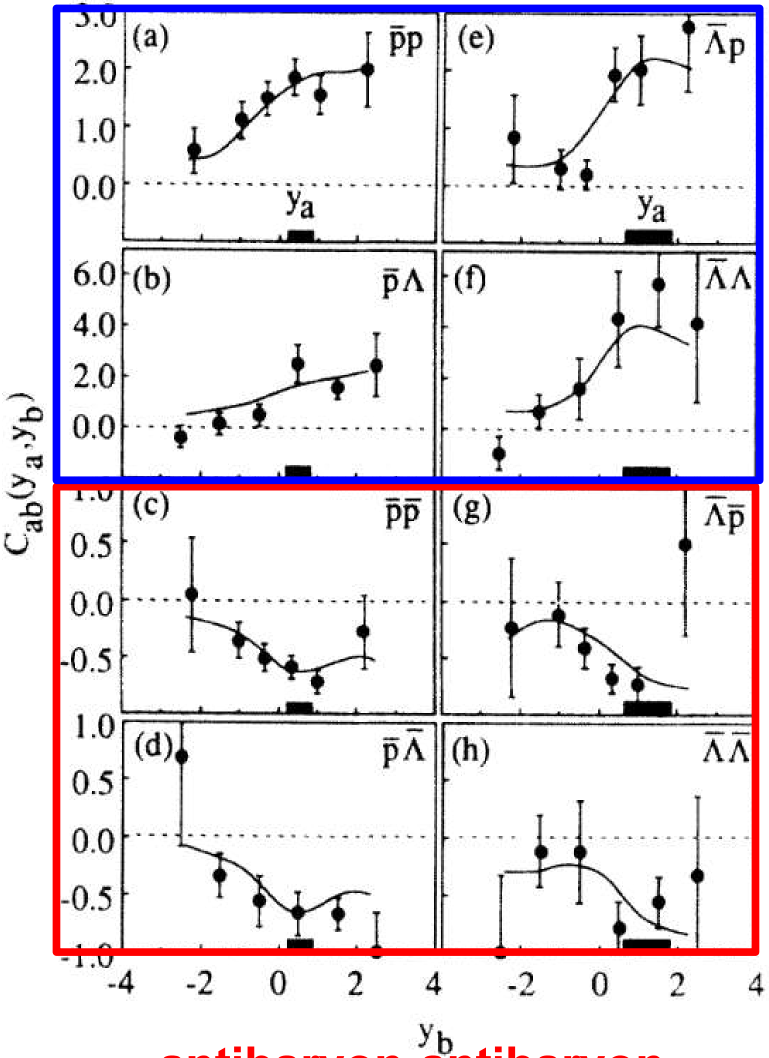

antibaryon-antibaryon
anticorrelation!

baryon-antibaryon
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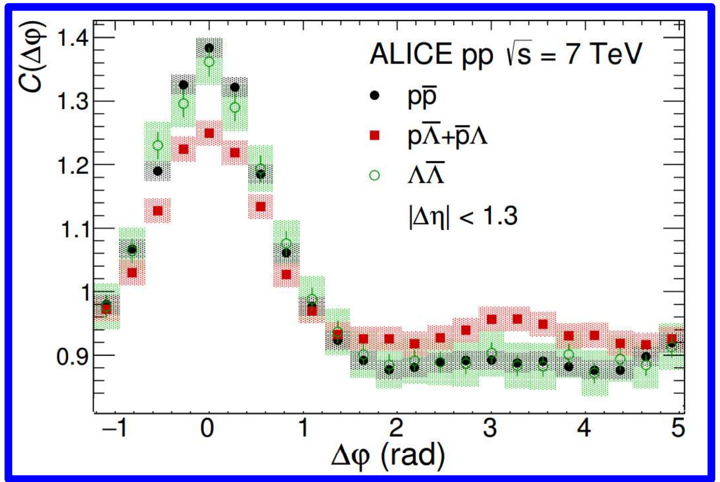
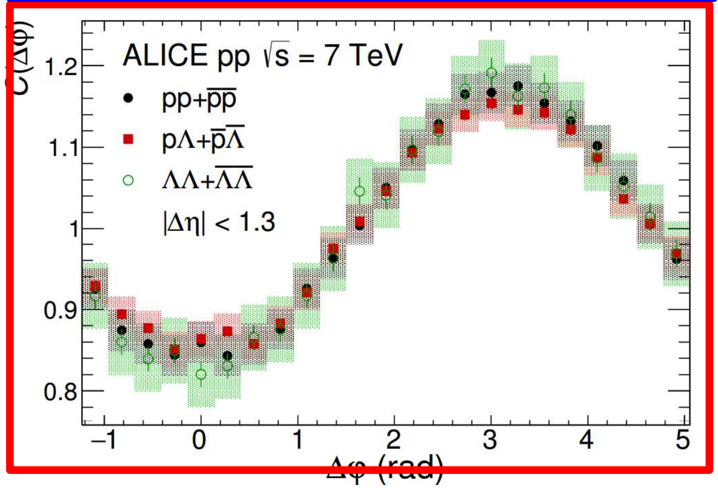
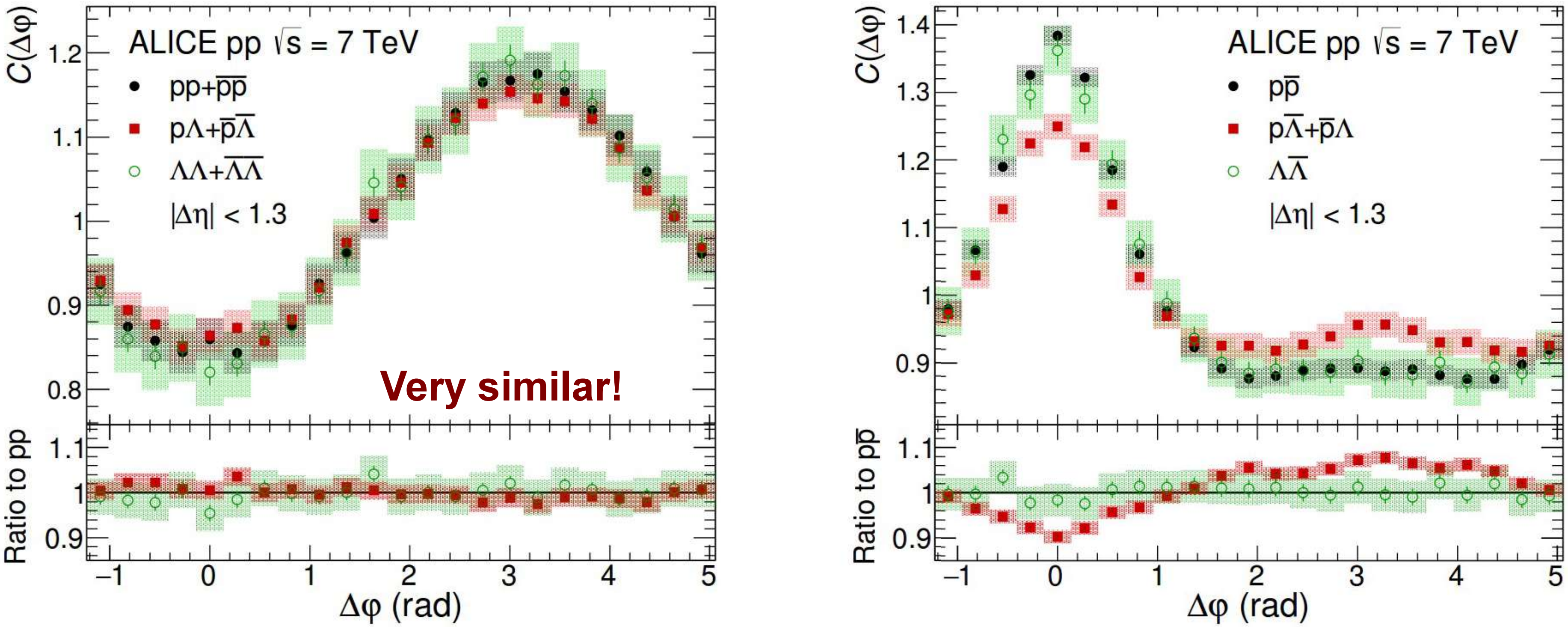




(anti)baryon-(anti)baryon
anticorrelation!

ALICE data

arXiv:1612.08975



Possible explanations:

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

Hypothesis from e^+e^- studies:

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

Rapidity correlations in e^+e^- collisions

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

baryon-antibaryon
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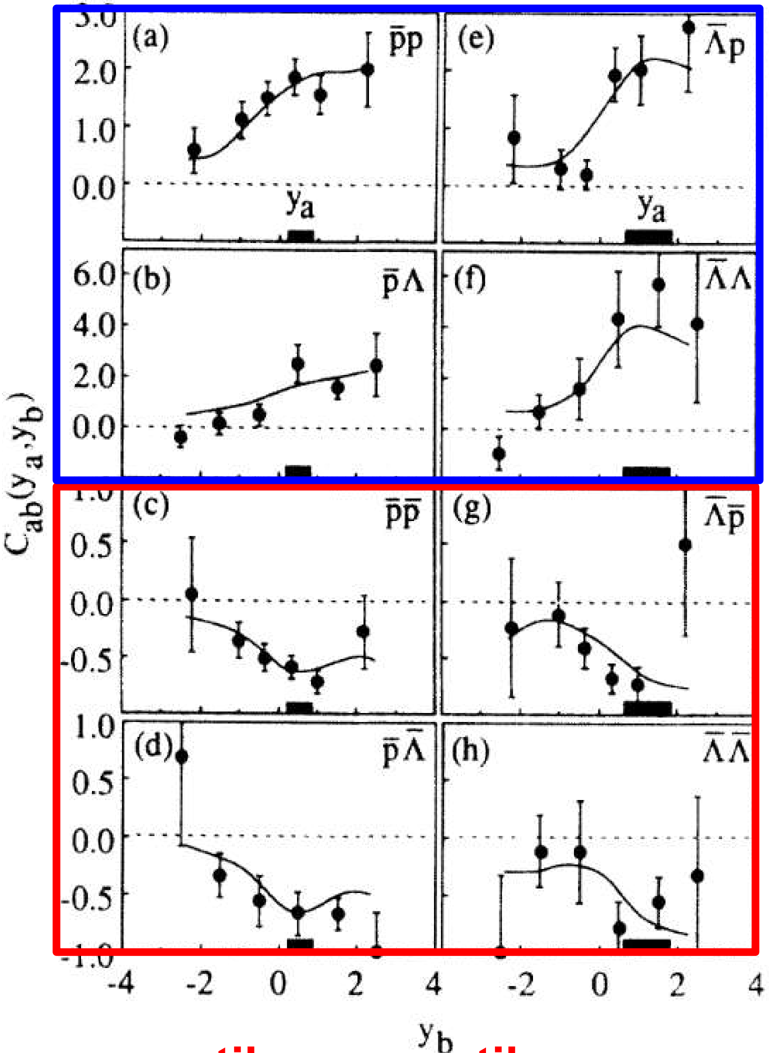
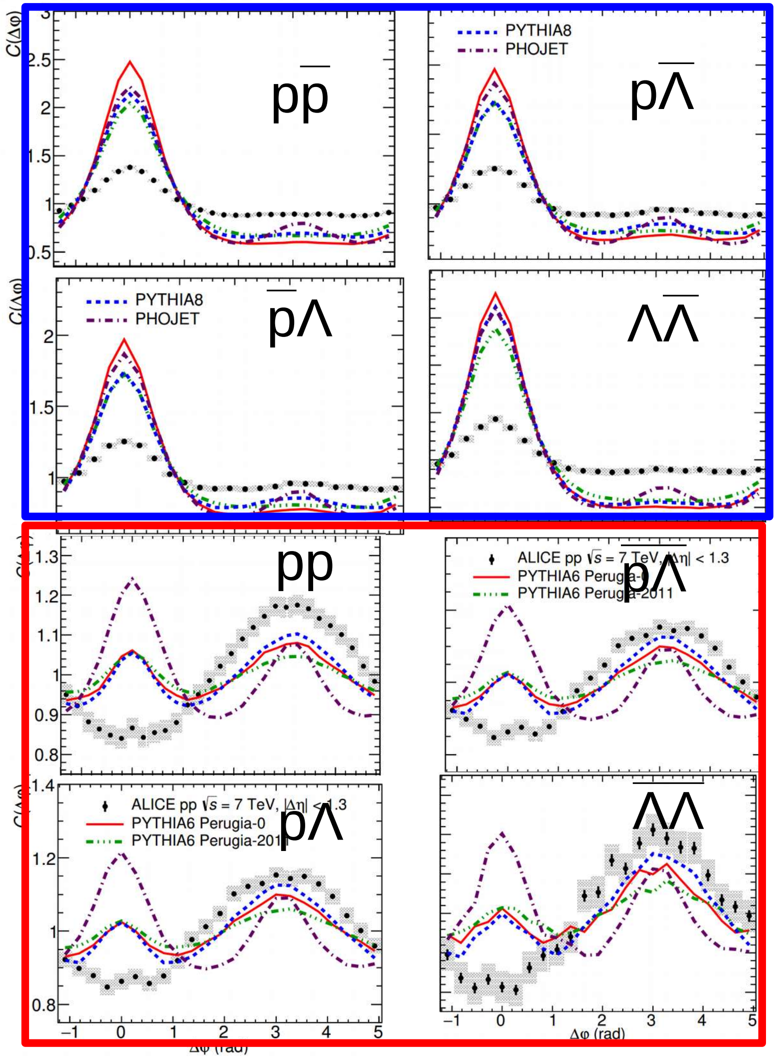


antibaryon-antibaryon
anticorrelation!

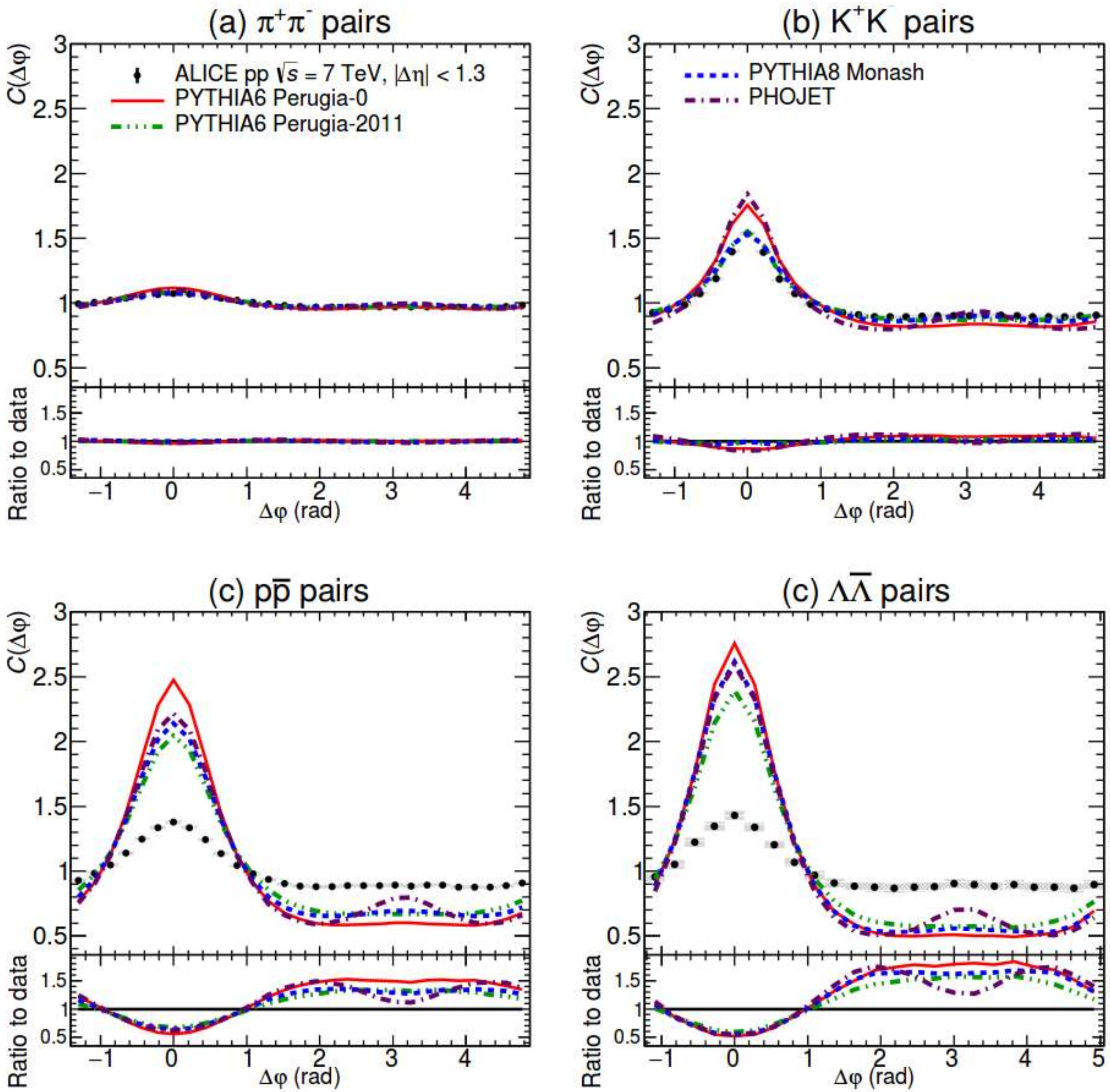
baryon-antibaryon
correlation



(anti)baryon-(anti)baryon
anticorrelation!

Comparison to MC models

arXiv:1612.08975



- PYTHIA and PHOJET were successfully used to describe non-femtoscopic background in HBT correlations for pions and kaons

- The models reproduce reasonably well the angular correlations for mesons as well

- The models fails to reproduce the results for baryons – apparently they produce 2 baryons close in the phase space

- **These results argue against the hypothesis that the combination of energy and baryon-number conservation is enough to explain the anti-correlation, since both local conservation laws are implemented in all studied models**

Comparison to MC models

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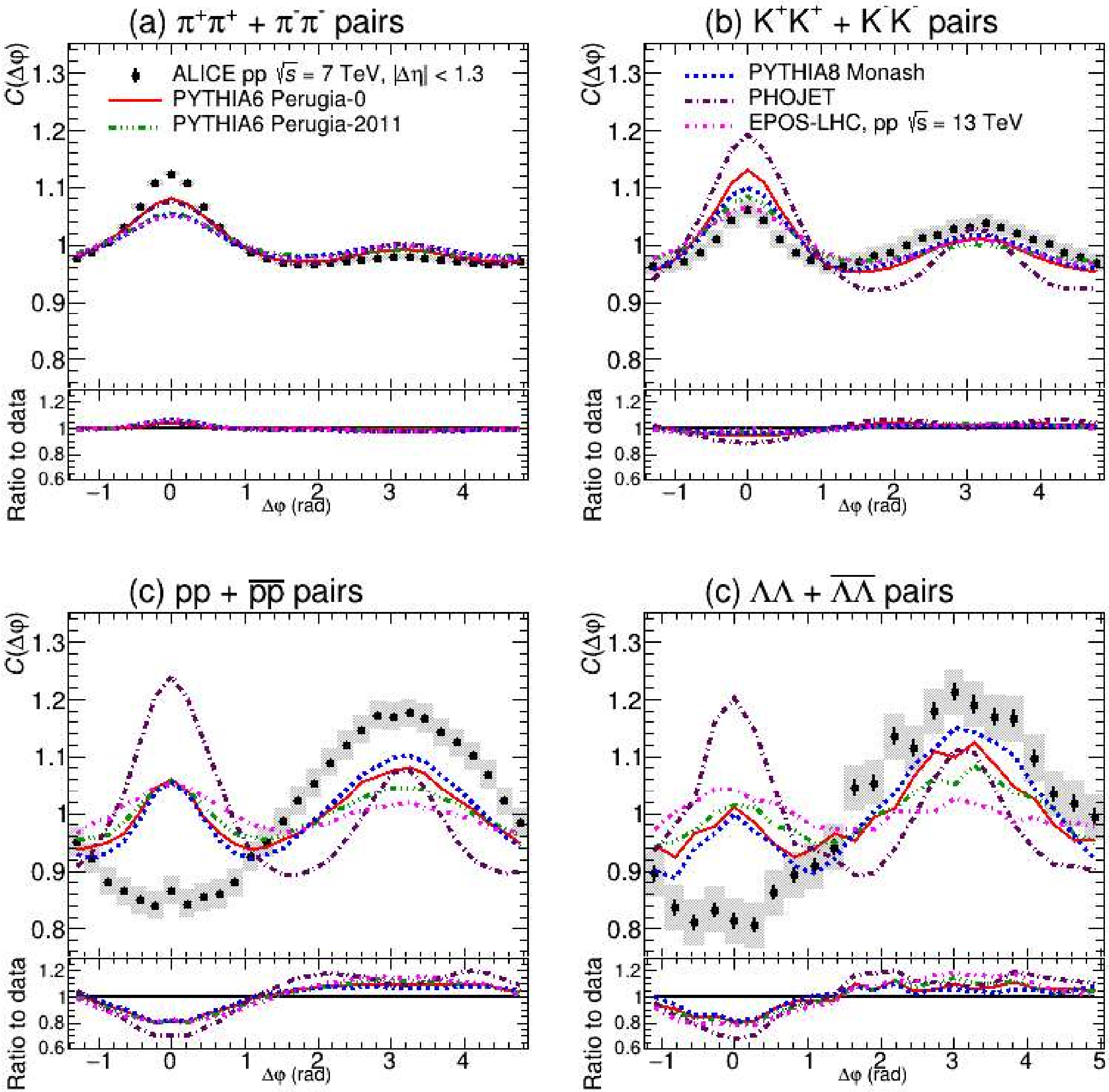

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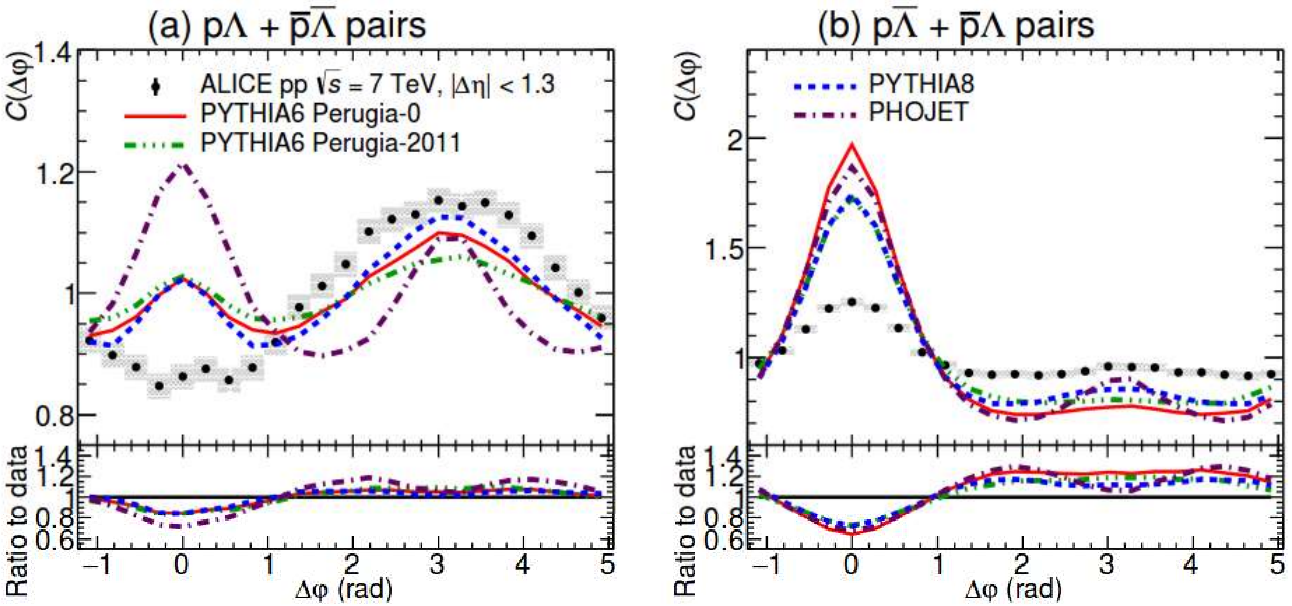

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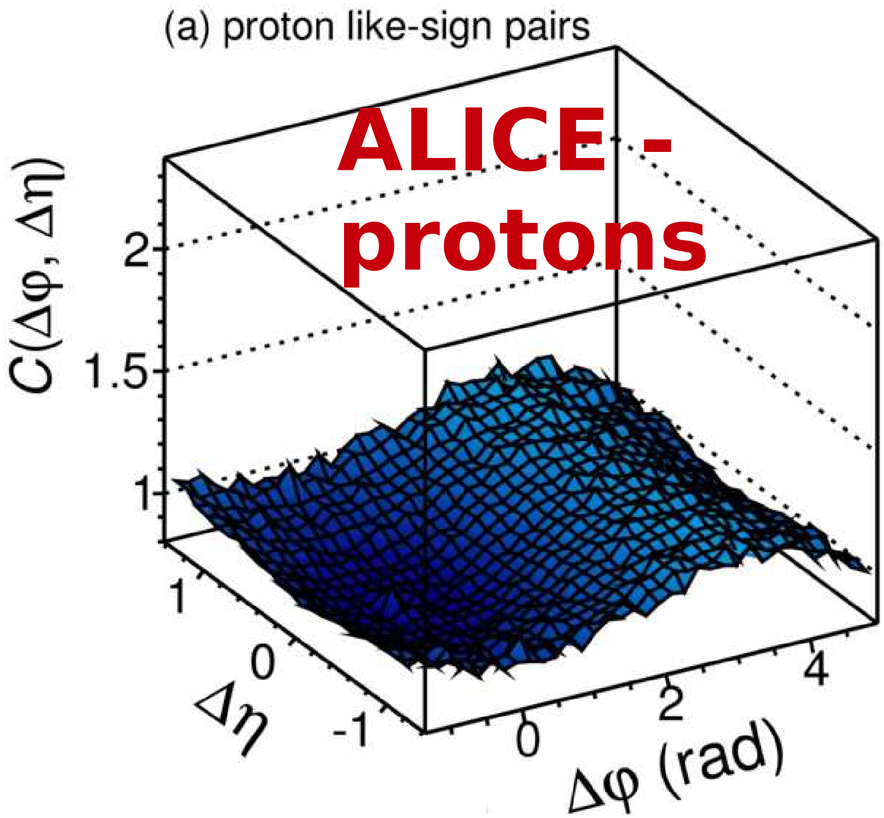
ΔηΔφ of identified particles of pp collisions



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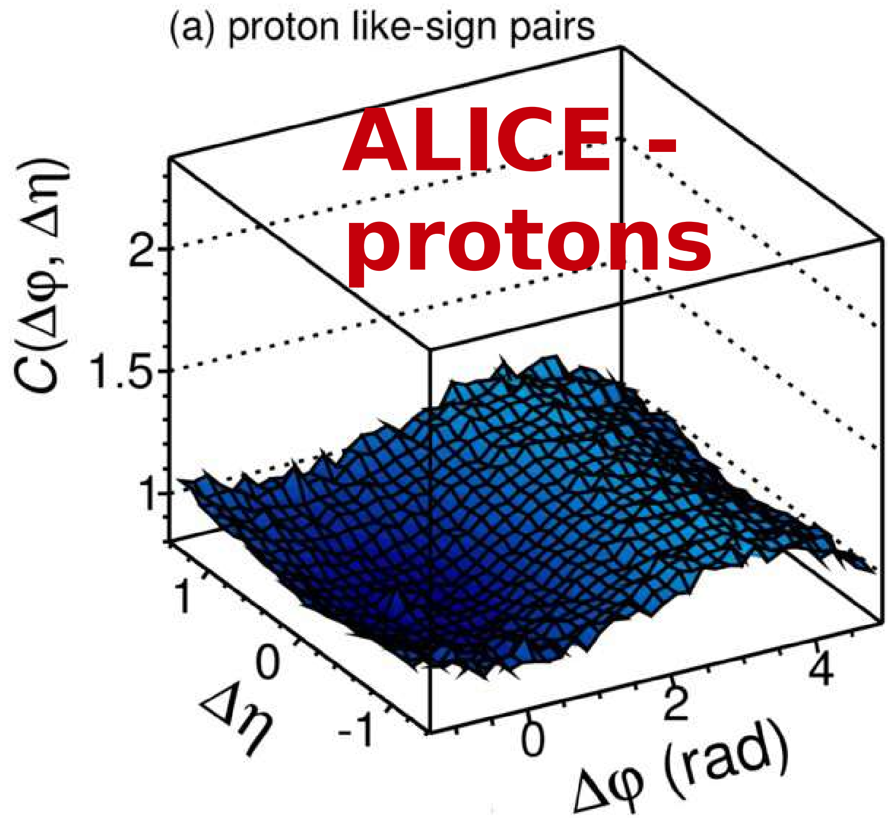
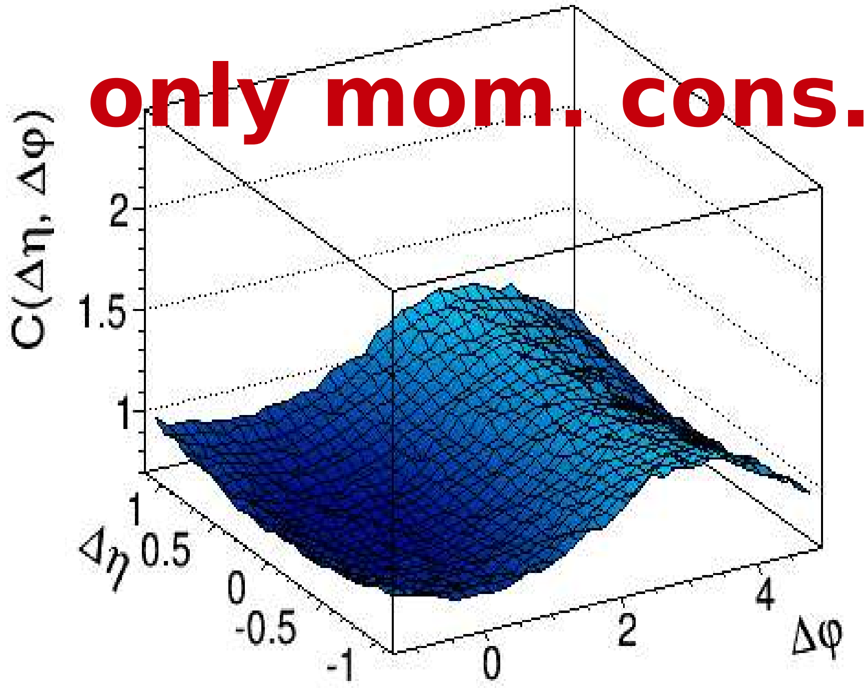
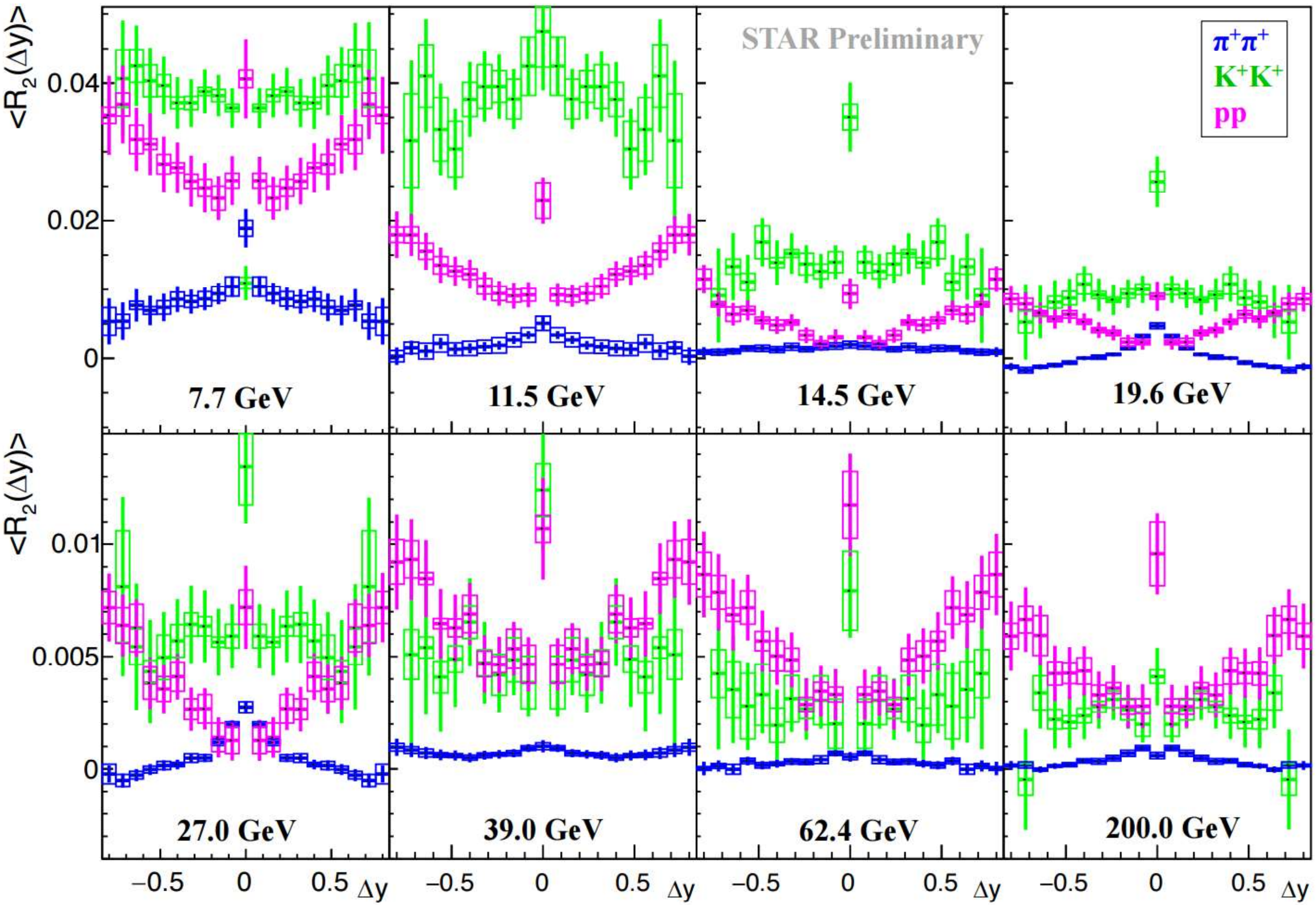




$\pi^+\pi^+$, K^+K^+ and **pp**, 0-5% centrality **SRC was not subtracted**



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

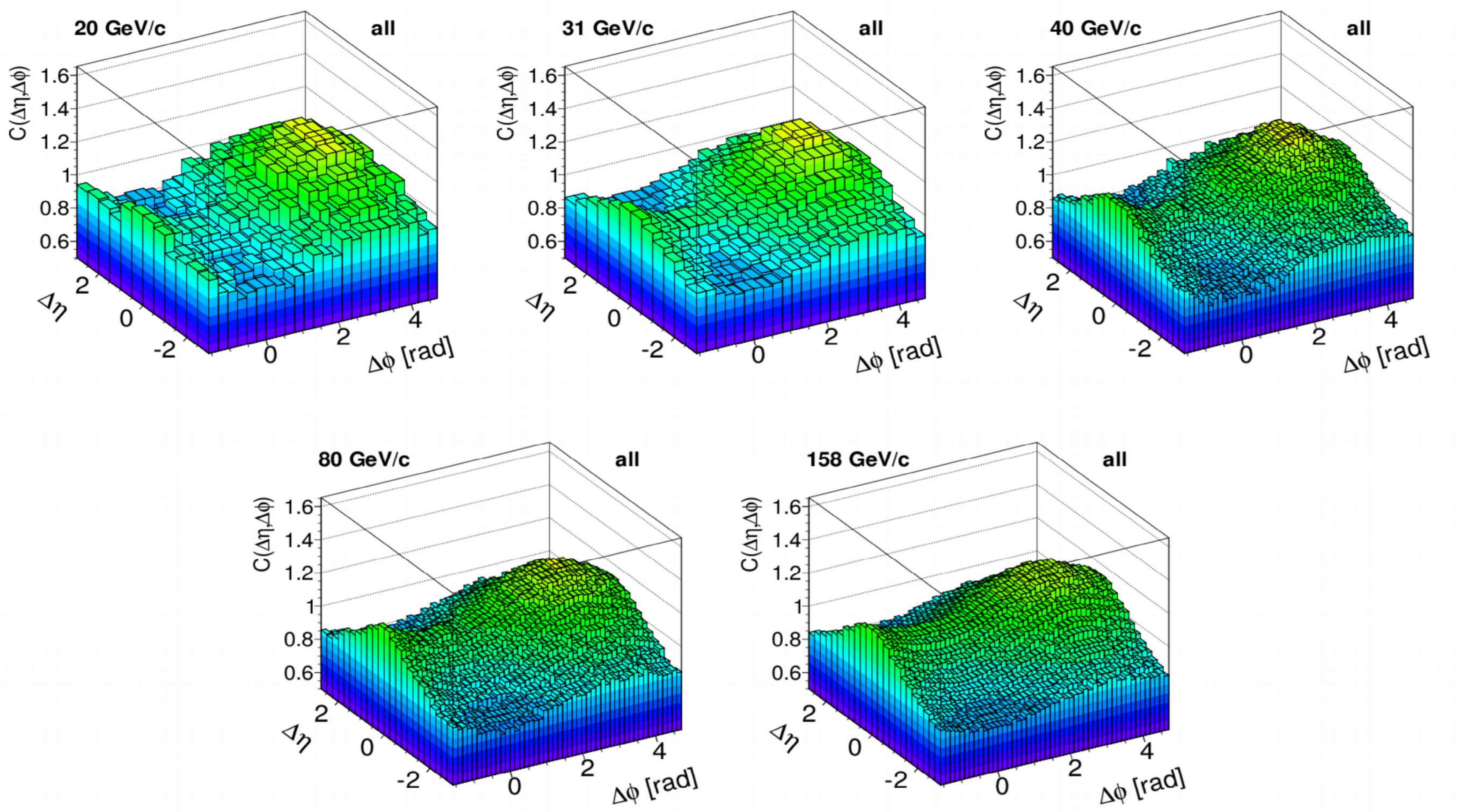
STAR ☆

S. Jowzaee, Quark Matter 2017

9

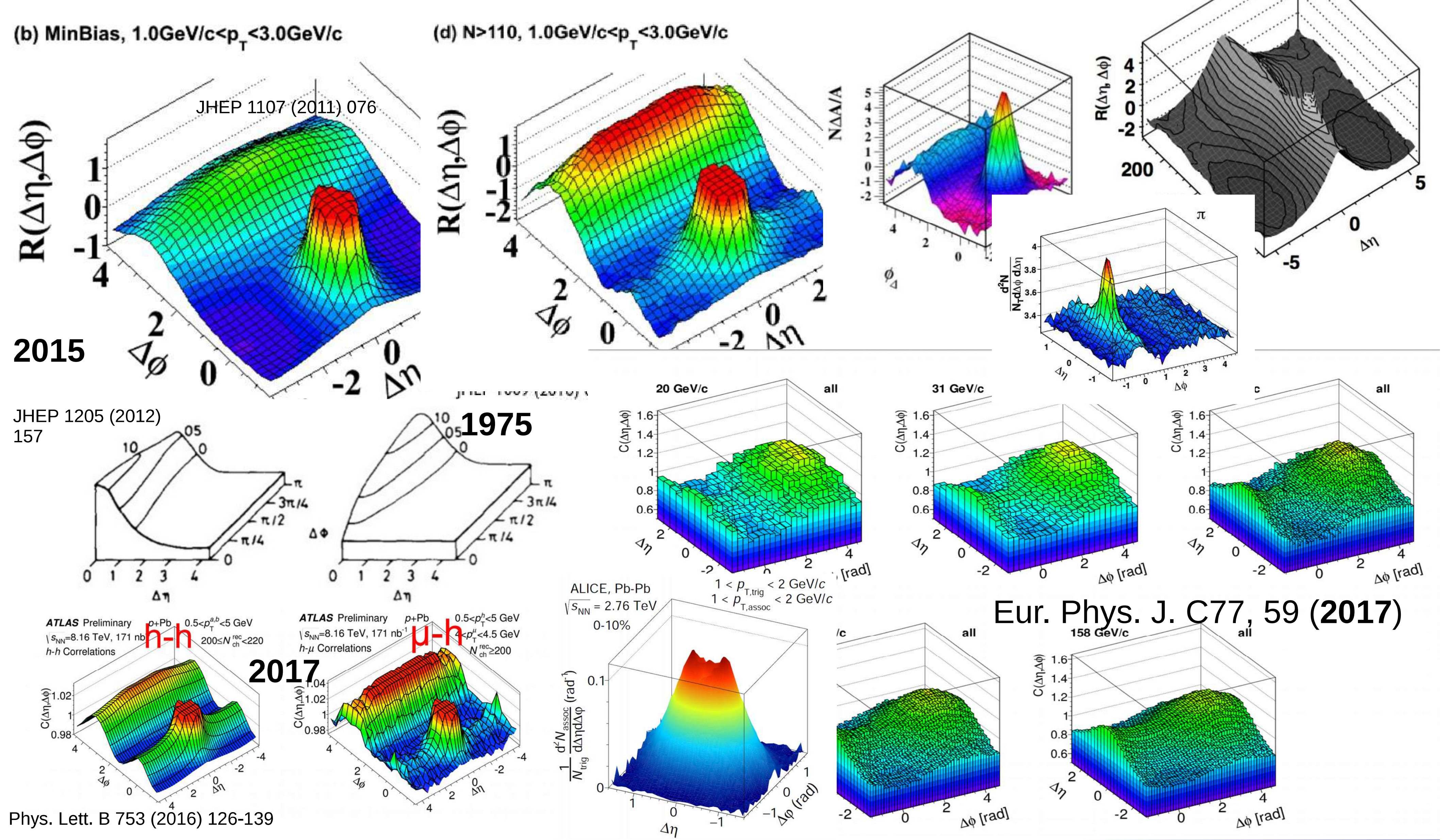
Low energy results from SPS: NA61

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



Summary

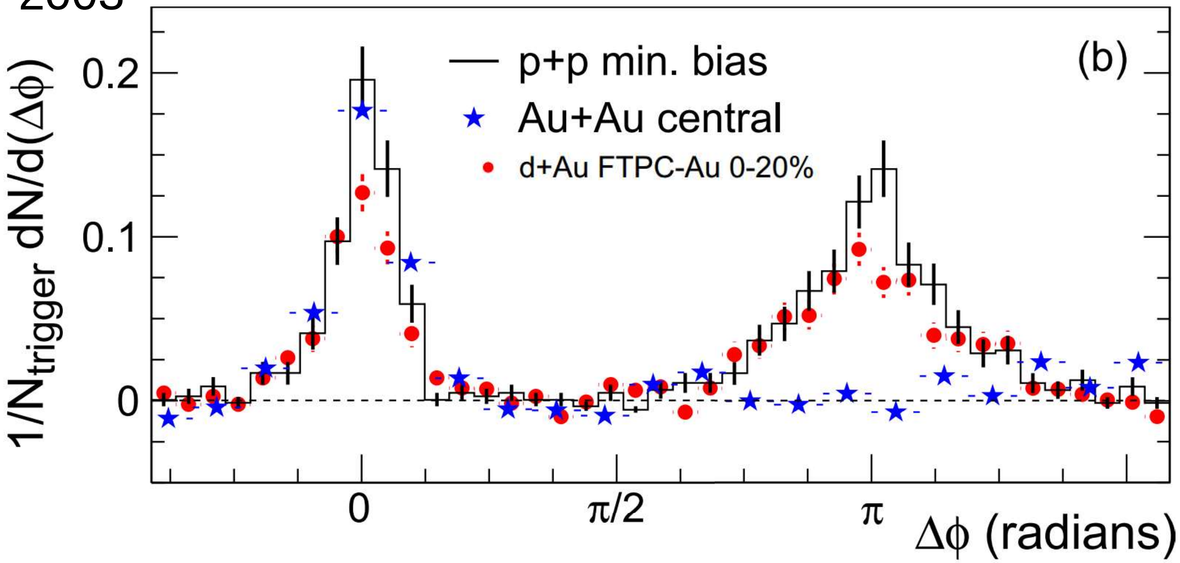
- **Allow to study wide range of physics phenomena**

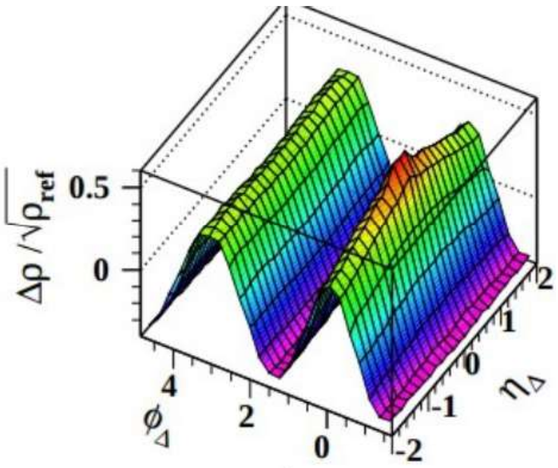


Summary

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

2003





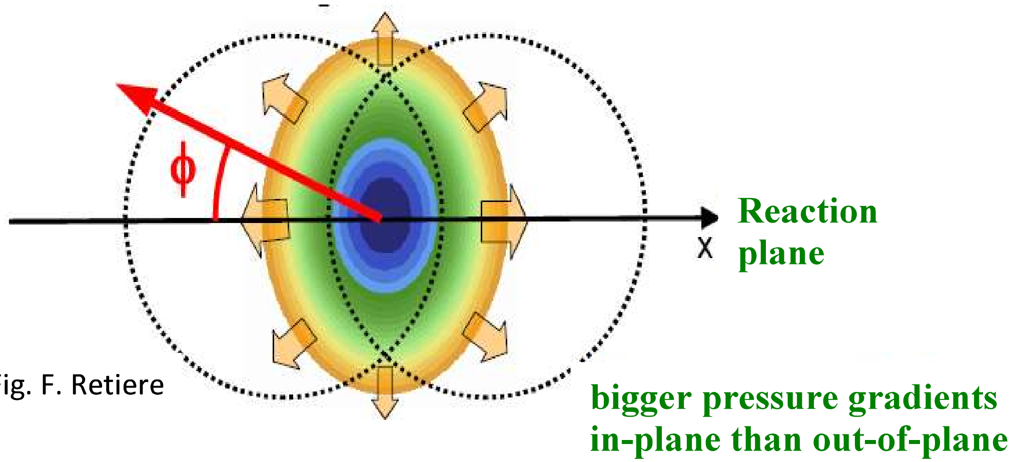
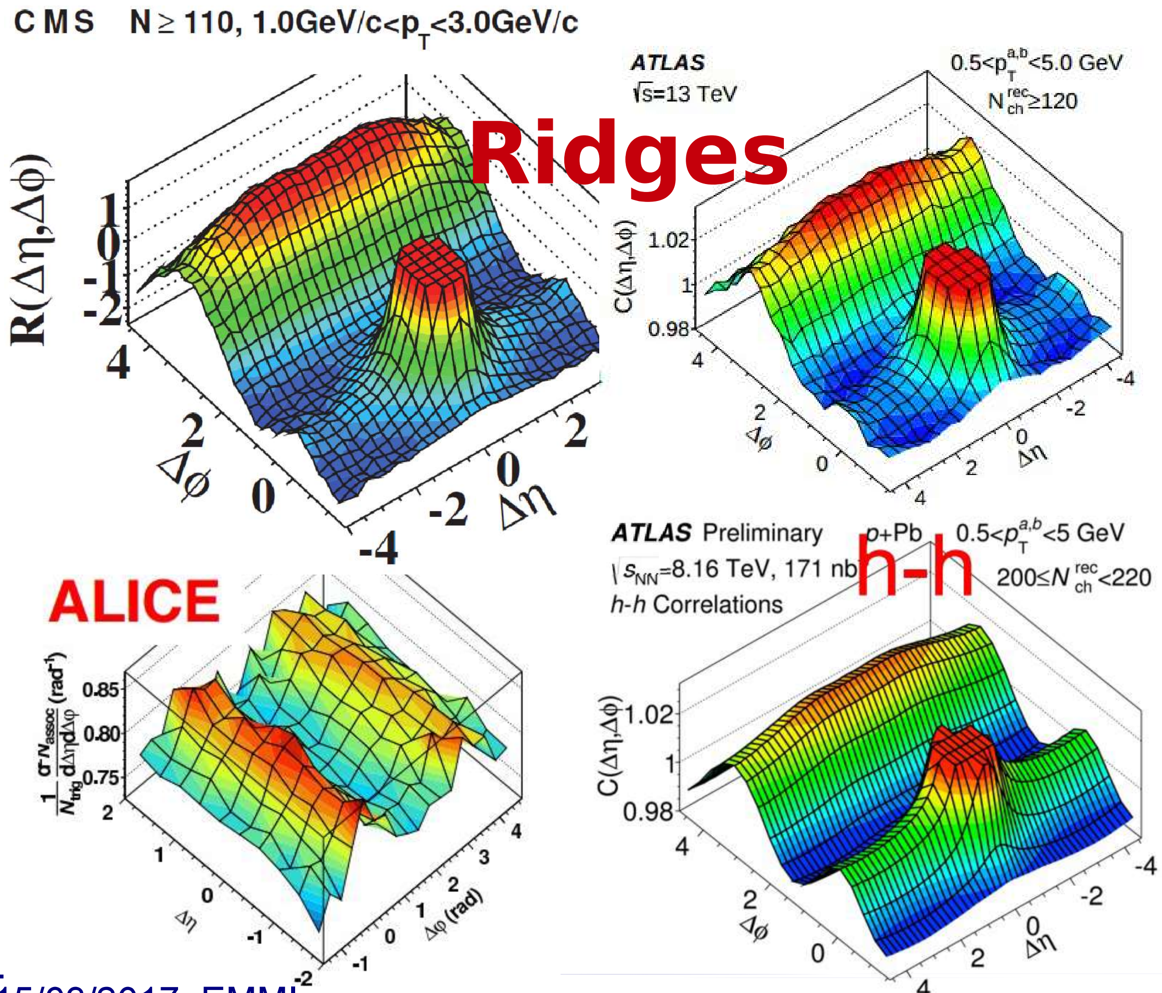
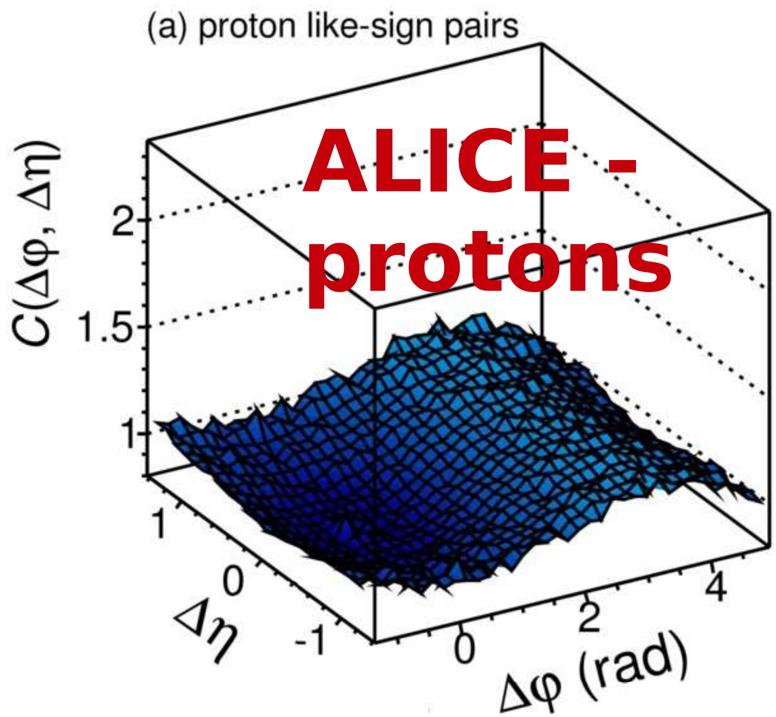


Fig. F. Retiere

Summary

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





The End

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