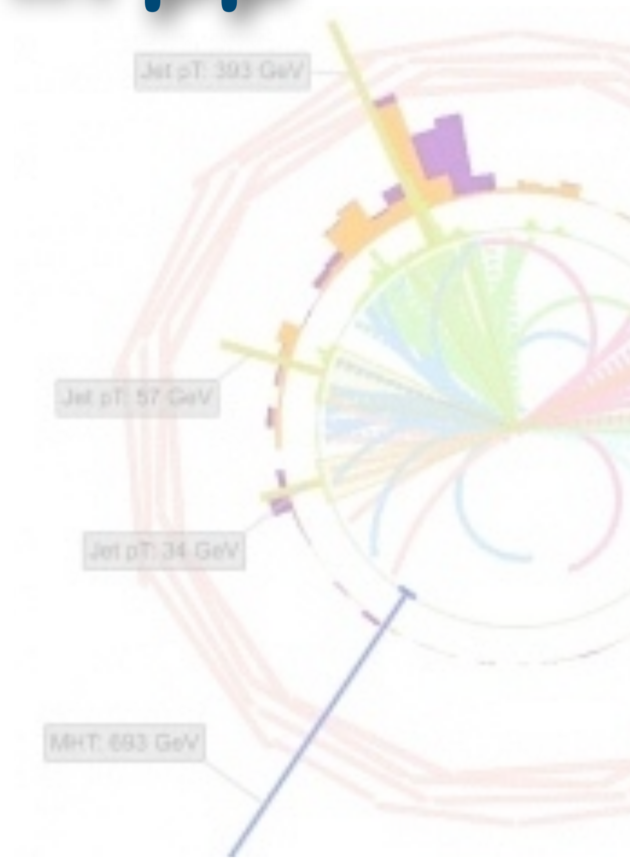
Measurement of long-range near-side two-particle correlations in pp collisions at 13 TeV



Arthur Moraes - CBPF

on behalf of the CMS Collaboration

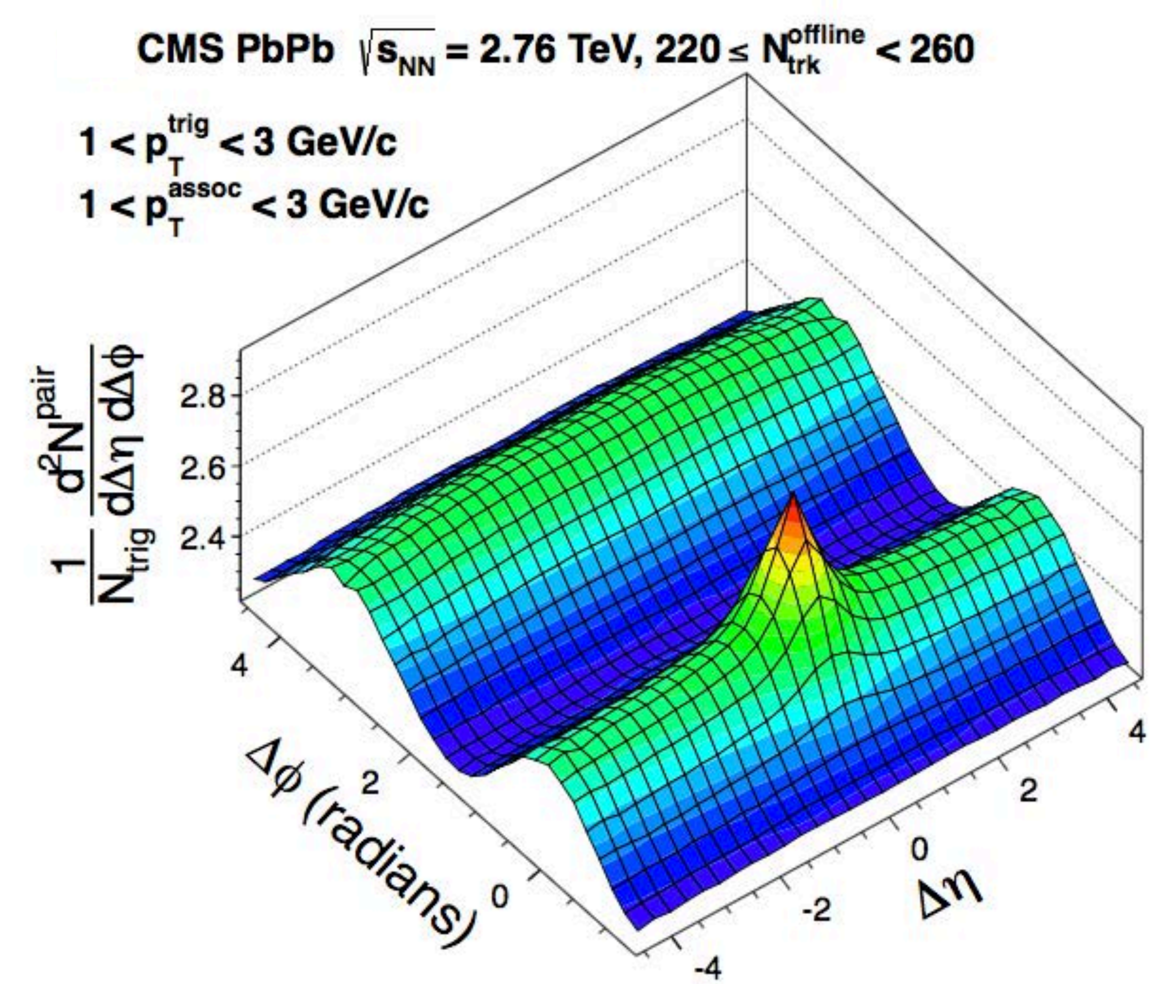
Outline:

Compact Muon Solenoid experiment at CERN's LHC

- Introduction: measuring two-particle correlations
  - *Investigating correlations in high-multiplicity events: AA, pA, pp systems*
- LHC Run 2: looking for the "ridge" in pp collisions at $\sqrt{s} = 13$ TeV
  - *Data sample*
  - *Systematic uncertainties*
  - *Two-particle correlations: results and comparisons*
- Summary

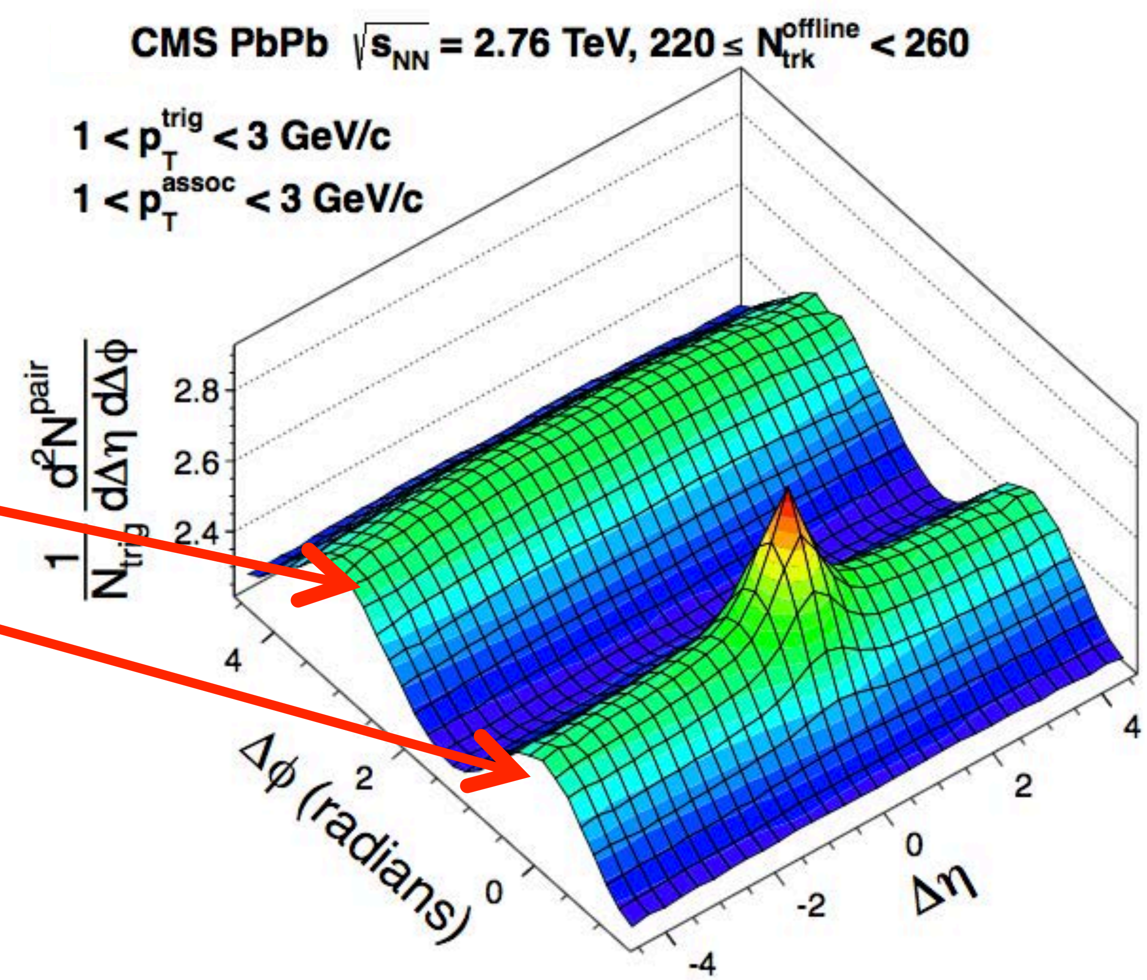
What is two-particle correlation used for?

- Double ridge structure in (Δη, Δϕ)



What is two-particle correlation used for?

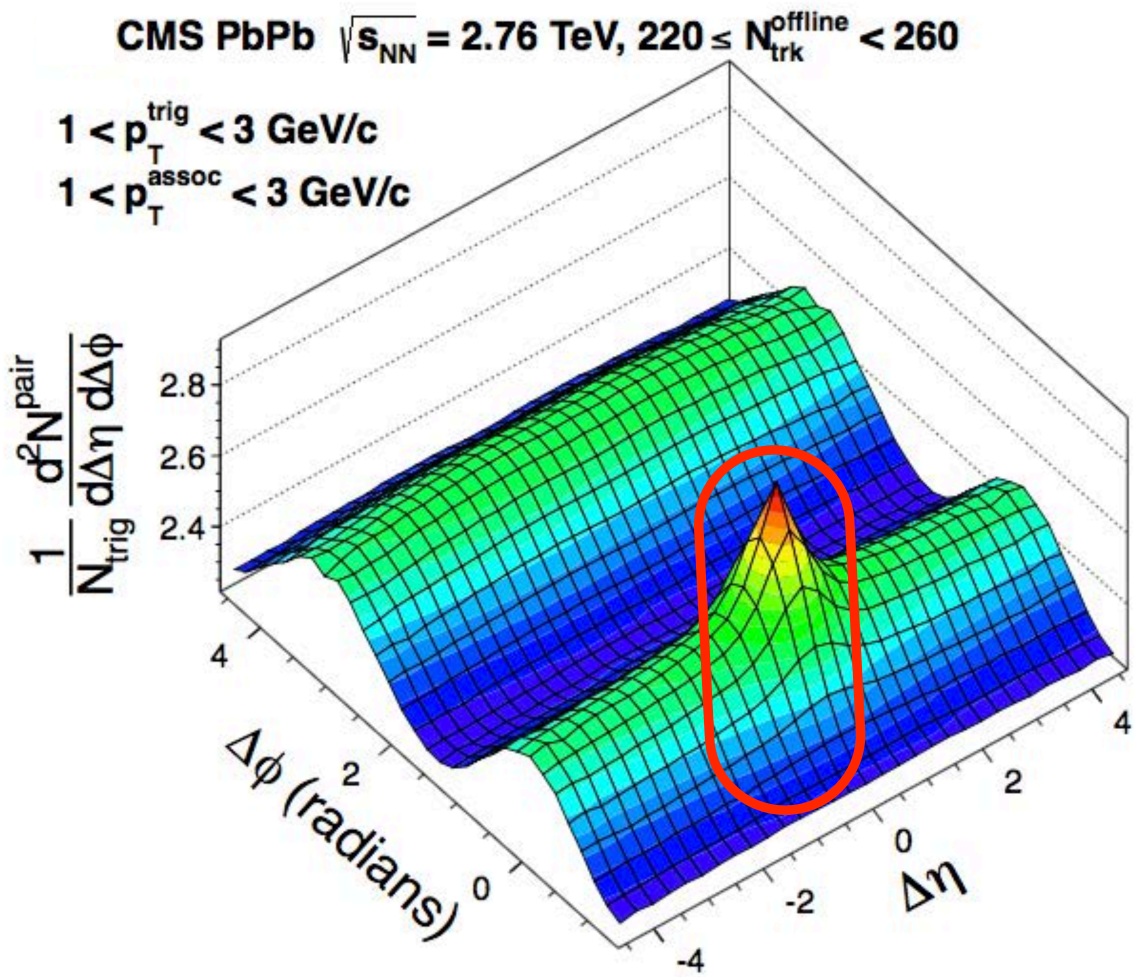
- Double ridge structure in ($\Delta\eta$, $\Delta\phi$)
- **Originally** used to probe **hydrodynamic** in heavy ion collision
  - Near side (around $\Delta\phi$ = 0)
  - Away side (around $\Delta\phi$ = π)



What is two-particle correlation used for?

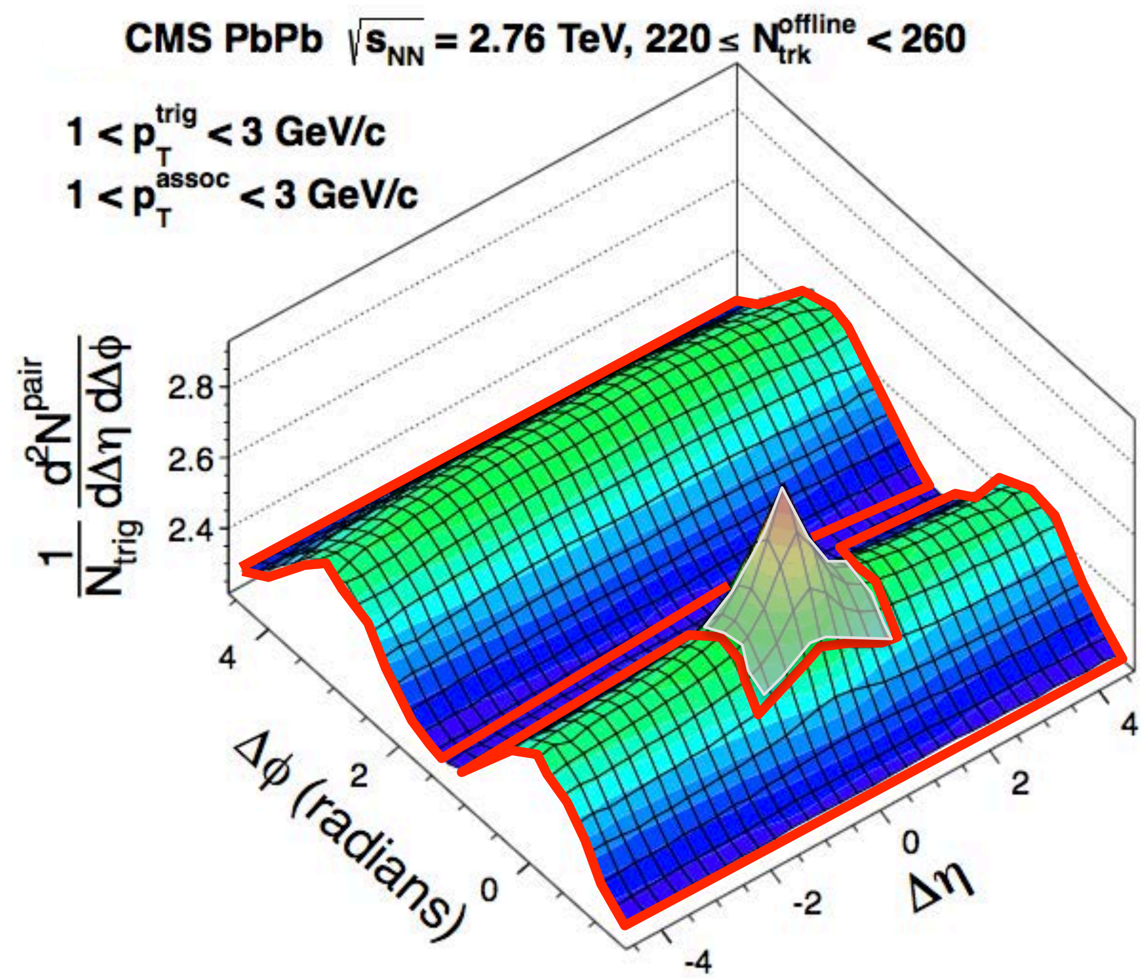
- Double ridge structure in ($\Delta\eta$, $\Delta\phi$)
- **Originally** used to probe **hydrodynamic** in heavy ion collision
  - Near side (around $\Delta\phi$ = 0)
  - Away side (around $\Delta\phi$ = π)
- 2D correlation function reflect two particle correlation origin;
  - Near side peak around (0,0): **Jets**

(and resonances)



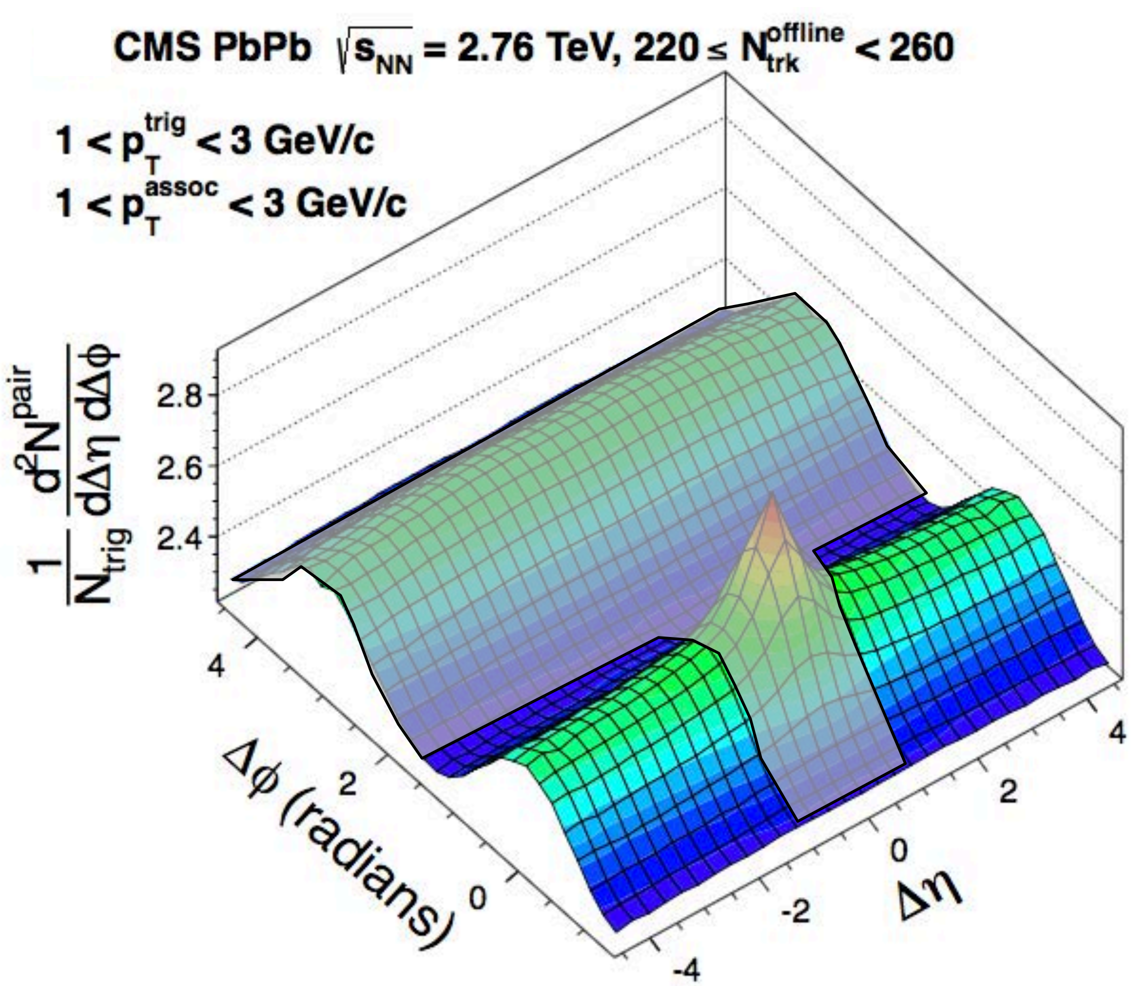
What is two-particle correlation used for?

- Double ridge structure in (Δη, Δϕ)
- **Originally** used to probe **hydrodynamic** in heavy ion collision
  - Near side (around Δϕ = 0)
  - Away side (around Δϕ = π)
- 2D correlation function reflect two particle correlation origin;
  - Near side peak around (0,0): **Jets**
  - Double side ridge structure: **Back to back jets + flow**



What is two-particle correlation used for?

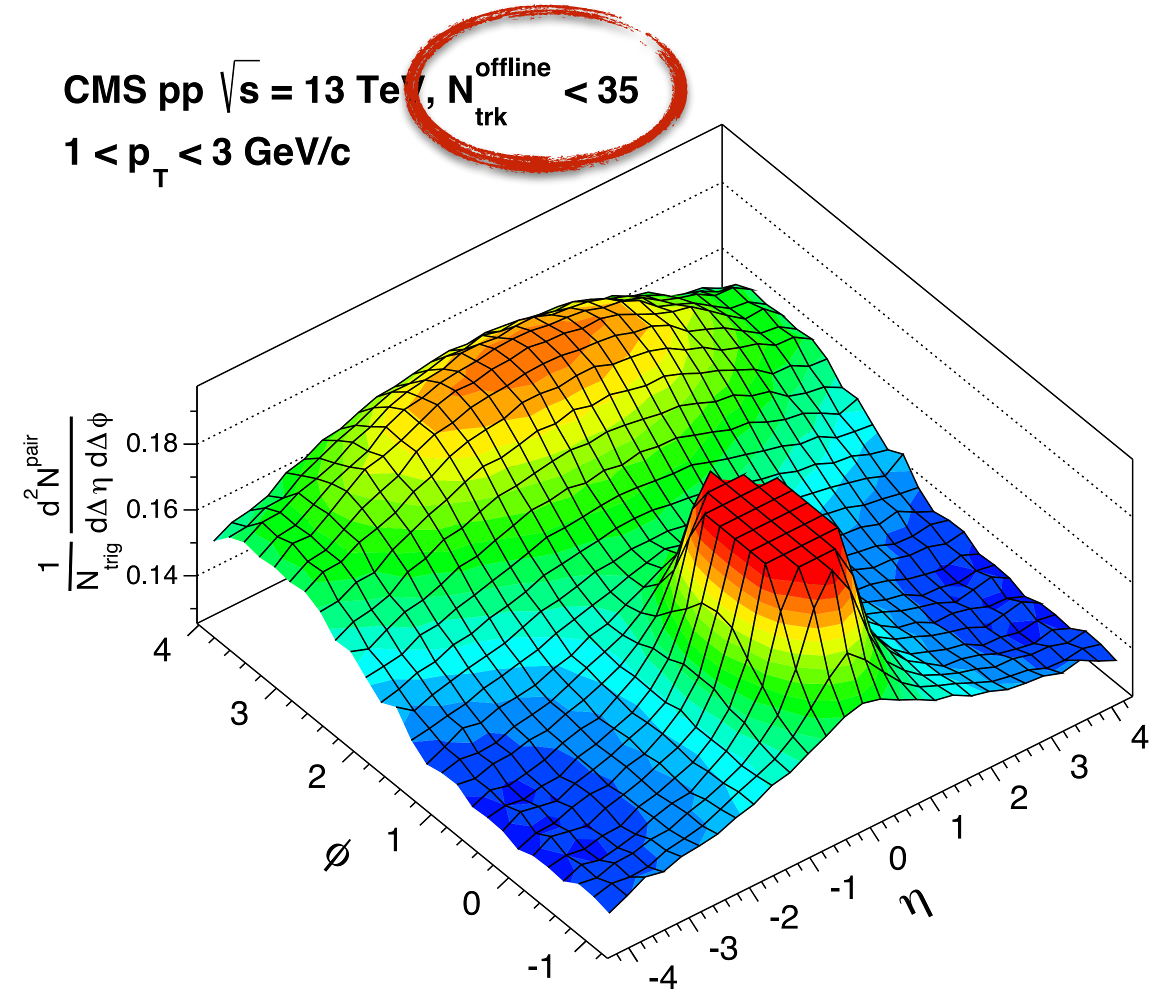
- Double ridge structure in ($\Delta\eta$, $\Delta\phi$)
- **Originally** used to probe **hydrodynamic** in heavy ion collision
  - Near side (around $\Delta\phi = 0$)
  - Away side (around $\Delta\phi = \pi$)
- 2D correlation function reflect two particle correlation origin;
  - Near side peak around (0,0): **Jets**
  - double side ridge structure: **Back to back jets + flow**
  - **Long range near side ridge structure?**



Reflect hydrodynamic properties of the medium. What about small system?

What is two-particle correlation used for?

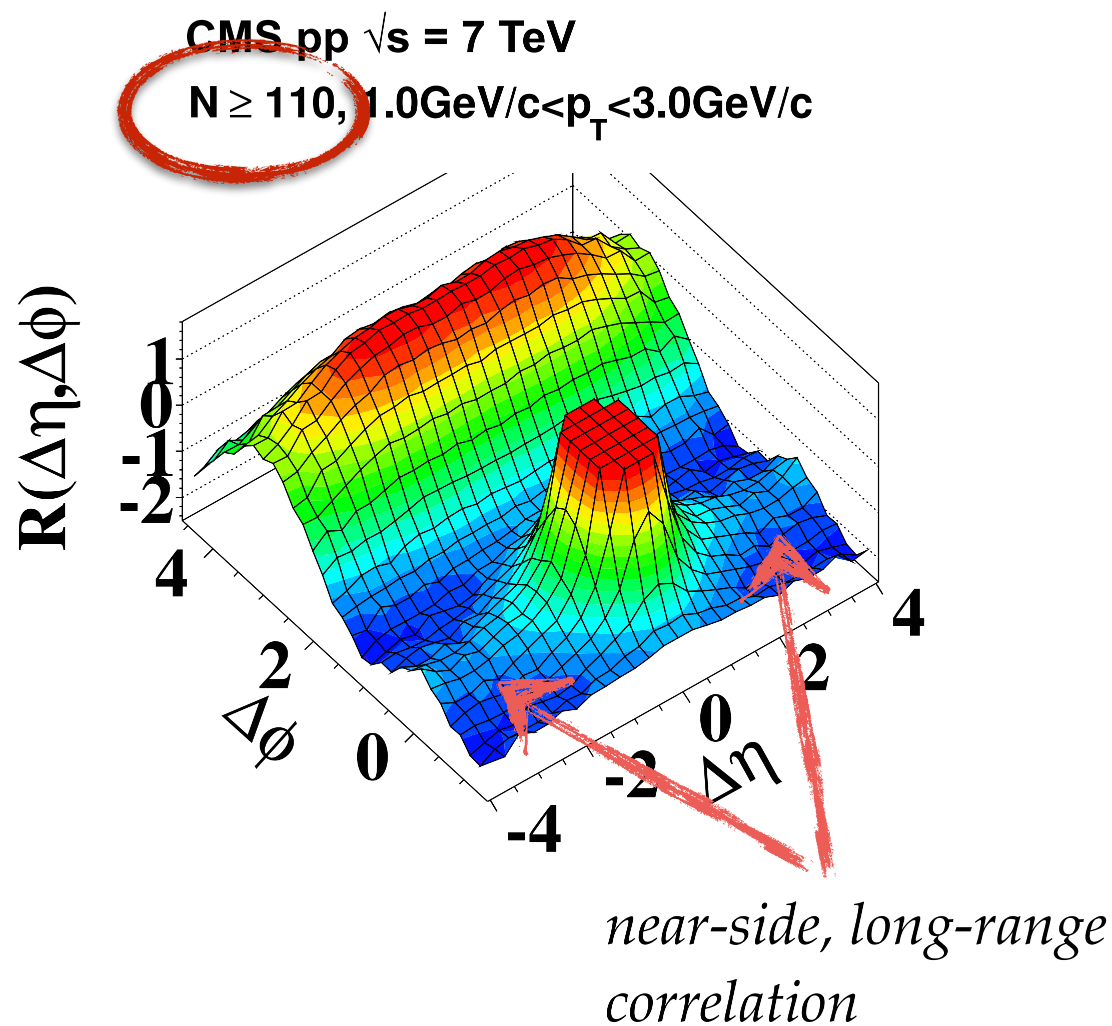
- Double ridge structure in ($\Delta\eta$, $\Delta\phi$)
- **Originally** used to probe **hydrodynamic** in heavy ion collision
  - Near side (around $\Delta\phi = 0$)
  - Away side (around $\Delta\phi = \pi$)
- 2D correlation function reflect two particle correlation origin;
  - Near side peak around (0,0): **Jets**
  - Away side ridge structure: **Back to back jets**
  - **No near-side long-range correlations in low multiplicity events**



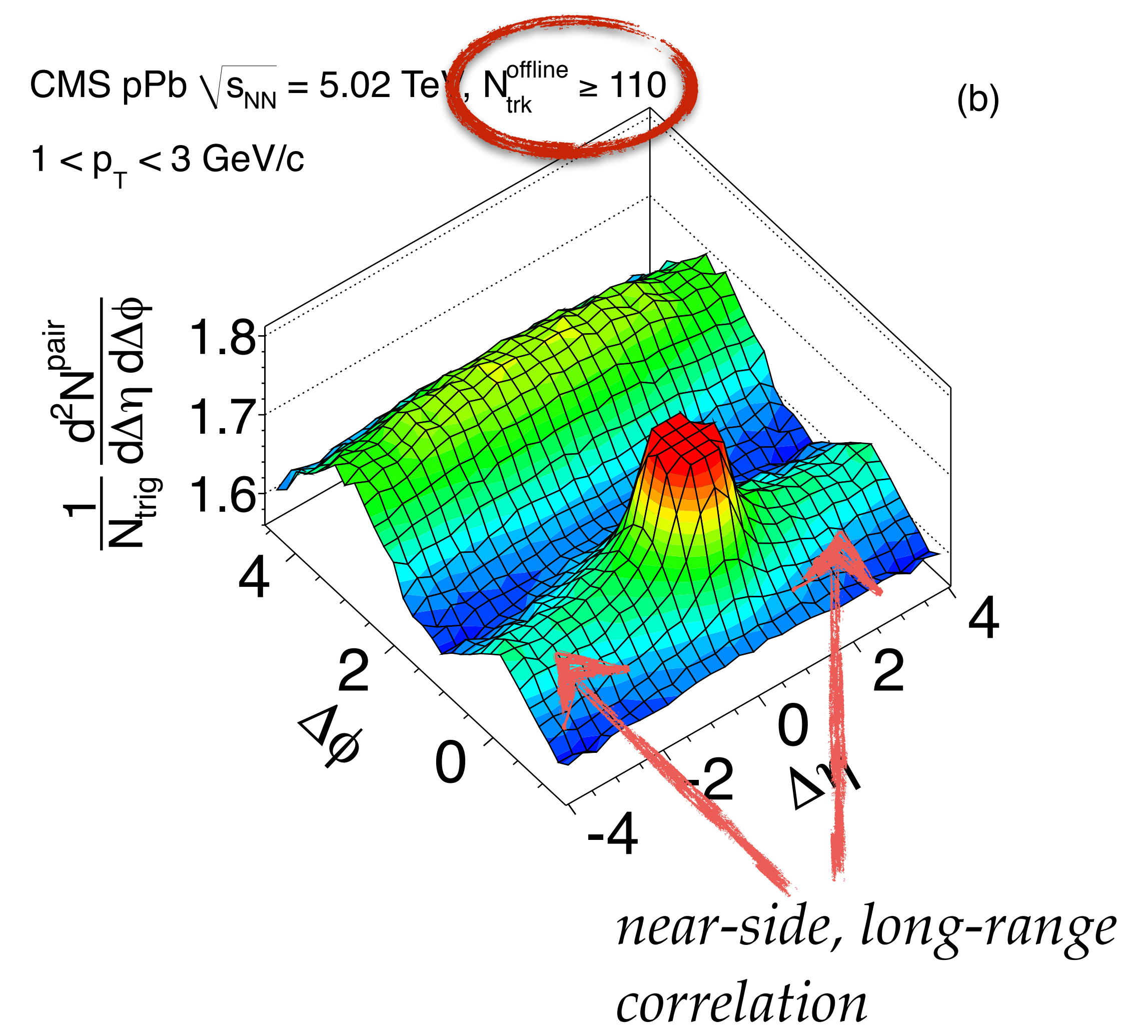
CMS Collaboration, JHEP 09 (2010) 091

Why is it interesting in smaller systems?

- Observation of near side long-range correlation in smaller system:
  - **Surprising!**
  - **CMS collaboration** was **the first** to discover it in small systems



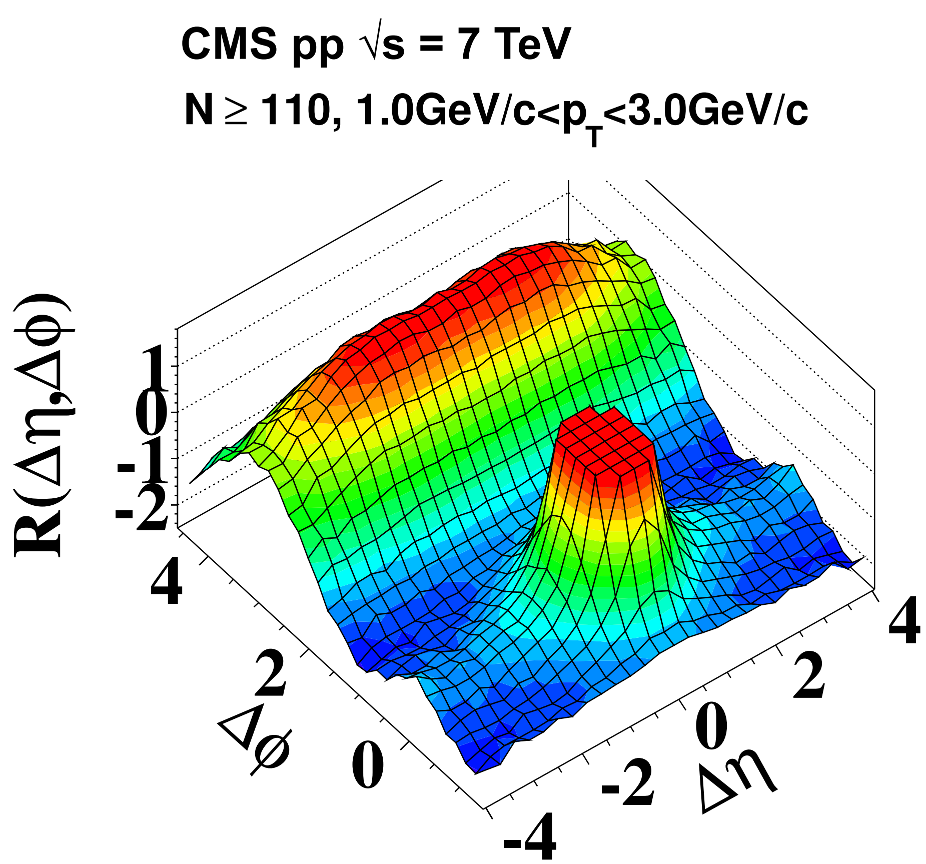
CMS Collaboration, JHEP 09 (2010) 091

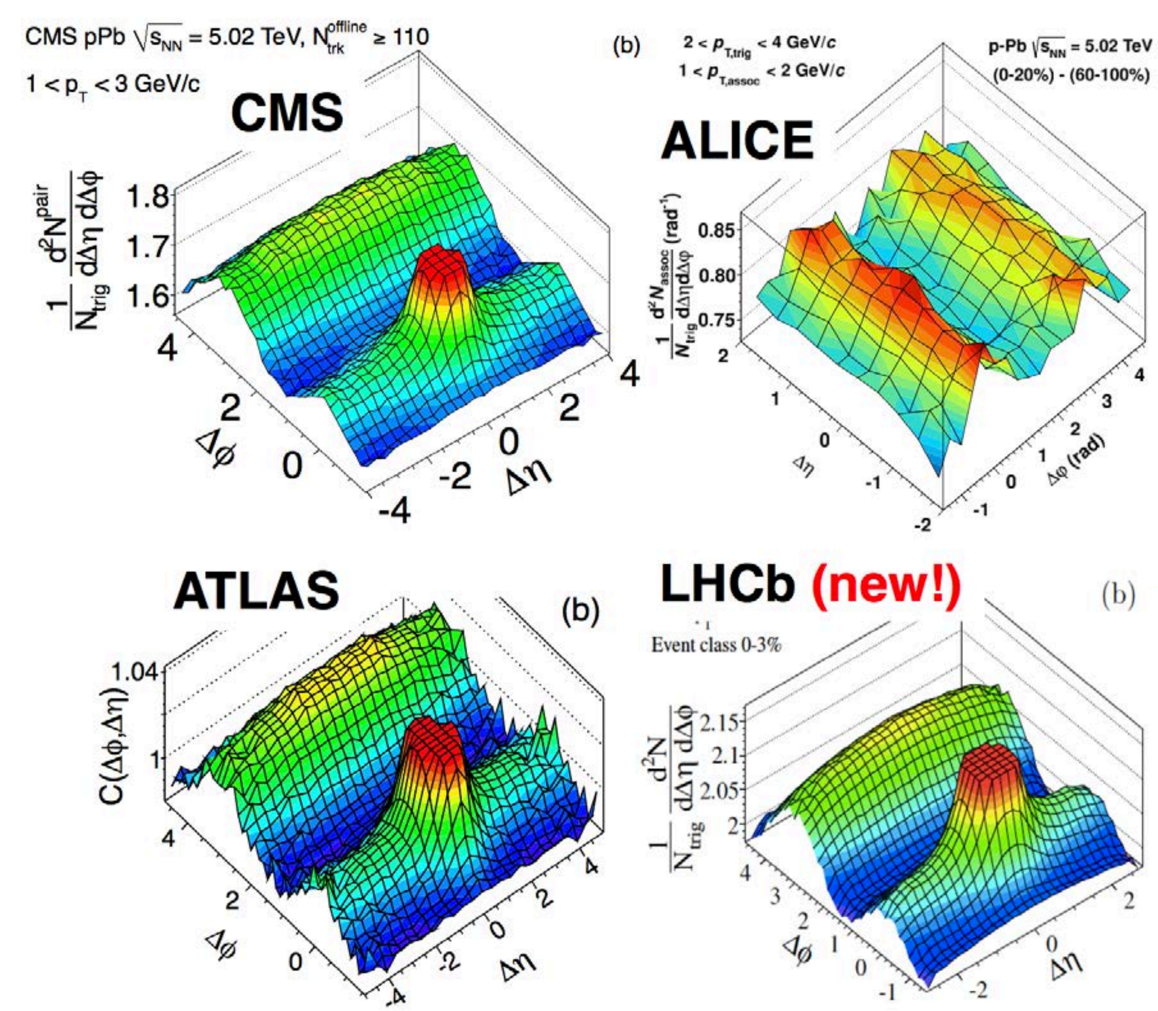


CMS Collaboration, PLB 718 (2013) 795-814

Why is it interesting in smaller systems?

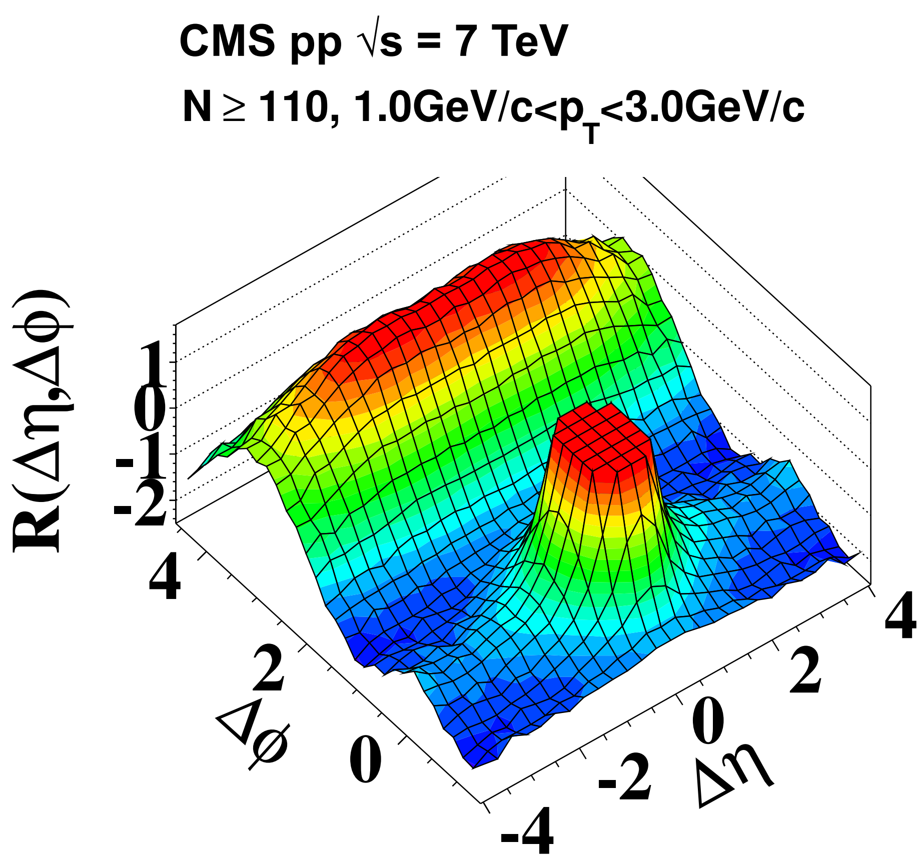
- Observation of near side long-range correlation in smaller system:
  - **Surprising!**
  - **CMS collaboration** was **the first** to discover it in small systems
  - **All LHC collaborations involved now!!!**



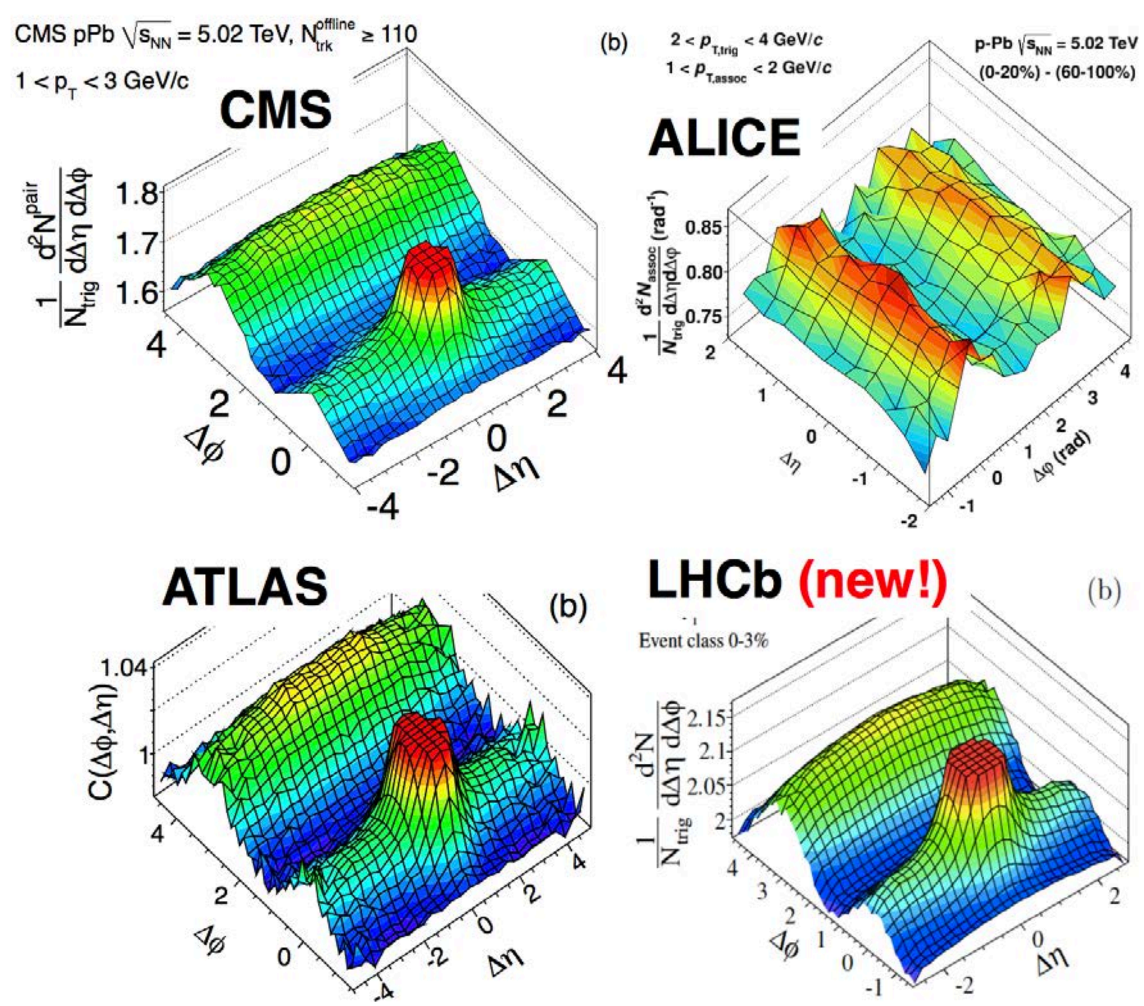


Where do these correlations come from?

- **p-p ridge origin:** remains unknown

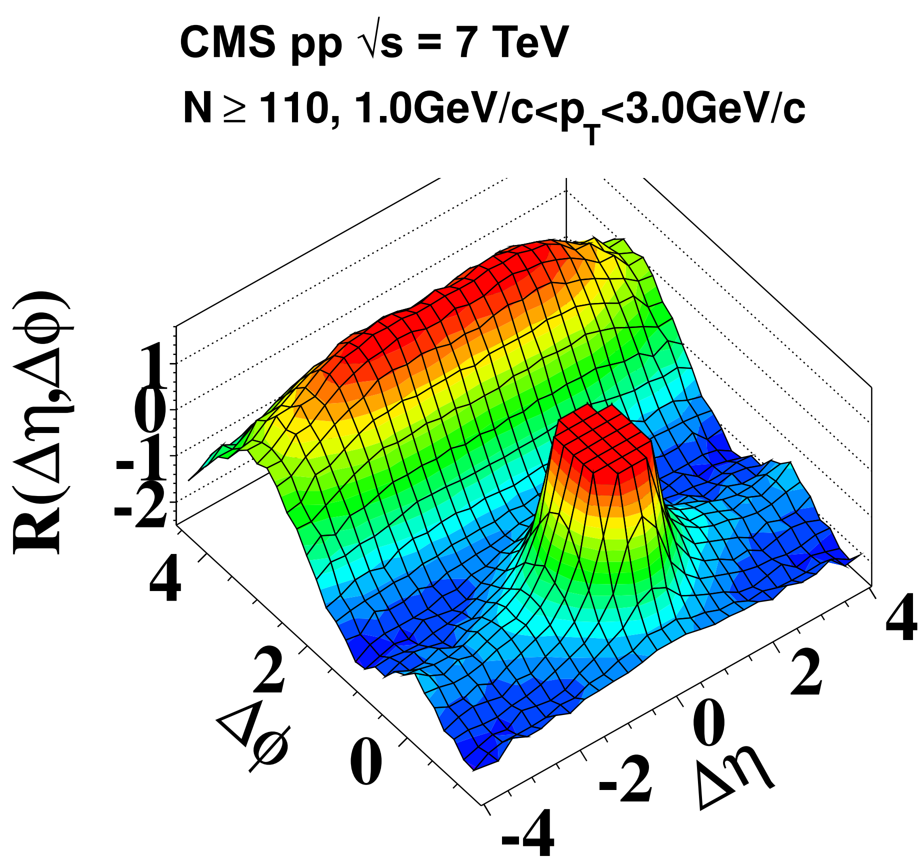


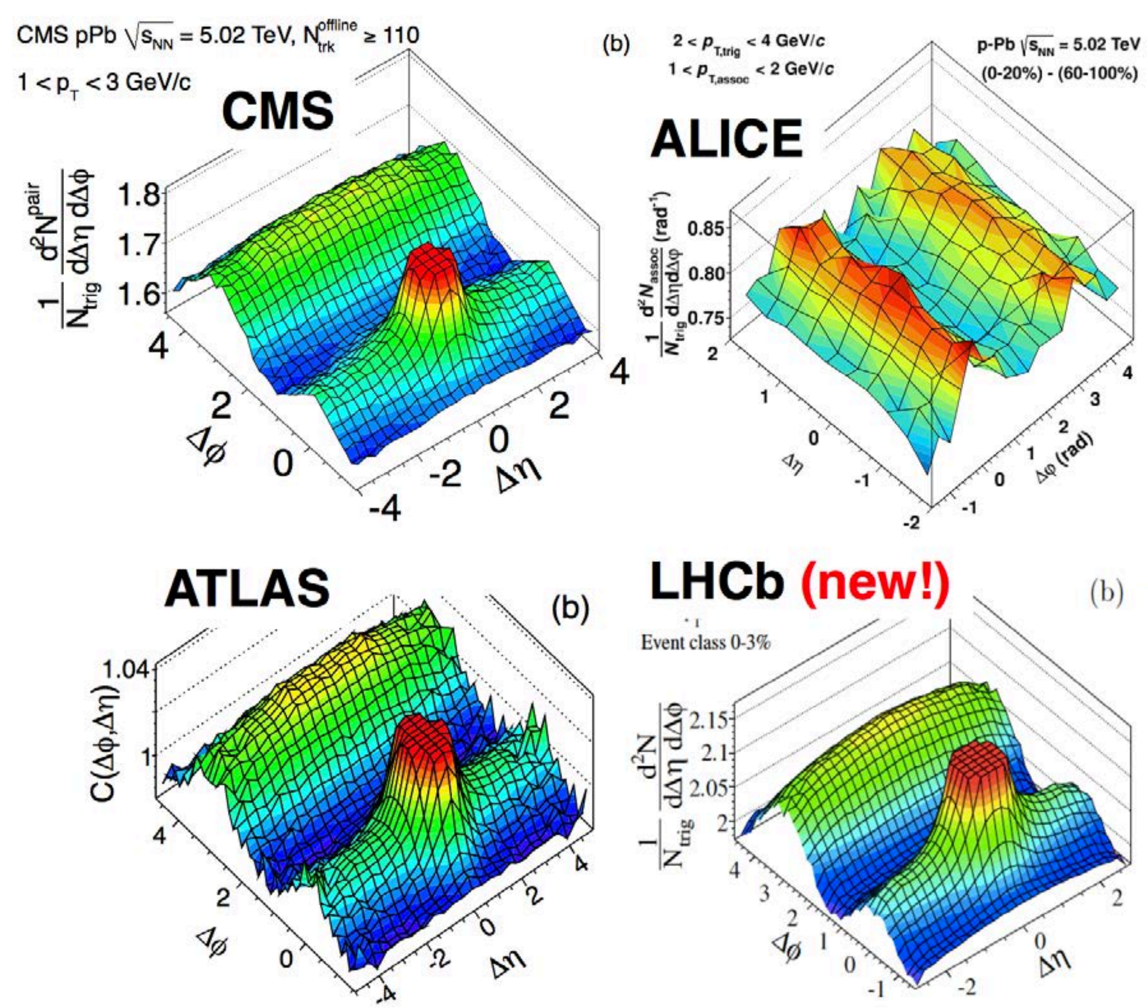
- **p-Pb ridge origin:** collectivity, hydrodynamics describe data well

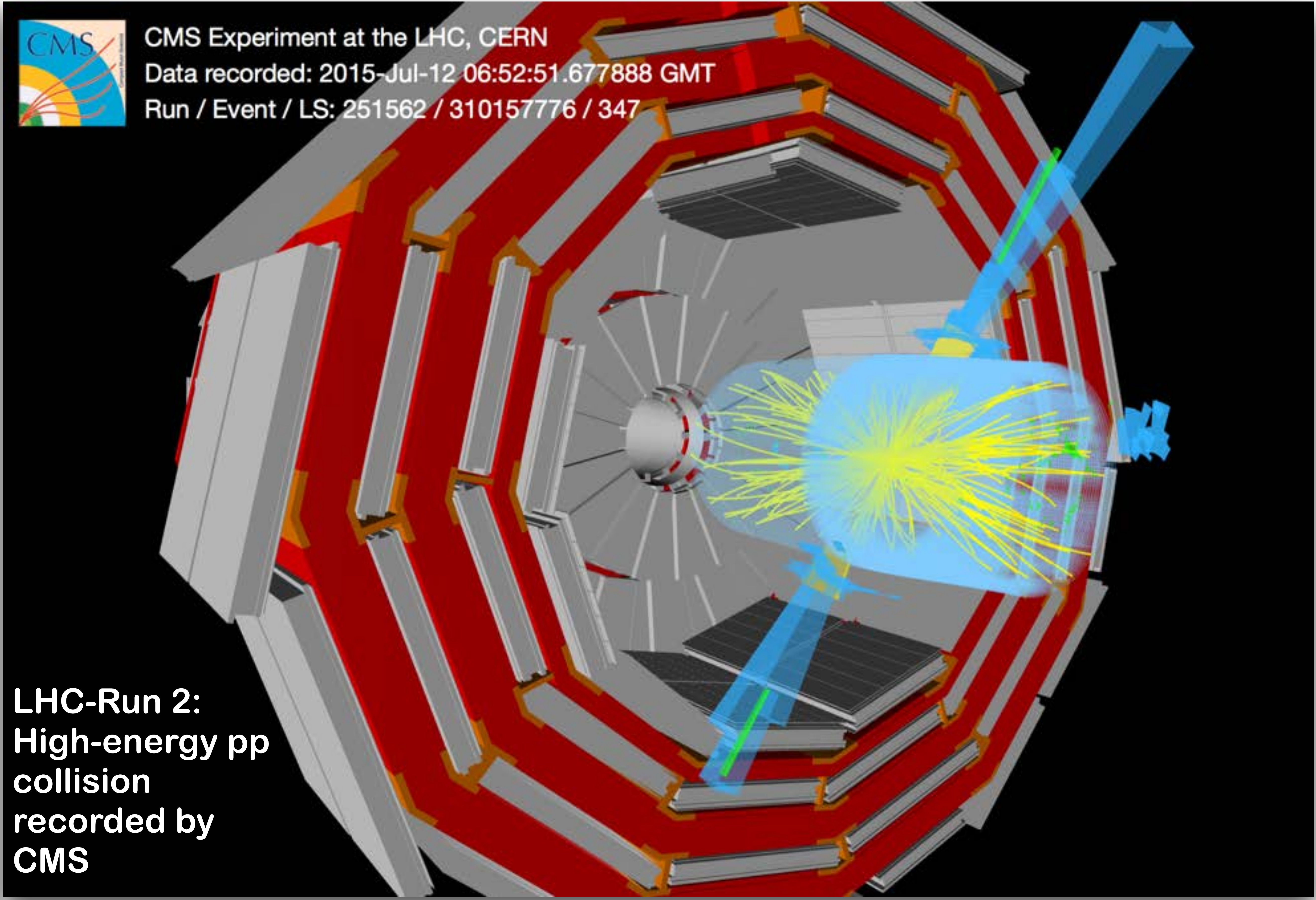


What do we want to learn (few questions only)?

- Does the ridge magnitude depends on √s?
  - Tighter constrains on models
- How the colliding system size affect such near-side long range correlations?







https://cms.web.cern.ch/news/cms-presents-first-results-13-tev-2015-eps-hep-conference

LHC Run 2 - data taking has successfully started!

Higher centre-of-mass energy: pp collisions at $\sqrt{s}$ = 13 TeV

Low pile-up runs (~1-2 collision/crossing) important for characterization of pp collisions at the new energy.

CMS-FSQ-15-002 ; CERN-PH-EP-2015-271

Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV

CMS Collaboration

11 October 2015

Submitted to Phys. Rev. Lett.

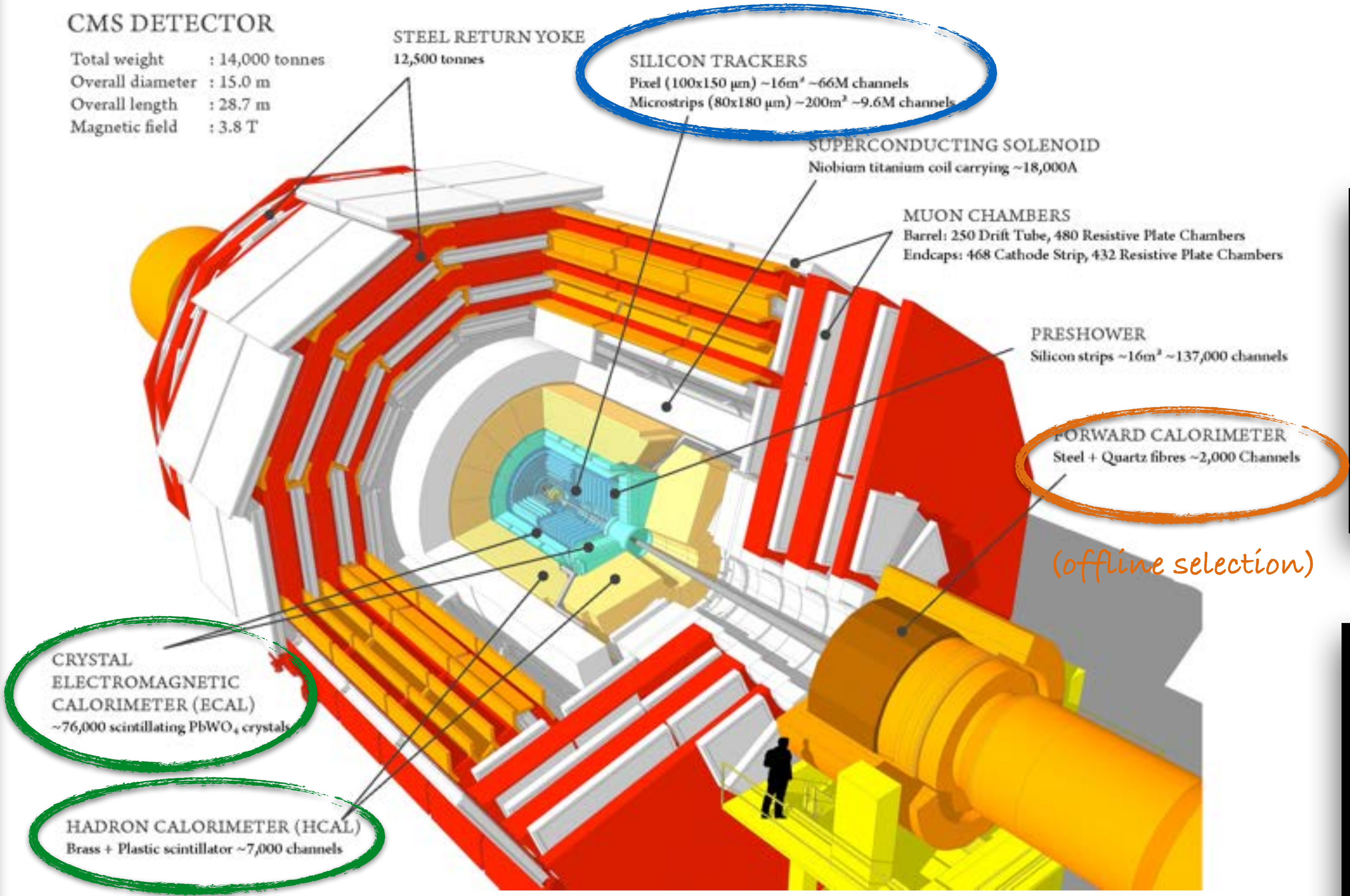
Abstract: Results on two-particle angular correlations for charged particles produced in pp collisions at a center-of-mass energy of 13 TeV are presented. The data were taken with the CMS detector at the LHC and correspond to an integrated luminosity of about 270 inverse-nanobarns. The correlations are studied over a broad range of pseudorapidity ($|\eta| < 2.4$) and over the full azimuth (ϕ) as a function of charged particle multiplicity and transverse momentum (p_T). In high-multiplicity events, a long-range ($|\Delta\eta| > 2.0$), near-side ($\Delta\phi \approx 0$) structure emerges in the two-particle $\Delta\eta$-$\Delta\phi$ correlation functions. The magnitude of the correlation exhibits a pronounced maximum in the range $1.0 < p_T < 2.0$ GeV/c and an approximately linear increase with the charged particle multiplicity. The overall correlation strength at $\sqrt{s} = 13$TeV is similar to that found in earlier pp data at $\sqrt{s} =$ 7 TeV, but is measured up to much higher multiplicity values. The observed long-range correlations are compared to those seen in pp, pPb, and PbPb collisions at lower collision energies.

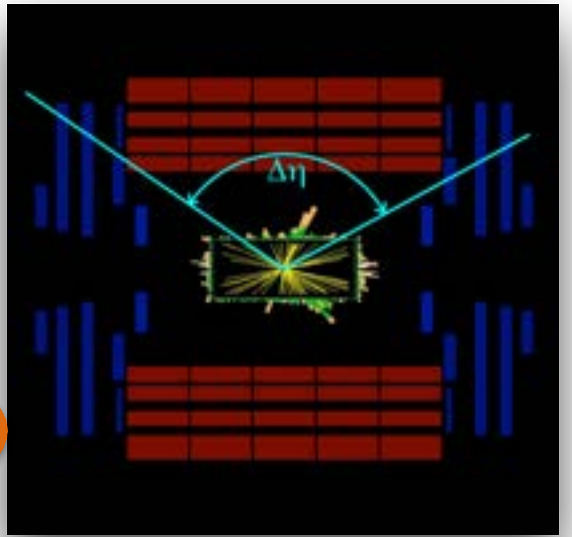
Links: e-print arXiv:1510.03068 [hep-ex] (PDF) ; CDS record ; inSPIRE record ; CADI line (restricted) ;

http://cms-results.web.cern.ch/cms-results/public-results/publications/FSQ-15-002/index.html

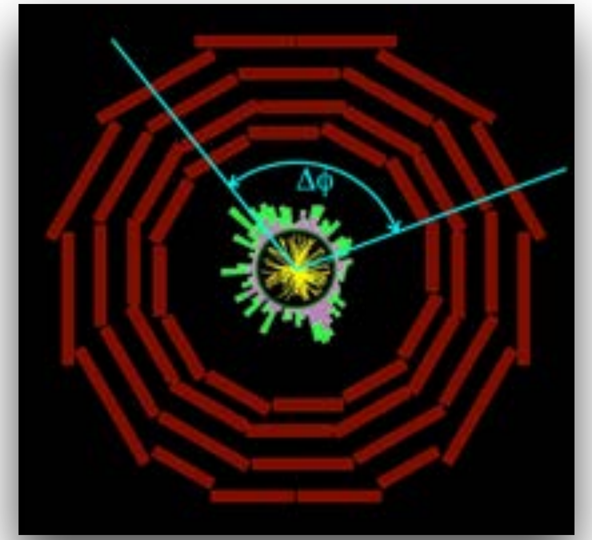
(submitted to PRL)

The Compact Muon Solenoid detector





(offline selection)



(online selection)

Data: proton-proton collisions at $\sqrt{s}$ = 13 TeV

Compact Muon Solenoid experiment at CERN's LHC

- Integrated luminosity: **270 nb^{-1}**
- Pile-up conditions: **1.3** (average number of collisions per bunch crossing)
- Data collected with full solenoid magnetic field (B = 3.8T)
- Extension of the 7 TeV results to **higher energy and higher multiplicity.**
- Trigger (online): $E_{CAL} > 15$ or 40 GeV (L1 trigger)

  pixel tracking $N_{trk} > 60, 85, 110$ with $|\eta|>2.4$, $p_T > 0.4$ GeV/c
- Trigger (offline): at least one tower in each of the two HF calorimeters ($3 < |\eta| < 5$) with more than 3 GeV (suppress diffraction)
- Pile-up rejection: vertices cannot be too close above some multiplicity
- Tracks are weighted by 1/efficiency

Multiplicity class ($N_{trk}^{offline}$)	Fraction	$\langle N_{trk}^{offline} \rangle$	$\langle N_{trk}^{corrected} \rangle$
Minimum bias	1.0	20	23 ± 1
[2, 34]	0.82	13	16 ± 1
[35, 79]	0.15	47	58 ± 2
[80, 104]	0.02	88	107 ± 4
[105, 134]	3.3×10^{-4}	113	131 ± 5
≥ 135	1.4×10^{-5}	145	168 ± 7

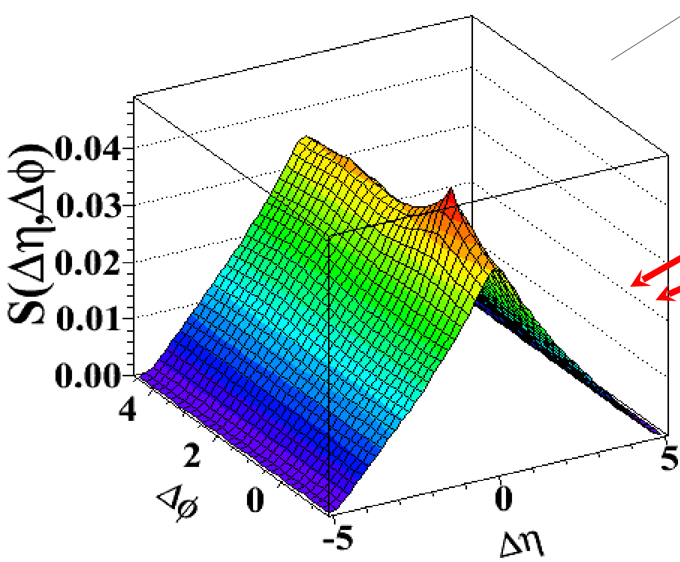
arXiv:1510.03068 [nucl-ex]

Constructing the correlation function

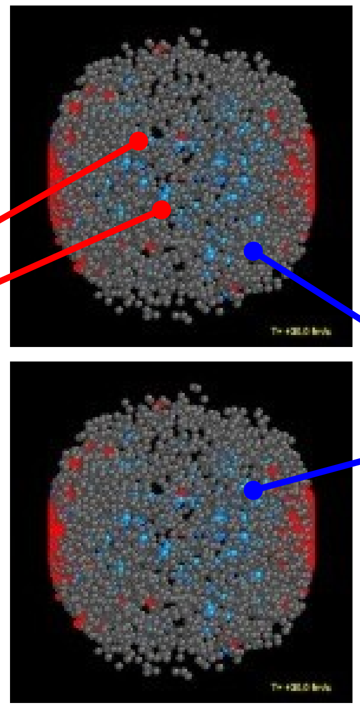
- Trigger particle: a hadron in a certain p_T bin
- Same and mixed event pair distributions

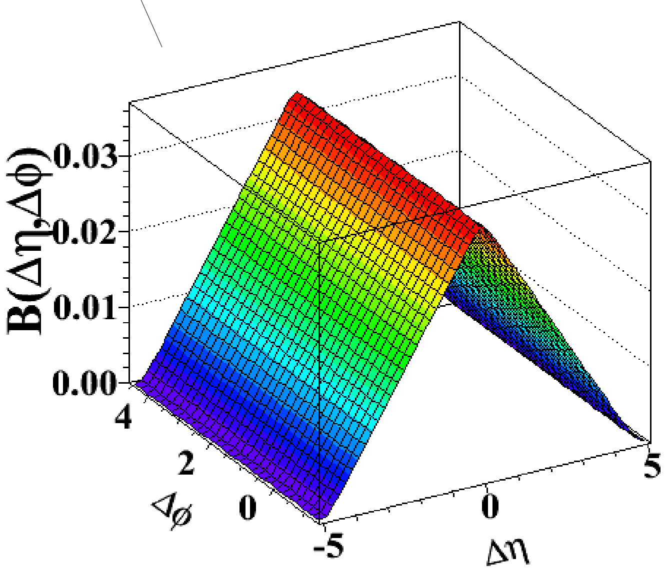
$$S(\Delta\eta, \Delta\phi) = \frac{1}{N_{\mathrm{trig}}} \frac{d^2 N^{\mathrm{same}}}{d\Delta\eta d\Delta\phi}$$

$$B(\Delta\eta, \Delta\phi) = \frac{1}{N_{\mathrm{trig}}} \frac{d^2 N^{\mathrm{mix}}}{d\Delta\eta d\Delta\phi}$$



Same event

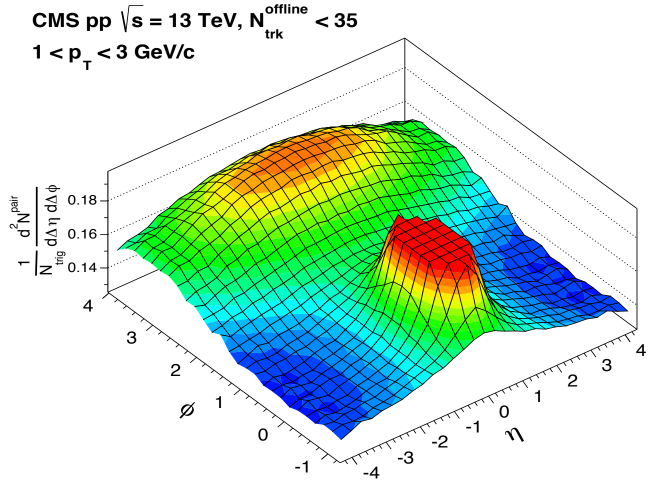




Mixed event

Constructing the correlation function

- Trigger particle: a hadron in a certain p_T bin
- Same and mixed event pair distributions
- 2D associated yield per trigger



$$\frac{1}{N_{\rm trig}}\frac{d^2N^{\rm pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\times\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$

Pair acceptance correction factor

- Fourier coefficients $V_{n\Delta}$ for $|\eta|>2$

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

Systematic uncertainties

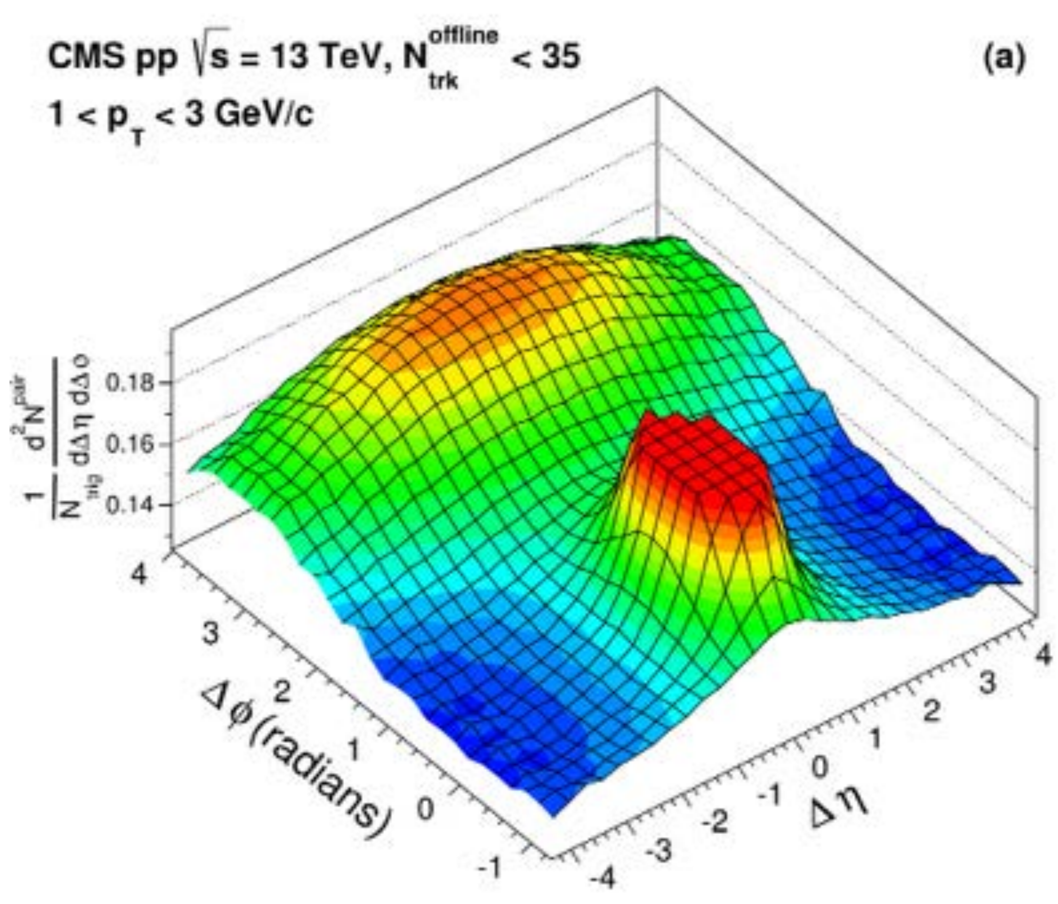
- Results are **insensitive** to tracking efficiency (ratios)
- Requiring 1 vertex and no pile-up rejection has only a small effect
- Different trigger combinations were tested
- Various fit functions to determine the ZYAM factor*

Systematic uncertainty sources	Abs. uncertainty ($\times 10^{-3}$)
Track quality requirements	0.6
Trigger efficiency	1.5
Correction for tracking efficiency	<0.08
Effect of pile-up events	0.6
Vertex selection	1.0
ZYAM procedure	0.7
Total	2.1

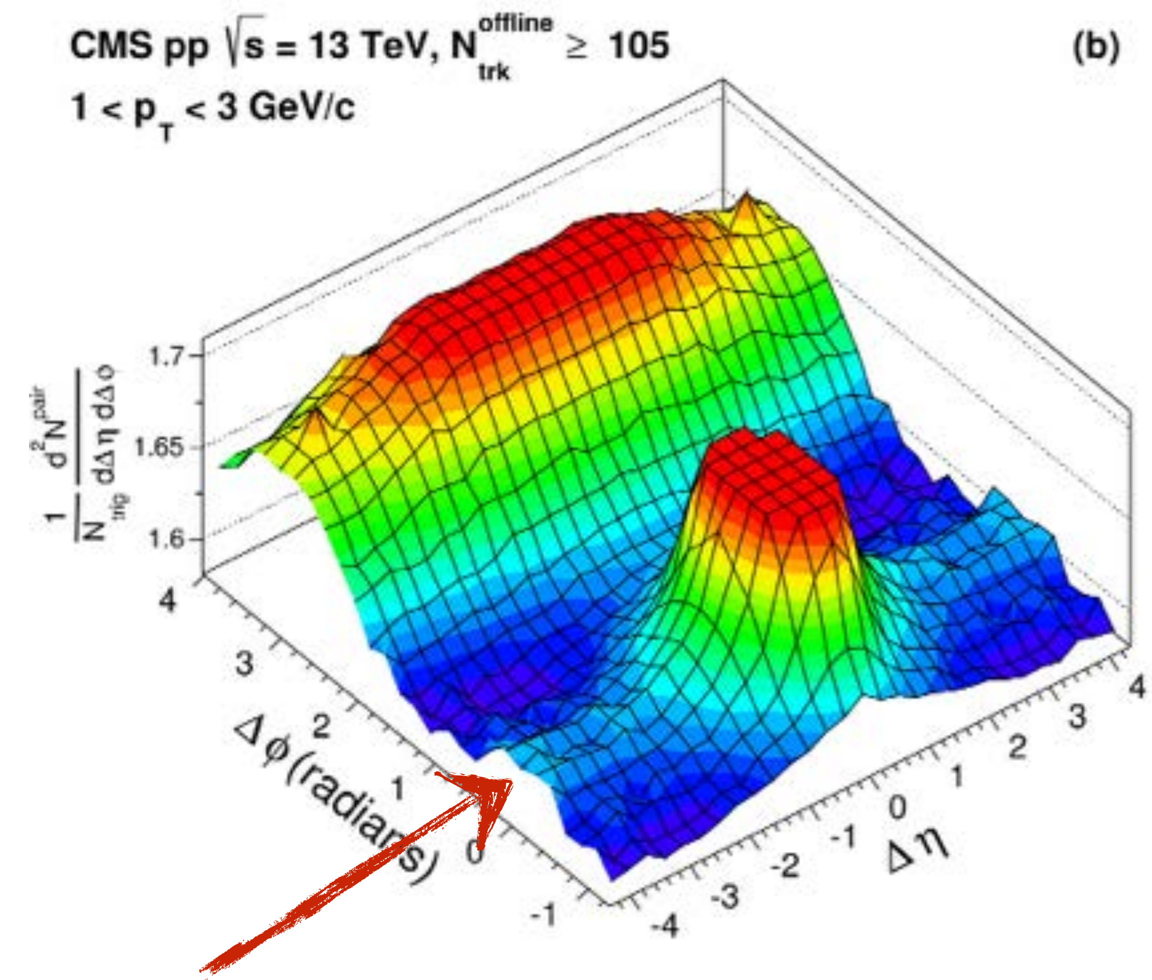
* **ZYAM**: **Z**ero **Y**ield **A**t **M**inimum (constant subtracted)

Two-particle correlations in pp at √s=13 TeV

Compact Muon Solenoid experiment at CERN's LHC



Low multiplicity

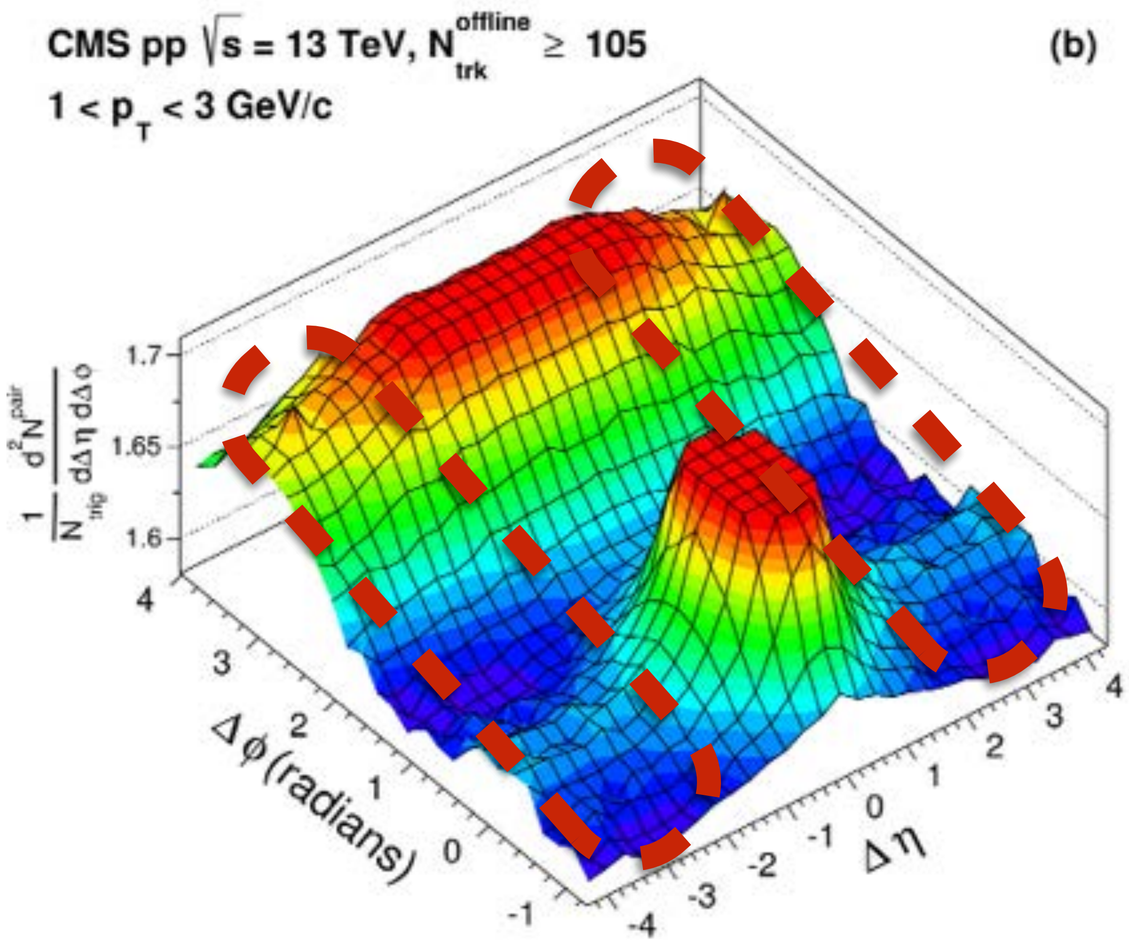


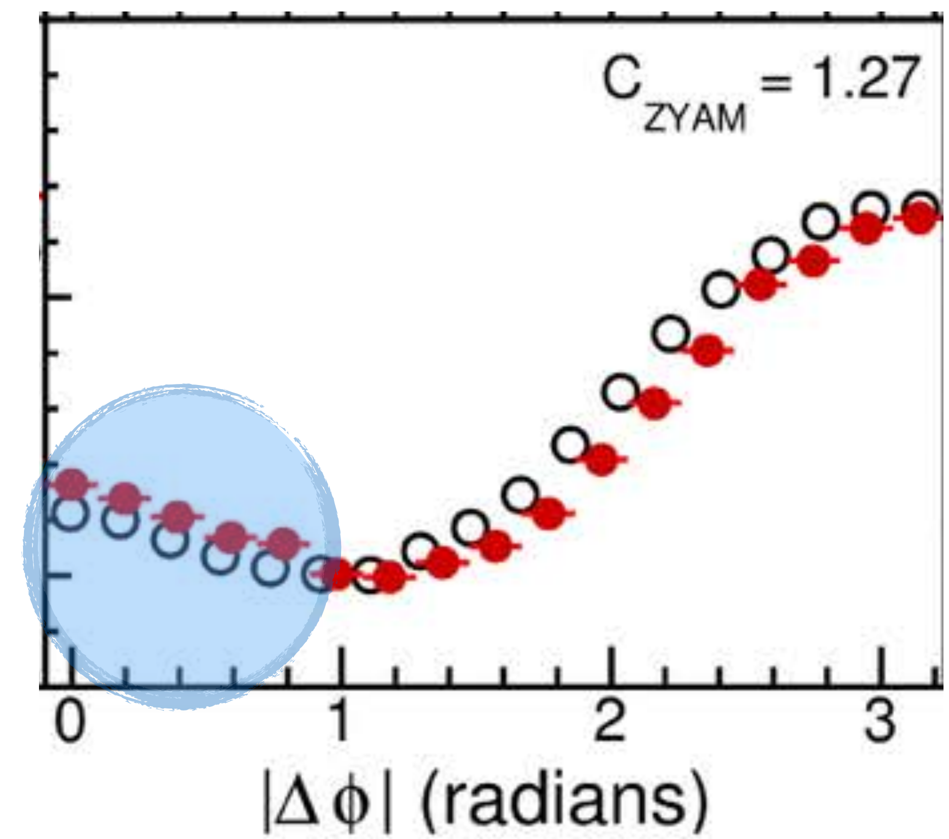
High multiplicity

Features:

- jet peak (truncated)
- away-side back-to-back jet correlation
- near-side, long-range “ridge”

Projection to 1D

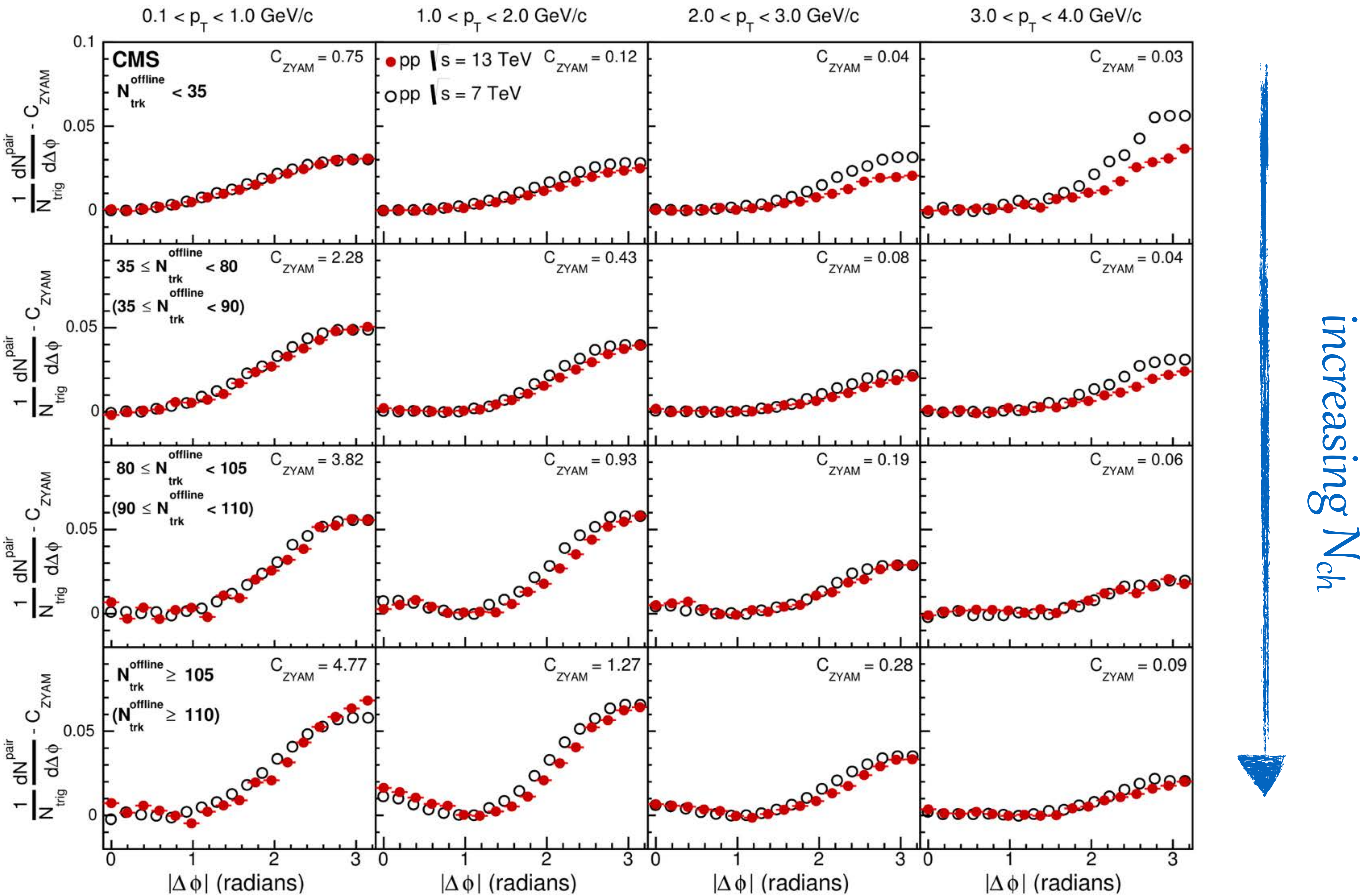




ZYAM: **Z**ero **Y**ield **A**t **M**inimum (constant subtracted)

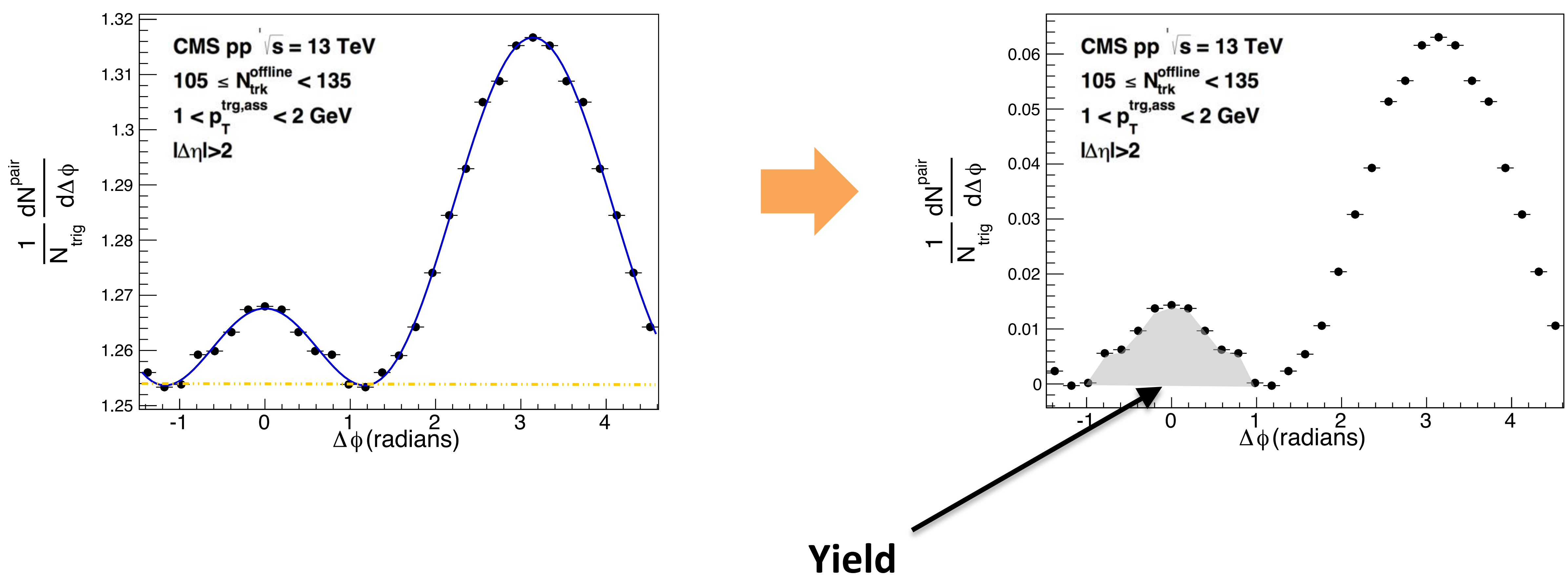
Allows comparisons to lower energy data and p+Pb and Pb+Pb

Near-side long range correlated yield increases with multiplicity.

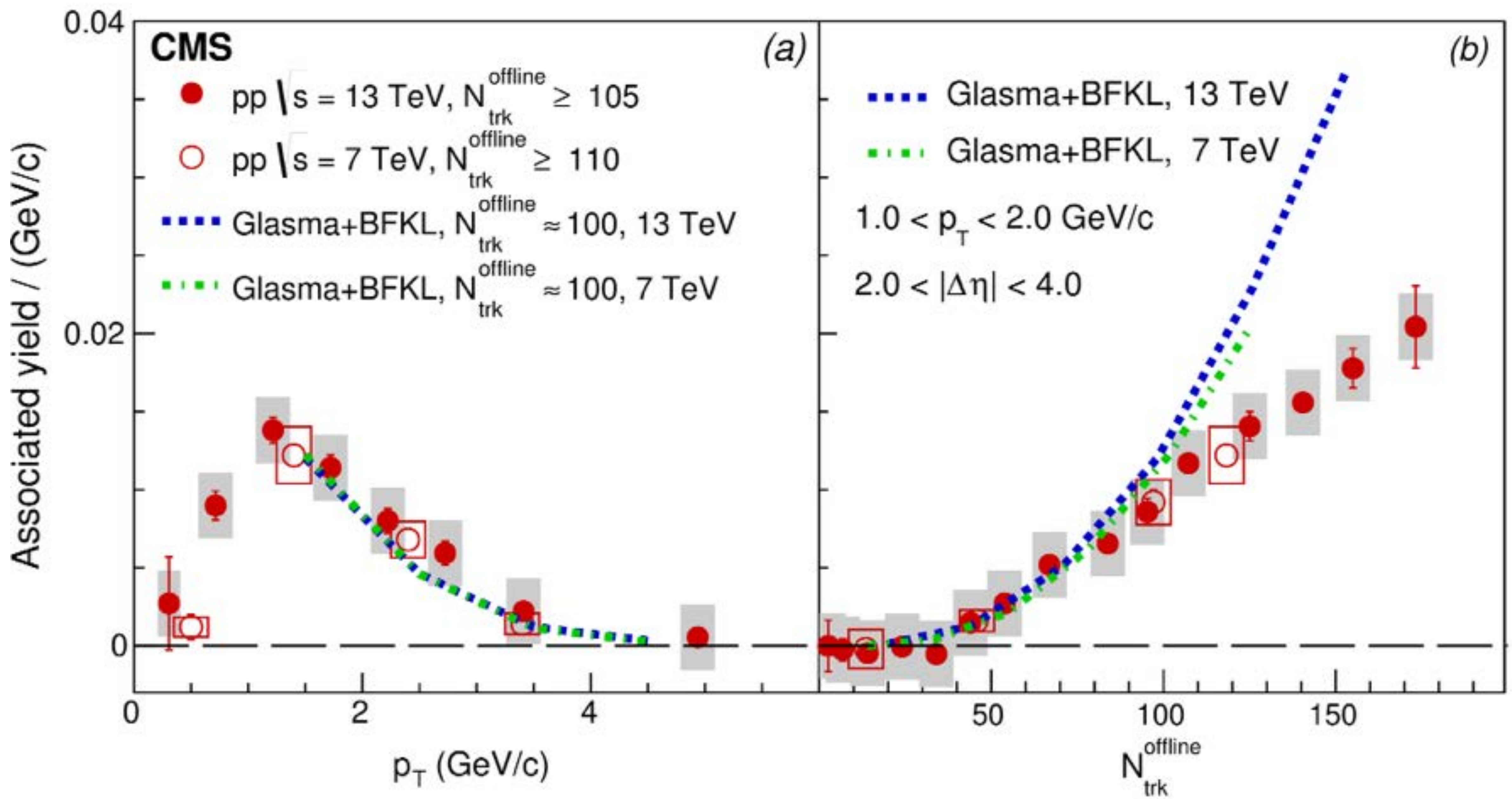


Calculating the yield

- **Fourier fit**
- **Background level** determined by ZYAM procedure and to be subtracted



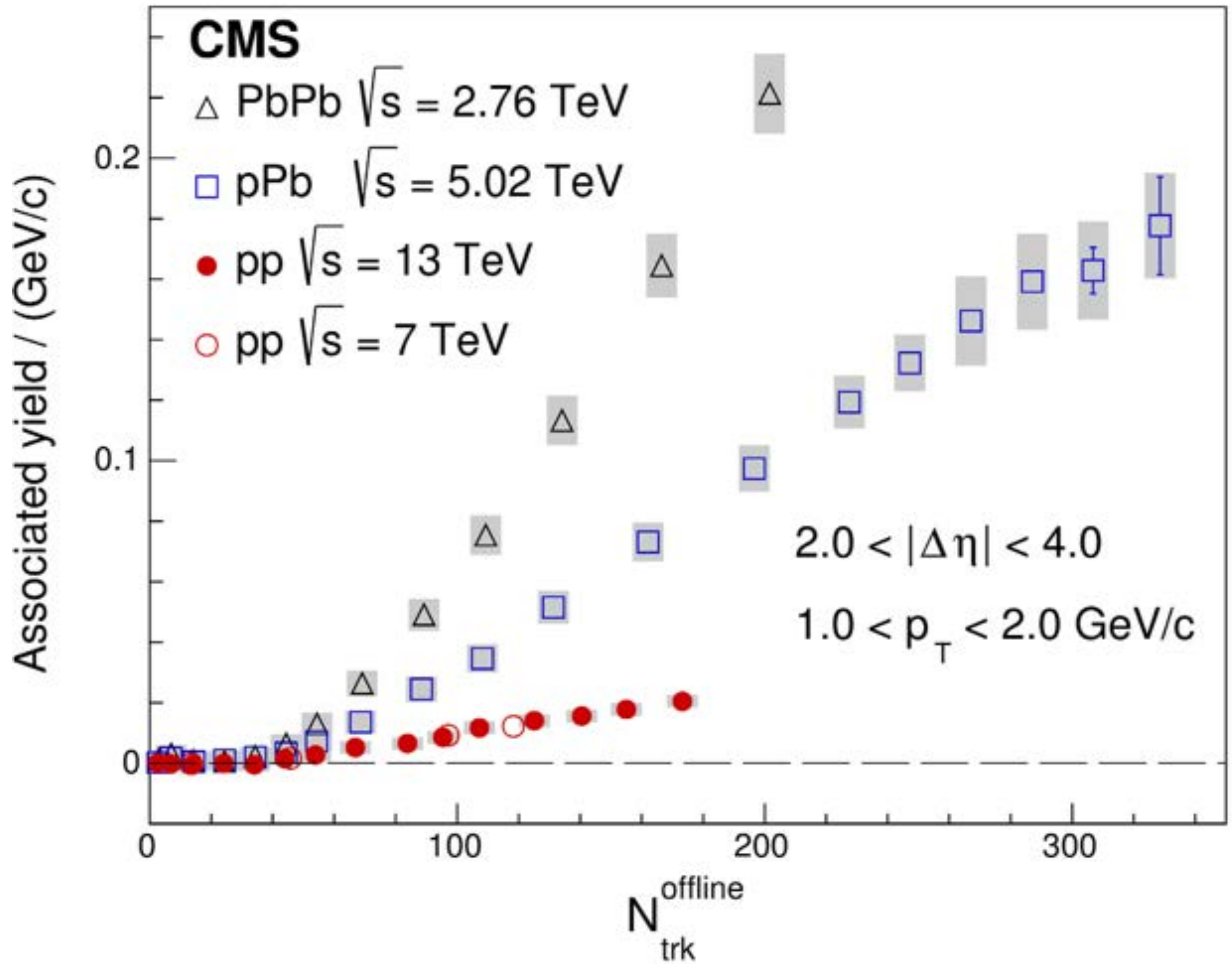
Very similar to what we observed at 7 TeV



Low-multiplicity: Ridge-like correlations are absent.

High-multiplicity: Ridge-like correlations emerge with an approximately linear rise.

Comparison with different systems



Ridge yield starts to increase linearly for the three systems from N_{trk} ~ 40 (approximately)

Strong system-size dependence of the Associated Yield slope increase

Summary:

- Two-particle angular correlations in pp collisions at $\sqrt{s} = 13$ TeV have been measured by the CMS experiment at the LHC.

  arXiv:1510.03068 (submitted to PRL)

- Two-particle azimuthal correlations in high-multiplicity pp collisions *exhibit a long-range structure in the near side* ($\Delta\varphi \approx 0$) extending over at least 4 units in η.
  - The effect is most evident in the intermediate transverse momentum region between 1 and 2 GeV/c.

- The near-side long-range yield obtained with the ZYAM procedure is found to be consistent with zero in the low-multiplicity region, with an approximately linear increase with multiplicity for $N_{\text{offline trk}} \geq 40$.

- A strong collision system size dependence is observed when comparing data from pp, pPb, and PbPb collisions.

- No collision energy dependence of the near-side associated yields is observed over the overlapping event multiplicity and pT ranges.

Compact Muon Solenoid experiment at CERN's LHC

News

LHC EXPERIMENTS

CMS observes long-range correlations in pp collisions at 13 TeV

The CMS collaboration has published its first particle-correlation result from proton–proton (pp) collisions at a centre-of-mass energy of 13 TeV. The paper describes the observation of a phenomenon first seen in nucleus–nucleus collisions, and also detected by CMS in 2010 in the initial LHC pp collision run, at a centre-of-mass energy of 7 TeV. CMS later also observed the phenomenon in proton–lead (pPb) collisions at a centre-of-mass energy of 5 TeV per nucleon pair. The phenomenon is an unexpected correlation between pairs of particles appearing in so-called high-multiplicity collisions, which are collisions that produce a large number of particles, i.e. approximately more than 100 charged particles with transverse momentum $p_T > 0.4$ GeV/c within the pseudorapidity region $|\eta| < 2.4$. The correlation manifests itself as a ridge-like structure in a 2D angular correlation function.

Following the CMS observation at 7 TeV, interest was expressed concerning the dependence of this phenomenon on the centre-of-mass energy. To more readily address this question, CMS collected a special 13 TeV data set, with an integrated luminosity of 270 nb^{-1}. Here, the average number of simultaneous collisions in a beam bunch crossing was as low as about 1.3, presenting conditions similar to those used for the 7 TeV analysis. Because the effect is expected to appear only in high-multiplicity events, a special trigger was developed based on the number of charged particles detected in the silicon tracker system.

Indeed, about once in every 3000 pp collisions with the highest produced particle multiplicity at 13 TeV, CMS observes an enhancement of particle pairs with small relative azimuthal angle $\Delta\phi$ (figure 1). It therefore appears that charged particles have a slight preference to be emitted pointing in nearly the same azimuthal direction, even if they are very far apart in terms of polar angle, which is measured by the quantity η.

Such correlations are reminiscent of effects first seen in nucleus–nucleus collisions at Brookhaven's RHIC and later in collisions of lead–lead nuclei (PbPb) at the LHC. Nucleus–nucleus collisions produce a hot, dense medium similar to the quark–gluon plasma thought to have existed in the first microseconds after the Big Bang. The long-range correlations in PbPb collisions are interpreted to result from a hydrodynamic expansion of this medium. Such a medium was not expected in the simpler pp system, and therefore the CMS results from 2010 led to a variety of theoretical models aiming for an explanation.

Remarkably, the new 13 TeV results demonstrate that, within the experimental uncertainties, the strength of the correlation (expressed in terms of associated particle yield) does not depend on the centre-of-mass energy of the pp collision but only on the particle multiplicity. This lack of energy dependence is similar to what is observed for hydrodynamic-flow coefficients measured in nucleus–nucleus collisions at RHIC and the LHC. Compared with the pp results, pPb and PbPb collisions produce correlations that are four and 10 times stronger, respectively, but which are qualitatively very similar to the pp results. The new results from pp collisions extend the measurements to much higher multiplicities compared with those at 7 TeV, and provide the opportunity to understand this curious phenomenon better.

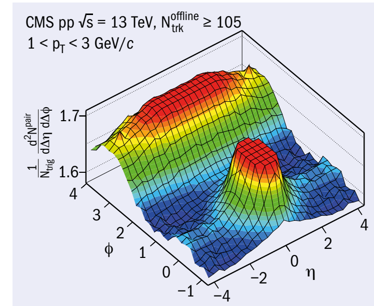


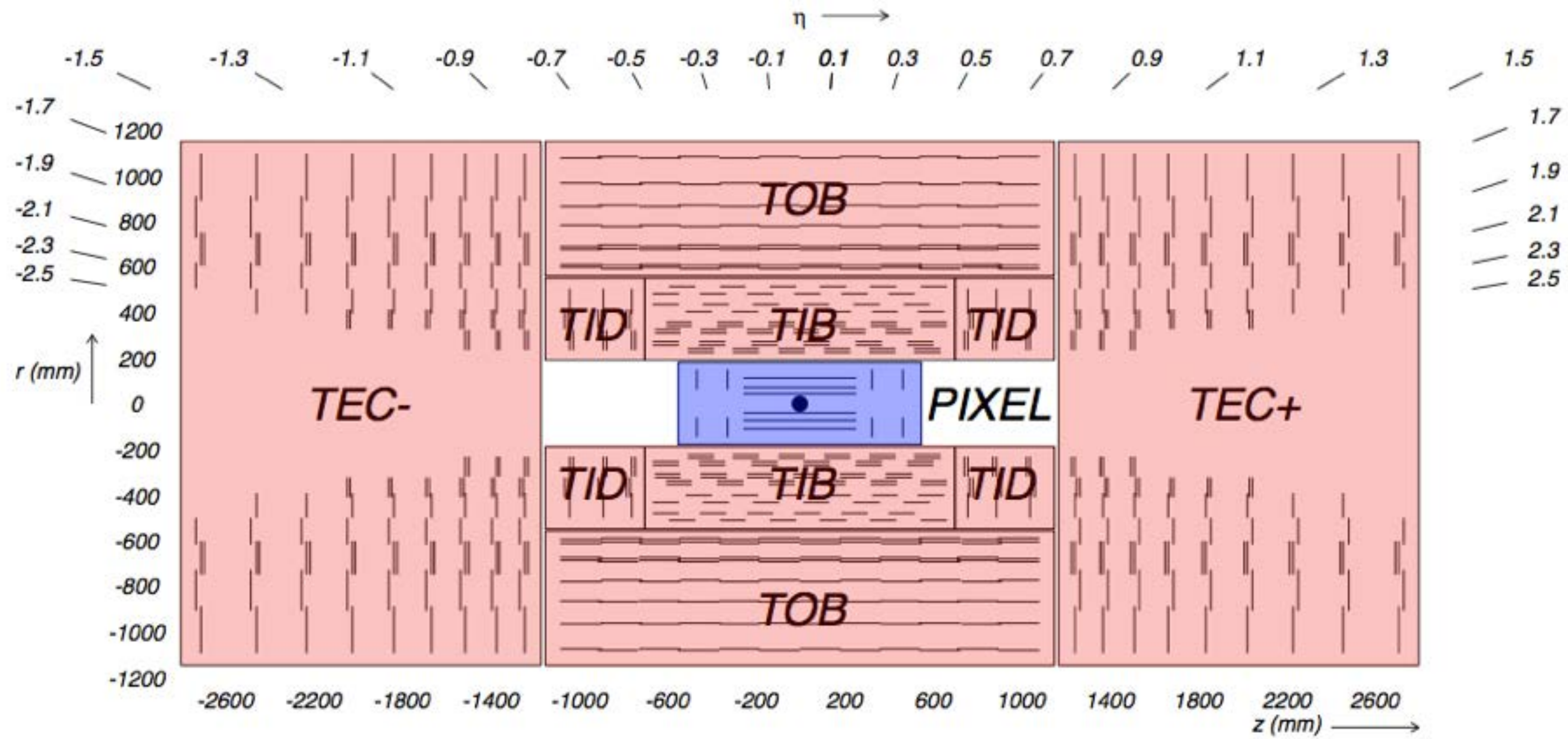
Fig. 1. 2D two-particle correlation function in pp collisions at $\sqrt{s} = 13$ TeV for pairs of charged particles, with each particle in the transverse-momentum range $1 < p_T < 3$ GeV/c. Results are shown for a high-multiplicity sample. The sharp peak from jet correlations around $(\Delta\eta, \Delta\phi) = (0, 0)$ is truncated to better exhibit the long-range correlation at $\Delta\phi \approx 0$.

- **Further reading**
cds.cern.ch/record/2056346

Extras...

CMS tracker:

Compact Muon Solenoid experiment at CERN's LHC



Disposition of the different detectors in the silicon tracker. PIXEL (blue) refers to silicon pixel detectors while TIB, TID, TOB and TEC (red) all refer to silicon strip detectors

Photo of silicon strip detectors in the barrel region.

Event display: high-multiplicity collision recorded in pp at $\sqrt{s} = 7$ TeV

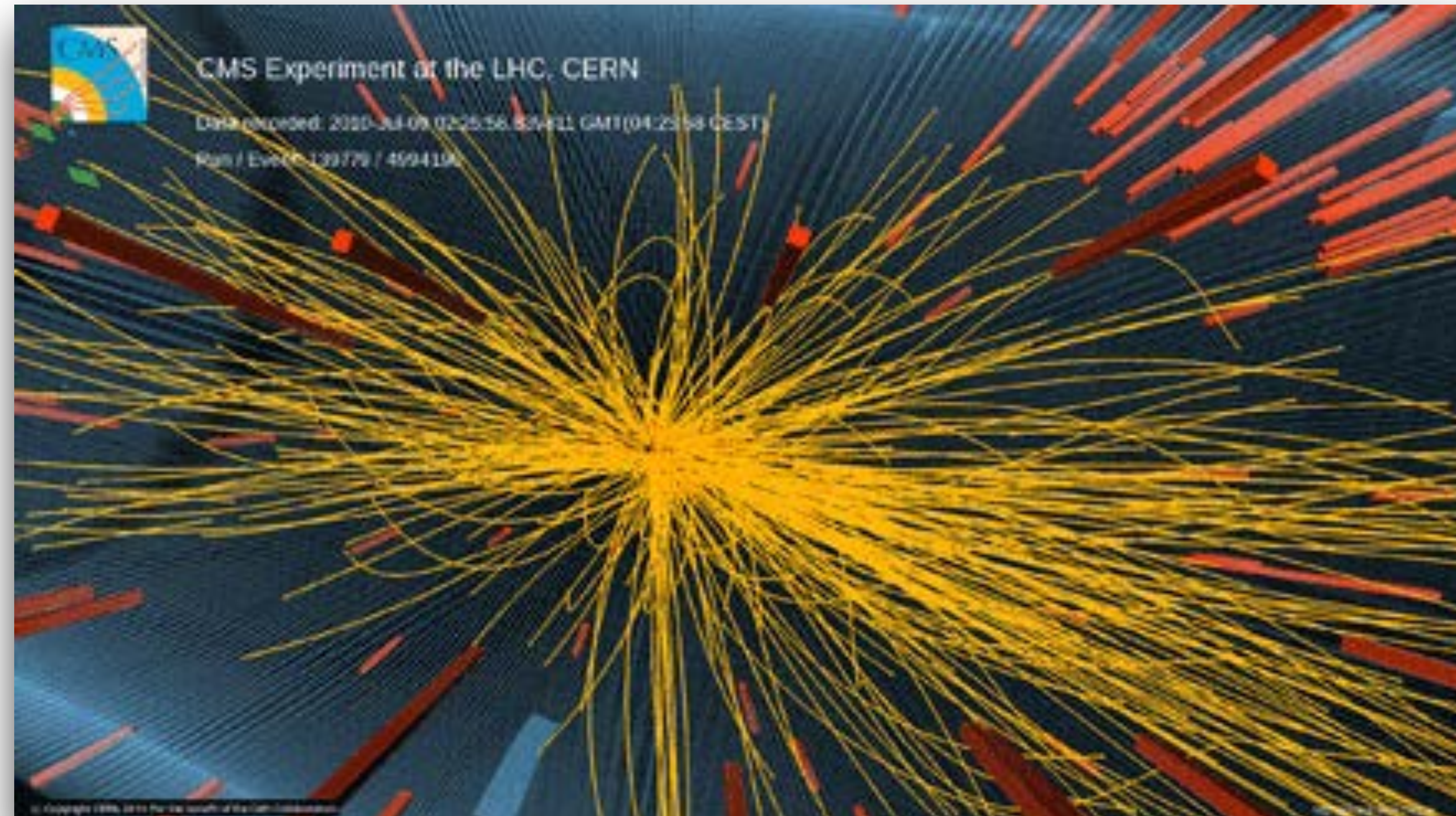
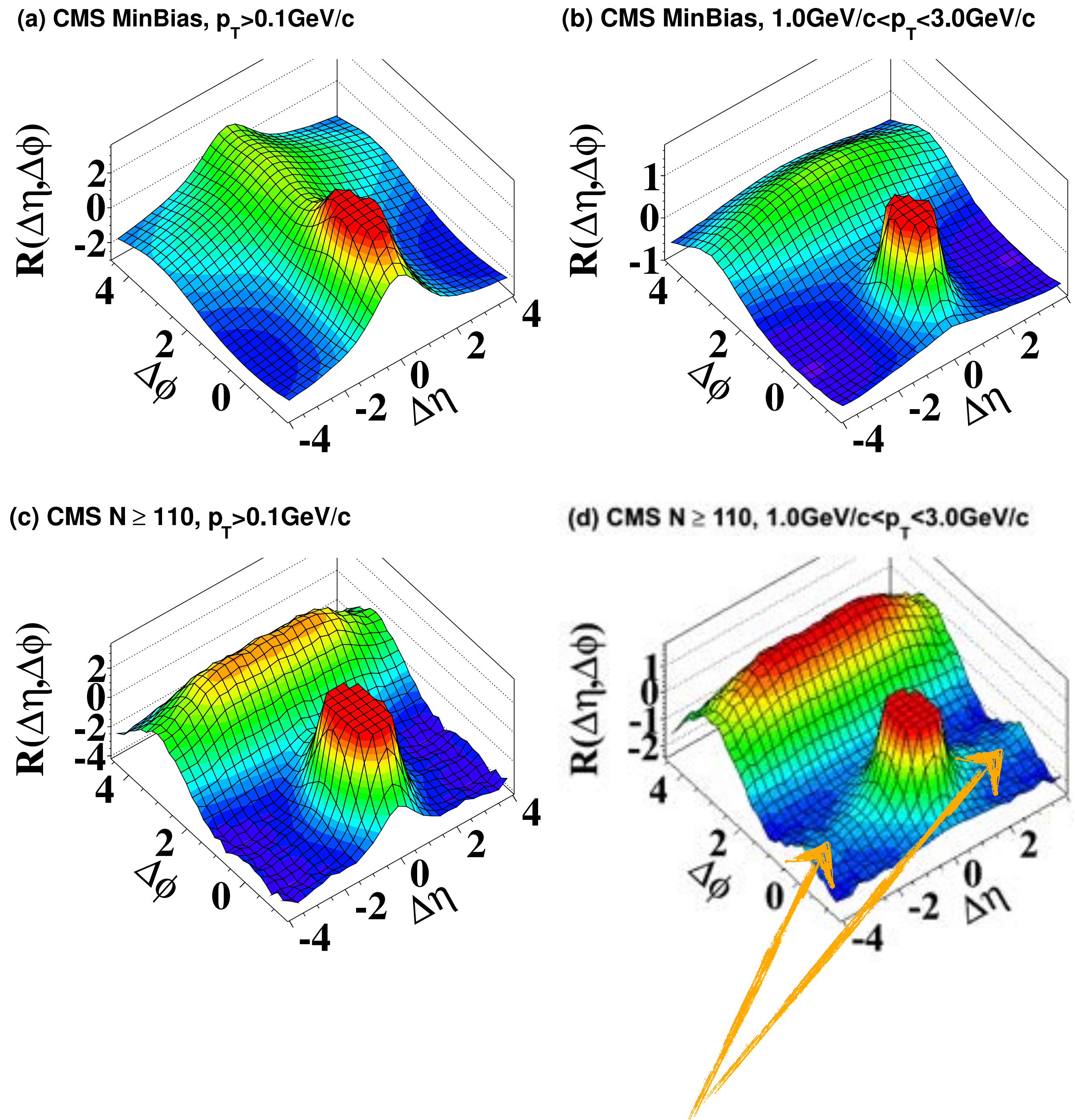
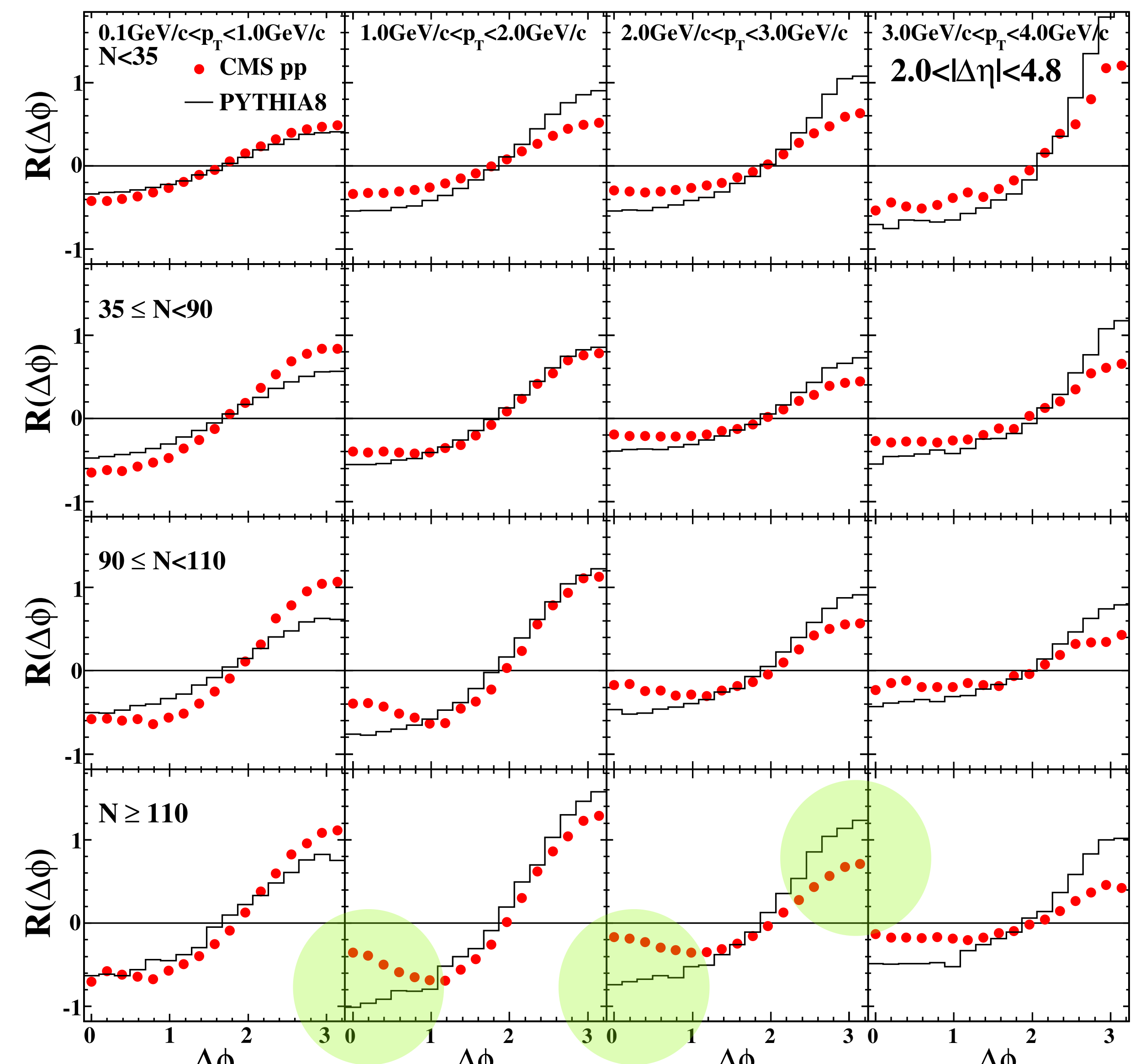


Image of a 7 TeV proton-proton collision in CMS producing more than 100 charged particles.

Two-particle correlation in pp at $\sqrt{s}$ = 7 TeV



An identical analysis of high multiplicity events in PYTHIA8 results in correlation functions which do not exhibit the extended ridge at Δφ ≈0, while all other structures of the correlation function are qualitatively reproduced.



The intermediate p_T range in high multiplicity events shows an unexpected effect: a clear and significant "ridge"-like structure emerges at Δφ ≈ 0 extending to |Δη| of at least 4 units. This is a novel feature of the data which has never been seen in two-particle correlation functions in pp or ppbar collisions.

Particle correlations in AA and pA collisions: comparison of similar multiplicity events in PbPb and pPb