THE HENRYK NIEWODNICZAŃSKI
INSTITUTE OF NUCLEAR PHYSICS
POLISH ACADEMY OF SCIENCES

ANGULAR CORRELATIONS AT LHCb

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On behalf of the LHCb Collaboration

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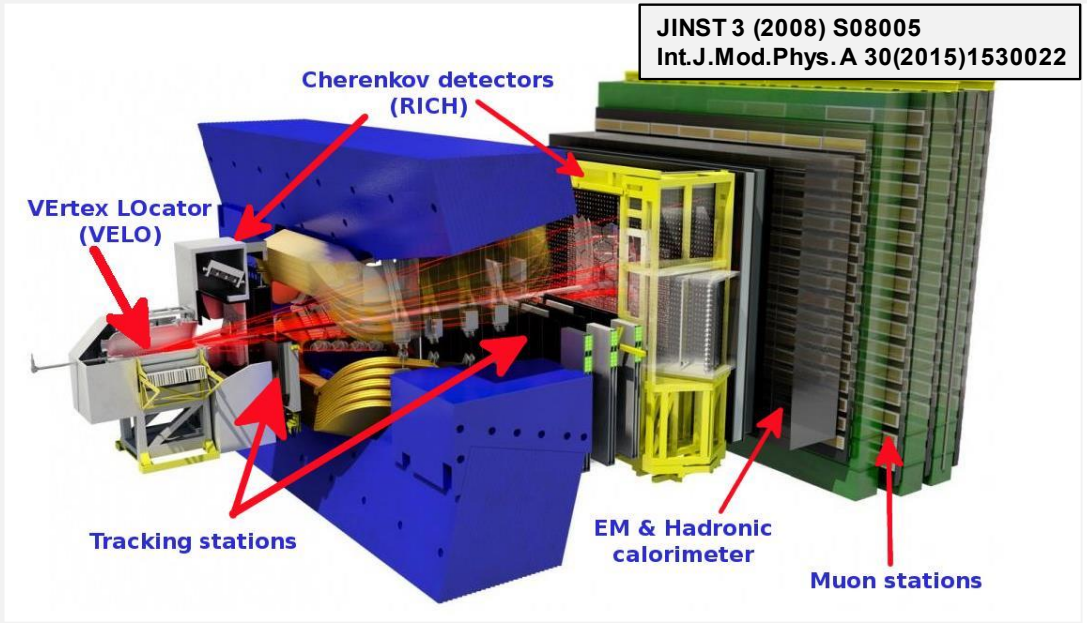
OUTLINE

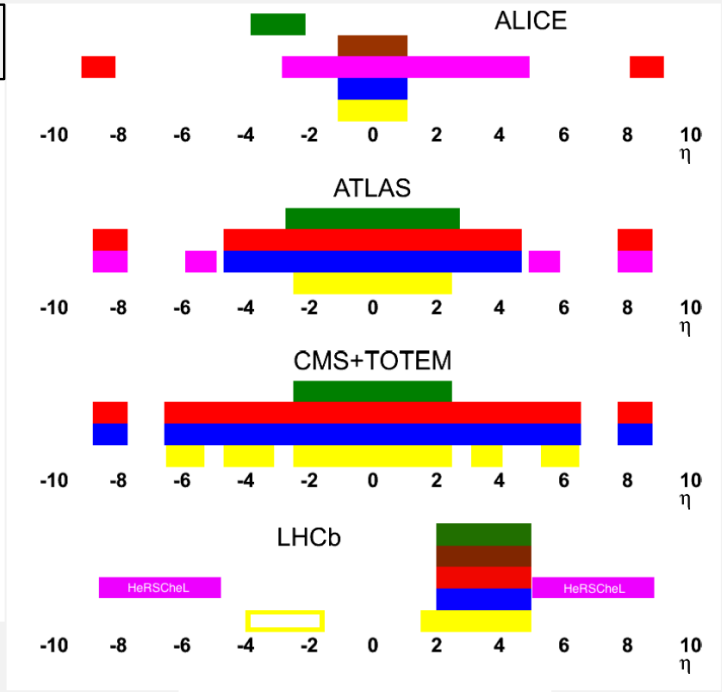
- Motivation
- The LHCb Experiment
- Angular correlations in:
  - Pb-Pb
  - Pb-p and p-Pb
- Summary

MOTIVATION AND GOALS

- Measurement of two particle angular correlation of prompt charged particles **in the forward region**
- Angular correlations in lead-lead for different centralities
- Search for a long-range angular correlations on the near side ("ridge") in small systems, previously observed in:
  - Pb-Pb collisions by RHIC experiment
  - Pb-Pb, p-Pb, and p-p collisions by CMS, ATLAS and ALICE at central rapidities ($|\eta|<2.5$)
- Comparison of long-range correlations in proton-lead for both hemispheres (p-Pb and Pb-p) in relative and absolute activity classes

THE LHCb EXPERIMENT





- Acceptance: $2 < \eta < 5$
- Impact parameter resolution: $20\ \mu m$
- Momentum resolution: $\Delta p/p = 0.5 - 1.0\%$ (5-200 GeV/c)
- Fully instrumented in the forward region
- Detector designed for flavour physics and searches for physics beyond SM, but also provides:
  - Results on heavy ion physics in the unique kinematic region
  - Complementary results to the other LHC experiments

ANGULAR CORRELATIONS IN Pb-Pb COLLISIONS AT LHCb

- Pb-Pb data collected by LHCb in 2018 at nucleon-nucleon center-of-mass energy of $\sqrt{S_{NN}} = 5.02\ TeV$, integrated luminosity 214 μb^{-1}
- Two centrality ranges: $65\text{-}75\%$ and $75\text{-}84\%$
- Data selection:
  - One primary vertex (PV) with a position ±3σ around mean interaction point
  - Centrality $65\text{-}84\%$
    - Lack of sufficient events below 65%
    - Upper bound to avoid contamination with ultraperipheral events
- Tracks selection:
  - $p > 2\ GeV/c \qquad p_T > 0.2\ GeV/c \qquad 2.0 < \eta < 4.9$

ANALYSIS METHOD

- Particles divided into $\mathrm{p_T}$ ranges, additionally:
  - Pb-Pb: one particle in $0.2 < p_{Ta} < 10\ GeV/c$ and second in $0.2 < p_{Tb} < 5\ GeV/c$
  - Pb-p and p-Pb: events divided into activity classes
- *Trigger* particles – for each event, all candidates within a given $\mathrm{p_T}$ interval
- *Associated* particles – all remaining candidates in $\mathrm{p_T}$ interval after selecting a trigger particle
- Pairs created by combining every trigger particle with each associated particle

CORRELATION FUNCTION

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

Same event pairs:

- All possible pairs within the event

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

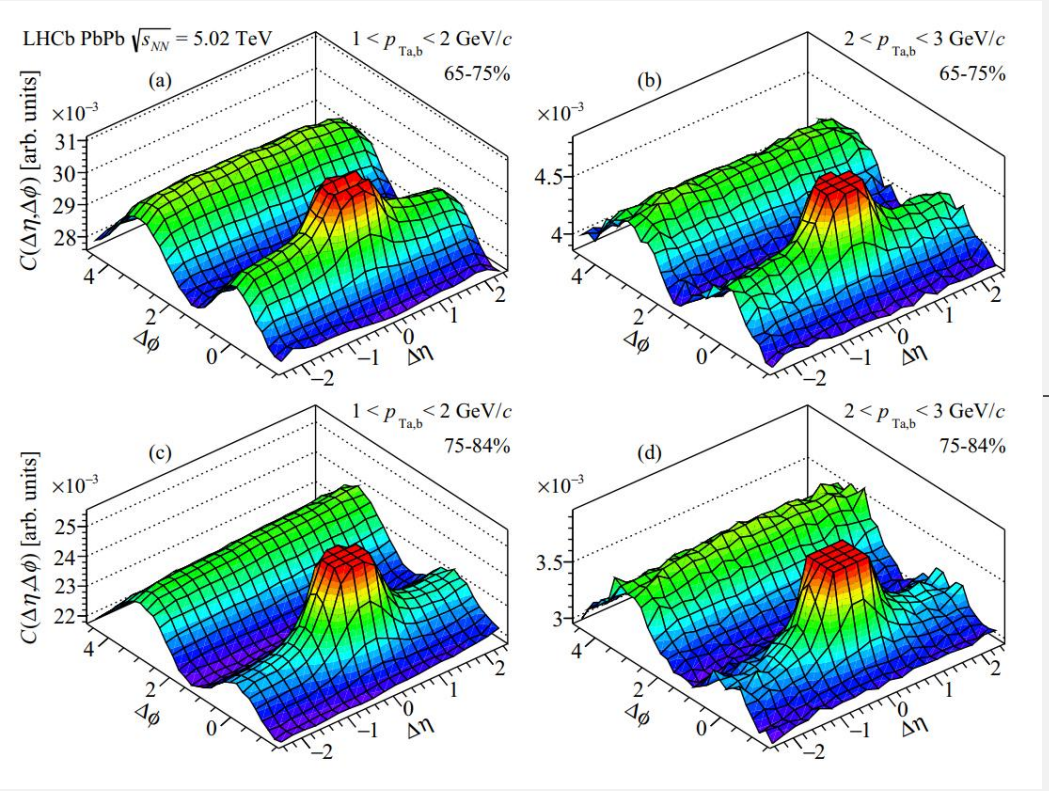
Normalization factor

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

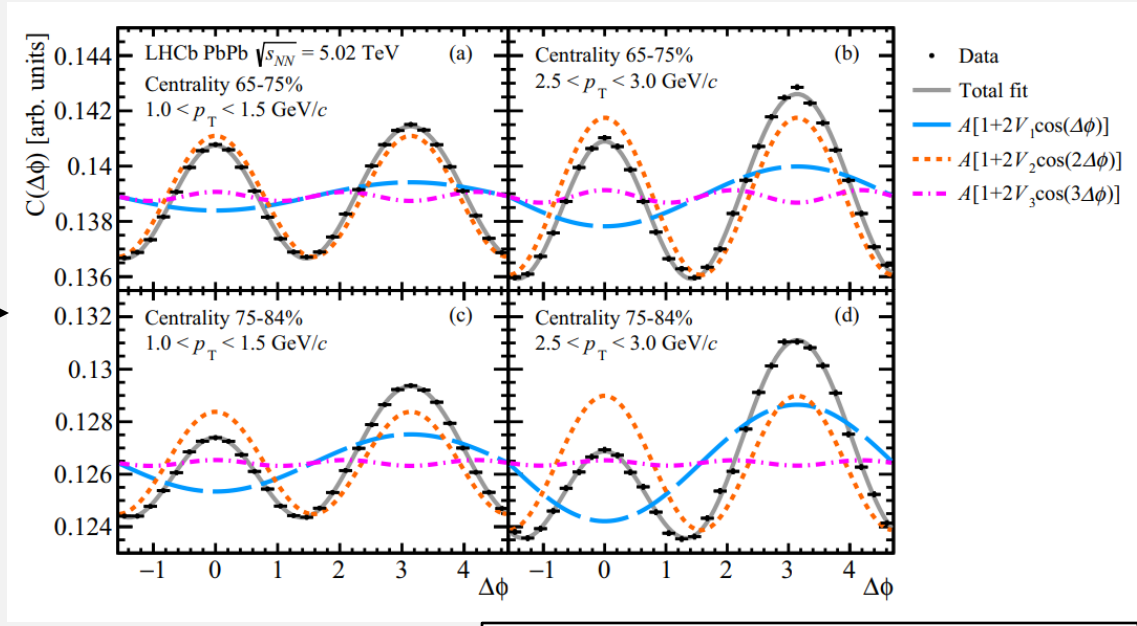
Mixed event pairs:

- Two hadrons from different events
- Correlated through detector effects, no physics correlation

ANGULAR CORRELATIONS IN Pb-Pb



Projection on $\Delta\varphi$ excluding the jet region $|\Delta\eta| < 1$



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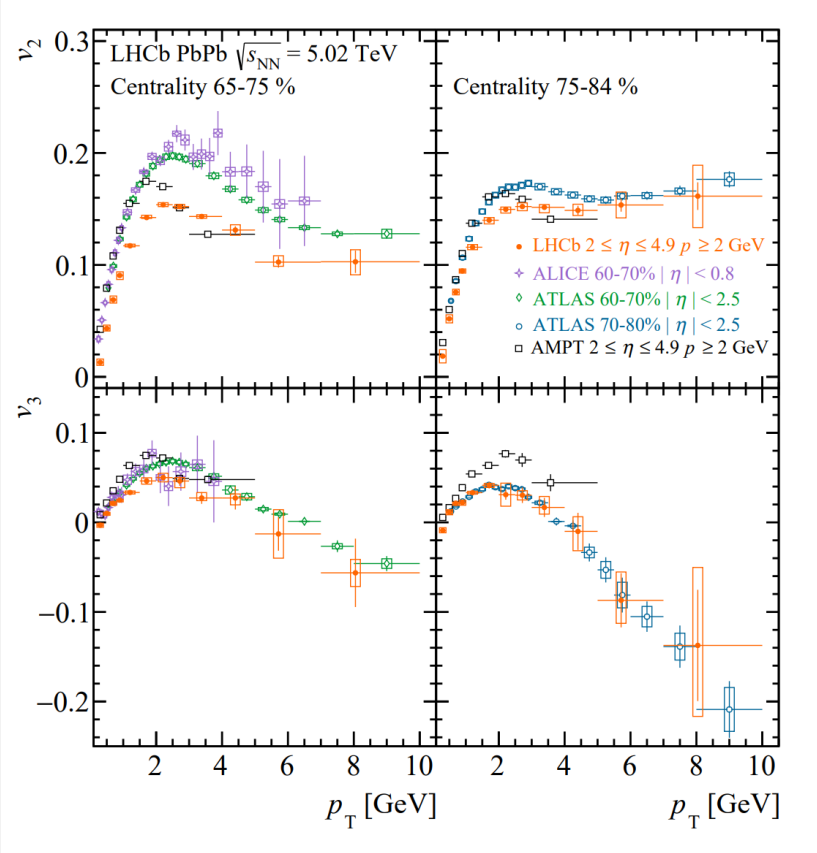
FLOW HARMONIC COEFFICIENTS

- First measurement in the forward region
- Results similar in features, but lower in values (difference in pseudorapidity ranges)
  - v_2 lower for the LHCb
  - v_3 compatible with other experiments



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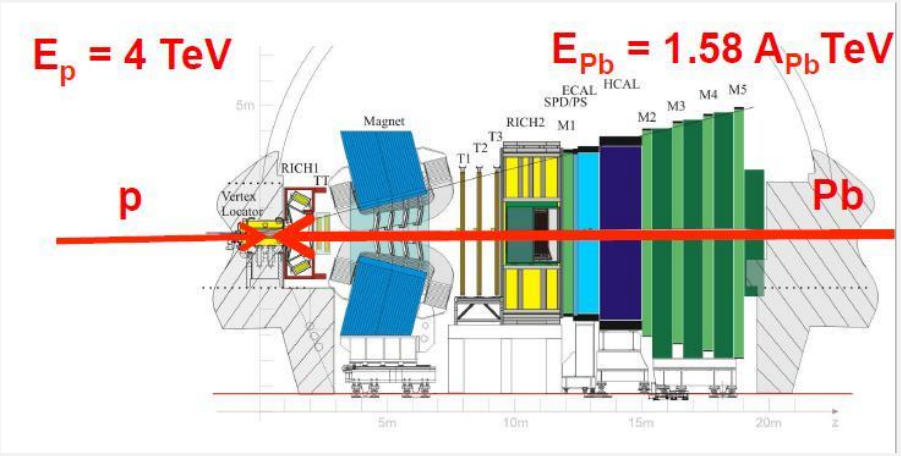
ANGULAR CORRELATIONS IN SMALL SYSTEMS

- Ridge effect in heavy ion collisions attributed to the hydrodynamic expansion of the QGP creating a pressure gradient causing particles to flow along the direction of the collision axis
- For smaller systems, the cause of the ridge is still under discussion
- Confirmation of the ridge effect at large pseudorapidities and comparison of the two beam configurations provide new input to the understanding of the underlying mechanism

p-Pb AND Pb-p COLLISIONS

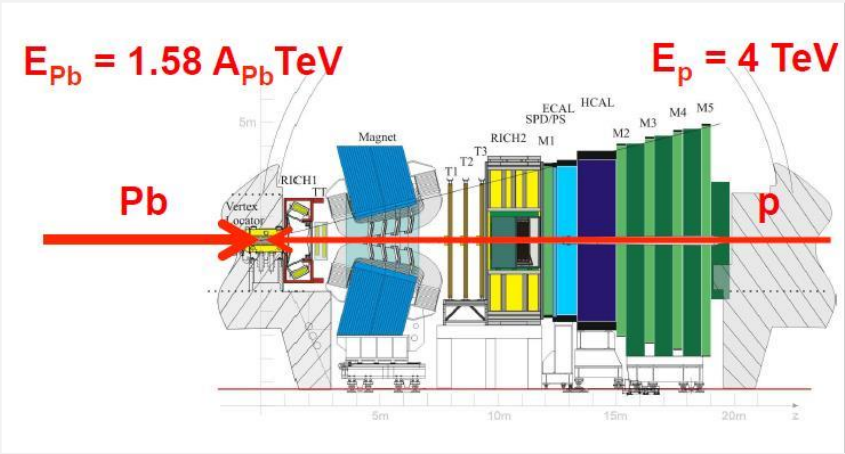
p-Pb

- $E_p = 4$ TeV, $E_{Pb} = 1.58$ TeV
- Rapidity range: $1.5 < y < 4.4$
- Sample used for the analysis: $0.46\ nb^{-1}$



Pb-p

- $E_{Pb} = 1.58$ TeV, $E_p = 4$ TeV
- Rapidity range: $-5.4 < y < -2.5$
- Sample used for the analysis: $0.30\ nb^{-1}$



- Data collected in 2013
- Asymmetric beams: nucleon-nucleon $\sqrt{S_{NN}} = 5\ TeV$
- Center of mass system shifted by $\Delta y = 0.47$ into proton beam direction
- Common rapidity range: $2.5 < |y| < 4.4$

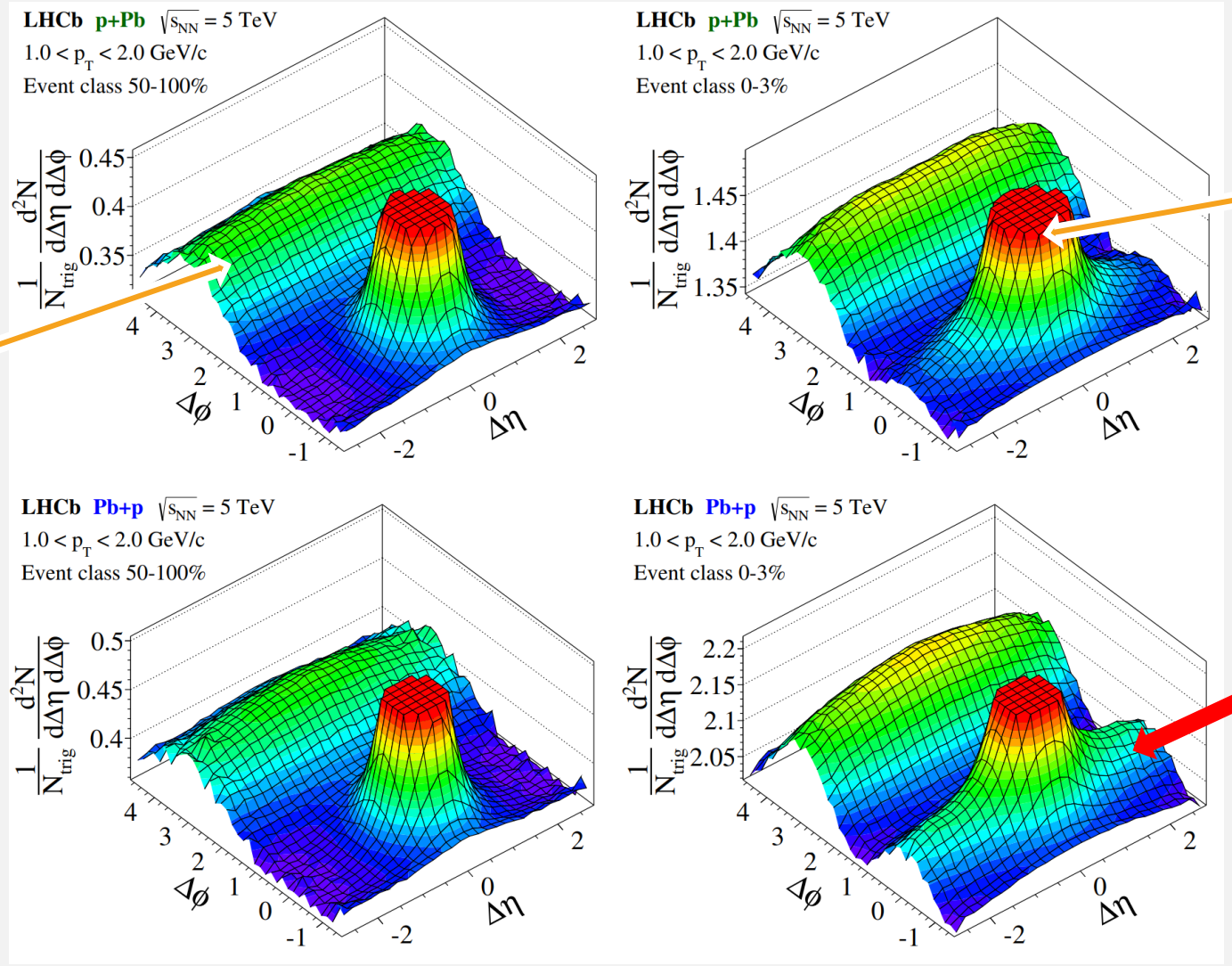
DATA SELECTION

- Event selection:
  - One primary vertex (PV) with a position ±3σ around mean interaction point (only 2% of interactions with more than one PV)
  - Events with too small ratio between the number of clusters in EM calorimeter and in the VELO are rejected (reduction of beam-gas and secondary interactions with detector material)
- Track selection:
  - Prompt particles (small IP with respect to PV)
  - Charged particles reconstructed in full tracking system (before and after the magnet)
  - Kinematic cuts: $p > 2\ \mathrm{GeV/c}$ $p_T > 150\ \mathrm{MeV/c}$ $2.0 < \eta < 4.9$
- Corrections:
  - Fake tracks suppressed by multivariate classifier while secondary tracks by IP cuts
  - Remaining effects taken into account by per track weights depending on track purity and track efficiency

DATA SAMPLES AND ACTIVITY CLASSES

- 1.1×10^8 minimum bias p-Pb and Pb-p events selected from the set about 10 times larger
- High multiplicity events with at least 2200 hits in VELO
- Strong dependence on the number of particles produced in the collision
  - The hit multiplicity in the VELO is proportional to the global counterpart
  - Five activity classes defined as fractions of the hit-multiplicity distributions of the minimum-bias samples

RESULTS

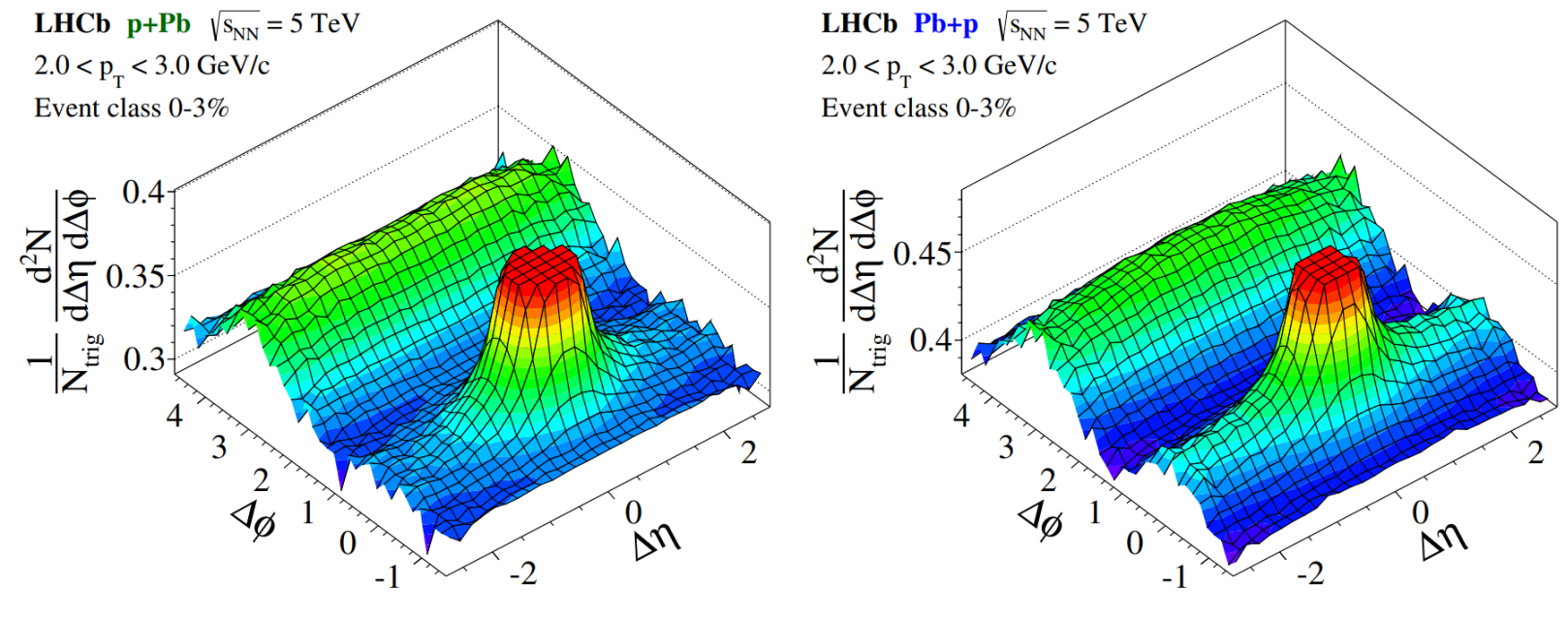


Far-side ridge

Jet peak (truncated)

Near-side ridge

RESULTS



Near-side ridge:

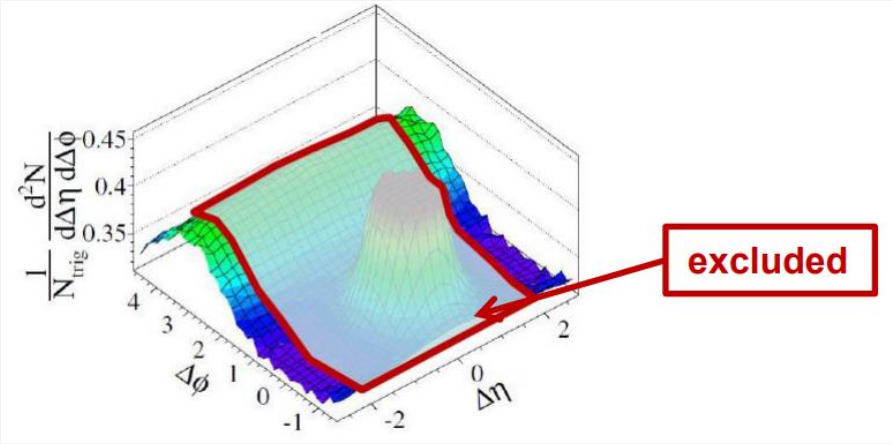
- Present in both beam configurations for high activity events
- More pronounced for Pb-p collisions

RIDGE EVOLUTION

- One-dimensional projections of the correlation function on $\Delta\varphi$:

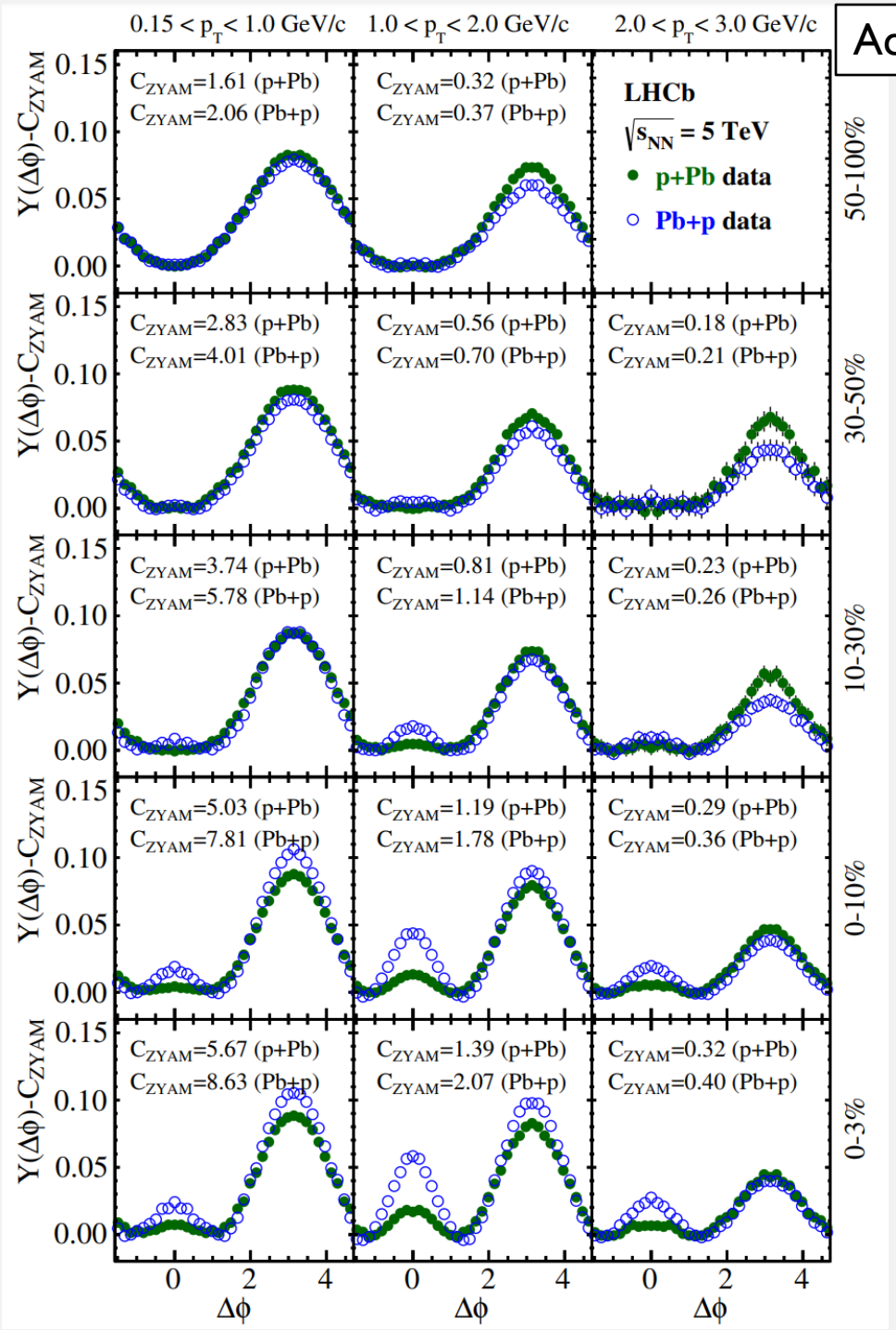
$$Y(\Delta\phi) \equiv \frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}N_{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{1}{\Delta\eta_b - \Delta\eta_a}\int_{\Delta\eta_a}^{\Delta\eta_b}\frac{1}{N_{\mathrm{trig}}}\frac{\mathrm{d}^2N_{\mathrm{pair}}}{\mathrm{d}\Delta\eta\mathrm{d}\Delta\phi}\mathrm{d}\Delta\eta$$

- Short range correlations, including the jet peak, excluded by averaging the two-dimensional yield over interval from $\Delta\eta_a = 2.0$ to $\Delta\eta_b = 2.9$
- Correlation structures extracted by using the zero-yield-at-minimum (ZYAM) method



RIDGE EVOLUTION

- Near-side maximum observed for $1 < p_T < 2$ GeV
- Away-side ridge amplitude increases with event activity and decreases towards higher p_T
- Correlation stronger for Pb-p in each activity class



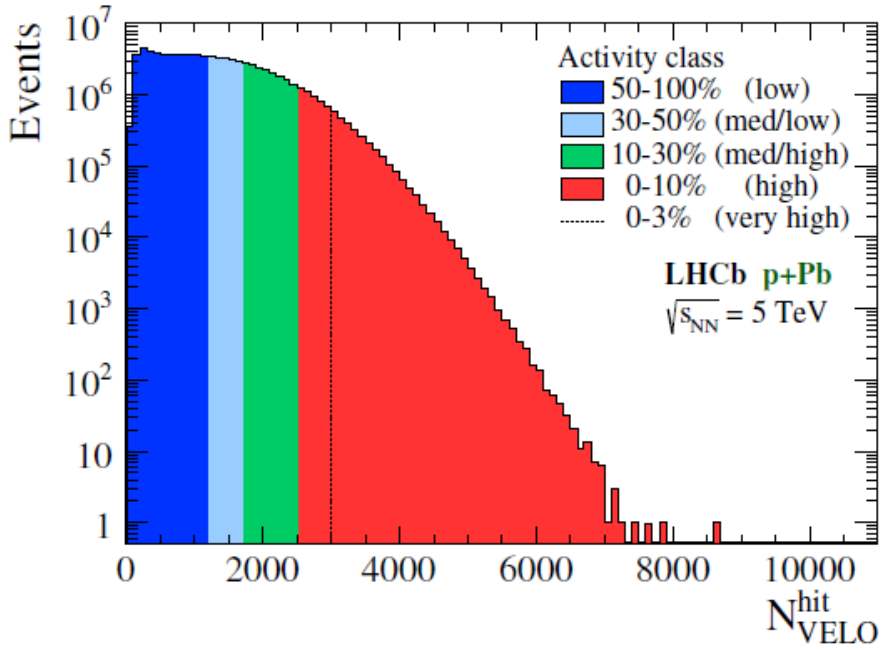
SUMMARY

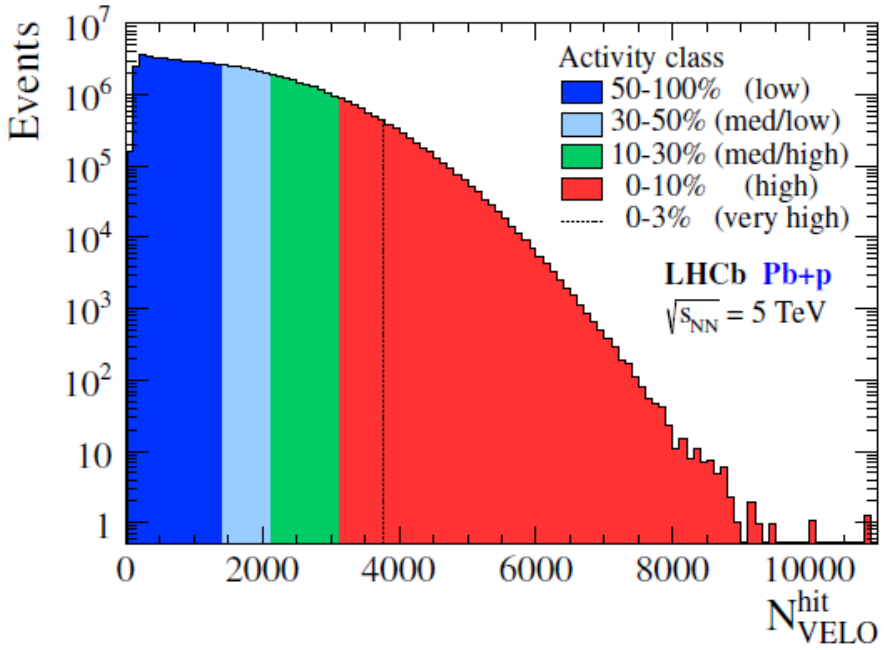
- First measurements of angular correlations in the unique acceptance of LHCb detector
- Near-side ridge smaller than the away-side
- Near-side ridges more pronounced for Pb-Pb than small systems indicate stronger collective flow in heavy ion collisions
- The near-side ridge effect observed in both p-Pb and Pb-p beam configurations, most pronounced for $1.0 < \mathrm{p_T} < 2.0\ \mathrm{GeV/c}$
- The correlation structures on the near and away sides grow with increasing event activity
- Ridge is stronger in the Pb direction for each event activity class
- Observed long-range correlation compatible in both hemispheres for identical absolute activity

QUESTIONS AND COMMENTS

BACKUP SLIDES

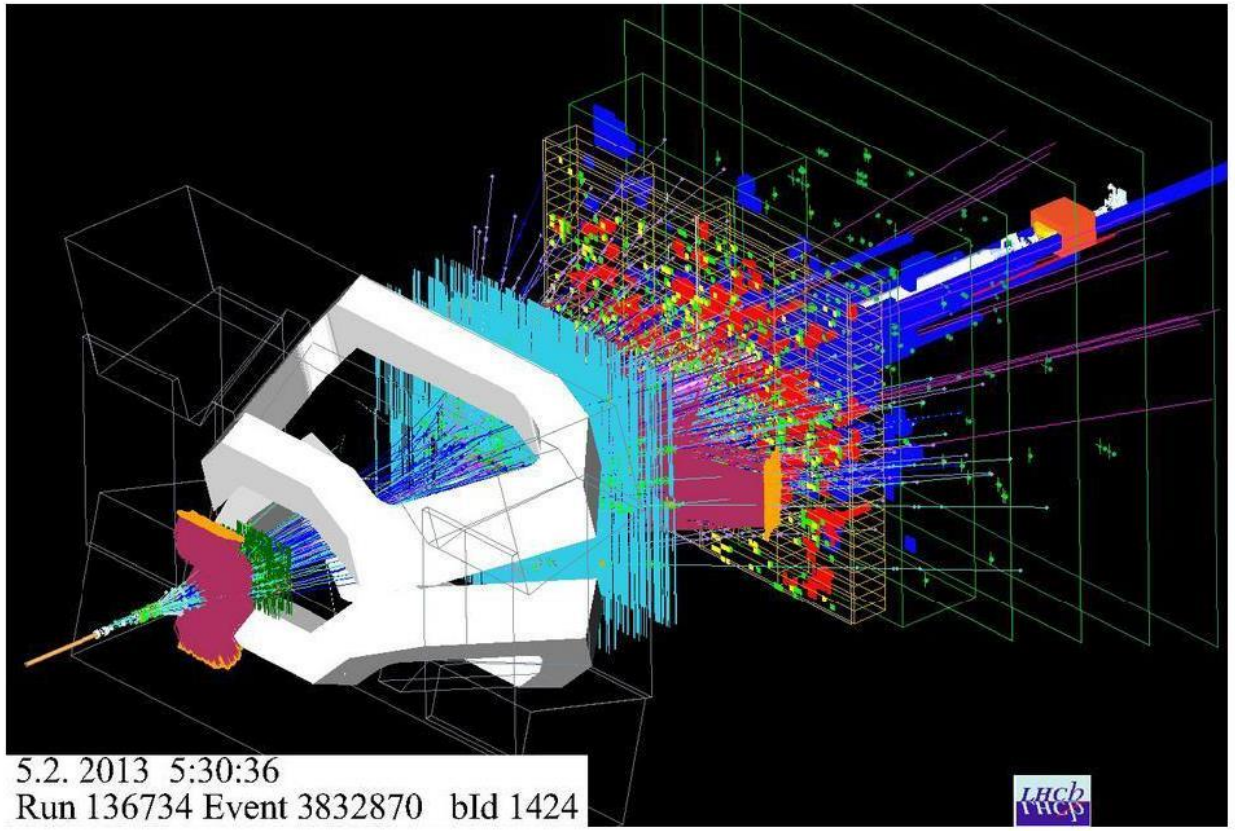
ACTIVITY CLASSES



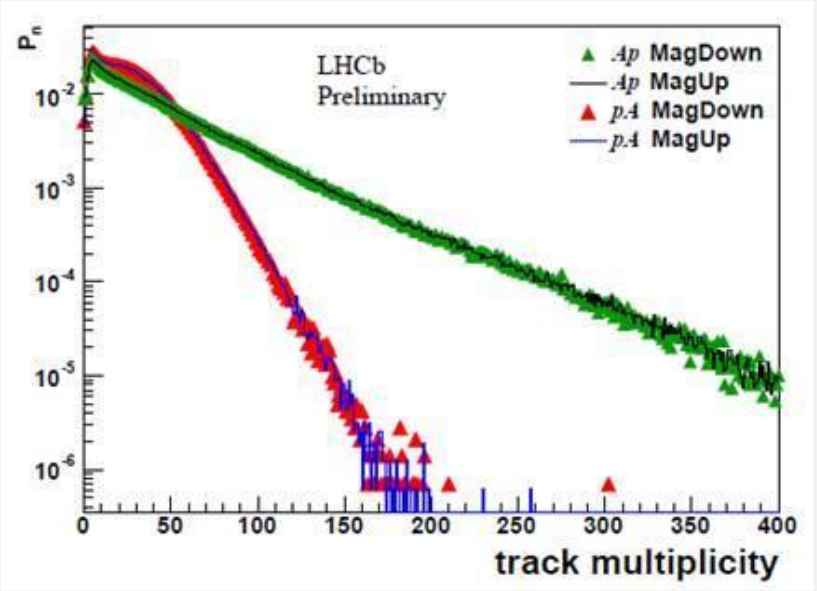


- Classes defined as fractions of full distribution
- The 0-3% class is a sub-sample of 0-10% class

THE p-Pb EVENT



Typical pA collision in LHCb



- Comparable distributions in the LHCb acceptance for p-p and p-Pb
- Higher multiplicity for Pb-b events

THE RIDGE IN COMMON ABSOLUTE ACTIVITY RANGES

- Similar number of charged particles emitted in the forward direction
- Five narrow activity bins
- Observed long-range correlations become compatible within the uncertainties

Common absolute activity bin	$\mathcal{N}^{\text{hit}}_{\text{VELO}}$-range in Pb+$p$ scale	p+Pb $\langle N_{ch}\rangle_{\text{MC}}$	Pb+p $\langle N_{ch}\rangle_{\text{MC}}$
Bin I	$2200 - 2400$	62.8 ± 6.6	64.4
Bin II	$2400 - 2600$	68.4 ± 7.1	67.0
Bin III	$2600 - 2800$	73.7 ± 7.6	76.4
Bin IV	$2800 - 3000$	79.2 ± 7.9	82.4
Bin V	$3000 - 3500$	86.7 ± 8.2	92.9

Different bins than before