Measurements of collectivity in the forward region at LHCb

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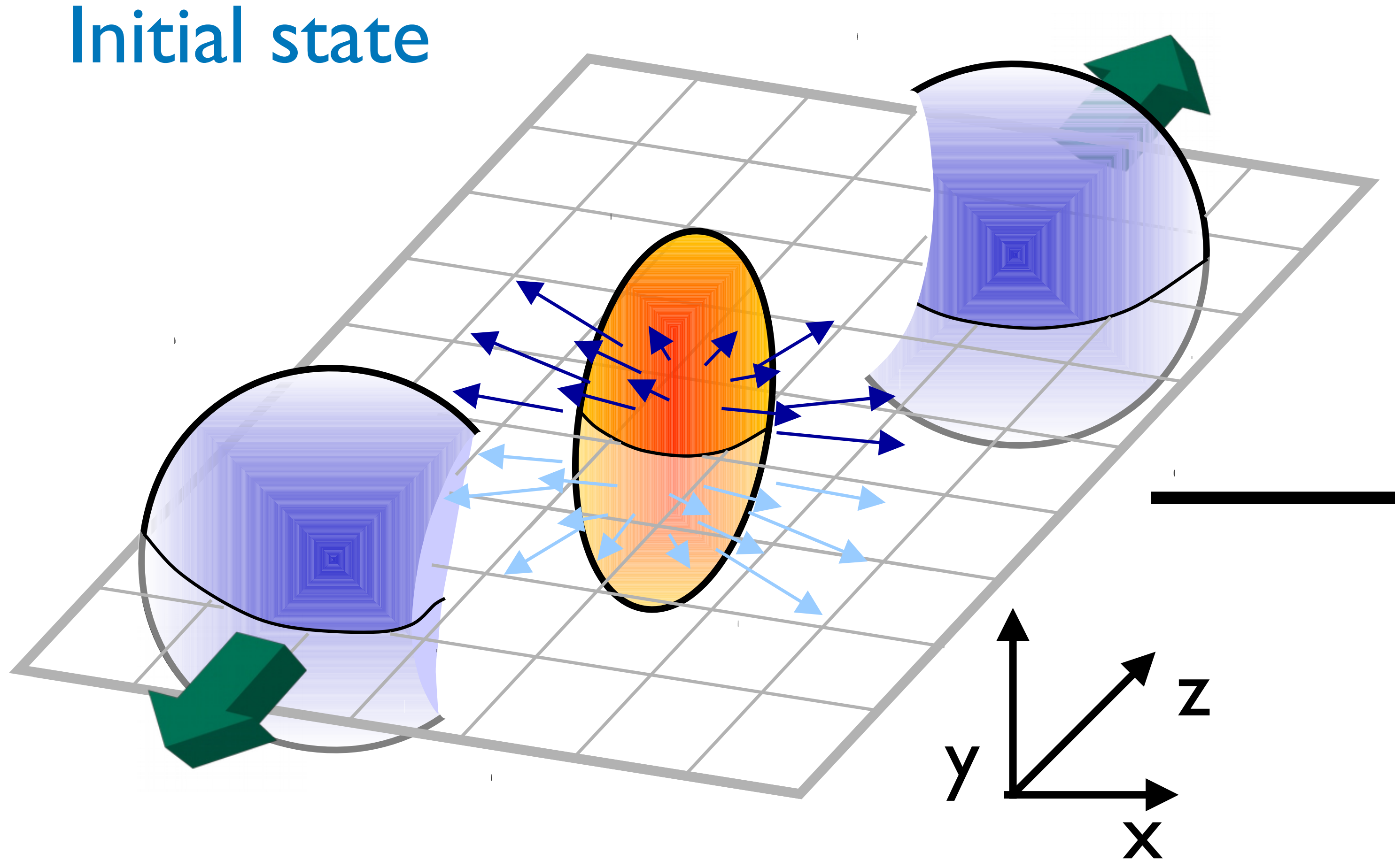
Outline

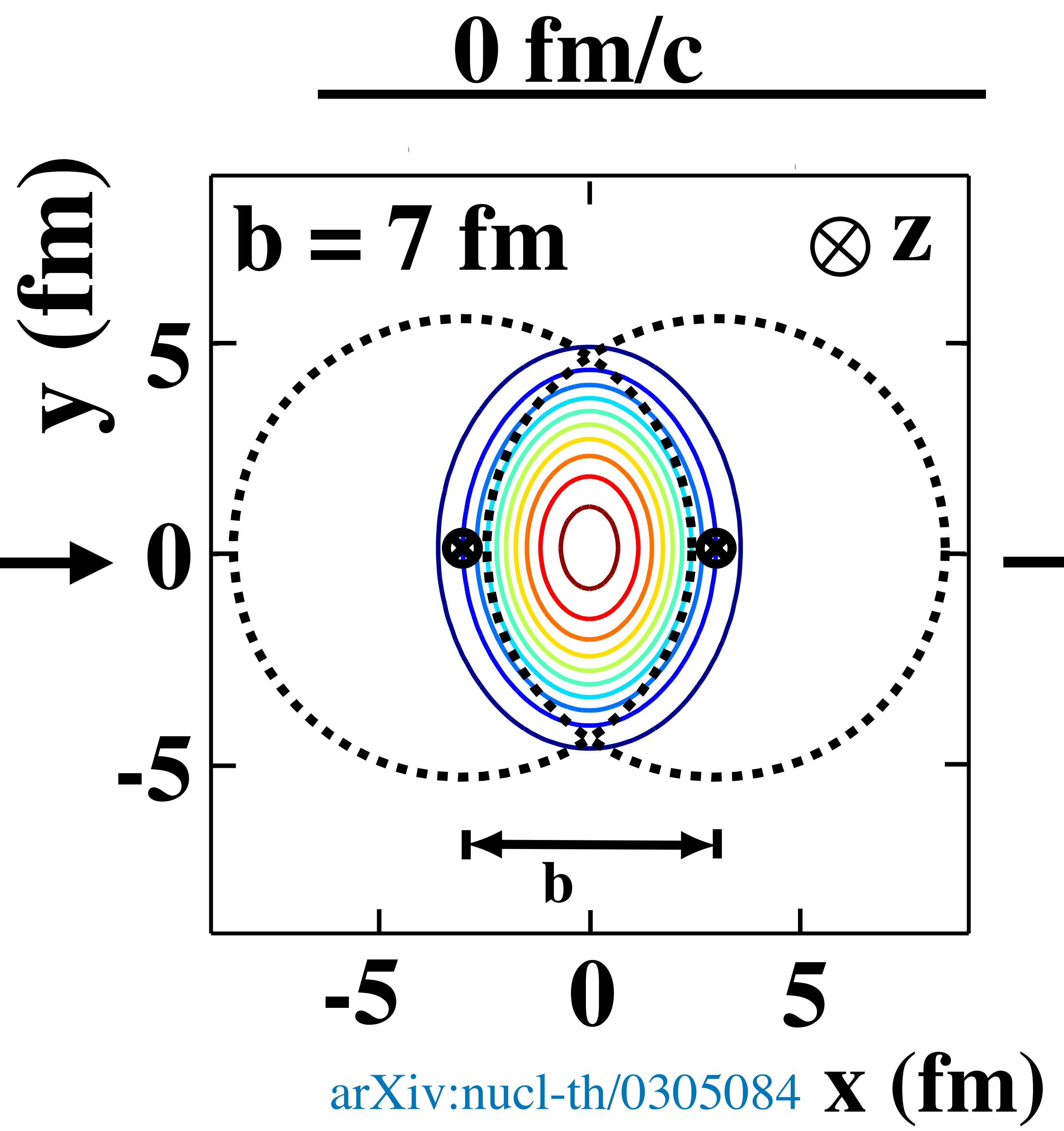
1. Introduction: Two-particle correlations and collectivity
2. LHCb capabilities
3. LHCb measurements:
   3.1. Two-particle angular correlations in pPb at $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$
   3.2. Centrality dependence of two-particle angular correlations in PbPb at $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$
   3.3. Multiplicity dependence of two-particle angular correlations in pPb at $\sqrt{s_{NN}} = 8\,\mathrm{TeV}$
   3.4. Study of the Bose-Einstein correlations of identical pions in pPb at $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$

Introduction

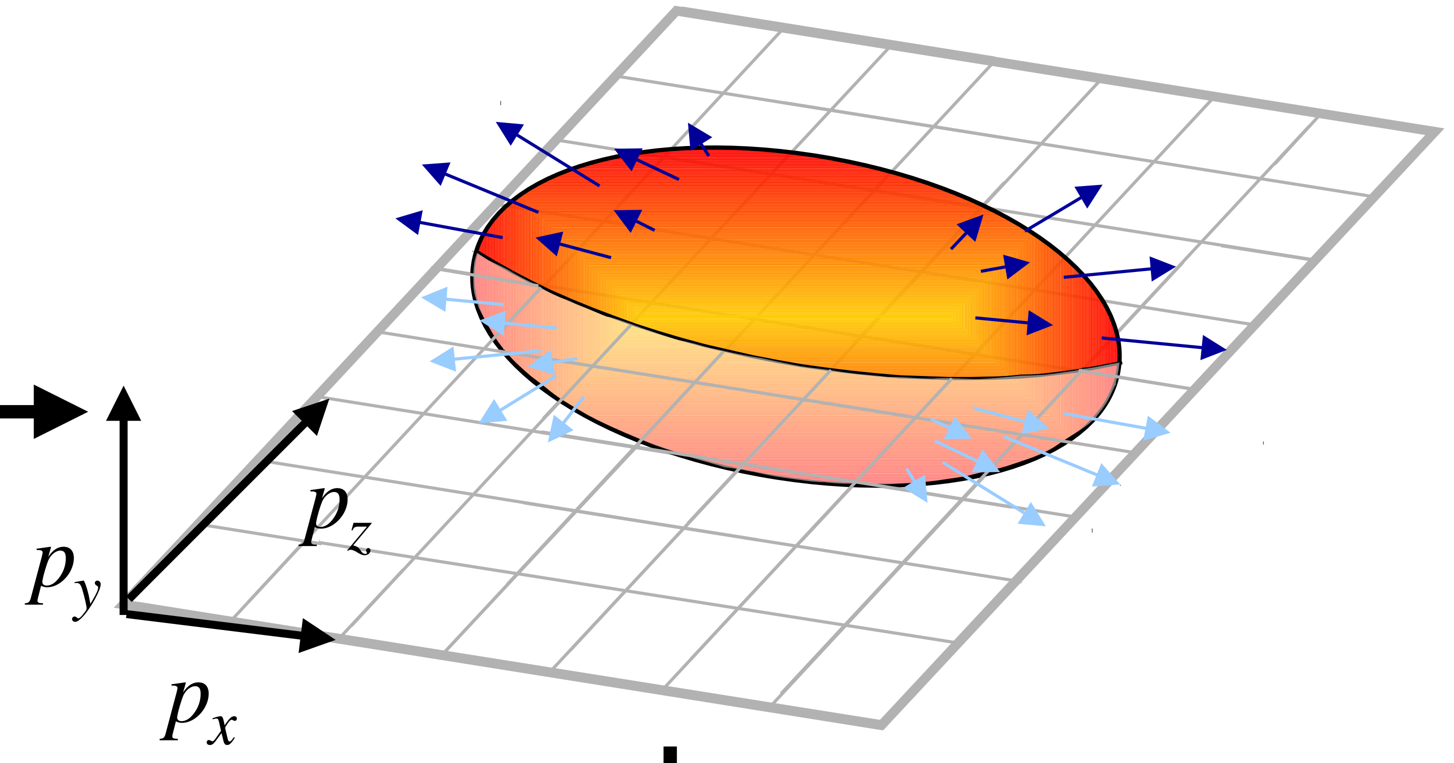
Initial state: Energy density spatial asymmetry in non-central ion collisions

Momentum and position asymmetry in the final state





arXiv:nucl-th/0305084



Macroscopically described by Energy-Momentum Tensor

Access to initial state properties

Introduction

Extracting Energy-Momentum tensor components from collective flow

Mainly Gluons

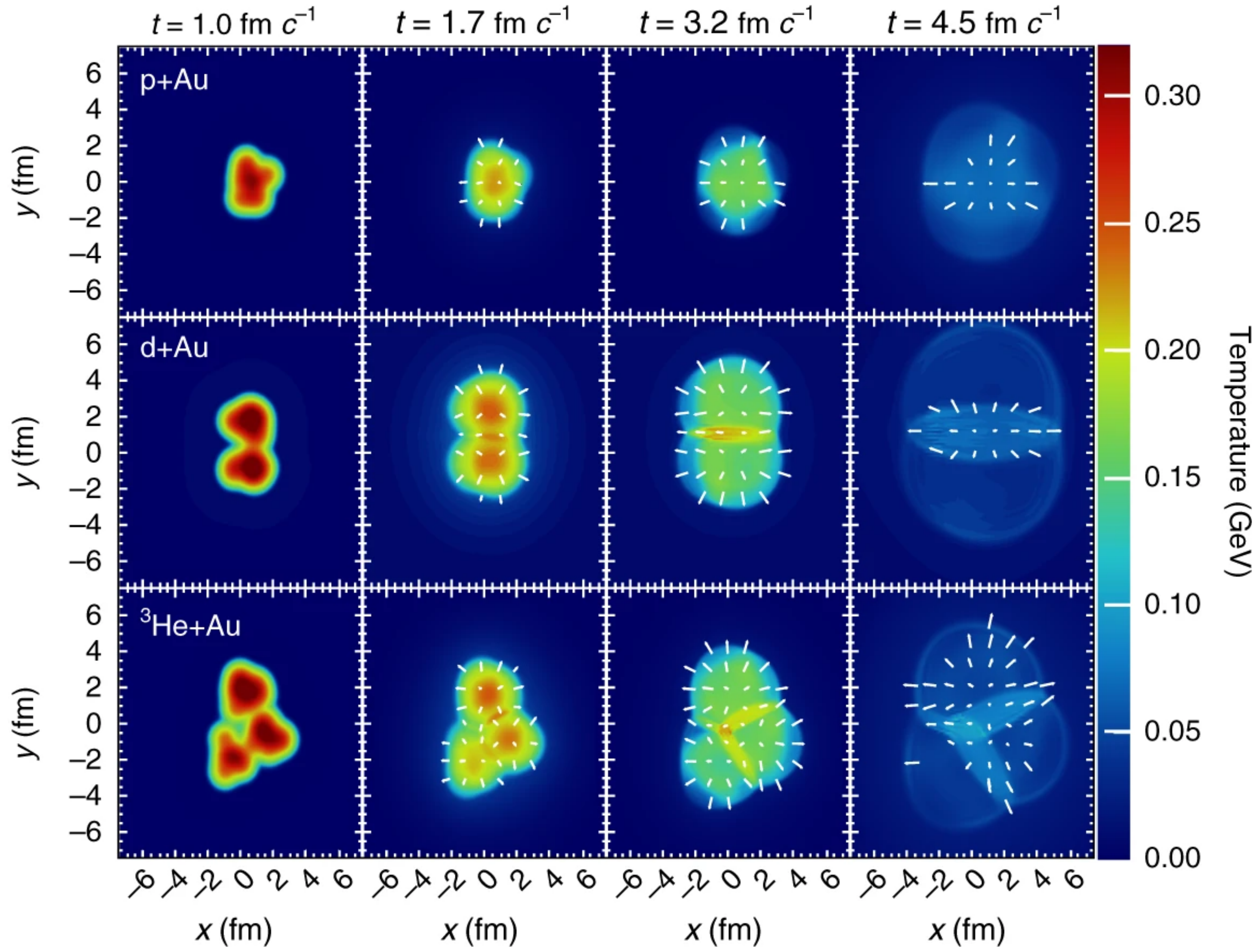
$$\langle T^{xy}(x,t)T^{xy}(0,0)\rangle$$

$$\langle T^{i}_{i}(x,t)T^{i}_{i}(0,0)\rangle$$

Shear viscosity η: anisotropic collective flow

Bulk viscosity ζ: transverse collective flow

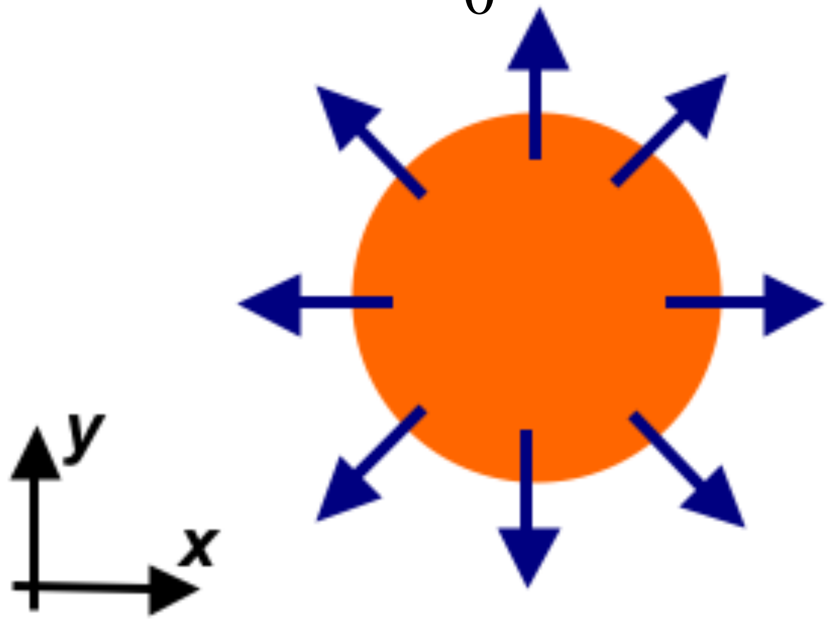
Also in small systems? Nat. Phys. 15, 214–220 (2019)



Measuring it with Fourier decomposition of particle correlations

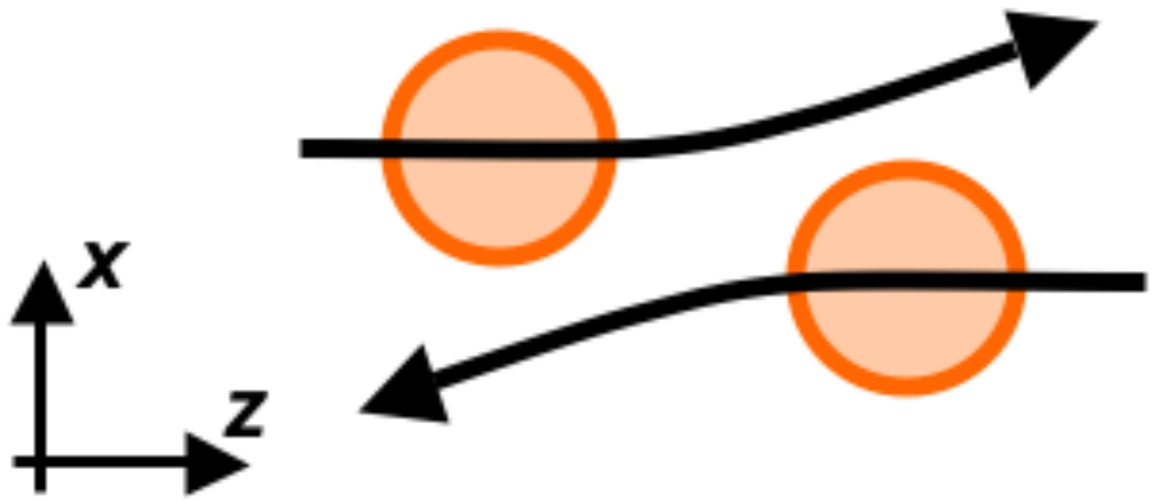
Experimentally →

Radial flow v_0

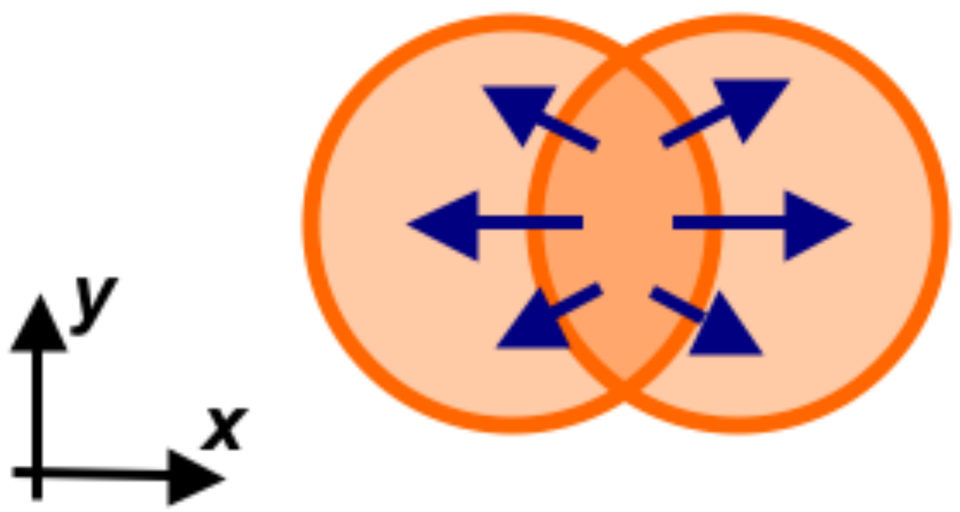


Direct flow v_1

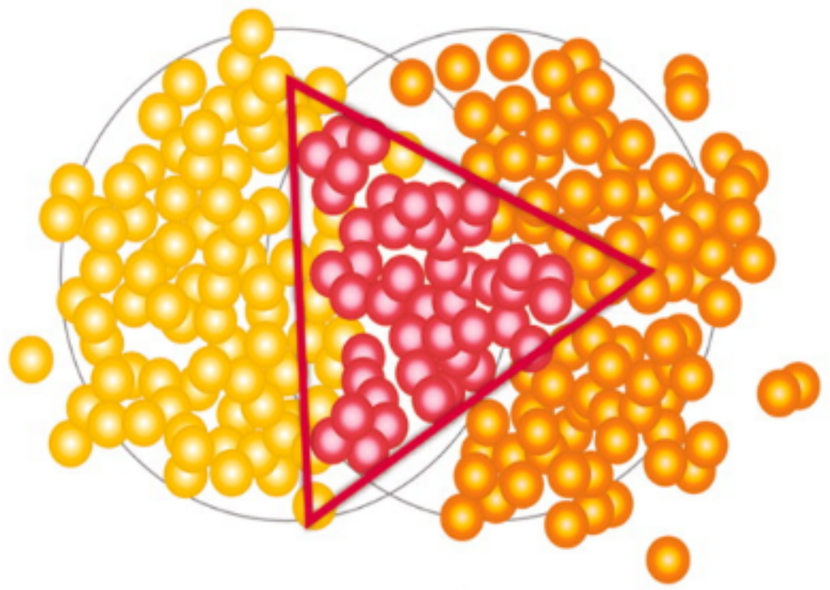
Only at forward rapidity



Elliptic flow v_2



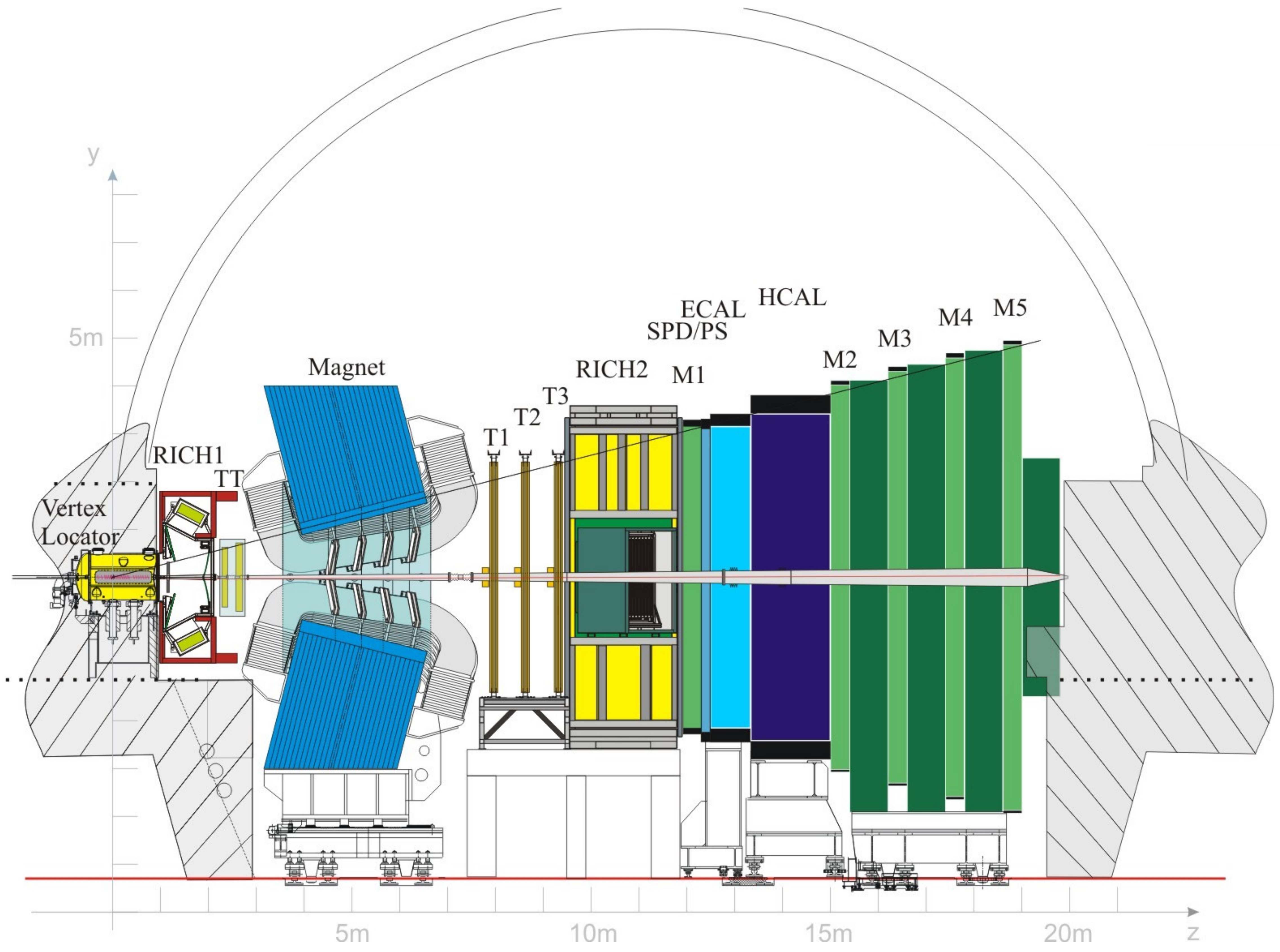
Triangular flow v_3



About LHCb

LHCb experiment

- Single-arm fully instrumented spectrometer in $\eta \in [2, 5]$
- pp, pPb, PbPb and fixed target modes
- Momentum resolution: $\Delta p/p = 0.5 - 1\,\%\,, p \in [2, 200]\,\mathrm{GeV/c}$
- Primary vertex resolution: $\in [10, 35]\,\mu\mathrm{m}$
- ECAL energy resolution: arXiv:2008.11556 $13.5\,\%/\sqrt{E/GeV} \oplus 5.2\% \oplus (0.32\,\mathrm{GeV})/E$



JINST 3 (2008) S08005

Accessing low-x phenomena

- Q^2: exchanged moments between interacting partons
- x: momentum fraction of the parton with respect to nucleus

$$Q^2 \sim m^2 + p_T^2, \qquad x \sim \frac{Q}{\sqrt{s_{NN}}} e^{-\eta}$$

- **LHCb coverage**
  - Forward, $10^{-6} \leq x \leq 10^{-4}$
  - Backward, $10^{-3} \leq x \leq 10^{-1}$

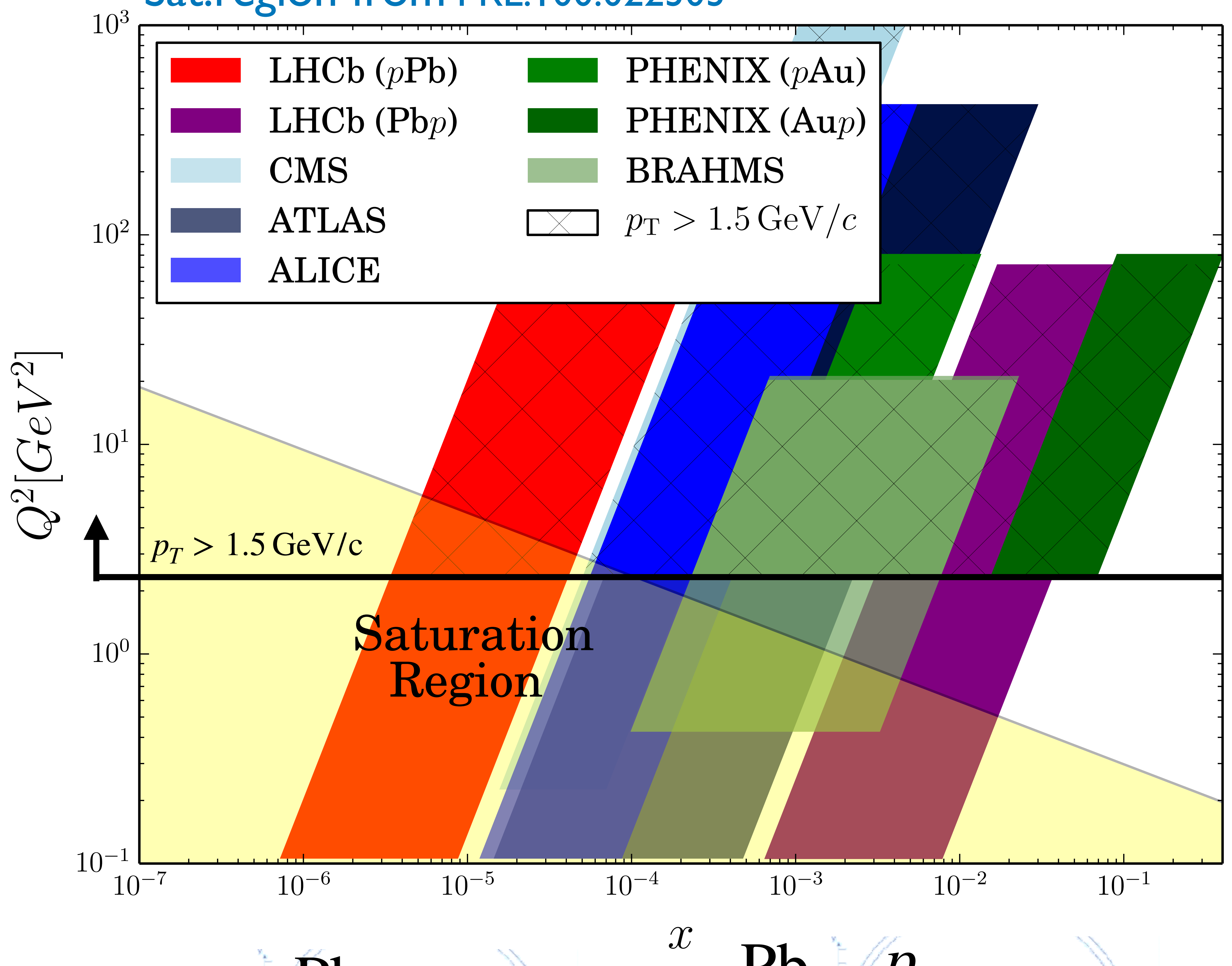
↓

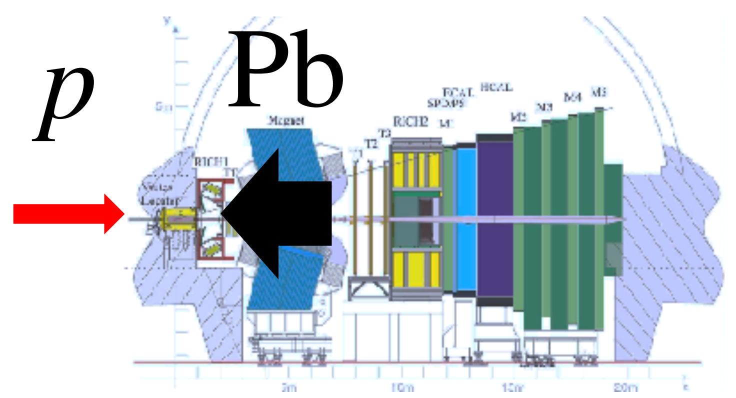
Unique access to low-x physics

<u>LHCb particular capabilities</u>

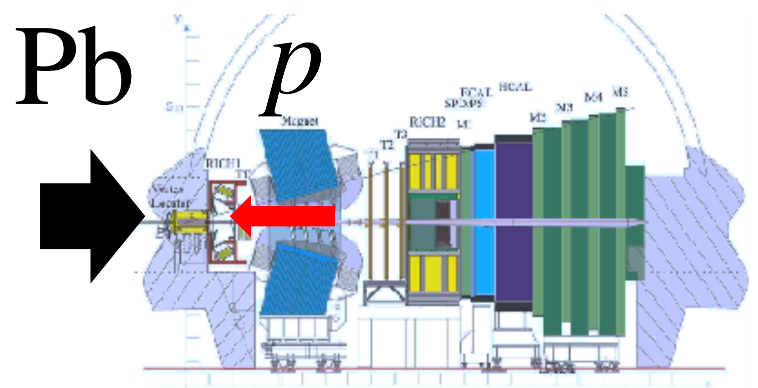
- Charged and neutral hadron production at small-x
- Capability to study one system in a wide range of x values:
  - Forward/Backward comparison
- Possible access to the *saturation region* →Non-linear dynamics

Sat.region from PRL.100.022303





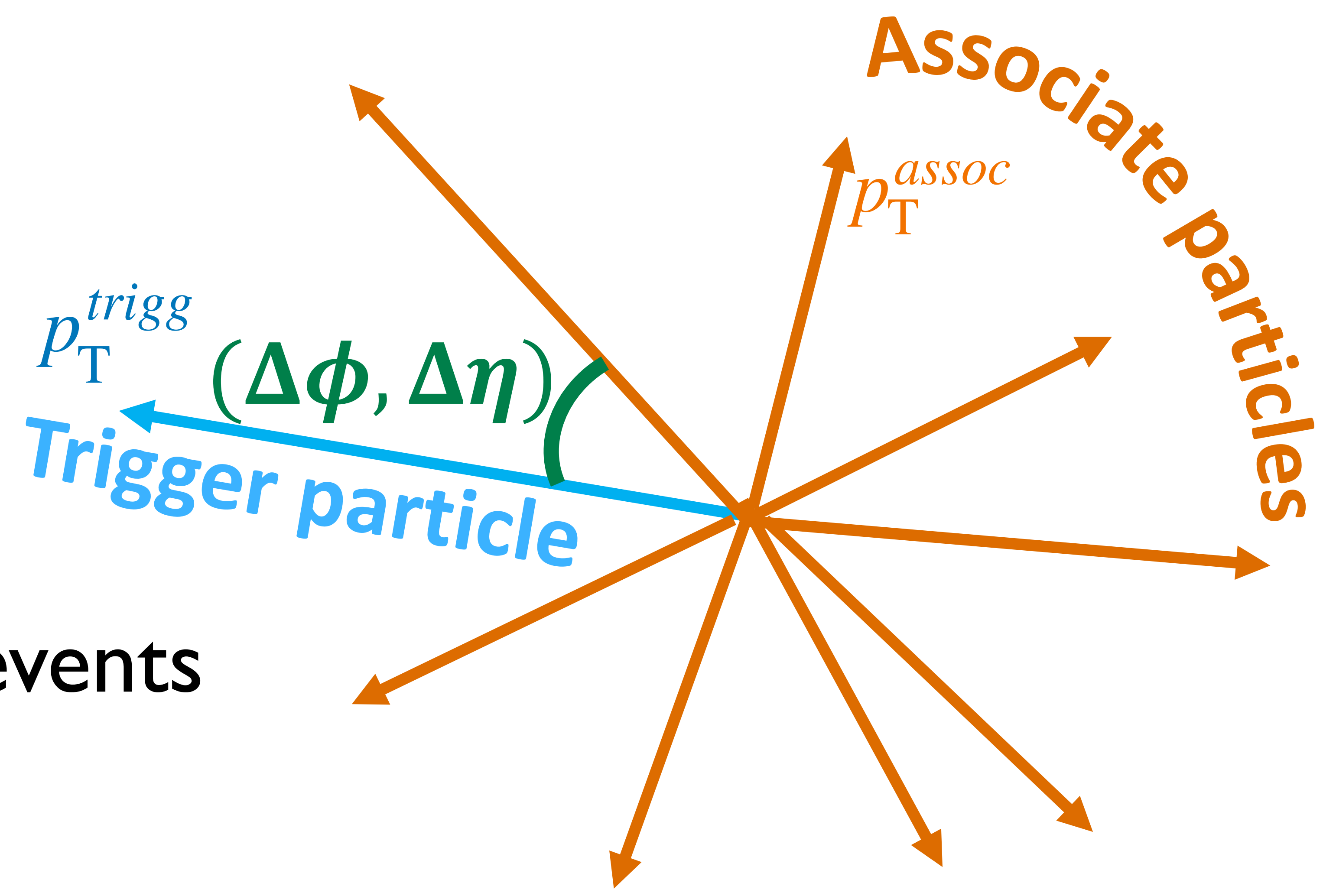
forward



backward

Two-particle angular correlations

Correlation function: $$\frac{1}{N_{trig}}\frac{d^2N_{pairs}}{d\Delta\phi d\Delta\eta} = B(0,0)\frac{S(\Delta\eta,\Delta\phi)}{B(\Delta\eta,\Delta\phi)}$$



Where

$$S(\Delta\eta,\Delta\phi) = \frac{1}{N_{trig}}\frac{dN^{same}_{pairs}}{d\Delta\phi}$$ → Correlated pairs from the same events

$$B(\Delta\eta,\Delta\phi) = \frac{1}{N_{pairs}(\Delta\phi=0)}\frac{dN^{mixed}_{pairs}}{d\Delta\phi}$$ → Uncorrelated pairs from mixed events

Background mixed events should have similar features with respect to signal

Fourier expansion

$$\frac{dN_{pairs}}{d\Delta\phi} = A\left[1 + 2\sum_{n=1}^{3}\langle V_n\rangle cos(n\cdot\Delta\phi)\right]$$

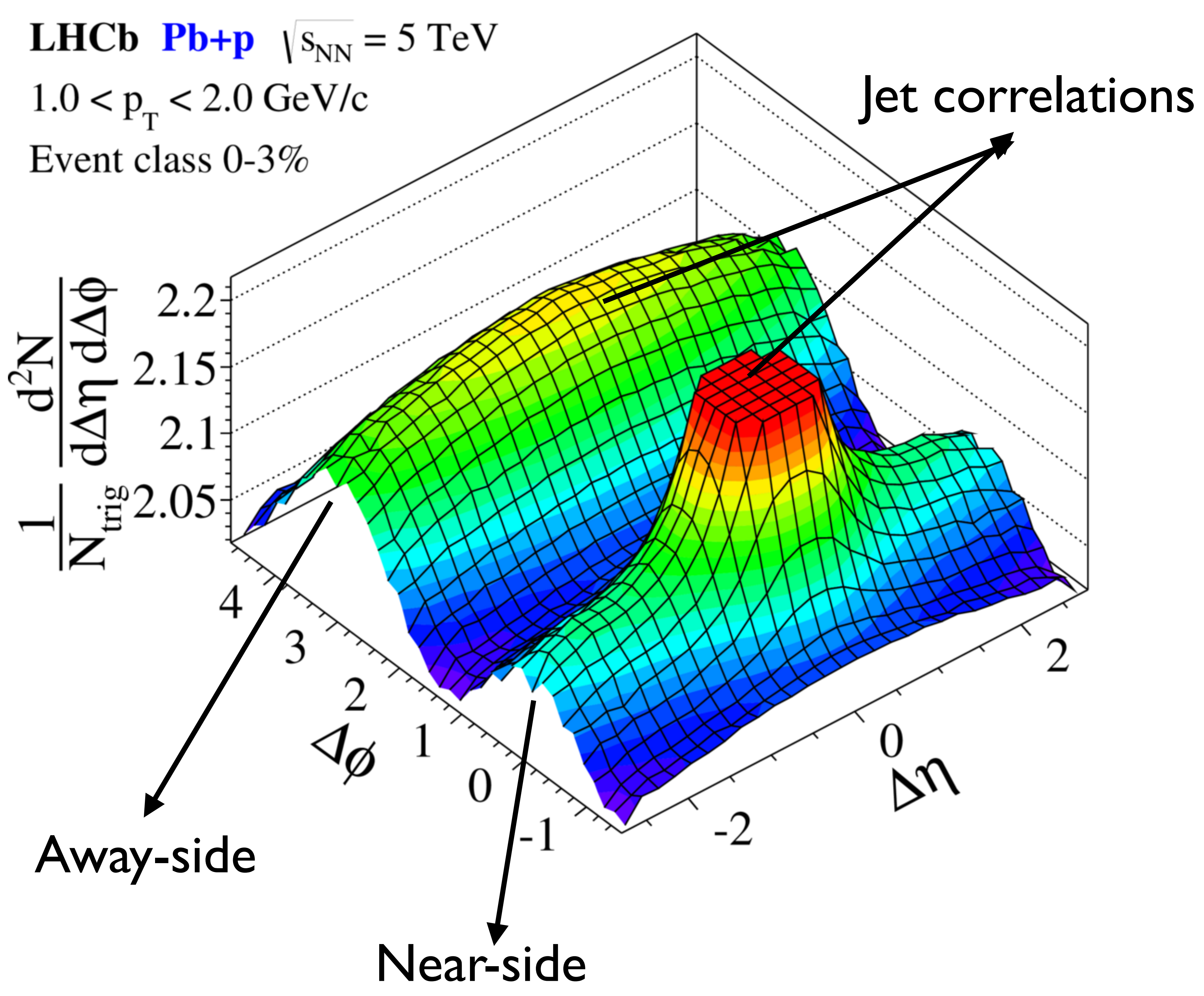
Fitting we extract → $v_n(p_T^{assoc}) = \frac{V_n(p_T^{assoc}, p_T^{trigg})}{\sqrt{V_n(p_T^{trigg}, p_T^{trigg})}}$

- v_1 → Directed flow
- v_2 → Eliptic flow
- v_3 → Triangular flow

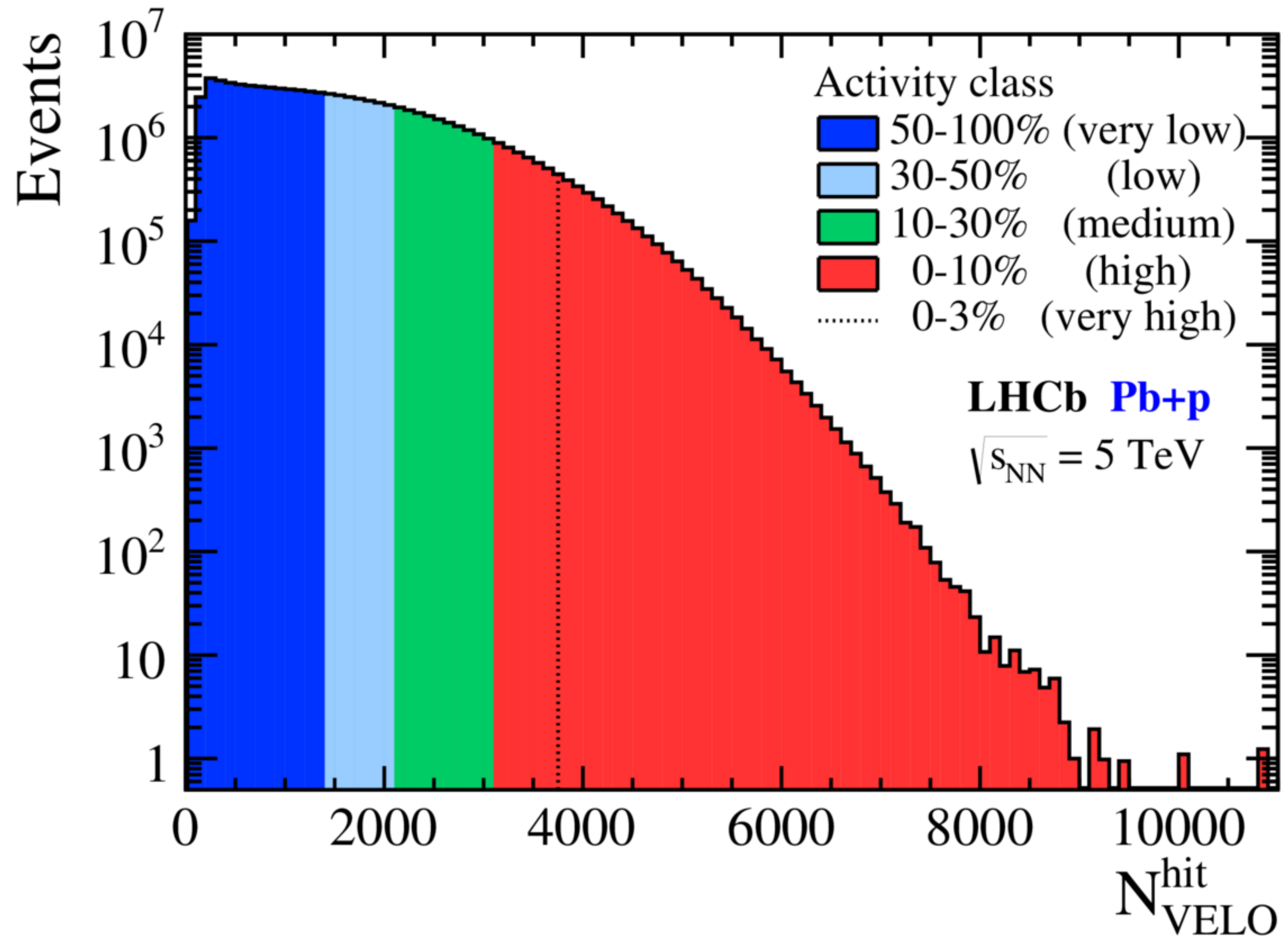
Two-particle angular correlations in pPb at 5 TeV

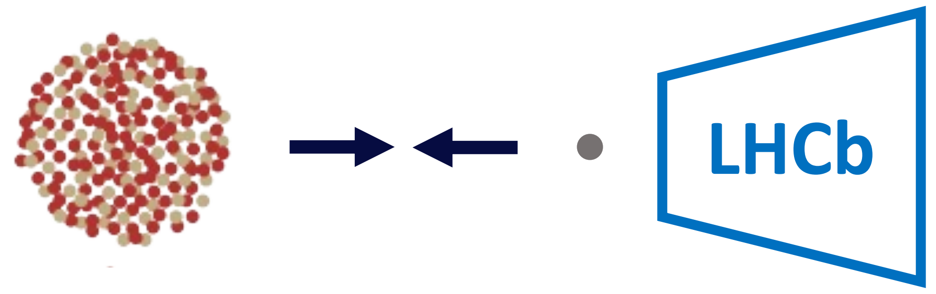
PLB.2016.09.064

- Correlation function: $\frac{1}{N_{trig}} \frac{d^2N_{pair}}{d\Delta\eta d\Delta\phi} = B(0,0)\frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$
- $\mathscr{L} = 95\,\mu b^{-1}$



Activity class definition based on percentiles of N_{VELO}^{hit} distribution*





*VErtex LOcator (VELO): LHCb Vertex detector

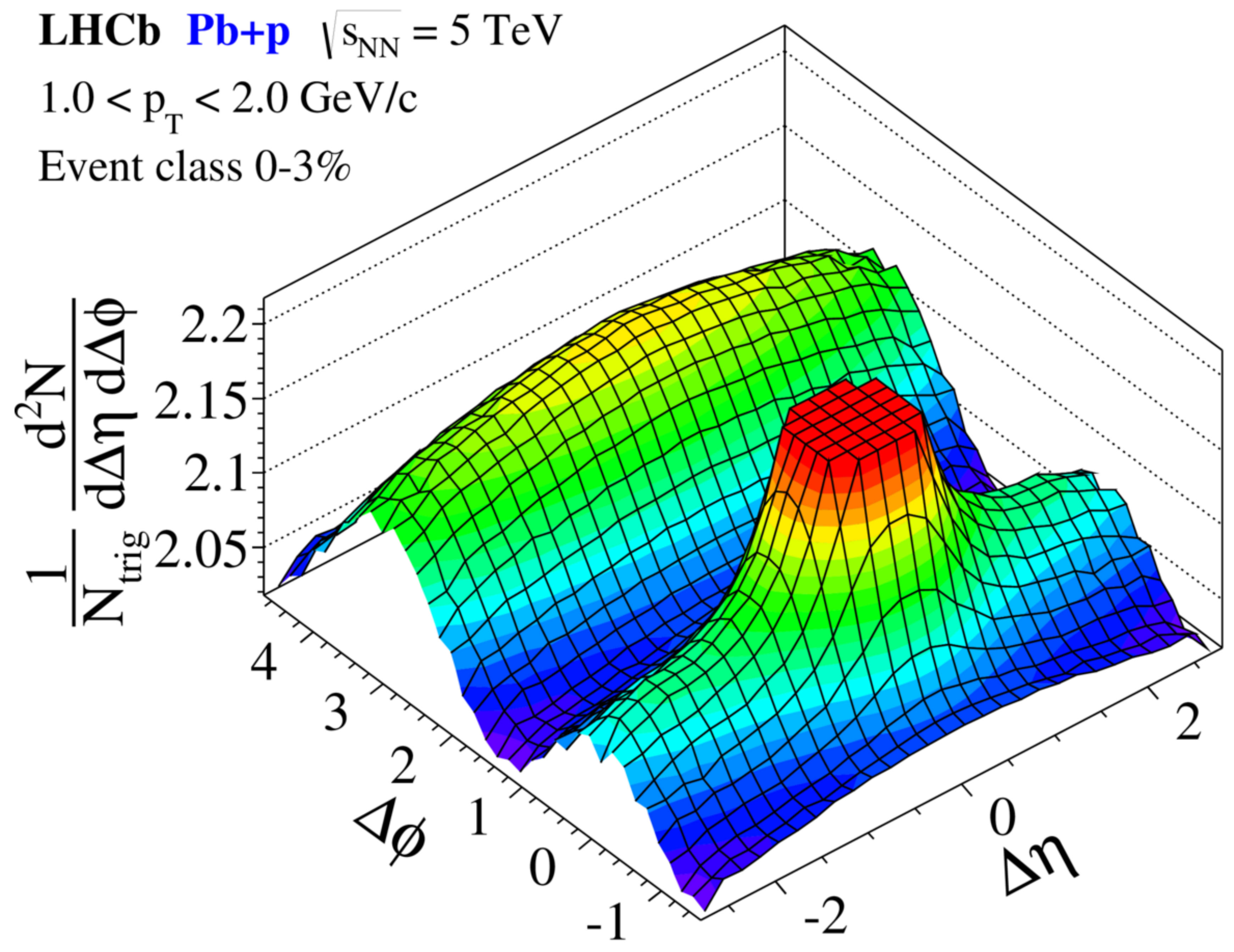
Two-particle angular correlations in pPb at 5 TeV

PLB.2016.09.064

Quantitative analysis:

- 1-dimensional yield: $Y(\Delta\phi) = \frac{1}{N_{trig}}\frac{dN_{pair}}{d\Delta\phi} = B(0,0)\frac{S(\Delta\phi)}{B(\Delta\phi)}$

- Integrating over $2 < |\Delta\eta| < 2.8$ to avoid short range (jet etc) contributions
- Using zero-yield-at-minimum (ZYAM) condition to remove flat pedestal $\rightarrow C_{ZYAM}$ from a second-order polynomial fit at $\Delta\phi_{min}$



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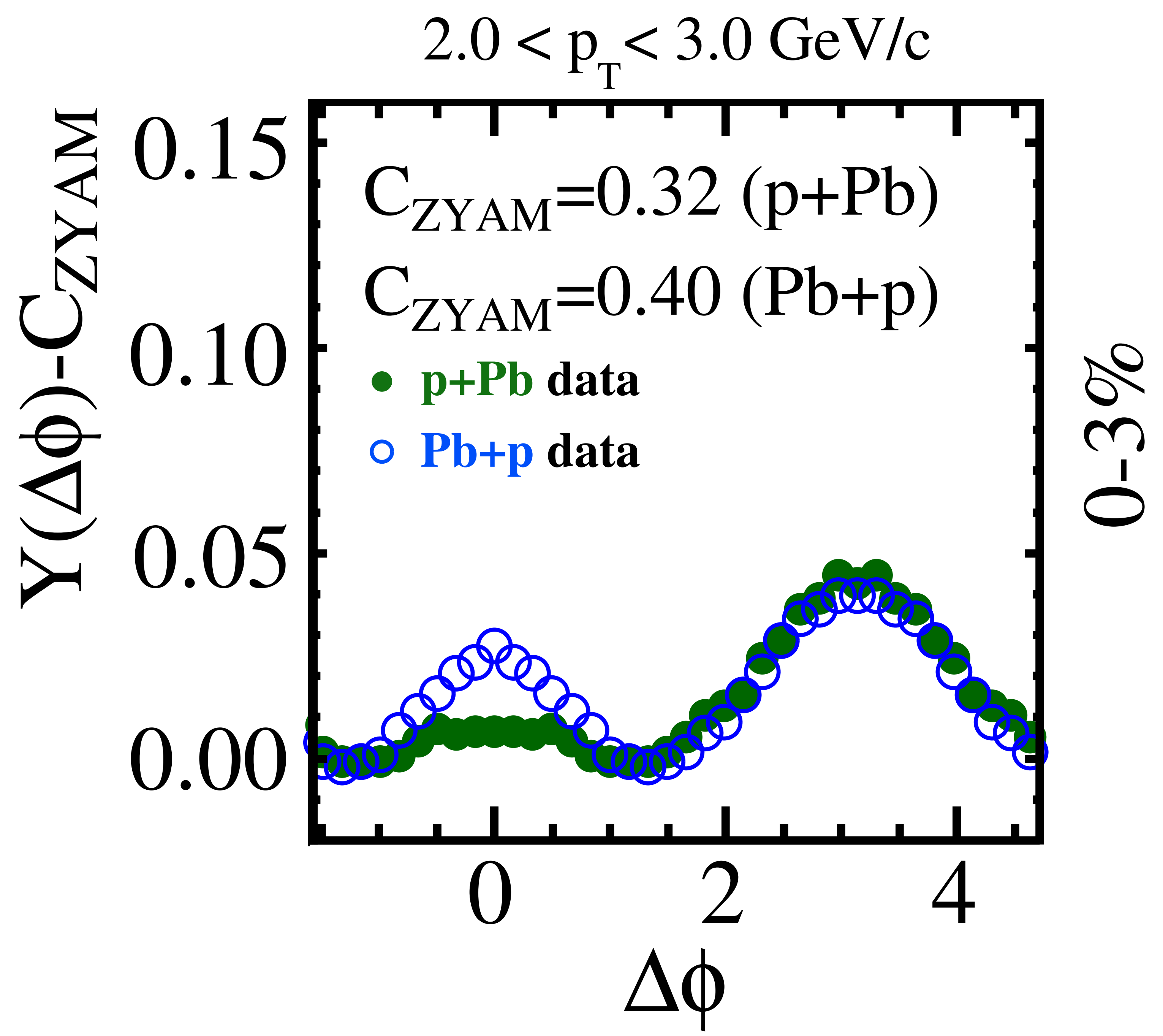

Two-particle angular correlations in pPb at 5 TeV

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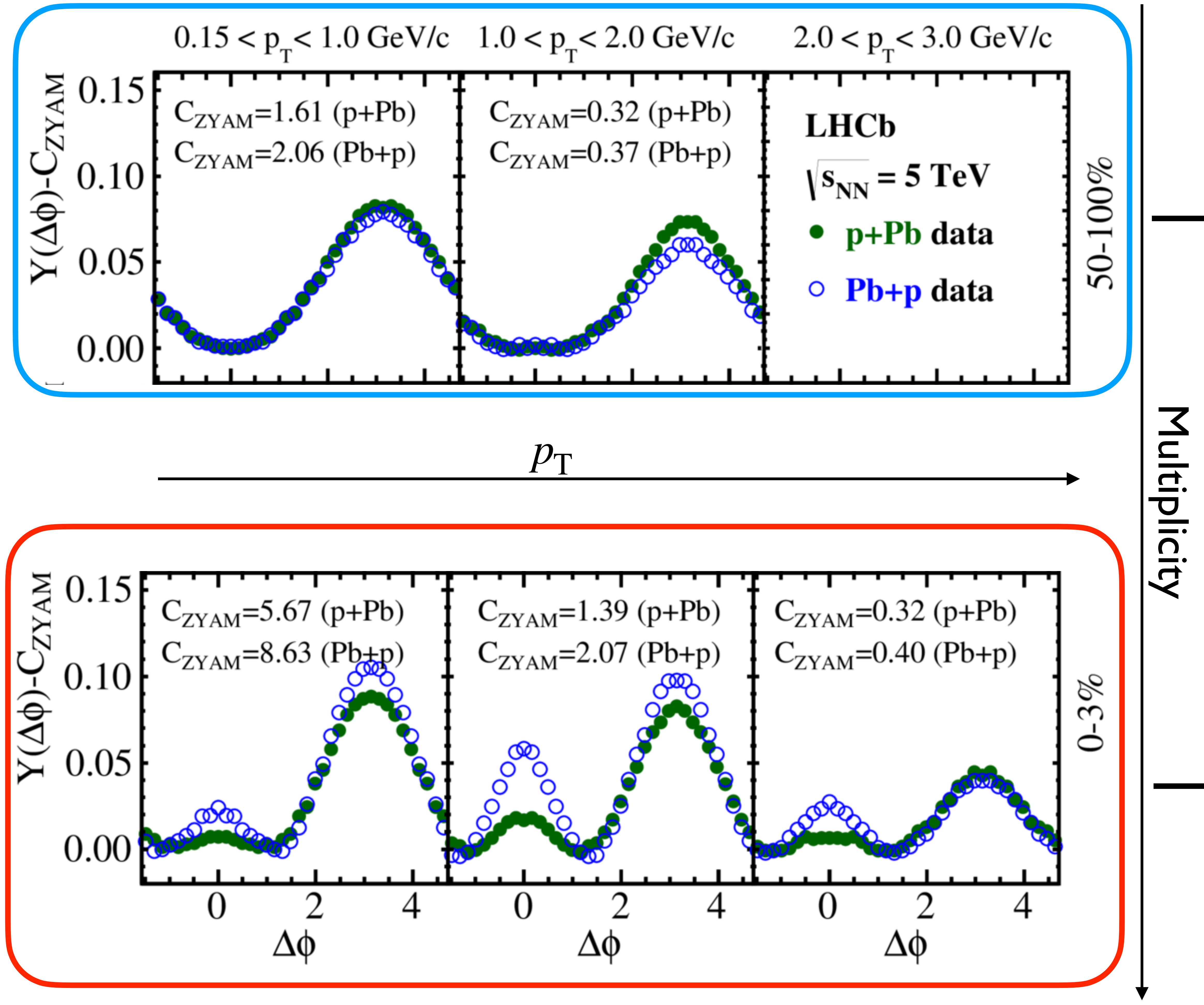


Lower activity events (>30%)

- No near-side peak
- Pronounced away-side peaks

High activity events (<30%)

- Near-side peak emerge
- Near-side peaks are higher in Pbp than in pPb
- p_T dependence for both near and away-side peak

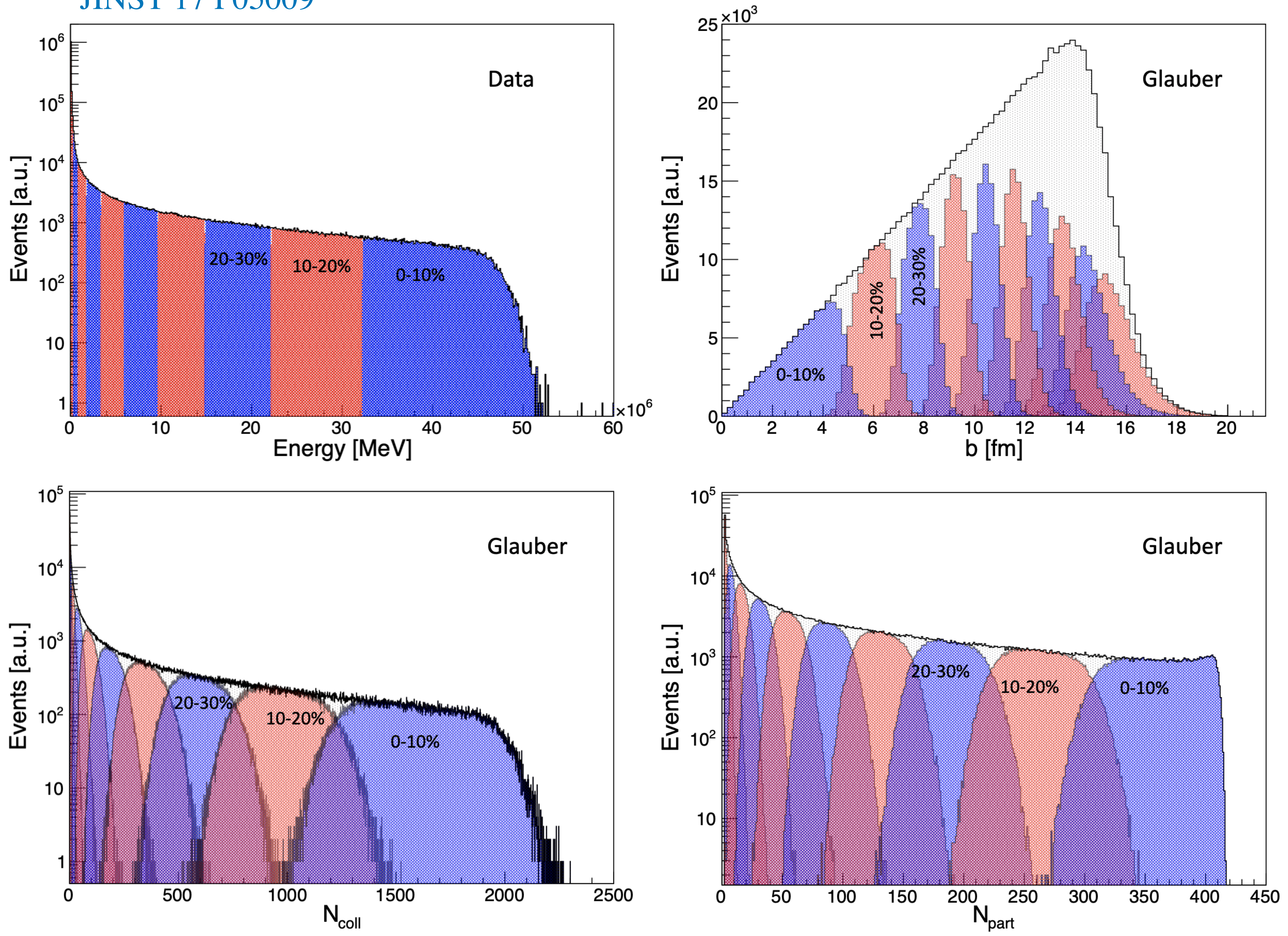
Ongoing analyses

Charged hadrons v_n in PbPb at $\sqrt{s_{NN}} = 5\,\text{TeV}$

- Charge hadron v_n in PbPb at 5TeV
- Centrality determination using calorimeter energy and MC Glauber
- Study direct flow in forward region
- $\mathscr{L} = 228\,\mu\text{b}^{-1}$

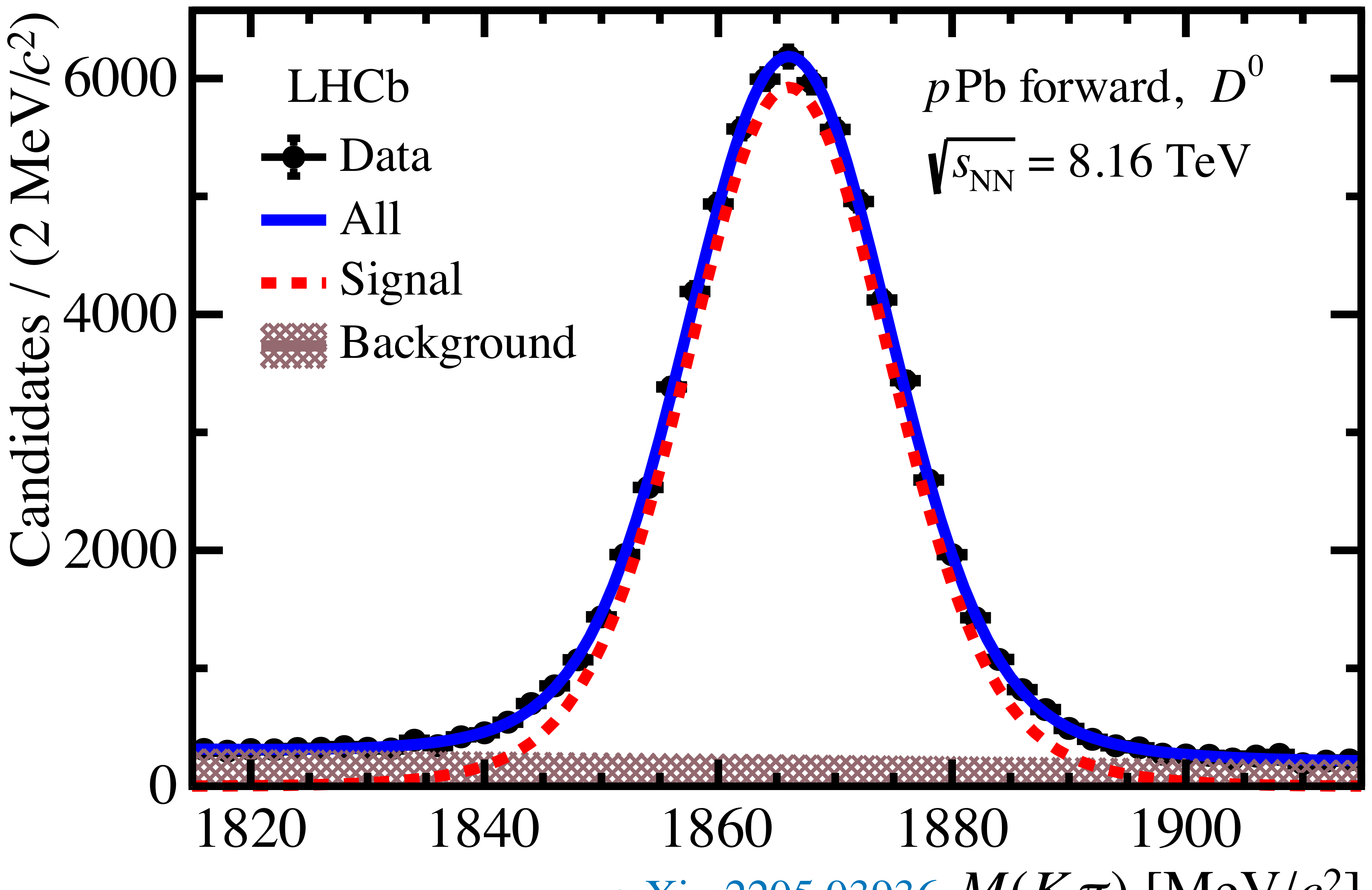
Events	Tracks	Pair
centrality 65 -100%	$p > 2\,\text{GeV}$ $2 \leq \eta \leq 4.9$	$\lvert\Delta\eta\rvert \geq 1$

JINST 17 P05009



Charged hadrons and charm v_n in pPb at $\sqrt{s_{NN}} = 8\,\text{TeV}$

- Study initial effects at low-x
- $\mathscr{L} \sim 15\,\text{nb}^{-1}$
- Multiplicity dependent measurement
- Multiplicity correction with response matrix
- Precise charmed mesons reconstruction→ High statistics



arXiv:2205.03936

Bose-Einstein correlations of identical pions in pPb

- Bose-Einstein correlations (BEC) → Enhanced production of identical particles with small momentum
- Measure scales that are referred to as *lengths of homogeneity* → Related with the geometrical size of the particle-emitting source
- Correlation radius scales universally with the cube root of the charge-particle multiplicity

Data sample: 2013 pPb/Pbp data at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$

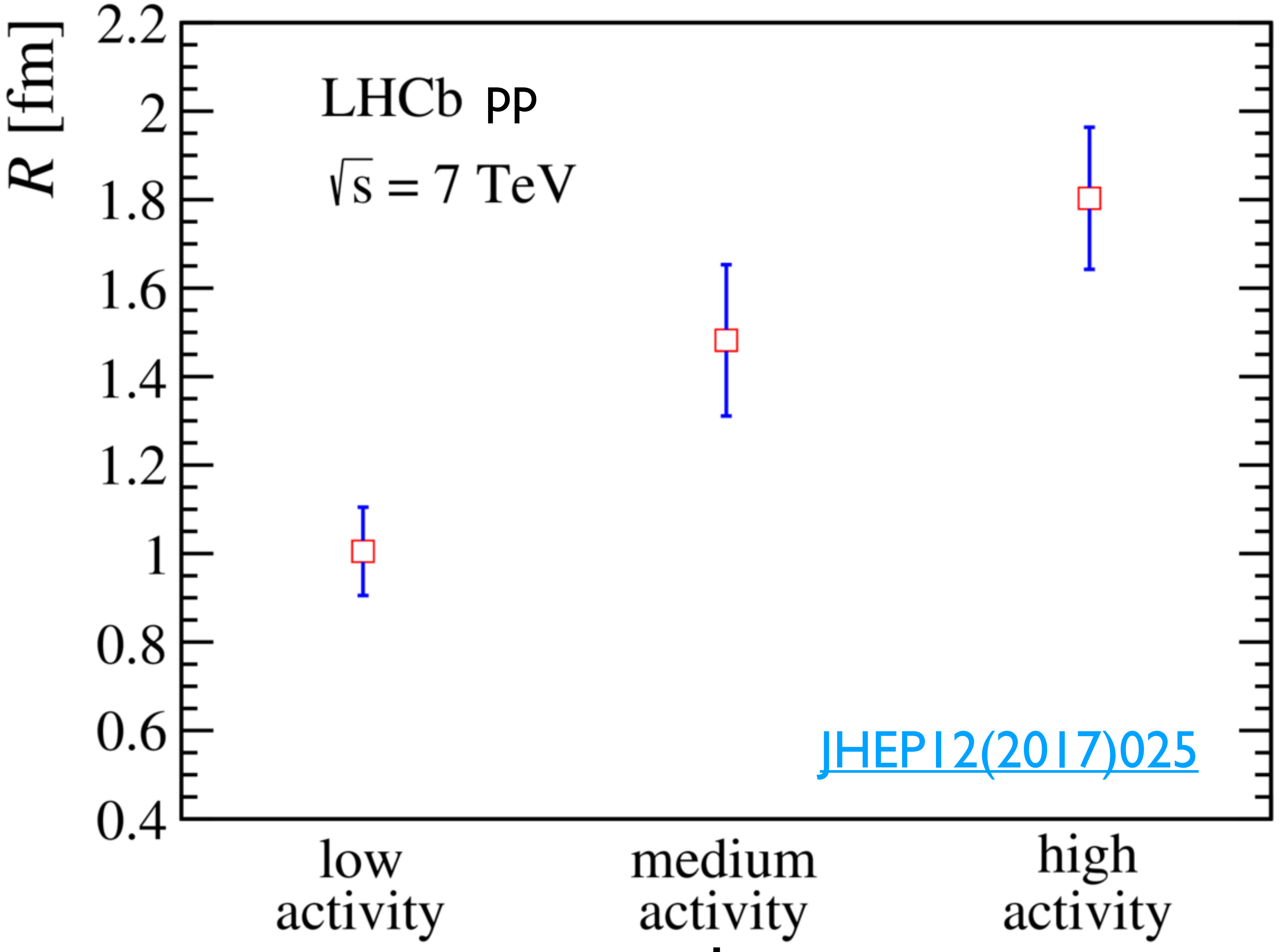
In progress

1. Two-particle correlation function

$$C_2(Q) = \left(\frac{N^{ref}}{N^{sig}}\right)\left(\frac{dN^{sig}(Q)/dQ}{dN^{ref}(Q)/dQ}\right) \text{ where } Q \equiv \sqrt{-q^2} = \sqrt{-(k_1 - k_2)^2}$$

Where
- N^{sig} → Sample with BEC. Same-sign charged particles
- N^{ref} → Sample free from BEC. Event-mixing method

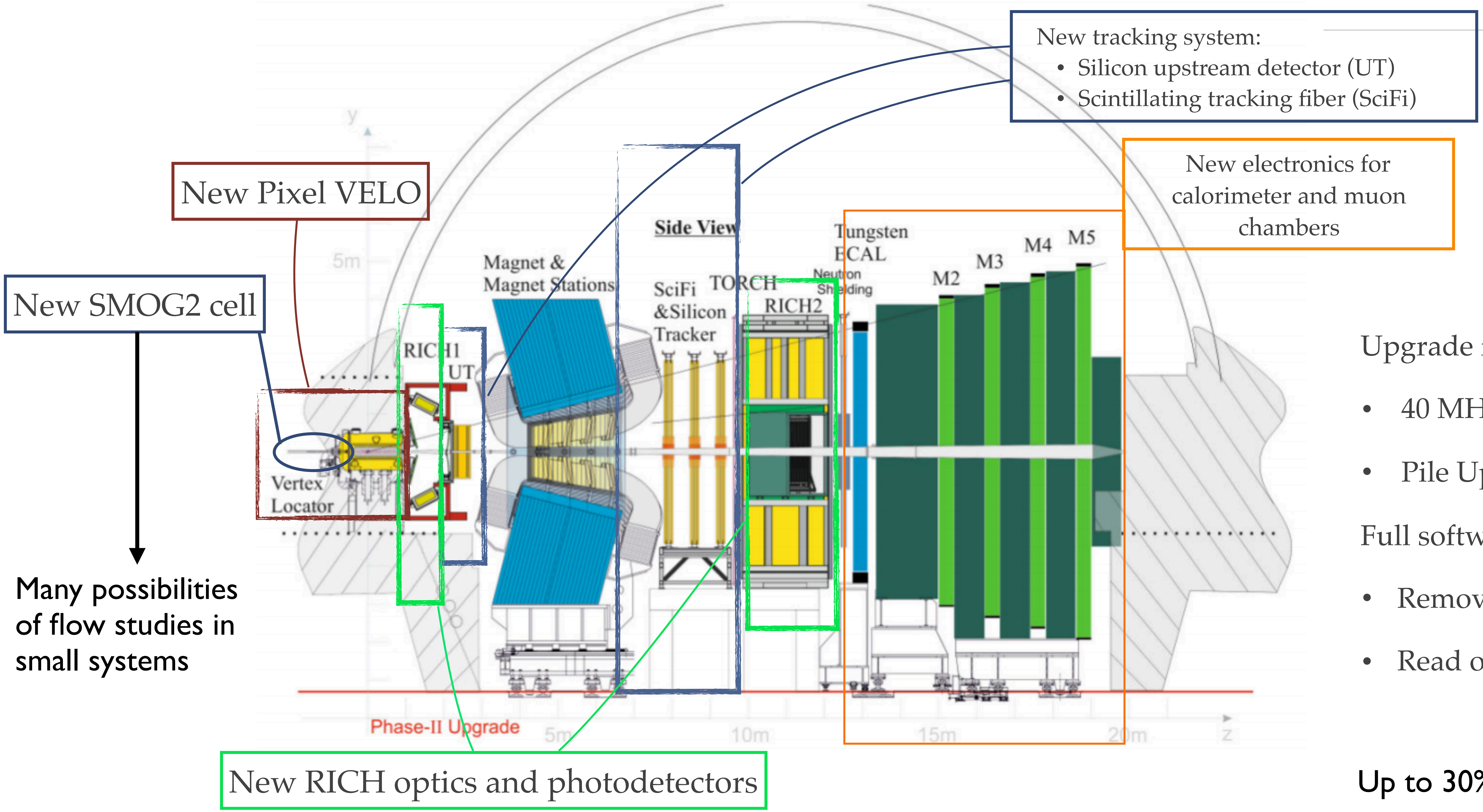
2. Levy-type parametrization: $C_2(Q) = 1 + e^{-|RQ|}$ → Correlation radius, R



VErtex LOcator activity based classification

LHCb at Run3

[CERN-LHCC-2012-007]



Many possibilities of flow studies in small systems

Upgrade for pp requirement

- 40 MHz collision rate
- Pile Up factor ~ 5

Full software trigger

- Remove L0 triggers.
- Read out full detector at 40 MHz.

Up to 30% centrality in PbPb

Summary

- Two-particle angular correlations → Initial state properties

- LHCb can
  - Access low-x physics in pPb and PbPb, $10^{-6} < x < 10^{-1}$
  - Measure two-particle correlations in a complementary pseudorapidy region to other experiments, $2.0 < \eta < 4.9$

Ongoing analysis:

- Centrality dependence of two-particle angular correlations in PbPb at $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$
- Multiplicity dependence of two-particle angular correlations in pPb at $\sqrt{s_{NN}} = 8\,\mathrm{TeV}$
- Study of the Bose-Einstein correlations of identical pions in pPb at $\sqrt{s_{NN}} = 5\,\mathrm{TeV}$

More LHCb results will come in the future →Stay tuned

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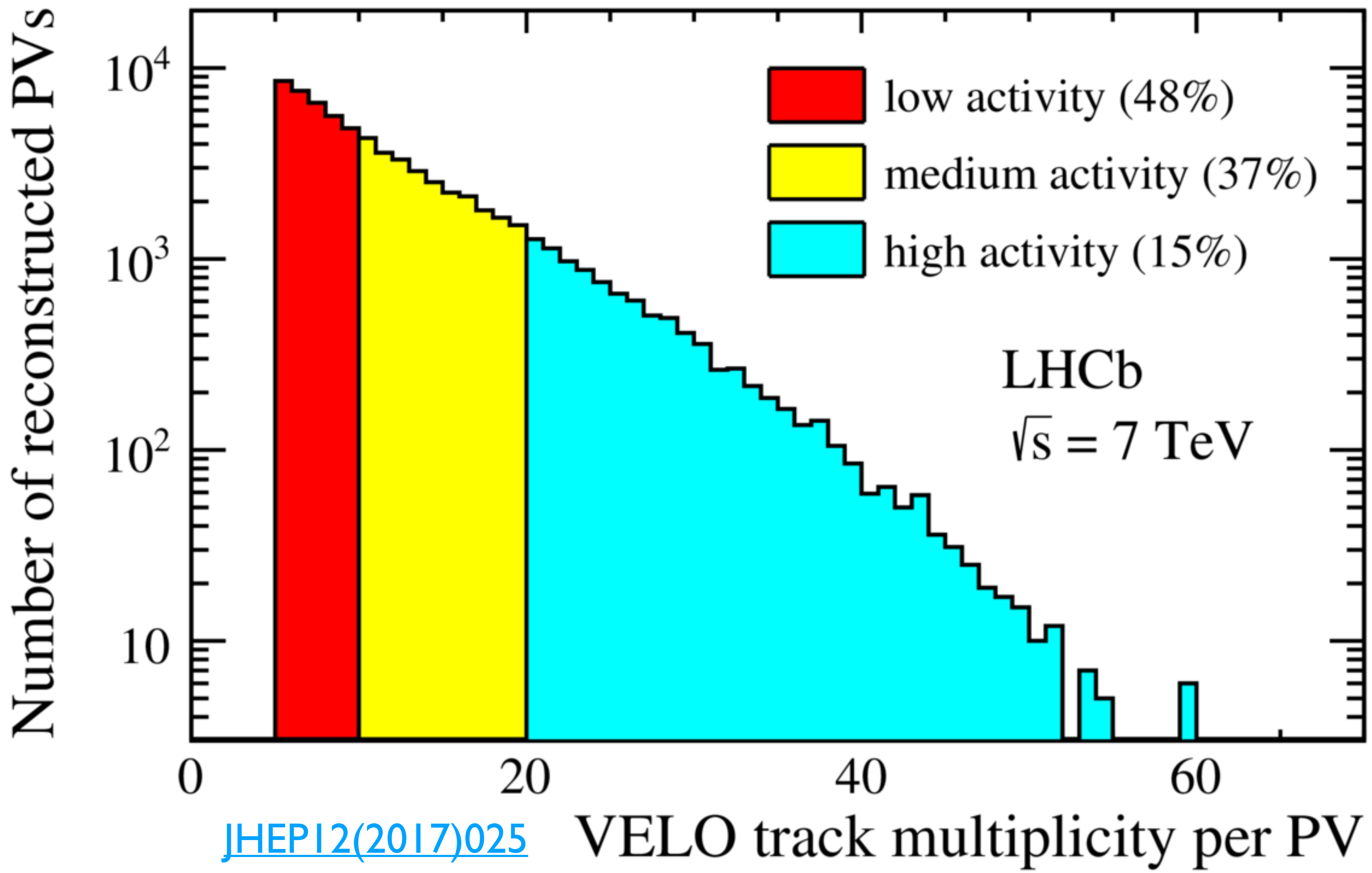
Backup: Event activity classification

- Multiplicity of reconstructed VELO tracks assigned to a PV for the 2011 no-bias sample.
- Different colours indicate three activity classes defined as fractions of the full distribution.
- The minimum value of the track multiplicity to accept reconstructed PV is five



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