



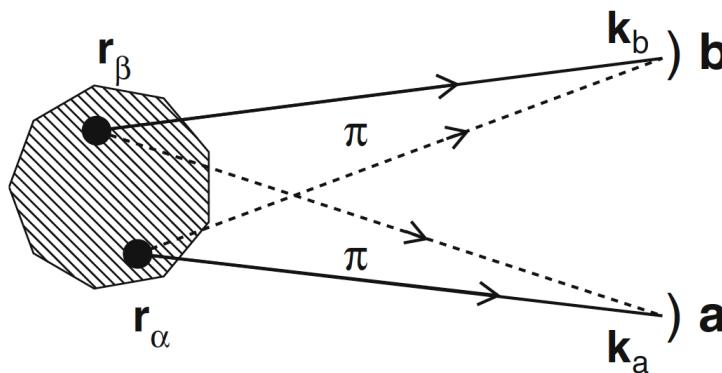
Bulk flow and correlation measurements at LHCb

Cheuk-Ping Wong [cwong1@bnl.gov]
on behalf of the LHCb Collaboration

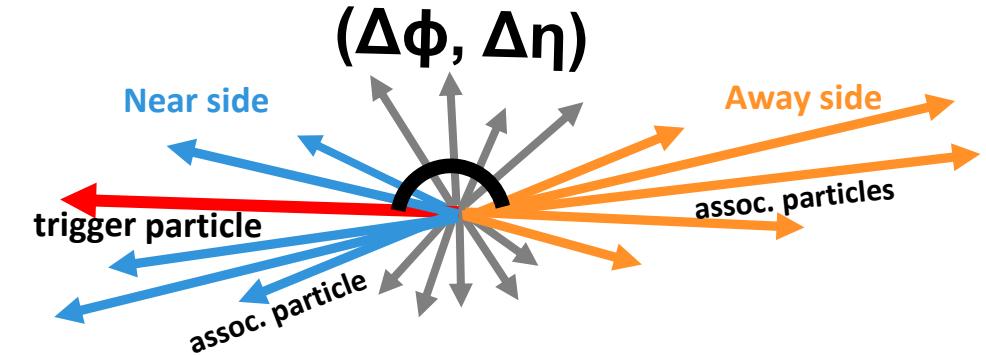
09-05-2023 / Quark Matter 2023 / Houston, Texas

Two-particle correlations in the forward region

Bose-Einstein correlations (BEC)
Momentum correlations

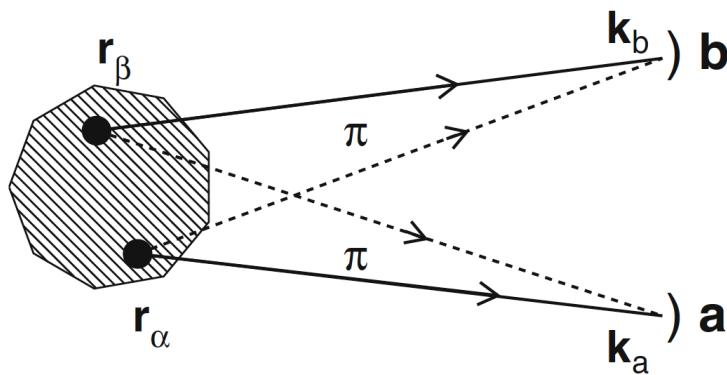


Particle flow harmonics
Angular correlations

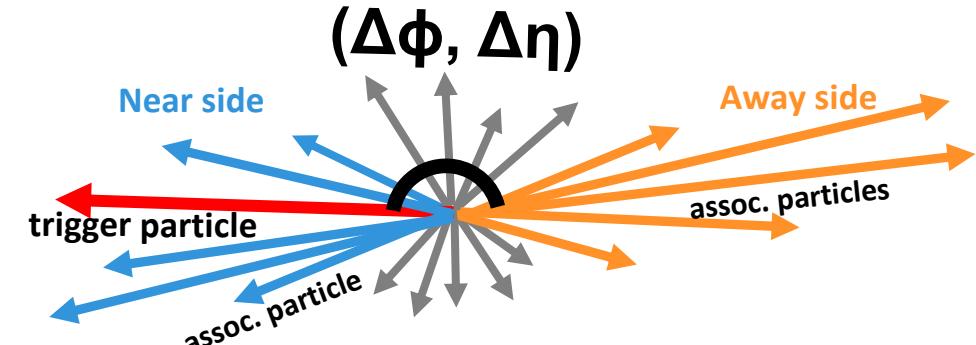


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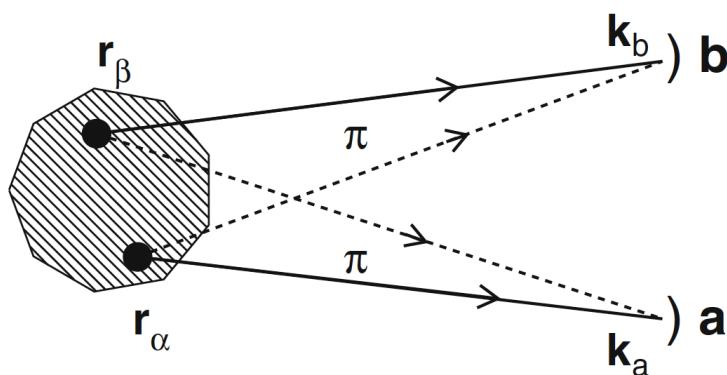


- Study the **space-time properties** of the particle-emitting source
- Small systems, like $p\text{Pb}$, with a shorter lifetime provide better probes to **the early system dynamics** and **the initial geometry**
- The forward region may contain information of **quantum interference effects**

Two-particle correlations in the forward region

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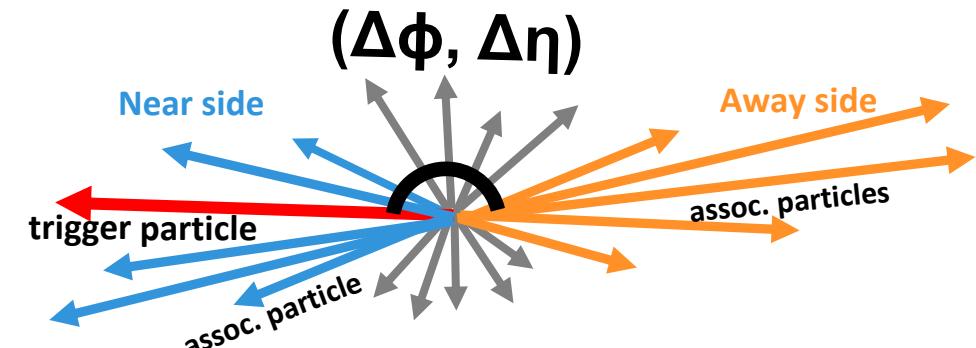
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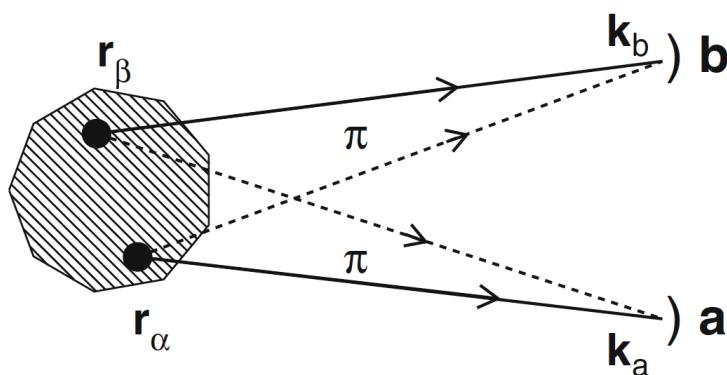
- Study the **evolution** and the **transport properties** of the QGP
- Forward region is dominated by the "**cooler" hadronic phase**"
→ Test hydrodynamic and transport models with the non-equilibrium hadronic phase

Complementary to other LHC results at mid rapidity

Two-particle correlations in the forward region

Bose-Einstein correlations (BEC)

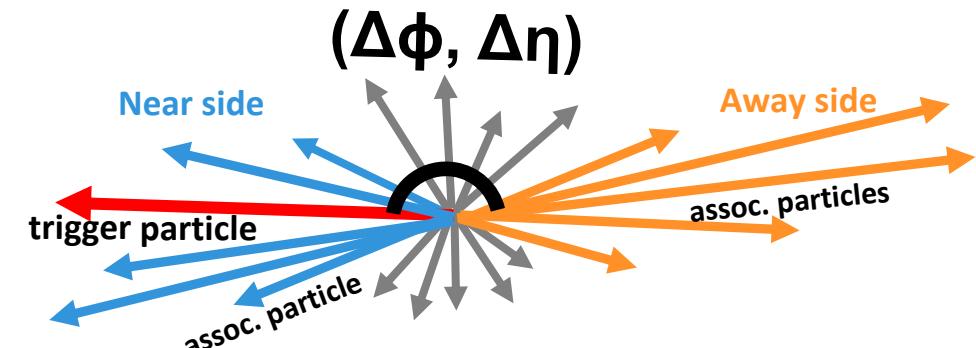
Momentum correlations



- $p\text{Pb}$ collisions at 5 TeV
 - 63M events
 - $\int Ldt = 1.06 \text{ nb}^{-1}$
- $\text{Pb}p$ collisions at 5 TeV
 - 57M events
 - $\int Ldt = 0.52 \text{ nb}^{-1}$
- Same-sign charged π

Particle flow harmonics

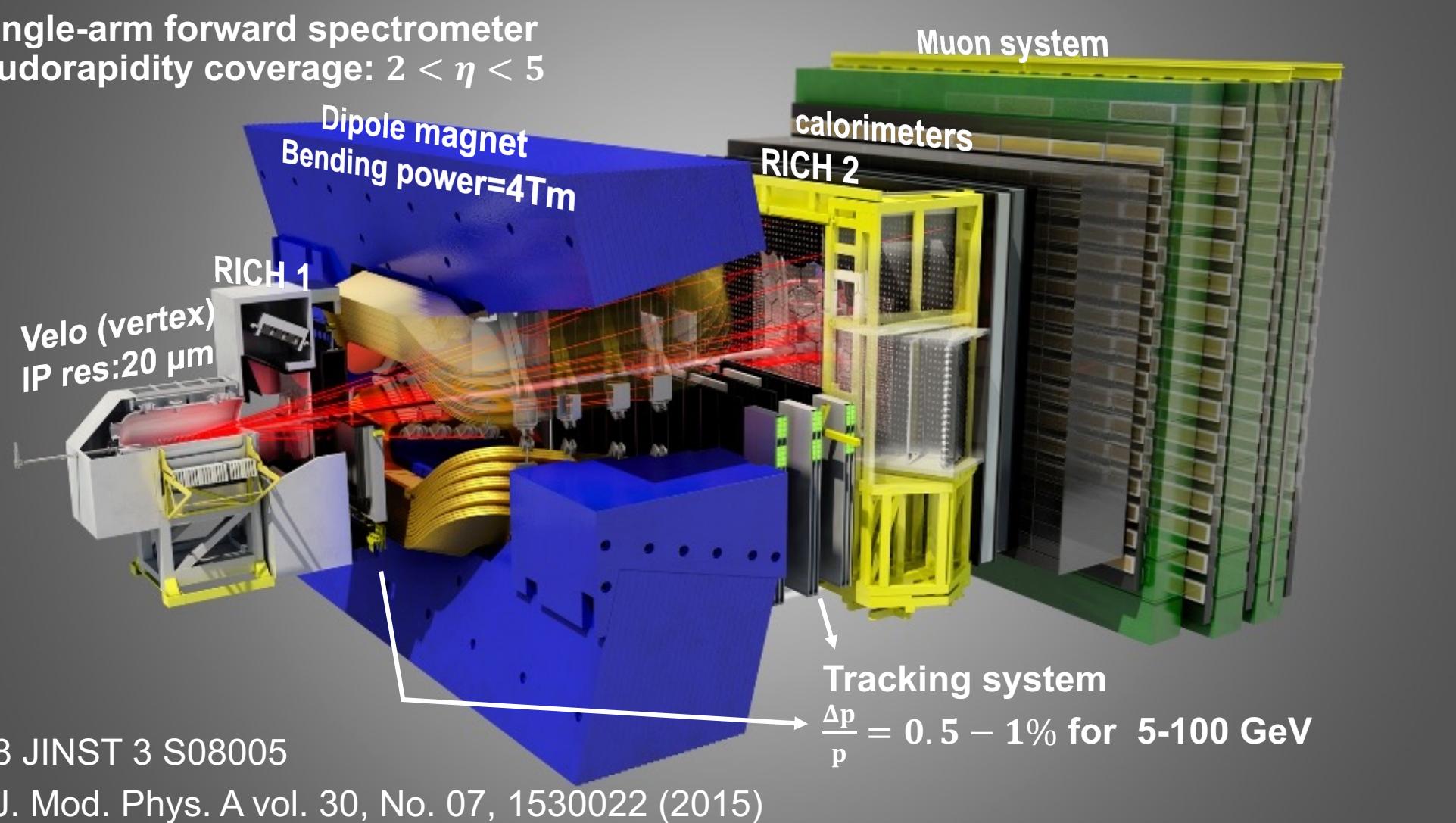
Angular correlations



- PbPb collisions at 5 TeV
 - 3B events
 - $\int Ldt = 214 \mu\text{b}^{-1}$
- Nonidentified charged hadrons

LHCb detector

A single-arm forward spectrometer
Pseudorapidity coverage: $2 < \eta < 5$

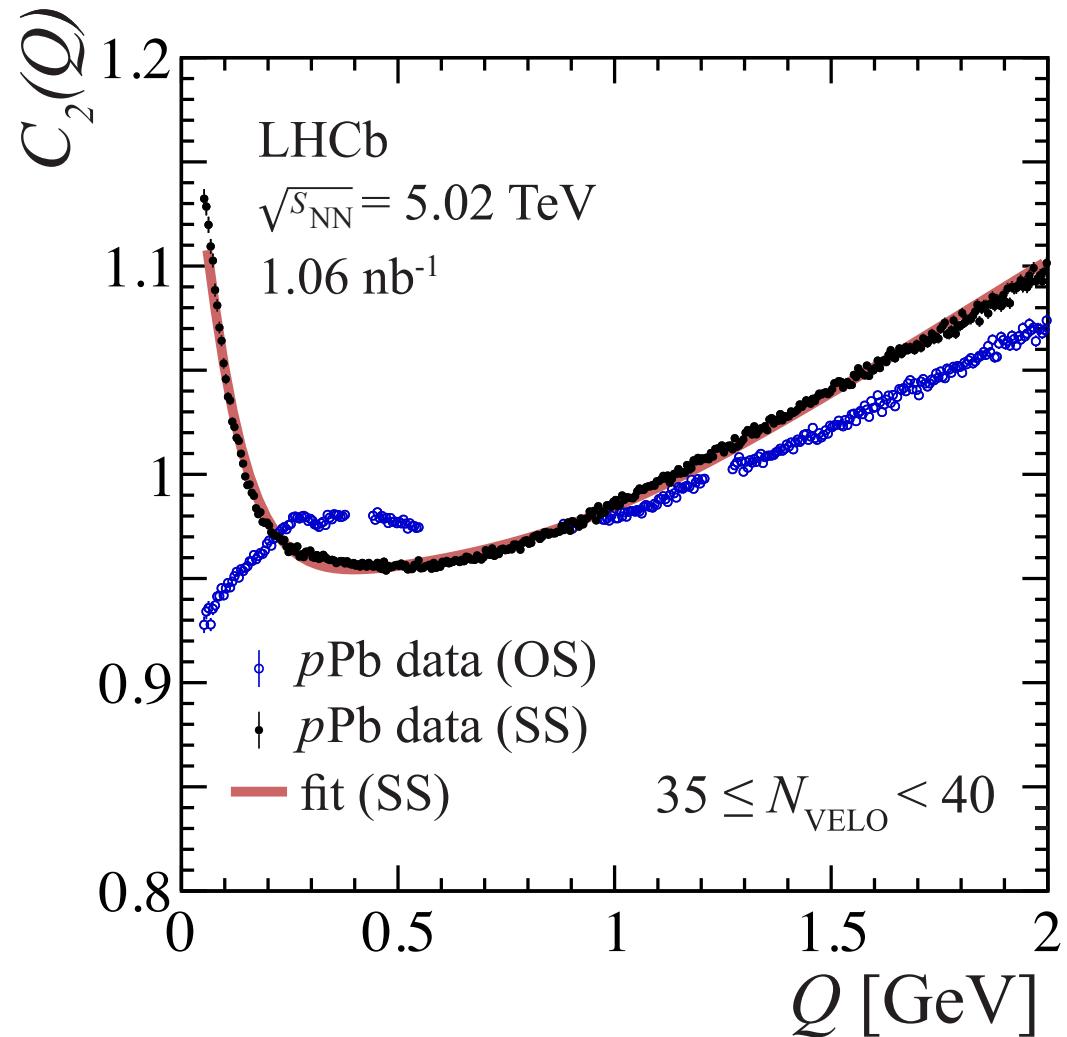


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Int. J. Mod. Phys. A vol. 30, No. 07, 1530022 (2015)

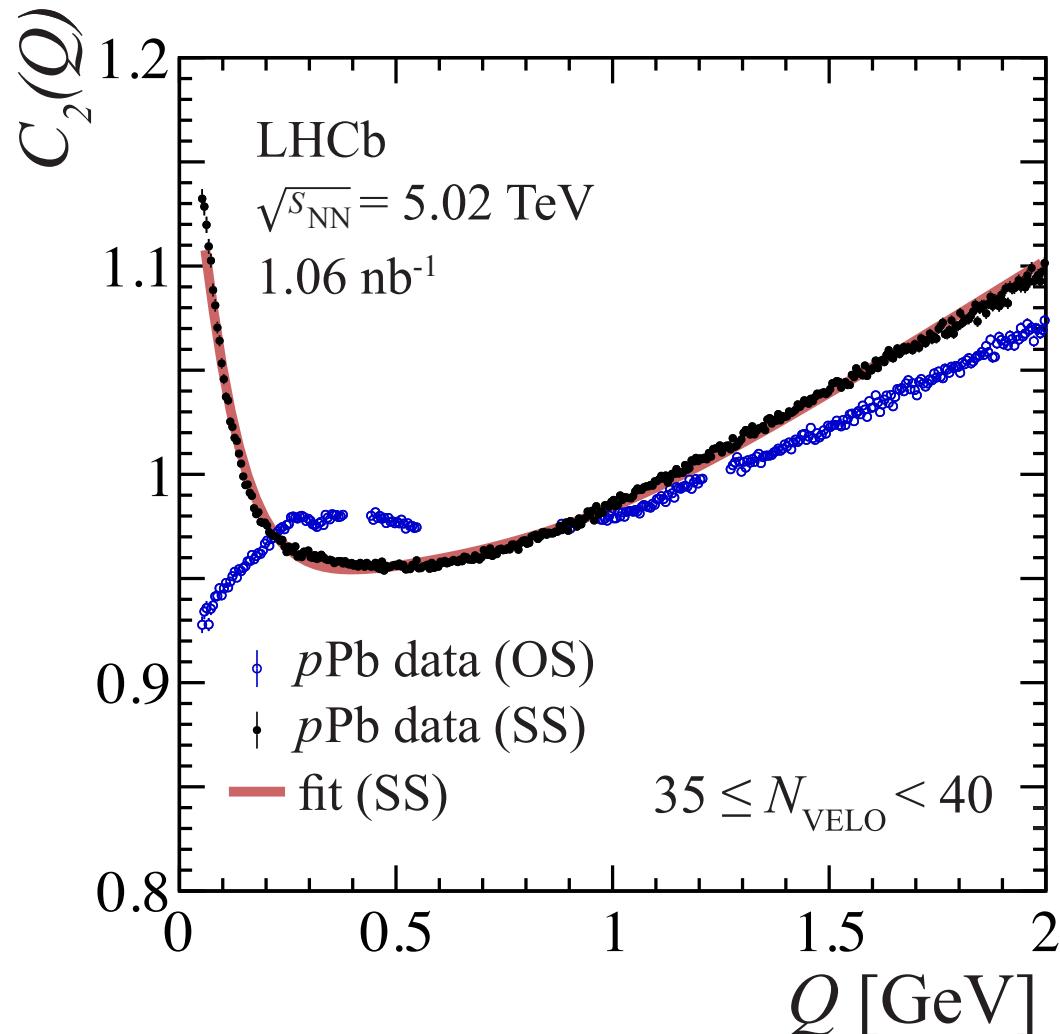
Bose-Einstein correlations in $p\text{Pb}$ and $\text{Pb}p$ collisions

BEC of same-sign π



- Same-sign (SS) charge π correlations
- Detector acceptance correction using event-mixing technique
- Use opposite-sign (OS) π pairs to extract nonfemtoscopic background

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- Parameterize using Bowler–Sinyukov formalism:

$$\sqrt{-(k_1 - k_2)^2}$$

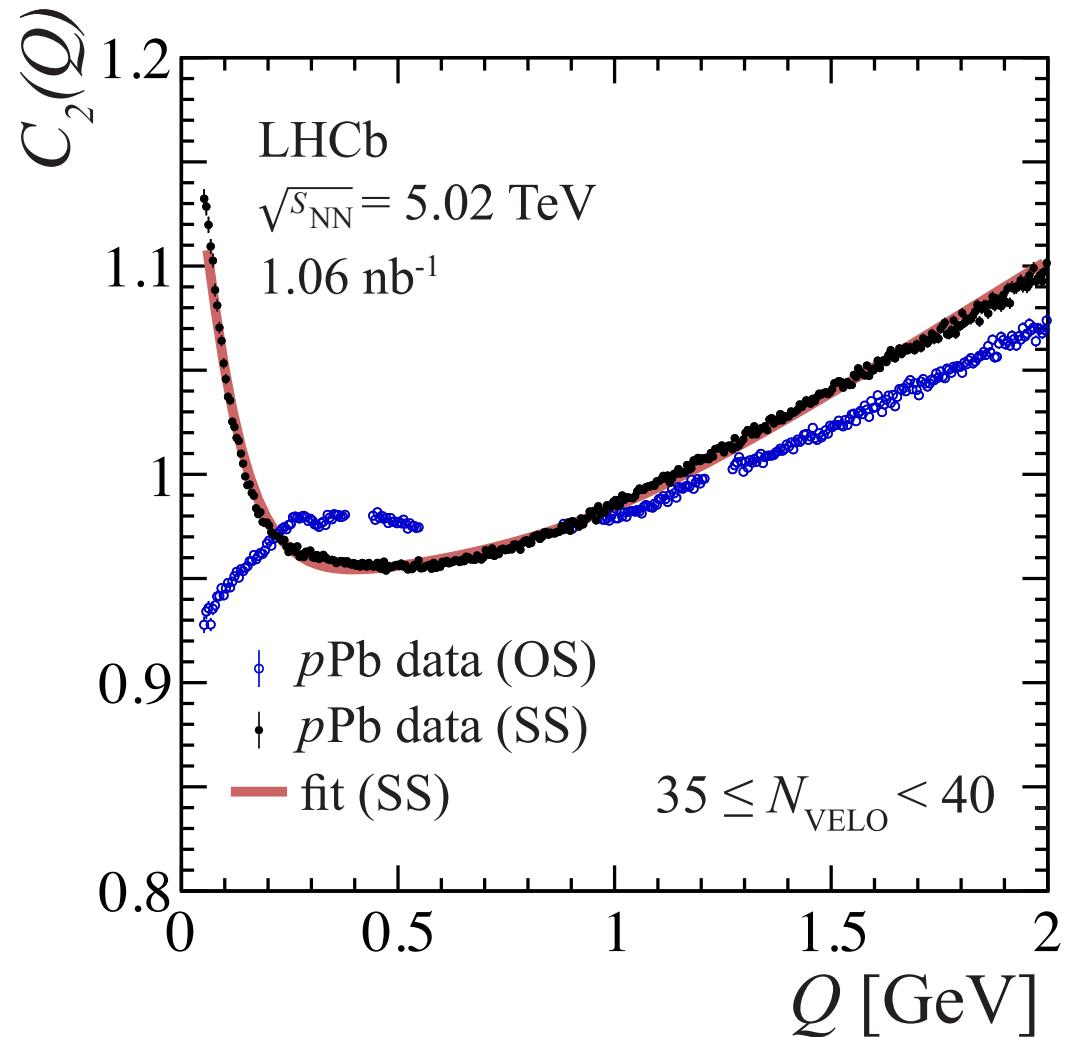
$$C_2(Q) = N[1 - \lambda + \lambda K(Q) \times (1 + e^{-|RQ|})] \times \Omega(Q)$$

Coulomb interaction term
for point-like source

Levy-type correlation
 $C_{2,\text{BEC}}(Q)$, with $a_L = 1$

Nonfemtoscopic
background contributions
Determined using OS pairs

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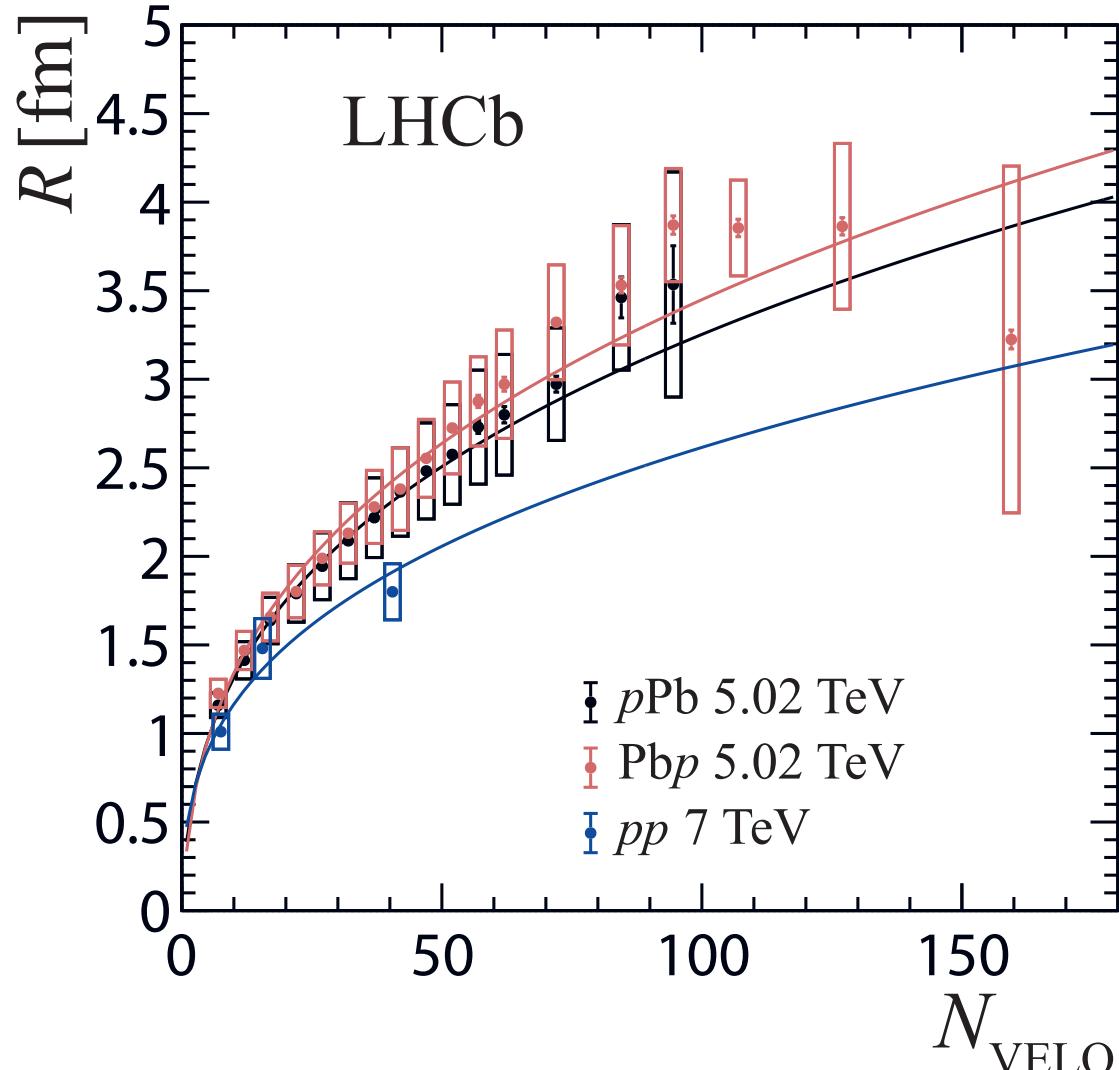
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Nonfemtoscopic
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Determined using OS pairs

- R : correlation radius
→ effective size of the particle emitting source
- λ : intercept parameter
→ correlation strength

Correlation radius vs multiplicity



$$\sqrt{-(k_1 - k_2)^2}$$
$$C_2(Q) = N[1 - \lambda + \lambda K(Q) \times (1 + e^{-|RQ|})] \times \Omega(Q)$$

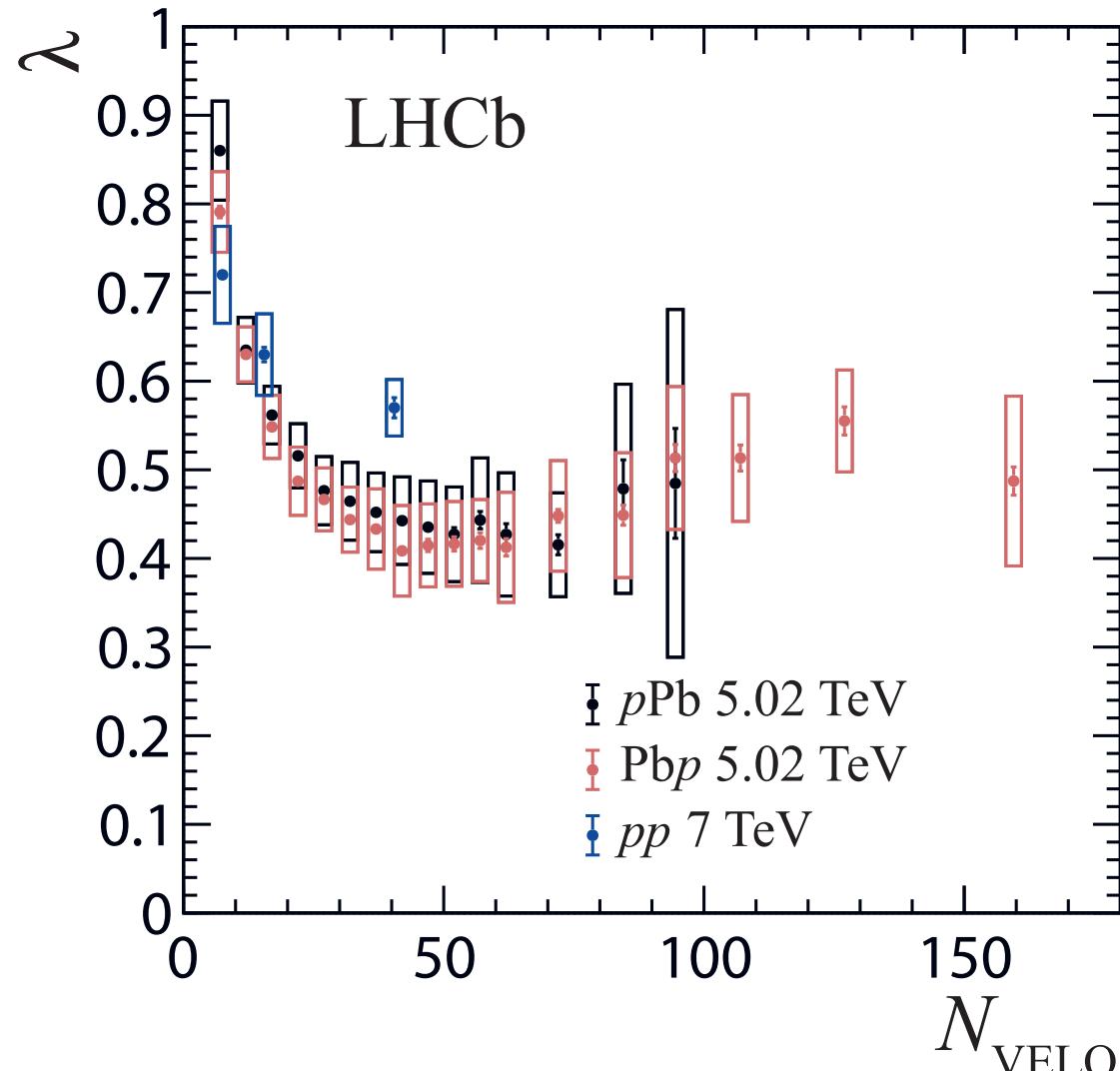
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- N_{VELO} : charged particle multiplicity measured using VELO
- The correlation radius increases with the charged-particle multiplicity
- $R \propto \sqrt[3]{N_{\text{VELO}}}$
- R of Pbp system is systematically higher than $p\text{Pb}$ and pp systems but the uncertainties prevent concise conclusions

Intercept parameter vs multiplicity



$$\lambda = \sqrt{-(k_1 - k_2)^2} C_2(Q) = N [1 - \lambda + \lambda K(Q) \times (1 + e^{-|RQ|})] \times \Omega(Q)$$

Coulomb interaction term
for point-like source

Levy-type correlation
 $C_{2,\text{BEC}}(Q)$, with $a_L = 1$

Nonfemtoscopic
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- The intercept parameter decreases with the charged-particle multiplicity
- Stronger correlation in high multiplicity events

Forward particle flow in PbPb at 5 TeV via two-particle angular correlations

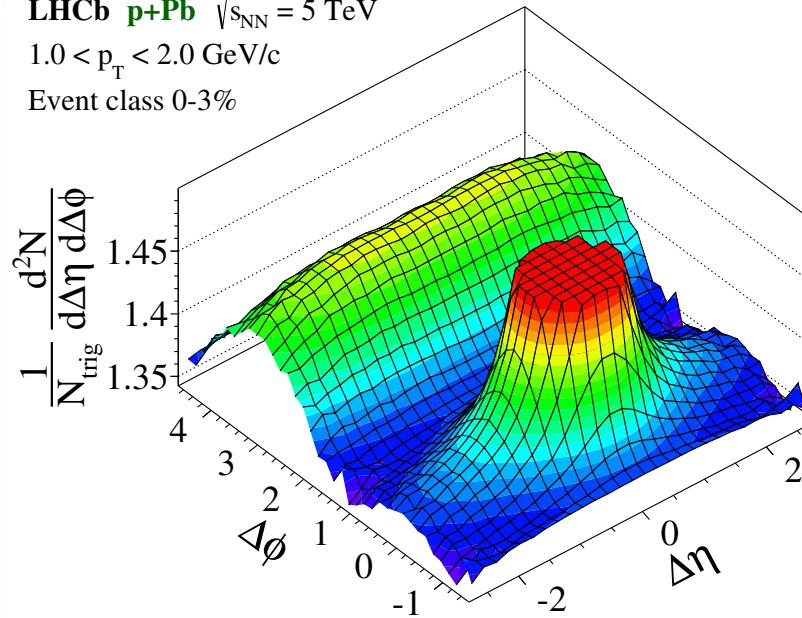
Forward charged-hadron correlations in small systems

PLB 762 (2016) 473

LHCb **p+Pb** $\sqrt{s_{NN}} = 5 \text{ TeV}$

$1.0 < p_T < 2.0 \text{ GeV}/c$

Event class 0-3%

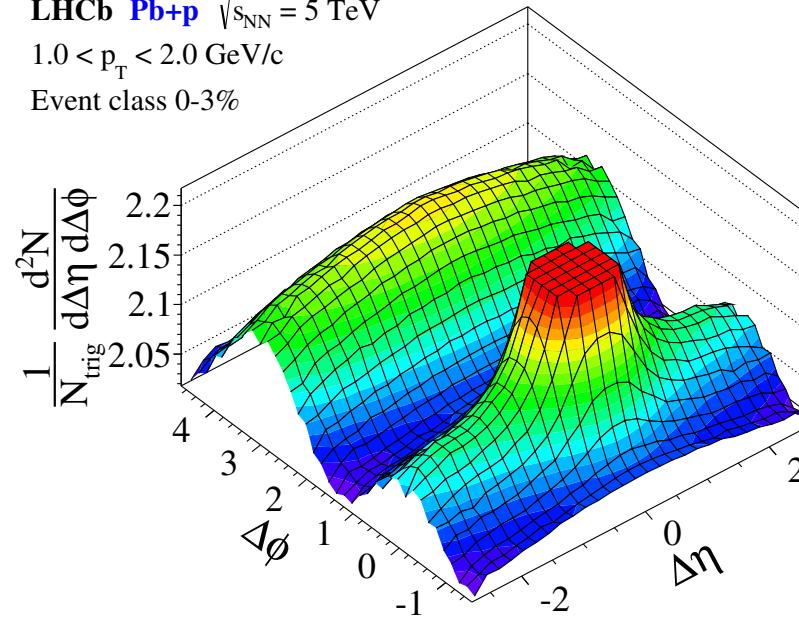


PLB 762 (2016) 473

LHCb **Pb+p** $\sqrt{s_{NN}} = 5 \text{ TeV}$

$1.0 < p_T < 2.0 \text{ GeV}/c$

Event class 0-3%



- Detector acceptance correction using event-mixing technique
- Noticeable near-side ridge in Pb_p compared to pPb events

Forward charged-hadron correlations in small and large systems

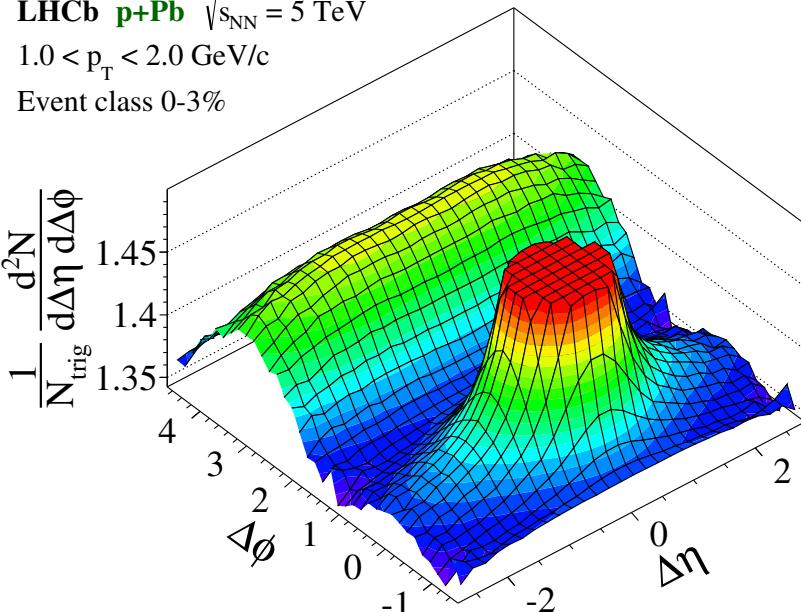
PbPb 5 TeV
LHCb-PAPER-2023-031
In preparation

PLB 762 (2016) 473

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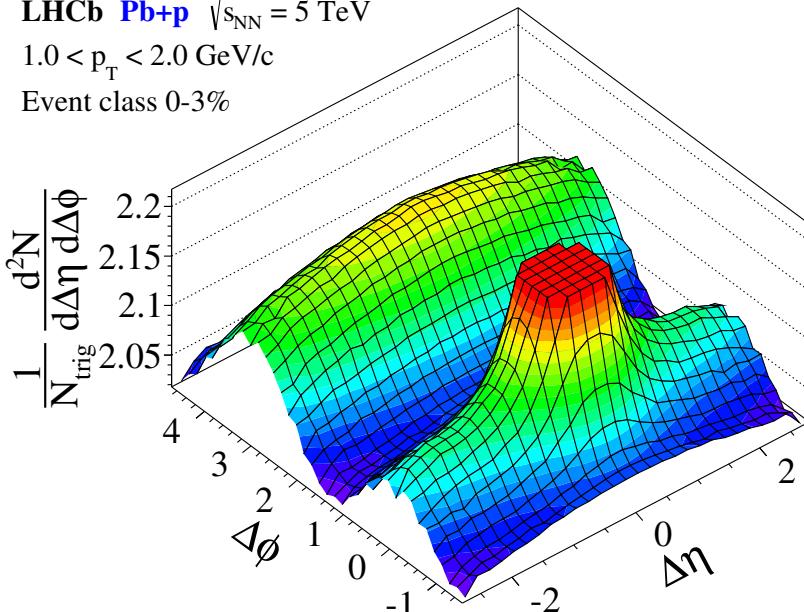


PLB 762 (2016) 473

LHCb $\text{Pb}+p$ $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$

$1.0 < p_{\text{T}} < 2.0 \text{ GeV/c}$

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New

PbPb $\sqrt{s_{\text{NN}}} = 5 \text{ TeV}$

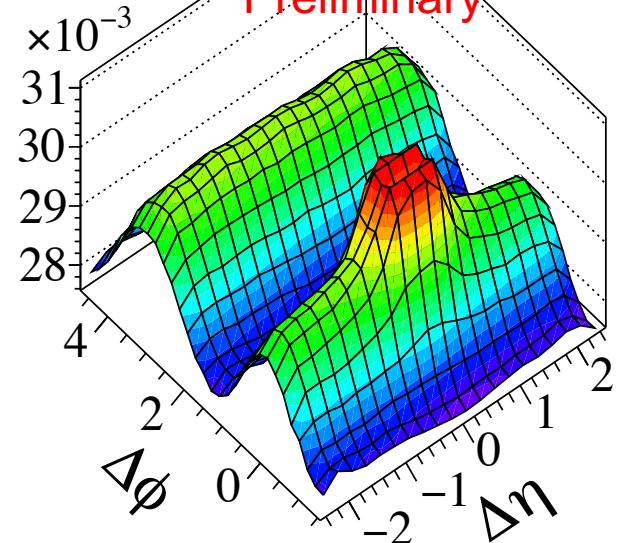
$1 < p_{\text{T},a,b} < 2 \text{ GeV}$

LHCb

65-75%

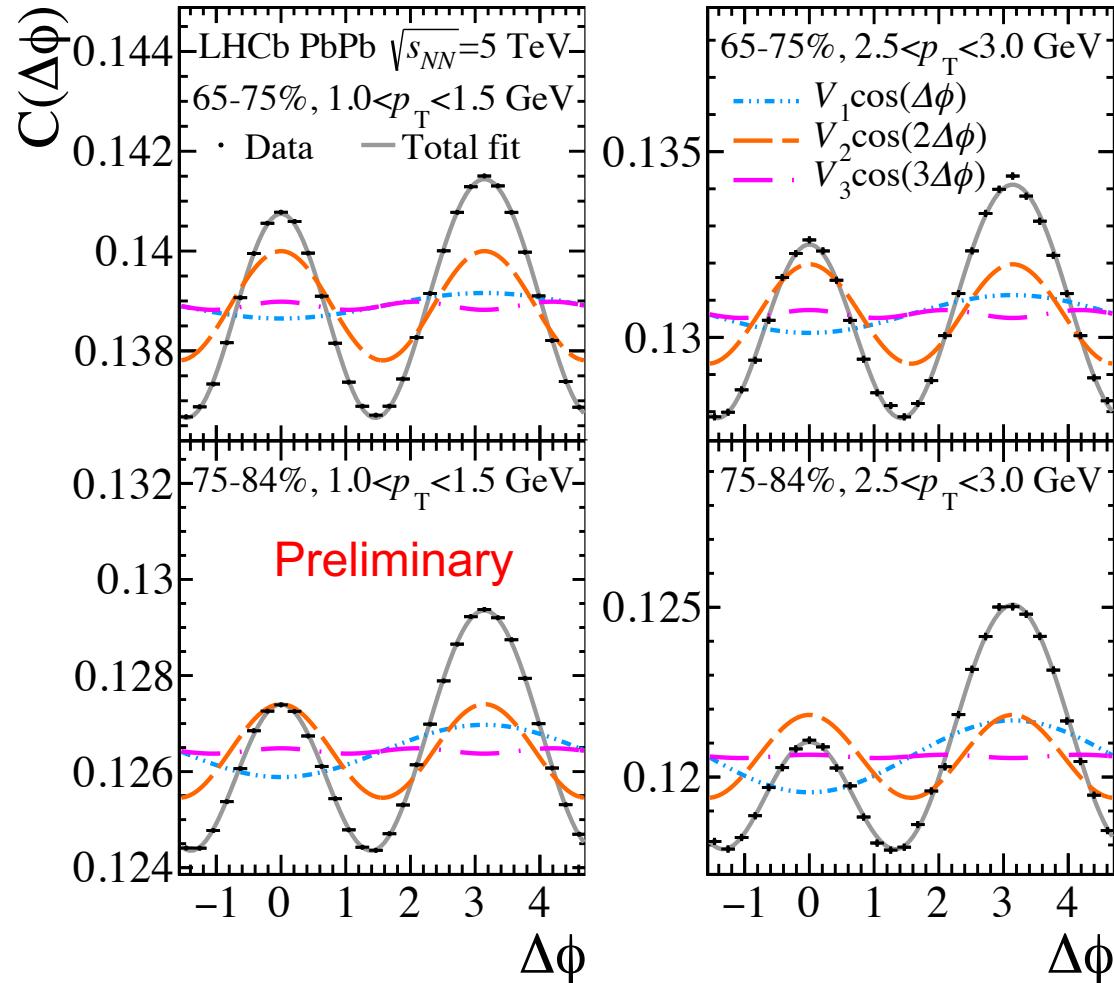
Preliminary

$C(\Delta\eta, \Delta\phi)$



New peripheral PbPb results show even stronger near-side ridge
→ stronger flow in peripheral PbPb collisions compared to $p\text{Pb}$ and $\text{Pb}p$

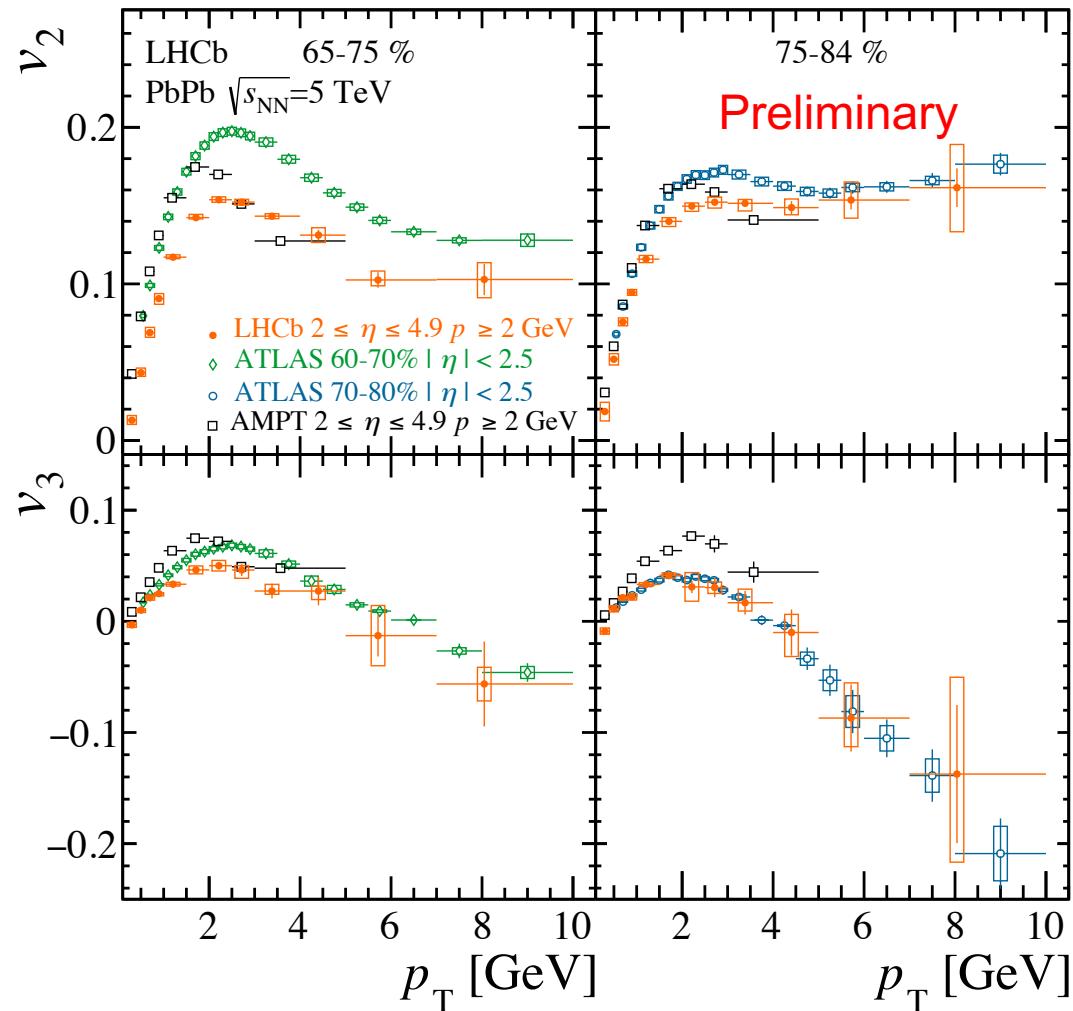
Forward charged-hadron correlations in PbPb at 5 TeV



- More results from 75-84% centrality class
- Centrality class above 84% is excluded due to potential UPC contamination
- Require $|\Delta\eta| > 1$ to avoid the short-range correlations
- Fourier series fit with the first, second and the third terms of harmonics

$$v_n(p_{Ta}) = V_n(p_{Ta}, p_{Tb}) / v_n(p_{Tb})$$
- First order flow harmonics coefficients are not reported due to factorization breaking in two-particle correlations analysis

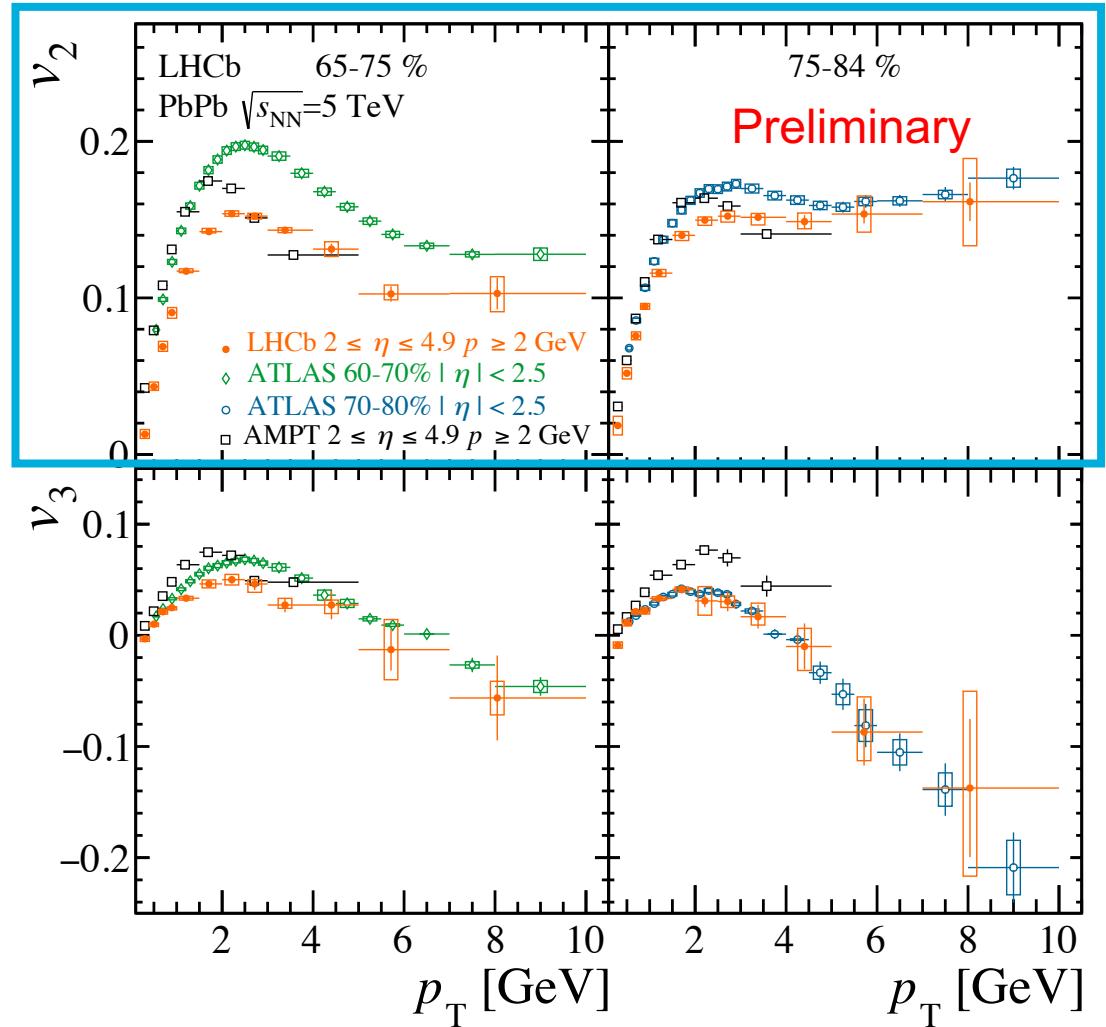
First forward measurement of charged hadron $v_n(p_T)$ at LHCb



PbPb collisions/simulations at 5 TeV

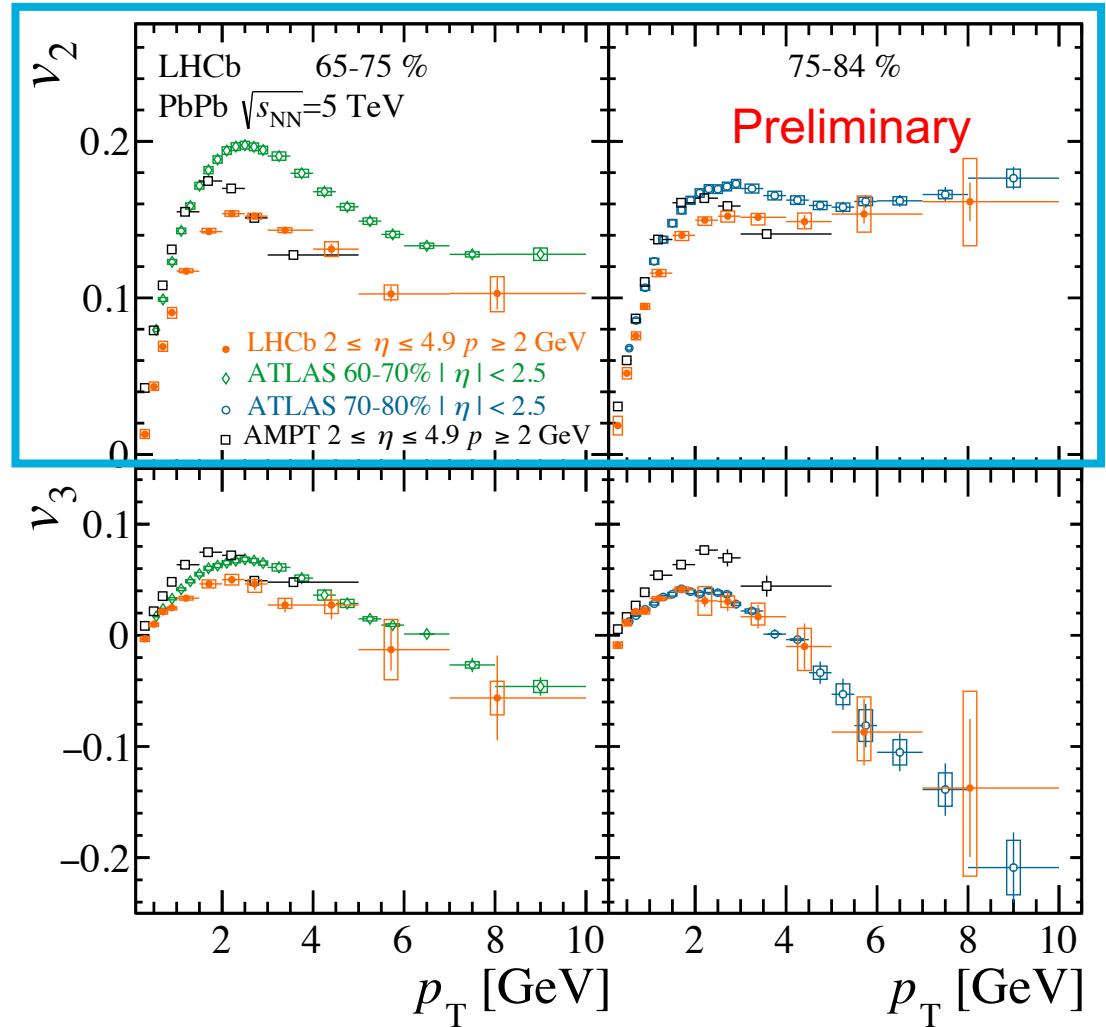
	Centrality class	Pseudorapidity
LHCb	65-75%	75-84%
ATLAS	60-70%	70-80%
AMPT	65-75%	75-84%
		$2 \leq \eta \leq 4.9$
		$ \eta < 2.5$
		$2 \leq \eta \leq 4.9$

First forward measurement of charged hadron $v_n(p_T)$ at LHCb



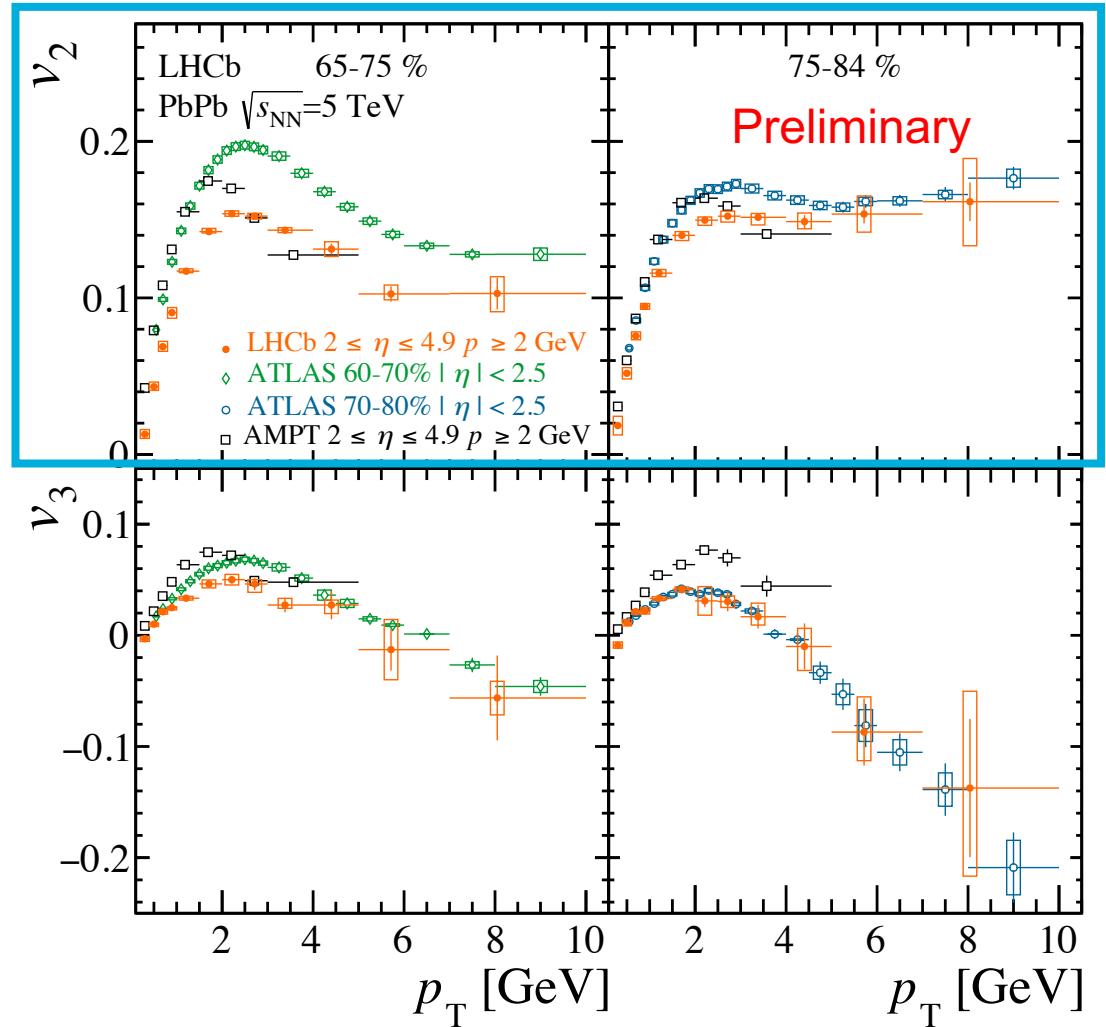
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- v_2 seems to plateau at $p_T > 5$ GeV

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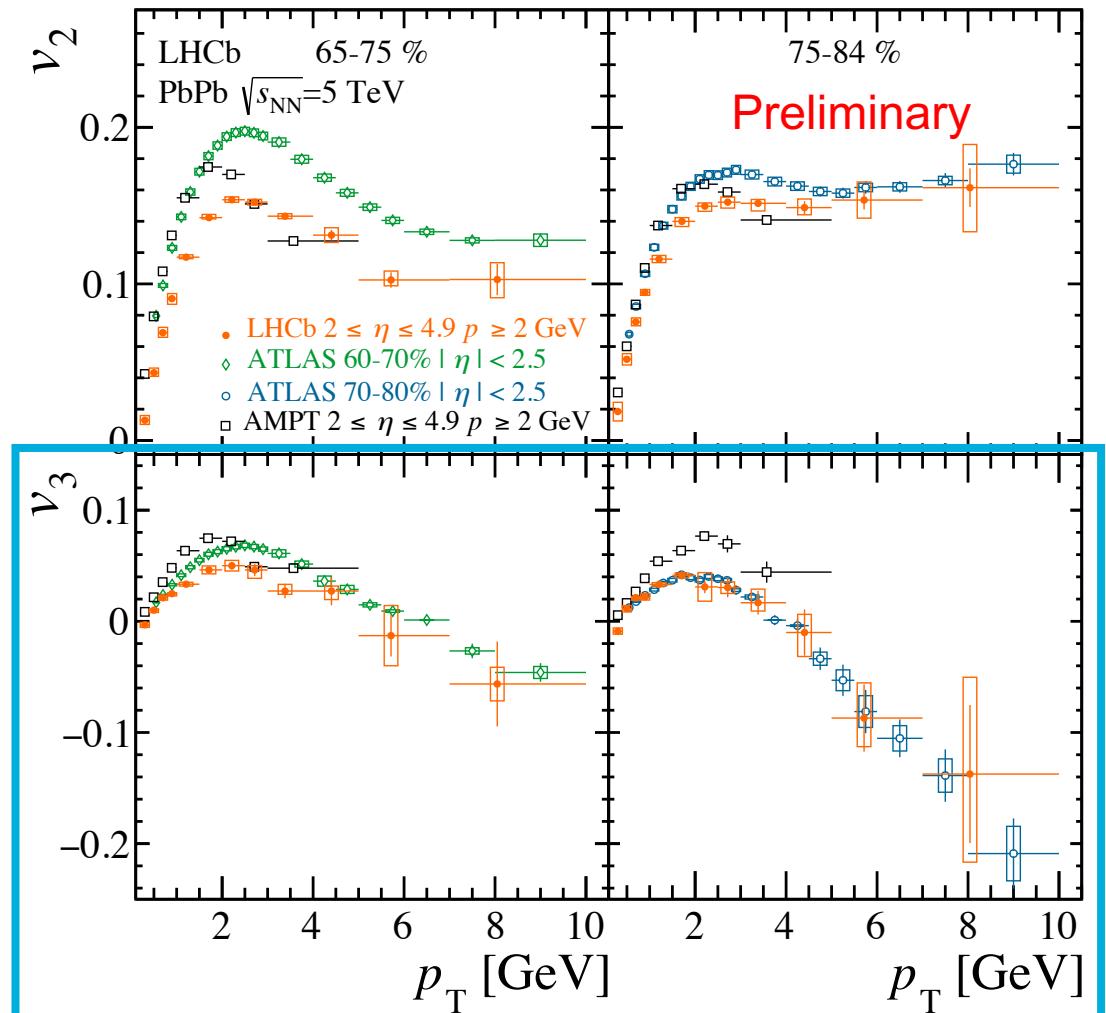
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First **forward** measurement of charged hadron $v_n(p_T)$ at LHCb



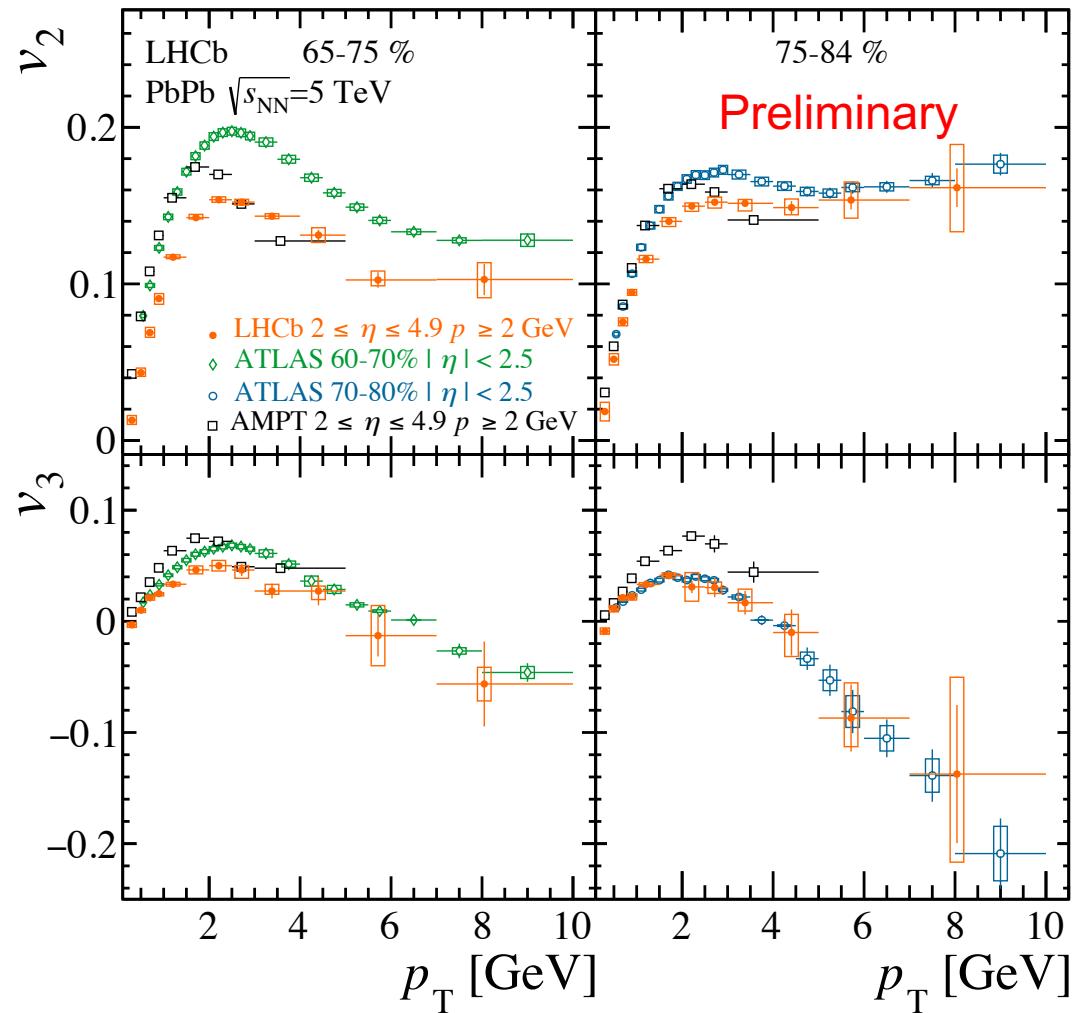
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- Rising v_2 at high p_T in 75-84% centrality may be due to non-flow contributions
- No noticeable centrality dependence of forward v_2
- Unlike v_2 , v_3 continues to decrease and reach below zero

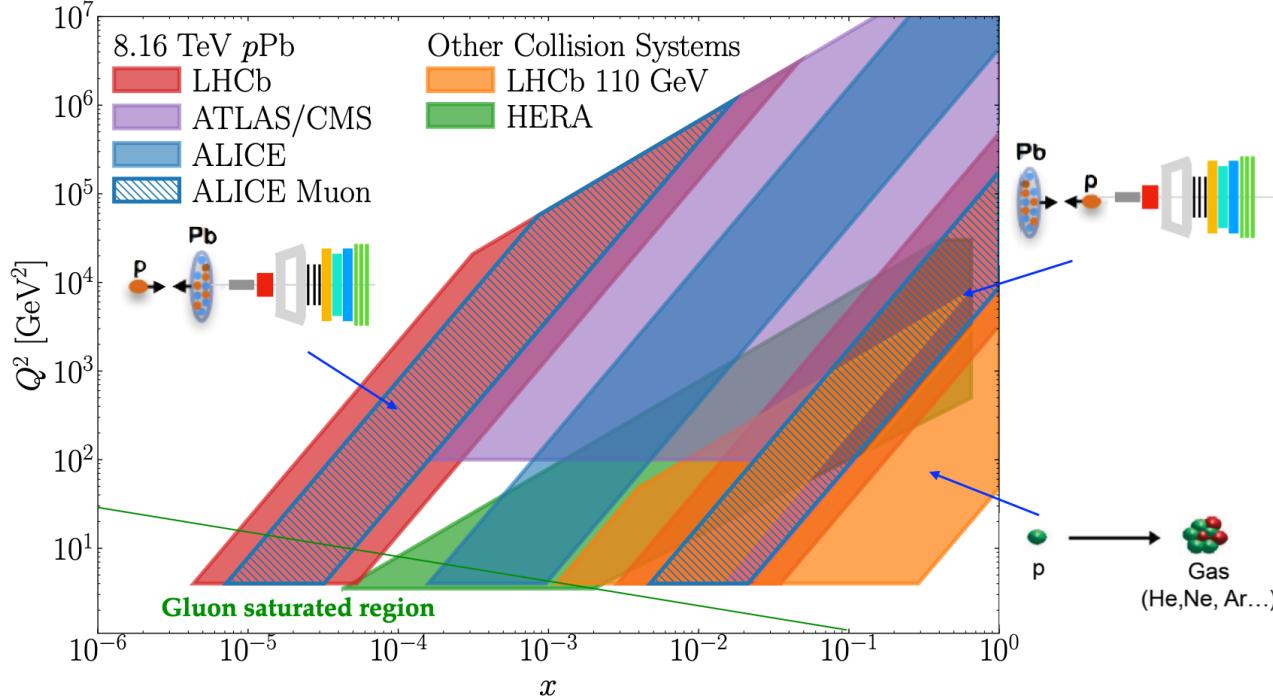
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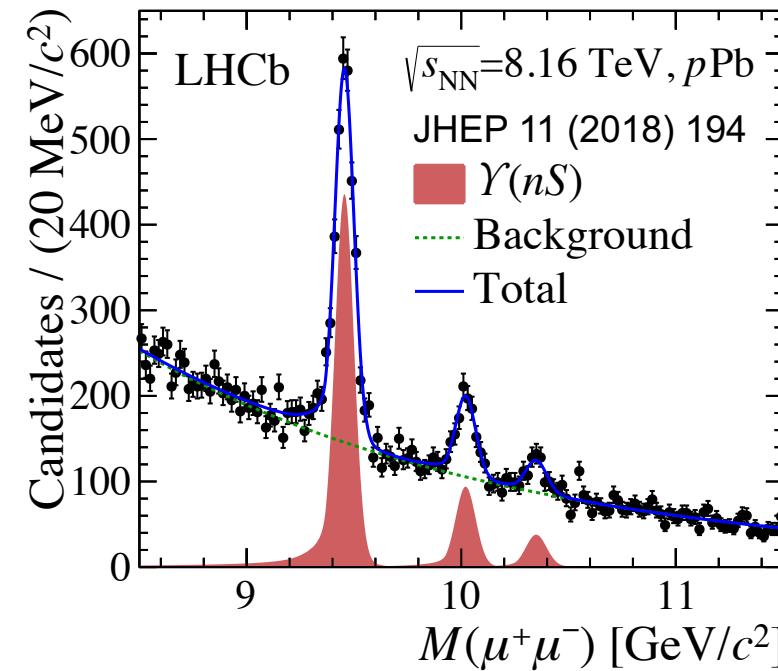
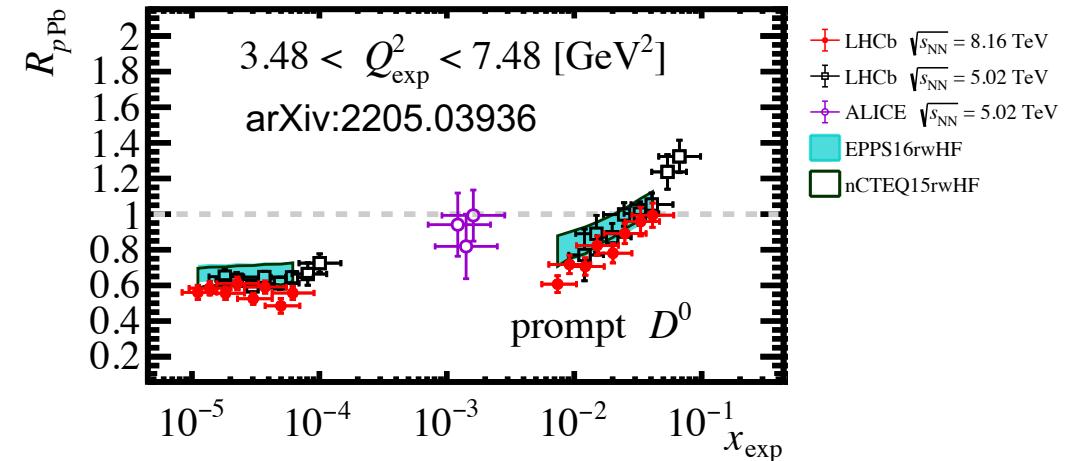
- LHCb results in the forward region shows weaker v_n compared to ATLAS results in centrality pseudorapidity
→ Forward region is dominated by hadronic phase leading to weaker flow
- AMPT simulations overestimate v_n
→ tuning on parton density and v_n model

Potential future flow measurements at LHCb

Small-x Physics



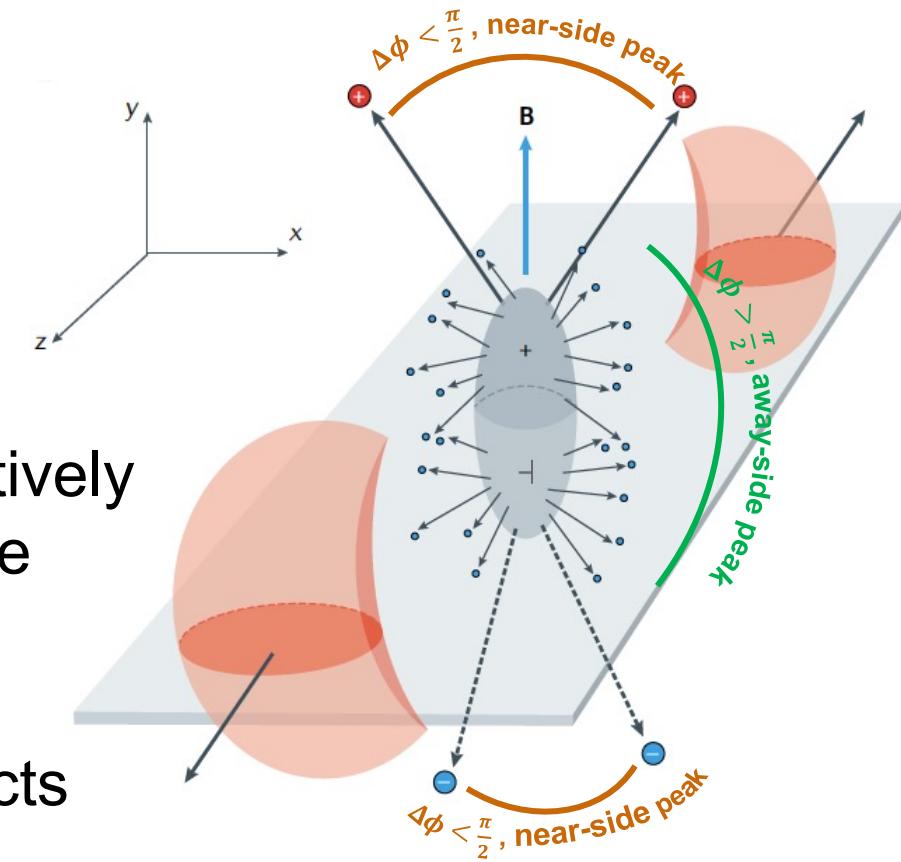
- Study initial state effects at small x with heavy-flavor flow
- Gluon density increases in the forward region
→ Test CGC models



Charge asymmetry in chiral magnetic effects

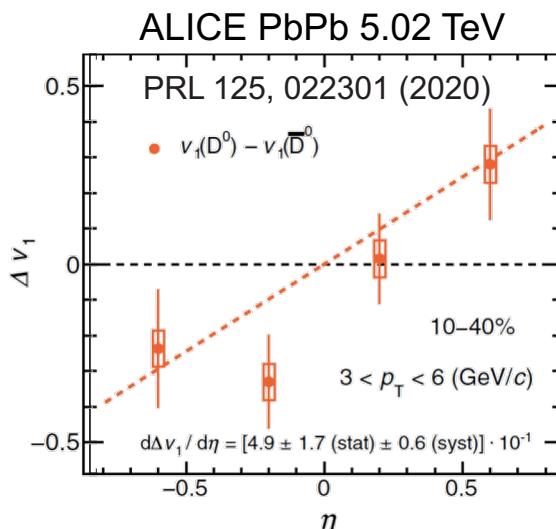
Nature vol3 (Jan 2021) 59

Positively and negatively charged particles are emitted in opposite directions due to chiral magnetic effects

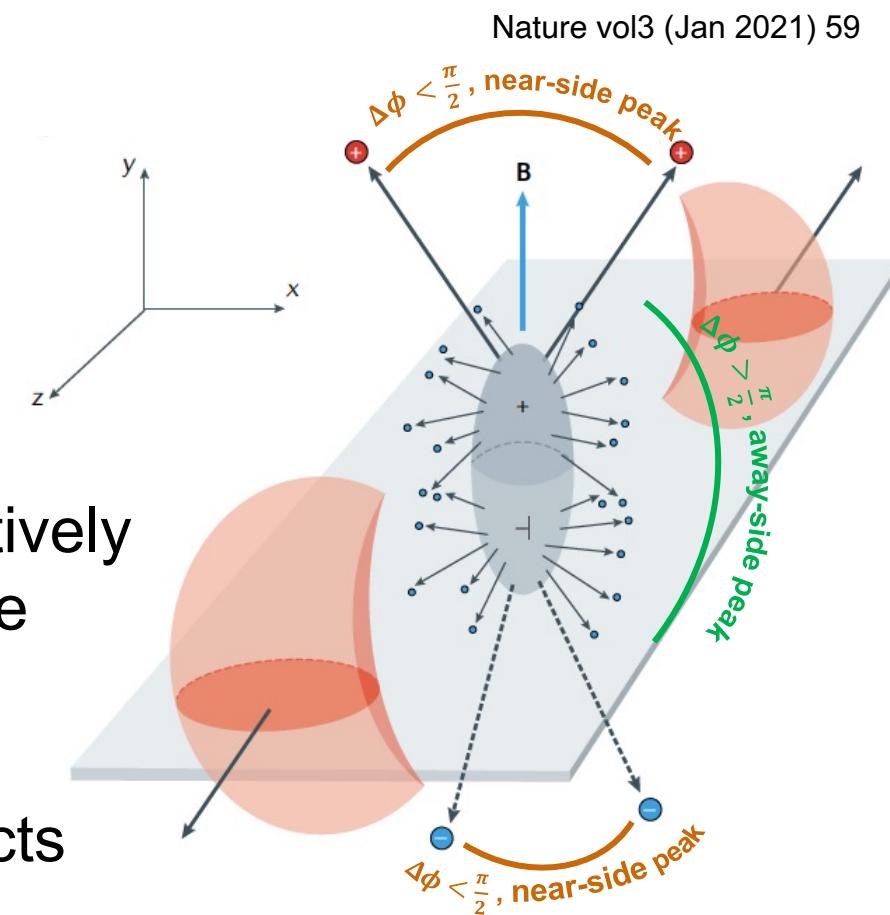


Charge asymmetry in chiral magnetic effects

- In the case of charge asymmetry
→ non-zero Δv_1 between positively and negatively charged hadrons

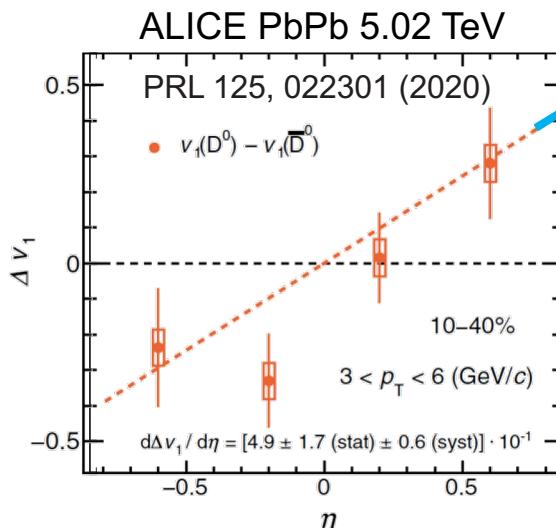


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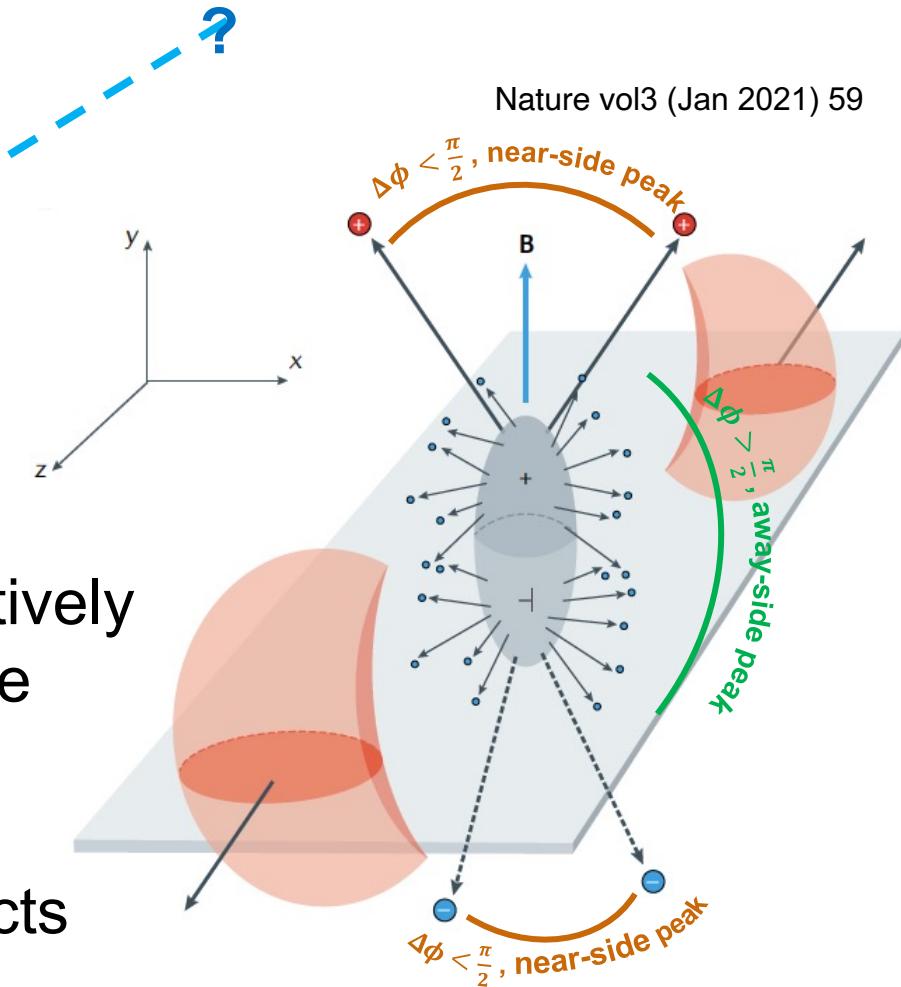


Charge asymmetry in chiral magnetic effects

- In the case of charge asymmetry
→ non-zero Δv_1 between positively and negatively charged hadrons
- v_1 is stronger in the forward region
- Forward results will help reduce the uncertainty



Positively and negatively charged particles are emitted in opposite directions due to chiral magnetic effects



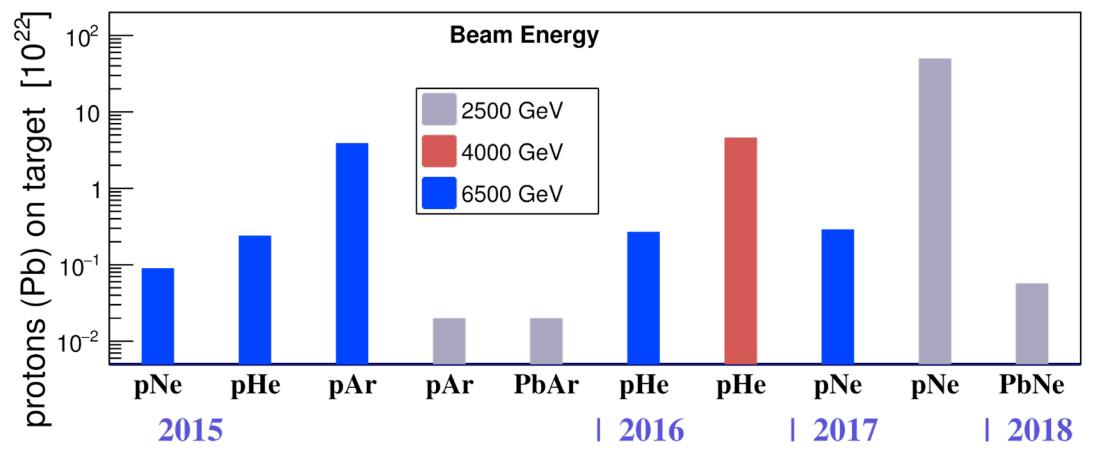
Flow in fixed-target collisions

- Comparable energy scale to the RHIC operation range
- intermediate system size between pA and AA collisions
- Study temperature dependence of η/s
- Study initial state effects

Huge opportunity!



Available LHCb SMOG datasets

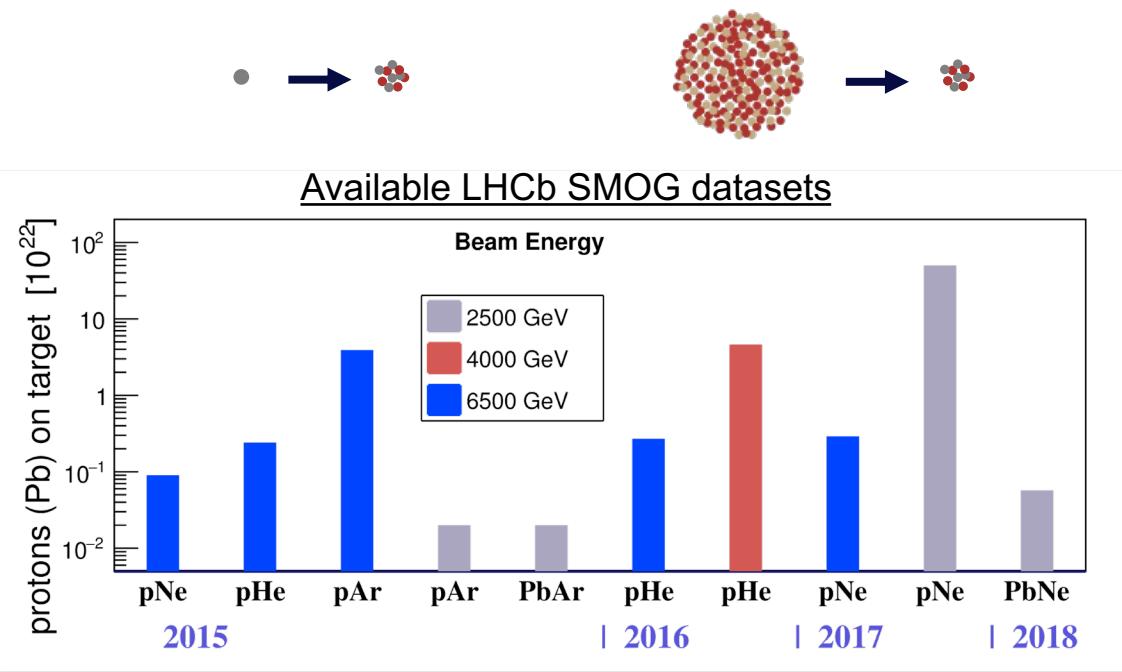


- [SMOG results – K. Mattioli, today at 4:30 pm, Ballroom C](#)
- [SMOG2 commissioning – S. Mariani, 09/06/23 at 1:20 pm, Ballroom D](#)

Flow in fixed-target collisions

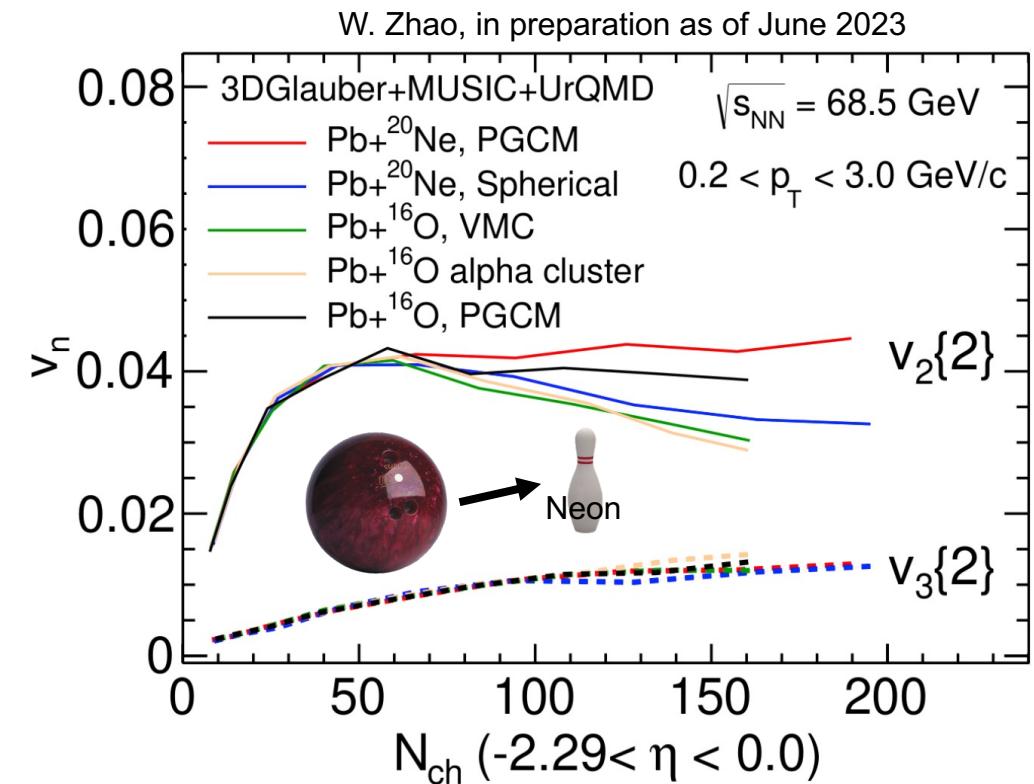
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- Study temperature dependence of η/s
- Study initial state effects:
 v_n is sensitive to light nuclei's nuclear structure in *PbA* collisions



Summary

Bose-Einstein correlations of same-sign pion

- System size (intercept parameter) increases (decreases) with event multiplicity
- Hints to larger system size in Pbp compared to pPb and pp

First forward measurement of charged hadron $v_n(p_T)$ at LHCb

- Weaker flow in the forward region compared to mid-rapidity results by ATLAS
→ hadronic phase v.s. partonic phase
- Transport models may require tuning in the forward region

Expand LHCb physics program with flow

- Small-x physics: initial state effects, CGC
- Forward direction: chiral magnetic effects
- Small system: temperature dependence of QGP transport properties
initial state effects

Backup

Beam Configurations

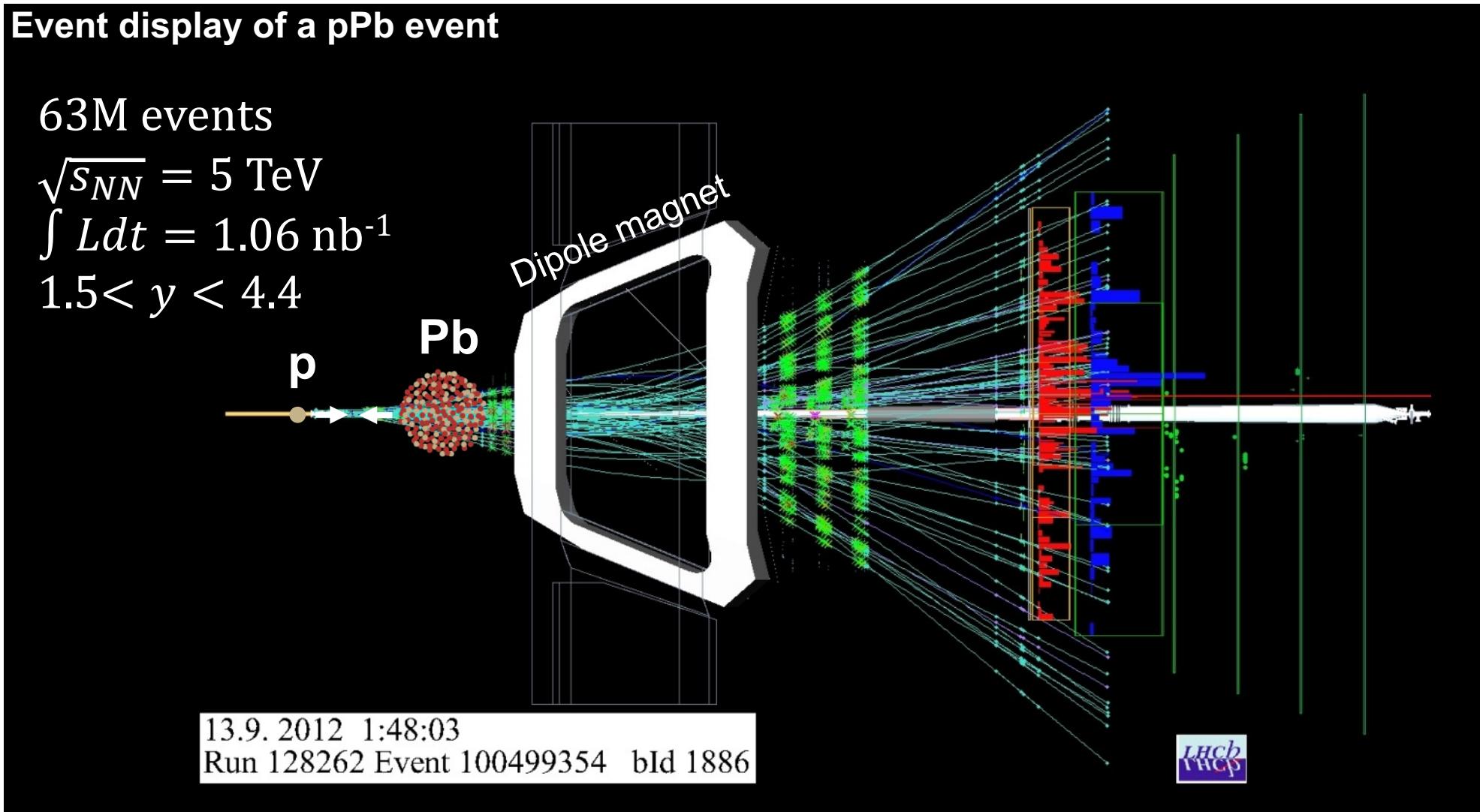
Event display of a pPb event

63M events

$\sqrt{s_{NN}} = 5 \text{ TeV}$

$\int L dt = 1.06 \text{ nb}^{-1}$

$1.5 < y < 4.4$



Beam Configurations

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57M events

$\sqrt{s_{NN}} = 5 \text{ TeV}$

$\int L dt = 0.52 \text{ nb}^{-1}$

$-5.4 < y < -2.5$

Pb p

