Search for Chiral Magnetic Wave in heavy-ion collisions

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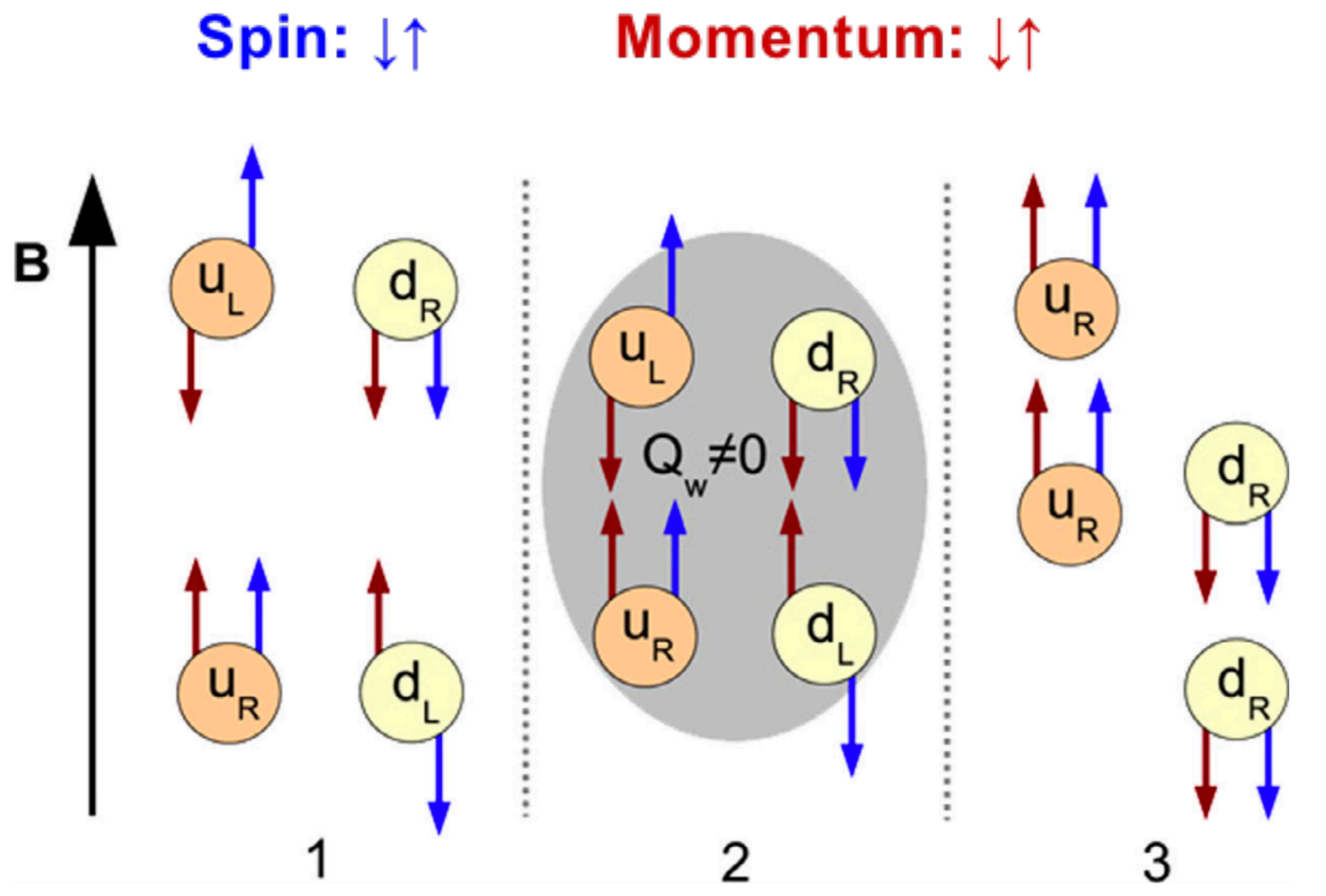
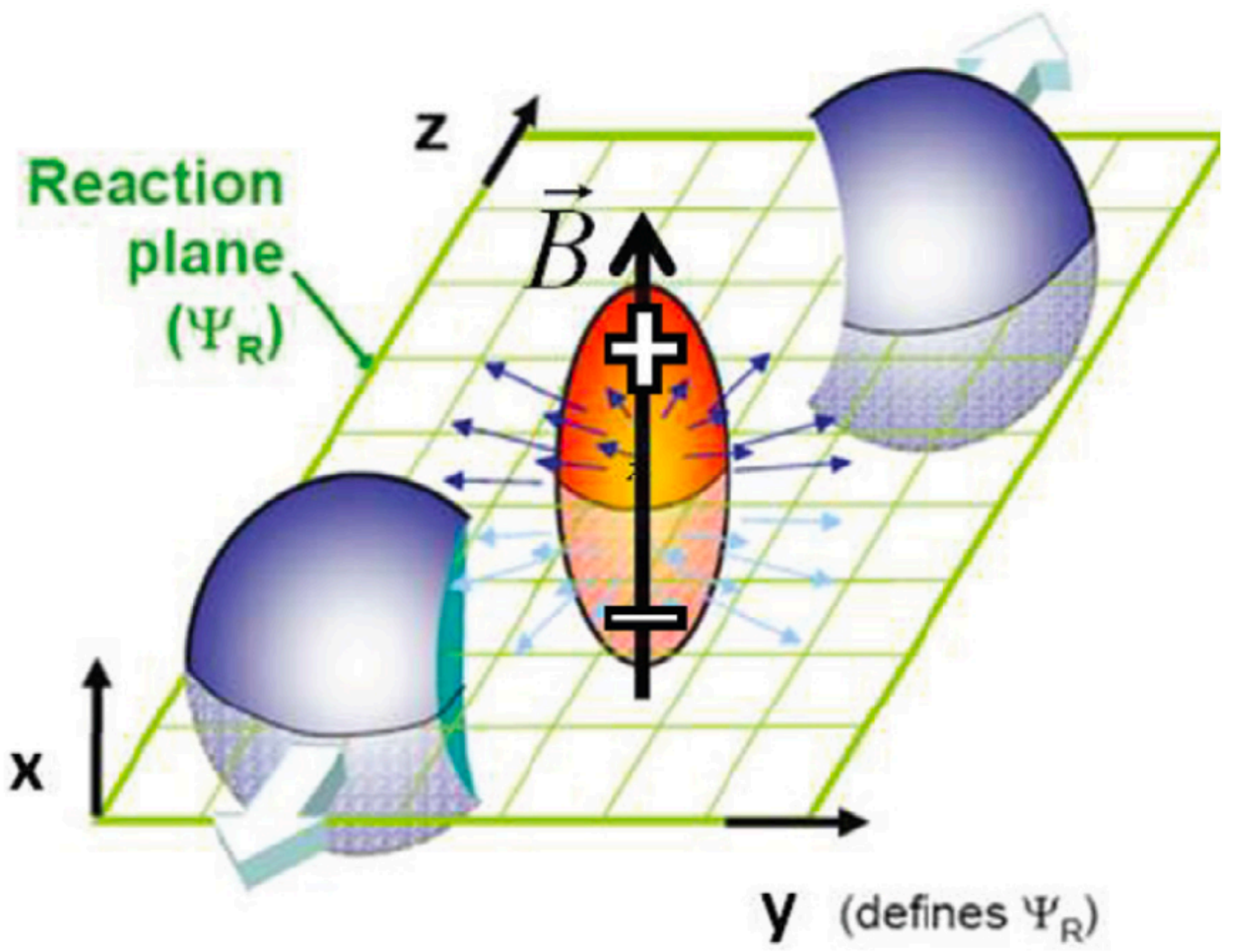
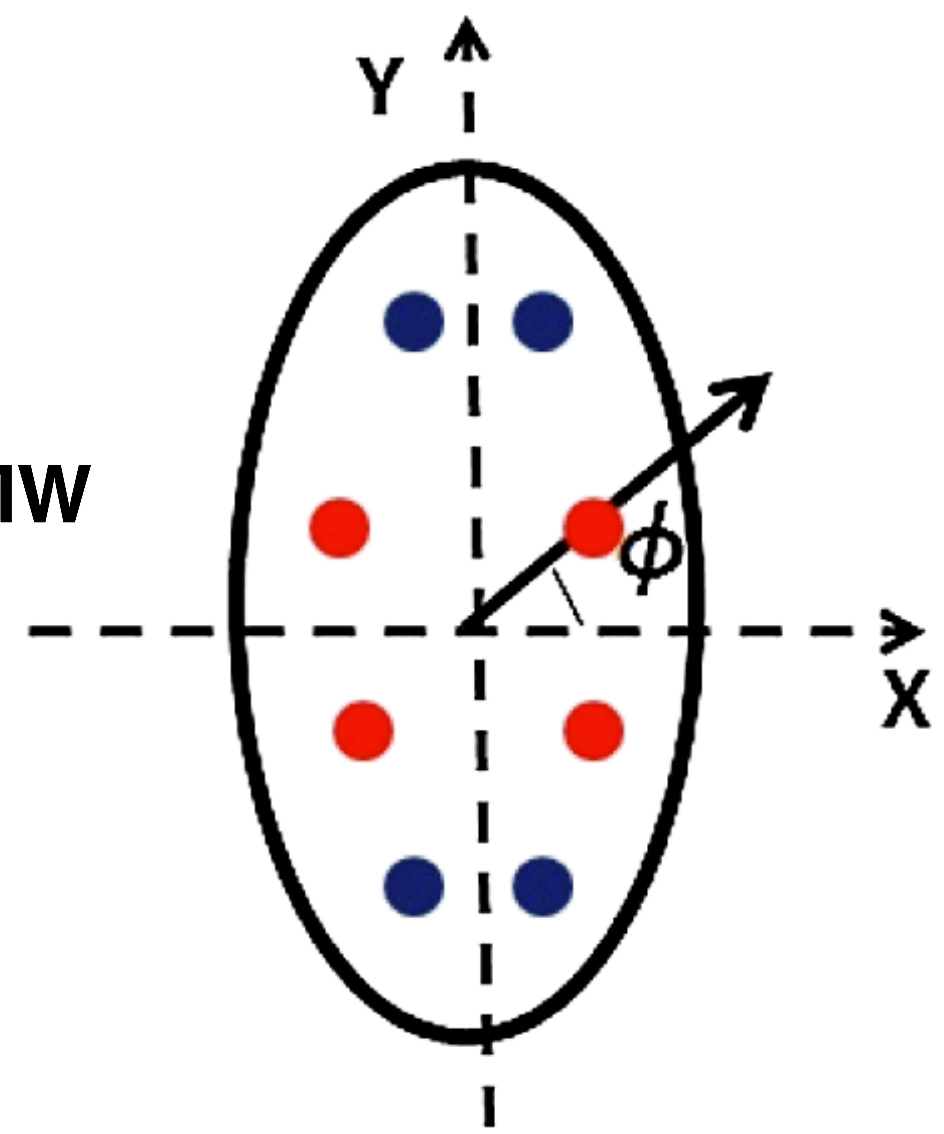
Chiral anomalous effect and **Chiral Magnetic Wave**







- **Chiral Magnetic Effect (CME)**: $j_\nu = \dfrac{N_c e}{2\pi^2}\mu_A B$
- **Chiral Separation Effect (CSE)**: $j_A = \dfrac{N_c e}{2\pi^2}\mu_\nu B$
- **Chiral Magnetic Wave (CMW)**: CME+CSE
- **Induces parity-odd domains**

Kharzeev Dmitri et al. Phys.Rev.Lett. 81 (1998) 512-515

Similar phenomena in condensmatter physics : Weyl Semimetals

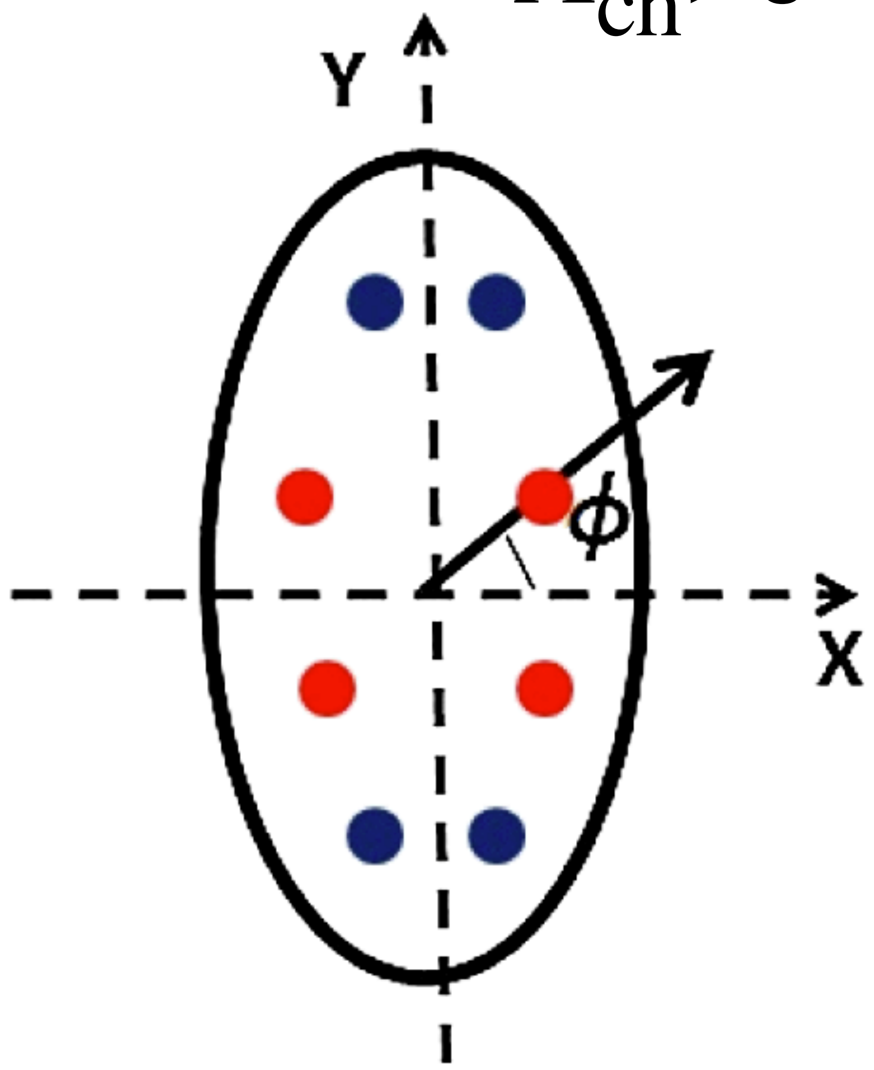
- Chiral symmetry restoration
- Deconfinement
- QCD vacuum fluctuation
- Extremely strong magnetic field (~10^{15} T)

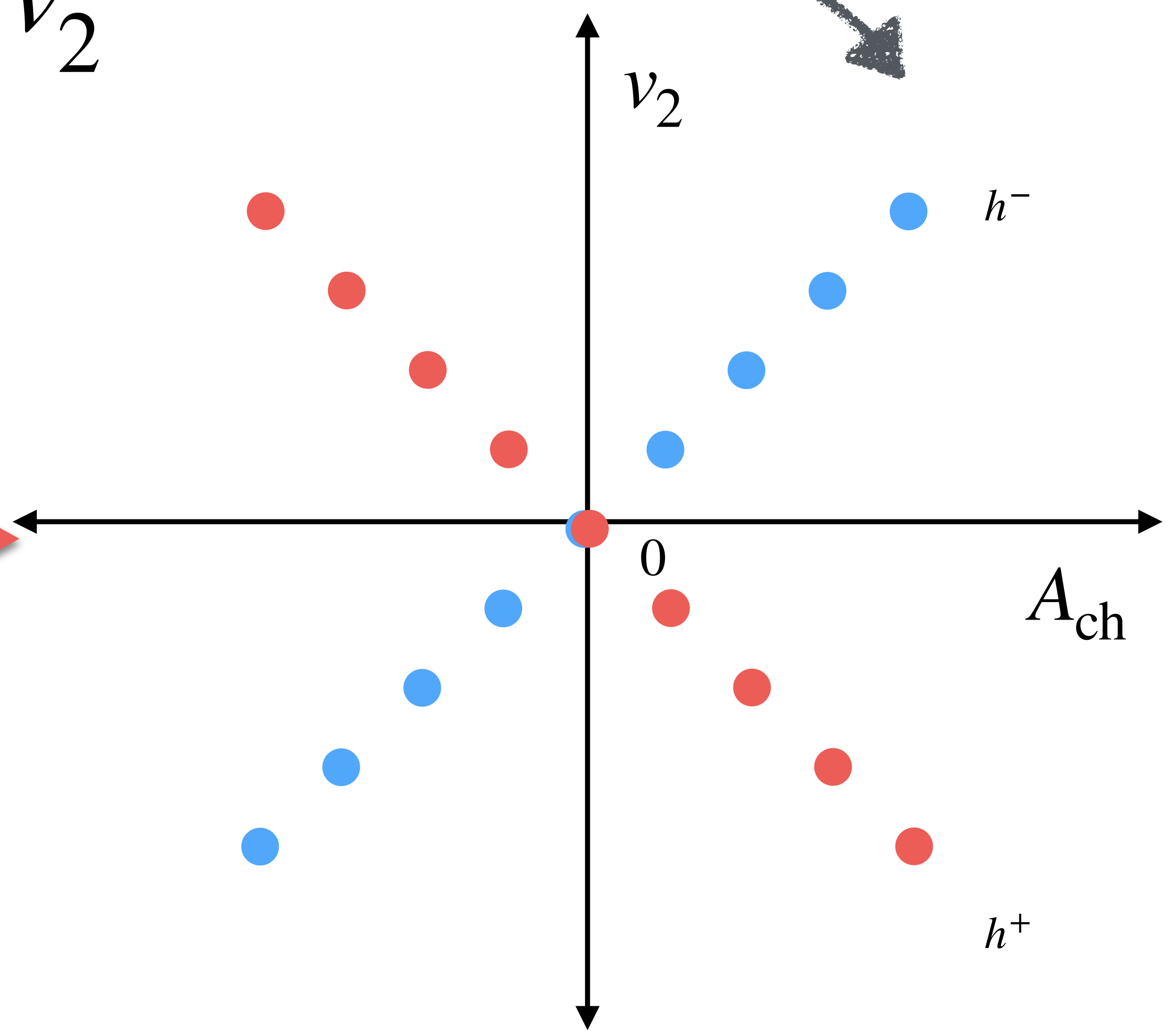
Would confirm several fundamental properties of QCD: the approximate chiral symmetry restoration, topological charge fluctuations, and P and CP violation — **strong CP problem**

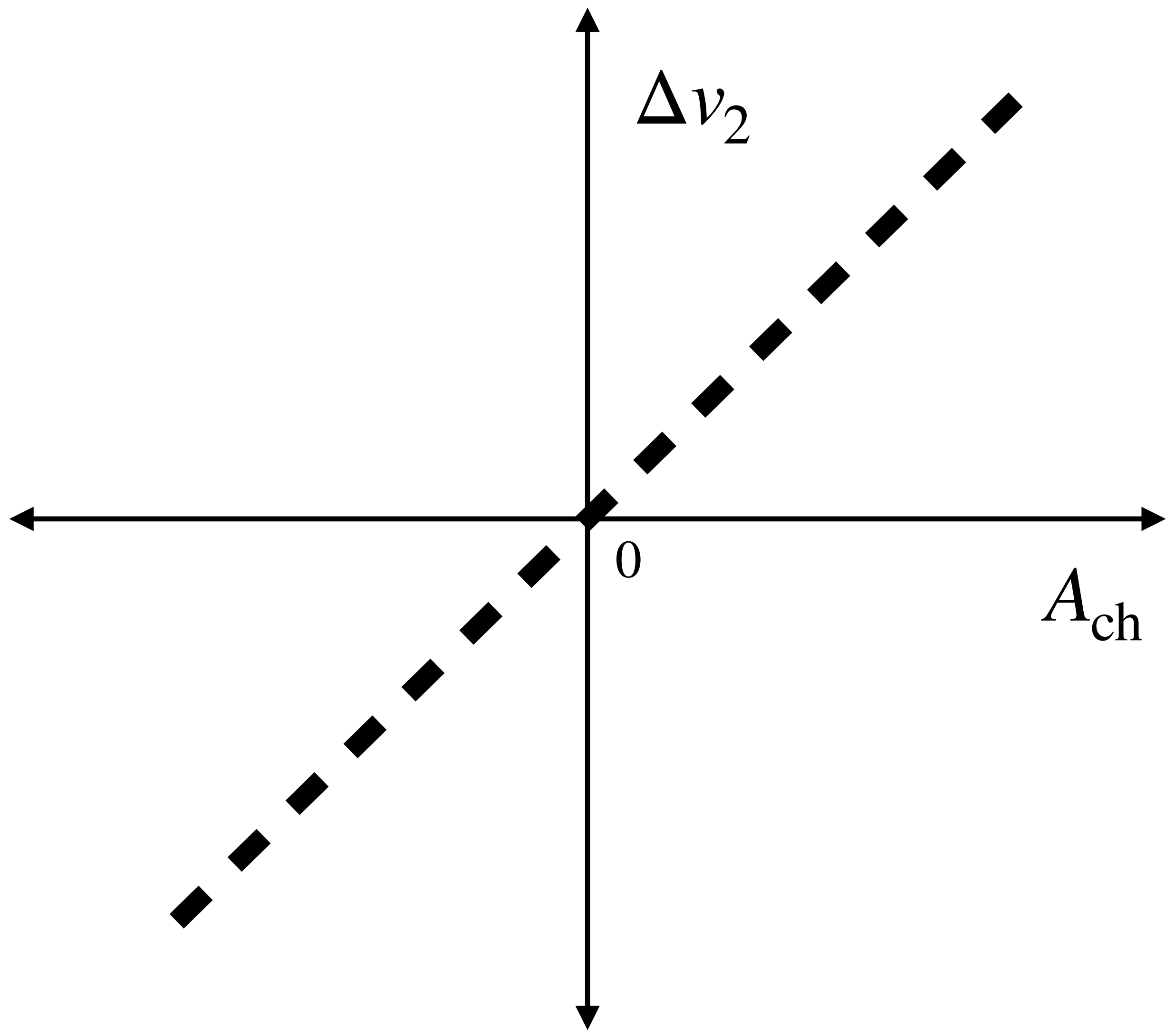
Experimental observable

Burnier Yannis et al. Phys. Rev. Lett. 107 (2011) 052303

$A_{\rm ch}$>0 —> $v_2^- > v_2^+$







$$N_+(\phi) - N_-(\phi) = (\bar{N}_+ - \bar{N}_-)[1 - rcos(2\phi)]$$

$$\frac{dN_\pm}{d\phi} = N_\pm[1 + 2v_2cos(2\phi)]$$

$$\approx \bar{N}_\pm[1 + 2v_2cos(2\phi) \mp A_{ch}rcos(2\phi)]$$

quadrupole, CMW contribution

$$q_e = \int RdRd\phi cos(2\phi)[j_e^0(R,\phi) - j_{e,B=0}^0(R,\phi)]$$

$$r \equiv \frac{2q_e}{\bar{\rho}_e}$$

Monopole,nonzero net charge density

$$\bar{\rho}_e = \int RdRd\phi cos(2\phi)[j_{e,B=0}^0(R,\phi)]$$

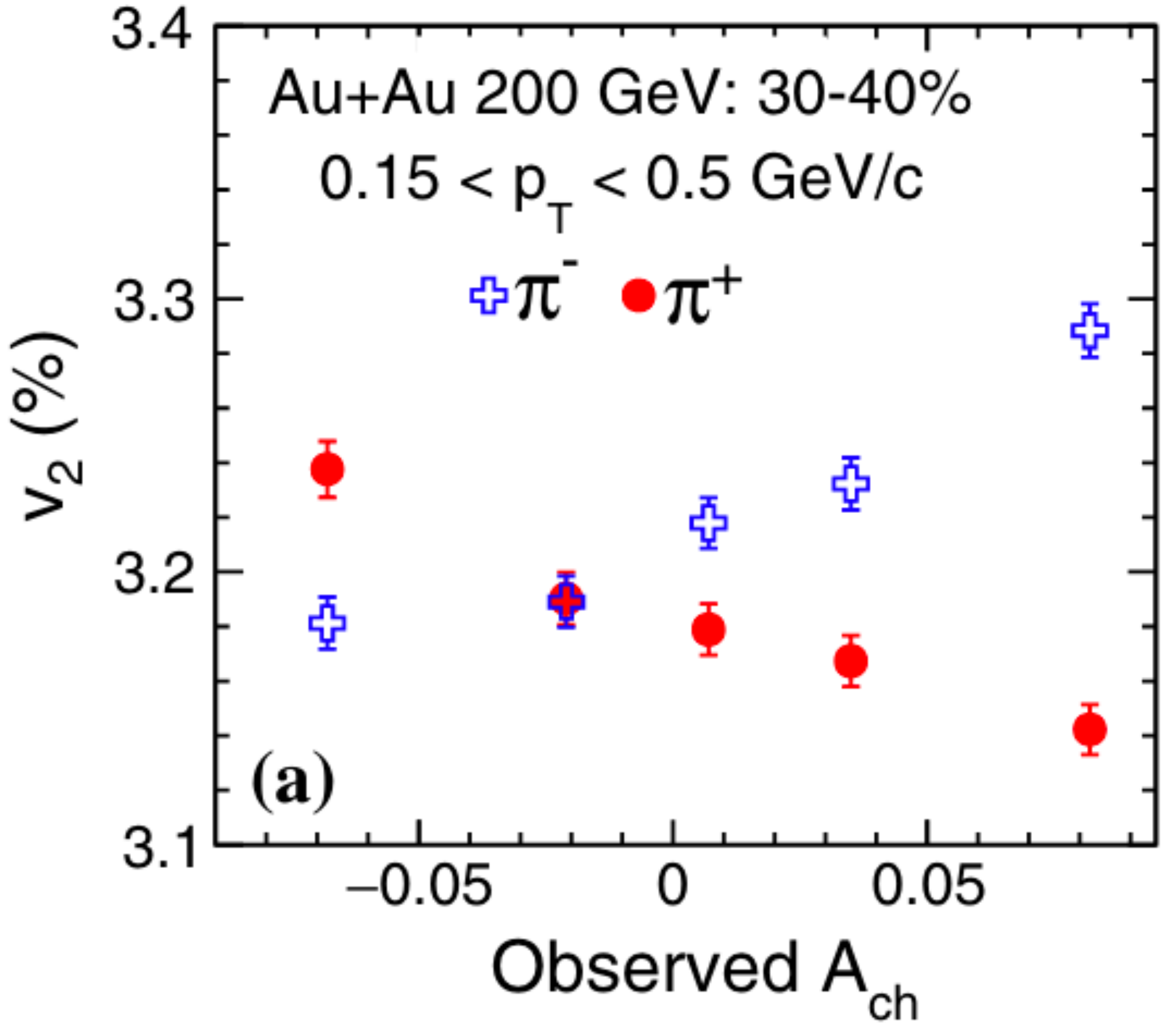
$$A_{\rm ch} = \frac{N^+ - N^-}{N^+ + N^-},$$

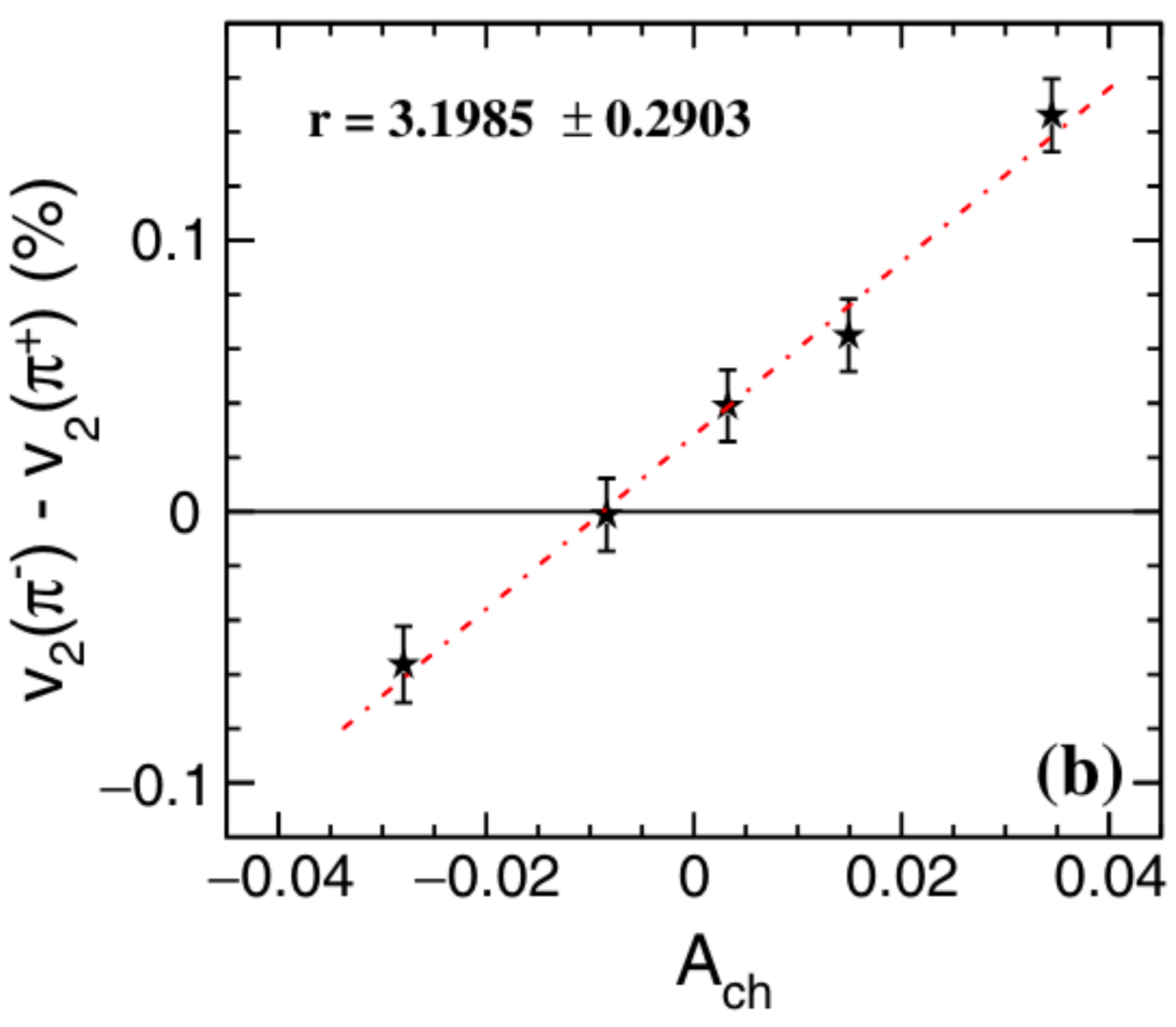
$$\Delta v_2 = v_2^- - v_2^+ = rA_{\rm ch}$$

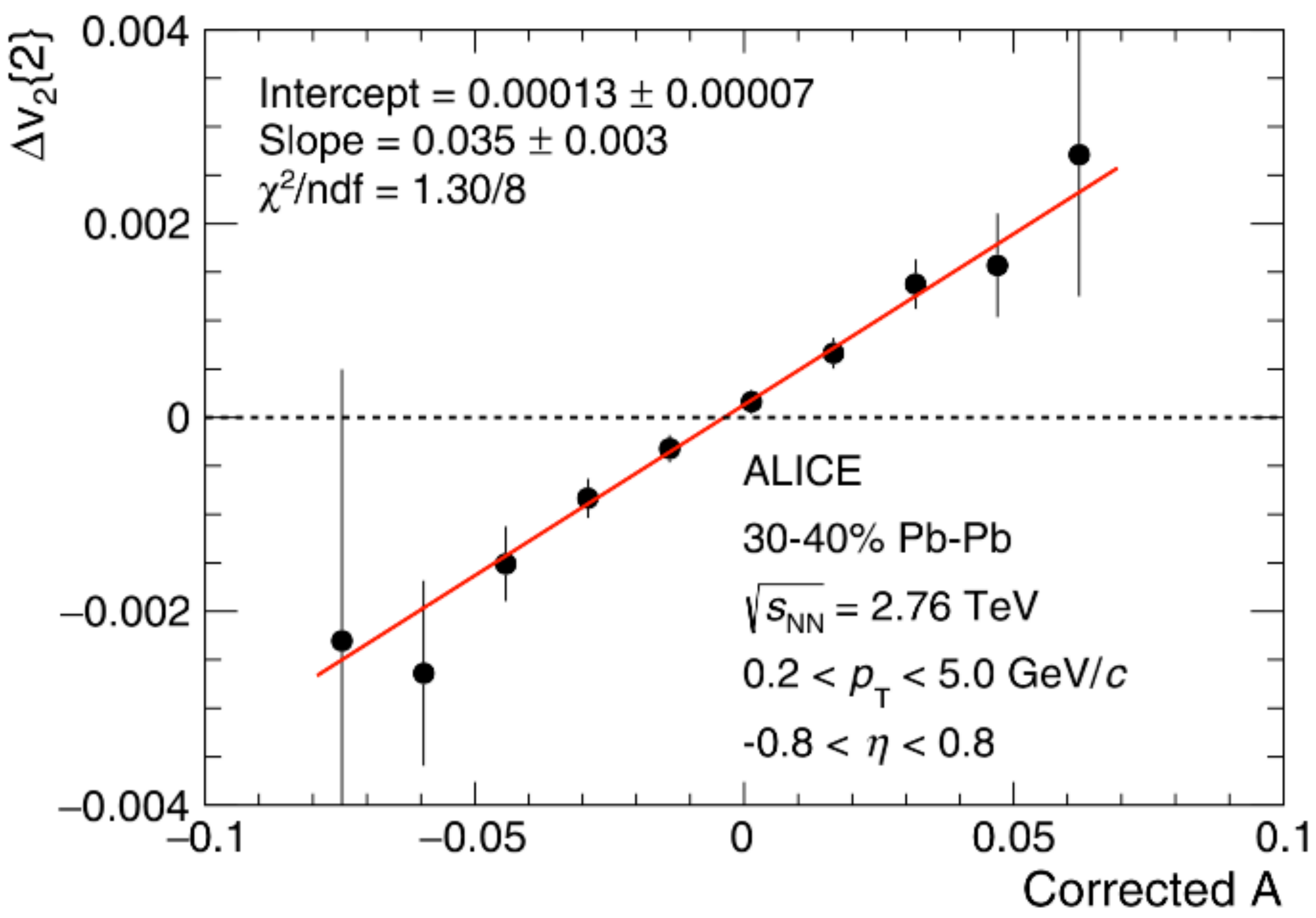
$$\langle v_2^\pm A_{\rm ch}\rangle - \langle A_{\rm ch}\rangle\langle v_2^\pm\rangle \approx \mp r\sigma_{A_{\rm ch}}^2/2$$

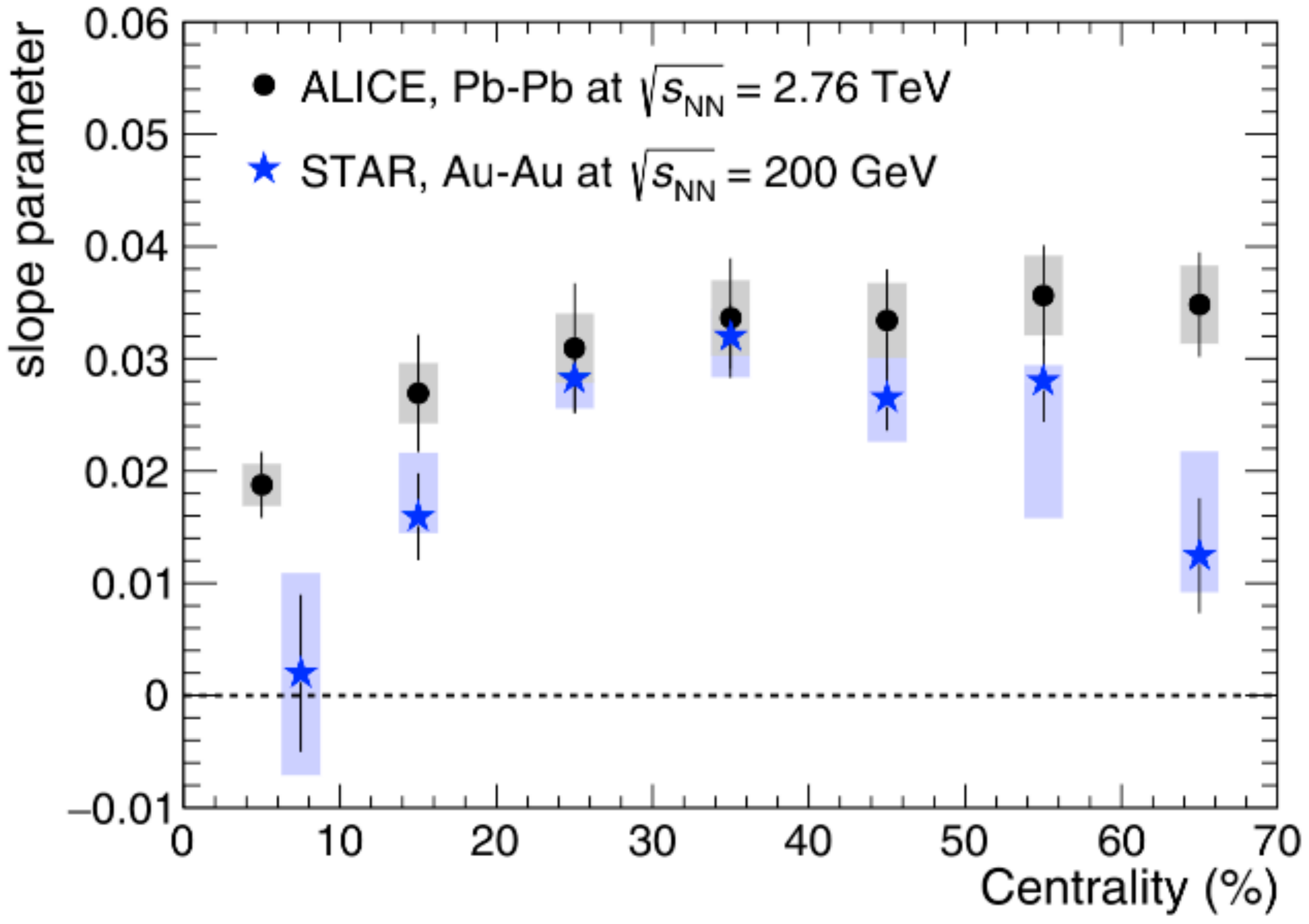
CMW observable: Normalized slope, $r_{\Delta v_2}^{Norm.} = \frac{d(\frac{\Delta v_2}{\langle v_2\rangle})}{dA_{\rm ch}}$, $\langle v_2\rangle = \frac{v_2^+ + v_2^-}{2}$

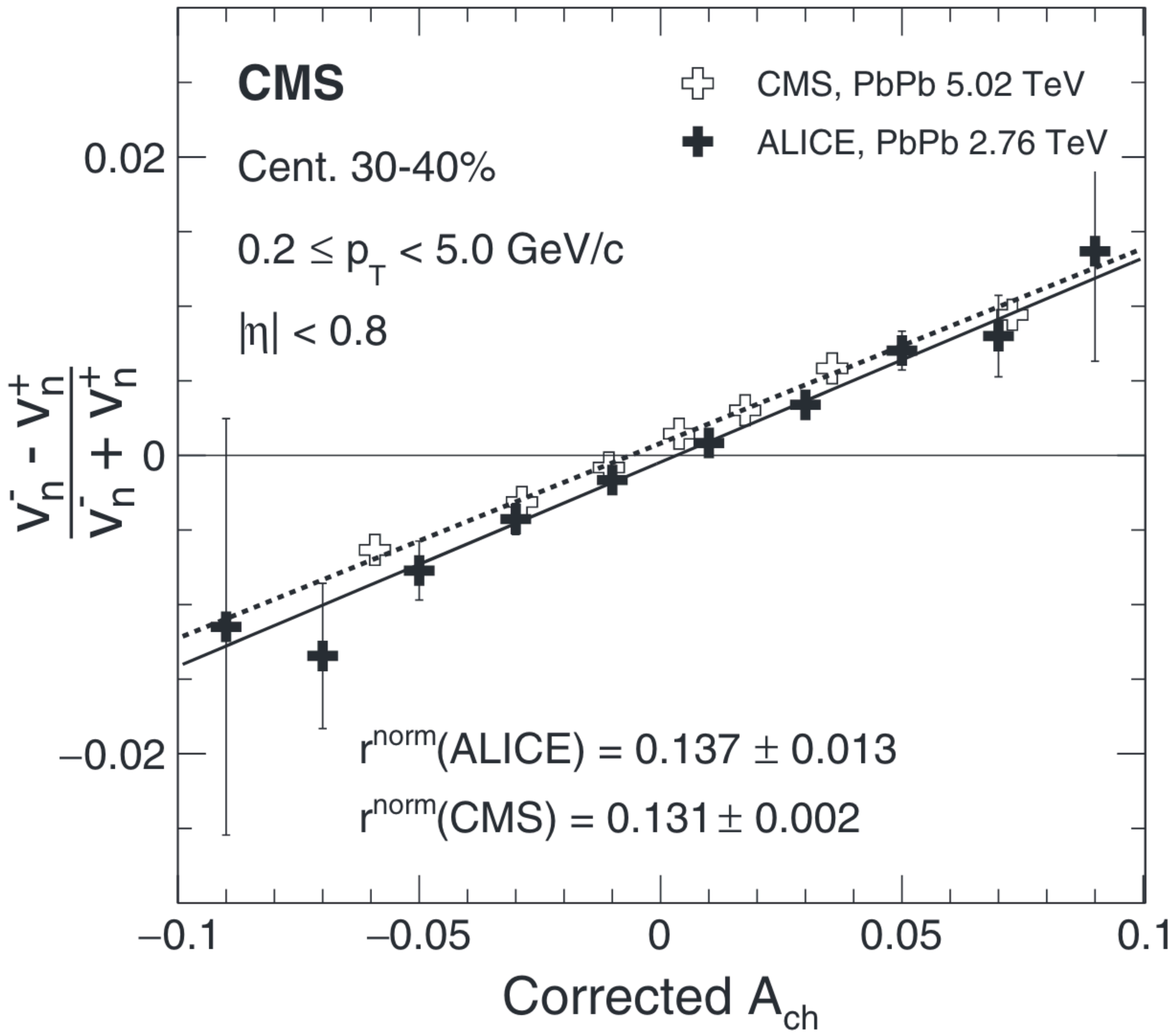
Experimental measurements in recent decades









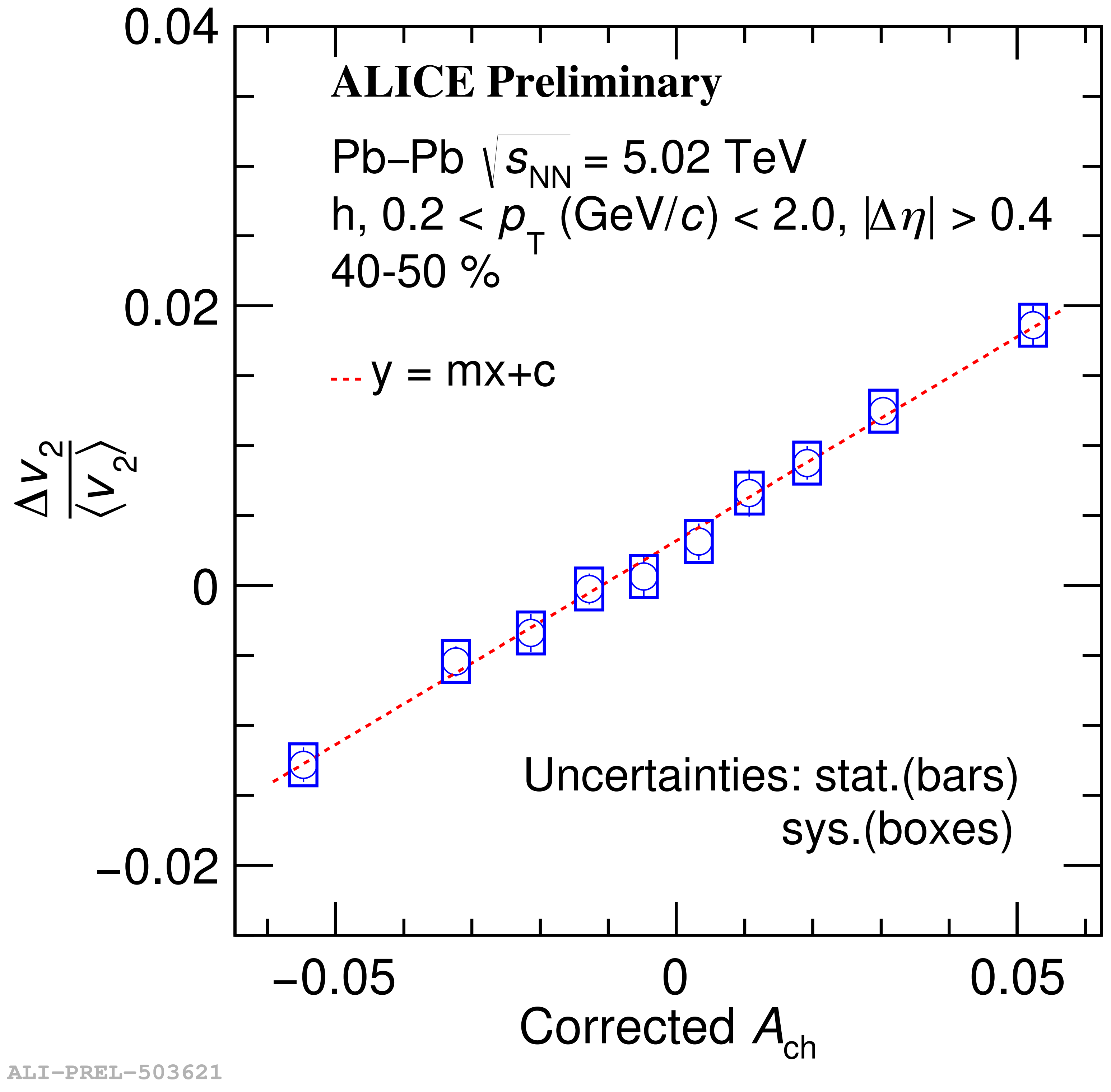


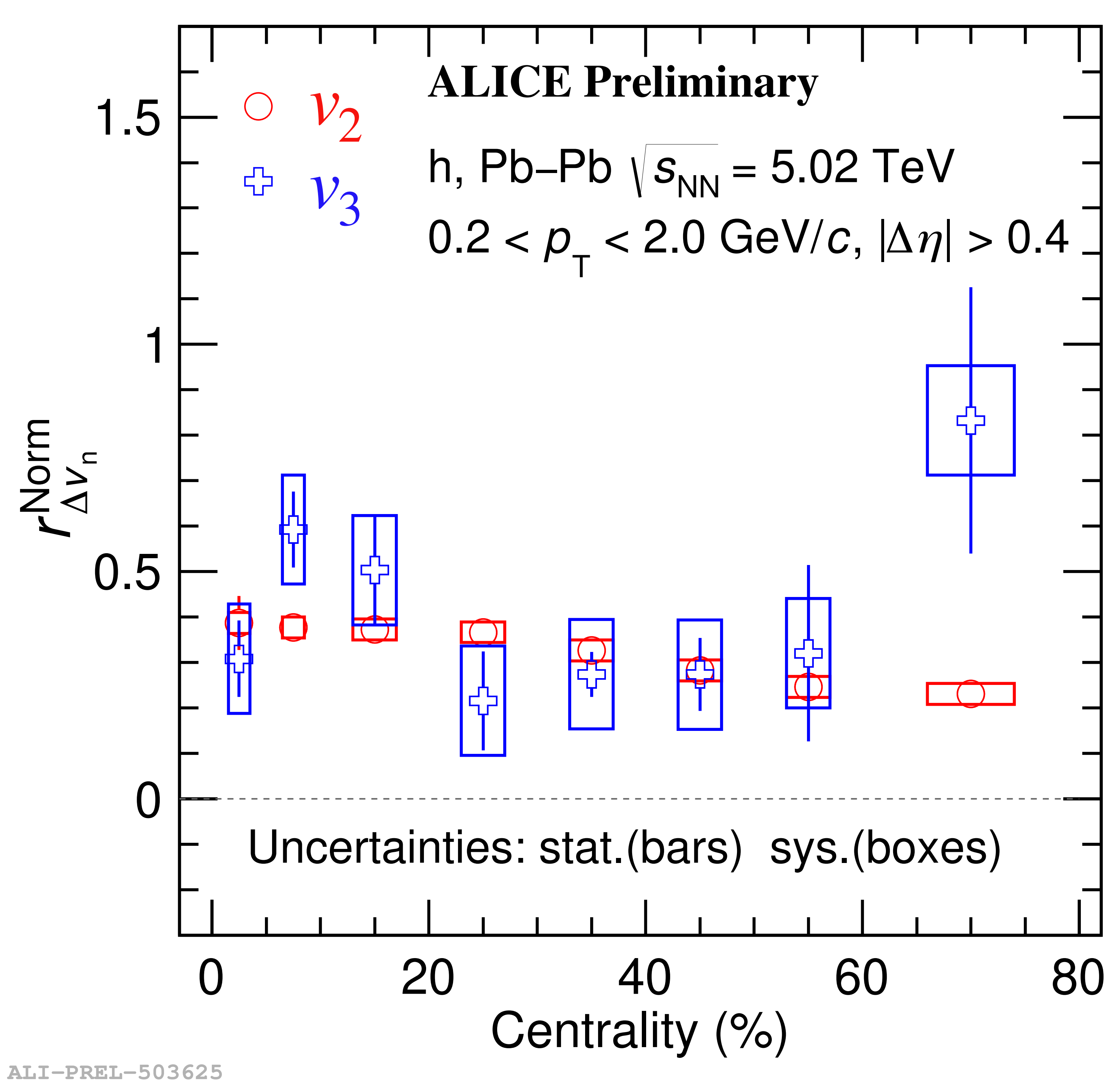
STAR Collaboration. PRL 114, 252302 (2015)

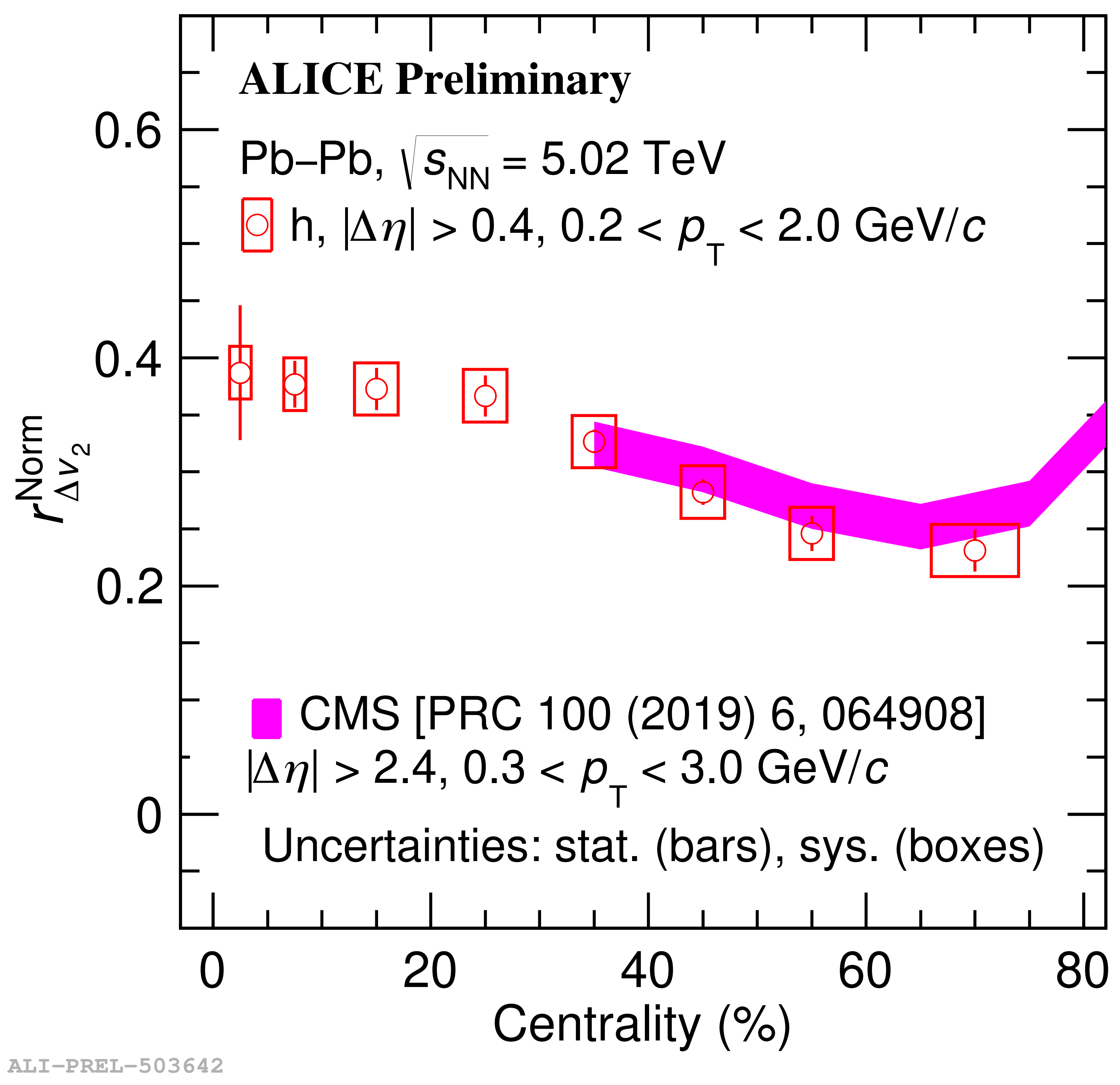
ALICE Collaboration. Phys. Rev. C 93, 044903 (2016)

CMS Collaboration Phys. Rev. C 100, 064908 (2019)

New measurement of ALICE—to be published





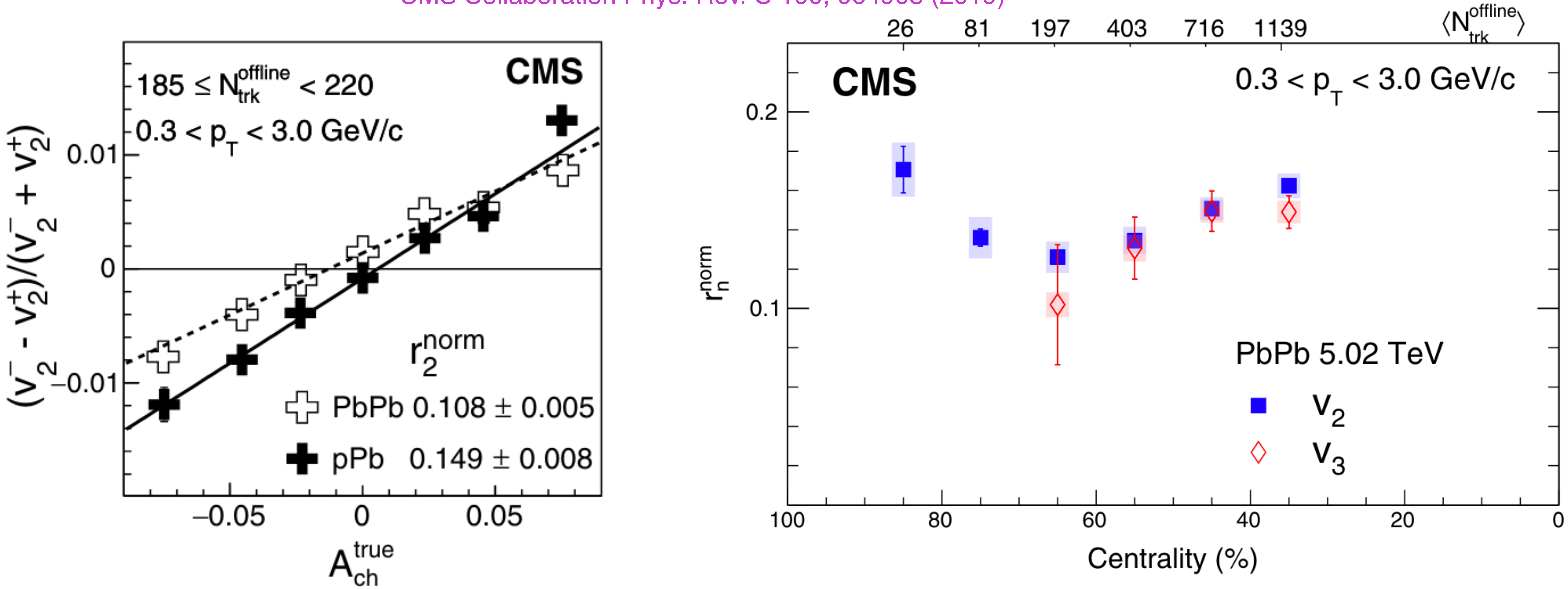


- ✓ Linear dependences between $\Delta v_2/\langle v_2 \rangle$ and A_{ch} in the left figure
- ✓ In the middle figure , $r^{Norm.}_{\Delta v_2}$ is consistent with $r^{Norm.}_{\Delta v_3}$ within uncertainties
- ✓ $r^{Norm(ALICE)}_{\Delta v_2} \approx r^{Norm(CMS)}_{\Delta v_2}$

A new ALICE paper for CMW measurement is expected in this year!

Evidence of background and interpreting the background

CMS Collaboration Phys. Rev. C 100, 064908 (2019)



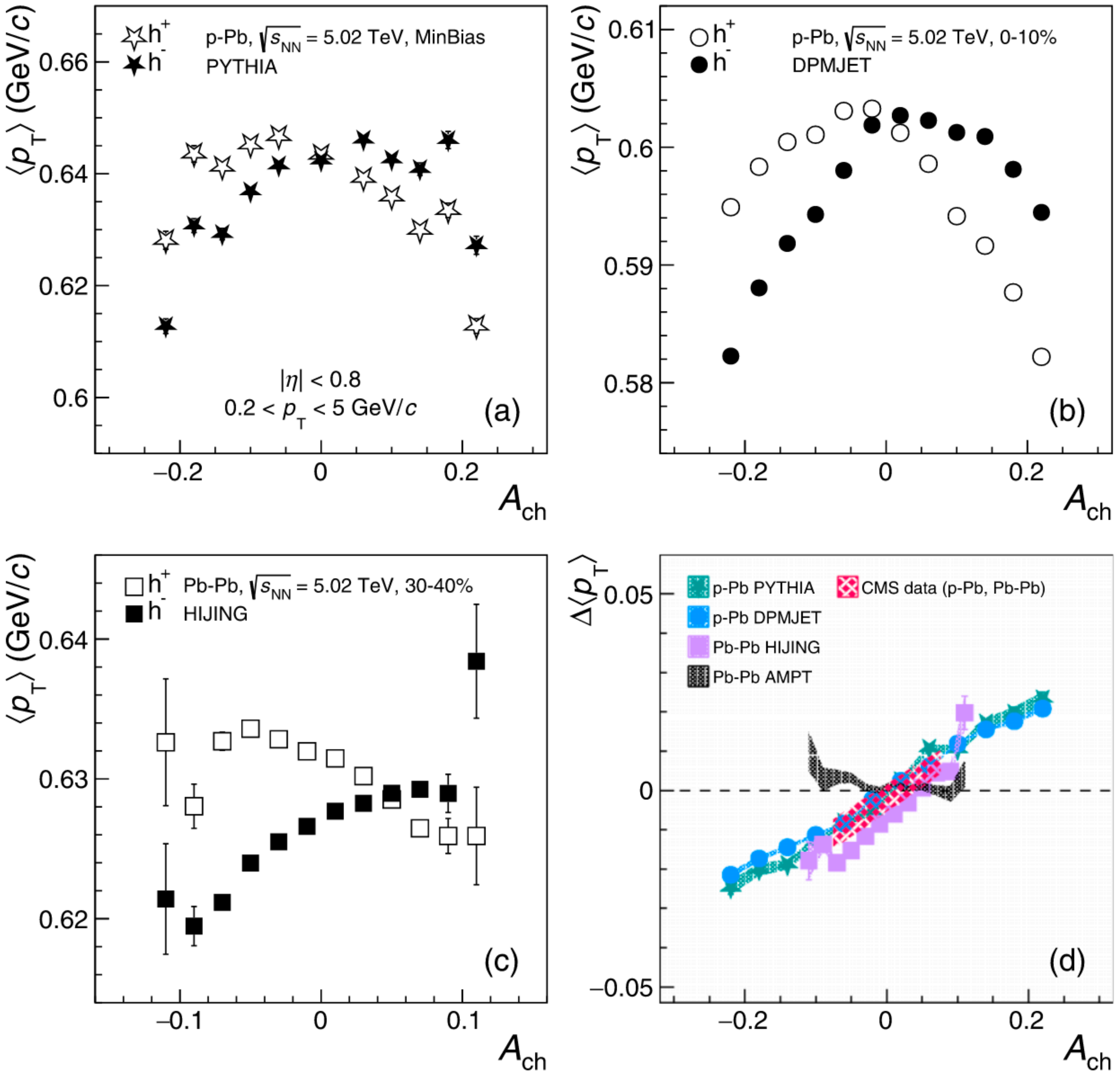
Most possible background: **local charge conservation (LCC) convoluted with v_2**

- ✓ The observable in p-Pb collision is in line with the one in Pb-Pb collisions
- ✓ Higher harmonic (v_3) observable with nonzero signal

How to separate the signal/background?

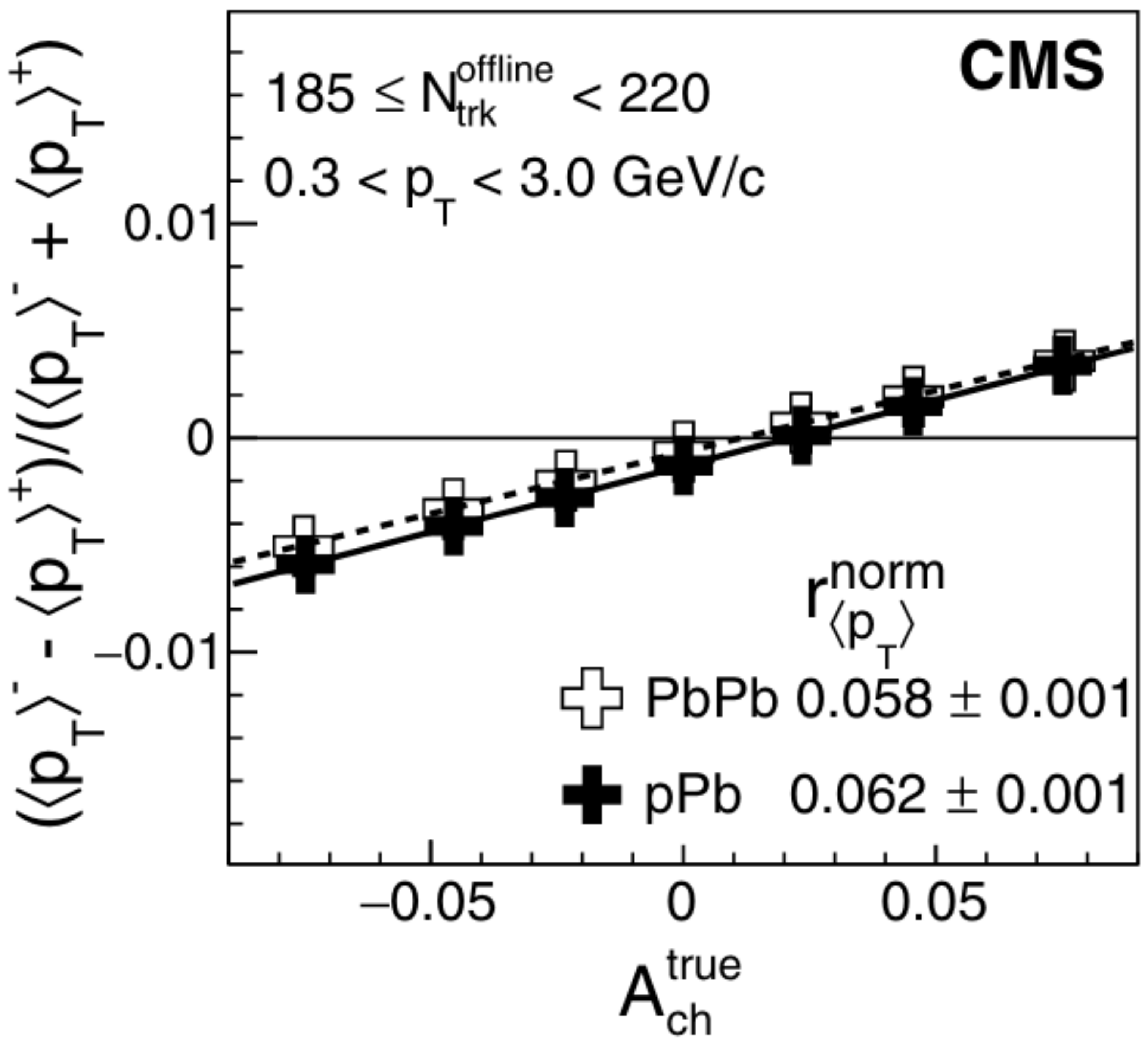
A. Bzdak et al. Phys. Lett. B 726 239243 (2013)
S. A. Voloshin et al. Nucl.Phys.A 931 992996 (2014)
W. Wu et al. Phys. Rev. C 103, 034906 (2021)

LCC effect resulting in the pT—Ach dependence



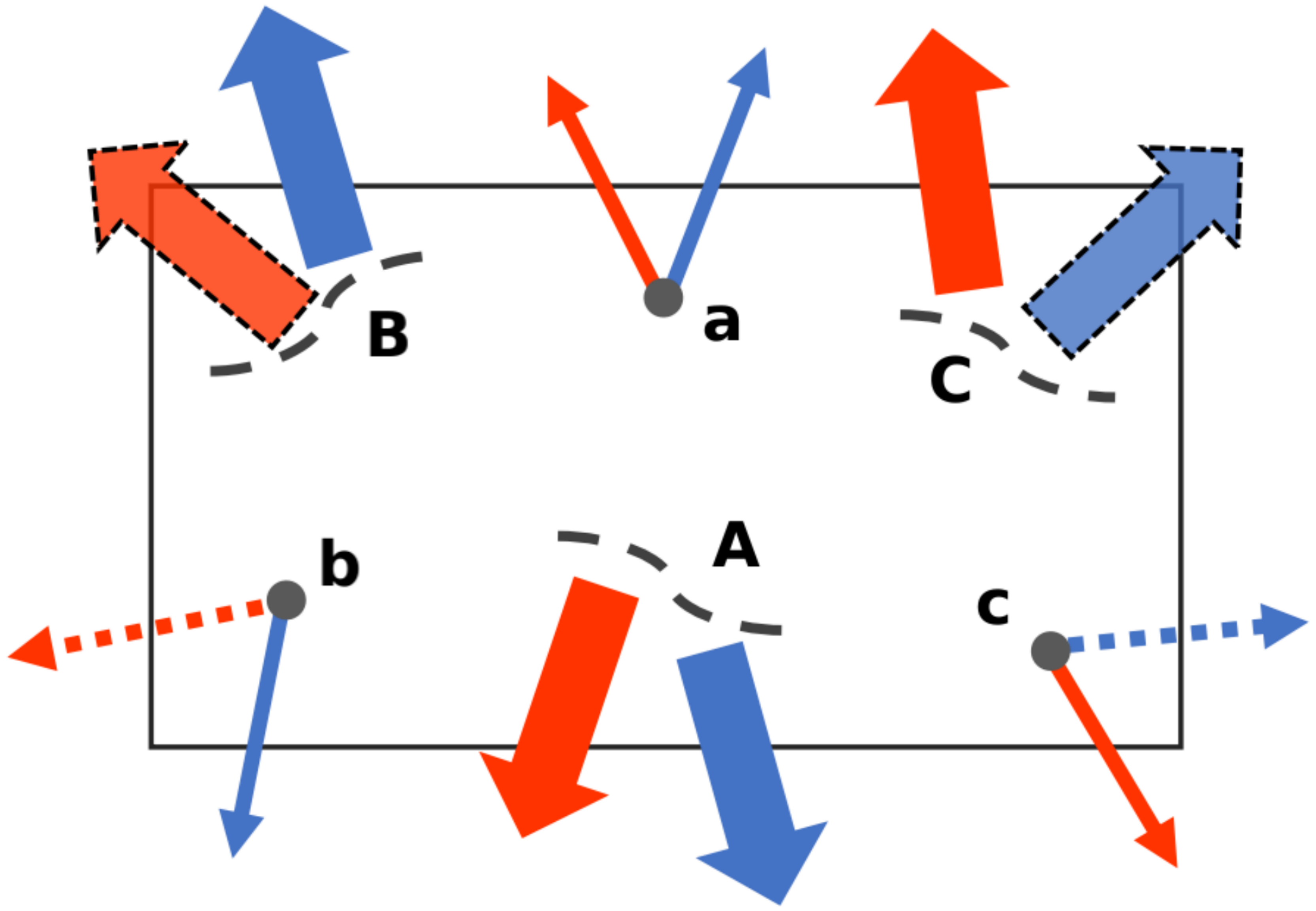
W. Wu et al. Phys. Rev. C 103, 034906 (2021)

CMS Collaboration Phys. Rev. C 100, 064908 (2019)



- Models (PYTHIA, DPMJET, HIJING) cam explain the CMS data, except for AMPT, as LCC is distorted by ZPC process
- $p_T - A_{ch}$, $\eta - A_{ch}$ are observed by experimental data
- Explanation and contribution to $v_2 - A_{ch}$, see next slide

LCC effect contributing to CMW observable



When selecting events with a specific A_{ch}, in practice, one preferentially applies nonuniform $p_T(\eta)$ cuts on the charged particles

A manifestation of LCC!

	$\rho^0 \to \pi^+\pi^-$		String frag.	
Type	unpaired (case b, c)	paired (case a)	unpaired (case B, C)	paired (case A)
Mother p_{T}	0.75	0.97	0.94	1.41
Mother $\lvert\eta\rvert$	1.17	0.53	2.15	2.12
Daughter p_{T}	0.59	0.64	0.68	0.74
Daughter $\lvert\eta\rvert$	0.41	0.39	0.41	0.40
Daughter $\lvert\Delta\eta\rvert$	1.27	0.48	1.03	0.69

$A_{ch} < 0(>0) \rightarrow$ B(C) and b(c) $\uparrow \rightarrow$ unpaired neg(pos) particles $\uparrow \rightarrow \langle p_T^- \rangle < \langle p_T^+ \rangle \big(\langle p_T^- \rangle > \langle p_T^+ \rangle\big)$

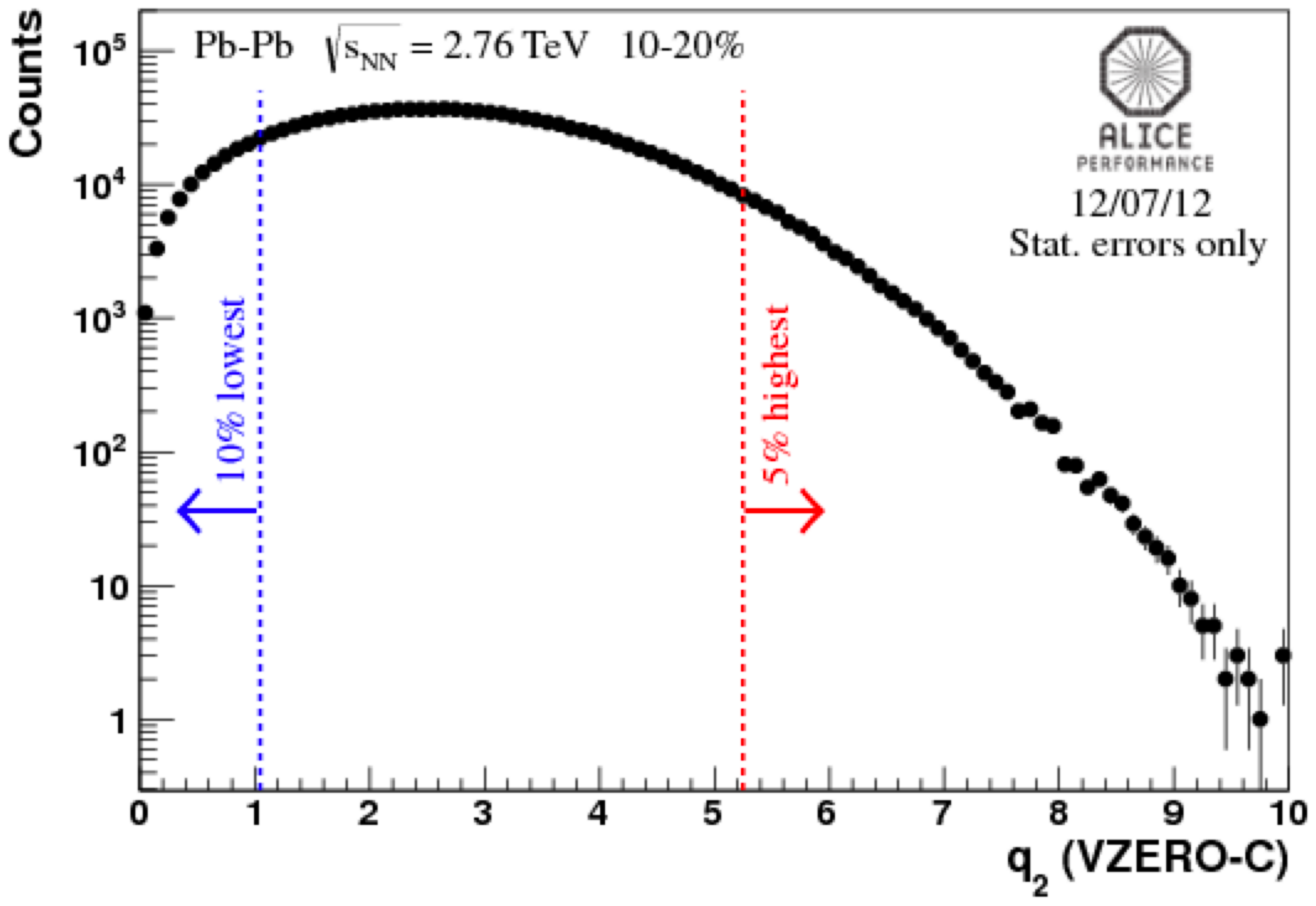
- **Resonance decay** (a,b,c): paired particle emitted at the same point
- **String fragmentation model** (A,B,C): hadronization process with a string consisting of q and $\bar{q}$ endpoints

CMW LCC:
W. Wu et al. Phys. Rev. C 103, 034906 (2021)
A. Bzdak et al. Phys. Lett. B 726 239243 (2013)
C. Wang, W. Wu et al. Phys. Lett. B 820 136580 (2021)

CME LCC:
S. Schlichting et al. Phys. Rev. C 83, 014913 (2011)

ESE method for the extraction of signal and background

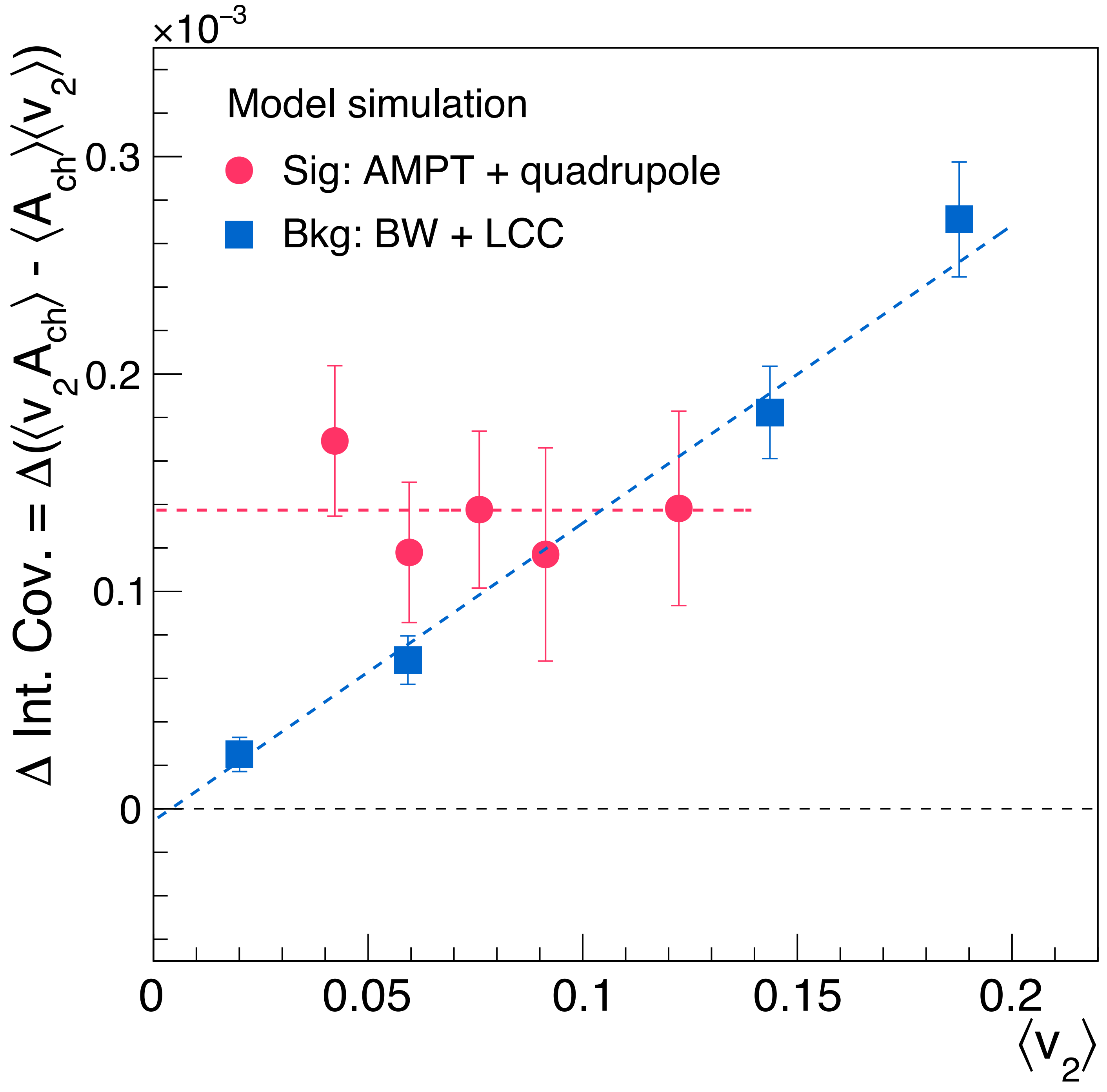
A. Dobrin et al. Nucl.Phys.A 904-905 455c-458c (2013)



- ✓ Classify events corresponding to q_2
- ✓ Sensitive to v_2 of collision ($q_2 \propto v_2$)
- ✓ Successfully used for CME

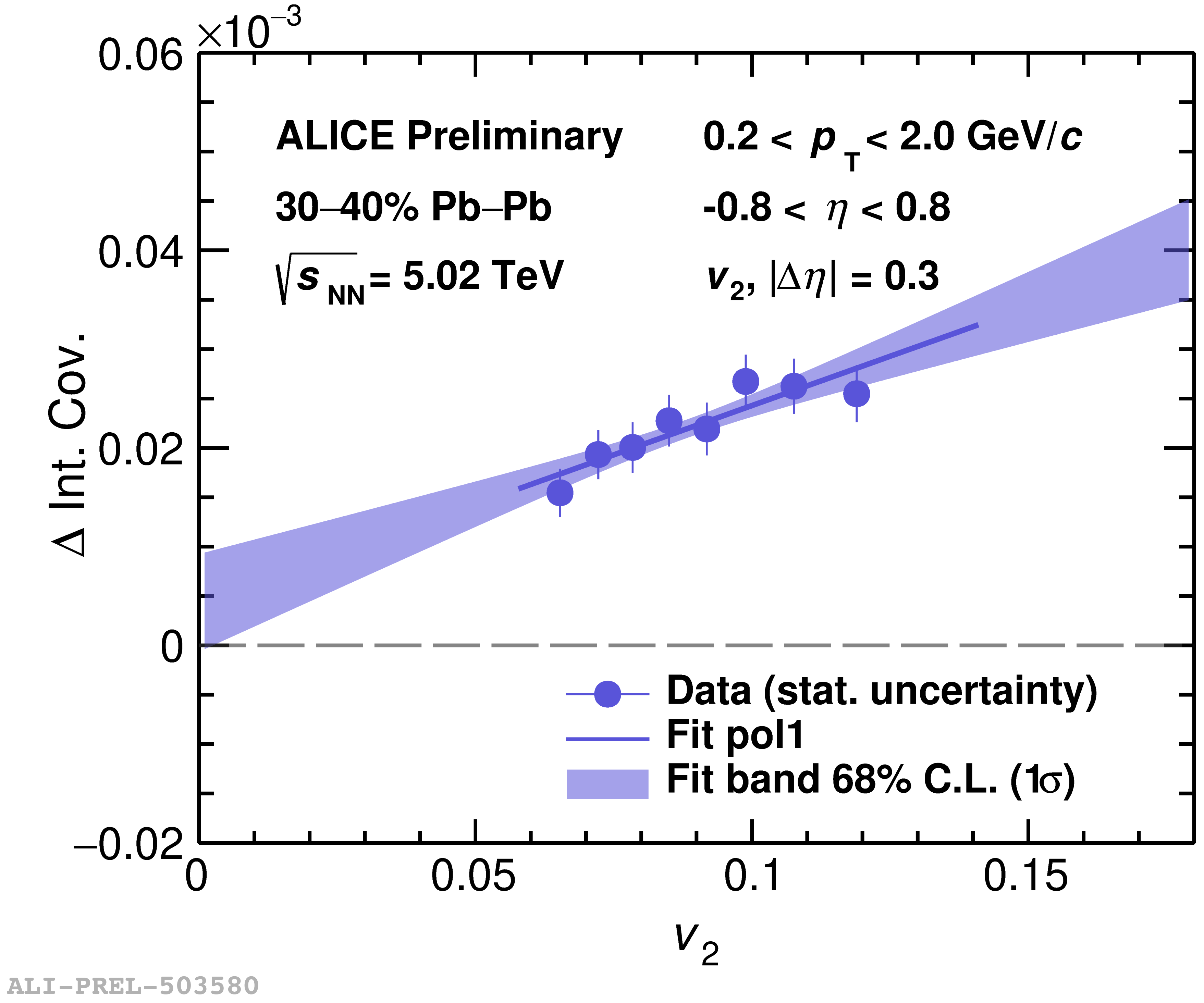
ESE technique
J. Schukraft et al. Phys. Lett. B 719 394398 (2013)
ALICE Collaboration Phys. Lett. B 777, 151162 (2018)
CMS Collaboration Phys. Rev. C 100, 064908 (2019)

C. Wang, W. Wu et al. Phys. Lett. B 820 136580 (2021)



- ✓ CMW signal (AMPT+quadrupole)
  ΔInt. Cov. vs. v_2 : finite intercept
- ✓ Background (BW+LCC)
  ΔInt. Cov. vs. v_2 : zero intercept

EPJ Web Conf. 276 (2023) 01001



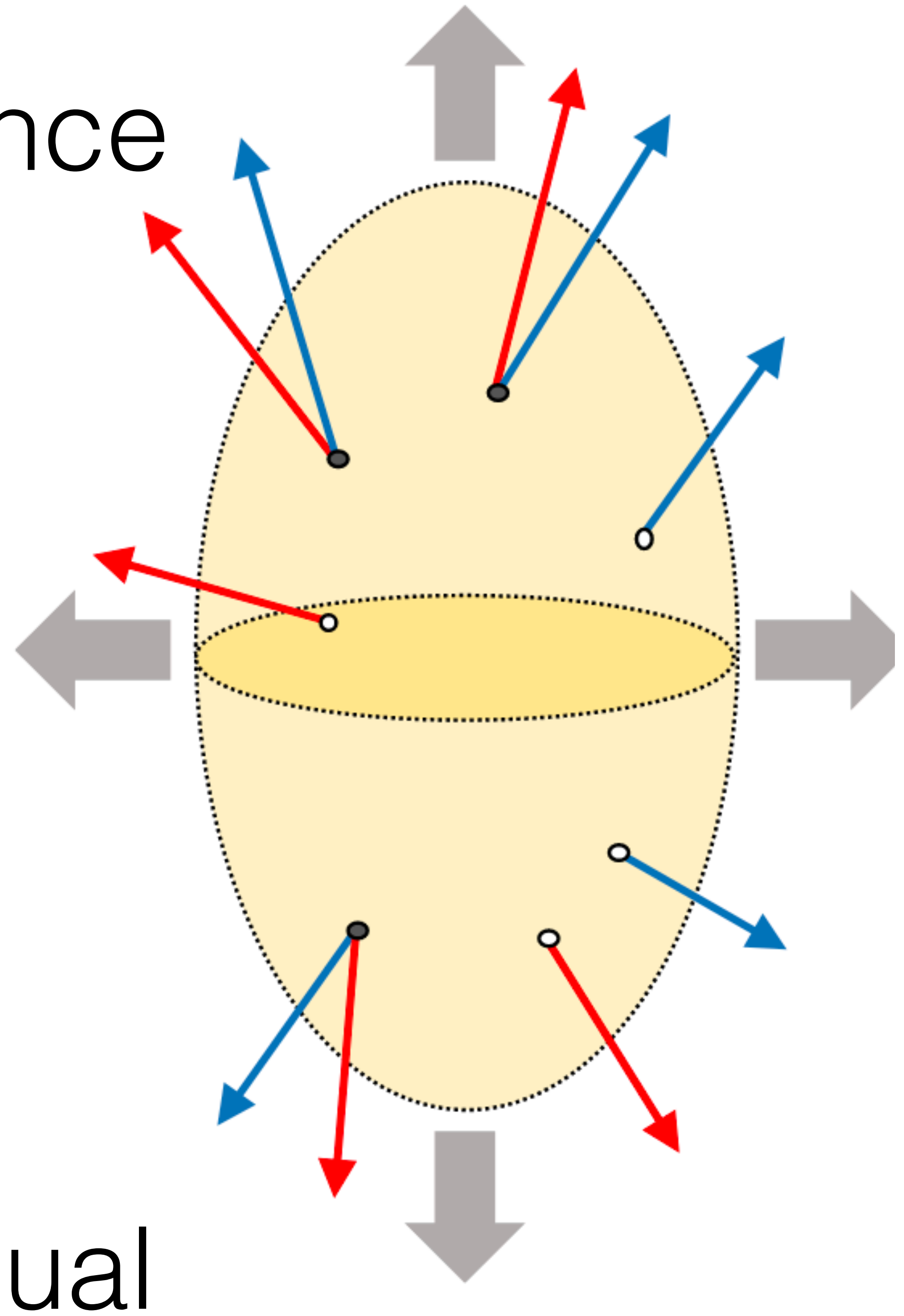
- ✓ In most centralities, the proportionality of ΔInt. Cov. changes with v_2 → indication of a large background
- ✓ Linear fit: $F(v_2) = a \times v_2 + b$
- ✓ Upper-limit of CMW fraction : 26.4% (95% C.L.)

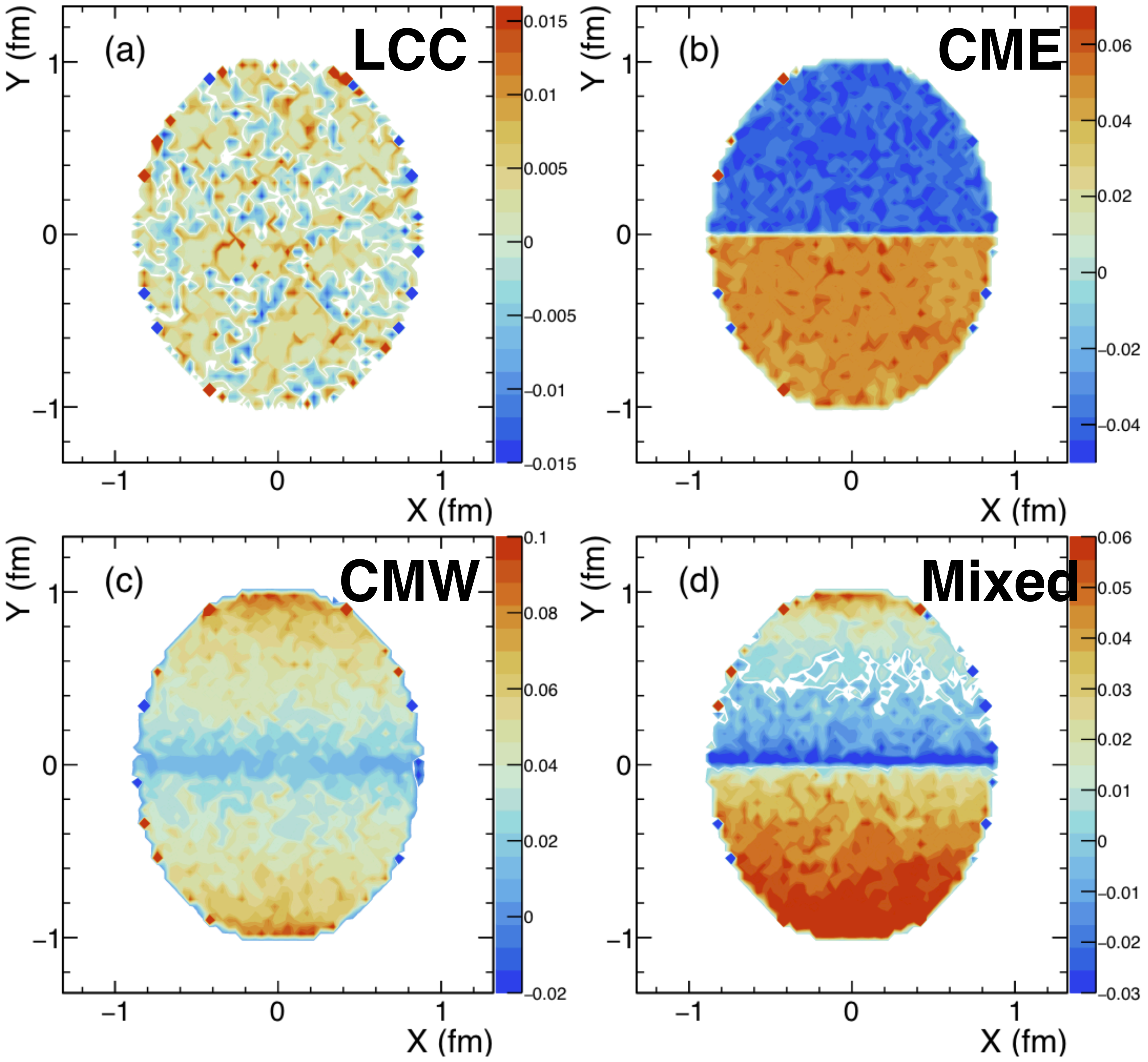
A new ALICE paper for CMW measurement is expected in this year!

Global constraint on the magnitude of anomalous chiral effects

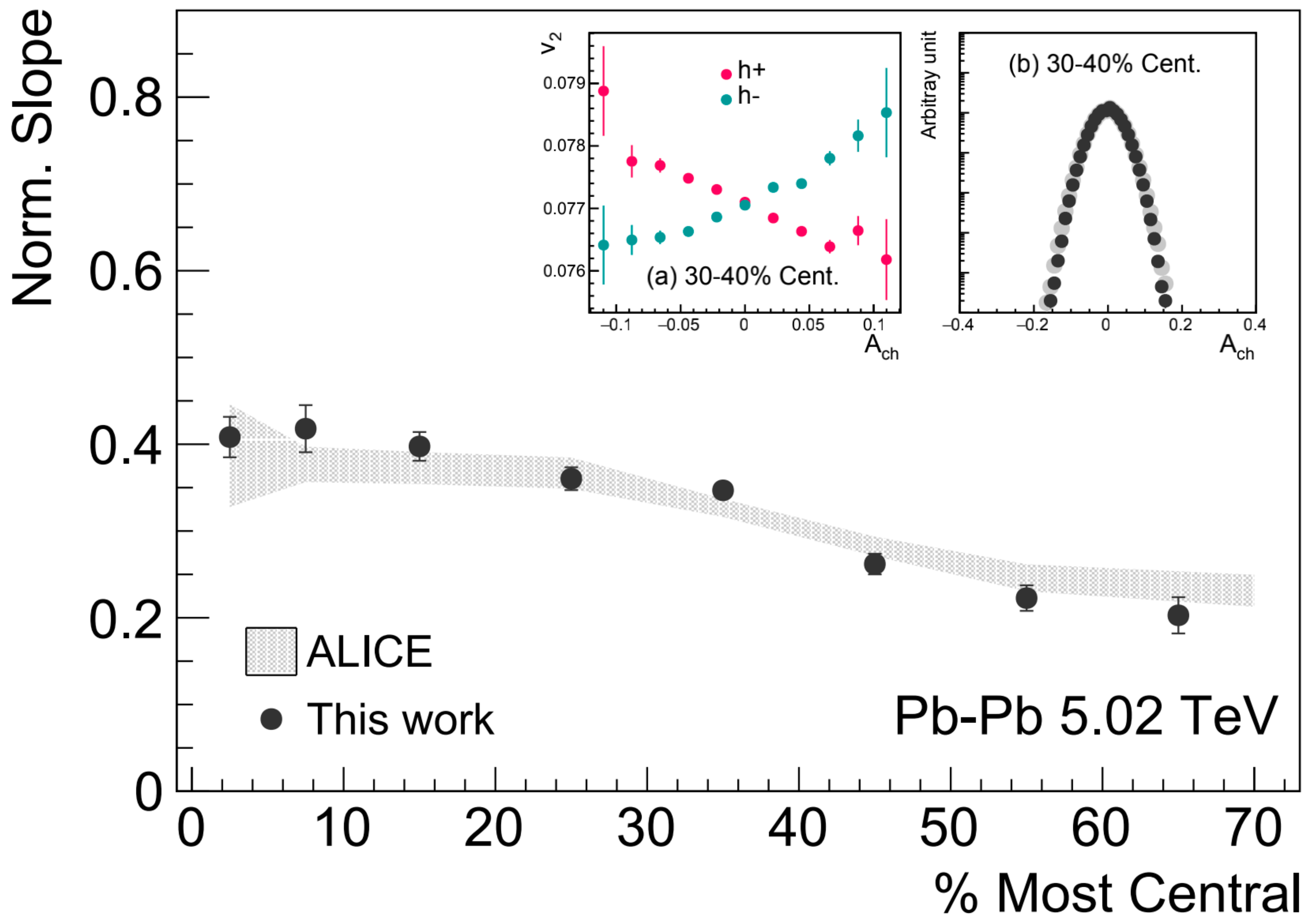
Simple blast-wave model

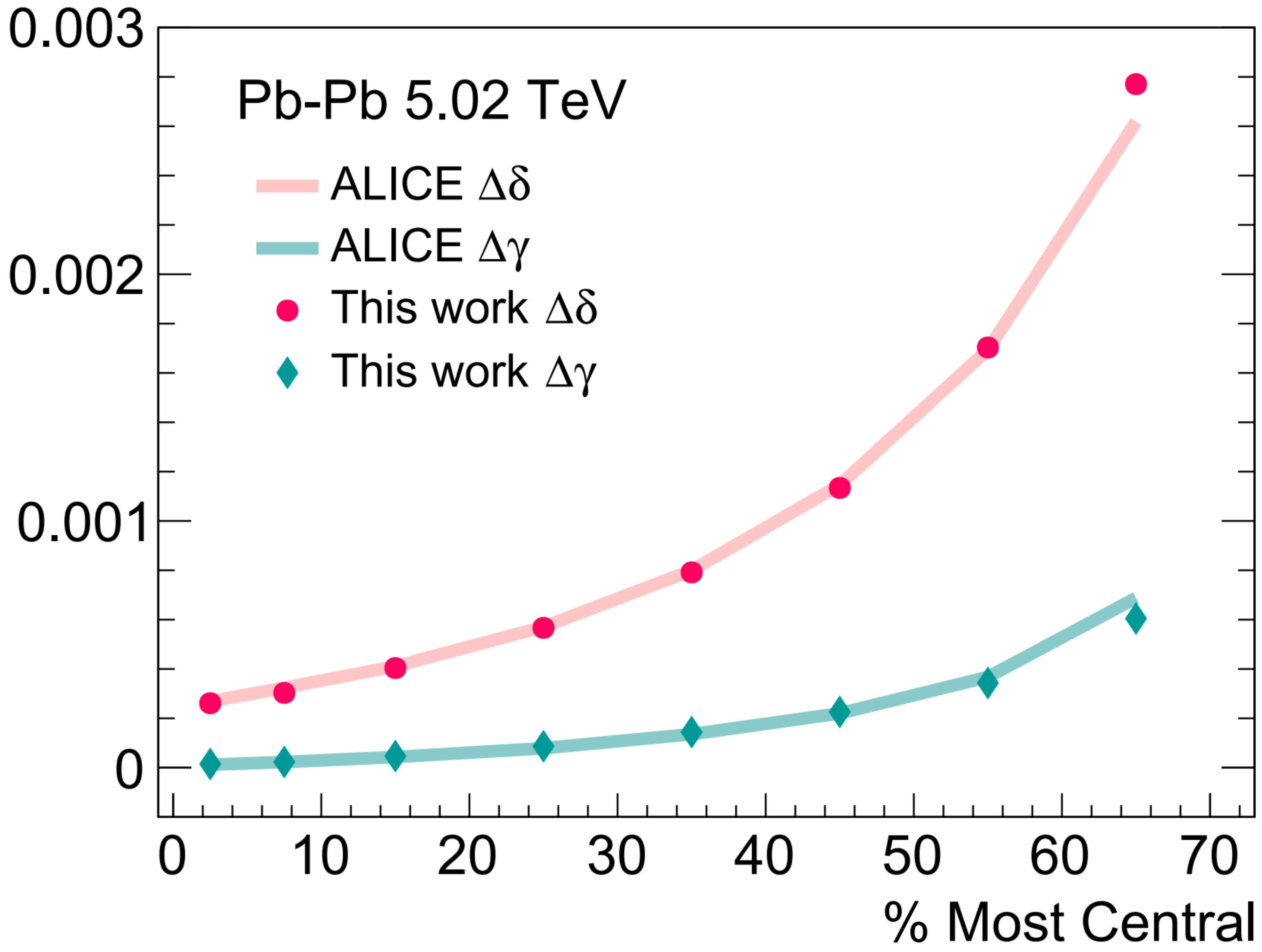
- Model without any evolution process
- Fit v2-pT, pT spectrum, fit Balance function
- Part of LCC background
- Tiny CME+CMW signal by switching charged particles manually
- Found
  - CMW/CME signal are individual
  - Observables of CME/CMW are very sensitive to the signal





Global constraint on the magnitude of anomalous chiral effects





Important conclusions:

- BW+LCC —> boost paired particles at a same point —> Blast wave model (thermal expansion) adding **finite** LCC effect can reproduce the ALICE experimental measurements of CMW(left) and CME(right) together —> measurements on both CMW and CME are dominated by the LCC background
- Observables of CMW and CME are **independent** and **very sensitive** to CMW/CME signal

Go back to the development of study on CMW

Summary

- ✓ The LCC effect is recognized as one of the most important background effect in the studies of chiral anomalous effects
- ✓ Δv_2-$A_{\rm ch}$ **method:** The normalized slope $r_{\Delta v_2}^{Norm.}$ is consistent with $r_{\Delta v_3}^{Norm.}$ within uncertainties implying that CMW signal is consistent with zero
- ✓ **ESE method:** First measurement of the CMW fraction with ESE method in Pb-Pb collisions, $f_{\rm CMW}$ is consistent with zero within uncertainties (There is no statistical significance to observe the CMW signal)

Thanks for your attention!