原子核结构与中高能重离子碰撞交叉学科理论讲习班

高能重离子碰撞中手征反常效应的实验测量

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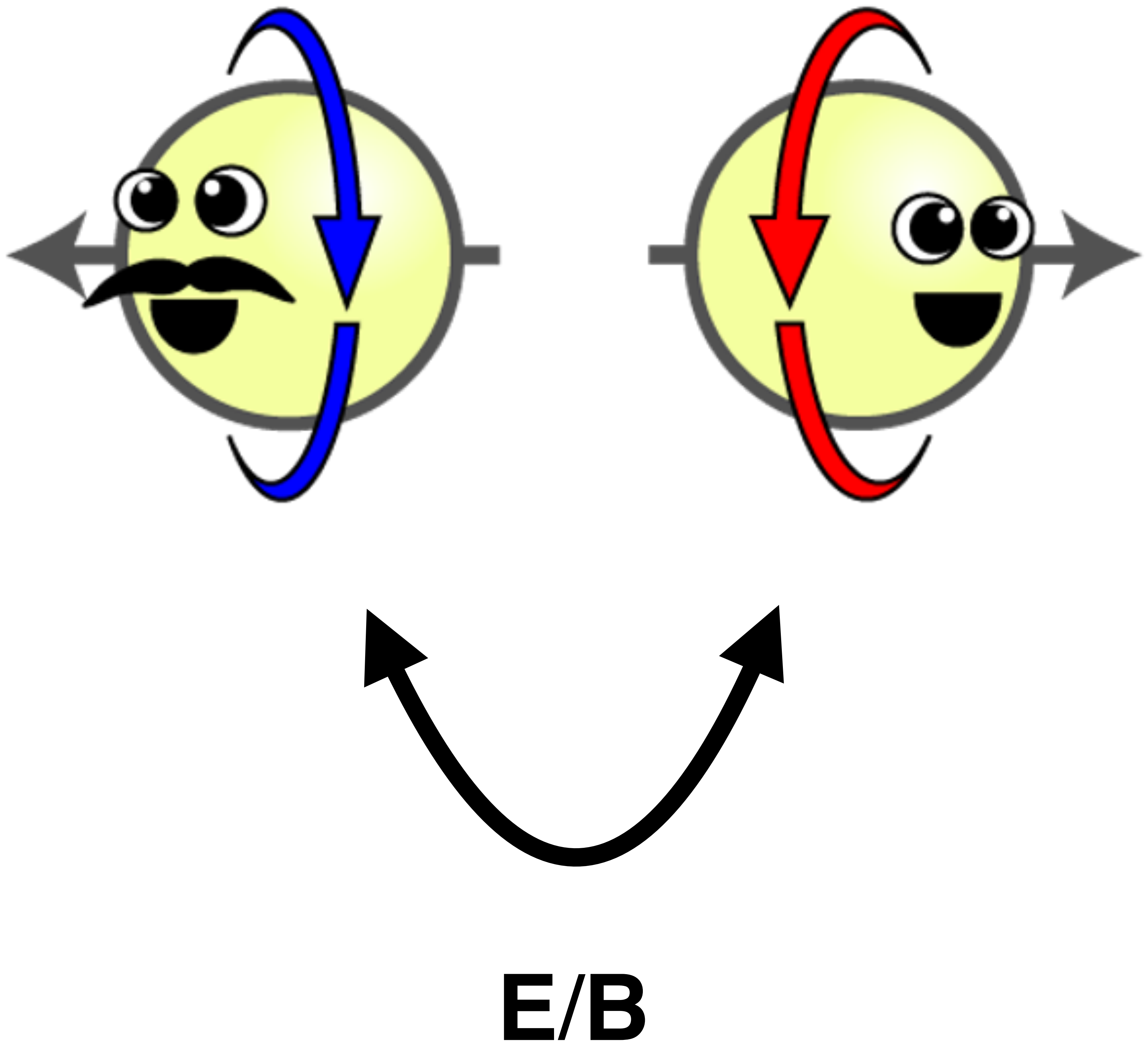
复旦大学

2021年7月，湖州

Outline

- Introduction from experimental perspective
- Search for the Chiral Magnetic Effect
- Search for the Chiral Magnetic Wave
- Summary

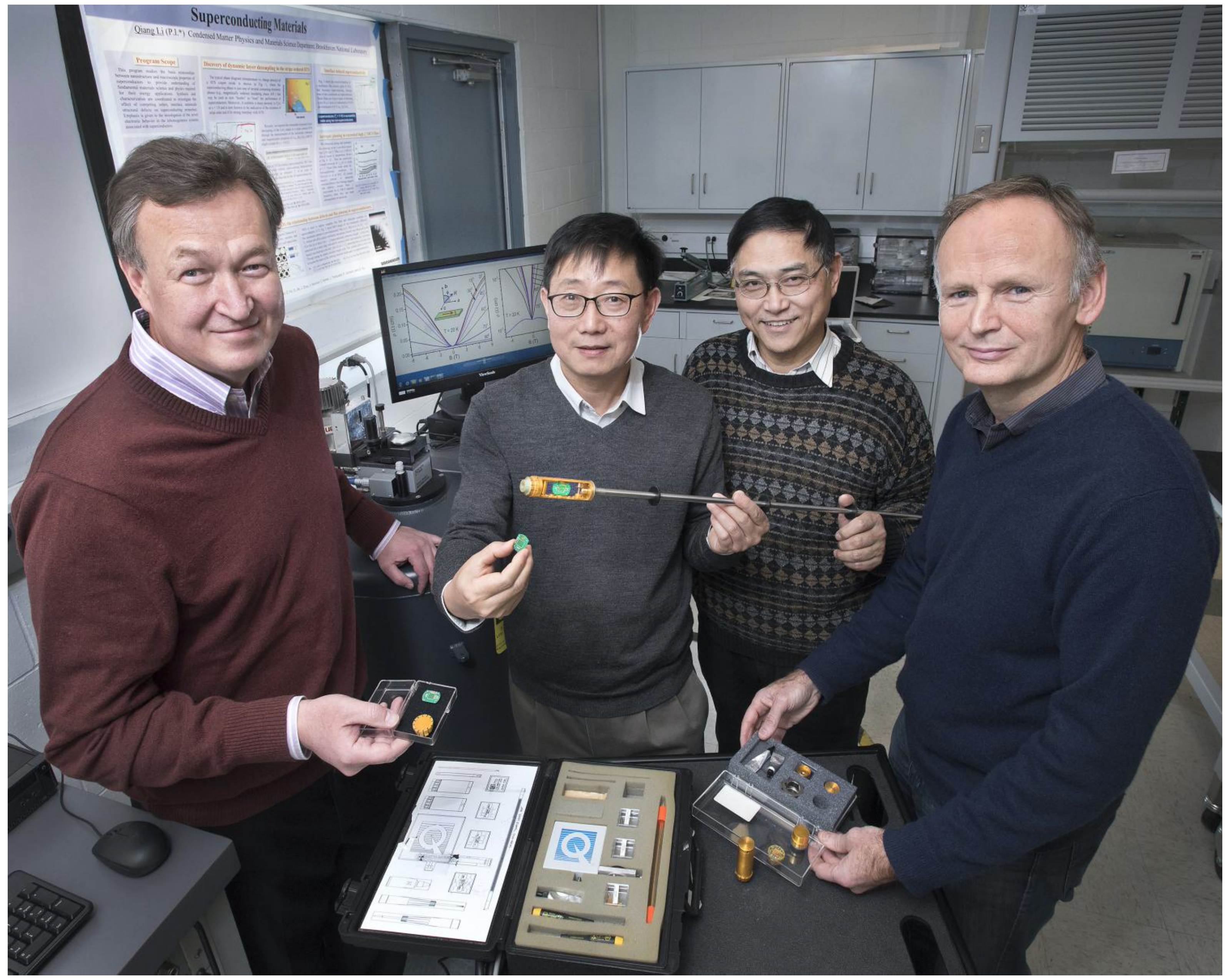
What is chiral anomaly?

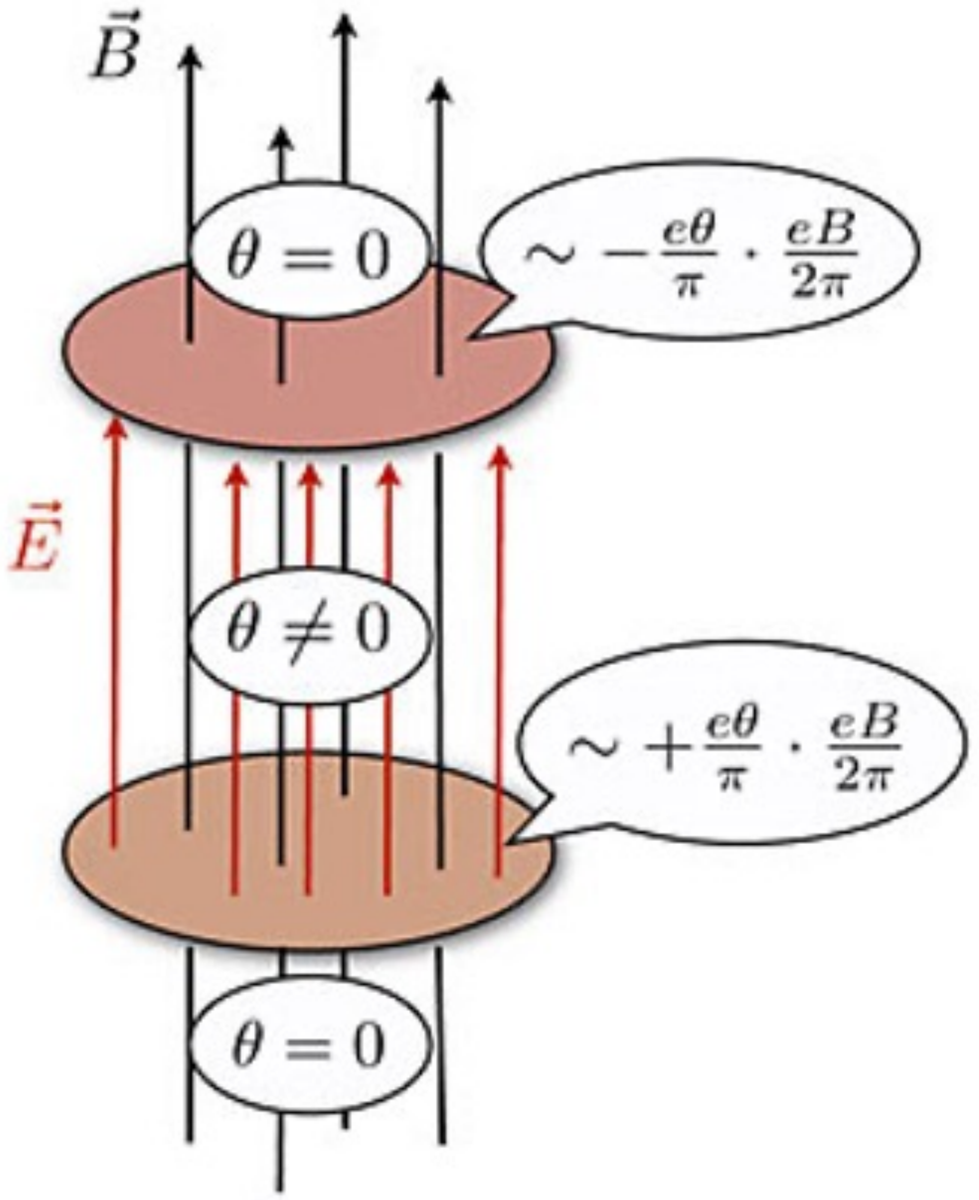


Chiral magnetic effect

Chiral anomaly in condensed matters

Dirac/Weyl semimetal + **E/B** $\longrightarrow$ **J**





BNL + 石溪团队
Chiral magnetic effect in ZrTe5
Nature Phys. 12, 550–554 (2016)

复旦修发贤、晏湖根课题组
The discovery of dynamic chiral anomaly in a Weyl semimetal NbAs
Nature Commun. 11, 1259 (2020)

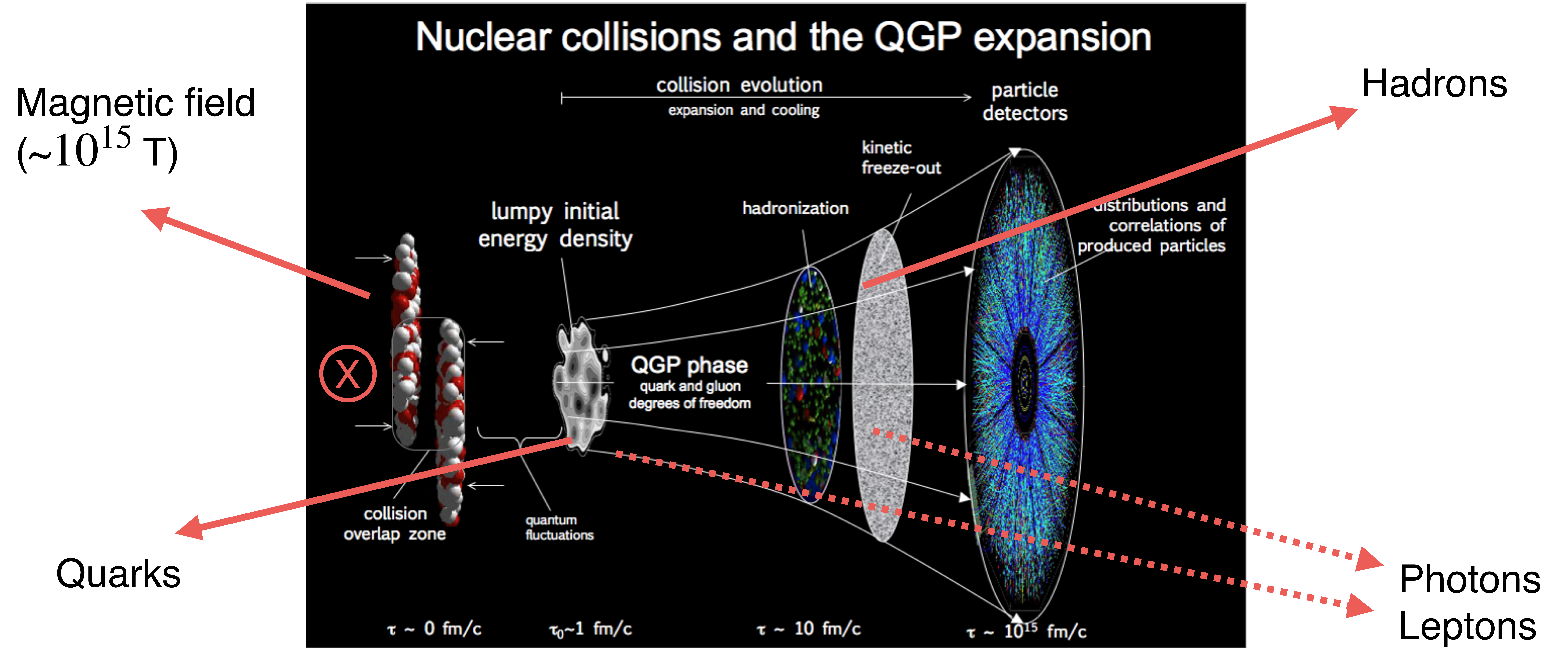
Beyond condensed matters, in heavy-ion collisions

Dirac/Weyl semimetal + **E**/**B** $\longrightarrow$ **J**

⬇

Quarks from QGP + **E**/**B** from spectators $\longrightarrow$ **J**

- Topological structure of vacuum gauge fields
- The possible local violation of P (parity) and/or CP (charge-parity) symmetries in strong interactions



Criticality, **Collectively**, **Chirality**

Anomalous chiral effects

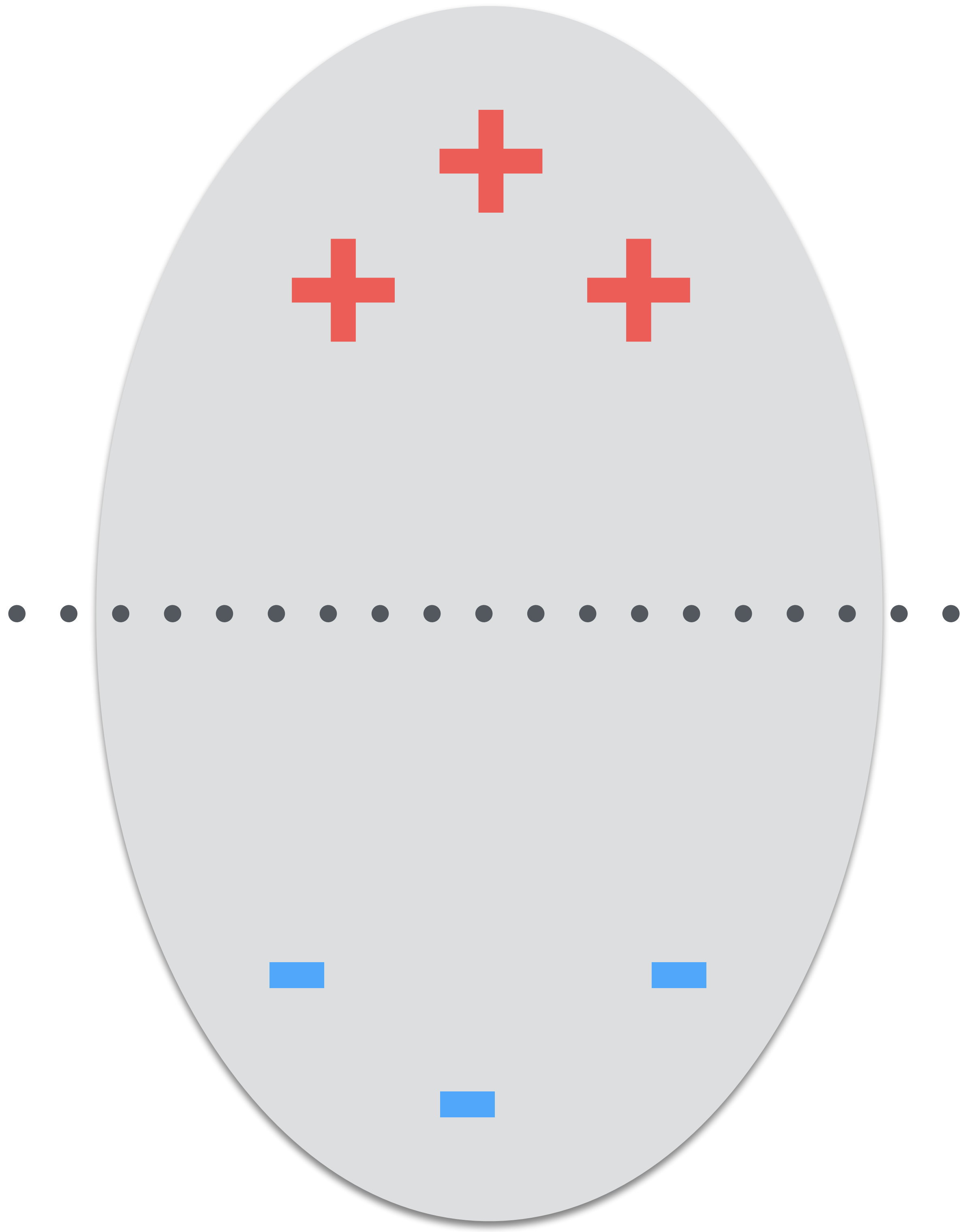
Chiral magnetic effect (CME)	$\overrightarrow{J} = \mu_5 \overrightarrow{B} \qquad (\overrightarrow{J_V} = \mu_A \overrightarrow{B})$
Chiral separation effect (CSE)	$\overrightarrow{J_A} = \mu_V \overrightarrow{B}$
Chiral electric separation effect (CESE)	$\overrightarrow{J_A} = \sigma_{\chi e}(e \overrightarrow{E})$
Chiral vortical effect (CVE)	$\overrightarrow{J} = \mu_5 \overrightarrow{\omega}$
Chiral magnetic wave (CMW = CSE + CME)	$\overrightarrow{J}^f_{V,A} = q_f \frac{N_c e}{2\pi^2} \mu^f_{A,F} \overrightarrow{B}$
Chiral vortical wave (CVW)	$\partial_t(\delta n) + \frac{\mu_0 \omega}{2\pi^2 \chi_{\mu_0}} \partial_x(\delta n) = 0$

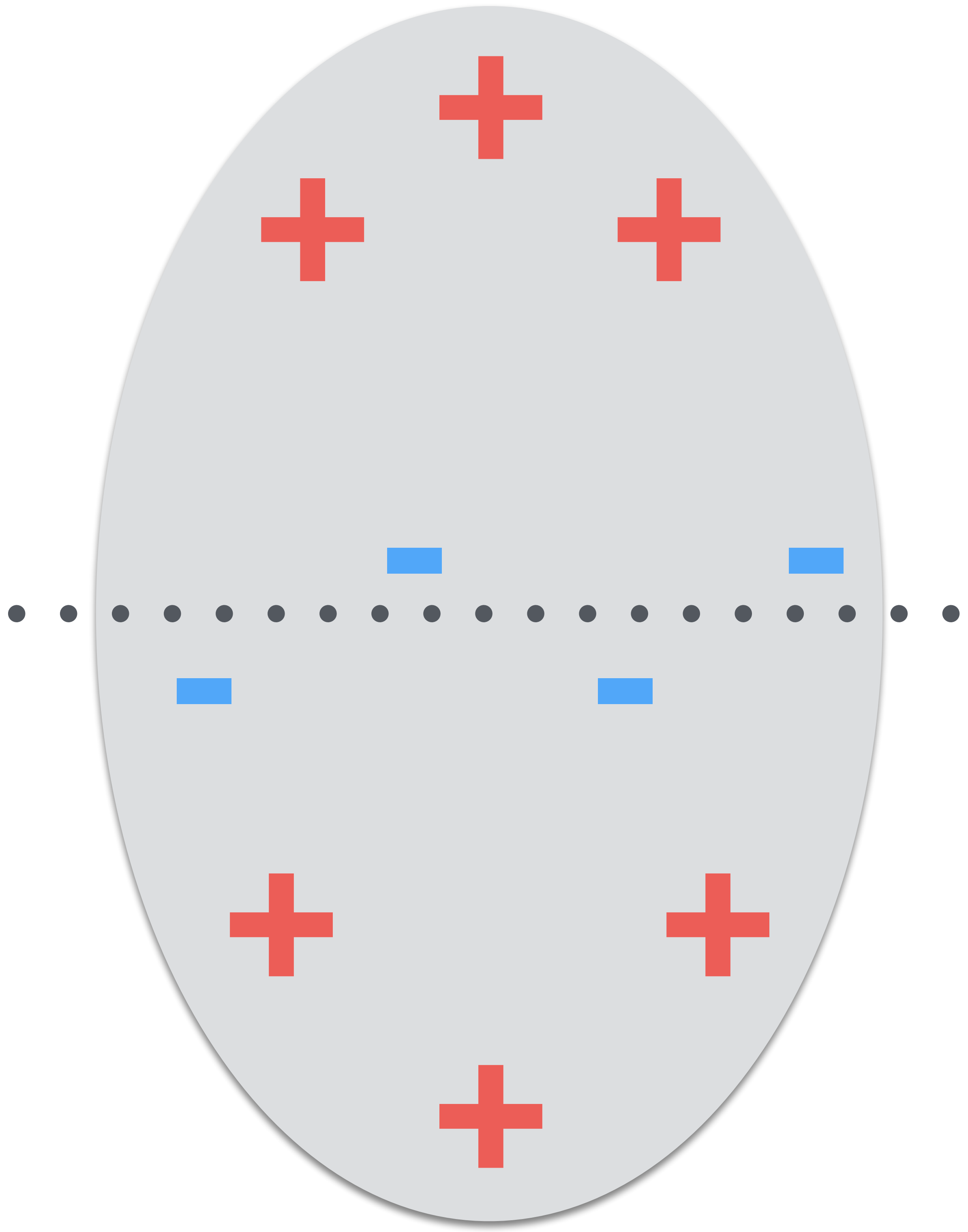
Experimental observables: various charge separations

Chiral magnetic effect (CME)	Out-of-plane electric dipole moment
Chiral separation effect (CSE)	/
Chiral electric separation effect (CESE)	In-plane electric dipole moment
Chiral vortical effect (CVE)	Out-of-plane baryonic dipole moment
Chiral magnetic wave (CMW = CSE + CME)	Out-of-plane electric quadrupole moment
Chiral vortical wave (CVW)	Out-of-plane baryonic quadrupole moment

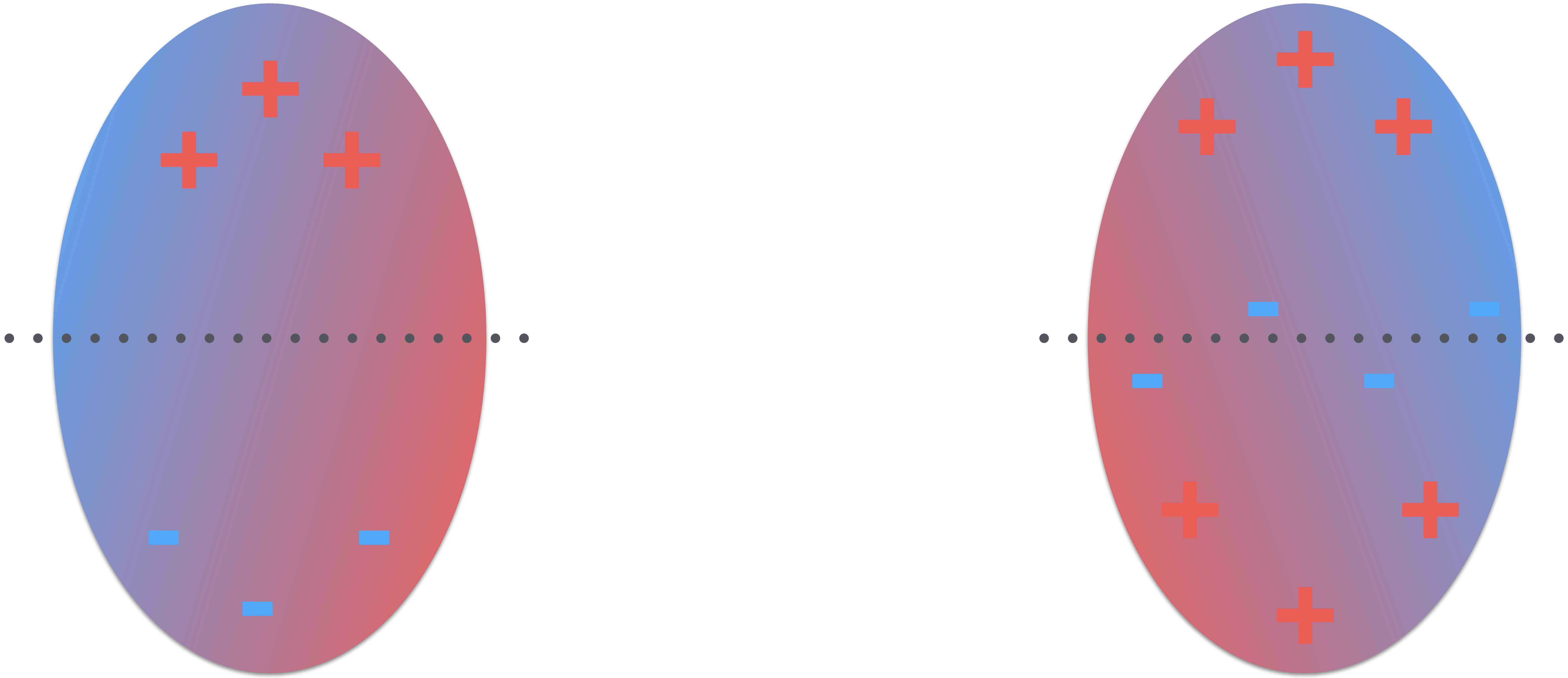
CME and CMW

Local effect, global phenomenon





How can we experimentally detect such kind of charge separations?



How can we experimentally detect such kind of charge separations?

A needle in a haystack

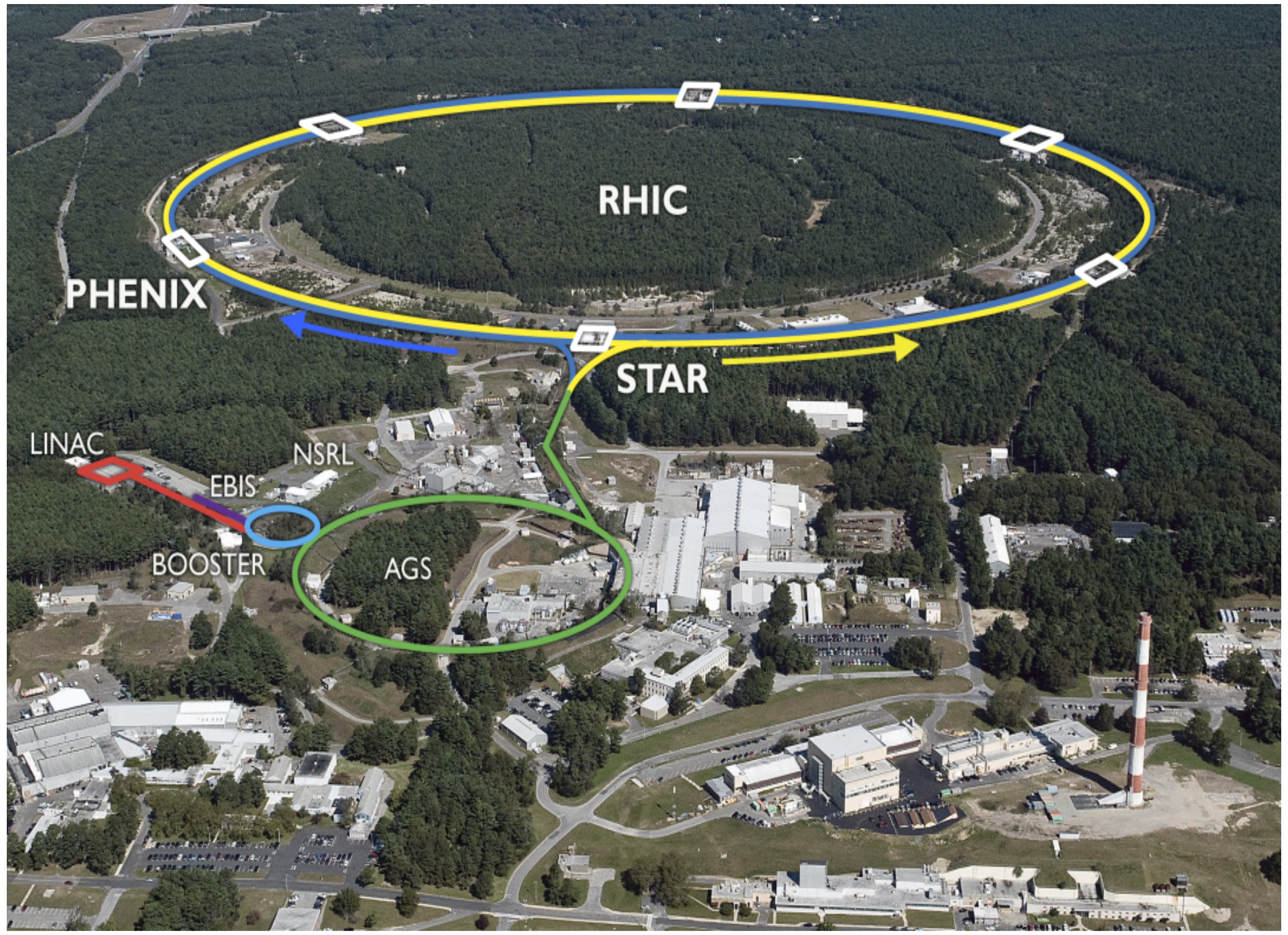
Signal and background in experiments

Ideal

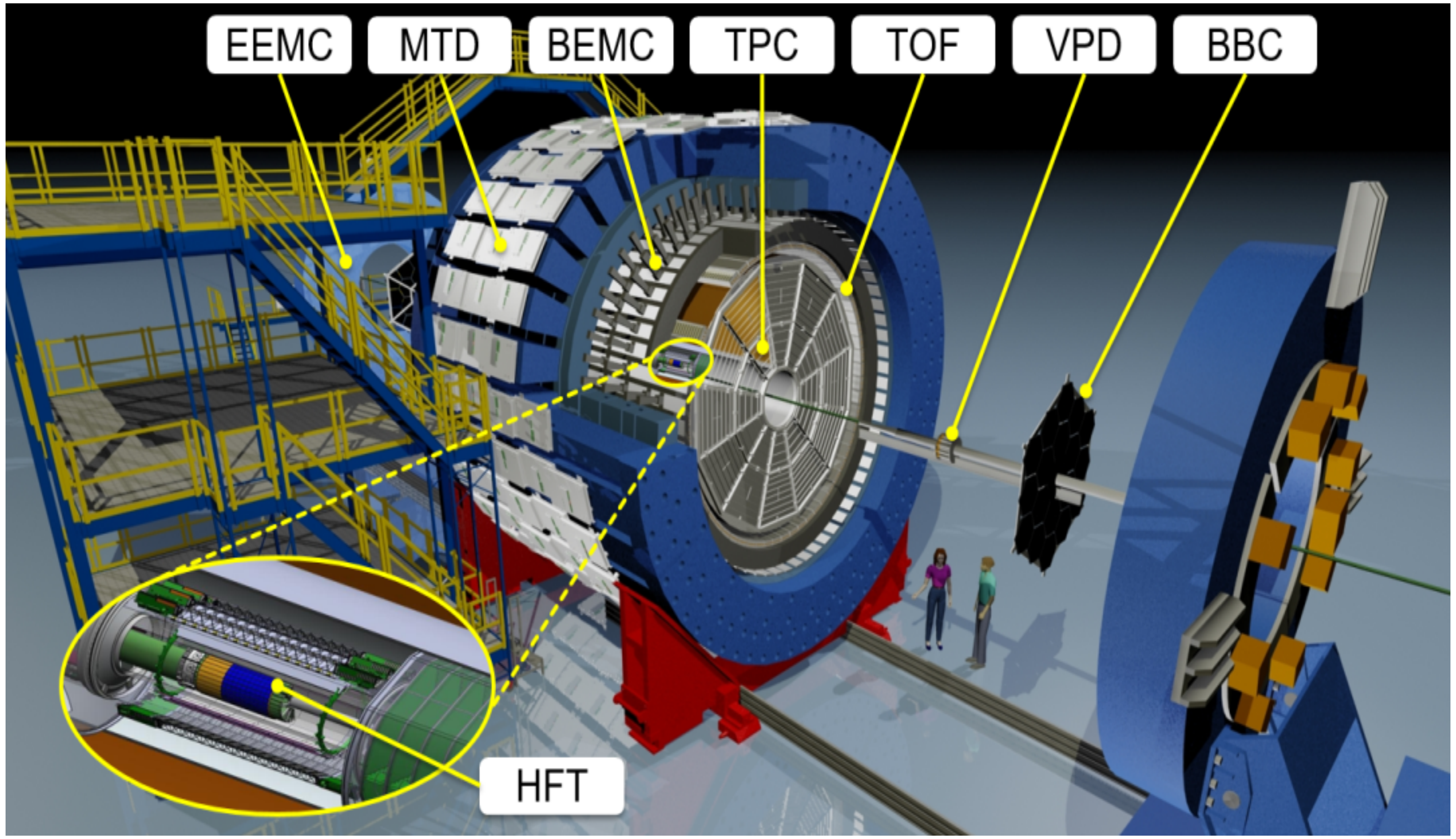
Reality

A good observable: sensitive to the signal rather than the background

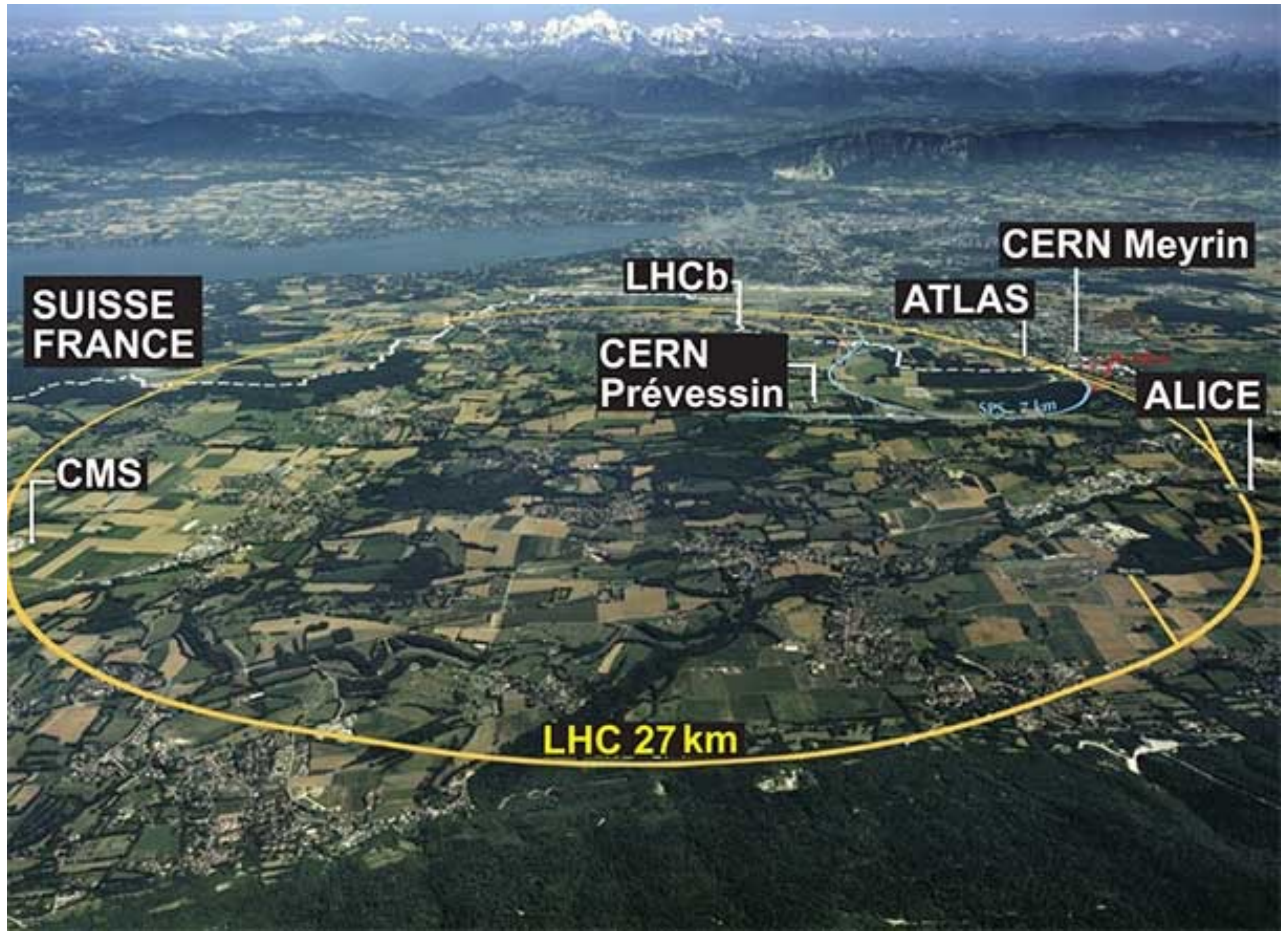
Solenoidal Tracker at RHIC



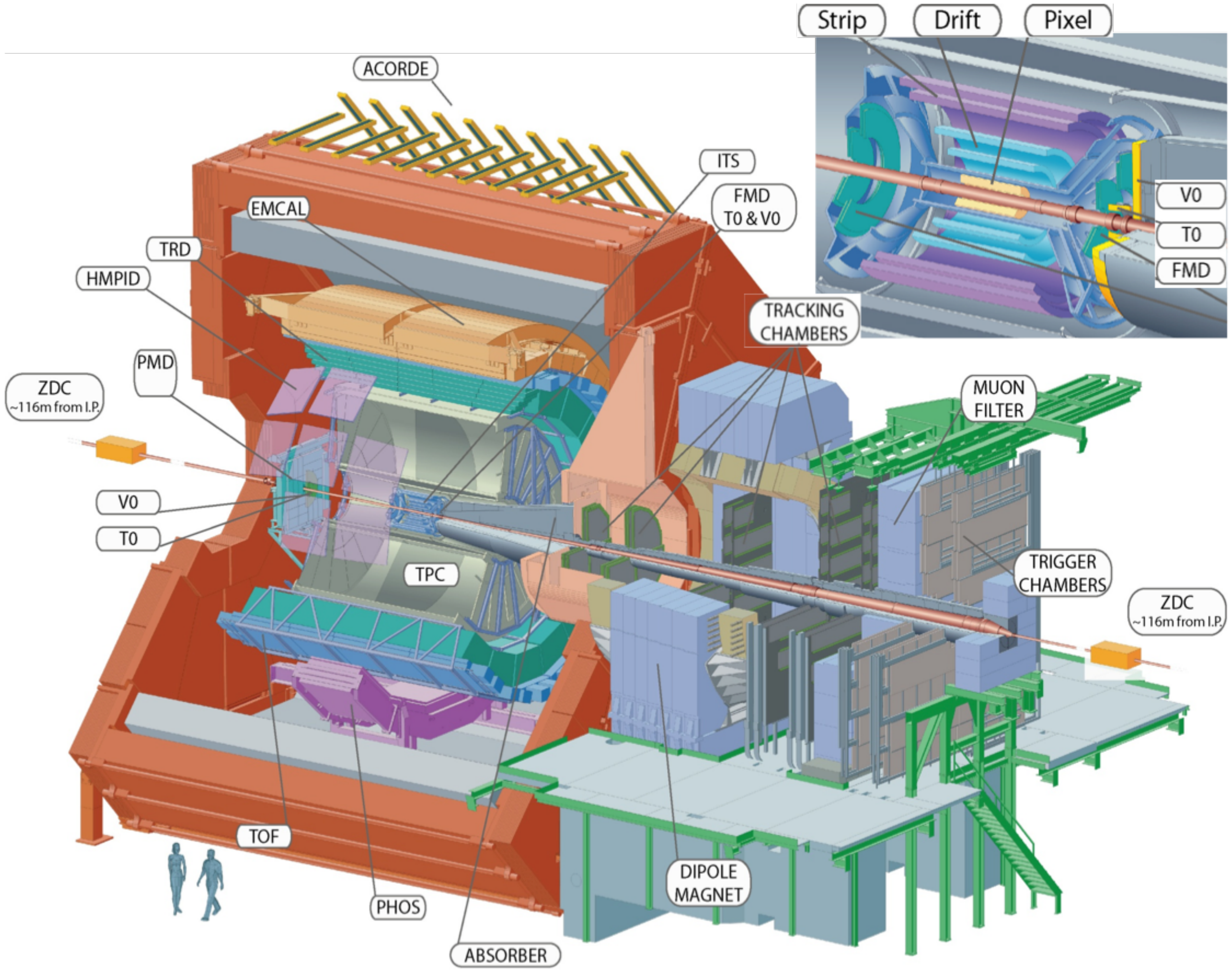
14 countries, 65 institutes, 668 members



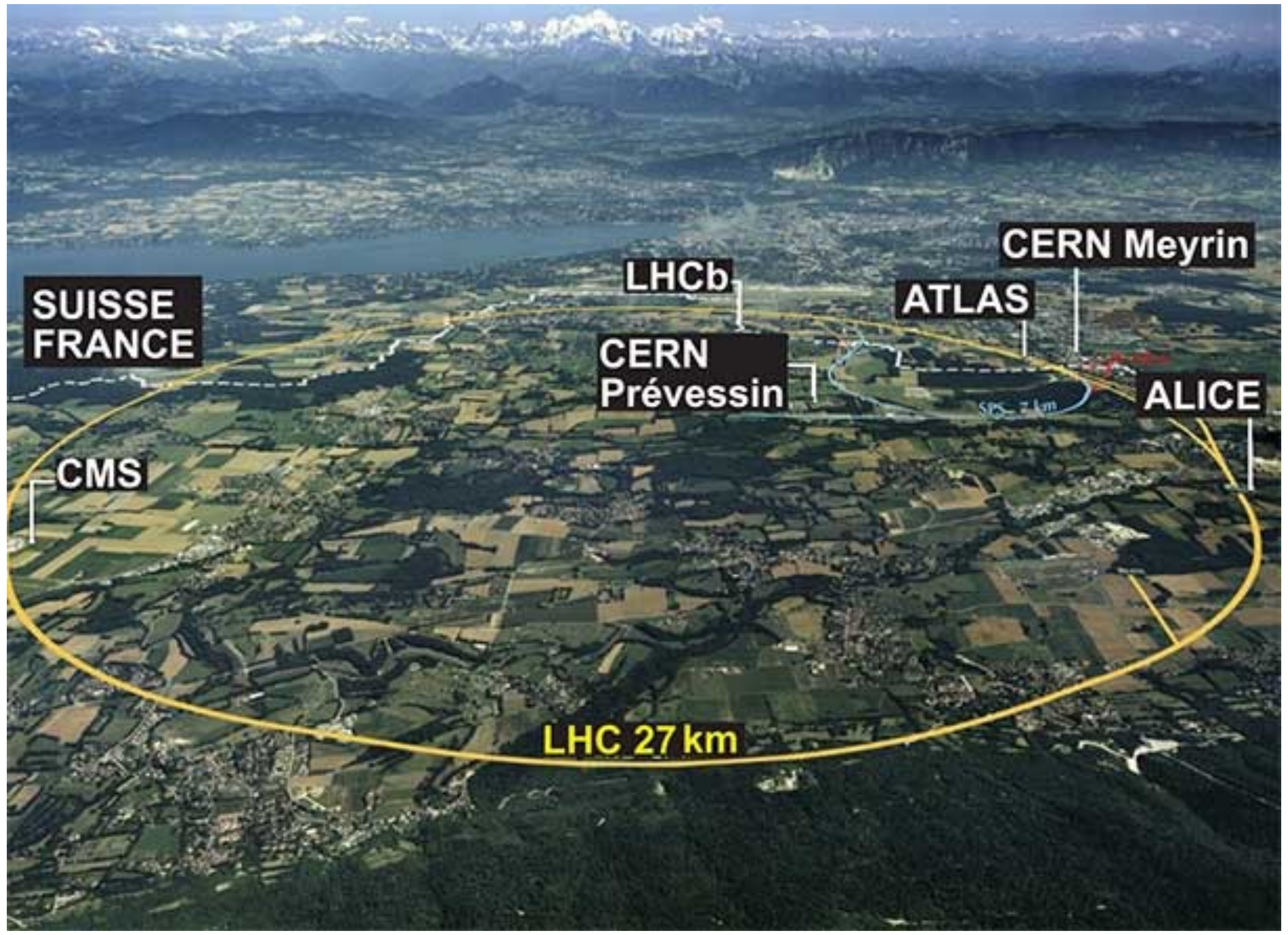
A Large Ion Collider Experiment



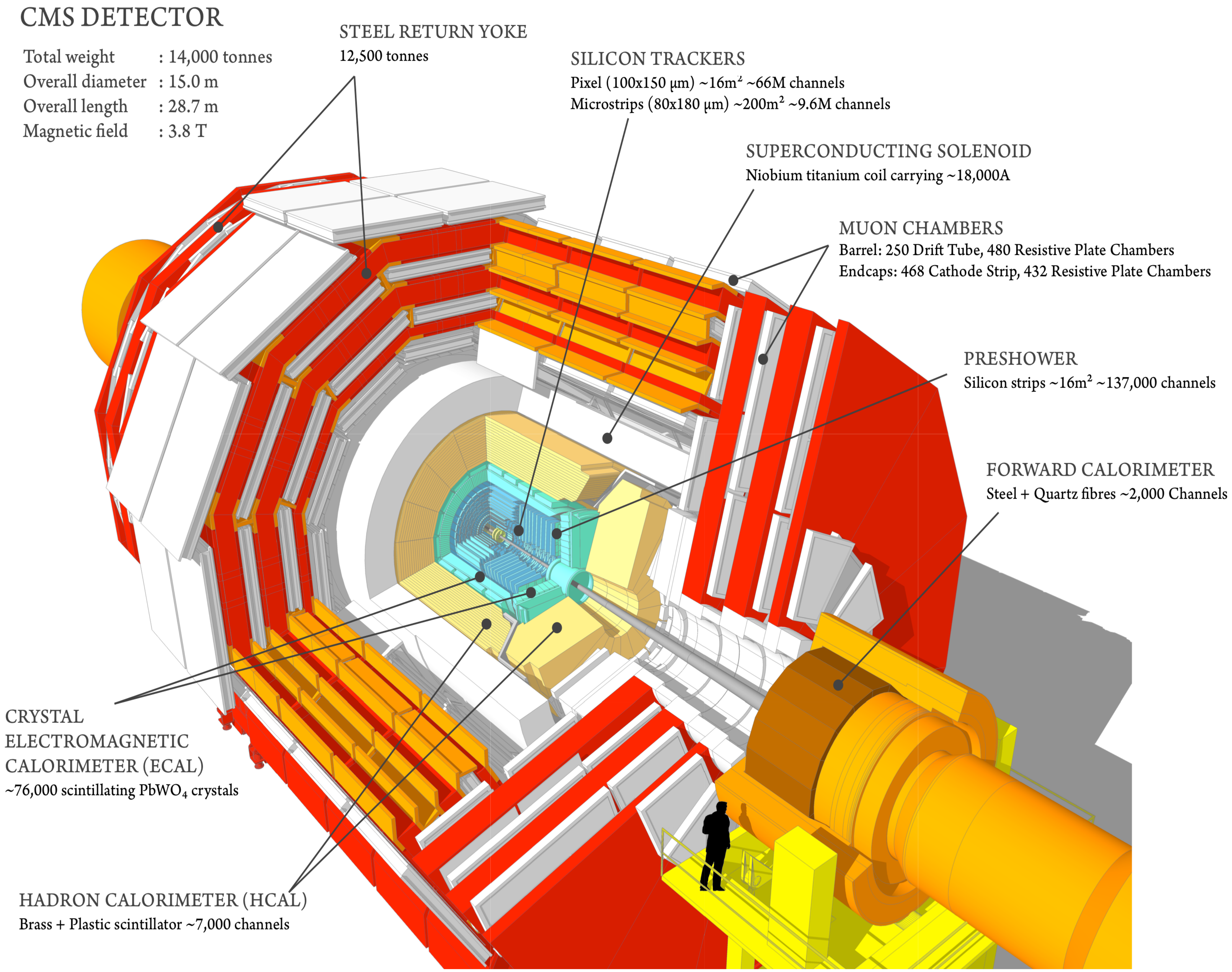
41 countries, 177 institutes, 1800 members



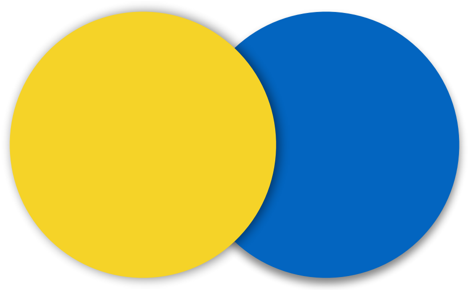
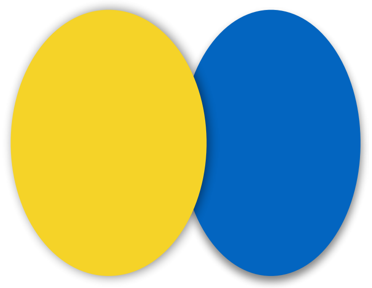
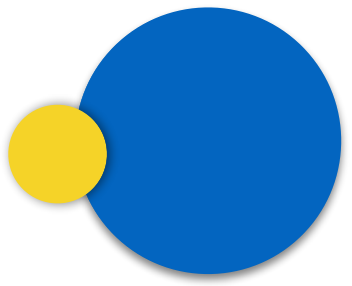
Compact Muon Solenoid



45 countries, 198 institutes, 2100 members

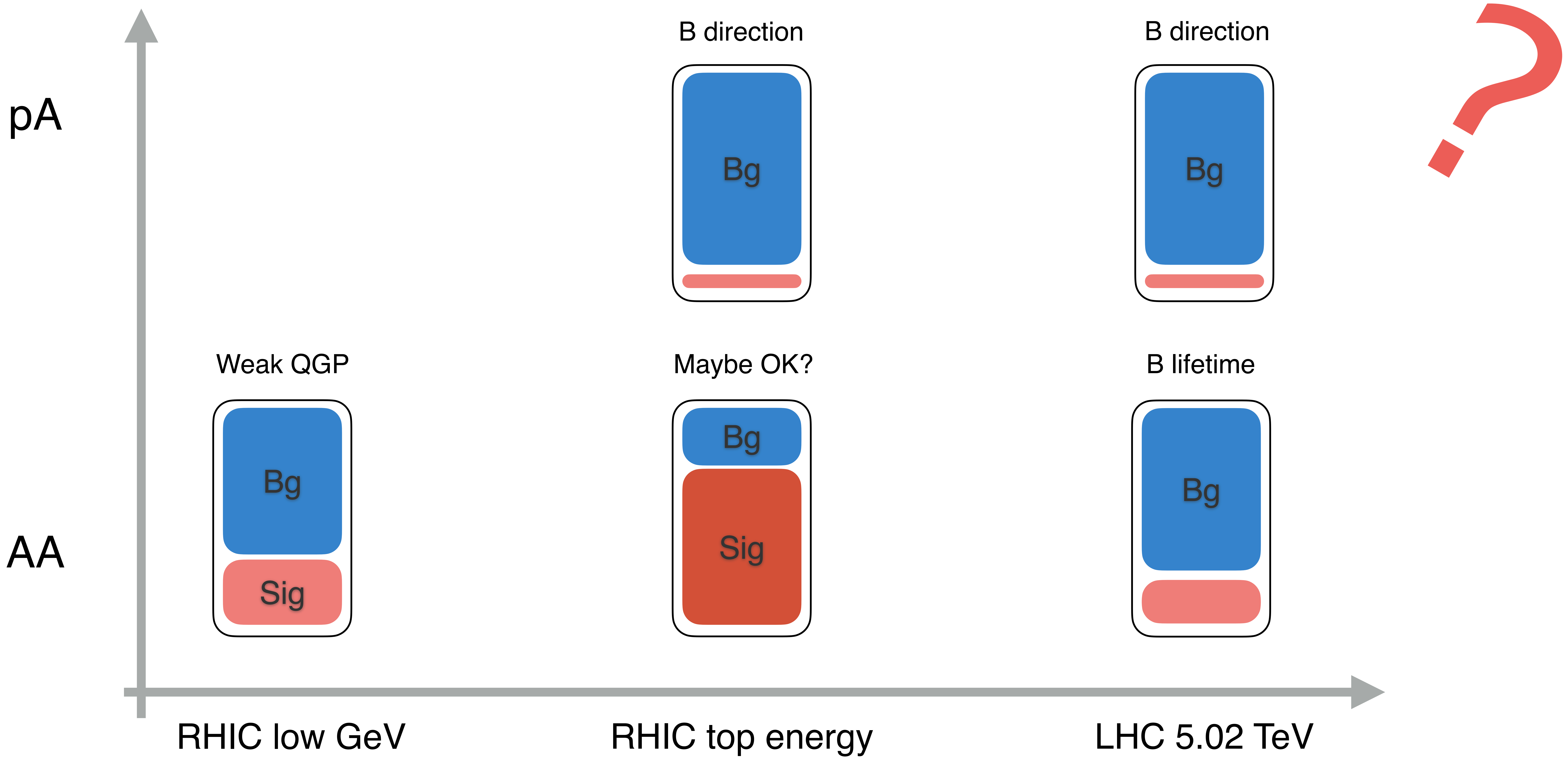


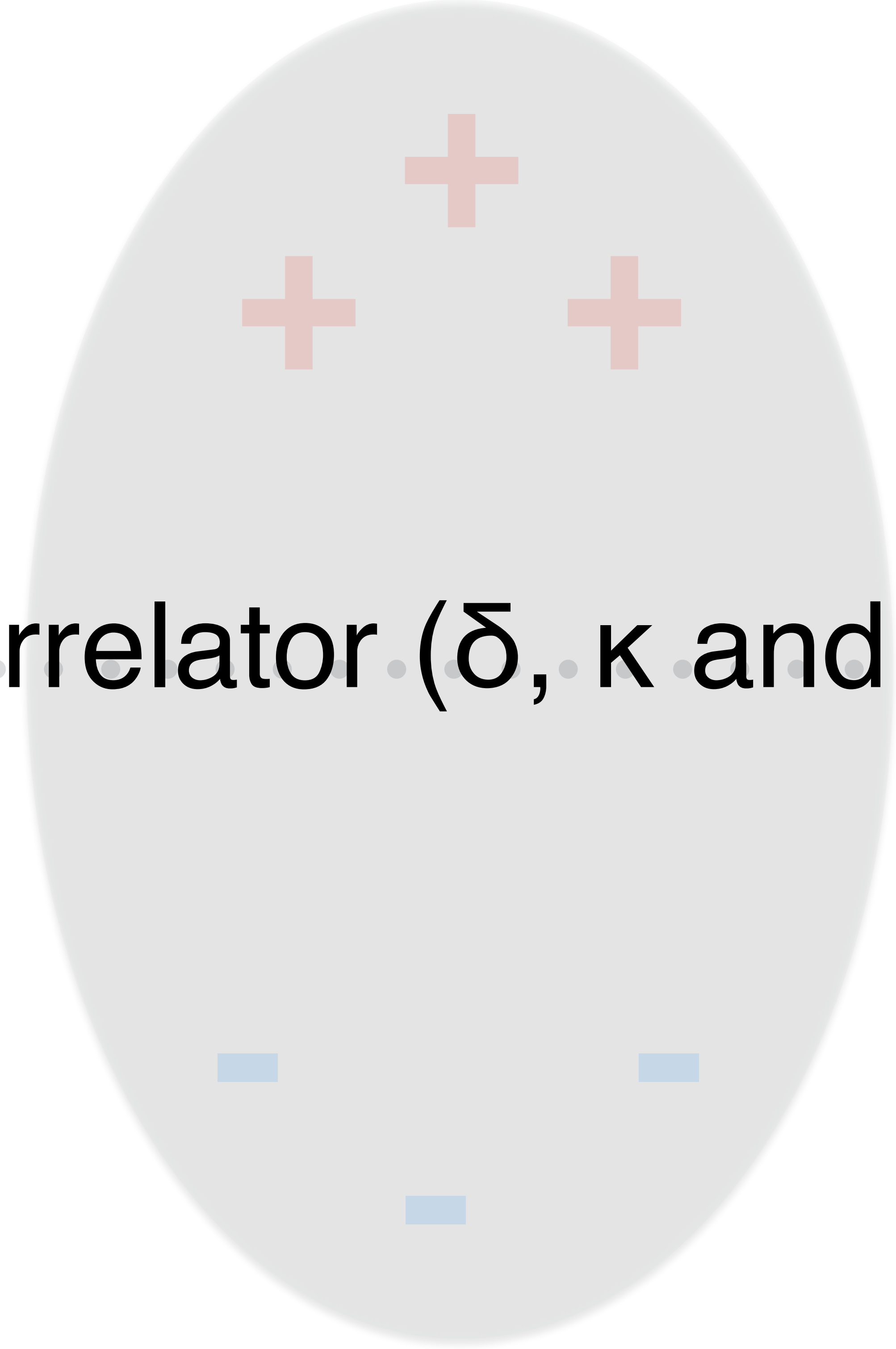
Experimental setup

	LHC	RHIC
	Pb-Pb 2.76 TeV Pb-Pb 5.02 TeV	Au+Au BES (7-62 GeV) Au+Au 200 GeV Cu+Cu Isobar (Zr+Zr)
	Xe-Xe 5.44 TeV	U+U 192 GeV Isobar (Ru+Ru)
	pPb 5.02 TeV pPb 8.16 TeV	p(d)+Au 200 GeV Cu+Au

With inclusive and identified particles at varied kinematic windows

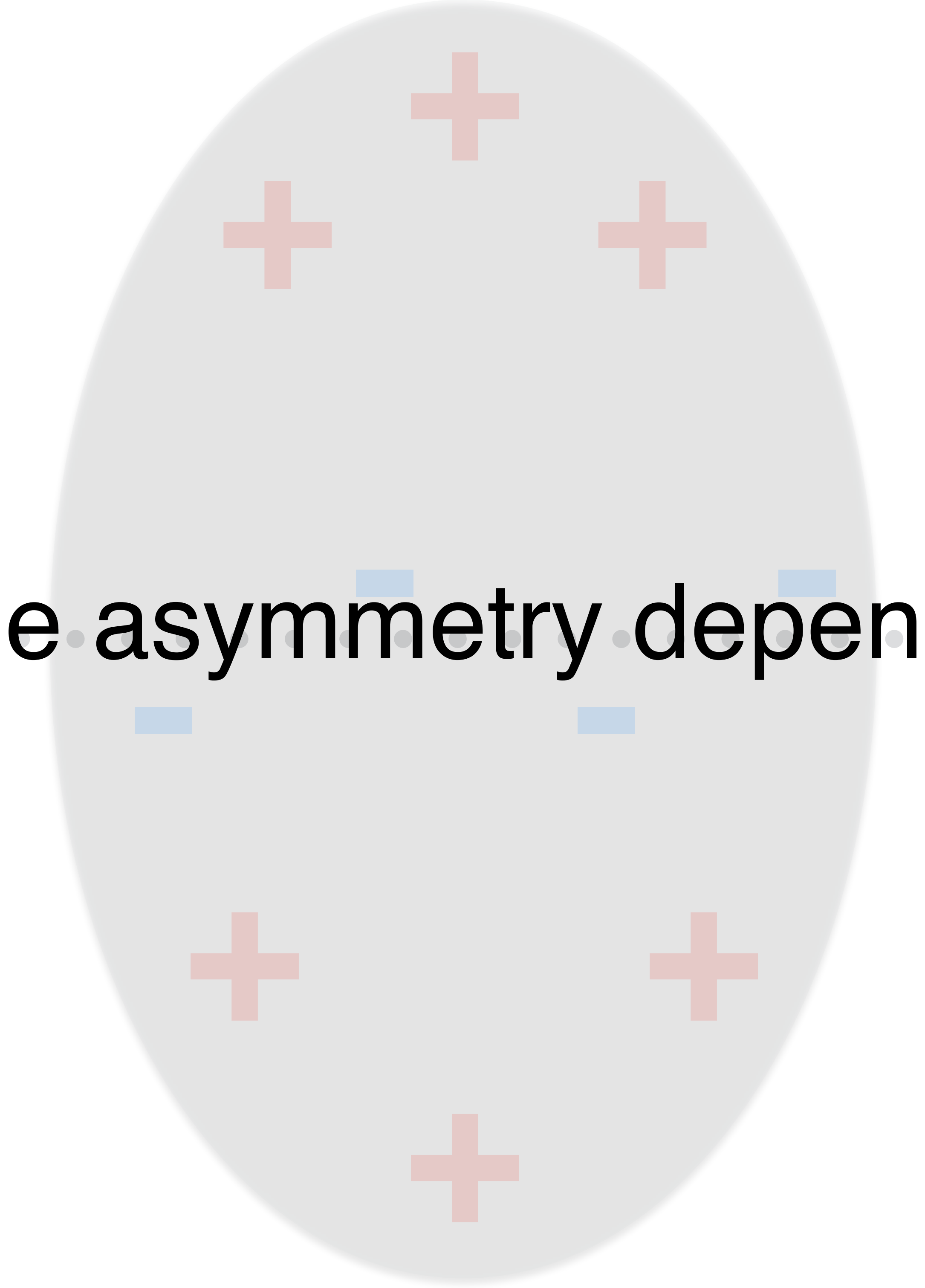
Intuitive expectation





γ correlator (δ, κ and H)

…



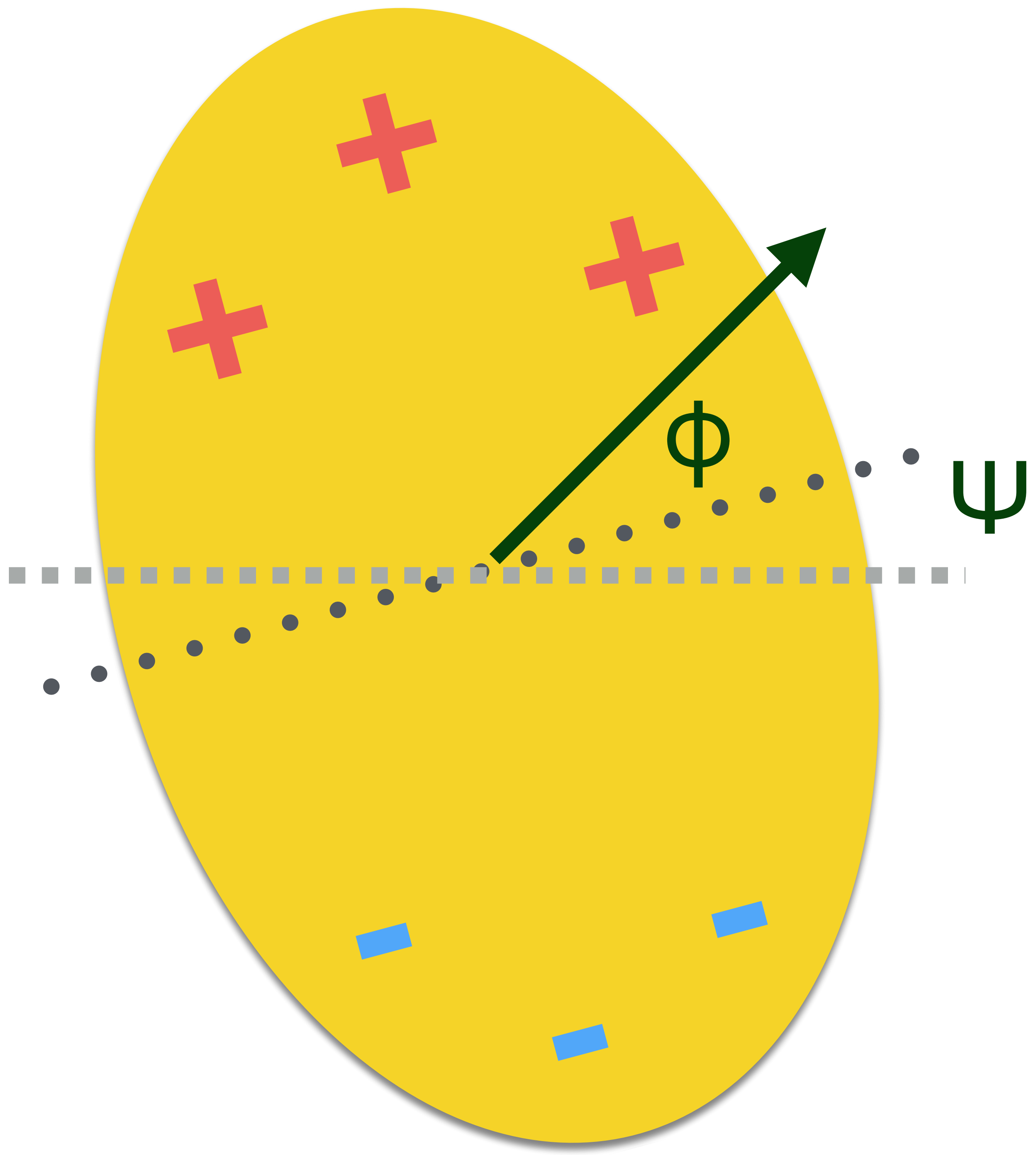
Charge asymmetry dependent flow

…

How can we experimentally detect such kind of charge separations?

A needle in a haystack

Measurement of CME with γ correlator



$dN_\alpha/d\phi = 1 + 2v_{1,\alpha}\cos\Delta\phi + 2v_{2,\alpha}\cos(2\Delta\phi) + \ldots$
$+ 2a_{1,\alpha}\sin\Delta\phi + 2a_{2,\alpha}\sin(2\Delta\phi) + \ldots$

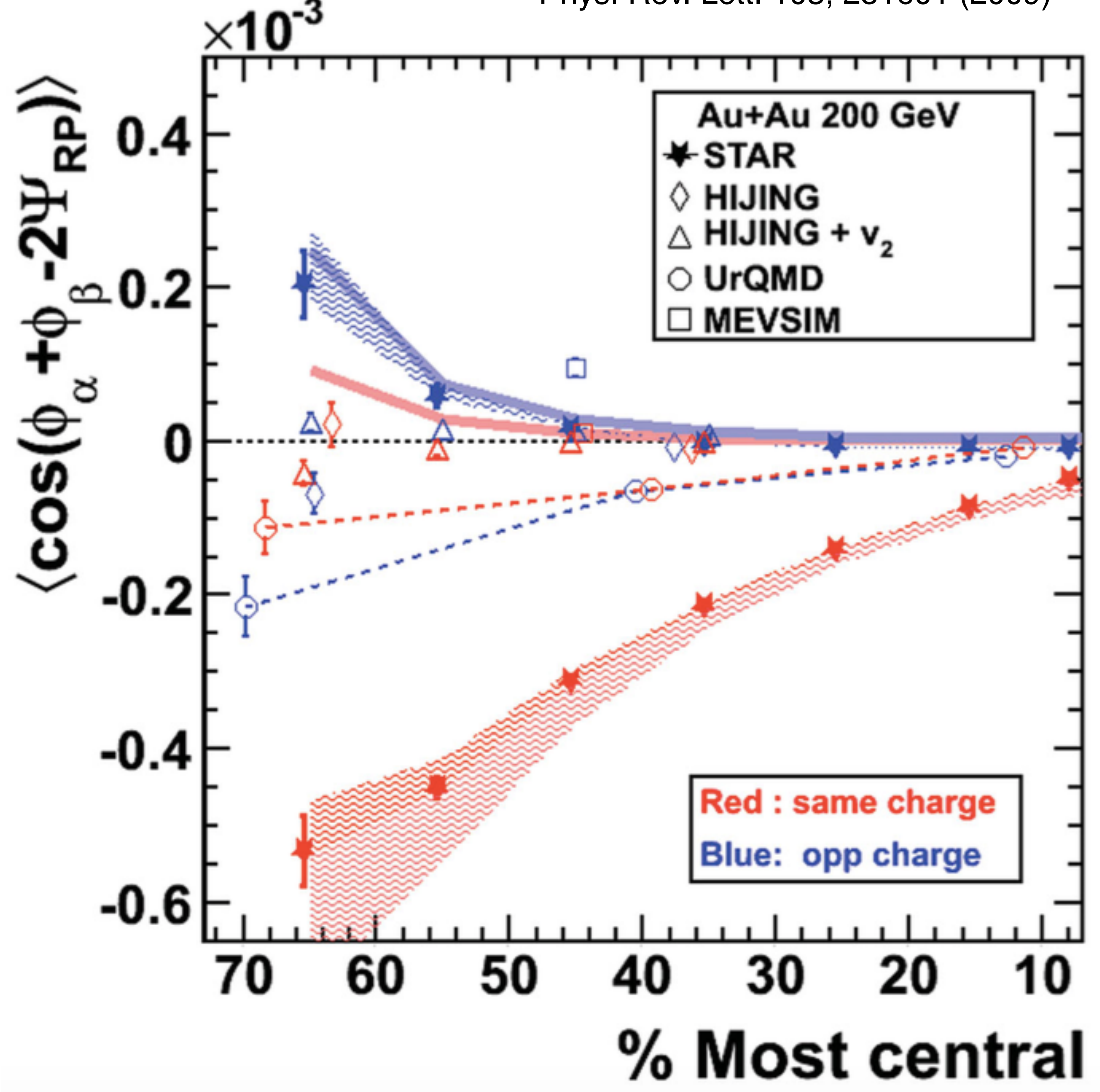
$\gamma_{112} = \langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_2)\rangle$
$= \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \mathbf{\langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle}$
$\delta_{11} = \langle\cos(\phi_\alpha - \phi_\beta)\rangle$
$= \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle + \mathbf{\langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle}$
Sensitive to CME

$\gamma_{112} = \kappa v_2 F - H$
$\delta_{11} = F + H$
$H = (\kappa v_2 \delta_{11} - \gamma_{112}) / (1 + \kappa v_2)$

$\gamma_{132} \equiv \langle\cos(\phi_\alpha - 3\phi_\beta + 2\Psi_2)\rangle$
$\gamma_{123} \equiv \langle\cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3)\rangle$
…
Not sensitive to CME

γ_{112} at RHIC

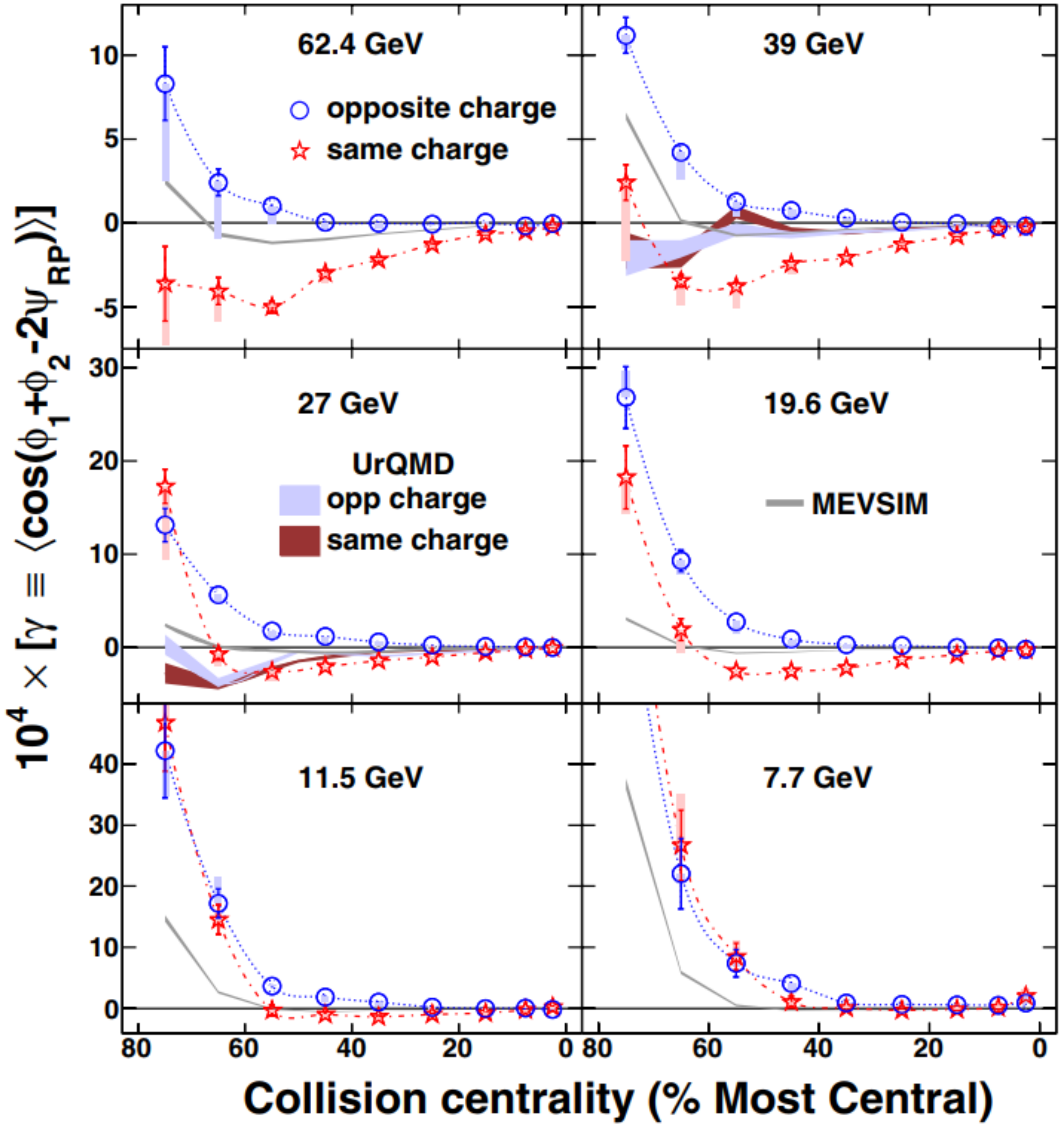
Phys. Rev. Lett. 103, 251601 (2009)

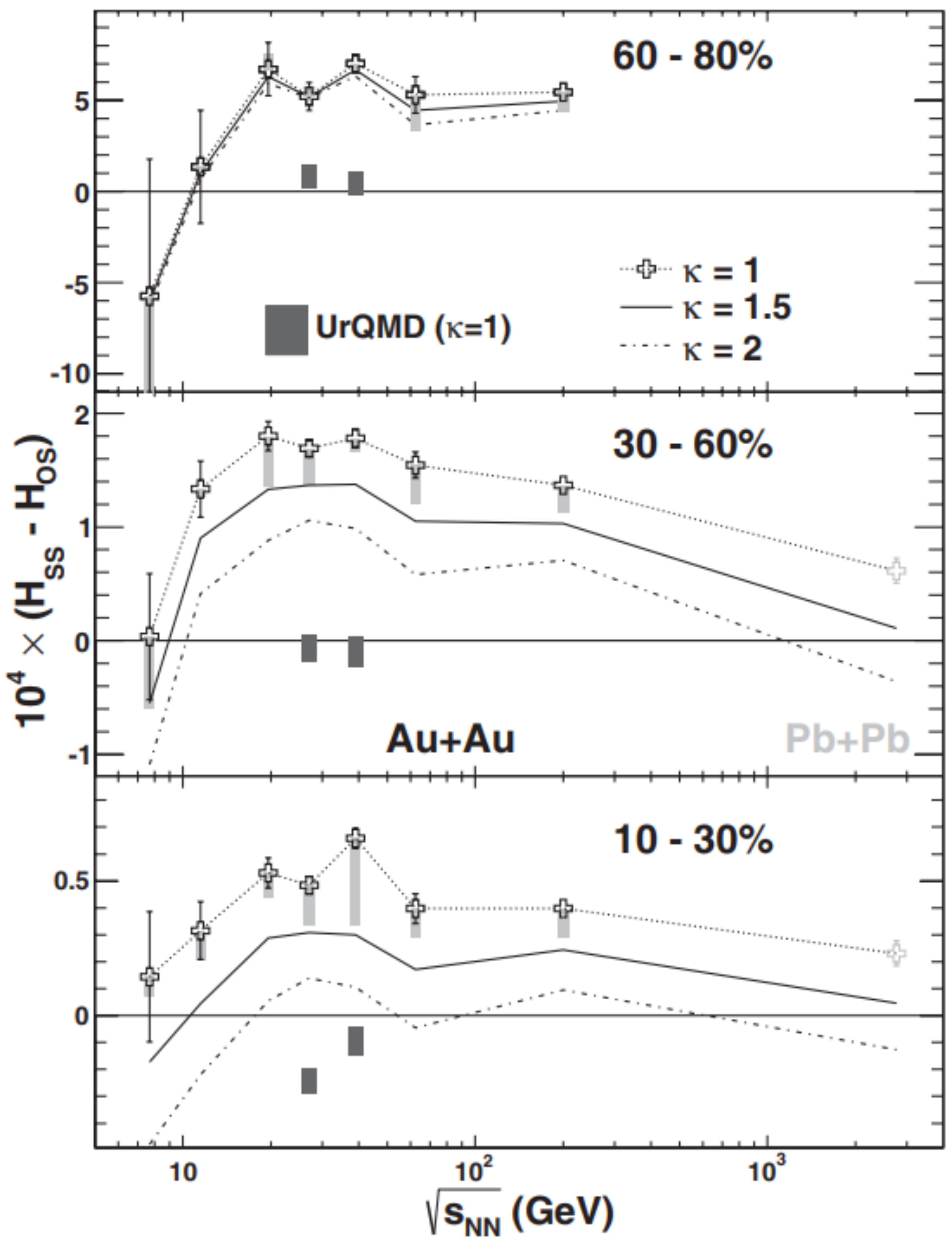


- The observed γ_{112} shows nontrivial structure
- Stronger centrality dependence of SS than that of OS

γ_{112} at RHIC

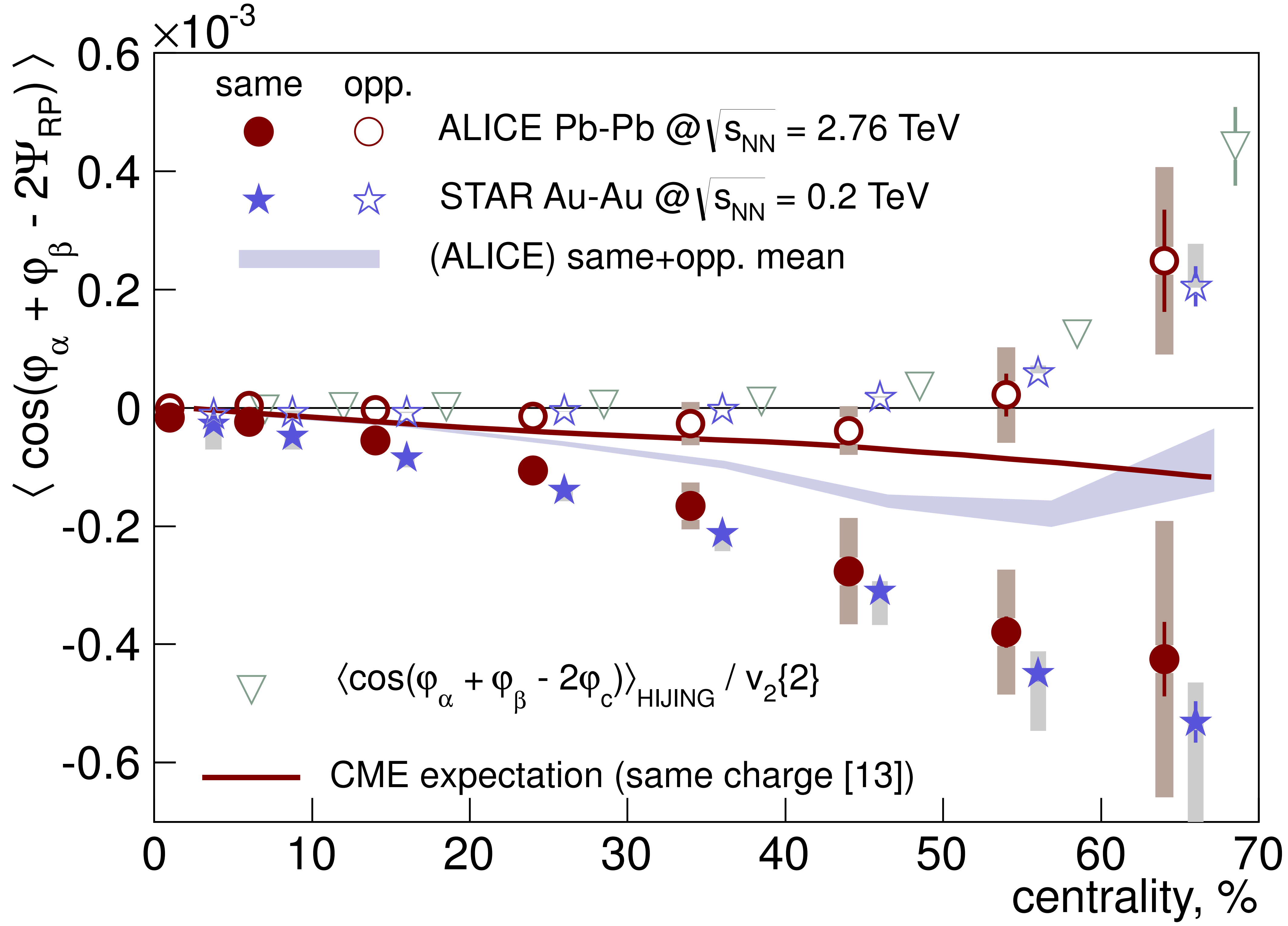
Phys. Rev. Lett. 113, 052302 (2014)



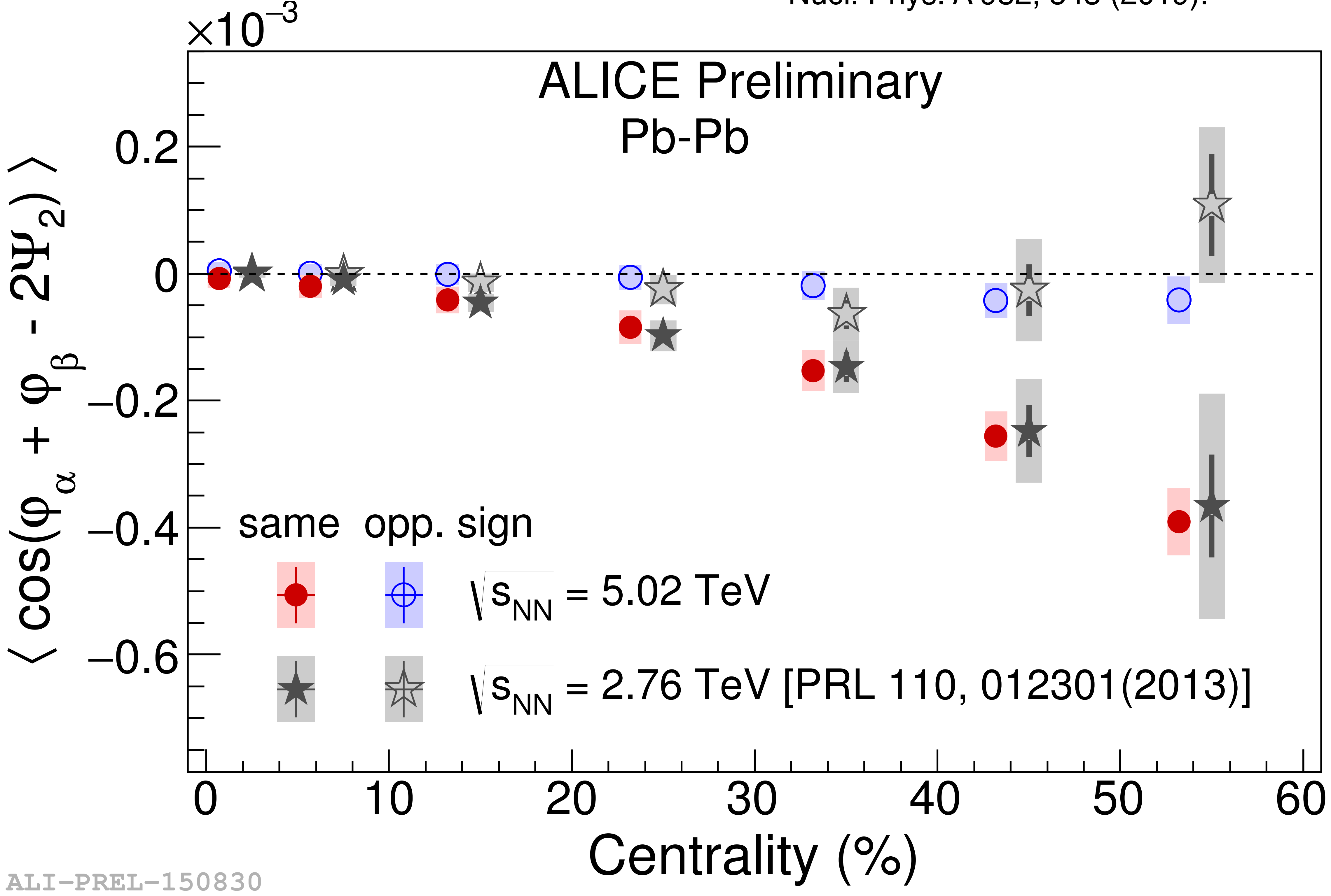


Strong collision energy dependence at RHIC BES

γ_{112} at LHC



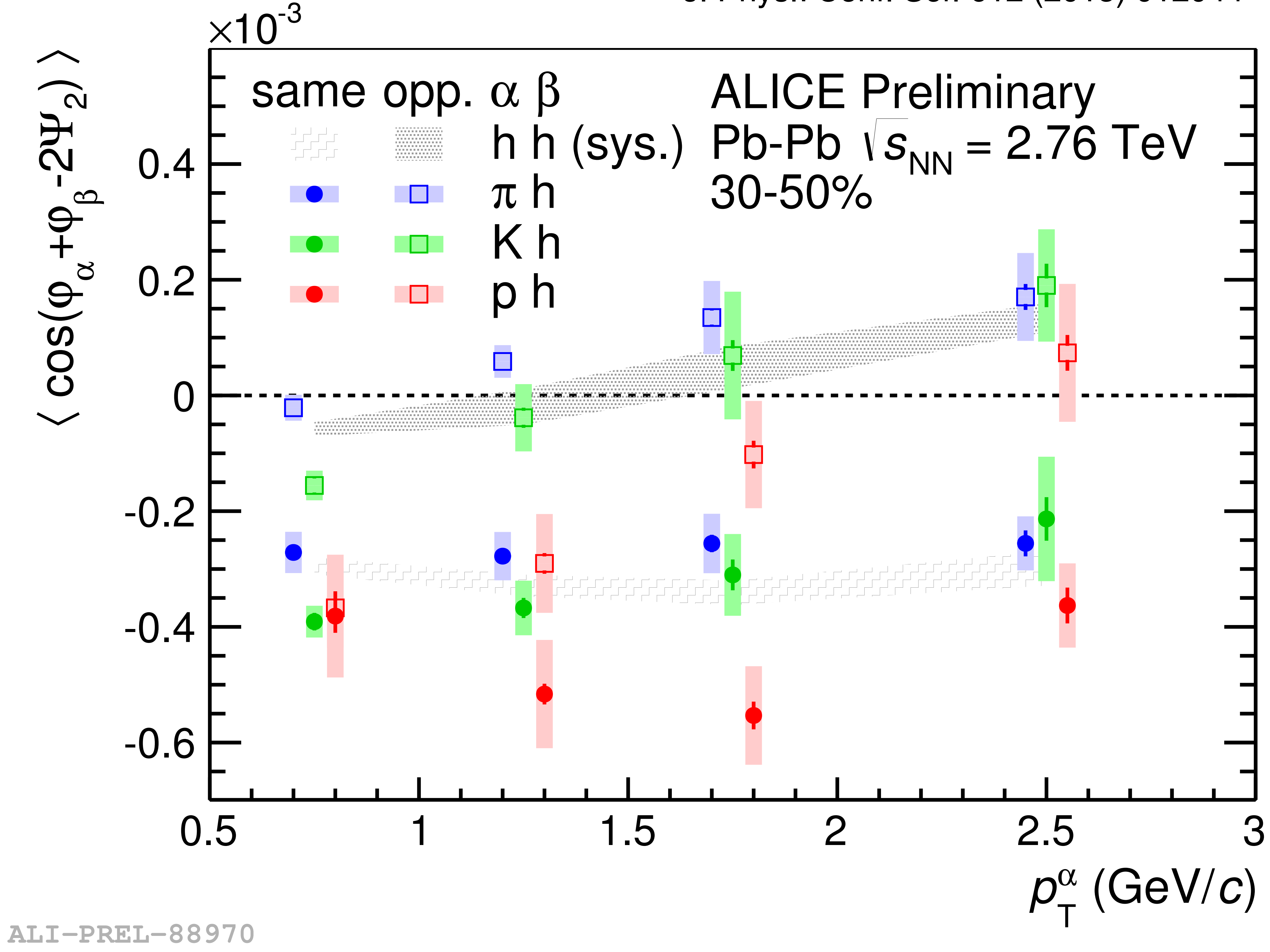
Phys. Rev. Lett. 110, 012301 (2013).
Nucl. Phys. A 982, 543 (2019).



- Little or no difference for γ_{112} between 0.2, 2.76 and 5.02 TeV collisions
- Stronger centrality dependence of SS than that of OS

γ_{112} at LHC

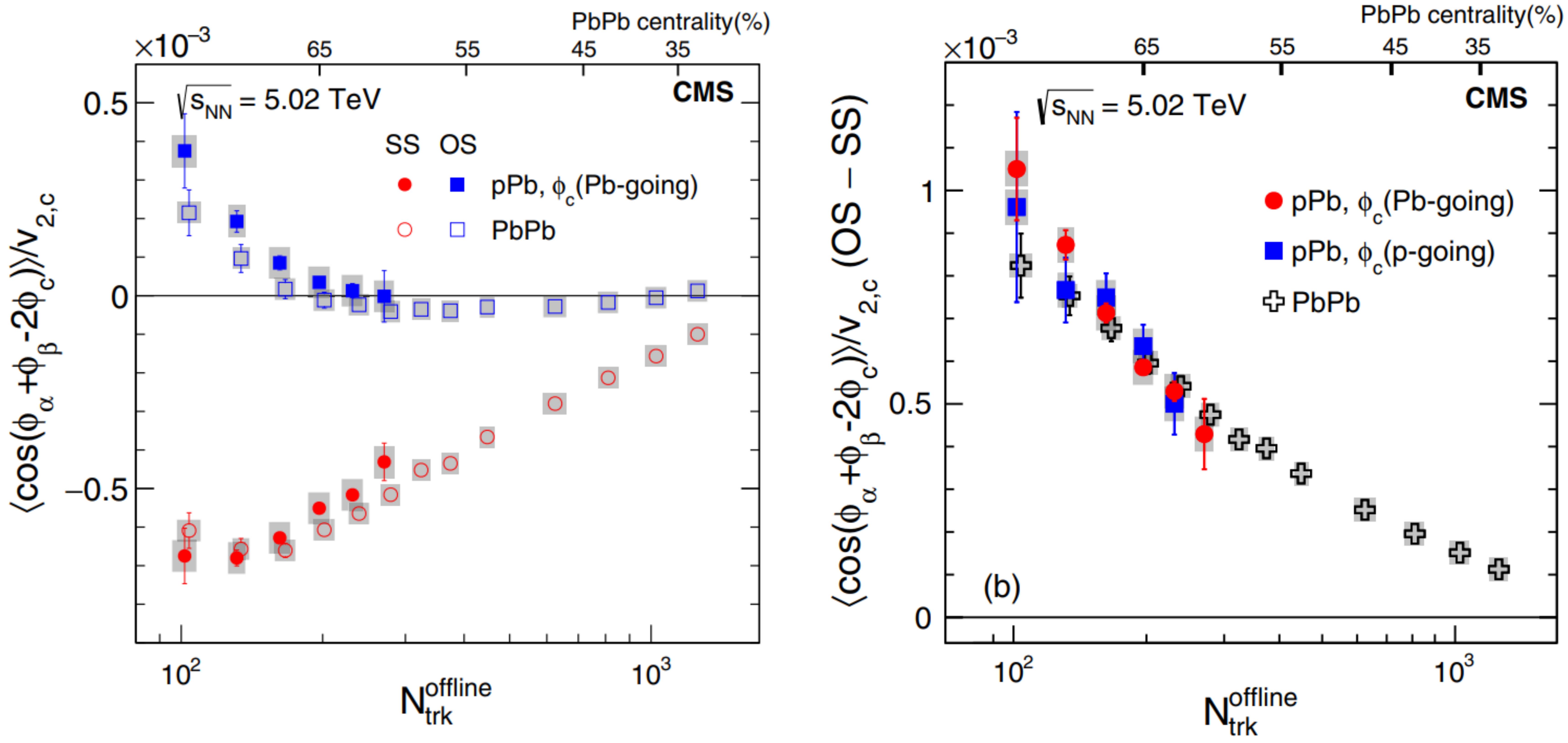
J. Phys.: Conf. Ser. 612 (2015) 012044



- $\gamma_{112}(\pi)$ and $\gamma_{112}(K)$ are quite similar
- Difference between $\gamma_{112}(p)$ and $\gamma_{112}(\pi)$

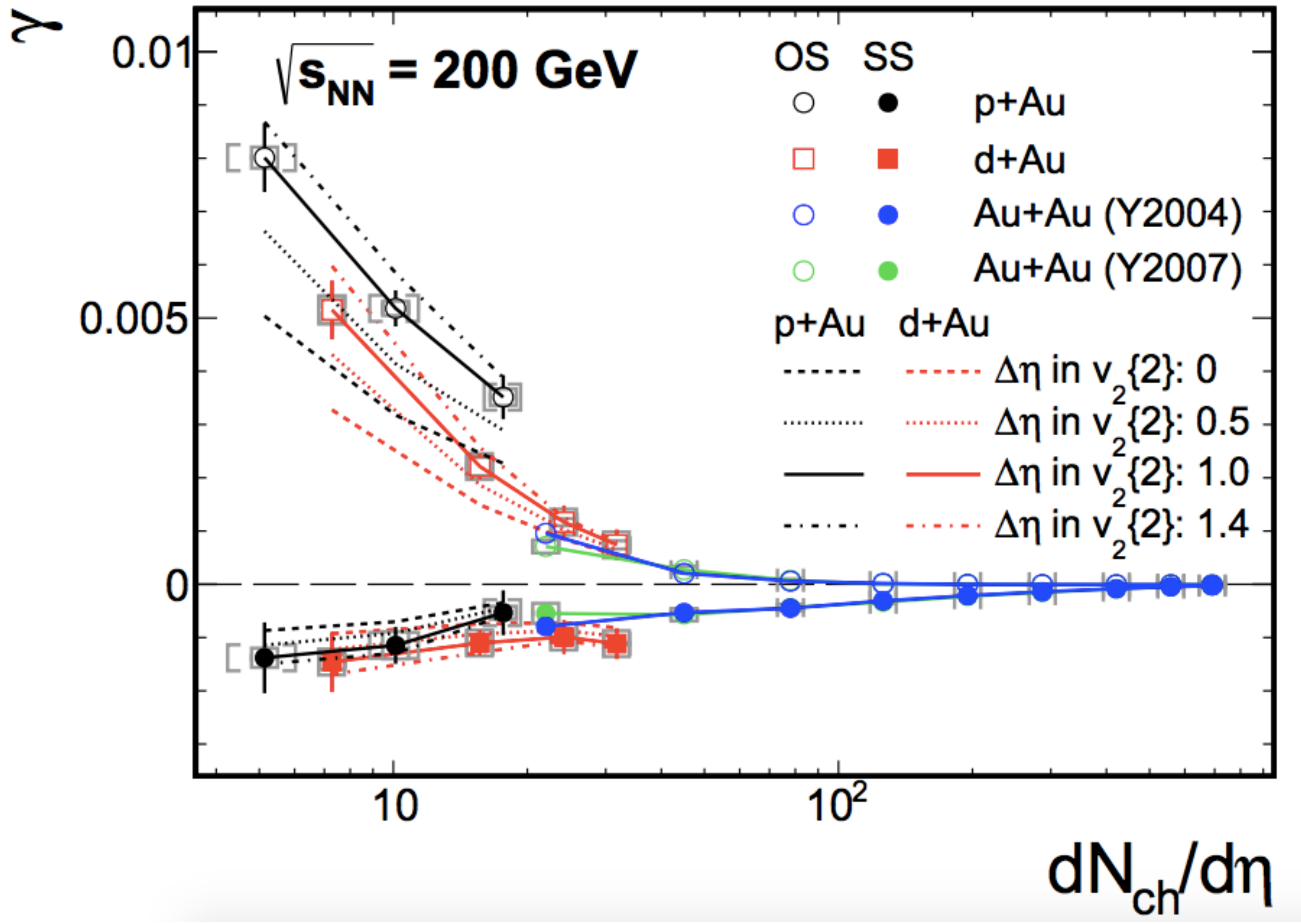
Interpretation?

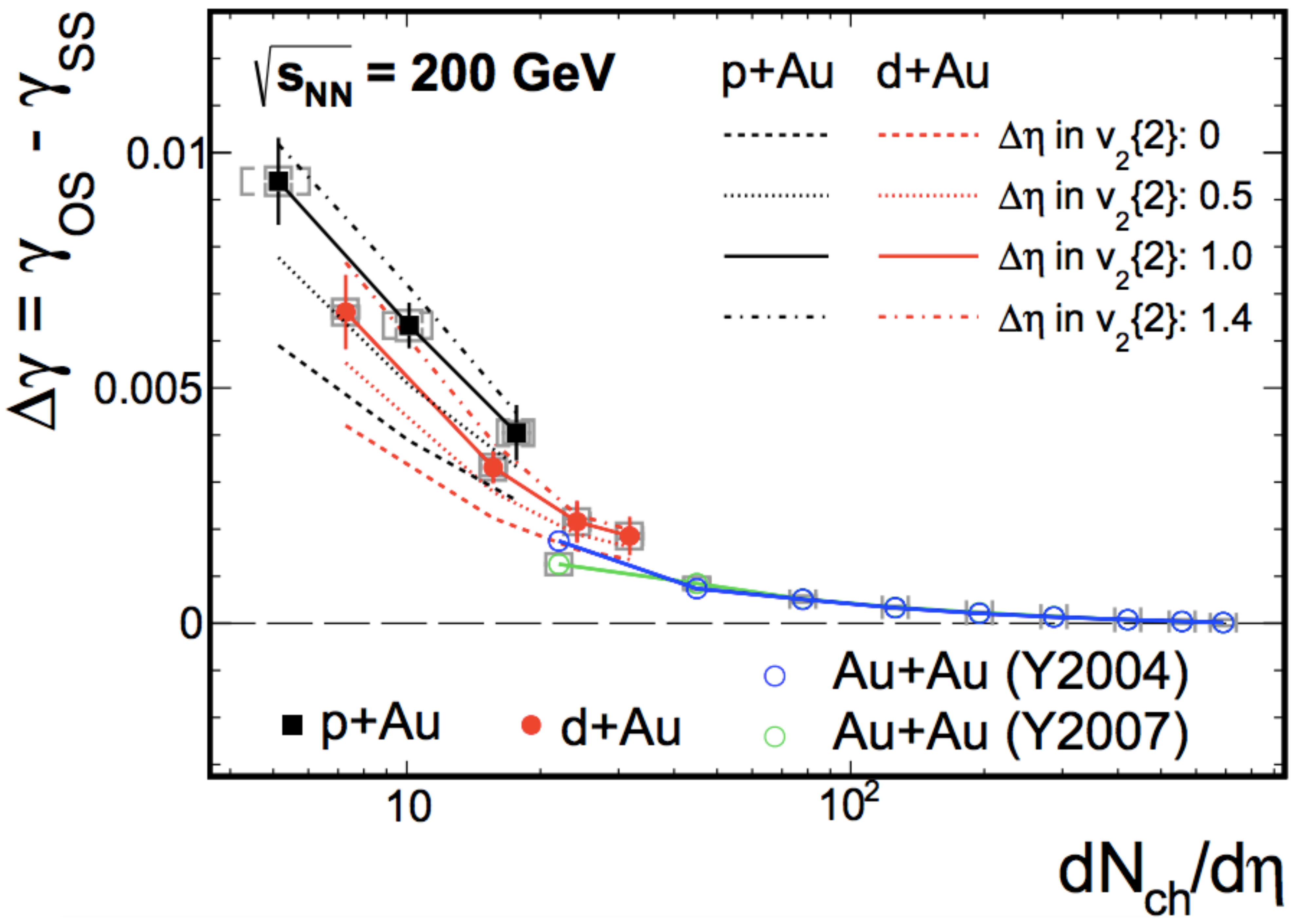
Surprise in the small system collisions



- Agreement between pPb and Pb-Pb results
- A common underlying mechanism that generates the observed γ_{112}

Surprise in the small system collisions

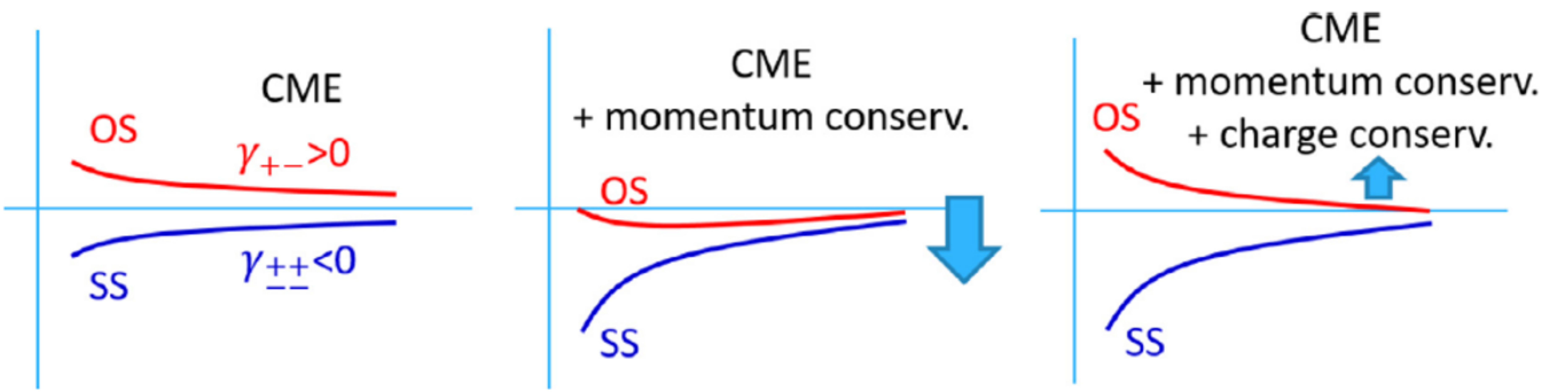




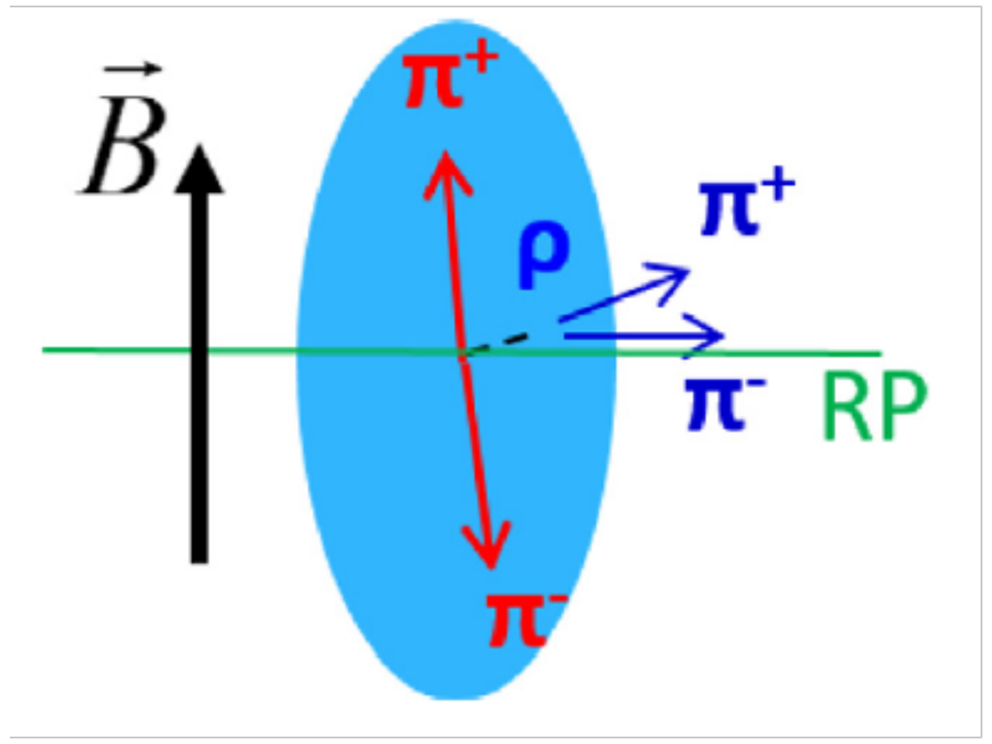
- Agreement between pPb and Pb-Pb results
- A common underlying mechanism that generates the observed γ_{112}

Study of the background: what are they and how large?

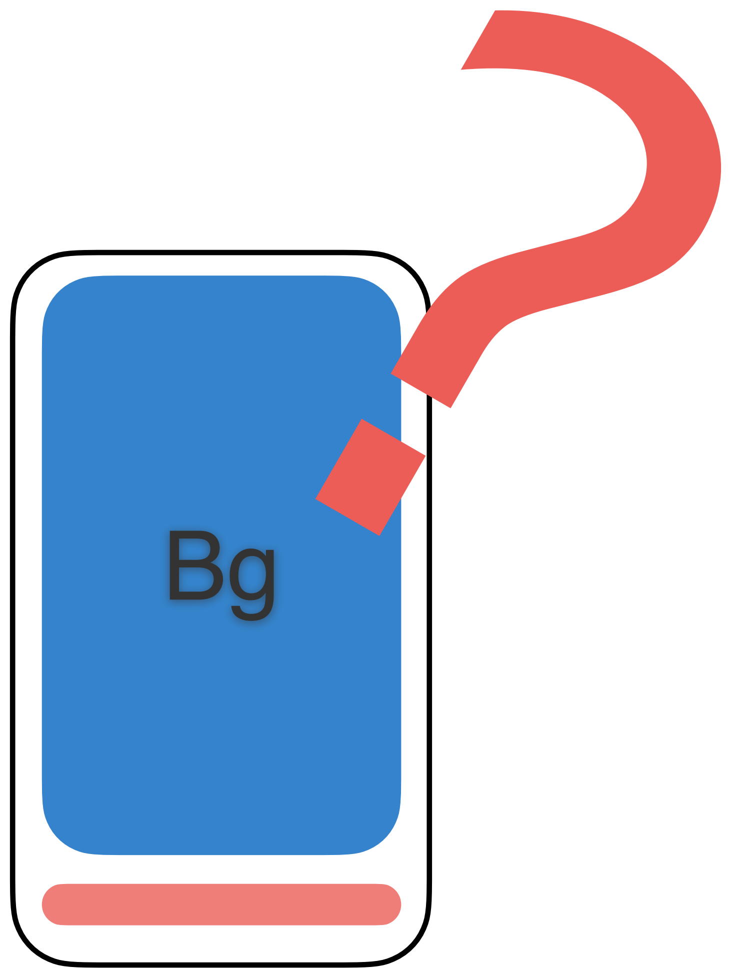
Transverse momentum conservation | Local charge conservation



Resonance decay



+flow



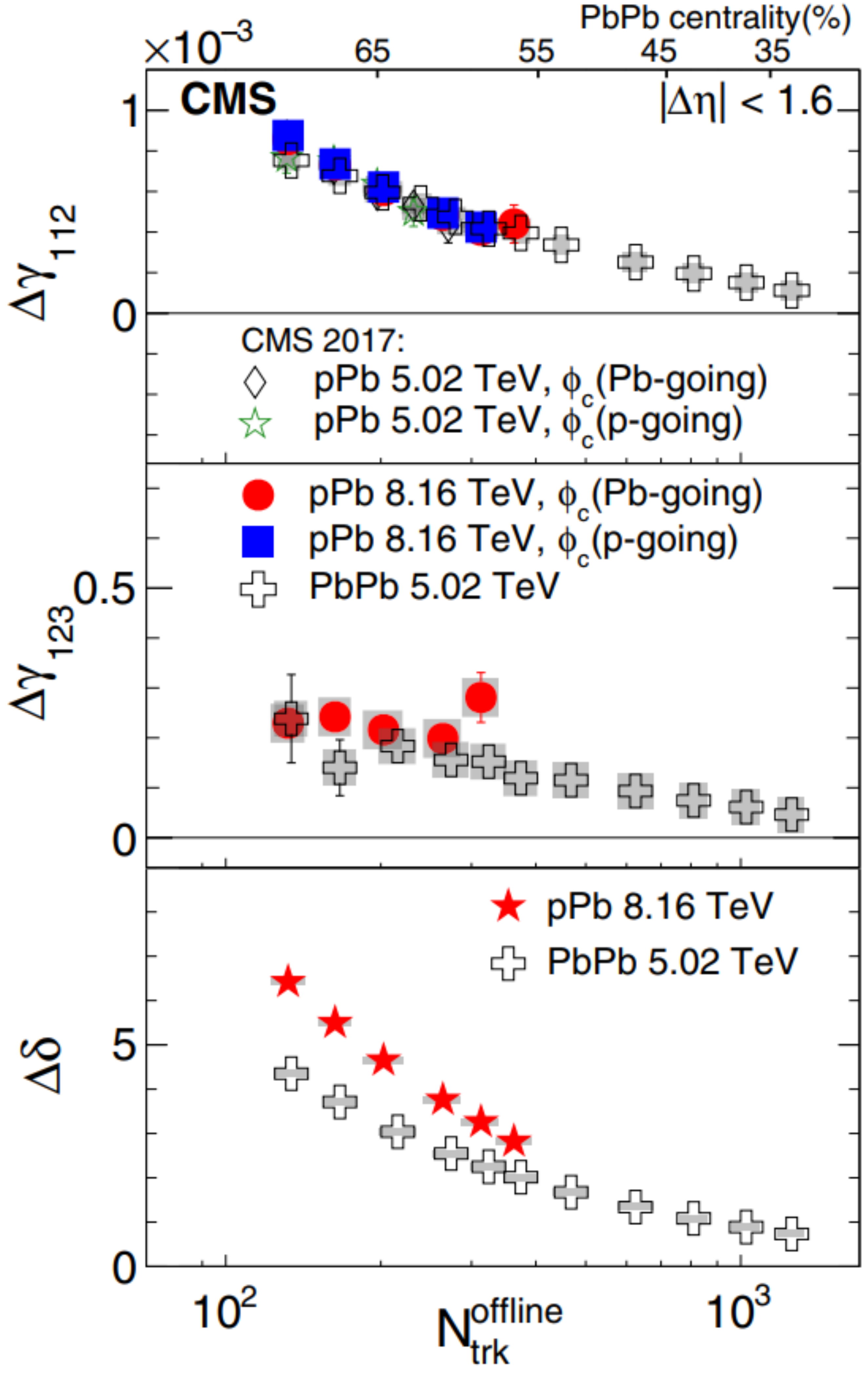
Study of the background: collective flow

$$\gamma_{112} \equiv \langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_2) \rangle$$
$$= \langle \cos(\phi_\alpha - \Psi_2) \cos(\phi_\beta - \Psi_2) \rangle$$
$$- \langle \sin(\phi_\alpha - \Psi_2) \sin(\phi_\beta - \Psi_2) \rangle$$
$$\gamma_{112}^{\mathrm{bkg}} = \kappa_2 \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 2(\phi_\beta - \Psi_{\mathrm{RP}}) \rangle = \kappa_2\, \delta\, v_2$$

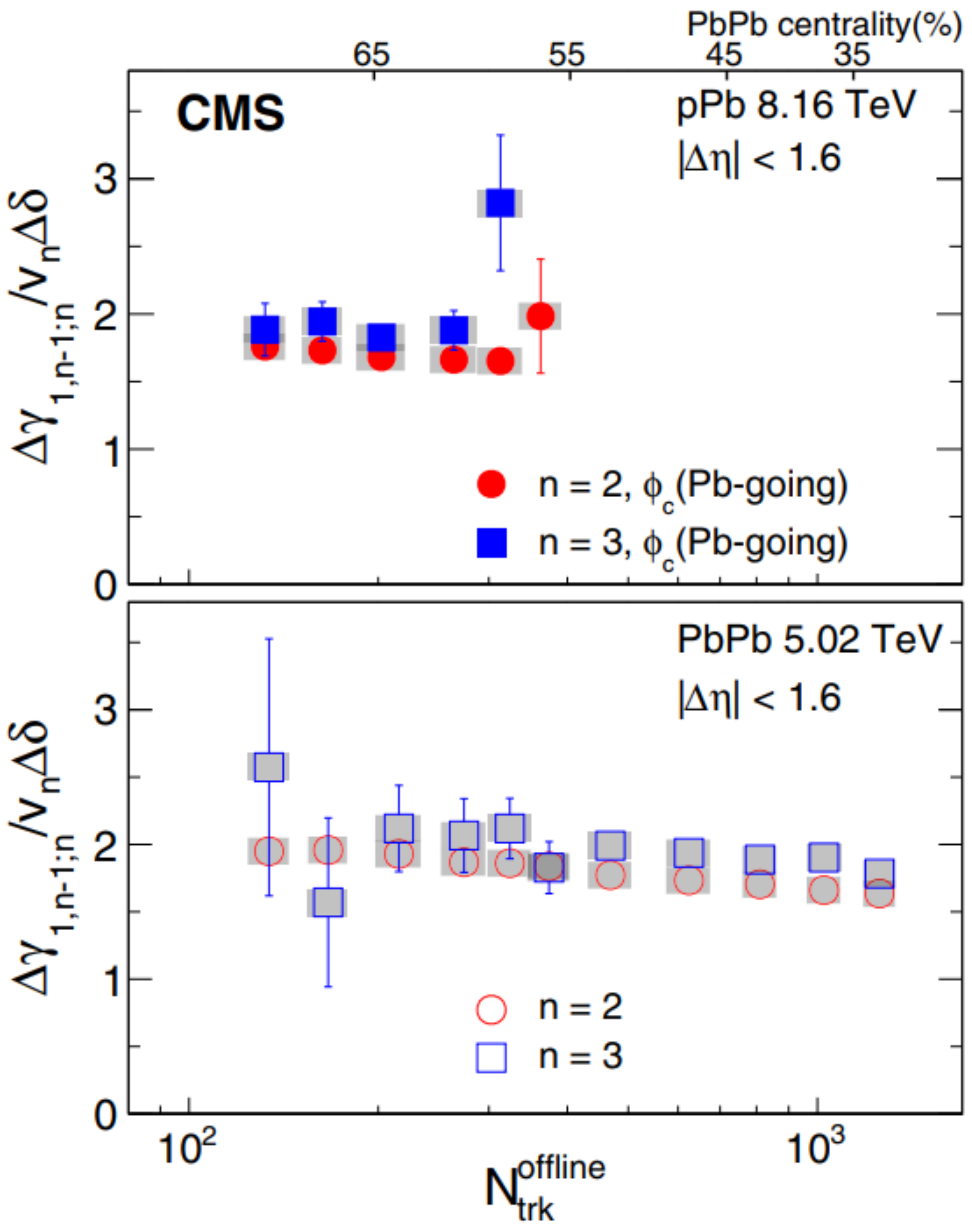
$$\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$
$$\gamma_{123}^{\mathrm{bkg}} = \kappa_3 \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 3(\phi_\beta - \Psi_3) \rangle$$
$$= \kappa_3\, \delta\, v_3,$$

If pure background:

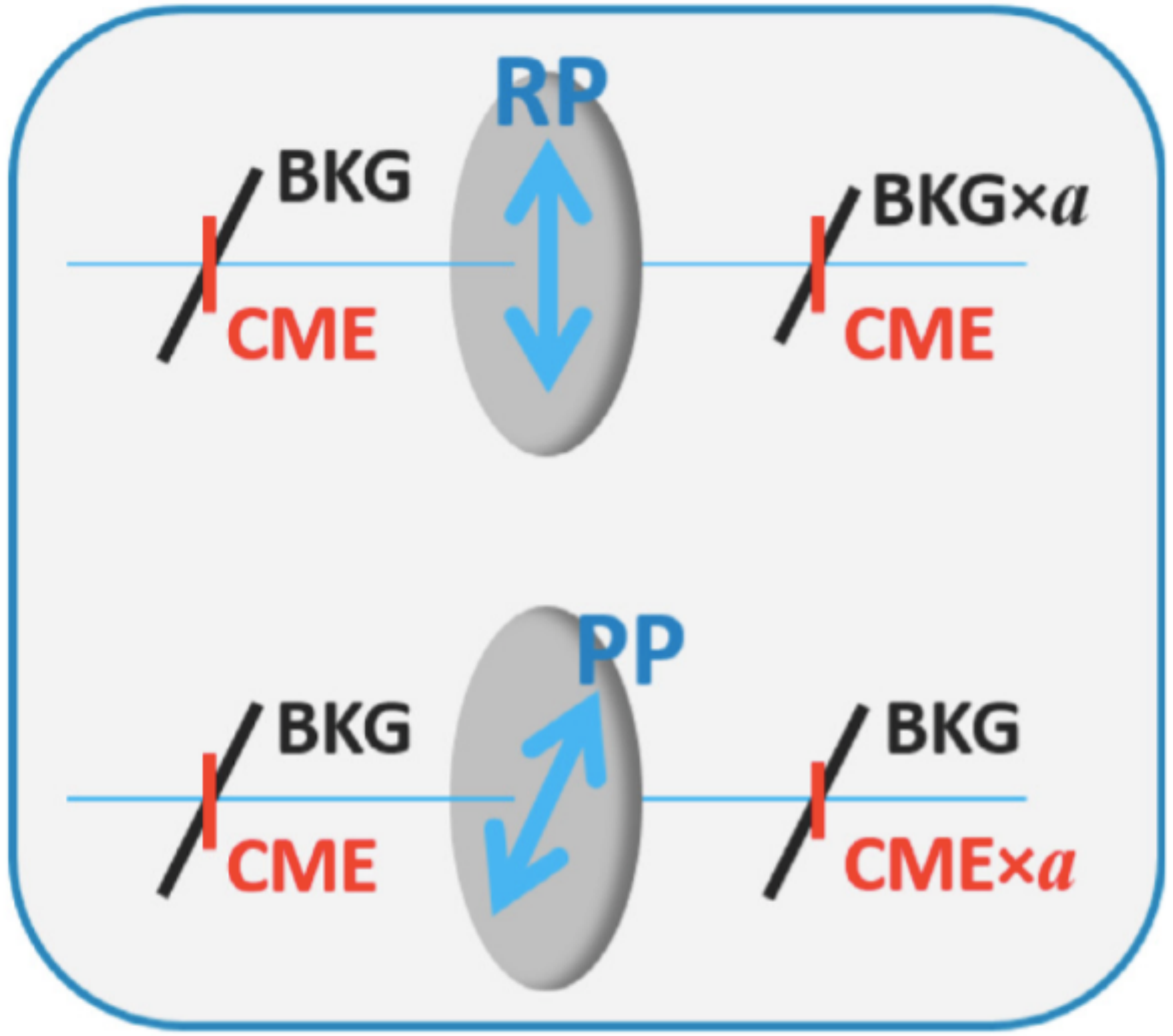
$$\frac{\Delta\gamma_{112}}{\Delta\delta\, v_2} \approx \frac{\Delta\gamma_{123}}{\Delta\delta\, v_3}$$



Phys. Rev. C. 97 (2018) 044912

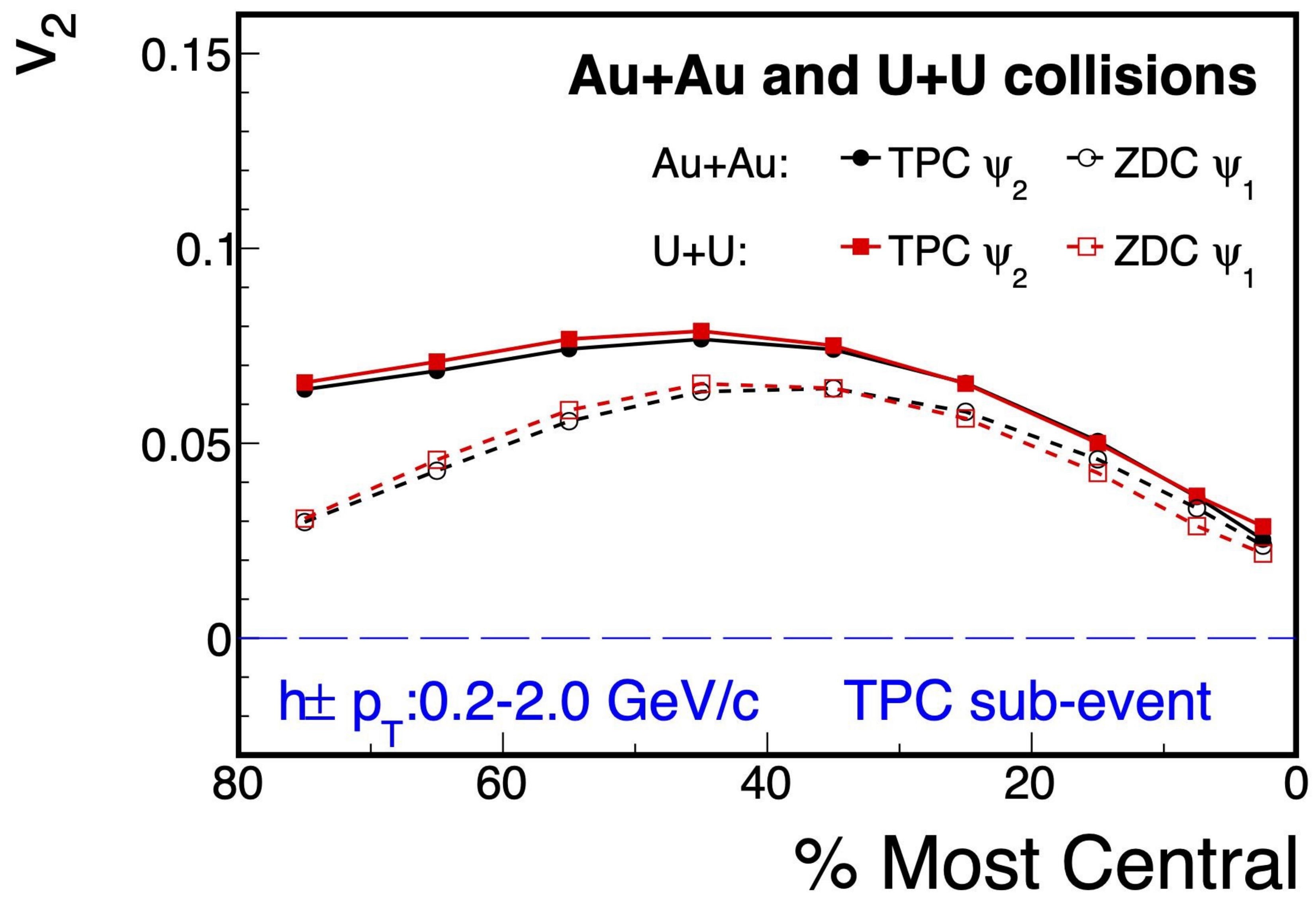


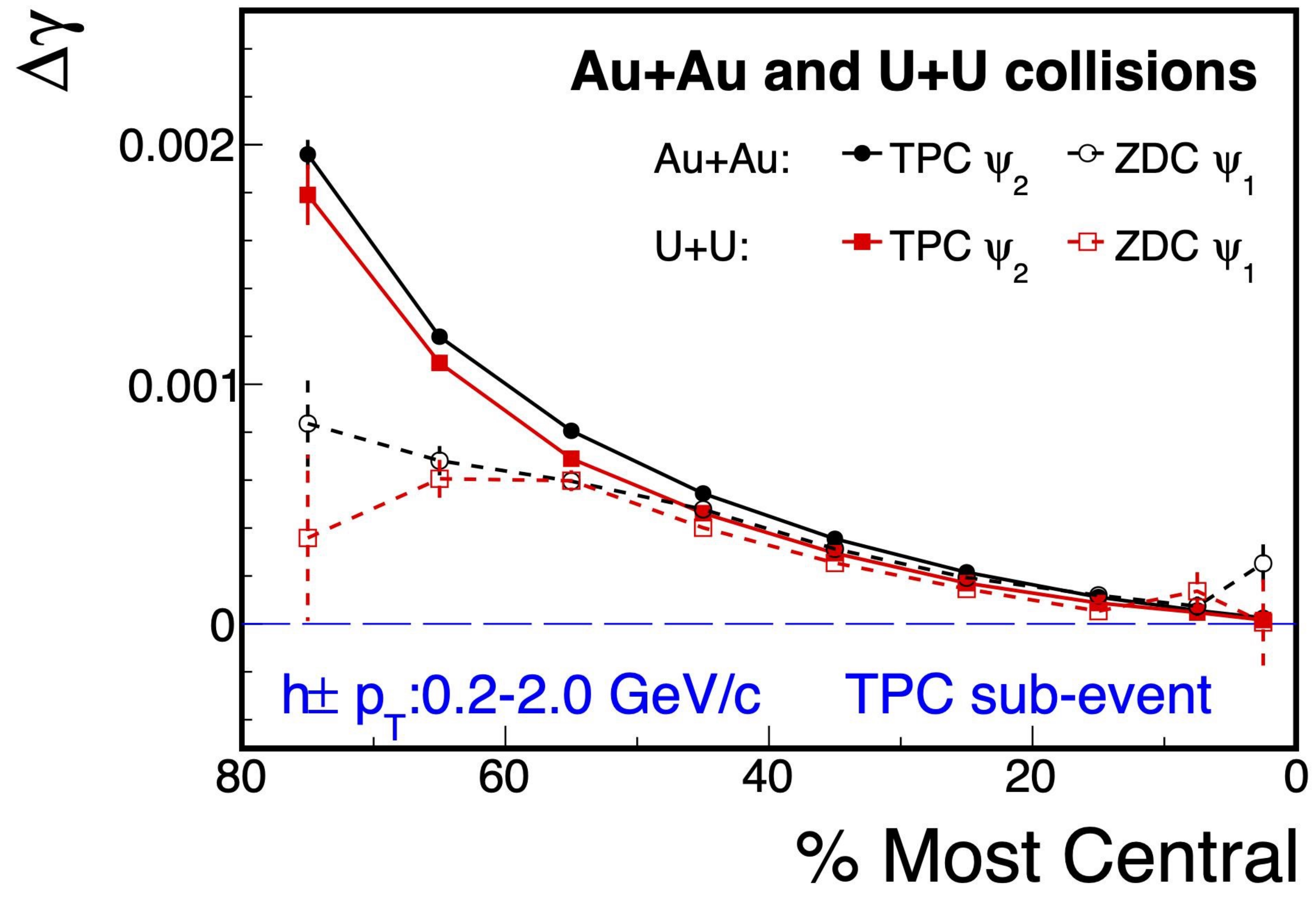
Study of the background: collective flow



Ψ_{PP} and Ψ_{RP} are sensitive to different component of γ_{112}

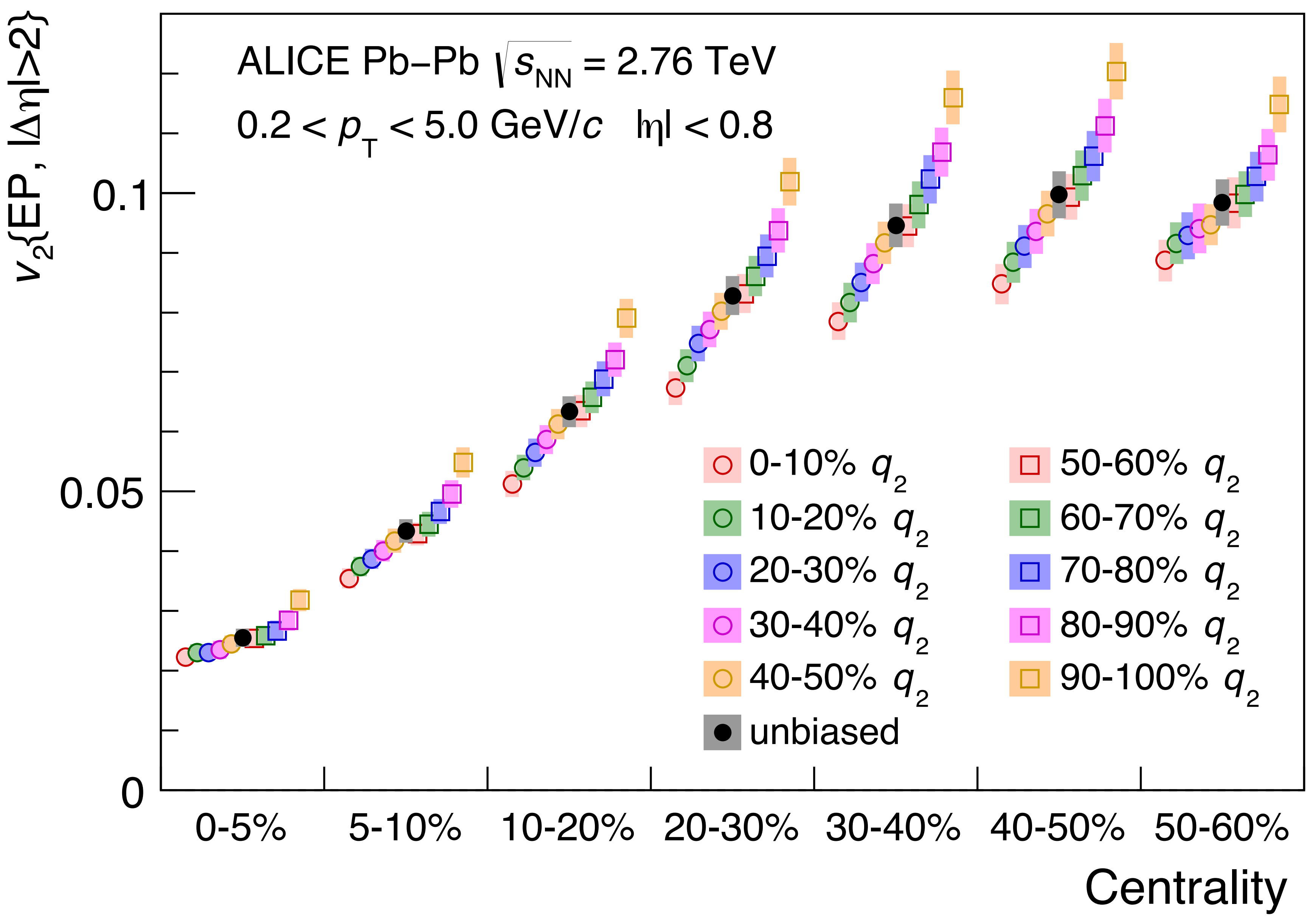
$a = v_2\{\Psi_{ZDC}\} / v_2\{\Psi_{TPC}\}$
$A = \Delta\gamma\{\Psi_{ZDC}\} / \Delta\gamma\{\Psi_{TPC}\}$
$f_{CME} = (A/a - 1) / (1/a^2 - 1)$



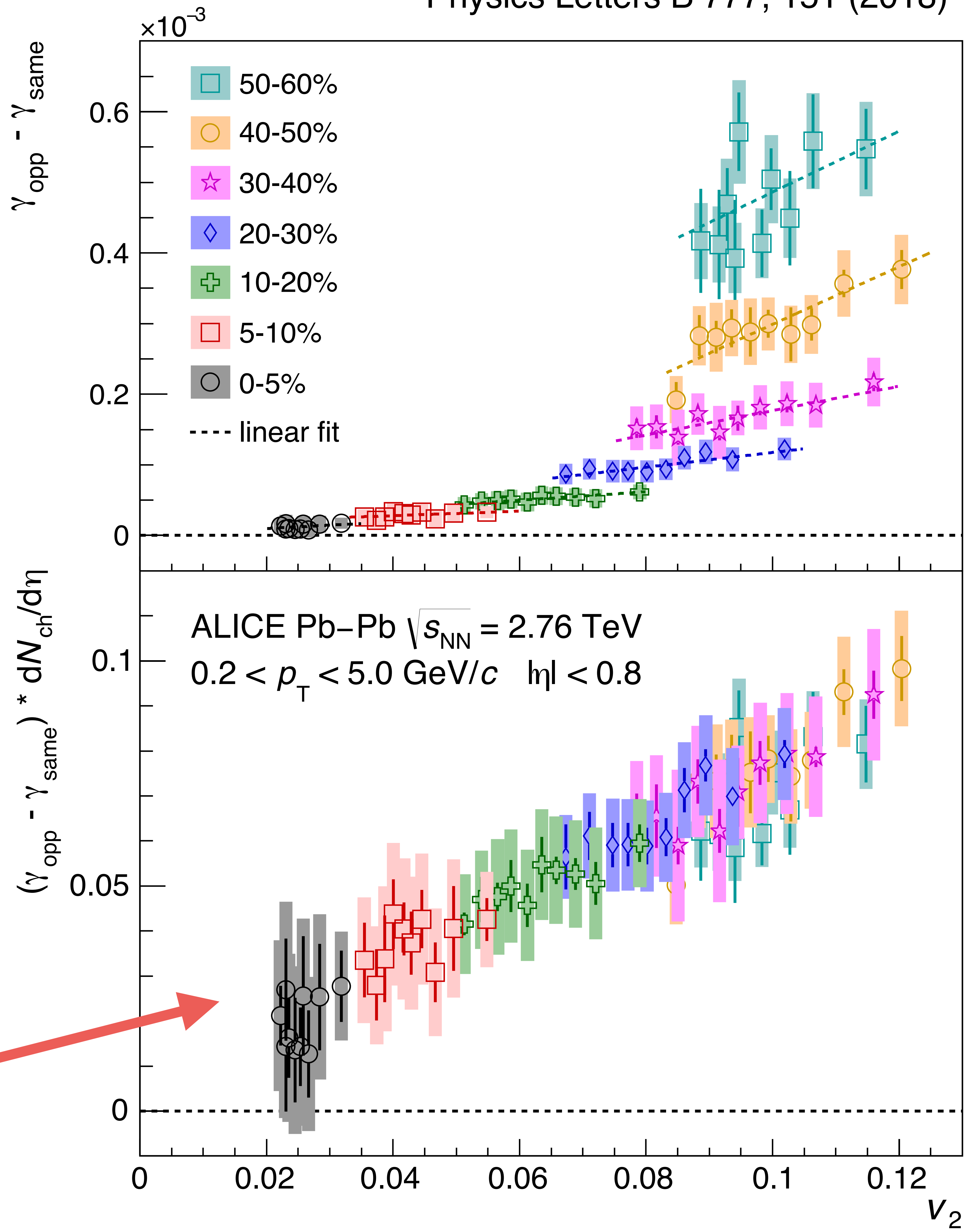


Study of the background: collective flow

Event Shape Engineering
Events with the desired initial spatial anisotropy can be experimentally selected by q_2

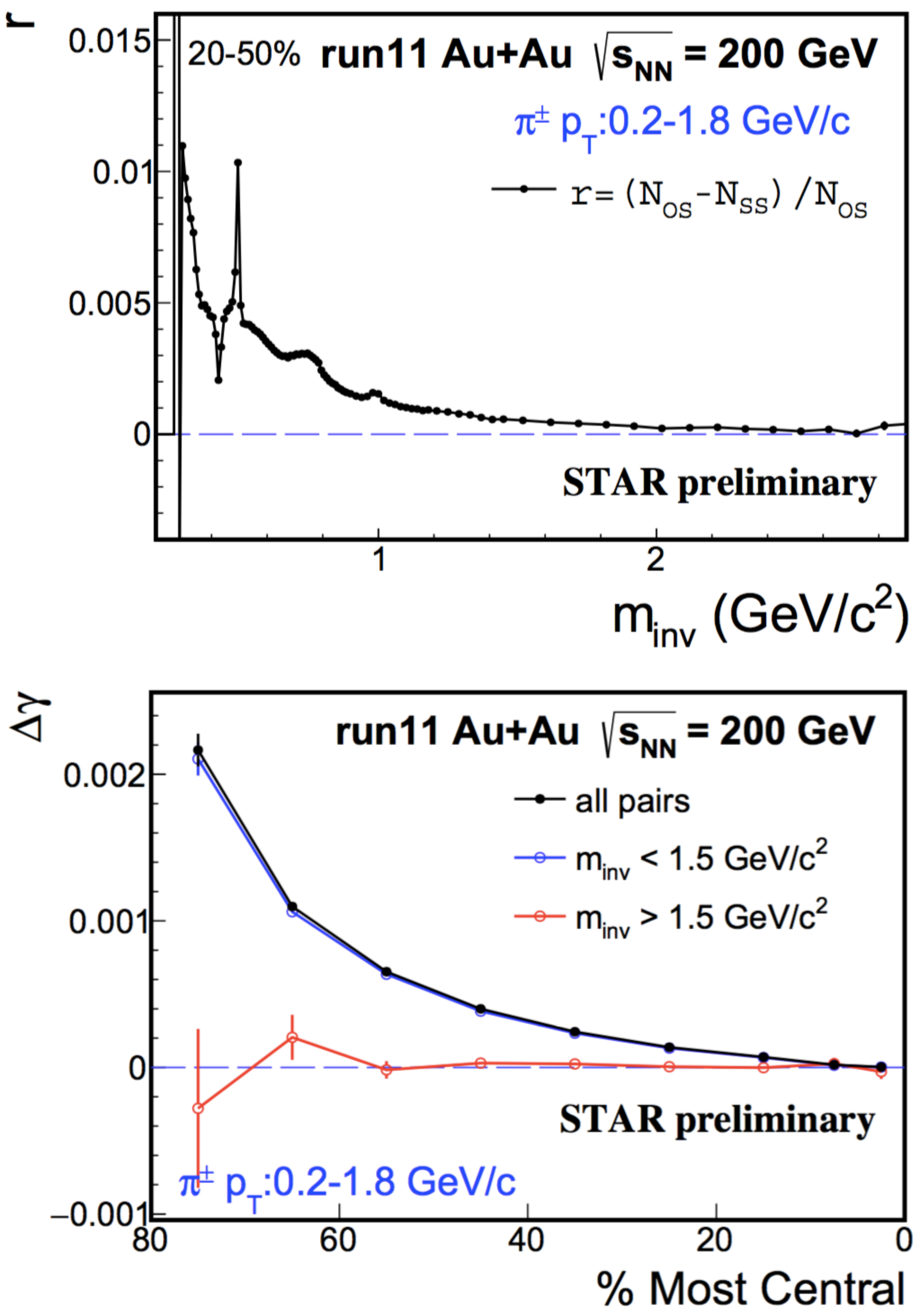


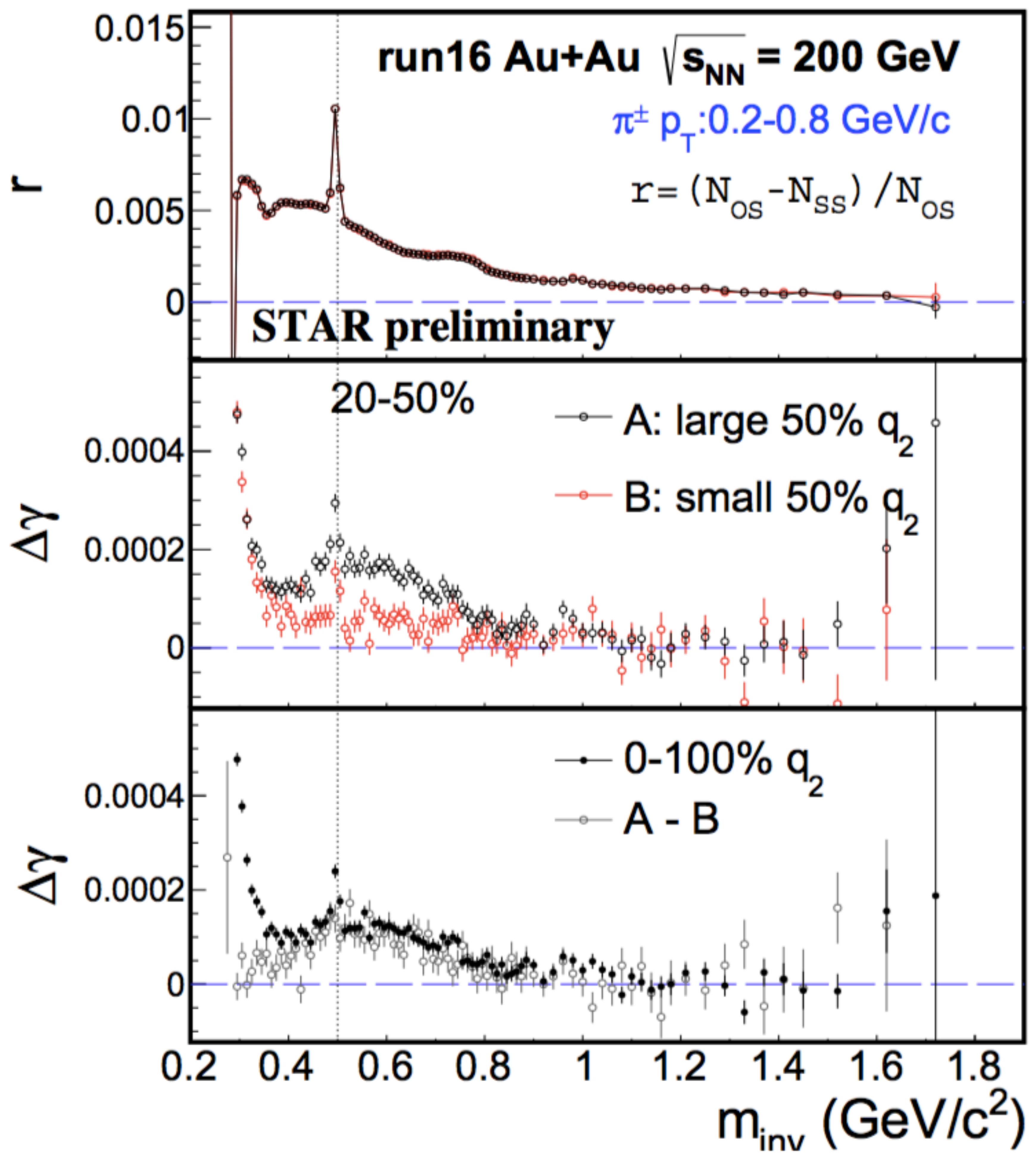
Physics Letters B 777, 151 (2018)



$\Delta\gamma_{112}$ is approximately proportional to v_2

Study of the background: resonance decay

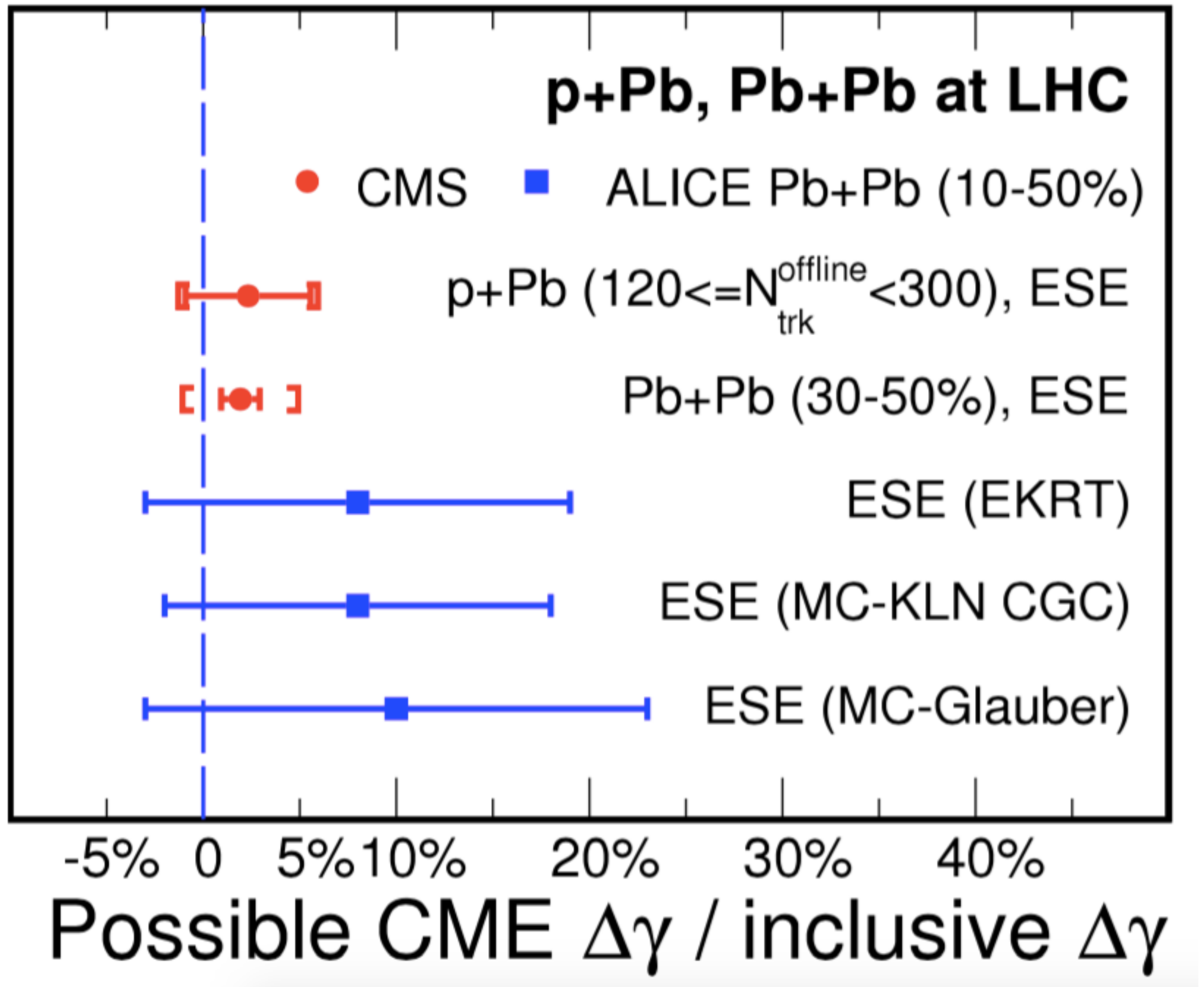


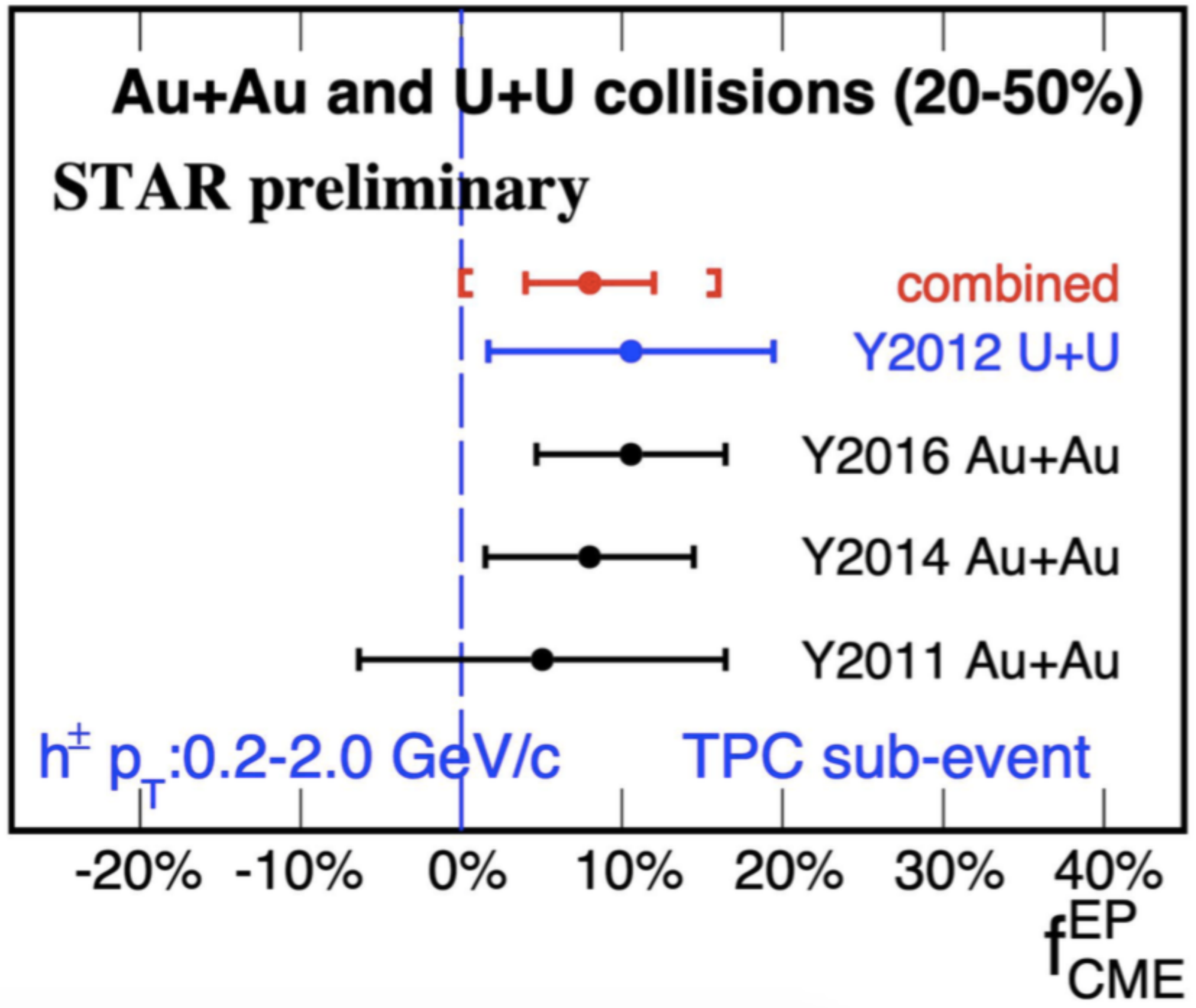


γ_{112} is contaminated by major backgrounds arising from local charge conservation/resonance decay coupled with the elliptical anisotropy

Nuclear Physics A 982, 535 (2019)

Experimental search for the CME: current status



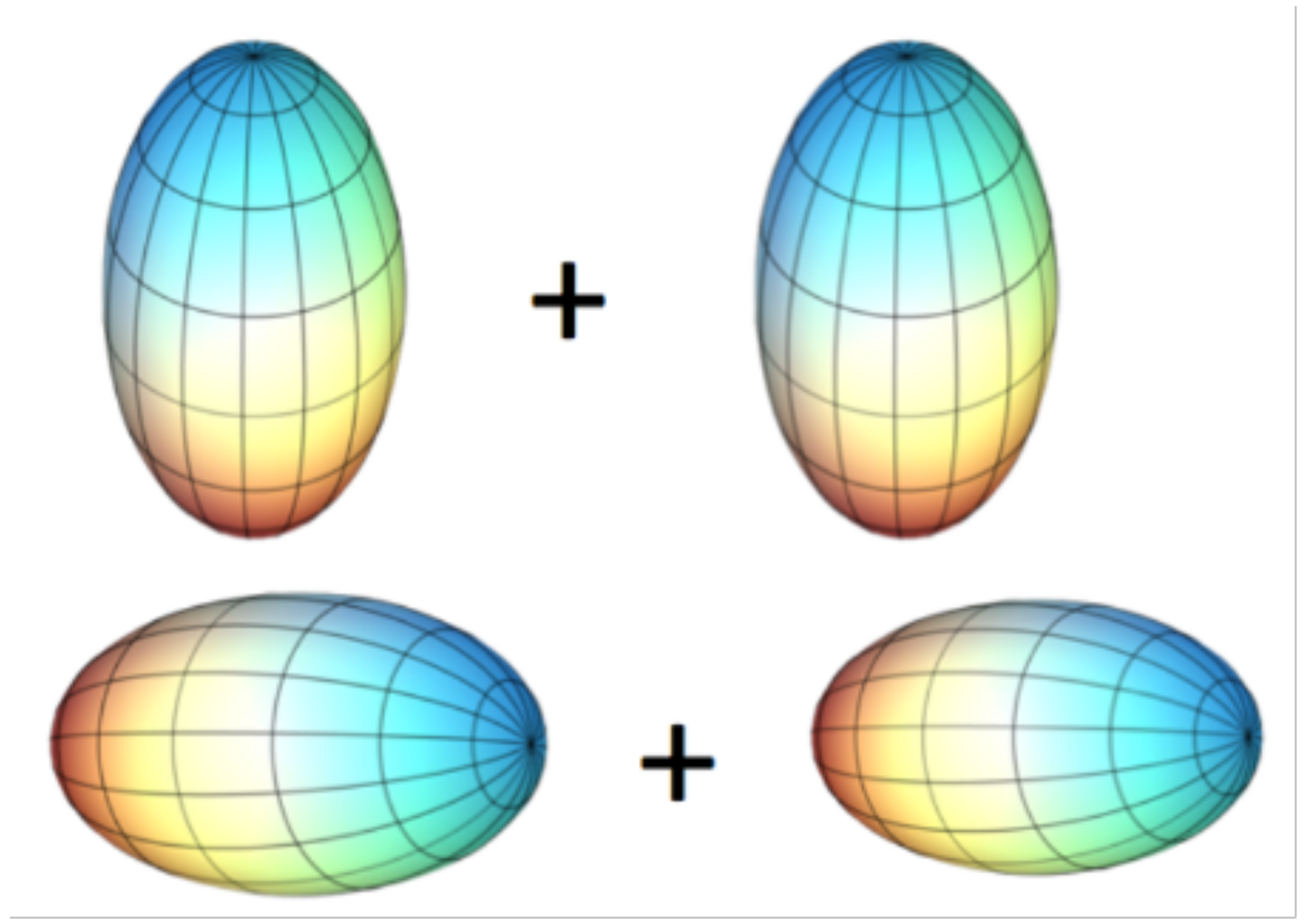


- γ correlator has been used to investigate charge separation for a decade, and it’s clear that the LCC+flow driven background as well as the contamination from the resonance decay play dominate roles
- Current consensus of the CME component (upper limit) in γ < 10%
- Important and urgent task: optimal observables and a comprehensive understanding, and …

Experimental search for the CME: current status

- Colliding deformed nuclei

vs



RHIC2012

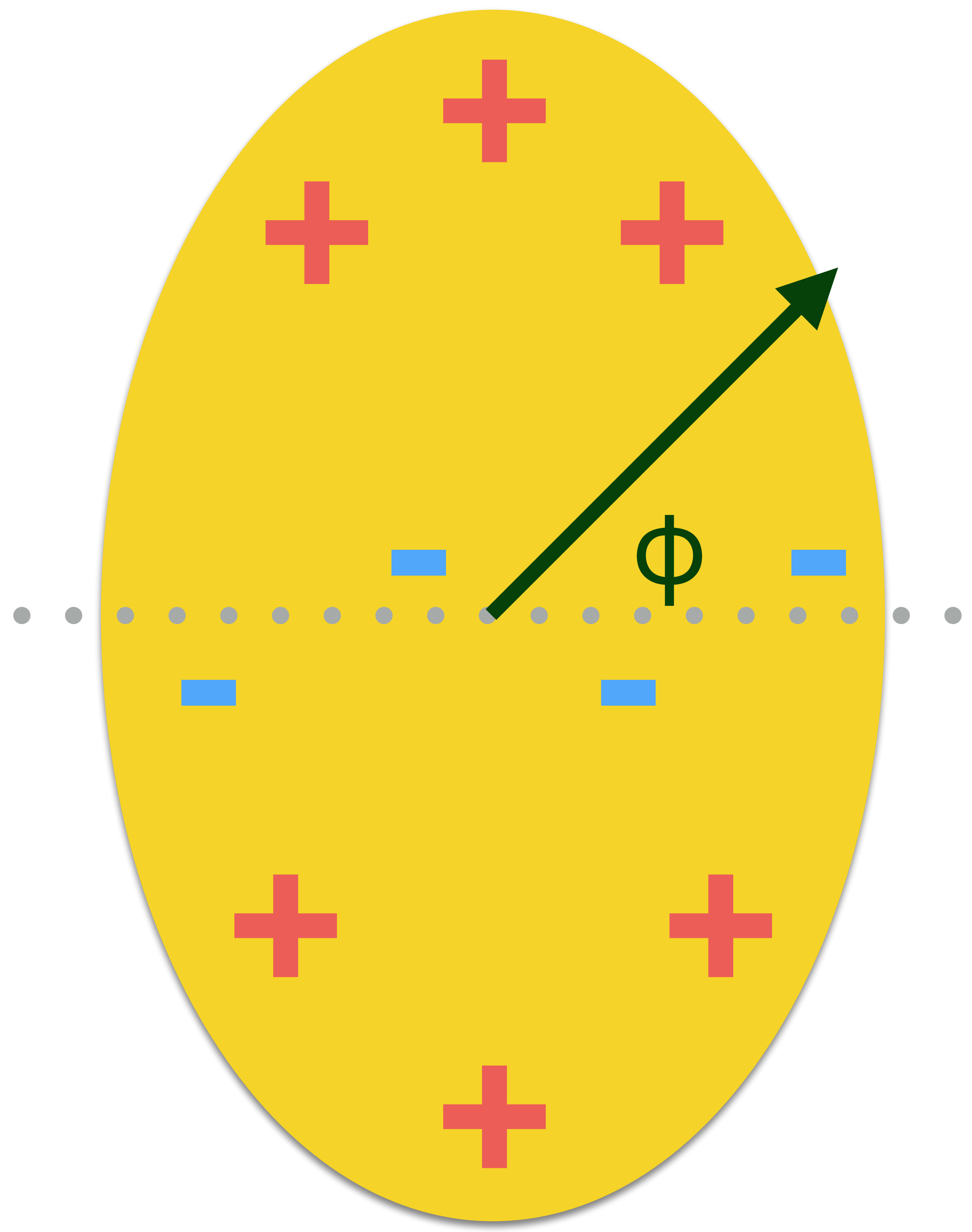
U238
Finite v2 + no B field
In most central collisions (body-body)

RHIC2018

- Isobars: different chemical elements that have the same number of nucleons.
  For example, ${}^{96}_{44}Ru$ (Ruthenium) and ${}^{96}_{40}Zr$ (Zirconium): up to 10% variation in B field

Observable	${}^{96}_{44}\mathrm{Ru} + {}^{96}_{44}\mathrm{Ru}$ vs ${}^{96}_{40}\mathrm{Zr} + {}^{96}_{40}\mathrm{Zr}$
Flow	$\approx$
CME	$>$
CMW	$>$
CVE	$\approx$

Measurement of CMW with charge asymmetry dependent flow



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

$$A_{ch} = (N^+ - N^-) / (N^+ + N^-)$$

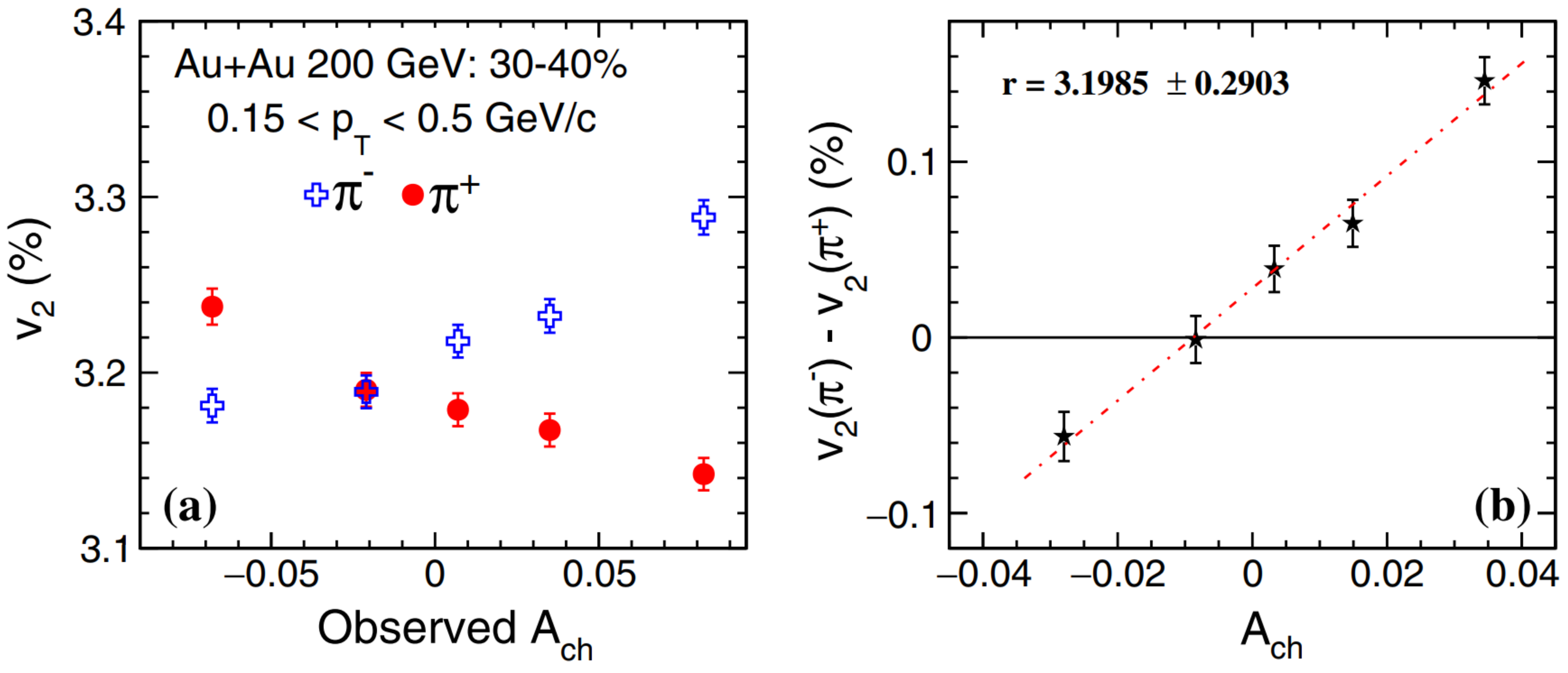
Sensitive to CMW

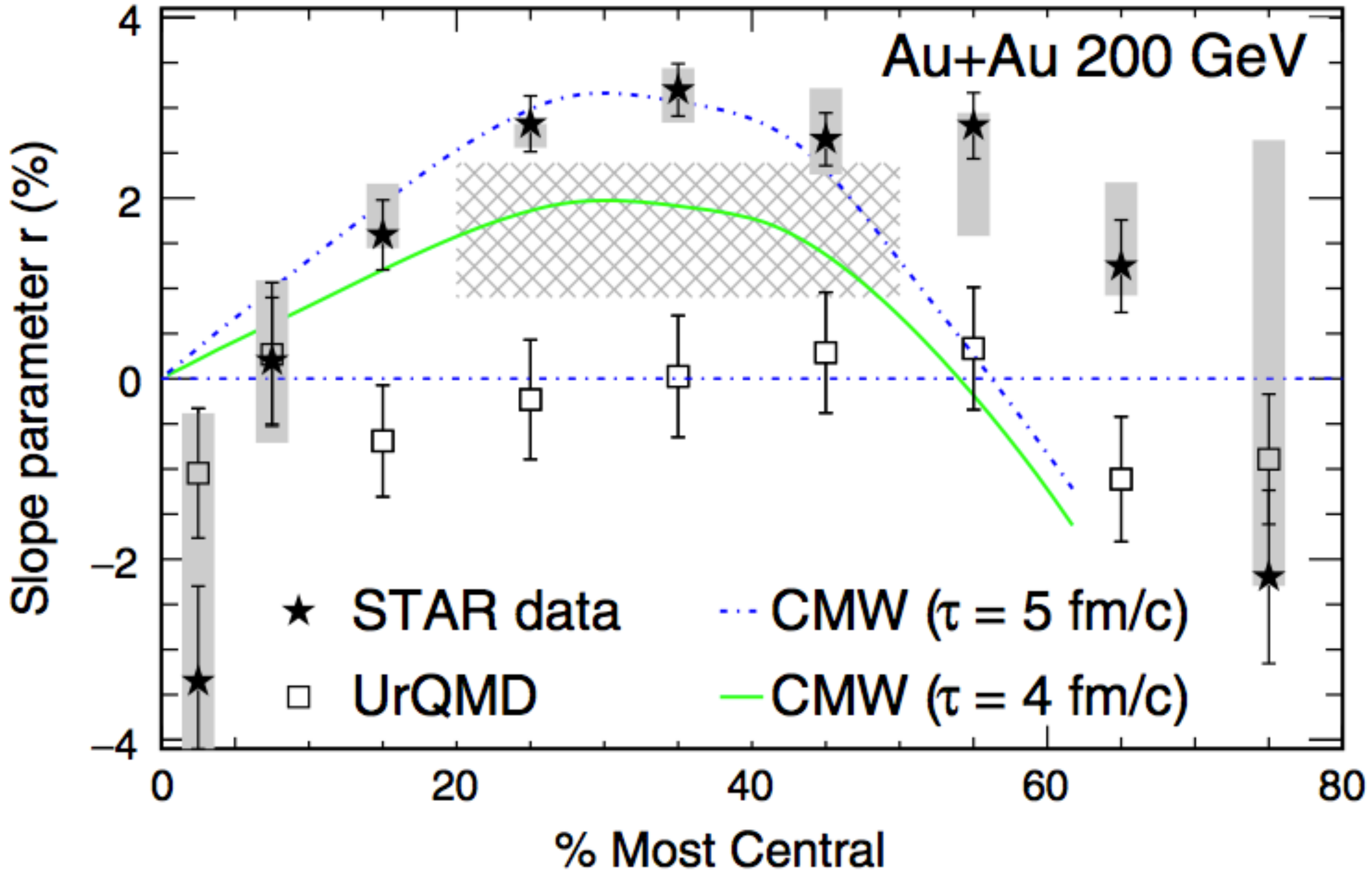
$$\Delta v_3 = v_3^- - v_3^+ \sim rA_{ch}$$

Not sensitive to CMW

v_2 vs A_{ch} at RHIC

Phys. Rev. Lett. 114, 252302 (2015)

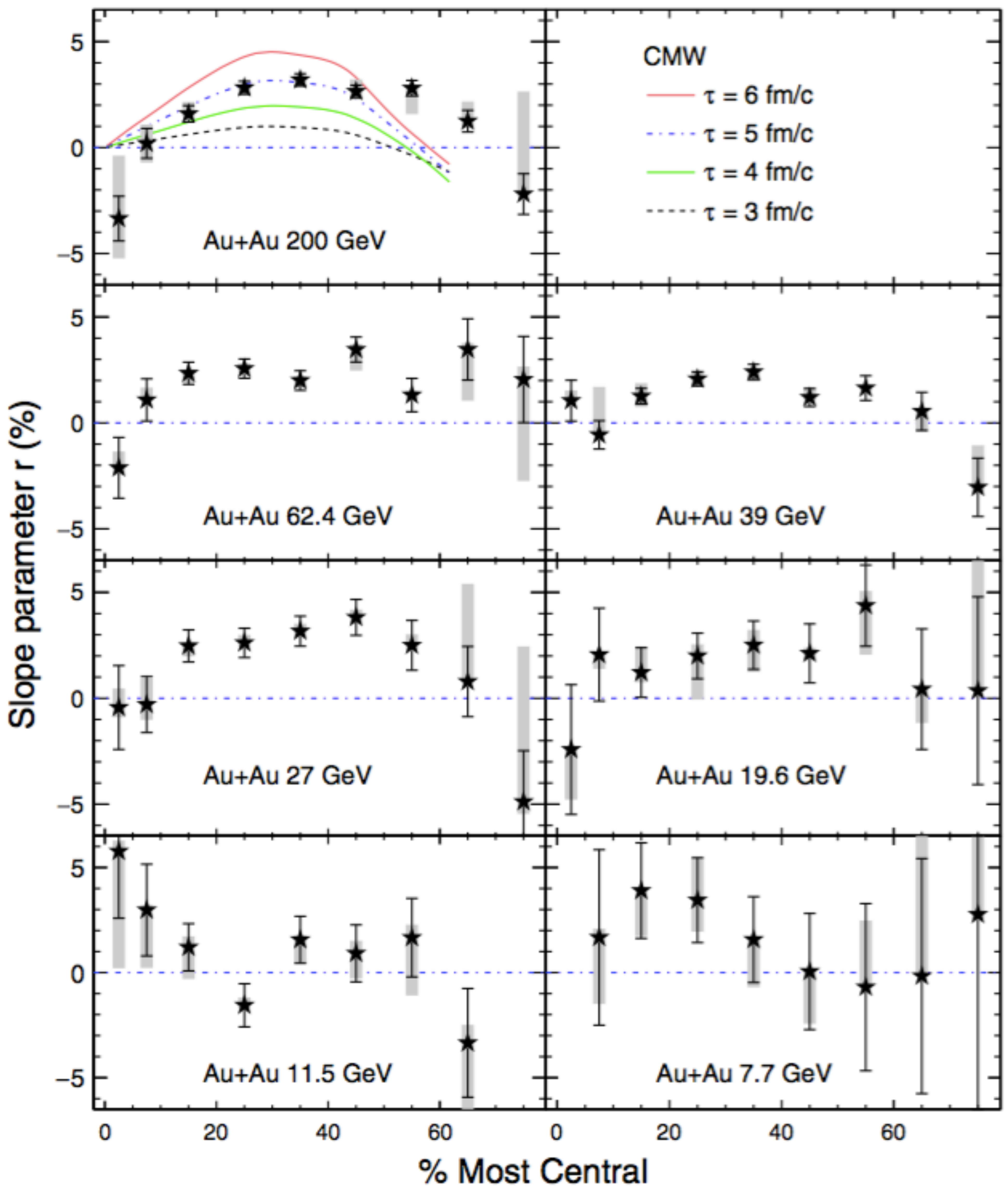




The linear dependences between v_2 and A_{ch} are clearly observed, matching CMW expectation

v_2 vs A_{ch} at RHIC

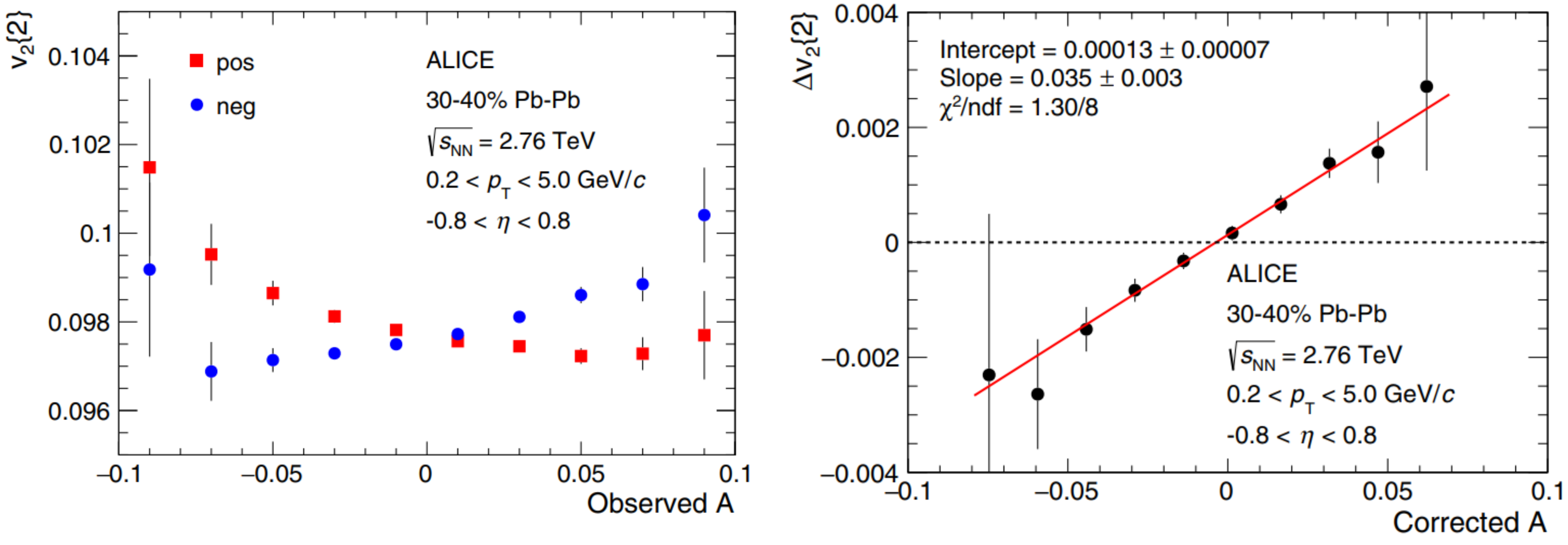
Phys. Rev. Lett. 114, 252302 (2015)

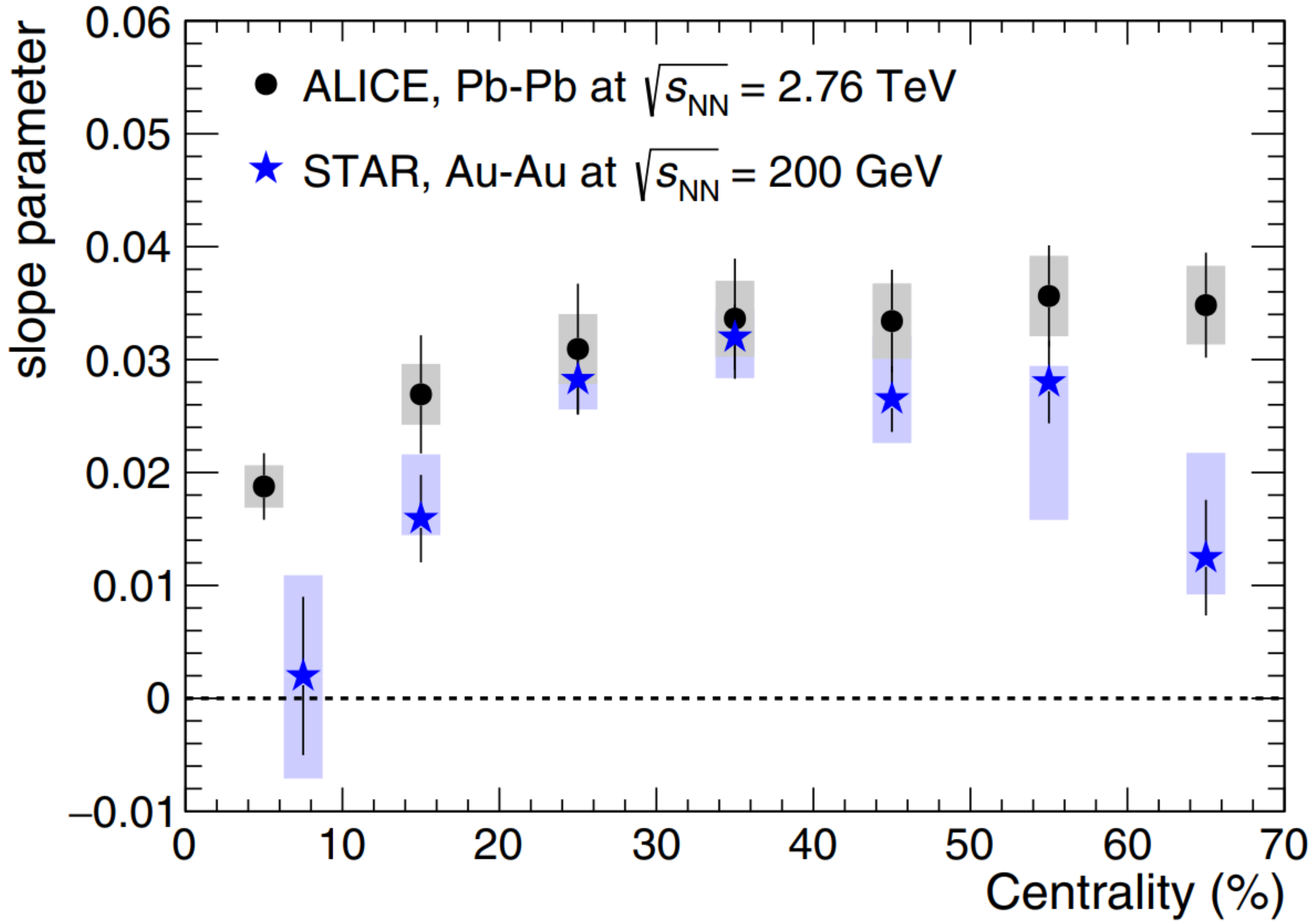


Positive slope and the rise-fall trend can be observed in BES

v_2 vs A_{ch} at LHC

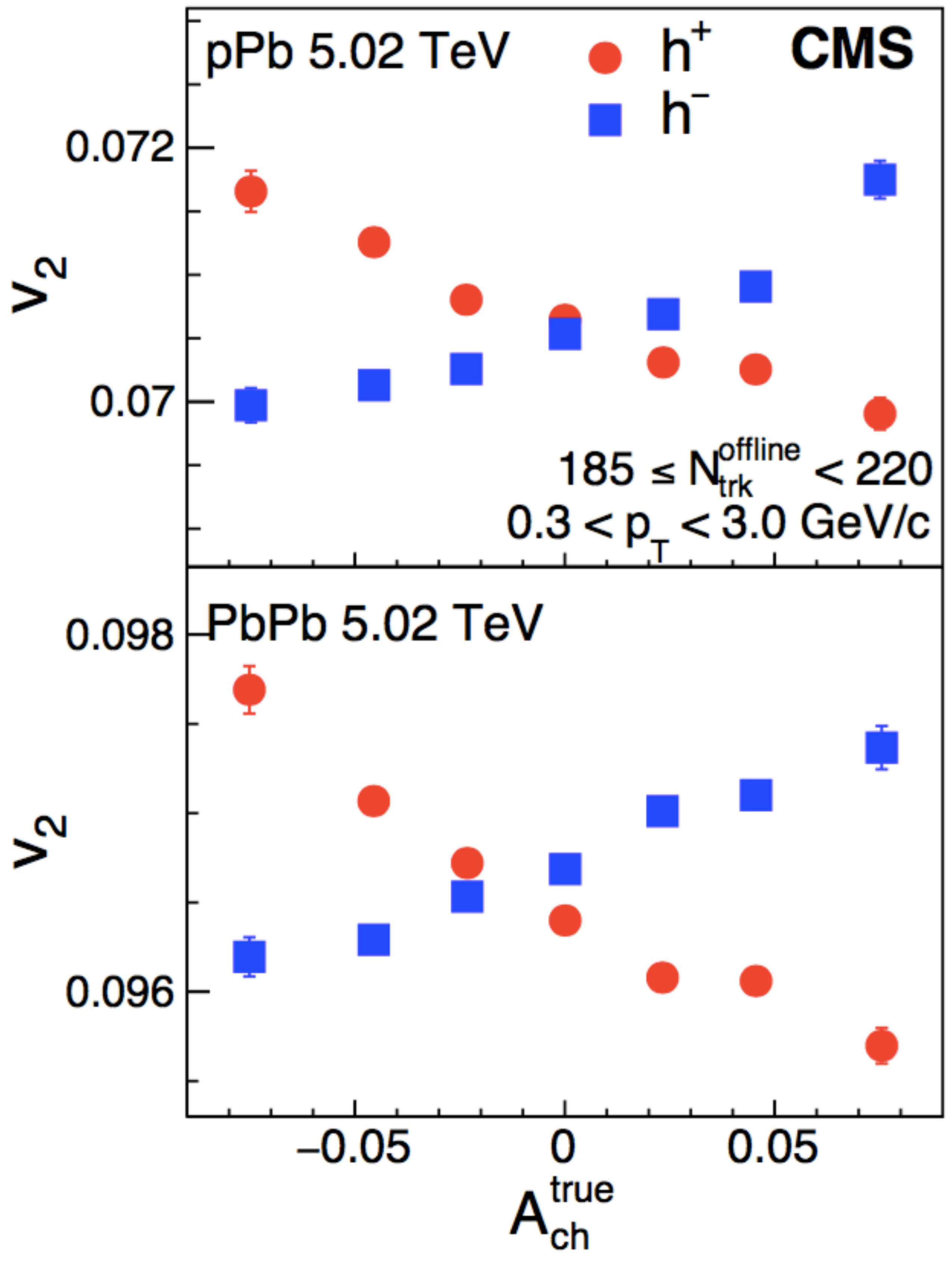
Phys. Rev. C 93, 044903 (2016)





- The linear dependences between v_2 and A_{ch} are clearly observed, matching CMW expectation
- Little difference between RHIC and LHC results

Surprise again in the small system collisions



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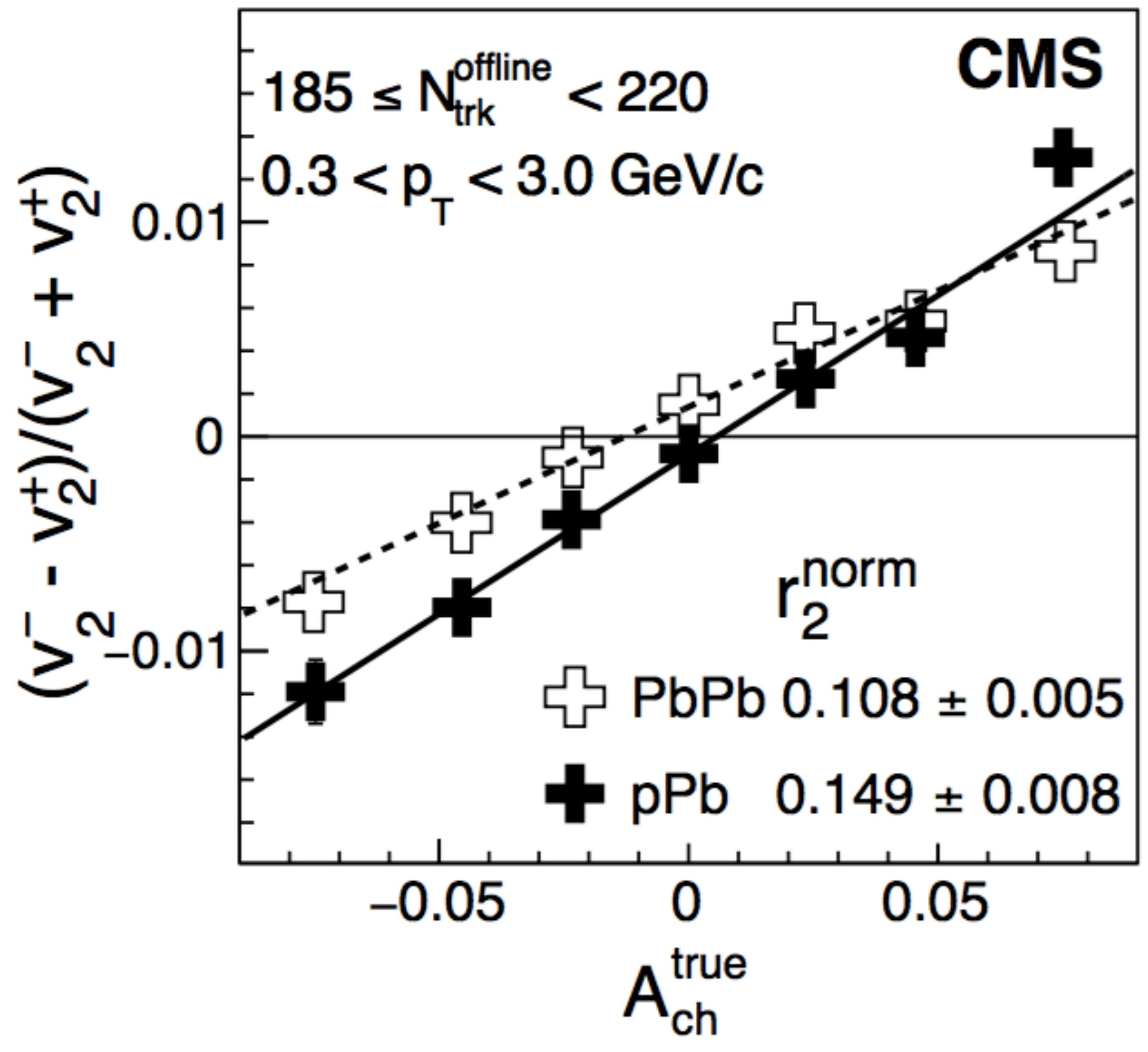
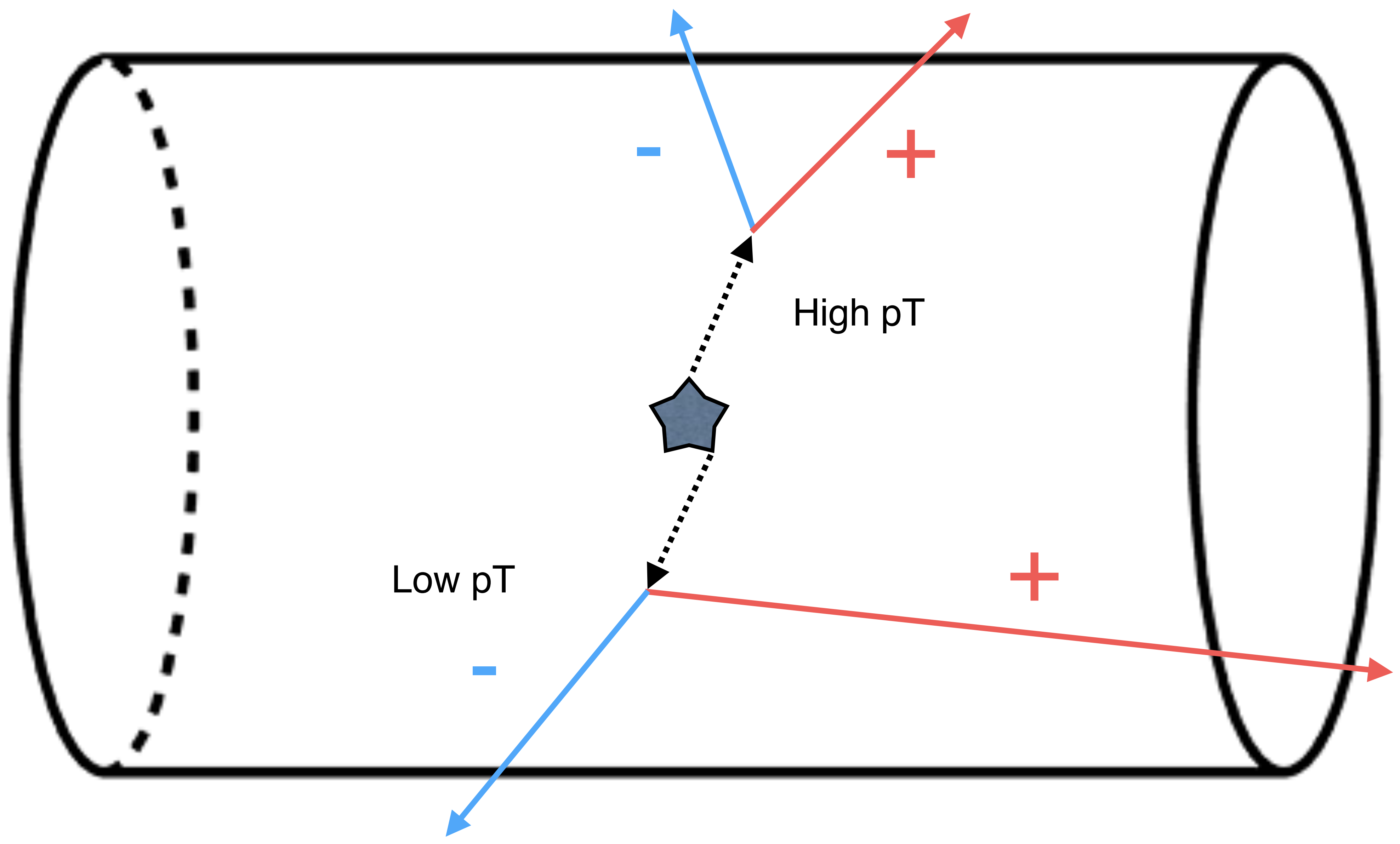


- Agreement between pPb and Pb-Pb results
- A common underlying mechanism generates the observed v_2 vs A_{ch}

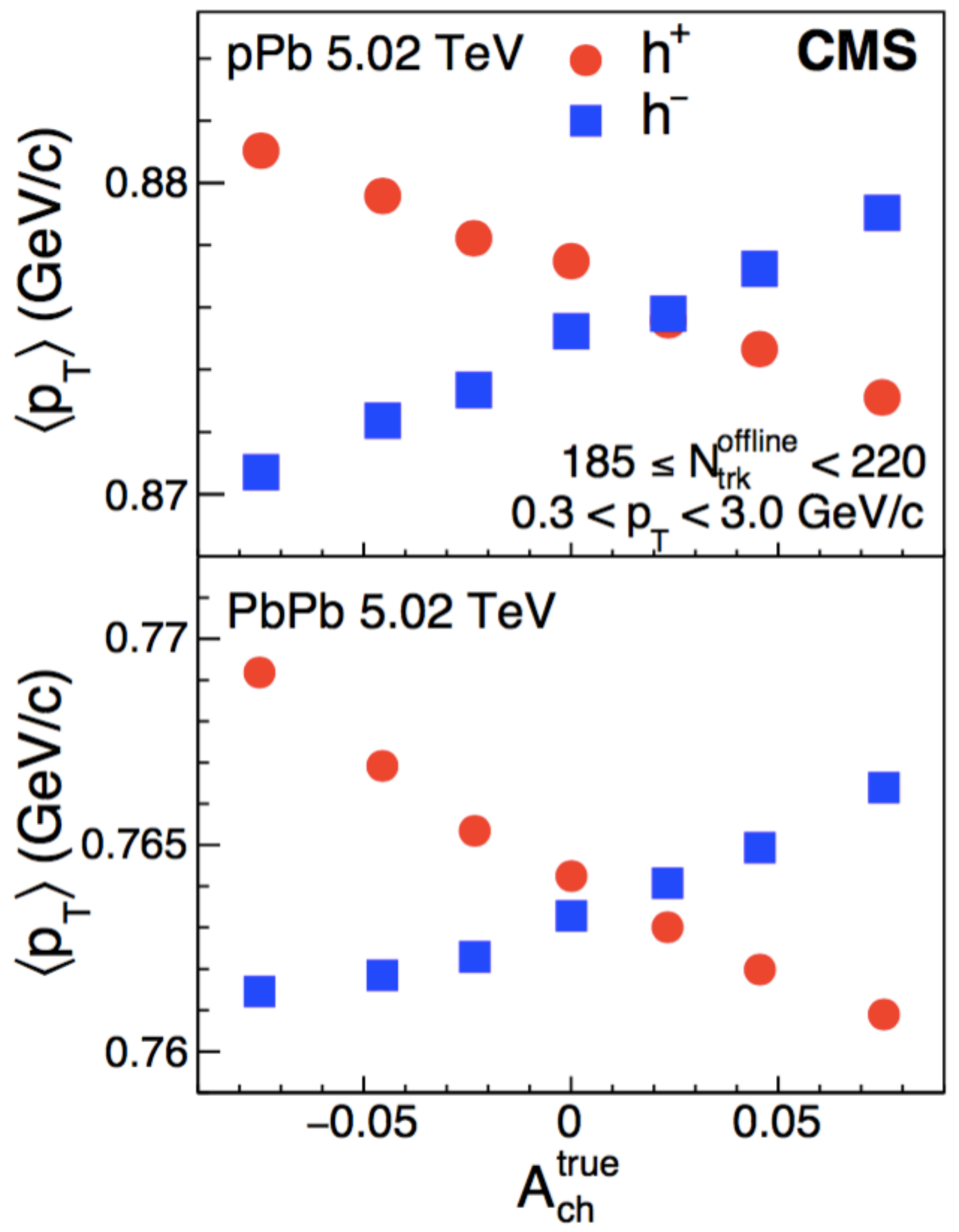
Study of the background: what are they and how large?

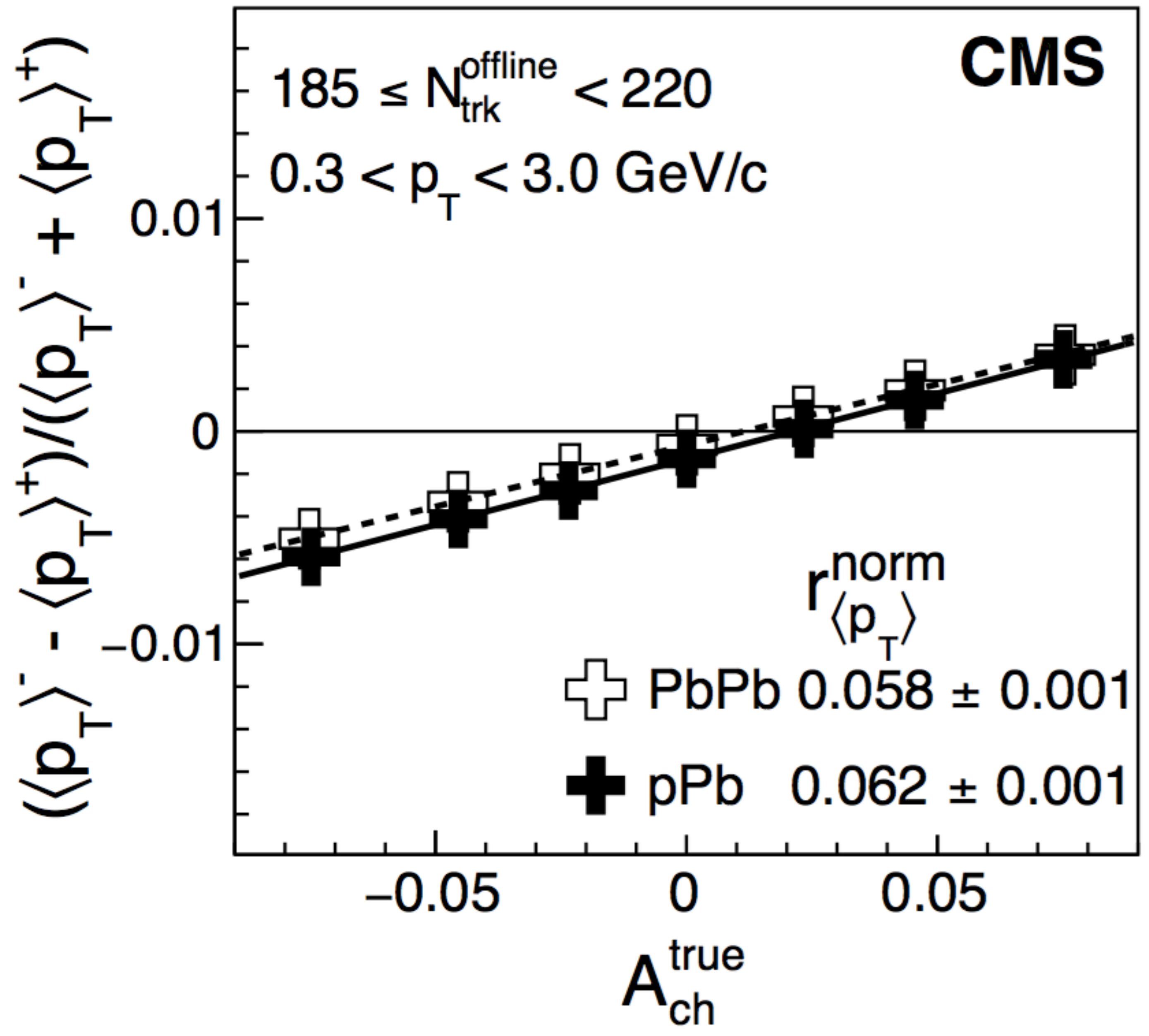


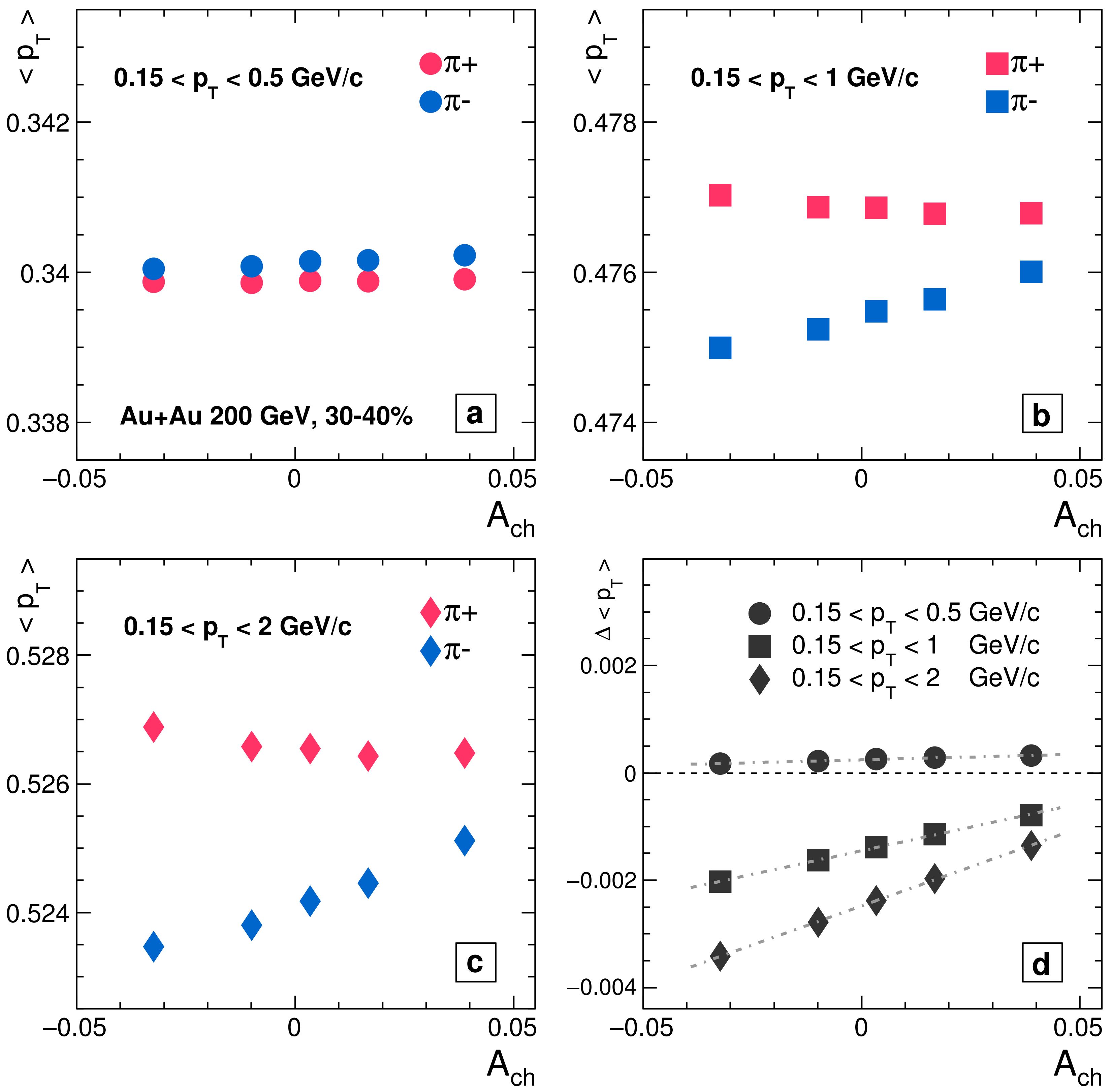
A_{ch} decrease
mean p_{T}^{-} < mean p_{T}^{+}
$v_2^{-} < v_2^{+}$

Local charge conservation

Study of the background: local charge conservation



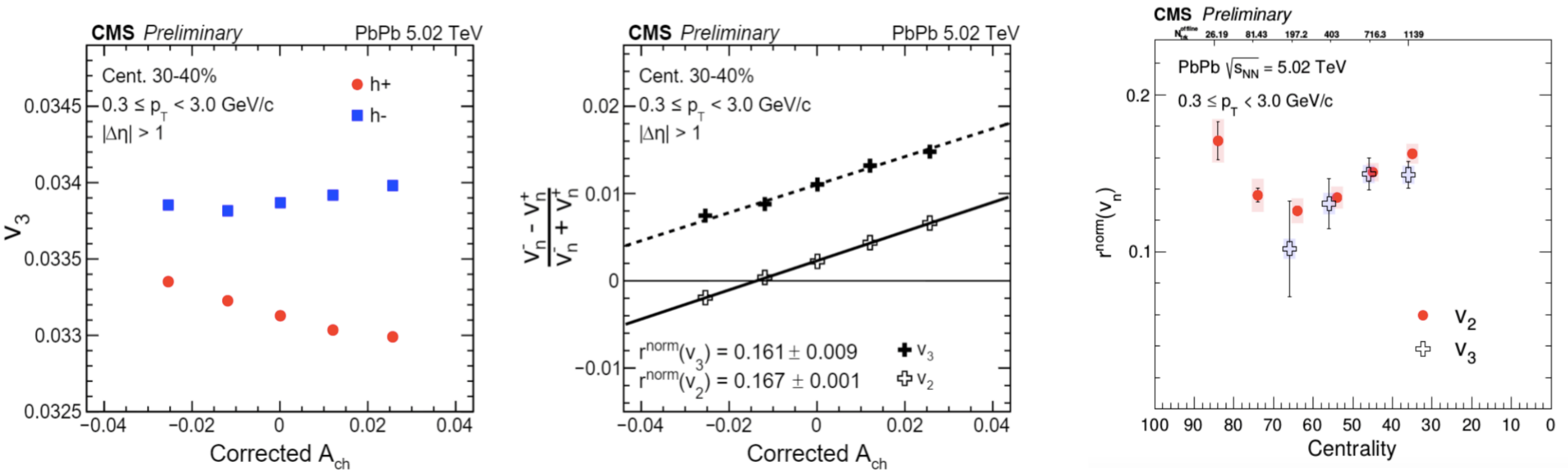




- p_{T} shows a clear A_{ch} dependence
- Indication of the local charge conservation

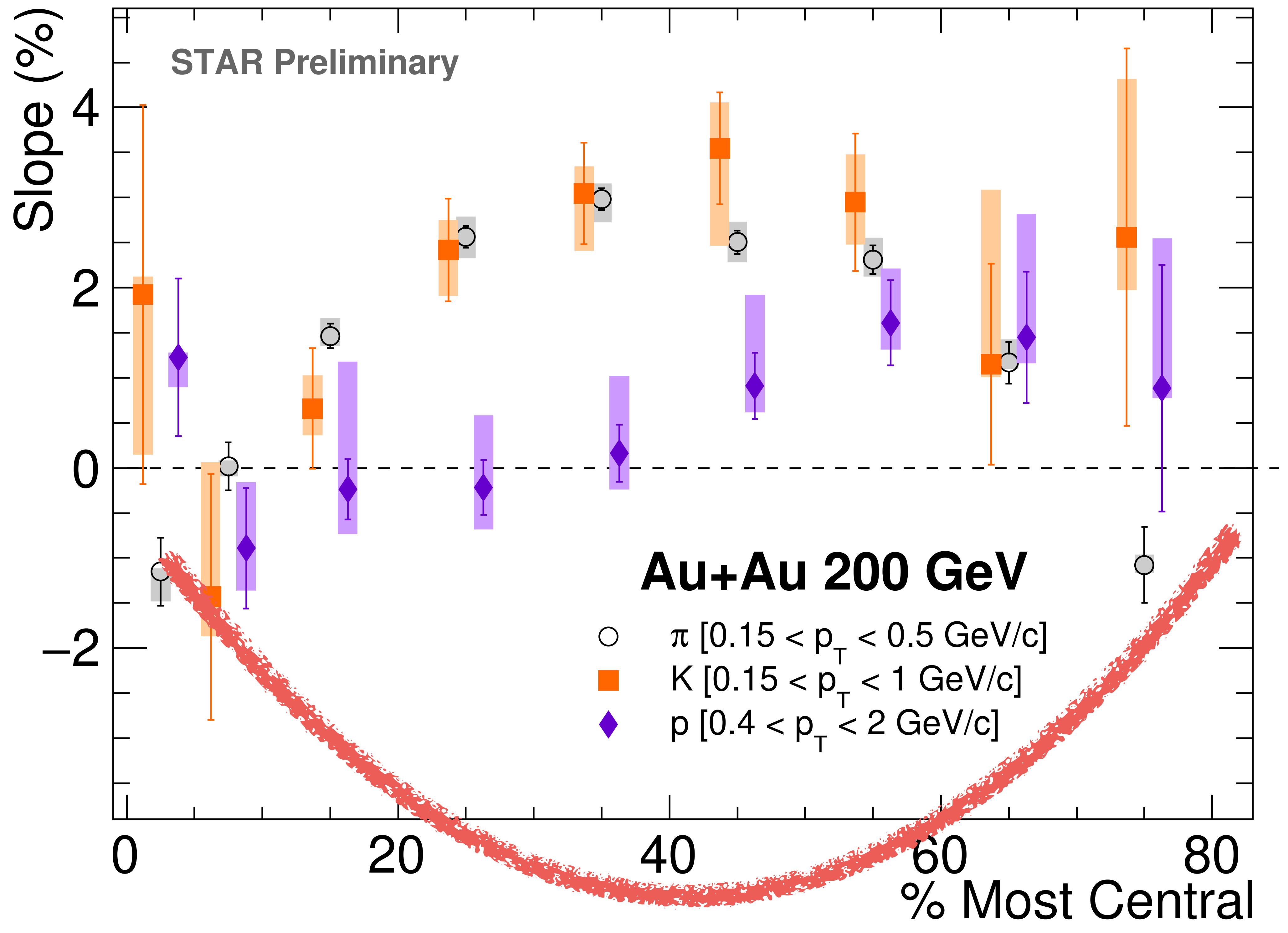
Study of the background - local charge conservation

If it's local charge conservation: $v_{2,3} \sim p_T \sim A_{ch}$



Study of the background - Isospin chemical potential

Isospin effect: $\Delta v_2 \sim \mu_I \sim A_{ch}$ (negative slope for K)



The isospin effect doesn’t play a significant role

Experimental search for the CMW: current status

- CMW couldn’t exist alone without CME, however, the observables and the mechanism are quite different

- The relationship of v_2 vs A_{ch} is contaminated by the local charge conservation

- Important and urgent task: extract the CMW fraction

Summary

How can we correctly capture the signal of the anomalous chiral effects, if they exist in QGP?

A ideal observable should
- be self-analysing
- clearly distinguish the signal and the background

We've already learnt a lot about the collectivity of the QGP no matter CME can be found or not.

Summary

- Theorists and experimentalists should always work together
- People used to only see what they believe — stay objective
- A good research takes time — be persistent

> It is by logic that we prove, but by intuition that we discover.
> To know how to criticize is good, to know how to create is better.
> —Henry Poincaré

Thank you for your attention!