第十一届华大QCD讲习班 The 11th HuaDa QCD School

高能重离子碰撞中手征反常效应的实验研究

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Outline

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

2007年9月4日，温家宝总理在人民日报文艺副刊发表《仰望星空》一诗。

“一个民族有一些关注天空的人，他们才有希望；一个民族只是关心脚下的事情，那是没有未来的。”在为这首诗做介绍时，温总理引用了他在同济大学的演讲。

我仰望星空，
它是那样寥廓而深邃；
那无穷的真理，
让我苦苦地求索、追随。
我仰望星空，
它是那样庄严而圣洁；
那凛然的正义，
让我充满热爱、感到敬畏。
我仰望星空，
它是那样自由而宁静；
那博大的胸怀，
让我的心灵栖息、依偎。
我仰望星空，
它是那样壮丽而光辉；
那永恒的炽热，
让我心中燃起希望的烈焰、响起春雷。

亲爱的莱德曼博士:

我工作努力，学习也不错，但是至今未在我学习的领域显出任何真正有希望的成绩。看来，我已陷入平平庸庸的人流之中。我常自问：为什么我要设法进研究生院去苦苦求读，然后进政府研究部门或其他学术研究机构?或许最好的结果只是发现一、二件其他人也可能发现的东西。我何不只拿一个学士学位，然后去当一个保险统计员，9点上班，17点下班，工资又很高。

我必须承认，做一个保险统计员并不能使人满足，因为我切望做推进人类福利的宏伟事业，并且相信，对我来说，科学是达此目的的最好途径。但令人失望的是，我最大的努力只换来平庸的结果，因此我就常常在想，为什么我要从事科学工作呢?在您的演讲里，您认为参加科学工作的报偿在于：当您发现了什么，认识到您懂得了某些别人不懂的东西，这样就给您带来了喜悦。假如我的过去可以说明将来的话，那么我相信，在我一生中，您说的这种时刻不大会出现。确实，在我看来，只有那些在过去做得很好并且成功地获过奖的人，才能在将来得奖。顺便说一句，在我看来，我们的社会只表彰那些已经获得的成果，而并不表彰导致这些成果而付出的艰苦劳动。那些付出辛勤劳动但并不成功的人，并不受到表彰，这一点使我感到沮丧!

我想提两个问题来结束这封信，第一个问题是和您有关的：是什么促使您从事科学事业？是什么使您感到您在科学上有才华，优于您的同学或同事？您从事科学研究工作40年，最终使您在1988年获得诺贝尔奖物理学奖，您在几十年前就知道您是拿诺贝尔奖的料子吗？或许最重要的是，是什么促使您在漫长的科学生涯中奋斗不息？

第二个问题涉及到像我们这样的一些人——那些有抱负的学生，不管他们如何努力，至今未能从平庸的潮流中脱颖而出。为什么我们要追求科学事业？我们成功的前景何在——不论是得到伟大的科学成就，还是脱颖而出？艰苦的劳动能代替天赋的才能吗？或者，除了艰苦劳动，还必须有天才，才能成功？最后，如何能使我们始终保持旺盛的斗志，特别是在我们成功之前的漫长的昼夜里？

一个年轻的大学生

亲爱的年轻大学生：

我吃不准是否能回答您提出的一系列复杂而棘手的问题，但我可以谈谈我自己的经历。我在高中时的成绩总是在B-到B+间徘徊。我大学毕业于纽约市立学院，它在当时是所相当不错又免收学费的学校。我的成绩平均为B+，可称得上优异了。我对科学有一种热情，但是我明白，不论是在高中还是在大学，比起班级里的尖子学生，我远远不如他们。他们是我的好朋友，是我乐于与之相处的人。在第二次世界大战中，我在美国陆军服役3年，它给了我思考的时间。然后，我就开始做物理学研究生，并且相信：假如我能与我的那些天才朋友们坦诚相处，那么我一定会生活得很好。我所经历的不景气的年代，使我得到教益，造成了我对金钱的一种宿命论的看法。在市立学院里，我经常说："我准备在化学界失业，你准备在哪里失业?"

今天，任何受过训练的科学工作者或工程技术人员，即使他们的成绩平平（B），他们都可确保就业，并得到相当不错的报酬。但我认为，您必须自问：您想从生活中得到什么?假如您能想象出，一早醒来就急不可待地切望去工作；假如一连30多小时的工作，是您热情的体现而不是切望得到超工时报酬；假如您是在工作中寻找真正的乐趣，而不管您在那里是一周工作40还是70小时（您的主要时间都花在工作上了）；假如上面所有这些对您都是真的话，那么您仍旧需要问一问，这些"乐趣"值不值得使您因放弃做保险统计员而放弃的一年两万美金的额外报酬。对您的生活，什么样的报酬是更好一点呢?

给莱德曼博士的一封信

我并不认为您需要超级科学家的大奖赏，集体性的工作是至关重要的。科学的享乐是一种带有观赏性的，您必须学会如何从别人的成就中获得乐趣。假如您通过辛勤劳动体会到了学术研究的全过程，并且得到了胜利的话，那么您是一个真正的科学家!立刻，您就成了令人敬畏的传统大师——牛顿、法拉第、爱因斯坦、费米……中的一部分。想一想，当您在晚上回家时如何向您的孩子们描述您一天的工作?

总结如下:

--现在成绩平平，并不是决定性的。寻找自我!您有没有梦想过，您有过新的想法没有，即使是错误的想法?您是否享受过科学的快乐，即使成为一个旁观者?

--定出的目标应比您认为是合理的更为高一点，是值得的。以后您可以稍退一点。我据所知，人的生命只有一次，它只给您一次机会。

--自己为自己提出一些尖锐的问题。尽可能地试图怀疑您自己的处世哲学、生活动机。什么是您真正的快乐?在这个星球上什么才是有价值的东西?在上一周，为什么您决定做这做那?在过去，什么是您的驱动力?如此等等。

给莱德曼博士的一封信

现在再回答您一些特定的问题。大约是在我得到博士学位5年之后，我开始认识到我颇有竞争力。在这10年之后，我惊奇地发现，与那些带我进入物理学世界的最好的朋友们相比，纵使他们比我懂得多，但是我与他们同样有成效。

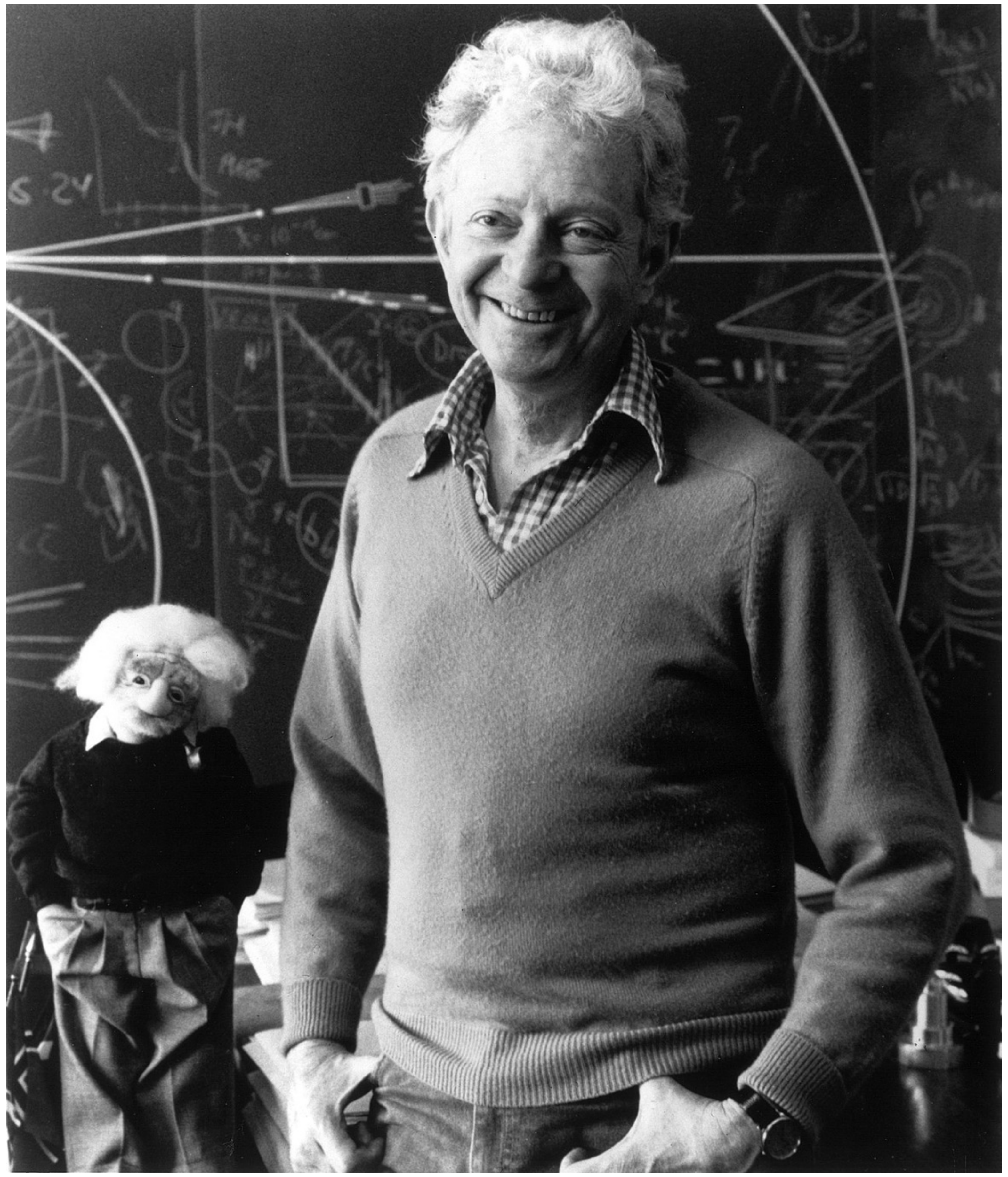
做了一个像我们中微子那样的好实验之后，使我有可能作一些有趣的演讲，它令人快乐无穷，但更迷人的是，它导致下一轮实验。

什么是连续不断的驱动力?科学本身!!成功会给人带来额外的动力。人处在低潮时（经常如此），会感到乏味，但是这就是工作，何况我有遍及世界的同事、学生、教师、朋友们的支持。

我已经或多或少地涉及到了您的第二个问题。努力工作，这确实是成功的要素。**大多数科学家并非才智横溢，其中有一些甚至很迟钝。具有坚实的基础是重要的，它意味着您真正懂得了您必须掌握什么，即使要花很多的时间，也应在所不惜。许多“聪明的”年轻人很肤浅。坚定的信念，顽强奋斗、努力工作，都是在一个集体中倍受称赞的品德，再加上想象力，那就是锦上添花了。**

https://physicstoday.scitation.org/doi/10.1063/1.2810390

给莱德曼博士的一封信



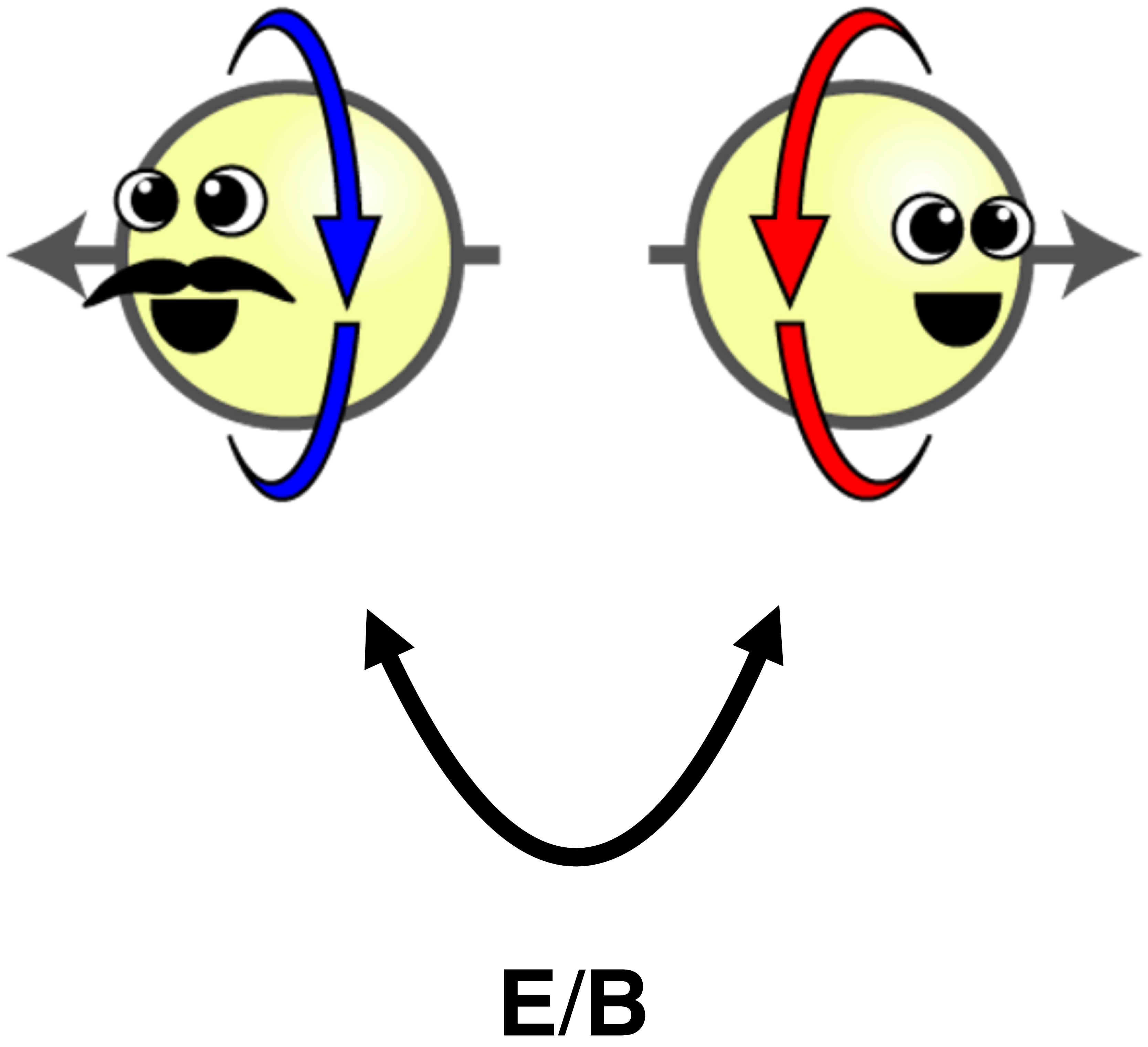
利昂·马克斯·莱德曼（英语：Leon Max Lederman，1922年7月15日—2018年10月3日），美国物理学家，1988年诺贝尔物理学奖获得者。

生于纽约1946年进入哥伦比亚大学物理系读研究生，1951年获得博士学位后留校工作，1958年后任该校教授，1979-1989年曾任费米国家加速器实验室主任。

莱德曼长期从事教育工作，曾任美国科学促进会理事会主席。他在粒子物理实验领域成果卓著，并因“中微子束方法及通过发现μ中微子验证轻子的二重态结构”而荣获1988年诺贝尔物理学奖。

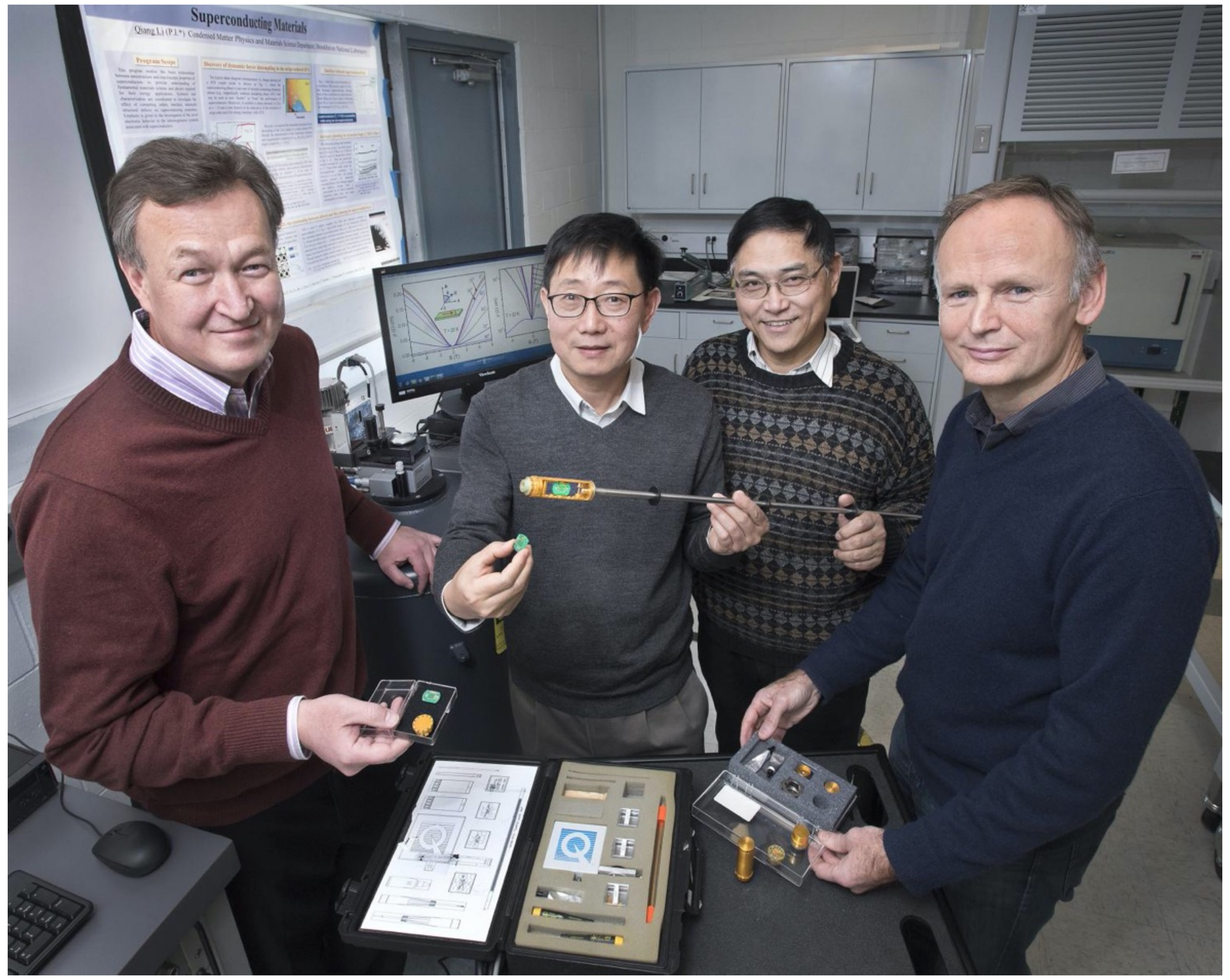
Introduction from experimental perspective

What is chiral anomaly?

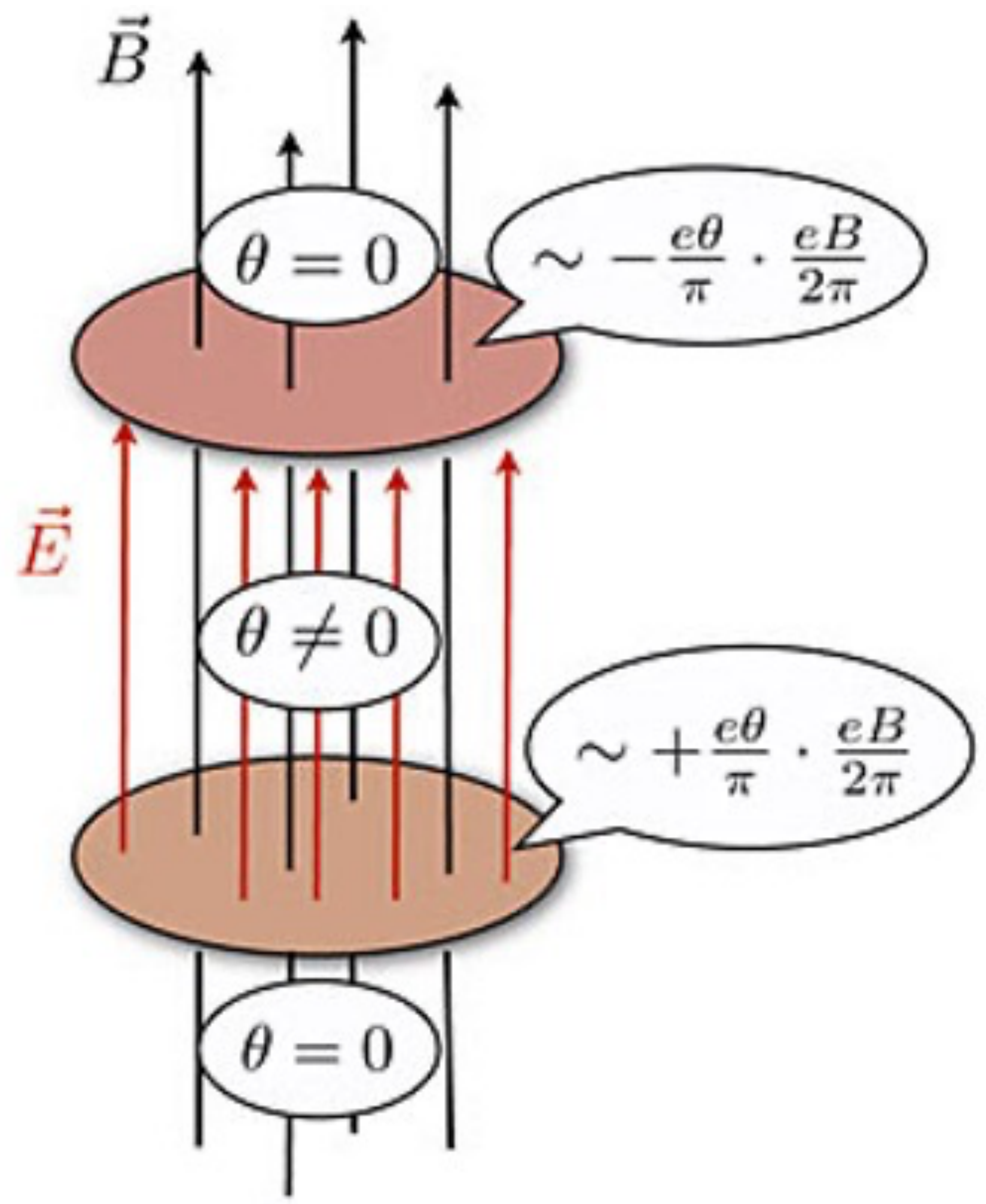


Chiral magnetic effect

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**

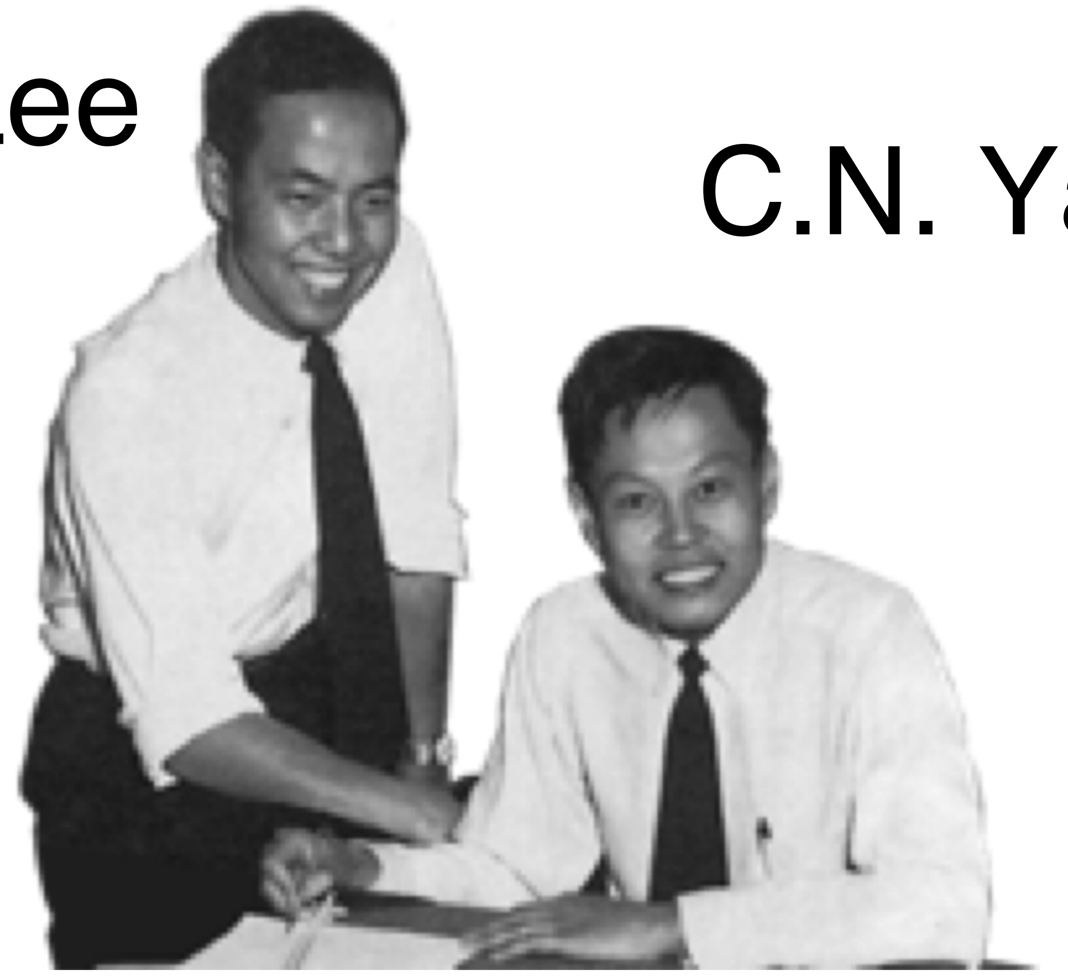
- Topological structure of vacuum gauge fields
- The possible local violation of P (parity) and/or CP (charge-parity) symmetries in strong interactions

P/CP symmetry in weak interaction

- Before 1950s, no one suspected the P/CP symmetry, until the Θ-τ puzzle:
  Similar features but different parity values $\Theta \to \pi^{+} + \pi^{0}$， $\tau \to \pi^{+} + \pi^{+} + \pi$
- C.N. Yang and T.D. Lee first noticed this. C.S. Wu did the experiment with Co60 β decay:
  Regardless of the left- or right-handed, β prefer to emit along the opposite direction of spin
  P violation in weak interaction!
- Cronin and Fitch further confirmed the CP violation in weak interaction.

T.D. Lee

C.N. Yang



C.S. Wu

P/CP symmetry in strong interaction?

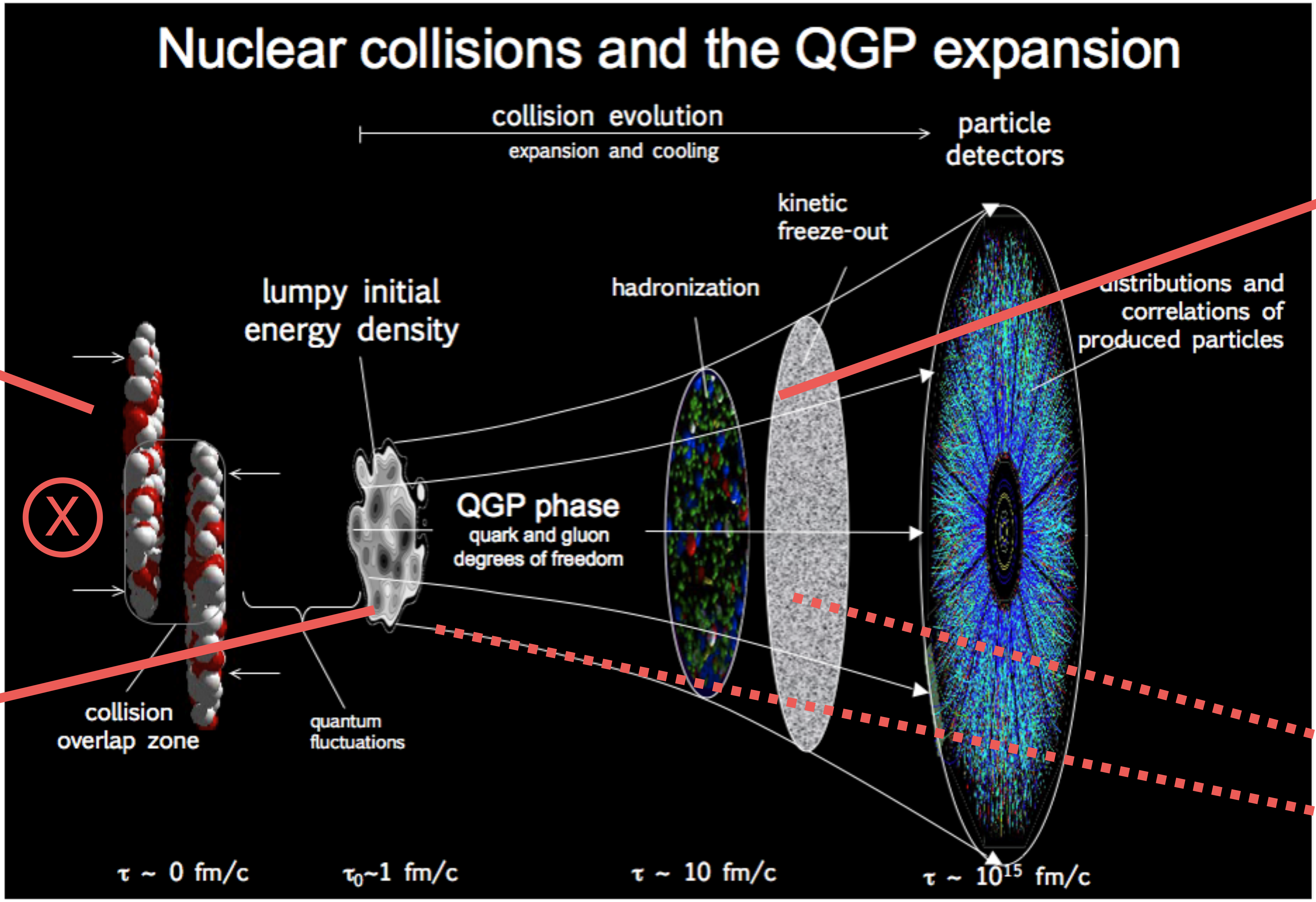
- Strong CP problem
  Why does QCD seem to preserve CP symmetry?
  No known reason in QCD for it to necessarily be conserved

- In this century, it is proposed that the chiral anomaly is possible in strong interaction and can be tested in **heavy-ion collisions**

Heavy-ion collisions

Magnetic field
($\sim 10^{15}$ T)

Hadrons



Quarks

Photons
Leptons

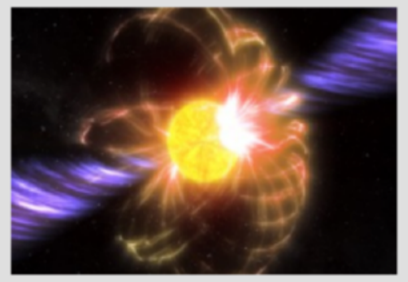
Criticality, **Collectivity**, **Chirality**

Strong magnetic field in HIC

- Thinking — human brain: 10^{-12} Tesla
- Earth's magnetic field: 10^{-5} Tesla
- Refrigerator magnet: 10^{-3} Tesla
- Loudspeaker magnet: 1 Tesla
- Levitating frogs: 10 Tesla
- Strongest field in Lab: 10^{3} Tesla
- Typical neutron star: 10^{6} Tesla
- Magnetar: $10^{7...10}$ Tesla
- Heavy-ion collisions: $10^{15...16}$ Tesla
- Early Universe: even (much) higher

IgNobel 2000 by A.Geim (got Nobel 2010 for graphene)

Destructive explosion



THE ASTROPHYSICAL JOURNAL LETTERS, 933:L3 (9pp), 2022 July 1 https://doi.org/10.3847/2041-8213/ac7711

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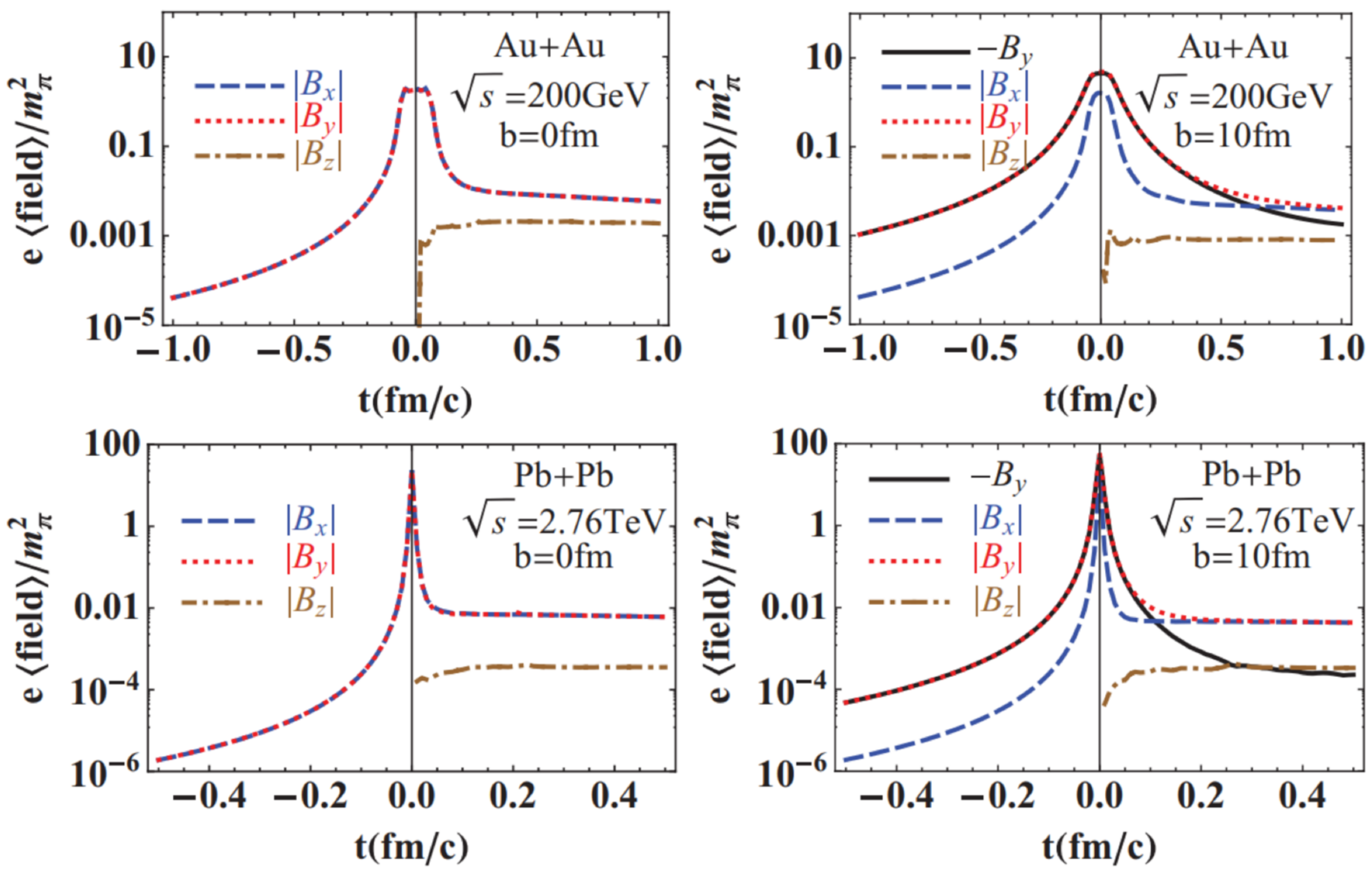
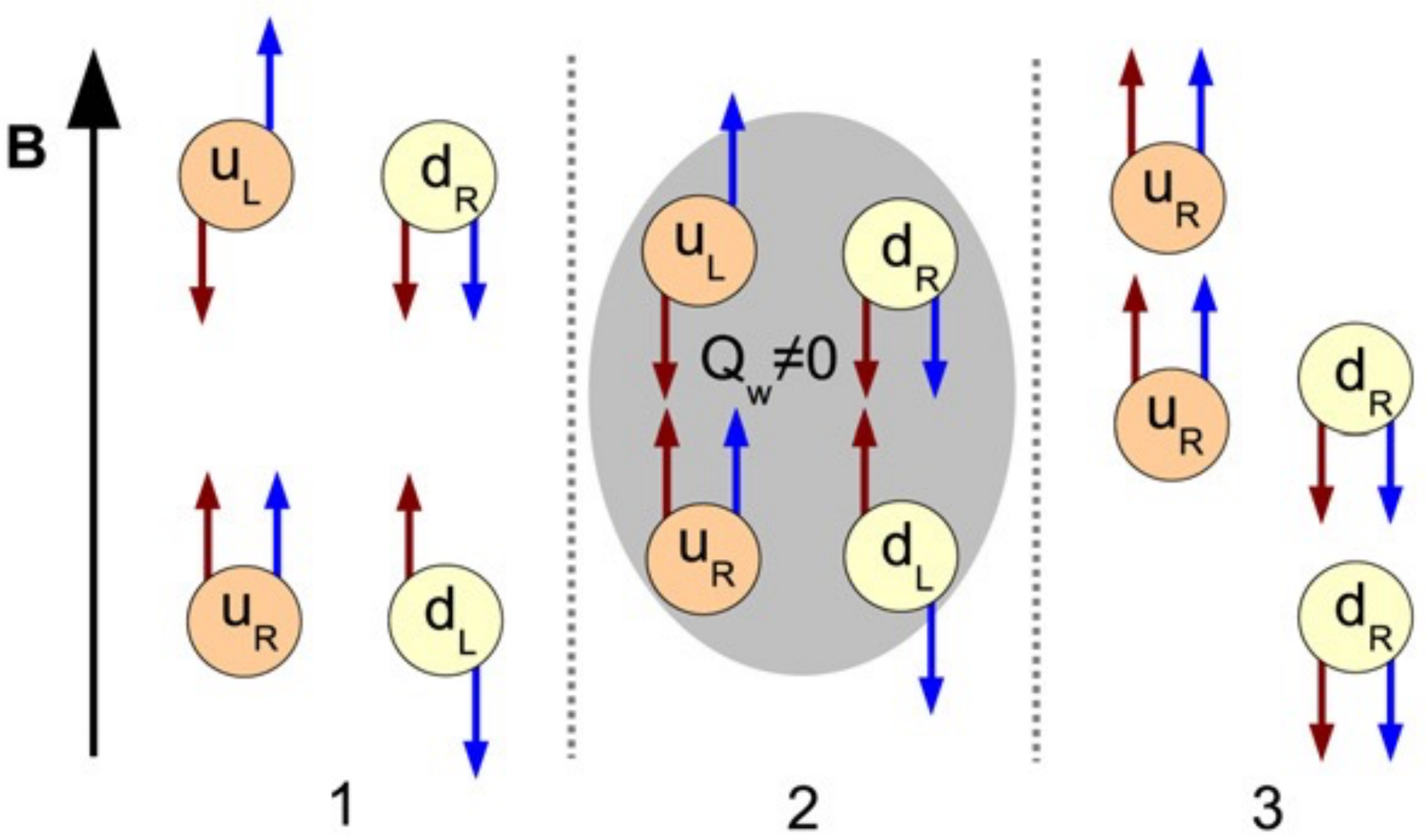
Insight-HXMT Discovery of the Highest-energy CRSF from the First Galactic Ultraluminous X-Ray Pulsar Swift J0243.6+6124

Phys. Rev. C 85, 044907 (2012)



Nucl. Phys. A 803, 227 (2008)

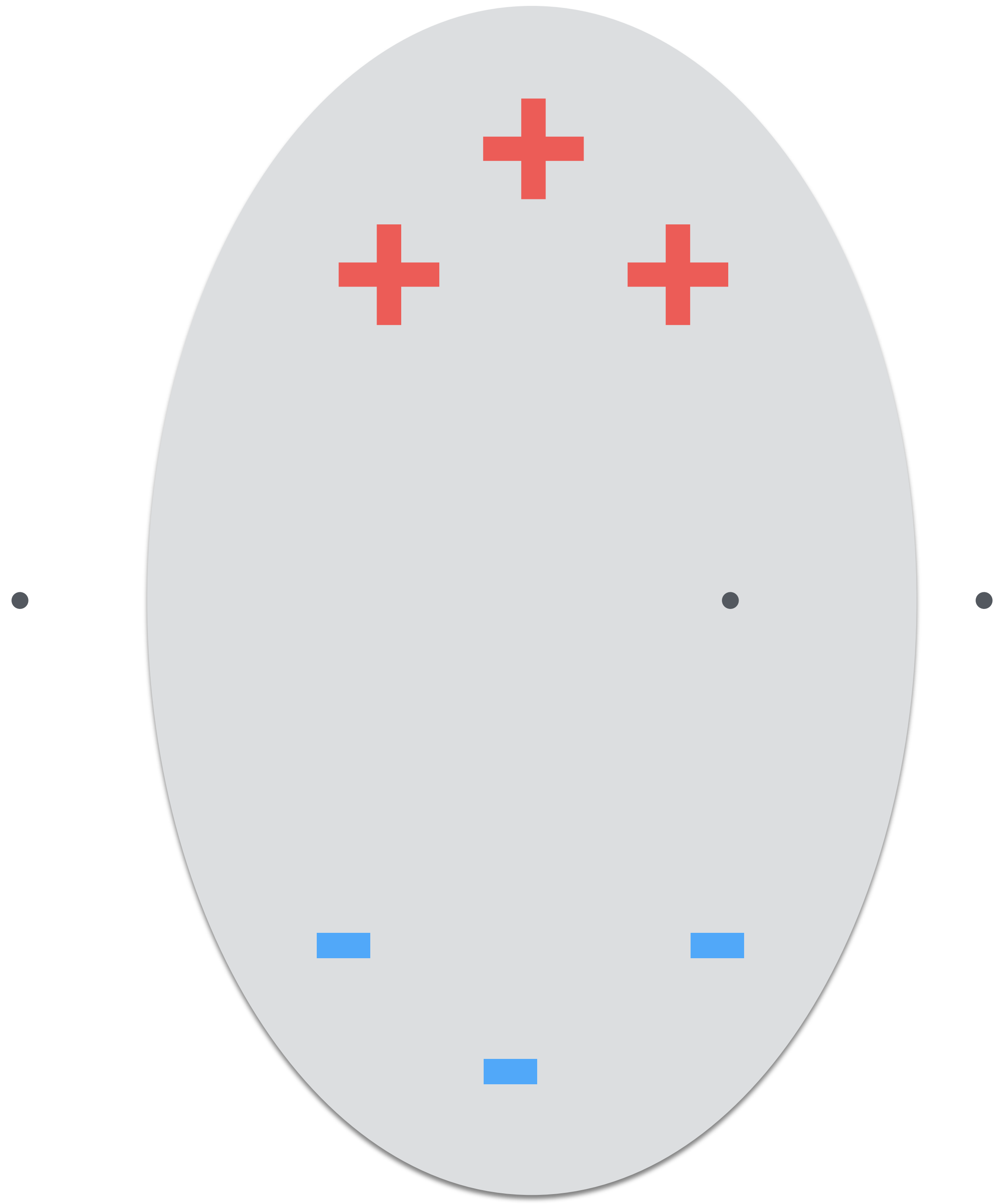


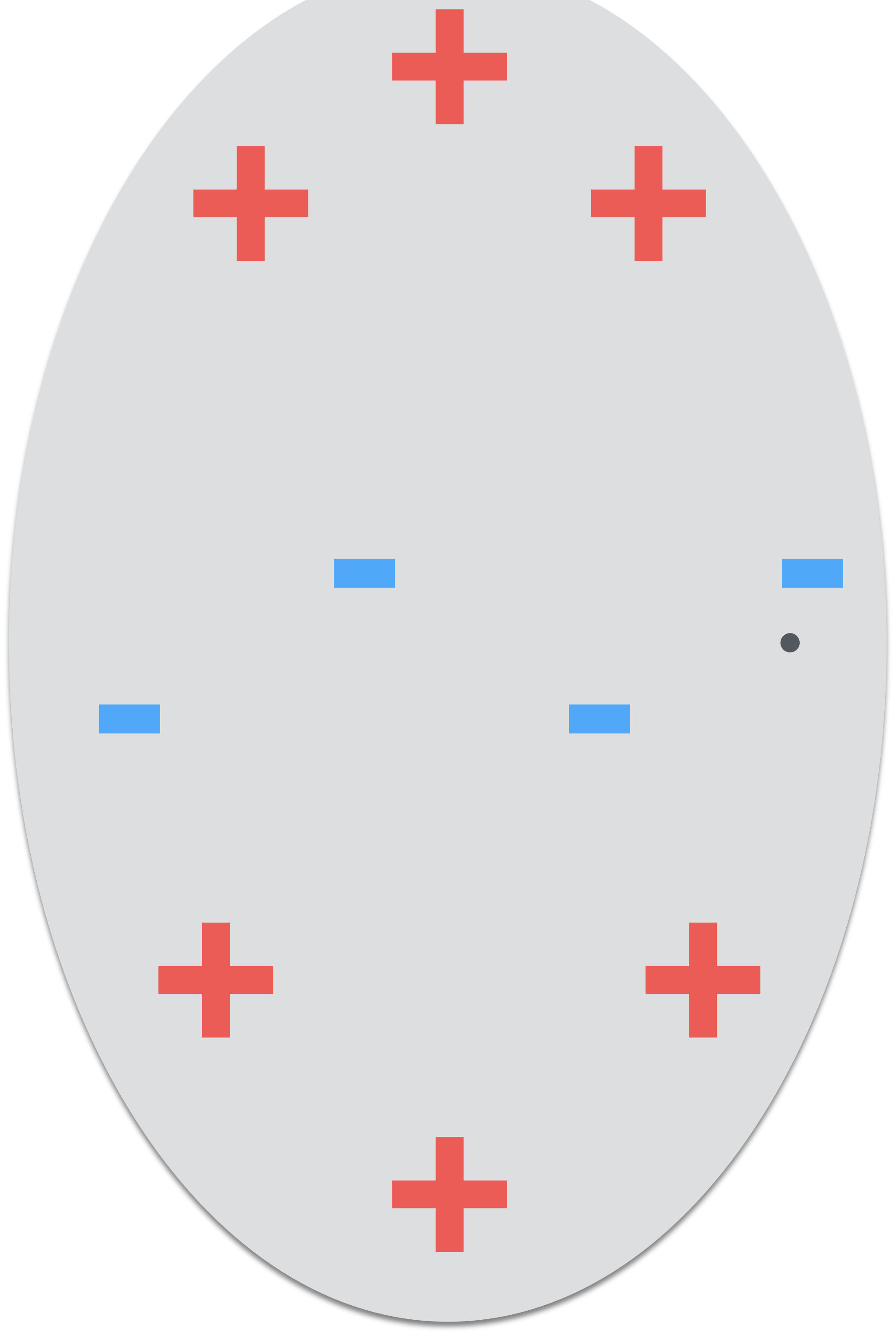
Anomalous chiral effects

Chiral magnetic effect (CME)	$J_V = \mu_A B$	Out-of-plane electric dipole moment
Chiral separation effect (CSE)	$J_A = \mu_V B$	/
Chiral electric separation effect (CESE)	$J_A = \sigma\,(eE)$	In-plane electric dipole moment
Chiral vortical effect (CVE)	$J = \mu_5\,\omega$	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?

CME and CMW

How can we experimentally detect such kind of charge separations?

A needle in a haystack

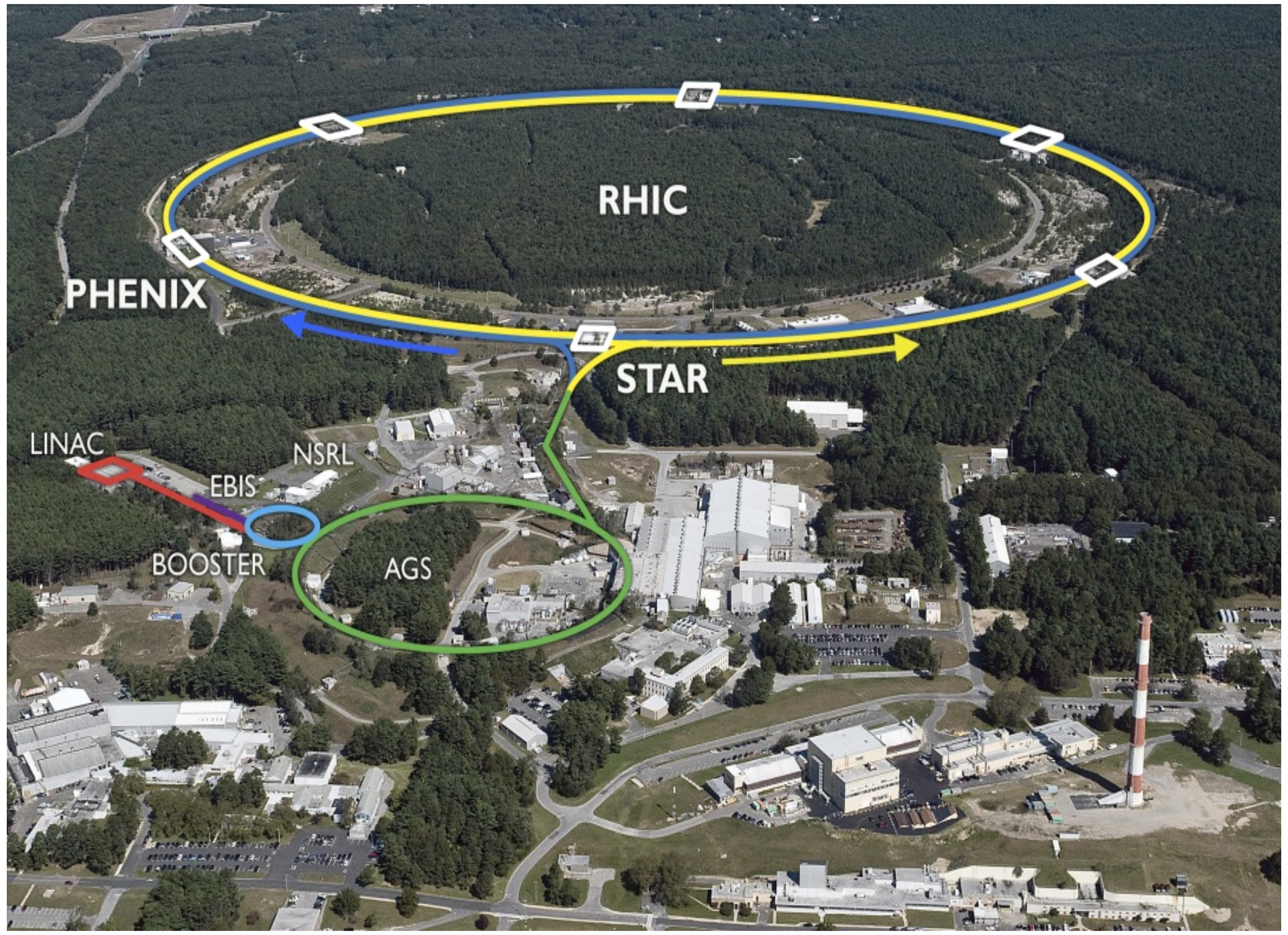
Signal and background in experiments

Ideal

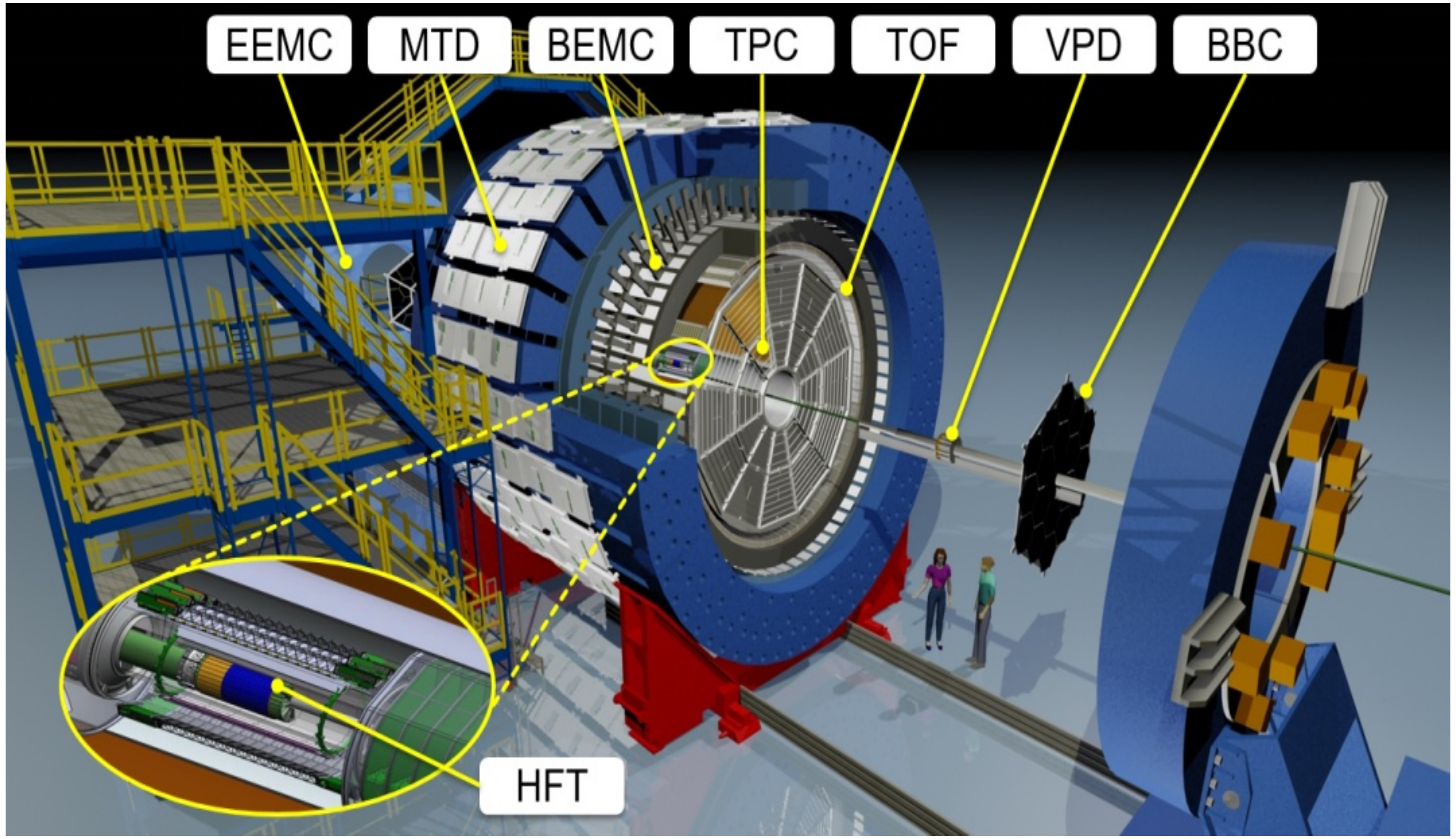
Reality

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

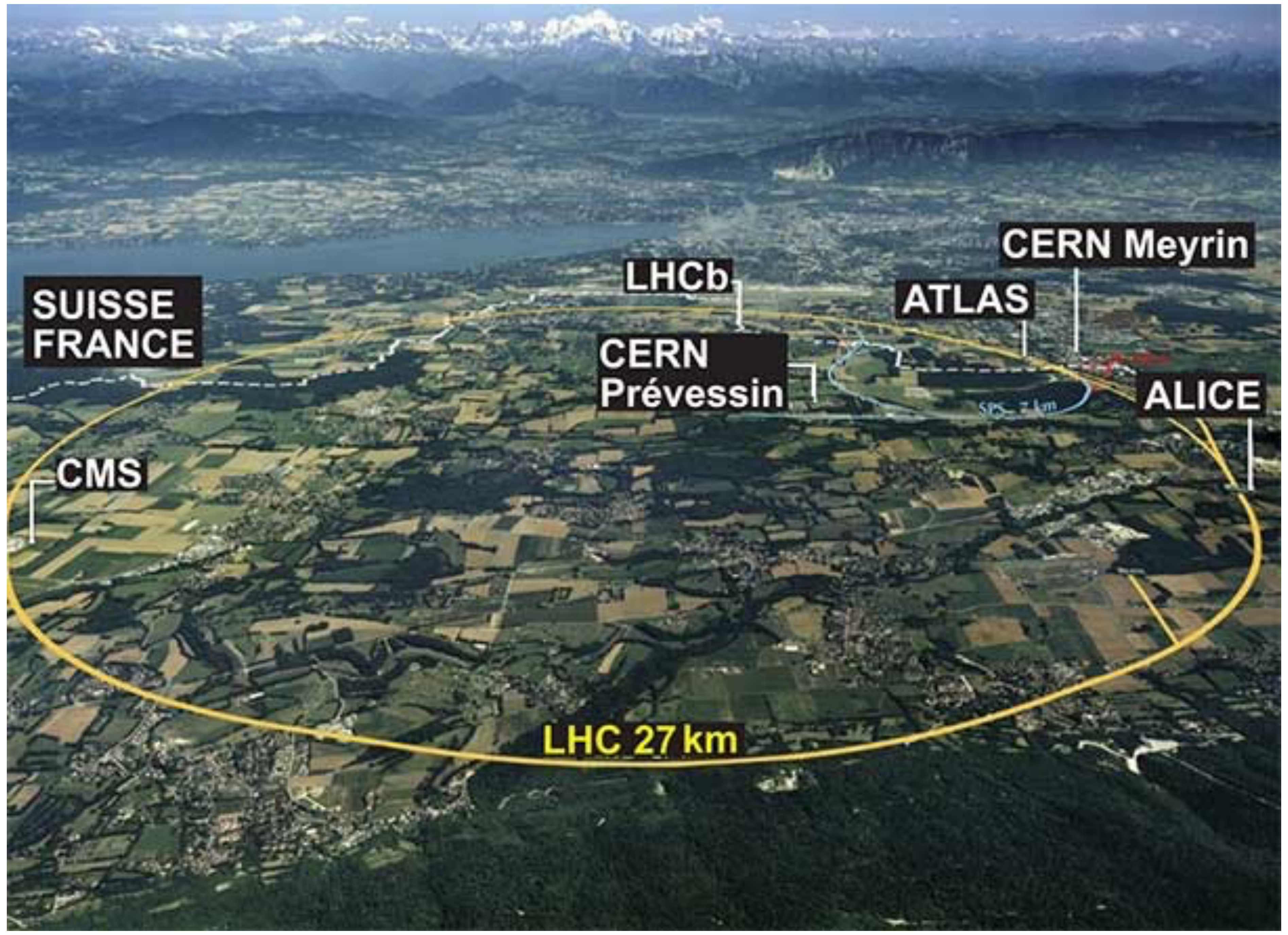
Solenoidal Tracker at RHIC



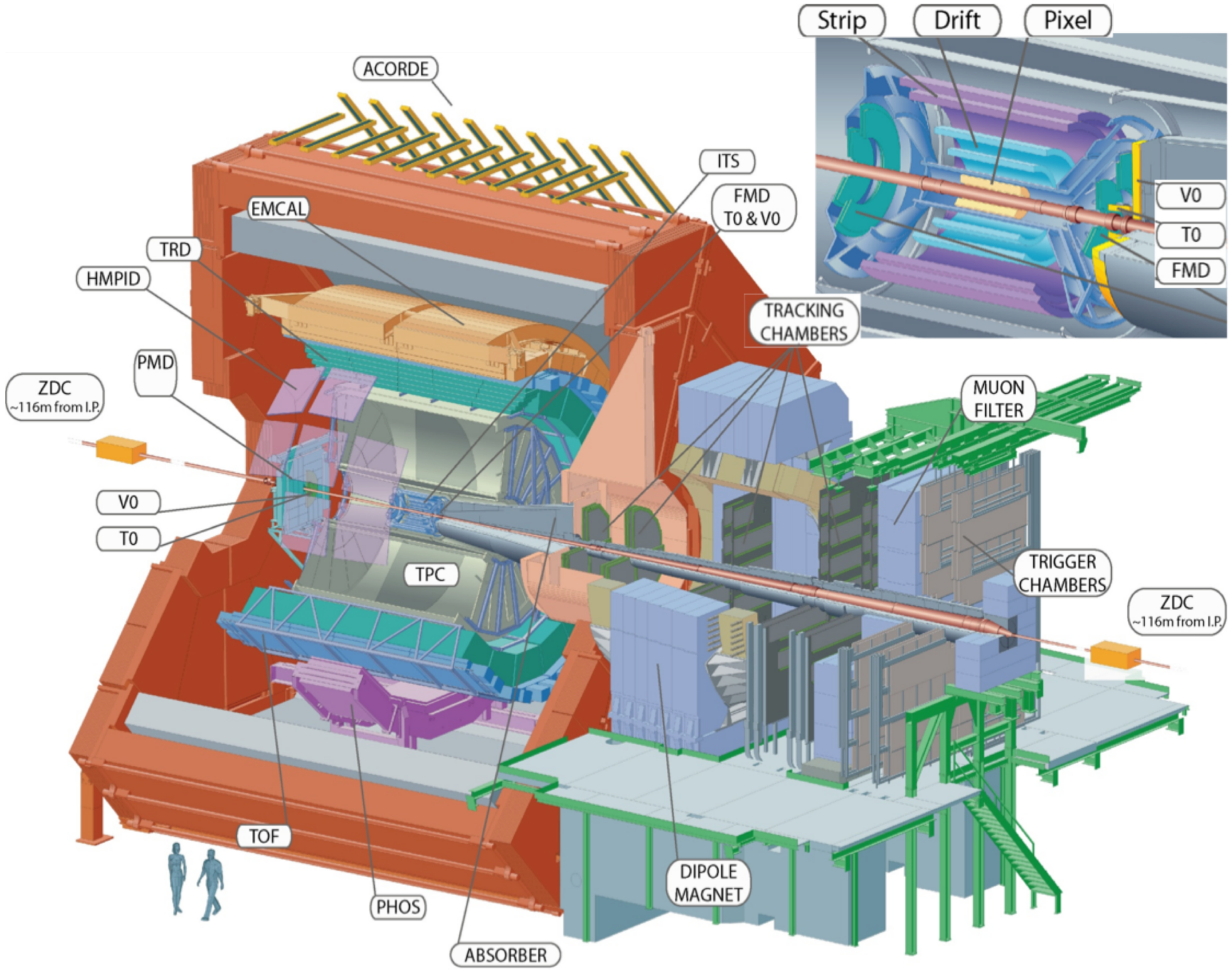
14 countries, 65 institutes, 668 members



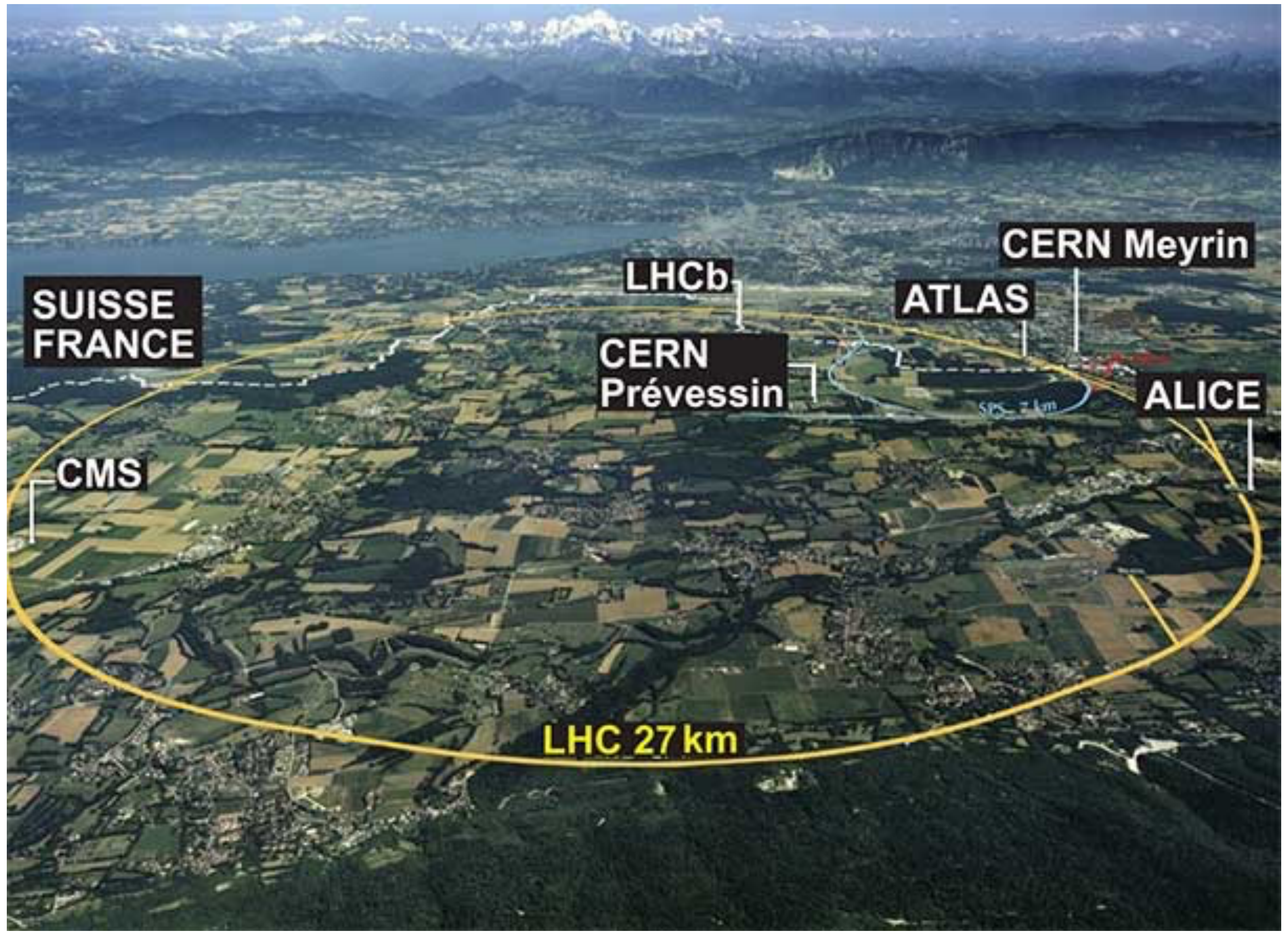
A Large Ion Collider Experiment



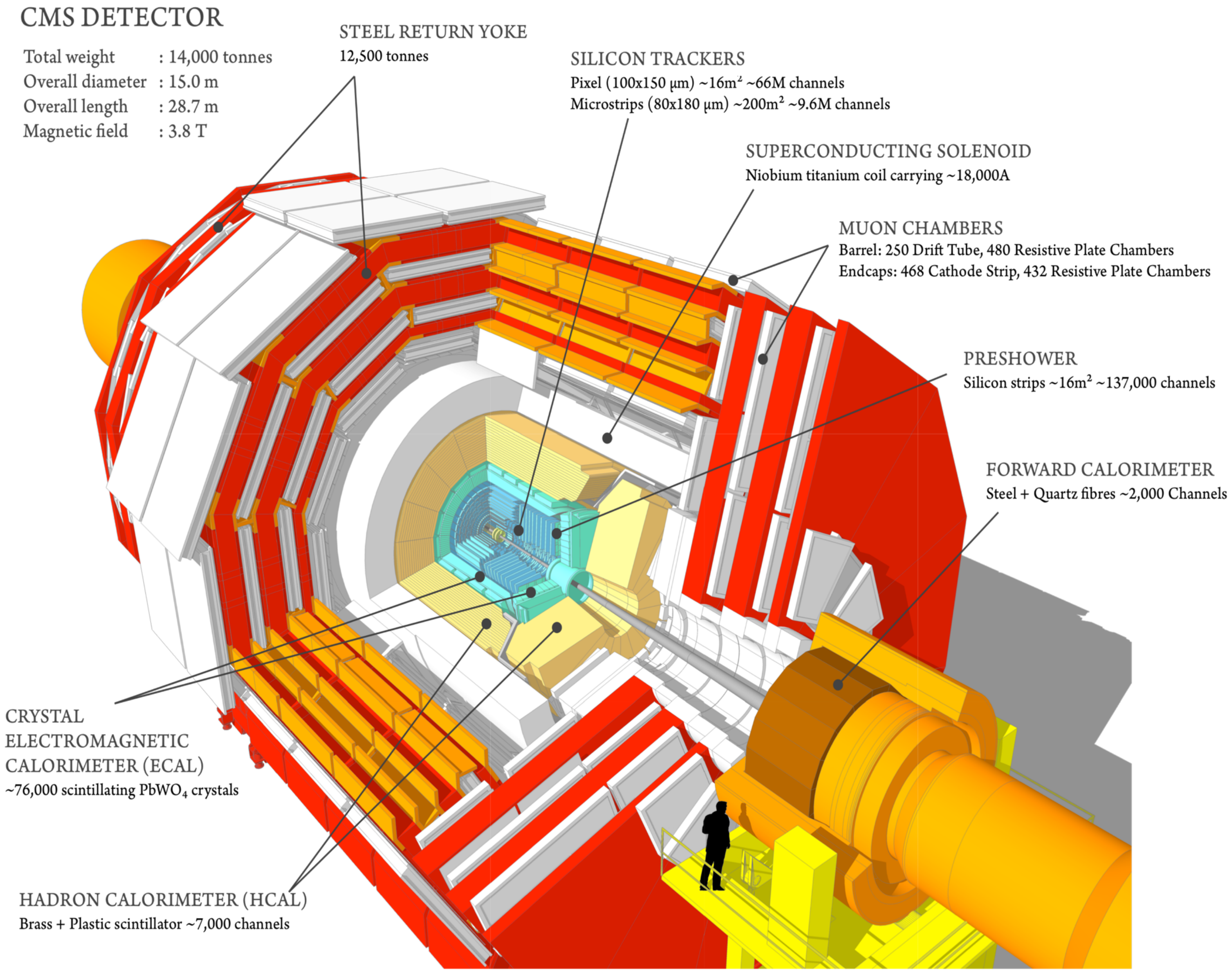
40 countries, 172 institutes, 2030 members



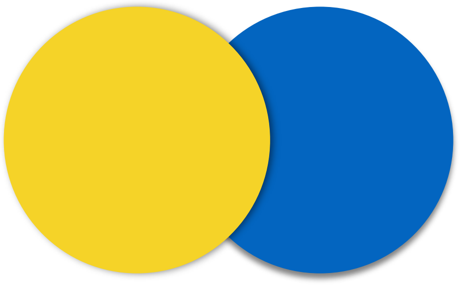
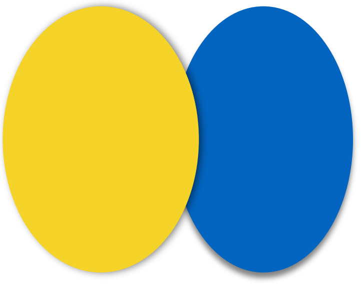
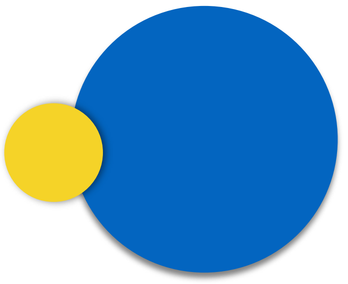
Compact Muon Solenoid



45 countries, 198 institutes, 2100 members

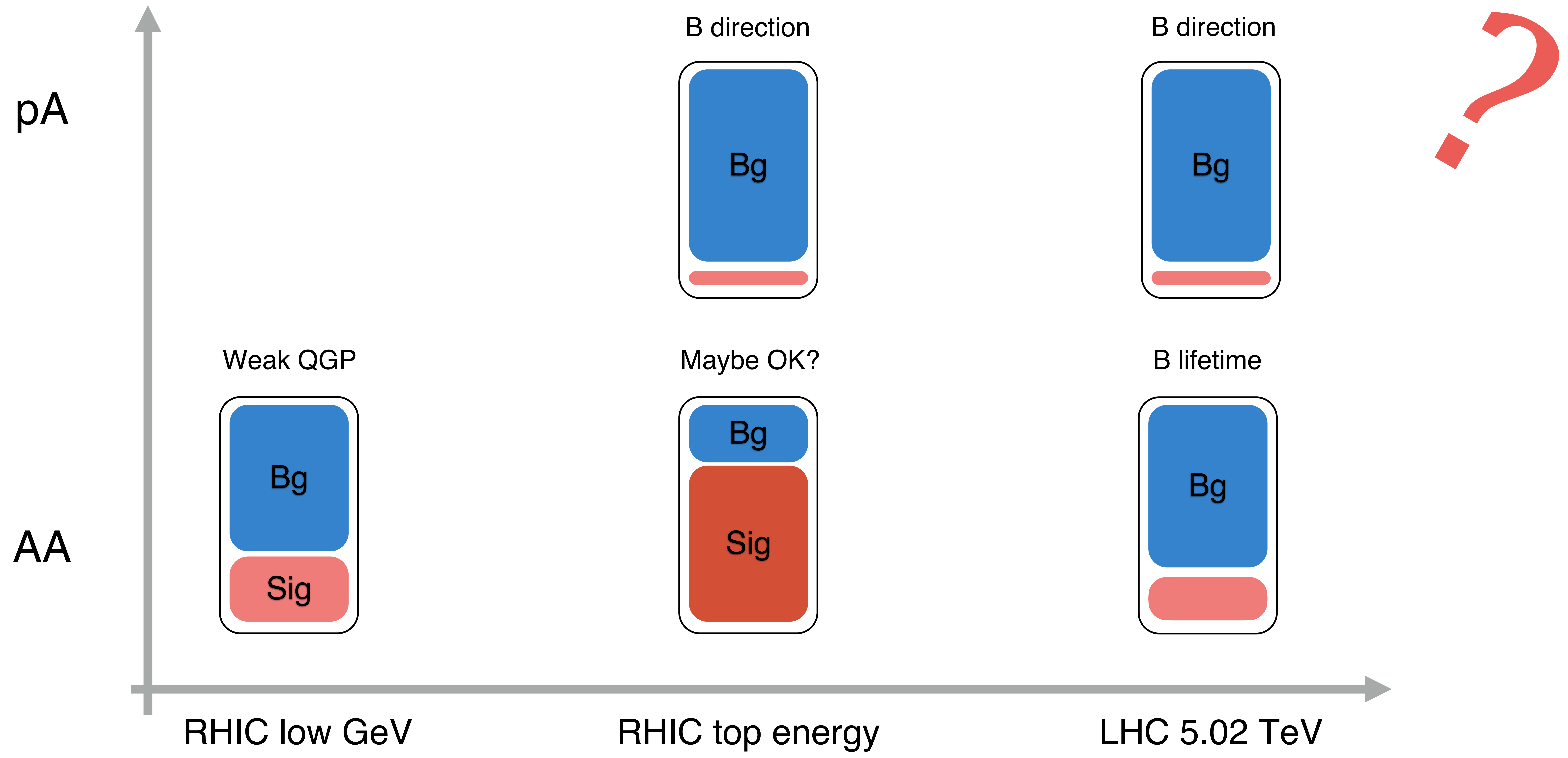


Experimental setup

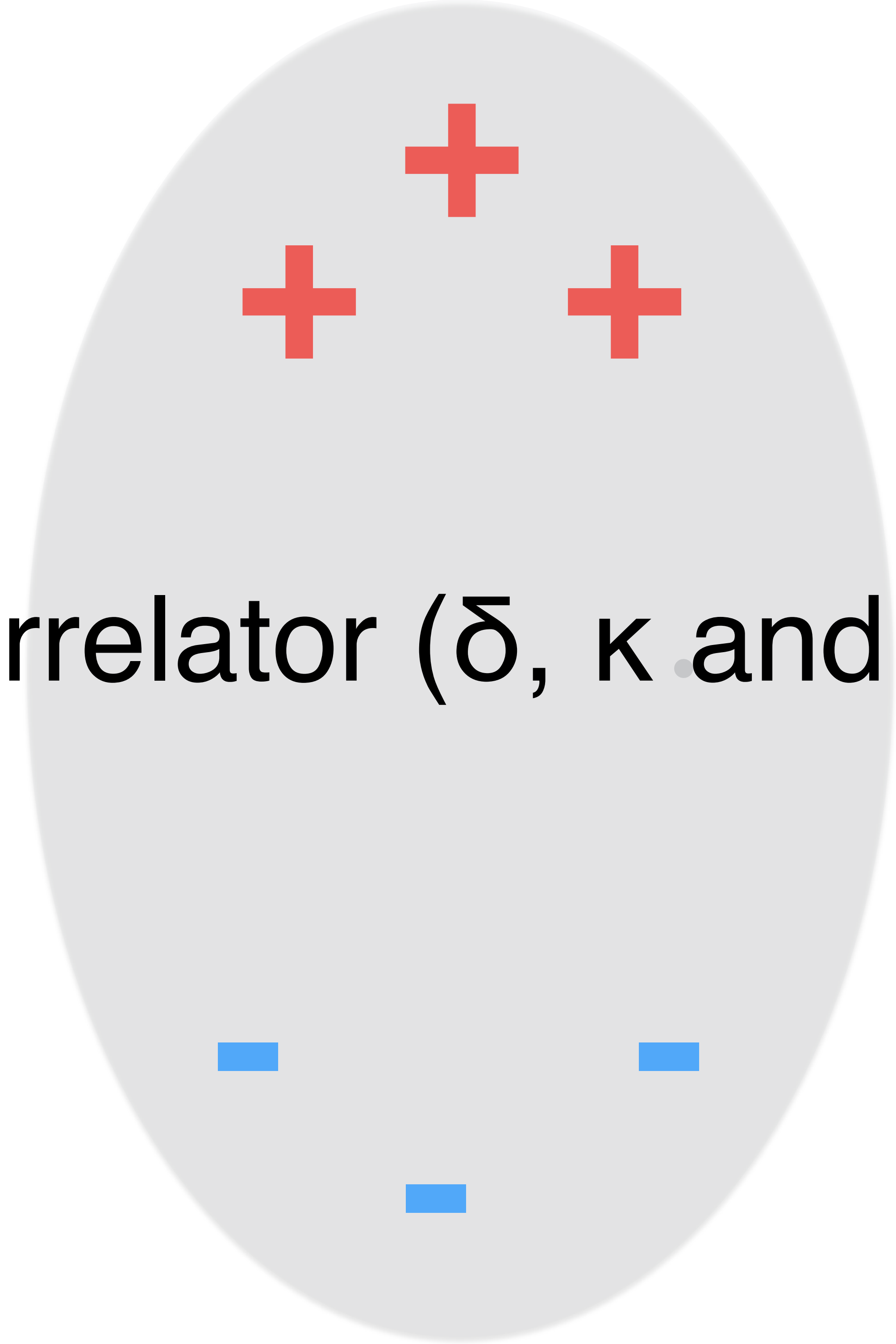
	LHC	RHIC
	Pb-Pb 2.76 TeV Pb-Pb 5.02 TeV	Au+Au BES (7-62 GeV) Au+Au 200 GeV Cu+Cu Isobar (Zr+Zr)
	Xe-Xe 5.44 TeV	U+U 192 GeV Isobar (Ru+Ru)
	pPb 5.02 TeV pPb 8.16 TeV	p(d)+Au 200 GeV Cu+Au

With inclusive and identified particles at varied kinematic windows

Intuitive expectation

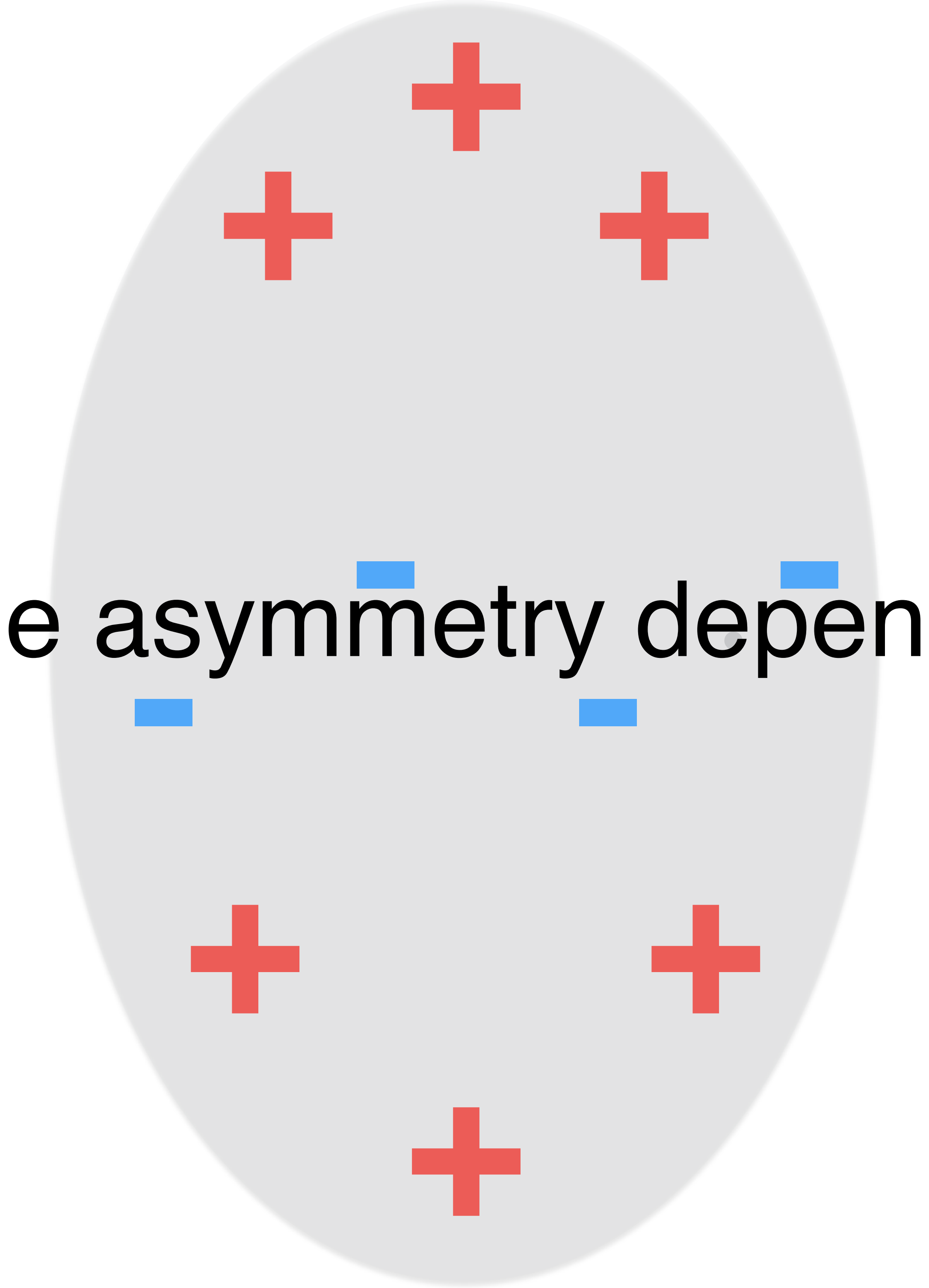


CME and CMW



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

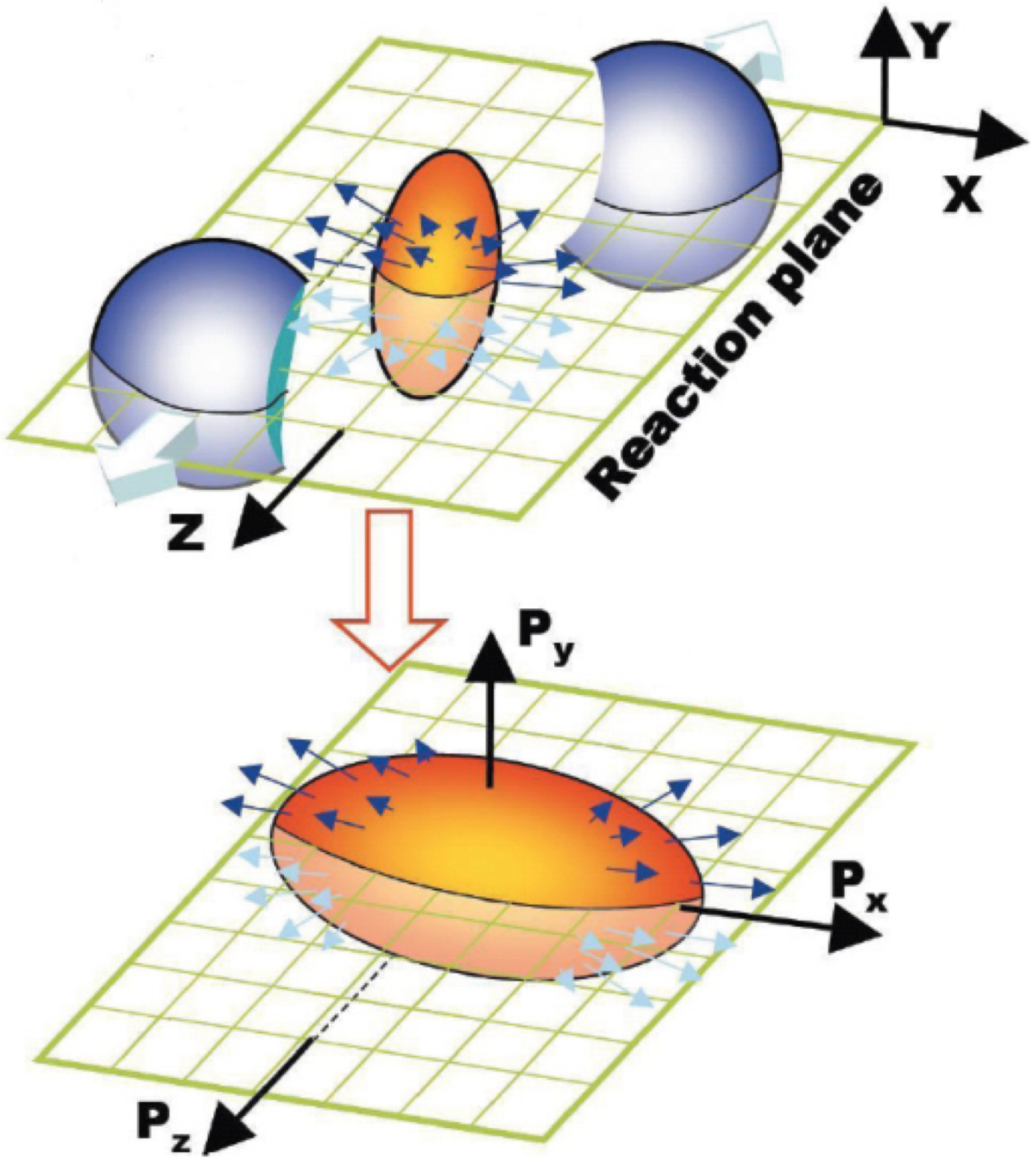
Prerequisite: anisotropic flow

Key property of QGP

- Anisotropy in initial-state coordinate space
- Anisotropy in final-state momentum space
- Azimuthal correlations of final state particles

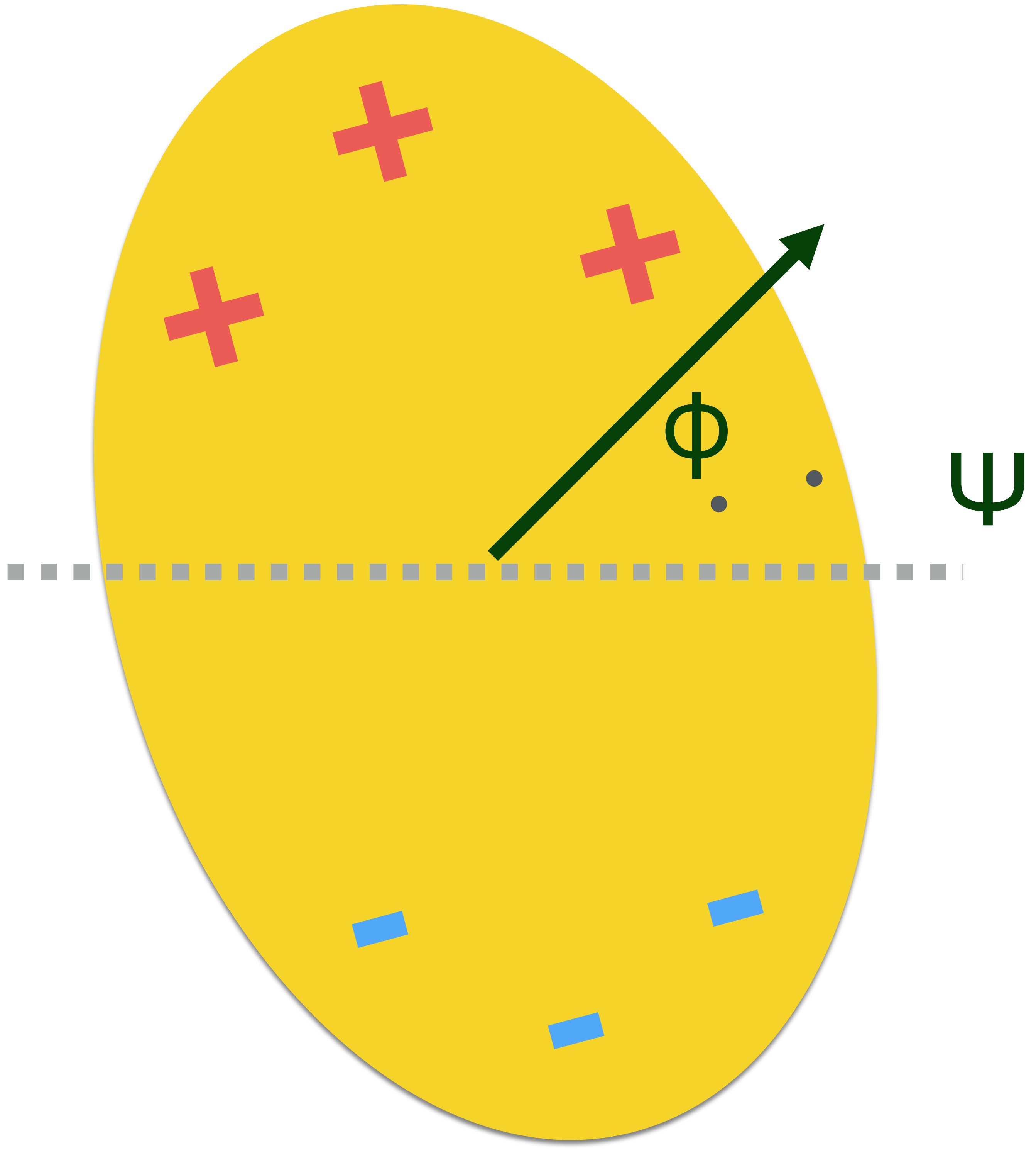
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right)$$

$$v_n(p_t, y) = \langle \cos[n(\varphi - \Psi_{RP})] \rangle$$



Search for the Chiral Magnetic Effect

Measurement of CME with γ correlator



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

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

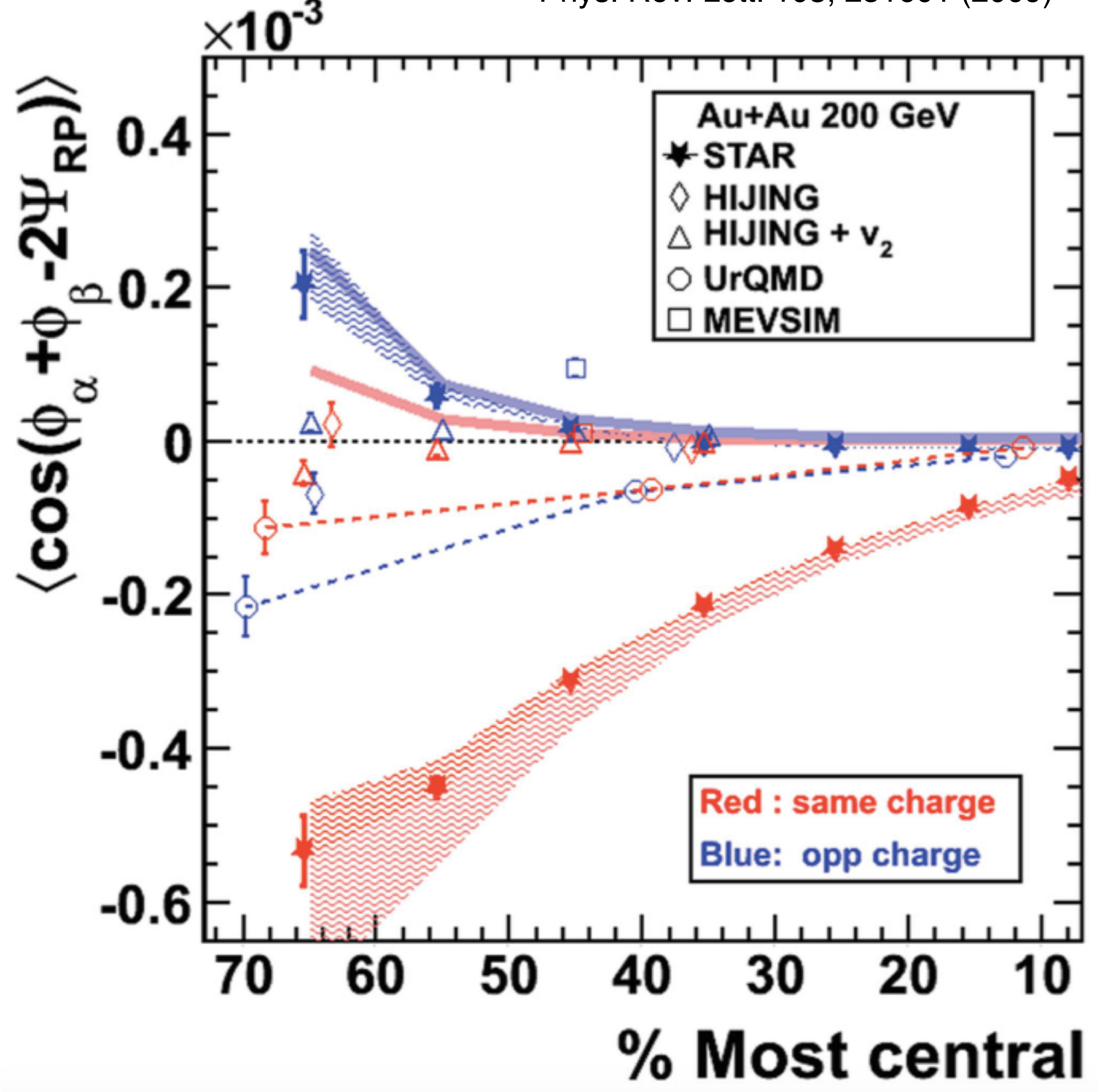
Sensitive to CME

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

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

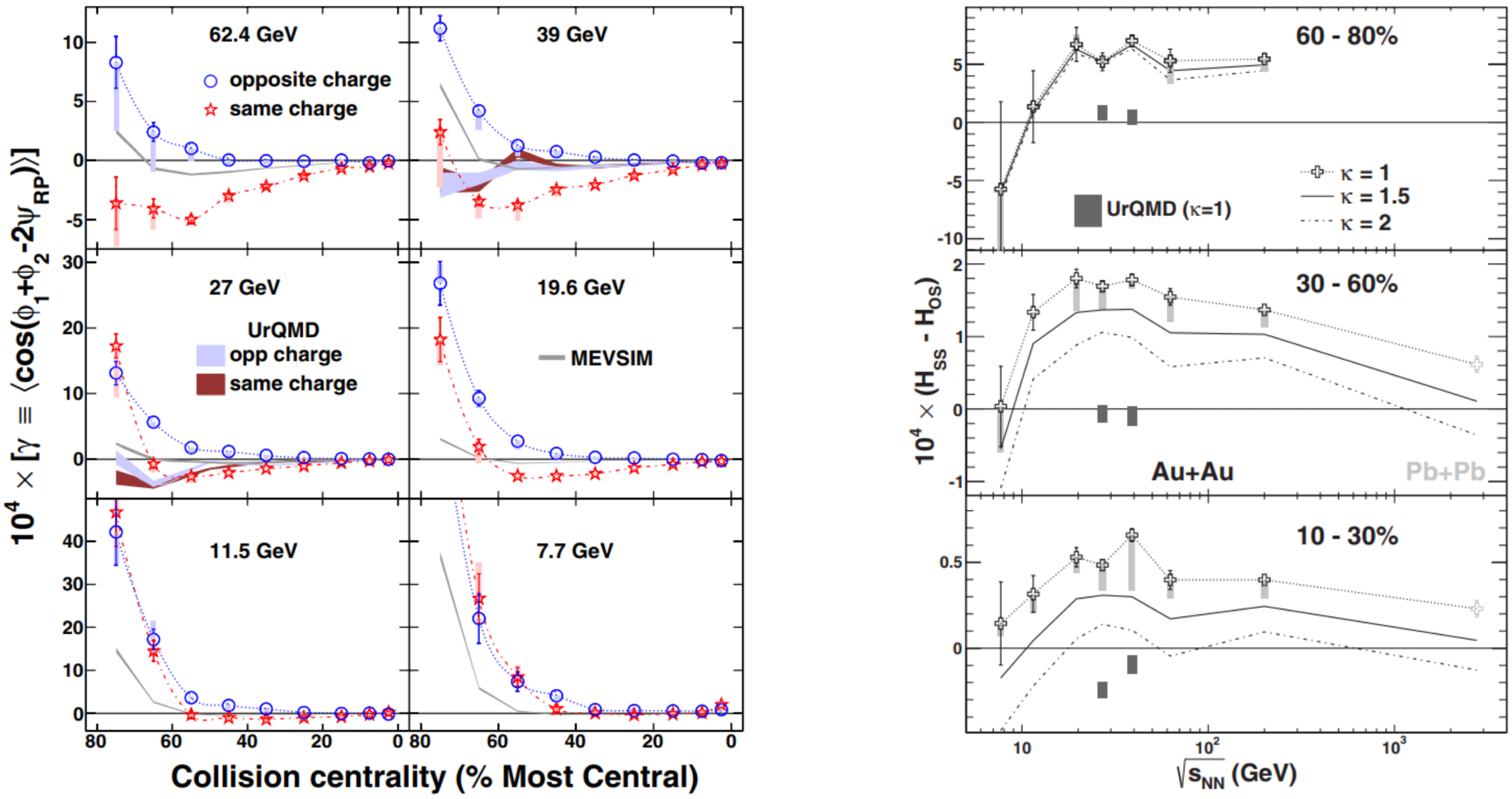
γ_{112} at RHIC

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



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

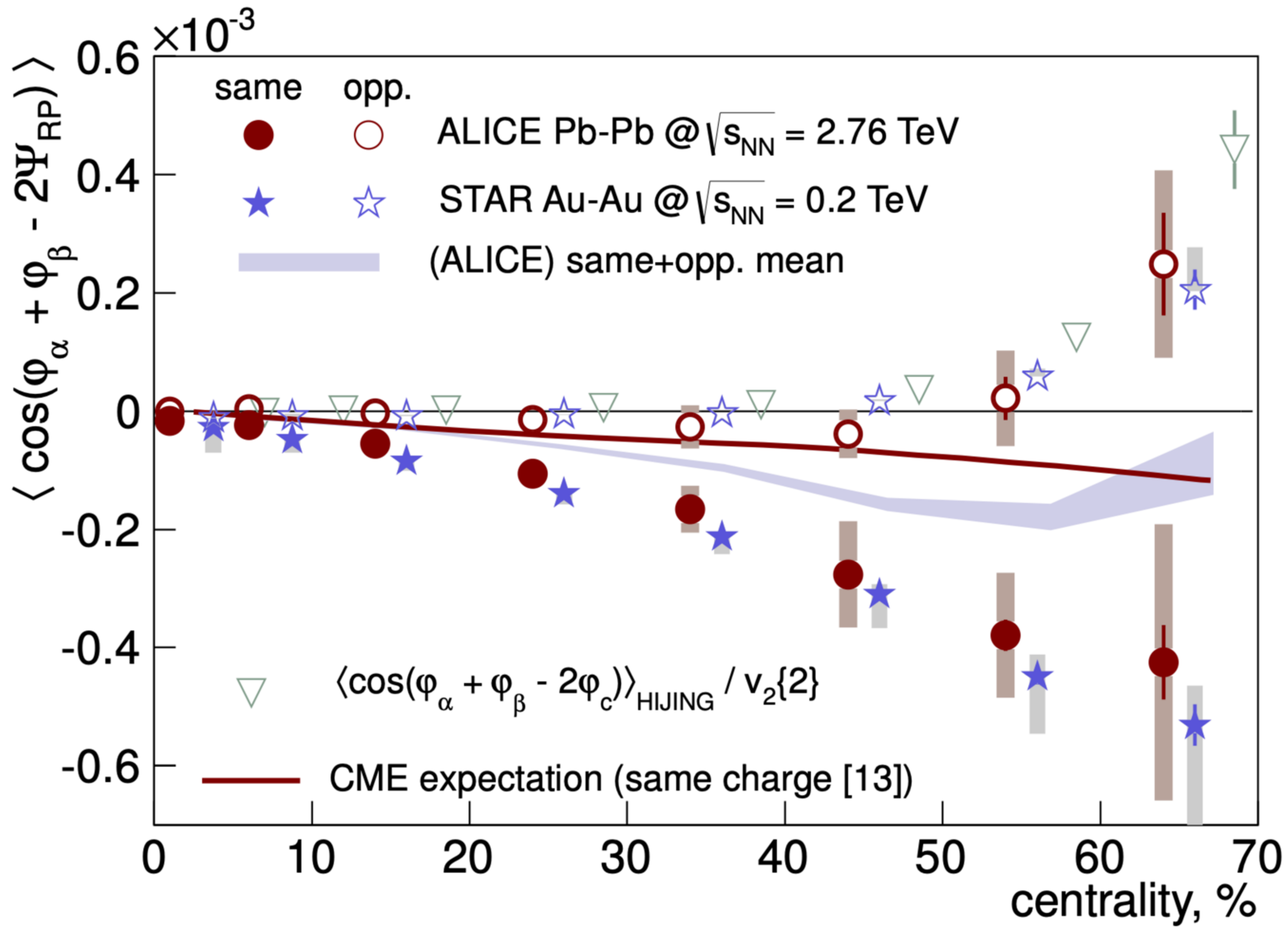
Phys. Rev. Lett. 113, 052302 (2014)

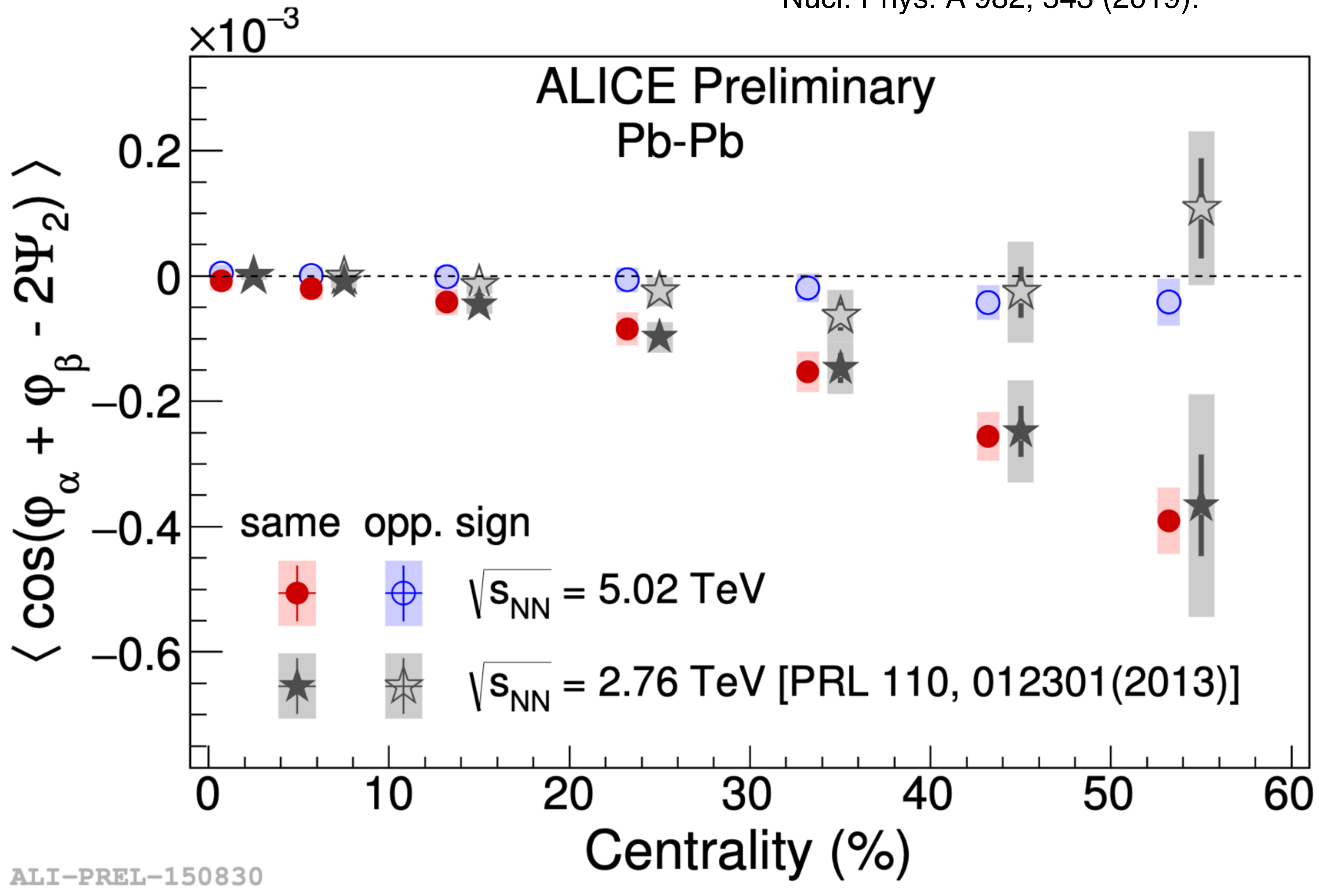


Strong collision energy dependence at RHIC BES

γ_{112} at LHC

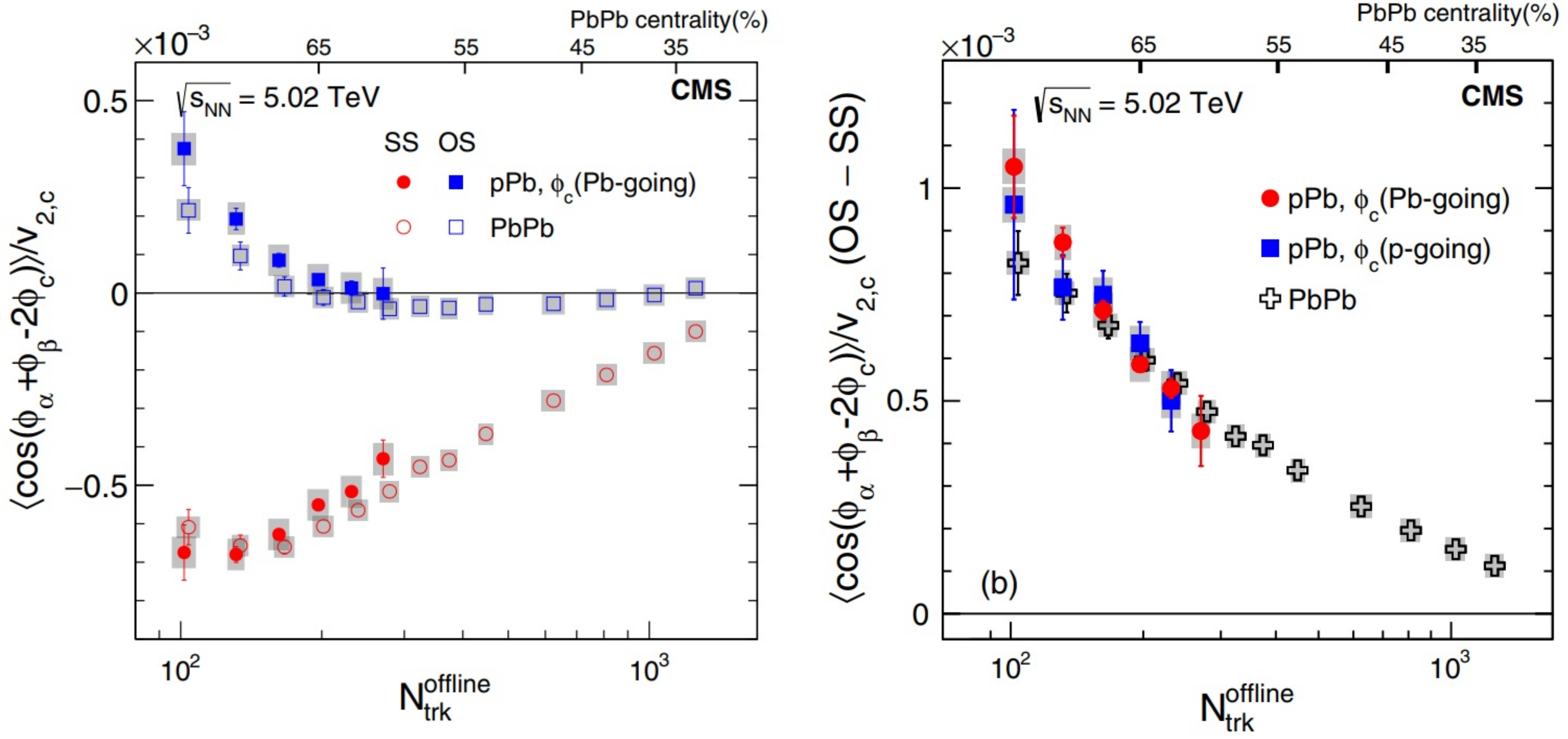
Phys. Rev. Lett. 110, 012301 (2013).
Nucl. Phys. A 982, 543 (2019).





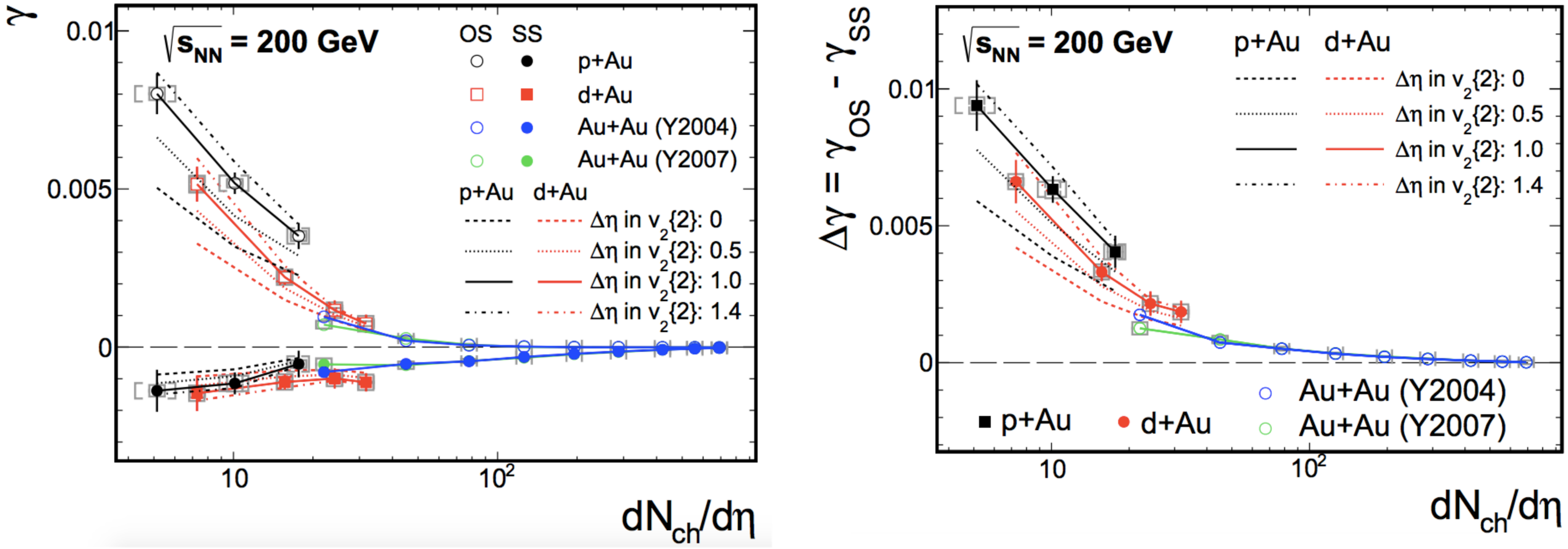
- Little or no difference for γ_{112} between 0.2, 2.76 and 5.02 TeV collisions
- Stronger centrality dependence of SS than that of OS

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

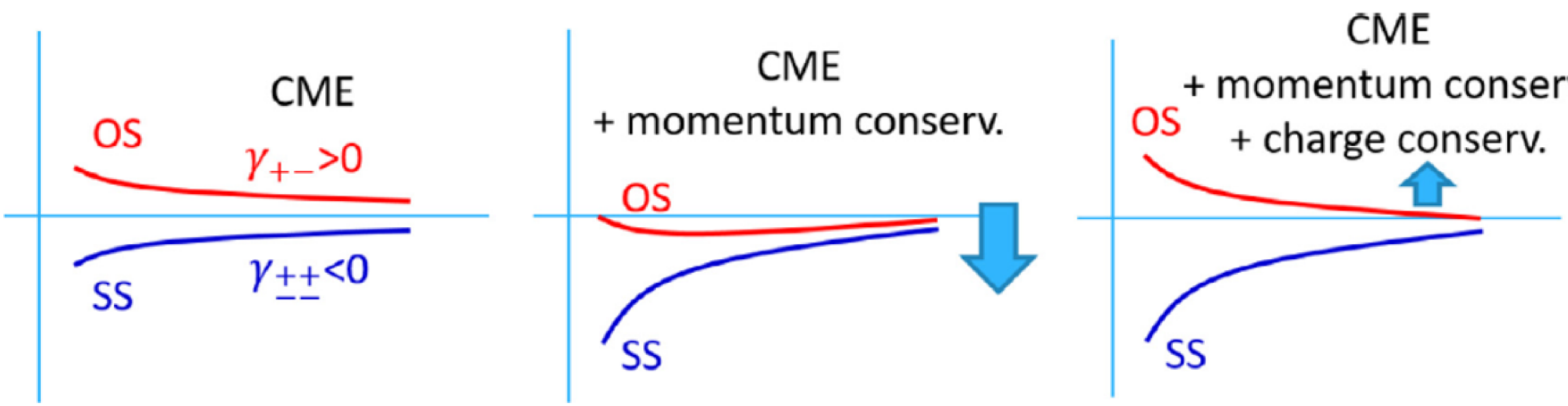


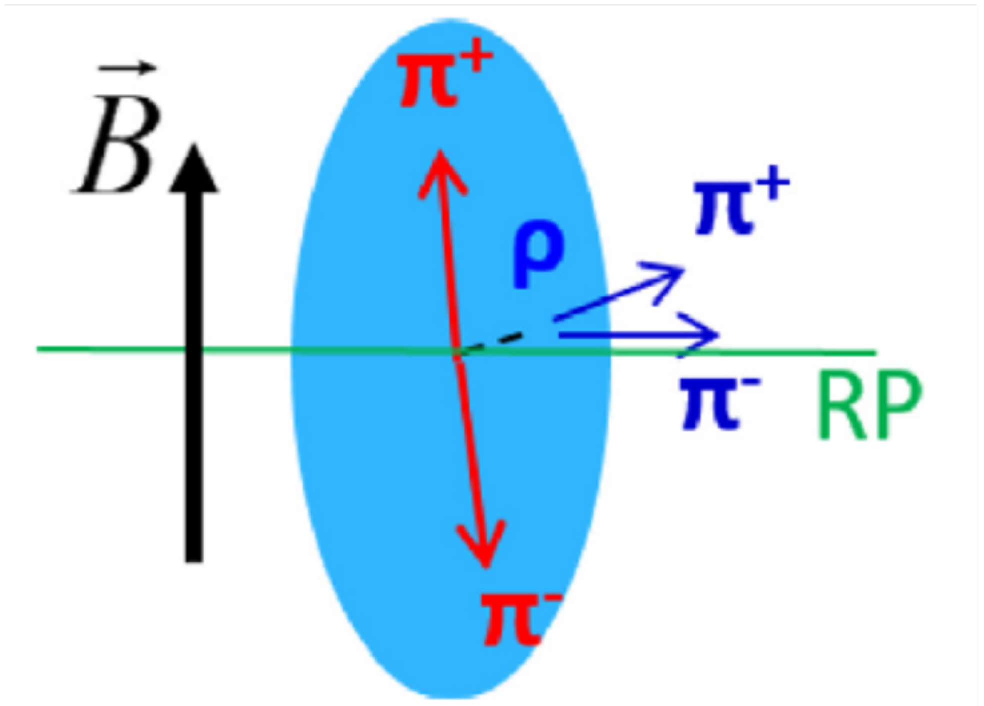
- Agreement between pPb and Pb-Pb results
- A common underlying mechanism that generates the observed γ_{112}

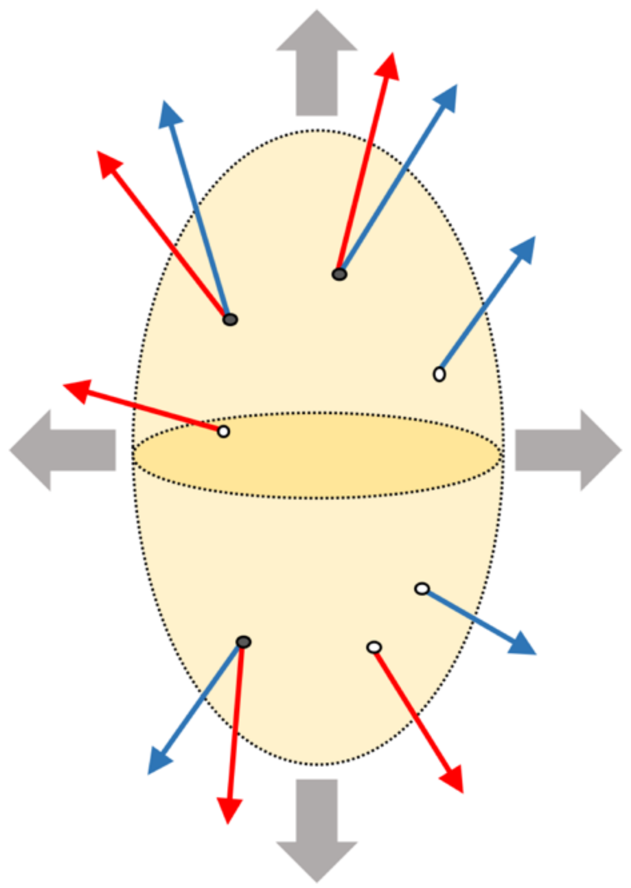
Study of the background: what are they and how large?

Transverse momentum conservation

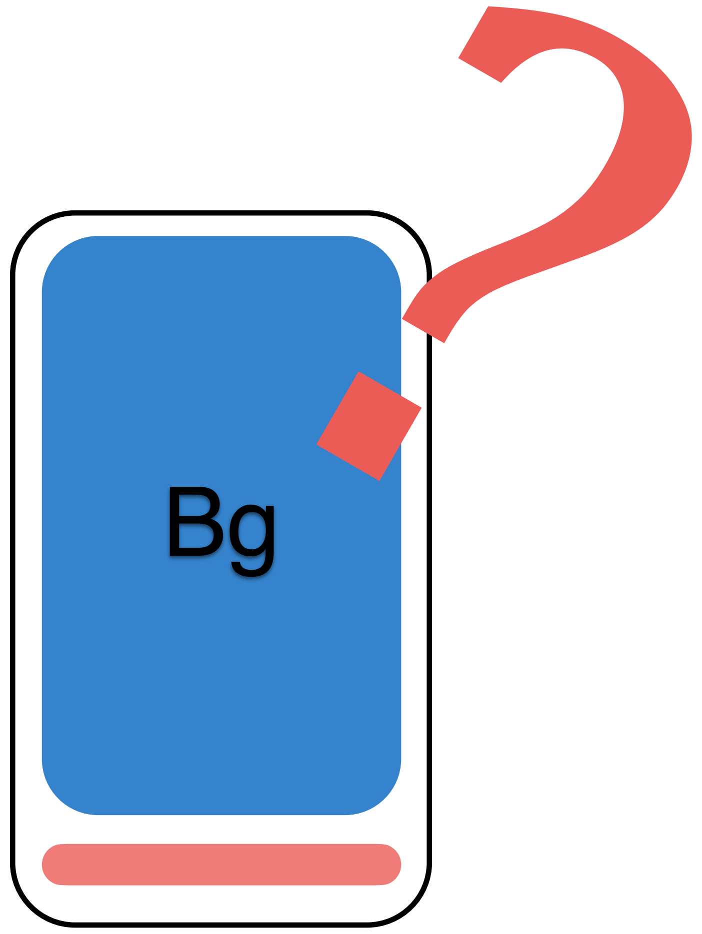
Local charge conservation





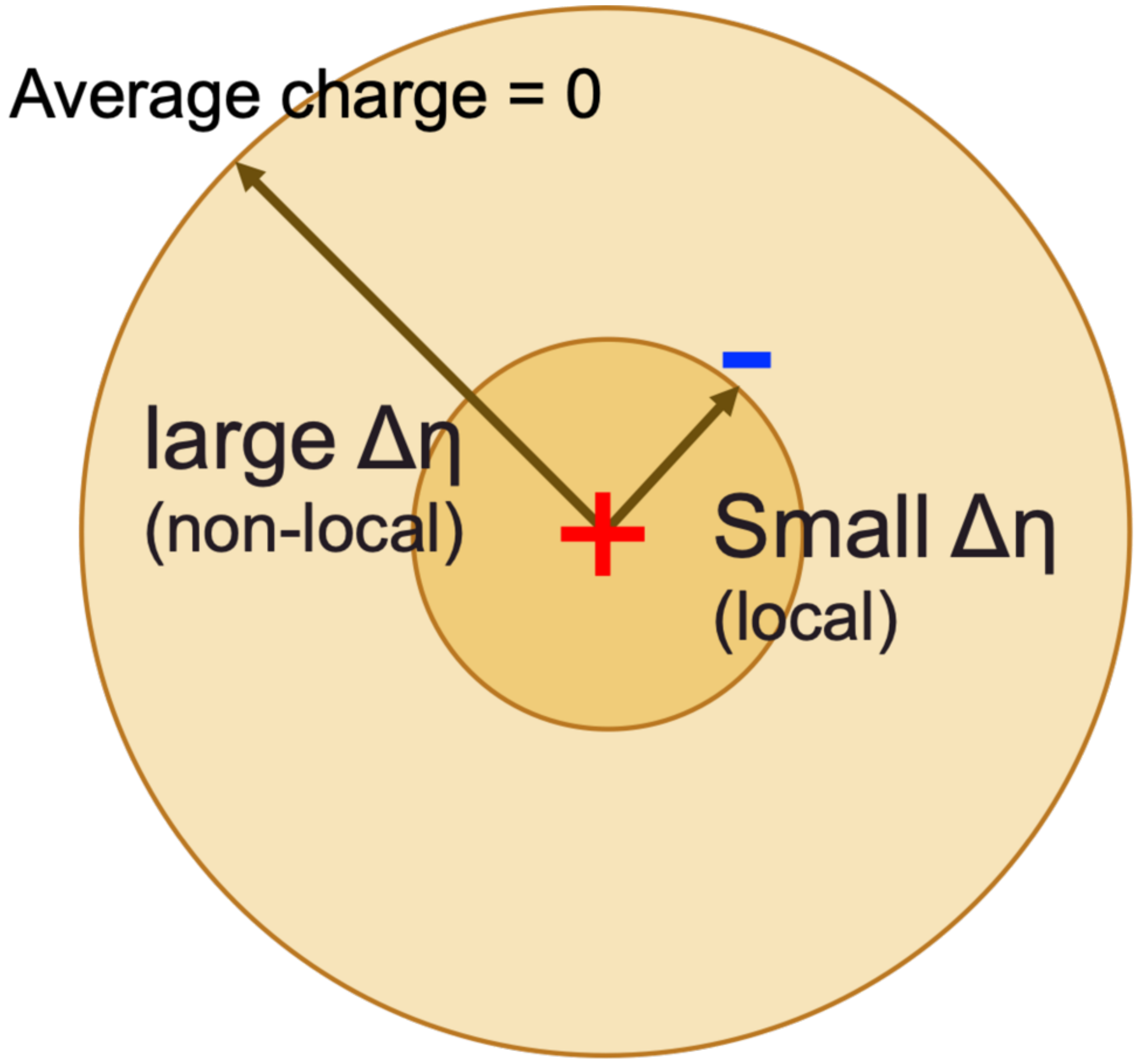


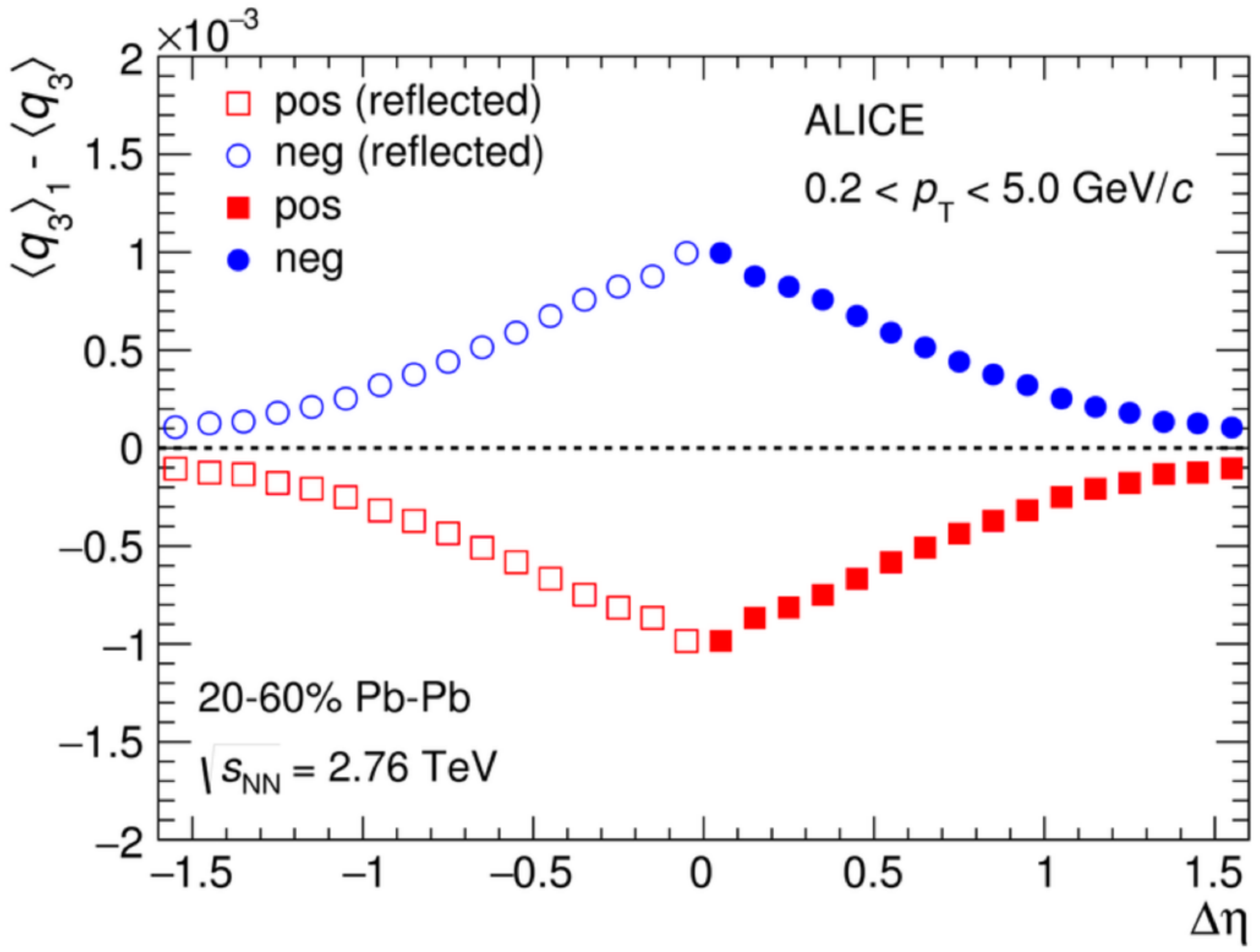
LCC + flow

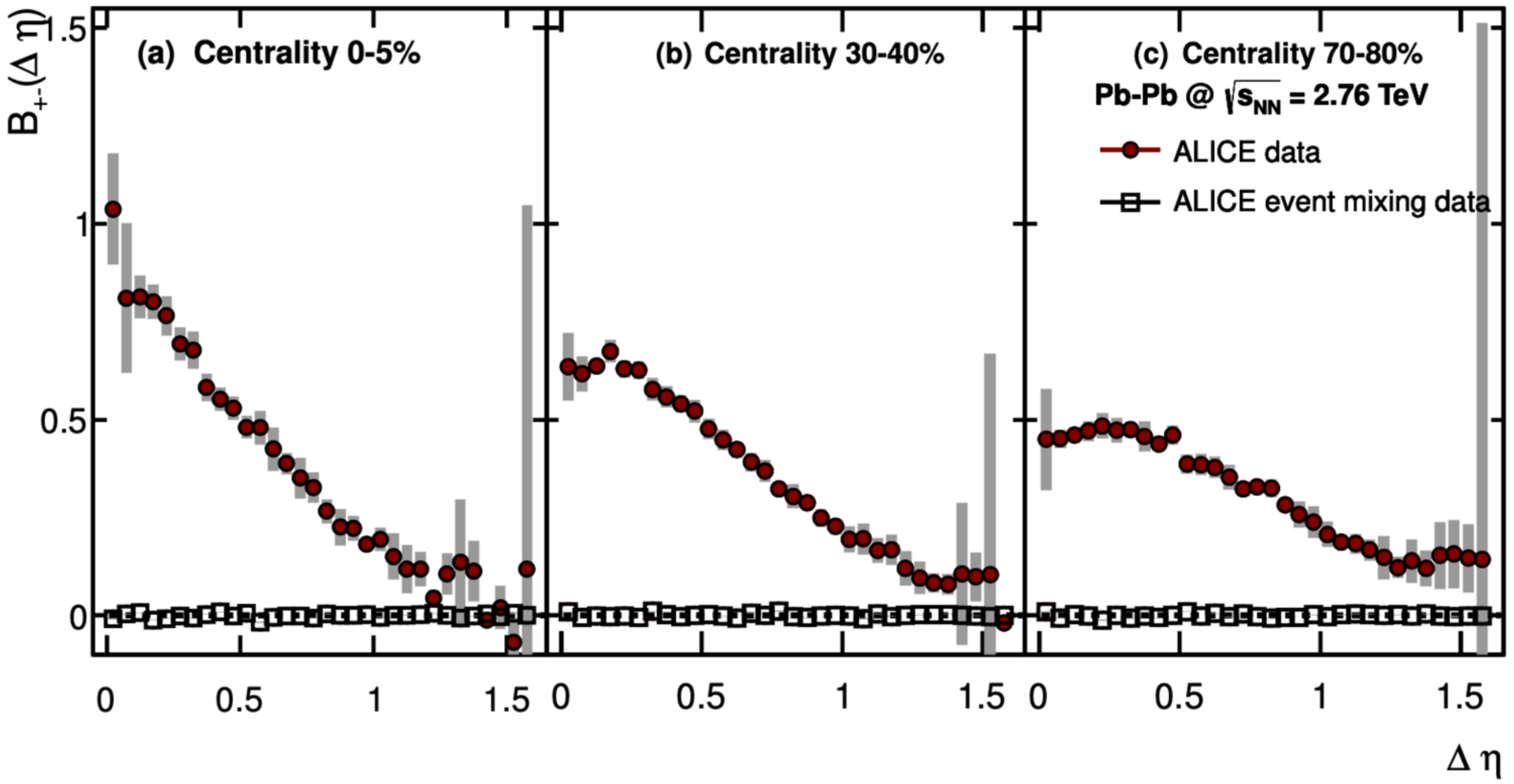


Study of the background: Local Charge Conservation

Local charge conservation: charges are locally balanced
The source can be either primordial or secondary (resonance decay)
Example :







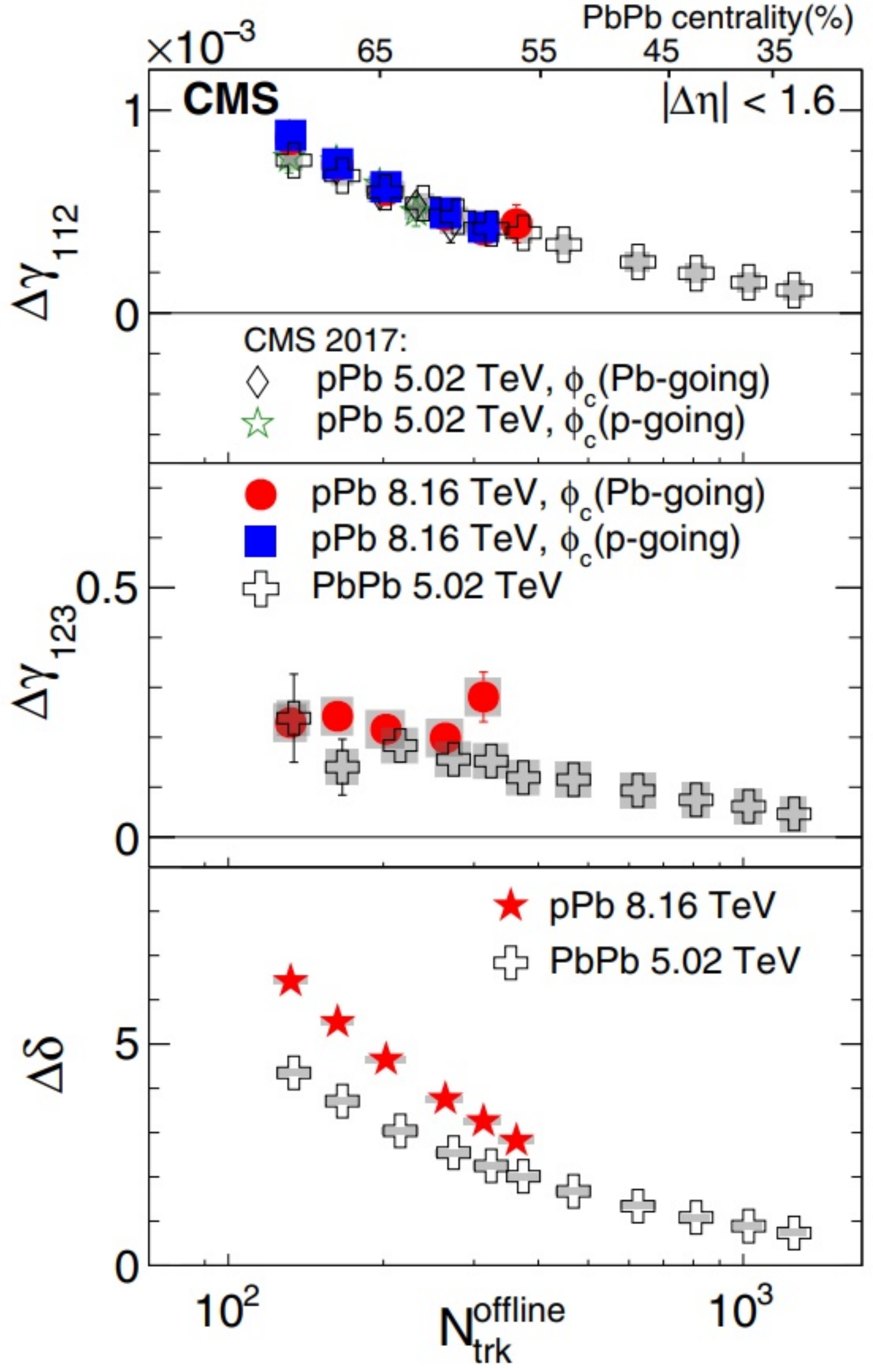
In the CME/CMW studies, flow serves as a carrier, conveying the initial charge separation (sig or bg) to the final state.

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

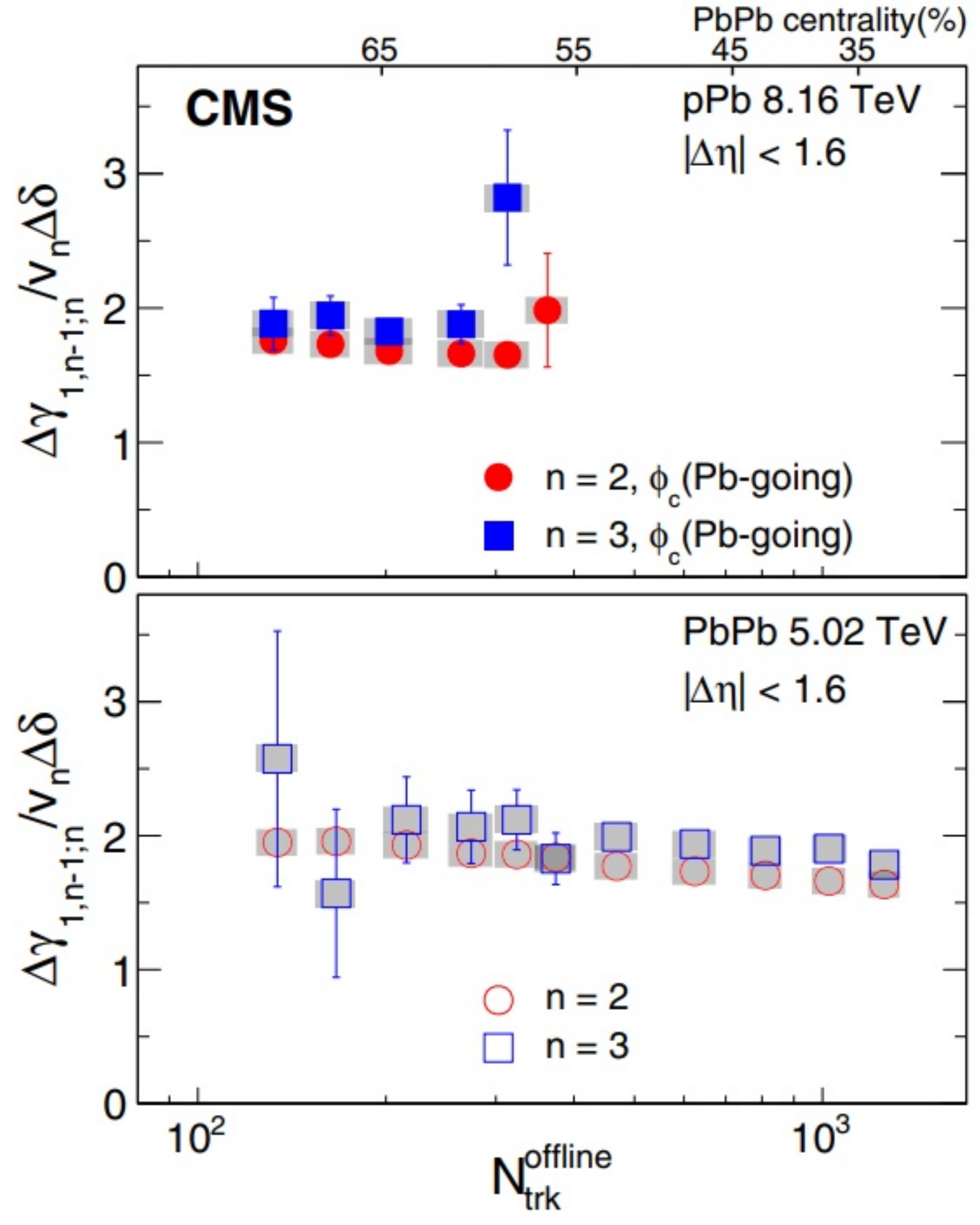
$$\gamma_{123} \equiv \langle \cos(\phi_\alpha + 2\phi_\beta - 3\Psi_3) \rangle$$
$$\gamma_{123}^{\text{bkg}} = \kappa_3 \langle \cos(\phi_\alpha - \phi_\beta) \rangle \langle \cos 3(\phi_\beta - \Psi_3) \rangle$$
$$= \kappa_3\, \delta\, v_3,$$

If pure background:

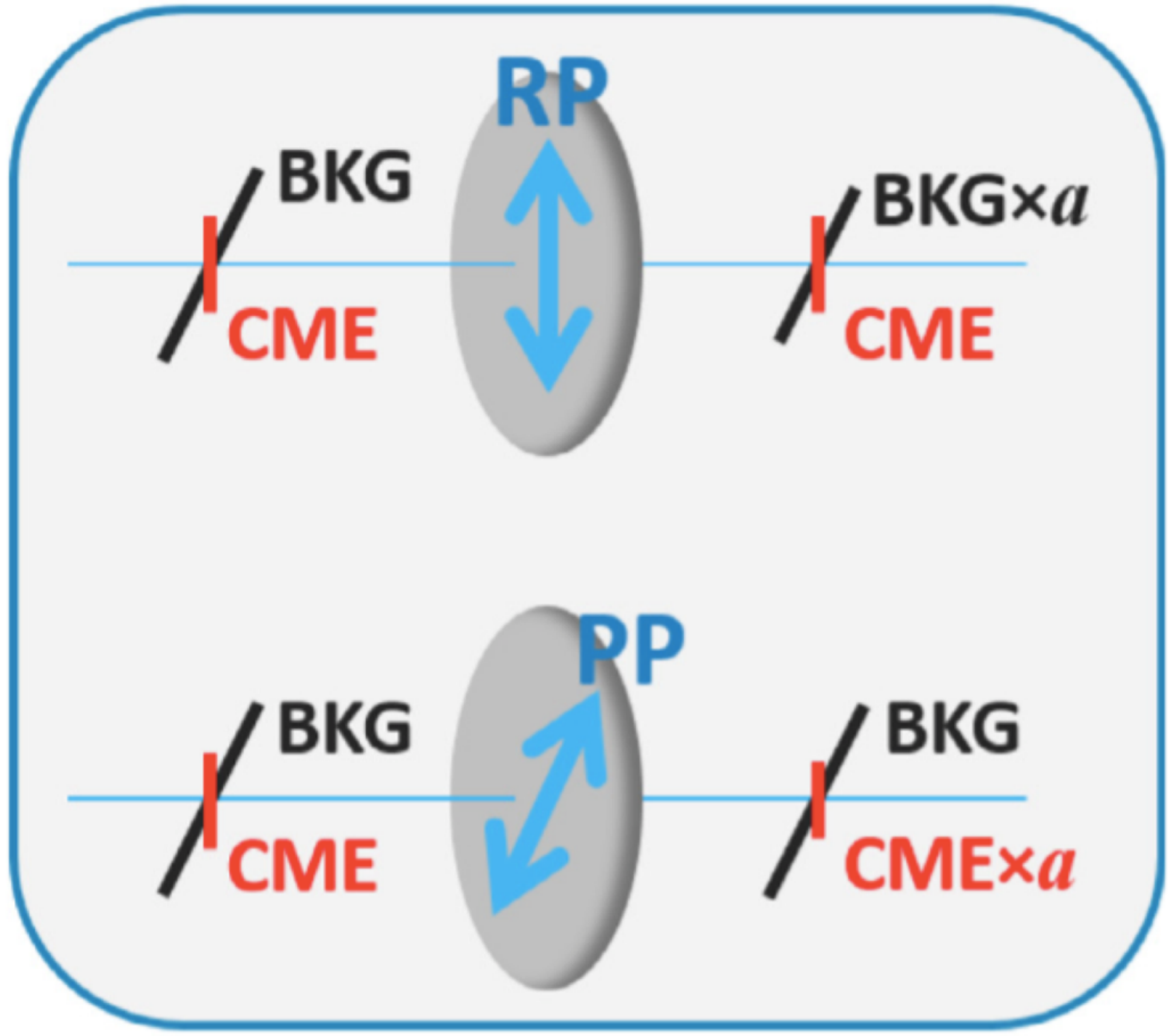
$$\frac{\Delta\gamma_{112}}{\Delta\delta\, v_2} \approx \frac{\Delta\gamma_{123}}{\Delta\delta\, v_3}$$



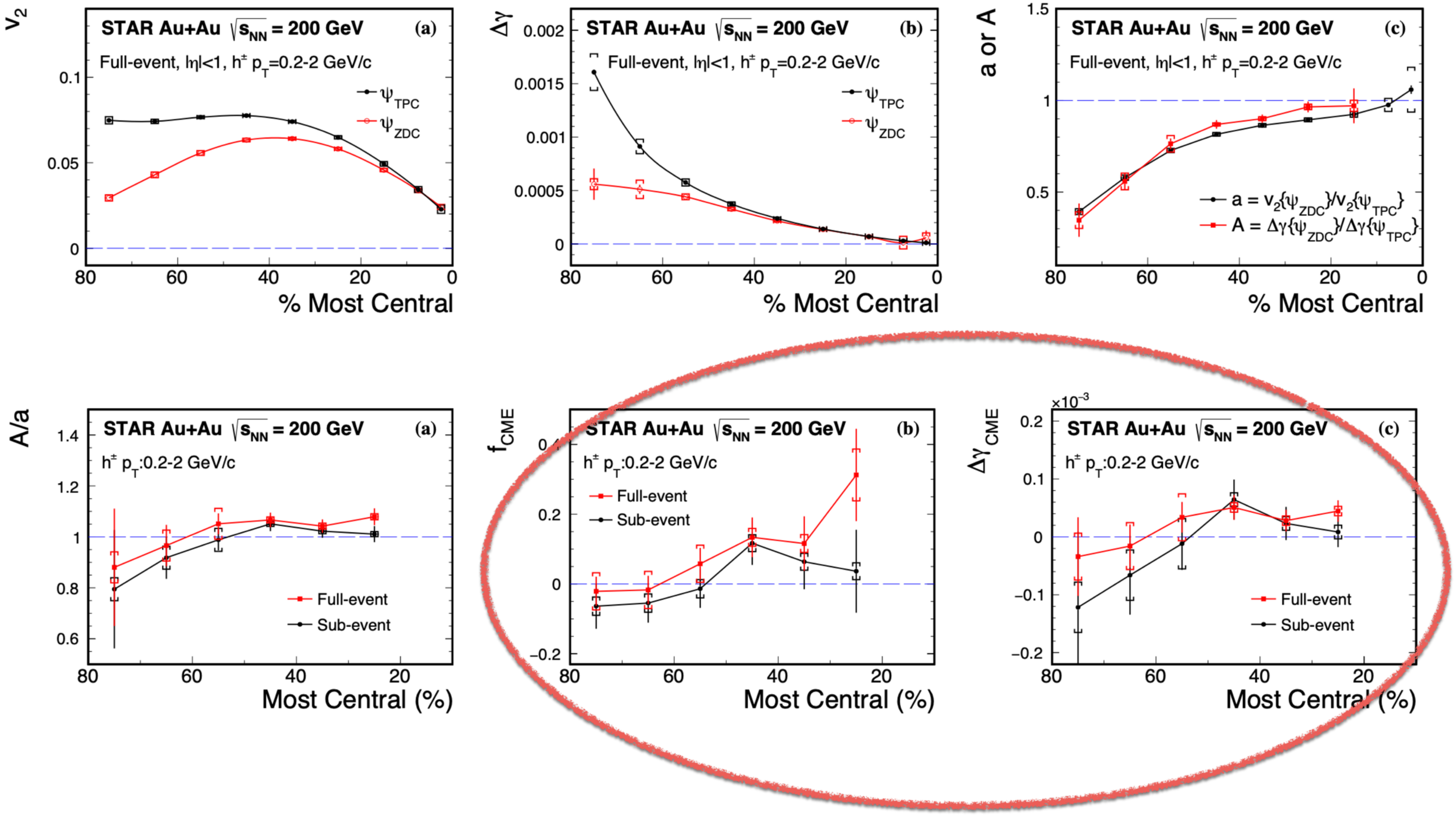
Phys. Rev. C. 97 (2018) 044912



Study of the background 2



Phys. Rev. Lett. 128, 092301 (2022).



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

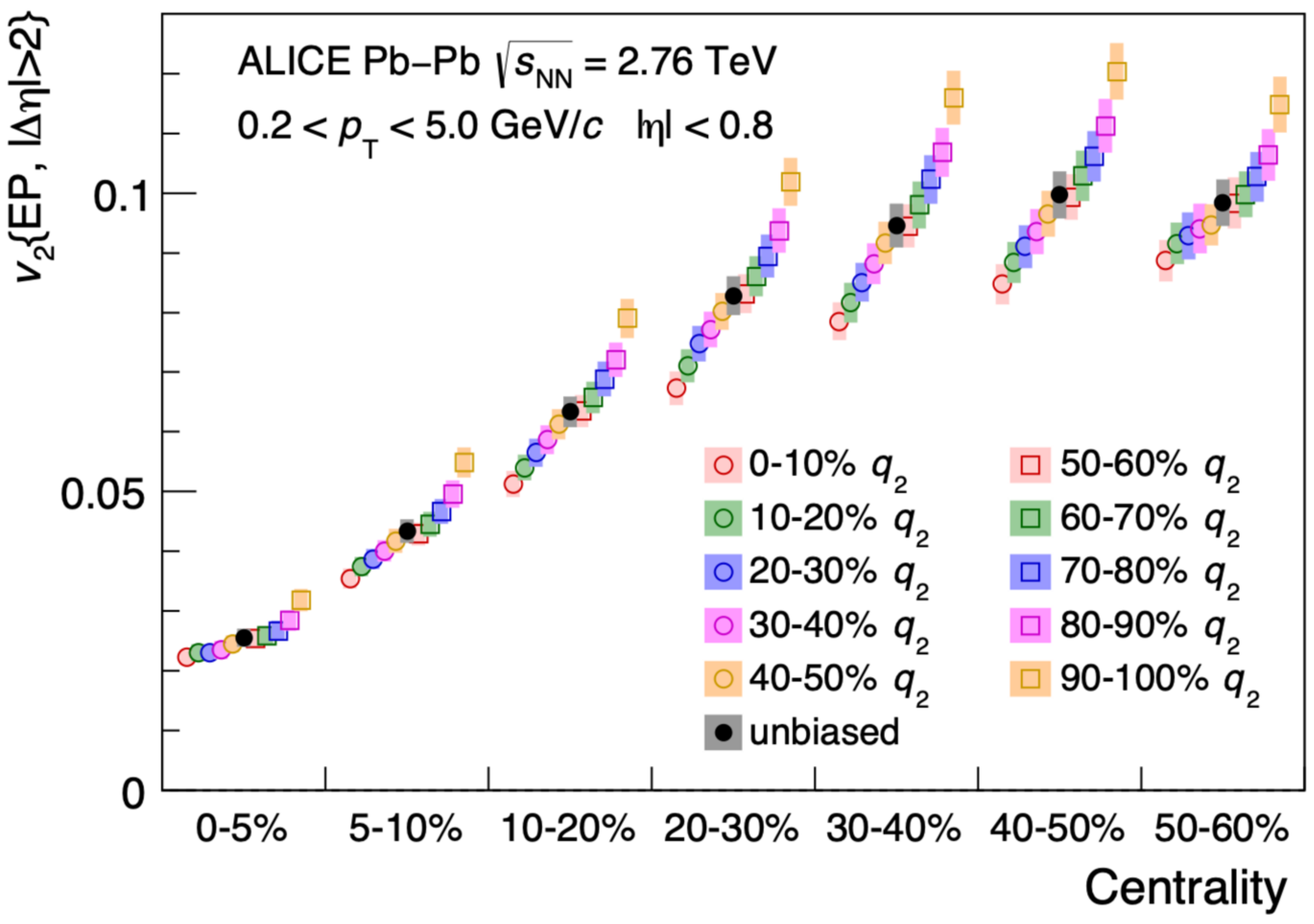
$a = v_2\{\Psi_{ZDC}\} / v_2\{\Psi_{TPC}\}$

$A = \Delta\gamma\{\Psi_{ZDC}\} / \Delta\gamma\{\Psi_{TPC}\}$

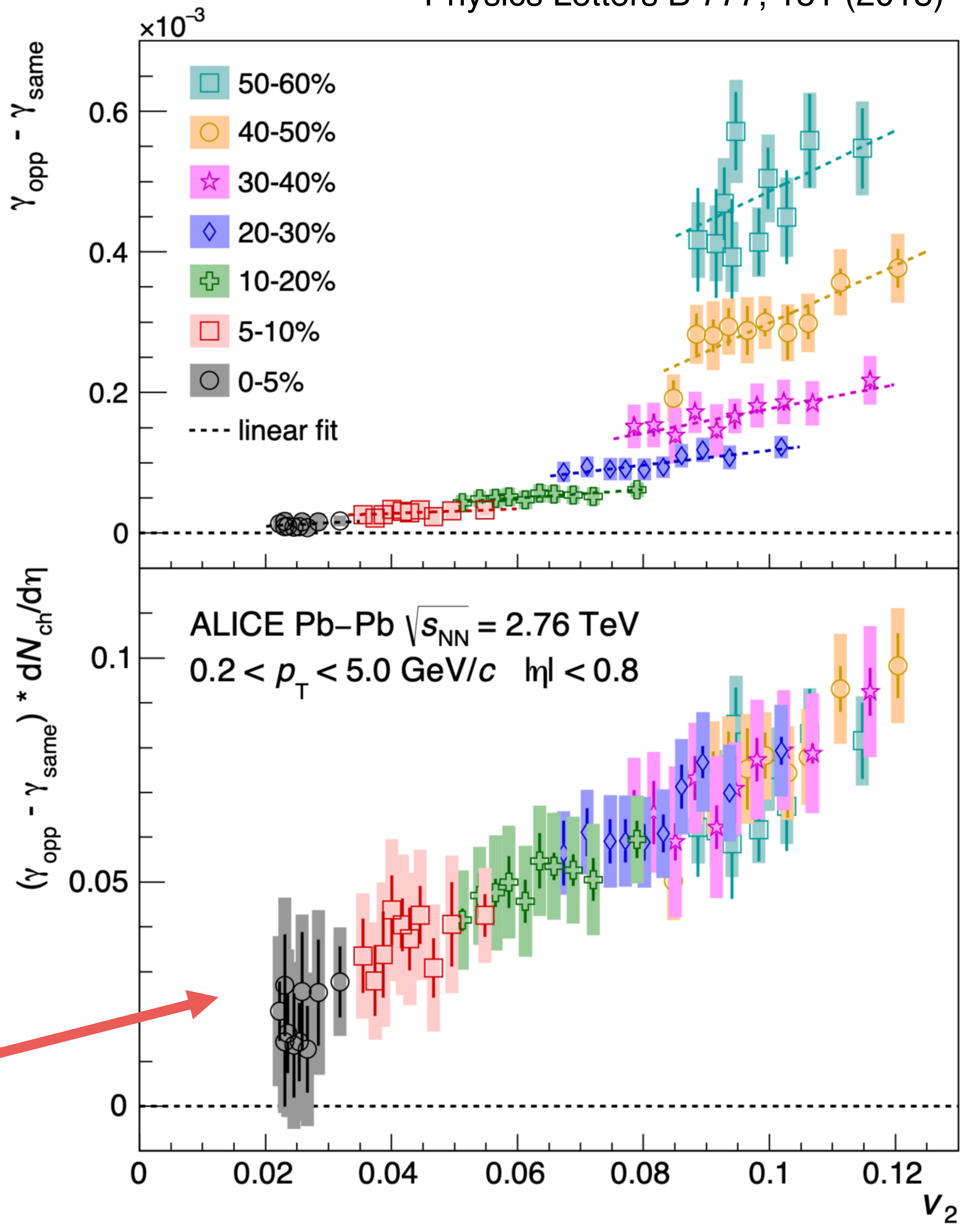
$f_{CME} = (A/a - 1) / (1/a^2 - 1)$

Study of the background 3

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

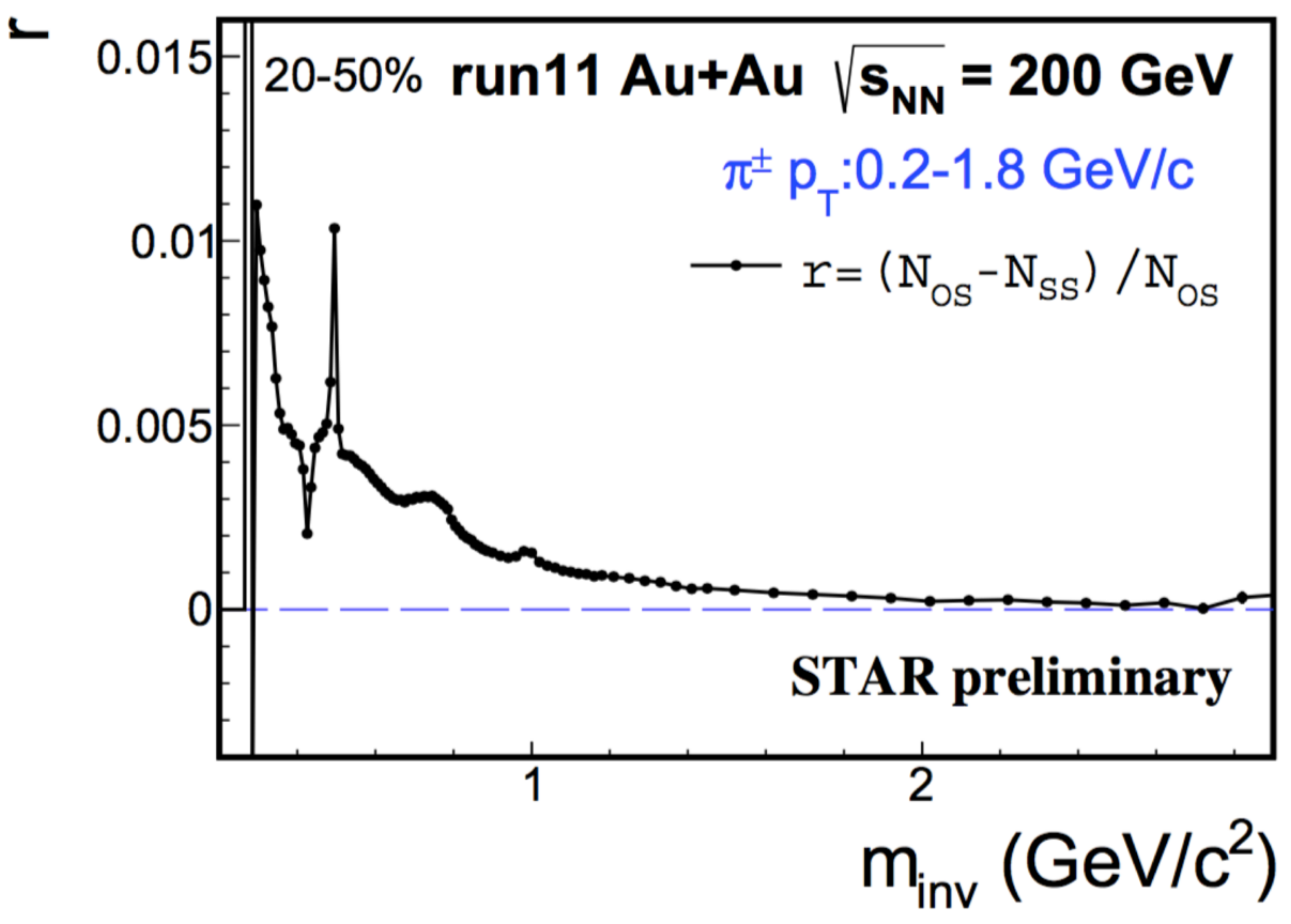


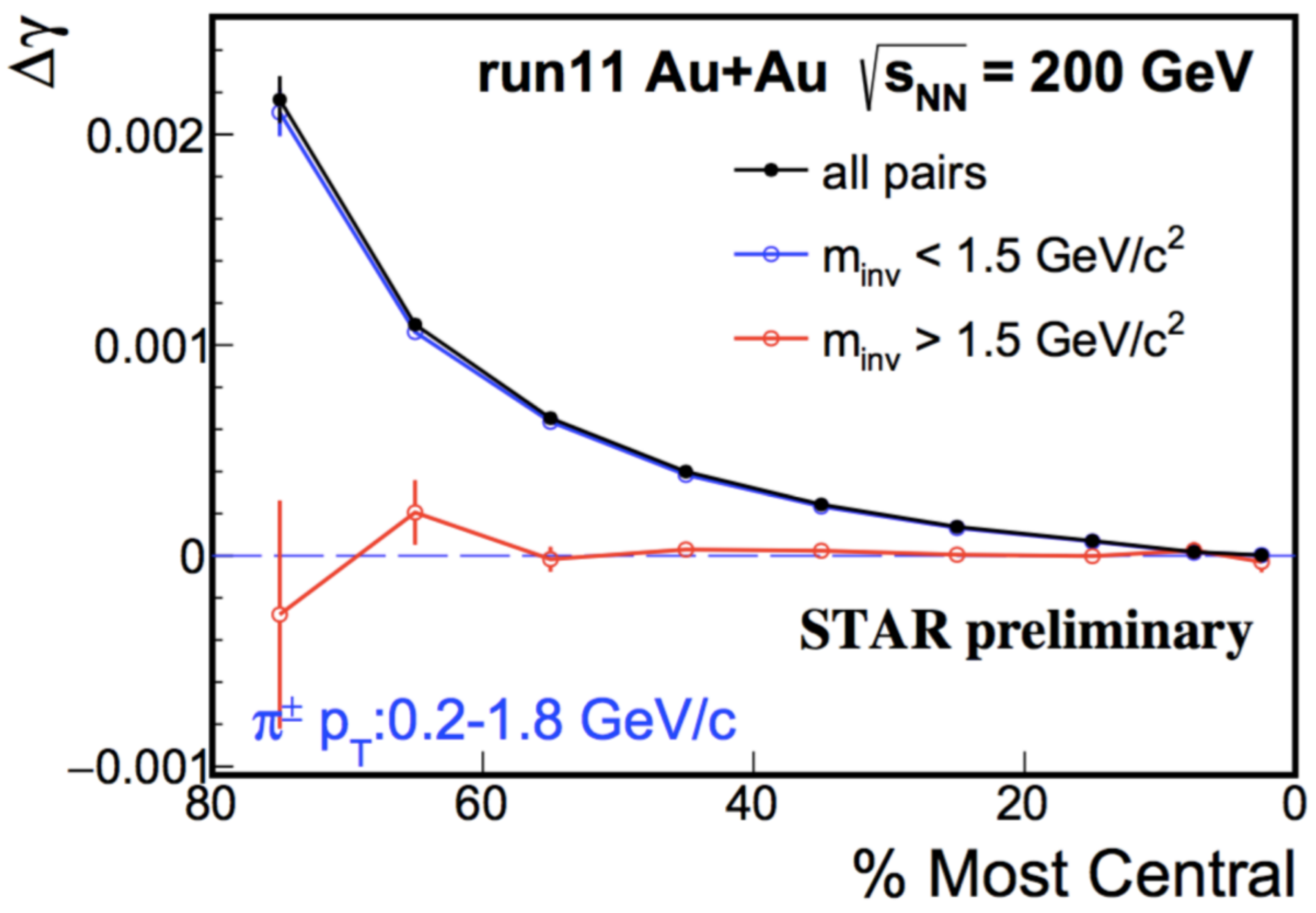
Physics Letters B 777, 151 (2018)

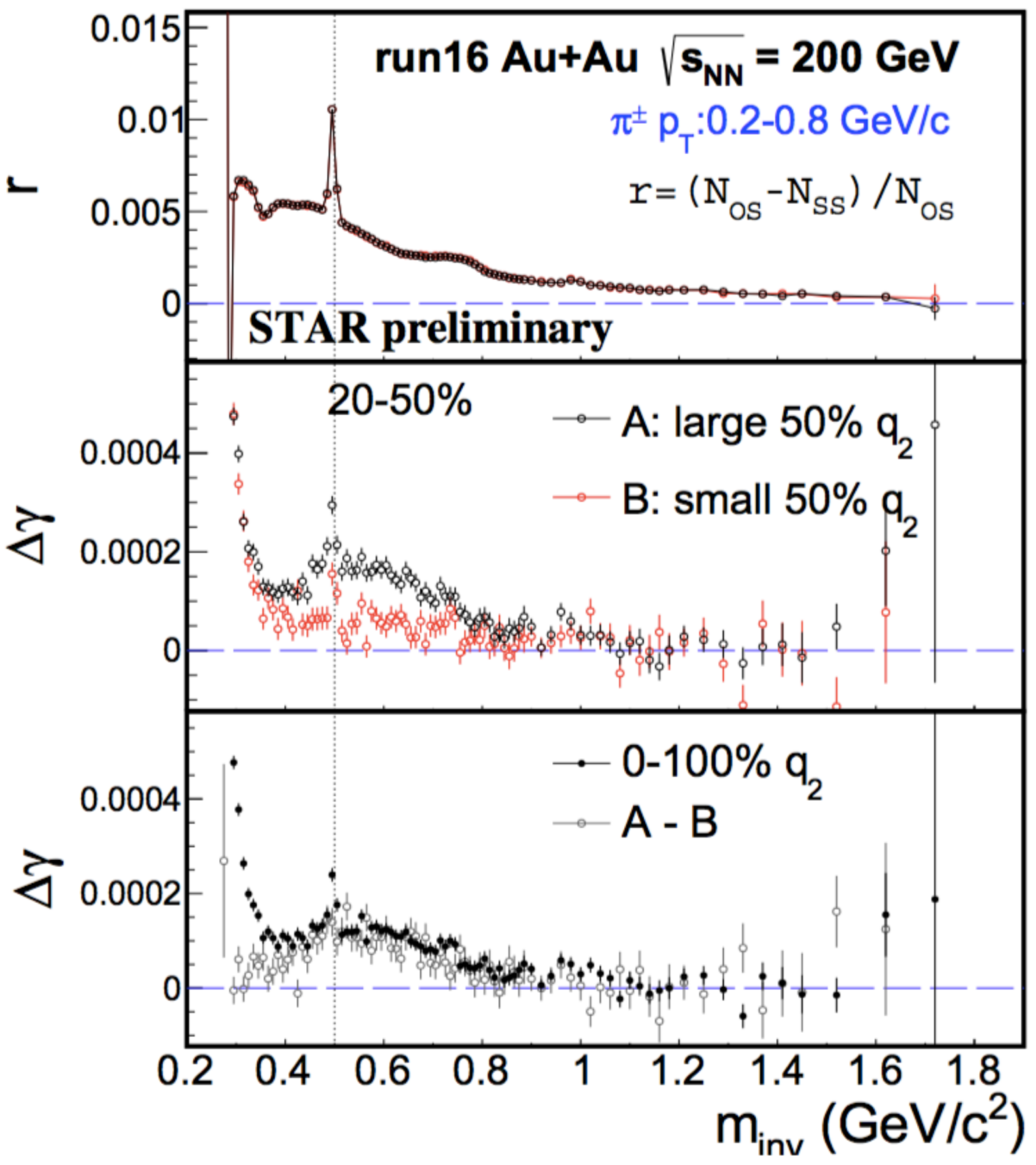


$\Delta\gamma_{112}$ is approximately proportional to v_2

Study of the background 4





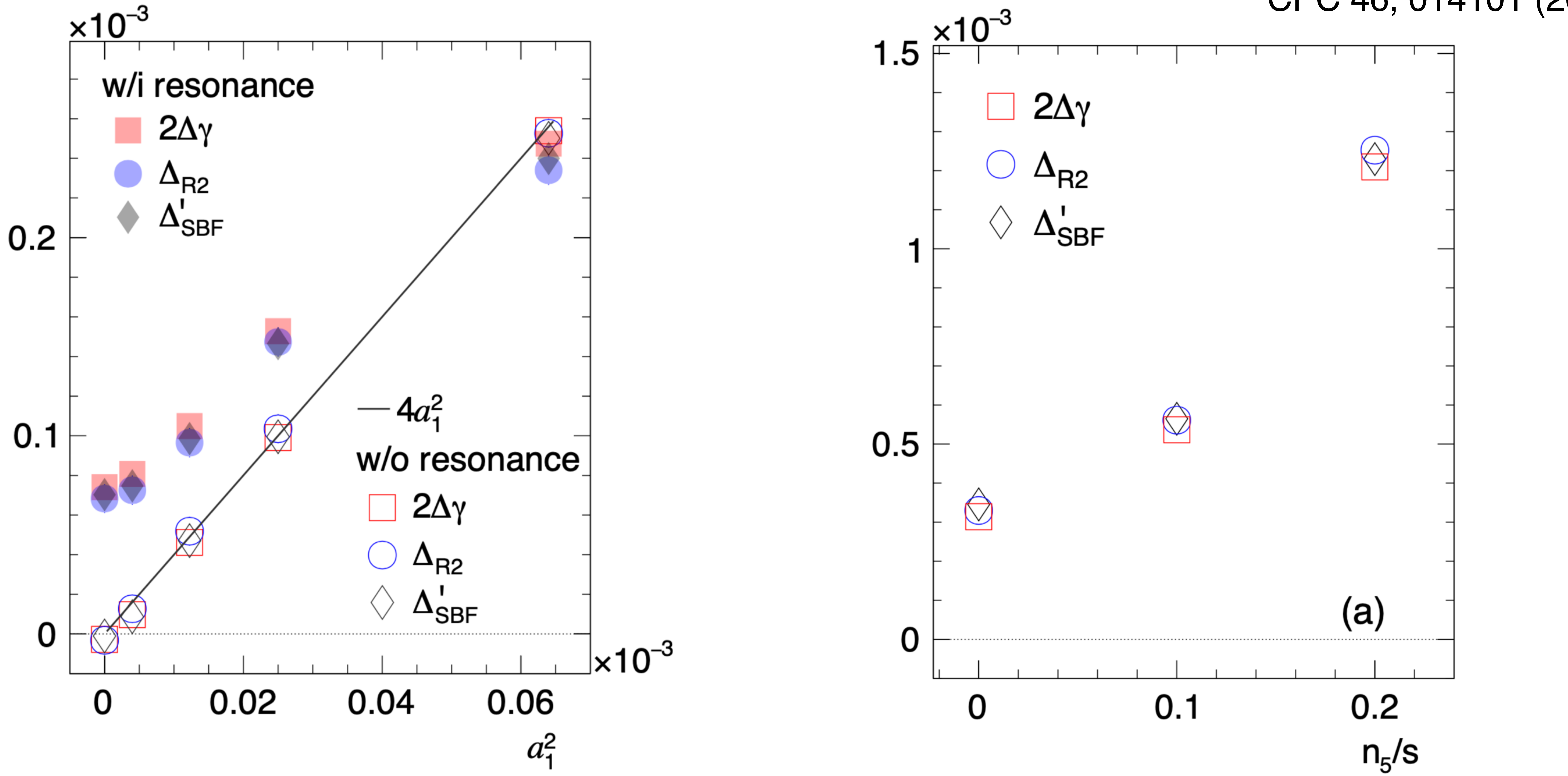


γ_{112} is contaminated by major backgrounds arising from local charge conservation/resonance decay coupled with the elliptical anisotropy

Nuclear Physics A 982, 535 (2019)

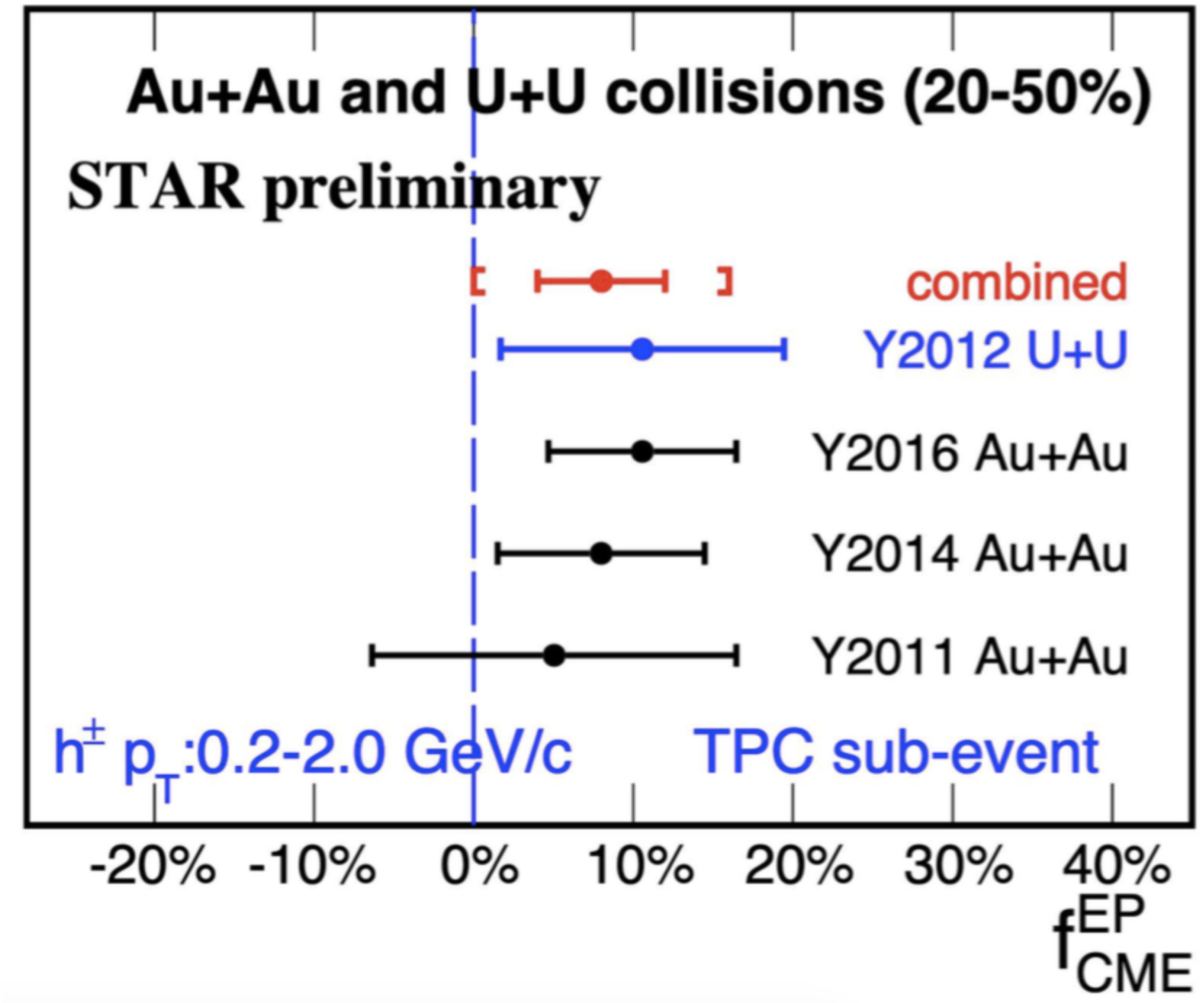
Comparison between observables

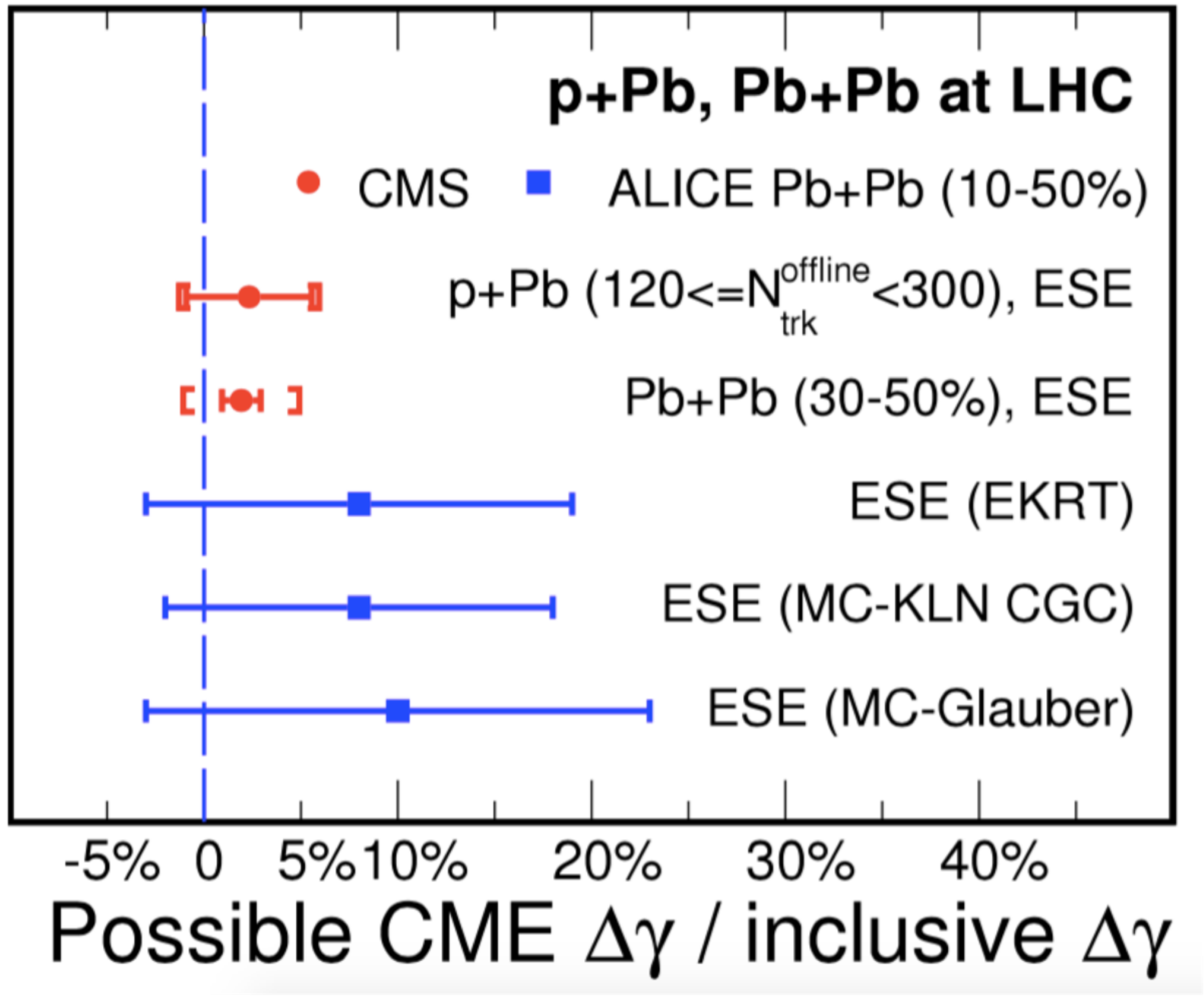
CPC 46, 014101 (2022).

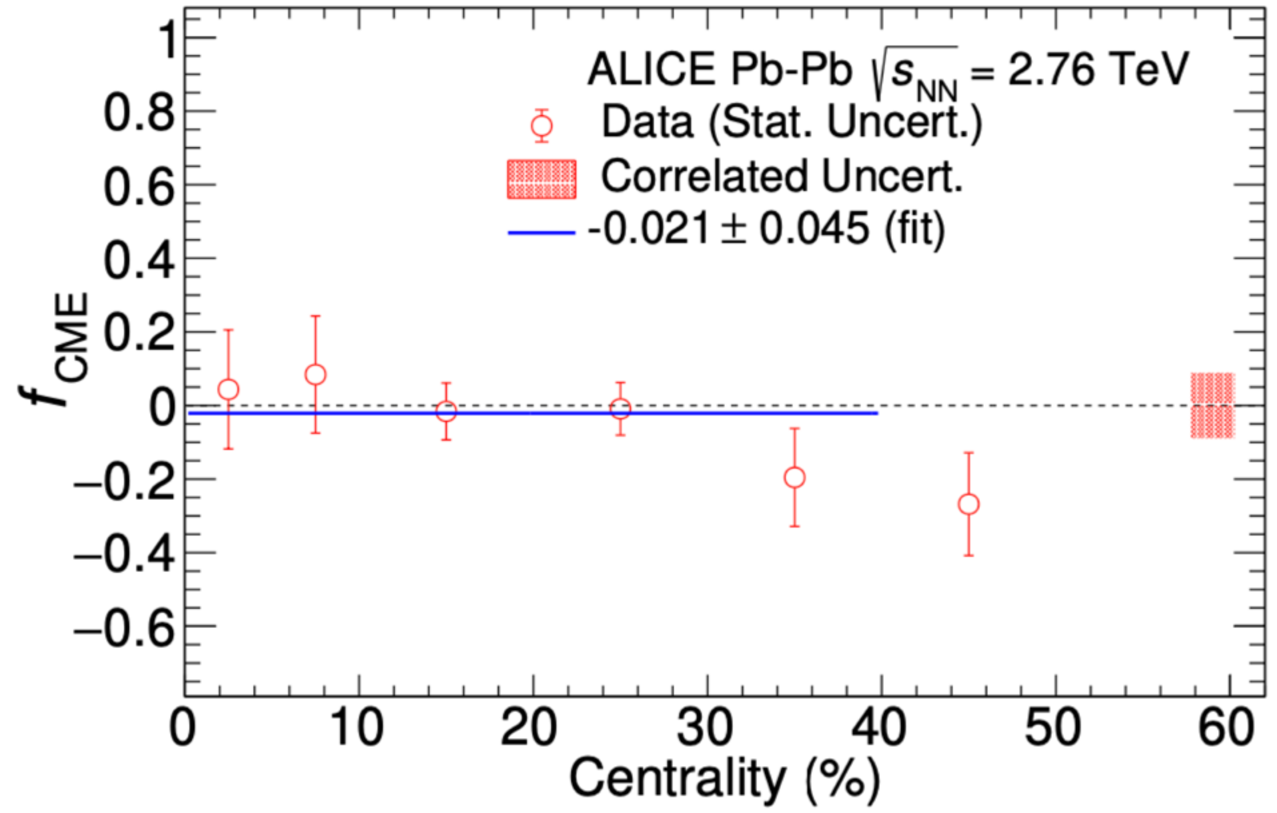


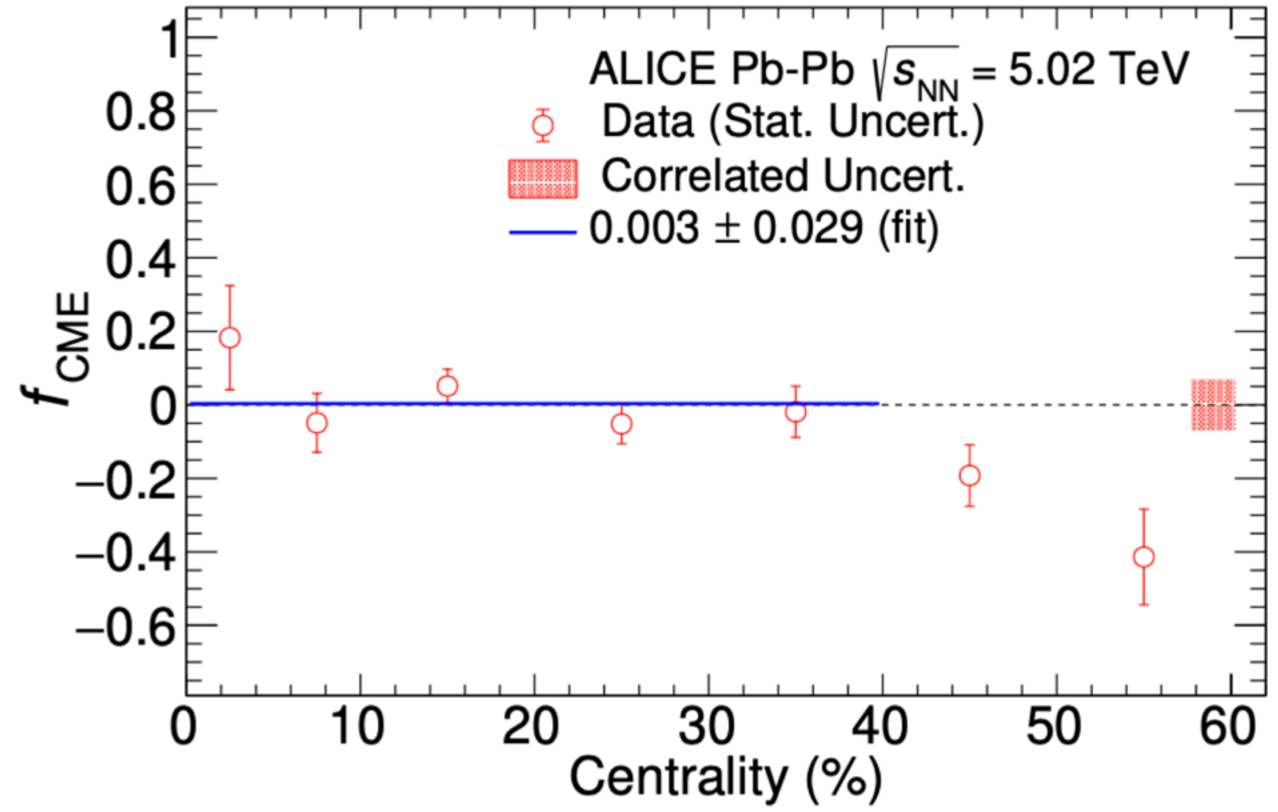
- EBE-AVFD framework for the signal
- Imported resonance/neutral pair for the background
- Three observables have the same response

Experimental search for the CME: current status





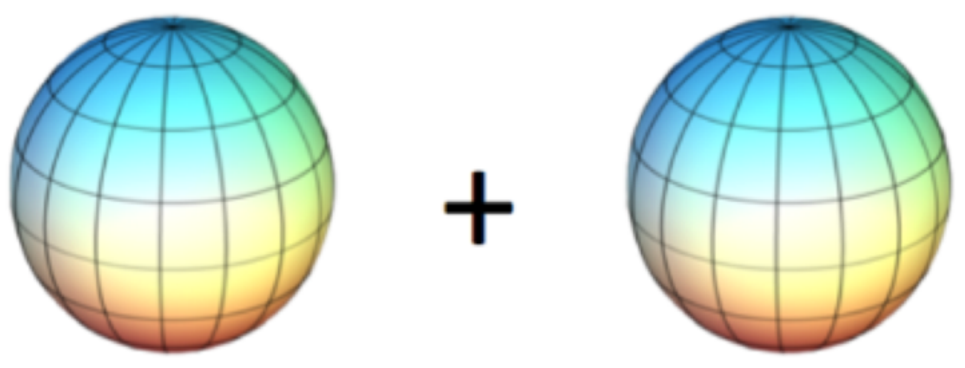




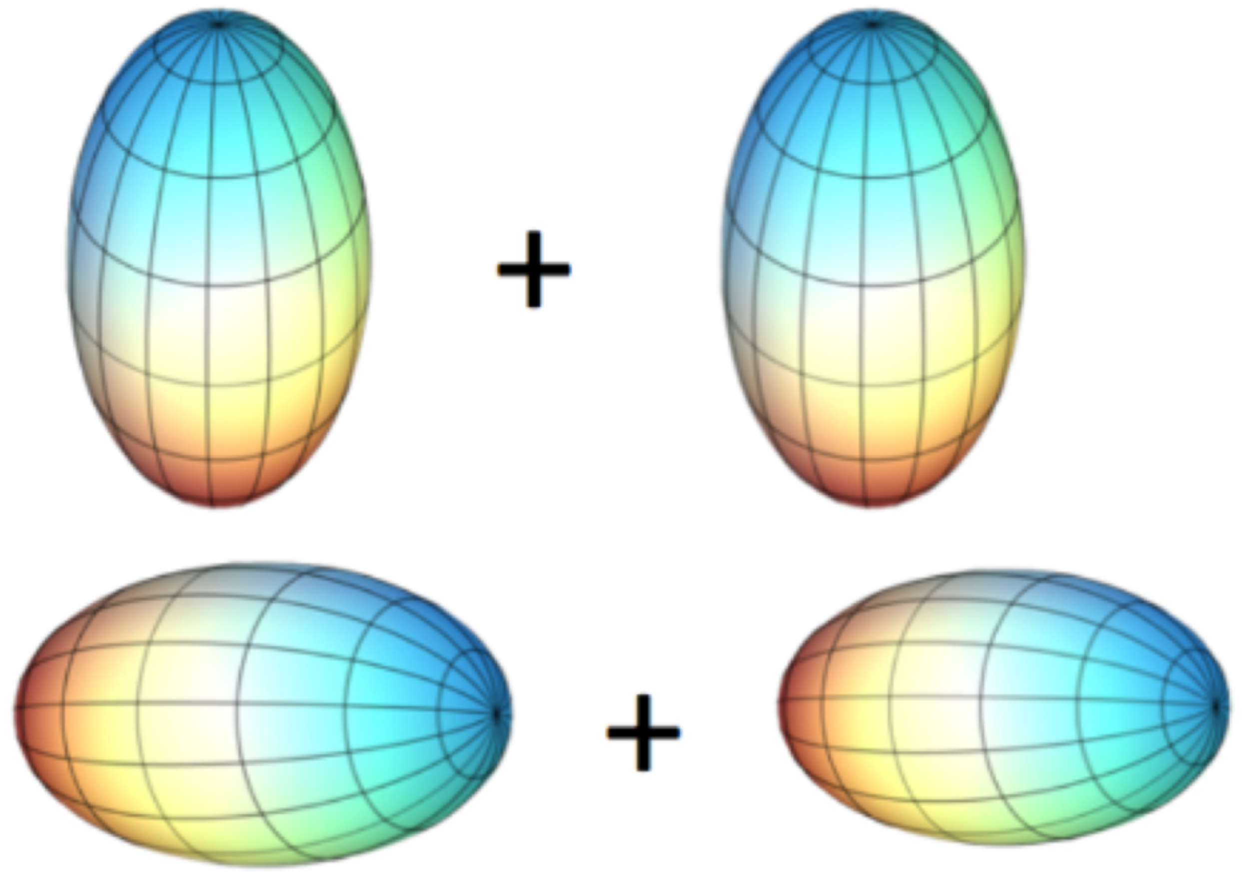
- γ correlator has been used to investigate charge separation for a decade, and it's clear that the LCC+flow driven background as well as the contamination from the resonance decay play dominate roles
- Current consensus of the CME component (upper limit) in γ < 10%

Experimental search for the CME: isobaric collisions

- Colliding deformed nuclei



vs



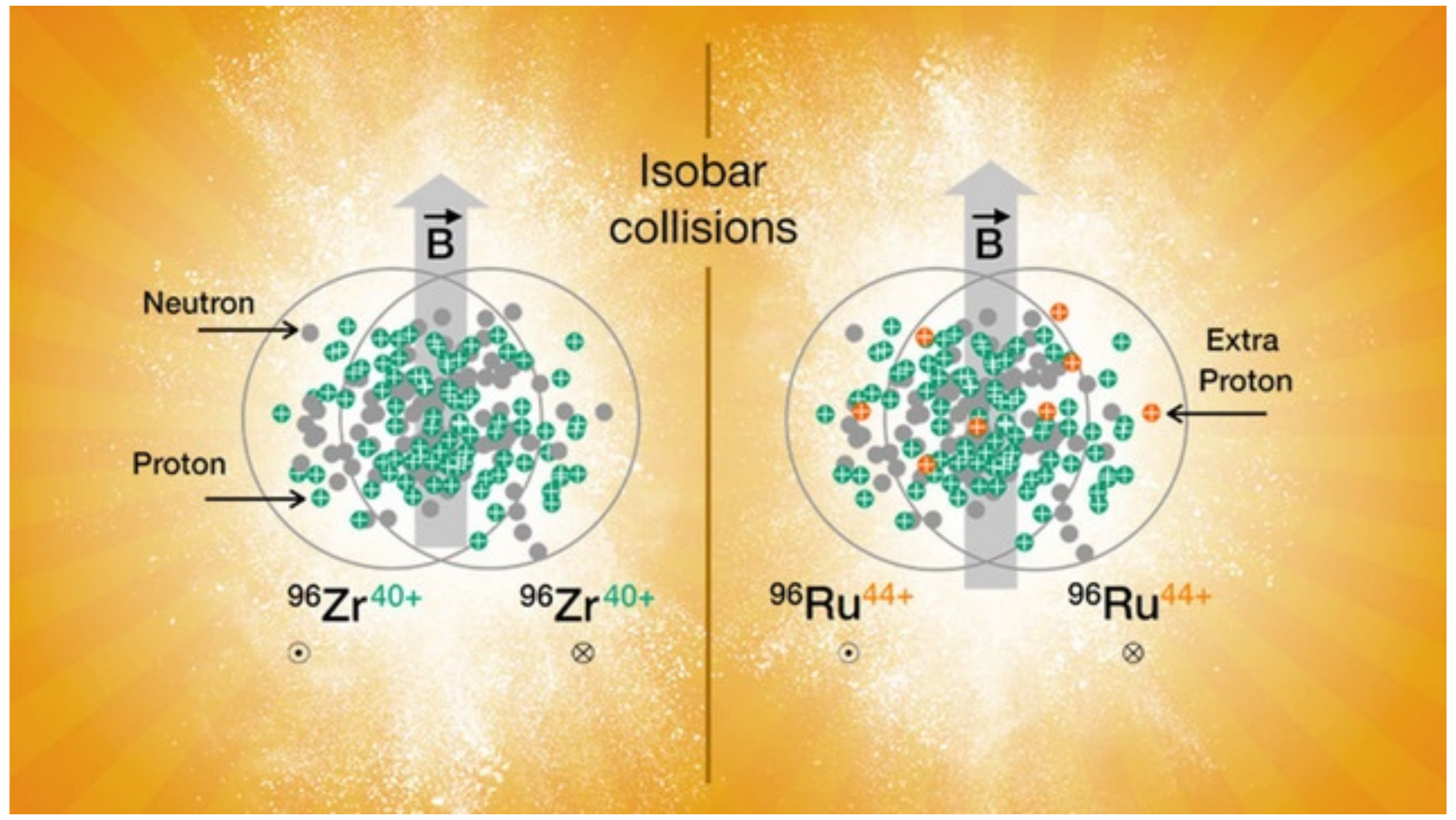
RHIC2012

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

- Isobars: different chemical elements that have the same number of nucleons.

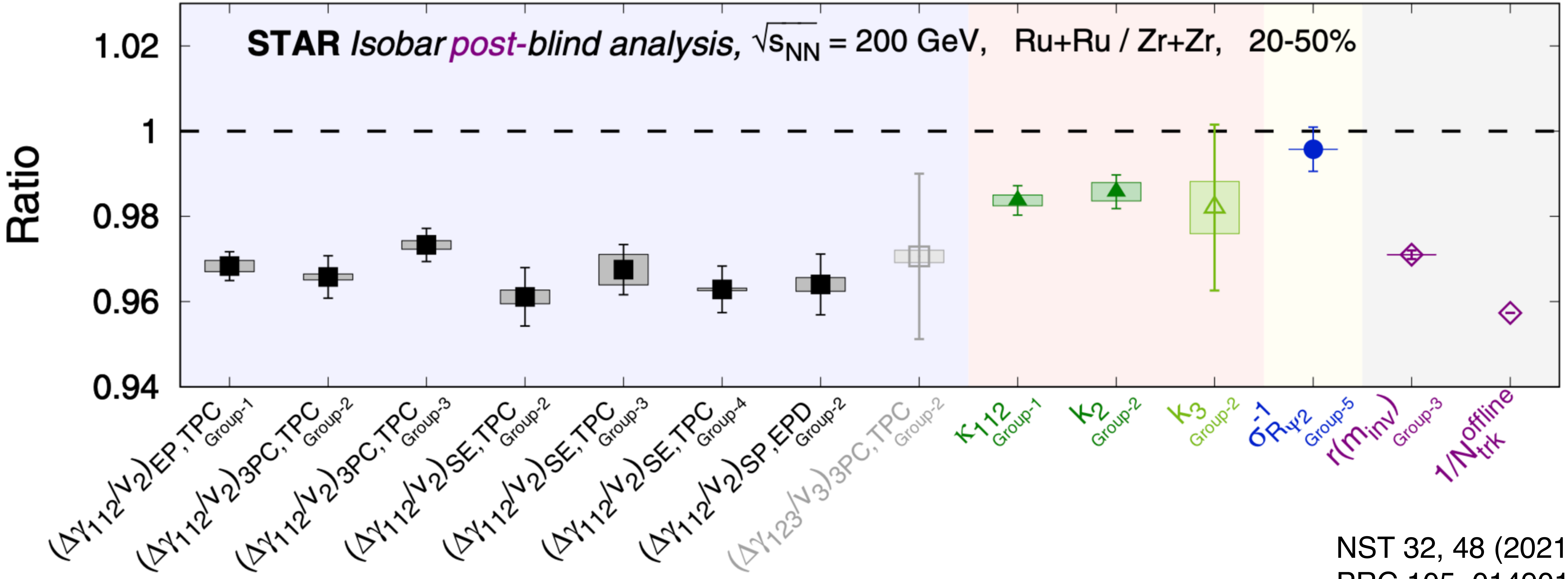
RHIC2018

For example, ${}^{96}_{44}Ru$ (Ruthenium) and ${}^{96}_{40}Zr$ (Zirconium): up to 10% variation in B field



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

Experimental search for the CME: isobaric collisions

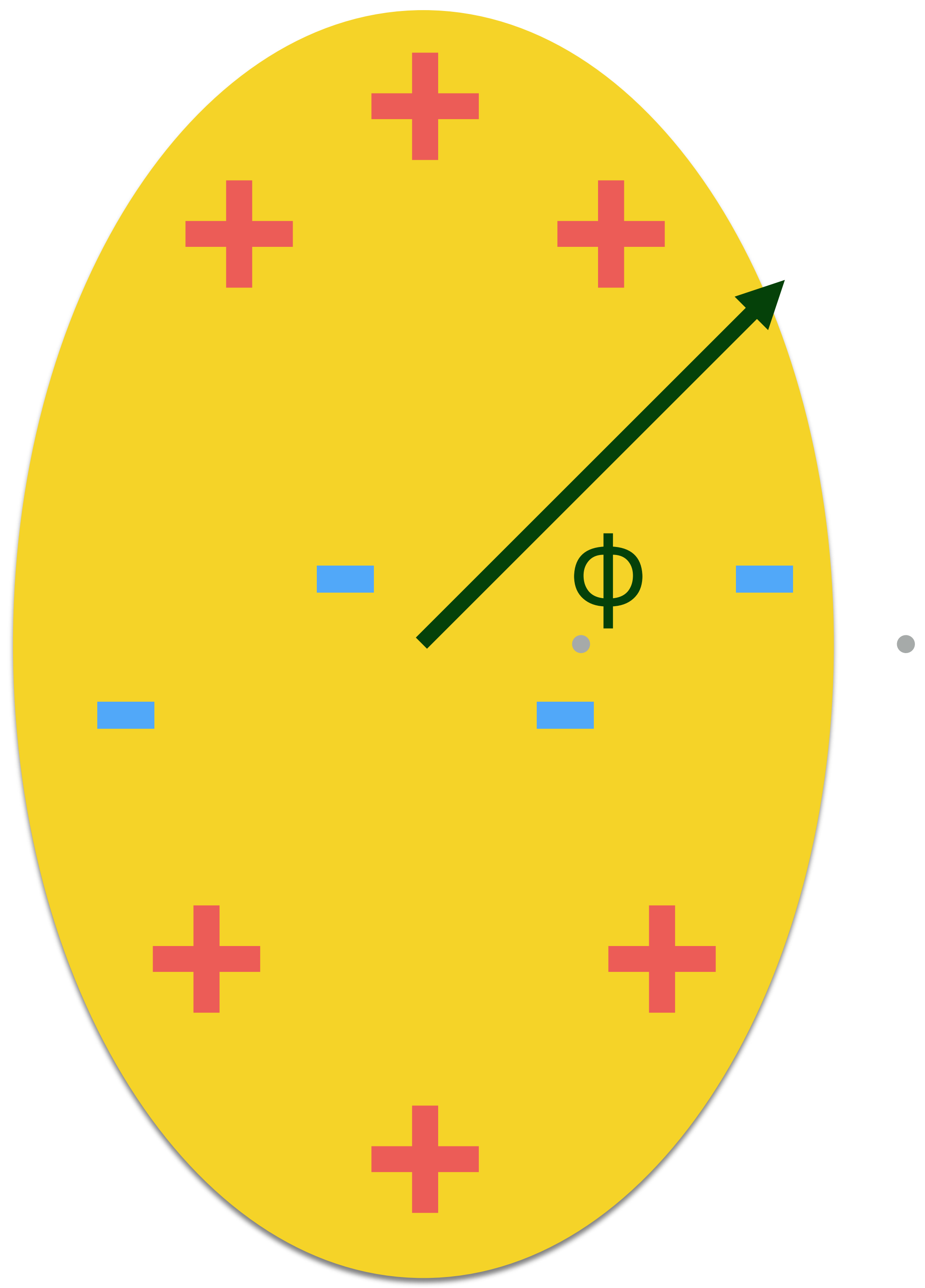


NST 32, 48 (2021).
PRC 105, 014901 (2022).

No predefined CME signatures are observed in this blind analysis

Search for the Chiral Magnetic Wave

Measurement of CMW with charge asymmetry dependent flow



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

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

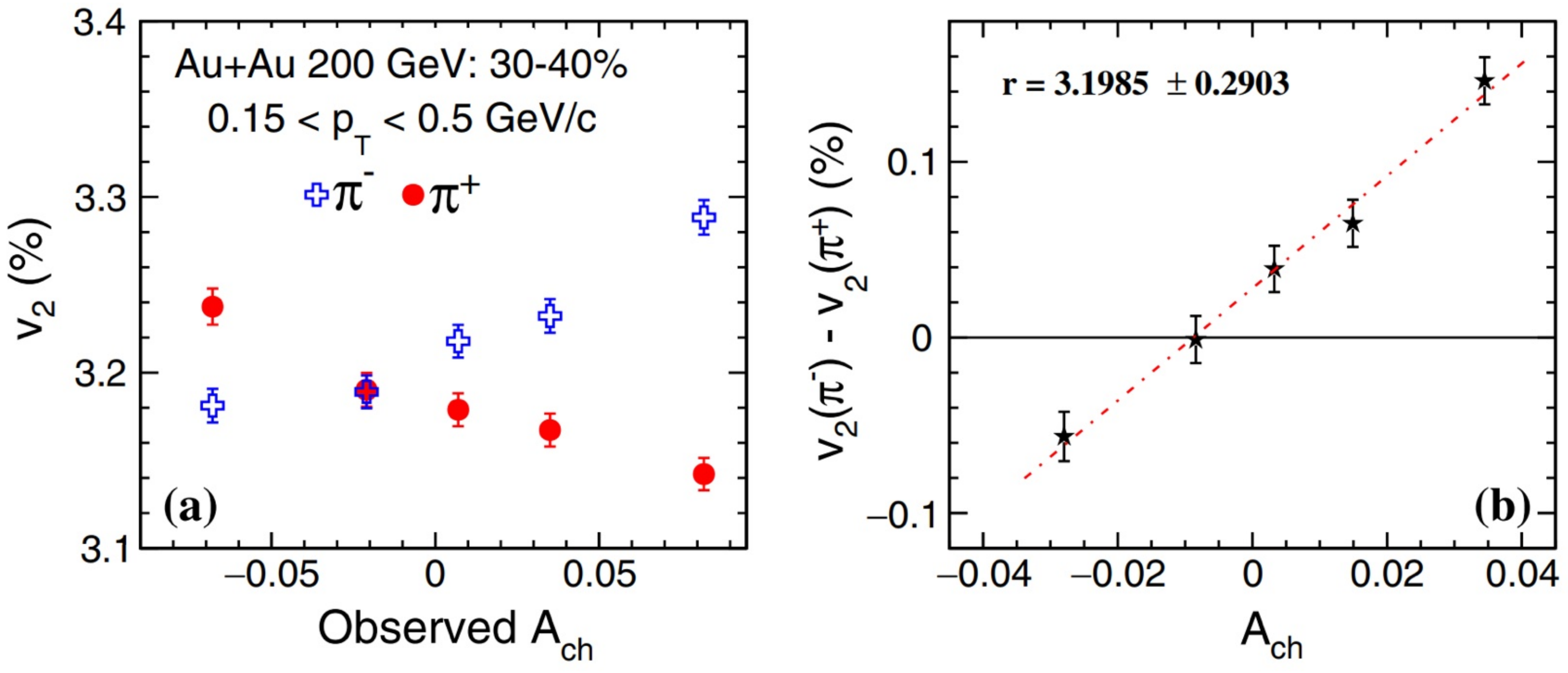
Sensitive to CMW

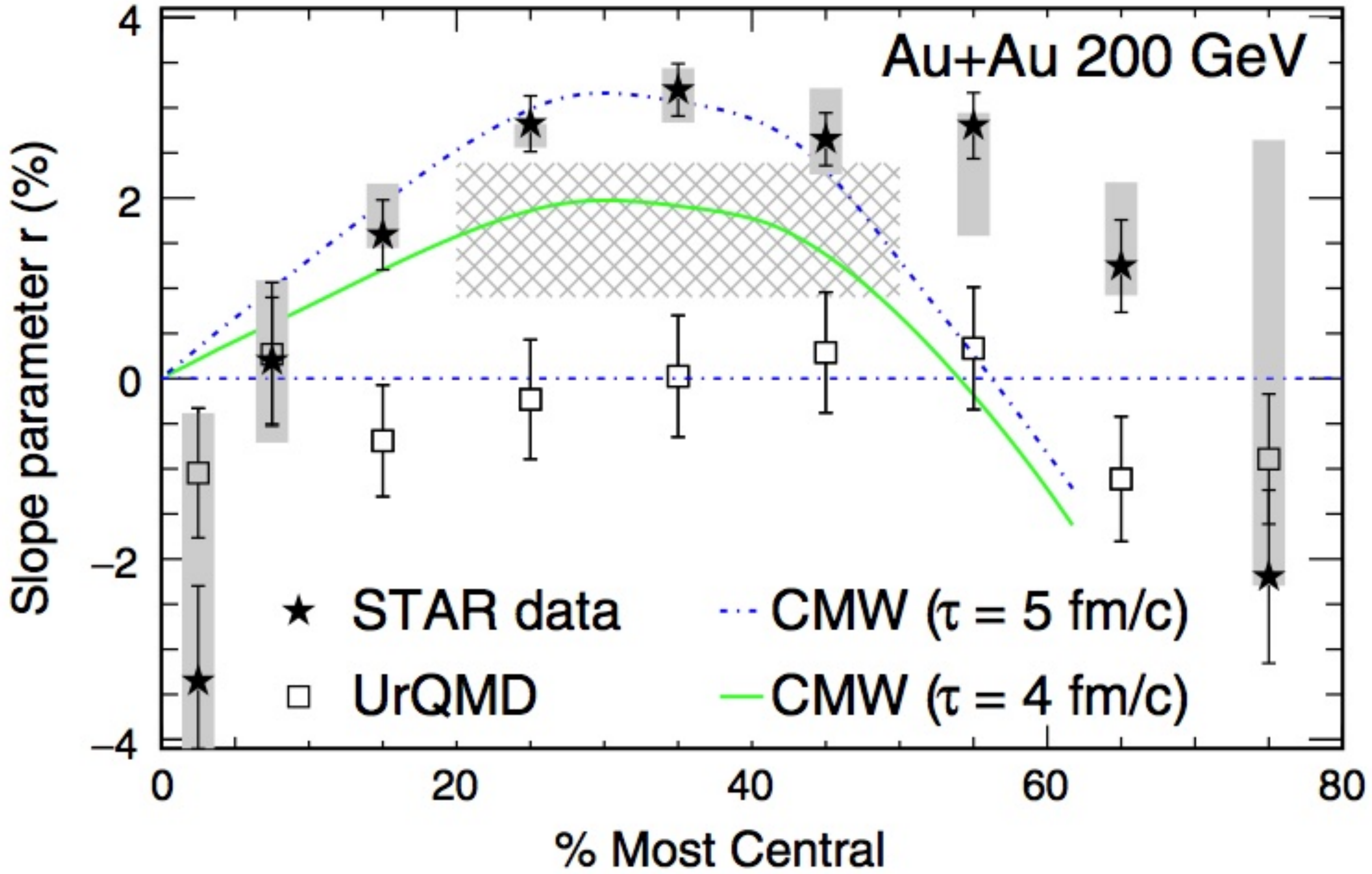
$$\Delta v_3 = v_3^- - v_3^+ \sim rA_{ch}$$

Not sensitive to CMW

v_2 vs A_{ch} at RHIC

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

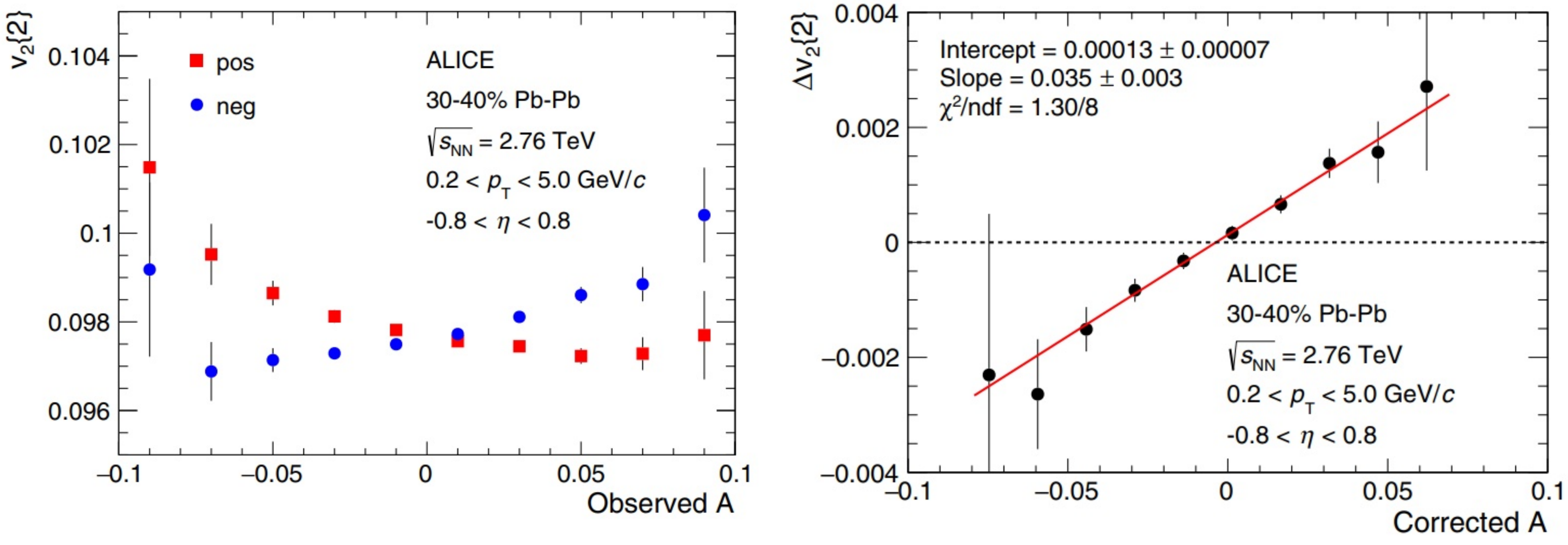


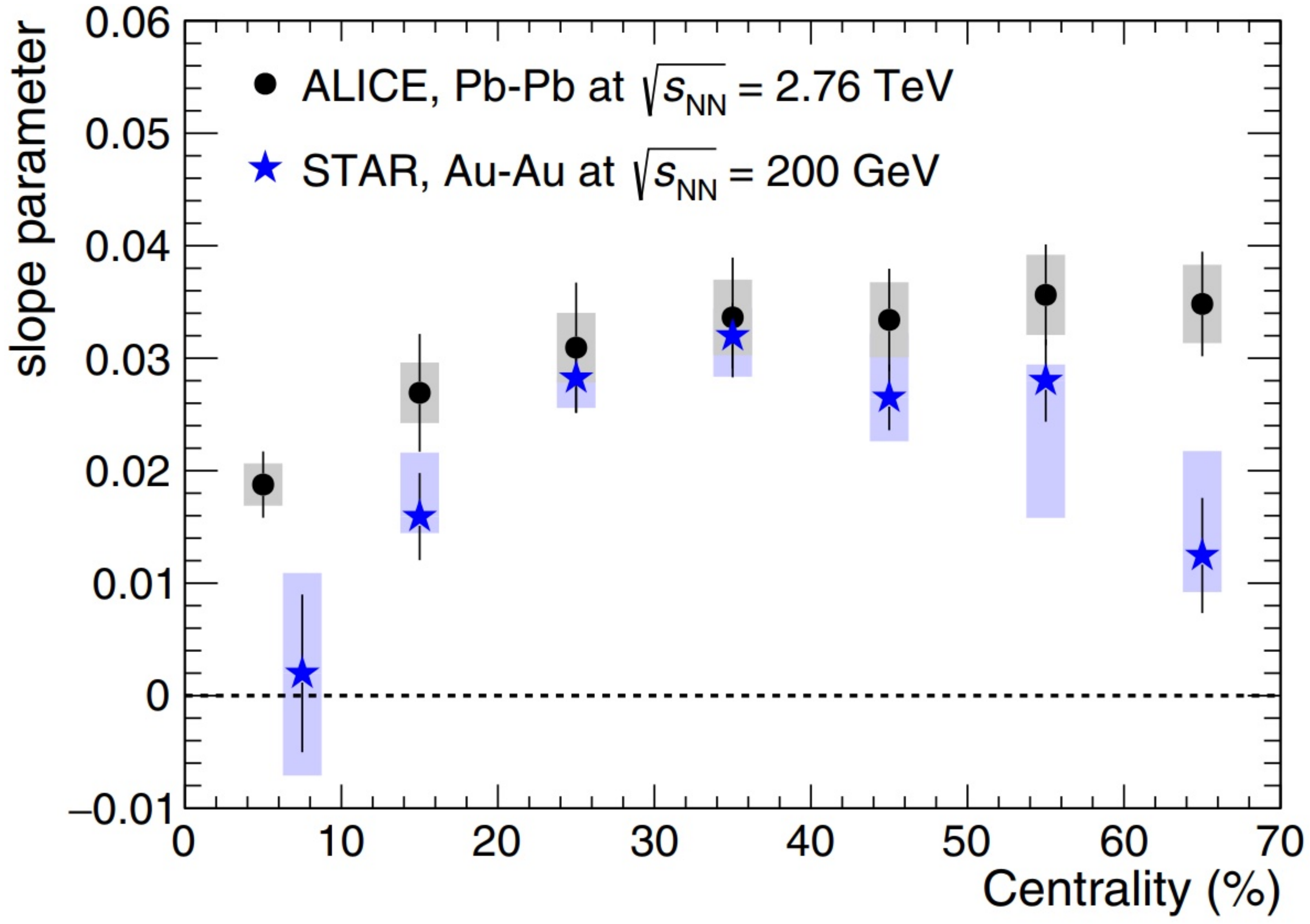


The linear dependences between v_2 and A_{ch} are clearly observed, matching CMW expectation

v_2 vs A_{ch} at LHC

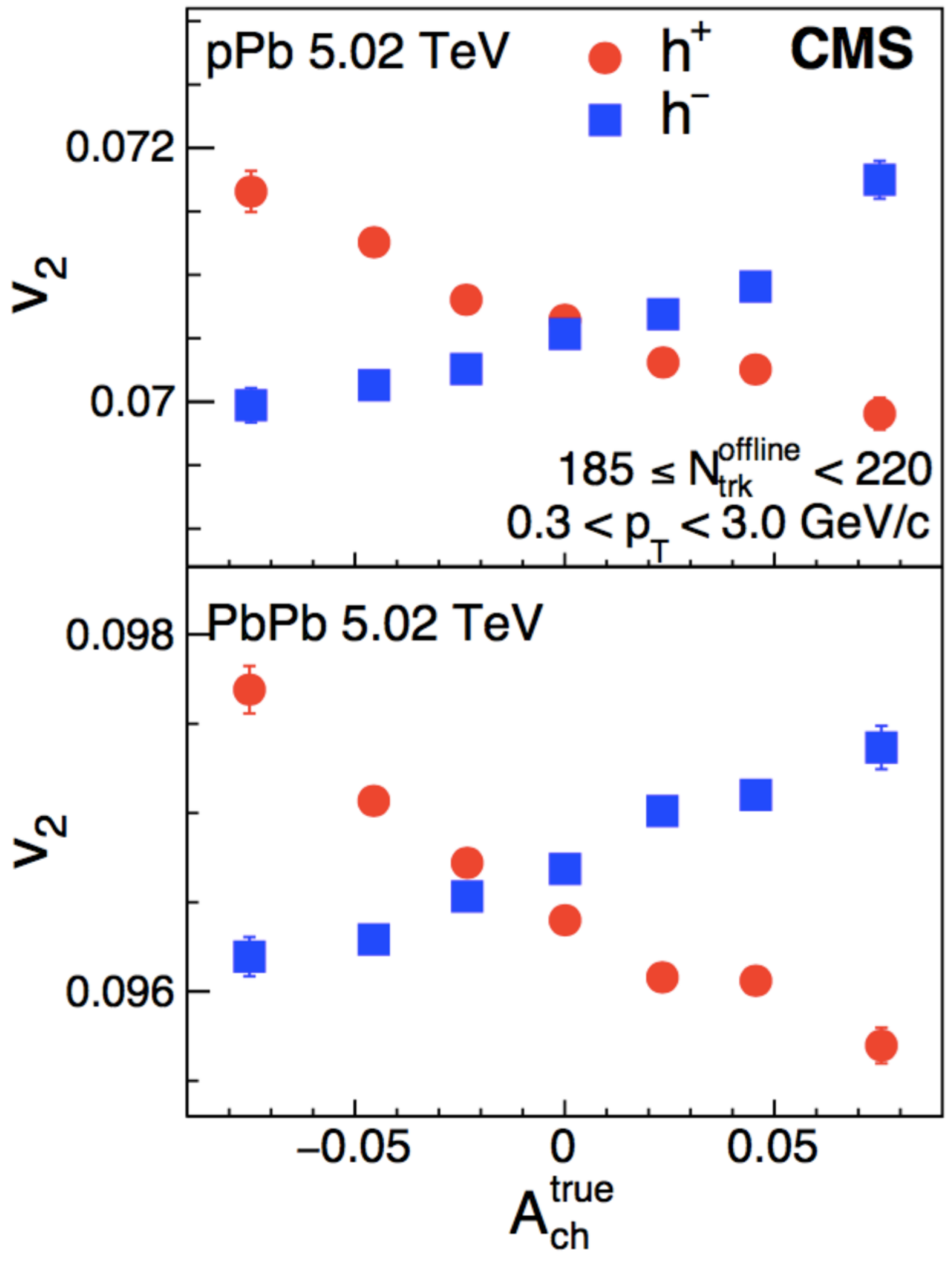
Phys. Rev. C 93, 044903 (2016)



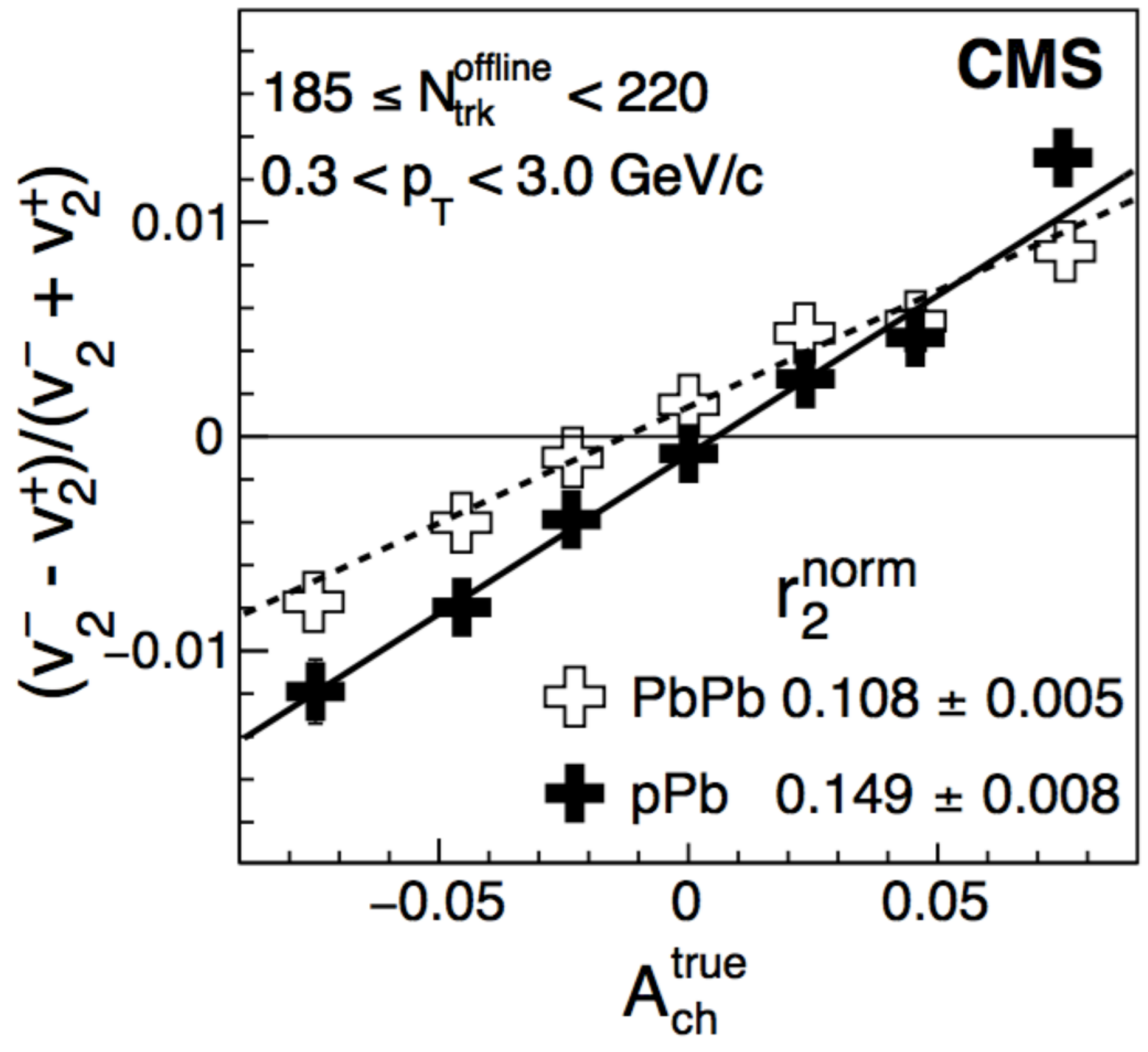


- The linear dependences between v_2 and A_{ch} are clearly observed, matching CMW expectation
- Little difference between RHIC and LHC results

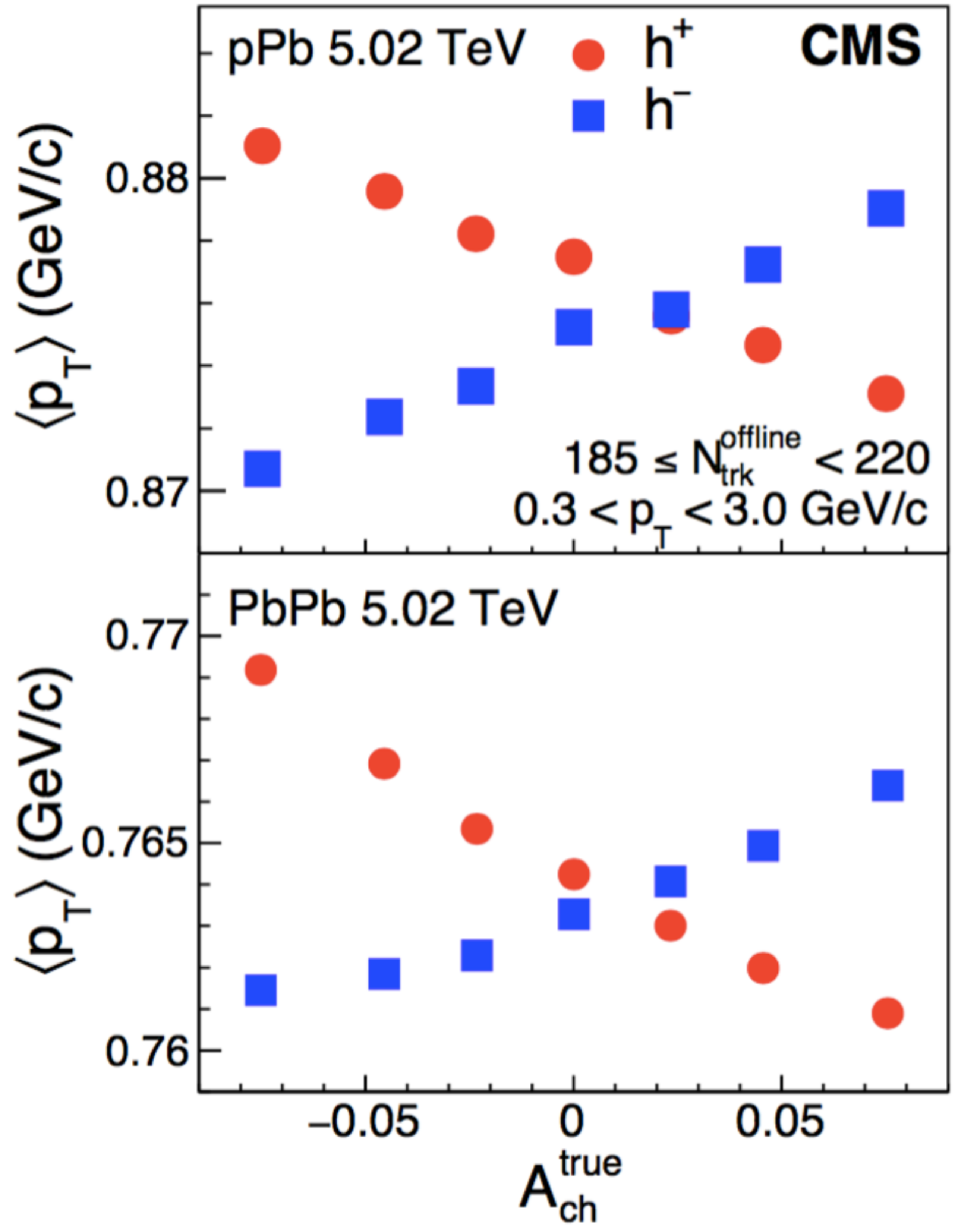
Surprise again in the small system collisions

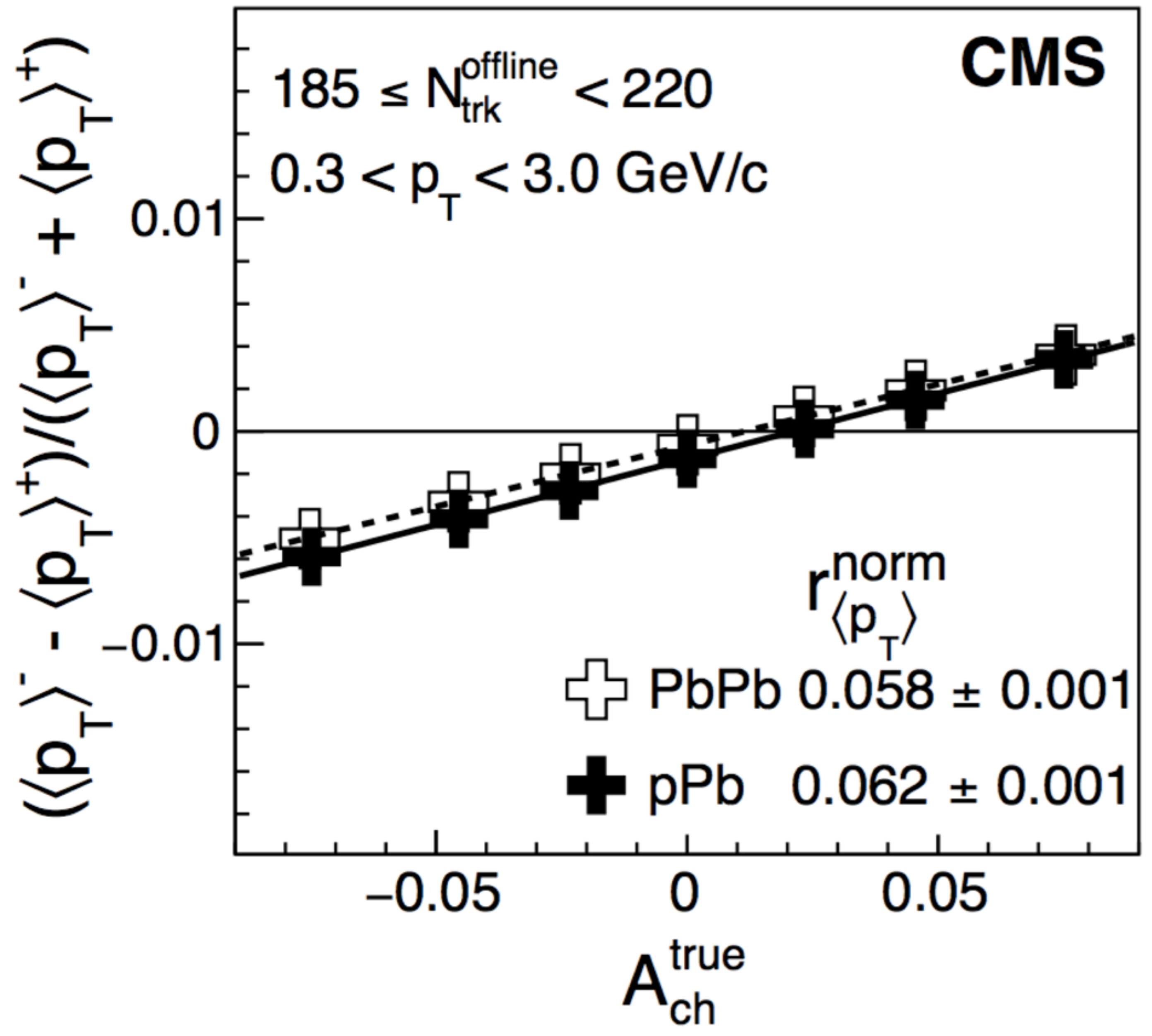


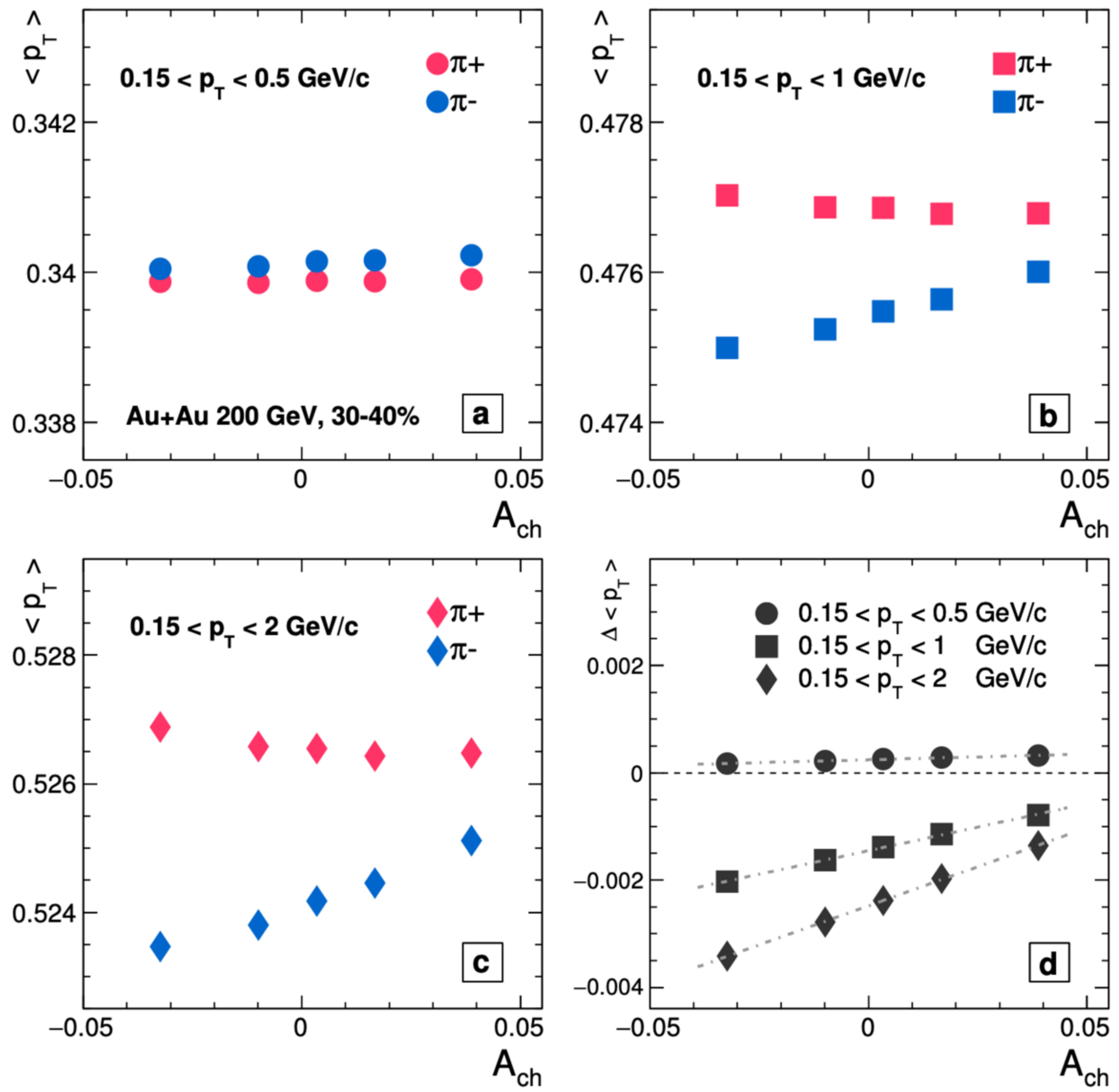
Phys. Rev. C. 100 (2019) 064908



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



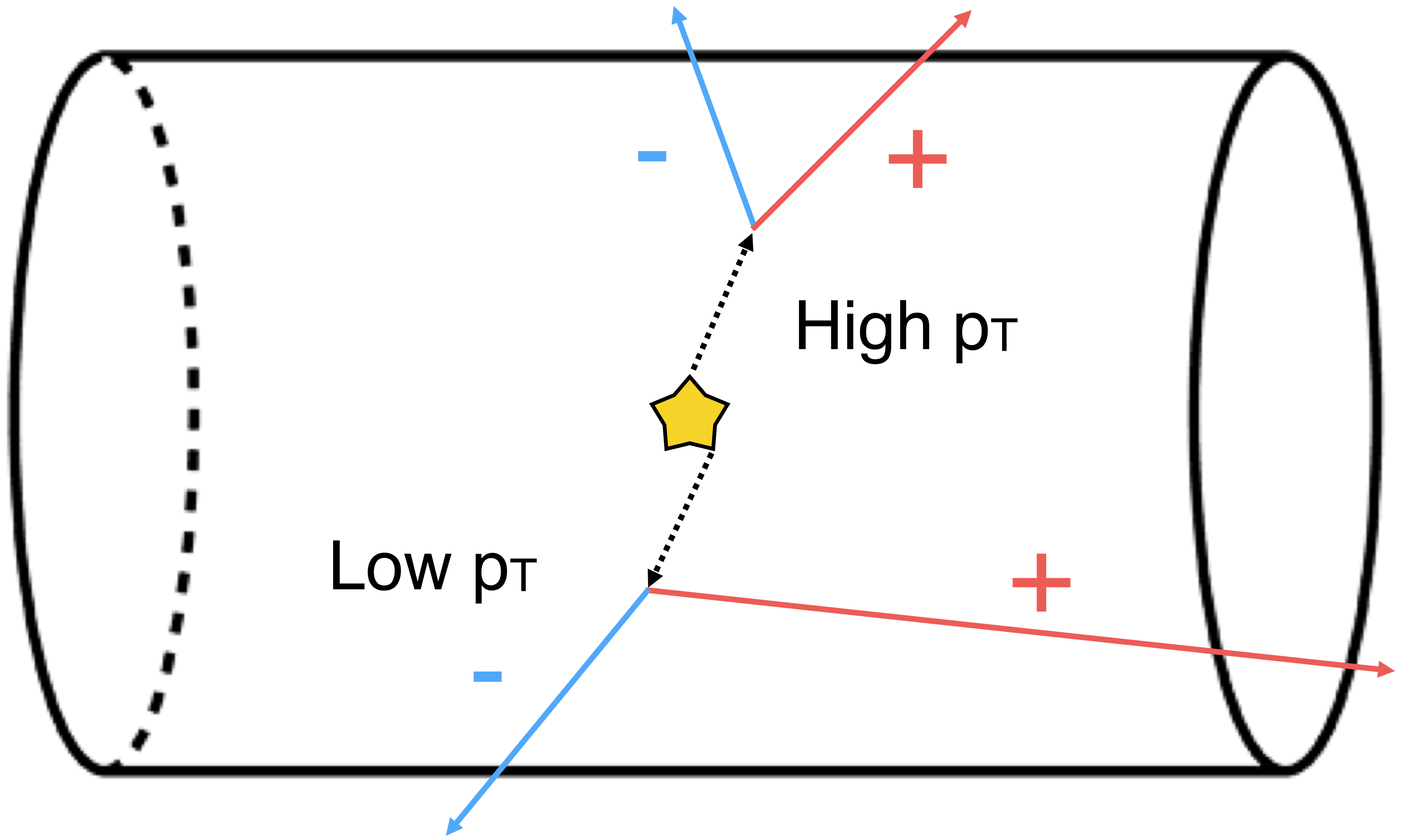




- p_{T} shows a clear A_{ch} dependence
- Indication of the local charge conservation

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

PLB, 726 (2013) 239–243
PRC, 103 (2021) 034906



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

LCC + flow

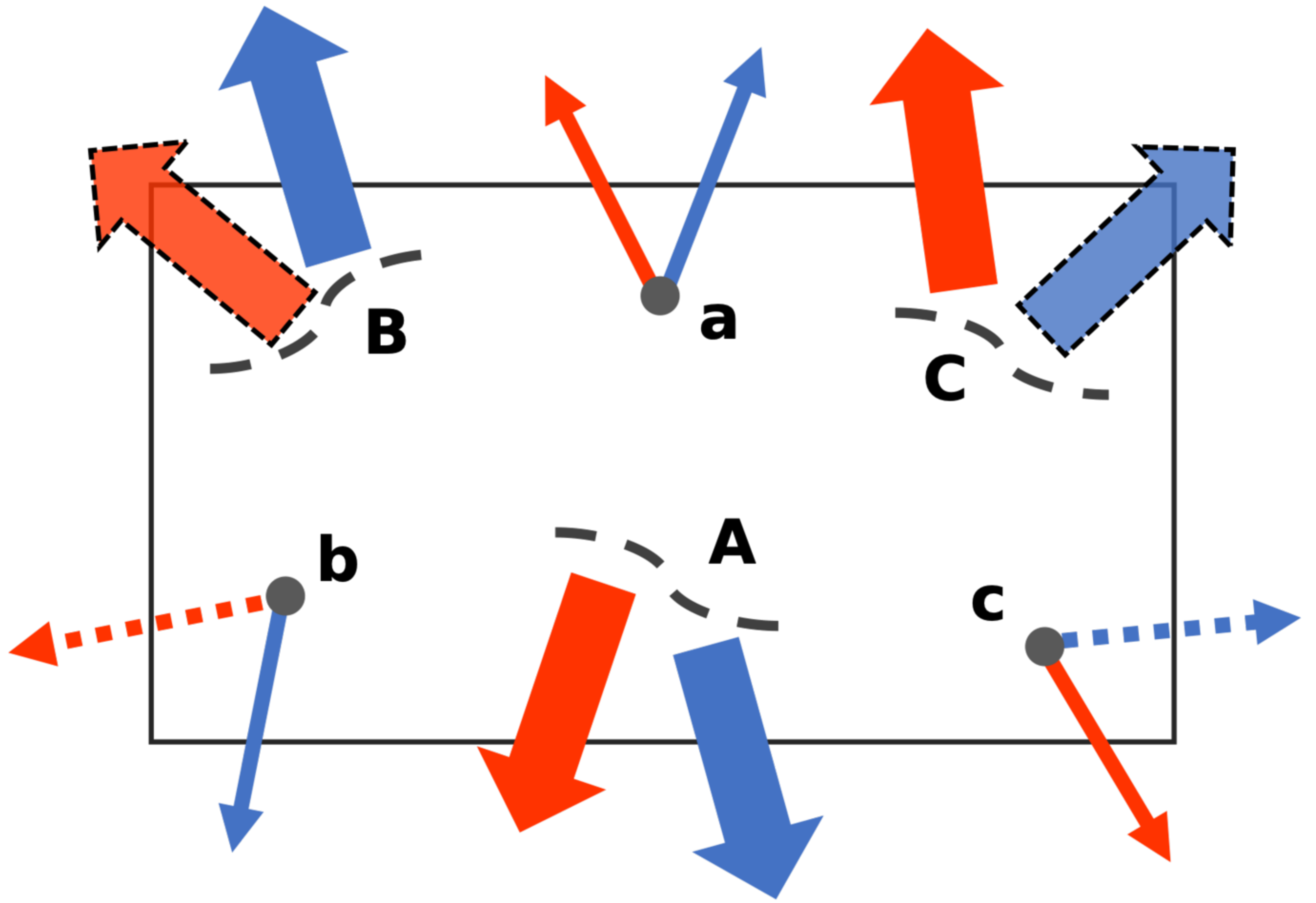
A_{ch} is a ***tricky*** observable!

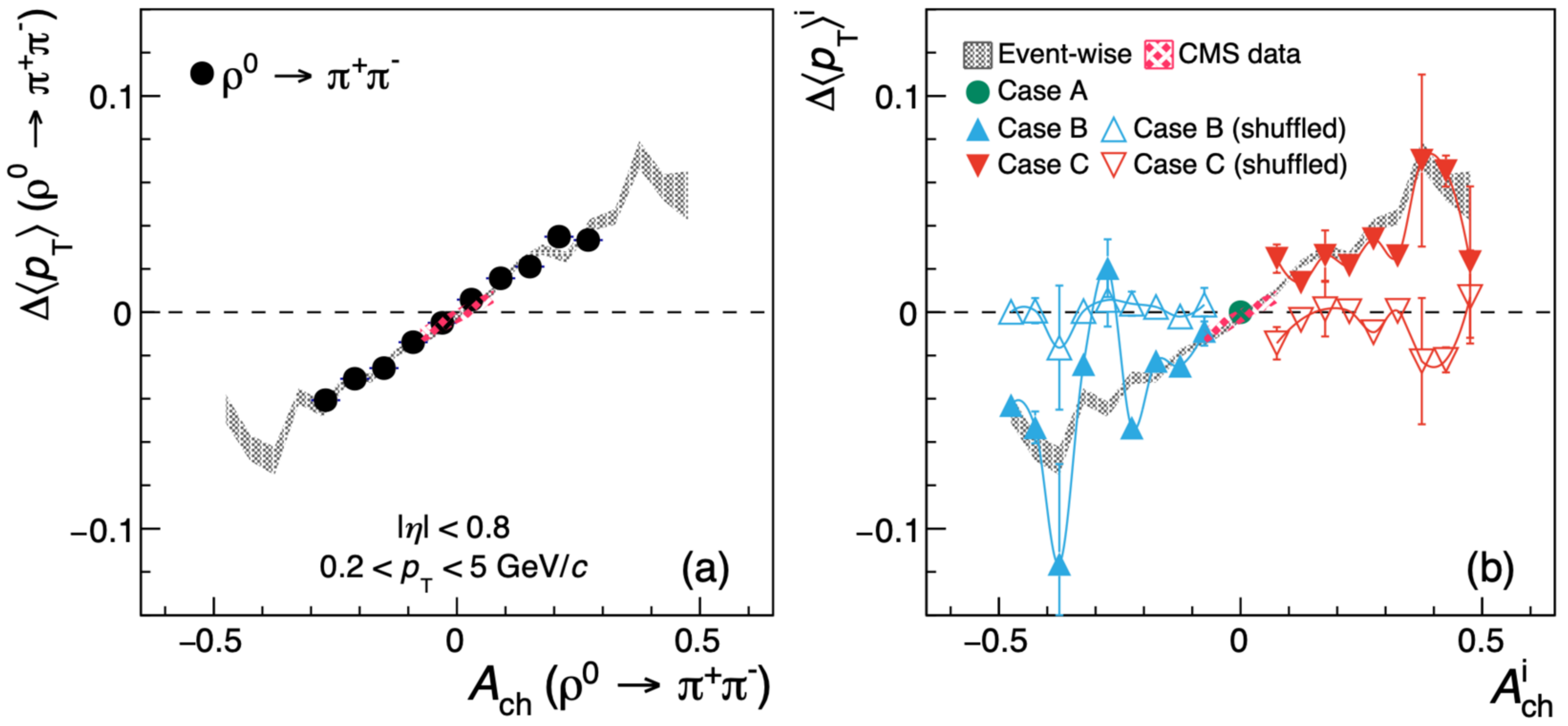
It doesn’t just cut on the number of particles as it appears to be

In practice, one preferentially applies nonuniform kinematic cuts on the charged particles

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

PLB, 726 (2013) 239–243
PRC, 103 (2021) 034906





LCC + flow

$A_{\rm ch}$ is a ***tricky*** observable!

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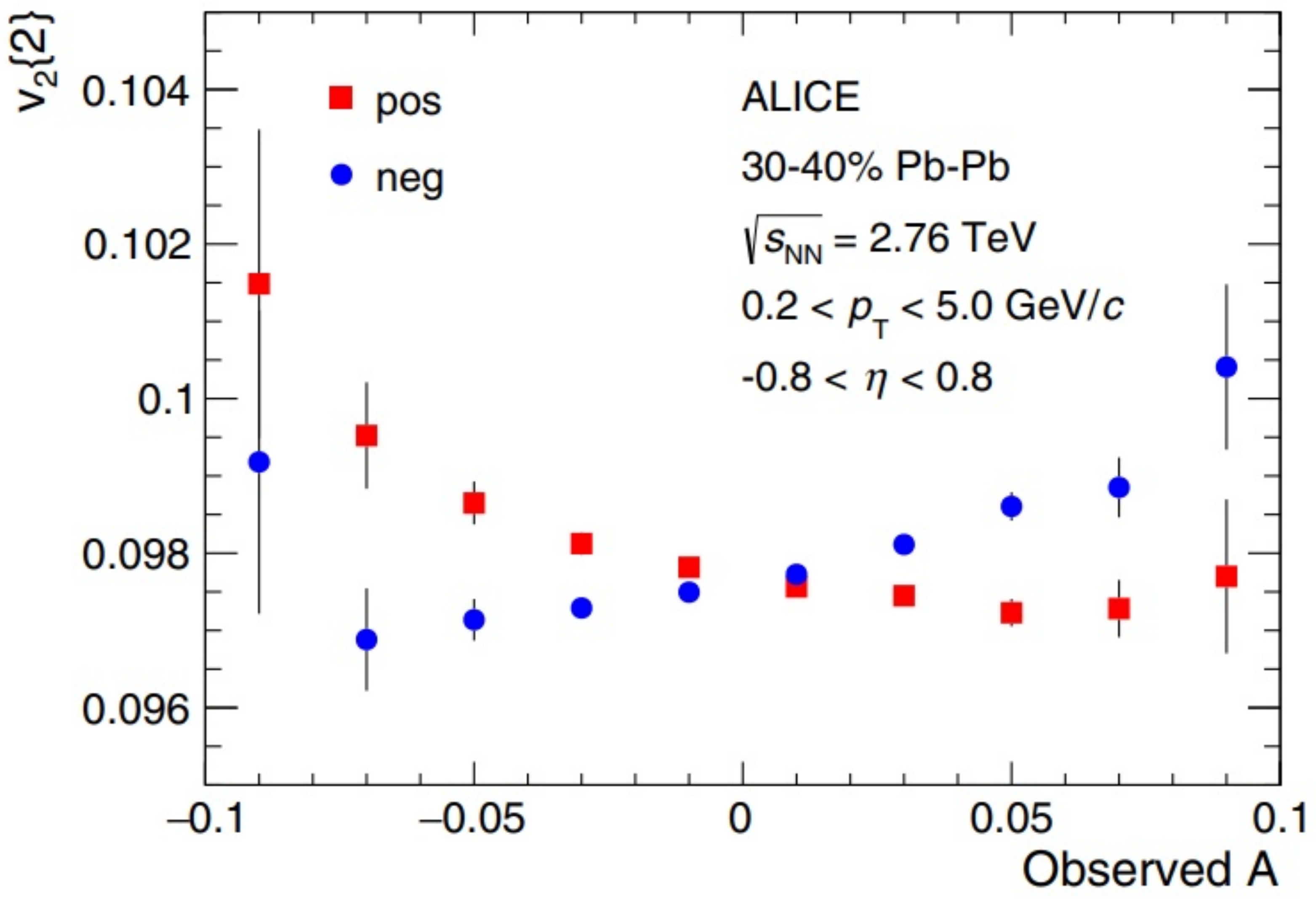
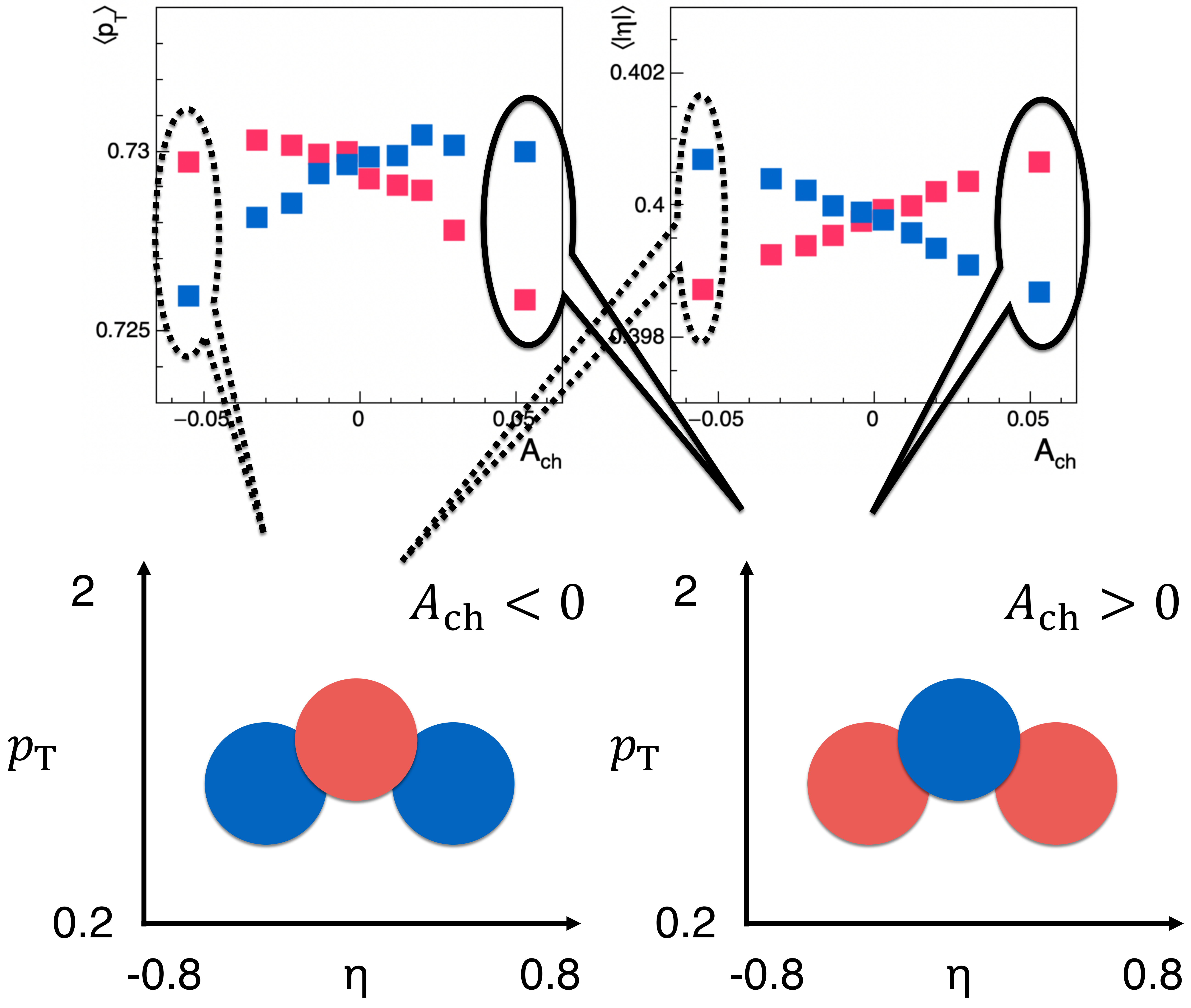
In practice, one preferentially applies nonuniform kinematic cuts on the charged particles

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



Same particles and cuts as measuring v_2. Stat. Unc. are invisible



Regardless of A_{ch}, $v_2^+(p_{\mathrm{T}},\eta) = v_2^-(p_{\mathrm{T}},\eta)$

When Introducing A_{ch},

v_2^+ = Integrate $v_2^+(p_{\mathrm{T}},\eta)$ in Red region

v_2^- = Integrate $v_2^-(p_{\mathrm{T}},\eta)$ in Blue region

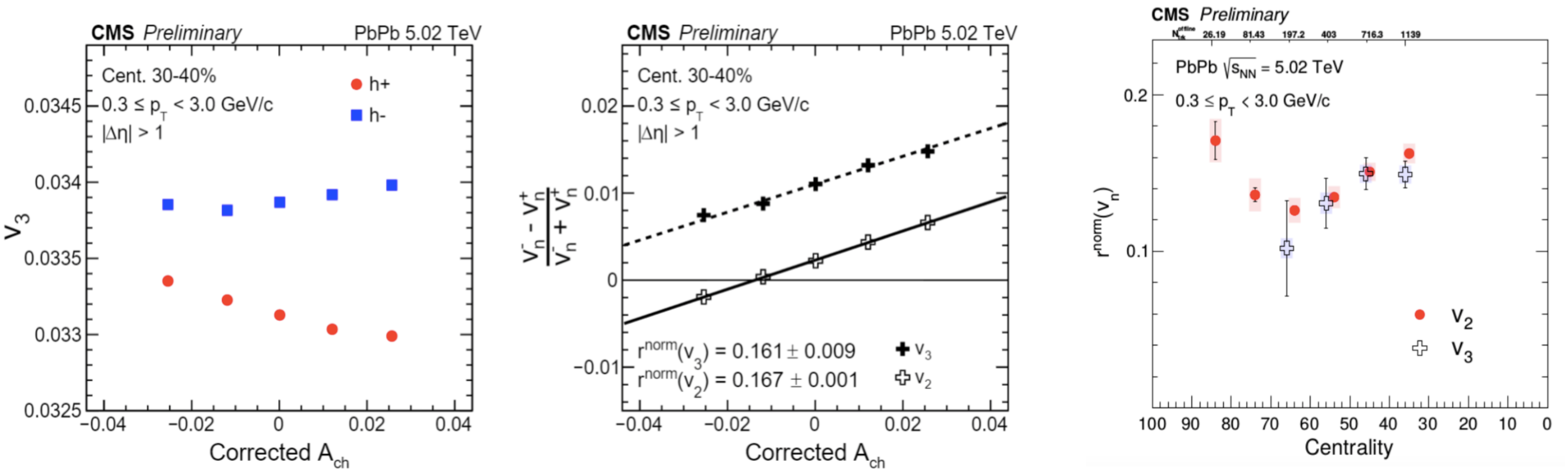
2D effect, NOT 1D!

If only consider the linear $v_2 \sim p_{\mathrm{T}}$, Wrong!

$\Delta p_{\mathrm{T}} \approx 0.004$, $\Delta v_2 \approx 0.002$ (not $v_2 \approx 0.1 * p_{\mathrm{T}}$)

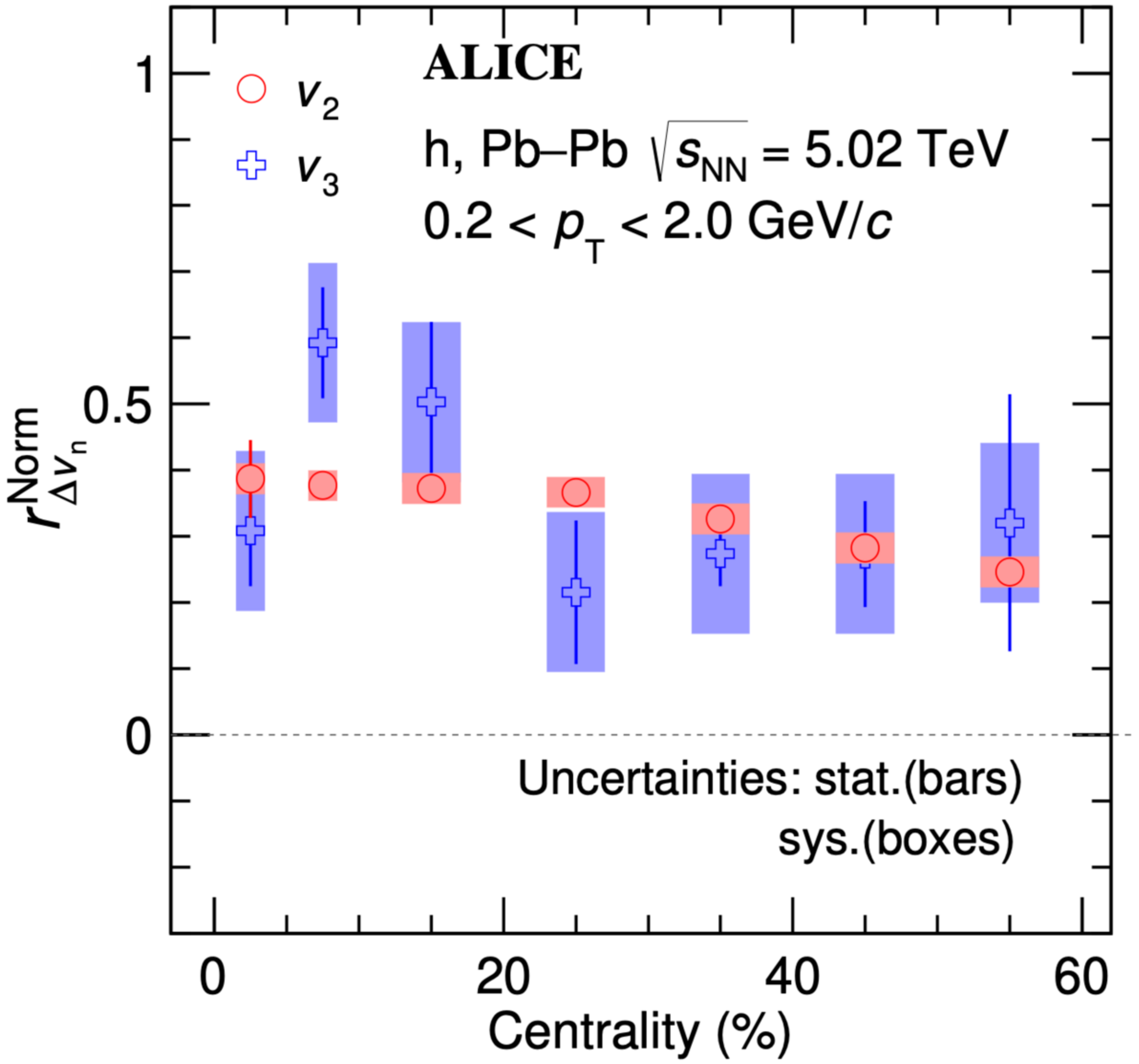
Can be reproduced by the LCC model very well!

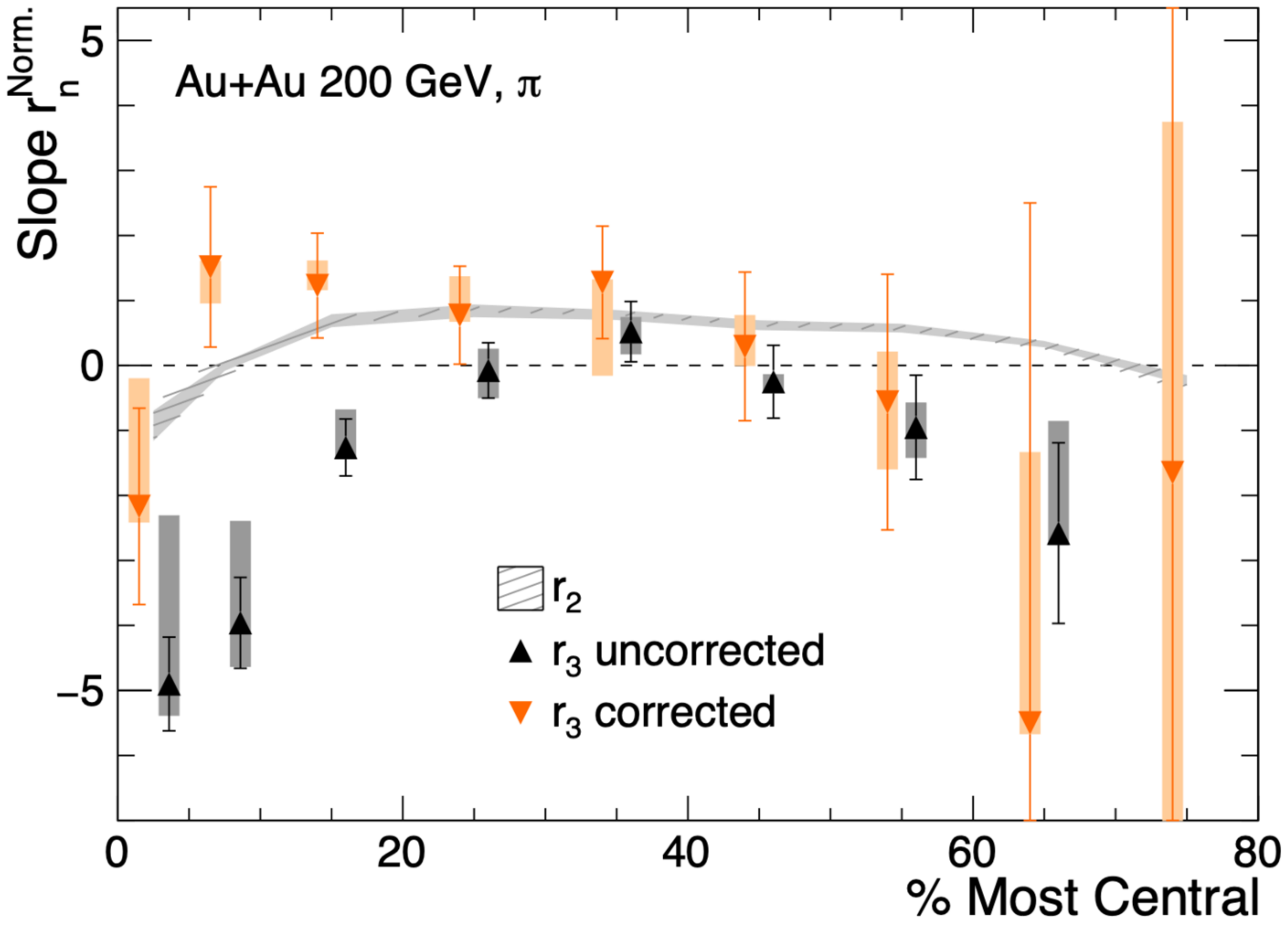
If it's local charge conservation: $v_{2,3} \sim A_{ch}$



Study of the background 2

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





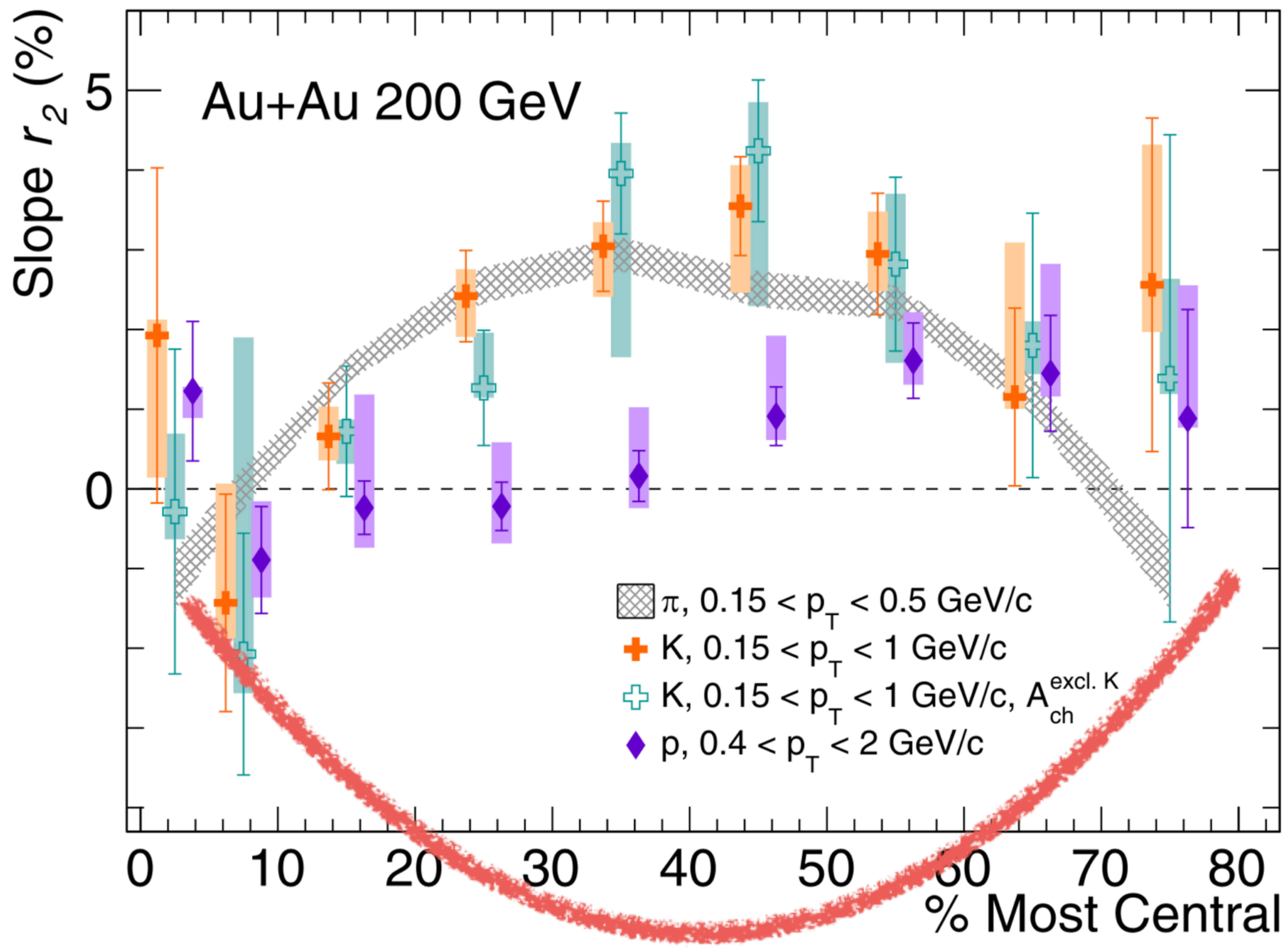
Contribution from:

$$d_n\{2;\pi^\pm h\} = \frac{d_n\{2;\pi^\pm h^+\} + d_n\{2;\pi^\pm h^-\}}{2} + \frac{d_n\{2;\pi^\pm h^+\} - d_n\{2;\pi^\pm h^-\}}{2} A_{ch}$$

as pointed out in NPA 1005, 121770 (2021)

Conclusion: No significant difference between v_2 and v_3 slopes, indicating the dominance of the LCC background.

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

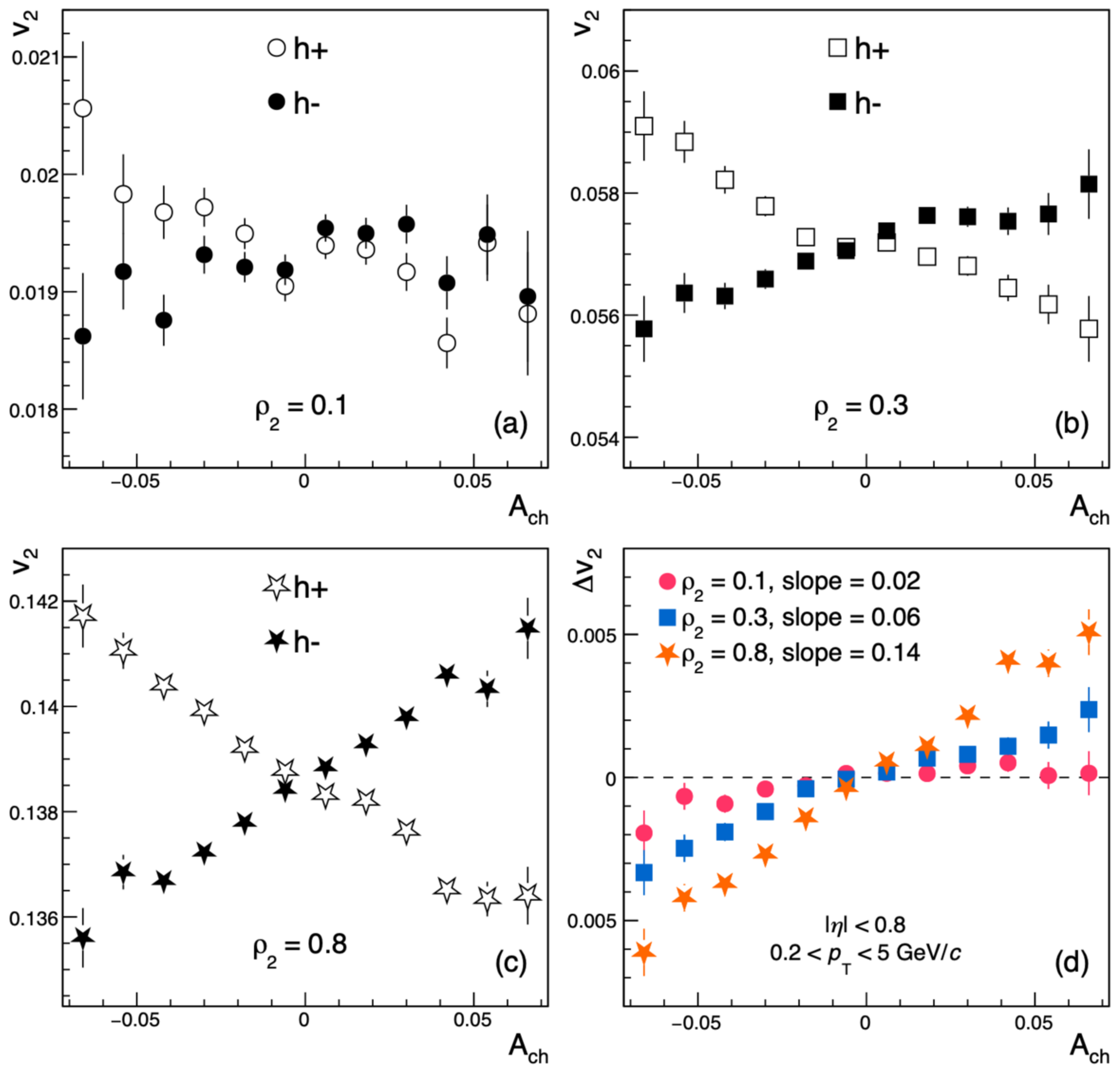


NPA 947, 155 (2016)
PRC 108, 014908 (2023)

The isospin effect doesn't play a significant role

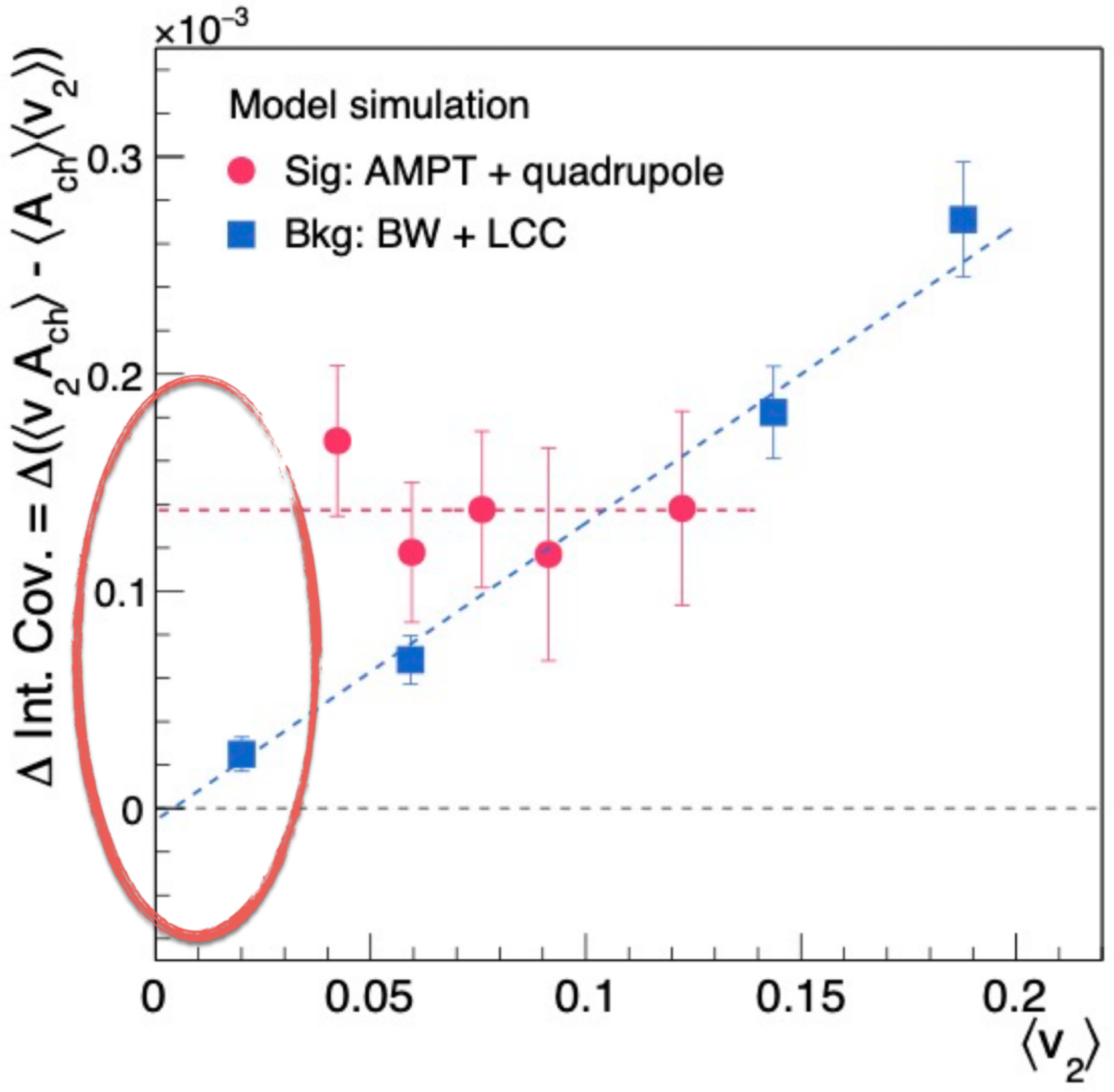
Distinguish the signal from the background

Model



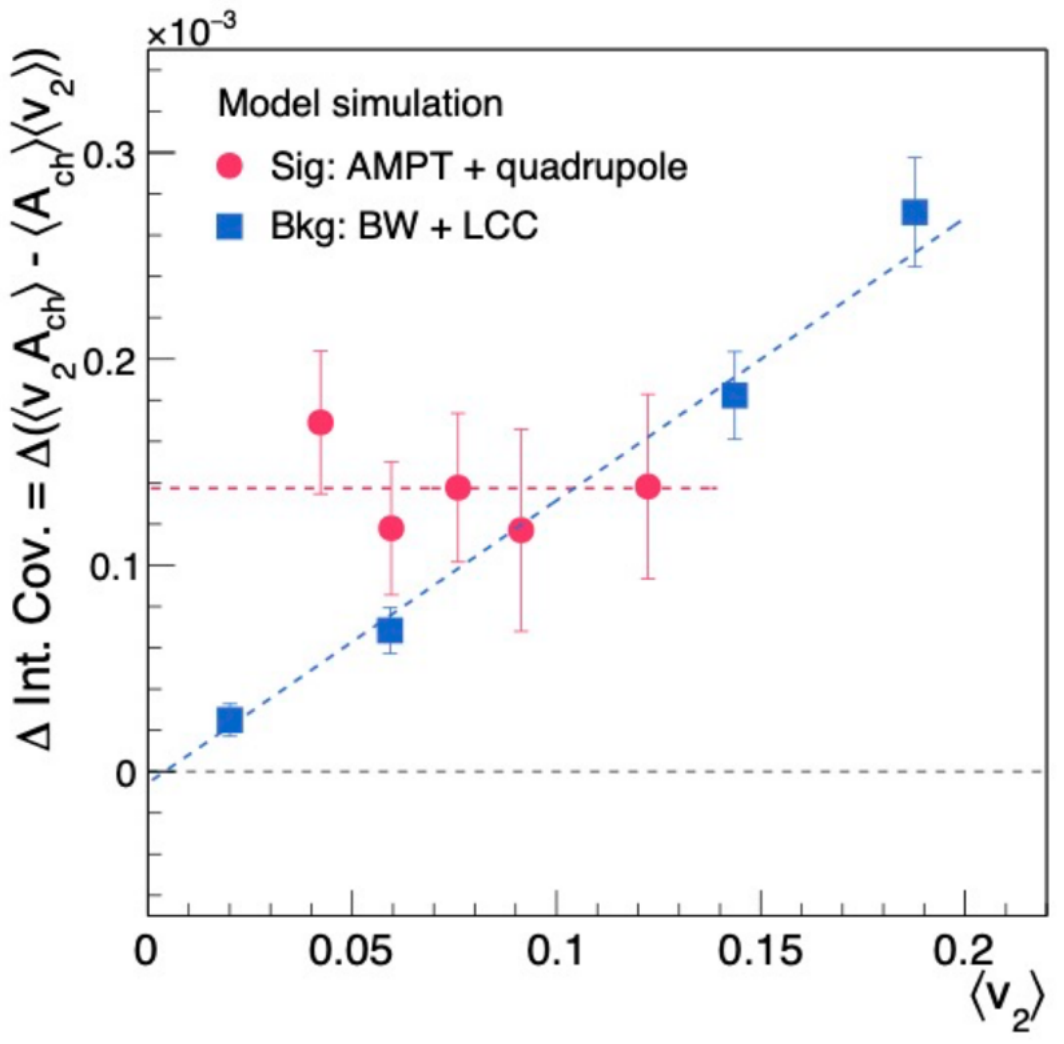
Event Shape Engineering again!

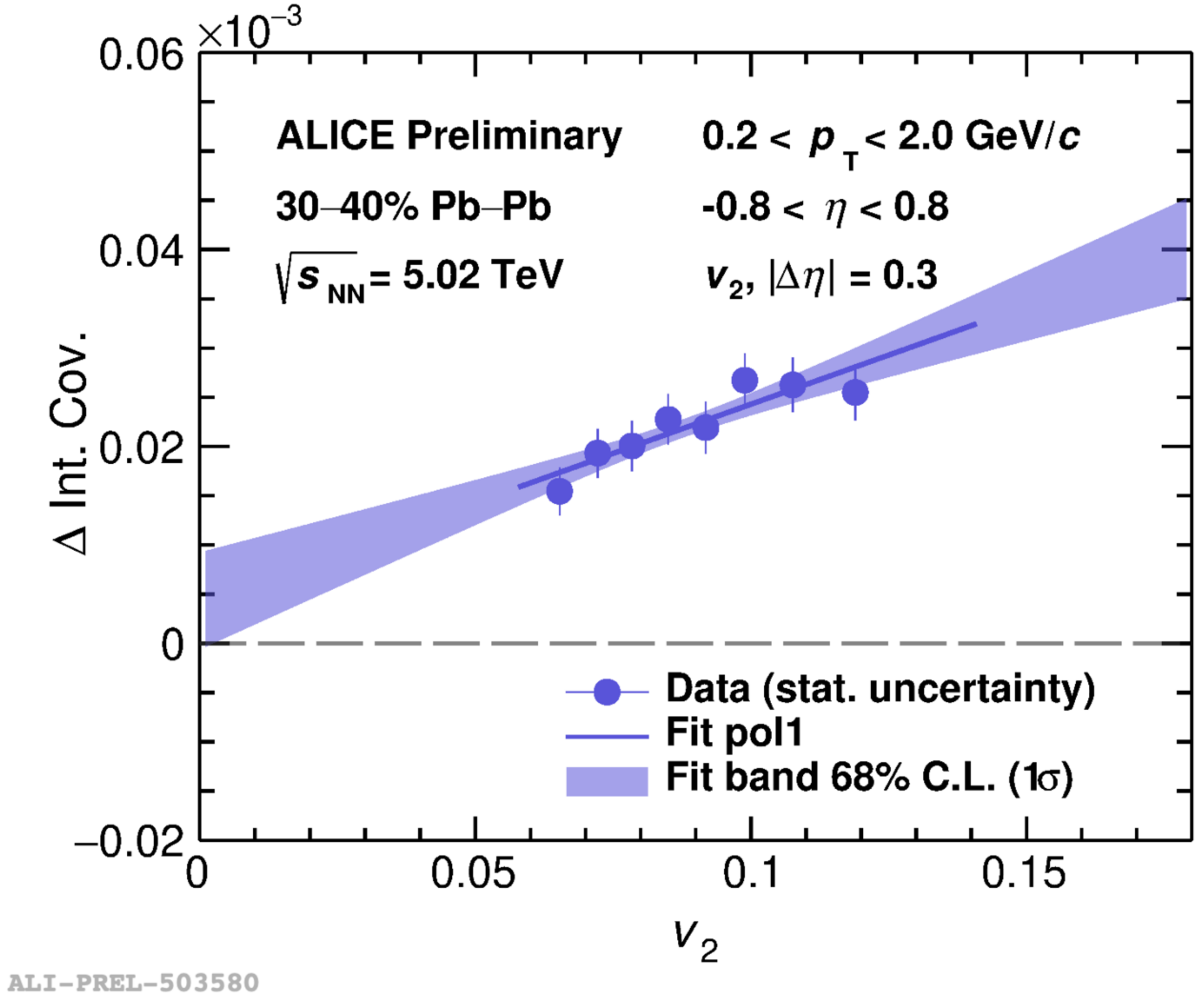
Phys. Lett. B 820, 136580 (2021)

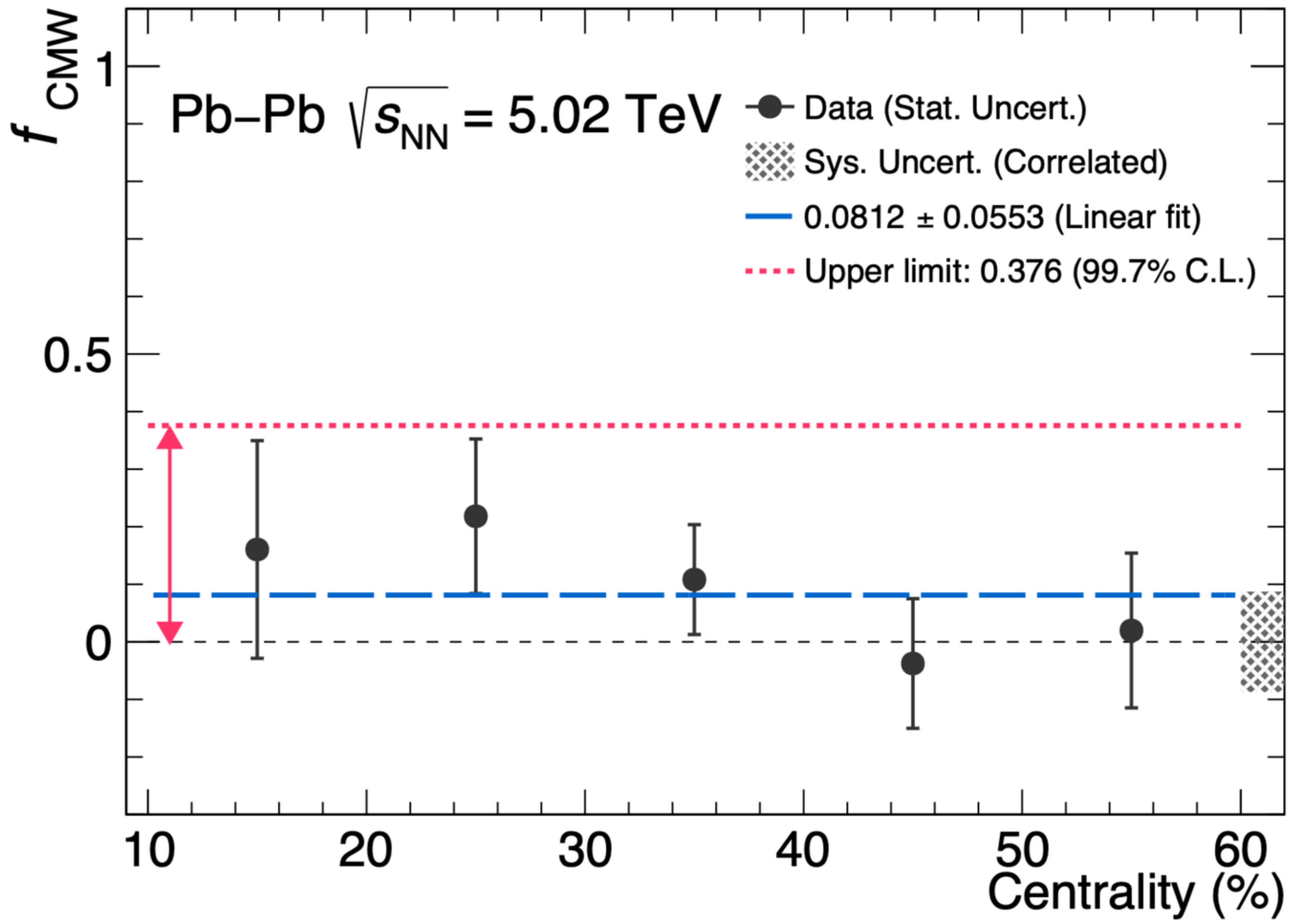


Experimental search for the CMW: current status

arxiv:2308.16123







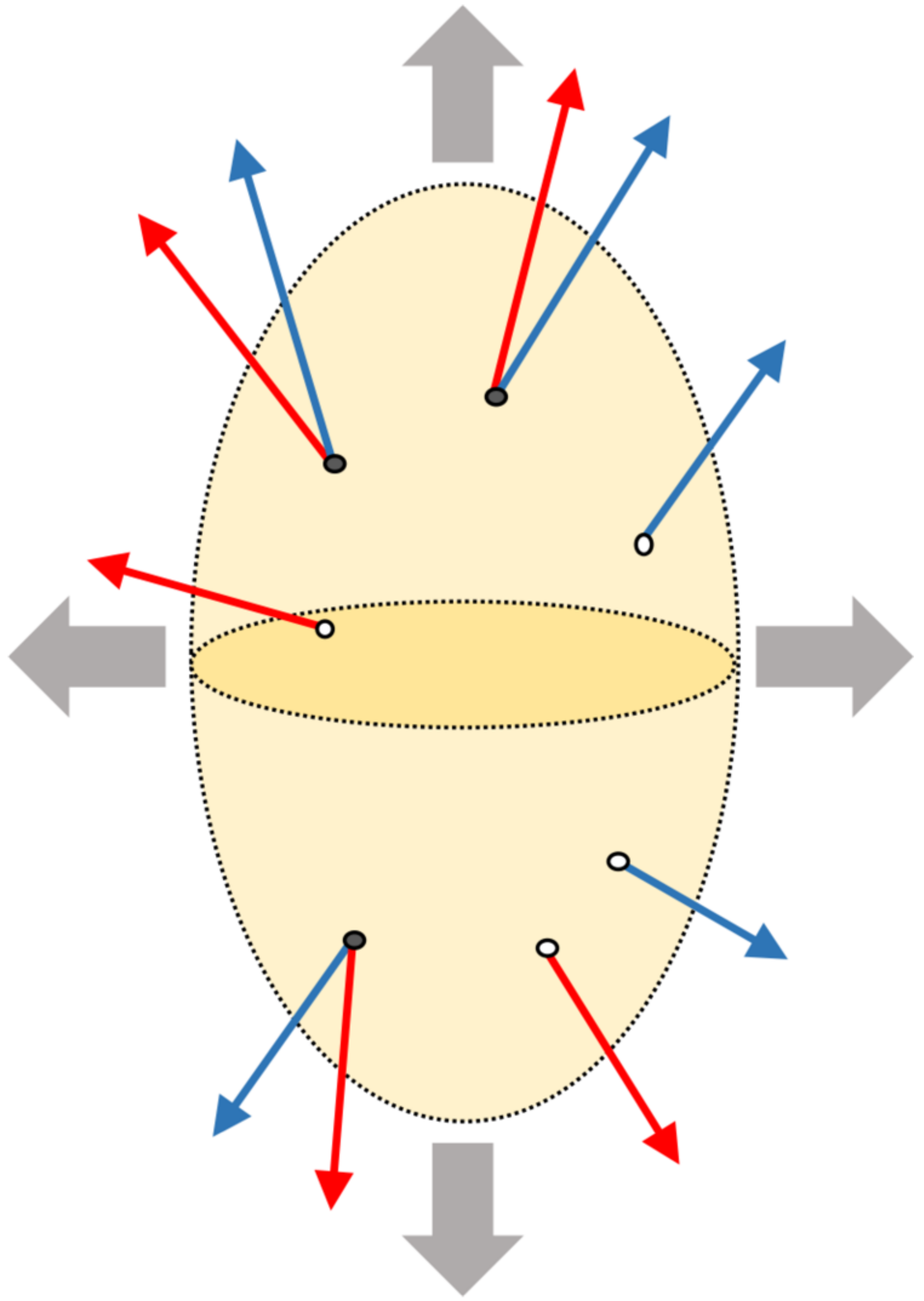
In 10-60% centrality: $f_{CMW} \sim 0.08 \pm 0.06$

A comparison between CME and CMW

	CME	CMW
Observable	Δγ, Δδ…	A_{ch}-v_2 slope
Signal	electric dipole	electric quadrupole
Background	LCC + collectivity	
Methods valid for both	2nd- and 3rd-order observables, ESE…	

A universal LCC background for CME and CMW

A modified
blast wave model



Single production: 4
Pair production: 3
fLCC = 3/7 ≈ 0.43

PHYSICAL REVIEW C **107**, L031902 (2023)

Letter

Global constraint on the magnitude of anomalous chiral effects in heavy-ion collisions

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TABLE I. List of the modified BW parameters for Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

Centrality	0–5 %	5–10 %	10–20 %	20–30 %	30–40 %	40–50 %	50–60 %	60–70 %
T_{kin}	111.34	106.96	104.78	107.37	111.63	115.14	118.14	128.20
R_x/R_y	0.956	0.934	0.905	0.872	0.845	0.823	0.807	0.786
ρ_0	1.262	1.267	1.254	1.226	1.196	1.148	1.087	0.994
ρ_2	0.054	0.063	0.11	0.135	0.15	0.145	0.121	0.115
N_{ch} ($\lvert\eta\rvert < 0.8$)	2290	1858	1334	904	608	369	222	117
f_{LCC}	0.71	0.62	0.58	0.56	0.54	0.48	0.47	0.46

Pure data-driven: all parameters are determined based on experimental results.
Now, inclusive spectra (no PID in this work), v2, mult., BF are all comparable with data.

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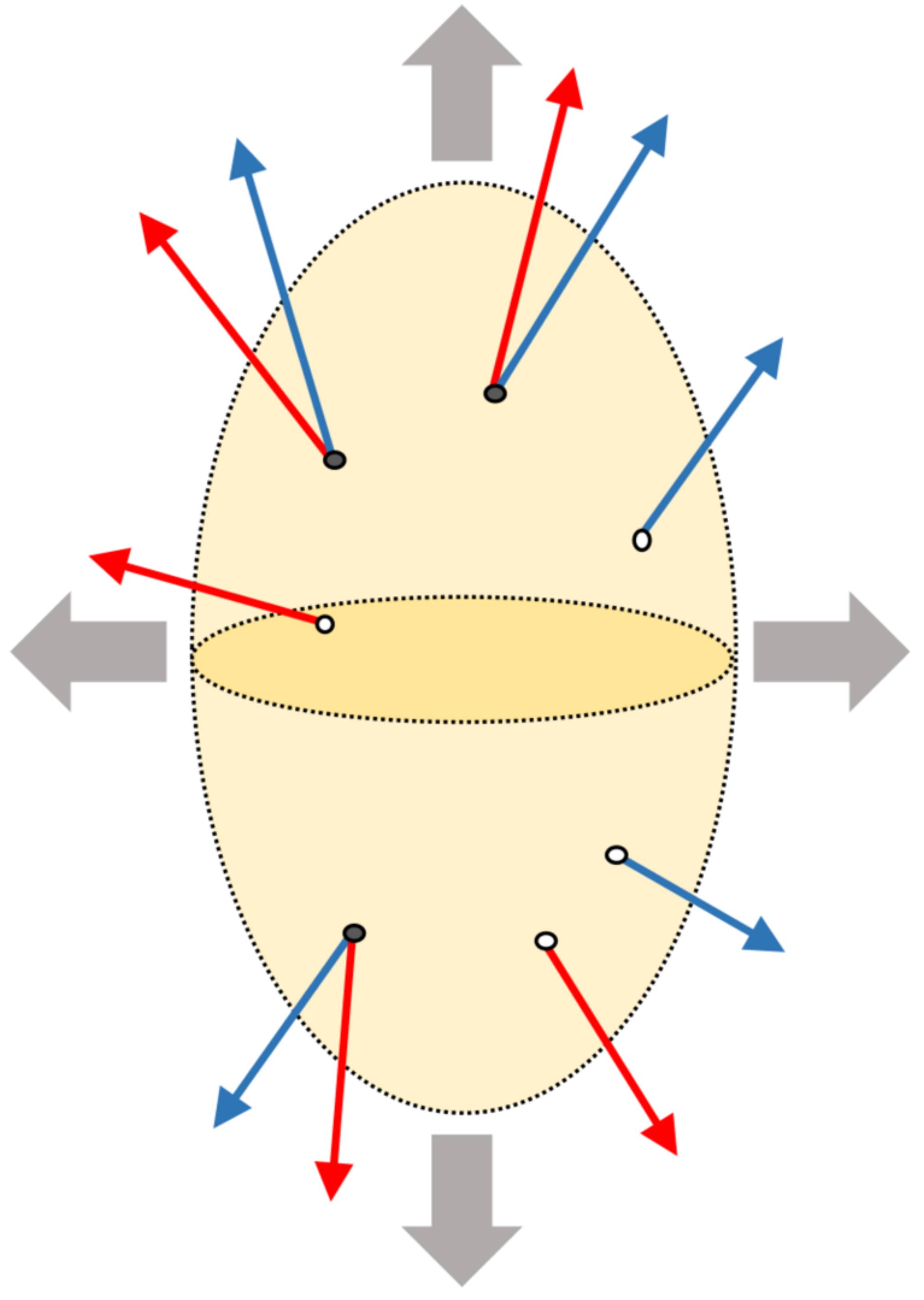
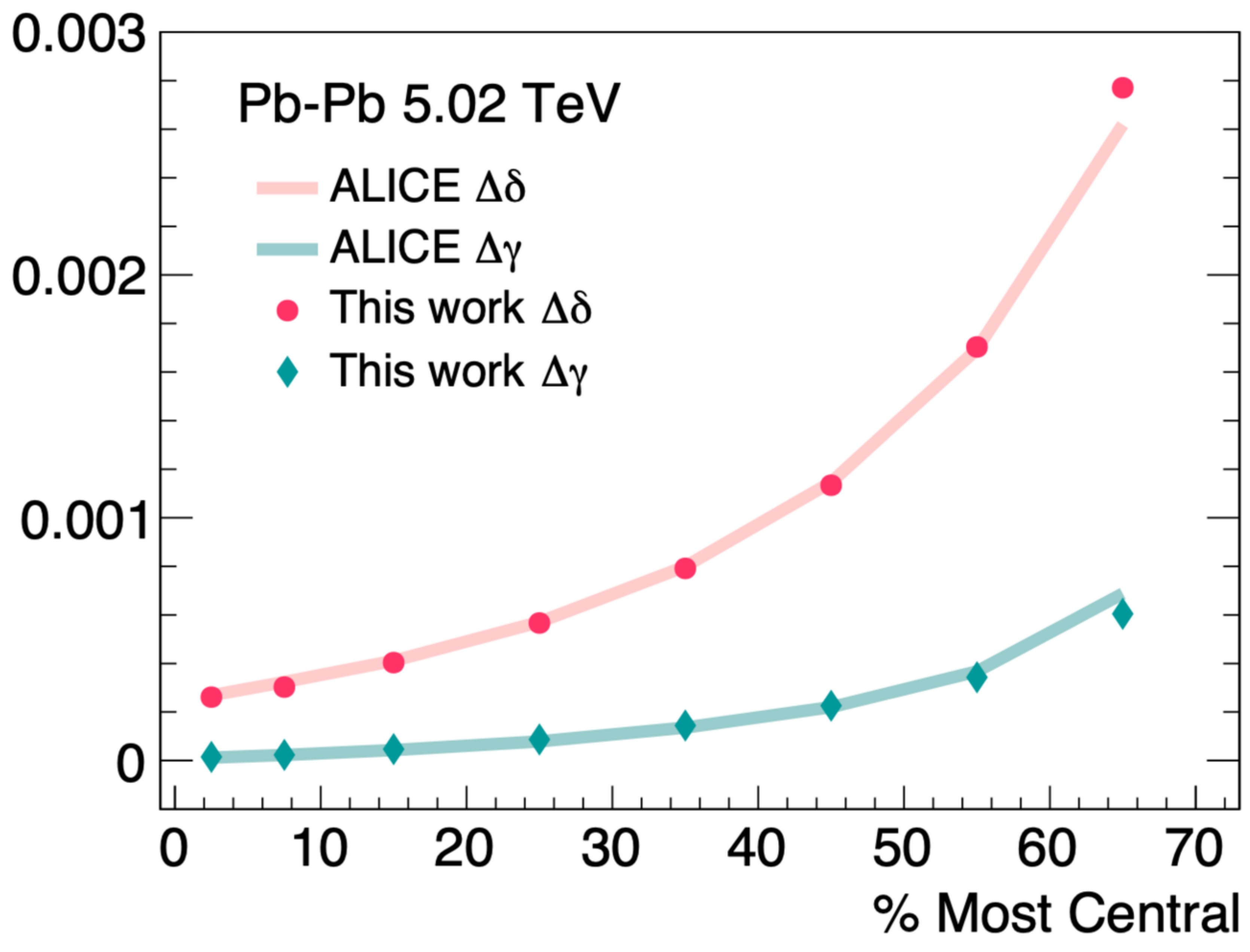
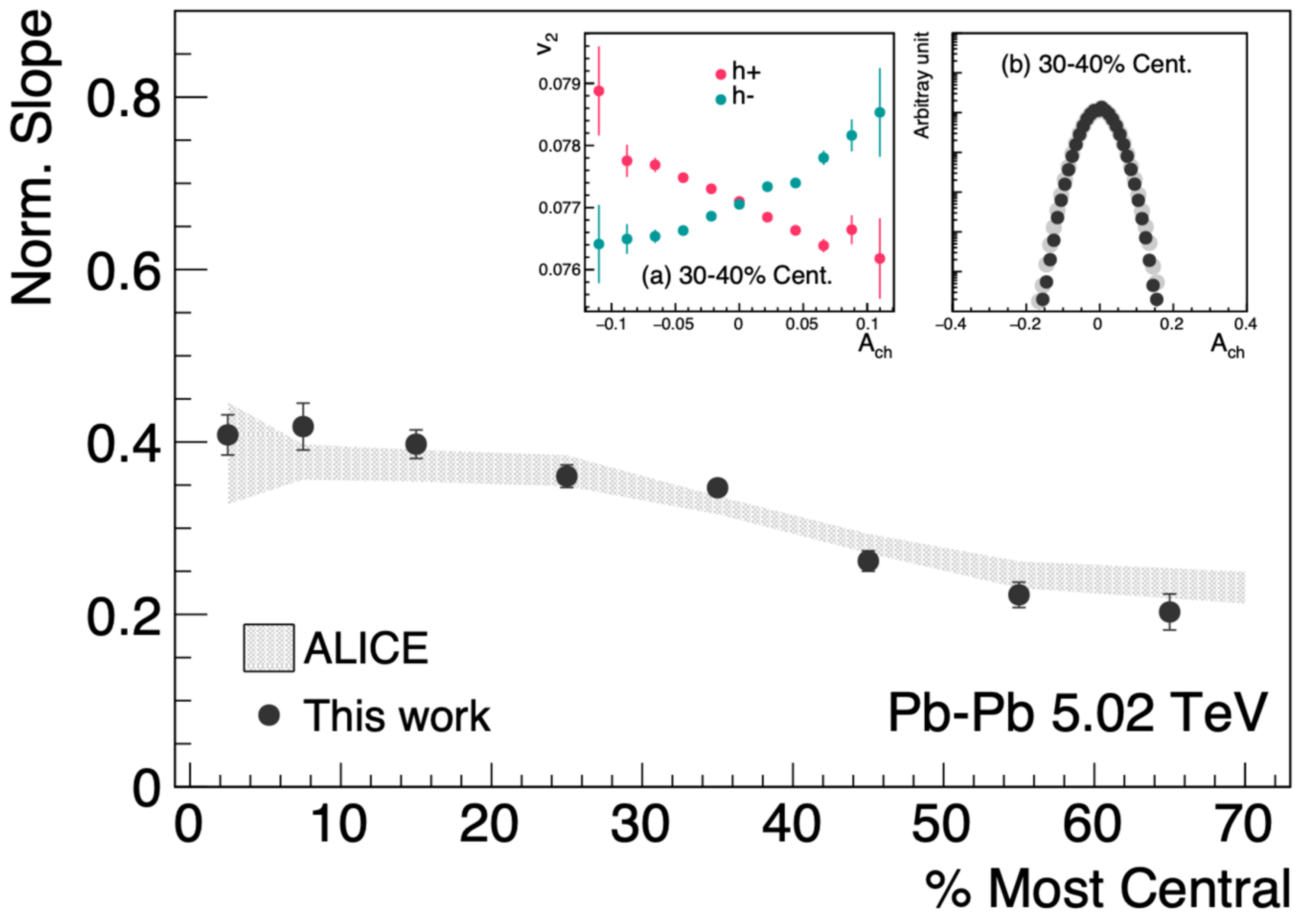
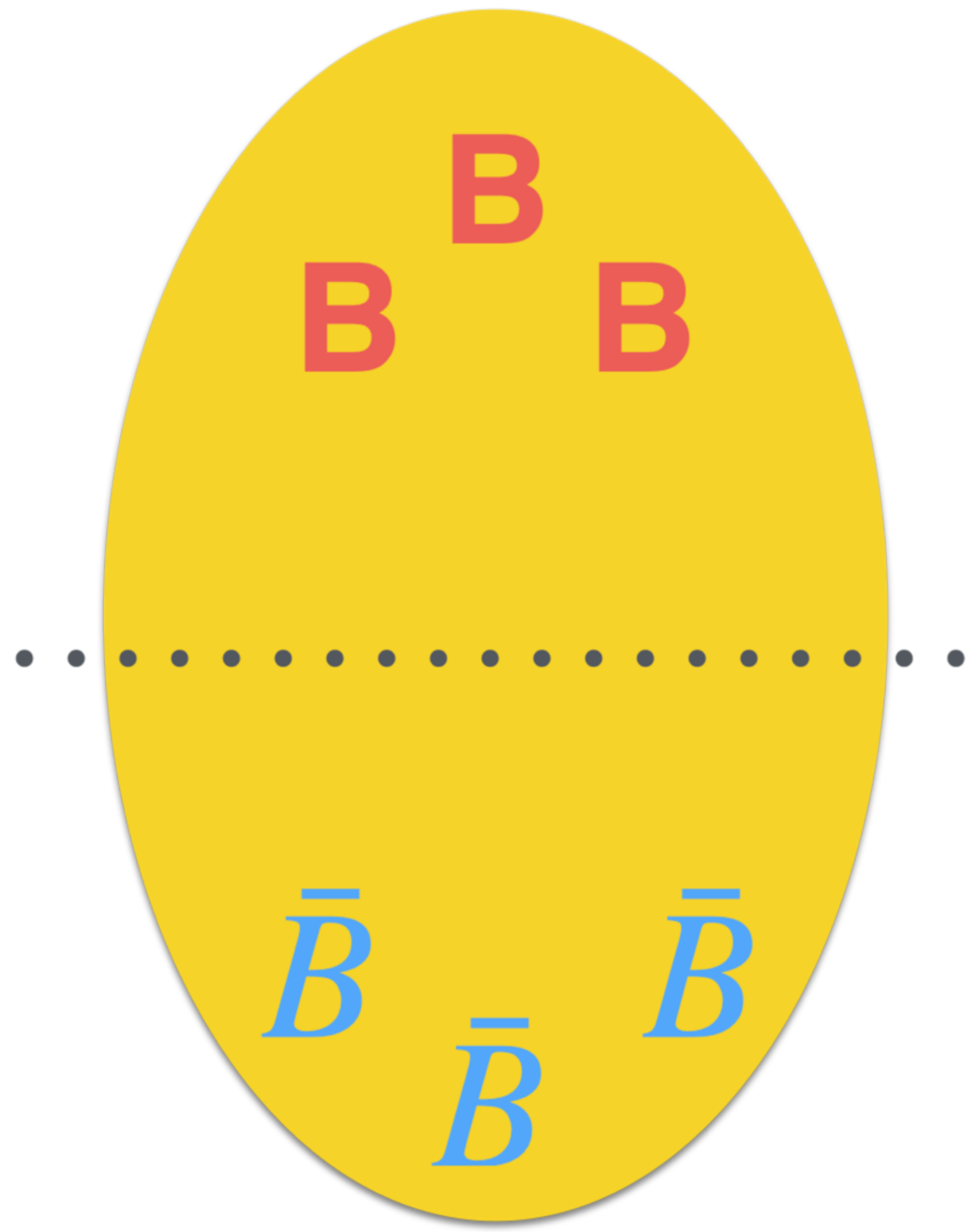






- The CME and the CMW observables can be simultaneously and perfectly described within 10% deviation.
- Unify studies of the CME and the CMW for the first time.
- Following the principle of parsimony, we argue that, in LHC energy, the measured results of the CME and the CMW can be interpreted by the LCC entwined with the collective flow.

The latest study on the CVE



CVE
Possible effect: Out-of-plane baryonic dipole moment
Observables: PID δ, γ correlator

Please refer to

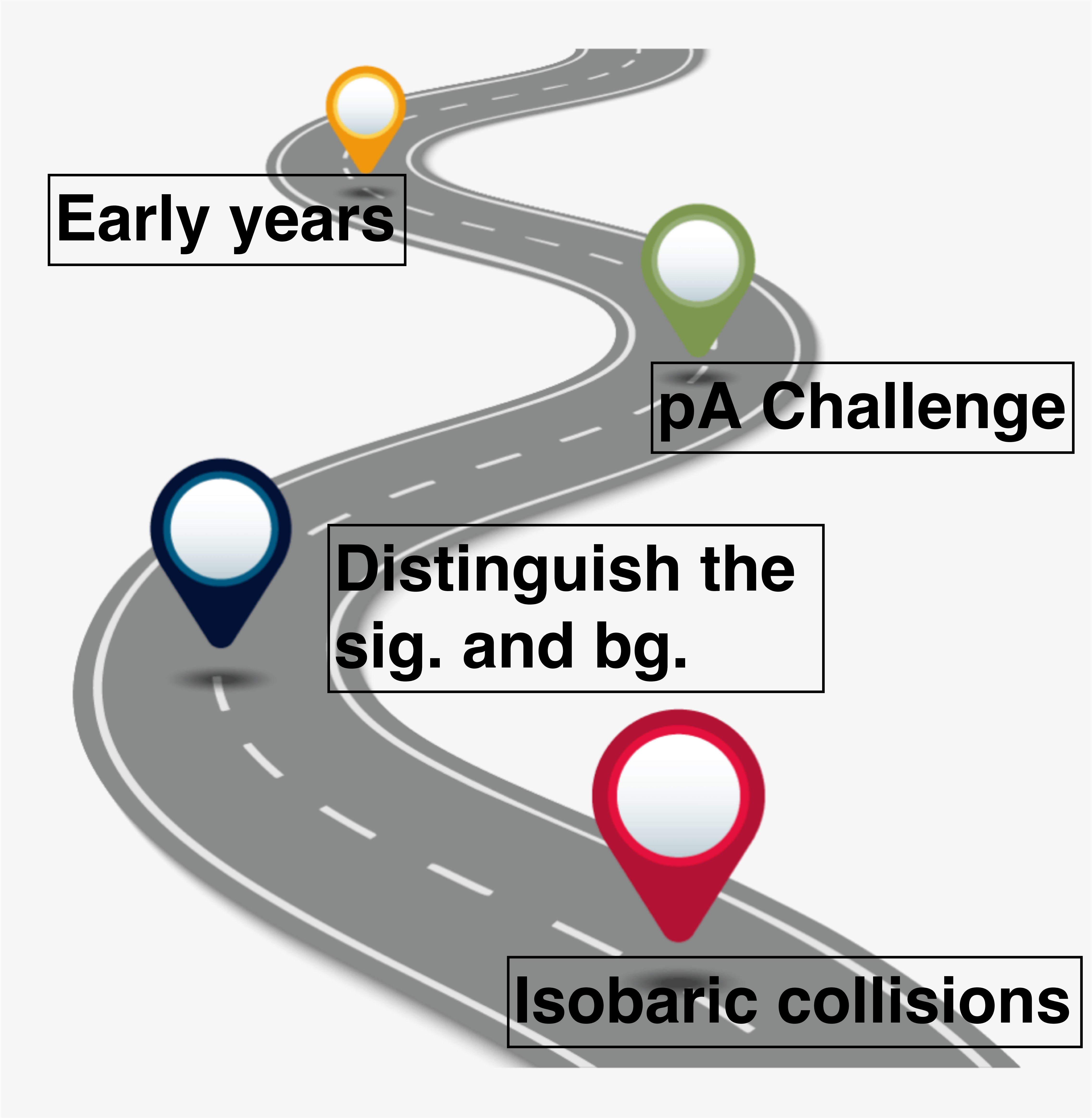
ALICE
Quark Matter 2023 (3-9 September 2023): Search for anomalous chiral effects in heavy-ion collisions with ALICE · Indico (cern.ch)

STAR
Quark Matter 2023 (3-9 September 2023): Search for the Chiral Magnetic and Vortical Effects Using Event Shape Variables in Au+Au Collisions at STAR · Indico (cern.ch)

Anomalous chiral effects have been deeply studied for a decade…

2009 ~ 2015
First attempt: early results favor the explanation of signals

Since 2016
Various new observables and methods are proposed to distinguish the signal from the background



Since 2015
Similarity between p-A and A-A collisions

2018 - present
Dedicated collisions and blind analysis
A unified background

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

Thank you for your attention!