Chirality, Magnetic Field and Quark-Gluon Plasma in Heavy Ion Collisions at RHIC

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T.D. Lee's Impact on me:

CUSPEA 1983

RHIC & STAR-China Collaboration

Parity Violation

Weak Interaction -- Neutrino Helicity (left-handed neutrino),
Goldhaber, Grodzins and Sunyar experiment
Neutrino mass, neutrinoless double beta decay experiment

Magnetic Effect – local parity violation in strong interaction

“细推物理须行乐”

What was Professor T.D Lee trying to tell us by this statement ?

Robert R. Crease:
Recombinant Science – The Birth of the Relativistic Heavy Ion Collider (RHIC)

“With Beaujolais,” Lee remarked later, “you can look into the future more easily.”

Three Physics Topics

Chiral Magnetic Effect

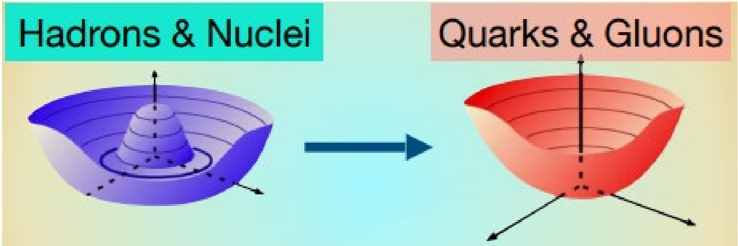
Magnetic Field in Heavy Ion Collisions

sPHENIX Experiment and the Physics Program

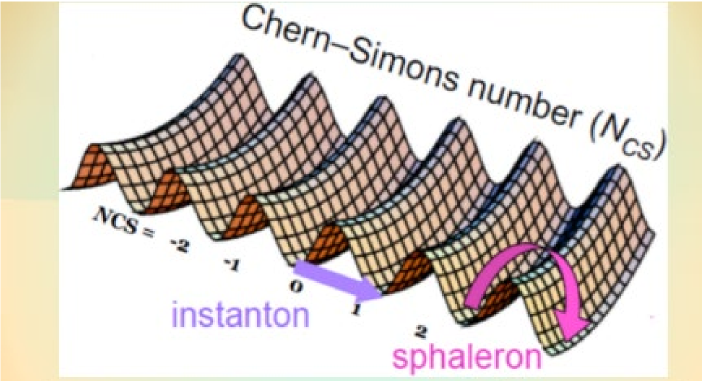
Chiral Magnetic Effect

- Introduction to CME
- Lessons from Previous Results
- Novel Approach of Event Shape Selection (ESS)
- STAR ESS Results from BES-II and 200 GeV Data
- Summary and Future Outlook

Chiral Magnetic Effect

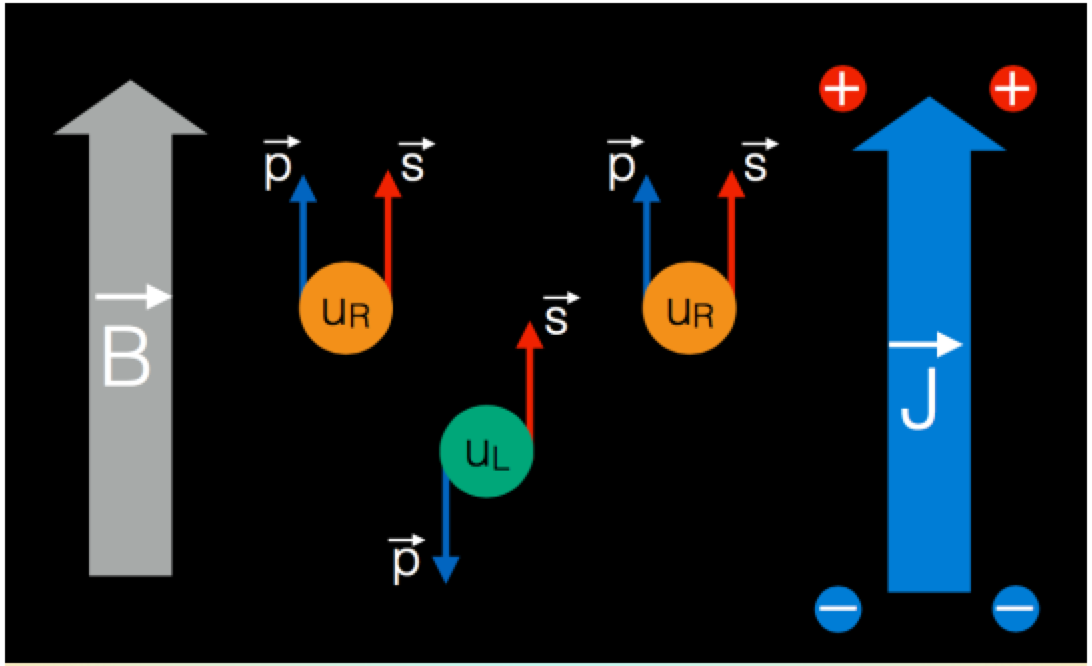


Chiral symmetry restoration (massless quarks)



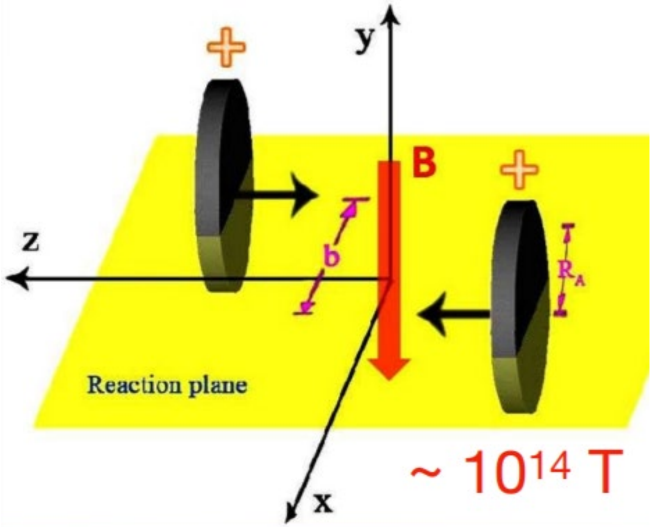
Chirality imbalance (finite μ_5)

A Rare Opportunity to Experimentally Access Key Intrinsic Properties of the QCD



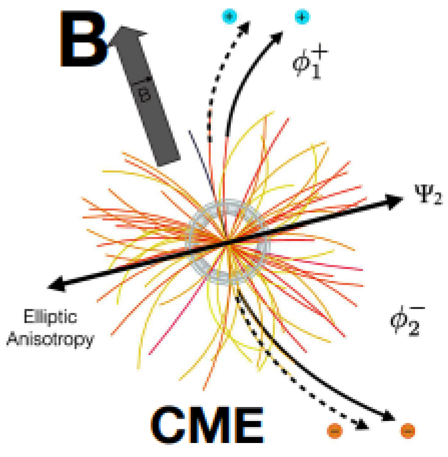
Chiral Magnetic Effect (J || B)

$$\vec{J} = \frac{e^2}{2\pi^2}\mu_5 \vec{B}$$



Strong magnetic field (B)

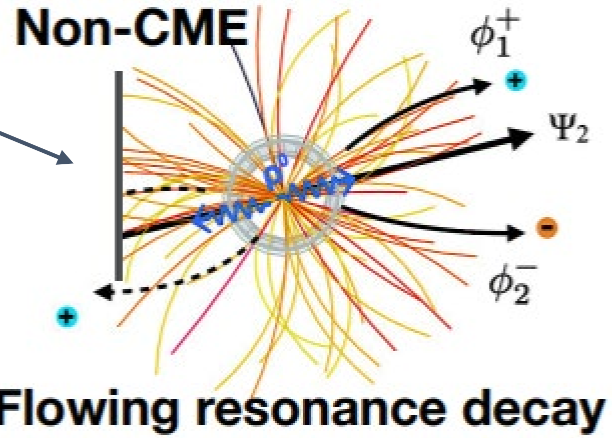
CME Observables



$$\frac{dN_\pm}{d\varphi} \propto 1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2a_1^\pm \sin(\varphi - \Psi_{RP}) + 2v_2\cos(2\varphi - 2\Psi_{RP}) + \ldots$$

$\propto \mu_5 B$

Parity odd, can not directly observe



Popular CME-sensitive observables:

- γ correlator

S.A. Voloshin, Phys. Rev. C70(2004)057901

- *R* correlator

N. N. Ajitanand et al., Phys. Rev. C83(2011)011901(R)

- Signed balance functions

A. H. Tang, Chin. Phys. C44, No.5 (2020)054101

Model studies show that these methods have similar sensitivities to the CME signal and to the background. (Best Paper Award 2023)

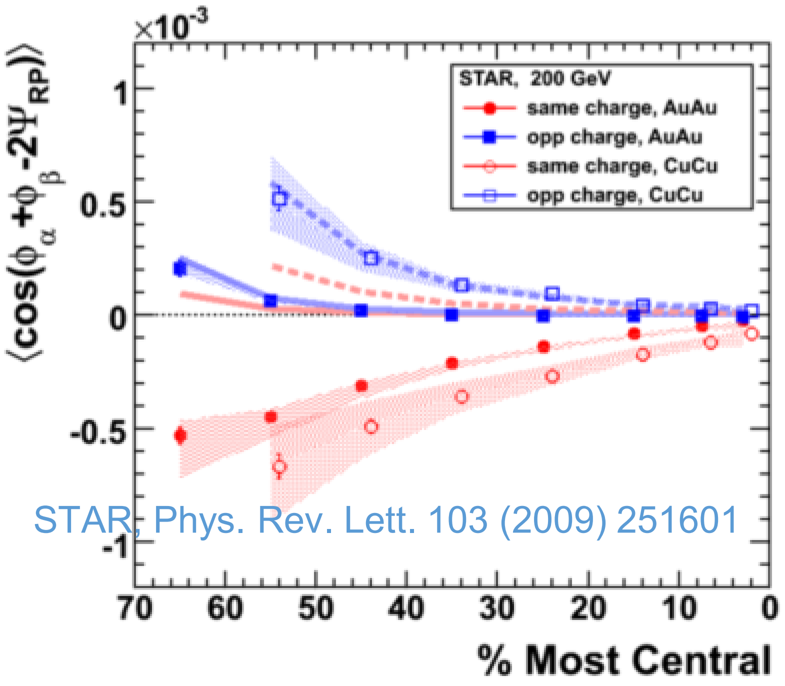
S. Choudhury et al.(STAR), Chin. Phys. C46(2022)014101

Here, we focus on $\gamma^{112} \equiv \langle \cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}) \rangle$

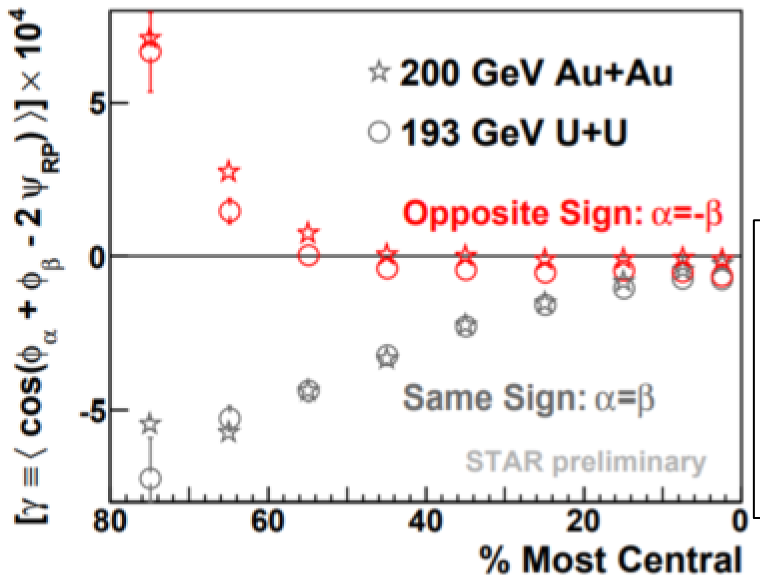
The CME causes $\Delta\gamma^{112} \equiv \gamma^{112}_{OS} - \gamma^{112}_{SS} > 0$

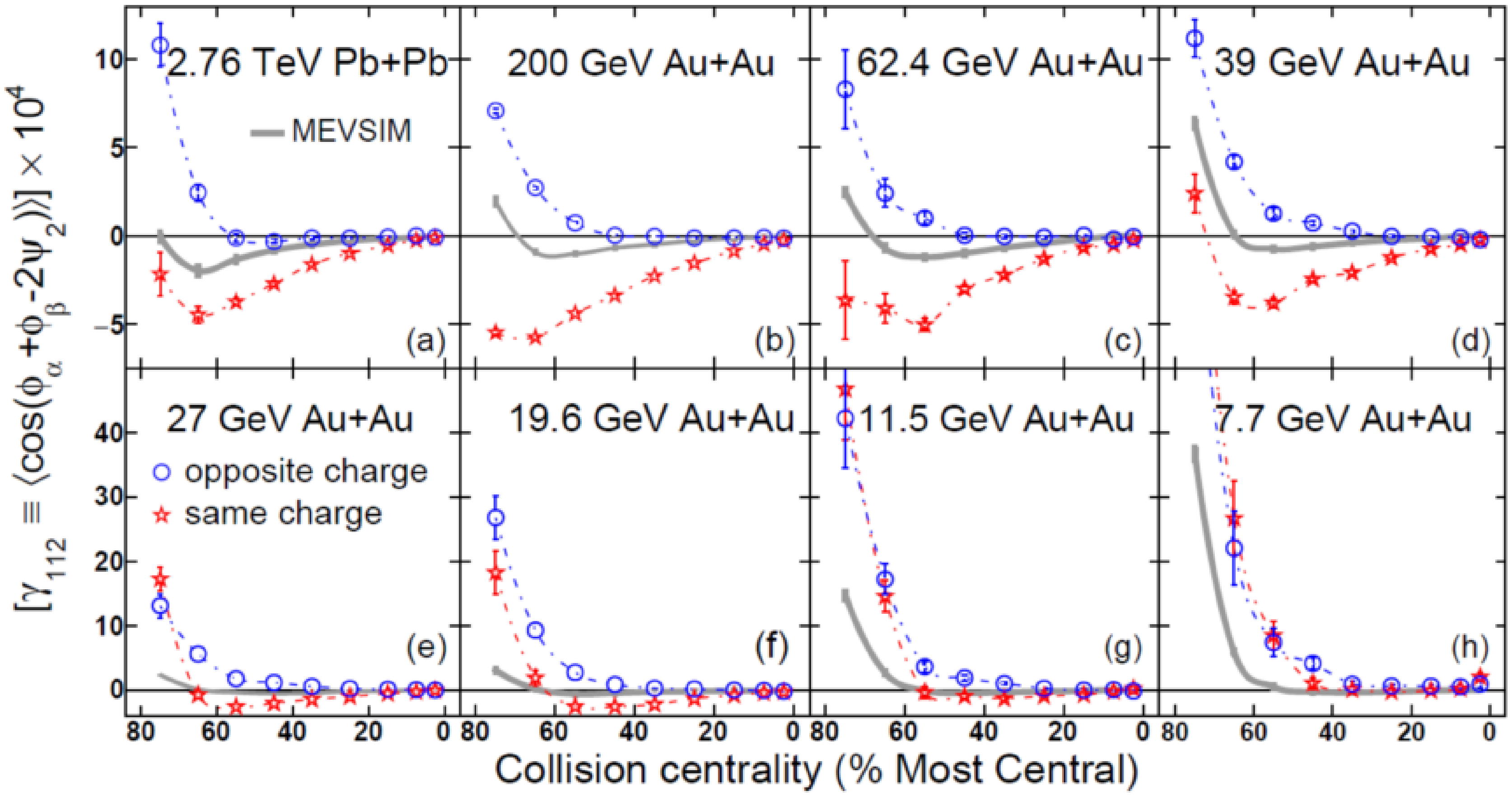
Background indicator $\gamma^{132} \equiv \langle \cos(\varphi_\alpha - 3\varphi_\beta + 2\Psi_{RP}) \rangle$

Initial Measuremets



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



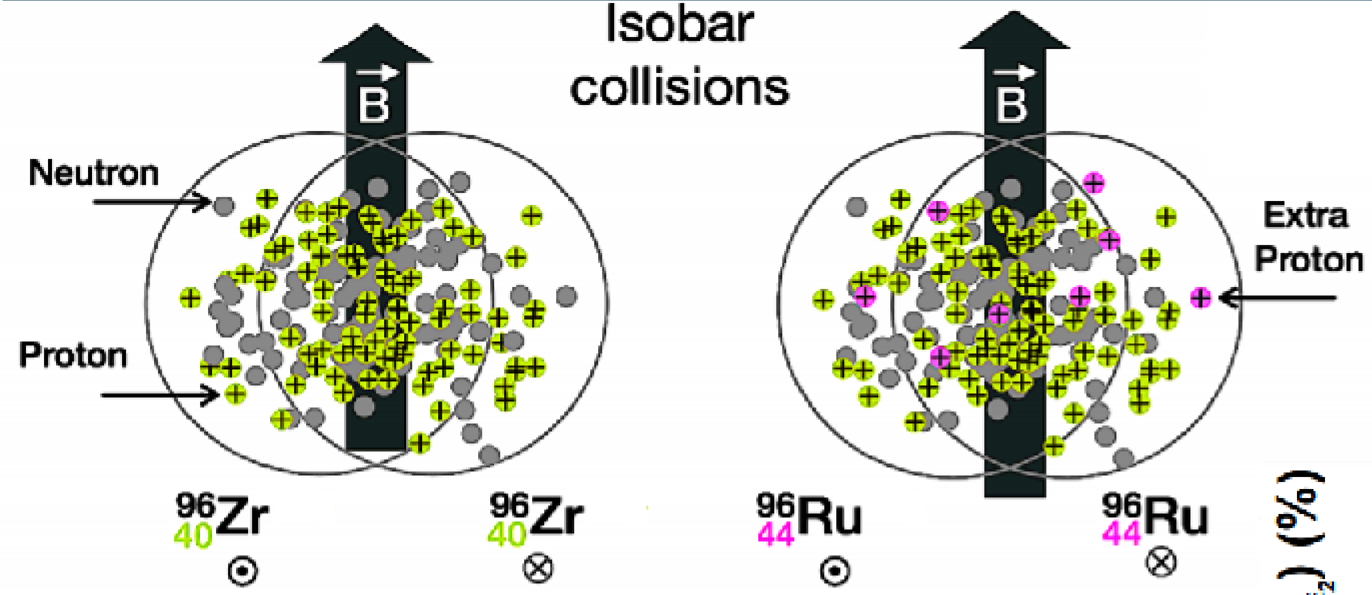


ALICE, Phys. Rev. Lett. 110(2013)012301. STAR, Phys. Rev. Lett. 113(2014)52302

In various collision systems and at different beam energies, positively finite $\Delta\gamma_{112}$ meets the CME expectation, but could contain contributions from:

- Flow-related background $\propto v_2$ (elliptic flow)
- Nonflow-related background (di-jets)

Isobar Collisions: An Excellent Idea



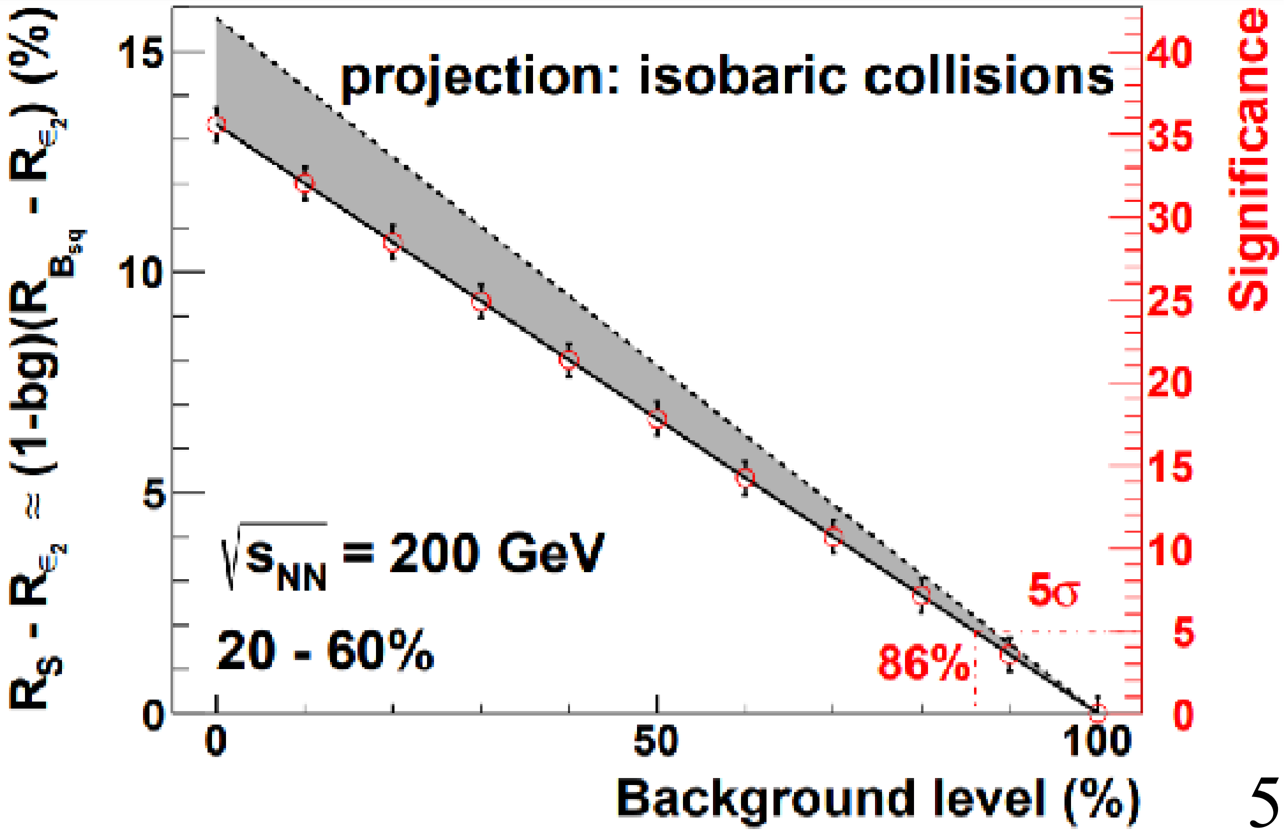
Compare the two isobaric systems:

- CME: B-field^2 is ~15% larger in Ru+Ru
- Flow-related BKG: utilize $\Delta\gamma_{112}/v_2$
- Nonflow-related BKG: almost same

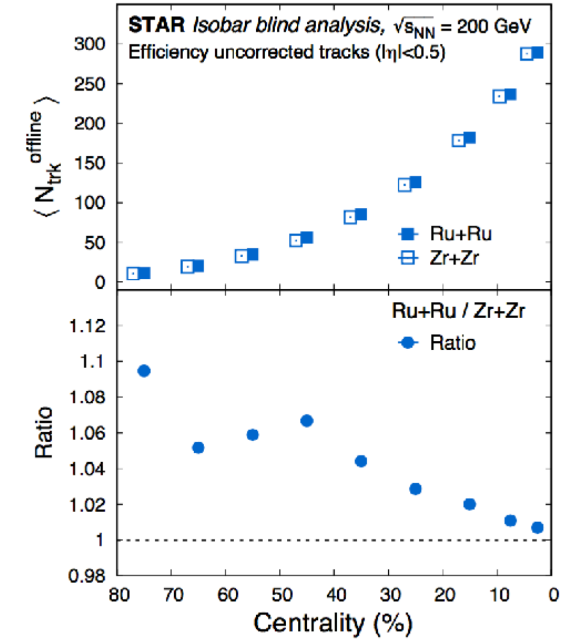
Isobar collisions provide a good control of signal and background.

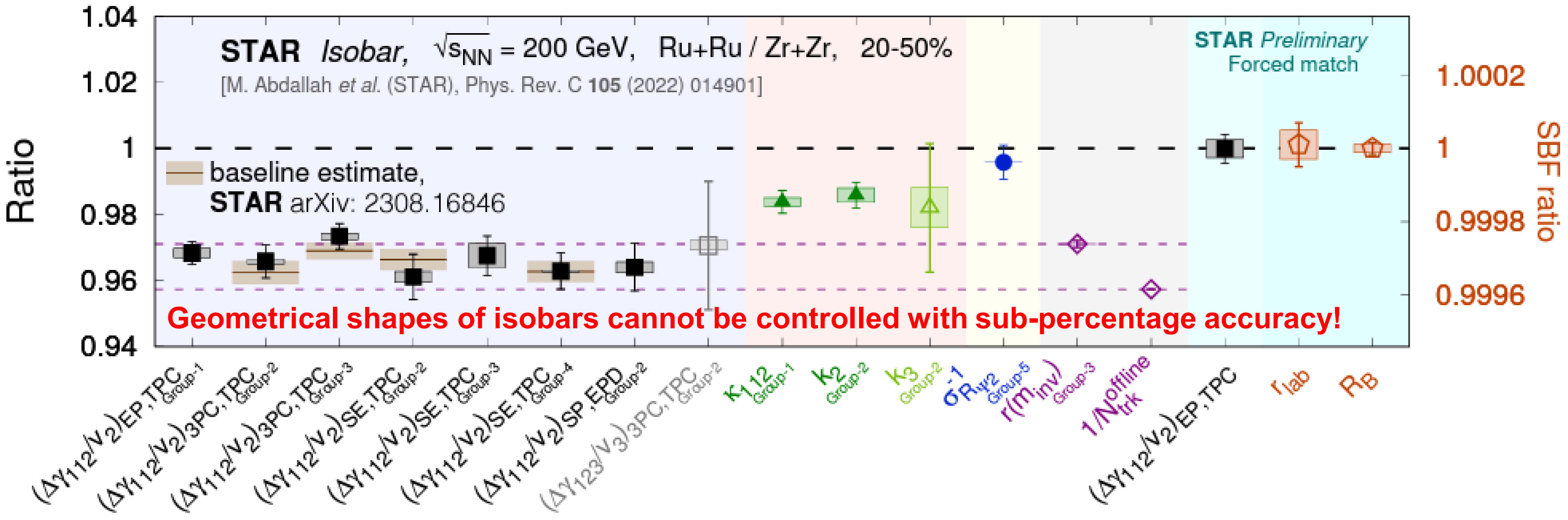
2.5 B events per species:

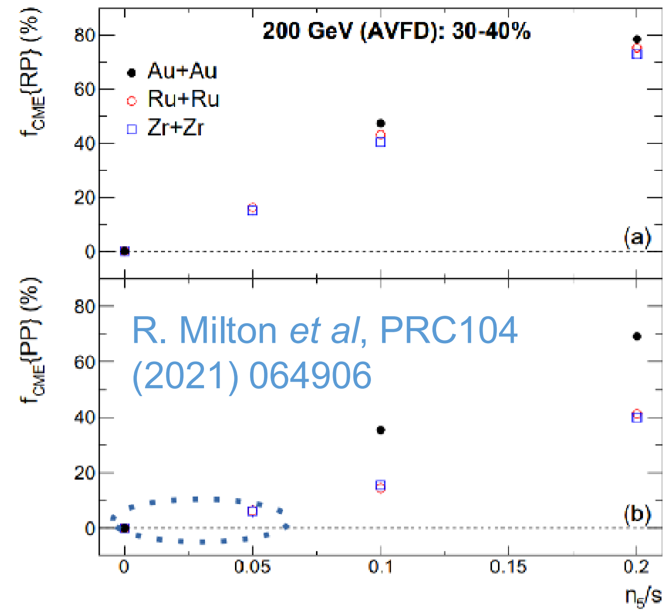
- uncertainty of 0.4% in the $\Delta\gamma_{112}/v_2$ ratio.
- if f_{CME} > 14%, $\Delta\gamma_{112}/v_2$ difference > 2%, yielding a 5σ significance.
- f_{CME} is the unknown CME fraction in $\Delta\gamma_{112}$.



Isobar Collision Results: Nature is Cruel







Why is f_{CME} so small?

AVFD simulations: f_{CME} is smaller in isobars than Au+Au, especially when using participant plane.

Smaller system → larger fluctuation
→ larger BKG & smaller CME signal → double-killed f_{CME}

We need to focus on large systems like Au+Au, and directly suppress the background.

Event Shape Selection (ESS)

Event Shape Selection Analysis Goals:

Suppress background from --

- **Flow-related** background $\propto v_2$ (elliptic flow)
- **Nonflow-related** background (di-jets)

Flow-related BKG can be reduced with --

selection of spherical event shape ($v_2 \sim 0$);

Nonflow can be suppressed – Low energy HIC and very forward EPs.

Event Shape variable:

***q_n*, the magnitude of flow vector**

$$\overrightarrow{q_n} = (q_{n,x}, q_{n,y})$$

$$q_{n,x} = \frac{1}{\sqrt{N}} \Sigma_i^N \cos(\mathrm{n}\,\phi_i)$$

$$q_{n,y} = \frac{1}{\sqrt{N}} \Sigma_i^N \sin(\mathrm{n}\,\phi_i)$$

Previous Event Shape Method

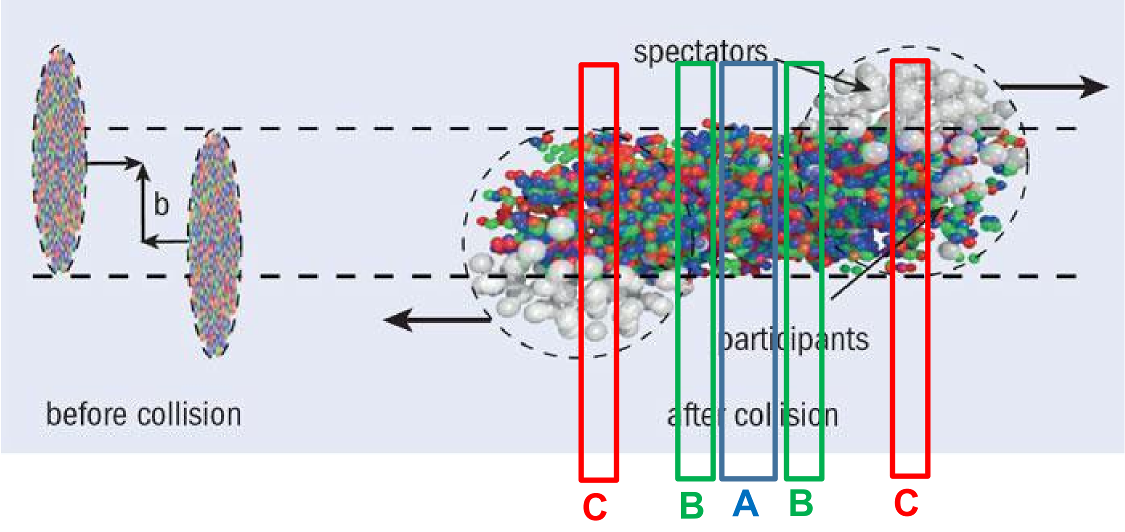
Previous Event Shape Engineering (ESE) Approach

"Standard" ESE splits an event into 3 sub-events

(A) particles of interest (POI)

(B) particles to construct q_n shape

(C) particles to reconstruct EP

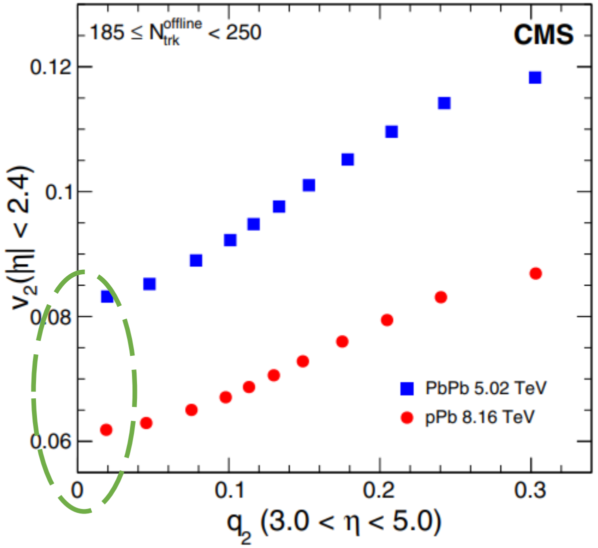


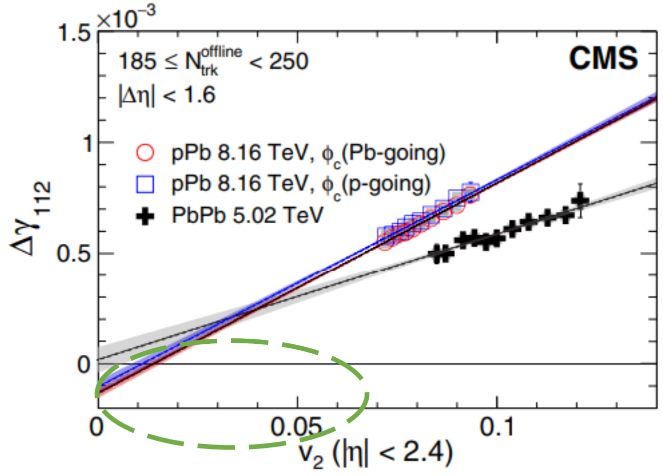
We found

Shape Observable flow vector q_n in region B not effective in selecting shape for particles A

Flow vector q from B correlated to $\langle v_2 \rangle$

Extreme shape fluctuations are largely local, not global feature!





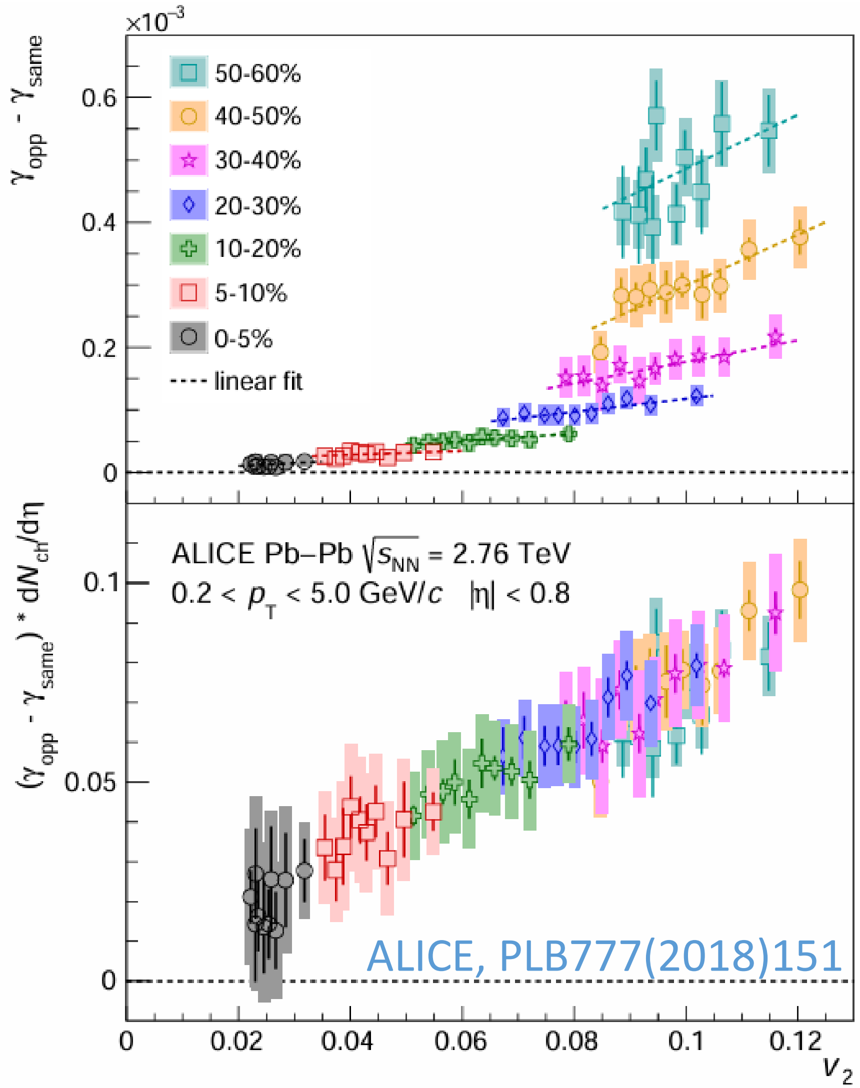
CMS, PRC 97(2018)044912

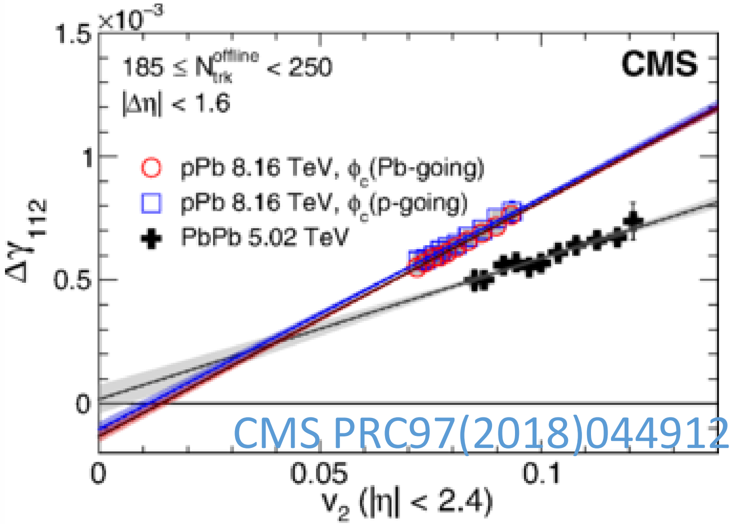
"Standard" Event Shape Engineering

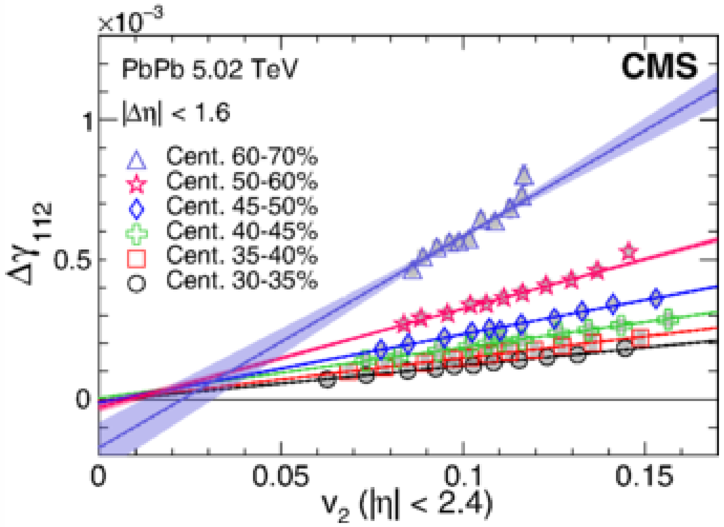
Three sub-events are used: one for POI, one for event plane, and one for event shape variable, q_2, the modulus of the flow vector.

$$q_x \equiv \frac{1}{\sqrt{N}} \sum_i^N \cos(2\phi_i)$$

$$q_y \equiv \frac{1}{\sqrt{N}} \sum_i^N \sin(2\phi_i)$$







- Measure $\Delta\gamma_{112}$ vs q_2 and v_2 vs q_2, then plot $\Delta\gamma_{112}$ vs v_2, and finally extrapolate $\Delta\gamma_{112}$ to zero v_2.
- At LHC energies, all the ESE results are consistent with zero. (too short duration of the *B* field?)
- Since particles of interest (POI) are excluded from q_2, the lever arm on v_2 is very weak, making the extrapolation unstable.

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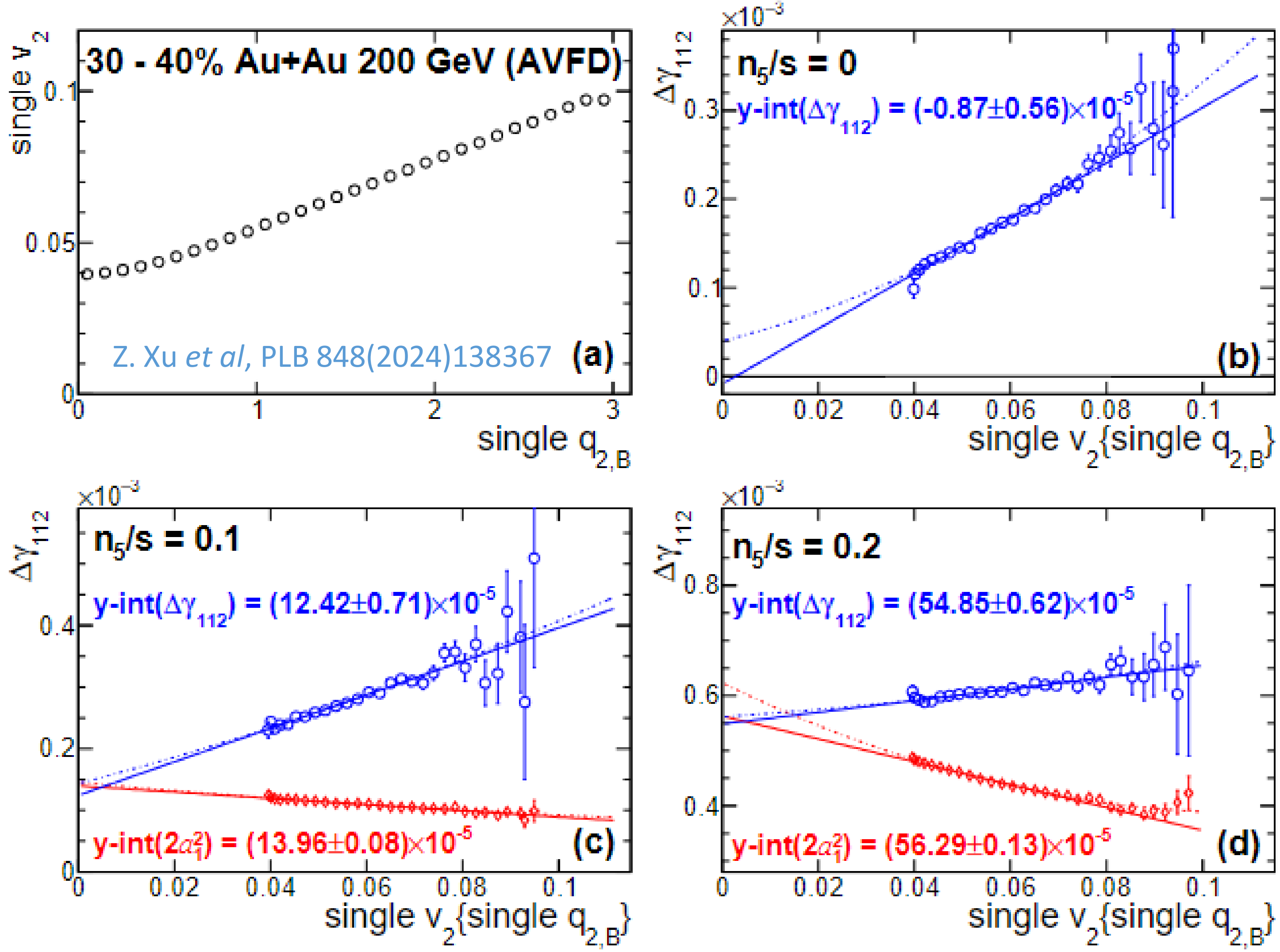

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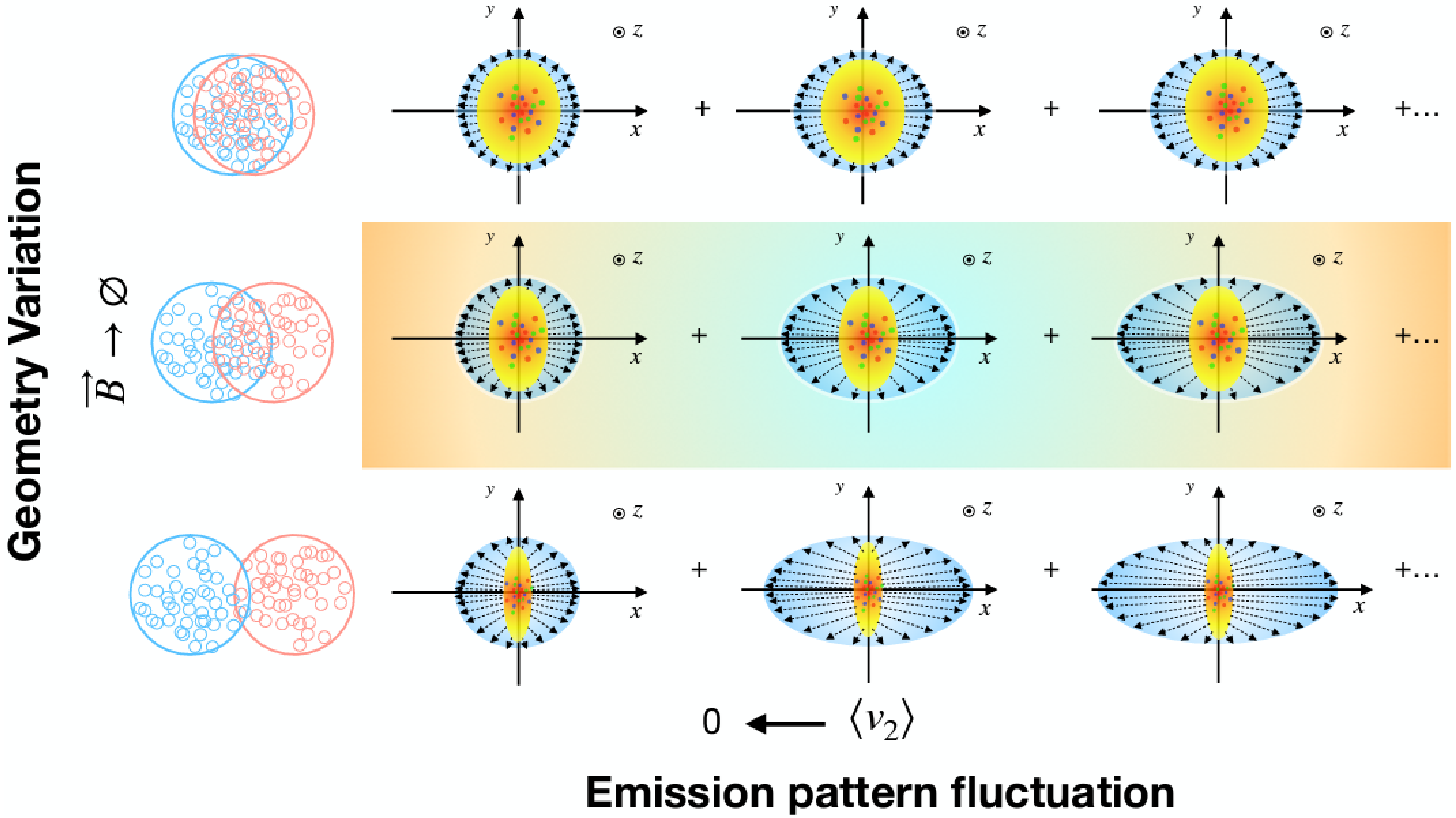
- Since particles of interest (POI) are excluded from q_2, the lever arm on v_2 is very weak, making the extrapolation unstable – **works if the signal is very large, no sensitivity for small signals**

Event Shape Selection (ESS)

Ideally, if we control eccentricity, we control flow for everything.
But large event-by-event fluctuations could dominate the observable.

- participant zone geometry: expected to be long ranged in rapidity emission
- pattern fluctuations: more localized, less correlated over rapidity

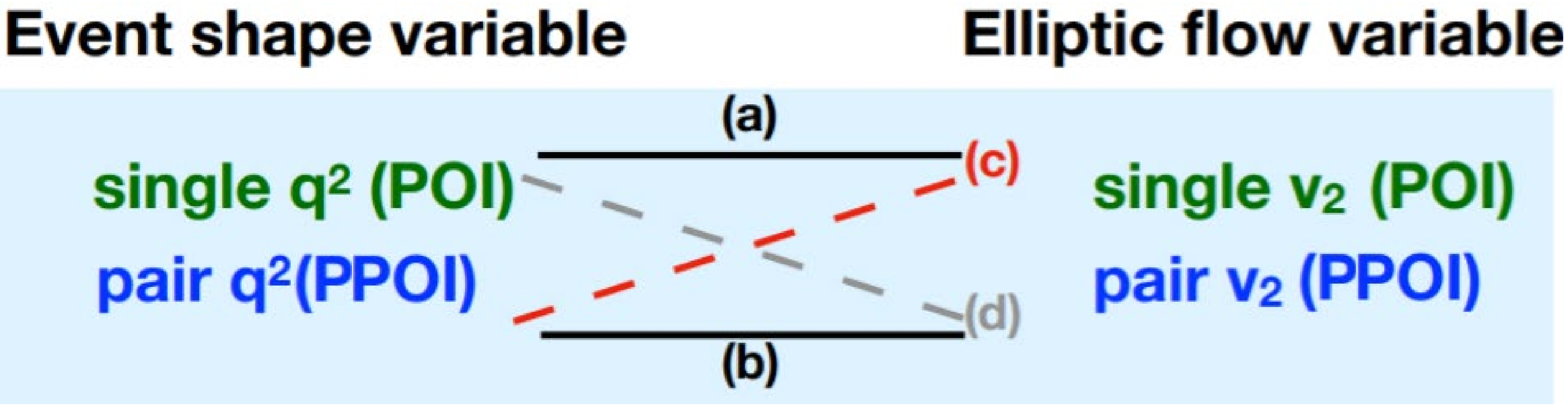


H. Petersen and B. Müller, Phys. Rev. C 88, 044918

Event shape variables based on **particles of interest (POI)** are sensitive to both geometry and emission pattern.

CME background e-by-e comes from combined eccentricity and emission patterns

Shape Variable and v2 Control



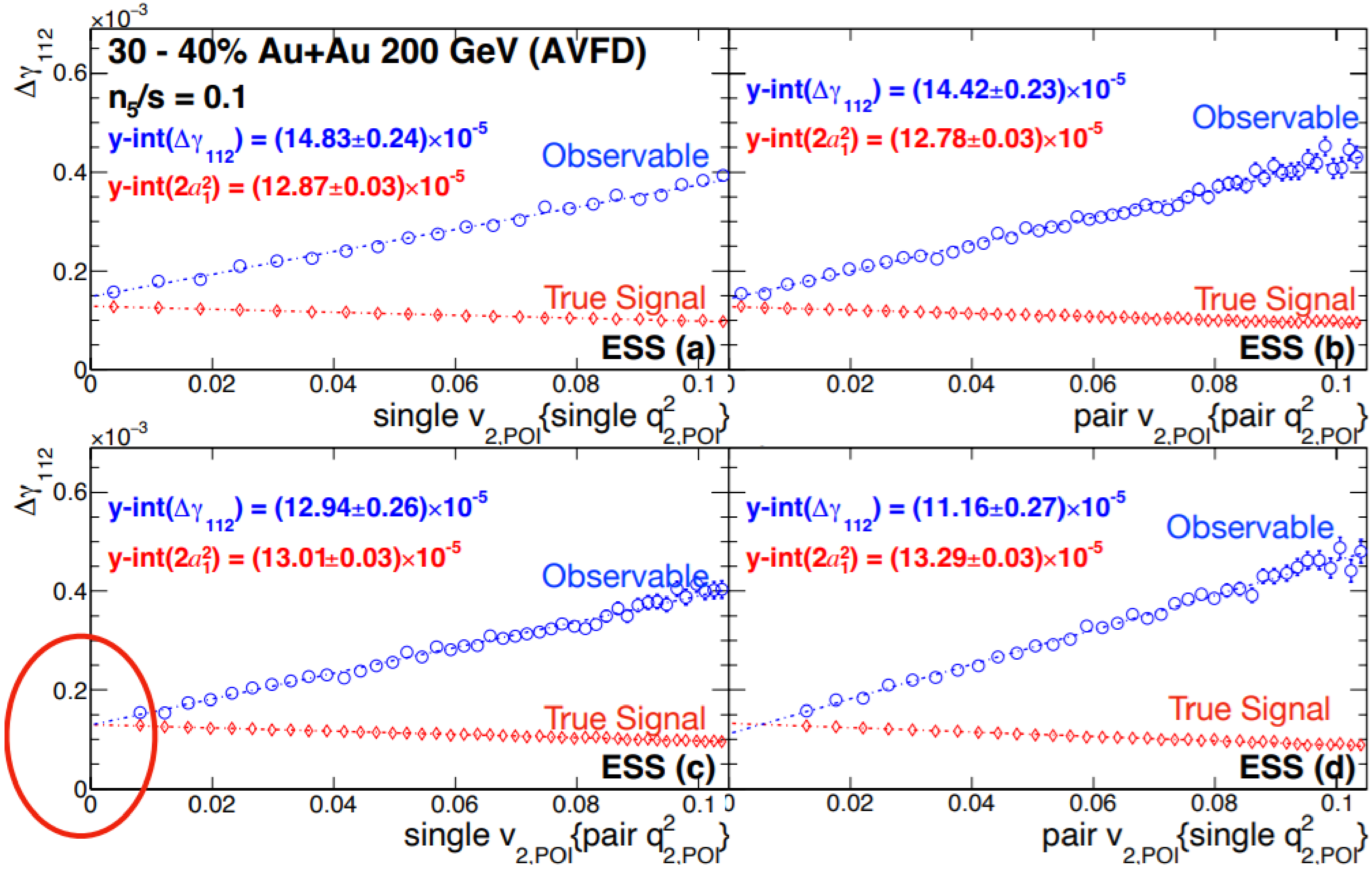
$$q_2^2 = \frac{1}{N}\left[\left(\sum_{i=1}^{N}\sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_i\right)^2\right]$$
$$= 1 + \frac{1}{N}\sum_{i\neq j}\cos[2(\varphi_i - \varphi_j)],$$

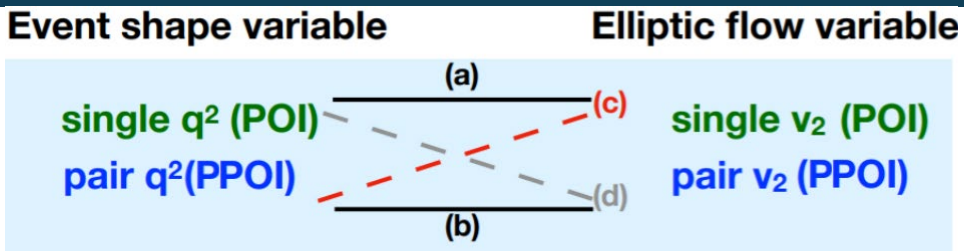
$$\langle q_2^2\rangle \approx 1 + N v_2^2\{2\}$$

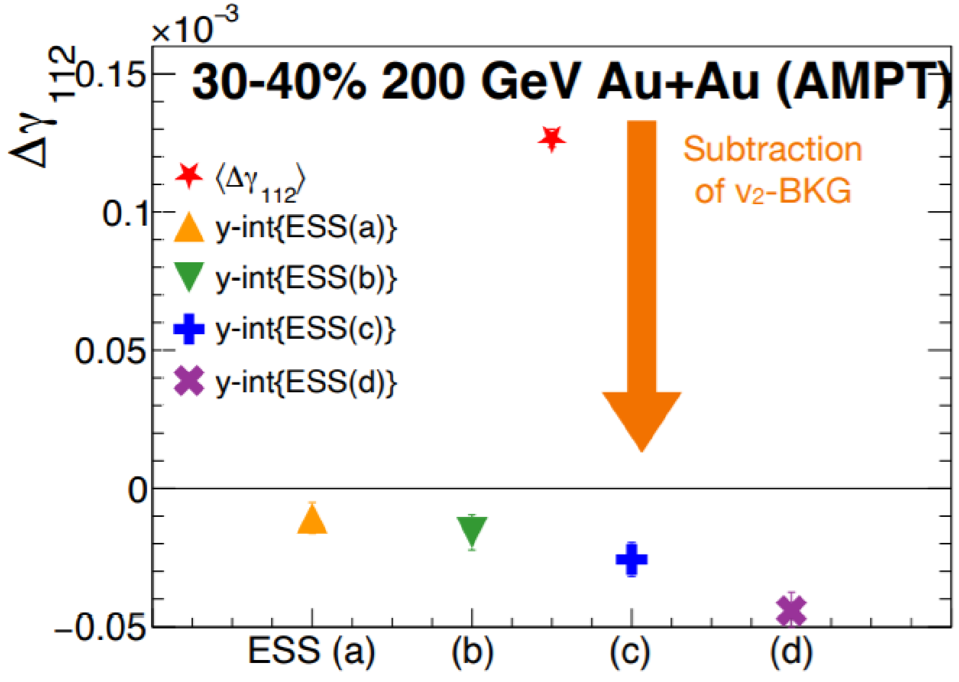
- ESS recipes (a) and (b) involve direct event-by-event correlations between $q_2{}^2$ and v_2, which will cause under-subtraction of background.
- We should use "mixed" recipes, (c) or (d).
- Redefine $q_2{}^2$ with an extra normalization.
- Pair $q_2{}^2$ and pair v_2 are based on $\boldsymbol{\varphi}_{\rm p}$.

$$q_2^2 = \frac{\left(\sum_{i=1}^{N}\sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N}\cos 2\varphi_i\right)^2}{N(1 + N v_2^2\{2\})}$$

Simulations







Z. Xu *et al*, PLB 848(2024)138367

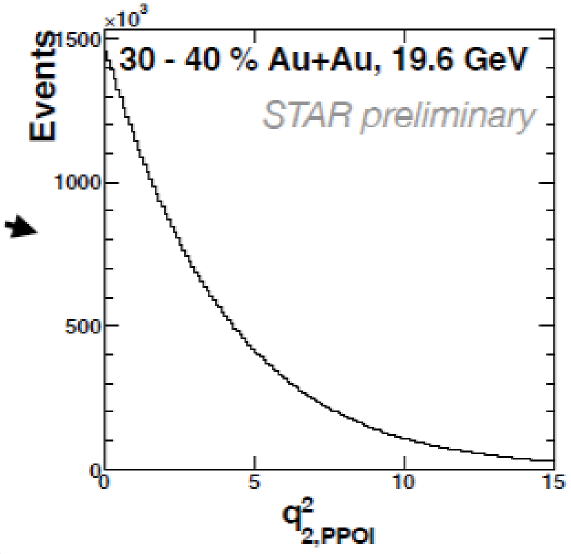
- AVFD: the optimal ESS recipe (c) accurately matches the input CME signal.
- Intercepts follow an ordering (a)>(b)>(c)>(d).
- AMPT: all ESS recipes over-estimate the BKG (with the same ordering as AVFD).

ESS procedures

1. Categorize events
Z. Xu et al, PLB 848(2024)138367

Flow vector with higher-order normalization

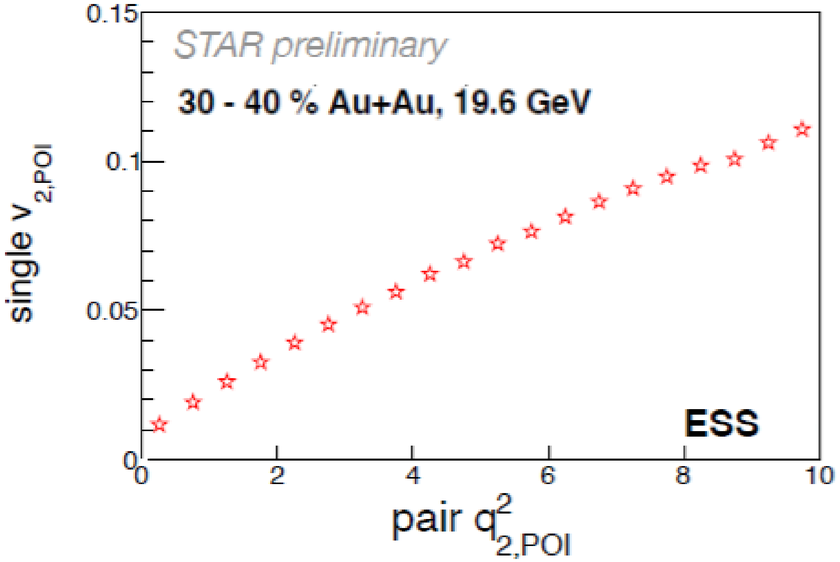
$$q_2^2 = \frac{\left(\sum_{i=1}^{N} \sin 2\varphi_i\right)^2 + \left(\sum_{i=1}^{N} \cos 2\varphi_i\right)^2}{N(1 + N\langle v_2 \rangle)}$$



2. Measure the Δγ Observable & v_2 flow

pair q_2 (PPOI) .... single v_2 (POI)

- **adding momenta of two POI particles**
  ~ mimic resonance decay

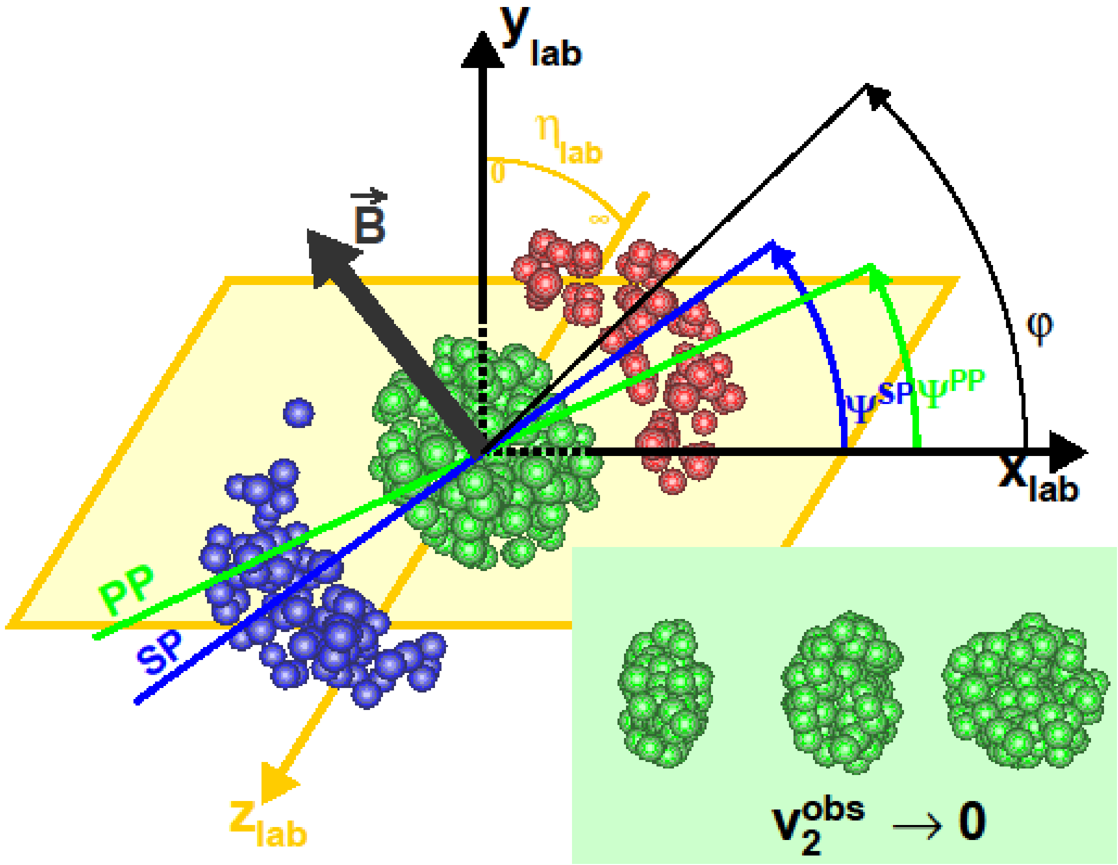


2. Plot Δγ against v_2 to extrapolate $\Delta\gamma_{ESS}^{112}$

$$\Delta\gamma_{ESS}^{112} = Intercept \times (1 - v_2)^2$$

Non-interdependent Flow, Z.Xu et al Phys. Rev. C 107, L061902

STAR Event Shape Selection (ESS)



STAR's Best ESS Approach for CME Background Suppression Beam Energy Scan Data !

STAR Event Plane Detector (EPD):

has coverage for spectator protons for BES II;
not possible for high energy 200 GeV collisions.

Spectator Proton Plane – Determine Magnetic Field B

Use spectator protons or forward charged particles for event plane – reduce non-flow effect

Use TPC tracks in the region of interest for shape selection – choose a slice of matter with azimuthally isotropic emission (almost zero v_2) !

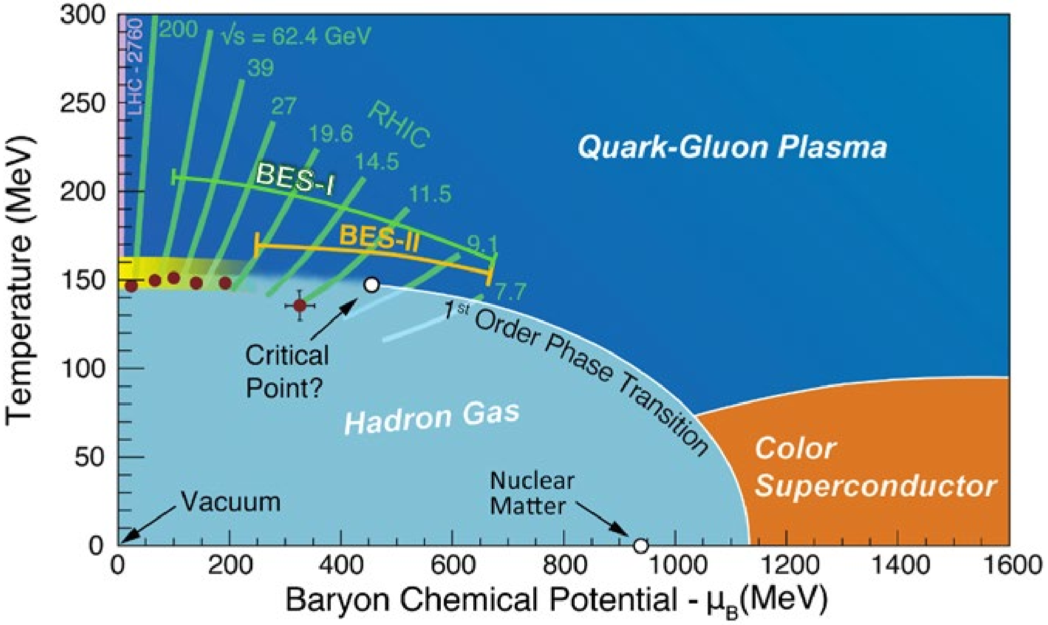
Application to STAR BES Data

BES-I

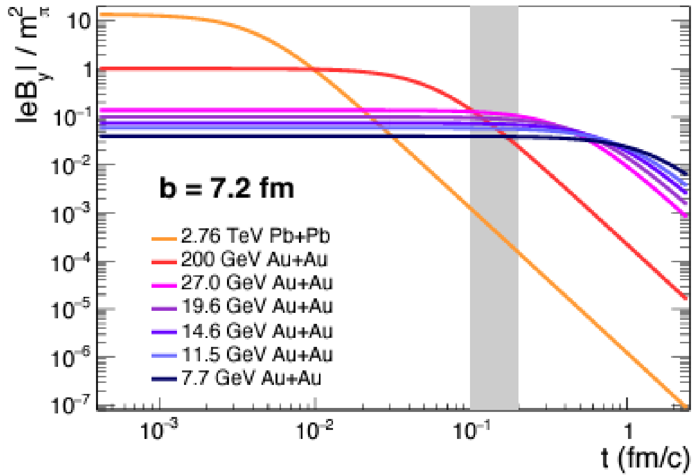
"Events" represents good events after quality cuts.

BES-II

$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
62.4	46	2010
39	86	2010
27	30	2011
19.6	15	2011
14.6	13	2014
11.5	7	2010
9.2	0.3	2008
7.7	4	2010



$\sqrt{S_{NN}}$(GeV)	Events (10^6)	Year
27	555	2018
19.6	478	2019
14.6	324	2019
11.5	230	2020
9.2	160	2020
7.7	101	2021

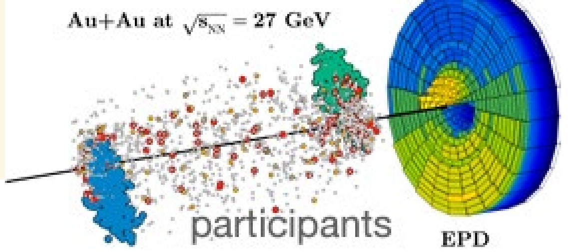


Event Shape Selection **Spectator Ψ_1**

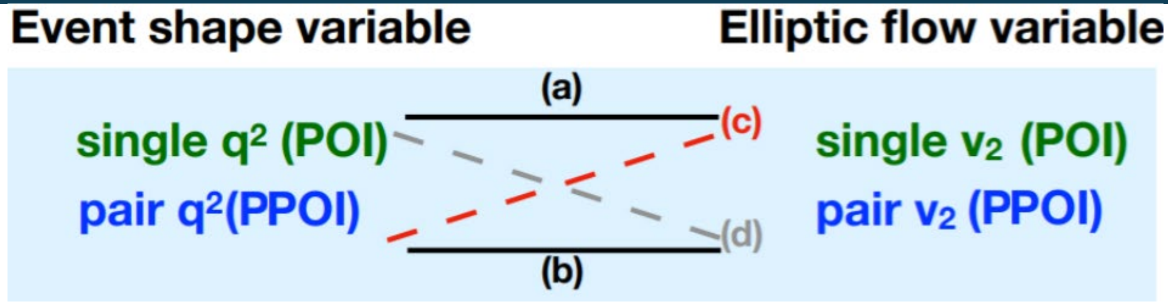
$$\Delta\gamma^{112} = \Delta\gamma^{\mathrm{CME}} + k\frac{v_2}{N} + \Delta\gamma^{\mathrm{non-flow}}$$

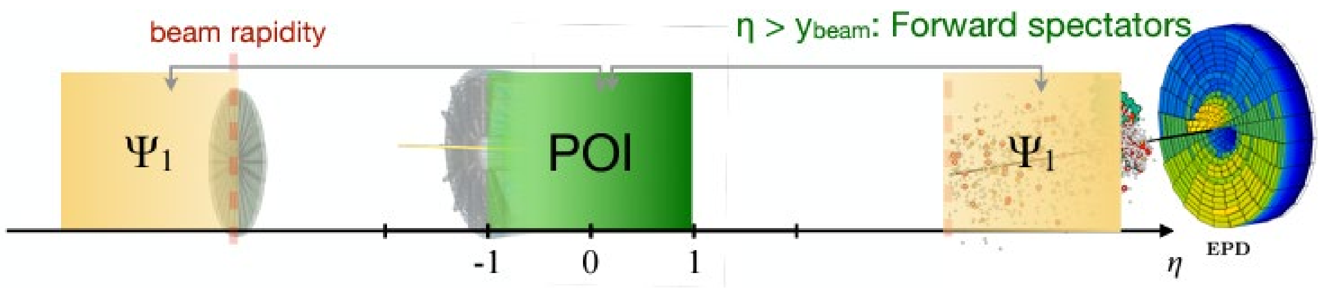
↓ **Measured** ↓ **Signal** ↘ **Backgrounds** ↙

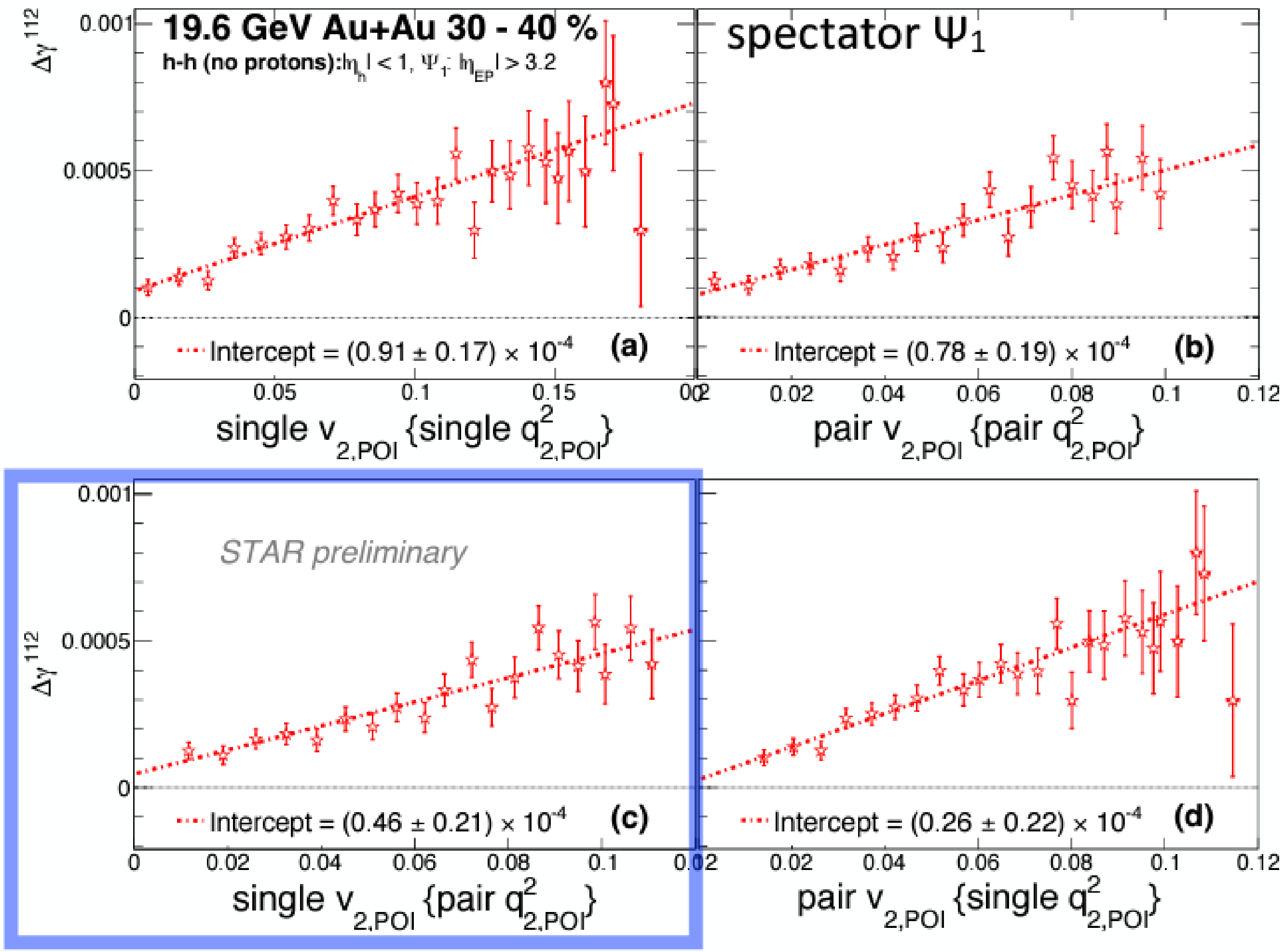
$\eta > y_{beam}$: Forward spectators



Au+Au at 19.6 GeV



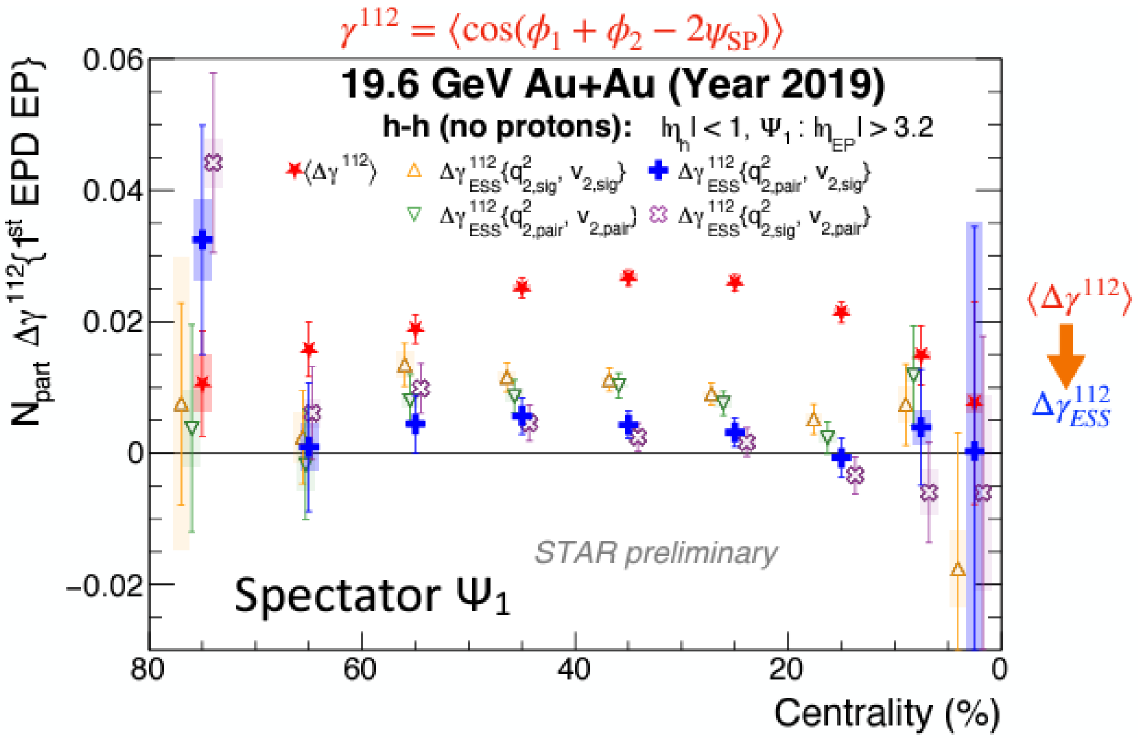


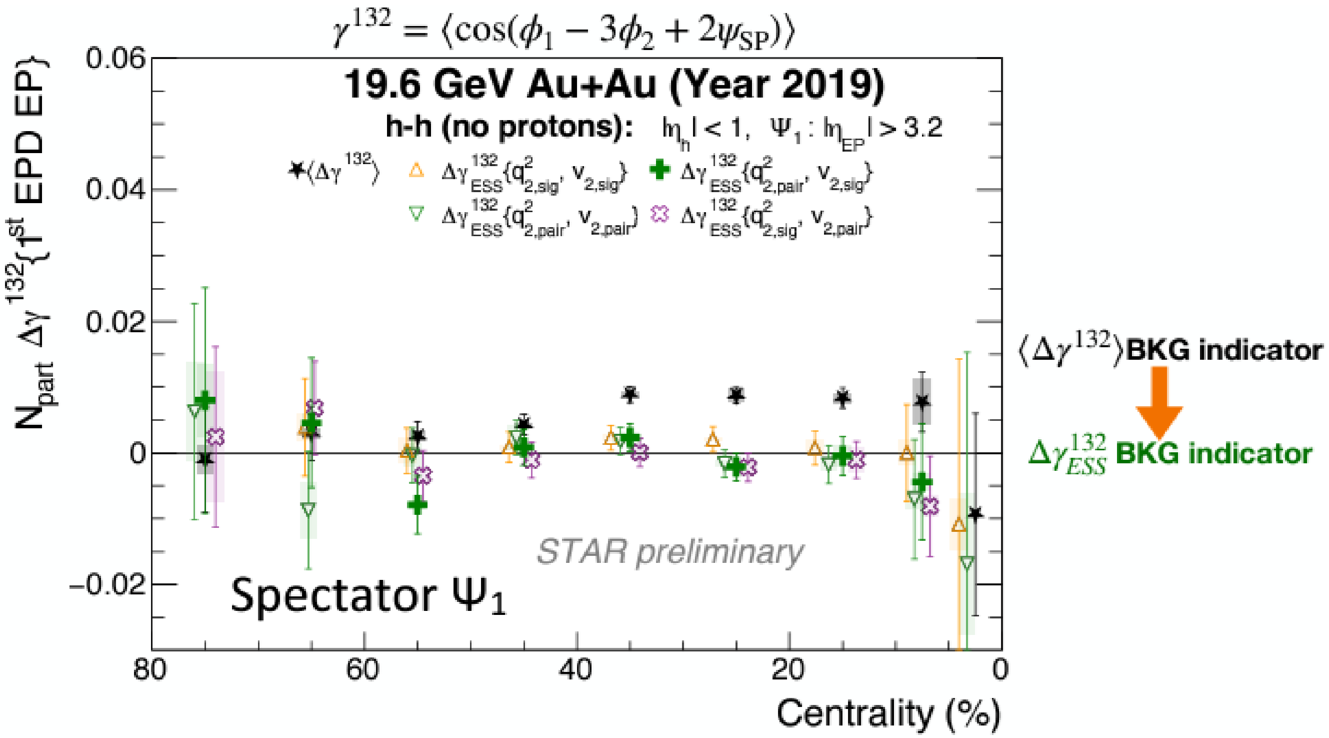


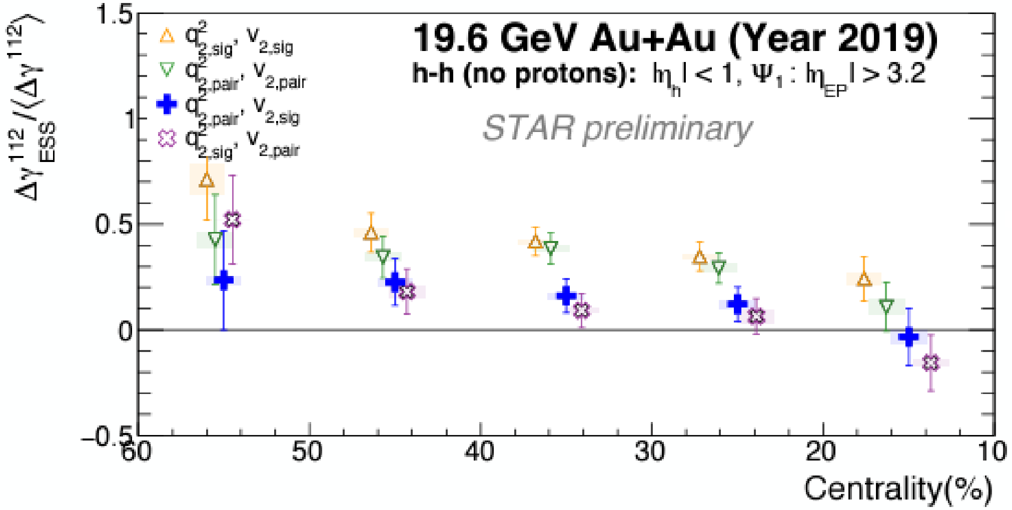
- **ESS using POI allows much shorter extrapolation to zero v_2.**
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT.**
- **The y-intercept requires a small conversion to restore the unbiased signal:** $\Delta\gamma^{112}_{ESS} = Intercept \times (1 - v_2)^2$

Z. Xu *et al.*, Phys. Rev. C 107, L061902

Au+Au at 19.6 GeV





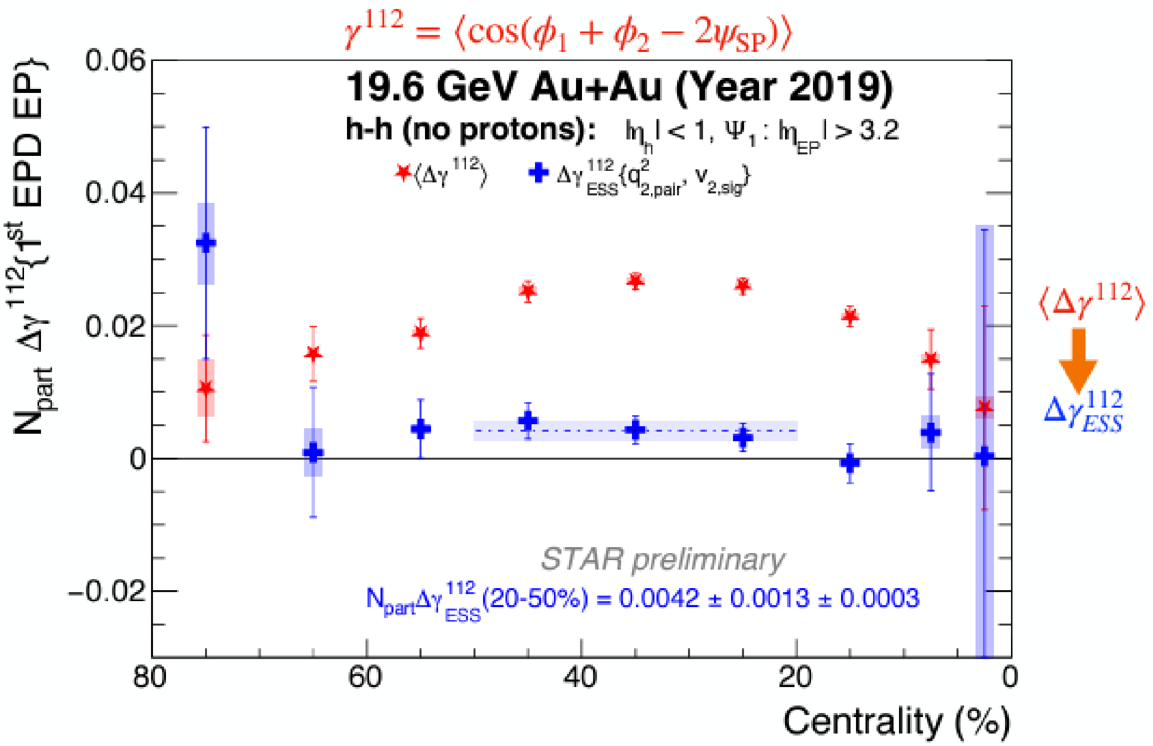


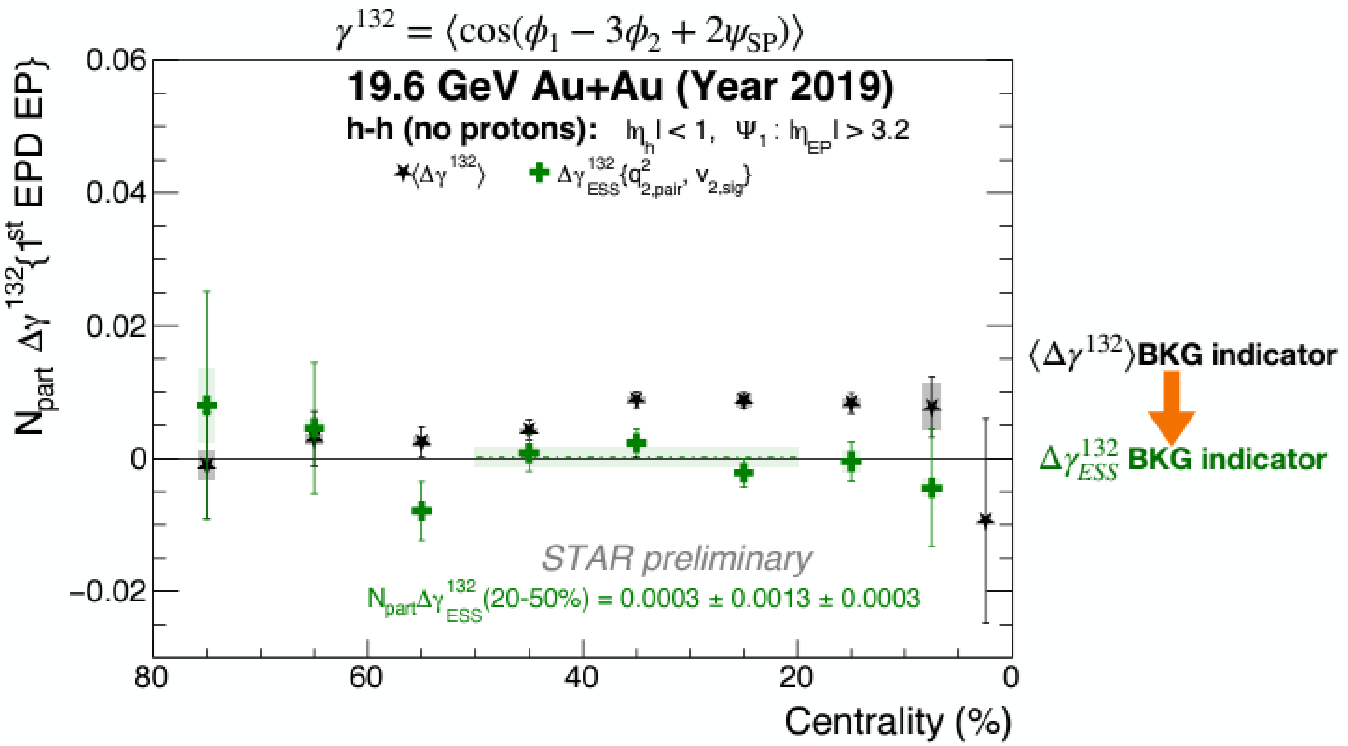
- **The ordering of y-intercepts follows predictions from both AVFD and AMPT.**

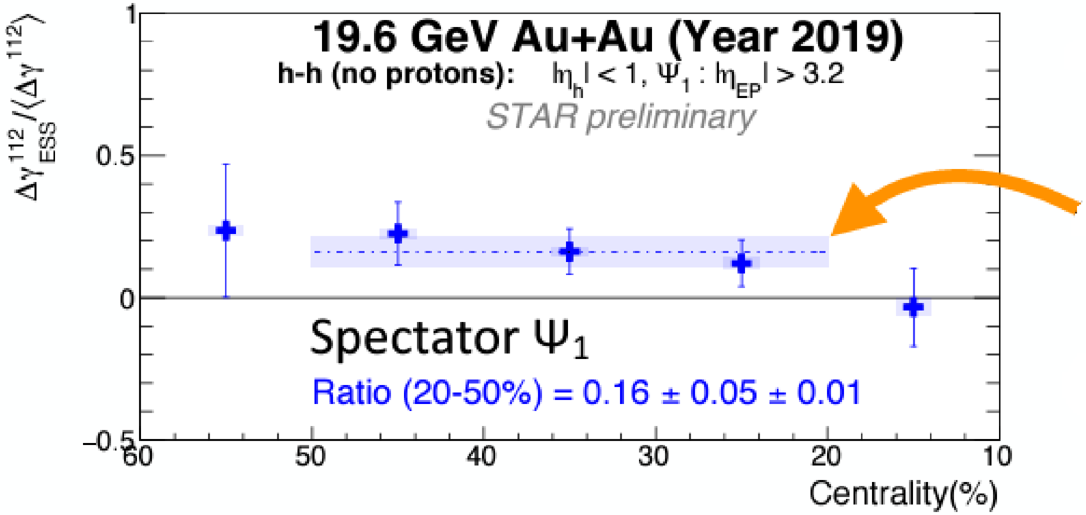
Not all event shape selections are equal, there is some model dependence
We need to optimize the method to suppress the hydro-related CME background

Also event shape selection optimized for CME search only, is not universally best !
Approach for hydro comparisons, for example, the ESE method would be better !

Au+Au at 19.6 GeV

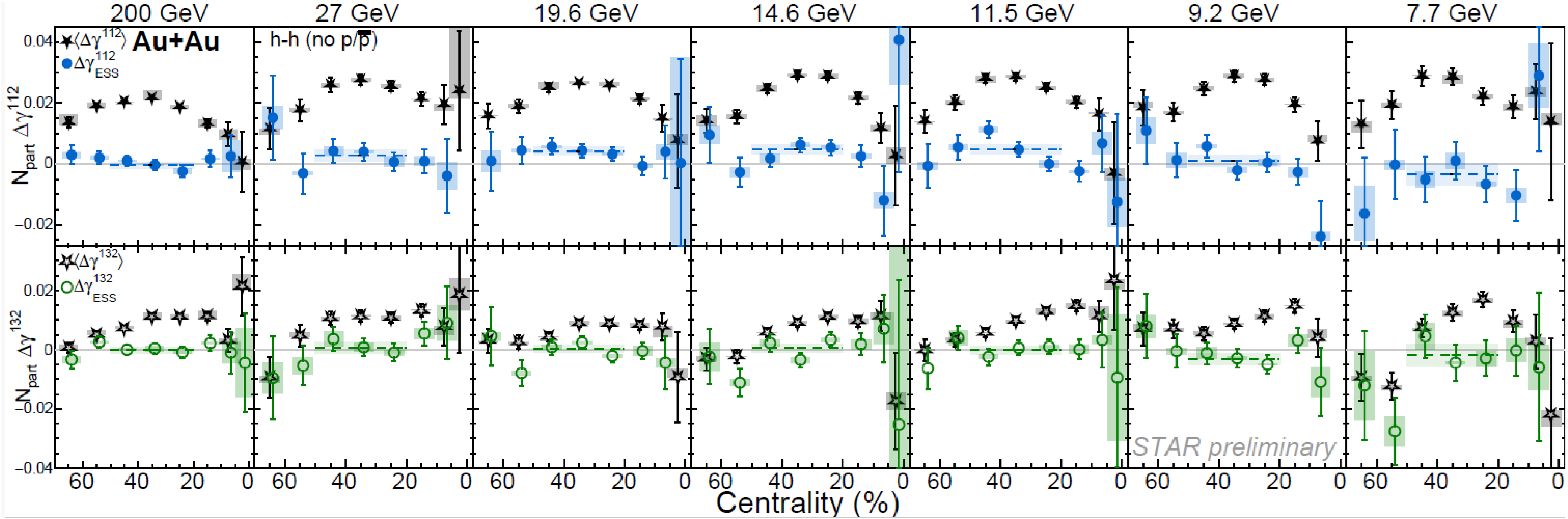






- **After v_2-BKG subtraction, a finite signal in mid-central (20-50%) events.**
- **Ratio from the optimal ESS (c), pair q_2 and single v_2, yields a 3σ significance in the 20-50% centrality.**
- **From the BKG indicator $\Delta\gamma^{132}$, ESS successfully suppresses v_2-BKG.**

Au+Au at 7.7 -- 200 GeV

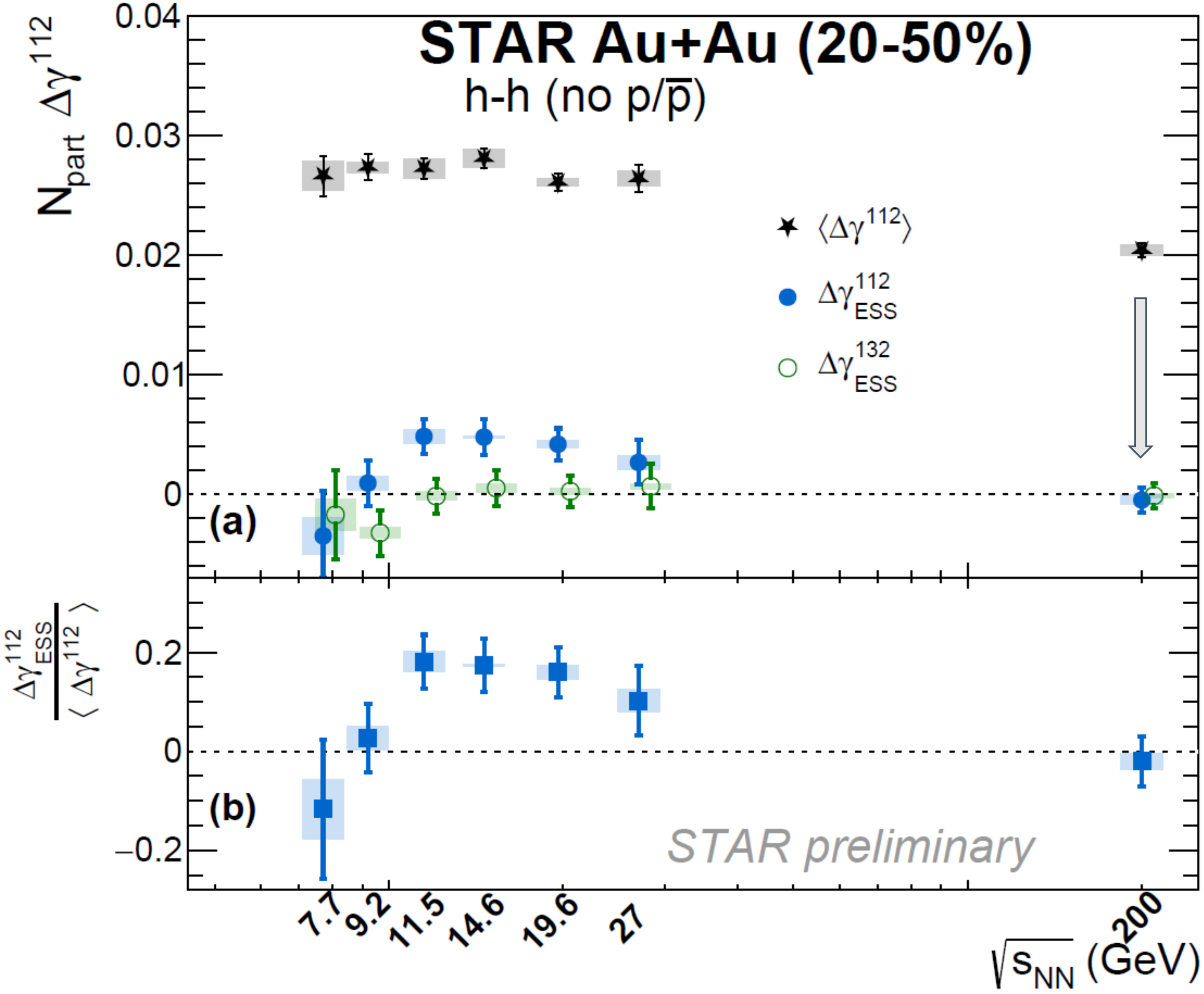


$\Delta\gamma^{112}_{ESS}$ from the optimal ESS (c), pair q_2 and single v_2:

- **At 200 GeV, using ZDC-SMD planes, no signal is observed.**
- **At 19.6, 14.6 and 11.5 GeV, a finite $\Delta\gamma^{112}_{ESS}$ (3σ significance) in the 20-50% centrality.**
- **At 9.2 and 7.7 GeV, data favor the zero-CME scenario limited by statistics.**

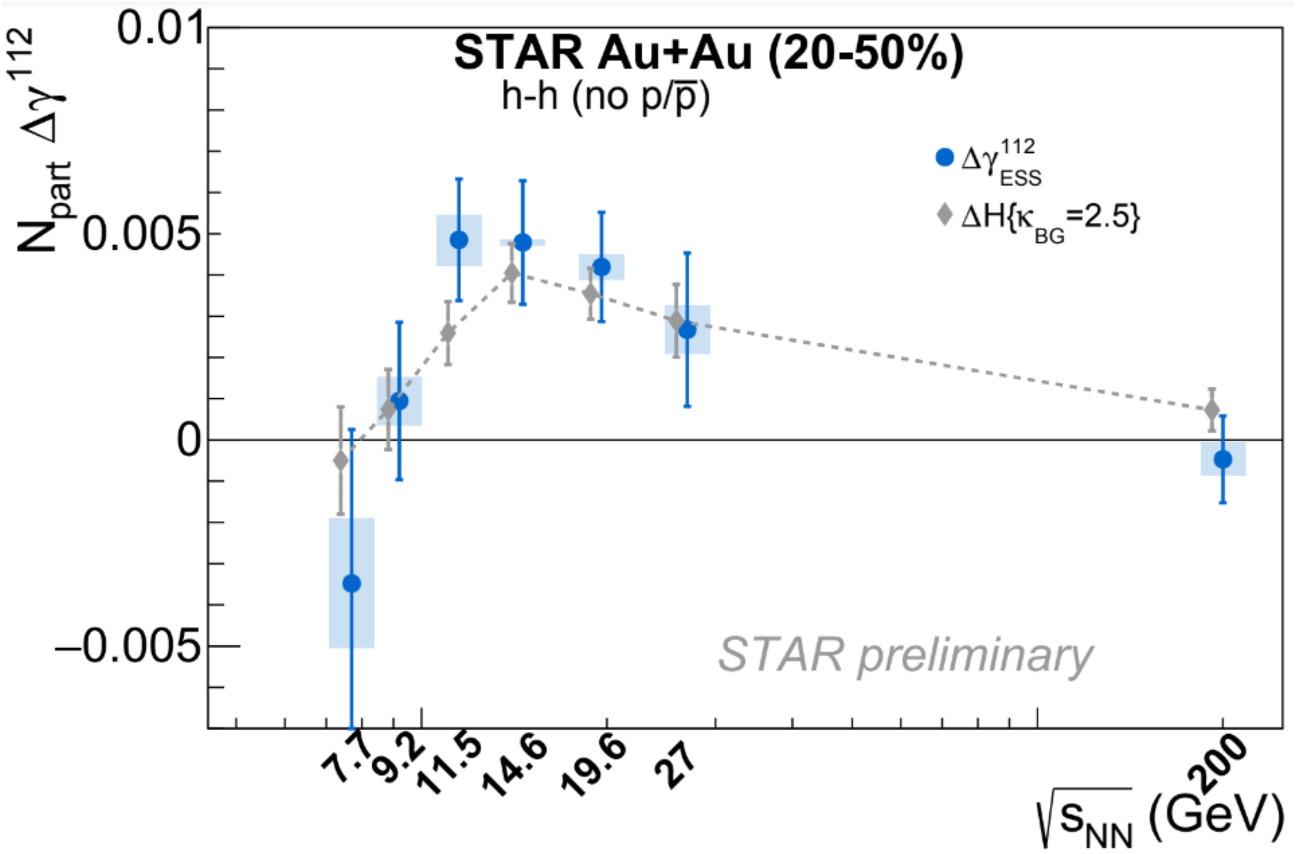
$\Delta\gamma^{132}_{ESS}$ is consistent with zero.

Beam Energy Dependence



- $\Delta\gamma^{132}_{ESS}$ consistent with zero.
- At least 80% of the measured $\Delta\gamma^{112}$ comes from BKG.
- At 200 GeV,
  - ratio is (-2 ± 5.1 ± 1.6)%
  - upper limit of f_{CME}~10% in Au+Au
  - upper limit of f_{CME}~ 5% in isobars using participant planes: 0.7% difference, too small to detect!
- If we combine three points at 19.6, 14.6 and 11.5 GeV, the literal average of the ESS results reaches an over 5σ significance (assuming similar physics conditions between 10 and 20 GeV).
- The ESS results approach zero around 9.2 and 7.7 GeV.

Connection between ESS and the *H* correlator



- In dealing with the BES-I data, we introduced the *H* correlator to subtract the flow BKG:

$$H(\kappa_{bg}) \equiv (\kappa_{bg} v_2 \delta - \gamma^{112})/(1+\kappa_{bg} v_2)$$

$$\Delta H \equiv H_{SS} - H_{OS} \qquad \delta = \cos(\phi_1 - \phi_2)$$

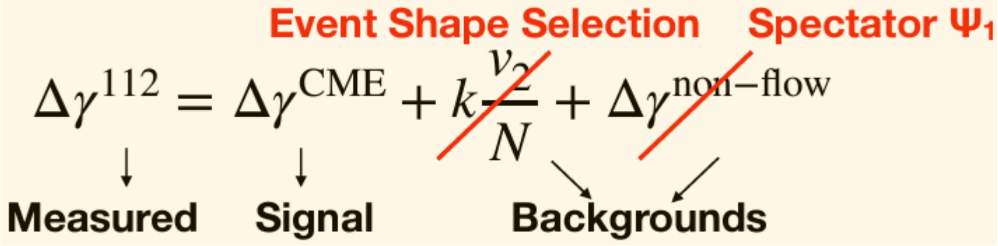
$$\gamma = \kappa v_2 B - H$$
$$\delta = B + H$$

- κ_{bg} is an adjustable parameter, unknown a priori. It quantifies the coupling between elliptic flow and other mechanisms manifested in the two-particle correlation.

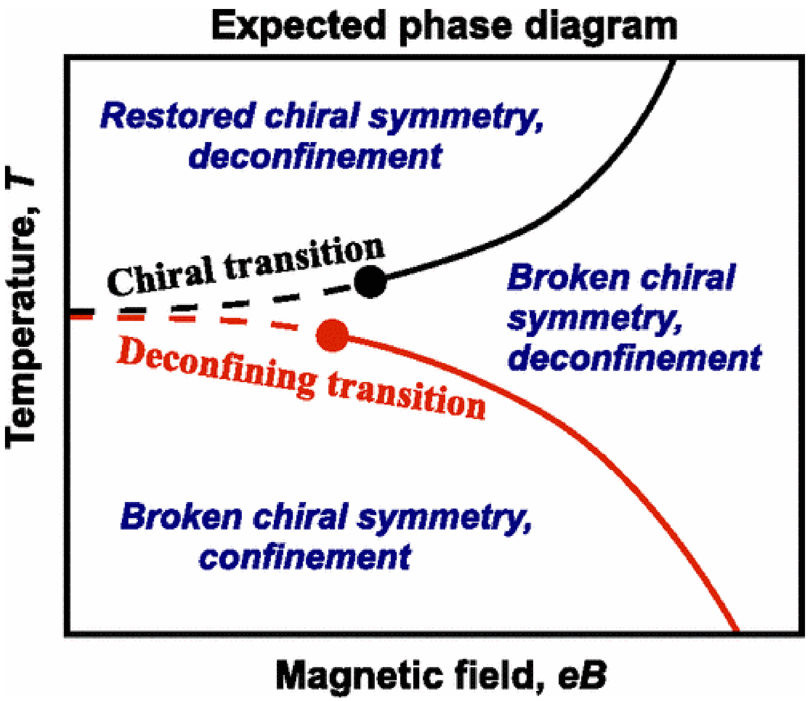
- **With κ_{bg} set to 2.5, ΔH agrees with the ESS result at all beam energies under study.**
- **The flow background can be reasonably well described by a near constant coupling between v_2 and the two-particle correlation.**

STAR ESS CME Search Summary

- The novel Event Shape Selection effectively suppresses flow-related backgrounds.
    - At 200 GeV, upper limit of f_{CME}~10%.
    - At each of 11.5, 14.6 and 19.6 GeV, a positively finite $\Delta\gamma^{112}_{\mathrm{ESS}}$ (>3σ). Over 5σ if combined.
    - Around 7.7 GeV, approaches zero CME limited with large uncertainties.
- More theoretical insights are needed:
    - The remaining B field too weak at 200 GeV?
    - Chiral symmetry breaking around 7.7 GeV?
    - The chance of the CME occurrence is enhanced near the critical point?
- We urge our LHC colleagues to try the ESS method with LHC data. Extrapolating the trend from the RHIC data, we would predict no significant CME signal at LHC.



A. J. Mizher, M. N. Chernodub, and E. S. Fraga, PRD 82 (2010) 105016



Future Prospect

Impact of Model Dependence on Event Shape Approaches

All event shape mthods will have some model dependence –
event shape – observable measured from final state particles in momentum space
shape -- preferably in the coordinate system (initial eccentricity or emission source)

What shape selection most related to CME background contributions

Event-Shape Engineering (ESE) – more sensitive to initial collision eccentricity

Event-Shape Selection (ESS) – Sensitive to combination of eccentricity and particle emission pattern

For preferred mid-centrality for CME searches (20-50% for example)

ESE – limited range of eccentricity variation --- cannot reach the v_2 zero limit for round shape to minimize CME bkgd
-- extrapolation to v_2 zero limit – model dependent and uncertain extrapolation
-- if the extrapolation follows the eccentricity variation, then initial eccentricity zero corresponds to the most central collisions – small B field and no CME!

ESS – with limited range of eccentricity the approach to v_2 zero is mostly due to emission pattern fluctuations
Any residual CME background when v_2 approaches zero limit – the intercept point
Dependence of shape observable versus v2 control method
For hydro-induced background, the optimized approach q_2(pair) vs v_2(single)

Be Critical, but also Be Truthful !

2407.14489v1

The goal of the ESE was to approach v2 = 0 limit, it is clear that the ESE method has a problem here !

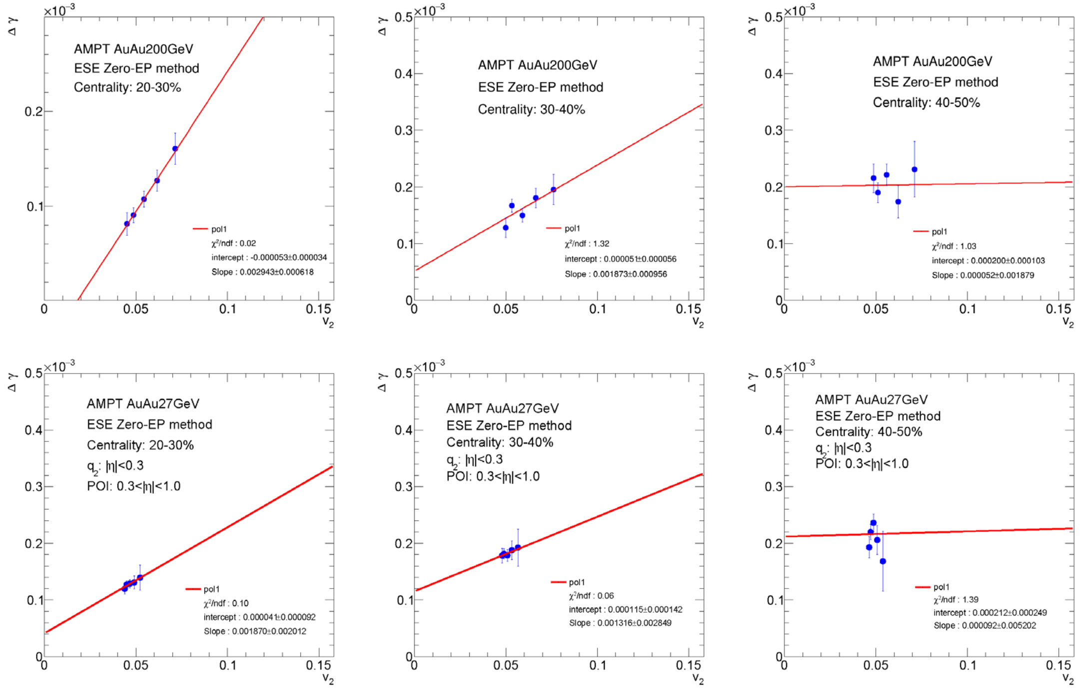


FIG. A.4. AMPT ESE results. Shown are three centralities of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (upper panels) and at 27 GeV (lower panels) simulated by AMPT, with approximately 5×10^6 events for each centrality at each energy. The $\Delta\gamma$ is plotted as a function of v_2 in events binned in $\hat{q}_2^2\{2\}$ (Eqs. 5,6). POIs are from acceptance $0.3 < |\eta| < 1$, and the event selection variable $\hat{q}_2^2\{2\}$ is computed from particles in $|\eta| < 0.3$, both with $0.2 < p_T < 2$ GeV/c. The model's known impact parameter direction $\psi = 0$ is taken as the EP in calculating $\Delta\gamma$ (Eqs. 2,3) and $\langle v_2 \rangle$ (Eq. 10).

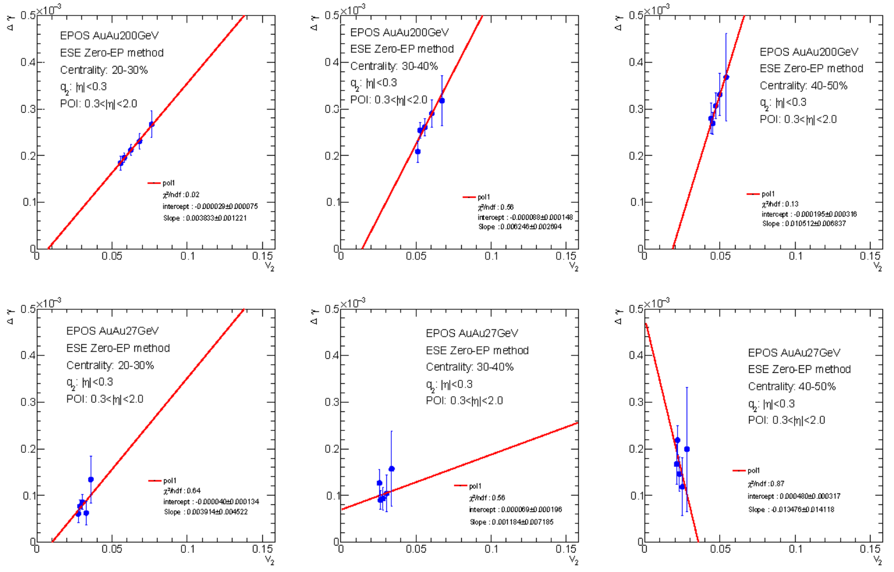


FIG. A.6. EPOS ESE results. Shown are three centralities of Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV (upper panels) and at 27 GeV (lower panels) simulated by EPOS4, with approximately 1.6×10^6 and 8×10^5 events for each centrality, respectively. The $\Delta\gamma$ is plotted as a function of v_2 in events binned in $\hat{q}_2^2\{2\}$ (Eqs. 5,6). POIs are from acceptance $0.3 < |\eta| < 2$ and $0.2 < p_T < 2$ GeV/c, and the event selection variable $\hat{q}_2^2\{2\}$ is computed from particles in $|\eta| < 0.3$, both with $0.2 < p_T < 2$ GeV/c. The model's known impact parameter direction $\psi = 0$ is taken as the EP in calculating $\Delta\gamma$ (Eqs. 2,3) and $\langle v_2 \rangle$ (Eq. 10).

Event Shape Analysis cannot solve all our physics problems – need to find the best approach for your particular physics

1) **Some toy models are indeed just toys, avoid playing "garbage in, garbage out" game !**
2) **Respect statistics: when you get 1+-1, result is consistent with zero, but is also consistent with many other scenarios**
   -- it does not mean your method working, it could also mean that your method does not have sensitivity

What Dynamics at RHIC 200 GeV and LHC

With ESS method we found the $\Delta\gamma^{112}_{ESS}$ close to ZERO in Au+Au 200 GeV !!
Expect $\Delta\gamma^{112}_{ESS}$ to be small at the LHC energy ?!

The magnetic field B magnitude at these energies are certainly larger at the initial collision t = 0 !!

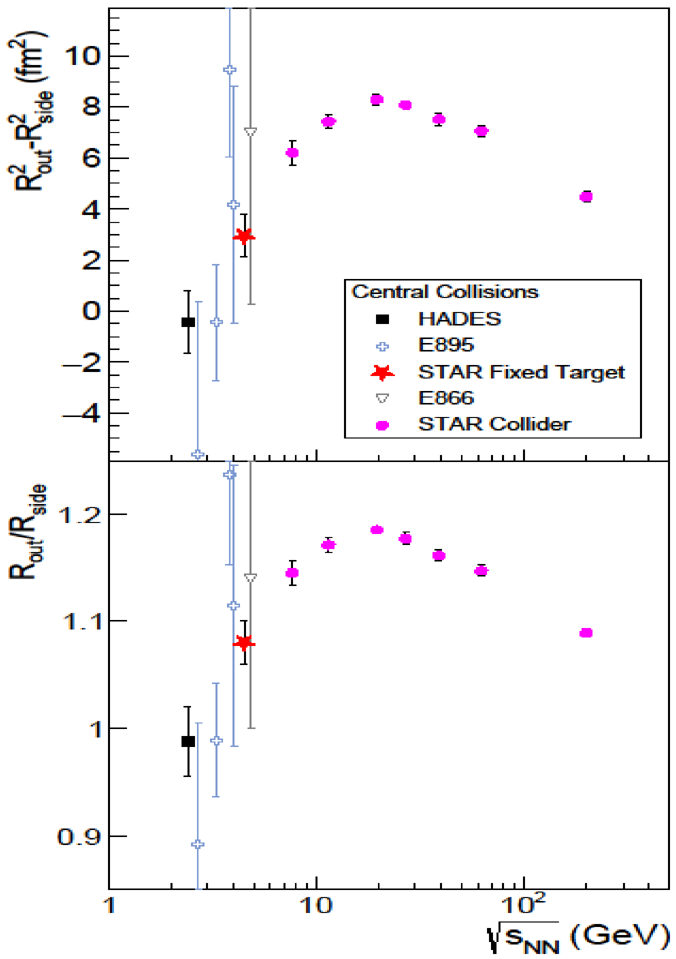
Why?

Please measure $\Delta\gamma^{112}_{ESS}$ at the LHC energy !

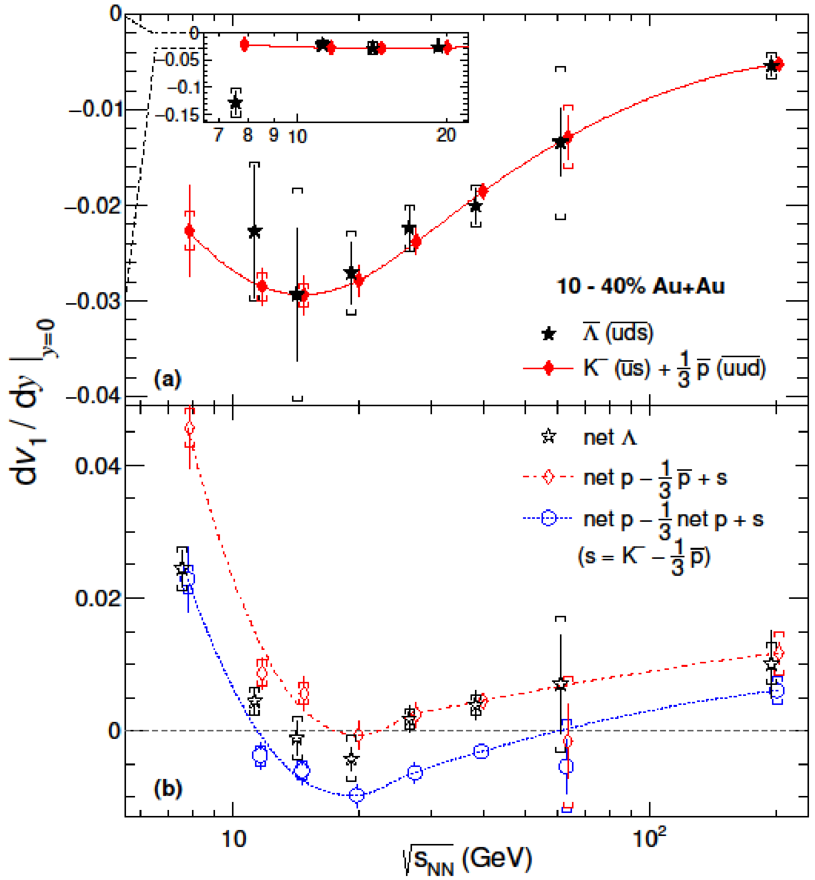
Please measure $v_2\delta$ background correlation as well !

What so Special for Collisions at 10-30 GeV

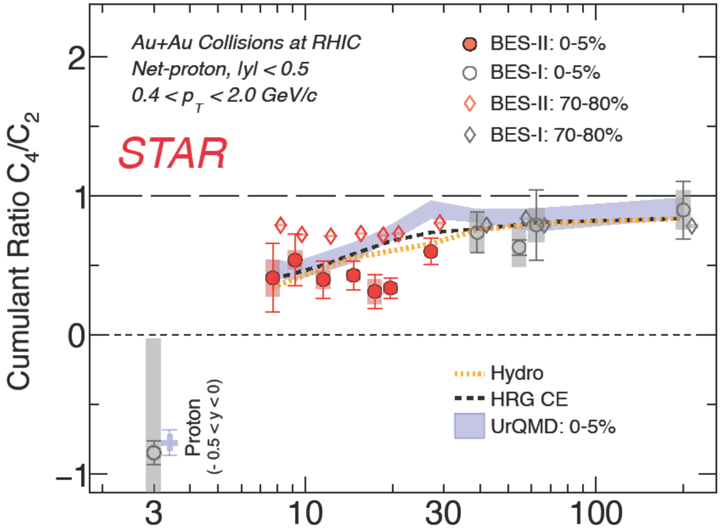
HBT Rout/Rside

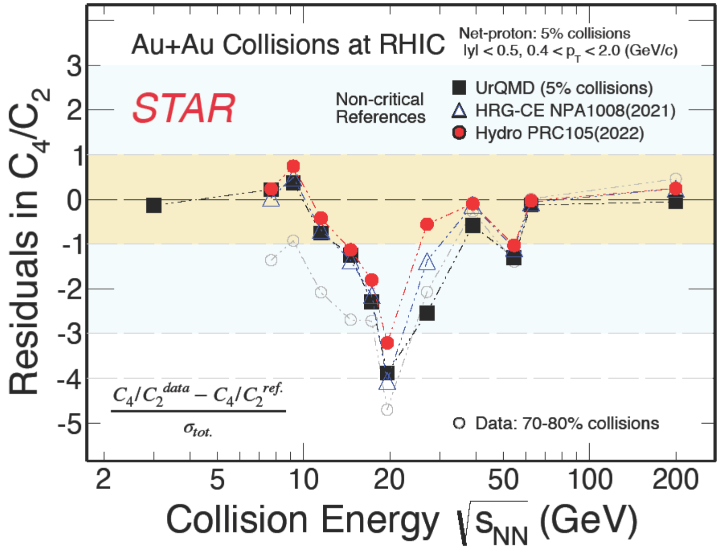


v_1 slope dv_1/dy



Critical Point: C_4/C_2





Future of Experimental CME Searches

Improve understanding background contributions !

Improve CME search approach !

We improved ESS approach and we are open to more optimizations

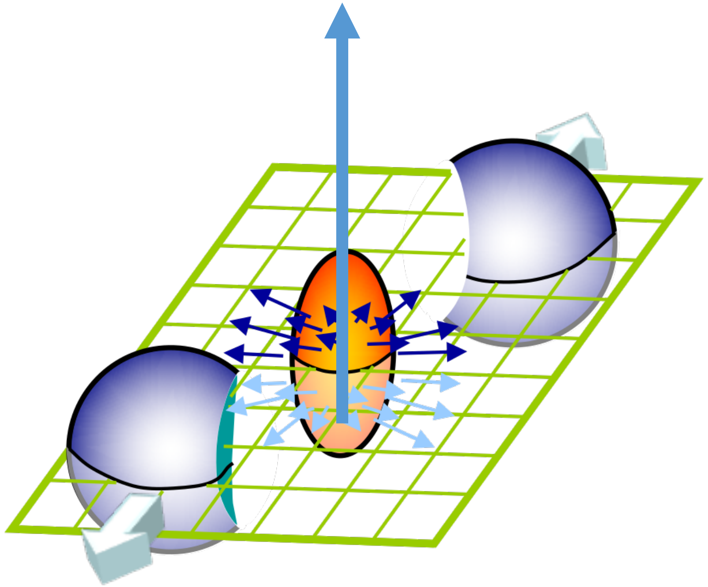
Understand magnetic field effect !

More theoretical insights !

Magnetic Field in Heavy Ion Collisions

Magnetic field

$$eB_y \propto \gamma \frac{Ze^2}{b^2}$$



Strongest magnetic field

RHIC: $eB_y \sim 10^{18}$ Gauss @ 200 GeV
LHC: $eB_y \sim 10^{19}$ Gauss @ 2760 GeV

Physics:

- Hyperon spin polarization
- Vector meson spin alignment
- Anomalous transport, e.g. CME, CMW…
- Breit-Wheeler process $\gamma\gamma \to l^+l^-$ and photon polarization
- Direct flow of D^0 meson
- …

Thanks for Dr. Hui Li, X.L. Xia, Xu-Guang Huang et al

Review on magnetic field

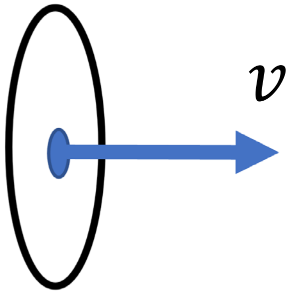
For a moving point charge

Lienard-Wiechert formula:

$$\mathbf{E}(t,\mathbf{x}) = \frac{q}{4\pi}\frac{\gamma_q \mathbf{R}}{[R^2 + (\gamma_q \mathbf{v}_q \cdot \mathbf{R})^2]^{3/2}},$$

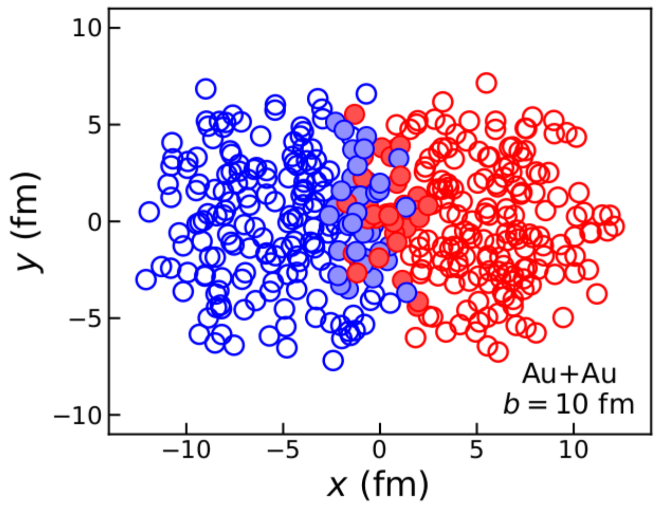
$$\mathbf{B}(t,\mathbf{x}) = \frac{q}{4\pi}\frac{\gamma_q \mathbf{v}_q \times \mathbf{R}}{[R^2 + (\gamma_q \mathbf{v}_q \cdot \mathbf{R})^2]^{3/2}},$$

$$\mathbf{R} = \mathbf{x} - \mathbf{x}_q$$



For heavy-ion collisions:

- Charge distribution:
  - Wood-Saxon distribution
  - Glauber sampling
- After collision:
  - Spectator nucleons keep moving
  - Wounded nucleons slow down (stopping effect)
  - Full transport model or empirical formula
- Magnetic field evolves in:
  - Vacuum
  - Conductive medium



Skokov et al. 2009
Deng, Huang 2012
Tuchin 2013
McLerran, Skokov 2014
Gursoy, Kharzeev, Rajapopal 2014
Li, Sheng, Wang 2016
…

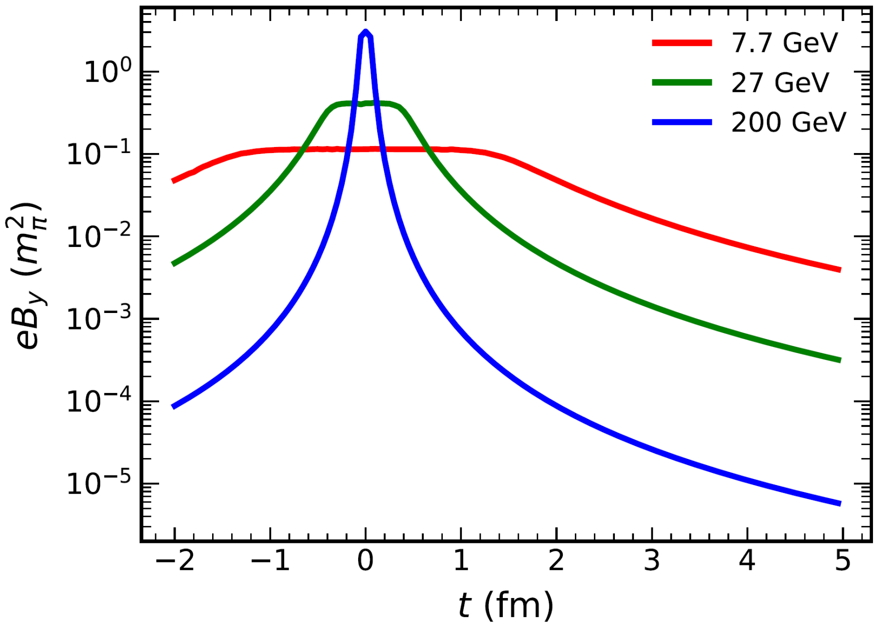
Magnetic field in vacuum

- Magnetic field drops rapidly in vacuum

$$B_y(t,\mathbf{x}) = \frac{q}{4\pi}\frac{\gamma v_z(x-x_0)}{[(x-x_0)^2+(y-y_0)^2+\gamma^2(z-z_0-v_z t)^2]^{3/2}},$$

- Magnitude $B \propto \gamma \propto \sqrt{s}$
- Lifetime $t_B \propto 1/\gamma \propto 1/\sqrt{s}$

- The larger the field is, the faster it drops.



- In vacuum, for spectator nucleons the field
  → symmetric evolution w.r.t. $t = 0$

Electric conductivity of QGP medium

- Lattice calculations $(T_c$ is critical temperature$)$

$$\sigma = (5.8 \pm 2.9)\,\frac{T}{T_c}\ \text{MeV},$$

- Transport simulation by BAMPS

$$\sigma = \frac{1}{3T}\tau \sum_i {q_i}^2 n_i \qquad \tau = \frac{3}{2}\frac{1}{\sum_i n_i \sigma_{22}} \qquad \sigma \propto {}^{1}/_{\sigma_{22}}$$

where τ is the relaxation time for deviation from equilibrium

In the case of T = 255 MeV,

$\sigma_{22} = 1$ mb	$\sigma = 11.6$ MeV
$\sigma_{22} = 2$ mb	$\sigma = 5.8$ MeV

It is small compared to typical QCD scale of ~200 MeV

But it has obvious effect on the lifetime of EM field.

H. T. Ding, et.al, Phys. Rev. D 83, 034504
Z. Y. Wang, et.al, Phys. Rev. C 105, L041901

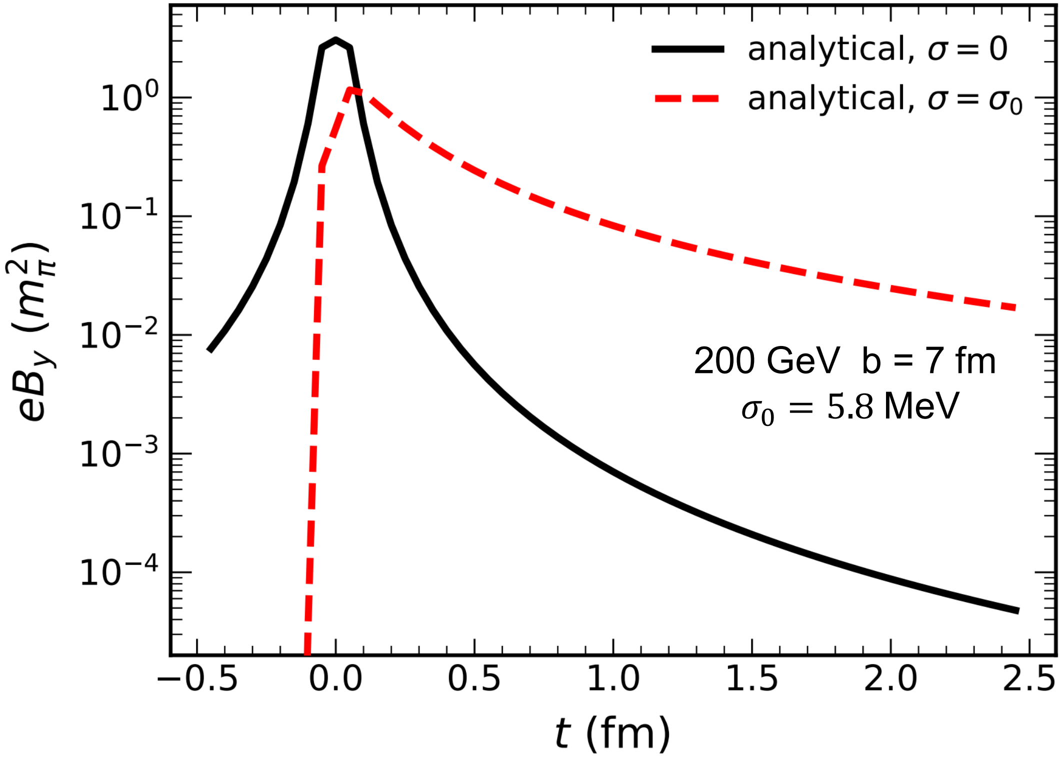
Magnetic field in conductive medium

Analytical formula:

$$\mathbf{B}(t,\mathbf{x}) = \frac{q}{4\pi}\frac{\gamma\mathbf{v}\times\mathbf{R}}{\Delta^{3/2}}\left(1+\frac{\gamma\sigma}{2}|\mathbf{v}|\sqrt{\Delta}\right)e^{A}$$

$$\Delta = R^2 + (\gamma\mathbf{v}\cdot\mathbf{R})^2$$

$$A = -\frac{\gamma\sigma}{2}(\gamma\mathbf{v}\cdot\mathbf{R} + |\mathbf{v}|\sqrt{\Delta})$$



K. Tuchin, 2013
U. Gursoy, et.al, 2014
H. Li, et.al, 2016
…

- σ =const at both $t>0$ and $t<0$ (not realistic)
- Delay the field increasing at $t<0$ (not realistic)
- Delay the field decreasing at $t>0$ (expected, but over-estimated)

Numerical Model Calculation

H. Li, X. L. Xia, X. G. Huang and H. Z. Huang, Phys. Rev. C 108, 044902, 2023.

Before collision (t<0):
Calculate the EM field in vacuum by L-W formula

After collision (t>0):
Numerically solve Maxwell's equations with non-zero σ

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \rho, \\
\nabla \cdot \mathbf{B} &= 0, \\
\nabla \times \mathbf{E} &= -\partial_t \mathbf{B}, \\
\nabla \times \mathbf{B} &= \mathbf{j} + \sigma \mathbf{E} + \partial_t \mathbf{E},
\end{aligned}
$$

We consider two cases

$$\boldsymbol{\sigma = \sigma_0 \theta(t)}$$

$$\boldsymbol{\sigma = \sigma_0 \theta(t)/(1 + t/t_0)^{1/3}}$$

In both, σ is non-zero only after collision

Woods-Saxon distribution (rest frame)

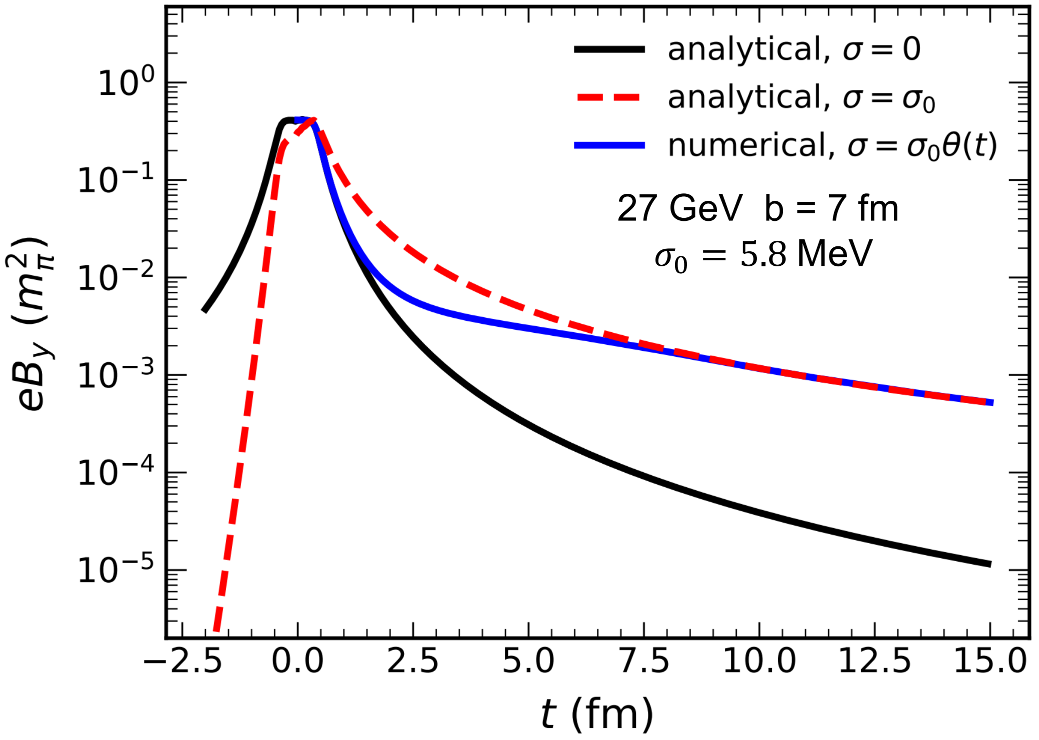
$$f(r) = \frac{\rho_0}{1 + e^{[(r-R)/a]}}$$

lab frame

- $\rho^{\pm} = \gamma f\left(\sqrt{(x \mp b/2)^2 + y^2 + \gamma(z \mp v_z t)^2}\right)$
- $j_x^{\pm} = j_y^{\pm} = 0$
- $j_z^{\pm} = \pm\gamma v_z f\left(\sqrt{(x \mp b/2)^2 + y^2 + \gamma(z \mp v_z t)^2}\right)$

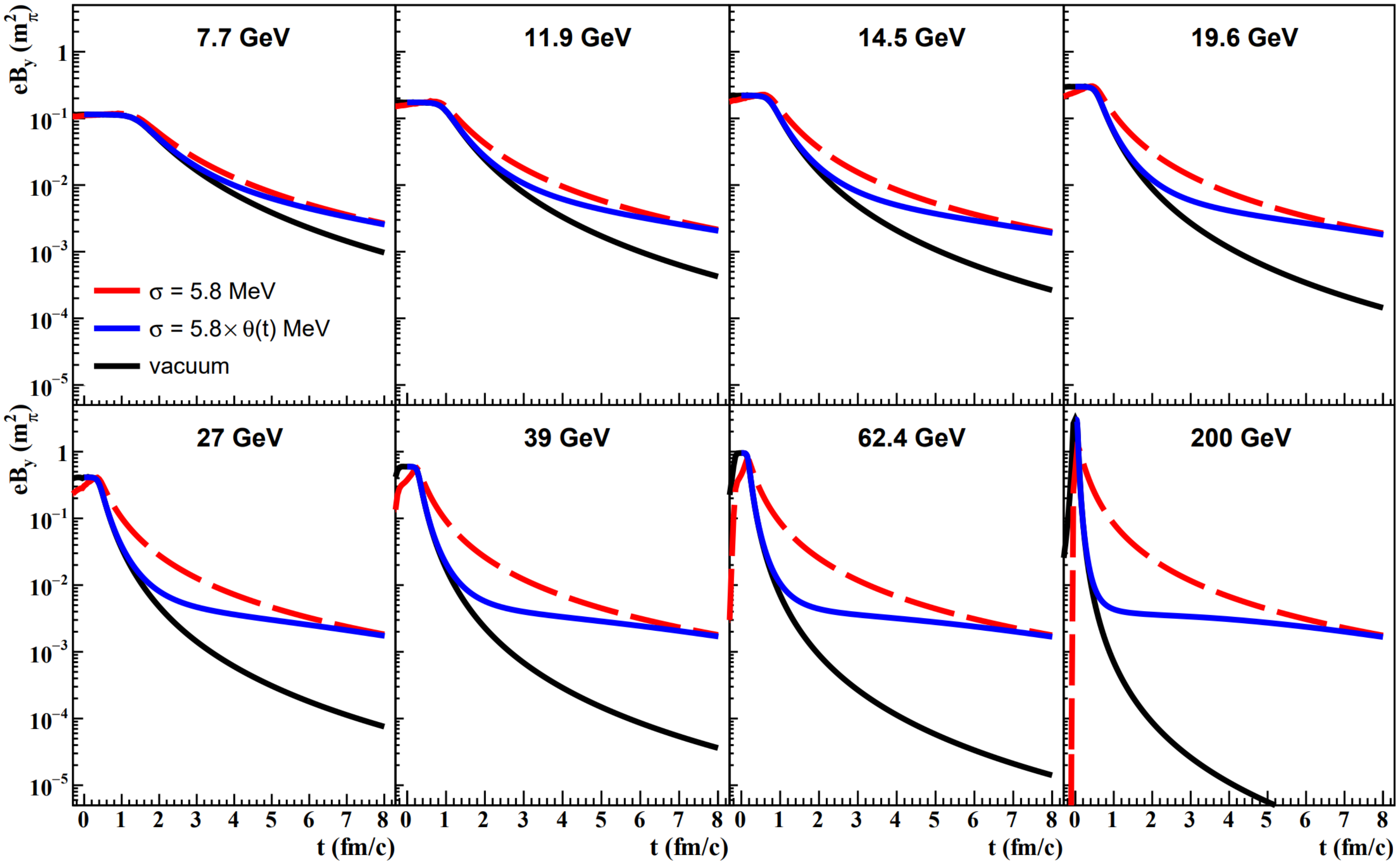
Simplification:
Nucleons fly freely without stopping

Analytical vs. Numerical



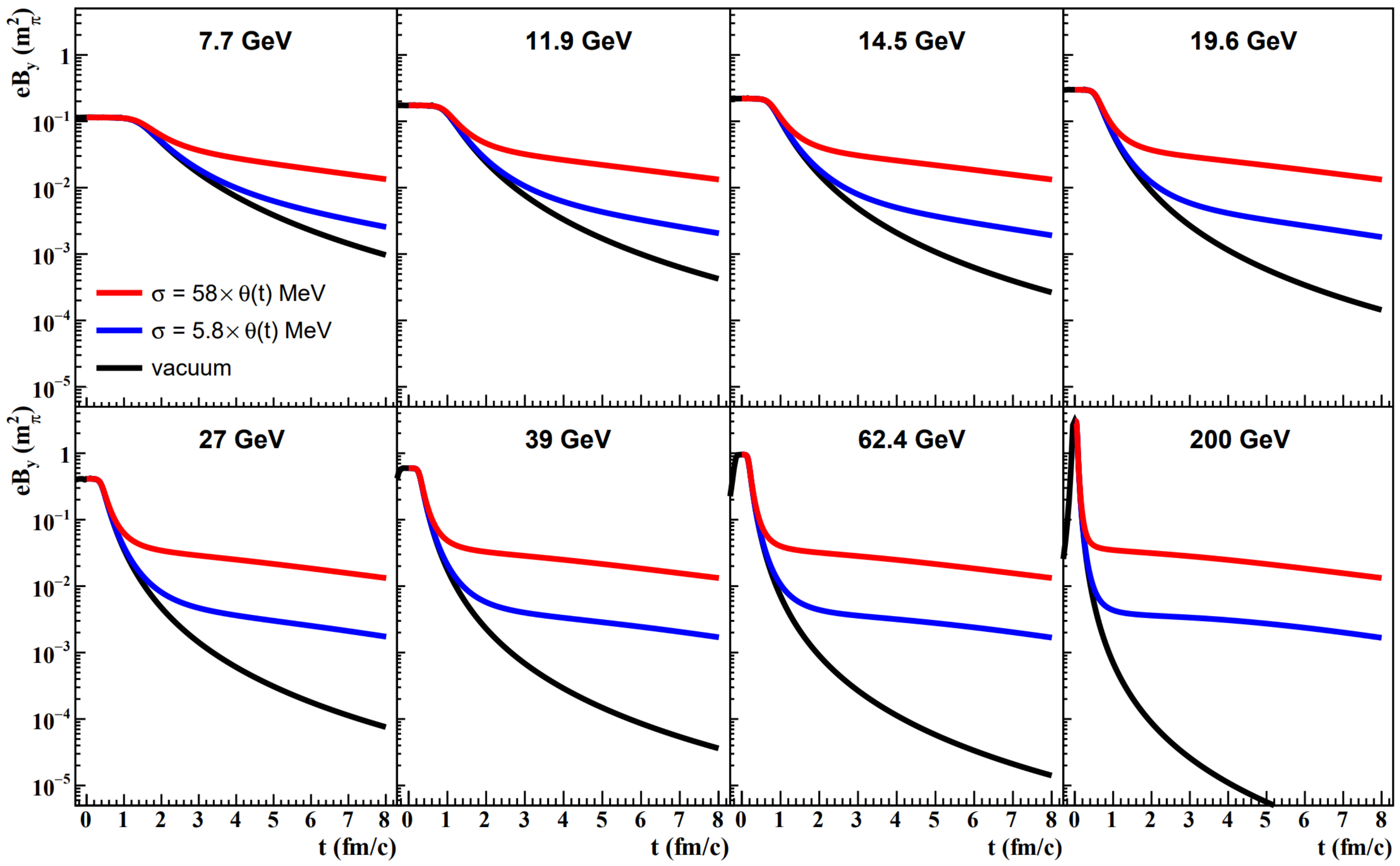
- **Effect of σ is not obvious at early time (t < 1.5 fm/c)**
- **At early time, the analytical formula over estimates the field**
- **At very late time (t > 10 fm/c), it agrees with the numerical solution,**
- **but the time is too late (the field has became very small)**

Analytical vs. Numerical



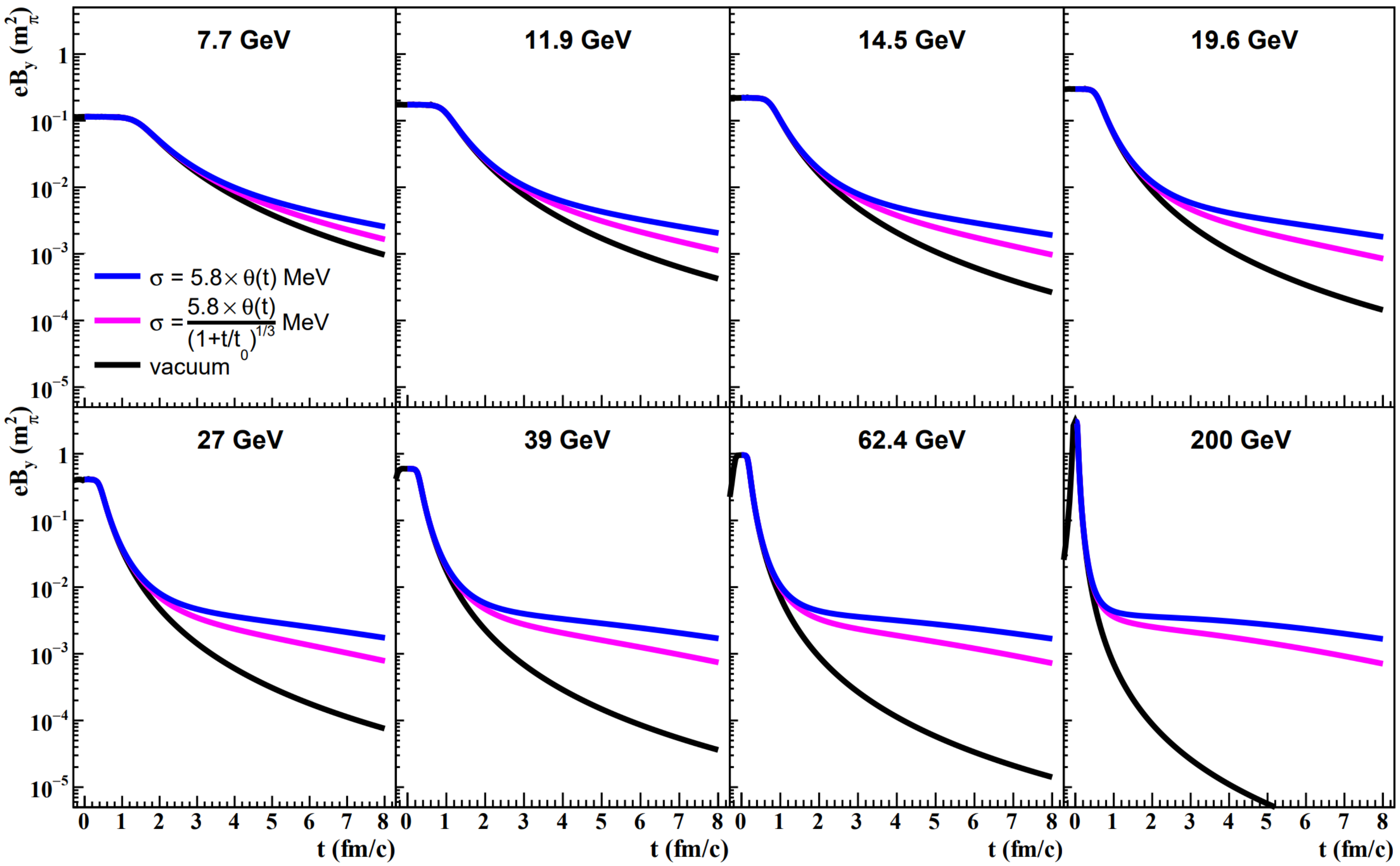
- The analytical formula over estimates the field at all energies

Magnetic field with $\sigma = \sigma_0 \theta(t)$



- At late time, the field is sensitive to the σ value, and less sensitive to v_z
- We have used the same σ value at different energies
- For $t > 4$ fm/c, the field is at the order of $10^{-3} \sim 10^{-2}$ ($\sigma = 5.8$ MeV)

Magnetic field with $\sigma = \sigma_0 \theta(t)/(1 + t/t_0)^{1/3}$

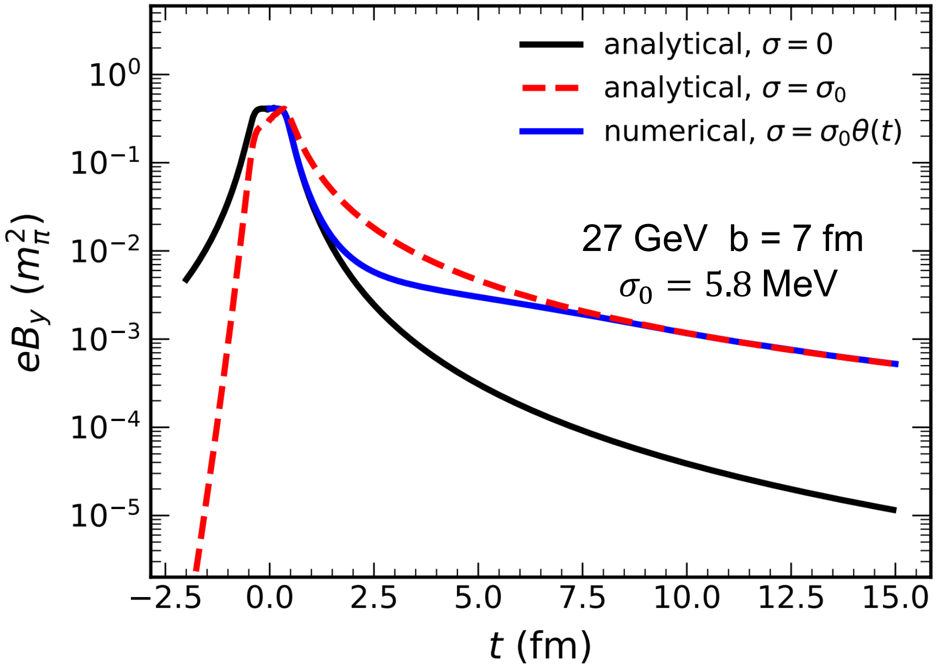


- The field also depends on σ's time behavior.
- When necessary, the numerical method can be applied to more accurate model.

Impact of the magnetic field

Effects at different time stage:

Dilepton production (initial time)	CME (early time)	Direct flow (middle time)	Spin polarization (late time)
$t = 0$	t_{QGP}		t_{hadron}
Maximum magnetic field	Field drops fast at early time. So, how early QGP is formed?	More accurate model is needed to simulate it.	The field is too small.

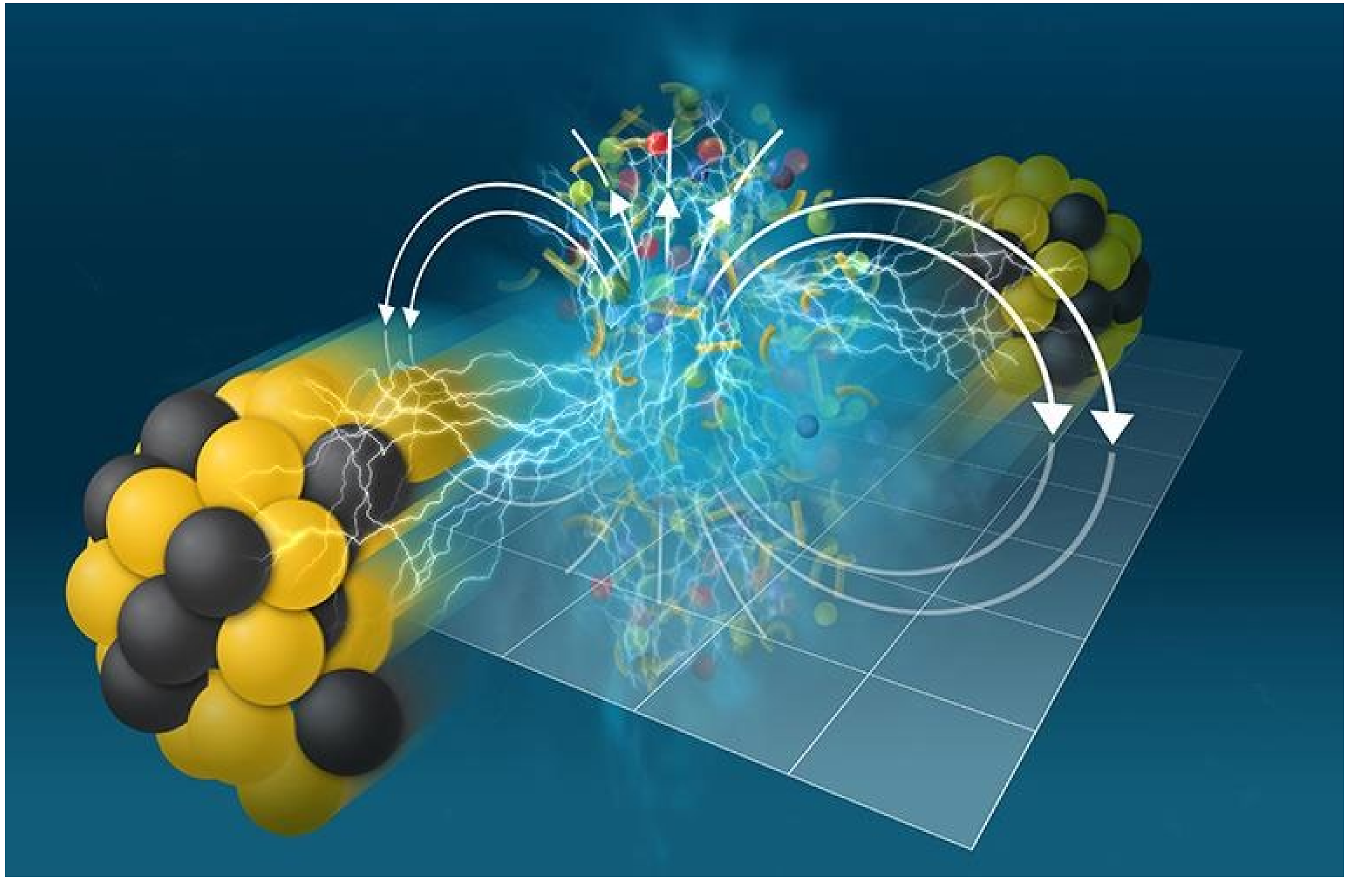


Super Strong Magnetic fields' Imprint

Analysis of electrical charge dependent deflections in quark-gluon plasma by the STAR Collaboration at the BNL Relativistic Heavy Ion Collider(RHIC)

- **Data confirm that super strong magnetic fields (~10^{18} Gauss) generated in off-center collisions could induce an electric current in the quark-gluon plasma**

- **The findings offer a measure that could relate to the electrical conductivity of the quark-gluon plasma to learn about nature's fundamental building blocks**



Observation of the Electromagnetic Field Effect via Charge-Dependent Directed Flow in Heavy-Ion Collisions at the Relativistic Heavy Ion Collider, Phys. Rev. X 14 (2024) 011028

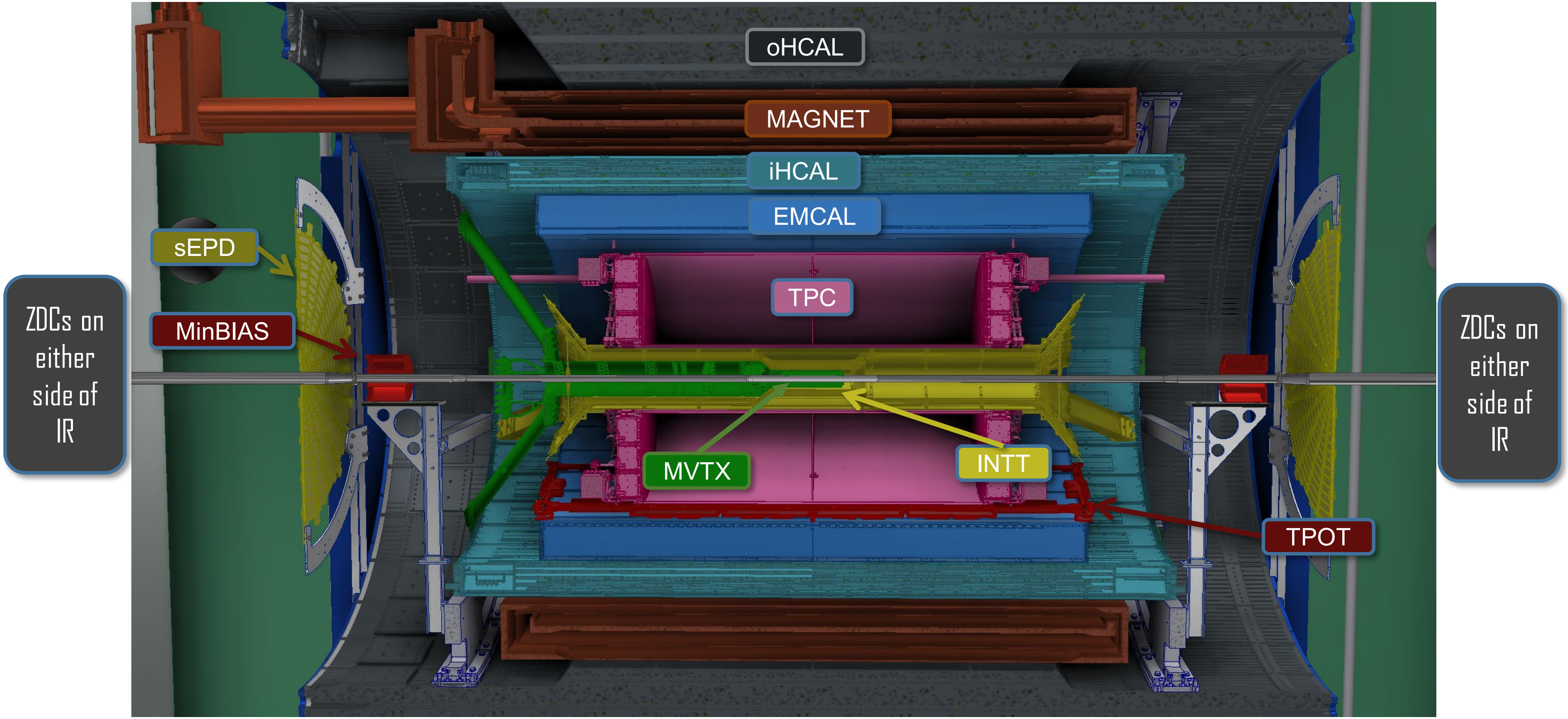
Electro-Magnetic Field in Heavy Ion Collisions

1) No doubt the presence of strongest E-M field known in the Universe created in ultra-relativistic heavy ion collisions

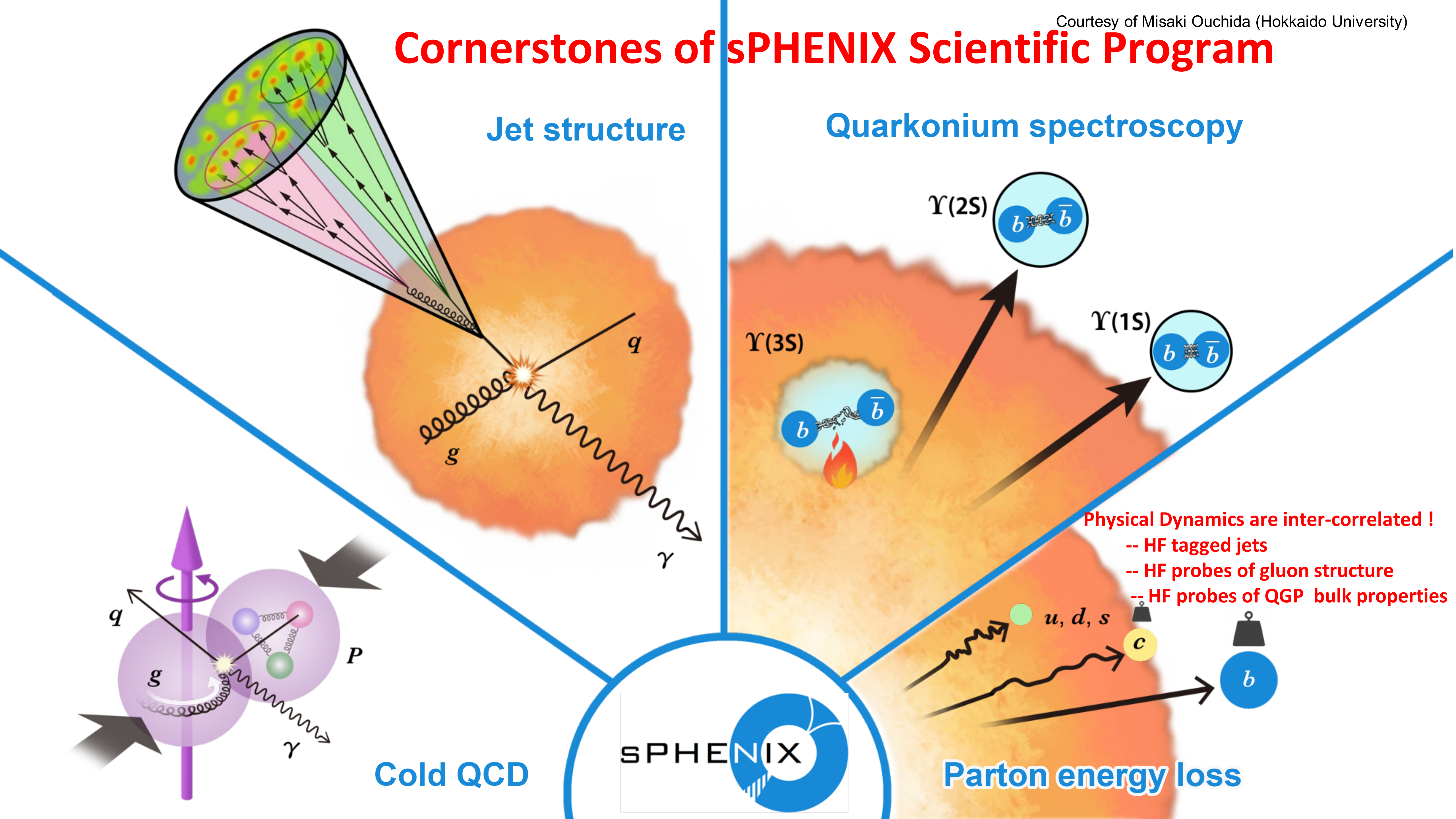
2) The time evolution and the conductivity of the QGP are important scientific questions to be addressed in heavy ion collisions

3) The answers to these questions have great impacts on studies of QCD properties of the QGP

The sPHENIX Experiment at RHIC



A Modern Collider Detector for Hard Probes of QGP at RHIC


Courtesy of Misaki Ouchida (Hokkaido University)
Cornerstones of sPHENIX Scientific Program
Jet structure
q
g
γ
Quarkonium spectroscopy
ϒ(2S)
b b̄
ϒ(1S)
b b̄
ϒ(3S)
b b̄
Physical Dynamics are inter-correlated !
-- HF tagged jets
-- HF probes of gluon structure
-- HF probes of QGP bulk properties
u, d, s
c
b
q
g
P
γ
Cold QCD
sPHENIX
Parton energy loss

sPHENIX Detectors All Critical for HF Physics

Unique sPHENIX Detector Capabilities – Enable

-- Direct Reconstruction from Hadronic Decays for D^0, $D^{\pm}$, D_S and Λ_C

-- Tagged charm and bottom decays:

semi-leptonic decays C → e+X and B → e+X

B → D+X

-- C/B tagged jets

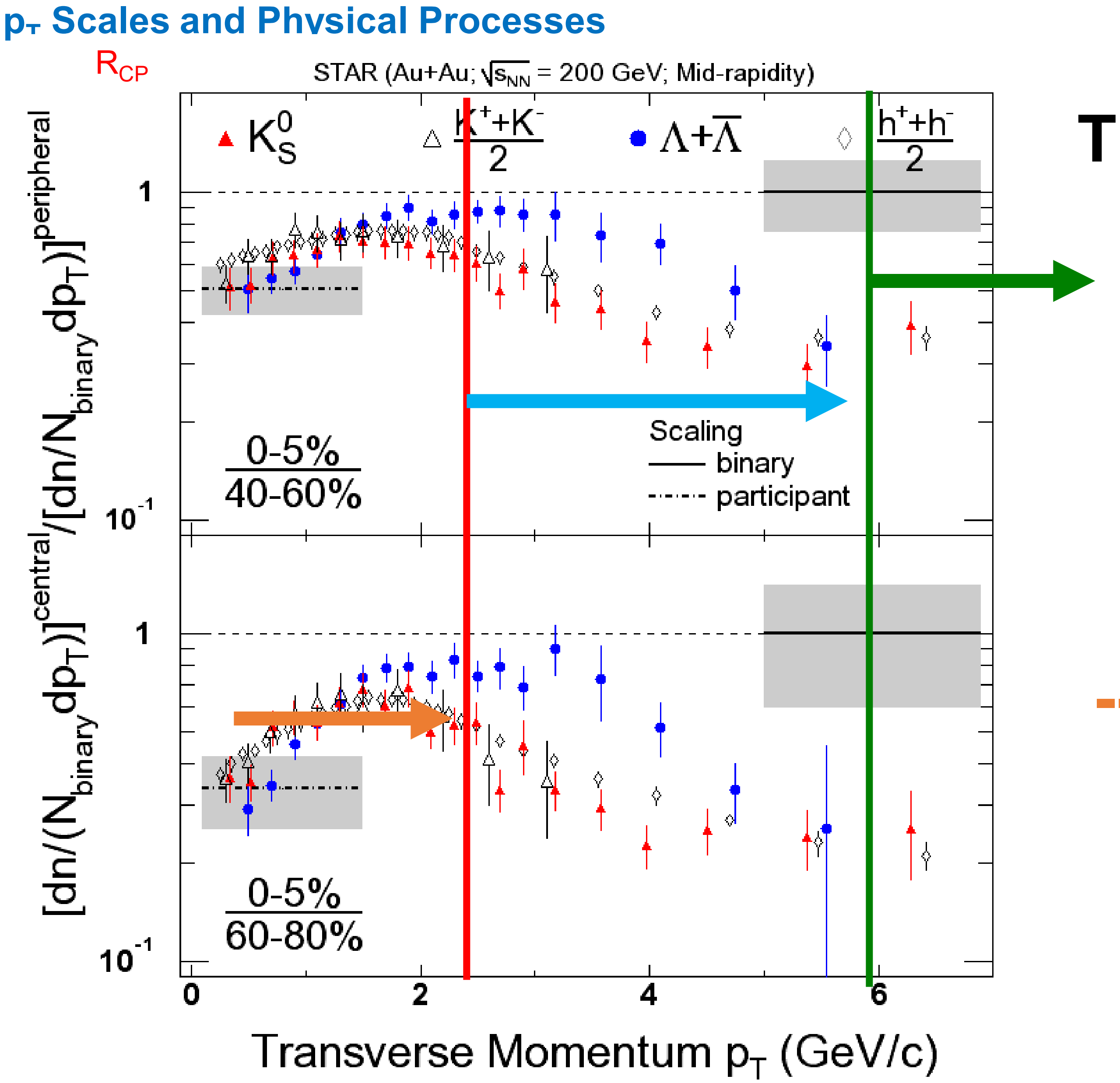
All sPHENIX Detectors Critical:

-- TPC, TPOT, INTT and MVTX + Stream Readout

-- EMCal, IHCal, OHCal

-- Min Bias Detector (MBD),
sPHENIX Event-Plane Detector (sEPD), ZDC

Hard Probes -- High p_T region means p_T > 6 GeV/c



Three Distinct P_T Regions:

-- Fragmentation

-- Multi-parton dynamics (recombination or coalescence or …)

-- Hydrodynamics (constituent quarks ? parton dynamics from gluons to constituent quarks?)

sPHENIX Heavy Flavor Physics – Broad Perspectives

P_T < 6 GeV/c Region

Hydrodynamics -- Diffusion in QGP
-- Particle mass effect

Coalescence/Recombination
-- baryon versus meson
-- Origin of collective flow

sPHENIX – greater statistics
-- rare heavy particles

P_T > 6 GeV/c Region

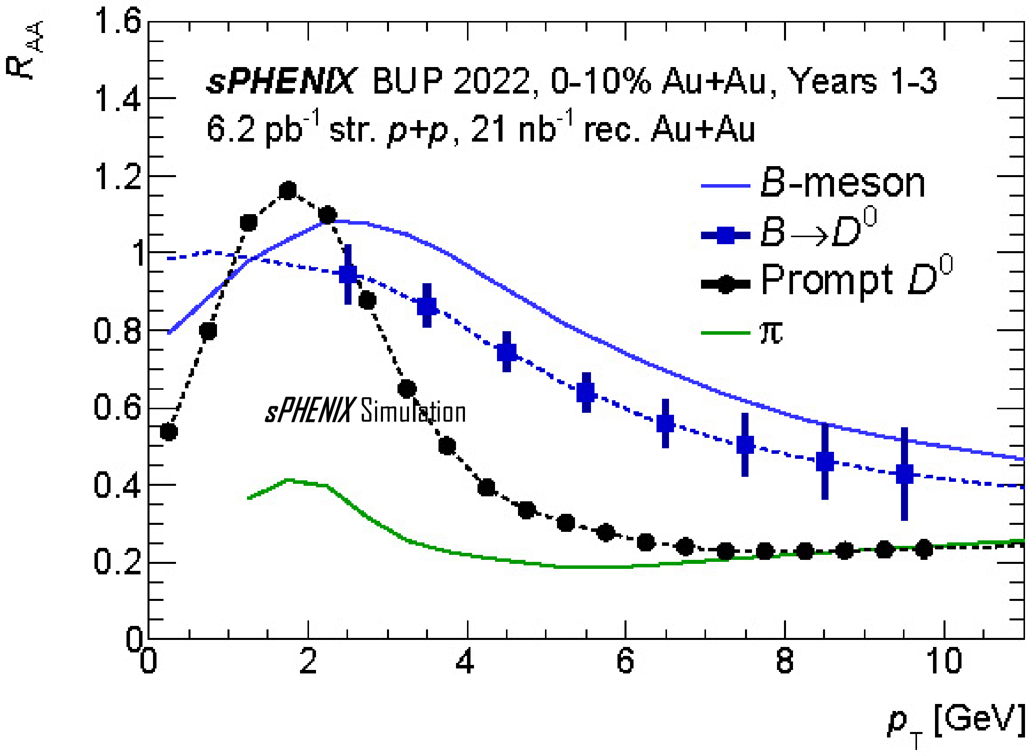
Jet energy loss mechanism:
-- quark mass dependence
-- radiative versus collisional

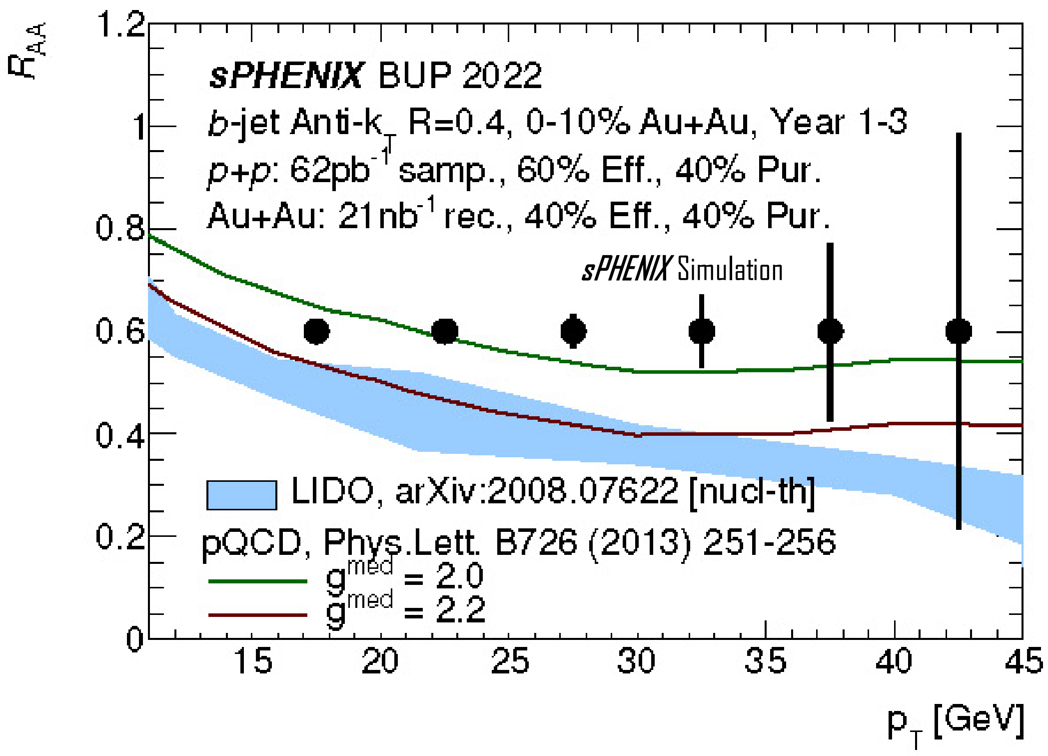
Origin of jet collectivity
-- path length dependence of parton energy loss
-- Non-flow correlations

Medium responses to jet energy loss

sPHENIX Unique @RHIC

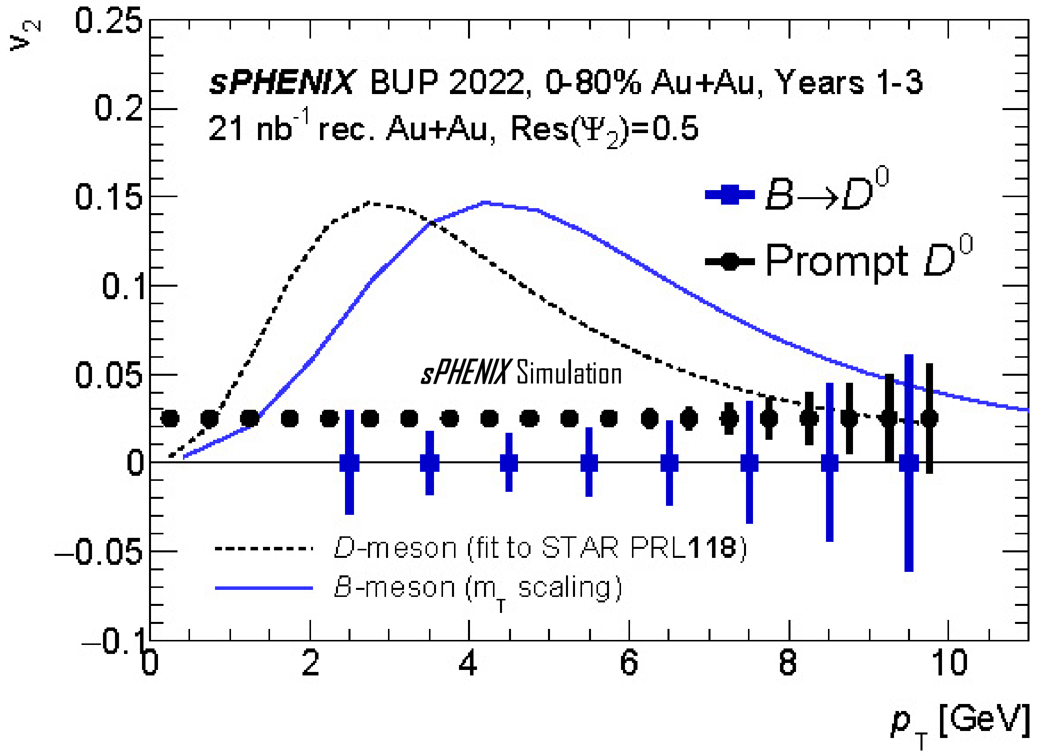
Expectations from sPHENIX Beam Use Request

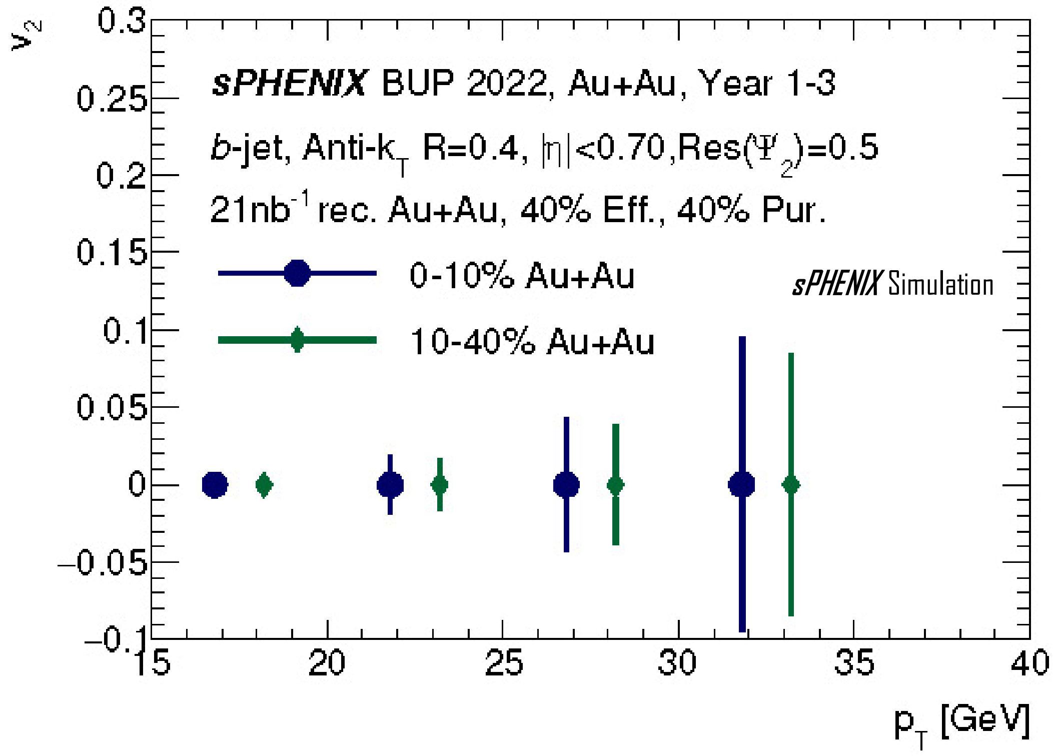




High pT region for single particle (pT > 6 GeV/c) and for jets – Key ingredients for sPHENIX science

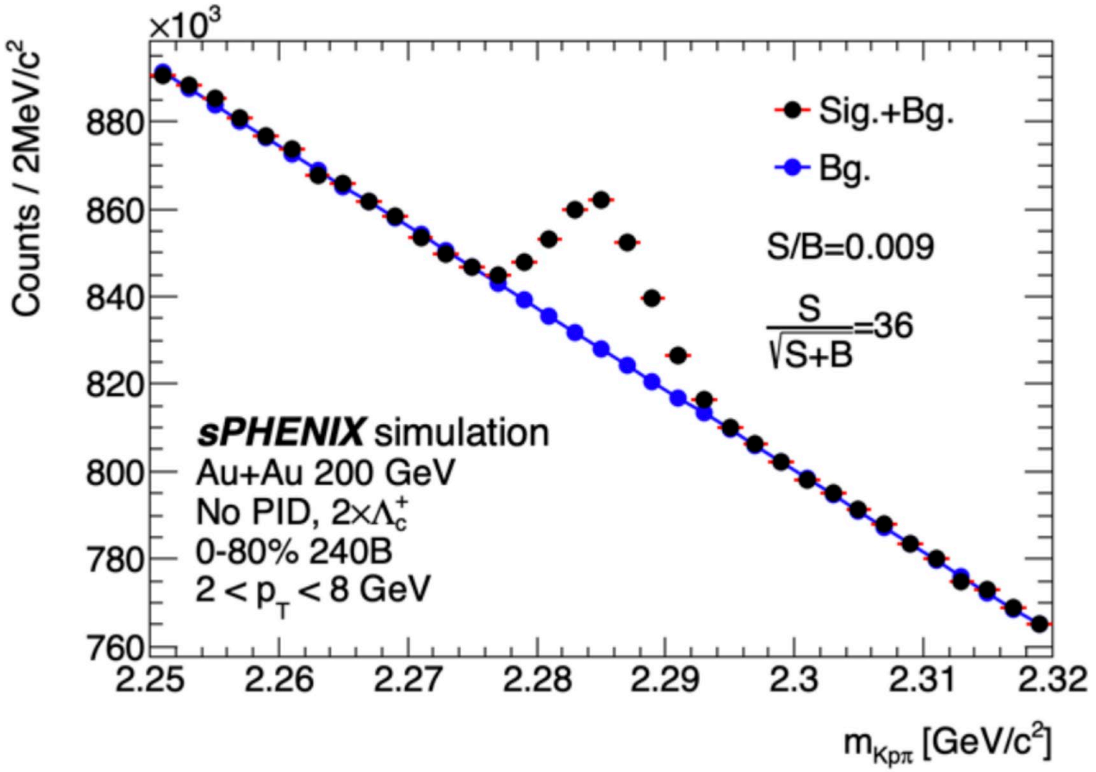
Expectations from sPHENIX Beam Use Request

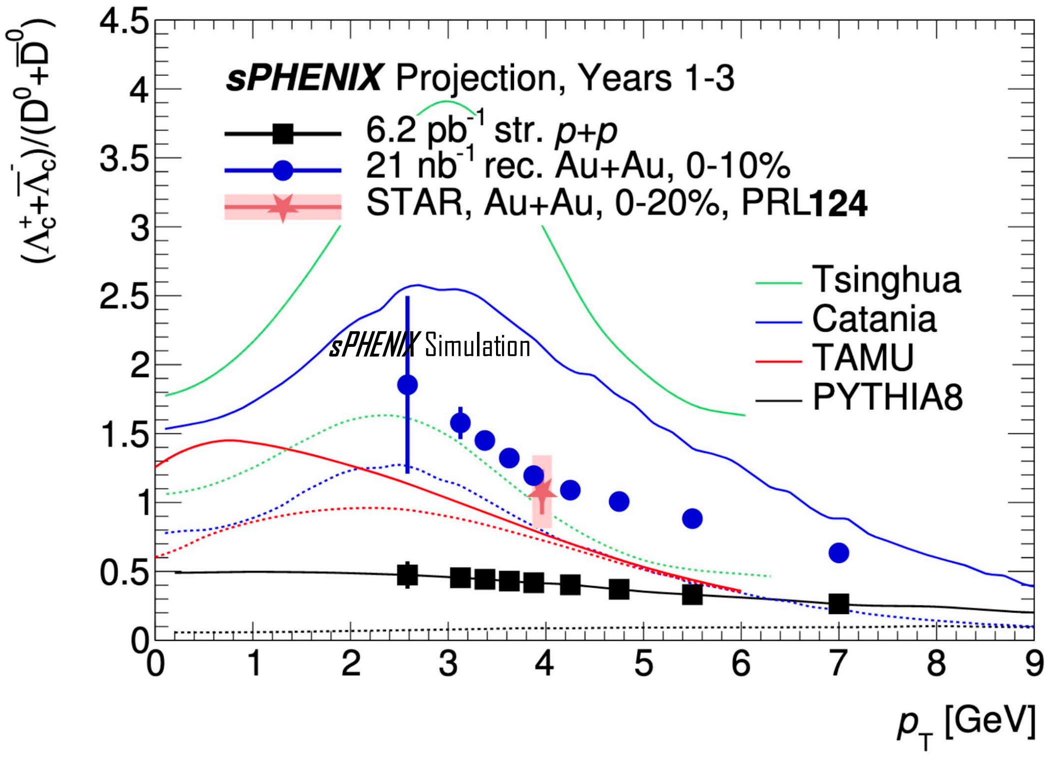




The B meson/jet measurements will always be statistics limited;
ML applications to improve efficiency and purity !

Charm Baryons – Key probe for hadronization dynamics and charm flow

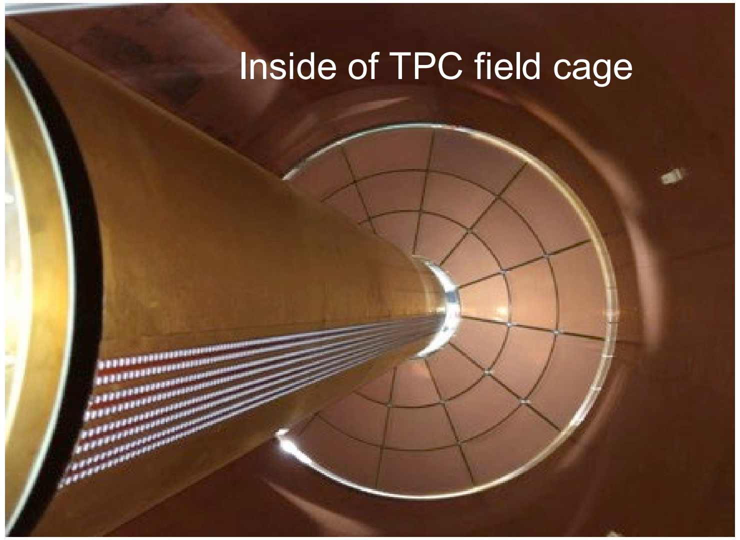


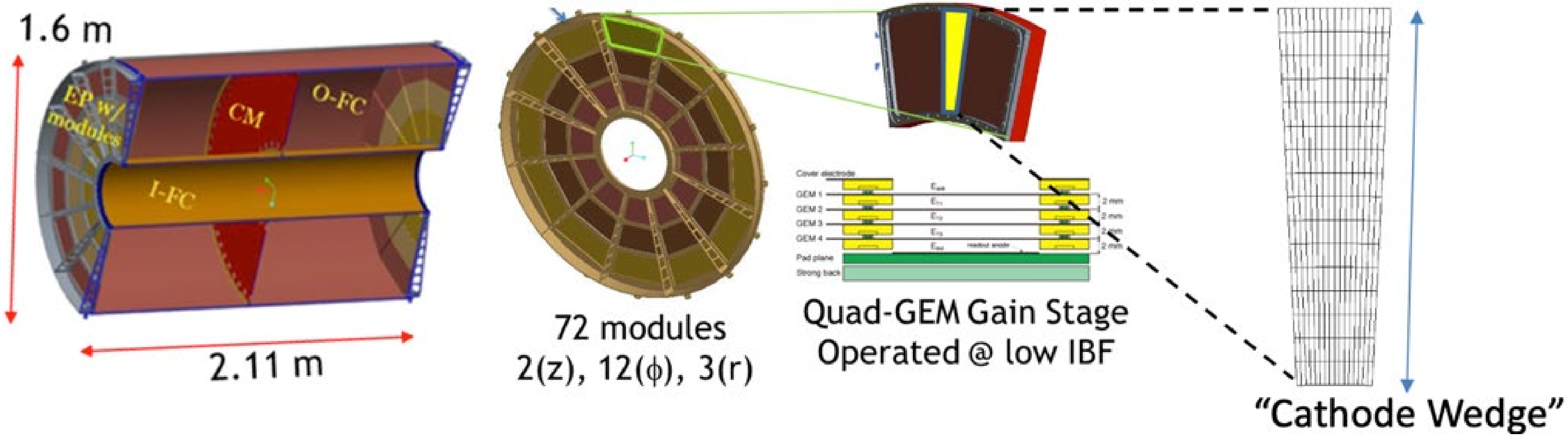


Tracking detectors Stream Readout for p+p collisions – major advantage for sPHENIX
-- allow for p+p reference data from the same experiment

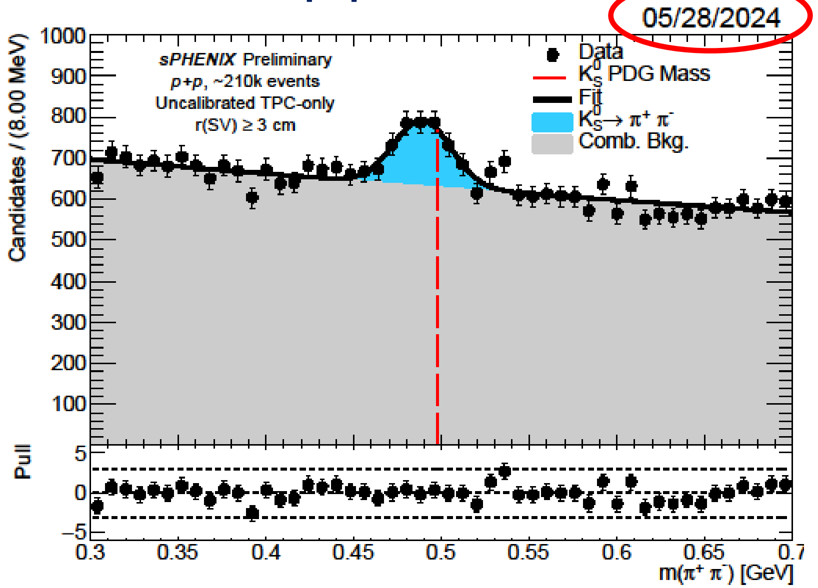
Other charm baryons Ξ_C Ω_C ?
$\Lambda_b \rightarrow \Lambda_C$ X ??

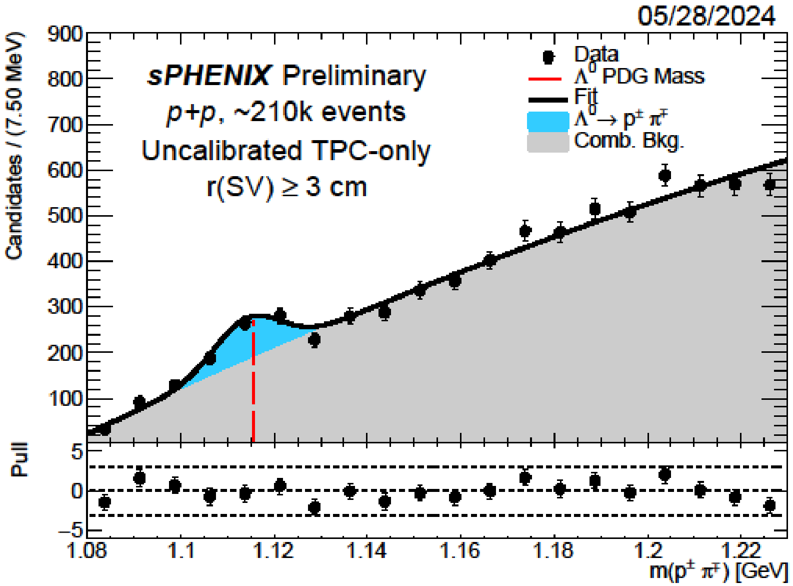
The Time-Projection Chamber





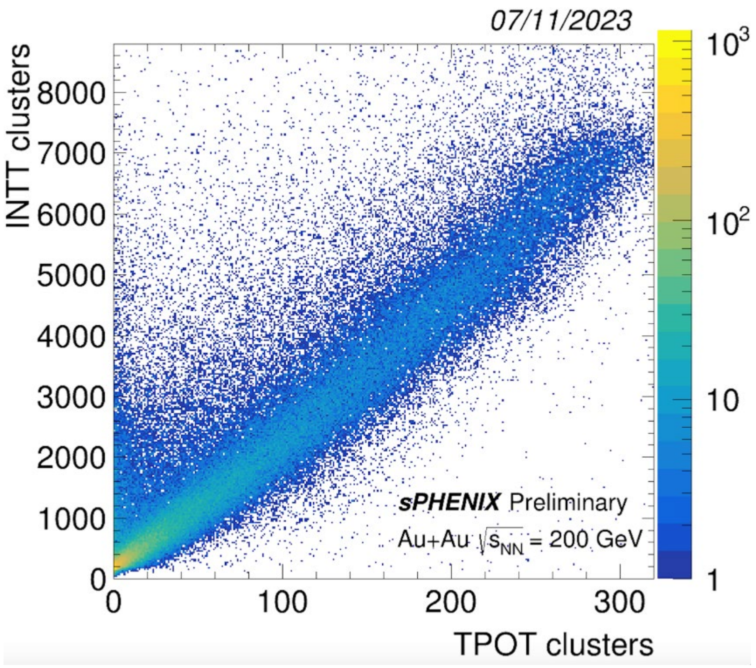
Run 2024 p+p Data



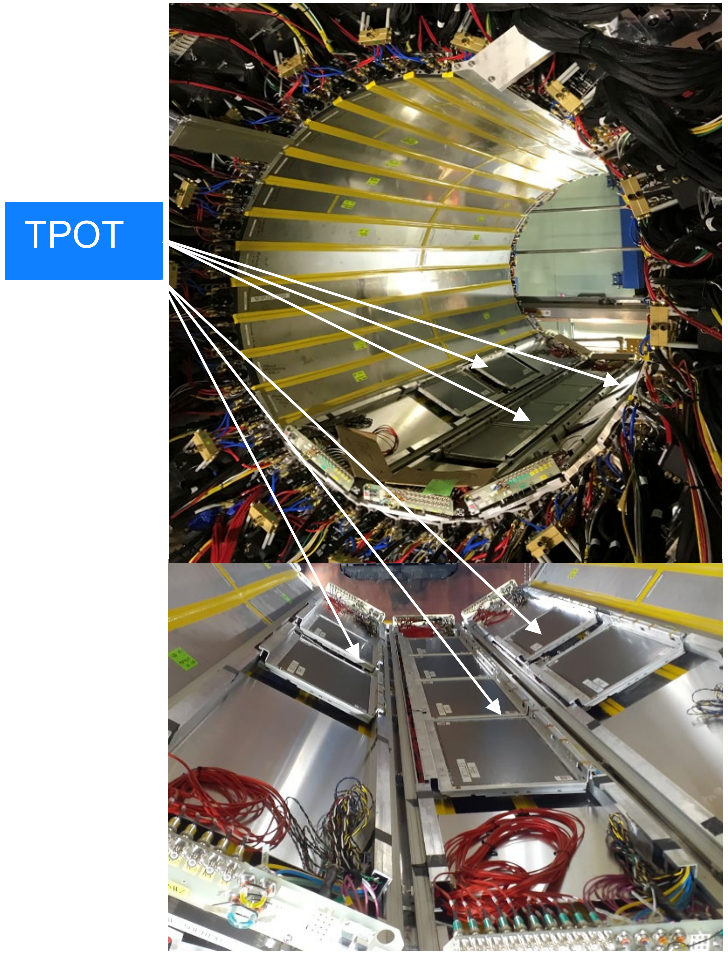


The Time Projection Outer Tracker (TPOT)

- The TPOT consists of eight identical modules, two Micromegas chambers/module. Each module is 56x32 cm^2.
- TPOT has approximately 8% coverage of the TPC acceptance.
- Gas is 95/5 Ar/iC4H10.
- TPOT provides additional spatial reference points outside of the TPC to calibrate for beam induced space charge distortions.



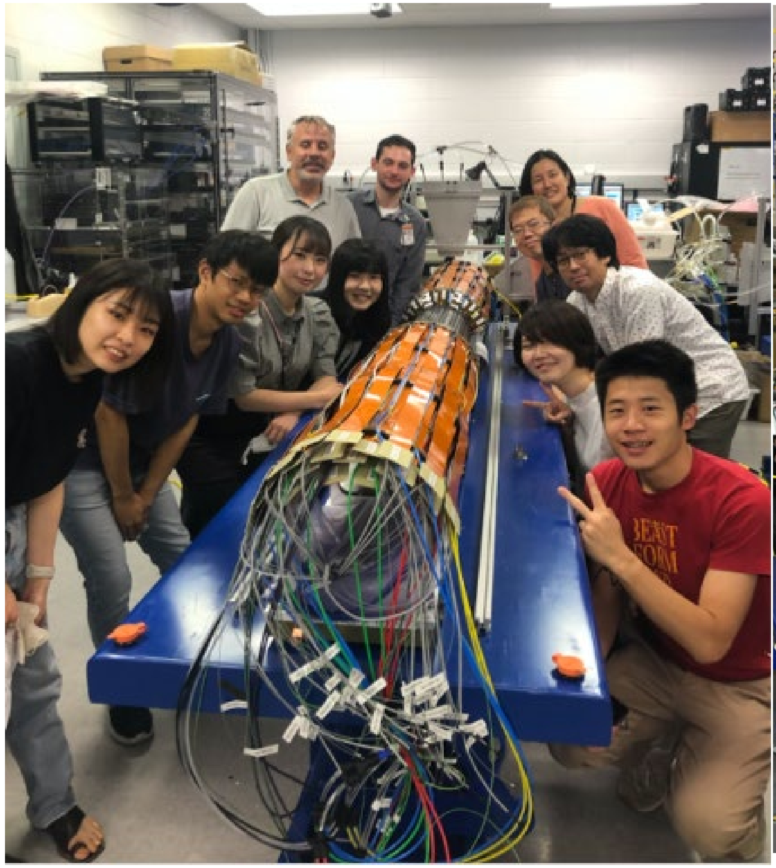
arXiv: 2403.13789, published in NIMA

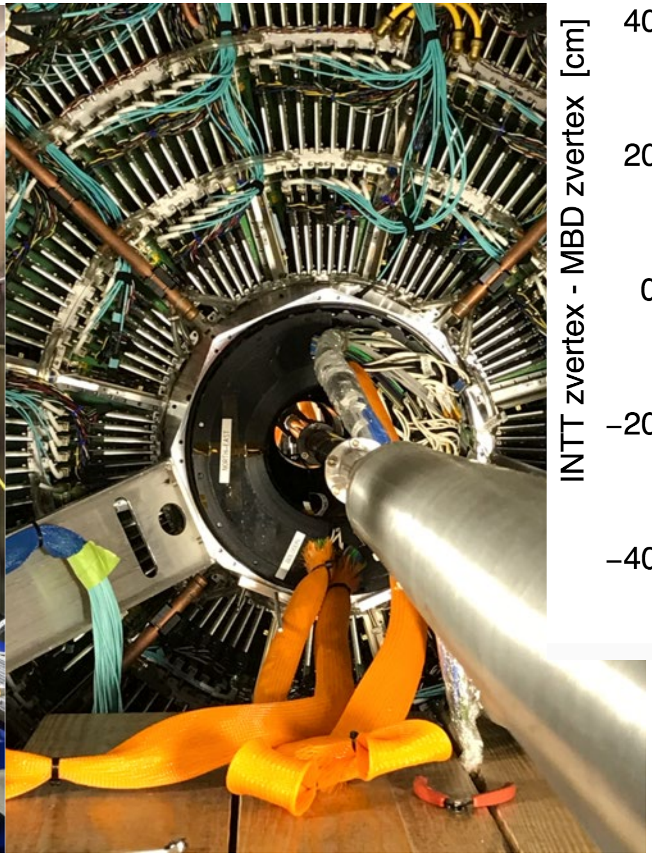


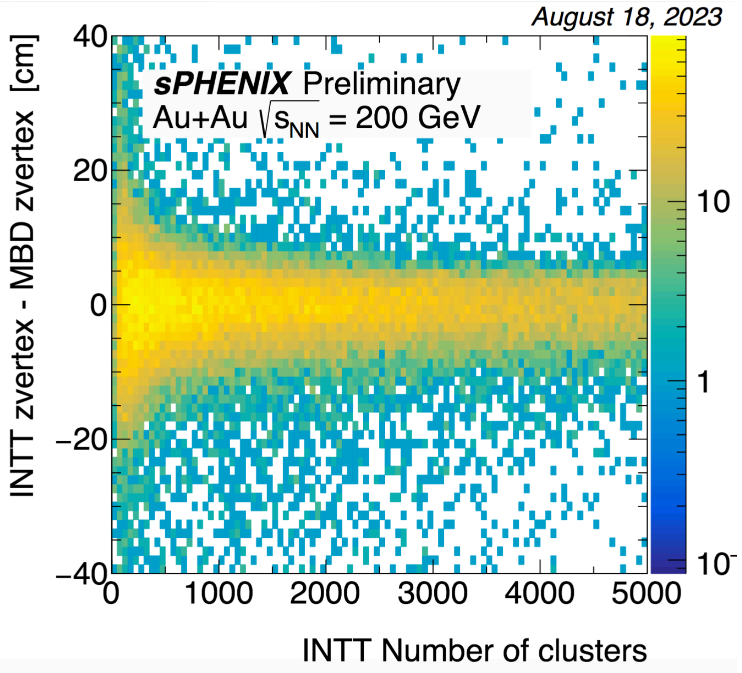
sPHENIX Intermediate Tracker (INTT)

Two-layer silicon-strip detector.

Fast response time of 60 ns allows for time stamp of collisions in stream readout for pile up rejections

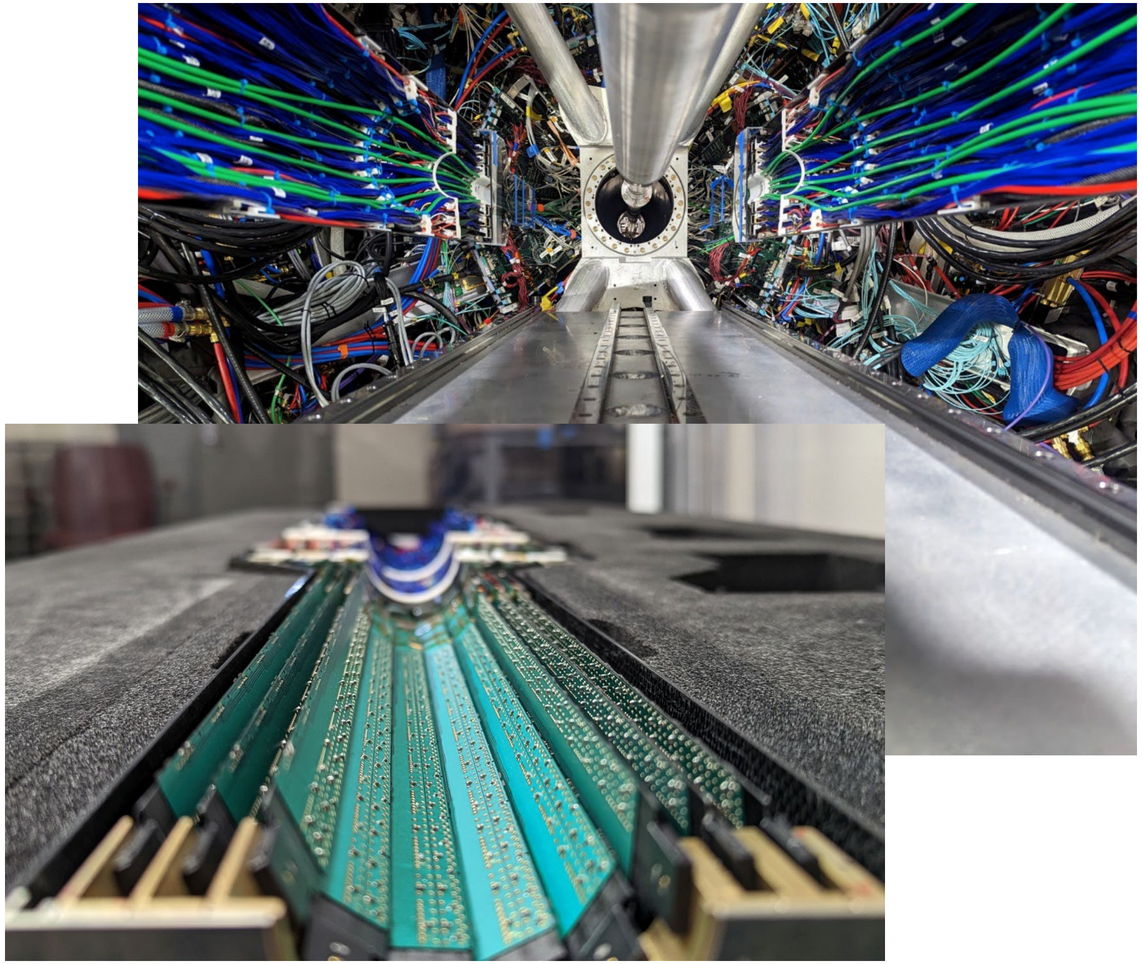


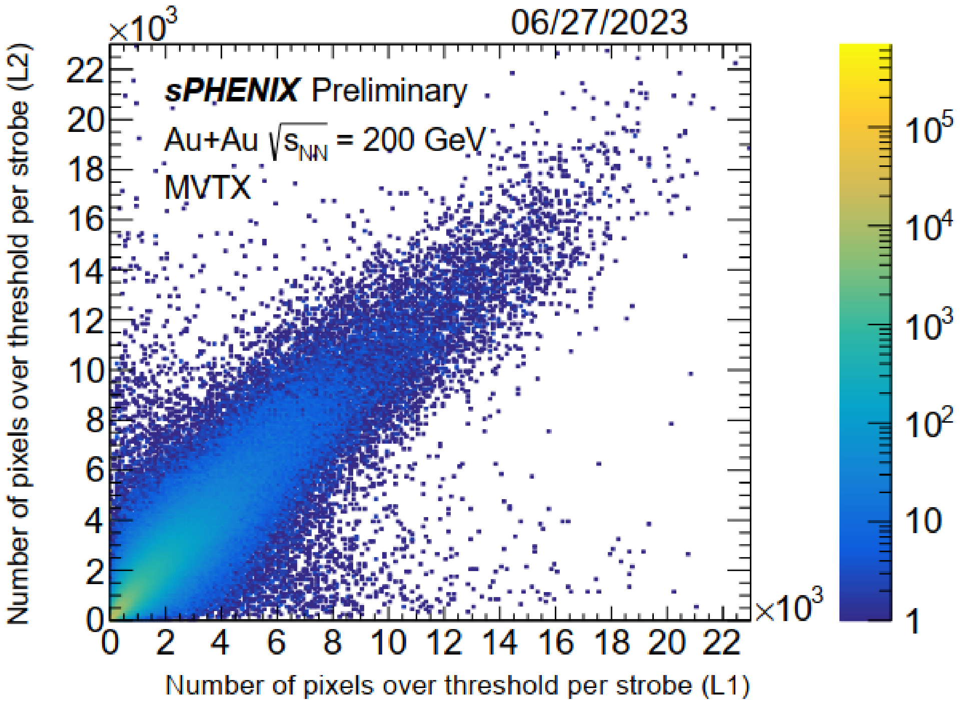




Monolithic Active Pixel Vertex Detector (MVTX)

- The MVTX is a 226M channel, 3-layer MAPS-based pixel detector.
- The MVTX is a copy of inner 3 layers of the ALICE ITS w/ a custom design of service supports
- Staves and ROCs produced at CERN w/ participation from sPHENIX collaborators

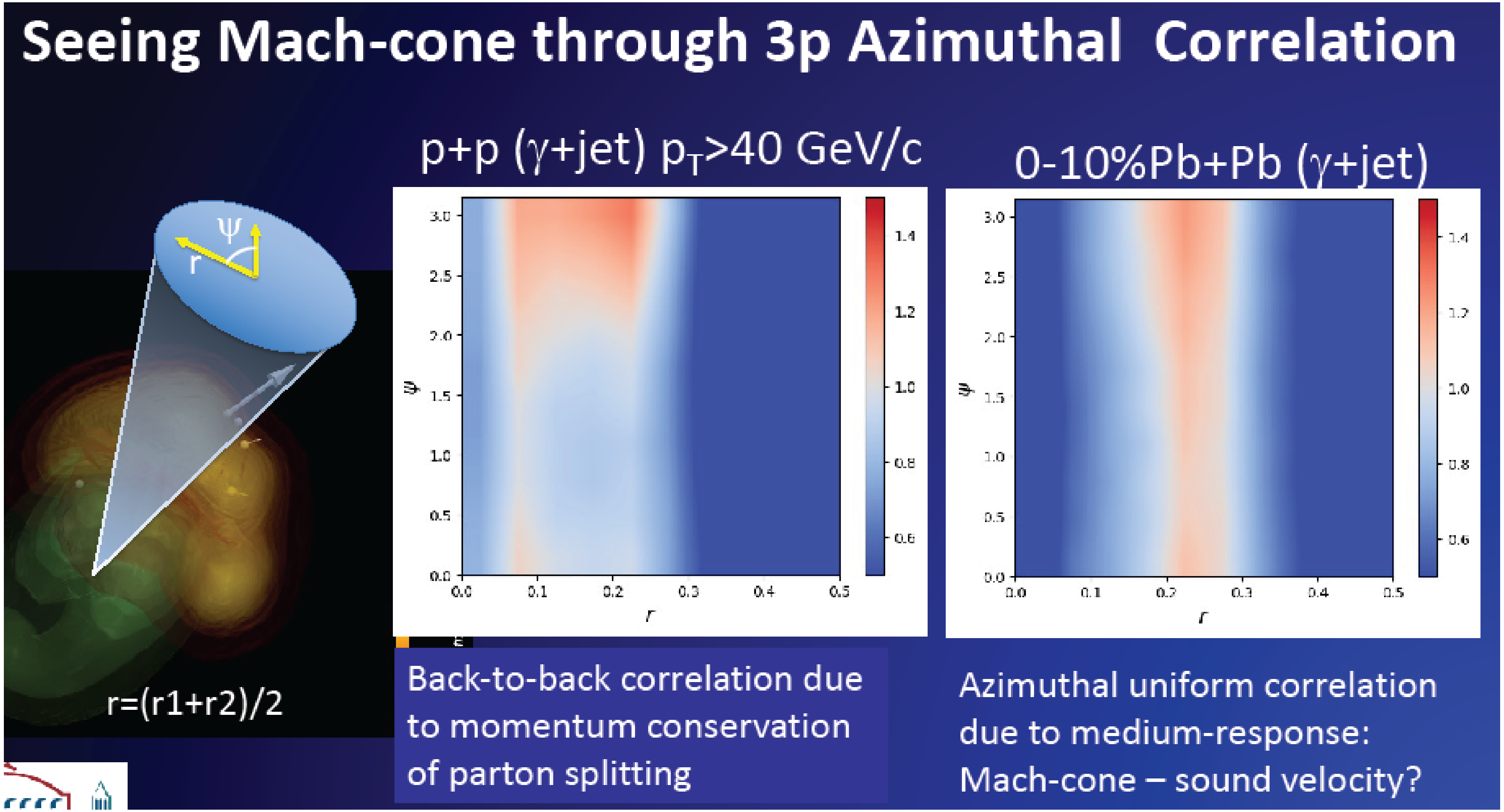




Stream readout

Exciting New Physics Opportunities to Explore at RHIC

XinNian Wang Recent Proposal for Mach-cone Search with γ-jet



We hope to extend the method for heavy flavor jets

Summary and Outlook

sPHENIX started p+p physics data-taking in Run 2024 after successfully commissioning all detectors !!

The major Au+Au physics data-taking will be Run 2025 !

Chinese sPHENIX Groups include Fudan, PKU, USTC, CCNU

Stay tuned for future sPHENIX results:
https://www.sphenix.bnl.gov/PublicResults

Great Opportunities in QCD and Neutrino Physics !!
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Thank You !