Probe Chiral Magnetic Effect with Signed Balance Function

arXiv:1903.04622

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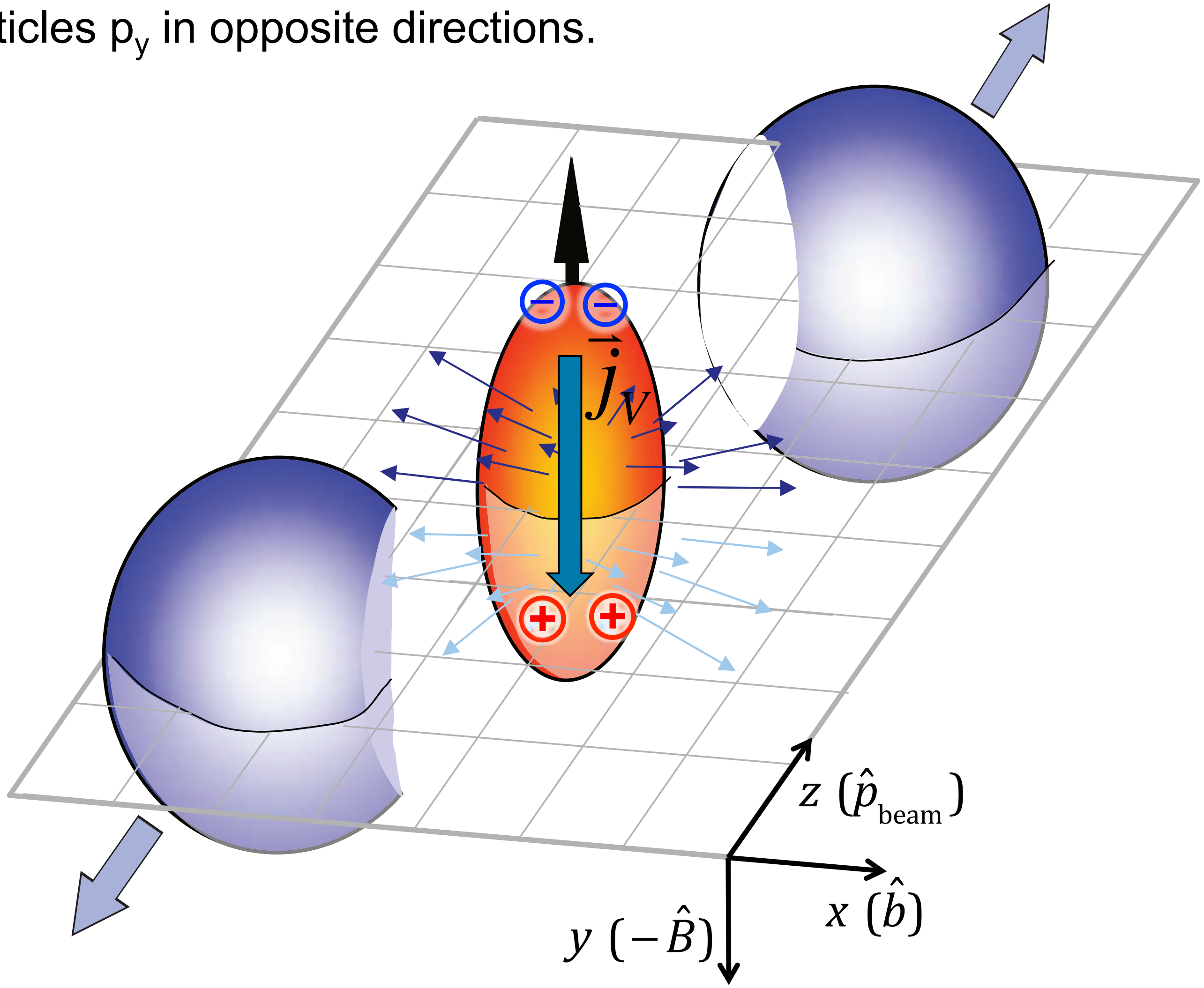
Motivation : CME-Induced Charge Separation

CME-induced charge separation shifts pos. and neg. particles p_y in opposite directions.

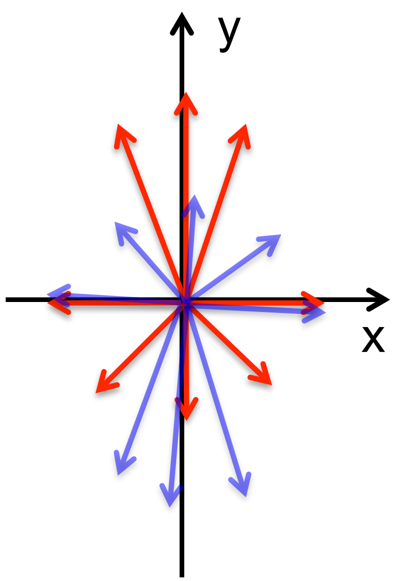


Motivation : CME-Induced Charge Separation

Conventional approach :

$$\frac{dN_{\pm}}{d\Delta\phi} \propto 1+2v_1\cos\Delta\phi+2v_2\cos 2\Delta\phi+2v_3\cos 3\Delta\phi+\cdots+2a_{\pm}\sin\Delta\phi+\cdots$$

Noting that $a_+ = -a_-$, $\langle a_+ \rangle = \langle a_- \rangle = 0$, define $a_1 \equiv |a_{\pm}|$,
Study of a_1 fluctuation $\langle a_1^2 \rangle$.
(out-of-plane "v_1" fluctuation) 🡨Taking advantage of flow knowledge !



🡨 Looking for "clustering" of charged particles in opposite directions along y-axis.

An angular correlation problem in conventional approach.

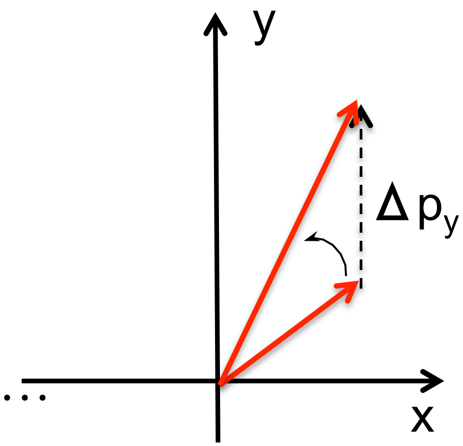

Where are we from ?

Motivation : CME-Induced Charge Separation

Conventional approach : Separation ➔ Rotation :

Shift in p_y will change azimuthal angle, thus it is appropriate and convenient to quantify such effect by writing the particle distribution as :

$$\frac{dN_{\pm}}{d\Delta\phi} \propto 1 + 2v_1\cos\Delta\phi + 2v_2\cos 2\Delta\phi + 2v_3\cos 3\Delta\phi + \cdots + 2a_{\pm}\sin\Delta\phi + \cdots$$



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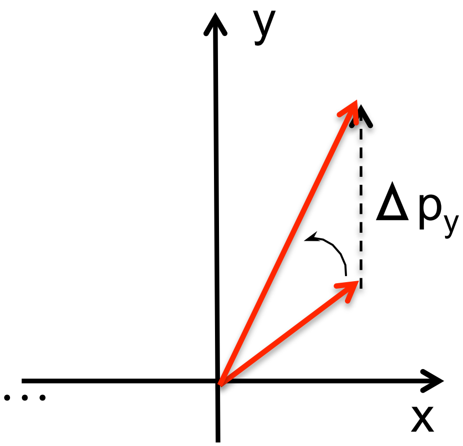

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$$\Delta p_y \quad \Rightarrow \quad \Delta\phi$$

cause   consequence

To study the separation, it is tempting to focus on Δp_y itself directly instead of $\Delta\phi$.

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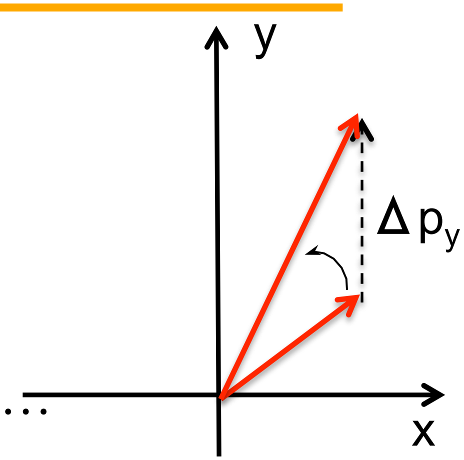

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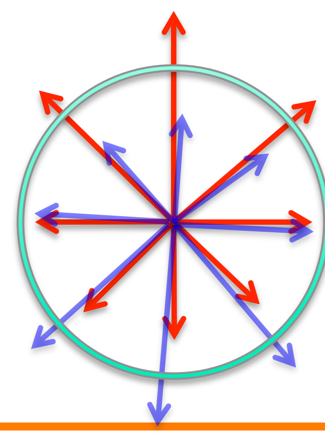
$$\Delta p_y \Rightarrow \Delta\phi$$

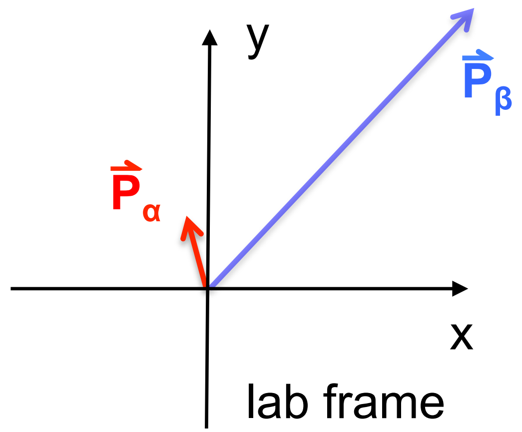
cause → consequence

To study the separation, it is tempting to focus on Δp_y itself directly instead of $\Delta\phi$.

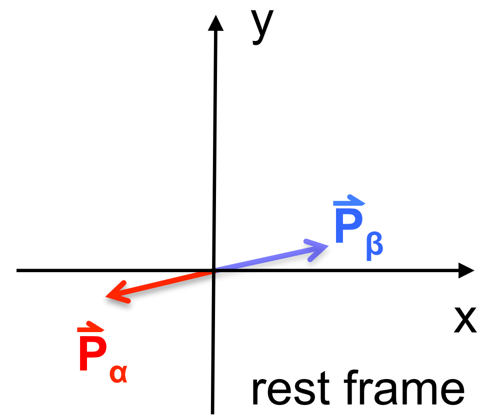
To consolidate this point :
an event can have charge separation
while being perfectly isotropic in azimuth ➔



Motivation : CME-Induced Charge Separation



Conventional view
(α is leading β)



Reality
(α is tailing β)

α is “leading” β if examined with the consideration of azimuthal angle only in lab frame (α being closer to y-axis than β). But the reality is the opposite when the same pair is viewed in the rest frame.

The rest frame holds the ultimate answer.
This is by definition.

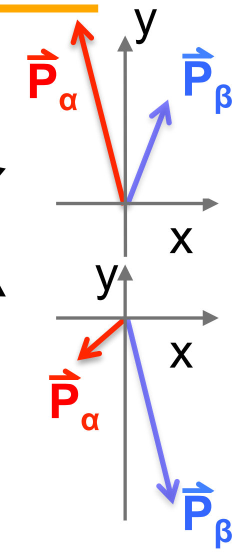
Signed Balance Function

$$B_{P,y}(S_y)=\frac{N_{+-}(S_y)-N_{++}(S_y)}{N_+},$$

$$B_{N,y}(S_y)=\frac{N_{-+}(S_y)-N_{--}(S_y)}{N_-}.$$

← Counting pairs with ordering in p_y.

where for $N_{\alpha\beta}$ terms, S_y is labeled as +1 if $p^{\alpha}_y > p^{\beta}_y$, and -1 if vice versa.

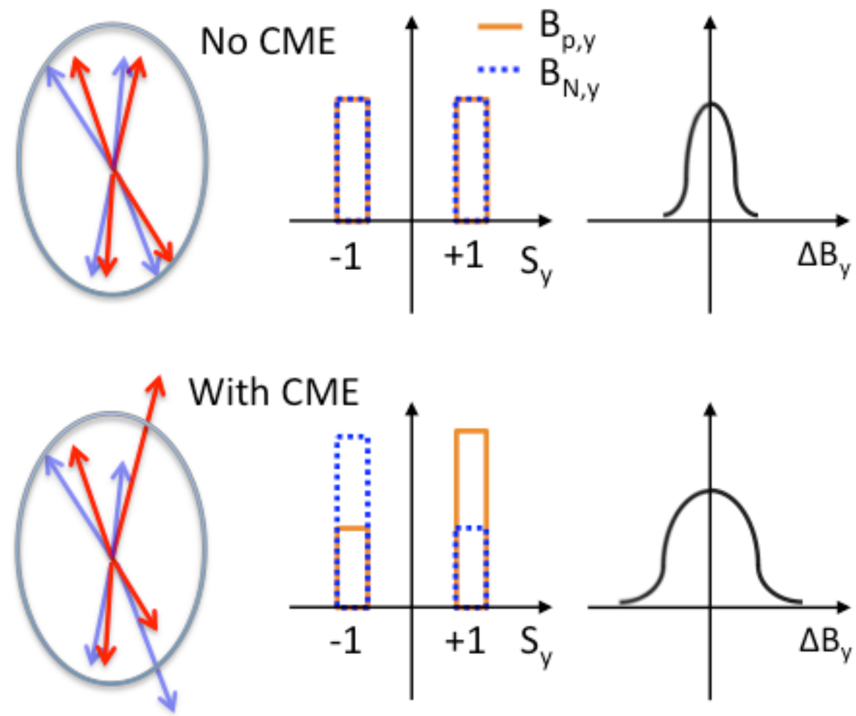


$$\delta B_y(\pm1)=B_{P,y}(\pm1)-B_{N,y}(\pm1),$$

$$\Delta B_y=\delta B_y(+1)-\delta B_y(-1)=2\delta B_y(+1).$$

← Excess of pos. leading neg.

Looking for enhanced event-by-event fluctuation of ΔB_y (relative to ΔB_x) ➔

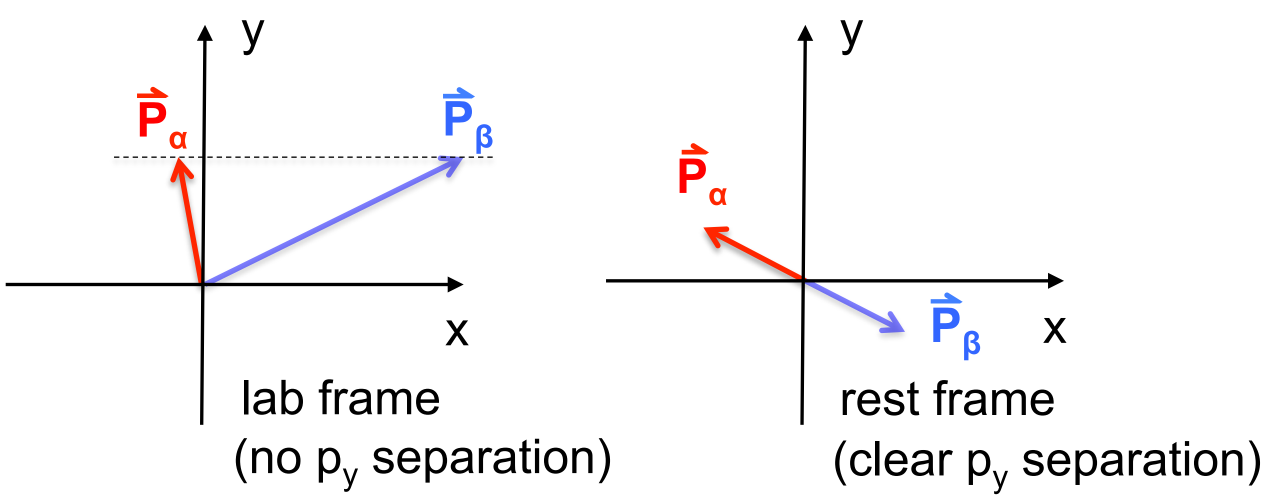


$$r=\frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}}. \quad (>1 \text{ with CME})$$

Signed Balance Function

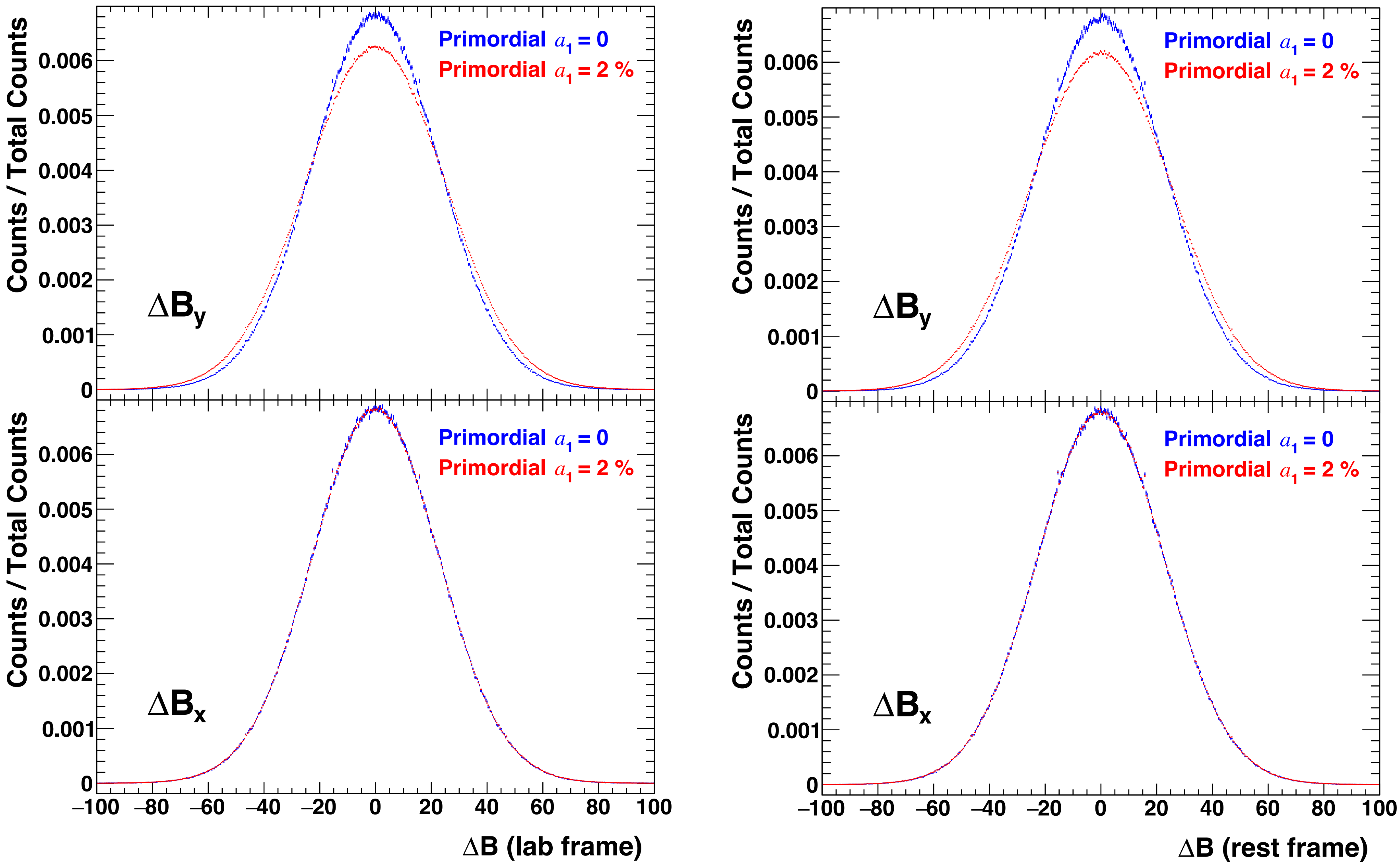
$$r = \frac{\sigma_{\Delta B_y}}{\sigma_{\Delta B_x}}. \quad (>1 \text{ with CME})$$

r can be calculated in both lab. (r_{lab}) and pair's rest frame (r_{rest}), the latter has the best sensitivity for real charge separation (but not guaranteed so for background).



To study separation, the natural and best choice of frame is pair's rest frame.

Signed Balance Function



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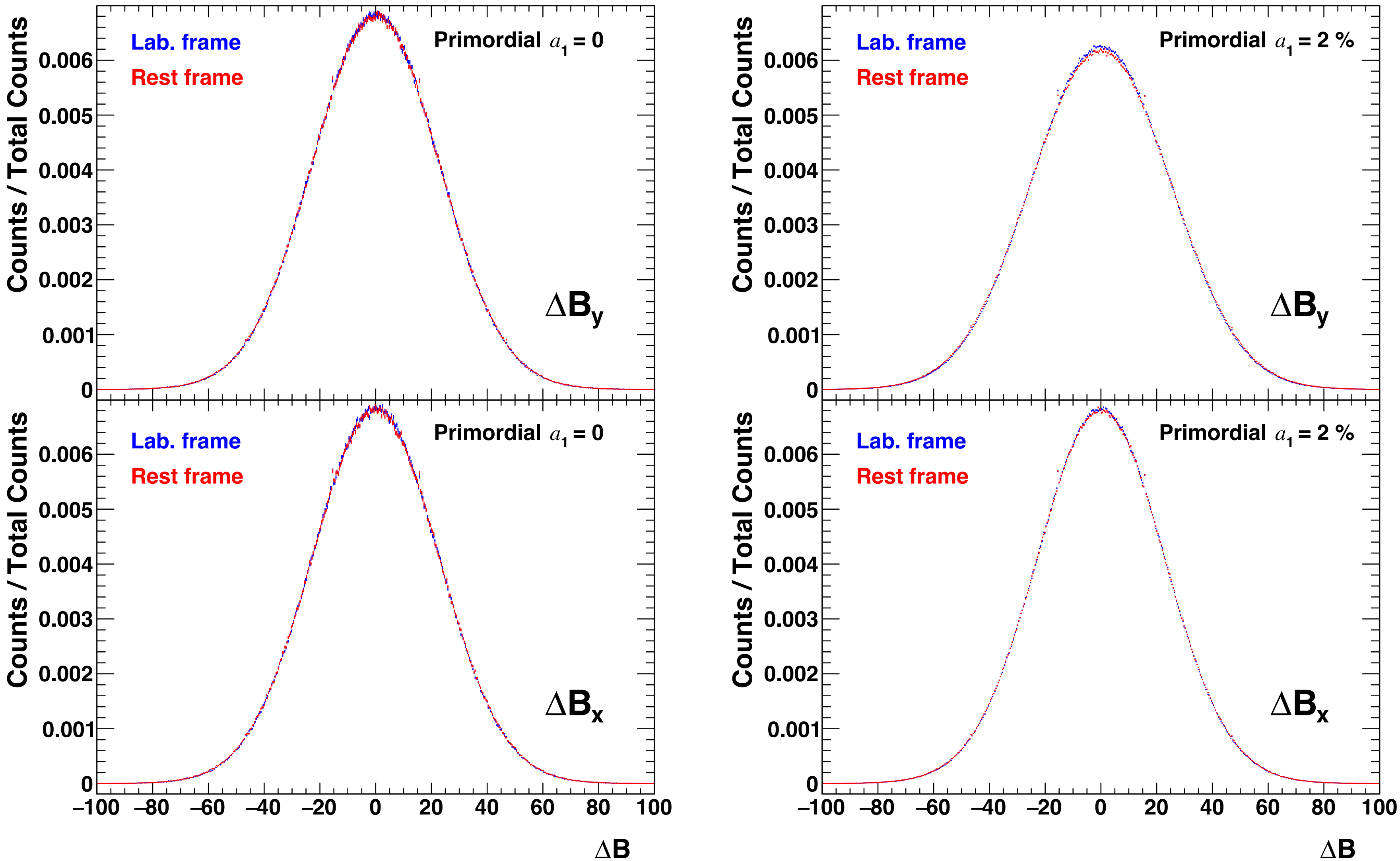
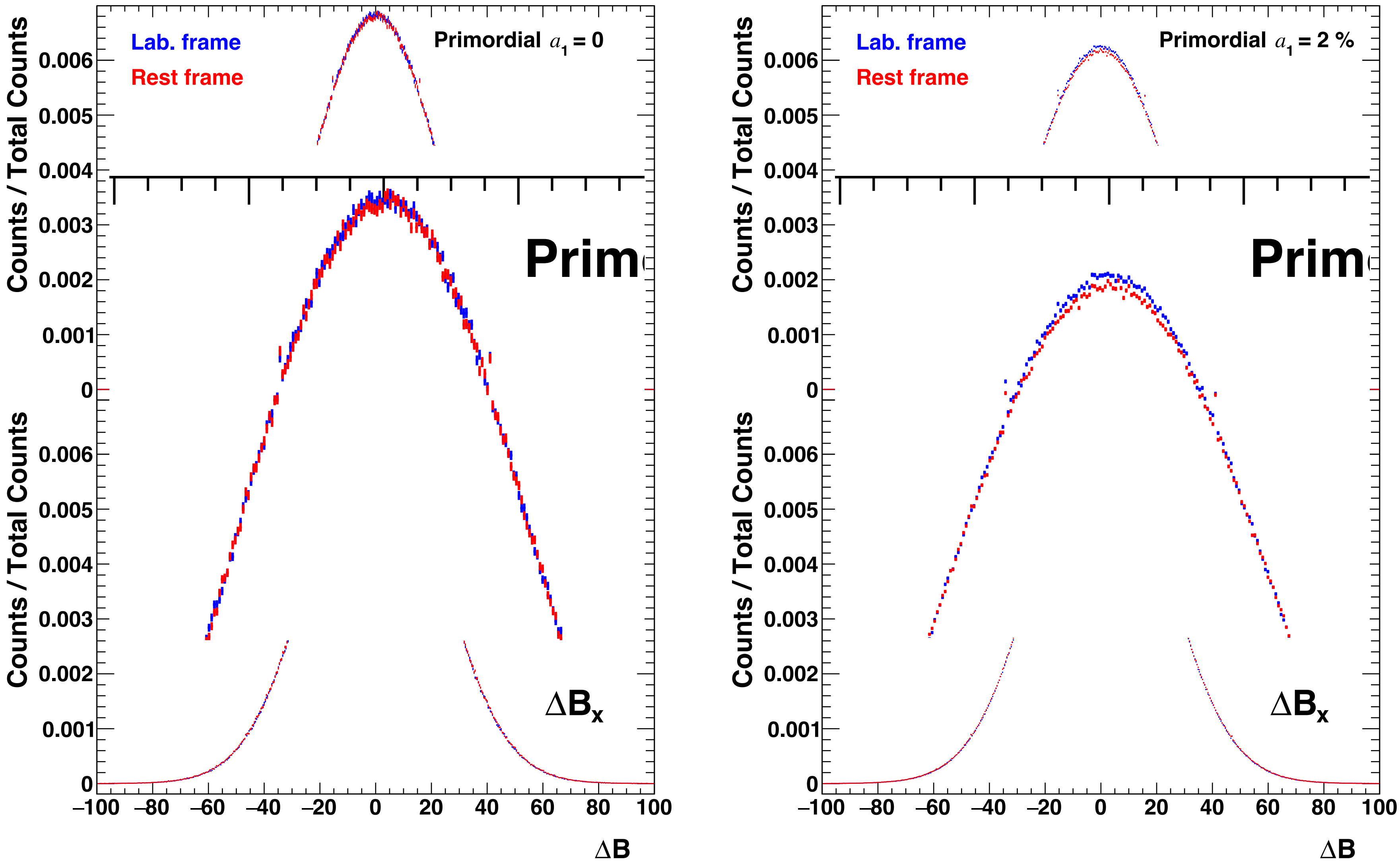
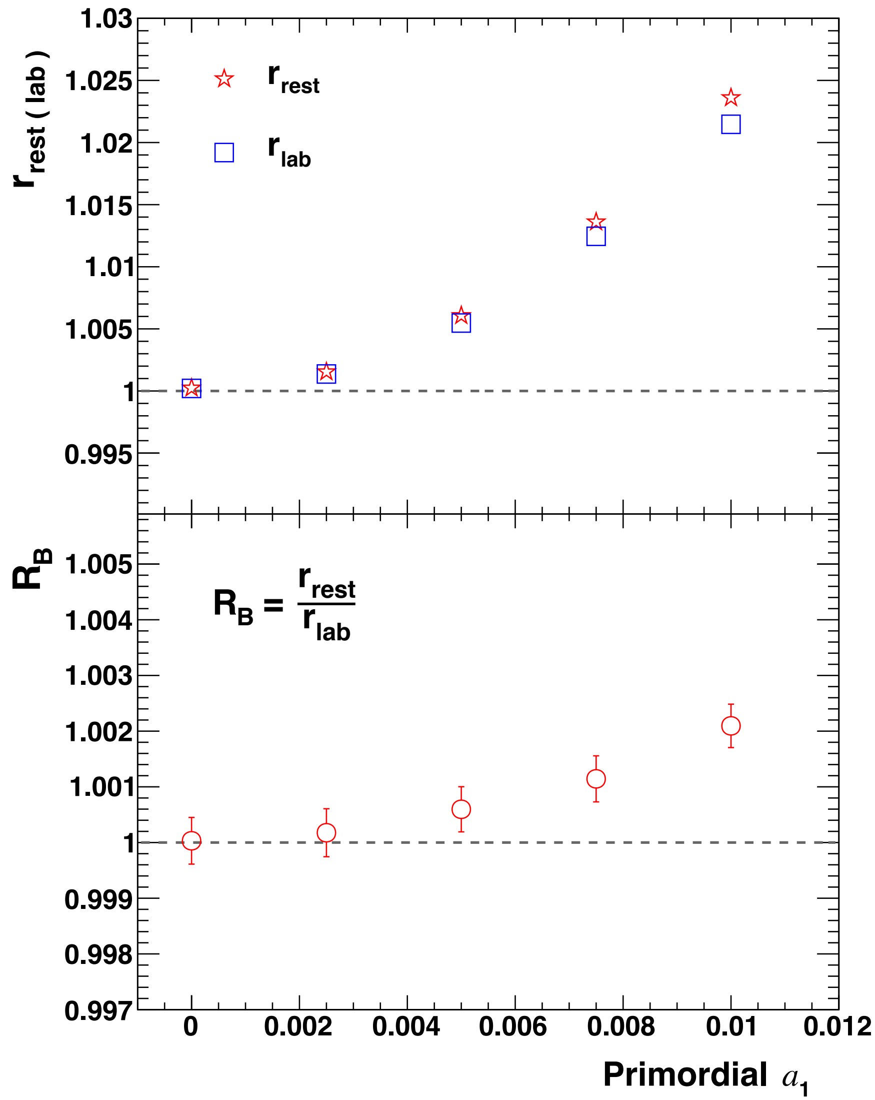


Signed Balance Function



Toy Model Simulation

Signal Only



324 primordial pions + 33 ρ (decay into $\pi^+\pi^-$)

- Matches total mult. For 30-40% AuAu[1]
- Matches ρ to neg. particle ratio ~ 17%[2]
- $\rho \rightarrow \pi^+ + \pi^-$ decay via PYTHIA6.

Primordial pion spectra :

$$\frac{dN_{\pi^\pm}}{dm_T^2} \propto \left(e^{m_T/T_{BE}} - 1\right)^{-1},$$ (Bose-Eistein distribution)[1][3]

$T_{BE} = 212$ MeV (for having $\langle p_T \rangle$ of 400 MeV)[1].

ρ specta [3]:

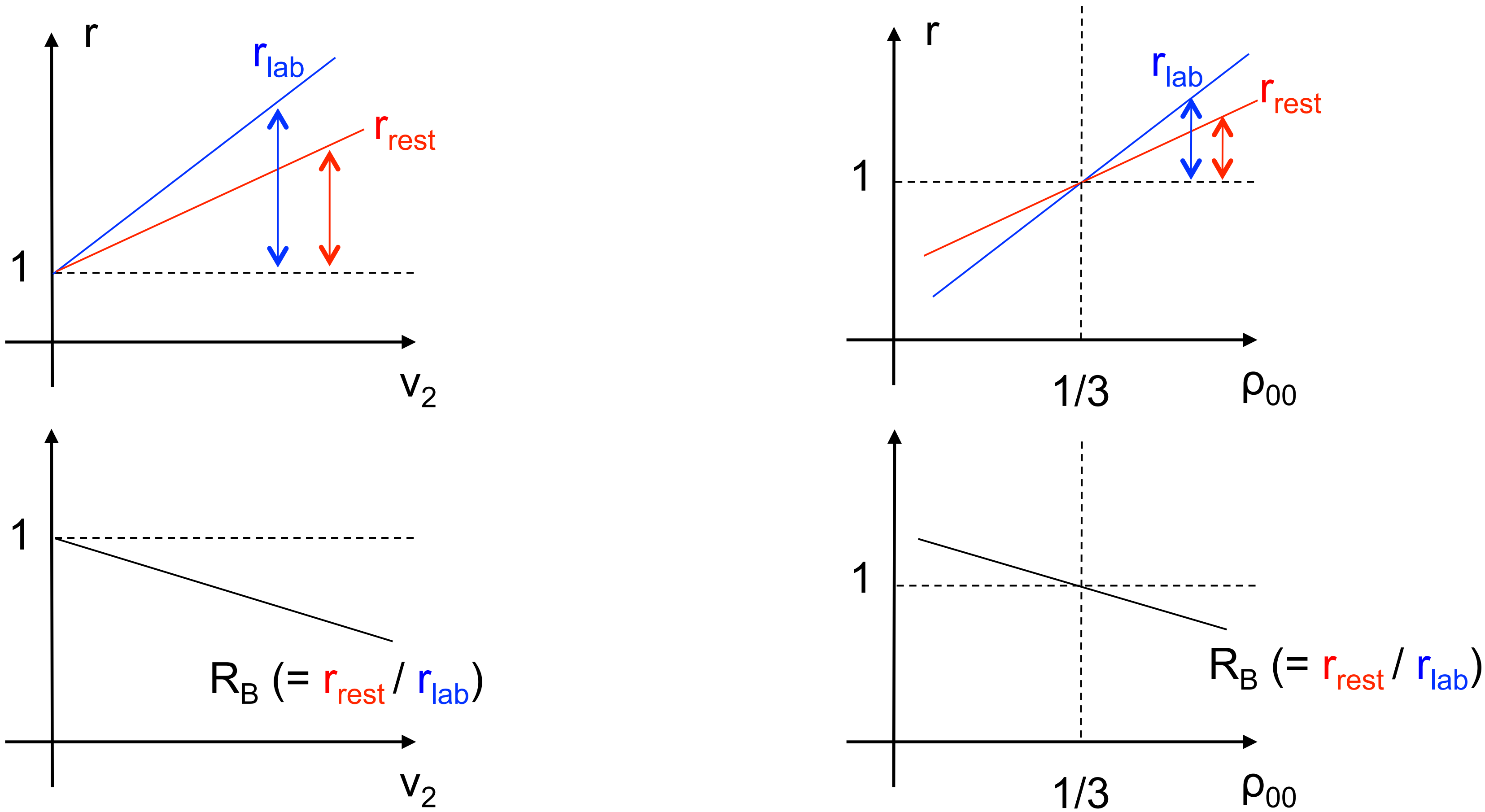
$$\frac{dN_\rho}{dm_T^2} \propto e^{-(m_T - m_\rho)/T} / [T(m_\rho + T)].$$

$T = 317$ MeV (for having $\langle p_T \rangle$ of 830 MeV)[2].

[1] STAR, PRC 79 034909 (2009)
[2] STAR, PRL 92, 092301 (2004)
[3] Wang & Zhao, PRC 95, 051901 (2017)

r_{lab} and r_{rest}

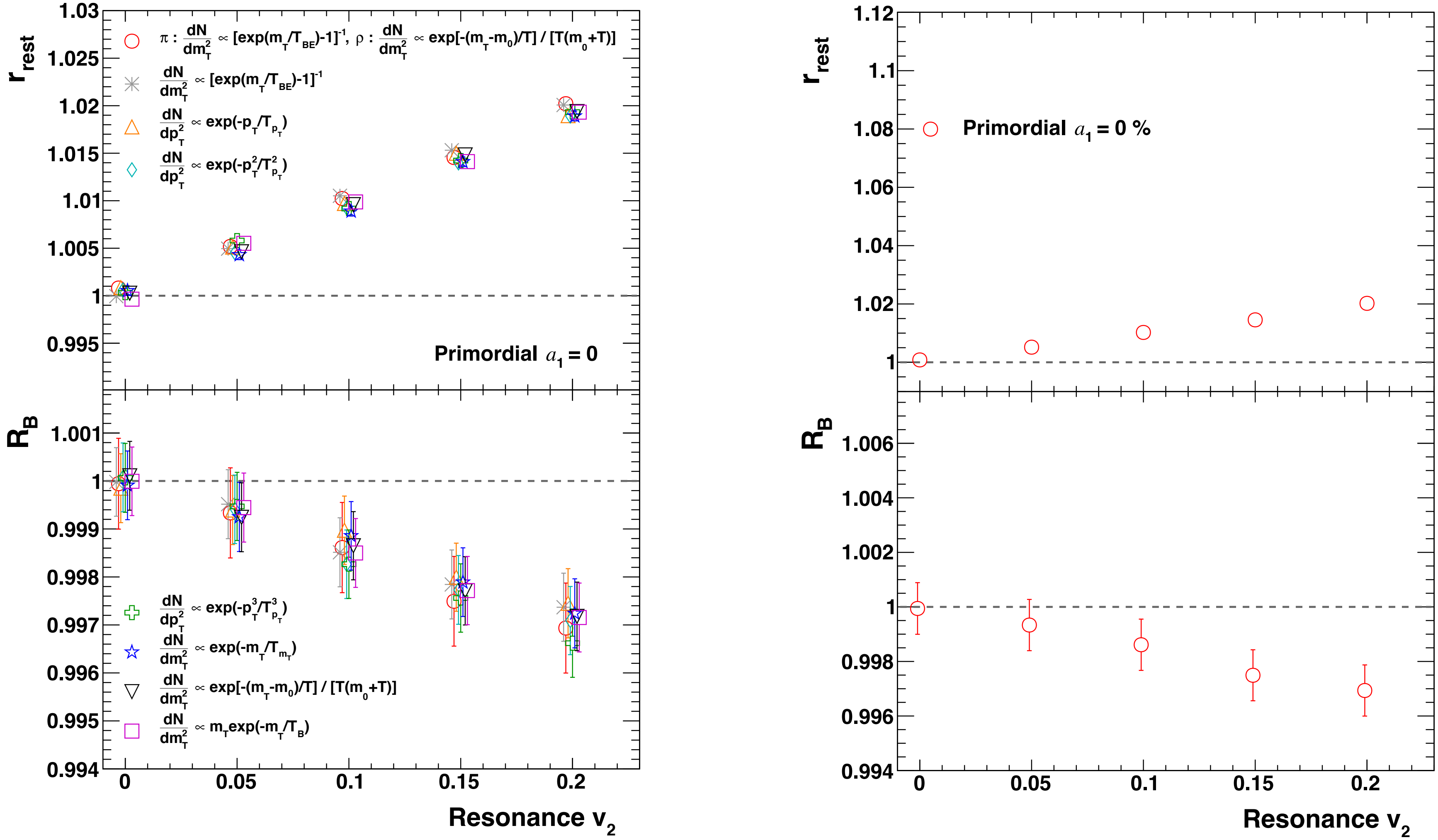
Exaggerated views of how r_{lab} and r_{rest} respond to backgrounds, to help navigating simulation plots in this talk:



r_{rest} is less sensitive than r_{lab} when responding to backgrounds.
(the opposite is true for signal)

Toy Model Simulation

Resonance v_2 as fixed value



r_{rest} and R_B responds in opposite directions to the change of resonance v_2

Toy Model Simulation

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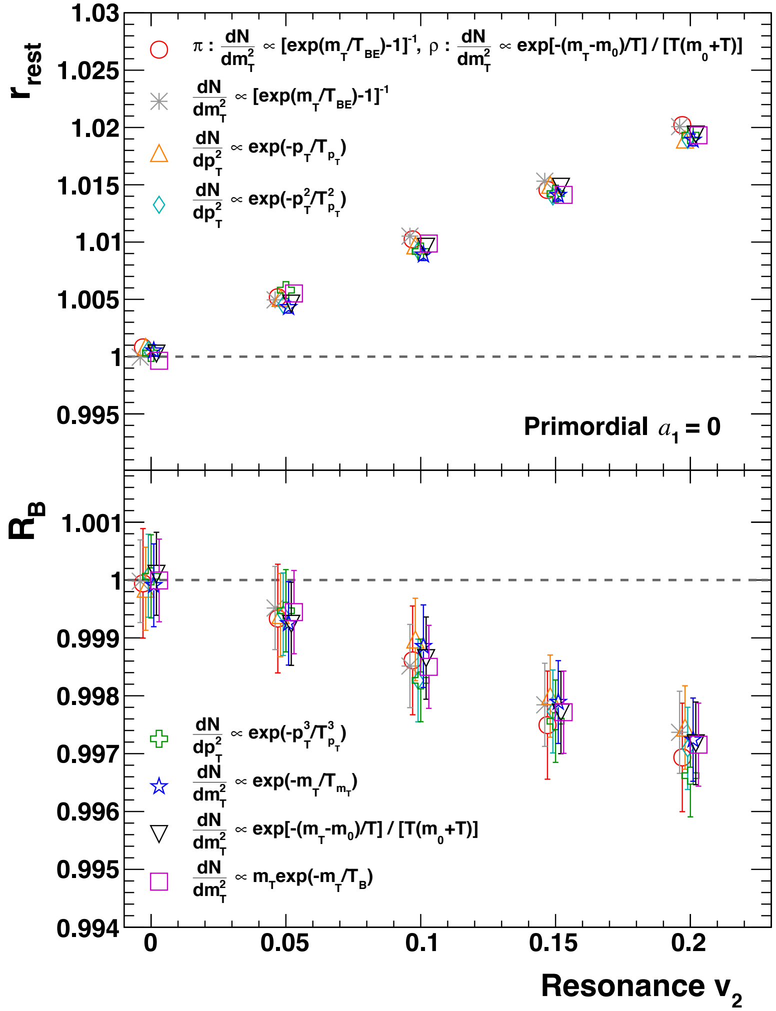

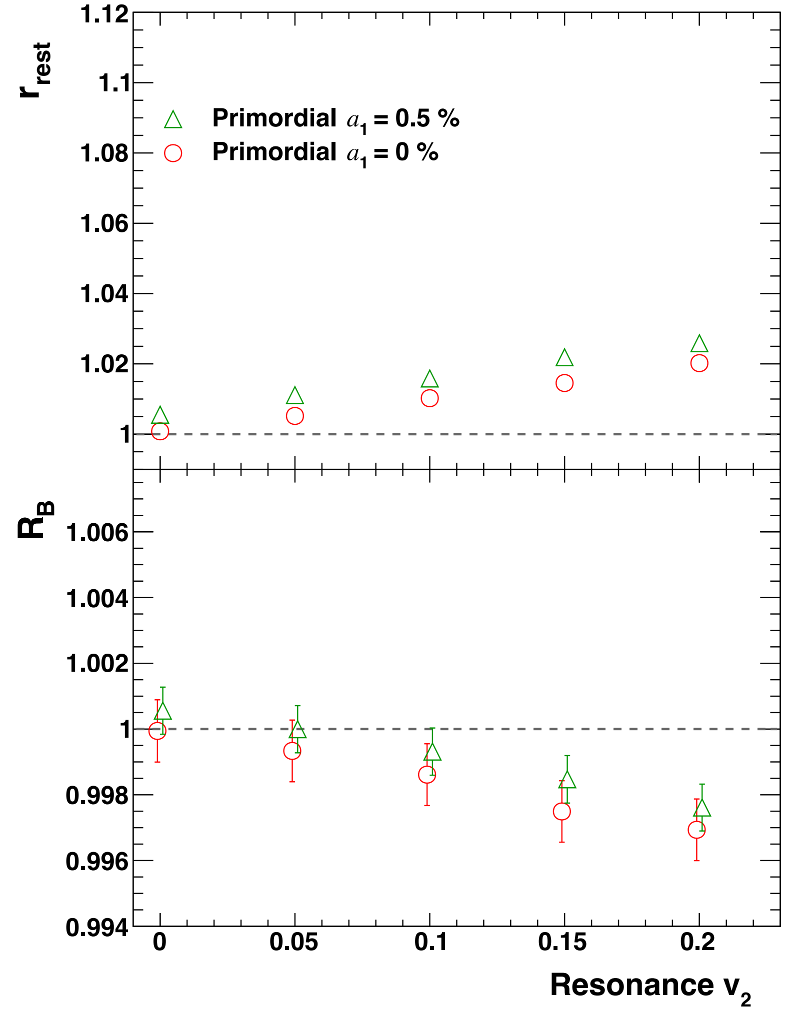

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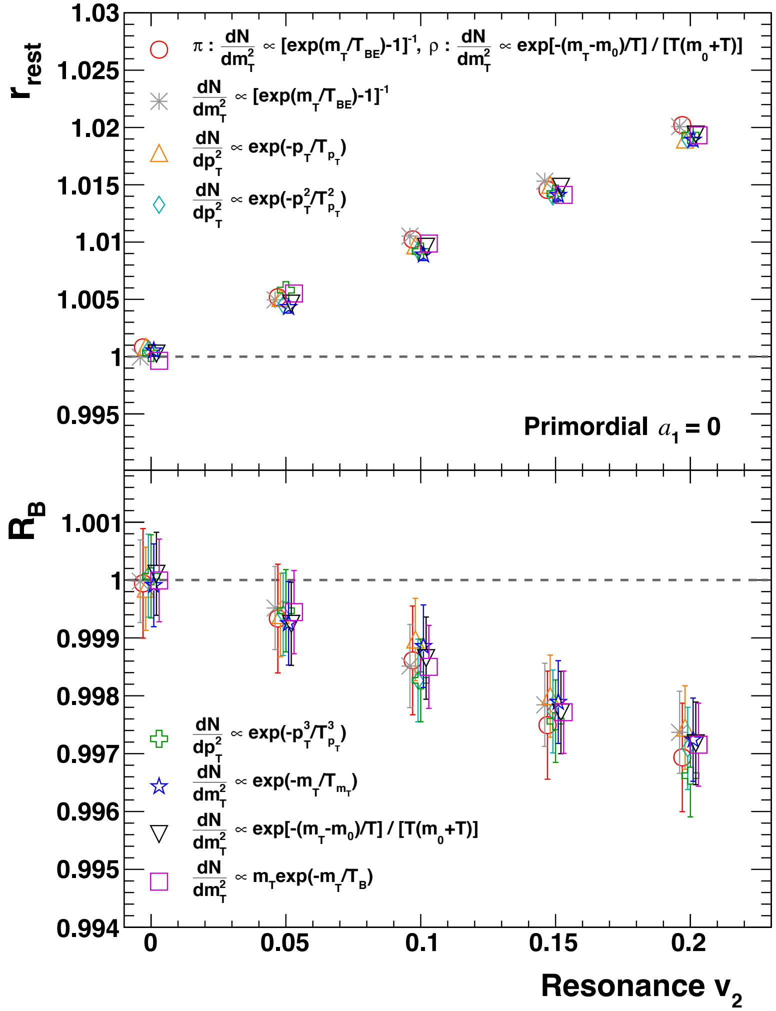

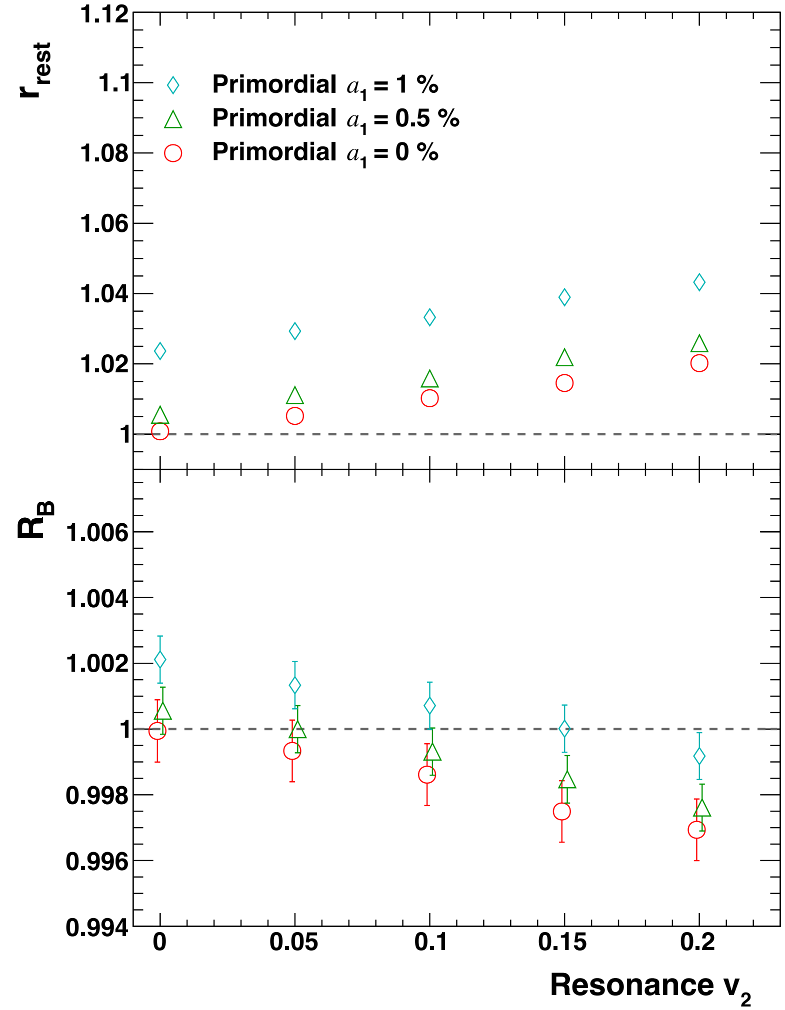

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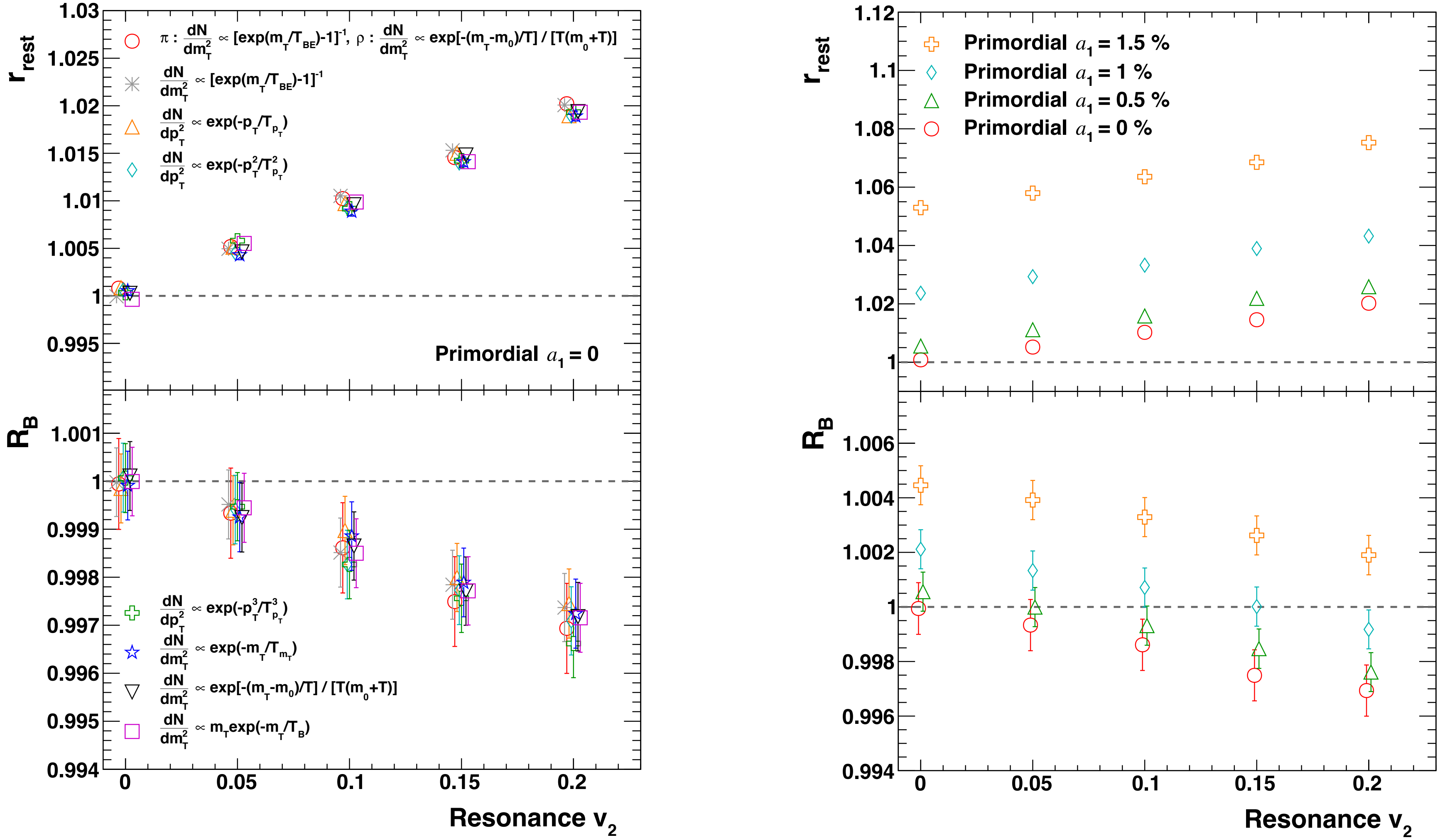
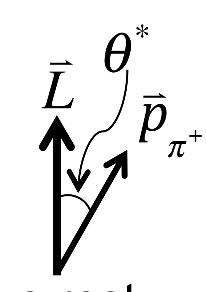


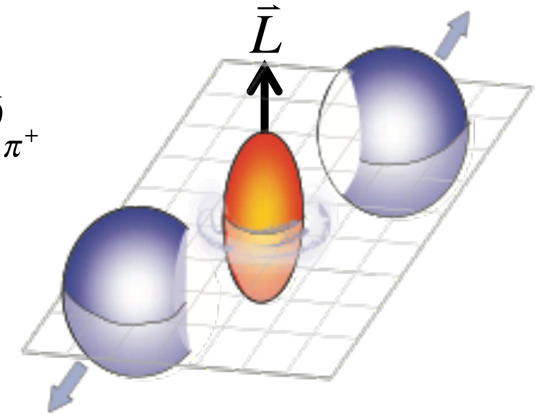
r_{rest} and R_B responds in opposite directions to the change of resonance v_2

Global Spin Alignment (ρ_{00})

The 00-component of spin density matrix (ρ_{00}) can be measured via angular distribution of decay daughter using :

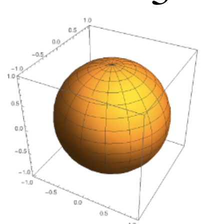
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \right]$$





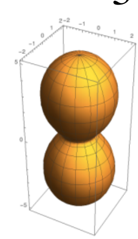
A deviation of ρ_{00} from 1/3 would indicate a non-zero spin alignment.

$\rho_{00} = \frac{1}{3}$



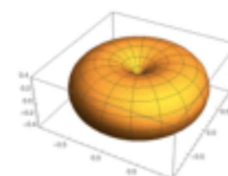
"v_2" = 0

$\rho_{00} > \frac{1}{3}$



"v_2" < 0

$\rho_{00} < \frac{1}{3}$

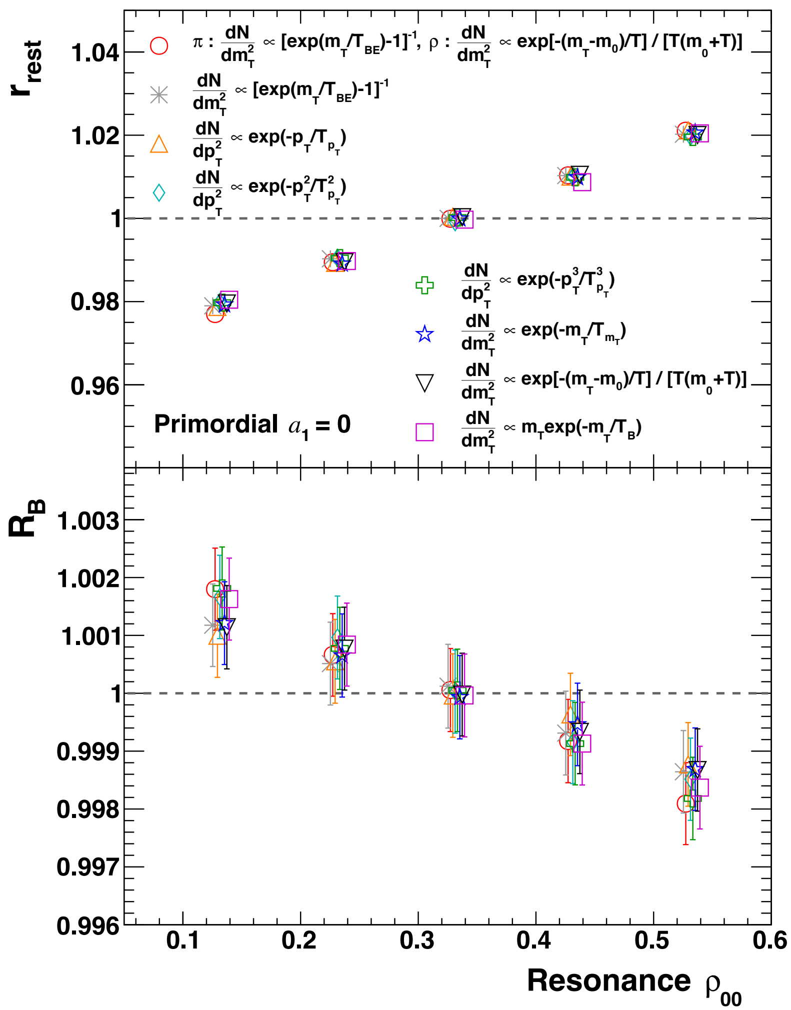


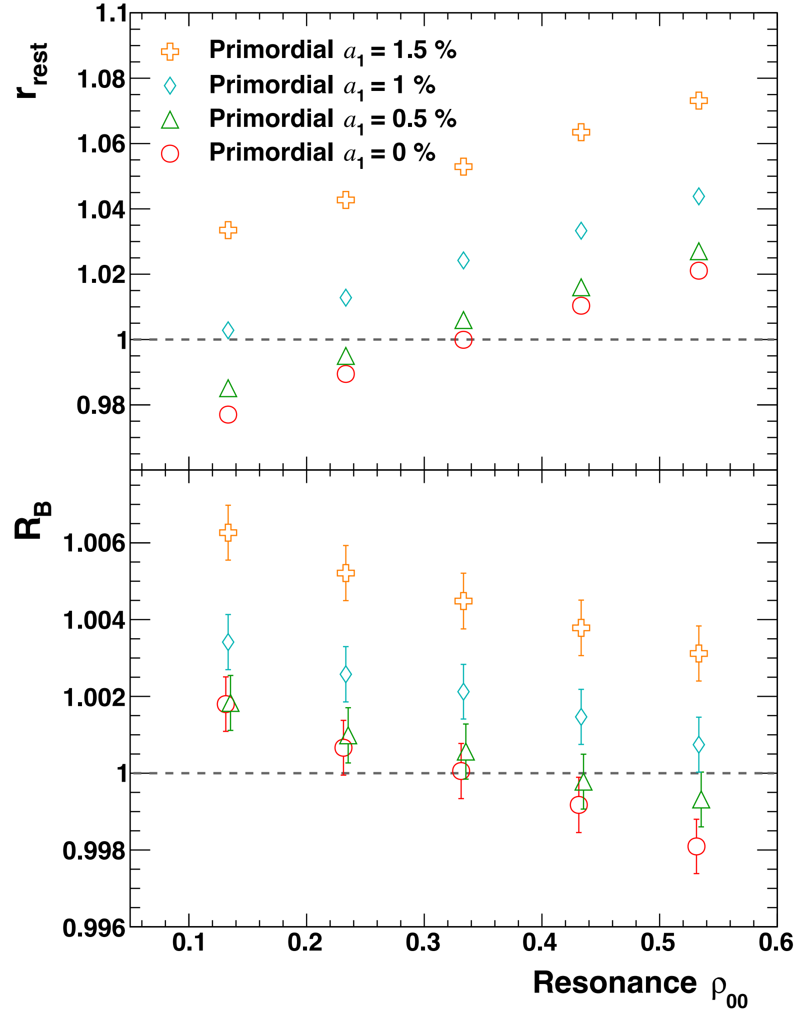
"v_2" > 0

Finite spin alignment acts like "elliptic flow" in rest frame.

Toy Model Simulation

Resonance ρ_{00}





r_{rest} and R_B responds in opposite directions to ρ_{00} change.

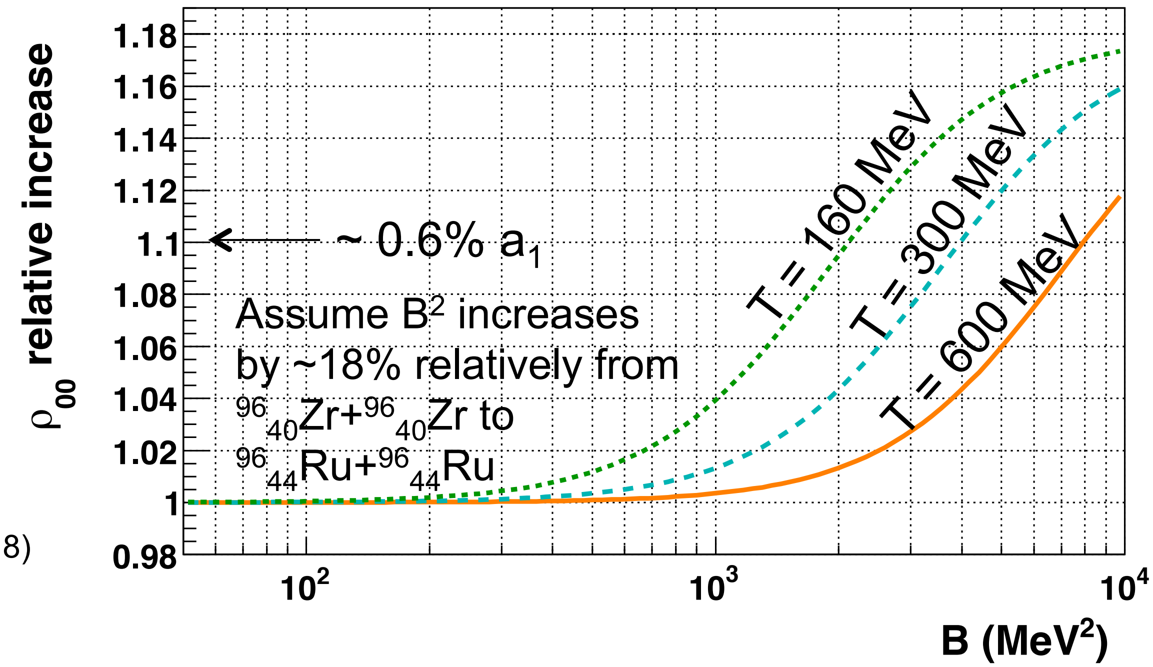
Global Spin Alignment (ρ_{00})

$$\rho_{00}(\omega) \approx \frac{1}{3} - \frac{1}{9}\left(\frac{\omega}{T}\right)^2 < \frac{1}{3}$$

$$\rho_{00}(B) \approx$$

$$\frac{1}{3} - \frac{1}{9}\left(\frac{B}{T}\right)^2 \frac{Q_1}{m_1}\frac{Q_2}{m_2} > \frac{1}{3} \text{ for } \rho^0 \text{ meson}$$

Yang, Fang, Wang & Wang, PRC 97 034917 (2018)



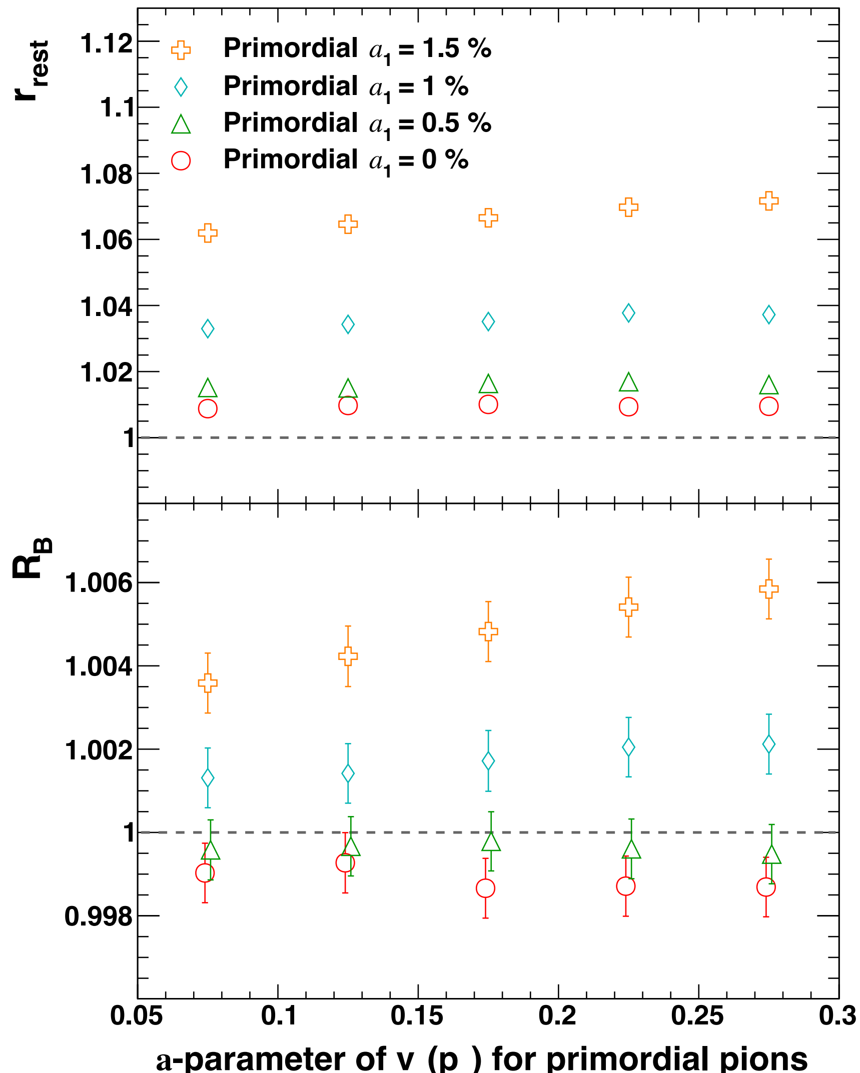
Implication for isobar collisions :

A stronger B in $^{96}_{44}Ru$ + $^{96}_{44}Ru$ than in $^{96}_{40}Zr$ + $^{96}_{40}Zr$ may cause artificial increase of CME observables via larger ρ_{00}.

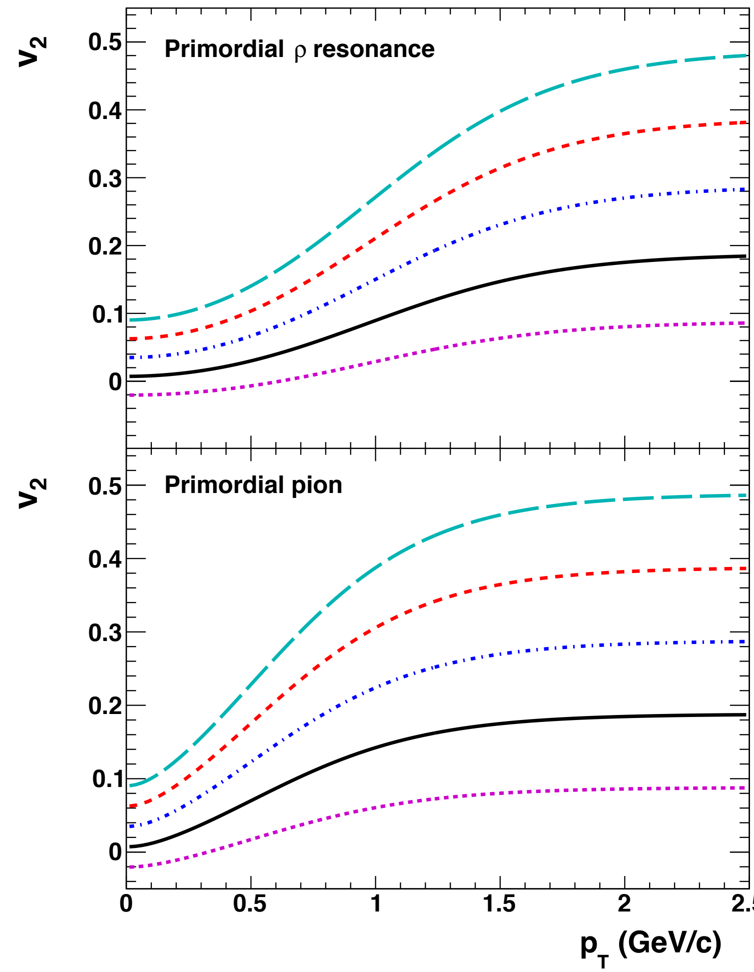
We need to check ρ_{00} of resonances !

Toy Model Simulation

p_T dependent v_2 and v_3 of primordial pions



$$v_2/n = a/(1+e^{-[(m_T-m_0)/n-b]/c}) - d$$ [1][2]

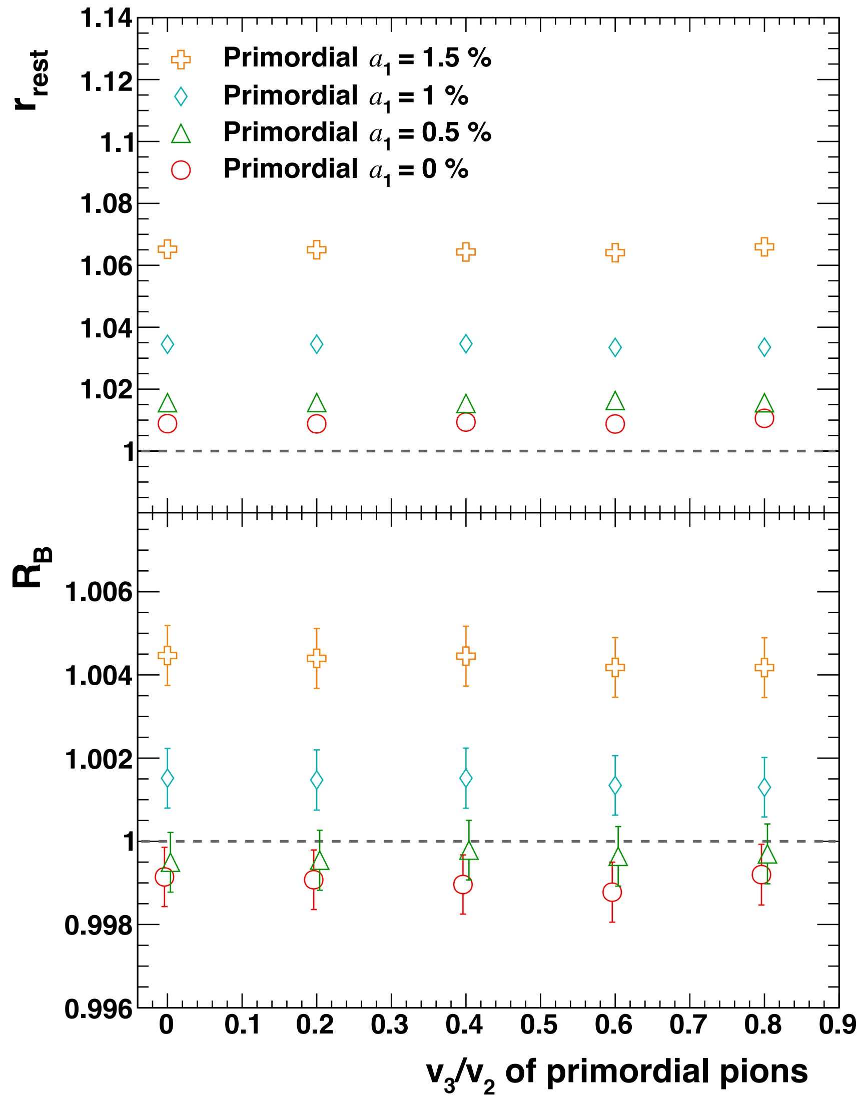


[1] Dong et. Al., PLB 597, 328 (2004)
[2] a-d param. from Wang & Zhao, PRC 95, 051901 (2017)

v_3 set to be 1/5 of v_2. Shou, NPA 931, 758 (2014).

Toy Model Simulation

v_3 of primordial pions

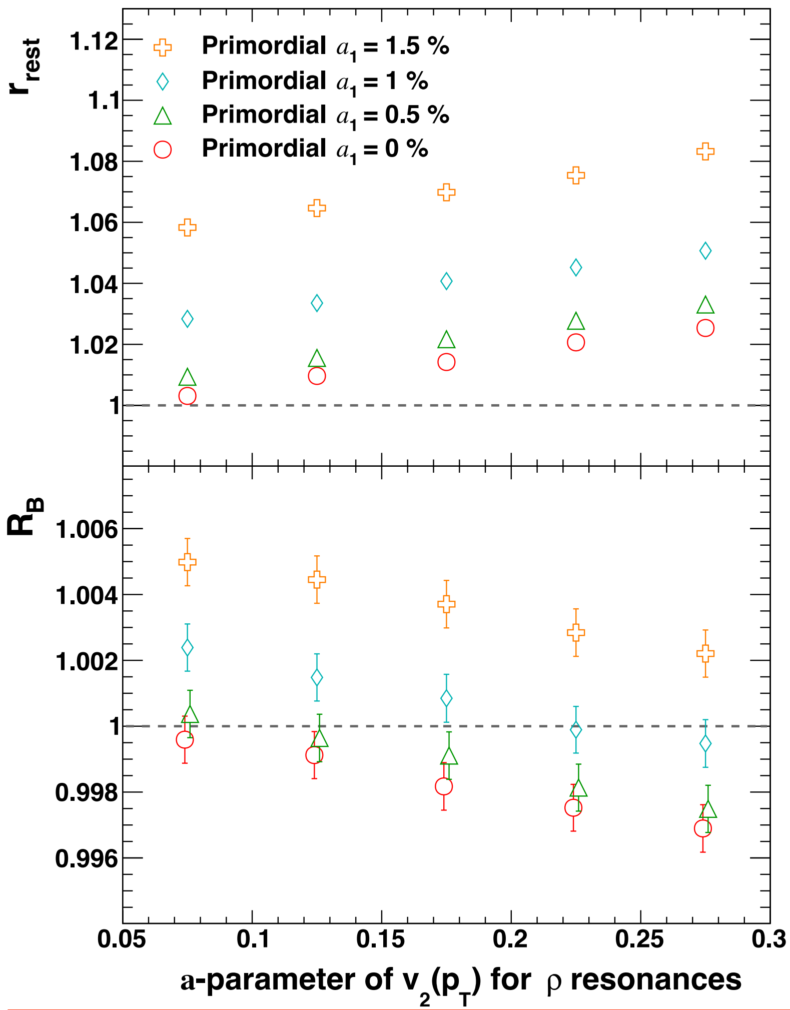


Keep $v_2(p_T)$ unchanged,
change v_3 so that v_3 / v_2 changes.

No noticeable v_3 effect.

Toy Model Simulation

p_T dependent v_2 and v_3 of resonance



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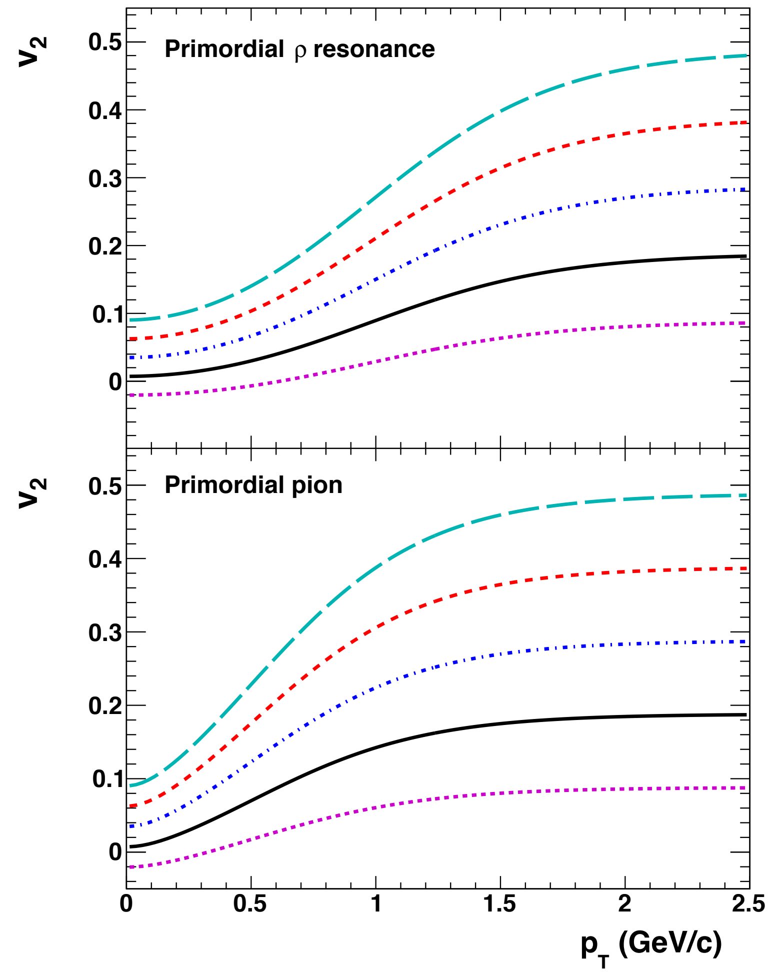

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Toy Model Simulation

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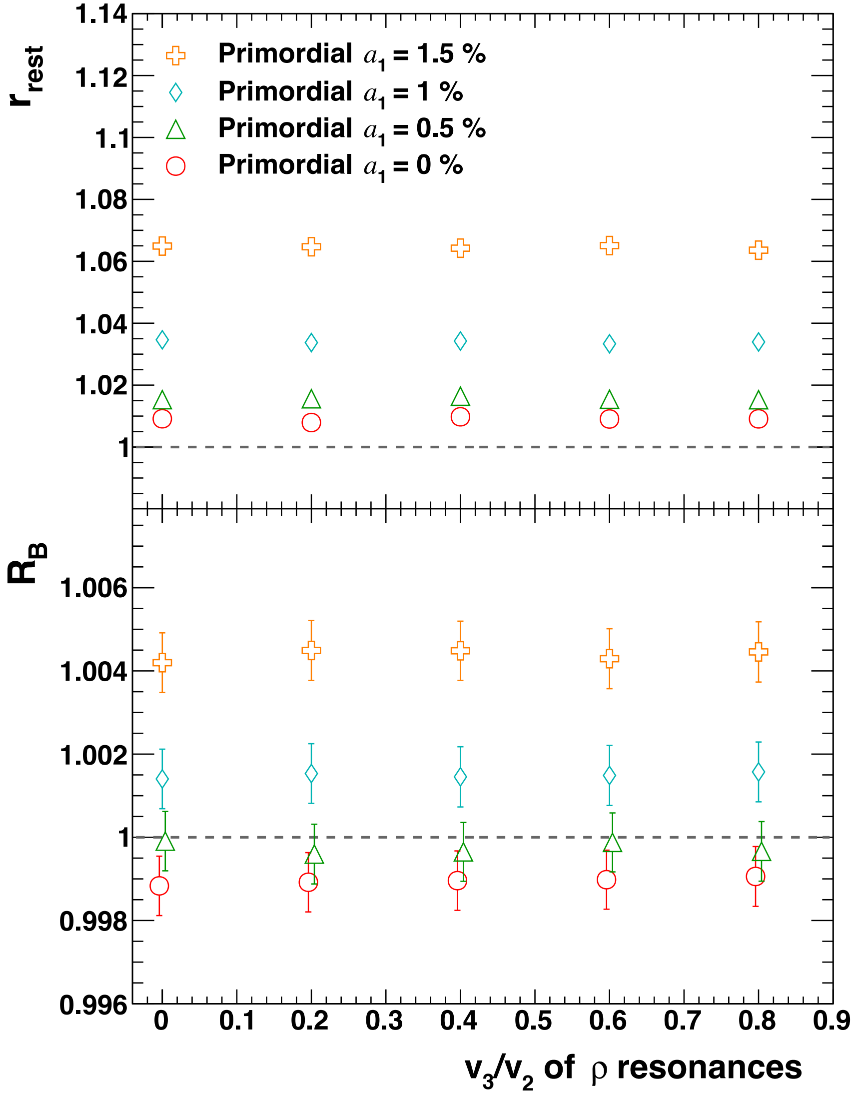

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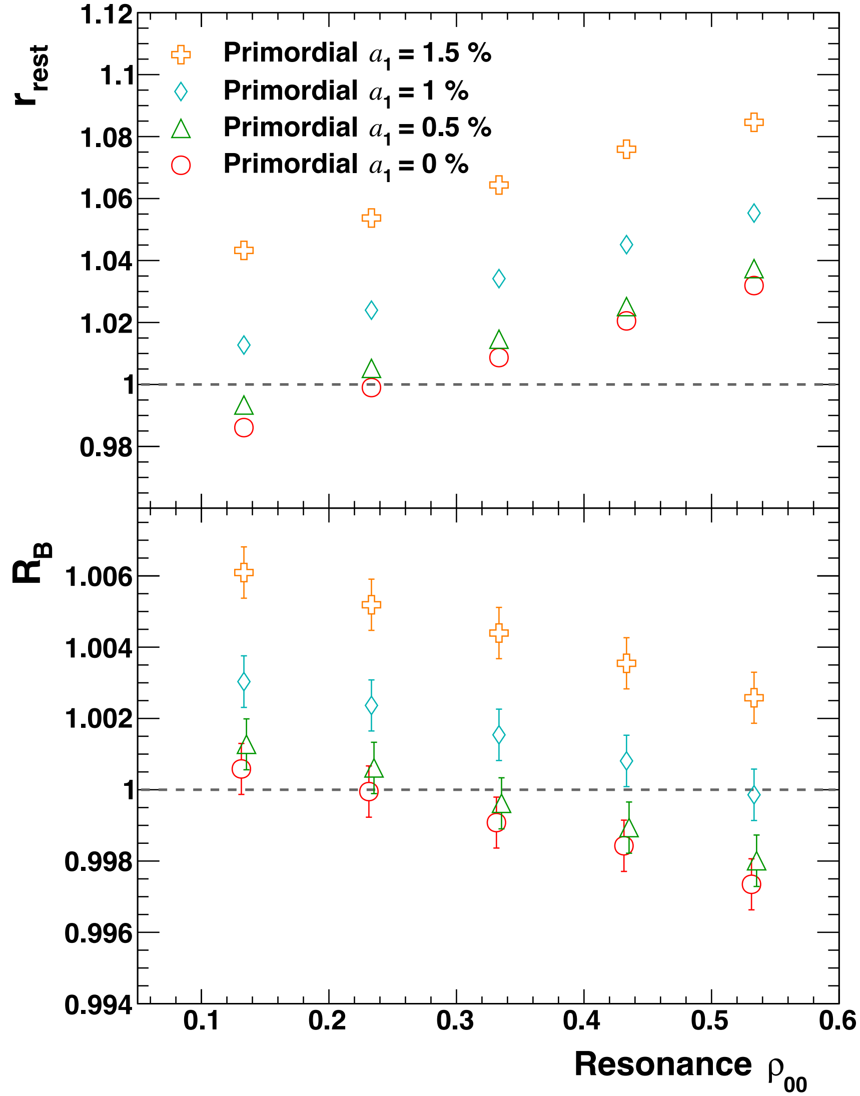
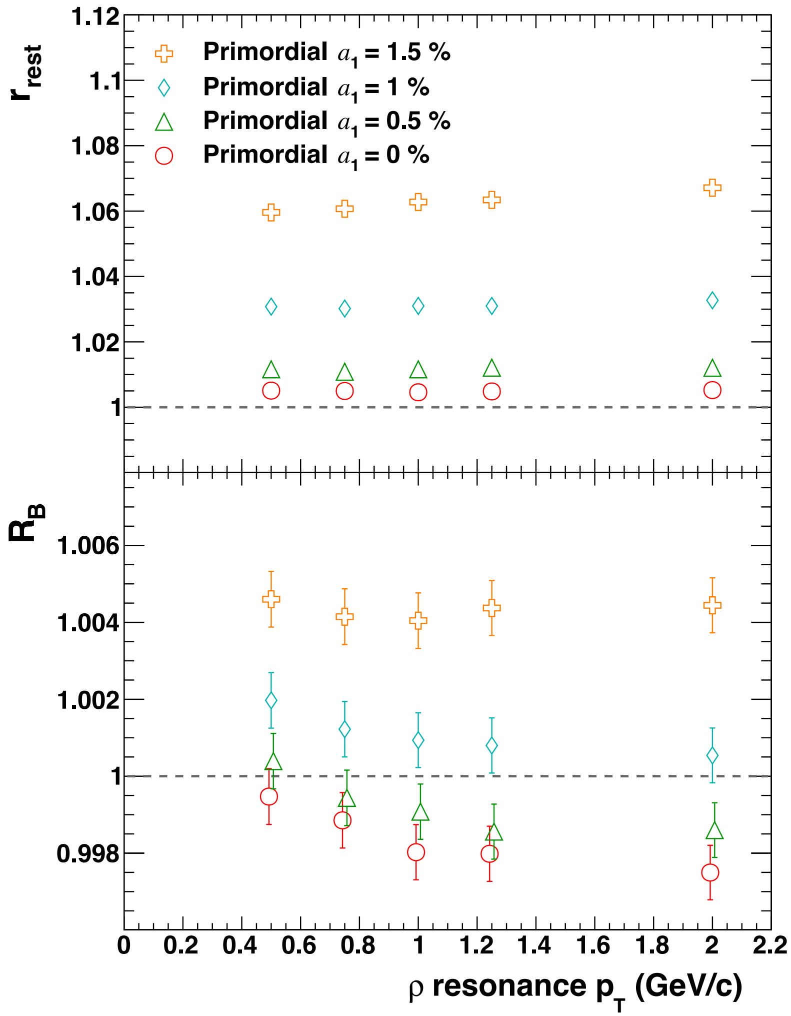


Resonance ρ_{00} together with p_T dependent v_2 & v_3 of primordial pions and ρ resonances

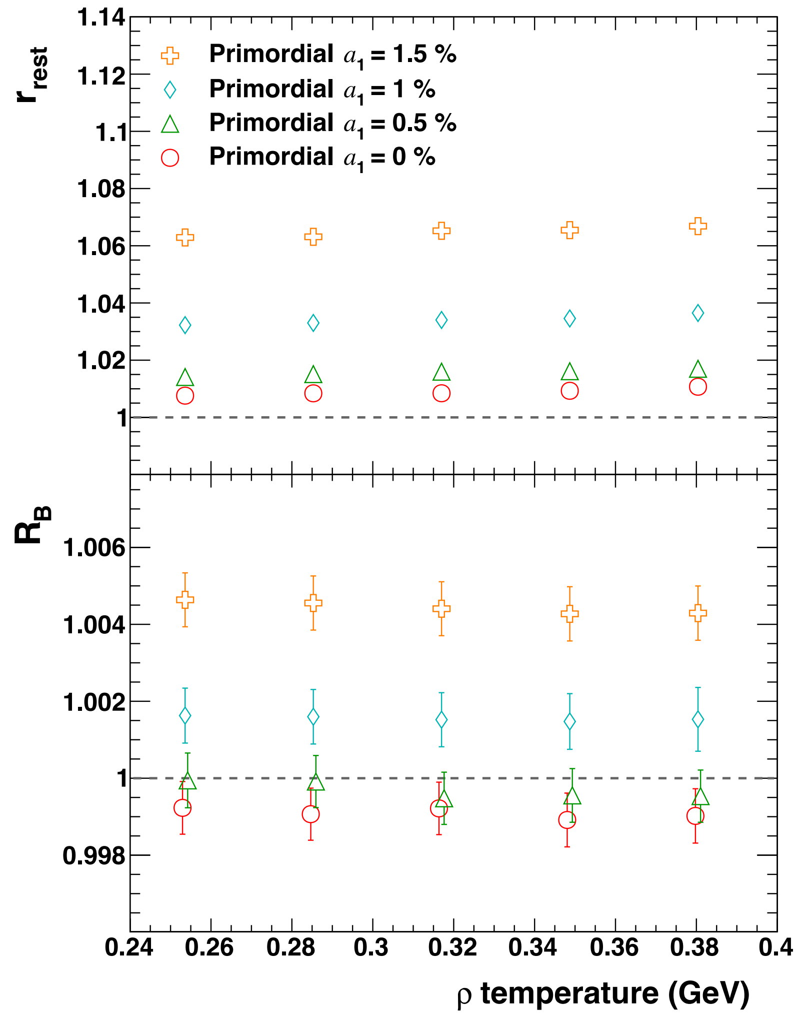
r_{rest} and R_B responds in opposite directions to ρ_{00} change.

Toy Model Simulation

Resonance p_T (as fixed value)

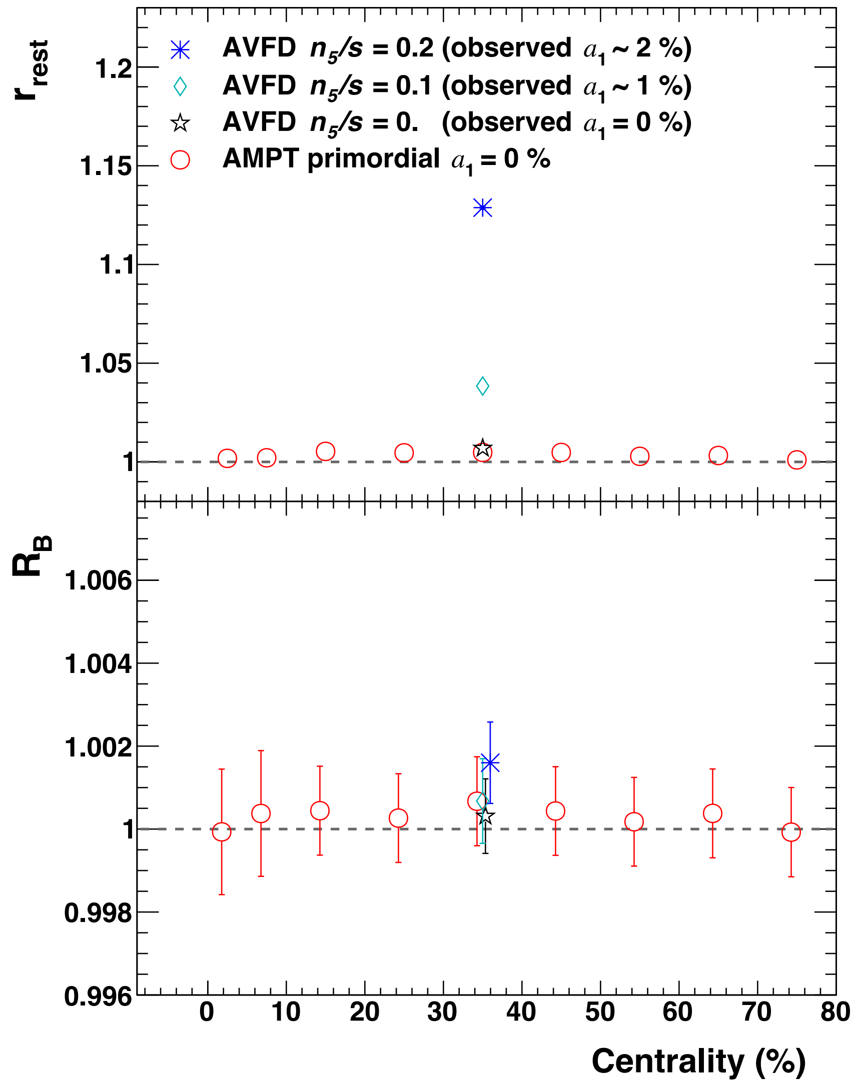


Resonance temperature



Noticeable effect due to resonance p_T. Similar to [PRC 98 034904].
However, a realistic change in spectra slope (T) causes no visible effect.
Not a new effect -- already taken into account in simulations with realistic p_T spectra.

AMPT and AVFD Models



AMPT[1] version v2.25t4cu
With string melting and **charge conservation assured.** No CME.

AVFD[2] (anomalous viscous fluid dynamics)
With CME implemented.
(See S. Shi's talk on Monday.)

r_{rest} and R_B behave as expected in realistic models.

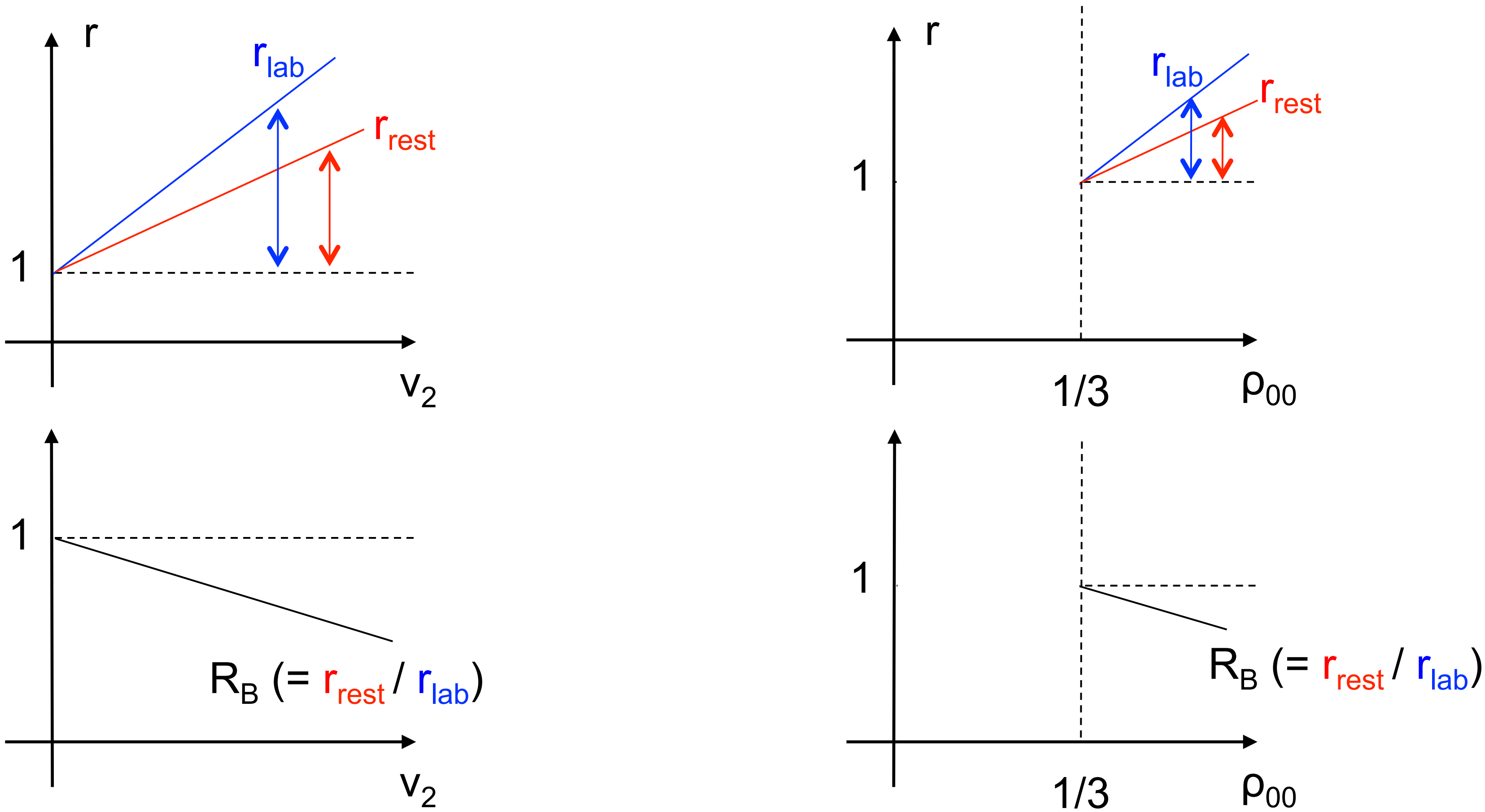
Even r_{rest} by itself is a sensitive probe.

[1] Lin, Ko, Li, Zhang & Pal, Phys. Rev. C 72 064901 (2005), and private communication with Z.W.Lin and G.L. Ma

[2] Jiang, Shi, Yin & Liao, Chin. Phys. C 42 n0. 1 011001 (2018)
Shi, Jiang, Lilleskov & Liao, Annals.Phys. 394, 50 (2018)

Recap : r_{lab} and r_{rest}

Exaggerated views of how r_{lab} and r_{rest} respond to backgrounds, to help navigating simulation plots in this talk:



if ρ_{00} > 1/3 and both r_{rest} and R_B > 1, then a strong case supporting CME

Summary

Proposed a pair of observables, r_{rest} and R_B, to probe CME effect. Verified with toy model as well as realistic models.

Finite spin alignment can cause an effect resembling CME.

The difference in B between isobars can cause fake CME signal via the change in spin alignment. We need to address it !

r_{rest} and R_B respond in opposite directions to identifiable backgrounds from resonance flow and spin alignment. Useful for CME study (e.g., if $\rho_{00} > 1/3$ and both r_{rest} and $R_B > 1$, then a strong case supporting CME)

arXiv:1903.04622

Thank G.Wang, J.Liao, S.Shi, N. Magdy, Z. Lin, G. Ma, B. Tu, H. Ke and Y.Lin for discussion/help !