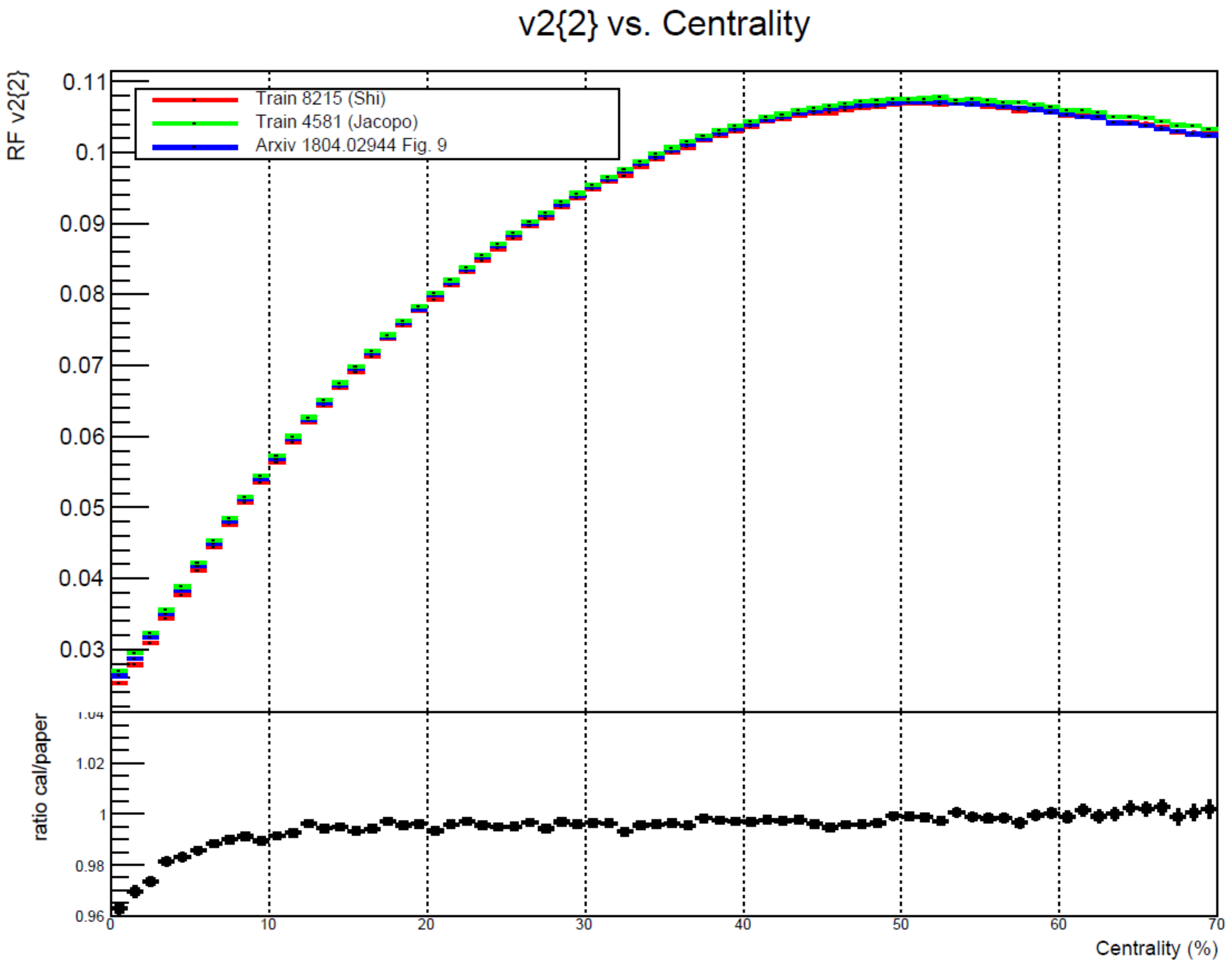
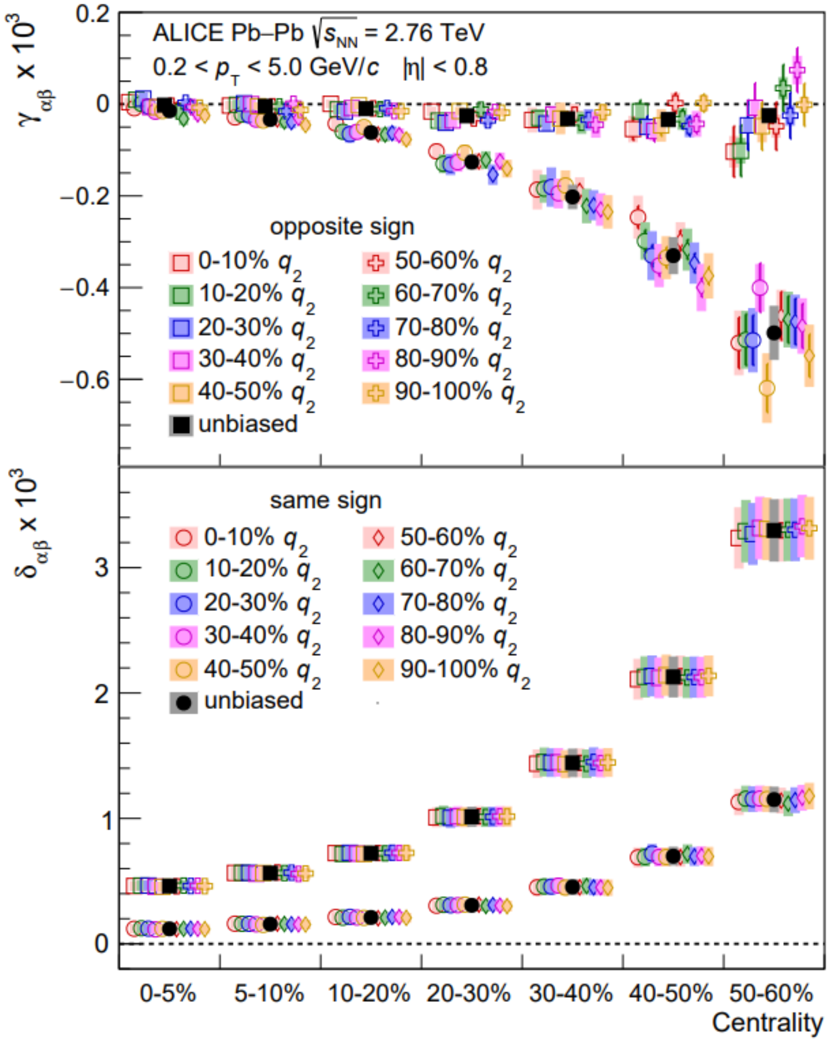
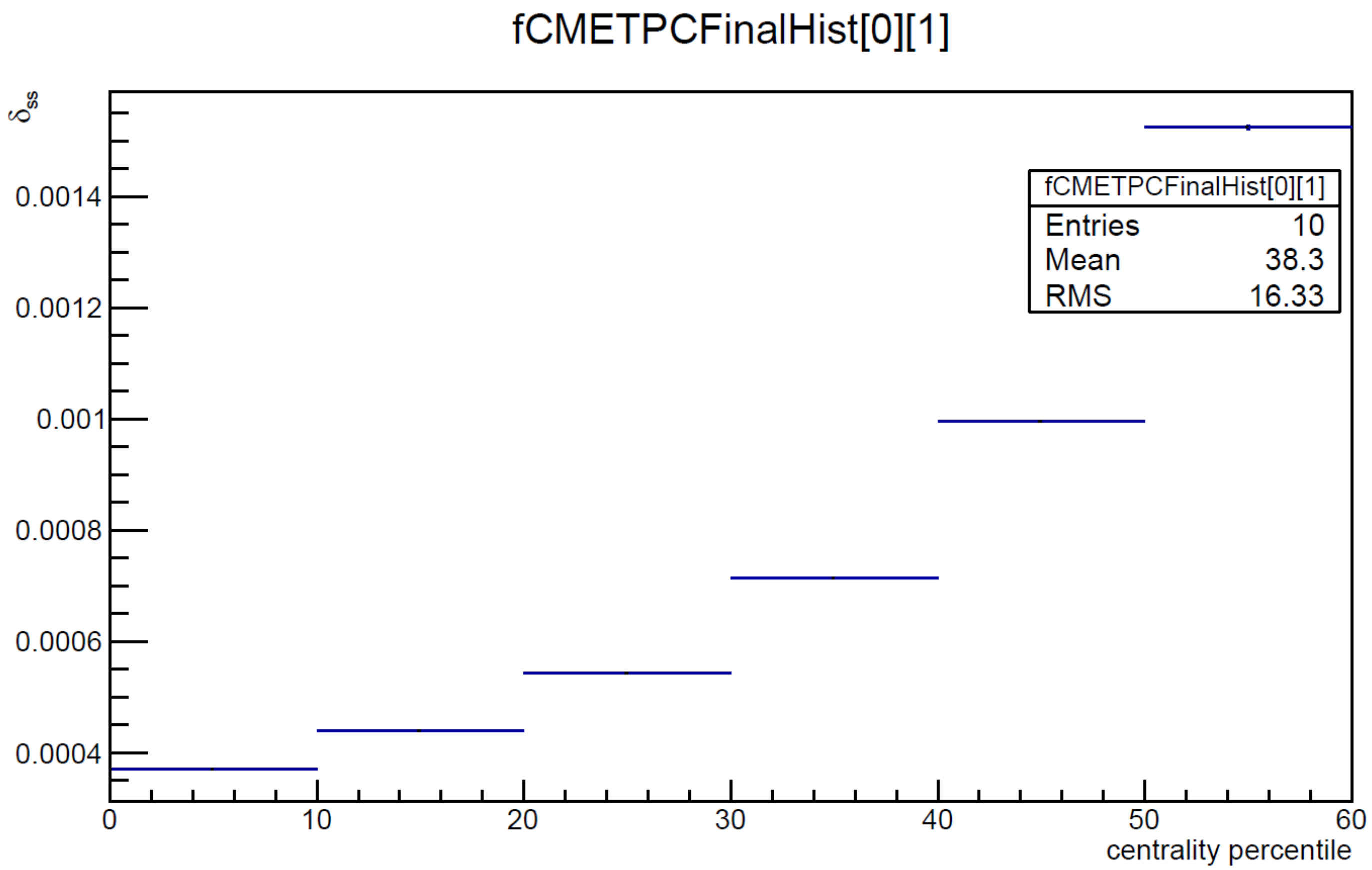
Elliptic flow v_2

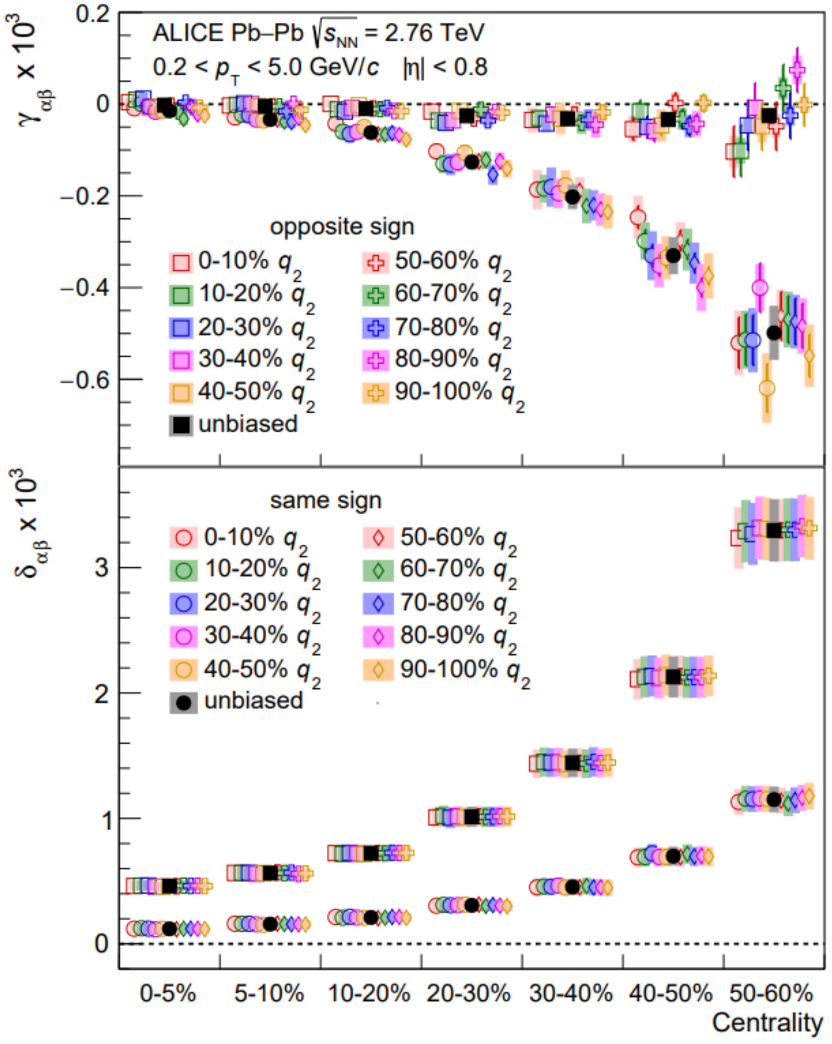


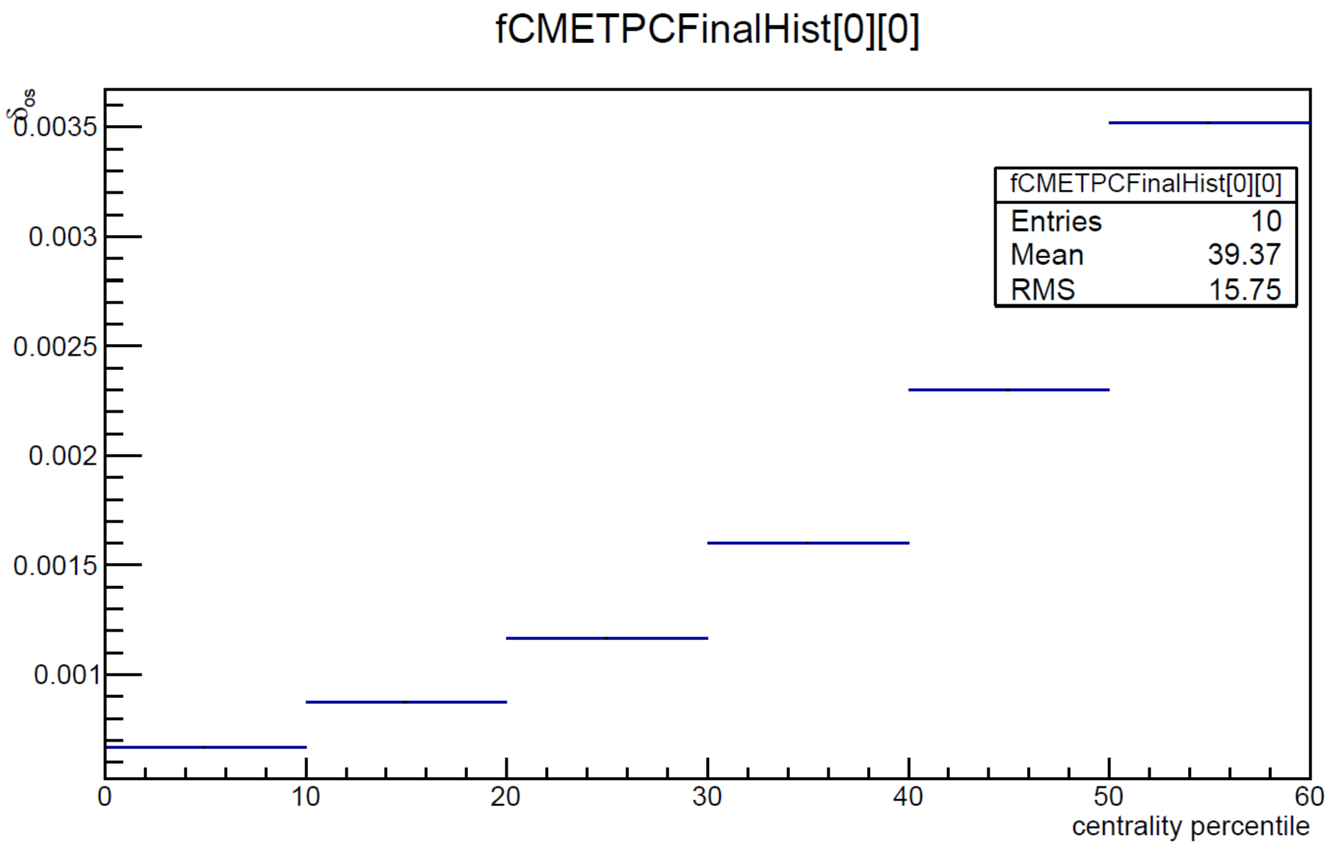
CME δ_{SS} correlator



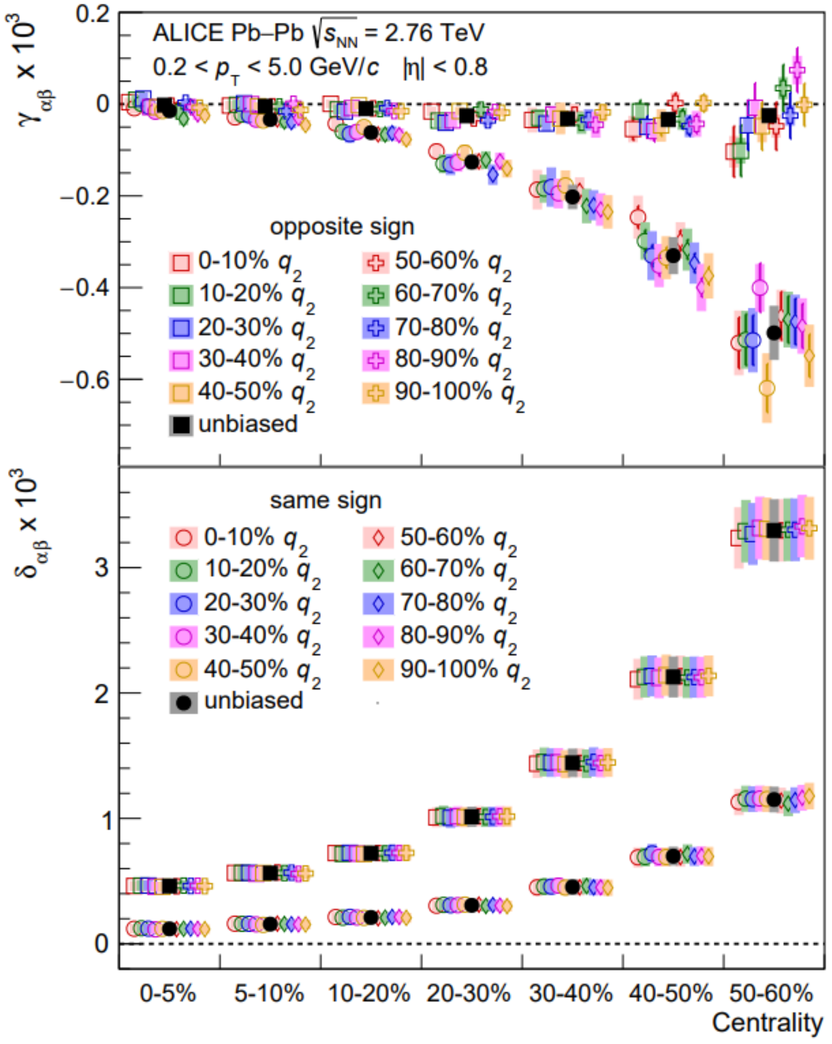


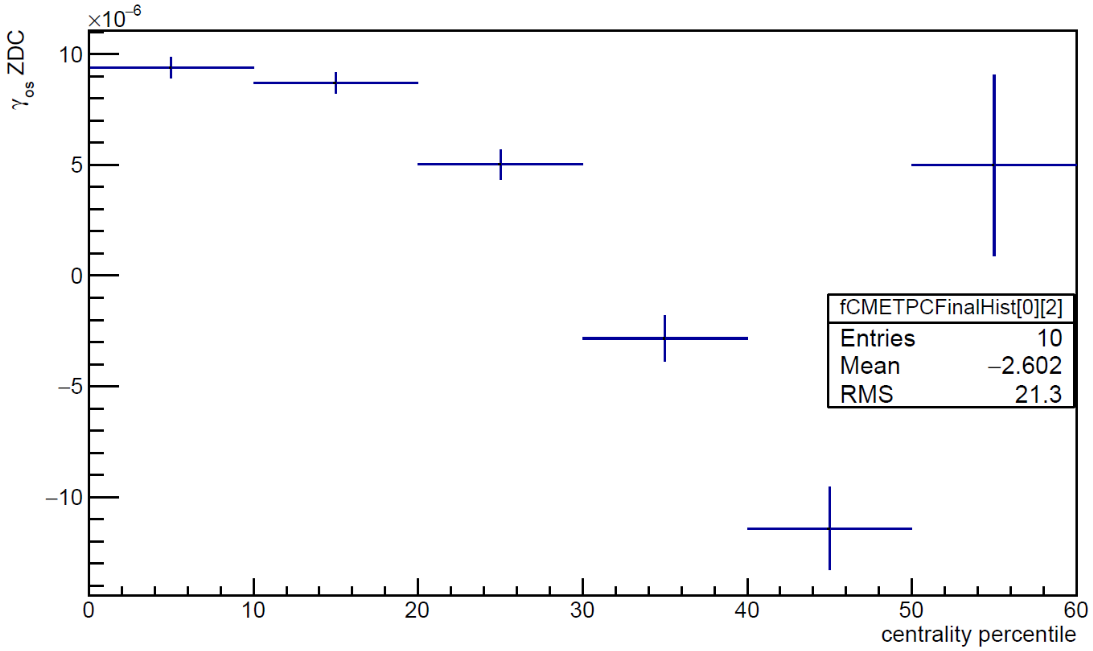
CME δ_{os} correlator

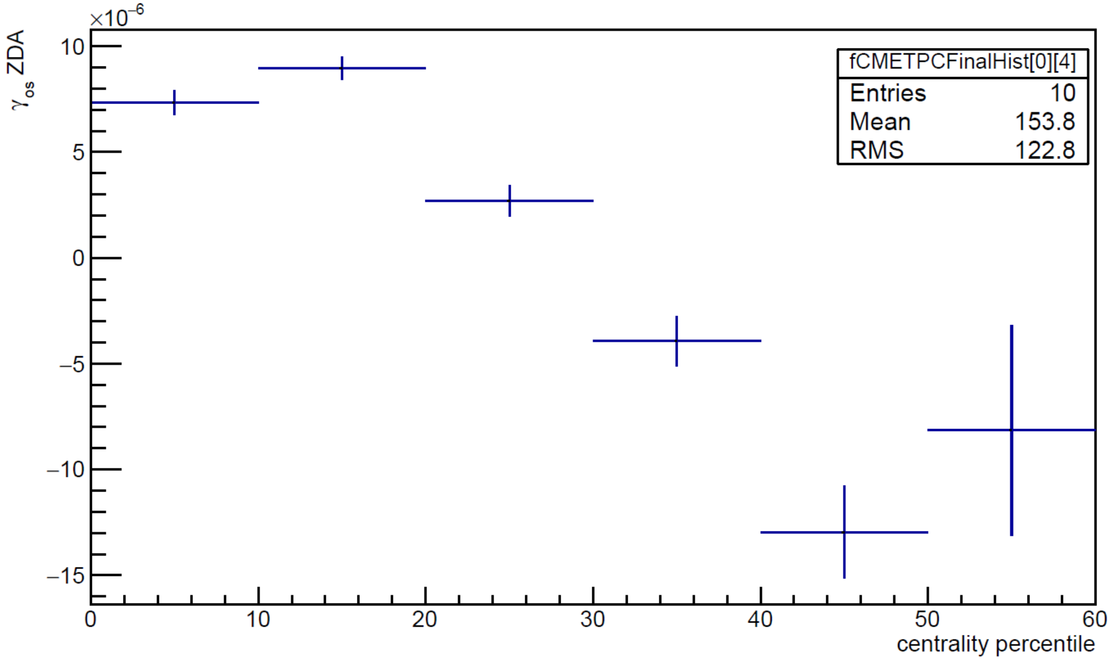




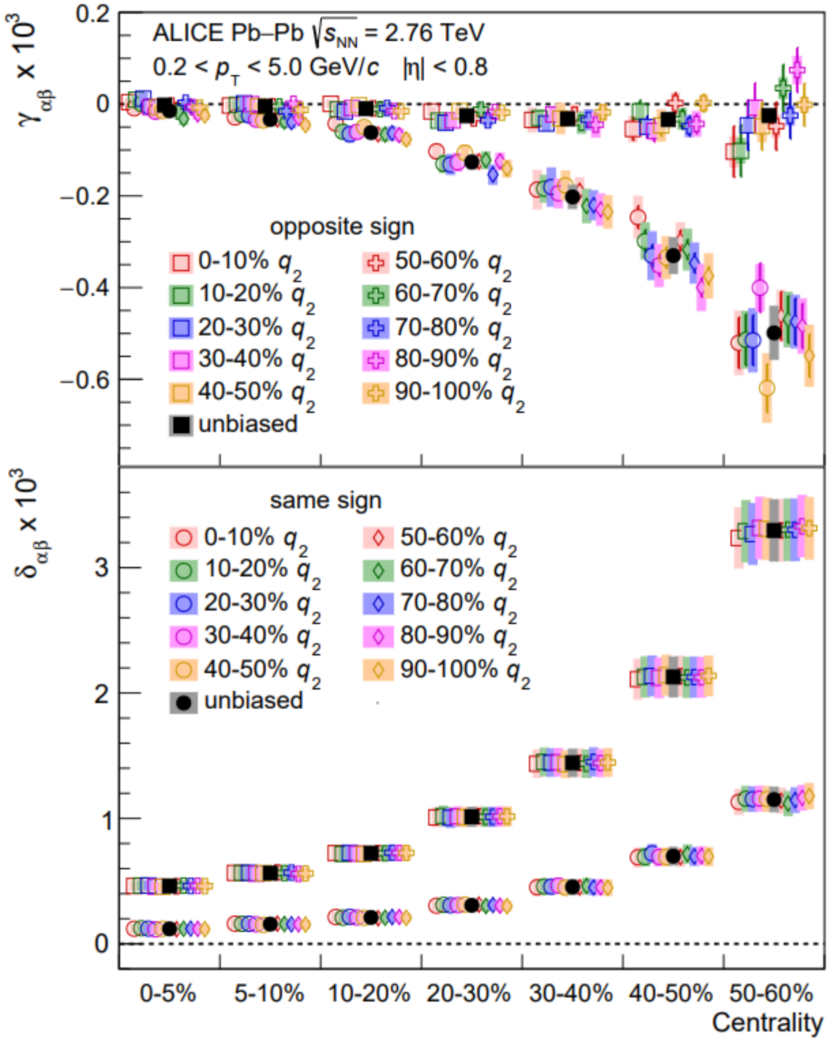
CME γ_{os} correlator

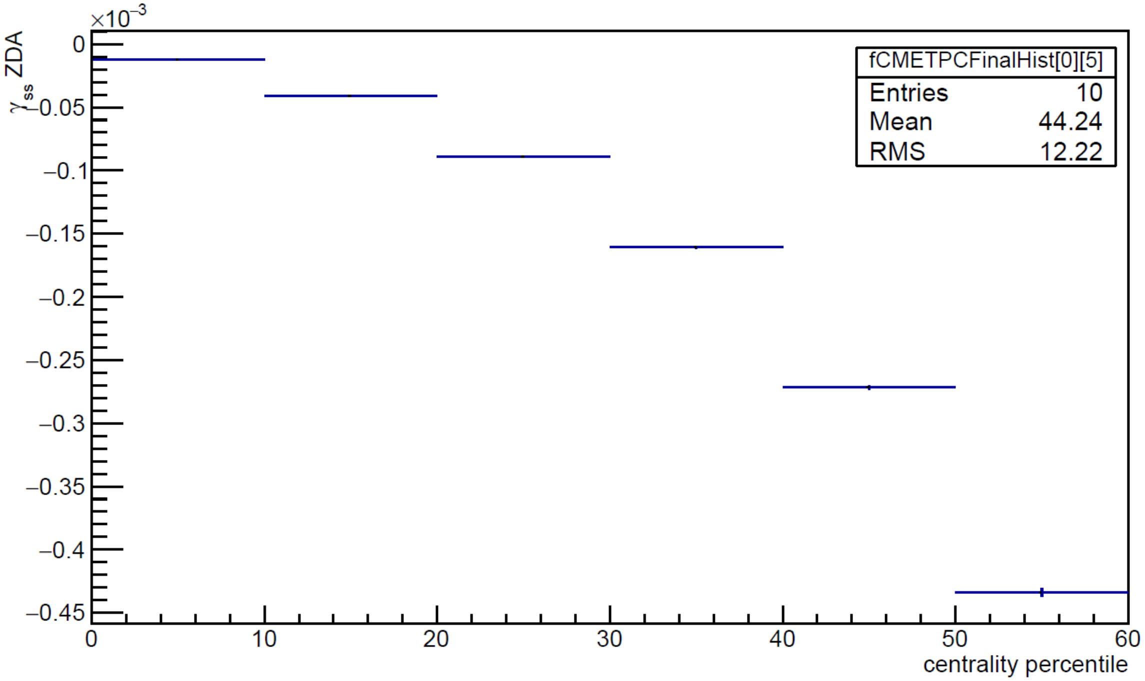


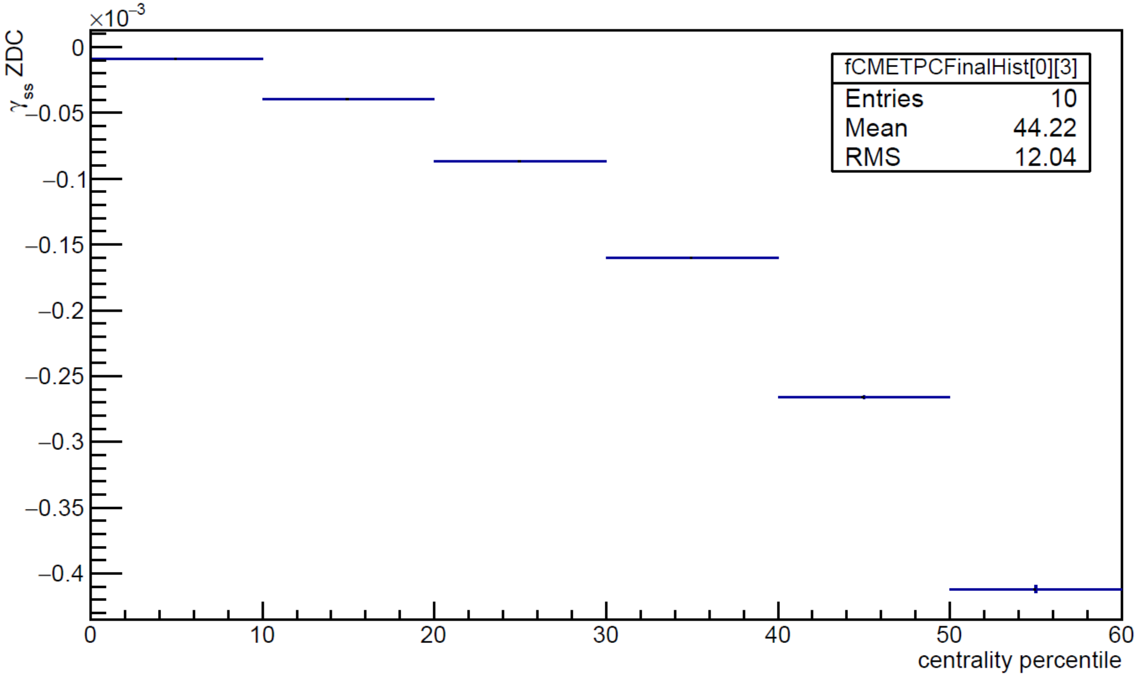




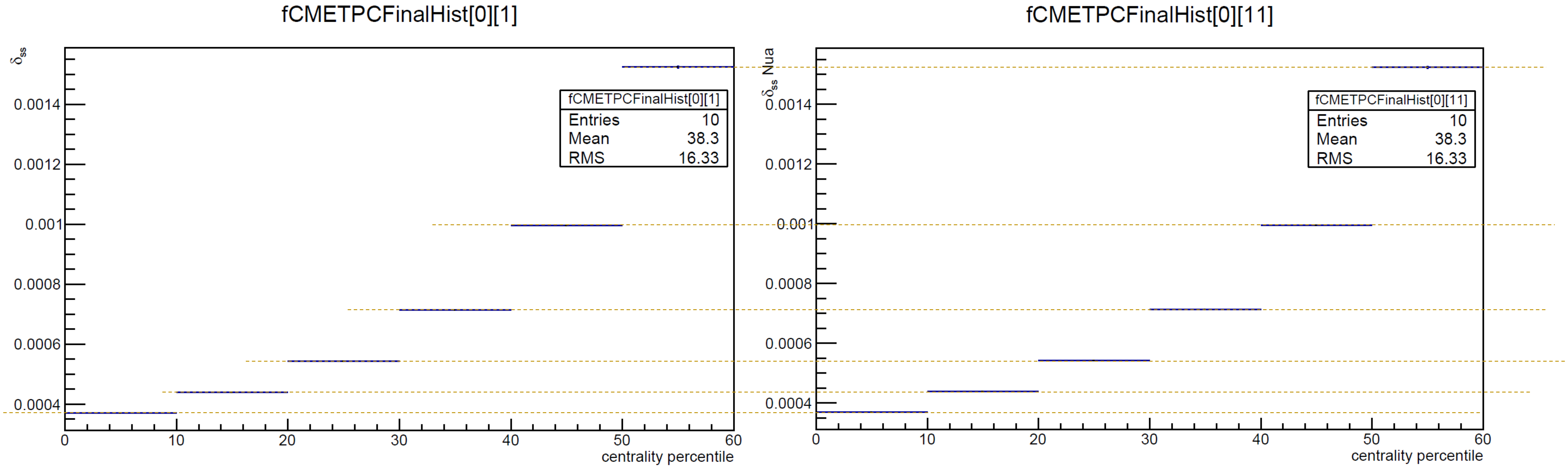
CME γ_{SS} correlator



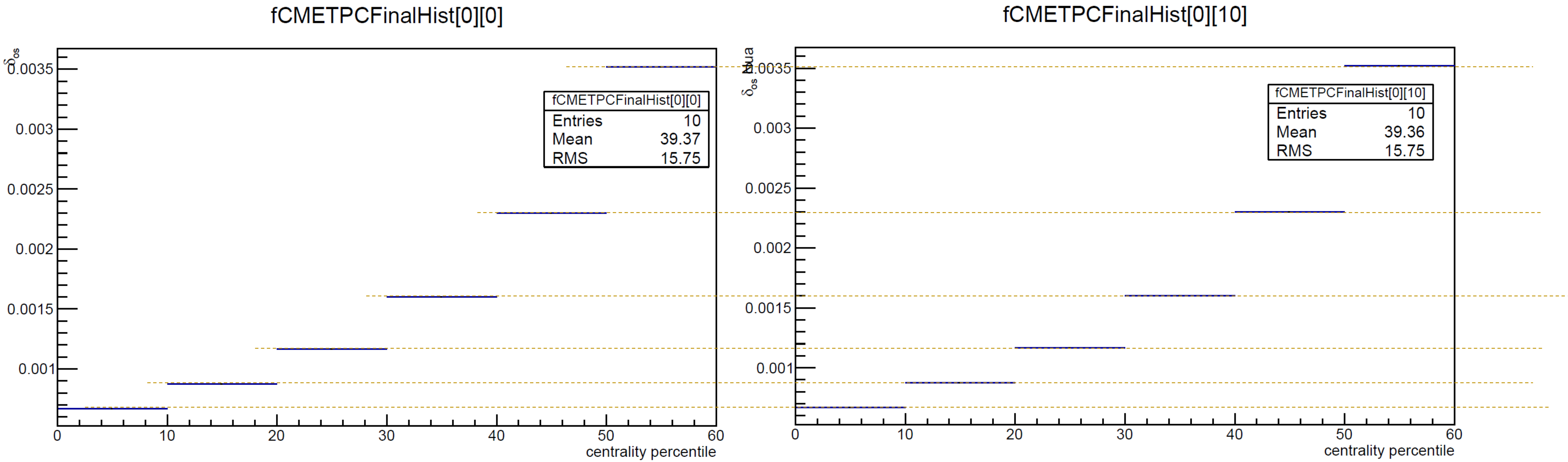




CME δ_{SS} (NUA) correlator



CME δ_{os} (NUA) correlator



Challenges in CME measurement

- Unsurety of the time scale of B field created in collisions. The bottom line is that the time scale of B field has to be approximately same as parity-violating local domains.
- The direction of B field is not strictly perpendicular to the RP. Fluctuations of the proton distributions lead to both ⊥ and ∥ w.r.t. the RP.
- Strong E field is also produced in collisions which influences on CME observables. It was found that E field can even reverse the sign of the CME observable in asymmetric e.g. Cu+Au collisions.
- Various backgrounds: momentum conservation & directed flow fluctuations (charge-independent) and local charge conservation (charge-dependent). Charge-independent backgrounds cancels out in $\Delta\delta$ and $\Delta\gamma$.
- The flow background is

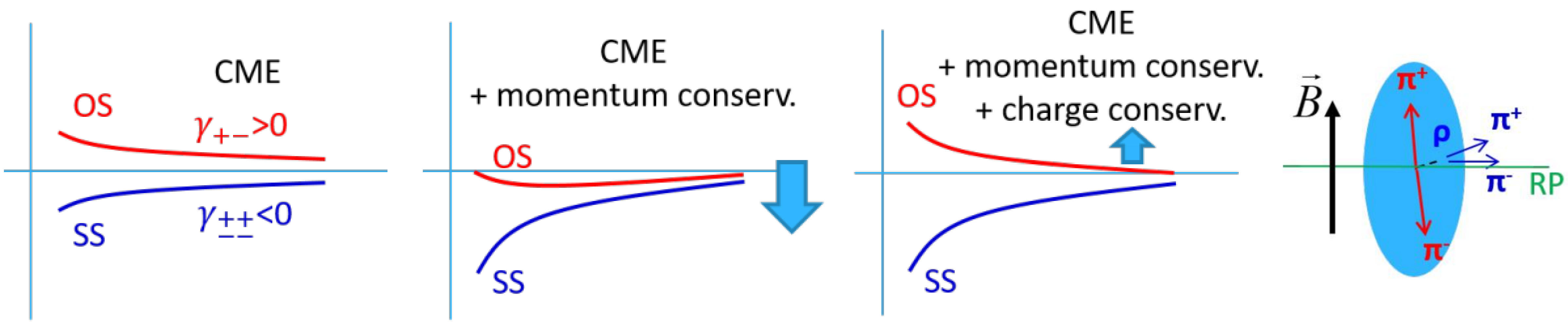
$$\Delta\gamma_{Bkg} \approx \frac{N_{\alpha\beta,\mathrm{clust}}}{N_\pi^2}\langle\cos(\varphi_\alpha + \varphi_\beta - 2\varphi_{\mathrm{clust}})\rangle v_{2,\mathrm{clust}}$$

where $N_{\alpha,\beta,\mathrm{clust}}$ is the number of pairs from cluster decays, $N_\pi \approx N_{\pi^+} \approx N_{\pi^-}$ is the number of single charge pions and $v_{2,\mathrm{clust}} = \langle\cos 2(\varphi_{\mathrm{clust}} - \psi_{RP})\rangle$.

https://arxiv.org/pdf/1906.11413.pdf

Physics backgrounds

- CME-induced γ_{SS} and γ_{OS} are originally symmetric about zero.
- Global transverse momentum conservation->more particles emitted in the RP direction ($\varphi_\alpha + \varphi_\beta - 2\Psi_{RP} \approx \pi$), the net effect of this background is negative.
- Resonance/cluster decays affect mainly OS pairs. This background is positive. The $\Delta\gamma$ variable is ambiguous between a back-to-back OS pair ($\varphi_\alpha + \varphi_\beta - 2\Psi_{RP} \approx 2\pi$) and an OS pair from a resonance decay along the RP ($\varphi_\alpha + \varphi_\beta - 2\Psi_{RP} \approx 0$ or 2π).



Background-only three-point correlator

- The CME signal is pertinent to the RP. The triangular component is mostly uncorrelated w.r.t. the RP. The CME signal is averaged to 0 when analysed w.r.t. ψ_3 by measuring $\langle\cos(\varphi_\alpha + \varphi_\beta - 2\psi_3)\rangle$.
- Adding extra randomized correlation $\varphi_\beta - \psi_3$ to make sure that no CME signal survive

$$\gamma_{123} \equiv \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\psi_3)\rangle$$

- The background for $\Delta\gamma_{123}$ is

$$\Delta\gamma_{123} = \Delta\gamma_{123}^{\mathrm{Bkg}} = \langle\cos(\varphi_\alpha + 2\varphi_\beta - 3\varphi_{\mathrm{clust}})\rangle v_{3,\mathrm{clust}}$$

which can provide insights into bkg issue in $\Delta\gamma$ observable.

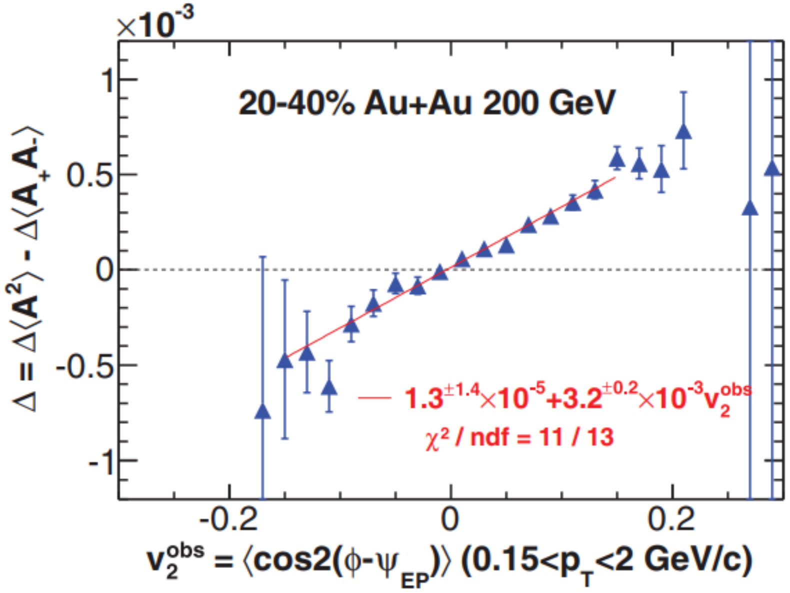
- γ_{123} does not provide a direct comparison to γ_{112}. Small-system collisions can give a hint. How to really be sure about the background in pb-pb?

Efforts to remove backgrounds

- Event-by-event v_2 method used by STAR

$$v_{2,\mathrm{ebye}} = Q_2^* \hat{Q}_{2,\mathrm{EP}} = \frac{Q_2^* Q_2}{|Q_n|} = \frac{1}{M}\left(\sum_{j=1}^{N} w_j e^{in\phi_j}\right)^* \times \frac{1}{M}\sum_{j=1}^{N} w_j e^{in\phi_j} / |Q_n|$$

Plot background observable w.r.t. $v_{2,\mathrm{ebye}}$. It turned out that $v_{2,\mathrm{ebye}} = 0$ result in zero background observable so that the backgrounds in signal is largely reduced.



Efforts to remove backgrounds

- Event-by-event q_n variable

$$q_n = Q_n/\sqrt{M}$$

To suppress the v2-induced background, a tight cut, $q_2 = 0$, is proposed.

- $q_2 = 0$ corresponds to a zero 2nd-order harmonic to any plane, while $v_{2,\mathbf{ebye}} = 0$ corresponds to the zero 2nd-order harmonic with respect only to the reconstructed EP in another phase space of the event.
- These methods extract the Δγ signal at zero $v_{2,\mathbf{ebye}}$ or q_n of the final-state particles. However, the results are likely still contaminated by flow backgrounds.
- These two methods exploit mainly the large statistical fluctuations due to finite multiplicities of individual events. But the backgrounds from resonances/clusters are not completely removed. This is because $v_{2,\mathbf{ebye}}$ or q_2 uses the same particles, i.e. the POIs, as those used for γ. **A zero anisotropy of those POIs does not guarantee a zero resonance anisotropy contribution to those same POIs on event-by-event basis.**

Innovative background removal methods

- Event-shape-engineering method
- To avoid the shortcoming from previous methods, the $\Delta\gamma$ observable of POIs is studied as a function of q_2 calculated using particles from a different phase space, so that their statistical fluctuations are independent.
- The advantage is that the extrapolated zero average v_2 of the POIs will likely correspond to also zero average v_2 of all particle species, including the CME background sources of resonances/clusters.
- The disadvantage is that an extrapolation to v_2 = 0 is required since the ESE q_2 sampling in its own phase space would not yield v_2 = 0 of the POI phase space. A dependence of the backgrounds on v2 that is not strictly linear would introduce inaccuracy in the extracted CME signal.
- The signal and background contribution to the $\Delta\gamma$

$$\Delta\gamma = \kappa_2 \Delta\delta v_2 + \Delta\gamma_{\mathrm{CME}}$$

Innovative background removal methods

- Invariant mass method
- Make measurements where resonance contributions are small or can be identified and removed.
- This can be achieved by differential measurements of the Δγ as a function of the particle pair invariant mass to identify and remove the resonance decay backgrounds.
- The $m_{\rm inv}$ dependence of the Δγ can be expressed as

$$\Delta\gamma(m_{\rm inv}) \approx r(m_{\rm inv})R(m_{\rm inv}) + \Delta\gamma_{\rm CME}(m_{\rm inv})$$

The first term is resonance contributions, where the response function $R(m_{\rm inv})$ should be a smooth function of $m_{\rm inv}$, while $r(m_{\rm inv})$ contains resonance mass shapes. The second term is the CME signal which should be a smooth function of $m_{\rm inv}$.

- One difficulty in the above method is that the exact functional form of $R(m_{\rm inv})$ is presently unknown and requires rigorous modelling and experimental inputs.

Innovative background removal methods

- Harmonic-plane comparison method
- Exploits comparative measurements of Δγ with respect to the RP and the PP taking advantage of the geometry fluctuation effects of the PP and the magnetic field directions.
- The 1st-order harmonic EP from ZDC, which measures spectator neutrons, is a good proxy for ψ_{RP}. The 2nd-order harmonic EP reconstructed from final-state particles is used as a proxy for ψ_{PP}.
- The reduction factor for the v_2-induced background in the $\Delta\gamma$ measurement w.r.t. PP (larger) and RP (smaller) is

$$a = \langle \cos 2(\psi_{\mathrm{PP}} - \psi_{\mathrm{RP}}) \rangle = v_2\{\psi_{\mathrm{RP}}\}/v_2\{\psi_{EP}\}$$

- The Δγ variable contains the CME signal and the v_2-induced background:

$$\Delta\gamma\{\psi\} = \Delta\gamma_{\mathrm{CME}}\big(B_{\mathrm{sq}}\{\psi\}\big) + \Delta\gamma_{\mathrm{Bkg}}(v_2\{\psi\})$$

where $B_{\mathrm{sq}} = \langle (eB/m_\pi^2)^2 \cos 2(\psi_B - \psi) \rangle$.

- The CME signal fraction in the measurements with respect to ψ_{EP} is then

$$f_{\mathrm{CME}}^{\mathrm{EP}} = \Delta\gamma_{\mathrm{CME}}\big(B_{\mathrm{sq}}\{\psi\}\big)/\Delta\gamma\{\psi_{\mathrm{EP}}\}$$

Innovative background removal methods

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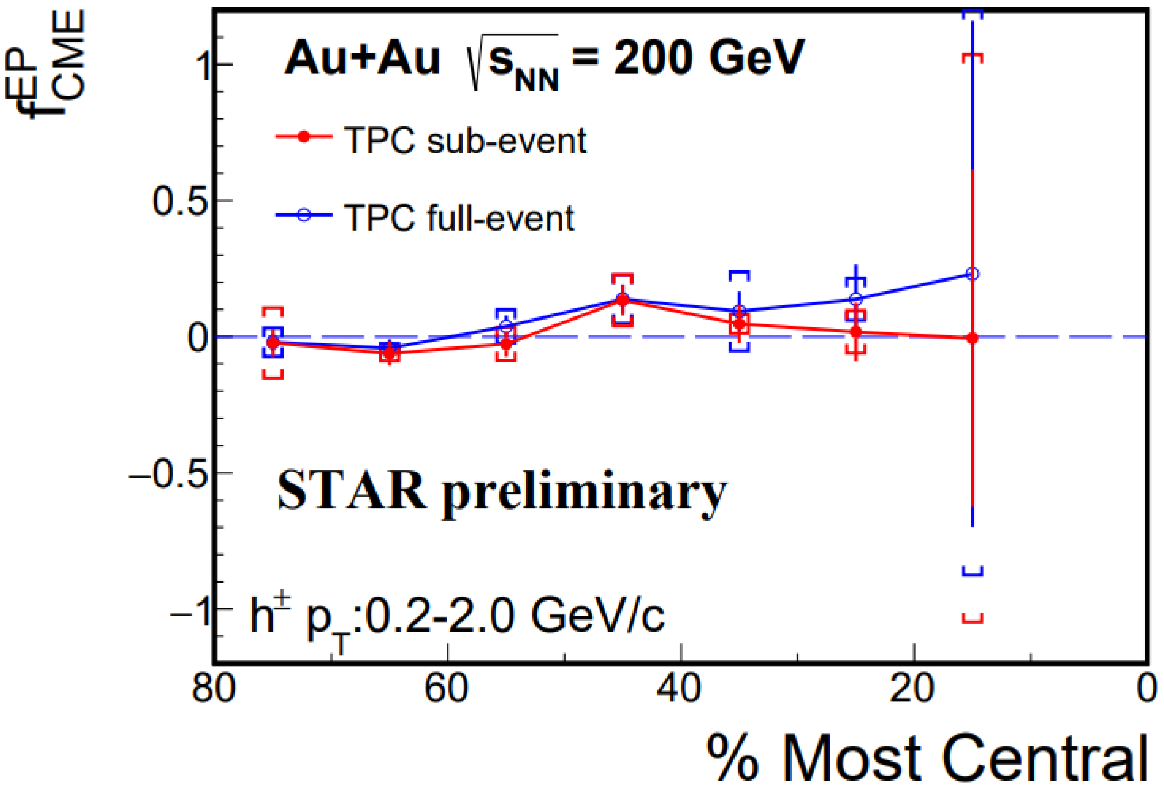

Arxiv 1805.05300

- In the case of a non-zero CME signal, consider the double ratio

$$\frac{(\Delta\gamma/v_2)_{\mathrm{SP}}}{(\Delta\gamma/v_2)_c} = \frac{\langle\cos(\alpha+\beta-2\psi_{1,\mathrm{SP}})\rangle/\langle\cos(2a-2\psi_{1,\mathrm{SP}})\rangle}{\langle\cos(\alpha+\beta-2c)\rangle/\langle v_{2,\mathrm{PP}}^2\rangle}$$

where as above the elliptic flow is assumed to be same for particles a and c.

- Introduce a non-measurable angle $\Psi_{2,\mathrm{B}}$ which is perpendicular to the magnetic field.
- Decompose the correlators to background and signal parts

$$\langle\cos(\alpha+\beta-2c)\rangle = \langle\cos(\alpha+\beta-2c)\rangle^{\mathrm{BG}} + \langle\cos(\alpha+\beta-2c)\rangle^{\mathrm{CME}} = b\langle v_{2,\mathrm{PP}}^2\rangle + \Delta\gamma^{\mathrm{CME}} v_2\{\Psi_{2,\mathrm{B}}\}$$

where $\Delta\gamma^{\mathrm{CME}} = \langle\cos(\alpha+\beta-2\Psi_{2,\mathrm{B}})\rangle^{\mathrm{CME}}$ and $v_2\{\Psi_{2,\mathrm{B}}\} = \langle\cos(2c-2\Psi_{2,\mathrm{B}})\rangle$.

- Similarly,

$$\begin{aligned}\langle\cos(\alpha+\beta-2\psi_{1,\mathrm{SP}})\rangle &= \langle\cos(\alpha+\beta-2\psi_{1,\mathrm{SP}})\rangle^{\mathrm{BG}} + \langle\cos(\alpha+\beta-2\psi_{1,\mathrm{SP}})\rangle^{\mathrm{CME}} \\ &= b\langle\cos(2a-2\psi_{1,\mathrm{SP}})\rangle + \Delta\gamma^{\mathrm{CME}}\langle\cos(2\Psi_{2,\mathrm{B}}-2\psi_{1,\mathrm{SP}})\rangle\end{aligned}$$

Arxiv 1805.05300

- Combine everything together

$$\frac{(\Delta\gamma/v_2)_{\mathrm{SP}}}{(\Delta\gamma/v_2)_c} = 1 + f_{\mathrm{PP}}^{\mathrm{CME}}\left(\frac{\langle\cos(2\Psi_{2,\mathrm{B}} - 2\psi_{1,\mathrm{SP}})\rangle\langle v_{2,\mathrm{PP}}^2\rangle}{\langle\cos(2a - 2\psi_{1,\mathrm{SP}})\rangle v_2\{\Psi_{2,\mathrm{B}}\}} - 1\right)$$

where

$$f_{\mathrm{PP}}^{\mathrm{CME}} = \frac{\langle\cos(\alpha + \beta - 2c)\rangle^{\mathrm{CME}}}{\langle\cos(\alpha + \beta - 2c)\rangle}$$

is the fraction of the CME signal in 3-particle correlator measured relative to the second harmonic participant plane.

- The angle $\psi_{1,\mathrm{SP}}$ fluctuates around the spectator plane $\Psi_{1,\mathrm{SP}}$, but the event plane resolution factors cancel out

$$\frac{(\Delta\gamma/v_2)_{\mathrm{SP}}}{(\Delta\gamma/v_2)_c} = 1 + f_{\mathrm{PP}}^{\mathrm{CME}}\left(\frac{\langle\cos(2\Psi_{2,\mathrm{B}} - 2\Psi_{1,\mathrm{SP}})\rangle\langle v_{2,\mathrm{PP}}^2\rangle}{v_2\{\Psi_{1,\mathrm{SP}}\}v_2\{\Psi_{2,\mathrm{B}}\}} - 1\right)$$

where $v_2\{\Psi_{1,\mathrm{SP}}\} = \langle\cos(2a - 2\psi_{1,\mathrm{SP}})\rangle$.

Some messages

- The CME is a parity violating effect, but the $\Delta\gamma$ observable is essentially two-particle correlations and is intrinsically parity even, and therefore has inevitably large background contaminations.
- Parity-odd observables would be intrinsically more sensitive to parity-odd effects like the CME. However, since the topological charge signs are random, it may not be possible to identify a parity odd observable to search for the CME. It is, however, important to continue to look for new observables that are less background prone.
- The major background is intrinsic two-particle correlations, mostly resonance decays. Three particle correlations might be one way to avoid most of the resonance decay contributions. However, given the smallness of the CME signal, three-particle correlations may, on the other hand, prove prohibitively difficult to identify the CME.

Small-system collisions

- In non-central heavy-ion collisions, the PP, although fluctuating, is generally aligned with the RP.
- The Δγ measurement with respect to the PP is thus entangled by the possible CME signal and the v_2-induced background.
- In small-system collisions, the PP arises from geometry fluctuations, which is uncorrelated to the impact parameter direction.
- Any CME signal would average to zero in the Δγ measurements with respect to the PP.
- Background sources from resonance/cluster decay contribute to small-system collisions similarly as to heavy-ion collisions.
- Small-system p+A collisions thus provide a control experiment, where the CME signal can be "turned off," whereas the v_2-related backgrounds remain.
- In general, small-system collisions are not idea to measure CME signals. Much weaker signal due to lower magnetic field and less QGP created.

δ and γ correlator

- The particle azimuthal distribution can be described by a Fourier decomposition

$$\frac{dN}{d\varphi_\alpha} \propto 1 + 2a_{1,\alpha}\sin(\varphi - \Psi_{RP}) + 2\sum_{n=1}^{+\infty} v_{n,\alpha}\cos\big(n(\varphi - \Psi_n)\big)$$

$$v_n = \frac{1}{2\pi}\int_0^{2\pi}\frac{dN}{d[\varphi - \Psi_n]}\cos\big(n(\varphi - \Psi_n)\big)\,d\varphi \approx \big\langle\cos\big(n(\varphi - \Psi_n)\big)\big\rangle$$

$$\delta_{\alpha\beta} = \langle\cos(\varphi_\alpha - \varphi_\beta)\rangle, \gamma_{\alpha\beta} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP})\rangle$$

$$\delta_{\alpha\beta} = \langle v_{1,\alpha}v_{1,\beta}\rangle + \langle a_{1,\alpha}a_{1,\beta}\rangle, \gamma_{\alpha\beta} = \langle v_{1,\alpha}v_{1,\beta}\rangle - \langle a_{1,\alpha}a_{1,\beta}\rangle$$

where $a_{1,+} = -a_{1,-}$ and $v_{1,+} = v_{1,-}$. The CME contribution to γ and δ are opposite in sign and same in magnitude:

$$\Delta\delta = \delta_{\pm\mp} - \delta_{\pm\pm} = -2\langle a_1^2\rangle, \Delta\gamma = \gamma_{\pm\mp} - \gamma_{\pm\pm} = 2\langle a_1^2\rangle$$

- Since charge separation is perpendicular to Ψ_{RP} on average, the sign of $\gamma_{SS} = -1$ and $\gamma_{OS} = +1$.
- Expectation value $E(x) = \int xf(x)dx$.

Efforts to remove backgrounds

- Event-by-event q_n variable

$$q_n = Q_n/\sqrt{M}$$

To suppress the v2-induced background, a tight cut, $q_2 = 0$, is proposed.

- $q_2 = 0$ corresponds to a zero 2nd-order harmonic to any plane, while $v_{2,\mathbf{ebye}} = 0$ corresponds to the zero 2nd-order harmonic with respect only to the reconstructed EP in another phase space of the event.
- These methods extract the Δγ signal at zero $v_{2,\mathbf{ebye}}$ or q_n of the final-state particles. However, the results are likely still contaminated by flow backgrounds.
- The backgrounds arise from resonance/cluster decay correlations coupled with the v_2 of the parent sources of the resonances/clusters, not that of all final-state particles. Since the $v_{2,\mathbf{ebye}}$ and q_2 quantities in these methods are the event-by-event quantities, the v_2 of the correlation sources (resonances/clusters) are not necessarily zero when the final-state particle $v_{2,\mathbf{ebye}}$ or q_2 is selected to be zero.

Innovative background removal methods

- ESE: Measuring $\Delta\gamma$ observable where the elliptical anisotropy is zero by ESE method exploiting dynamic fluctuations in v_2.
- To avoid the shortcoming from previous methods, the $\Delta\gamma$ observable of POIs is studied as a function of q_2 calculated using particles from a different phase space, so that their statistical fluctuations are independent.
- The q_2 variable selects different event shapes. A given q_2 range samples a different average v_2 of the POIs, therefore, assess only the dynamical fluctuations from the initial-state participant geometry within the given narrow centrality bin.
- The extrapolated zero average v_2 of the POIs will likely correspond to also zero average v_2 of all particle species, including the CME background sources of resonances/clusters.