The Chiral Magnetic Effect in isobaric nuclei at LHC energies

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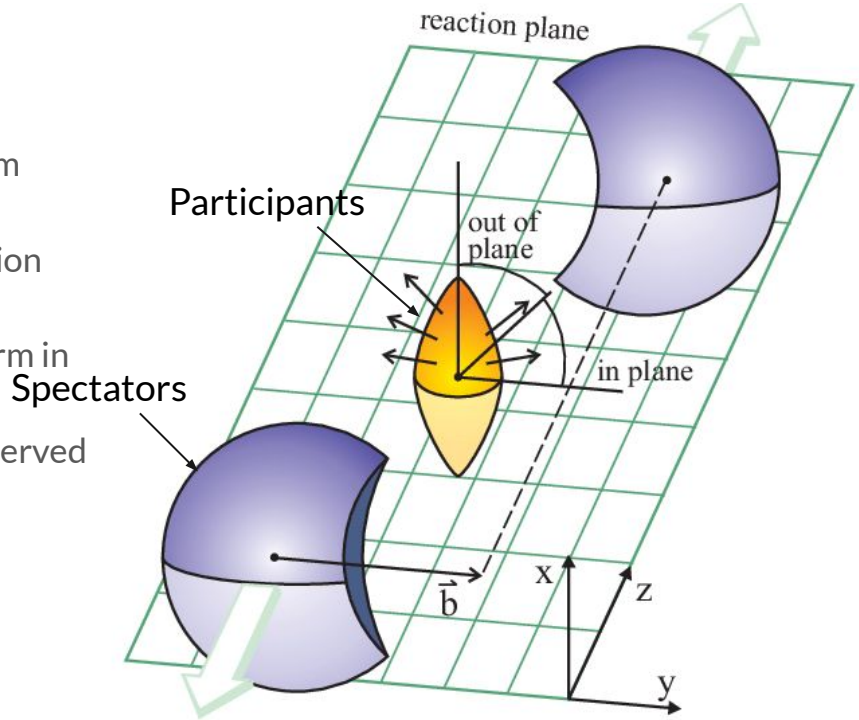
NNV Lunteren, 3 November

Quantum ChromoDynamics (QCD) and heavy ion collisions

- The strong coupling constant decreases as the momentum transfer increases
- Large momentum transfer→Asymptotic freedom
- Low momentum transfer→Confinement
- Deconfined state of quarks and gluons in heavy ion collisions, Quark Gluon Plasma (QGP)
- Chiral anomaly leads to addition CP violating term in QCD
- No global P and CP violation experimentally observed in QCD, while it is theoretically possible
- Local P and CP violation also possible in QCD

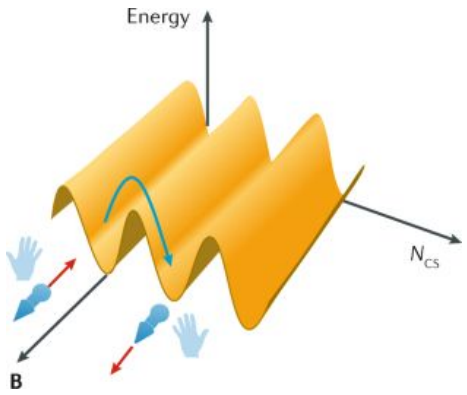


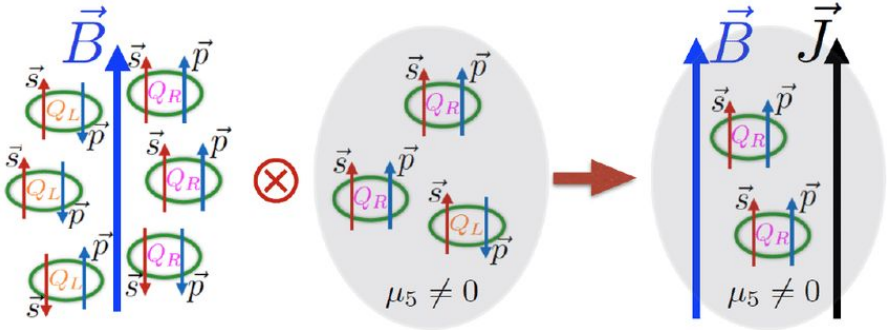
What is the Chiral Magnetic Effect (CME)?

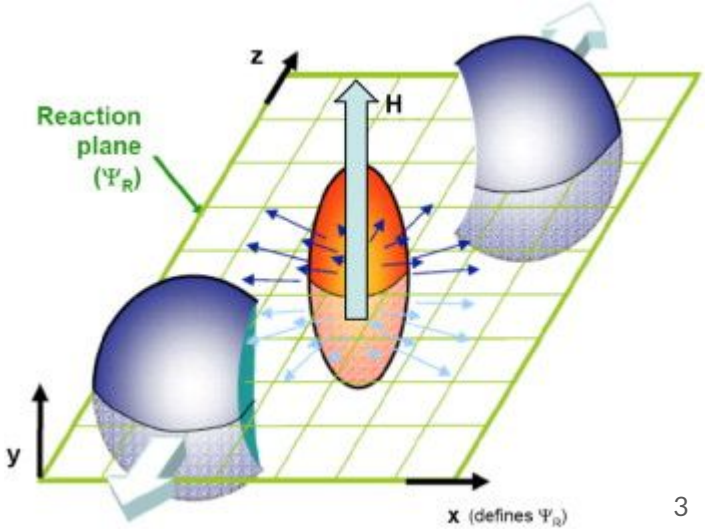
- A current in the direction of a magnetic field:

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

- Local P and CP violation is predicted to be possible
- Local domains in heavy ion collisions with chirality imbalance
- Strongest magnetic field in nature we know of ~10^{20} Gauss



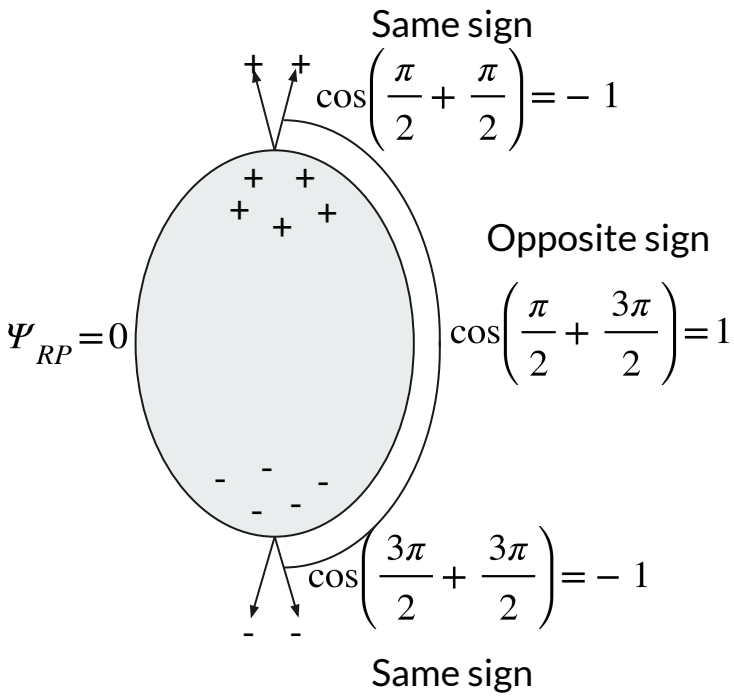




Observables and backgrounds

- Fourier decomposition of φ spectrum:
- $\frac{dN}{d\varphi_\alpha} = 1 + 2\sum_{n=1}^{\infty} a_{n,\alpha}\sin\left(n\left(\varphi - \Psi_{RP}\right)\right) + v_{n,\alpha}\cos\left(n\left(\varphi - \Psi_n\right)\right)$
- Coefficient a_1 quantifies the charge separation, v_n quantifies anisotropic flow
- $\gamma_{11}^{\alpha,\beta} = \left\langle \cos\left(\varphi_\alpha + \varphi_\beta - 2\Psi_{RP}\right)\right\rangle$
- Opposite sign (OS) - Same Sign (SS)
- $\Delta\gamma = \gamma_{\pm,\mp} - \gamma_{\pm,\pm} = 2\left\langle a_1^2\right\rangle + \Delta\gamma_{bkgd}$
- Backgrounds dominate
- $\Delta\gamma_{bkgd} \propto \frac{v_2}{N_{ch}}$

CME signal



Isobar collisions at RHIC[1]

- Ru-96 has 4 protons more than Zr-96
- $\left(B_{Ru+Ru}/B_{Zr+Zr}\right)^2 - 1 = 0.10 - 0.18$
- $\Delta\gamma_{Ru+Ru}/v_2 = \Delta\gamma_{CME} + \Delta\gamma_{bkgd}$

  $\not\approx \qquad \approx$

  $\Delta\gamma_{Zr+Zr}/v_2 = \Delta\gamma_{CME} + \Delta\gamma_{bkgd}$

[1] STAR collaboration, *Search for the Chiral Magnetic Effect with Isobar Collisions at $\sqrt{s_{NN}}$ = 200 GeV by the STAR Collaboration at RHIC.*

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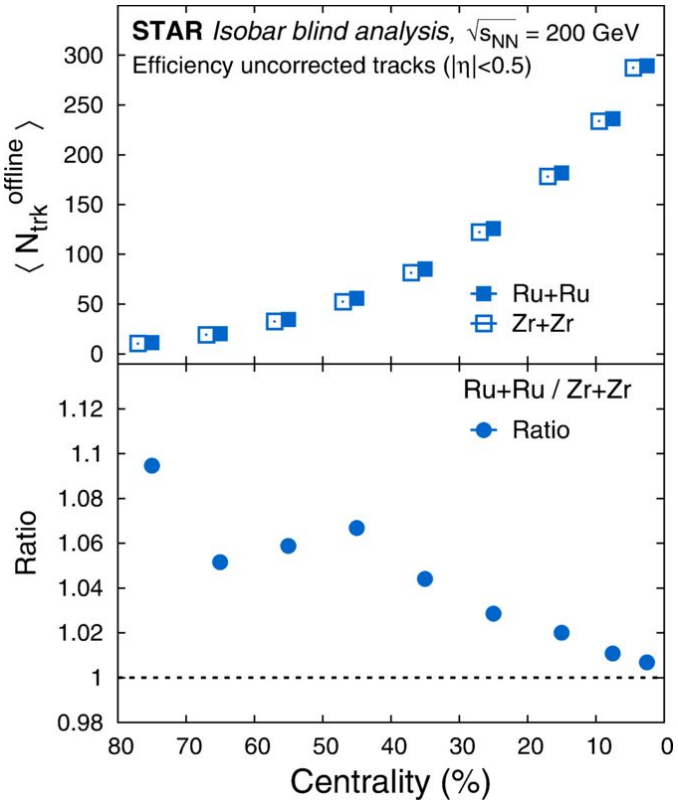

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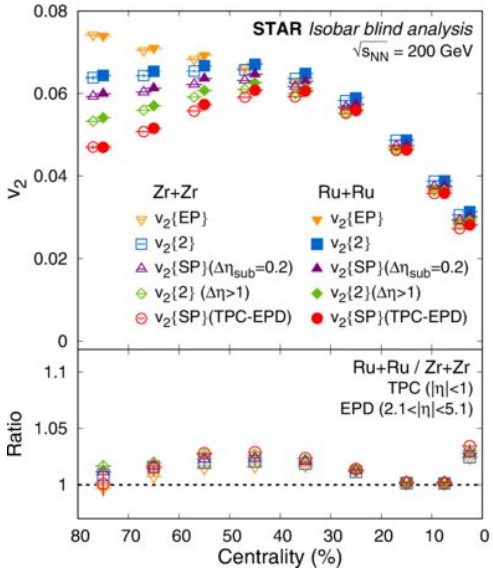

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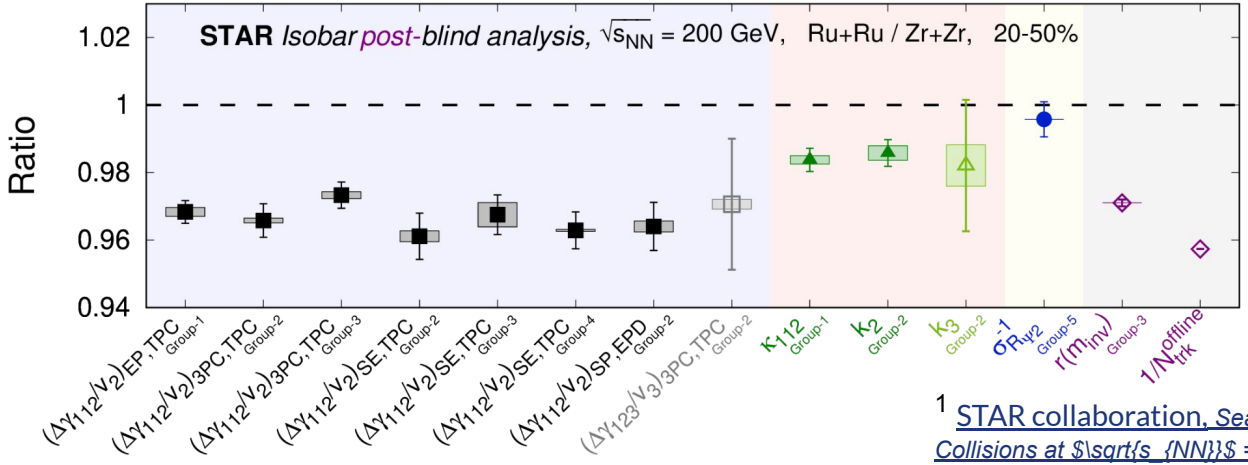
Caused by difference in nuclear structure
Predefined criteria are invalid



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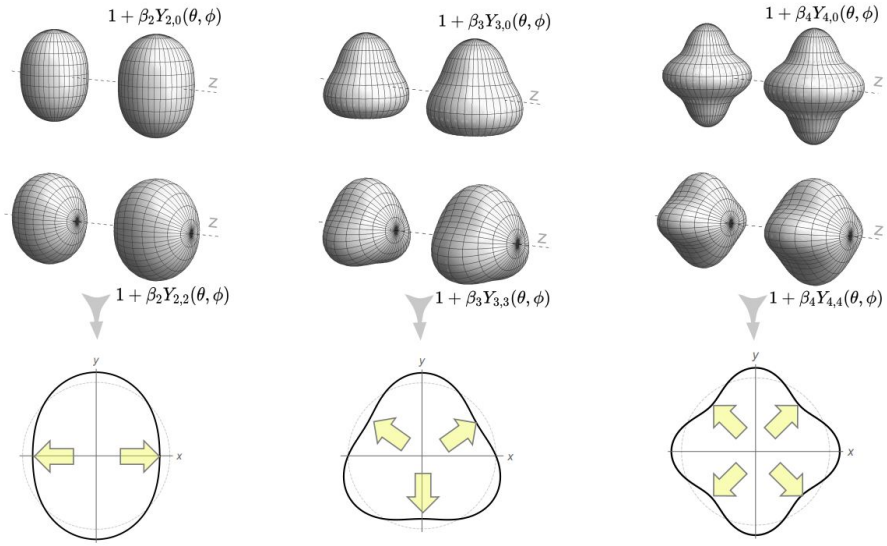
Nuclear deformations and effect on observables

- Deformed Woods-Saxon density
- Effect on isobar ratio:

$$R_{\mathcal{O}} = \frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$



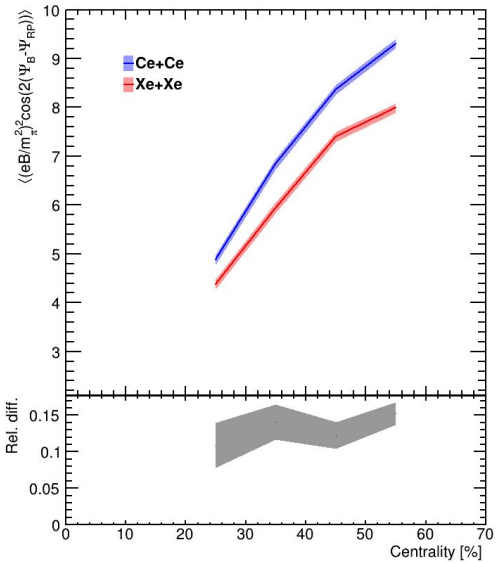
$$\rho(r,\theta,\varphi) = \frac{\rho_0}{1+e^{[r-R(\theta,\varphi)]/a}}, \quad R(\theta,\varphi) = R_0\left(1+\beta_2 Y_2^0(\theta,\varphi)+\beta_3 Y_3^0(\theta,\varphi)\right)$$

Jia, J., & Zhang, C.-J. (2021). Scaling approach to nuclear structure in high-energy heavy-ion collisions. *Physical Review C, 107*(2).

Jia, J. (2021). Shape of atomic nuclei in heavy ion collisions. *Physical Review C, 105*(1).

Isobar collisions at LHC energies?

- Investigate the use of isobar collisions of Ce-136 + Ce-136 and Xe-136 + Xe-136 at an energy of 5.02 TeV
- Bigger magnetic field compared to Ru-96 and Zr-96
- Magnetic field in Ce-136 is 10-15% larger than in Xe-136
- Nuclear structure from DFT calculations
- Smaller difference in nuclear structure
- Also take into account possible difference in multiplicity: $N_{ch}\Delta\gamma/v_2$



Species	β_2	β_3	a	R_0
$^{96}_{44}$Ru	0.162	0	0.46 fm	5.09 fm
$^{96}_{40}$Zr	0.06	0.20	0.52 fm	5.02 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa	ΔR_0
	0.0226	-0.04	-0.06 fm	0.07 fm

$^{136}_{58}$Ce	0.17	0	0.51 fm	5.78 fm
$^{136}_{54}$Xe	0.086	0	0.50 fm	5.79 fm
difference	$\Delta\beta_2^2$	$\Delta\beta_3^2$	Δa	ΔR_0
	0.022	0.0	0.01 fm	-0.01 fm

Simulations

A MultiPhase Transport model (AMPT)[1]

- Based on a transport approach
- No magnetic field or CME
- Nuclear structure with deformations

- MCGlauber (HIJING) → Lund string fragmentation → Parton Cascade (ZPC) → Quark Coalescence → Hadron Cascade (ART)

[1] Lin, Z. W., Ko, C. M., Li, B. A., Zhang, B., & Pal, S. (2005). Multiphase transport model for relativistic heavy ion collisions. *Physical Review C - Nuclear Physics*, *72*(6), 064901.

Anomalous Viscous Fluid Dynamics (AVFD)[2]

- Based on hybrid approach (hydrodynamics and hadron cascade)
- CME current as a perturbation on top of bulk evolution
- Control the strength of CME with n_5/s
- Nuclear structure with deformations
- Controllable amount of background (Local Charge Conservation)

- MCGlauber → Hydrodynamic expansion (VISH2+1D)→ Cooper Frye (iSS)→ Hadron Cascade (UrQMD)

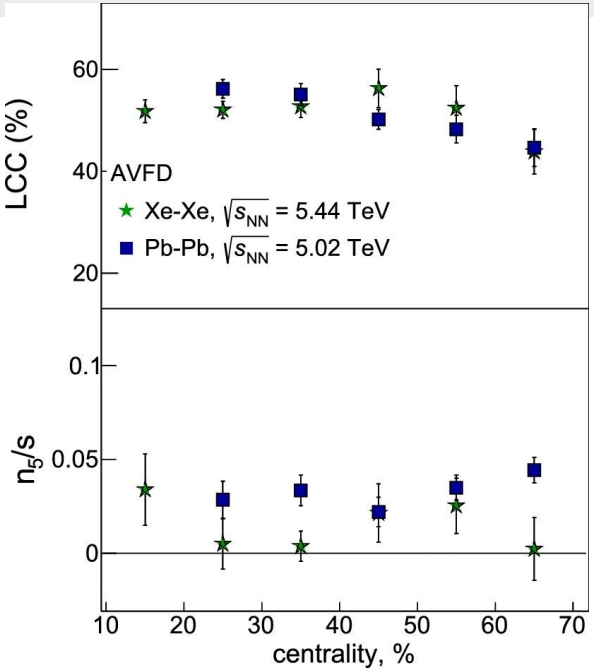
[2] Shi, S., Jiang, Y., Lilleskov, E., & Liao, J. (2017). Anomalous Chiral Transport in Heavy Ion Collisions from Anomalous-Viscous Fluid Dynamics. *Annals of Physics*, *394*, 50–72.

Datasets and analysis details

- AMPT: Impact parameter from 3 fm to 15 fm, 10^5 collisions of Ce+Ce and Xe+Xe with and without deformations
- AVFD: 10^5 collisions in 10% to 50% centrality in steps of 10% Ce+Ce and Xe+Xe with and without deformations
- AVFD tuned to describe correlations in Xe-129
- AVFD dataset to investigate the CME:

Species	Settings	Centrality 20-30%	30-40%	40-50%	50-60%
Ce+Ce	LCC and β_2 on	6.8×10^4	8.0×10^5	8.6×10^5	9.0×10^5
	LCC, n_5/s and β_2 on	7.2×10^4	7.9×10^5	8.3×10^5	8.8×10^5
Xe+Xe	LCC and β_2 on	7.0×10^4	8.0×10^5	8.6×10^5	9.0×10^5
	LCC, n_5/s and β_2 on	7.3×10^4	8.0×10^5	8.5×10^5	8.9×10^5

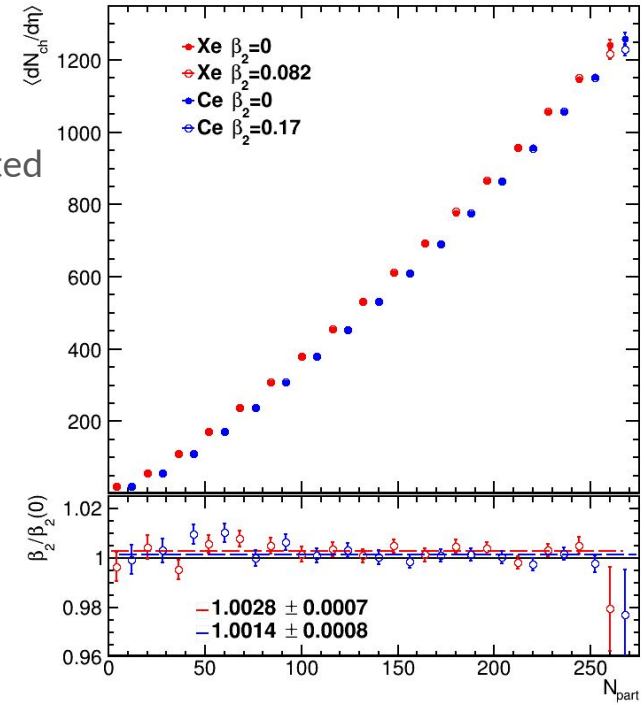
- Use particles with $|\eta|<0.8$ and $0.2 < p_T < 5$ GeV/c

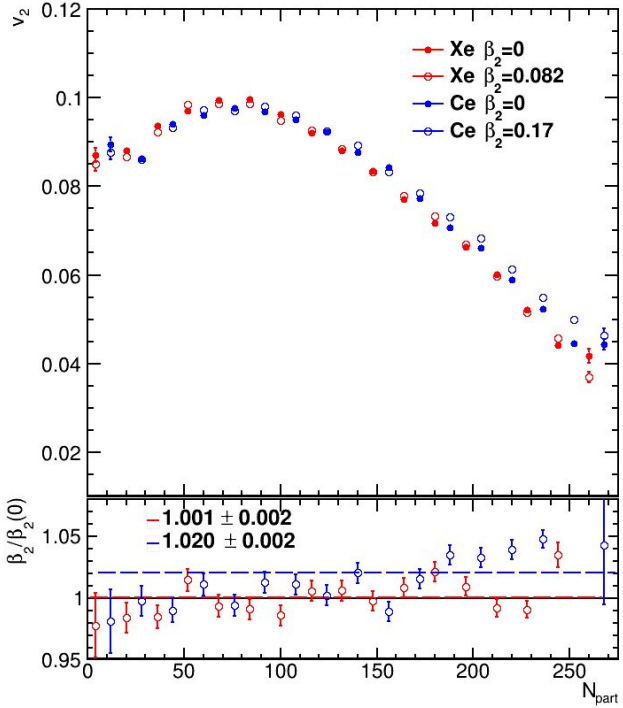


Christakoglou, P., Qiu, S., & Staa, J. (2021). Systematic study of the chiral magnetic effect with the AVFD model at LHC energies. *The European Physical Journal C 2021 81:8, 81*(8), 1–10.

Results - CME background from nuclear structure AMPT

Datapoints are shifted horizontally for visibility!





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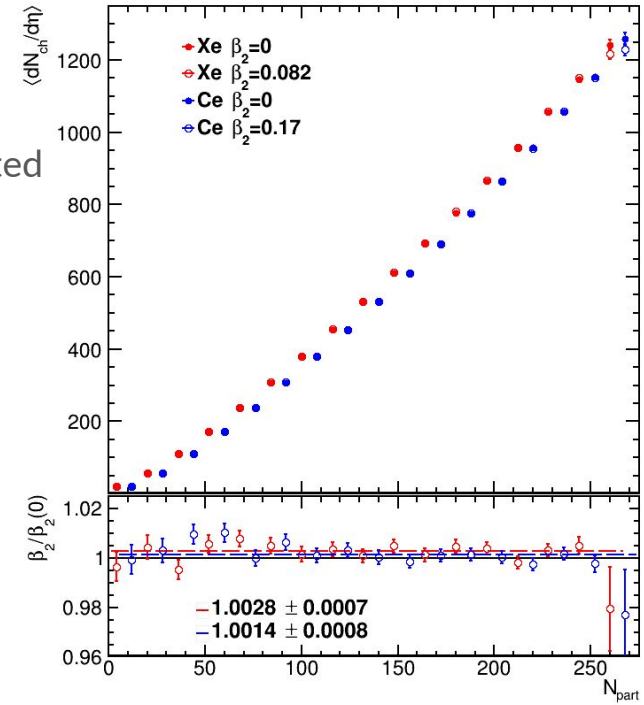
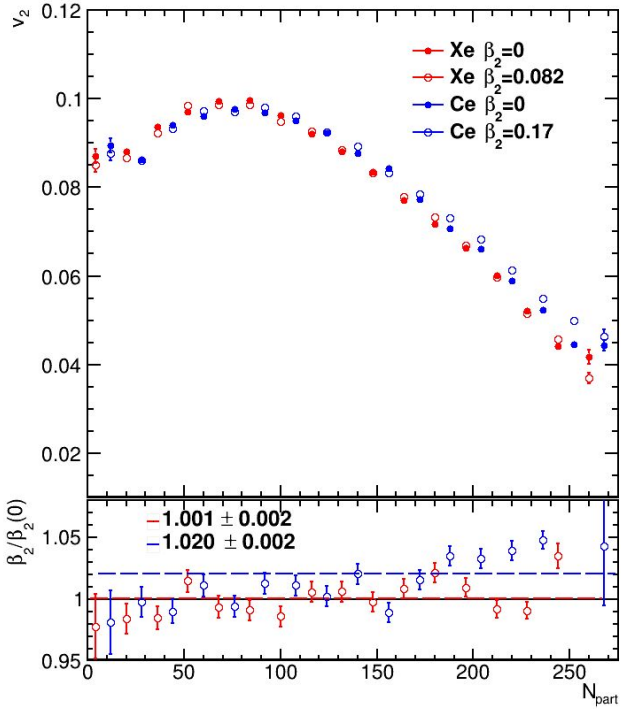
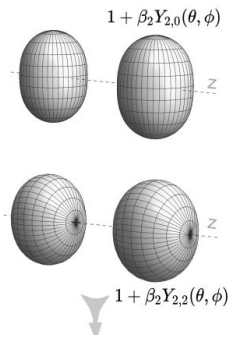




Multiplicity is not significantly changed, elliptic flow changes mainly in central collisions in Ce

Results - Isobar ratio of v_2 in AMPT



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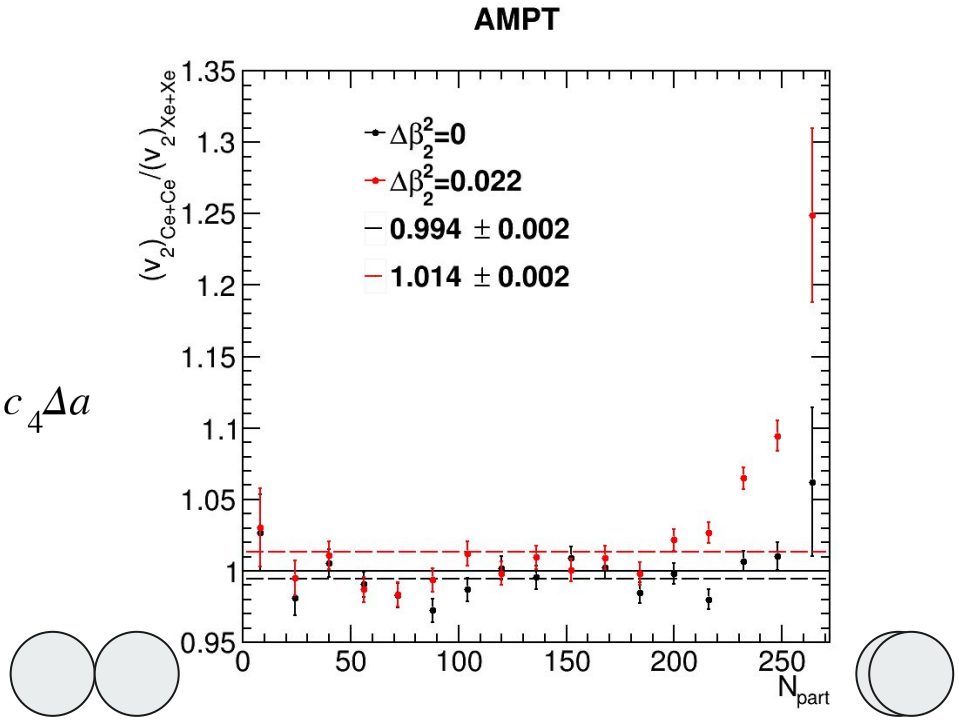

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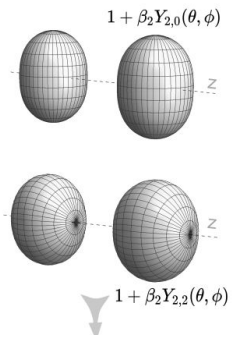

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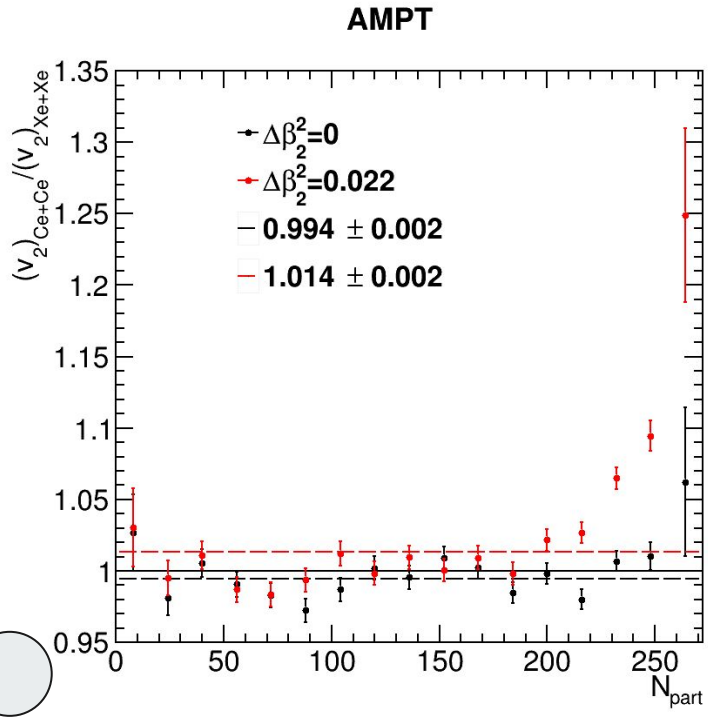


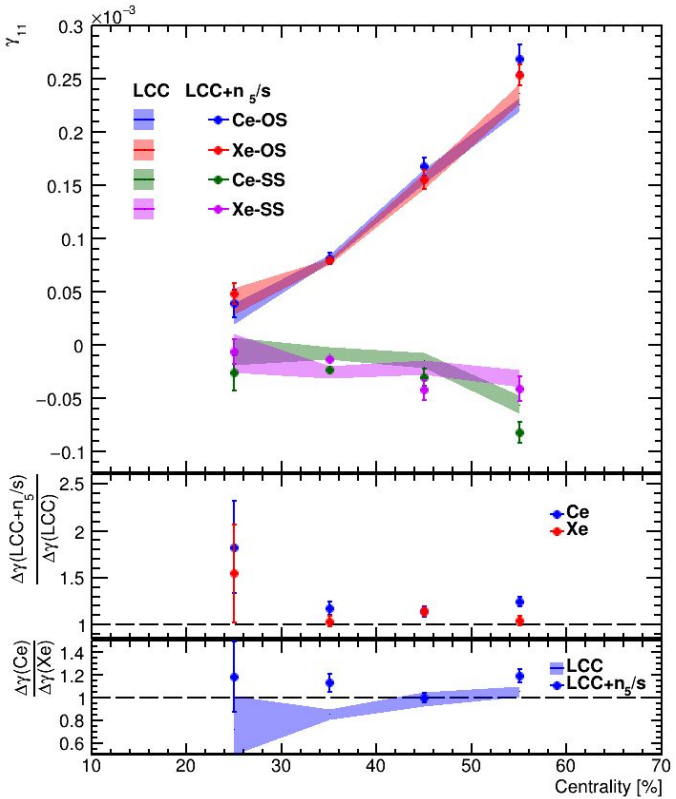
AMPT shows that elliptic flow in Ce-136 is larger than Xe-136 mainly in central events

AMPT and AVFD results are comparable

Results - γ correlator

- Use only positive-positive SS correlations due to incorrect implementation of LCC in AVFD

$$\Delta\gamma = \gamma_{\pm,\mp} - \gamma_{\pm,\pm} = 2\left\langle a_1^2 \right\rangle + \Delta\gamma_{bkgd}$$



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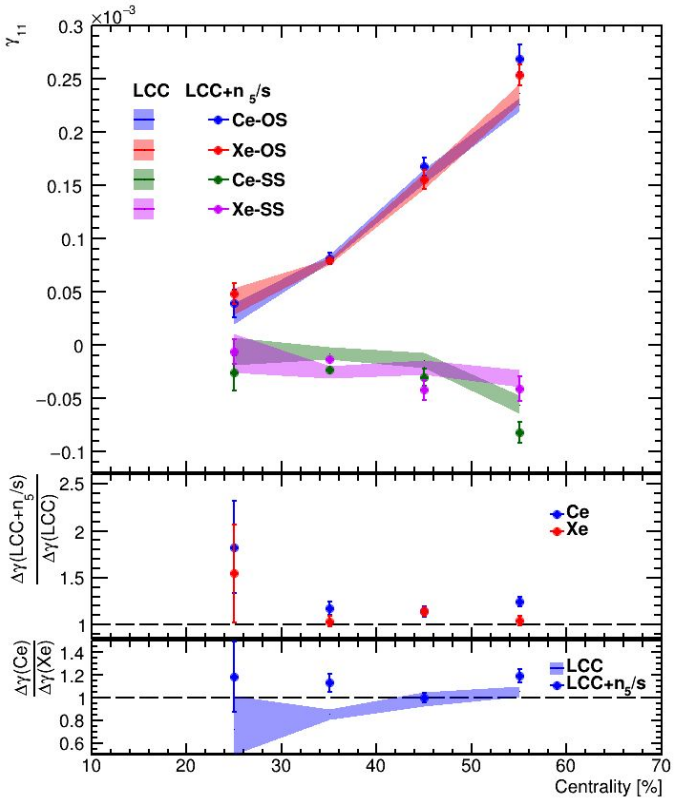
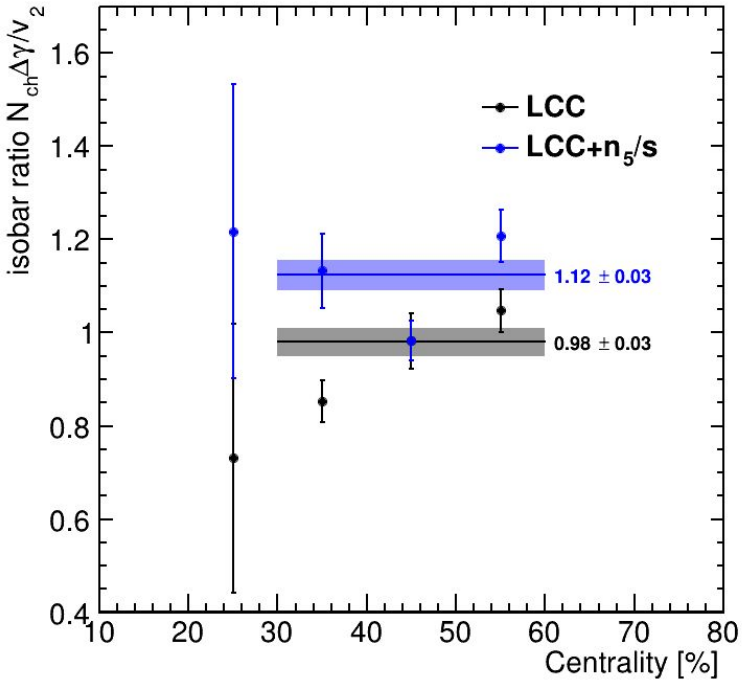
$\Delta\gamma$ is enhanced by the CME signal, stronger in Ce



Results - Isobar ratio

- Rescale $\Delta\gamma$ as: $N_{ch}\Delta\gamma/v_2$ and take the ratio between the isobars



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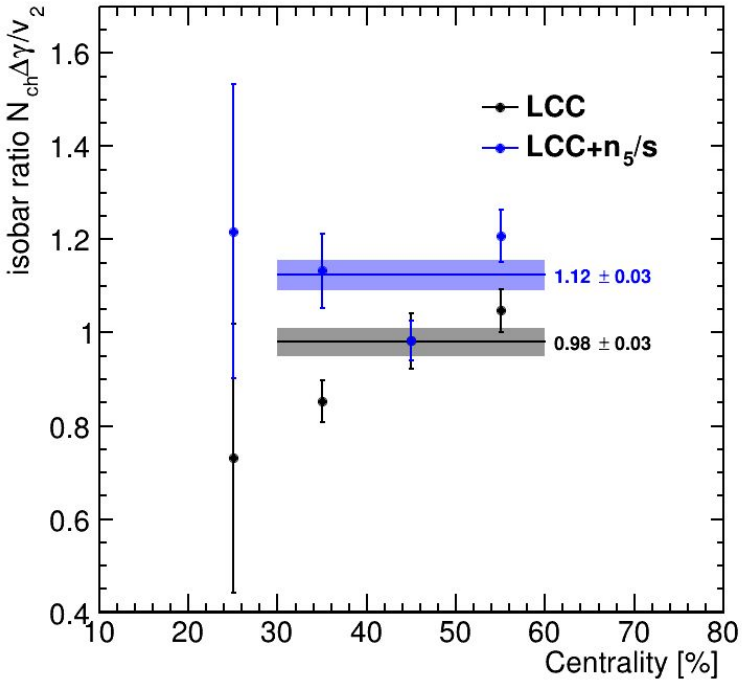
Background baseline ~1 in $N_{ch}\Delta\gamma/v_2$, (14 ± 4)% stronger CME signal in Ce in $N_{ch}\Delta\gamma/v_2$

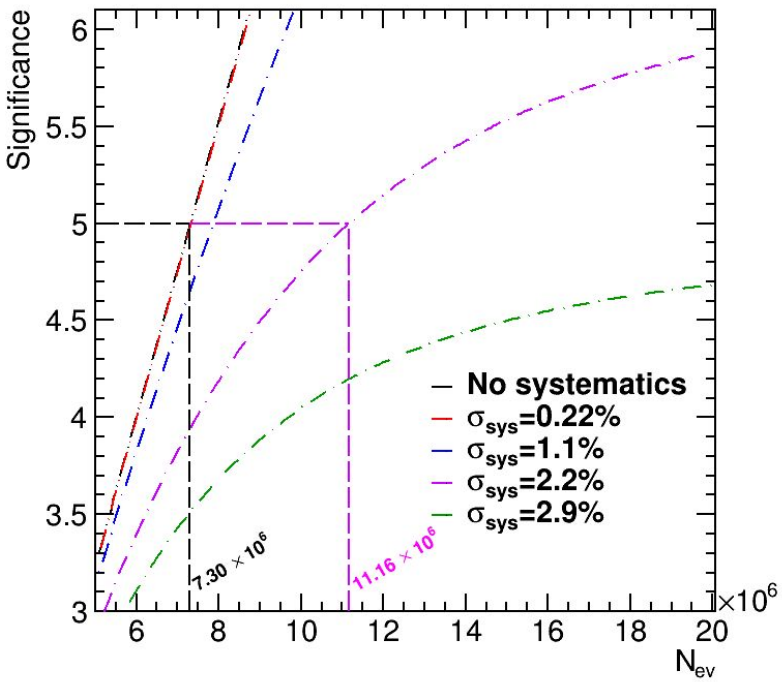
Significance of 3.2 σ



Results - Significance

- Fit of statistical uncertainties: $\frac{a}{N_{ev}^{b}}$

- CME signal: a = (4 ± 2) × 10^7 and b = 1.36 ± 0.04
- Baseline: a = (3 ± 1) × 10^4 and b = 0.91 ± 0.02
- Add systematic uncertainties



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Total systematic uncertainty [%]	N_{ev} and 1σ upper limit per isobar in 30-60% centrality for 5σ	Maximum significance
0.0	3.65M, 7.81M	-
0.22	3.66M, 7.83M	64.2
1.1	3.93M, 8.41M	12.8
2.2	5.58M, 11.9M	6.4
2.9	-	4.9

Conclusion and outlook

- Small difference in nuclear structure between Ce-136 and Xe-136
- Enhancement of elliptic flow for central events in Ce-136
- (14 ± 4)% stronger CME signal in Ce-136 compared to Xe-136 in $\Delta\gamma$
- Total systematic uncertainty needs to be smaller than 2.9%
- 5.58M to 11.9M events per isobar needed for 5 σ significance

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- Improvement of LCC in AVFD
- Isobars can be used to probe nuclear structure and initial conditions
- Use other observables for background baseline in a data-driven way

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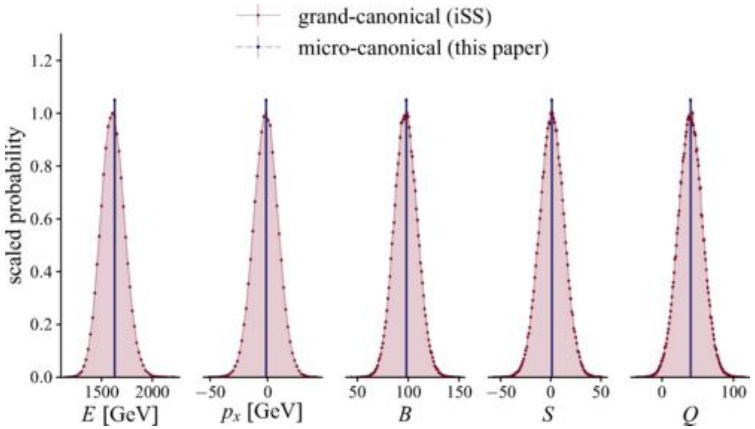
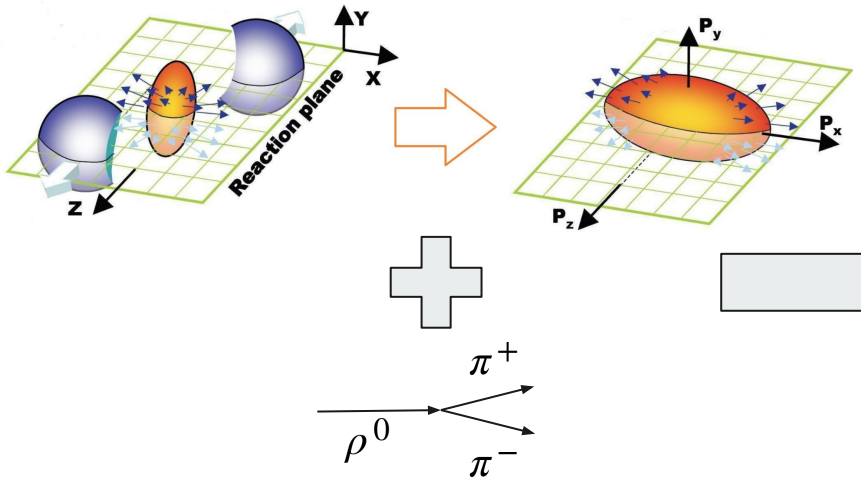


Backup

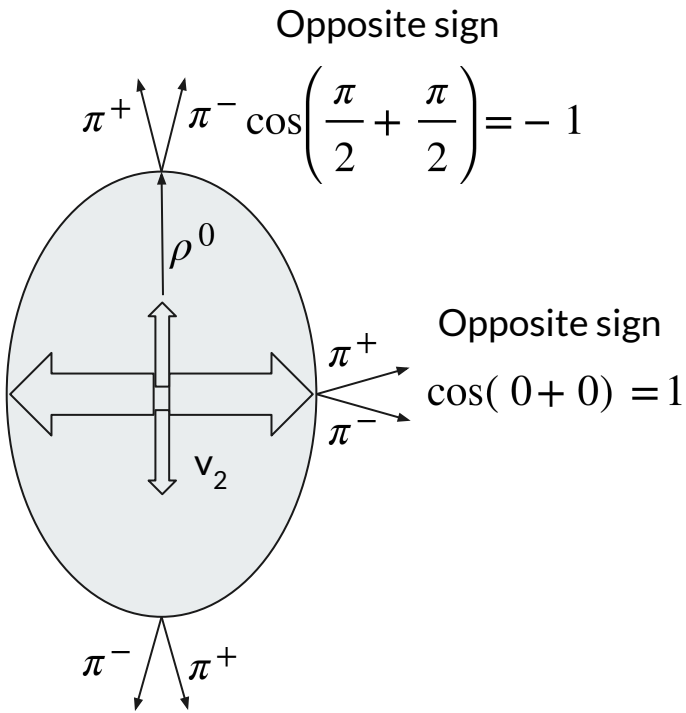
Backgrounds CME

- Fourier decomposition of φ spectrum:

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

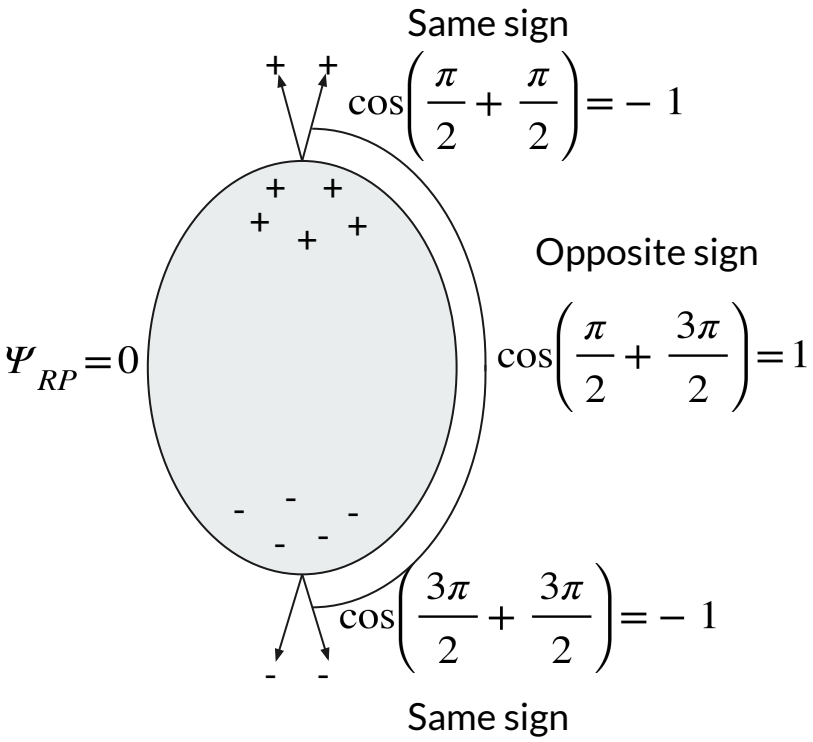


Local Charge Conservation (LCC) coupled to elliptic flow



Backgrounds and the CME signal

CME signal



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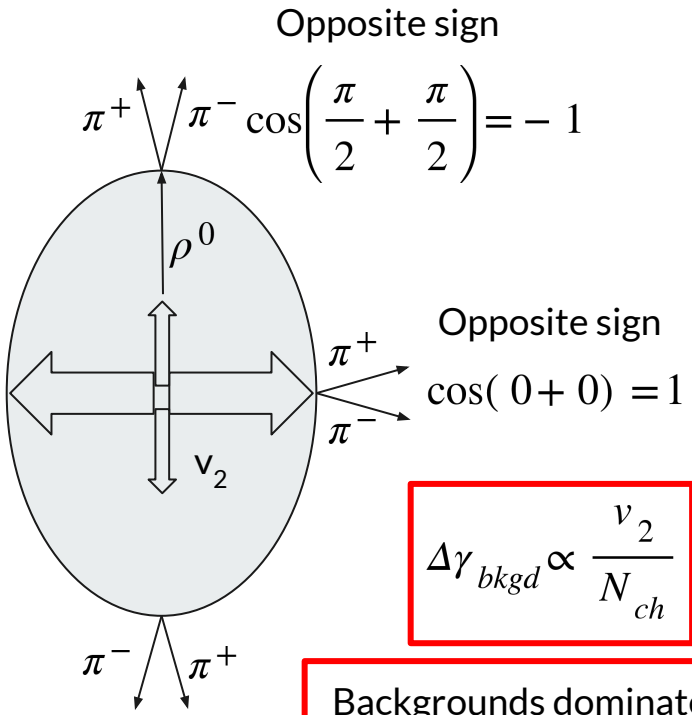
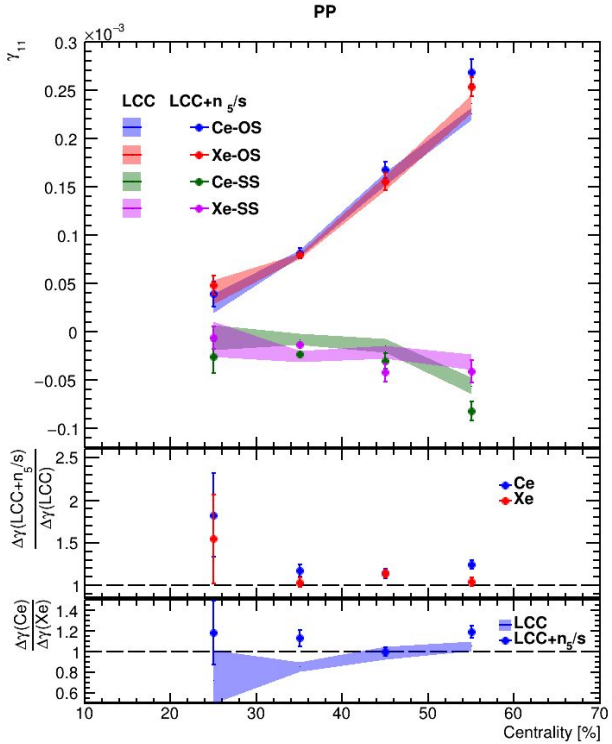
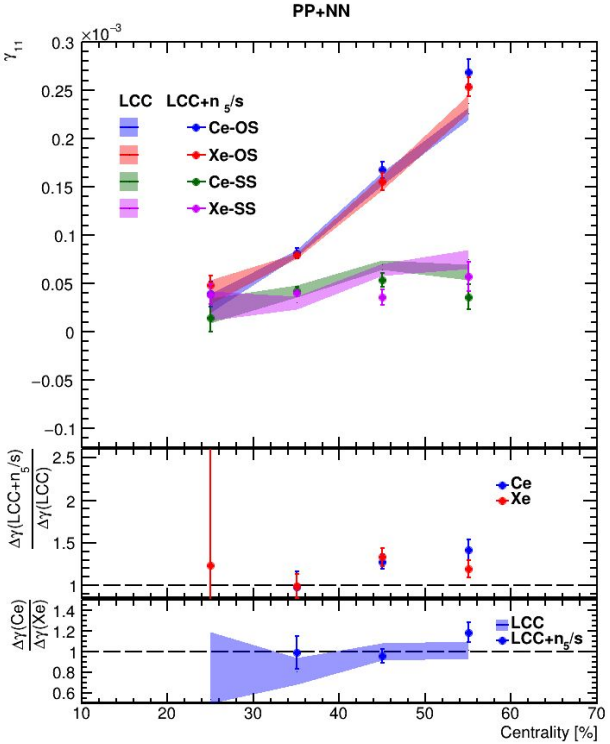


$$\Delta\gamma_{bkgd} \propto \frac{v_2}{N_{ch}}$$

Backgrounds dominate

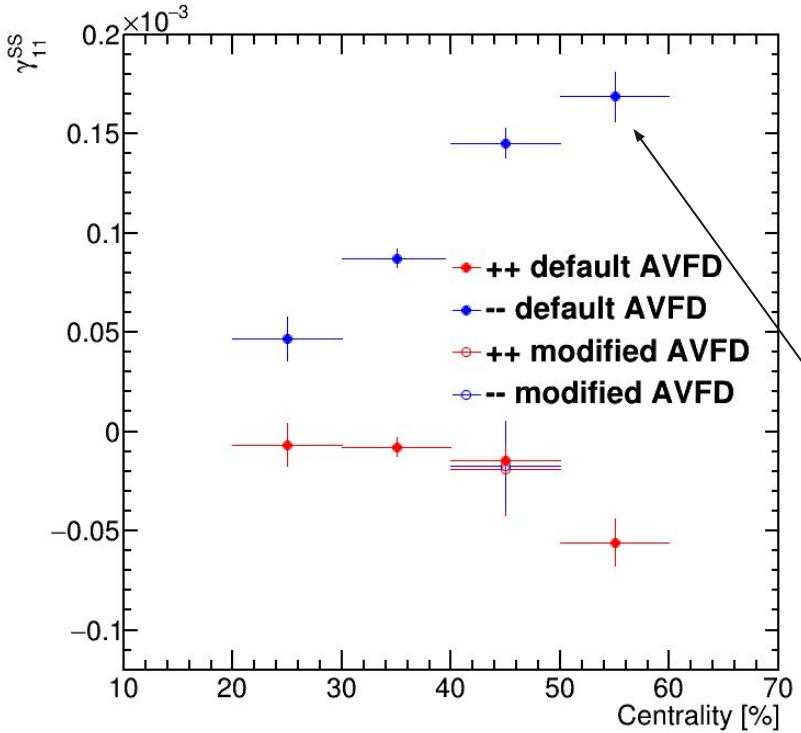
Results - PP and PP+NN SS correlations

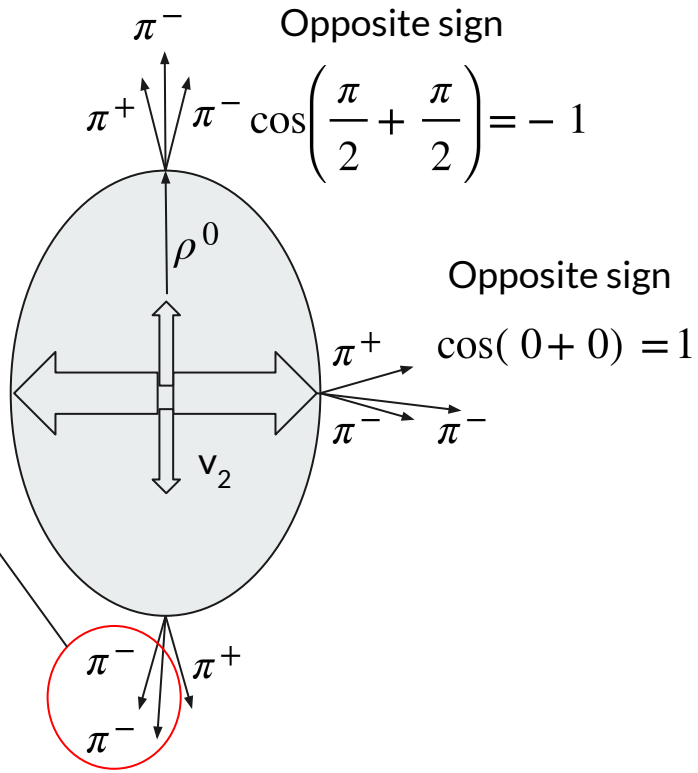




Big difference in PP and NN correlations

Results - LCC in AVFD





PP correlations describe SS correlation correctly

Simulations

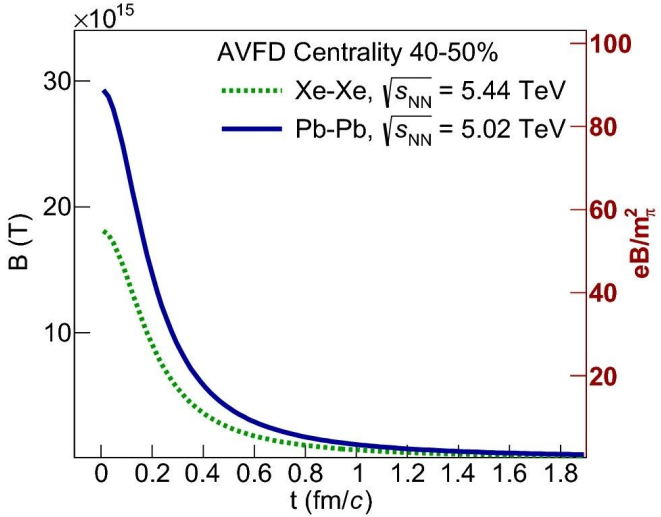
A MultiPhase Transport model (AMPT)

- Based on a transport approach
- No magnetic field or CME
- Nuclear structure with deformations

- MCGlauber (HIJING) → Lund string fragmentation → Parton Cascade (ZPC) → Quark Coalescence → Hadron Cascade (ART)

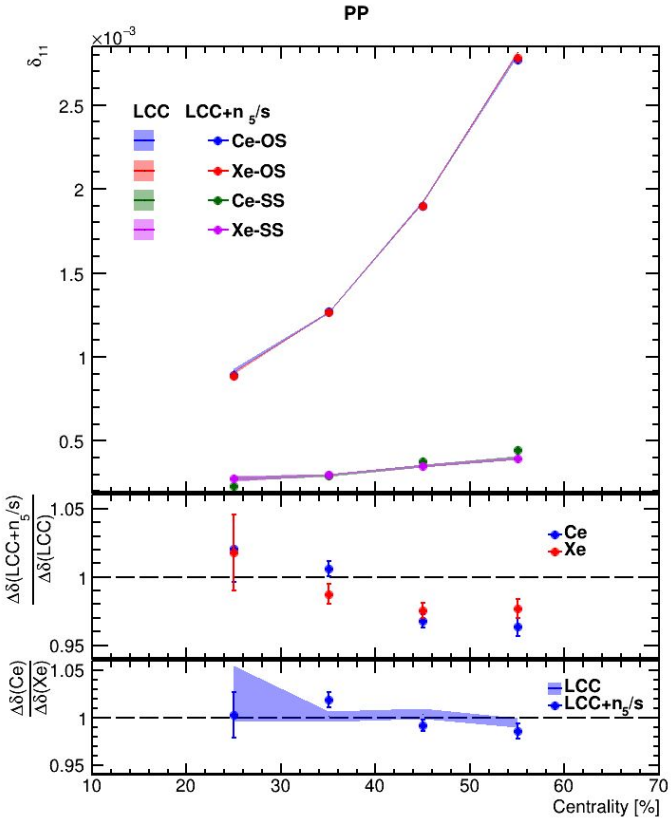
Anomalous Viscous Fluid Dynamics (AVFD)

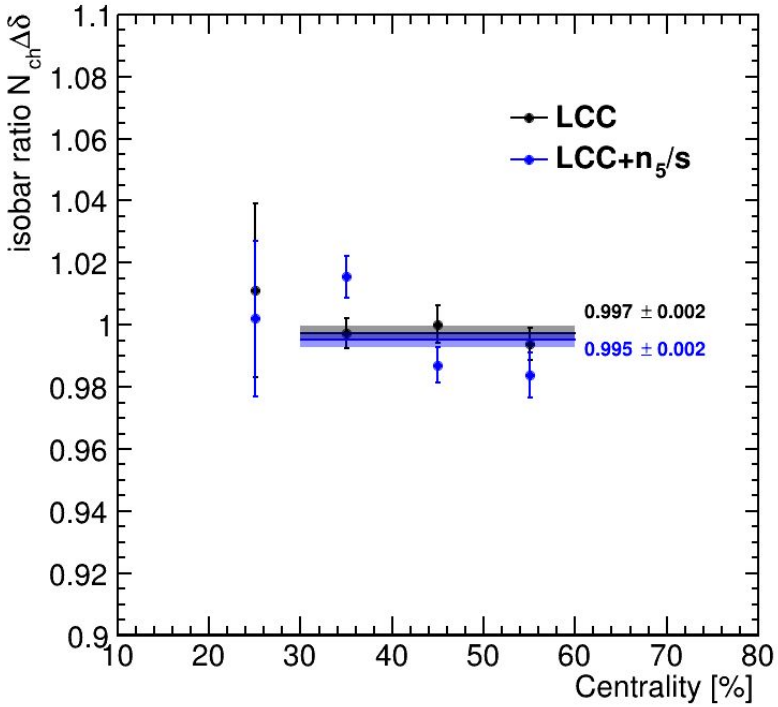
- $$B(\tau, x) = \frac{B_0}{1 + \tau^2/\tau_B^2}, \quad \tau_B = 0.2 \text{ fm/c}$$



Christakoglou, P., Qiu, S., & Staa, J. (2021). Systematic study of the chiral magnetic effect with the AVFD model at LHC energies. *The European Physical Journal C 2021 81:8*, *81*(8), 1–10.

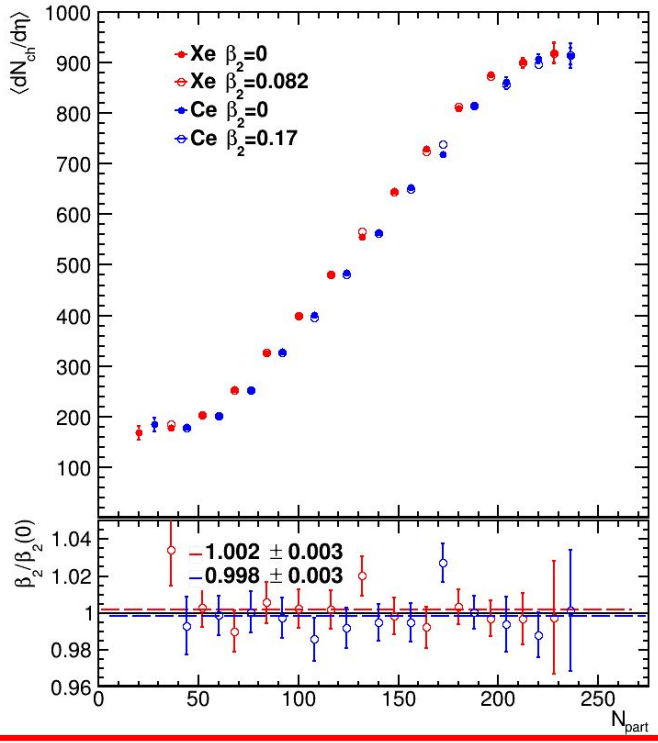
Δδ results

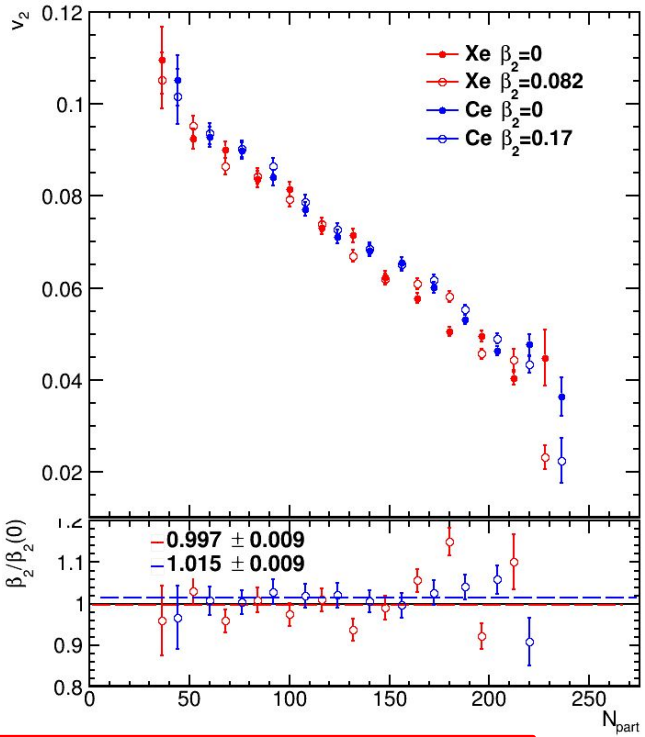

PP
δ_{11}
$\times 10^{-3}$
LCC LCC+n $_5$/s
Ce-OS
Xe-OS
Ce-SS
Xe-SS
$\frac{\Delta\delta(LCC+n_5/s)}{\Delta\delta(LCC)}$
Ce
Xe
$\frac{\Delta\delta(Ce)}{\Delta\delta(Xe)}$
LCC
LCC+n_5/s
Centrality [%]


isobar ratio $N_{ch}\Delta\delta$
LCC
LCC+n_5/s
0.997 ± 0.002
0.995 ± 0.002
Centrality [%]

Results - CME background from nuclear structure AVFD

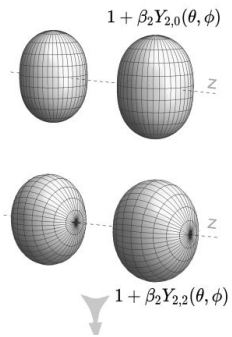
Datapoints are shifted horizontally for visibility!





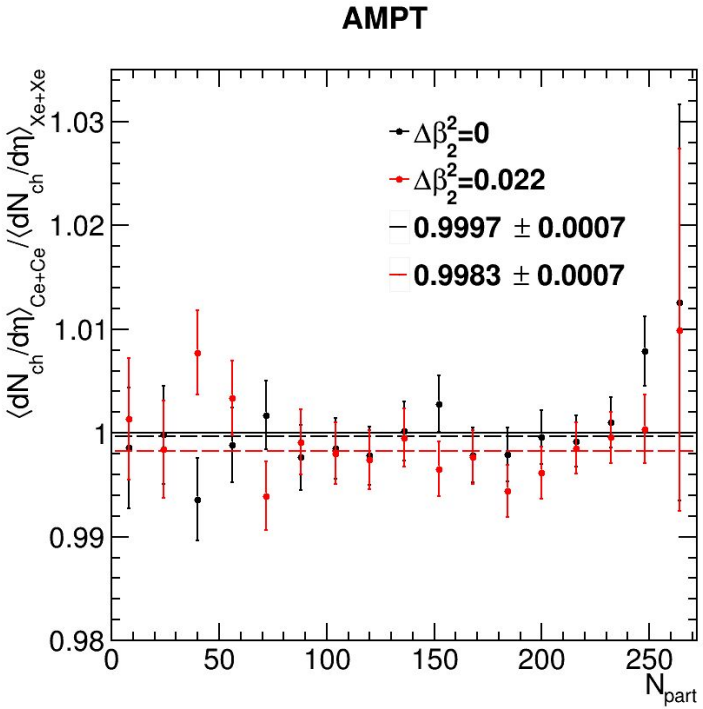
Multiplicity is not significantly changed, elliptic flow is also not significantly changed

Results - Isobar ratios in AMPT

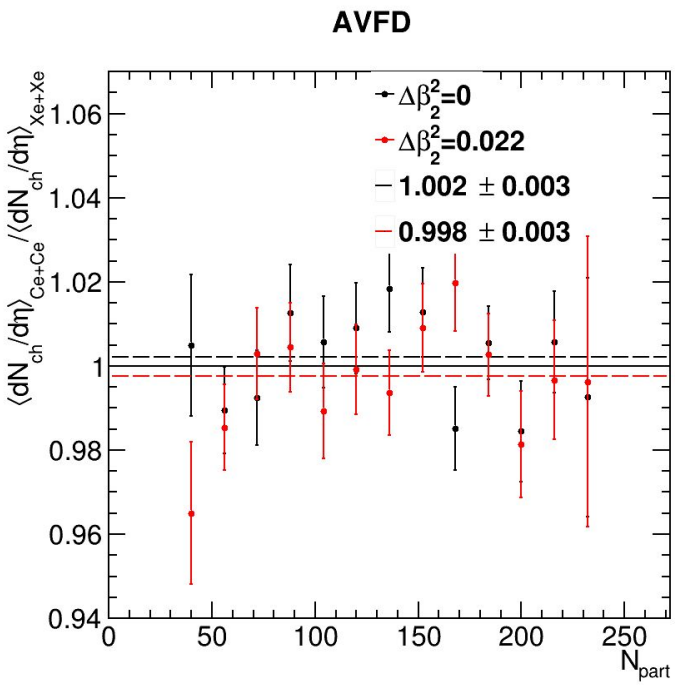


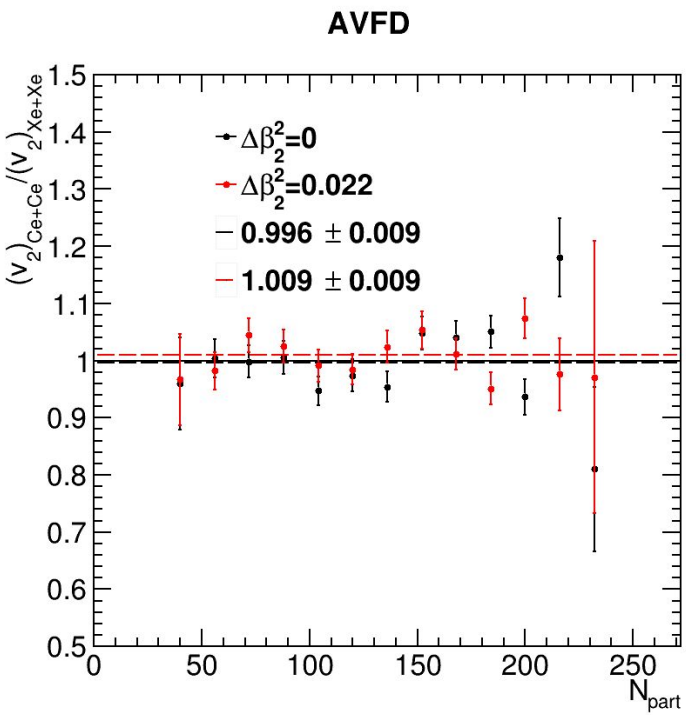
$$R_{\mathcal{O}} = \frac{\mathcal{O}_{X+X}}{\mathcal{O}_{Y+Y}} \approx 1 + c_1 \Delta\beta_2^2 + c_2 \Delta\beta_3^2 + c_3 \Delta R_0 + c_4 \Delta a$$

Multiplicity is not significantly different in Ce-136 compared to Xe-136 in both AMPT and AVFD

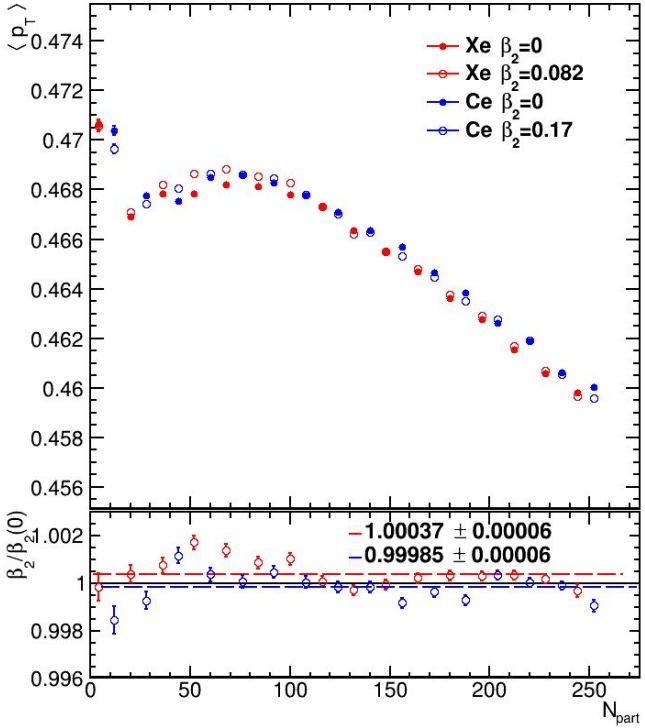


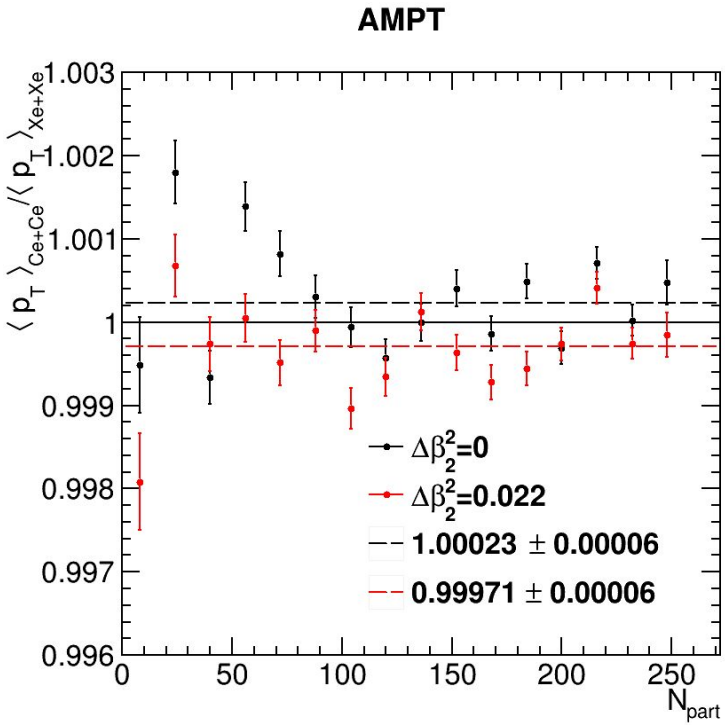
Isobar ratios AVFD



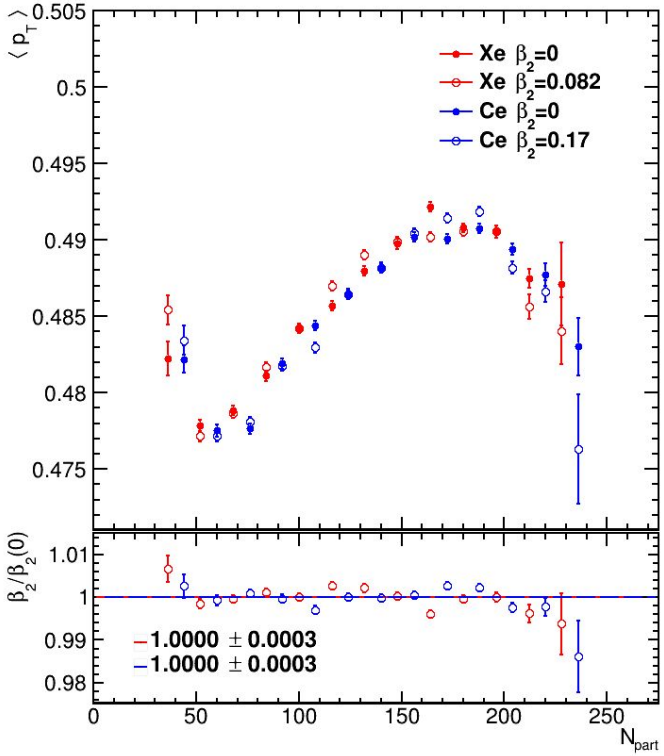


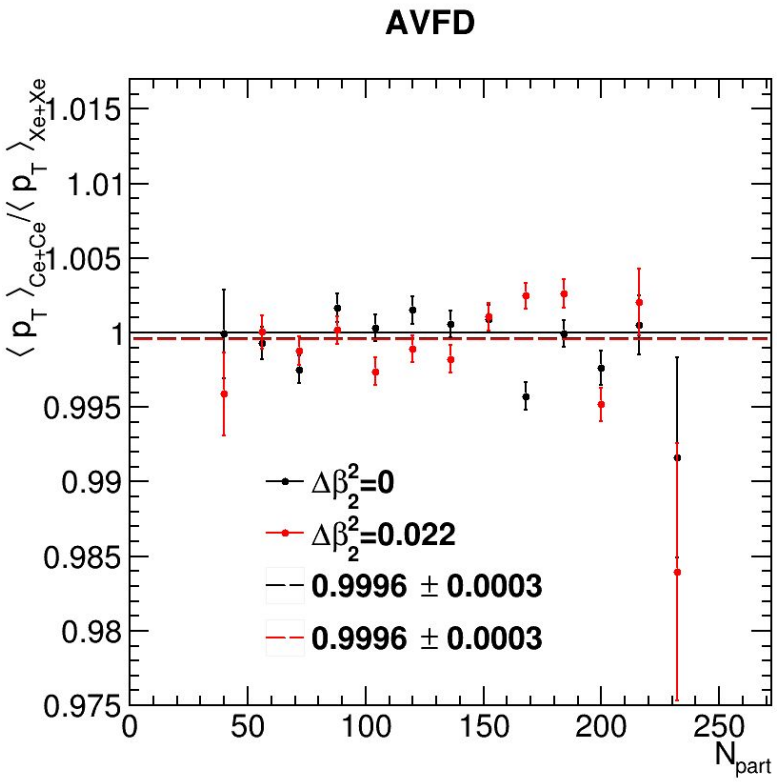
AMPT mean Pt results



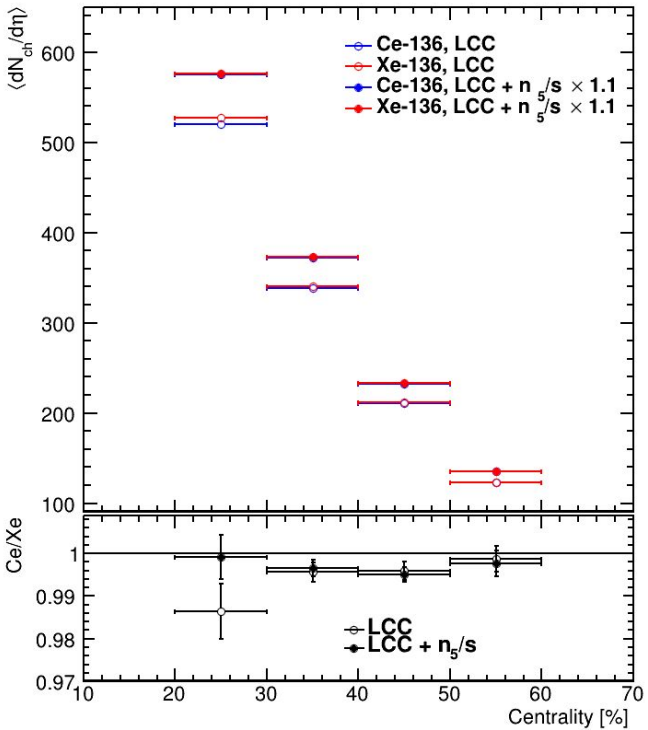


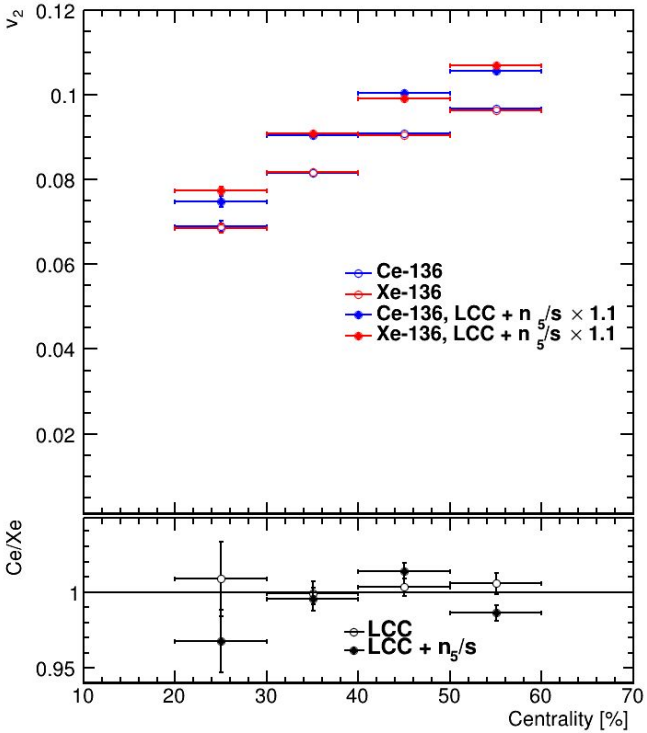
AVFD mean Pt results





AVFD multiplicity and flow



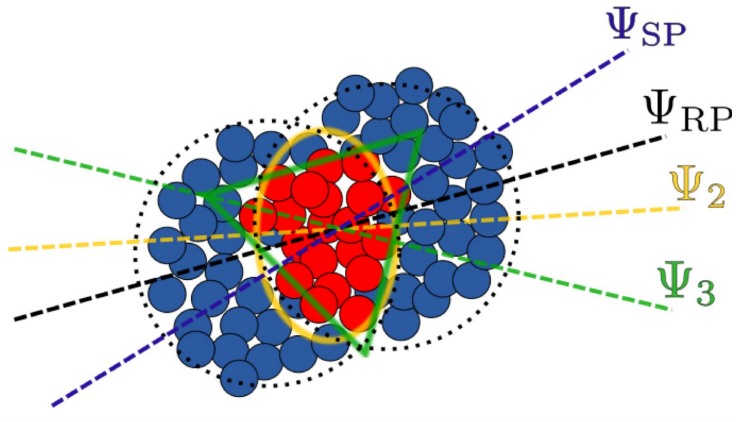


Correlators

$$
\begin{aligned}
\gamma_{11}^{\alpha,\beta} &= \langle \cos((\varphi_\alpha - \Psi_{\mathrm{RP}}) + (\varphi_\beta - \Psi_{\mathrm{RP}}))\rangle \\
&= \langle \cos(\Delta\varphi_\alpha + \Delta\varphi_\beta)\rangle \\
&= \langle \cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle - \langle \sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle \\
&= \langle v_{1,\alpha} v_{1,\beta}\rangle + \mathrm{B}_{\mathrm{in}} - \langle a_{1,\alpha} a_{1,\beta}\rangle - \mathrm{B}_{\mathrm{out}},
\end{aligned}
$$

$$
\begin{aligned}
\delta_{1}^{\alpha,\beta} &= \langle \cos((\varphi_\alpha - \varphi_\beta))\rangle \\
&= \langle \cos((\varphi_\alpha - \Psi_{\mathrm{RP}}) - (\varphi_\beta - \Psi_{\mathrm{RP}}))\rangle \\
&= \langle \cos(\Delta\varphi_\alpha - \Delta\varphi_\beta)\rangle \\
&= \langle \cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle + \langle \sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle \\
&= \langle v_{1,\alpha} v_{1,\beta}\rangle + \mathrm{B}_{\mathrm{in}} + \langle a_{1,\alpha} a_{1,\beta}\rangle + \mathrm{B}_{\mathrm{out}}.
\end{aligned}
$$

Anisotropic flow

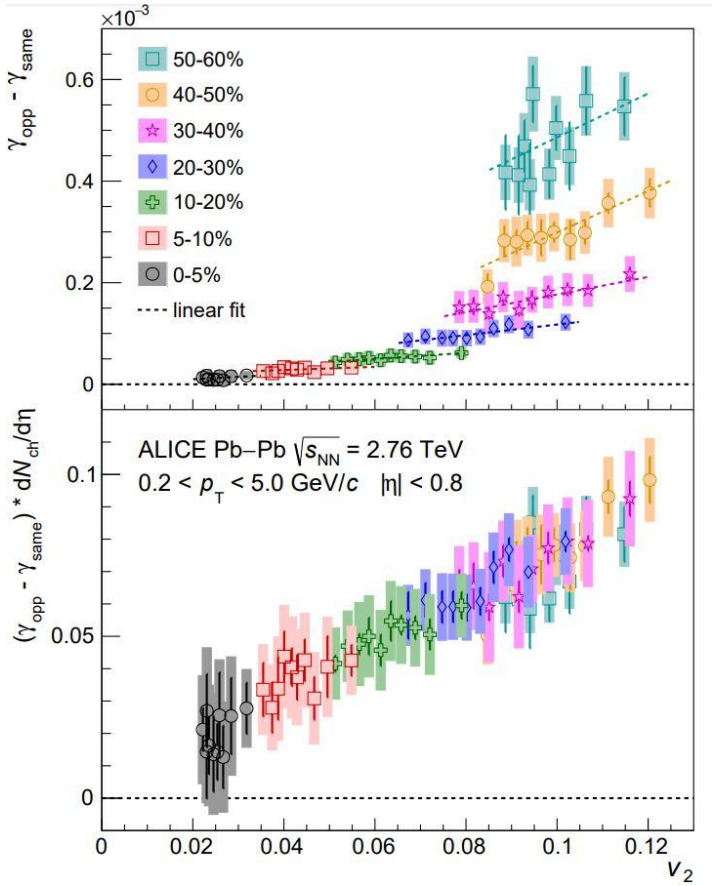


$$\frac{dN}{d\varphi_\alpha} = 1 + 2\sum_{n=1}^{\infty} a_{n,\alpha}\sin\left(n\left(\varphi - \Psi_{RP}\right)\right) + v_{n,\alpha}\cos\left(n\left(\varphi - \Psi_n\right)\right)$$

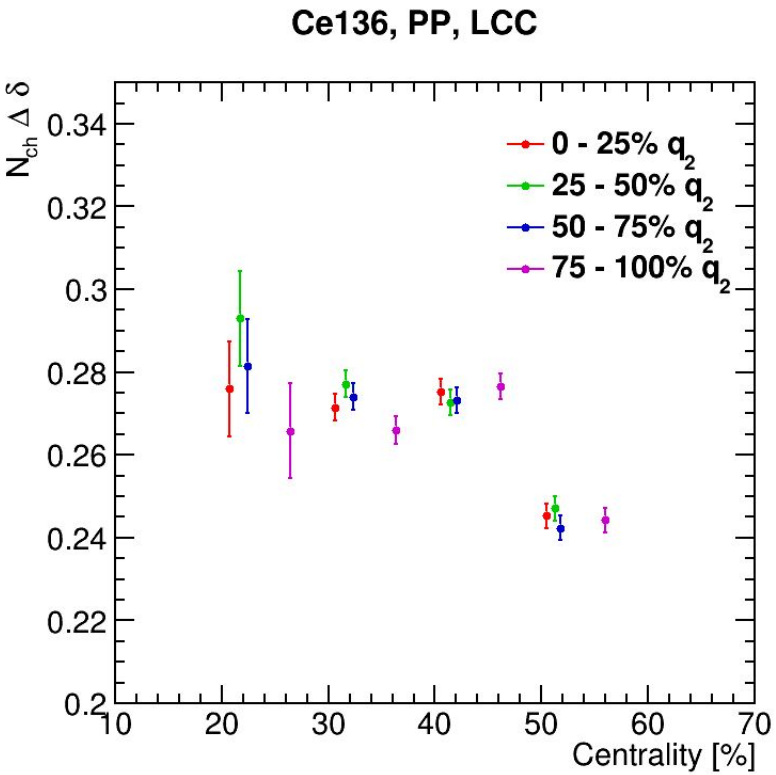
ESE

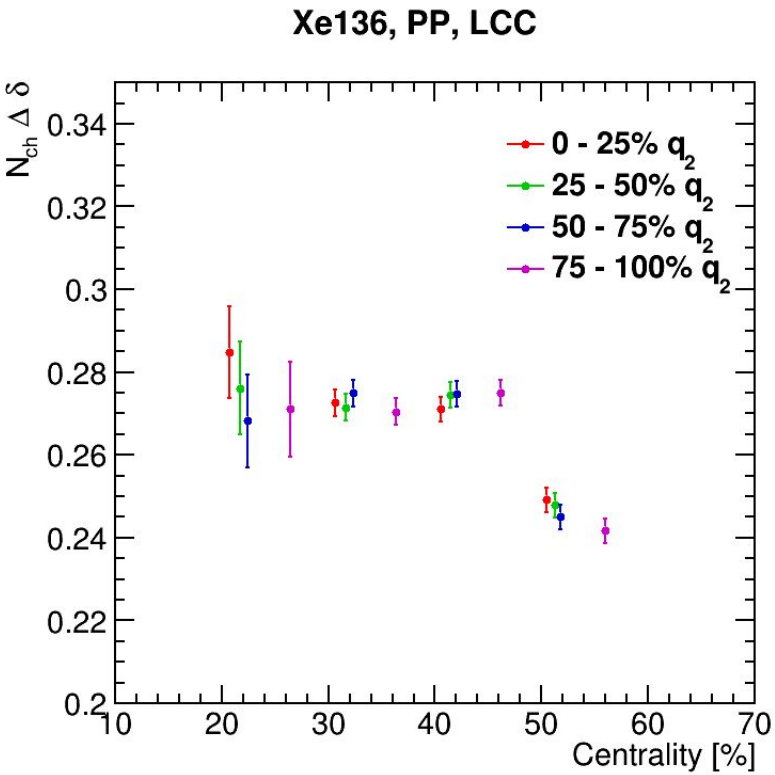
- $q_2 = \frac{|Q_2|}{\sqrt{M}}$

$$Q_{n,m} = \sum_{j=1}^{N_{\mathrm{ch}}} w_j^m e^{in\varphi_j},$$

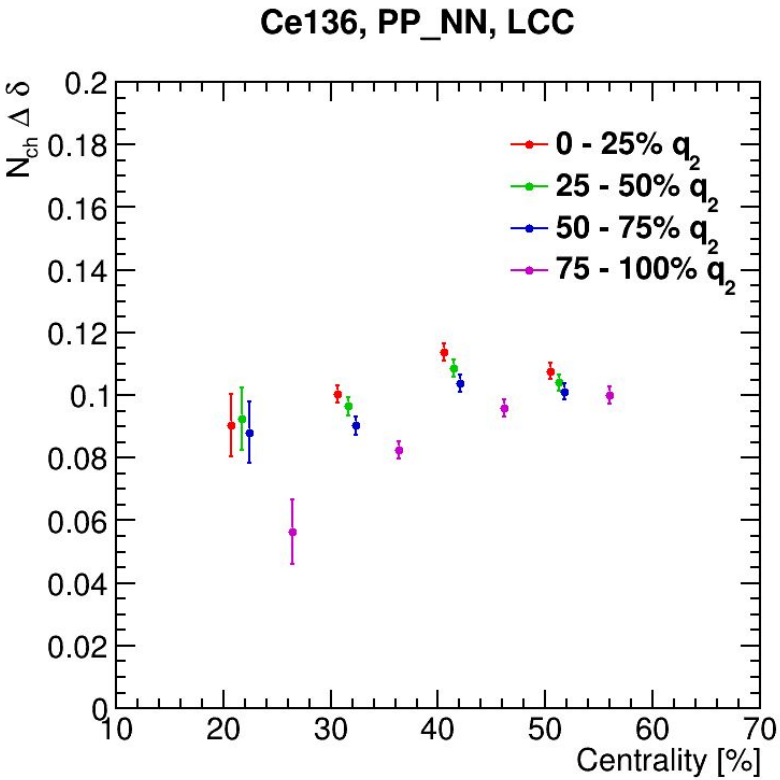


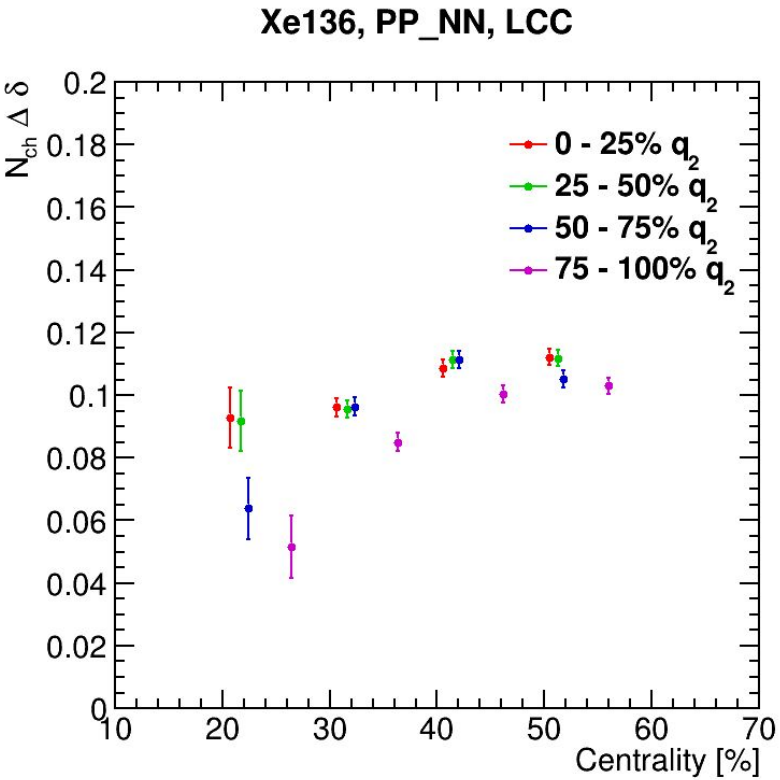
ESE - Only LCC


Ce136, PP, LCC
$N_{ch}\ \Delta\ \delta$
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
10
20
30
40
50
60
70
Centrality [%]
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2

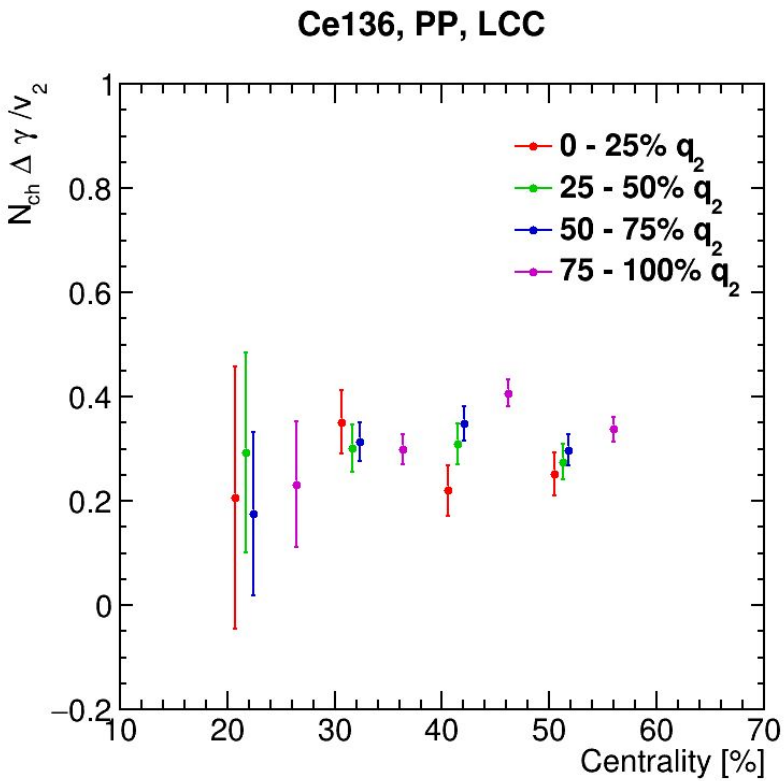

Xe136, PP, LCC
$N_{ch}\ \Delta\ \delta$
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
10
20
30
40
50
60
70
Centrality [%]
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2

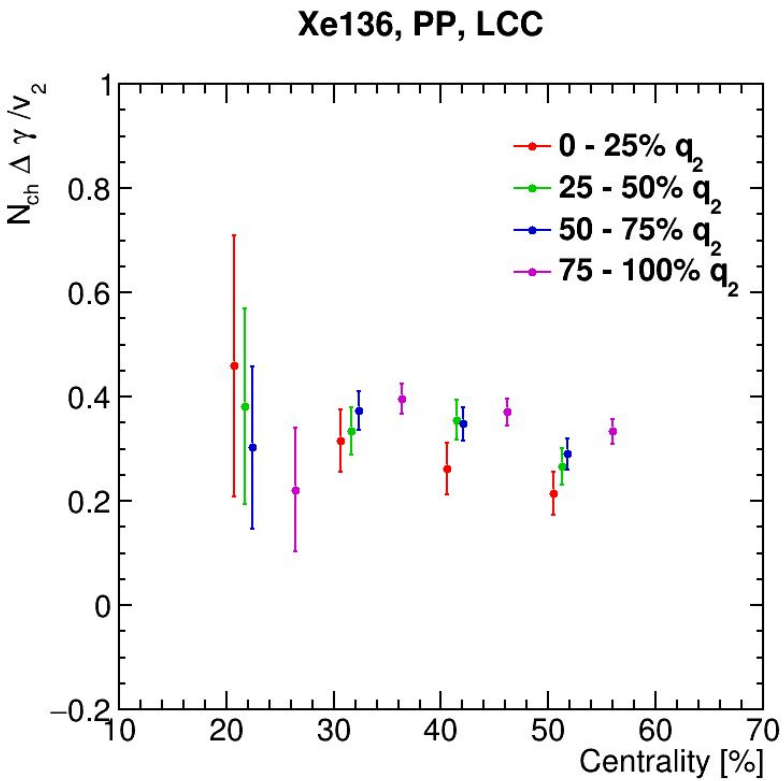
ESE - Only LCC


Ce136, PP_NN, LCC
$N_{ch}\ \Delta\ \delta$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

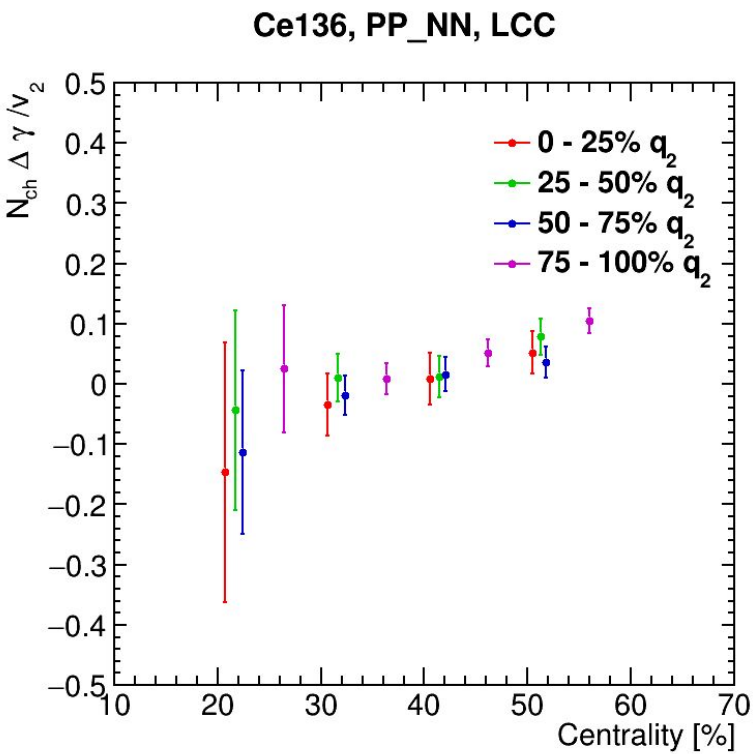

Xe136, PP_NN, LCC
$N_{ch}\ \Delta\ \delta$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

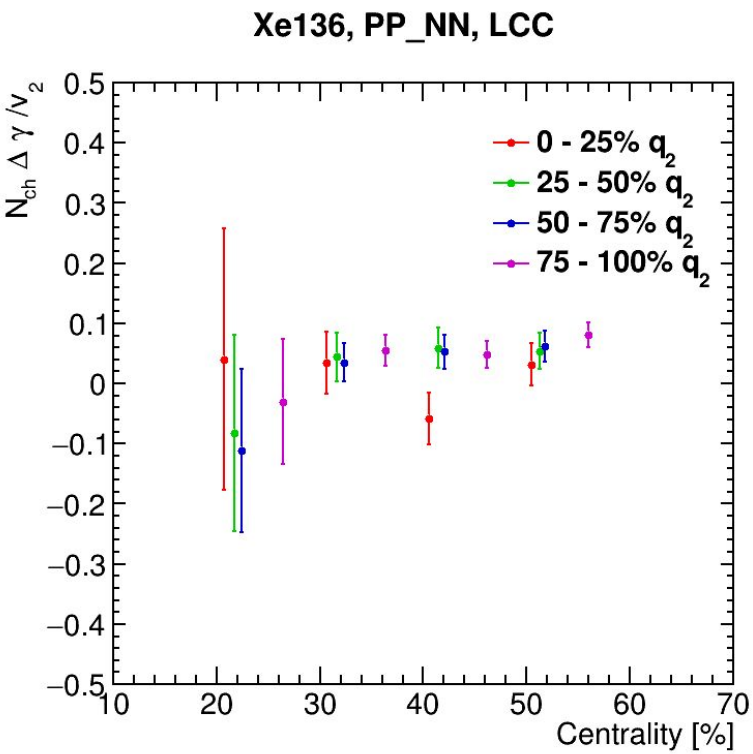
ESE - Only LCC


Ce136, PP, LCC
$N_{ch}\ \Delta\ \gamma\ /v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

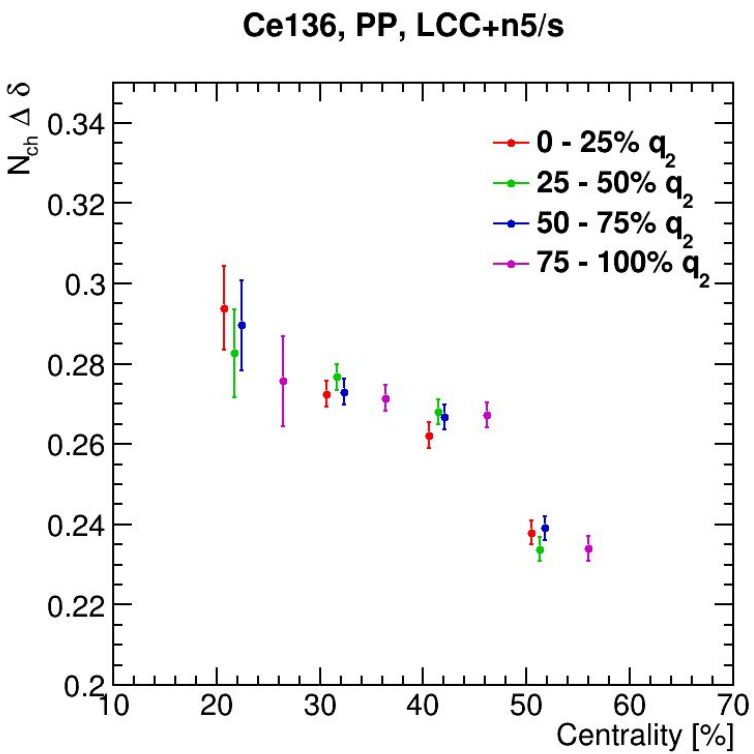

Xe136, PP, LCC
$N_{ch}\ \Delta\ \gamma\ /v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

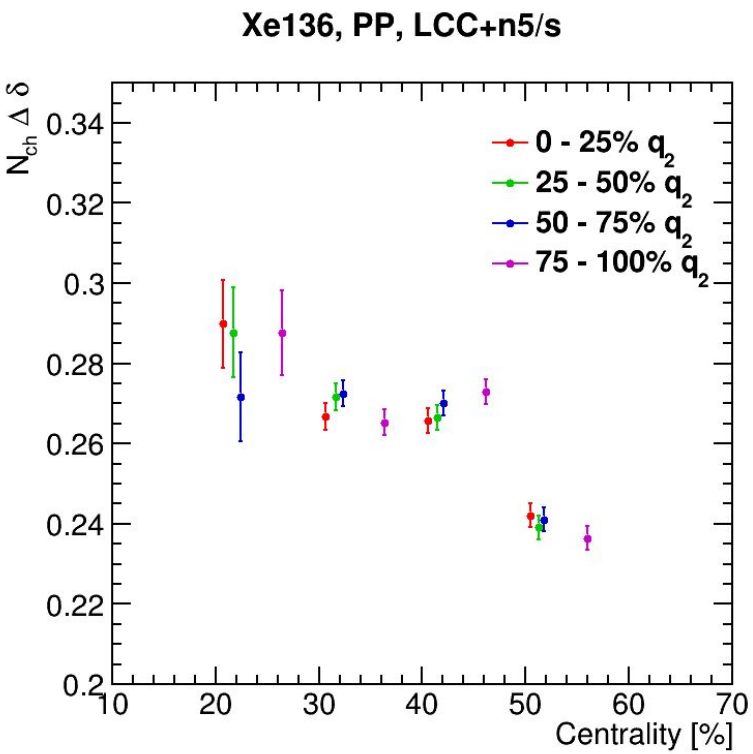
ESE - Only LCC


Ce136, PP_NN, LCC
$N_{ch}\ \Delta\gamma/v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]


Xe136, PP_NN, LCC
$N_{ch}\ \Delta\gamma/v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

ESE - LCC + n_5/s


Ce136, PP, LCC+n5/s
$N_{ch}\ \Delta\ \delta$
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
10
20
30
40
50
60
70
Centrality [%]
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2


Xe136, PP, LCC+n5/s
$N_{ch}\ \Delta\ \delta$
0.34
0.32
0.3
0.28
0.26
0.24
0.22
0.2
10
20
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40
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60
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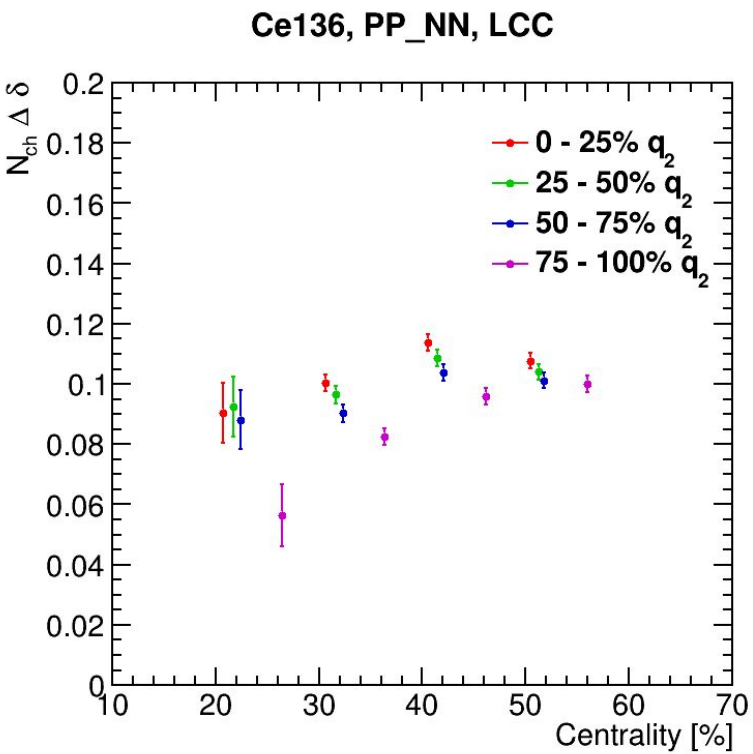
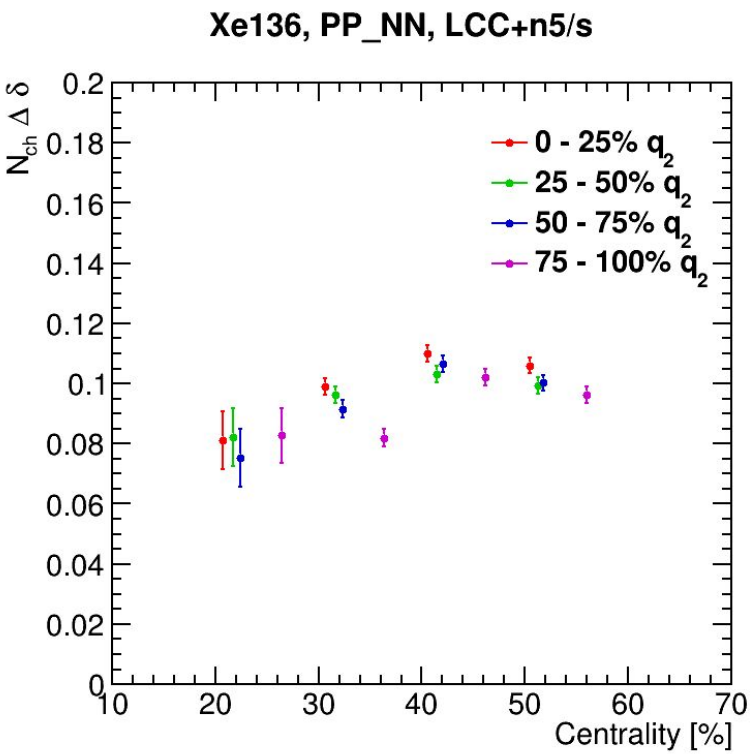
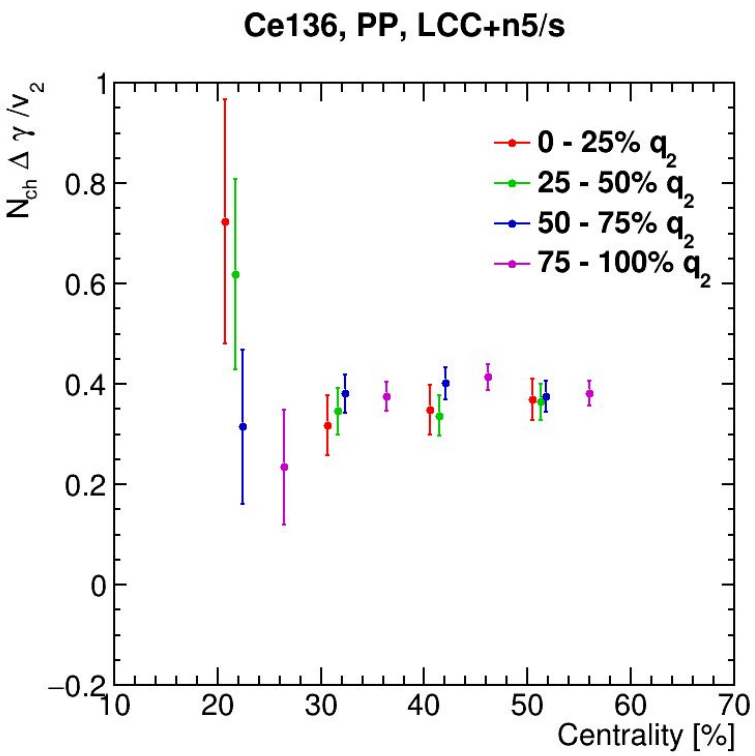
Centrality [%]
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2

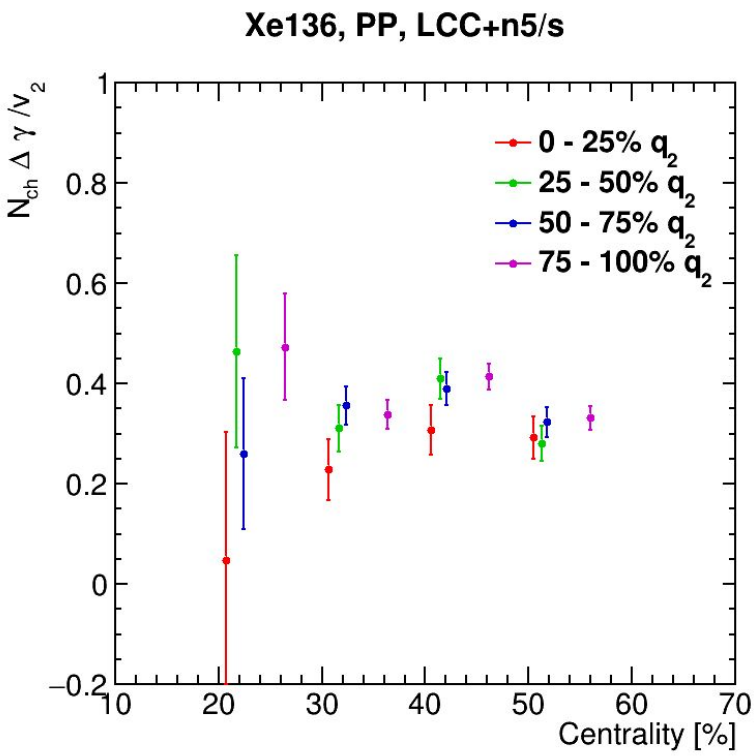
ESE - LCC + n_5/s


Ce136, PP_NN, LCC
$N_{ch}\ \Delta\ \delta$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

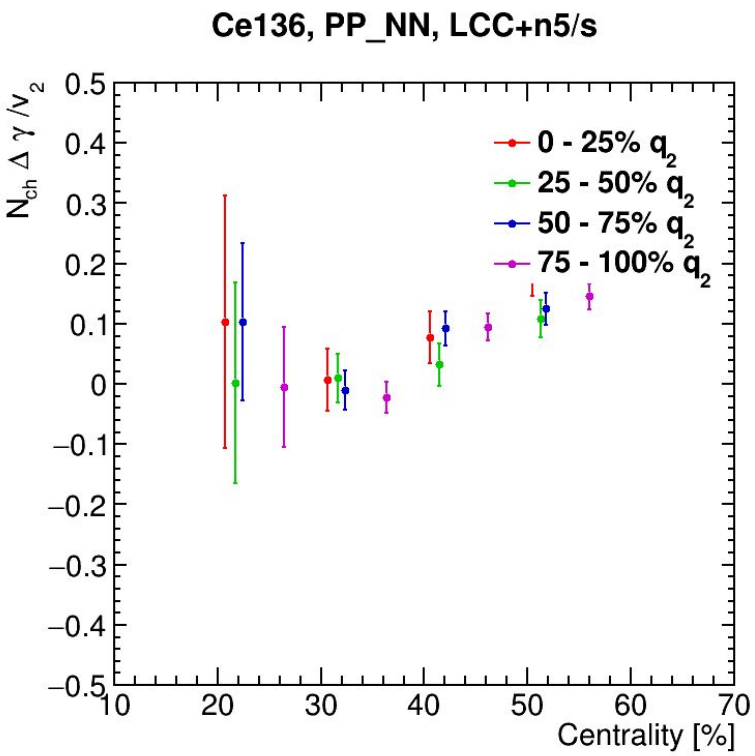

Xe136, PP_NN, LCC+n5/s
$N_{ch}\ \Delta\ \delta$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

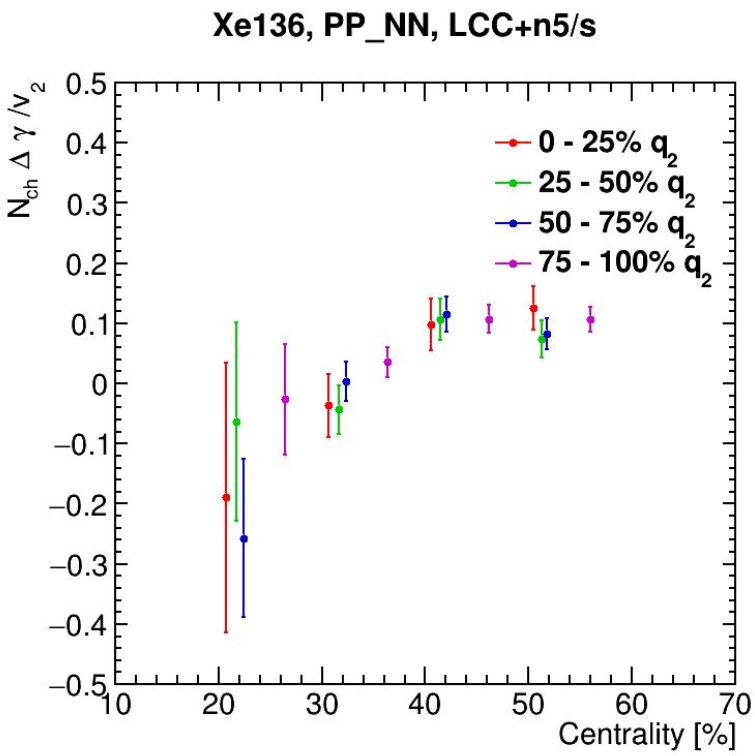
ESE - LCC + n_5/s


Ce136, PP, LCC+n5/s
$N_{ch}\ \Delta\gamma/v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]


Xe136, PP, LCC+n5/s
$N_{ch}\ \Delta\gamma/v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]

ESE - LCC + n_5/s


Ce136, PP_NN, LCC+n5/s
$N_{ch}\ \Delta\gamma/v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]


Xe136, PP_NN, LCC+n5/s
$N_{ch}\ \Delta\gamma/v_2$
0 - 25% q_2
25 - 50% q_2
50 - 75% q_2
75 - 100% q_2
Centrality [%]