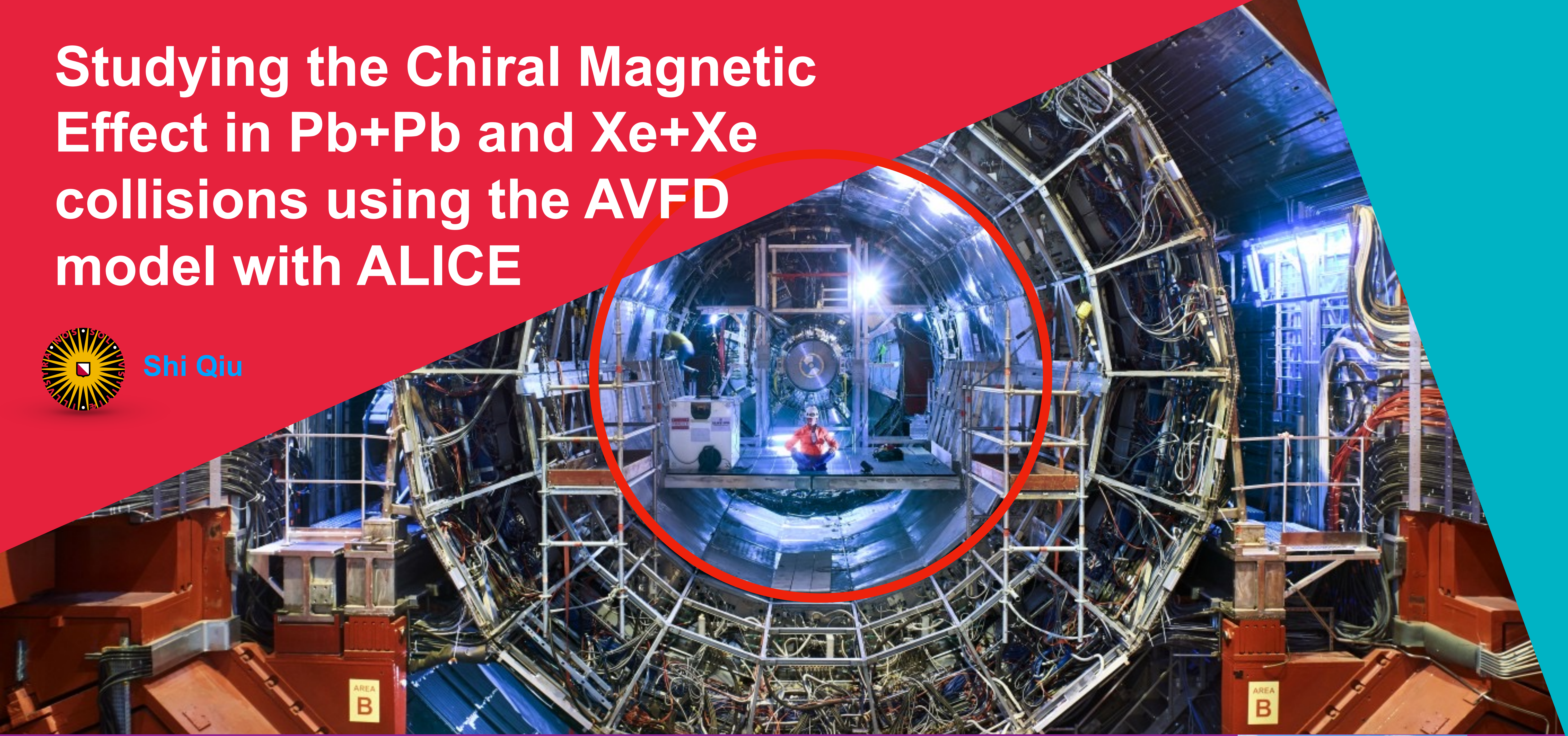
Studying the Chiral Magnetic Effect in Pb+Pb and Xe+Xe collisions using the AVFD model with ALICE



Shi Qiu

Collaborated with Panos Christakoglou, Joey Staa

The European Physical Journal C volume 81, Article number: 717 (2021)

The XVth Quark Confinement and the Hadron Spectrum Conference, *5/8/2022*

Chiral magnetic effect

θ term: energy dependent, becomes non-negligible in QGP

- The strong interaction

$$L_{QCD} = \sum_q \left(\overline{\Psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G_\mu^\alpha t_\alpha\right)_{ij}\right]\Psi_{qj} - m_q \overline{\Psi}_{qi}\Psi_{qi}\right) - \frac{1}{4} G_{\mu\nu}^\alpha G_\alpha^{\mu\nu} + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^\alpha \tilde{G}_\alpha^{\mu\nu}$$

quarks

quark-gluon interactions

$= \frac{1}{2}(E_\alpha^2 - B_\alpha^2)$

gluons

$= -\theta \frac{\alpha_s}{2\pi} \vec{E}_\alpha \cdot \vec{B}_\alpha$

't Hooft vacuum
Violating P, T

The term leads to imbalance of the densities of left-handed and right-handed chiral fermions

- CME: The generation of electric current along an external magnetic field induced by chirality imbalance.

Nikhef

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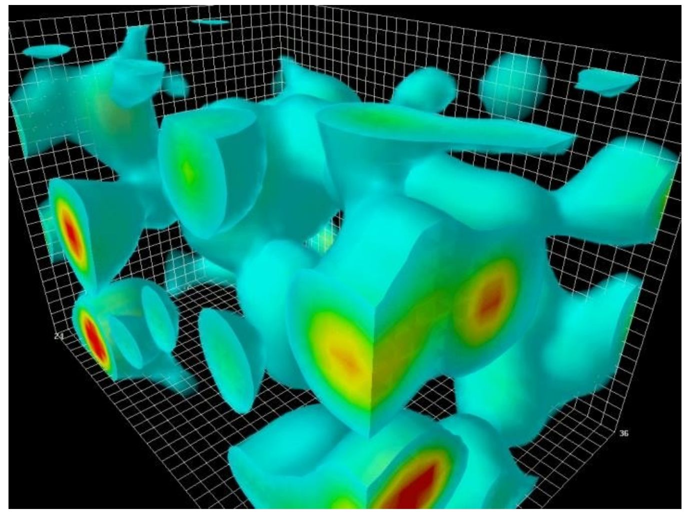
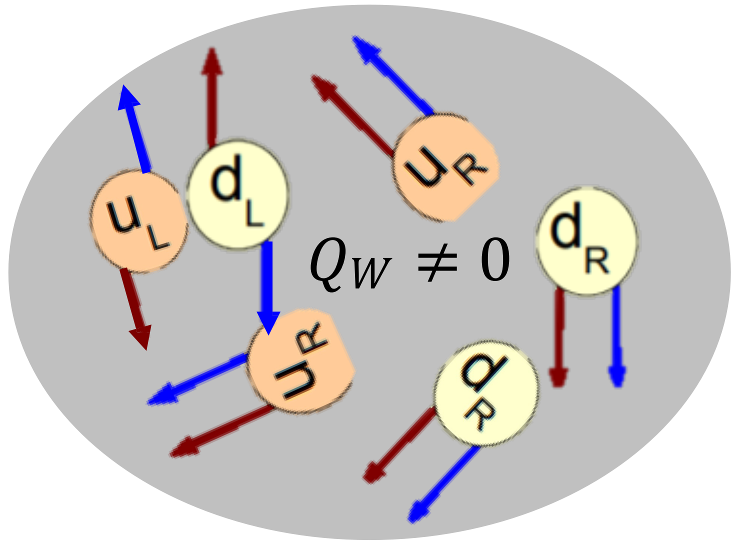
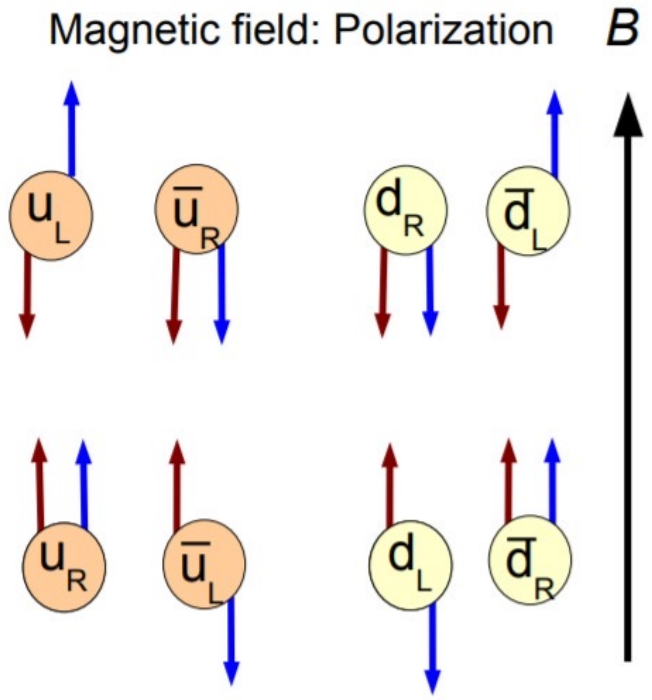


Non-trivial QCD vacuum structure



Chirality imbalance



Under B field, LH quarks have $\vec{p}$ oposite to RH quarks

Chiral magnetic effect

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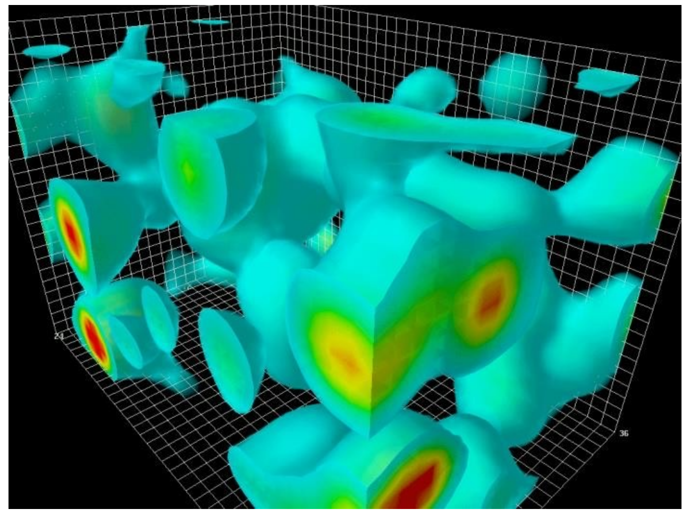
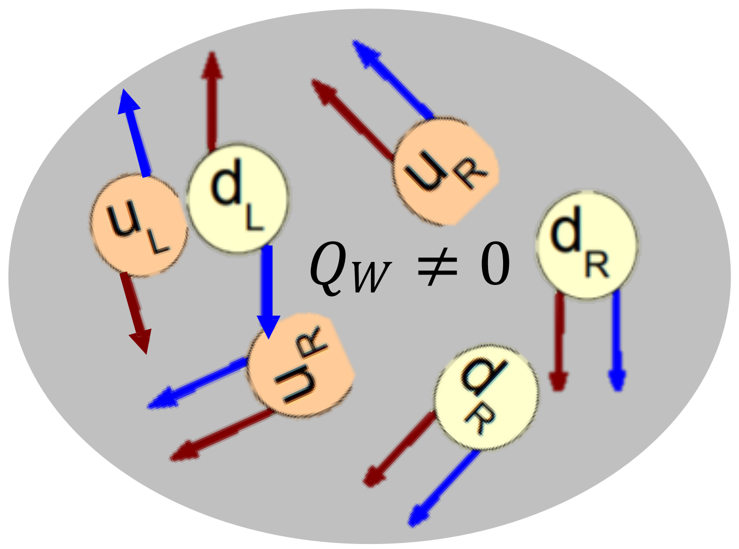
Violating P, T

The term leads to imbalance of the densities of left-handed and right-handed chiral fermions

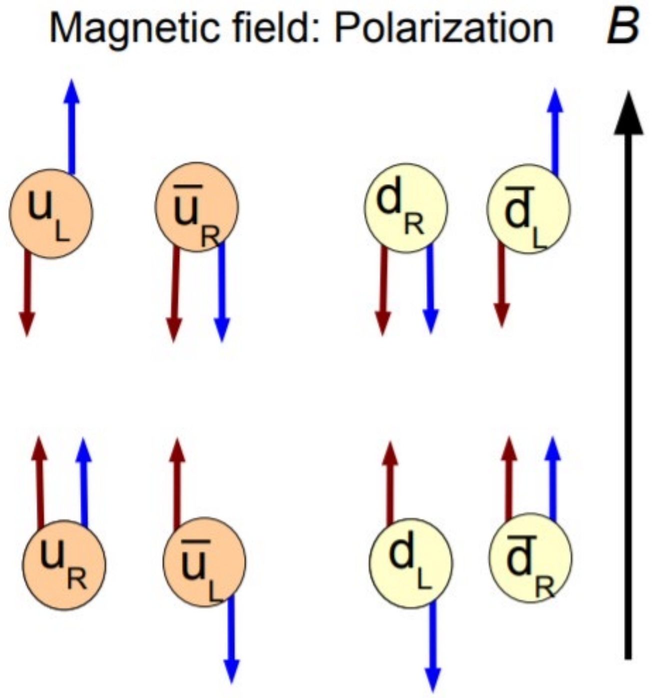
- CME: The generation of electric current along an external magnetic field induced by chirality imbalance.
- Discovery of the CME implies: chiral symmetry restoration, local P/CP violation that may solve the strong CP problem



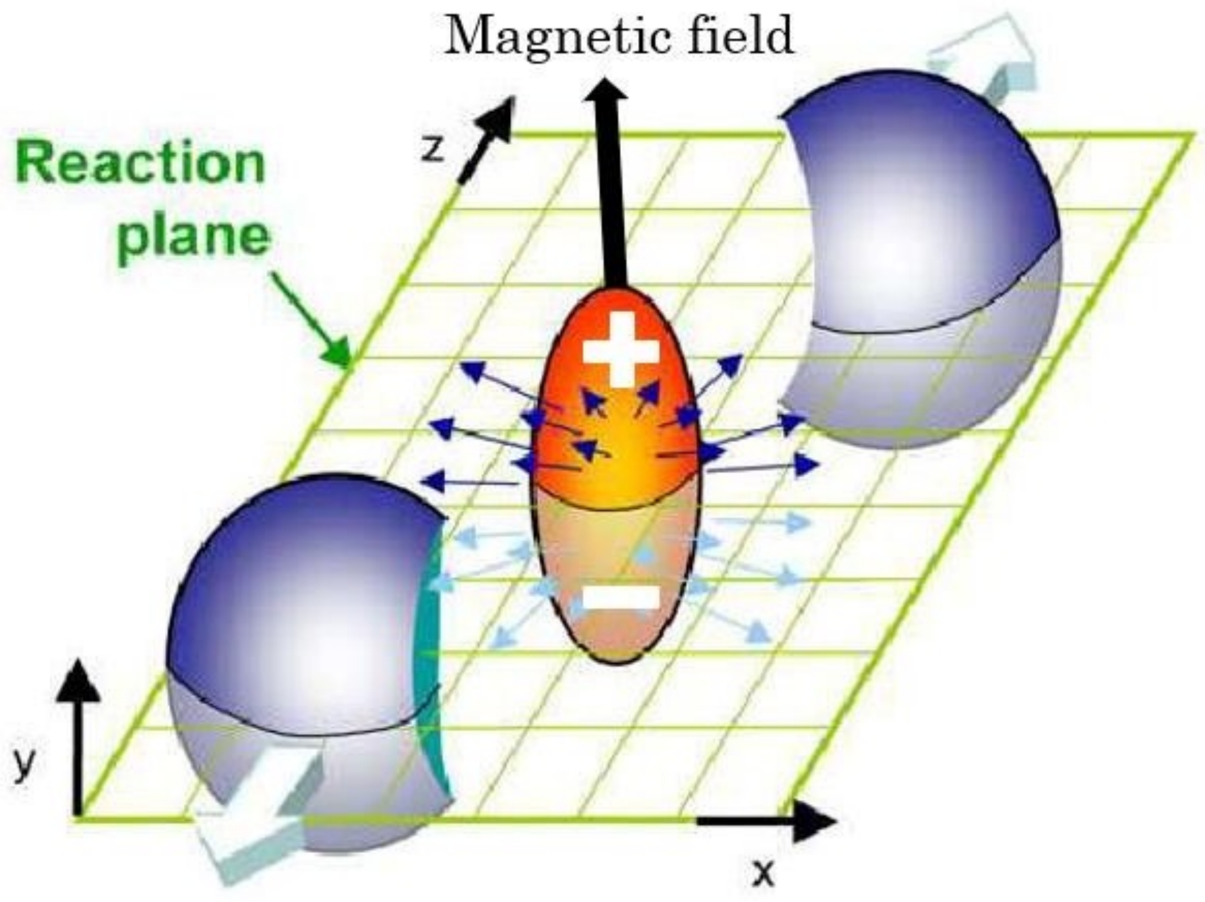
Non-trivial QCD vacuum structure



Chirality imbalance



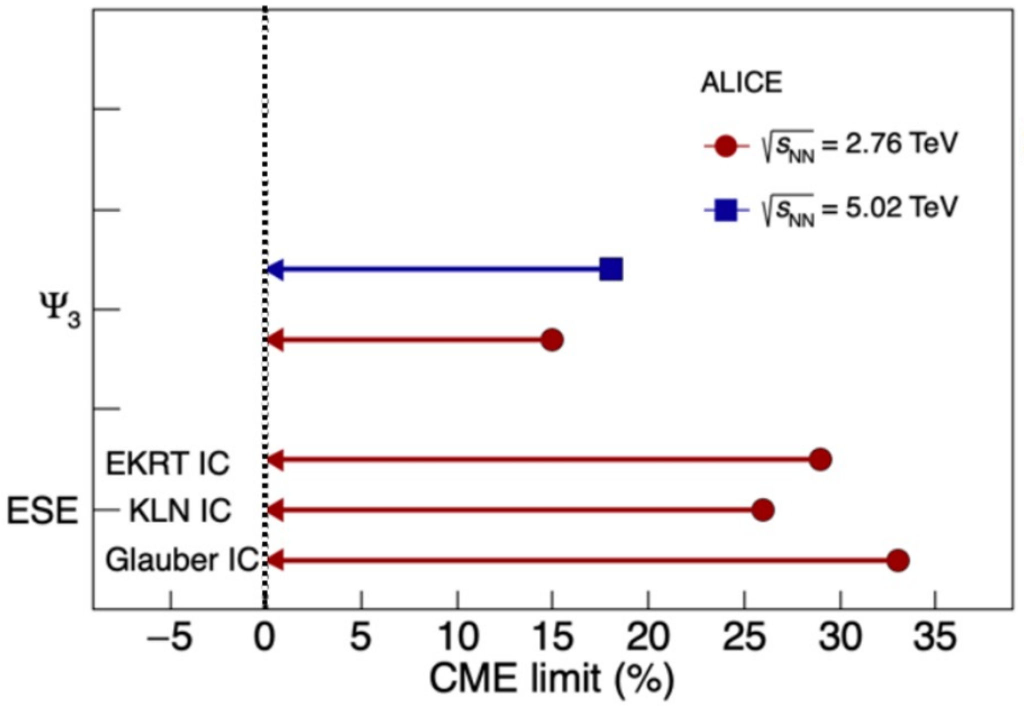
Under B field, LH quarks have $\vec{p}$ oposite to RH quarks



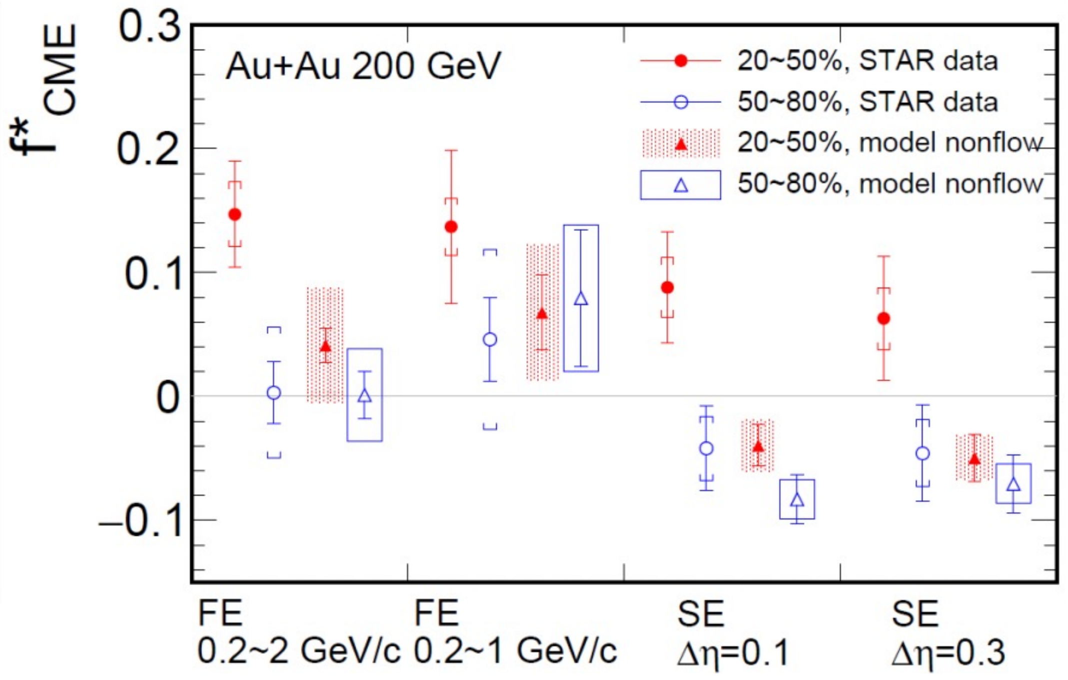
Current along B field

Aim of this study

- ALICE and STAR have both done extensive searches for CME

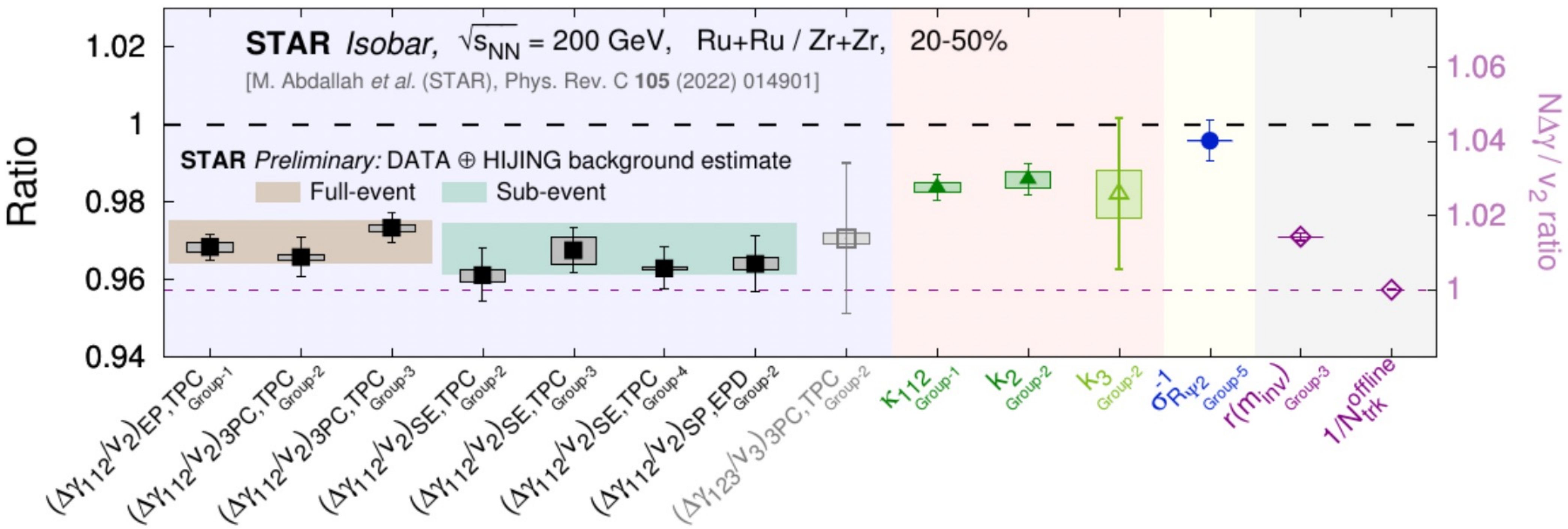


fCME upper limit for Mix Harmonic and ESE method at ALICE
[1] Qiu, Shi (ALICE): Track D Monday 16:10-16:40



fCME for Au+Au shows some hint of
[1] STAR, PRL 128 (2022) 092301
[2] Feng, FW, et al., PRC 105 (2022) 024913

Ratio>background estimate => CME

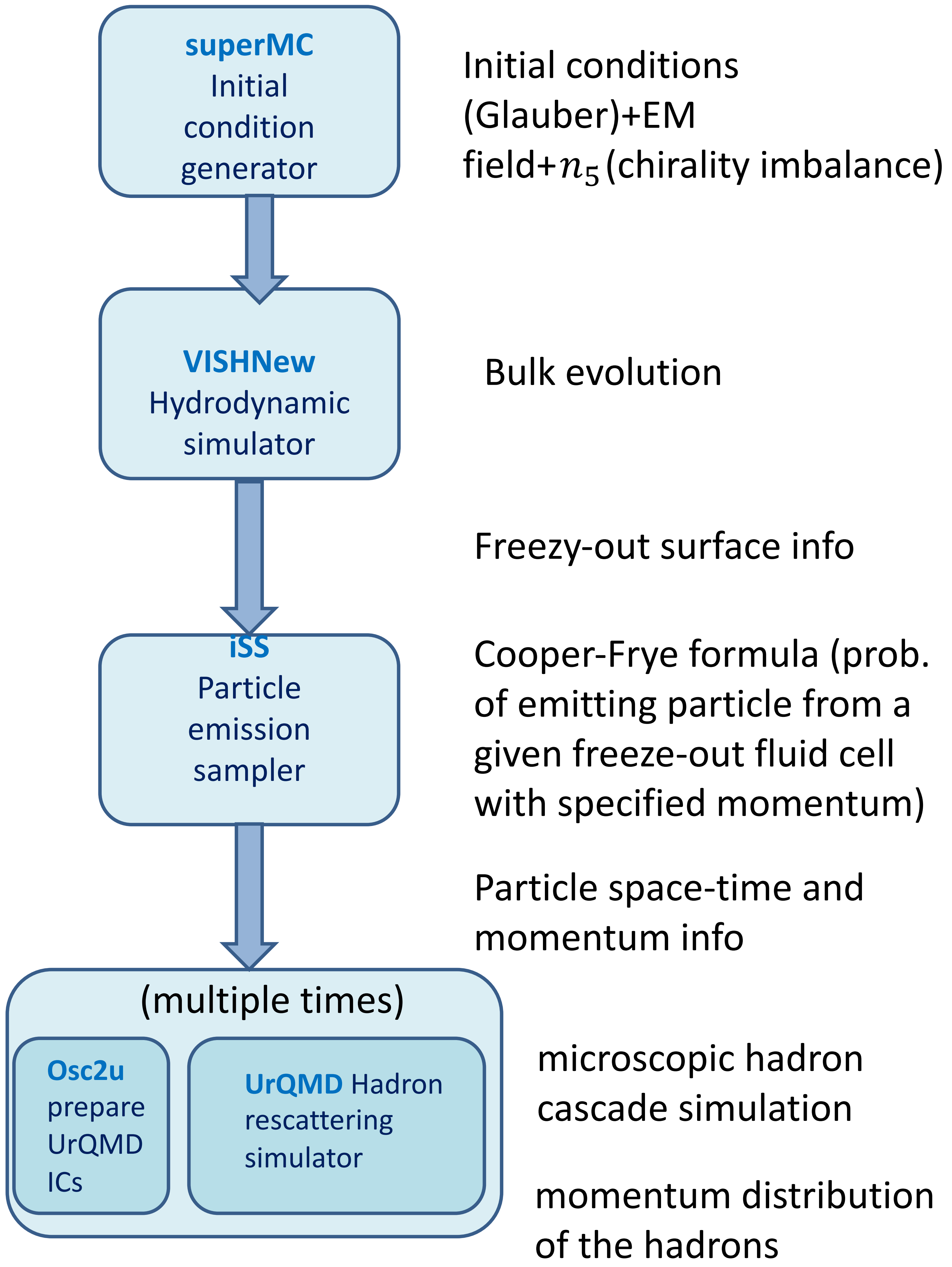


Isobar run shows measurements consistent with background
[1] STAR arXiv:2109.00131
[2] Feng, FW, et al., PRC 105 (2022) 024913

- The goal of this study is to extract the values that control the CME signal and the background in the AVFD model
- The parameter that dictates the CME signal is the value of the **axial current density** (n_5/s)
- The parameter that governs the background is the **local charge conservation**, which is the amount of positive and negative charged partners emitted from the same fluid element relative to the total multiplicity of the event

Anomalous Viscous Fluid Dynamics model (AVFD) [1,2]

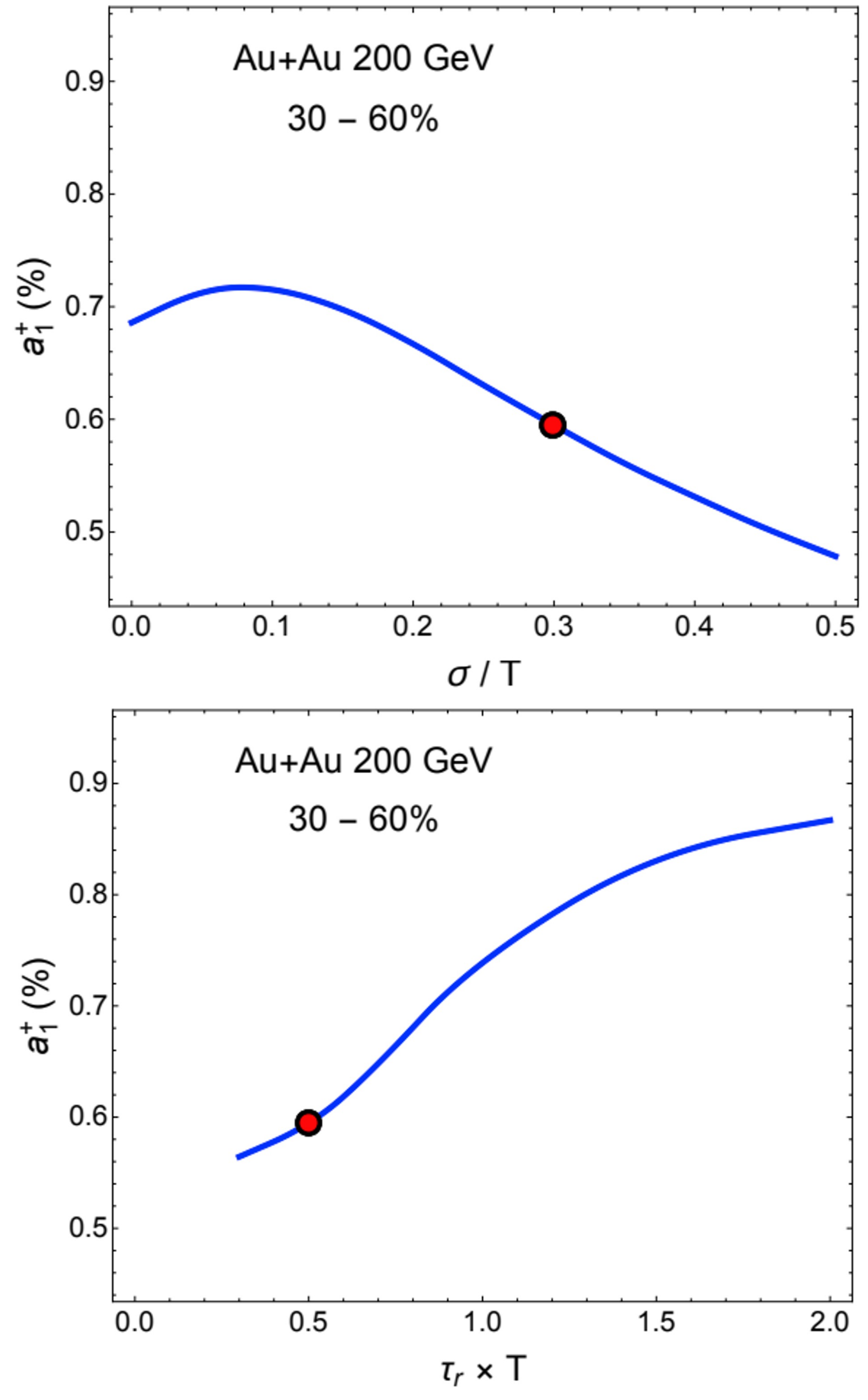
- Describe the transport of the light fermions in the hydrodynamic framework and to account for anomaly.
- Simulation process in AVFD
  - **SuperMC:** generates fluctuating initial conditions using the Monte-Carlo Glauber model or MCKLN model
  - **VISHNew:** solves viscous hydrodynamic equations with given initial conditions from SuperMC
    - CME
    - $J_\chi^\mu = n_\chi u^\mu + \nu_\chi^\mu + \boxed{\chi \frac{N_c Q_f}{4\pi^2} \mu_\chi B^\mu}$, $\chi = \pm$ (RH/LH Chirality)
  - **ISS:** generate sets of momenta and positions for actual particles emitted at the end of the hydrodynamic simulation
  - **Osu2u:** synchronize all particles by propagating particles backwards in time to prepare for UrQMD
  - **UrQMD:** hadron cascade simulation



[1] Annals of Physics 394 (2018) 50-72
[2] Chinese Physics C Vol. 42, No. 1 (2018) 011001

Anomalous Viscous Fluid Dynamics model (AVFD)

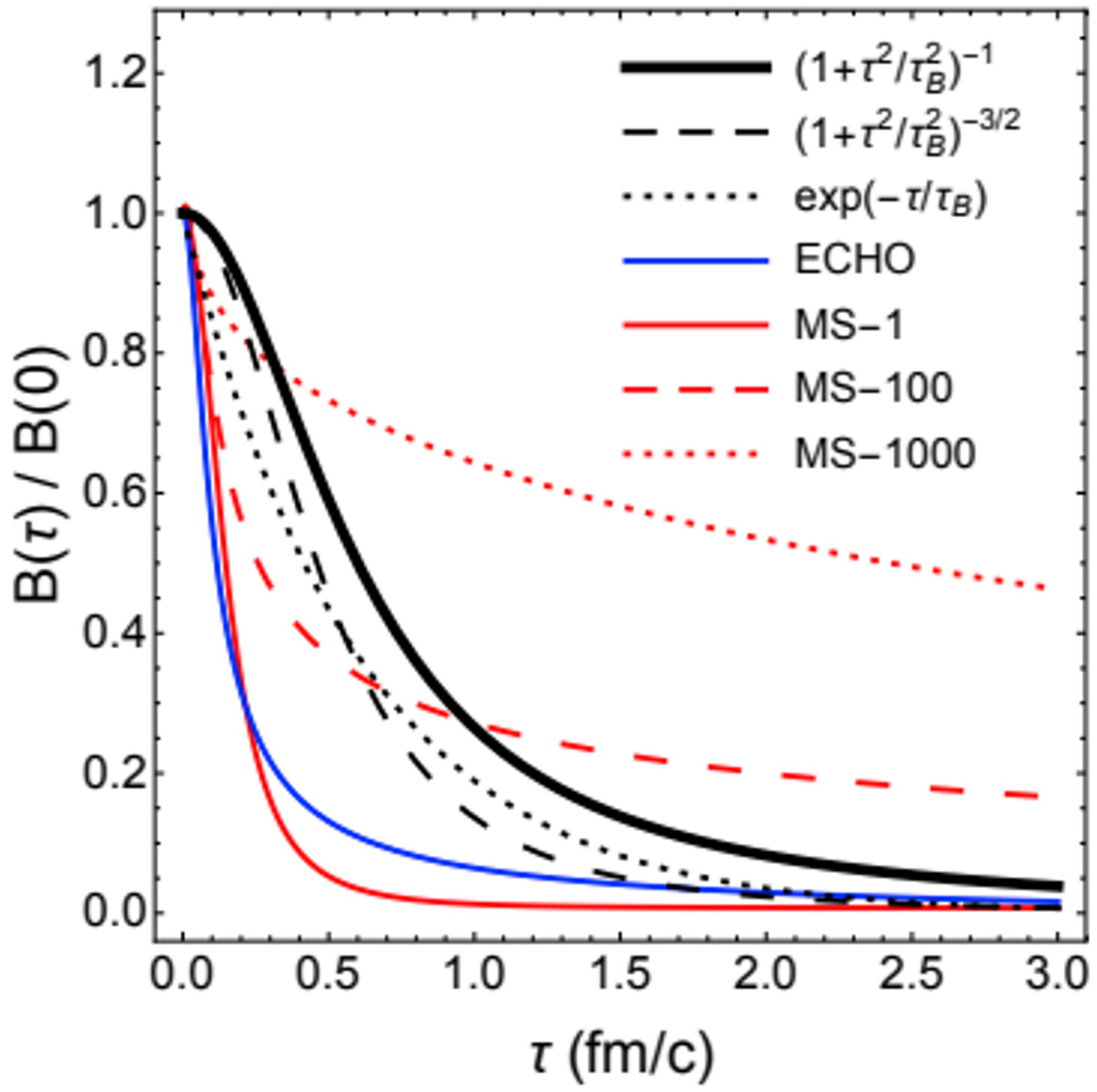
- Diffusion effect (σ): controls how fast the diffusion process transports charges around under the presence of density gradient
- Relaxation time (τ_r): controls the time scale that is needed to build up the "diffusion current" in response to the density gradient.
  - Small relaxation time → faster build up of diffusion current → stronger diffusion effect → suppressed CME



Red dot is the default value used in this study
a_1 represents CME-induced charge separation

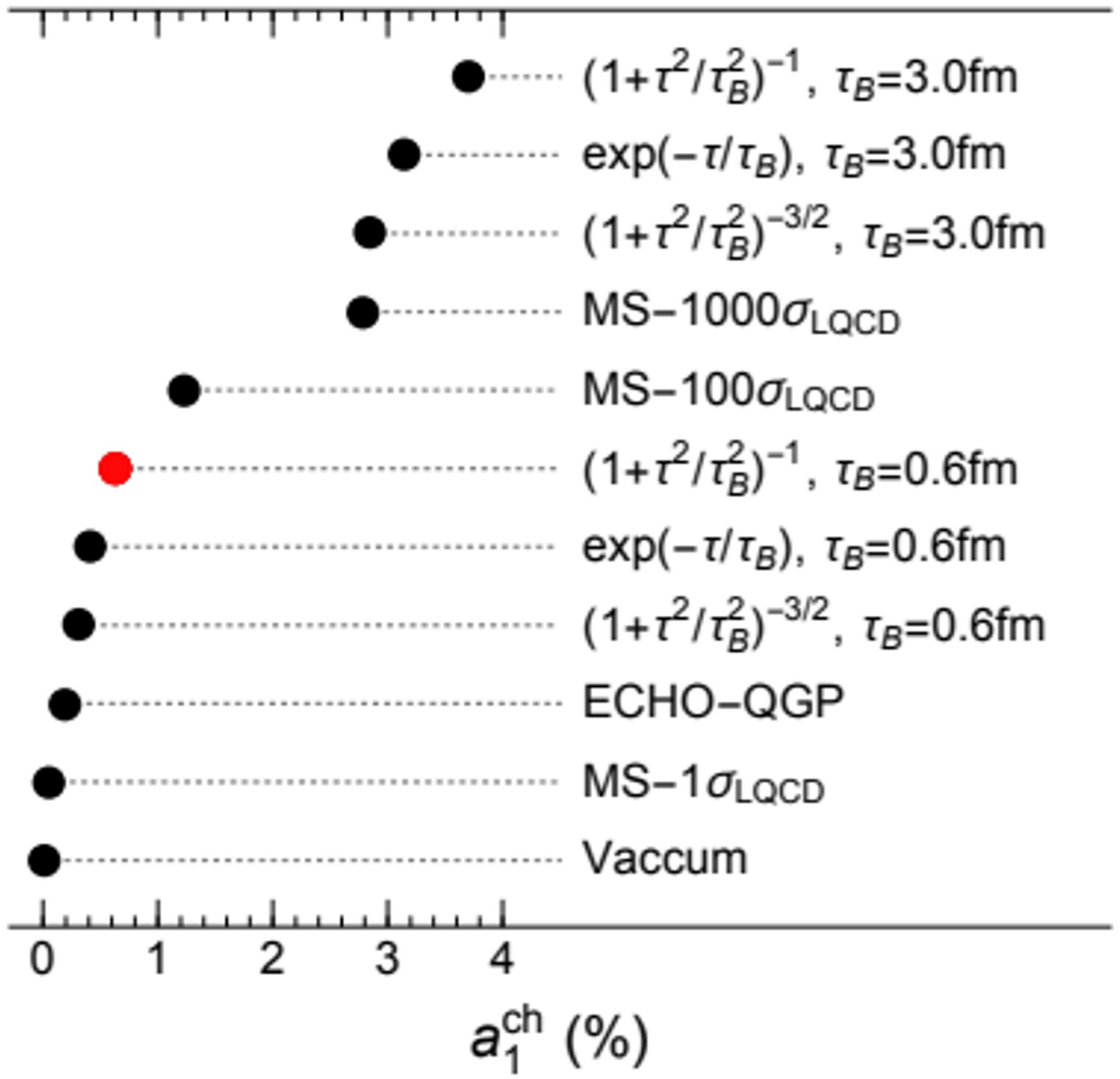
Anomalous Viscous Fluid Dynamics model (AVFD)

- Magnetic field strength as well as its time dependence



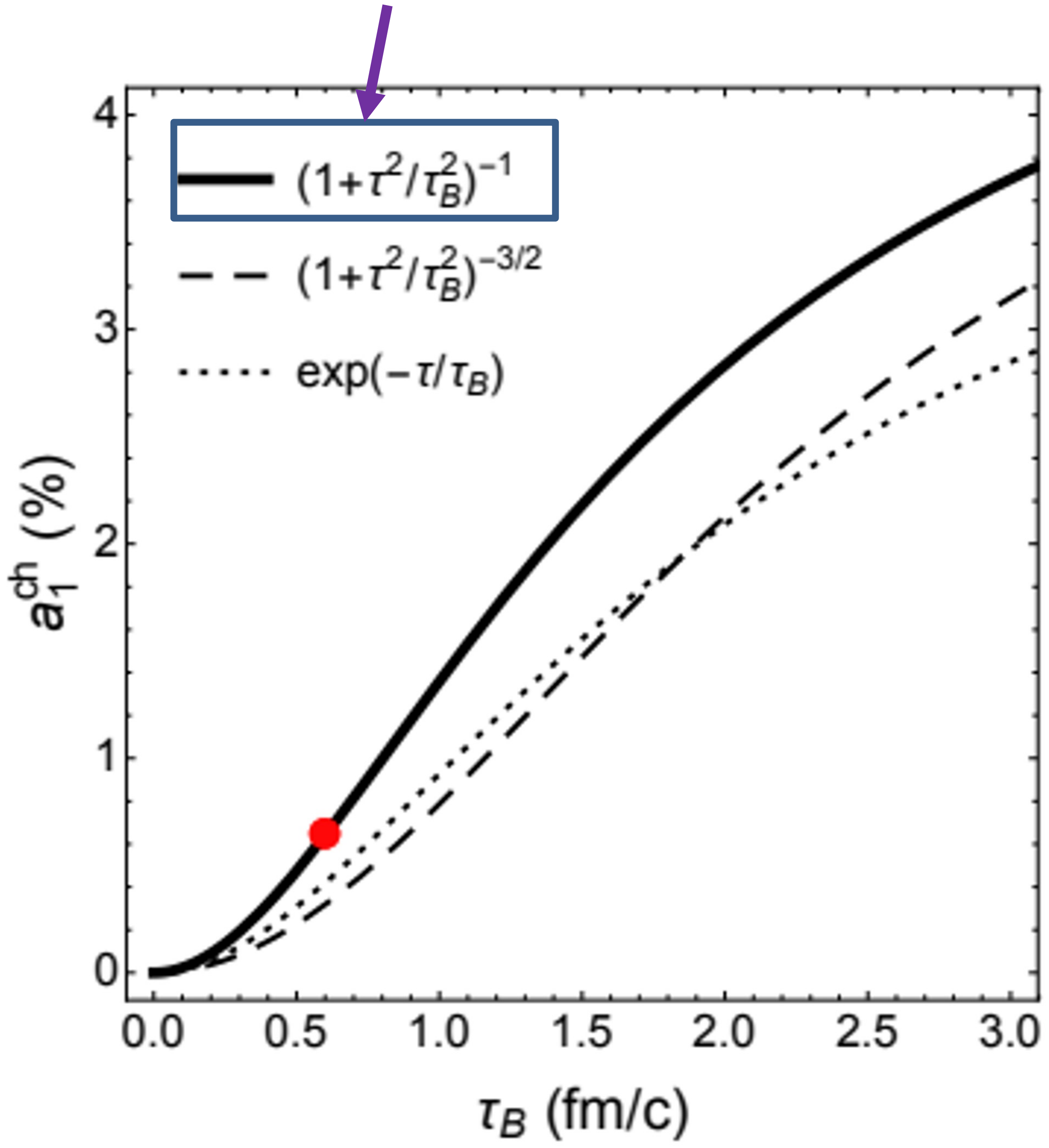
The time dependence of the magnetic field from different study

[1] Annals of Physics 394 (2018) 50-72



Charge separation predicted by different time dependences of magnetic field.

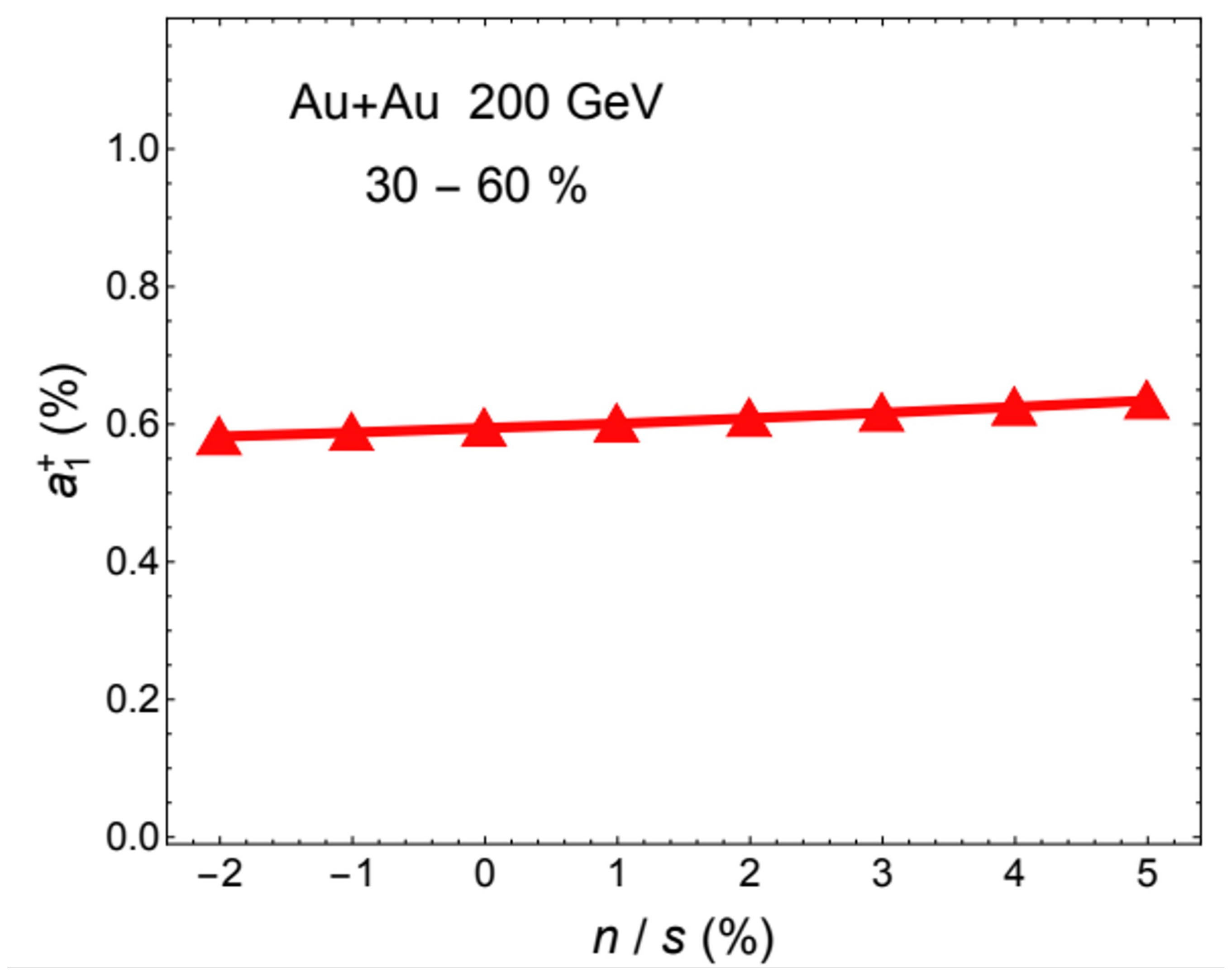
Chosen in this study

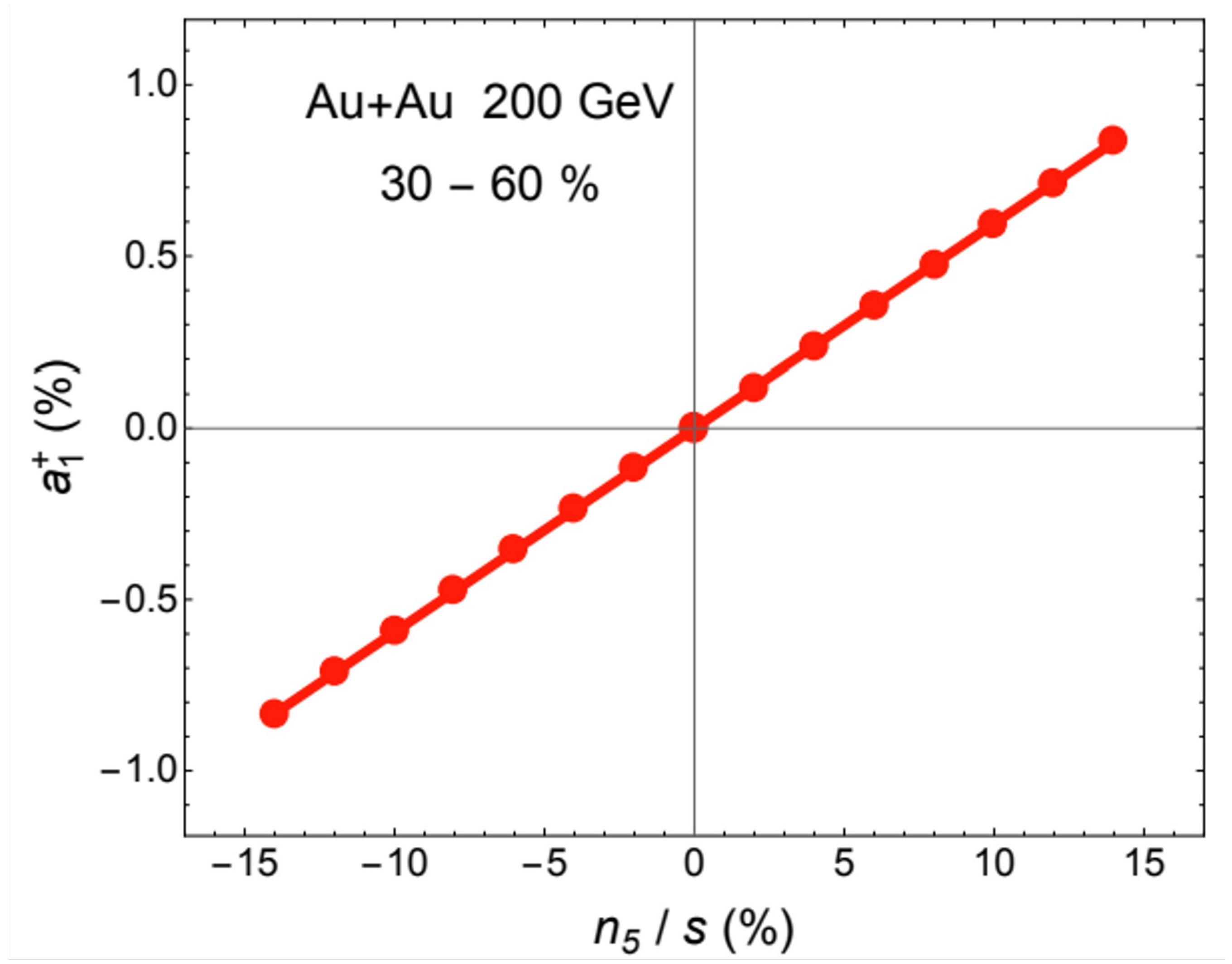


Charge separation a1 predicted by different magnetic field life time

Anomalous Viscous Fluid Dynamics model (AVFD)

- Initial conditions for the fermion charge densities (chirality imbalance), namely the initial four-current $J^{\mu}_{\chi,f}(\tau = \tau_0)$ for each flavour f as well as chirality χ.
- One can set for each flavor the initial vector and axial charge densities $n = J^0_R + J^0_L$ and $n_5 = J^0_R - J^0_L$. One expects $J^{\mu}_{CME} = C_A \mu_5 B^{\mu} \propto n_5$.



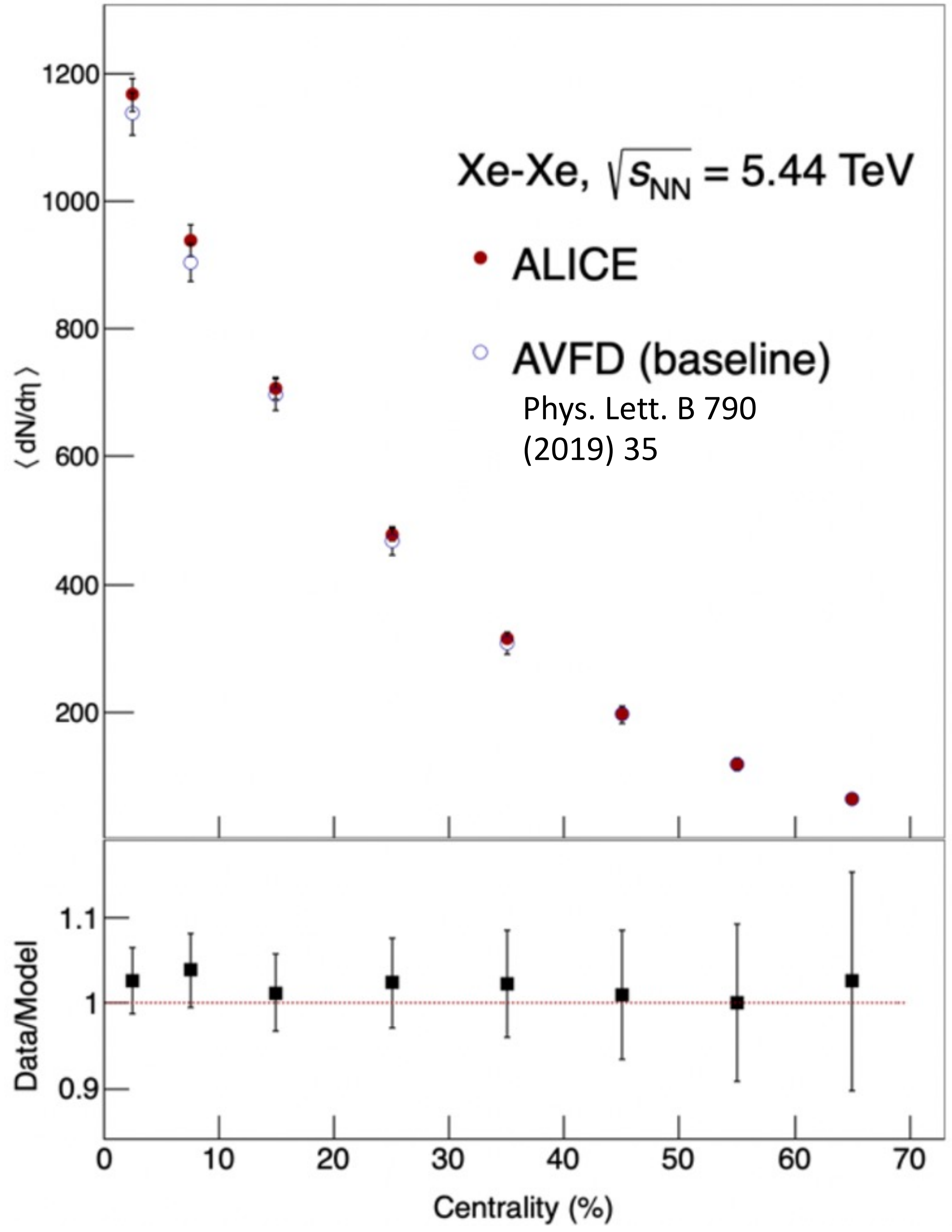


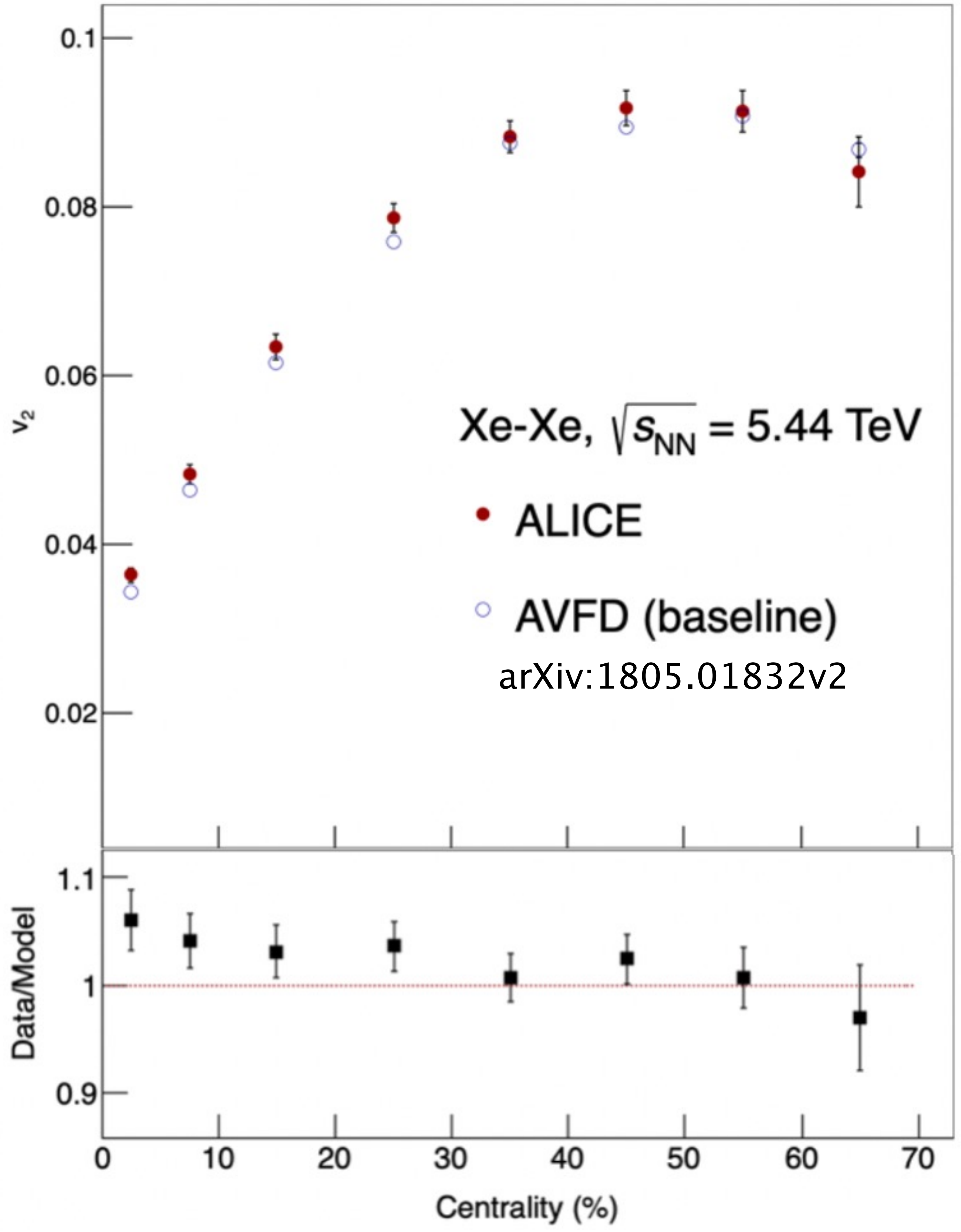
Calibrating the AVFD model

Xe-Xe as an example

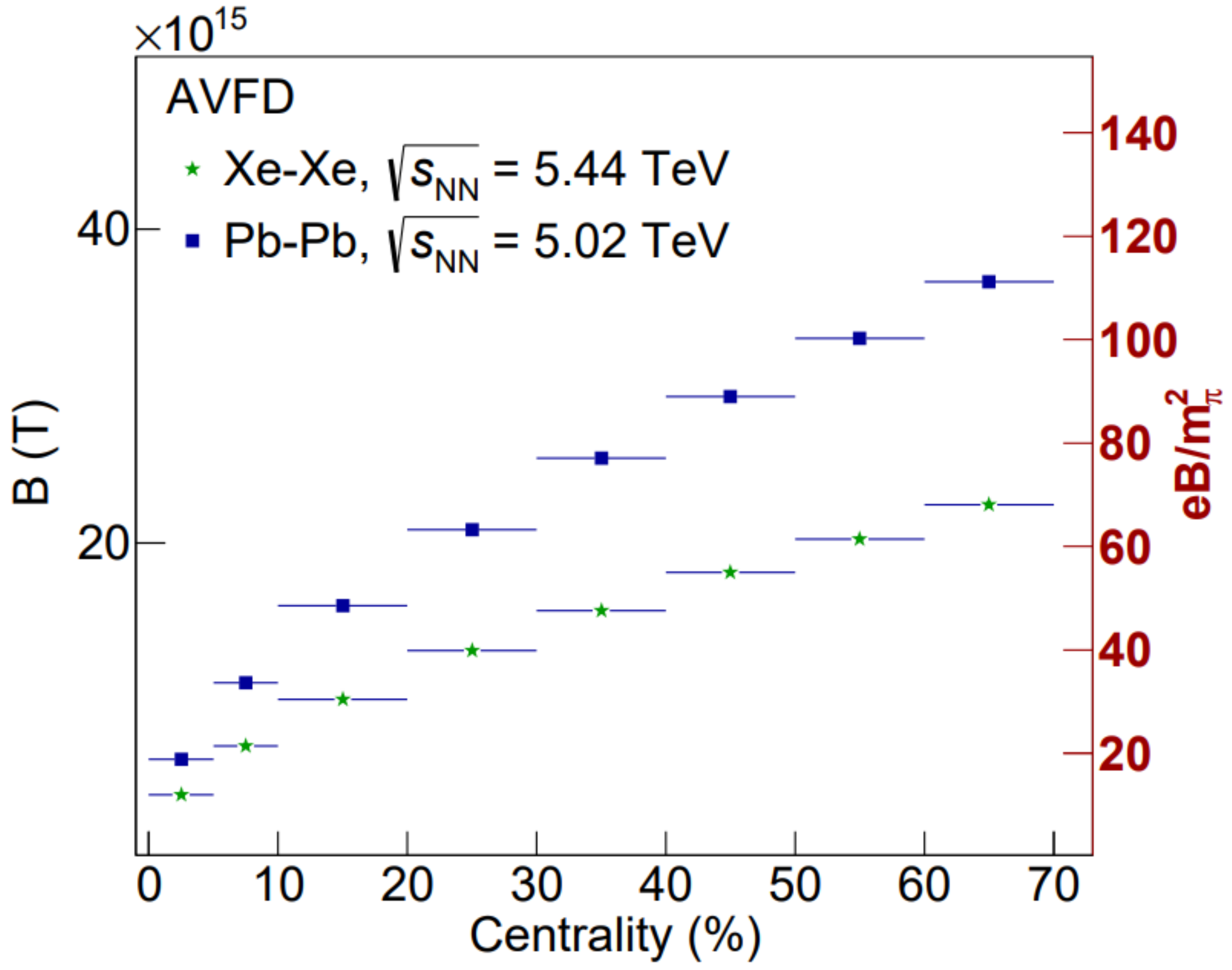
- Tune the baseline sample (no CME) to reproduce $dN/d\eta$, pion, kaon, proton p_T spectra and v_2 (elliptic flow) measured in ALICE Pb-Pb and Xe-Xe data
- Nucleon parameters for Pb and Xe from AVFD authors
- Use Gaussian nucleon distribution
- Key parameters for hydro:

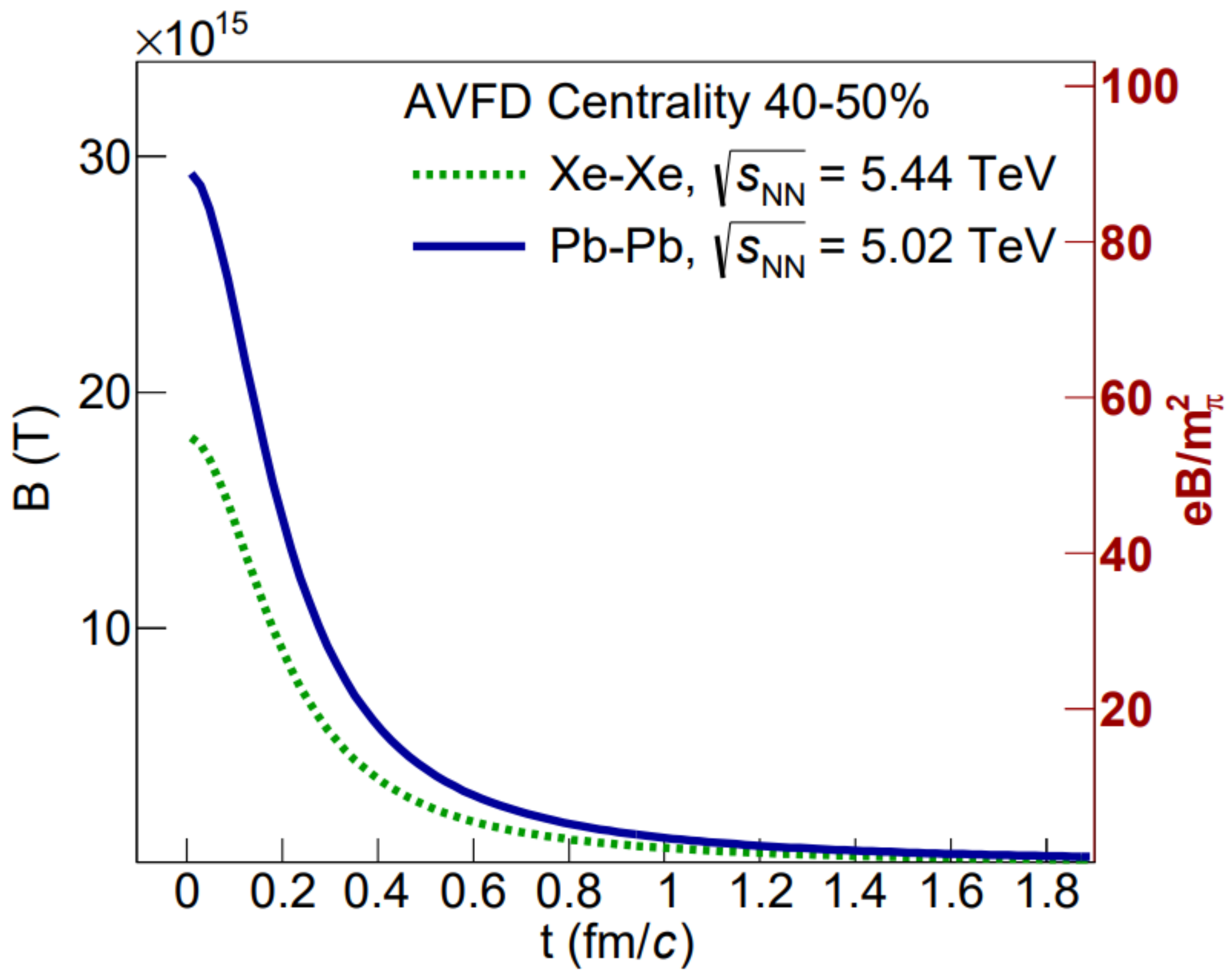
AVFD hydro config	
Initial time T_0 (fm/c)	0.6
Decoupling energy density E_{dec} (GeV/fm³)	0.18
Shear viscosity η/s	0.08
Bulk viscosity C ($\xi/s = C\times(\xi/s)_{\min}$)	0





B field simulated at $t_0 = 0$



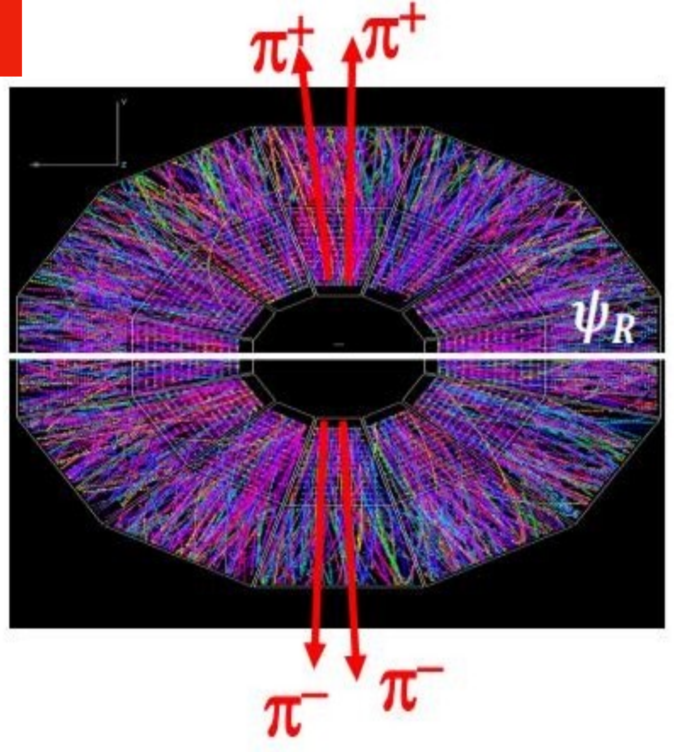


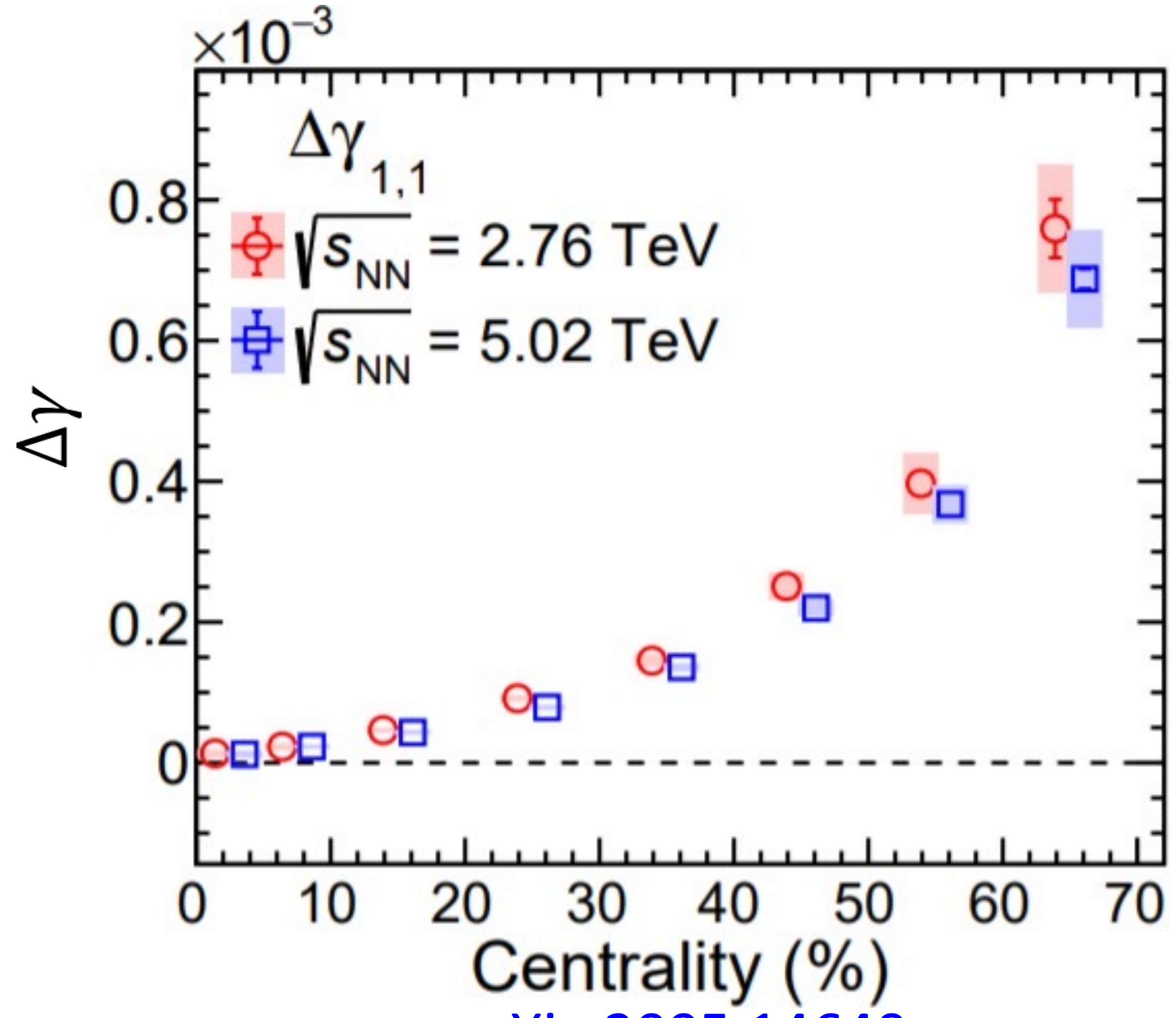
- B field in Pb-Pb more than 1.5 times larger than Xe-Xe
- Lifetime of B field in both system was set to a rather conservative value 0.2 fm/c

The $\Delta\delta$ and $\Delta\gamma$ observable for CME

- Charge dependent correlator:
  $\delta_{\alpha\beta} = \langle\cos(\varphi_\alpha - \varphi_\beta)\rangle, \qquad \gamma_{\alpha\beta} = \langle\cos(\varphi_\alpha + \varphi_\beta - 2\Psi_{\mathrm{RP}})\rangle$

  where $\alpha, \beta = \pm$ refer to charge.
- $\delta_{\alpha\beta}$ sensitive to correlations independent to RP (e.g. resonance decay, non-flow, jets)
- $\gamma_{\alpha\beta}$ sensitive to RP dependent background (e.g. flowing cluster, elliptic flow, v_1^2 fluctuation)
- ALICE previous measurement showed that $\Delta\gamma$ and $\Delta\delta$ significantly > 0. Indicating charge separation.





arXiv:2005.14640

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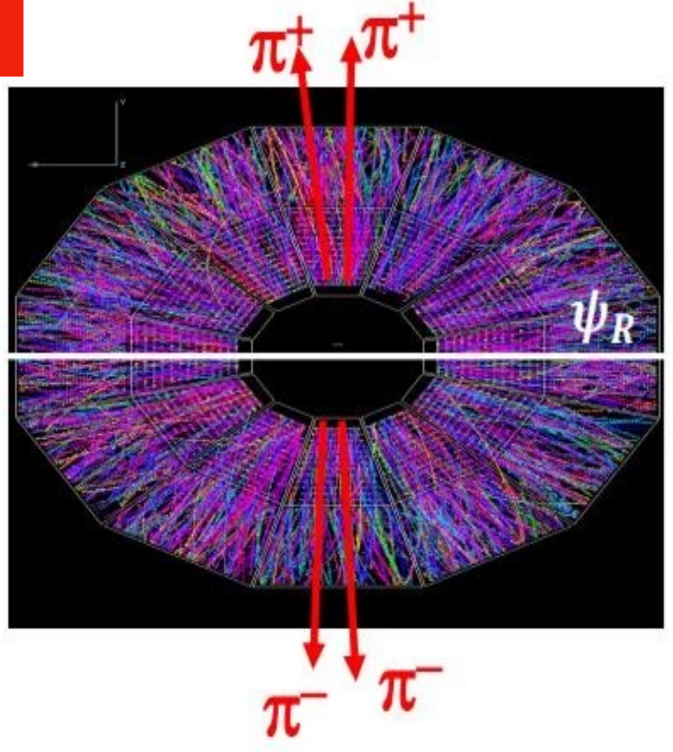
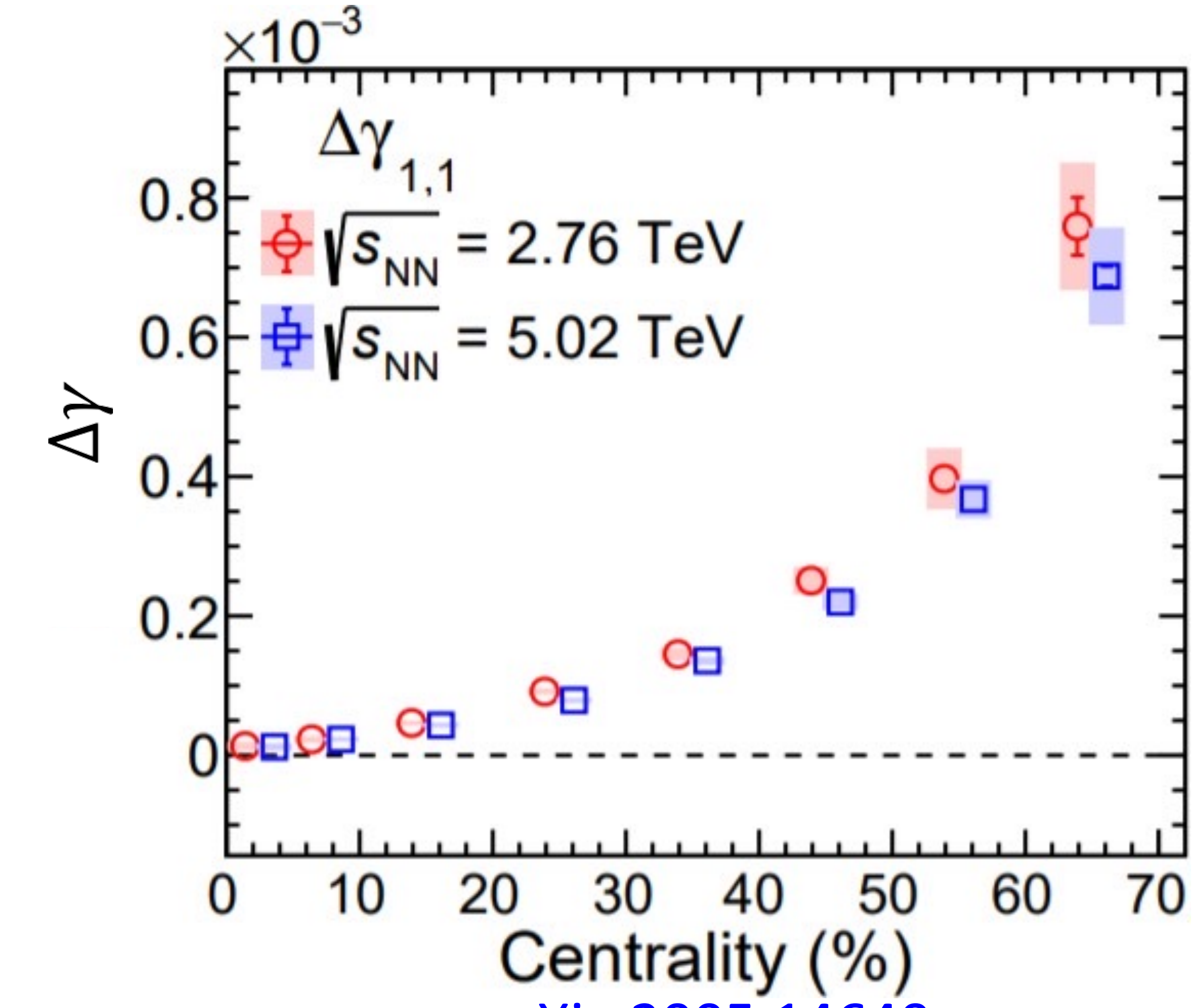
- $\delta_{\alpha\beta}$ sensitive to correlations independent to RP (e.g. resonance decay, non-flow, jets)
- $\gamma_{\alpha\beta}$ sensitive to RP dependent background (e.g. flowing cluster, elliptic flow, v_1^2 fluctuation)
- ALICE previous measurement showed that $\Delta\gamma$ and $\Delta\delta$ significantly > 0. Indicating charge separation.
- However, $\Delta\delta$ and $\Delta\gamma$ are heavily contaminated by local charge conservation (LCC) and resonance decays, mainly coupled with elliptic flow (noted as v_2)
  - e.g. $\rho^0 \rightarrow \pi^+\pi^-$, more OS pairs align in the Ψ_{RP} than B direction
- Similar value of γ observed in small system (no CME expected, pPb) confirming that the background is huge





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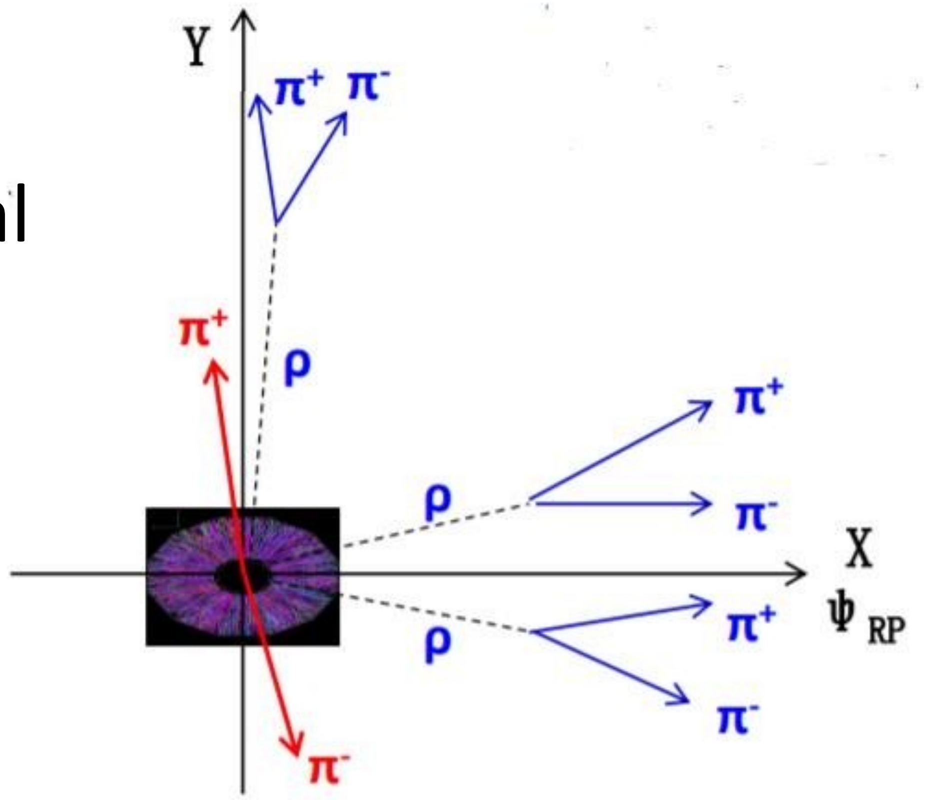

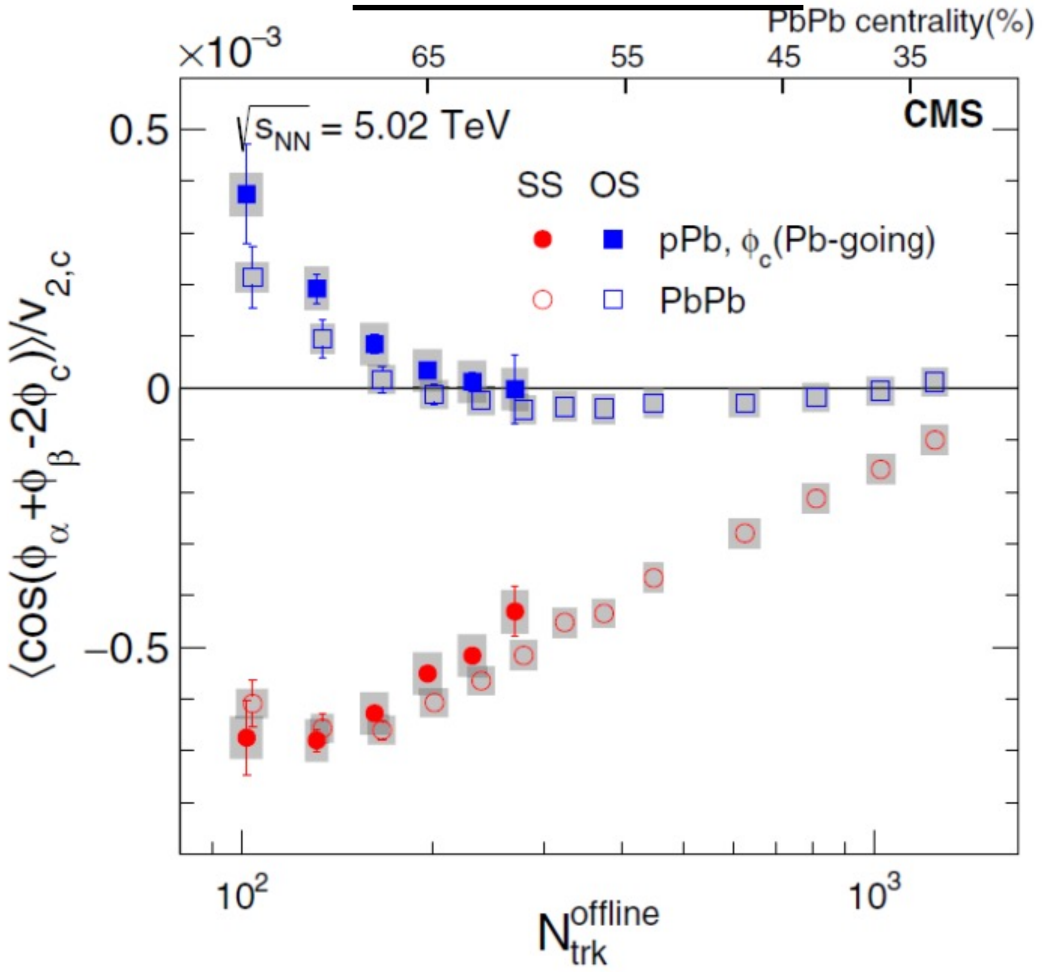

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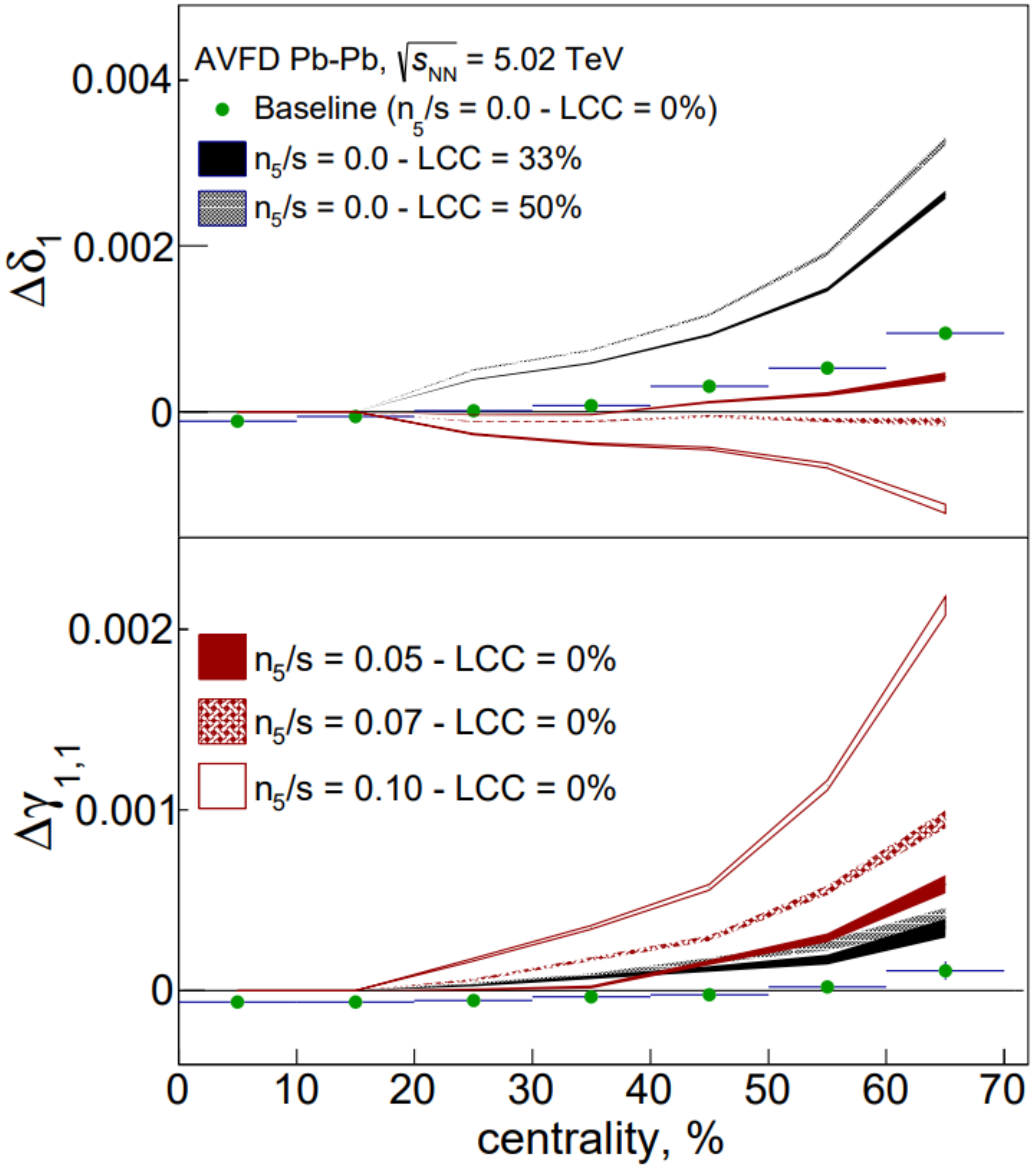
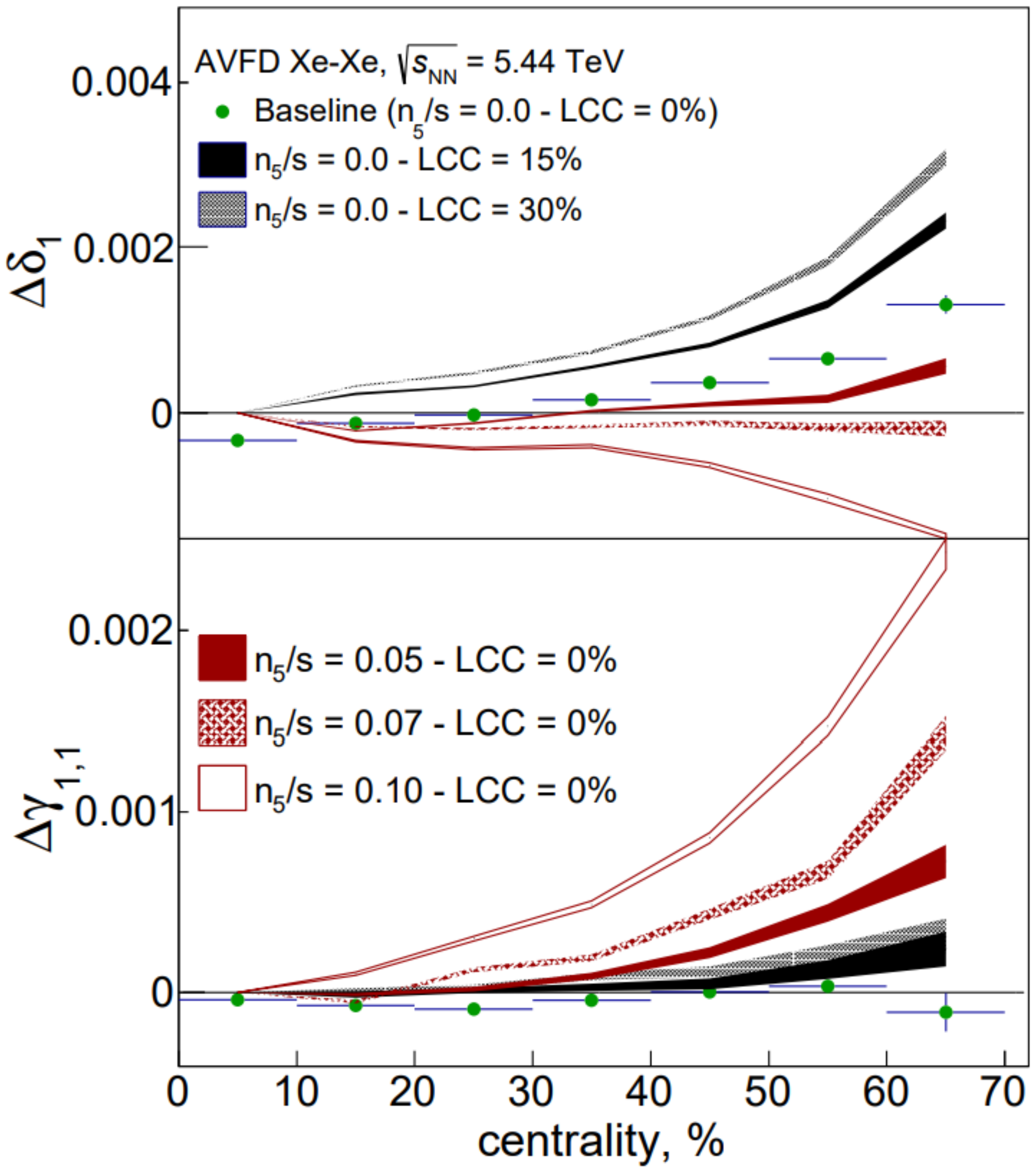
$\Delta\delta_1$ and $\Delta\gamma_{1,1}$ for Pb-Pb and Xe-Xe

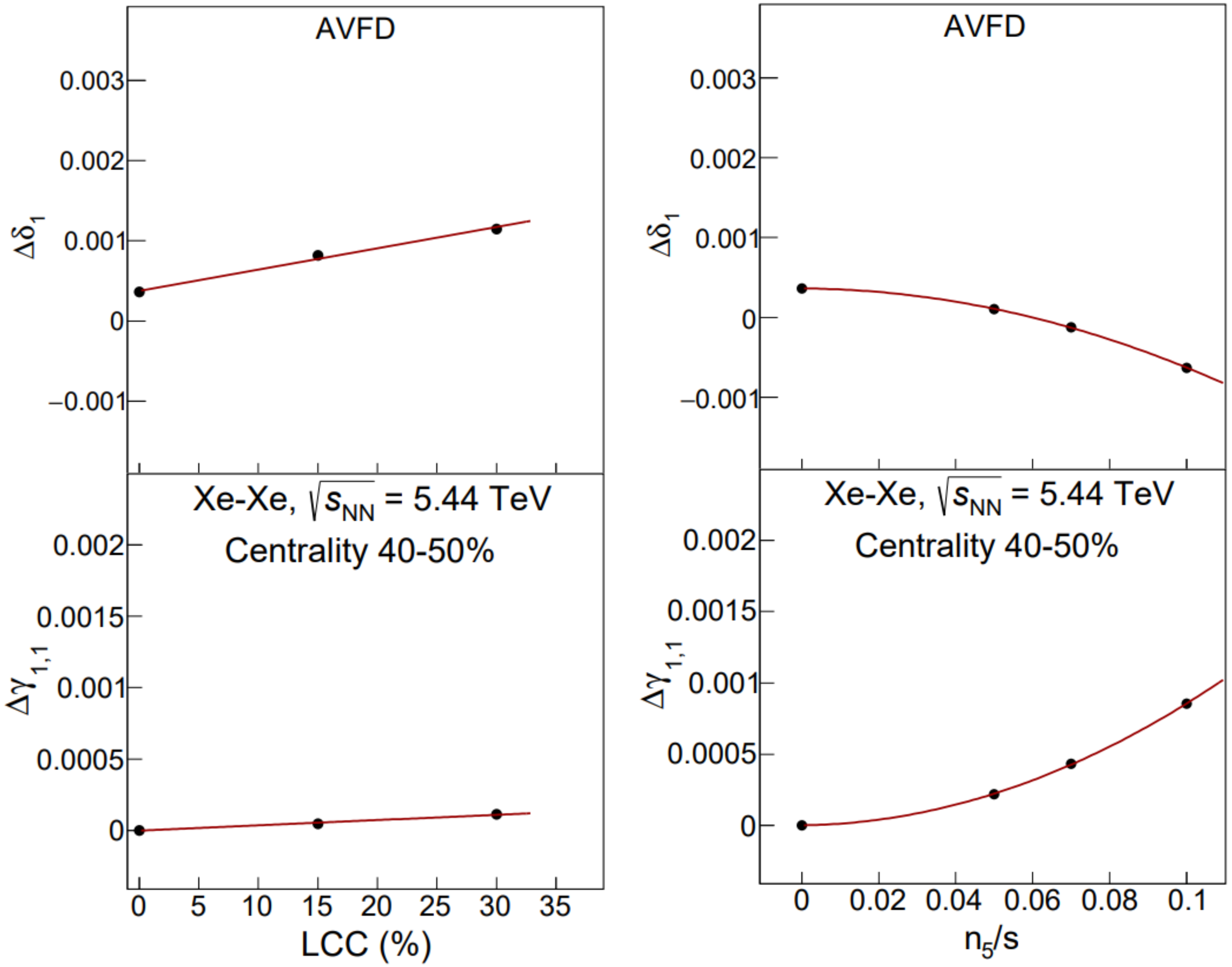




Approximate 100k events per centrality bin

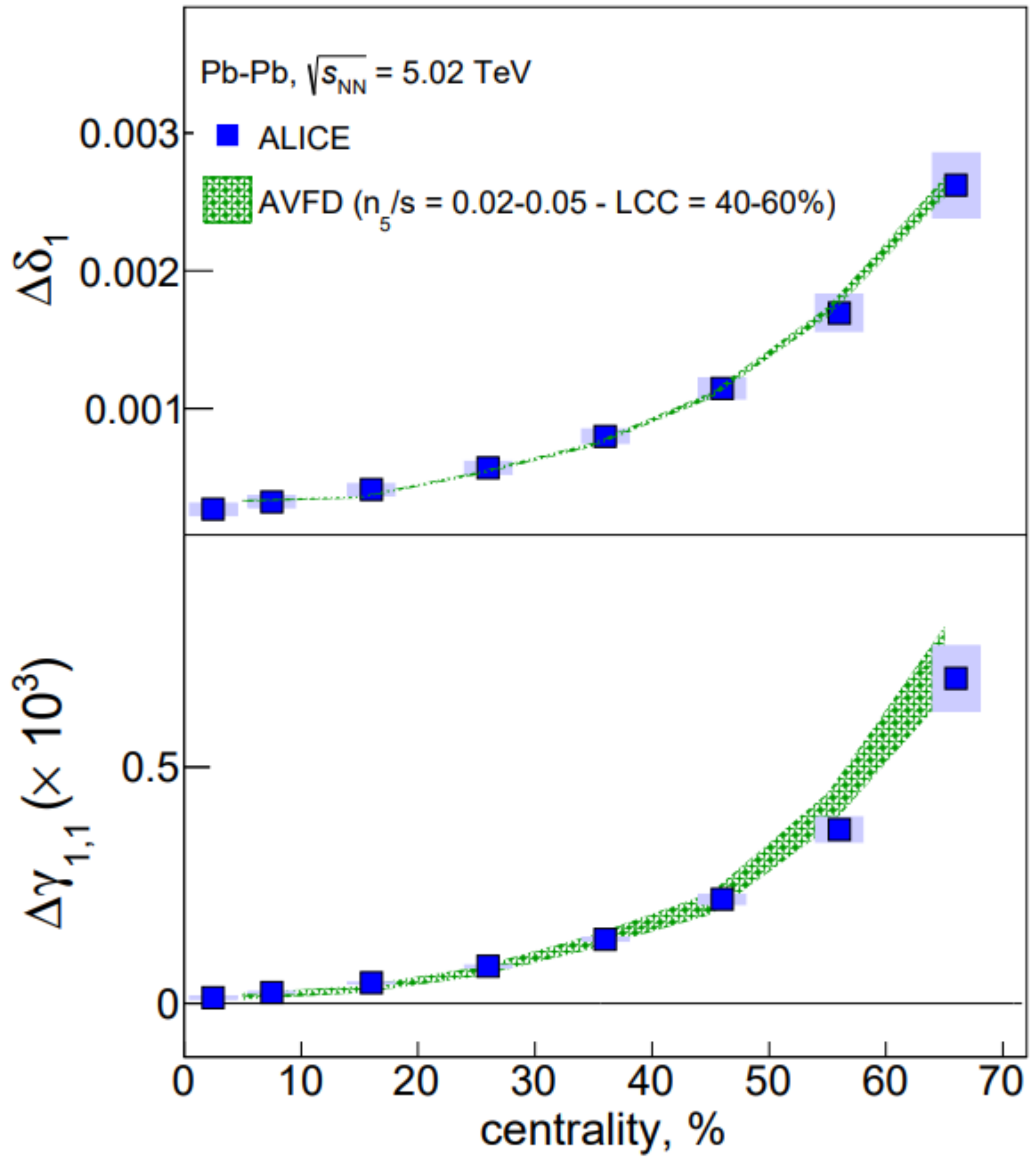
Parametrization

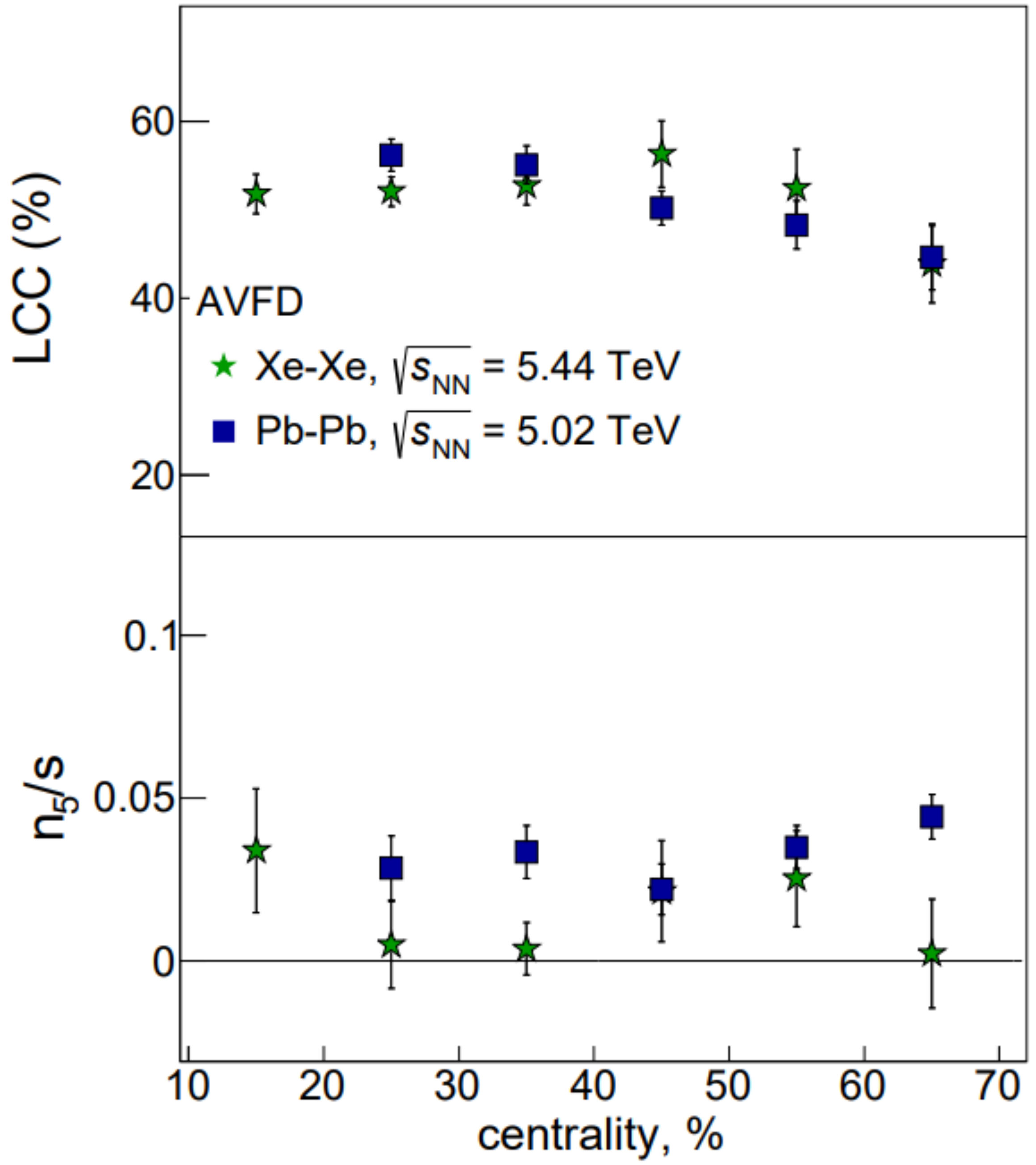
- For each centrality bin:
- $\Delta\delta_1 = c_2 \cdot (n_5/s)^2 + c_1 \cdot (n_5/s) + b_1 \cdot (\mathrm{LCC}) + b_0$
- $\Delta\gamma_{1,1} = e_2 \cdot (n_5/s)^2 + e_1 \cdot (n_5/s) + d_1 \cdot (\mathrm{LCC}) + d_0$



Final results

- The best fitted value of LCC and n_5/s can reproduce $\Delta\delta$ and $\Delta\gamma$ nicely
- A fit with a constant function for n_5/s indicates that:
  - For Xe-Xe, avg % of n_5/s is 0.011 ± 0.005. Compatible with zero
  - For Pb-Pb, avg % of n_5/s is 0.034 ± 0.003. Significantly above background only scenario



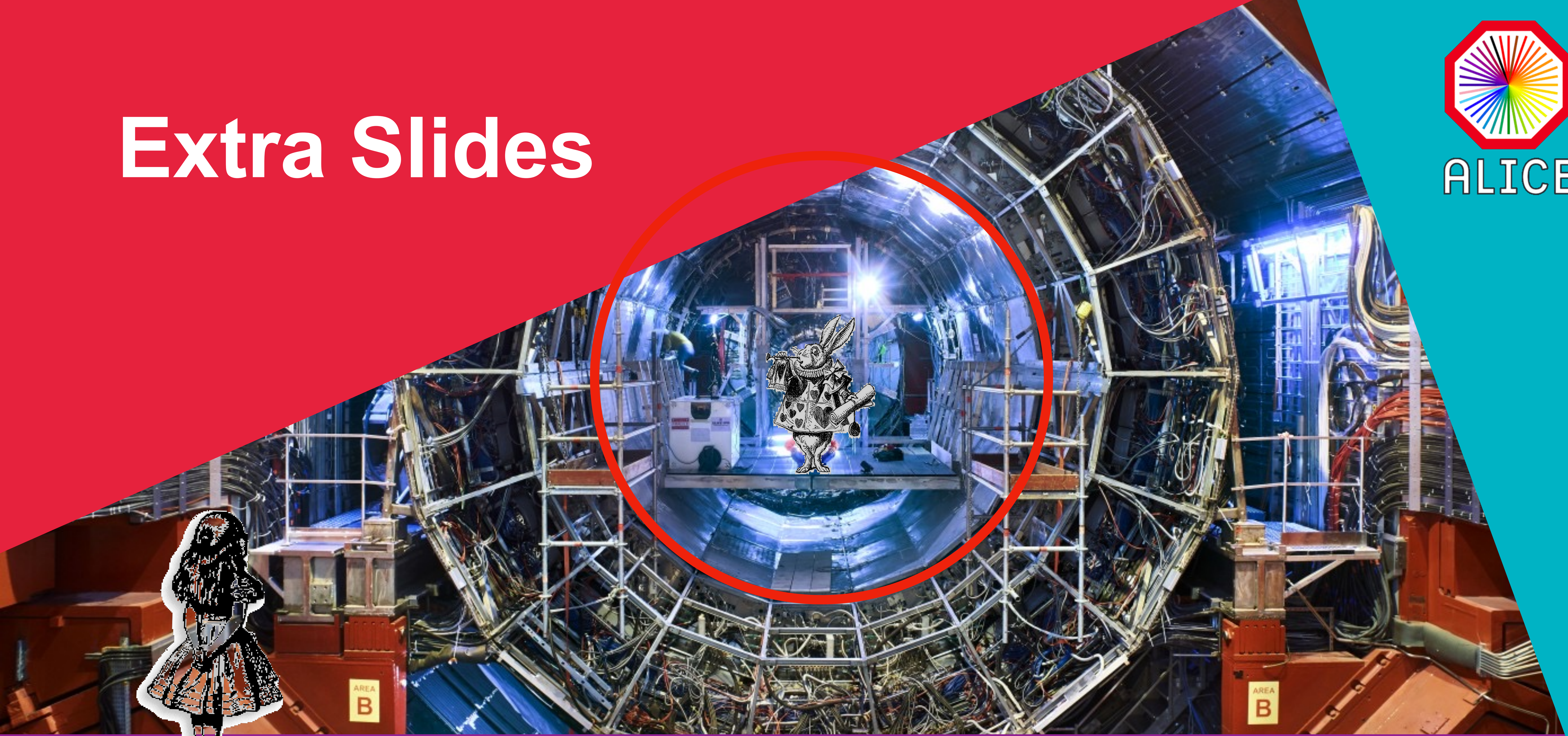


Conclusion

- This parametrisation allowed for the estimation of the values of both the LCC percentage and n5/s needed to describe quantitatively
- The measurements in Xe–Xe are consistent with a background only scenario
- The results of Pb–Pb collisions require n5/s with significantly non-zero values

THANKS

Extra Slides



Shi Qiu

Nikhef Jamboree, 10*th* 5/2022

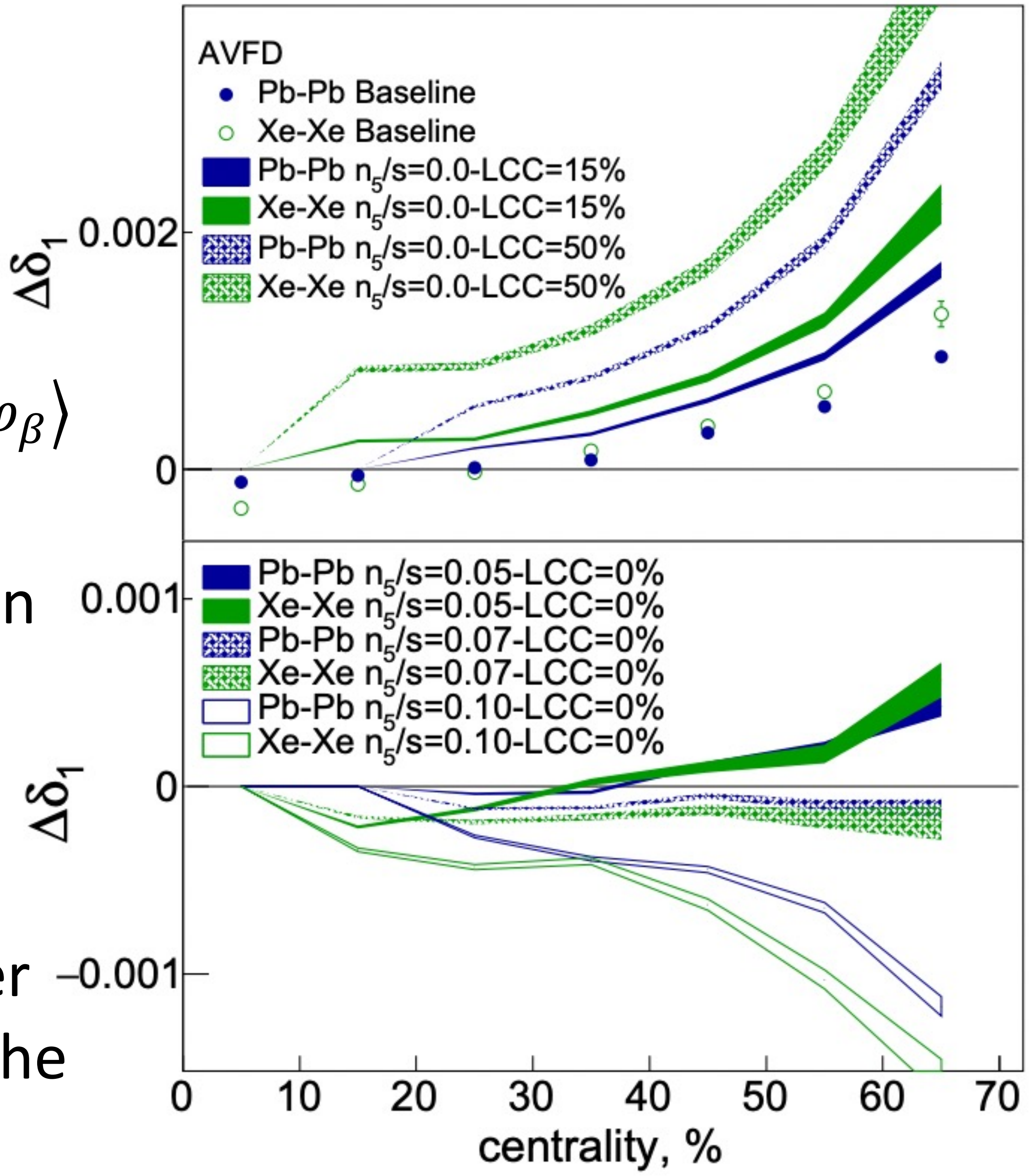
Understanding shifting of $\Delta\delta_1$ and

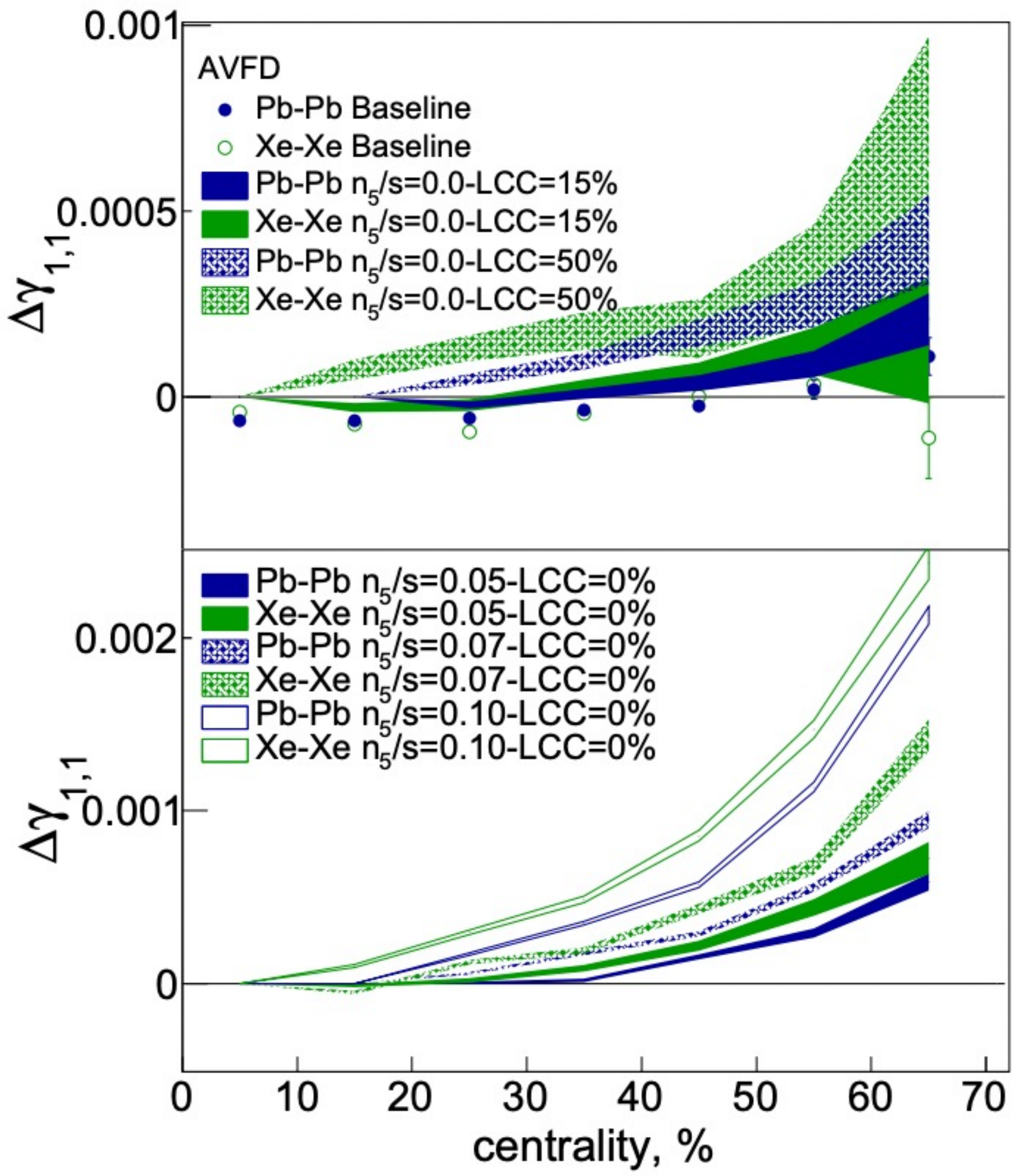
- Such results follow the expecatation. Expand $\delta_{\alpha\beta}$ and $\gamma_{\alpha\beta}$:

$\langle\cos(\varphi_\alpha - \varphi_\beta)\rangle = \cdots = \langle\cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle + \langle\sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle$=…

$\langle\cos(\varphi_\alpha \mp \varphi_\beta - 2\Psi_{\mathrm{RP}})\rangle = \cdots = \langle\cos\Delta\varphi_\alpha \cos\Delta\varphi_\beta\rangle - \langle\sin\Delta\varphi_\alpha \sin\Delta\varphi_\beta\rangle$=…

- For a fixed LCC, $\Delta\delta$ is higher for Xe-Xe than Pb-Pb
  - the radial flow between these two systems is similar
  - the charge multiplicity is 60-70% higher for Pb-Pb leading to faster dilution of the correlations induced by the LCC mechanism in the larger system





Pb-Pb calibration