Universiteit Utrecht

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Spin and Magnetic fields in Heavy-Ion Collisions

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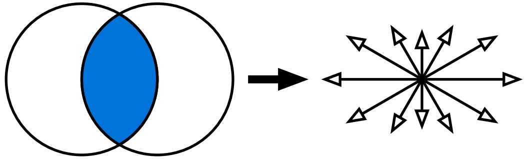
Hydrodynamics and Geometry

- Hydrodynamics translates initial-state geometry to momentum-space



- Ingredients for this mechanism:
  1. EoM is a conservation law (e.g. $\nabla_\mu T^{\mu\nu} = 0$), hydrodynamic quantities are **transported**
  2. Mean free path is smaller than average (pseudo)particle separation

Takeaway: hydro is a geometry machine; what you put in, comes out.

- Fitting hydro models is a two-way street:
  - well-known hydro $\Rightarrow$ constrains initial state geometry
  - well-known initial state $\Rightarrow$ constrains hydro parameters
- Don't know either? Do a Global (Bayesian) fit!

Hydrodynamics and Geometry

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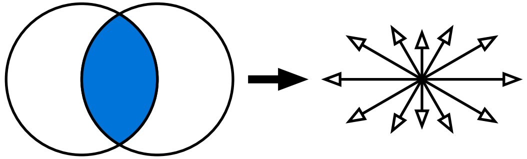

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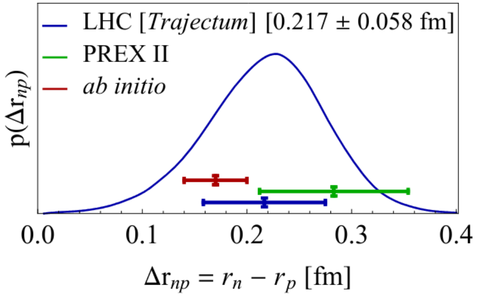
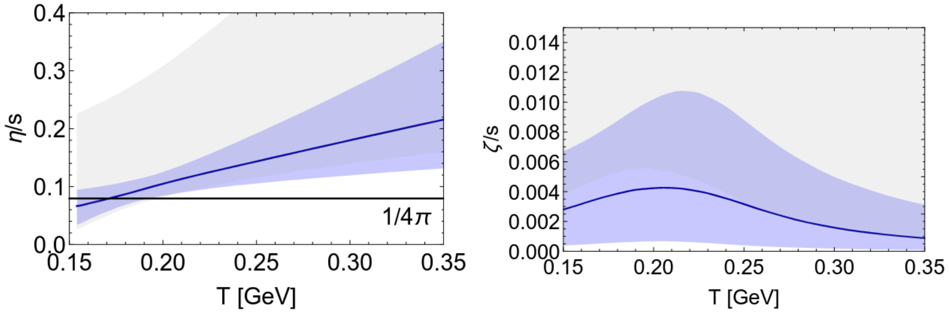
Examples of fits using the hydro model *Trajectum*:

1. Neutron skin of $^{208}\mathrm{Pb}$ from ALICE data [1]



2. Bulk and shear viscosities from global p_T-analysis [2]



Overview of the "Trajectum" nuclear collision framework

Trajectum[3] is…
… a hydrodynamical nuclear collision framework…
… for modeling AA and pA collisions at LHC energies…
… purpose-built for doing Bayesian Analyses (BA).

Being purpose-built for BA means that

- We put a lot of effort into replicating event-by-event, particle based experimental observables.
- Computational efficiency is a priority, $\mathcal{O}(10^3)$ faster in comparison to models with similar physics content.

Physics content

- Projectile geometry input from nuclear community (NLEFT, PCGM, VMC, no-core shell model etc.)
- Various initial conditions (TRENTO, MCGlauber, MCDipper)
- Hybrid (holography + free streaming) prehydro stage
- 3+1D DNMR 2nd order viscous hydro evolution
- Cooper-Frye hadronization

TRAJECTUM

DEVELOPED ON Codeberg

See https://codeberg.org/Trajectum/Trajectum-Releases | [3]: Nijs, van der Schee, Gürsoy & Snellings, PRC 103(2021) 054909

Overview of the "Trajectum" nuclear collision framework

Trajectum Event Generator

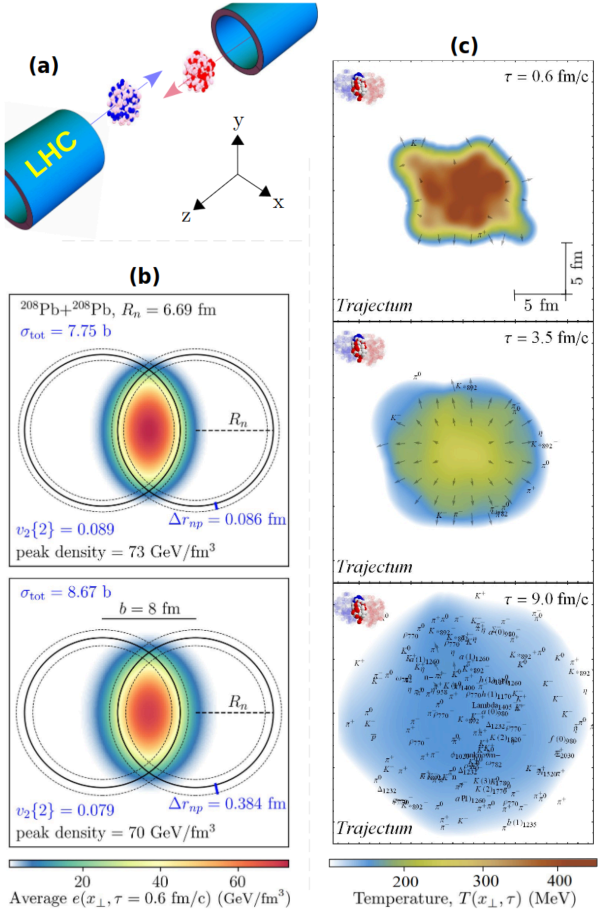
Initial Condition $\lim_{\tau\downarrow 0} \tau\varepsilon(\vec{x}_\perp, \eta)$

Prehydrodynamic stage $\tau = \tau_{\text{hydro}}$

Hydro evolution $\tau_{\text{hydro}} < \tau < \tau_{\text{fs}}(x)$

Isothermal hadronisation $\tau = \tau_{\text{fs}}(x)$

Afterburner (*external*, SMASH or UrQMD) $\tau > \tau_{\text{fs}}(x)$



Spin and angular momentum in heavy-ion collisions

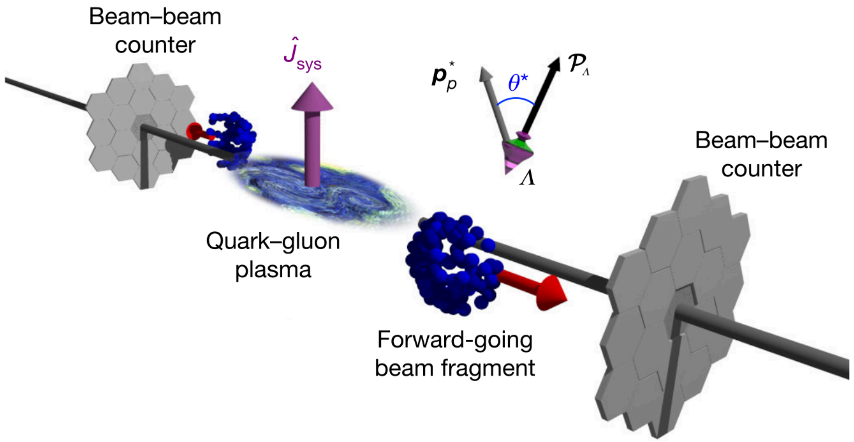
Mantra: hydro is a geometry machine
⇒ *geometric explanation for spin observables?*

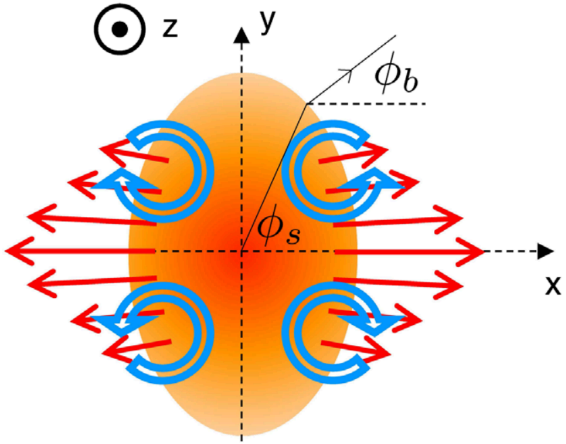
- It is possible to measure the spin of weakly-decaying baryons by the angle between the decay products
- Spin of final-state hadrons is related to the vorticity and shear in the fluid through spin-orbit coupling
- We use a computation by [4], [5] of the expectation value of the Pauli-Lubaǹski pseudo-vector $\widehat{W}^\mu$ of a Dirac field in a thermal rotating state, normalised as $P^\mu = W^\mu / W$:

$$P^\mu(k) = \frac{1}{8m}\epsilon^{\mu\alpha\beta\gamma}(n_F(k)-1)\left[2\frac{k_\beta \Sigma_\gamma}{\Sigma \cdot k}\xi_{\alpha\delta}k^\delta + \varpi_{\alpha\beta}k_\gamma\right]$$

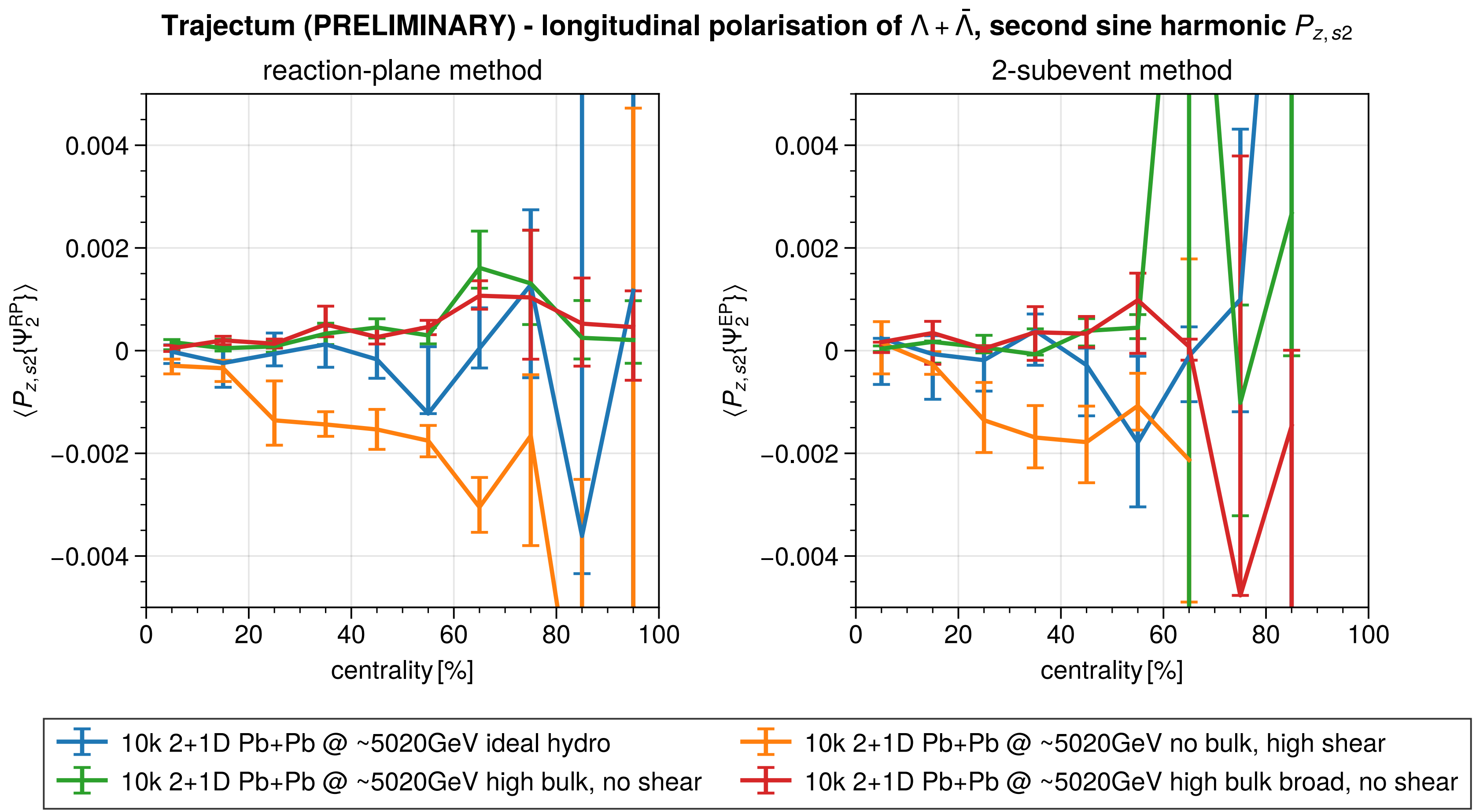
Two terms:

1. Thermal vorticity $\varpi_{\mu\nu} = -\partial_{[\mu}\beta_{\nu]}$ (yes really with a minus)
2. Thermal shear $\xi_{\mu\nu} = \partial_{(\mu}\beta_{\nu)}$

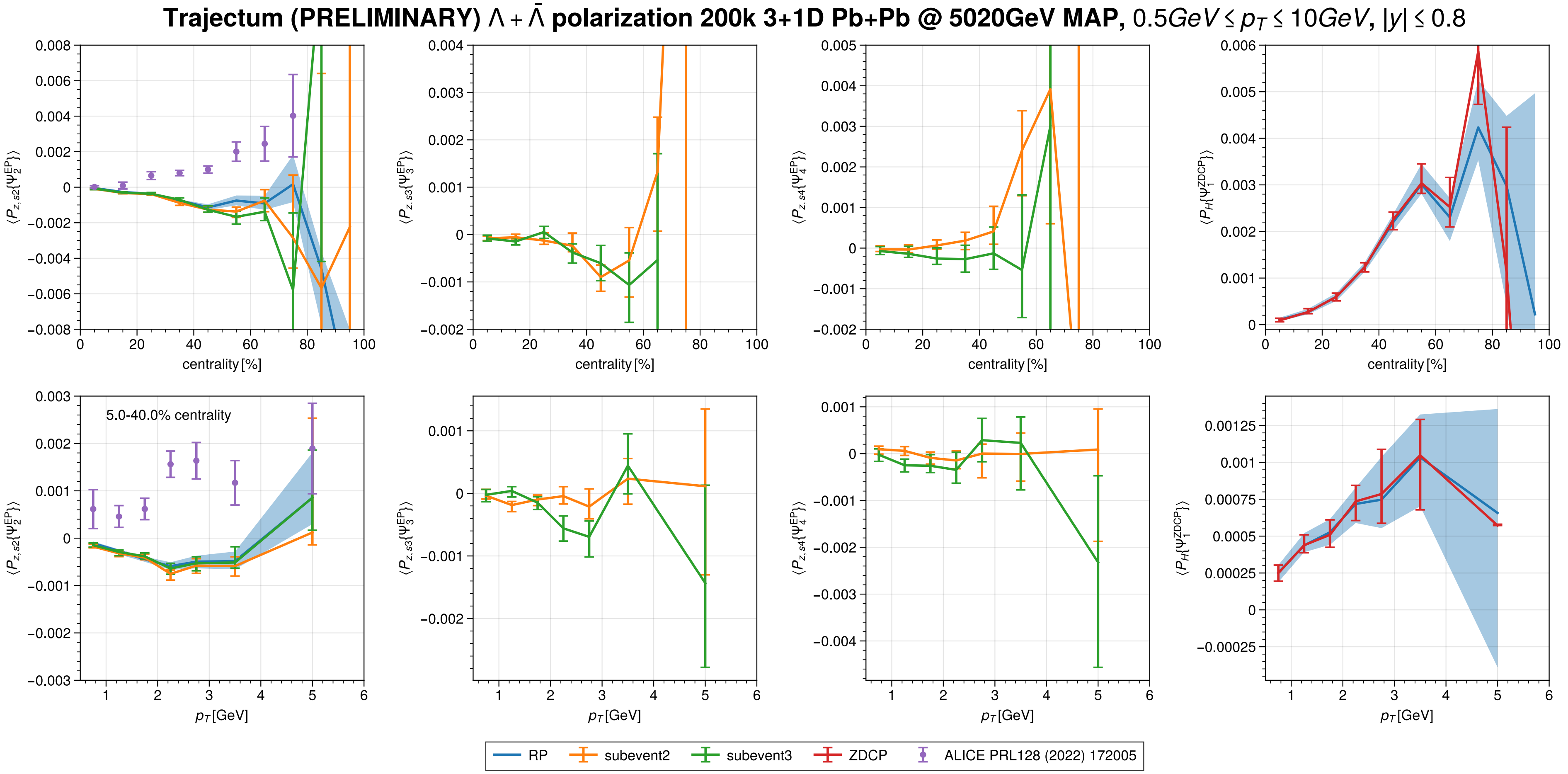




Polarization turns out to be very sensitive to viscosity



Tension between 3+1D fit* MAP value and ALICE



Magnetic fields in Heavy-Ion collisions

- Anisotropic electric and magnetic fields induce a difference in flow observables for charged particle/antiparticle pairs $\Rightarrow$ **charge-identified flow $\boldsymbol{\Delta v_n}$**
- Model EM effect as perturbation to flow at freeze-out [6]:
  - EM fields are sourced by point charges with four-current:

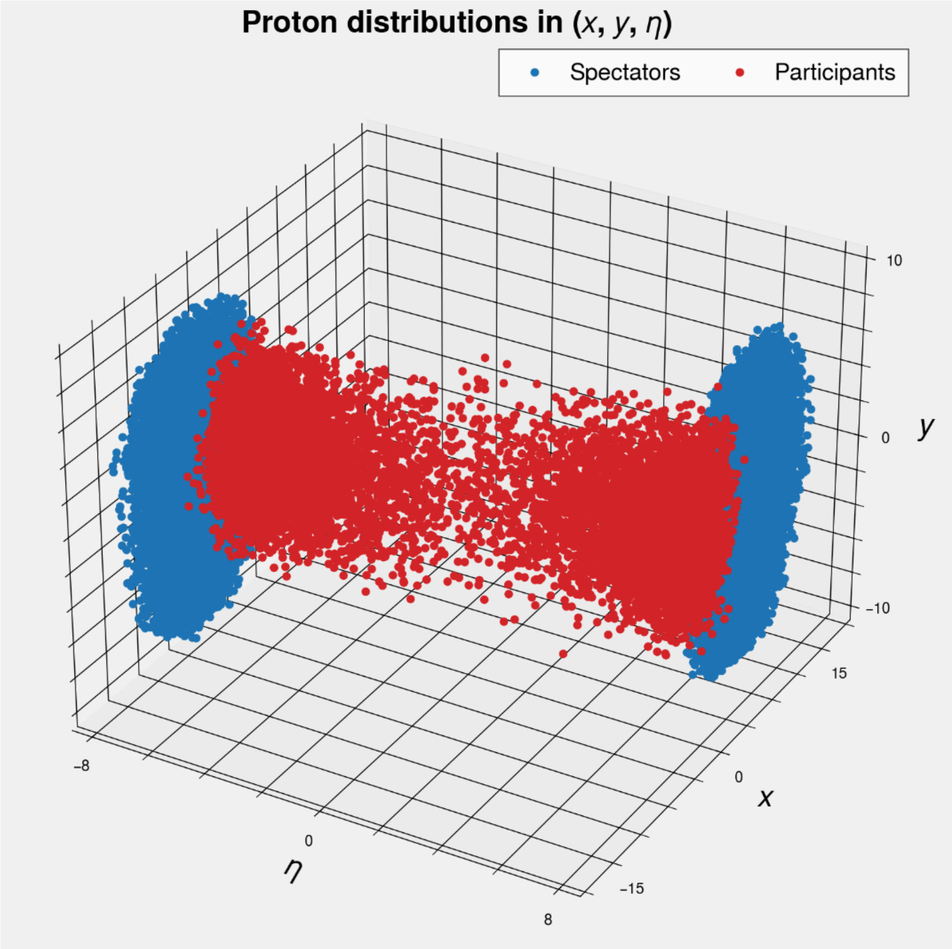
$$j^{\mu}_{\text{free}}(y) = \sum_{\text{protons},i} q \int d\tau V_i^{\mu} \tau \delta^4(y - b_i(\tau))$$
$$= q\delta^3\left(\vec{y}_\perp - \vec{b}_{\perp,i} - V_i^0 y^0 \boldsymbol{e}_3\right)[1, 0, 0, V_i]^T$$

  - Solve Maxwell equations in presence of conducting (conductivity σ) stationary ($\Upsilon^\mu = \left(1, \vec{0}\right)$) medium:

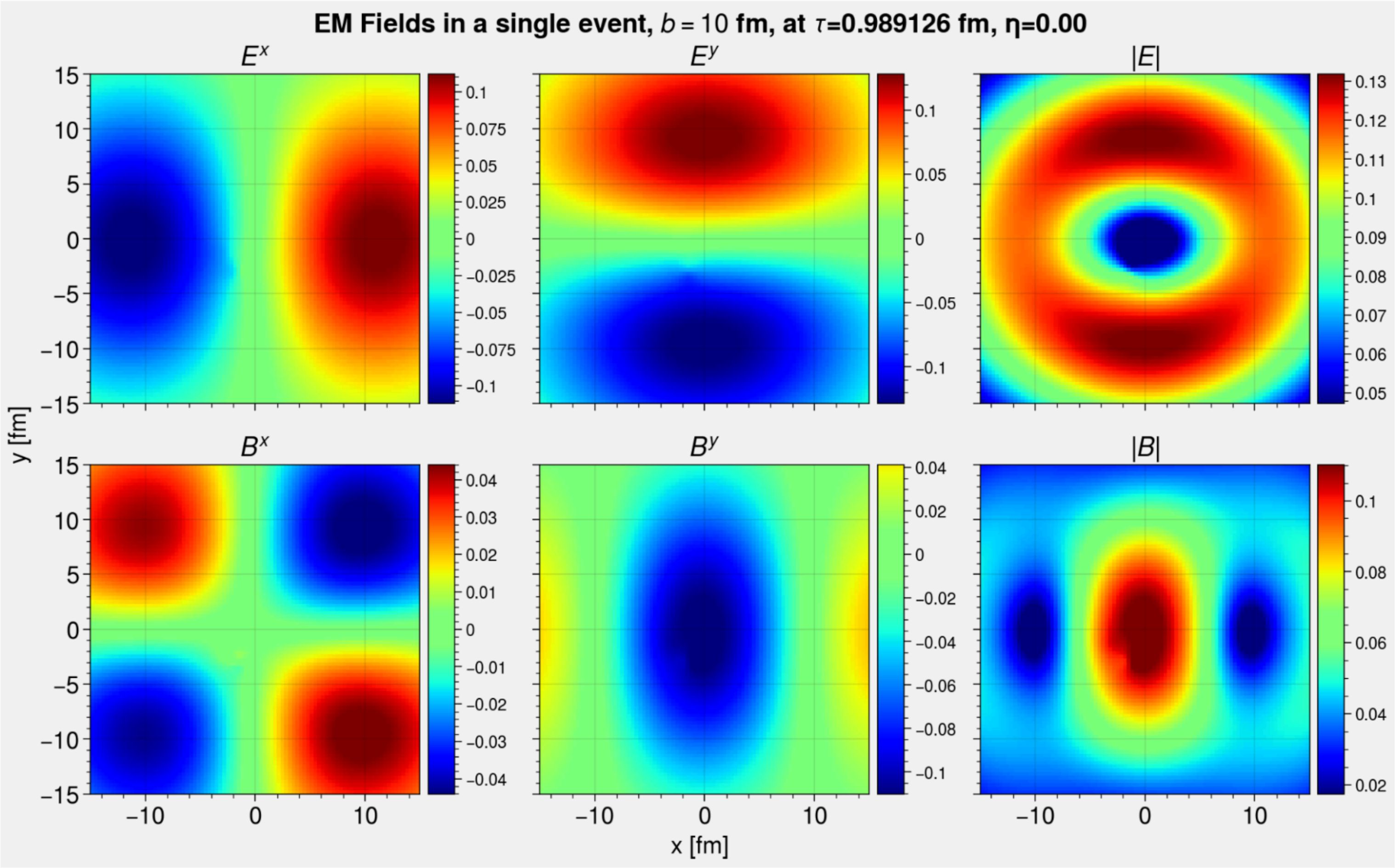
$$\left[\Box - \sigma\Upsilon^\mu\partial_\mu\right]\vec{B}(x) = -\nabla \times \vec{j}_{\text{free}}$$
$$\left[\Box - \sigma\Upsilon^\mu\partial_\mu\right]\vec{E}(x) = \nabla j^0_{\text{free}} + \partial_0 \vec{j}_{\text{free}}$$

  - Balance the force due to the EMF by adding a small drift velocity $u' = u + v$, that feels a drag force:

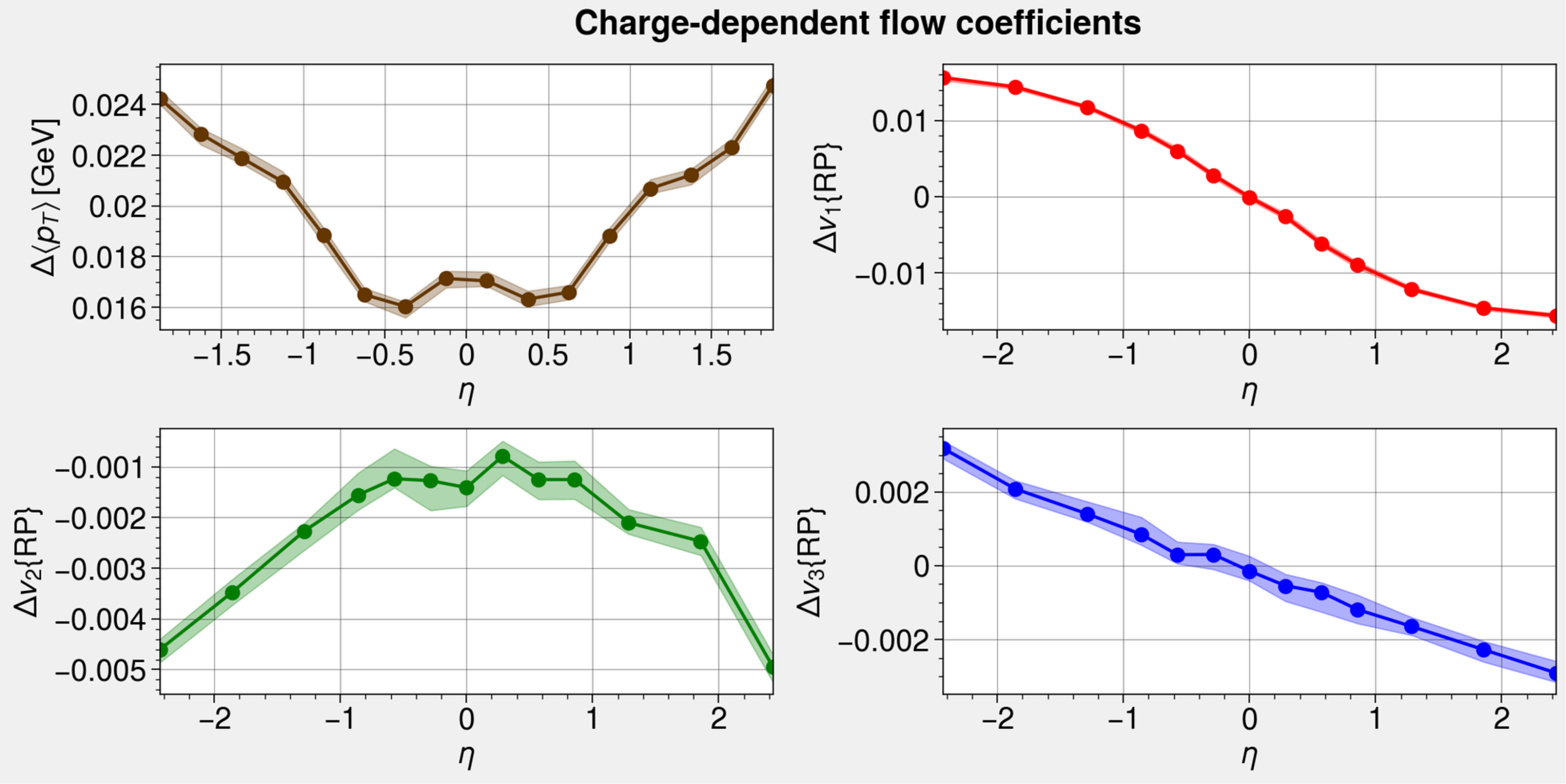
$$q_{\text{part.}}\left(\vec{E} - \vec{B} \times \vec{v}\right) = \mu m \vec{v}$$



External EMF from initial state charge distribution



Charge identified observables @ ~5020GeV



NOTE: Not a fit, magnitude of effect is sensitive to 3+1D parameters.

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shaping tomorrow

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[2] G. Nijs, W. van der Schee, U. Gürsoy, and R. Snellings, "Transverse Momentum Differential Global Analysis of Heavy-Ion Collisions," *Phys. Rev. Lett.*, vol. 126, no. 20, p. 202301, May 2021, doi: 10.1103/PhysRevLett.126.202301.

[3] G. Nijs, W. van der Schee, U. Gürsoy, and R. Snellings, "Bayesian analysis of heavy ion collisions with the heavy ion computational framework 'Trajectum'," *Physical Review C*, vol. 103, no. 5, May 2021, doi: 10.1103/physrevc.103.054909.

[4] F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, "Relativistic distribution function for particles with spin at local thermodynamical equilibrium," *Annals of Physics*, vol. 338, pp. 32–49, Nov. 2013, doi: 10.1016/j.aop.2013.07.004.

[5] F. Becattini, "Polarization in Relativistic Fluids: A Quantum Field Theoretical Derivation," in *Strongly Interacting Matter under Rotation*, Springer International Publishing, 2021, pp. 15–52. doi: 10.1007/978-3-030-71427-7_2.

[6] U. Gürsoy, D. Kharzeev, E. Marcus, K. Rajagopal, and C. Shen, "Charge-dependent flow induced by magnetic and electric fields in heavy ion collisions," *Phys. Rev. C*, vol. 98, no. 5, p. 55201, Nov. 2018, doi: 10.1103/PhysRevC.98.055201.