

BARYON NUMBER, STRANGENESS, AND ELECTRIC CHARGE FLUCTUATIONS IN HYDRODYNAMICS AT LHC HIGH ENERGY COLLISIONS

Christopher Plumberg, **Dekrayat Almaalol**, Travis Dore , Debora Mroczek , Patrick Carzon , Jordi Salinas San Martin, Lydia Spychalla , Matthew Sievert, Jacquelyn Noronha-Hostler



(Theory: [Arxiv.2209-11210](#)- Phenomenology: Arxiv.2311-xxxx)

University of Illinois at Urbana-Champaign

The 30th International Conference on Ultra-relativistic Nucleus-Nucleus Collisions

UH (Sep 03-09), HOUSTON, TEXAS

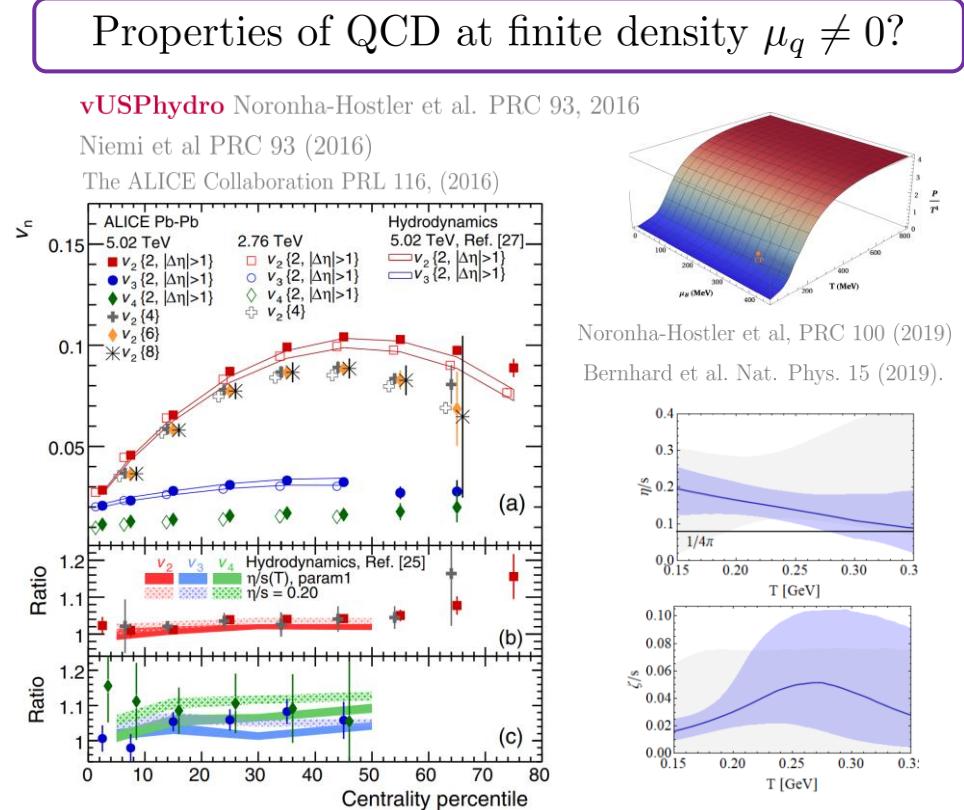
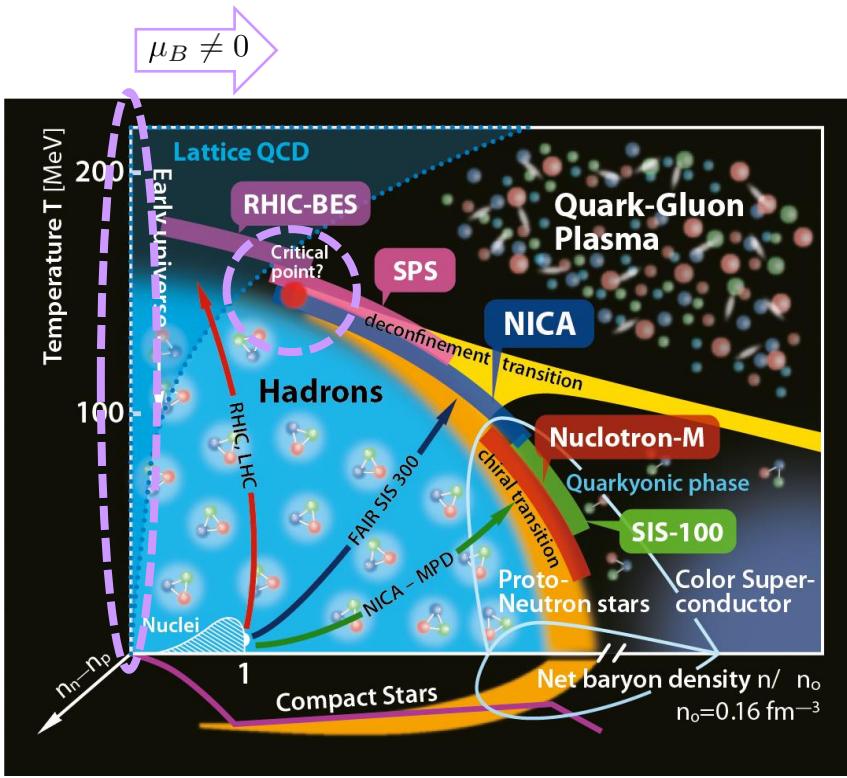


Illinois Center for Advanced Studies of the Universe



BIG PICTURE | HEAVY ION SIMULATIONS AND THE QCD MATTER PROPERTIES

- Extensive investigation of the $\mu_q = 0$ region of the QCD phase diagram using model-to-data comparison in heavy ion collision simulations.

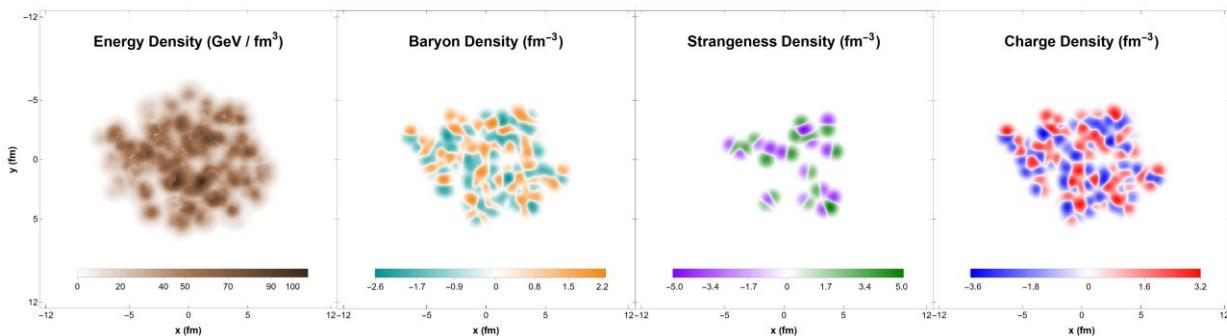


AN OPPORTUNITY | LOCAL CHARGE FLUCTUATIONS AT LHC ENERGY

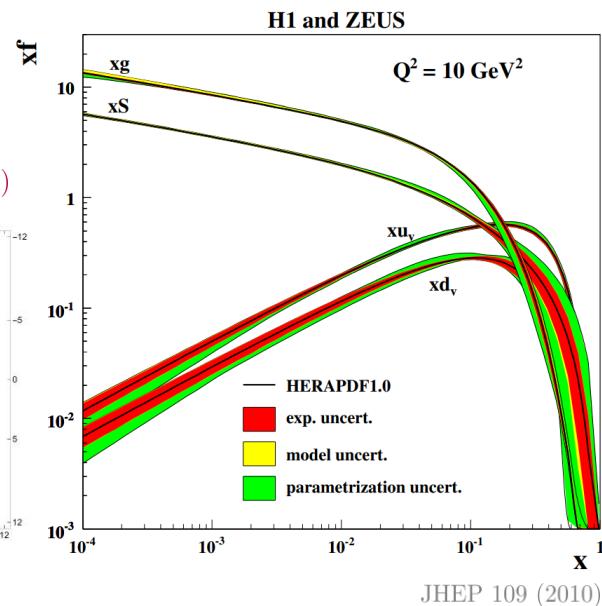
Local baryon, strange, and electric BSQ charge fluctuations (Net=0)

- Charges are produced in early stages by gluon splittings into $q\bar{q}$ pairs.

ICCING model Carzon et al, PRC 105 (2022)

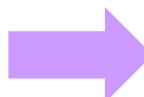


T. Dore (Wed at 4:30pm)



JHEP 109 (2010)

Studying charge fluctuations in the well controlled top LHC collider energy.



OPEN QUESTIONS | QCD AT FINITE CHARGE DENSITY

Initial state+pre-equilibrium:

- Do charge event-by-event fluctuations map into final charge and flavor dependent correlations?. Is it an observable effect?

Hydrodynamics evolution

- What dynamical trajectories could the collision system explore due to the hydrodynamics of local BSQ charge fluctuations?
- How robust is the thermodynamics of the LQCD EoS beyond $\mu_B = 0$?.

Freezeout+Criticality

- Can the initial BSQ local fluctuations reproduce a measurable charge fluctuations at freezeout at LHC energy?

FRAMEWORK |

Conserved ChArges Hydrodynamik Evolution [CCAKE](#)

- Smoothed Particle Hydrodynamics simulation with charge fluctuations.
- First implementation of lattice QCD EoS at finite BSQ charge density.
- Open Source Code based on vUSPhydro with NEW upgrades.



THEORY | TRANSIENT MULTIPLE COMPONENT FLUID DYNAMICS

The state of the system is described by: $\varphi_i = \{u^\mu, \varepsilon, \rho_q, \Pi, \pi^{\mu\nu}, n_q^\mu\}$ ($q = B, S, Q$)

$$D_\mu T^{\mu\nu} = 0 \quad \text{Energy-momentum conservation} \quad \text{Maximum entropy principle}$$

$$D_\mu N_q^\mu = 0 \quad \text{Charge conservation} \quad \nabla_\mu S^\mu = \frac{1}{2\eta T} \pi_{\mu\nu} \pi^{\mu\nu} + \frac{1}{\zeta T} \Pi^2 + \frac{1}{\kappa_{qq'} T^2} n_\mu^q n_{q'}^\mu \geq 0$$

IS Relaxation type equations

vUSPhydro: Noronha-Hostler et al PRC 90, 2014

$$\tau_\Pi (D\Pi + \Pi\theta) + \Pi + \zeta\theta = 0$$

$$\tau_\pi \left(\Delta_{\mu\nu\alpha\beta} D\pi^{\alpha\beta} + \frac{4}{3} \pi_{\mu\nu} \theta \right) + \pi_{\mu\nu} = 2\eta\sigma_{\mu\nu}$$

THEORY | TRANSIENT MULTIPLE COMPONENT FLUID DYNAMICS

The state of the system is described by: $\varphi_i = \{u^\mu, \varepsilon, \rho_q, \Pi, \pi^{\mu\nu}, n_q^\mu\}$ ($q = B, S, Q$)

New DoF!

$$D_\mu T^{\mu\nu} = 0 \quad \text{Energy-momentum conservation} \quad \text{Maximum entropy principle}$$

$$D_\mu N_q^\mu = 0 \quad \text{Charge conservation} \quad \nabla_\mu S^\mu = \frac{1}{2\eta T} \pi_{\mu\nu} \pi^{\mu\nu} + \frac{1}{\zeta T} \Pi^2 + \frac{1}{\kappa_{qq'} T^2} n_\mu^q n_{q'}^\mu \geq 0$$

IS Relaxation type equations

$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \frac{\tau_\Pi}{2} \Pi) \theta - \underbrace{\frac{\tau_\Pi}{2\beta_\Pi} \dot{\beta}_\Pi \Pi}_{\dot{\beta}} + \underbrace{\frac{\zeta \lambda_\Pi^q}{\beta} n_q^\mu \nabla_\mu \delta_{n\Pi}^q - \frac{\zeta \delta_{n\Pi}^q}{\beta} \partial_\mu n_q^\mu + \frac{\zeta \delta_{\Pi\pi}}{2\beta} \pi^{\mu\nu} \sigma_{\mu\nu}}_{\text{dissipative couplings}},$$

NEW: BSQ diffusion + non-linear coupling terms

DA, Dore, Noronha-Hostler arxiv.2209-11210

$$\tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} = 2\eta \sigma^{\mu\nu} + \frac{\tau_\pi}{2} \pi^{\mu\nu} \theta + \frac{\tau_\pi \dot{\beta}_\pi}{2\beta_\pi} \pi^{\mu\nu} - \underbrace{\frac{2\eta \delta_{n\pi}^q}{\beta} \nabla^{\langle \mu} n_{q'}^{\nu \rangle}}_{\dot{\beta}} + \underbrace{\frac{2\eta \lambda_\pi^q}{\beta} n_q^{\langle \mu} \nabla^{\nu \rangle} \delta_{n\pi}^q - \frac{\eta \delta_{\Pi\pi}}{\beta} \Pi \sigma_{\mu\nu}}_{\text{dissipative couplings}},$$

$$\tau_{qq'} \dot{n}_{q'}^\mu + n_q^\mu = -\kappa_{qq'} \nabla^\mu \alpha_{q'} + \frac{\tau_{qq'} n_{q'}^\mu}{2\beta} \theta - \underbrace{\frac{\tau_{qq'}}{2\beta} \dot{\beta}_{q'} l n_l^\mu}_{\dot{\beta}} - \left[\frac{\kappa_{qq'} \delta_{n\Pi}^{q'}}{\beta} \nabla^\mu \Pi + \frac{\kappa_{qq'} \delta_{n\pi}^{q'}}{\beta} \nabla_\nu \pi^{\mu\nu} \frac{\kappa_{qq'} \tilde{\lambda}_\Pi^{q'}}{\beta} \Pi \nabla^\mu \delta_{n\Pi}^{q'} + \frac{\kappa_{qq'} \tilde{\lambda}_\pi^{q'}}{\beta} \pi^{\mu\nu} \nabla_\nu \delta_{n\pi}^{q'} \right].$$

STABILITY & CAUSALITY ANALYSIS | MULTI COMPONENT FLUID DYNAMICS

$$\nabla_\mu T^{\mu\nu} = 0$$

$$\nabla_\mu N_q^\mu = 0$$

$$\nabla_\mu S^\mu = \frac{1}{2\eta T} \pi_{\mu\nu} \pi^{\mu\nu} + \frac{1}{\zeta T} \Pi^2 + \frac{1}{\kappa_{qq'} T^2} n_\mu^q n_{q'}^\mu \geq 0$$

Key: Dissipation drives the system to equilibrium as $\tau \rightarrow \infty$

DA, Dore, Noronha-Hostler arxiv.2209-11210

Thermodynamics constraints $\frac{1}{\varepsilon + p} \left. \frac{\partial \varepsilon}{\partial p} \right|_s \geq 0 \quad \frac{1}{\varepsilon + p} \left. \frac{\partial \varepsilon}{\partial s} \right|_p \left. \frac{\partial p}{\partial s} \right|_{\alpha_B} \geq 0$

Transport constraints $\beta_\Pi \geq 0 \quad \beta_\pi \geq 0$

Mixed constraints $\frac{\kappa_n^{BB}}{2\lambda^2} - \frac{(\gamma_{n\Pi}^B)^2}{\beta_\Pi} - \frac{(\gamma_{n\pi}^B)^2}{\beta_\pi} \geq (\varepsilon + p) \left(T^2 \left. \frac{\partial s}{\partial \varepsilon} \right|_p \left. \frac{\partial s}{\partial p} \right|_{\alpha_B} \left(\left. \frac{\partial \alpha_B}{\partial s} \right|_p \right)^2 - \frac{1}{4} \left. \frac{\partial p}{\partial \varepsilon} \right|_s \left(\left. \frac{\partial \alpha_B}{\partial p} \right|_s \right)^2 \right)$

Method: Gavassino, Class.Quant.Grav. 38 (2021)

TESTING LATTICE EOS AT FINITE DENSITY

- 4D interpolation and root-finding:

Equation of State \Rightarrow Hydrodynamics fields
 $P_0(\varepsilon, \rho_B, \rho_S, \rho_q) \rightarrow P_0(T, \mu_B, \mu_S, \mu_Q)$

- Update to the EOS code

Incorporate thermodynamics derivatives required by the hydro simulation:

$$\frac{dw}{d\tau} = \sum_{\varphi \in \Phi} \frac{\partial w}{\partial \varphi} \frac{d\varphi}{d\tau}$$

- Fallbacks EoSs

Taylor expansion around $\mu_B = 0$

Noronha-Hostler et al PRC 100 (2019), P. Alba et al., PRD 96(2017)

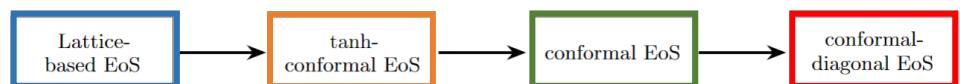
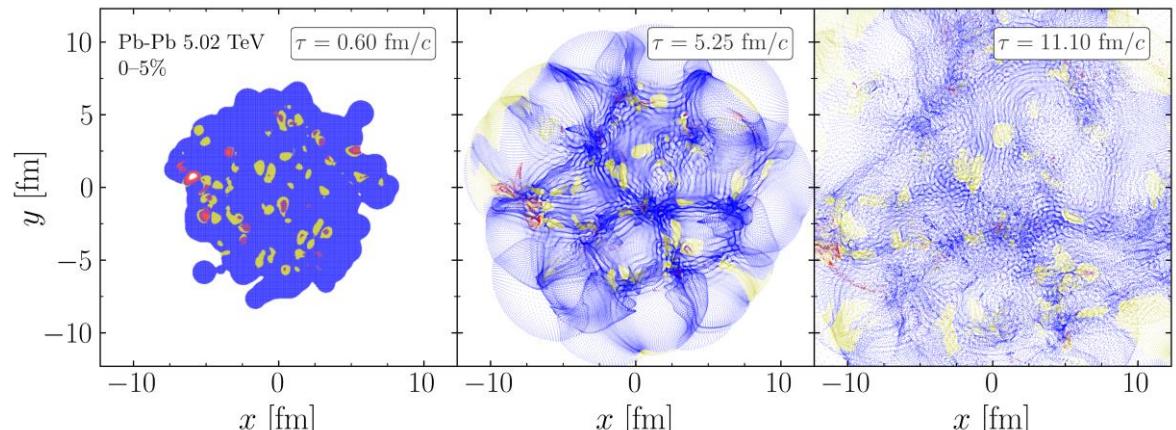
$$\frac{P_0(T, \mu_B, \mu_Q, \mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{i,j,k}^{BQS} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

$$\chi_{ijk}^{BQS} = \left. \frac{\partial^{i+j+k} (p/T^4)}{\partial (\frac{\mu_B}{T})^i \partial (\frac{\mu_Q}{T})^j \partial (\frac{\mu_S}{T})^k} \right|_{\mu_B, \mu_Q, \mu_S=0}$$

(valid only until about ($\mu_B/T \leq 2$))

- less than 5 – 10% at τ_0
- mostly at low T regions

C. Plumberg, DA , T. Dore , D. Mroczek , P. Carzon , J. Salina San Martin, L. Spychara , M. Sievert, and J. Noronha-Hostler, in preparation(2023)



OPEN SOURCE/ easily adapted to new EoS options

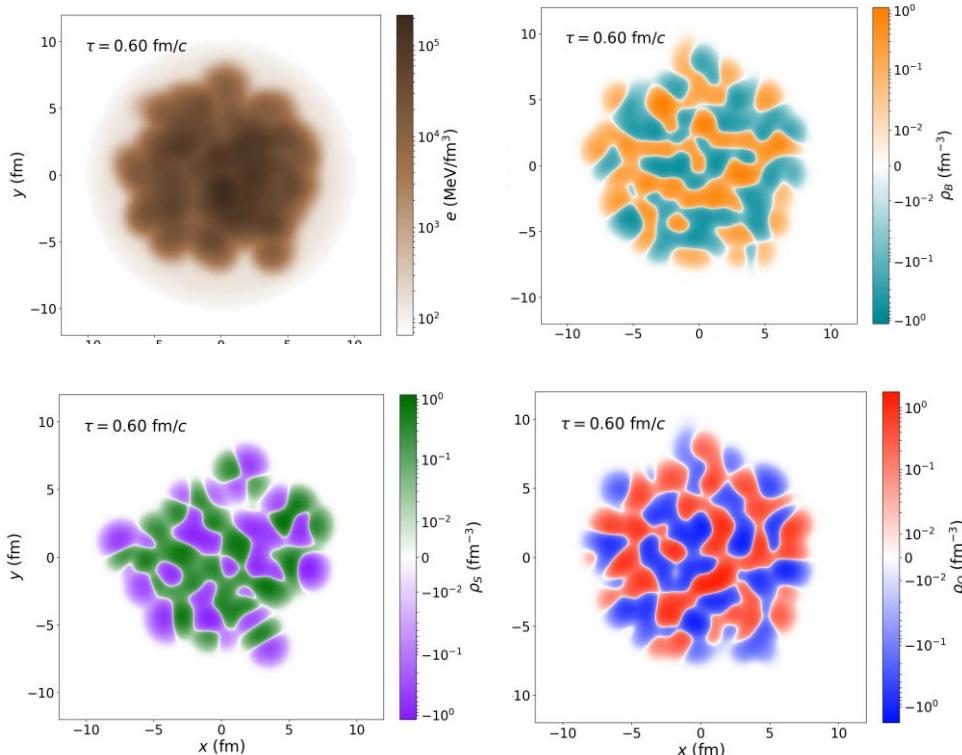
2+1D DISSIPATIVE FLUID DYNAMICS WITH IDEAL BSQ EVOLUTION

Conserved ChArges Hydrodynamik Evolution

[CCAKE](#)

C. Plumberg, DA , T. Dore , D. Mroczek , P. Carzon , J. Salina San Martin, L. Spychalla , M. Sievert, and J. Noronha-Hostler, in preparation(2023)

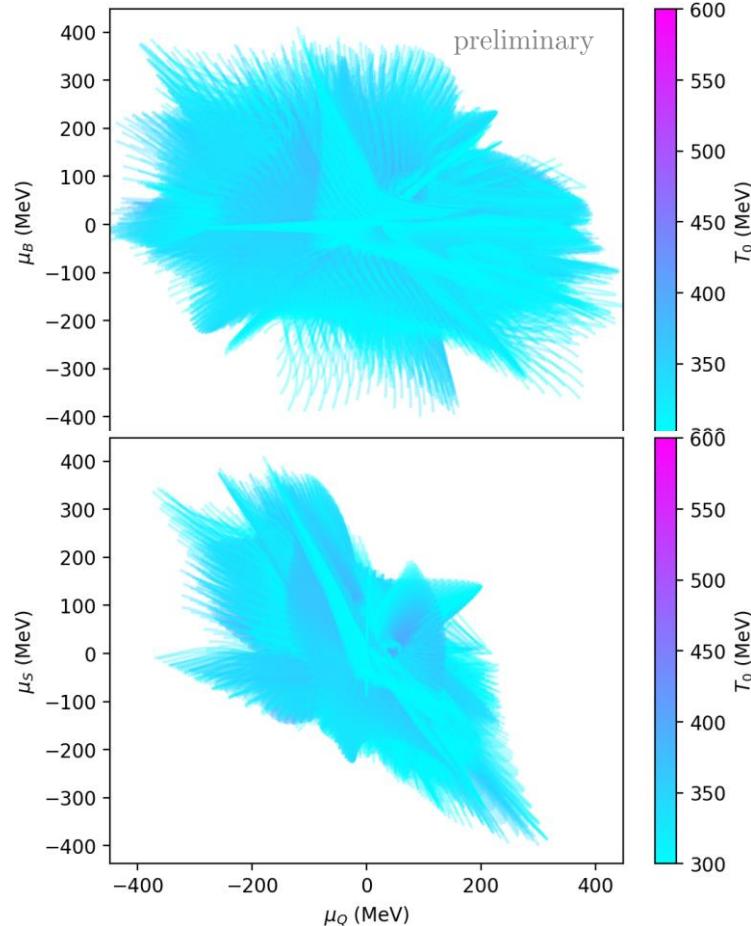
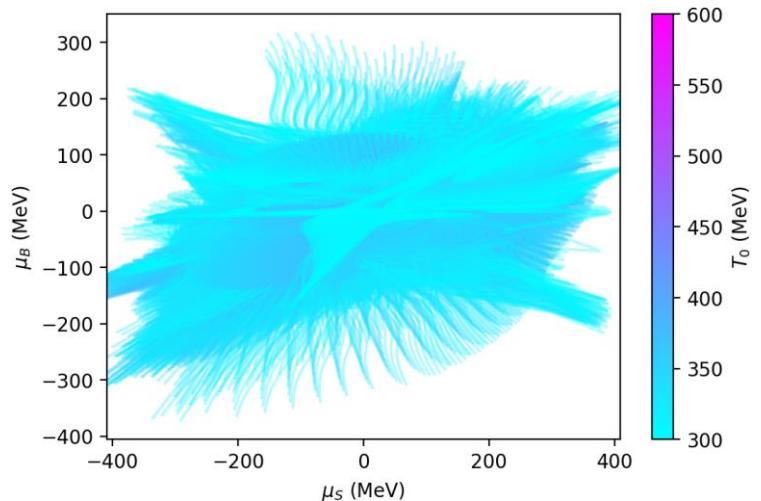
- BSQ charge densities evolution mimics the energy transport
- The code passes the Gubser test
- Energy and charge densities are simultaneousl conserved during the full dynamical evolution
- Dynamical evolution is highly non-trivial
- How would coupled diffusion modify the dynamics of charge sectors?



BSQ CHARGE CORRELATIONS | DYNAMICAL TRAJECTORIES 0-5%

Central (0 – 5%) Pb+Pb at 5.02 TeV

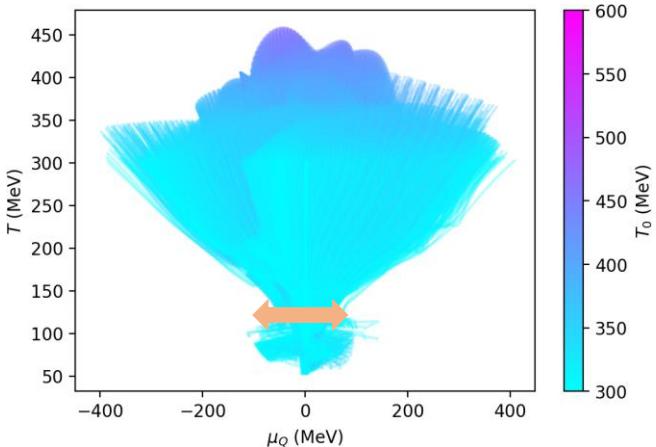
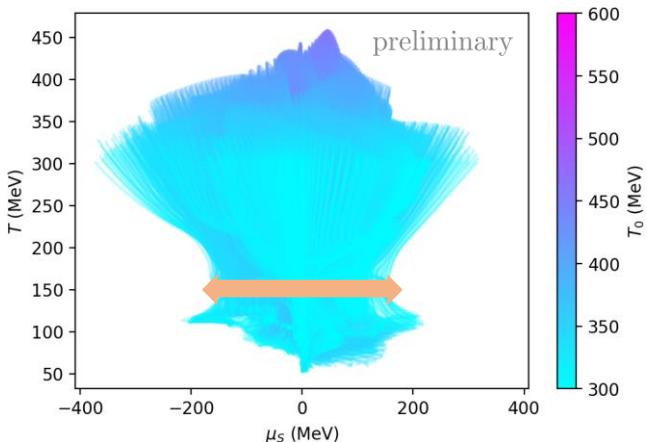
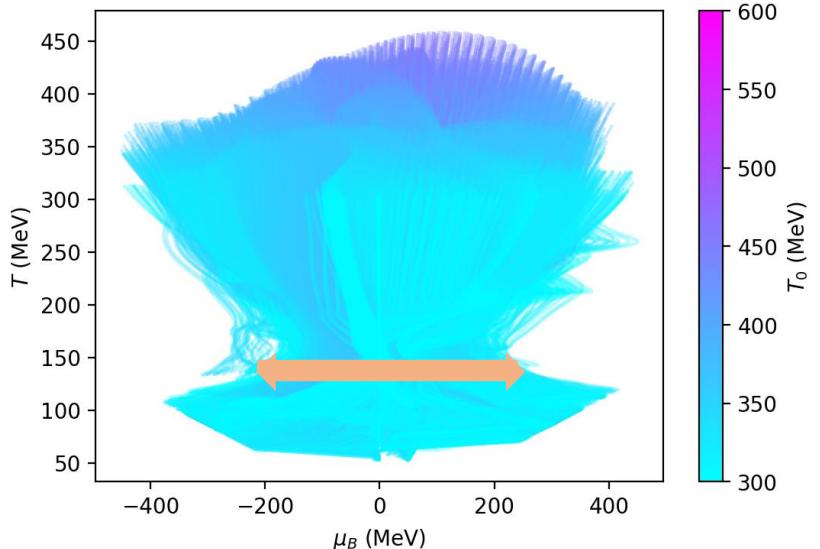
- Signs of charge correlations imprints consistent with thermal model predictions ($\mu_Q \sim -0.1\mu_B, \mu_S \sim 1/3\mu_B$), but agreement is not dominant
- Evolution is highly nonlinear in the energy-charge sectors



BSQ CHEMICAL POTENTIALS | FREEZE-OUT

Fluctuations of BSQ Charge fluctuations are preserved until freezeout!

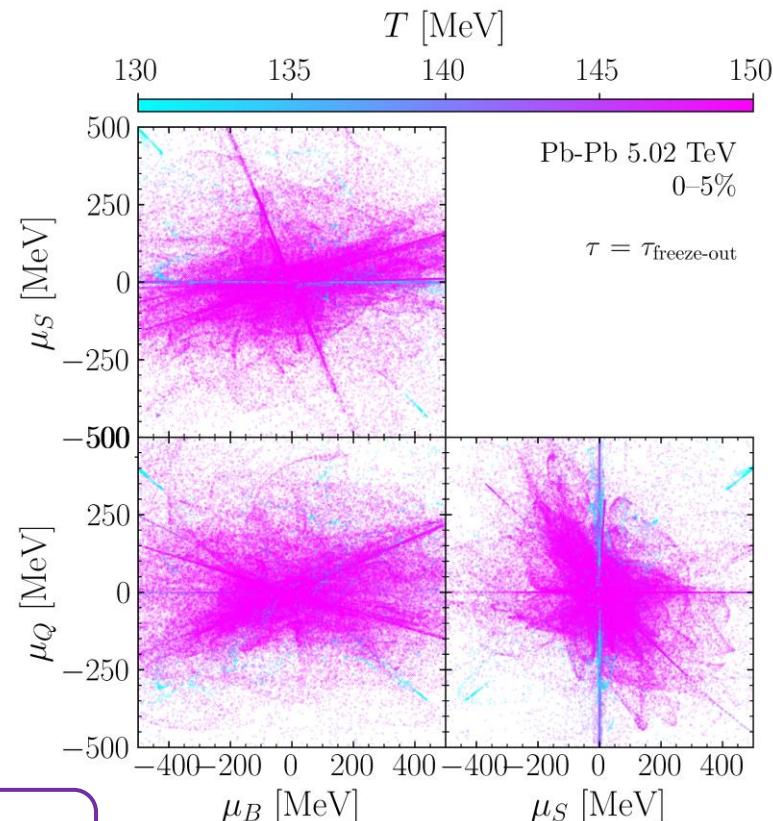
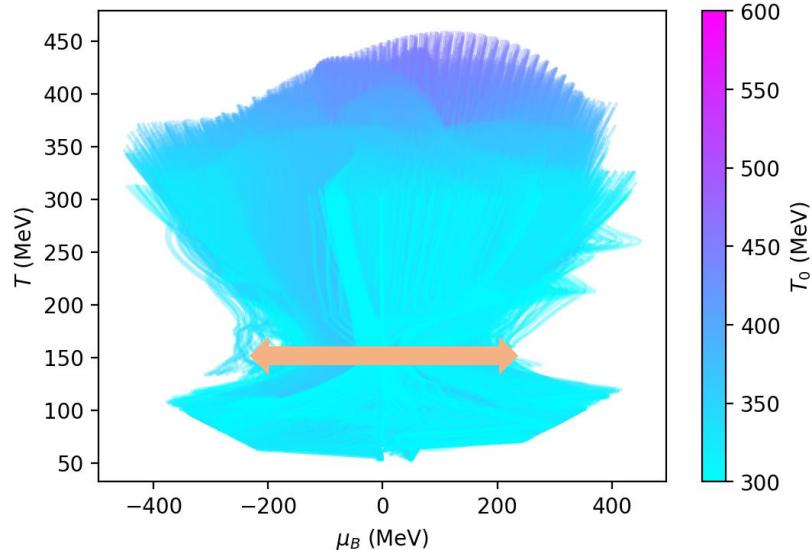
- Deviations in the range of the μ_q at freezeout (100 – 200 MeV)
- Central events show larger fluctuations of charges at freeze-out
- additional information from the initial state geometry?
- How do these fluctuations manifest themselves in the final flow?



BSQ CHEMICAL POTENTIALS | FREEZE-OUT

BSQ Charge fluctuations are preserved until freezeout!

- Deviations in the range $(\mu_q)_{FO}$ at $(100 - 400 \text{ MeV})$
- Central events show larger fluctuations at freeze-out

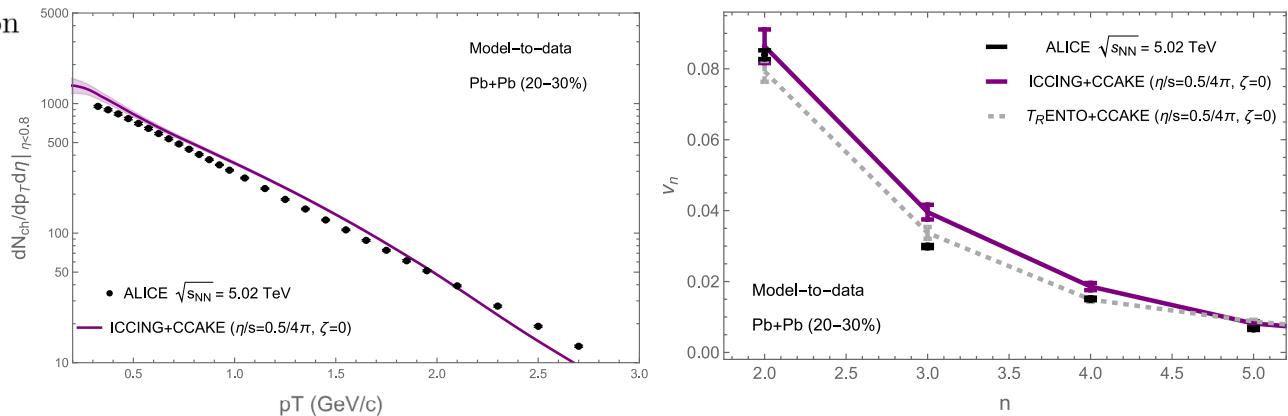


How do these fluctuations manifest themselves in the final flow?

FLOW | OBSERVABLES AT LHC WITH CHARGE FLUCTUATIONS

C. Plumberg, DA , T. Dore , D. Mroczek , P. Carzon , J. Salinas San Martin, L. Spychalla , M. Sievert, and J. Noronha-Hostler, in preparation (2023)

- preliminary: out-of-the box comparison show more sensitivity to BSQ charge fluctuations in central collisions
- parametrize: $\eta(T, \mu_q)$ and $\zeta(T, \mu_q)$.



Charged spectra: S. Acharya et al. (The ALICE Collaboration) JHEP 1811 (2018)

Multiplicity: J. Adam et al. (The ALICE Collaboration) PRL. 116, 2016

Integrated vns: J. Adam et al. (The ALICE Collaboration) PRL. 116, 2016

Minimum bias and Bayesian tools
are in progress run to systematically
constrain the model parameters .

CONCLUSIONS AND OUTLOOK

- **BSQ Hydrodynamics theory:**

Multi components Israel Stewart transient hydrodynamics including **new** coupling terms

- **Theoretical consistency checks:**

Linear stability and causality constraints on BSQ hydrodynamics evolution

- **Developments:**

4D interpolation of the lattice QCD EoS at finite μ_q . (**Open Source**)

- **Outcome:**

First integrated framework at LHC to study flow and flow analysis with BSQ conserved charged

(**Open Source**)

(**ICCING code**)

(**2+1D CCAKE**)

- **Outlook and challenges**

- Finite potential dependence of transport coefficients
- Towards full dynamics || BSQ Diffusion.
- Challenge || Out of equilibrium corrections at freezeout
- Background for CME observables.

- **CCAKE Numerical Upgrades**

- (3+1D) coming soon in version.2 Serenone, W
- Full IS + coupling terms
- Adaptive SPH hydrodynamics
- Upgrades to run on GPUs Serenone, W

Thank you for your attention

BACK-UP

NUMERICAL BENCHMARK || GUBSER FLOW

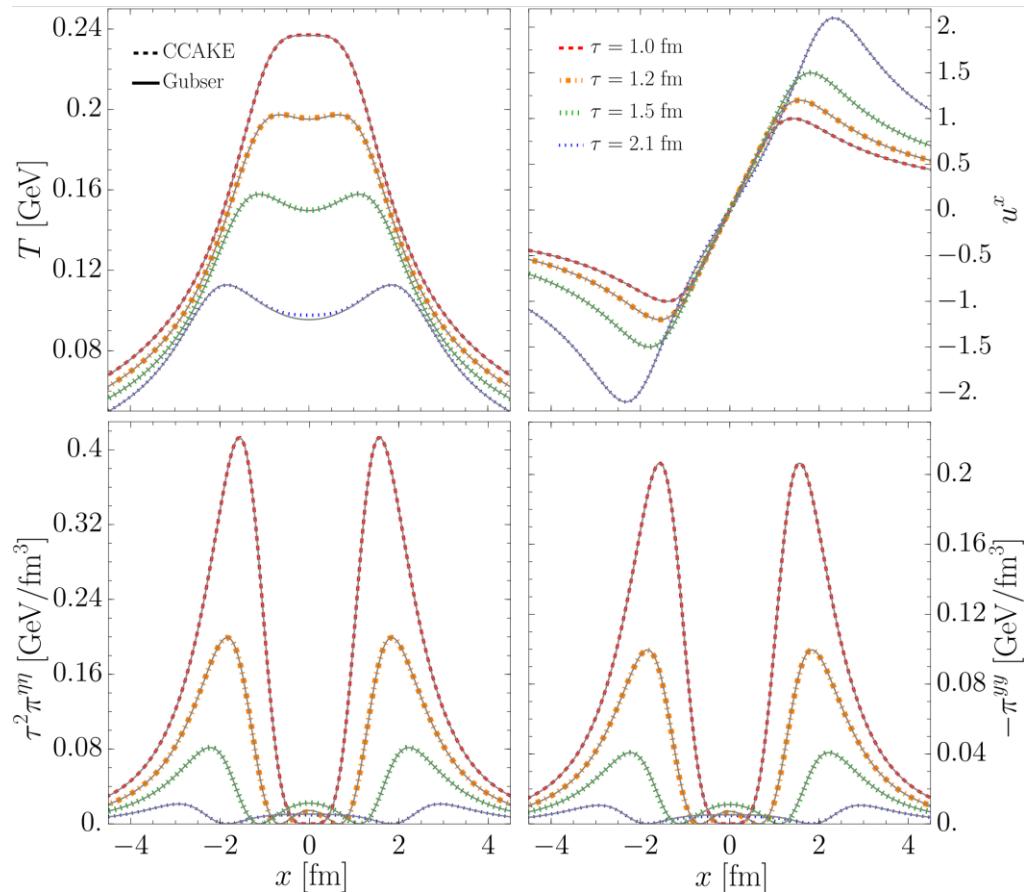
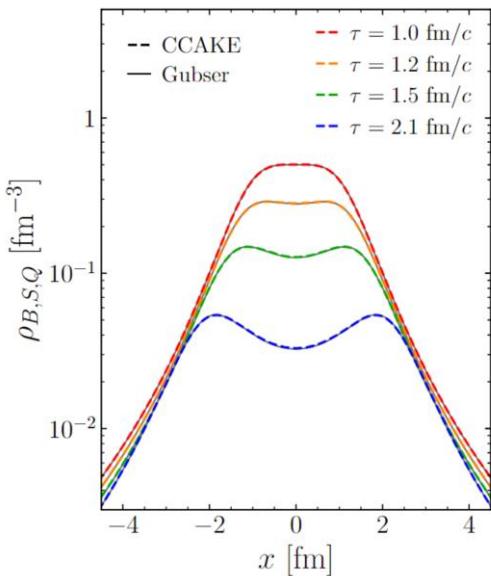
- **Numerical benchmark:**

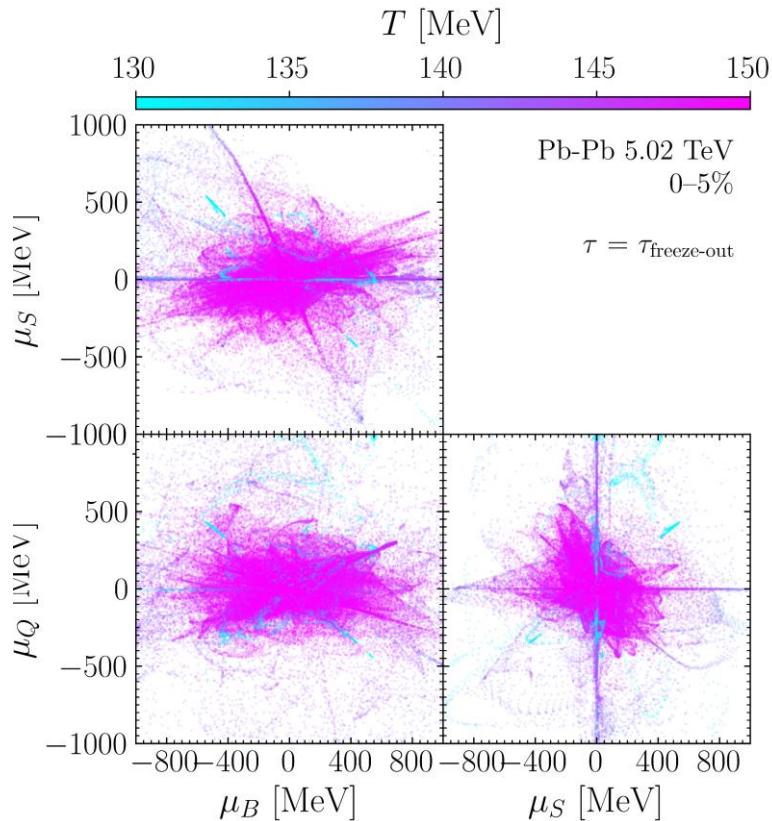
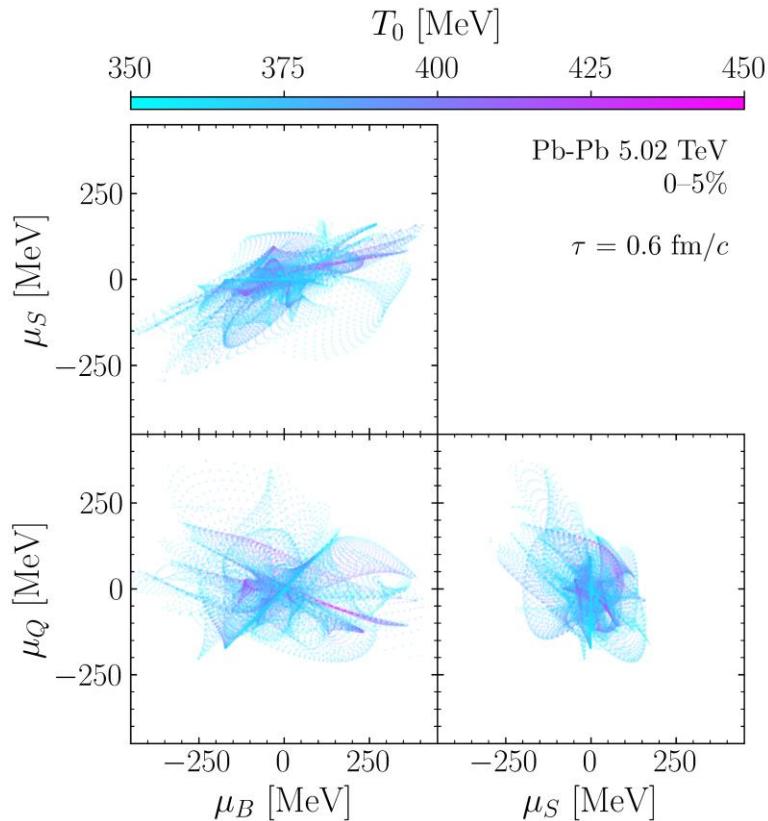
The code passes Gubser test of ideal BSQ

$(\mu_B = 0)$ case Denicol et al, PRC 98 (2018)

- **Hydrodynamics applicability:**

Quantitative study of K_n, R_n^{-1}





SMOOTHED PARTICLE HYDRODYNAMICS

SPH parametrize the matter flow in terms of a set of lagrangian coordinates $\{\vec{r}_i(t)\}$ or “SPH particles” which follow the flow of the fluid

The density of an extensive quantity A is parametrized by the ansatz,

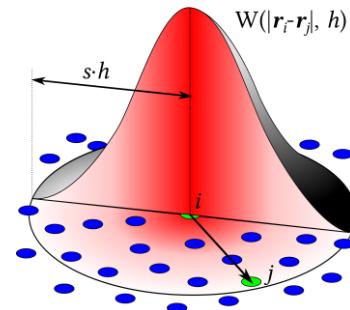
$$a_{SPH}(\mathbf{r}, t) = \sum_{\alpha}^{N_{SPH}} A_{\alpha}(t) W(|\mathbf{r} - \mathbf{r}_{\alpha}(t)|; h)$$

The parameter h is the smoothing scale “short wavelength cut” used to enforce the coarse-graining, with

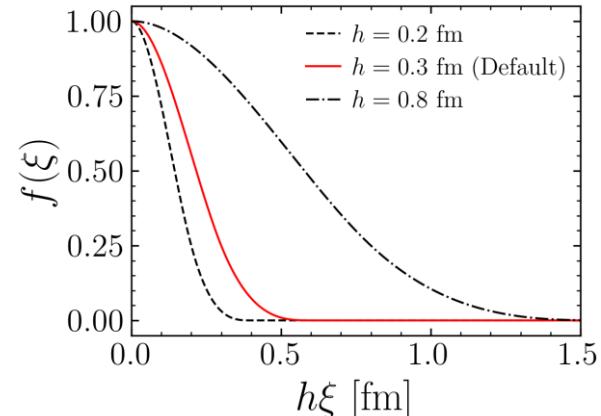
$$\lim_{h \rightarrow 0} W(|\mathbf{r} - \mathbf{r}'|; h) = \delta(|\mathbf{r} - \mathbf{r}'|)$$

- Conservation laws are obeyed by construction.
- Possibility to smooth out undesirable degrees of freedom.
- Robustness against geometry.

Monaghan, Ann. Rev. Astron. Astrophys. 30(1992)



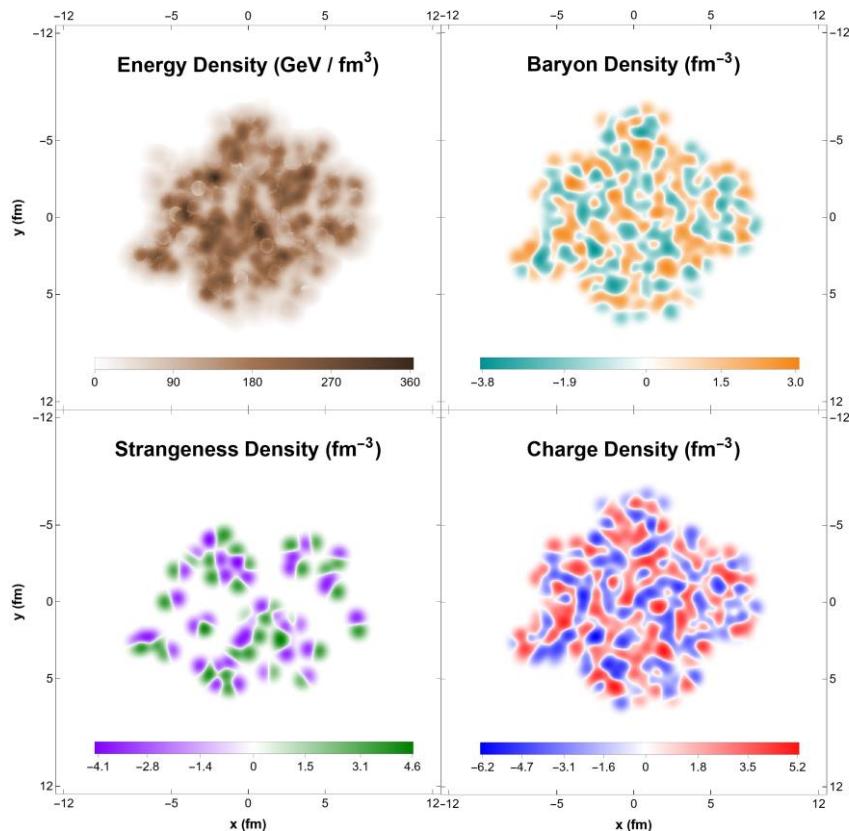
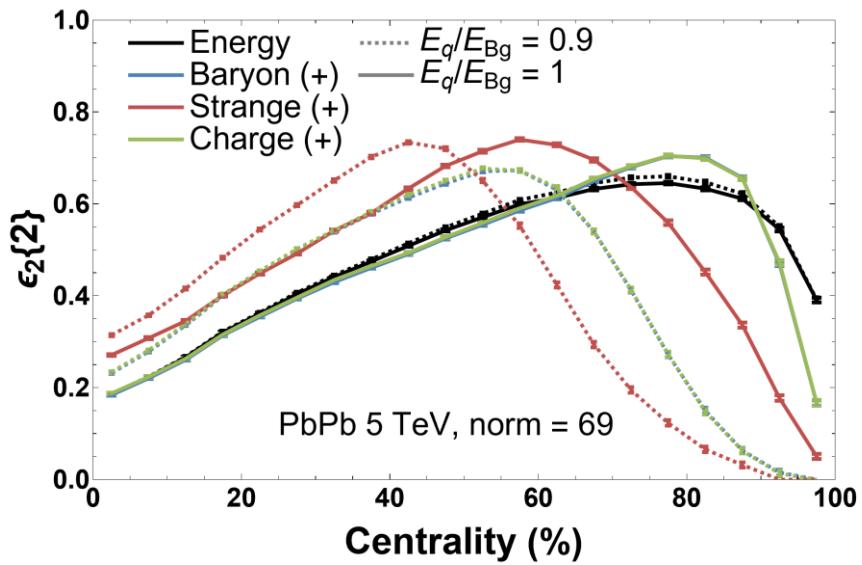
$$\int W(|\mathbf{r} - \mathbf{r}'|; h) d\mathbf{r}' = 1$$



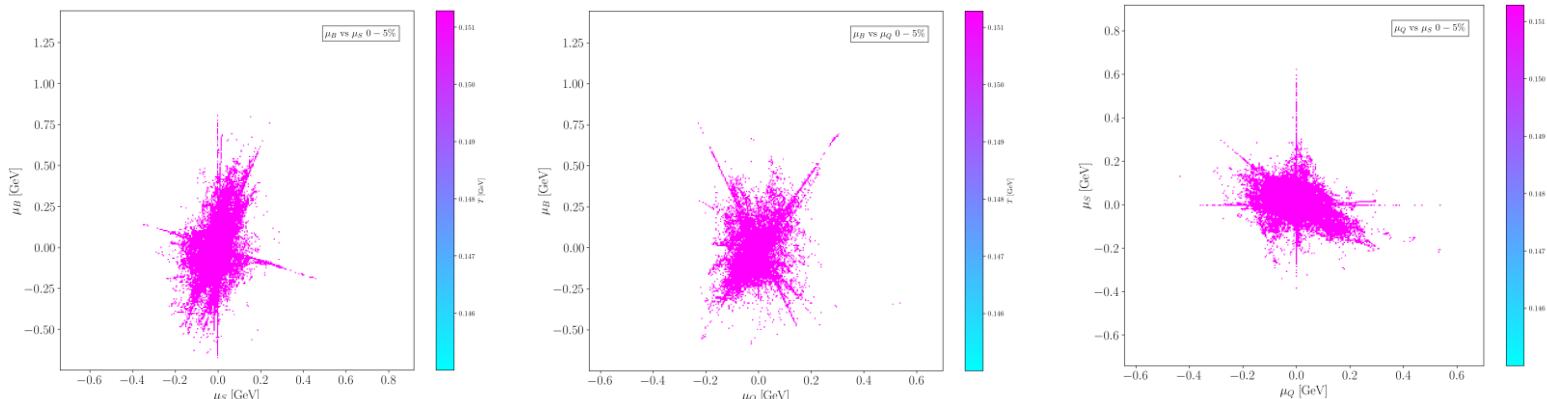
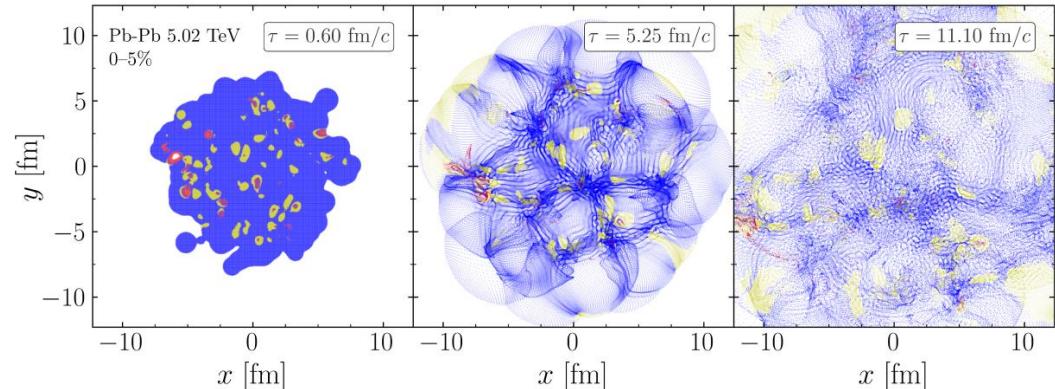
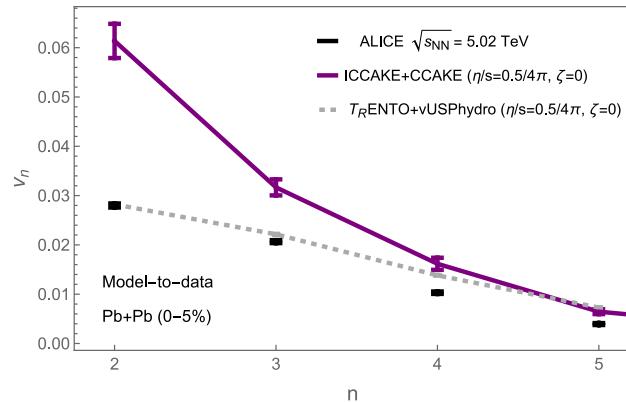
INITIAL STATE || LOCAL BSQ FLUCTUATIONS AT LHC

ICCING model

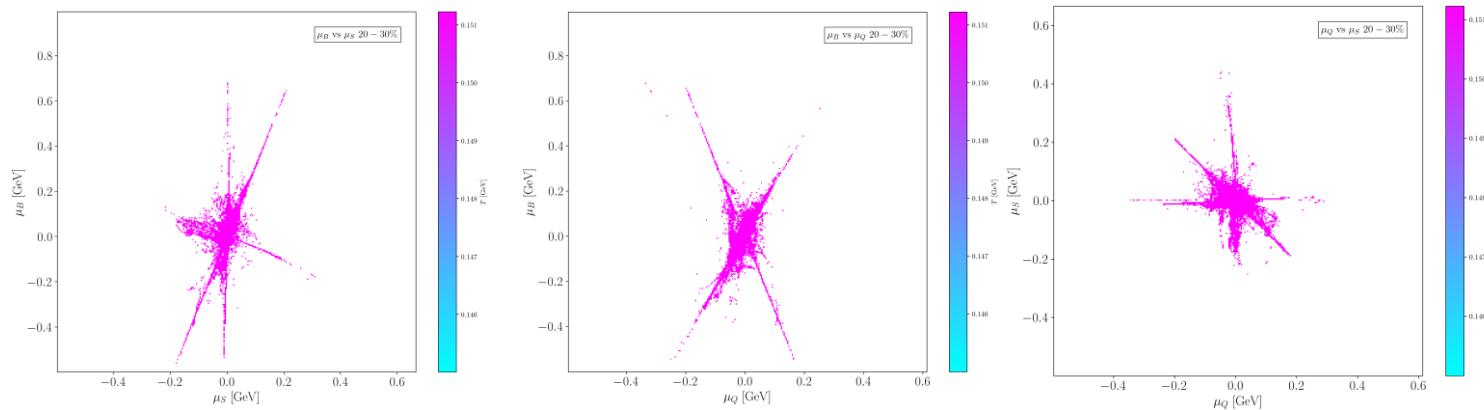
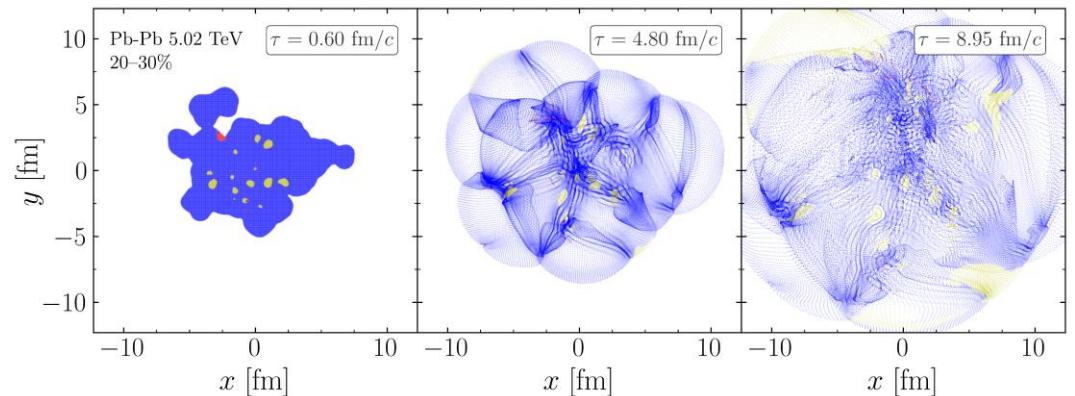
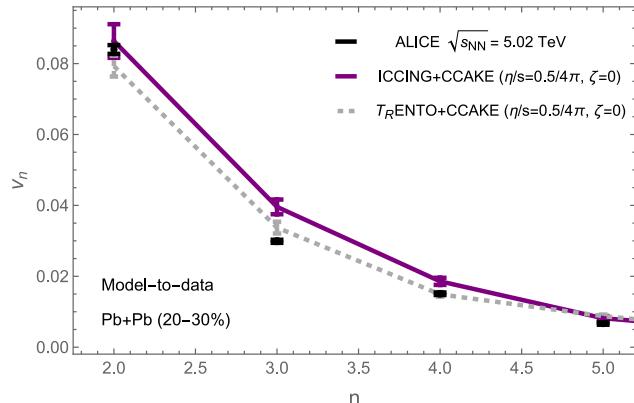
- 4D Initial state input $[\varepsilon_0(\tau_0), \rho_0^B(\tau_0), \rho_0^S(\tau_0), \rho_0^Q(\tau_0)]$
- Gradients in $\{\nabla P, \nabla \frac{\mu_B}{T}, \nabla \frac{\mu_S}{T}, \nabla \frac{\mu_Q}{T}\}$
- A pre-equilibrium evolution for the charge densities [Carzon et al](#), soon to appear



CHARGE FLUCTUATIONS AT FREEZE-OUT



CHARGE FLUCTUATIONS AT FREEZE-OUT



Multi-component Hydrodynamics as an effective field theory

Maximum entropy principle: 2nd order

Israel, Stewart, Ann. Phys. 118 (1979)

$$S^\mu = su^\mu - \sum_q^{B,S,Q} \alpha_q n_q^\mu - \frac{1}{2} u^\mu \left(\beta_\Pi \Pi^2 + \beta_\pi \pi^{\mu\nu} \pi_{\mu\nu} + \sum_q^{B,S,Q} \beta_n^{qq'} n_q^\mu n_{q'}^\mu \right) - \sum_q \left(\gamma_{n\Pi}^q n_q^\mu \Pi + \gamma_{n\pi}^q n_q^\nu \pi_\nu^\mu \right) - \frac{1}{2} (u^\nu \beta_{\Pi\pi} \Pi \pi_{\mu\nu})$$

$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \frac{\tau_\Pi}{2} \Pi) \theta - \underbrace{\frac{\tau_\Pi}{2\beta_\Pi} \dot{\beta}_\Pi \Pi}_{\dot{\beta}} + \underbrace{\frac{\zeta \lambda_\Pi^q}{\beta} n_q^\mu \nabla_\mu \delta_{n\Pi}^q - \frac{\zeta \delta_{n\Pi}^q}{\beta} \partial_\mu n_q^\mu + \frac{\zeta \delta_{\Pi\pi}}{2\beta} \pi^{\mu\nu} \sigma_{\mu\nu}}_{\text{dissipative couplings}},$$

$$\tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} = 2\eta \sigma^{\mu\nu} + \frac{\tau_\pi}{2} \pi^{\mu\nu} \theta + \frac{\tau_\pi \dot{\beta}_\pi}{2\beta_\pi} \pi^{\mu\nu} - \underbrace{\frac{2\eta \delta_{n\pi}^q}{\beta} \nabla^{\langle \mu} n_q^{\nu \rangle}}_{\dot{\beta}} + \underbrace{\frac{2\eta \lambda_\pi^q}{\beta} n_q^{\langle \mu} \nabla^{\nu \rangle} \delta_{n\pi}^q - \frac{\eta \delta_{\Pi\pi}}{\beta} \Pi \sigma_{\mu\nu}}_{\text{dissipative couplings}},$$

$$\tau_{qq'} \dot{n}_{q'}^\mu + n_q^\mu = -\kappa_{qq'} \nabla^\mu \alpha_{q'} + \frac{\tau_{qq'} n_{q'}^\mu}{2\beta} \theta - \underbrace{\frac{\tau_{qq'} \dot{\beta}_{q'l} n_l^\mu}{2\beta}}_{\dot{\beta}} - \underbrace{\left[\frac{\kappa_{qq'} \delta_{n\Pi}^{q'}}{\beta} \nabla^\mu \Pi + \frac{\kappa_{qq'} \delta_{n\pi}^{q'}}{\beta} \nabla_\nu \pi^{\mu\nu} \frac{\kappa_{qq'} \tilde{\lambda}_\Pi^{q'}}{\beta} \Pi \nabla^\mu \delta_{n\Pi}^{q'} + \frac{\kappa_{qq'} \tilde{\lambda}_\pi^{q'}}{\beta} \pi^{\mu\nu} \nabla_\nu \delta_{n\pi}^{q'} \right]}_{\text{dissipative couplings}}.$$

linear Stability analysis

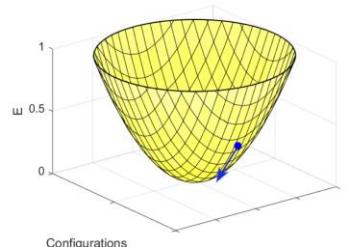
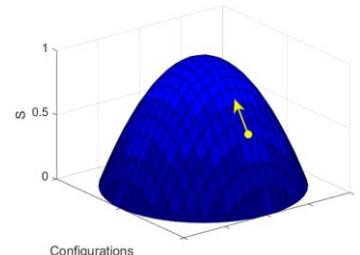
DA, Dore, Noronha-Hostler (Arxiv.2209-11210)

Key: Dissipation drives the system to equilibrium as $\tau \rightarrow \infty$

The entropy difference between the $S(\varphi + \delta\varphi) - S(\varphi)$ can be quantified as an information current E^μ

E is the net information carried by the perturbation

- $E^\mu n_\mu \geq 0$ E^μ is time/light like (connection to causality!)
- $E^\mu = 0; \forall \delta\varphi = 0$
- $\nabla_\mu E^\mu \leq 0$ Information are lost in time



Task: Determine the form of the Lyapunov energy functional

BACKUP || CCAKE

- CCAKE (current status)

Initial State

4D Initial input $[\varepsilon_0(\tau_0), \rho_0^q(\tau_0)]$

ICCING model

+ Pre-equilibrium

Transport: $\eta, \zeta, \kappa_{q'}$

Hydrodynamics

$$\begin{aligned}\partial_\mu(T^{\mu\nu} + \Pi^{\mu\nu}) &= 0 ; \\ \partial_\mu(N_B^\mu + n_B^\mu) &= 0 ; \\ \partial_\mu(N_S^\mu + n_S^\mu) &= 0 ; \\ \partial_\mu(N_Q^\mu + n_Q^\mu) &= 0 ;\end{aligned}$$

SPH lagrangian method

Equation of state

$$P_0(T) \rightarrow P_0(T, \mu_B, \mu_S, \mu_Q)$$

4D Interpolator of EoS

Freezeout

Ideal Distribution

Or $\delta f_\Pi, \delta f_\pi, \delta f_{n_q}$

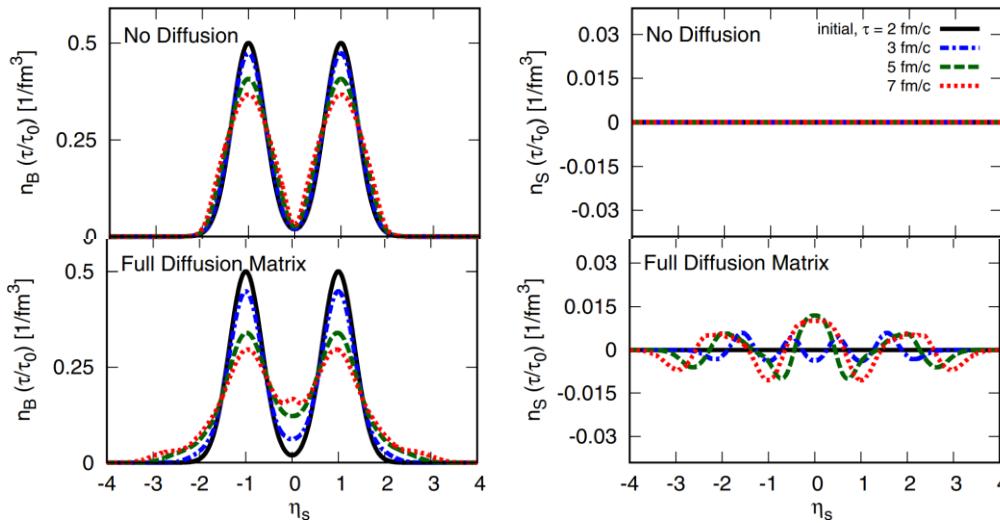
One component fluid

Next || BSQ Diffusion: what to expect ?

Diffusion is crucial to reveal the chemical aspects of the QGP matter

- Coupled diffusion modifies all charge sectors

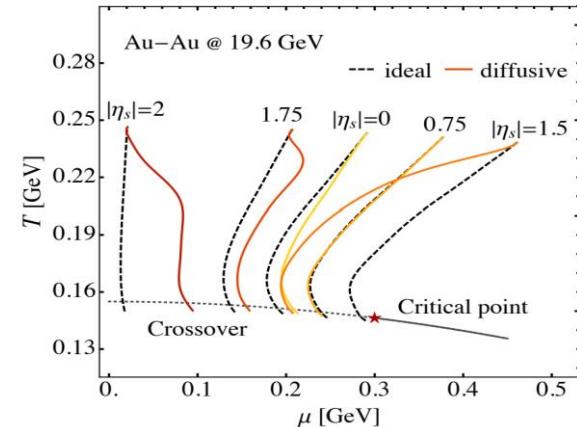
Greif, Fotakis et al., PRL 120, (2018) , Fotakis, Greif et al., PRD 101, (2020)



See : Denicol, Gale, Sangyong, Monnai, Schenke, Shen PRC 98 (2018)

- How does diffusion modify the out of equilibrium dynamics

L. Du and U. Heinz, Comput. Phys. Commun. 251, (2020)



OPEN QUESTIONS: QCD DYNAMICS AT FINITE CHARGE DENSITY

- Charge fluctuations at freezeout

Rustamov A (ALICE) Nucl. Phys. A 967(2017)

ALICE collaboration, PLB 832 (2022)

- Systematics of the search for critical point

Rajagopal et al PRD 102(2020)

Dore et al PRD 102(2020) Du et al PRC 104, (2021)

- Testing the QCD EoS beyond $\mu_B = 0$

Noronha-Hostler et al PRC 100 (2019)

Monnai et al Mod.Phys.A 36 (2021) Monnai et al PRC 100(2019)

- Quantify QGP transport: $\eta(T, \mu_q), \zeta(T, \mu_q)$

Holography, kinetic theory, HRG

- Access to the chemistry (diffusion) of the QGP medium

Fotakis et al PRL 120 (2018)

- Pre-equilibrium dynamics at finite density

Kurkela, Mazeliauskas, PRD99 (2019)

Du, Schlichting, PRL 127 (2021) Carzon et al arxiv.2301.04572 (2023)

- Mapping event-by-event fluctuations.

Martinez, Sievert, Wertepny, and Noronha-Hostler, (2019)

Carzon, Martinez, Sievert, Wertepny, Noronha-Hostler, PRC 105, (2022)

Studying charge fluctuations in the well controlled LHC regime.

Final momentum distribution

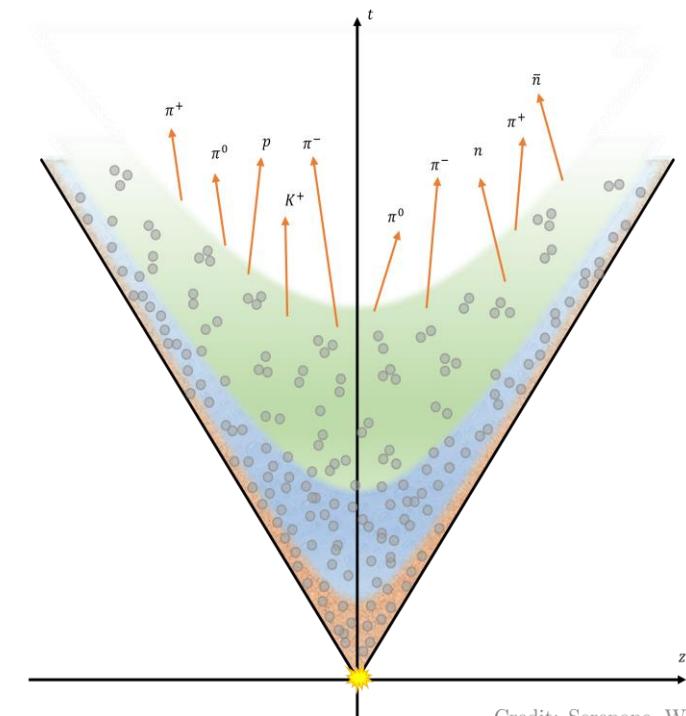
Hadronic Afterburner

Cooper Frye

Relativistic Dissipative Hydrodynamics

Pre-equilibrium

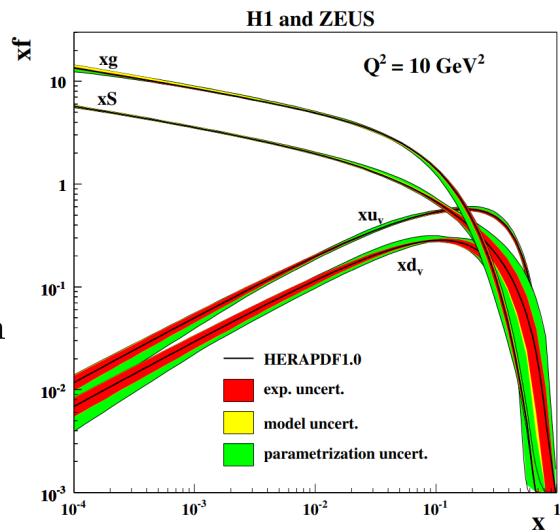
Initial Conditions



AN OPPORTUNITY || LOCAL CHARGE FLUCTUATIONS IN LHC COLLISIONS

- Charges are produced in early stages by gluon splittings into $q\bar{q}$ pairs.
- ICCING model
Carzon et al, PRC 105 (2022)
- Introduce new Gradients in $\{\nabla P, \nabla \frac{\mu_B}{T}, \nabla \frac{\mu_S}{T}, \nabla \frac{\mu_Q}{T}\}$
- Potential access to different information in the initial state geometry.

BSQ fluctuations (Net=0)



C. Plumberg, DA , T. Dore , D. Mroczek , P. Carzon , J. Salina San Martin, L. Spychalla , M. Sievert, and J. Noronha-Hostler, in preparation(2023)

