Initializing BSQ with Open-Source ICCING

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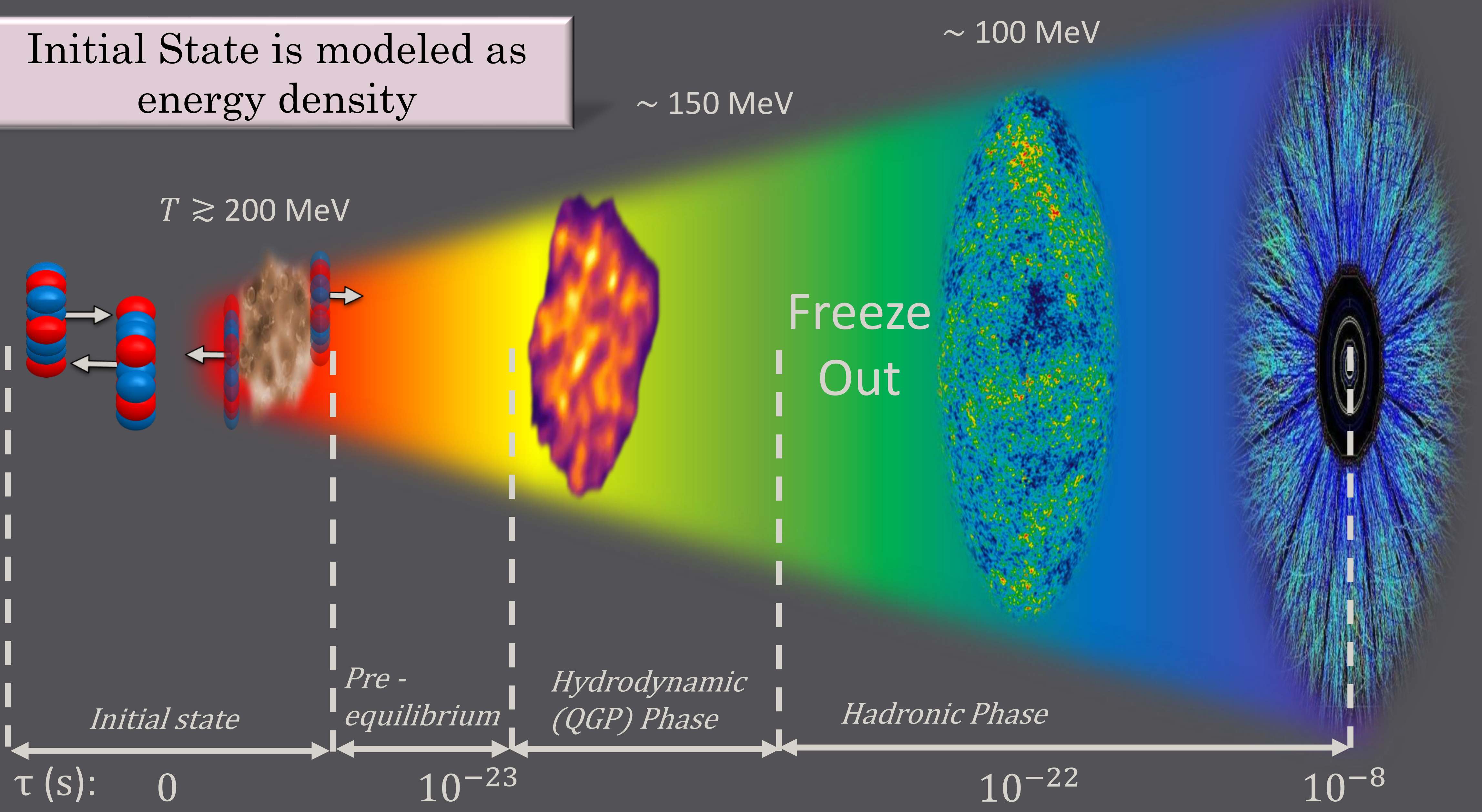
37th Winter Workshop on Nuclear Dynamics

March 2nd, 2022

Nuclear Collisions

Initial State is modeled as energy density



Contents

I. Connecting of Initial State to Final State
II. Conserved Charges in Initial State
III. ICCING Algorithm
IV. Results
V. Future
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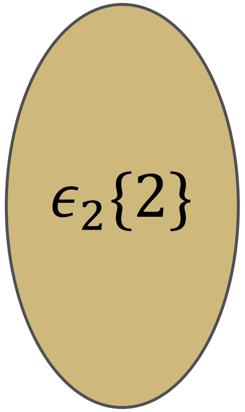
Geometry Observables

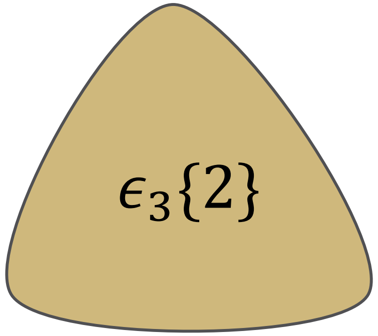
Fourier Series of Initial State

$$E_n = \epsilon_n e^{in\phi_n}$$



2-Particle Correlation

$$\epsilon_n\{2\} = \sqrt{\langle \epsilon_n^2 \rangle}$$



4-Particle Correlation

$$\epsilon_n\{4\} = \sqrt[4]{2\langle \epsilon_n^2 \rangle^2 - \langle \epsilon_n^4 \rangle}$$

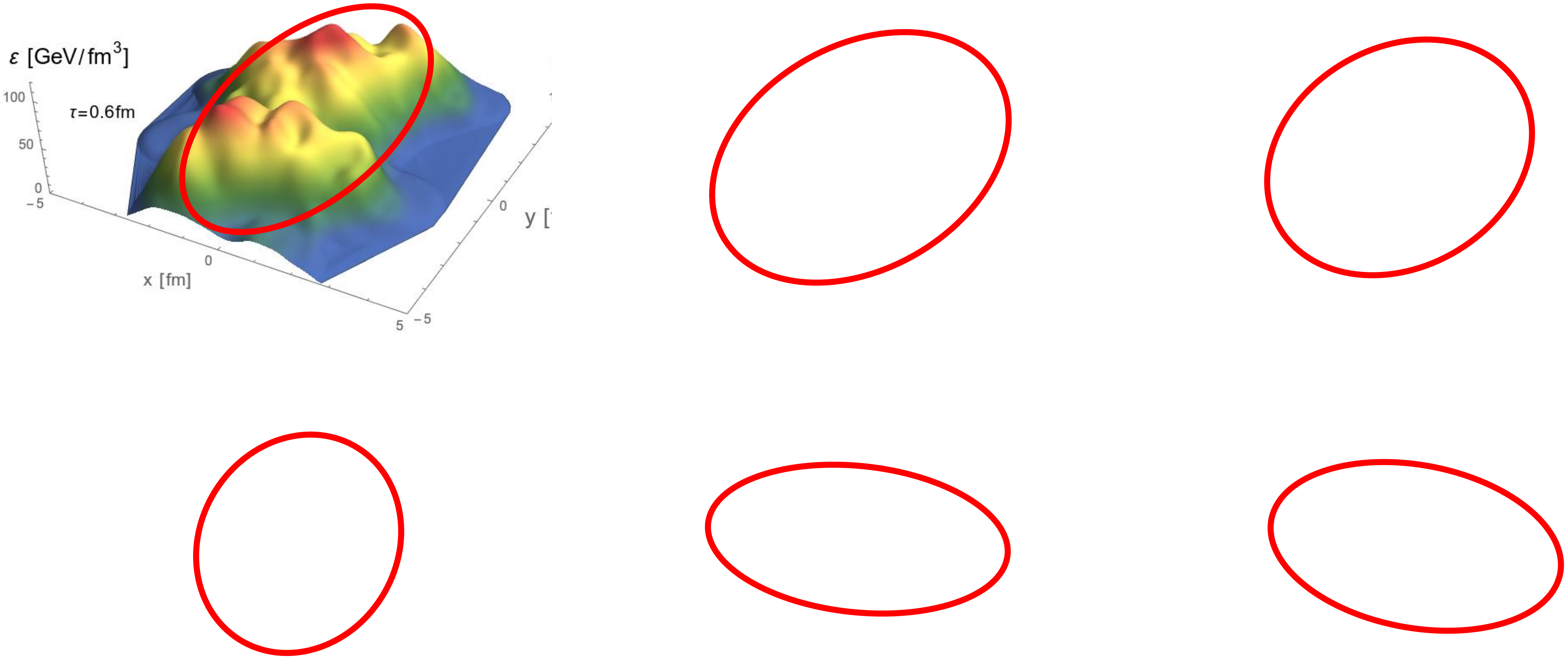
Fluctuations of Geometry Eccentricities

Less

More

$$\frac{\epsilon_n\{4\}}{\epsilon_n\{2\}} = \sqrt[4]{1 - \frac{Var(\epsilon_n^2)}{\langle \epsilon_n^2 \rangle^2}}$$

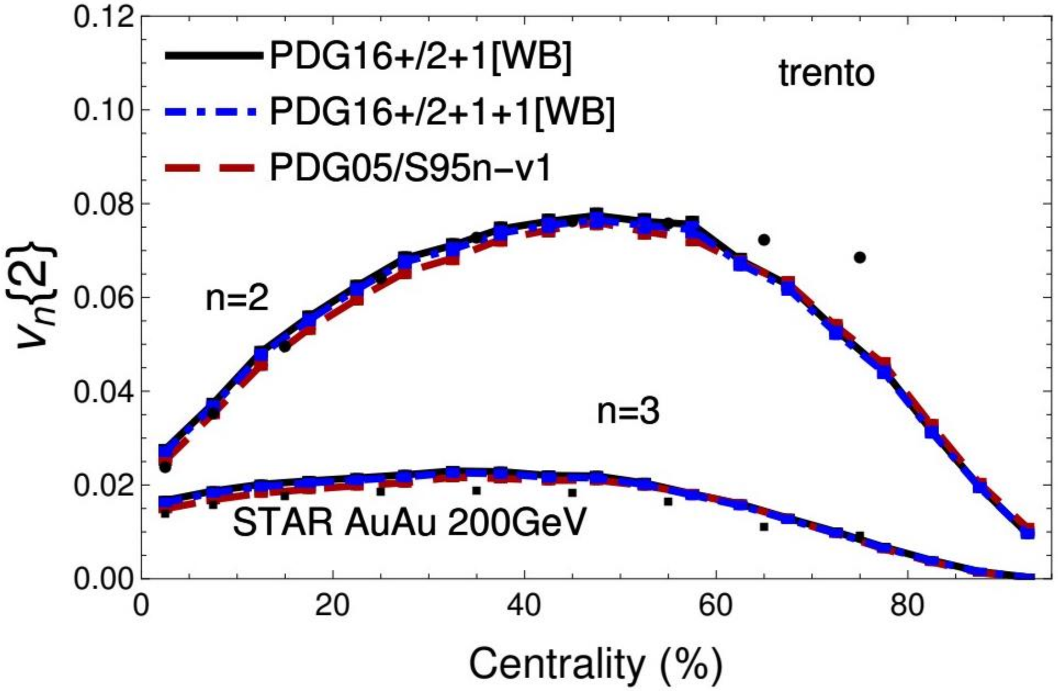
Hydrodynamic Evolution

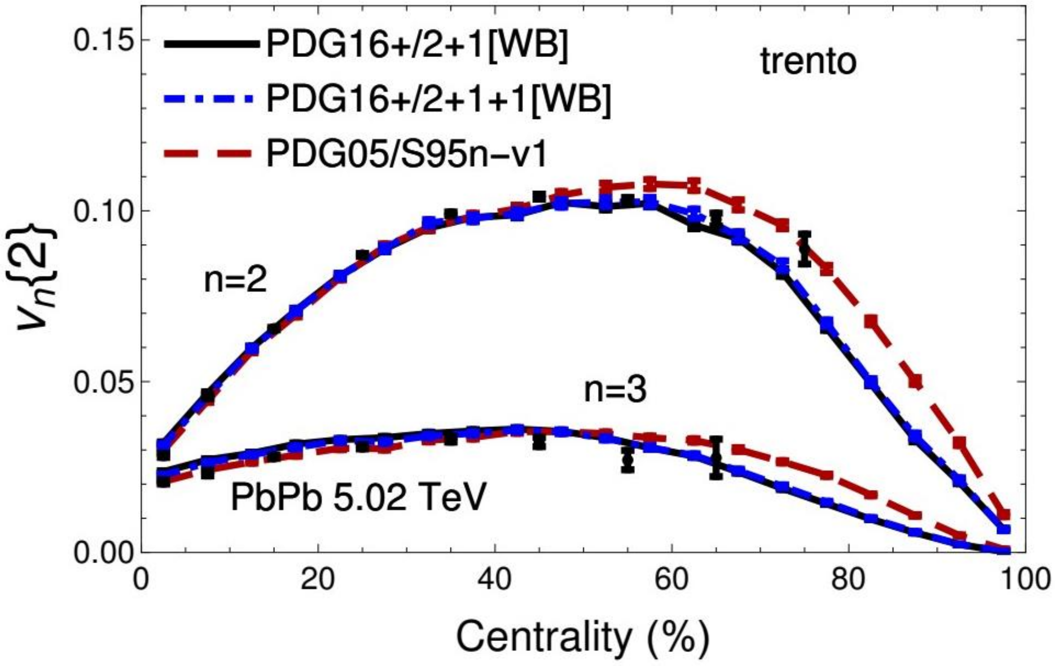


Noronha-Hostler et al,
Phys.Rev. C90 (2014), 034907

Trento Matches Experiment

Trento can match experimental data despite different choices for evolution



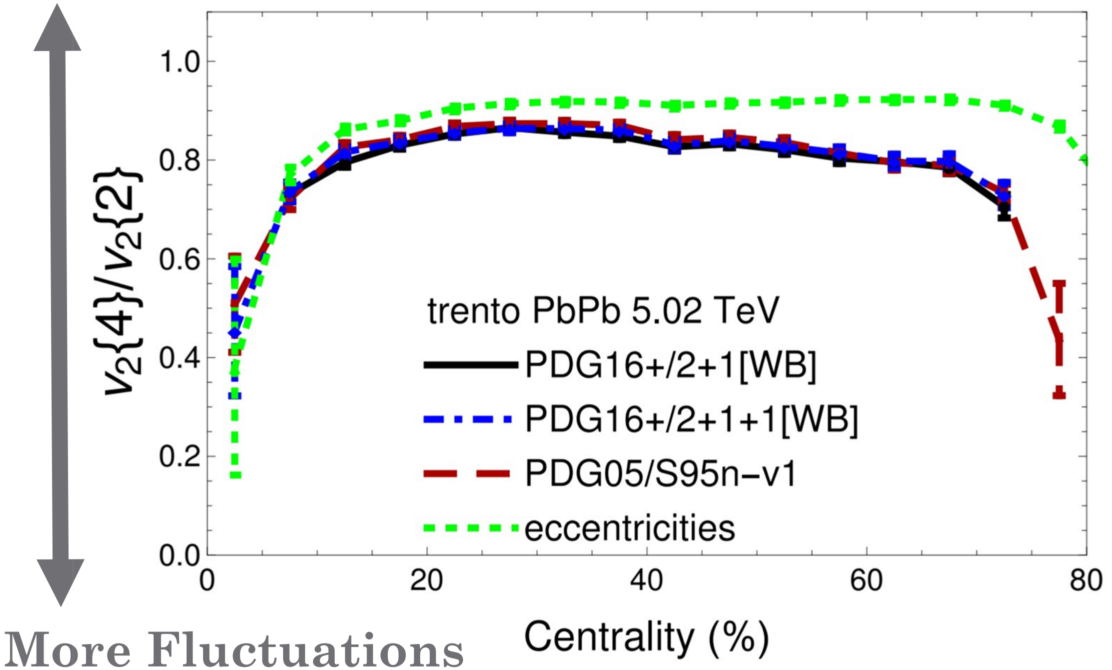


Alba et al,
Phys.Rev. C98 (2018), 034909

Canceling Medium Effects

Mostly linear response cancels out across different models that have varying viscosity

Fewer Fluctuations



More Fluctuations

Alba et al,
Phys.Rev. C98 (2018), 034909

Initial State
$E_n = \epsilon_n e^{in\phi_n}$

$V_n \approx \kappa_n E_n$
Mostly linear response

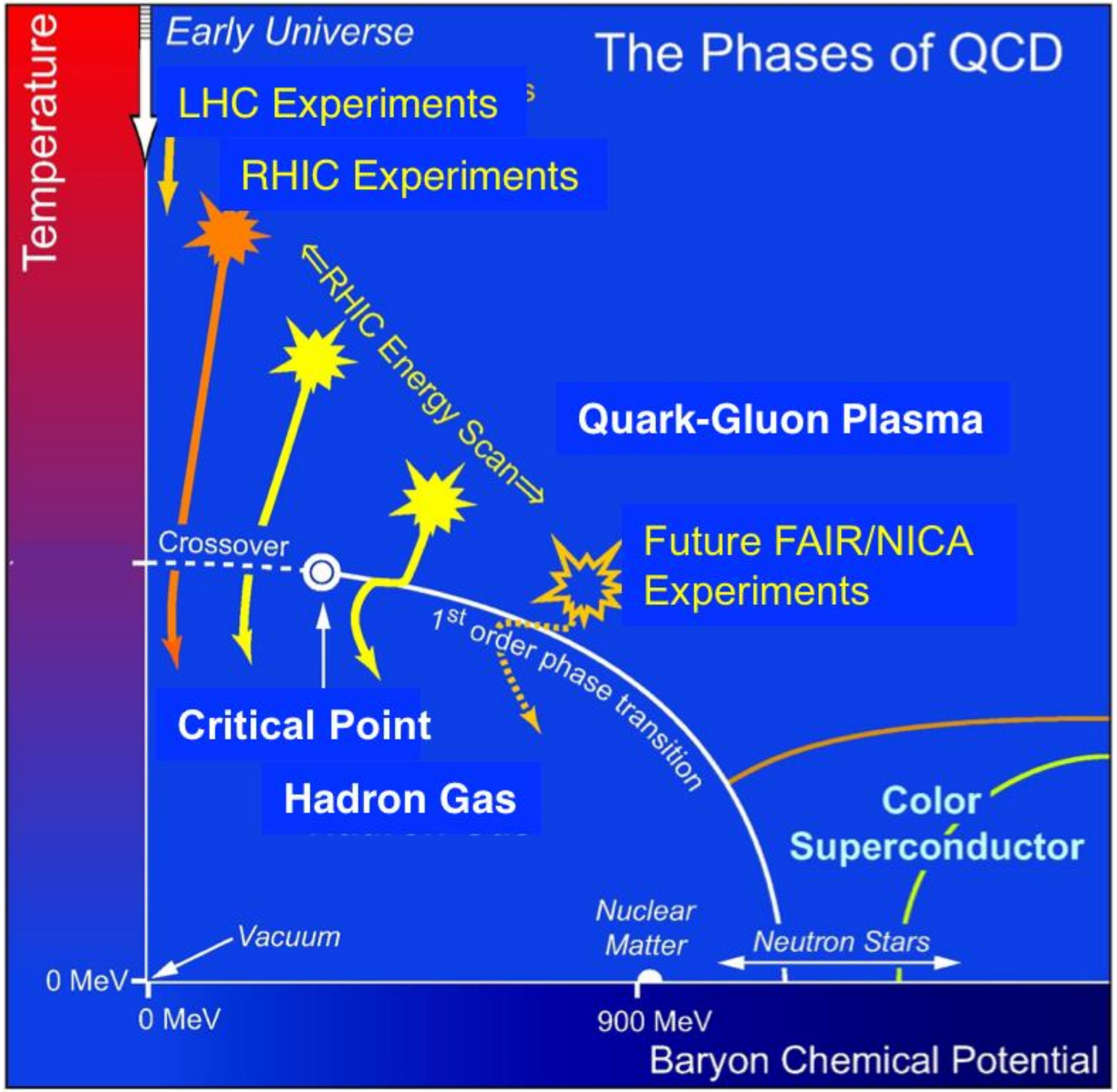
Final State
$V_n = v_n e^{in\phi_n}$

$$\frac{v_n\{4\}}{v_n\{2\}} \approx \frac{\kappa_n \epsilon_n\{4\}}{\kappa_n \epsilon_n\{2\}}$$

Teaney et al, PRC 83, 064904 (2011), PRC 86, 044908 (2012);
Qiu et al, PRC 84, 024911 (2011);
Gardim et al, Noronha-Hostler et al,
Phys.Rev. C93 (2016) no.1, 014909
Giacalone et al, **Phys.Rev. C95 (2017) no.5, 054910**

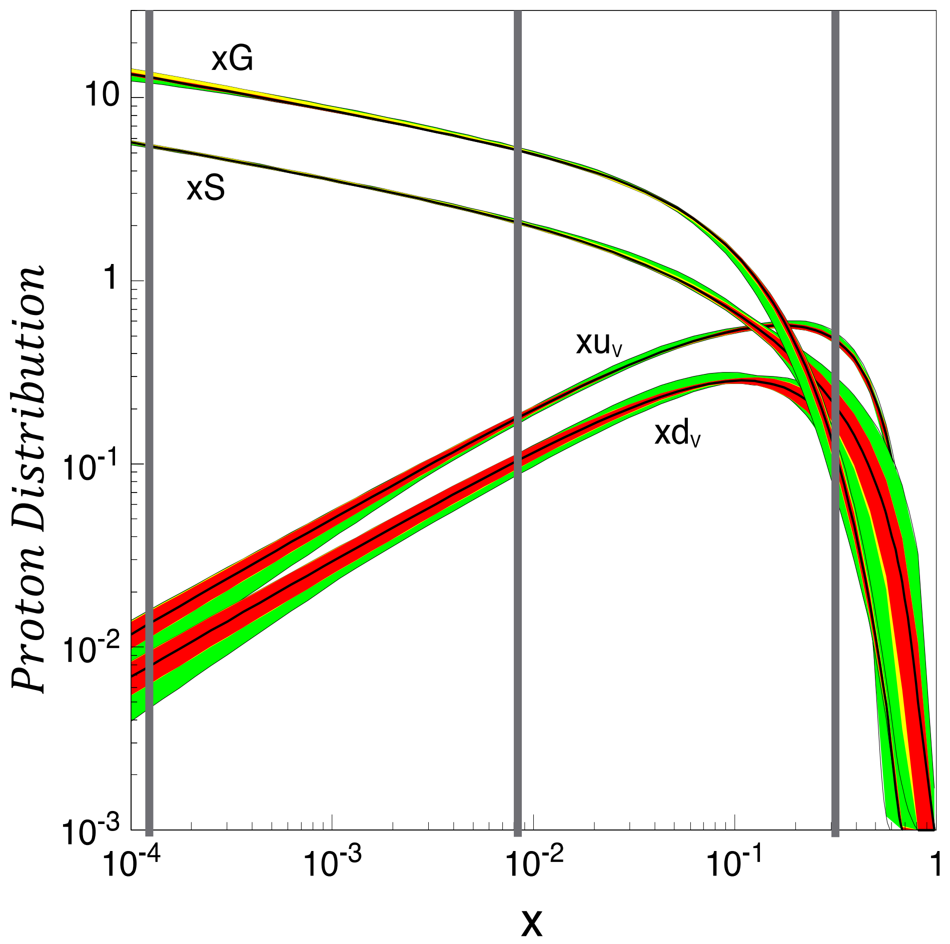
Why Initialize Charges?

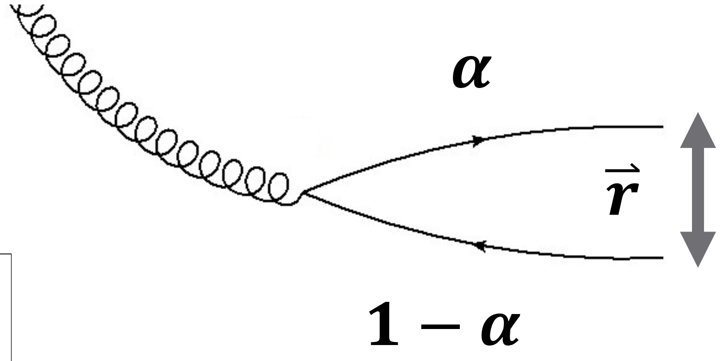
- Beam Energy Scan (BES) is on-going
  - Search for QCD critical point
- As you go to low beam energies, hydro phase runs for shorter time than hadron phase
  - This means transport coefficients will become more important
- There are many unknowns in these systems
  - Using LHC data we can start to constrain transports for lower energies
- Another limiting factor, hydro must be 3D for low energy systems and makes them harder to study



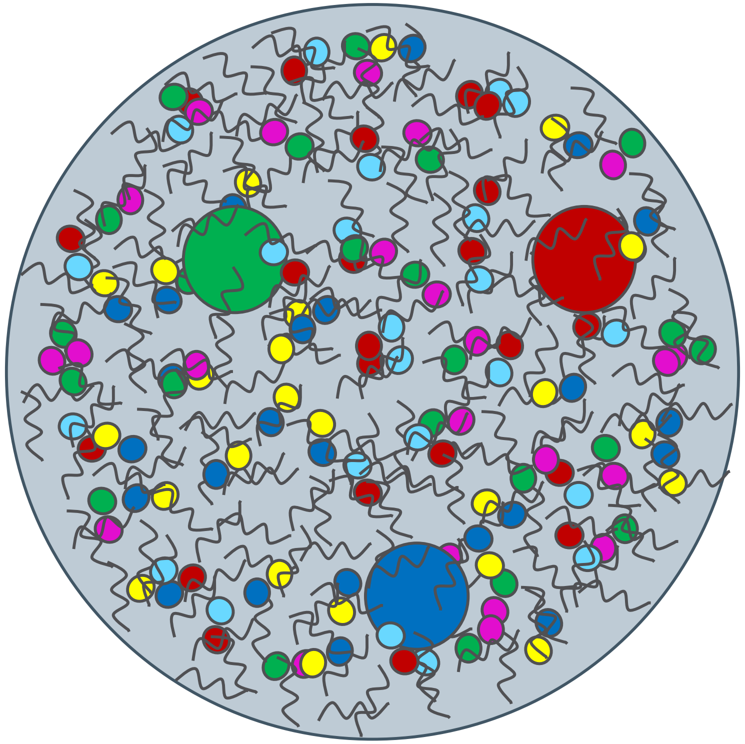
Structure of the Proton

$$x \sim \frac{p_T}{\sqrt{s}} \sim \frac{1}{Collision\ Energy}$$





Assuming gluon saturation, we can sample $g \rightarrow q\bar{q}$ splittings

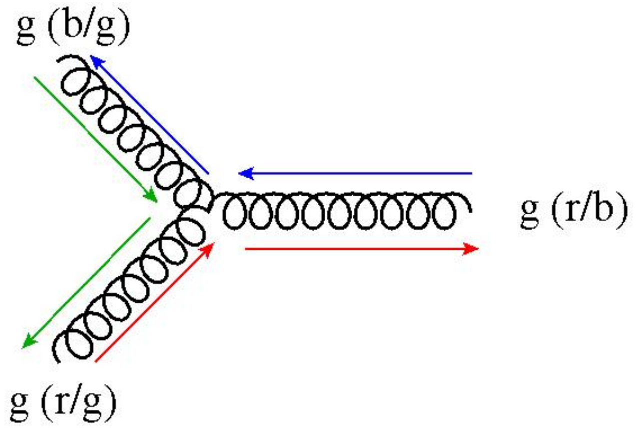


Introducing Conserved Charges

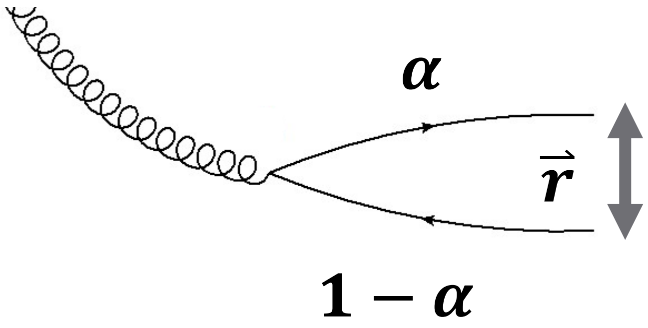
Initial
Conserved
Charges
In
Nuclear
Geometry

Carzon, Martinez, Sievert, Wertepny, Noronoha-Hosler
arXiv: 1911.12454 [nucl-th]

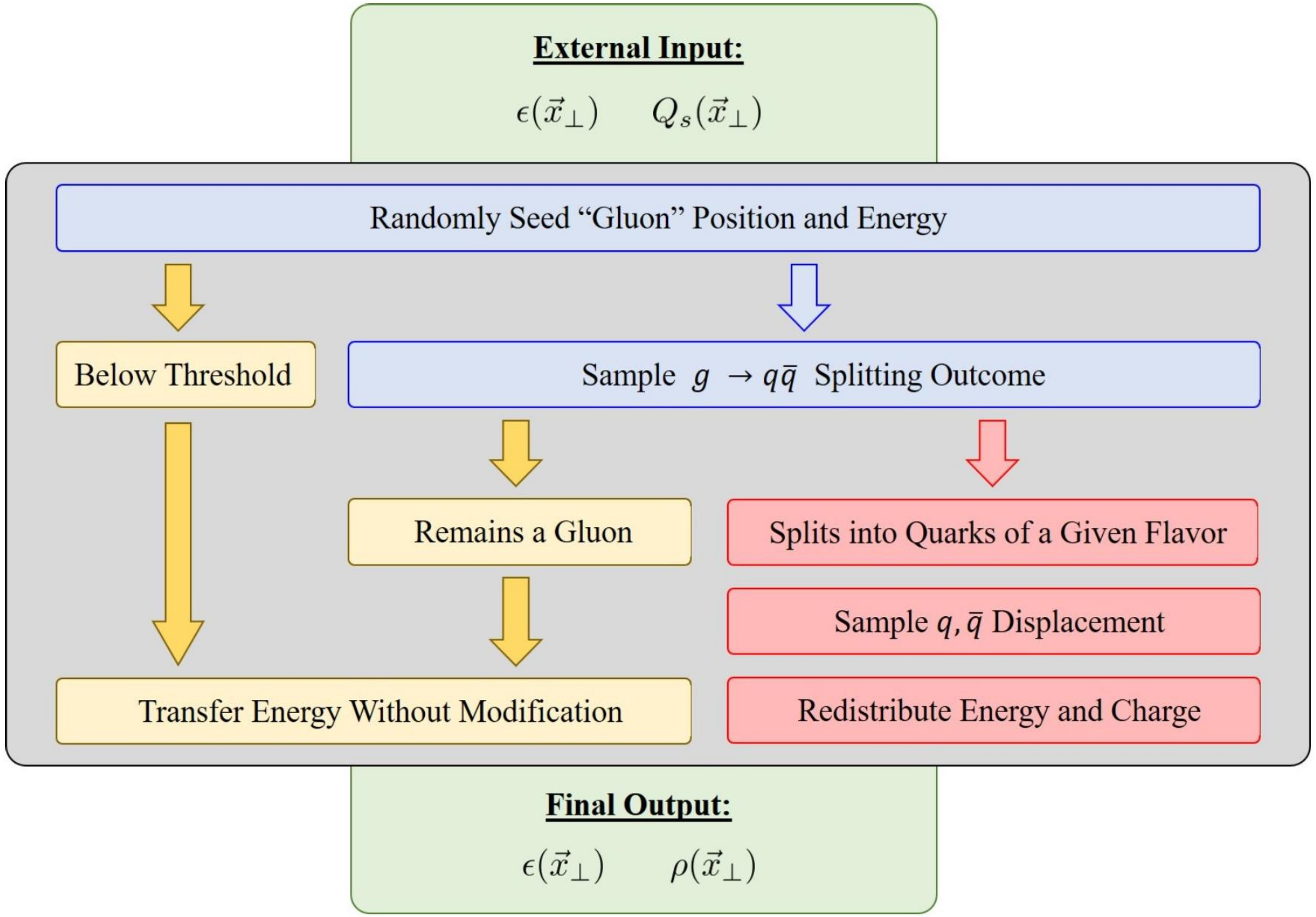
Gluon Self-Interaction



Quark Splitting



Flow Chart



PC, MM, MS, DW, JNH
arXiv: 1911.12454 [nucl-th]

Input

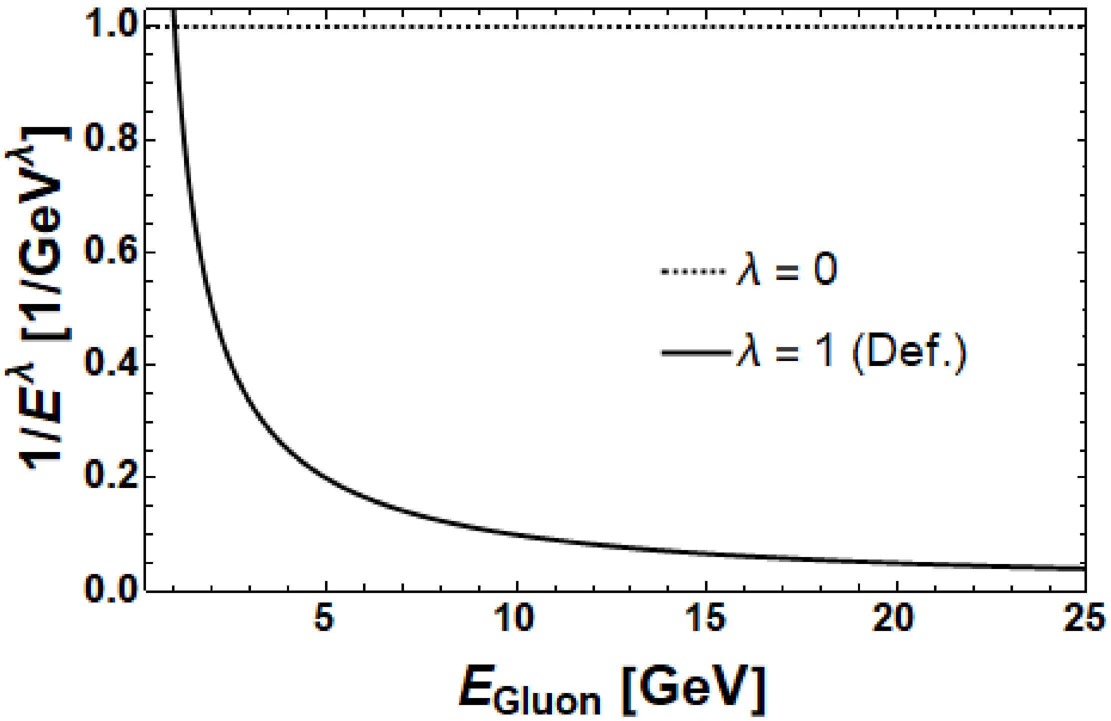
Energy Density, $\epsilon(\vec{x}_\perp)$
Saturation Density, $Q_s(\vec{x}_\perp)$
Quark Splitting Prob.
(Model agnostic)
Quark Spatial Corr. Func.

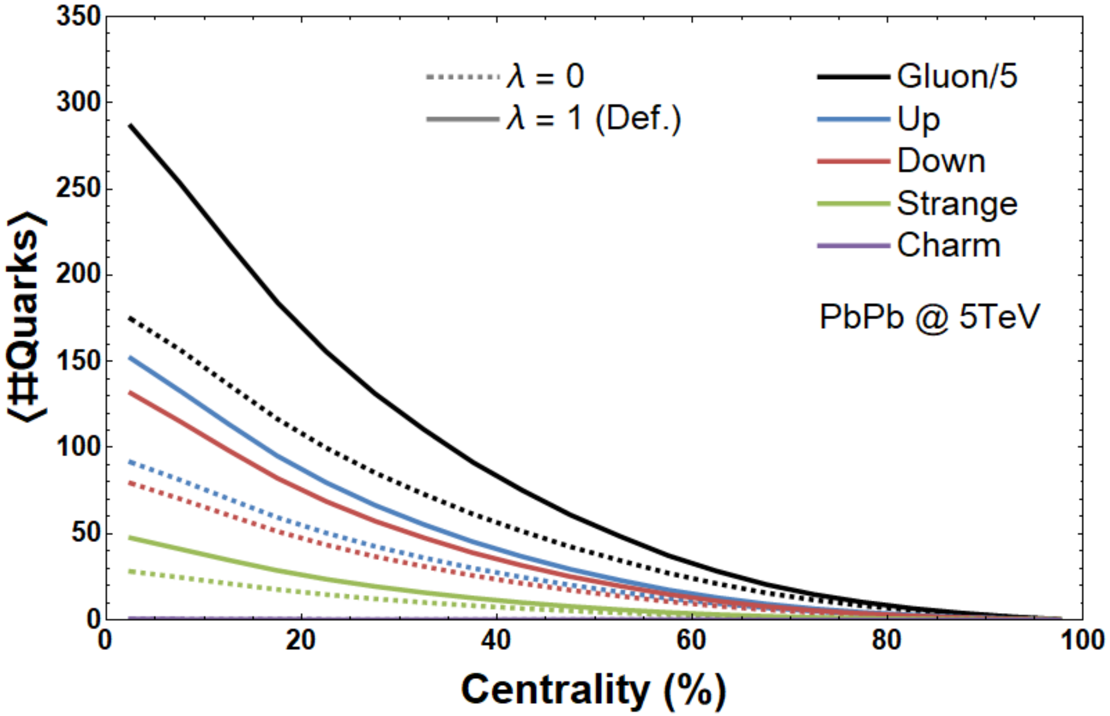
Output

Energy Density, $\epsilon(\vec{x}_\perp)$
BSQ Charge Densities, $\rho(\vec{x}_\perp)$

Quark Multiplicities

An increase in low energy gluons leads to a proportional increase in all flavors of quark

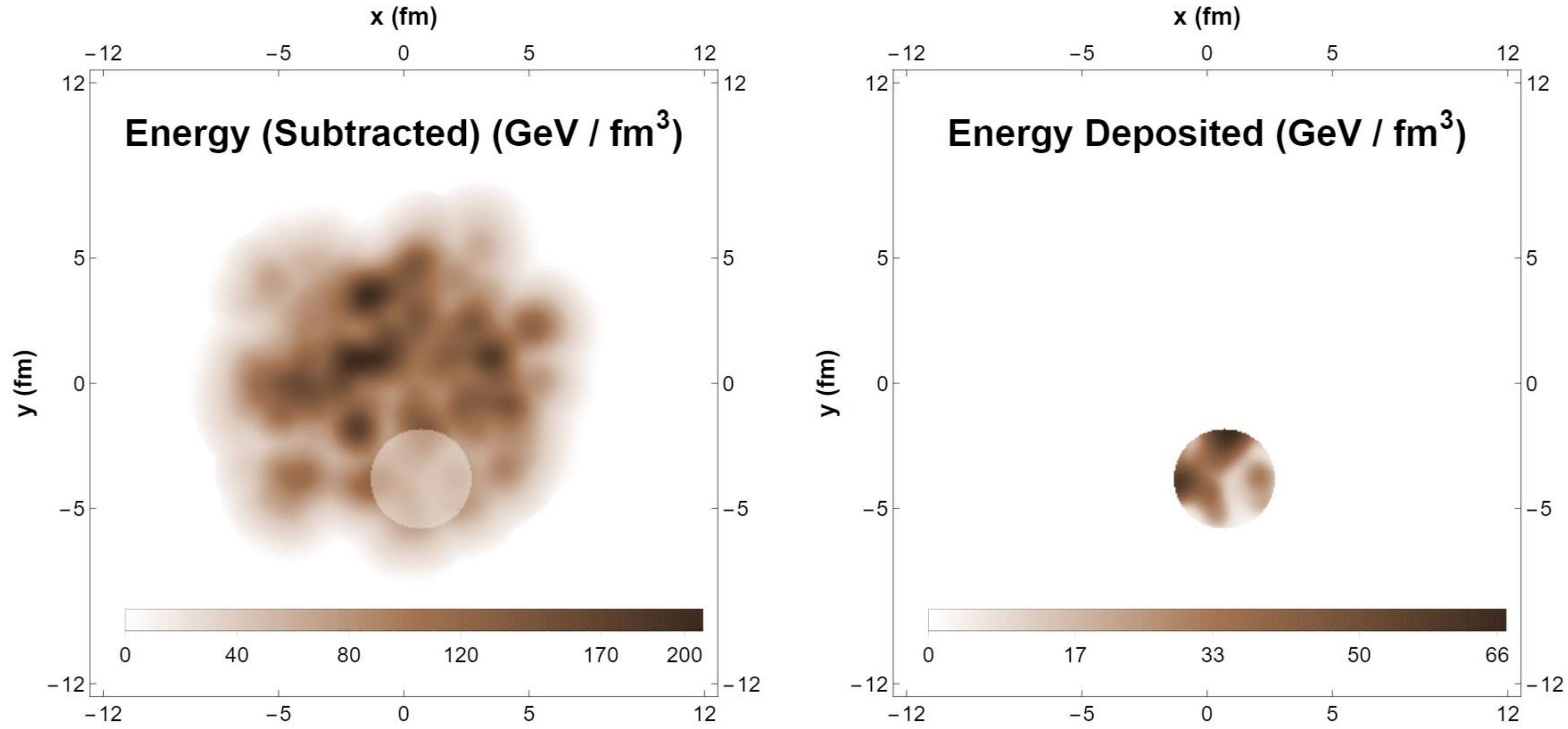




PC, MM, MS, DW, JNH
arXiv: 1911.12454 [nucl-th]

Transferring a Gluon

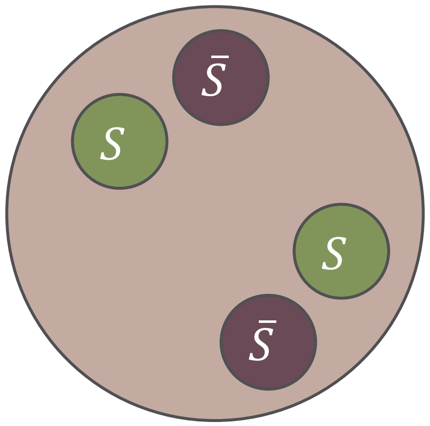
Gluons are subtracted proportionally so, when deposited, structure remains

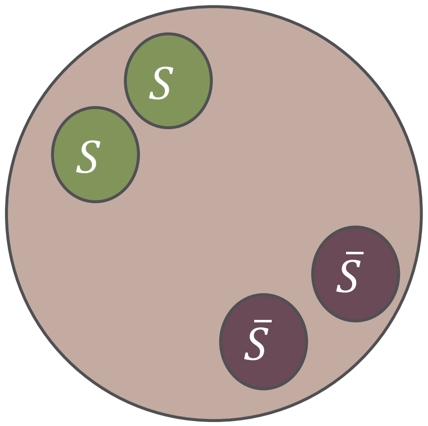


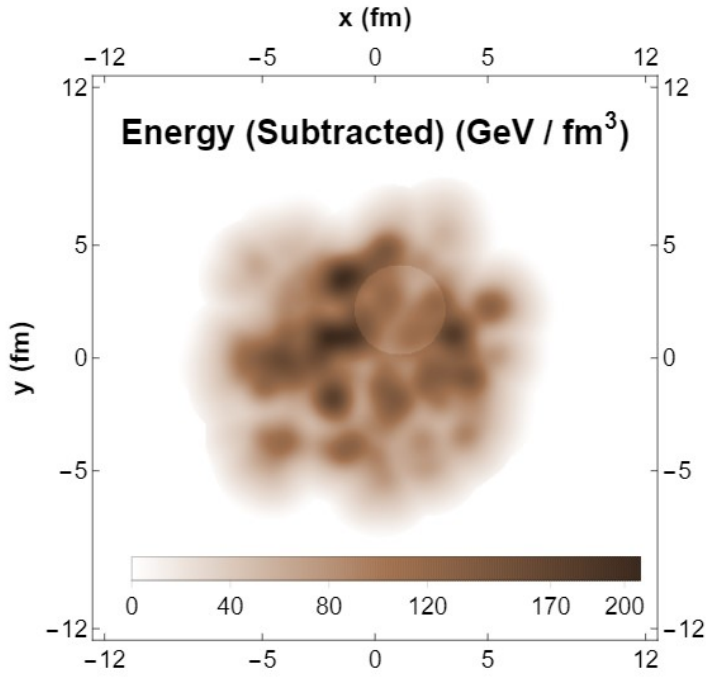
PC, MM, MS, DW, JNH
arXiv: 1911.12454 [nucl-th]

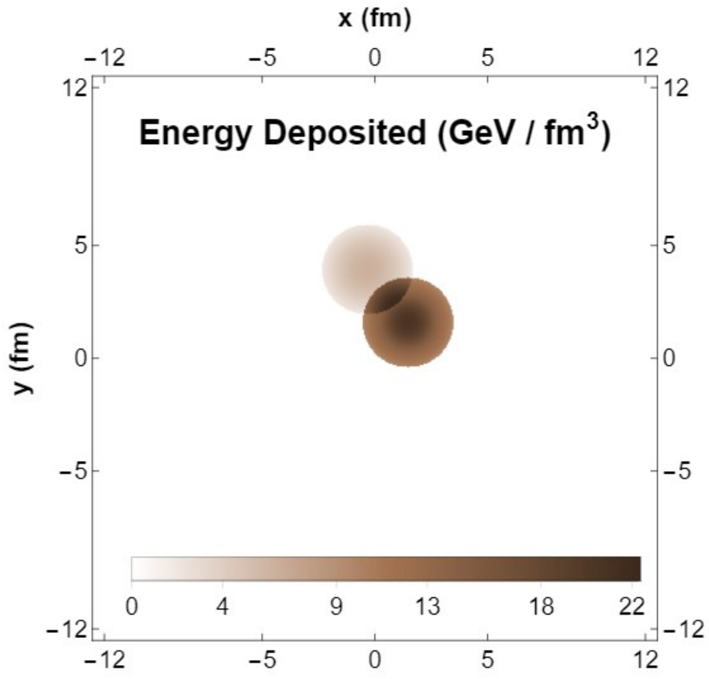
Distribution of Quark Pair

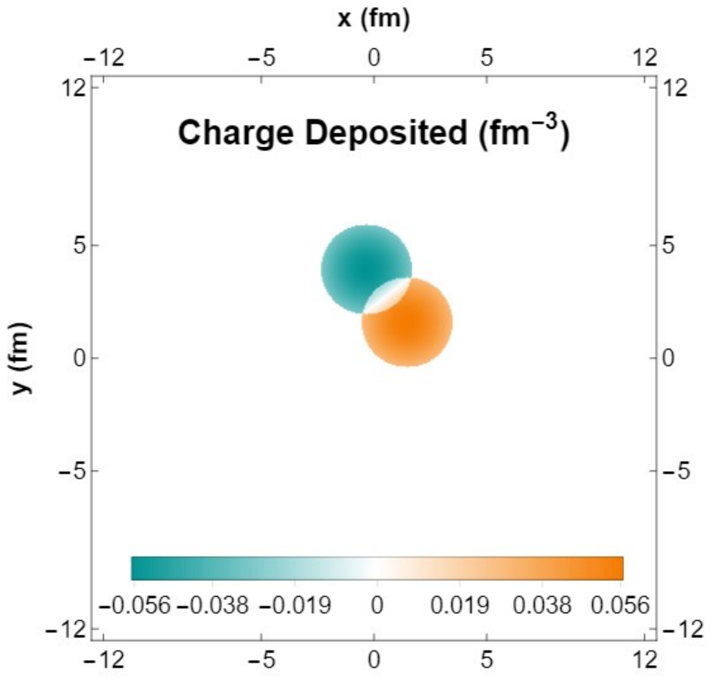
Quarks deposited as gaussian blobs; energy contains information about momentum fraction







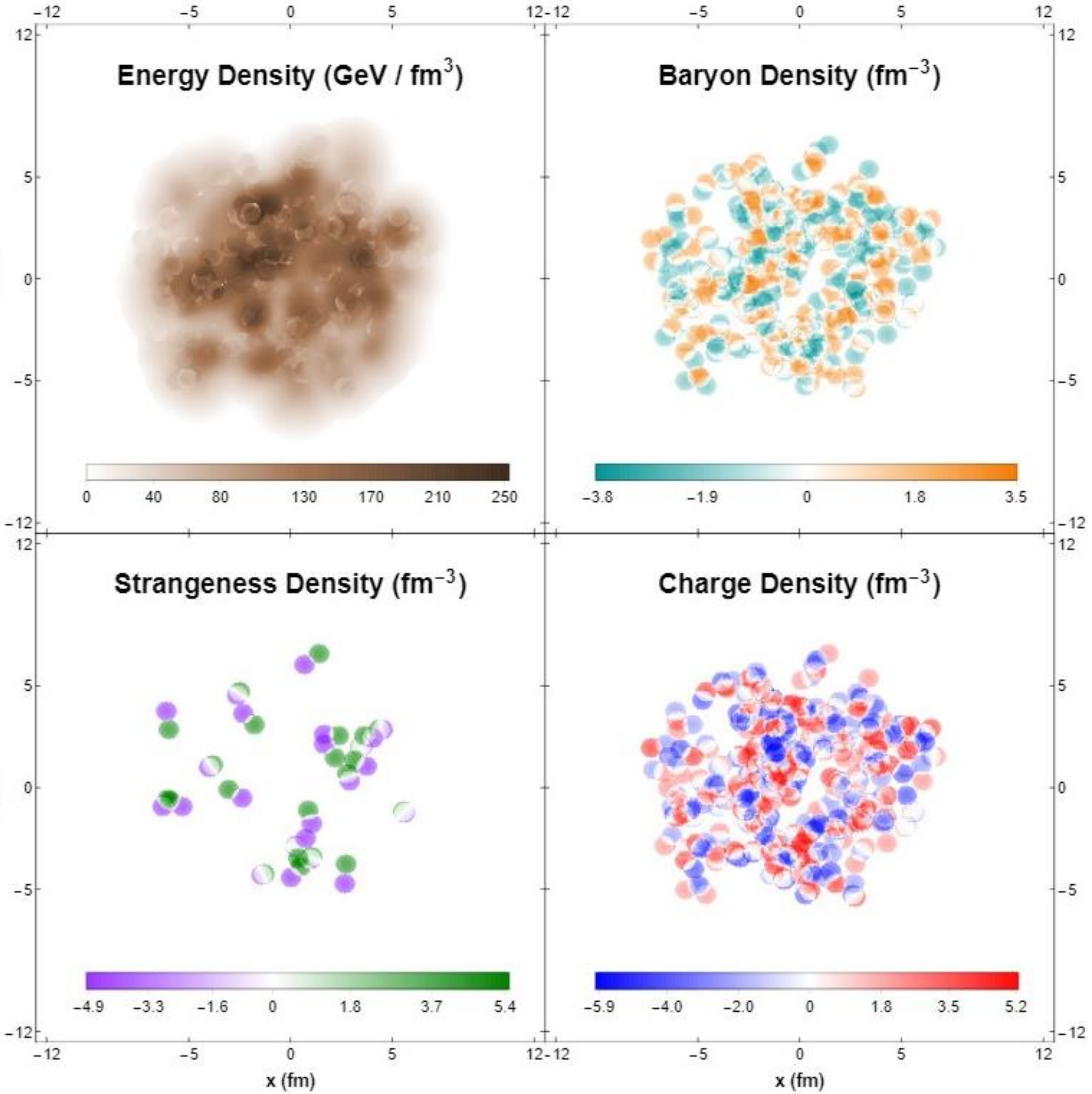




PC, MM, MS, DW, JNH
arXiv: 1911.12454 [nucl-th]

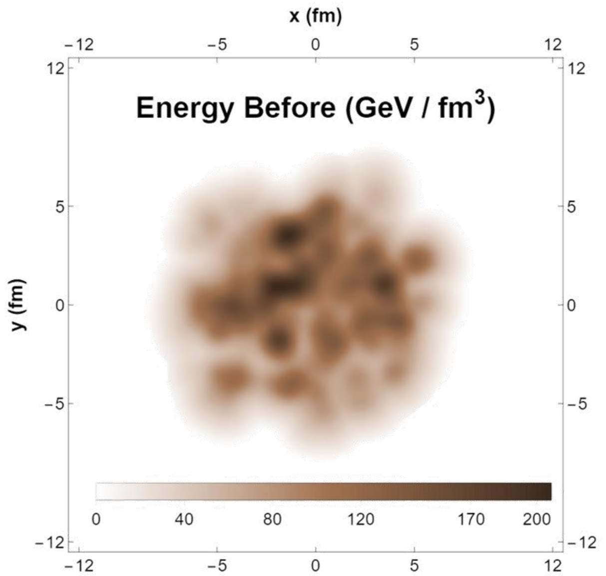
Final Densities

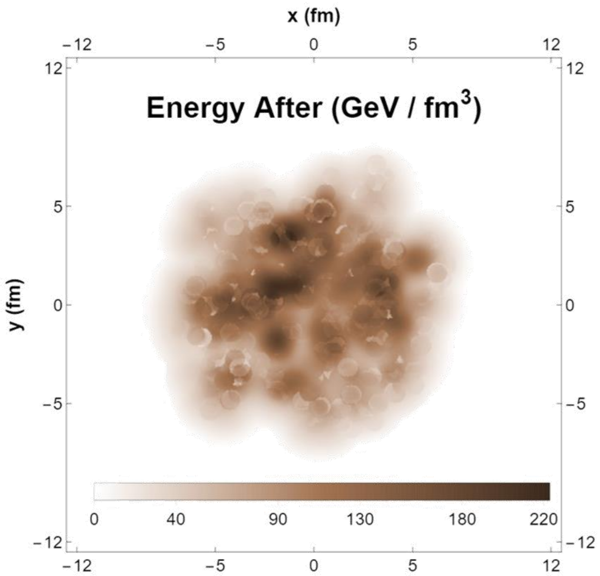
- ICCING is model agnostic
  - Choose Initial Energy Density
  - Choose Splitting Probs.
  - Choose Spatial Corr. Funcs.
  - Choose Output Format
- Strangeness sees a different geometry
- ICCING is open source, [pcarzon/ICCING (github.com)](https://github.com/pcarzon/ICCING)

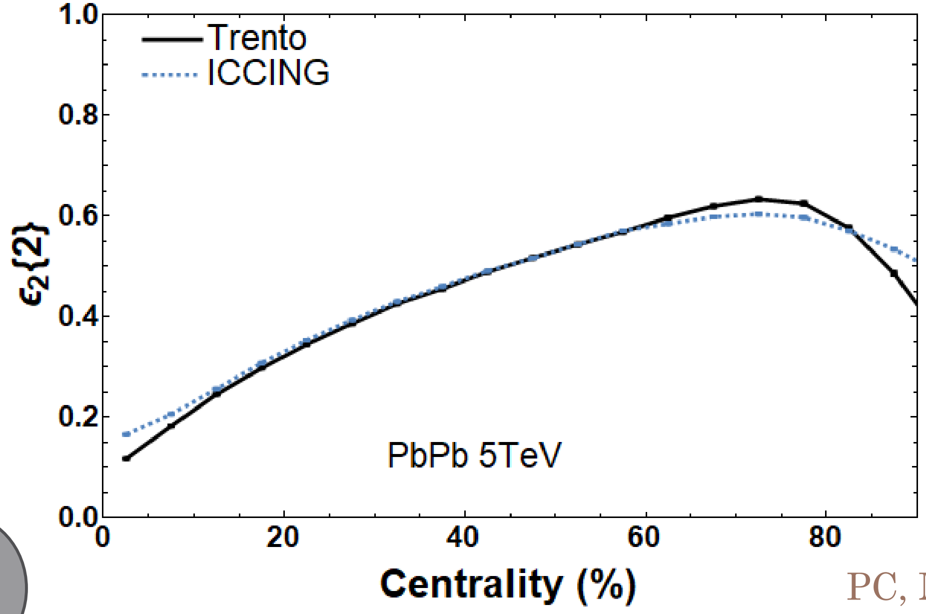


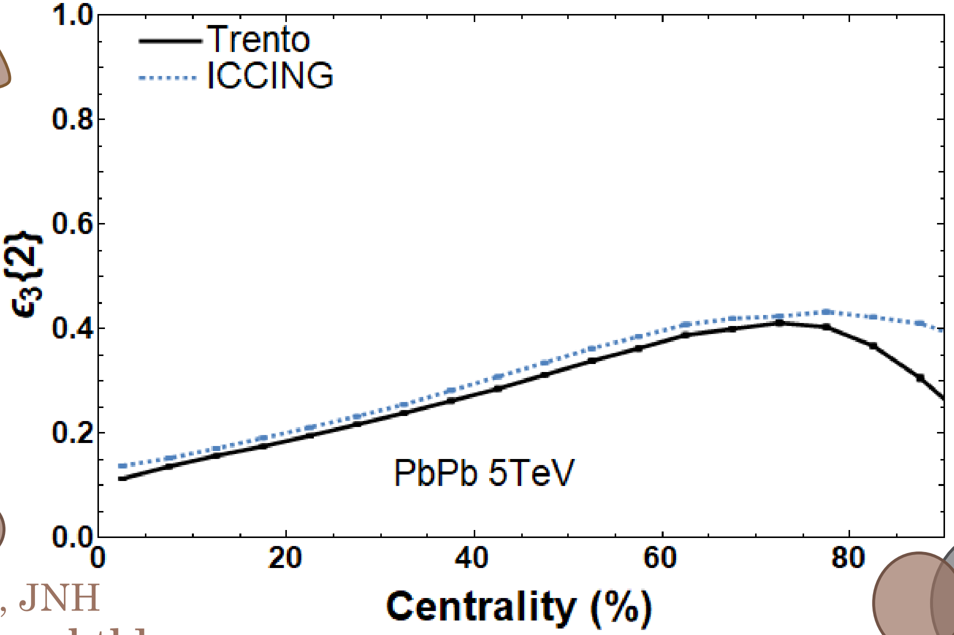
PC, MM, MS, DW, JNH
arXiv: 1911.12454 [nucl-th]

Effect on Energy









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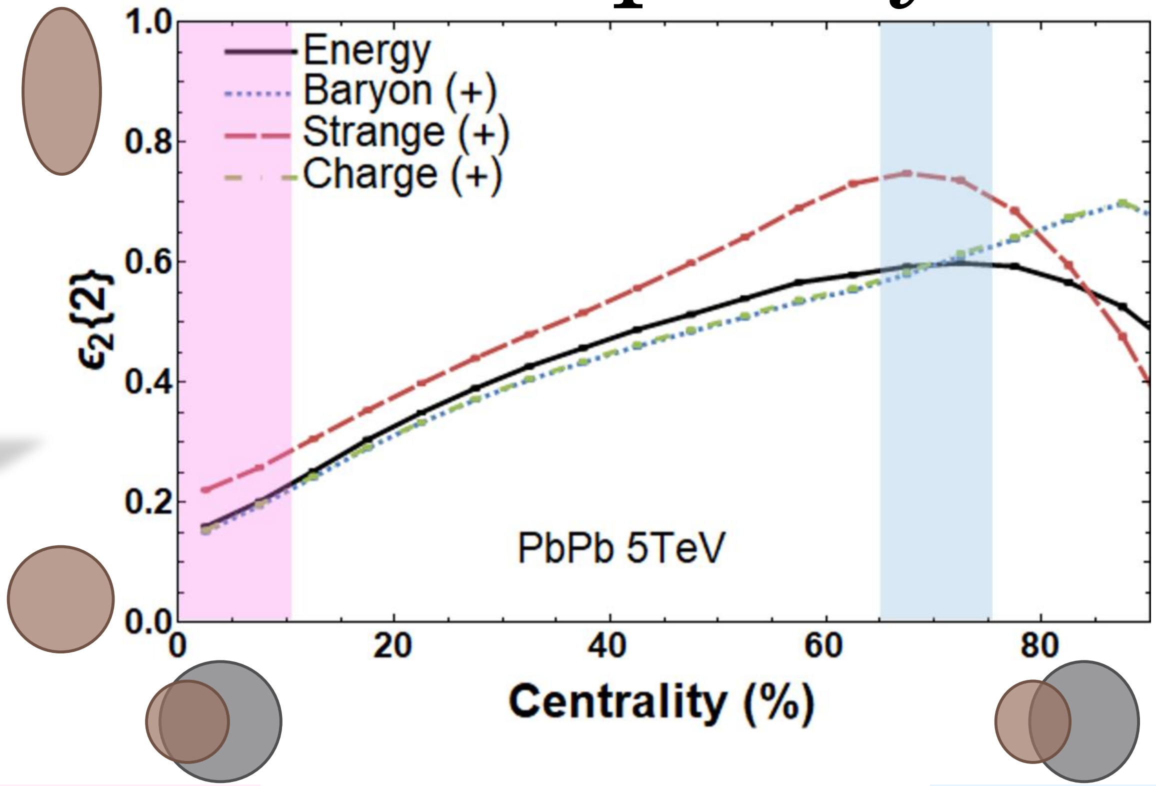
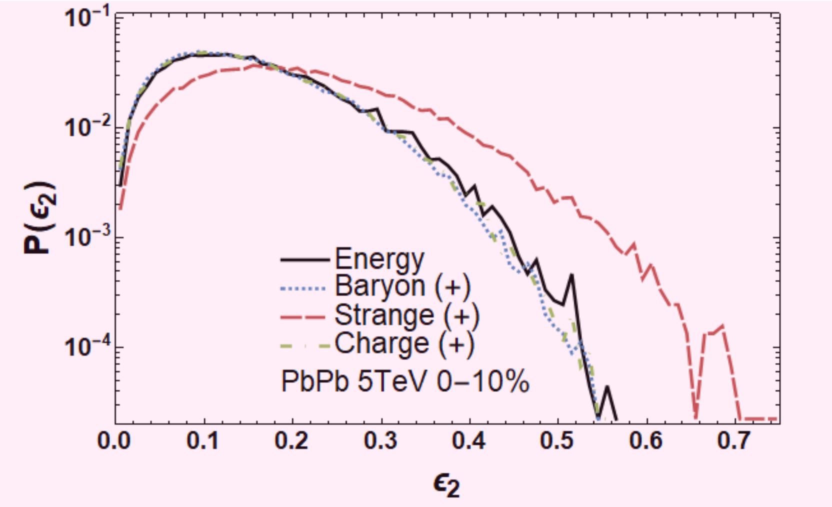
Ellipticity

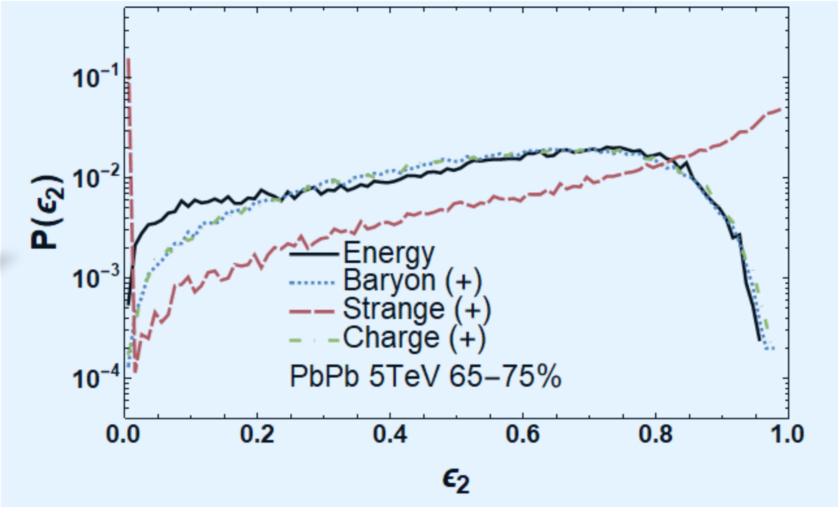


Geometry effects at central collisions

Number effects at peripheral collisions



$E \sim all\ charged\ particles$
$S \sim strangeness\ particles$



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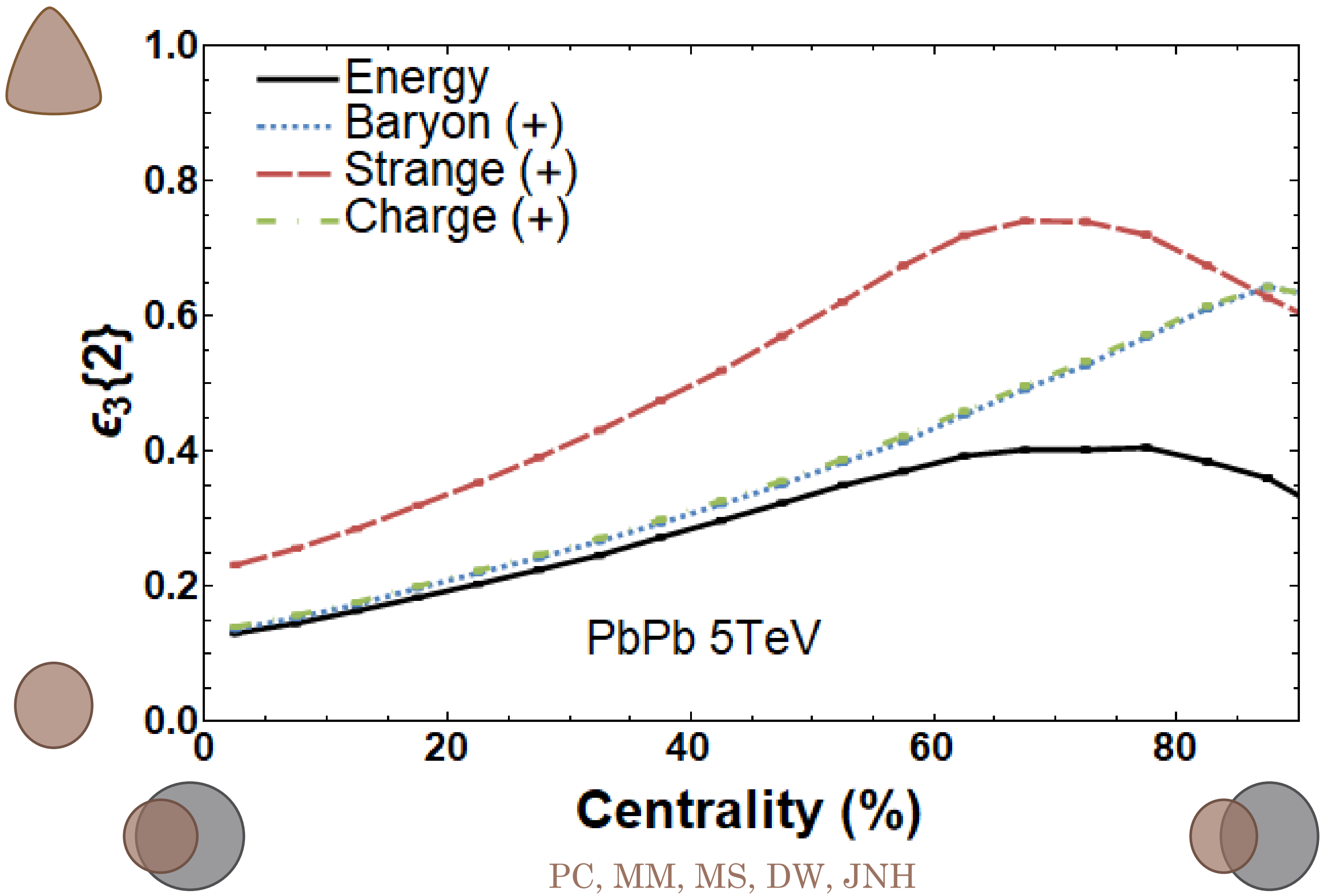
arXiv: 1911.12454 [nucl-th]

Triangularity

Triangularity sees larger effect

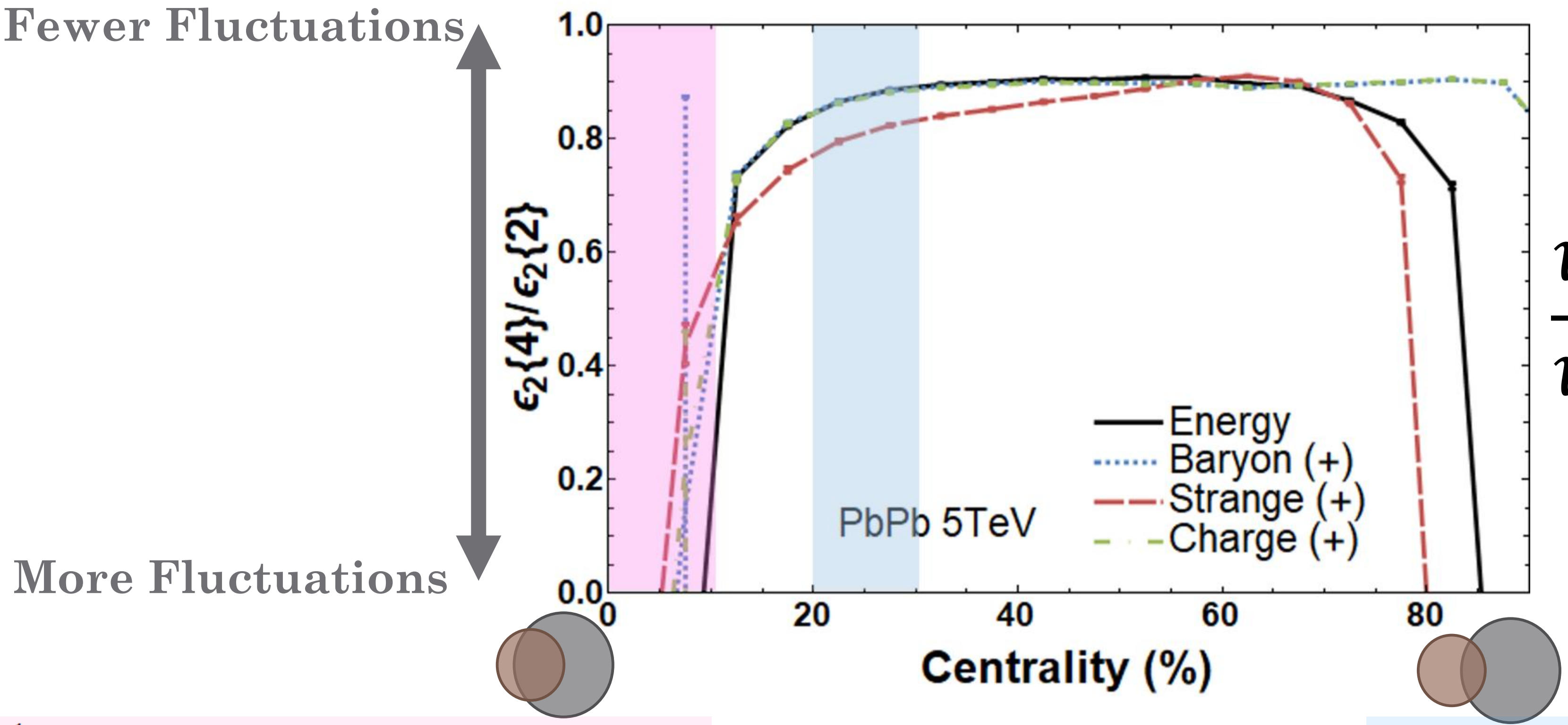


PC, MM, MS, DW, JNH
arXiv: 1911.12454 [nucl-th]

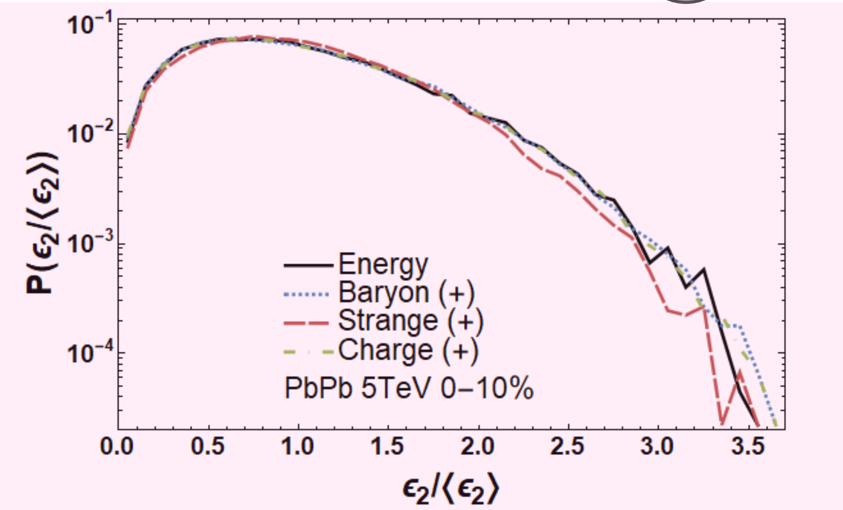
ε_n is not well defined for charge geometries, thus selecting on positive charge only. Currently working on new estimators of this geometry.

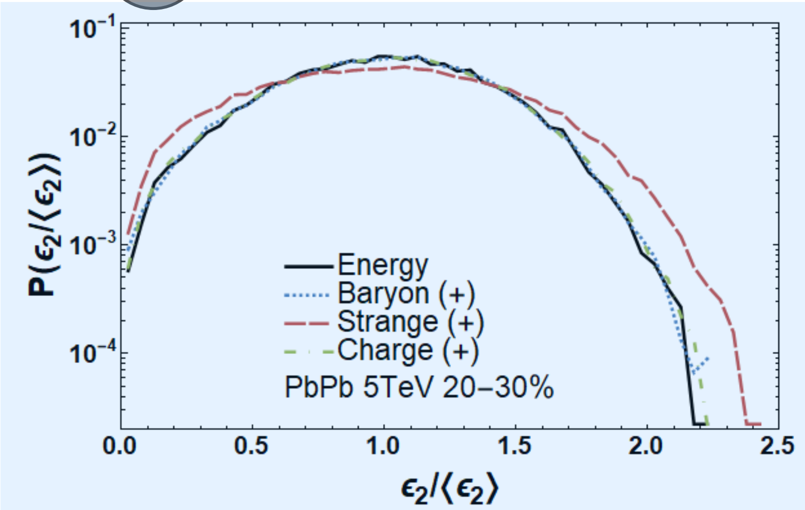
Almaalol, Carzon, Sievert, Noronha-Hostler, Noronha, Luzum in progress

Eccentricity Ratio



$$\frac{v_n\{4\}}{v_n\{2\}} \approx \frac{\color{red}{\kappa_n}\epsilon_n\{4\}}{\color{red}{\kappa_n}\epsilon_n\{2\}}$$





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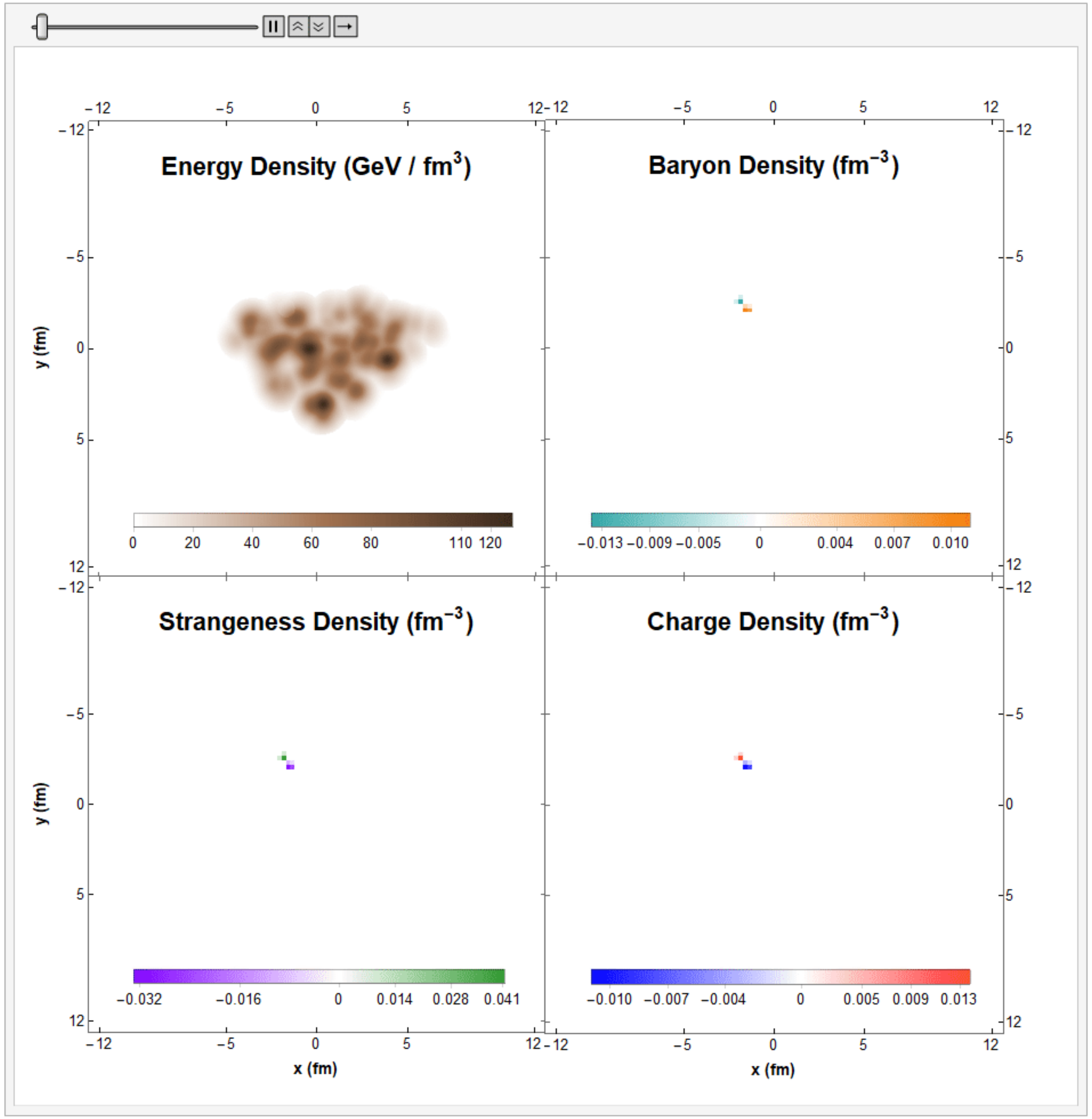
Pre-Hydrodynamic Evolution

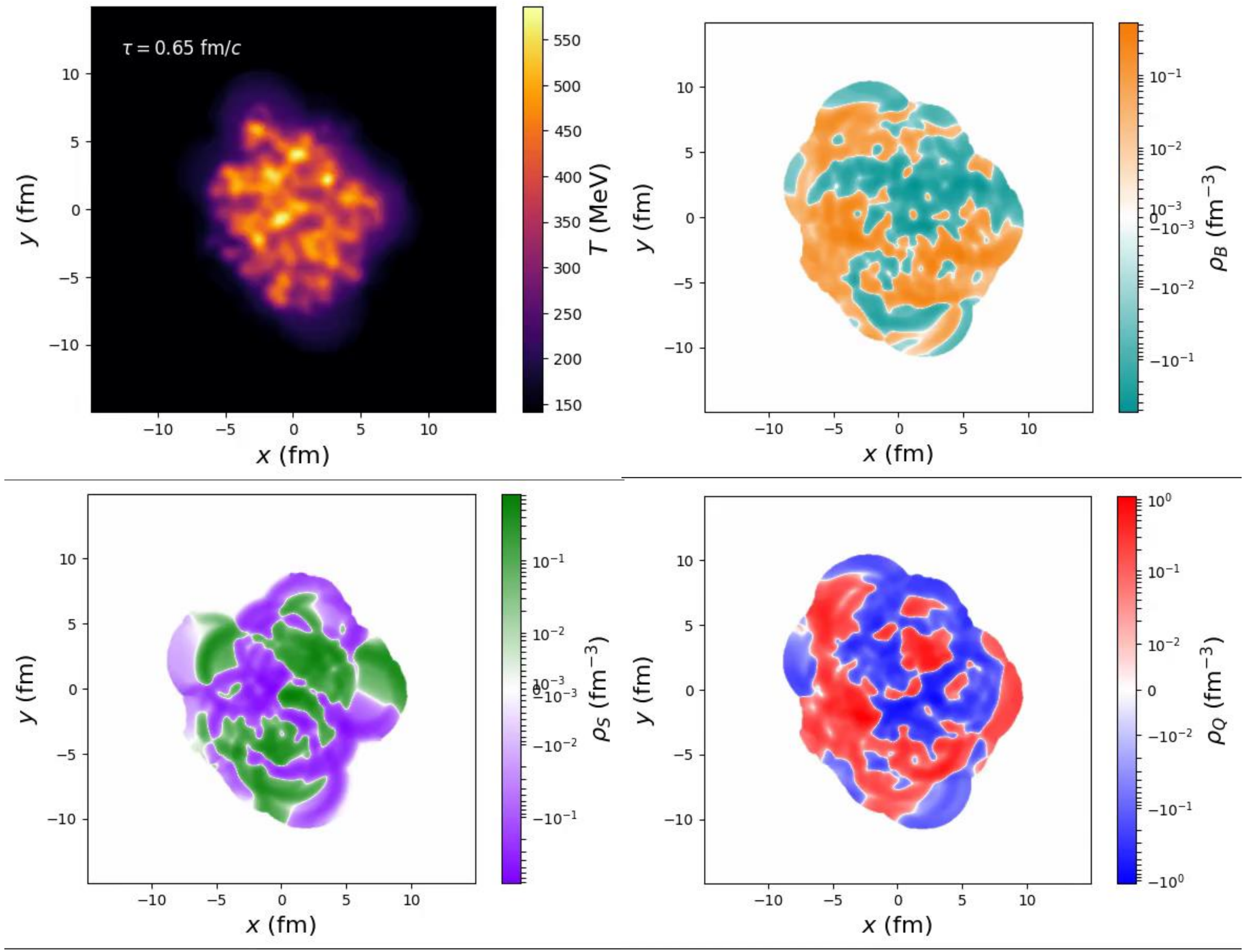


- Early evolution of quarks using KøMPøST method
- Greens Functions introduce time dependent quark radius
- Will be released in a future version of ICCING

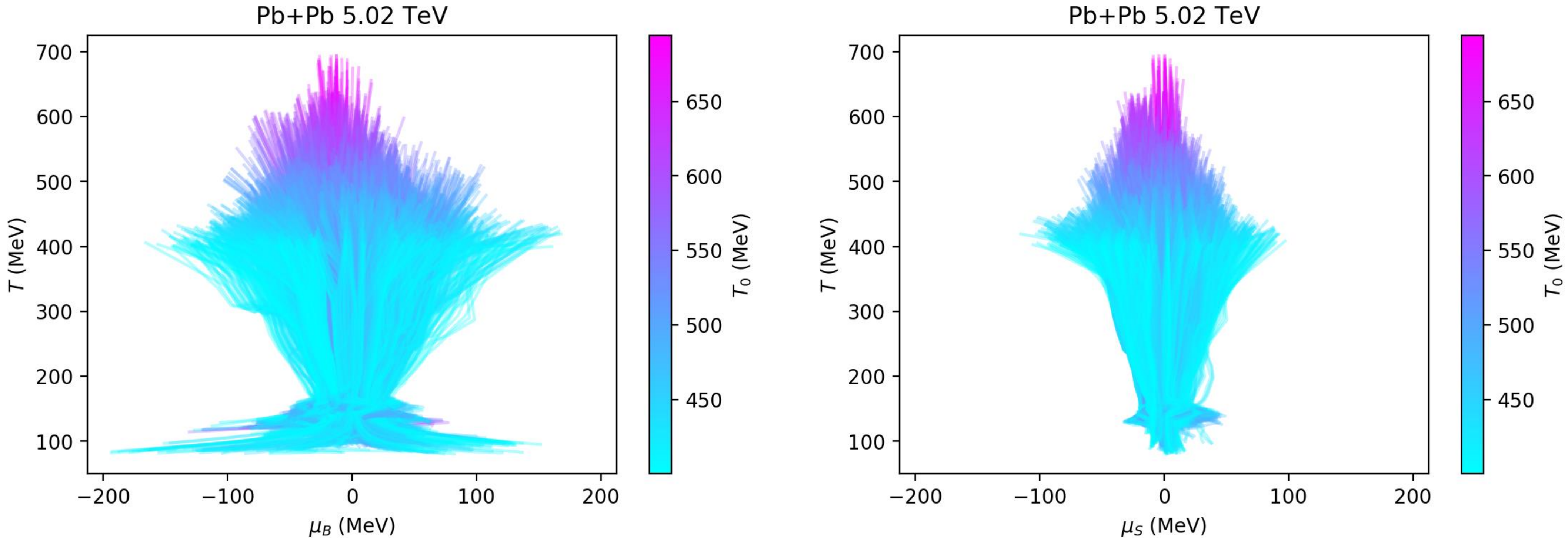
Carzon, Plaschke, Martinez, Schlichting, Sievert, Noronha-Hostler to appear soon

Hydrodynamics with BSQ Charges

- Contains BSQ evolution
- EOS: Noronha-Hostler, Parotto, Ratti, Stafford [PRC100 064910 (2019)]
- Modular Hydro Code with many new features planned
- Will be made open-source



Hydrodynamics with BSQ Charges

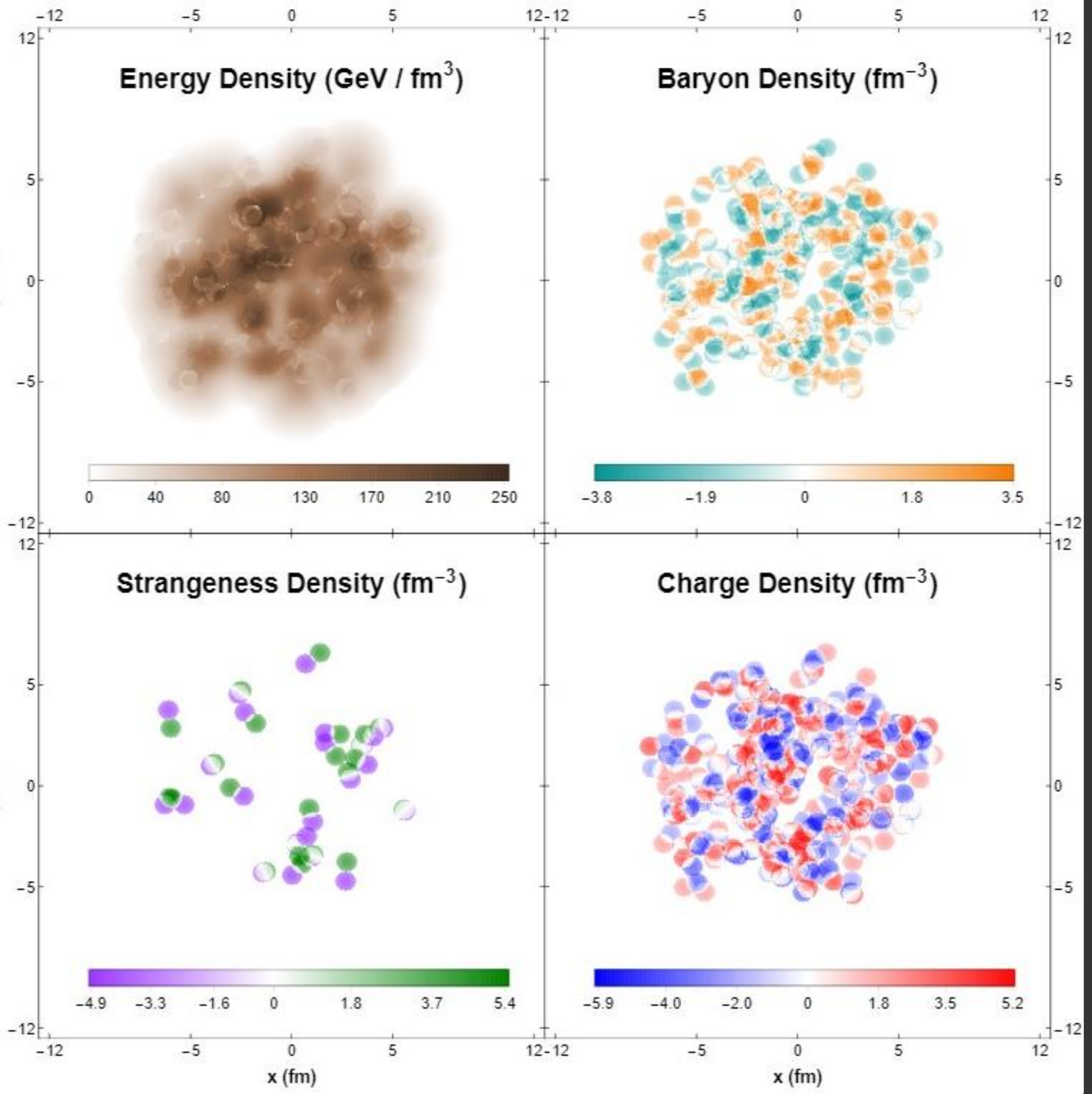


Fluid cells with $\mu_B \neq 0$ survive Hydrodynamic evolution!!!!

Almaalol, Carzon, Cruz Camacho, Dore, Mroczek, Plumberg, Spychalla, Sievert, Noronha-Hostler to appear soon

Thank you!

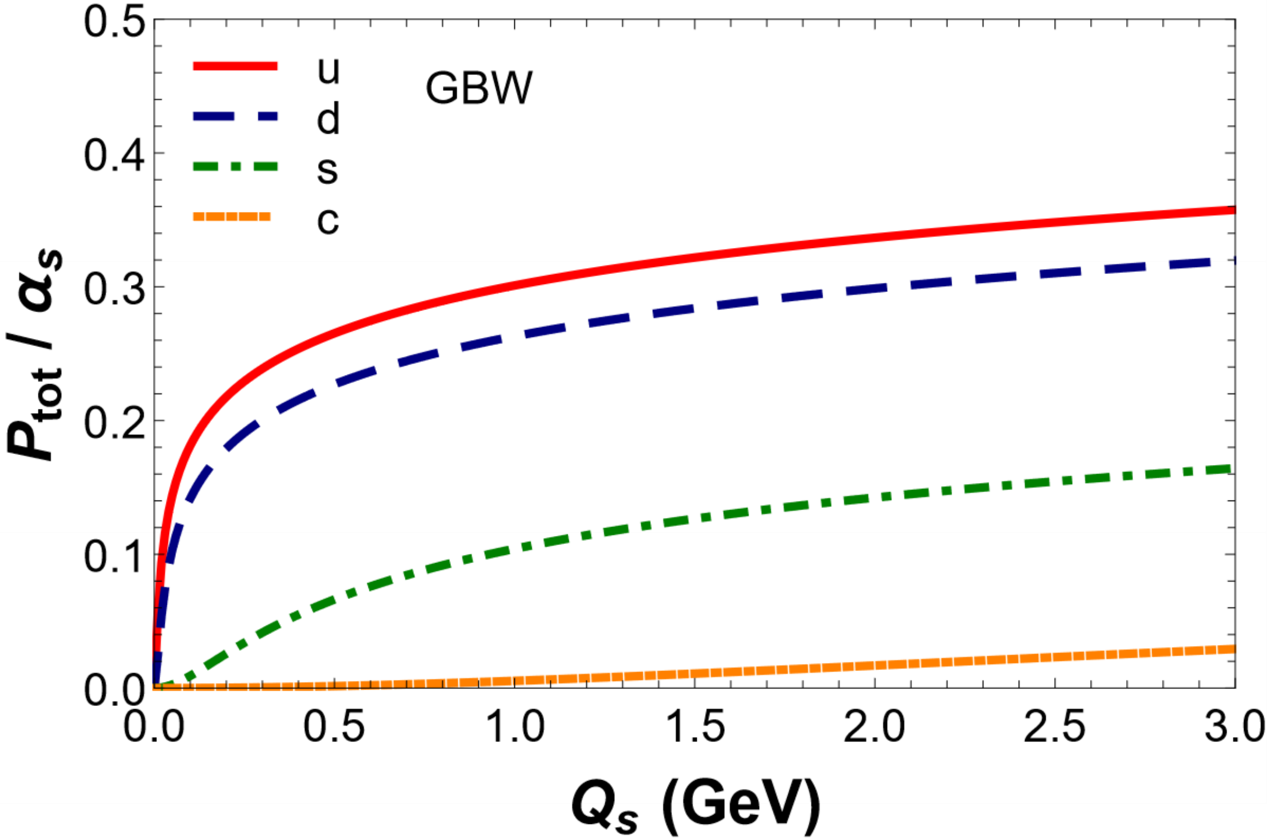
- $B_{tot} = S_{tot} = Q_{tot} = 0$ in IS, but there can be local fluctuations of charge
- Gluon splitting can introduce charge fluctuations while preserving experimental agreement
- ICCING is open source, [pcarzon/ICCING (github.com)](https://github.com/pcarzon/ICCING)
- ICCING is model agnostic
- Effects of ICCING remain even after hydro expansion
- Flow observables of identified particles will help understand this further



Backup

Algorithm: Selecting Quark

Up and Down behave similarly, Strange has a shallower increase and levels out further



Strange is in Hot spots!