

# Initializing and Evolving Conserved Charges using Open-Source ICCING with Green's Functions

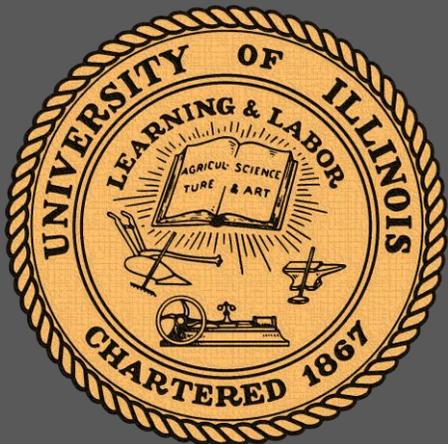
Patrick Carzon

Initial Stages

June 20<sup>th</sup>, 2023

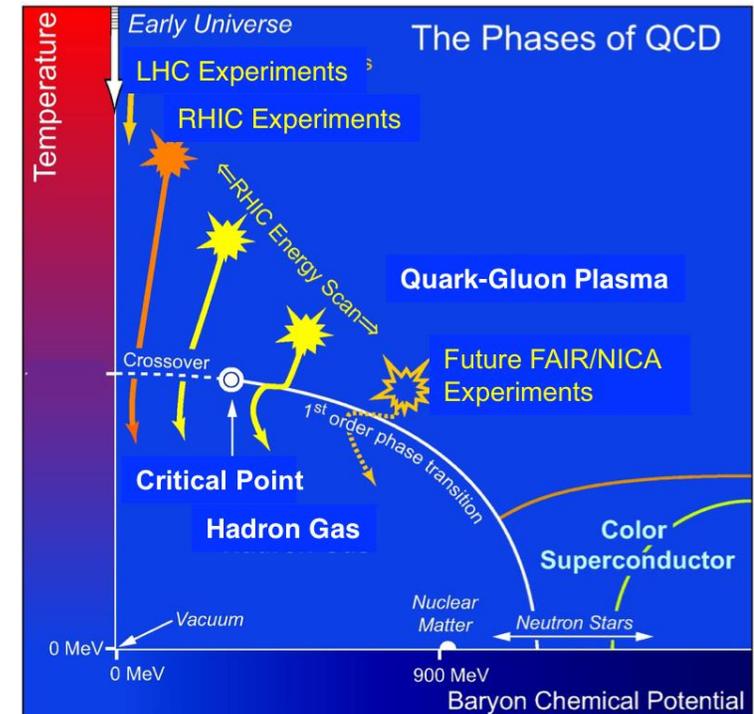
PC, Martinez, Sievert, Wertepny, Noronha-Hostler  
Phys. Rev. C 105, 034908 (2022), arXiv: 1911.12454 [nucl-th]

PC, Plaschke, Martinez, Noronha-Hostler, Schlichting, Sievert  
arXiv: 2301.04572 [nucl-th]



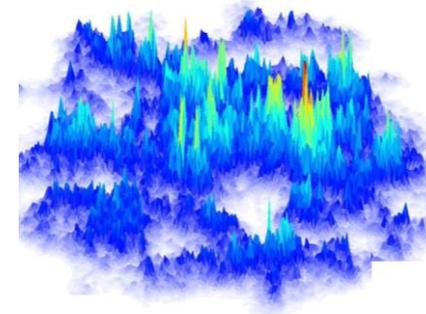
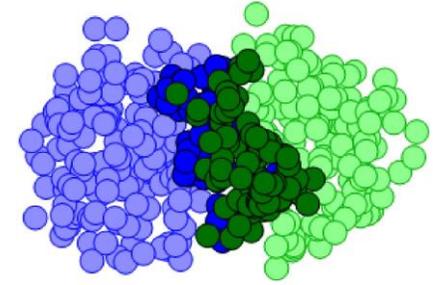
# Initial State Models

- Search for **critical point** requires **finite  $\mu_B$**
- Transports are important in **low energy** collisions
  - Constrain using **high energy**
- $B_{tot} = S_{tot} = Q_{tot} = 0$  at **high energy**, but there can be **local fluctuations**

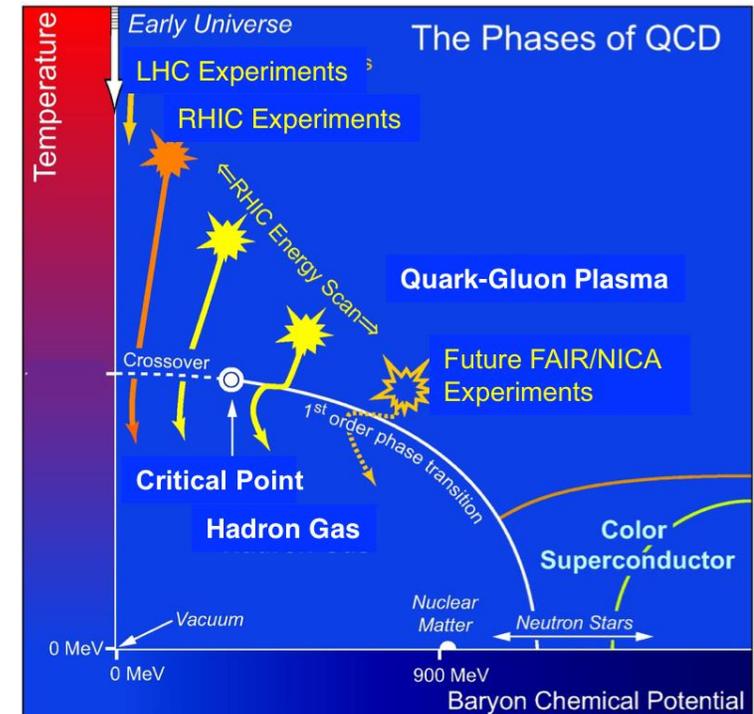


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- All **initial state models** begin with a **Monte Carlo** sampling of **nuclear geometry**
- Initial state is often characterized **only** by **energy** with rare inclusion of other degrees of freedom
- For models based on microscopic pQCD, spatial **density of gluons** can be computed
  - Can be mapped onto **quark pair production**

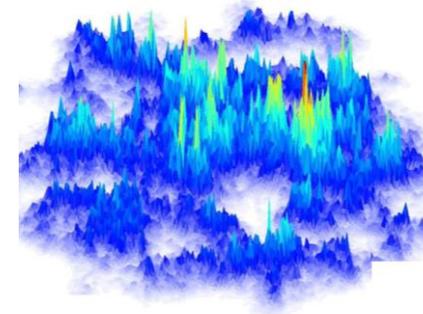
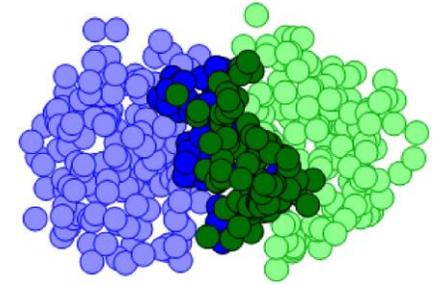


*B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. **108** (2012) 252301*



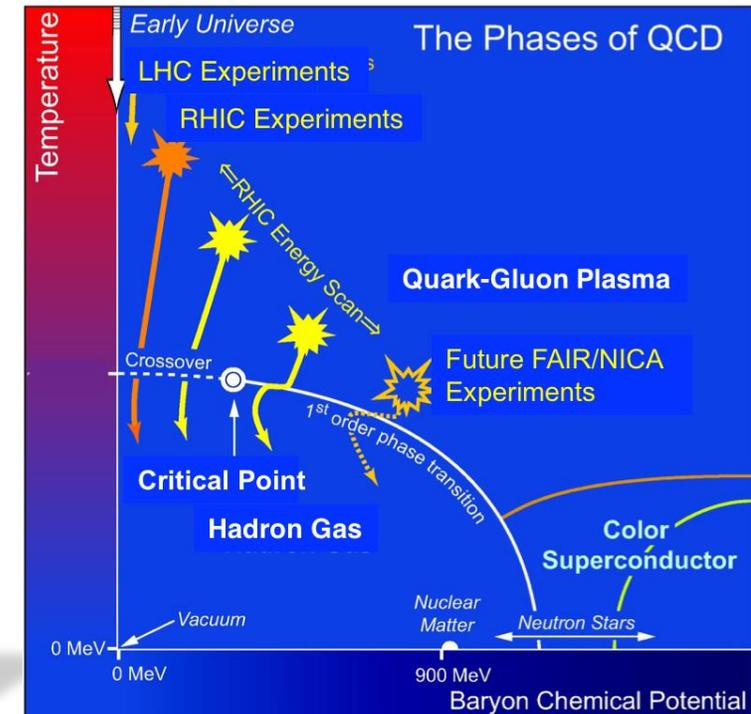
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If initial  $T^{\mu\nu}$  (energy momentum tensor) can be interpreted as gluons, it can be converted to generate  $J^\mu$  (charge currents)



# Structure of the Proton

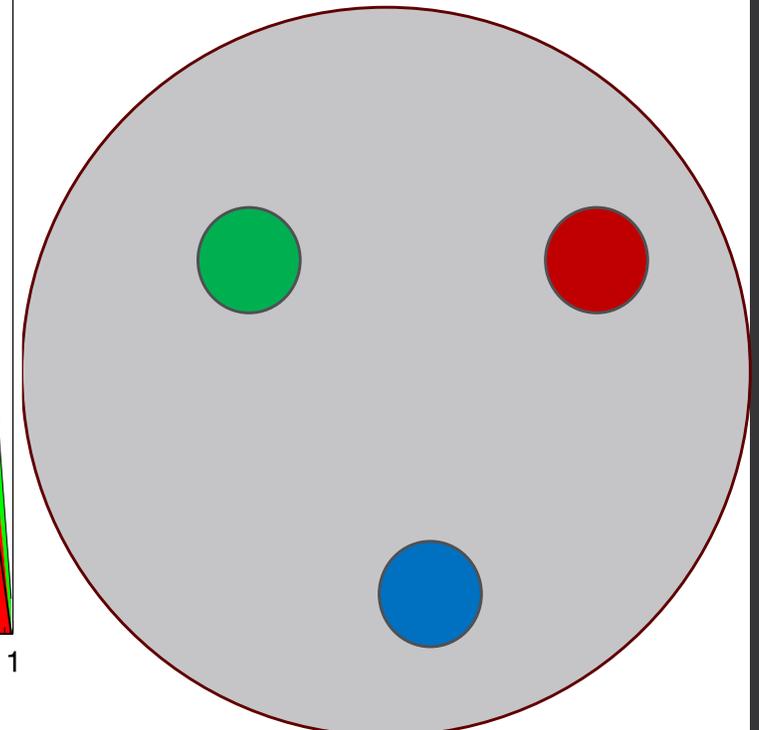
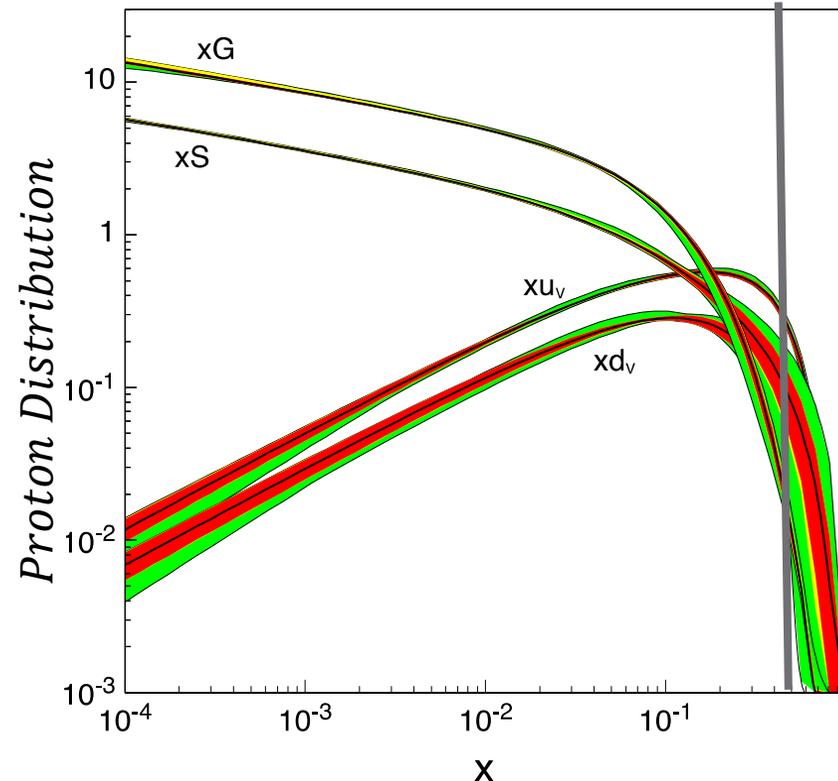
- Heavy ion collisions at mid rapidity possess **small-x kinematics**
  - Dominated by **gluons**
- Consistent **LO picture**:
  - Initial state composed of gluons
  - $\epsilon(x, y), \quad \rho(x, y) = 0$
- But **neglects** a significant presence of **sea quarks**
  - Plus **additional pair production** due to **strong gluon field interactions**

*N. Tanji, R. Venugopalan,  
Phys. Rev. D 95, 094009 (2017)*

# Structure of the Proton

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

*H1 and ZEUS Collaborations,  
JHEP 1001 (2010) 109*



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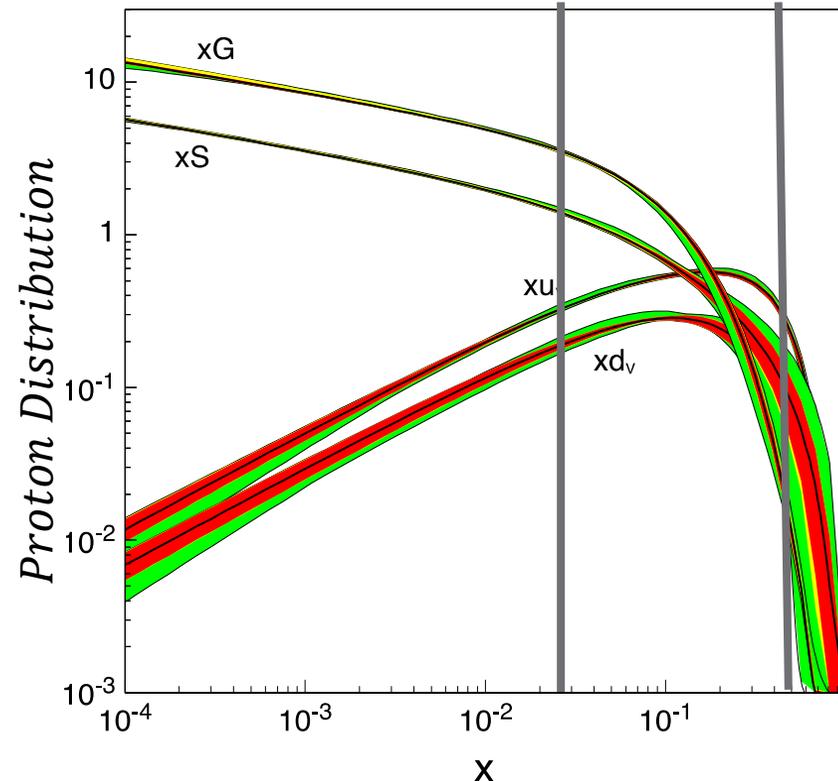
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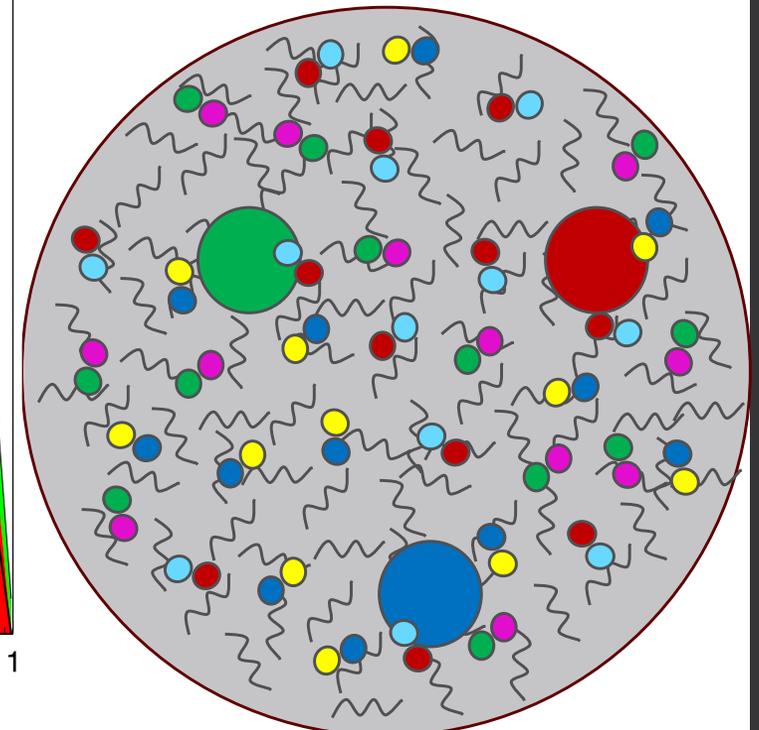
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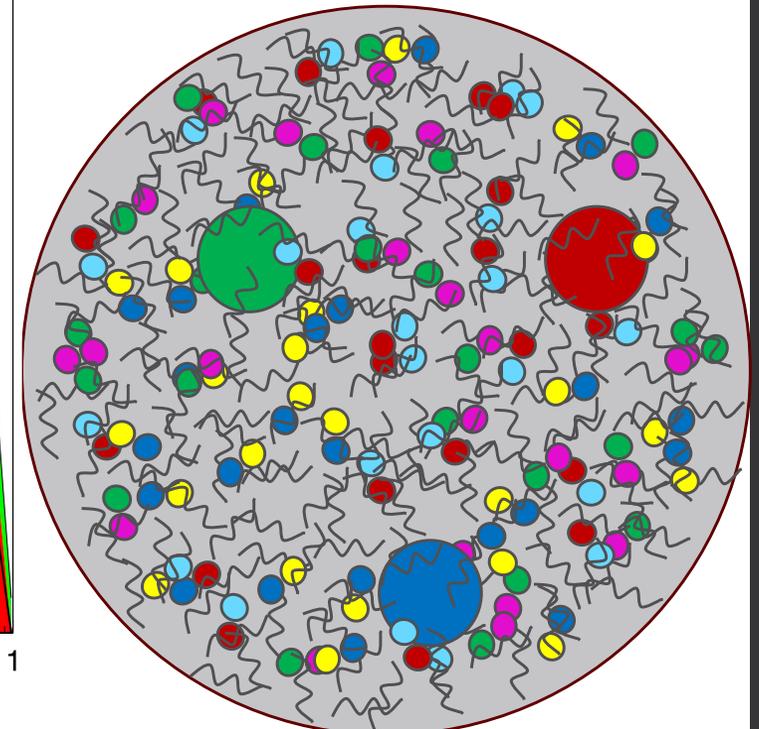
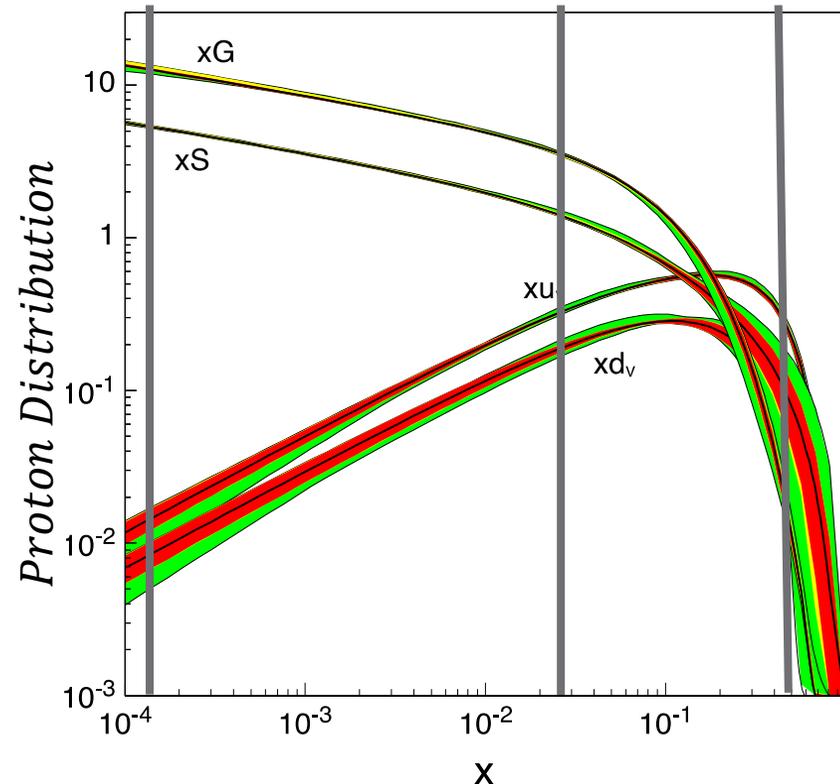


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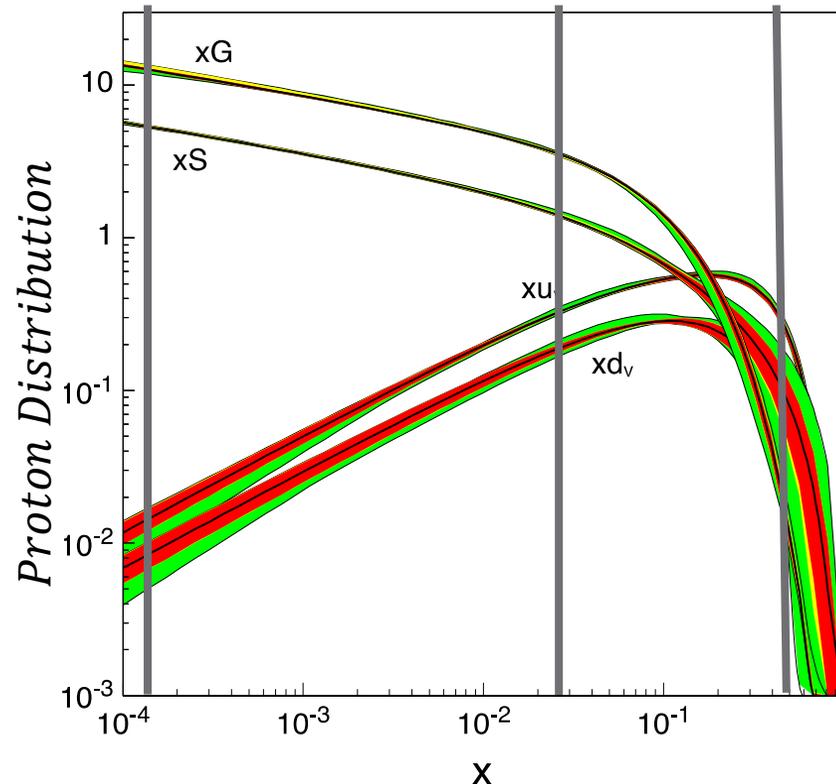
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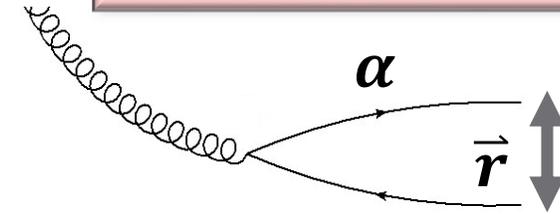
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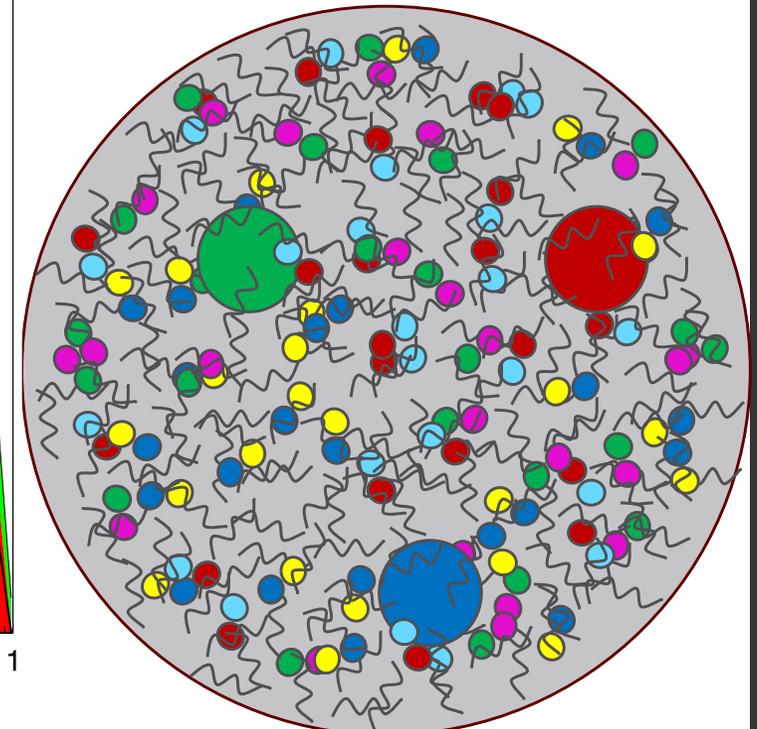
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Assuming gluon saturation, we can sample  $g \rightarrow q\bar{q}$  splittings



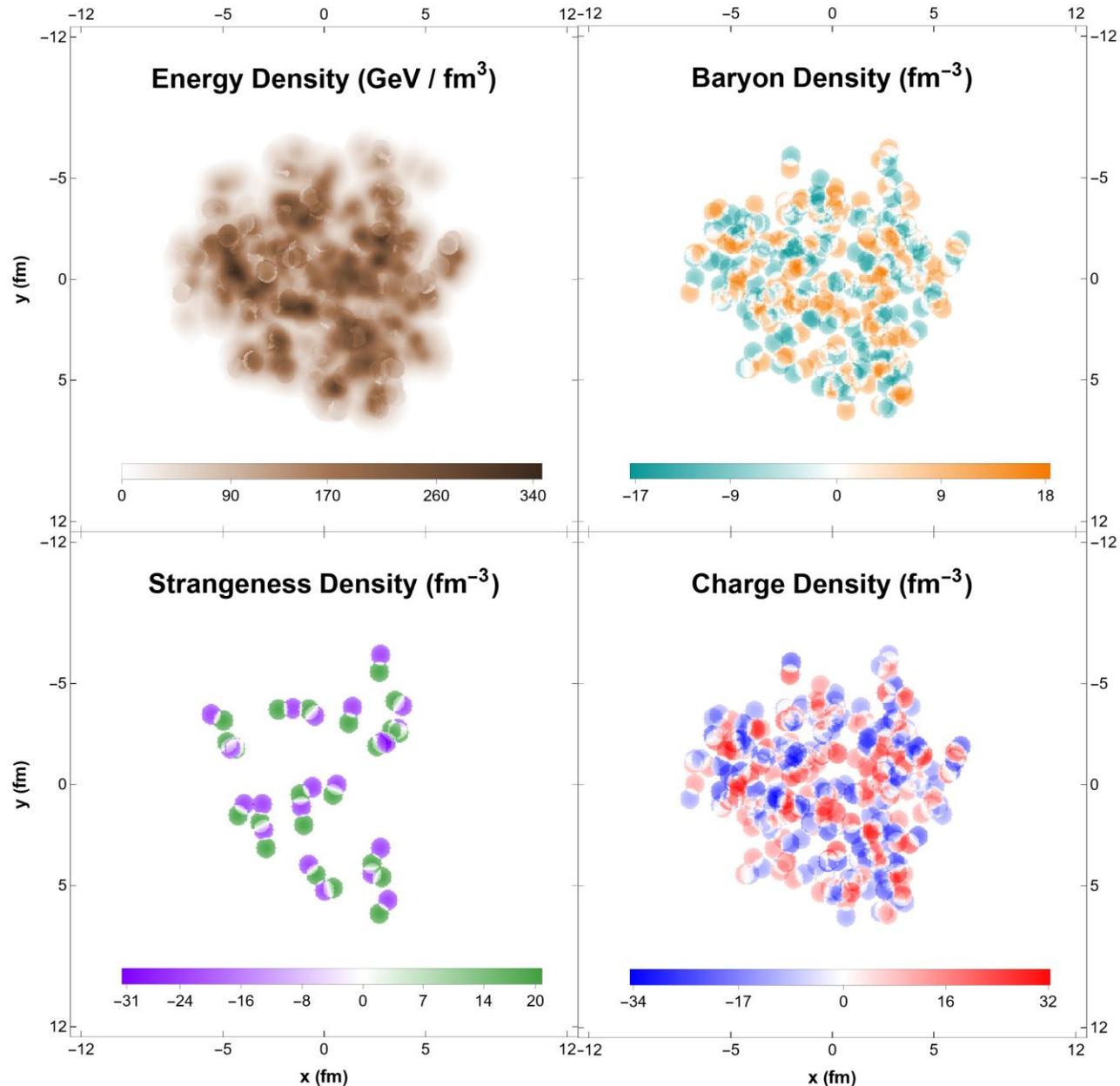
$1 - \alpha$



# Introducing Conserved Charges

## Initial Conserved Charges In Nuclear Geometry

PC, Martinez, Sievert, Wertepny,  
Noronha-Hostler  
Phys. Rev. C 105, 034908 (2022)  
arXiv: 1911.12454 [nucl-th]



# Trento Matches Experiment

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**

Fourier Series of Initial State

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



Fourier Series of Final State

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

$V_n \approx \kappa_n E_n$   
Mostly linear response

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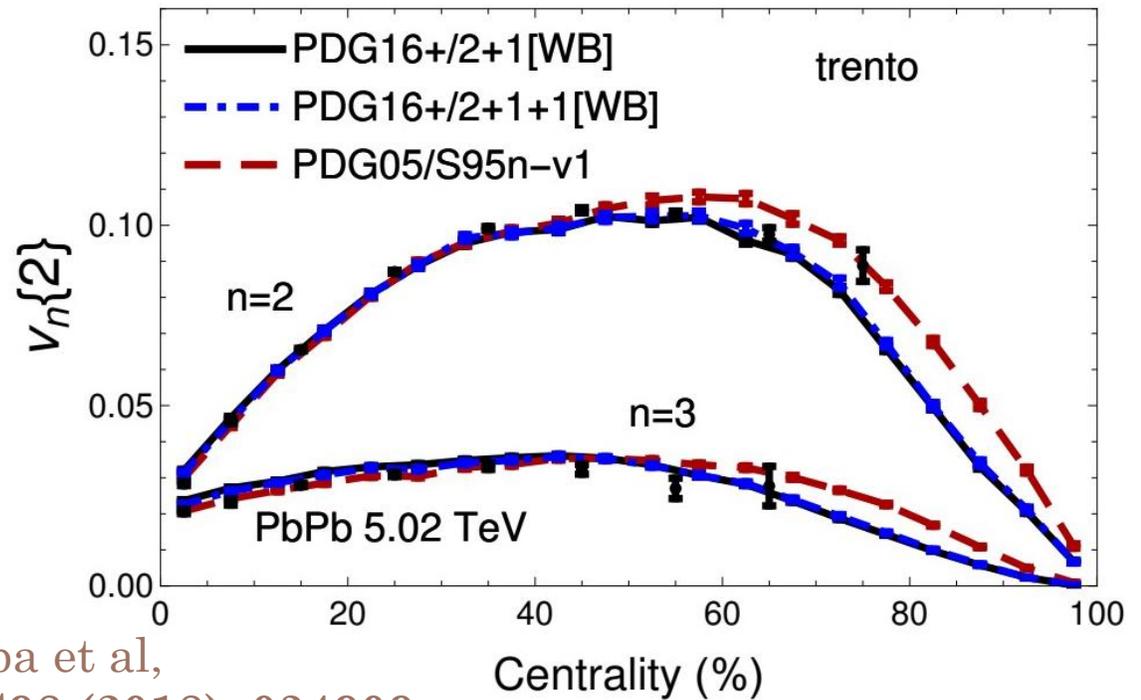
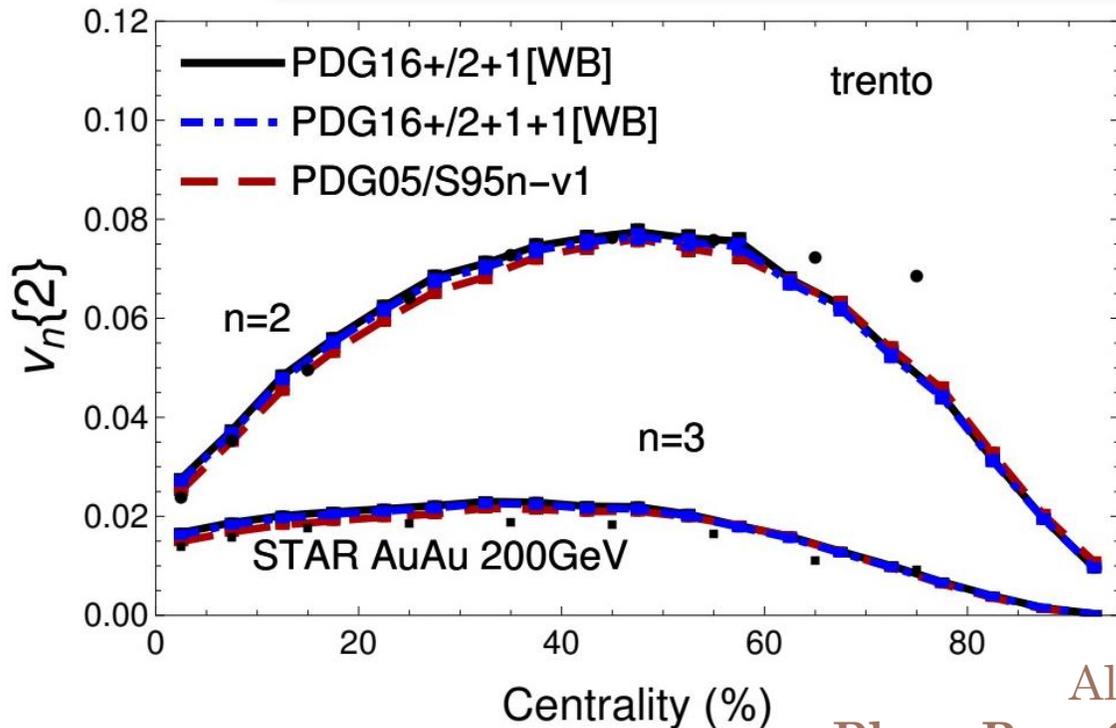
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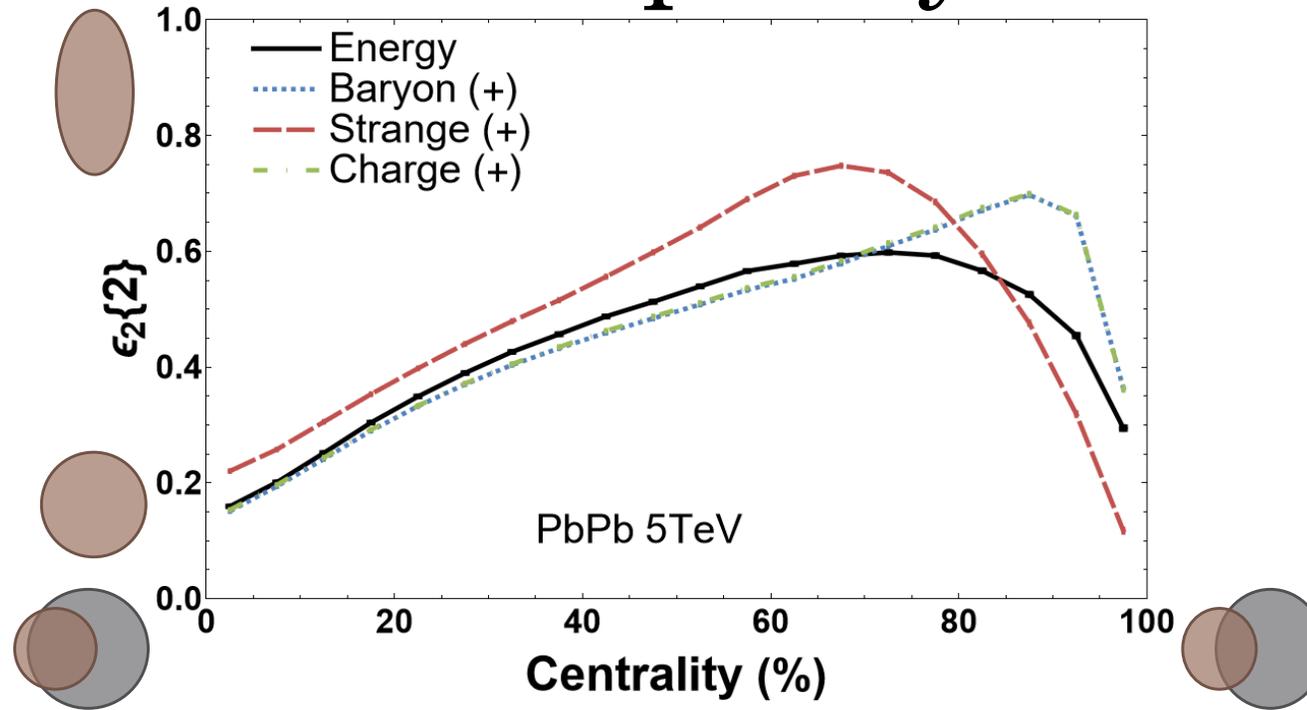
Mostly linear response

Trento can match experimental data despite different choices for evolution



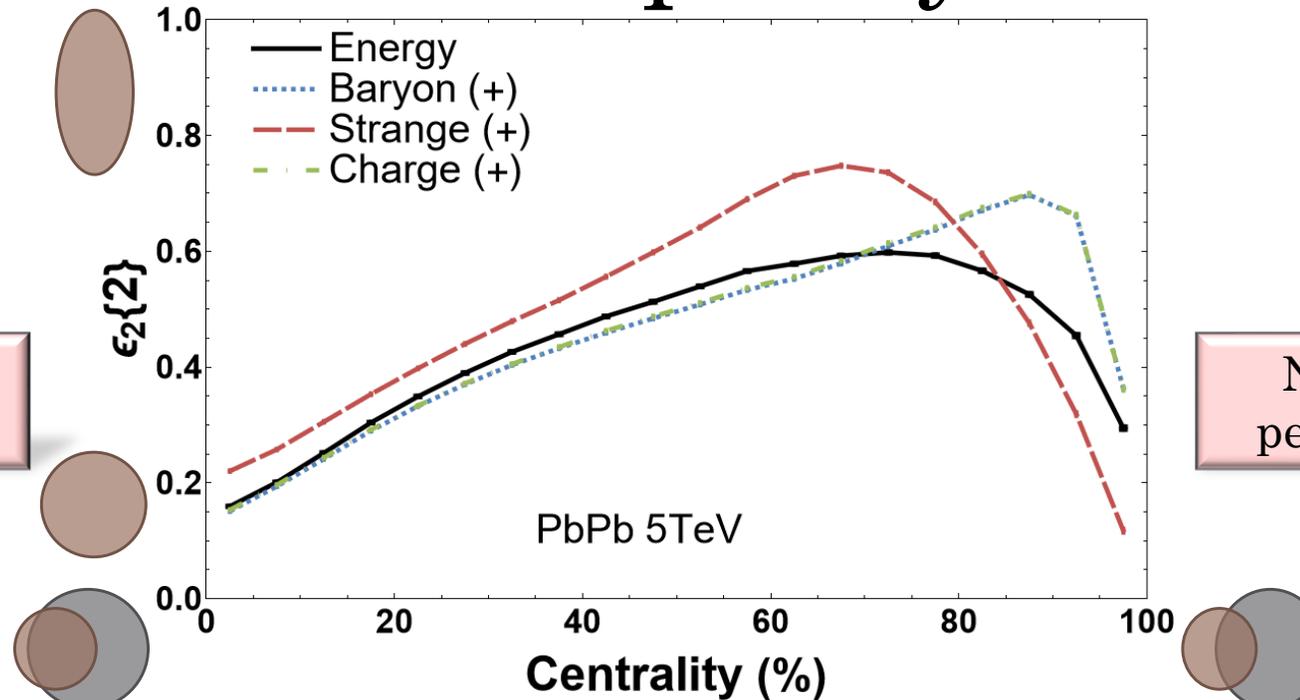
Alba et al, Phys. Rev. C98 (2018), 034909

# Ellipticity



PC, Martinez, Sievert, Wertepny,  
Noronha-Hostler  
*Phys. Rev. C* 105, 034908 (2022)  
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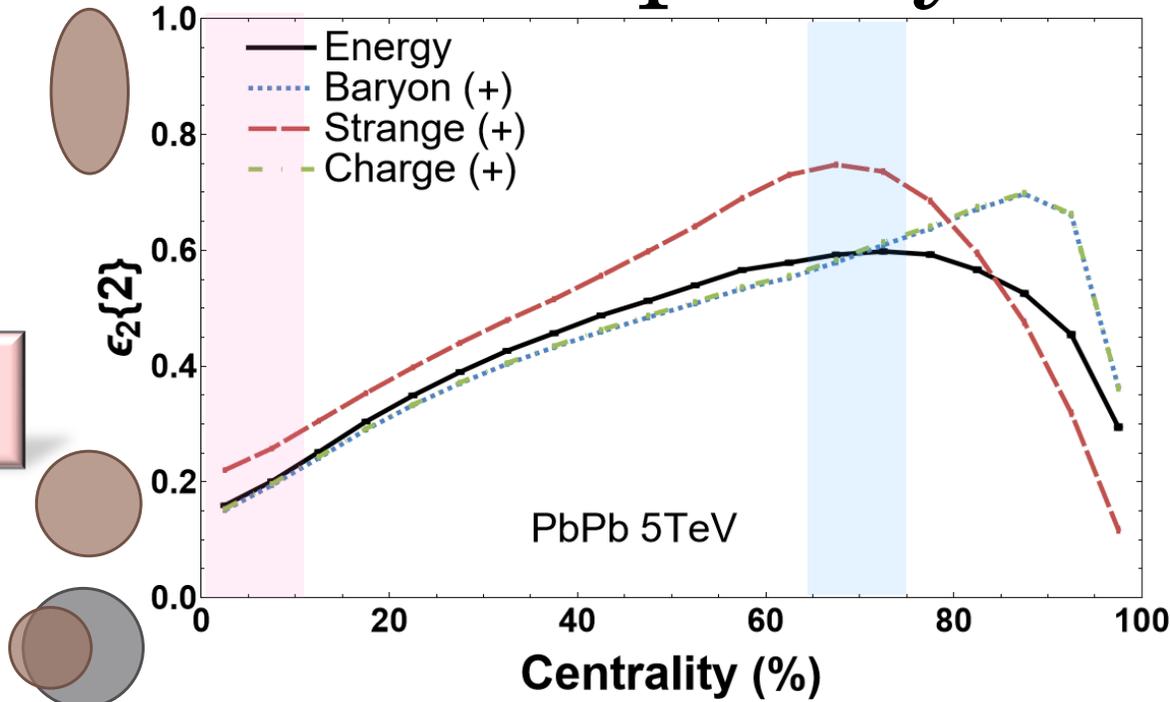


Geometry effects at central collisions

Number effects at peripheral collisions

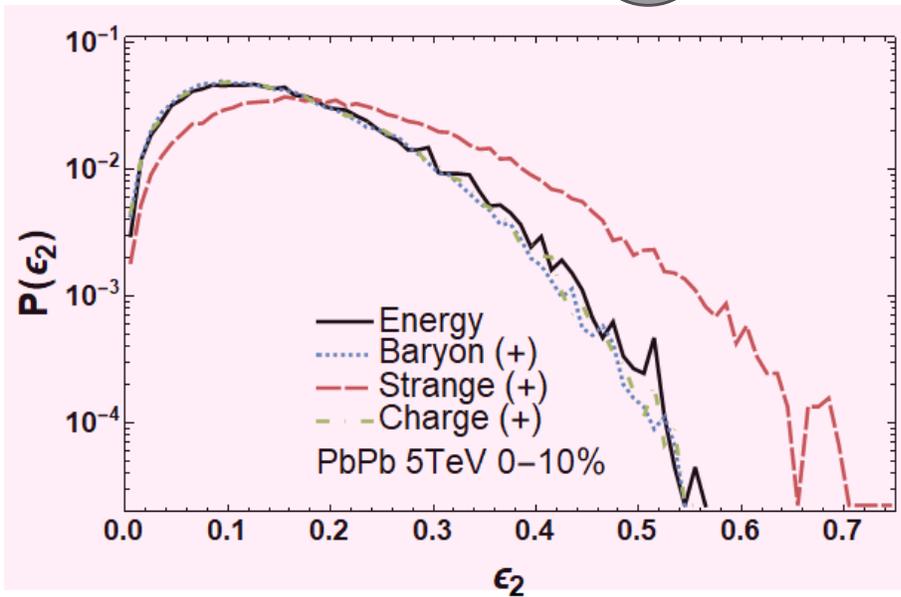
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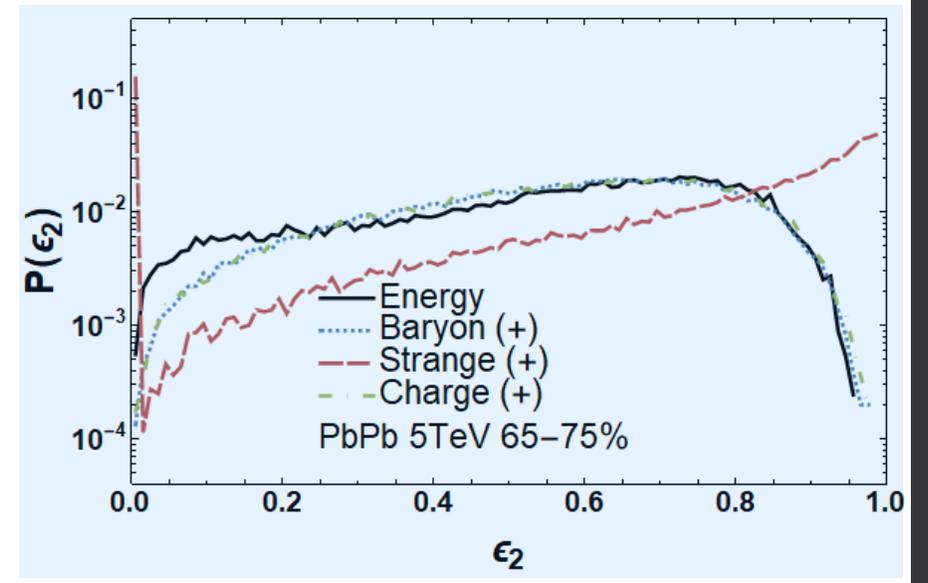


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# Canceling Medium Effects

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

4-Particle Correlation

Less



More

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

Fluctuations of Geometry  
Eccentricities

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Giacalone et al, Phys.Rev. C95 (2017) no.5, 054910

Can be used to constrain  
Initial Condition Parameters

# Canceling Medium Effects

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

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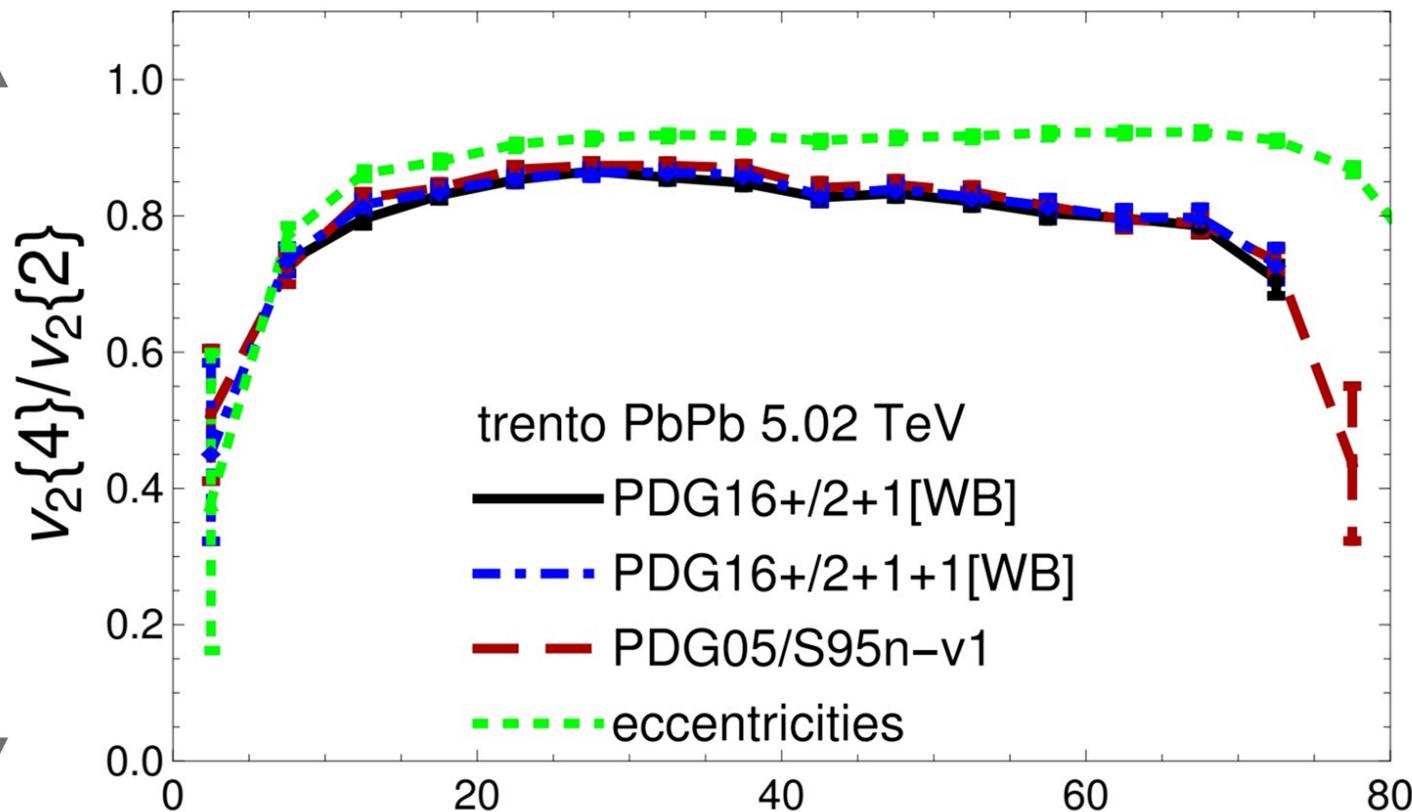
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Can be used to constrain  
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Fewer Fluctuations



Less



More

More Fluctuations

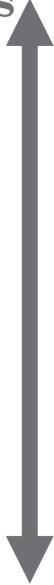
Centrality (%)

Alba et al,

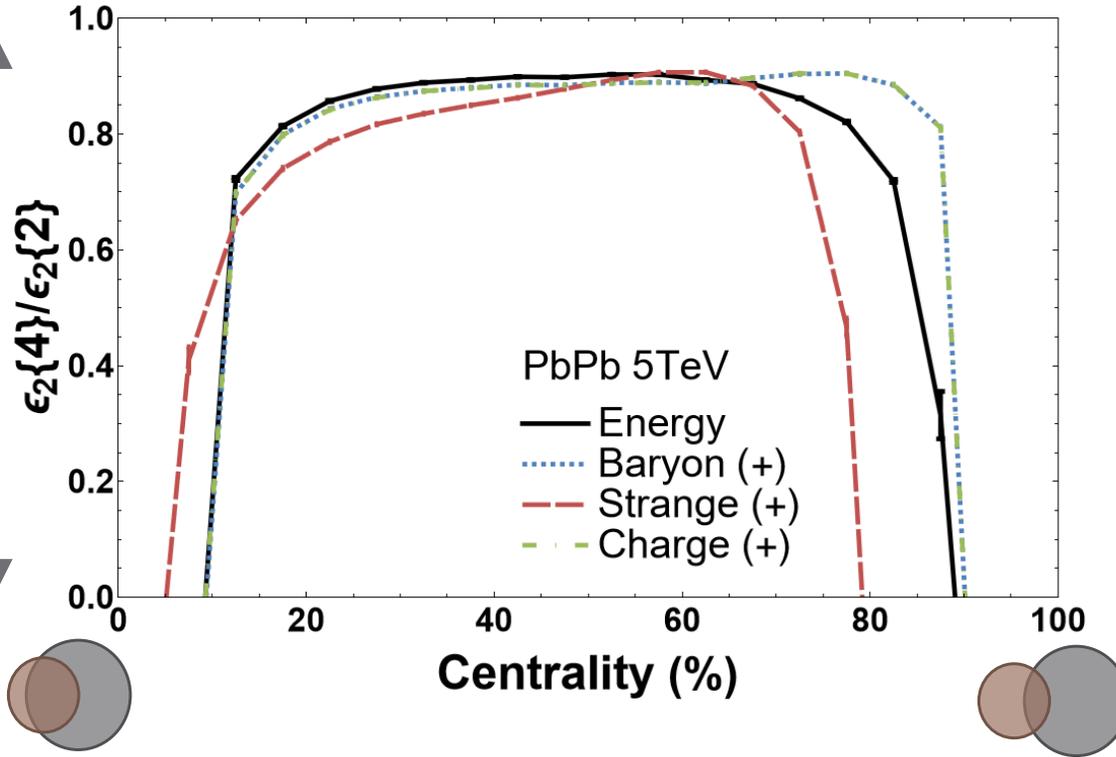
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# Eccentricity Ratio

Fewer Fluctuations



More Fluctuations

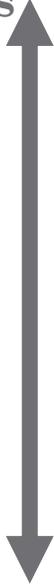


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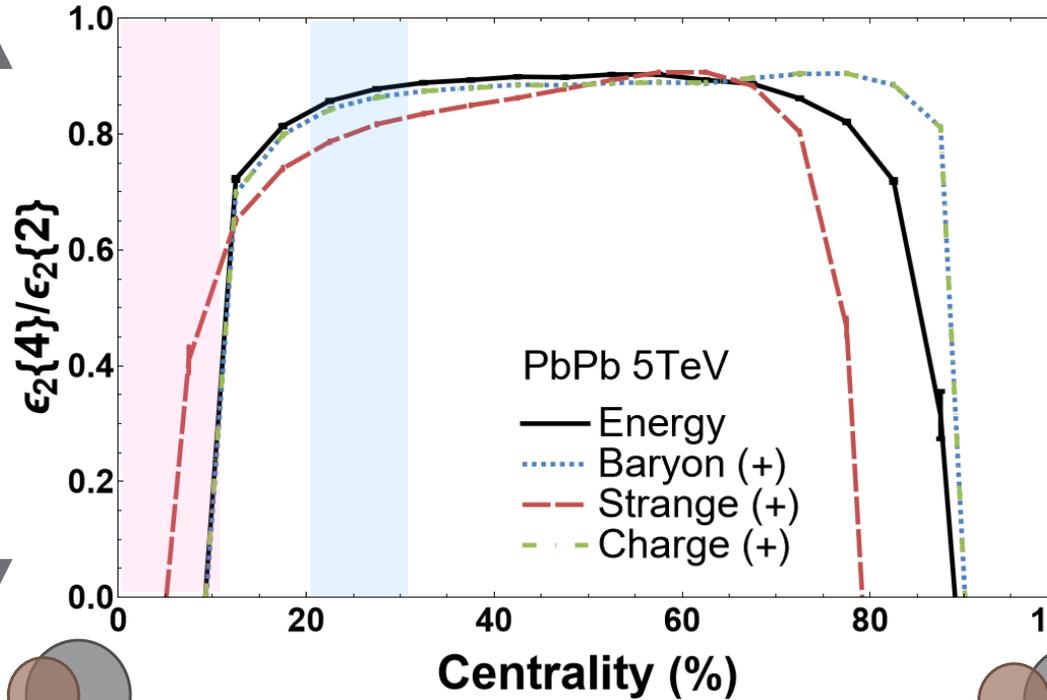
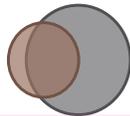
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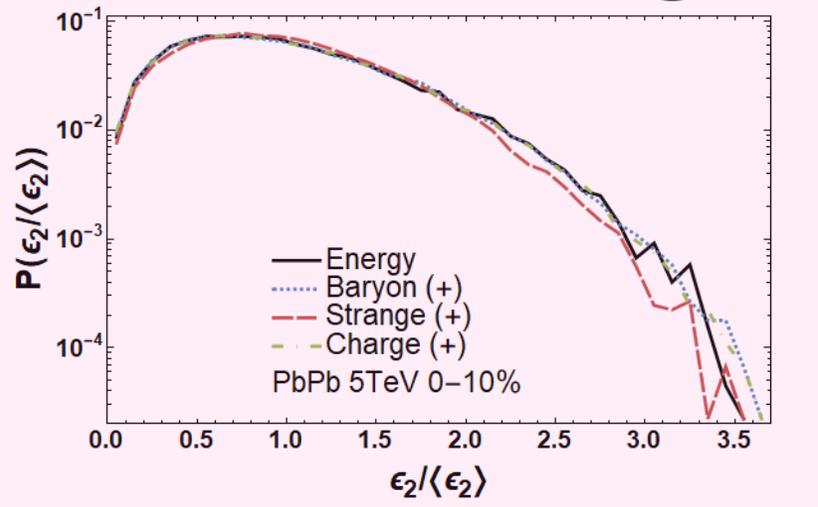
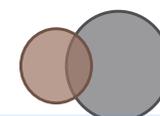
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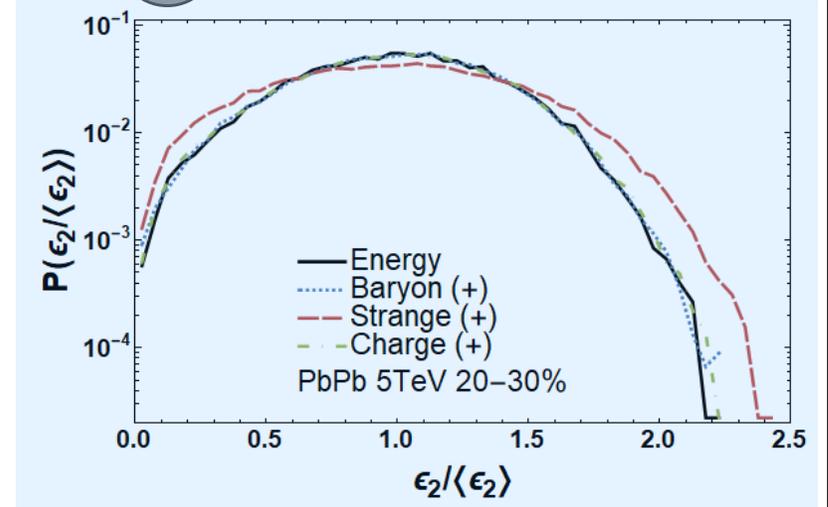
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# Why Pre-Equilibrium?

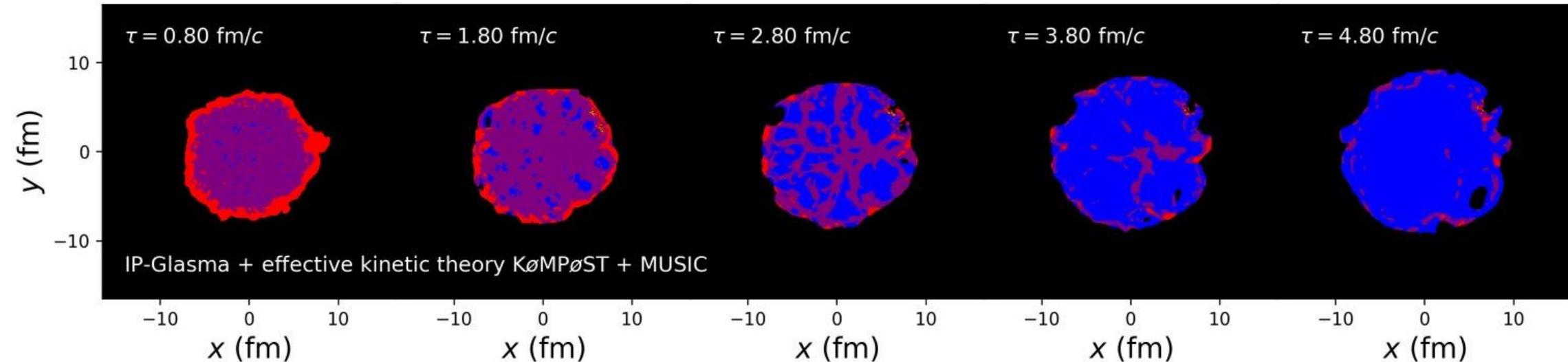
- Initial conditions are far from equilibrium
  - ~30% of cells in hydro violate nonlinear causality constraints
- Pre-equilibrium evolution reduces acausal cells
- $K\phi MP\phi ST$  uses microscopic description of QCD kinetic theory to propagate

$$T^{\mu\nu}(\tau_0) \rightarrow T^{\mu\nu}(\tau_{hydro})$$

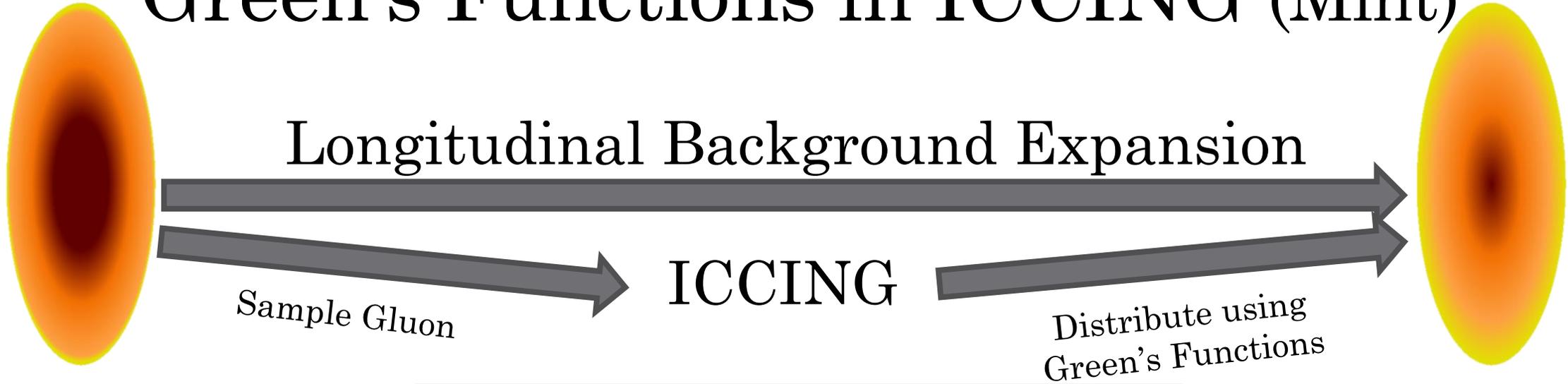
A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney, Phys. Rev. Lett. 122, 122302 (2019), 1805.01604

A. Kurkela, A. Mazeliauskas, J.-F. Paquet, S. Schlichting, and D. Teaney, Phys. Rev. C 99, 034910 (2019), 1805.00961

- We use Green's Functions, using  $K\phi MP\phi ST$  formalism, to propagate conserved charges around a vanishing background



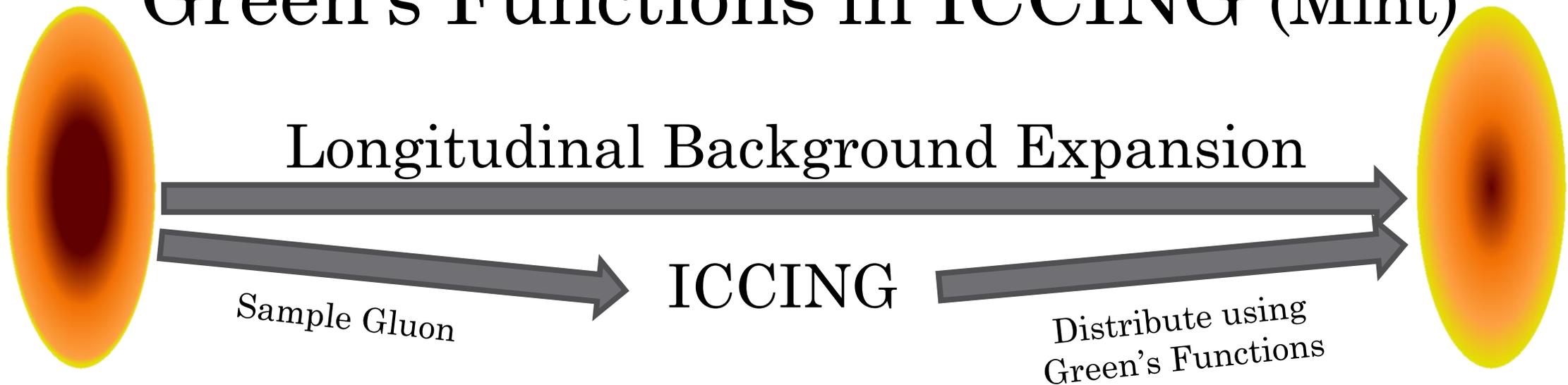
# Green's Functions in ICCING (Mint)



PC, Plaschke, Martinez,  
Noronha-Hostler, Schlichting,  
Sievert  
arXiv: 2301.04572 [nucl-th]

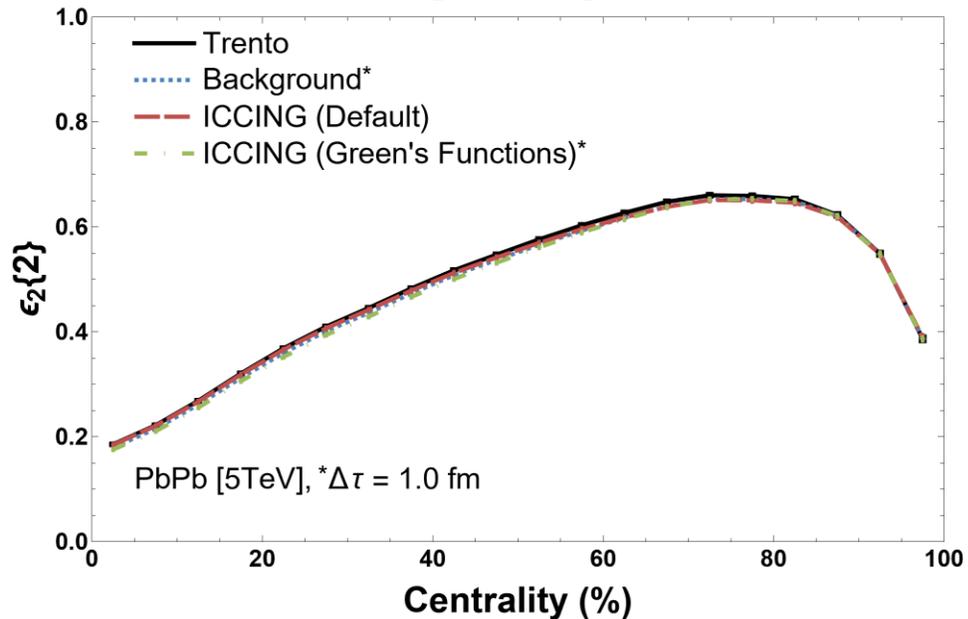
Modular ICCING can accommodate  
complex structural additions

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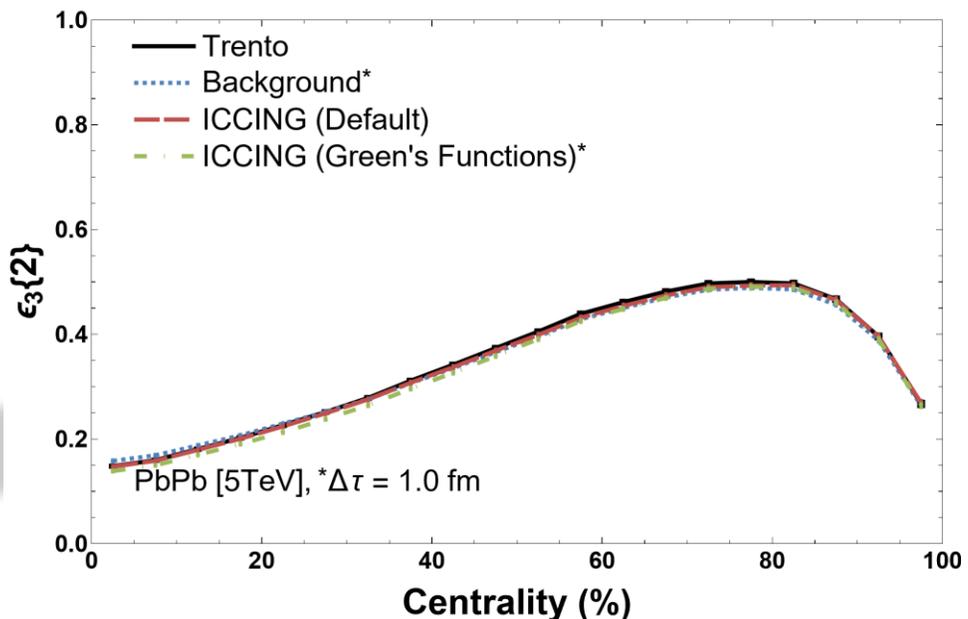


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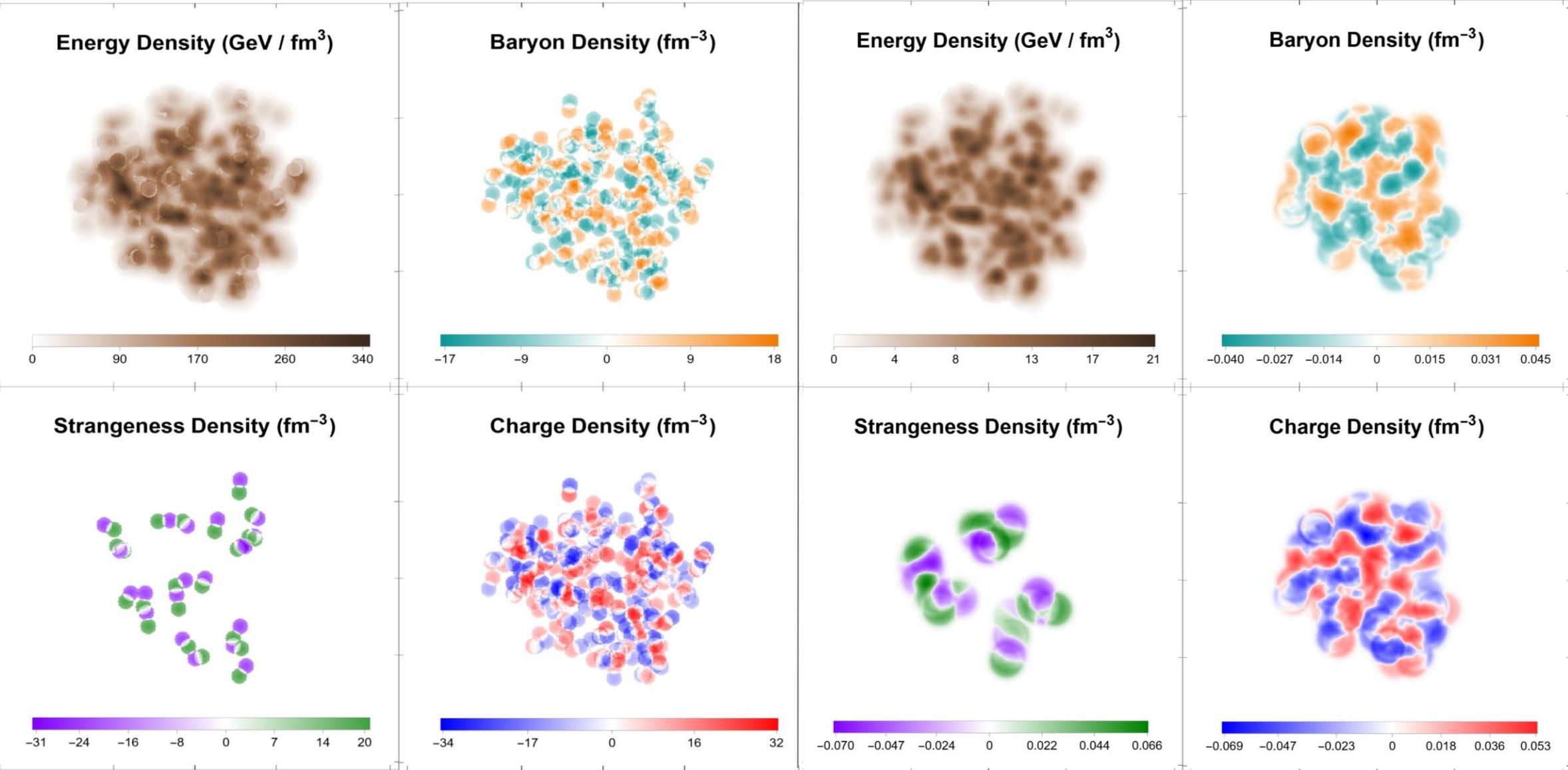
Energy geometry is largely unaffected by perturbative processes



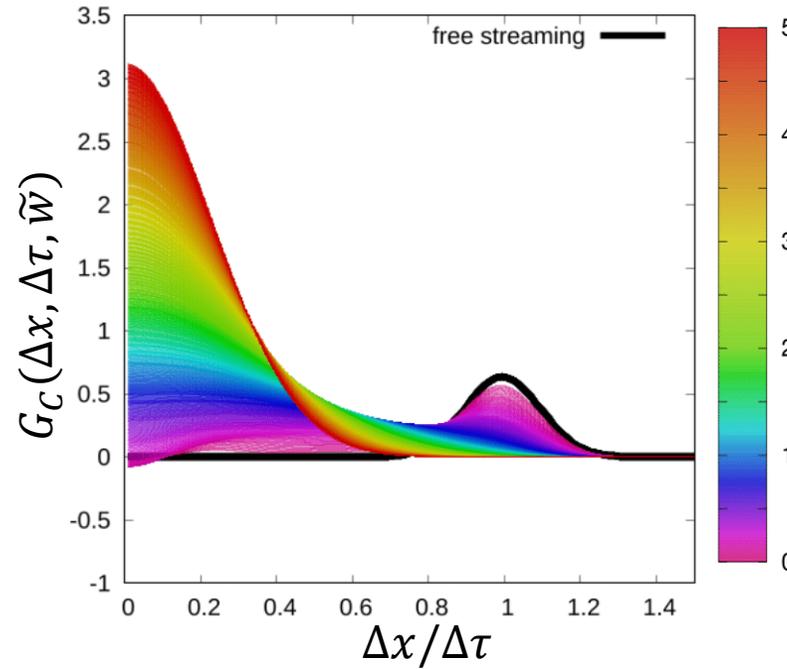
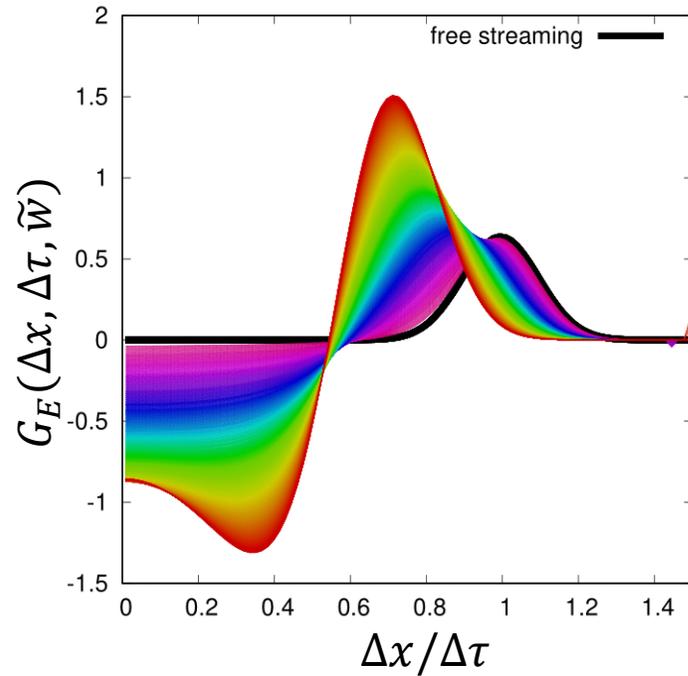
# Density Comparison

## Default

## Green's Functions



# Temperature Dependence

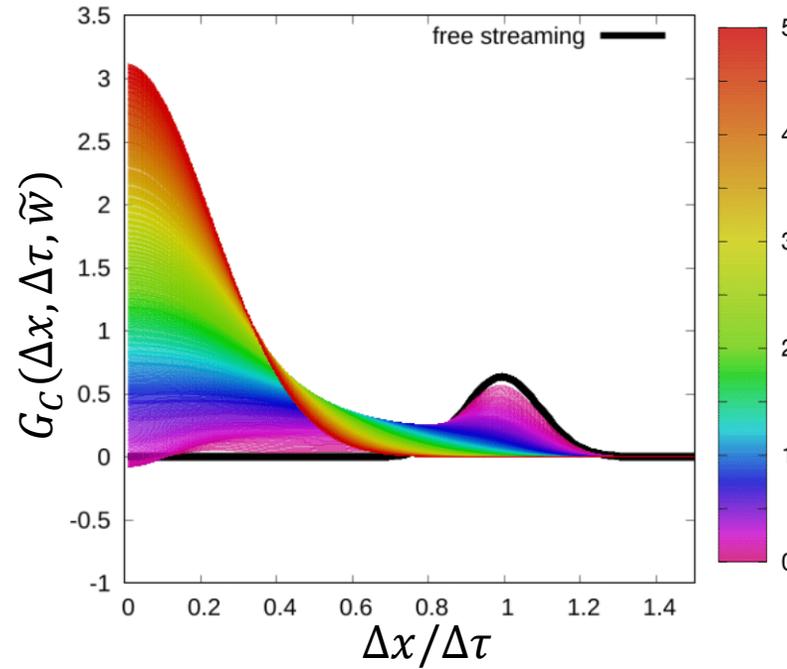
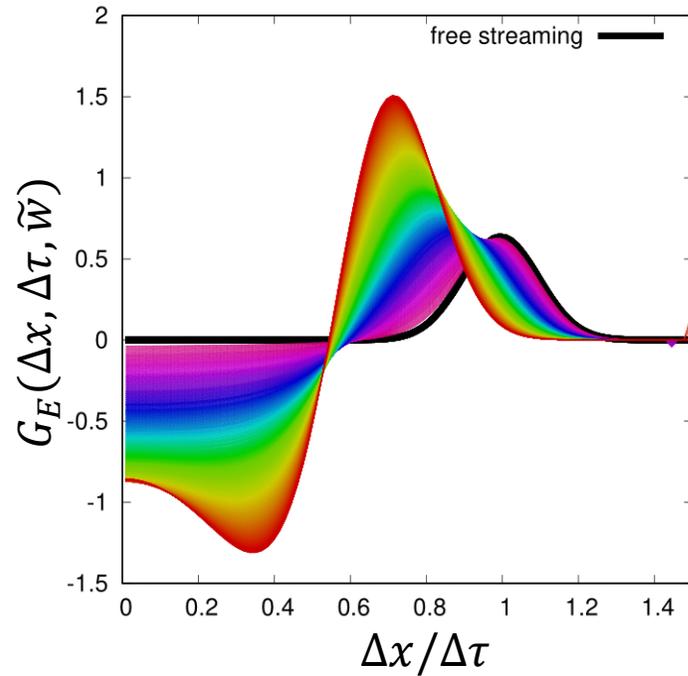


$$\tilde{w} \sim \frac{T(\tau_0)\Delta\tau}{4\pi \frac{\eta}{s}}$$

- Form of Green's Functions depends on local temperature of gluon splitting

PC, Plaschke, Martinez, Noronha-Hostler,  
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# Temperature Dependence



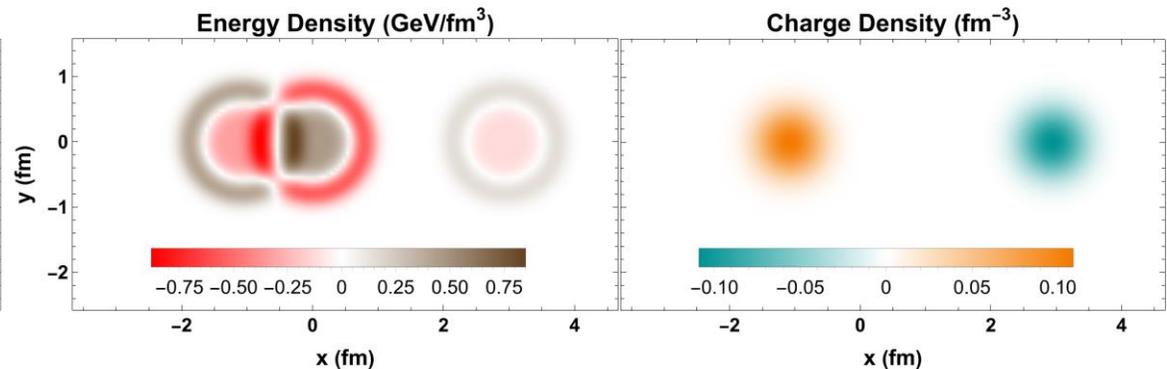
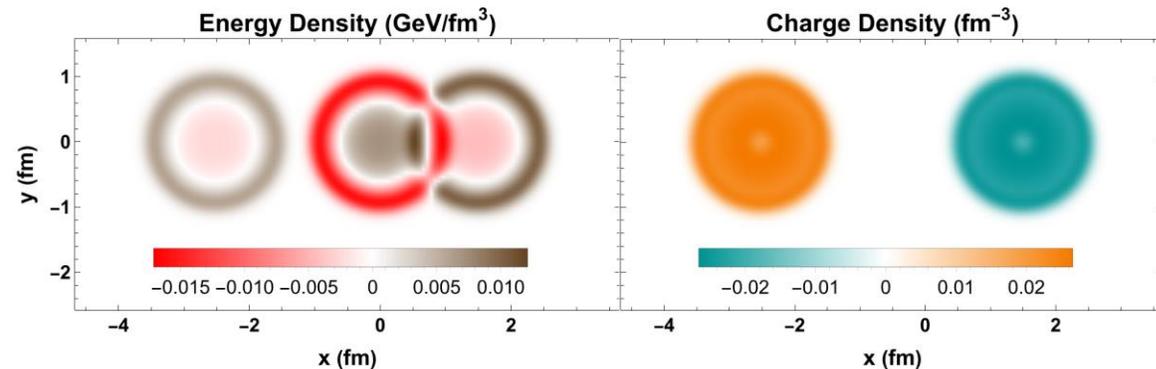
$$\tilde{w} \sim \frac{T(\tau_0)\Delta\tau}{4\pi\frac{\eta}{s}}$$

- Form of Green's Functions depends on local temperature of gluon splitting
- Hot quarks are more gaussian while cold quarks contain wave structure
- Non-local evolution and presence of negative energy

Cold

PC, Plaschke, Martinez, Noronha-Hostler,  
Schlichting, Sievert  
arXiv: 2301.04572 [nucl-th]

Hot

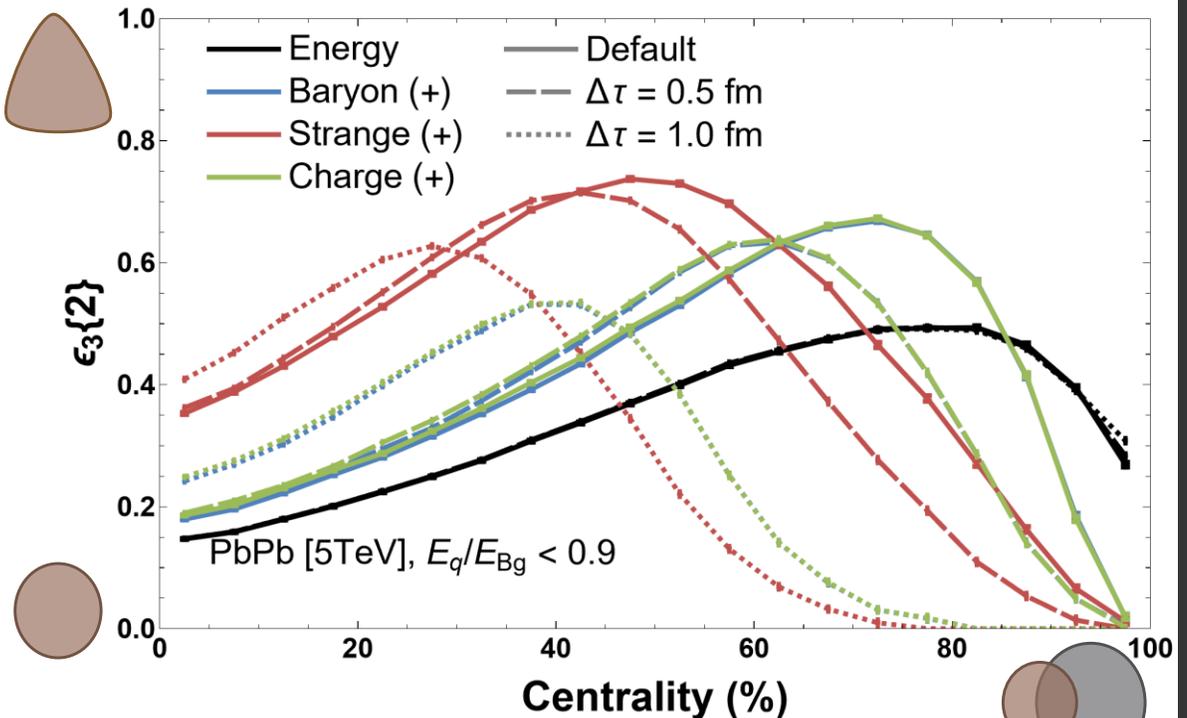
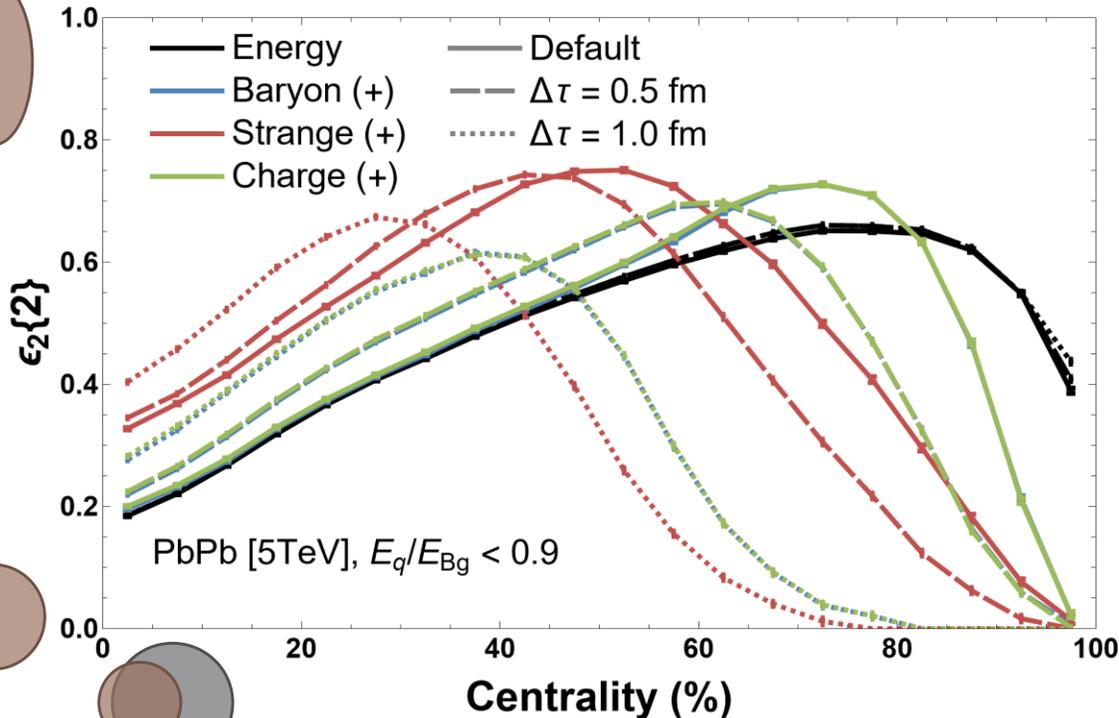


# ICcing + Green's Functions (Mint)

PC, Plaschke, Martinez,  
Noronha-Hostler,  
Schlichting, Sievert  
arXiv: 2301.04572 [nucl-th]

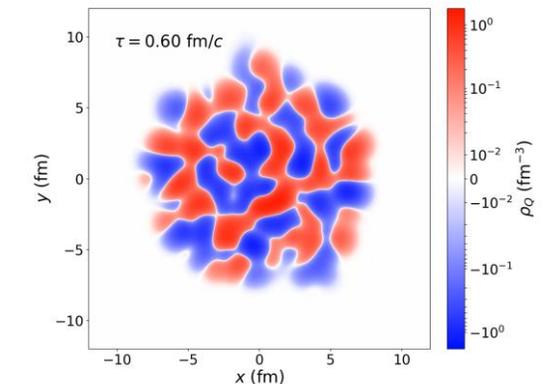
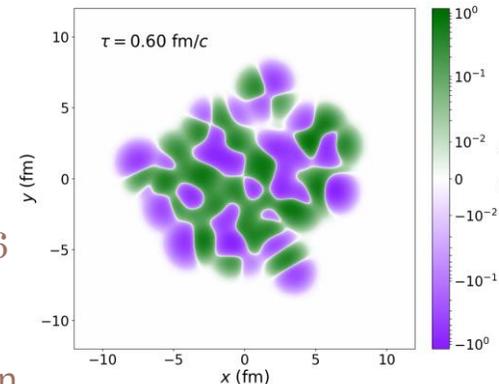
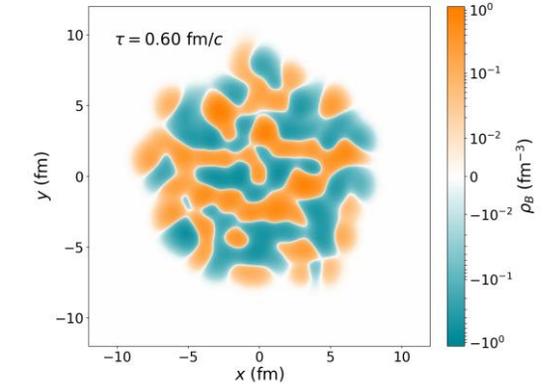
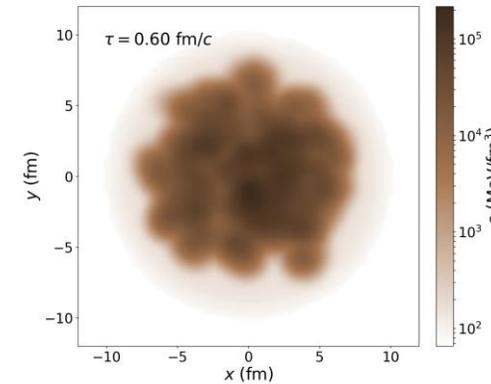
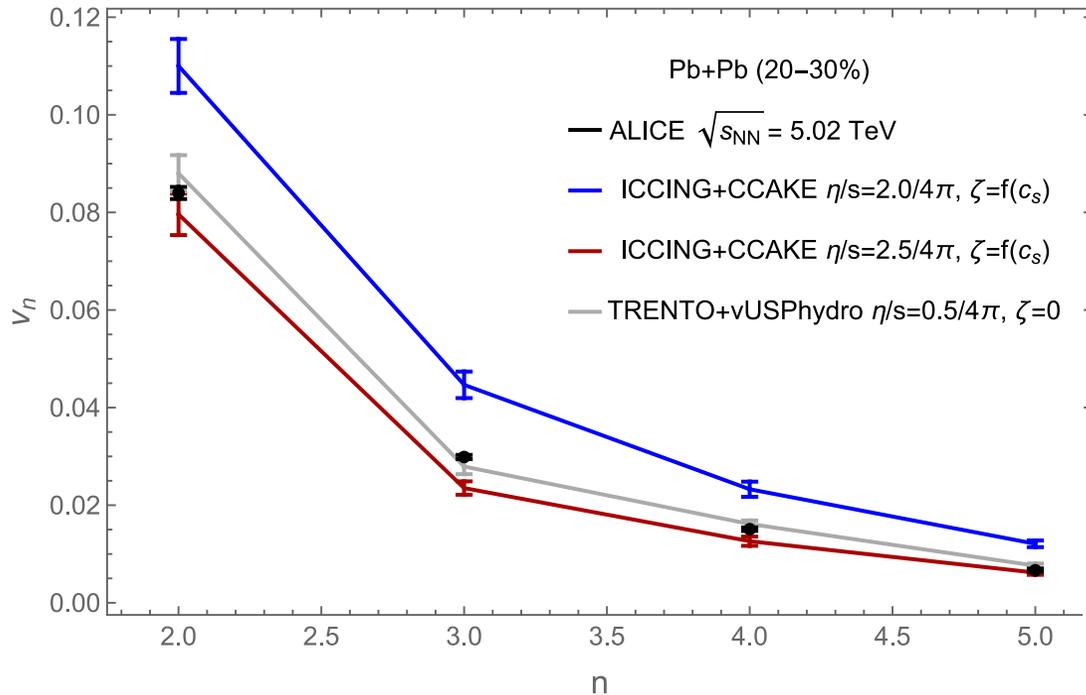
Evolution of Green's Functions modifies geometry consistently over time, but fails in peripheral collisions due to suppression of quark production

Other effects (radial expansion, time dependence, perturbation cut off) are included here and discussed in backup



# Conserved Charge Hydrodynamics

ICcing(Vanilla)+CCAKE(Conserved ChArGes in hydrodynamik Evolution)  
increases viscosity to reasonably fit flow harmonics

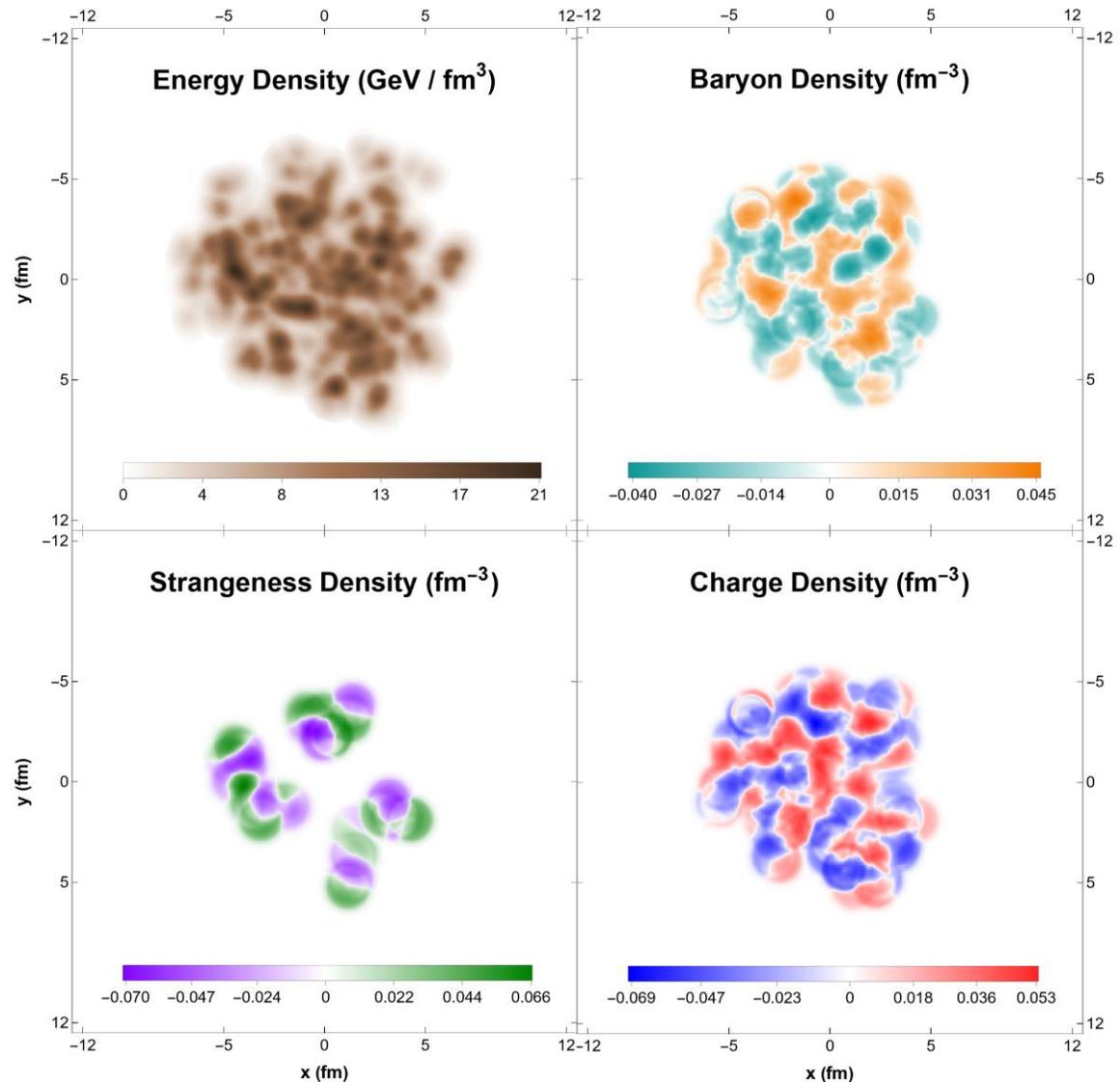


ALICE: J. Adam et al. (The ALICE Collaboration), PRL. 116, 2016  
TRENTO+vUSPhydro: Noronha-Hostler, Luzum, and Ollitrault, PRC 93, 2016

ICcing+CCAKE: Plumberg, Almaalol, Dore, Mroczek, Salinas San Martin, Szychalla, Carzon, Sievert, Noronha-Hostler to appear soon

# Thank you!

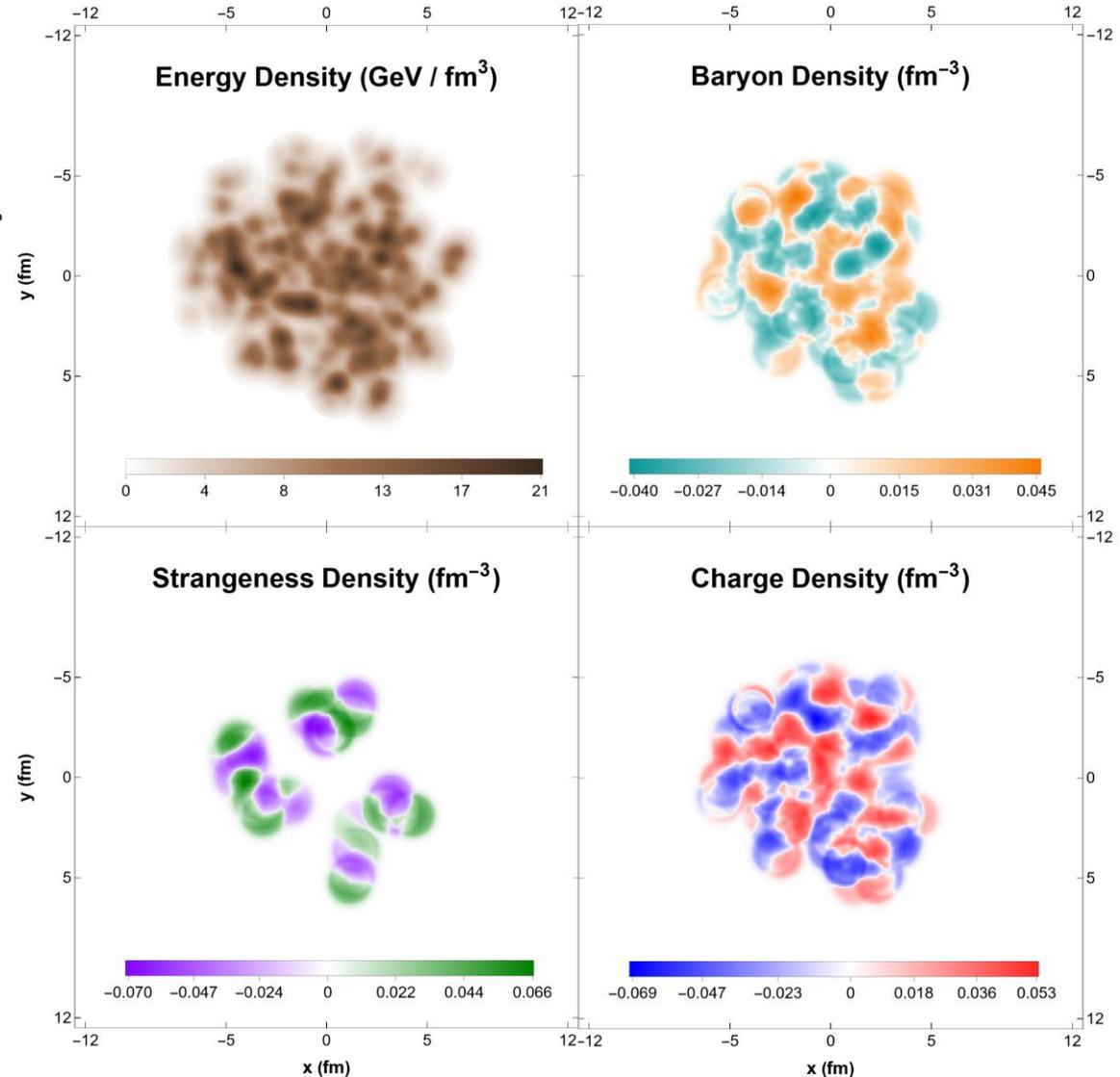
- ICCING uses  $g \rightarrow q\bar{q}$  to initialize local fluctuations of charge around vanishing background
  - Public version with Green's Functions coming in future update [pcarzon/ICcing \(github.com\)](https://github.com/pcarzon/ICcing)
- Pre-equilibrium evolution, such as  $K\phi MP\phi ST$ , reduces acausal cells in hydro evolution
- Green's Functions modeled after  $K\phi MP\phi ST$  can be used to evolve charge densities
- Invalid in peripheral collisions due to suppression of quark production
- Implementation of pre-equilibrium Charge Evolution in  $K\phi MP\phi ST$
- Dore, Du, Schlichting (In Preparation)



# Backup

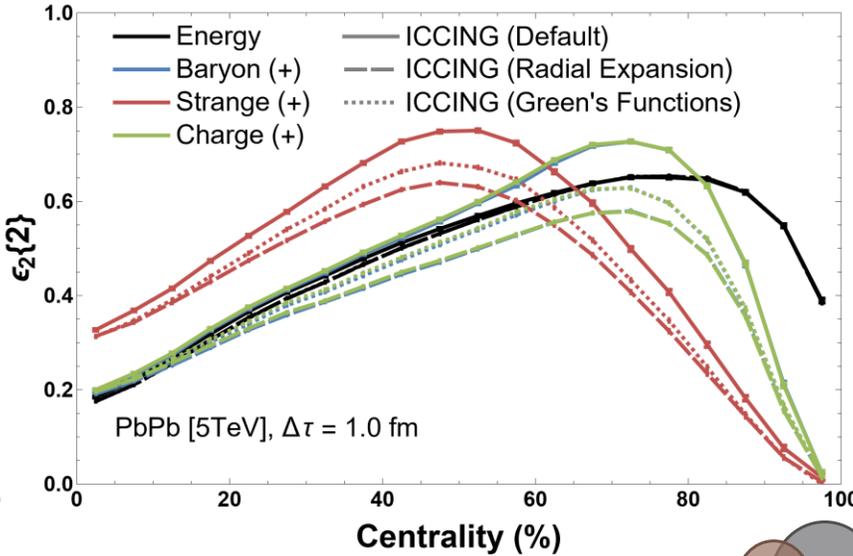
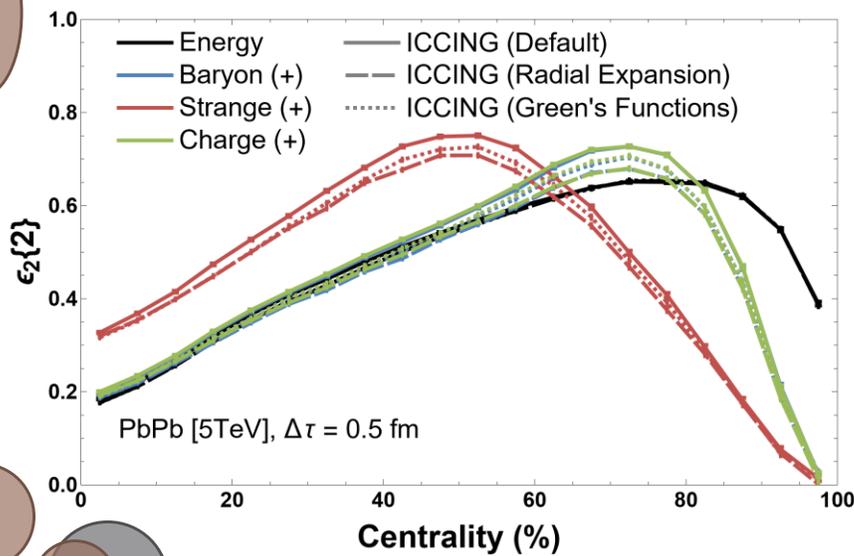
# Future Development

- **Quark Spin Sampling**
  - EIC will provide new spin-dependent PDFs that can be used to initial quark spin
  - Which contribution to spin is larger, quark or nucleon?
- **Azimuthal Structure**
  - Complicated and require initial energy density input
- **Charge Estimators**
  - Eccentricity definition is insufficient for charge densities so we are investigating new estimators
  - Would be useful for Bayesian Analysis
- **Alternative Thickness Function**
  - Reflect gluon saturation assumption and connect well with ICCING framework



# Green's Function Backup

# Geometric Effects

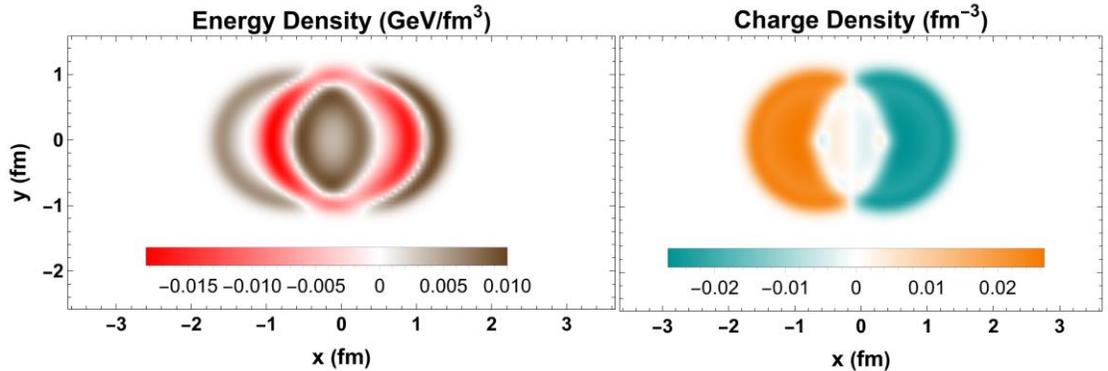
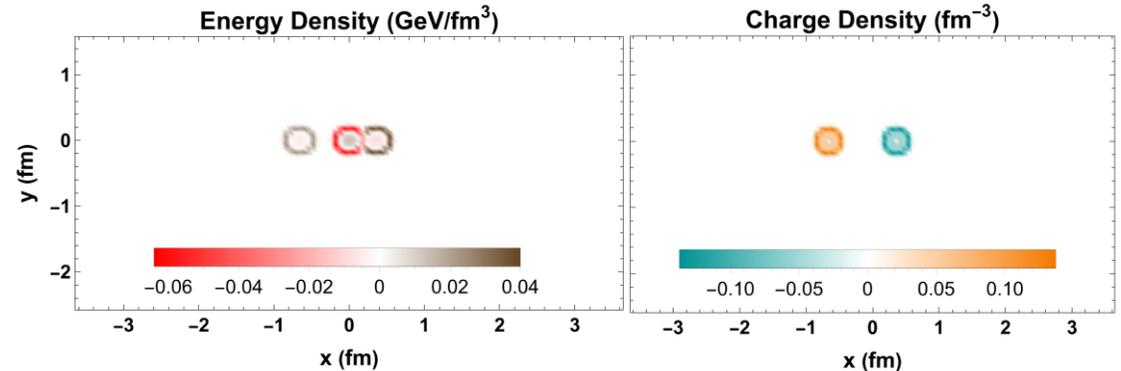


- Dominant effect is from density radius, which suppresses geometry
- Green's Functions are a 'correction' that enhances geometry and increases with time

PC, Plaschke, Martinez, Noronha-Hostler,  
Schlichting, Sievert  
(In Preparation)

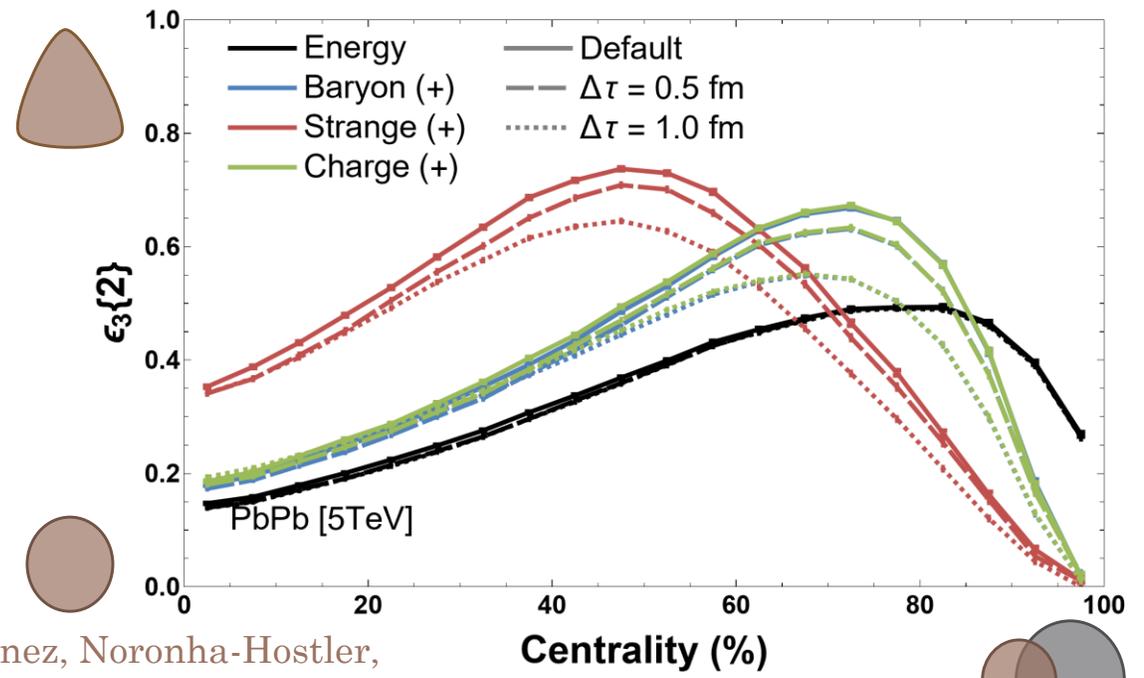
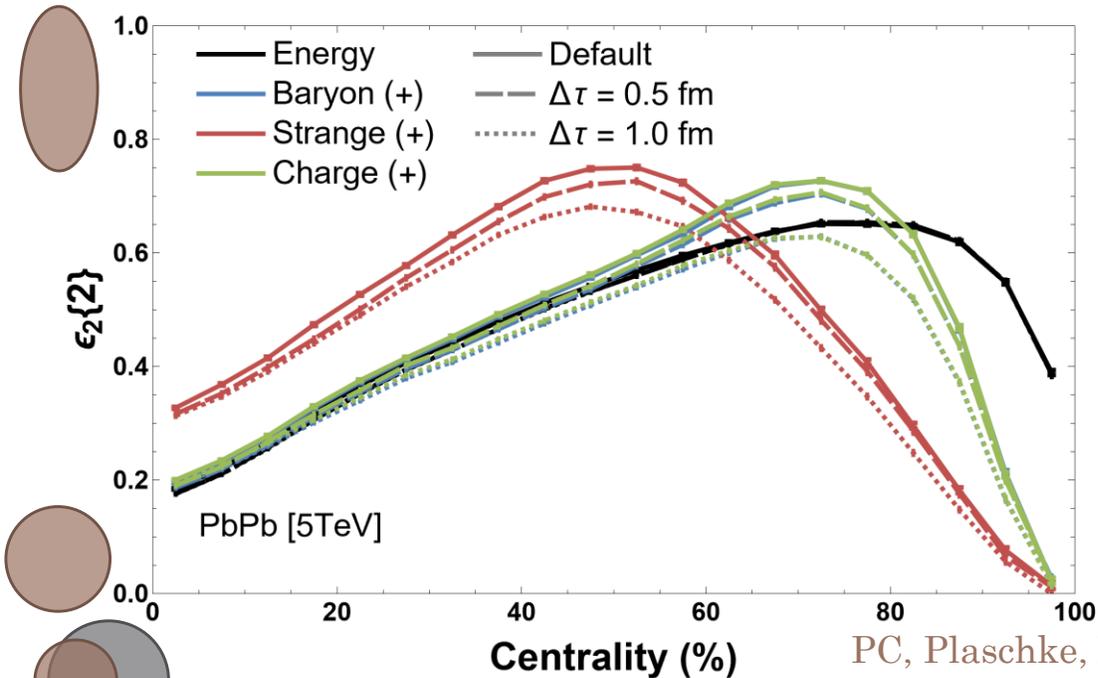
$\Delta\tau = 0.1 \text{ fm}/c$

$\Delta\tau = 1 \text{ fm}/c$



# Time Dependence

Evolution by Green's Functions suppresses charge geometry



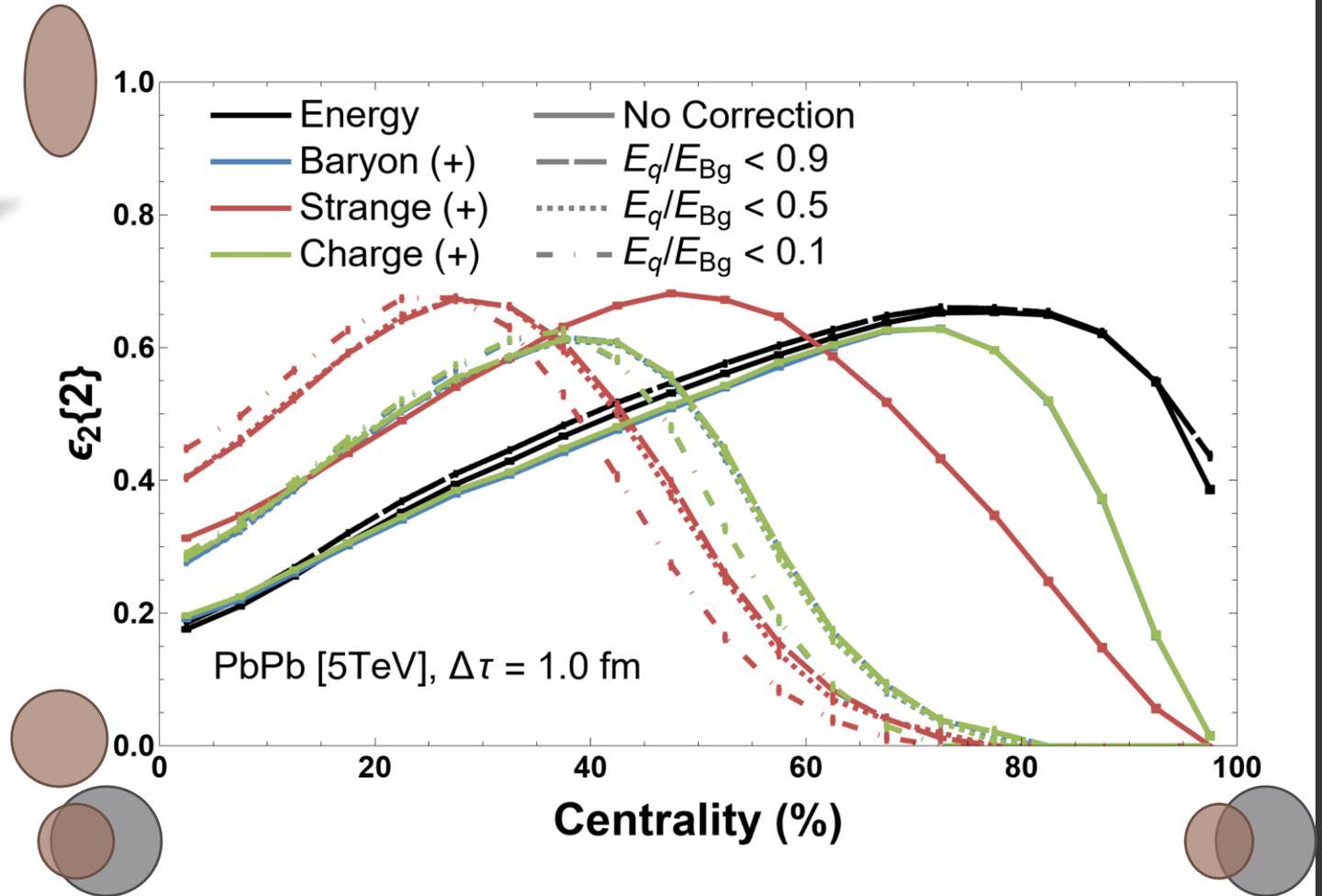
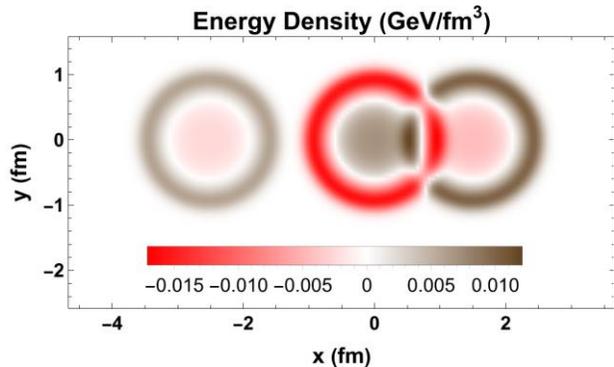
PC, Plaschke, Martinez, Noronha-Hostler,  
Schlichting, Sievert  
(In Preparation)

# Negative Energy Correction

Mismatch between background (local) and quark (non-local) evolution leads to negative energy in output

This becomes more of a problem at longer evolution times

Green's Functions are most pesky due to large negative wake from hole



PC, Plaschke, Martinez, Noronha-Hostler,  
Schlichting, Sievert  
(In Preparation)

# Background Backup

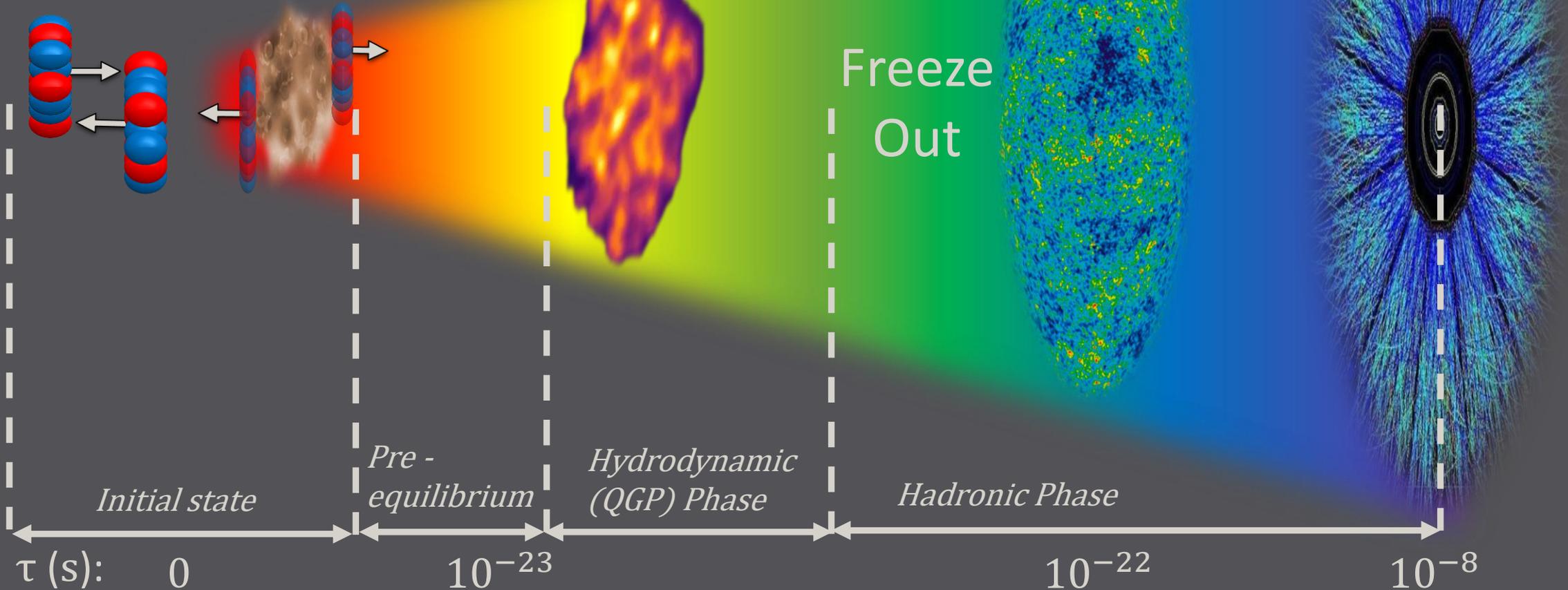
# Nuclear Collisions

Initial State is modeled as energy density

$\sim 100$  MeV

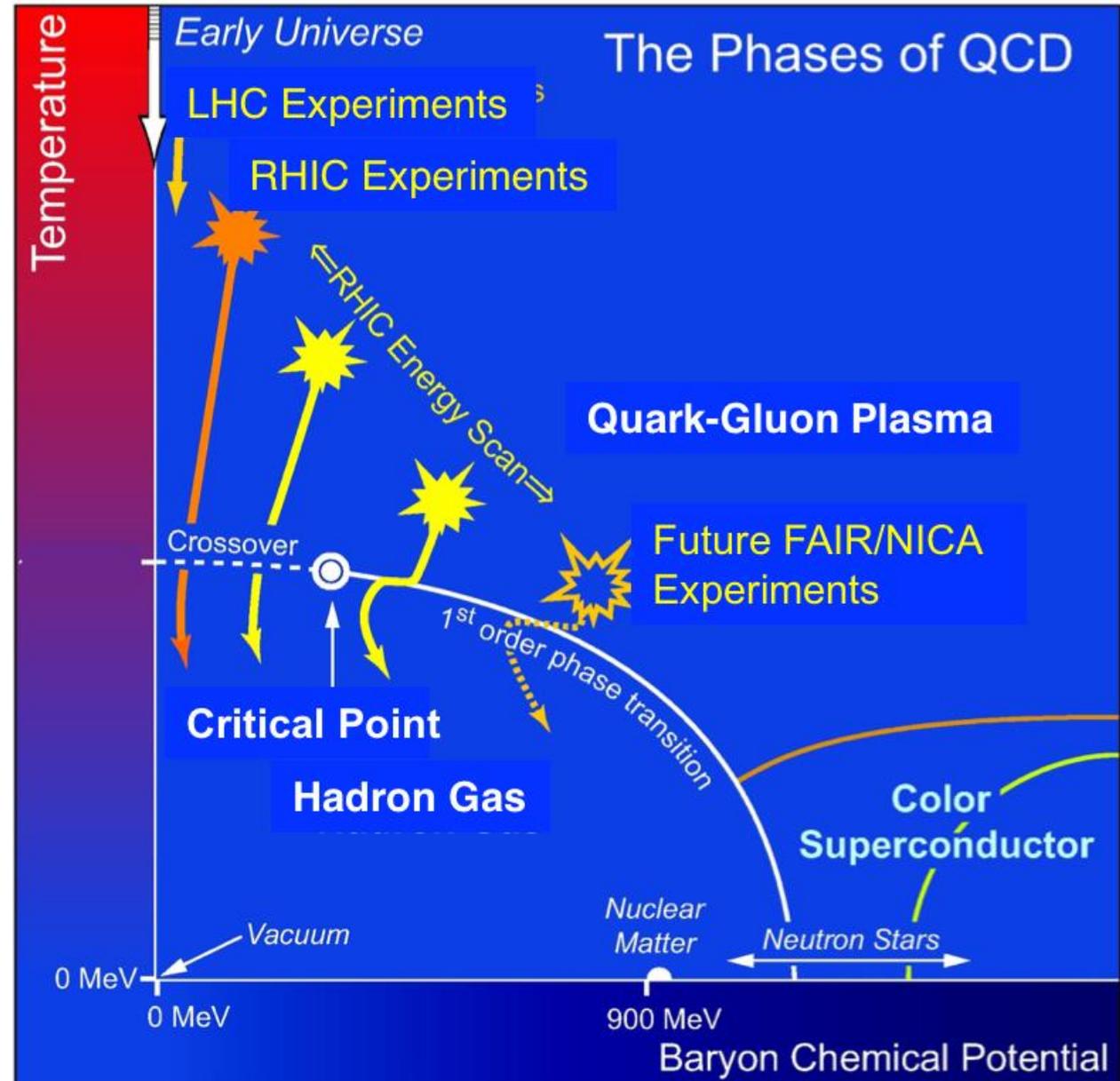
$\sim 150$  MeV

$T \gtrsim 200$  MeV



# Why Initialize Charges?

- Beam Energy Scan (BES) is on-going
  - Search for QCD critical point
  - At top energies you can assume your degree is gluons but you can include fluctuations of charges
- 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



# Gluon Splitting

- **pQCD** predicts vacuum **splitting probabilities**

*S. J. Brodsky, H.-C. Pauli, S. S. Pinsky, Phys. Rept. 301 (1998)*

- **Additional generation** of  $q\bar{q}$  pairs from early-time dynamics

- Strong gluon fields  $\rightarrow$  Classical Yang-Mills + Dirac Equation

*N. Tanji, R. Venugopalan, Phys. Rev. D (2017)*

*Boguslavski et al, 2106.11319*

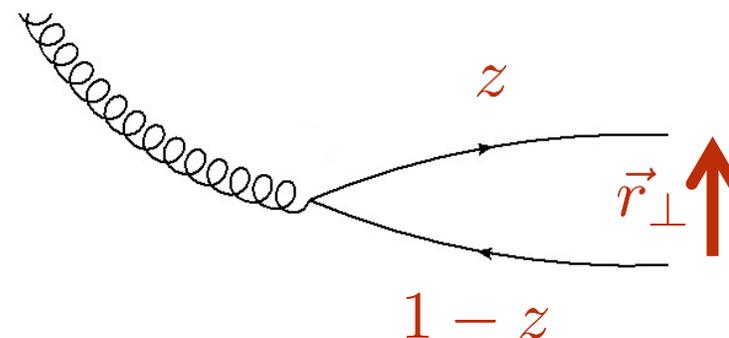
- If **initial condition for  $T^{\mu\nu}$**  can be interpreted as a **gluon density...**

- We can use **input** for the  $g \rightarrow q\bar{q}$  splitting to **reconstruct an associated  $J^\mu$**

*Martinez et al, JHEP 07(2018), 003*

*Martinez et al, [1911.12454](#)*

*Martinez et al, [1911.10272](#)*

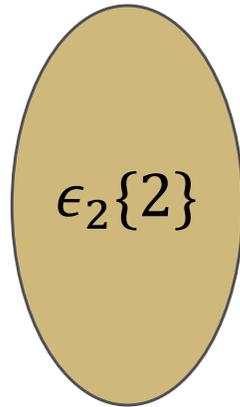


# Geometry Observables

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

Fourier Series of Initial State

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



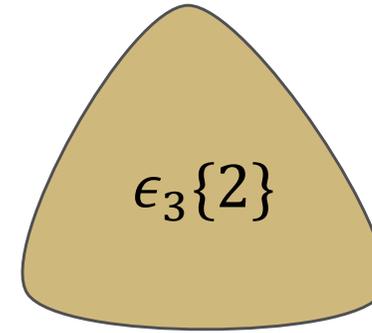
$V_n \approx \kappa_n E_n$   
Mostly linear response

Fourier Series of Final State

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

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

Geometry Eccentricities  
2-Particle Correlation



**10-20%**

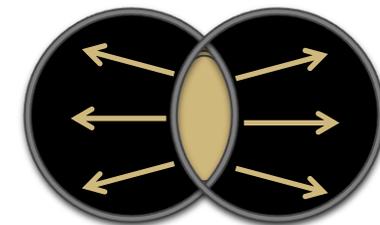
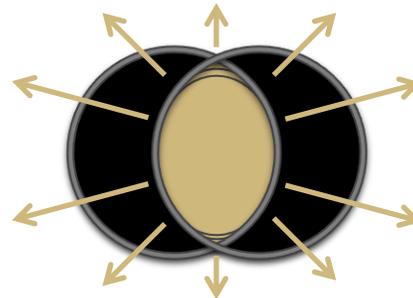
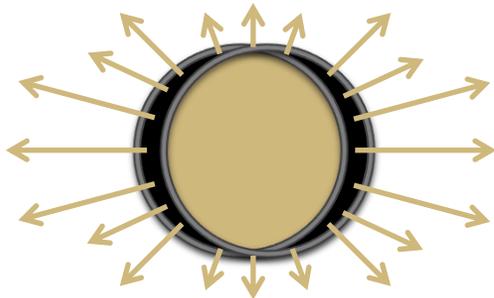
Most Central Events

**50-60%**

Mid-Central Events

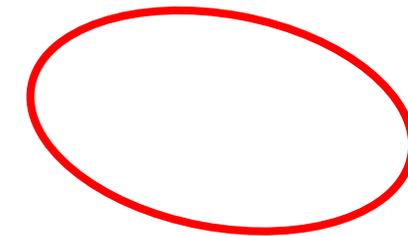
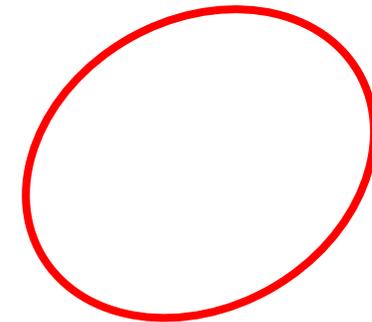
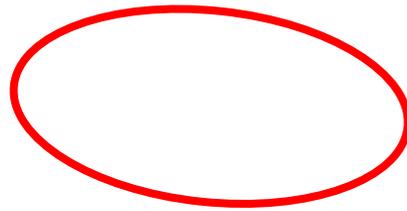
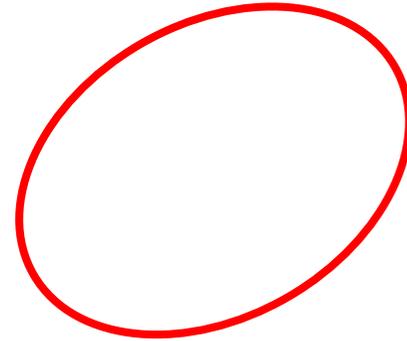
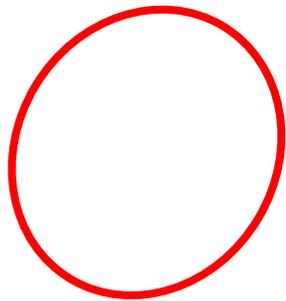
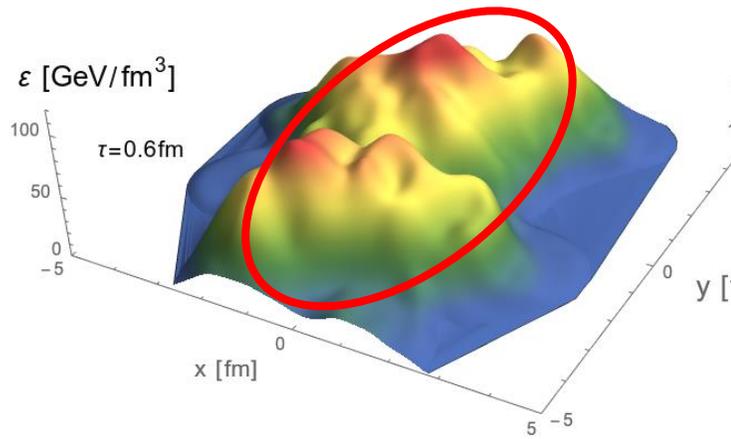
**80-90%**

Peripheral Events



Initial to Final State

# Hydrodynamic Evolution

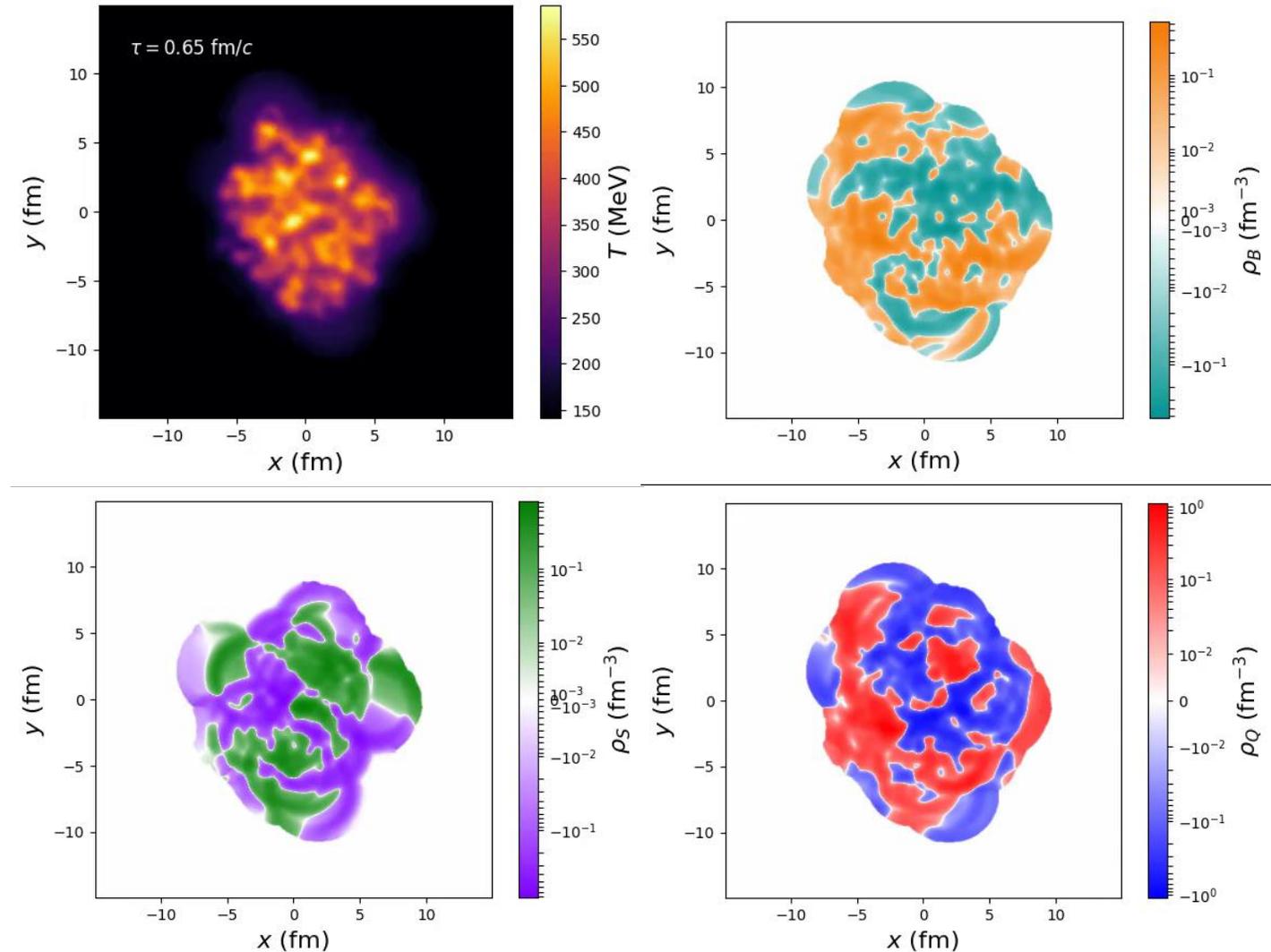


Noronha-Hostler et al,  
Phys.Rev. C90 (2014), 034907

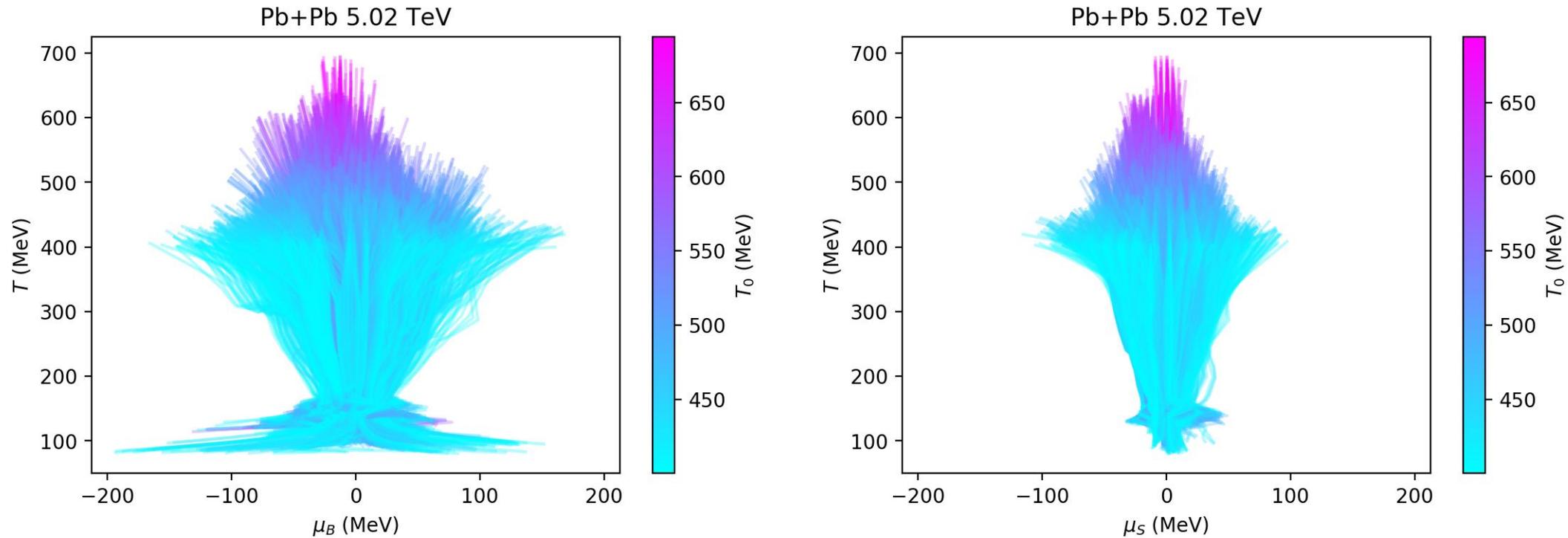
# Hydro Backup

# 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

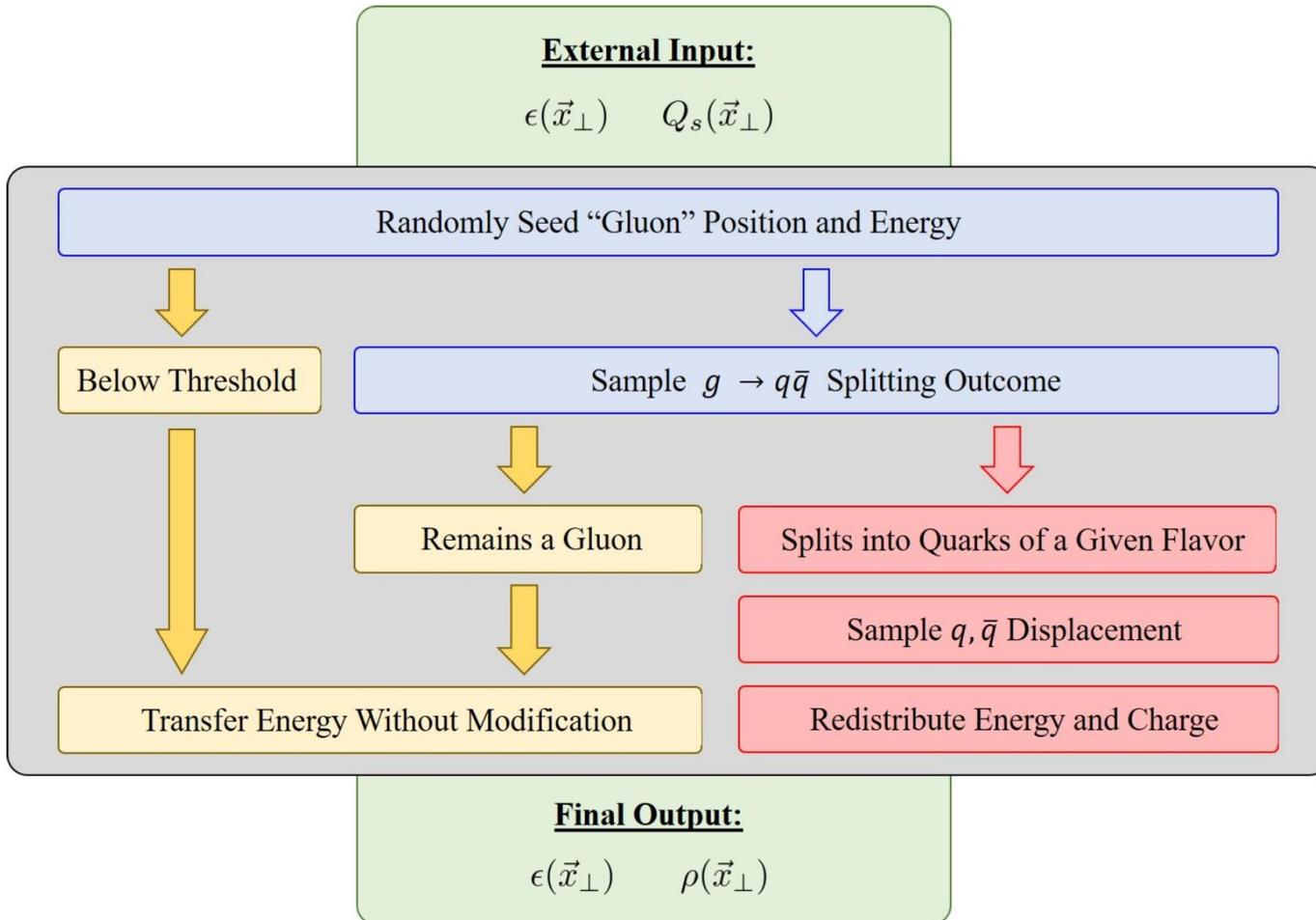


Fluid cells with  $\mu_B \neq 0$  survive Hydrodynamic evolution!!!!

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

# Default ICCING Backup

# Flow Chart



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

**Default**  
Trento  
GBW, MV

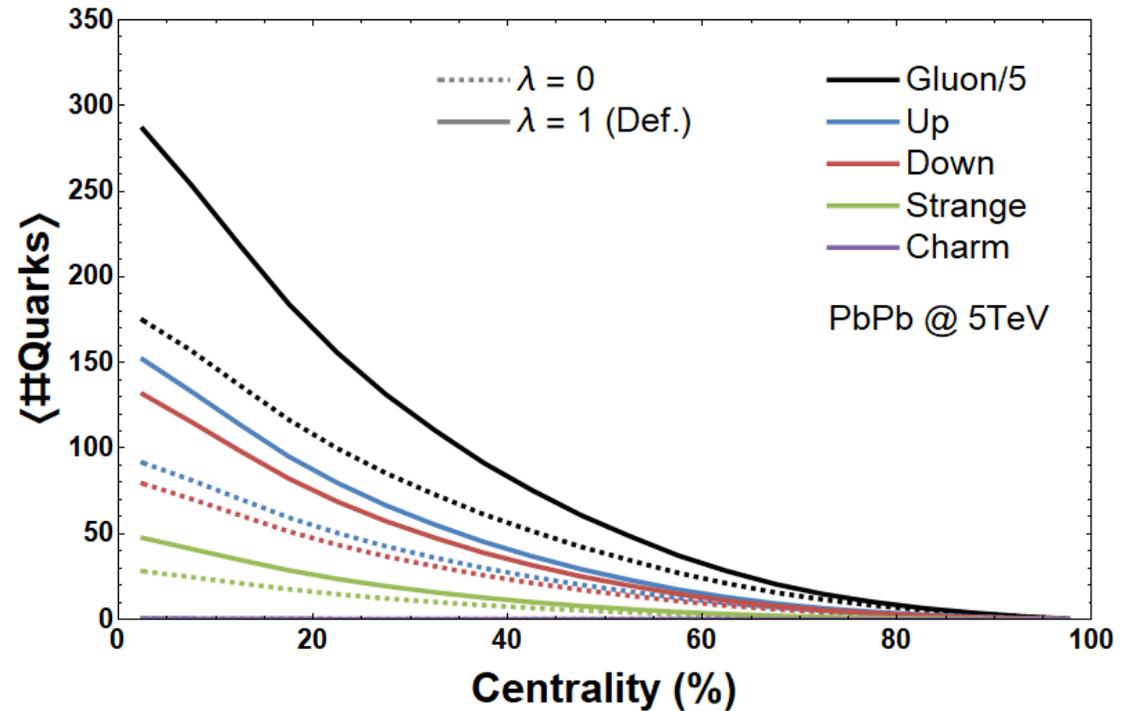
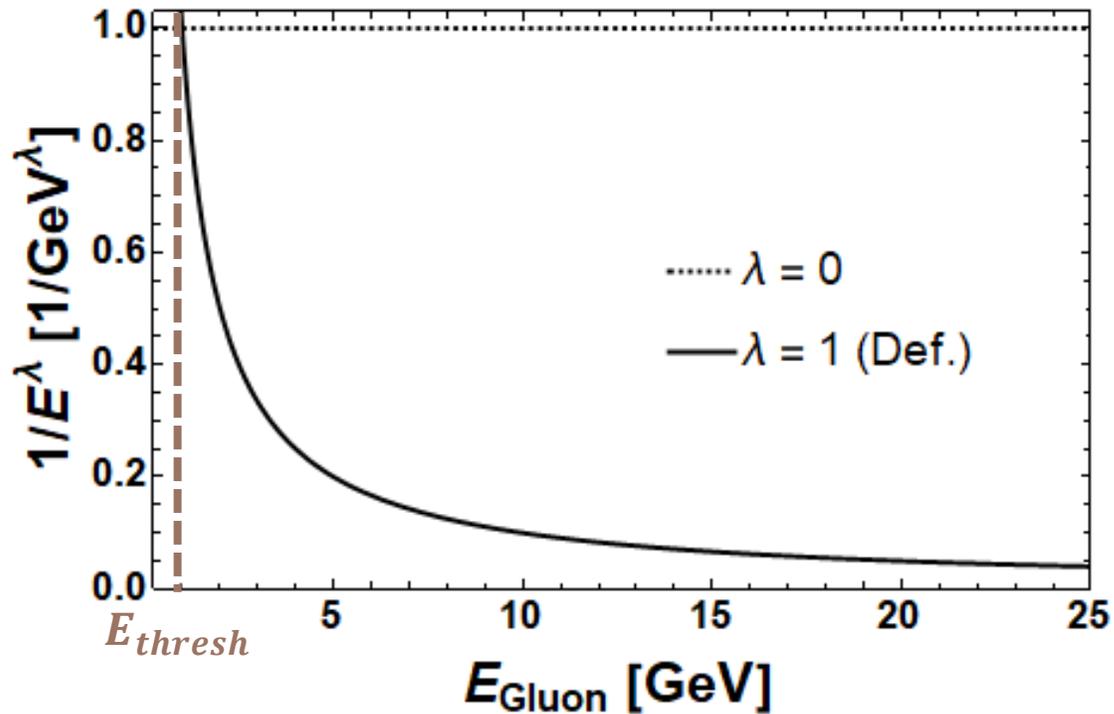
**Output**  
Energy Density,  $\epsilon(\vec{x}_\perp)$   
BSQ Charge Densities,  $\rho(\vec{x}_\perp)$

PC, Martinez, Sievert, Wertepny, Noronoha-Hosler  
Phys. Rev. C 105, 034908 (2022)  
arXiv: 1911.12454 [nucl-th]

# Quark Multiplicities

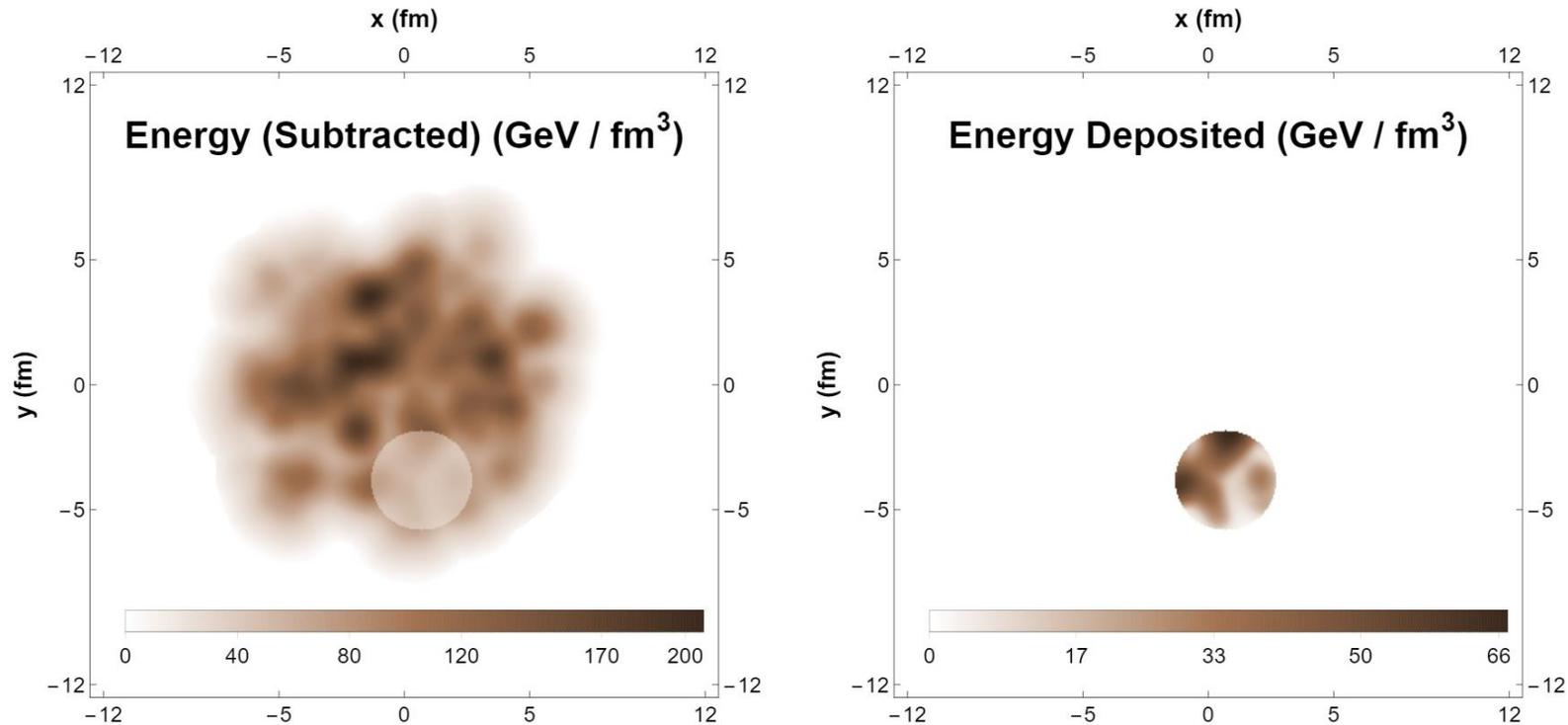
Controlled by  
 $\lambda = 1$  (Default)  
 $E_{thresh} = 0.25$  (Default)

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



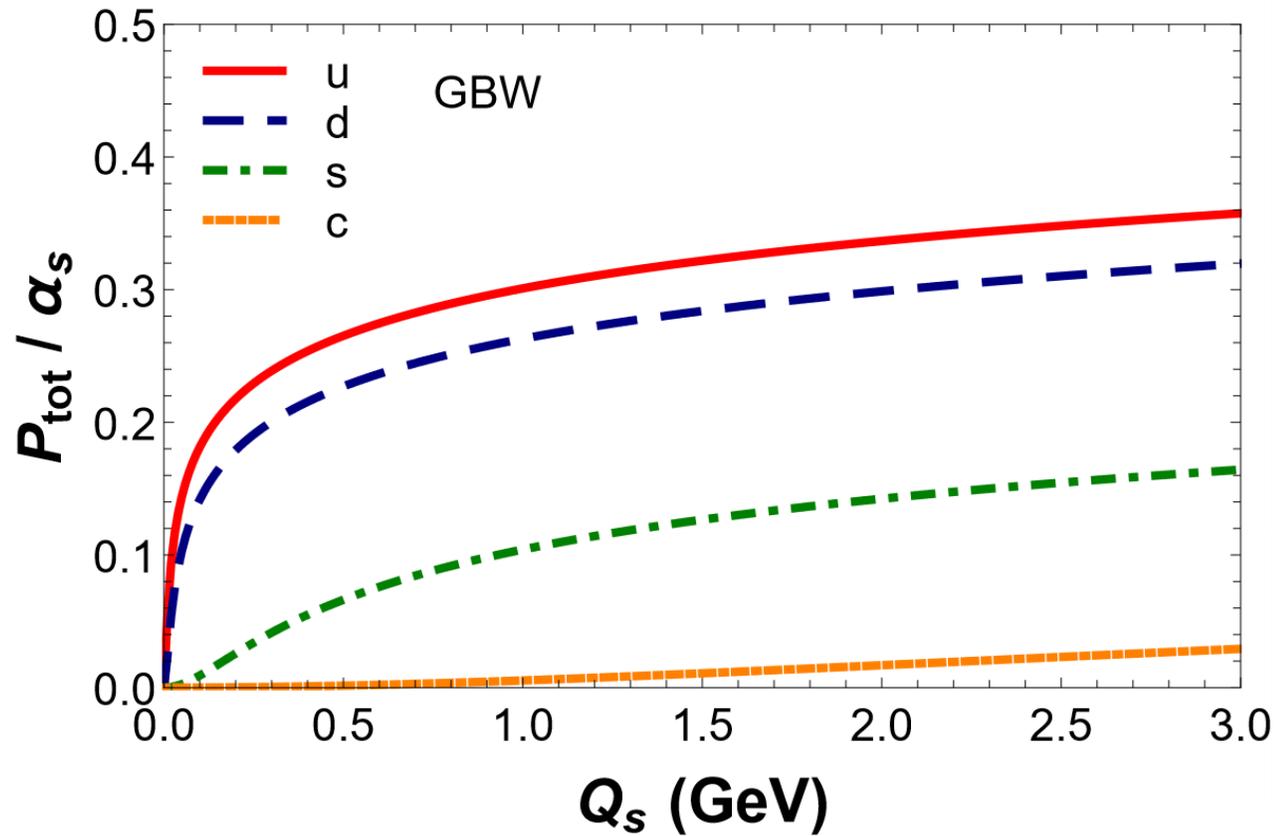
# Transferring a Gluon

Gluons are subtracted proportionally so, when deposited, structure remains



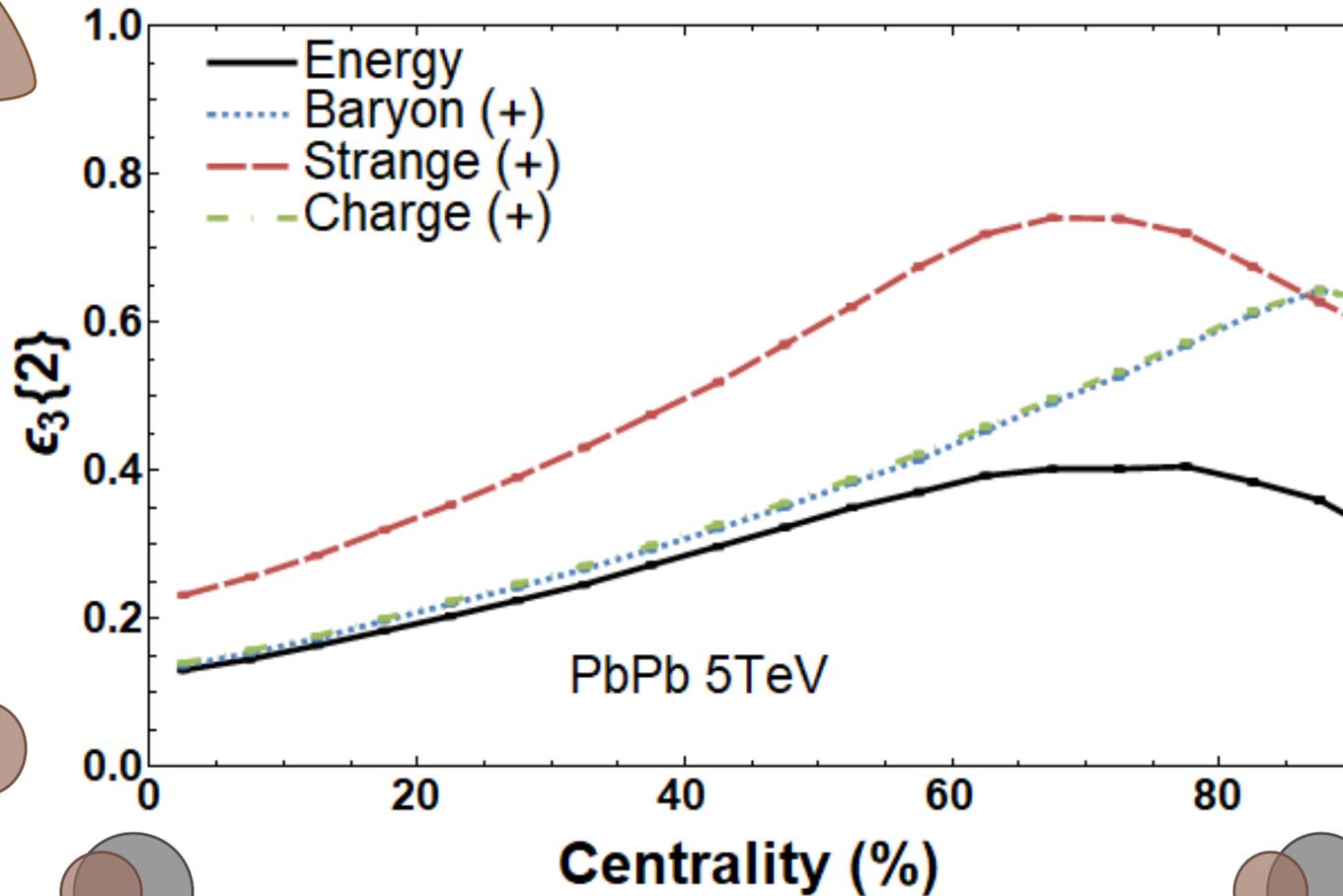
# Algorithm: Selecting Quark

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



# Triangularity

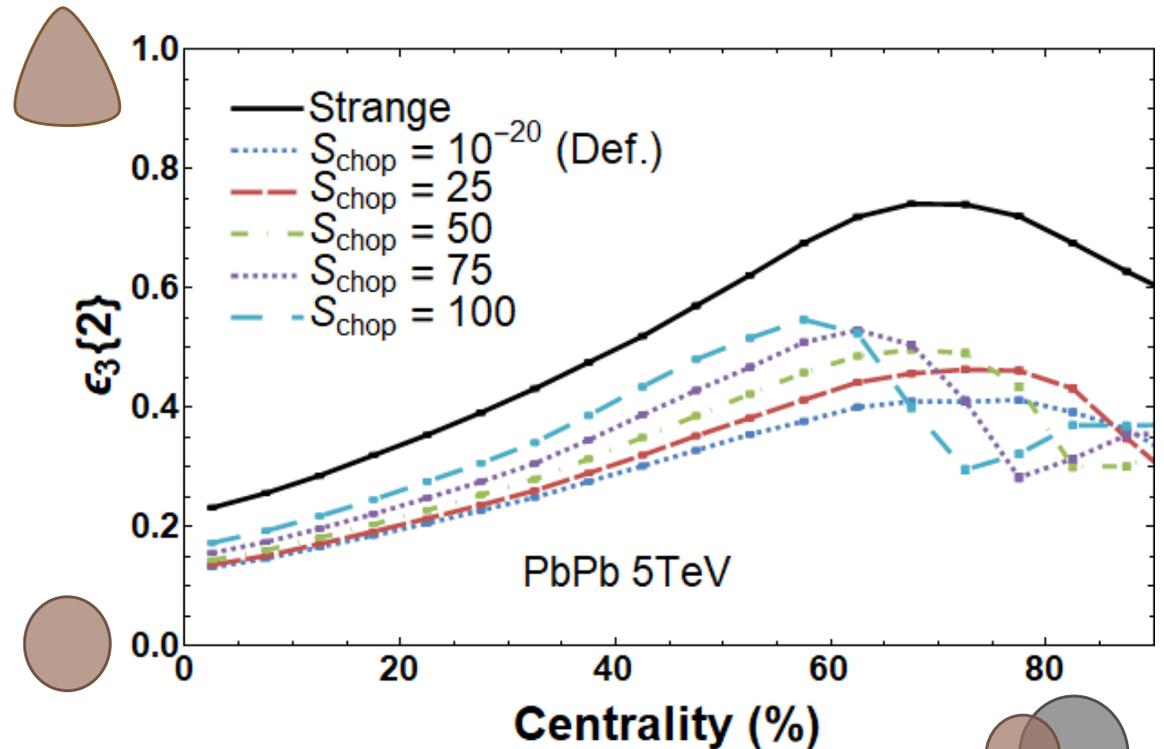
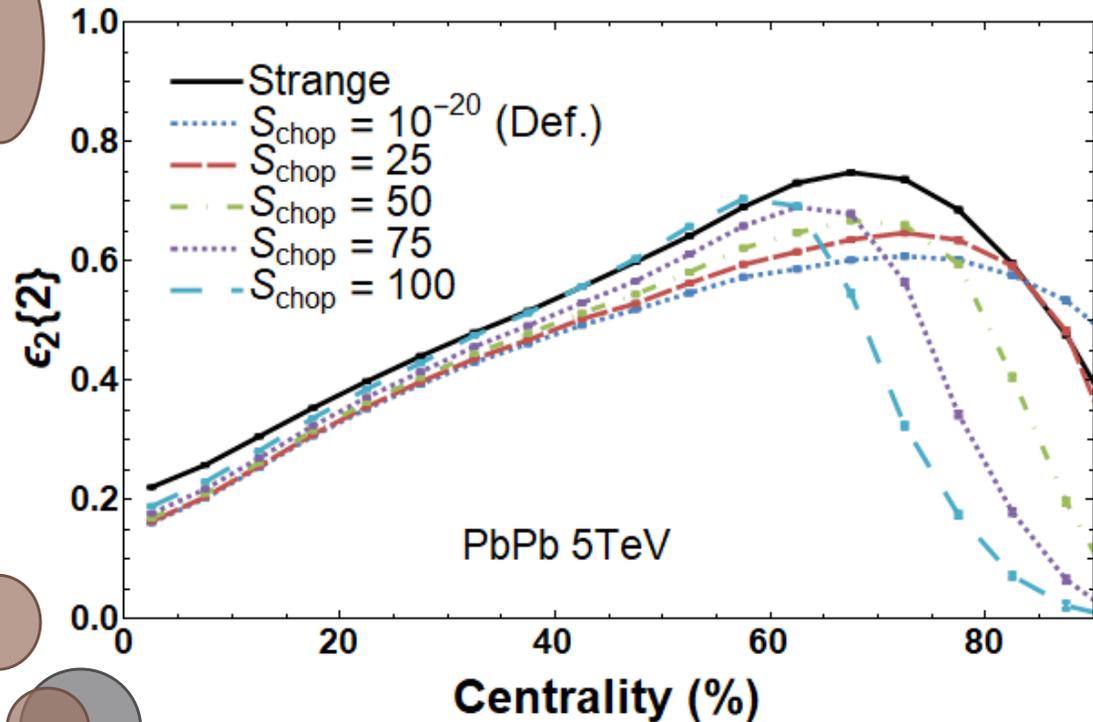
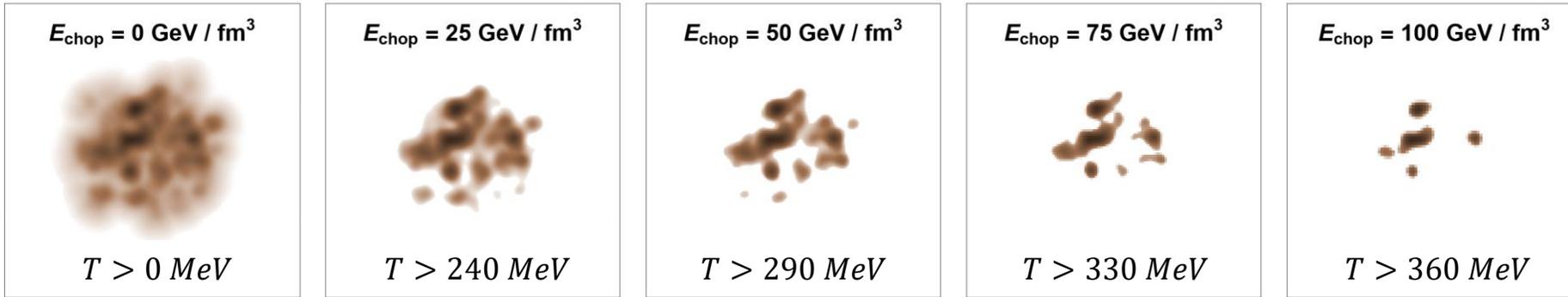
Triangularity sees larger effect



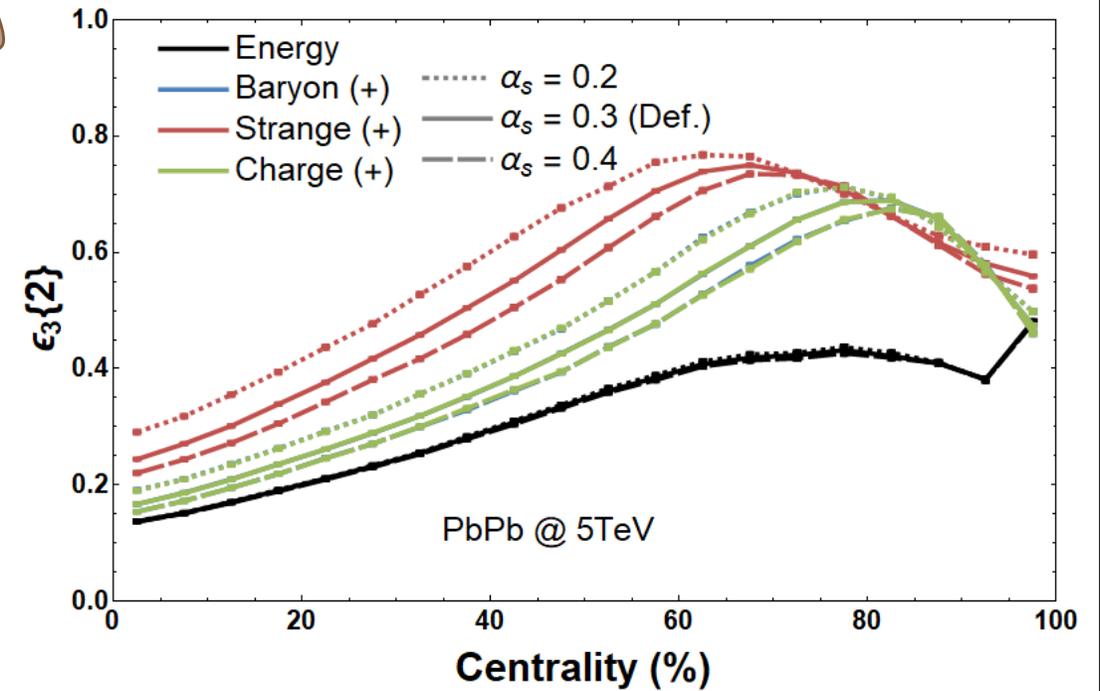
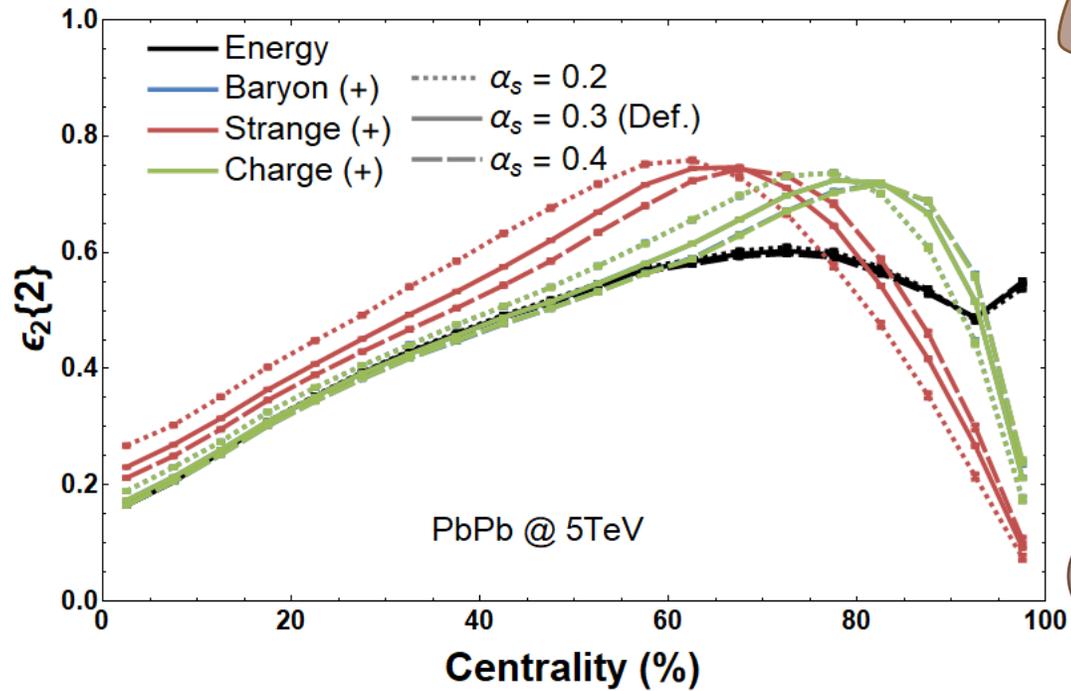
$\varepsilon_n$  is not well defined for charge geometries, thus selecting on positive charge only. Currently working on new estimators of this geometry.

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

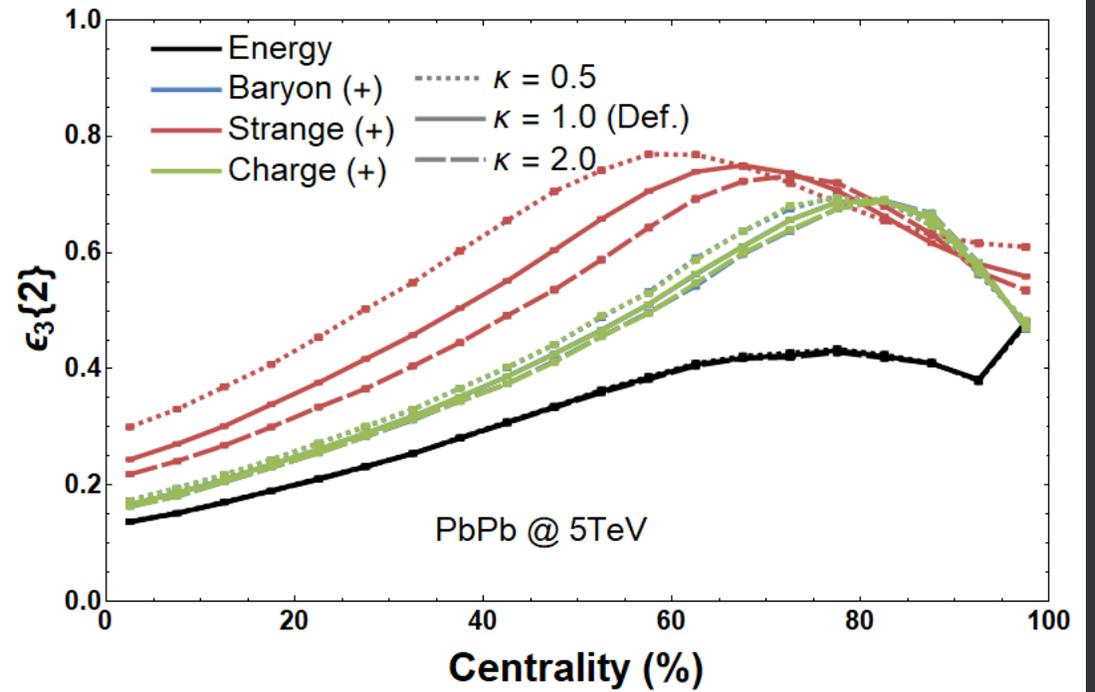
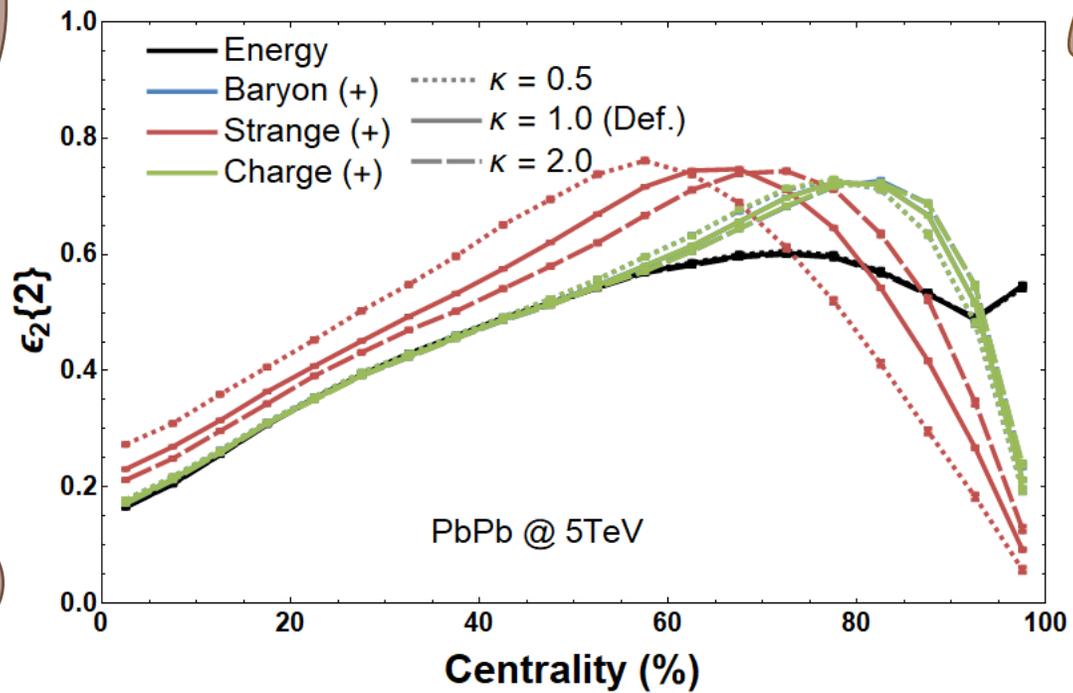
# Strange is in Hot spots!



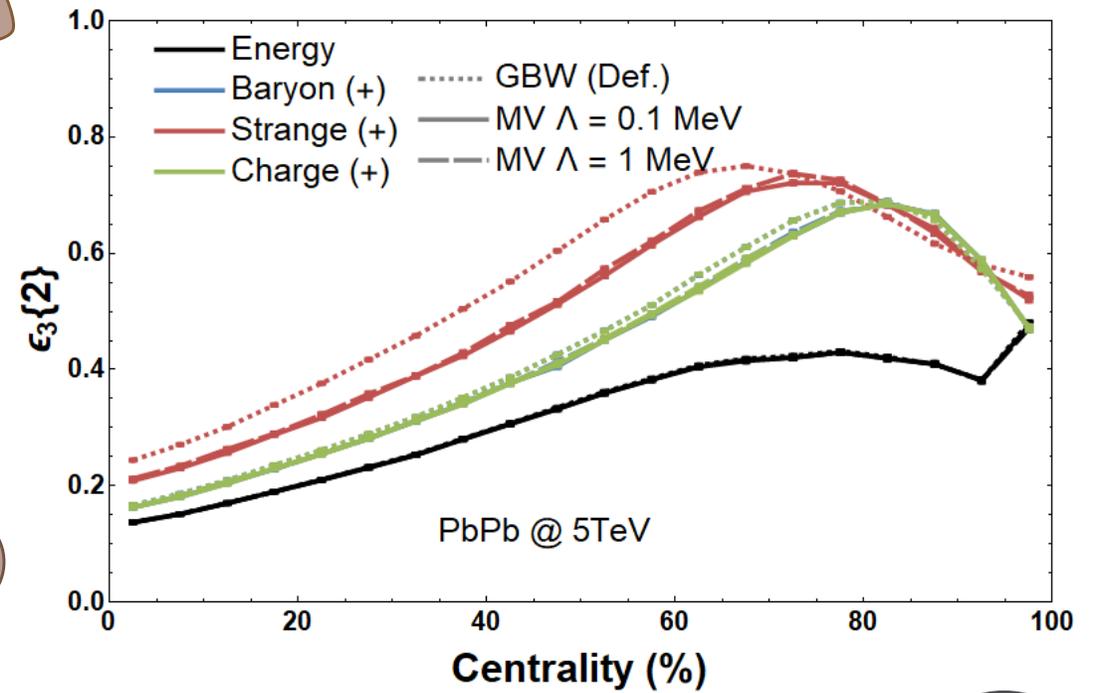
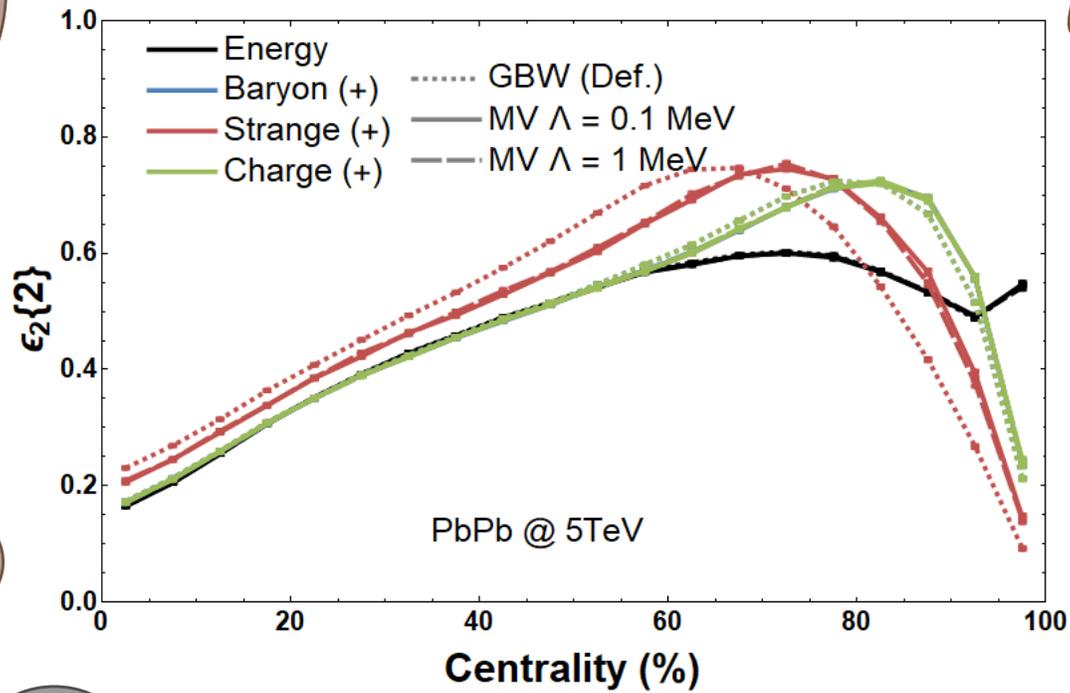
# ICCING Eccentricity Results



# ICCING Eccentricity Results

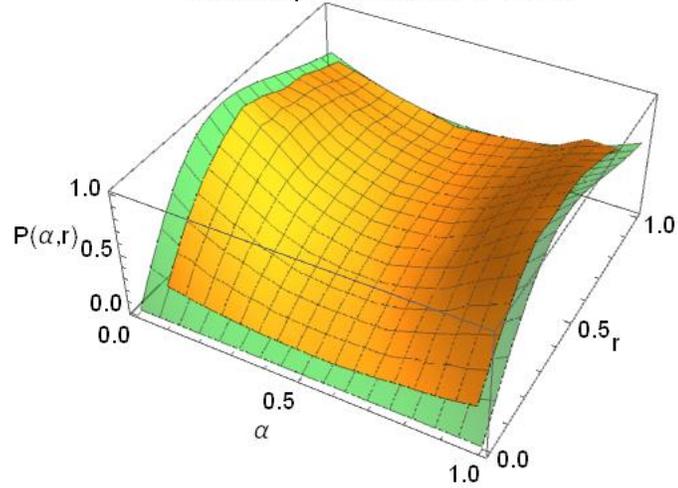


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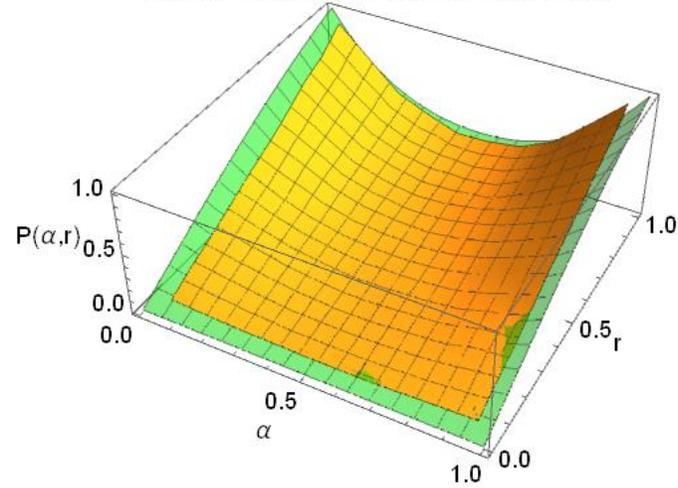


# ICcing Correlation Function Comparison

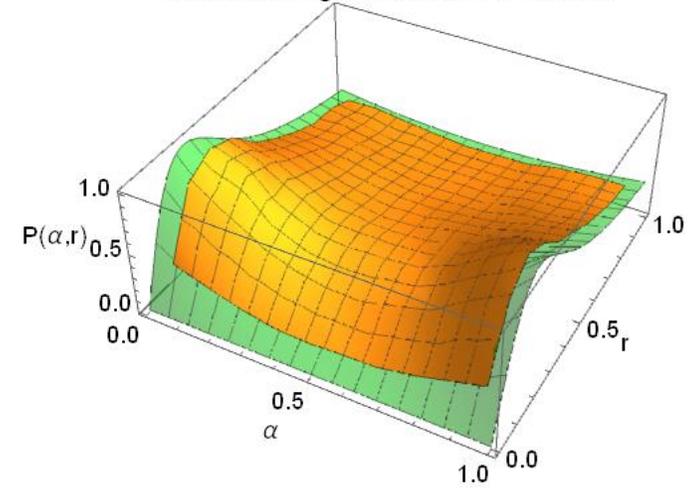
GBW: Up Quarks,  $Q_s = 1$  GeV



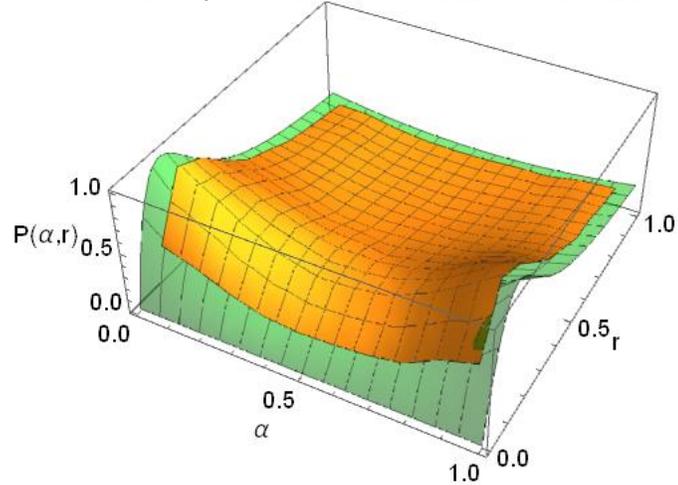
GBW: Down Quarks,  $Q_s = 0.25$  GeV



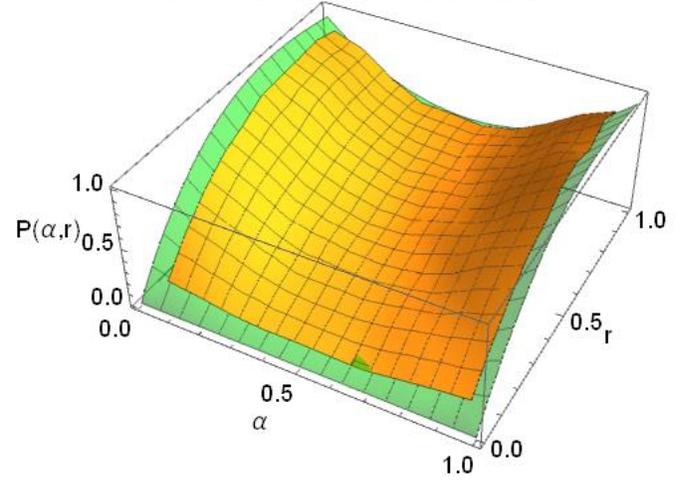
GBW: Strange Quarks,  $Q_s = 2$  GeV



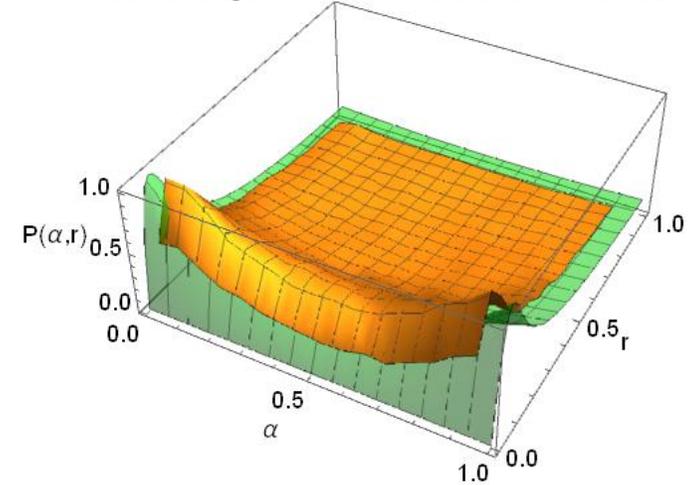
MV: Up Quarks,  $Q_s = 1$  GeV,  $\Lambda = 1$  MeV



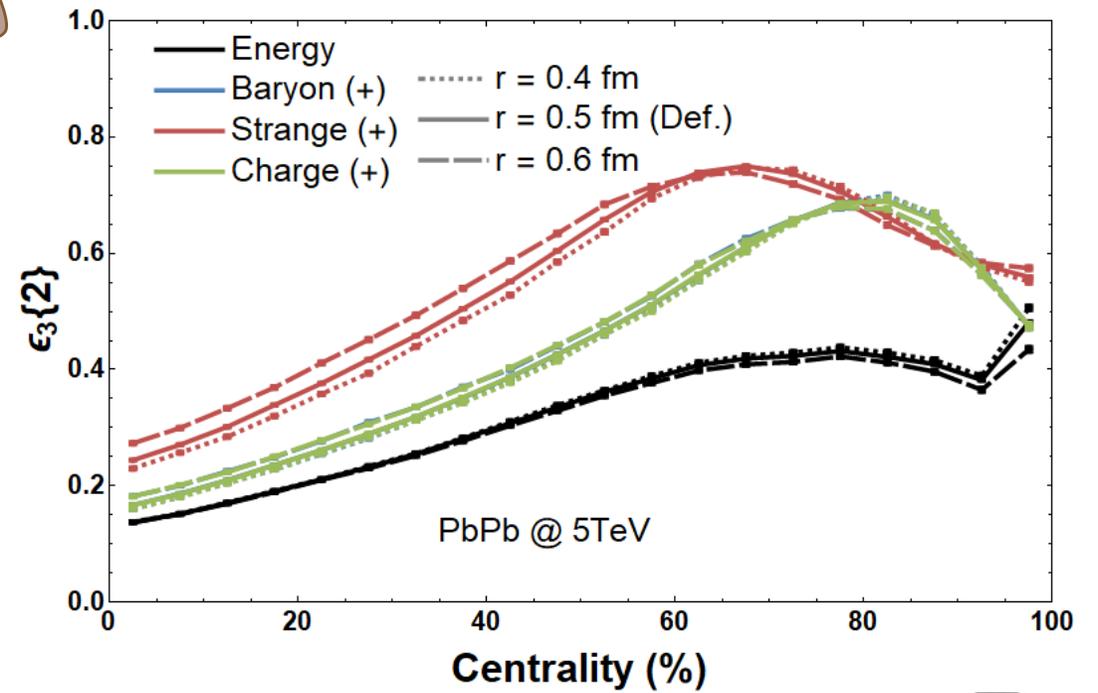
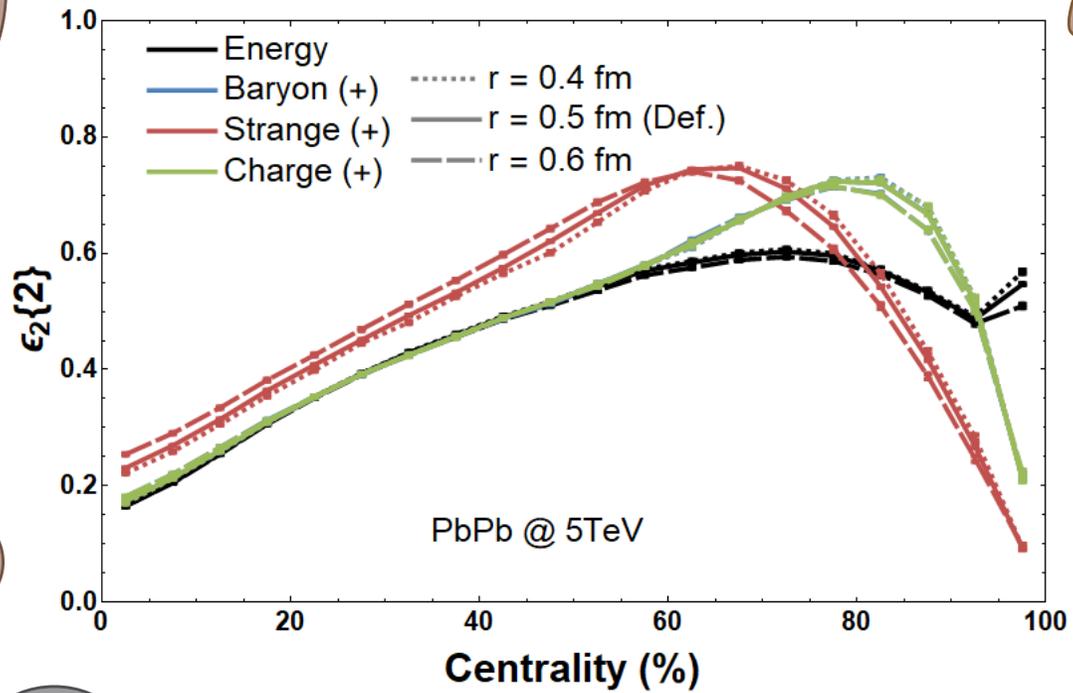
MV: Down Quarks,  $Q_s = 0.25$  GeV,  $\Lambda = 1$  MeV



MV: Strange Quarks,  $Q_s = 2$  GeV,  $\Lambda = 1$  MeV



# ICCING Eccentricity Results



# ICCING Eccentricity Results

