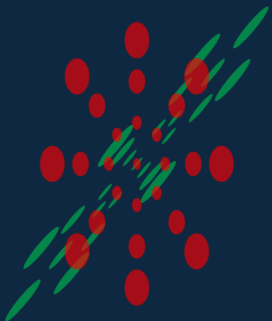


# Rapidity scan of conserved charges in a dynamical soft-hard correlated approach

S. Fujii *et al.*, in preparation



SOPHIA  
HADRON  
PHYSICS  
GROUP

Shin-ei Fujii<sup>1</sup>, Yasuki Tachibana<sup>2,1</sup>, Tetsufumi Hirano<sup>1</sup>

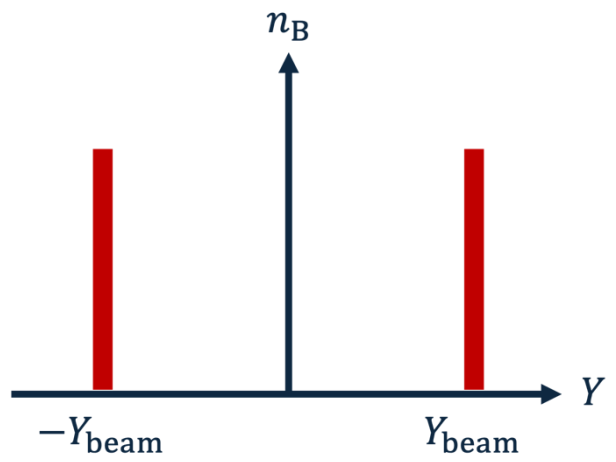
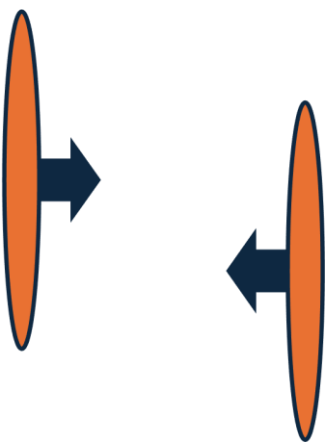
Sophia University<sup>1</sup>, Akita International University<sup>2</sup>

# Introduction

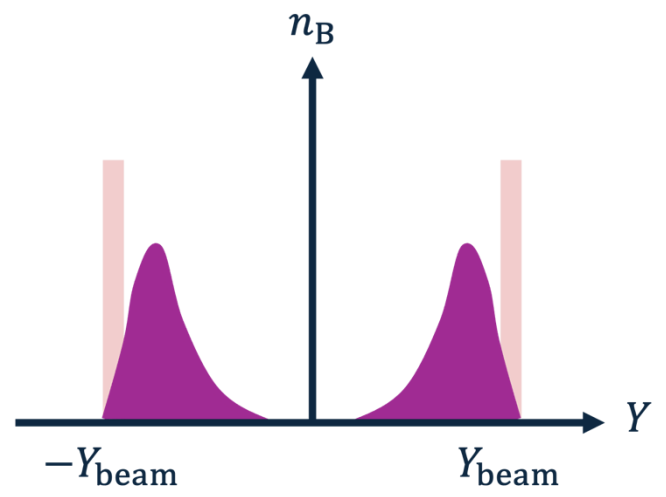
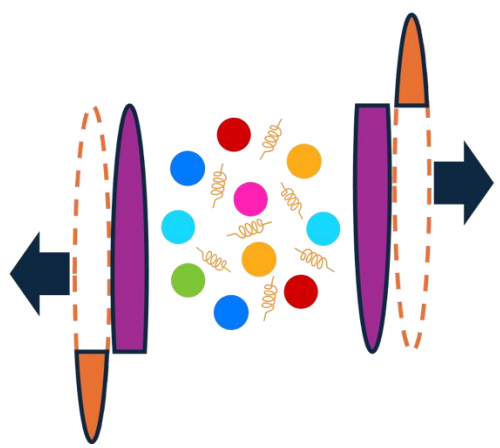
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# Longitudinal structure in high-energy nuclear collisions

## Before collision



## After collision



## Midrapidity

- Mostly equilibrium in central events
- Almost zero chemical potentials

## Forward rapidity

- Degree of equilibration?
- Large chemical potentials?

M. Li and J. I. Kapusta, Phys. Rev. C 99, 014906 (2019)

Longitudinal structure of matter in high-energy collisions is still unclear...

# Open questions in forward rapidity

**Q1** How much are the conserved charges (BQS) equilibrated?

**Q2** How large are the chemical potentials achieved?

**Q3** After all, how are the conserved charges distributed?

To address these questions, one must describe...

- Equilibrium and non-equilibrium components simultaneously
- Dynamical equilibration and evolution of conserved charges

 **Dynamical core-corona picture + charge dynamics**

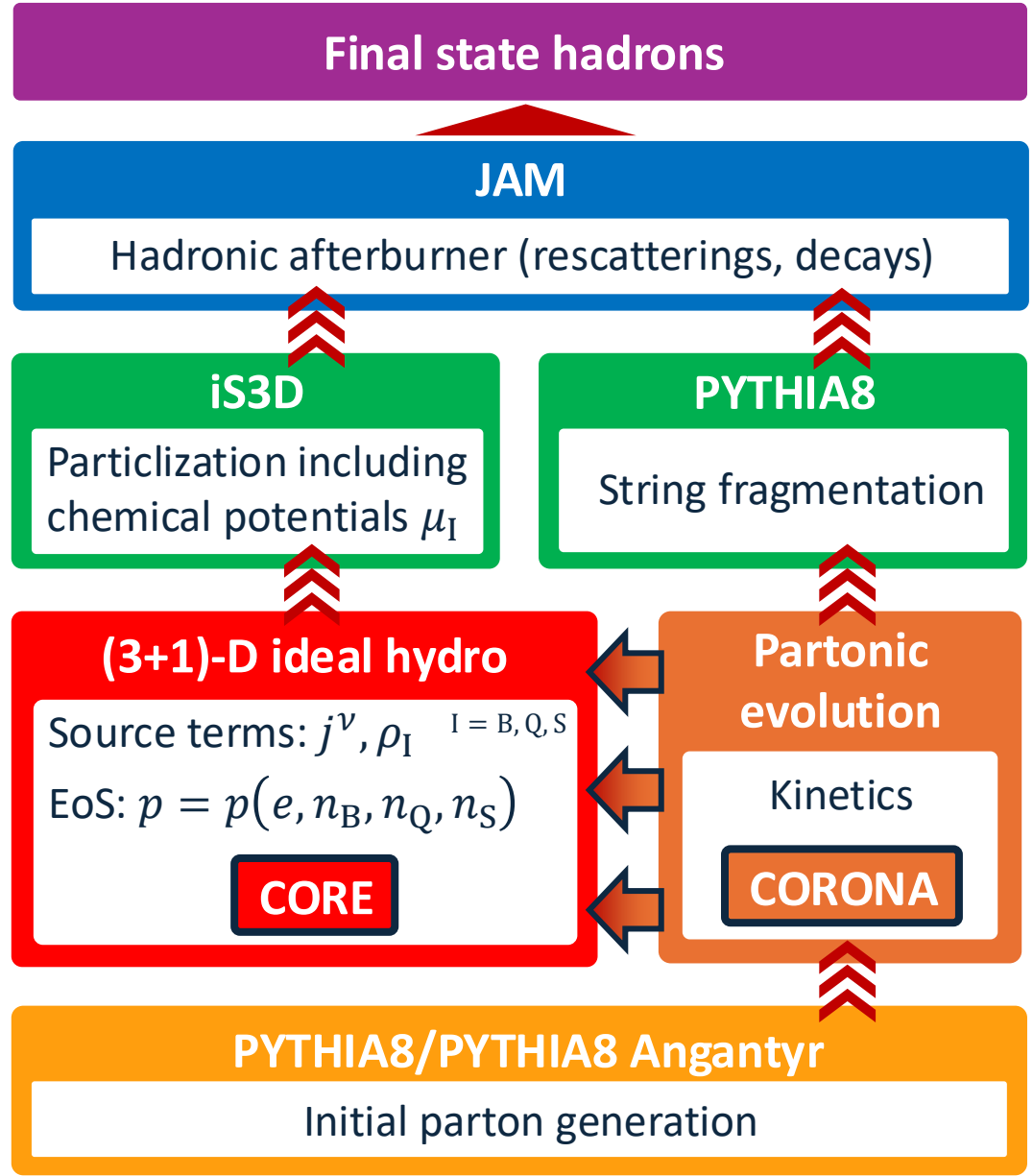
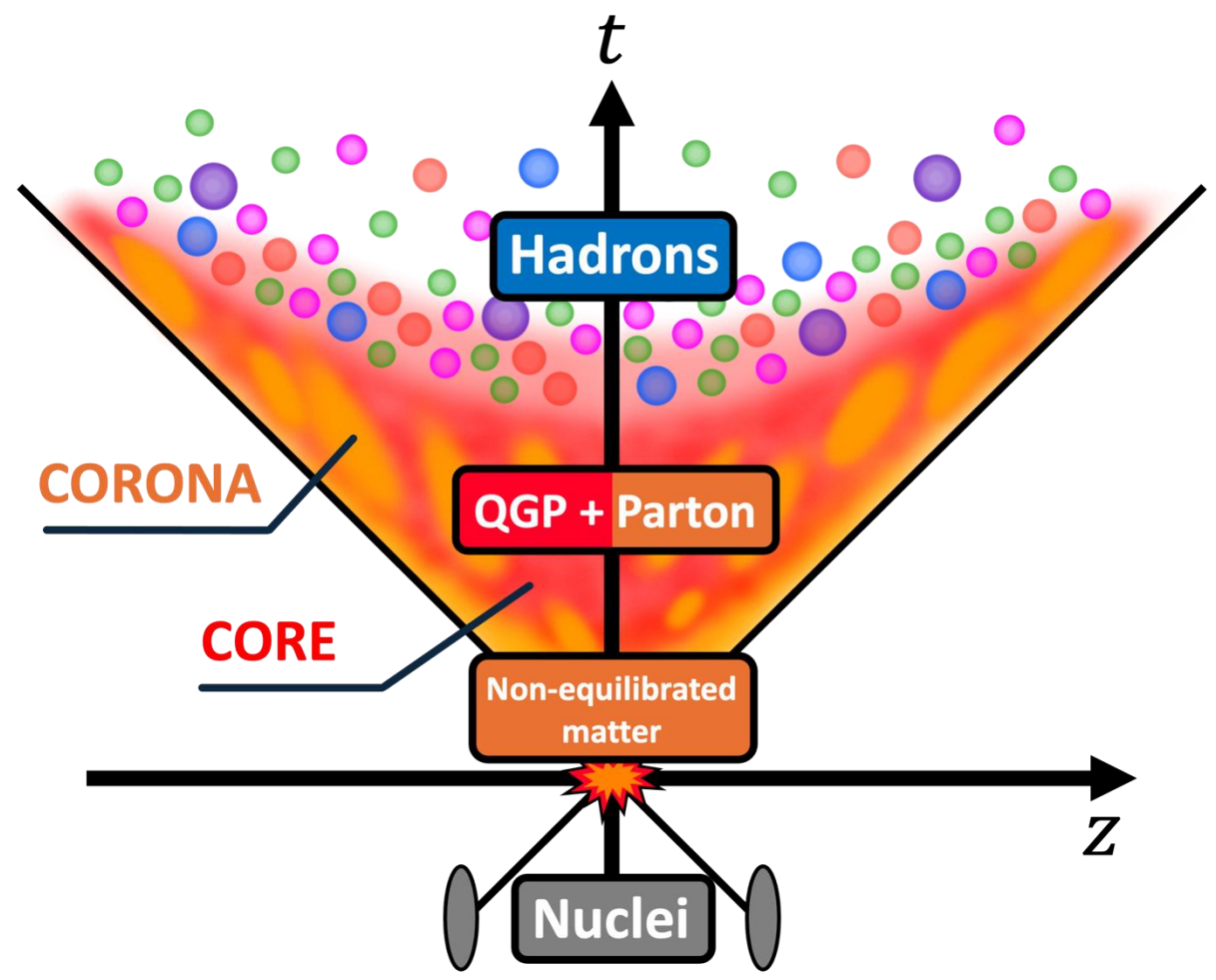
# Model

---

**Dynamical Core-Corona Initialization model (DCCI3)**

# Dynamical Core-Corona Initialization model (DCCI3)

Coexistence of **equilibrium** and **non-equilibrium** including conserved charge (BQS) dynamics



# Dynamical Core-Corona Initialization

Y. Kanakubo *et al.*, Phys. Rev. C **105**, 024905 (2022)

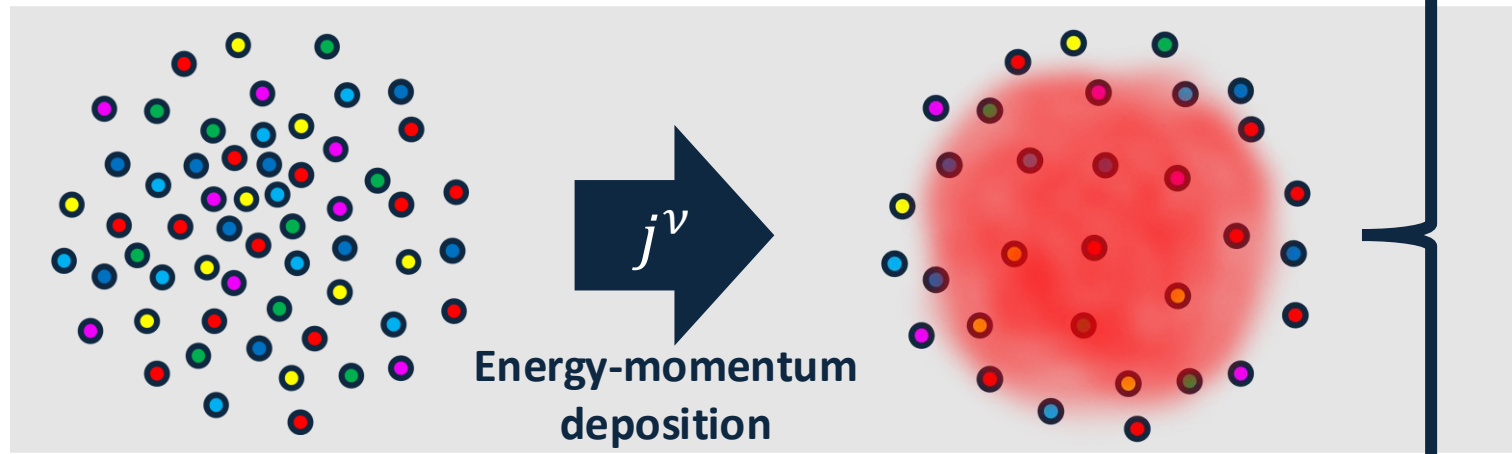
## Initial partons

by PYTHIA8/PYTHIA8 Angantyr

T. Sjöstrand *et al.*, Comput. Phys. Commun. **191**, 159 (2015)  
 C. Bierlich *et al.*, JHEP **1610**, 139 (2016)

## Dynamical initialization

through the energy-momentum source term  $j^\nu$  in (3+1)D hydro



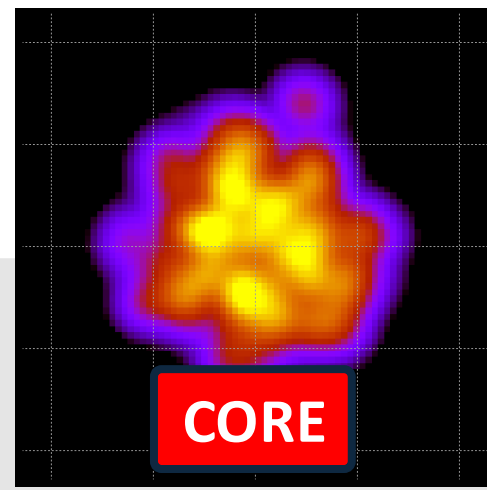
$$T_{\text{fluid}}^{\mu\nu} = 0$$

$$T_{\text{parton}}^{\mu\nu} \neq 0$$

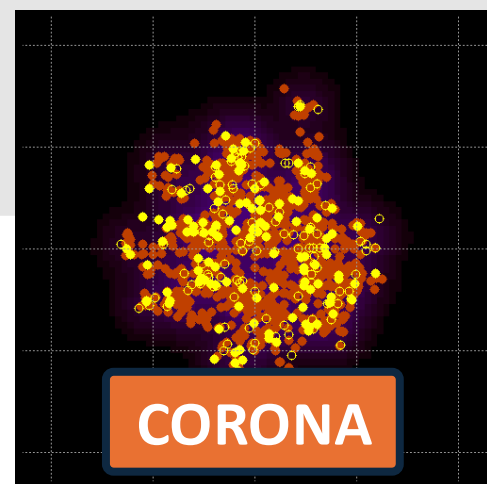
$$\partial_\mu T_{\text{fluid}}^{\mu\nu} = j^\nu$$

$$\partial_\mu T_{\text{parton}}^{\mu\nu} = -j^\nu$$

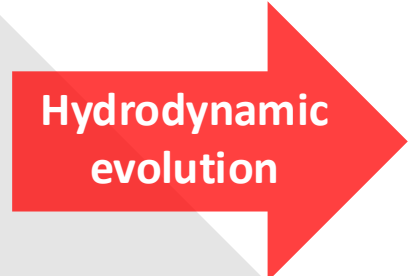
## Core-corona picture



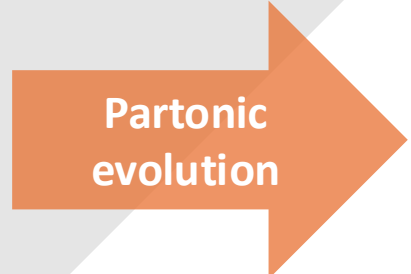
**CORE**



**CORONA**



**Equilibrium**



**Non-equilibrium**

# Energy-momentum source term

- Continuity eq. for entire system

$$\partial_\mu (T_{\text{fluid}}^{\mu\nu} + T_{\text{parton}}^{\mu\nu}) = 0$$

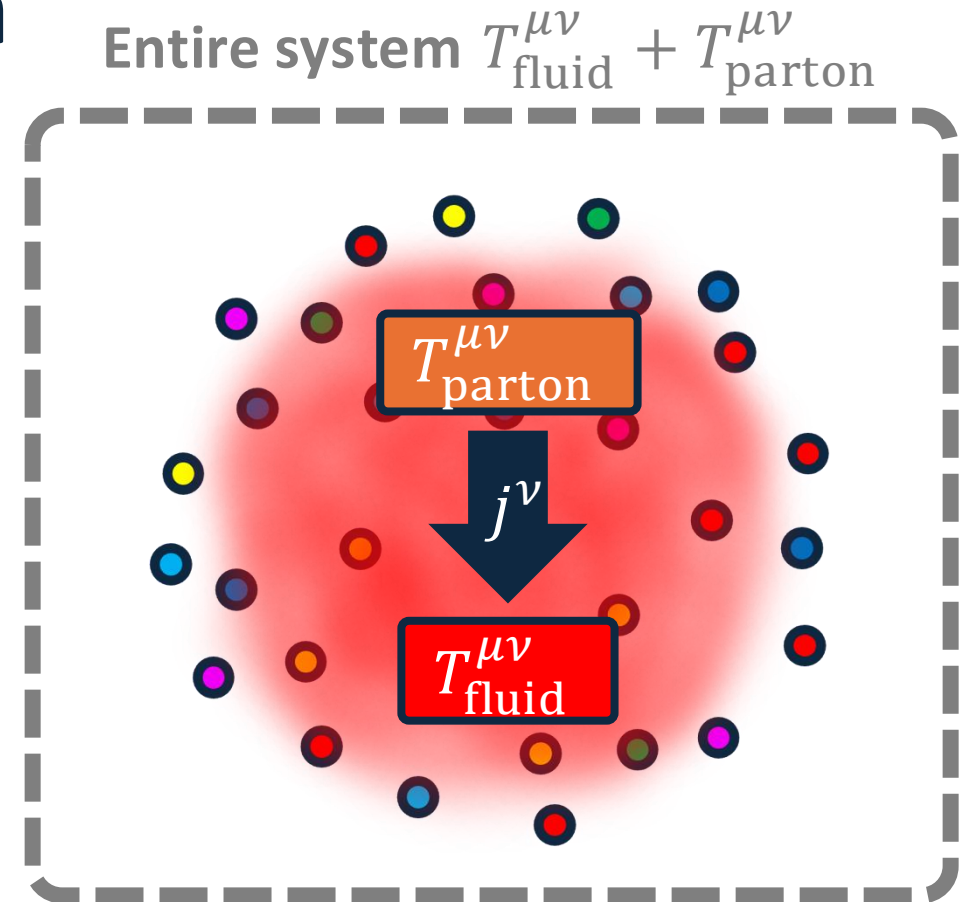
- Hydrodynamic eqs. with E-M source term

$$\partial_\mu T_{\text{fluid}}^{\mu\nu} = j^\nu \quad j^\nu = -\partial_\mu T_{\text{parton}}^{\mu\nu}$$

$$j^\nu = - \sum_i^{N_{\text{parton}}} \frac{dp_i^\nu(t)}{dt} G(\mathbf{x} - \mathbf{x}_i(t))$$

$p_i^\nu$ : Four-momentum of  $i_{\text{th}}$  parton

$G$ : Gaussian function     $\mathbf{x}_i$ : Position of  $i_{\text{th}}$  parton



## Assumptions

- Straight trajectory of partons
- Instant equilibration of deposited E-M
- Gaussian profile

# Fluidization rate

Phenomenological **fluidization rate** in DCCI

$$\frac{dp_i^\mu}{d\tau} = - \sum_j^{N_{scat}} \rho_{i,j} \sigma_{i,j} |v_{rel,i,j}| p_i^\mu$$

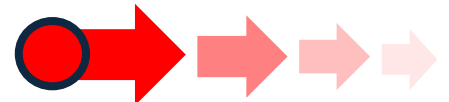
$\rho_{i,j}$ : Effective density of  $j_{th}$  seen from  $i_{th}$

$\sigma_{i,j}$ : Cross section between  $i_{th}$  and  $j_{th}$      $v_{rel,i,j}$ : Relative velocity between  $i_{th}$  and  $j_{th}$

cf.) Drag force

$$\frac{dp^\mu}{dt} = -\eta p^\mu$$

$\eta$ : drag coefficient



= **energy-momentum deposition into the medium**

**➔ Drag coefficient depends on density, cross section, relative velocity**

Soft (low  $p_T$ ) / Dense



**CORE**

Hard (high  $p_T$ ) / Dilute



**CORONA**

**Partial equilibration induced by multiple parton scatterings**

# Conserved charge source term

Conserved charges in HIC: Baryon number(**B**), Electric charge(**Q**), Strangeness(**S**) etc.

- Continuity eq. for entire system

$$\partial_\mu \left( N_{\text{fluid}, I}^\mu + N_{\text{parton}, I}^\mu \right) = 0$$

$N^\mu$ : charge current

- Hydrodynamic eqs. with charge source term

$$\partial_\mu N_{\text{fluid}, I}^\mu = \rho_I \quad \rho_I = -\partial_\mu N_{\text{parton}, I}^\mu$$

I: B, Q, S

\*Source term works only for partons that have fully lost their energy (dead partons)

↑ **discreteness of conserved charges**

## Conserved charge source term

$$\rho_I = - \sum_j^{N_{\text{dead}}} \frac{dI_j}{dt} G \left( \mathbf{x} - \mathbf{x}_j(t) \right)$$

$I_j$ : Charge  $I$  of  $j_{\text{th}}$  dead parton

$G$ : Gaussian function     $\mathbf{x}_i$ : Position of  $j_{\text{th}}$  parton

**New in DCCI3**

**Fluidization and hydrodynamic evolution of conserved charges!**

# Summary of hydrodynamic equations

## Energy-momentum

$$\partial_\mu T^{\mu\nu} = j^\nu$$

$$T^{\mu\nu} = (e + P)u^\mu u^\nu - P g^{\mu\nu}$$

## Conserved charges

$$\partial_\mu N_B^\mu = \rho_B$$

$$N_B^\mu = n_B u^\mu$$

$$\partial_\mu N_Q^\mu = \rho_Q$$

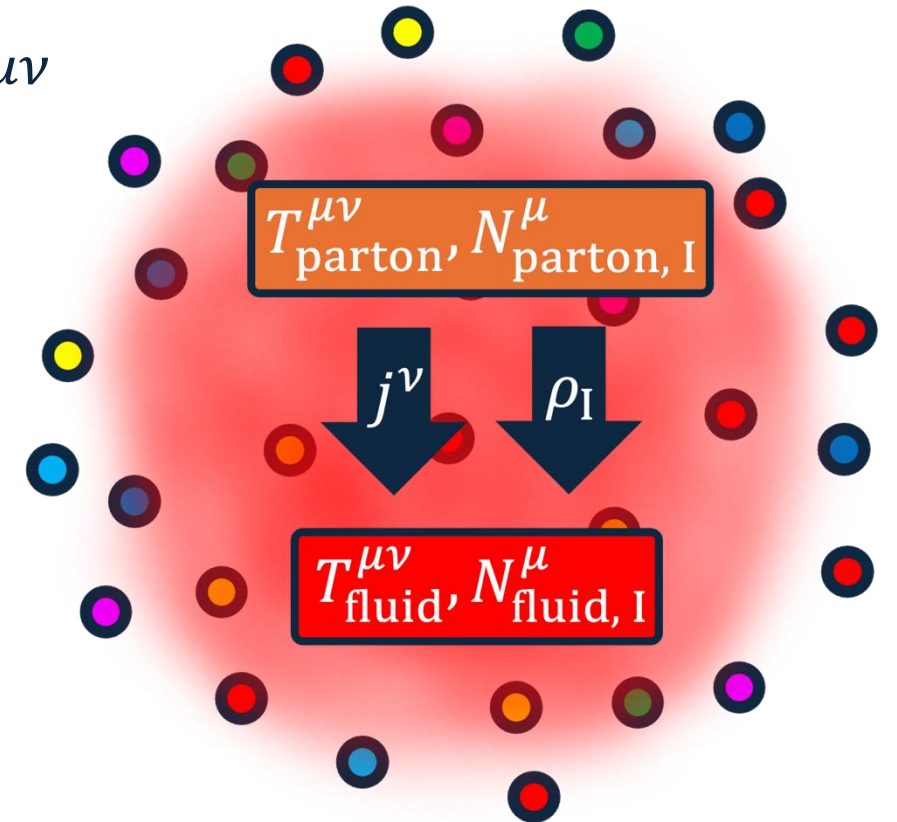
$$N_Q^\mu = n_Q u^\mu$$

$$\partial_\mu N_S^\mu = \rho_S$$

$$N_S^\mu = n_S u^\mu$$

- Ideal hydrodynamics with source terms

- Need 4D equation of state  $(e, n_B, n_Q, n_S) \rightarrow (T, \mu_B, \mu_Q, \mu_S)$



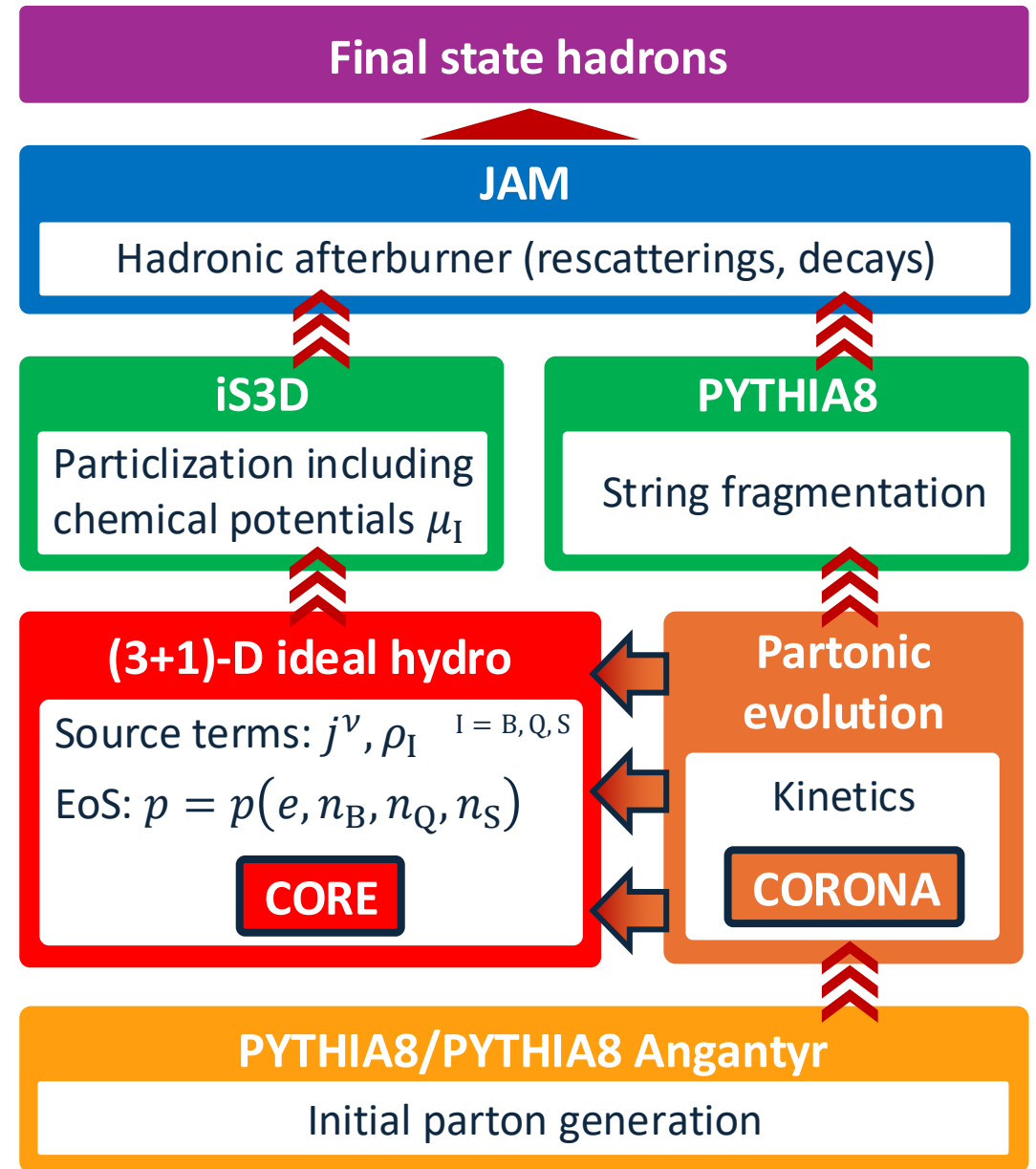
# Results

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Pb+Pb,  $\sqrt{s_{NN}} = 2.76$  TeV

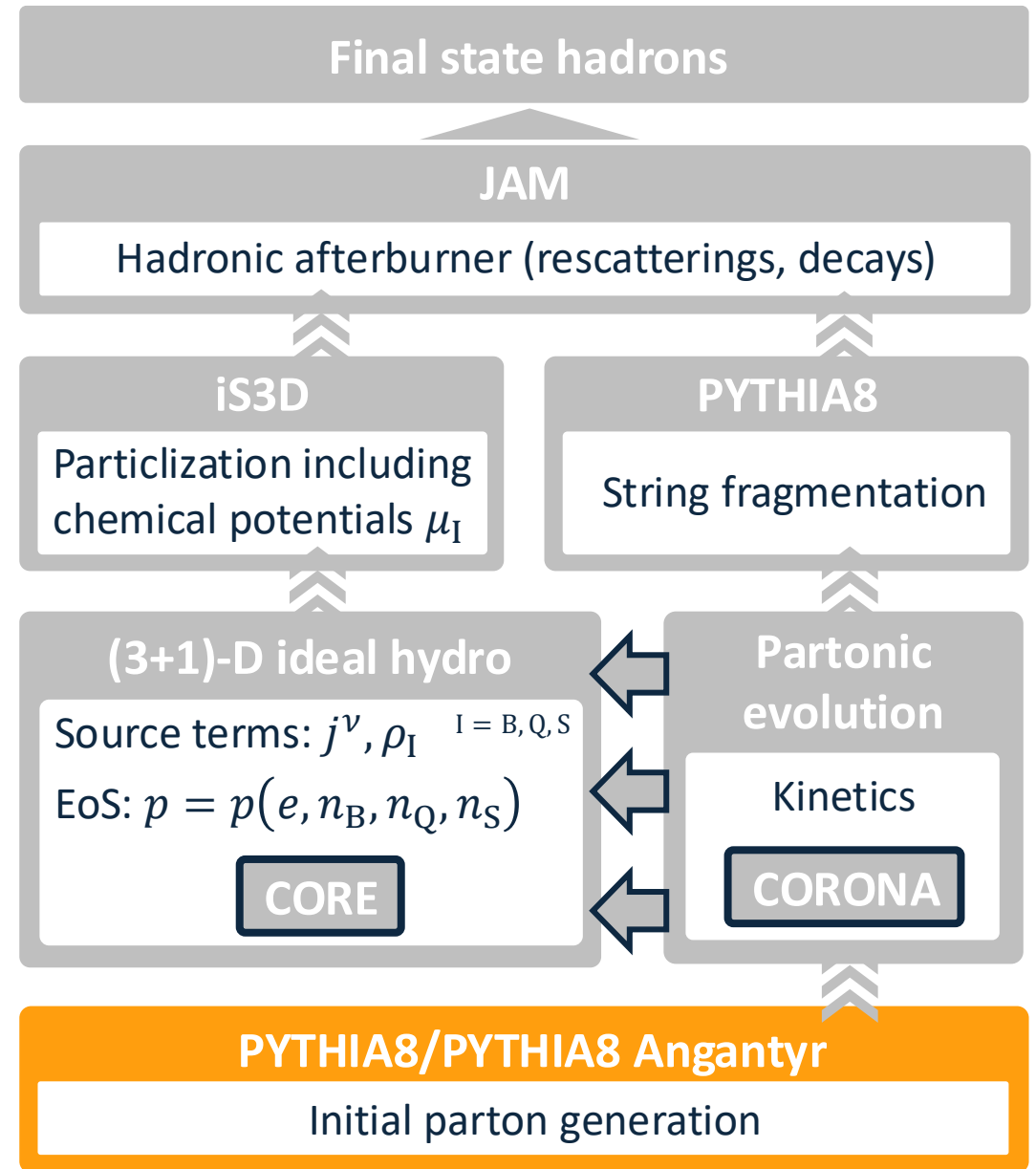
# Results

1. Initial conditions
2. Space-time evolution
3. Switching hypersurface
4. Particle yields
5. Charge distribution
6. Core-corona fraction
7. Strange hadron yield ratios



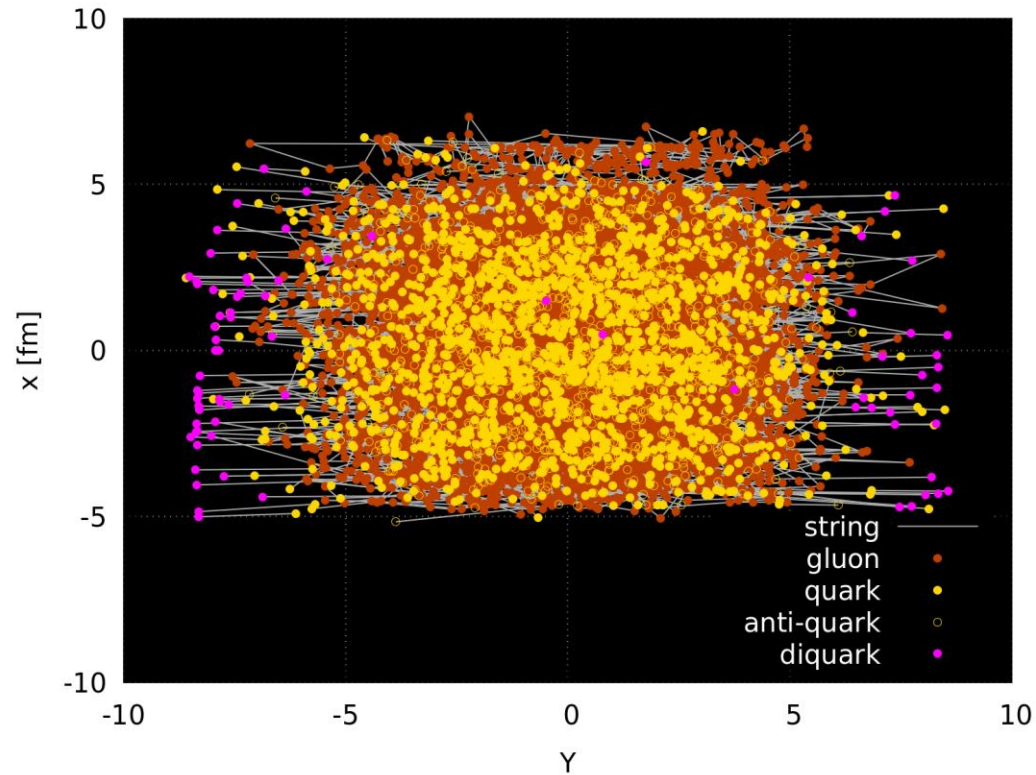
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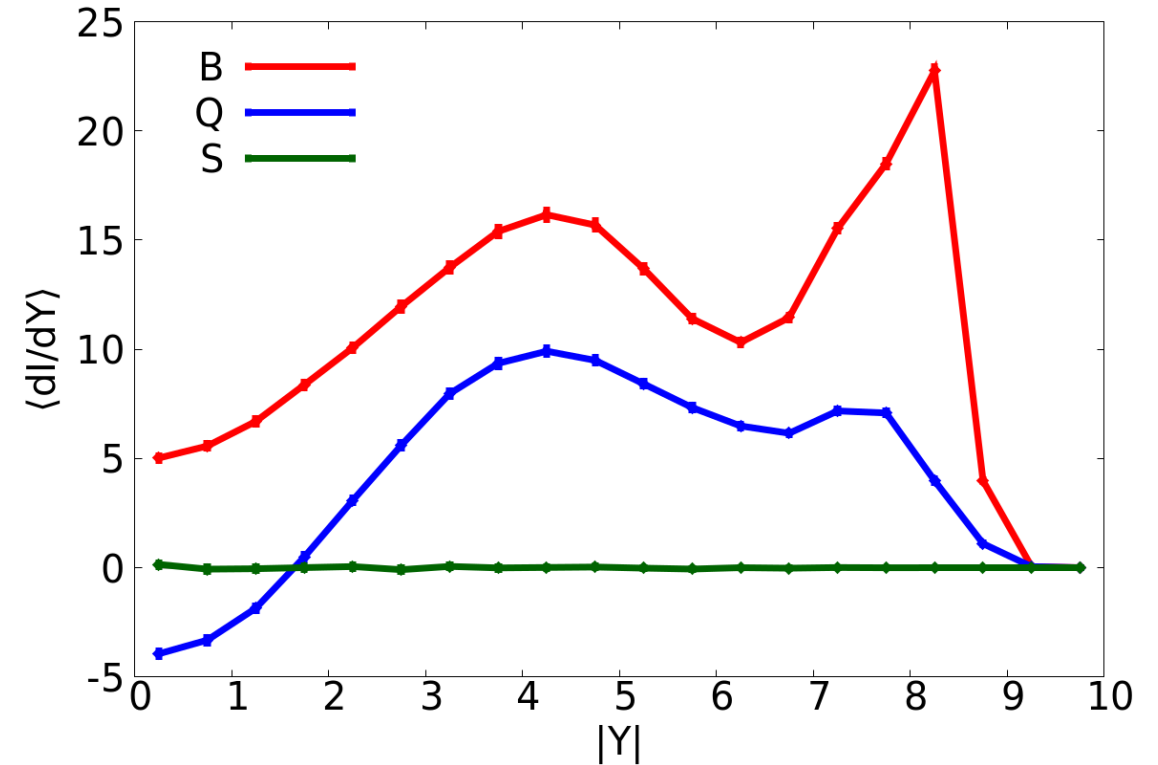
# Initial partons

## Parton distribution



- Midrapidity: (Anti-)quark and gluon dominant
- Forward rapidity: diquark dominant
- Connected by “strings”

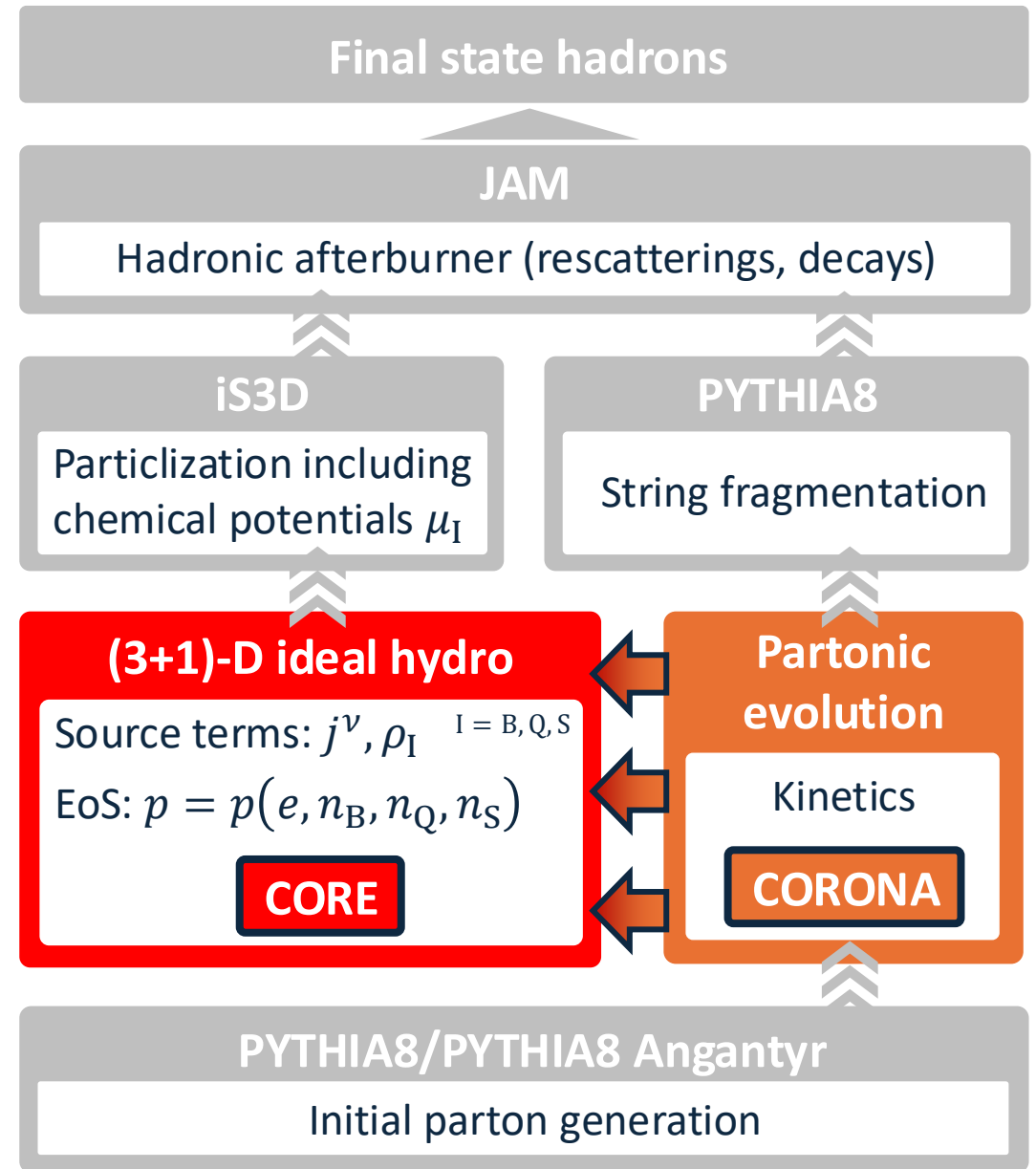
## Averaged charge distribution



- Peaks around  $Y \approx 4 - 5$  and  $Y_{\text{beam}}$   
baryon stopping    leading baryon
- Strangeness neutrality on average

# Results

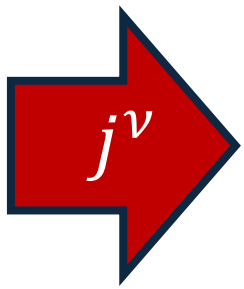
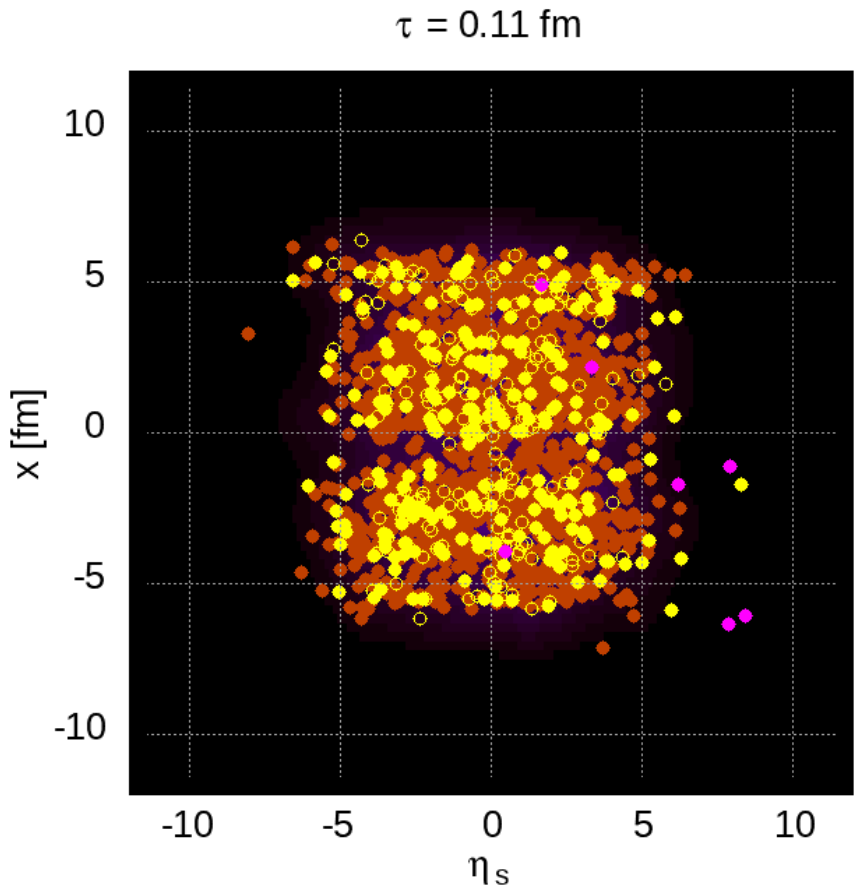
1. Initial conditions
2. Space-time evolution
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4. Particle yields
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# Dynamical core-corona initialization

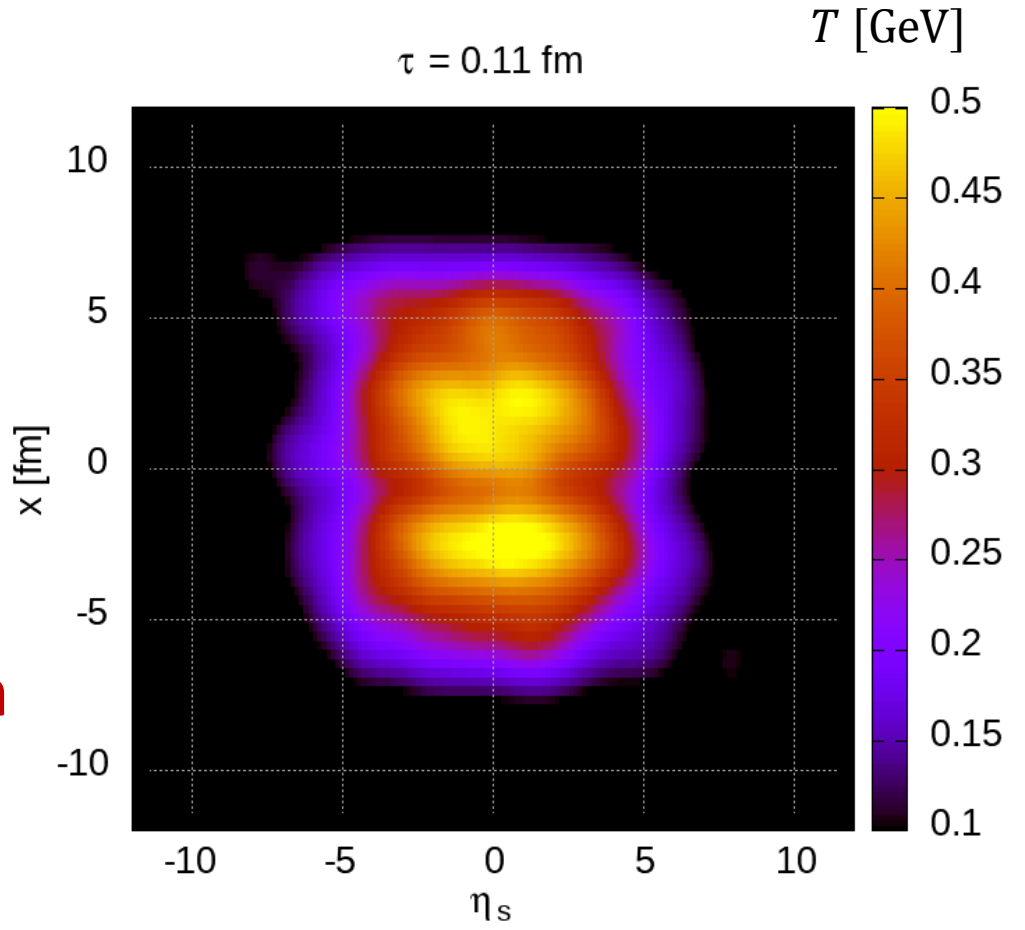
$$\eta_s = \frac{1}{2} \ln \left( \frac{t+z}{t-z} \right): \text{space-time rapidity}$$

Non-equilibrium parton (corona)



Dynamical fluid formation

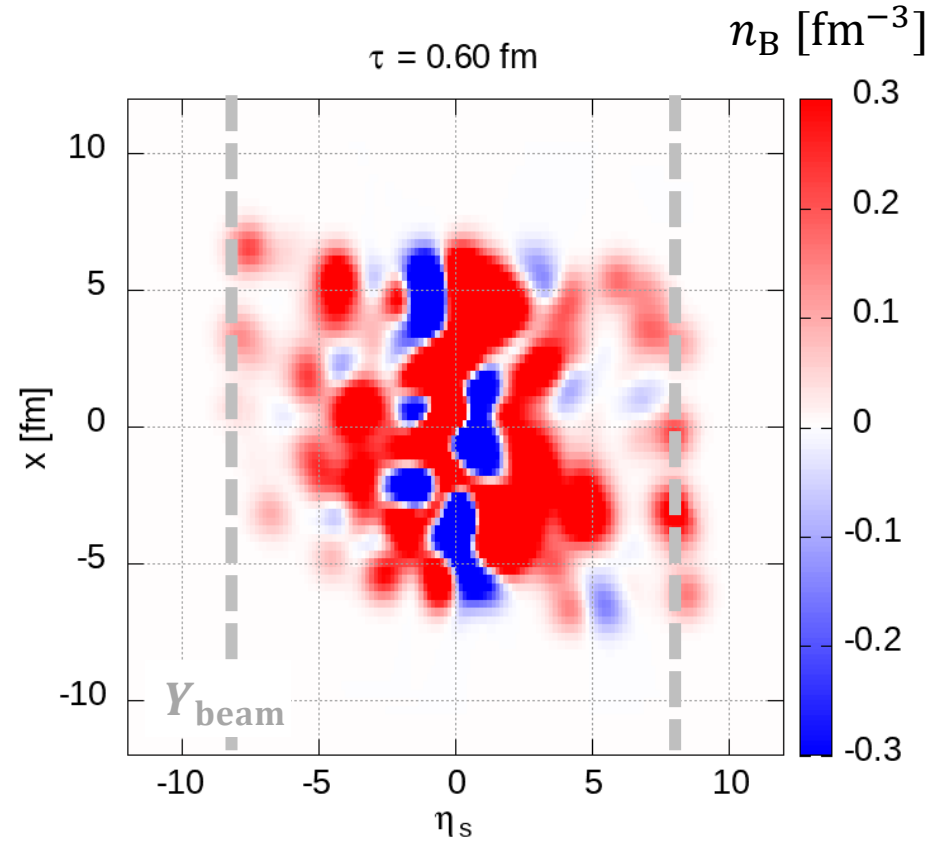
Fluid (core)



Event-by-event initial conditions of the fluid including **fluctuations**

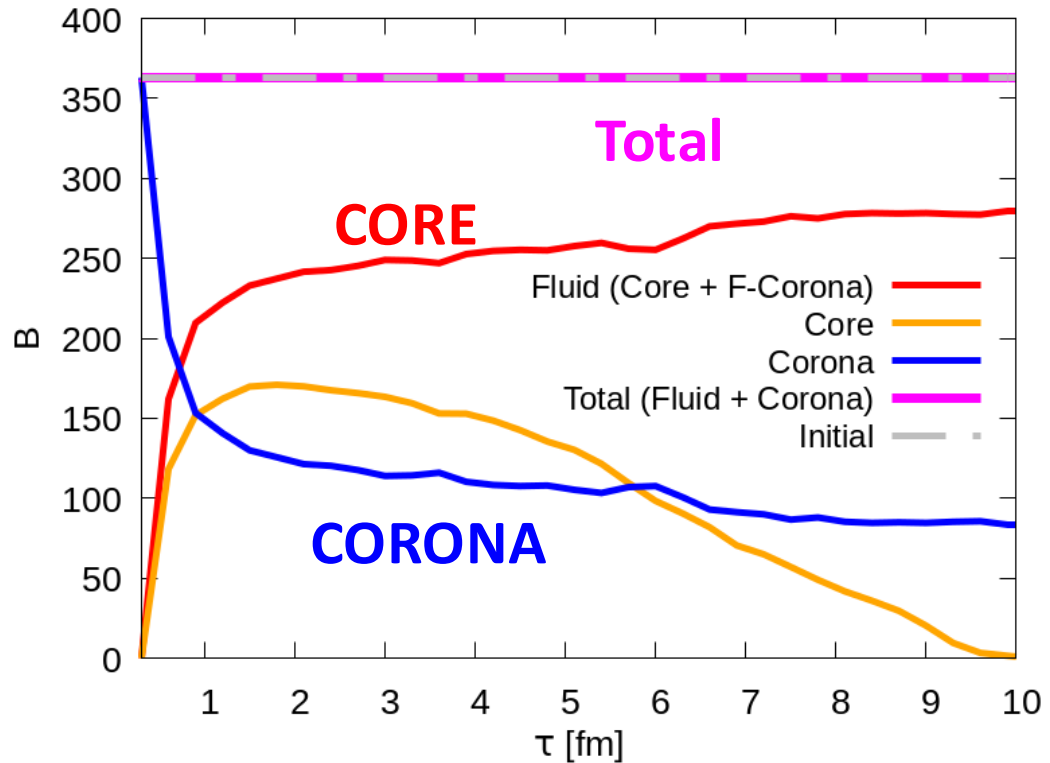
# Equilibration of baryon number

## Equilibrated baryon number



- Widely equilibrated in rapidity
- Locally **negative**  $n_B$  ← **Fluctuation!!**

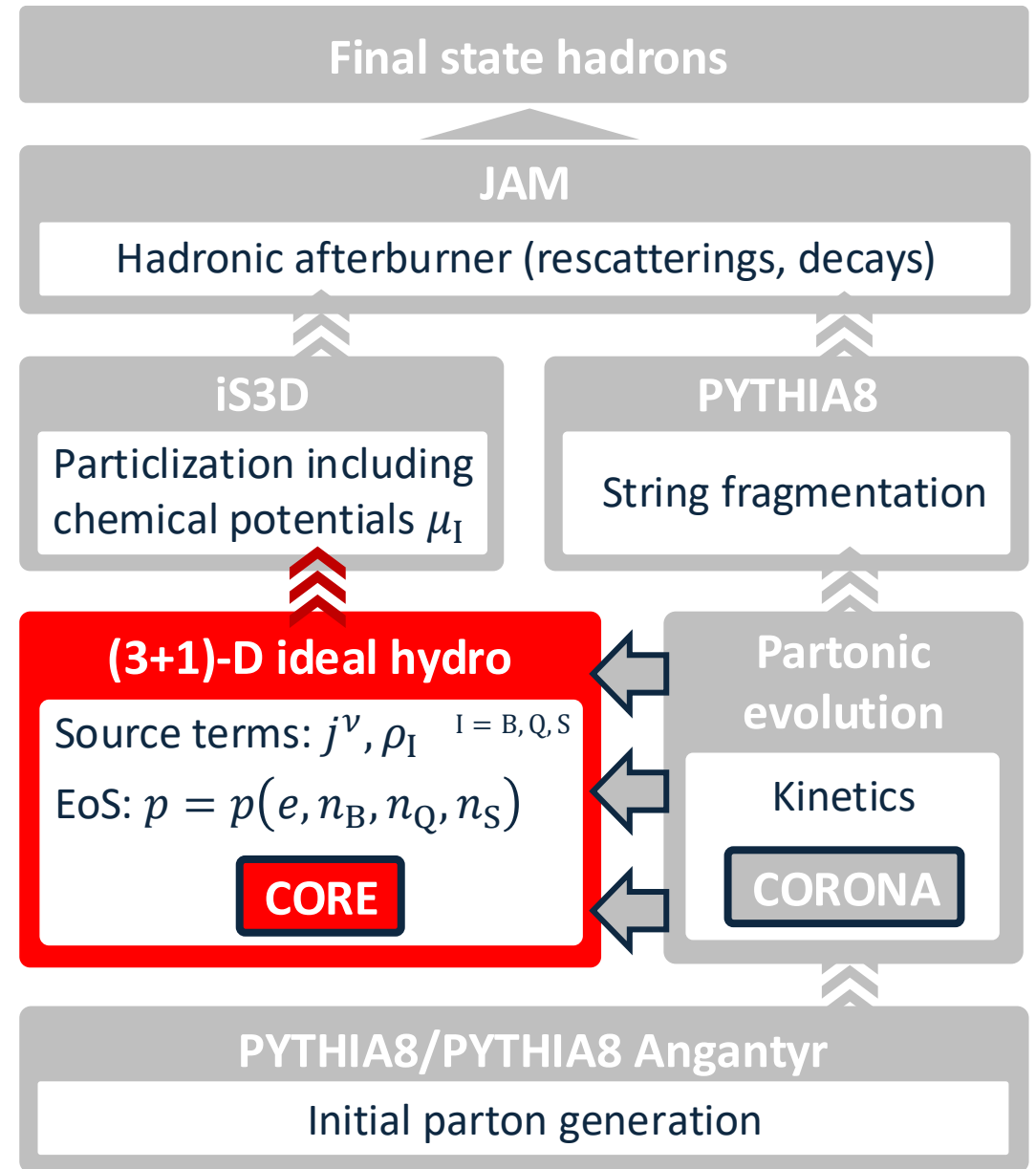
## Baryon number in CORE/CORONA



- Rapid equilibration of baryon number
- Exactly conserved during the DCCI process

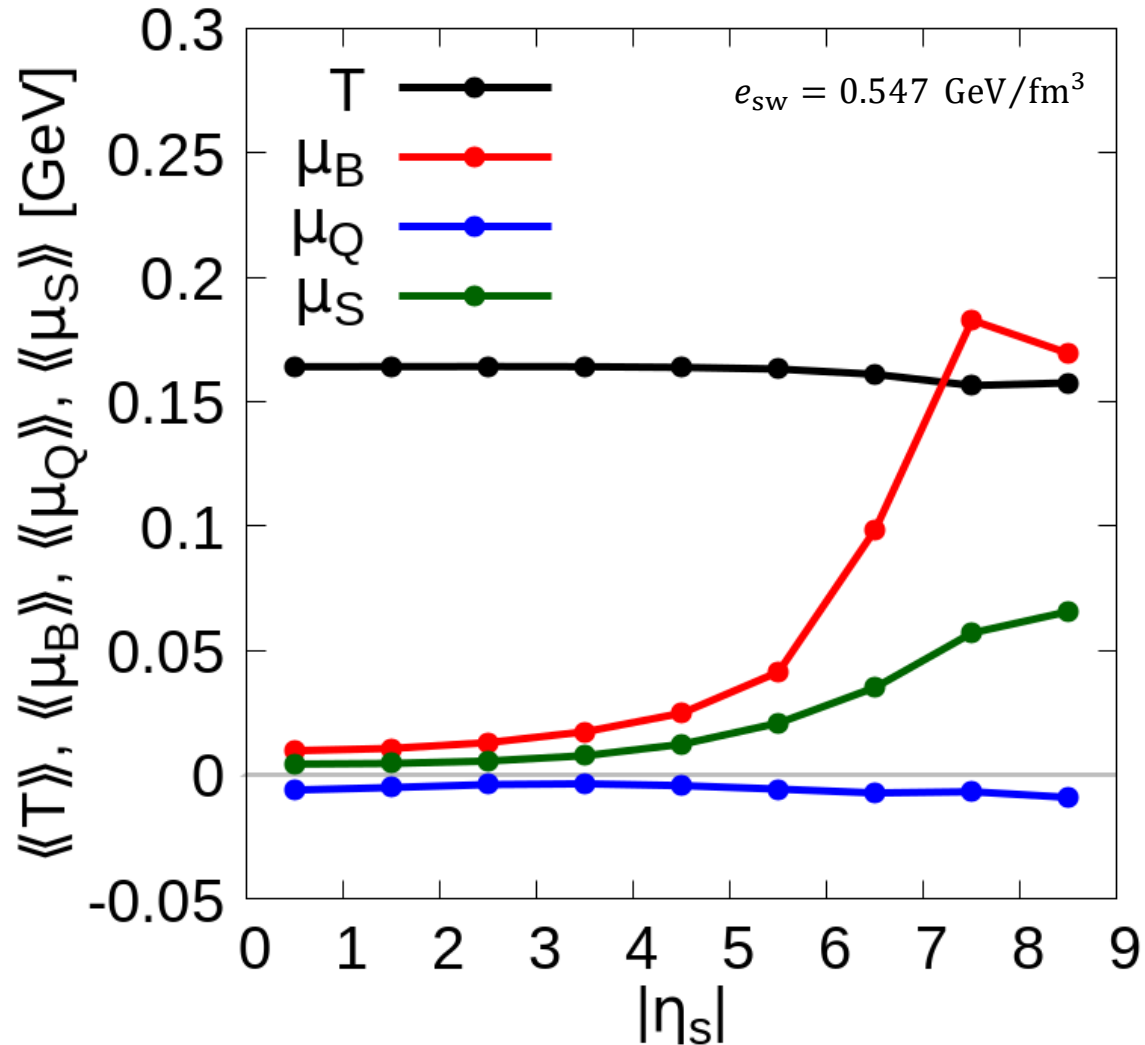
# Results

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# Averaged chemical potentials on switching hypersurface

$\langle\langle \dots \rangle\rangle$ : events & hypersurface average

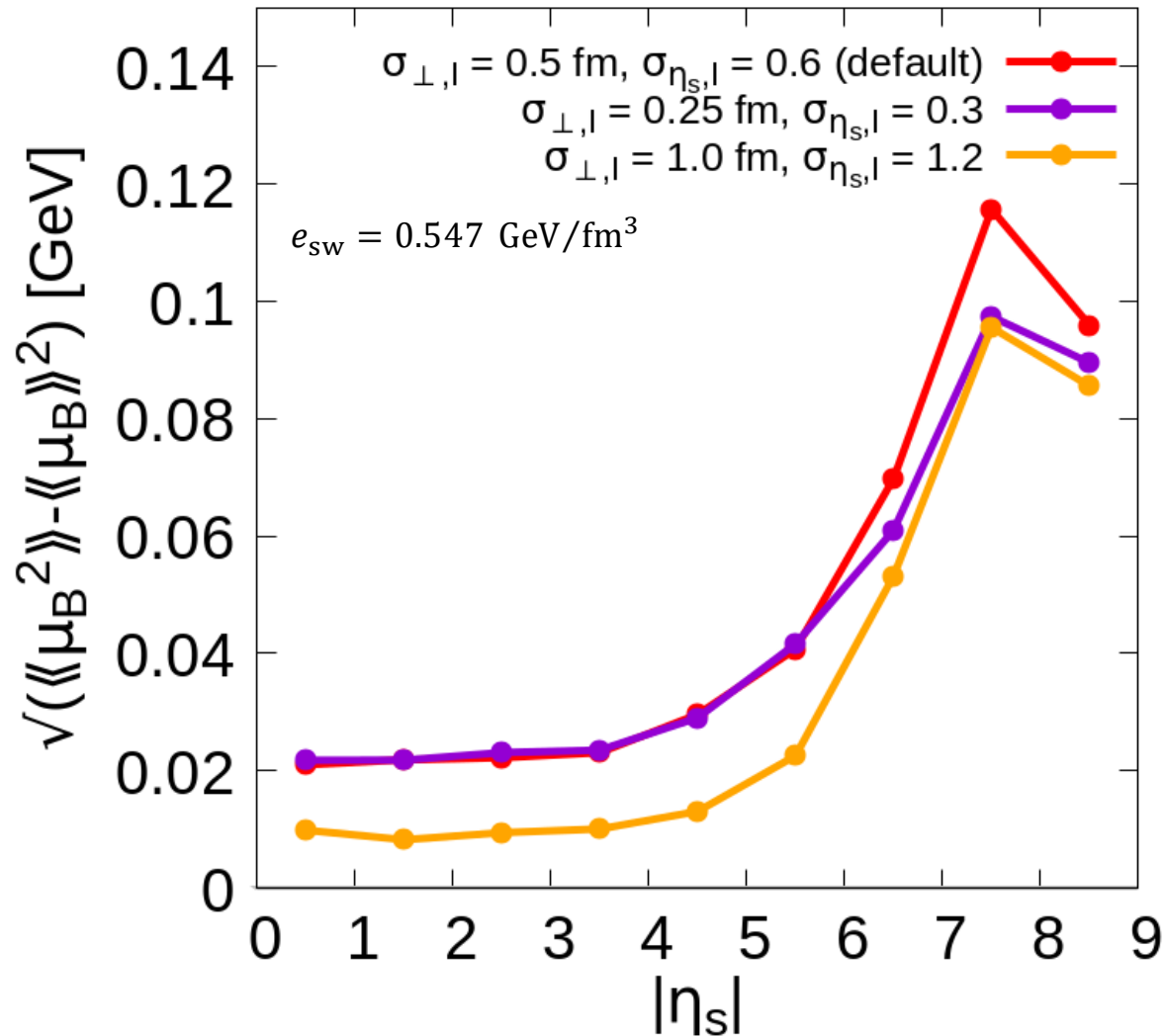


- $\mu_B \uparrow$  and  $\mu_S \uparrow$  along rapidity
- $\mu_Q$  is almost uniform along rapidity with slightly negative value
- Baryon chemical potential reaches  $\mu_B \approx 200 \text{ MeV}$  in forward rapidity  
\*minimum-bias events

**Rapidity Scan** in high-energy nuclear collisions is useful as a complementary way to BES?

# Typical fluctuation of chemical potentials

$\langle\langle \dots \rangle\rangle$ : events & hypersurface average



- Fluctuations tend to be suppressed for larger Gaussian smearing length

- Typical fluctuation of  $\mu_B$  around midrapidity:  $\approx \pm 20$  MeV

- Typical fluctuation of  $\mu_B$  around forward rapidity:  $\approx \pm 100$  MeV

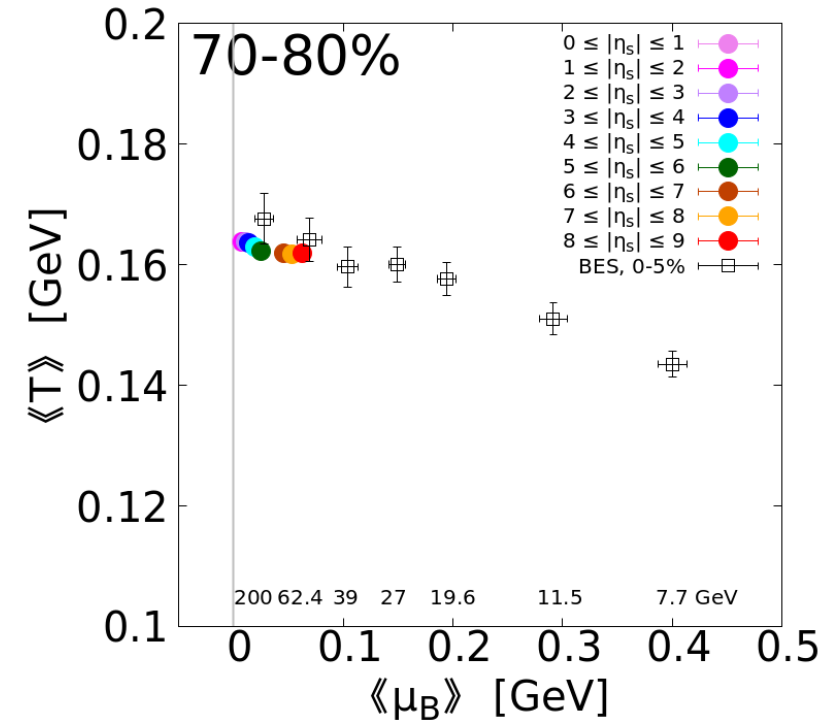
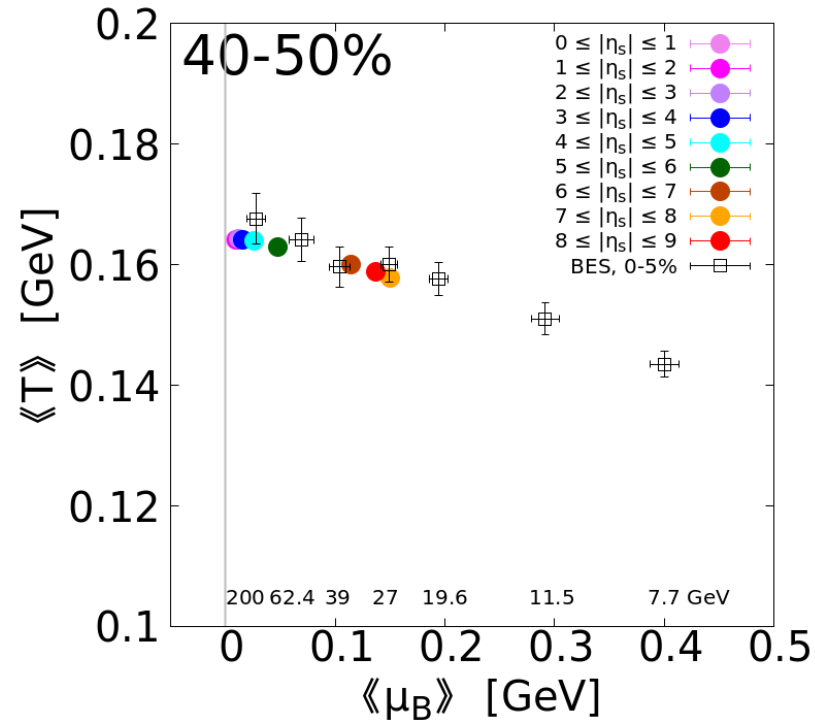
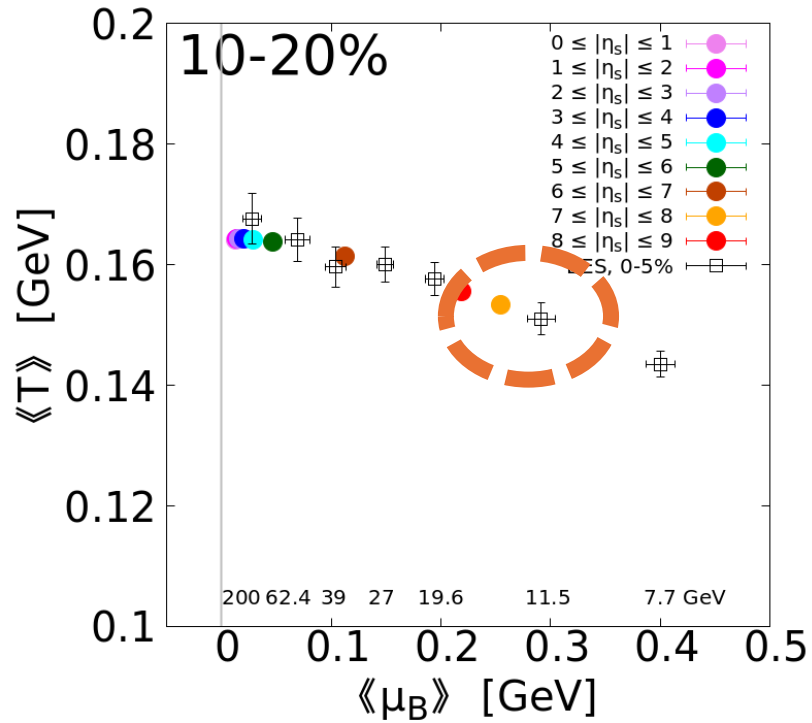
Midrapidity

$$\mu_B \approx 10 \pm 20 \text{ MeV}$$

Forward rapidity

$$\mu_B \approx 200 \pm 100 \text{ MeV}$$

# Centrality dependence

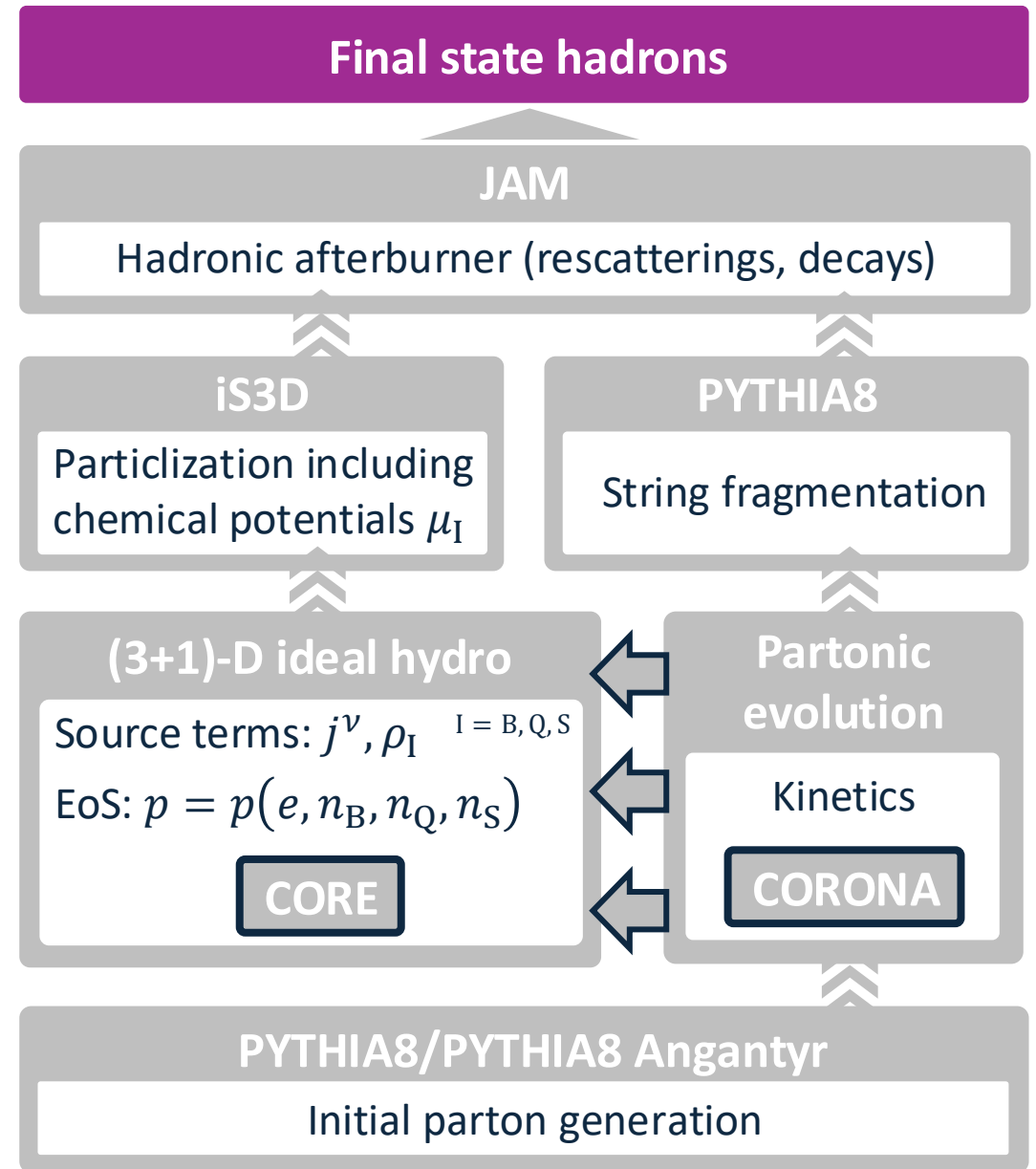


- Colored markers follow the BES results ← **Appropriate hypersurface ( $e_{sw} = 0.547 \text{ GeV}/\text{fm}^3$ )**
- Large baryon chemical potentials in central events ← **Strong baryon stopping & equilibration**

**Rapidity Scan ( $7 \leq |\eta_s| \leq 8$ )  $\approx$  Beam Energy Scan ( $\sqrt{s_{NN}} = 11.5 \text{ GeV}$ )**

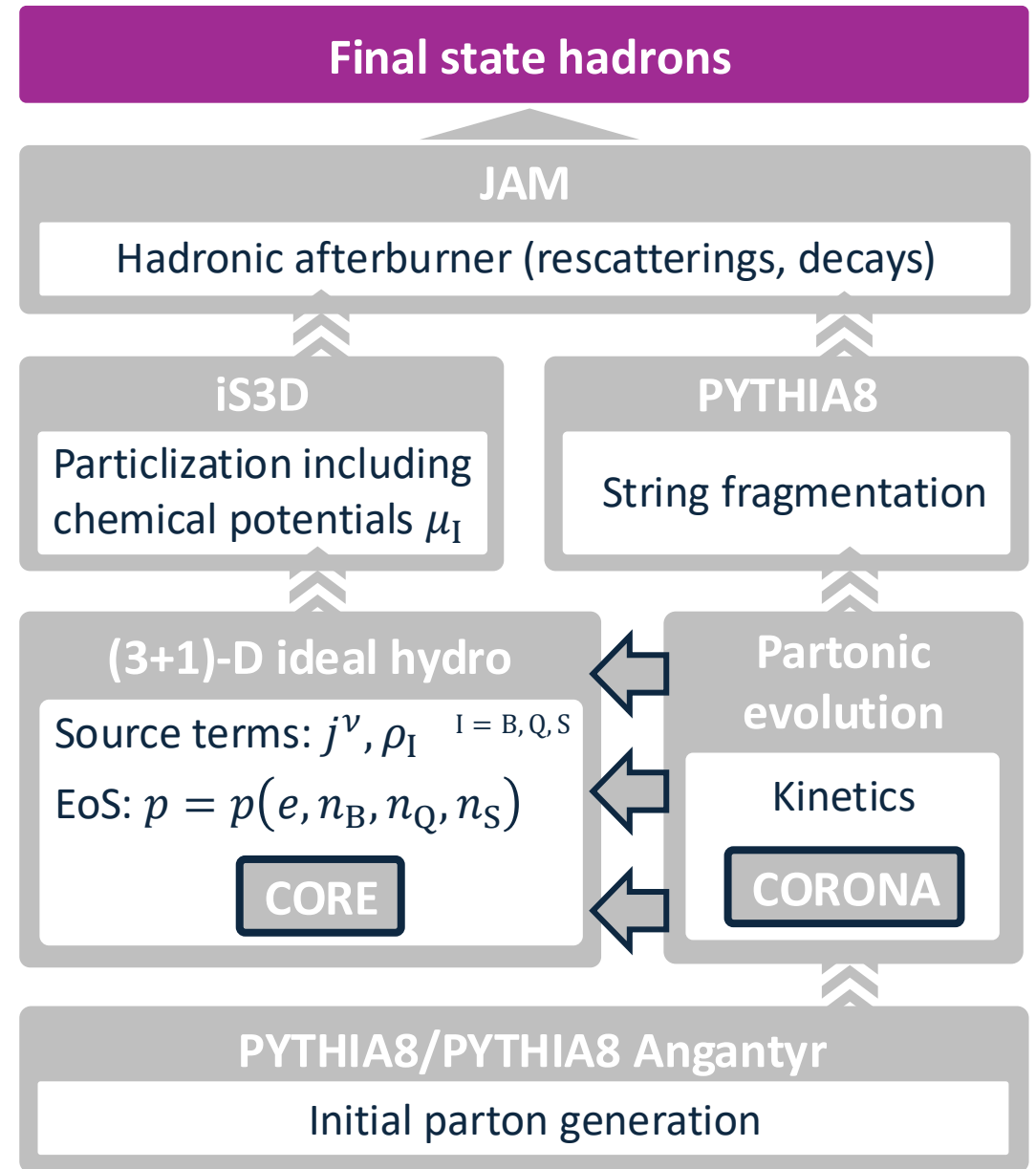
# Results

1. Initial conditions
2. Space-time evolution
3. Switching hypersurface
- 4. Particle yields (backup)**
- 5. Charge distribution (backup)**
6. Core-corona fraction
7. Strange hadron yield ratios

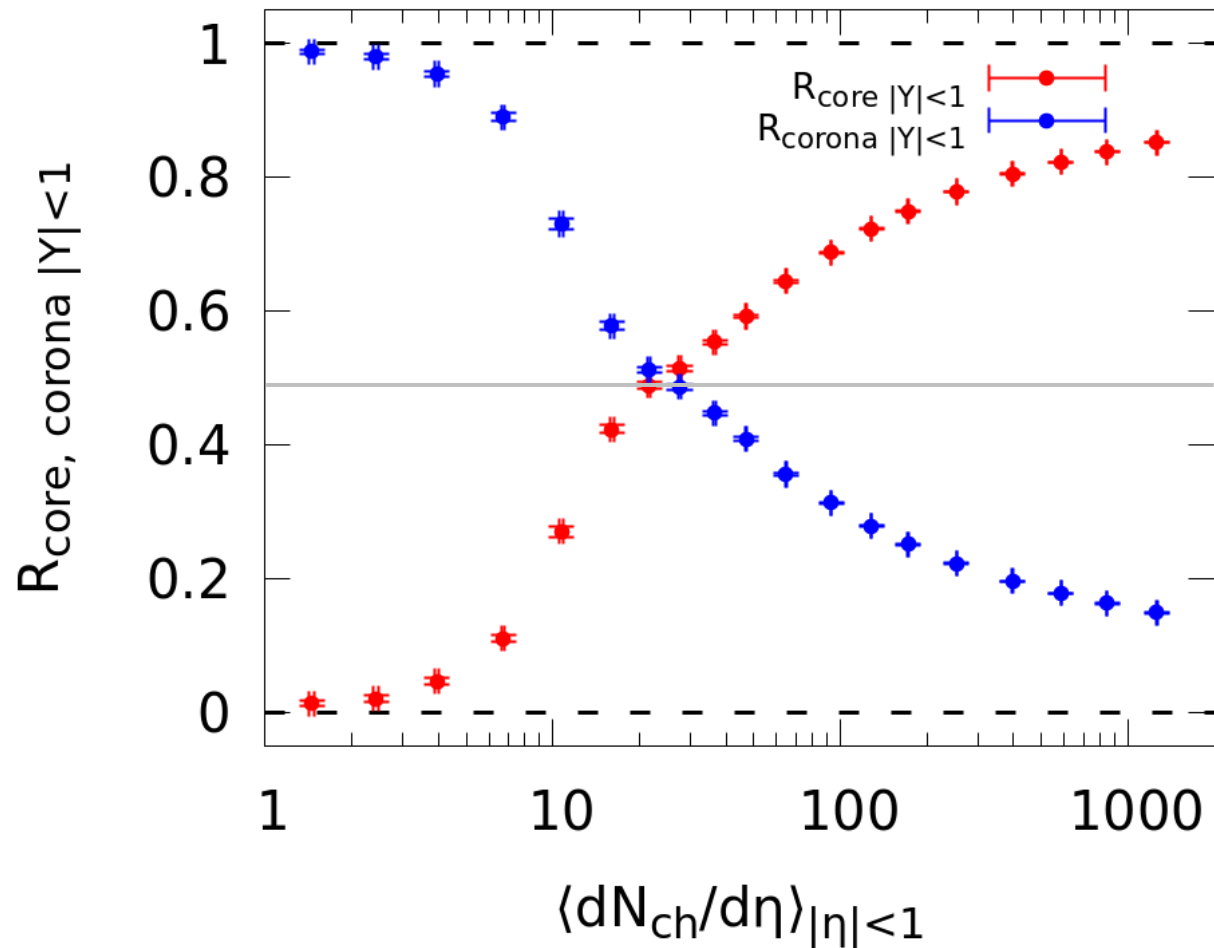


# Results

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# Core-corona fraction



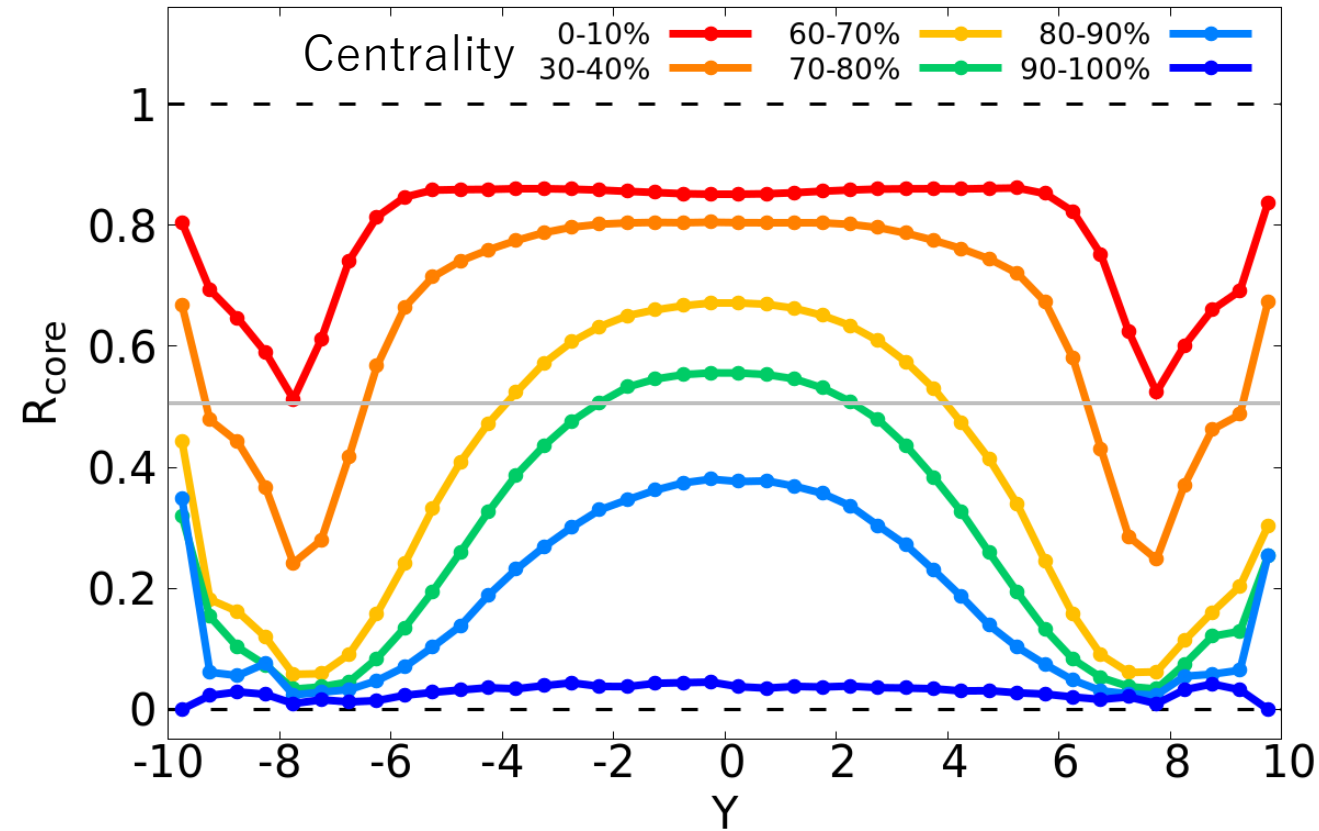
$$R_{core}(Y) = \frac{\left(\frac{dN_{all}}{dY}\right)_{core}}{\left(\frac{dN_{all}}{dY}\right)_{core} + \left(\frac{dN_{all}}{dY}\right)_{corona}} = \text{Degree of equilibration}$$

- Toward high multiplicity,  $R_{core} \uparrow$
- Core becomes dominant at  $dN_{ch}/d\eta \approx 20$
- $R_{core}$  is at most 0.85

Y. Kanakubo *et al.*, Phys. Rev. C **105**, 024905 (2022)

**The core and corona coexist at all multiplicities!**

# Core fraction

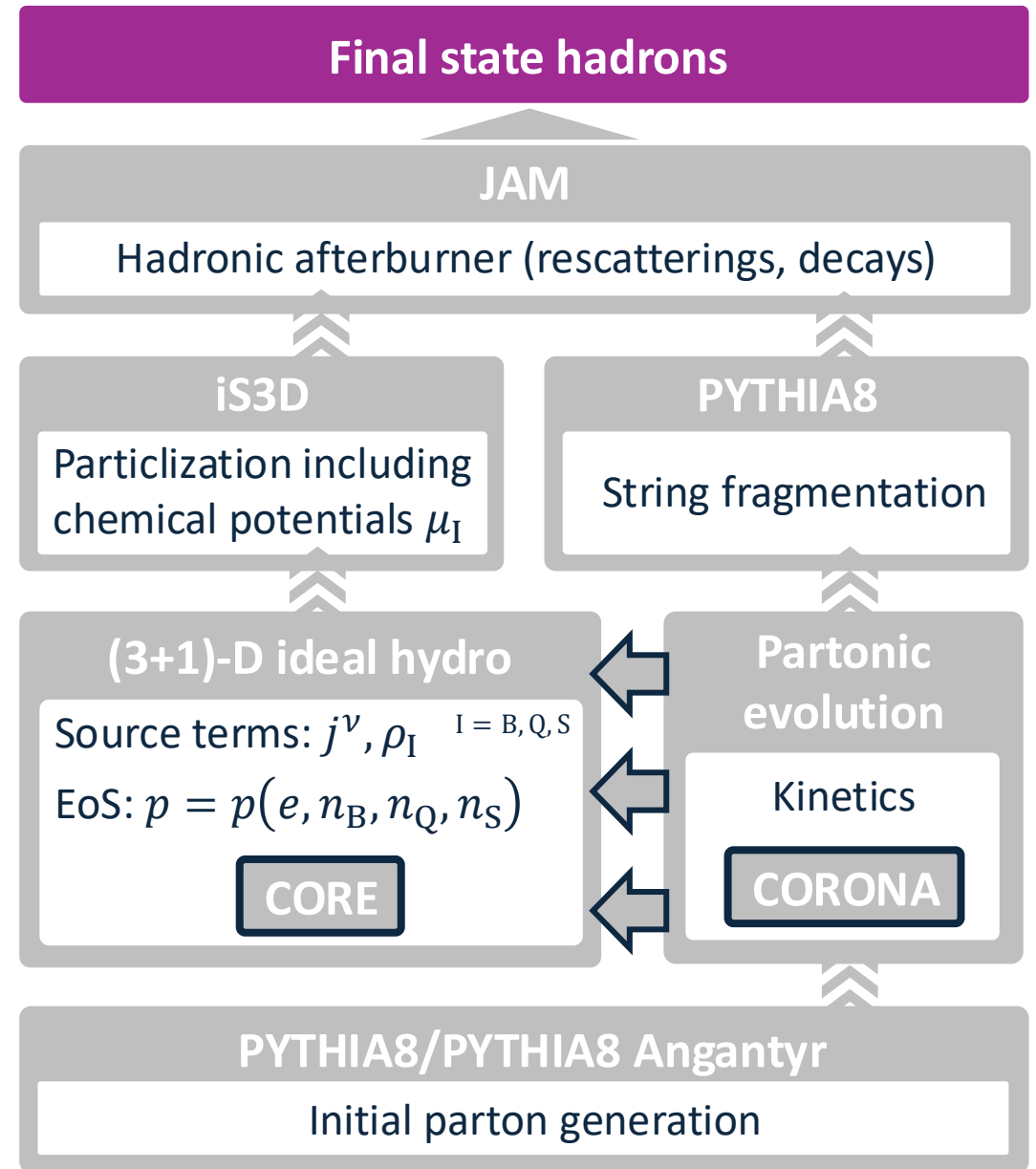


- Entirely core dominated for central (0-10%) events
- Core dominated until  $|Y| \lesssim 2$  for 70-80% events
- Violation of boost invariance for peripheral events

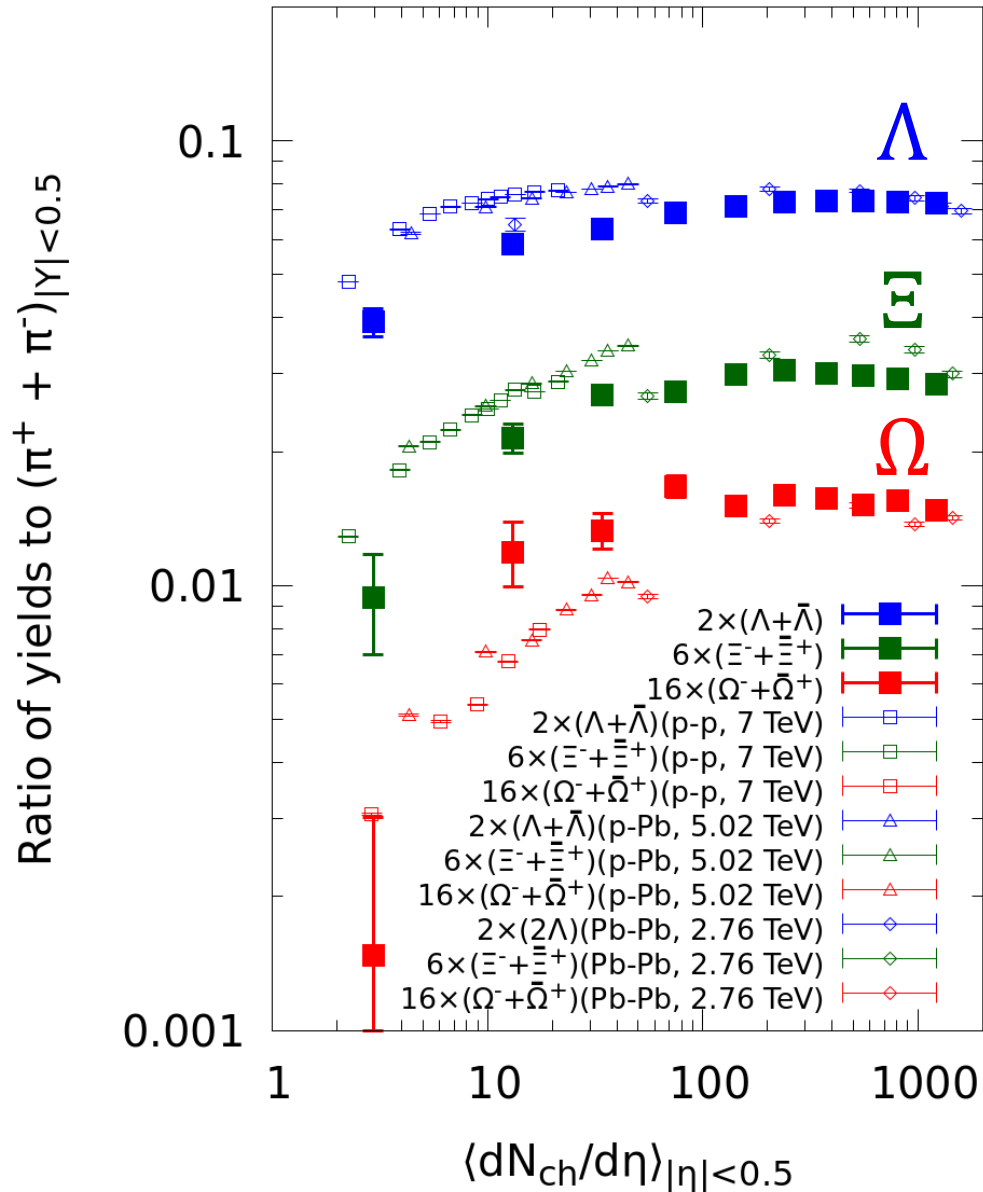
**Equilibration exhibits a strong dependence on both rapidity and centrality**

# Results

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# Strange hadron yield ratio



- Strange hadron yield ratios increase with multiplicity

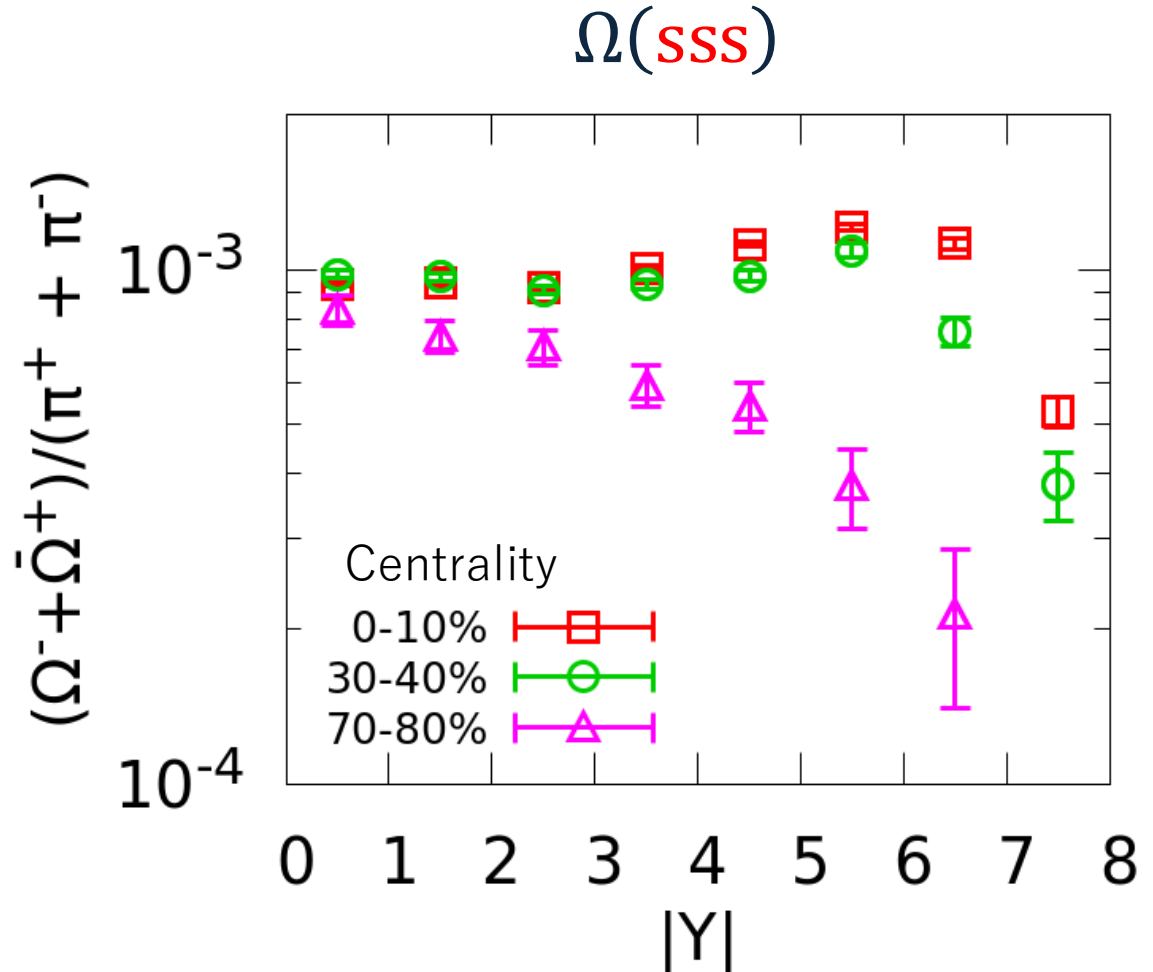
→ **strangeness enhancement**  
(signature of QGP production)

- Scaling behavior regardless of system size (p+p, p+Pb, Pb+Pb)

**DCCI reproduces strangeness enhancement through the balance between the core and corona**

- What happens in forward rapidity?

# Rapidity-dependent strange hadron yield ratio



- Order 0-10% > 30-40% > 70-80%  
→ strangeness enhancement
- 70-80%:  
consistent with  $R_{core} \downarrow$  in forward
- 0-10% and 30-40%:  
non-trivial peak around  $|Y| \approx 4 - 7$

$R_{core} \downarrow$  VS  $\mu_B \uparrow$  + leading baryon

**Baryons in forward rapidity play an important role in hyperon production!**

# Summary

---

# Summary

Description of entire system, **from midrapidity to forward rapidity**, using the DCCI model including conserved charge (BQS) dynamics

## **Baryon chemical potential $\mu_B$**

- Strong fluctuation of  $\mu_B$
- Large  $\mu_B$  in forward rapidity

## **Degree of equilibration $R_{\text{core}}$**

- Strong dependence on rapidity
- Strong dependence on centrality

## **Strange hadron production**

- Different production mechanisms emerge in forward rapidity

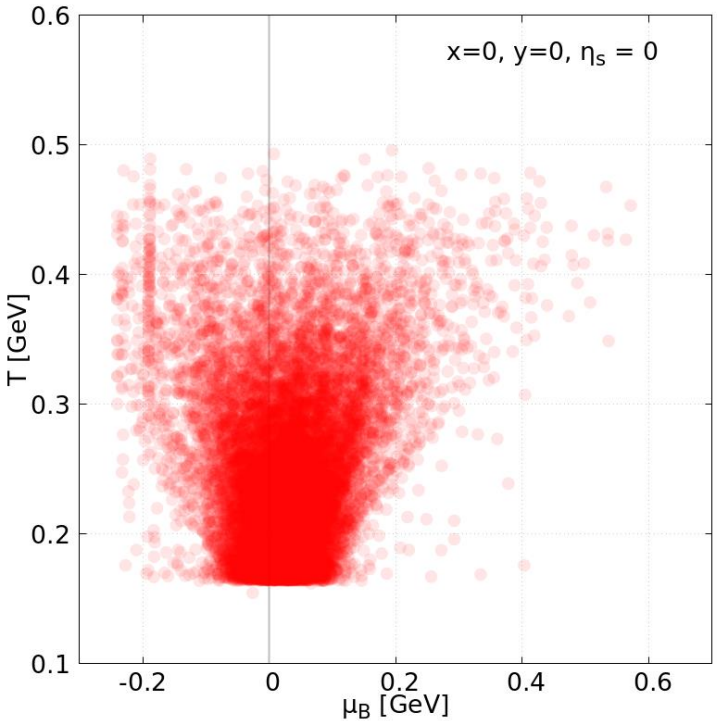
**Important results toward understanding full 3D structure of matter in high-energy heavy-ion collisions!**

# Backups

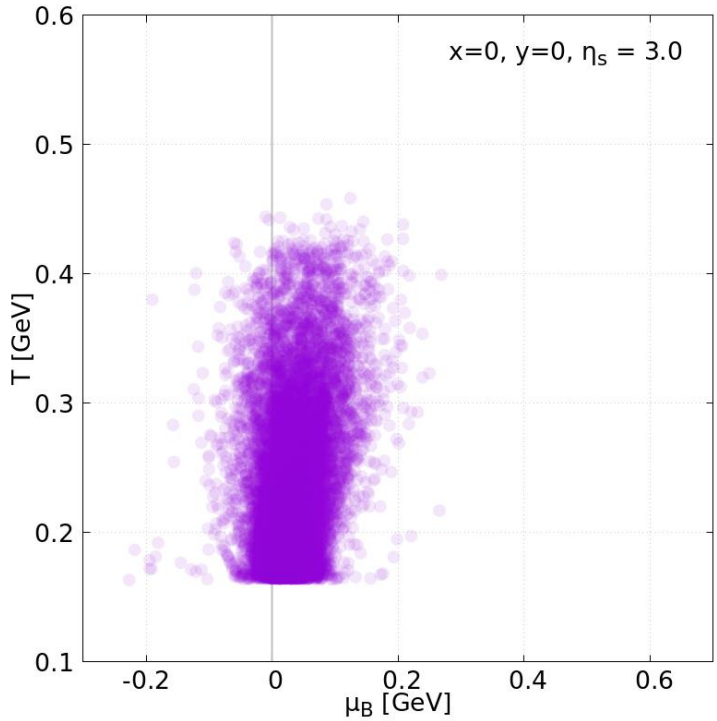
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# Baryon chemical potentials on QCD phase diagram

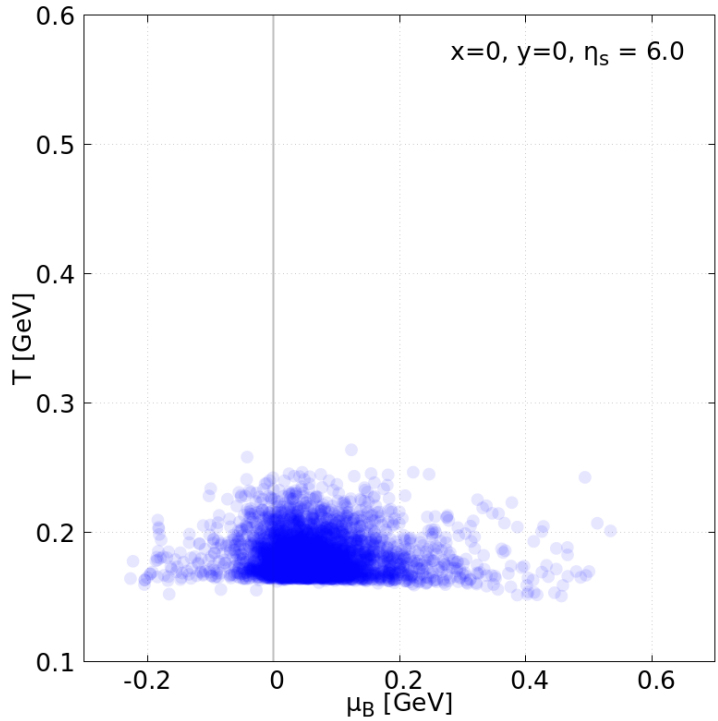
Midrapidity ( $\eta_s = 0$ )



Intermediate rapidity ( $\eta_s = 3$ )



Forward rapidity ( $\eta_s = 6$ )



$\mu_B$  fluctuation: large  $T$ : large

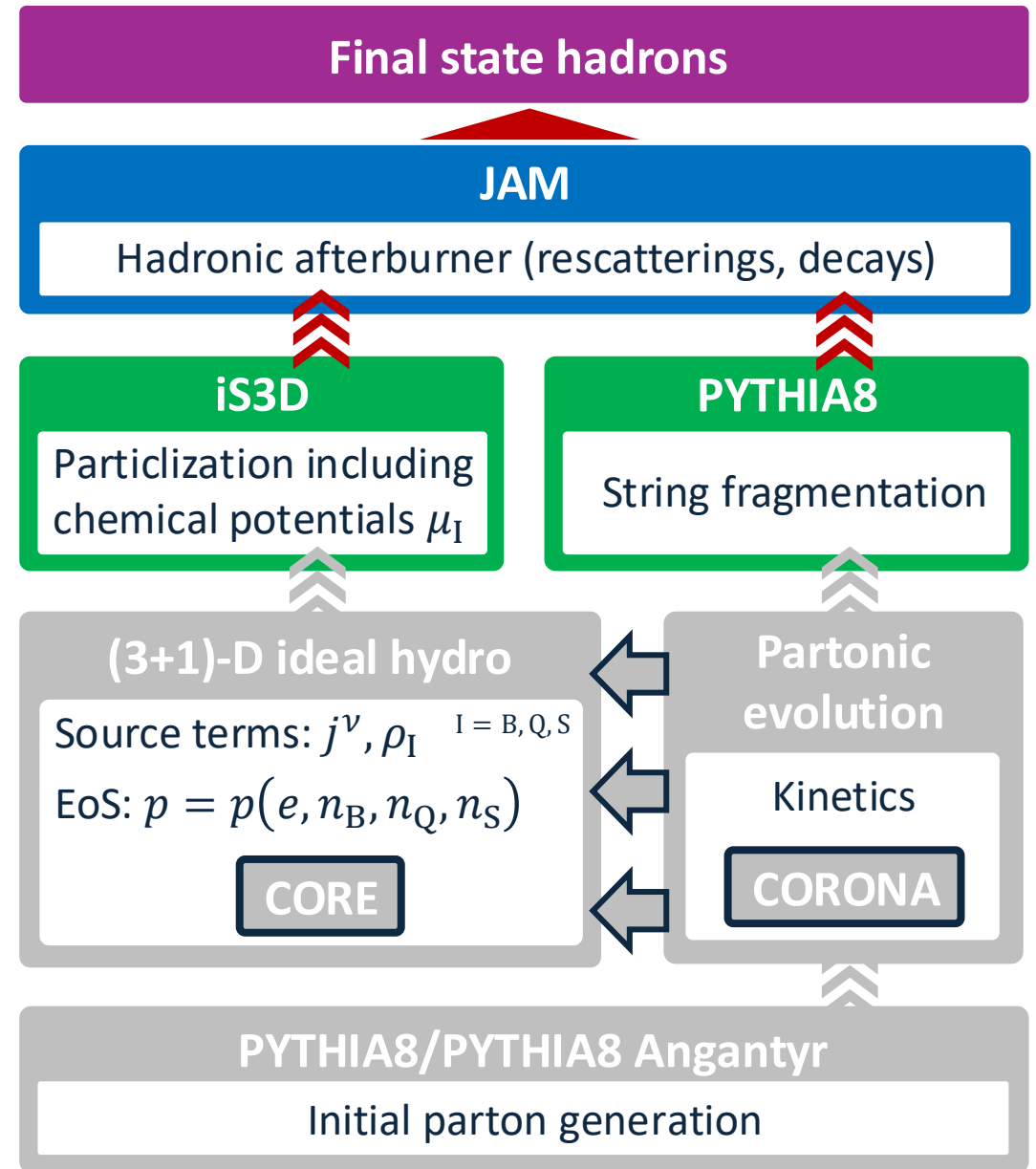
$\mu_B$  fluctuation: small  $T$ : large

$\mu_B$  fluctuation: large  $T$ : small

Different behavior along rapidity  $\Rightarrow$  Importance of rapidity-dependent analysis

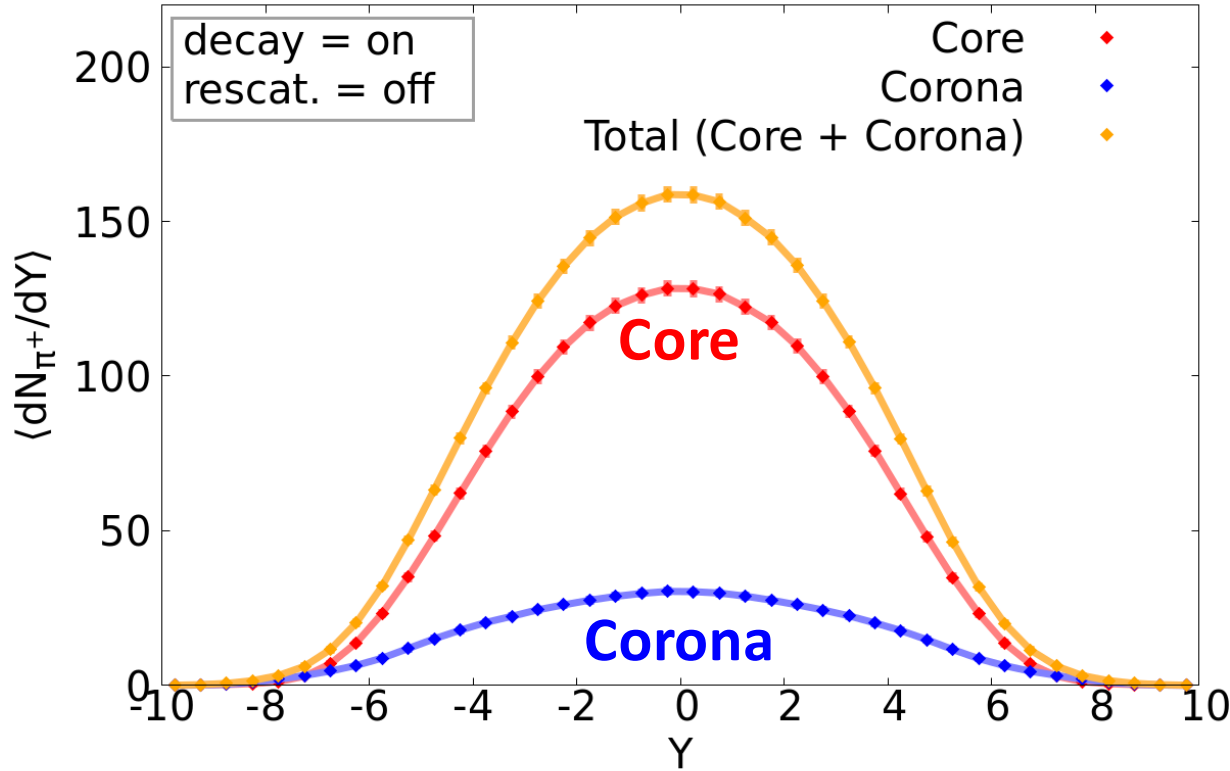
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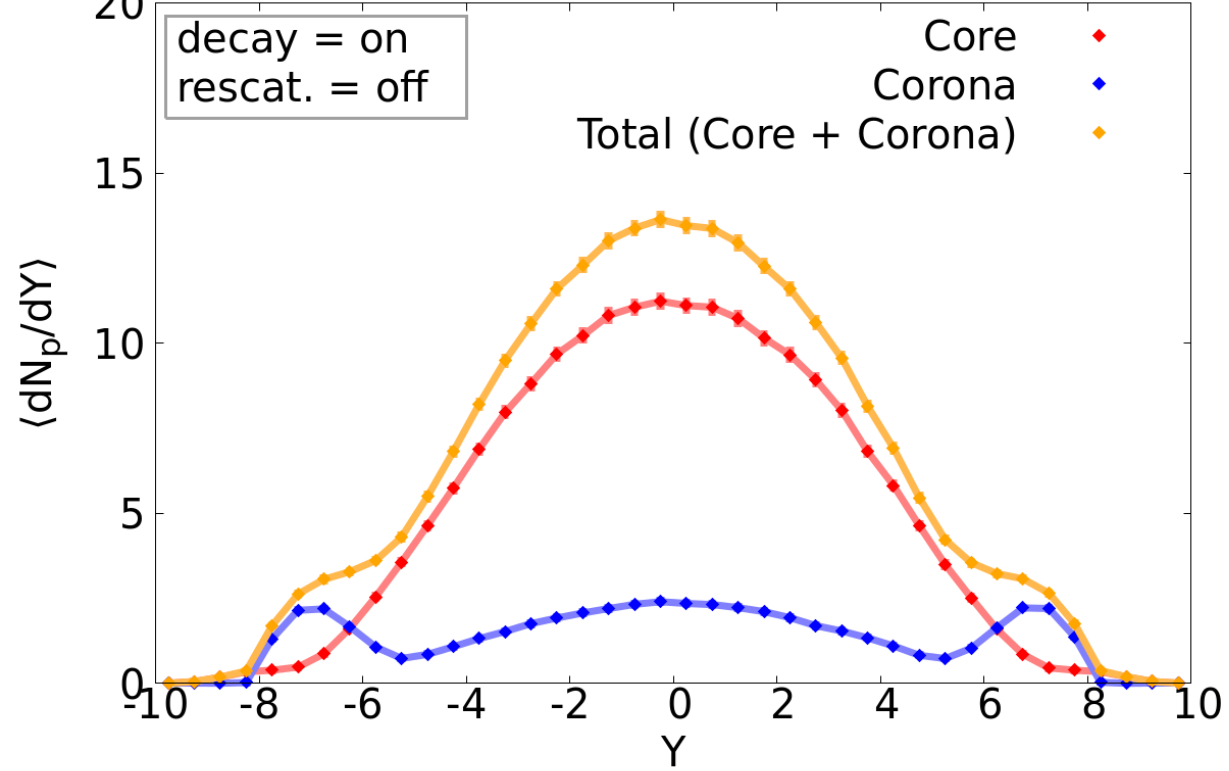


# Identified particle yields

## Charged pion



## Proton



### Core-corona separation of particle yields

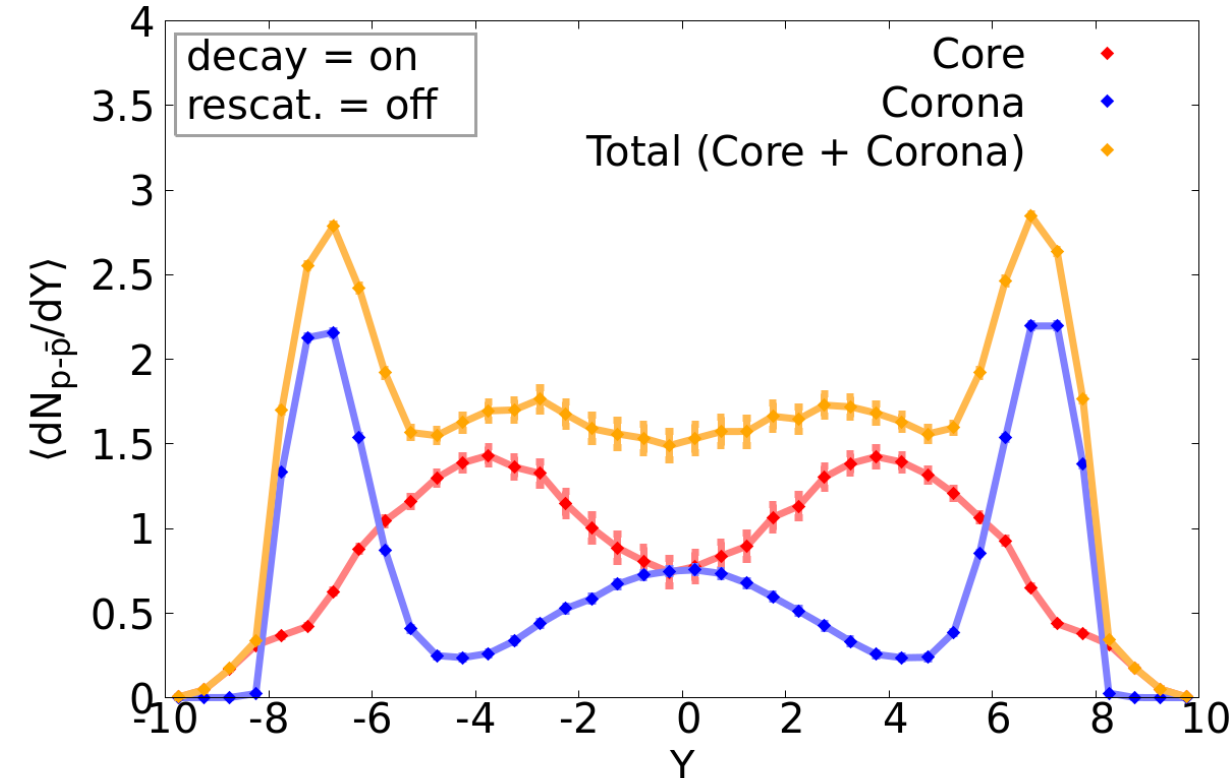
- **Core** dominant around midrapidity
- **Corona** dominant around forward rapidity

### Peaks around beam rapidity in corona

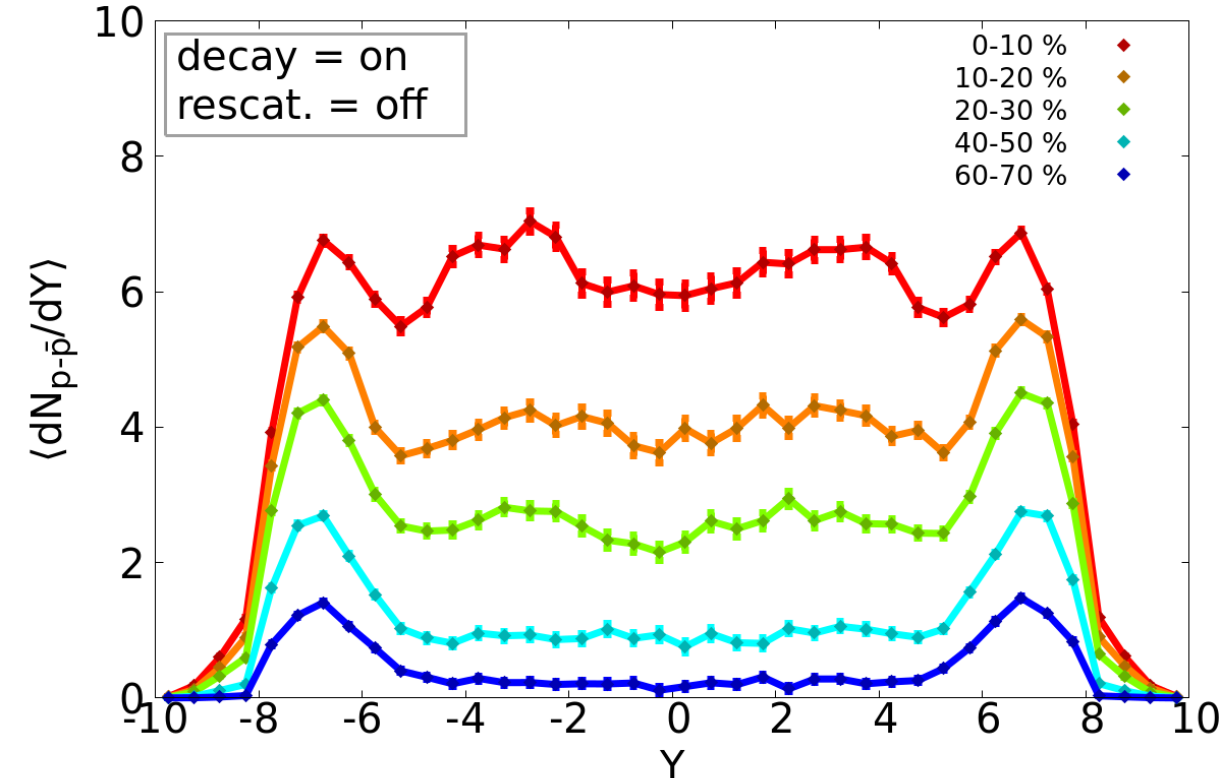
- Contribution from **leading baryons**

# Net-proton yields

## Core-corona separation



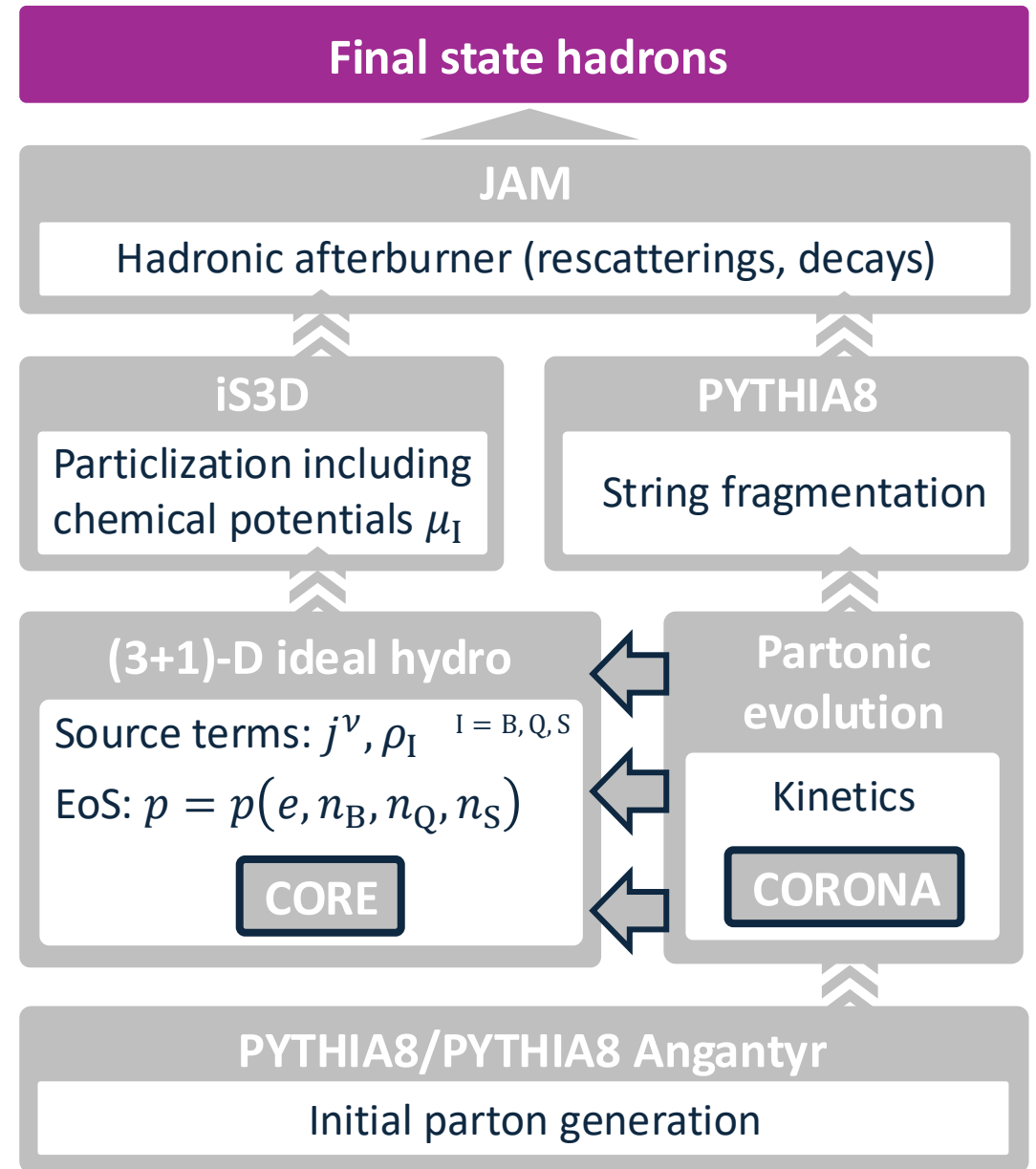
## Centrality dependence



- Enhanced production from the core in forward rapidity due to the large  $\mu_B$
- Baryon deposition becomes more significant for central events

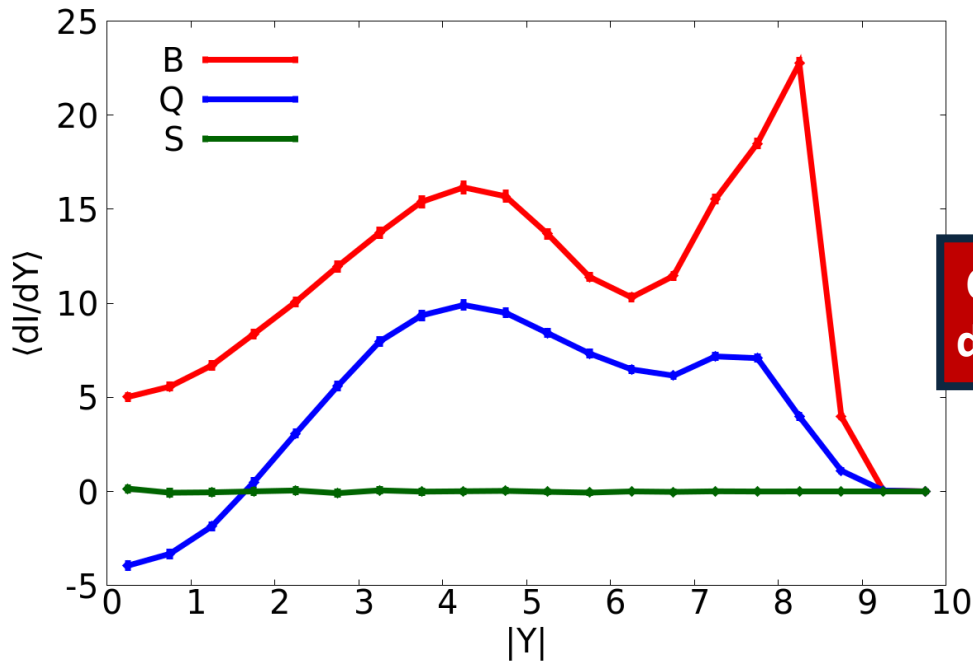
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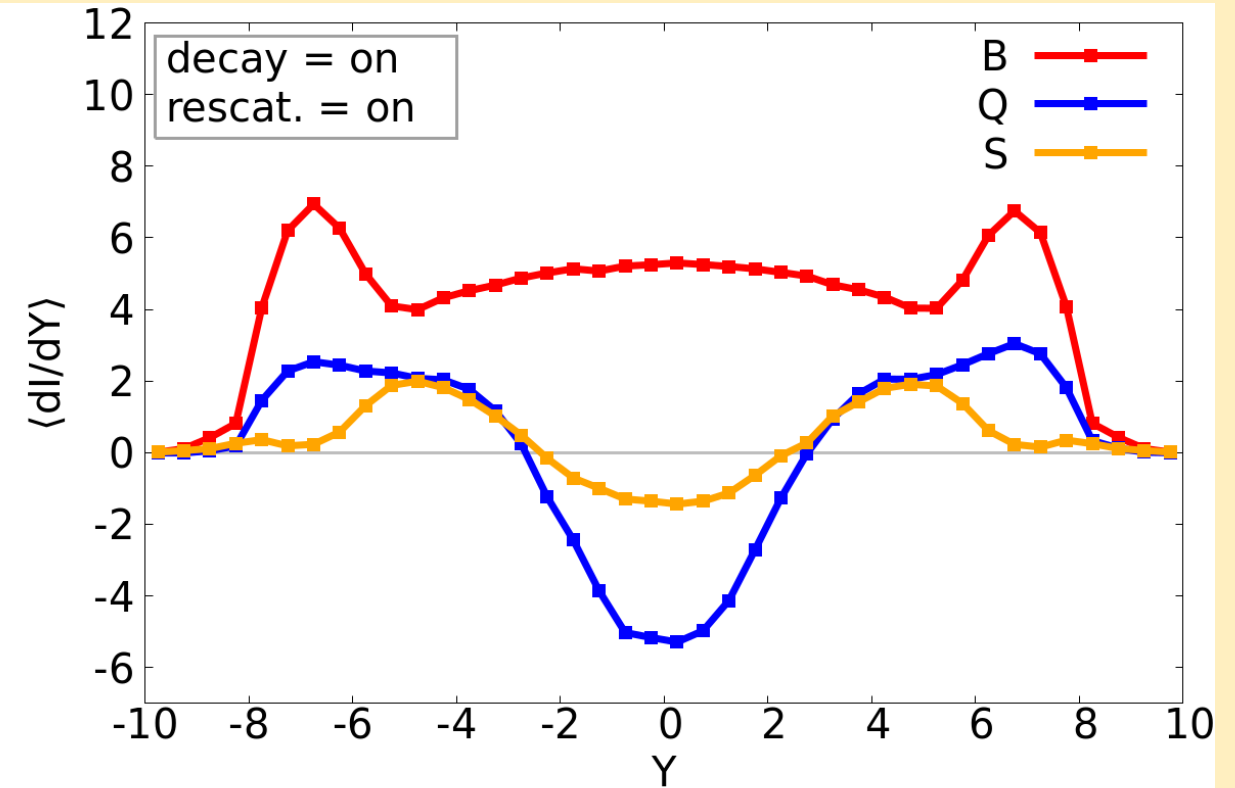
# Charge distribution

## Initial charge distribution (PYTHIA)



Collision dynamics

## Final charge distribution (DCCI3)



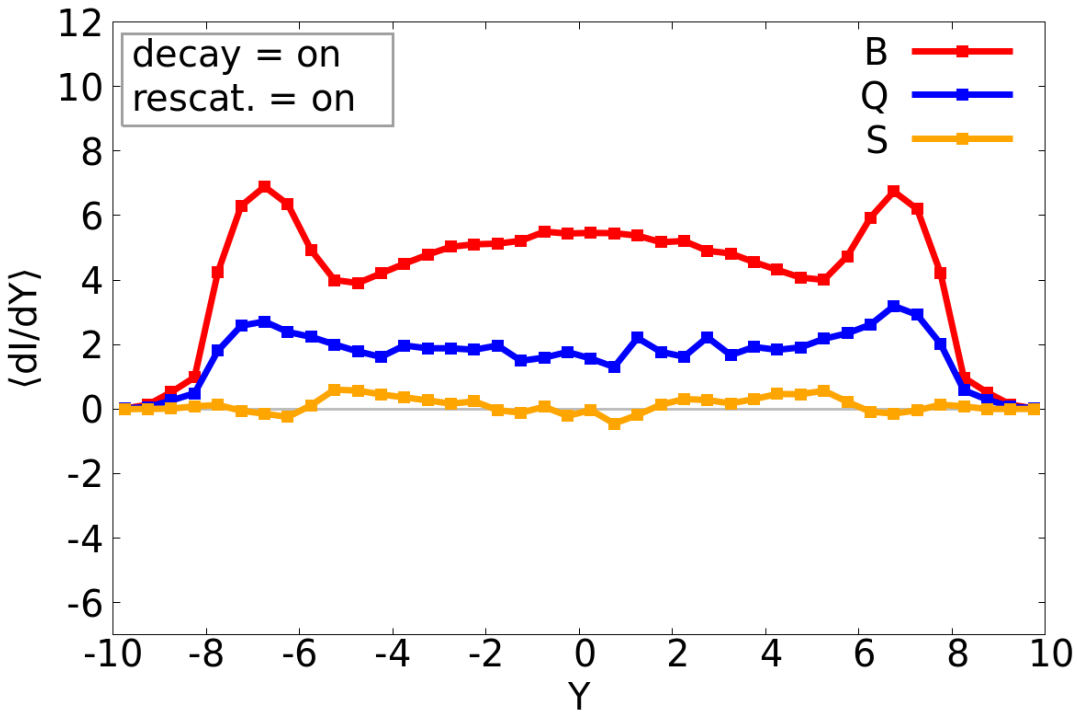
## Charge distributions change through the collision dynamics

- **Chemical potentials** play an important role in charge distribution
- Strangeness distribution exhibits non-trivial structure beyond strangeness neutrality

# Charge distribution

## NEOS-BQS

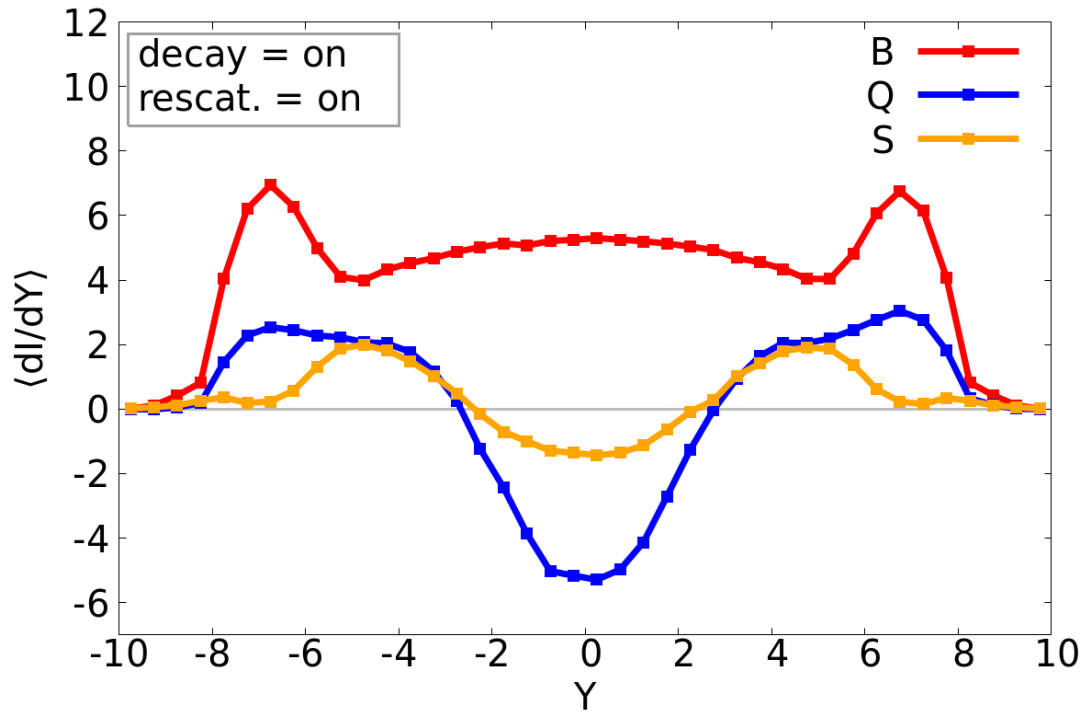
A. Monnai, B. Schenke and C. Shen, Phys. Rev. C **100**, 024907 (2019)



**NEOS-BQS**  
Constraints:  $n_Q/n_B = 0.4$ ,  $n_S = 0$

## NEOS-4D

A. Monnai, B. Schenke and C. Shen, Phys. Rev. C **110**, 044905 (2024)



**NEOS-4D**  
No constraints on charge densities

Non-trivial structures of **Q** and **S** originate from deviations from the condition in the nuclei

## Four-dimensional equation of state based on QCD

- Taylor expansion using Lattice results (high  $T$ )

$$\frac{P_{\text{lat}}}{T^4} = \frac{P_0}{T^4} + \sum_{l,m,n} \frac{x_{l,m,n}^{\text{B,Q,S}}}{l! m! n!} \left(\frac{\mu_{\text{B}}}{T}\right)^l \left(\frac{\mu_{\text{Q}}}{T}\right)^m \left(\frac{\mu_{\text{S}}}{T}\right)^n$$

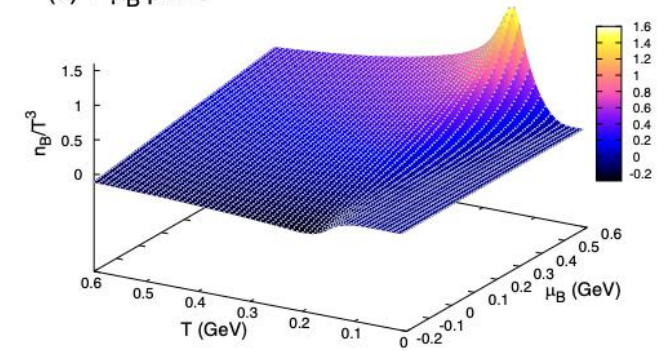
- Hadron gas (low  $T$ )

$$P_{\text{had}} = \pm T \sum_i \int \frac{g_i d^3 p}{(2\pi)^3} \ln[1 \pm e^{-(E_i - \mu_i)/T}]$$

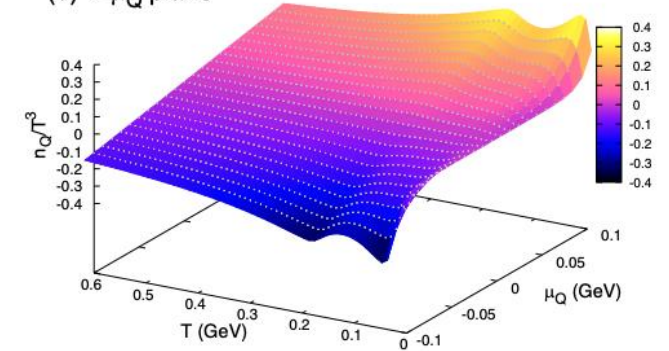
CONNECT

$$\frac{P}{T^4} = \frac{1}{2} \left[ 1 - \tanh \frac{T - T_c}{\Delta T_c} \right] \frac{P_{\text{had}}}{T^4} + \frac{1}{2} \left[ 1 + \tanh \frac{T - T_c}{\Delta T_c} \right] \frac{P_{\text{lat}}}{T^4}$$

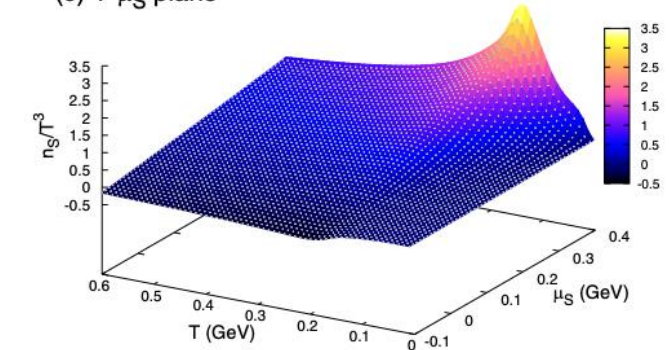
(a)  $T$ - $\mu_{\text{B}}$  plane



(b)  $T$ - $\mu_{\text{Q}}$  plane

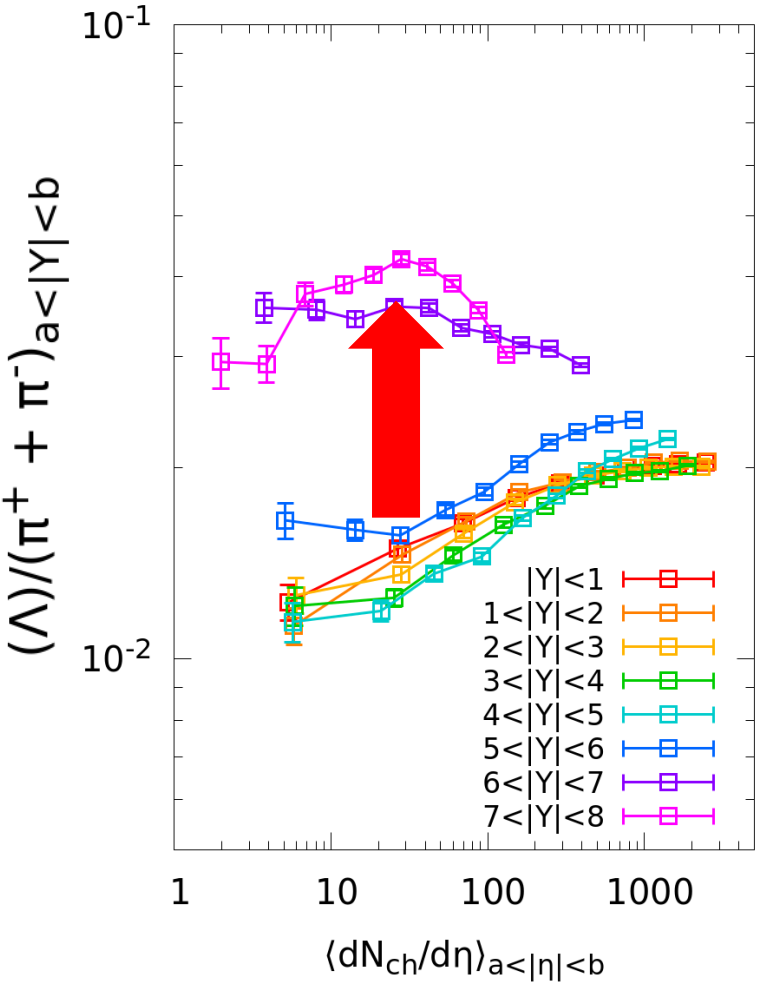


(c)  $T$ - $\mu_{\text{S}}$  plane

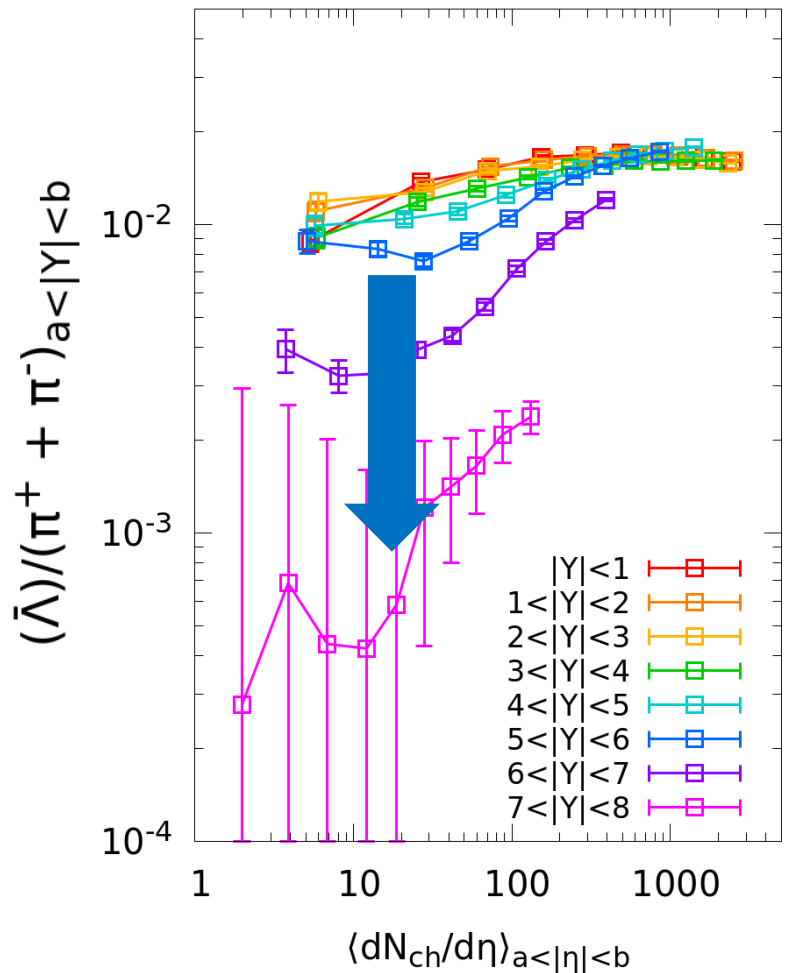


# Rapidity-dependent strange hadron yield ratio

$\Lambda(uds)$



$\bar{\Lambda}(\bar{u}\bar{d}\bar{s})$



- Similar multiplicity scaling behavior around midrapidity
- Rapid change in forward rapidity

**Baryon enhancement**  
and  
**Anti-baryon suppression**  
from the corona

**Different mechanisms of strange hadron production emerge in forward rapidity!**