

Hadron yield ratios in dynamical core-corona initialization from small to large systems

Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)

Y. Kanakubo *et al.*, PTEP 2018 12, 121D01 (2018)

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Introduction

QGP signals in small systems

- Long range correlation
- Flow harmonics
- Strangeness enhancement
-



Which would be
a robust signal?

QGP (T, μ_B)

→ Local thermal & chemical equilibrium

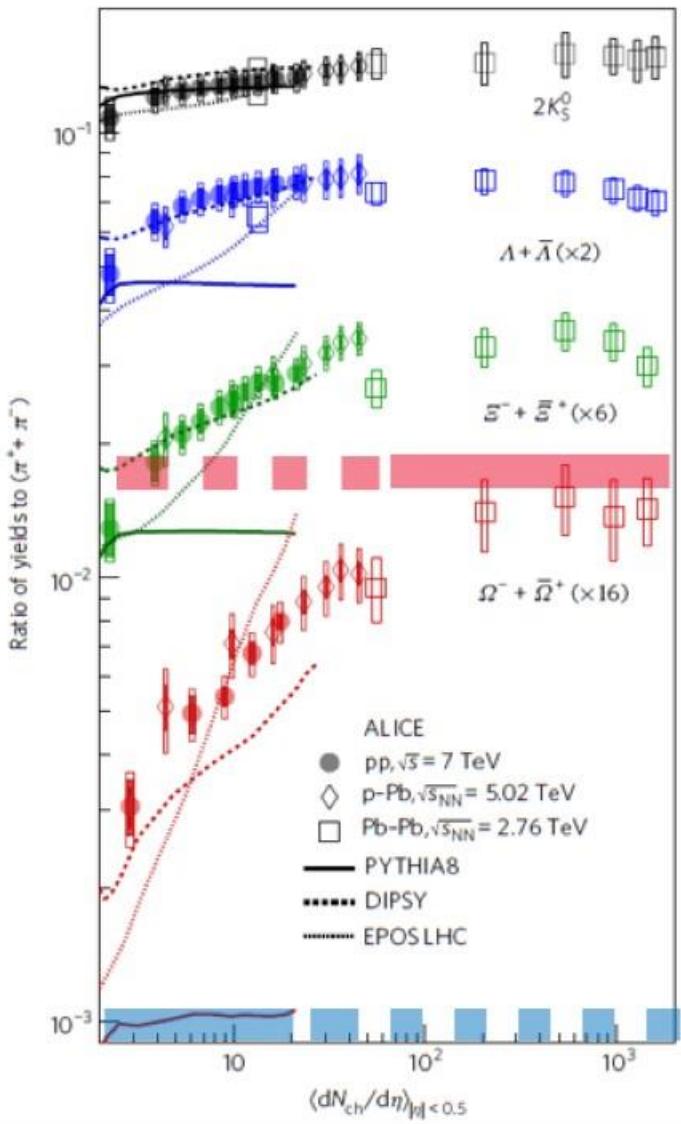
↳ Strangeness enhancement (particle yield ratio)

- Basic bulk observable
- Possible to discuss based on statistical thermodynamics

Not only correlation and flow but also yield ratio

Strangeness enhancement

Nature Phys. 13 535-539 (2017)



Smooth transition of particle yield ratios as a function of multiplicity

Chemical & thermal equilibrium (grand canonical)

$$P_i \sim \frac{1}{\exp\left(\sqrt{m_i^2 + p^2}/T\right)^{\pm 1}}$$

T: temperature

(Conventional) string fragmentation

$$P_i \sim \exp(-\pi m_{\perp,i}^2/\kappa),$$

κ : string tension

Both do not depend on volume (multiplicity)

→ How can we interpret this data?

Dynamical core-corona initialization

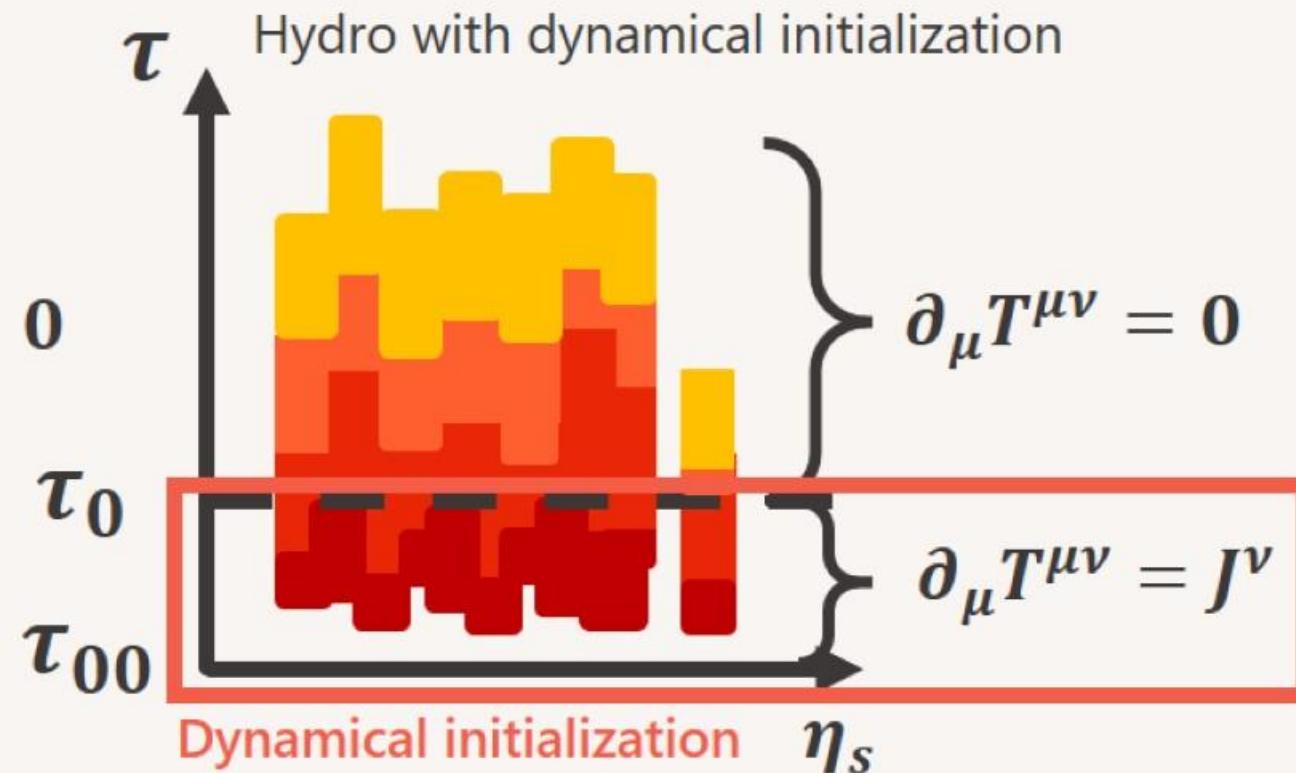
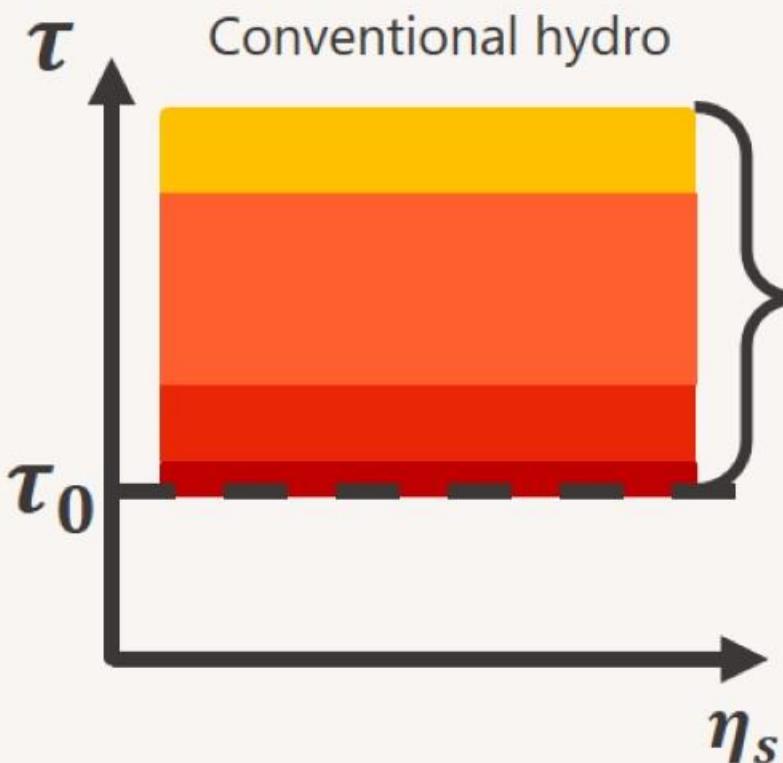


Dynamical Core-Corona Initialization model

Dynamical initialization with $\partial_\mu T^{\mu\nu} = J^\nu$

M. Okai *et al.*, Phys. Rev. C 95, 054914 (2017)

Dynamical initialization: dynamical generation of an initial condition of hydro



→ Put an initial condition at fixed τ_0

→ Generate an initial condition through a source J^μ from τ_{00} to τ_0 .

Source terms

M. Okai *et al.*, Phys. Rev. C 95, 054914 (2017)

Assumption 1. Initial partons are generated just after a collision of nuclei

Assumption 2. Instant thermalization of deposited energy and momentum

Assumption 3. Gaussian profile/straight trajectories for a parton

Continuum eq. for fluid+parton

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



Energy & momentum conservation
of a whole system, fluids +
traversing partons

Hydrodynamic eq. with source term

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

"Source" = "Four-momentum
deposition rate of partons"



$$J^\nu = - \sum_i \frac{dp_i^\nu(t)}{dt} G(\mathbf{x} - \mathbf{x}_i(t))$$

p_i^μ : Four-momentum
of the i^{th} parton
 G : Gaussian function

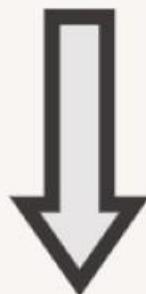
Dynamical core-corona initialization (DCCI)

Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)

Four-momentum deposition rate of a parton

$$\frac{dp_i^\mu(t)}{dt} = -a_0 p_i^\mu(t)$$

in the previous work



+Core-corona
picture

How can we introduce core-corona
picture?

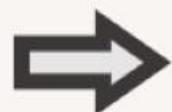
- QGP fluids from high density areas with sufficient scatterings
- Surviving partons from low density areas with no/few scatterings

$$\frac{dp_i^\mu(t)}{dt} = -a_0 \left[\frac{\rho_i(\mathbf{x}_i(t))}{|\mathbf{p}|_i^2(t)} \right] p_i^\mu(t)$$

a_0 : Free parameter

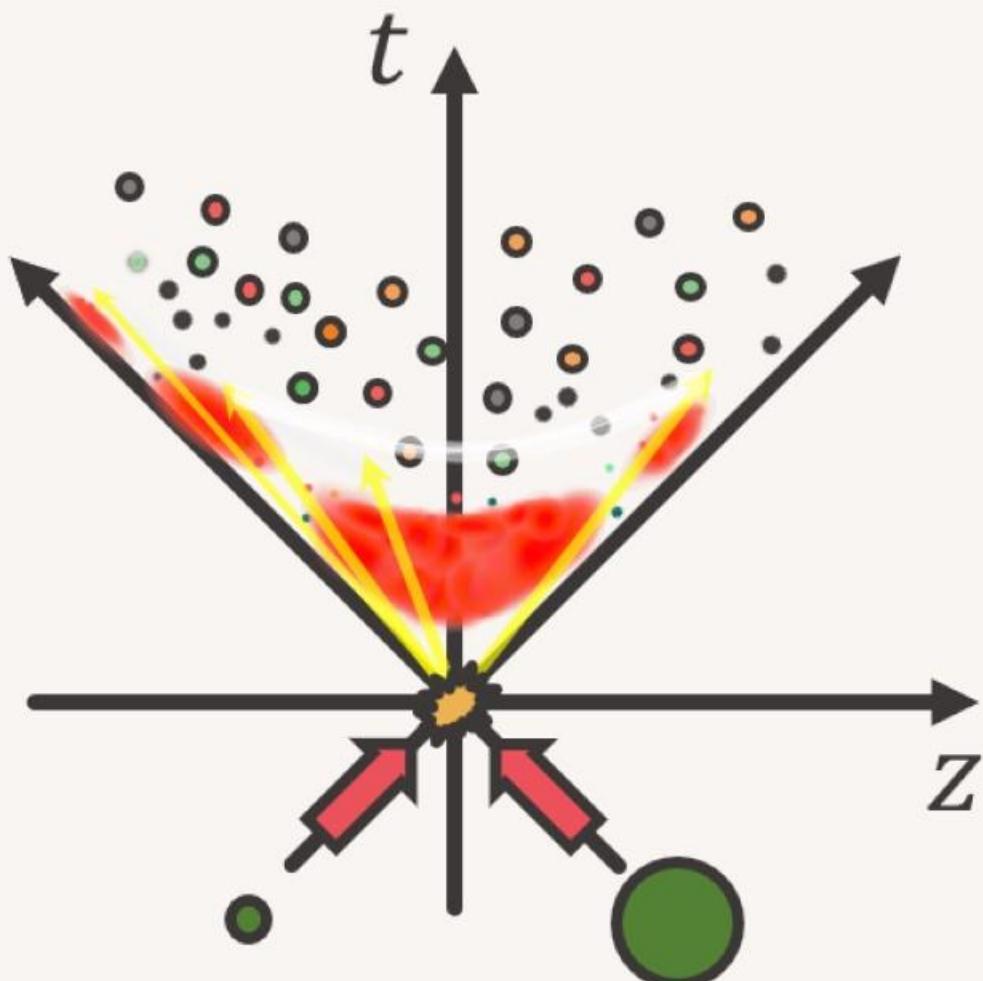
ρ_i : Density of partons

$$\rho_i(\mathbf{x}) = \sum_{j \neq i} G(\mathbf{x} - \mathbf{x}_j(t))$$



Large ρ , small $|\mathbf{p}|$ → QGP fluids
(core)

Small ρ , large $|\mathbf{p}|$ → Surviving partons
(corona)



Hadronization (particlization)

Core → Hadron distribution via

Cooper-Frye formula ($T_{fo} = 160$ MeV)

F. Cooper and G. Frye, Phys. Rev. D10, 186 (1974)

+ Resonance correction

A. Andronic *et al.*, Nature 561 (2018) no.7723, 321-330 (2017)

Corona → String fragmentation (PYTHIA)

Evolution of QGP fluids

Dynamical core-corona initialization

(3+1)-D ideal hydro, Lattice EoS (2+1 flavor)

Y. Tachibana and T. Hirano,
Nucl. Phys. A904-905 (2013)

S. Borsanyi *et al.*,
Phys. Lett. B730, 155 (2014)

Parton generation

PYTHIA ver 8.230 (HadronLevel:all= off)

T. Sjöstrand *et al.*, Comput. Phys. Commun. 191, 159 (2015)

C. Bierlich *et al.*, JHEP 1610 139 (2016)



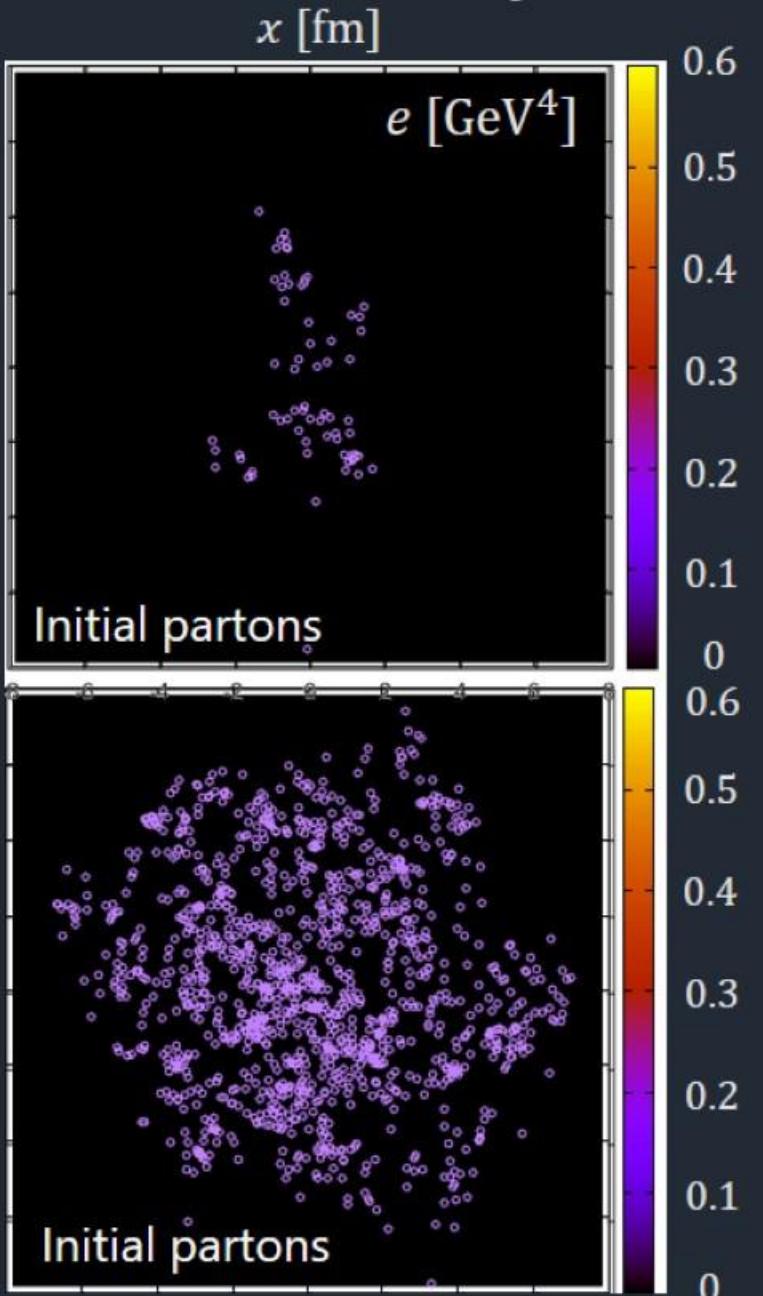
Results from DCCI

Result: Time evolution of dynamical core-corona initialization

$\tau = 0.10$ fm

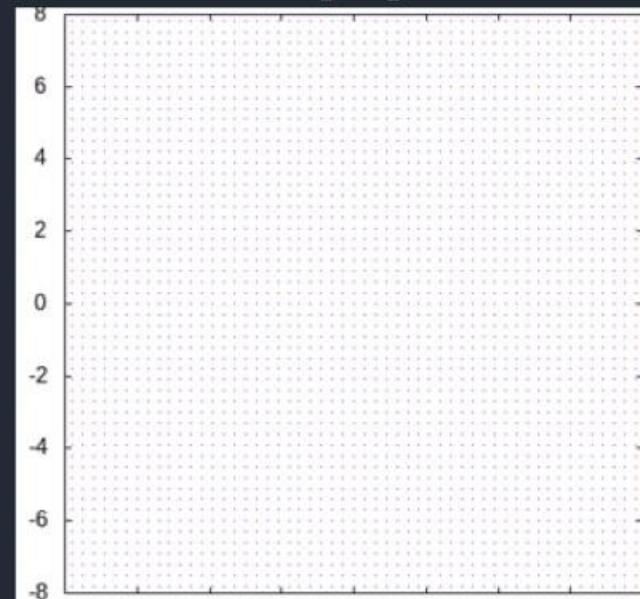
Pb+Pb
(2.76 TeV)
peripheral

y [fm]

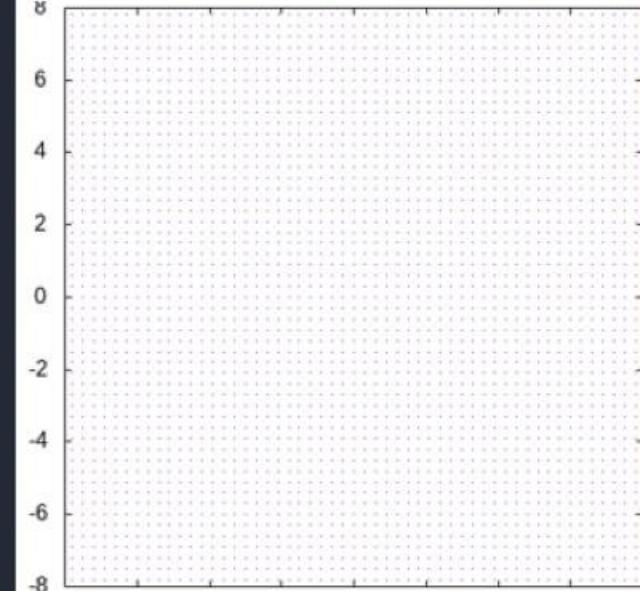


x [fm]

y [fm]



v_\perp

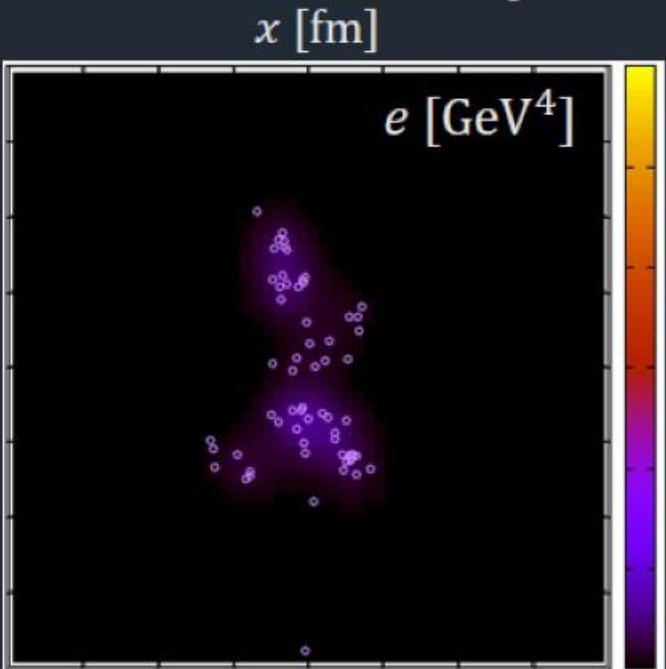


Result: Time evolution of dynamical core-corona initialization

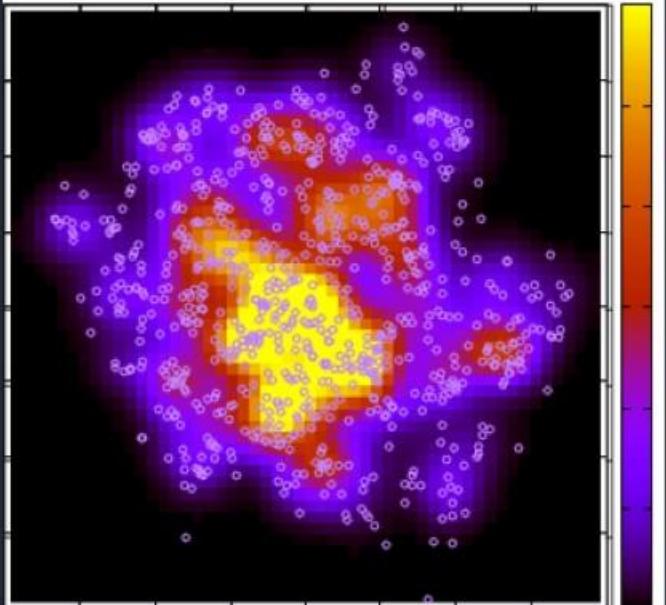
$\tau = 0.11 \text{ fm}$

Pb+Pb
(2.76 TeV)
peripheral

y [fm]



Pb+Pb
(2.76 TeV)
central

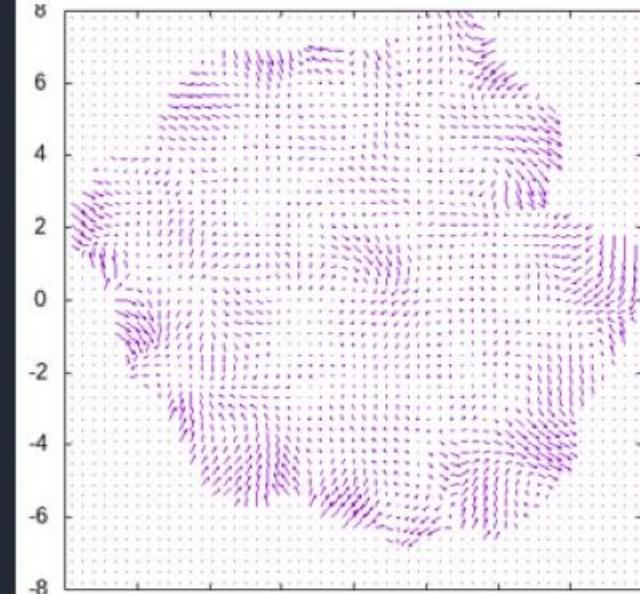
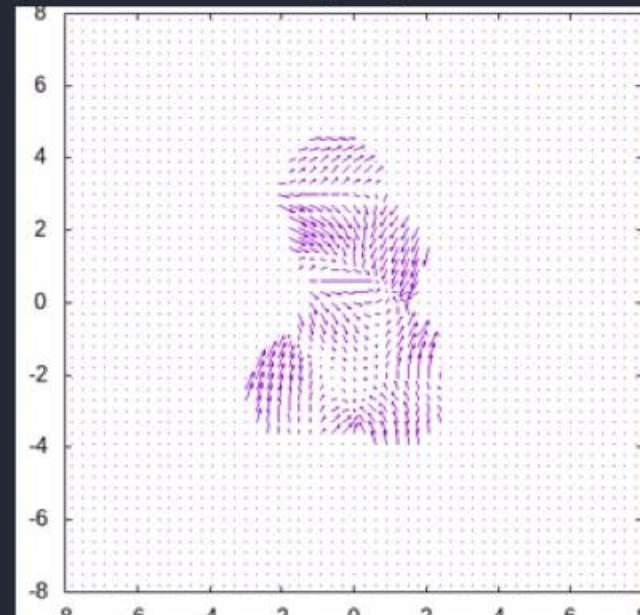


x [fm]

y [fm]

x [fm]

v_\perp

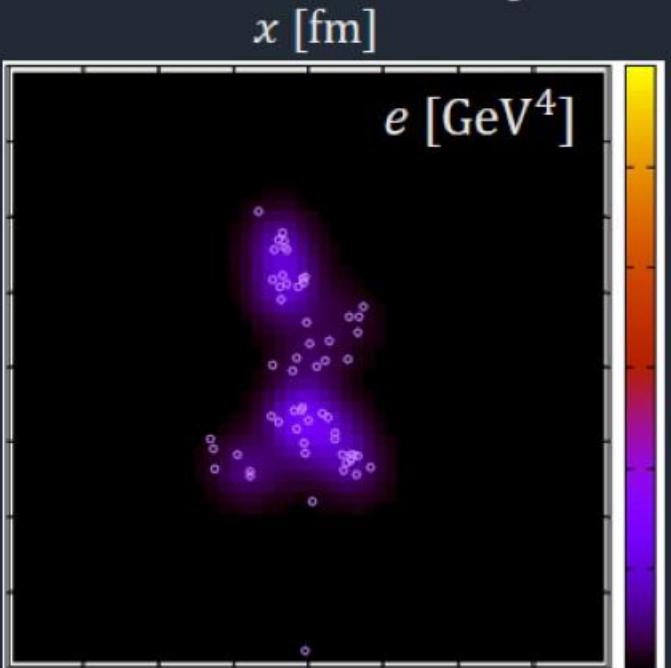


Result: Time evolution of dynamical core-corona initialization

$\tau = 0.12 \text{ fm}$

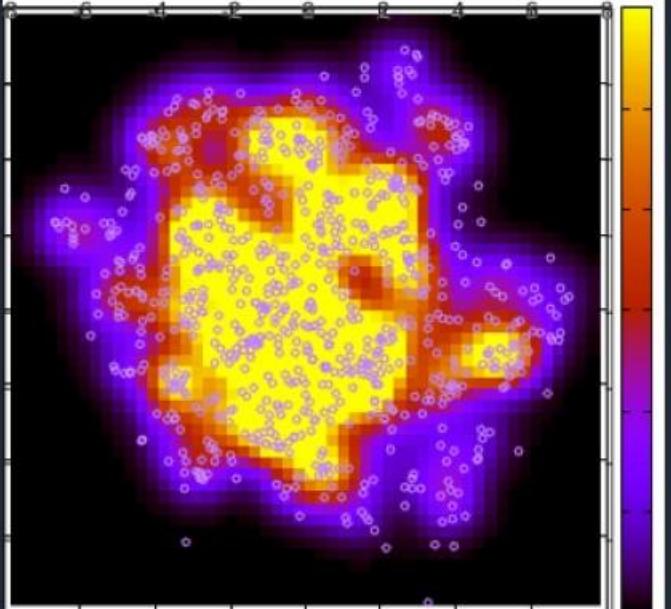
Pb+Pb
(2.76 TeV)
peripheral

$y \text{ [fm]}$



$e \text{ [GeV}^4]$

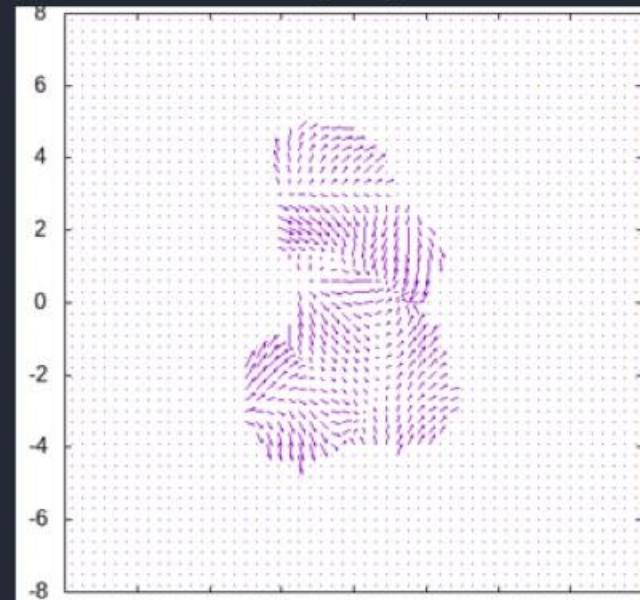
Pb+Pb
(2.76 TeV)
central



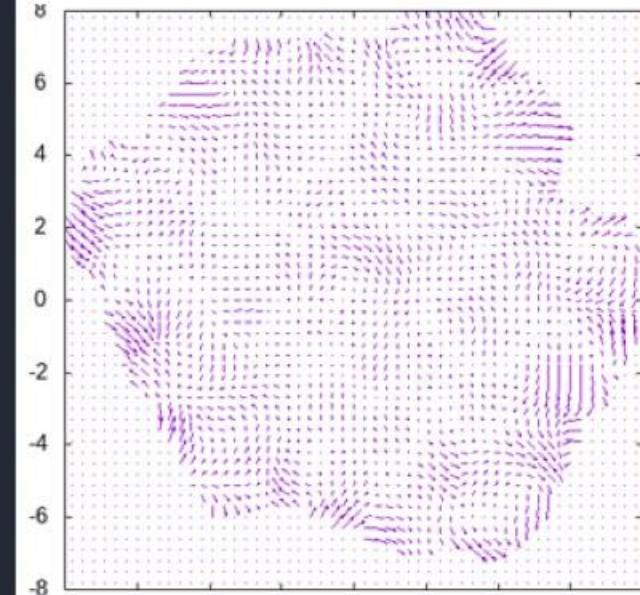
$x \text{ [fm]}$

$x \text{ [fm]}$

$y \text{ [fm]}$



v_\perp

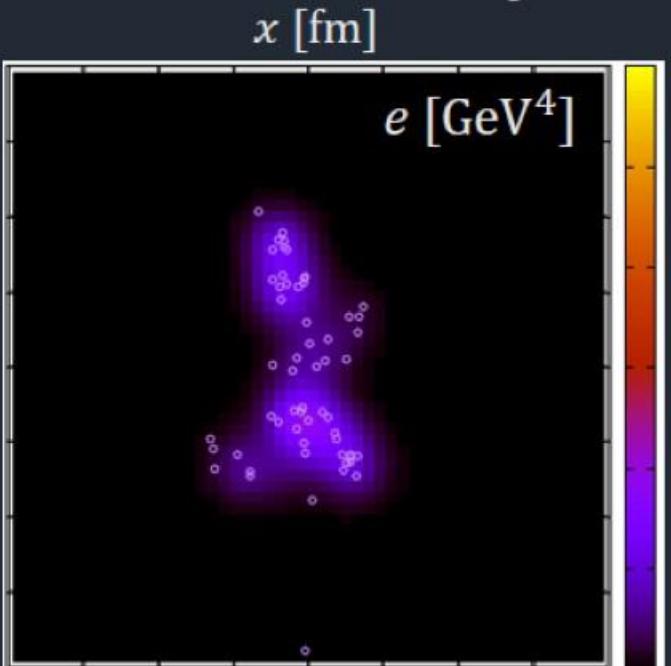


Result: Time evolution of dynamical core-corona initialization

$\tau = 0.13 \text{ fm}$

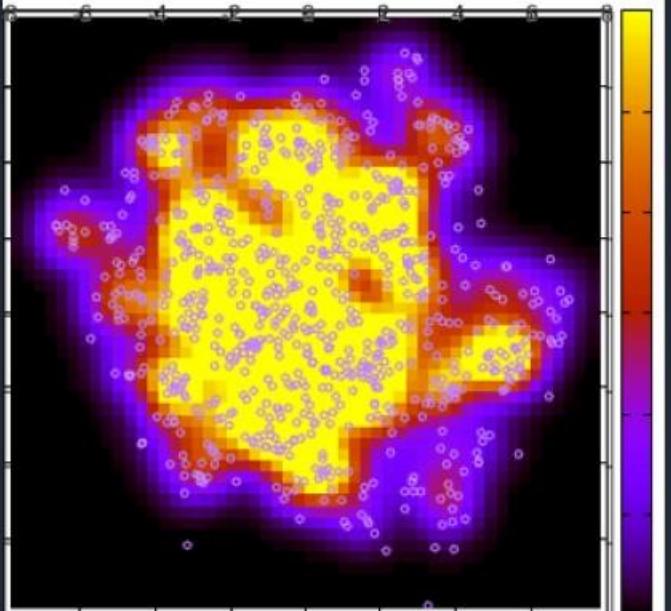
Pb+Pb
(2.76 TeV)
peripheral

$y \text{ [fm]}$

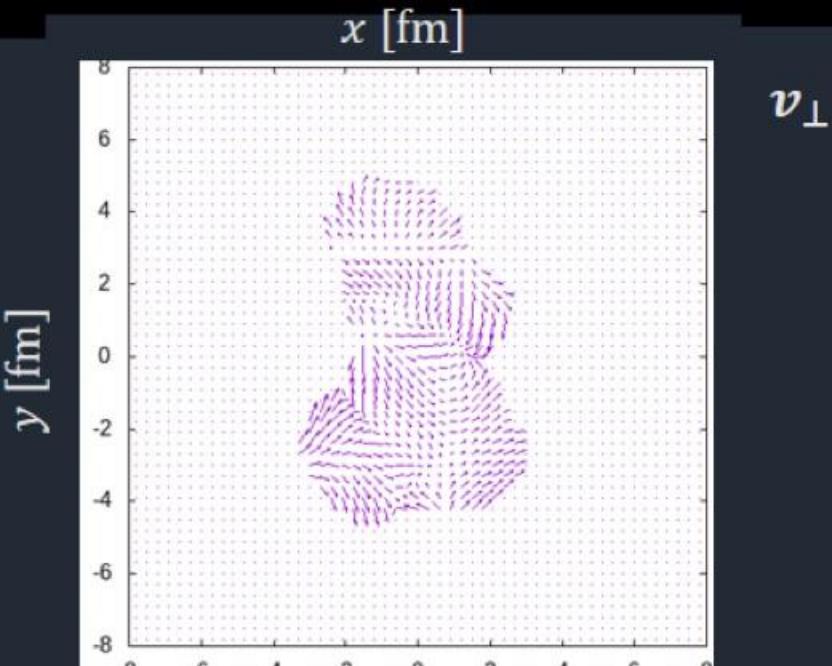


$e \text{ [GeV}^4]$

Pb+Pb
(2.76 TeV)
central

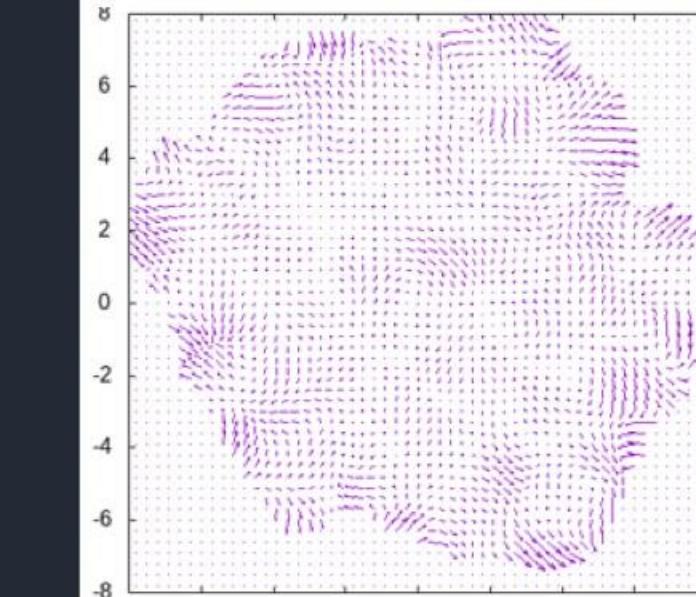


$e \text{ [GeV}^4]$



$x \text{ [fm]}$

v_\perp

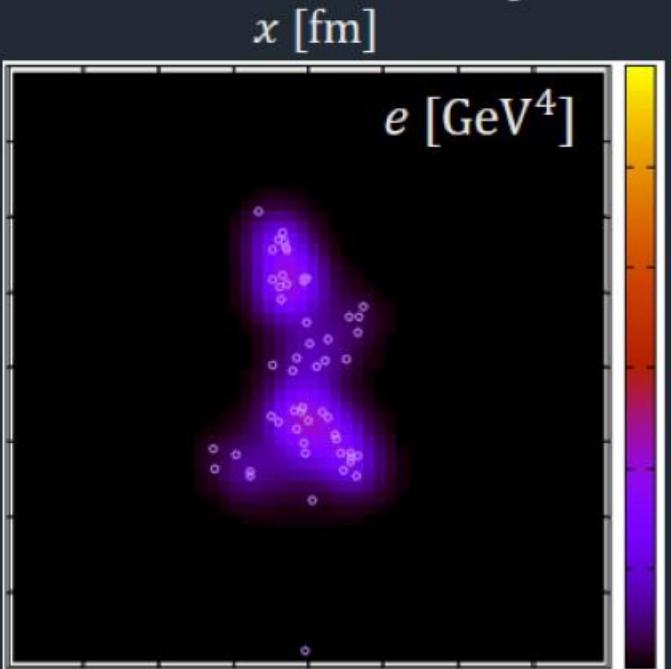


Result: Time evolution of dynamical core-corona initialization

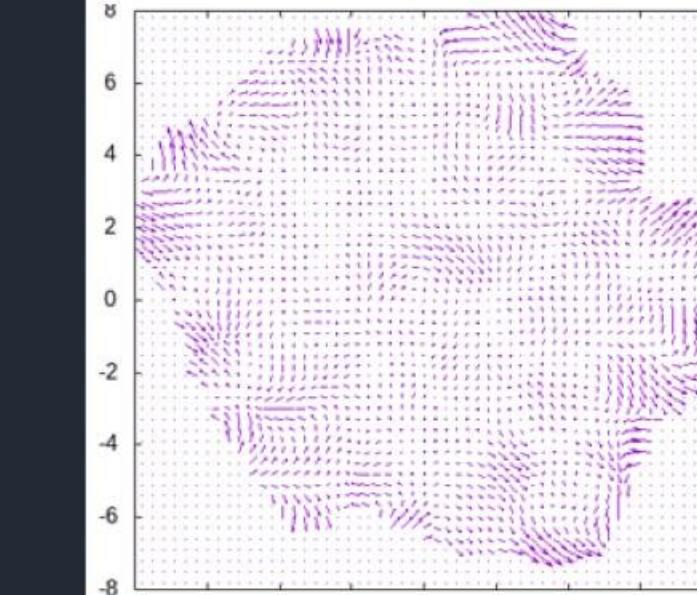
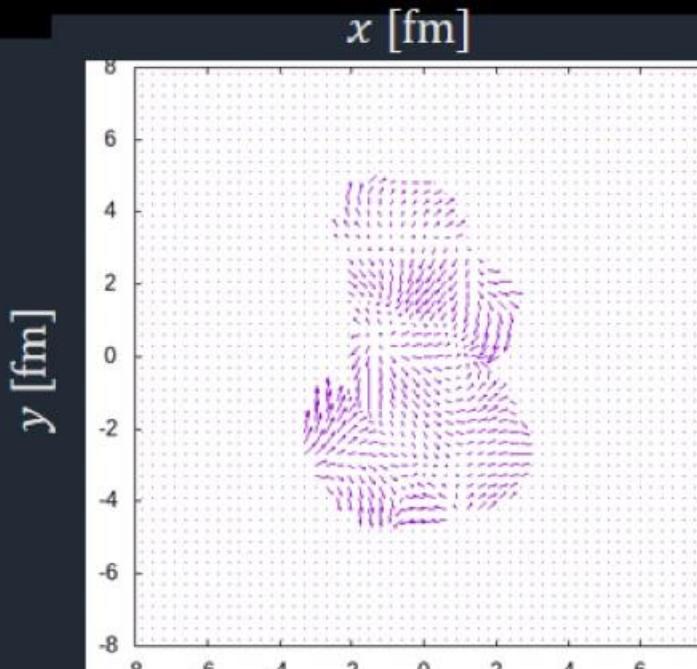
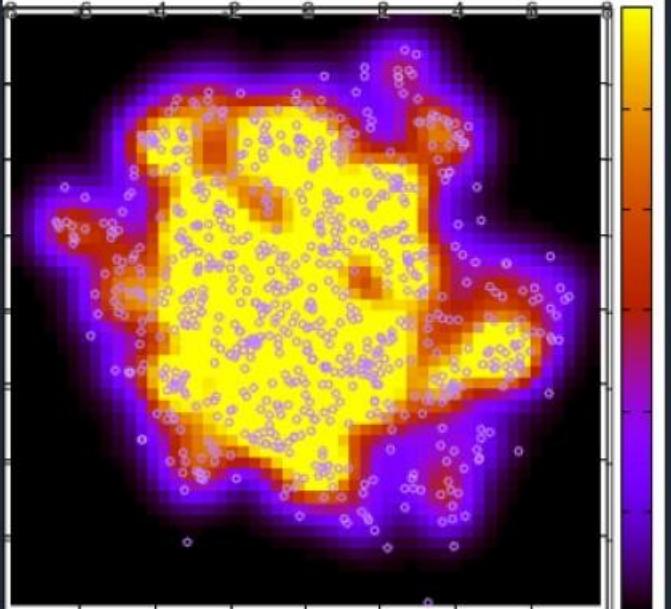
$\tau = 0.14 \text{ fm}$

Pb+Pb
(2.76 TeV)
peripheral

y [fm]



Pb+Pb
(2.76 TeV)
central

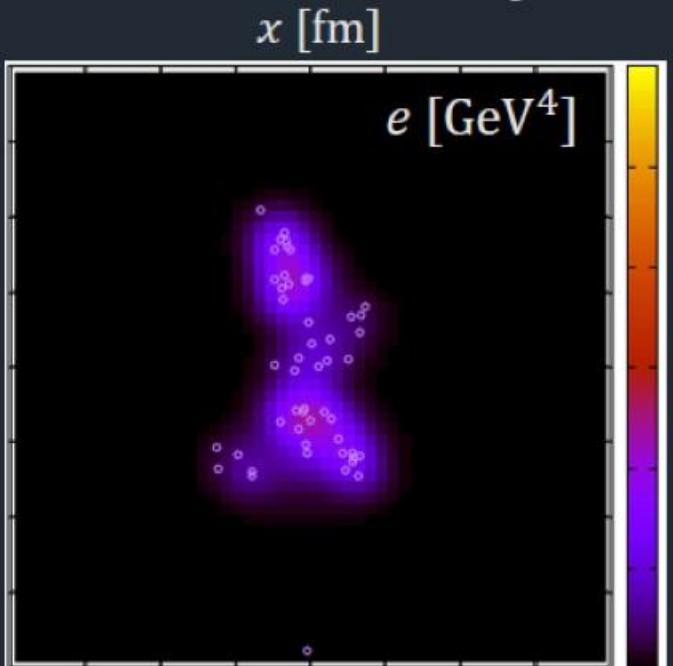


Result: Time evolution of dynamical core-corona initialization

$\tau = 0.15 \text{ fm}$

Pb+Pb
(2.76 TeV)
peripheral

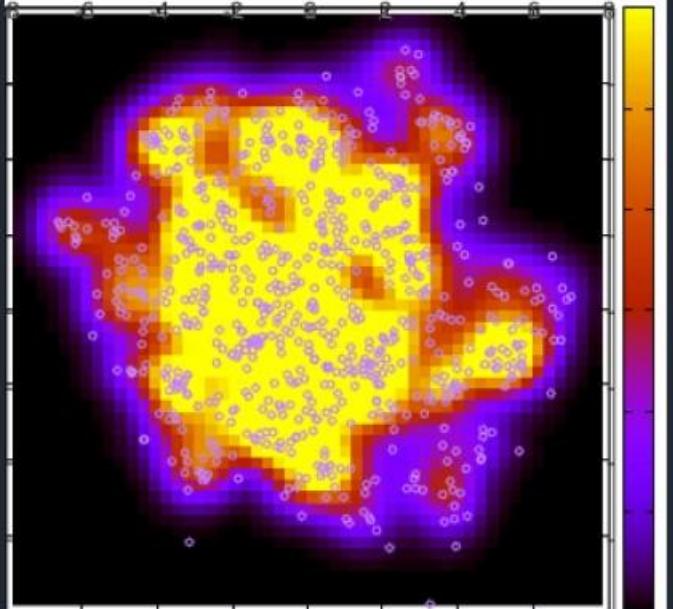
y [fm]



x [fm]

e [GeV⁴]

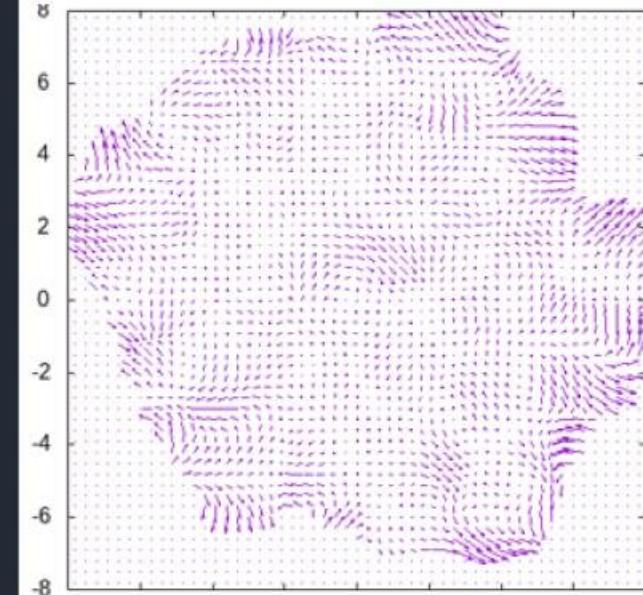
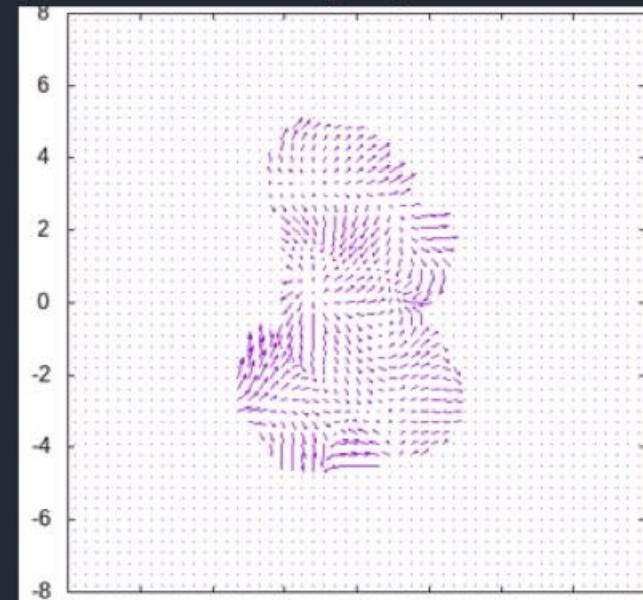
y [fm]



x [fm]

x [fm]

v_{\perp}

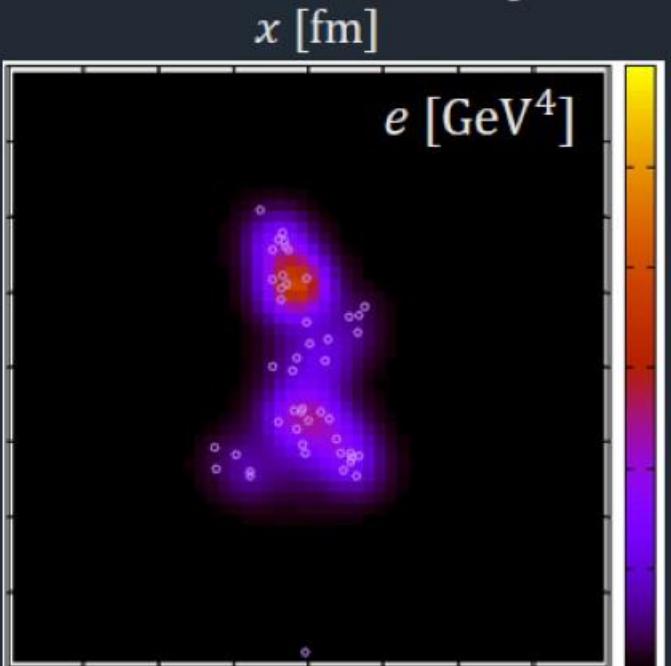


Result: Time evolution of dynamical core-corona initialization

$\tau = 0.16 \text{ fm}$

Pb+Pb
(2.76 TeV)
peripheral

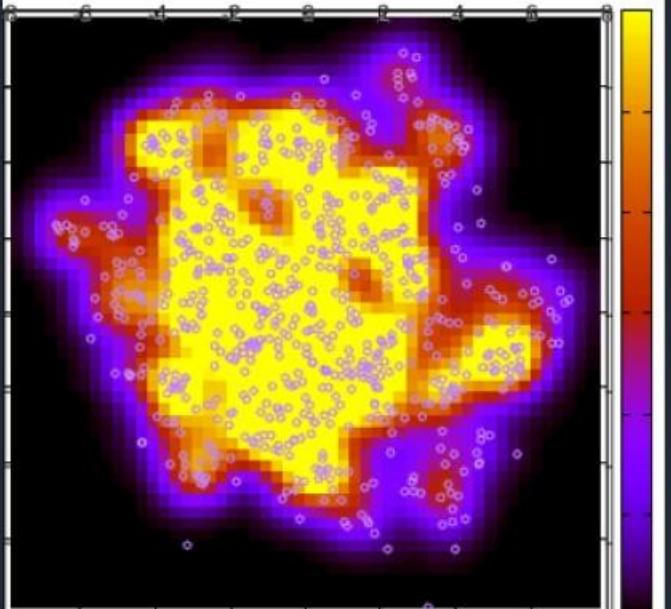
y [fm]



x [fm]

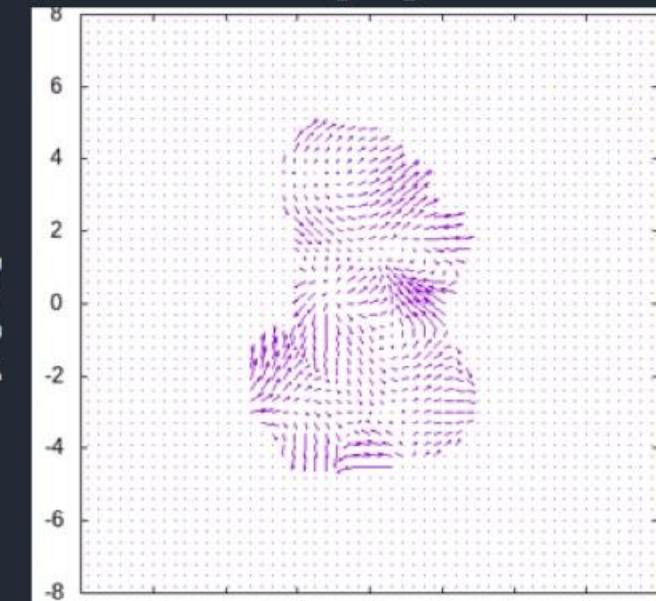
e [GeV^4]

Pb+Pb
(2.76 TeV)
central

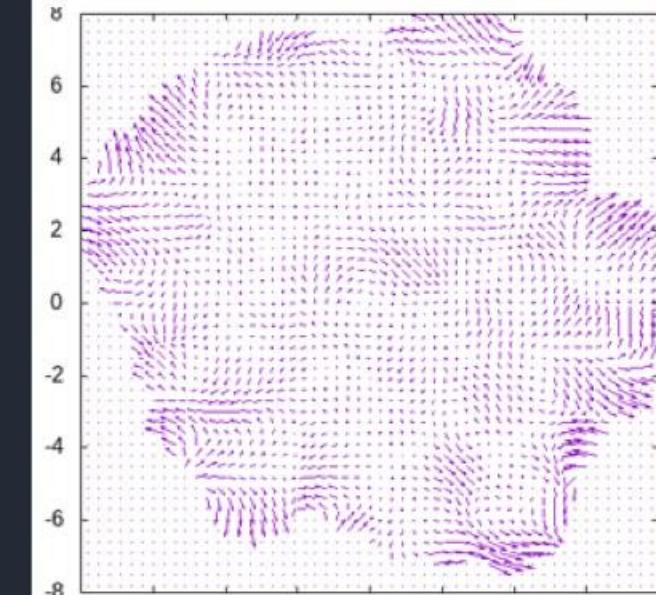


y [fm]

x [fm]



v_\perp

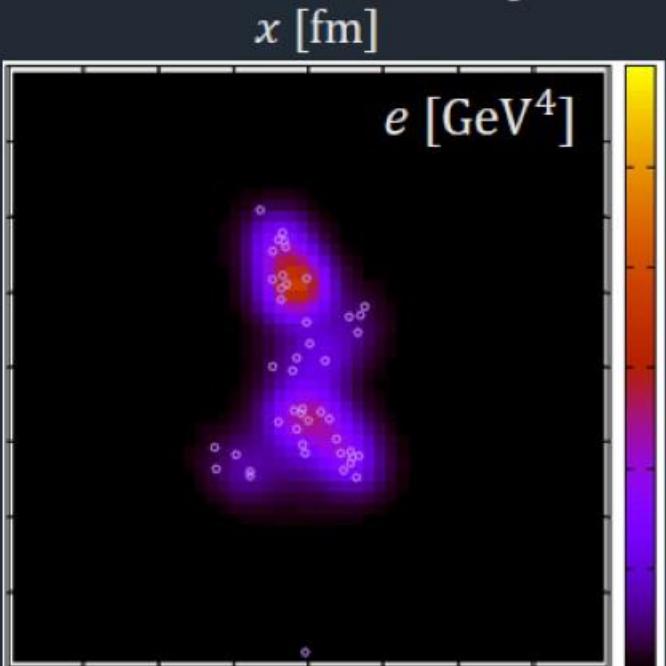


Result: Time evolution of dynamical core-corona initialization

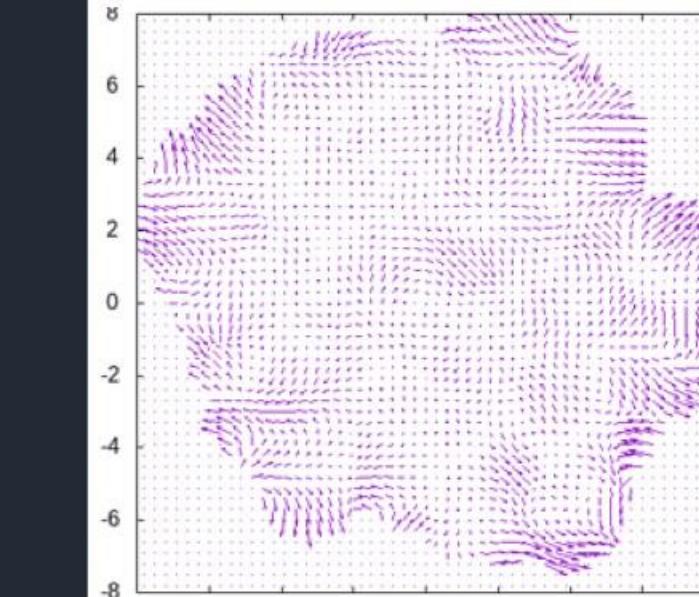
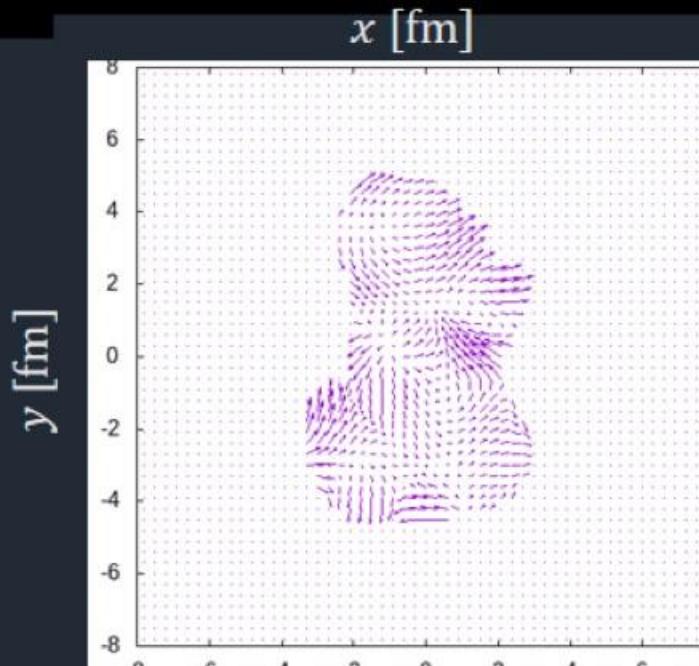
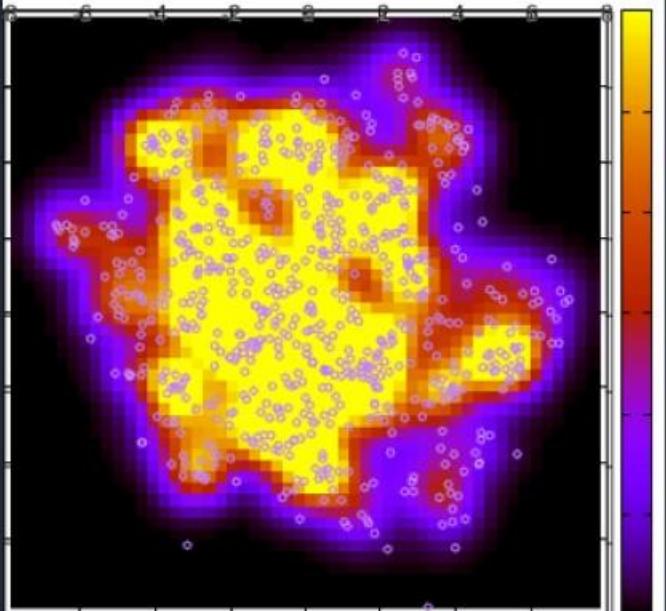
$\tau = 0.17 \text{ fm}$

Pb+Pb
(2.76 TeV)
peripheral

y [fm]



Pb+Pb
(2.76 TeV)
central

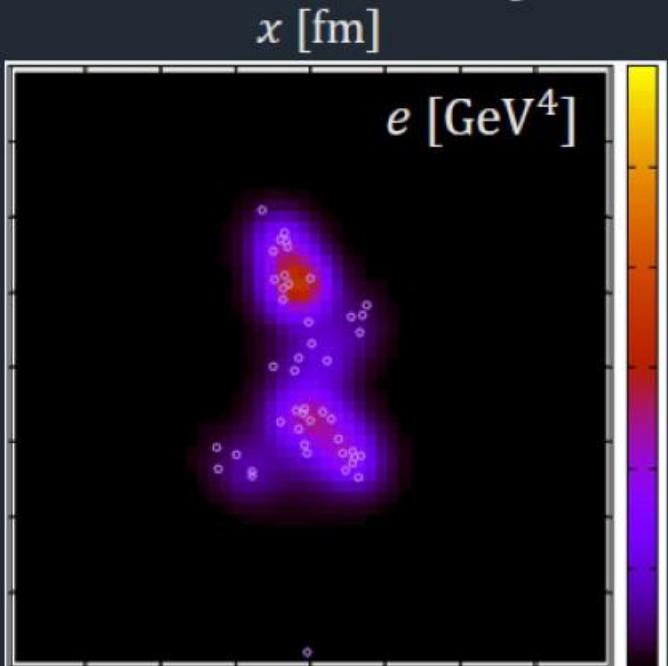


Result: Time evolution of dynamical core-corona initialization

$\tau = 0.18 \text{ fm}$

Pb+Pb
(2.76 TeV)
peripheral

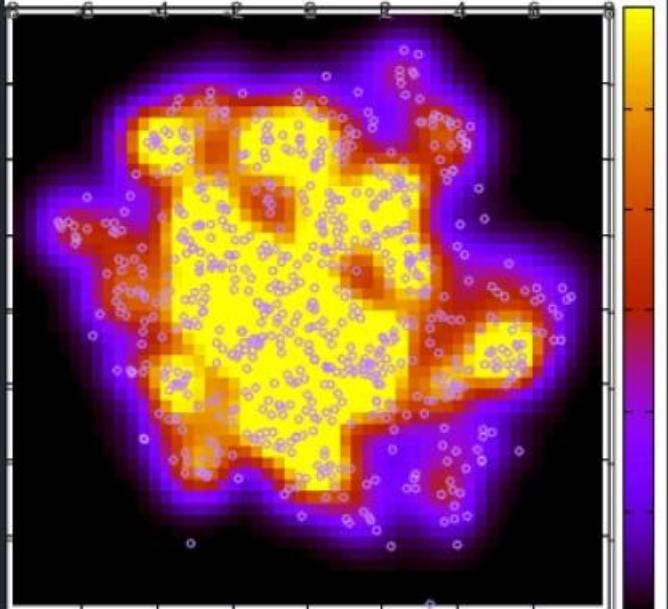
y [fm]



x [fm]

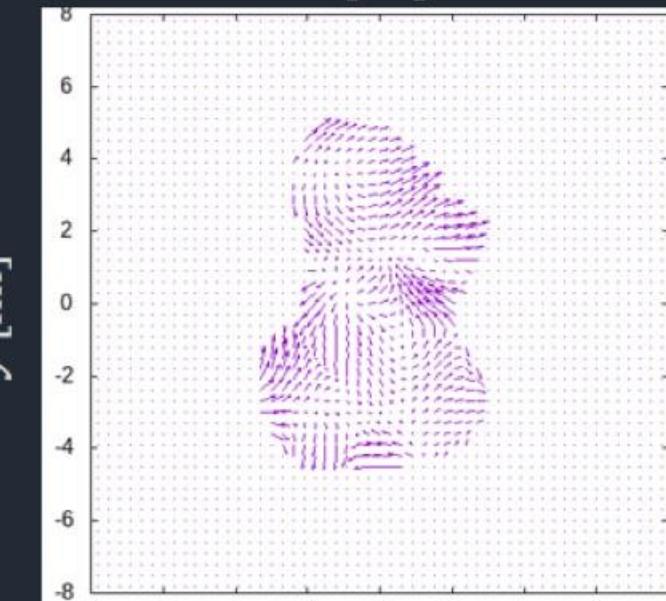
e [GeV^4]

Pb+Pb
(2.76 TeV)
central

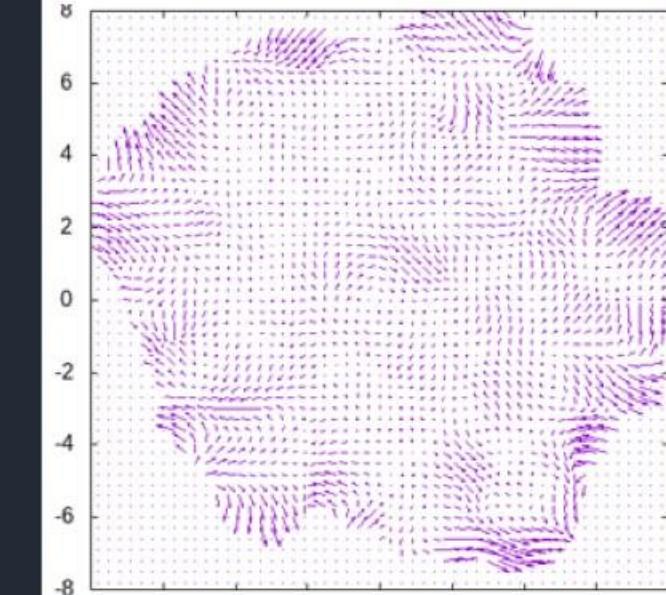


y [fm]

x [fm]

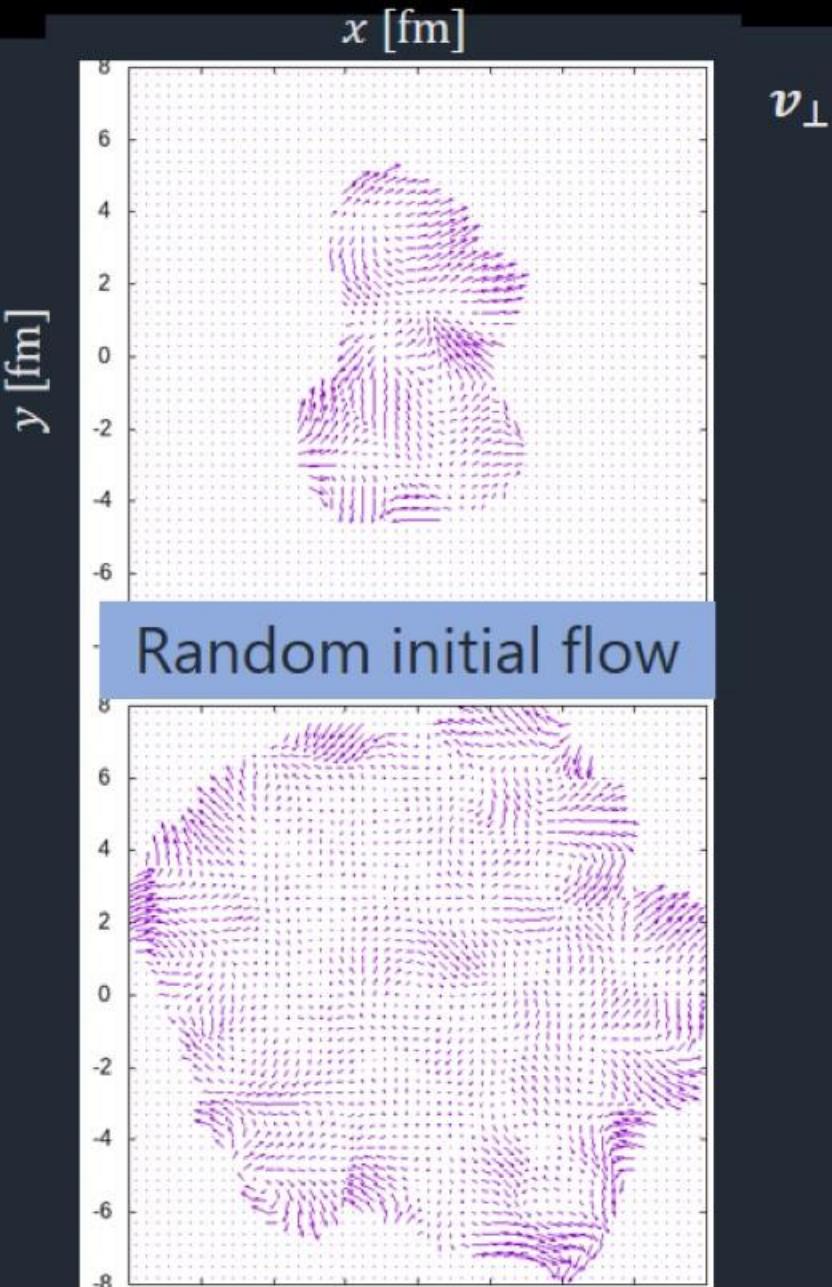
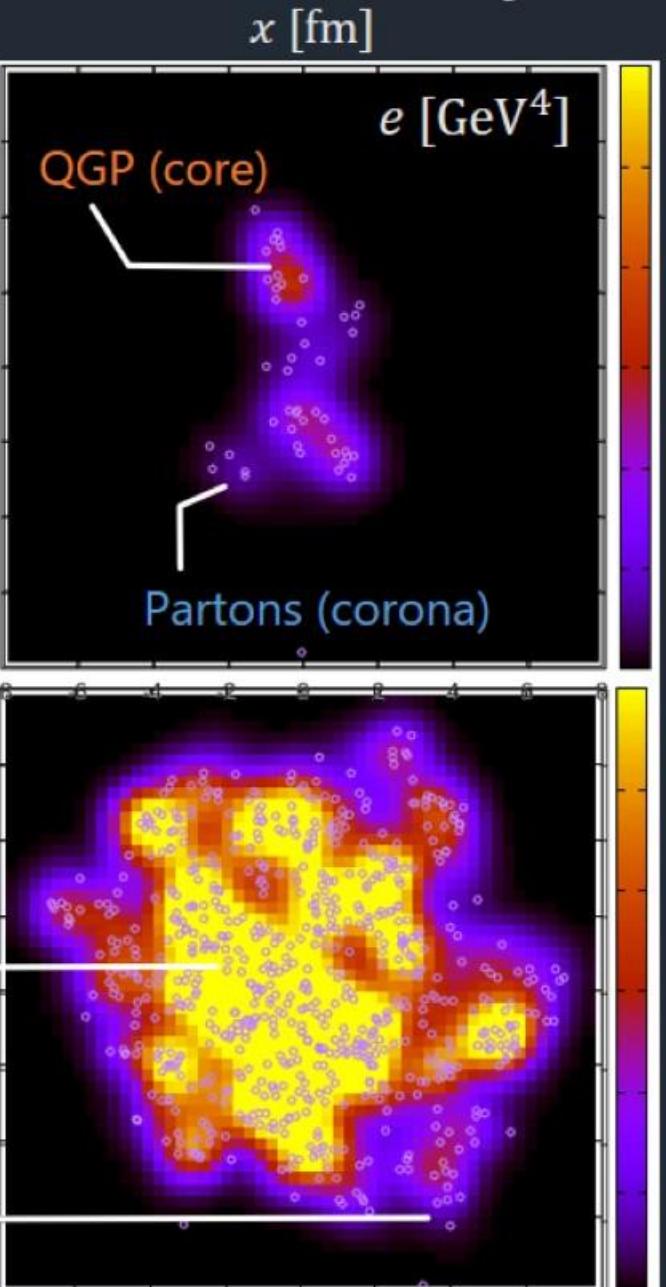


v_\perp



Result: Time evolution of dynamical core-corona initialization

$\tau = 0.19 \text{ fm}$

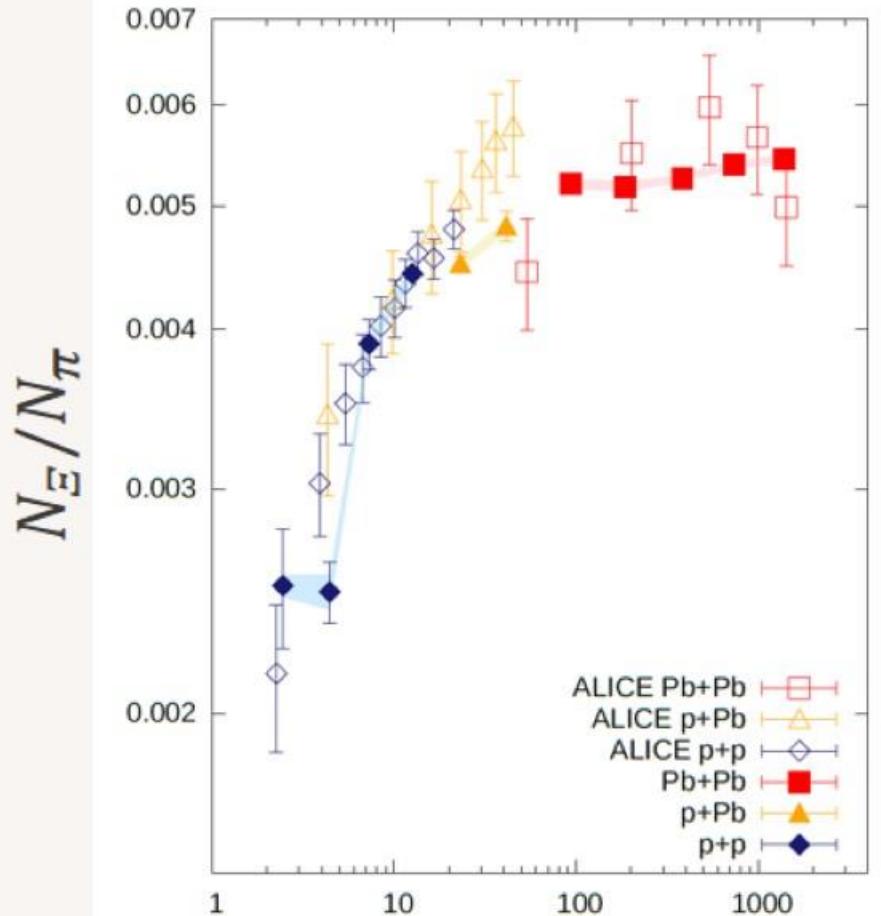


Particle ratios

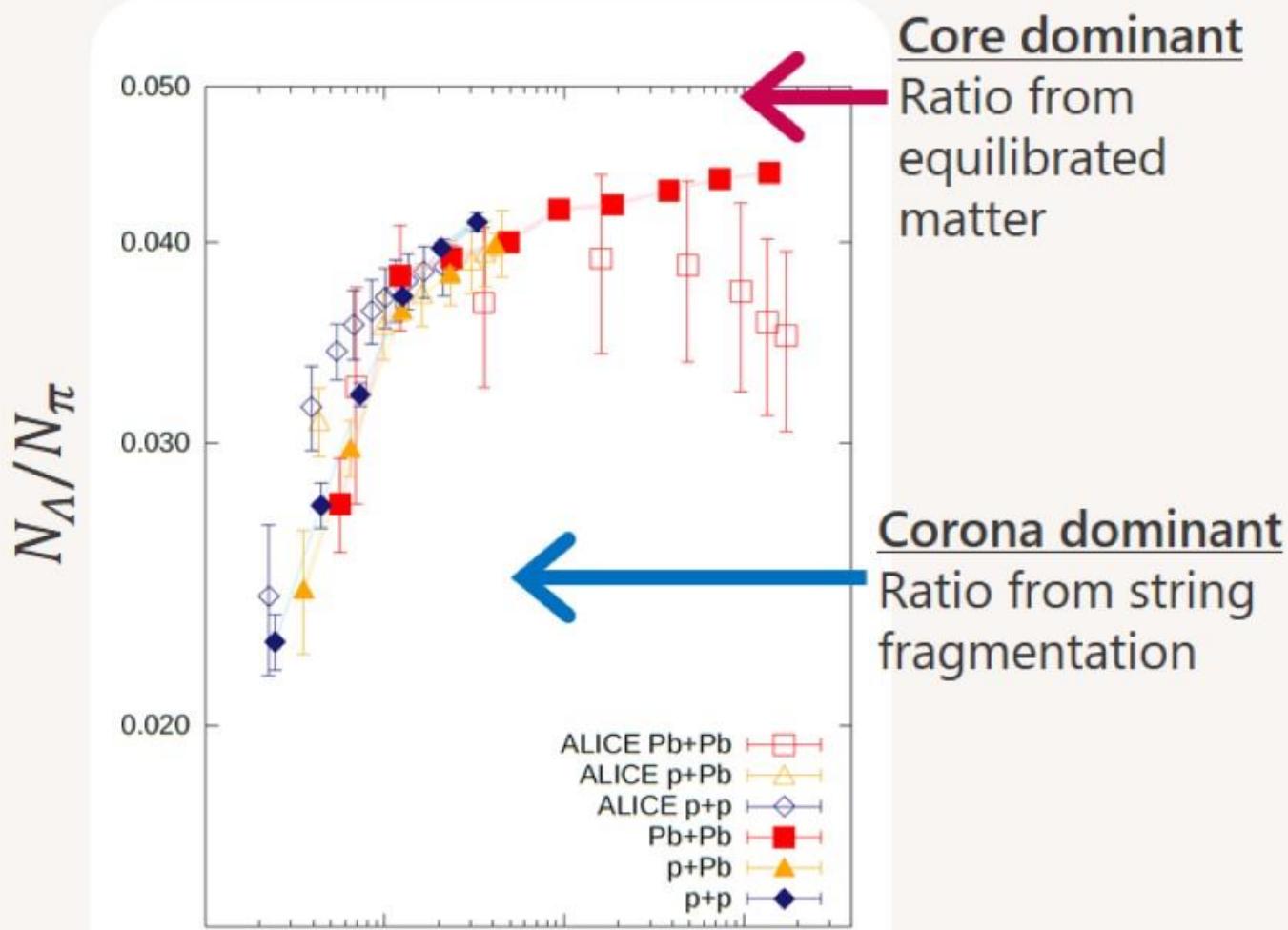
Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)

J. Adam *et al.*, Nature Phys. 13, 535 (2017), J. Adam *et al.*, Phys. Lett. B758, 389 (2016)

B. B. Abelev *et al.*, Phys. Lett. B728, 25 (2014)



$$\langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5}$$



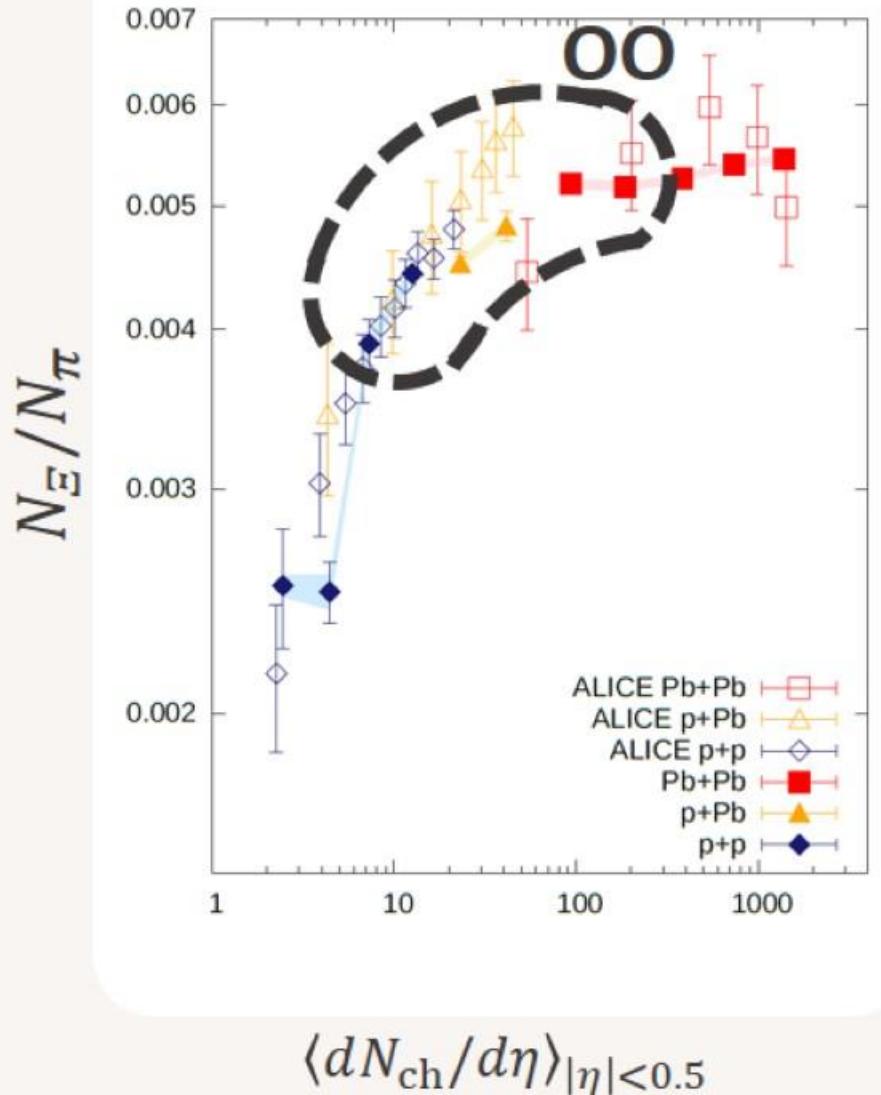
$$\langle dN_{\text{ch}}/d\eta \rangle_{|\eta|<0.5}$$

Particle ratios

Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)

J. Adam *et al.*, Nature Phys. 13, 535 (2017) J. Adam *et al.*, Phys. Lett. B758, 389 (2016)

B. B. Abelev *et al.*, Phys. Lett. B728, 25 (2014)



pp

OO: expected to cover the **sweet** multiplicity region
in particle yield ratios
→ Fully thermalized matter
at mid-rapidity above
 $\langle dN_{ch}/d\eta \rangle \sim 50 - 100$
→ Pin down the onset?

0-0.95% multiplicity class
from Angantyr Pythia

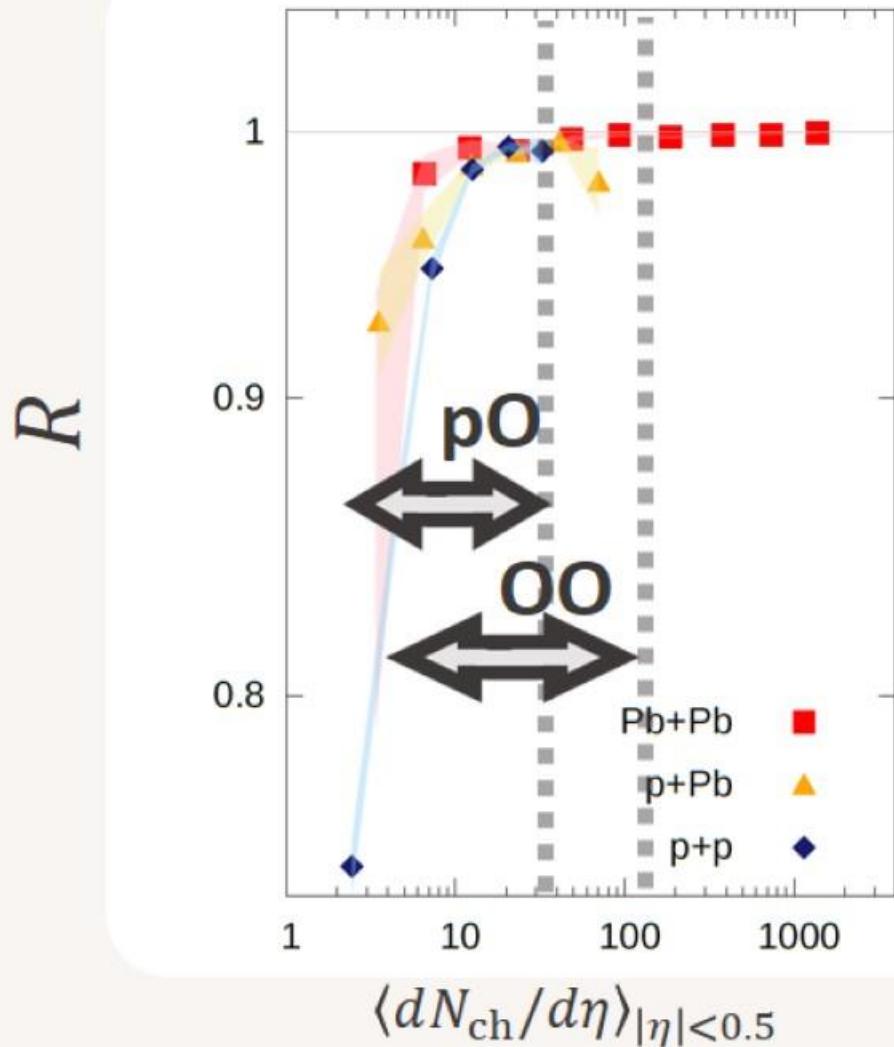
OO: $\sqrt{s_{NN}} = 7 \text{ TeV}$

pO: $\sqrt{s_{NN}} = 9.9 \text{ TeV}$

→ $\langle dN_{ch}/d\eta \rangle \sim 138$
 $\langle dN_{ch}/d\eta \rangle \sim 35$

Fraction of fluids

Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)



*J. Adam *et al.*, Eur. Phys. J. C77, 33 (2017)

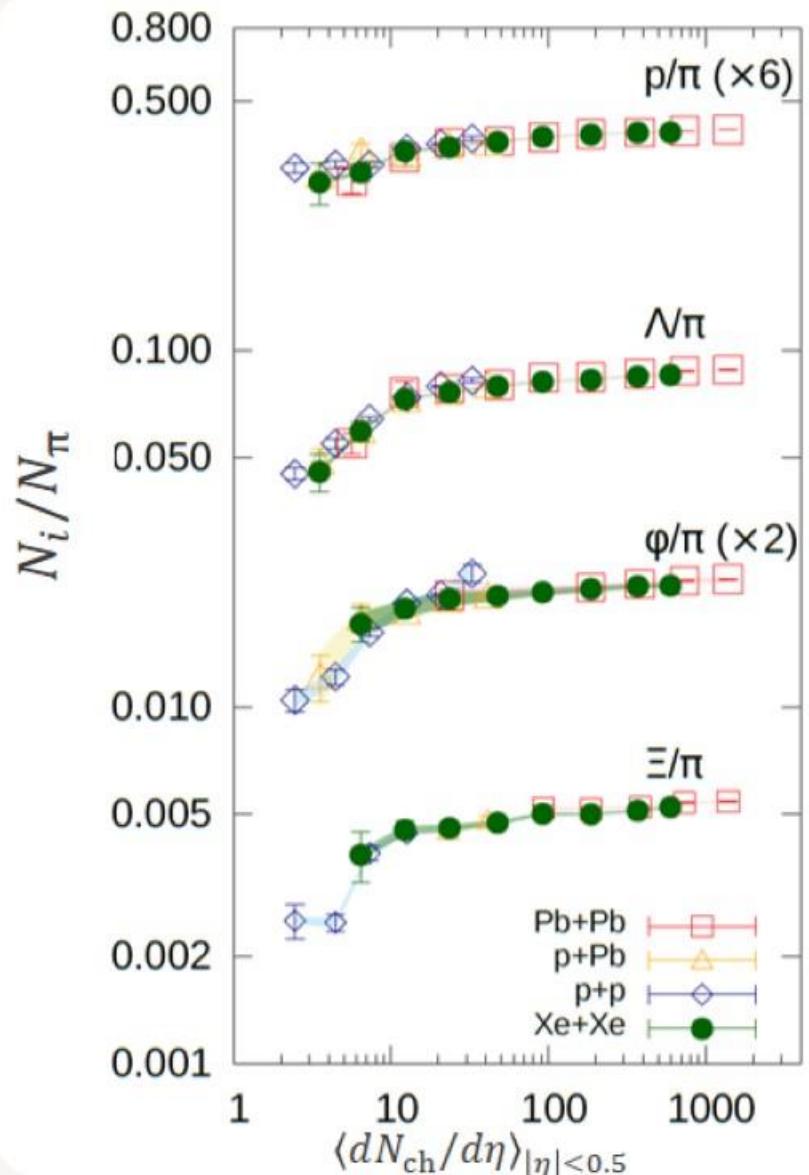
$$R = \frac{\int_{\tau_{00}}^{\tau_0} d\tau \int dx_{\perp} \tau J^{\tau}(\tau, x_{\perp}, \eta_s = 0)}{\int_{\tau_{00}}^{\tau_0} d\tau \int dx_{\perp} \tau J_{\text{tot}}^{\tau}(\tau, x_{\perp}, \eta_s = 0)}$$
$$= \frac{(\text{Core energy at midrapidity})}{(\text{Total energy at midrapidity})}$$



Partial QGP formation is expected in pO and OO
→ Need non-thermalized components

Collision size independence

Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)



Particle yield ratios
→ almost scaled with multiplicity
among various collision systems (XeXe)
→ Multiplicity plays an important role
for thermalization of partons



Multiplicity scaling
“hypothesis” in pO and OO?



Summary

Summary

Dynamical core-corona initialization model (DCCI)

dynamical initialization

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

& core-corona picture

$$\Delta E_i \propto -\rho_i E_i / |\mathbf{p}|_i^2$$

- Dynamical core-corona separation
- Phenomenological description of thermalization of initial partons

According to the results of particle ratios & fraction of fluids

- Experimental data of Ξ/π and Λ/π are reasonably described by DCCI
- QGP is partially formed even at MB multiplicity in pp collisions



Particle ratios: a powerful signal to discuss QGP formation
(equilibrated matter) in small colliding systems!

Need non-thermalized components in flow analysis in pO and OO

New version of DCCI

able to access...

Particle ratios in forward & backward rapidity

Particle ratios in p_T direction

Flow coefficients in small systems (*ideal hydro)

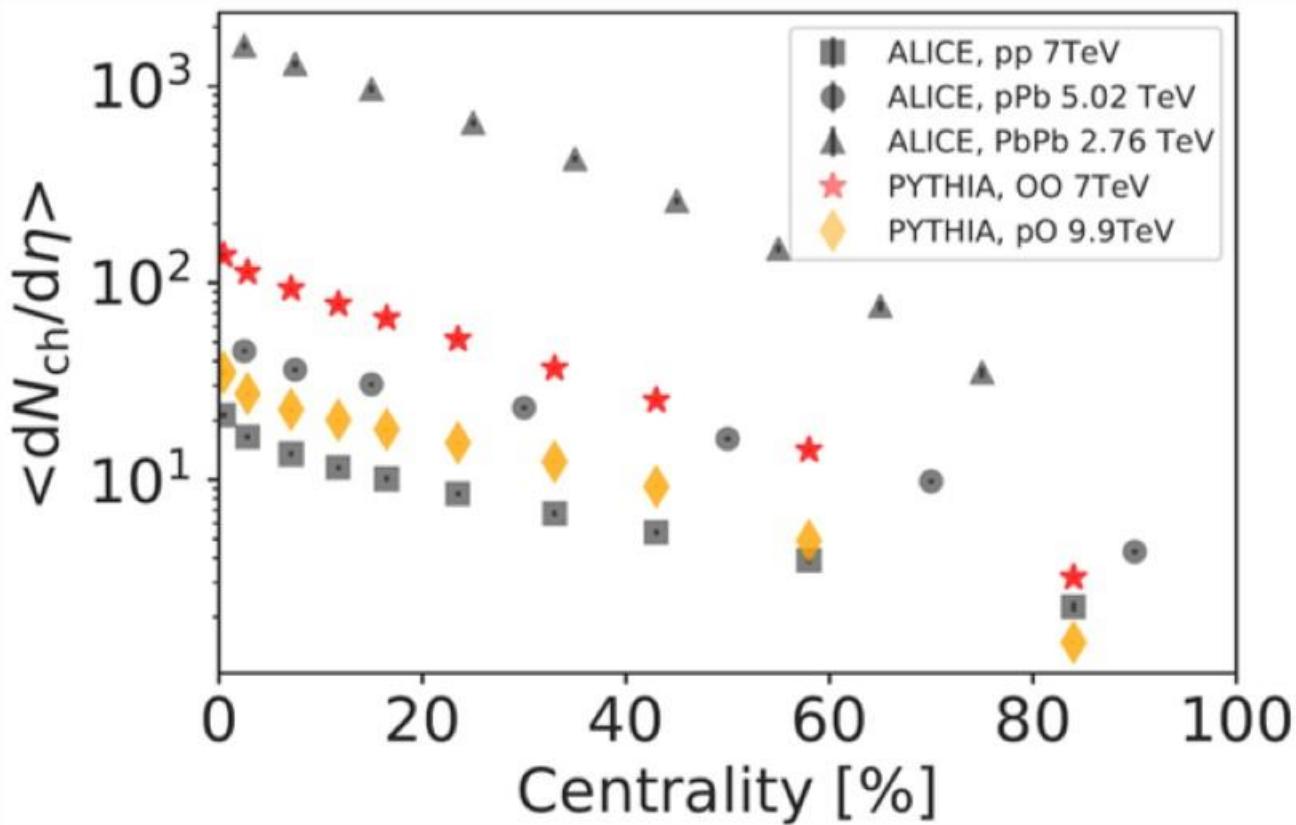
PID observables associated with hard components
etc.

Coming soon:)



Back up

Multiplicity in pO and OO collisions at LHC



pO: $\sqrt{s_{NN}} = 9.9$ TeV

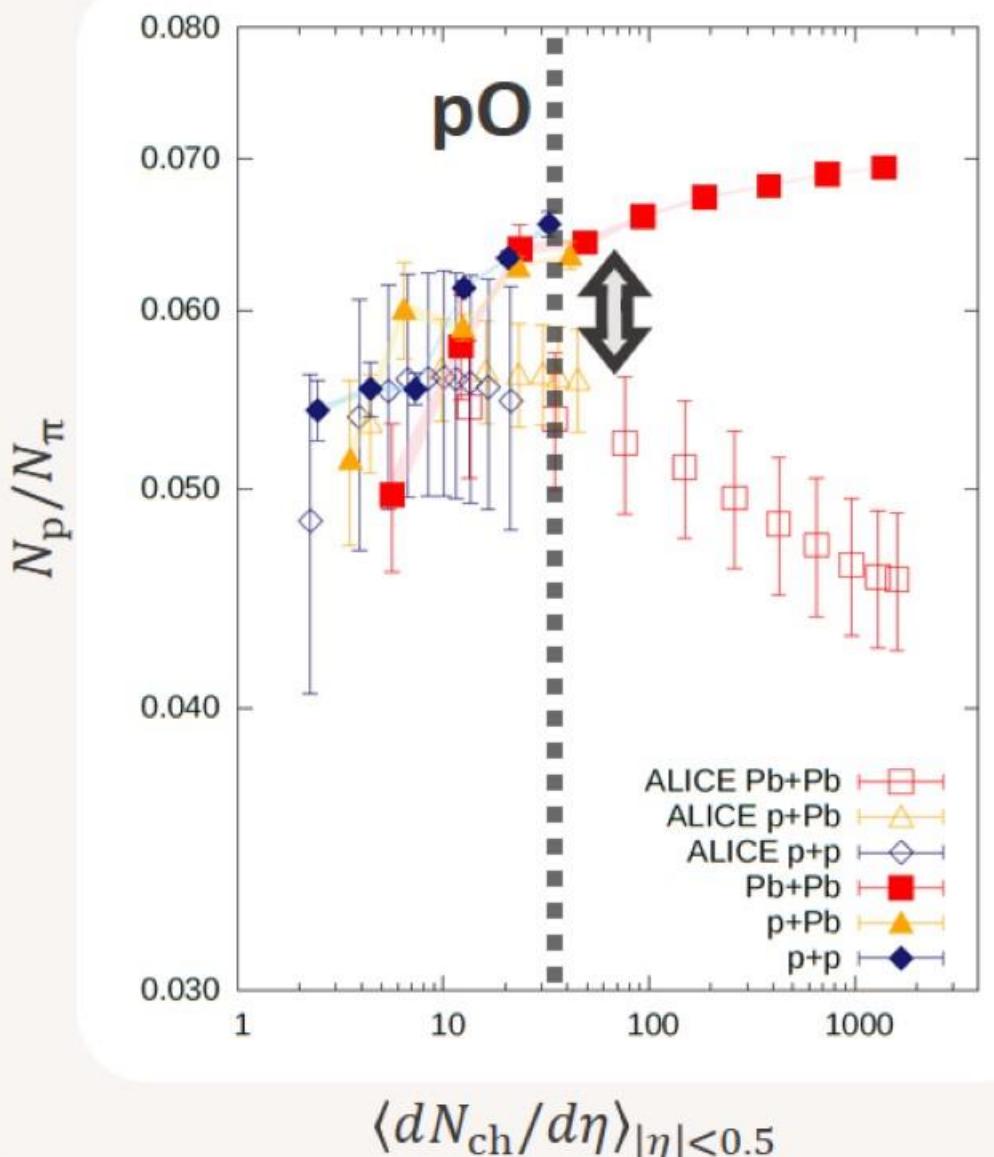
OO: $\sqrt{s_{NN}} = 7$ TeV

CERN Yellow Rep. Monogr. 7 (2019) 1159-1410

Yields vs centrality/multiplicity class from Angantyr Pythia

C. Bierlich *et al.*, JHEP 1610 139 (2016)

Re-scatterings in small systems(?)



Baryon anti-baryon annihilation
in hadronic re-scatterings at
 $\langle dN_{ch}/d\eta \rangle \sim 35$ in pO?

More chance to investigate such
an effect in small systems

0-0.95% multiplicity class
from Angantyr Pythia

$\rightarrow \langle dN_{ch}/d\eta \rangle \sim 138$

$\rightarrow \langle dN_{ch}/d\eta \rangle \sim 35$

Remaining issues in DCCI

- Implementation of hadronic afterburner
- Process to local equilibrium
- Color flow modification
- Considering formation time of partons
- Multiplicity from full DCCI
- Considering fluid density in DCCI
- Jet quenching
- Charge conservation

.....

Settings

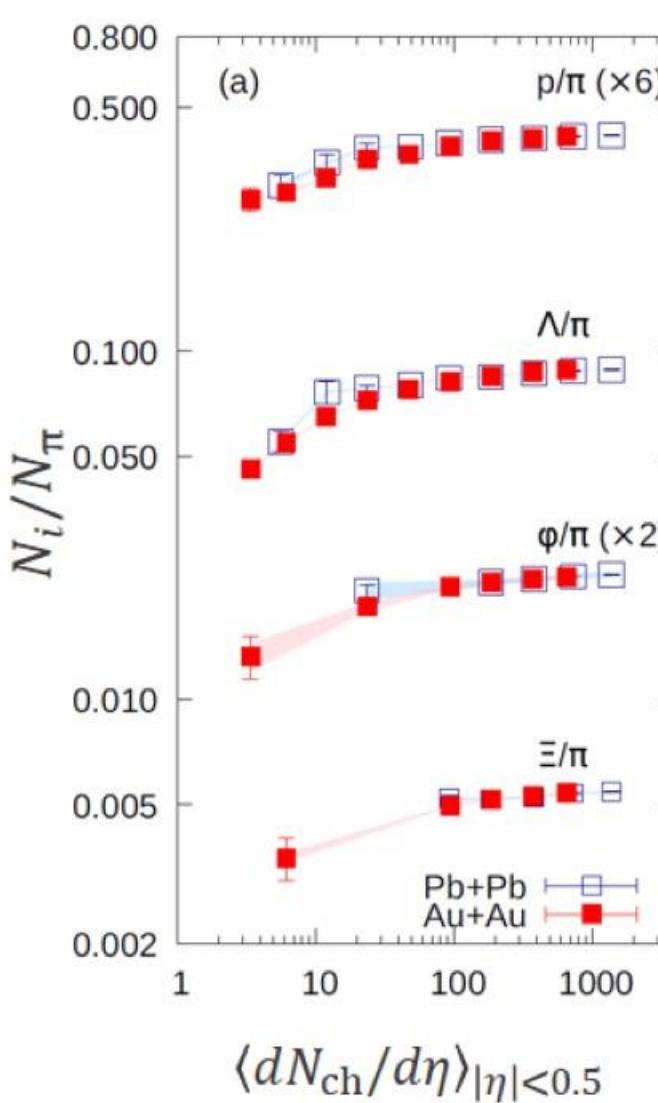
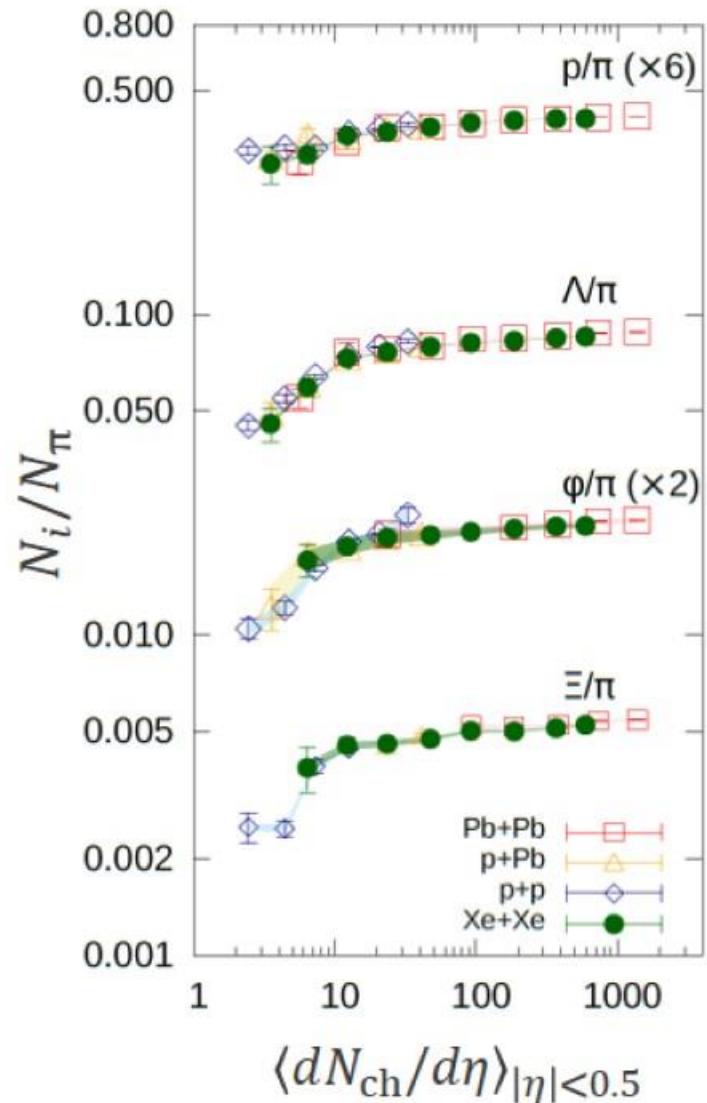
- Gaussian function in Milne coordinate

$$G(x - x_i(t)) d^3x \\ \rightarrow \frac{1}{2\pi\sigma_{\perp}^2} \exp\left[-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma_{\perp}^2}\right] \frac{1}{\sqrt{2\pi}\sigma_{\eta_s}\tau} \exp\left[-\frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}\right] dx dy \tau d\eta_s$$

Smearing and core-corona density $\rightarrow \sigma_{\perp} = 0.5$ fm, $\sigma_{\eta_s} = 0.5$

- Cell width $\rightarrow \Delta x_{\perp} = 0.3$ fm, $\Delta \eta_s = 0.15$
- Time step $\rightarrow \Delta \tau = 0.01$ fm (during dynamical initialization)
 $\Delta \tau = 0.3$ fm (after the initial time of fluid)

Collision & energy independence



- Particle ratios are almost scaled with multiplicity
 - No significant dependence on system size or collision energy (XeXe: LHC, AuAu: RHIC)
- Multiplicity plays an important role for thermalization of partons

Dynamical core-corona picture

Extending core-corona picture...

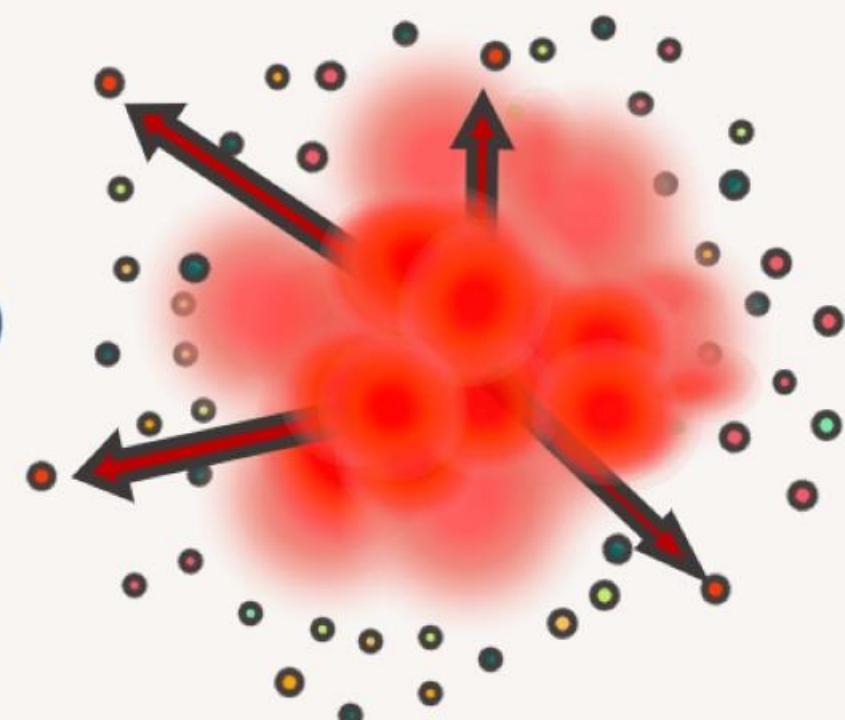
NEW

Y. Kanakubo *et al.*, PTEP 2018 (2018) 12, 121D01

Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020)

Dynamical separation of core and corona

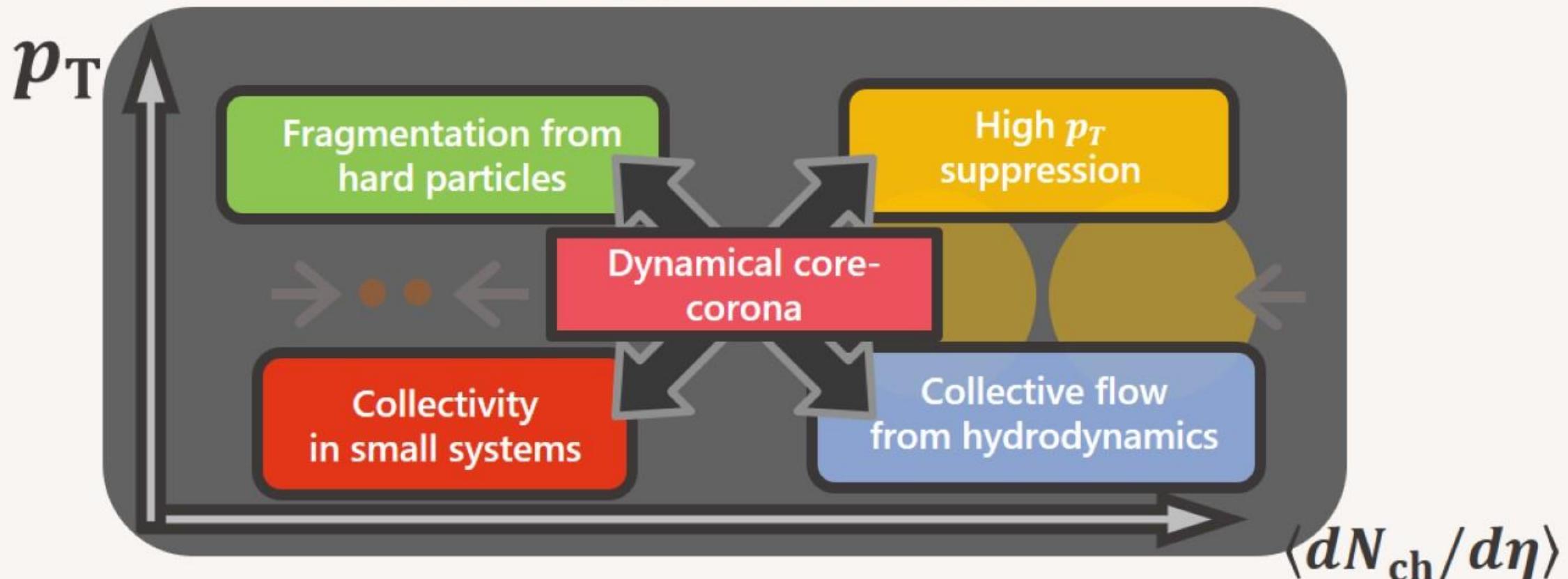
- Constituents: partons
→ Deposition of energy-momentum traversing fluid (~jet quenching-like picture)
- A gradual separation of core and corona in spatial and momentum space



Mimicking a thermalization process of initially produced partons

Towards unified description

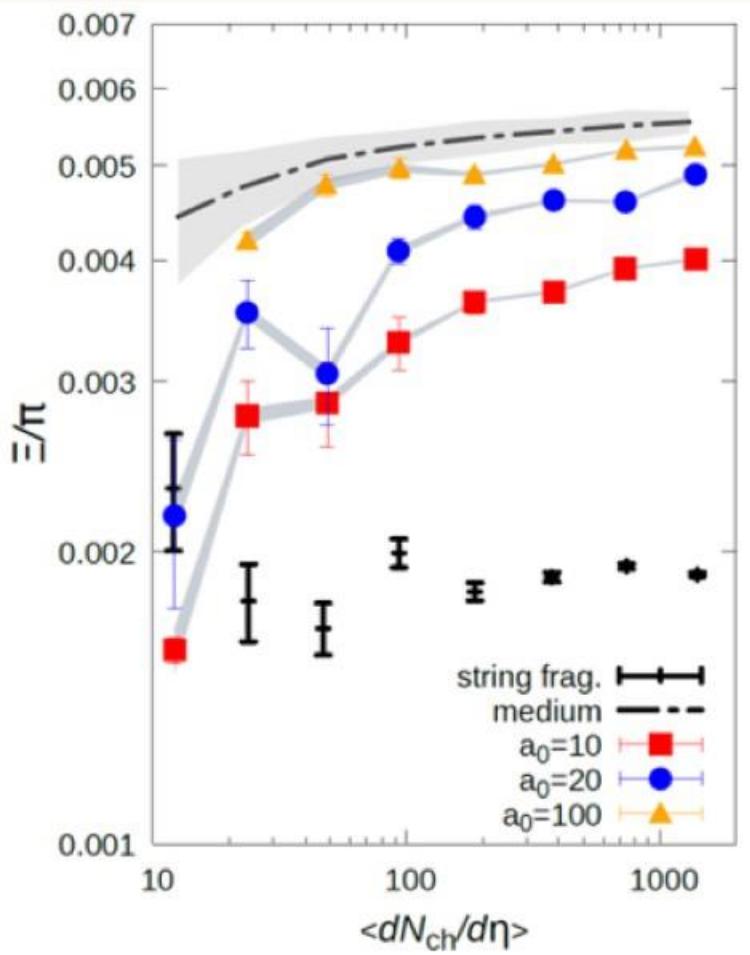
Big goal: To build a unified dynamical description of high-energy nuclear collisions



Current goal: To reveal the detail of QGP signals in small system

→ Have the same origin as ones observed in heavy-ion collisions?

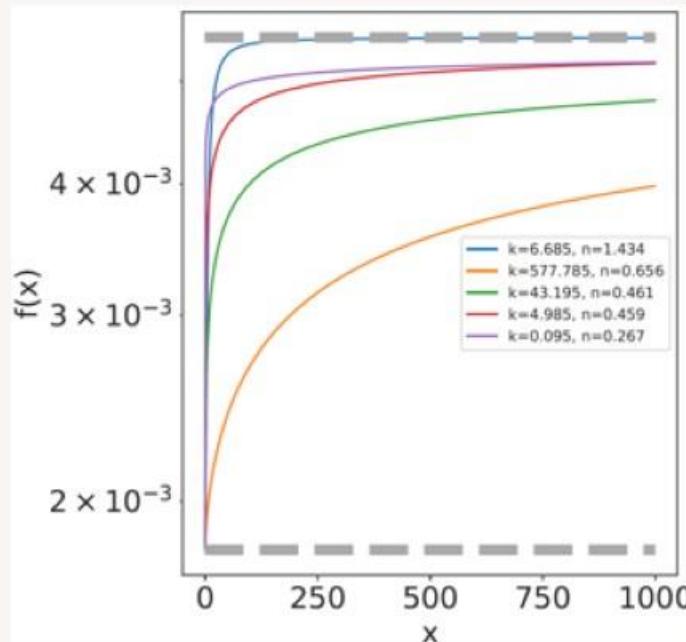
How we determined a_0



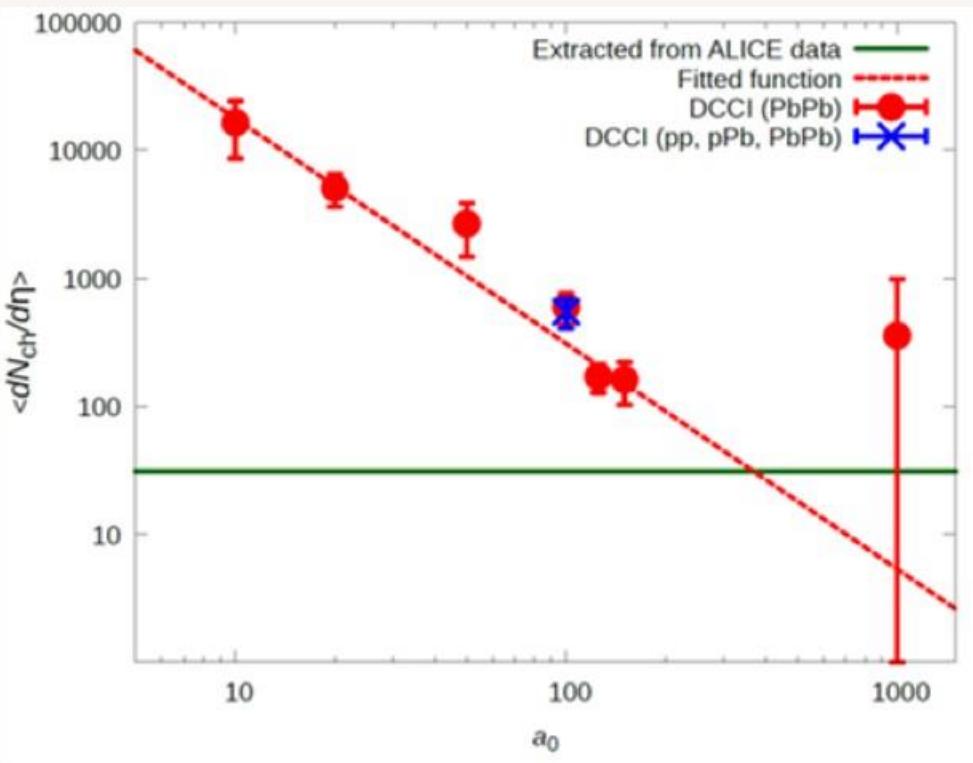
1. Perform function fitting for Ξ/π vs. $\langle dN_{\text{ch}}/d\eta \rangle$ with chi-square in different a_0

$$f(x) = (F - S) \frac{x^n}{x^n + k^n} + S, \quad F: \Xi/\pi \text{ from pure hydro}, \\ S: \Xi/\pi \text{ from pure string frag.}$$

2. Obtain $\langle dN_{\text{ch}}/d\eta \rangle$ where the ratio reaches $\sim 90\%$ value of pure hydro

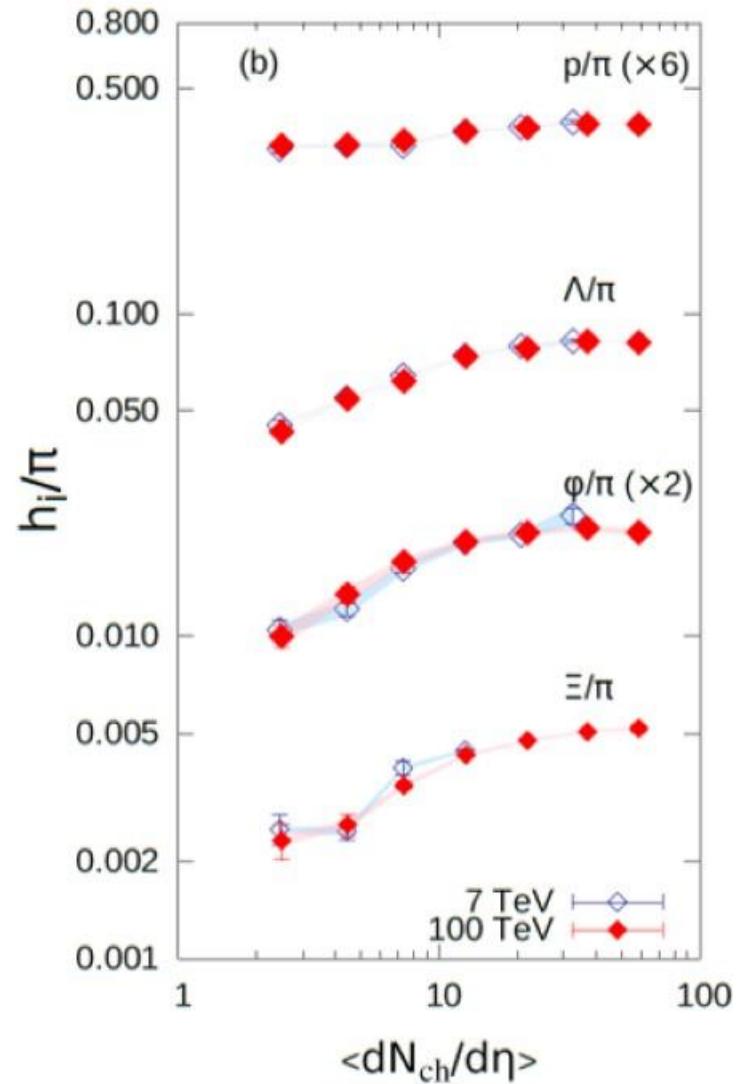


How we determined a_0 (cont'd)

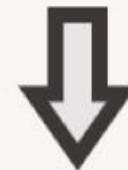


3. Plot a_0 dependence of $\langle dN_{ch}/d\eta \rangle_{core/tot \sim 90\%}$
4. Fit those data with a power function (dashed red line).
4. Perform fitting for the experimental data and plot $\langle dN_{ch}/d\eta \rangle_{core/tot \sim 90\%}$. (green line)
6. Obtain the crossing point of the two lines

FCC energy



- FCC: possibly performed in 2040-2050
- $\sqrt{s} = 100$ TeV

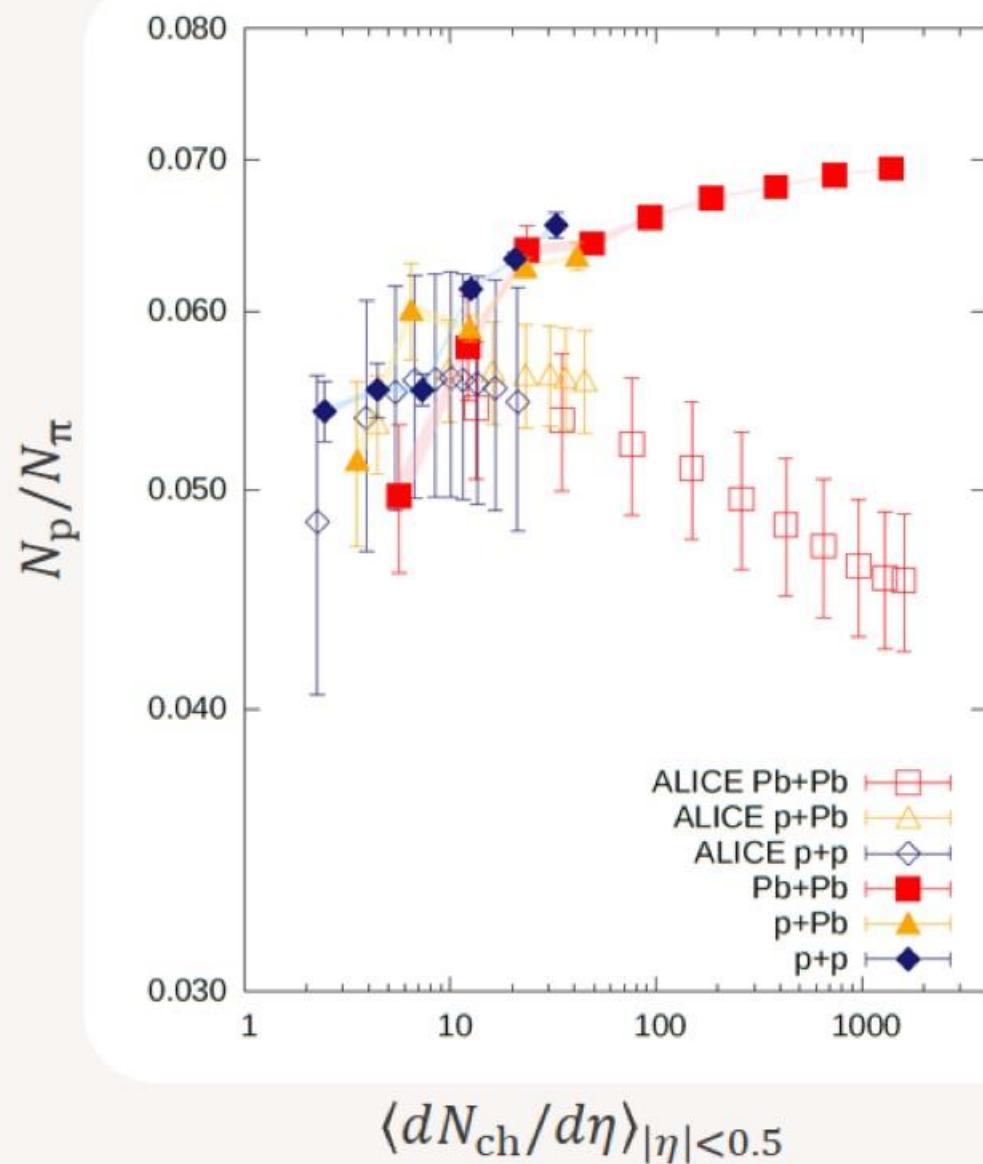


More multiplicity is expected in pp

More possibility to find QGP signals?

Prediction: At FCC energy, saturation of multi-strangeness ratios is seen in high multiplicity events.

Particle ratios



Our results

→ Enhancement with multiplicity

Exp. data

→ Decrease with multiplicity

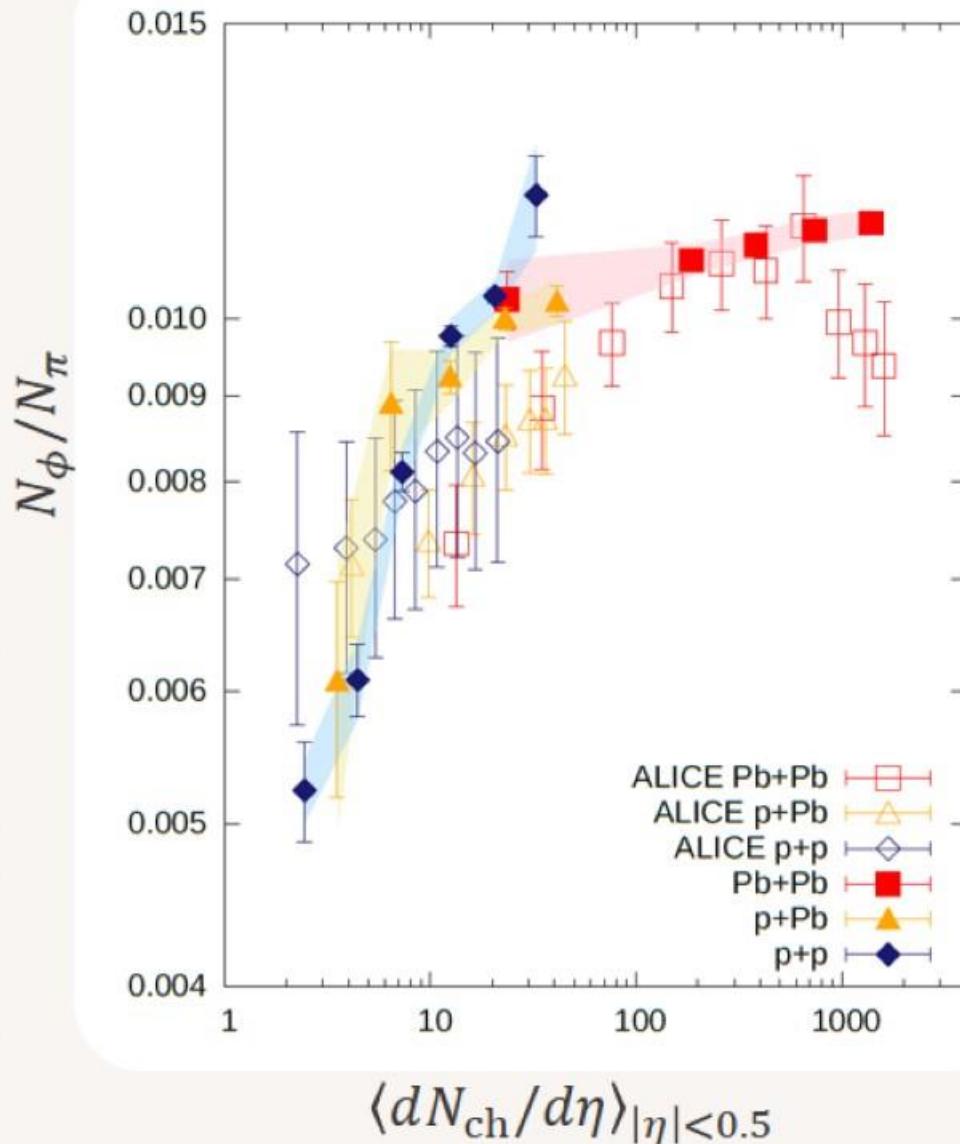
→ Deviation from statistical thermodynamics

Baryon and anti-baryon annihilation in late stage would be important at high multiplicity events

Need to introduce hadronic re-scatterings

Particle ratios

S. Acharya *et al.*, Phys. Rev. C99, 024906 (2019) J. Adam *et al.*, Eur. Phys. J. C76, 245 (2016)
B. Abelev *et al.*, Phys. Rev. C91, 024609 (2015)



$\phi(s\bar{s})$: hidden strangeness $S = 0$

Core-corona (our results)

→ Describe qualitative behavior of multiplicity dependence

Canonical suppression

→ Not affected by canonical suppression

J. Sollfrank *et al.*, Nucl. Phys. A 638, 399C (1998)

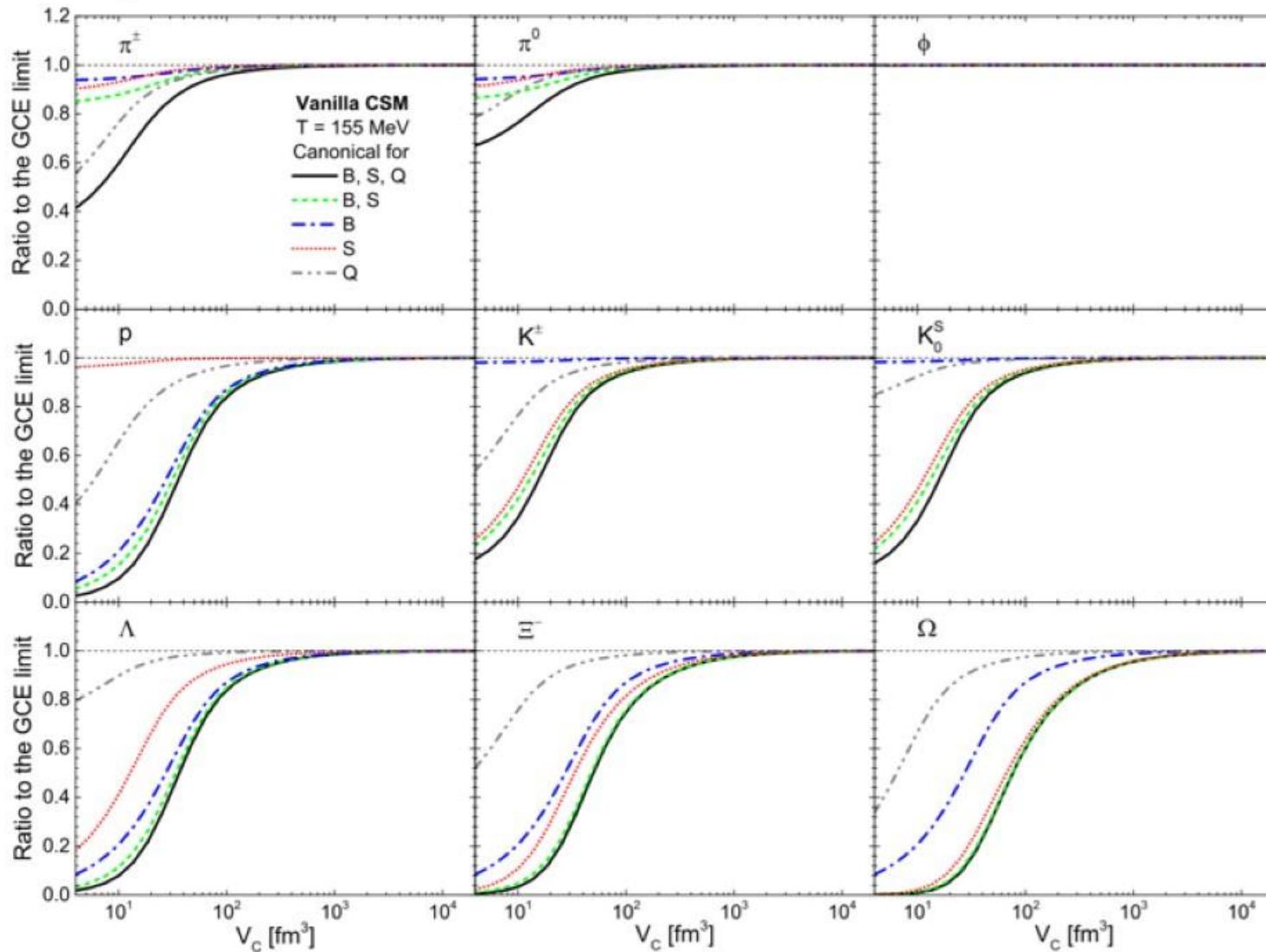
→ Need to incorporate non-equilibrium picture for strangeness

V. Vovchenko *et al.*, Phys. Rev. C 100 5, 054906 (2019)

Both suggest a need of contributions besides equilibrated matter for strangeness at small multiplicity

Canonical suppression model

V. Vovchenko *et al.*, Phys. Rev. C 100 5, 054906 (2019)



Initial condition in DCCI

PYTHIA with "HadronLevel:all=off", "PartonVertex:setVertex=on"

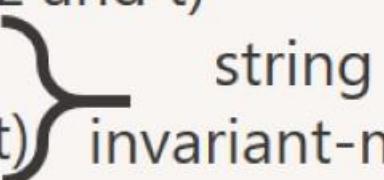


Phase-space data of initial partons

- Angantyr for heavy ion collisions
- Default settings except above ones

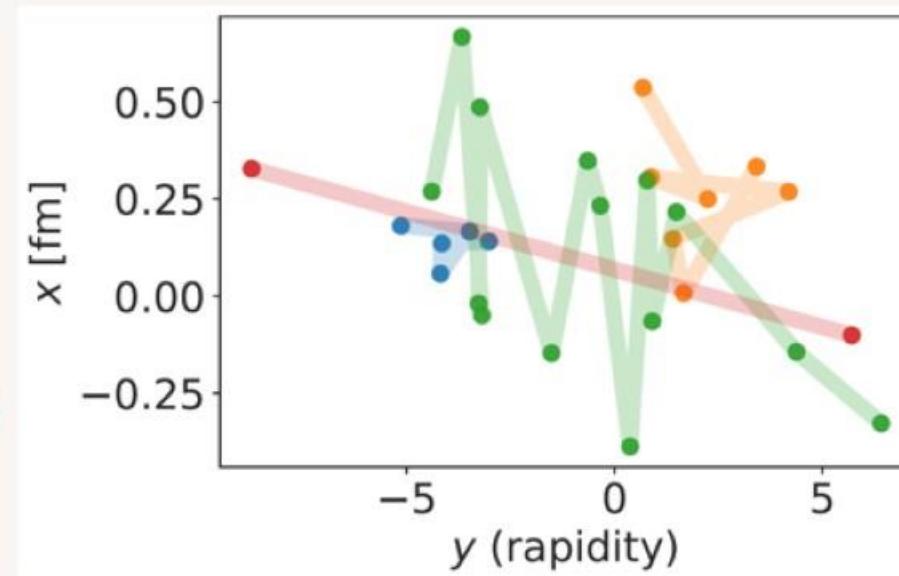
C. Bierlich *et al.*, JHEP 10 134 (2018)

Information needed in DCCI

- Particle IDs
- Phase-space information (except z and t)
- Color and anti-color
- (Junction information in the event)  string invariant-mass

Strings with an invariant mass $M < M_{\text{th}}$

- Cannot undergoes normal string fragmentation
- Force constituent partons of the string to be fluidized



Hadronization in DCCI

- Core: Numerical integration of Cooper-Frye formula
Resonance factors of them

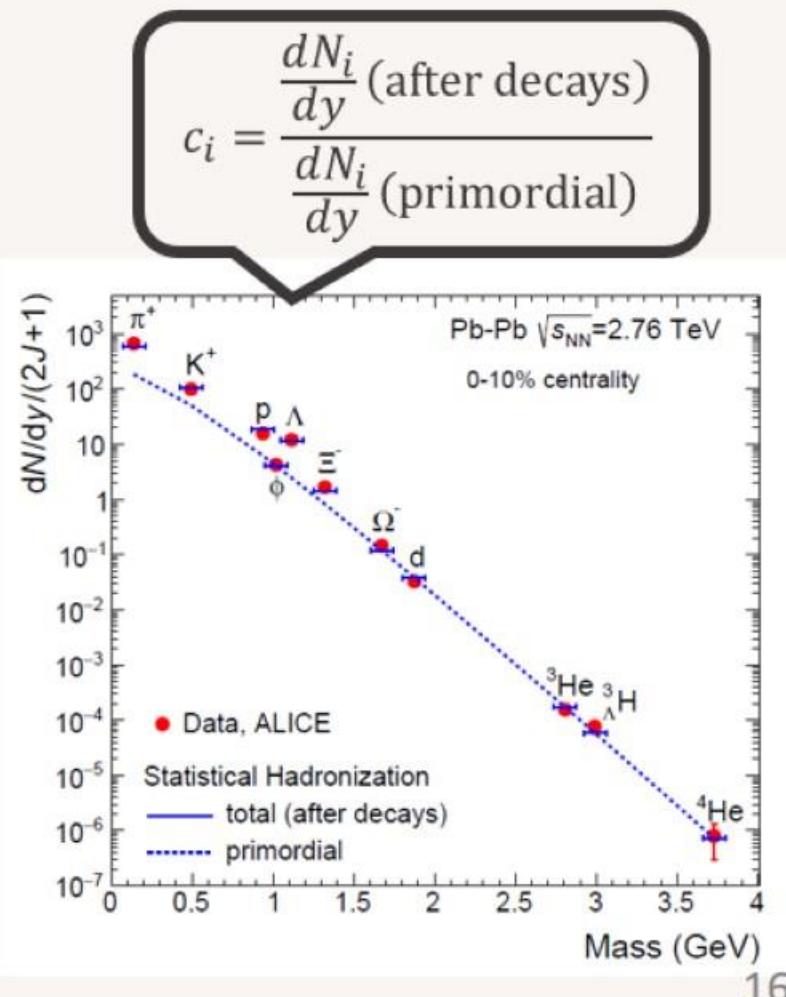
Final yield = direct yield $\times c_i$ (resonance factor)

$$c_\pi = 3.2, \quad c_\Lambda = 4.7, \quad c_p = 3.0, \\ c_E = 1.7, \quad c_\phi = 1.0$$

- Corona: String fragmentation using PYTHIA with "forceHadronLevel()"

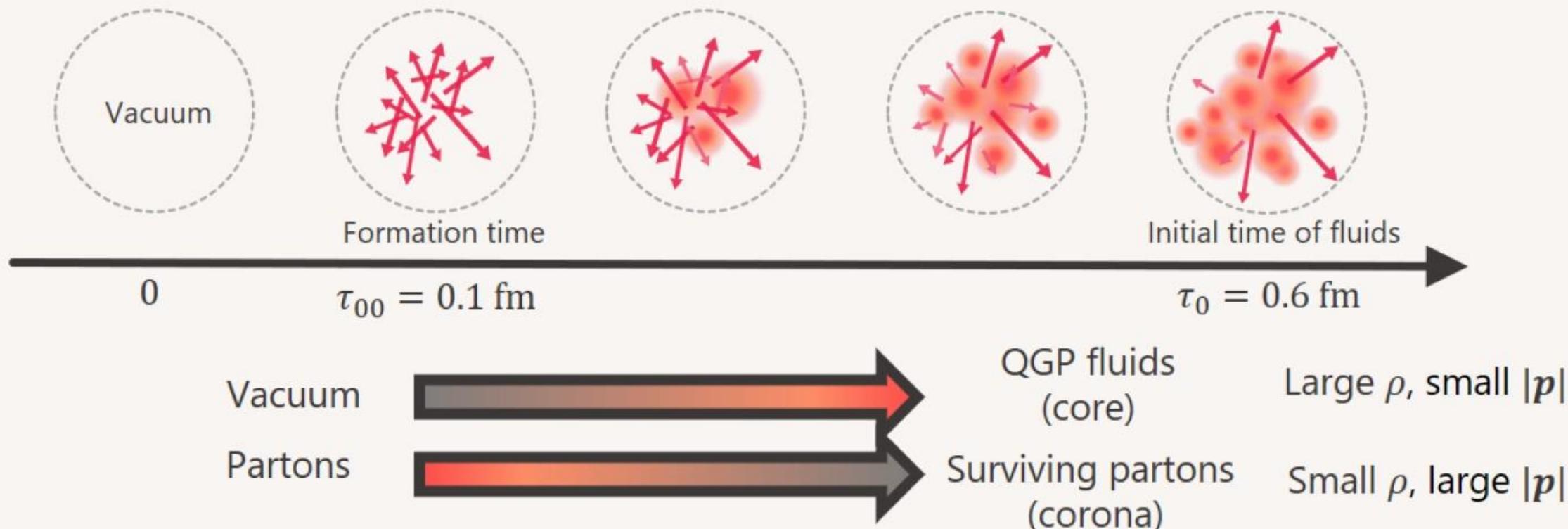
Information to put in PYTHIA

- Particle IDs
- Four momentum
- Color and anti-color
- (Junction information in the event)



What happens under this modeling

$$\partial_\mu T_{\text{fluid}}^{\mu\nu} = J^\nu, \quad \Delta E_i \propto -\rho_i E_i / |\mathbf{p}|_i^2$$



- A parton with small energy and high density tends to be fluidized
- Energy & momentum conservation as a whole system, fluids + traversing partons

Core-corona picture

Superposition of two different sources, core and corona

Core: constituents in high density areas

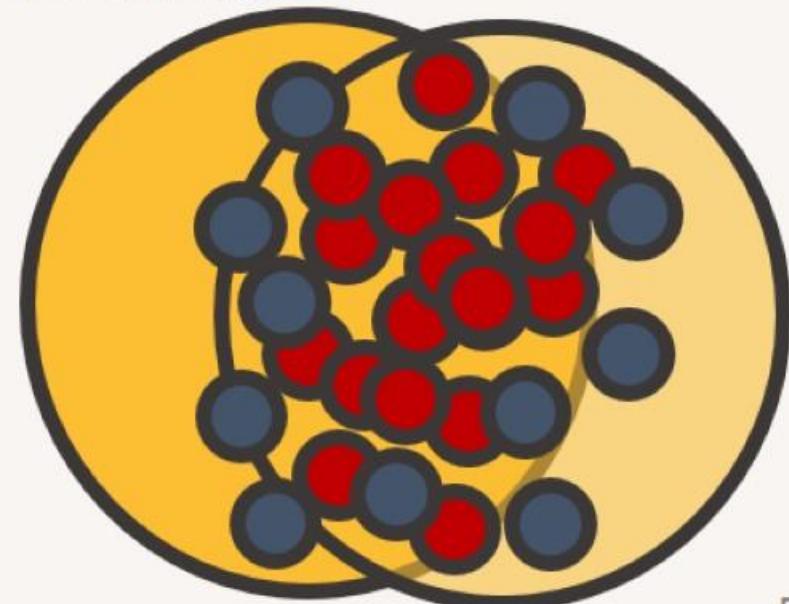
→ QGP fluids (thermalized, soft)

Corona: constituents in low density areas

→ undergoes string fragmentation
(non-thermalized, hard)

→ Multiplicity dependence of ratio coming from
a change of a fraction of core/corona

- Constituents: nucleons/string segments
- Considering initial spatial distribution
- Core-corona separation at a fixed time



DCCI

