2021/09/24 QCD相転移やQGP生成のモデル化による重イオン衝突の
時空発展の理解に向けた理論・実験共同研究会

パートンから流体へ

Y. Kanakubo *et al.*, arXiv:2108.07943

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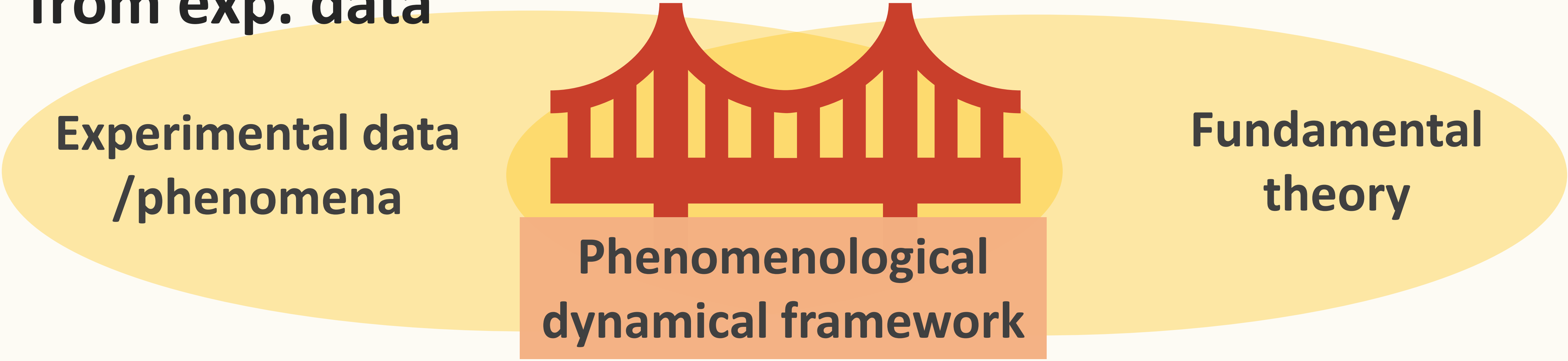
GROUP

Introduction

Powerful tool to tease out QGP properties from exp. data



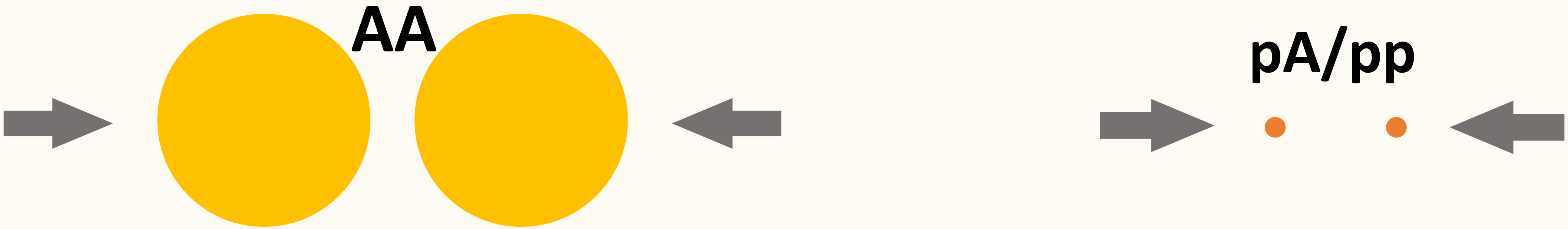
As a bridge between experiment and fundamental theory

Accurate studies of QGP properties!

e.g., Bayesian parameter estimation with hydro-based frameworks

Call for a hydro-based framework that is capable of accounting for experimental data

Remaining basic issues in hydro-based framework



Local equilibrium for a whole system?

Incorporation of jet production in hydro?

Conservation of beam energy-momentum?

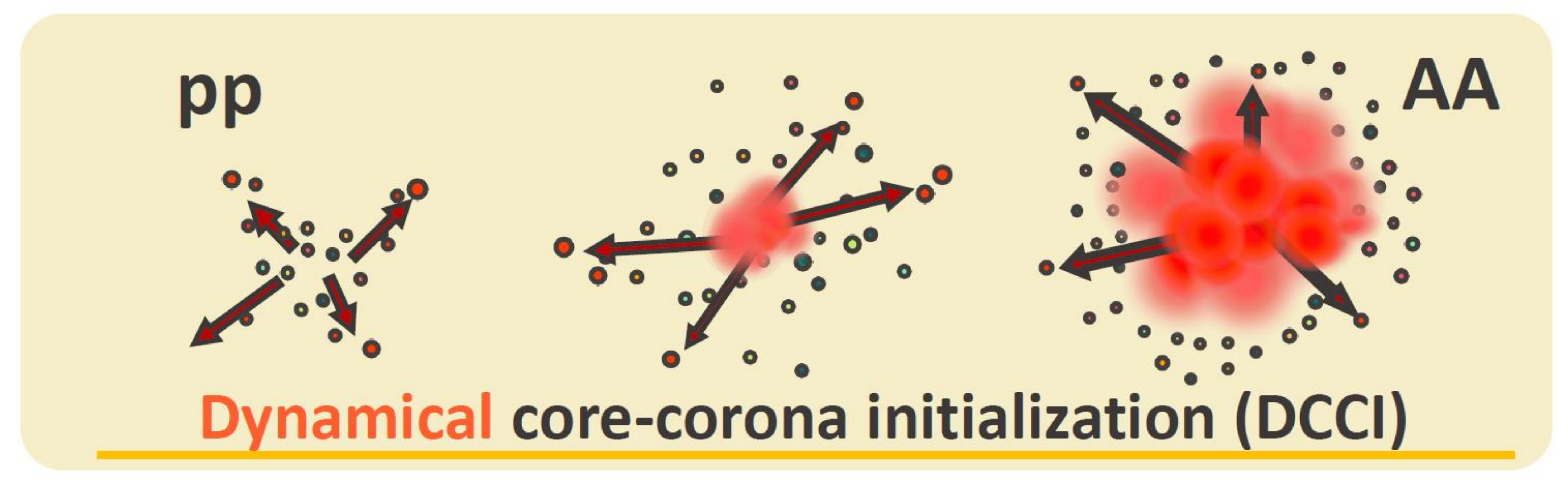
Hydro description in low multiplicity event?

Hydro-based MC event generator

- Respect beam energy (as a MC event generator)
- Both equilibrated and non-equilibrated matter

➔ From low to high p_T, from pp to AA

Hydro-based MC event generator



Core: fluids (equilibrated matter)

Corona: non-equilibrated partons

Dynamical generation of QGP fluids based on the core-corona picture

Description of entire system generated in a collision as a MC event generator from pp to AA

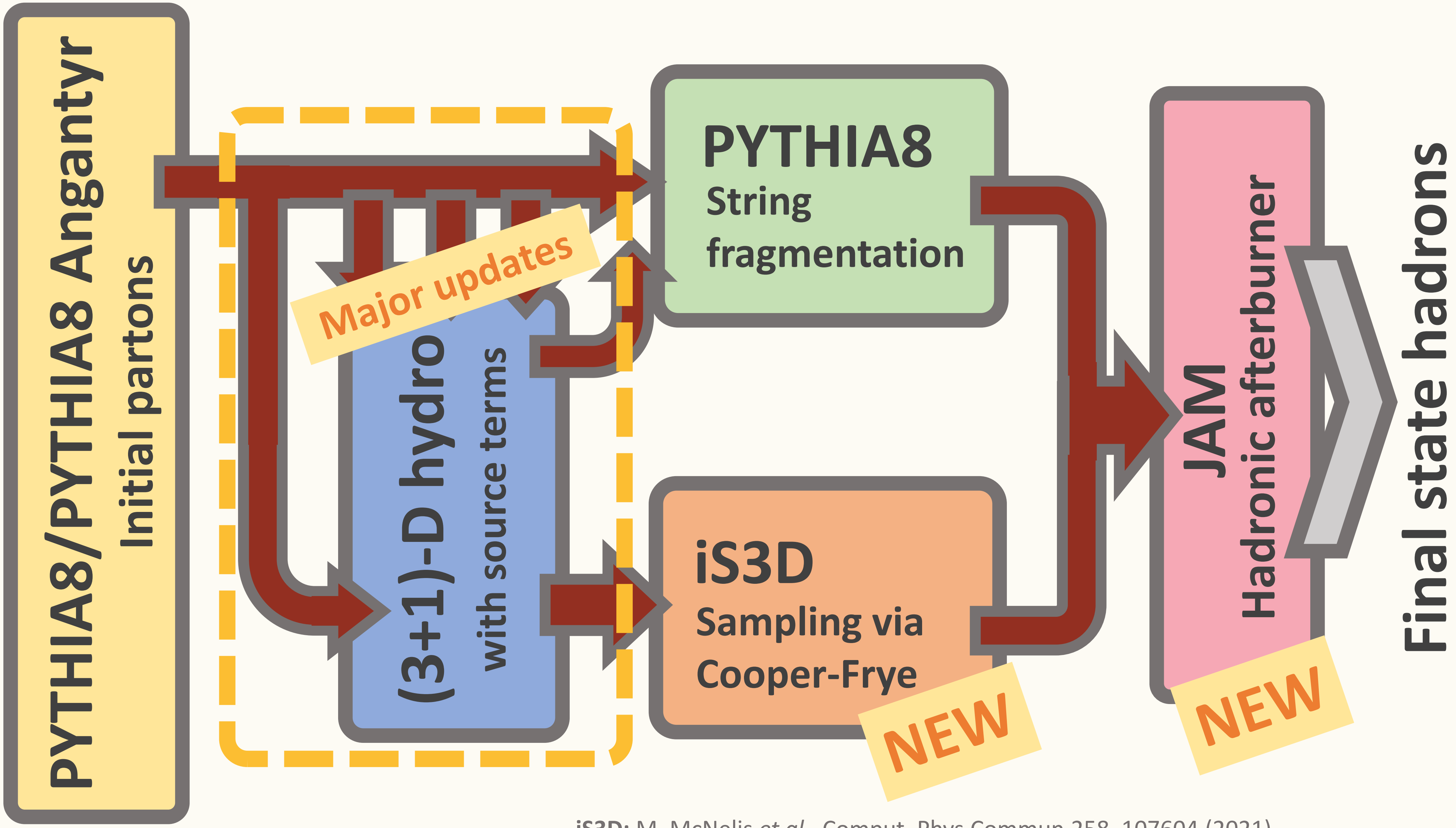
Y. Kanakubo *et al.*, PTEP 2018 12, 121D01 (2018); Phys. Rev. C 101 2, 024912 (2020); arXiv:2108.07943

Dynamical Core-Corona Initialization model 2

Y. Kanakubo *et al.*, arXiv:2108.07943

Model flowchart of DCCI2

Y. Kanakubo *et al.*, arXiv:2108.07943



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

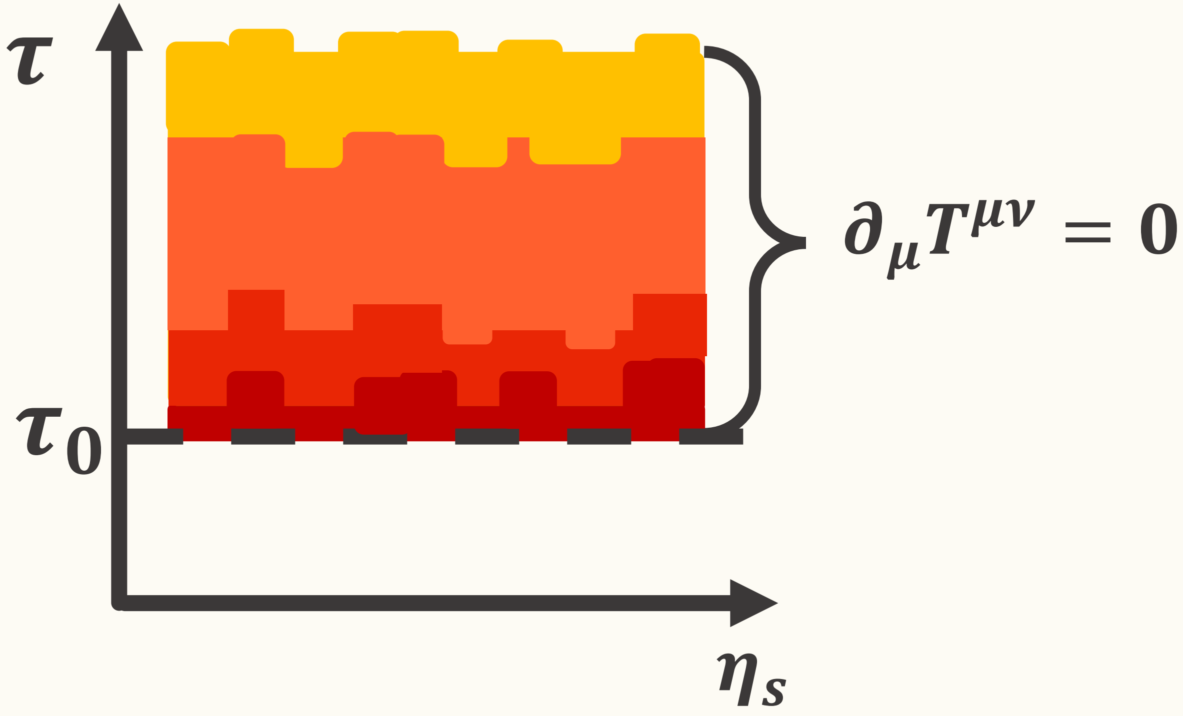
JAM: Y. Nara *et al.*, Phys. Rev. C61, 024901 (2000)

iS3D: M. McNelis *et al.*, Comput. Phys.Commun.258, 107604 (2021)

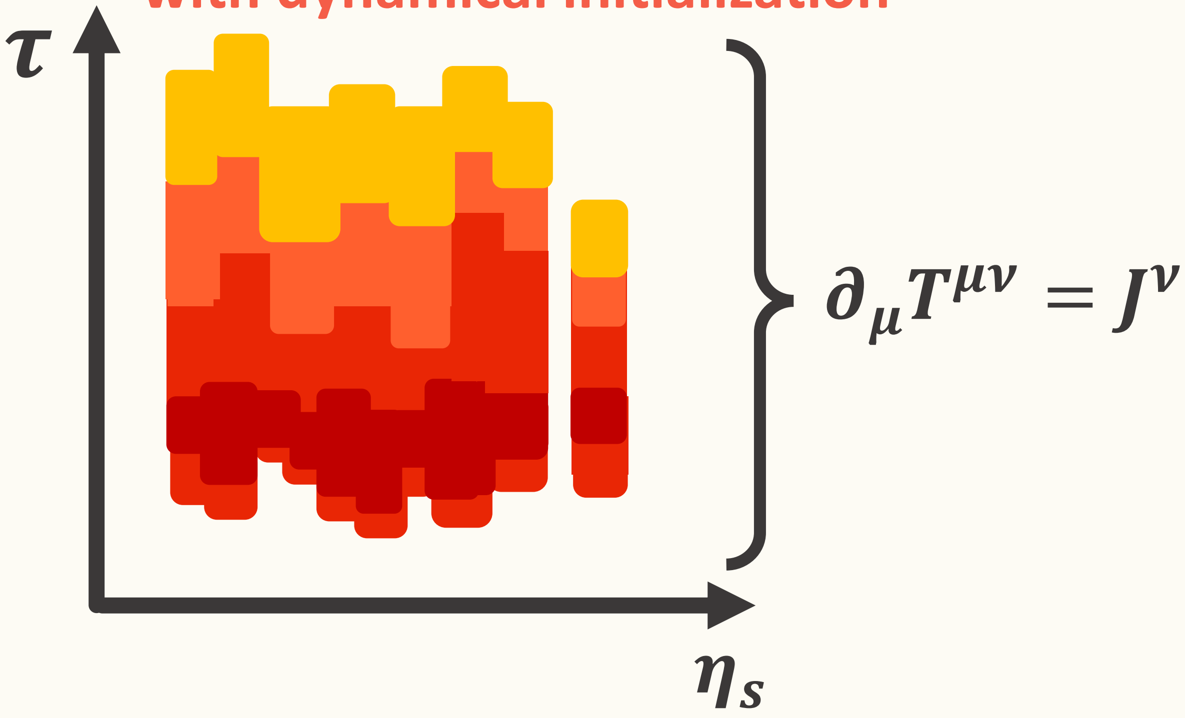
Dynamical initialization framework

➔ Dynamical generation of hydro initial conditions

Conventional hydro



Hydro
with dynamical initialization



→ Put initial condition at fixed τ_0

→ Generate initial condition locally through sources J^μ

Dynamical initialization framework (cont'd)

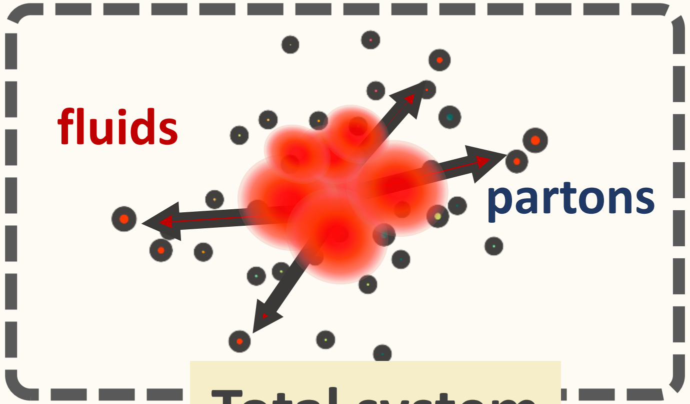
M. Okai *et al.*, Phys. Rev. C 95, 054914 (2017)

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

Assumption 2. Instant equilibration of deposited energy and momentum

Continuum eq. for fluid+parton

$$\partial_\mu \left(T^{\mu\nu}_{\text{fluid}} + T^{\mu\nu}_{\text{parton}} \right) = 0$$



Hydrodynamic eq. with source term

$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^\nu$$

Assuming Gaussian profile and straight trajectory for a parton

$$J^\nu \to -\sum_i \frac{dp_i{}^\nu(t)}{dt} G\left(x - x_i(t)\right)$$

G: Gaussian function

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

"Sources of fluids" = "Four-momentum deposition from partons"

Dynamical core-corona initialization

Core-corona picture

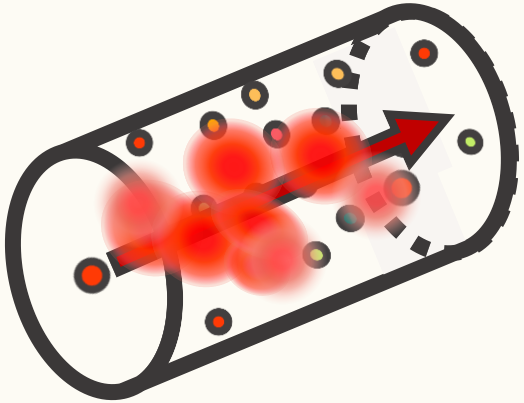
~ EoM with a drag force due to secondary scatterings

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

Defined at a co-moving frame with $\eta_{s,i}$

Note 1. Energy and momentum ➔ direct conversion into fluids

Note 2. Phenomenological model to capture dynamical aspect of core-corona



Low p_T and/or dense region

⇨ Core (fluids)

High p_T and/or dilute region

⇨ Corona (non-equilibrated partons)

Dynamical core-corona initialization

Core-corona picture
$\sim$ EoM with a drag force due to secondary scatterings

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

Defined at a co-moving frame with $\eta_{s,i}$

- Collision criterion

$$b_{i,j} \leq \sqrt{\frac{\sigma_{i,j}}{\pi}}$$

→Geometrical interpretation of a cross-section

- Parametrized cross-section of a parton-parton scattering

$$\sigma_{i,j} = \frac{\sigma_0}{s_{i,j}/[\mathrm{GeV}^2]}$$

→Collision at a CM frame

- Density of non-equilibrated partons

$$\rho_{i,j} \propto \exp\left[-\frac{\left(\vec{x}_{\perp,i}-\vec{x}_{\perp,j}\right)^2}{2\sigma_{x_\perp}^2} - \frac{\left(\eta_i-\eta_j\right)^2}{2\sigma_\eta^2}\right]$$

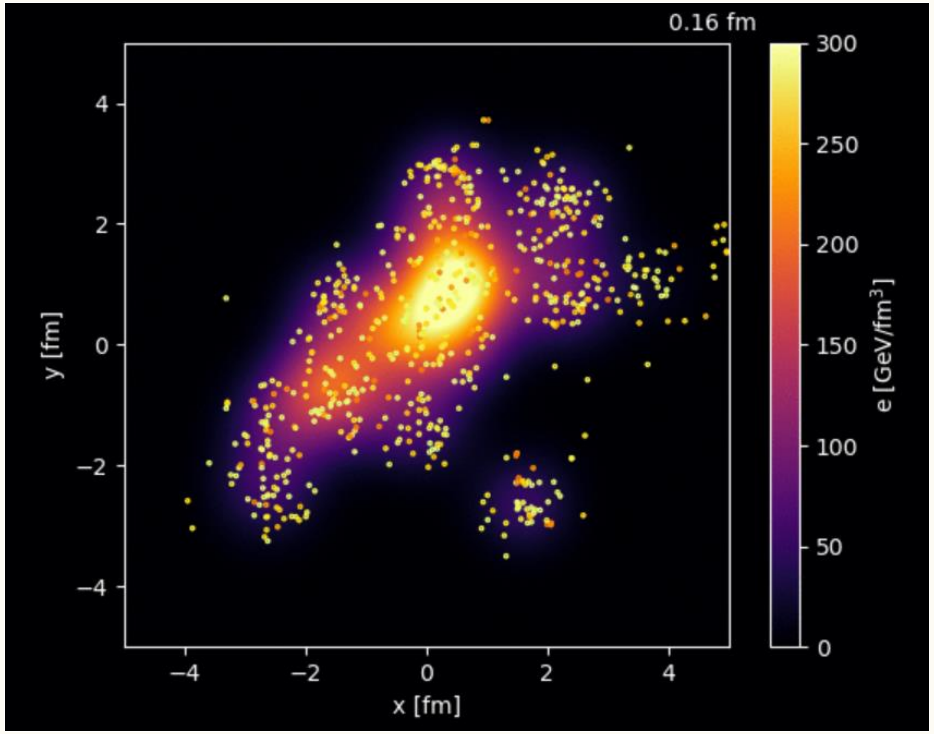
→Gaussian profile of a parton

N_{scat}: # of (non-equilibrated and equilibrated) partons scattered with *i*th parton

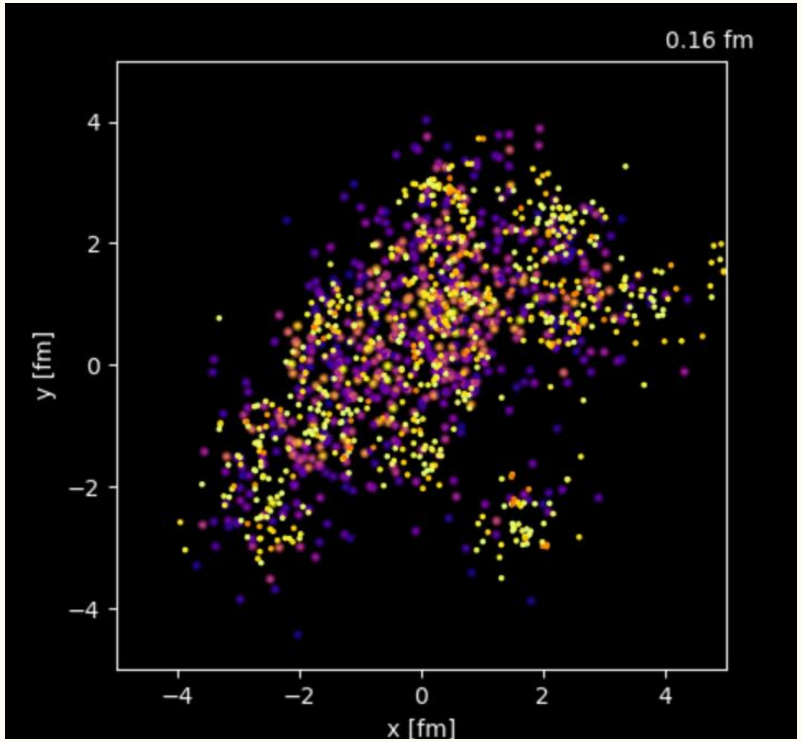
Thermal parton sampling in dynamical core-corona initialization

$$\frac{d{p_i}^{\mu}}{d\tau} = -\sum_{j}^{N_{\mathrm{scat}}} \rho_{i,j}\sigma_{i,j}\left|v_{\mathrm{rel},i,j}\right| {p_i}^{\mu}$$

➔ **Applied to both core (QGP fluids) and corona (non-equilibrated partons)**



Sampling of equilibrated partons at each time step

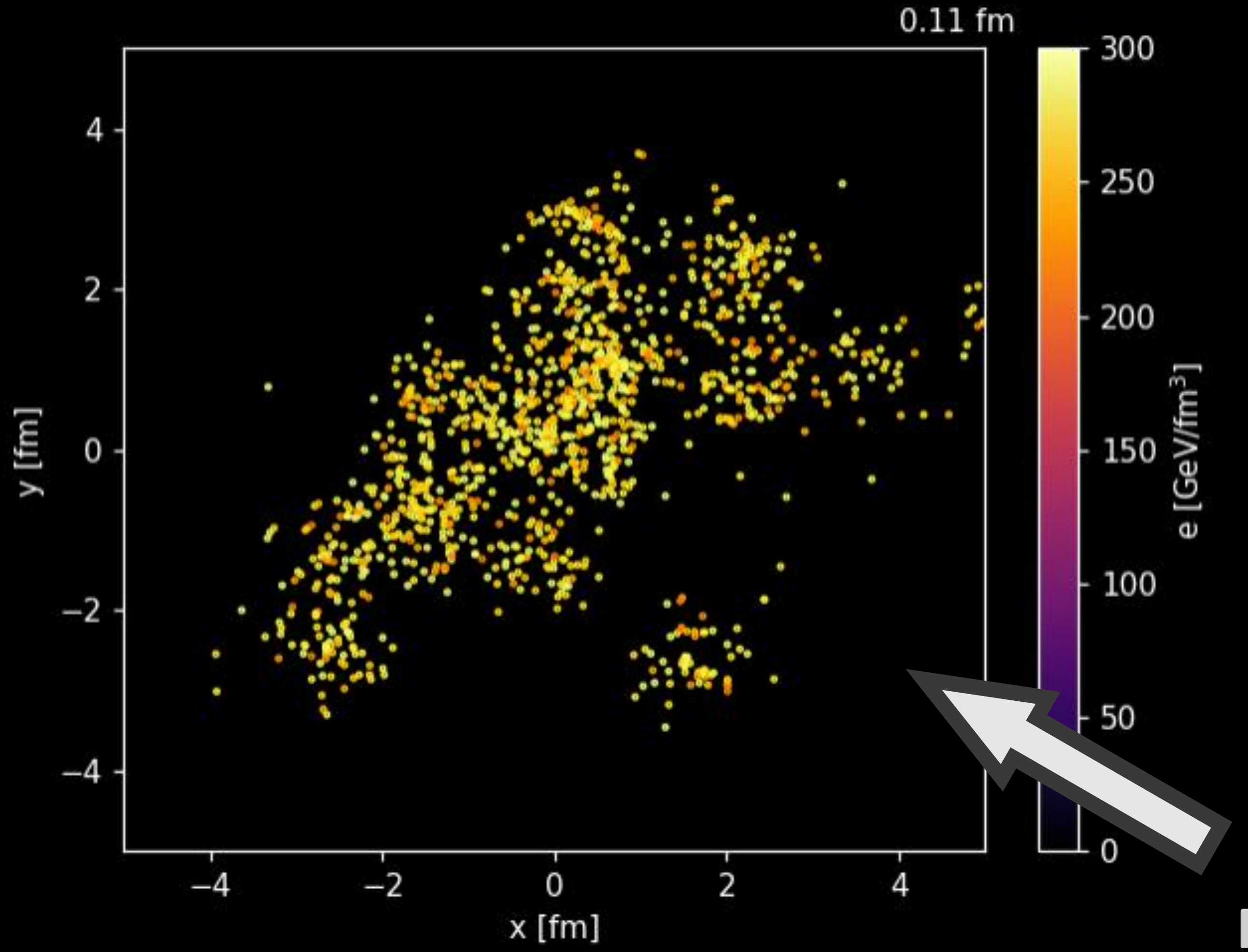


*with mass-less ideal gas approximation

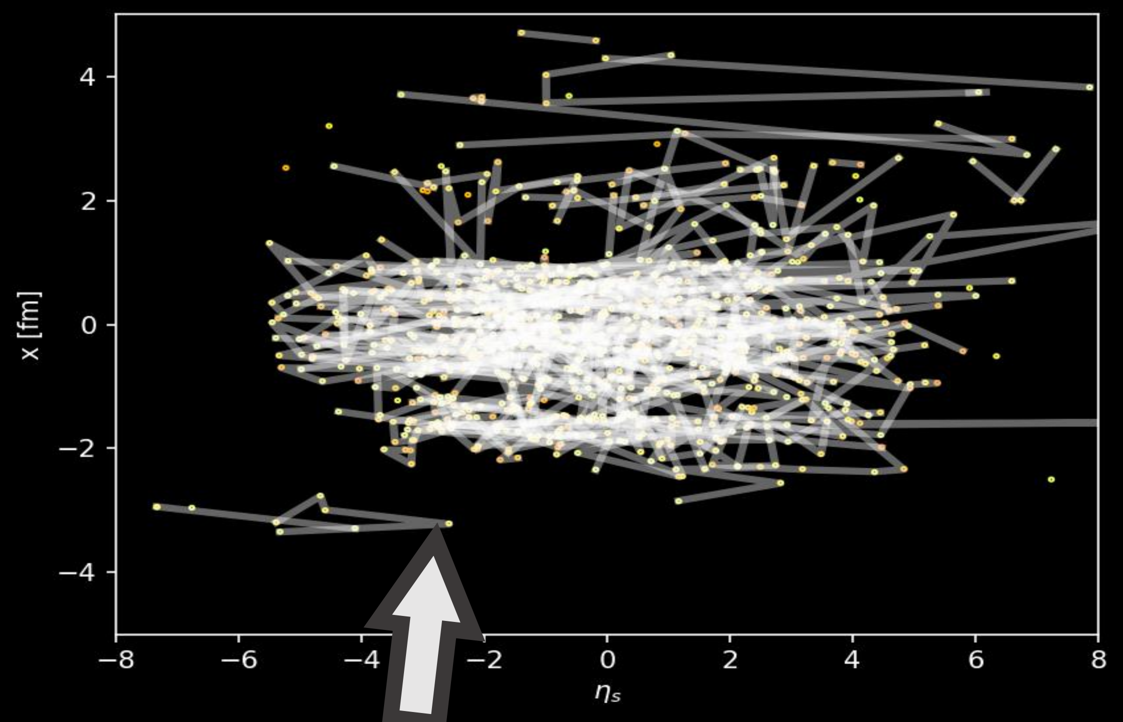
Demonstration of dynamical core-corona initialization

PbPb 2.76 TeV

Transverse plane



$x - \eta_s$ plane ($y \sim 0$)

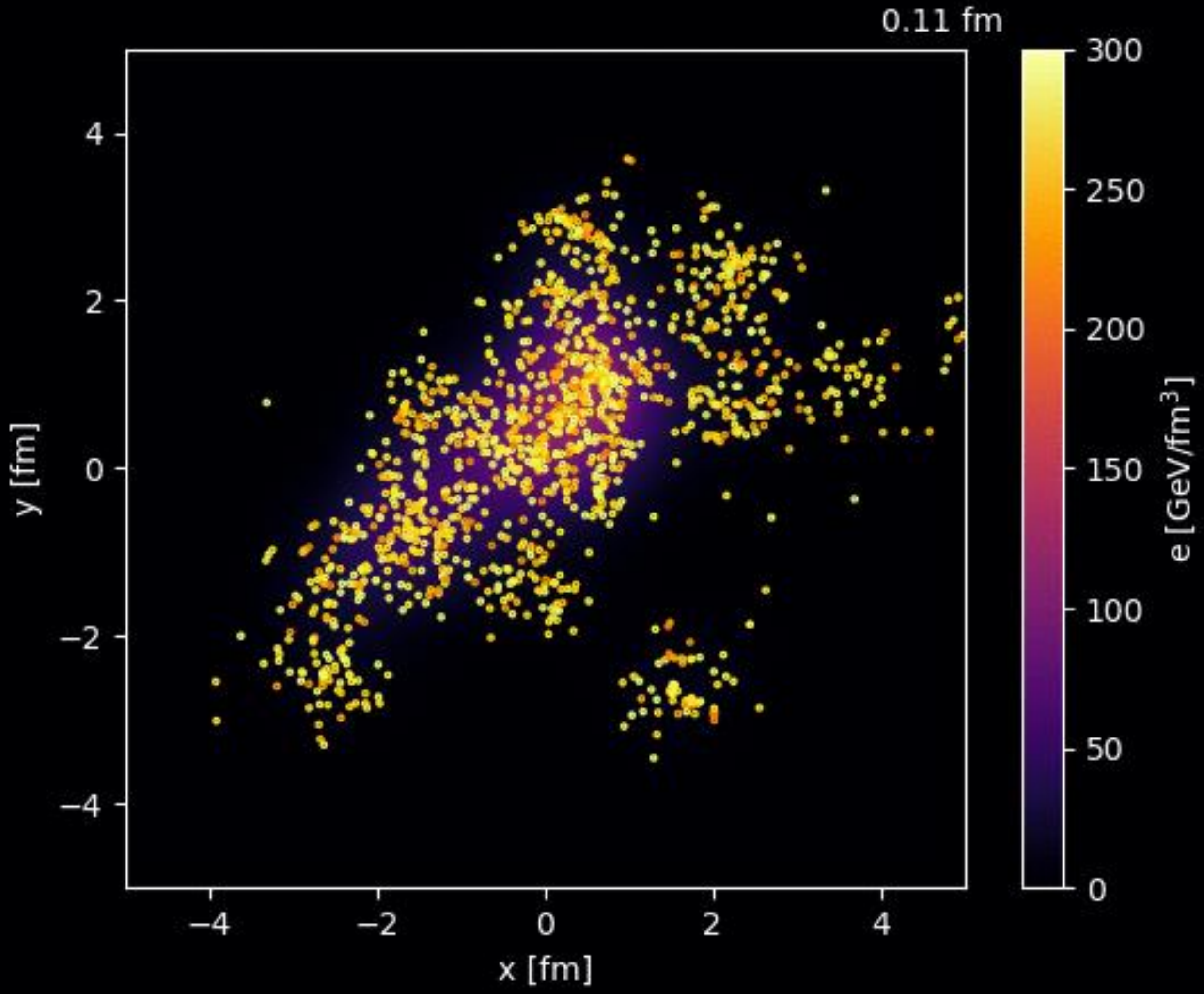


Initial partons from
PYTHIA8/PYTHIA8 Angantyr

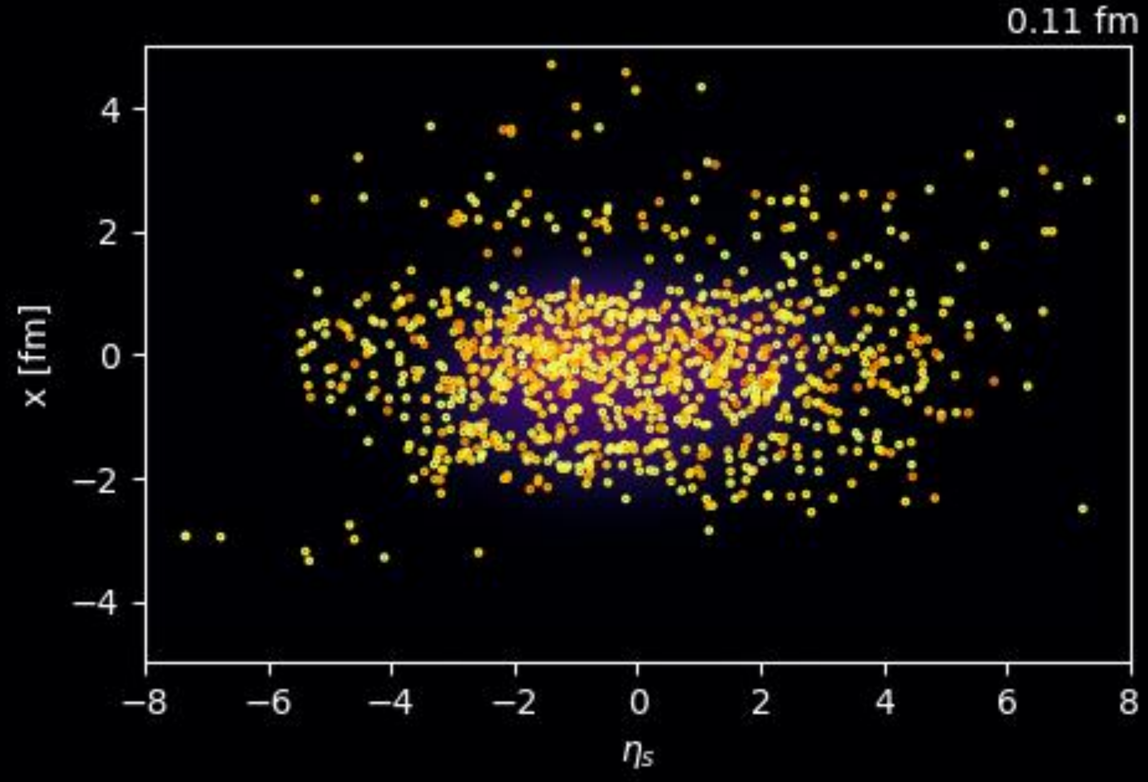
Demonstration of dynamical core-corona initialization

PbPb 2.76 TeV

Transverse plane



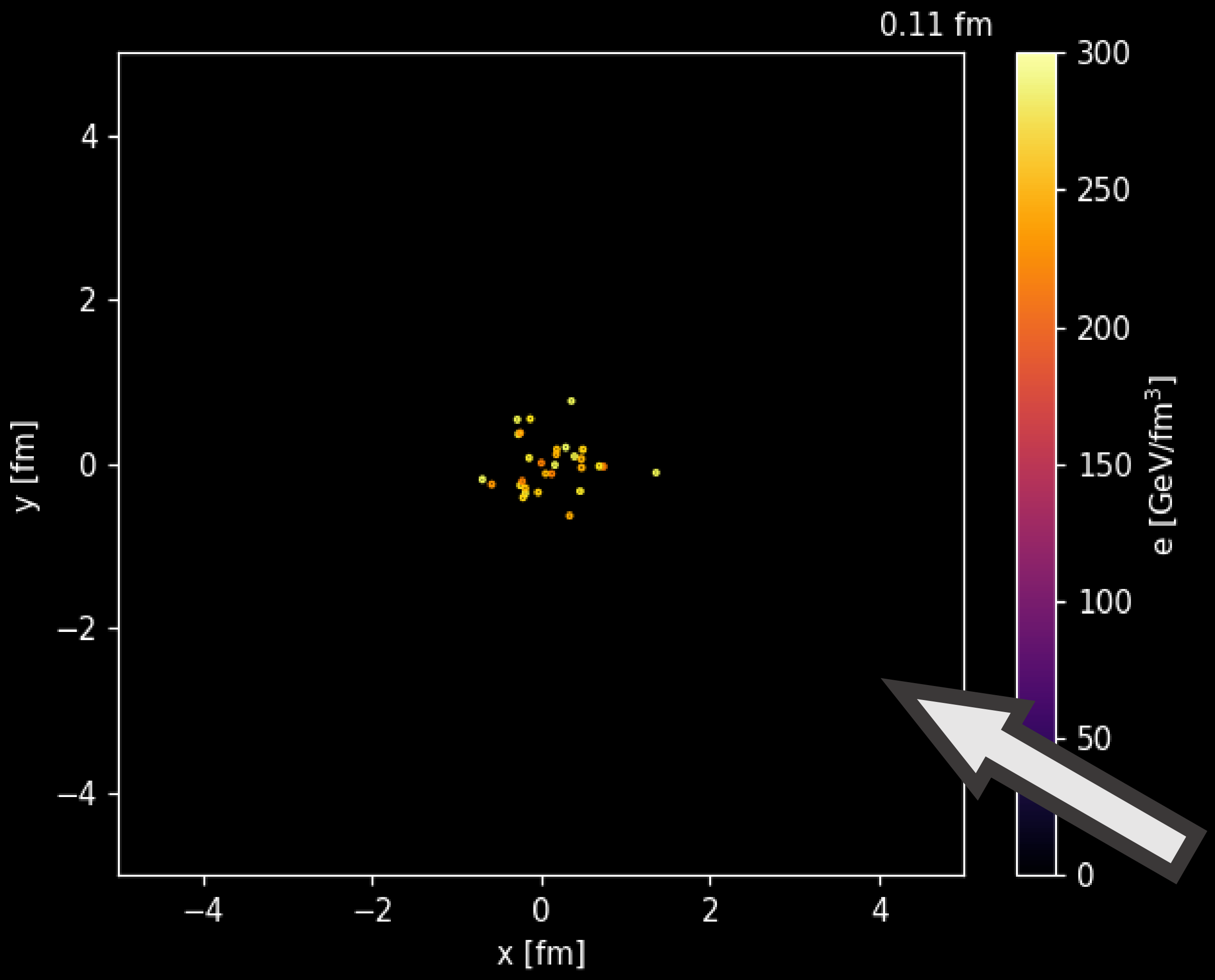
$x - \eta_s$ plane ($y \sim 0$)



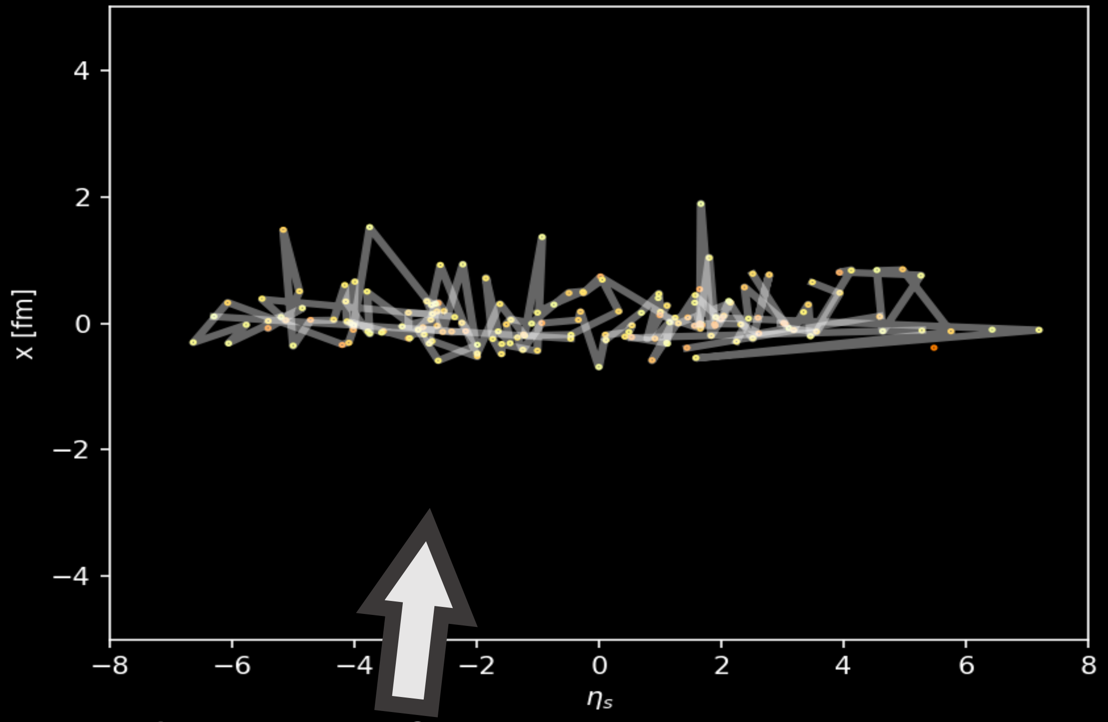
Demonstration of dynamical core-corona initialization

pp 7 TeV

Transverse plane



$x - \eta_s$ plane ($y \sim 0$)

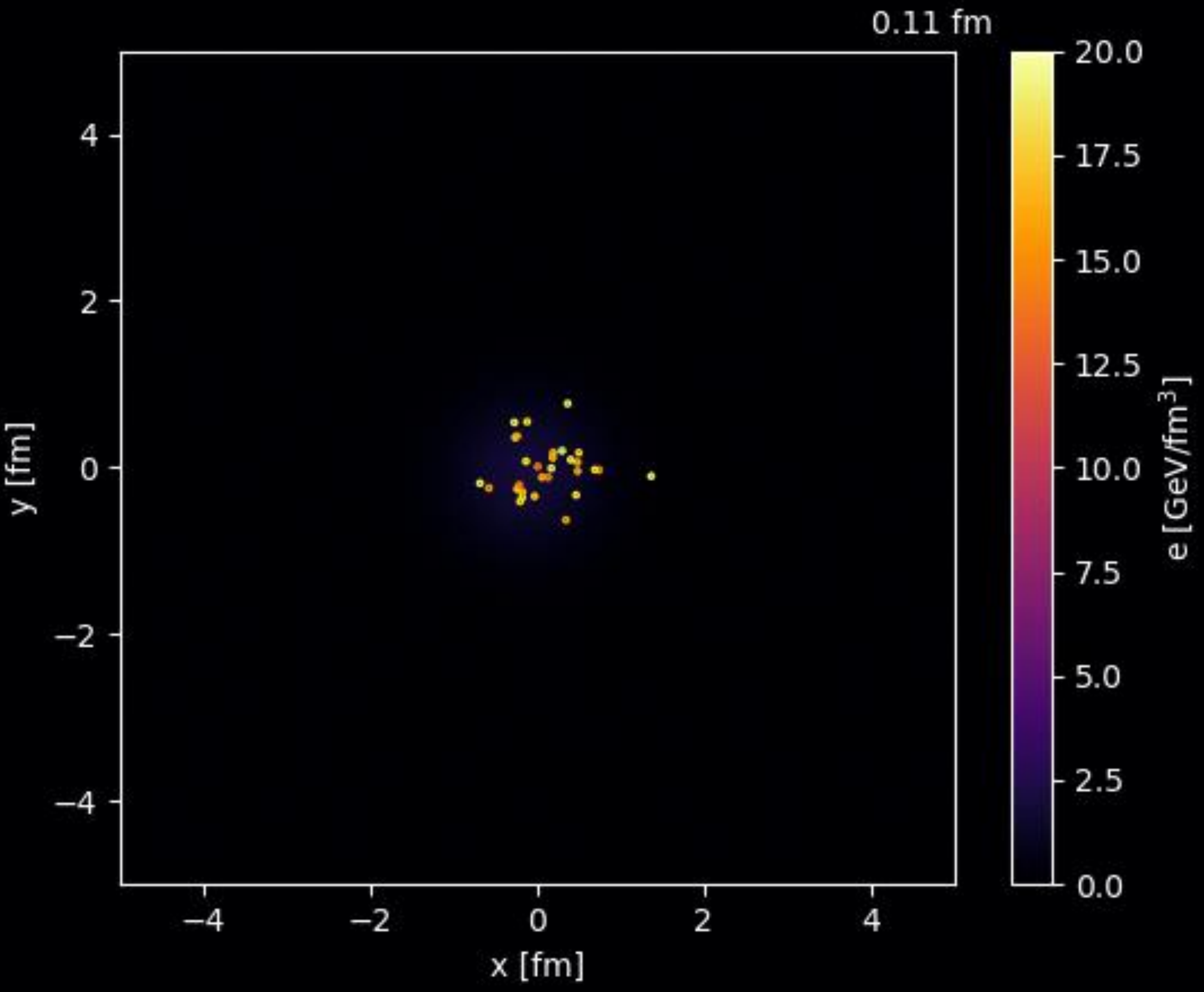


Initial partons from PYTHIA8/PYTHIA8 Angantyr

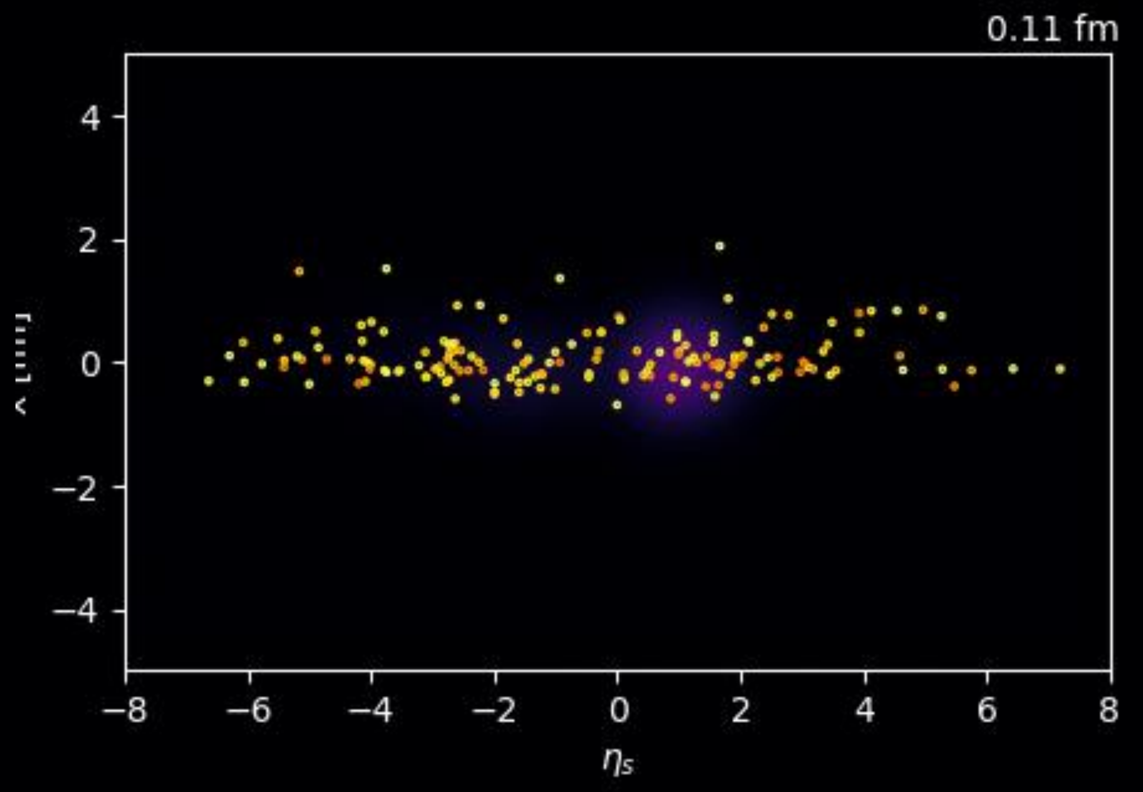
Demonstration of dynamical core-corona initialization

pp 7 TeV

Transverse plane



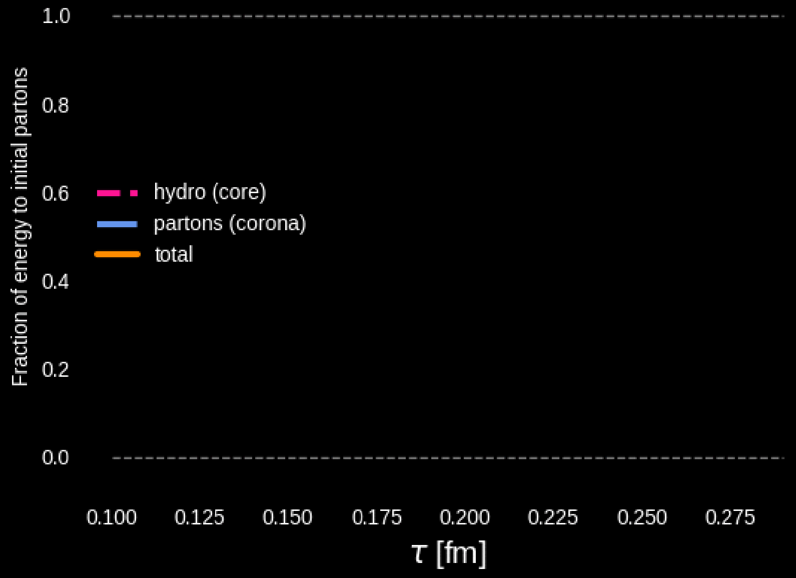
$x - \eta_s$ plane ($y \sim 0$)



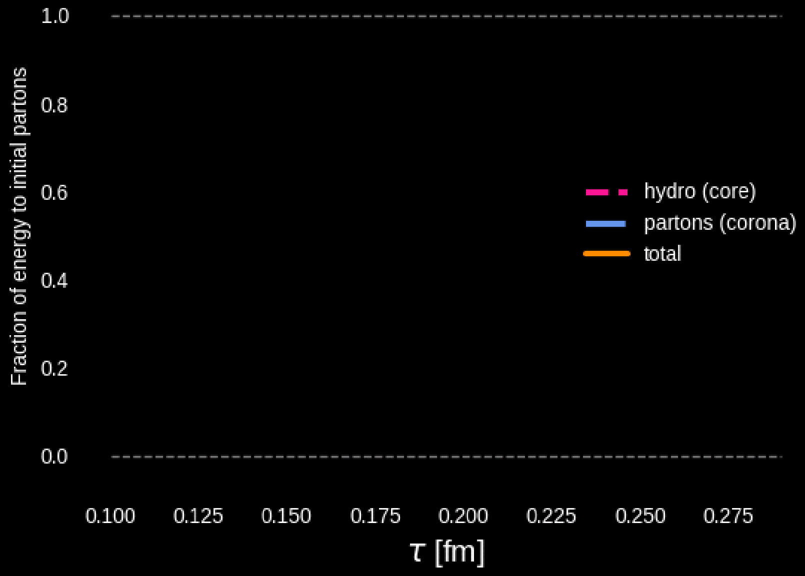
Energy budget in dynamical core-corona initialization

Dynamical energy conversion from initial partons (corona) to fluids (core)

PbPb



pp

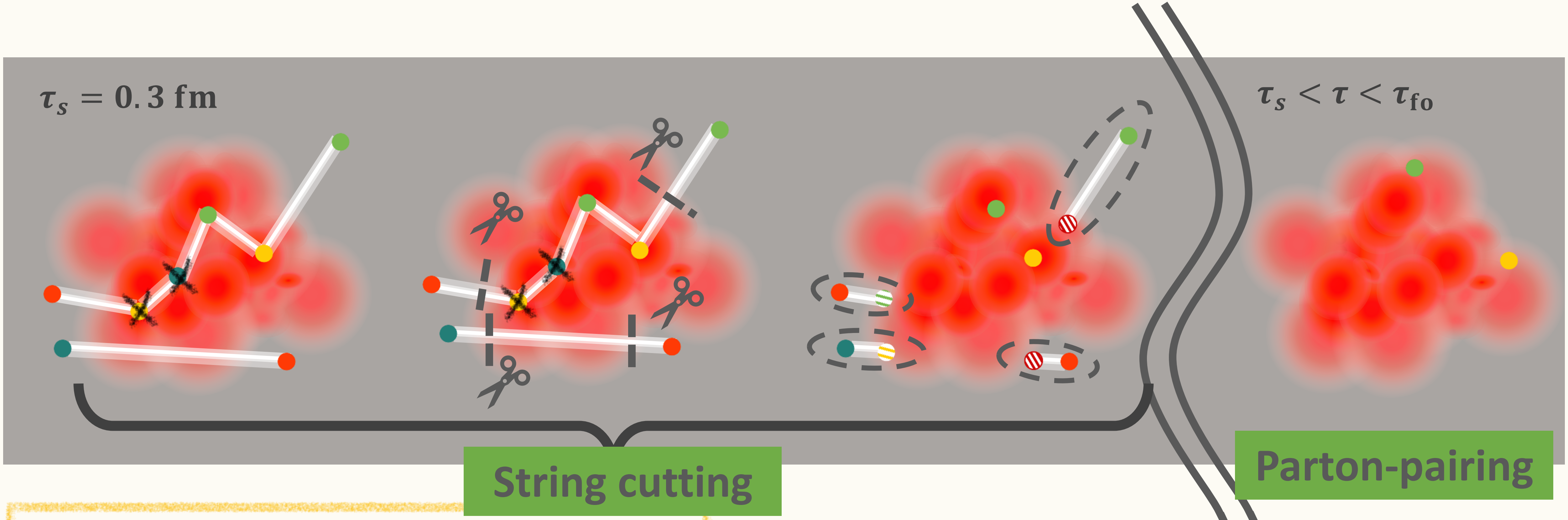


- **Starting from vacuum $T^{\mu\nu} = 0$ for fluids**
- **Energy & momentum conservation as total system**

Characteristic of DCCI2?

Dynamical realization **of core-corona picture**

Corona components from string modification

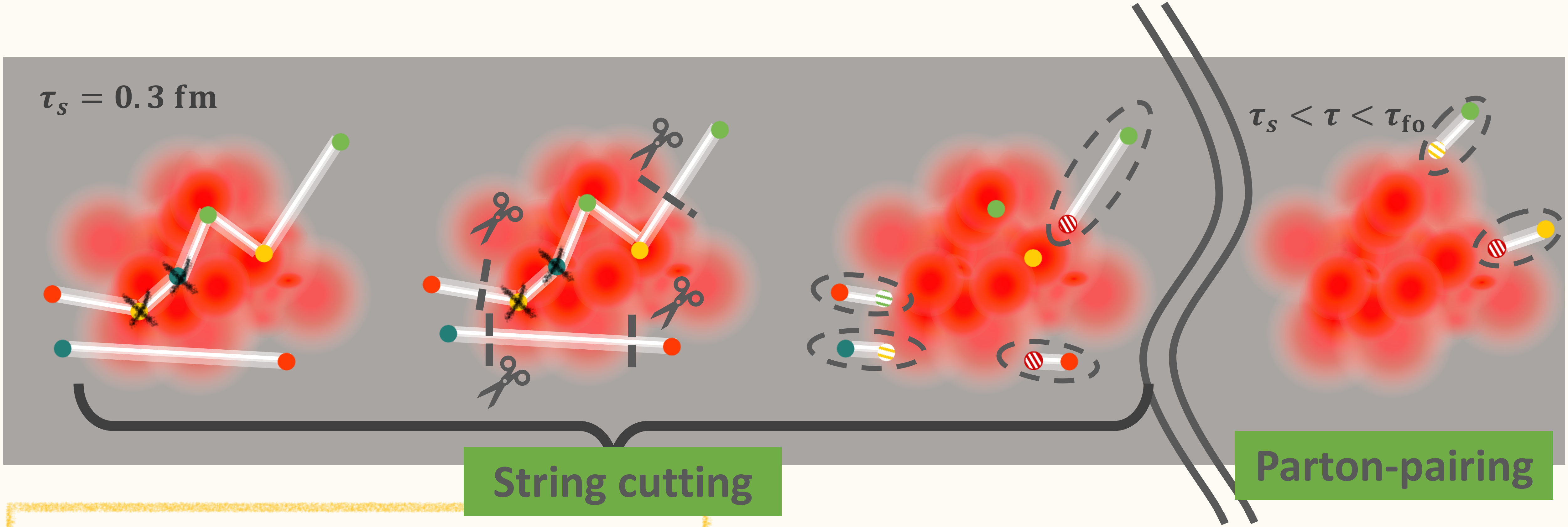


String modification caused by ..

- Spatial overlap of strings and medium
- Completely fluidized partons

1. Discard dead partons
2. Find hypersurface boundaries T_{sw}
3. Sample partons using Fermi/Bose distribution & boost with v_{fluid} at the boundary (recreation of color singlet)

Corona components from string modification (cont'd)



String modification caused by ..

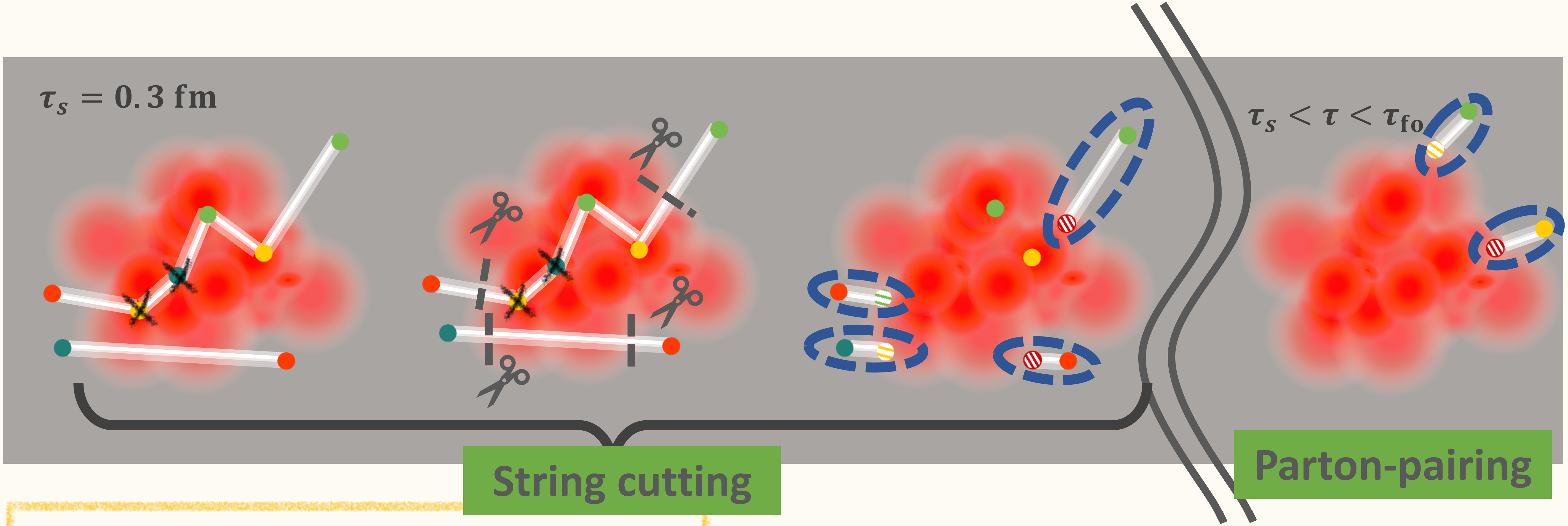
- Spatial overlap of strings and medium
- Completely fluidized partons

4. Surviving partons traverse medium
5. Make a pair for a parton coming out from medium

*Sampling of thermal partons: Bose/Fermi (massive)

*$p_{T,\rm cut}$: threshold to/not to modify a string

Corona components from string modification (cont'd)



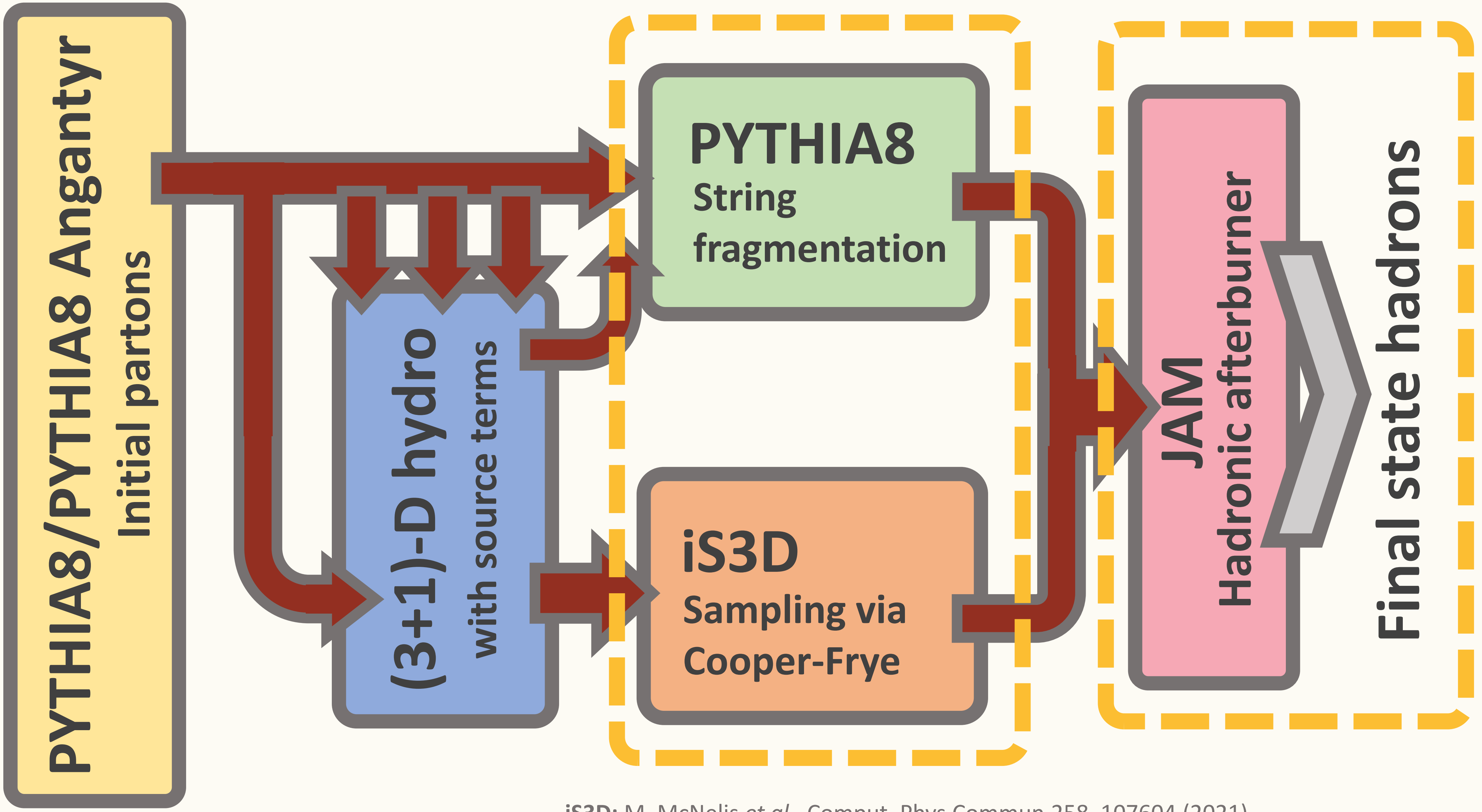
String modification caused by ..

- Spatial overlap of strings and medium
- Completely fluidized partons

Hadronized via string fragmentation
➔ Corona components

Model flowchart of DCCI2

Y. Kanakubo *et al.*, arXiv:2108.07943



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

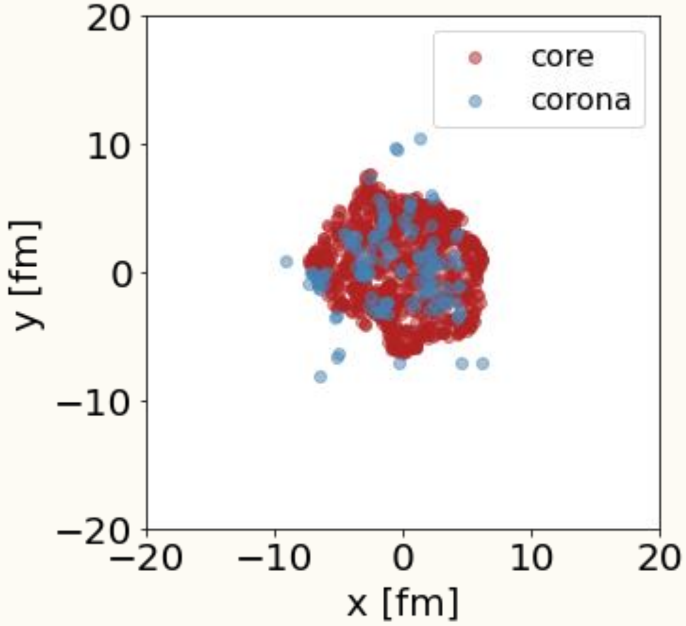
JAM: Y. Nara *et al.*,Phys. Rev. C61, 024901 (2000)

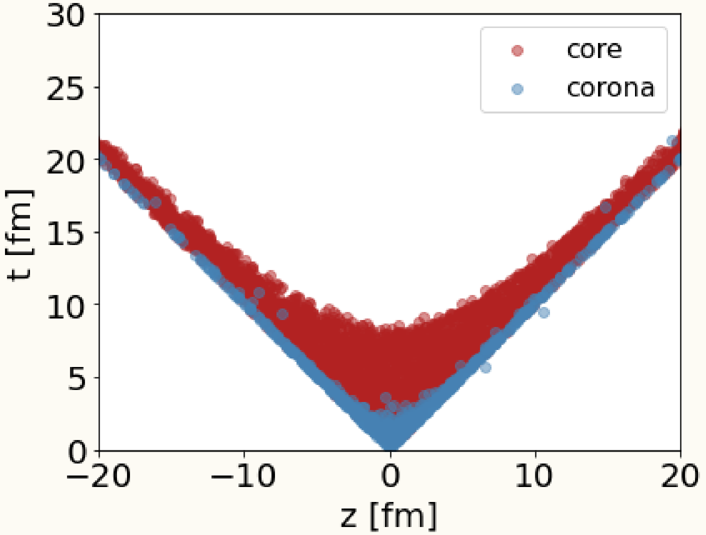
iS3D: M. McNelis *et al.*, Comput. Phys.Commun.258, 107604 (2021)

Space-time distribution of direct hadrons

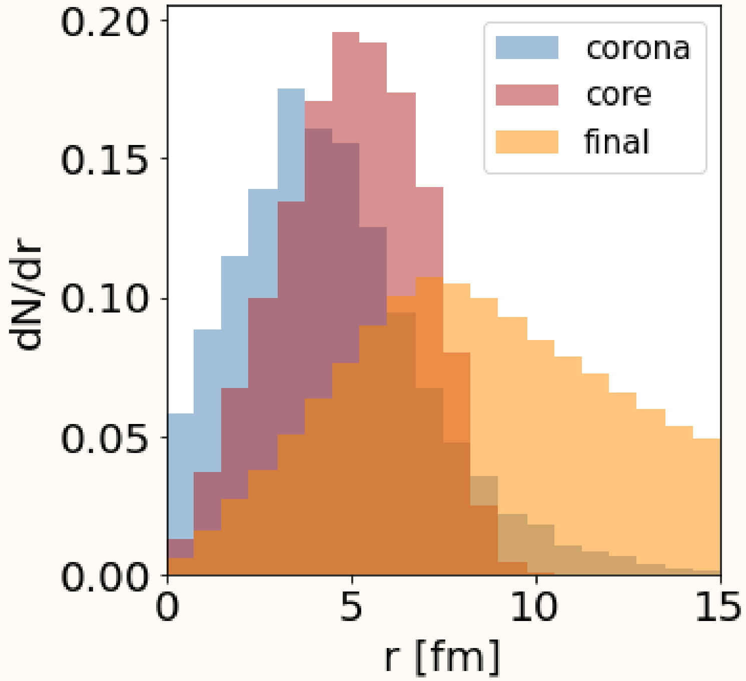
PbPb 2.76 TeV

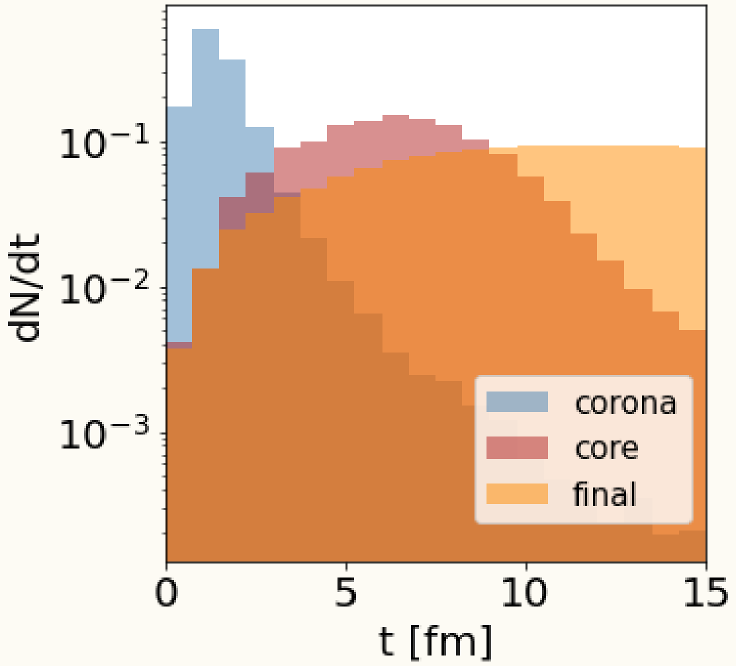
1 sampled event





Probability distribution ($|\eta| < 0.5$)



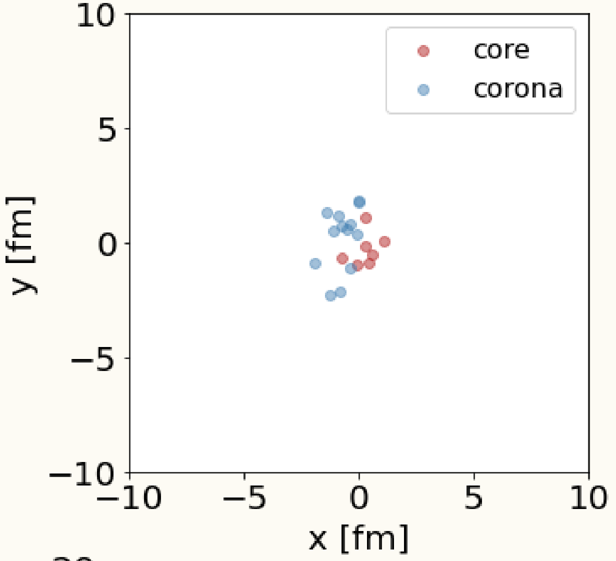


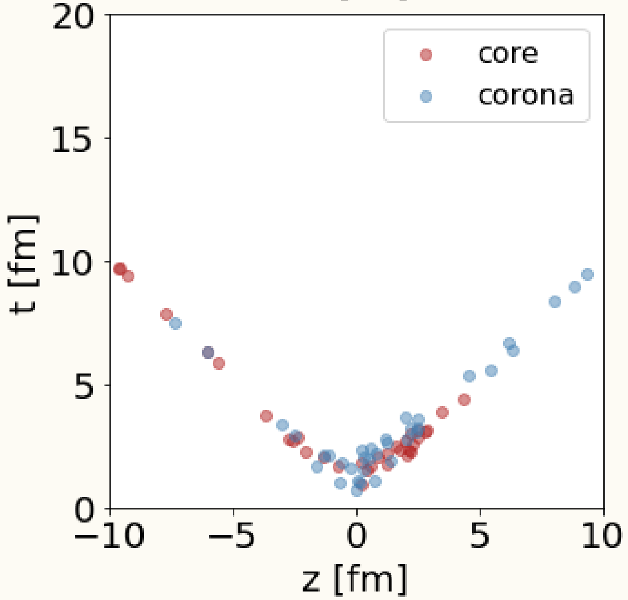
Double peaks of hadron vertices from core and corona before hadronic rescatterings

Space-time distribution of direct hadrons

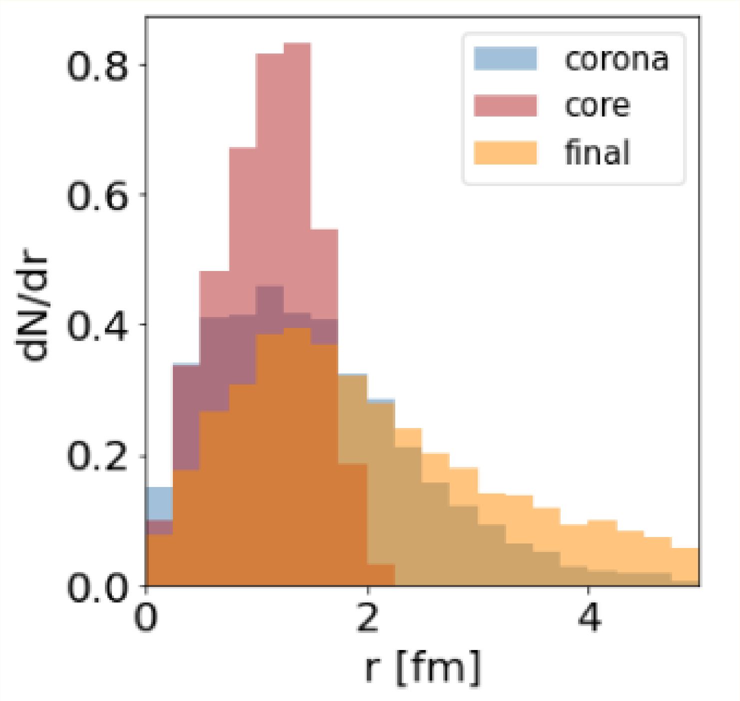
pp 7 TeV

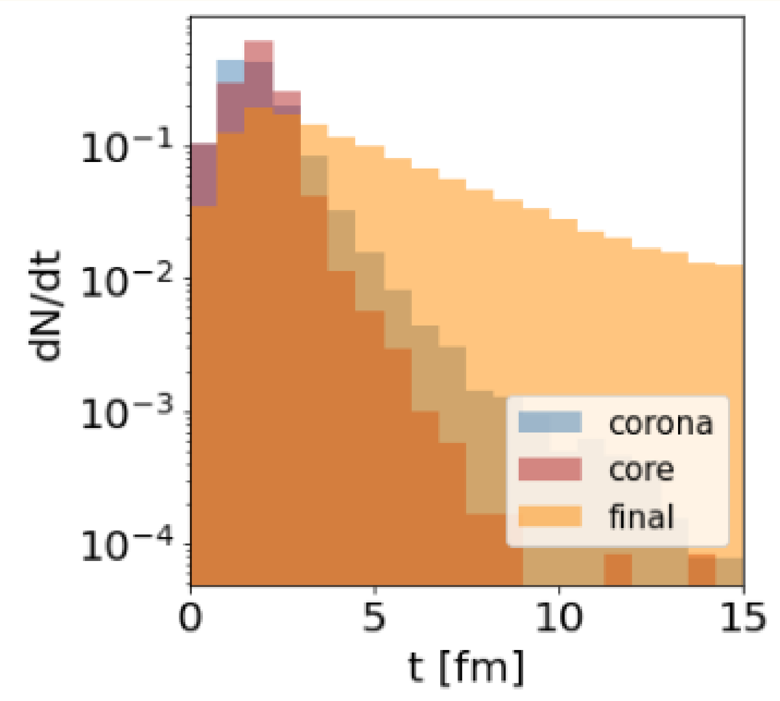
1 sampled event





Probability distribution ($|\eta| < 0.5$)





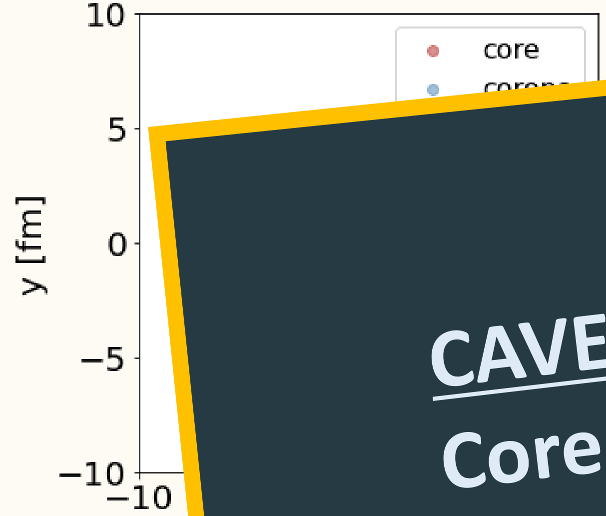
- Short lifetime of hydro ($\sim 1\,\mathrm{fm}$) in pp
- Direct hadrons from core and corona
  ➔ closely produced in space-time coordinate

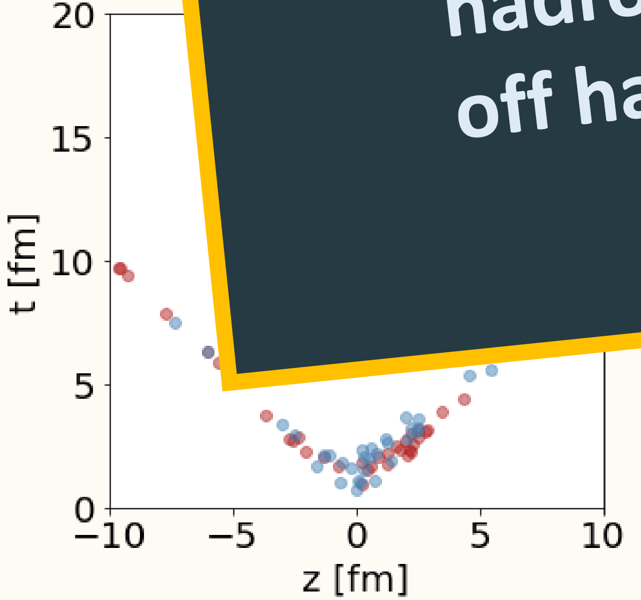
Space-time distribution of direct hadrons

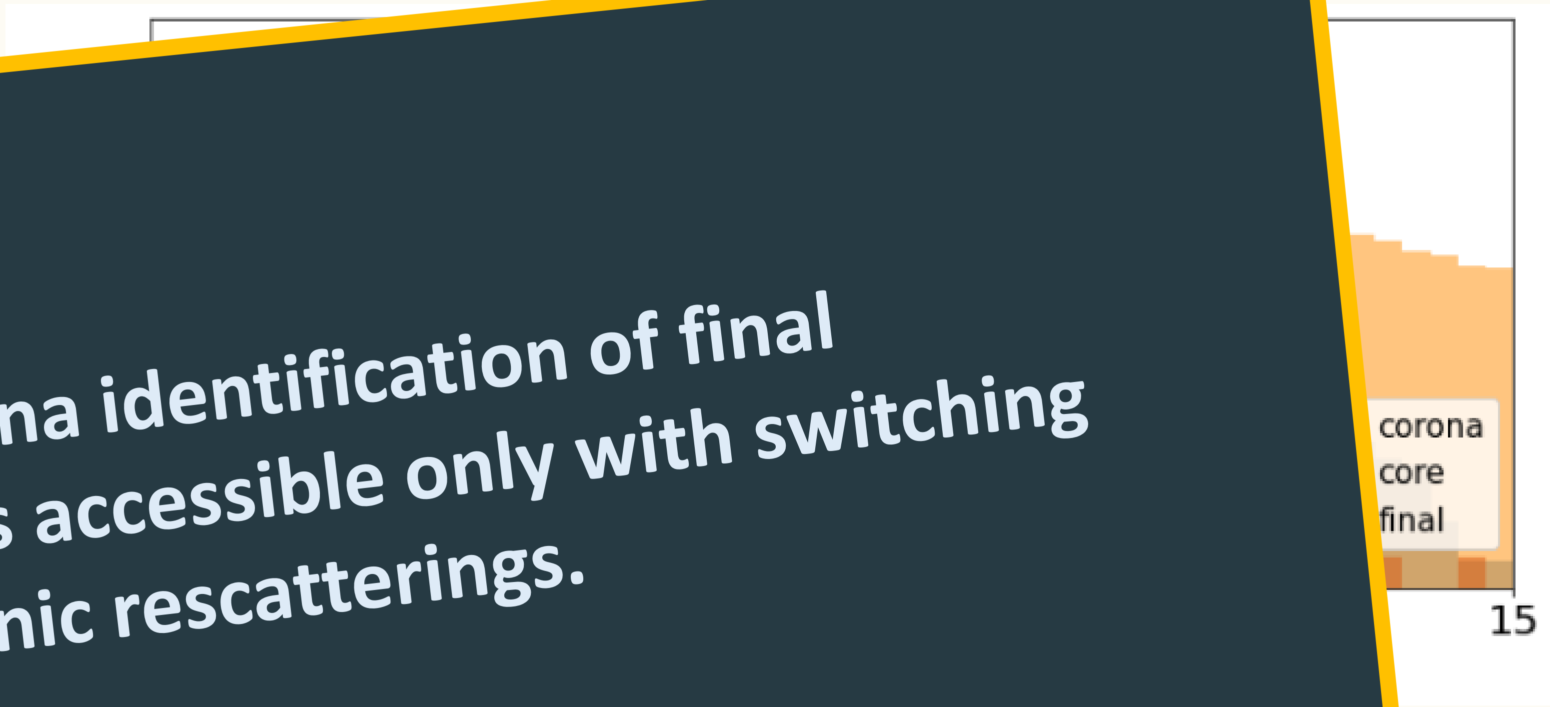
pp 7 TeV

1 sampled event

Probability distribution (|η| ... 5)







CAVEAT!
Core/corona identification of final hadrons is accessible only with switching off hadronic rescatterings.

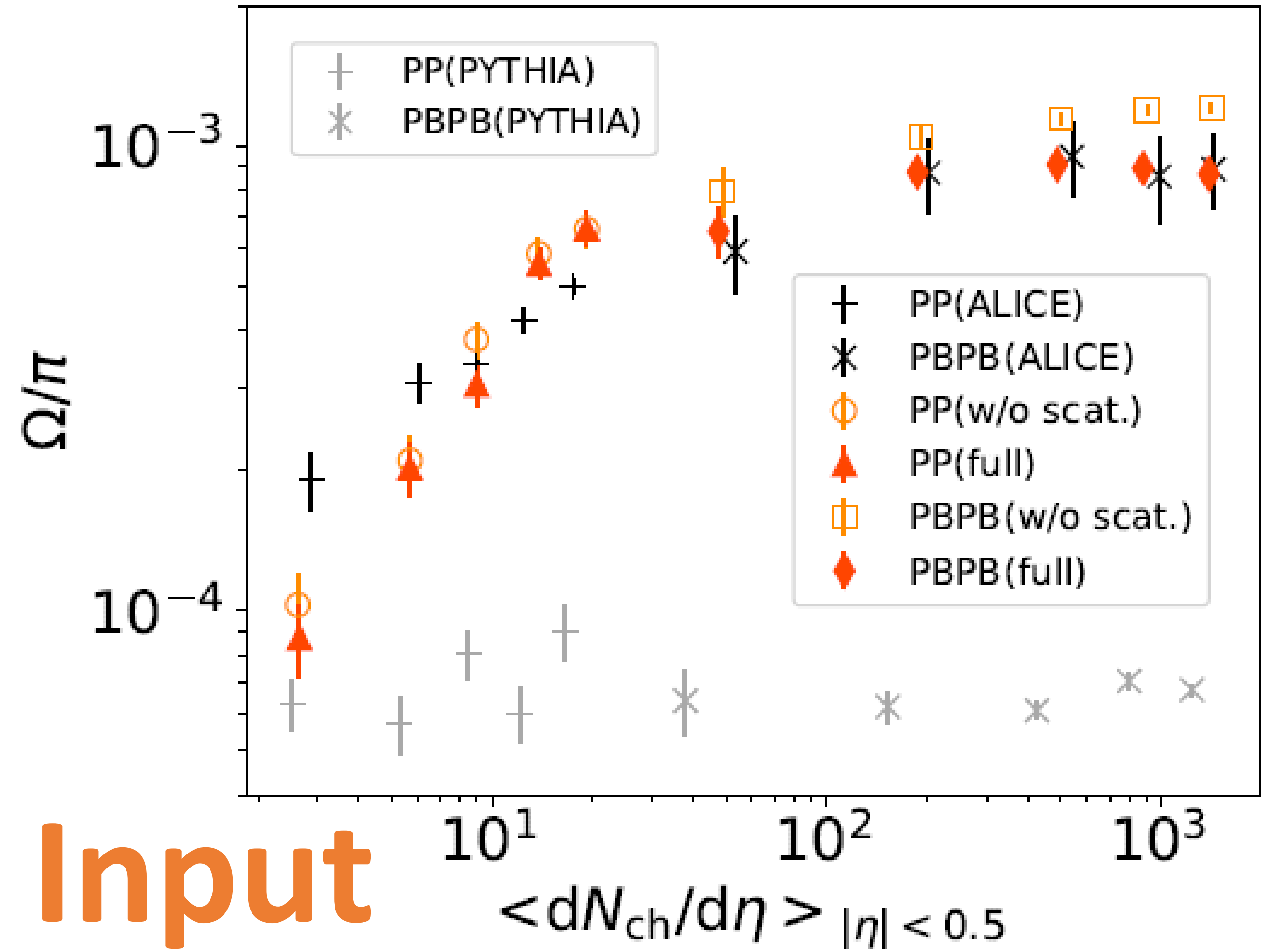
... of hydro ($\sim 1\ \mathrm{fm}$) in pp

- Direct hadrons from core and corona
  ➔ closely produced in space-time coordinate

Results from DCCI2

Ω/π ratio from pp and PbPb

Parameter fixing with Ω/π



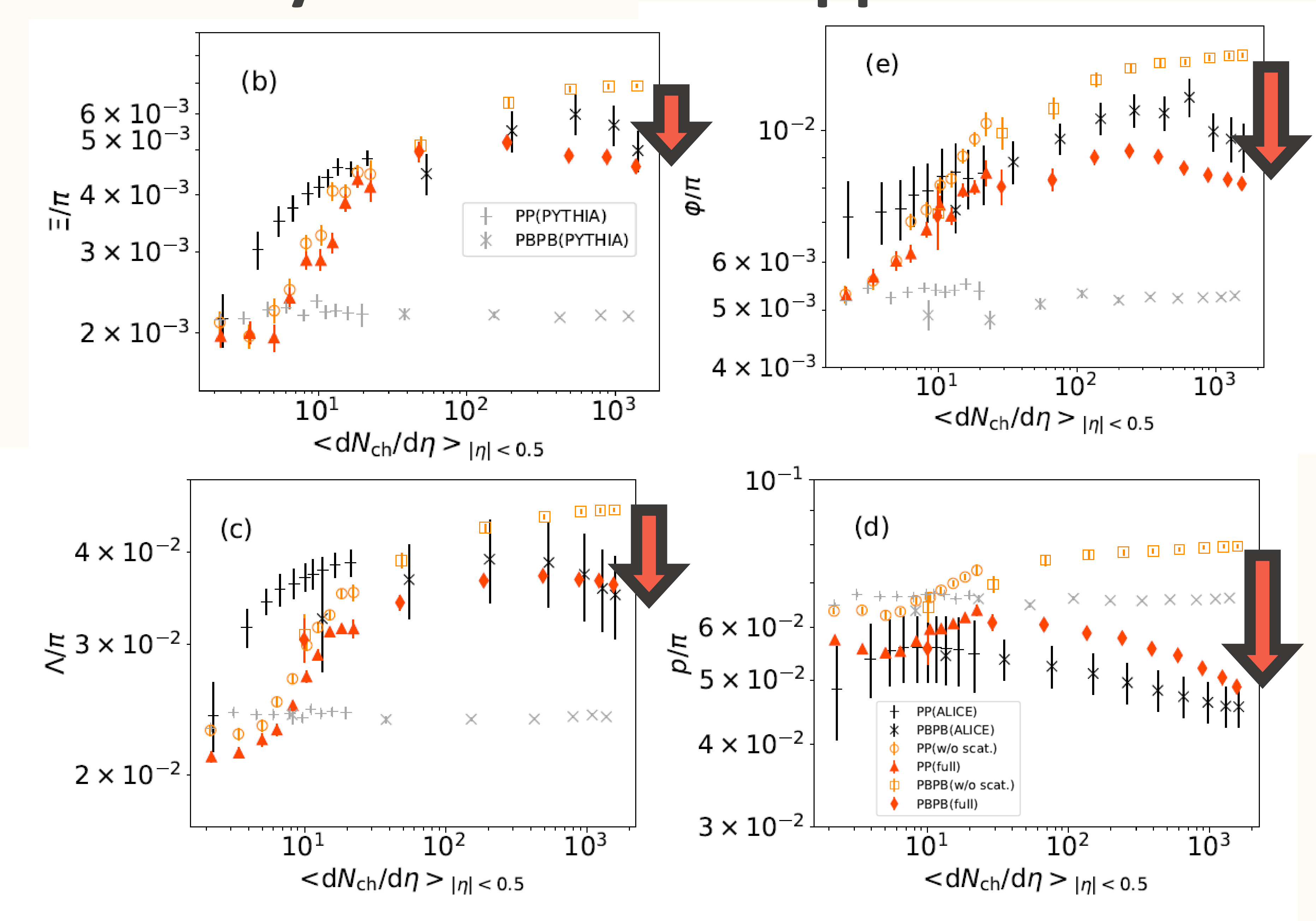
Input

Smooth enhancement of the ratio
➔ smooth increase of core contribution

QGP fluids
➔ Forced to be generated to describe strangeness enhancement from pp to PbPb

J. Adam *et al.*, (ALICE Collaboration), Nature Phys. 13 535-539 (2017)
B. Abelev *et al.* (ALICE Collaboration), Phys. Lett. B 728, 216-227 (2014); erratum 734, 409-410 (2014)

Particle yield ratios from pp and PbPb



Effects of hadronic rescatterings

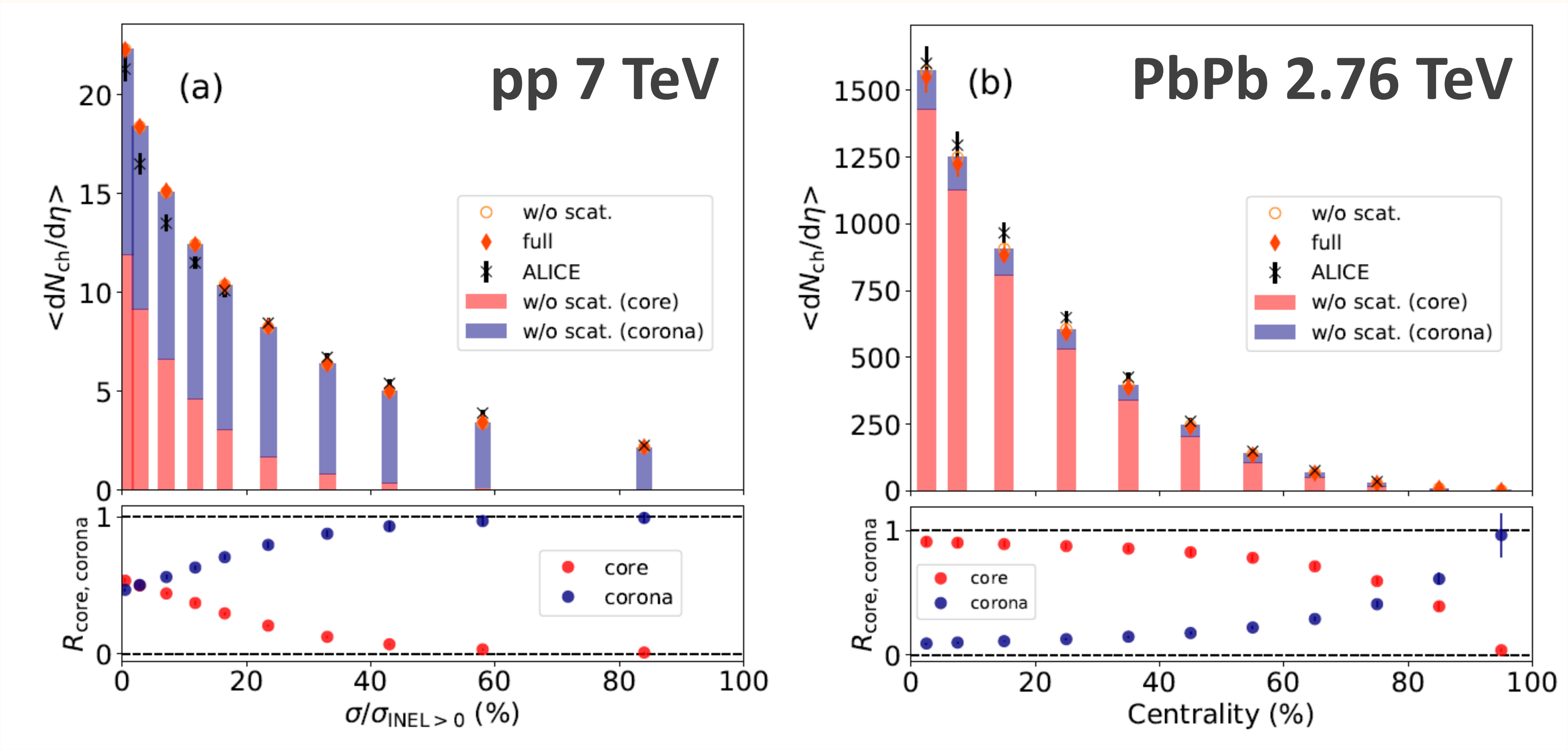
➔

Suppress particle yield ratios (dissociation/annihilation)

➔ Reproduction of qualitative behavior in exp.data

Core/corona fraction in multiplicity/centrality class

J. Adam *et al.*, (ALICE Collaboration), Nature Phys. 13 535-539 (2017)

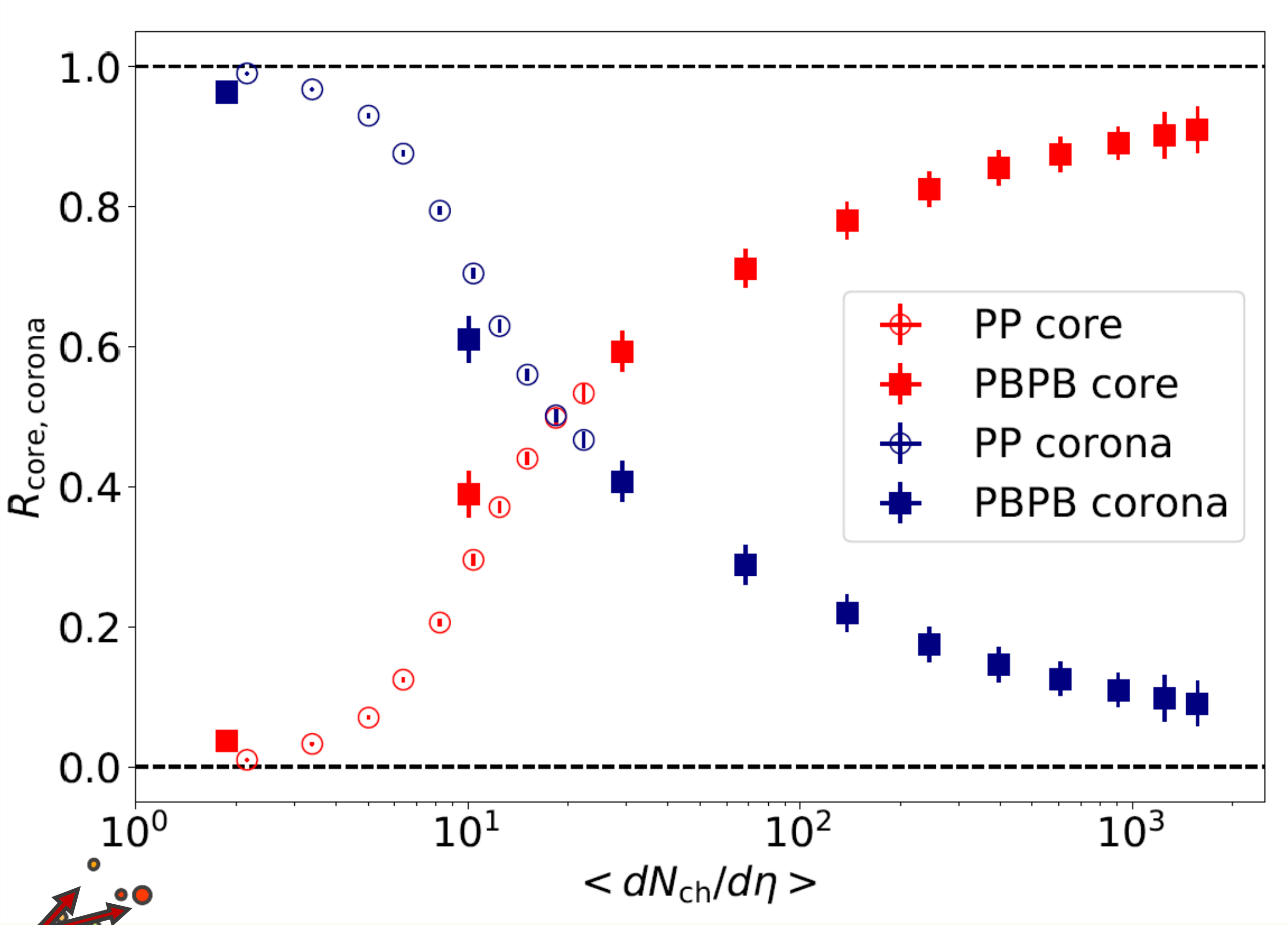


K. Aamodt *et al.*, (ALICE Collaboration), Phys. Rev. Lett. 106 032301 (2011)

- **pp: Excess of core contribution at the highest multiplicity class (0-0.95%)**
- **PbPb: $\sim 20\%$ fraction of corona in intermediate central events (40-60%)**

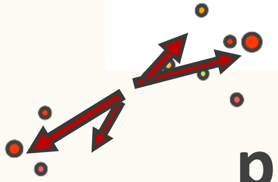
➔ Need both of core and corona in pp and AA!

Fraction of core and corona vs. $\langle dN_{\mathrm{ch}}/d\eta \rangle$ from pp to PbPb



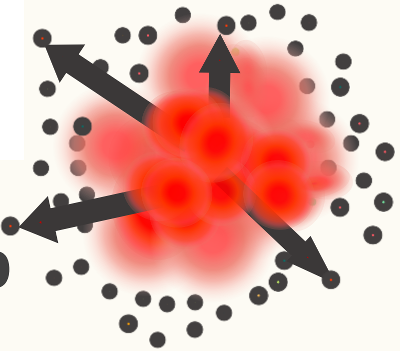
Clear scaling with multiplicity

Change of dominant contribution at $\langle dN_{\mathrm{ch}}/d\eta \rangle \sim 18$

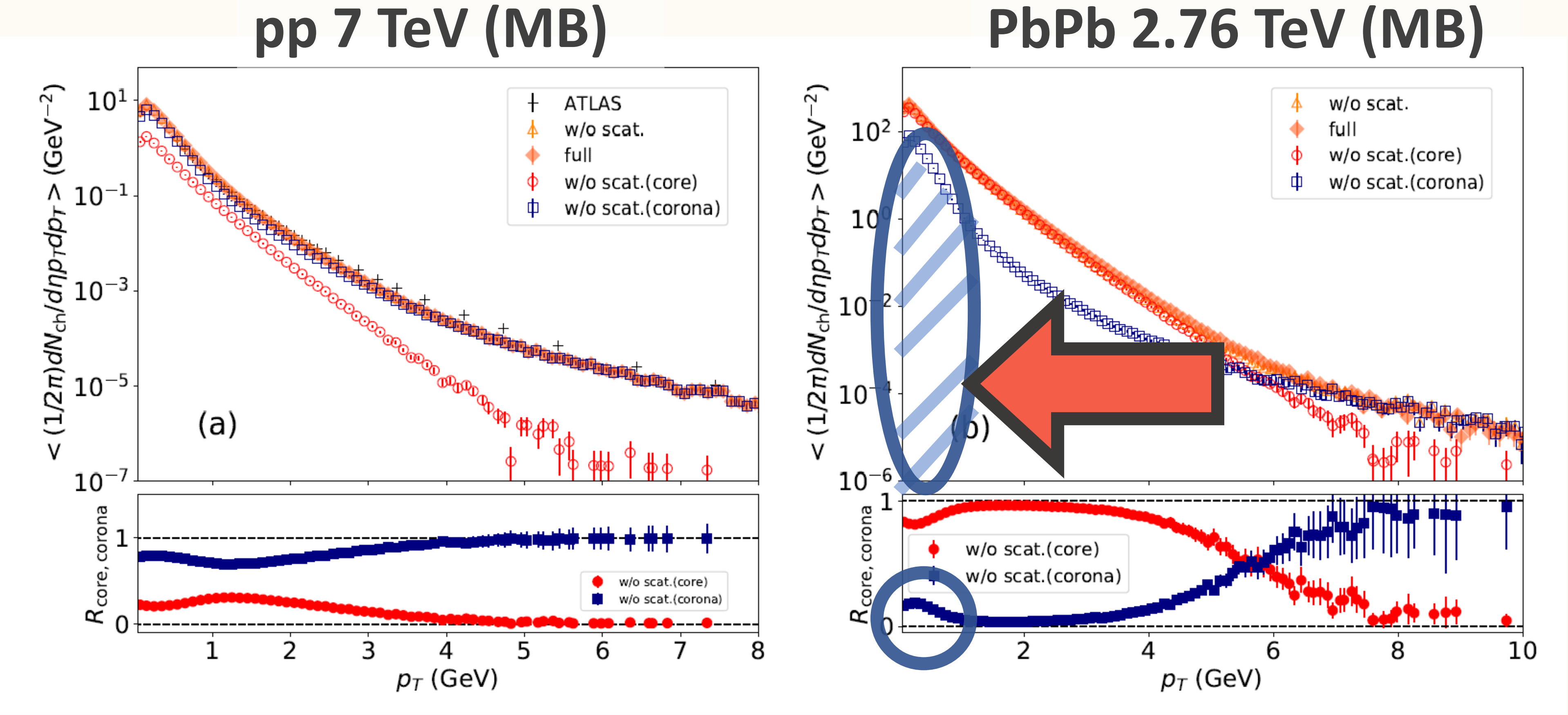


pp

PbPb



Smooth description from low to high p_T



G. Aad *et al.*, (ATLAS Collaboration), New J. Phys. 13 053033 (2011)

pp: Dominant corona contribution for all p_T range

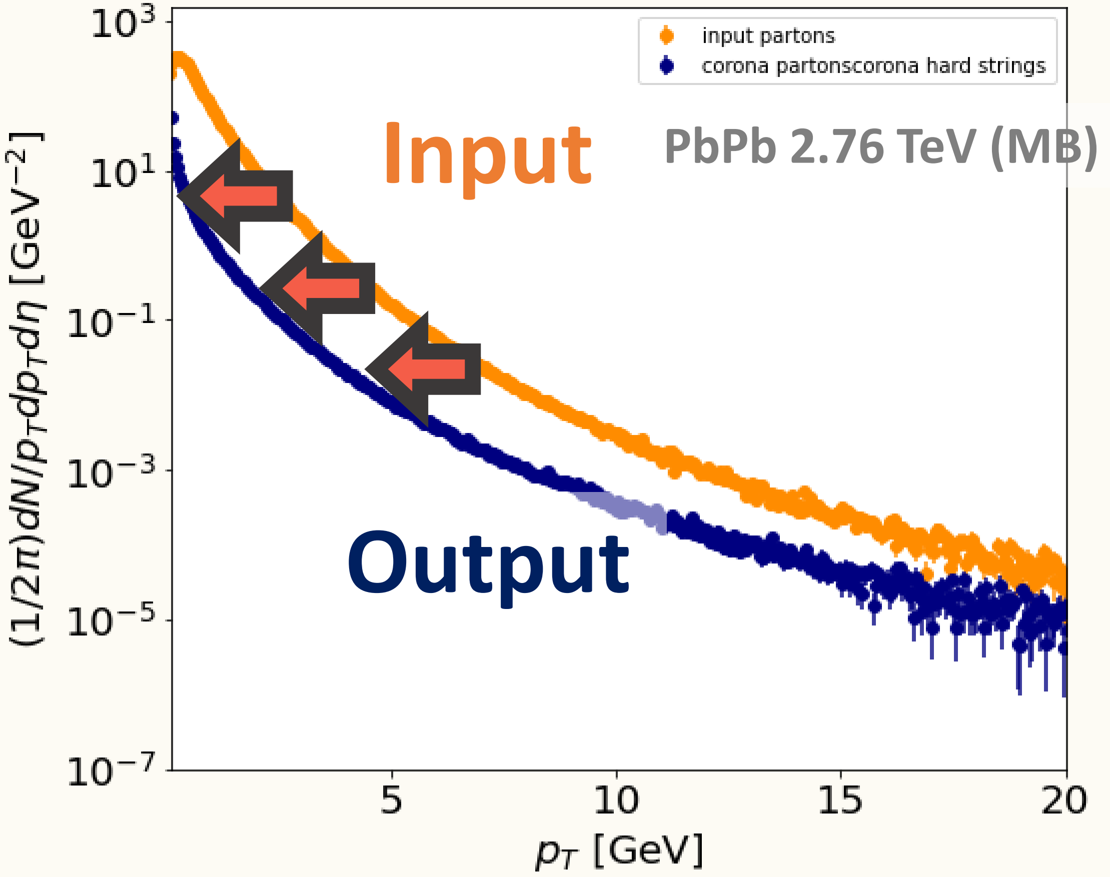
PbPb: Dominant contribution flips at ~ 5.5 GeV.

Non-negligible corona contribution ($\sim 20\%$) at very low p_T (< 1 GeV)

Keep in mind soft from corona!

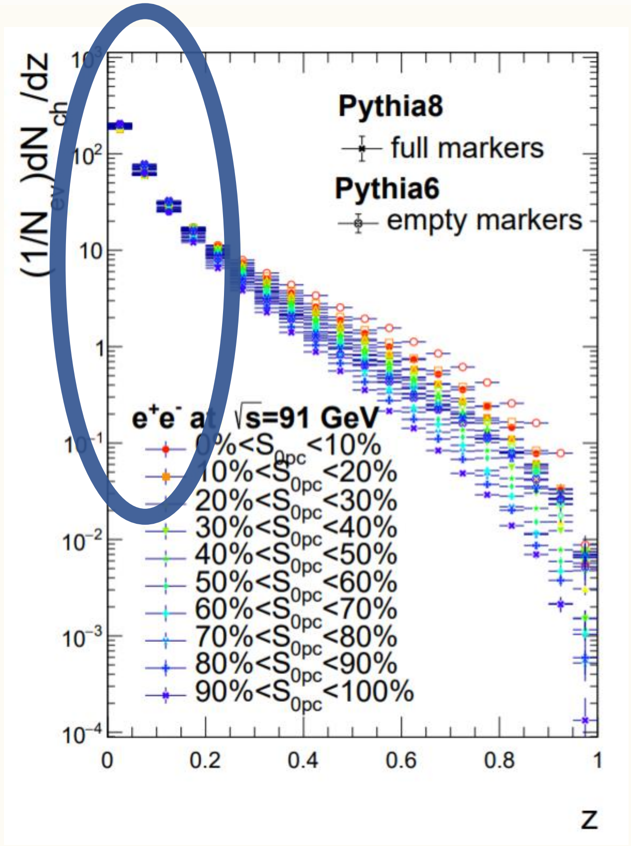
Origin of corona contribution at low p_T

p_T distribution of partons (corona)



Dynamical deposition of p_T ➔ shift of p_T

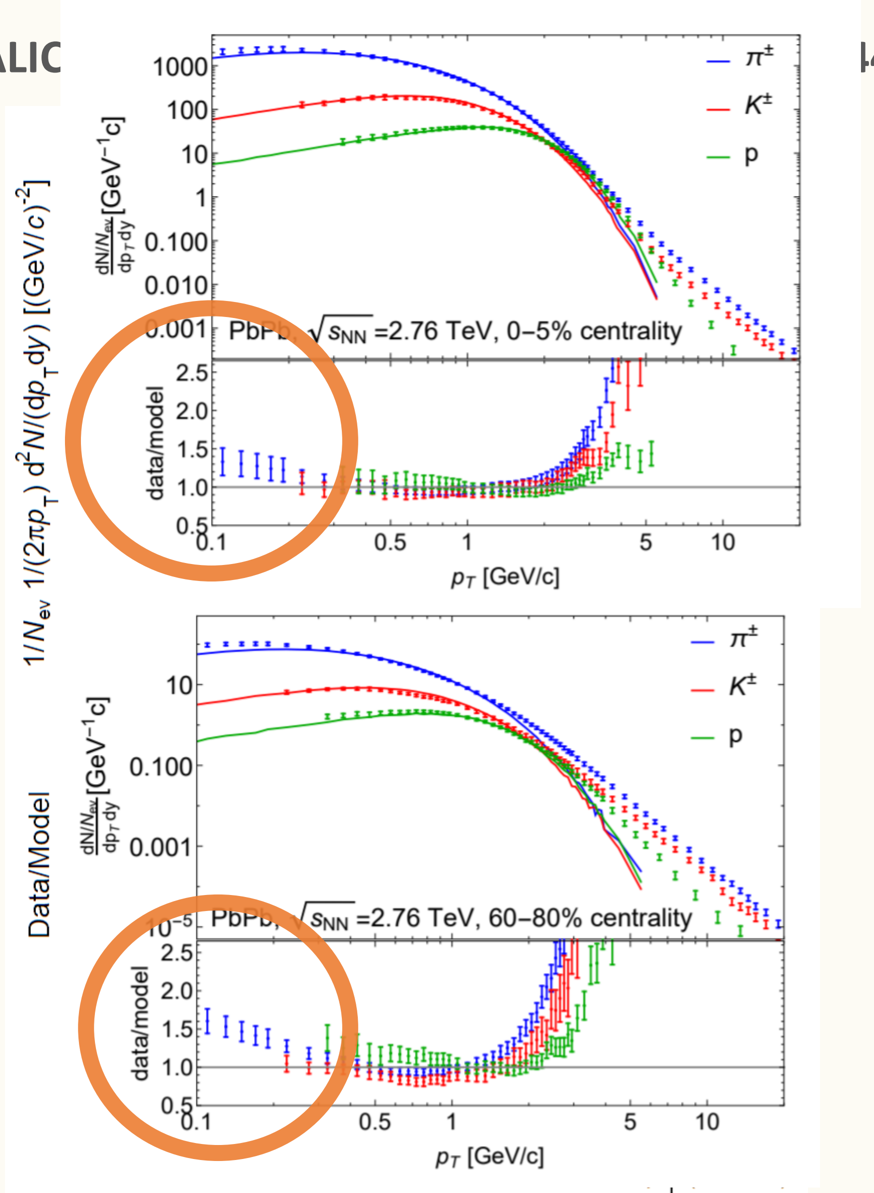
Fragmentation function in PYTHIA



PoS LHCP2019 (2019) 050

➔ Low z (soft) production should appear

Lack of low p_T yield from Hydro



Phys.Rev.C 103 (2021) 5, 054909

Comparisons between exp. data and hydro models

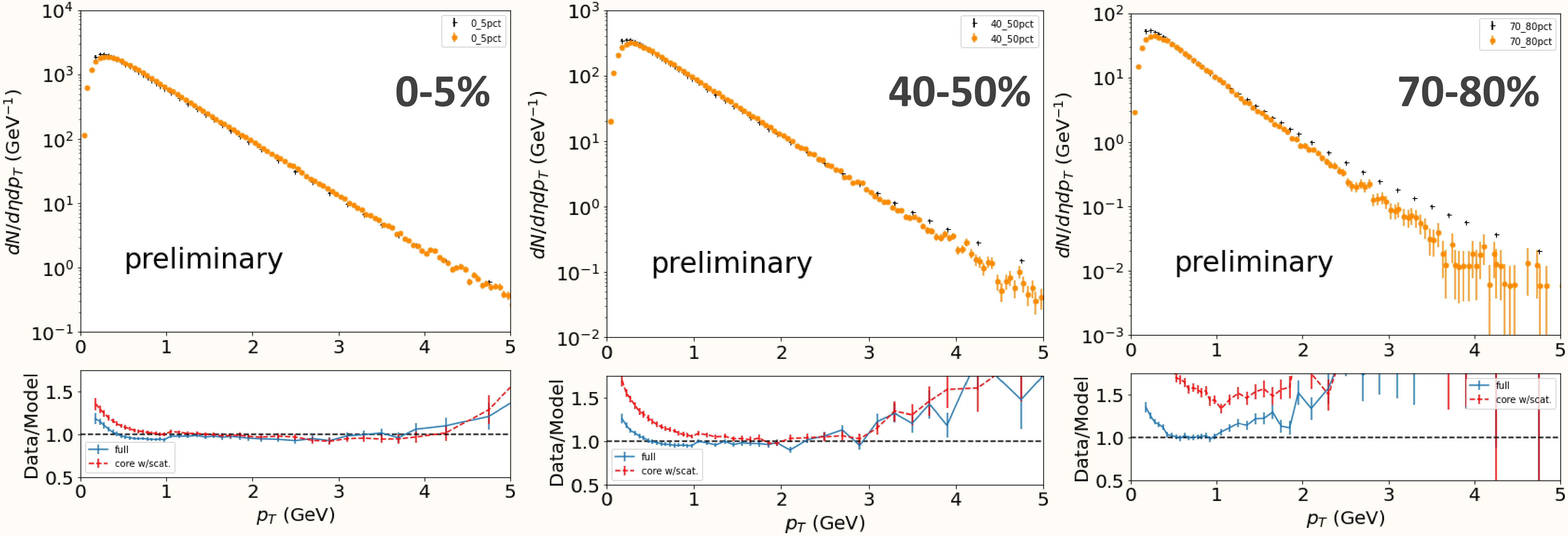
➔ **Lack of (very) low p_T yield in hydro models**

Be careful with semi-log plot!

Other sources to compensate the low p_T yield?

Comparisons of charged p_T spectra between DCCI and exp. data

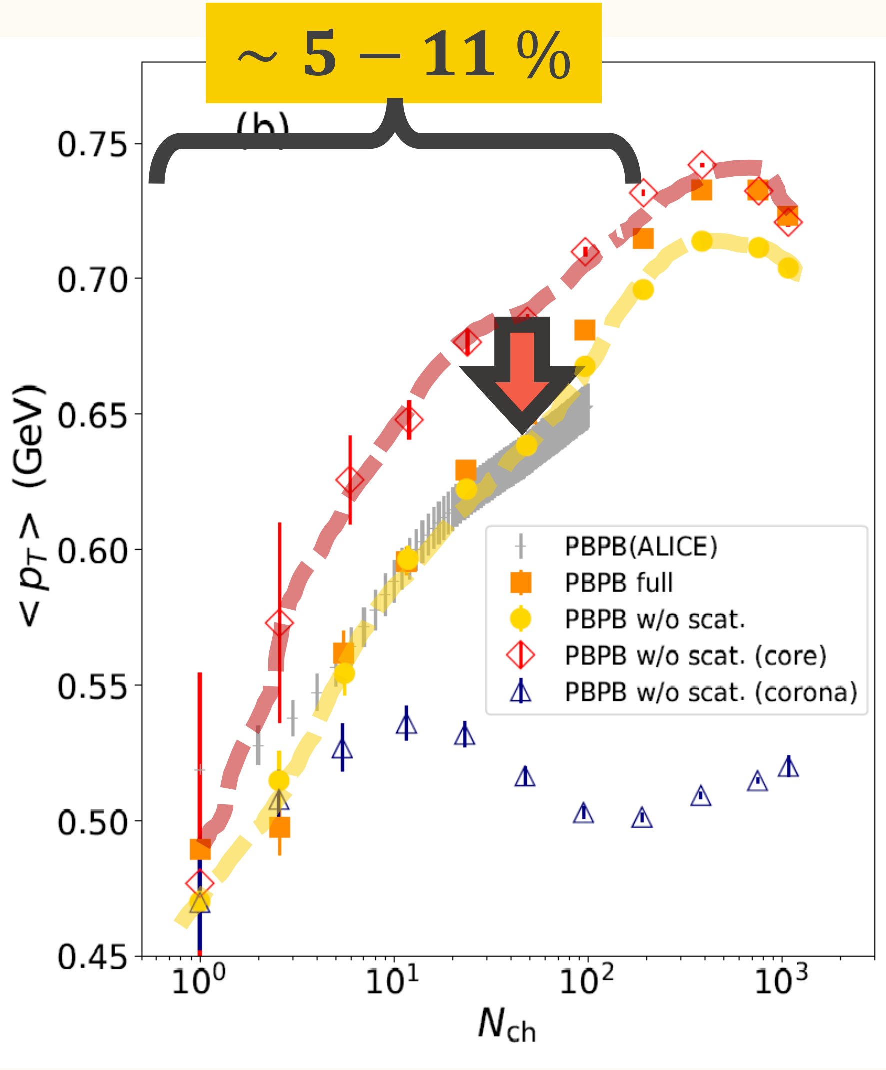
ALICE Collaboration, JHEP 11 (2018) 013

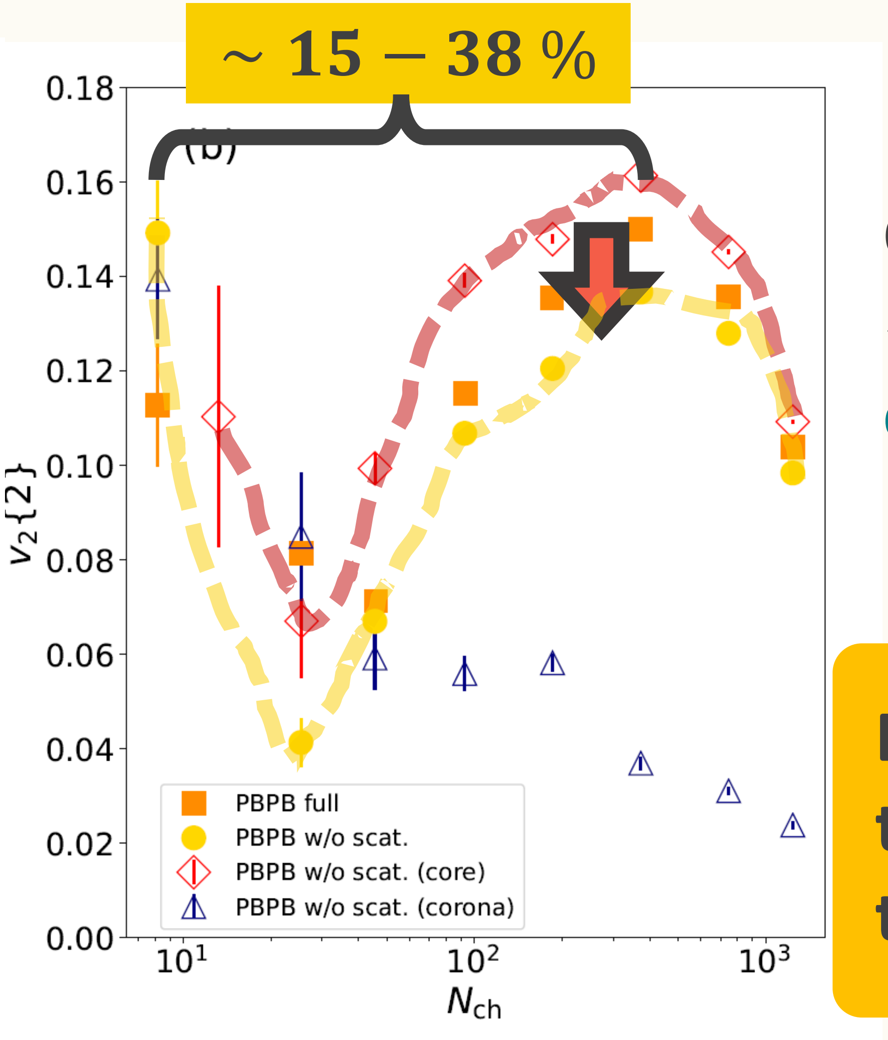


Pure hydro results cannot reproduce the slopes of spectra obtained in experimental data

⇨ **Possible compensation of low p_T production with corona contribution**

Corona correction in PbPb





Corona contribution
$\sim$ "Far from" equilibrium correction to hydro!

Even PbPb needs corona to properly extract transport coefficients(?)

Summary

Dynamical core-corona initialization model (DCCI2)

- Respect beam energy (as a MC event generator)
- Both equilibrated and non-equilibrated matter

➔ From low to high p_T, from pp to AA

Extraction of core/corona fraction in multiplicity/centrality classes
➔ Excess of core contribution over corona contribution at $\langle dN_{\mathrm{ch}}/d\eta \rangle \sim 18$ regardless of collision systems or energy.

Non-negligible contribution of corona at very low p_T $(< 1\ \mathrm{GeV})$ in PbPb
➔ Corona dilutes $\langle p_T \rangle$ by $\sim 5 - 11\%$ and $v_2\{2\}$ by $\sim 15 - 38\%$.

Towards accurate study of QGP properties!
➔ Importance of interplay between core and corona

Outlooks

- Extension to viscous (& fluctuating) hydro
- Process to local equilibrium
- Jet quenching
- Charge conservation

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A ton of work to do. Stay tuned!

Thank you!