JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

SUOMEN AKATEMIA
FINLANDS AKADEMI
ACADEMY OF FINLAND

HELSINKI INSTITUTE OF PHYSICS

CoE QM

Interplay between core and corona from small to large colliding systems

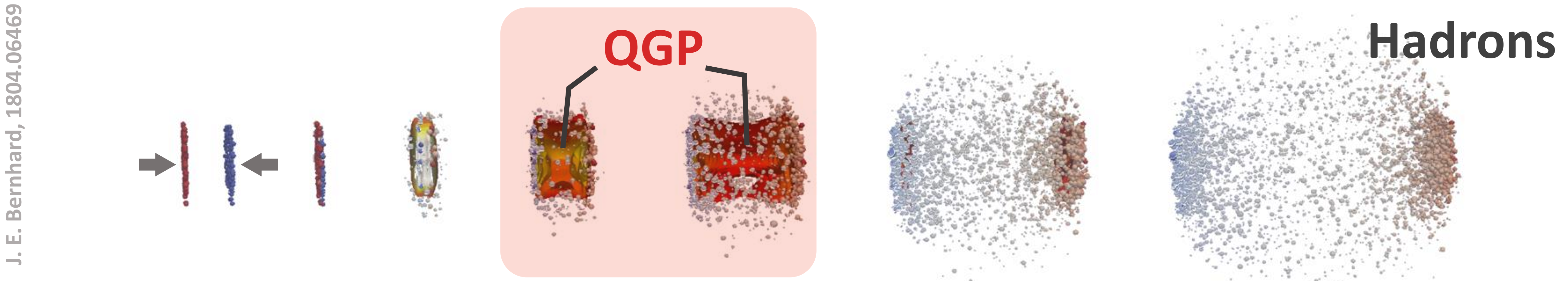
Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905   Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908

Yuuka Kanakubo[1,2]
[1] University of Jyväskylä, Centre of Excellence in Quark Matter

Collaborators: Yasuki Tachibana[2,3], Tetsufumi Hirano[2]
[2] Sophia University, [3]Akita International University

QGP study via relativistic heavy-ion collisions

Extraction of properties from direct comparisons with data



Initial state | Evolution of QGP | Hadronic afterburner

Initial condition

Relativistic hydrodynamics

Fluids to particles

Hadronic transport

QGP signals in small colliding systems

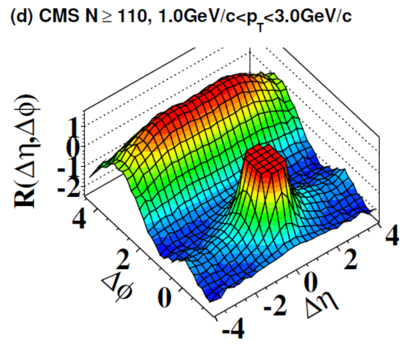
In **high-multiplicity** small systems (pp, pA)…

Thermal strange hadron productions

Hydro-like collectivity

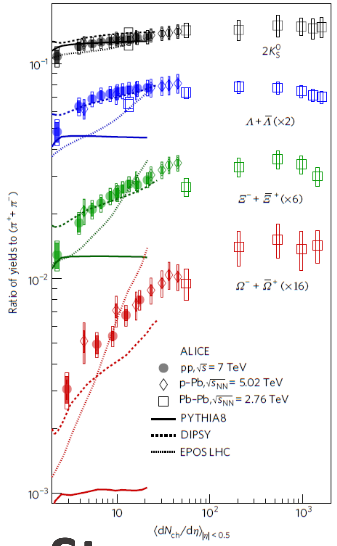
Challenge to interpret the universal behavior from pp to AA

… within a single dynamical framework?



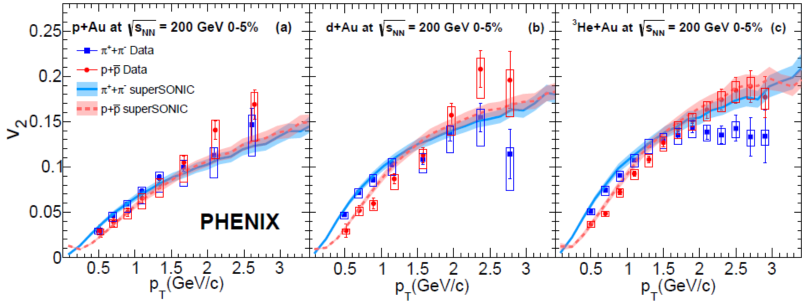
Long range correlation

CMS Collaboration, JHEP 09 091 (2010)



Strangeness enhancement

ALICE Collaboration, Nature Phys. 13 535-539 (2017)

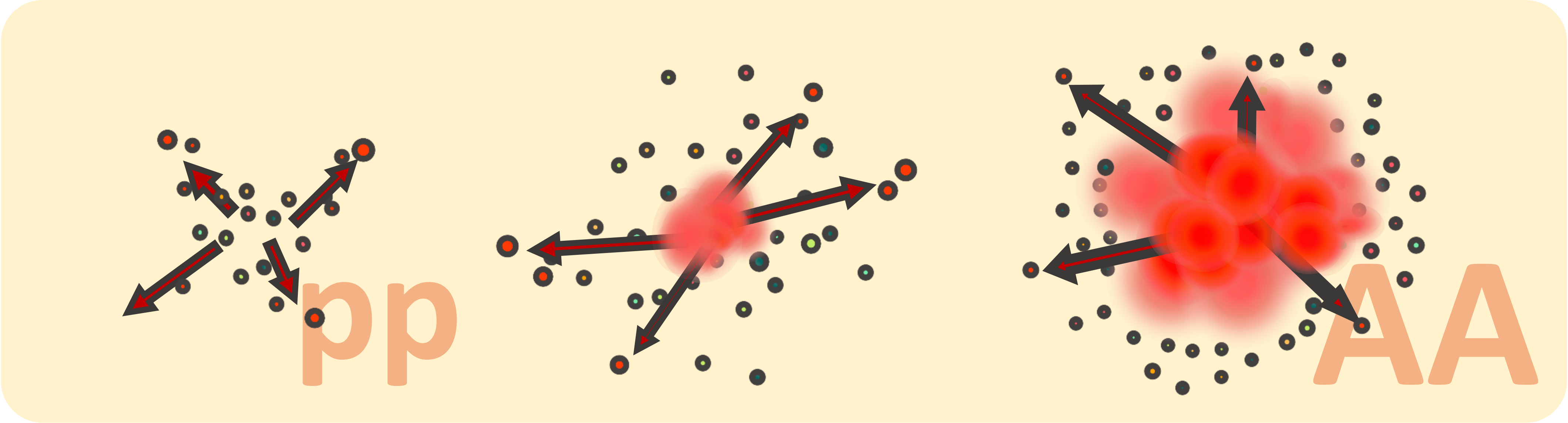


Flow harmonics

PHENIX Collaboration, Phys. Rev. C 97, 064904 (2018)

Dynamical Core-Corona Initialisation framework

Core-corona: K. Werner, Phys. Rev. Lett. 98 (2007) 152301



Core: fluids (equilibrated matter) ➔ Hydrodynamics

Corona: non-equilibrated partons ➔ String fragmentation

Two different components/hadronisation

From pp to AA, from low to high p_T **Dynamical initialisation $\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = J^\nu$**

Y. Kanakubo *et al.*, PTEP 2018 12, 121D01 (2018);
Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020);
Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905

Dynamical Core-Corona Initialization model 2

Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905

Model flowchart of DCCI2

Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905

Initial partons: PYTHIA8/PYTHIA8 Angantyr

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

Dynamical initialization of QGP fluids based on core-corona

Equilibrated matter (core)

(3+1)-D hydro with source terms

Y. Tachibana *et al.*, Phys. Rev. C 90, 021902 (2014)

iS3D (thermal hadron sampling)

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

Non-equilibrated partons (corona)

PYTHIA8 (string fragmentation)

Hadronic afterburner: JAM

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

Dynamical initialization framework

New framework to dynamically generate initial condition

M. Okai *et al.*, Phys.Rev.C 95 (2017) 5, 054914   C. Shen and B. Schenke, Phys.Rev.C 97 (2018) 2, 024907

Continuum eq. for fluids + partons

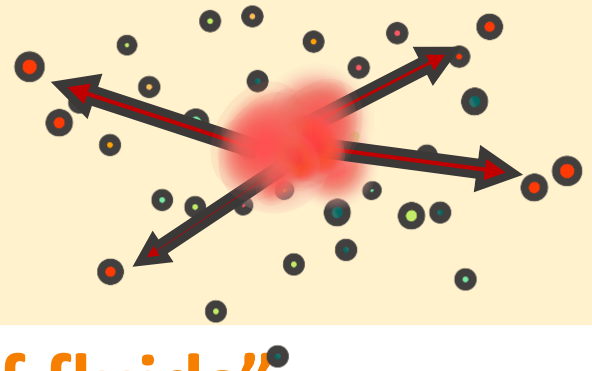
$$\partial_\mu \left(T^{\mu\nu}_{\text{fluid}} + T^{\mu\nu}_{\text{parton}} \right) = 0$$

Hydrodynamic eq. with source term

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

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

Energy-momentum conservation in fluid + parton



"Sources of fluids"
= "energy-momentum of partons"

Dynamical core-corona picture

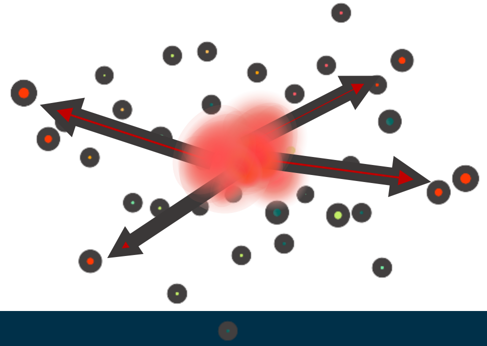
Multiple scatterings among partons ➔ partial equilibration

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

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

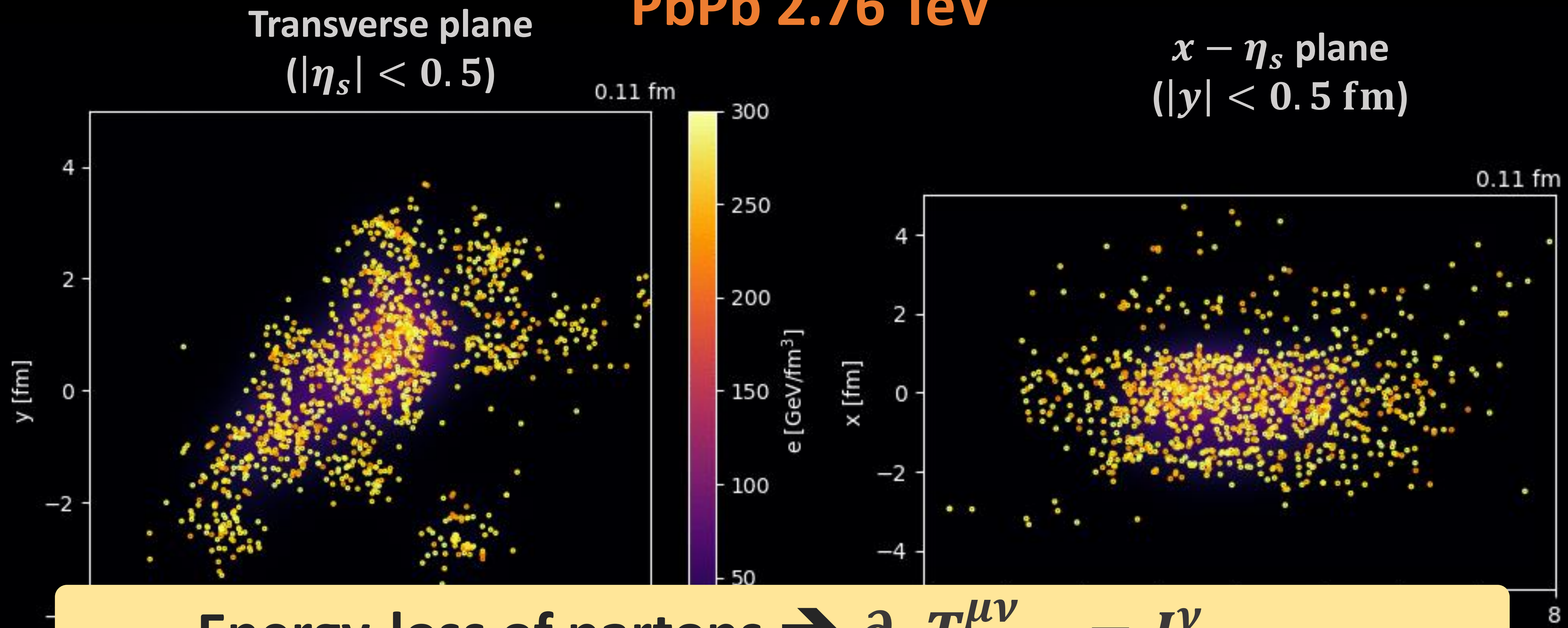
Energy-momentum deposition
➔ # of scatterings with partons (non-equilibrated and equilibrated)

Low p_T and/or dense region ➔ Core (fluids)
High p_T and/or dilute region ➔ Corona (partons)



Dynamical core-corona initialization

PbPb 2.76 TeV

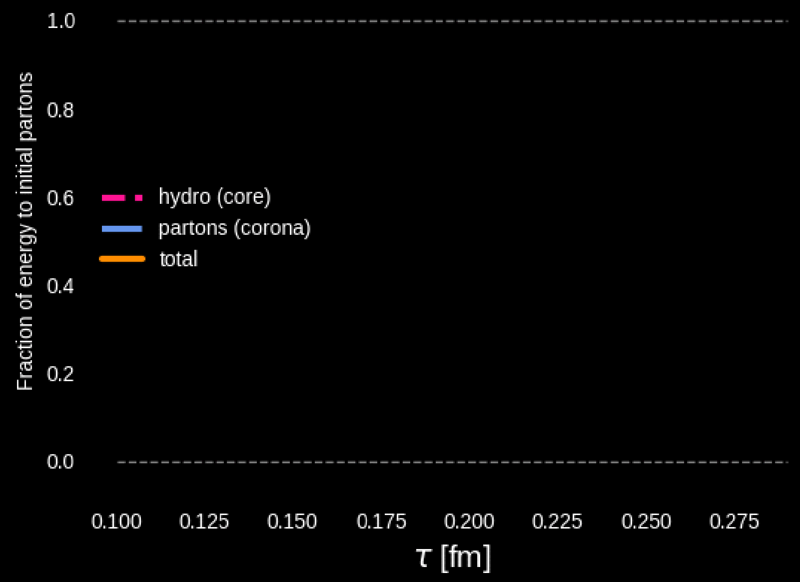


Energy-loss of partons ➔ $\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^{\nu}_{\text{parton}}$
Jet-quenching + medium response

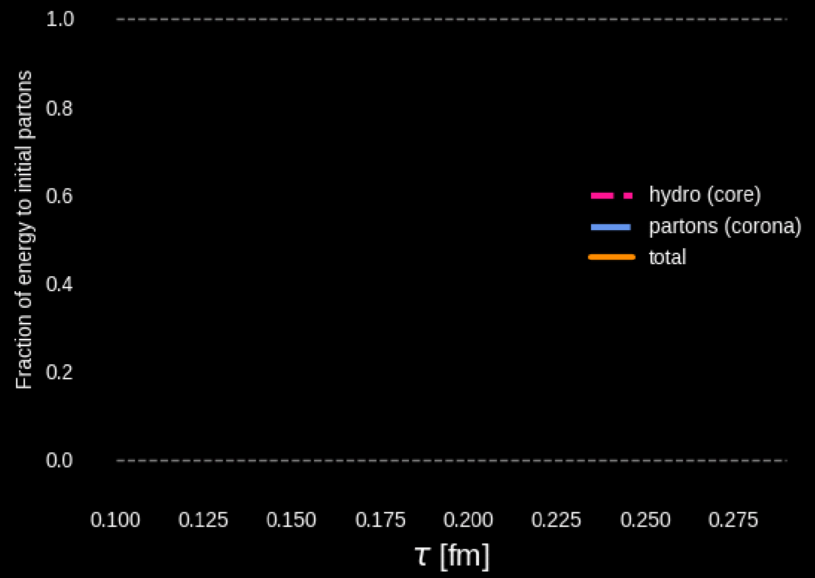
Energy budget in dynamical core-corona initialization

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

PbPb



pp



- Starting from vacuum $T^{\mu\nu} = 0$ for fluids
- Dynamical conversion of energy-momentum from corona to core

Attempt to realize equilibration process phenomenologically

Result 1

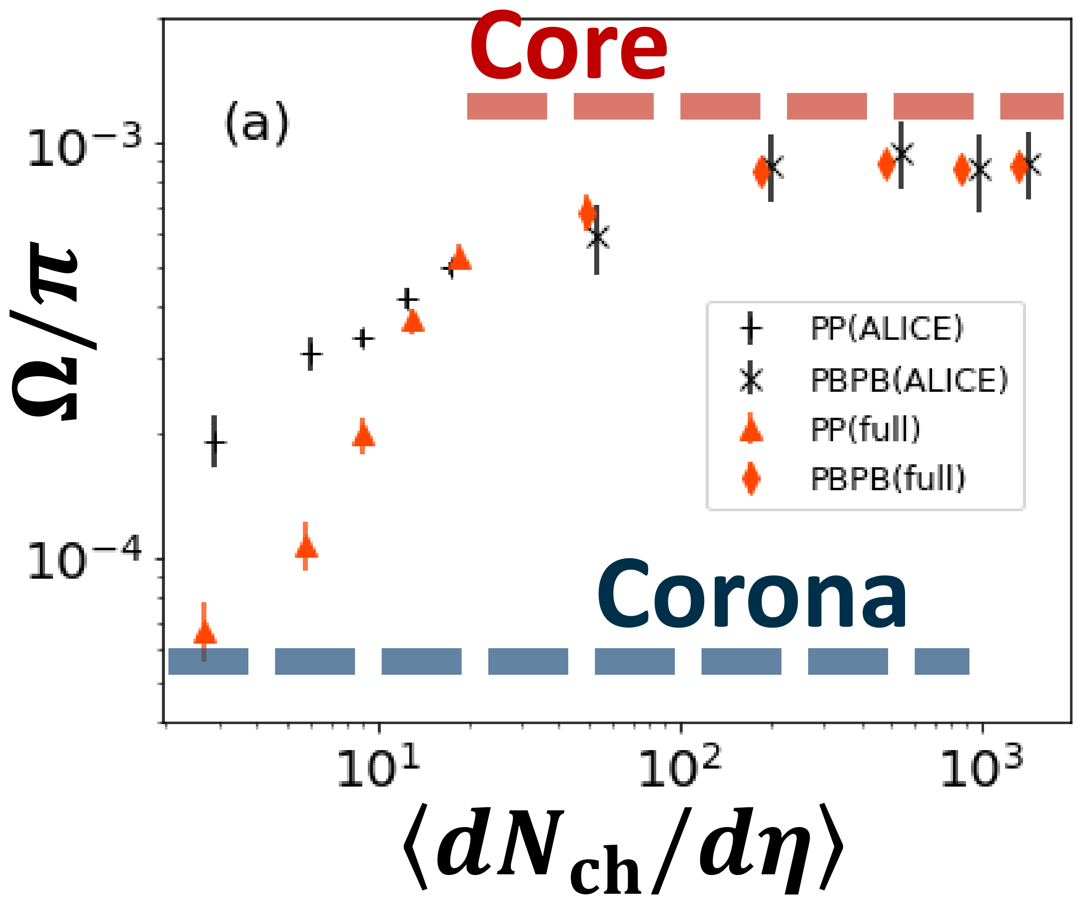
Need both core and corona in both pp and AA!

Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905

Input: Ω/π ratio from pp to PbPb

➡ Fixing parameters to control fraction of core/corona

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)



Interplay between…

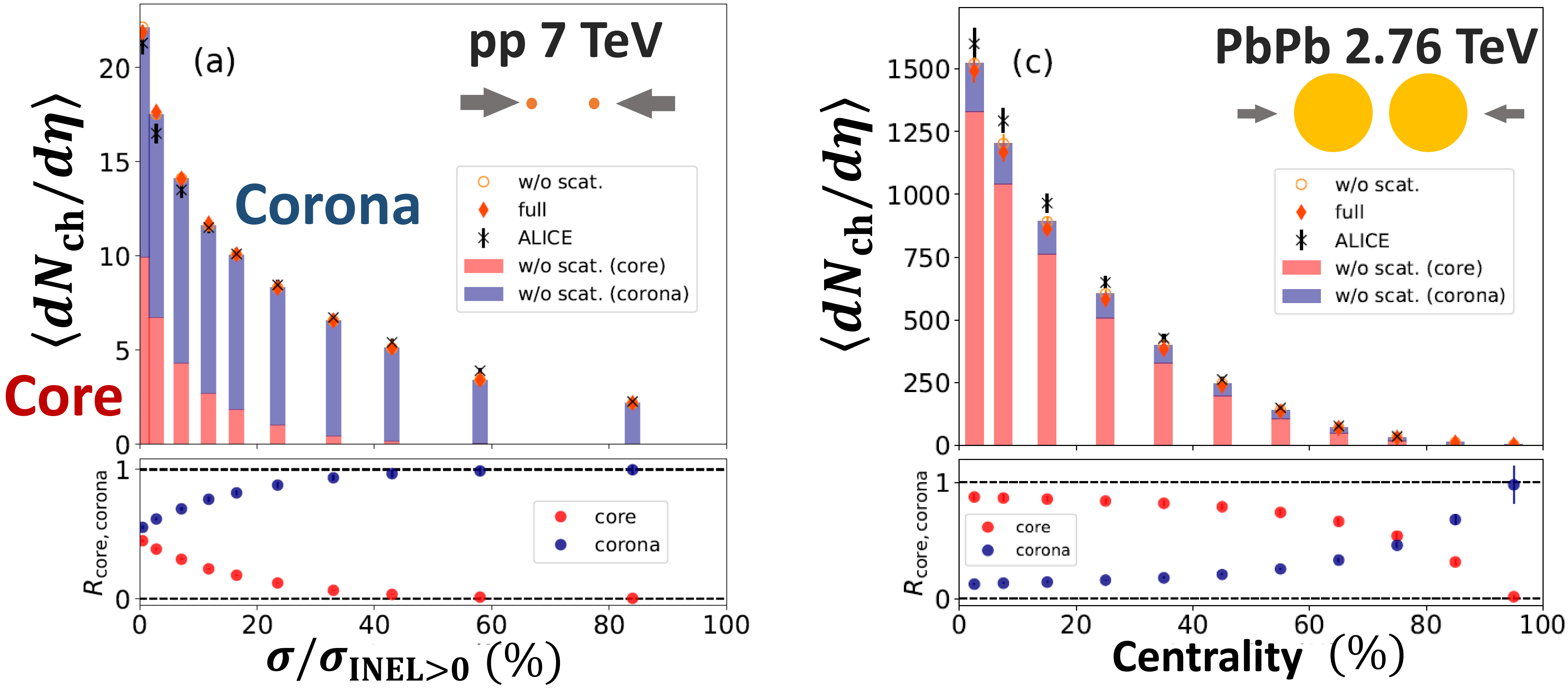
QGP hydro (core) &

String frag. (corona)

➔ Multiplicity dependence of Ω/π ☑

Forcing equilibration of the system according to Ω/π

Fraction of core and corona in pp and PbPb



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

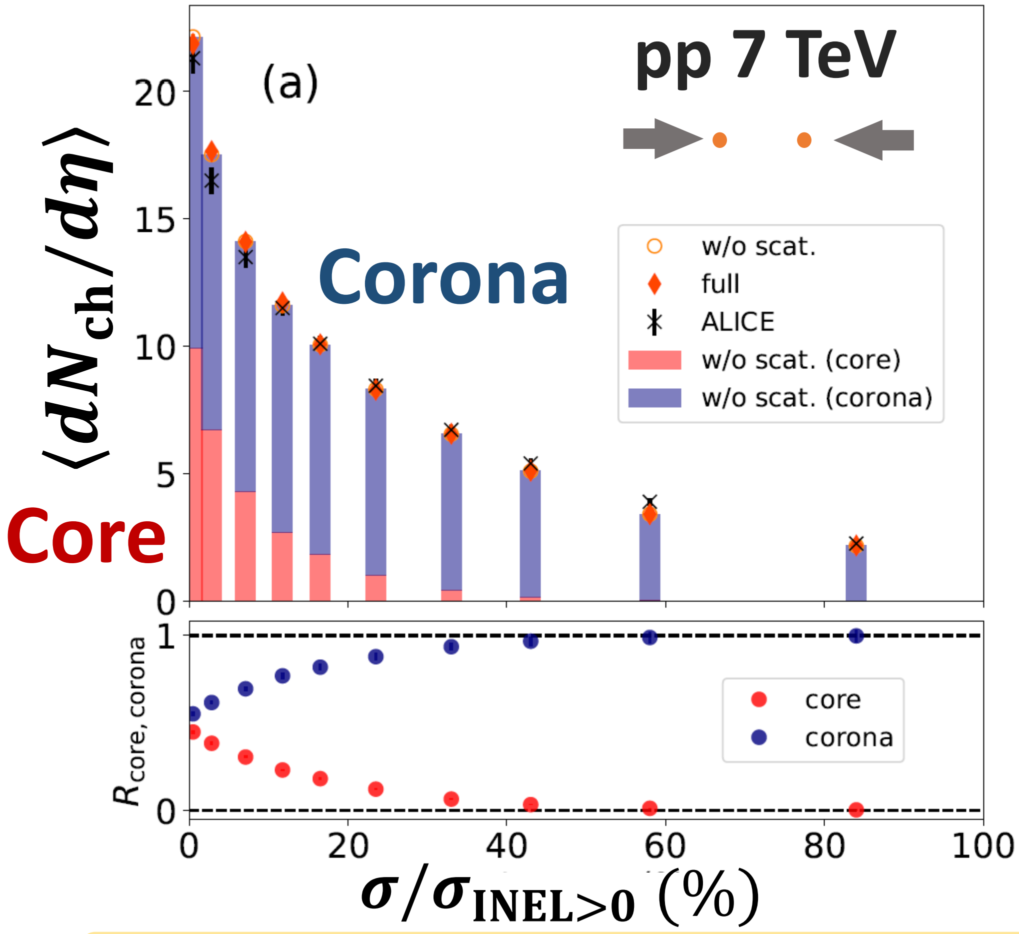
K. Aamodt *et al.*, (ALICE Collaboration), Phys. Rev. Lett. 106 032301 (2011)

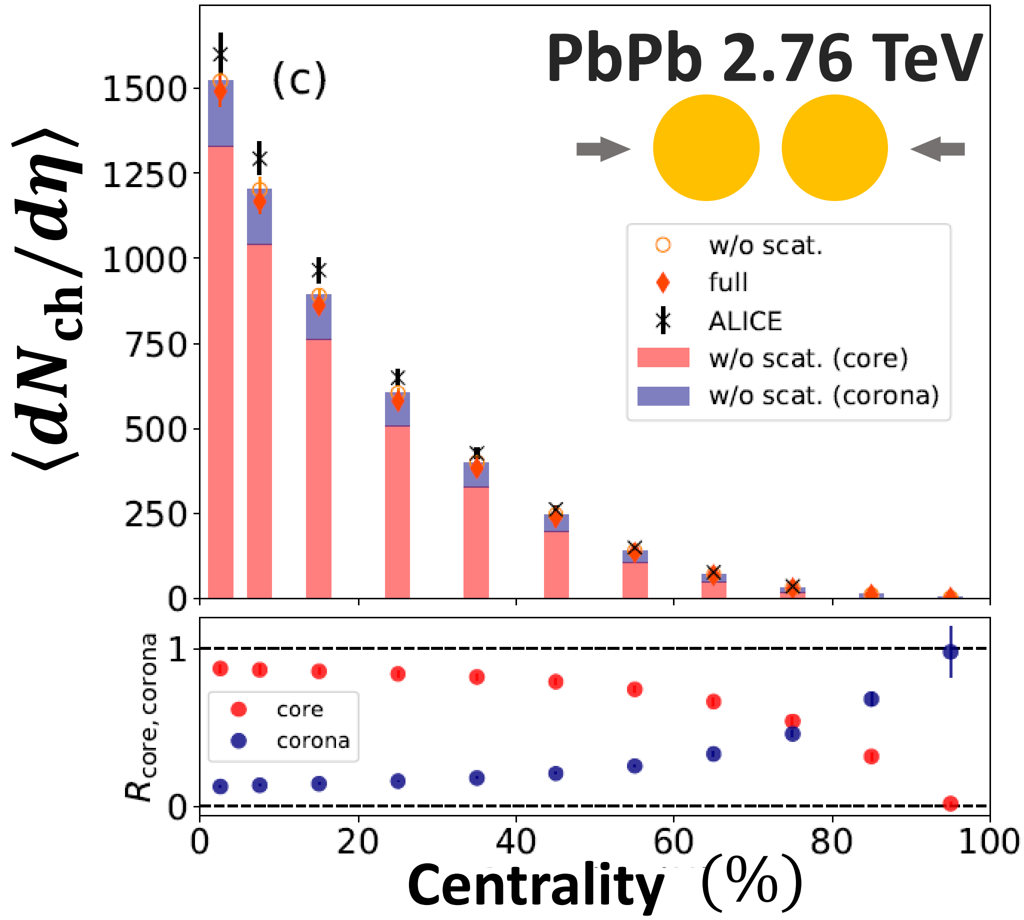
pp: core/corona ~ 50% at the highest multiplicity class (0-0.95%)

PbPb: corona ~ 20% at intermediate centralities (40-60%)

Fraction of core and corona in pp and PbPb

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

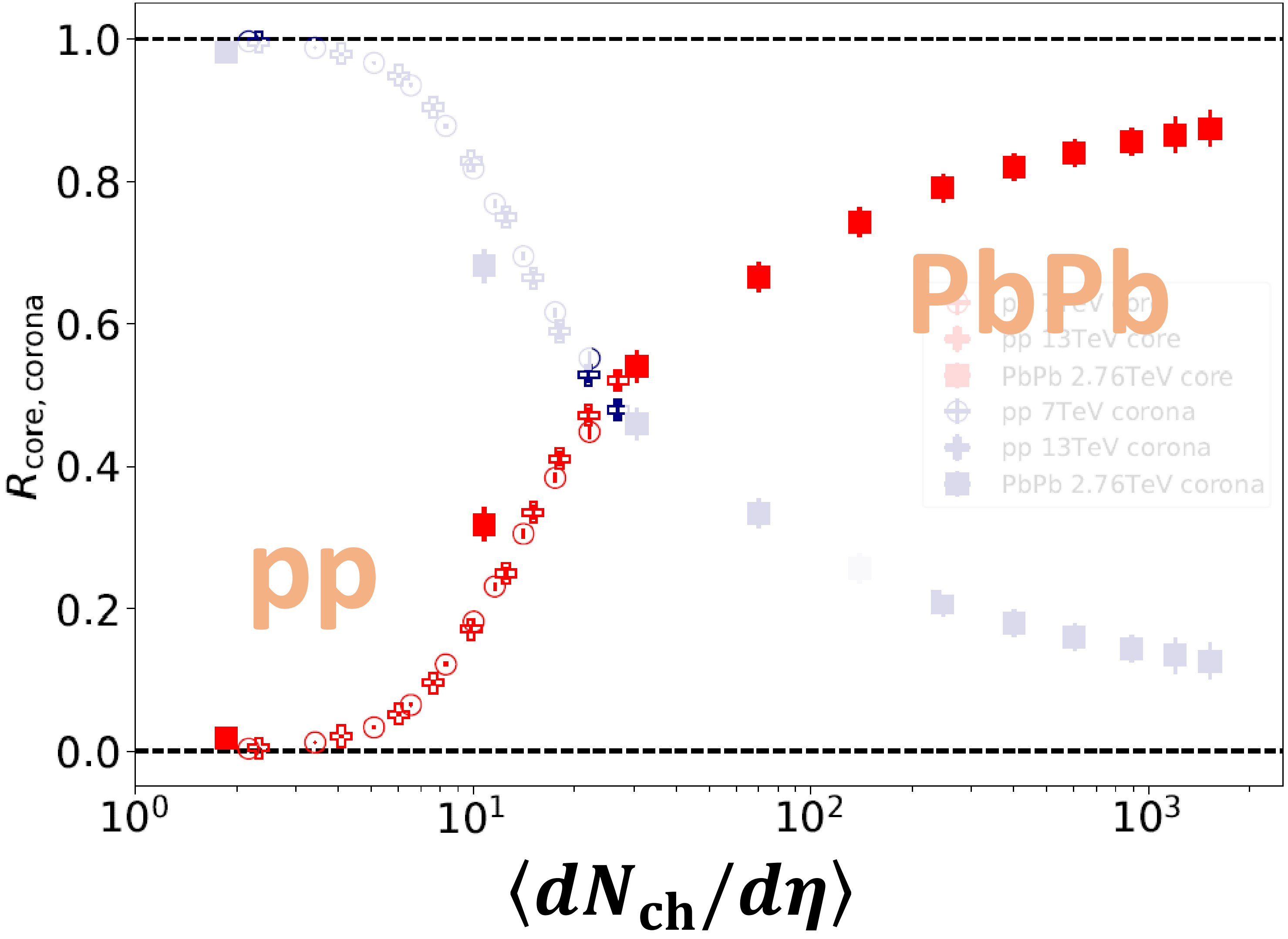




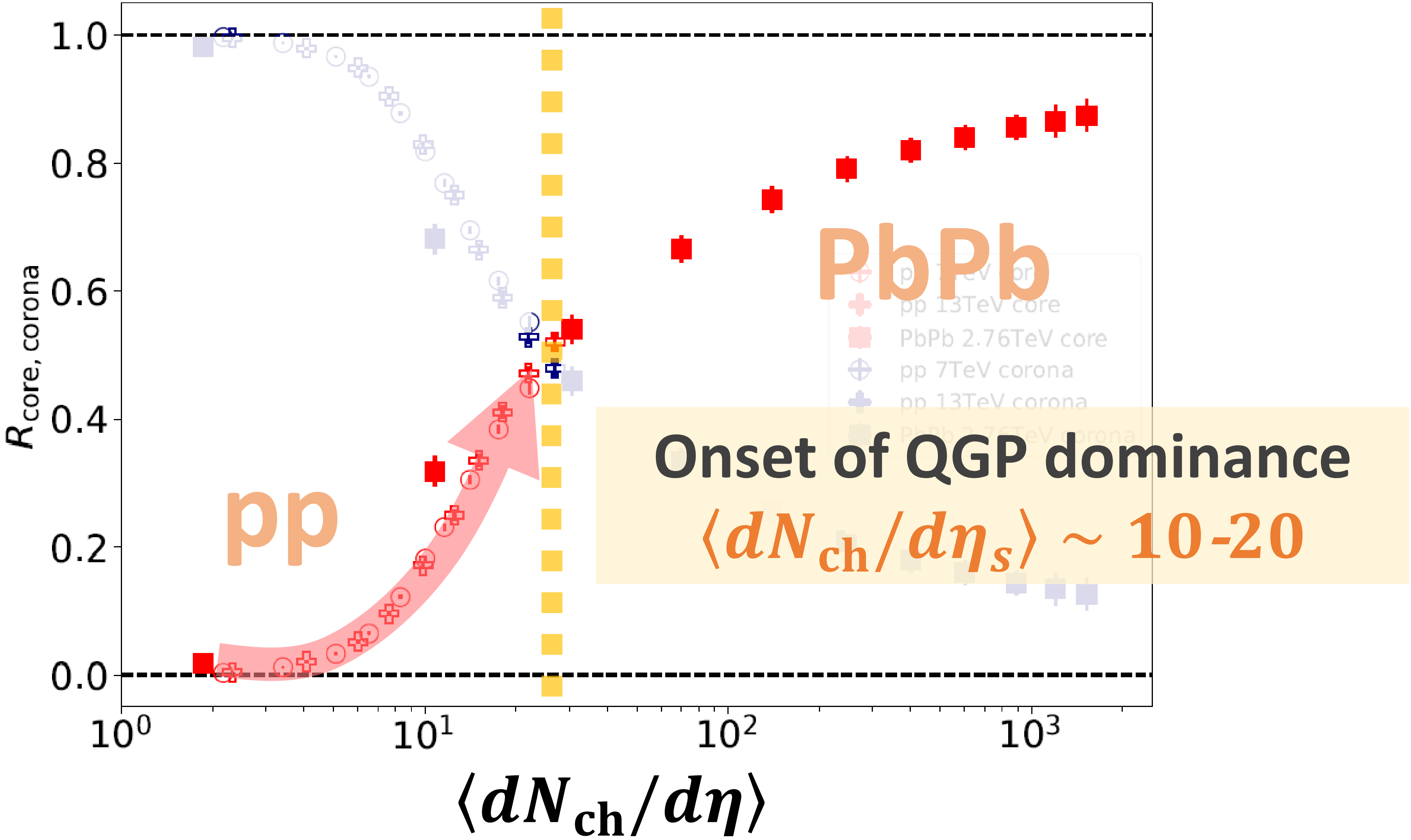
K. Aamodt *et al.*, (ALICE Collaboration), Phys. Rev. Lett. 106 032301 (2011)

➔ **Need both equilibrated and non-equilibrated matter in both pp and AA**

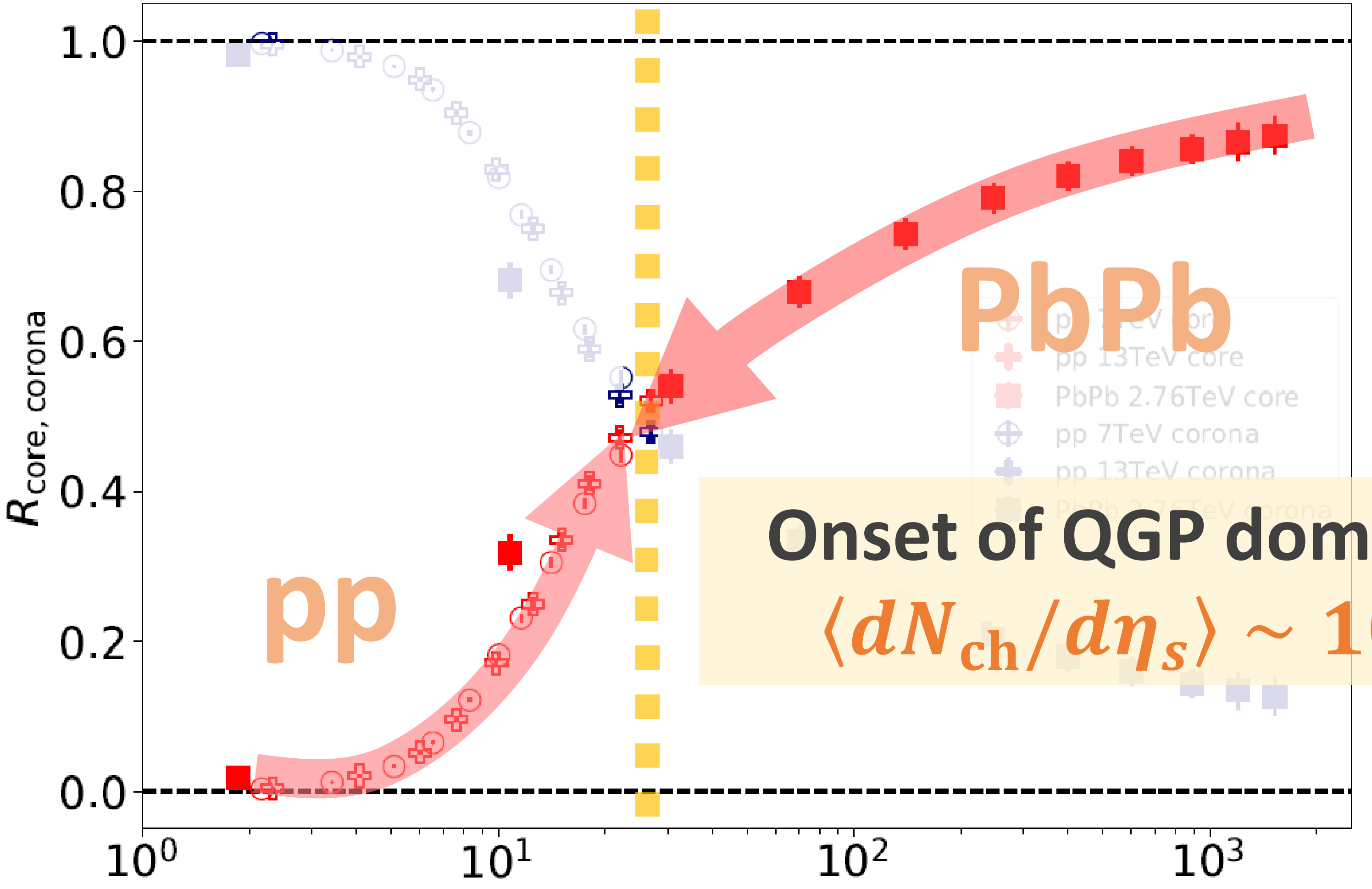
Fraction of production from QGP



Fraction of production from QGP



Fraction of production from QGP

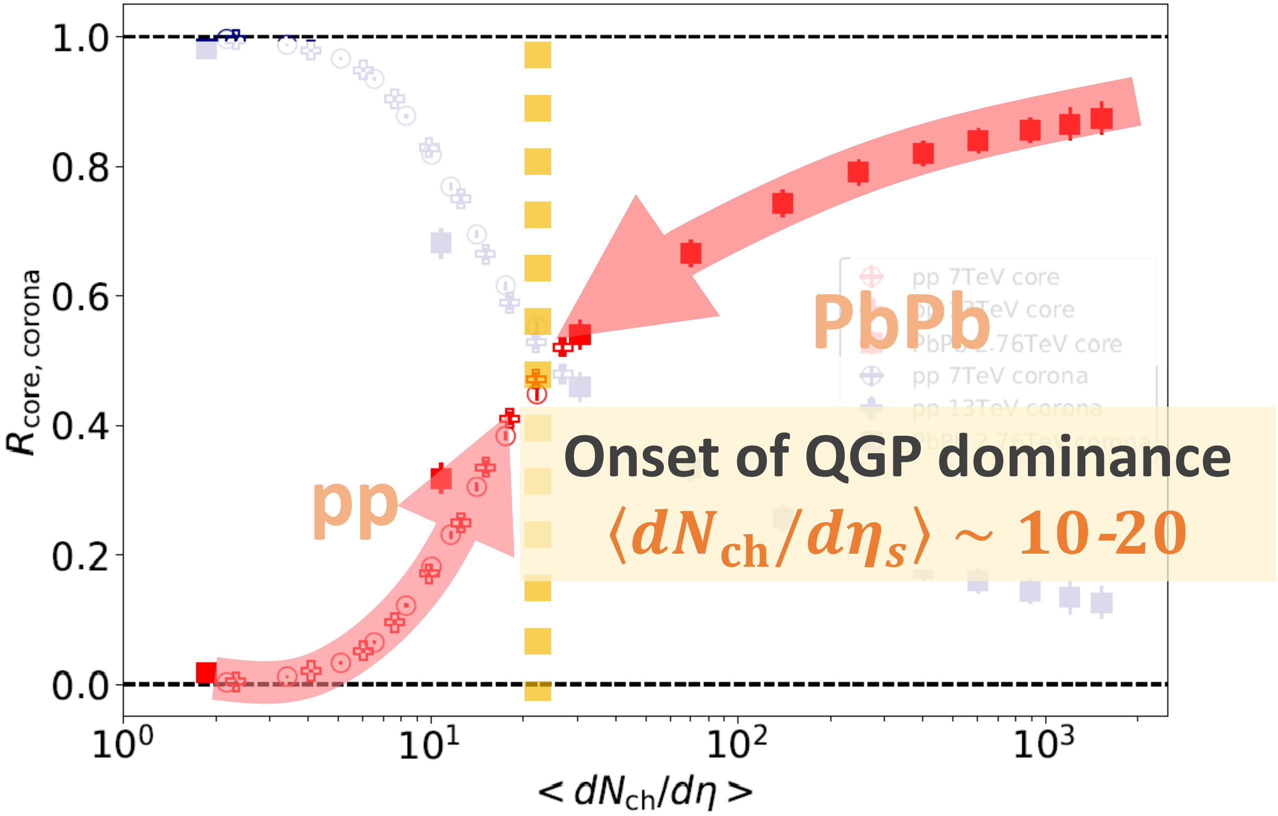


$\langle dN_{\text{ch}}/d\eta \rangle$

Onset of QGP dominance
$\langle dN_{\text{ch}}/d\eta_s \rangle \sim 10\text{-}20$

Fraction of production from QGP

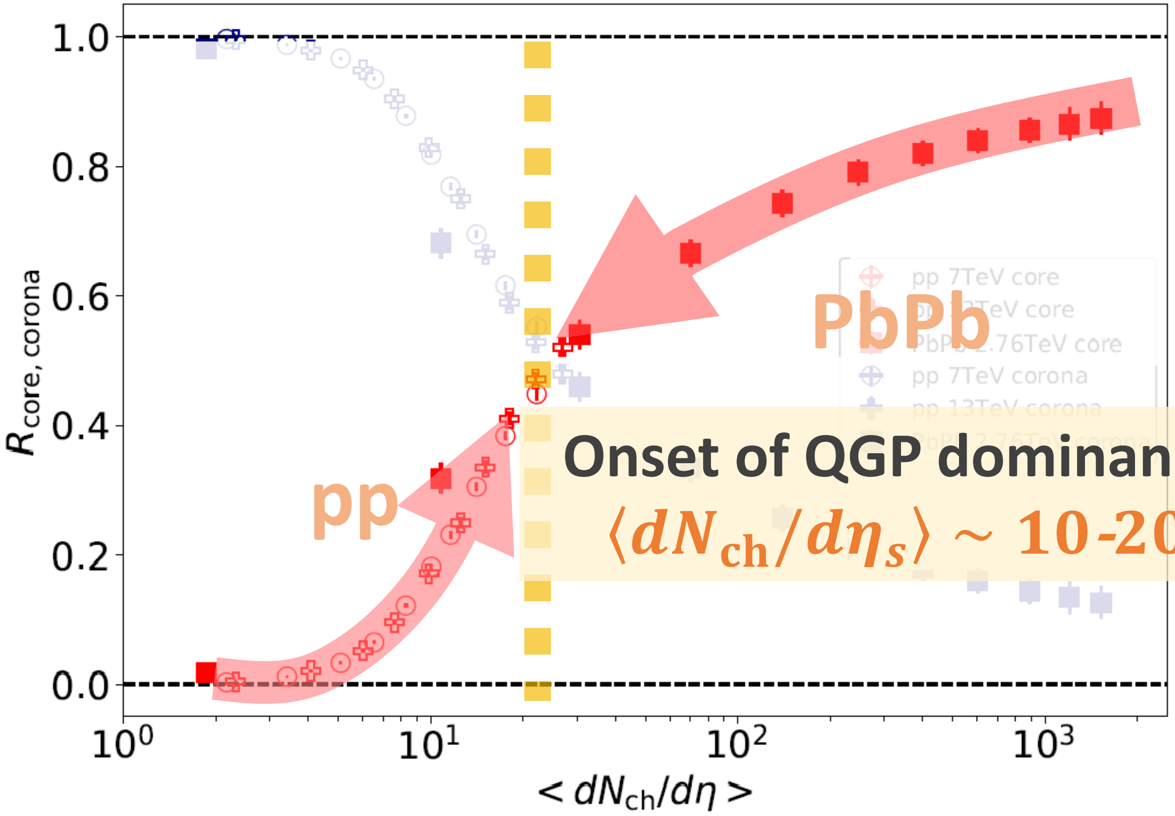
DCCI2 Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905



Fraction of production from QGP

DCCI2

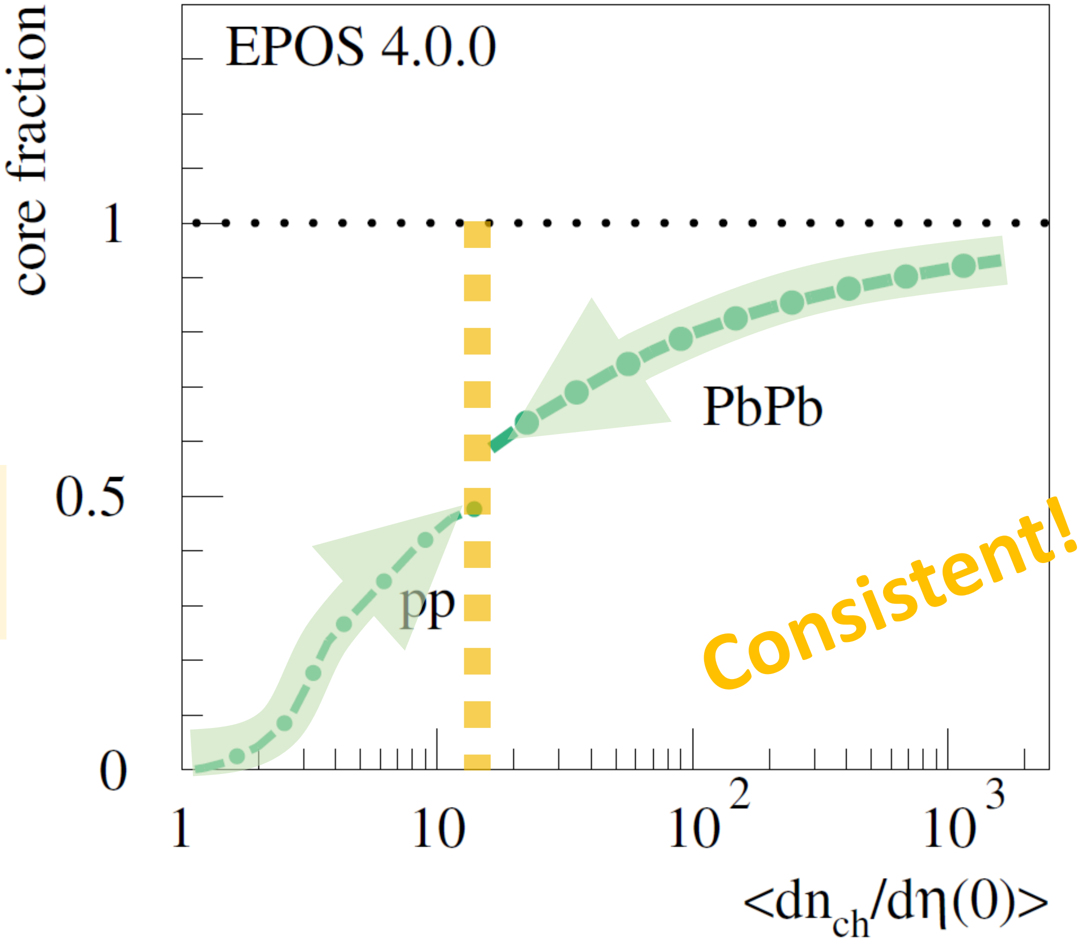
Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905



Onset of QGP dominance
$\langle dN_{ch}/d\eta_s \rangle \sim$ 10-20

EPOS4

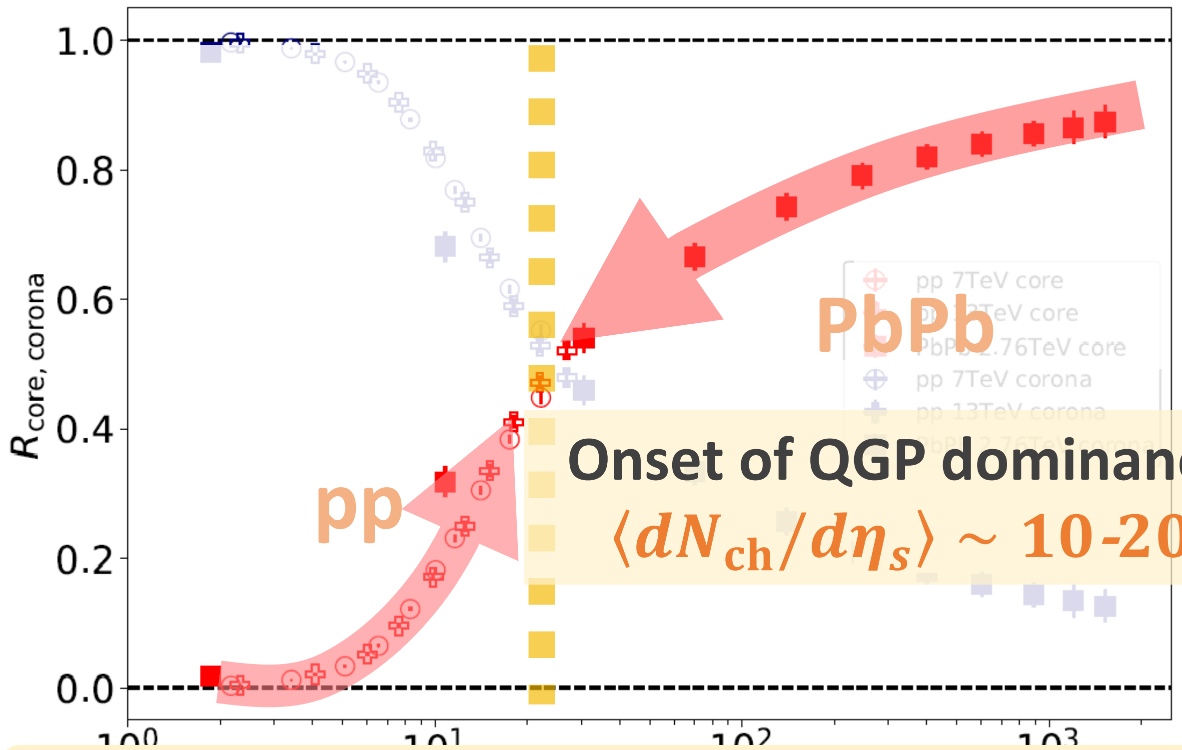
K. Werner, 2301.12517



Consistent!

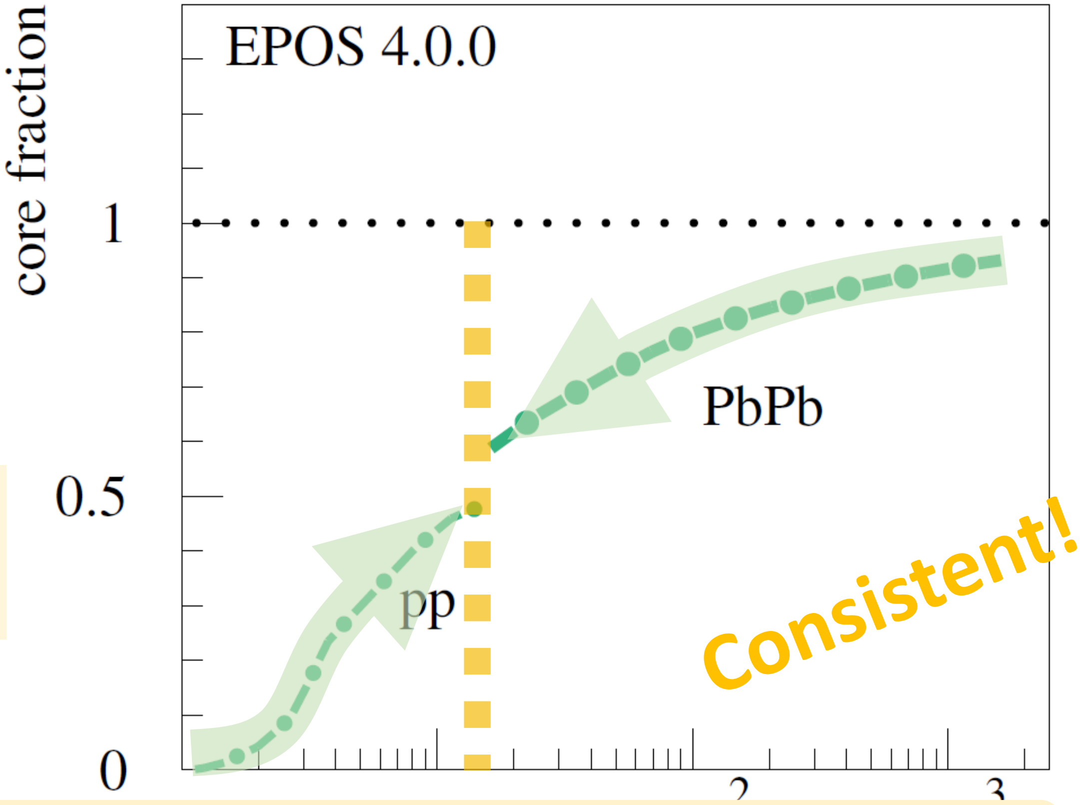
Fraction of production from QGP

DCCI2 Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905



Onset of QGP dominance
$\langle dN_{ch}/d\eta_s \rangle \sim$ 10-20

EPOS4 K. Werner, 2301.12517



Consistent!

Hadron chemistry (Ω/π , Ξ/π…): strong candidates for global analysis

Both equilibrated and non-equilibrated not only in pp but also in AA

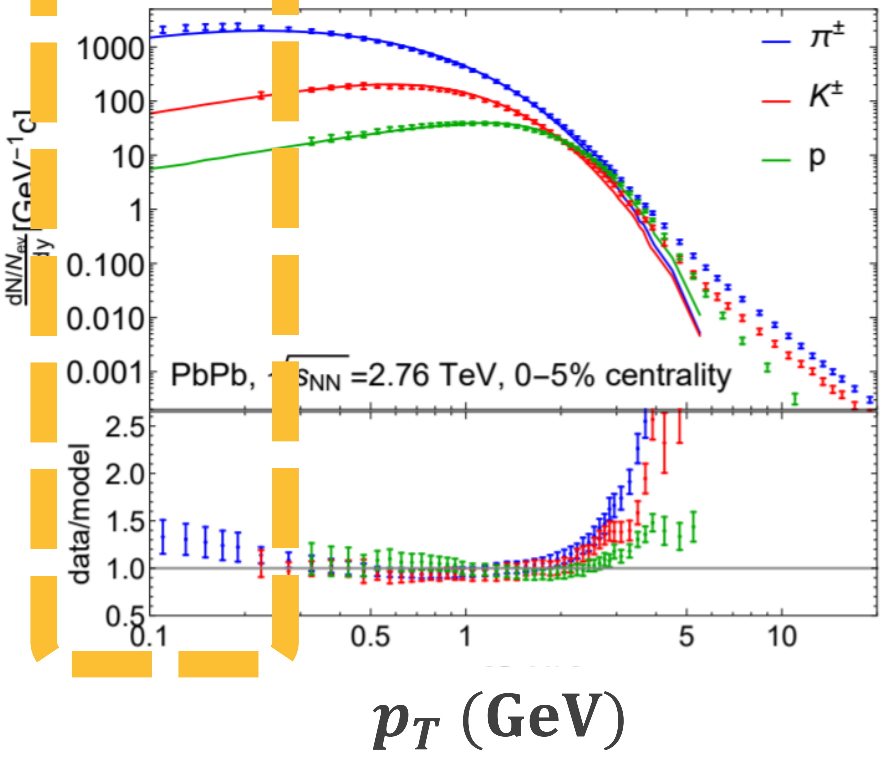
Result 2

Be careful with corona correction at low p_T in AA!

Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908

Longstanding problem in hydro

p_T spectra



G. Nijs *et al.*, Phys. Rev. C 103 (2021) 5, 054909

Lack of very low p_T hadron yields from hydro

J. Zimanyi *et al.*, Phys. Rev. Lett. 43, 1705 (1979);
M. Kataja and P. V. Ruuskanen, Phys. Lett. B 243, 181 (1990);
J. Sollfrank *et al.*, Z. Phys. C 52, 593 (1991);
U. Ornik and R. M. Weiner, Phys. Lett. B 263, 503 (1991);

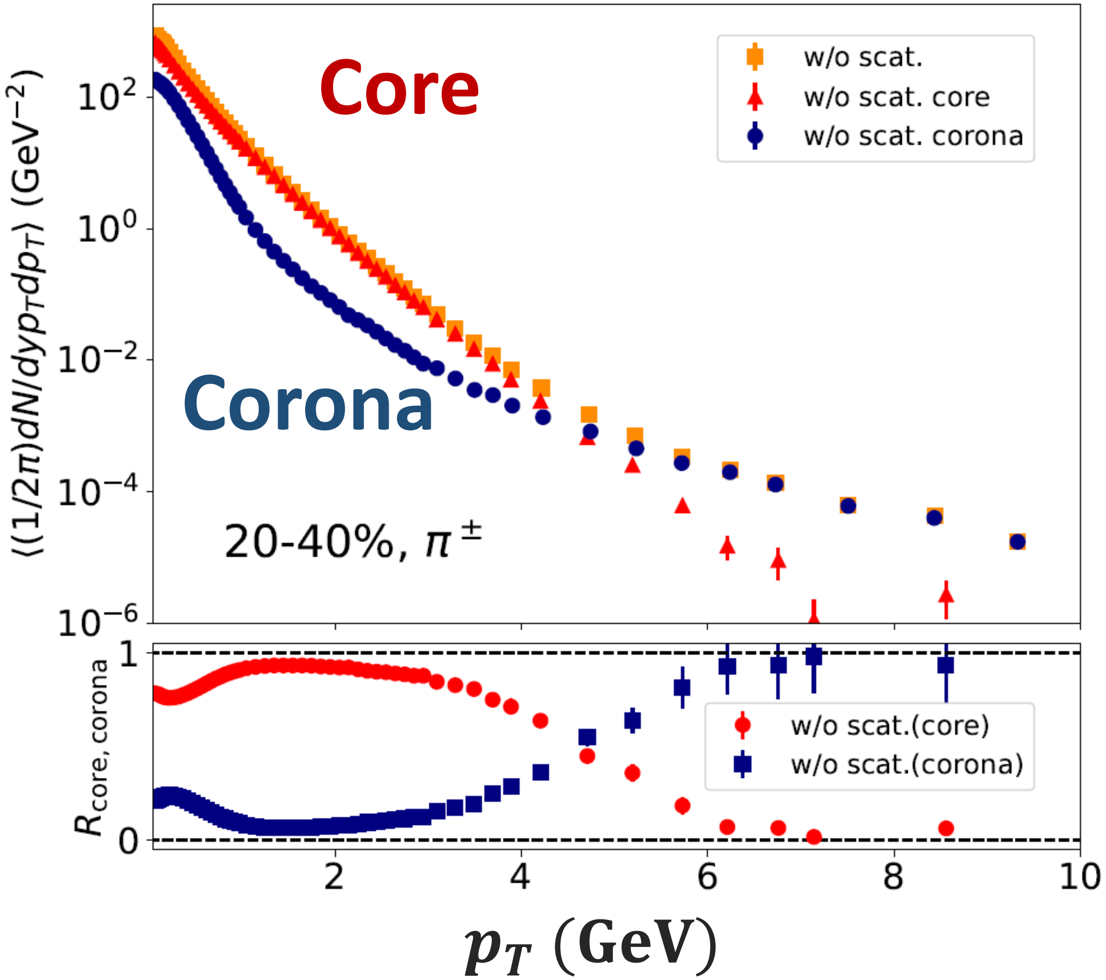
V. Begun *et al*., Phys. Rev. C 90, 014906 (2014); Phys. Rev. C 90, 054912 (2014); Phys. Rev. C 91, 054909 (2015);
P. Huovinen *et al.*, Phys. Lett. B 769, 509 (2017);
E. Grossi *et al.*, Phys. Rev. D 104, 034025 (2021)

➔ **Non-equilibrated components？**

Fraction of core and corona vs. p_T

Charged π, PbPb 2.76 TeV, 20-40%

Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908



Low p_T: core dominance

high p_T: corona dominance

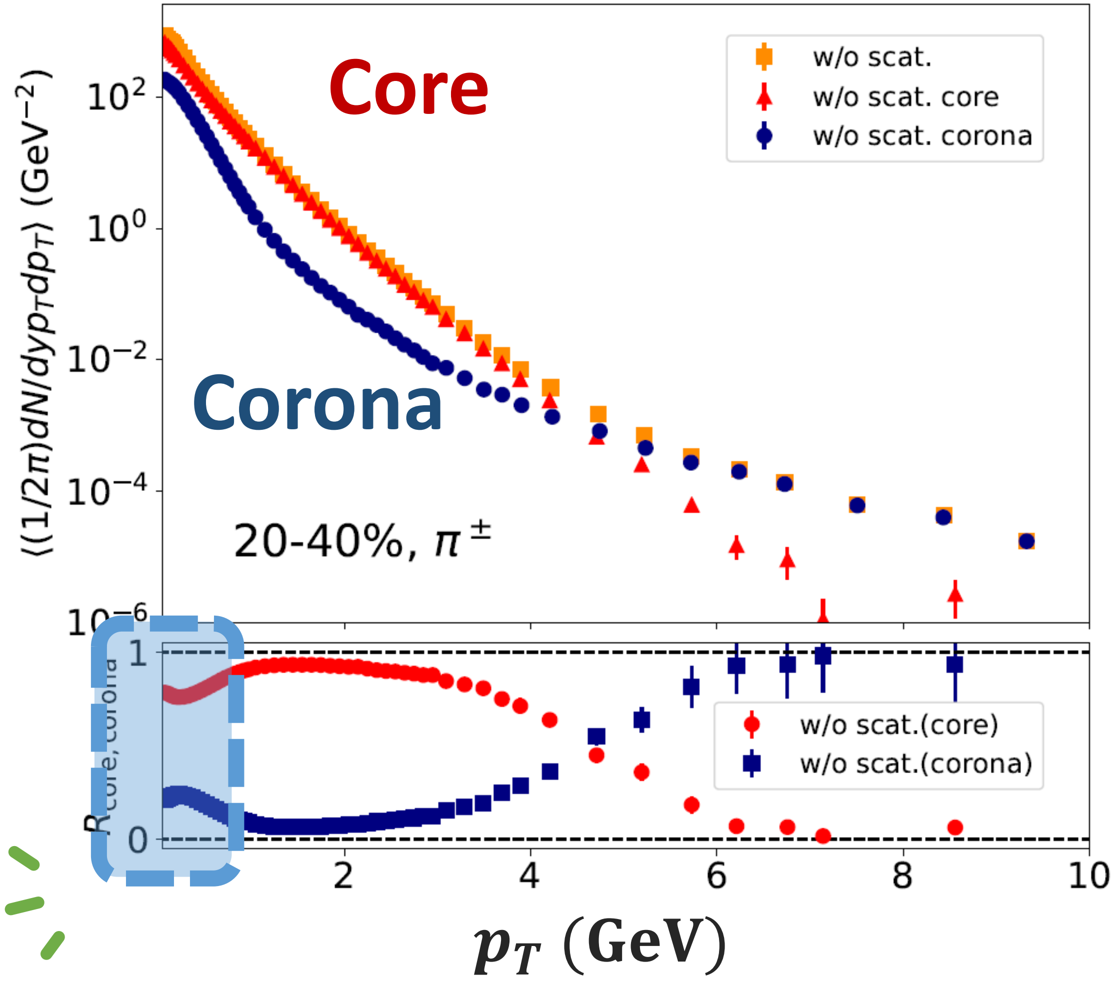
Core-corona picture

➔ From low to high p_T within one framework

Fraction of core and corona vs. p_T

Charged π, PbPb 2.76 TeV, 20-40%

Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908



Very low p_T (< 1 GeV)

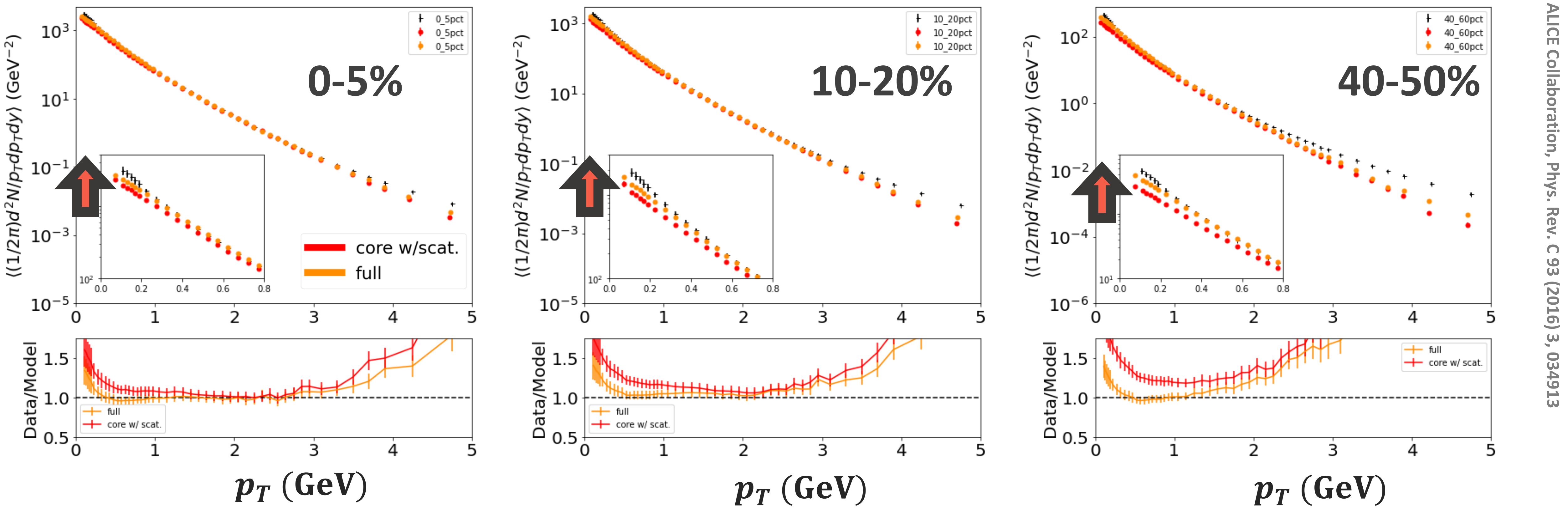
Slight enhancement of corona components

Non-equilibrium corrections to core (equilibrium)

Comparison with exp. data

PbPb 2.76 TeV, $\pi^{\pm}$

Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908

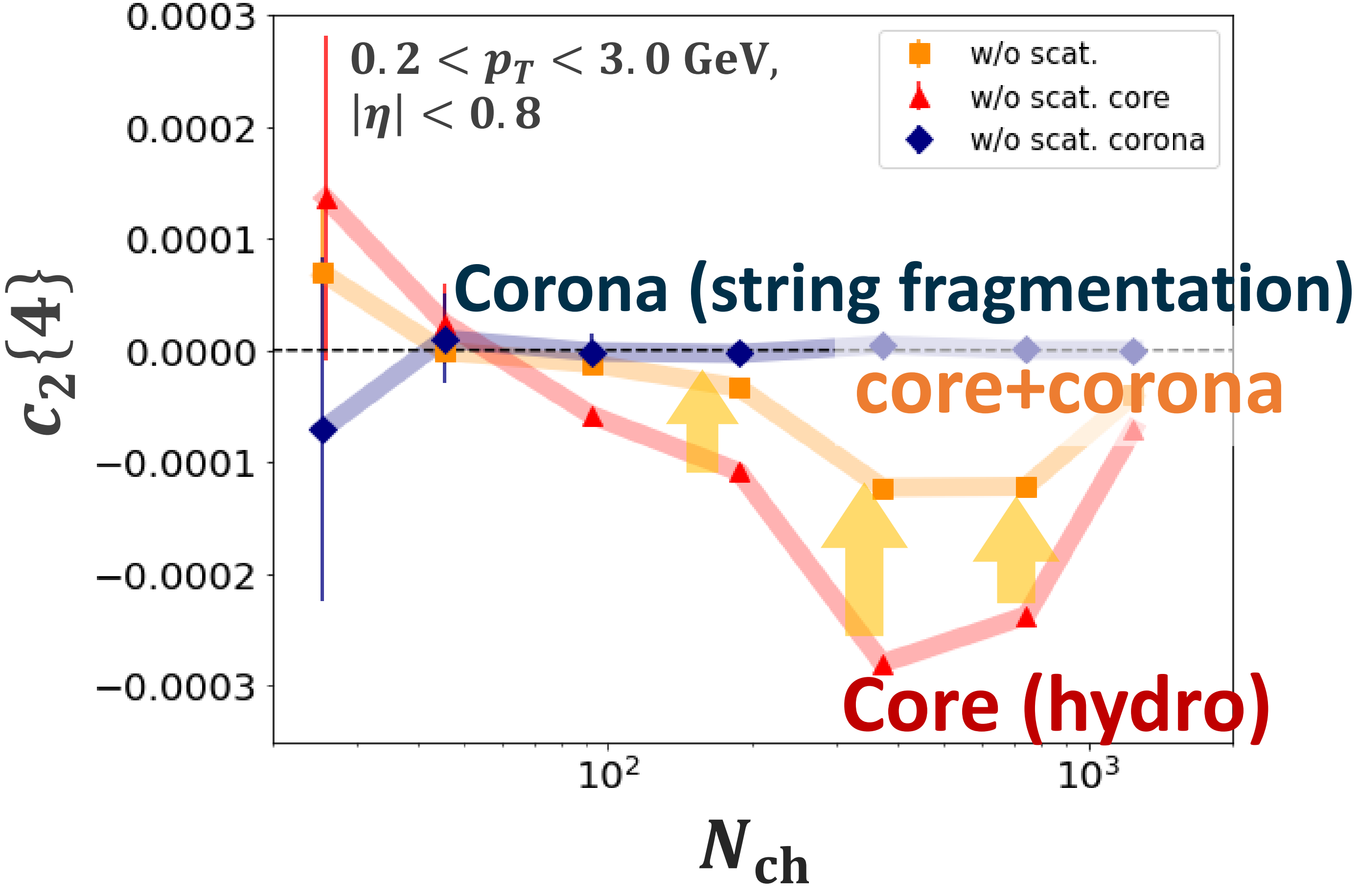


Corona at very low p_T: possible compensation of yield

Non-equilibrium contribution to collectivity in AA

Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908

$c_2\{4\}$ from PbPb 2.76 TeV



$c_2\{4\}_{core} \neq c_2\{4\}_{tot}$

Collectivity is diluted by corona

Caution on η/s, ζ/s... from model-data comparison

Both equilibrium and non-equilibrium contribution in dynamical models

➔ Interplay of soft and hard

Summary

Dynamical core-corona initialization (DCCI2)

- Respect beam energy in initialization of QGP
- Both equilibrated and non-equilibrated matter

➔ From low to high p_T, from forward to backward, and from pp to AA

Hadron chemistry: yield ratios of strange hadrons from pp to PbPb

Quantitative analysis of QGP properties from data to model comparisons?

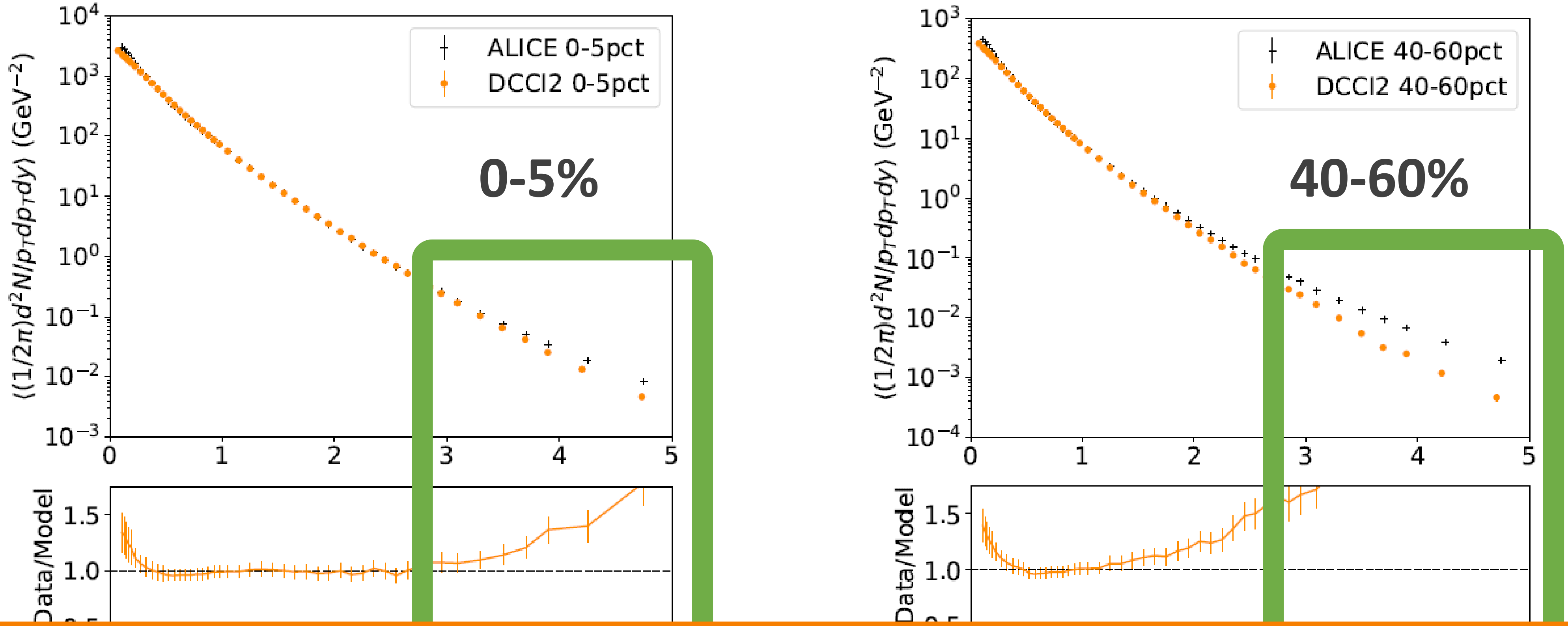
Need both equilibrated and non-equilibrated matter in both pp and AA

Thank you!

Backup

1. Yields at high p_T

PbPb 2.76 TeV, $\pi^{\pm}$

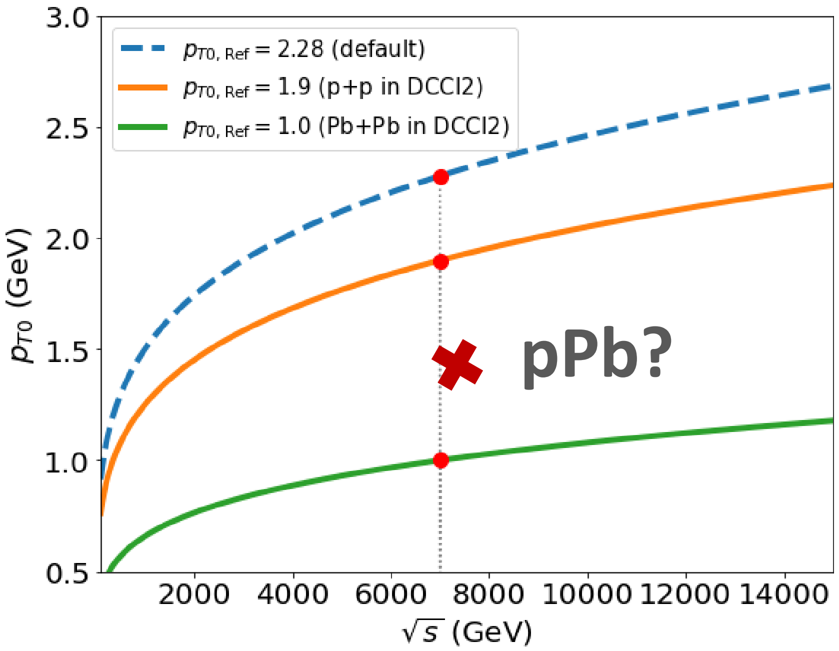


ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

Need to sophisticate jet quenching in DCCI2
+ Need N_{coll} scaling at high p_T?

2. Multiplicity distribution in pPB

Multiplicity in DCCI2 ➔ controlled at initial parton generations

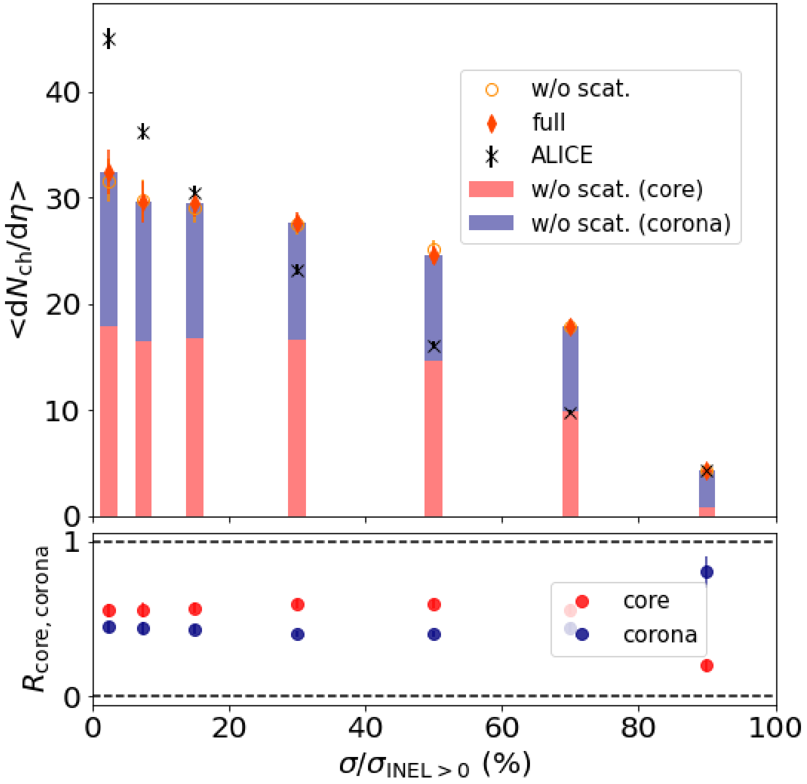


$$\frac{d\sigma_{2\to2}}{dp_T^2} \propto \frac{\alpha_s^2(p_T^2)}{p_T^4} \to \frac{\alpha_s^2(p_T^2 + p_{T,0}^2)}{(p_T^2 + p_{T,0}^2)^2}$$

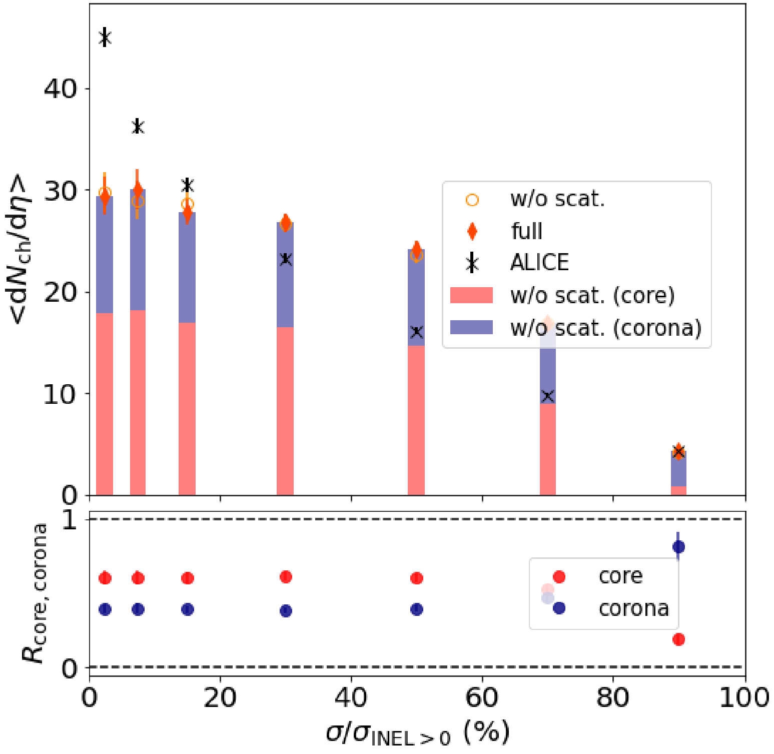
- $\sim$ Infrared cutoff
- Tuning parameter in PYTHIA.
- $p_{T,0\mathrm{Ref}} = 2.28$ GeV (default)

Smaller $p_{T,0\mathrm{Ref}}$ ➔ More MPI ➔ More partonic productions at mid-rapidity

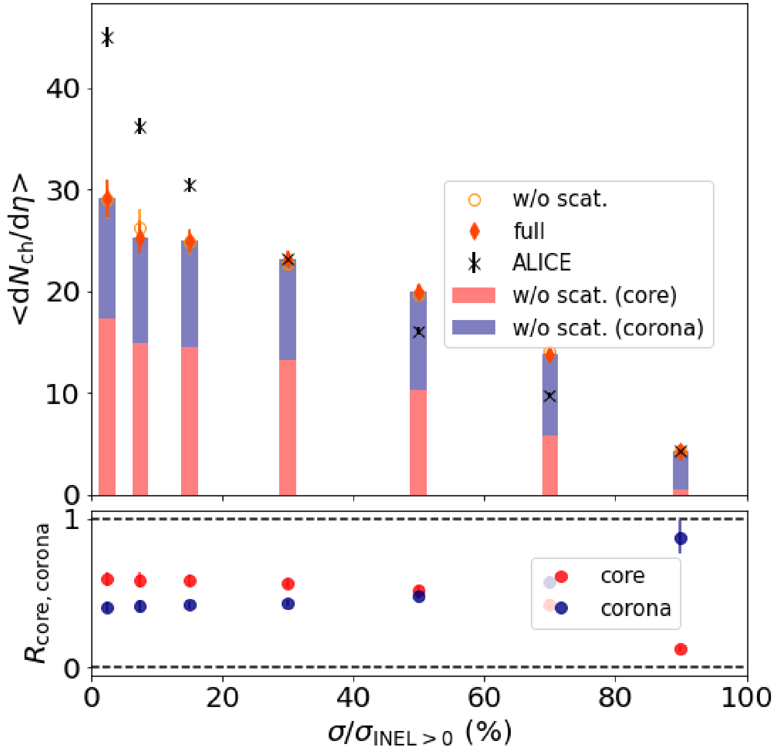
Parameter $p_{T0\mathrm{Ref}}$ dependence in DCCI2



$p_{T0\mathrm{Ref}} = 0.8$ GeV



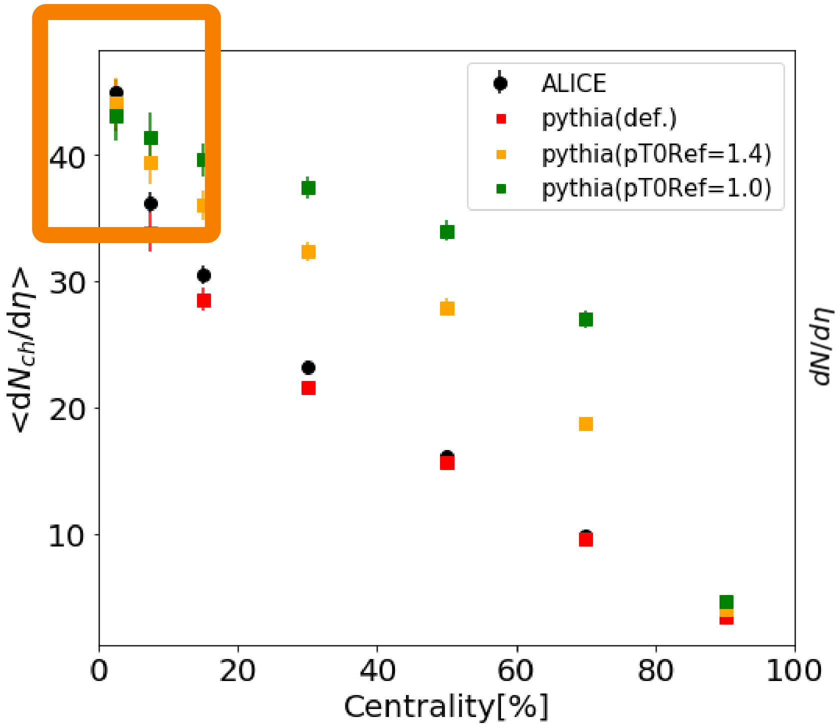
$p_{T0\mathrm{Ref}} = 1.0$ GeV

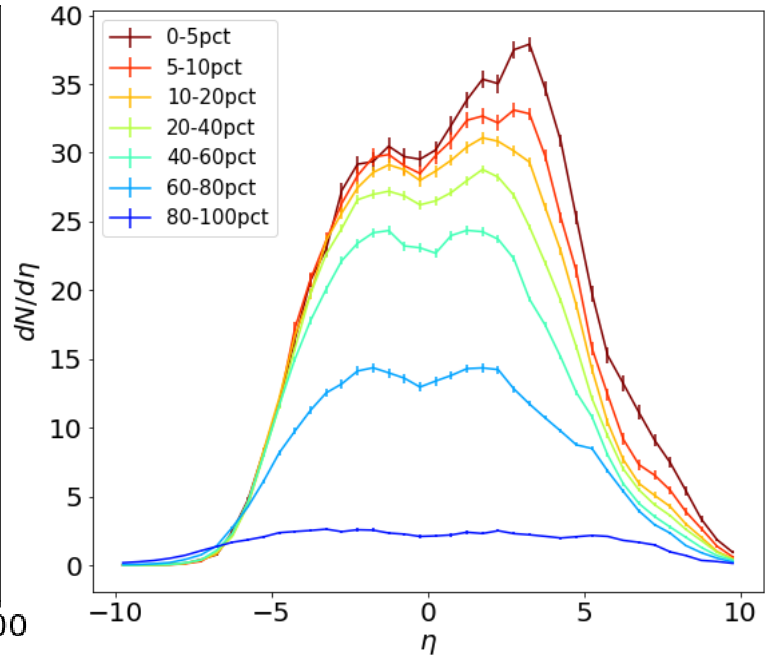


$p_{T0\mathrm{Ref}} = 1.4$ GeV

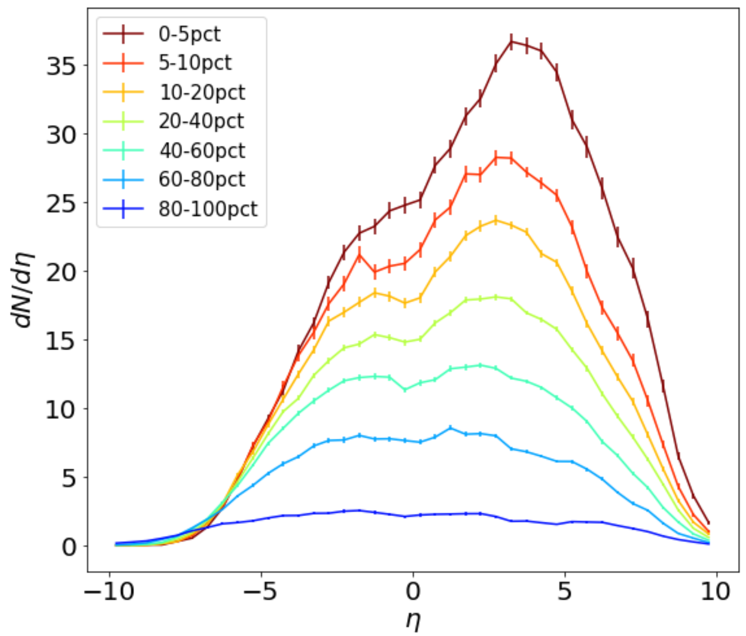
Difficulty ➔ interplay of two different particle production mechanisms within a given total collision energy

Parameter $p_{T0\mathrm{Ref}}$ dependence in default PYTHIA





$p_{T0\mathrm{Ref}} = 1.0\ \mathrm{GeV}$



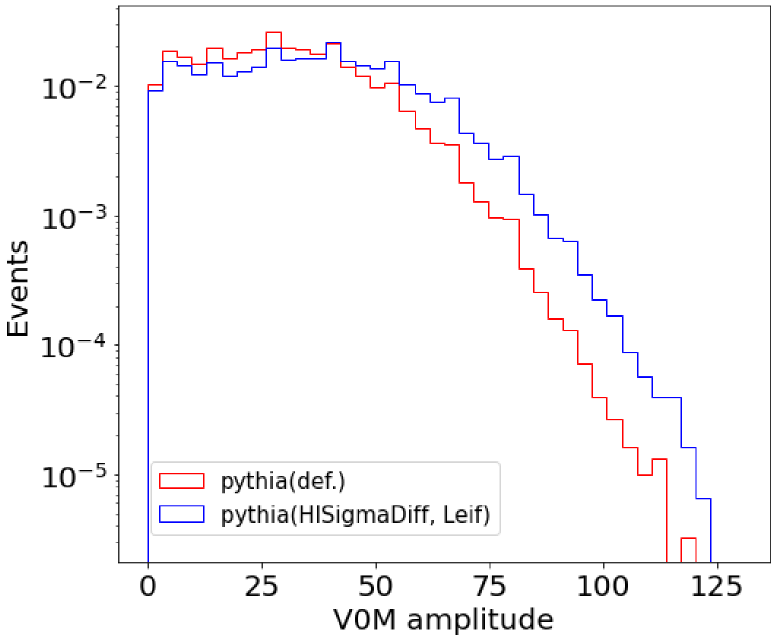
Default ($p_{T0\mathrm{Ref}} = 2.28\ \mathrm{GeV}$)

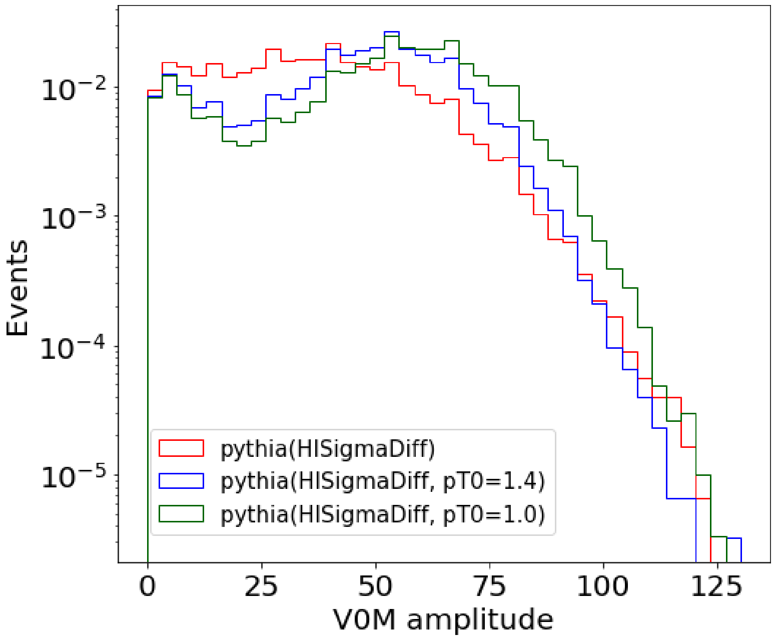
Maximum multiplicity ➔ saturated

Multiplicity distribution in pPB default PYTHIA

Any dependence on some parameters related to 2nd absorptive collisions?

pPB 5020 GeV





σ_{diff} ↓

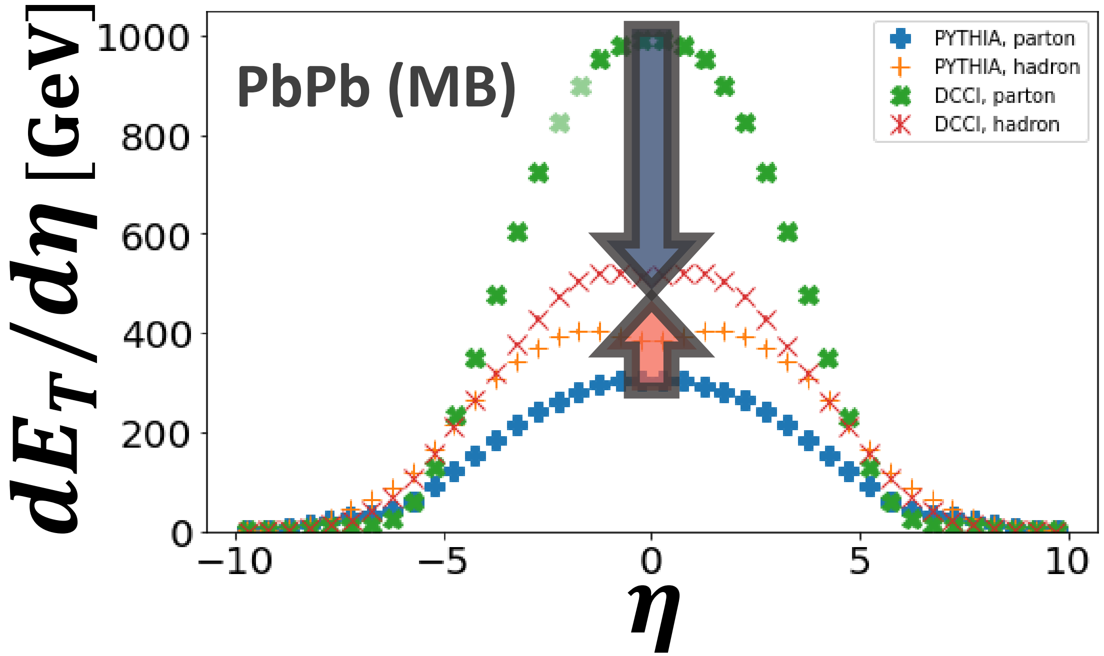
σ_{abs} ↑

➔ No significant enhancement?

Difficulty: reproduction of multiplicity distribution given a fixed collision energy

Charged particle multiplicity

Difference of E_T evolution between hydro and string frag.



<ins>Hydro</ins>: E_T decrease due to pdV work in longitudinal direction

<ins>String fragmentation</ins>:
E_T enhance

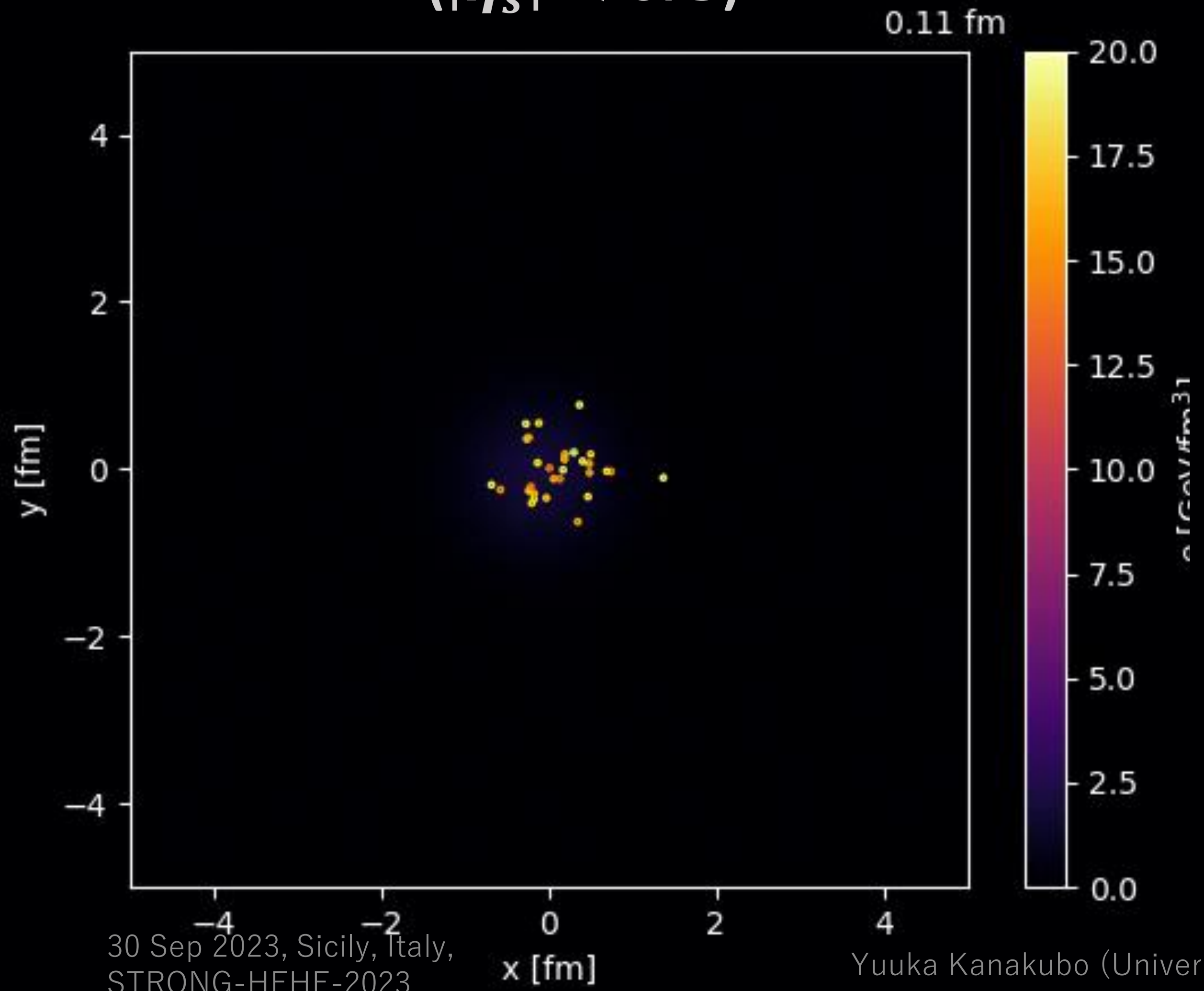
Different dynamics in later stage
➔ Require different initial energy profile

$p_{T0\mathrm{Ref}}$: infrared cut off of 2→2 in PYTHIA

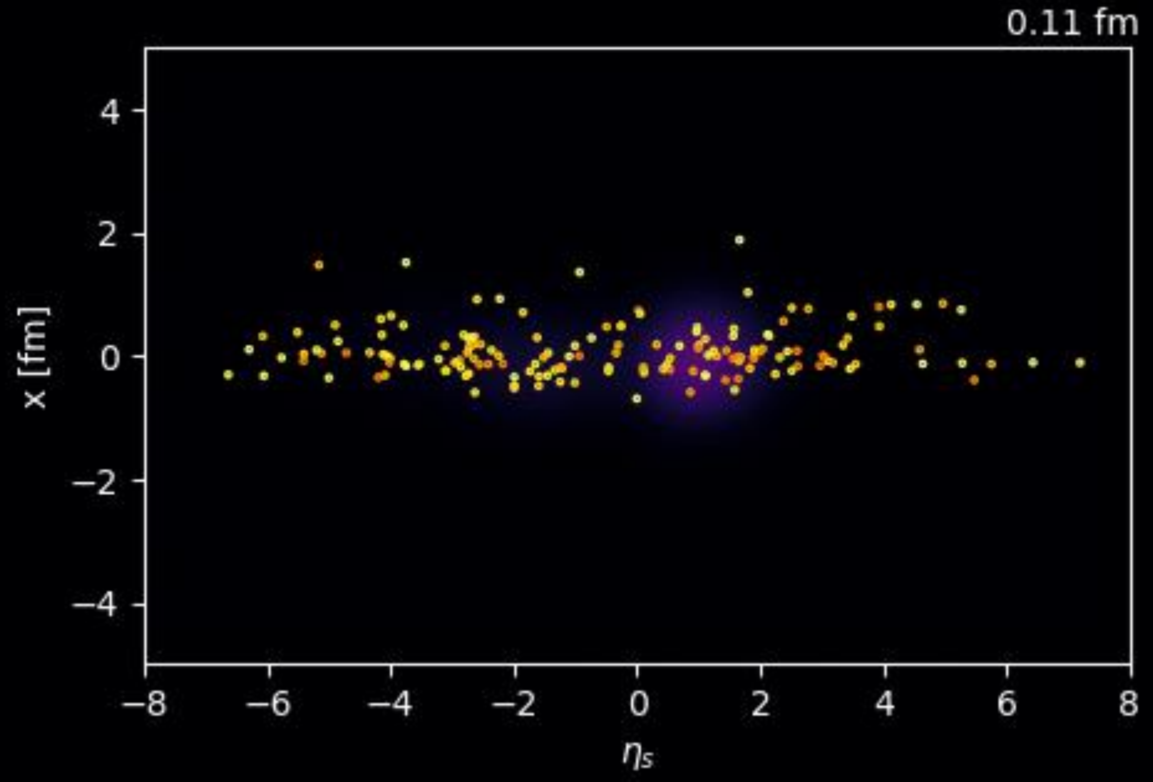
Dynamical core-corona initialization

pp 7 TeV

Transverse plane
($|\eta_s| < 0.5$)



$x - \eta_s$ plane
($|y| < 0.5$ fm)



Parameter set for PYTHIA part: almost Monash Tune

Parameters	values
p_{T0Ref} (p+p)	1.8 GeV
p_{T0Ref} (Pb+Pb)	0.9 GeV
τ_0	0.1 fm
τ_s	0.3 fm
T_{sw}	0.165 GeV
σ_0	0.4 fm^2
b_{cut}	1.0 fm
$p_{T,\mathrm{cut}}$	3.0 GeV
$\sigma_\perp$	0.5 fm
σ_{η_s}	0.5
Δx	0.3 fm
Δy	0.3 fm
$\Delta \eta_s$	0.15

PYTHIA

Hydro with dynamical core-corona

How far can we go as a naive combination of hydro and PYTHIA

…with simple starting point

Default parameter values except $p_{T0\mathrm{Ref}}$ in initial parton generation

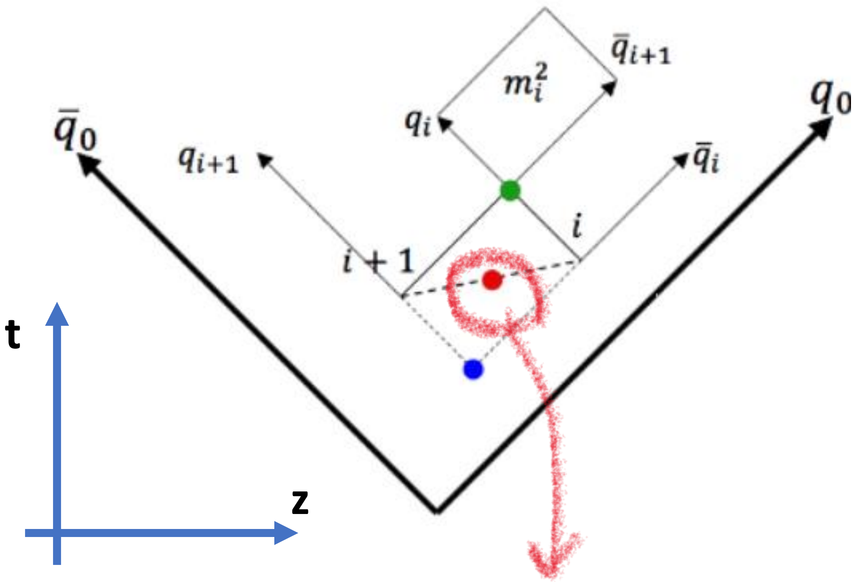
$$\frac{d\sigma_{2\to2}}{dp_T^2} \propto \frac{\alpha_s^2(p_T^2)}{p_T^4} \to \frac{\alpha_s^2(p_T^2+p_{T,0}^2)}{(p_T^2+p_{T,0}^2)^2}$$

p_{T0} ~ Infrared cutoff for 2→2 cross section

Hadron vertices model in PYTHIA

S. Ferreres-Solé and T. Sjöstrand, Eur. Phys. J., vol. C78, no. 11, p. 983, 2018.

The production vertex of the hadron is taken to be the average of the two break-up vertices producing it.



The vertex of the hadron with mass m_i

Option

flag Fragmentation:setVertices = on

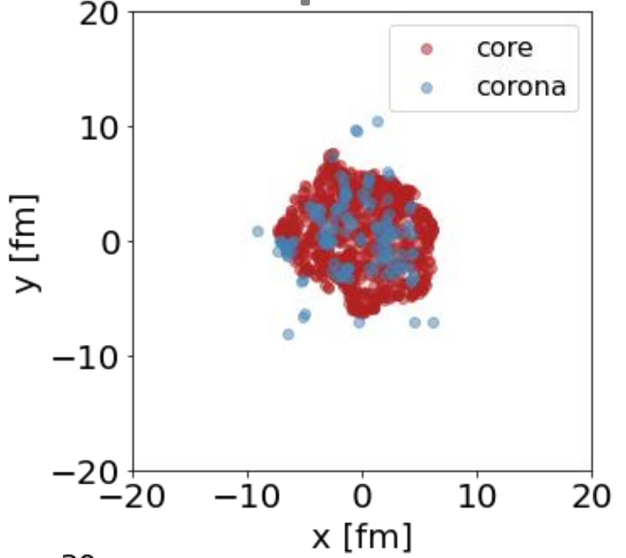
Information of production vertices

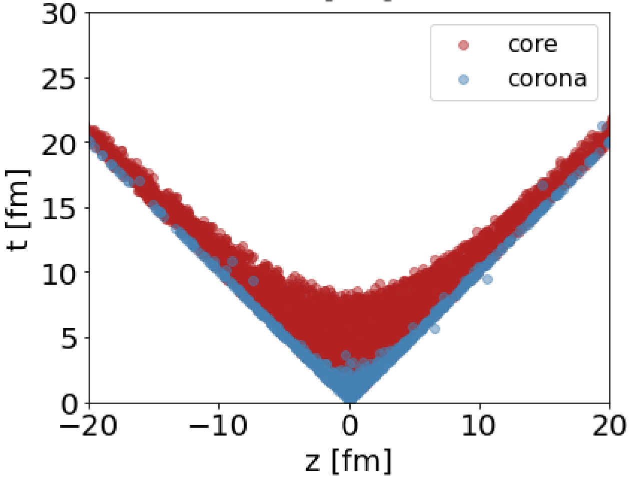
event[i].xProd(), event[i].yProd(), event[i].zProd(), event[i].tProd()

PbPb 2.76 TeV

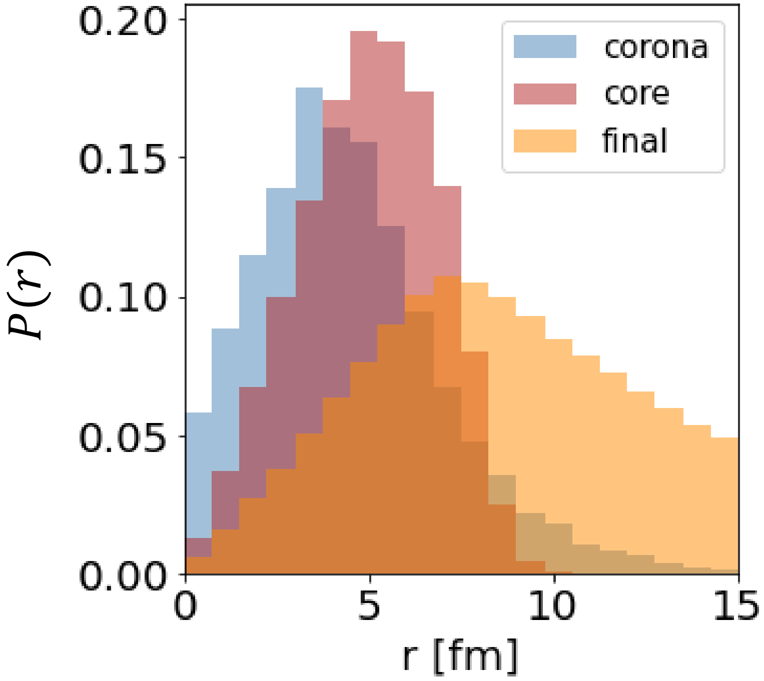
Space-time distribution of direct hadrons

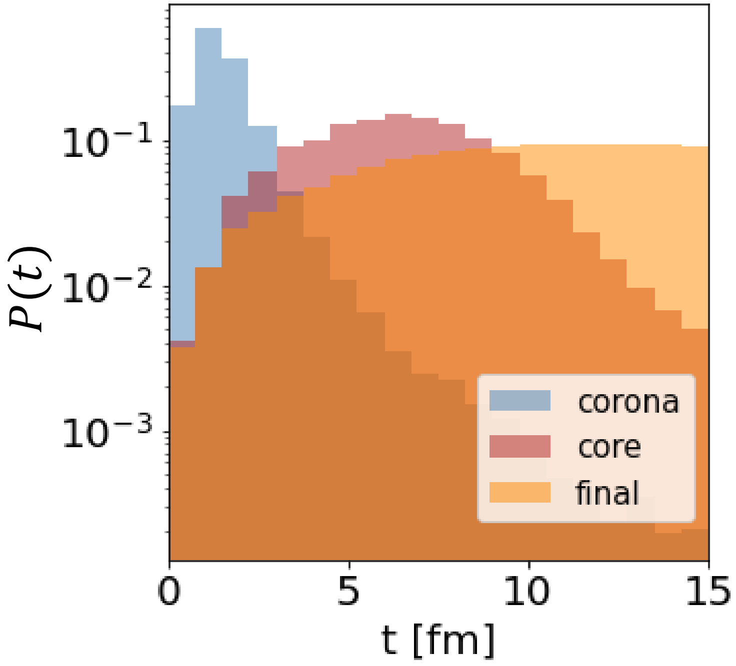
1 sampled event





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



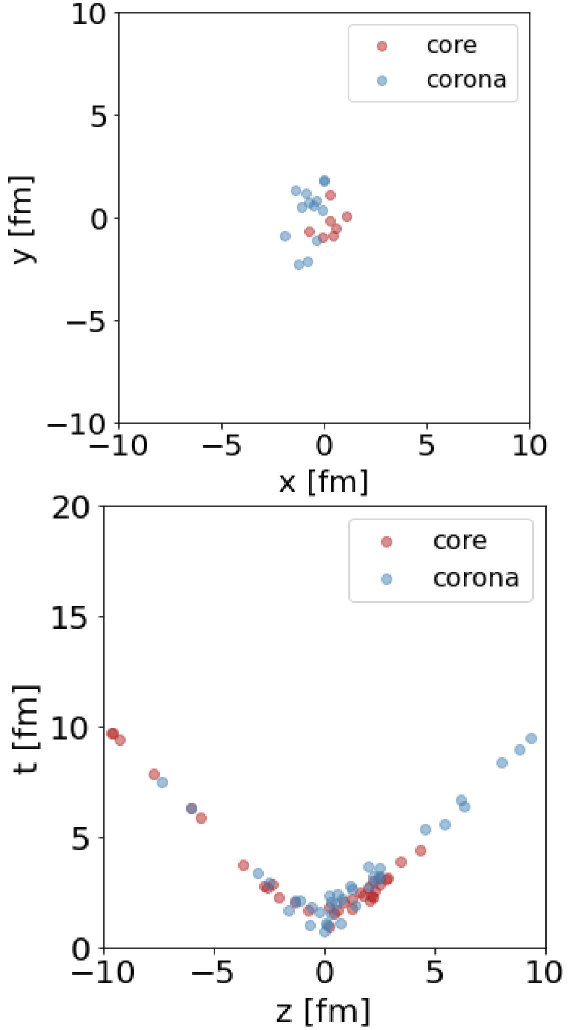


Double peaks of hadron vertices from core and corona before hadronic rescatterings

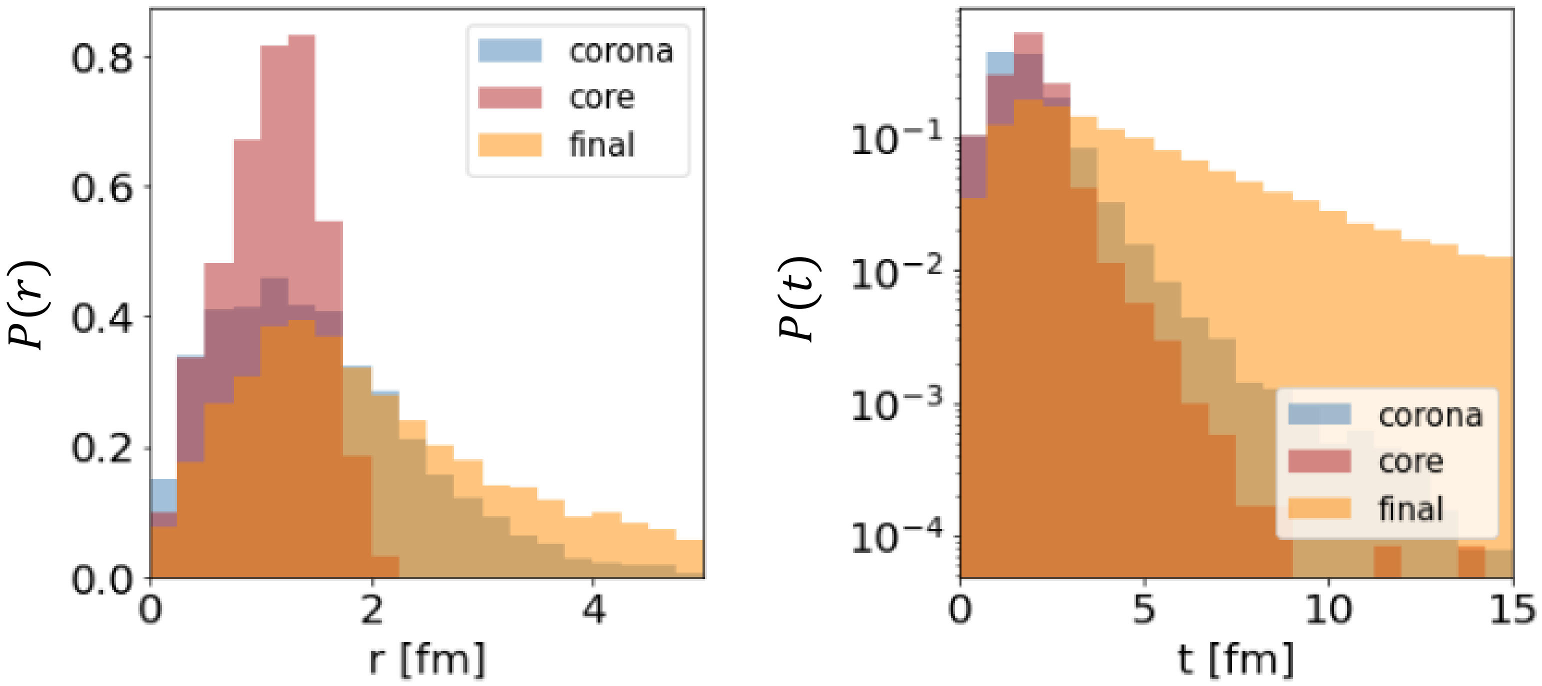
pp 7 TeV

Space-time distribution of direct hadrons

1 sampled event

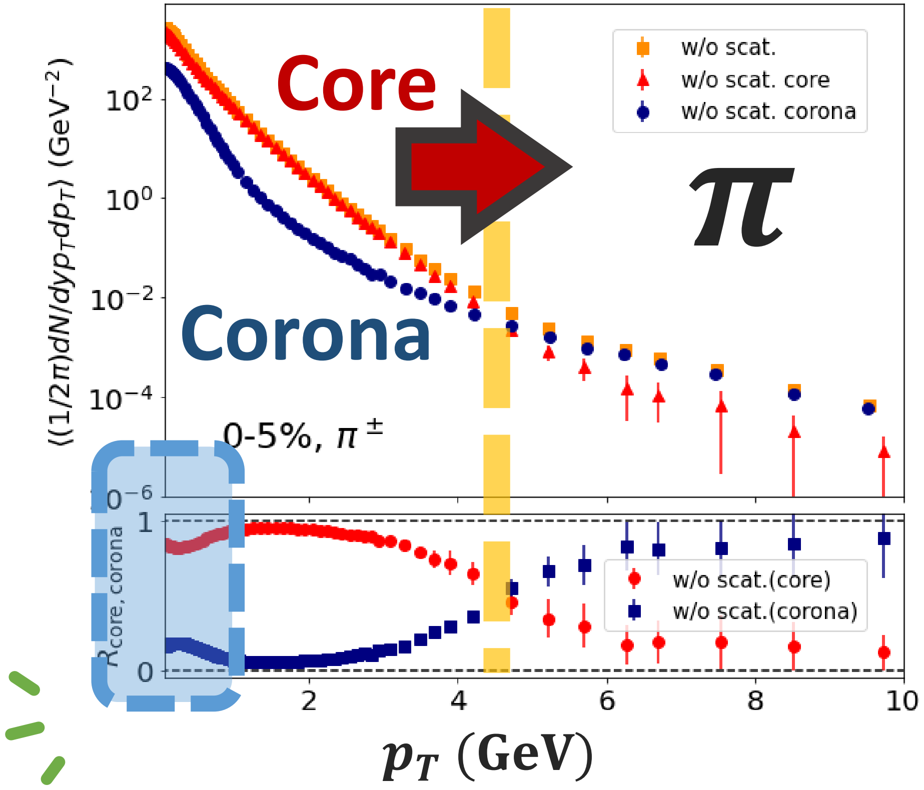


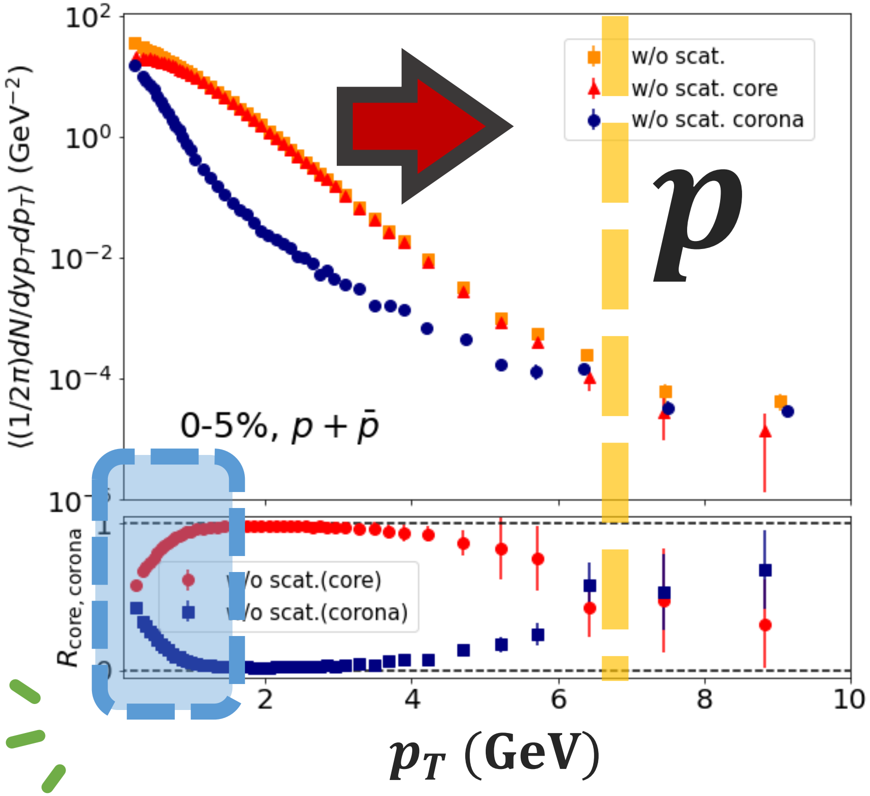
Probability distribution ($|\eta| < 0.5$)



- Short lifetime of hydro (~ 1 fm) in pp
- Direct hadrons from core and corona
  ➔ closely produced in space-time coordinate

Fraction of core and corona vs. p_T with PID





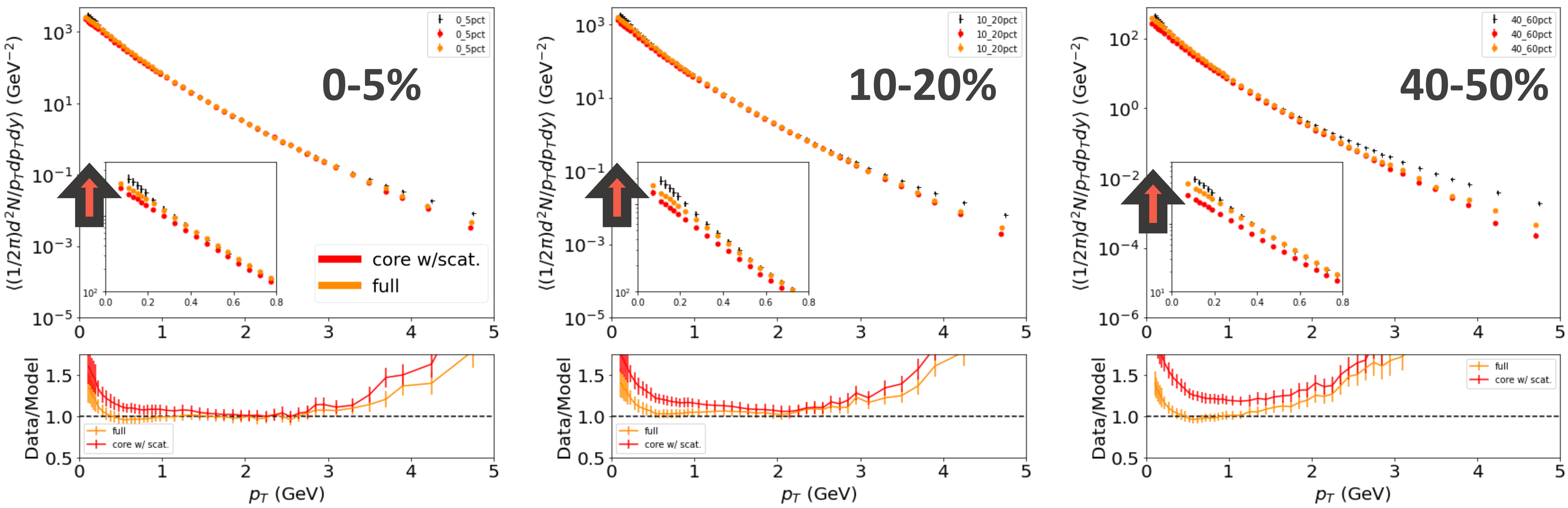
Core dominance up to higher p_T for heavier hadrons

T. Hirano and Y. Nara, Phys. Rev. C 69, 034908 (2004).

Core/corona fraction $\sim$ 50% at $p_T \to 0$ GeV in proton spectra

Comparison with exp. data

PbPb 2.76 TeV, $\pi^{\pm}$

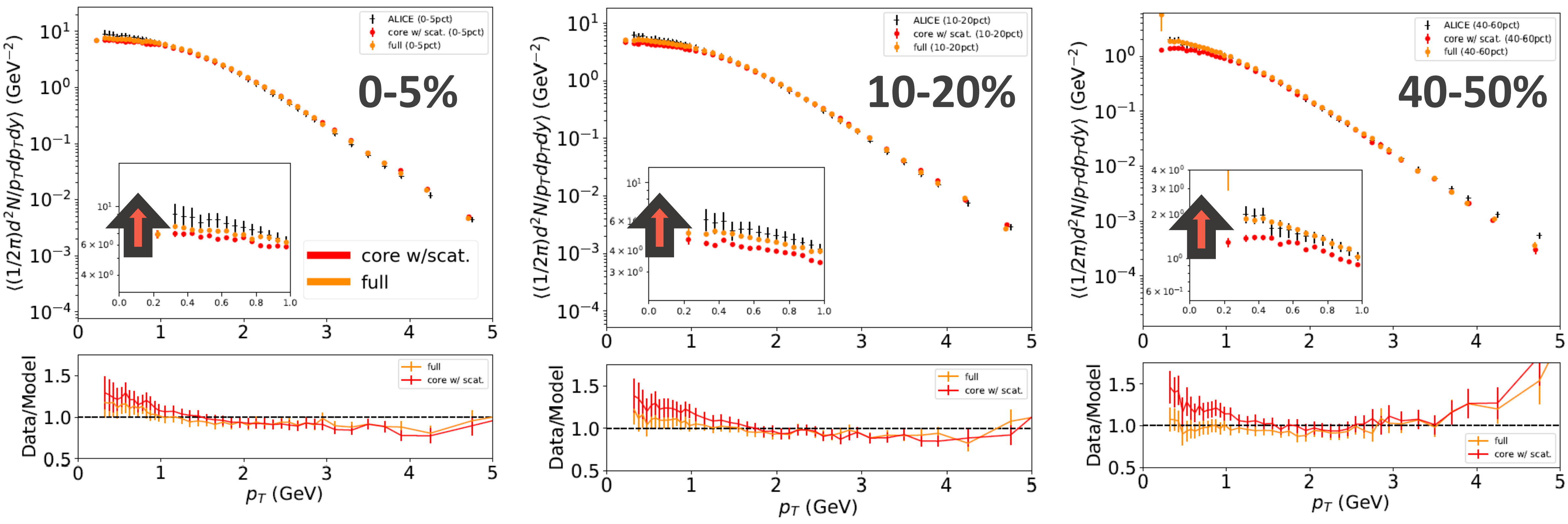


ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

Corona at very low p_T: possible compensation of yield

Comparison with exp. data

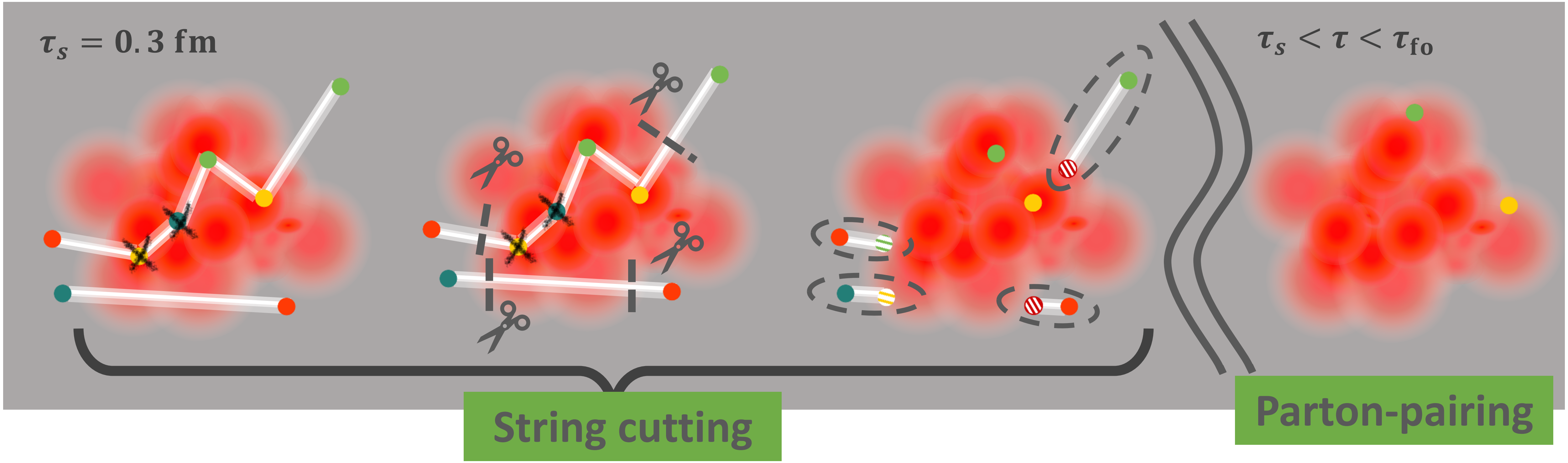
PbPb 2.76 TeV, $p + \overline{p}$



ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

Corona at very low p_T: possible compensation of yield

Corona components from string modification

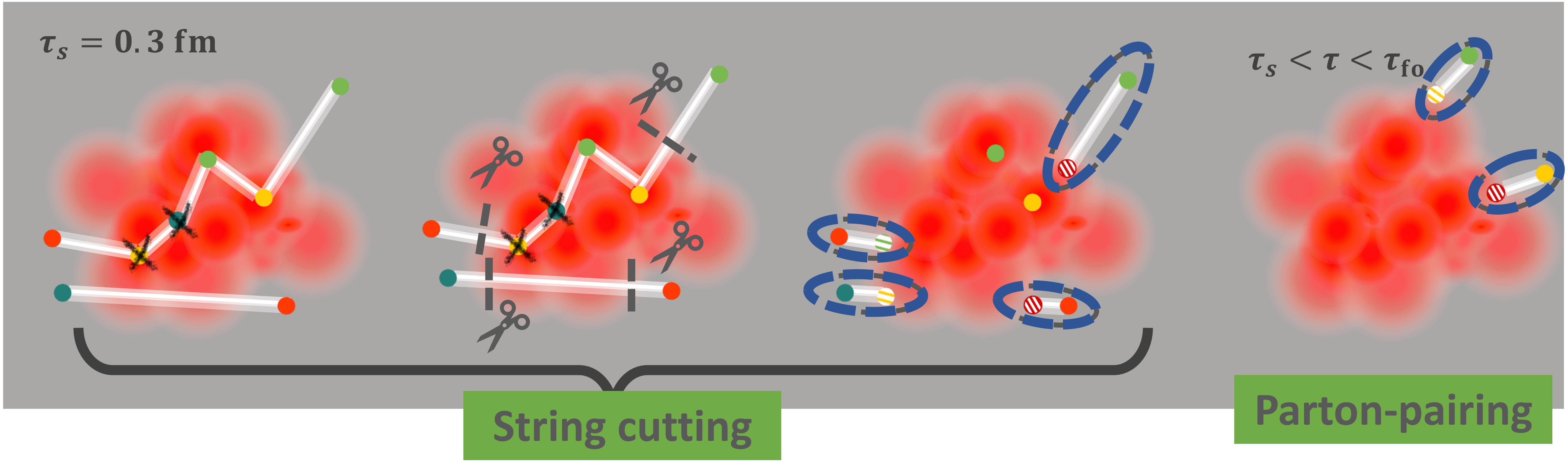


String modification caused by ..

- Spatial overlap of strings and medium
- Completely fluidized partons

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

Corona components from string modification (cont'd)



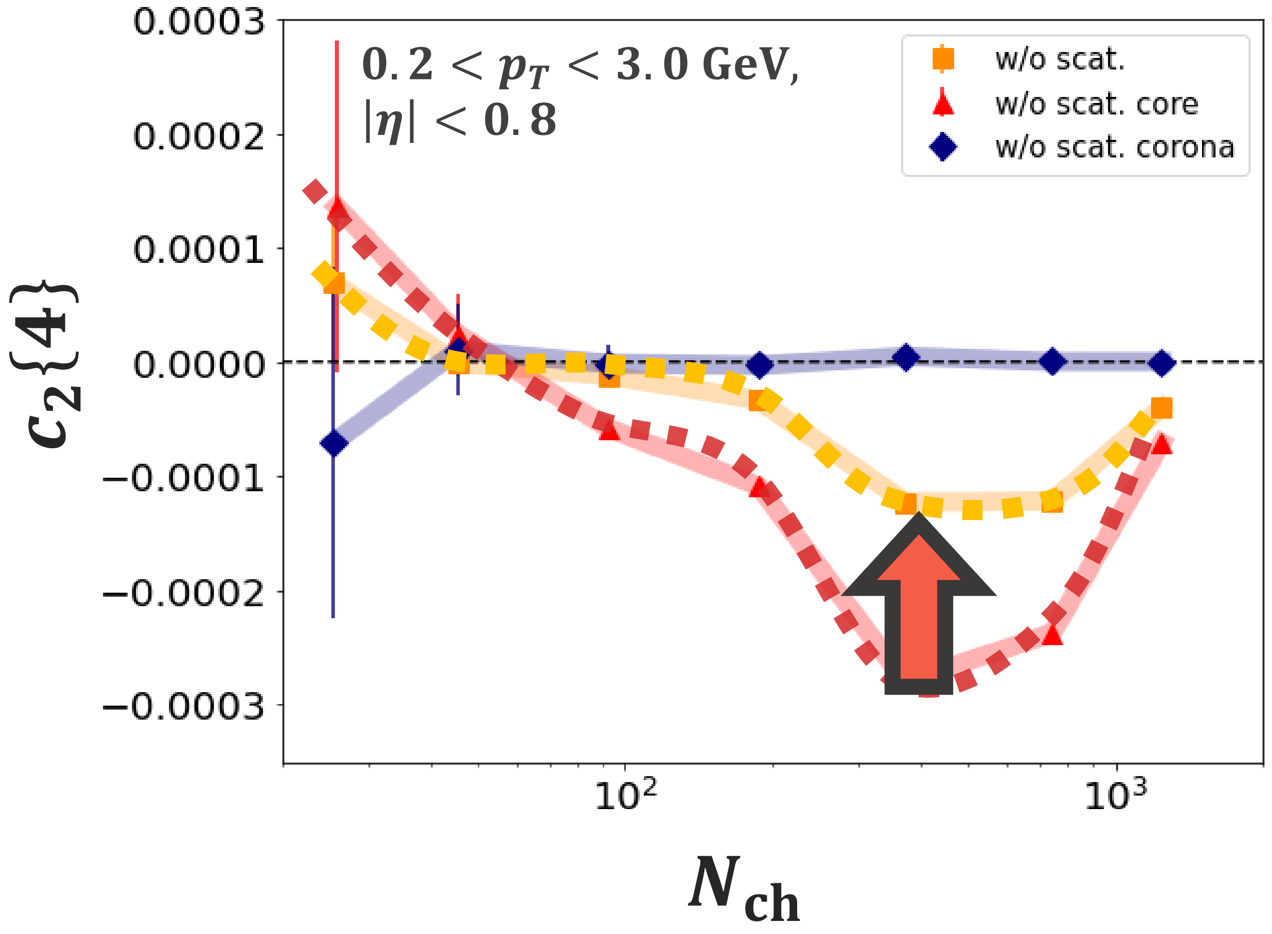
4. Surviving partons traverse medium
5. Make a pair for a parton coming out from medium

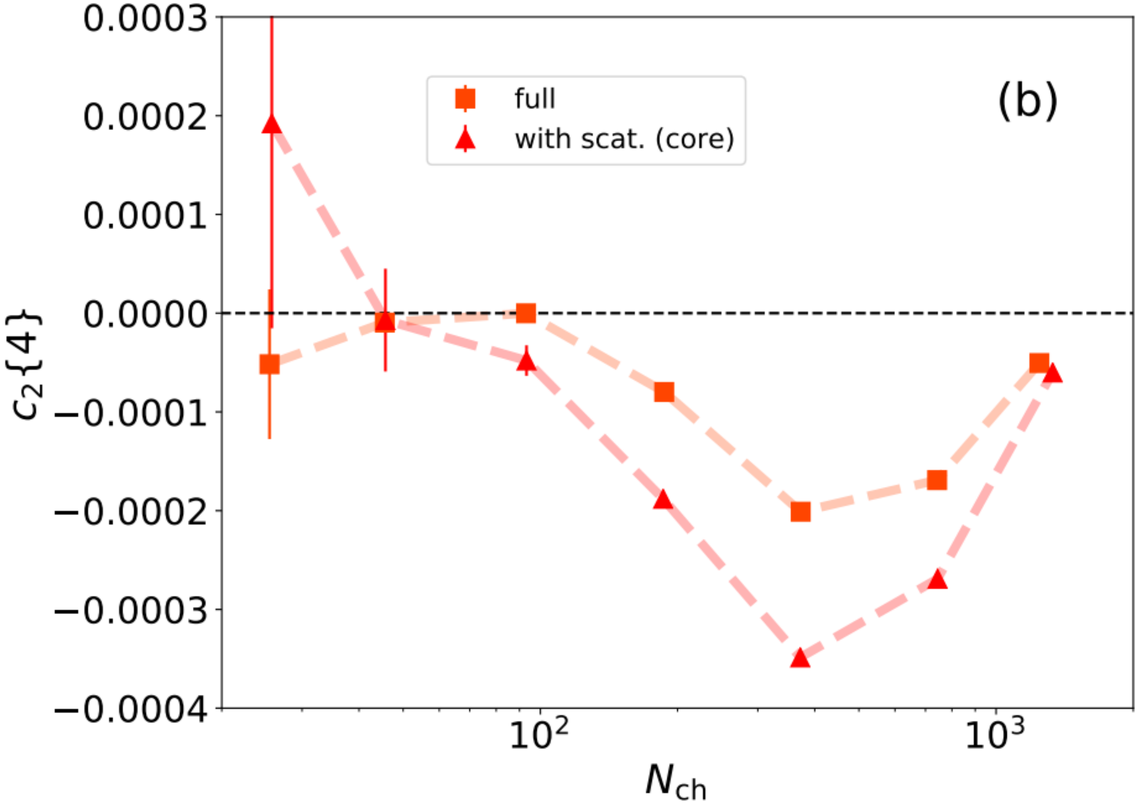
*$p_{T,\mathrm{cut}}$: threshold to/not to modify a string

Non-thermal & thermal
➔ Contributes as corona components

Corona corrections to flow

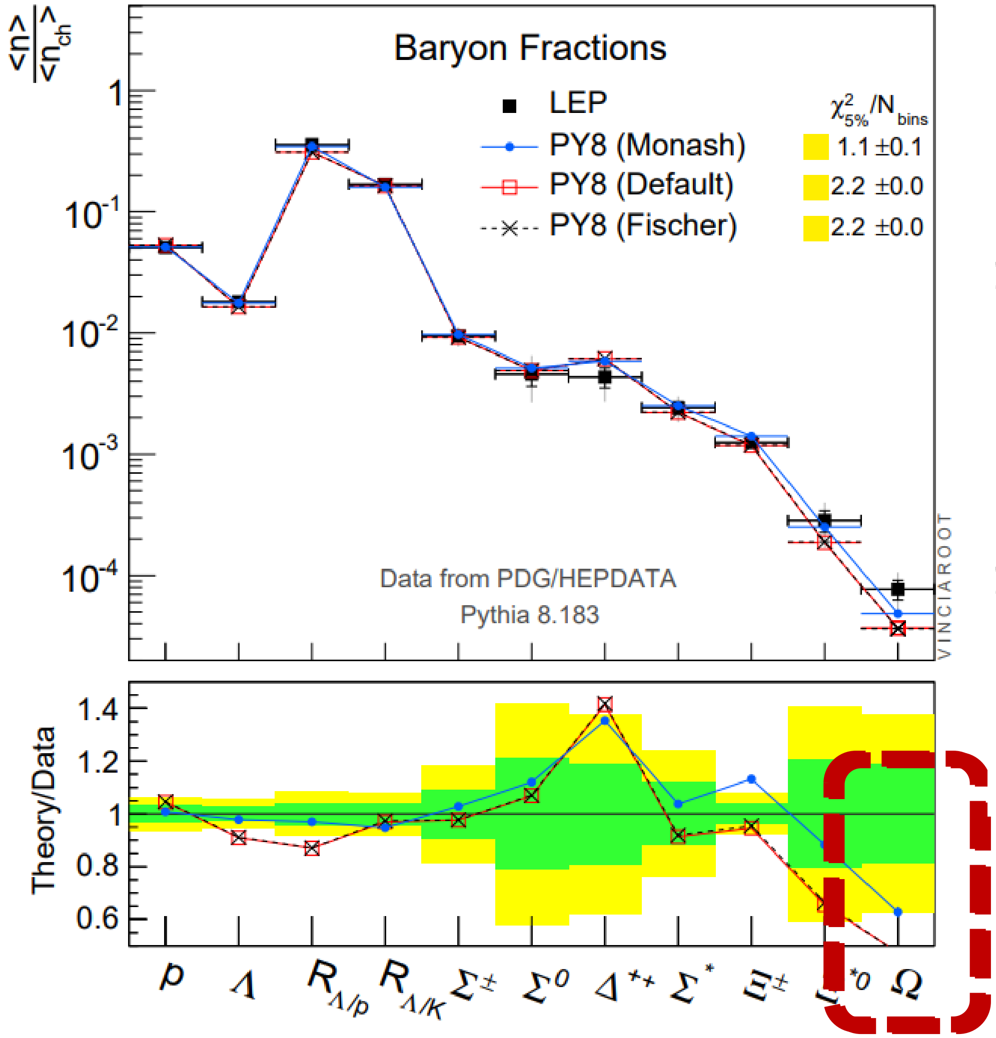
$c_2\{4\}$ from PbPb 2.76 TeV

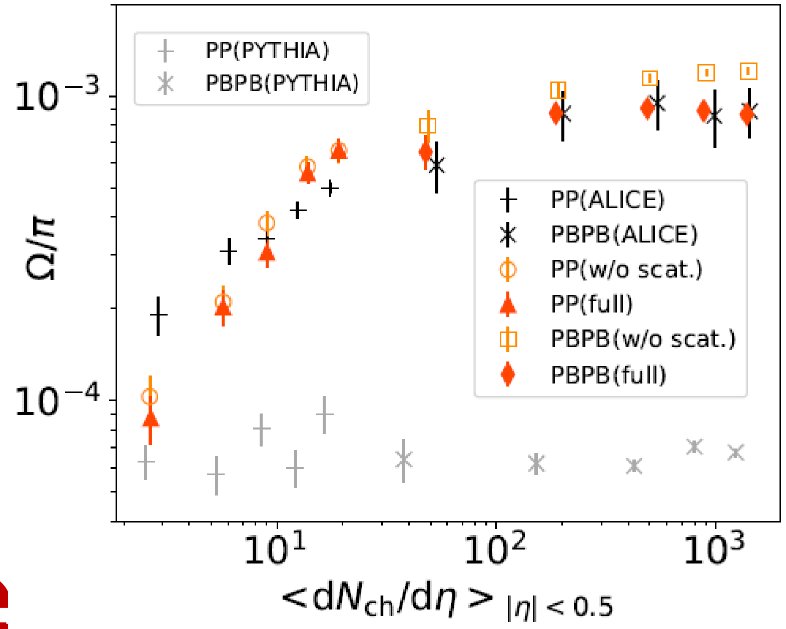




Ω yields from e^+e^- with Monash Tune

P. Skands *et al.*, Eur.Phys.J.C 74 (2014) 8, 3024





Dynamical 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: Instant equilibration of deposited energy and momentum

- Collision criterion

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

- Parametrized cross-section

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

- Density of partons

$$\rho_{i,j} = G(x_i - x_j)$$

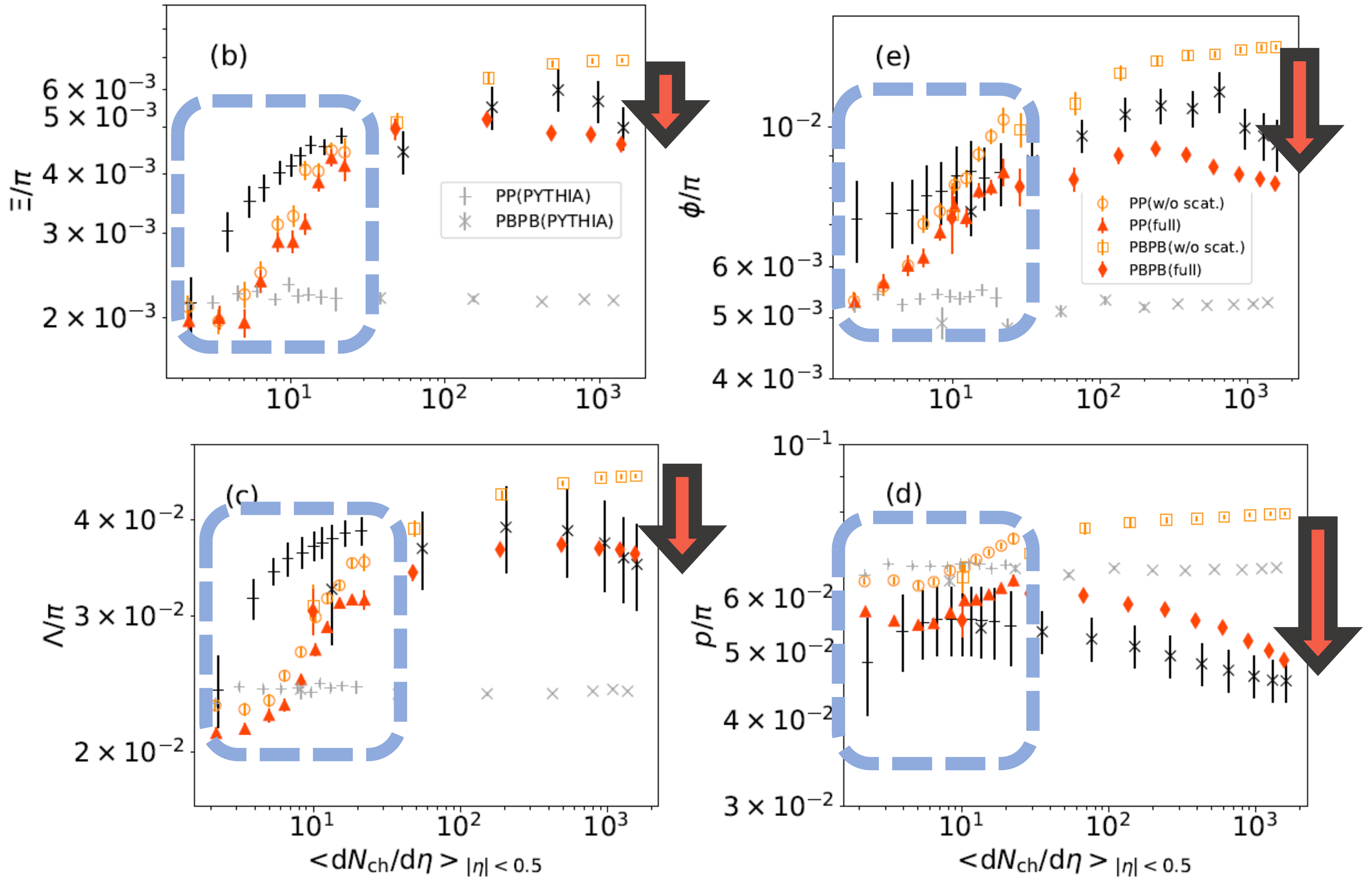
G : Gaussian

of (non-equilibrated and equilibrated) partons scattered with *i*th parton

Low p_T and/or dense region ⇒ Core (fluids)

High p_T and/or dilute region ⇒ Corona (non-equilibrated partons)

Effects of hadronic rescatterings

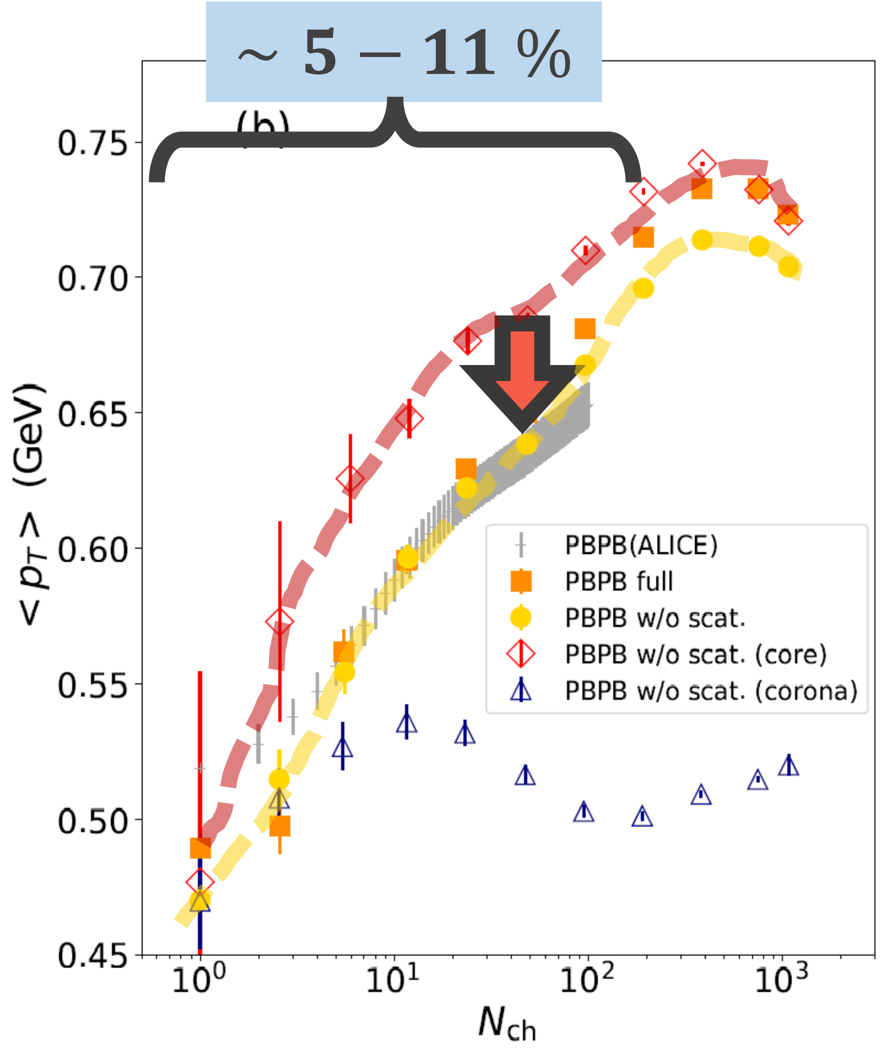


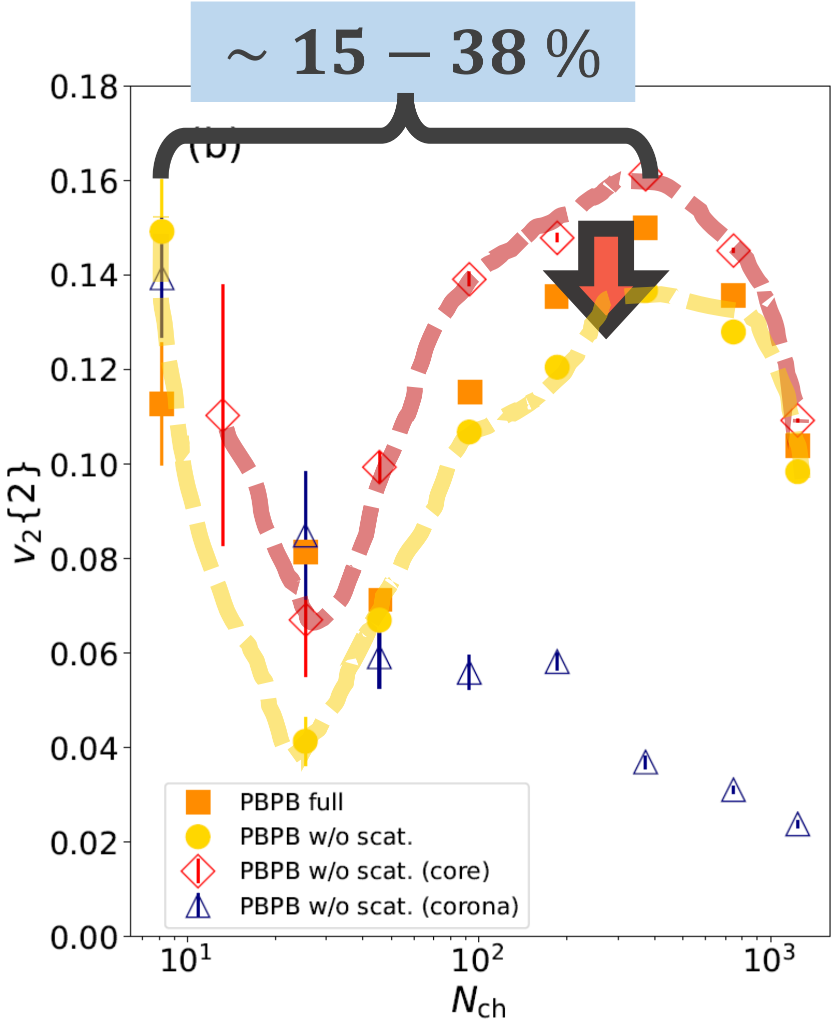
Significant suppression of yield ratios at central PbPb

✓ Captured with dissociation/annihilation of hadrons in late stage

Visible hadronic rescattering effects even in pp collisions

Corona correction in PbPb



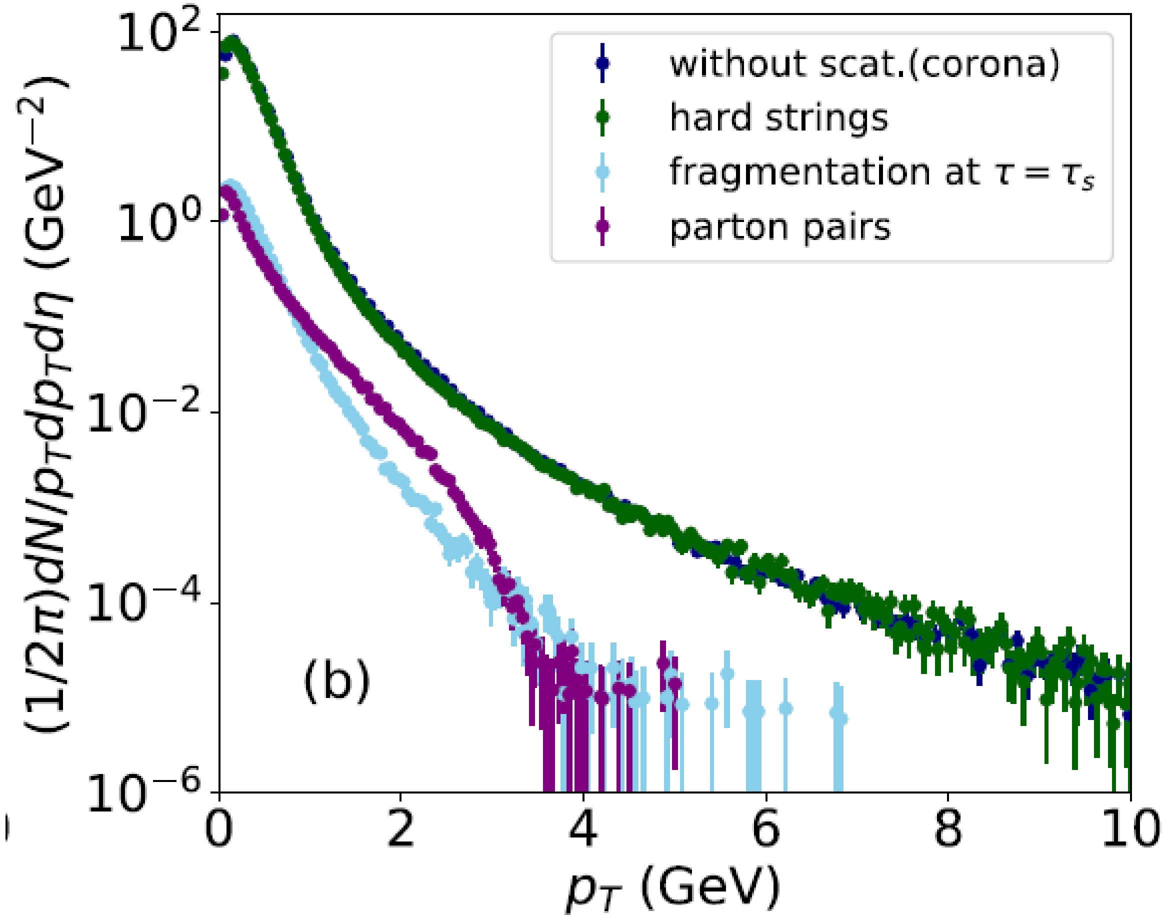


- Mean p_T and momentum anisotropy ➔ non-negligible effect of corona

- Pure hydro calculation can bring misinterpretation of exp. data even in PBPB

Origin of corona contribution

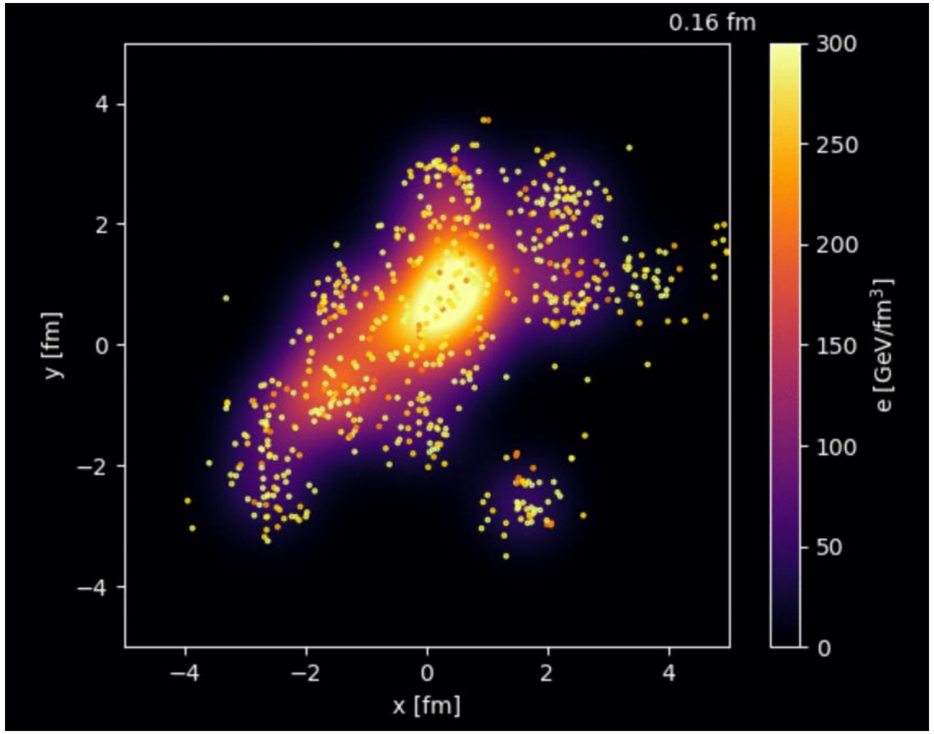
PbPb 2.76 TeV



Collision with constituent partons of QGP fluids

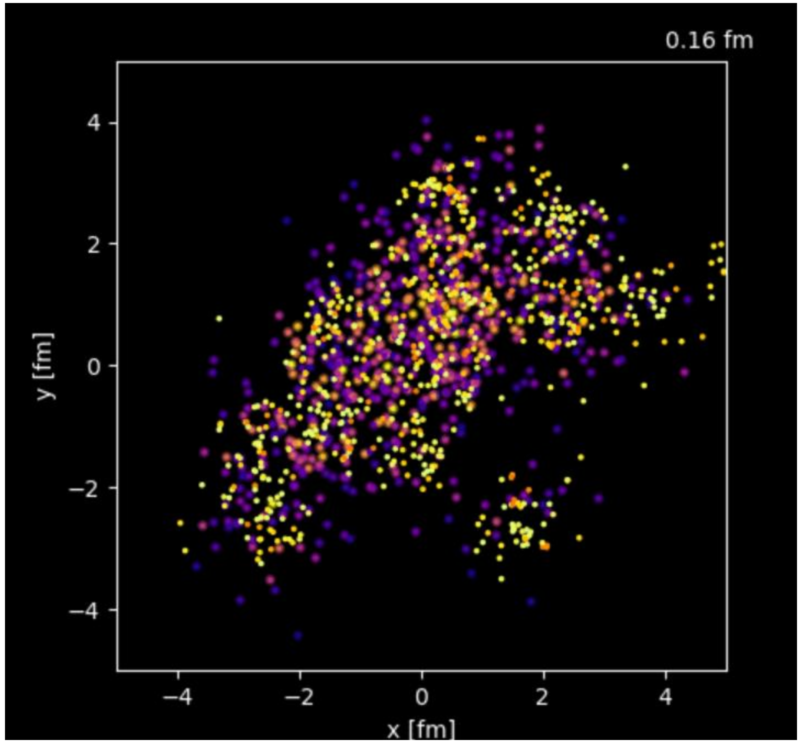
$$\frac{d{p_i}^{\mu}}{d\tau} = -\sum_{j}^{N_{\mathrm{scat}}} \rho_{i,j}\sigma_{i,j}\left|v_{\mathrm{rel},i,j}\right| {p_i}^{\mu}$$

➔ **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



QGP study with relativistic hydrodynamics

Energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = 0$$

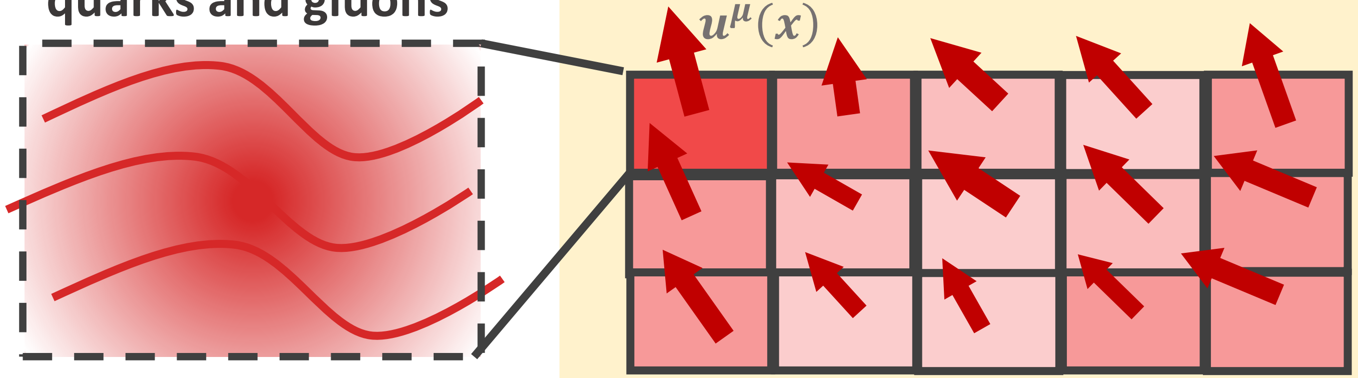
Energy-momentum tensor $T^{\mu\nu}$
➔decomposed with four velocity of fluids $u^\mu(x)$

➕

Equation of state (EoS) $P = P(e)$

- Lattice EoS (high T)
- Hadronic resonance gas EoS (low T)

Many-body system of quarks and gluons



➔ Local equilibration

Dynamics of locally-equilibrated patches