JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

ACADEMY OF FINLAND

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

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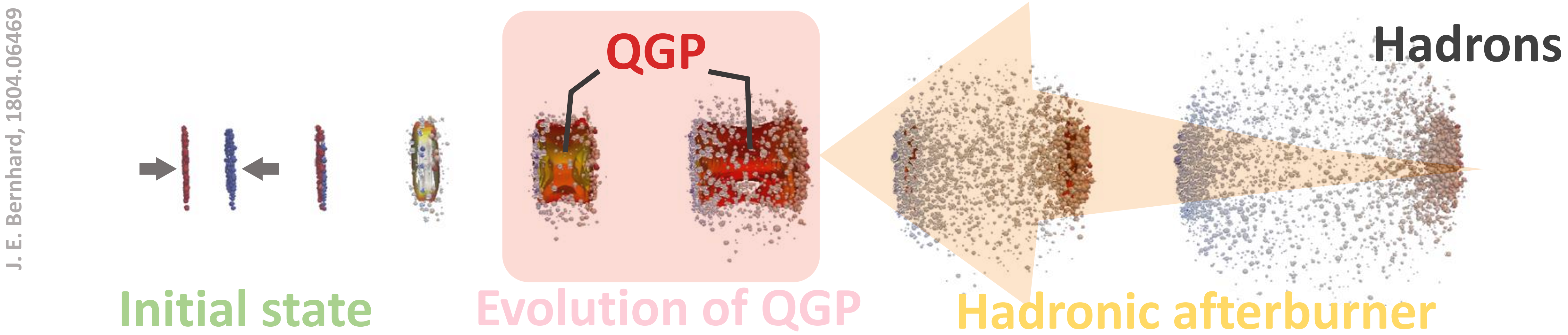
[2] Sophia University, [3]Akita International University

QGP study via relativistic heavy-ion collisions

Only possible research method based on observation on the earth



Description of the **multi-stage process**

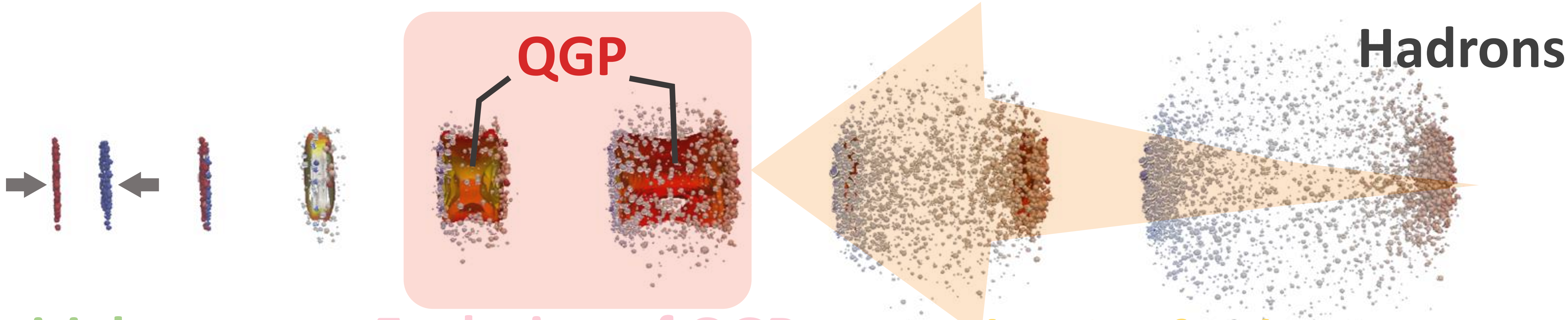
➔ Rewinding the process to "see" QGP

Hydro-based multi-stage dynamical model

Standard model in HIC

Extraction of QGP properties from direct comparisons with data

J. E. Bernhard, 1804.06469



Initial state | Evolution of QGP | Hadronic afterburner

Initial condition → Relativistic hydrodynamics → Fluids to particles → Hadronic transport

QGP signals in small colliding systems

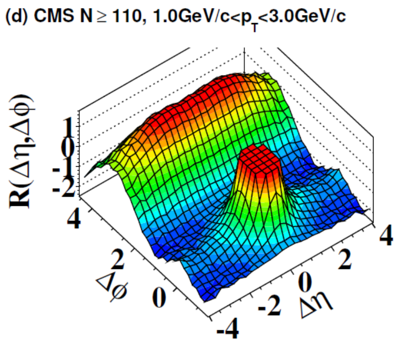
In **high-multiplicity** small systems (pp, pA)...

Thermal strange hadron productions

Hydro-like collectivity

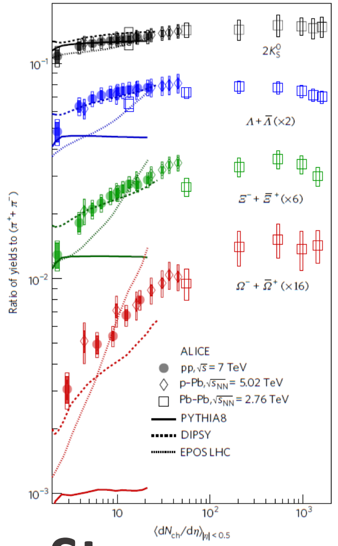
Challenge to interpret the universal behavior from pp to AA

... within a single dynamical framework?



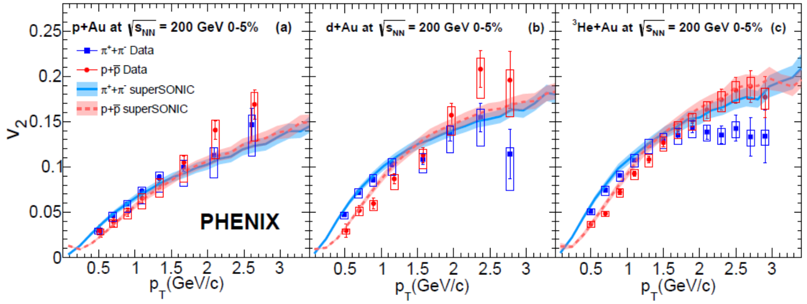
Long range correlation

CMS Collaboration, JHEP 09 091 (2010)



Strangeness enhancement

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

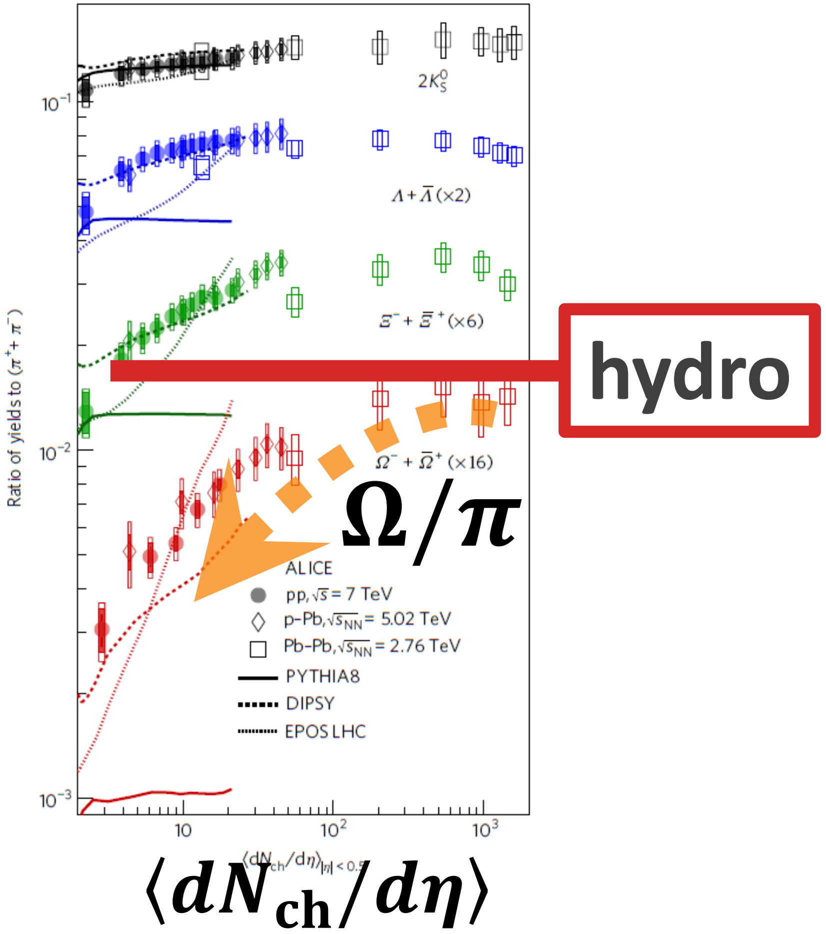


Flow harmonics

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

Need of far-from equilibrium components

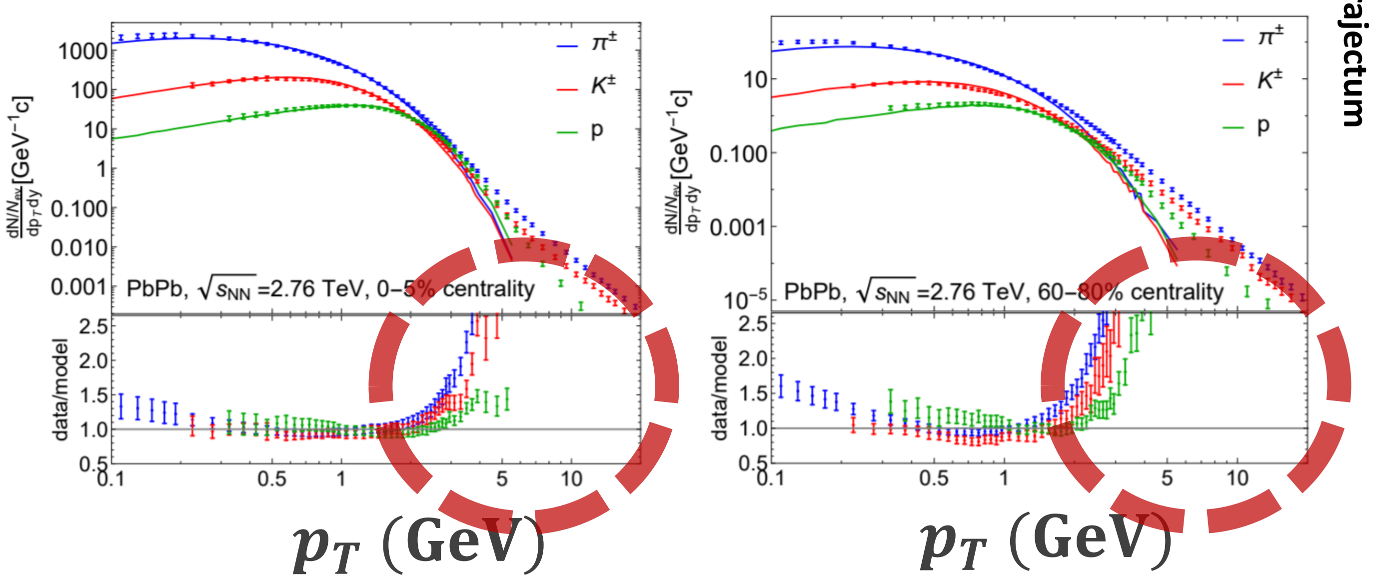
1. In peripheral AA, small systems



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

2. At high p_T (and very low p_T)

p_T spectra

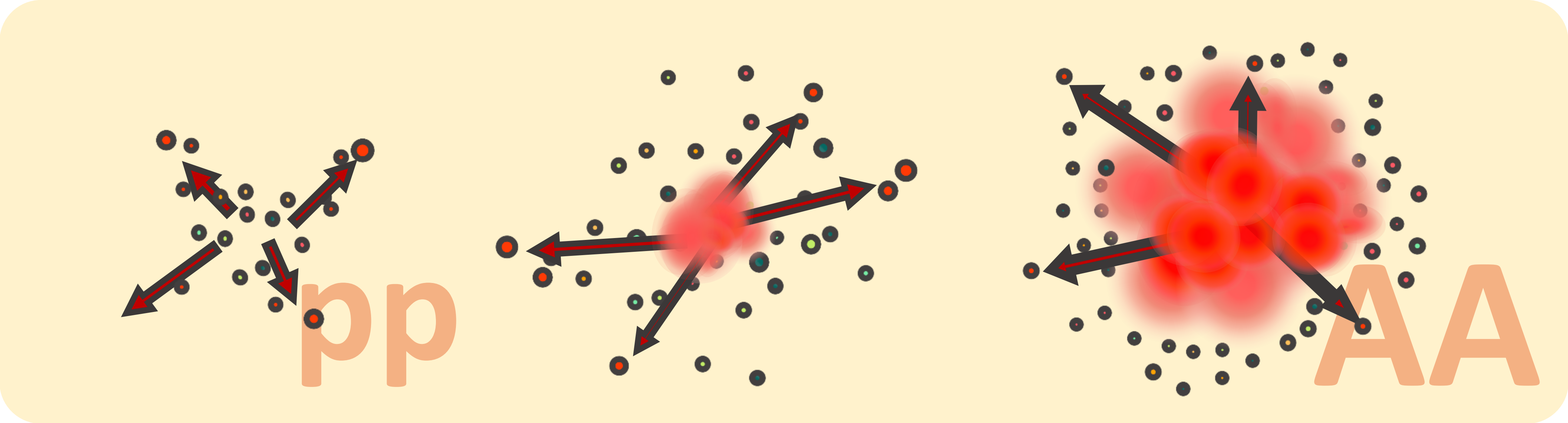


Phys. Rev. C 103 (2021) 5, 054909 Trajectum

✖ **Picture of global local-equilibrium**

Need to extend applicability of dynamical frameworks

Dynamical Core-Corona Initialization framework



Core: fluids (equilibrated matter) ➔ **Hydrodynamics**

Corona: non-equilibrated partons ➔ **String fragmentation**

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

Energy-momentum conservation of incoming beam

From pp to AA, from low to high p_T

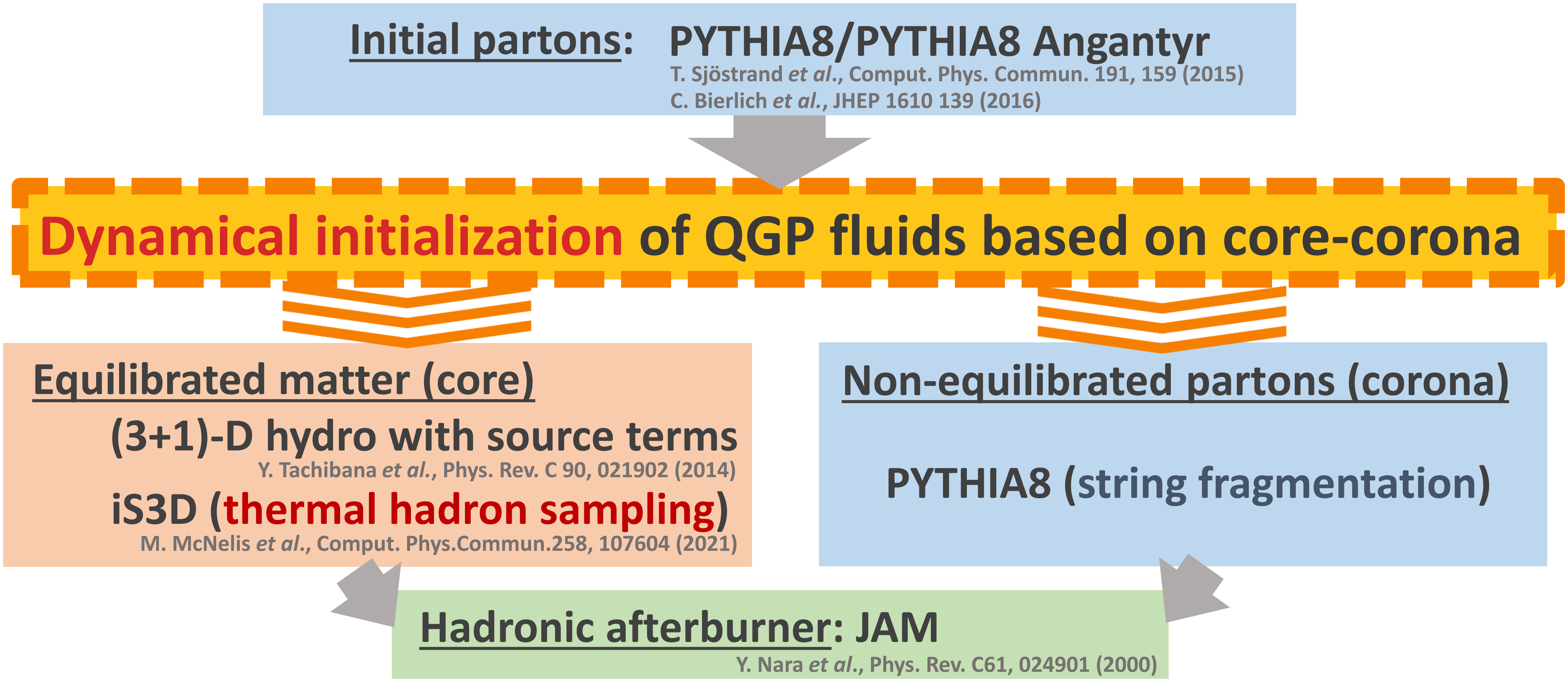
Y. Kanakubo *et al.*, PTEP 2018 12, 121D01 (2018);
Y. Kanakubo *et al.*, Phys. Rev. C 101 2, 024912 (2020);
Y. Kanakubo *et al.*, Phys. Rev. C 105 (2022) 2, 024905

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



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

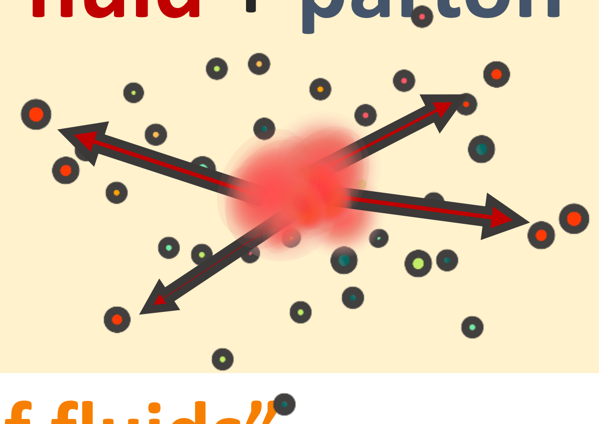
$$\partial_\mu\left(T^{\mu\nu}_{\mathbf{fluid}} + T^{\mu\nu}_{\mathbf{parton}}\right) = 0$$

Hydrodynamic eq. with source term

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

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

Energy-momentum conservation in fluid + parton



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

Dynamical core-corona picture

Multiple scatterings among partons ➔ partial equilibration

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

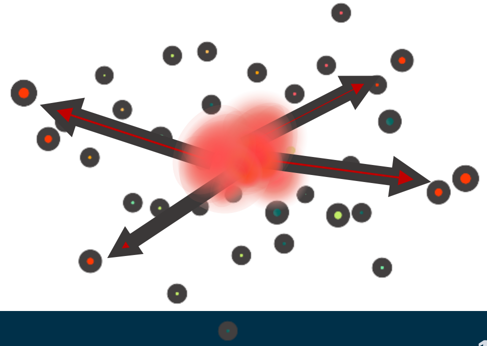
Defined at a co-moving frame with $\eta_{s,i}$

Energy-momentum deposition

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

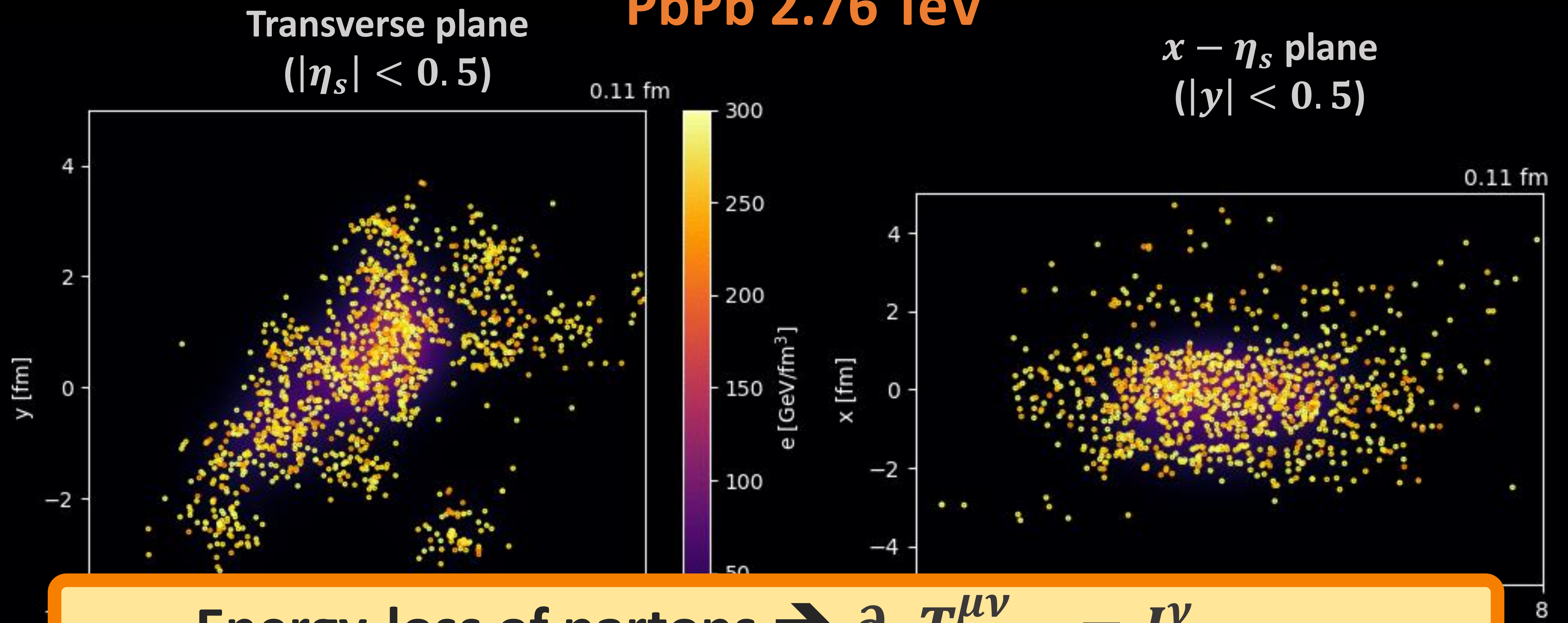
Low p_T and/or dense region ➔ Core (fluids)

High p_T and/or dilute region ➔ Corona (partons)



Dynamical core-corona initialization

PbPb 2.76 TeV

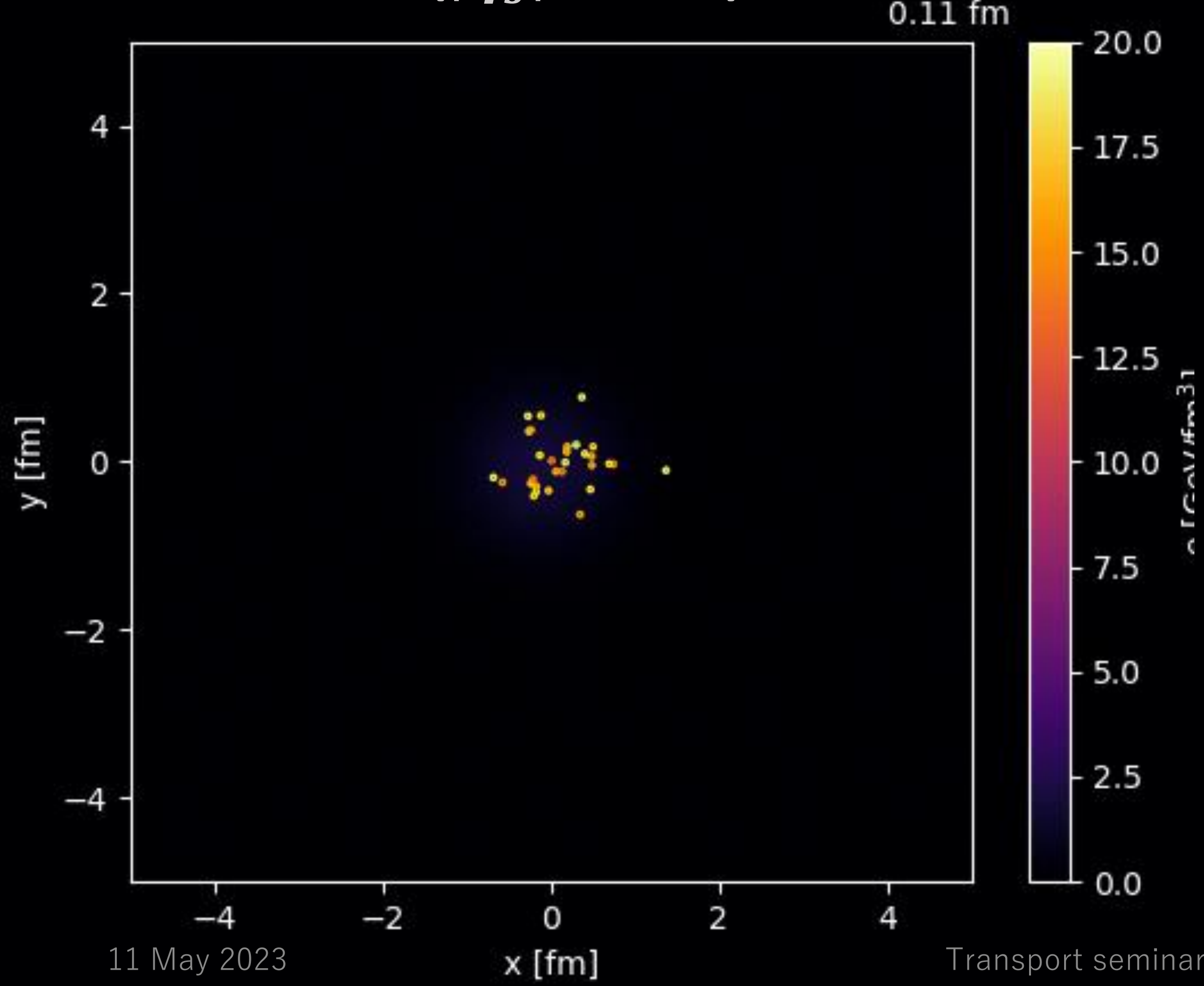


Energy-loss of partons ➔ $\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^{\nu}_{\text{parton}}$
Jet-quenching + medium response

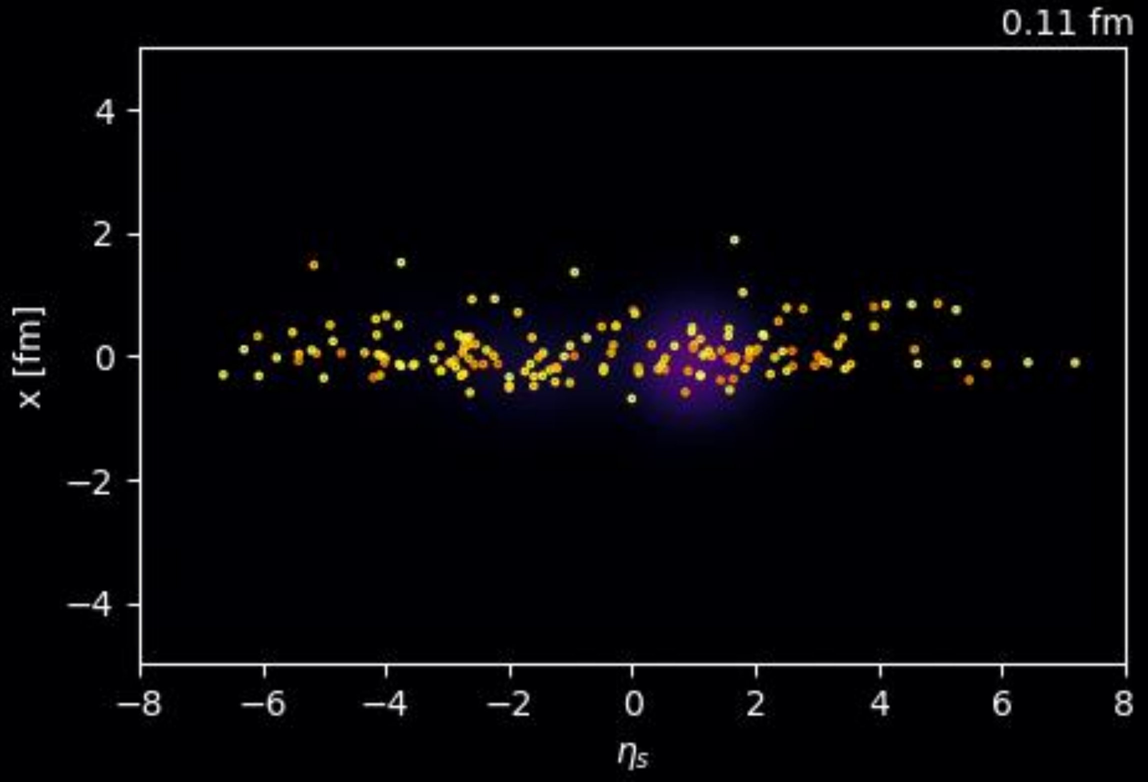
Dynamical core-corona initialization

pp 7 TeV

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



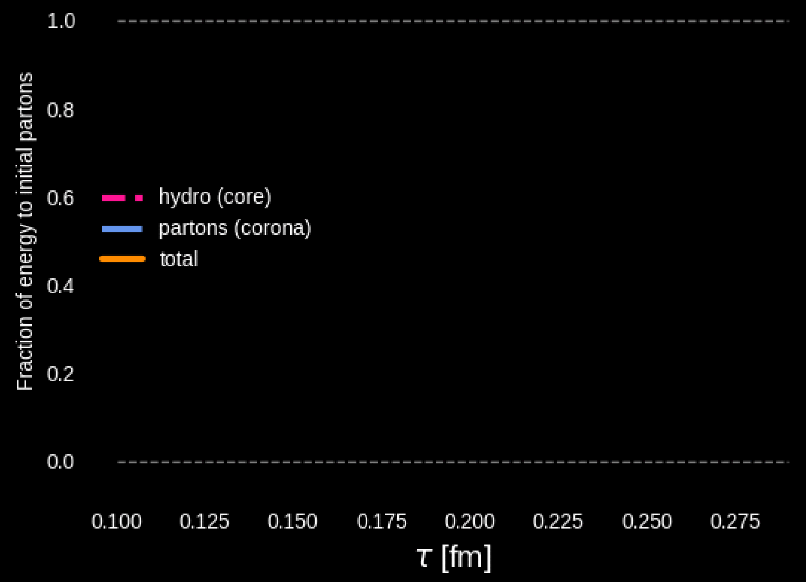
$x - \eta_s$ plane
$(|y| < 0.5)$



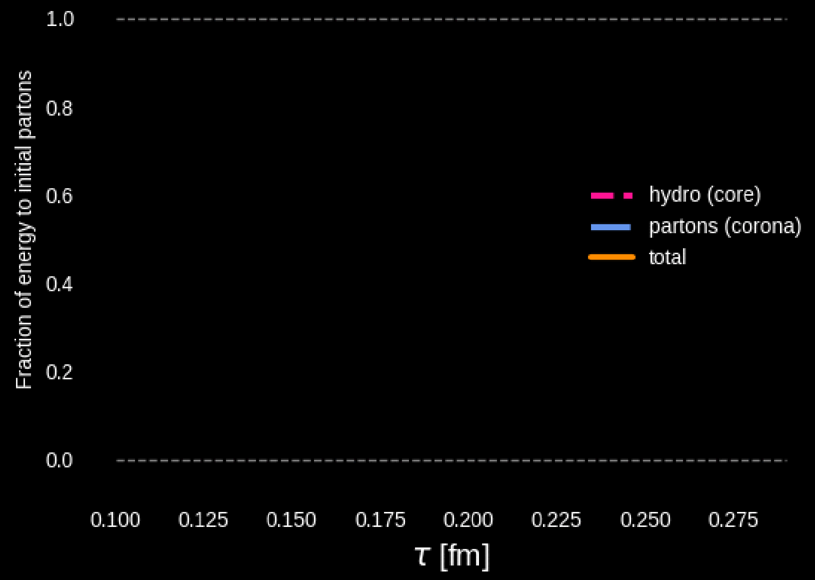
Energy budget in dynamical core-corona initialization

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

PbPb



pp



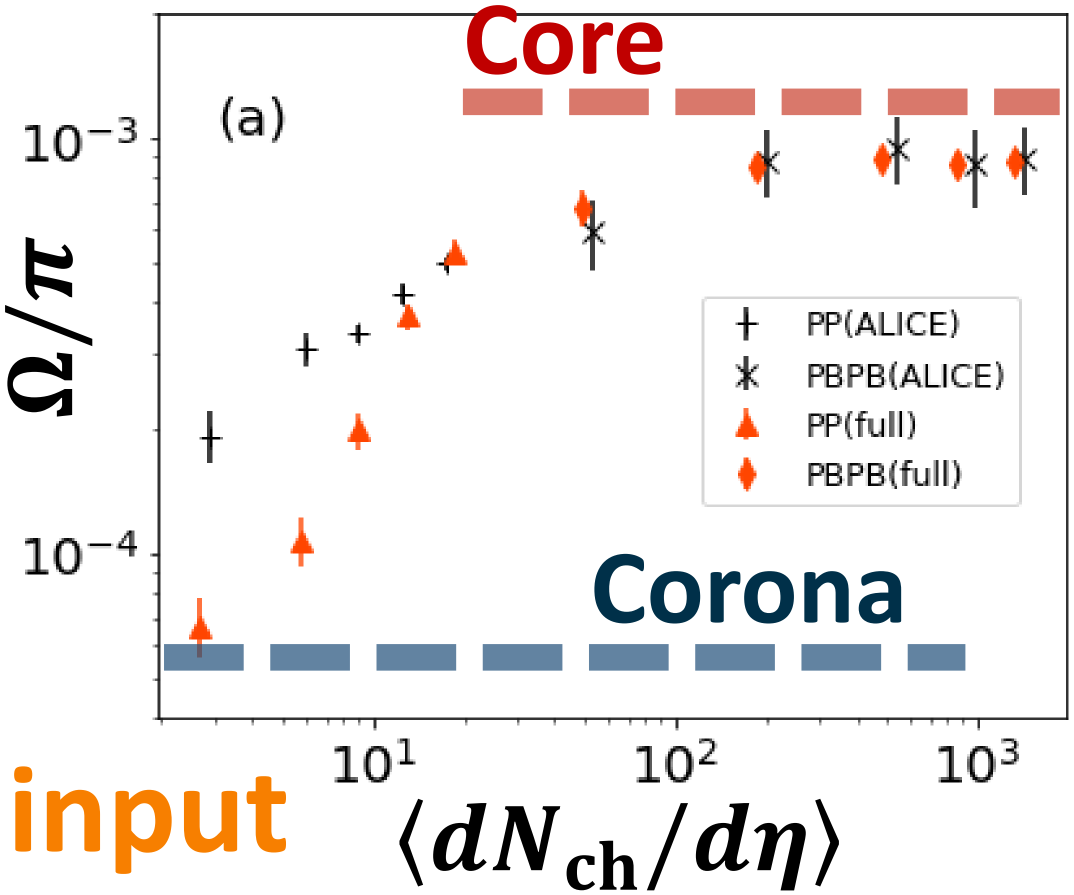
- Starting from vacuum $T^{\mu\nu} = 0$ for fluids
- Dynamical conversion of energy-momentum from corona to core

Conservation of incoming beam energy in QGP generation event-by-event

Fixing parameters

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)

Smooth enhancement of Ω/π

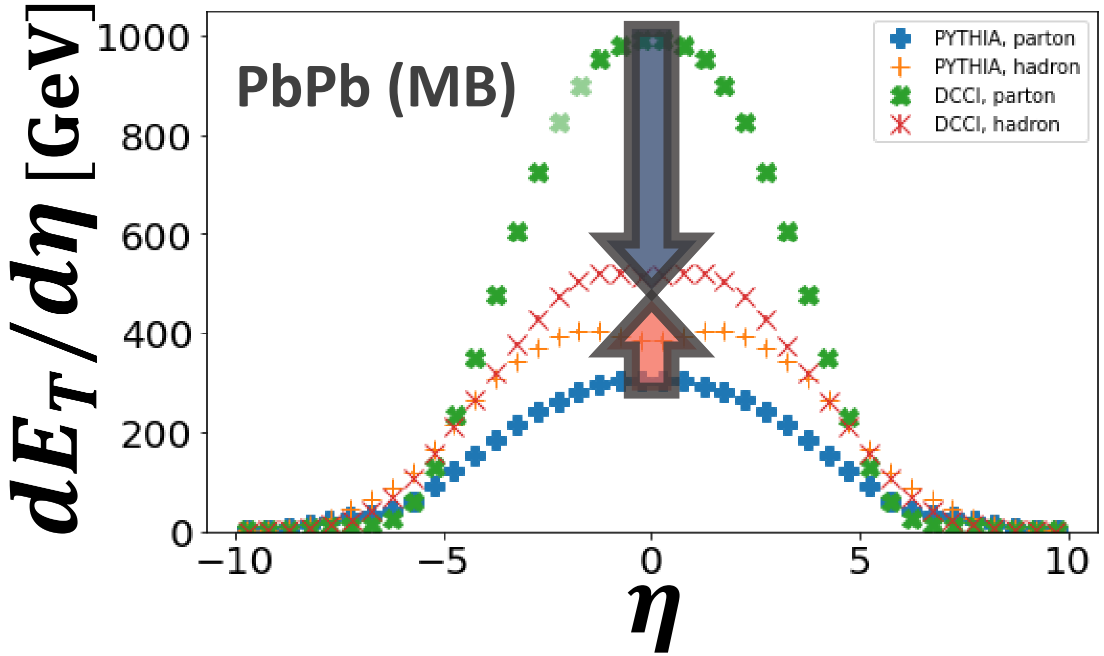
➔ Smooth increase of **core** contribution

➔ Controlled by σ

☑ Describe composition of matter

Charged particle multiplicity

Difference of E_T evolution between hydro and string frag.



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

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

Different dynamics in later stage
➔ Require different initial energy profile

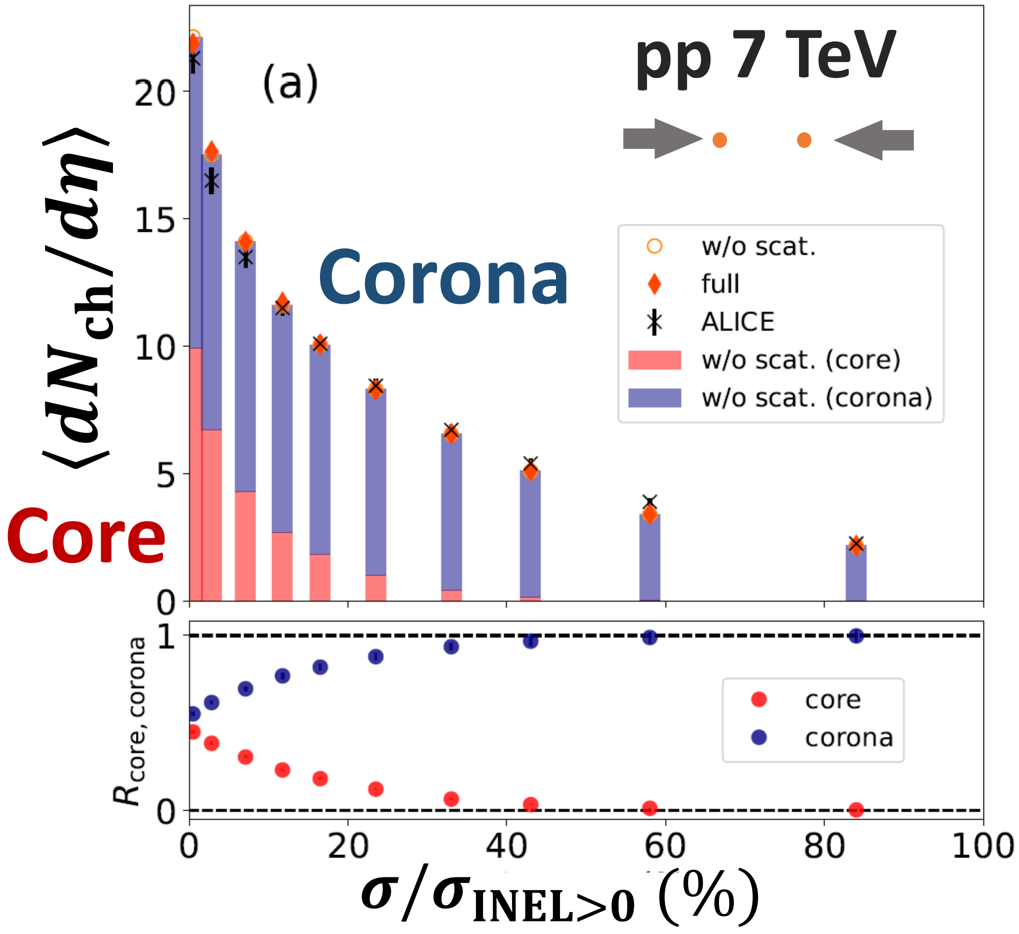
$p_{T0\mathrm{Ref}}$: infrared cut off of 2→2 in PYTHIA

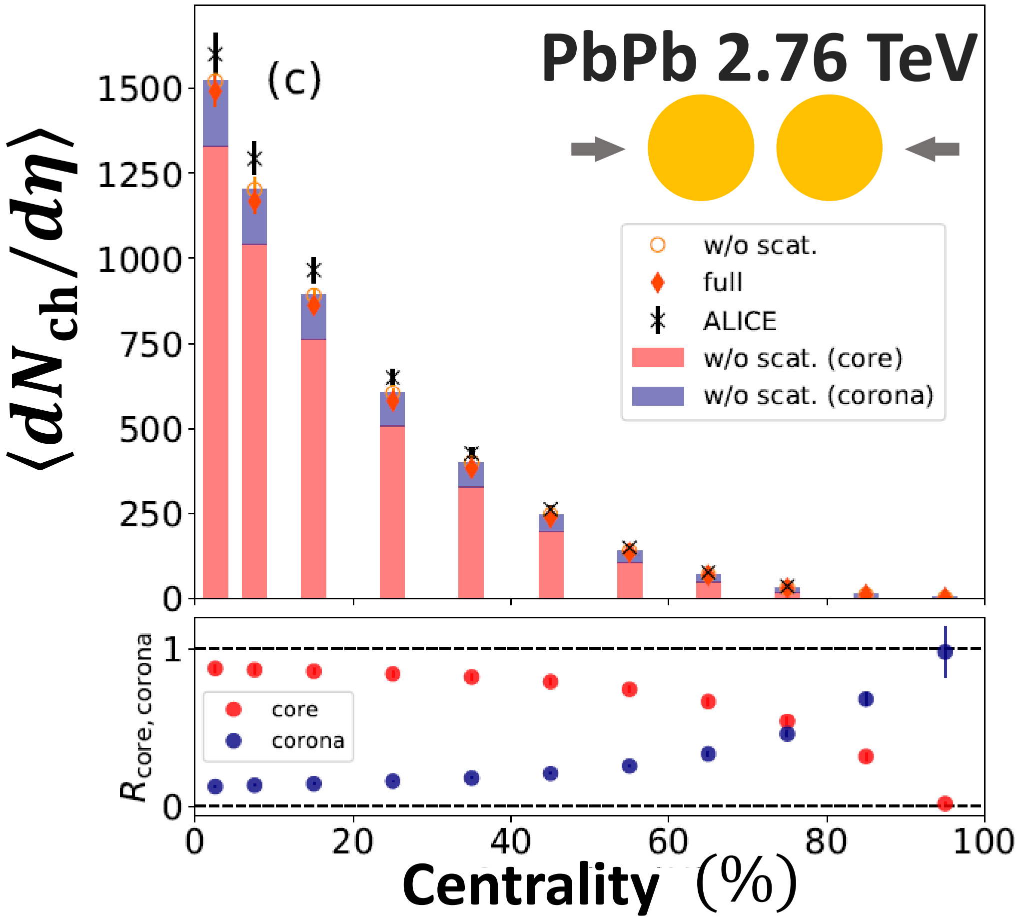
Result 1

Need both core and corona in both pp and AA!

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

Fraction of core and corona in pp and PbPb





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

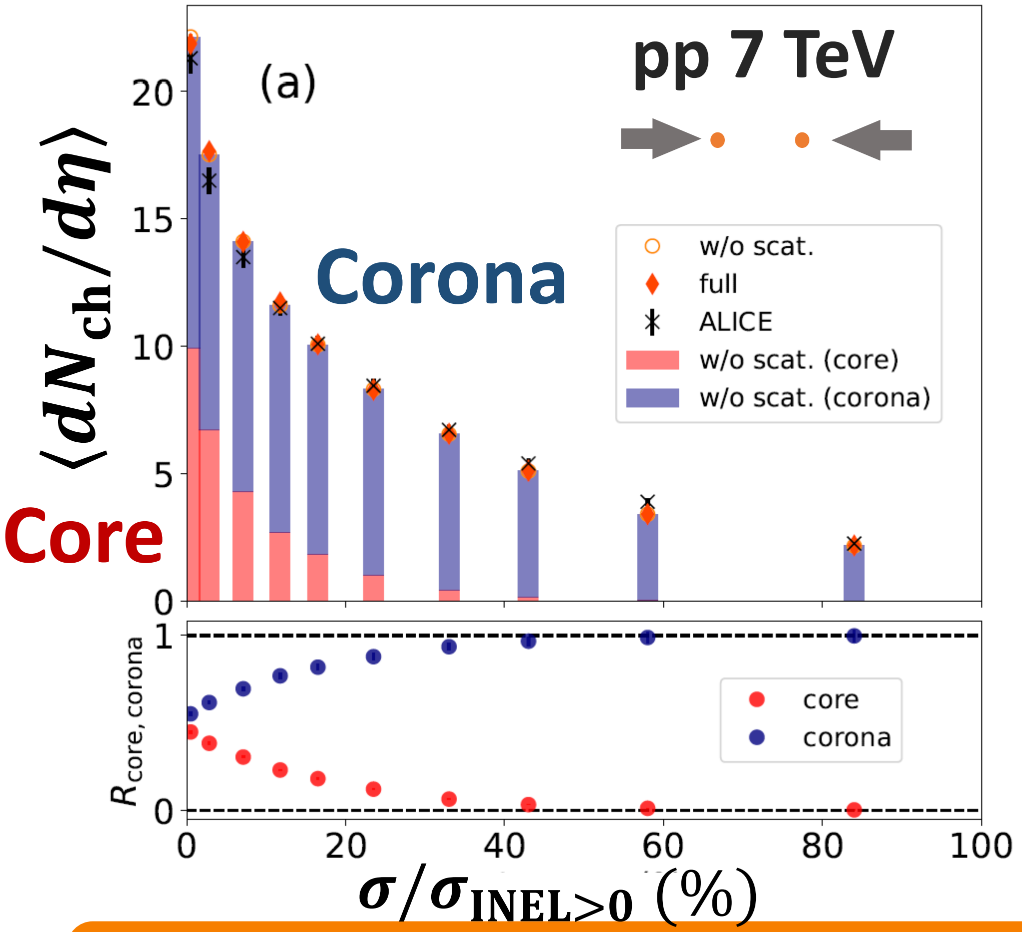
K. Aamodt *et al.*, (ALICE Collaboration), Phys. Rev. Lett. 106 032301 (2011)

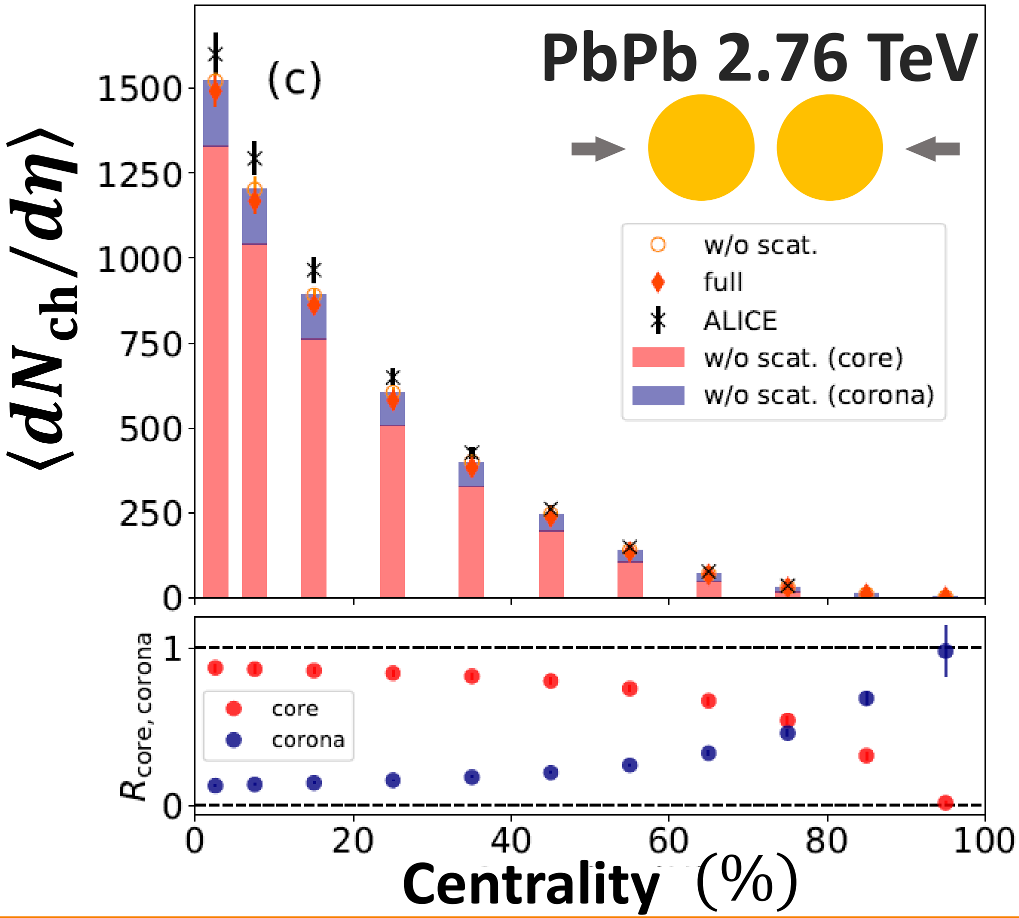
pp: core/corona $\sim 50\%$ at the highest multiplicity class (0-0.95%)

PbPb: corona $\sim 20\%$ 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)

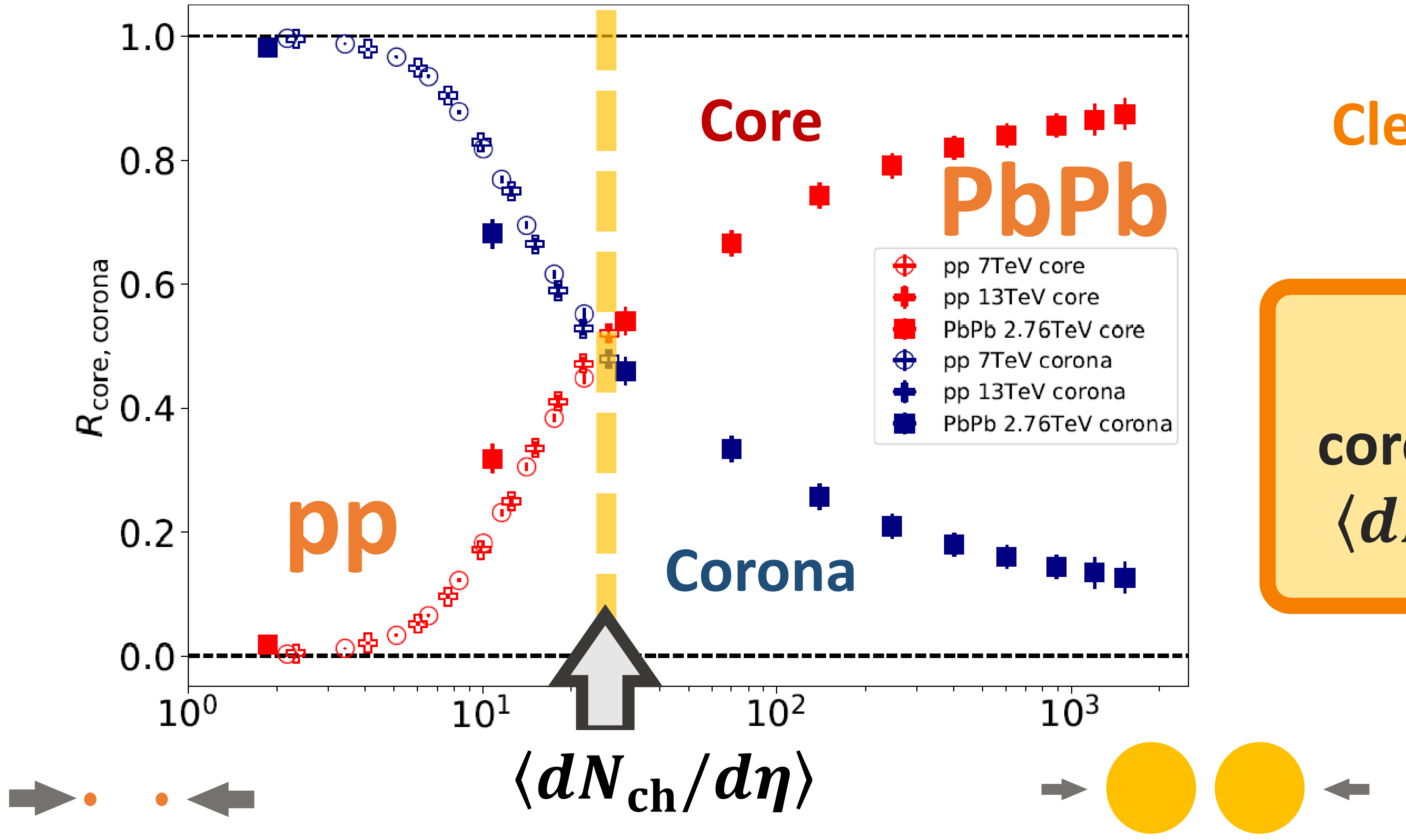




K. Aamodt *et al.*, (ALICE Collaboration), Phys. Rev. Lett. 106 032301 (2011)

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

Onset $\langle dN_{\mathrm{ch}}/d\eta \rangle$ of core dominance



Clear scaling with multiplicity

Onset of core dominance at $\langle dN_{\mathrm{ch}}/d\eta \rangle \sim 20$

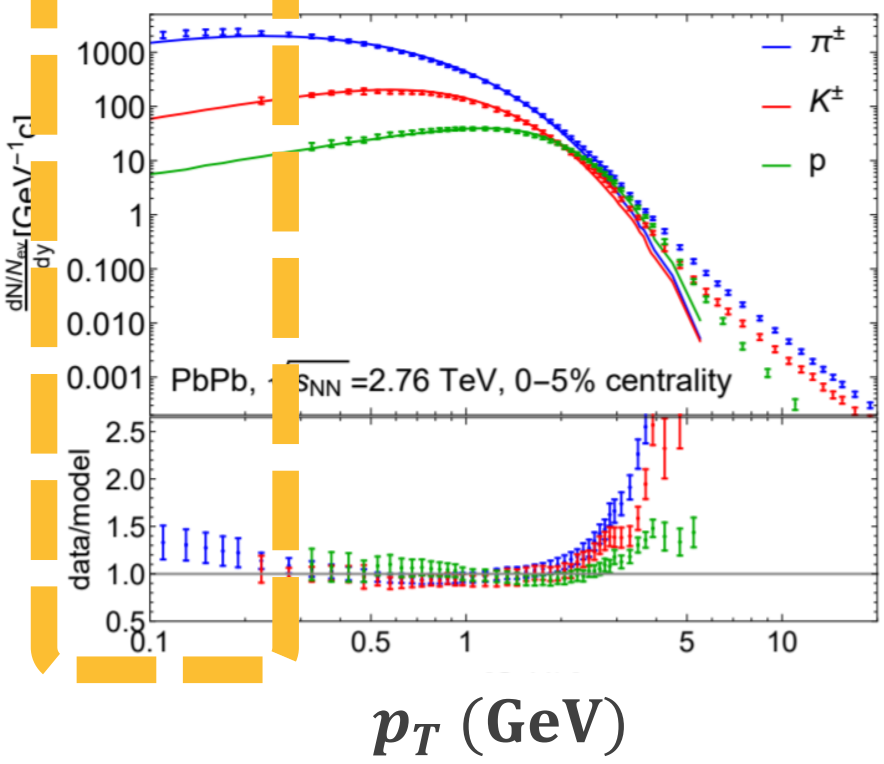
Result 2

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



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);

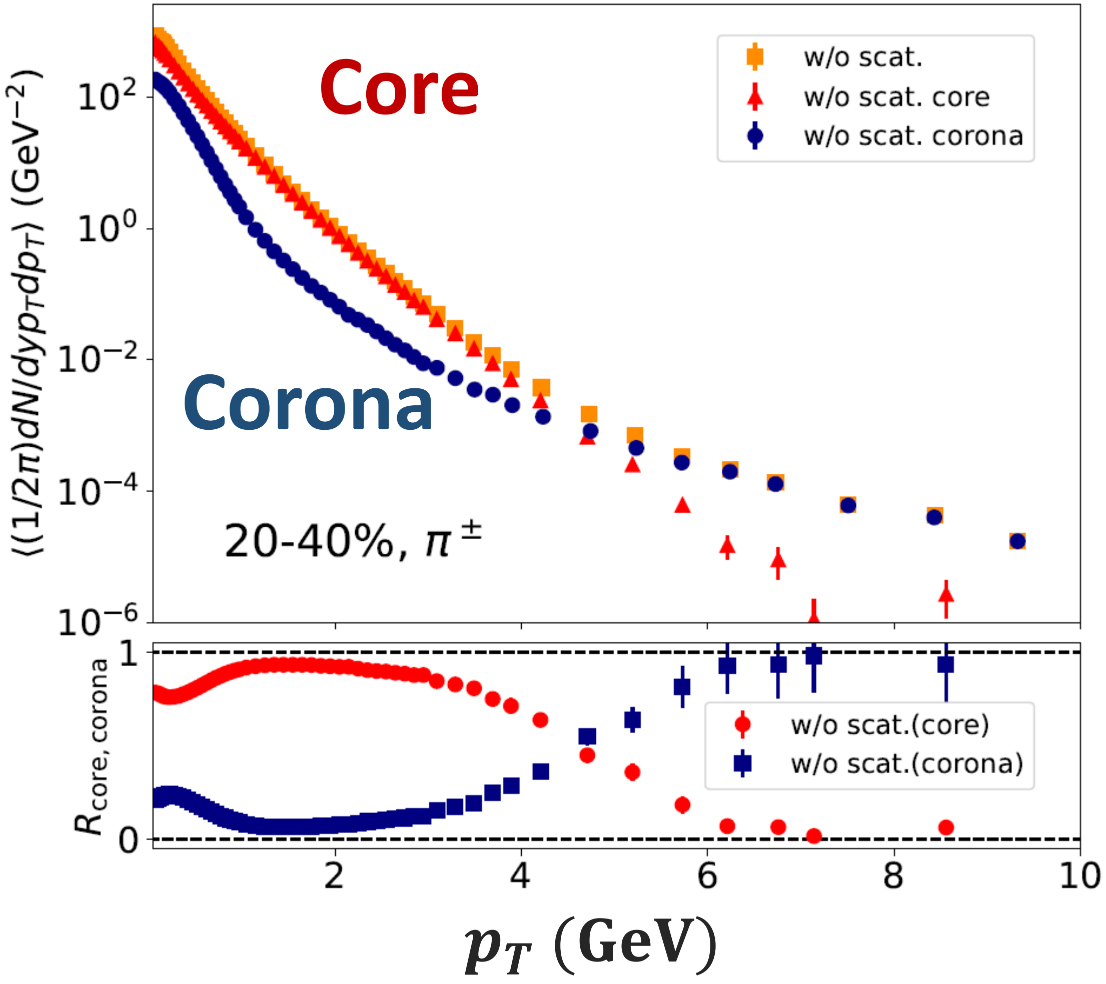
V. Begun *et al*., Phys. Rev. C 90, 014906 (2014); Phys. Rev. C 90, 054912 (2014); Phys. Rev. C 91, 054909 (2015);
P. Huovinen *et al*., Phys. Lett. B 769, 509 (2017);
E. Grossi *et al*., Phys. Rev. D 104, 034025 (2021)

➔ **Non-hydro 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

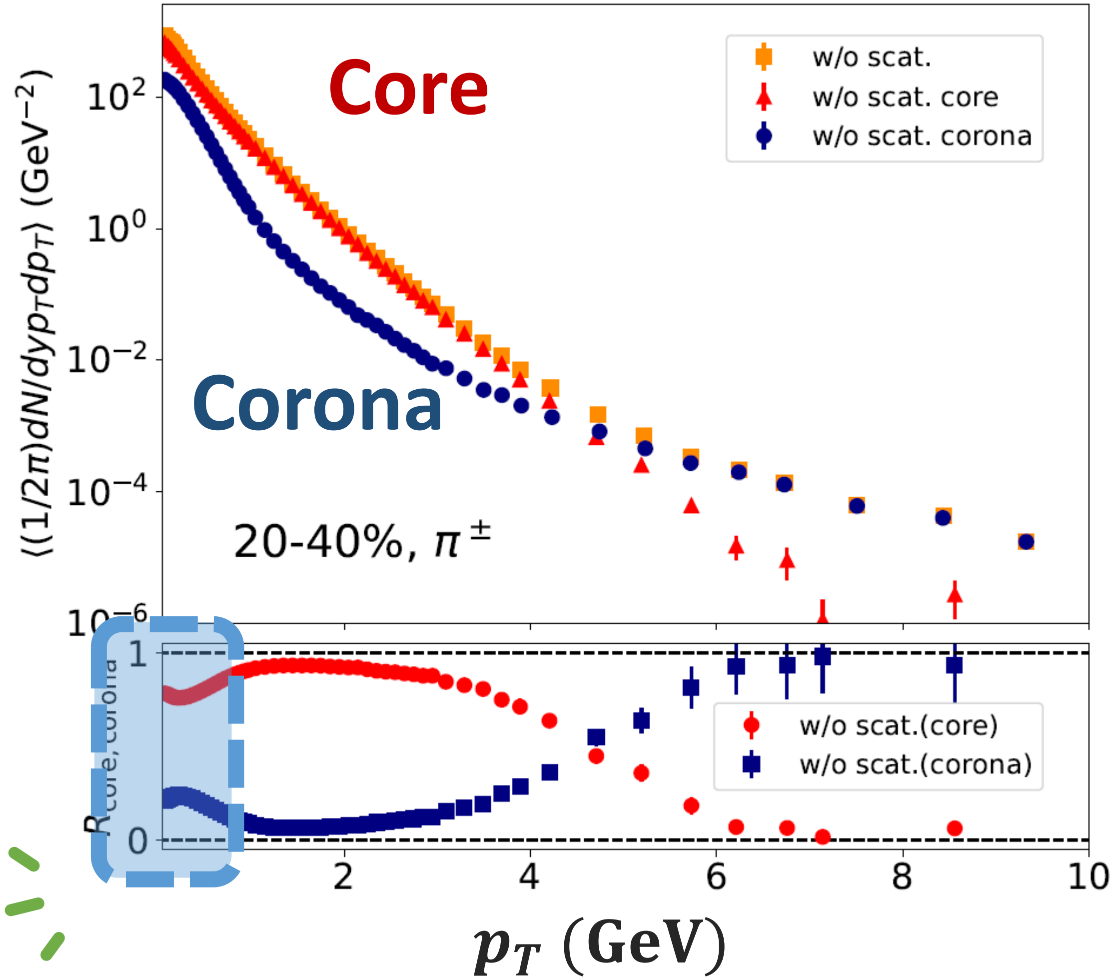
Core-corona picture

➔ 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)

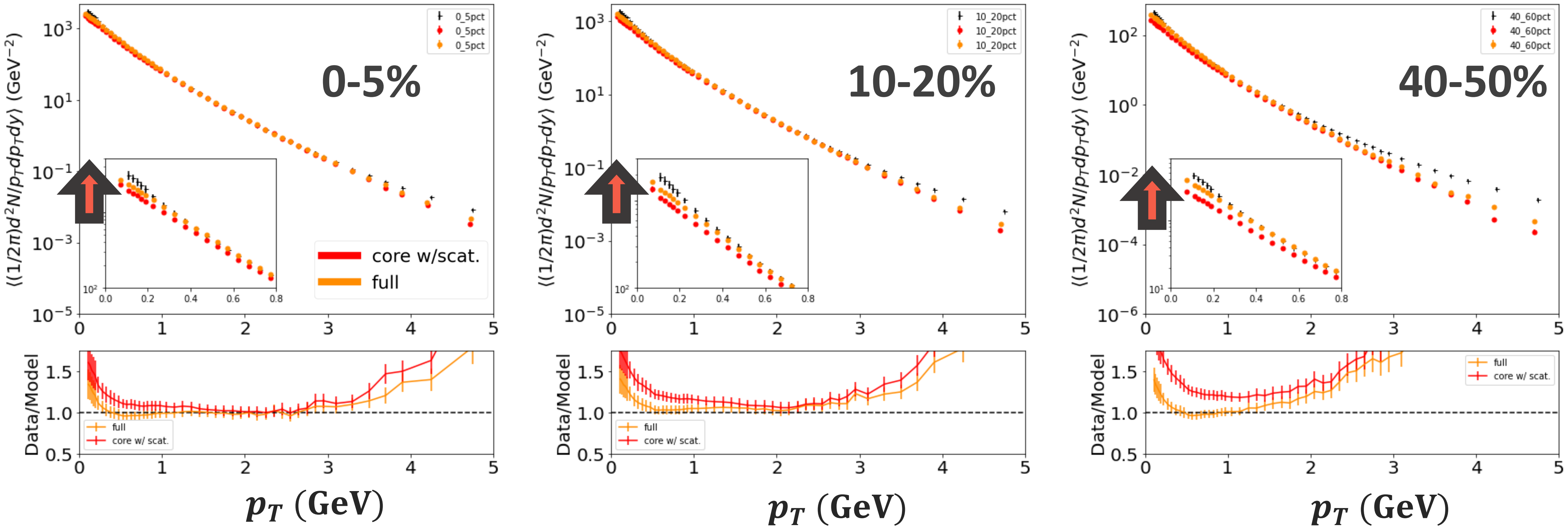
Slight enhancement of corona components

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



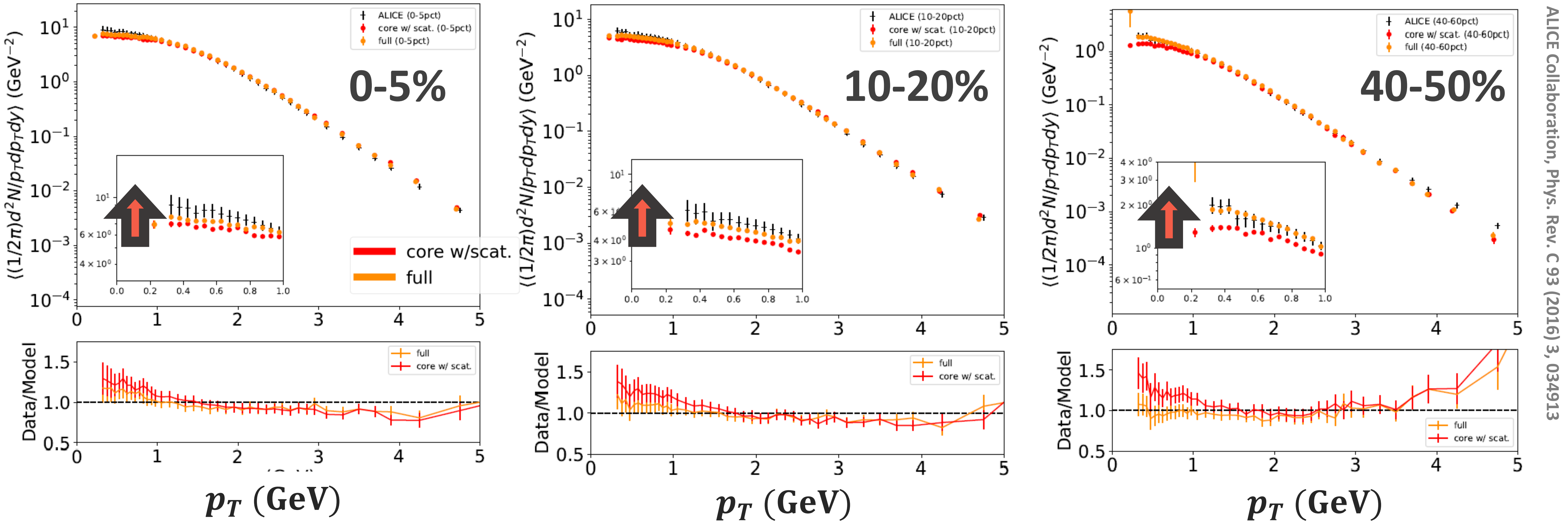
ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

Corona at very low p_T: possible compensation of yield

Comparison with exp. data

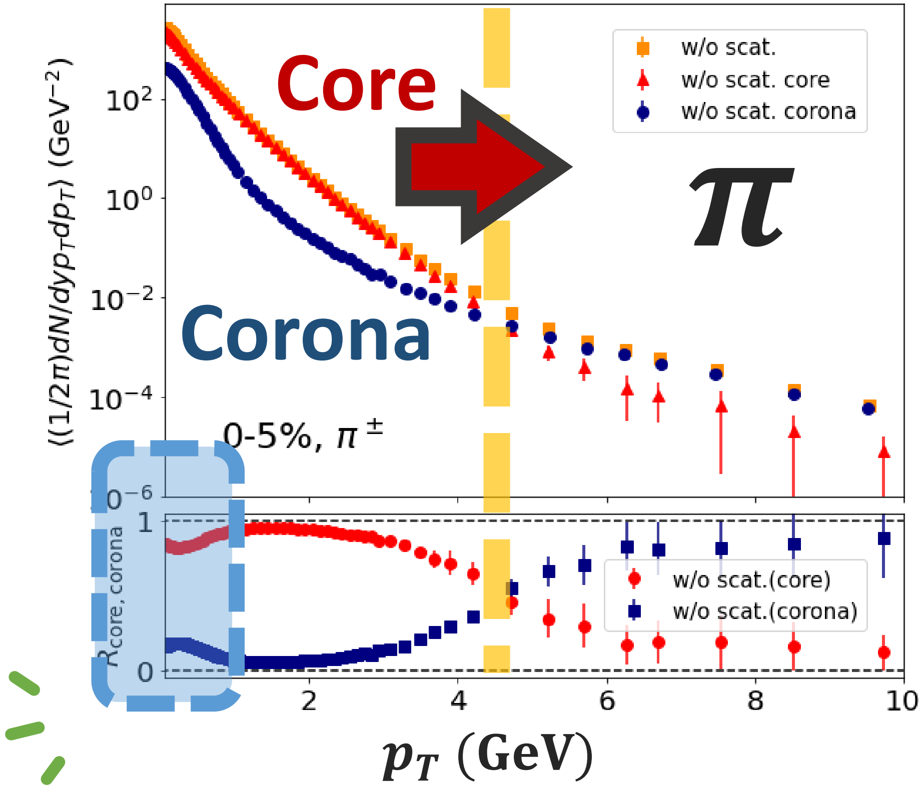
PbPb 2.76 TeV, $p+\overline{p}$

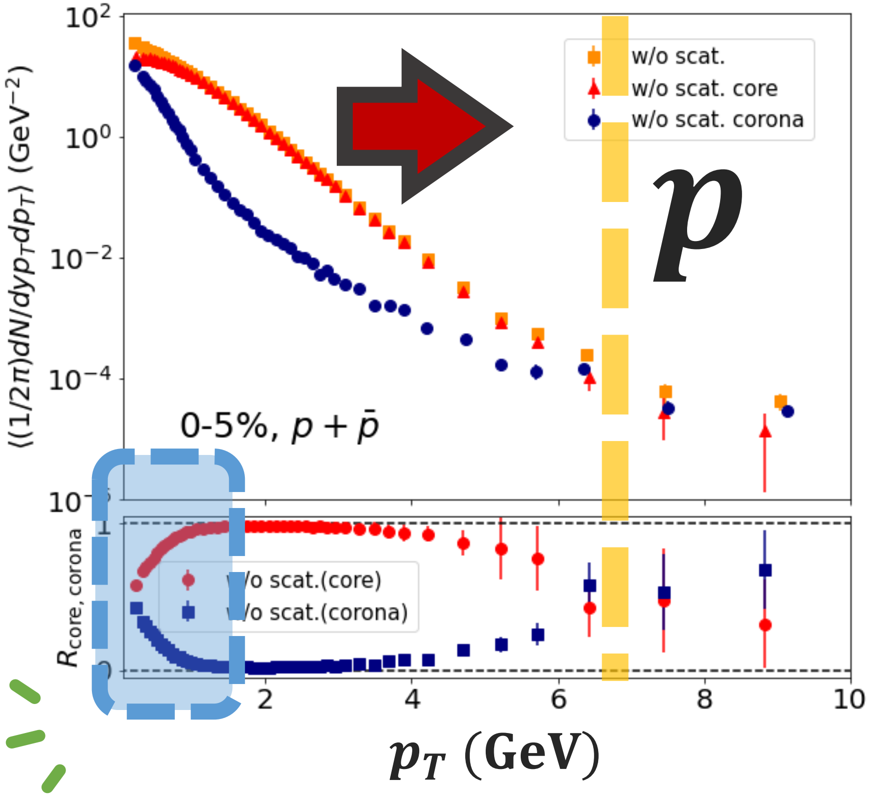
Y. Kanakubo *et al.*, Phys. Rev. C 106 (2022) 5, 054908



Corona at very low p_T: possible compensation of yield

Fraction of core and corona vs. p_T with PID





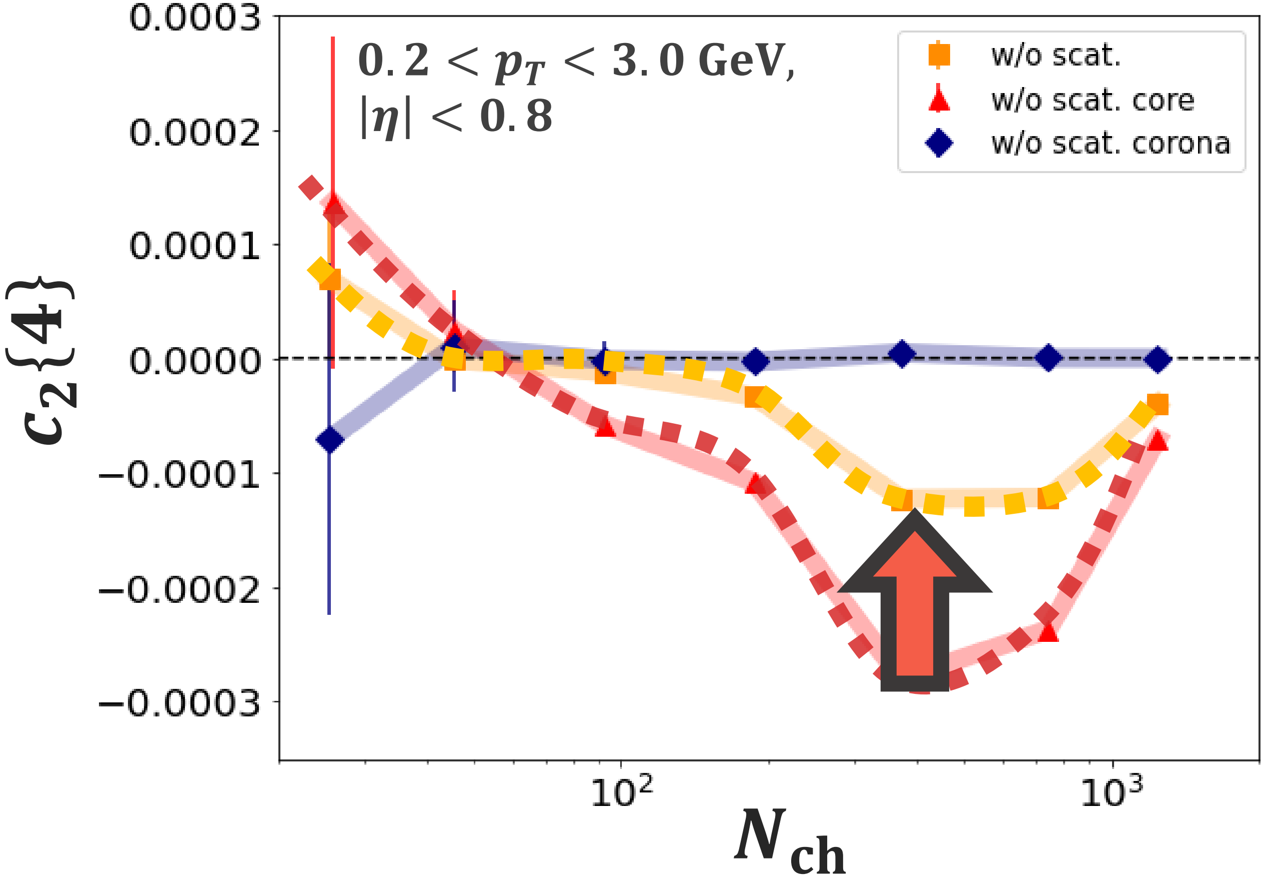
Core dominance up to higher p_T for heavier hadrons

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

Corona corrections to flow

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



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

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

➔ Diluted by corona

Conventional Hydro model

✖Comparison

Experiment

Extraction of QGP properties from quantitative comparison of data to model with core-corona?

Summary & outlook

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

Yield ratios of strange hadrons from pp to PbPb

Onset of core dominance at $\langle dN_{\mathrm{ch}}/d\eta \rangle \sim 20$

Non-equilibrium corrections to core (equilibrium)

Quantitative analysis of QGP properties from data to model comparisons?

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

Outlook

What we still don't have…

Hydro (+ hadron sampling)

- Viscosity
- Ebye energy-momentum conservation in hadron sampling

D. Oliinychenko *et al.*, Phys. Rev. Lett. 123 (2019) 18, 182302, Phys.Rev.C 102 (2020) 3, 034904

Initial condition

- Pre-equilibrium dynamics: matching of $T^{\mu\nu}$

A. Kurkela *et al.*, Phys. Rev. Lett. 122 (2019) 12, 122302

- Reasonable description of high p_T productions

Full 3D MC EKRT initial condition: M. Kuha *et al.*, in progress

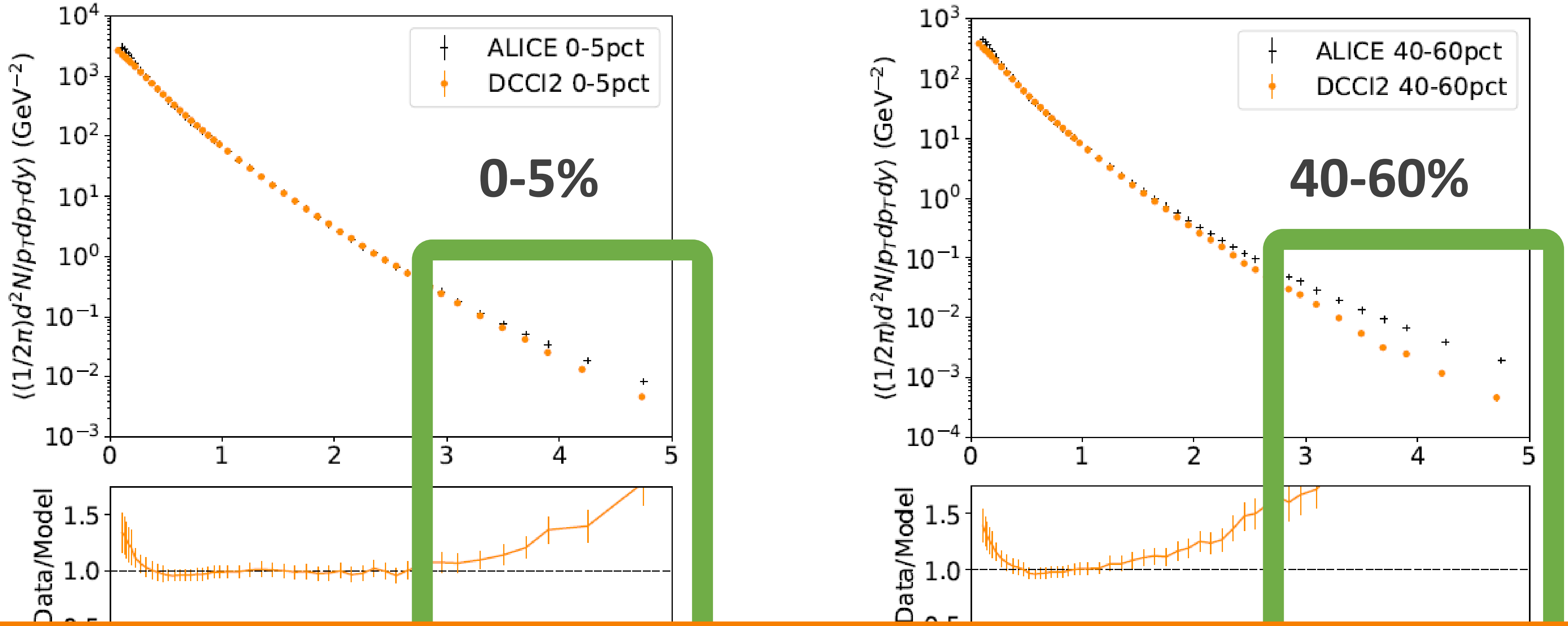
Dynamical core-corona initialization with EKRT in JYU hydro

Thank you!

Problems in DCCI2

1. Yields at high p_T

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



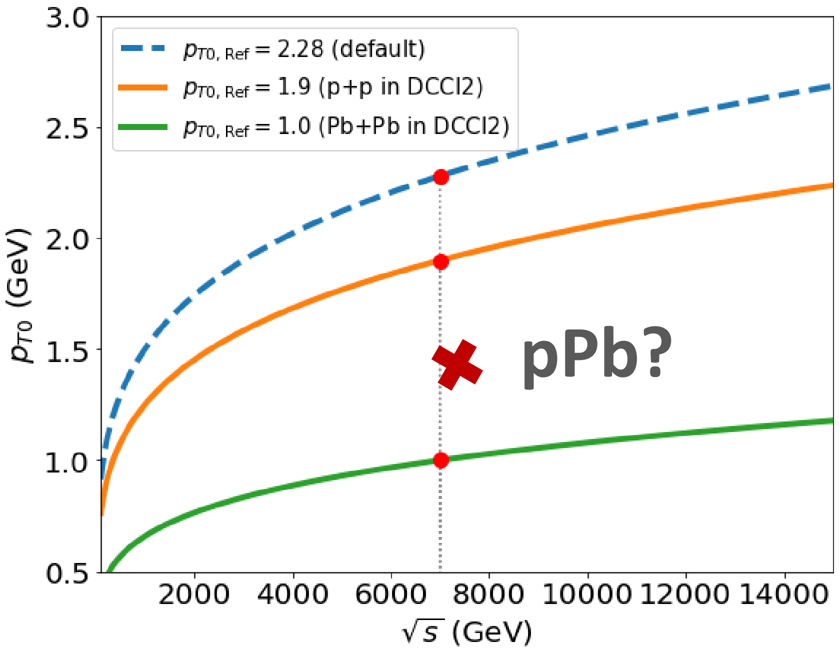
ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

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

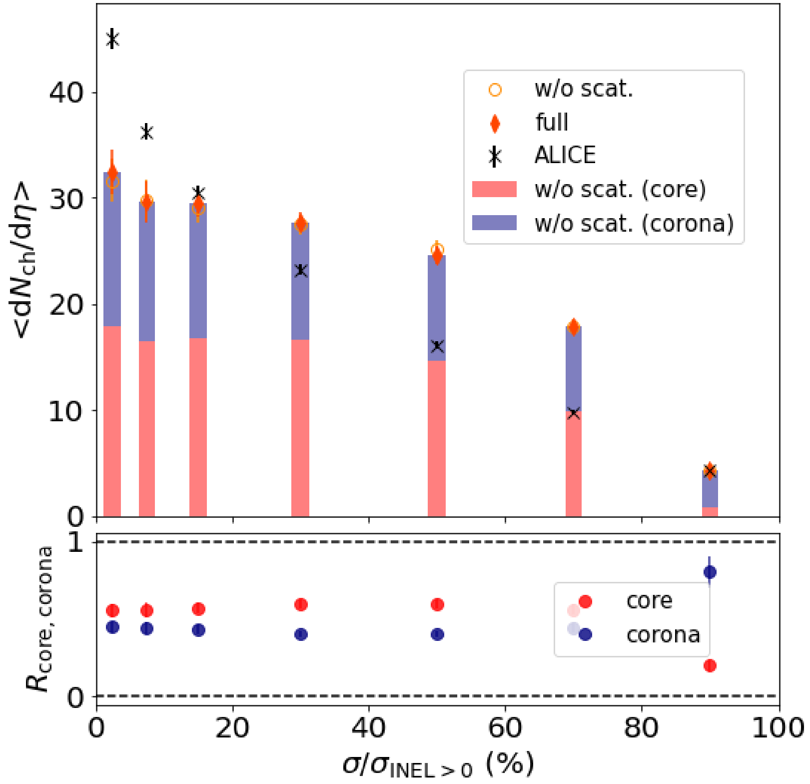


$$\frac{d\sigma_{2\to2}}{dp_T^2} \propto \frac{\alpha_s^2(p_T^2)}{p_T^4} \to \frac{\alpha_s^2(p_T^2 + p_{T,0}^2)}{(p_T^2 + p_{T,0}^2)^2}$$

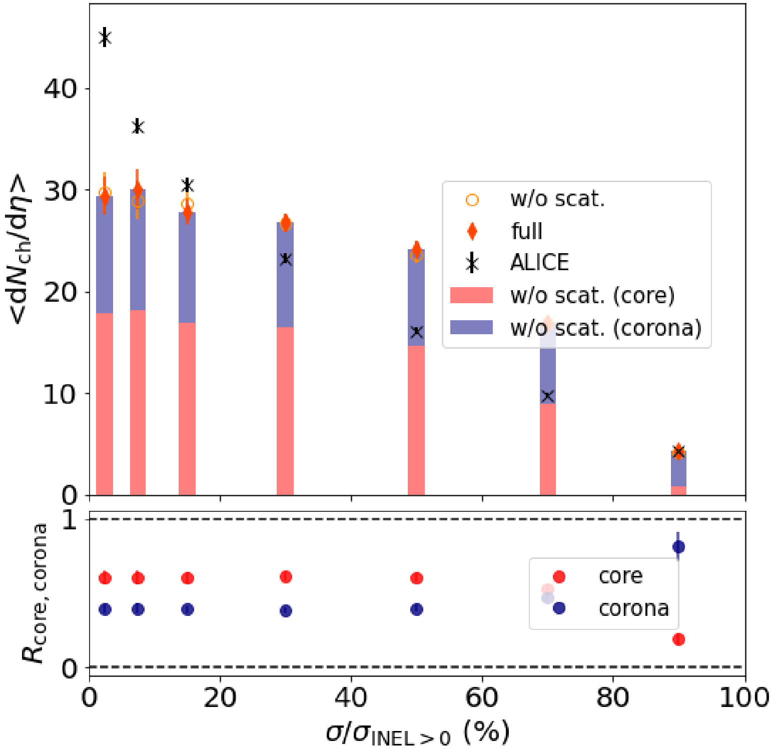
- $\sim$ Infrared cutoff
- Tuning parameter in PYTHIA.
- $p_{T,0\mathrm{Ref}} = 2.28$ GeV (default)

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

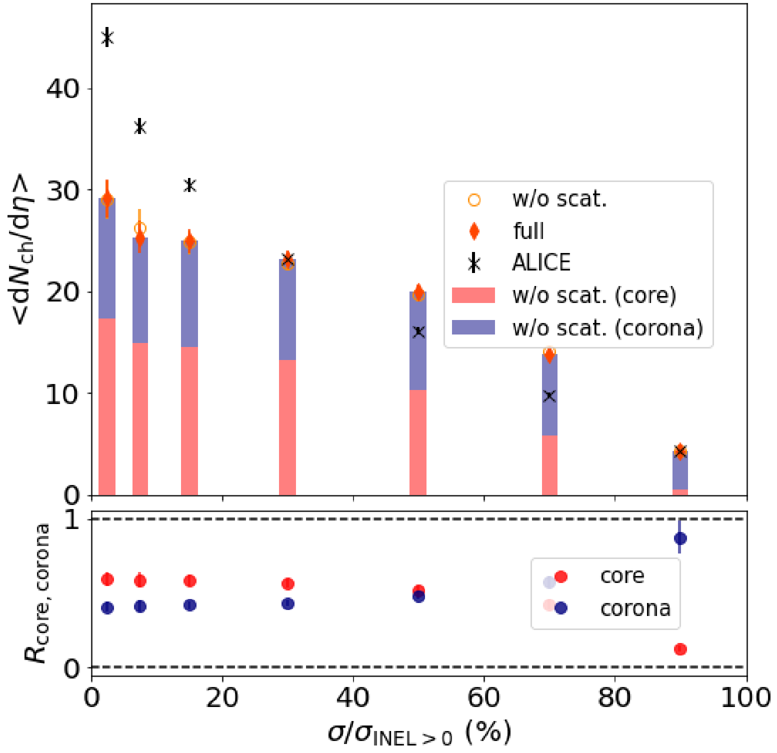
Parameter $p_{T0\mathrm{Ref}}$ dependence in DCCI2



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



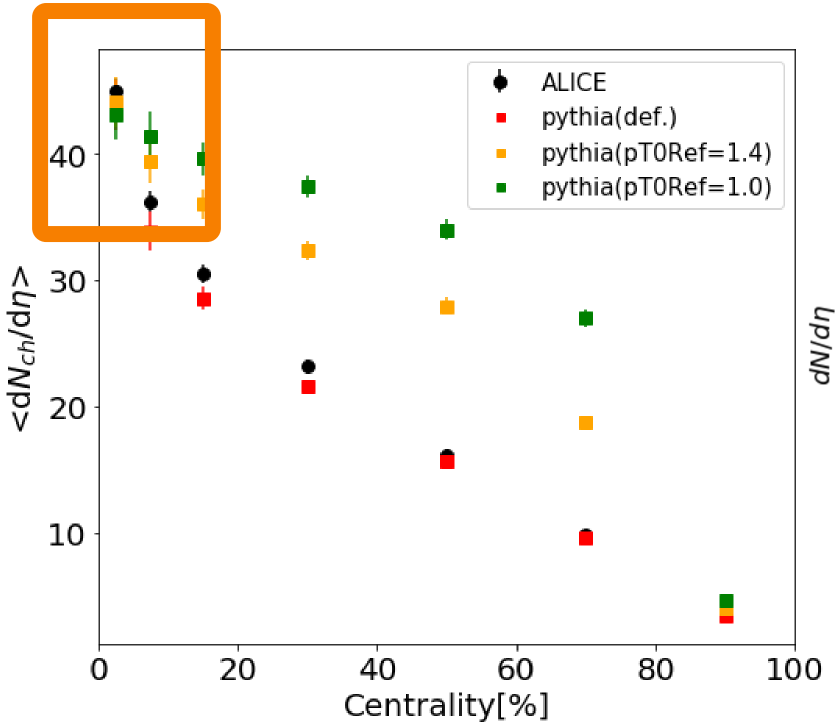
$p_{T0\mathrm{Ref}} = 1.0$ GeV

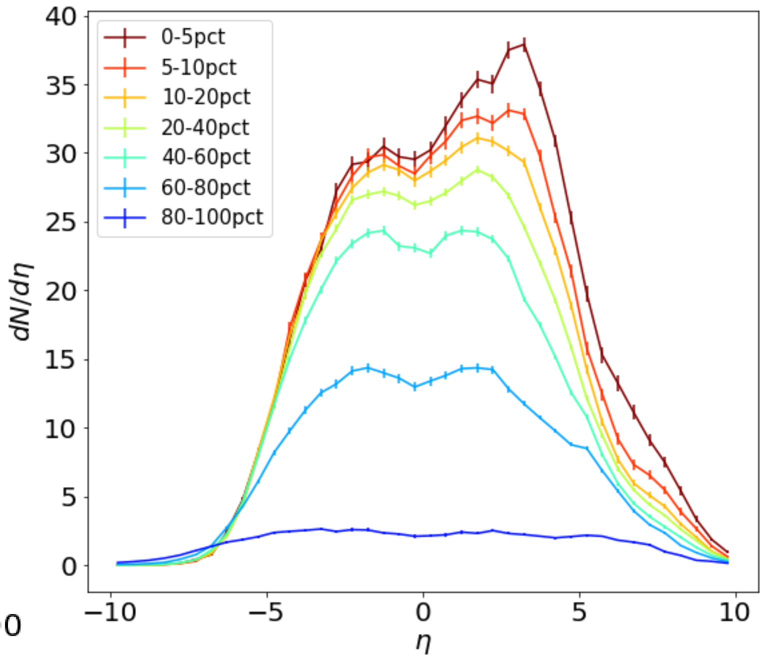


$p_{T0\mathrm{Ref}} = 1.4$ GeV

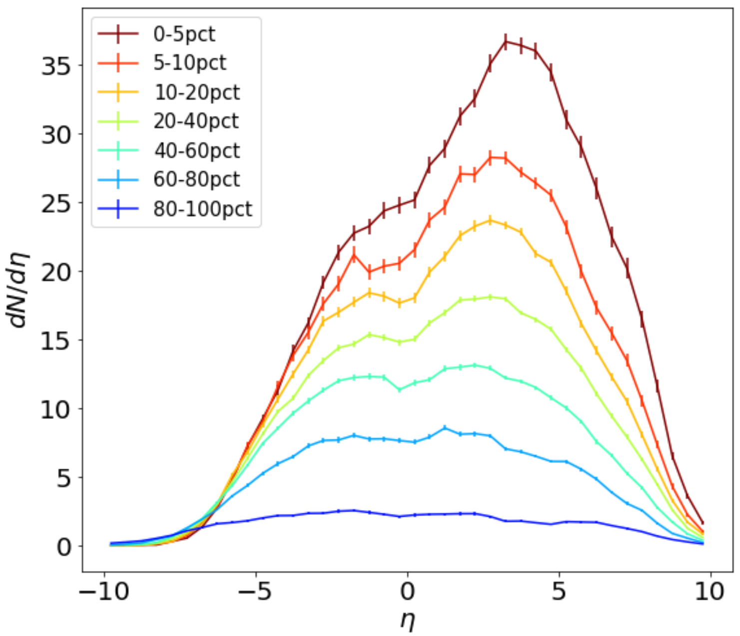
Difficulty ➔ interplay of two different particle production mechanisms within a given total collision energy

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





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



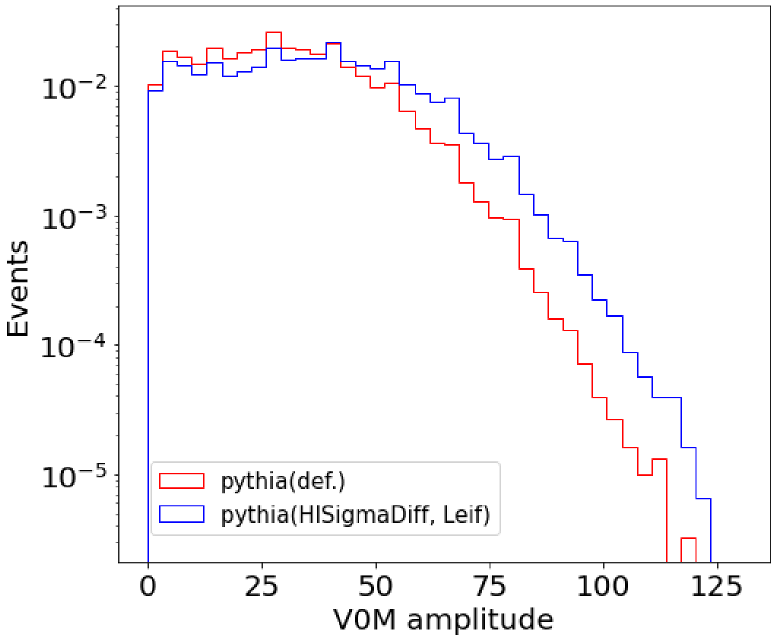
Default ($p_{T0\mathrm{Ref}} = 2.28\ \mathrm{GeV}$)

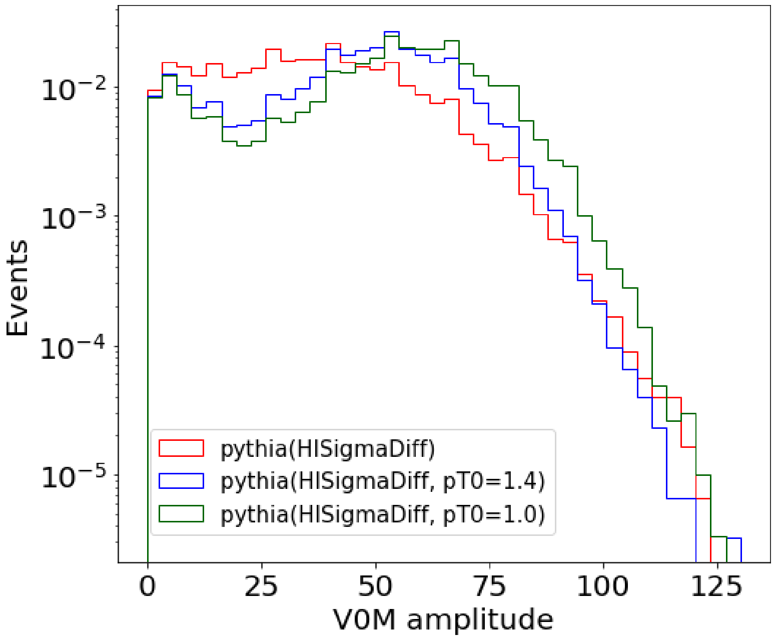
Maximum multiplicity ➔ saturated

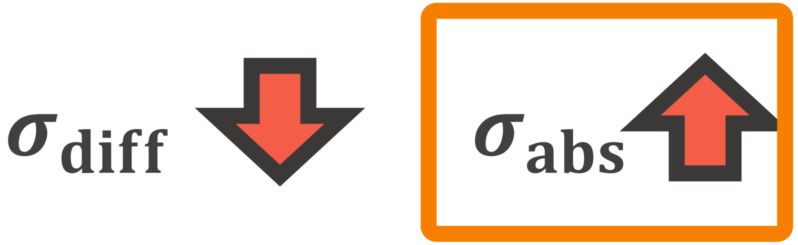
Multiplicity distribution in pPB default PYTHIA

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

pPB 5020 GeV







➔ No significant enhancement?

Difficulty: reproduction of multiplicity distribution given a fixed collision energy

Backup

Parameter set for PYTHIA part: almost Monash Tune

PYTHIA

Hydro with dynamical core-corona

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

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

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

$p_{\mathrm{T0}} \sim$ **Infrared cutoff for 2→2 cross section**

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)

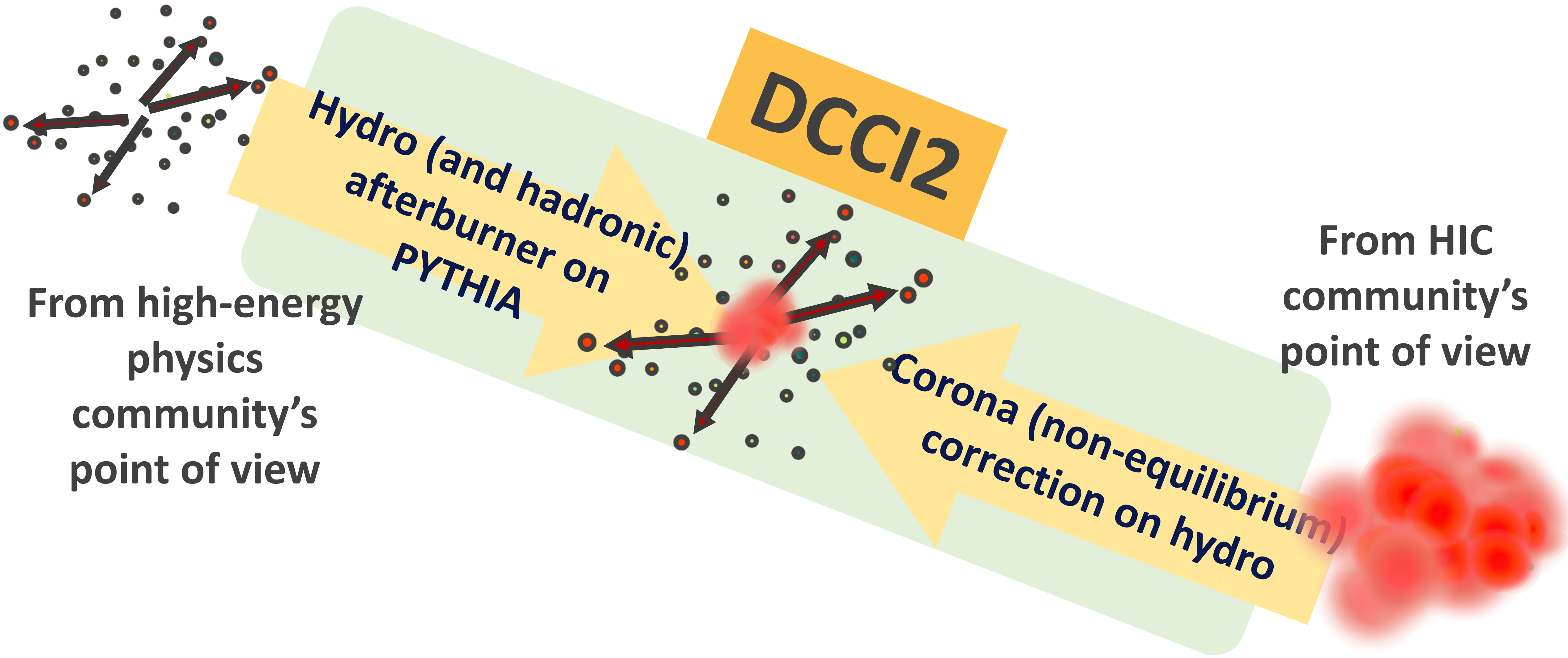
Non-equilibrated partons (corona)

PYTHIA8 (string fragmentation)

Hadronic afterburner: JAM

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

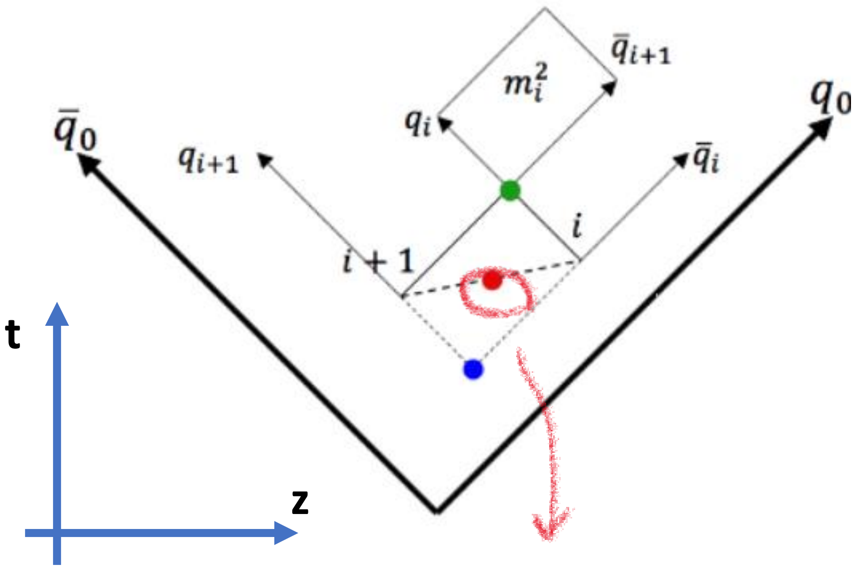
DCCI2: combination of hydro and PYTHIA



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

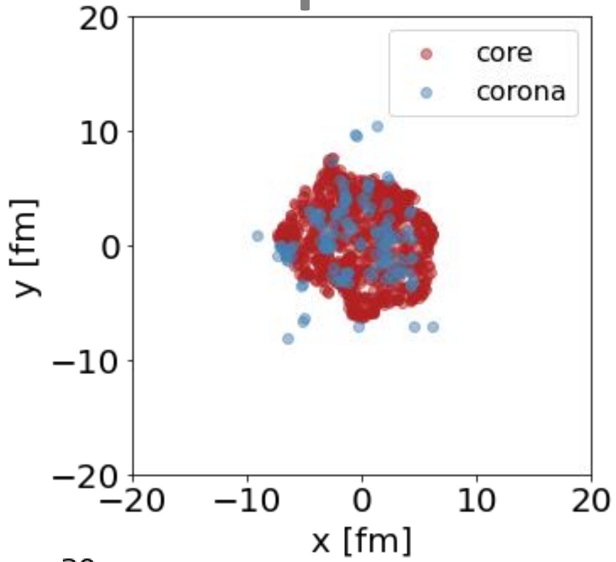
Information of production vertices

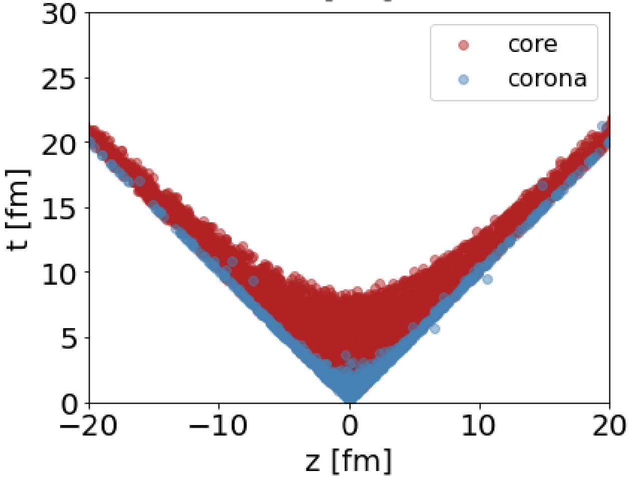
event[i].xProd(), event[i].yProd(), event[i].zProd(), event[i].tProd()

PbPb 2.76 TeV

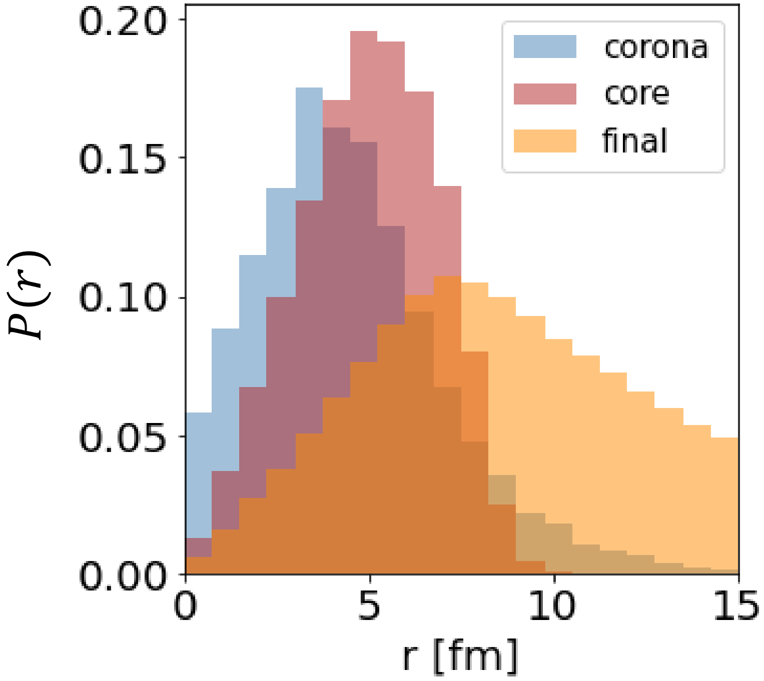
Space-time distribution of direct hadrons

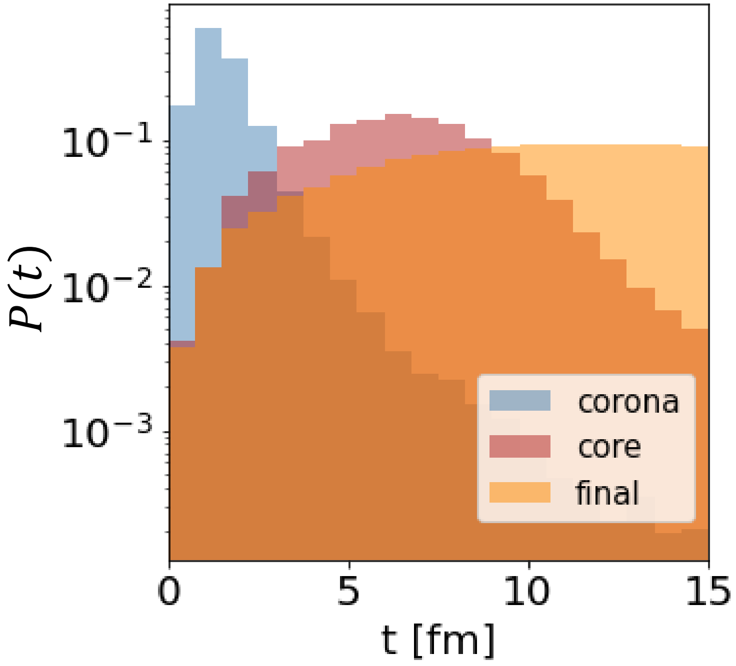
1 sampled event





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

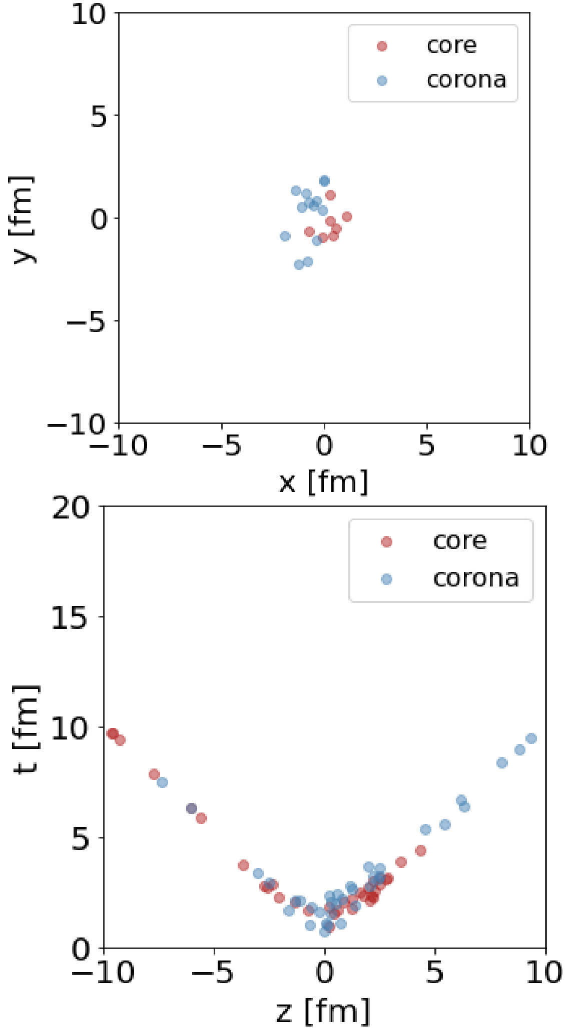




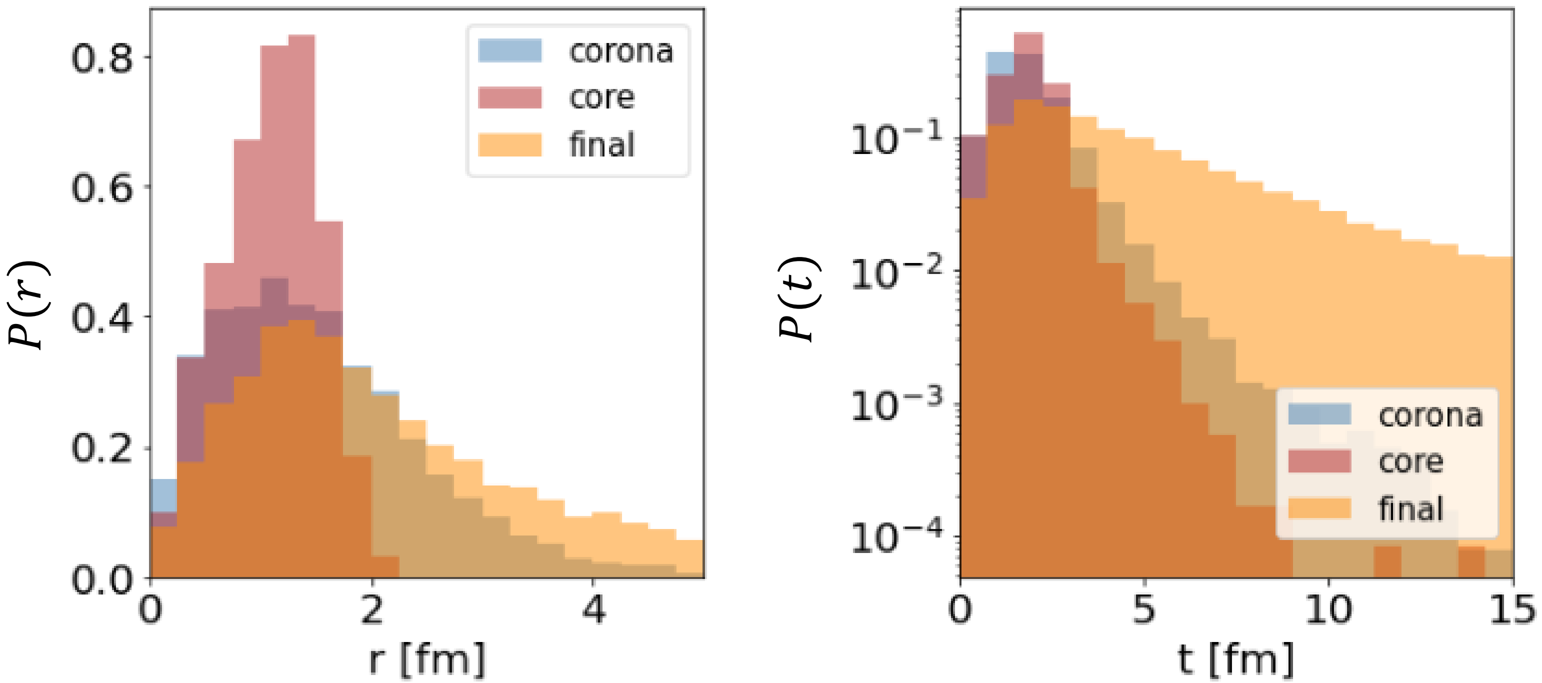
Double peaks of hadron vertices from core and corona before hadronic rescatterings

Space-time distribution of direct hadrons

1 sampled event

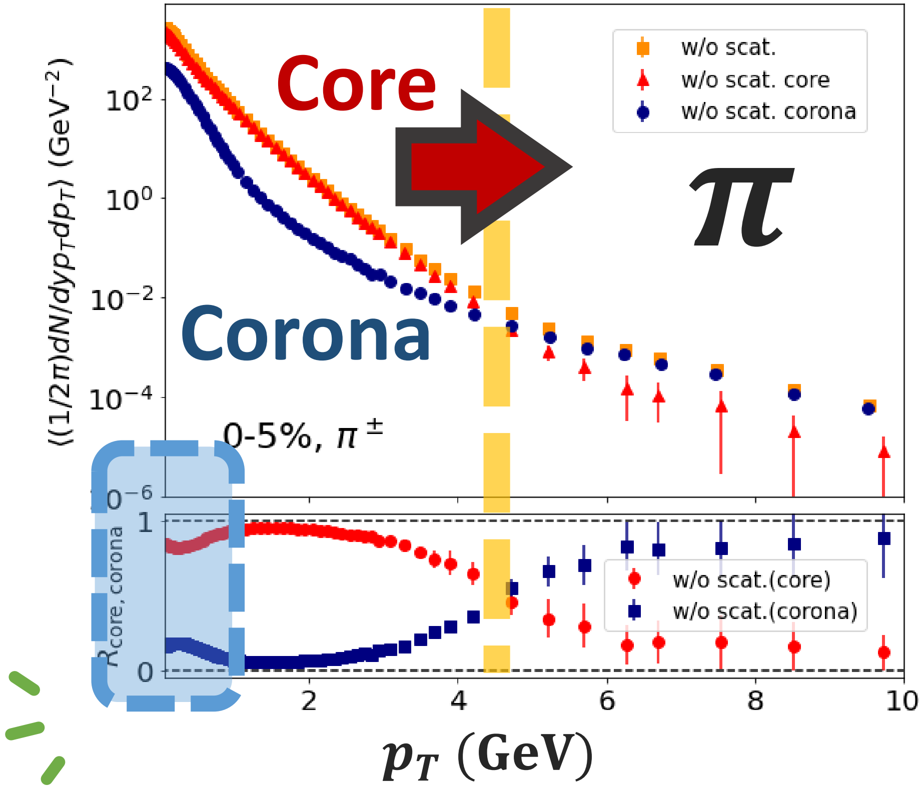


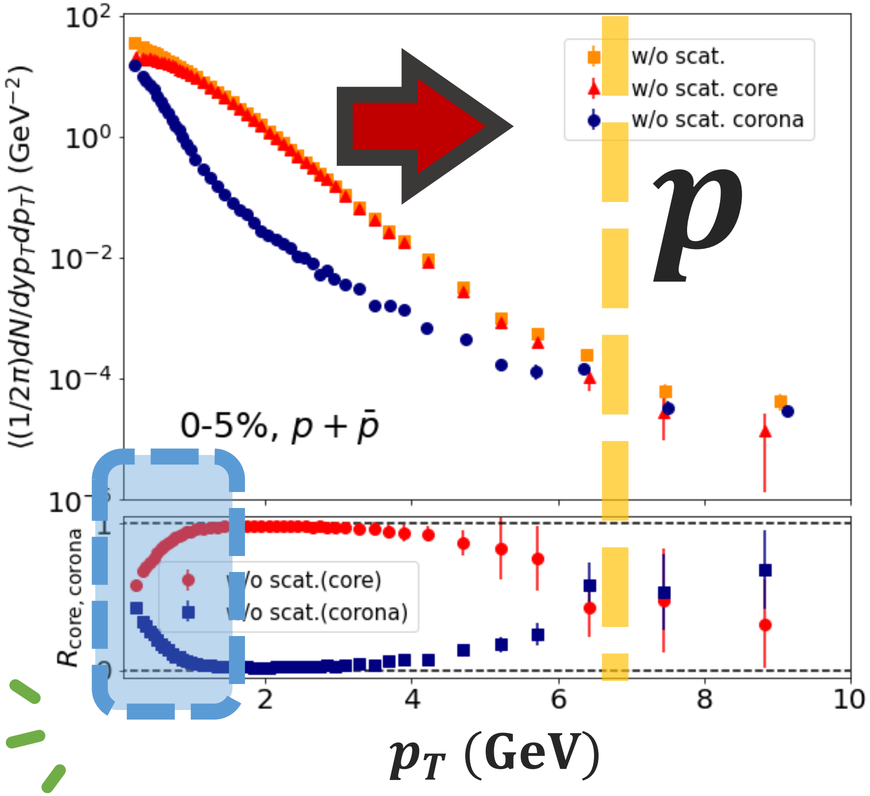
Probability distribution ($|\eta| < 0.5$)



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

Fraction of core and corona vs. p_T with PID





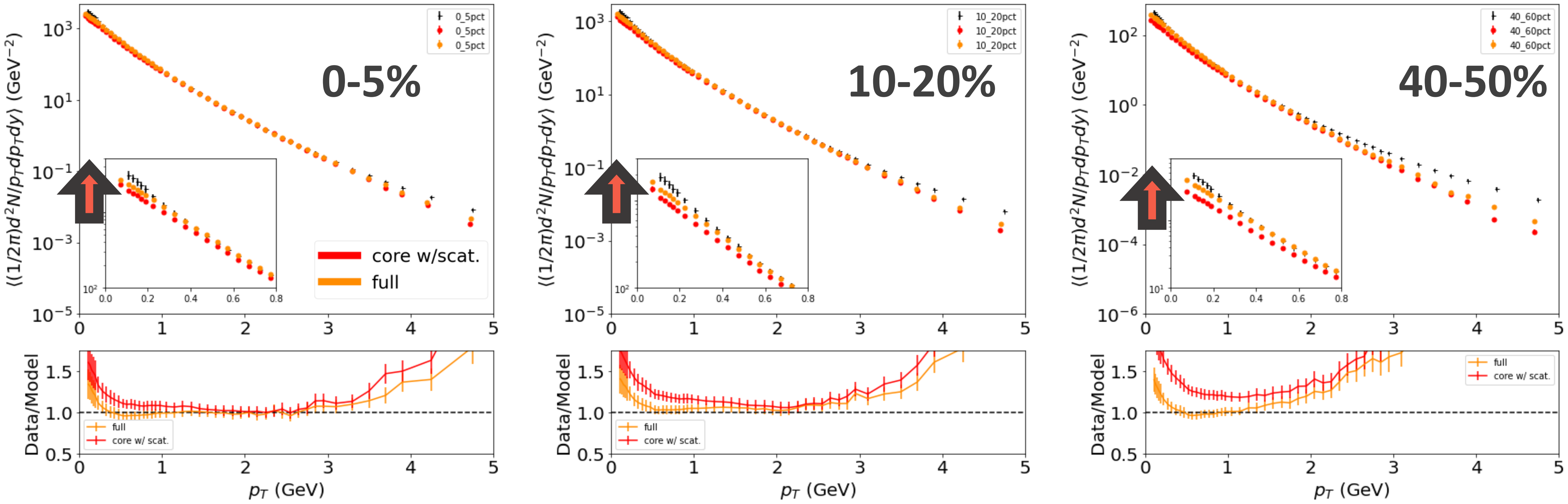
Core dominance up to higher p_T for heavier hadrons

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, $\pi^{\pm}$

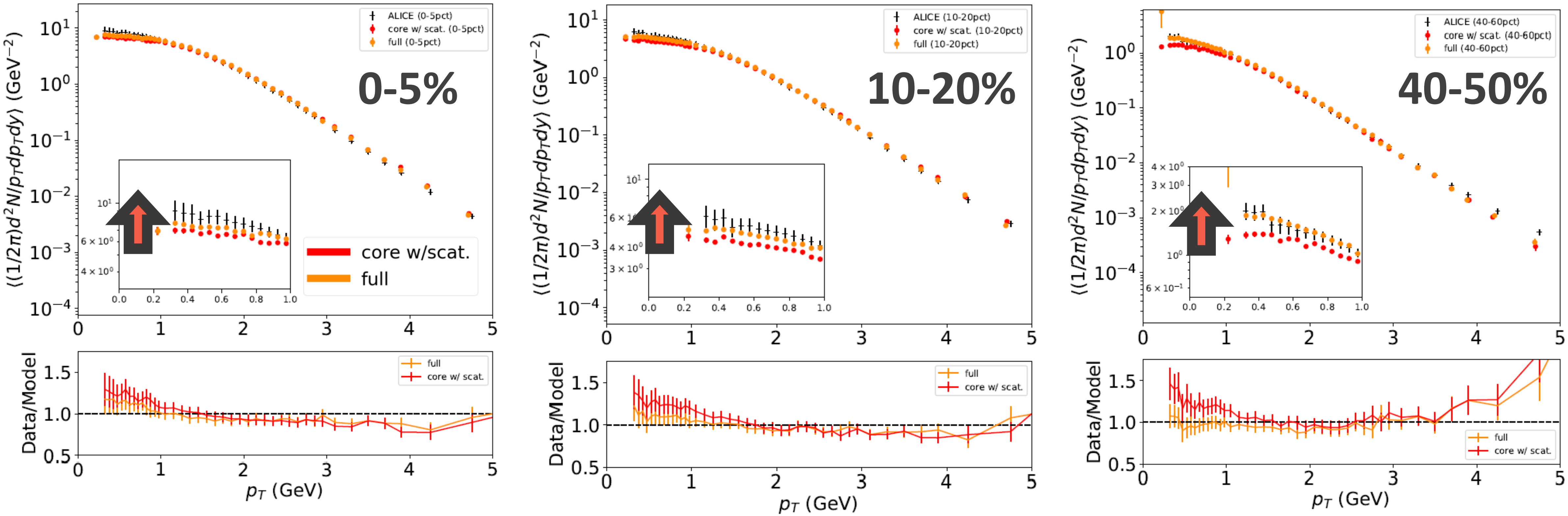


ALICE Collaboration, Phys. Rev. C 93 (2016) 3, 034913

Corona at very low p_T: possible compensation of yield

Comparison with exp. data

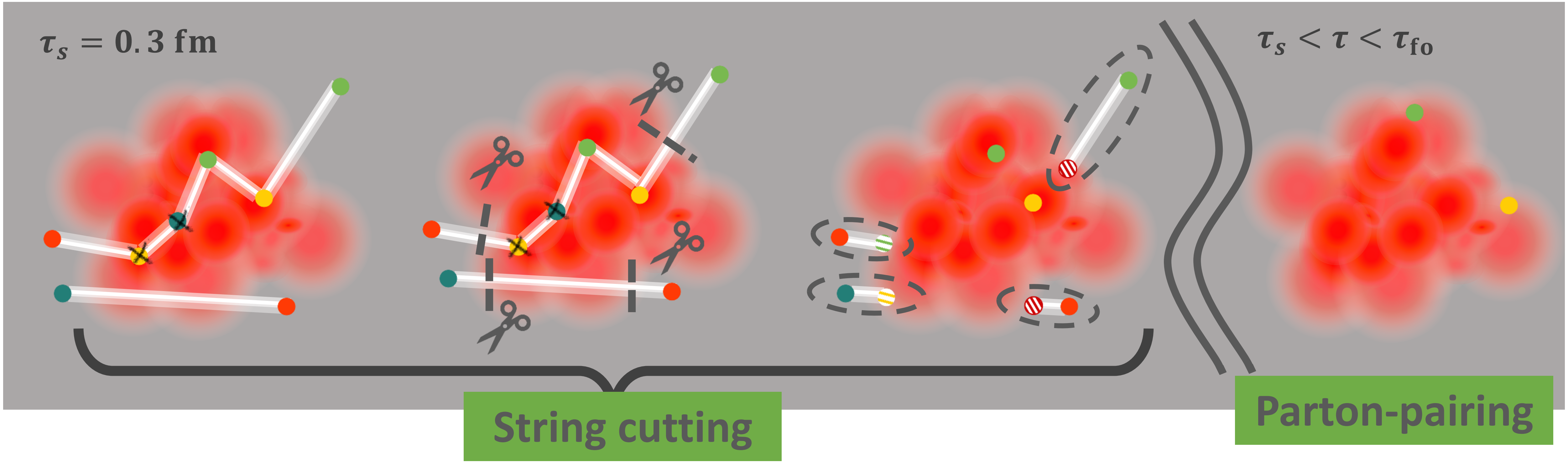
PbPb 2.76 TeV, $p + \overline{p}$



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

Corona at very low p_T: possible compensation of yield

Corona components from string modification

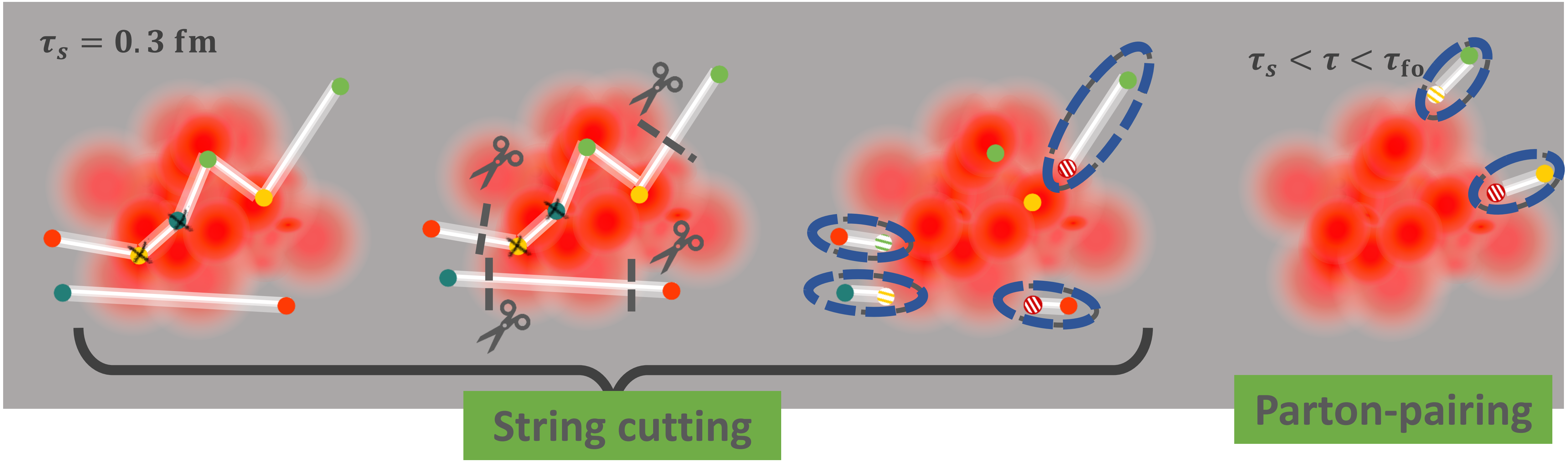


String modification caused by ..

- Spatial overlap of strings and medium
- Completely fluidized partons

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

Corona components from string modification (cont'd)

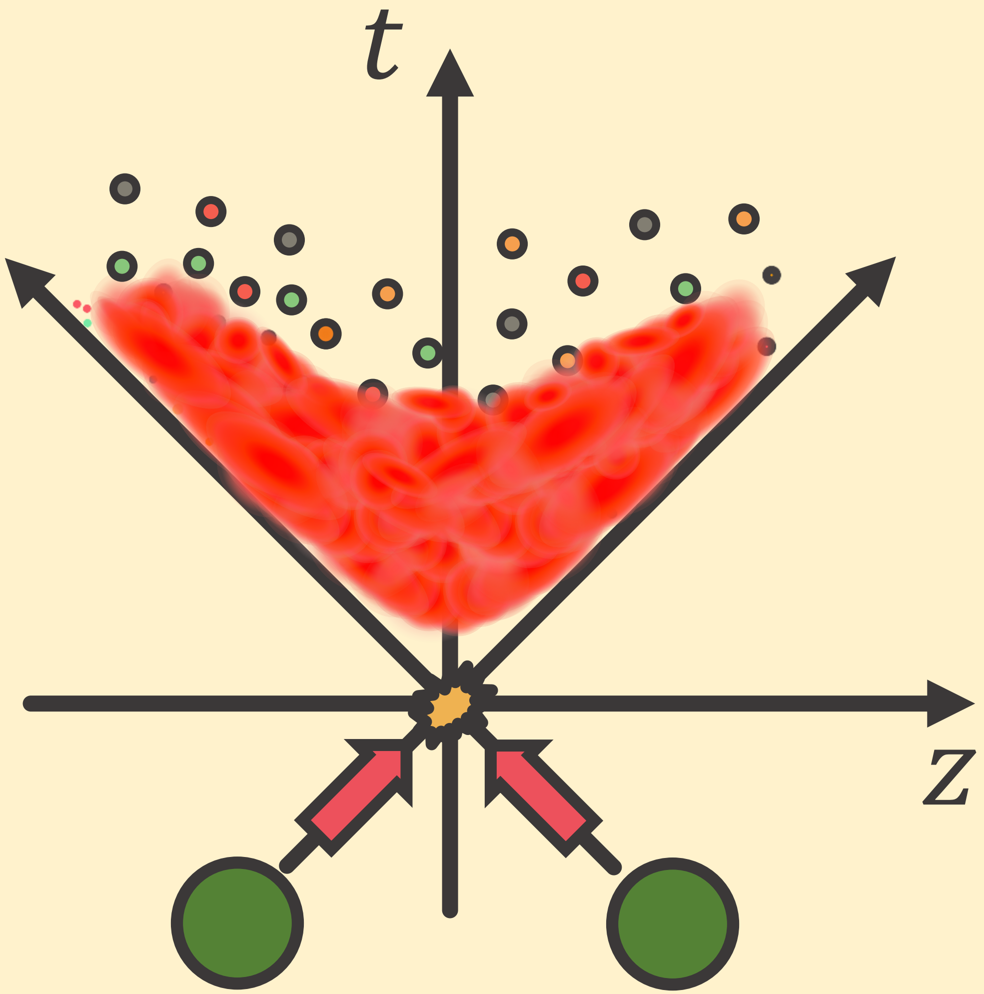


4. Surviving partons traverse medium
5. Make a pair for a parton coming out from medium

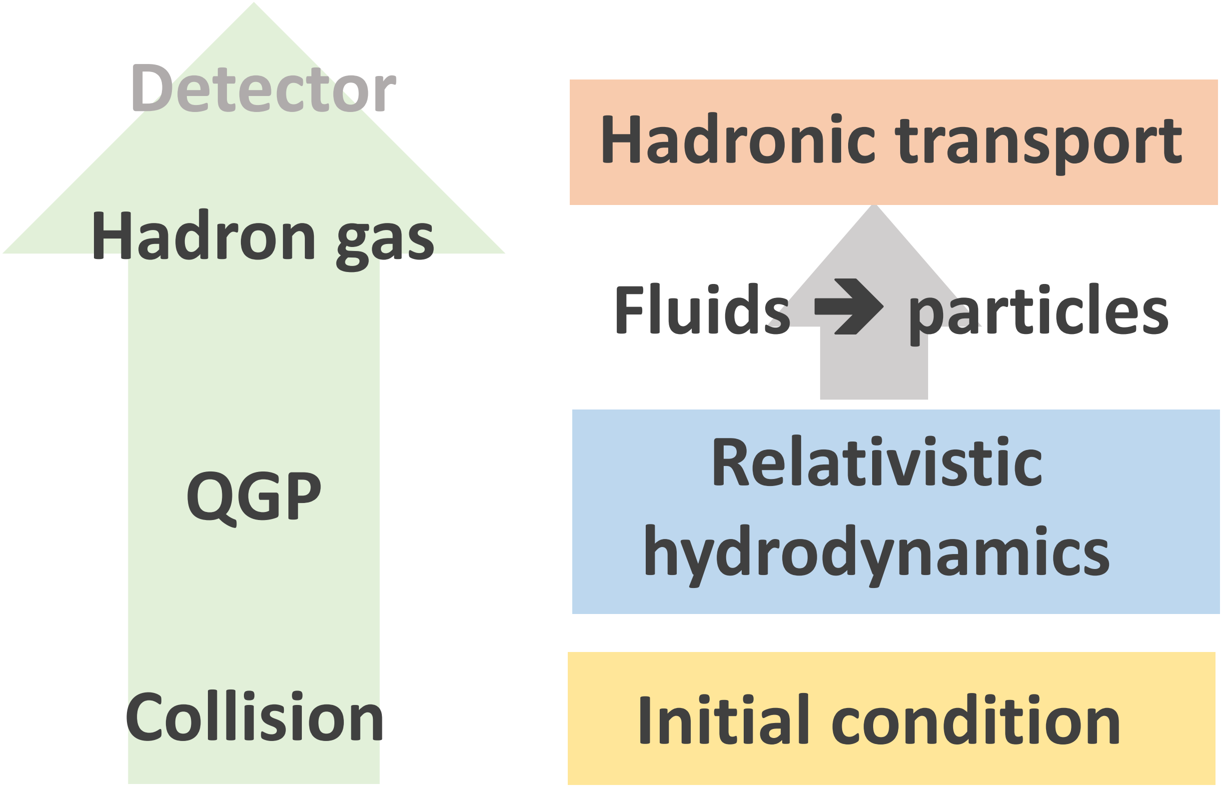
*$p_{T,\mathrm{cut}}$: threshold to/not to modify a string

Non-thermal & thermal
➔ Contributes as corona components

Hydro-based multi-stage dynamical model



Space-time evolution of HIC

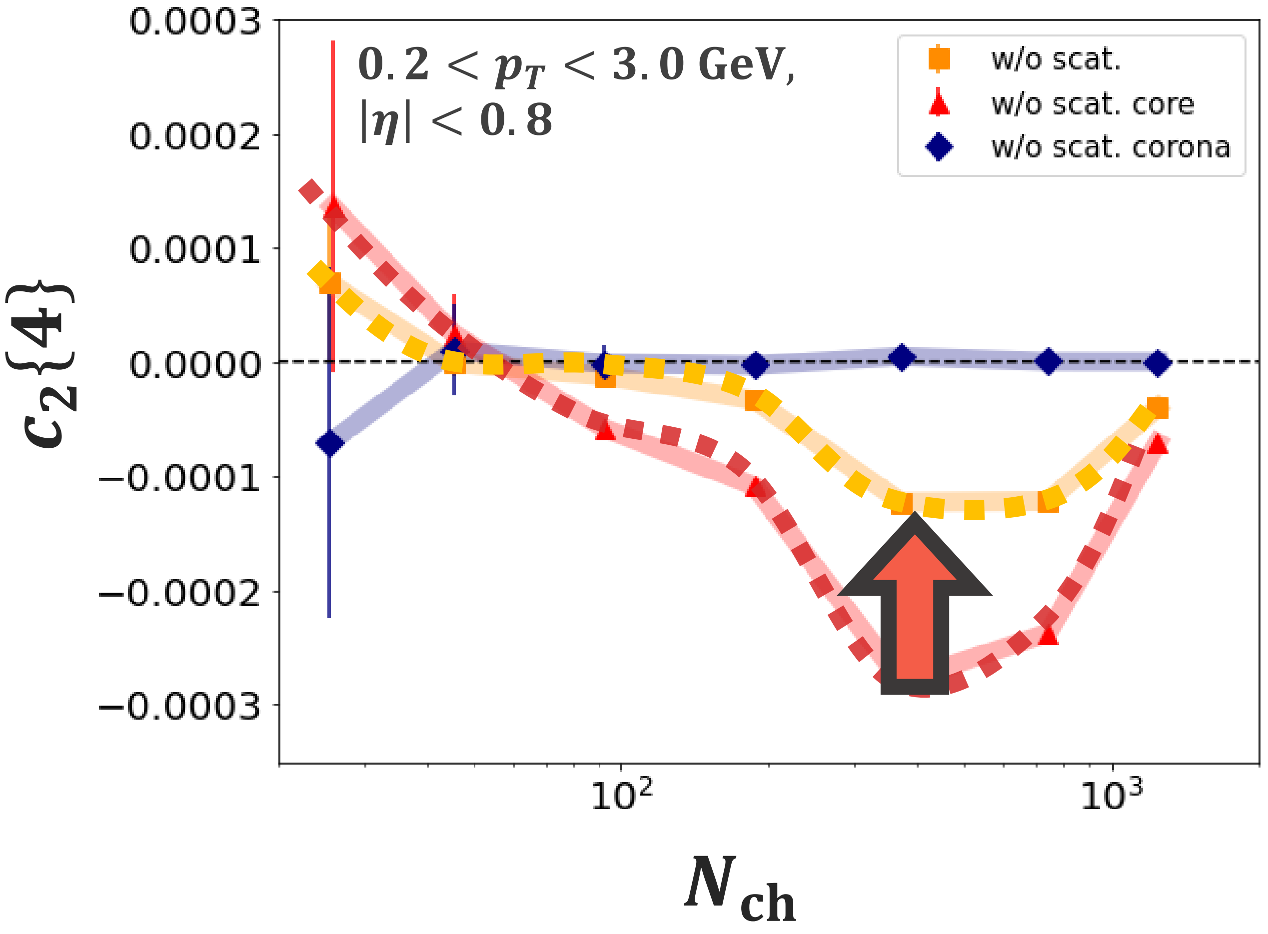


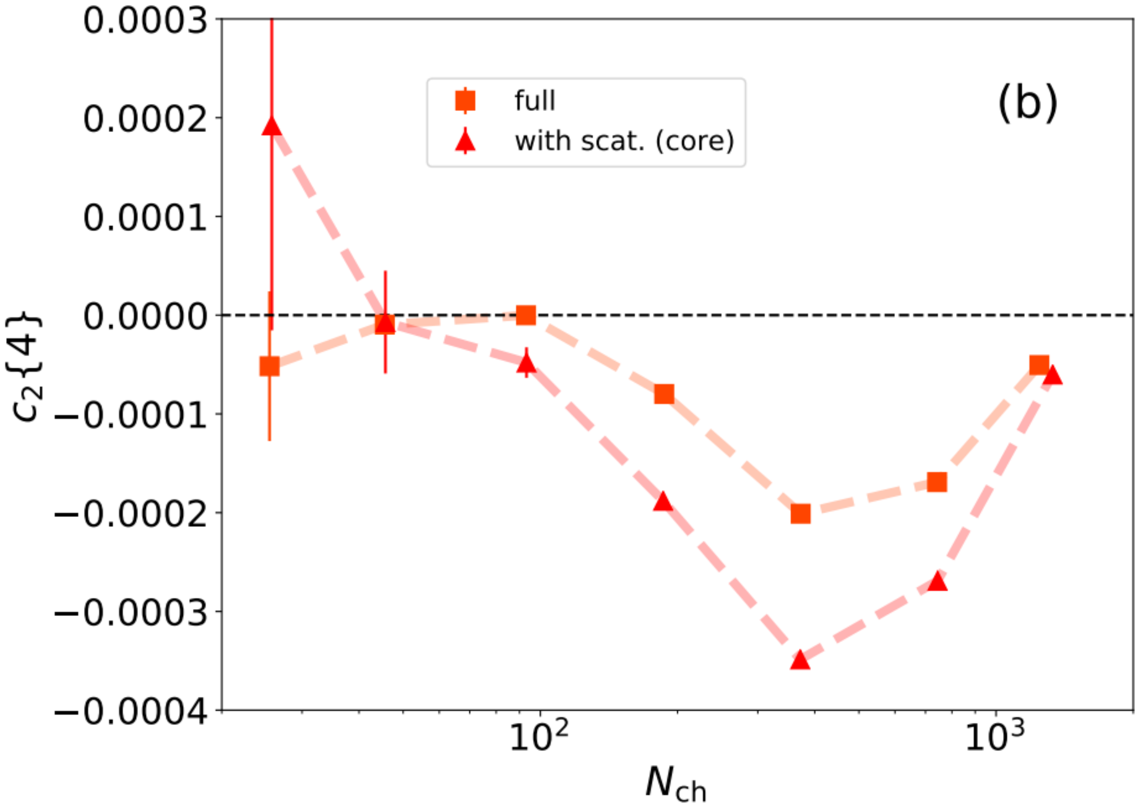
Standard model in HIC

Powerful tool to extract QGP info from experimental observation

Corona corrections to flow

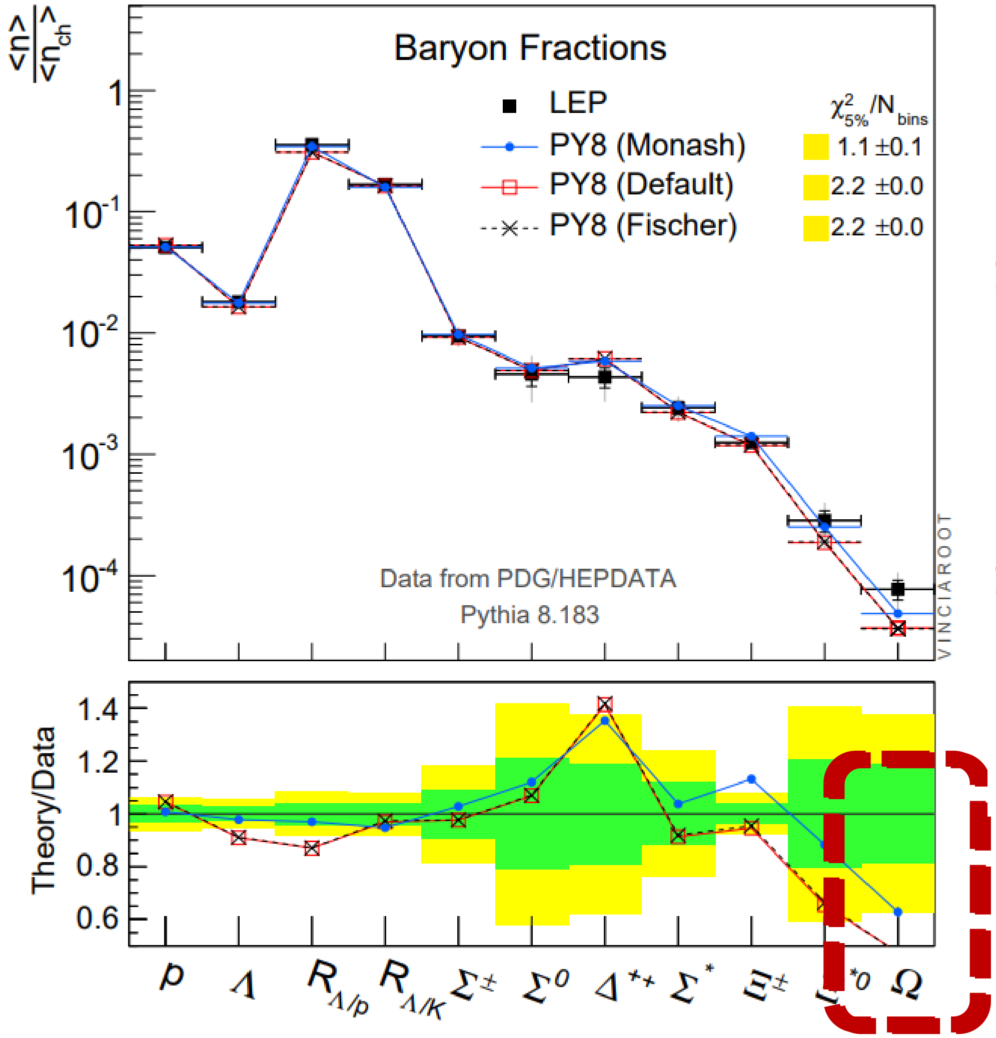
$c_2\{4\}$ from PbPb 2.76 TeV

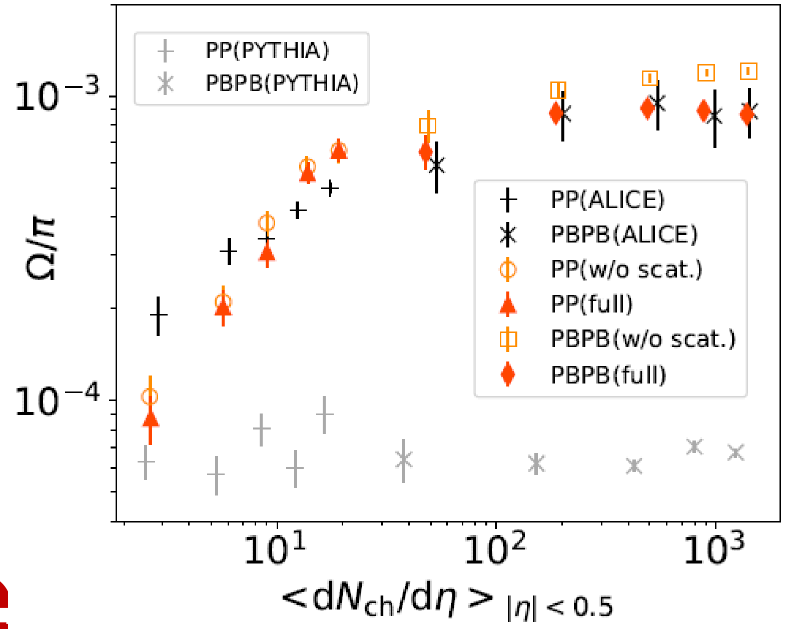




Ω yields from e^+e^- with Monash Tune

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





QGP study with relativistic hydrodynamics

Many body system of quarks and gluons under local equilibrium

$$\partial_\mu T^{\mu\nu} = 0 \quad + \quad P = P(e)$$

Energy-momentum conservation — **Equation of state (EoS)**

$$\eta/s(T)\ ,\zeta/s(T)\ldots$$

-- Basic information of matter --

A lots of developments on hydro theory…

How should we apply them on QGP study?

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

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

- Parametrized cross-section

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

- Density of partons

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

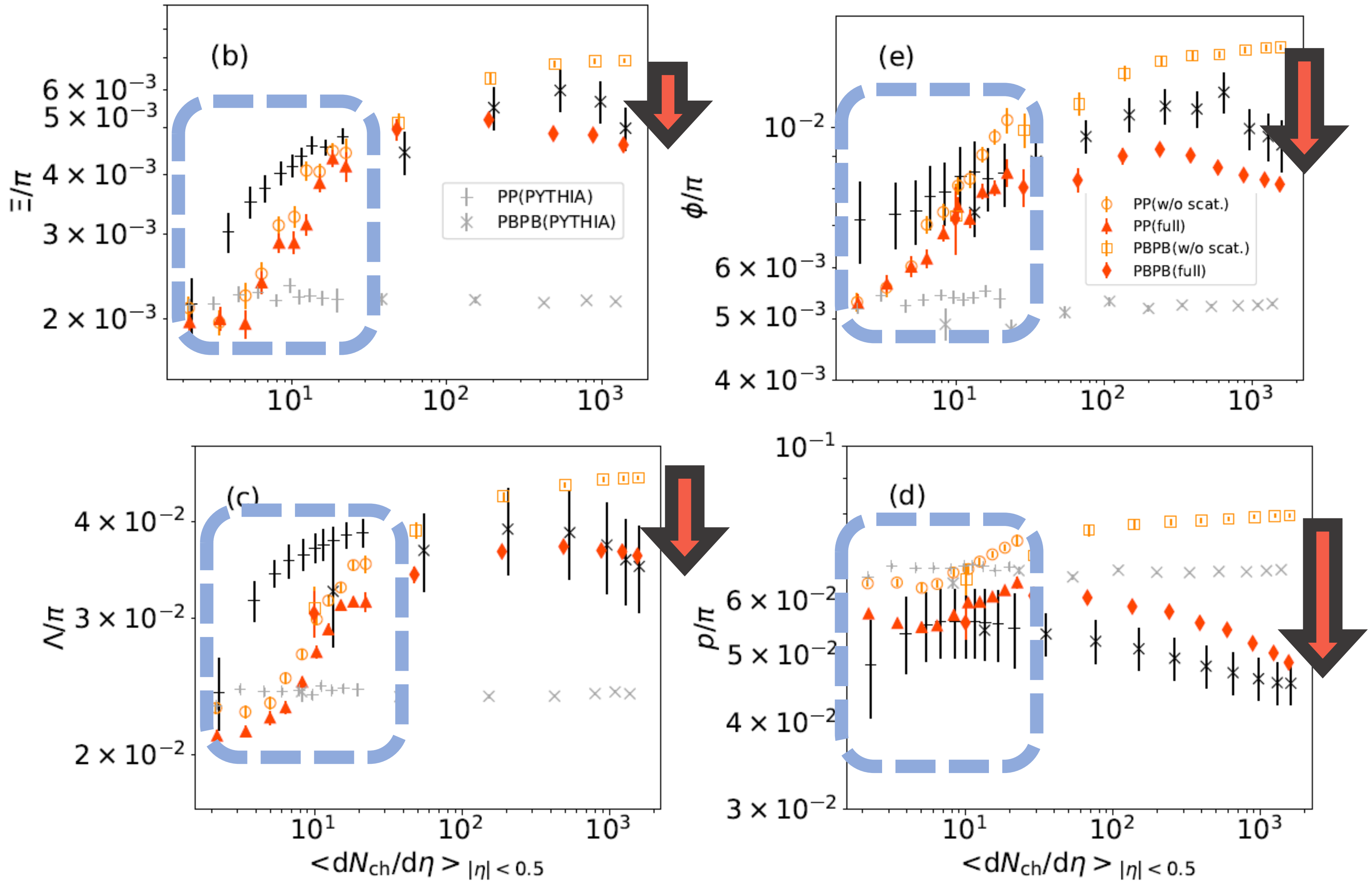
G : Gaussian

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

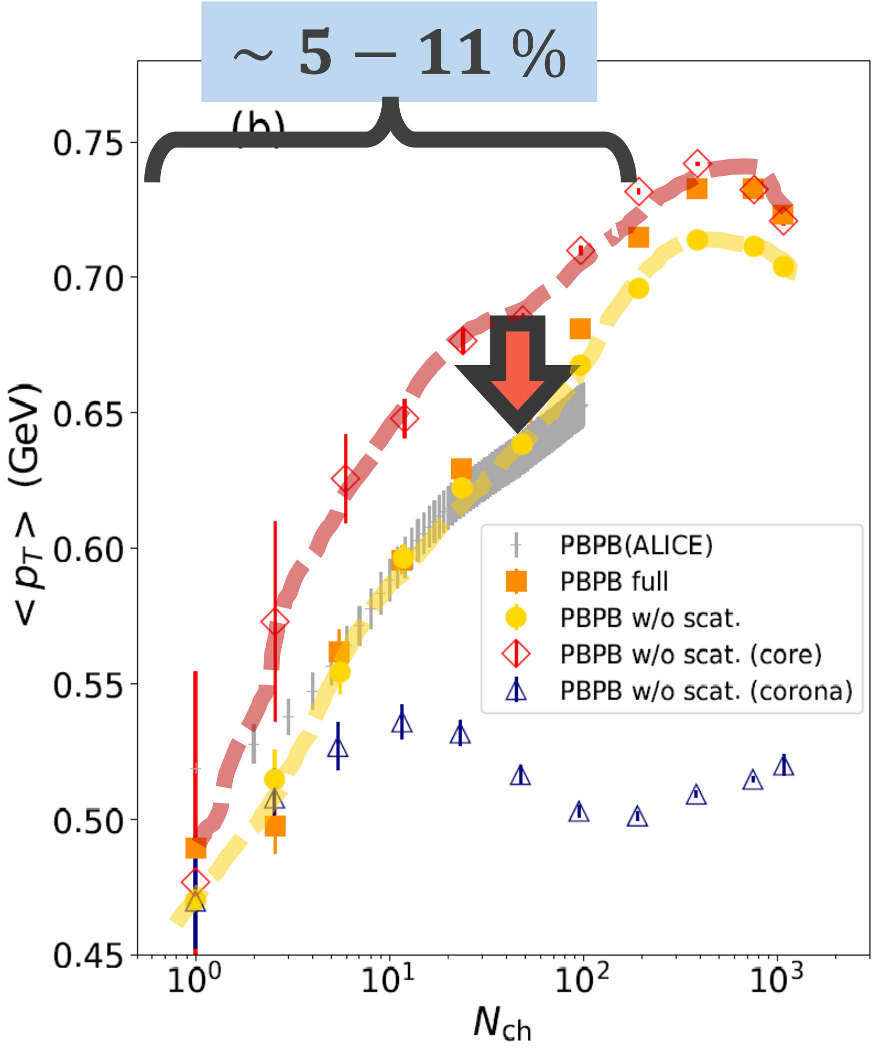


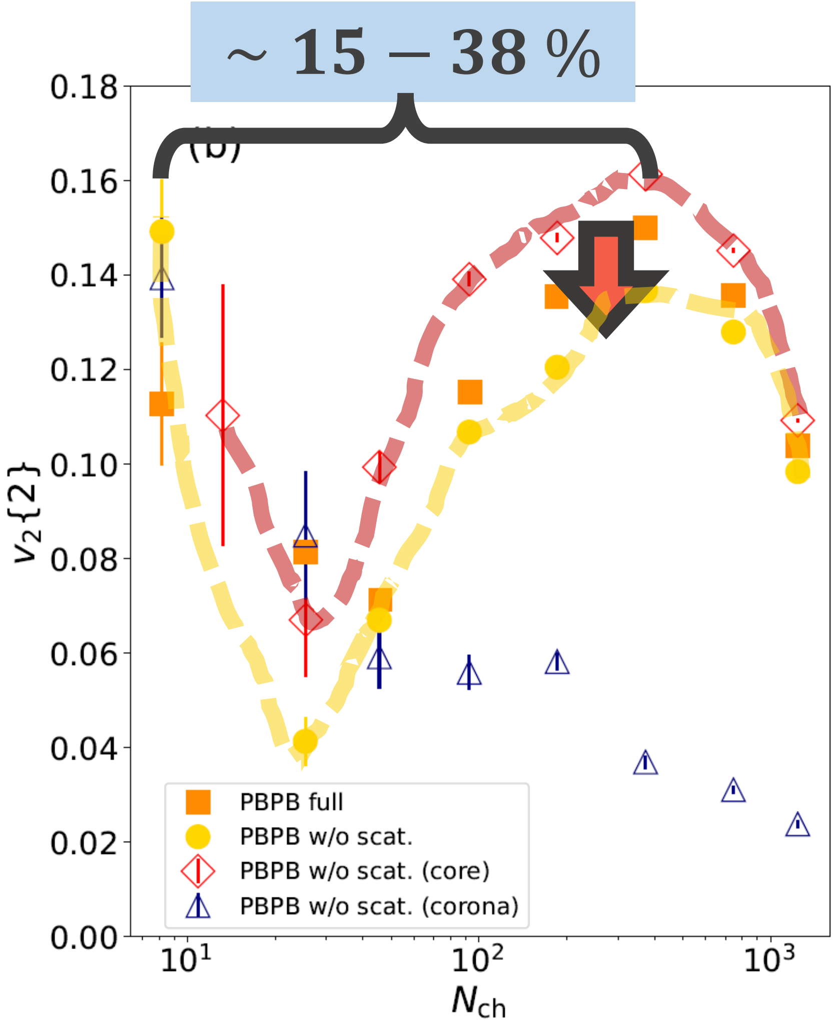
Significant suppression of yield ratios at central PbPb

✓ Captured with dissociation/annihilation of hadrons in late stage

Visible hadronic rescattering effects even in pp collisions

Corona correction in PbPb



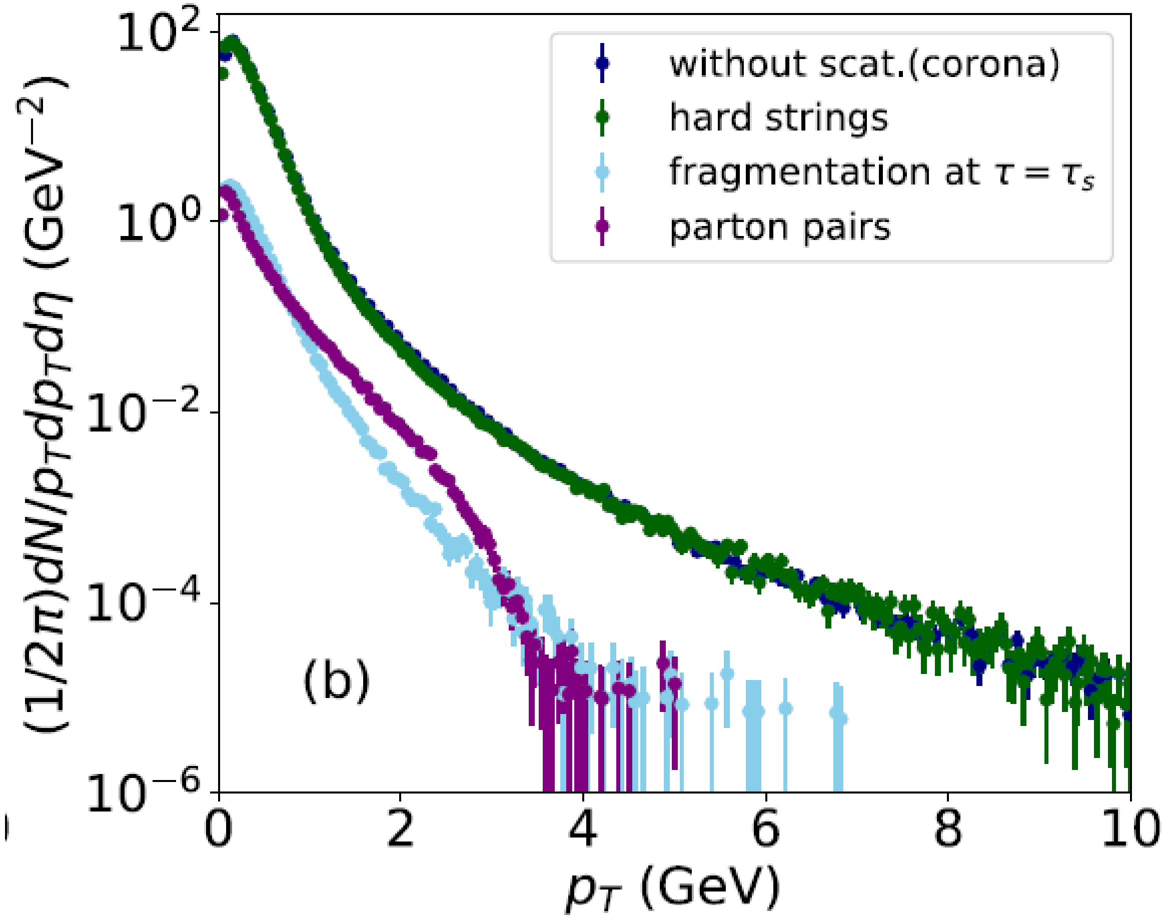


- Mean p_T and momentum anisotropy ➔ non-negligible effect of corona

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

Origin of corona contribution

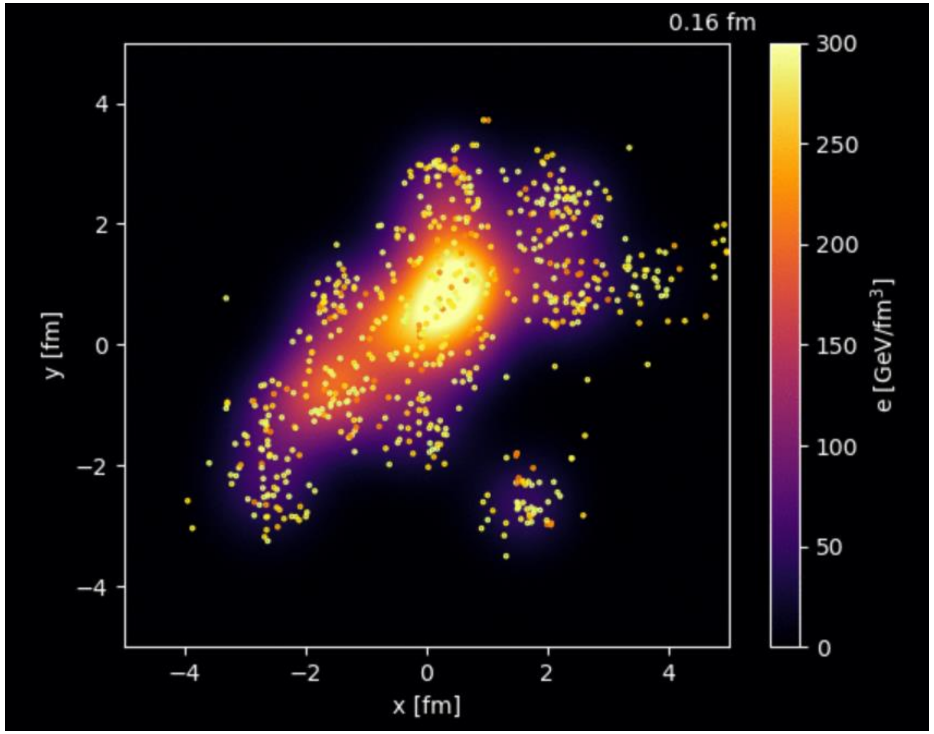
PbPb 2.76 TeV



Collision with constituent partons of QGP fluids

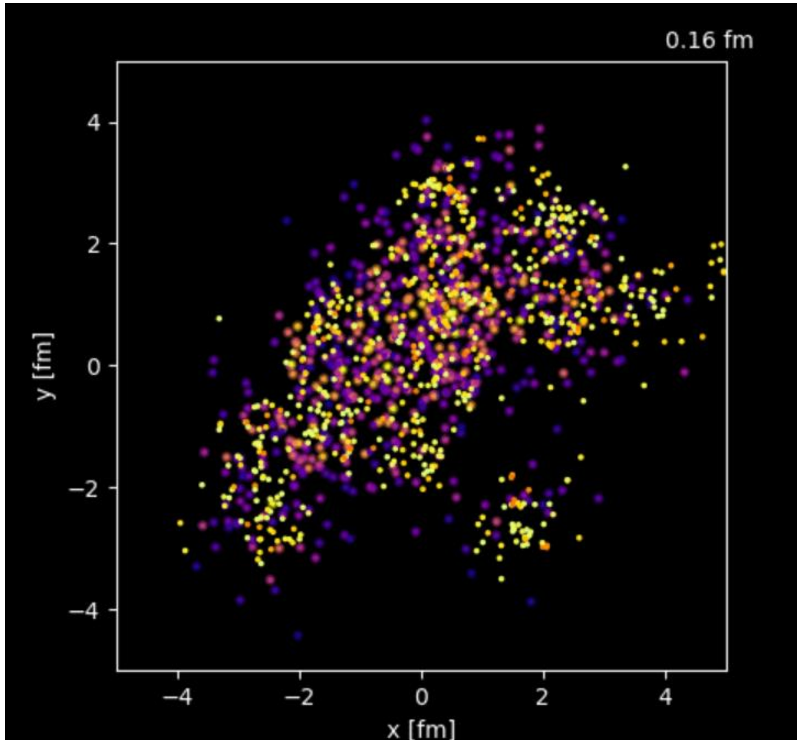
$$\frac{dp_i{}^{\mu}}{d\tau} = -\sum_{j}^{N_{\mathrm{scat}}} \rho_{i,j}\sigma_{i,j}\left|v_{\mathrm{rel},i,j}\right| p_i{}^{\mu}$$

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



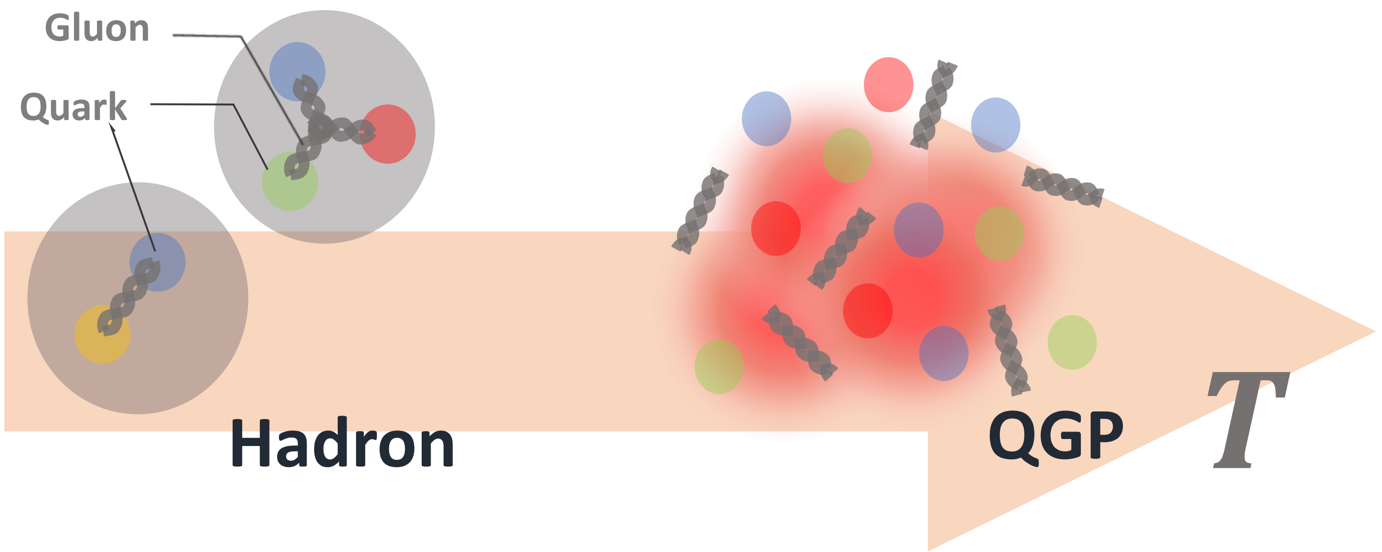
Sampling of equilibrated partons at each time step

*with mass-less ideal gas approximation



Quark gluon plasma (QGP)

A state of quarks and gluons under thermal & chemical equilibrium



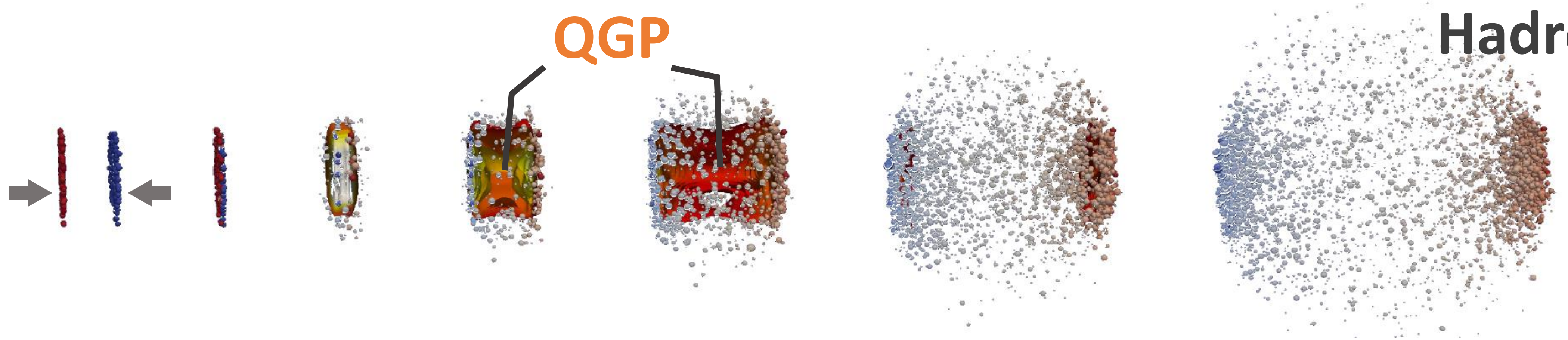
- Extremely high temperature ($T \sim 2$ trillion degrees)
- Early universe

Goal: Revealing the properties of the primordial matter

Only way to create QGP on the earth…

⇨ **High energy heavy-ion collisions**

High-energy heavy-ion collisions



How can we access the properties of QGP from HIC experimental data?

Dynamics of locally equilibrated matter

→ Relativistic hydrodynamics

Press release on 2005/04/18


RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

https://www.bnl.gov/newsroom/news.php?a=110303

QGP study with relativistic hydrodynamics

Energy-momentum conservation

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

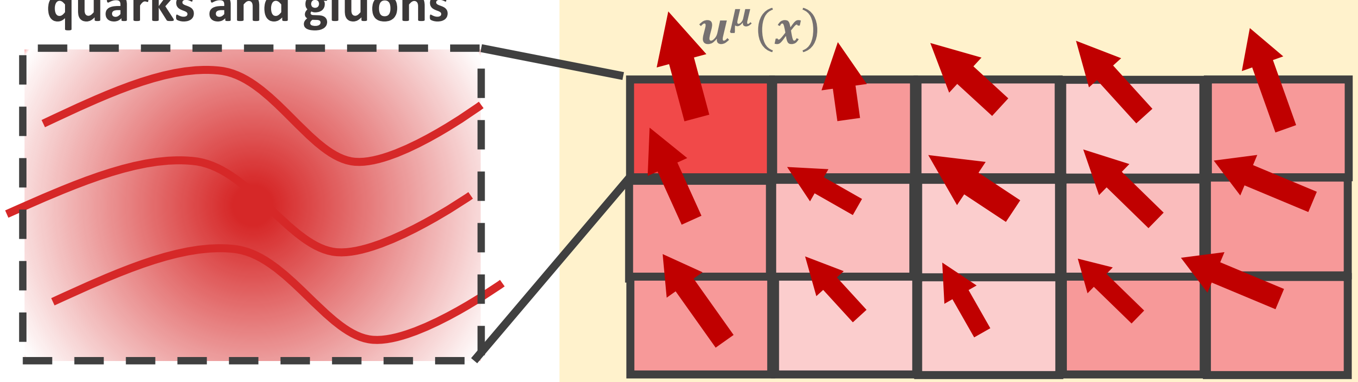
Energy-momentum tensor $T^{\mu\nu}$
➔decomposed with four velocity of fluids $u^\mu(x)$

+

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

Comparison among different descriptions

Glasma+jets: D. Avramescu *et al.*, arXiv:2303.05599; A. Ipp *et al.*, Phys. Lett. B 810 (2020) 135810; M. E. Carrington *et al.*, Phys. Rev. C 105 (2022) 6, 064910...

Fermion productions: N. Tanji *et al.*, Phys. Rev. D 97 (2018) 3, 034013; V. Kasper *et al.*, Phys. Rev. D 90 (2014) 2, 025016...

etc.

Problems to consider

Energy-momentum conservation of incoming beam energy

Only gluon fields

➔ Missing q and $\bar{q}$ carrying energy-momentum

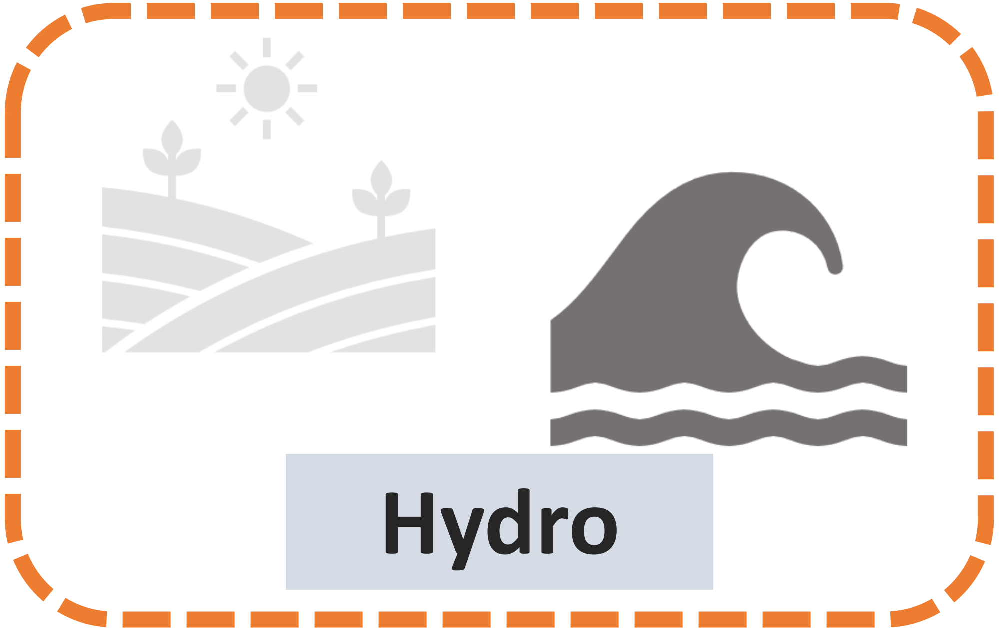
➔ Talk by Taya on Monday, Plenary session

Entire momentum space (from low to high p_T)

Effective description at small x

➔ Jets are missing

Comparison among different descriptions



Full 3D MC EKRT initial condition: M. Kuha *et al.*, in progress

Microcanonical Particlization: D. Oliinychenko *et al.*, Phys. Rev. Lett. 123 (2019) 18, 182302, Phys.Rev.C 102 (2020) 3, 034904

Core-corona: T. Pierog *et al.*, Phys. Rev. C 92 (2015) 3, 034906; Y. Kanakubo et al., Phys. Rev. C 105 (2022) 2, 024905

etc.

Problems to consider

Energy-momentum conservation of incoming beam energy

- Initial condition: parametrized or scaled to describe final state multiplicity

- Cooper-Frye: grand canonical

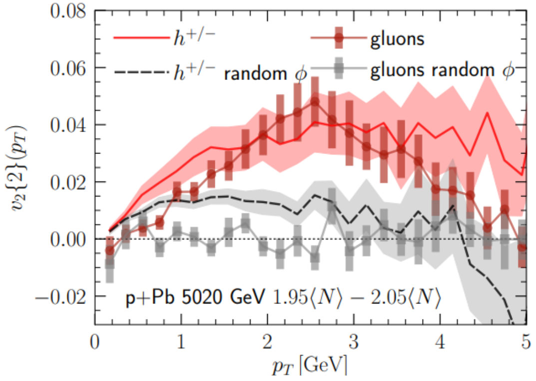
Entire momentum space (from low to high p_T)

Effective theory in long wavelength limit

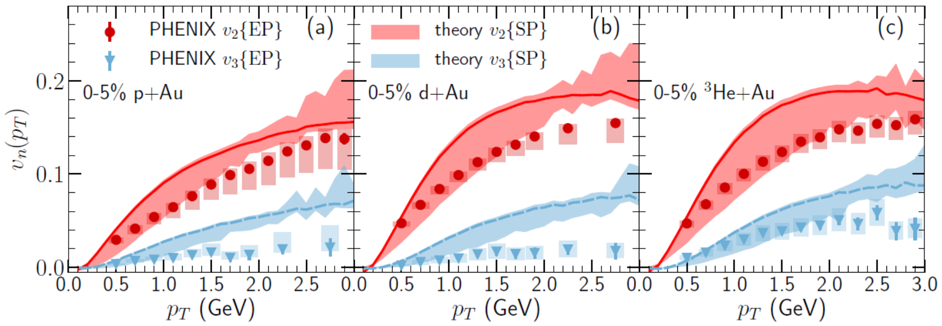
➔ Jets are missing

Assume local equilibrium for entire system

Discussion on origin of QGP signals

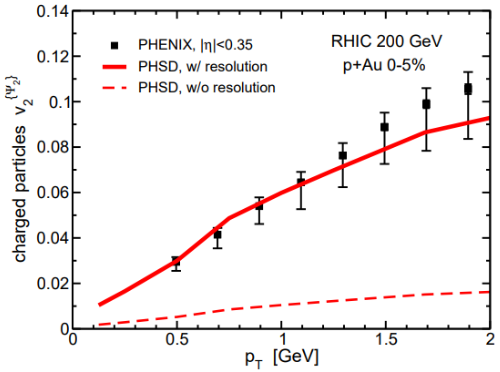


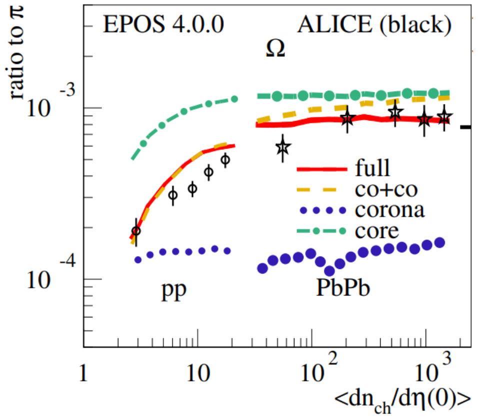
M. Greif *et al.*, Phys. Rev. D 103 (2021) 5, 054011



B. Schenke *et al.*, Phys. Lett. B 803 (2020) 135322

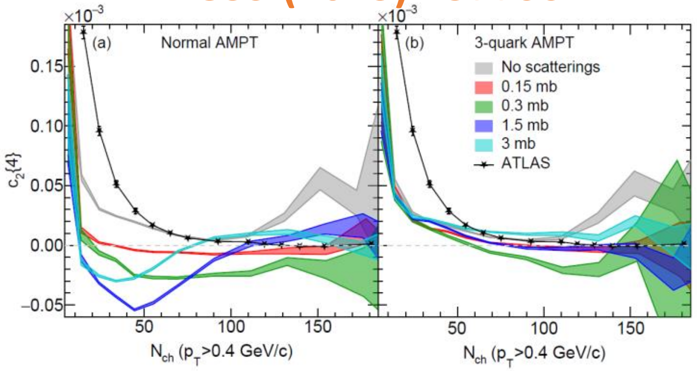
L. Oliva *et al.*, Phys. Rev. C 101 (2020) 1, 014917

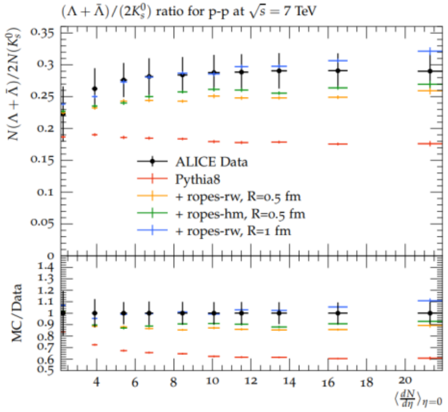




K. Werner, arXiv: 2301.12517

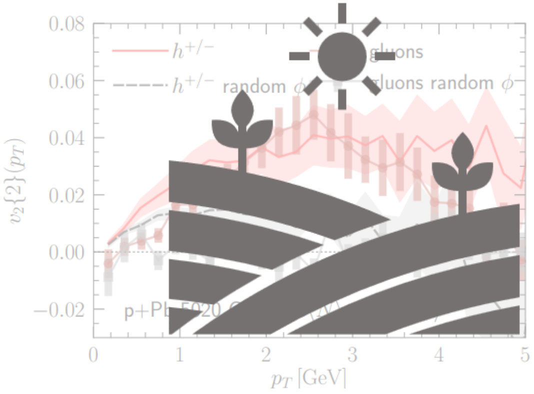
X. Zhao *et al.*, Phys. Lett. B 839 (2023) 137799





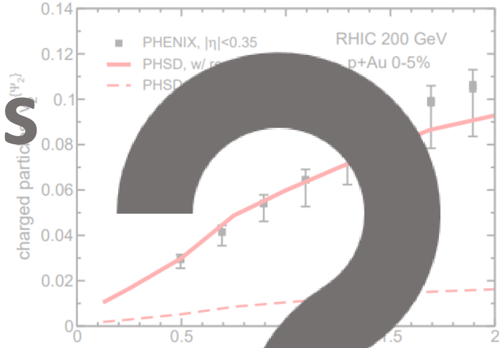
C. Bierlich *et al.*, Phys. Lett. B 835 (2022) 137571

Discussion on origin of QGP signals

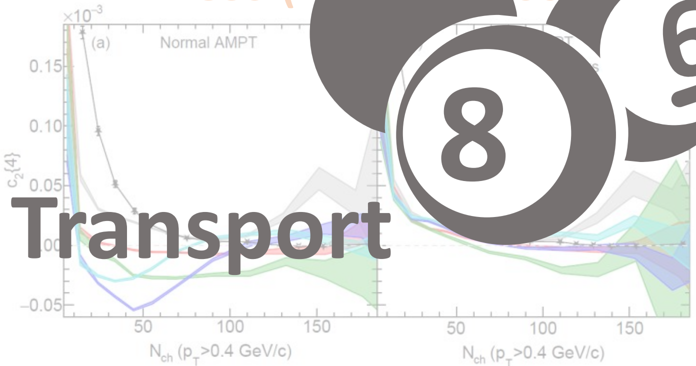


M. Greif *et al.*, Phys. Rev. D 103 (2021) 5, 054011

Color fields

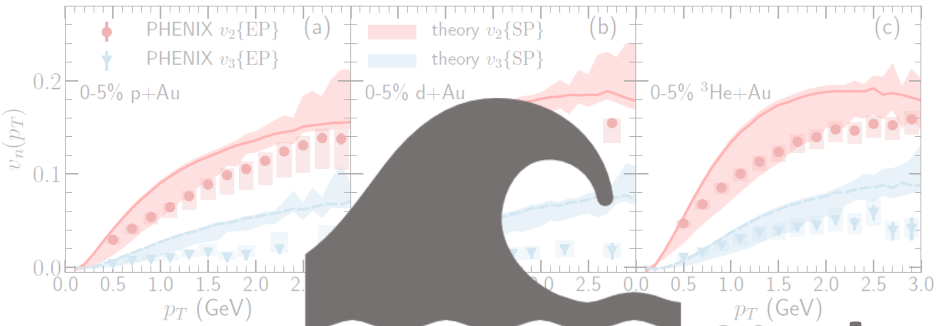


L. Oliva *et al.*, Phys. Rev. C 101 (2020) 1, 014917



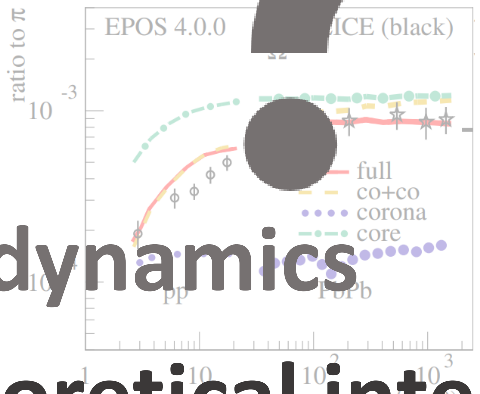
X. Zhao *et al.*, Phys. Lett. B 839 (2[...]) [...]799

Transport

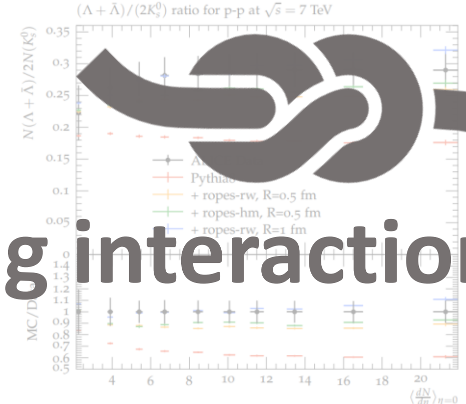


B. Schenke *et al.*, Phys. Lett. B 803 (2020) 135322

Hydrodynamics



K. Werner, arXiv: 2301.12517



C. Bierlich *et al.*, Phys. Lett. B 835 (2022) 137571

String interactions

etc.

Several possible theoretical interpretations since 2010

➔ Still remain open question…!