SOPHIA
HADRON
PHYSICS
GROUP

Dynamical core-corona initialisation in p+p and O+O collisions

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In collaboration with
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Plan of this talk

1. Introduction
2. Framework of Dynamical Core-Corona Initialisation (ver.2)
3. Recent Results from DCCI2
    - Results in O+O collisions
    - Bayesian analysis of p+p data
4. Summary and outlook

1. Introduction

Basic questions and purpose

p+p physics

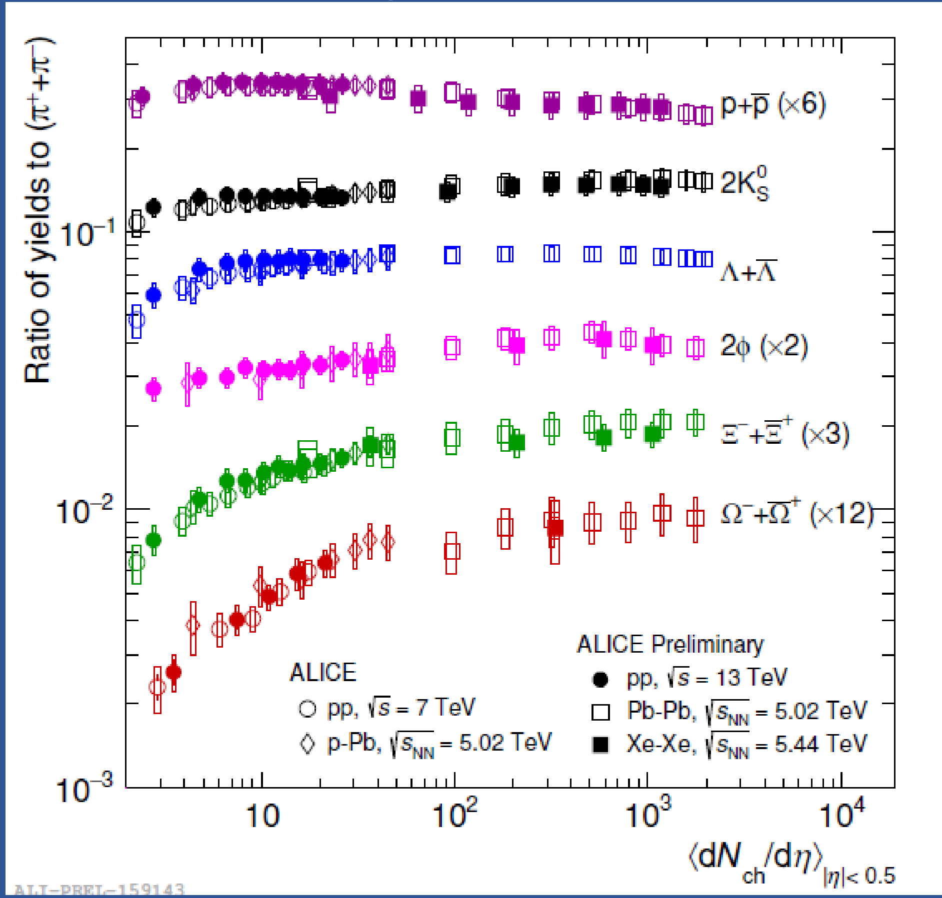
A+A physics

- Is collectivity emergent in small colliding systems?
- How small can QGP fluids be?

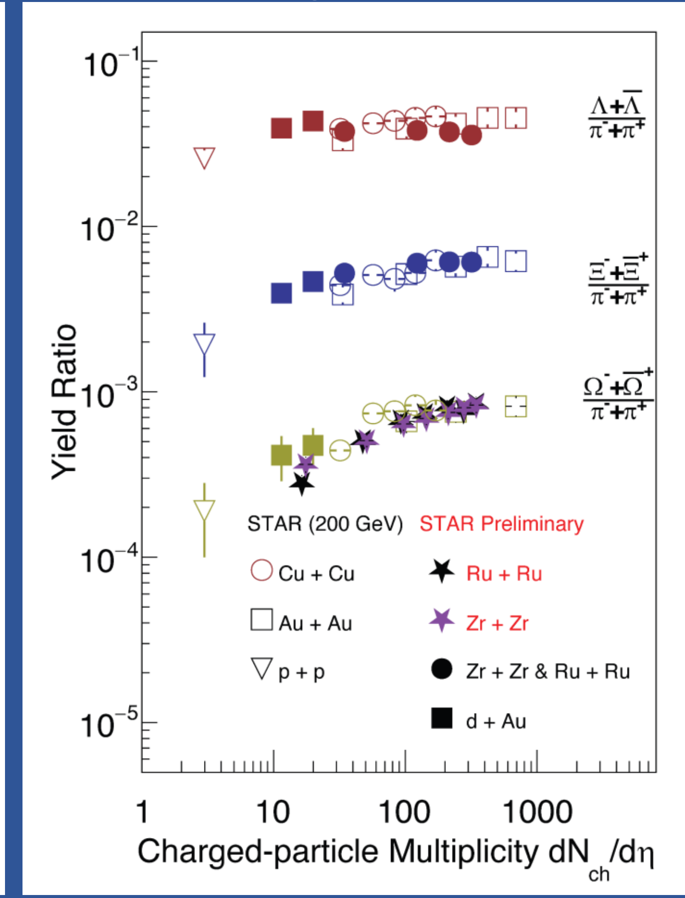
→ Development of a fully integrated dynamical model
toward understanding QGP properties
in high-energy nuclear collisions

Strangeness enhancement

Multiplicity dependence of particle yield ratio



ALICE overview, talk at QM2018

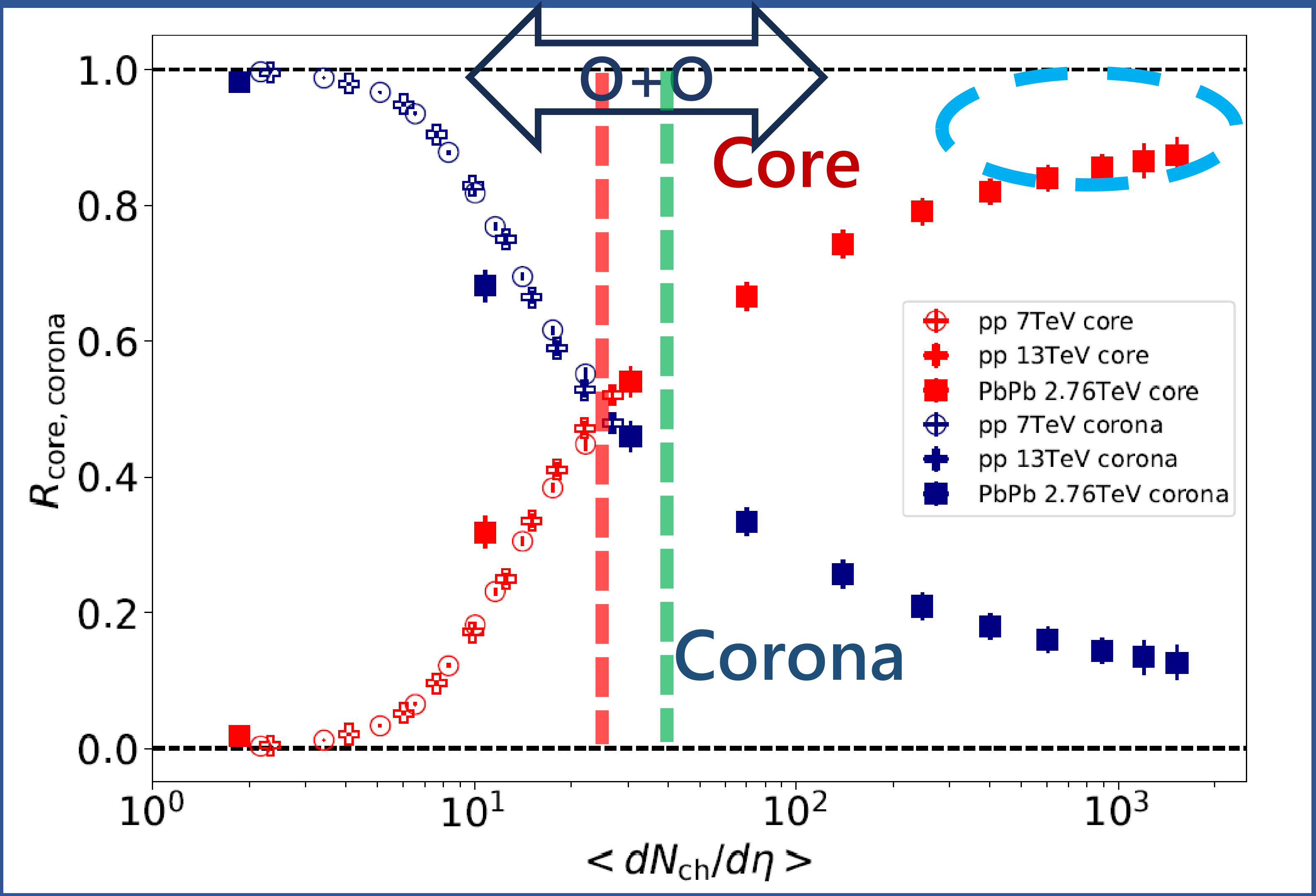


W.Yuan (STAR), talk at QM2025

Interpretation of universal behaviour in a **single** framework?

Understanding bulk particle production before discussion on collectivity

Fraction of core and corona



Kanakubo *et al.* (2022).

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

$R_{\mathrm{core}} \sim 0.85$ at central PbPb?

$\langle dN_{\mathrm{ch}}/d\eta \rangle \sim 40$ min. bias O+O at 5.36 TeV (CMS)

*O+O at sqrt_snn = 5.36 TeV from ALICE preliminary (Talk by Jan Fiete Grosse-Oetringhausat IS2025)

2. Framework of Dynamical Core-Corona Initialisation (ver.2)

Dynamical initialisation

Okai *et al.* (2018); see also Shen, Schenke (2018).

Conservation of the whole system

$$\partial_\mu\left(T^{\mu\nu}_{\mathrm{fluid}} + T^{\mu\nu}_{\mathrm{parton}}\right) = 0 \Rightarrow \begin{aligned} \partial_\mu T^{\mu\nu}_{\mathrm{fluid}} &= J^\nu_{\mathrm{p}\to\mathrm{f}} \\ \partial_\mu T^{\mu\nu}_{\mathrm{parton}} &= -J^\nu_{\mathrm{p}\to\mathrm{f}} \end{aligned}$$

→ Hydrodynamic equations **with source terms**

Step 1
Generate initial partons

$$T^{\mu\nu}_{\mathrm{parton}}(0^+)$$

⇒

Step 2
Model source term

$$J^\nu_{\mathrm{p}\to\mathrm{f}} = -\partial_\mu T^{\mu\nu}_{\mathrm{parton}}(t)$$

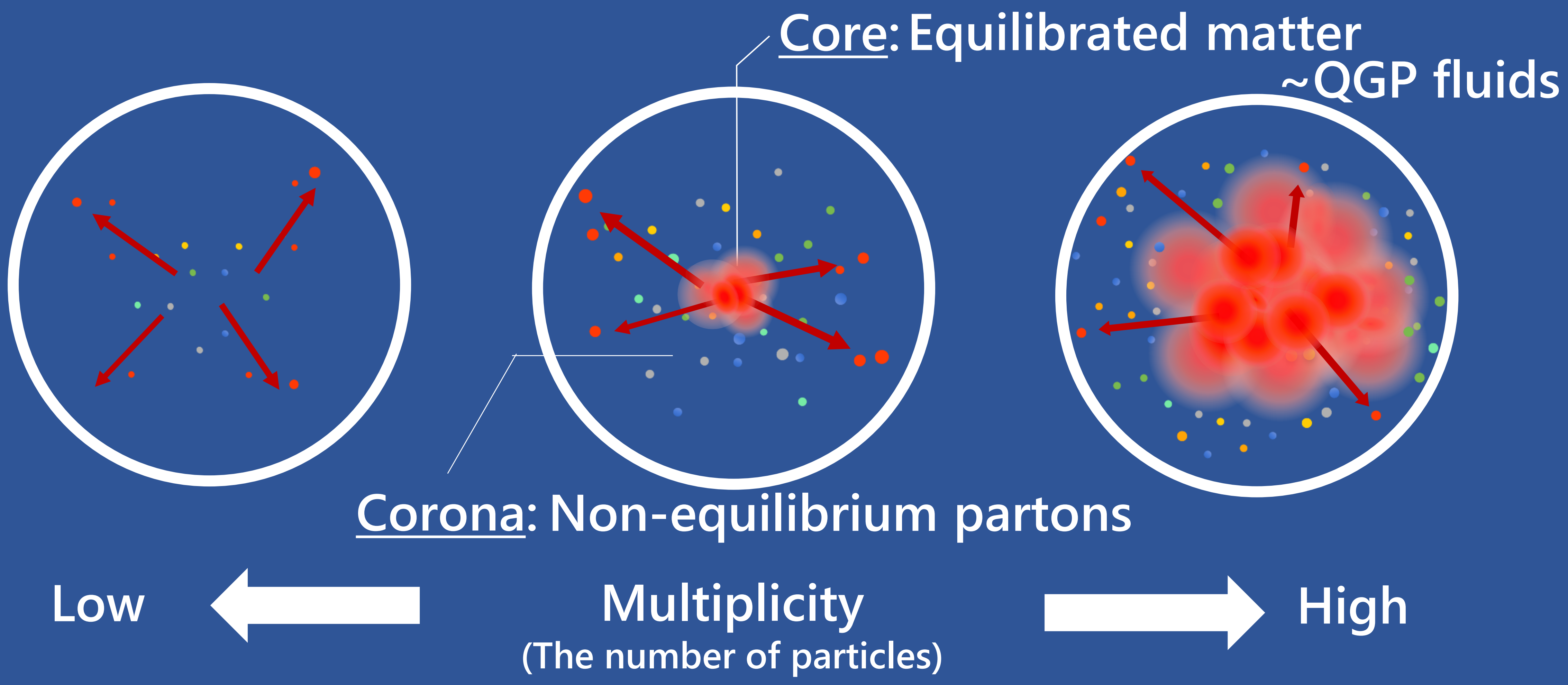
⇒

Step 3
Solve hydro eqs. with vacuum initial condition

$$\partial_\mu T^{\mu\nu}_{\mathrm{fluid}} = J^\nu_{\mathrm{p}\to\mathrm{f}}$$

with $T^{\mu\nu}_{\mathrm{fluid}}(t_0) = 0$

Core-corona picture



Figures: Courtesy of Y.Kanakubo

Bozek (2005, 2009), Aichelin, Werner (2009, + many), Becattini, Manninen (2009), Pierog *et al.* (2015), Akamatsu *et al.* (2018), Kanakubo *et al.* (2018, 2020, 2022a, 2022b)

Modeling of energy-momentum deposition

Source term from kinetic approach

Kanakubo *et al.* (2020).

$$J^{\mu}_{\mathrm{p}\to\mathrm{f}}(t,\boldsymbol{x}) = -\sum_i \frac{d{p_i}^{\mu}}{dt} G(\boldsymbol{x} - \boldsymbol{x}_i(t))$$

G : Gaussian smearing of $\delta^{(3)}(\boldsymbol{x} - \boldsymbol{x}_i(t))$

p_i : Four momentum of ith parton

$\boldsymbol{x}_i$: Position of ith parton

Phenomenological fluidization rate per particle

Kanakubo *et al.* (2022).

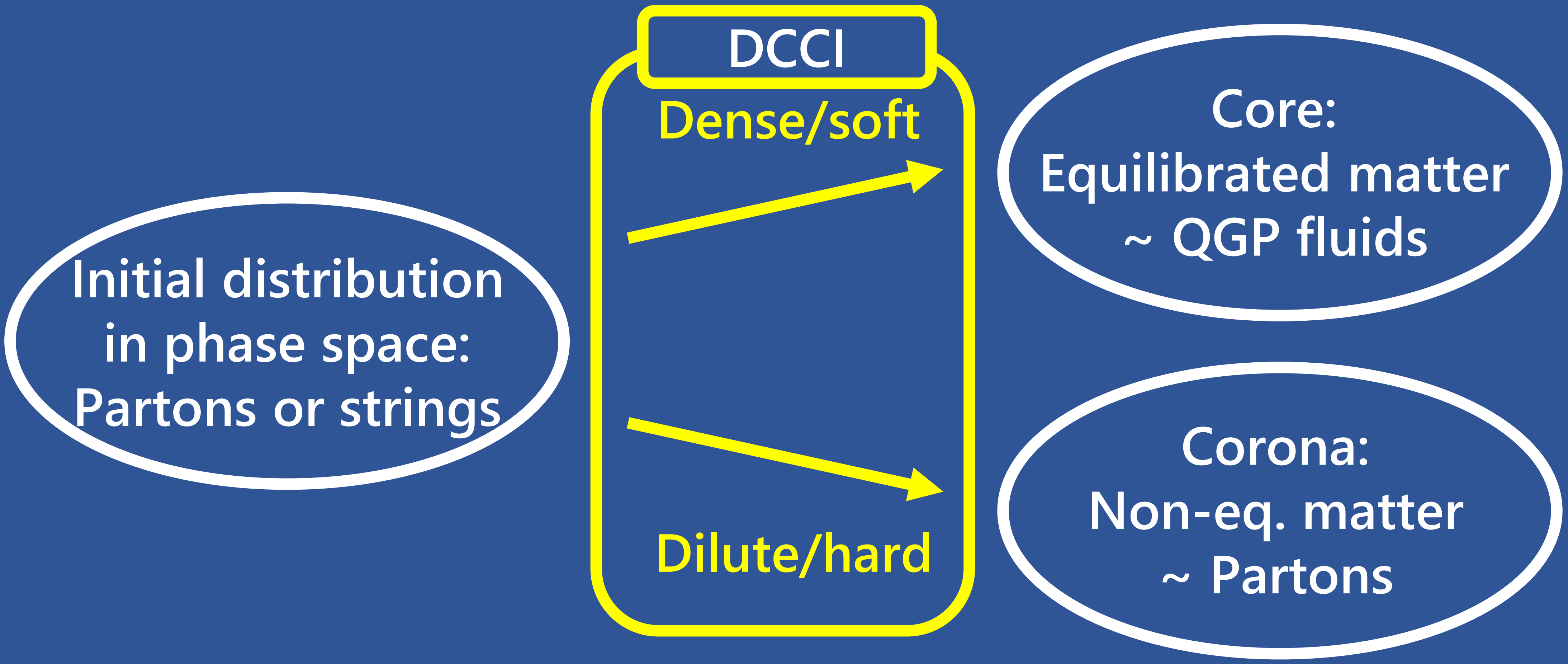
$$\frac{d{p_i}^{\mu}}{d\tau} = -\sum_j^{N_{\mathrm{scat}}} \rho_{i,j}\sigma_{i,j}\left|v_{\mathrm{rel},i,j}\right| {p_i}^{\mu}$$

$\rho_{i,j}$: Profile of jth parton

$\sigma_{i,j}$: Cross section btwn. ith and jth

$v_{\mathrm{rel},i,j}$: Rel. velocity btwn. ith and jth

Dynamical Core-Corona Initialisation



Separation of initial system just after collision dynamically

Fully integrated DCCI framework

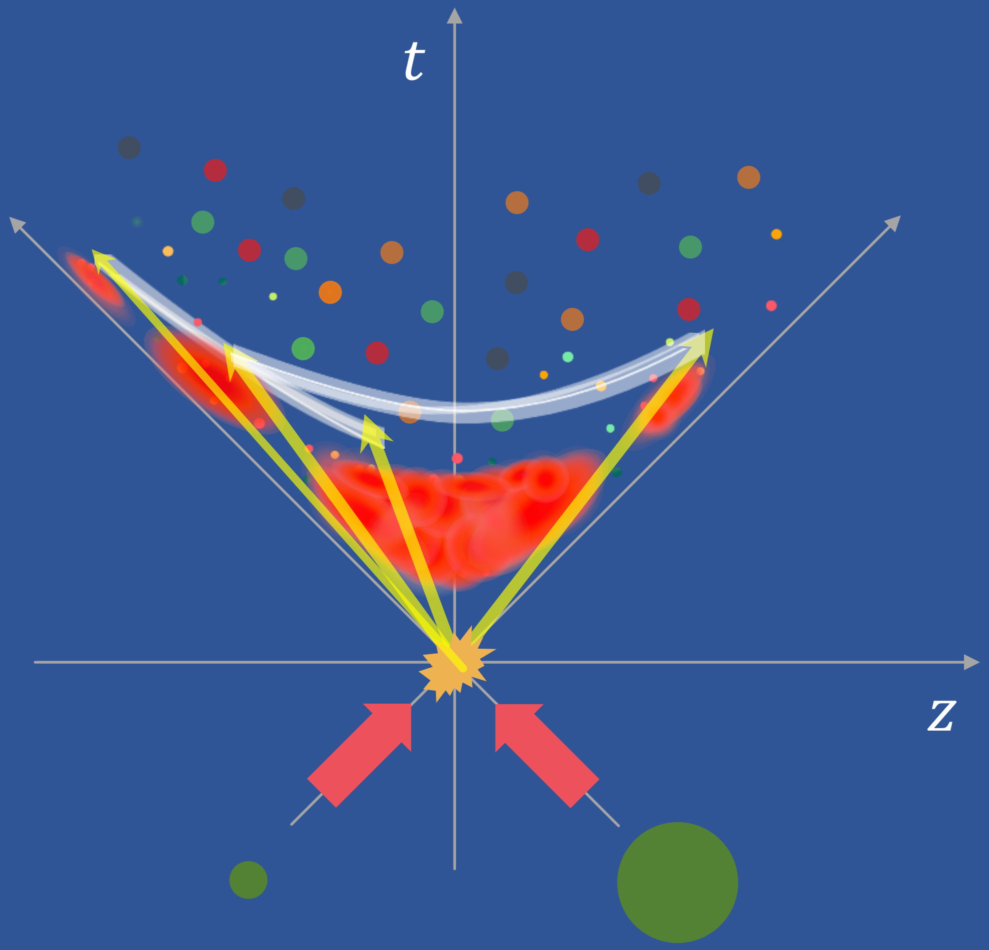


Figure: Courtesy of Y.Kanakubo

Kanakubo *et al.*, (2020, 2022a, 2022b)

Hadronic afterburner

JAM — Nara *et al.*, (2000)

Hadronisation

PYTHIA8 (string fragmentation)

iS3D (thermal hadron sampling) — M. McNelis *et al.*, (2021)

DCCI + QGP dynamics

(3+1)-D hydro with source terms — Tachibana and TH, (2014)

EoS: s95p-v1.1 — Huovinen and Petreczky (2010)

Initial parton production

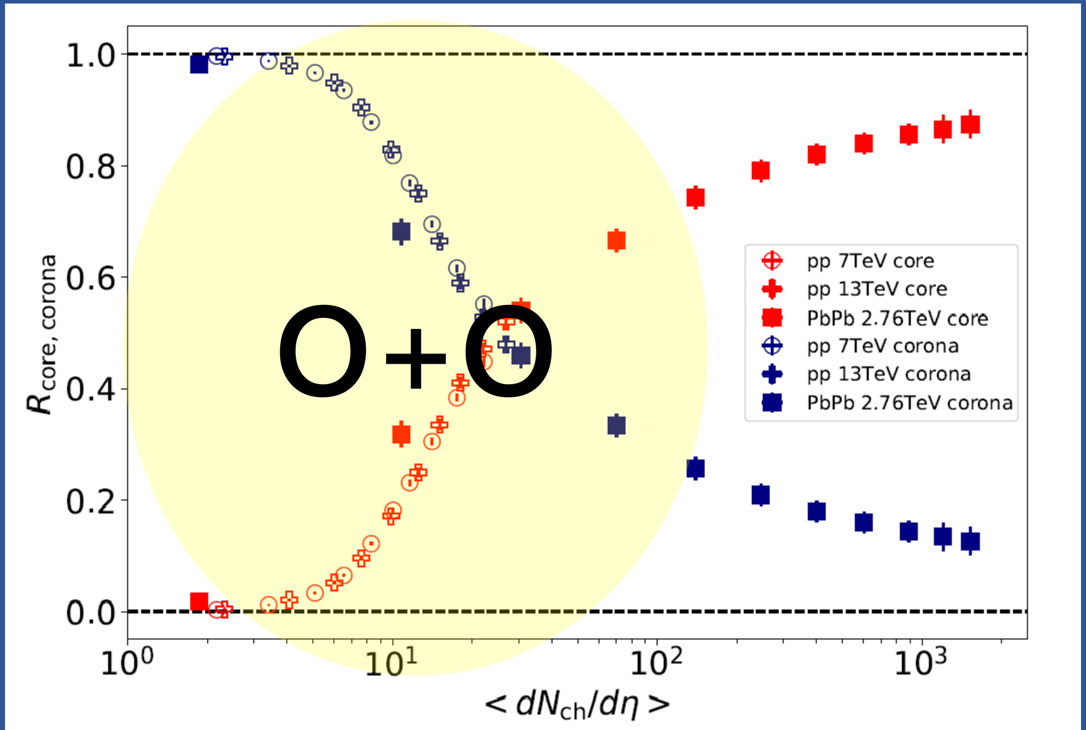
PYTHIA8/PYTHIA8 Angantyr

Sjöstrand *et al.*, (2015); C. Bierlich *et al.*, (2016)

3. Results in O+O Collisions

N. Ito and T. Hirano, arXiv:2604.05307

Degree of equilibration in intermediate system size?

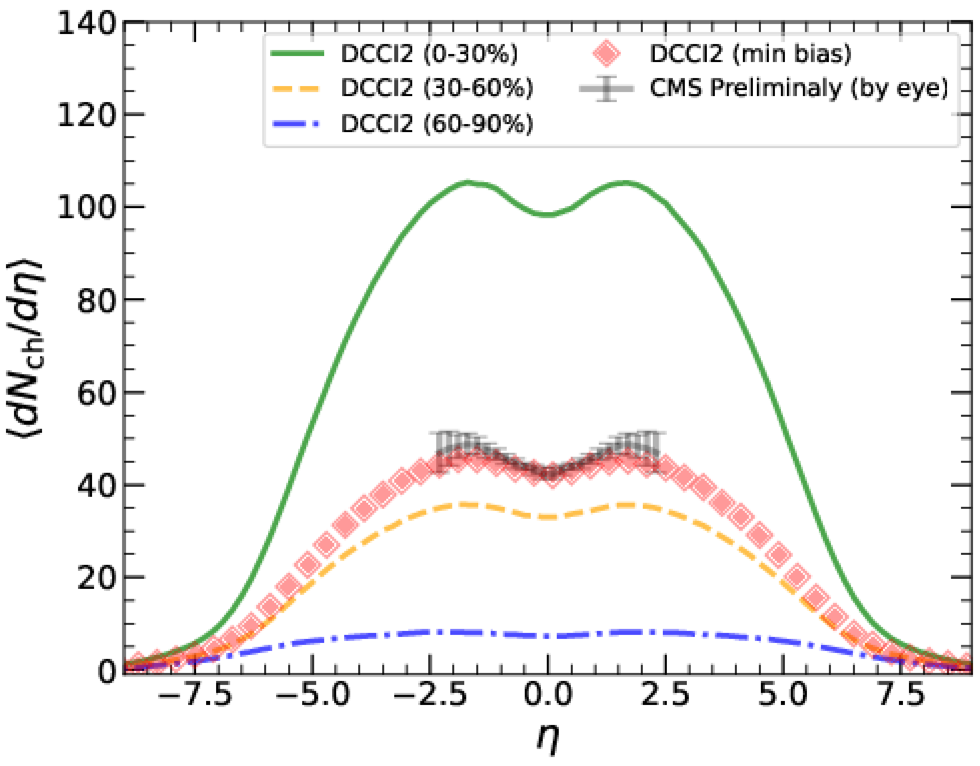


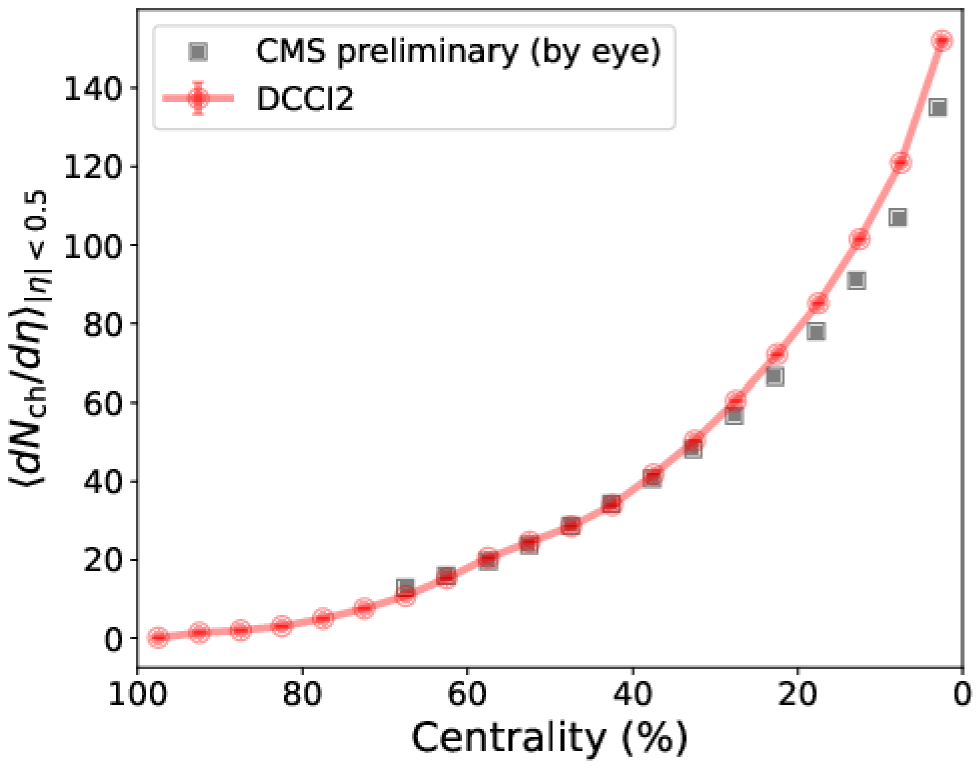
Anisotropic flow

Spatial anisotropy ? Momentum anisotropy

Nontrivial if the system does not reach complete local equilibrium

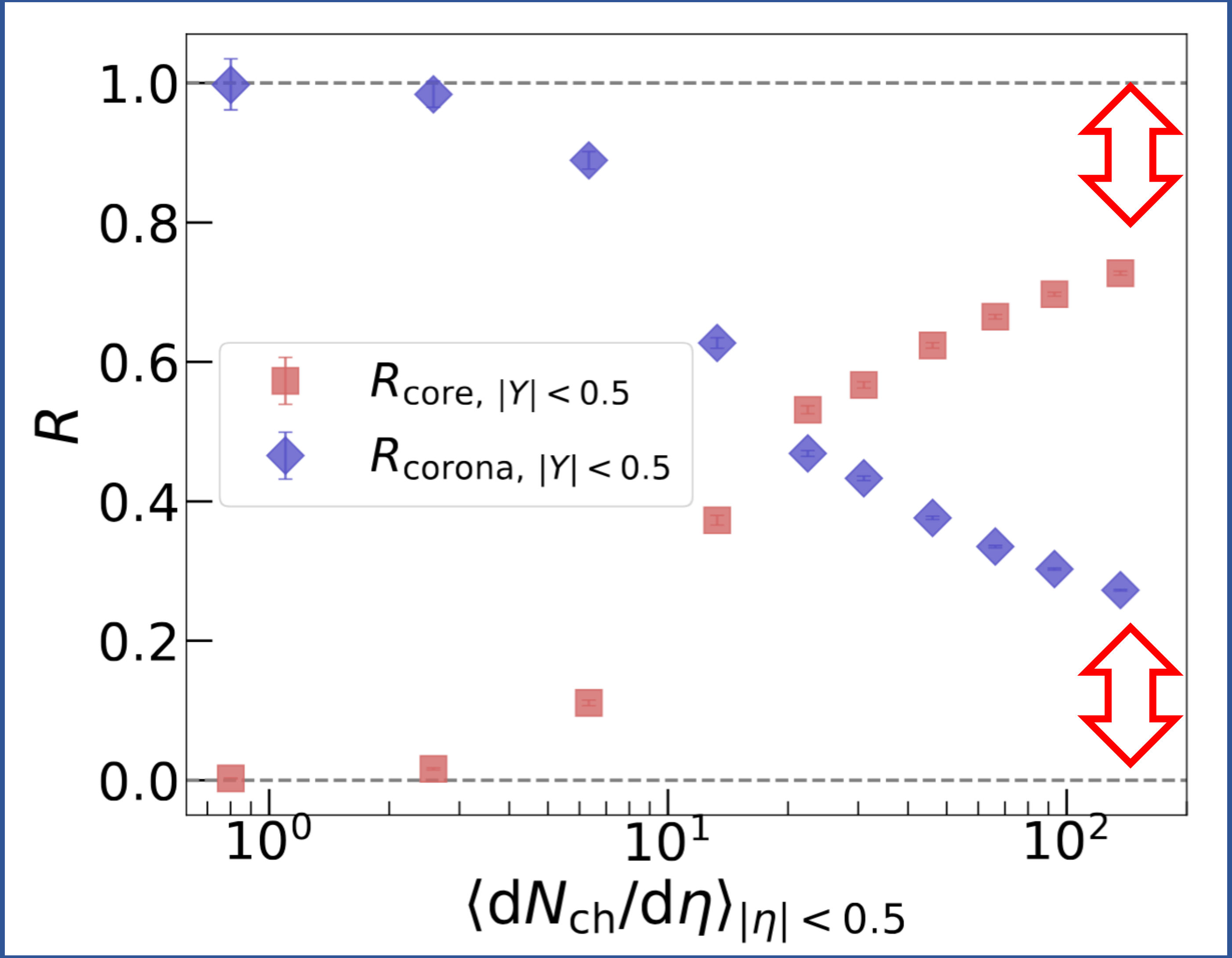
Rapidity and centrality dependence of charged hadrons





Default DCCI2 model → Reasonable reproduction of trends in rapidity and centrality dependence of charged hadron yields

Core-corona fraction in O+O collisions

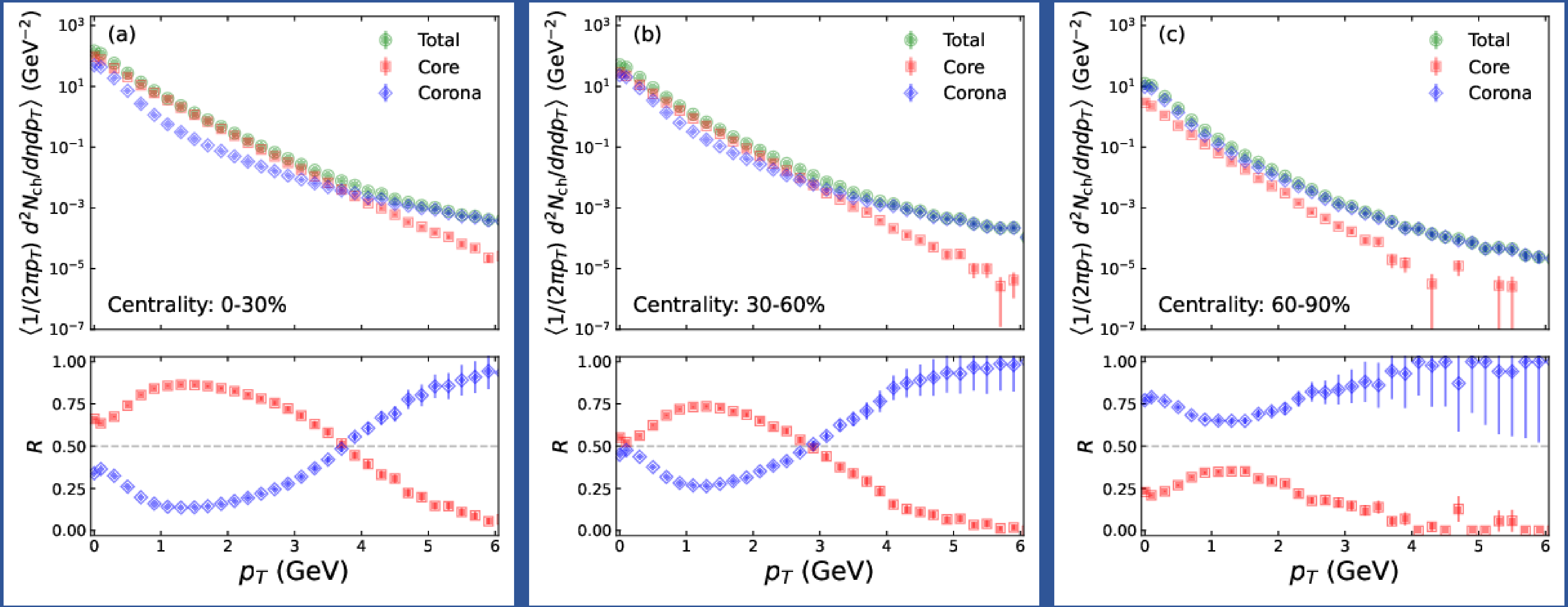


Monotonic increase (decrease) of core (corona) components as total multiplicity

Transition point
→ dN_{ch}/deta ~ 20

~30% of corona components remains in central collisions (Never depleting corona)

p_T distributions of charged hadrons

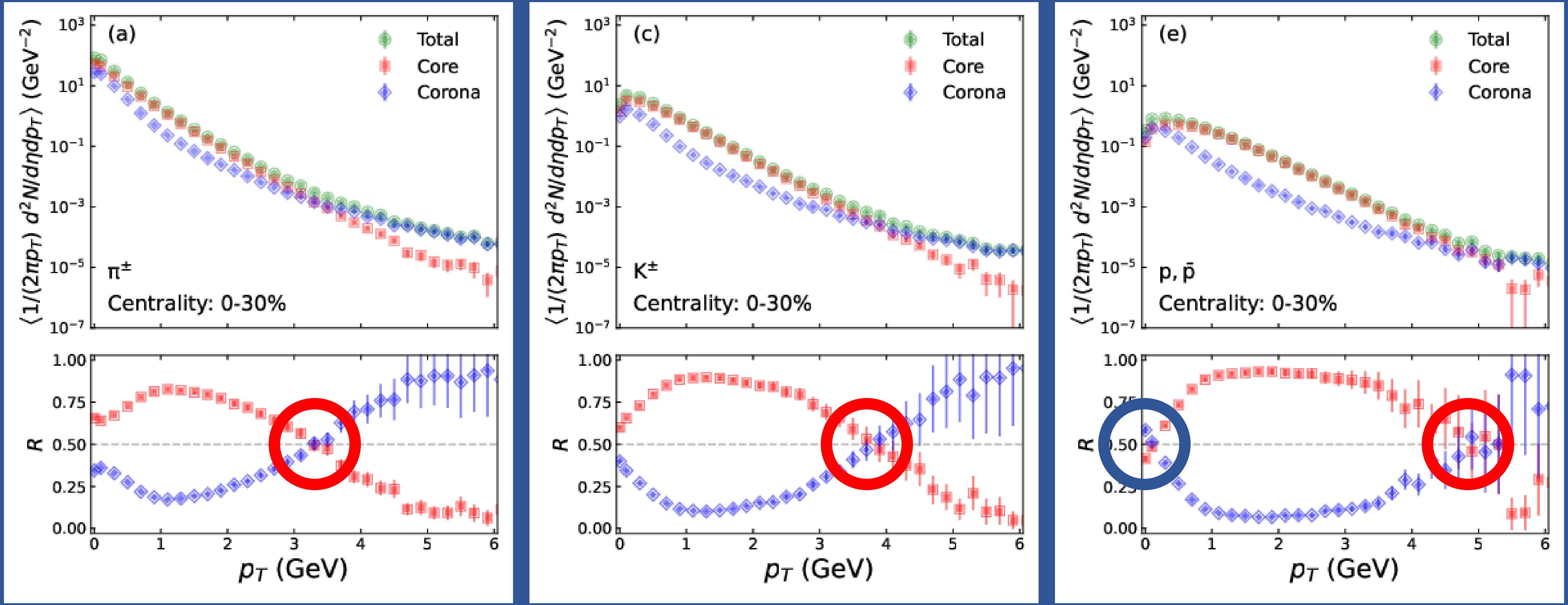


Core dominance below ~3.7 GeV

Soft from corona at very low p_T

No more core dominant p_T region

p_T distribution of PID hadrons



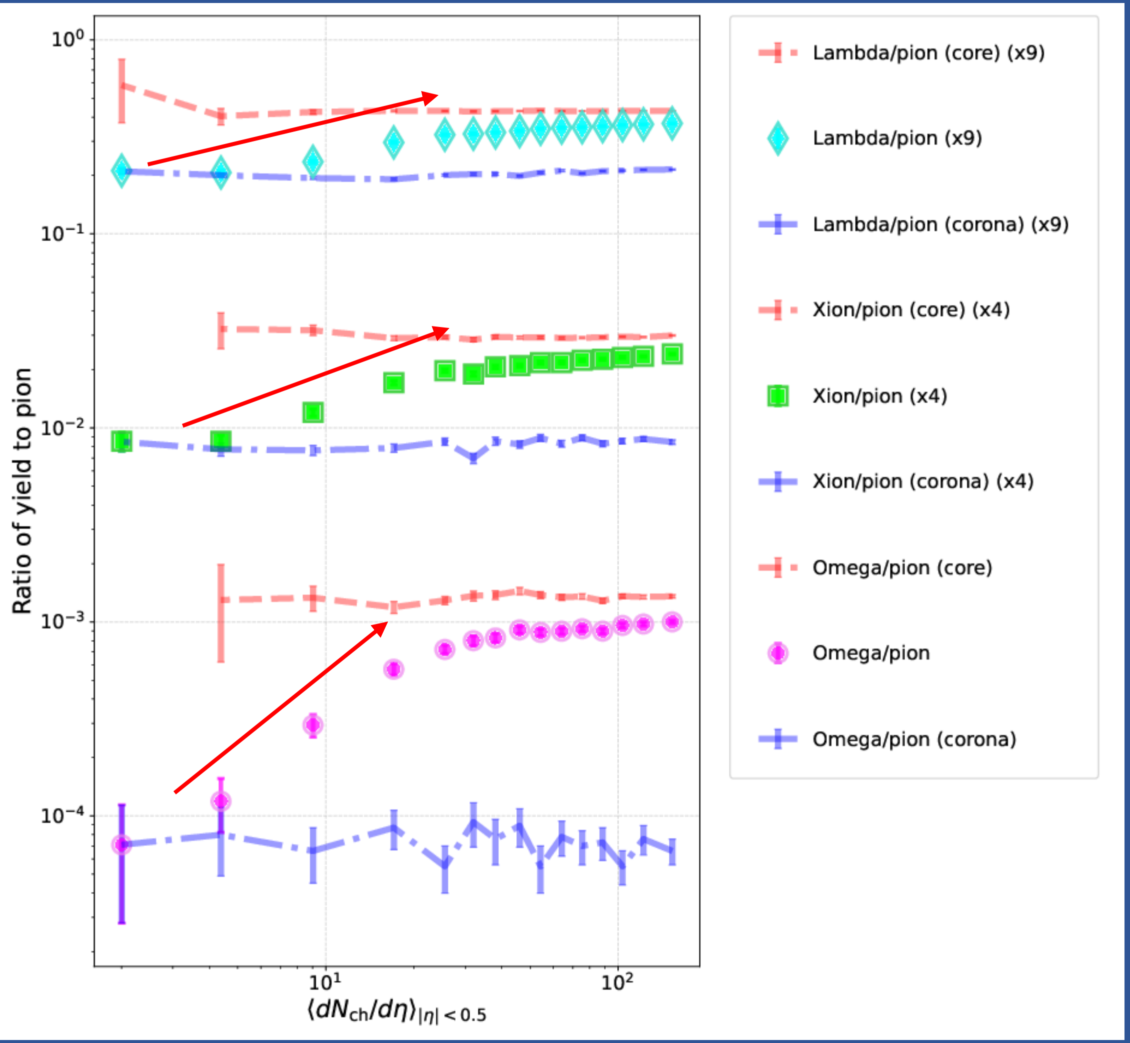
Hadron mass ↑ → Transition point ↑

Mass ordering due to radial flow

Soft from corona

due to radial flow

Strangeness enhancement in O+O collisions



Ratios of corona
← String fragmentation in PYTHIA

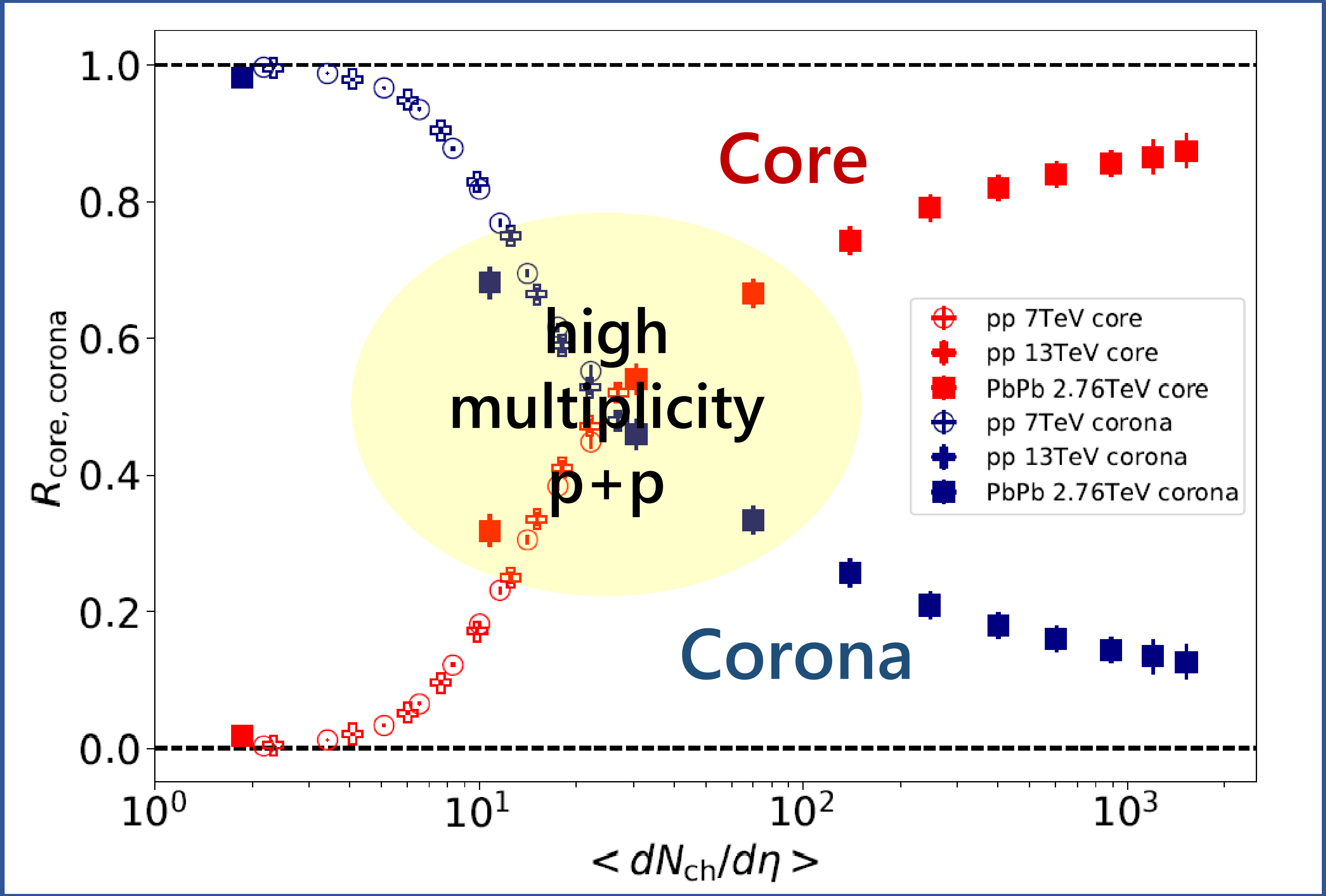
Ratios of core
← Chemical freezeout

Interplay between core and corona
→ Monotonic increase of ratios
→ More enhancement for multi-strange hadrons

4. Bayesian Analysis of p+p Data

A. Shigeyoshi, K. Kuroki, and T. Hirano, (in preparation)

Fraction of core and corona



Kanakubo *et al.* (2022).

Bayesian analysis of p+p collisions at LHC

Experimental data set in p+p collisions at LHC
- p_T dist. of PID hadrons
- Λ/π, Ξ/π, and $dN_{\mathrm{ch}}/d\eta$
- vs. multiplicity class

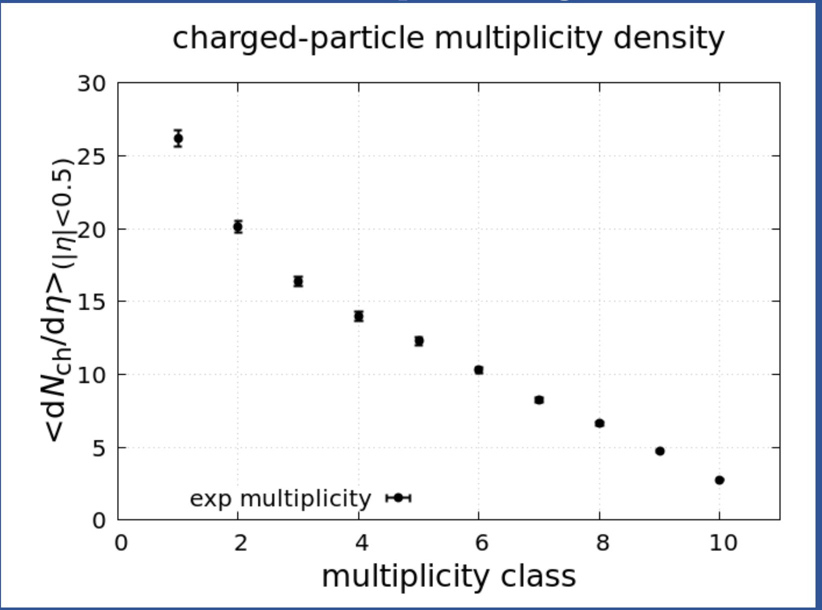
Bayesian parameter estimation

90% credible interval
Maximum a Posteriori (MAP)

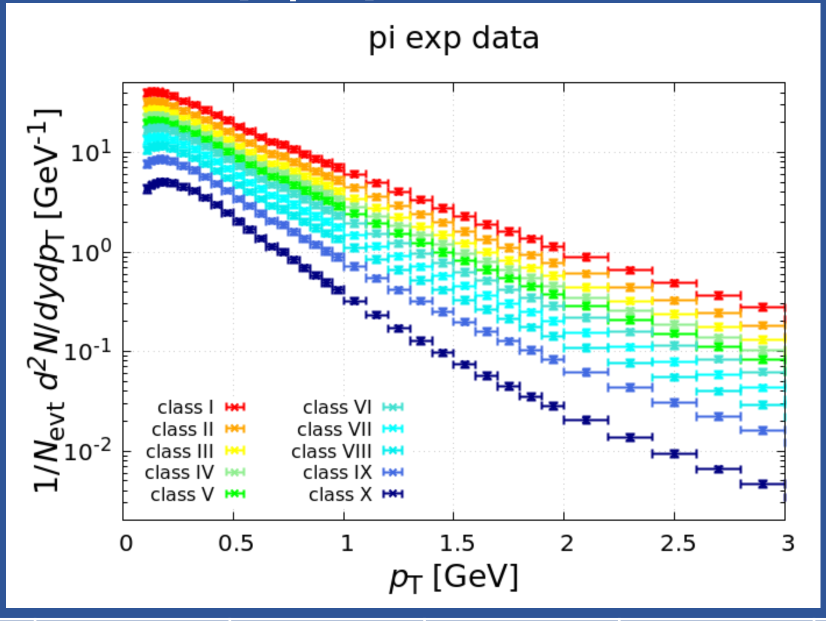
Purpose:
Scrutinisation of the core production in statistical analysis from DCCI2 model

Choice of exp. data

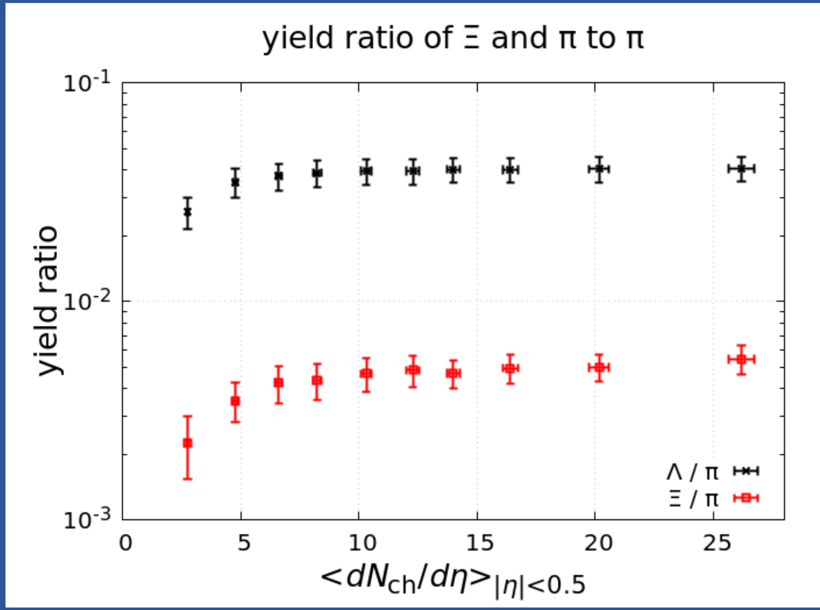
Multiplicity



p_T spectra



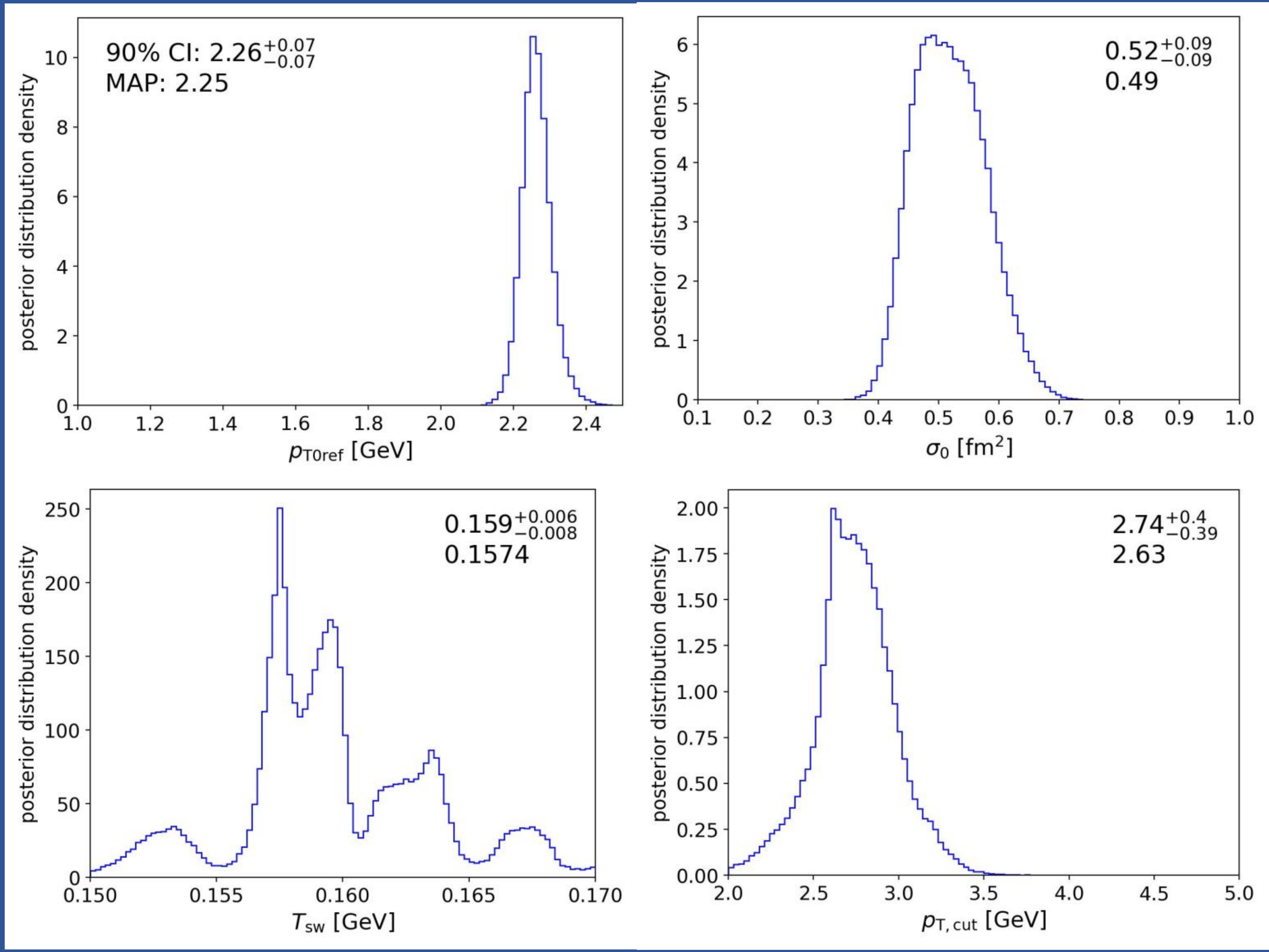
Yield ratios



V0M class	I	II	III	IV	V	VI	VII	VIII	IX	X
$\sigma/\sigma_{\mathrm{INEL}>0}(\%)$	$0-0.92$	$0.92-4.6$	$4.6-9.2$	$9.2-13.8$	$13.8-18.4$	$18.4-27.6$	$27.6-36.8$	$36.8-46.0$	$46.0-64.5$	$64.5-100$
$\langle dN_{\mathrm{ch}}/d\eta\rangle$	26.02 ± 0.35	20.02 ± 0.37	16.17 ± 0.22	13.77 ± 0.19	12.04 ± 0.17	10.02 ± 0.14	7.95 ± 0.11	6.32 ± 0.09	4.50 ± 0.07	2.55 ± 0.04

S. Acharya *et al.* [ALICE Collaboration], (2020).

Posterior distribution



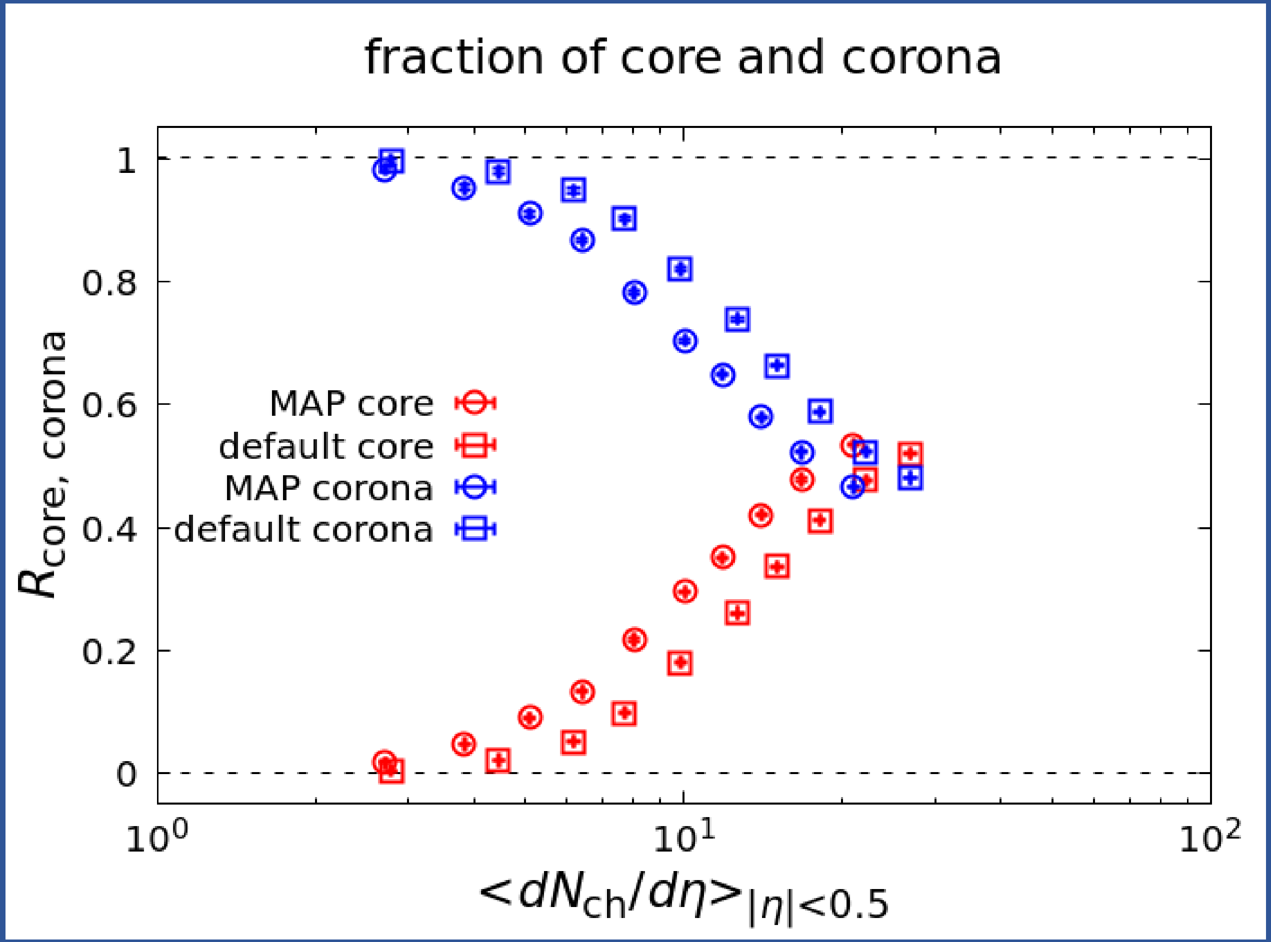
4 out of 14 parameters in DCCI2 model

← Relevant parameters to control particle yields and core production

Clear peaks of posteriors within prior ranges

MAP: Maximum A Posteriori

Core-corona fraction in p+p collisions at LHC



MAP vs. Default* comparison

Core production confirmed even after Bayesian parameter estimation

⬇

Strong indication of QGP production in p+p collisions?

*Kanakubo *et al.* (2022).

Summary

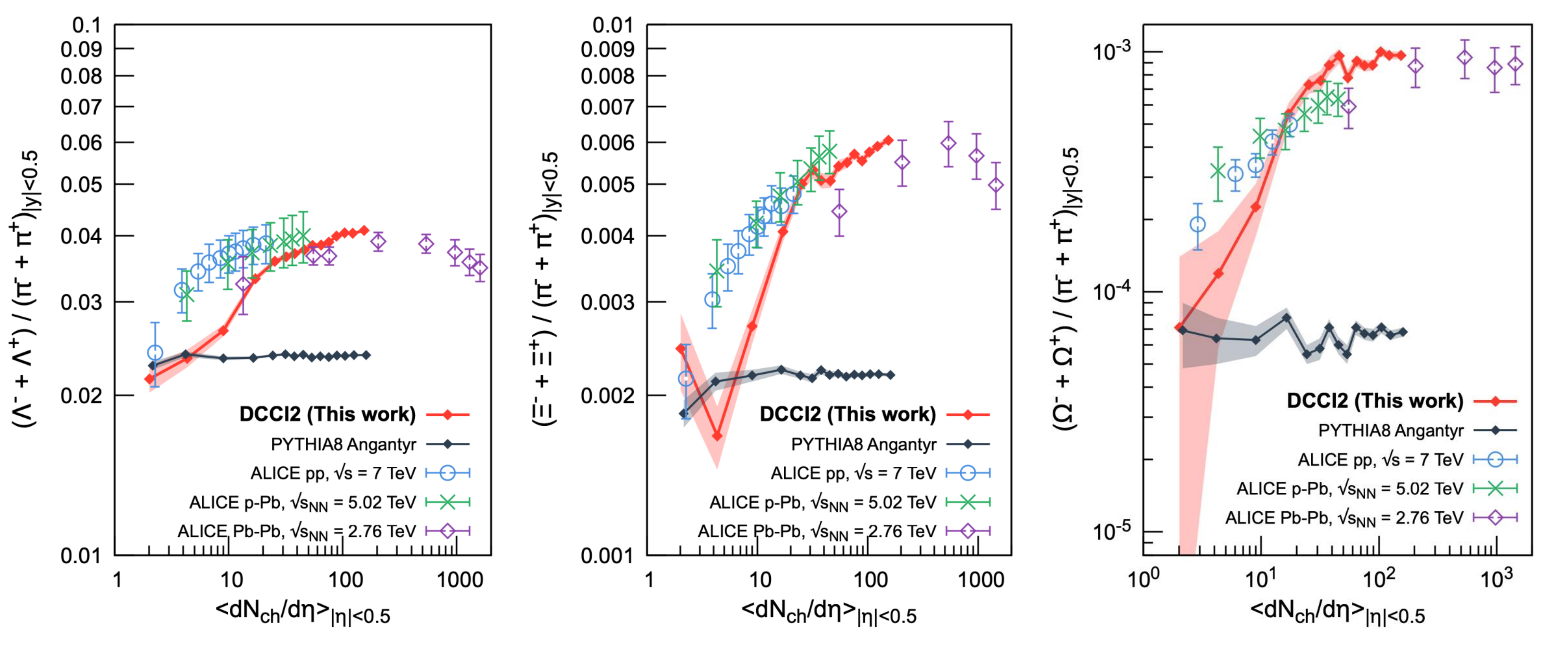
- Investigation of small colliding systems from Dynamical Core-Corona Initialisation model (ver.2)
- O+O collisions
  - Transition point $dN_{ch}/deta \sim 20$
  - Mass ordering of transition point in p_T distributions
  - Soft-from-corona in very low p_T region
  - Yet sizable corona components (~30%) even in central collisions
- p+p collisions
  - Bayesian parameter estimation
  - Confirmation of core production (~50%) in high-multiplicity events

Outlook

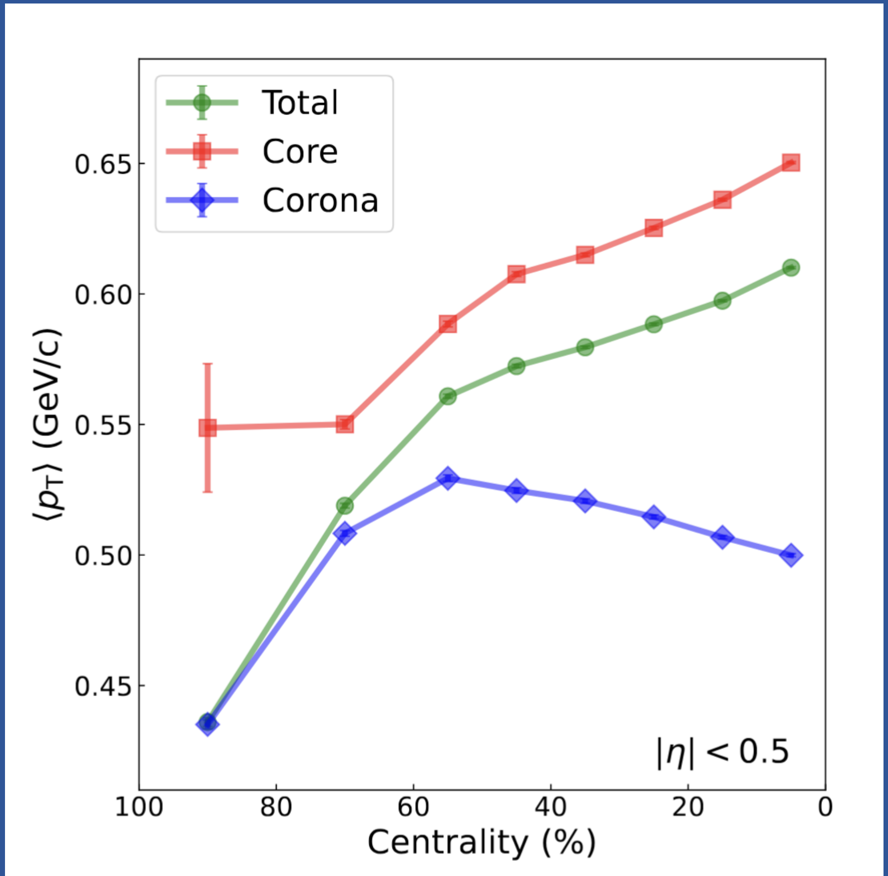
Work in progress:

- Effects of core-corona on nuclear shape studies
- Strangeness enhancement in Au+Au collisions at RHIC
- Sophistication of dynamical initialization processes based on string picture (baryon junction)
- Hard probes using HIJING instead of PYTHIA
- \+ more

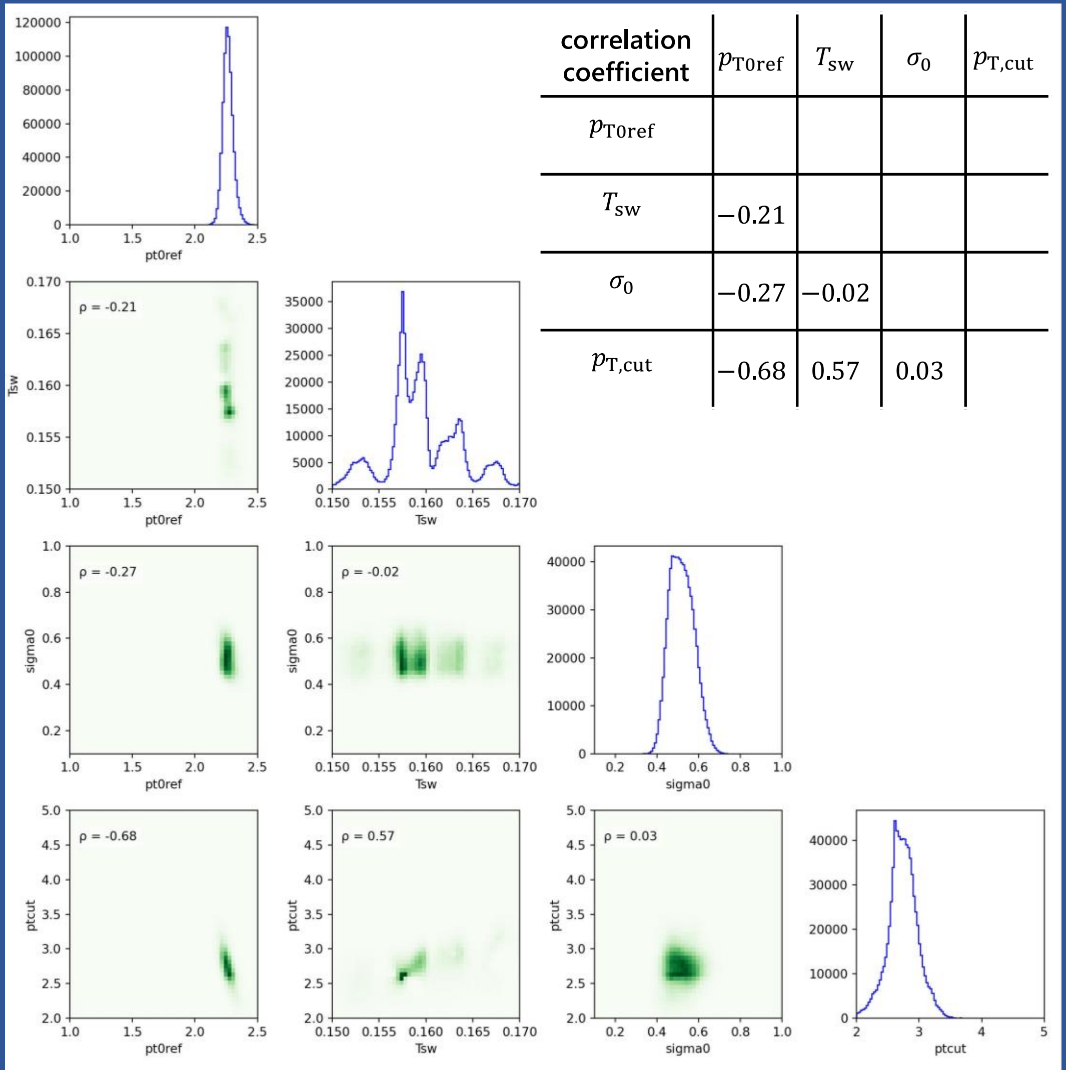
Comparison with ALICE data



Mean transverse momentum



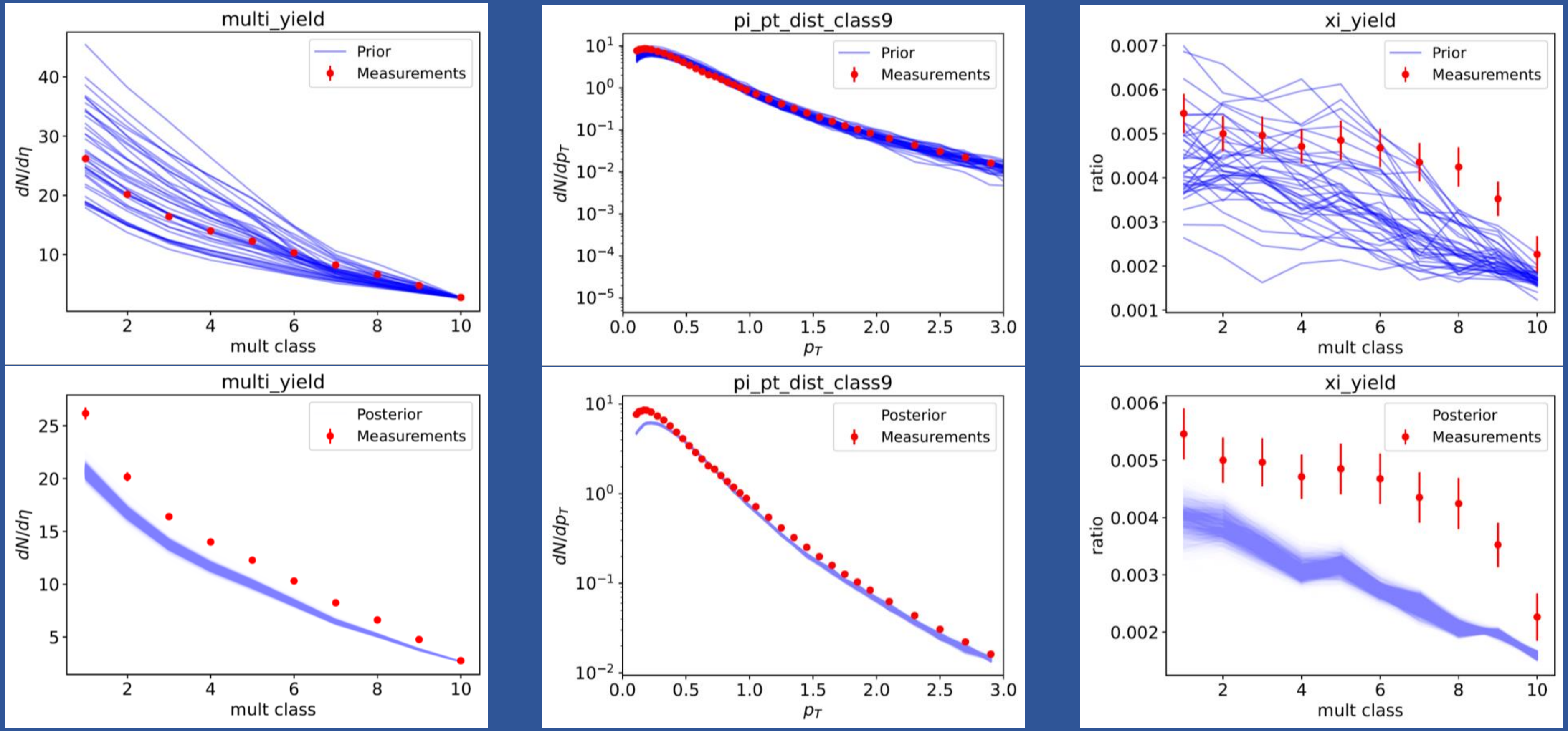
Correlation among parameters



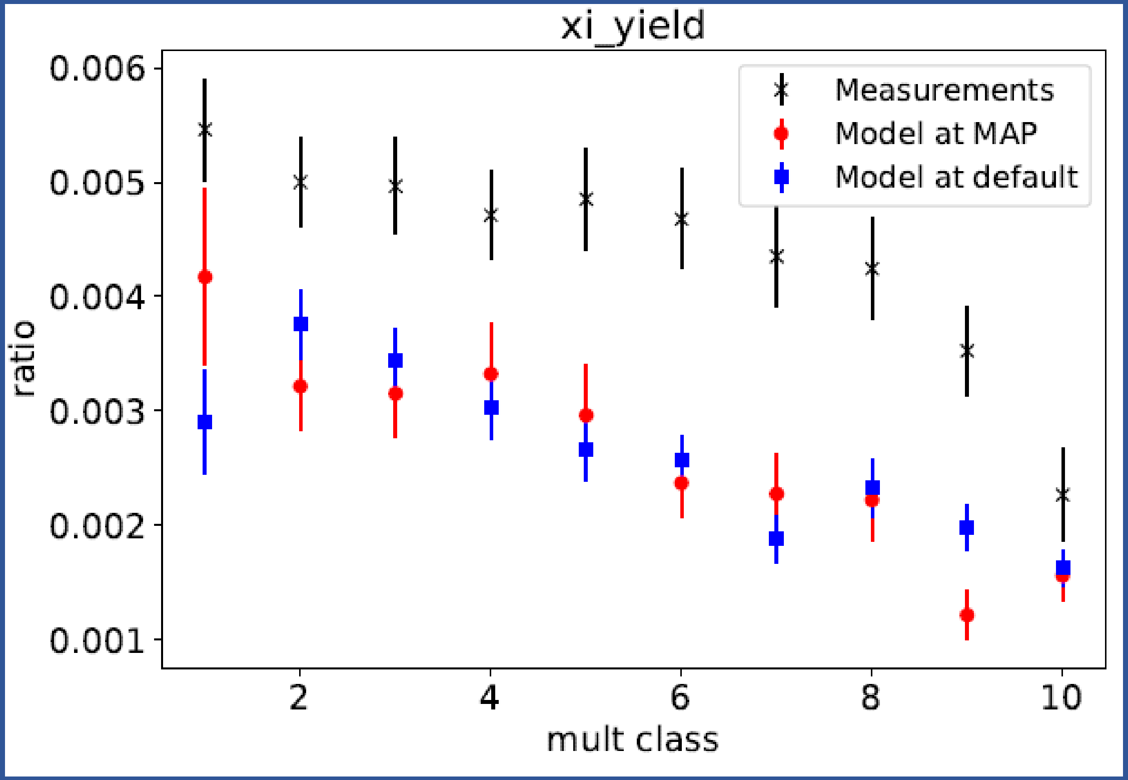
correlation coefficient	p_{T0ref}	T_{sw}	σ_0	$p_{\mathrm{T,cut}}$
p_{T0ref}				
T_{sw}	-0.21			
σ_0	-0.27	-0.02		
$p_{\mathrm{T,cut}}$	-0.68	0.57	0.03	

Some correlation between two parameters
→ Necessity of simultaneous fitting

Results from prior and posterior

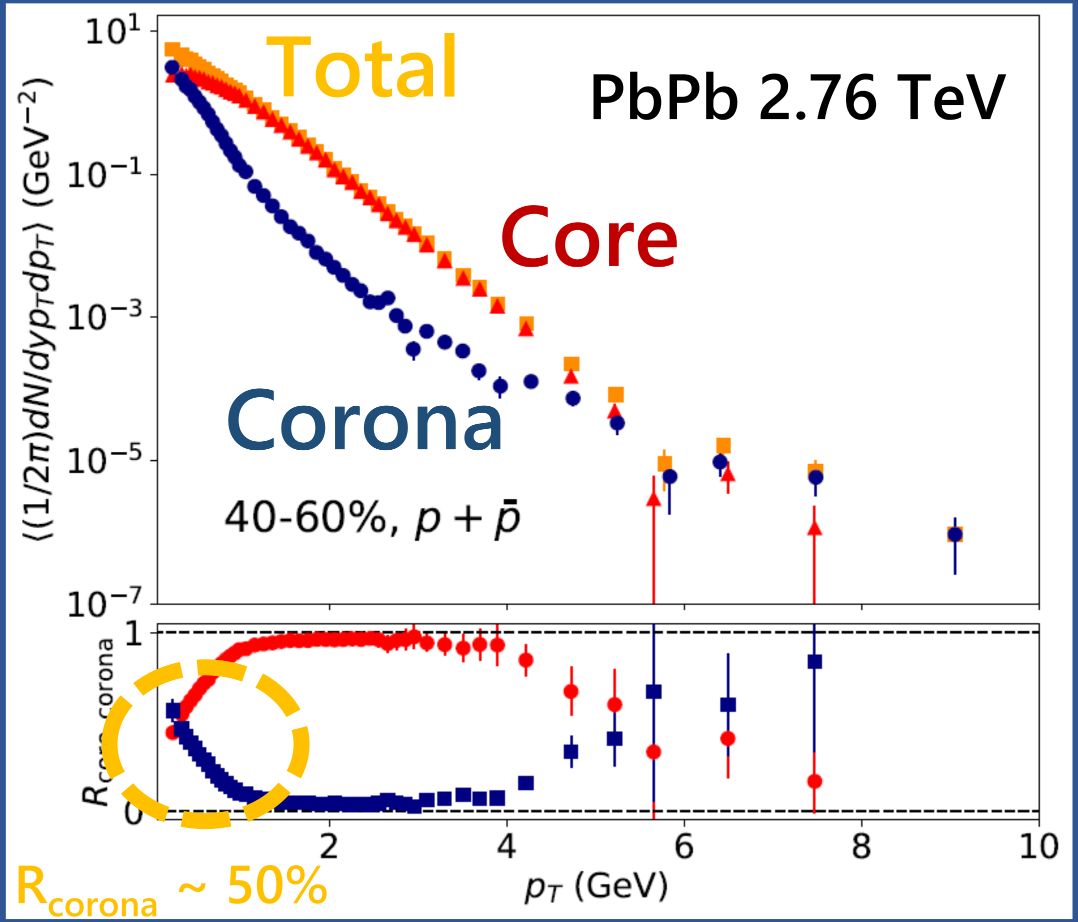


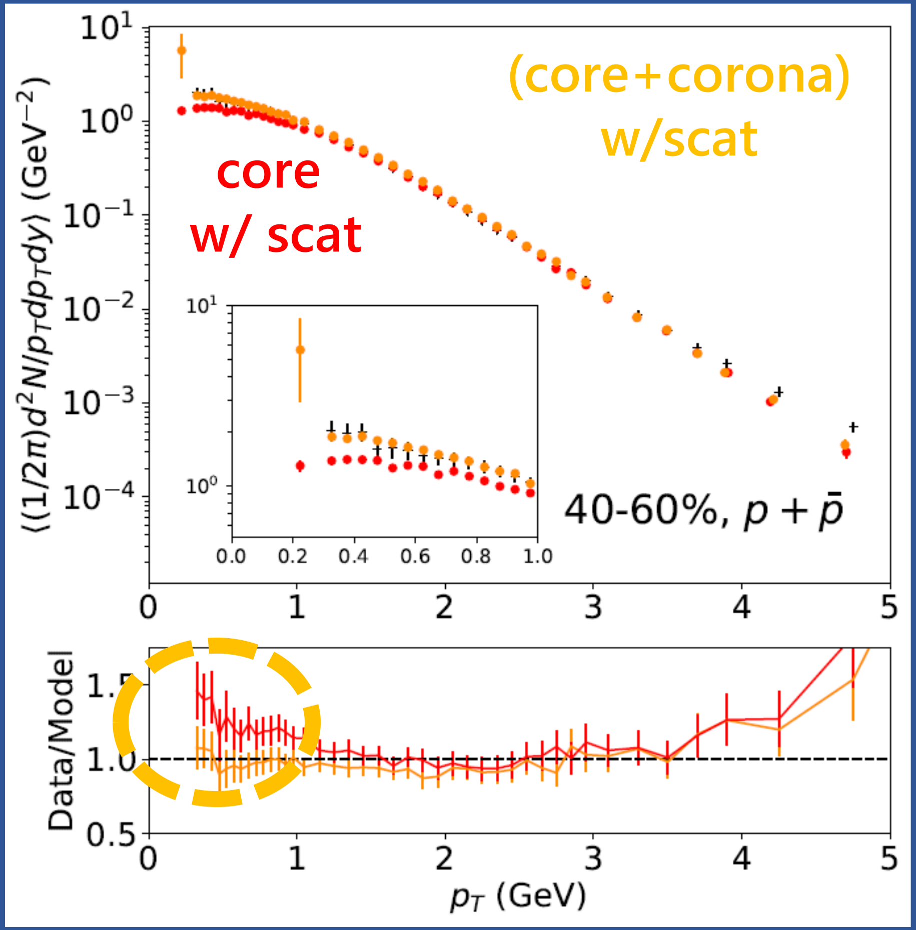
Particle Yield Ratios



Low p_T enhancement from corona

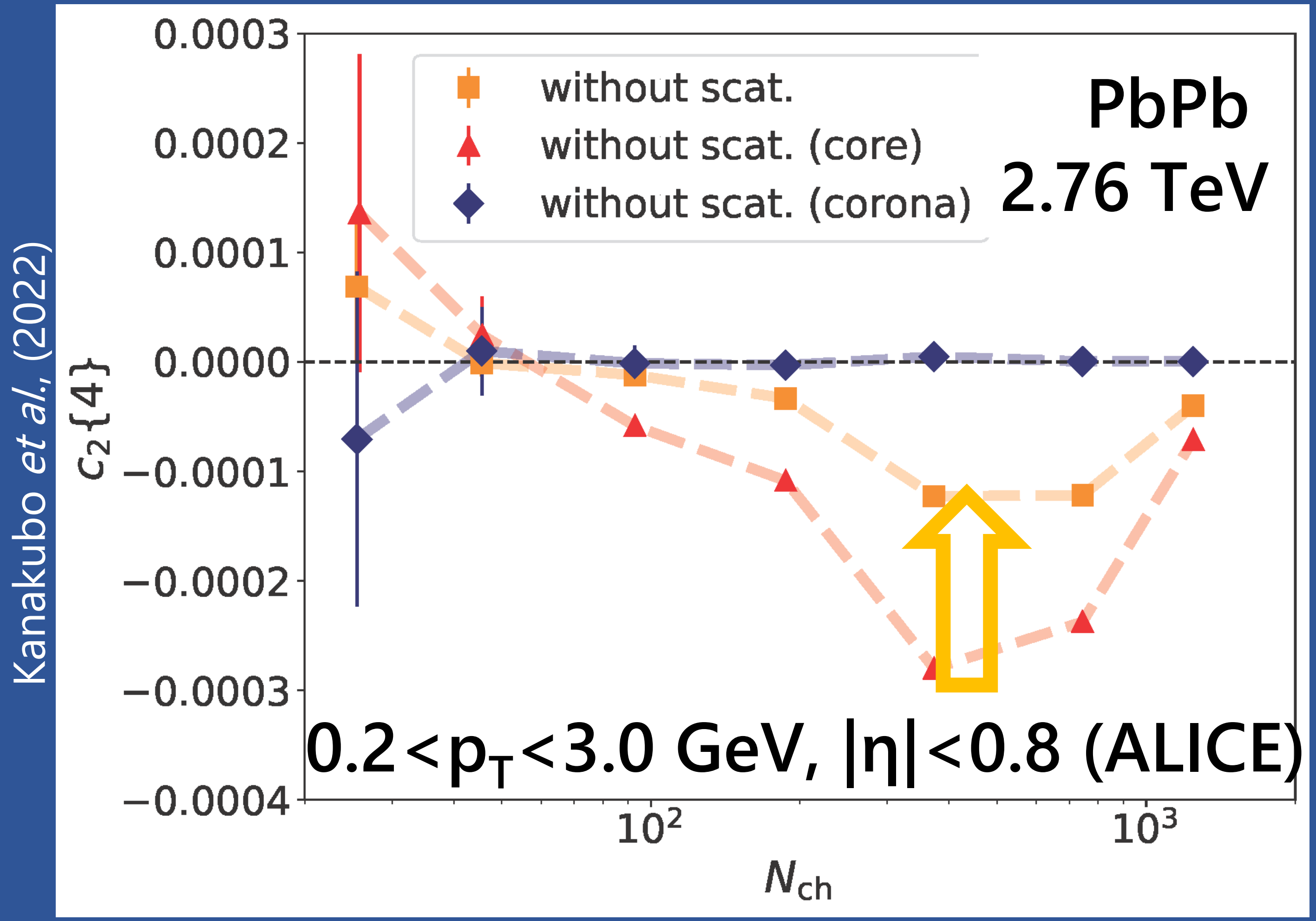
Kanakubo *et al.*, (2022)





Interplay between exponential thermal spectrum and power-law string fragmentation

Corona dilutes $c_2\{4\}$

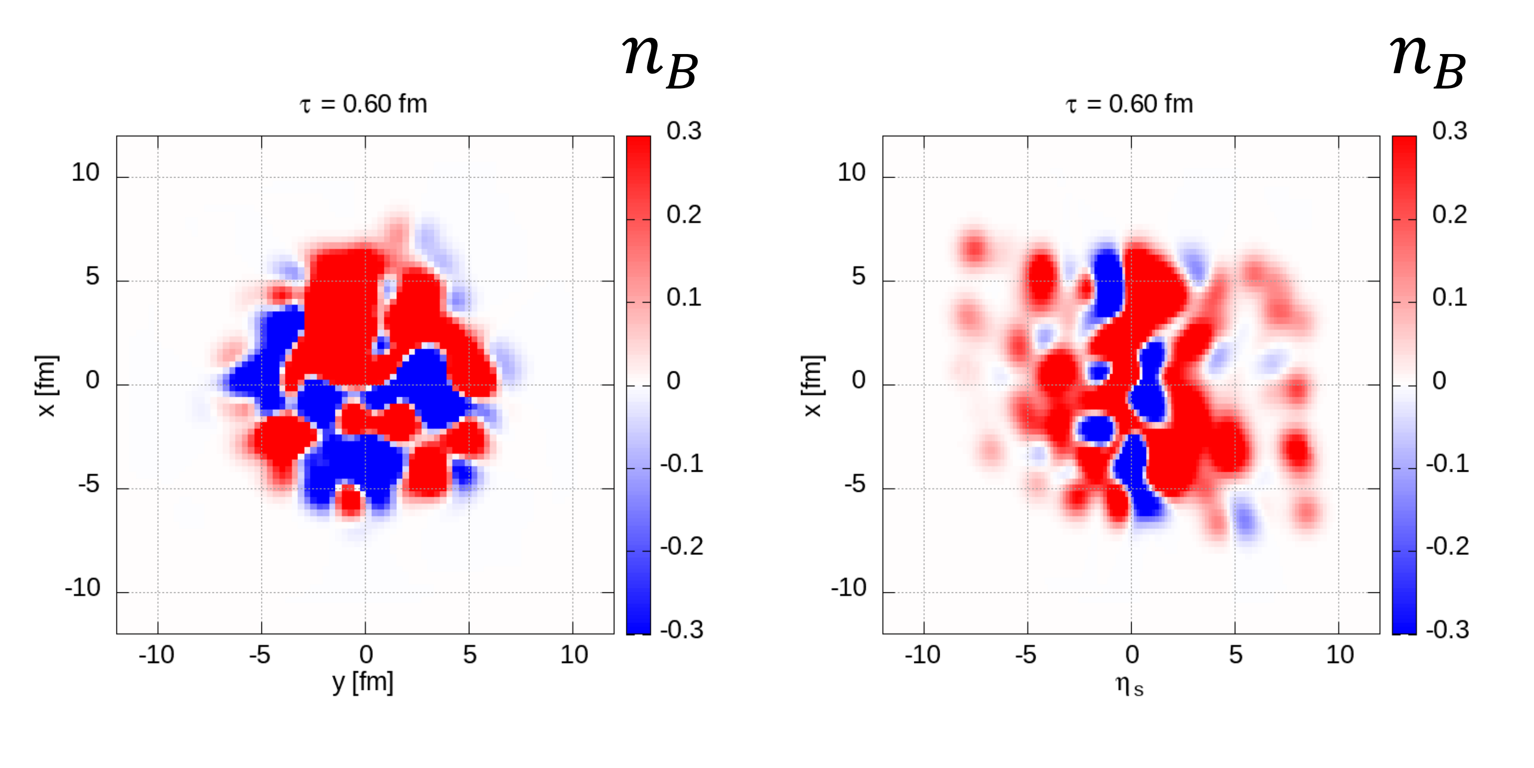


Dilution effect even after non-flow subtraction

Importance in p_T integrated observables

Larger non-equilibrium effects than viscosity

Time evolution of baryon number density

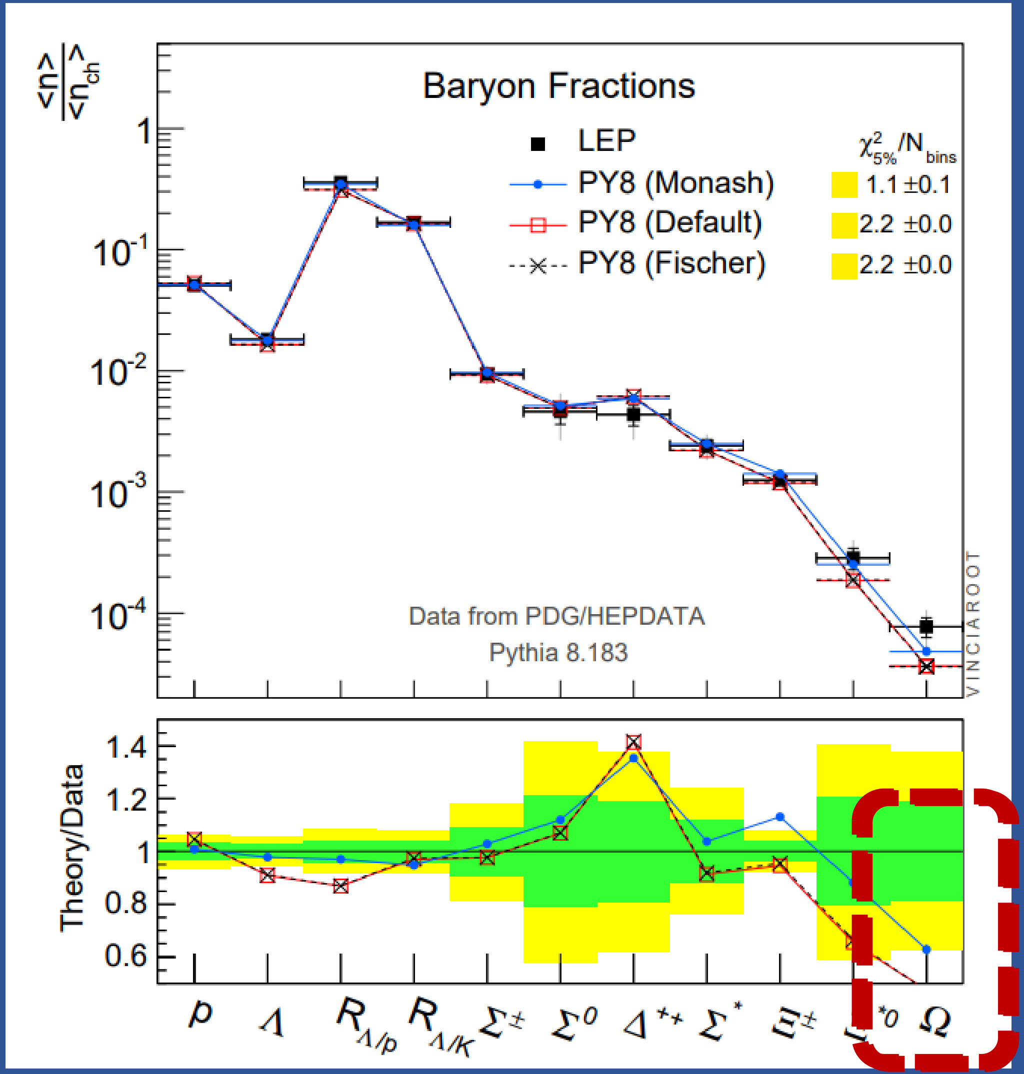


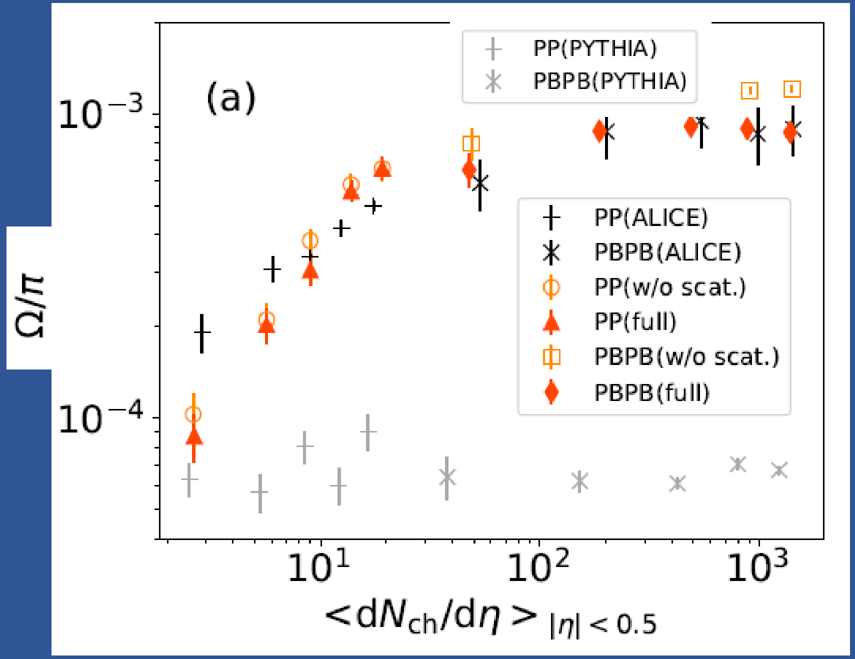
Transverse plane   Longitudinal plane

Appearance of negative baryon number domain at midrapidity due to fluctuations
← Affects production of anti-nuclei?

Pb+Pb 2.76 TeV, one central event

Ω yields from e^+e^- with Monash Tune





P. Skands *et al.*, Eur.Phys.J.C 74 (2014) 8, 2024