

Bayesian analysis of QGP formation based on core–corona picture in high-energy proton–proton collisions



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Overview

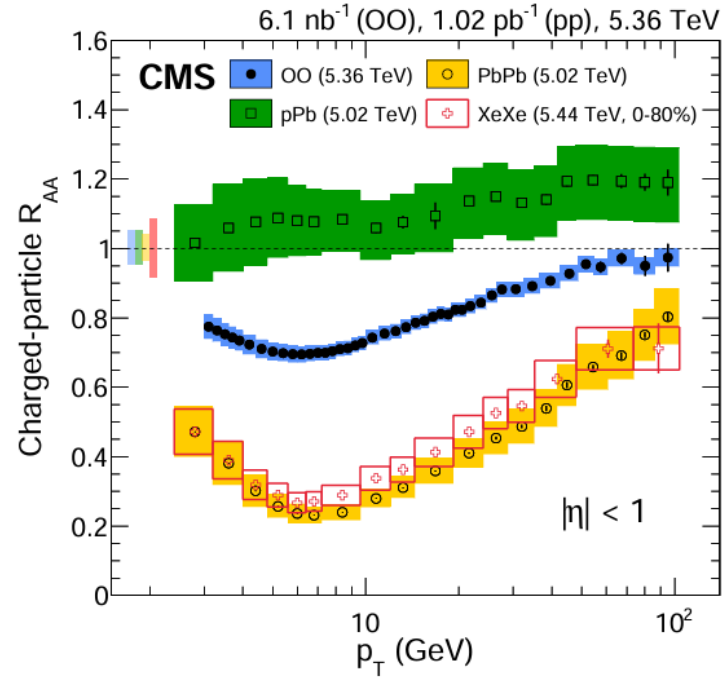
◆ Introduction

◆ Analysis and results

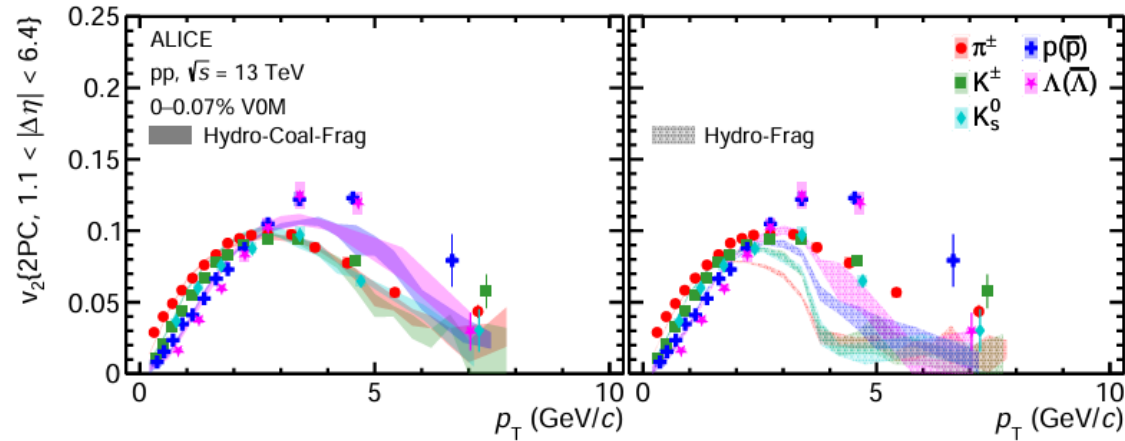
◆ Summary and Outlook

QGP formation in small system?

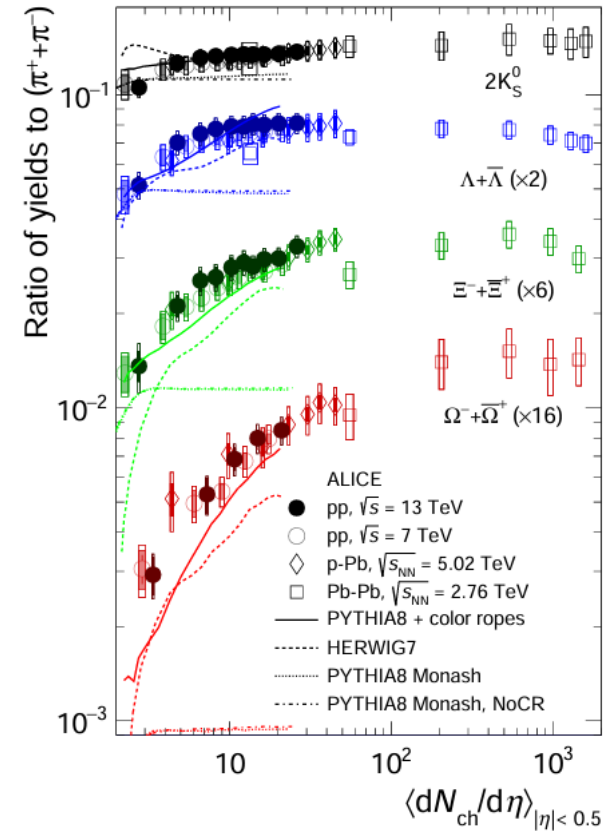
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A. Hayrapetyan *et al.* [CMS],
Phys. Rev. Lett. **136**, no.16, 162301 (2026)



S. Acharya *et al.* [ALICE],
Nature Commun. **17**, no.1, 2585 (2026)



S. Acharya *et al.* [ALICE],
Eur. Phys. J. C **80**, 693 (2020).

- QGP formed in heavy ion collisions
 - Signal of formation recently observed in small system
- Importance in understanding QGP formation mechanism in small system

Bayesian analysis in pp collision

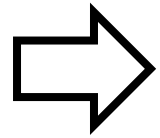
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Need for quantitative analysis

Observed signals in pp collisions
→ How much QGP formed?



Discussion with
hydro-based model



Essential to discuss QGP formation quantitatively

Bayesian analysis

- Statistical method
- Scrutinizing experimental data by using hydro-based model

Quantitative evaluation of QGP formation in pp collisions

Bayesian analysis

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Bayes rule

$$\pi(\boldsymbol{\theta}|\mathbf{y}) = \frac{f(\mathbf{y}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{\int f(\mathbf{y}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})d\boldsymbol{\theta}} = \frac{f(\mathbf{y}|\boldsymbol{\theta})\pi(\boldsymbol{\theta})}{f(\mathbf{y})}$$

$\boldsymbol{\theta}$: input (model parameters)

$\mathbf{y}$: output (observables)

$\pi(\boldsymbol{\theta}|\mathbf{y})$: Posterior distribution

$\pi(\boldsymbol{\theta})$: Prior distribution

$f(\mathbf{y}|\boldsymbol{\theta})$: Likelihood

Bayesian inference

- Statistical analysis method with bayes rule
- Effective in constraining model parameters

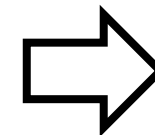
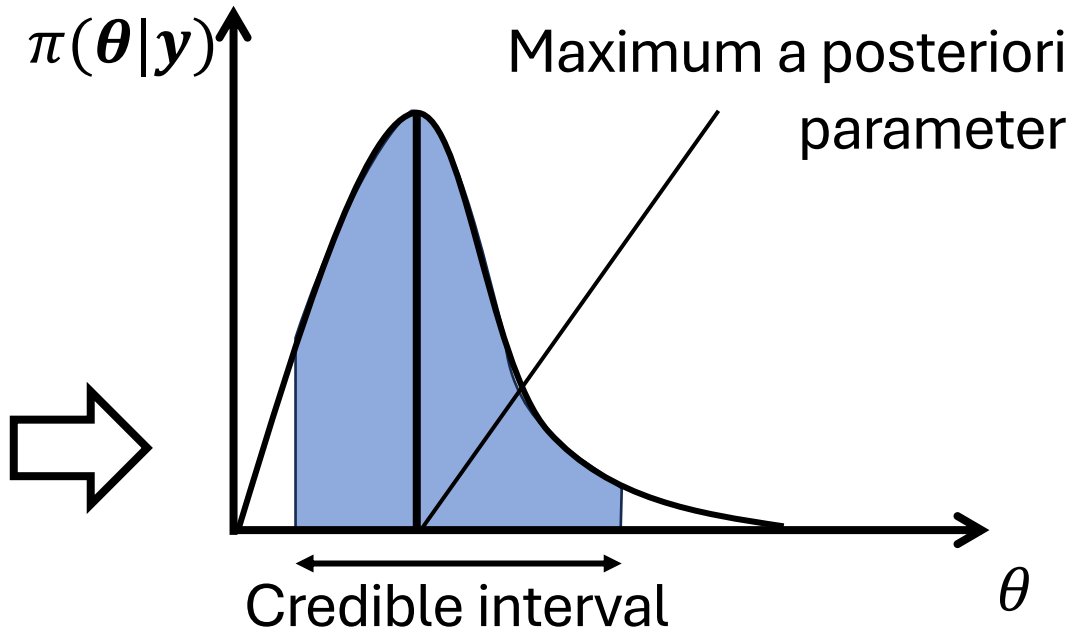
Prior of parameters

$\pi(\boldsymbol{\theta})$



Exp.data
Model.calc

$f(\mathbf{y}|\boldsymbol{\theta})$



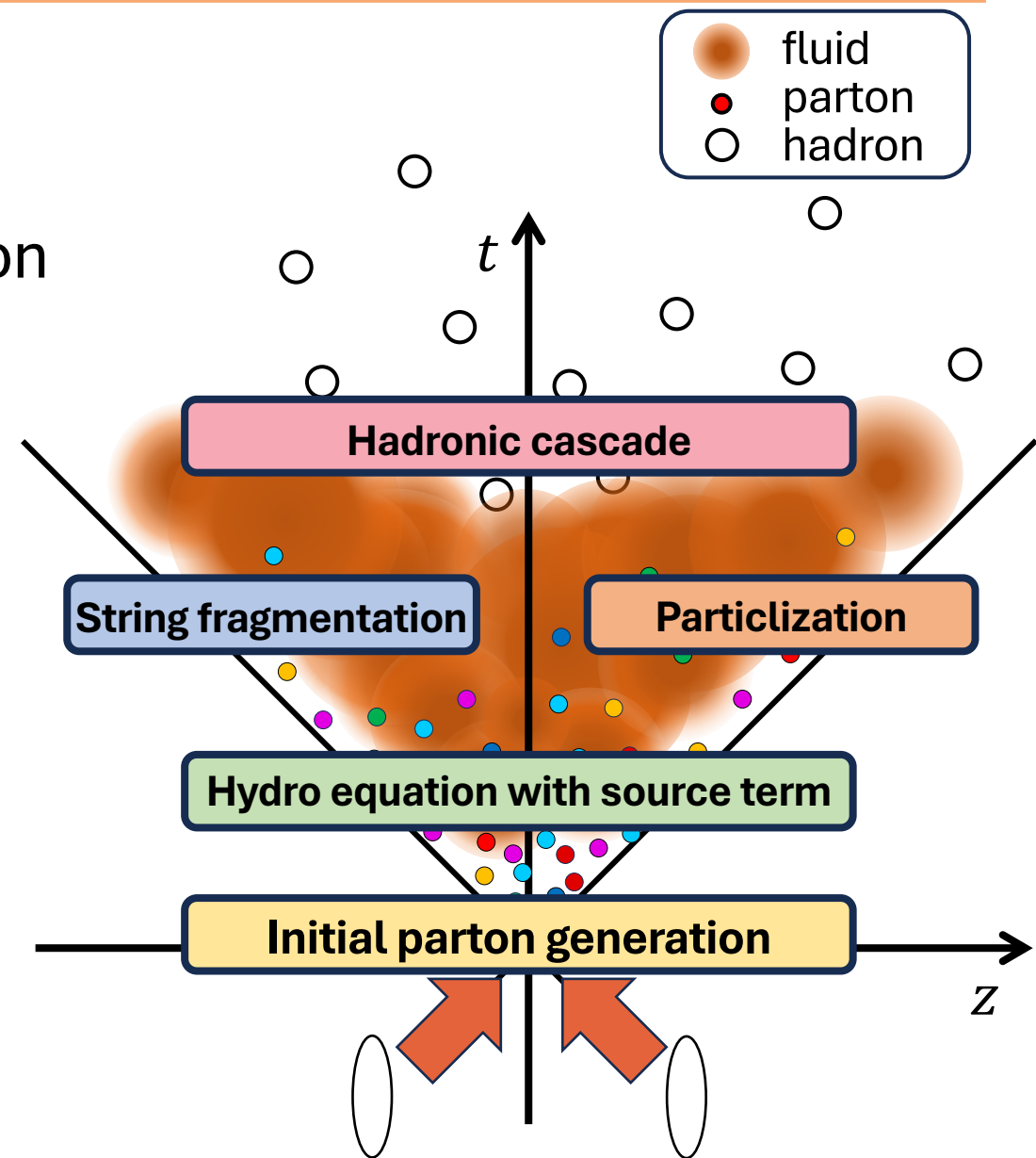
Dynamical core–corona initialization model

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Features

- Description of entire collision reaction based on energy–momentum conservation
- Dynamical initialization
Classification of produced matter into
 - core: equilibrium matter($\sim$ QGP)
 - corona: non-equilibrium matter

Appropriate model to discuss QGP formation quantitatively



Focus of Bayesian inference

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Estimation of parameters in the model through Bayesian inference

Target:

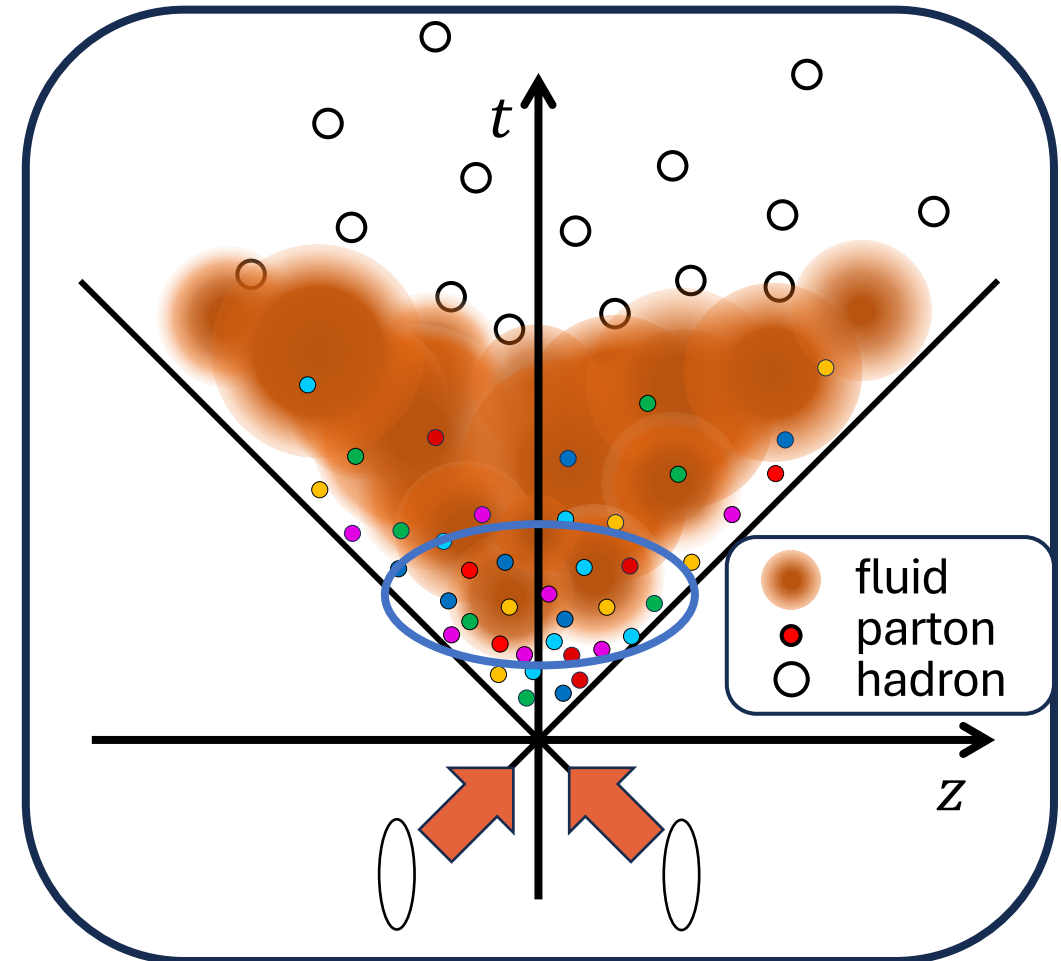
Parameters related to core generation

$$\sigma_0, p_{T0ref}, T_{sw}, p_{T,cut}$$

σ_0 [fm²]

- Cross section between partons
- Control how much equilibrium matter formed

Prior: uniform distribution, [0.1–1.0]

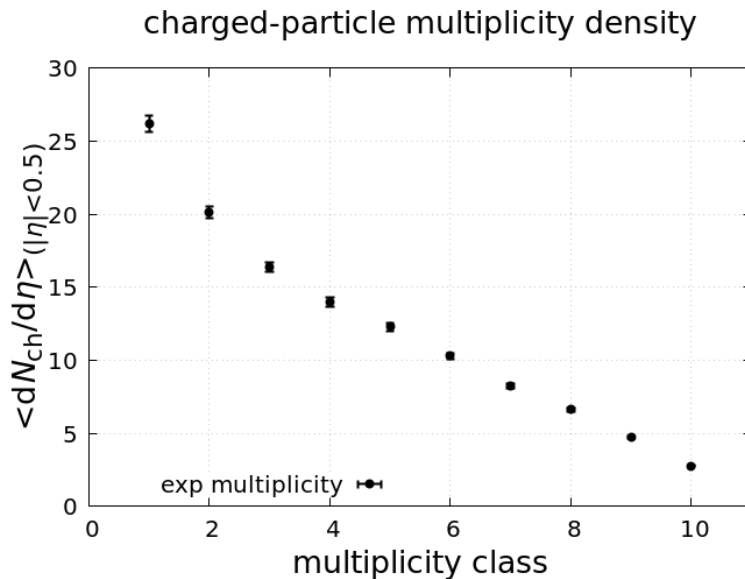
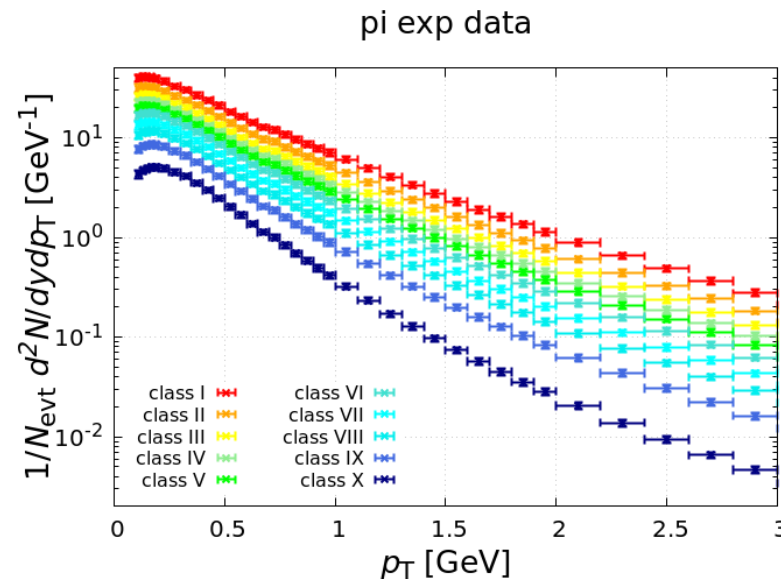
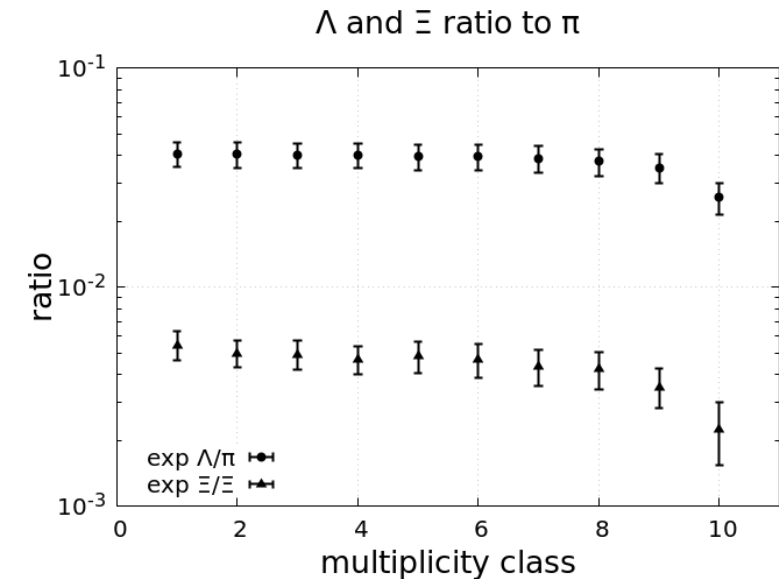


Observables for Bayesian inference

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p-p, $\sqrt{s} = 13$ TeV

- Charged multiplicity ($|\eta| < 0.5$)
 - p_T distributions ($p_T \leq 3.0$ GeV)
 - Yield ratios of strange hadron
- ... Typical observables in HIC
- ... Reflect QGP formation?



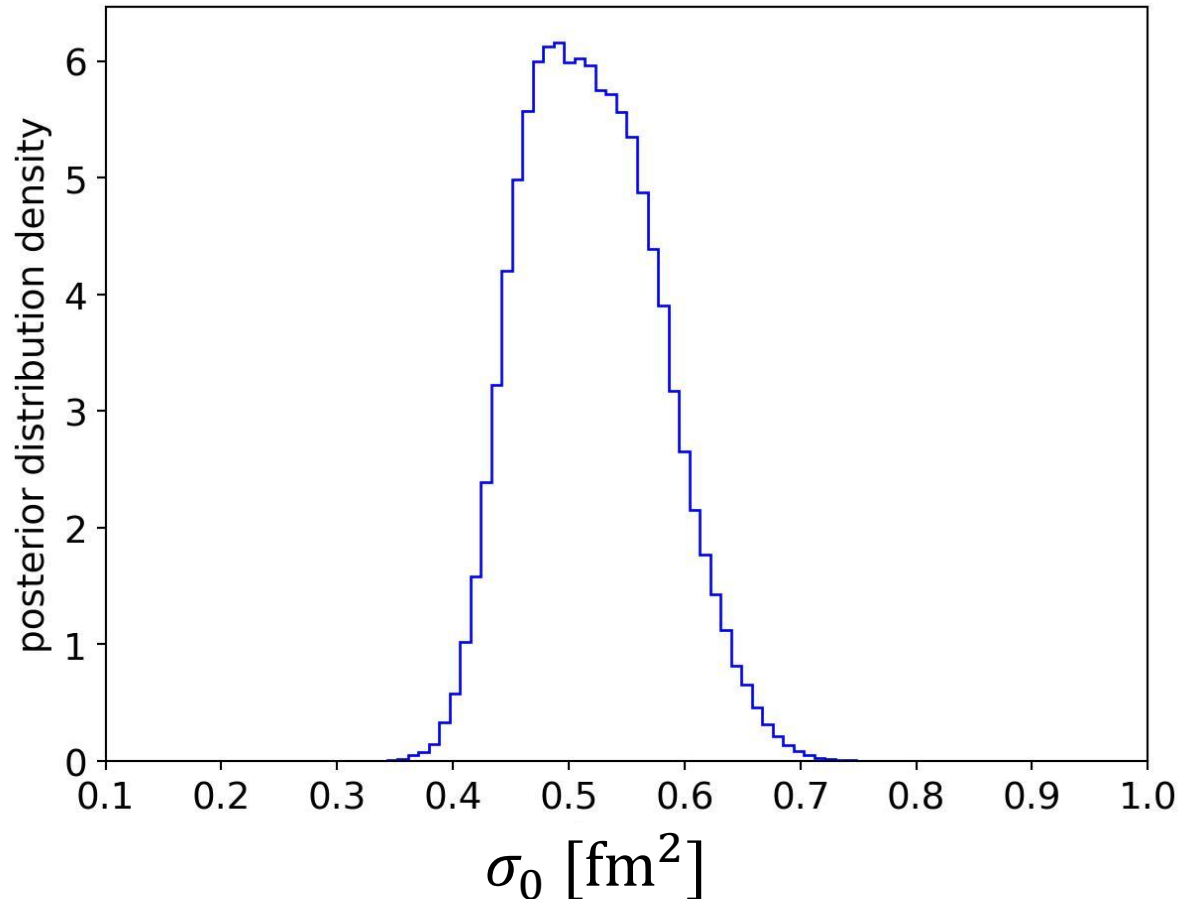
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Fluidization parameter



- Maximum a posteriori(MAP) parameters
 0.487 fm^2
- 90% credible interval
(median $\pm$ boundary)
 $0.51^{+0.10}_{-0.09} \text{ fm}^2$
- Clear peak in prior range

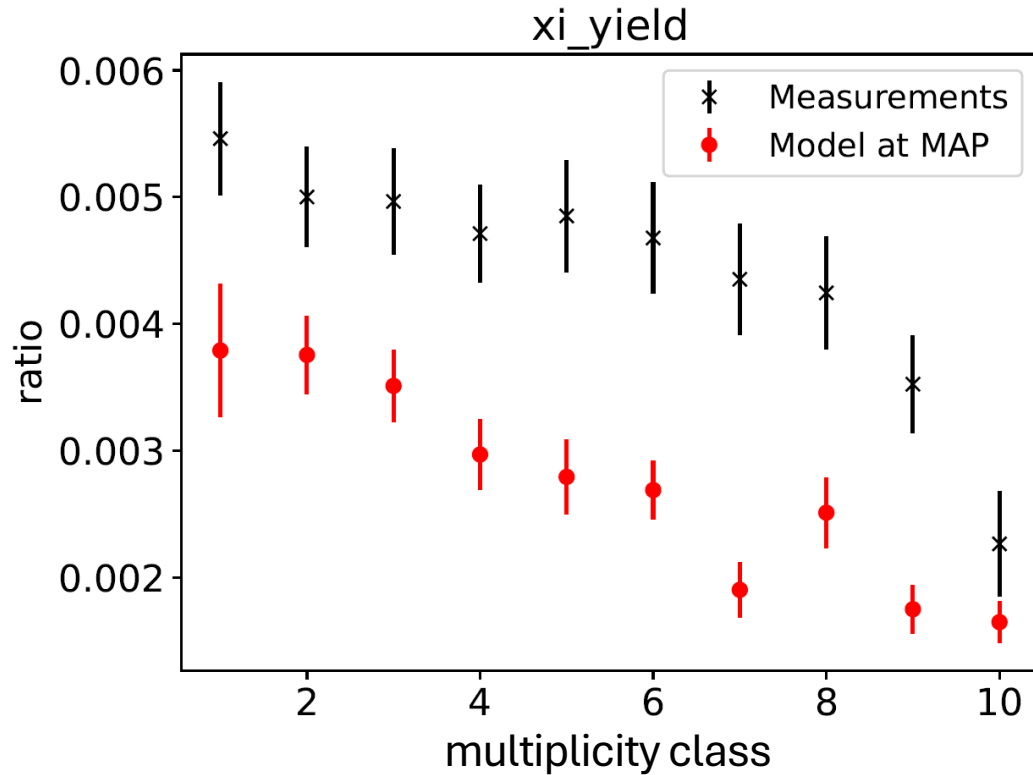
Larger value than previous study: 0.3 fm^2

→ Larger cross section of partons

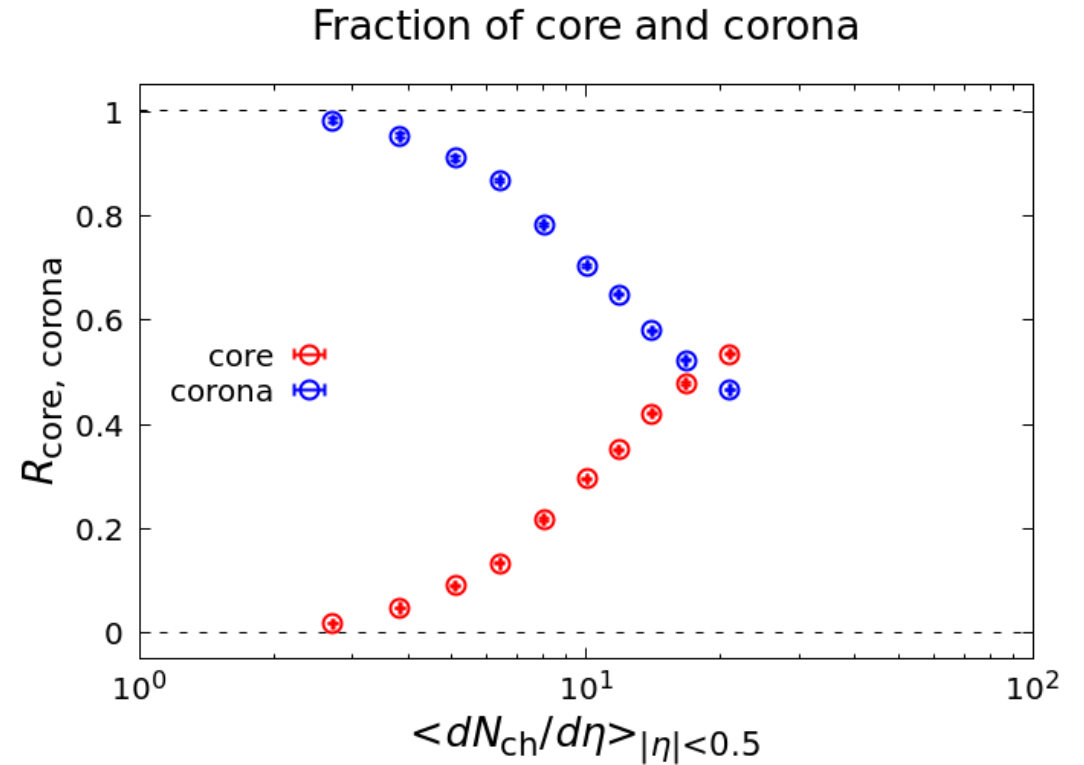
→ More core($\sim$ QGP) formation

Model output using MAP parameters

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- Not perfect reproduction
→ open problem



R_{core} : Fraction of final hadron
from core component
over 50% → QGP formed

Indication of onset of QGP formation in pp collisions at $dN_{\text{ch}}/d\eta \sim 20$

Parameter sensitivity of observables

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Q. Sensitive observables?
How to quantify?

A. See parameter sensitivity of each observable

Response matrix

H. Roch *et al.*, Phys. Rev. C **110**, 044904 (2024).

$$R_{ij}(\theta_j = \theta_{j;\text{MAP}}) = \left. \frac{\partial y_i(\theta)}{\partial \theta_j} \frac{\theta_j}{y_i} \right|_{\theta_j = \theta_{j;\text{MAP}}}$$

y_i : Observable predicted
from surrogate model

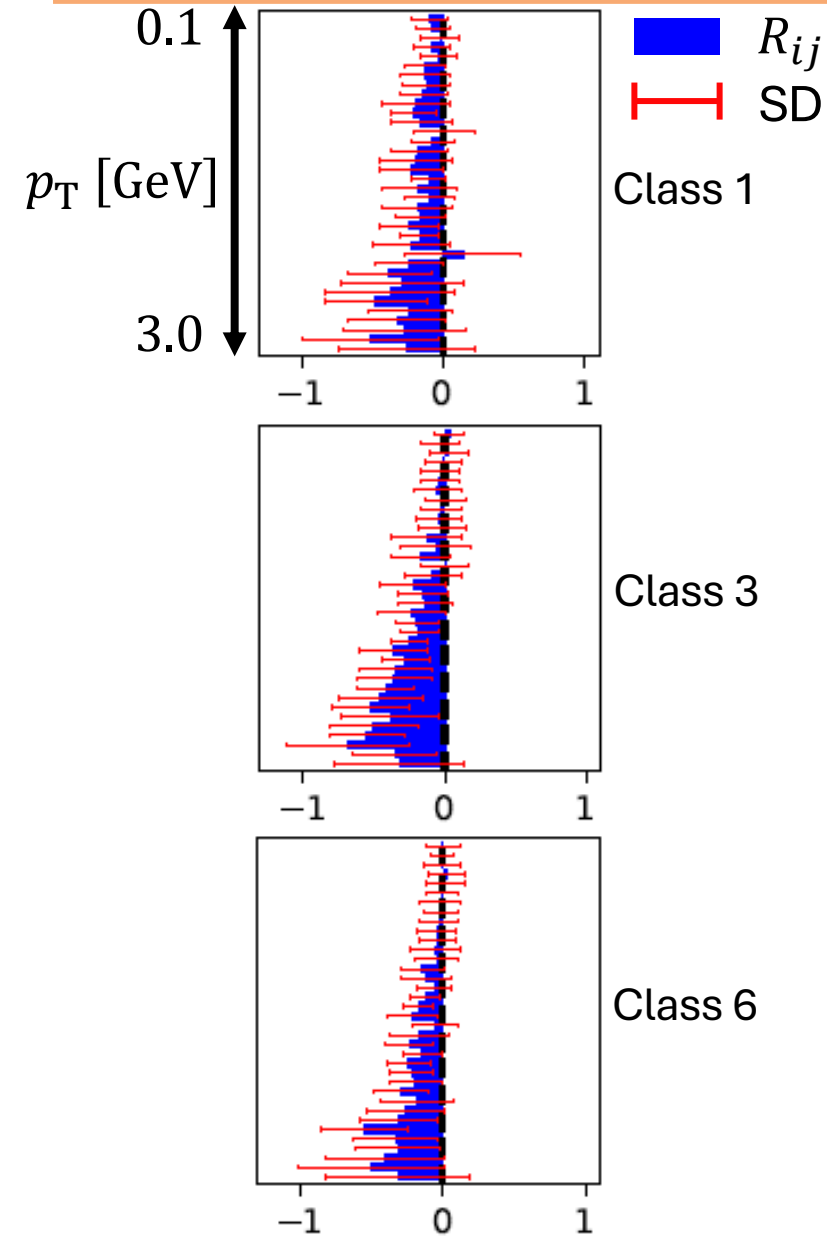
θ_j : Model parameter

Discuss sensitivity around MAP parameter

Search for sensitive observables through parameter sensitivity

Sensitivity to fluidization parameter

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Response of p_T distribution(π)

- Negative response
→ Less yield with more fluid
- Peak of sensitivity around 3.0 GeV regardless of multiplicity class
- Largest sensitivity = $\text{abs}(R_{ij})$ at medium multiplicity event (class 3)

p_T distributions of π around 3.0 GeV for elucidating QGP formation

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Summary

- Discuss QGP formation in small system with core–corona model and Bayesian analysis
→ Constraint imply QGP formation in high multiplicity pp collisions
- Reproduction using MAP parameters leaves open problem
- Search for sensitive observables through response matrix
→ p_T distribution of π at p_T around 3.0 GeV

Outlook

- Extend analysis to other observables
- Improve model and adjust parameters with suitable observables