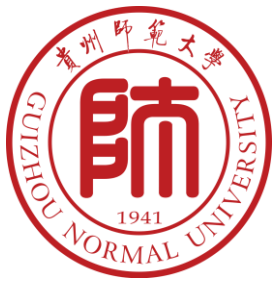
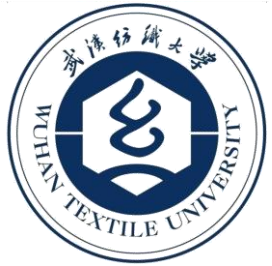
Production of open-flavor hadrons from PACIAE model

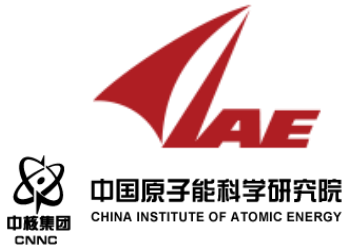
An-Ke Lei (雷安科)

Guizhou Normal University (贵州师范大学)

With Qiang Wang(王强), Zhi-Lei She(佘智磊), Dai-Mei Zhou(周代梅),
Yu-Liang Yan(闫玉良), Larissa Bravina(UiO), Evgeny Zabrodin(UiO),
Hua Zheng(郑华), Wen-Chao Zhang(张文超) and Ben-Hao Sa(萨本豪)







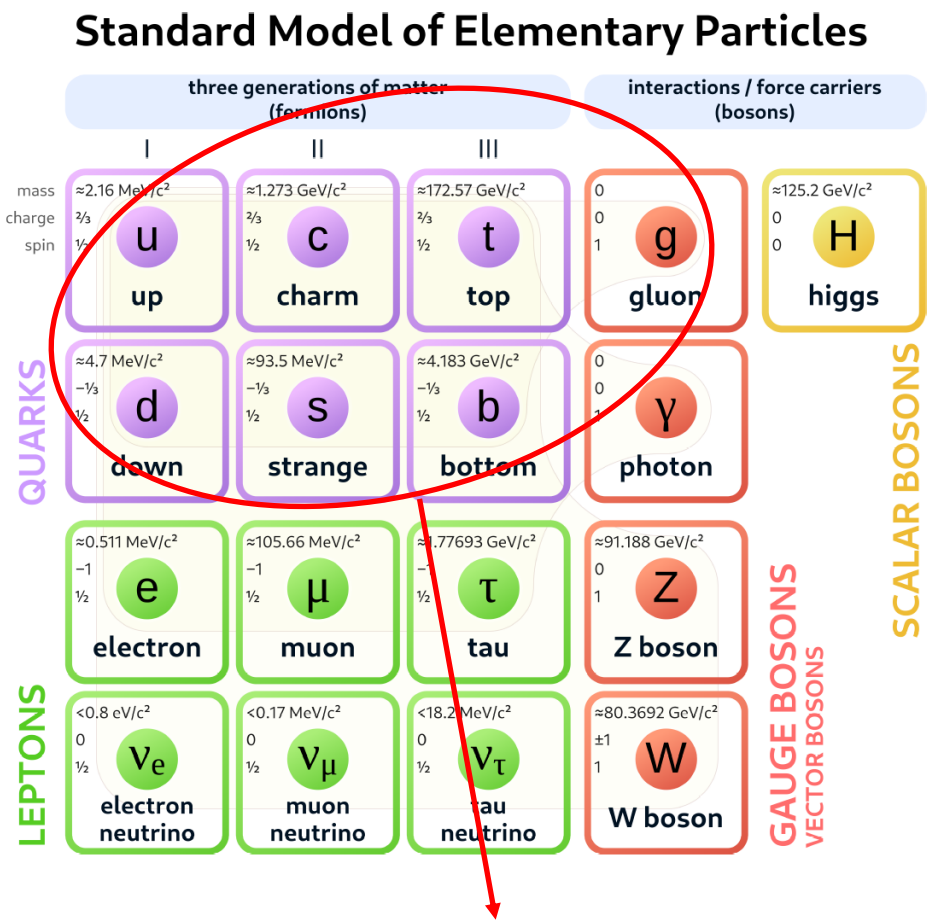
Jan 25, 2026, Wuhan, JAQ2026

OUTLINE

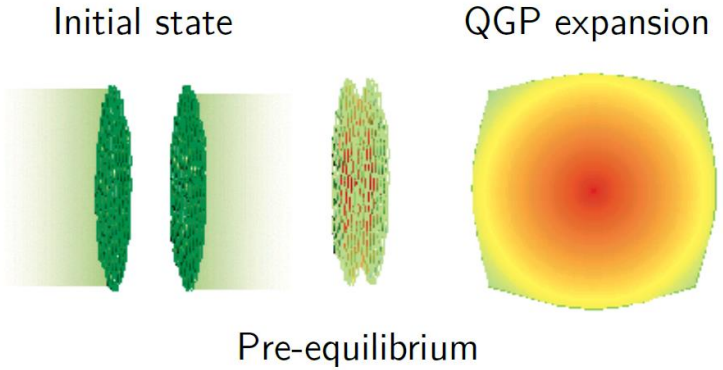
1. Introduction and motivation
2. Microscopic transport model PACIAE
3. Production of open-flavor hadrons
4. Summary and outlook

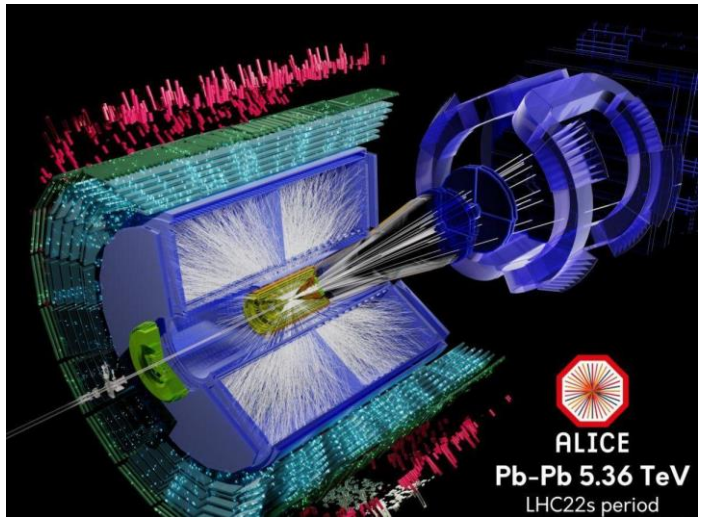
Introduction and motivation

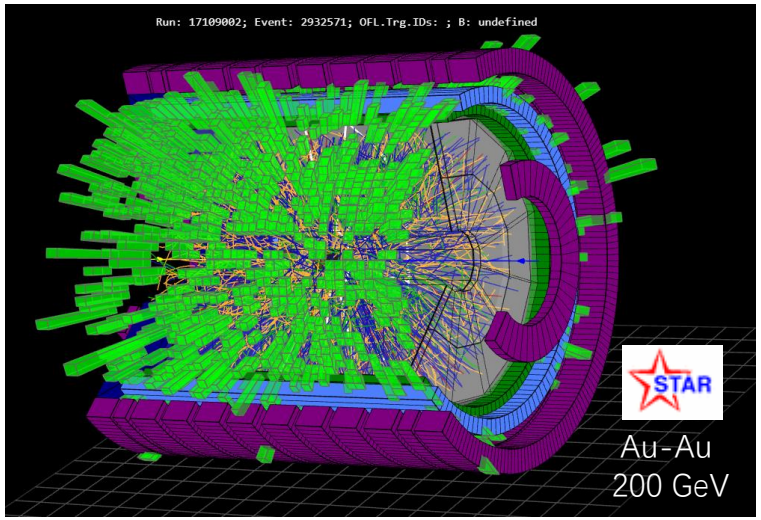
Standard model and heavy-ion collisions



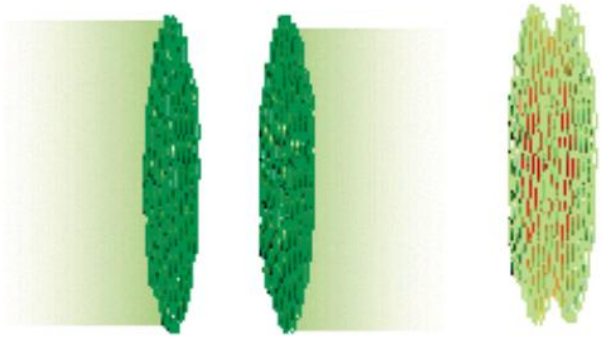
QCD: Asymptotic freedom & Color confinement

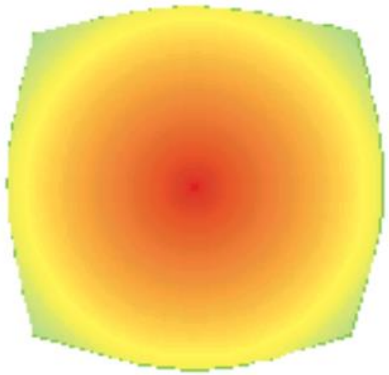


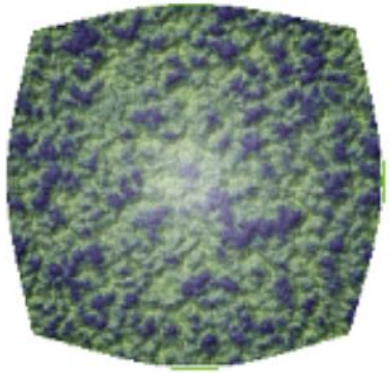


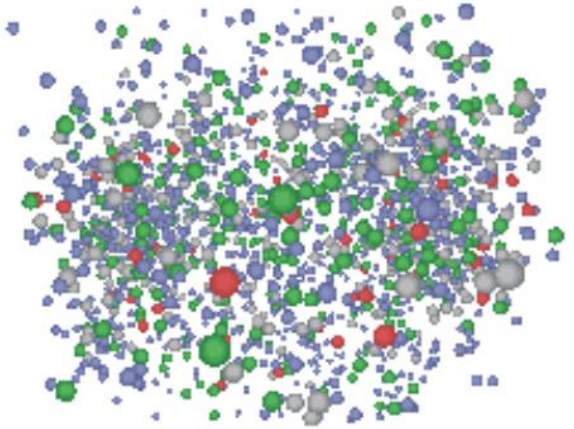


Heavy-flavor probes









Hard scatterings → pQCD

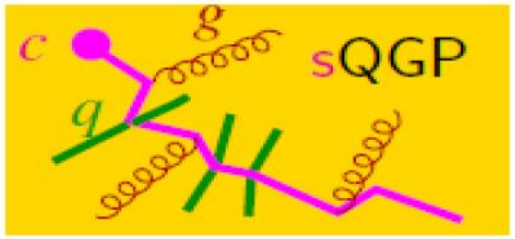
c & b quarks

Large masses:

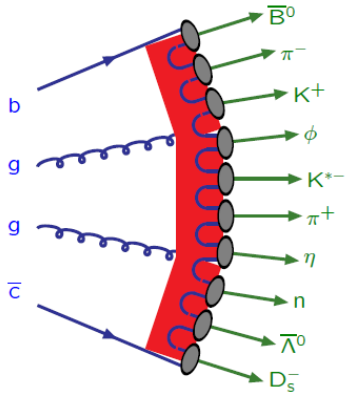
$m_Q \sim \mathrm{GeV}$

$\gg \Lambda_{QCD}, T_{QGP} \sim \mathrm{MeV}$

QGP → clean



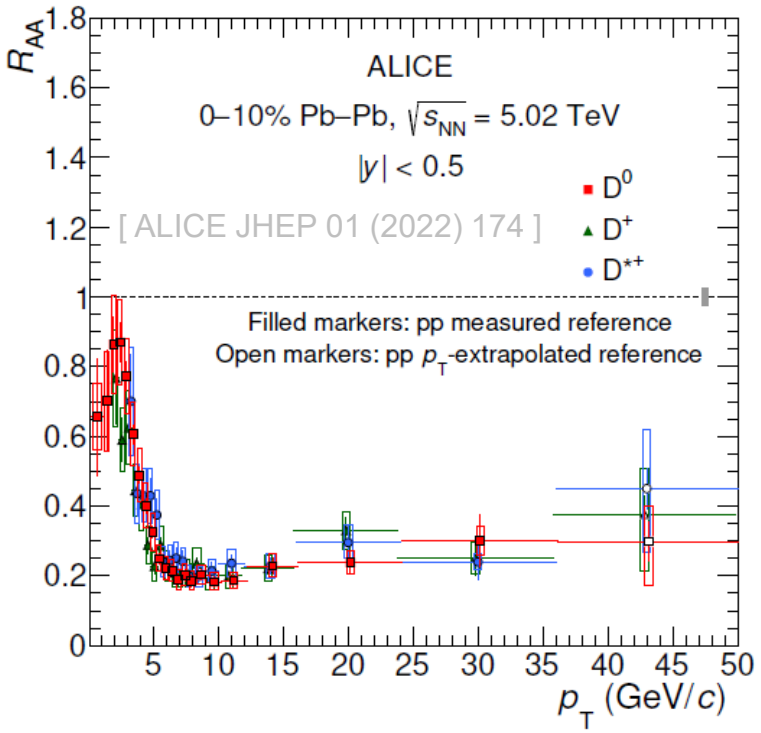
Hadronization → non-perturbative



pp baseline

Nuclear modification factor:

$$R_{AA}(p_T) = \frac{1}{\langle N_{coll} \rangle} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$



Fragmentation of heavy-flavor (HF) hadrons:

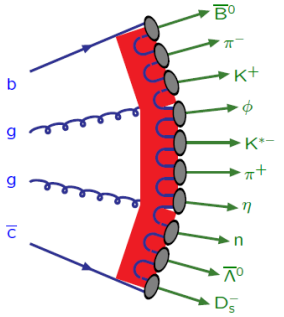
$$\sigma_{pp\to H_Q} = \sum_{i,\ j} f_i^{h_1} \otimes f_j^{h_2} \otimes \hat{\sigma}_{ij\to Q} \otimes D_Q^{H_Q}$$

Parton distribution function (PDF)

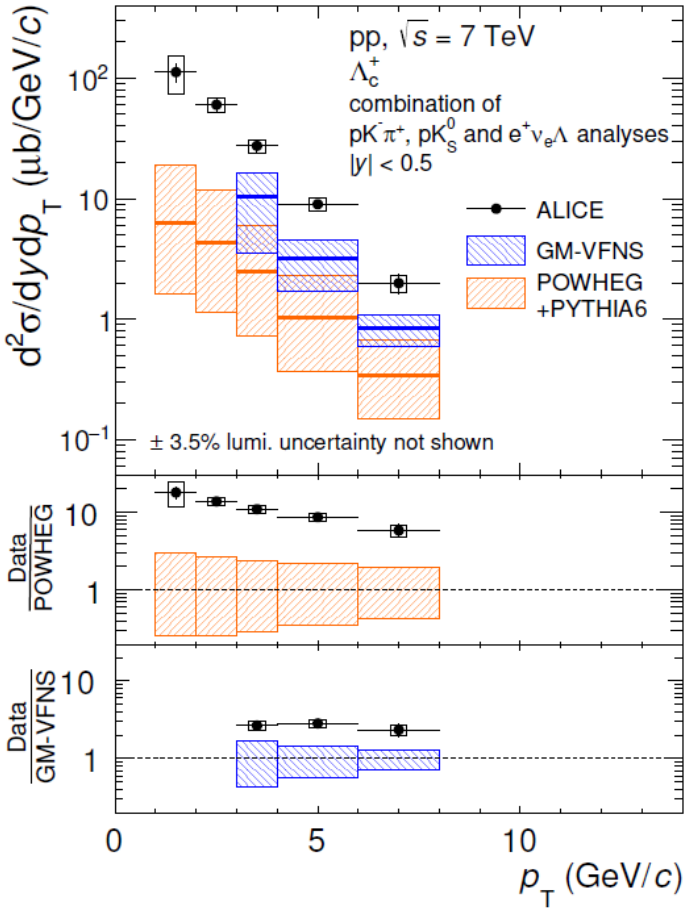
Hard scattering cross section (pQCD)

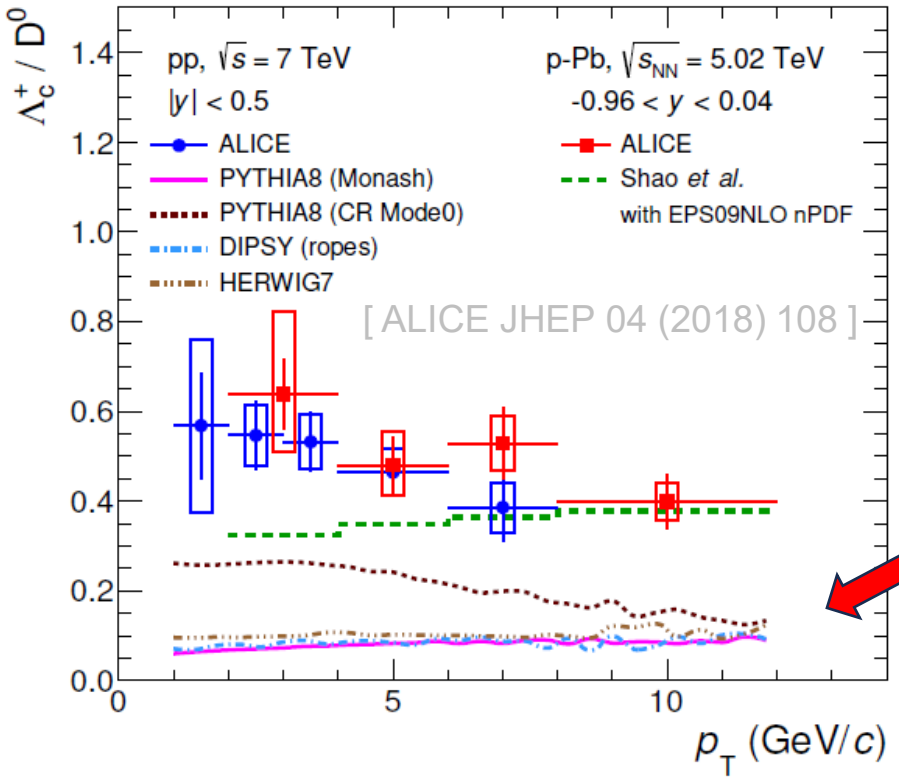
Fragmentation function (hadronization)

FF is extracted from e^+e^- experiments.



Heavy baryon enhancement

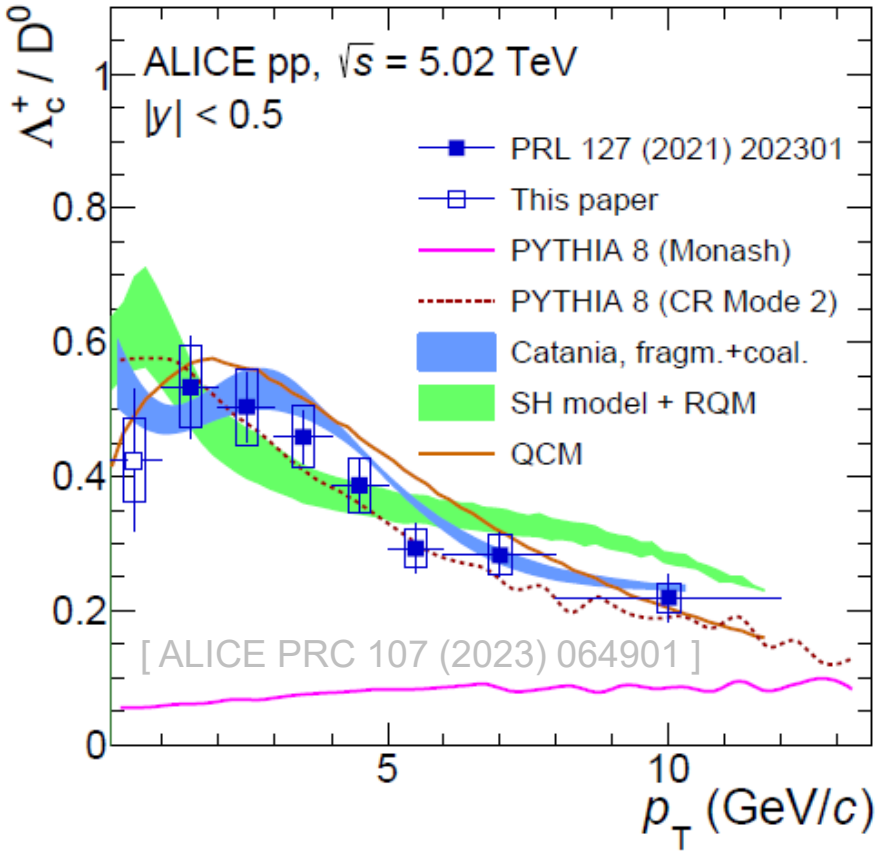


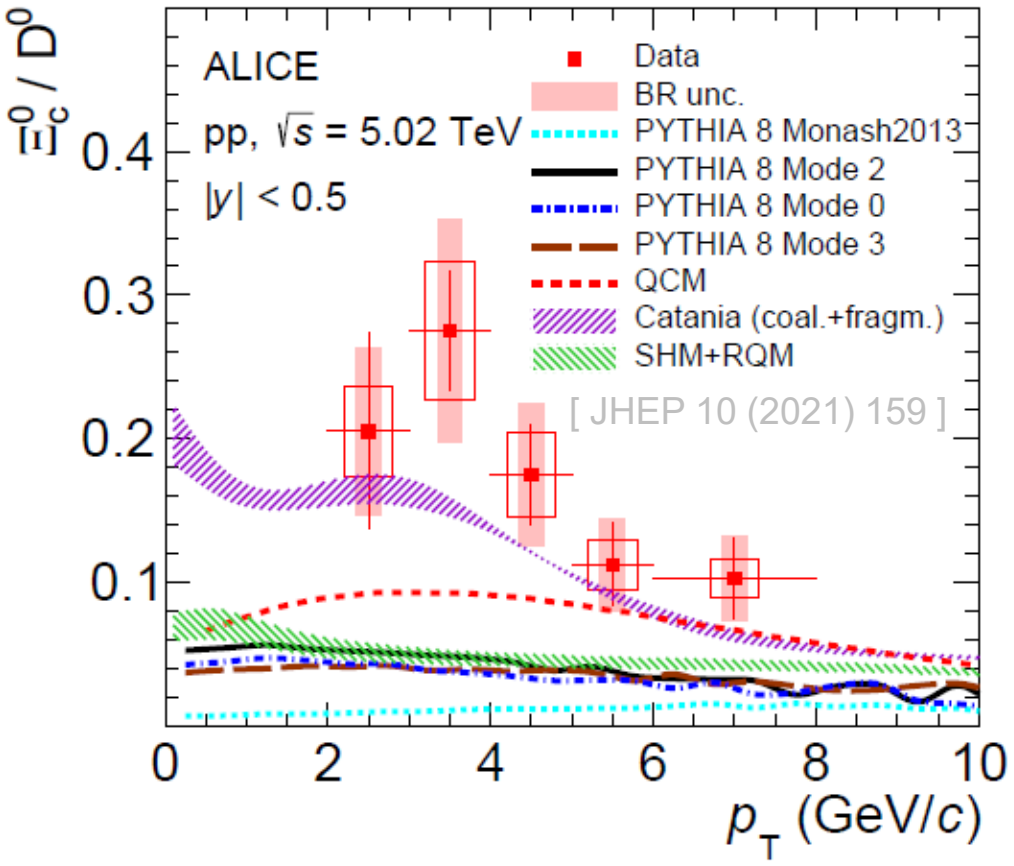


	$\Lambda_c^+/D^0 \pm$ stat. $\pm$ syst.	System
CLEO [43]	$0.119 \pm 0.021 \pm 0.019$	ee
ARGUS [42, 98]	0.127 ± 0.031	ee
LEP average [80]	$0.113 \pm 0.013 \pm 0.006$	ee
ZEUS DIS [51]	$0.124 \pm 0.034^{+0.025}_{-0.022}$	ep
ZEUS γp, HERA I [49]	$0.220 \pm 0.035^{+0.027}_{-0.037}$	ep
ZEUS γp, HERA II [50]	$0.107 \pm 0.018^{+0.009}_{-0.014}$	ep

- Significant enhancement.
- Different hadronization mechanisms?

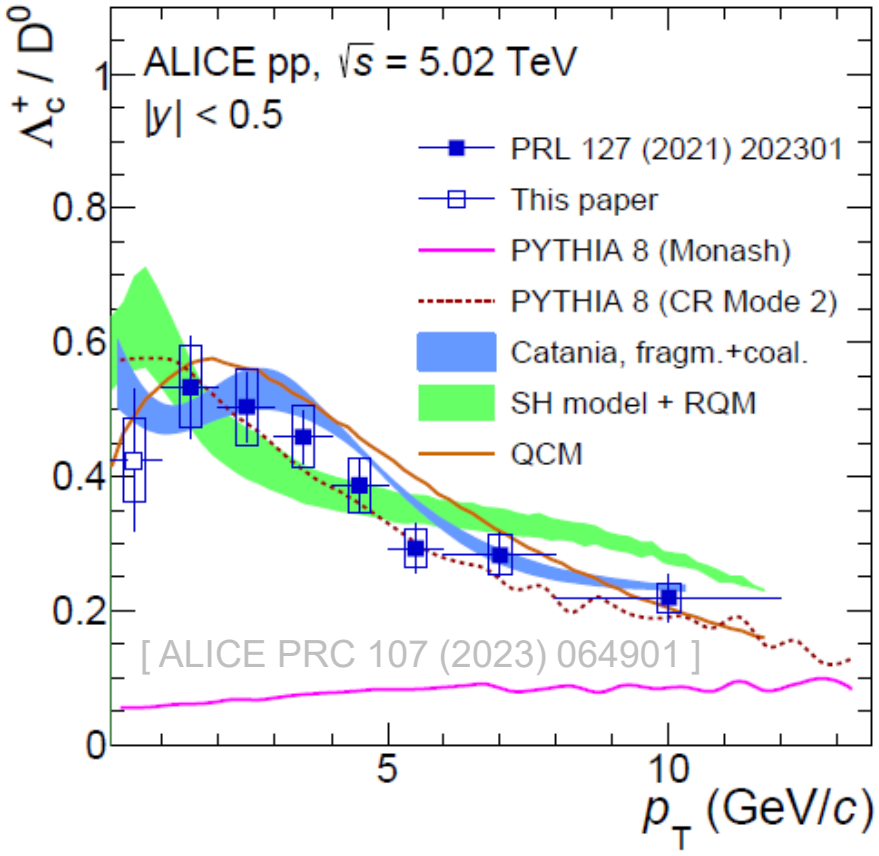
Hadronization challenging

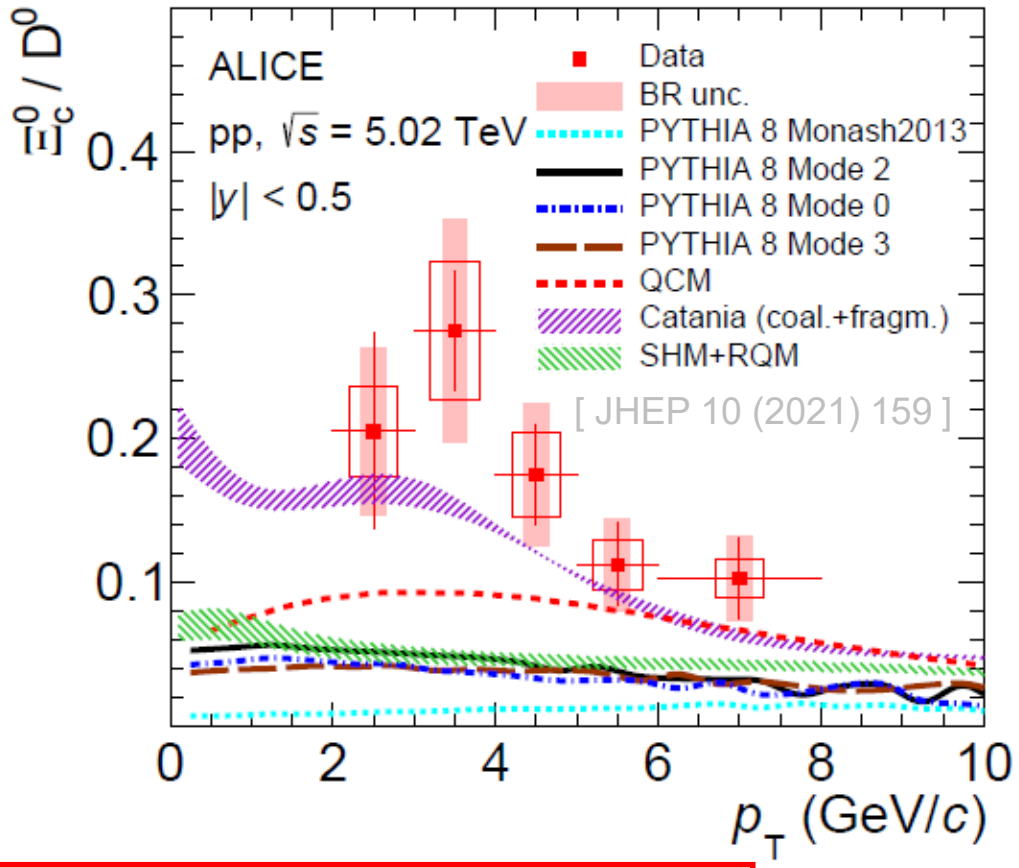




- String fragmentation + color reconnection
- Quark coalescence (recombination)
- Statistical hadronization
- Hybrid frag. + coal., ...

Hadronization challenging



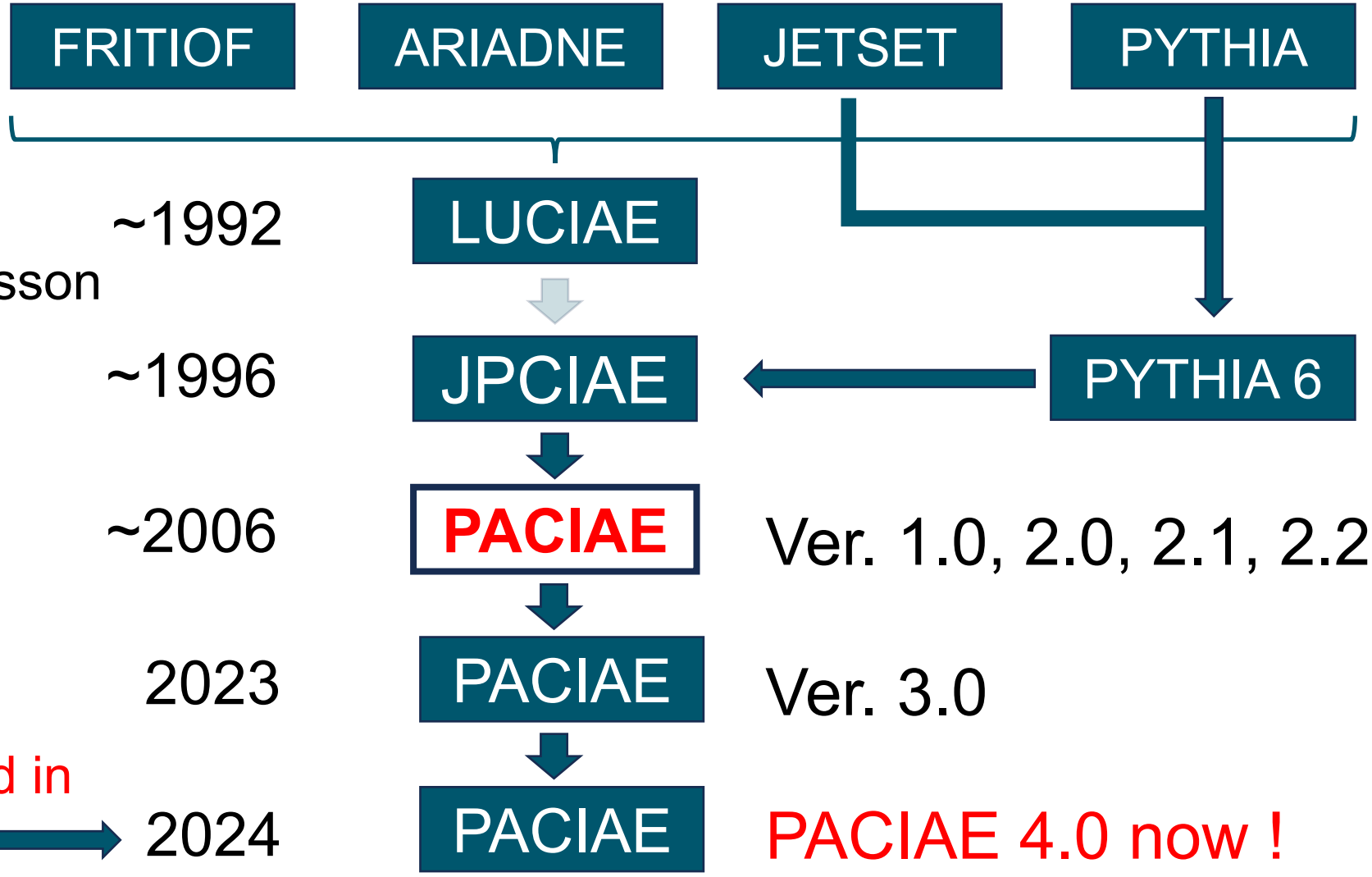


- String fragmentation + color reconnection
- Quark coalescence (recombination)
- Statistical hadronization
- Hybrid frag. + coal., ...

Microscopic transport model PACIAE

Development of PACIAE model

Parton And-hadron China Institute of Atomic Energy (PACIAE)



LUnd-CIAE
Ben-Hao Sa (萨本豪),
An Tai (台安), Bo Andersson

~1992

~1996

~2006

Ver. 1.0, 2.0, 2.1, 2.2

2023

Ver. 3.0

interfaced in

PYTHIA 8

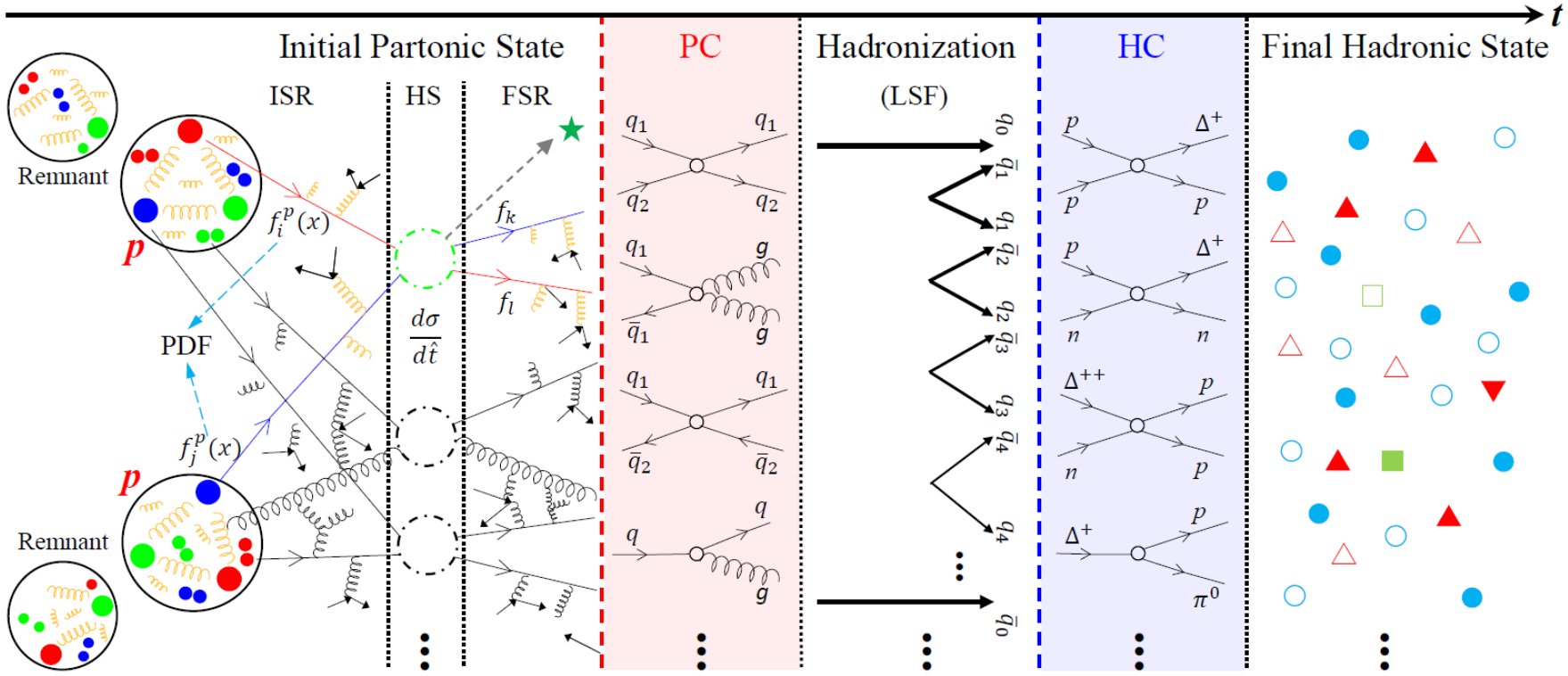
2024

PACIAE 4.0 now !

PACIAE model: Ver. 4.0

Simulation flow:

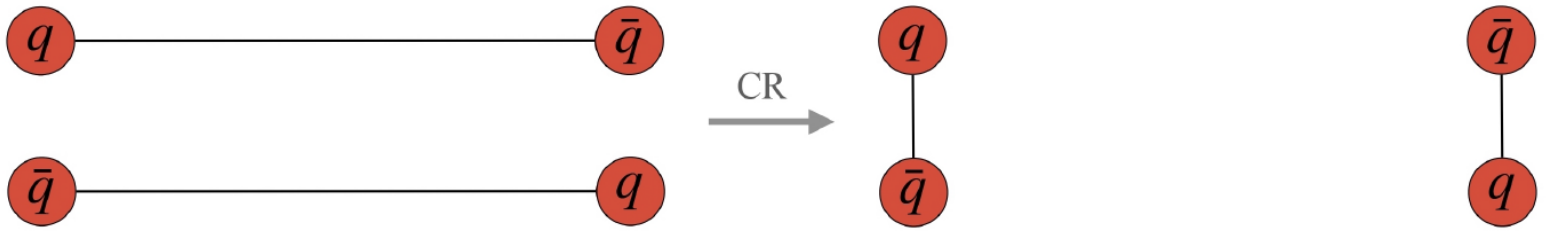
- *Initial state*
- *Parton cascade*
- *Hadronization*
- *Hadron cascade*



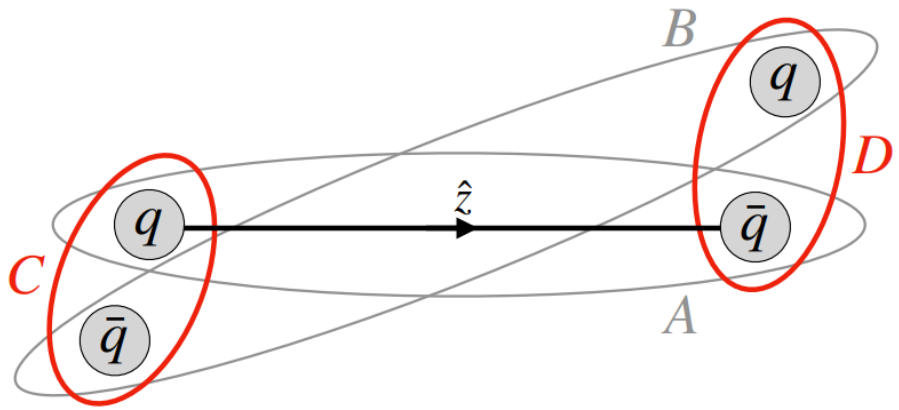
Color reconnection (CR)

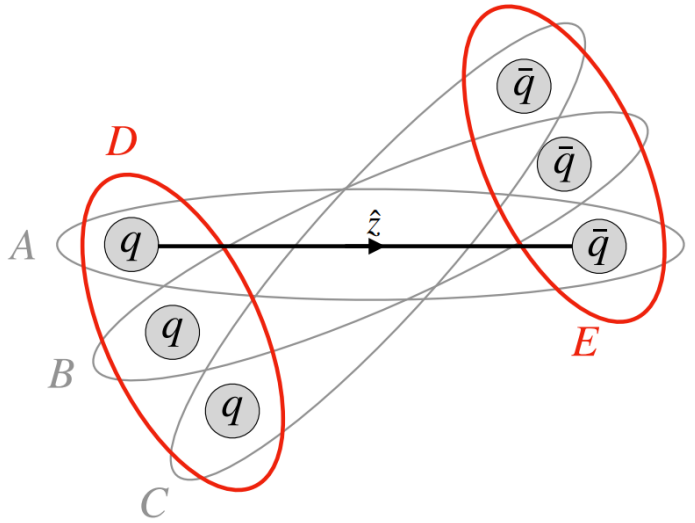
The color charges (configurations) are allowed to be reconnected.

In PYTHIA (string picture):



In HERWIG (cluster picture):





Beyond-leading color (BLC)

SU(3) color algebra (QCD):

$$3 \otimes \bar{3} = 8 \oplus 1$$

color-triplet quark anti- color-octet gluon color-singlet

More generally:

$$N_c \otimes \bar{N}_c = (N_c^2 - 1) \oplus 1$$

Leading color (LC) / large N_c approximation: $N_c \longrightarrow \infty$.

For MC implementation, no repeating colors will appear,

i.e. each colored particle is assigned a unique color/anticolor tag.

PYTHIA

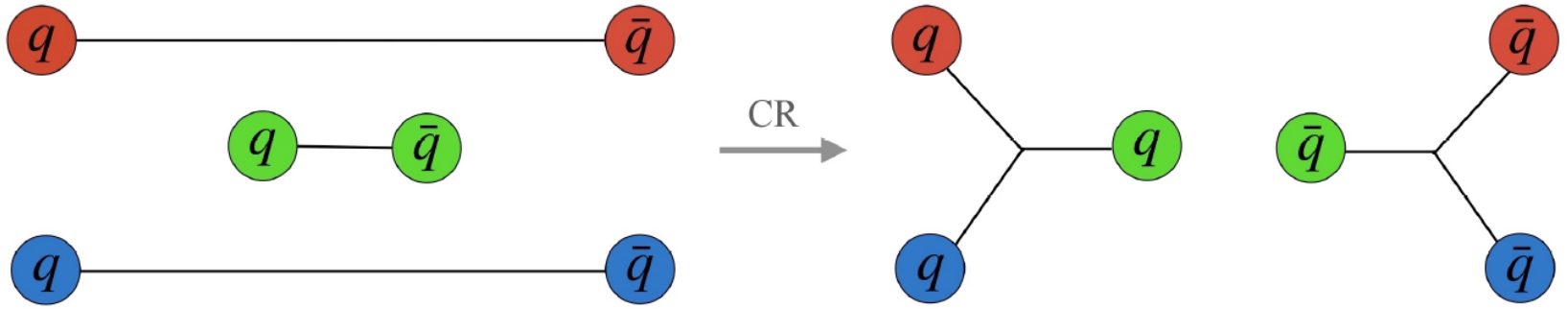
HERWIG

SHERPA

Beyond-leading color (BLC)

Recover/re-introduce the beyond-leading color (BLC) effect, in string picture, the junction topology is allowed by CR according to the QCD color rule (QCD-CR)!

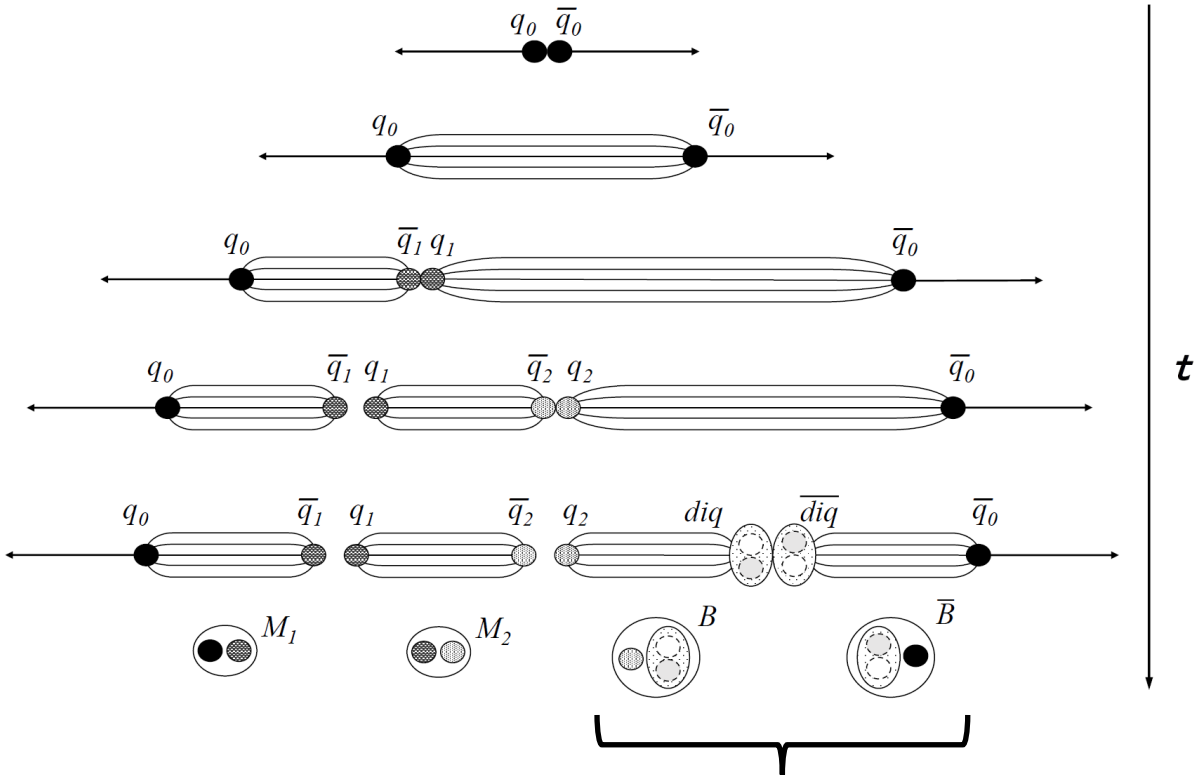
$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$



String fragmentation

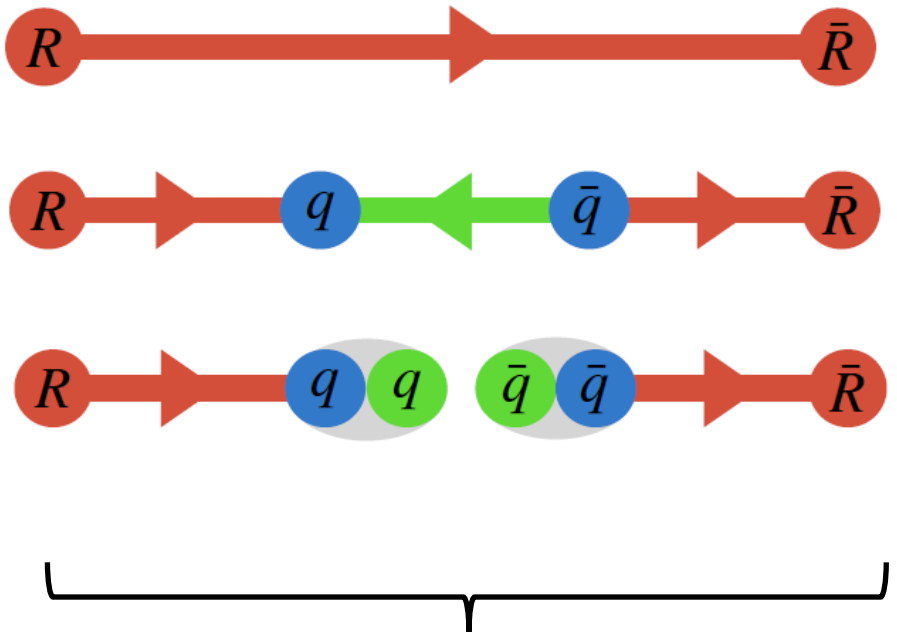
Baryon source in the String fragmentation model: diquark formation!

(1) Diquark excited from vacuum.



Normal baryon.

(2) Diquark combined by fluctuated $q(\bar{q})$, i.e. the popcorn mechanism.

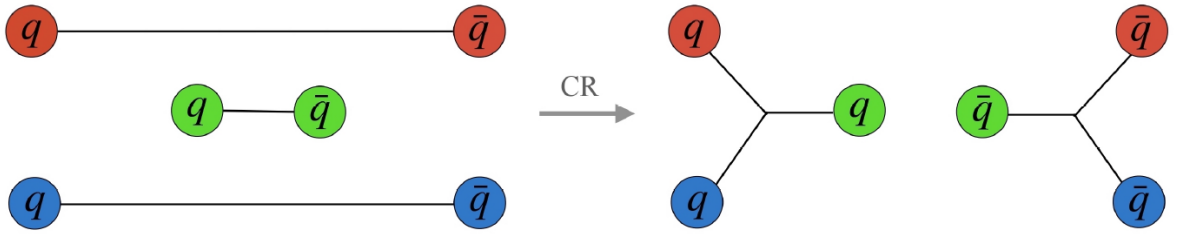


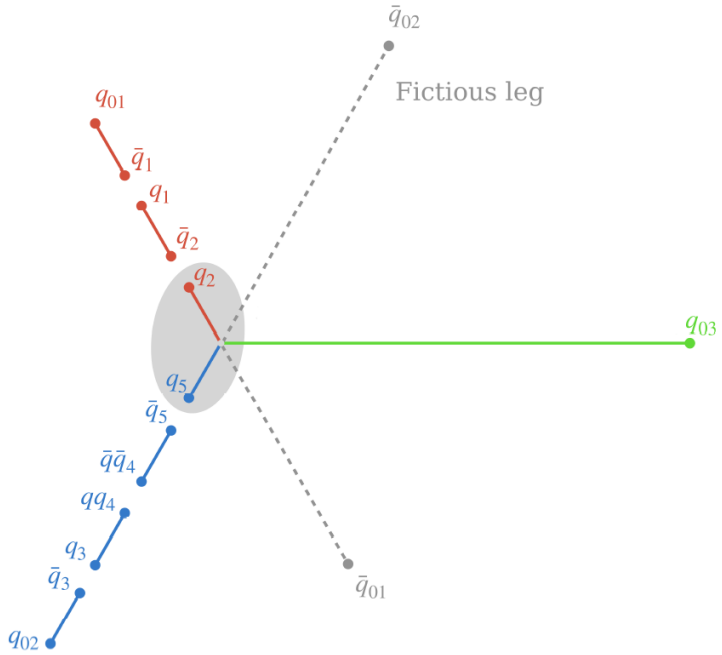
Popcorn baryon.

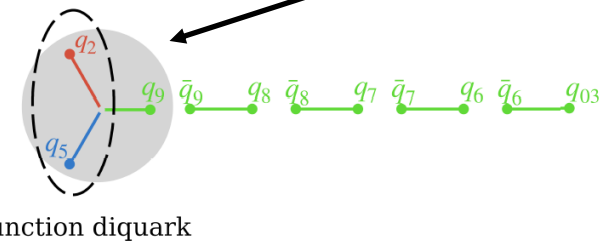
String fragmentation

Baryon source in the String fragmentation model: diquark formation!

(3) Diquark combined by junction $q(\bar{q})$, stemming from QCD-CR + junction frag.





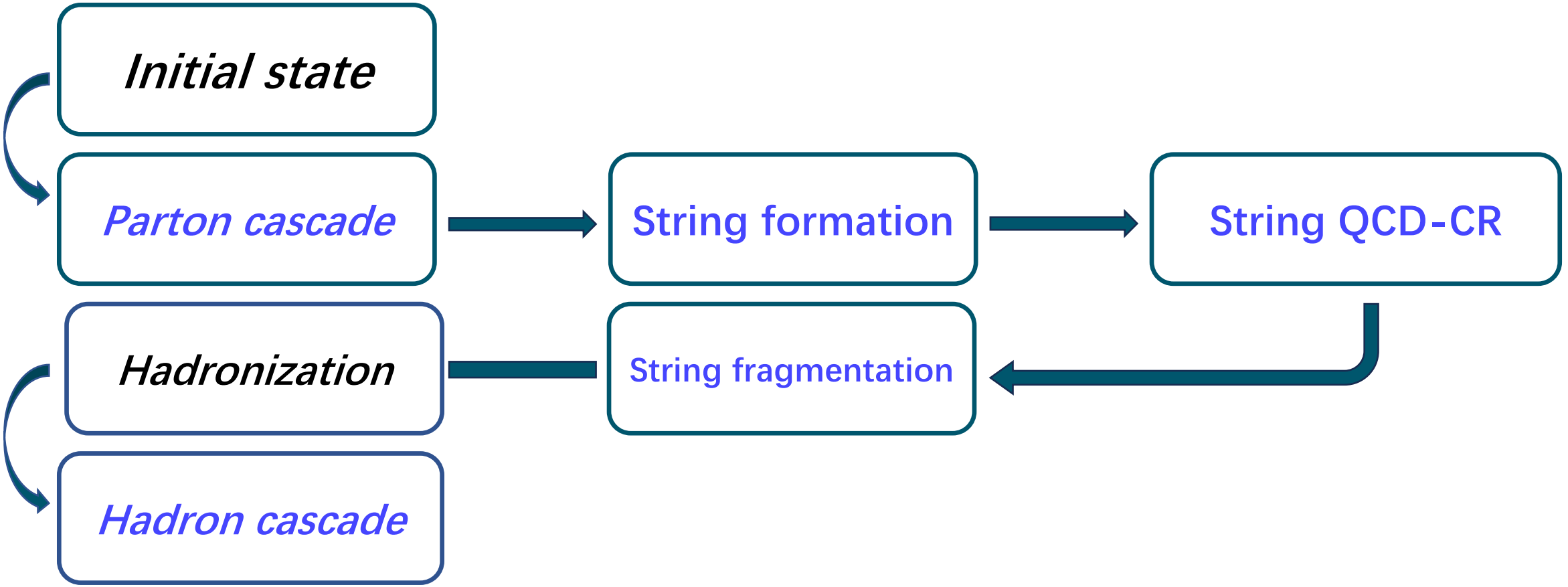


Junction baryon.

Another source of baryons.

Implementation of QCD-CR in PACIAE4

PACIAE4:

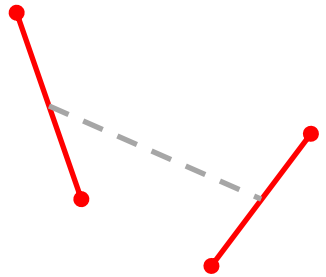


Dynamical Space-Time Constrained QCD-CR in PACIAE4

(1) 3D spatial constraint:

For two dipoles to be reconnected, their distance:

$$\left\| r_{dip1} - r_{dip2} \right\| < d_{CR} = 4 \text{ fm}$$

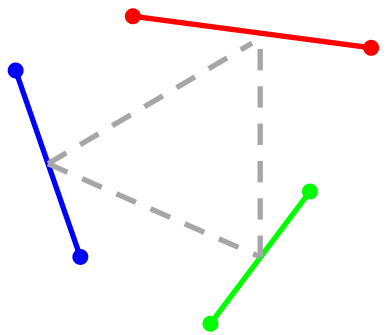


For three dipoles

$$\left\| r_{dip1} - r_{dip2} \right\| < d_{CR},$$

$$\left\| r_{dip1} - r_{dip3} \right\| < d_{CR},$$

$$\left\| r_{dip2} - r_{dip3} \right\| < d_{CR}$$



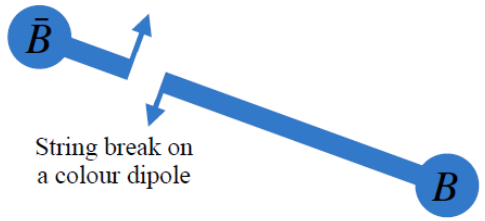
where the position of a dipole (r_{dip}) is represented by the midpoint between two parton ends (lab frame).

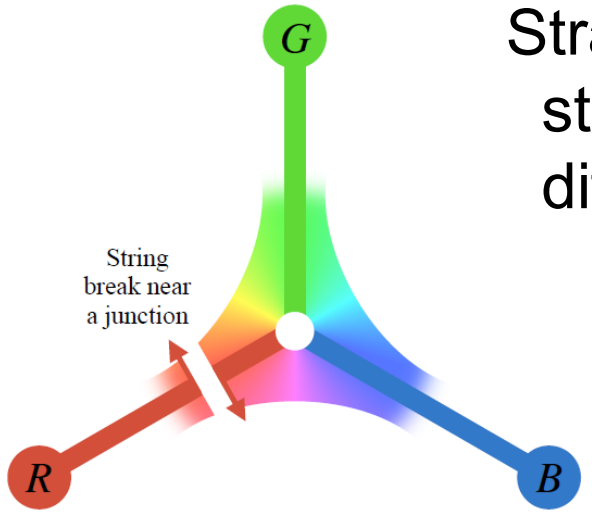
(2) Temporal constraint:

For dipoles to be reconnected, their ends should be at a same time point, i.e. propagate partons to the maximum time among them before the distance checking.

Junction String Tension Enhancement

[arXiv: 2512.00671]





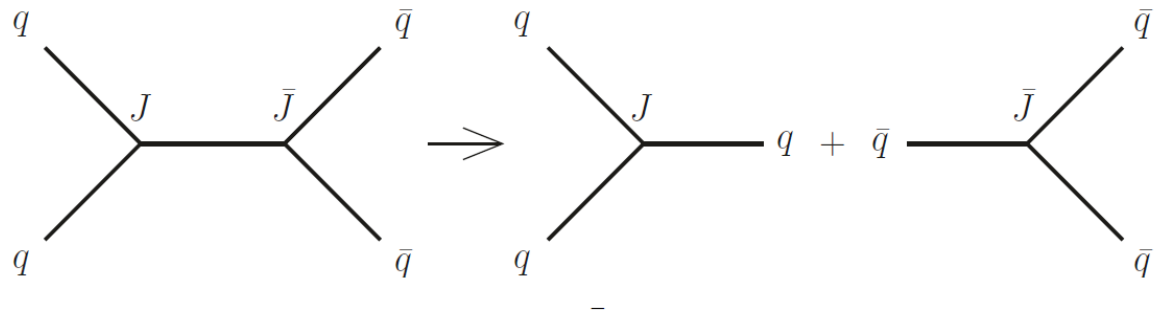
Strange junction: The excited probability ratio of strange $q\bar{q}$ over the u/d one around junction differs from that of the normal string.

$$P'(s:u/d) = P(s:u/d)^{1-J_s}$$

Instead, we use the string tension scaling:

$$P_s' = P_s^{\kappa_0/\kappa_{eff}}$$

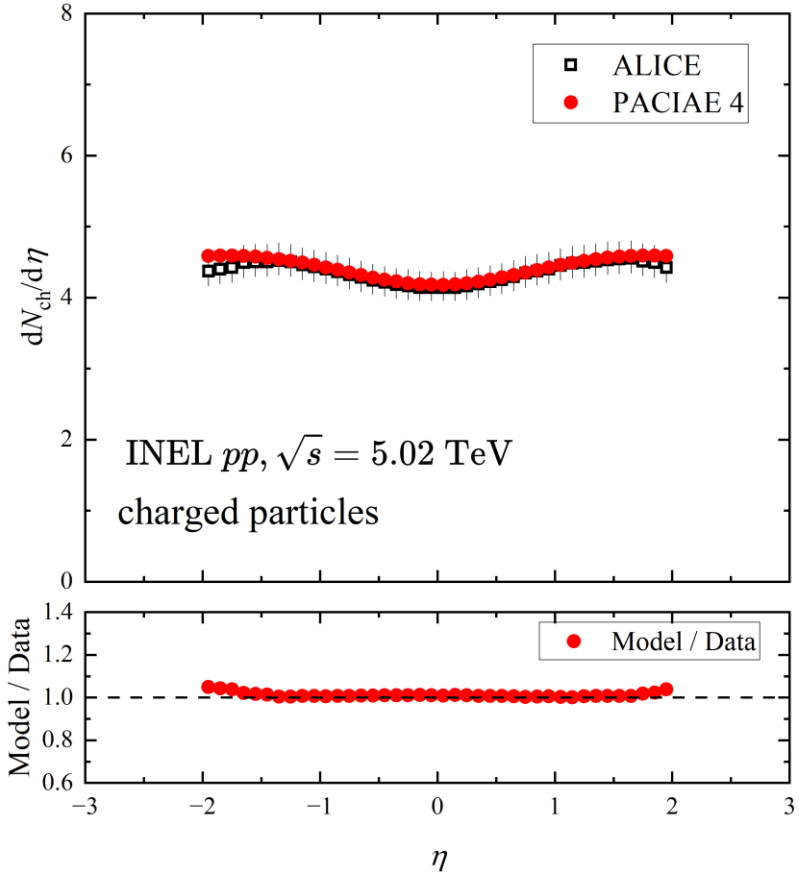
$$h := \kappa_{eff}/\kappa_0 \ (= 3)$$

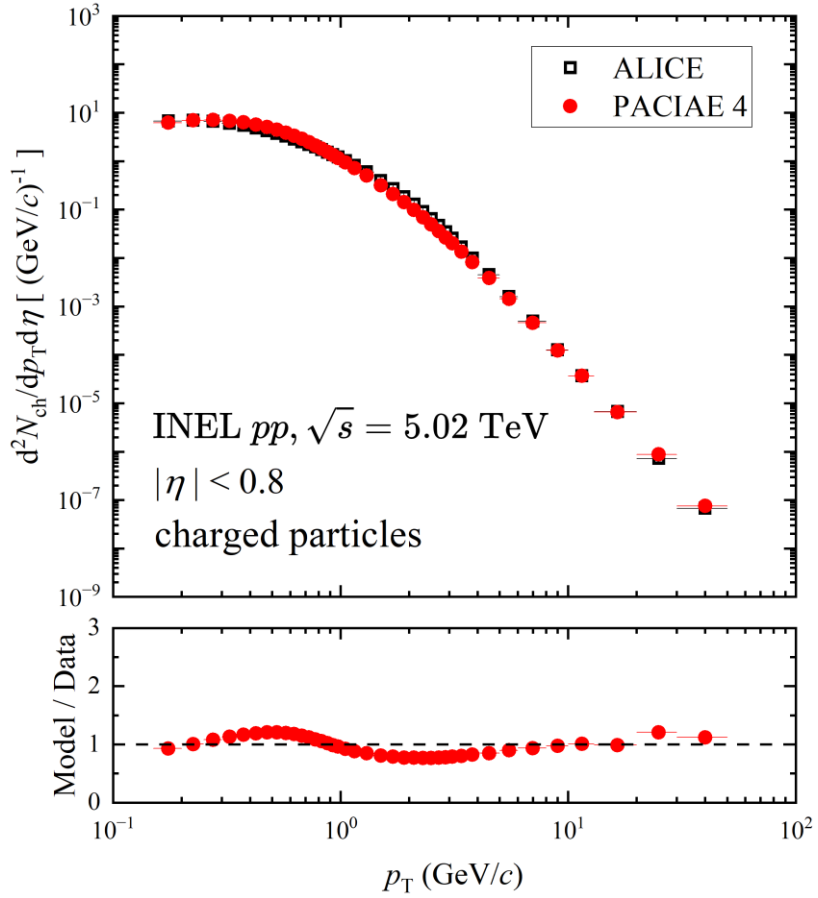


Furthermore, we take the tension enhancement between the junction-antijunction into account, i.e. for the break to decouple junction-antijunction system.
An additional factor of 5/3.

Production of open-flavor hadrons

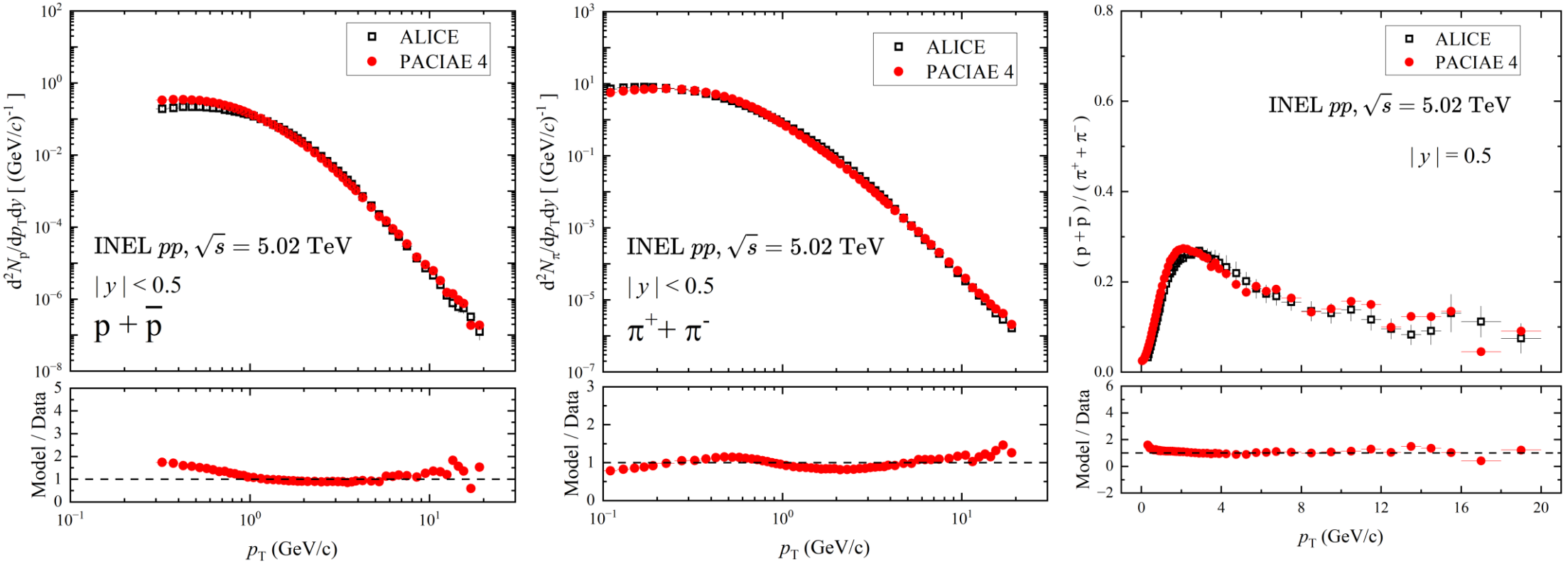
Charged hadrons





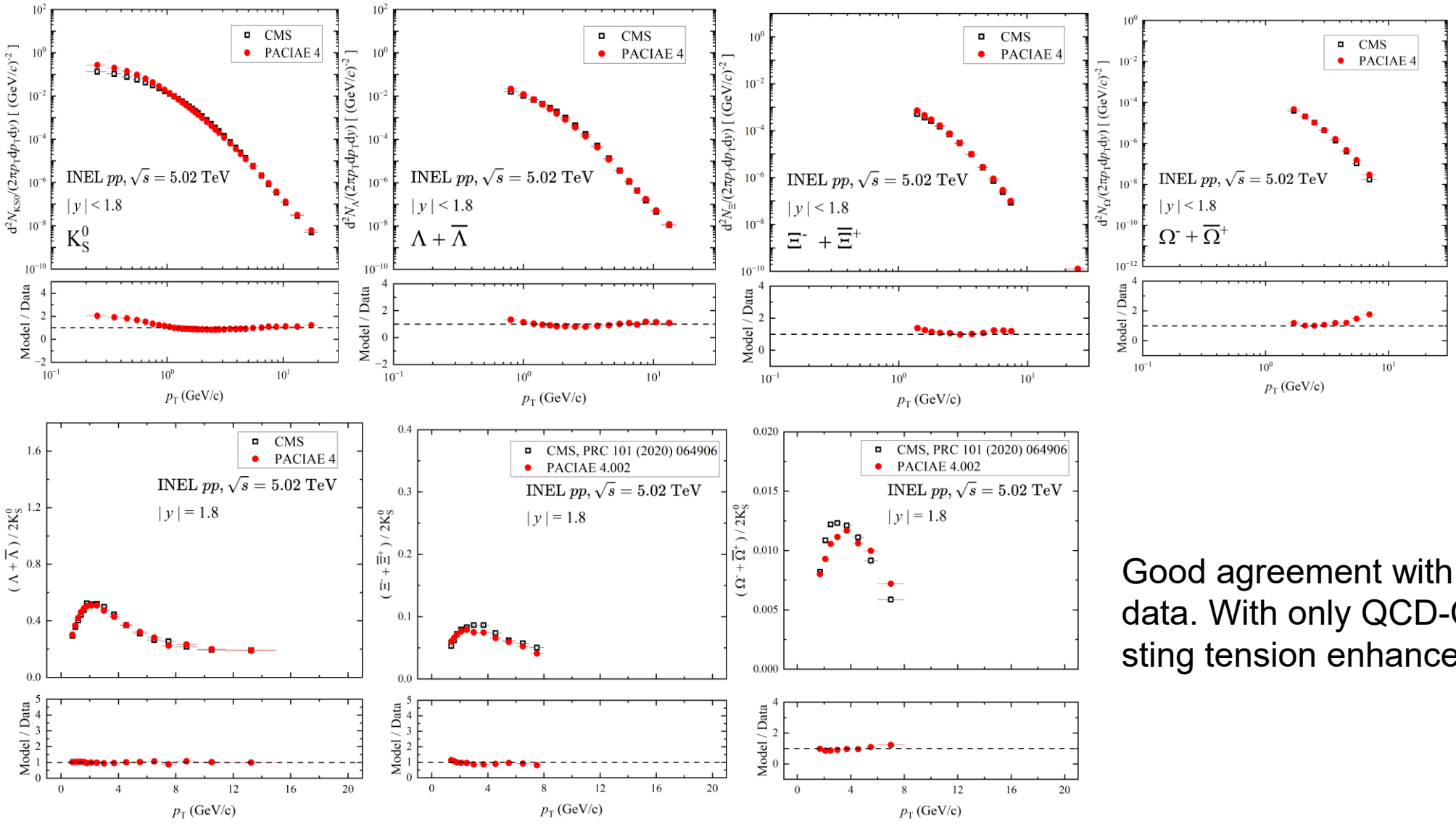
PACIAE4 well describes the charged particle data.

Light sector



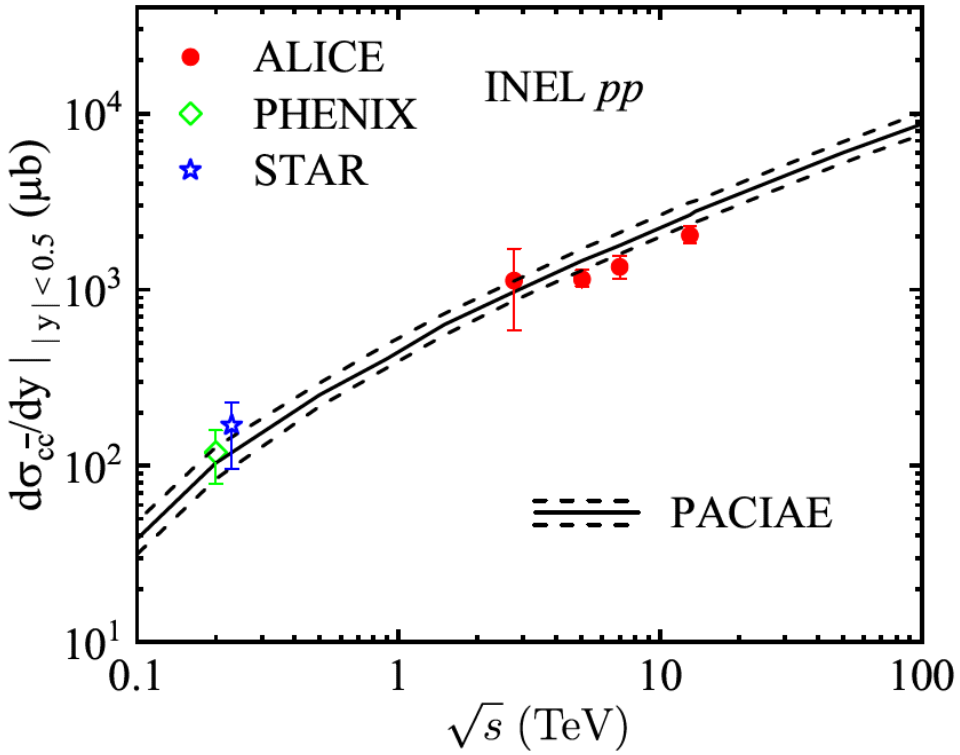
PACIAE4 well describes the light p and π data , along with the p/π ratio.

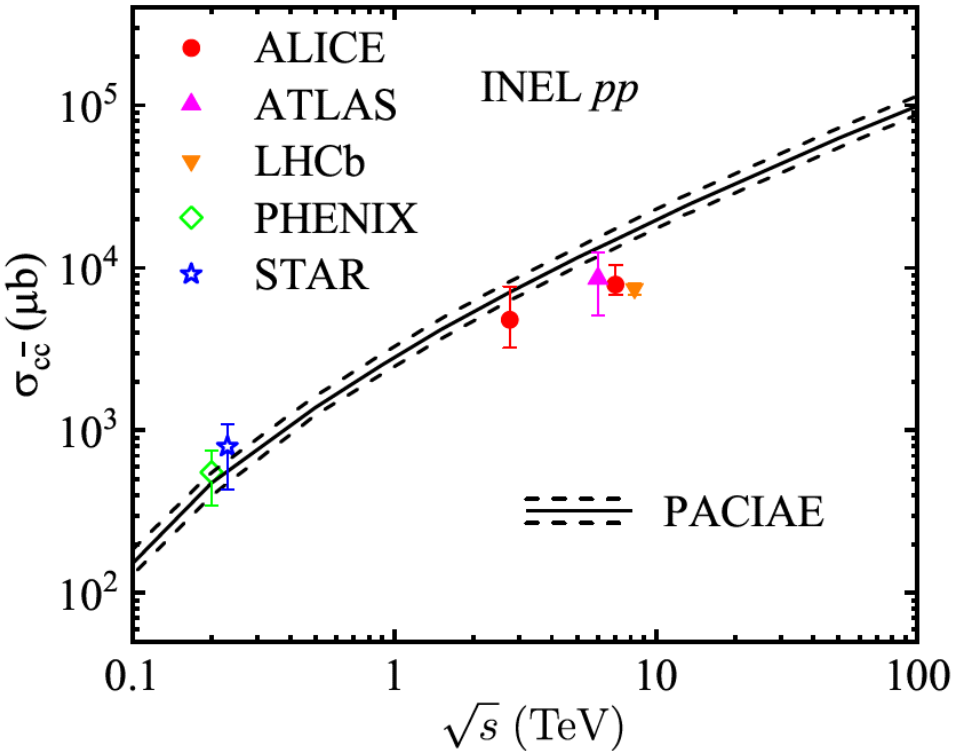
Strange sector



Good agreement with experimental data. With only QCD-CR + junction sting tension enhancement!

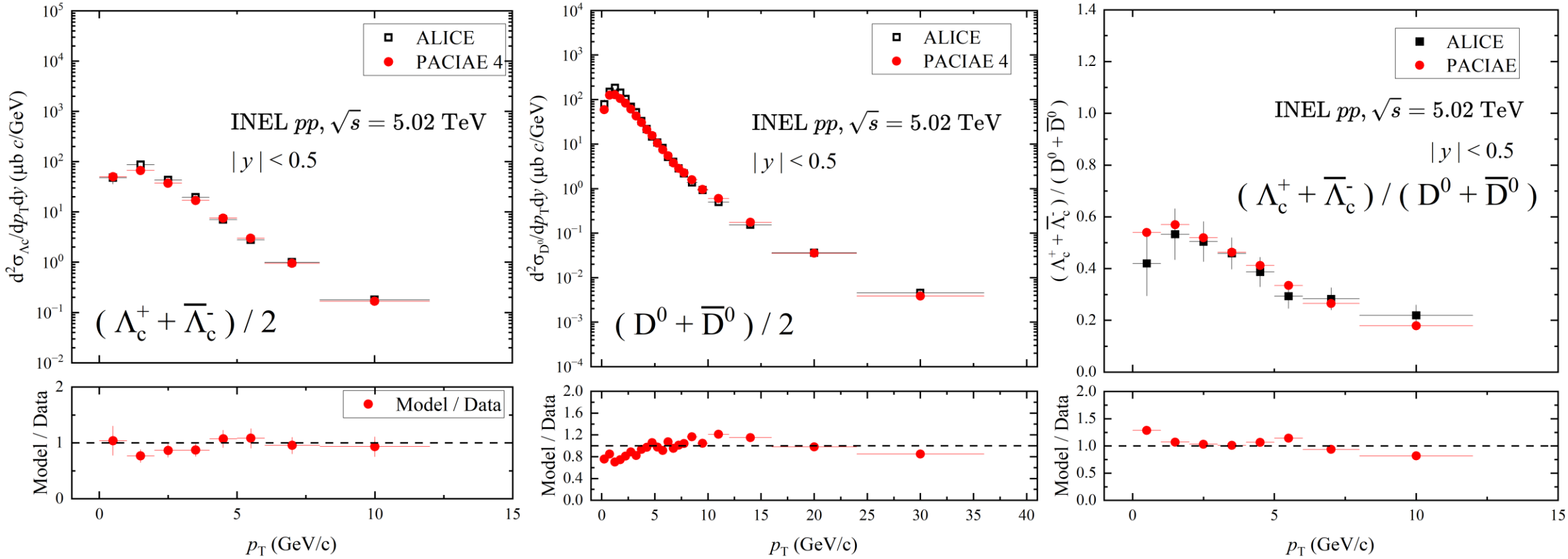
Charm sector





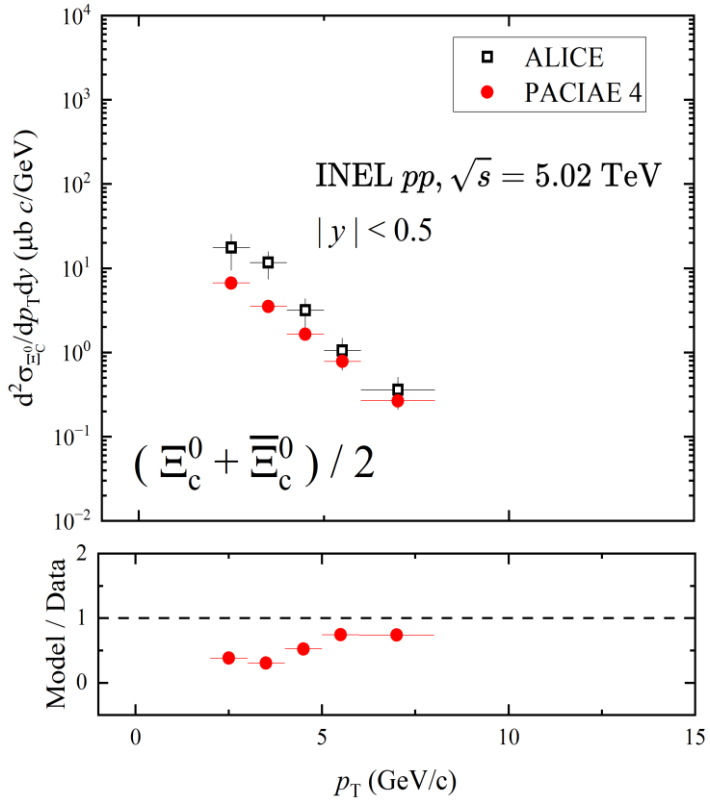
The $c\bar{c}$ production cross sections in PACIAE.

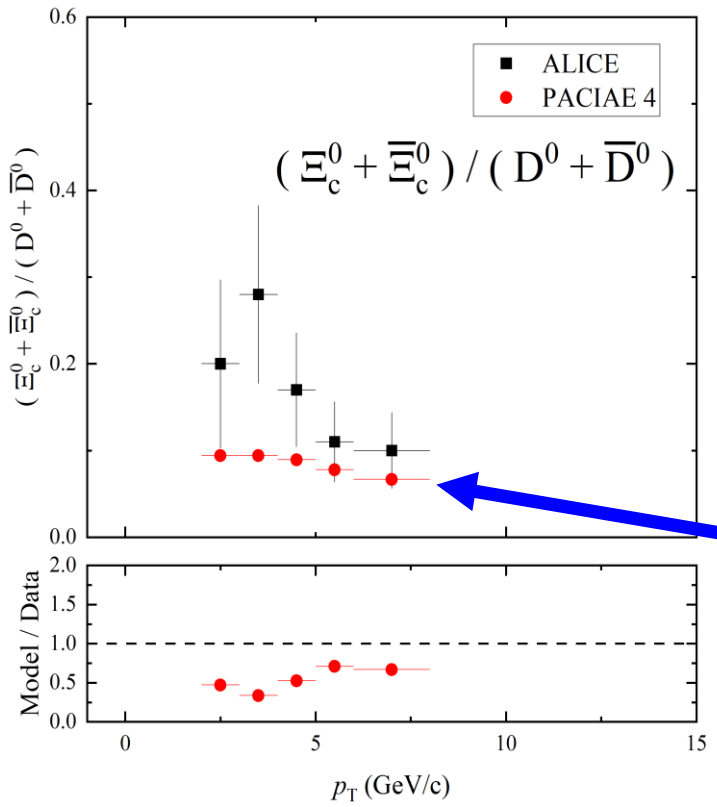
Charm sector

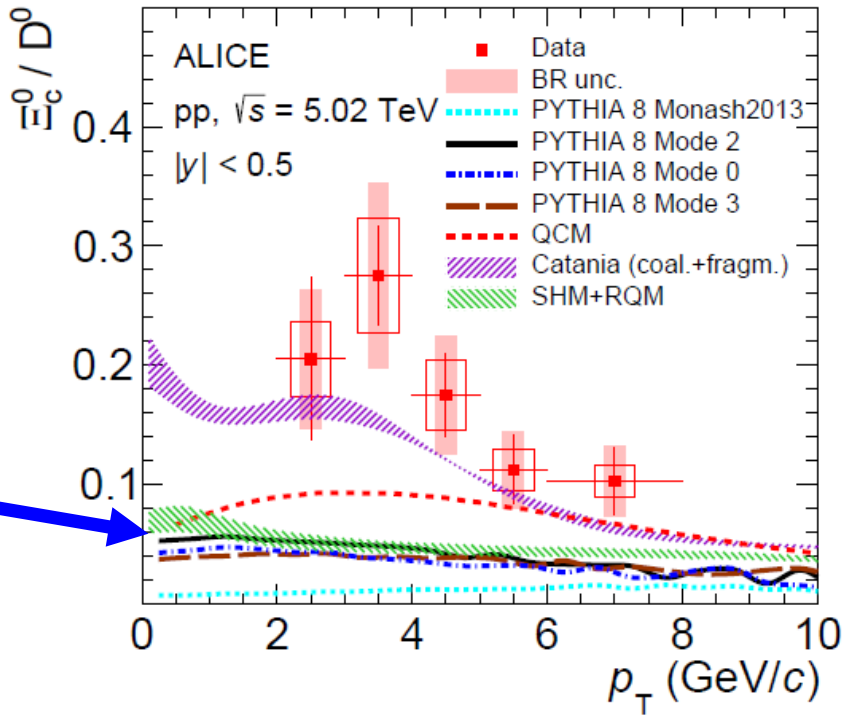


Successfully describe the Λ_c and D^0 data!

Charm sector

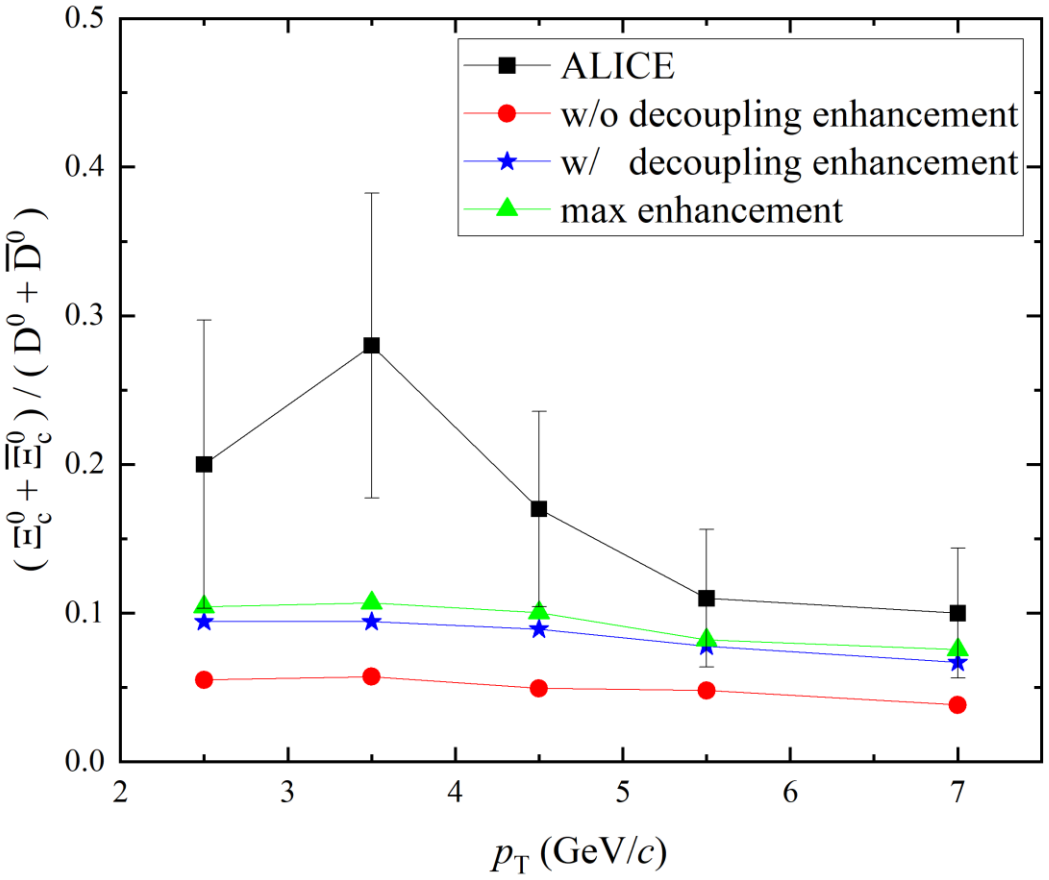


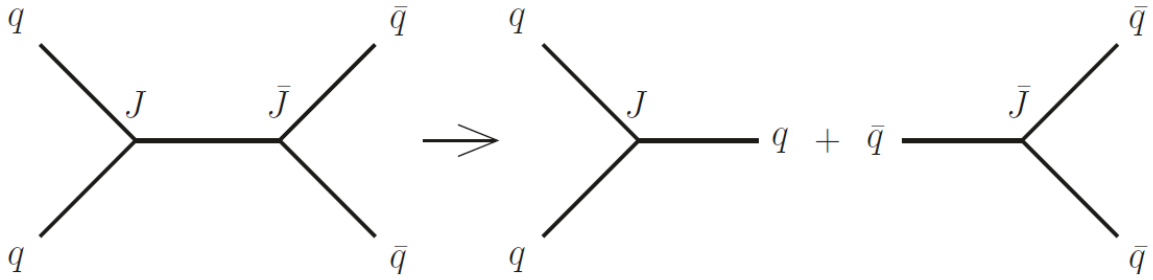




Our model enhances Ξ_c. But still underestimate.

Charm sector





Max enhancement: $s\bar{s}: u\bar{u}: d\bar{d} = 1:1:1$

The decoupling strange enhancement / multiple junction structure?

Summary and outlook

Summary and outlook

1. We introduce a dynamical space-time constrained QCD color reconnection and a junction string tension enhancement mechanism in PACIAE4.

2. With the framework, we successfully describe the p_T spectra and baryon-to-meson ratios of open light and heavy hadrons in *pp* collisions at $\sqrt{s} = 5.02\ \mathrm{TeV}$.

3. The production of charm-strange Ξ_c^0 baryons is enhanced in the string fragmentation regime, but still underestimates the experimental data.

3. Multi-junction structures play an essential role in the production of charm baryons.

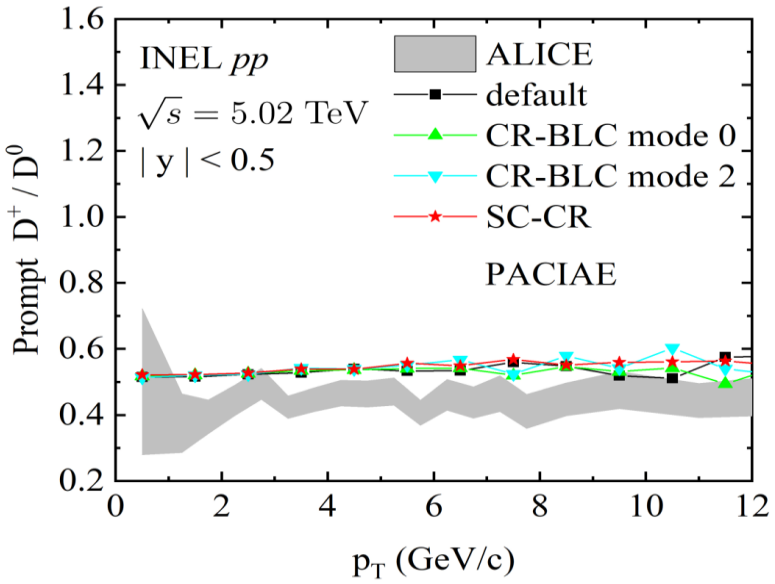
4. More detailed study for junction structure is required in string phenomenology.

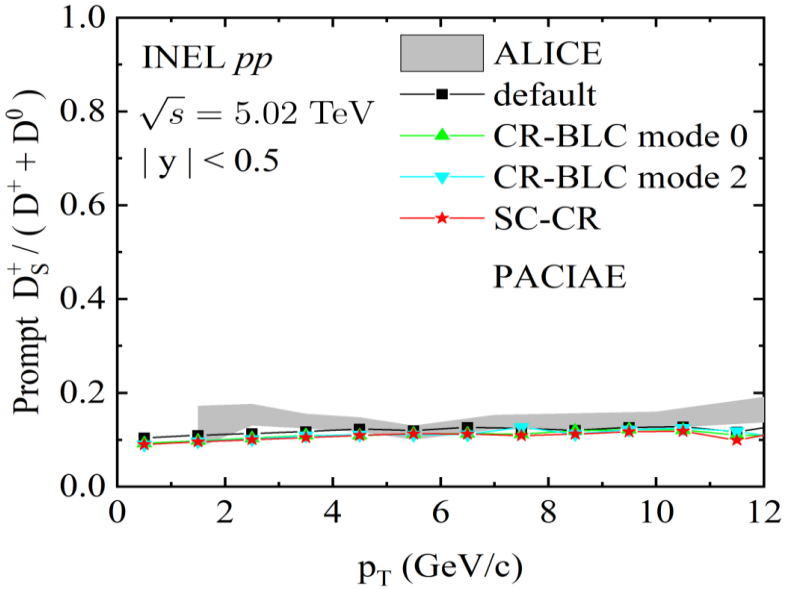
5. From small systems from *pp* to *p*A, to large AA…

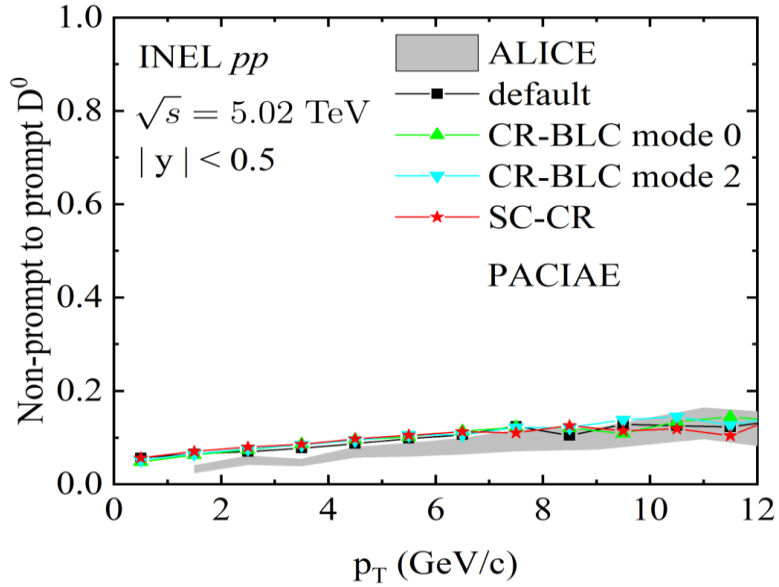
Thanks!

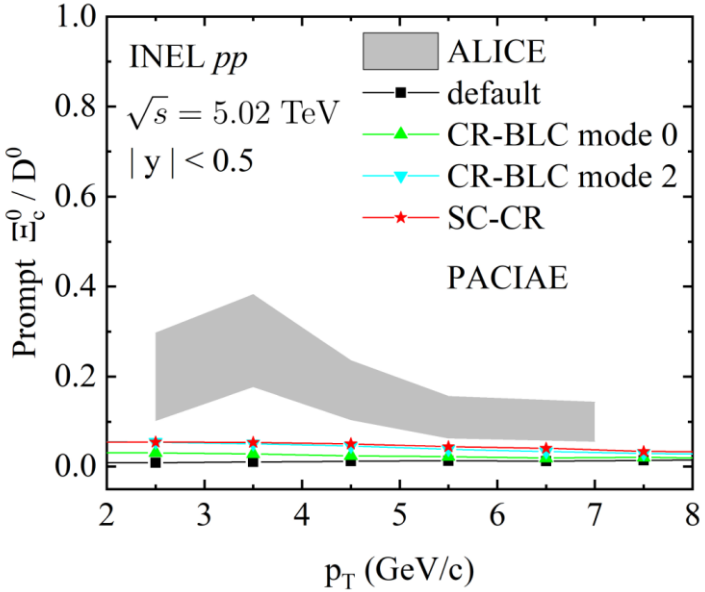
Backup

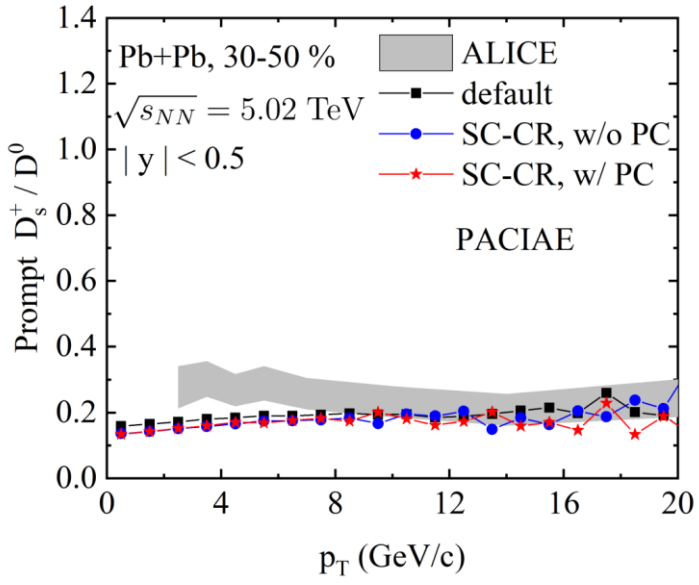
Other HF species









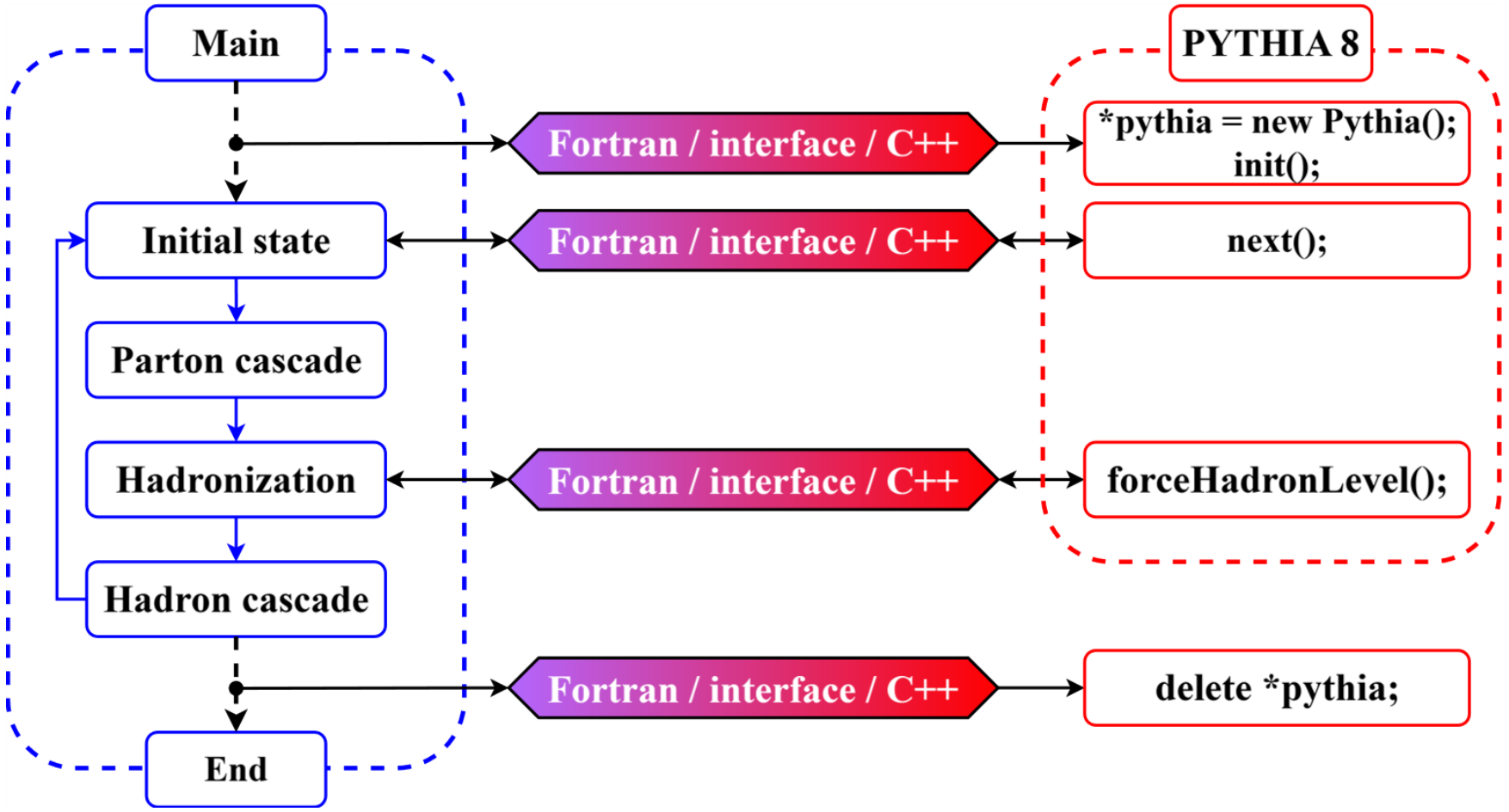


32

PACIAE model: Ver. 4.0

PACIAE: *Parton And-hadron CIAE*

(based on PYTHIA 6 & 8, refactoring and rewriting in modern Fortran + C++)



Open-source: https://github.com/ArcsaberHep/PACIAE4

Beyond-leading color (BLC)

SU(3) color algebra (QCD):

$$3 \otimes \bar{3} = 8 \oplus 1$$

color-triplet quark anti- color-octet gluon color-singlet

More generally:

$$N_c \otimes \bar{N}_c = (N_c^2 - 1) \oplus 1$$

Conversely, in the LC limit , the gluon color state (adjoint) can be reduced to the direct product of the quark color state (fundamental) and the antiquark one (antifundamental).

PYTHIA

HERWIG

SHERPA

貴州師範大學

Guizhou Normal University