p-ϕ Correlation and Interaction Using a Dynamical Model

Kenshi Kuroki (Sophia Univ.) and Tetsufumi Hirano (Sophia Univ.)
k-kuroki-e23@eagle.sophia.ac.jp hirano@sophia.ac.jp

SOPHIA HADRON PHYSICS GROUP

1. Femtoscopy: Phenomenological way to study low-energy hadron interactions in high-energy nuclear collisions

■ **Correlation Function (CF)**

$$C(\boldsymbol{q}, \boldsymbol{P}=0) := \frac{N_{\mathrm{pair}}(\boldsymbol{p}_a, \boldsymbol{p}_b)}{N_a(\boldsymbol{p}_a)\, N_b(\boldsymbol{p}_b)}$$

$\boldsymbol{q}$: Relative momentum, $\boldsymbol{P}$: Total momentum

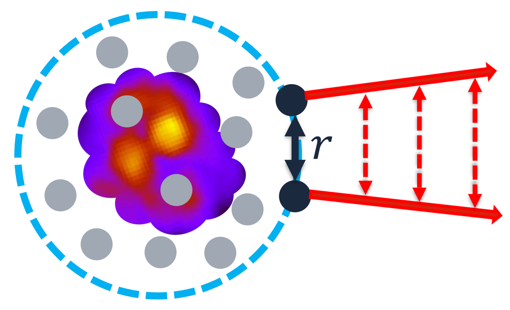
Correlation = Deviation of $C(q)$ from 1

■ **Koonin-Pratt (KP) formula** S. E. Koonin, PLB **70**, 43 (1977); S. Pratt, PRD **33**, 1314(1986)

Settings: non-identical pairs, only s-wave scatt. w/o Coulomb, spherical source

$$C(q) = 1 + \int_0^\infty dr\; 4\pi r^2 S(q;r)\; \{|\varphi_0(q;r)|^2 - [j_0(qr)]^2\}$$

Source Func. (SF) with Jacobian — Weight Func. (WF) Increase/Decrease of w.f. by interaction



φ_0: s-wave wave func.
j_0: Spherical Bessel func.

Correlation = How much SF "picks up" WF

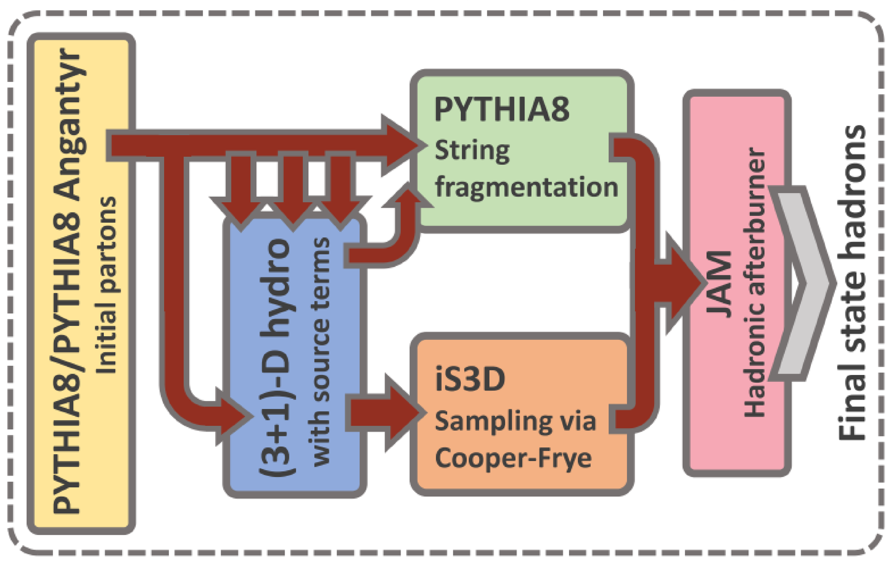
From experimental hadron correlation function, input: source function → output: hadron interaction

2. Overview of This Study

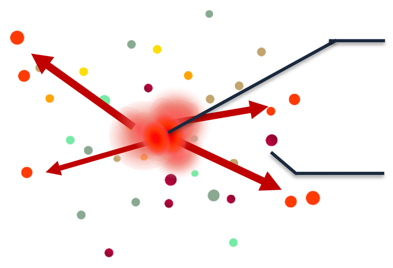
- New: p-ϕ SF from **a dynamical model** — Reflecting collision dynamics
- p-ϕ potential: $^4S_{3/2}$: HAL QCD, $^2S_{1/2}$: **Parametrization**
- Schrödinger eq. → WF
- KP formula → New: p-ϕ CF from **a dynamical model**
- p-ϕ CF (Experiment)
- Scattering length a_0, Binding energy E_B, ⋮

3. Source Function from DCCI2

Y. Kanakubo, Y. Tachibana, and T. Hirano, PRC **105**, 024905 (2022)

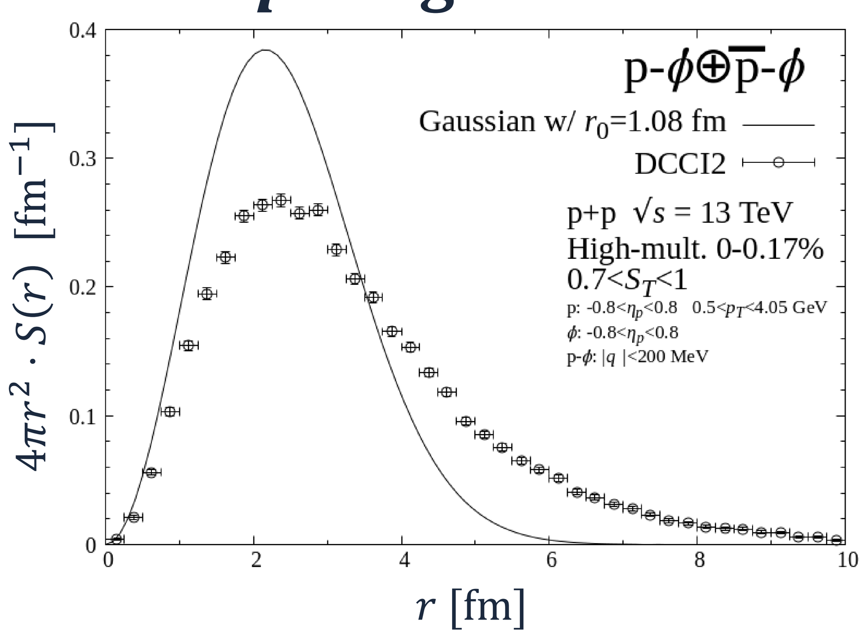


A state-of-the-art dynamical model based on the **core–corona picture**

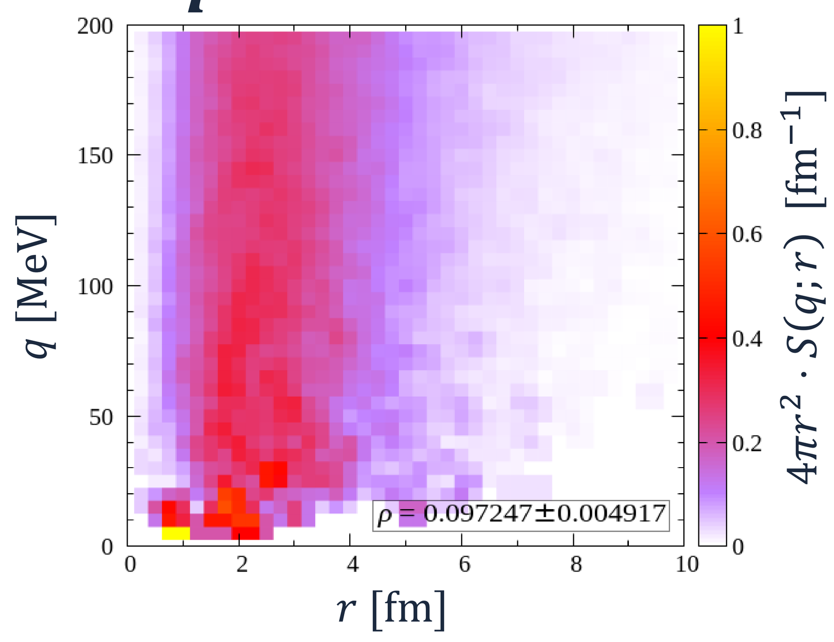


Applicable to HM p+p collisions

q-integrated SF



q-differential SF



➢ **Larger source size $\langle r^2 \rangle$** ← Non-Gaussian long-tail
Mainly due to **hadronic rescatterings** (e.g., p rescatterings w/ pion gas)
➢ **Positive q–r correlation**
Due to e.g., **collectivity** of generated matter

4. Potential and Weight Function

■ **$^4S_{3/2}$: HAL QCD** Y. Lyu *et al.*, PRD **106**, 074507 (2022)

Attraction w/o bound states → **Enhancement of WF**

■ **$^2S_{1/2}$: Parametrization** E. Chizzali *et al.*, PLB **848**, 138358 (2023)

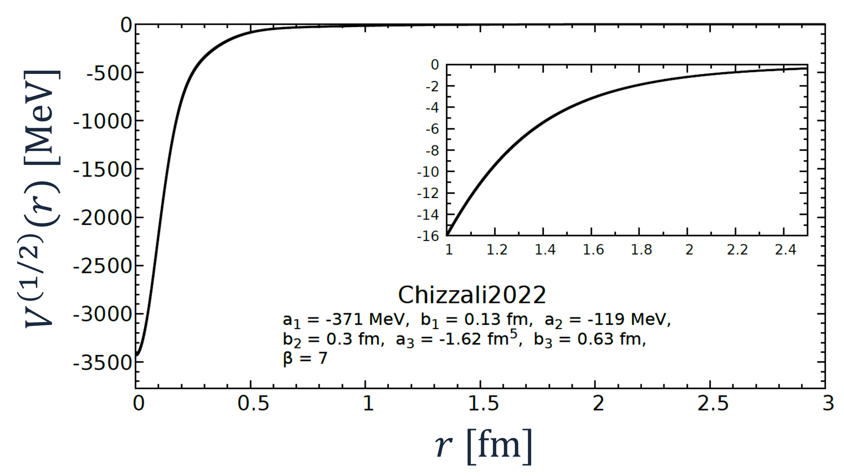
Channel-couplings are neglected for simplicity

$$V^{(1/2)}(r) = \beta\left[a_1 e^{-(r/b_1)^2} + a_2 e^{-(r/b_2)^2}\right] + a_3 m_\pi^4 f(r;b_3)\frac{e^{-2m_\pi r}}{r^2}$$

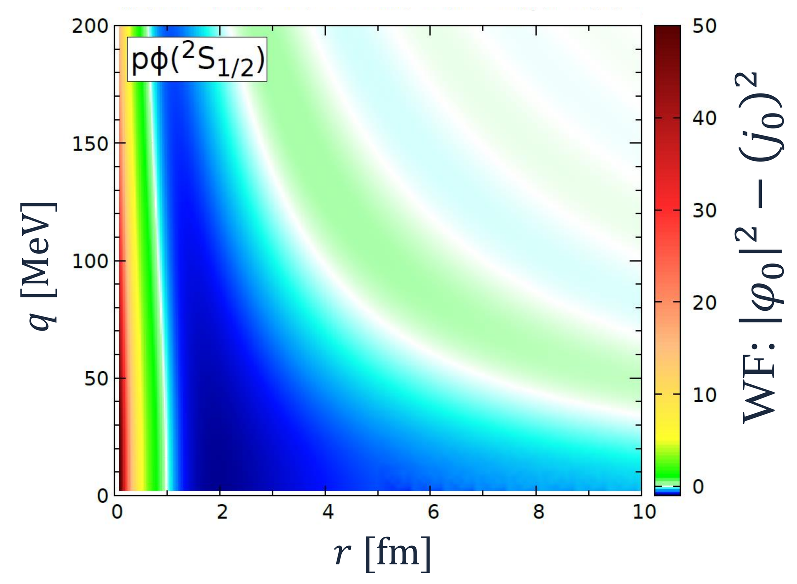
Short-range interaction — TPE

Only one adjustable parameter β (default: $\beta = 7$)

Argonne-type FF: $f(r;b_3) = \left[1 - e^{-(r/b_3)^2}\right]^2$



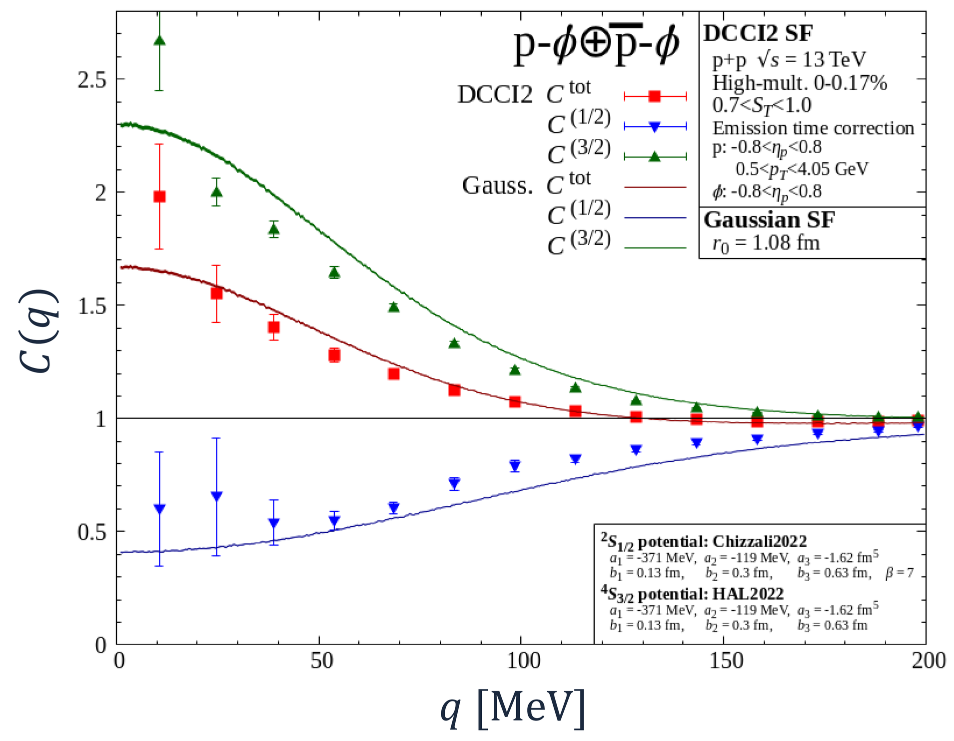
$\beta = 7 \rightarrow$ A bound state



➢ **Strong enhancement of WF at small qr**
➢ **"Negative valley" of WF around a_0** ← Node of φ_0 due to a bound state

5. Correlation Function

DCCI2 SF vs Gaussian SF



➢ **Slightly weaker correlation**
Larger source size from DCCI2
➢ **Non-trivial behavior at small q**
Sensitive to w.f. in scatt. region

Small but statistically significant effects of collision dynamics

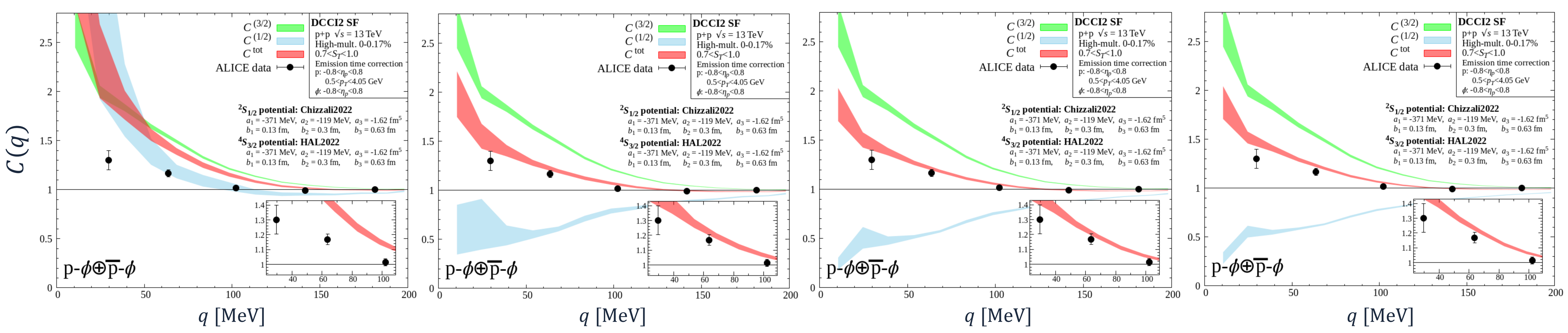
6. Constraint on Interaction

$C^{(3/2)}$: Fixed, $C^{(1/2)}$: Changed with β

Compare $C^{\mathrm{tot}} = \frac{2}{3}C^{(3/2)} + \frac{1}{3}C^{(1/2)}$ with ALICE data

ALICE, PRL, **127**, 172301 (2021)

Indication of a p-ϕ bound state in $^2S_{1/2}$ ($E_B \cong$ 10–70 MeV)



$\beta = 6$	$\beta = 7$	$\beta = 8$	$\beta = 9$
a_0 = 4.54 fm	a_0 = 1.99 fm	a_0 = 1.23 fm	a_0 = 0.85 fm
E_B = 2.3 MeV	E_B = 13.3 MeV	E_B = 37.5 MeV	E_B = 93.1 MeV

Overestimate ← Agree within errors → Overestimate

7. Summary

➢ Effects of collision dynamics on CF: **Statistically significant difference** due to e.g., hadronic rescatterings and collectivity
➢ Comparison w/ ALICE data: Indication of **a p-ϕ bound state** in $^2S_{1/2}$ channel

Importance of using SF that reflects collision dynamics for precision interaction study via femtoscopy