# Macroscopic study of $\phi$-mesic nuclei in $pp$ collisions at $\sqrt{s}$ = 7 TeV with the PACIAE model

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**Central China Normal University**

**Oct. 12 th, 2026 @ Guilin**

**in collaboration with**

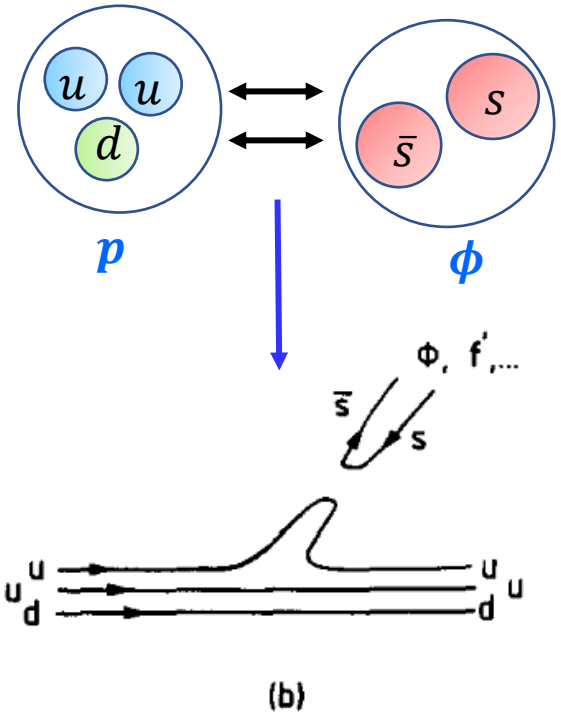
**Zhi-Lei She, An-Ke Lei, Dai-Mei Zhou, Wen-Chao Zhang, Hua Zheng, Li-Lin Zhu, Yu-Liang Yan, Ben-Hao Sa …**

# Outline

- $\phi$-N interaction
- Microscopic calculations
- PACIAE and DCPC model
- Results of $\phi$-mesic nuclei
- Summary and outlook

# $\phi$-N interaction

# $\phi$-$N$ interaction




**Suppressed $\phi$-$N$ interaction**

OZI rule

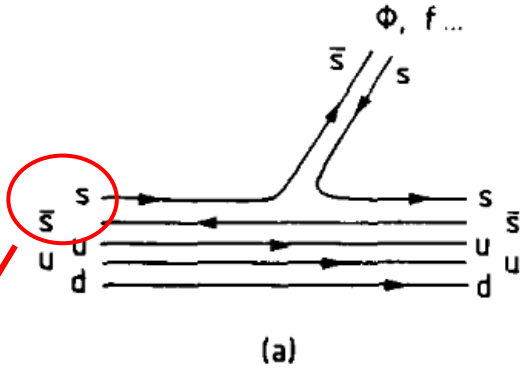
Phys.Lett. 5 (1963) 165-168

Report No. CERN-TH-412, 1964

Prog.Theor.Phys.Suppl. 37 (1966) 21-34

The **mechanism** can explain direct $\phi$-$N$ interaction :

1. Coupling of $\phi$ to hidden **strangeness** content of $N$

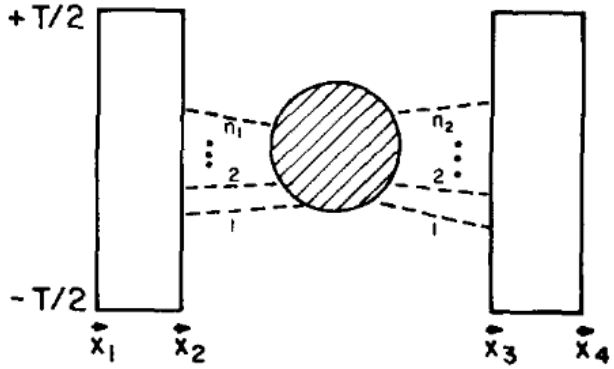



**non-valence $s\bar{s}$** quarks of $N$

OZI-**violating**

Phys.Lett.B 217 (1989) 173-180

2. QCD van der Waals interaction via **multi-gluon exchange**




Phys.Lett.B 77 (1978) 405-410

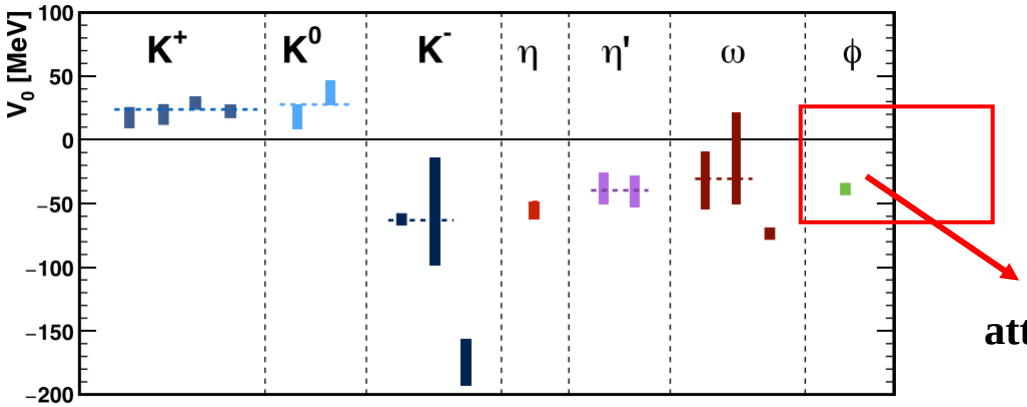
3. Others ...

$\phi N$ systems are exotic few-body systems with strong interaction.

# Meson–nucleus potential

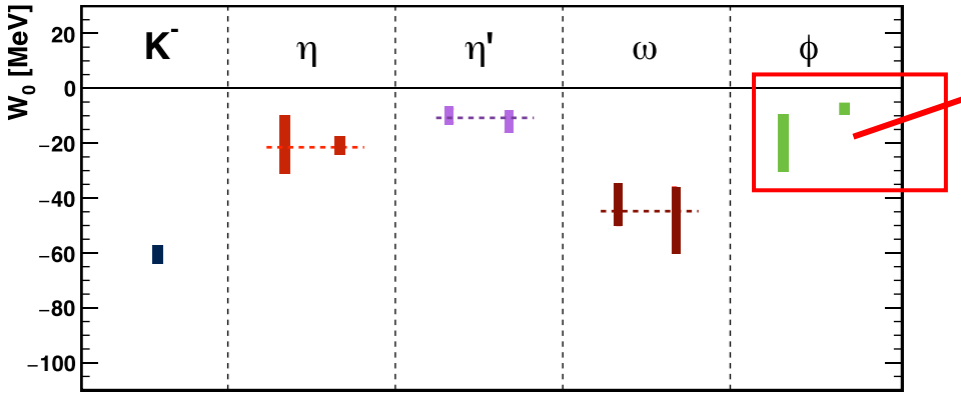
The **complex** meson–nucleus potential: $U(r) = V(r) + iW(r)$

**real** part:

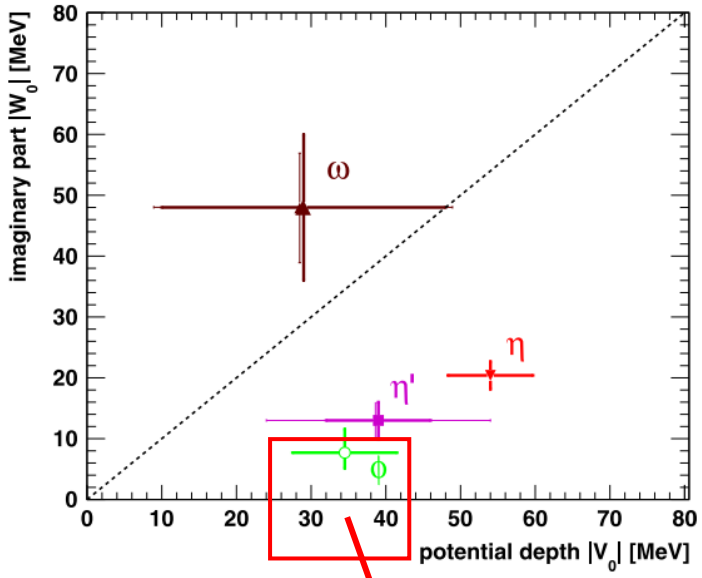



**attractive**

**imaginary** part:




**meson absorption** in the nuclear medium




$|V| > |W|$ :

the potential **depth** > the **width** of the state

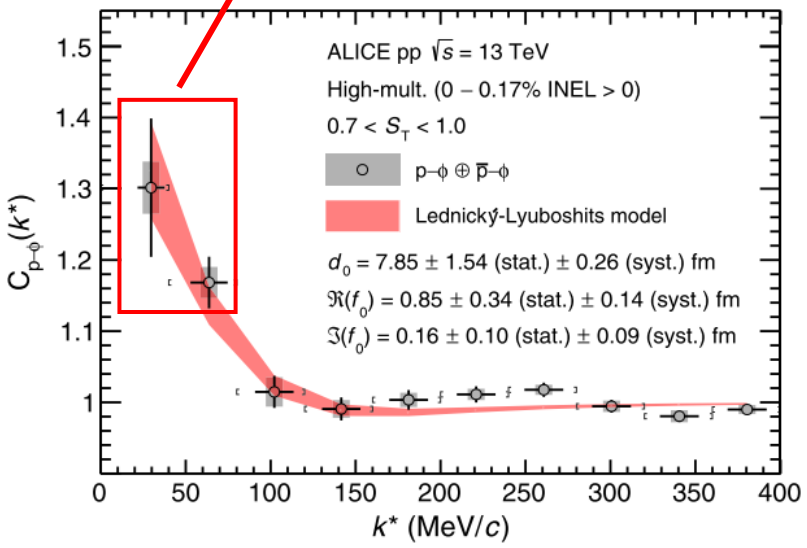
Possibility of **quasi-bound state**

Prog.Part.Nucl.Phys. 97 (2017) 199-260

# Microscopic calculations

# $N-\phi$ potential

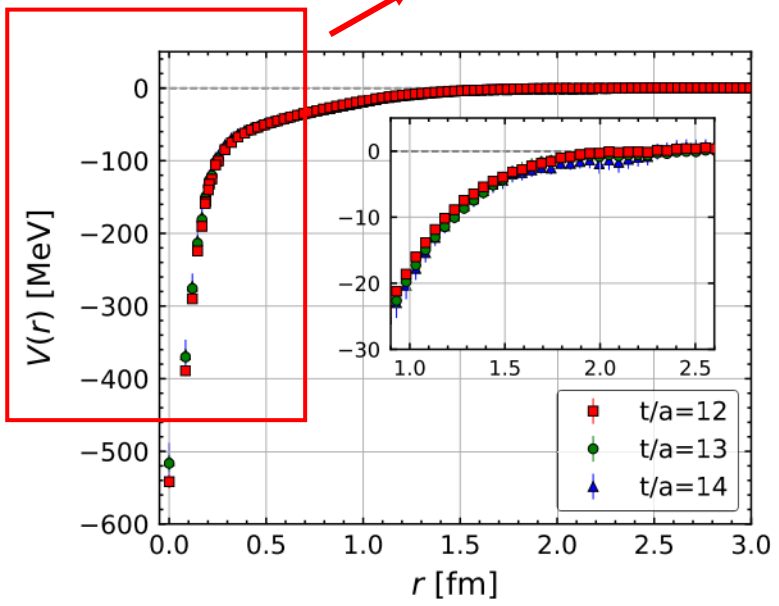
Pronounced **enhancement** respect to the unity: **attraction**




Experimental Evidence for an **Attractive** $\boldsymbol{p-\phi}$ Interaction

Phys.Rev.Lett. 127 (2021) 17, 172301

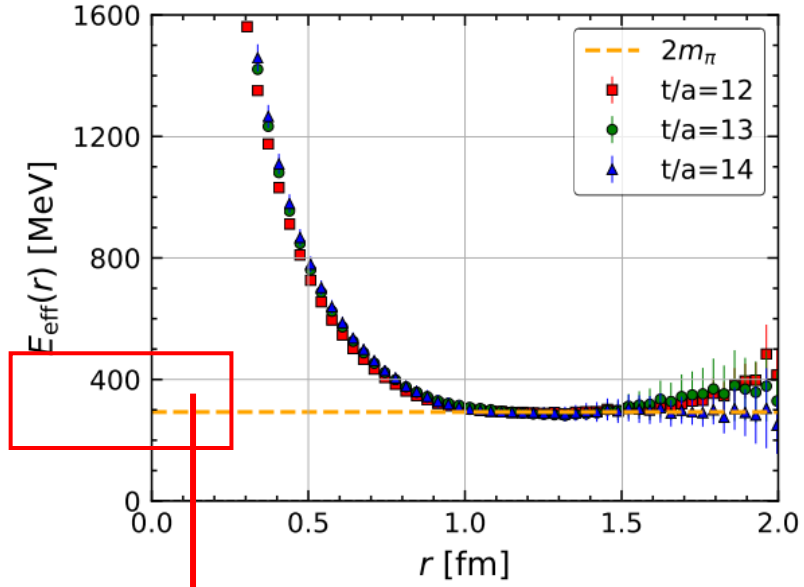
V(r) < 0 : **attractive** for all distances




HAL QCD $\boldsymbol{N-\phi}$ potential

$N-\phi$ $^4S_{3/2}$ channel

Phys.Rev.D 106 (2022) 7, 074507




**long-range attractive tail** dominated by the **TPE (two-pion exchange)**

$$V_{\phi N}(r) = \sum_{i=1}^{2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r;b_3)\left(\frac{e^{-m_\pi r}}{r}\right)^2$$

**short-range** Gaussians

$^{2S+1}L_J$

S: total **spin** angular momentum

L: total **orbital** angular momentum

J: **total** angular momentum

# $N-\phi$ potential

HAL QCD $N-\phi$ potential ( ${}^4S_{3/2}$ channel ) :

$$V_{\phi N}(r)=\sum_{i=1}^{2} a_i e^{-(r/b_i)^2}+a_3 m_\pi^4 f(r;b_3)\left(\frac{e^{-m_\pi r}}{r}\right)^2$$

**short-range** Gaussians

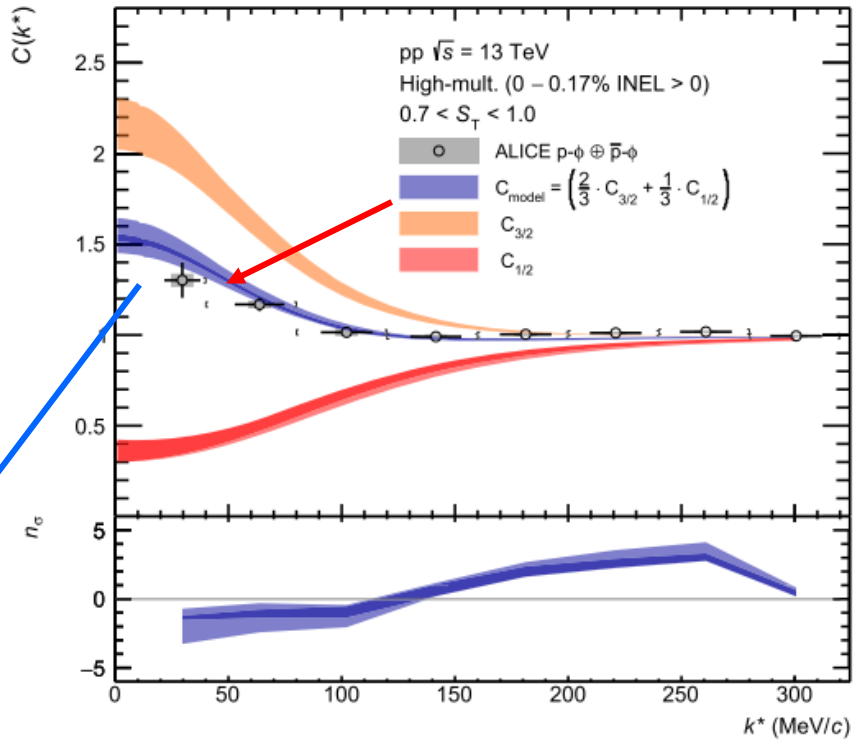
**long-range attractive tail** dominated by the **TPE (two-pion exchange)**

Phys.Rev.D 106 (2022) 7, 074507

$N-\phi$ potential ( ${}^2S_{1/2}$channel ) :

$$V_{\phi N}(r)=\beta\left(\sum_{i=1}^{2} a_i e^{-(r/b_i)^2}\right)+a_3 m_\pi^4 f(r;b_3)\left(\frac{e^{-m_\pi r}}{r}\right)^2$$

$\beta$: short-range attraction parameter




Phys.Lett.B 848 (2024) 138358

**Fit** to the experimental p-$\phi$ correction function

**enhanced** attraction in the ${}^2S_{1/2}$ channel → possible bound state $p-\phi$ ${}^2S_{1/2}$ channel

# Microscopic calculations

Different $\boldsymbol{\phi N}$ interactions

1. Yukawa-type $\boldsymbol{\phi N}$ potential : $V_{\phi N}(r) = -\alpha e^{-\mu r}/r$ Phys.Rev.C 63 (2001) 022201

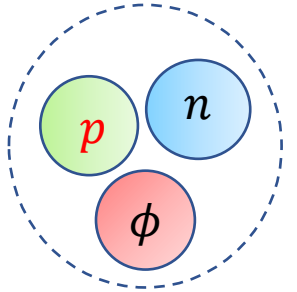
2. HAL QCD type $\boldsymbol{\phi N}$ potential : $V_{\phi N}(r) = \sum_{i=1}^{2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r; b_3) \left(\frac{e^{-m_\pi r}}{r}\right)^2$

Phys.Rev.D 106 (2022) 7, 074507 Phys.Lett.B 848 (2024) 138358

**Three**-body calculations of the $\boldsymbol{\phi NN}$ systems :

**Microscopic** calculations

- Faddeev equations — Phys.Rev.D 110 (2024) 3, L031502 arXiv:0903.1703; J. Phys. G: Nucl. Part. Phys. 37, 085109 (2010); Phys.Lett.B 877 (2026) 140496 .....
- Variational — Few Body Syst. 44 (2008) 347-349 .....
- Hyperspherical expansions — Phys.Rev.C 109 (2024) 5, 054002 .....
- Coupled-channel complex-scaling approaches — Phys.Rev.D 111 (2025) 11, 114004 .....
- ……




$^{3}_{\phi}\mathrm{H}$

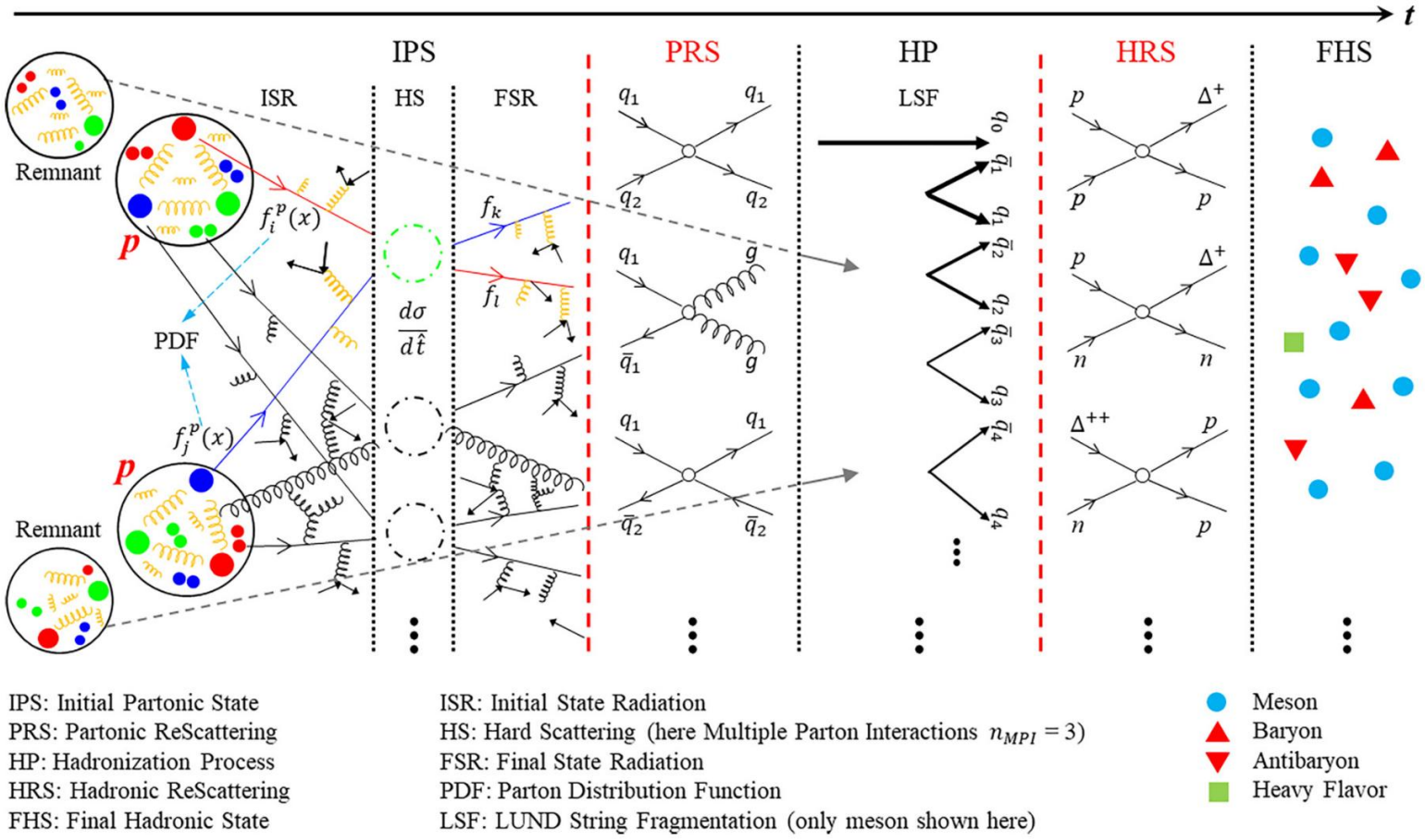
**$\boldsymbol{\phi}$-mesic nuclei**

**Q**: How about the **macroscopic** methods for $\boldsymbol{\phi NN}$ and $\boldsymbol{\phi NNN}$ systems?

Such as the **phenomenological** model …

# PACIAE and DCPC model

# The PACIAE model




Phys.Rev.C 108 (2023) 6, 064909

Comput.Phys.Commun. 310 (2025) 109520

Sketch for the physical routines in a high-energy pp simulation

**macroscopic** methods

**PACIAE**： **P**arton **A**nd-hadron **CIAE** ( the parton and hadron cascade model )

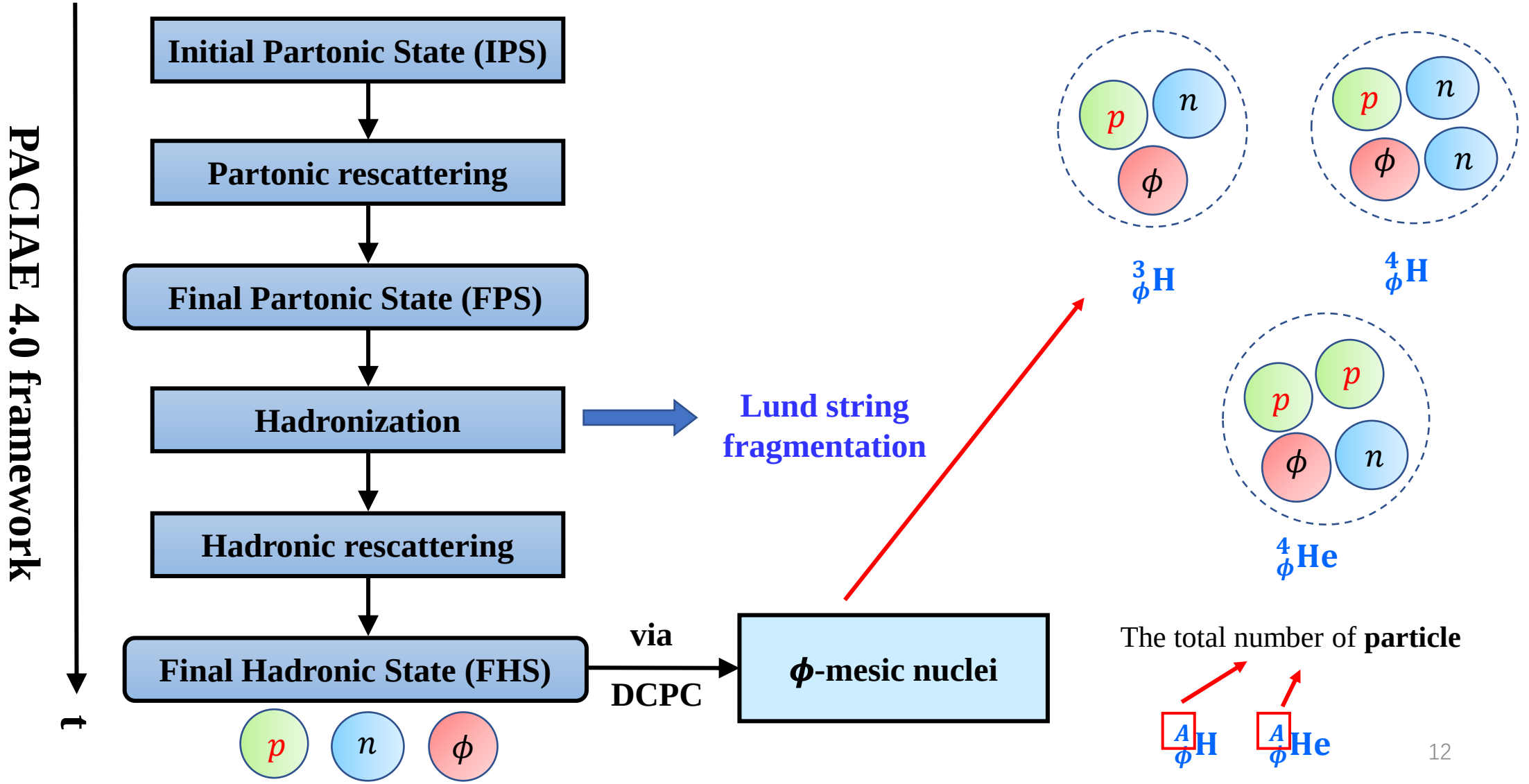
The model is based on the **PYTHIA** model , can be used to describe elementary particle collisions and heavy-ion collisions.

Open source : https://github.com/ArcsaberHep/PACIAE

# Sketch of PACIAE+DCPC



**pp** collisions at $\sqrt{s_{NN}}$ = 7 TeV



# The DCPC model

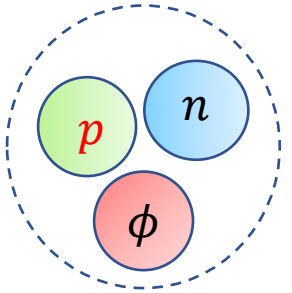
**DCPC：** **D**ynamically **C**onstrained **P**hase-space **C**oalescence model

- The cluster yield containing *N* particles is: $Y_N = \int \dots \int_{E_a \le H \le E_b} \frac{\mathrm{d}\vec{r}_1 \mathrm{d}\vec{p}_1 \dots \mathrm{d}\vec{r}_N \mathrm{d}\vec{p}_N}{h^{3N}},$

  $E_a$ and $E_b$ : the lower and upper energy thresholds

- The yield of ${}^{3}_{\phi}\mathrm{H}$ can be written:

$$Y_{{}^{3}_{\phi}\mathrm{H}} = \int \dots \int \delta_{123} \prod_{i=1}^{3} \frac{\mathrm{d}\vec{r}_i \mathrm{d}\vec{p}_i}{h^3},$$




${}^{3}_{\phi}\mathbf{H}$

- Where

$$\delta_{123} = \begin{cases} 1 & \text{if} \quad 1 \equiv \phi, \quad 2 \equiv \mathrm{p}, \quad 3 \equiv \mathrm{n} \\ & m_0 - \Delta m \le m_{\mathrm{inv}} \le m_0 + \Delta m, \\ & r_{i0} \le R_0, (i = 1, 2, 3) \\ 0 & \text{otherwise.} \end{cases}$$

→ Component constraint

→ Momentum constraint

→ Spatial coordinate constraint

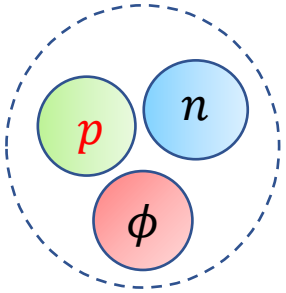
- The invariant mass of cluster can be calculated: $m_{\mathrm{inv}} = \sqrt{\left(\sum_{i=1}^{3} E_i\right)^2 - \left(\sum_{i=1}^{3} \vec{p}_i\right)^2}.$

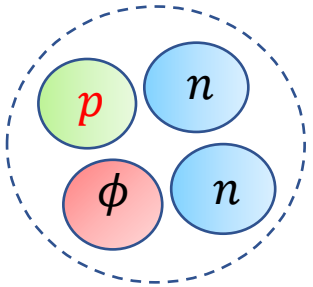
Phys.Rev.C 85 (2012) 024907

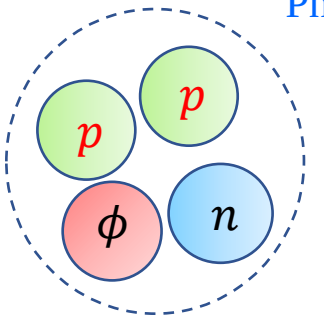
# The constraints of DCPC

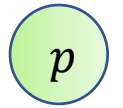
Phys.Rev.D 110 (2024) 3, 030001

PGG 2024

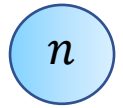


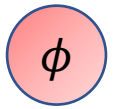




938.27 MeV




939.56 MeV




1019.461 MeV

The **mass** of $\phi$-mesic nuclei

| | $^{3}_{\phi}$H | $^{4}_{\phi}$H | $^{4}_{\phi}$He |
|---|---|---|---|
| $m_0$ ( MeV/$c^2$ ) | 2897 | 3837 | 3836 |
| $\Delta m$ ( MeV/$c^2$ ) | 50.255 | 55.55 | 54.71 |

$m_0 - \Delta m \leq m_{inv} \leq m_0 + \Delta m$

Mass uncertainty

The **sum** of component hadron mass

The **binding energies** of $\phi$-mesic nuclei

Phys.Lett.B 877 (2026) 140496

$r_{i0} \leq R_0$

The **radius** of cluster

$1.0\ \text{fm} < R_0 < 5.0\ \text{fm}$

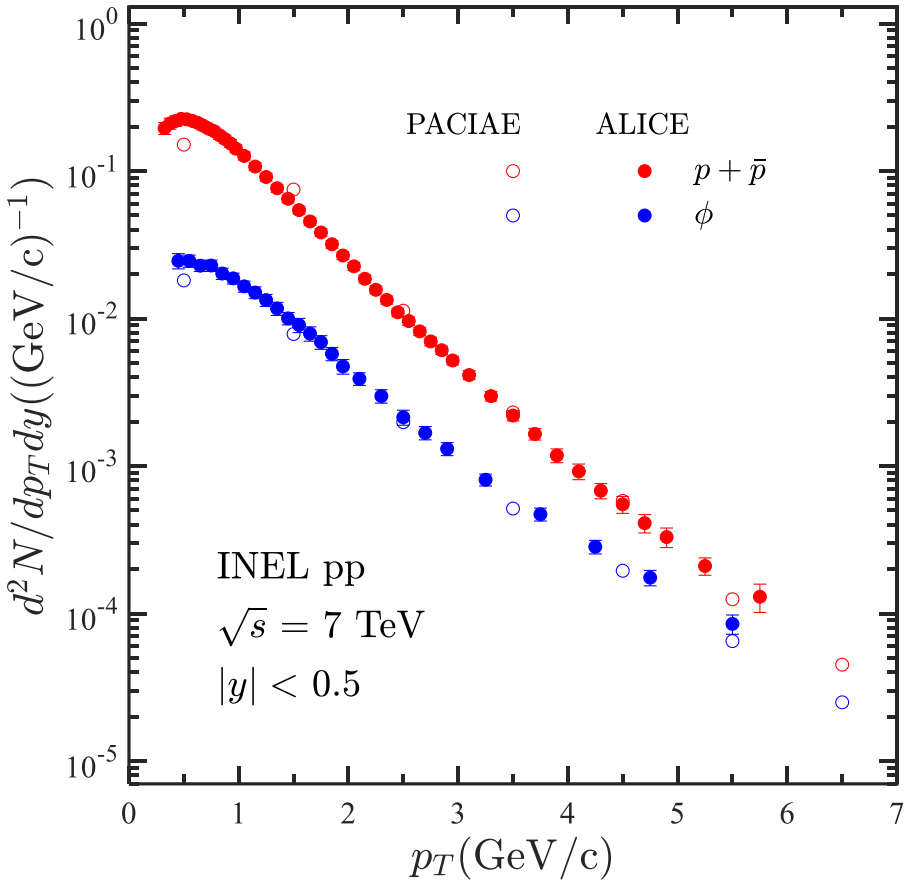
$1.0\ \text{fm} < R_0 < 3.0\ \text{fm}$

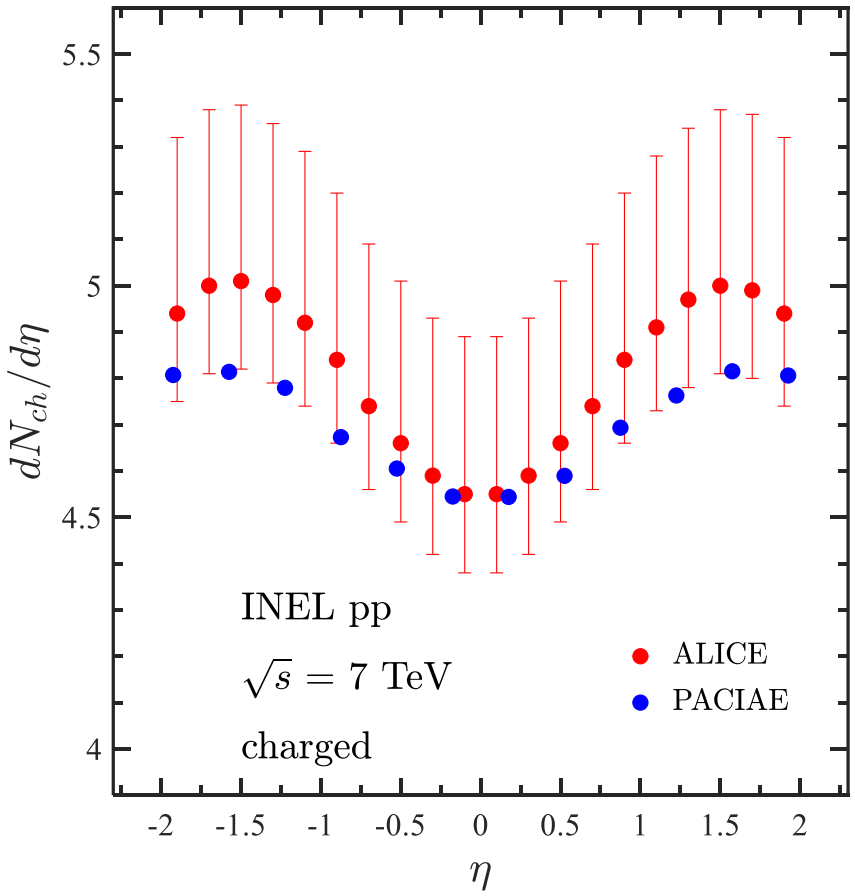
$1.0\ \text{fm} < R_0 < 2.0\ \text{fm}$

Discuss the **dependence** of $\phi$-mesic nuclei production on $R_0$

# Results about $\phi$-mesic nuclei

# Fitted results of hadrons



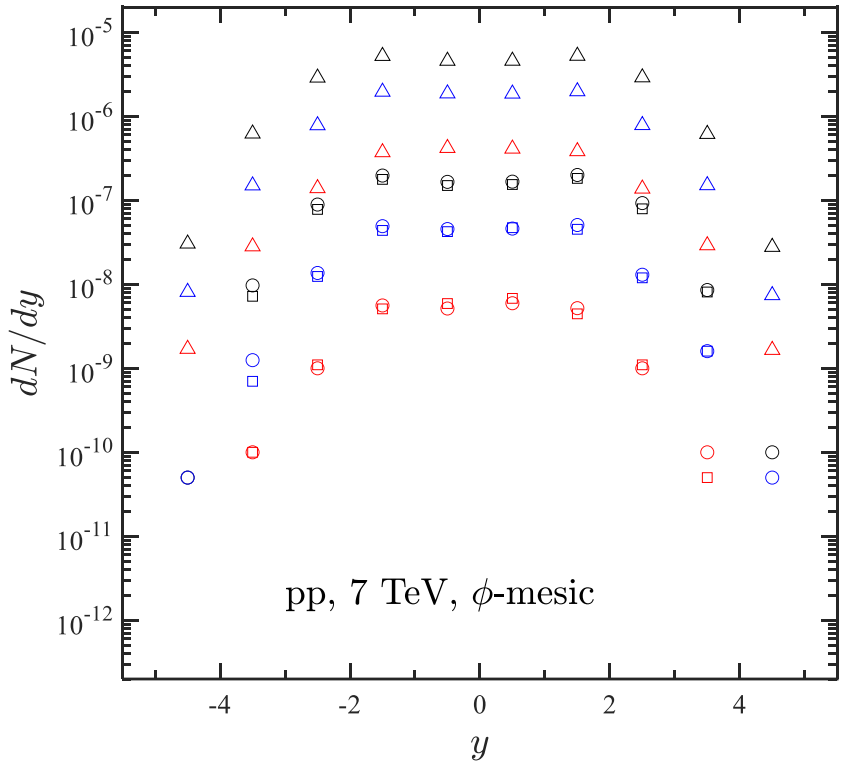




ALICE data: Eur.Phys.J.C 75 (2015) 5, 226

Eur.Phys.J.C 72 (2012) 2183

Eur.Phys.J.C 77 (2017) 1, 33

# Simulated results of $\phi$-mesic nuclei



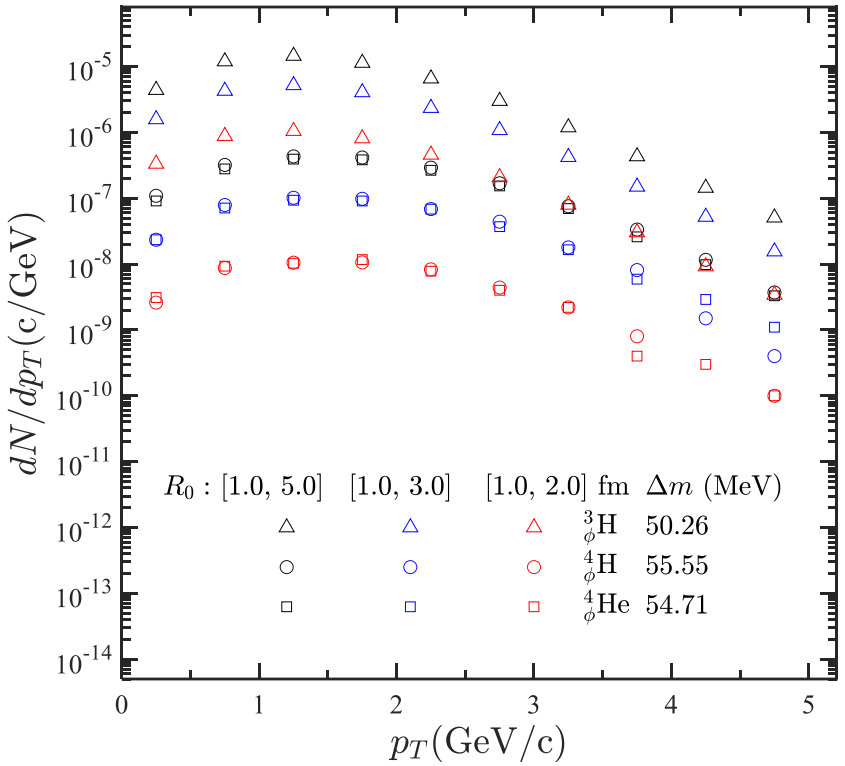




TABLE II. The simulated yields of $^3_\phi$H, $^4_\phi$H, and $^4_\phi$He for three $R_0$ ranges, [1.0, 2.0], [1.0, 3.0] and [1.0, 5.0] fm.

| $\phi$-mesic nuclei | [1.0, 2.0] fm | [1.0, 3.0] fm | [1.0, 5.0] fm |
|---|---|---|---|
| $^3_\phi$H | $1.92 \times 10^{-6}$ | $9.50 \times 10^{-6}$ | $2.66 \times 10^{-5}$ |
| $^4_\phi$H | $2.02 \times 10^{-8}$ | $2.09 \times 10^{-7}$ | $9.25 \times 10^{-7}$ |
| $^4_\phi$He | $2.44 \times 10^{-8}$ | $2.06 \times 10^{-7}$ | $8.36 \times 10^{-7}$ |

# Summary and outlook

# Summary and outlook

- We recombined the $\phi$-mesic nuclei: ${}^{3}_{\phi}\mathrm{H}$, ${}^{4}_{\phi}\mathrm{H}$, and ${}^{4}_{\phi}\mathrm{He}$ based on the PACIAE + DCPC model in $pp$ collisions at $\sqrt{s}$ = 7 TeV.
- The simulated yields of ${}^{4}_{\phi}\mathrm{H}$ and ${}^{4}_{\phi}\mathrm{He}$ are much lower than that of ${}^{3}_{\phi}\mathrm{H}$, while the yields of ${}^{4}_{\phi}\mathrm{H}$ and ${}^{4}_{\phi}\mathrm{He}$ are almost identical.
- The simulated transverse momentum ($p_T$) spectra and rapidity ($y$) distributions of $\phi$-mesic nuclei require experimental verification.

Next studies:

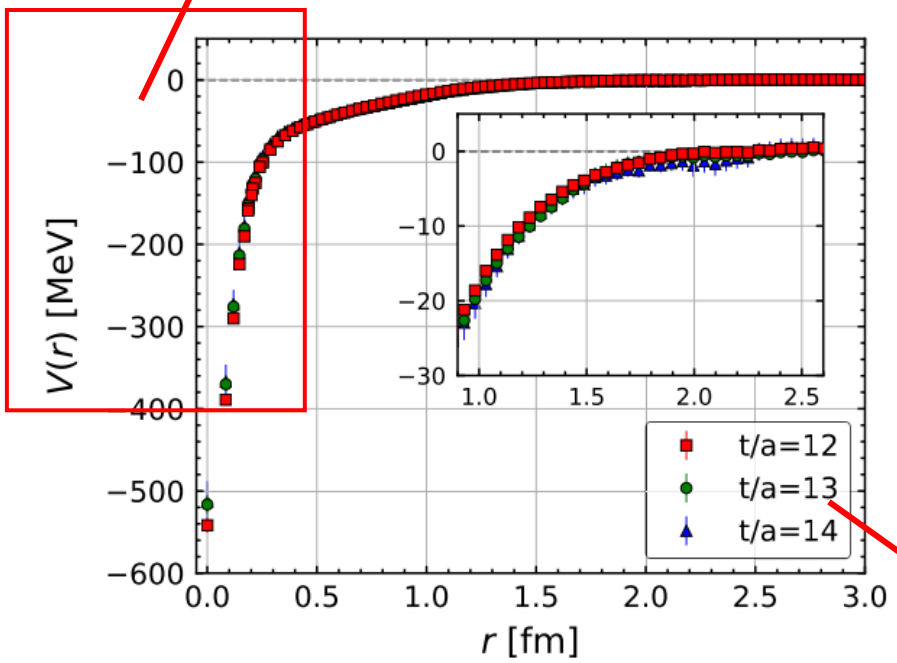
- Further research on the $\phi$-mesic nuclei with five or more bodies is necessary. Extending to $p$-Pb and Pb-Pb collisions is also required.
- New observables such as elliptic flow and nuclear modification factor are also worthy of investigation.

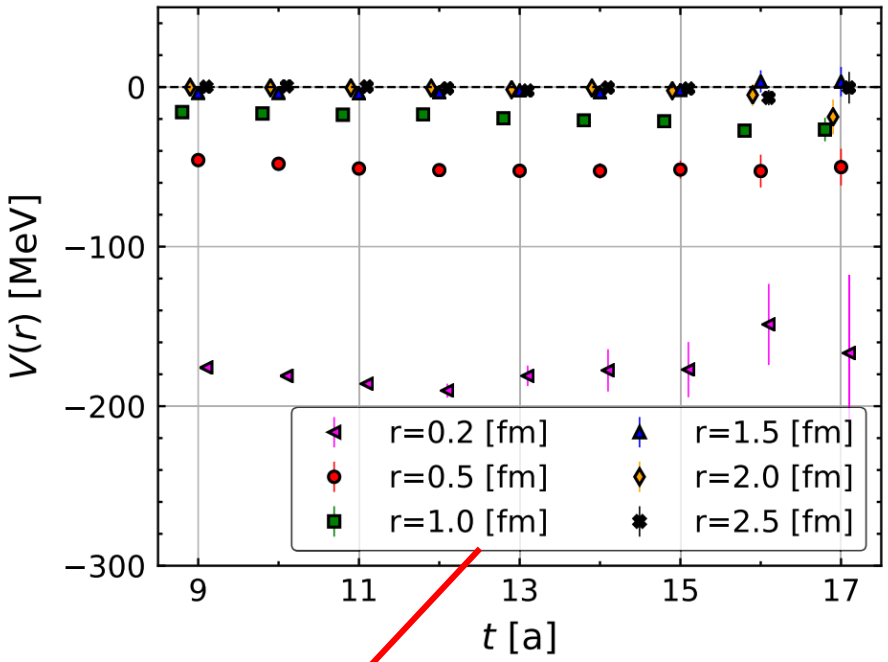
# 谢 谢 观 看

THANK YOU FOR WATCHING

# Dominant elastic scattering

V(r) < 0 : **attractive** for all distances




HAL QCD $\boldsymbol{N-\phi}$ potential

$N-\phi$ ${}^4S_{3/2}$ channel

Potential varies **slowly** with t
**elastic** scattering : **dominant** role
**inelastic** scattering: **suppressed**

Phys.Rev.D 106 (2022) 7, 074507

Phys.Rev.D 99 (2019) 1, 014514

Prog.Part.Nucl.Phys. 121 (2021) 103888