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Trials to determine the eta-nucleon and phi-nucleon low-energy scattering parameters

Clusters & Hierarchies

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第8回クラスター階層領域研究会
10 February 2023

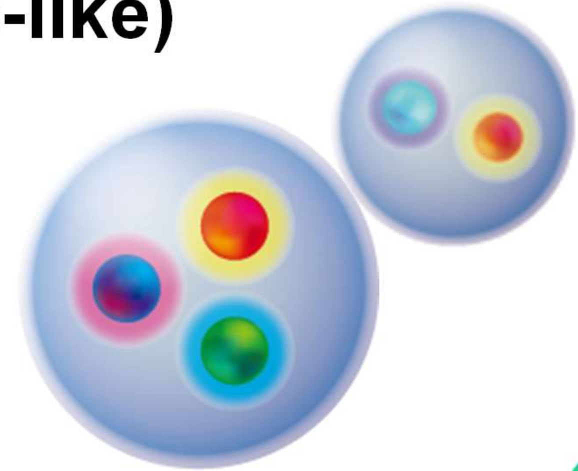
Introduction

Introduction

Internal structure of a baryon

qqq state (elementary-like)

meson-baryon state (molecule-like)



other effective degrees of freedom?

Introduction

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Compositeness X

Overlap of a bound state with the two-body scattering state X is directly given by the scattering length a and effective range r

$$a = \frac{2X}{X+1}R,\ r = \frac{X-1}{X}R,\ R = (2\mu B)^{-1/2}$$

S. Weinberg, Phys. Rev. 137, B672 (1965).

X can be extended to near-threshold resonances

T. Hyodo, Phys. Rev. Lett. 111, 132002 (2013).

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Low-energy scattering parameters

low-energy scattering is characterized with the S-wave phase shift $\delta(p)$

$$p\cot\delta(p) = \pm\frac{1}{a} + \frac{1}{2}rp^2 + O(p^4)$$

a: scattering length
r: effective range

$+$ definition: often used in meson-baryon scattering

positive (negative) a provides attraction (repulsion)

a is negative if a bound state exists

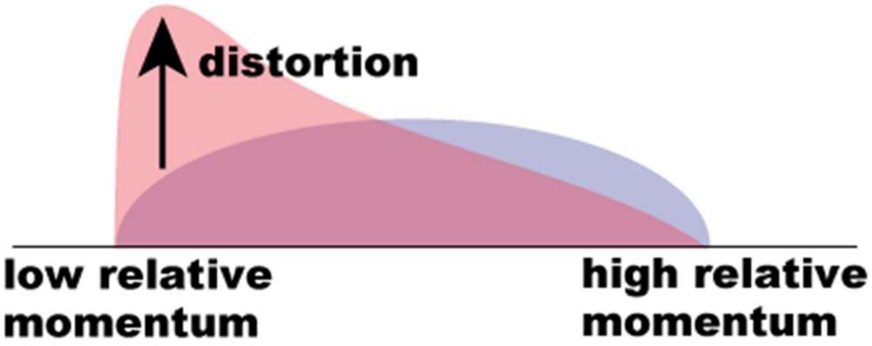
$-$ definition: often used in baryon-baryon scattering

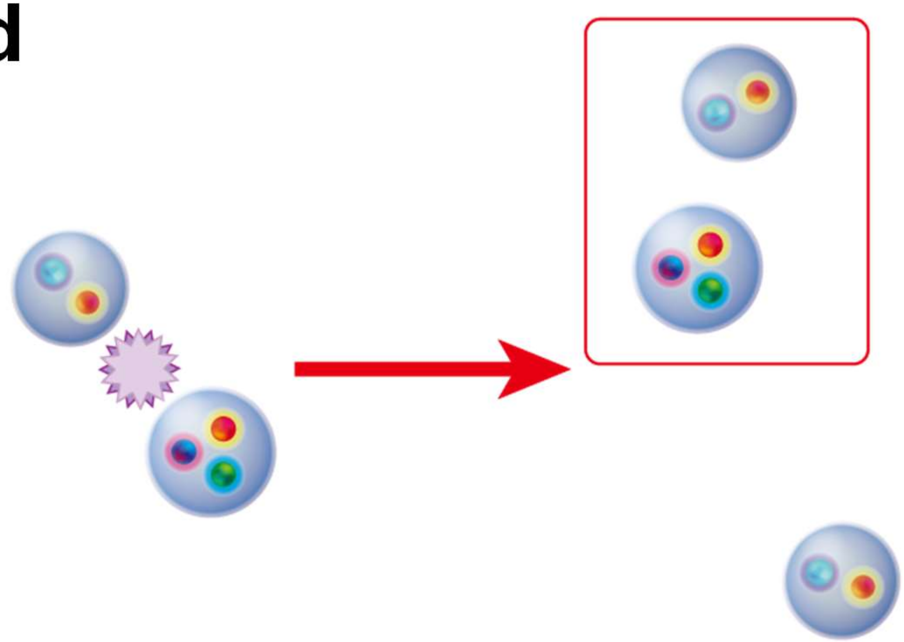
opposite

Introduction

Final-state interaction (FSI)

often utilized when a direct scattering experiment is difficult to be realized





1) low relative momentum between the two hadrons of interest
2) small or well-known FSI effects for the others
3) well-known production mechanism effects

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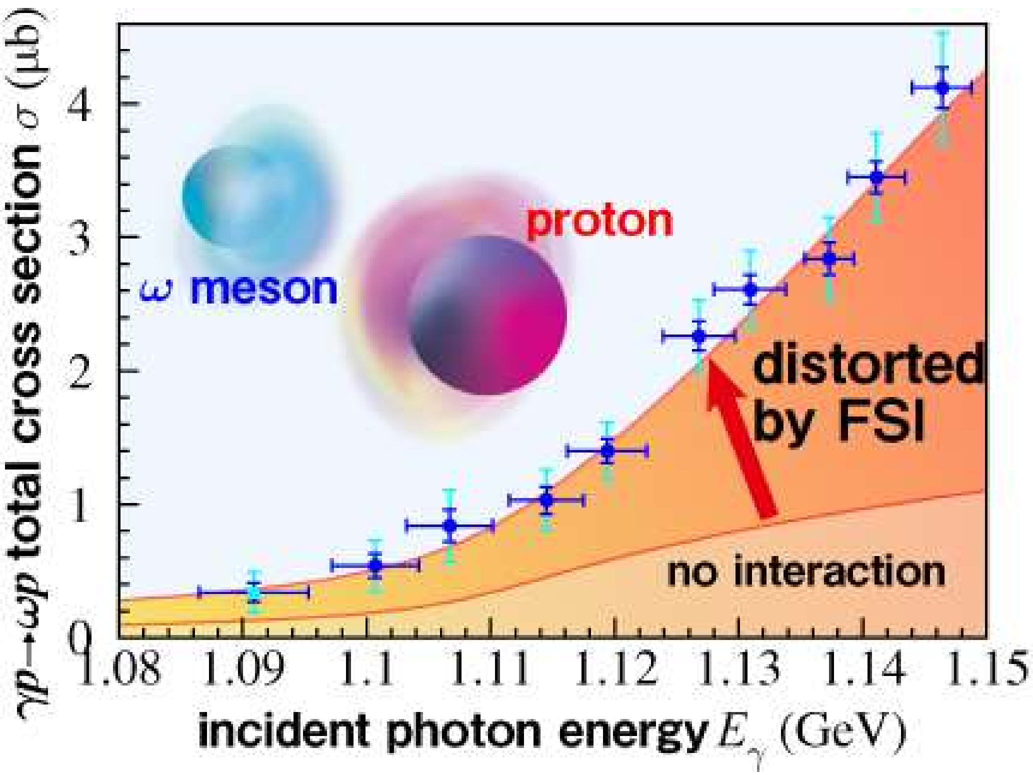
Final-state interaction (FSI)

ωN scattering length from ω photoproduction on the proton near the reaction threshold,

T. Ishikawa *et al.*, Phys. Rev. C101, 052201 (R) (2020).



$\gamma p \to \omega p$ near the threshold

1) relative momentum: low
2) FSI with another: no
3) production: small effects

Repulsive low-energy scattering parameters

No bound state
No resonance state

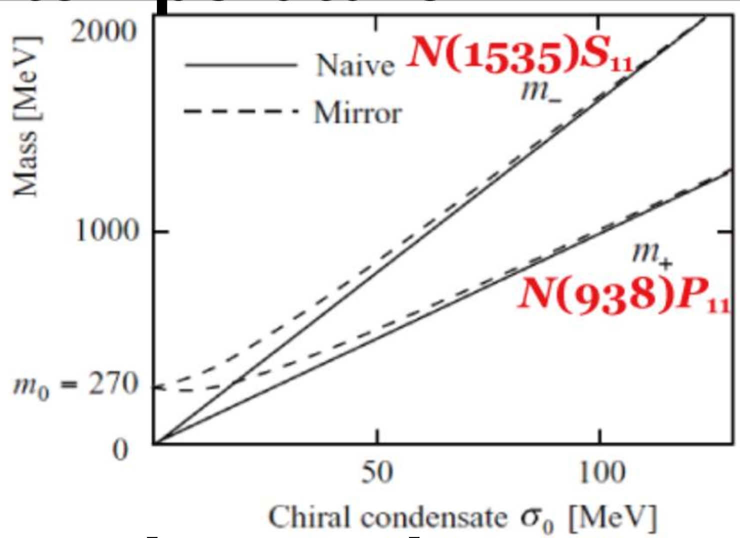
ηN system

ηN system

Nucleon resonance $N(1535)1/2^-$

Chiral partner of the nucleon $N(940)1/2^+$ (elementary-like?)

$N(940)$ and $N(1535)$ degenerate at high density and/or high temperature



C. DeTar and T. Kunihiro, Phys. Rev. D 39, 2805 (1989);

T. Hatsuda and M. Prakash, Phys. Lett. B 224, 11 (1989);

D. Jido, M. Oka, and A. Hosaka, Prog. Theor. Phys. 106, 873 (2001).

$N(1535)$ strongly couples to ηN (molecule-like?)

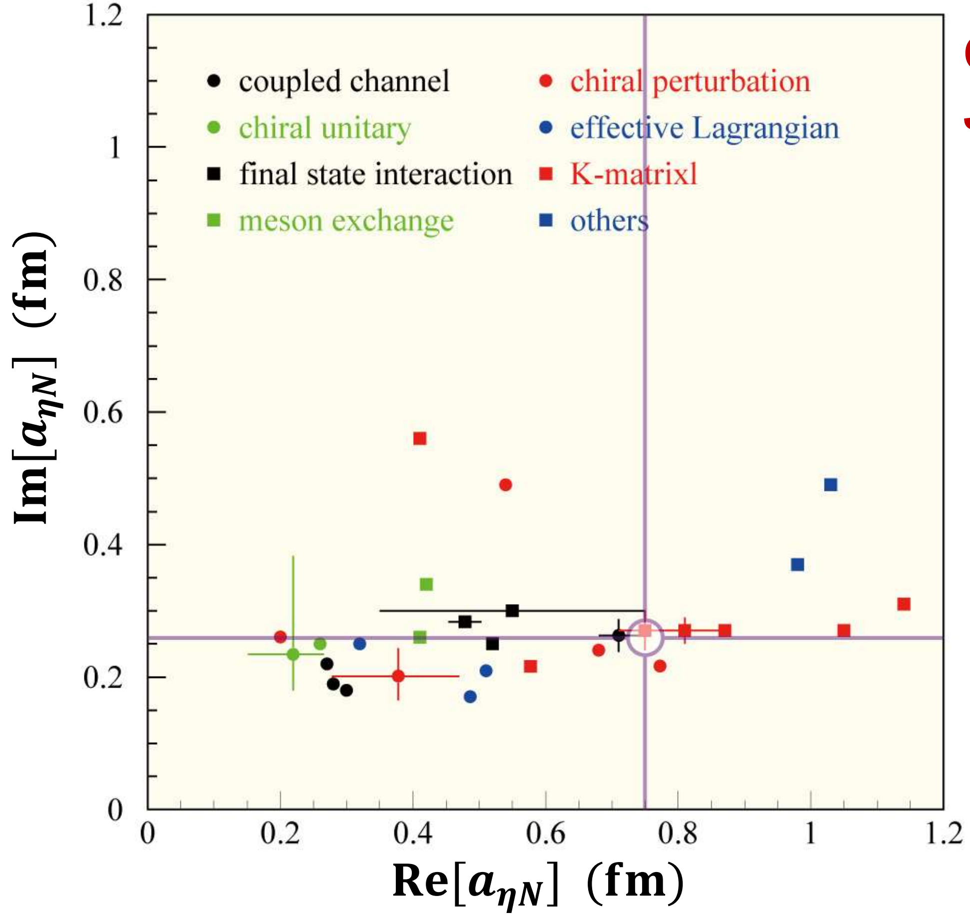
$$X_{\eta N} = 0.04 + i0.37$$

T. Sekihara *et al.*, Phys. Rev. C 93, 035204 (2016).

ηN system

Low-energy ηN scattering parameters

Chiral partner of the nucleon $N(940)1/2^+$ (elementary-like?)



Q. Haider and L.C. Liu,
J. Mod. Phys. E 24, 1530009 (2015).

determined from

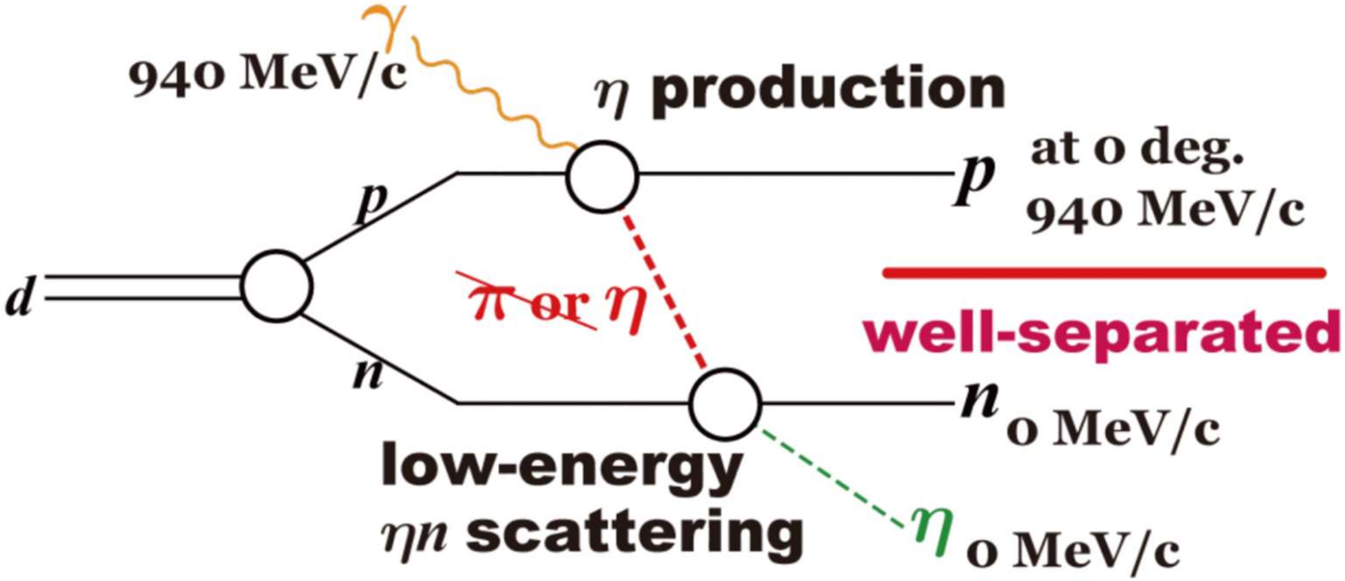
$\pi N \to \pi N, \pi N \to \eta N,$
$\gamma N \to \pi N, \gamma N \to \eta N$

$\mathrm{Im}[a_{\eta N}] \sim 0.25\ \mathrm{fm}$

$\mathrm{Re}[a_{\eta N}]$: widely distributed

ηN system

Final-state interaction (FSI)



S.X. Nakamura, H. Kamano, and T. Ishikawa, Phys. Rev. C 96, 042201 (R) (2017).

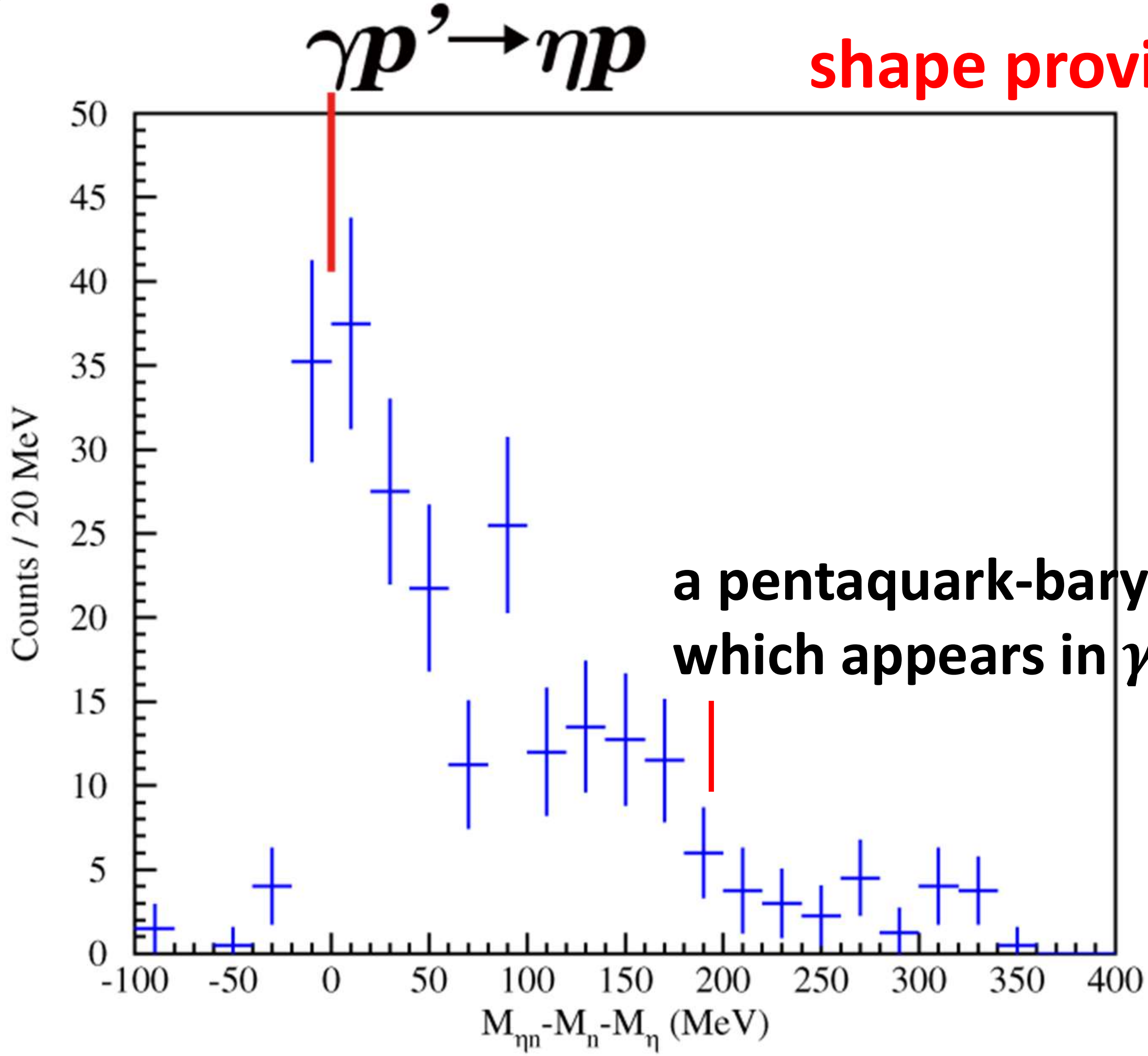
The yields are enhanced at low relative momentum between ηN corresponding to $a_{\eta N}$

1) **relative momentum:** low
2) **FSI with another:** known & small
3) **production:** known & small effects

ηN system

ηn invariant mass distribution

shape provides ηn rescattering



a pentaquark-baryon candidate $N(1680)$, which appears in $\gamma n \rightarrow \eta n$ is not observed

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ηN system

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Clusters & Hierarchies

Resonance-like structure near the ηd threshold in the $\gamma d \to \pi^0 \eta d$ reaction,

T. Ishikawa *et al.*, Phys. Rev. C104, L052201 (2021).

Coherent photoproduction of the neutral-pion and η-meson on the deuteron at incident energies below 1.15 GeV,

T. Ishikawa *et al.*, Phys. Rev. C105, 045201 (2022).

<u>$\gamma d \to \pi^0 \eta d$</u>

two sequential processes:

$$\gamma d \to \mathcal{D}_{\rm IV} \to \pi^0 \mathcal{D}_{\rm IS} \to \pi^0 \eta d$$

$$\gamma d \to \mathcal{D}_{\rm IV} \to \eta \mathcal{D}'_{\rm IV} \to \pi^0 \eta d$$

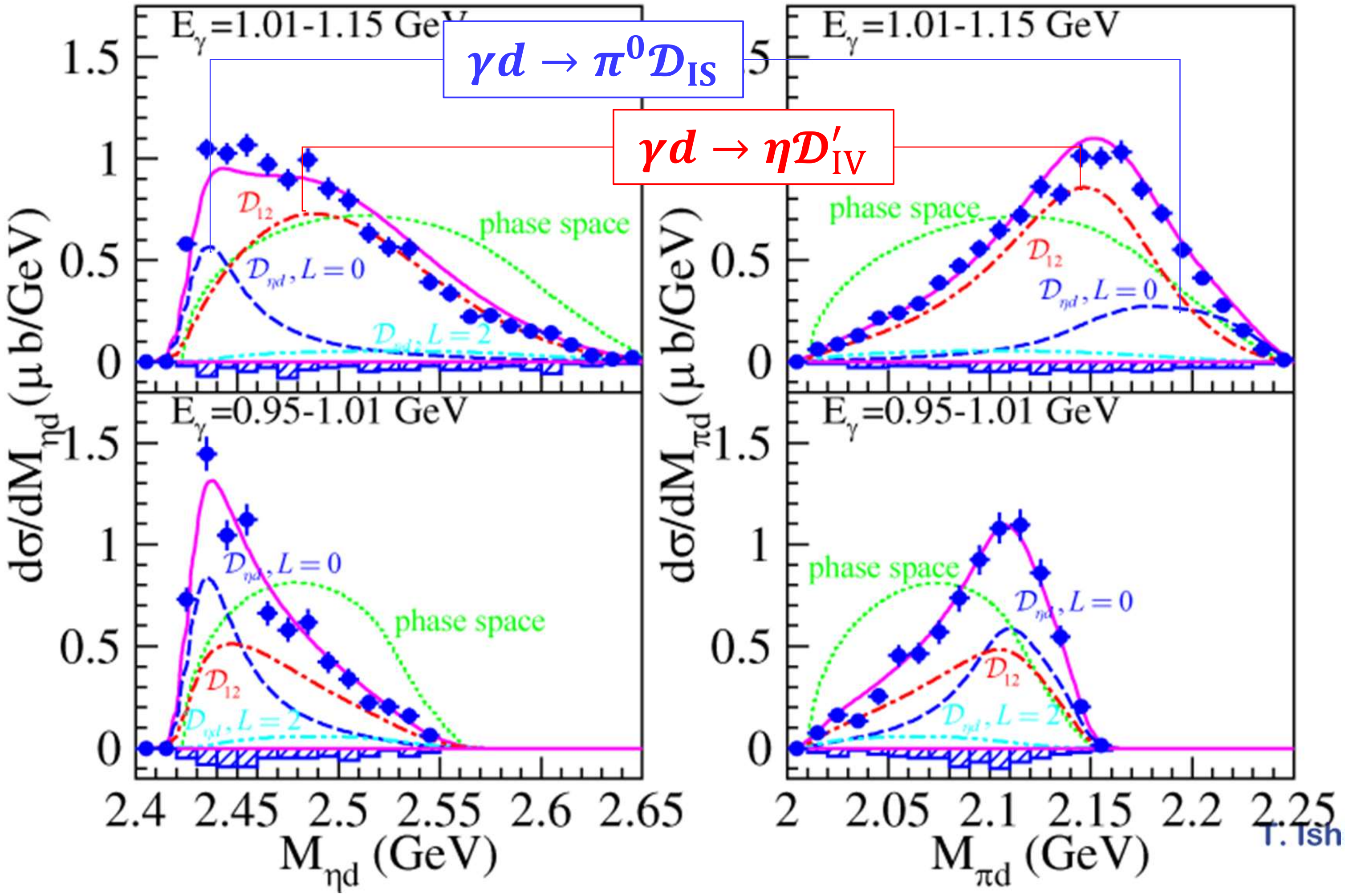
isotropic deuteron emission in γd-CM

ηN system

for the first time

Mass distributions $d\sigma/dM_{\eta d}$ and $d\sigma/dM_{\pi d}$

$\mathcal{D}_{\mathrm{IS}}$: $M = 2.427^{+0.013}_{-0.006}$ GeV, $\Gamma = 0.029^{+0.006}_{-0.029}$ GeV $+ 0.00^{+0.41}_{-0.00} pc$



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ηN system

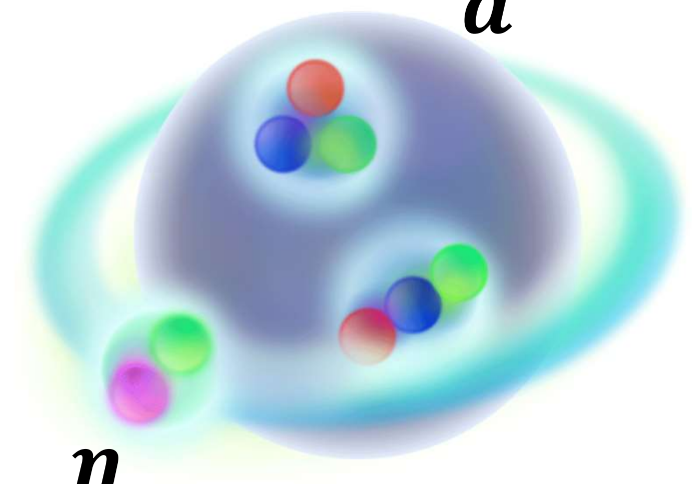
ηd attraction

bound state or

$$\Gamma = \Gamma_0 \text{ and } M_{\eta d} < M_\eta + M_d$$

virtual state

$$\Gamma = gpc$$



Low-energy ηd scattering parameters

$$a_{\eta d} = \pm\left(0.7^{+0.8}_{-0.6}\right) + i\left(0.0^{+1.5}_{-0.0}\right)\ \mathrm{fm}$$

$$r_{\eta d} = \mp\left(4.3^{+8.6}_{-2.9}\right) - i\left(6.7^{+6.0}_{-8.4}\right)\ \mathrm{fm}$$

Consistent with theoretical three-body calculation with $a_{\eta N} = 0.50 + i0.33\ \mathrm{fm}$:

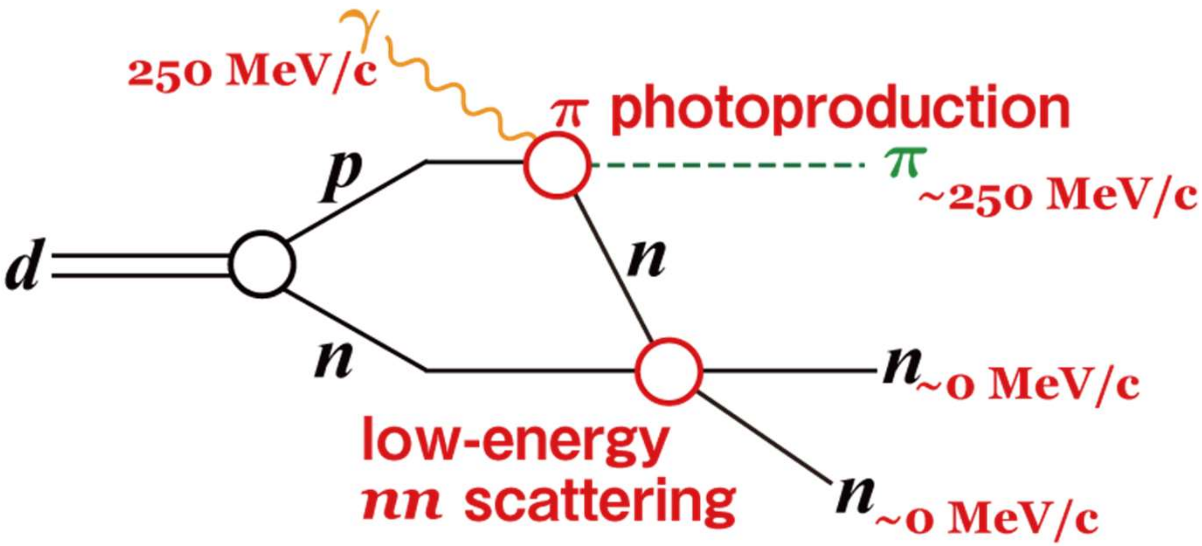
$$a_{\eta d} = 1.23 + i1.11\ \mathrm{fm}$$

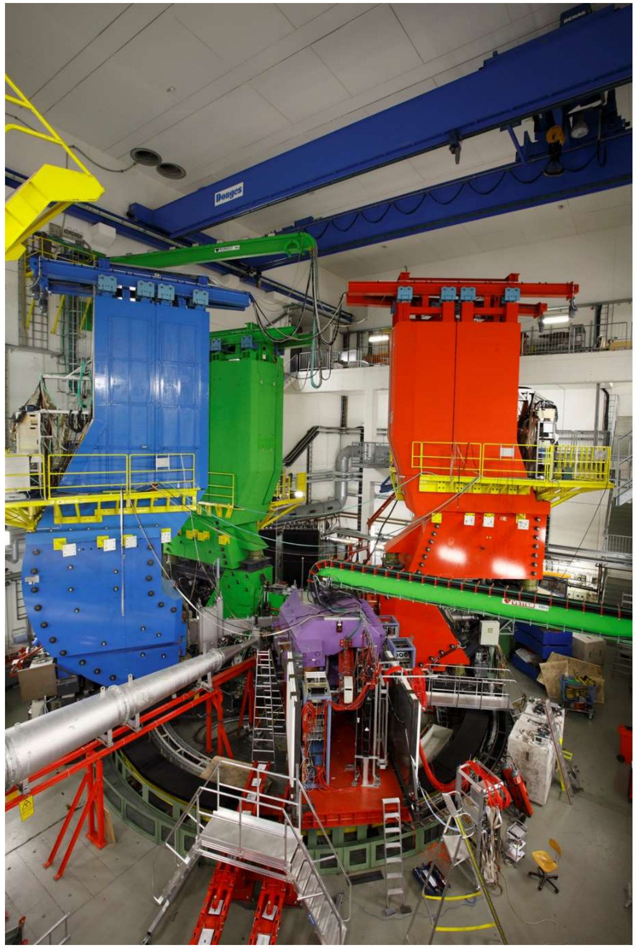
Rather weak attraction

ηN system

Application to nuclear physics

We plan to determine nn scattering length at Mainz MAMI for studying charge symmetry breaking using virtual photons from electron scattering.





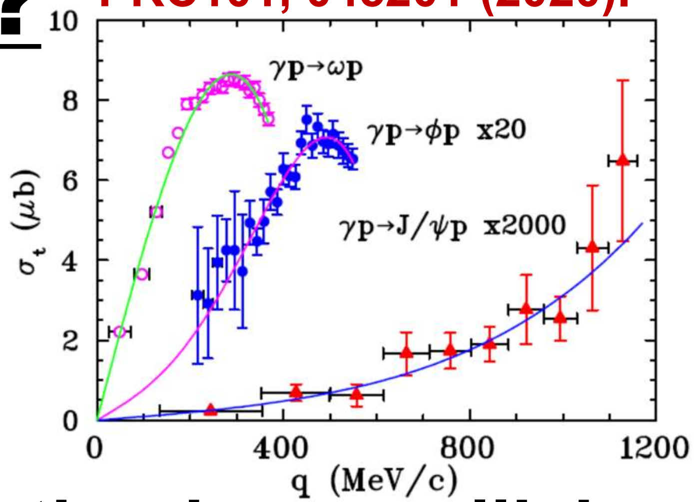
S.X. Nakamura, T. Ishikawa, T. Sato, arXiv: 2003.02497 (2020).

ϕN system

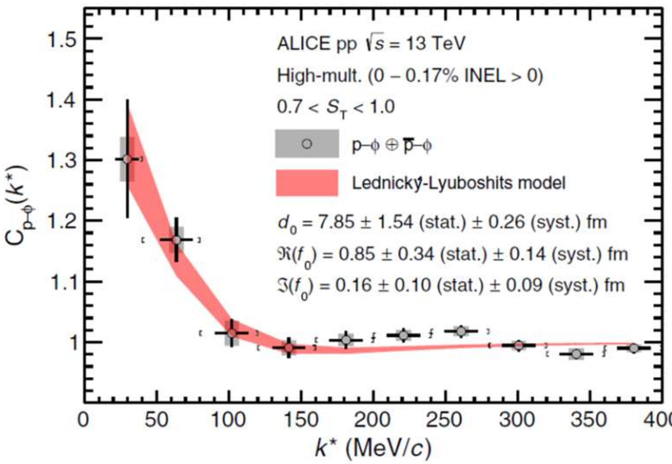
Different ϕN scattering lengths

Is VN interaction weak?

I.I. Strakovsky *et al.*, PRC101, 045201 (2020).



a_{VN} from photoproduction
vector meson dominance model
$|a_{\phi p}| = 0.063 \pm 0.010$ **fm**
Okubo-Zweig-Iizuka (OZI) rule
little admixture of $\bar{s}s$ in N



S. Acharya et al. (ALICE), PRL127, 172301 (2021).

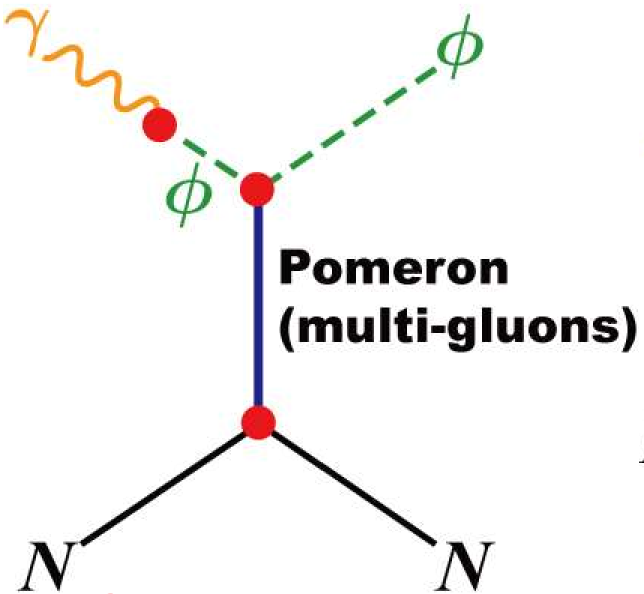
correlation function in pp collision
Lednický-Lyuboshits model
$a_{\phi p} = (0.85 \pm 0.34 \pm 0.14) + i(0.16 \pm 0.10 \pm 0.09)$ **fm**

HAL QCD calculation
$a_{\phi N}^{(3/2)} =\sim 1.25$ fm
Y. Lyu et al., PRD105, 074512 (2022).

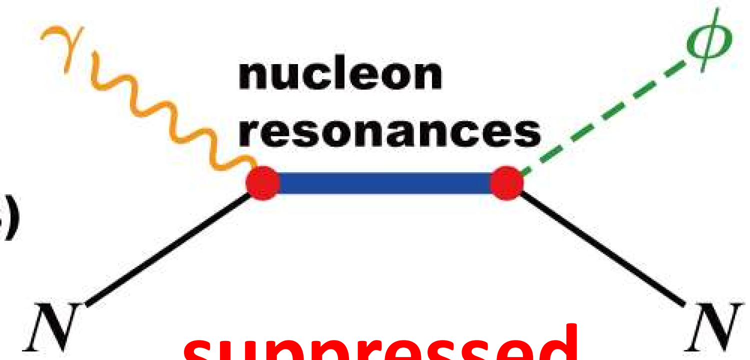
$\gamma p \to \phi p$ reaction

vector meson photoproduction

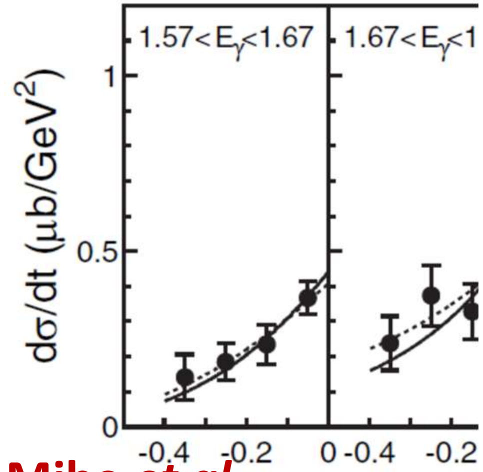
1. Vector meson properties of the photon
2. The t-channel exchange process is dominant even at low incident energies



dominant



suppressed



T. Mibe *et al.*, PRL95, 182001 (2005)

Strong exponential behavior near the threshold

$\gamma p \to \phi p$ is insensitive to ϕN systems

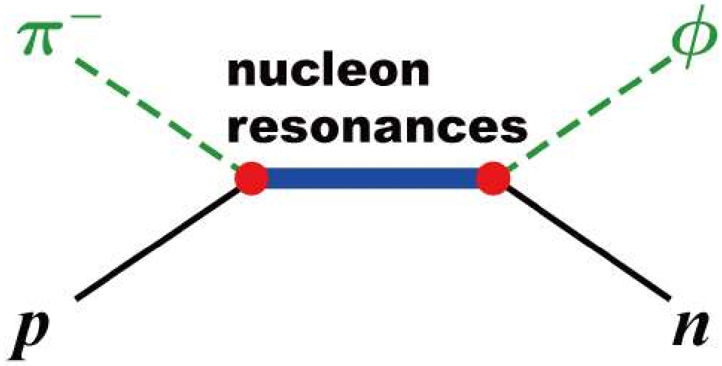
Reactions to study ϕN system

$\pi^- p \to \phi n$ at J-PARC [P95 / E45]

s-channel ϕN production

near the threshold:

ϕN scattering parameters



$W \sim 2.2$ GeV:

hidden-strangeness pentaquark baryon P_s

$\gamma p \to \pi^0 \phi p$ at LEPS2

similar to studies of the ηd interaction in $\gamma d \to \pi^0 \eta d$

$$\gamma p \to \pi^0 P_s \to \pi^0 \phi p$$
$$\gamma p \to \phi \Delta \to \pi^0 \phi p$$

Summary

Summary

Summary

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Final-state interaction

$\gamma p \to \omega p$: **repulsion**

T. Ishikawa *et al.*, PRC101, 052201 (R) (2020).

$ed \to e'\pi^+ nn$: **planned experiment at Mainz**

S.X. Nakamura et al., arXiv:200302497 (2020).

ηN system

$\gamma d \to p\eta n$: **analysis still on going**

S.X. Nakamura et al., PRC 96, 042201 (R) (2017).

$\gamma d \to \pi^0 \eta d$: **rather weak ηN attraction**

T. Ishikawa *et al.*, PRC104, L052201 (2021); PRC105, 045201 (2022).

ϕN system

$\pi^- p \to \phi n$ at J-PARC [P95]

$\gamma p \to \pi^0 \phi p$ at LEPS2

Backup

Backup

Low-energy ϕN scattering

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Near-threshold ϕ production

1. S-wave ϕN scattering
   (low relative ϕN momentum)
   the data taken are relevant to the ϕN scattering length ($a_{\phi N}$)
2. spin-averaged $a_{\phi N}$
   (spin-parity of a ϕN system is $1/2^{-}$ or $3/2^{-}$)

Two methods for $a_{\phi N}$ determination:

1. Imaginary part of $a_{\phi N}$
   $\mathrm{Im}[a_{\eta N}]$ determination
2. Complex $a_{\phi N}$
   $a_{\omega N}$ determination

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Imaginary part of $a_{\eta N}$

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Method 1

$\mathrm{Im}[a_{\eta N}]$ has been determined by fitting a linear function to $\sigma(P_\eta)$ for $\pi^- p \to \eta n$

Optical theorem leads:

$$\mathrm{Im}[a_{\eta N}] = \frac{p_\eta}{4\pi}\sigma_{\eta n}$$

negligibly small near the threshold

$$= \frac{p_\eta}{4\pi}\left(\sigma_{\eta n\to\pi N} + \sigma_{\eta n\to\pi\pi N} \boxed{+ \sigma_{\eta n\to\pi\pi\pi N}} + \sigma_{\eta n\to\eta N}\right)$$

$$\simeq \frac{3p_\pi^2}{8\pi p_\eta}\sigma_{\pi^- p\to\eta n} + \frac{p_\eta}{4\pi}\left(\sigma_{\eta n\to\pi\pi N} + \sigma_{\eta n\to\eta N}\right)$$

$$\geq \frac{3p_\pi^2}{8\pi p_\eta}\sigma_{\pi^- p\to\eta n}$$

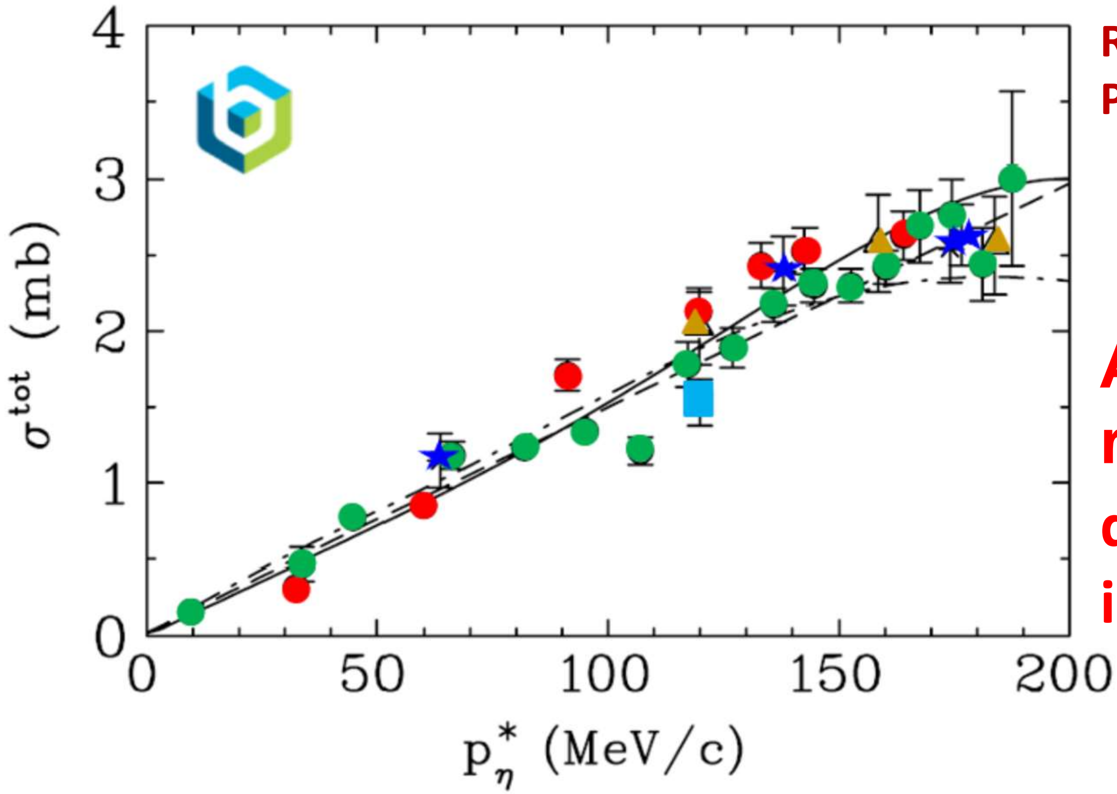
R.A. Arndt, I.I. Strakovsky et al.,
PRC74, 045202 (2005)

Imaginary part of $a_{\eta N}$

Method 1

Fitting result

$$\sigma_{\pi^- p\to\eta n}/p_\eta = 15.2 \pm 0.8\ \mu\mathrm{b/MeV}$$



R.A. Arndt, I.I. Strakovsky et al., PRC74, 045202 (2005)

A special treatment is required for $a_{\phi N}$ determination since ϕ width is ~ 4 MeV

$$\mathrm{Im}[a_{\eta N}] \geq 0.172 \pm 0.009\ \mathrm{fm}$$

Complex $a_{\omega N}$

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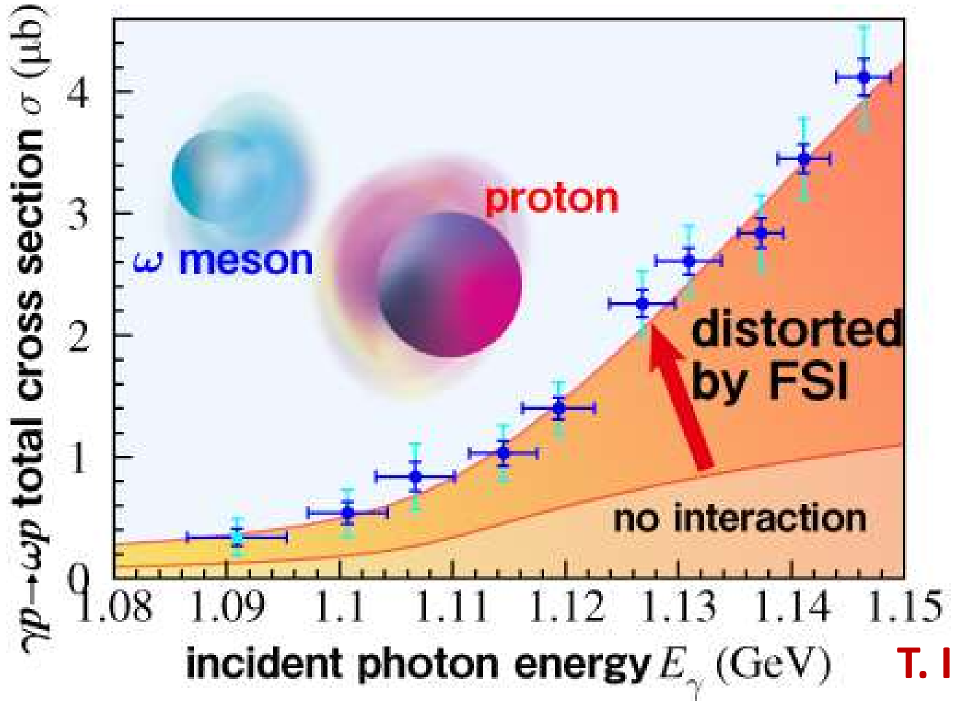
Method 2

$a_{\omega N}$ has been determined from $\sigma(E_\gamma)$ for $\gamma p \to \omega p$



T. Ishikawa et al., PRC101, 052201 (R) (2020).

complex ωN scattering parameters are determined for the first time

1) low relative momentum between ωp
2) no FSI effects for others (ωp alone in the final states)
3) insensitive production mechanism effects

Low-energy ϕN scattering

Method 2

a model with ωp final-state interaction (FSI) based on Lippmann-Schwinger equation

$$T_{\gamma p \to \omega p} = \left(1 + T_{\omega p \to \omega p} G_{\omega p}\right) V_{\gamma p \to \omega p}$$

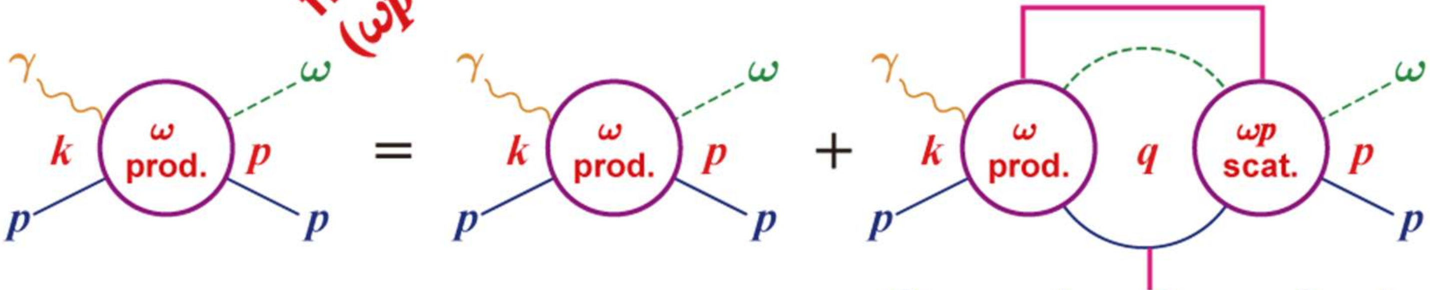
final-state interaction (ωp scattering)

ωp propagator

ω production

$V_{\gamma p \to \omega p}$ is assumed to be constant

on-shell approximation



Gaussian form factor

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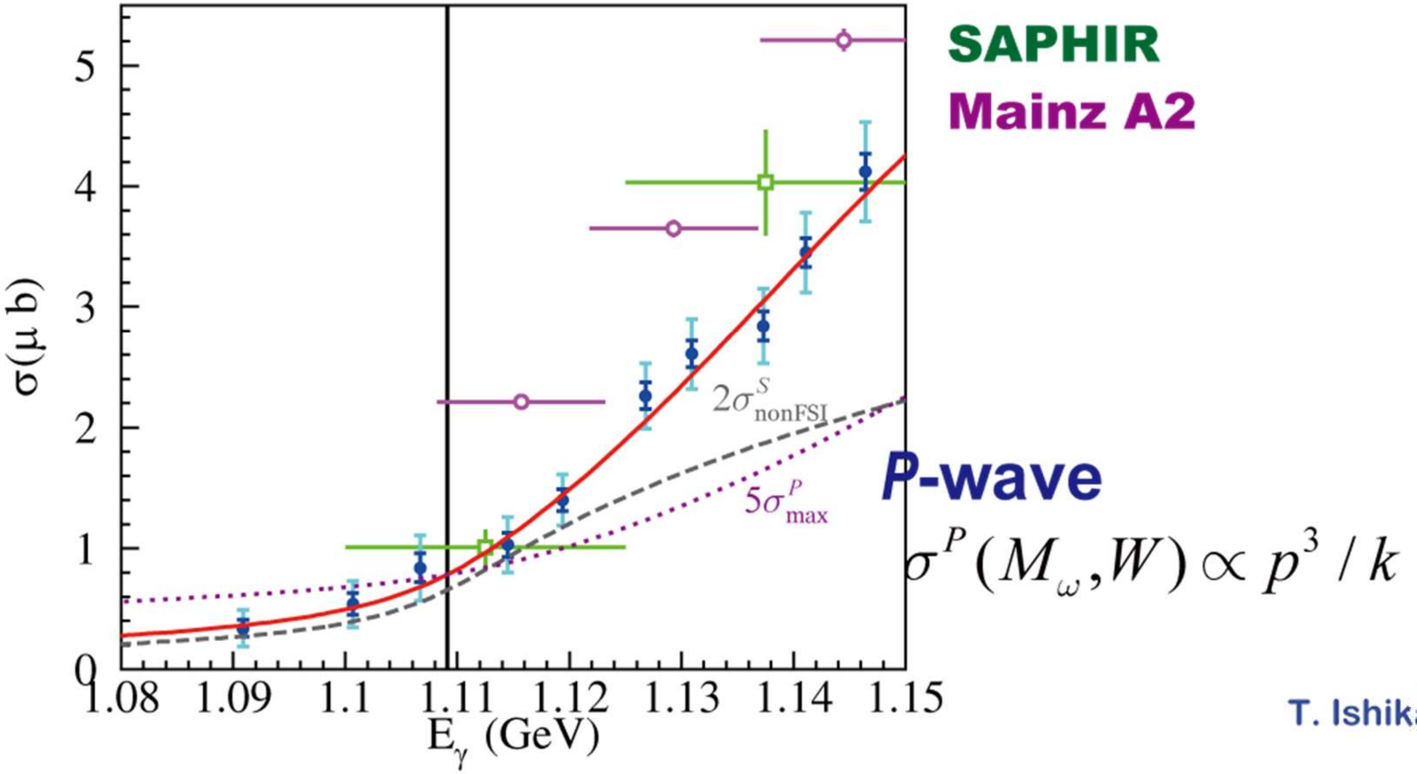
Low-energy ϕN scattering

Method 2

$$a_{\omega p} = \left(-0.97^{+0.16+0.03}_{-0.16-0.00}\right) + i\left(+0.07^{+0.15+0.17}_{-0.14-0.09}\right)\ \mathrm{fm}$$

$$r_{\omega p} = \left(+2.78^{+0.67+0.11}_{-0.54-0.12}\right) + i\left(-0.01^{+0.46+0.06}_{-0.50-0.00}\right)\ \mathrm{fm}$$

A small *P*-wave contribution does not affect the obtained values.



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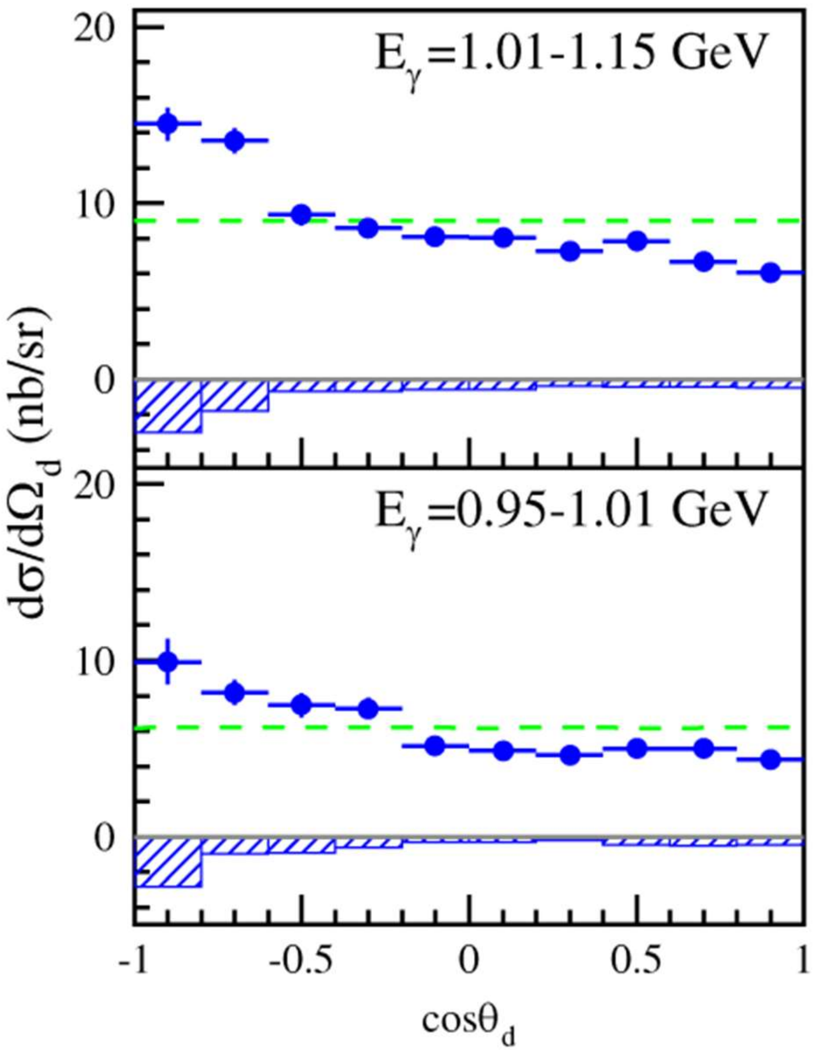
ηN system

Angular distribution $d\sigma/d\Omega_d$ for the first time



angular distribution of deuteron emission in the γd-CM frame

It does not show a strongly backward-peaking behavior but shows a rather flat distribution, suggesting a sequential process

Bump at $E_\gamma = 2\ \mathrm{GeV}$ in $\gamma p \to \phi p$

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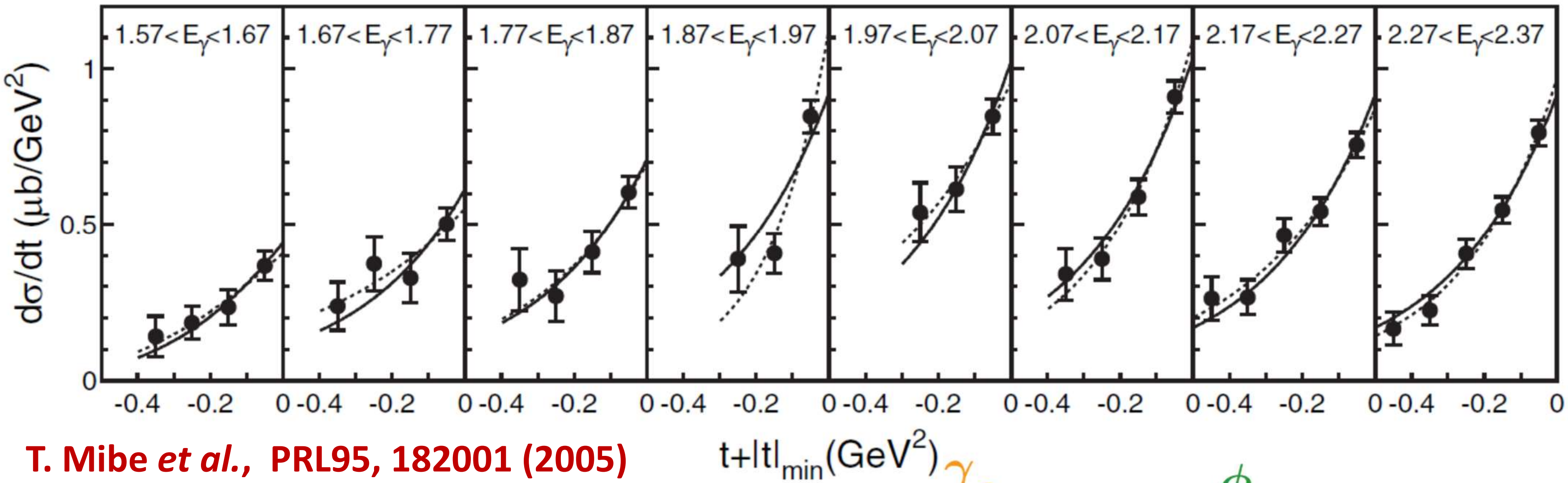
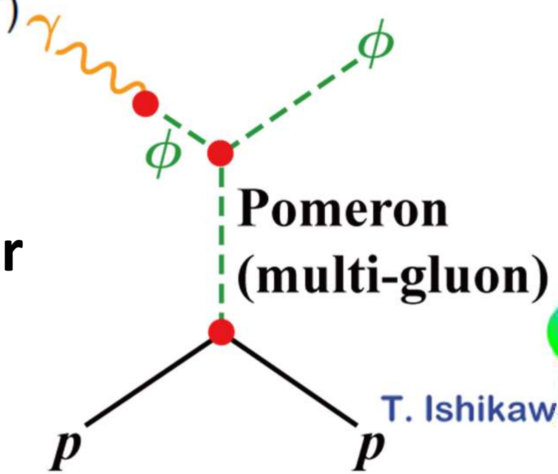
$d\sigma/dt$ at $t = -|t|_{\min}$ as a function of E_γ shows a bump at 2 GeV in $\gamma p \to \phi p$



T. Mibe *et al.*, PRL95, 182001 (2005)

$$\frac{d\sigma}{dt} = C_\phi \exp(-B_\phi |t - t_0|)$$

momentum transfer

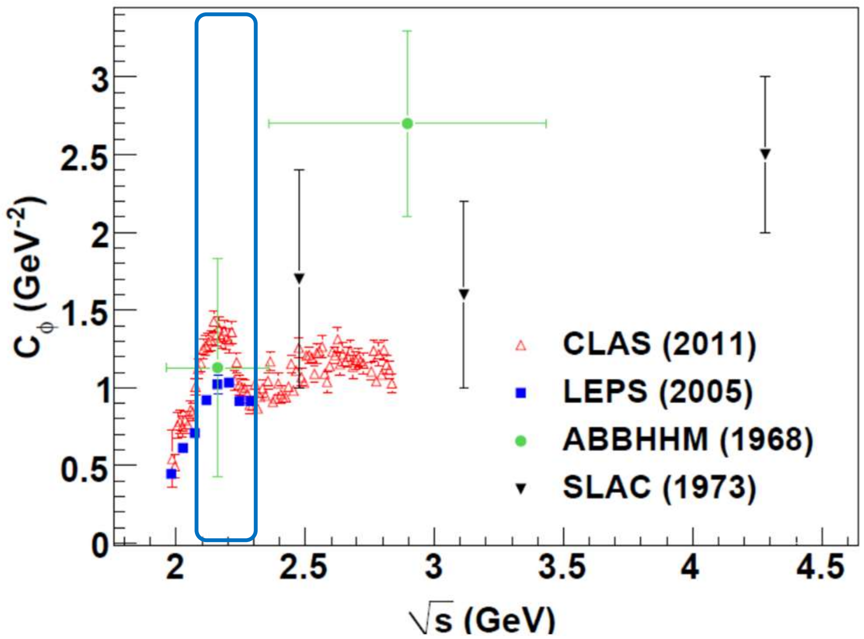


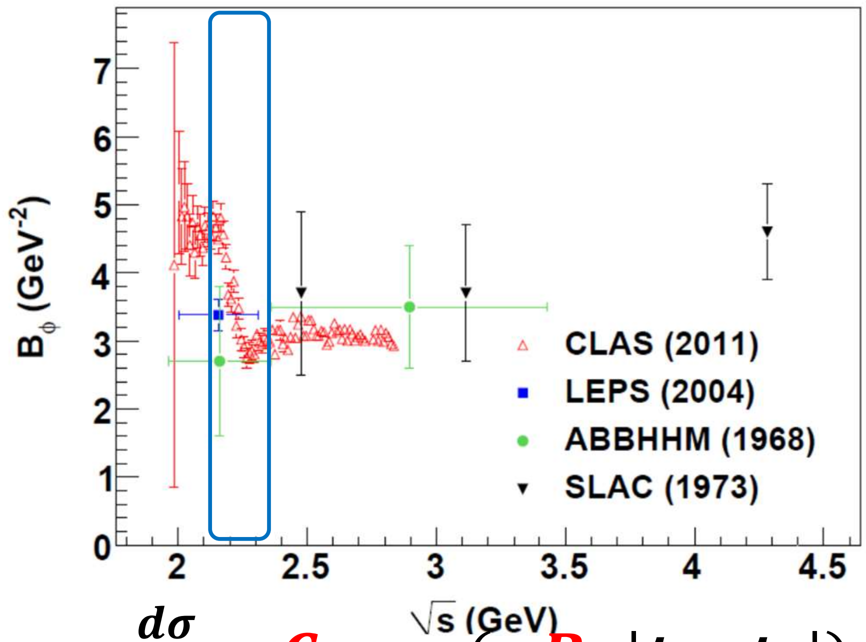
T. Ishikawa

Bump at $E_\gamma = 2\ \mathrm{GeV}$ in $\gamma p \to \phi p$

Bump at 2 GeV in $\gamma p \to \phi p$

B. Dey *et al.*, PRC89, 055208 (2014).





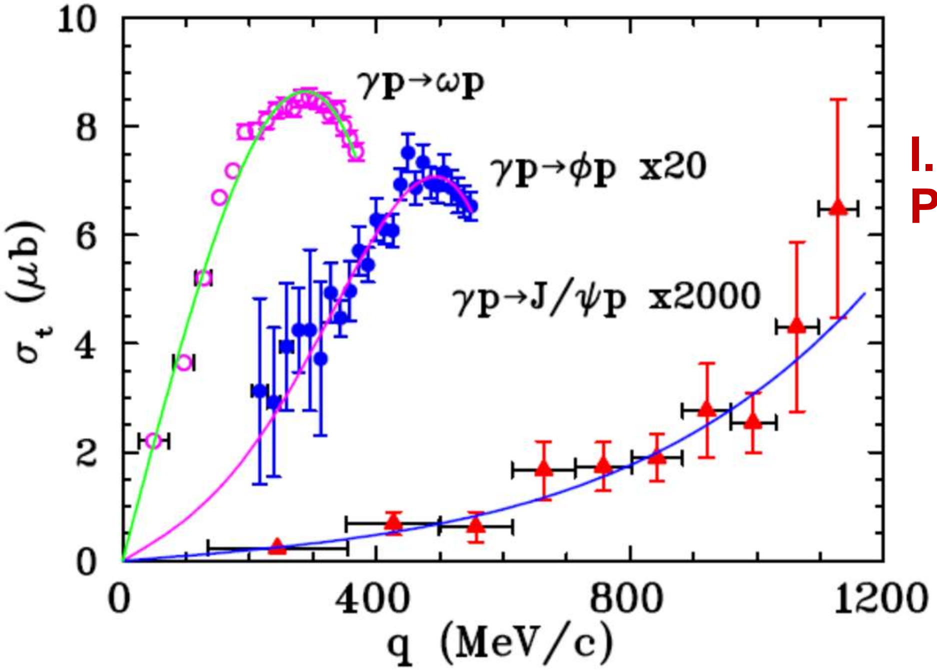
$$\frac{d\sigma}{dt} = C_\phi \exp(-B_\phi |t - t_0|)$$

- nucleon resonance
- interference between ϕp and $K^+\Lambda(1520)$
- $K^+\Lambda(1520)$ rescattering
- two-gluon-exchange
- daughter Pomeron

Different ϕN scattering lengths

weak VN interaction

Okubo-Zweig-Iizuka (OZI) rule
little admixture of $\bar{s}s$, $\bar{c}c$ in the nucleon wave function



I.I. Strakovsky, L. Pentchev, A.I. Titov, PRC101, 045201 (2020).

photoproduction near the threshold is related to a_{VN}
vector meson dominance model
$|a_{\phi p}| = 0.063 \pm 0.010$ fm

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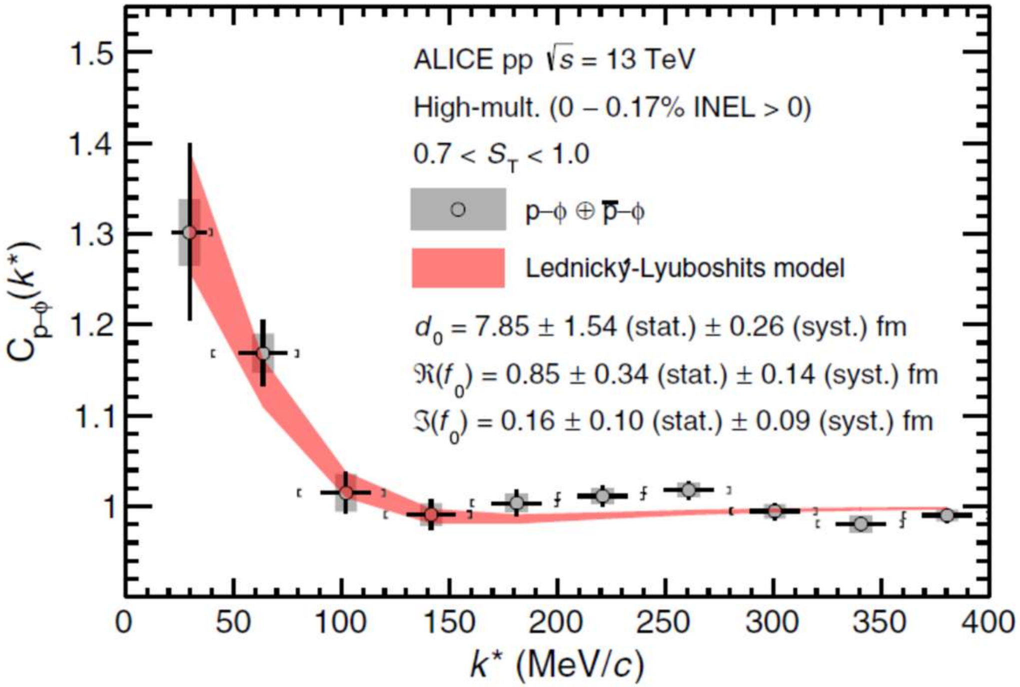
Different ϕN scattering lengths

Strong VN interaction



S. Acharya et al. (ALICE), PRL127, 172301 (2021).

correlation function in pp collision at $\sqrt{s} = 13\ \mathrm{TeV}$
Lednický-Lyuboshits model

$a_{\phi p} = (0.85 \pm 0.34 \pm 0.14) + i(0.16 \pm 0.10 \pm 0.09)$ fm

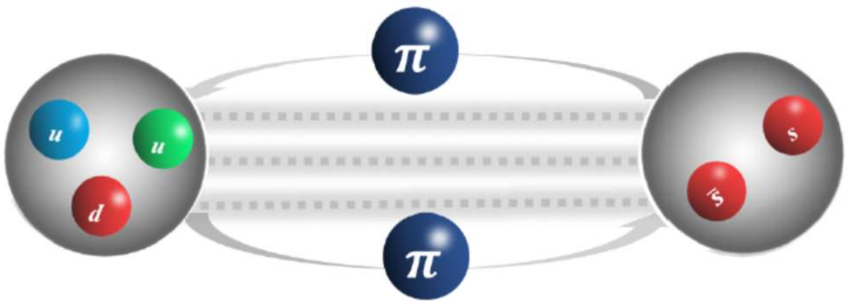
too small imaginary part

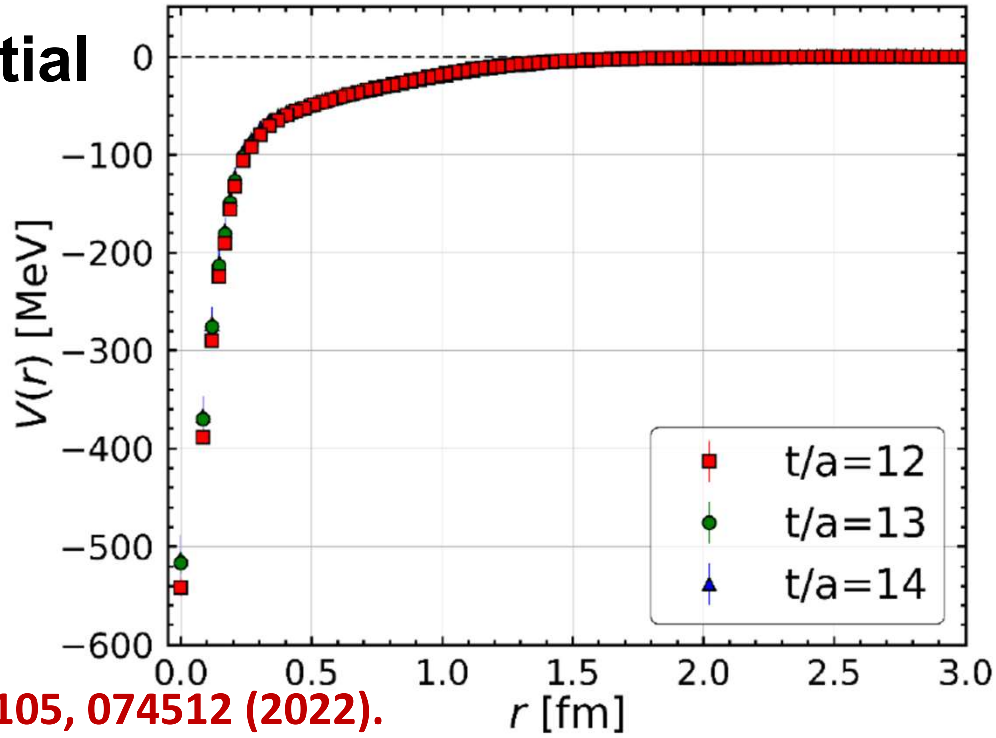
$\phi p \to K^+ \Lambda, \ldots$

Different ϕN scattering lengths

Strong VN interaction

$N\phi(\,^4S_{3/2})$ potential





Y. Lyu et al., PRD105, 074512 (2022).

HAL QCD calculation shows strong attraction and two-pion exchange tail

$a_{\phi N}^{(3/2)} =\sim 1.25$ fm and $r_{\phi N}^{(3/2)} =\sim 2.49$ fm

VN puzzles

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Three puzzles in systems between the vector meson and nucleon

- $d\sigma/dt$ at $t = -|t|_{\mathrm{min}}$ as a function of E_γ shows a bump at 2 GeV in $\gamma p \to \phi p$

- Non observation of P_c baryons in $\gamma p \to J/\psi\, p$

- Different ϕN scattering lengths are obtained from $\gamma p \to \phi p$ and from the correlation function