Evidence of a p-ϕ bound state

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arXiv:2212.12690 [nucl-ex]

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[2]Physik Department E62, Technische Universität München
[3]Helmholtz Institut für Strahlen- und Kernphysik and Bethe Center for Theoretical Physics, Universität Bonn
[4]RIKEN Interdisciplinary Theoretical and Mathematical Science Program (iTHEMS)
[5]State Key Laboratory of Nuclear Physics and Technology, School of Physics, Peking University

EMMI Workshop: Bound states and particle interactions in the 21st century
3-6 July 2023, Trieste, Italy

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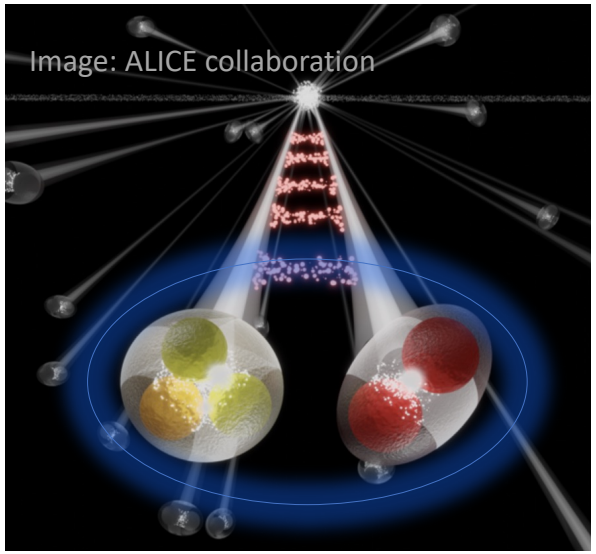
Motivation

- Predicted by various theoretical calculations
- No experimental evidence
  - Standart method of invariant mass measurment not yet available
- Accessible by studying **interaction** among constituents



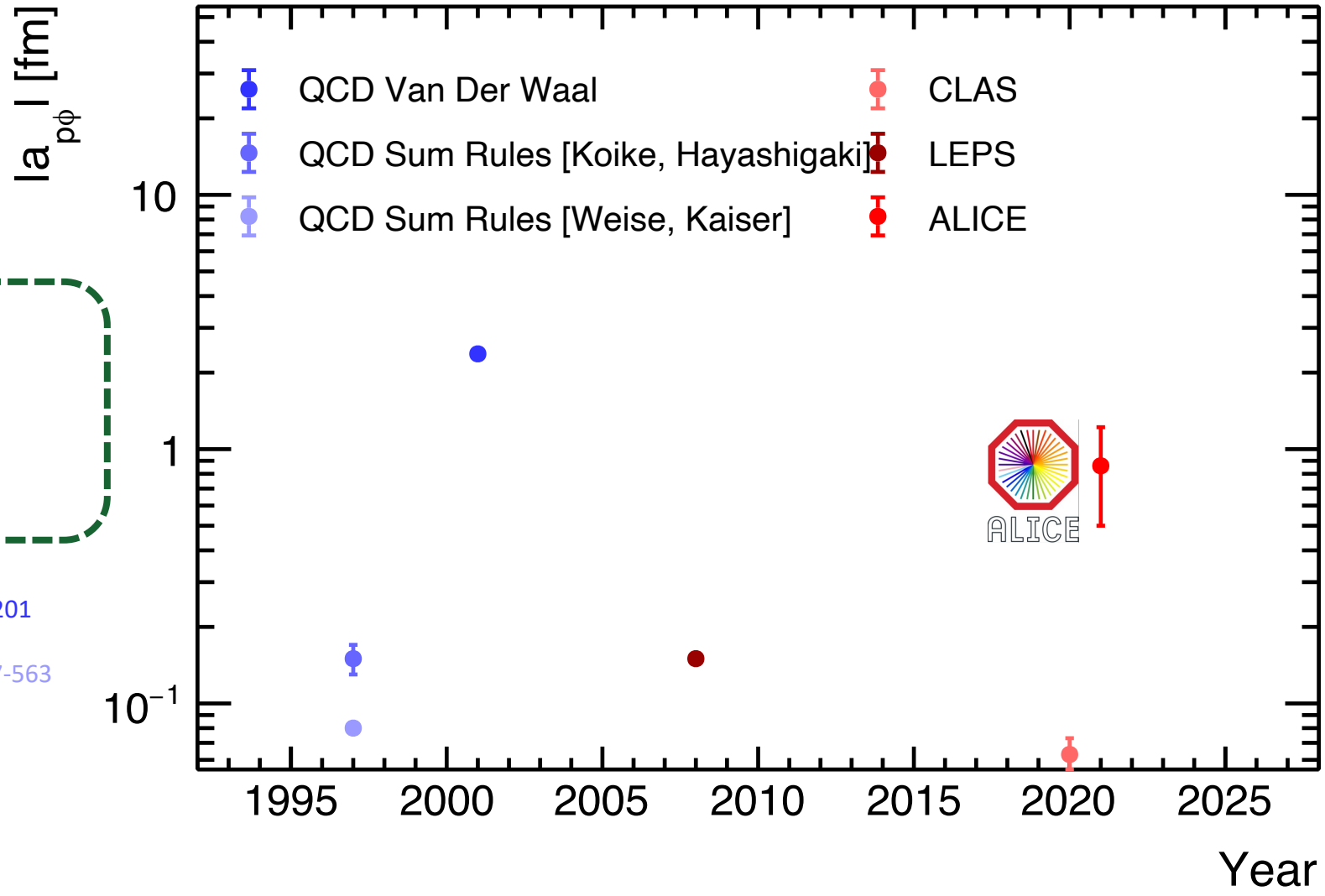
	System	E_B [MeV]
QCD Van der Waal using Yukawa type Potential[1]	ϕN	1.8
Chiral quark model[2]	ϕN	3.0
Monte Carlo study of ϕ photoproduction from nuclear targets[3]	ϕN	2.5
Quark delocalization color screening model[4]	ϕN	0.3-8.8
Unitary coupled-channel approximation anchored to ALICE pϕ scattering data[5]	ϕN	9.0
Phenomenological potential+variational method[6]	ϕN	9.3/9.23
	ϕNN	10.0/17.5
Phenomenological potential+variational method[7]	ϕN	9.5
	ϕNN	39.8
	ϕϕNN	124.6

[1]H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C **63** (2001) 022201(R)
[2]F. Huang, Z.Y. Zhang, and Y.W. Yu, *Phys. Rev. C* **73** (2006) 025207
[3]H. Gao et al., *Phys. Rev. C* **95** (2017) 055202
[4]S. Liska, H. Gao, W. Chen, and X. Qian, Phys. Rev. C **75** (2007) 058201
[5]B.-X. Sun, Y.-Y. Fan, and Q.-Q. Cao, arXiv , 2206.02961 (2022)
[6]V. B. Belyaev, W. Sandhas, and I. I. Shlyk, *Few-Body Syst.* **44** (2008) 347
[7]S. A. Sofianos, G. J. Rampho, M. Braun, and R. M. Adam, *J. Phys. G.* **37** (2010) 085109

What we know so far

- ϕN interaction not well constrained so far

To avoid theoretical uncertainties/conventions, no
- Sign
- extract spin contributions
- separated Re/Im



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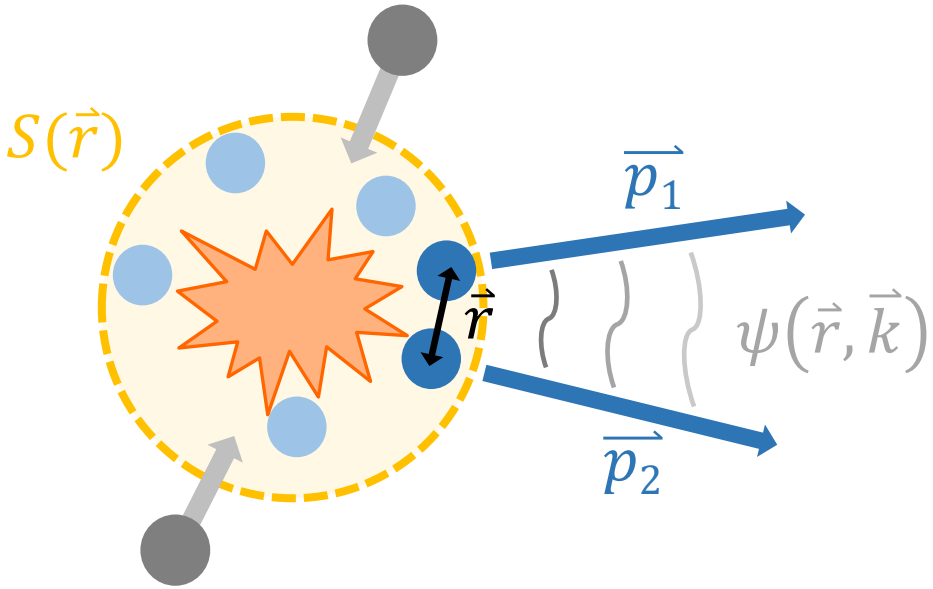
W.C. Chang *et al*, Phys Lett B **658**, 209 (2008)
S. Acharya *et al*, Phys. Rev. Lett. **127** (2021) 172301

The correlation function



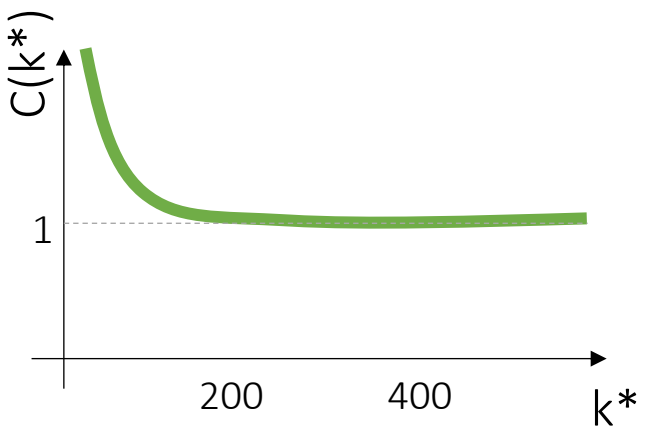
$$C(k^*) = \underbrace{\mathcal{N}\frac{\mathrm{N}_{same}(k^*)}{\mathrm{N}_{mixed}(k^*)}}_{\text{experimental definition}} = \underbrace{\int S(\vec{r}^*)\left|\psi(\vec{k}^*,\vec{r}^*)\right|^2 d^3\vec{r}^*}_{\text{theoretical definition}} \xrightarrow{k^*\to\infty} 1$$

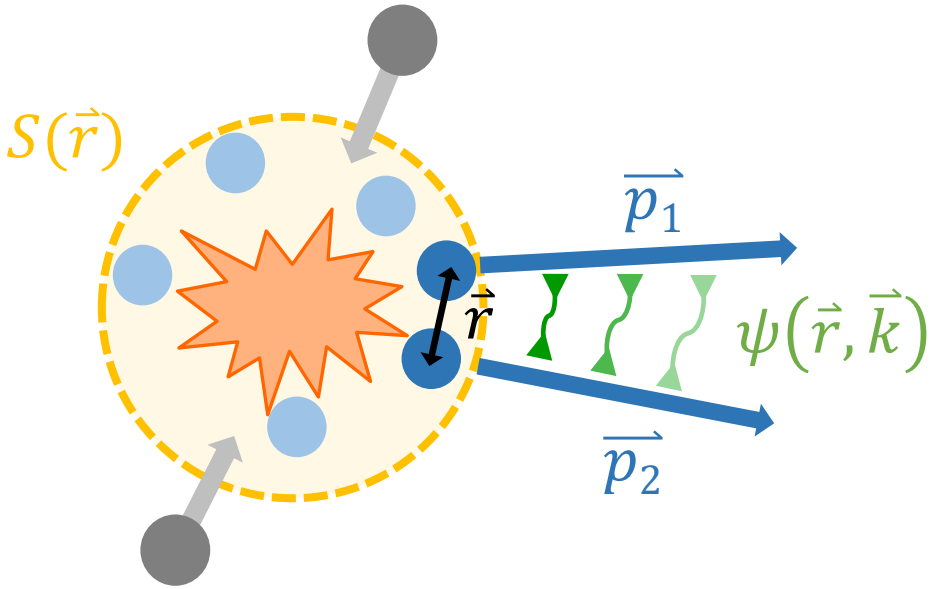
S. E. Koonin, *Physics Letters B* **70** (1977) 43-47
S. Pratt, *Phys. Rev. C* **42** (1990) 2646-2652

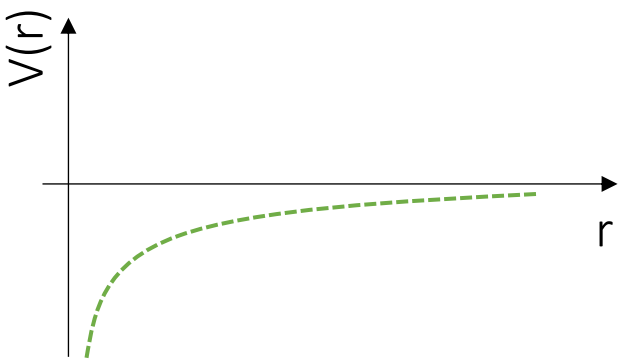
Relative momentum $\vec{k}^* = \frac{1}{2}\,|\,\vec{p}_1^* - \vec{p}_2^*\,|$ and $\vec{p}_1^* + \vec{p}_2^* = 0$

Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

The correlation function







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attraction

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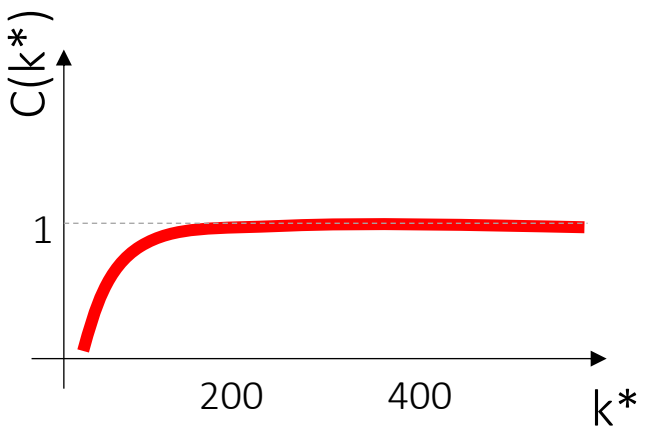

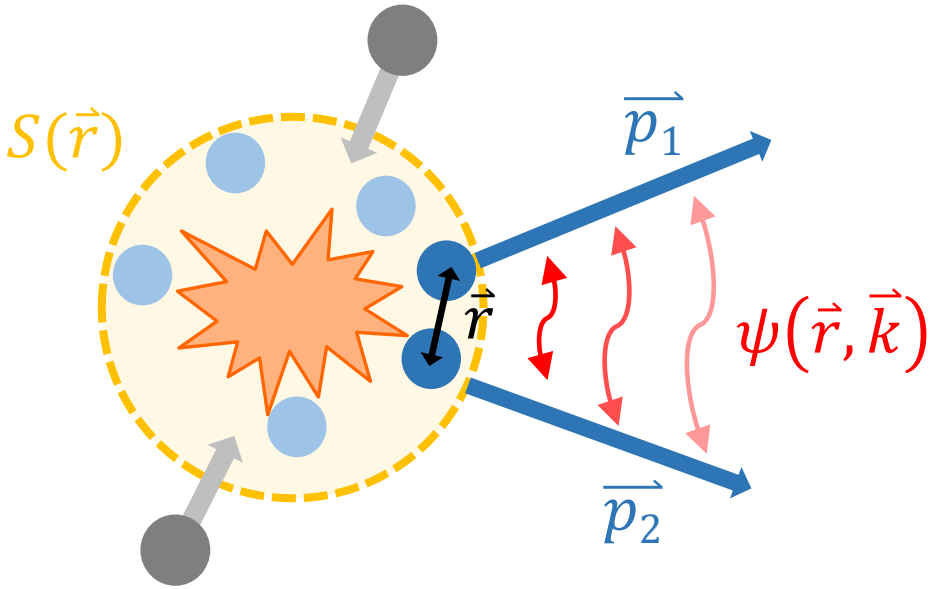

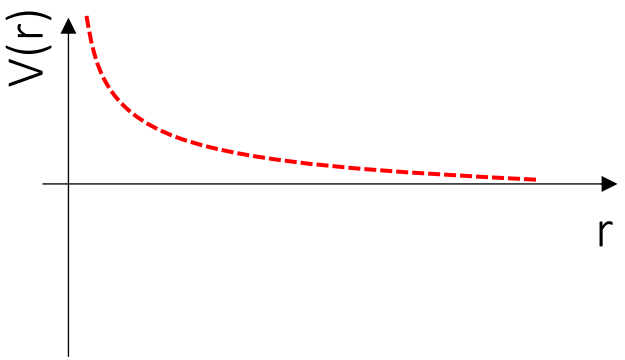

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repulsion

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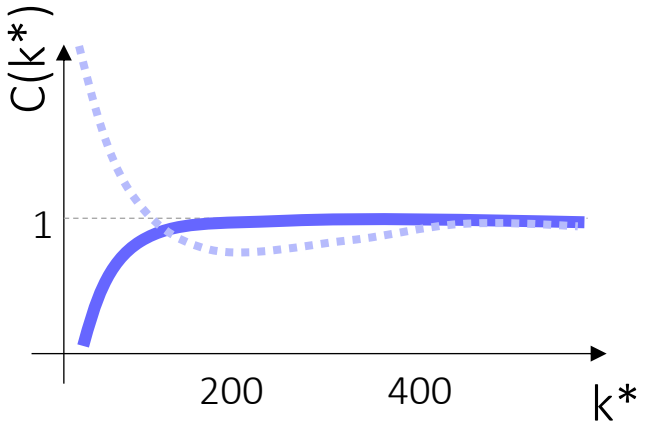

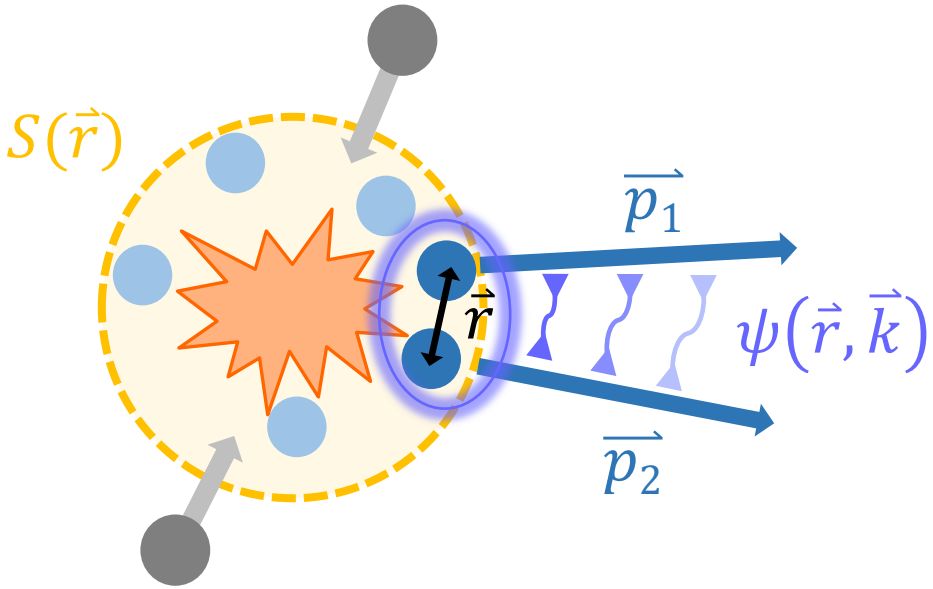

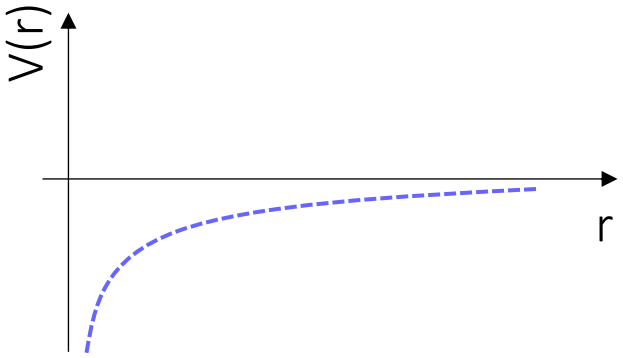

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Bound state

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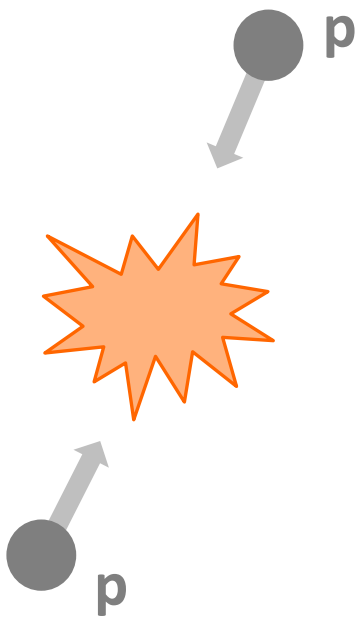
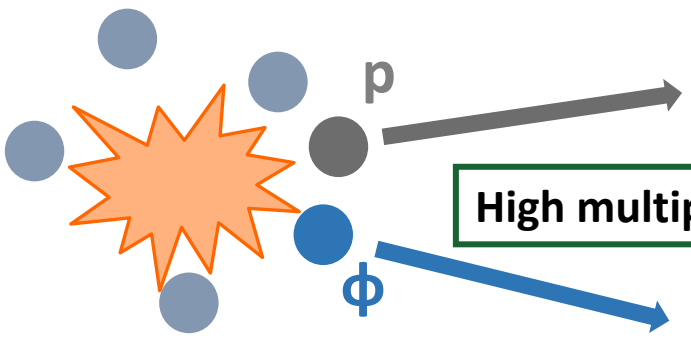
The ALICE measurement



High multiplicity (HM) **pp collisions** at √s = 13 TeV

The ALICE measurement



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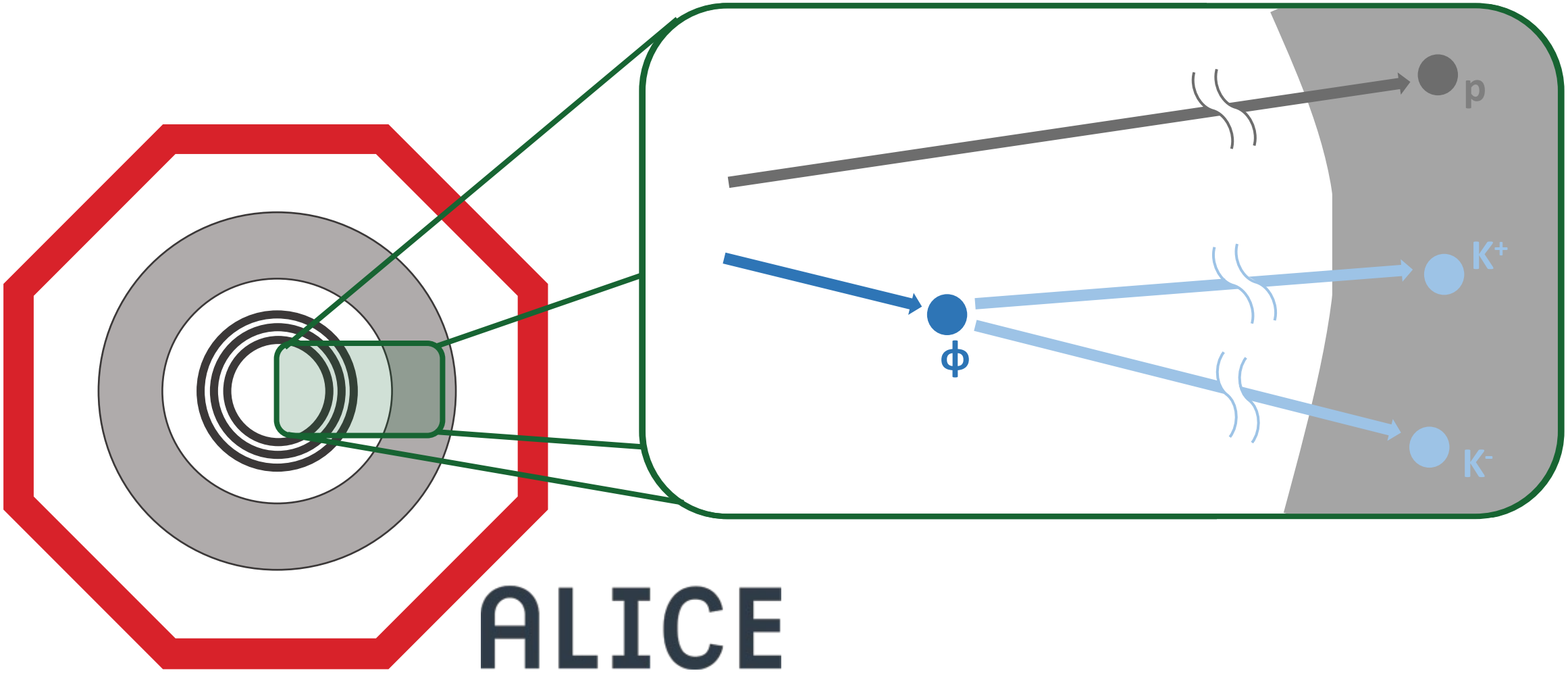

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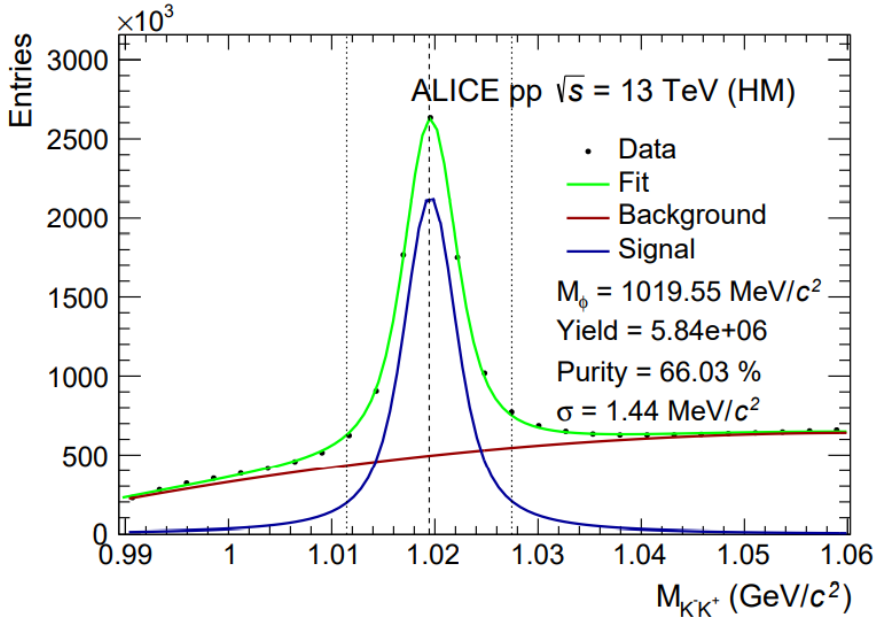

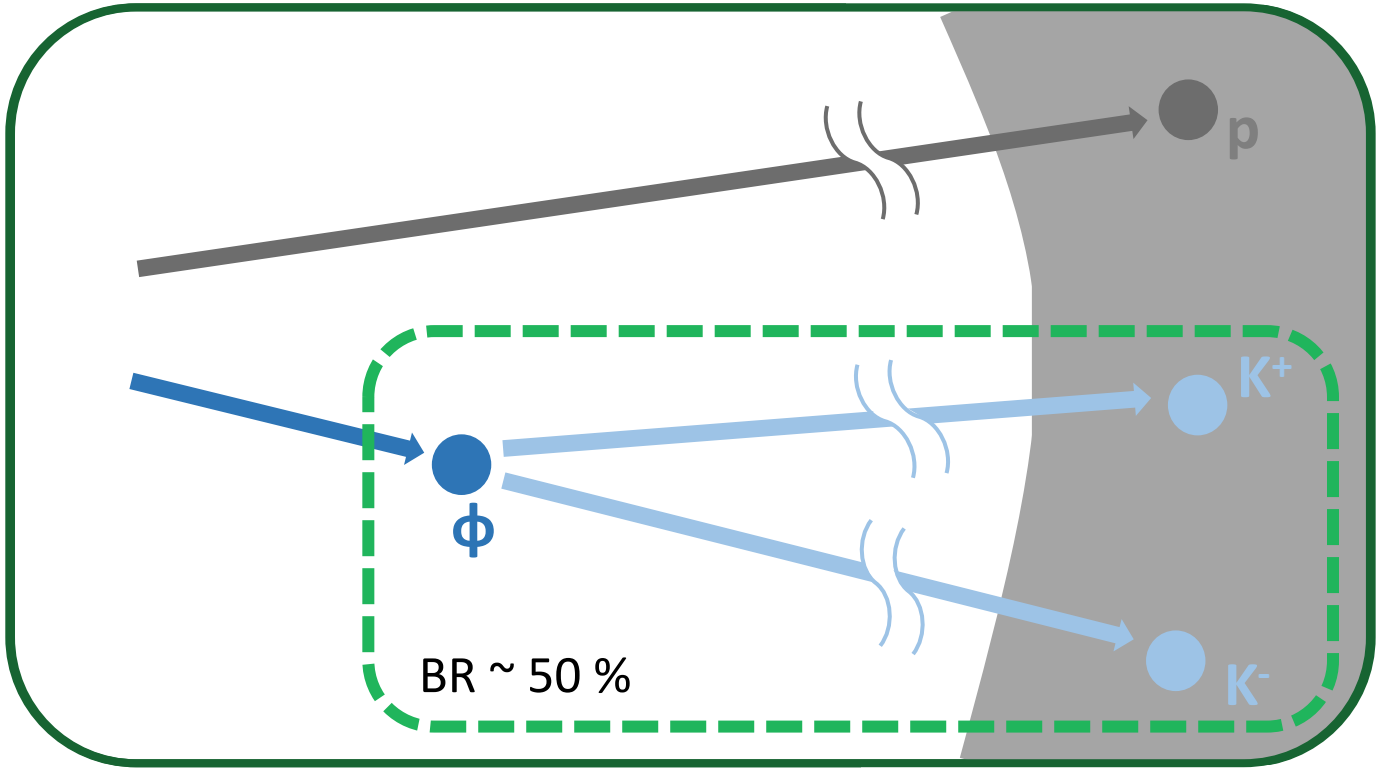

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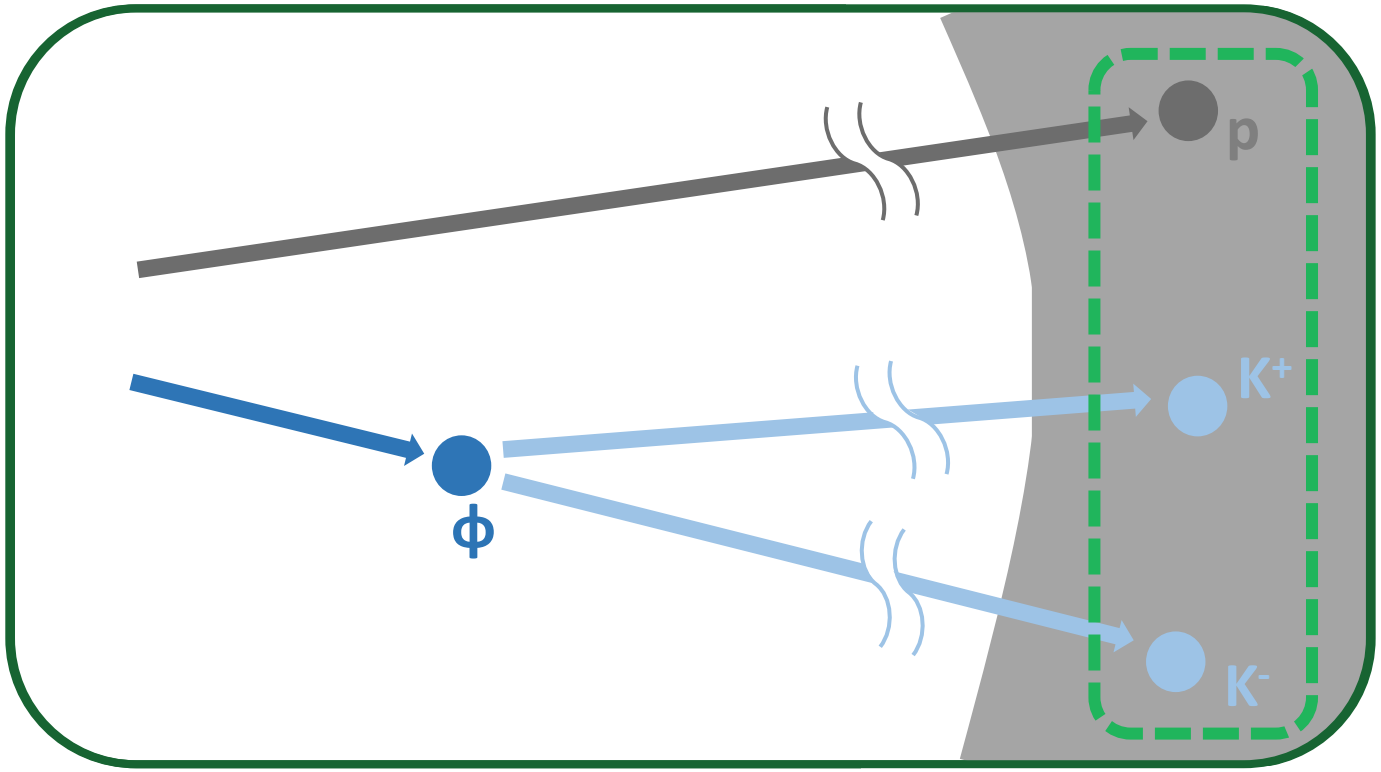
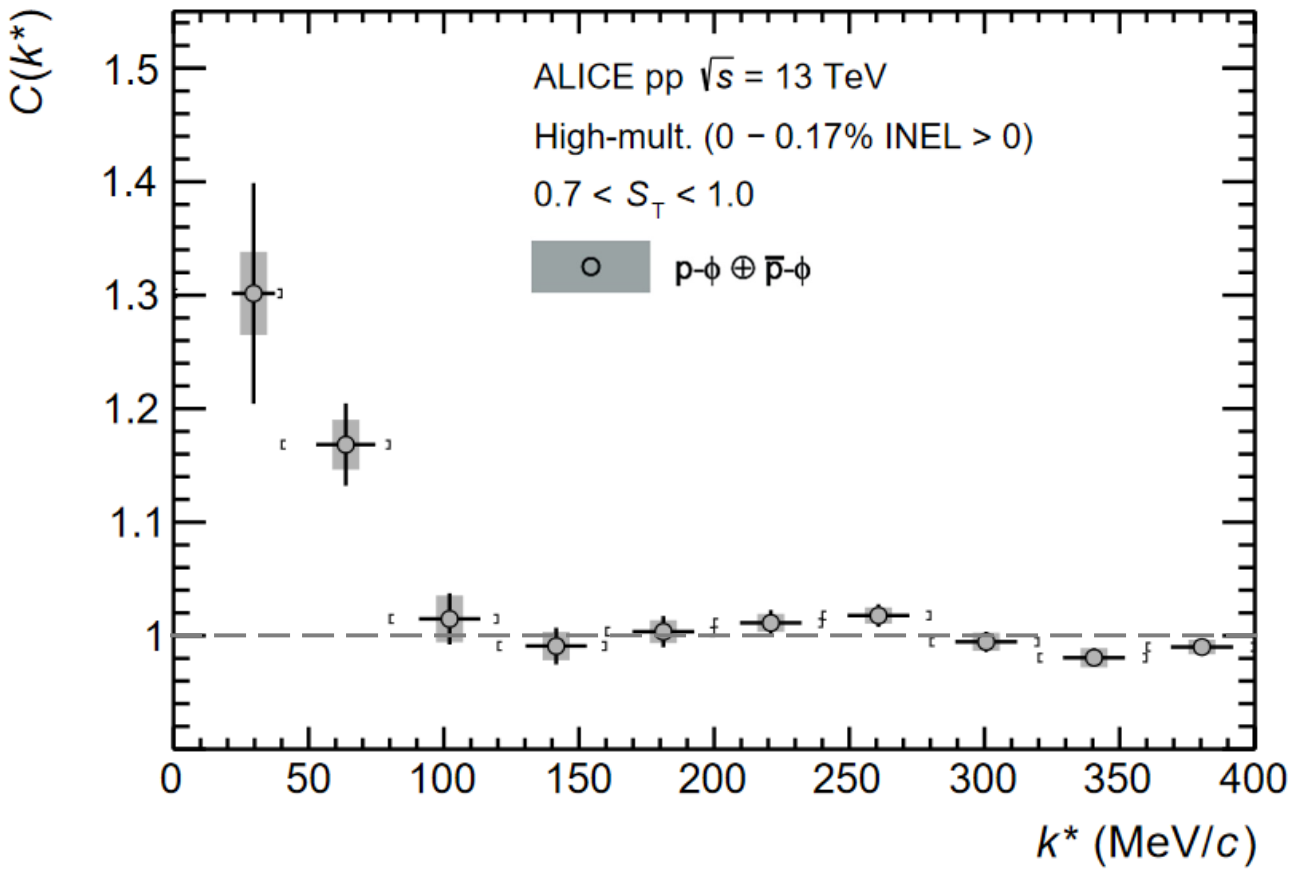


Excellent PID with ALICE Detector → charged particles measured directly with purities ~ 99%

Spin averaged scattering parameters

- Observation of **attractive** p–ϕ interaction

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



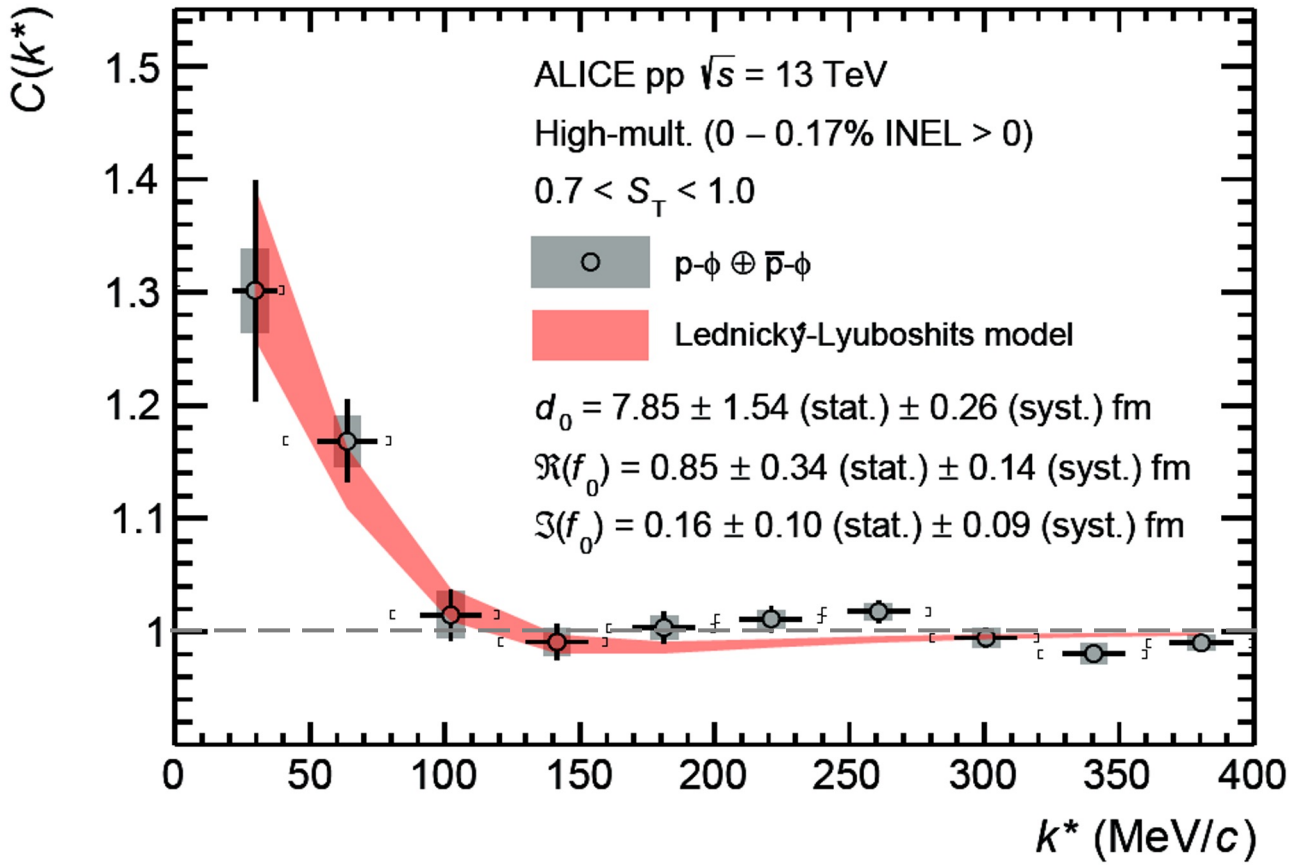
Spin averaged scattering parameters

- Observation of **attractive** p–ϕ interaction
- **Spin-averaged scattering parameters** extracted by employing the analytical Lednicky-Lyuboshits approach
  R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys.* **53** (1982) 770
- Imaginary contribution to the scattering length f_0 accounts for inelastic channels

$$\Re(f_0) = 0.85 \pm 0.34(stat.) \pm 0.14(syst.)\ \text{fm}$$
$$\Im(f_0) = 0.16 \pm 0.10(stat.) \pm 0.09(syst.)\ \text{fm}$$
$$d_0 = 7.85 \pm 1.54\ (stat.) \pm 0.26(syst.)\ \text{fm}$$

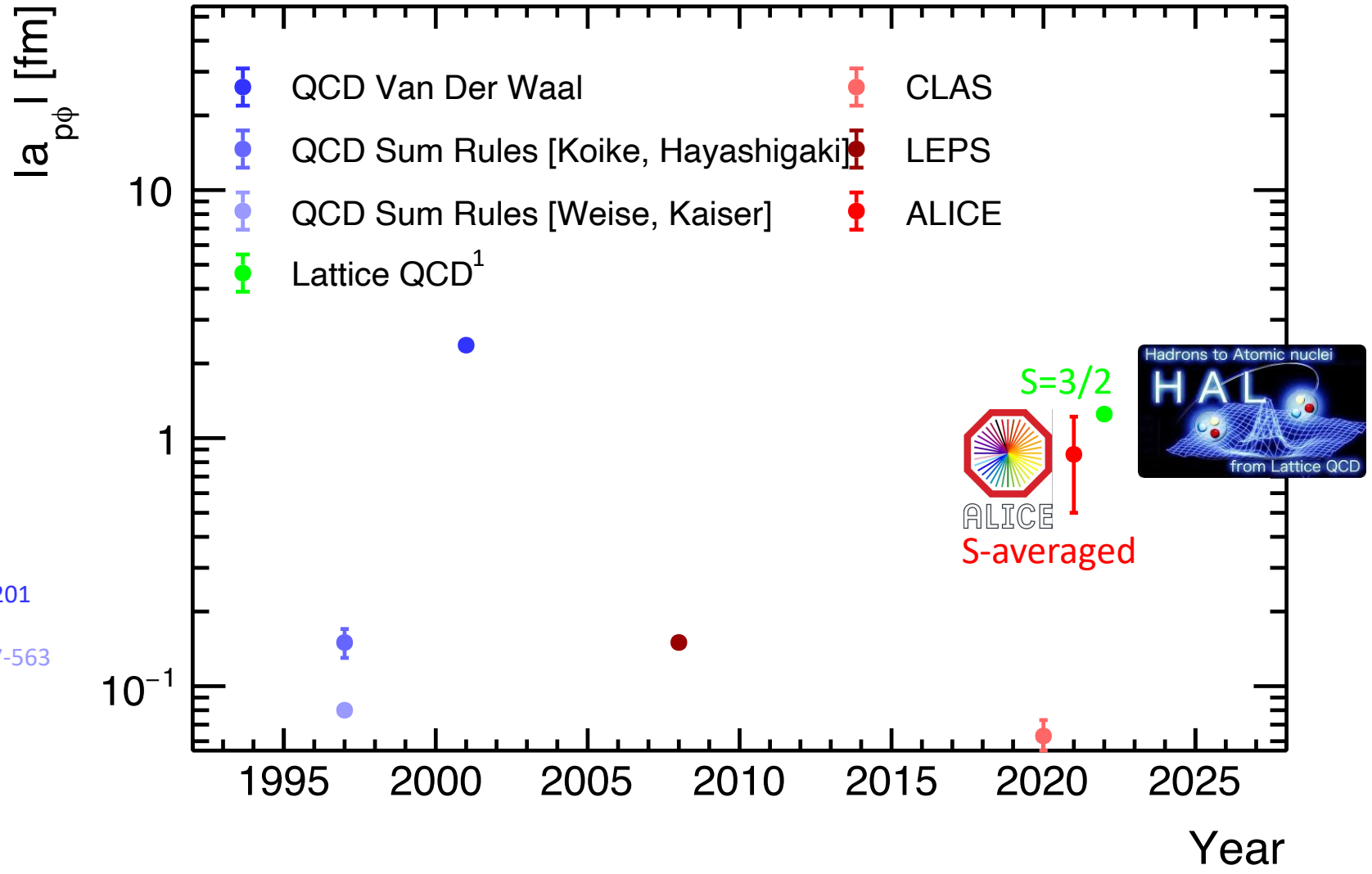
- Elastic p–ϕ coupling dominant contribution to the interaction in vacuum

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



Lattice Calculation

To avoid theoretical uncertainties/conventions, no
- Sign
- extract spin contributions
- separated Re/Im



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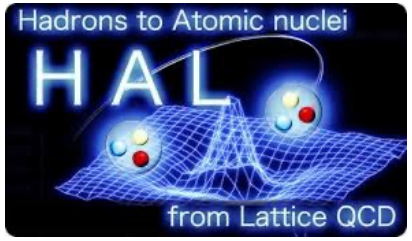
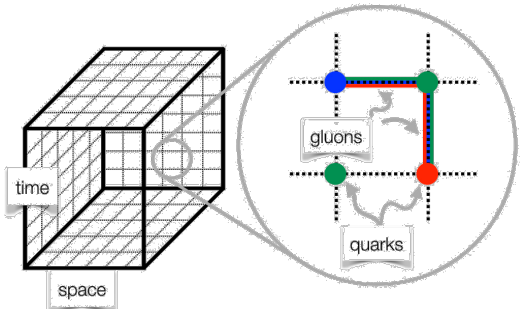
S. Acharya *et al*, Phys. Rev. Lett. **127** (2021) 172301
Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507

[1] estimated by extrapolating results to physical masses

Lattice potential $^4S_{3/2}$

- First simulation of the N-ϕ system in large lattice volume ≃ (8.1 fm)^3 and lattice spacing a ≃ 0.08 fm



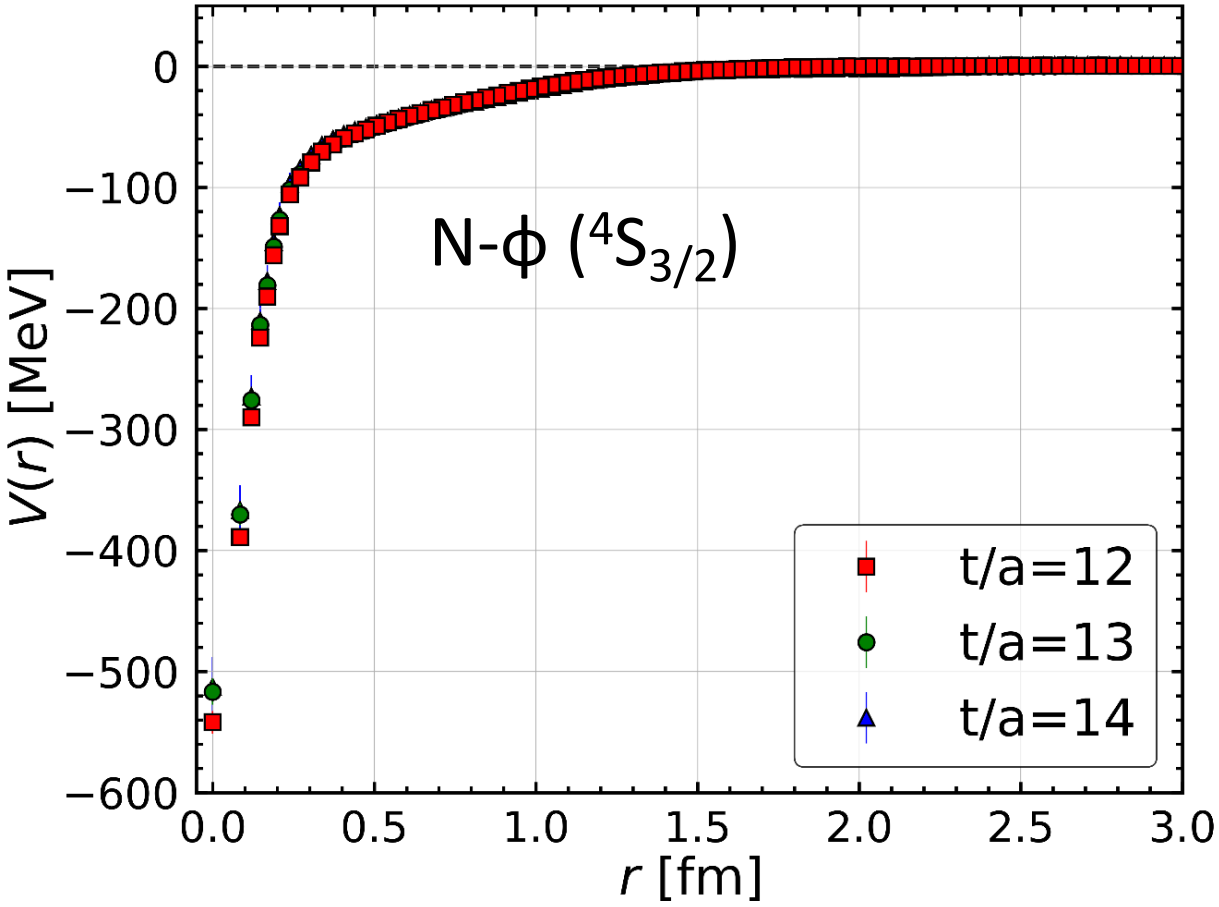


- Light dynamical quarks near the physical point

Hadron	Lattice [MeV]	Expt. [MeV]
π	146.4(4)	138.0
K	524.7(2)	495.6
ϕ	1048.0(4)	1019.5
N	954.0(2.9)	938.9

- Attractive core → Pauli exclusion principle does not operate due to no common quarks
- Long-ranged attractive tail, hints of pion dynamics

Yan Lyu et al., *Phys. Rev. D* 106 (2022) 074507



$$f_0 = 1.43^{+0.23}_{-0.23}(stat.)^{+0.06}_{-0.36}(syst.)\ \text{fm}\ ^*$$
$$d_0 = 2.36^{+0.10}_{-0.10}(stat.)^{+0.48}_{-0.02}(syst.)\ \text{fm}$$

* At unpysical masses, for physical mass estimated to be f_0~1.25 fm and d_0~2.49 fm

Lattice Calculation

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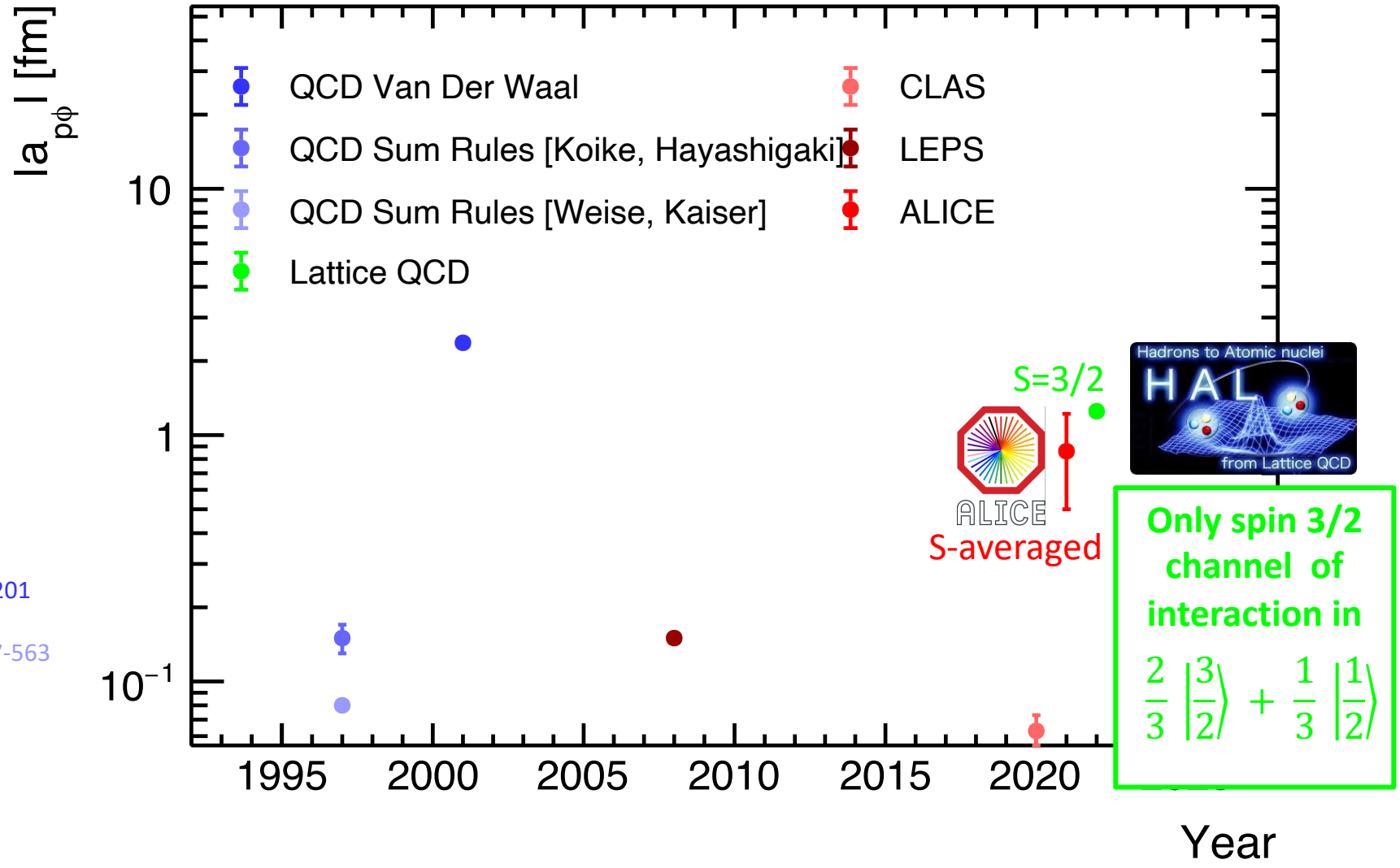

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Studying spin dependent interaction

$^4S_{3/2}$ channel

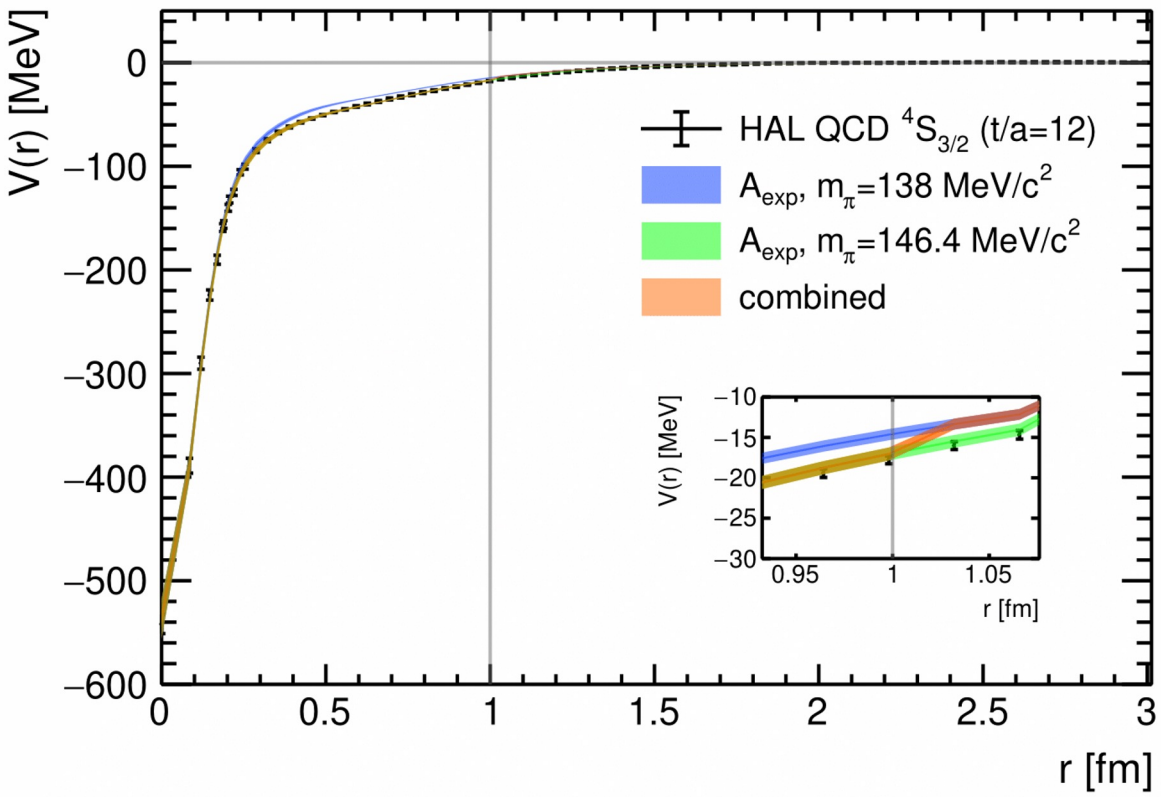
- Dominated by elastic scattering states
- Modelled using HAL QCD potential

Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507

Argonne-type form factor $f(r;b_3) = \left(1 - e^{-(r/b_3)^2}\right)^2$

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

Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507



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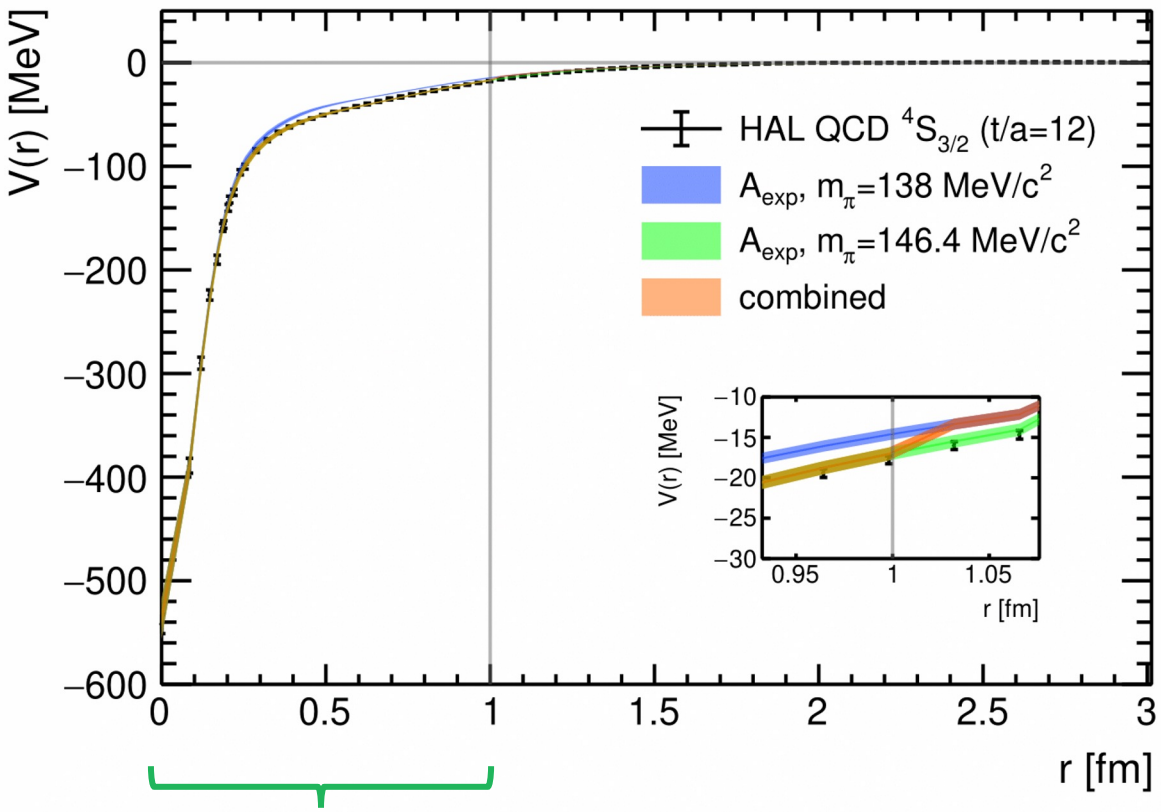

Short range attraction

Studying spin dependent interaction

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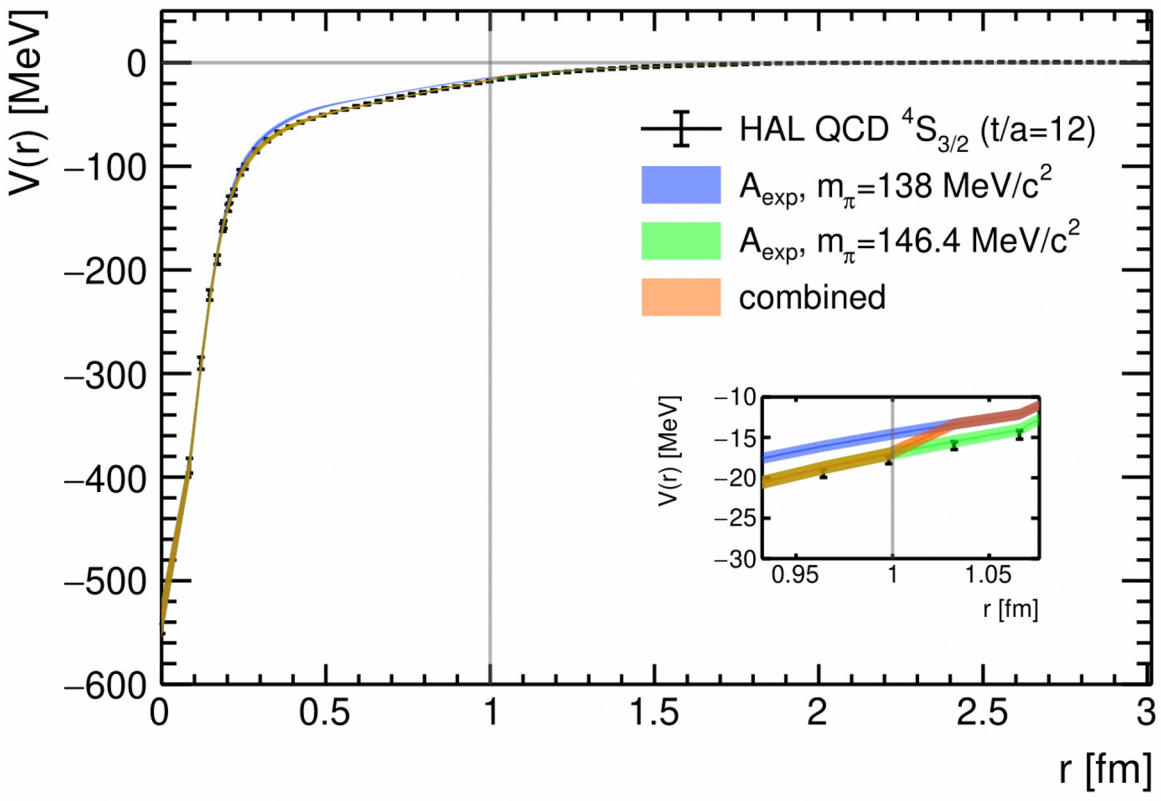
Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507



2-pion exchange

dominant at long ranges > 1fm

Studying spin dependent interaction

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  Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
- Potential at physical-pion mass

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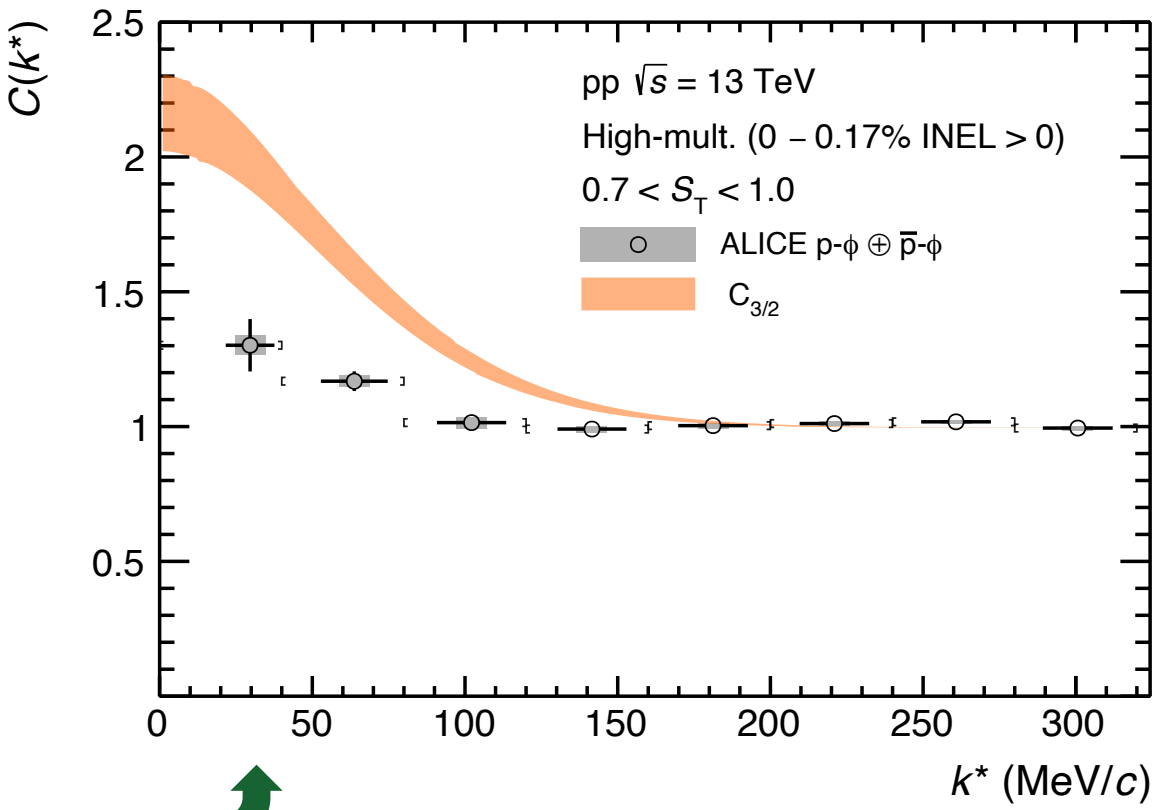
Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507



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CATS framework solves $\hat{\mathcal{H}}\psi(\vec{k}^*,\vec{r}^*) = E\psi(\vec{k}^*,\vec{r}^*)$

D.L. Mihaylov et al, *Eur. Phys. J.* **C78** (2018) no.5, 394

Studying spin dependent interaction

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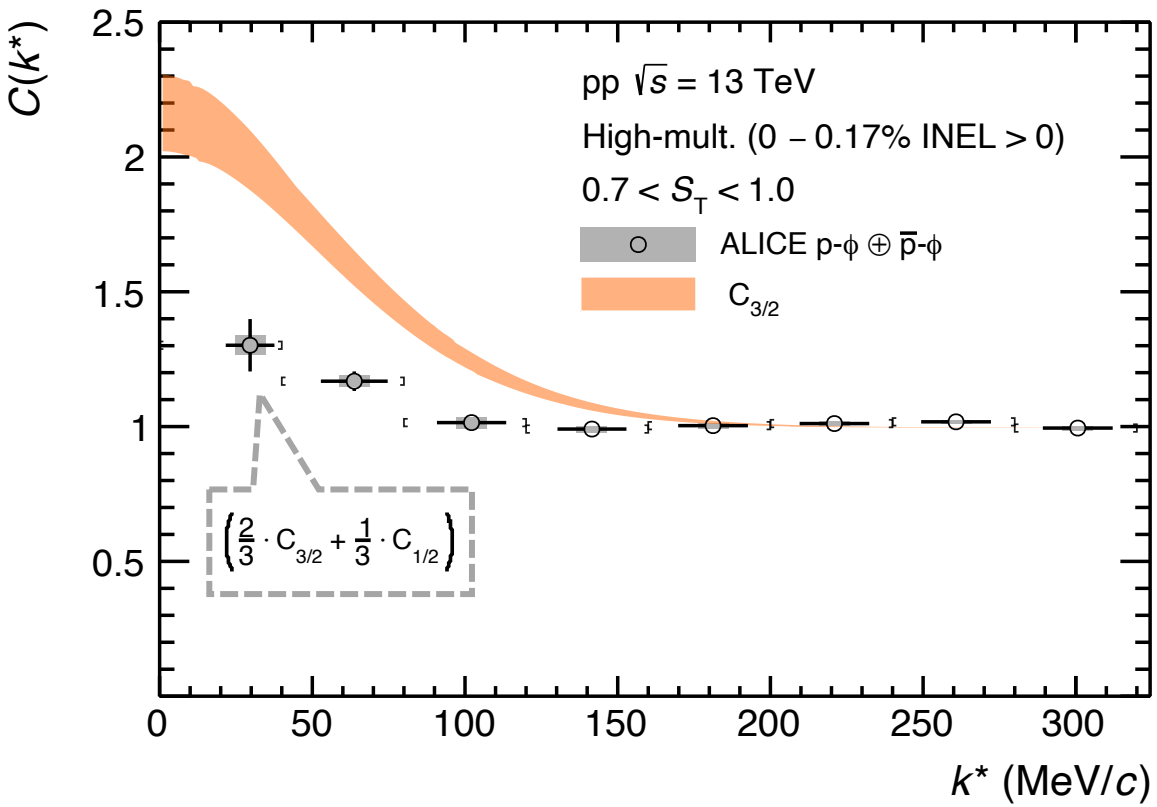

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$$V_{LATTICE}(r) = \underbrace{\sum_{i=1,2} a_i e^{-(r/b_i)^2}}_{V_{short}(r)} + \underbrace{a_3 m_\pi^4 f(r;b_3) \frac{e^{-2m_\pi r}}{r^2}}_{V_{2\pi}(r)}$$

Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507

$^2S_{1/2}$ channel

- Shows signs of open channels
  - ΛK ($^2S_{1/2}$), ΣK ($^2S_{1/2}$)
- No potential available from lattice QCD yet, due to possible effects from these open channels
- Modelled using complex potential provided by Dr. Yuki Kamiya

$$V_{\frac{1}{2}}(r) = V_{LATTICE,\,MOD}(r) + i \cdot \sqrt{f(r;b_3)} \cdot \frac{\gamma}{r} e^{-m_K \cdot r}$$

Studying spin dependent interaction

$^4S_{3/2}$ channel

- Dominated by elastic scattering states
- Modelled using HAL QCD potential
  Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
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Kaon exchange considered to give most significant contribution to coupling of decay channels

Studying spin dependent interaction

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Real Part of Pot

$$V_{LATTICE,\,MOD}(r) = \beta \cdot V_{short}(r) + V_{2\pi}(r)$$

Studying spin dependent interaction

TECHNISCHE UNIVERSITÄT MÜNCHEN

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Imaginary Part of Pot

Kaon exchange considered to give most significant contribution to coupling of decay channels

Real Part of Pot

$$V_{LATTICE,\,MOD}(r) = \beta \cdot V_{short}(r) + V_{2\pi}(r)$$

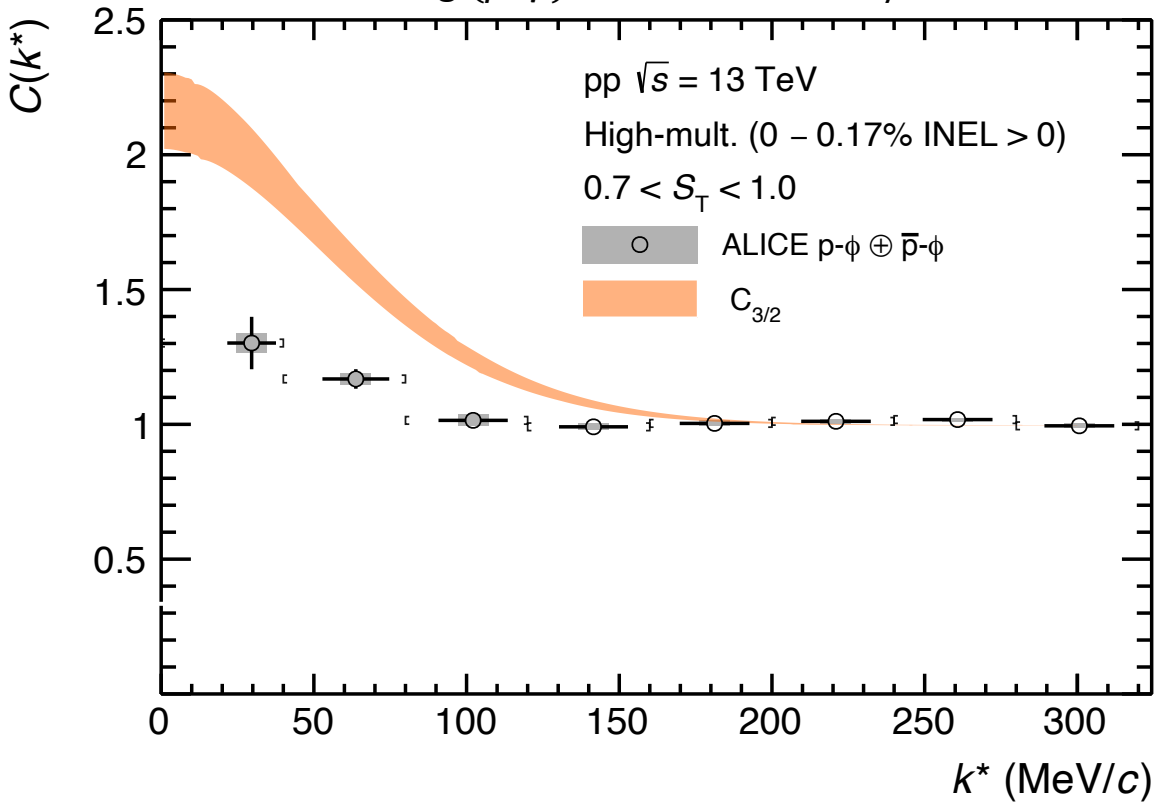
$$C_{1/2}^{(\beta,\gamma)}(k^*)$$

Studying spin dependent interaction

$^4S_{3/2}$ channel | $^2S_{1/2}$ channel

$$C_{model}^{(\beta,\gamma)}(k^*) = \frac{2}{3}C_{3/2}(k^*) + \frac{1}{3}C_{1/2}^{(\beta,\gamma)}(k^*)$$

χ^2 minimization to find best fitting (β,γ) in $k^* < 200\ MeV/c$ to describe the ALICE data



Studying spin dependent interaction

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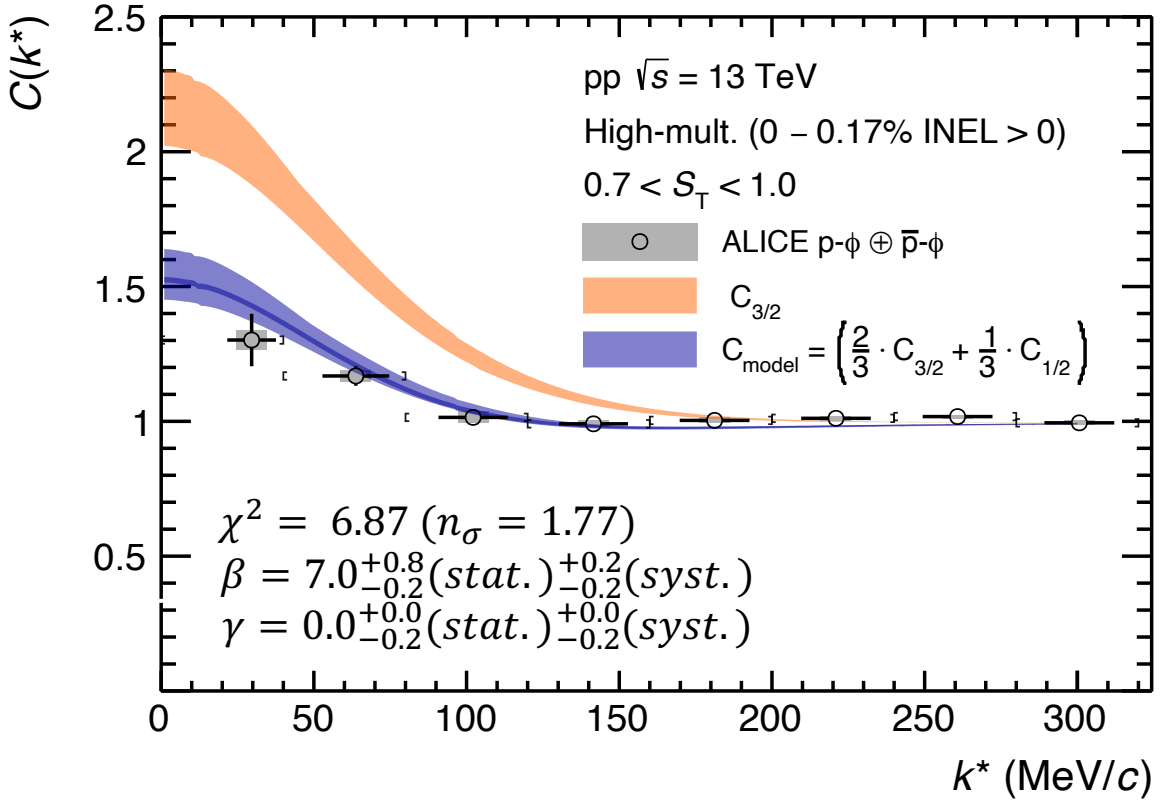


Uncertainties:

- fit range
- Lattice pot uncertainties
- source radius

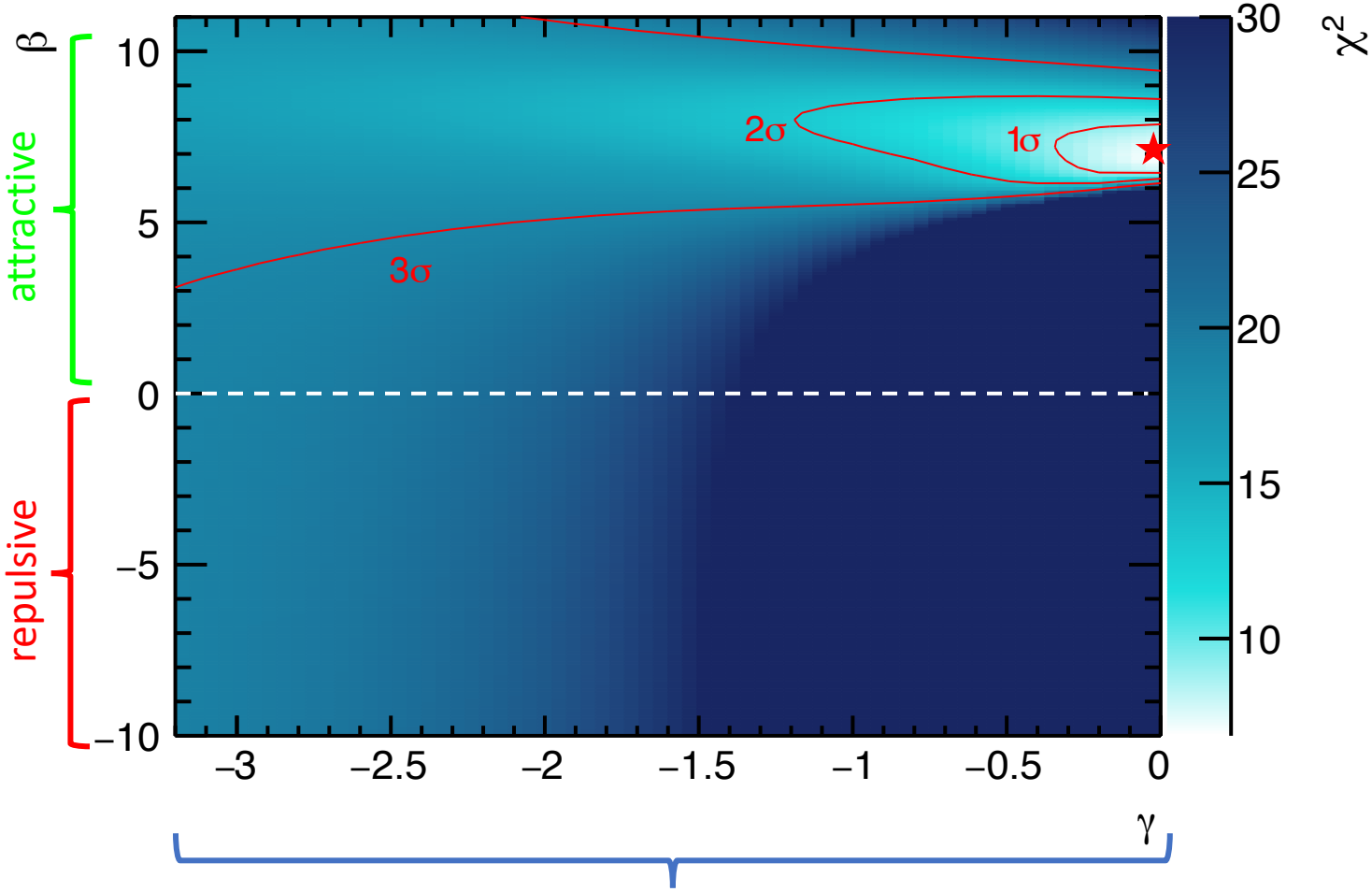
Complex $^2S_{1/2}$ Potential

$$V_{\frac{1}{2}}(r) = V_{LATTIC,MOD}(r) + i \cdot \sqrt{f(r;b_3)} \cdot \frac{\gamma}{r} e^{-m_K \cdot r}$$

$$\beta \cdot V_{short}(r) + V_{2\pi}(r)$$

- Best fit to data obtained for attractive potential
  - $\beta = 7.0^{+0.8}_{-0.2}(stat.)^{+0.2}_{-0.2}(syst.)$
  - $\gamma = 0.0^{+0.0}_{-0.2}(stat.)^{+0.0}_{-0.2}(syst.)$
- Repulsive potential (β<0) excluded by over 3σ
- Within uncertainties room for inelastic contributions expected by theory

arXiv:2212.12690 [nucl-ex]



Imaginary Pot restricted to γ<0 (attractive) to model absorption processes

Complex $^2S_{1/2}$ Potential

$$V_{\frac{1}{2}}(r) = V_{LATTIC,MOD}(r) + i \cdot \sqrt{f(r;b_3)} \cdot \frac{\gamma}{r} e^{-m_K \cdot r}$$

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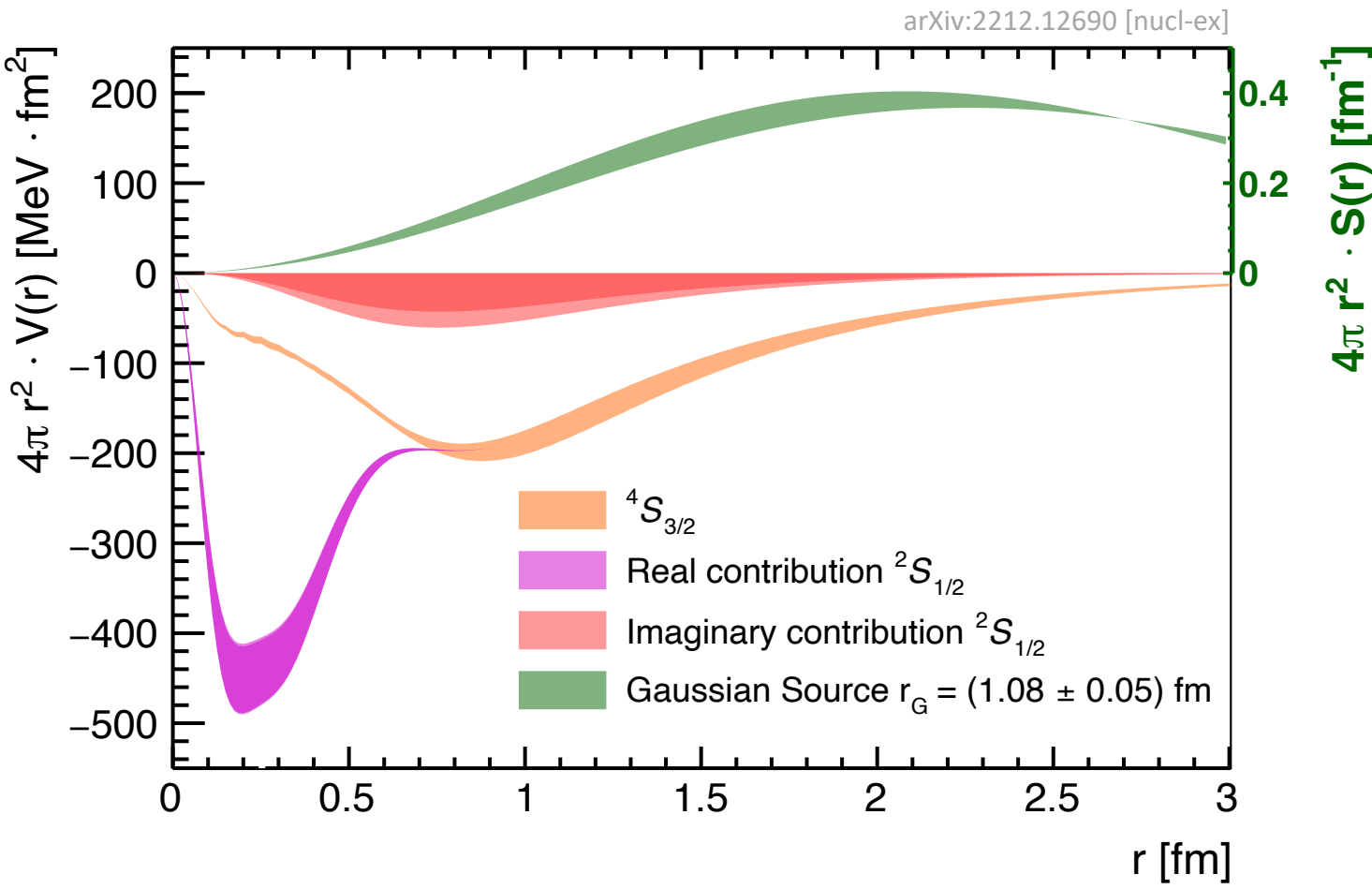


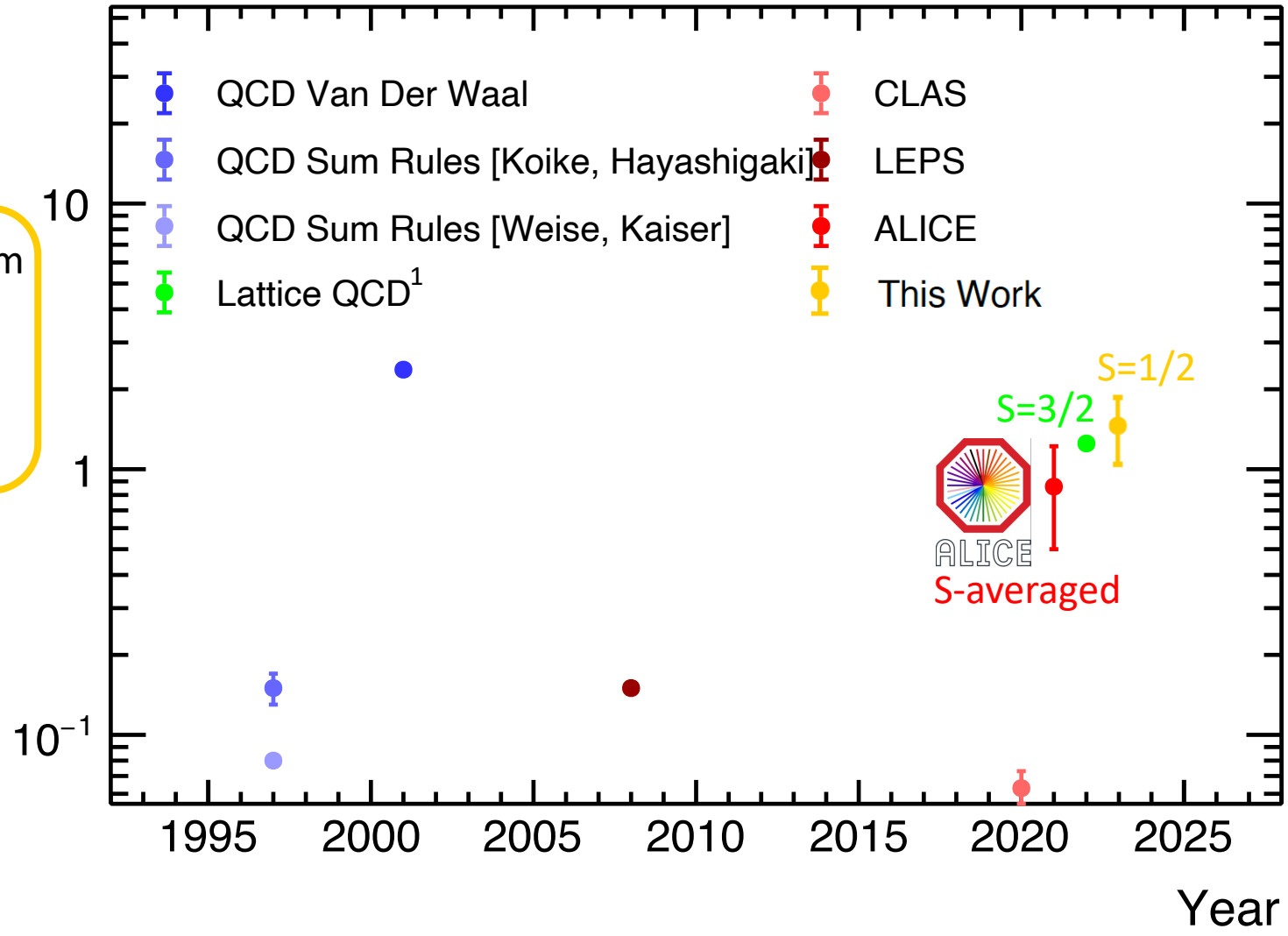
Scattering parameters of $^2S_{1/2}$

To avoid theoretical uncertainties/conventions, no
- sign
- extract spin contributions
- separated Re/Im

- Scattering parameters of S=1/2 extracted from phase-shift using effective range expansion

$$\Re(f_0) = -1.47^{+0.44}_{-0.37}(stat.)^{+0.14}_{-0.17}(syst.)\ \text{fm}$$
$$\Im(f_0) = 0.00^{+0.26}_{-0.00}(stat.)^{+0.15}_{-0.00}(syst.)\ \text{fm}$$

$$\Re(d_0) = 0.37^{+0.07}_{-0.08}(stat.)^{+0.03}_{-0.03}(syst.)\ \text{fm}$$
$$\Im(d_0) = 0.00^{+0.00}_{-0.02}(stat.)^{+0.00}_{-0.01}(syst.)\ \text{fm}$$



H. Gao, T.S.H. Lee & V. Marinov, Phys Rev C **63** (2001) 022201
Y. Koike & A. Hayashigaki, Prog Theor Phys **98** (1997) 631
F. Kling, N. Kaiser & W. Weise, Nucl.Phys. A **624** (1997) 527-563
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101** (2020)
W.C. Chang *et al*, Phys Lett B **658**, 209 (2008)
S. Acharya *et al*, Phys. Rev. Lett. **127** (2021) 172301
Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
arXiv:2212.12690 [nucl-ex]

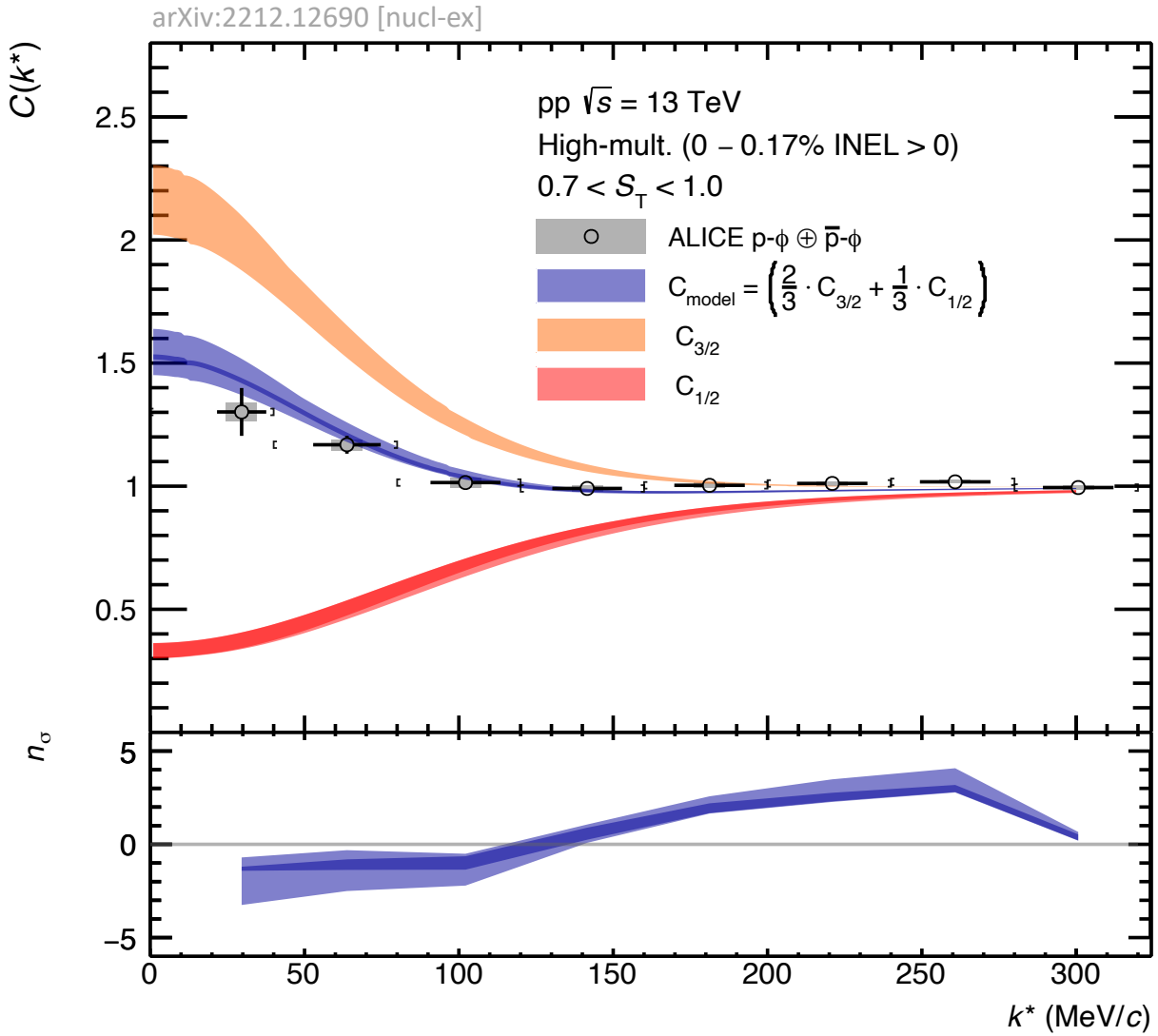
[1] estimated by extrapolating results to physical masses

Complex $^2S_{1/2}$ Potential

- $C_{1/2}(k^*) < 1$ ("repulsive"-type with negative scattering length $Re(f_0)$)
- **attractive** $^2S_{1/2}$ potential

→ FIRST EVIDENCE of a bound state in S=1/2 channel

- Variation of the form of the potential does not affect the results of the analysis



Bound state

- Estimation of binding energy E_B for S=1/2
  - Scattering parameters

$$E_B = \frac{1}{2\mu d_0^2}\left(1 - \sqrt{1 + 2\frac{d_0}{f_0}}\right) = 13.6{-}92.0\ MeV$$

  - Schrödinger Equation

$$E_B = 14.7{-}56.6\ MeV$$

- Results compatible/larger than theory predictions
- Sizable binding energy predicted by theory

H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C **63** (2001) 022201(R)
F. Huang, Z.Y. Zhang, and Y.W. Yu, *Phys. Rev. C* **73** (2006) 025207
S. A. Sofianos, G. J. Rampho, M. Braun, and R. M. Adam, *J. Phys. G.* **37** (2010) 085109
V. B. Belyaev, W. Sandhas, and I. I. Shlyk, *Few-Body Syst.* **44** (2008) 347

  - $E_{\phi N}$ up to 10 MeV
  - Even larger for A-Body systems ($E_{\phi NN}$ up to 40 MeV, $E_{\phi\phi NN}$ up to 125 MeV)

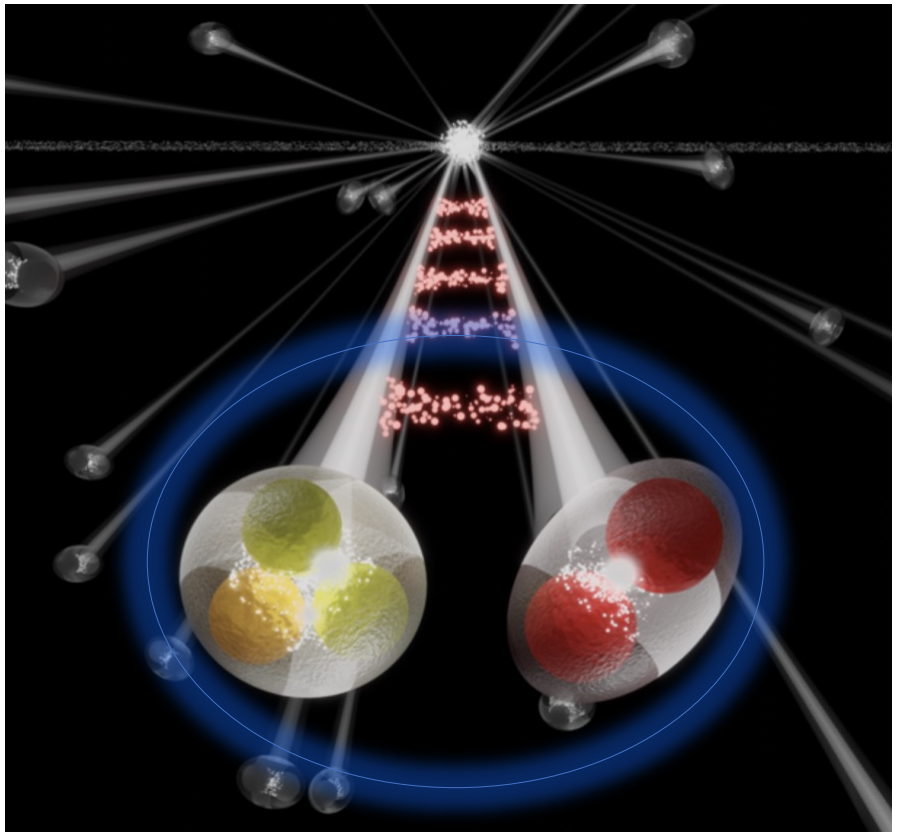


Image: ALICE collaboration

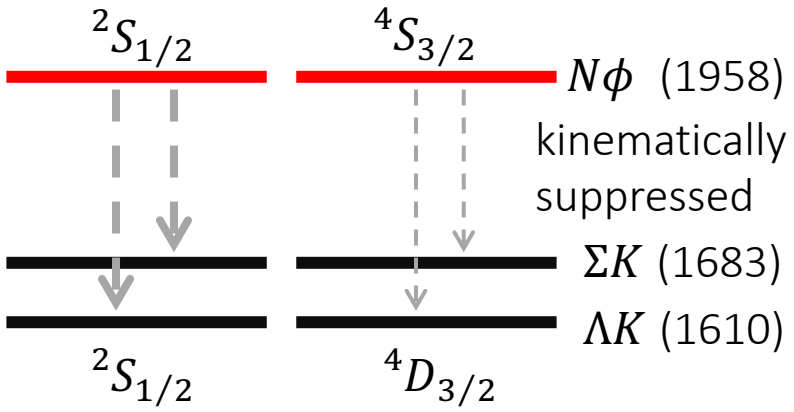
Summary and outlook

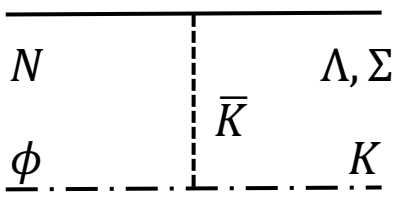
- Bound state study via correlation analysis
  - Experimental p–ϕ correlation function by ALICE
    ALICE Collab., *PRL* **127** (2021) 172301
  - Published lattice potential for S=3/2
    Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
- Spin S=1/2 component of interaction extracted for the first time
  arXiv:2212.12690 [nucl-ex]
  - Strongly attractive potential, supporting a bound state
  - Room for absorbtion due to sizable imaginary contirbution to the potential
- Motivation for
  - Further bound state studies using correlation approach
  - Invariant mass analysis of possible decay products of the ϕN bound state

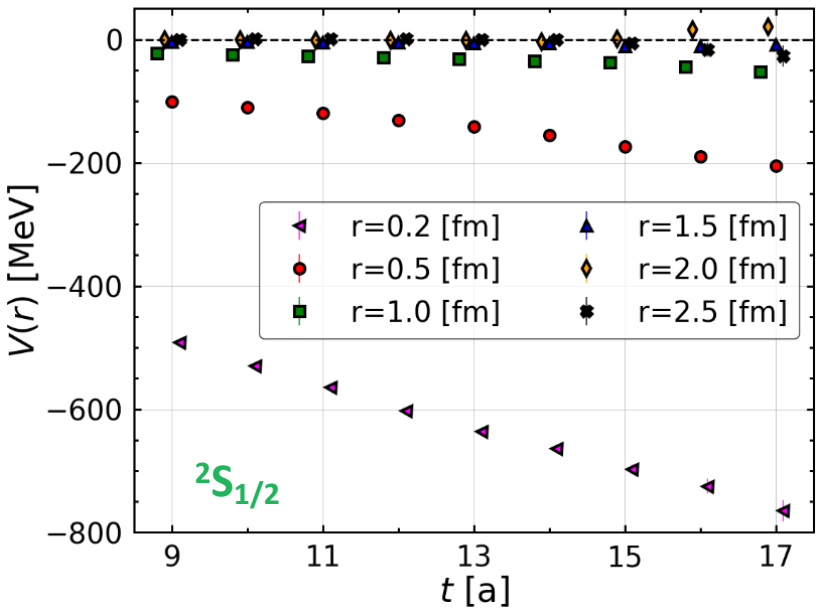
Additional material

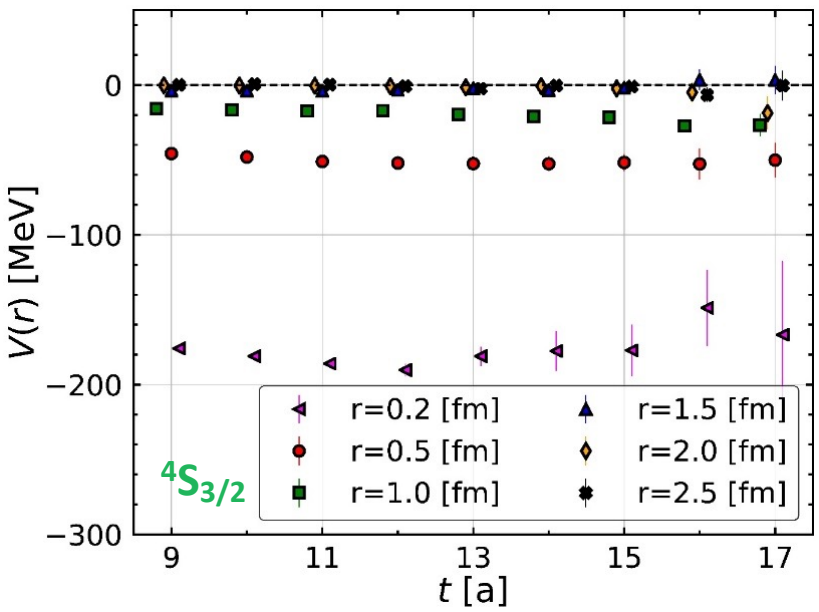
What about $^2S_{1/2}$

- Two body channels
- Time dependence of potential
  - clear open channel effect in $^2S_{1/2}$ case
- No lattice Potential available at the moment



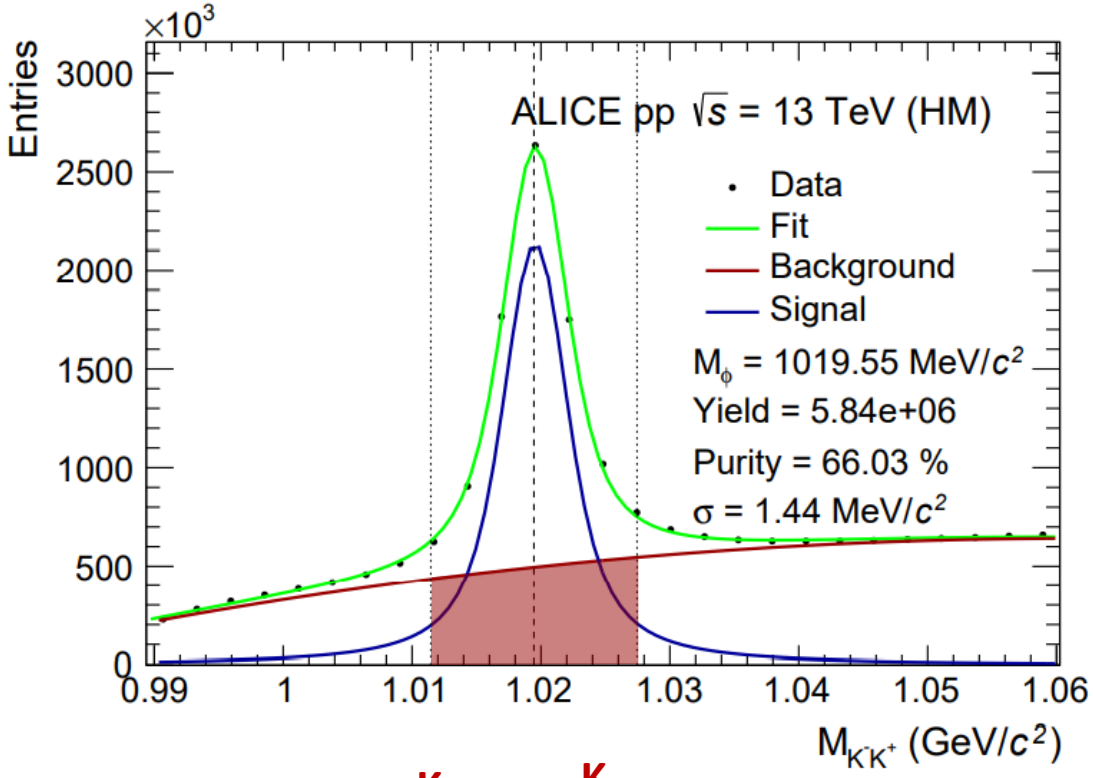


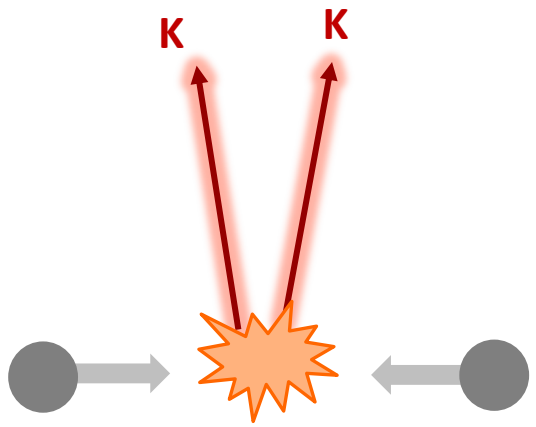




Analysis details

- LHC Run 2 dataset (2016-2018)
- High multiplicity (HM) pp collisions at √s = 13 TeV
- Excellent PID with ALICE Detector
  - Proton candidates measured directly (purity ~99%)
  - ϕ meson reconstruction
    - Decay channel $\phi \rightarrow K^{+}K^{-}$
    - Candidates consist of
      - Combinatorial background → random combination of uncorrelated kaons





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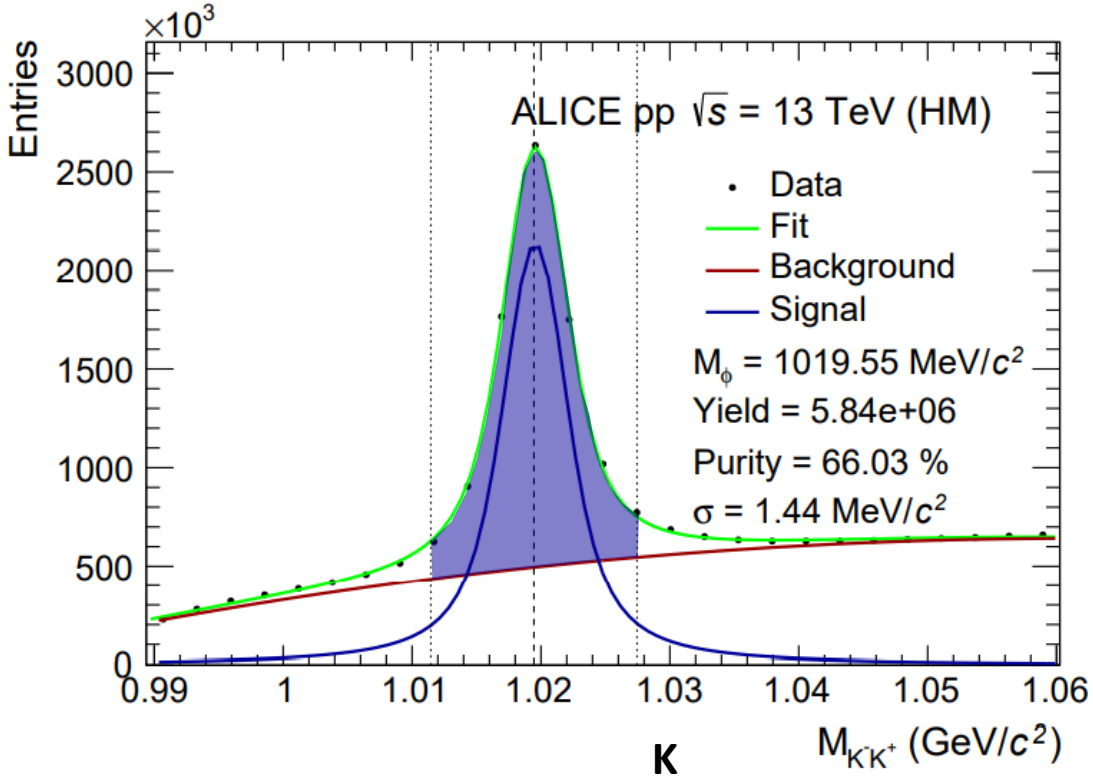

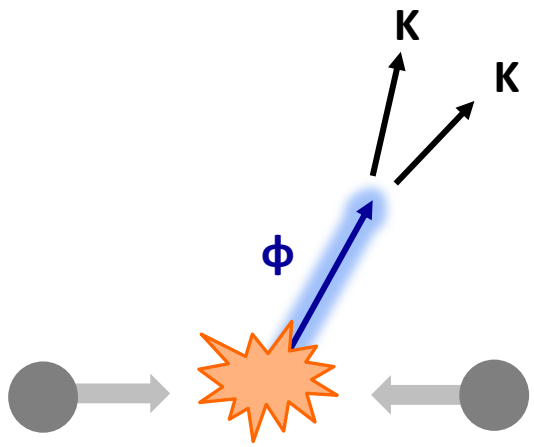

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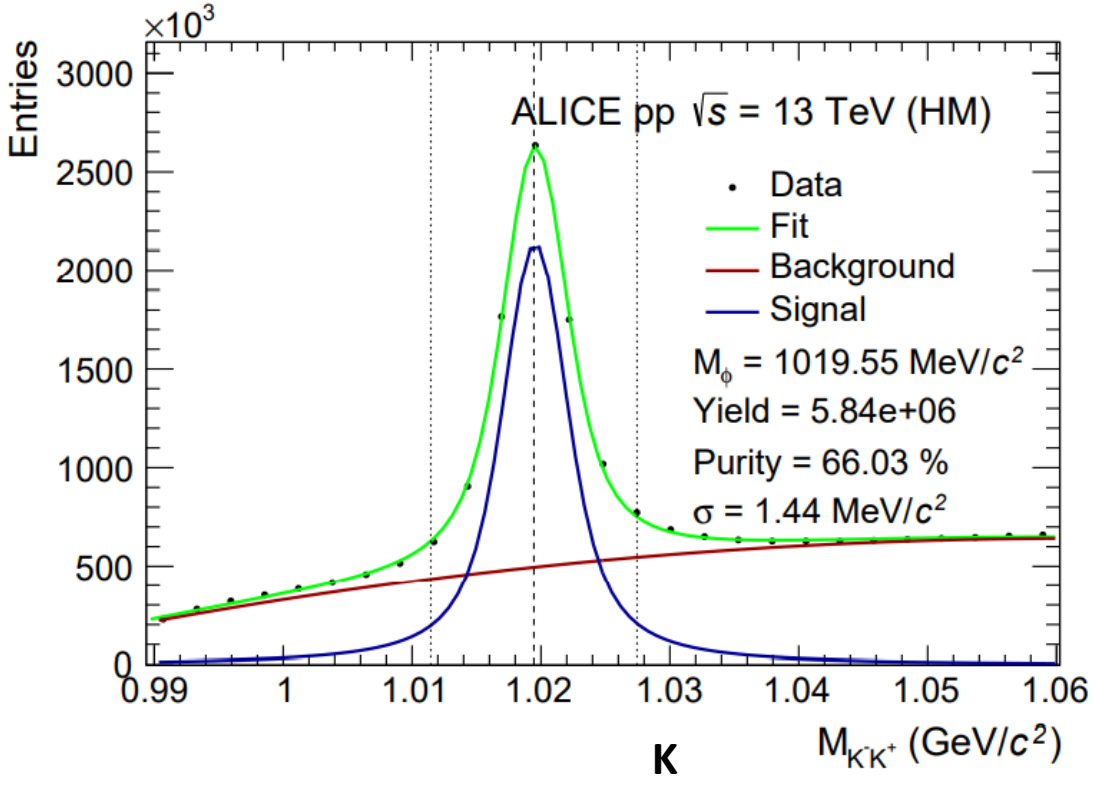
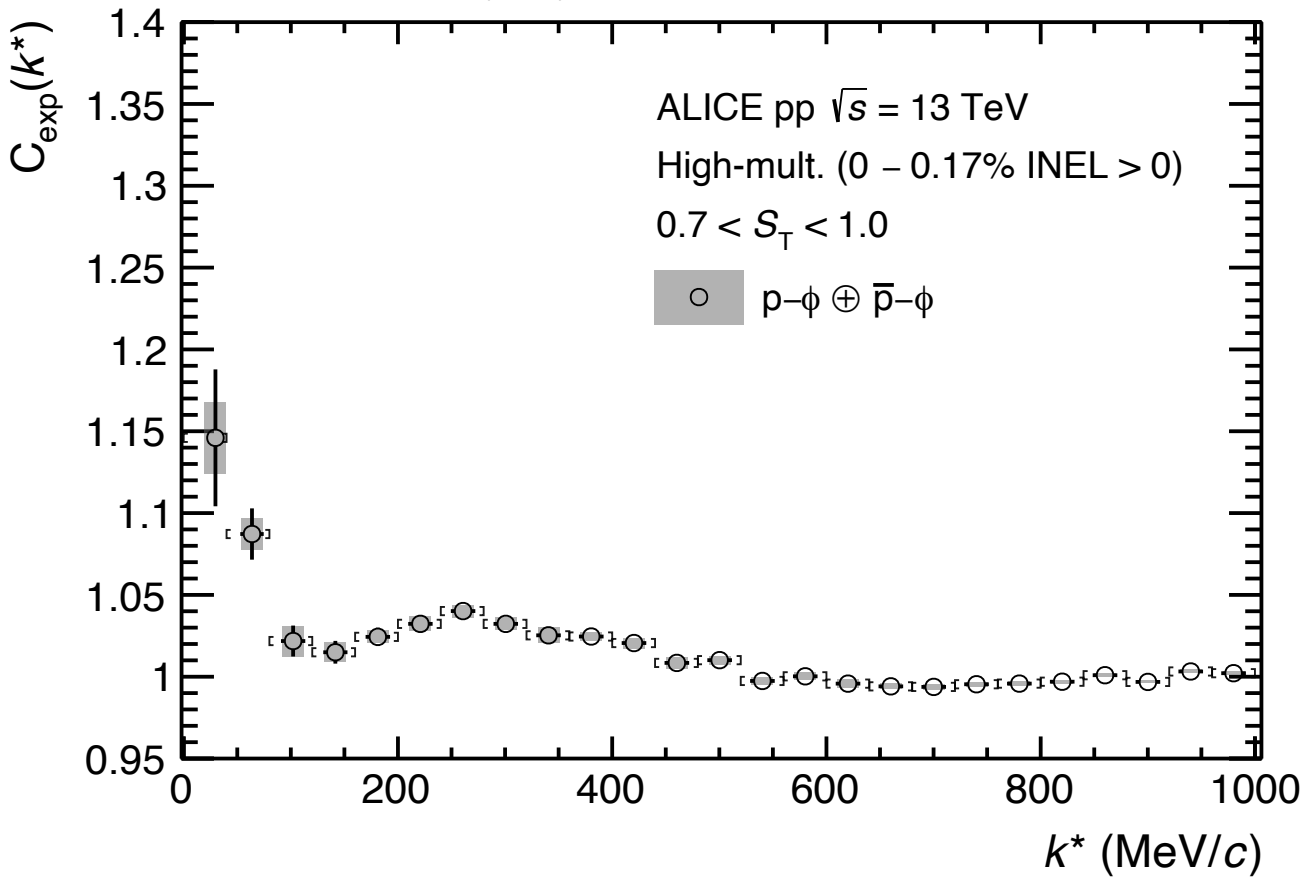
      - Signal → real ϕ mesons
    - Purity of ϕ meson candidates ~66%



Raw correlation function

Includes additional background contributions besides the one arising from genuine FSI interaction

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



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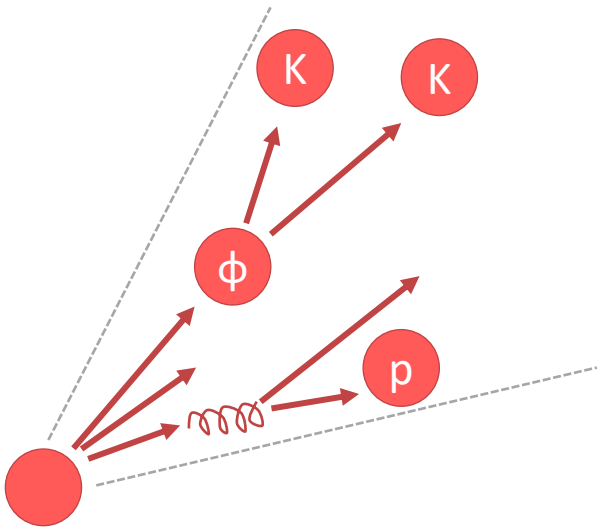
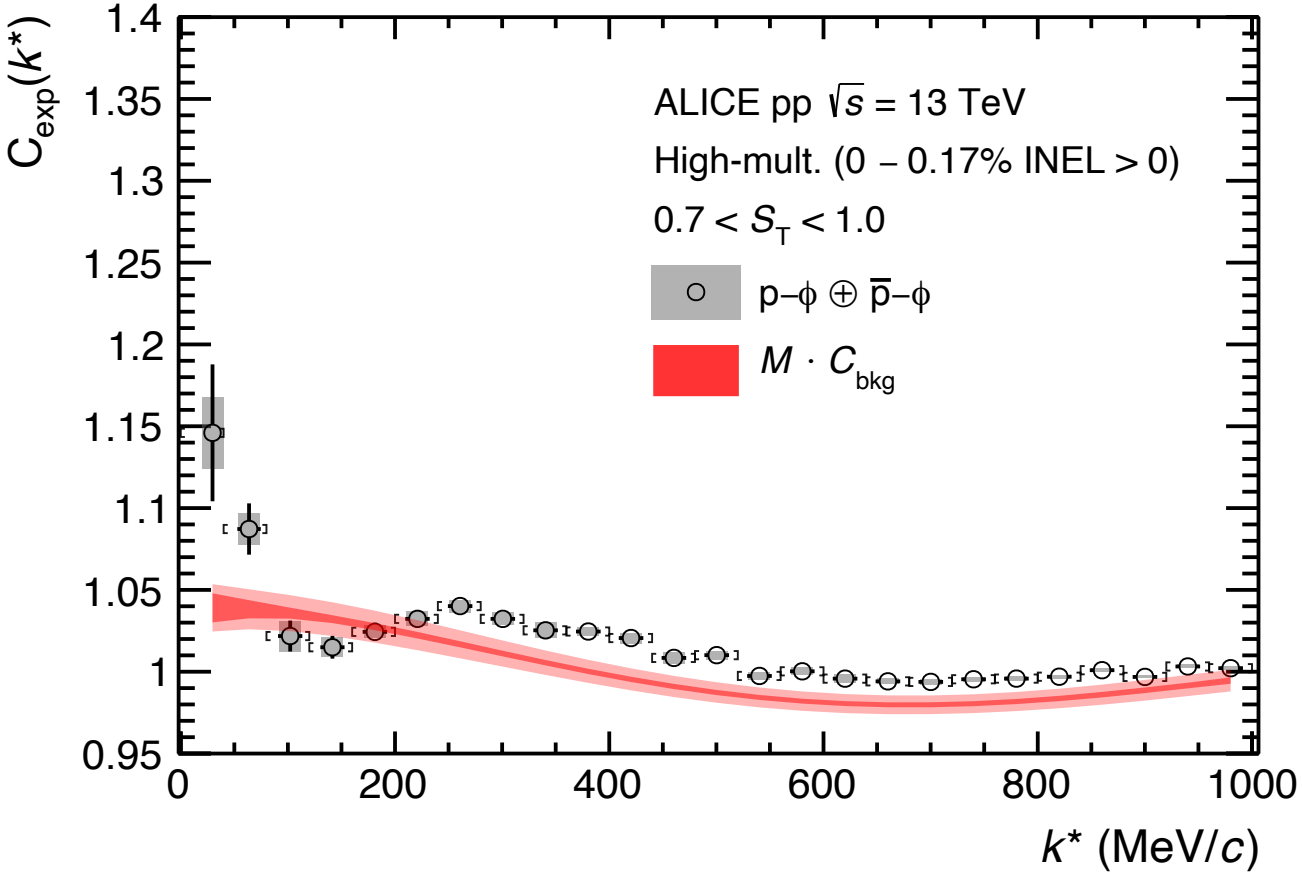
- Non-femtoscopic background
  Minijet contribution estimated with PYTHIA 8 + baseline



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



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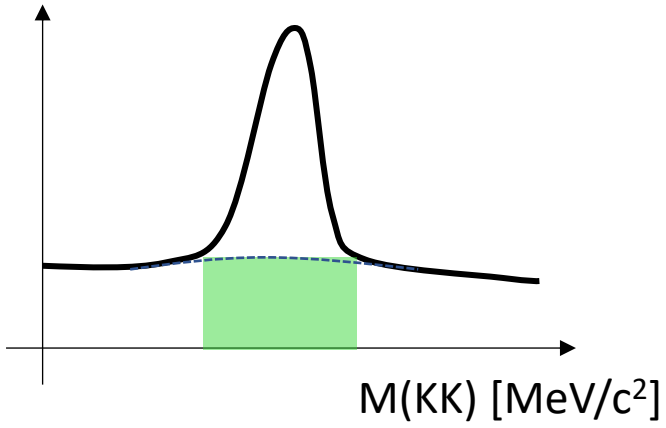
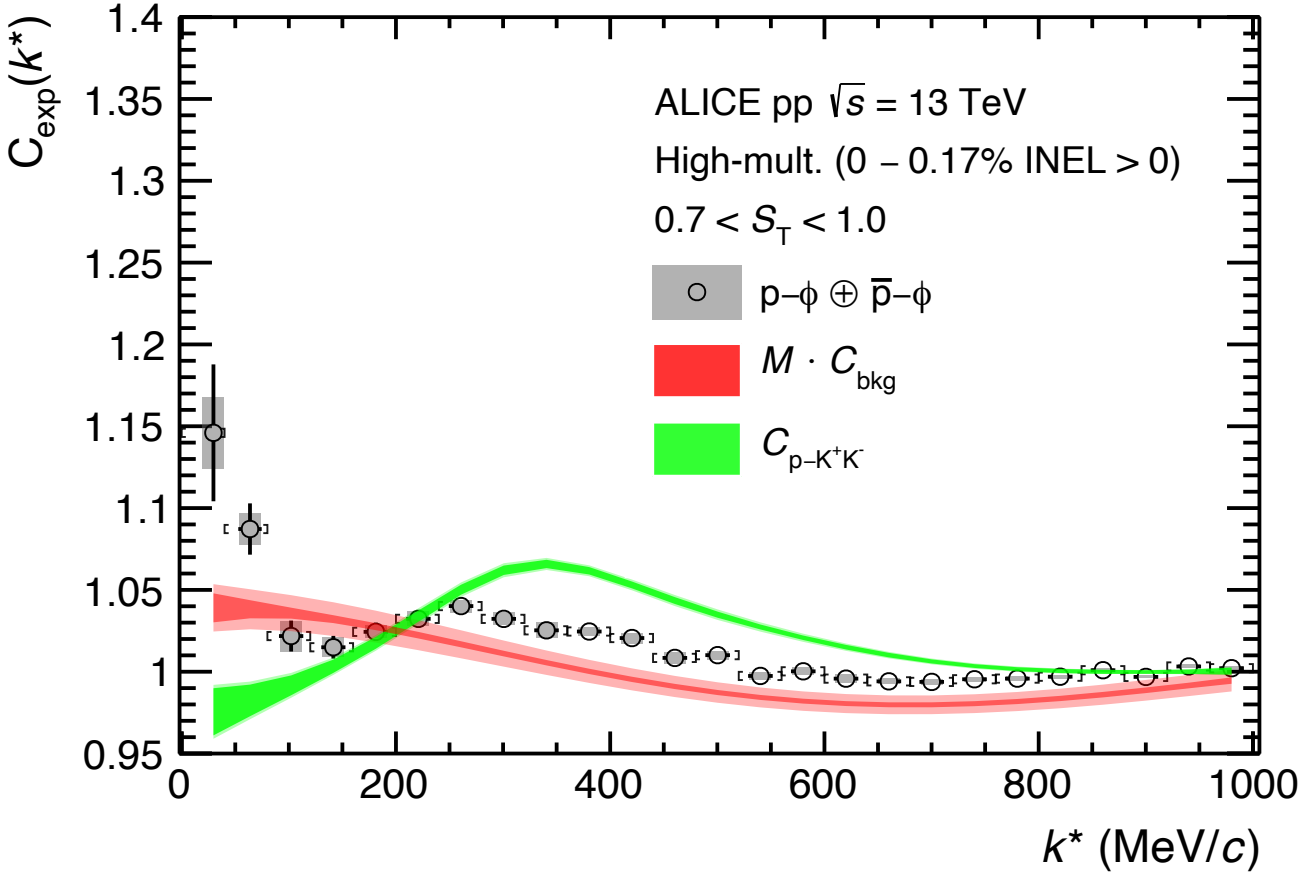


ALICE Collab., *PRL* **127** (2021) 172301



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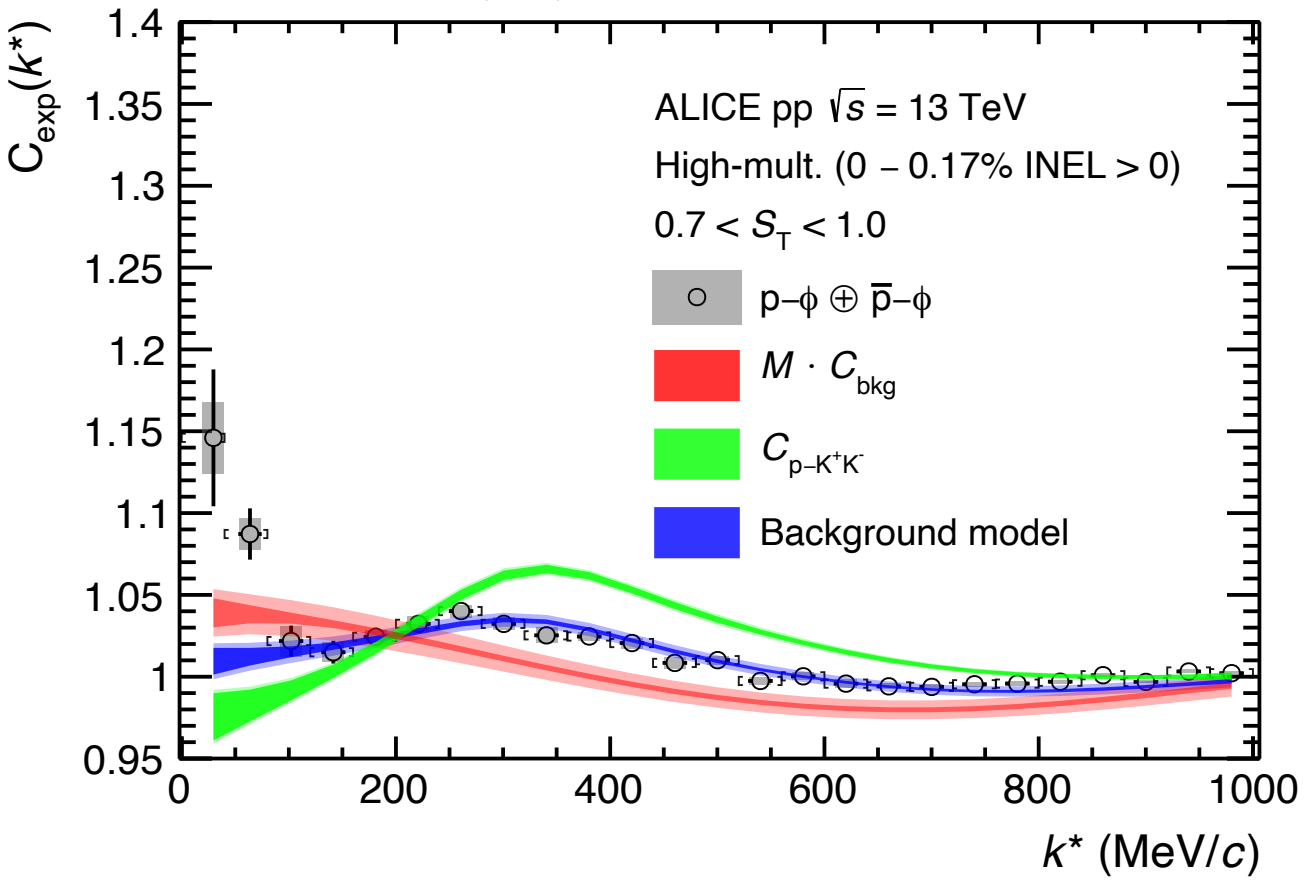
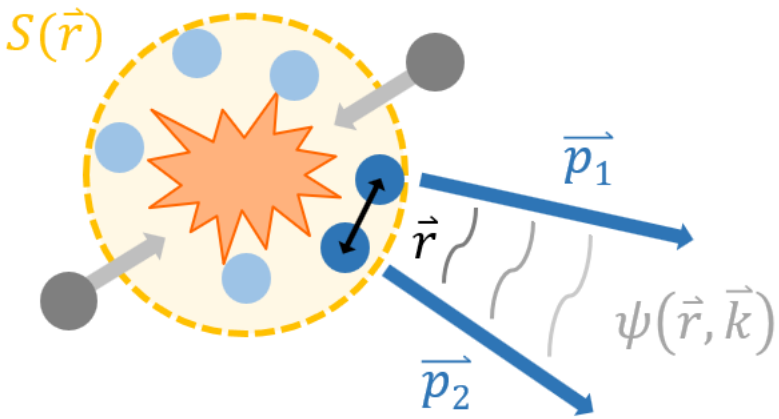
→ Combined to total background used to extract genuine correlation function from data

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



The Source

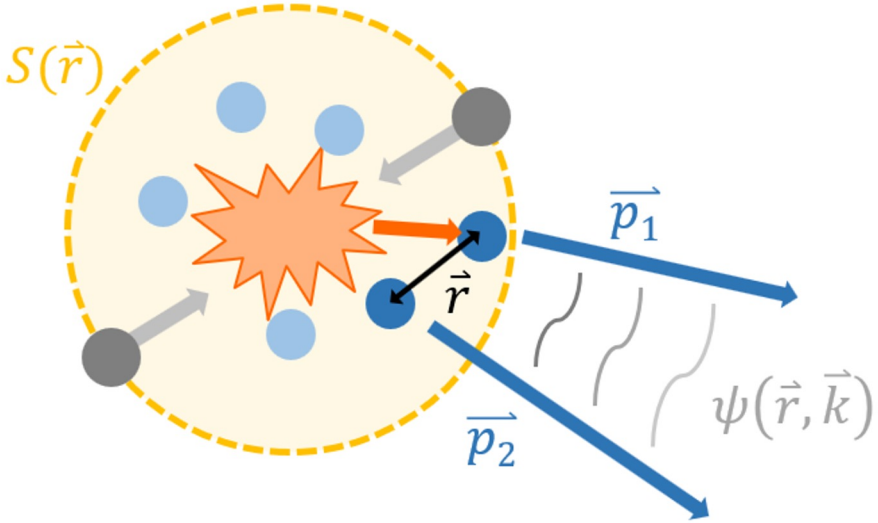
- Particle emission from **Gaussian core** source



The Source

- Particle emission from **Gaussian core** source
- Core radius effectively increased by short-lived strongly decaying **resonances** ($c\tau \approx r_{core}$)
- Universal source model constrained from pp pairs (well-known interaction)

ALICE Collab., *Physics Letters B*, **811** (2020) 135849



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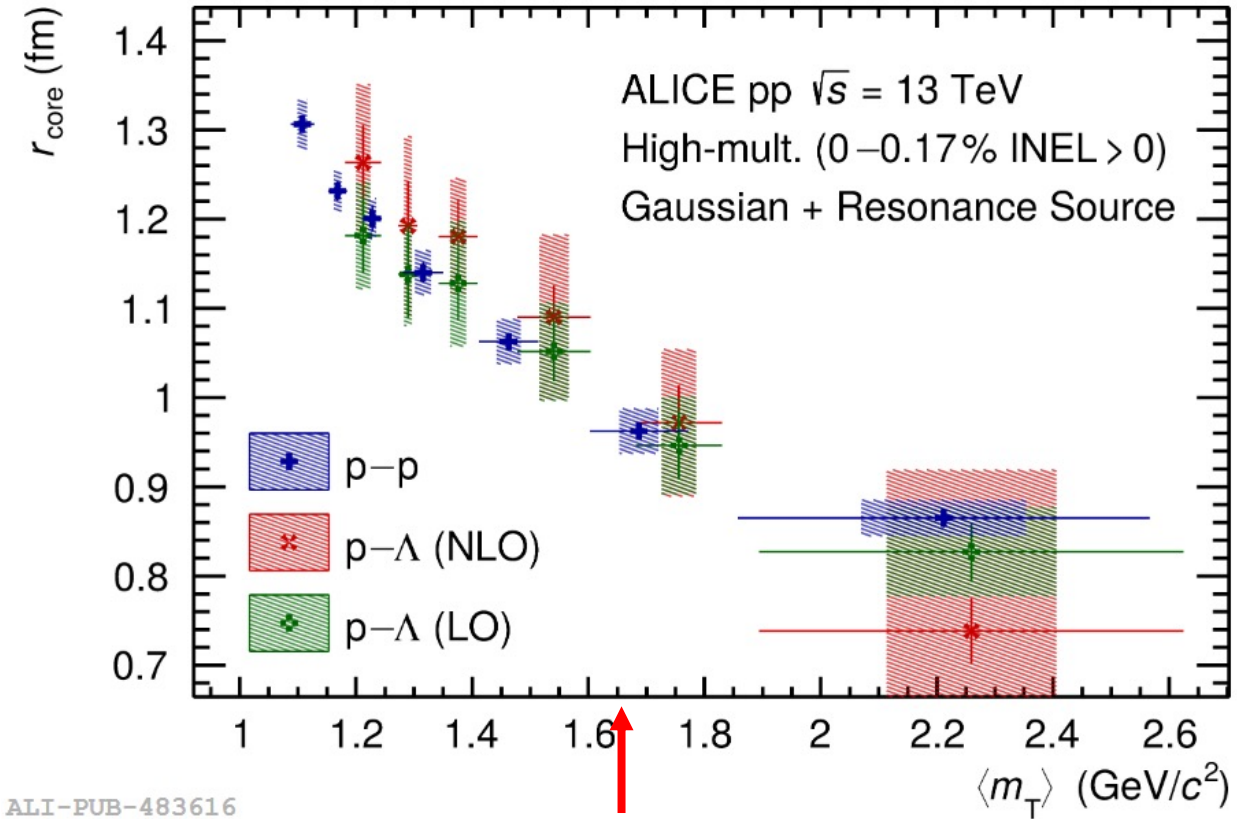
- Universal source model constrained from pp pairs (well-known interaction)
  ALICE Collab., *Physics Letters B*, **811** (2020) 135849
- Gaussian core source scales with $\langle m_T \rangle$
  - r_{core} **= 0.98 ± 0.04 fm**
- Effects from short-lived resonances
  - no relevant contribution from strongly decaying resonances feeding to the ϕ
  - Sizable amount of protons from decay of e.g. Delta resonances (only ~33% primordial protons)
  - effective Gaussian size: r_{eff} **= 1.08 ± 0.05 fm**



$\langle m_{T,\,p\phi} \rangle$ = 1.66 GeV/c^2

Lednicky-Lyuboshits Model

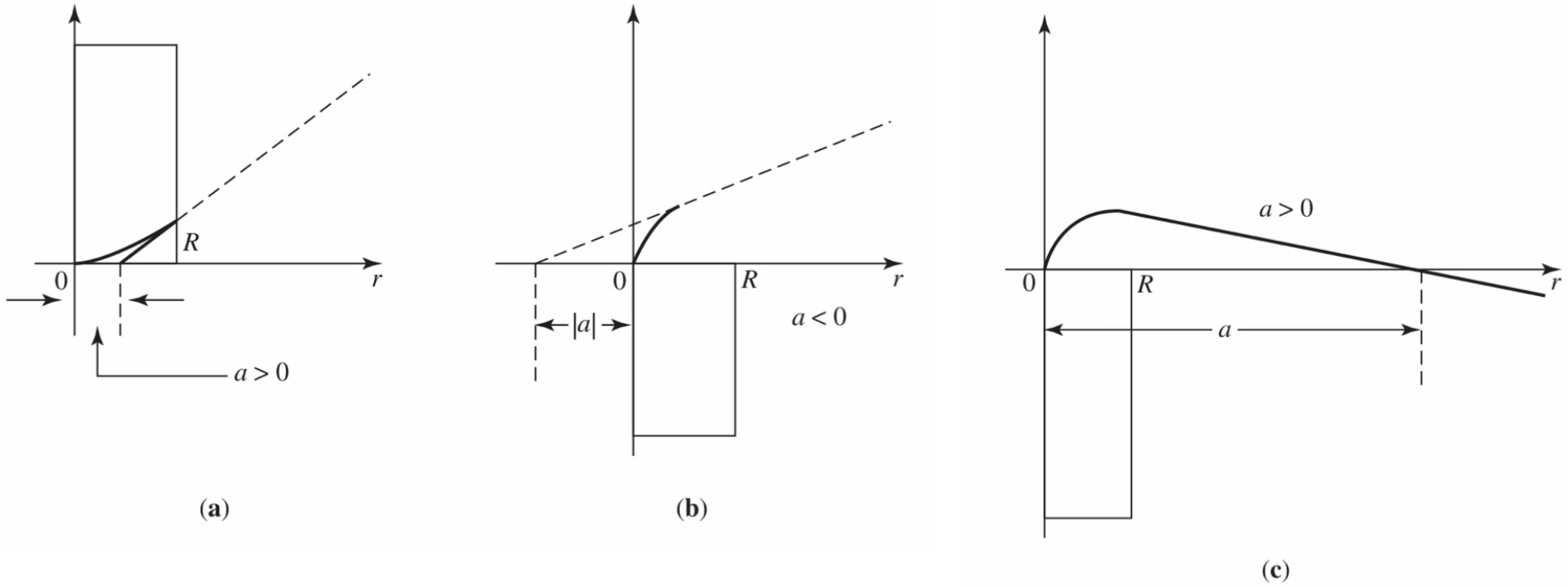
$$C(k^*) = \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f(k^*)}{r_{eff}} \right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi} r_{eff}} \right) + \frac{2\Re f(k^*)}{\sqrt{\pi} r_{eff}} F_1(2k^* r_{eff}) - \frac{\Im f(k^*)}{r_{eff}} F_2(2k^* r_{eff}) \right]$$

Analytical approach to model CF for strong final state interaction within effective range expansion

R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys.* **53** (1982) 770

- Isotropic source of Gaussian profile $S(r^*)$
- Scattering amplitude: $f(k^*) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - i k^* \right)^{-1}$
  - Effective range d_0 and scattering length f_0
- Spin averaged scattering parameters

Scattering length



Different sign convention f0, a0 = -a !

Figure 2.6: Reduced wave-function $u(r)$ for zero-energy ($k^* \approx 0$) as function of r for a repulsive potential (a), an attractive potential (b) and increased attractive potential (c). The intercept of the outside $u(r)$ with the r-axis gives the scattering length a. Figures taken from [113].

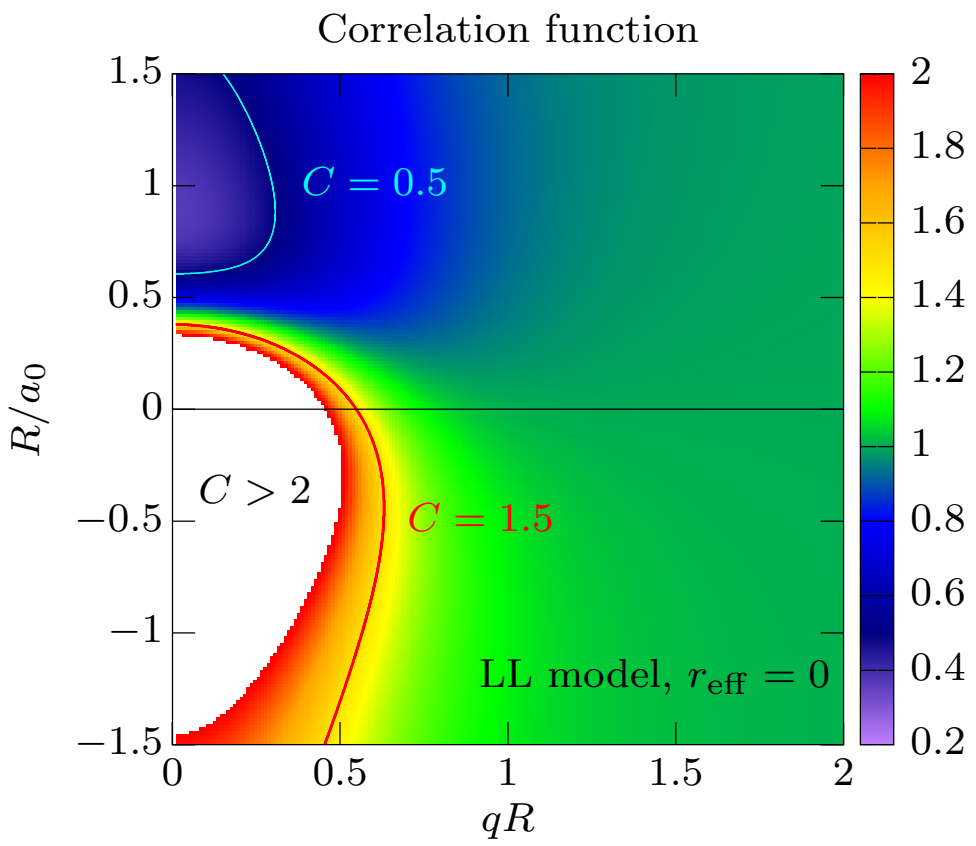
Correlation function and bound states

- Correlation functions can be used to study the existence of bound states
- Interplay between system size and scattering length can lead to a size-dependent modification of the correlation function in presence of a bound state

$$C(q) = 1 + \frac{1}{x^2+y^2}\left[\frac{1}{2} - \frac{2y}{\sqrt{\pi}}\int_0^{2x} dt \frac{e^{t^2-4x^2}}{x} - \frac{(1-e^{-4x^2})}{2}\right]$$

$$x = qR \quad y = \frac{R}{a_0}$$

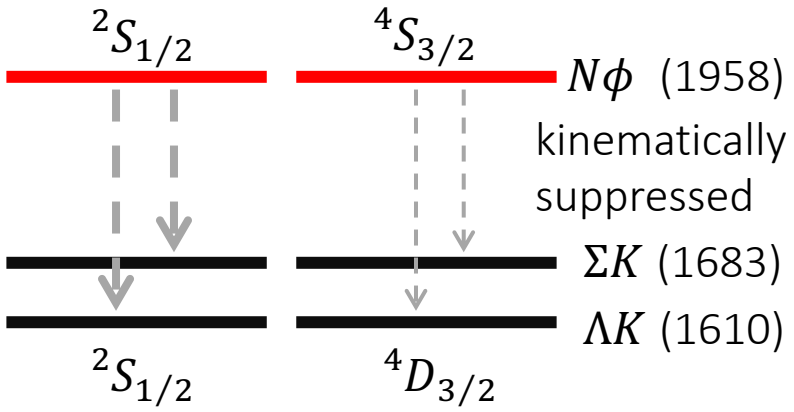
R= source size
q= invariant relative momentum
a_0= scattering length

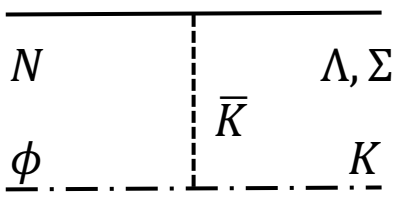


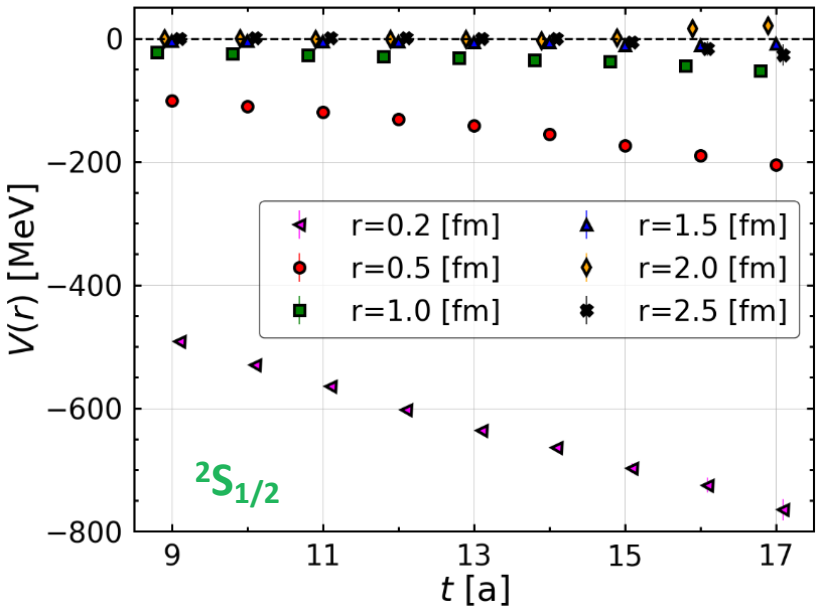
Y. Kamiya et al. arXiv:2108.09644v1

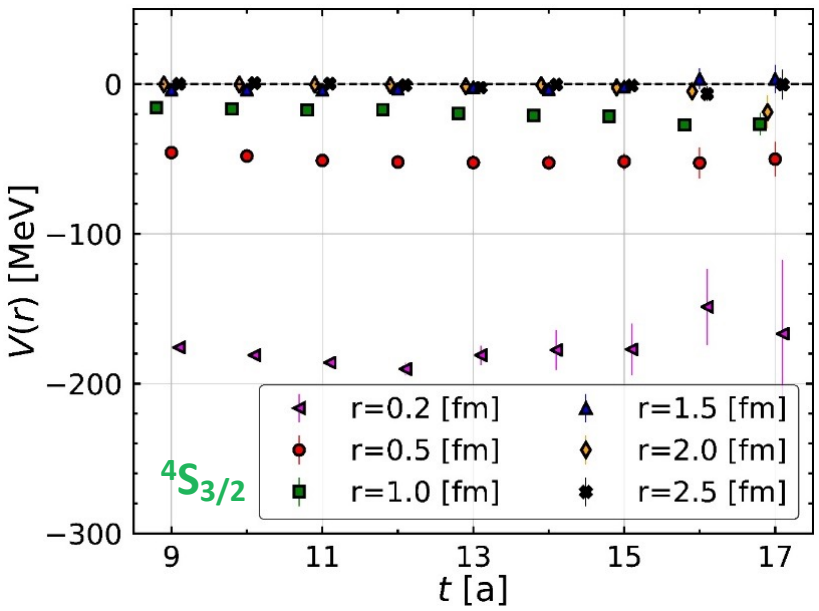
What about $^2S_{1/2}$

- Two body channels
- Time dependence of potential
  - clear open channel effect in $^2S_{1/2}$ case





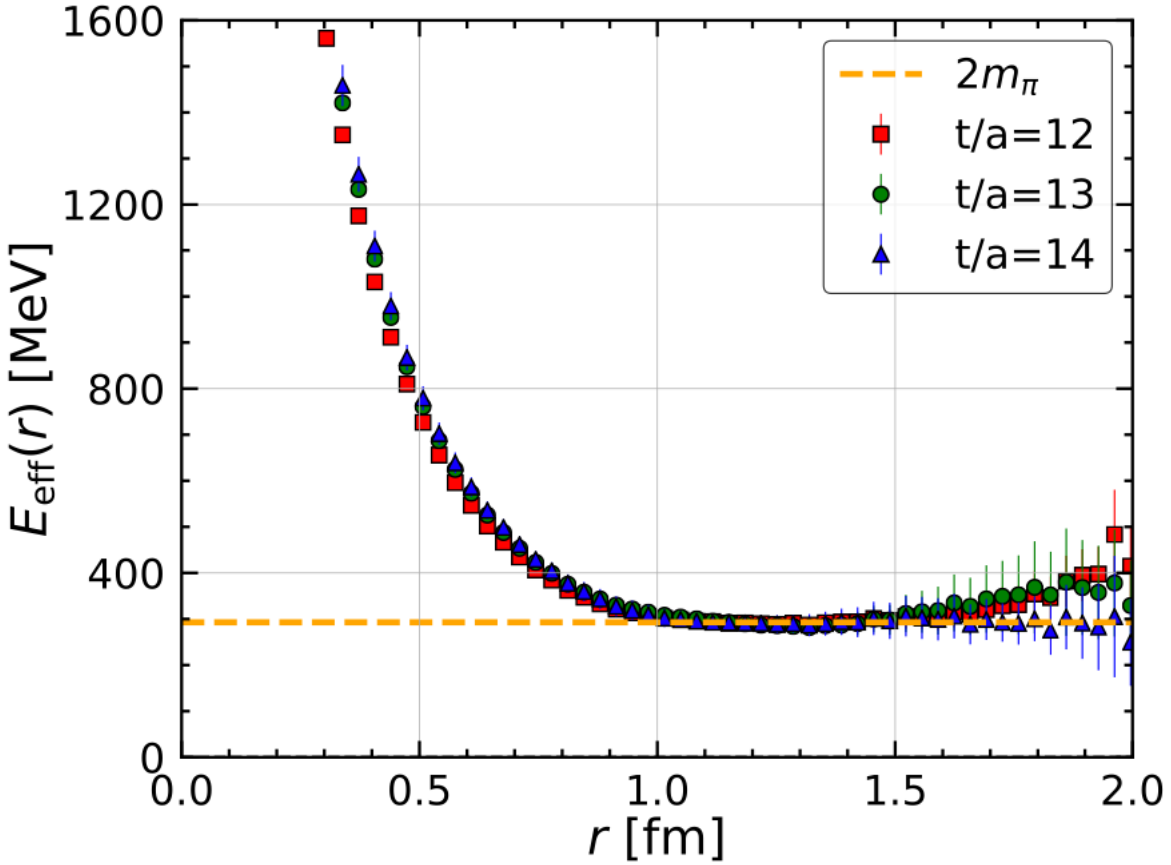




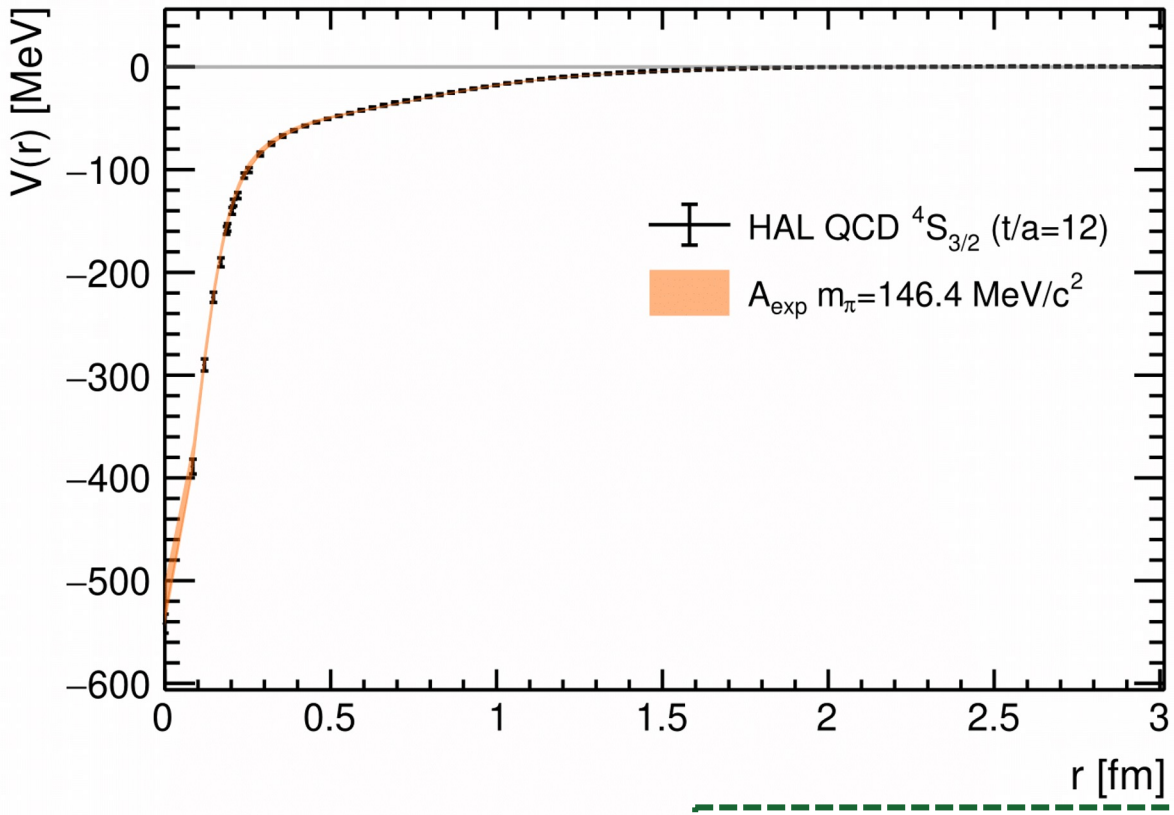
Two Pion Exchange

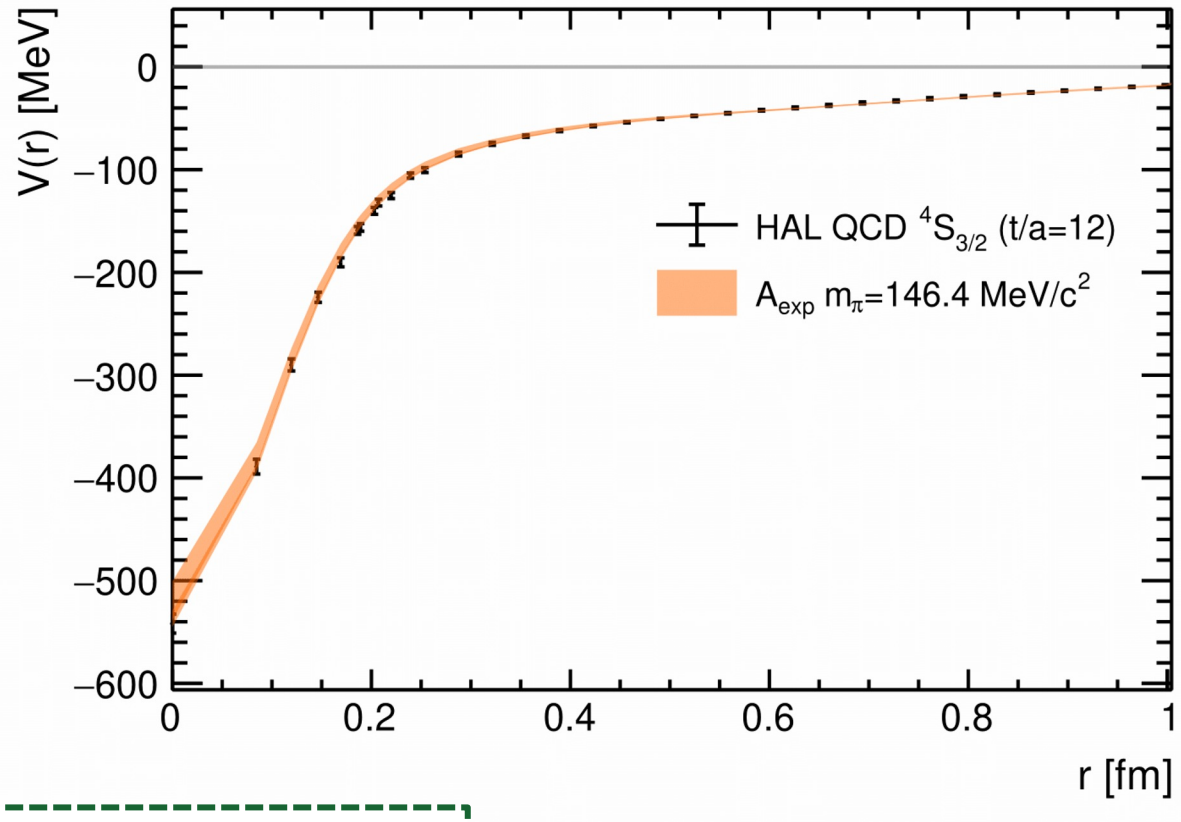
- Non-perturbative gluon exchange expected to appear in the form of the TPE at long distance
- Spatial effective energy fitted to lattice data

$$E_{\text{eff}}(r) = -\frac{\ln[-V(r)r^2/\alpha]}{r},$$



Parametrization of the $^4S_{3/2}$ potential



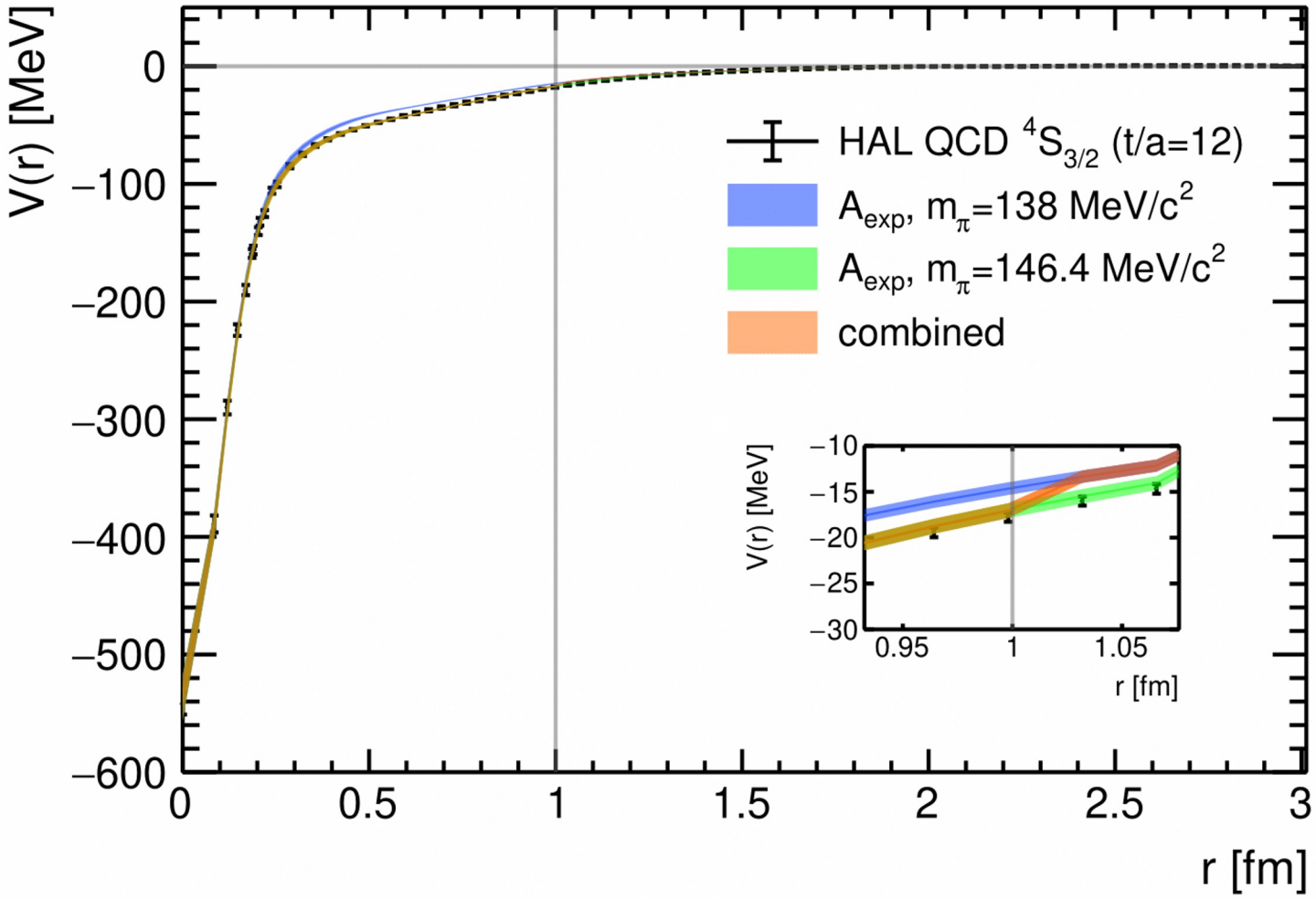


Argonne-type form factor $f(r;b_3) = \left(1 - e^{-(r/b_3)^2}\right)^2$

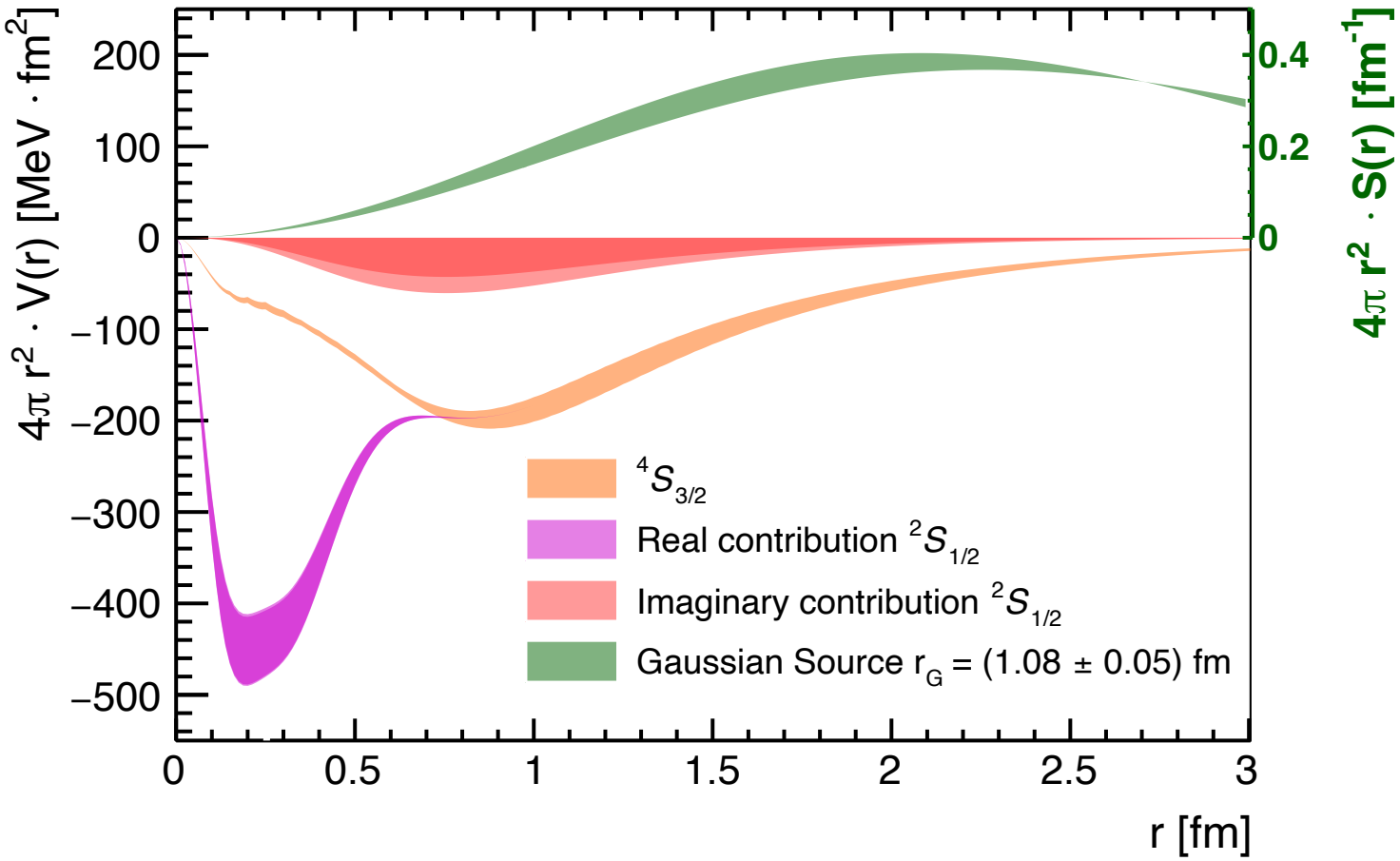
$$V_{LATTICE}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r;b_3) \frac{e^{-2m_\pi r}}{r^2}$$

Pionmass variation

- Pion mass of 146.4 MeV used in lattice calculations unphysical → leads to larger scattering parameters
- To estimate potential at physical pion mass:
  - Fit of lattice potential performed using pion mass of 146.4 MeV
  - Changing pion mass to the isospin-average of 138.0 MeV, while potential parameters remain fixed from fit to data



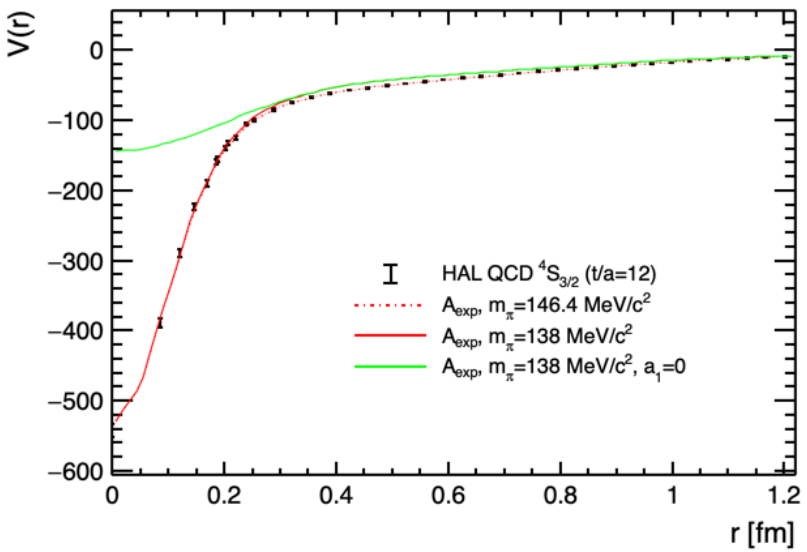
Potentials

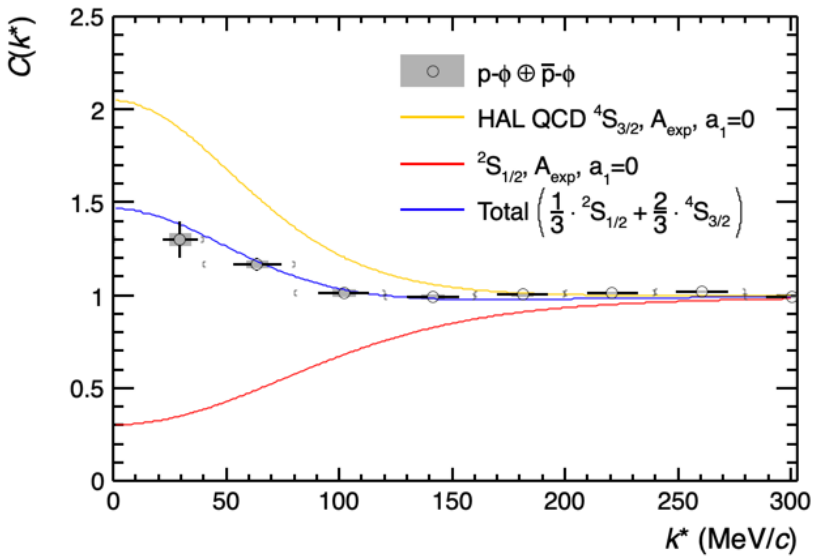

$4\pi\, r^2 \cdot V(r)$ [MeV · fm^2]
200
100
0
−100
−200
−300
−400
−500
0
0.5
1
1.5
2
2.5
3
r [fm]
0.4
0.2
0
$4\pi\, r^2 \cdot S(r)$ [fm^{-1}]
$^4S_{3/2}$
Real contribution $^2S_{1/2}$
Imaginary contribution $^2S_{1/2}$
Gaussian Source r_G = (1.08 ± 0.05) fm

Potentials

- Removing the short range part of the potential the result does not change

Potential		Fit results			Scatt length S=1/2	
S=1/2	S=3/2	min χ^2	β	γ	Re(f0)	Im(f0)
standard	standard	6.8	7.0	0.0	-1.47	0.00
standard	a1=0	5.0	6.8	0.0	-1.63	0.00
a1=0	a1=0	5.1	10.2	0.0	-1.66	0.00
a1=0	standard	6.9	10.4	0.0	-1.56	0.00





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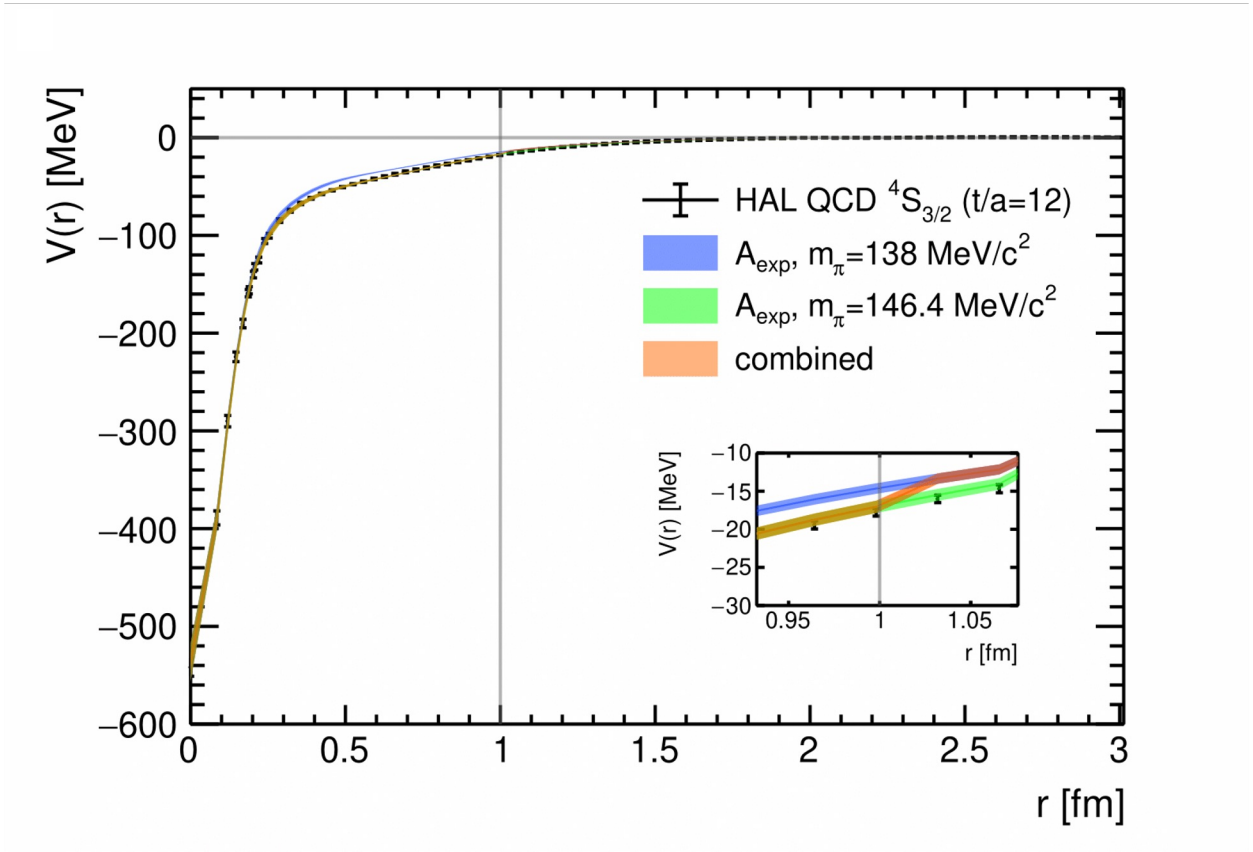

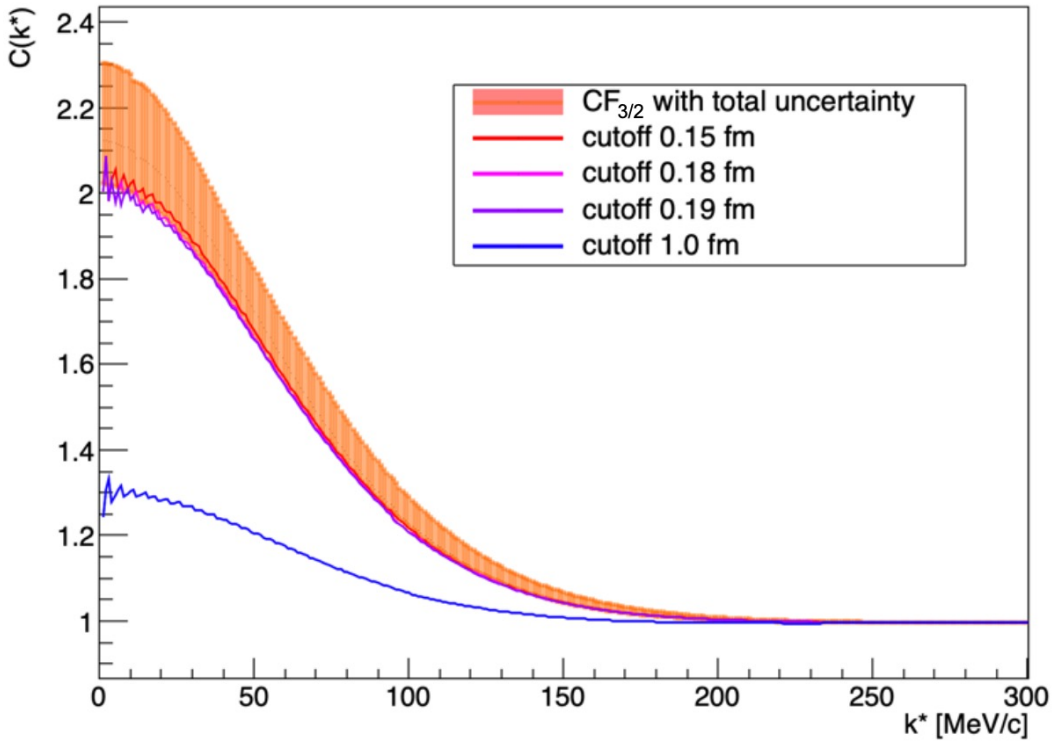

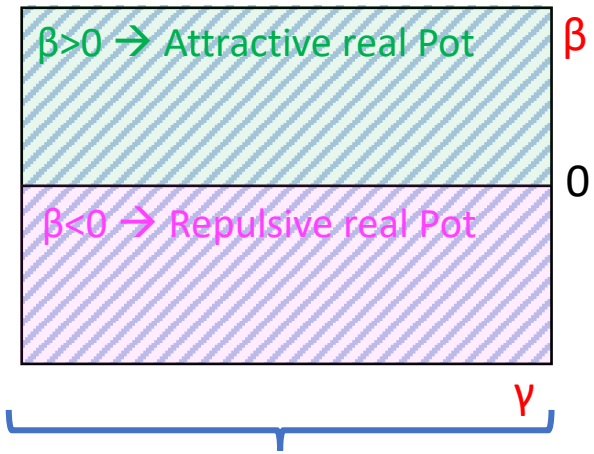

γ<0 → Imaginary Pot
restricted to be attractive to
model absorption processes