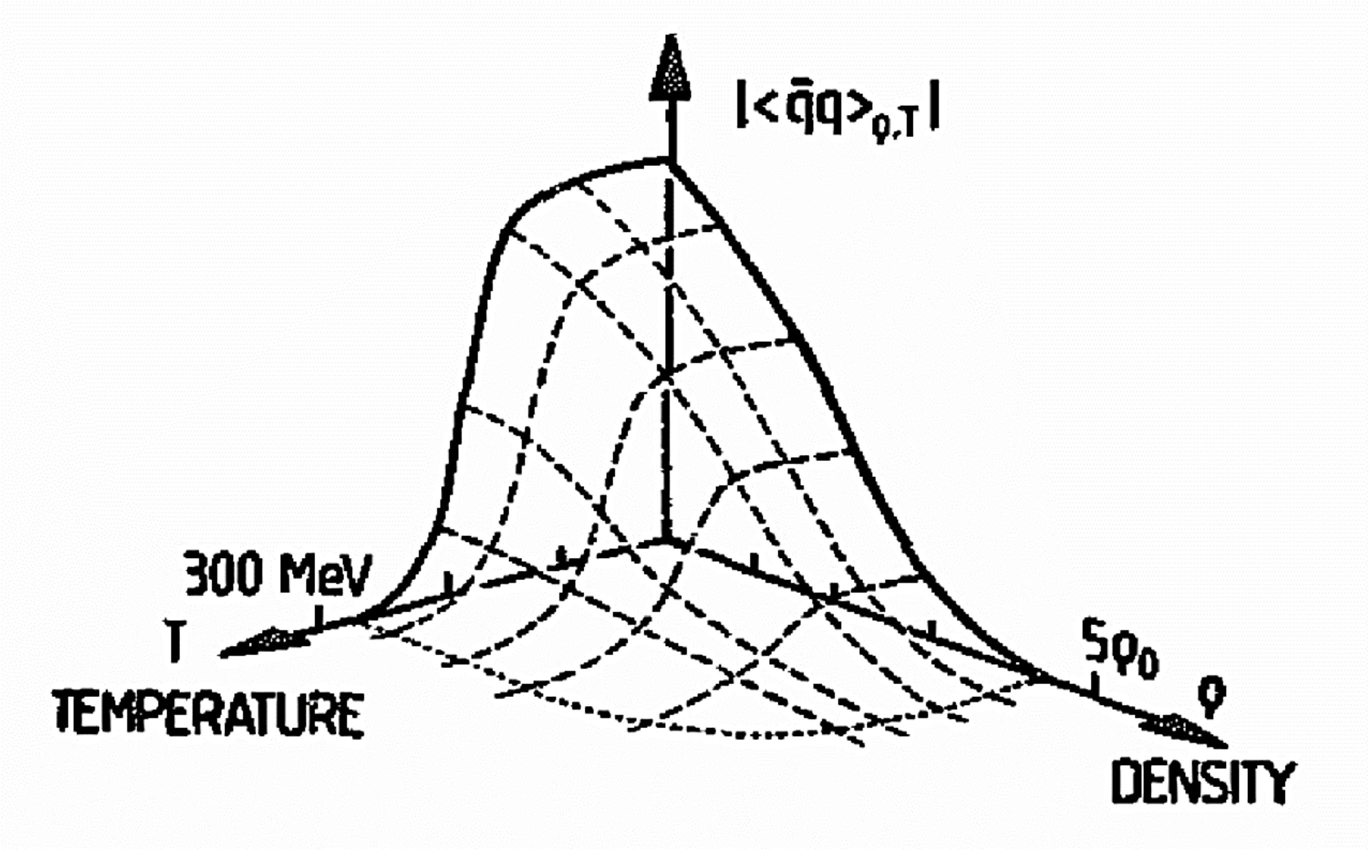
pϕ interaction from femtoscopy and comparison to lattice QCD

Emma Chizzali
EXOTICO Workshop, Trento
19/10/2022

Motivation

- Fundamental input for studying
    - Meson properties in nuclear matter
    - Modification of QCD condensates relervant to chiral symmetry

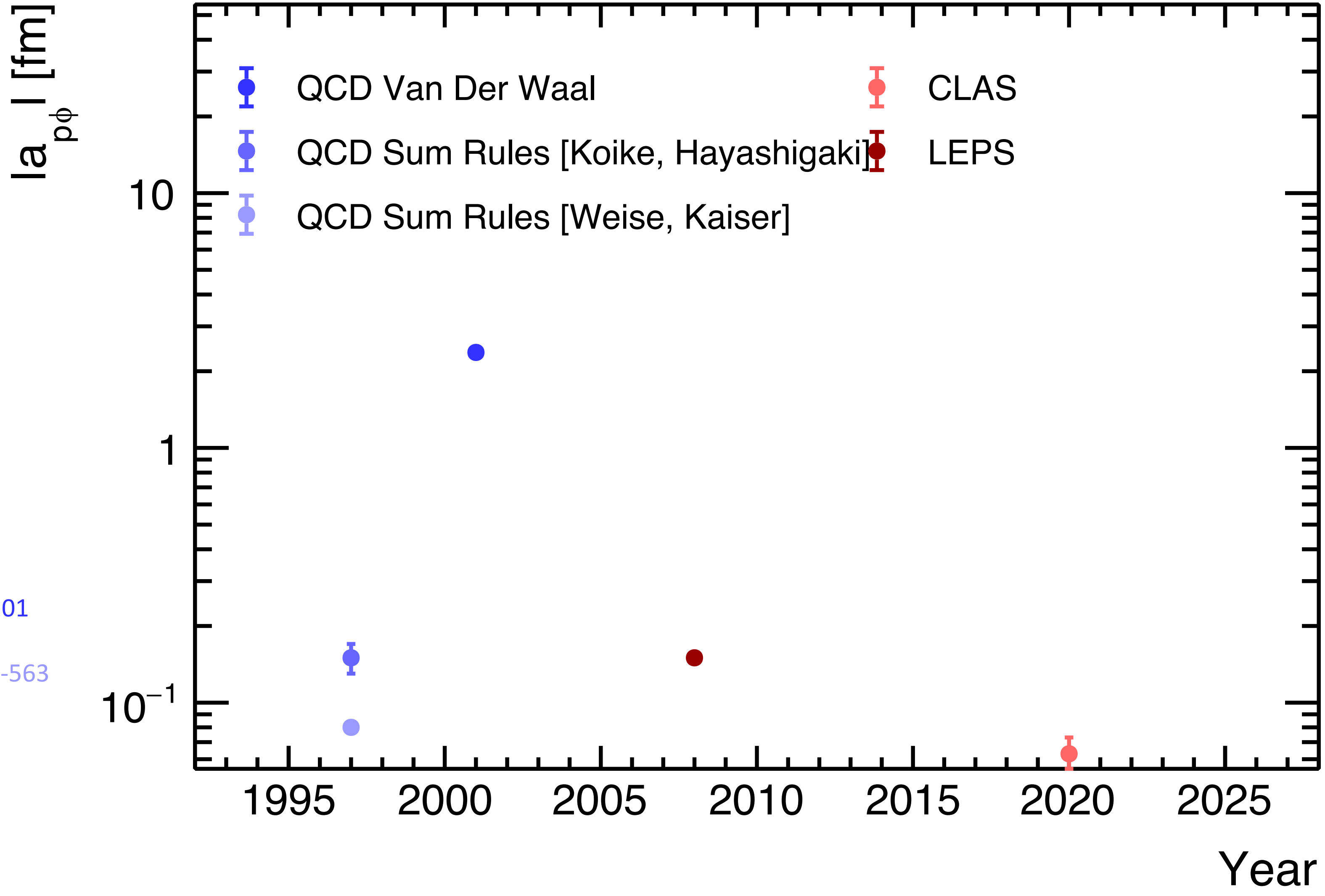


Weise, *Nuc. Phys. A* **55** (1993) 59-72

Motivation

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

- Fundamental input for studying
  - Meson properties in nuclear matter
  - Modification of QCD condensates relervant to chiral symmetry
- Not well constrained so far



H. Gao, T.S.H. Lee & V. Marinov, Phys Rev C **63** (2001) 022201

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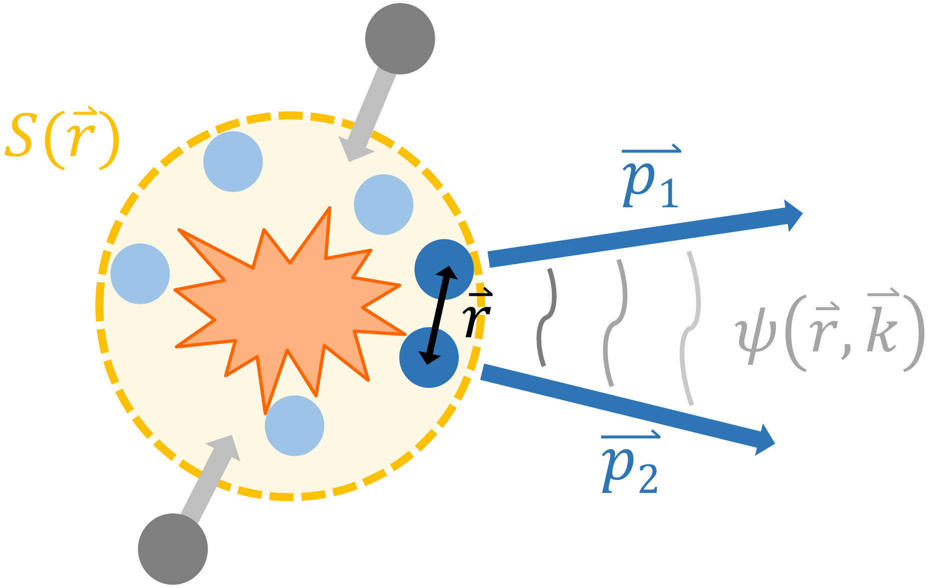
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101** (2020)

W.C. Chang *et al,* Phys Lett B **658**, 209 (2008)

The correlation function



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

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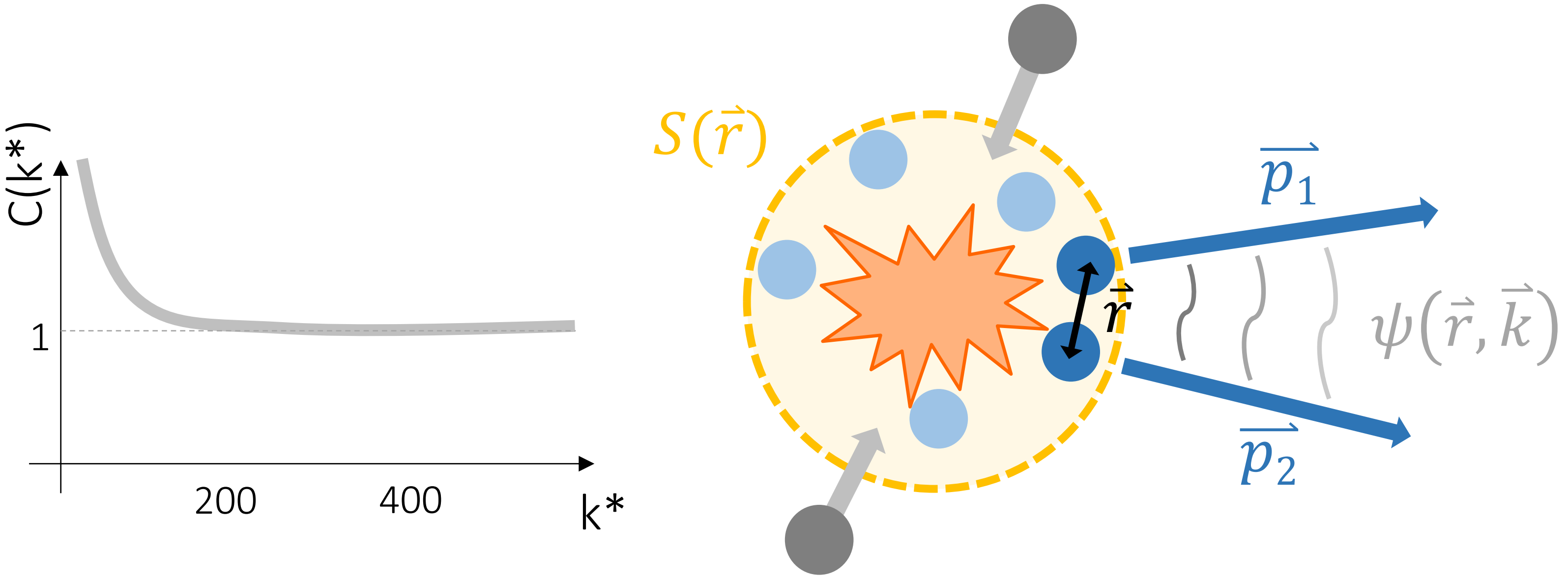

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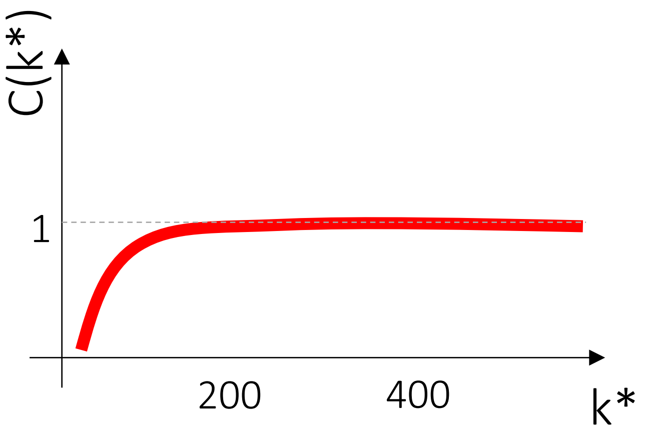

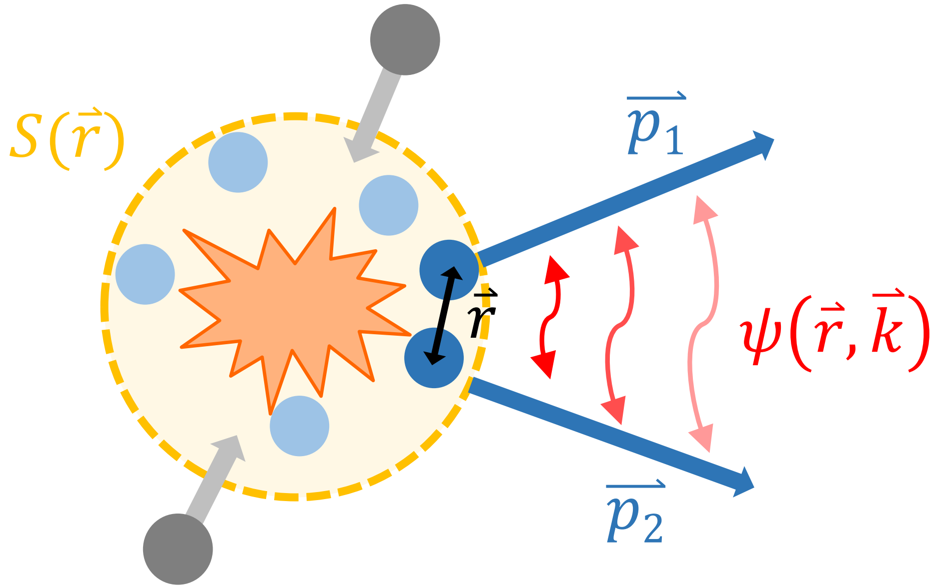

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repulsion

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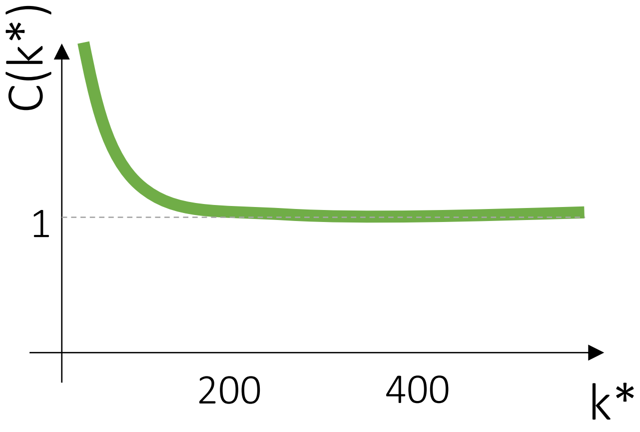

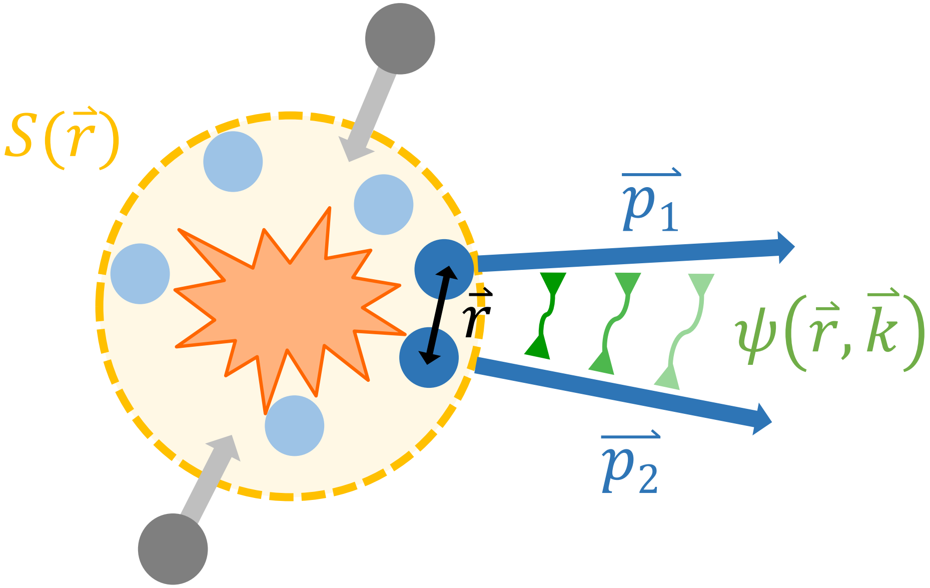

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attraction

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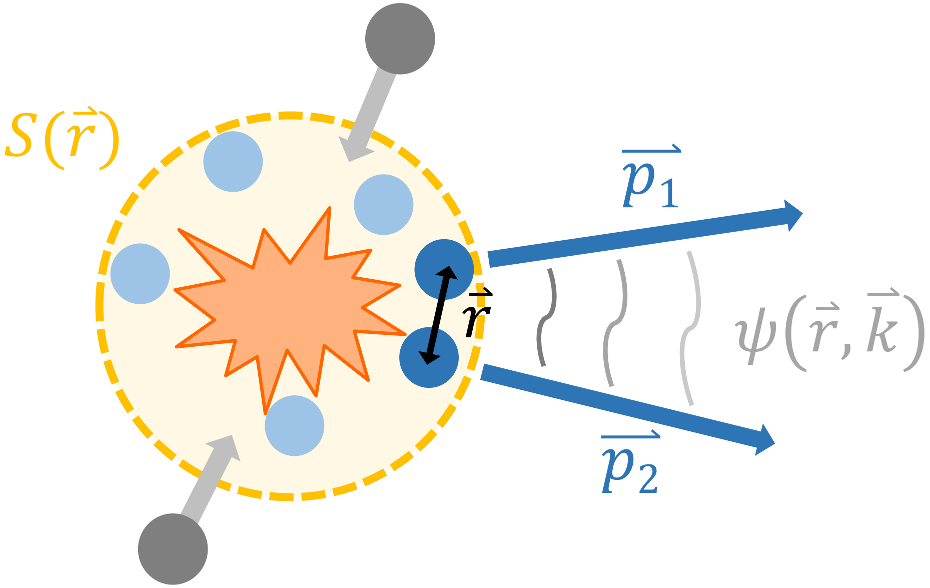

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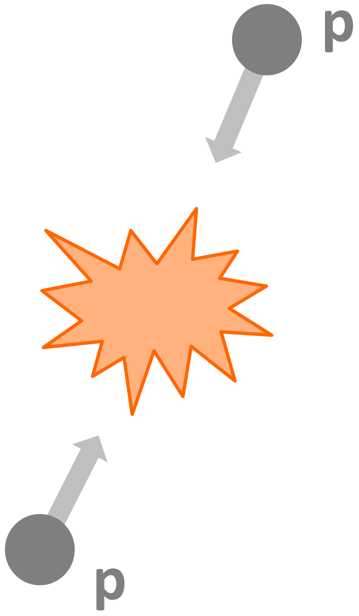
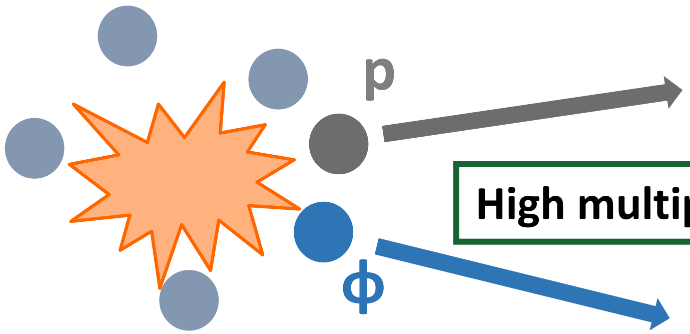


High multiplicity (HM) **pp collisions** at √s = 13 TeV

The correlation function



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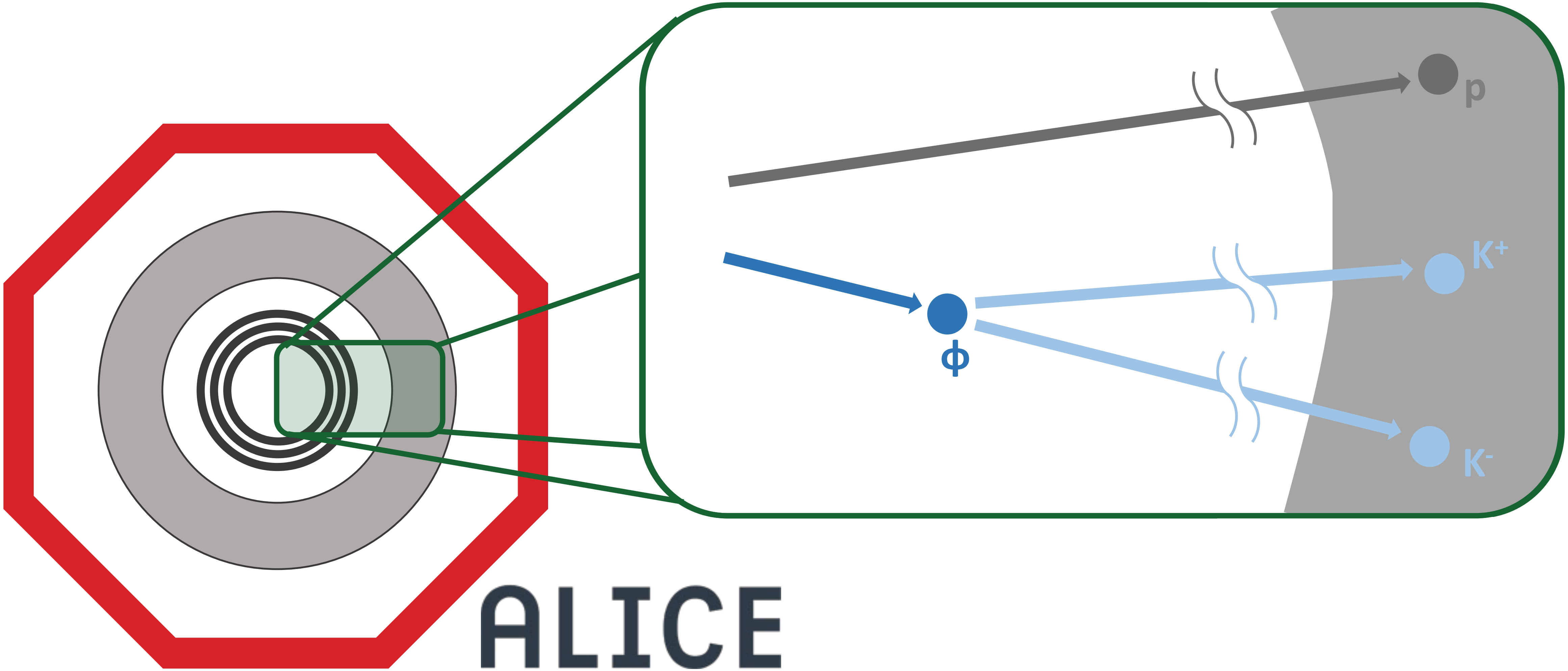

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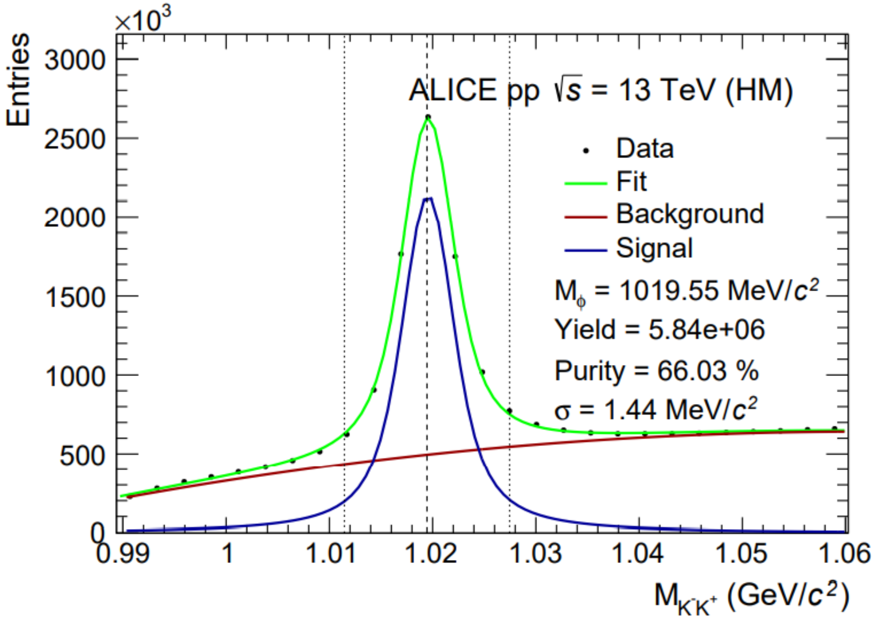

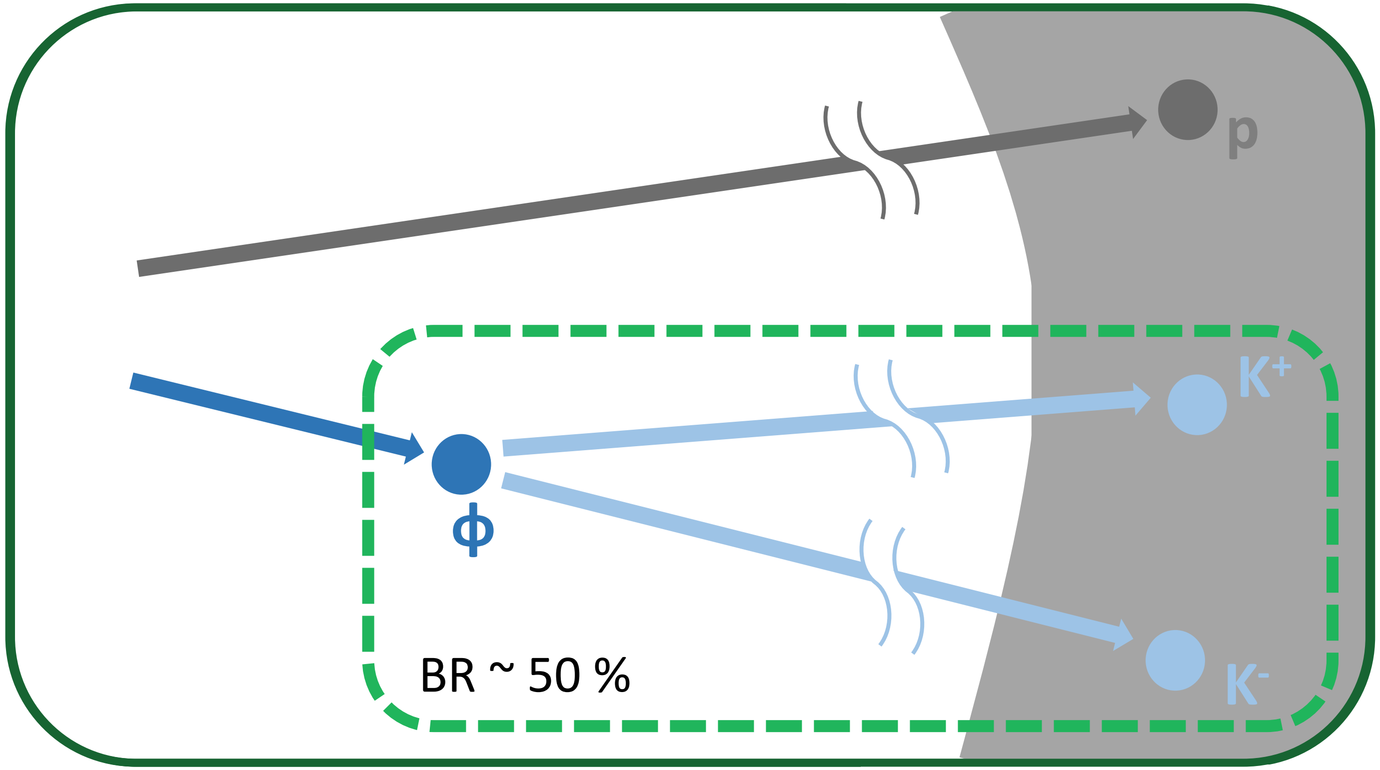

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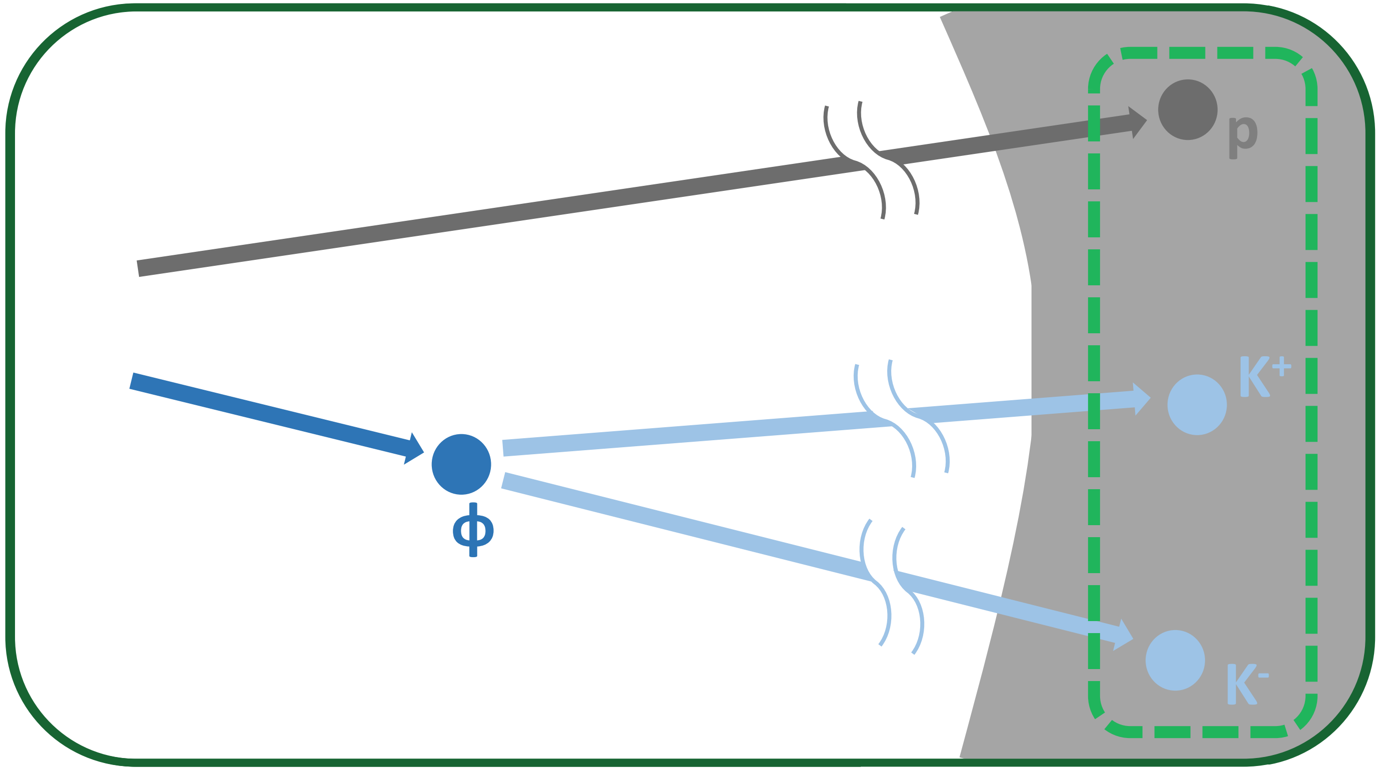
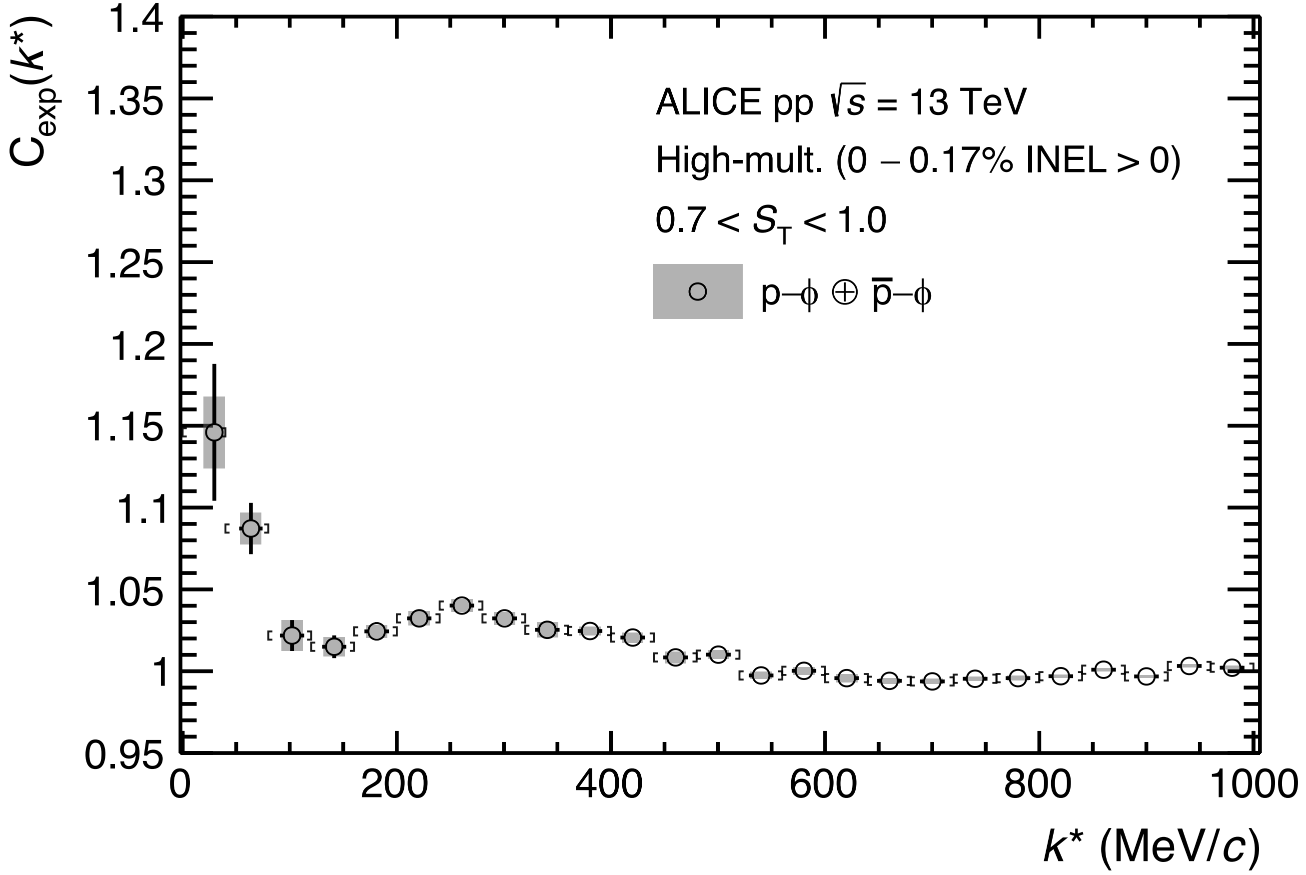


Excellent PID with ALICE Detector → charged particles measured directly with purities ~ 99%

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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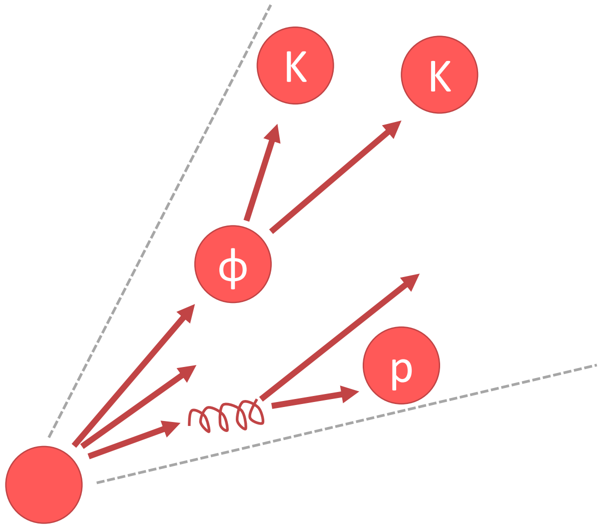
  Minijet contribution estimated with PYTHIA 8 + baseline



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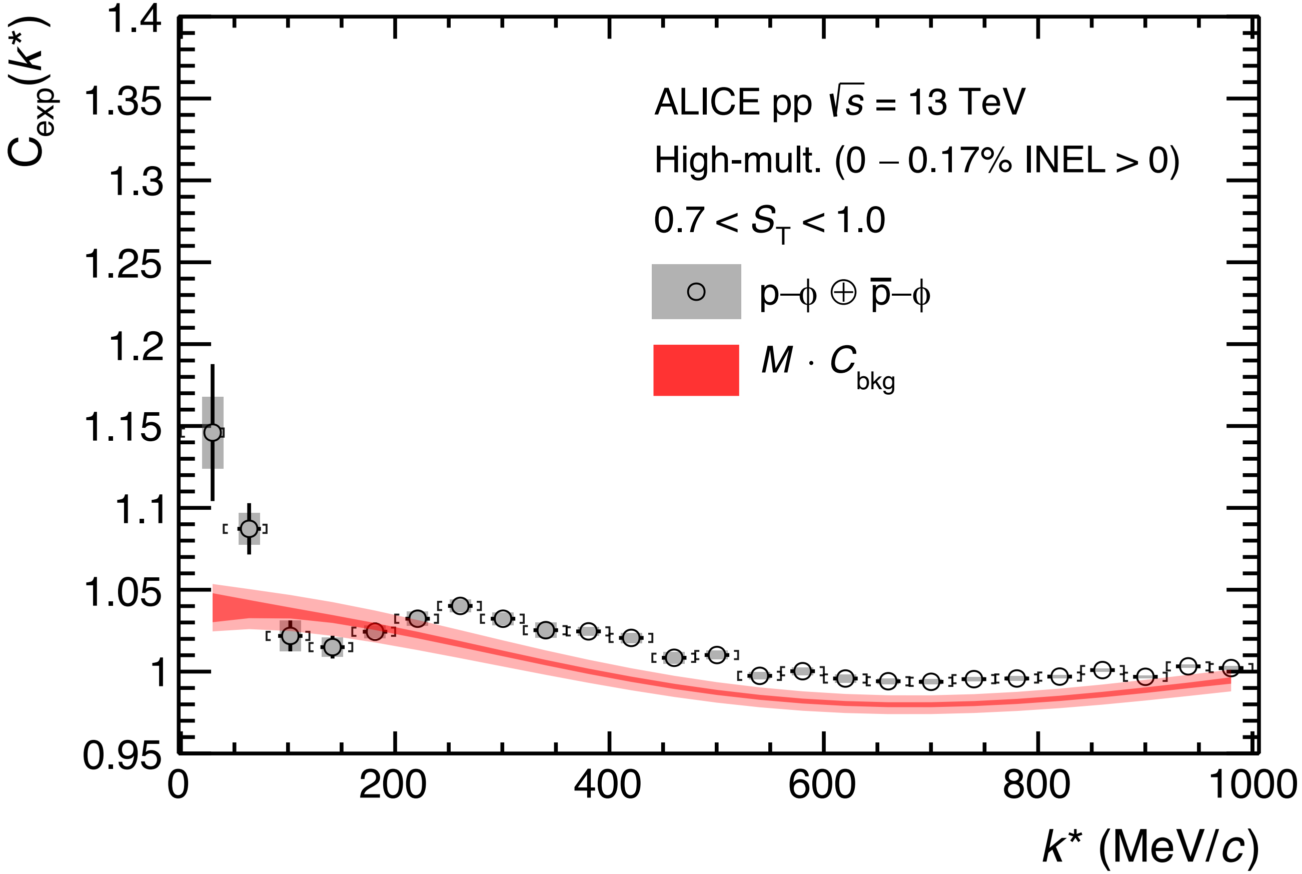

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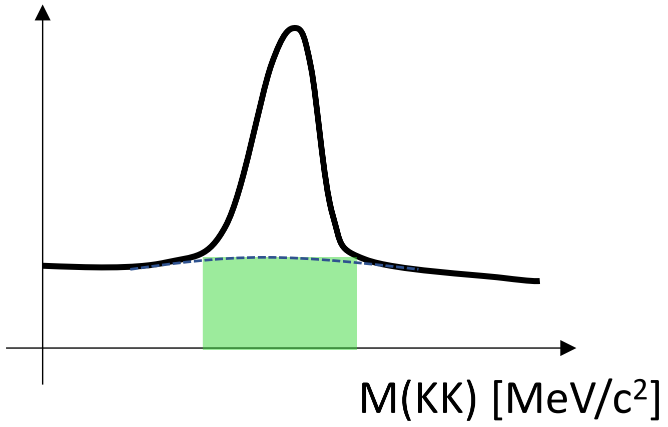

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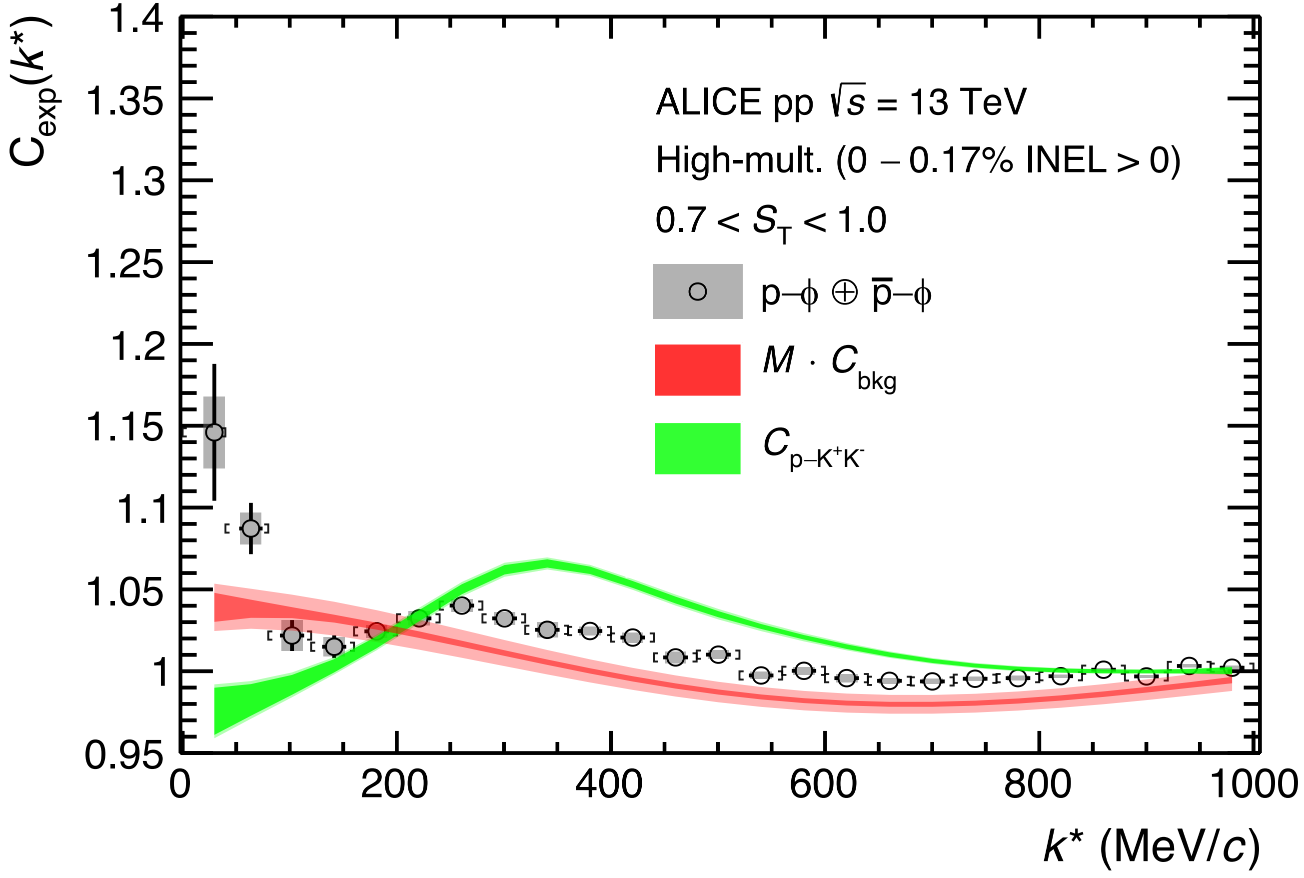

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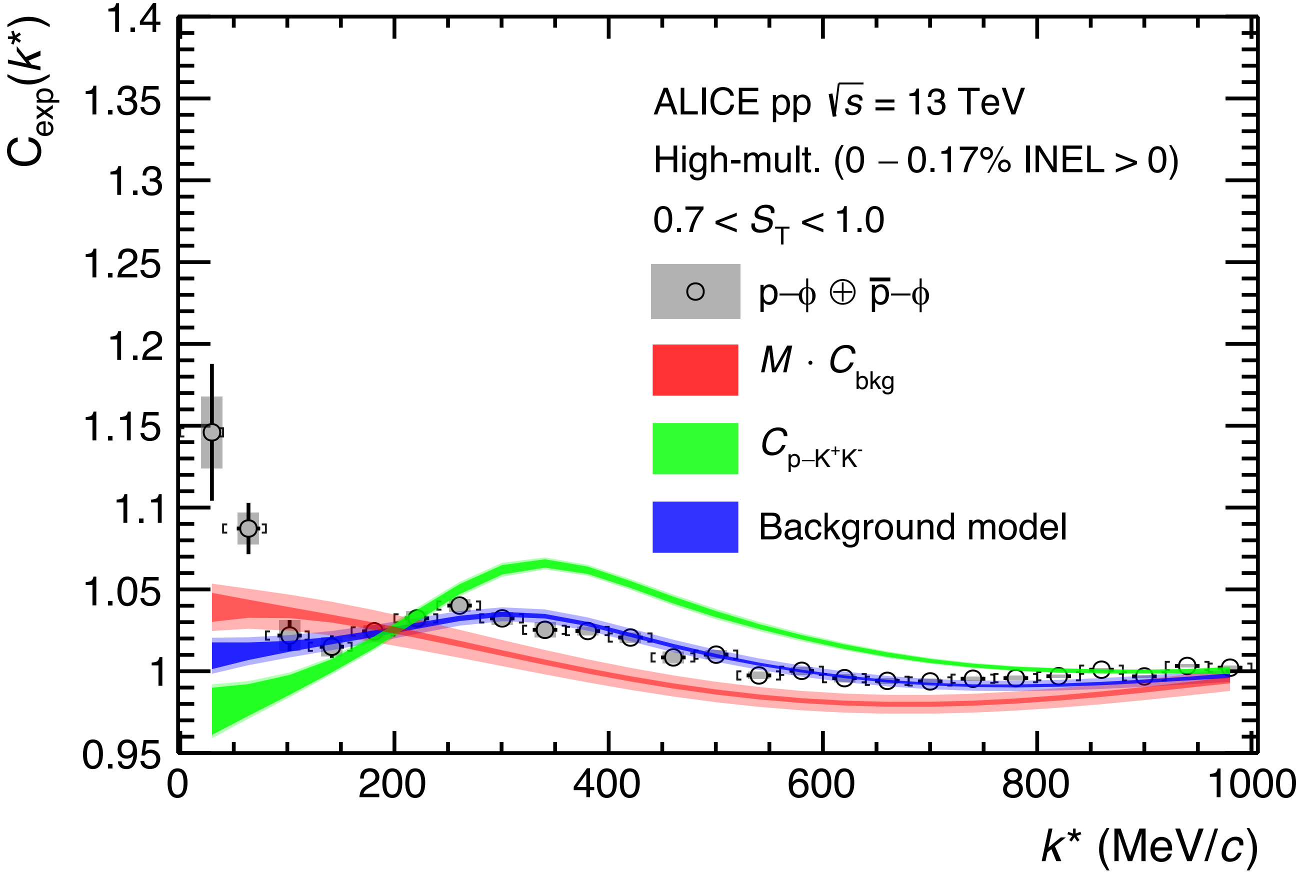
→ Combined to total background used to extract genuine correlation function from data

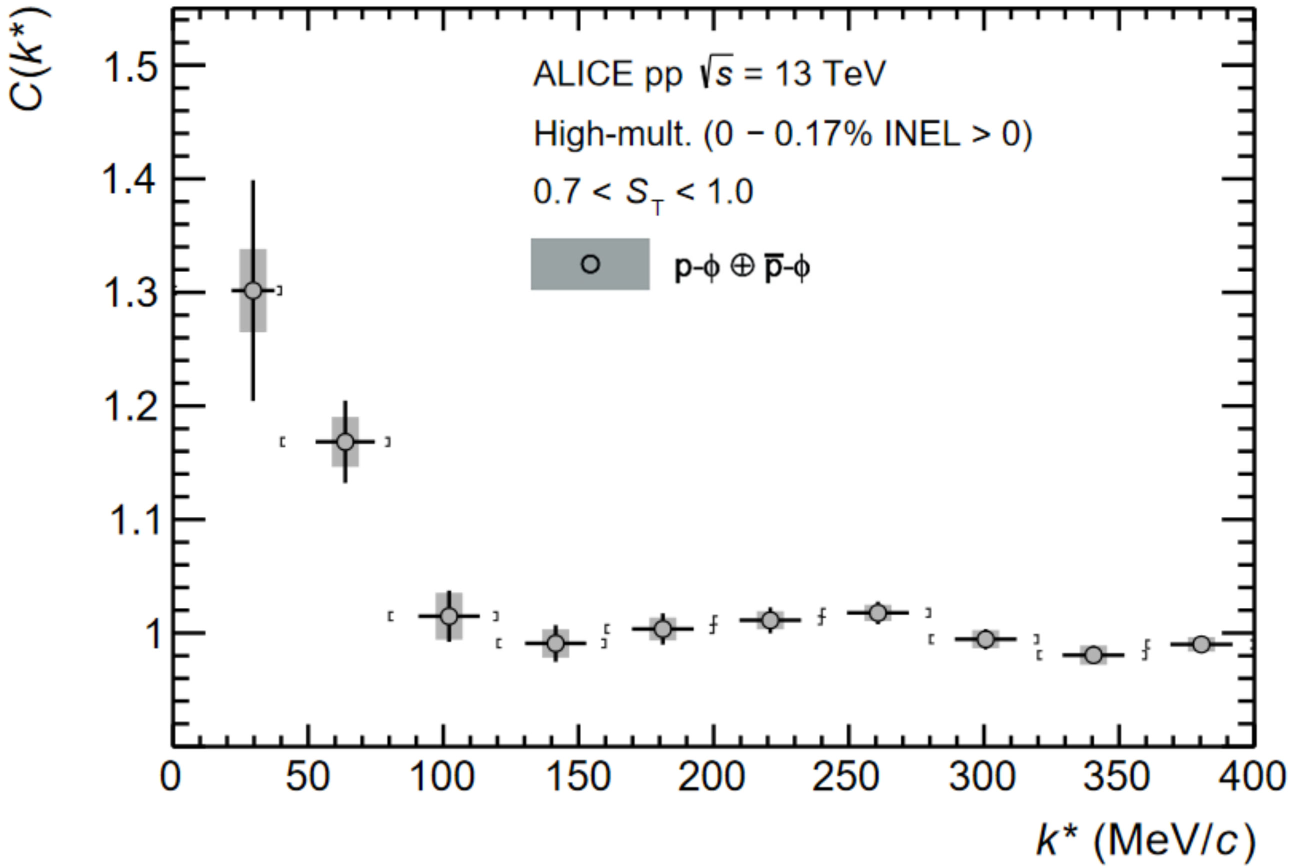
ALICE Collab., *PRL* **127** (2021) 172301



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

d_0=7.85±1.54(stat.) ±0.26(syst.) fm

Re(f_0)=0.85±0.34(stat.) ±0.14(syst.) fm

Im(f_0)=0.16±0.10(stat.) ±0.09(syst.) fm

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

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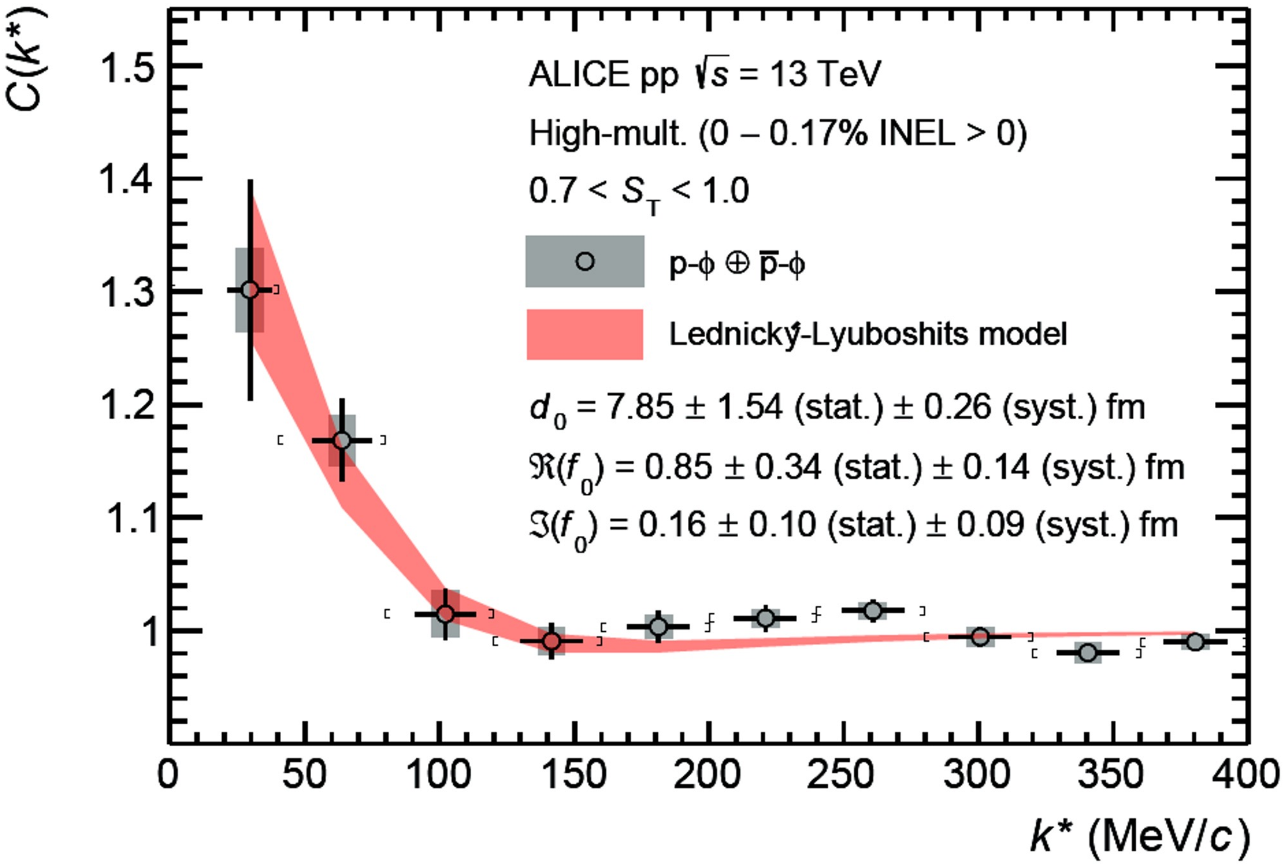

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- Elastic p–ϕ coupling dominant contribution to the interaction in vacuum
- Zero effective range approximation (d_0=0 fm)

Re(f_0)=0.29±0.05(stat.) ±0.03(syst.) fm

Im(f_0)=0.15±0.04(stat.) ±0.06(syst.) fm

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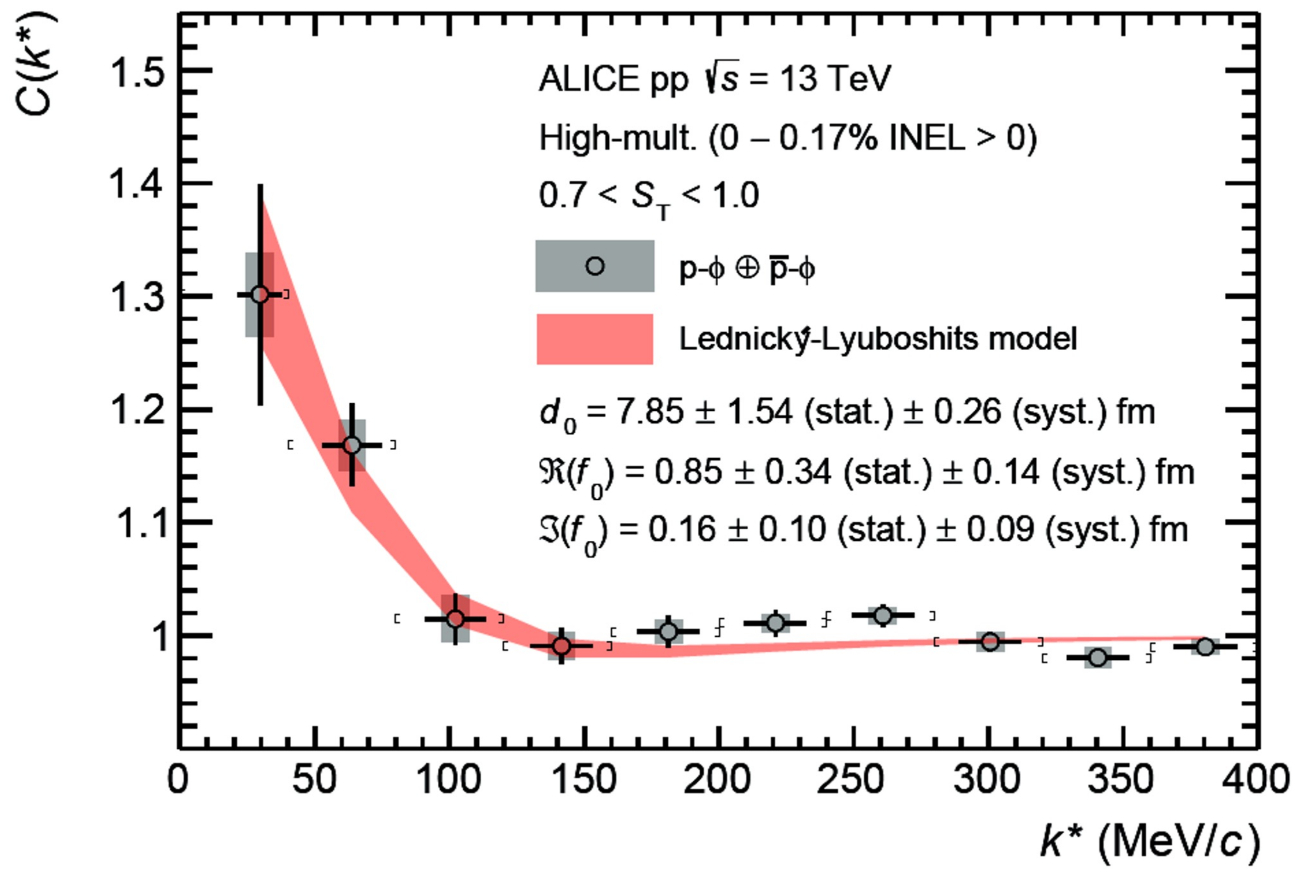


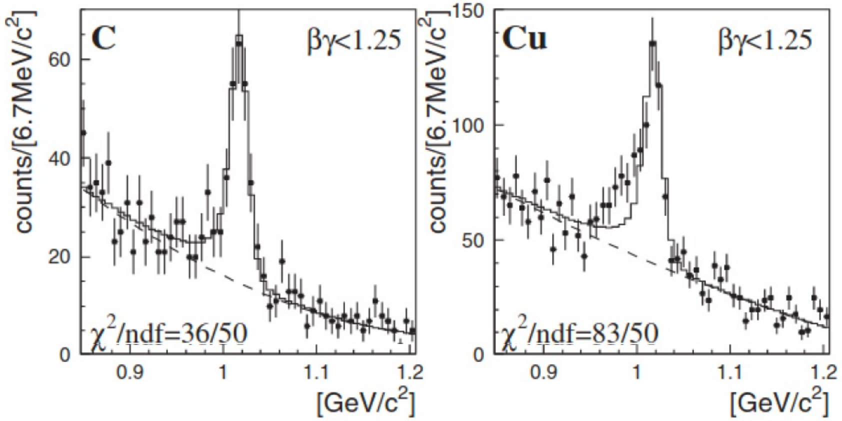
In medium properties

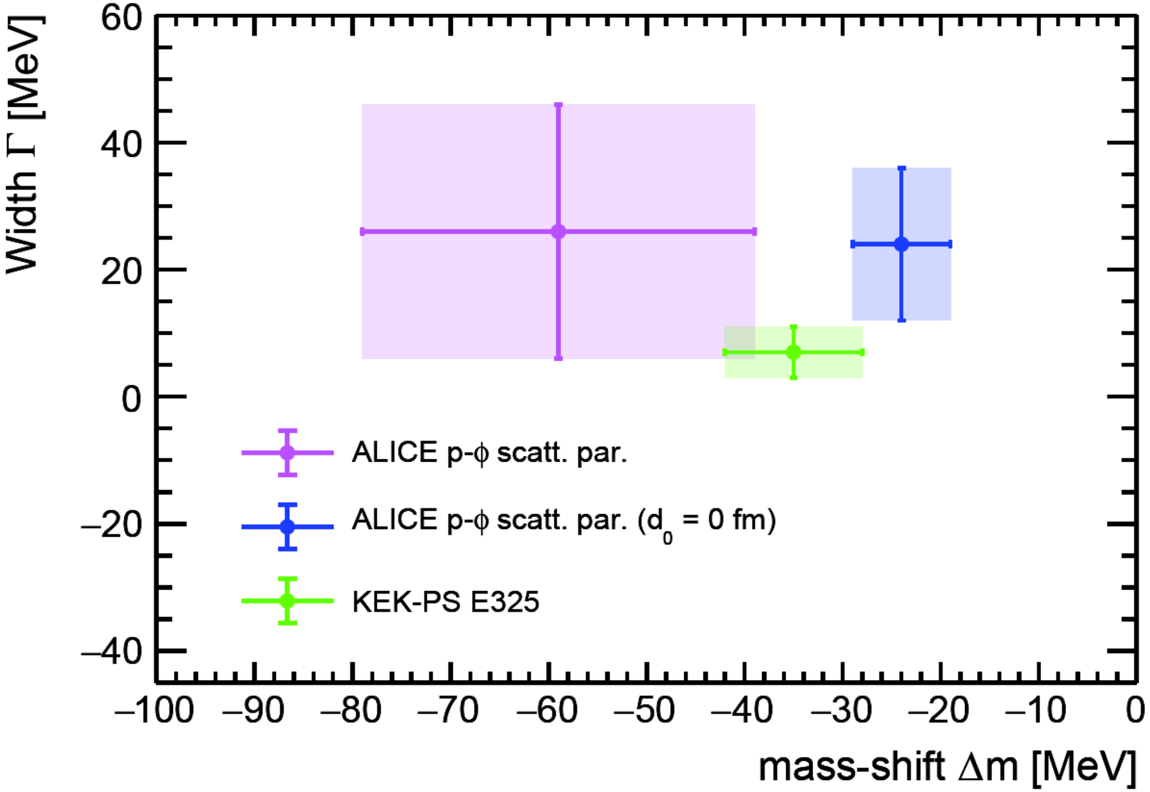
- Scattering length can be related to first order optical potential $U(r) \approx \frac{1}{2m}\ 4\pi\rho\ \frac{b}{1+b/d_0}\ \approx$ $\frac{1}{2m}\ 4\pi\rho\ b$ with $b = f_0\left(1+\frac{m_\phi}{m_{proton}}\right)$

V.A. Baskov et al. *arXiv:nucl-ex/0306011v1* (2003)

- Real part related to mass-shift V(r) ≈ Δm
- Imaginary part related to width W(r) ≈ -Γ/2
- Similar to results of E325 Collab. of Δm =- (35 ± 7) MeV and Γ = -(7± 4) MeV

KEK-PS E325 Collab., Phys. Rev. Lett. **98** (2007) 042501





What we know so far

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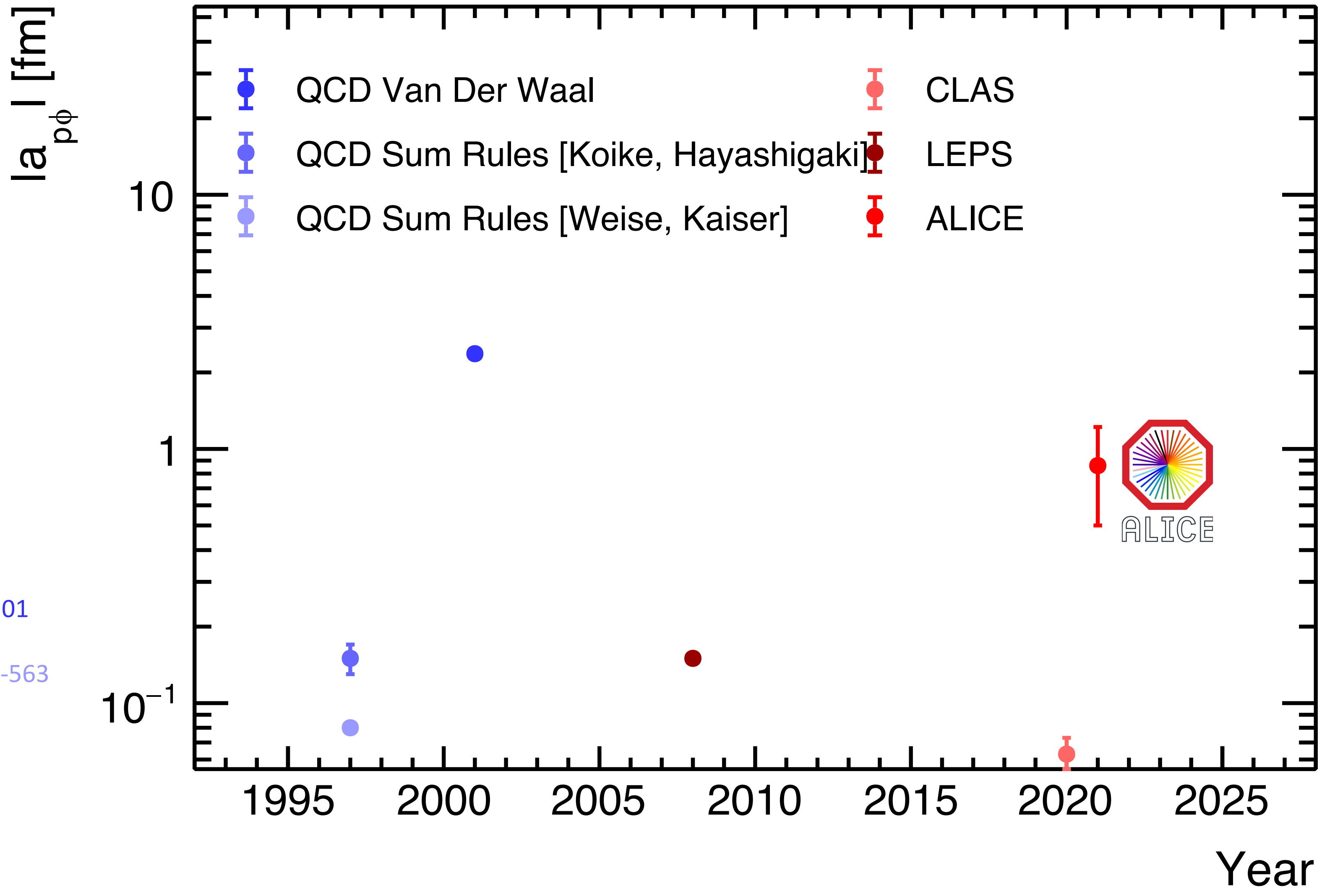

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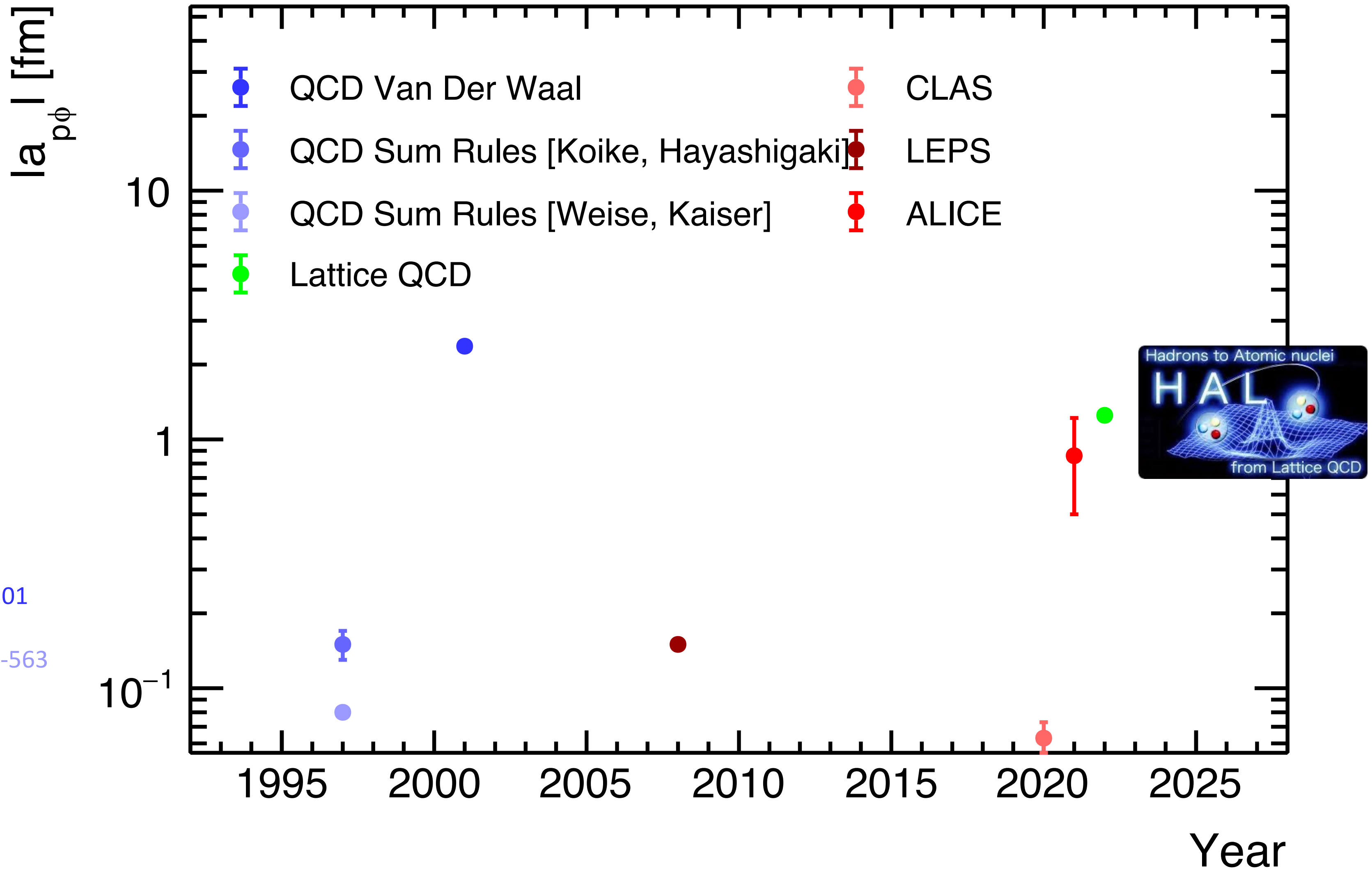

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Yan Lyu *et al* arXiv:2205.10544 [hep-lat]

Accessing both spin states

Work in collaboration with Raffaele Del Grande, Takumi Doi, Laura Fabbietti, Tetsuo Hatsuda, Yuki Kamiya and Yan Lyu

Studying both spin states

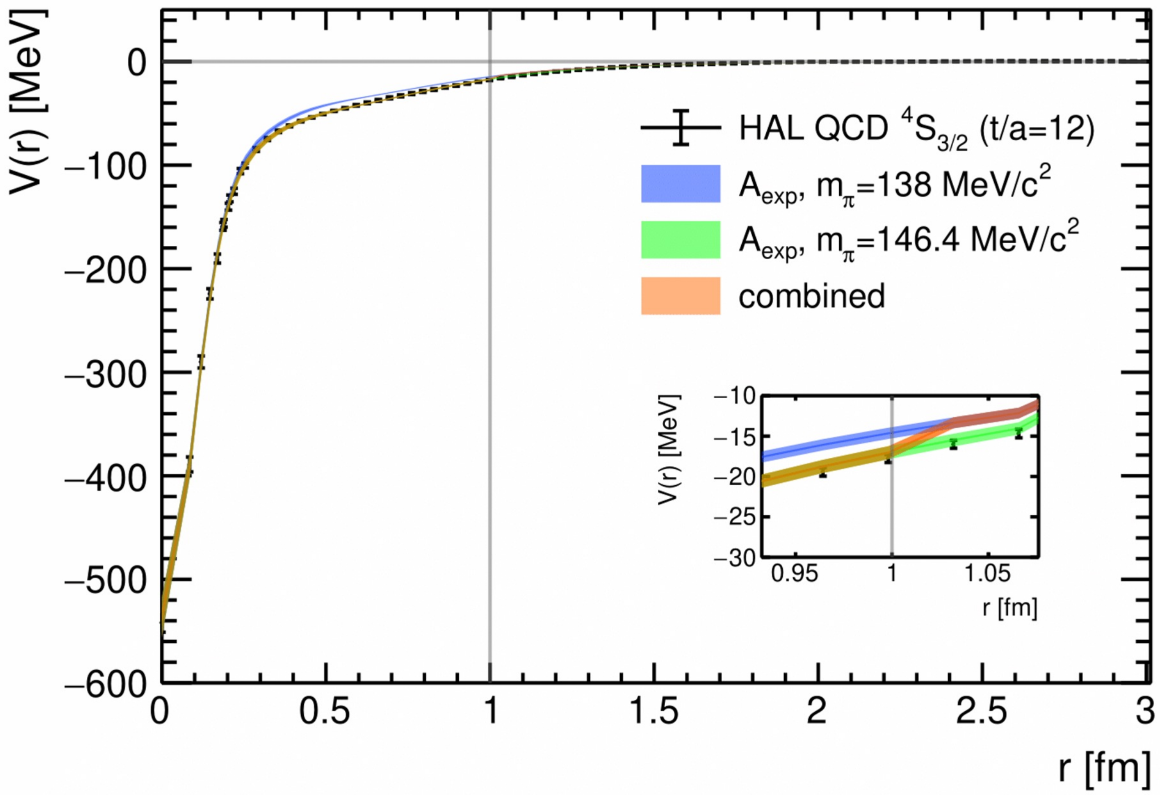
$^4S_{3/2}$ channel

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

Yan Lyu et al arXiv:2205.10544 [hep-lat]

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

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



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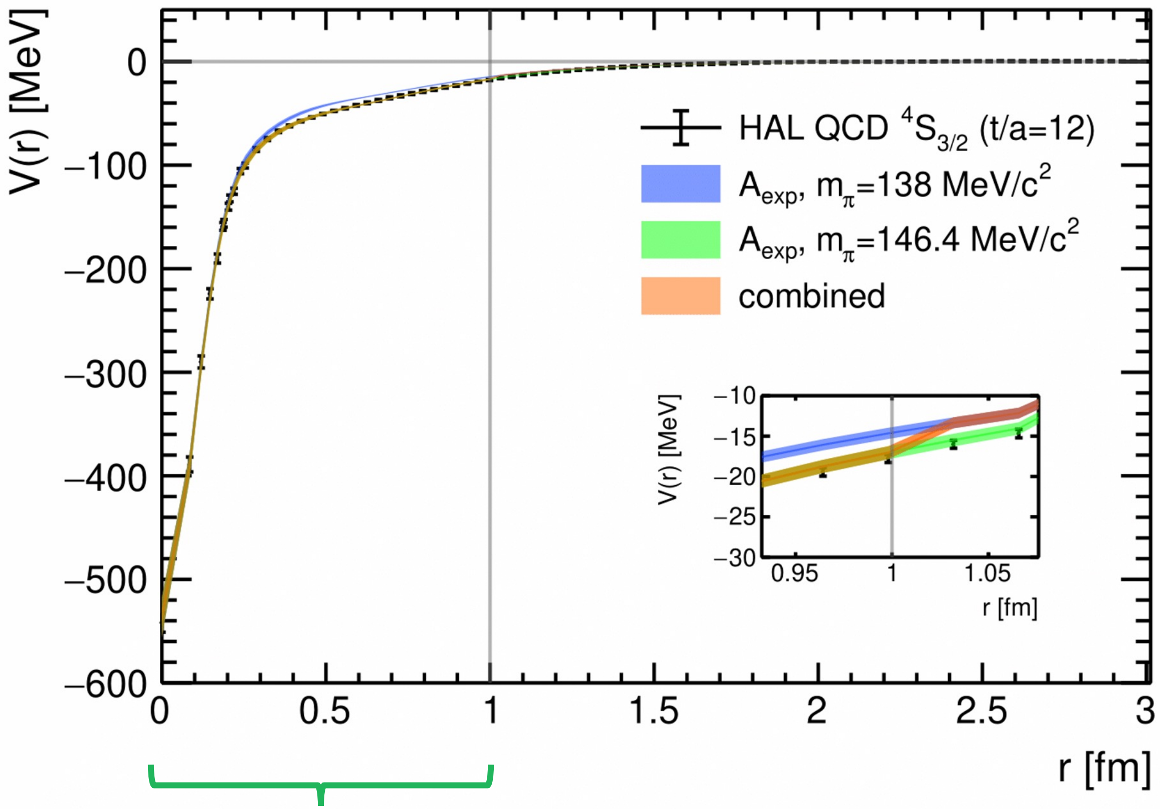

Short range attraction

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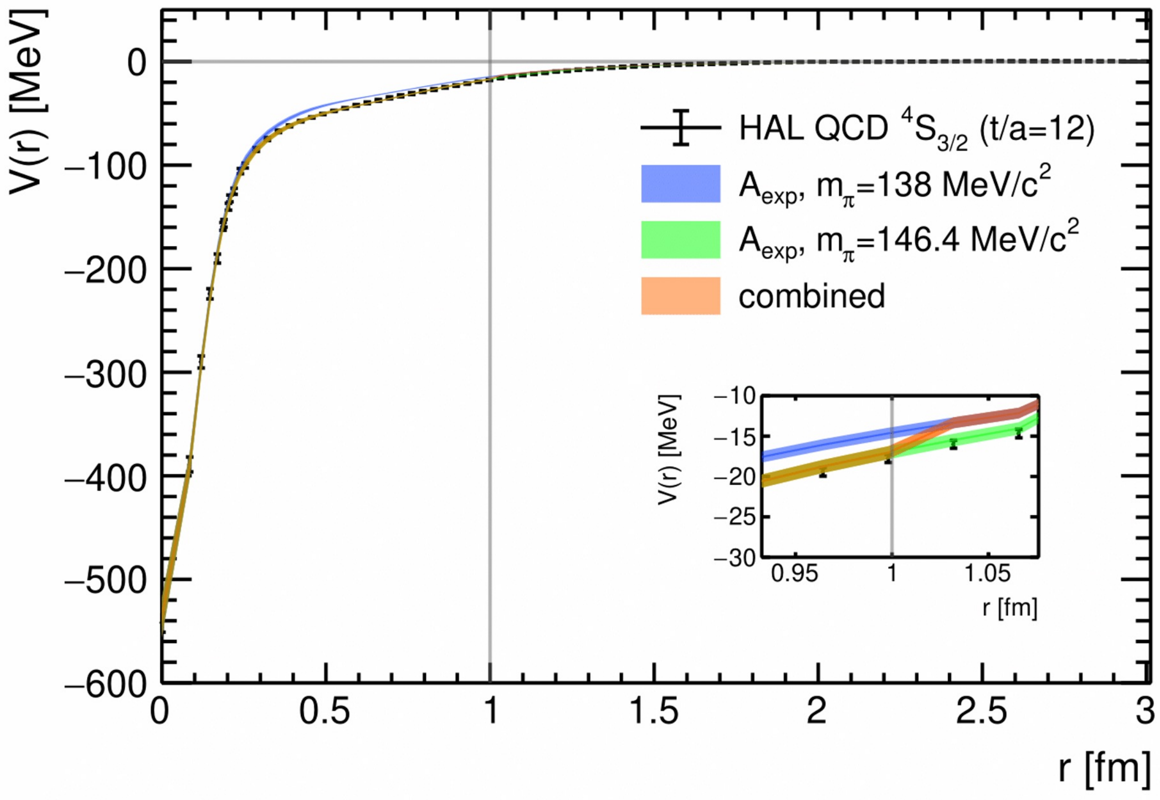

2-pion exchange

dominant at long ranges > 1fm

Studying both spin states

$^4S_{3/2}$ channel

- Dominated by elastic scattering states
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  Yan Lyu et al arXiv:2205.10544 [hep-lat]
- Potential at physical-pion mass

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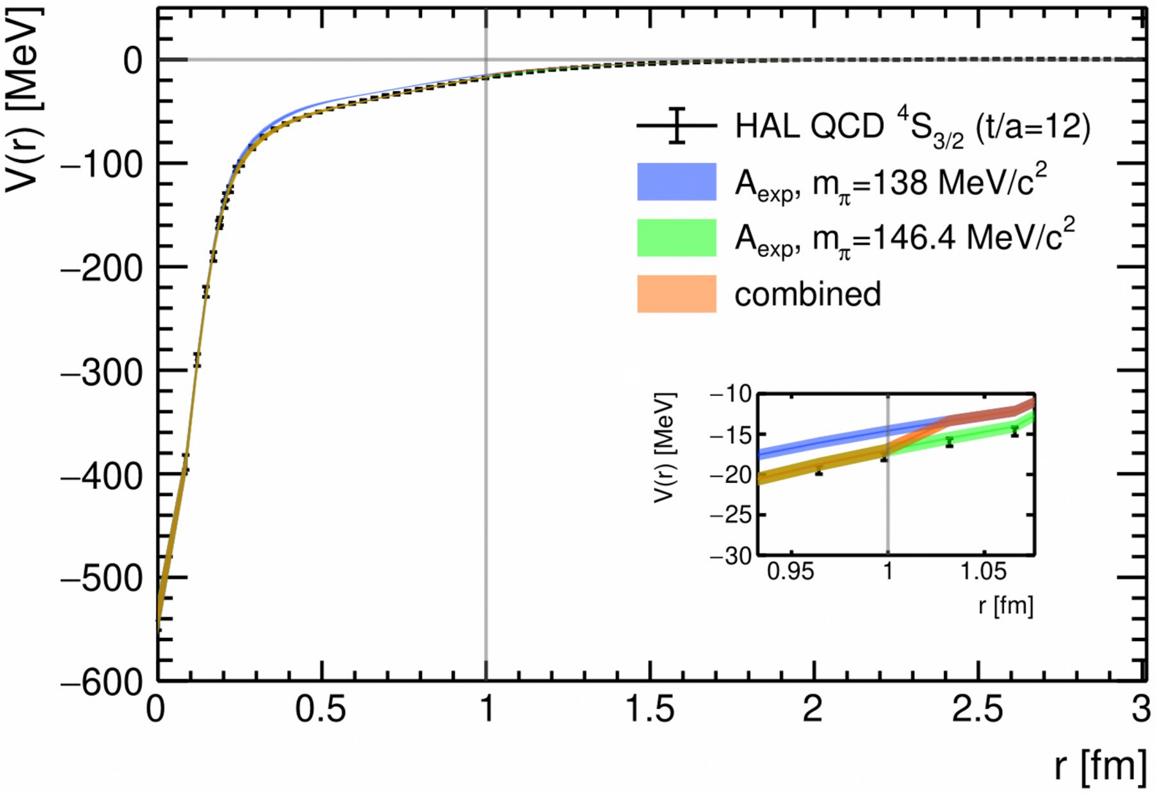

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$^2S_{1/2}$ channel

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

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

Imaginary Part of Pot

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

Real Part of Pot

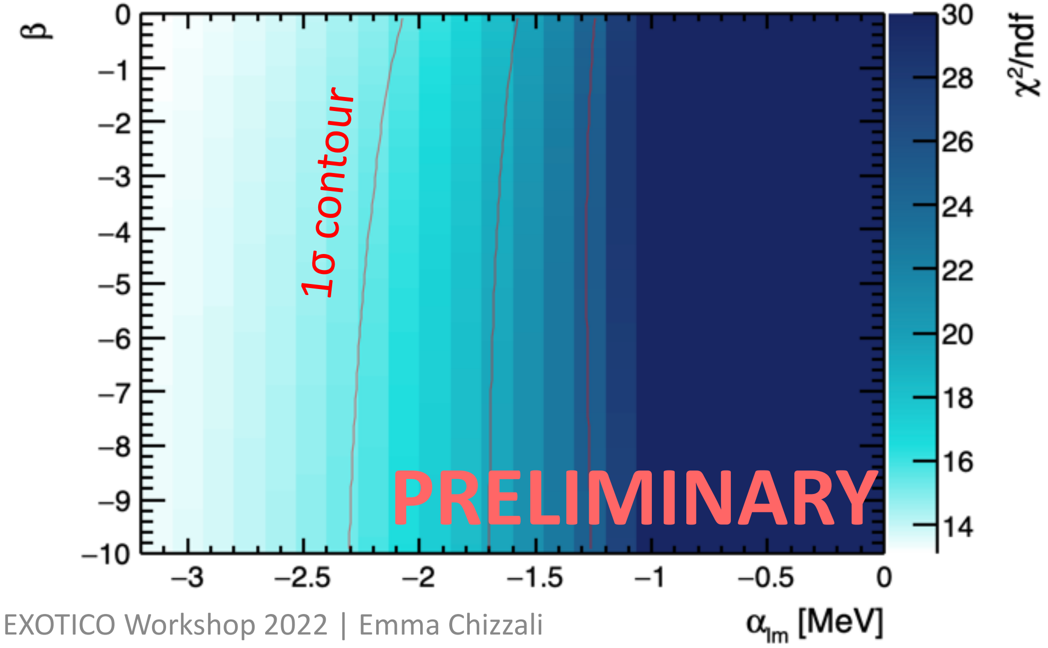
$$V_{LATTICE,\,MOD}(r) = \beta \cdot V_{short}(r) + V_{2\pi}(r)$$

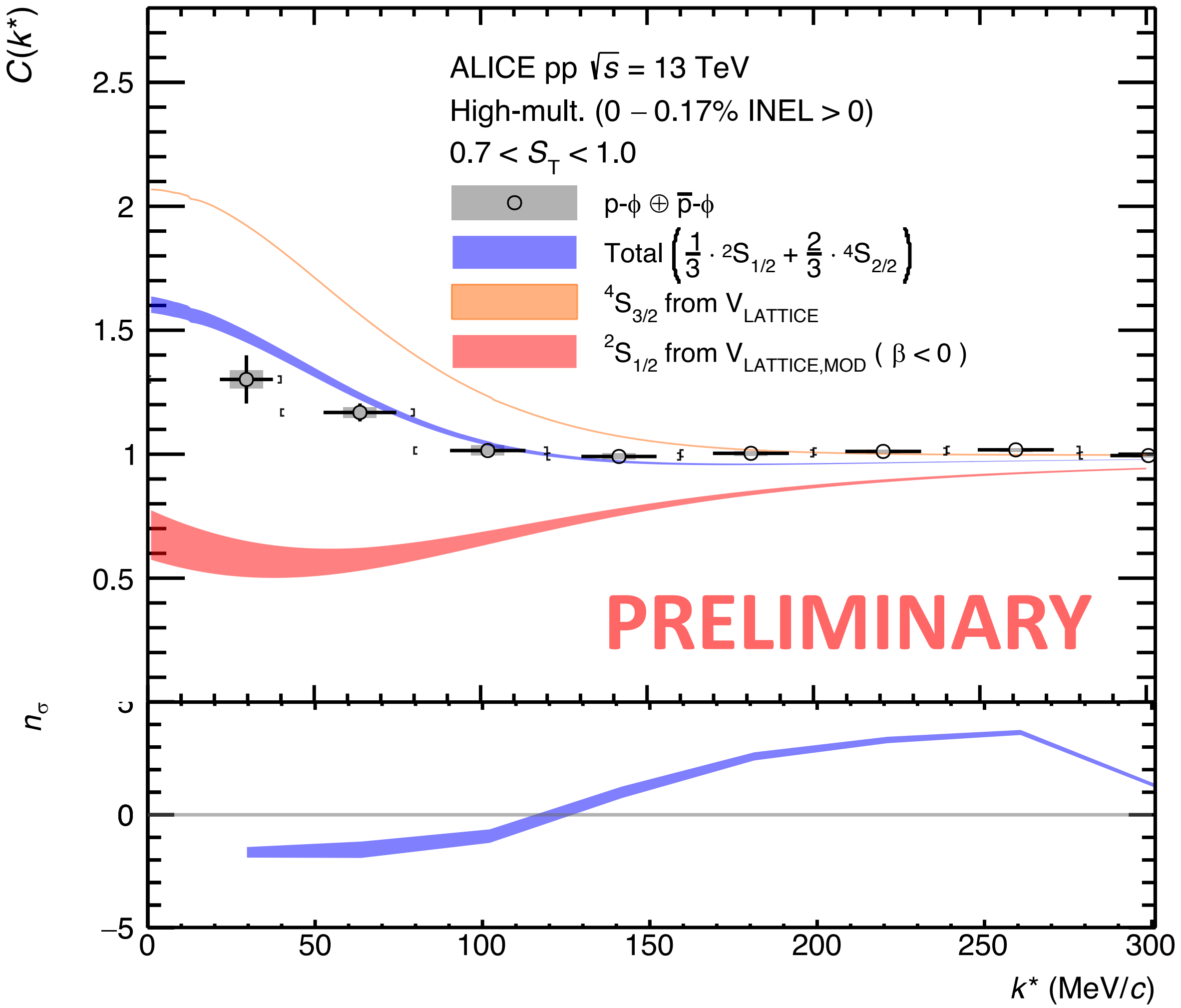
Complex $^2S_{1/2}$ Potential

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

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

- **Repulsive real part** of potential ($\beta < 0$)
- Minimum for α_{Im}=-3.2 MeV and β=0 (n_σ=2.8, χ^2=13.1)
- No sensitivity on β, small α_{Im} excluded

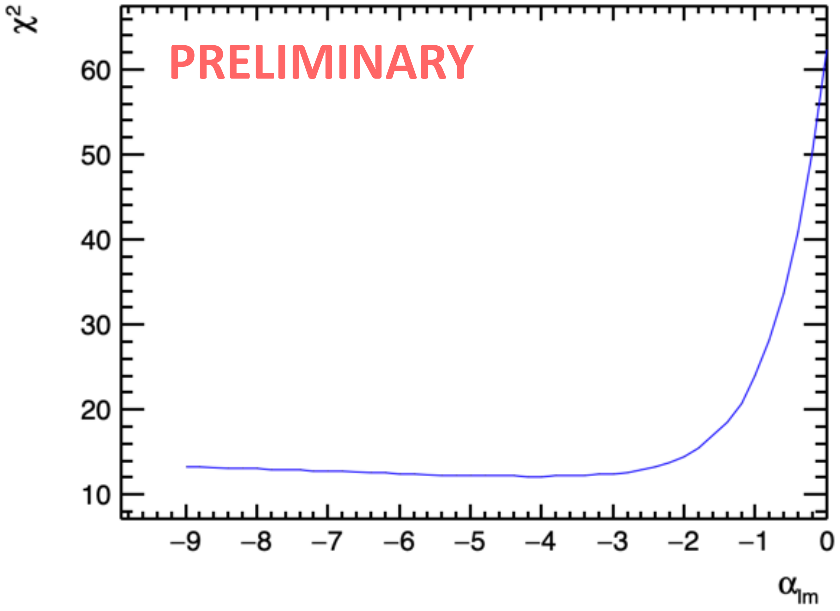


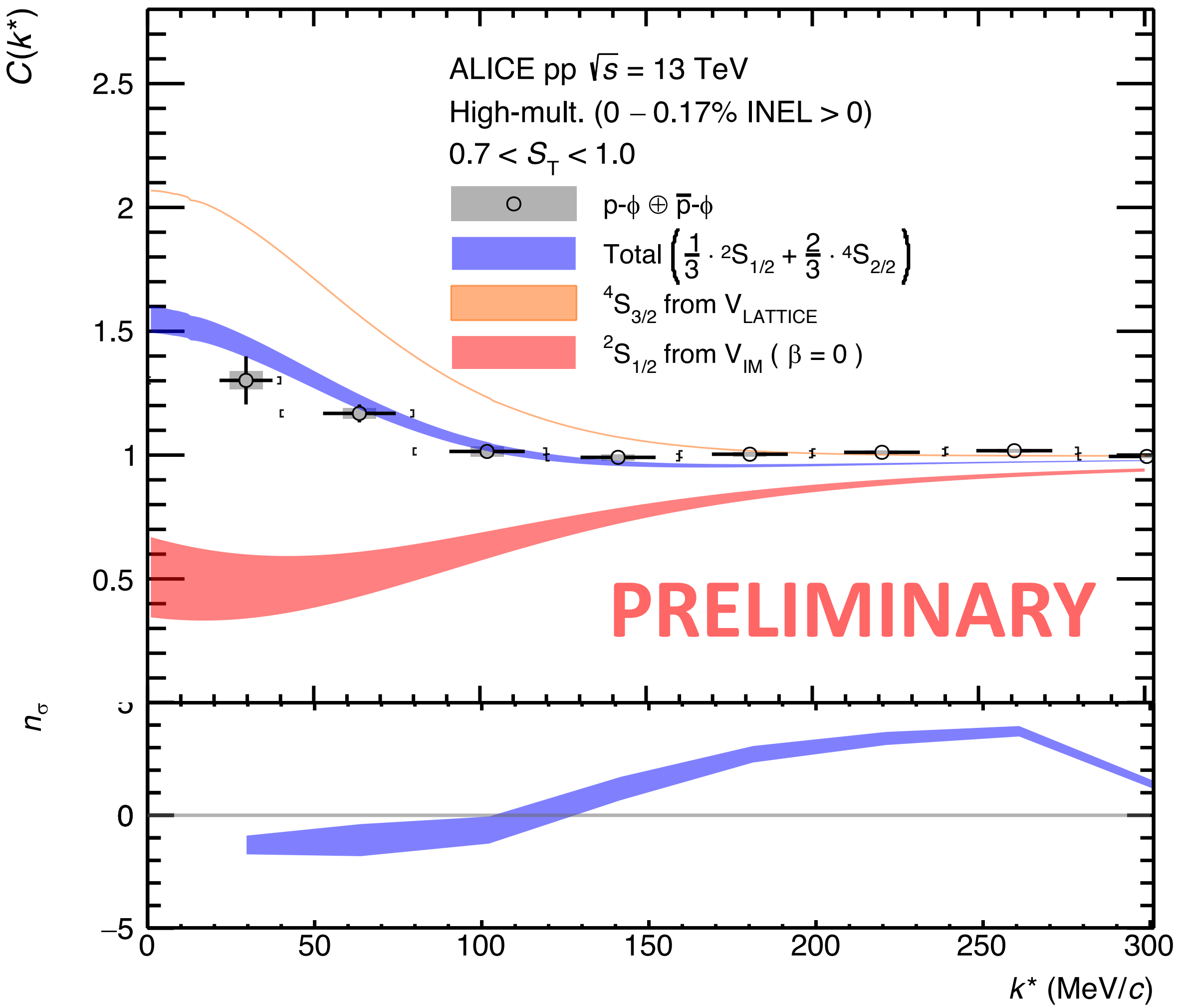


Complex $^2S_{1/2}$ Potential

$$V_{\frac{1}{2}}(r) = i \cdot \sqrt{f(r;b_3)} \cdot \frac{\alpha_{Im}}{r} e^{-m_K \cdot r}$$

- **Imaginary only** potential
- Minimum for α_{Im}=-4.2 MeV (n_σ=2.4, χ^2=12.1)
- Small α_{Im} excluded, for larger values again no sensitivity

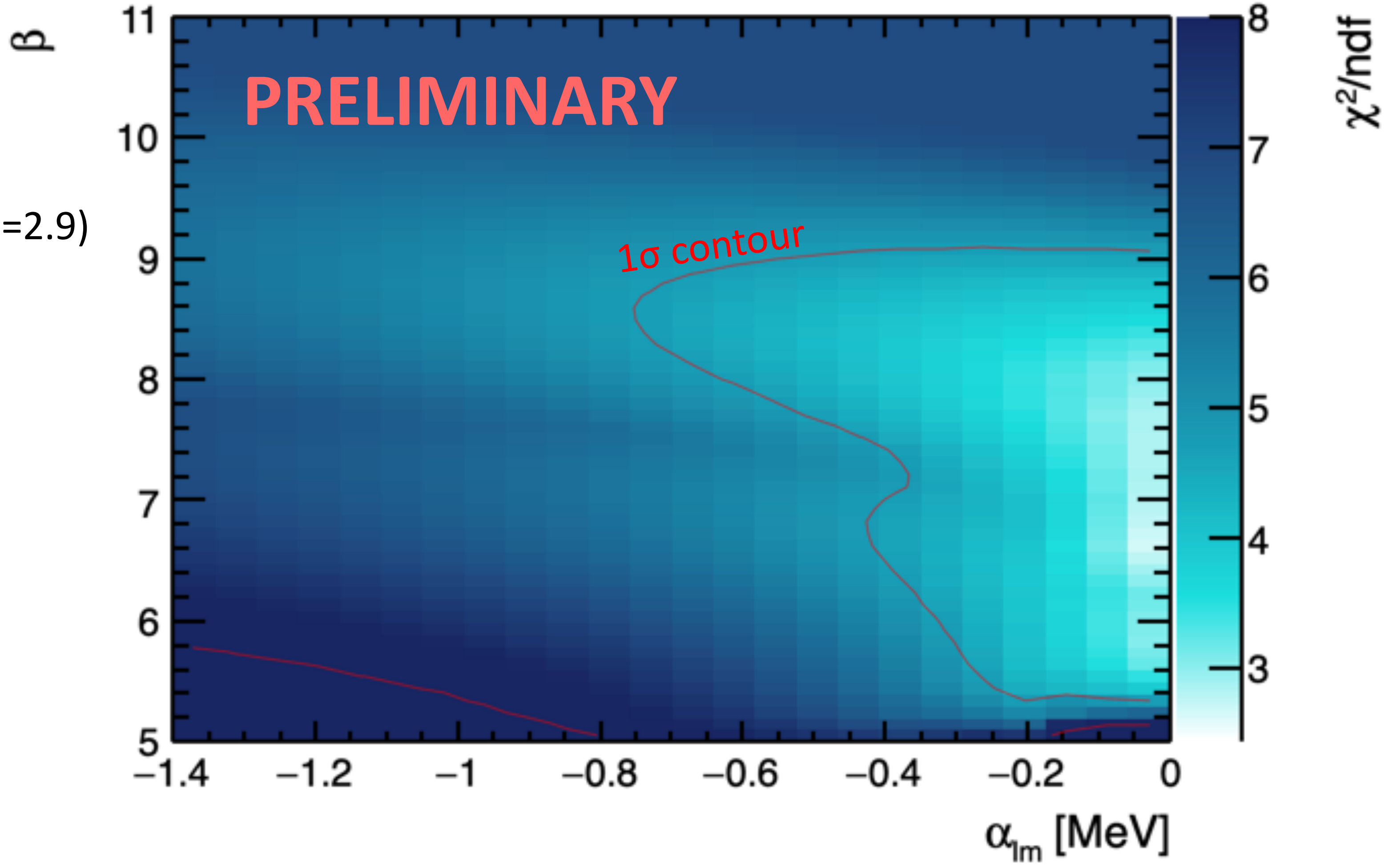




Complex $^2S_{1/2}$ Potential

$$V_{\frac{1}{2}}(r) = \underbrace{V_{LATTIC,MOD}(r)}_{\beta \cdot V_{short}(r) + V_{2\pi}(r)} + i \cdot \sqrt{f(r;b_3)} \cdot \frac{\alpha_{Im}}{r}\, e^{-m_K \cdot r}$$

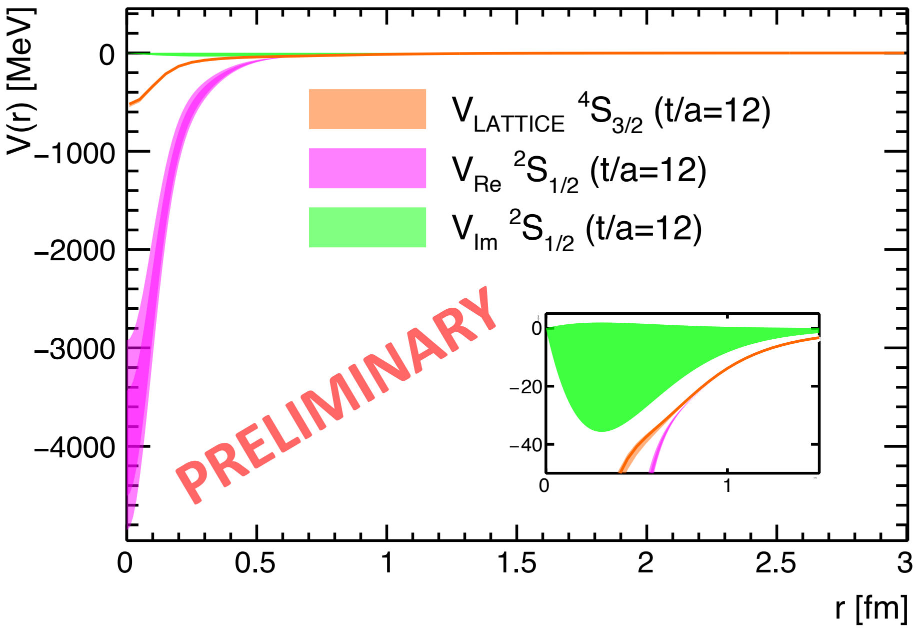
- **Attractive real part** of potential ($\beta > 0$)
- Minimum for α_{Im}=0 MeV and β=6.8 (n_σ=0.8, χ^2=2.9)
- Compatible with small imaginary part

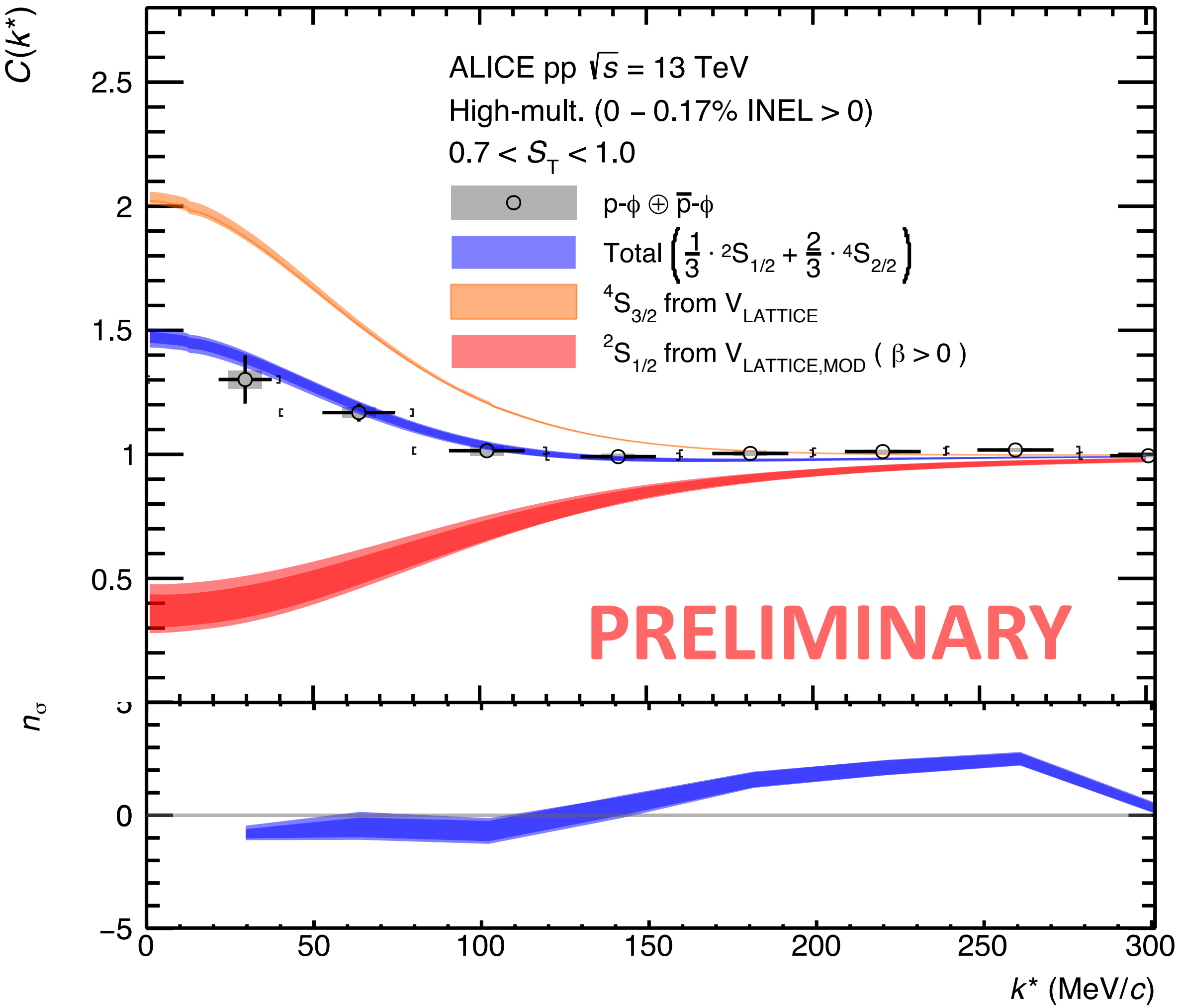


Complex $^2S_{1/2}$ Potential

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

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





Scattering parameters

- Scattering parameters extracted from phase-shift using effective range expansion

$$k^* \cot \delta_0(k^*) \xrightarrow[k^* \to 0]{} \frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} + \mathcal{O}(k^{*4})$$

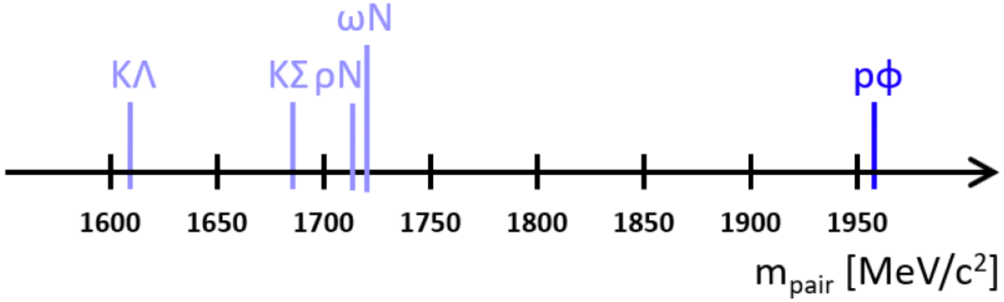
$\rightarrow \Re(f_0) = -1.21^{+0.4}_{-0.9}(stat.)^{+0.66}_{-2.92}(syst.)$ and $\Im(f_0) = 0.08^{+0.27}_{-0.08}(stat.)^{+2.46}_{-0.17}(syst.)$

- Strongly attractive potential with repulsive scattering lenght
  → possible Nϕ bound state in S=1/2 with E_B ~ 2.2-200 MeV

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

  - E_B < 10 MeV predicted by theory
    H. Gao, T.-S. H. Lee, and V. Marinov, Phys. Rev. C 63, 022201(R)
    F. Huang, Z.Y. Zhang, and Y.W. Yu, Phys. Rev. C 71, 064001 (2006)
    S. Liska, H. Gao, W. Chen, X. Qian, Phys. Rev. C 75, 058201 (2007)

- Within uncertainties, sizable $\Im(f_0)$ → Nϕ interaction expected to proceed via coupled channels



Summary and outlook

- First measurement of the p–ϕ correlation function

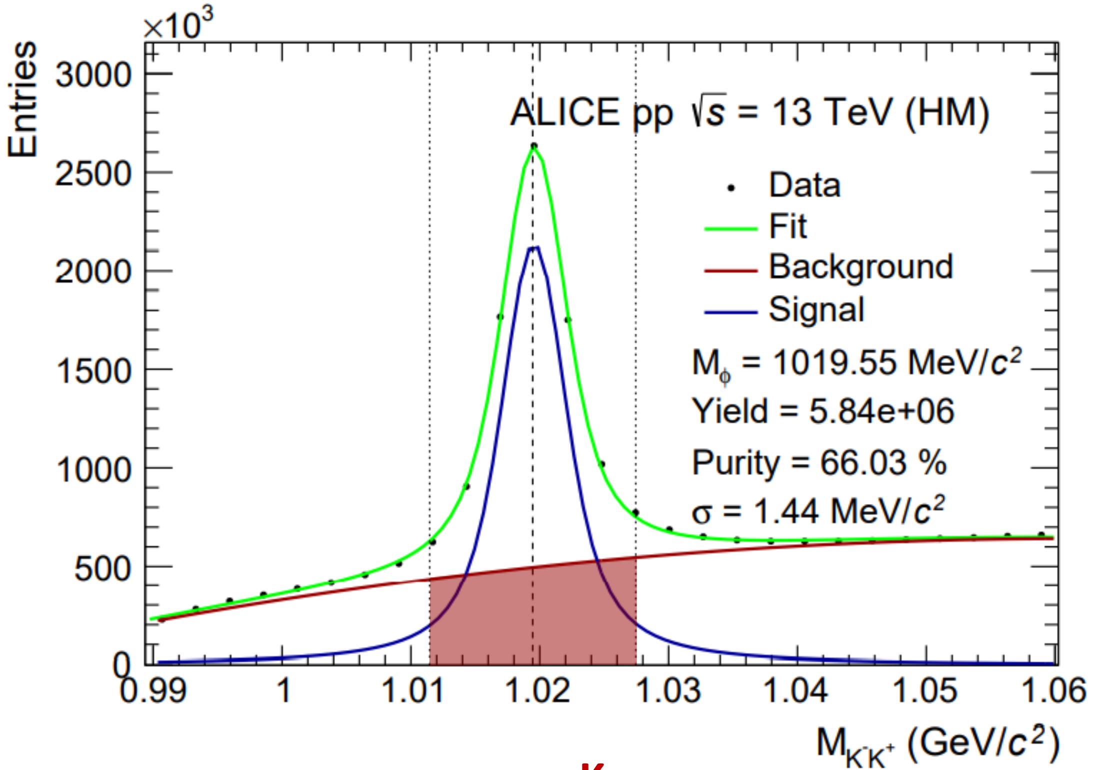
  ALICE Collab., *PRL* **127** (2021) 172301
  - Attractive p–ϕ interaction dominated by elastic contributions in vacuum (spin-averaged scattering parameters)
- Study p–ϕ interaction in S=1/2 using the published lattice potential for S=3/2

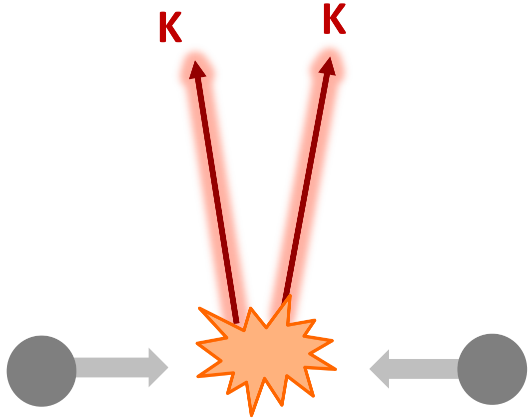
  Yan Lyu *et al* arXiv:2205.10544 [hep-lat]
- Results for now suggest
  - Strongly attractive potential with bound state in S=1/2
  - Room for absorbtion term due to sizable imaginary contirbution

Additional material

Analysis details

- LHC Run 2 dataset (2016-2018)
- High multiplicity (HM) pp collisions at $\sqrt{s} = 13$ 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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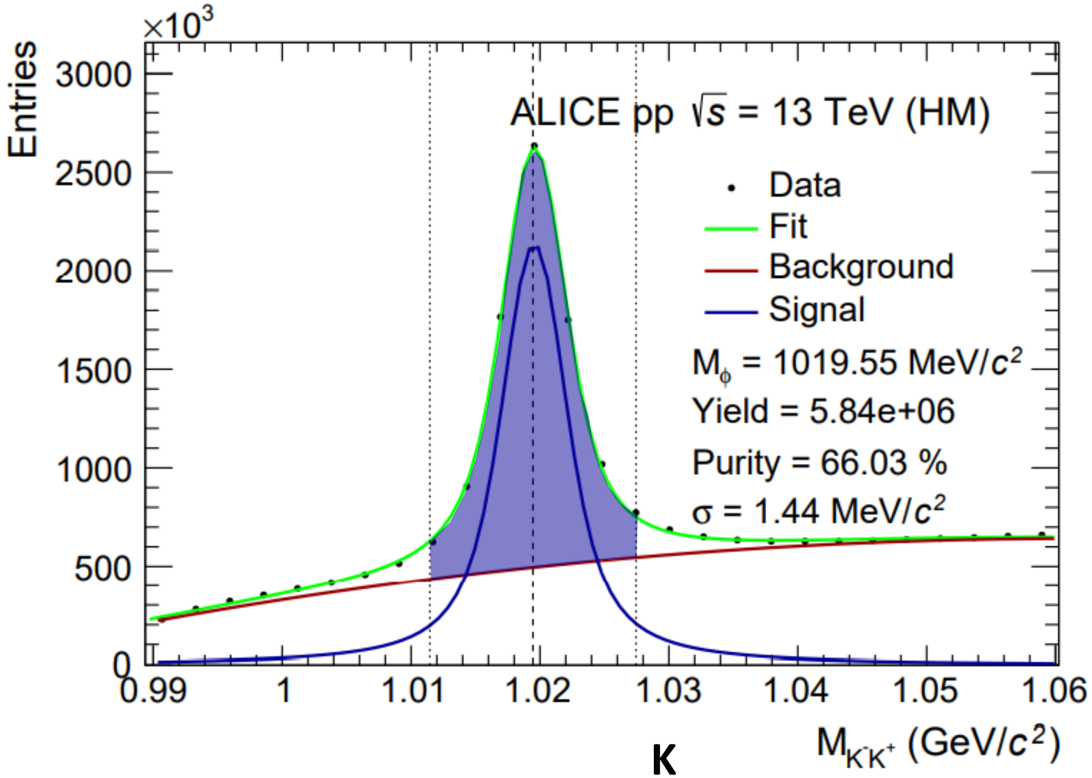
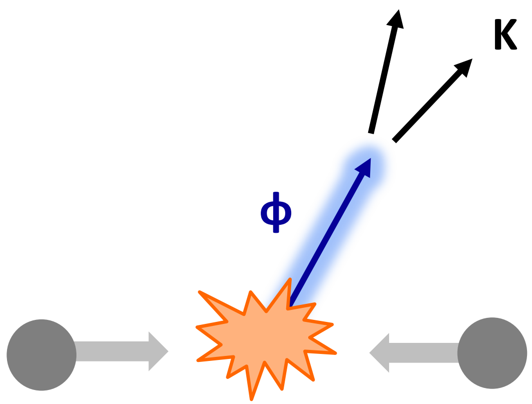
      - Signal → real ϕ mesons





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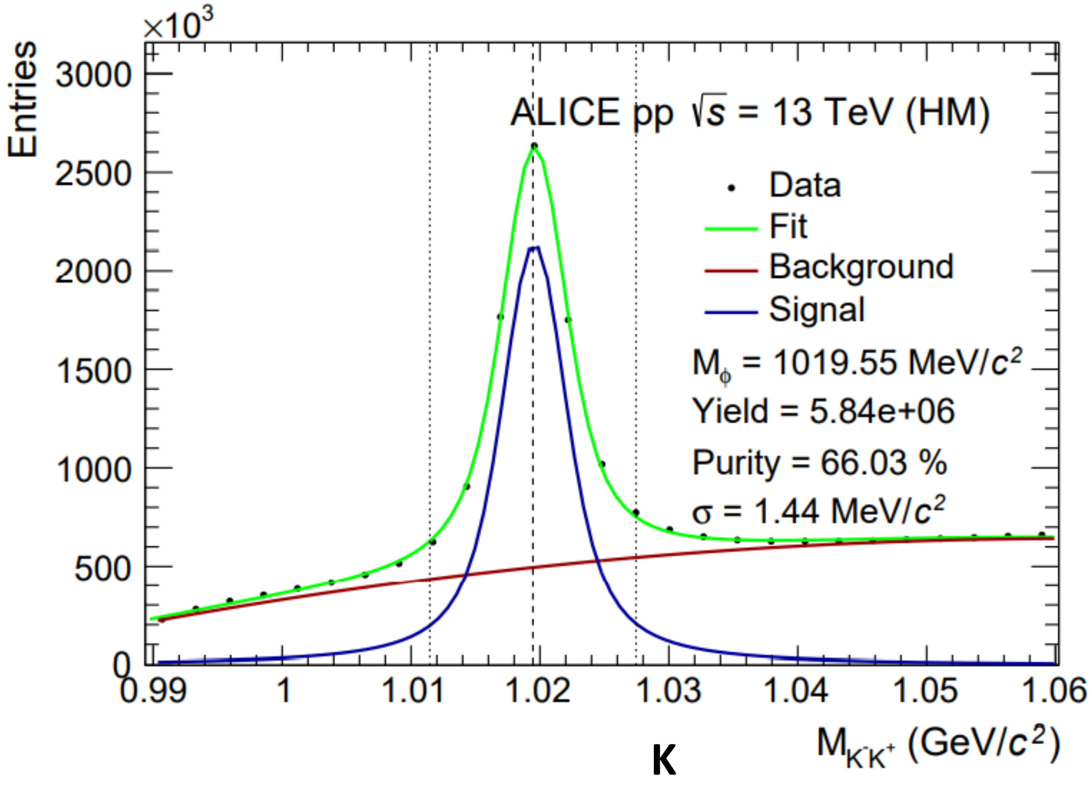
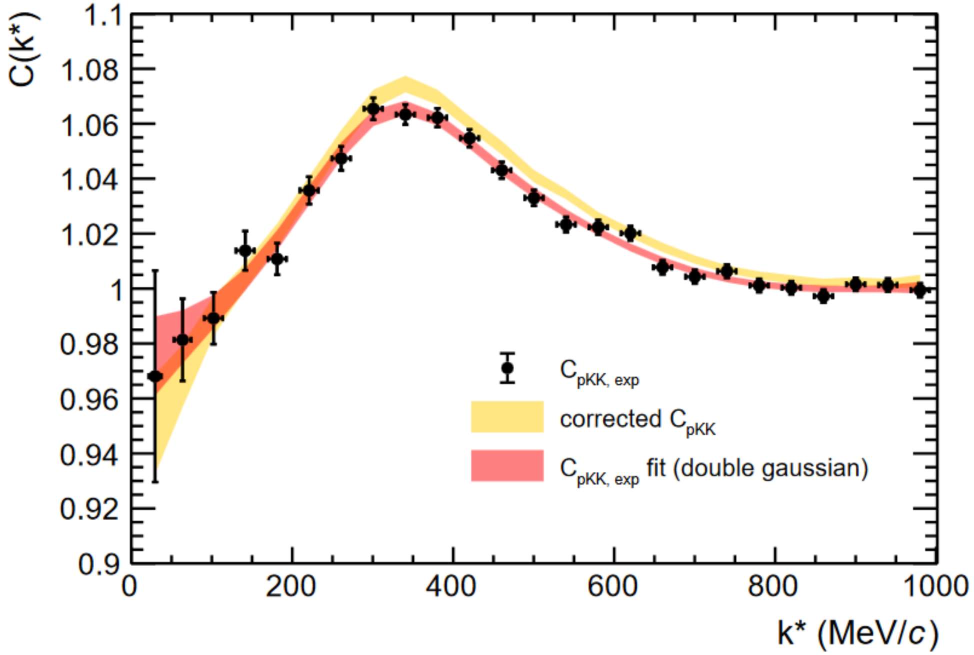
    - Decay channel $\phi \rightarrow K^{+}K^{-}$
    - Candidates consist of
      - Combinatorial background → random combination of uncorrelated kaons
      - Signal → real ϕ mesons
    - Purity of ϕ meson candidates ∼66%



Correction for φ contamination

- Lack of experimental data of pure combinatorial BG $C_{p-KK}(k^*)$
- Measured signal $C_{p-KK,\boldsymbol{exp}}(k^*)$ does not describe pure combinatorial background due to phi contamination in sidebands
  - Consists of 7% genuine p-phi ($\alpha = 0.07$)and 93% actual combinatorial p-KK background
  - Additionally MJ, BL etc.
- $C_{p-KK,\boldsymbol{exp}}(k^*) = (1-\alpha)\cdot C_{p-KK}(k^*) + \mathcal{N}\cdot\left(MJ_{p-\phi}(k^*)+BL\right)\cdot\alpha\cdot C_{gen}(k^*)$
  - Rearrange in terms of $C_{p-KK}(k^*)$ and enter into equation of CF model



Model and correction

$\lambda_{gen} = 46.3\%$
$\lambda_{p-KK} = 43.3\%$
$\lambda_{flat} = 10.4\%$

Original:

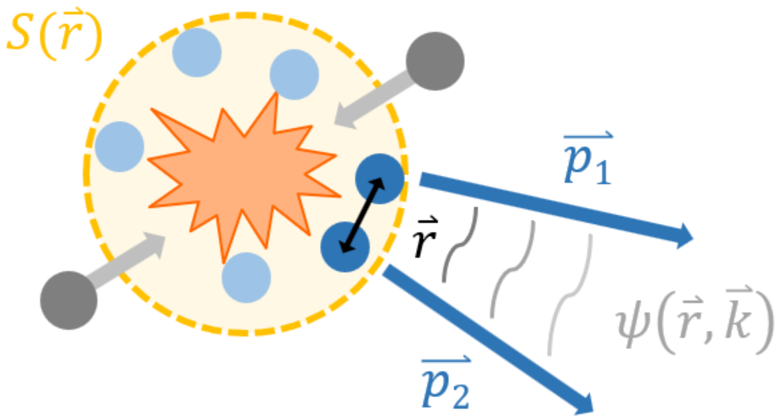
$$C_{tot}(k^*) = \mathcal{N} \cdot \left(MJ_{p-\phi}(k^*) + BL\right) \cdot (\lambda_{gen} \cdot C_{gen}(k^*) + \lambda_{flat} \cdot C_{flat}(k^*)) + \lambda_{p-KK} \cdot C_{p-KK}(k^*)$$

Modification due to lack of pure experimental data of combinatorial BG $C_{p-KK}(k^*)$:

$$\begin{aligned} &C_{tot}(k^*) \\ &= \mathcal{N} \cdot \underbrace{\left(MJ_{p-\phi}(k^*)\right.}_{\text{Data parametrized by a polynomial of fifth order}} \left. + BL\right) \cdot \left[\left(\lambda_{gen} - \frac{\lambda_{p-KK} \cdot \alpha}{(1-\alpha)}\right) \cdot C_{gen}(k^*) + \lambda_{flat} \cdot C_{flat}(k^*)\right] + \frac{\lambda_{p-KK}}{(1-\alpha)} \cdot \underbrace{C_{p-KK,\boldsymbol{exp}}(k^*)}_{\text{Data parametrized by a double Gaussian}} \end{aligned}$$

The Source

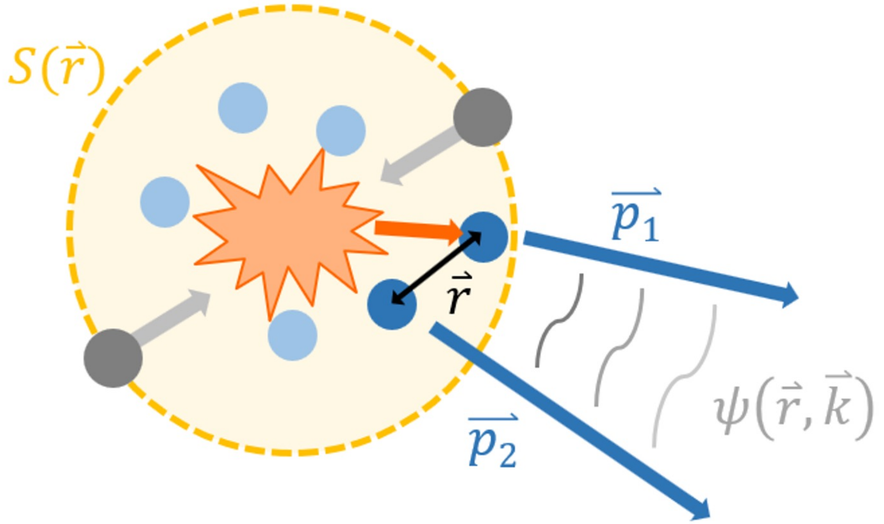
- Particle emission from **Gaussian core** source



The Source

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

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



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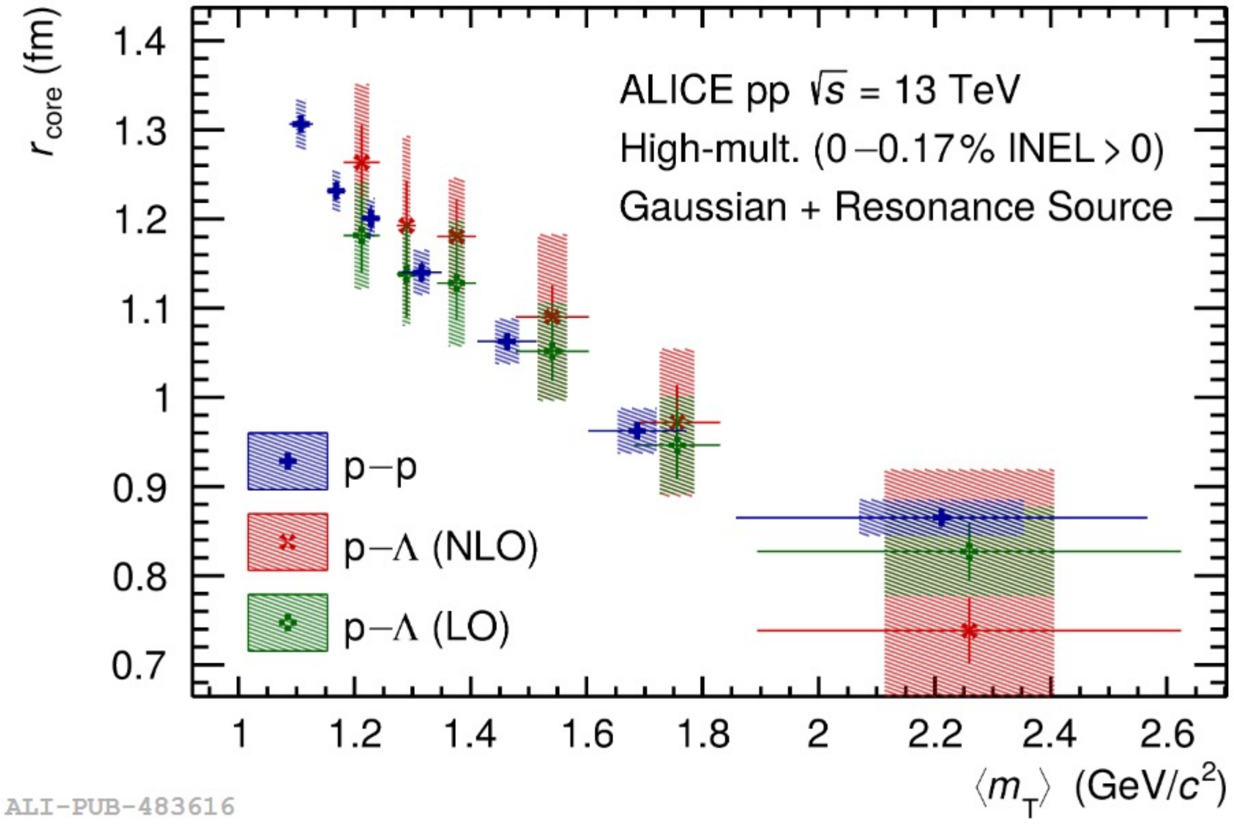
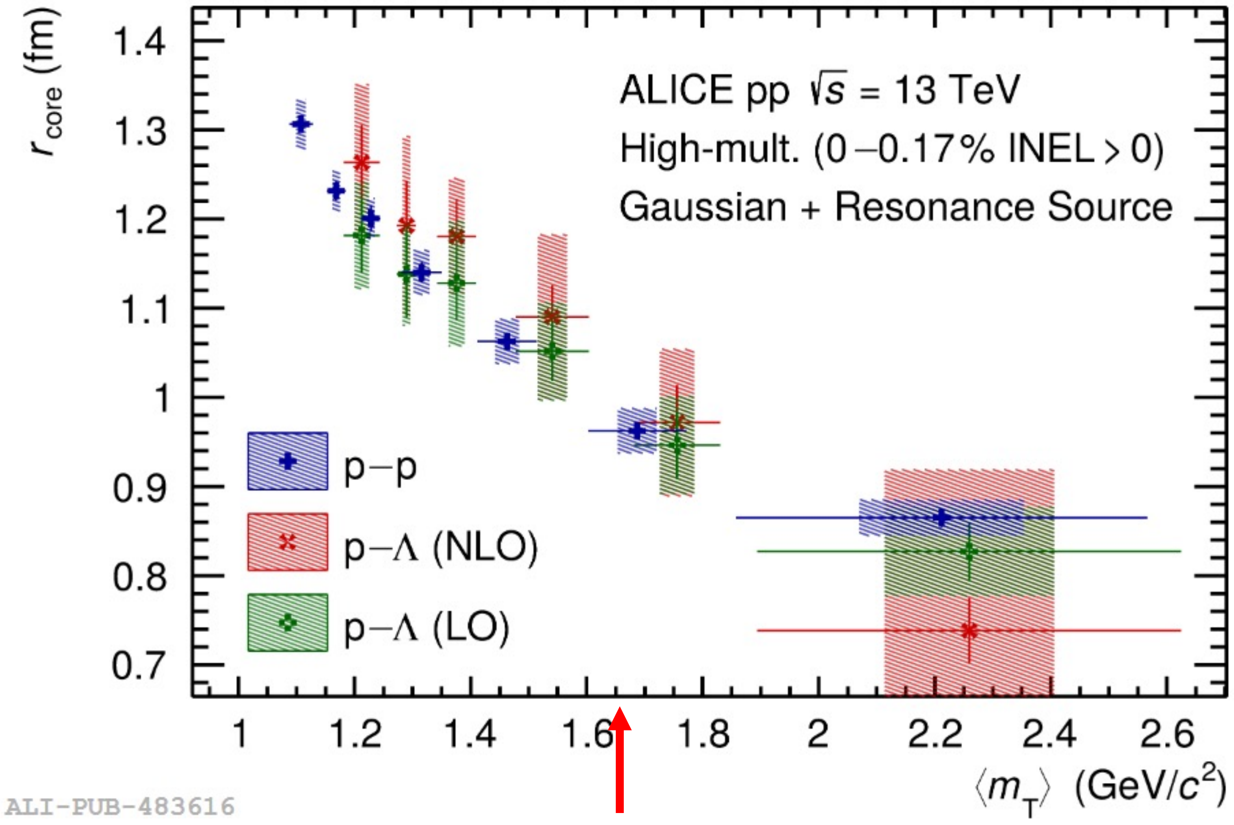


The Source

- Particle emission from **Gaussian core** source
- Core radius effectively increased by short-lived strongly decaying **resonances** ($c\tau \approx r_{\mathrm{core}}$)
- Universal source model constrained from pp pairs (well-known interaction)
  ALICE Collab., *Physics Letters B*, **811** (2020) 135849
- Gaussian core source scales with $\langle m_T \rangle$
  - $\boldsymbol{r_{\mathrm{core}} = 0.98 \pm 0.04}$ **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: $\boldsymbol{r_{\mathrm{eff}} = 1.08 \pm 0.05}$ **fm**



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

Lednicky-Lyuboshits Model

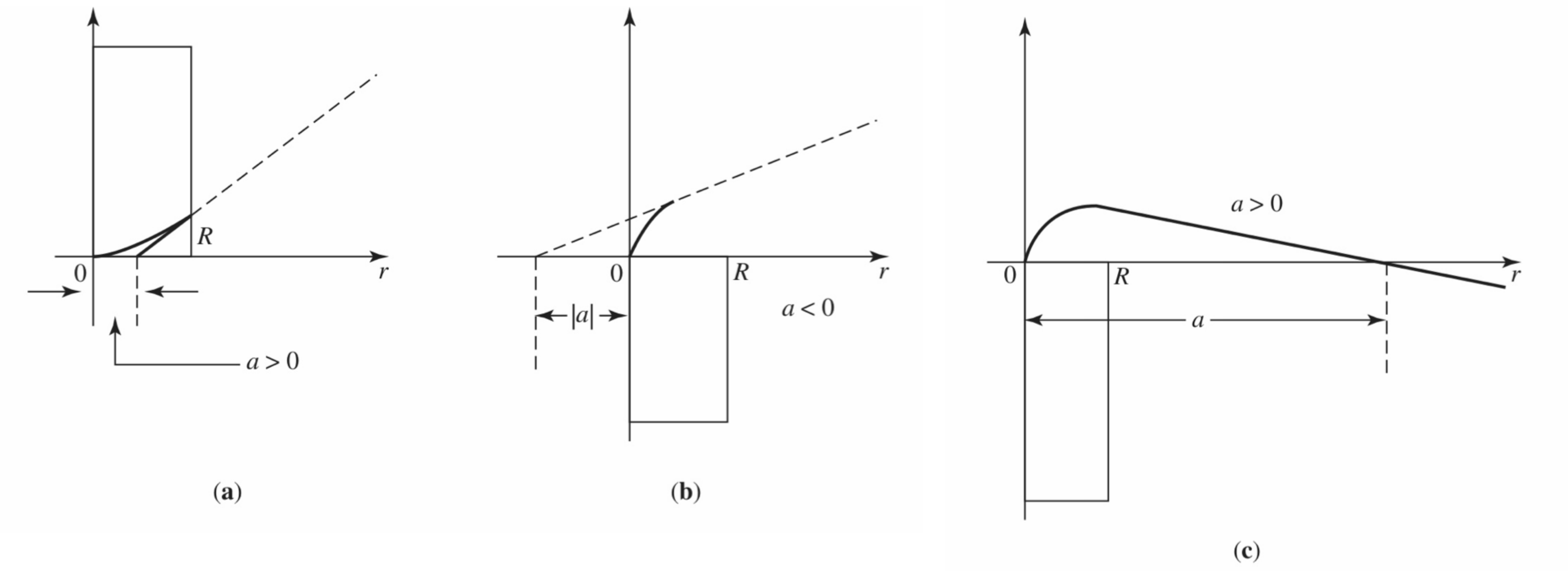
$$C(k^*) = \sum_S \rho_S \left[\frac{1}{2}\left|\frac{f(k^*)}{r_{eff}}\right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi} r_{eff}}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi} r_{eff}} F_1(2k^* r_{eff}) - \frac{\Im f(k^*)}{r_{eff}} F_2(2k^* r_{eff})\right]$$

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: $f(k^*) = \left(\frac{1}{f_0} + \frac{1}{2} d_0 k^{*2} - ik^*\right)^{-1}$
    - Effective range d_0 and scattering length f_0
- Spin averaged scattering parameters

Scattering length

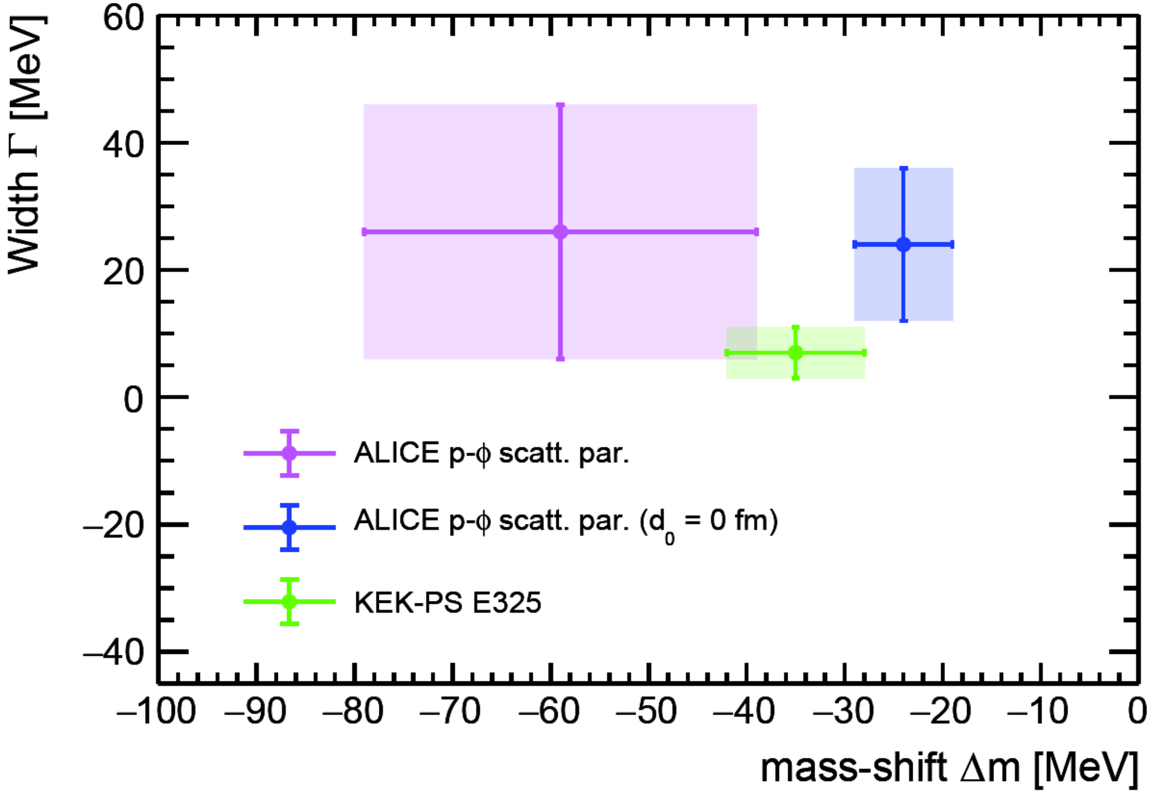


Different sign convention
f0, a0 = -a !

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].

In medium properties

- Scattering length can be related to first order optical potential $U(r) \approx \frac{1}{2m}\ 4\pi\rho\ \frac{b}{1+b/d_0}\ \approx \frac{1}{2m}\ 4\pi\rho\ b$ with $b = f_0\left(1+\frac{m_\phi}{m_{proton}}\right)$
  V.A. Baskov et al. *arXiv:nucl-ex/0306011v1* (2003)
- Real part related to mass-shift V(r) ≈ Δm
- Imaginary part related to width W(r) ≈ -Γ/2
- Similar to results of E325 Collab. of Δm =- (35 ± 7) MeV and Γ = -(7± 4) MeV
  KEK-PS E325 Collab., Phys. Rev. Lett. **98** (2007) 042501



N–φ coupling constant

- Yukawa-type of potential with real parameters
  Phys. Rev. Lett. **98** (2007) 042501
  - $V(r) = -A \cdot \frac{e^{-\alpha r}}{r}$
- CF obtained **numerically** using CATS framework
  D.L. Mihaylov et al, *Eur. Phys. J.* **C78** (2018) no.5, 394

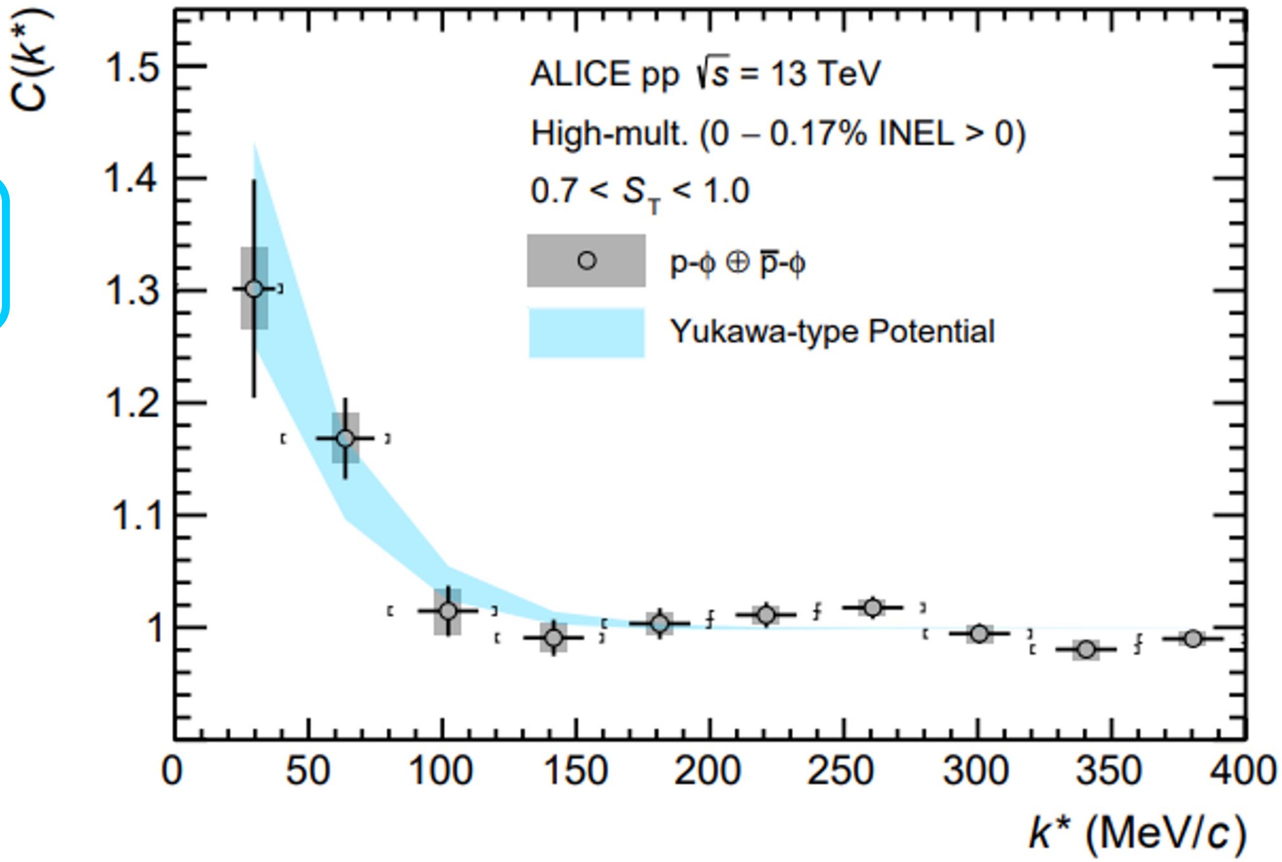
Strength A = 0.021 ± 0.009(stat.) ± 0.006(syst.)

Inverse range α = 65.9 ± 38.0(stat.) ± 17.5(syst.)MeV

- Extraction of N–ϕ coupling constant as $\sqrt{A}$

$g_{\phi N}$=0.14±0.03(stat.)±0.02(syst.)

  - Link to Y–Y interaction $g_{\phi Y} \propto g_{\phi N}$
    S. Weissborn et al., *Nuclear Physics A*, **881** (2012) 62-77



Relativistic mean fiel model

$$\mathcal{L}_{YY} = \underbrace{\sum_{B} \overline{\psi_B}\left(g_{\sigma^* B}\sigma^* - g_{\phi B}\gamma_\mu \phi^\mu\right)\psi_B}_{\text{Meson-Baryon interaction}} + \underbrace{\frac{1}{2}\left(\partial_\mu \sigma^* \partial^\mu \sigma^* - m_{\sigma^*}^2 \sigma^{*2}\right)}_{\text{Scalar meson term}} - \underbrace{\left(\frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} - \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu\right)}_{\text{Vector meson term}}$$

Info on φΛ Coupling

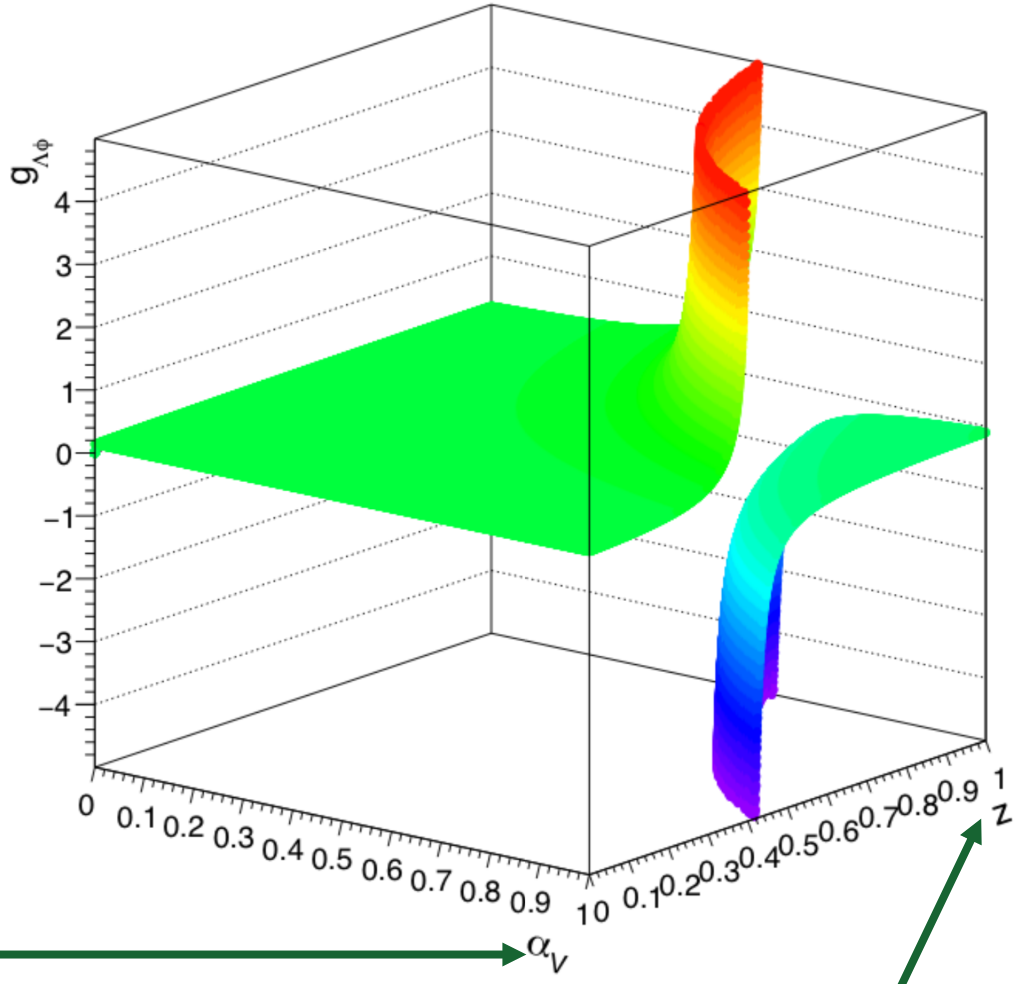
$$\frac{g_{N\phi}}{g_{N\omega}} = -\frac{\sqrt{3}-\sqrt{2}(4\alpha_V-1)z}{\sqrt{6}+(4\alpha_V-1)z},$$

$$\frac{g_{\Lambda\phi}}{g_{N\omega}} = -\frac{\sqrt{3}+2\sqrt{2}(1-\alpha_V)z}{\sqrt{6}+(4\alpha_V-1)z},$$

$$\frac{g_{\Sigma\phi}}{g_{N\omega}} = -\frac{\sqrt{3}-2\sqrt{2}(1-\alpha_V)z}{\sqrt{6}+(4\alpha_V-1)z},$$

$$\frac{g_{\Xi\phi}}{g_{N\omega}} = -\frac{\sqrt{3}+\sqrt{2}(1+2\alpha_V)z}{\sqrt{6}+(4\alpha_V-1)z},$$

Relate expression of $g_{\phi\Lambda}$ to $g_{\phi N}$=0.14

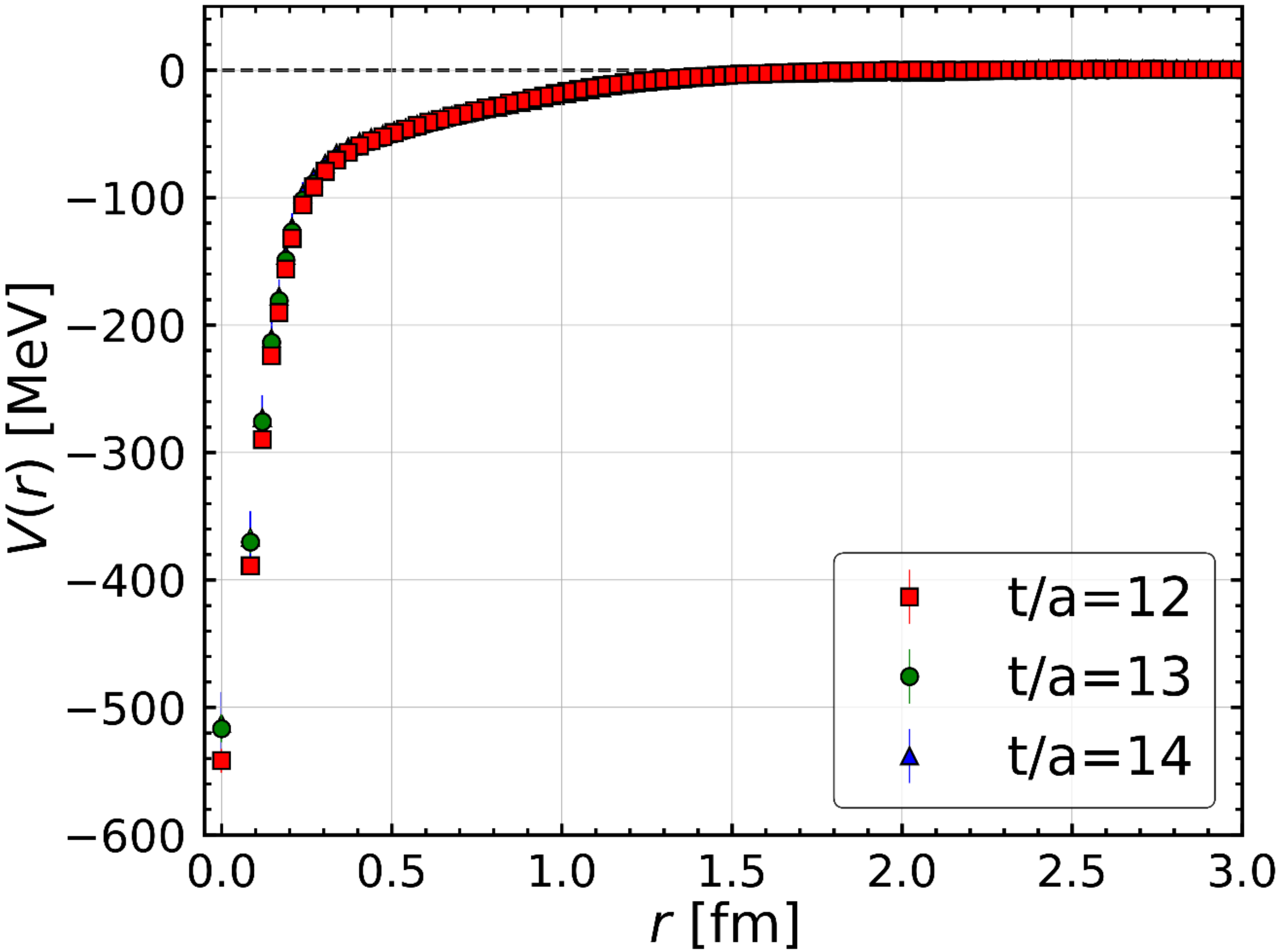


Weights the symmetric (D) and anti-symmetric part (F) of the octet-octet interaction
α_V=F/(F+D)

Ratio of meson singlet and octet coupling constants
$z=g_8/g_1$

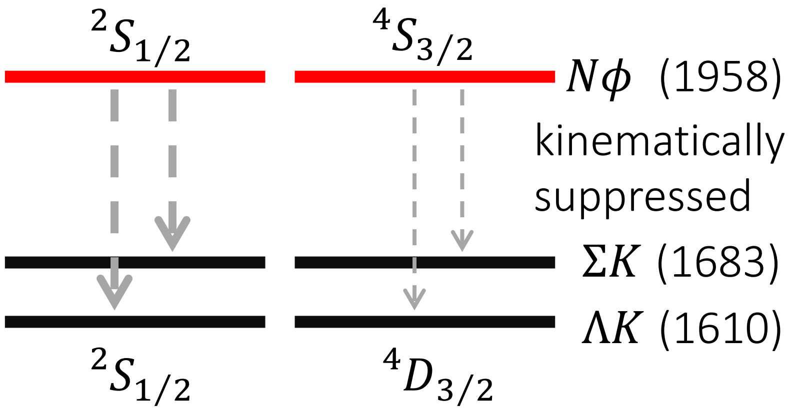
Lattice potential $^4S_{3/2}$

- $N\phi(^4S_{3/2})$ potential at Euclidean time 12, 13 and 14
- Attractive core, Pauli exclusion does not operate due to no common quarks
- Long-ranged attractive tail, hints of pion dynamics
- Weak t dependence



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

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



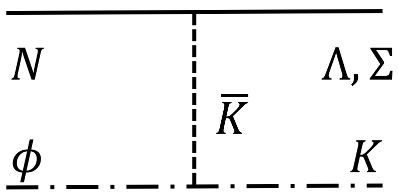
$^2S_{1/2}$ $^4S_{3/2}$ $N\phi$ (1958)

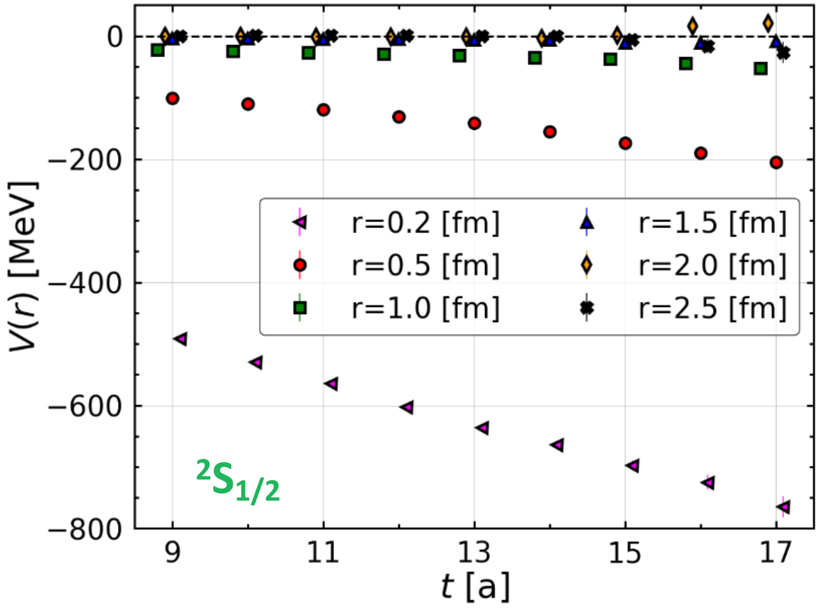
kinematically suppressed

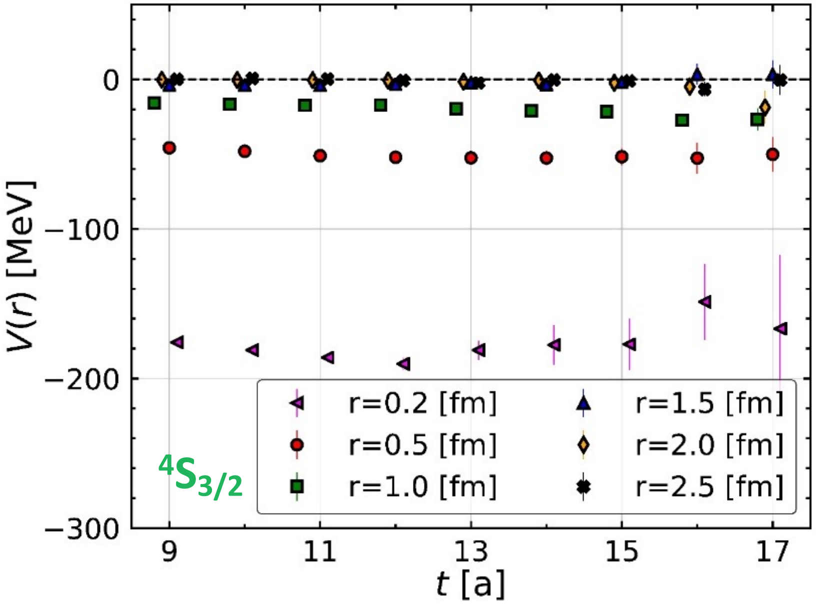
ΣK (1683)

ΛK (1610)

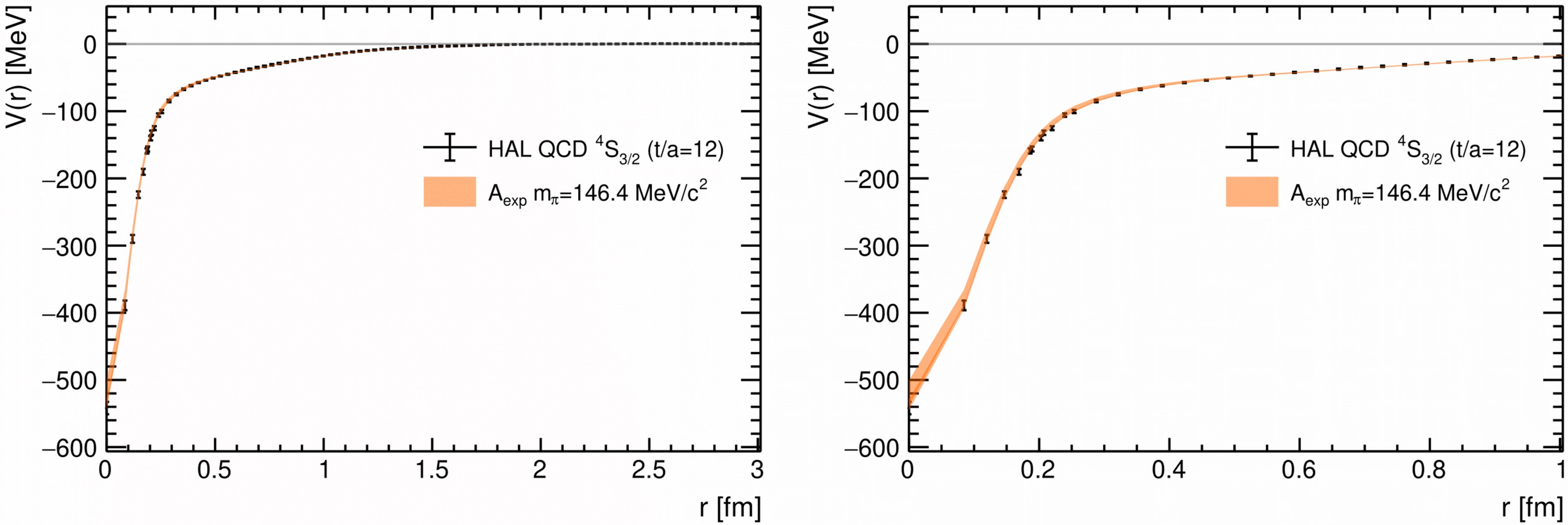
$^2S_{1/2}$ $^4D_{3/2}$







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

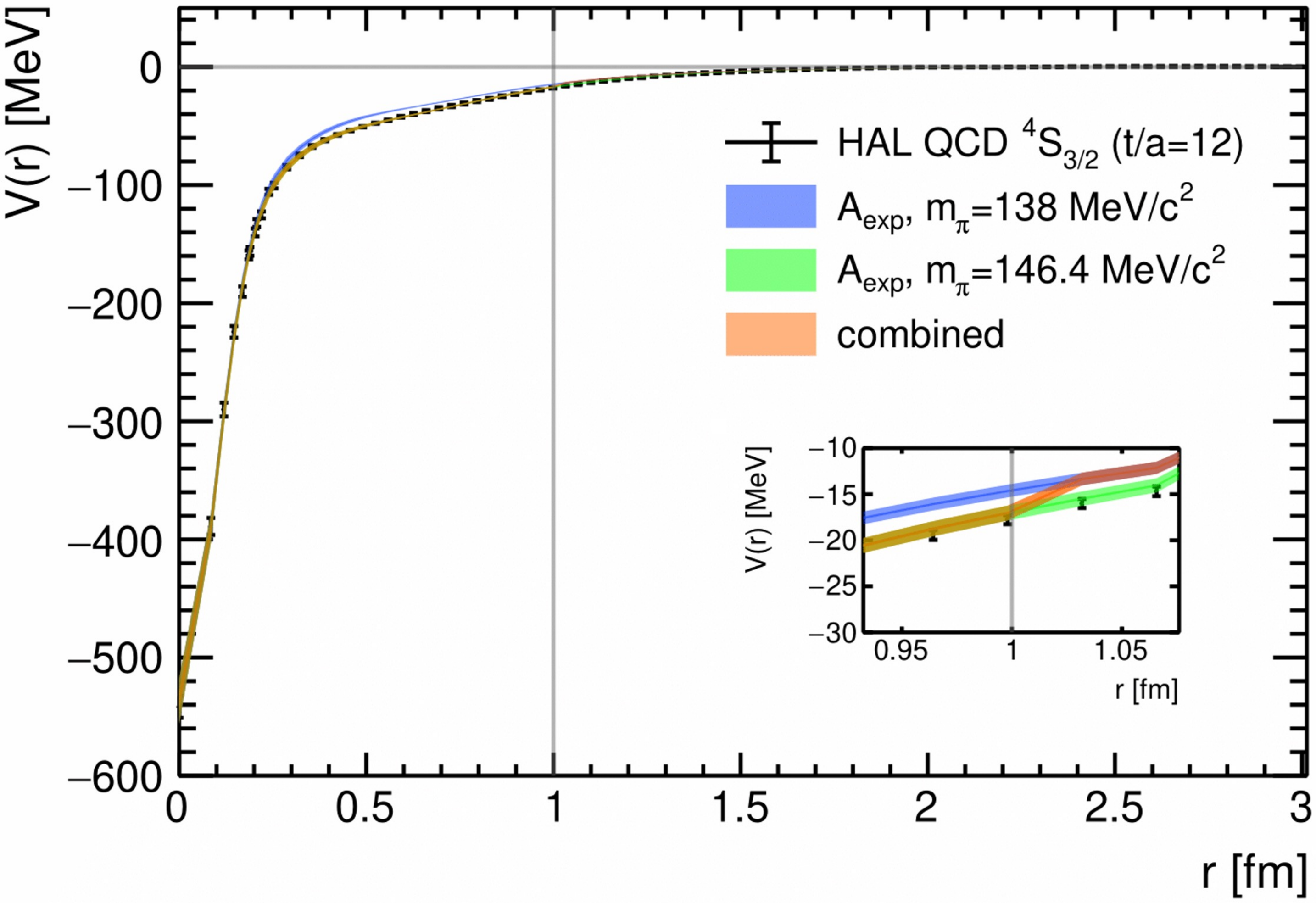


Argonne-type form factor $f(r;b_3) = \left(1 - e^{-(r/b_3)^2}\right)^2$

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

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



Real Potential only in $^2S_{1/2}$

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

- From fit to data β=(7.02 ± 0.07$_{stat}$ ± 0.15$_{syst}$)
- χ^2/ndf (k*<200 MeV/c) = 1.98