Precise experimental constraints of the strong interaction between a proton and a |S|= 3 baryon using femtoscopy

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for the ALICE Collaboration

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150 Jahre culture of excellence

SFB 1258 Neutrinos Dark Matter Messengers

The goal

- Experimental **study on the interaction between a proton and a multi-strange baryon**
  - Ω^- is a hyperon with quark content: sss

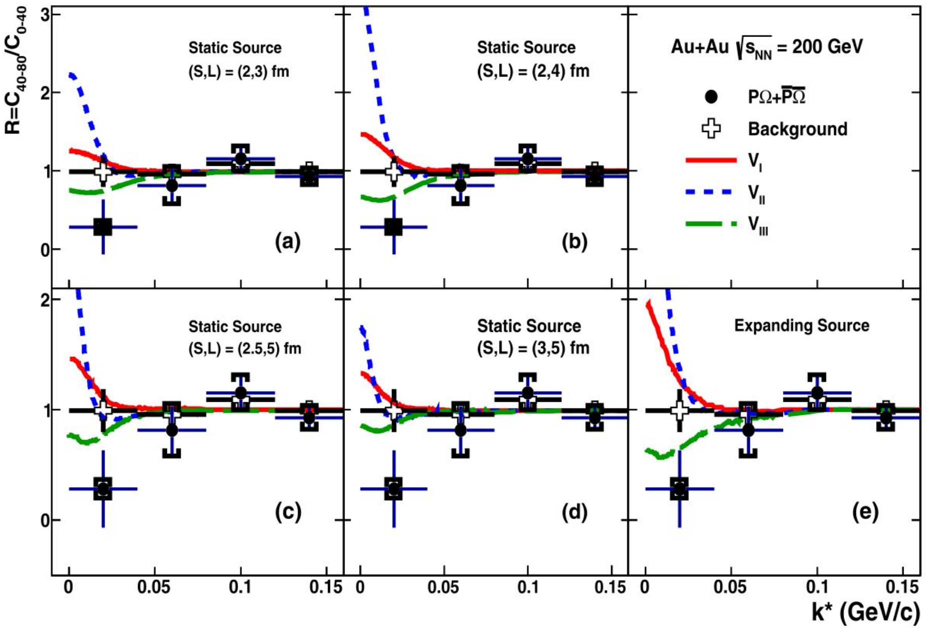
- Use the most recent datasets to test recent models of the p-Ω interaction:
  - Lattice QCD: HAL-QCD Collaboration
  - Meson exchange (Sekihara, Kamiya, Hyodo)

- Femtoscopy delivers precise data in the low momentum range, that cannot be accessed with other experimental approaches (hypernuclei, scattering experiments)
  - In particular for p-Ω interaction femtoscopy is the only experimental method!

- **NΩ di-baryon** (strangeness = -3, spin = 2, isospin = 1/2)
  - Lattice QCD simulations predict an N-Ω interaction attractive at all distances, leading to the possible existence of a NΩ di-baryon
  - Pauli principle does not apply to this system, the absence of a repulsive core favors the existence of a compact state.

Previously available experimental data: STAR

- Study of the p-Ω^- correlation function in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV STAR Collaboration. Phys. Lett. B790 (2019) 490-497
- Observable: ratio of the correlation function peripheral/central collisions.
- Comparison with Lattice QCD calculations (with large masses)



- Test different fits to Lattice QCD data (delivering **three different binding energies of the NΩ**):

Binding energy ($\mathbf{E_b}$), scattering length ($\mathbf{a_0}$) and effective range ($\mathbf{r_{eff}}$) for the Spin-2 proton–Ω potentials [24].

Spin-2 pΩ potentials	V_I	V_{II}	V_{III}
$\mathbf{E_b}$ (MeV)	–	6.3	26.9
$\mathbf{a_0}$ (fm)	−1.12	5.79	1.29
$\mathbf{r_{eff}}$ (fm)	1.16	0.96	0.65

[24] K. Morita, A. Ohnishi, F. Etminan, T. Hatsuda, Phys. Rev. C 94 (2016), 031901

STAR data favor V_{III}, with $\mathbf{E_b}$ **= 27 MeV**

The method

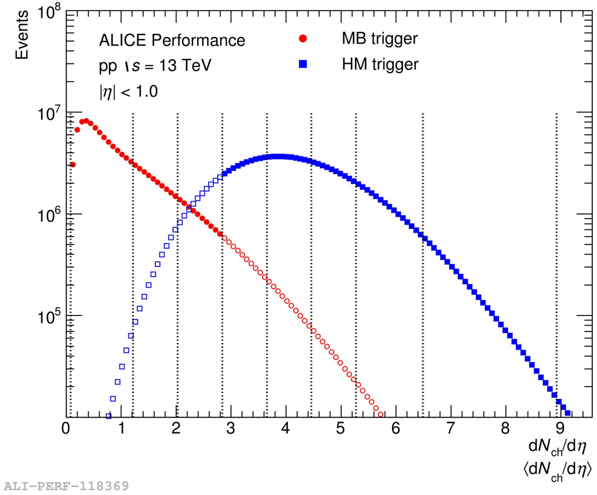
- Study the correlation function of p-Ω^- pairs as a function of k*:
  - proton-proton (pp) collisions ⇒ small particle source (of the order of 1 fm)

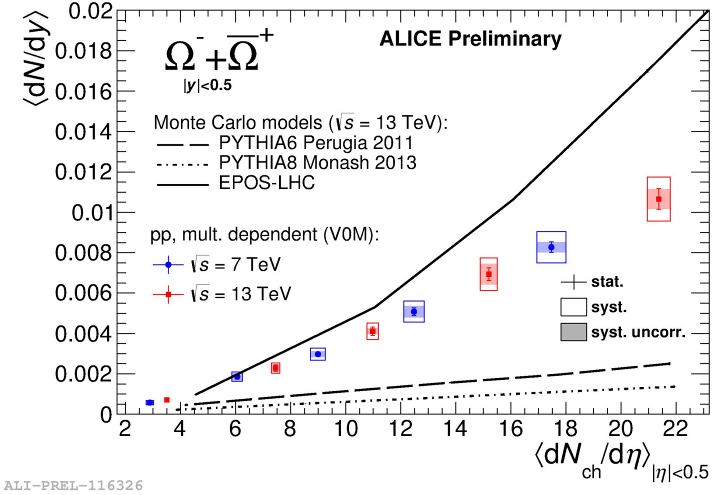
- The size of the source core is determined from the femtoscopic analysis of the **p-p correlation function performed differentially in <m_T> bins**
  - Assume a p-p known interaction → determination of the source size
  - Effect of resonances is taken into account
  - **Assume a common source and the same <m_T> dependence for all pairs:**
    - The radius of the source core is obtained for the p-Ω^- pairs considering the corresponding pair <m_T>

- The theoretical correlation function is computed by CATS from the shape of the local potential provided by the different models. D. L. Mihaylov et al., EPJ C 78 (2018) 394

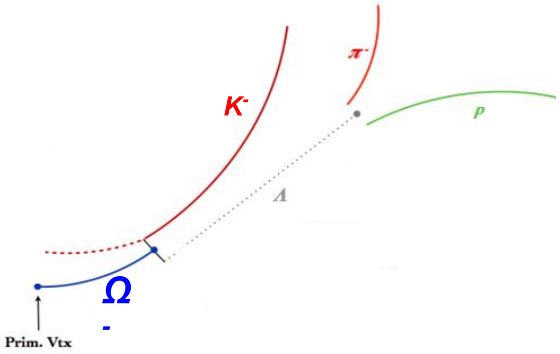
ALICE high-mult. data

- Analyzed 10^9 events data of ALICE Run2 (2016, 2017, 2018), pp collisions at $\sqrt{s}$ = 13 TeV
- **High multiplicity trigger**: 0.1% highest multiplicity with respect to Minimum Bias events (V0M, forward rapidities: $2.8 < \eta < 5.1$, $-3.7 < \eta < -1.7$).
  - Increased yield of Ω baryon

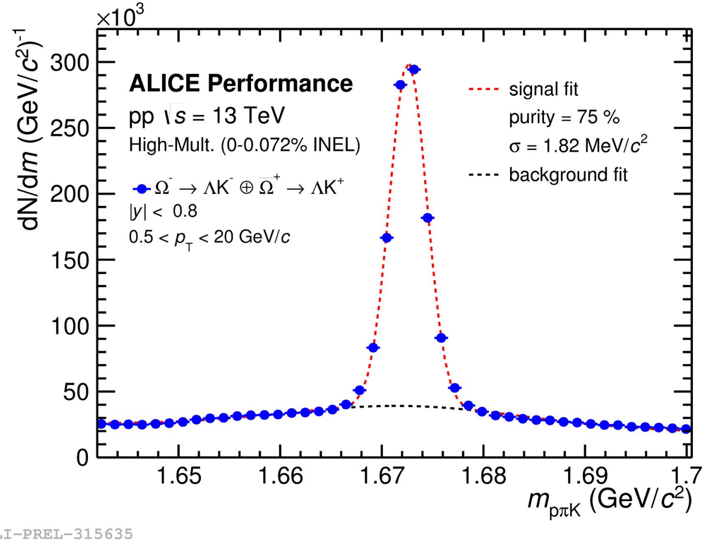




Selection of Ω^- candidates

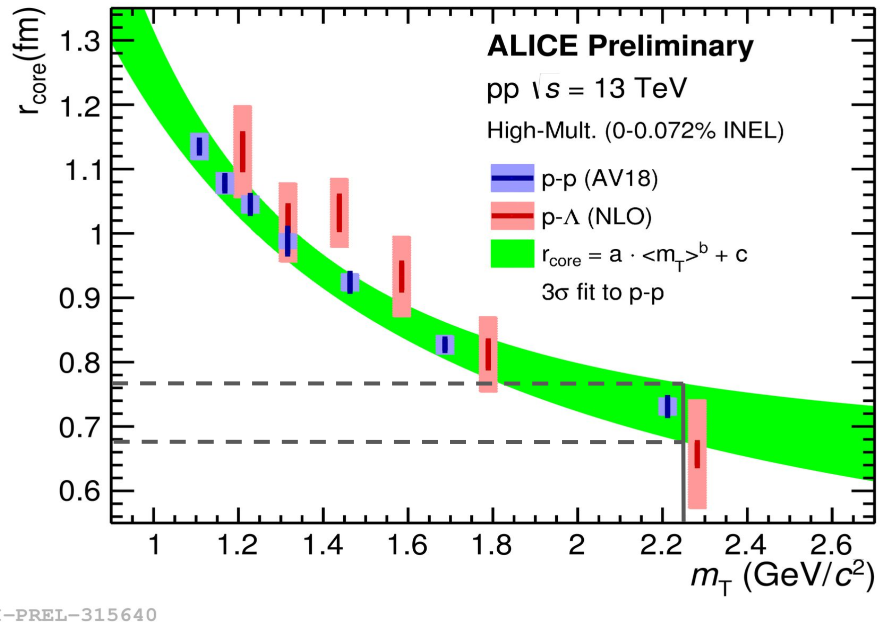


- Identified by its decay: $\Omega^- \rightarrow \Lambda K^- \rightarrow (p\pi^-)K^-$
- Total of 1.2×10^6 selected $(\Omega^- + \Omega^+)$ candidates
- **Purity** of the sample = **75%**
- Sidebands analysis delivers the shape of the background correlation function

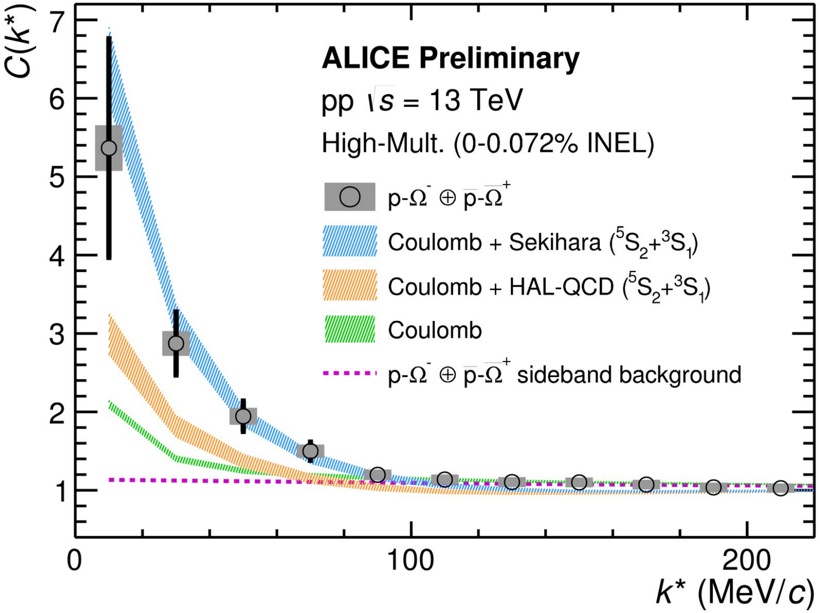


Source core for pΩ⁻ pairs

- Source core dependence on <m_T> of p-p pairs fitted with power law
- For pΩ pairs <m_T> = 2.21 GeV/c^2 → **r_{core} = 0.72 ± 0.03 fm**



p-Ω^- ⊕ $\overline{p}$-$\overline{\Omega}^+$ correlation function



- 0.6x10^6 p-Ω^-⊕$\overline{p}$-$\overline{\Omega}^+$ pairs
- ~700 pairs at k* < 100 MeV/*c*
- Strong enhancement of the correlation function: the "**Coulomb only**" scenario is discarded by a χ^2 comparison to the data, n_σ~6
- λ parameters:

Pair	λ [%]
p–Ω^-	61.5
p_Λ–Ω^-	8.3
p_{Σ^+}–Ω^-	3.8
$\tilde{p}$–Ω^-	1.5
p–$\tilde{\Omega}^-$	20.5
p_Λ–$\tilde{\Omega}^-$	2.8
p_{Σ^+}–$\tilde{\Omega}^-$	1.3
$\tilde{p}$–$\tilde{\Omega}^-$	0.5

Comparison with models: p-Ω^- interaction potentials

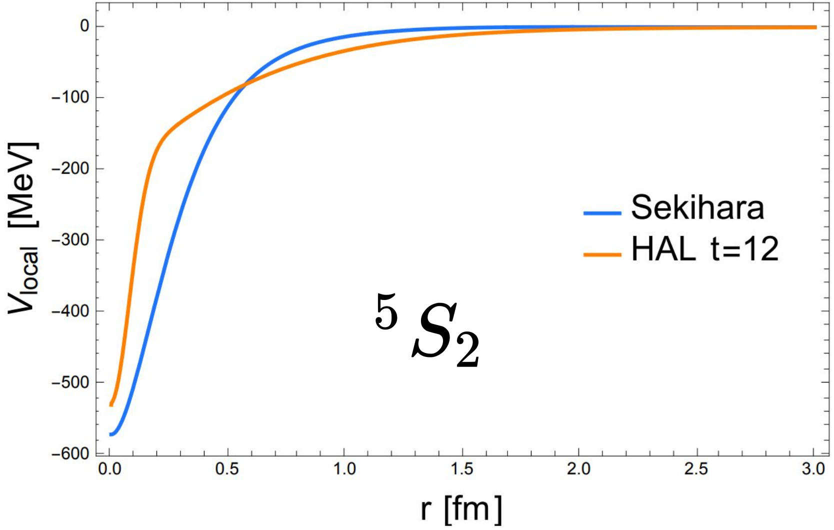
- Lattice **HAL-QCD** potential with physical quark masses ($^5S_2$ channel)
  - m_π = 146 MeV/c^2
  - m_K = 525 MeV/c^2

T. Iritani et al., arXiv:1810.03416

- **Sekihara**: Meson-exchange model ($^5S_2$ channel)
  - Including inelastic channels (strong decays into XΞ) → small contributions, neglected for now
  - Short range attractive interaction fitted to HAL-QCD scattering parameters

T. Sekihara et al., Phys. Rev. C 98, 015205 (2018)

Model	NΩ binding energy
HAL-QCD	1.54 MeV/c^2
Sekihara	0.1 MeV/c^2



Lattice HAL-QCD potential with heavy quarks

- Based on Lattice calculations with heavy quark masses F. Etminan et al.(HAL QCD Collaboration),Nucl. Phys. A928,89(2014)
  - m_π = 875 MeV/c^2
  - m_K = 916 MeV/c^2
- Used in the STAR pΩ analysis in Au-Au collisions at $\sqrt{s_{NN}}$ = 200GeV
- Lattice calculations fitted by an attractive Gaussian core + an attractive tail, varying the range parameter at long distance (b_5)
  - V_{II}: best fit to Lattice calculations
  - V_I / V_{III}: weaker / stronger attraction

$$V(r) = b_1 e^{-b_2 r^2} + b_3(1 - e^{-b_4 r^2})(e^{-b_5 r}/r)^2$$

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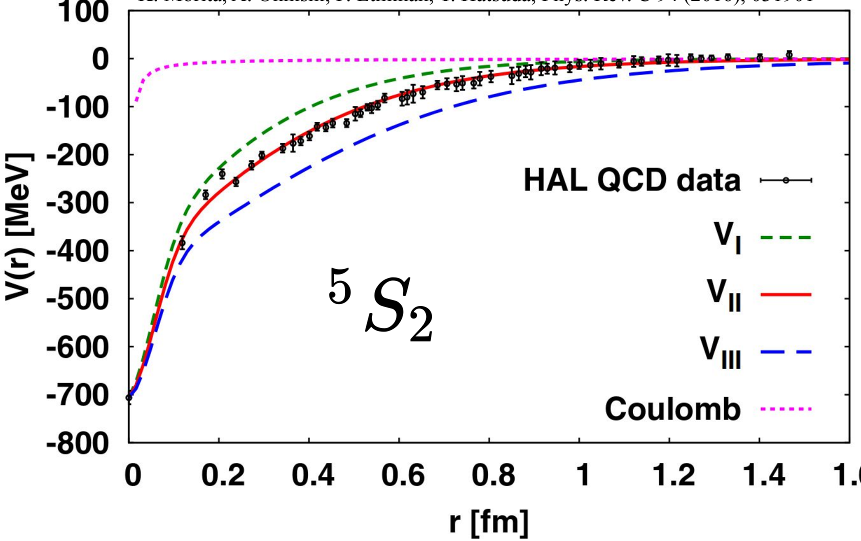

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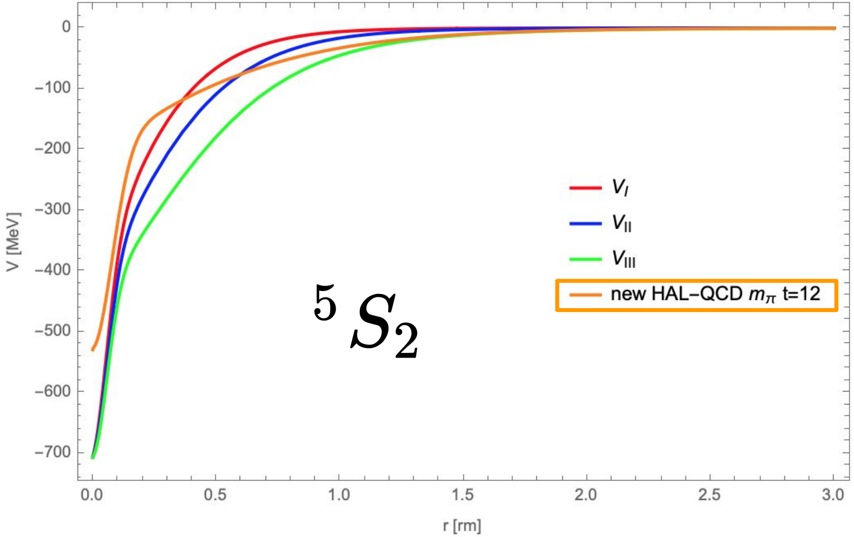
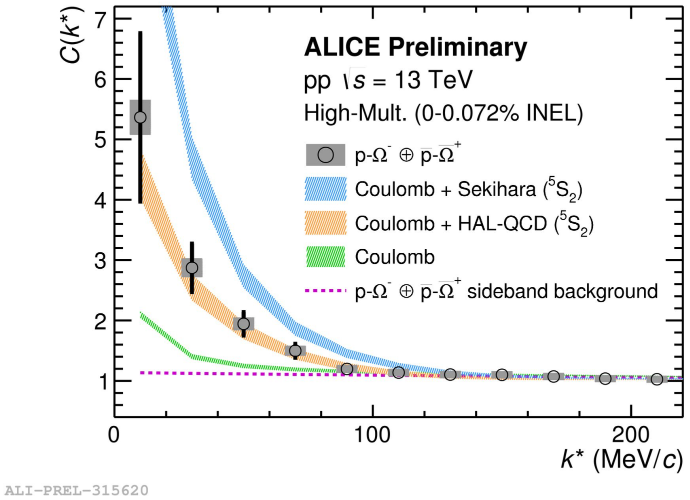
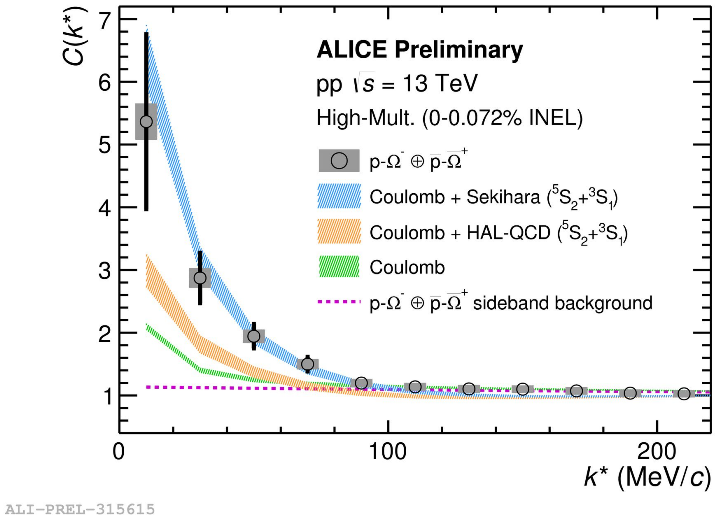


p-Ω^- correlation function: comparison with models

- Calculations from Lattice and phenomenological models provide the potential shape for th $^5S_2$ channel.
- The $^3S_1$ channel, with weight ⅜, is modelled following the recipe in K. Morita et al., Phys. Rev. C 94 (2016), 031901
  - Complete absorption of the NΩ wave function at short distance $r < r_0$
  - r_0 = 2 fm (for r > 2 fm Coulomb dominates over the strong potential)
  - Implemented in CATS by adding the “repulsive core”-like potential with an infinite barrier for $r < r_0$





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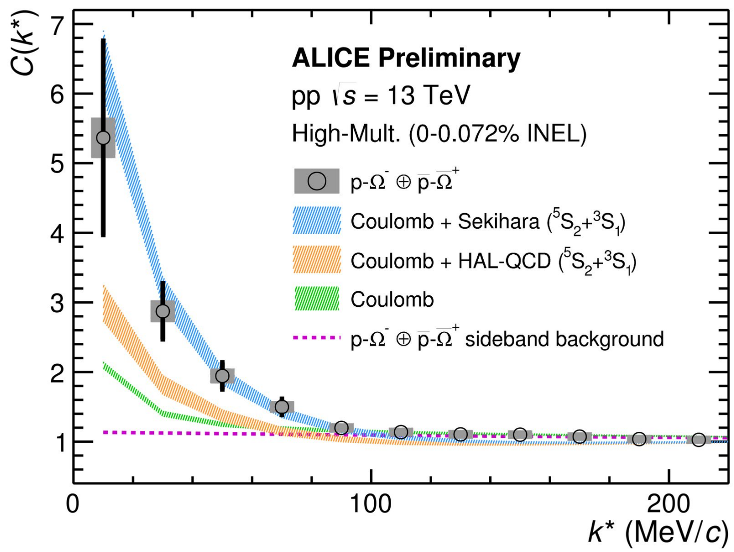

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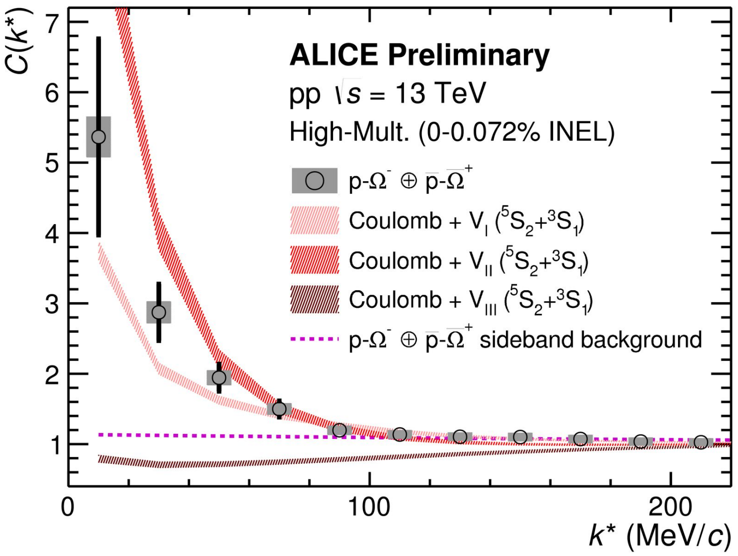

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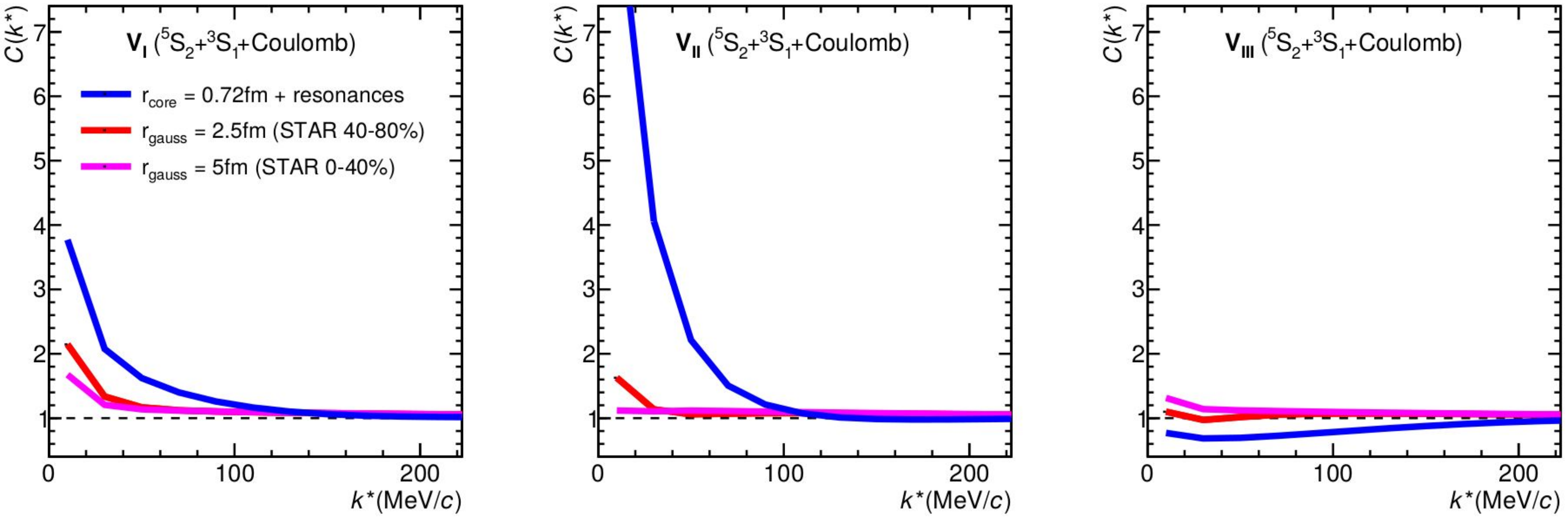
- The comparison of the model expectation with the experimental C(k*) by ALICE is **very sensitive to the shape of the model potential**.
- Models predicting large binding energies for the NΩ di-baryon are **excluded** by ALICE data (V_{III}, E_b ~ 27 MeV/c^2, n_σ > 10)

Sensitivity of ALICE and STAR data

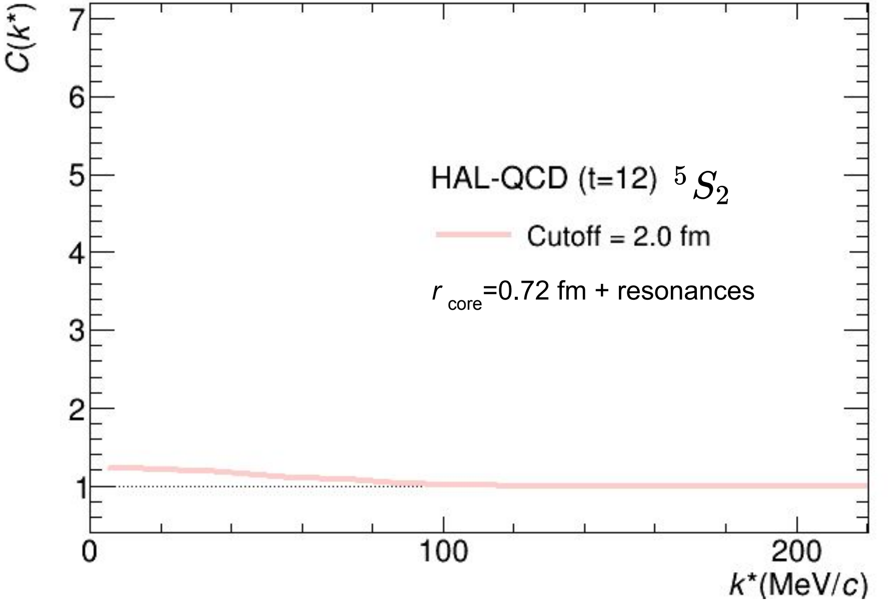
- Expected correlation function from heavy quark Lattice QCD potentials
- **Smaller radius** source offers the ideal conditions to test the models
- **Better purity** of ALICE data increases the **sensitivity** of the test

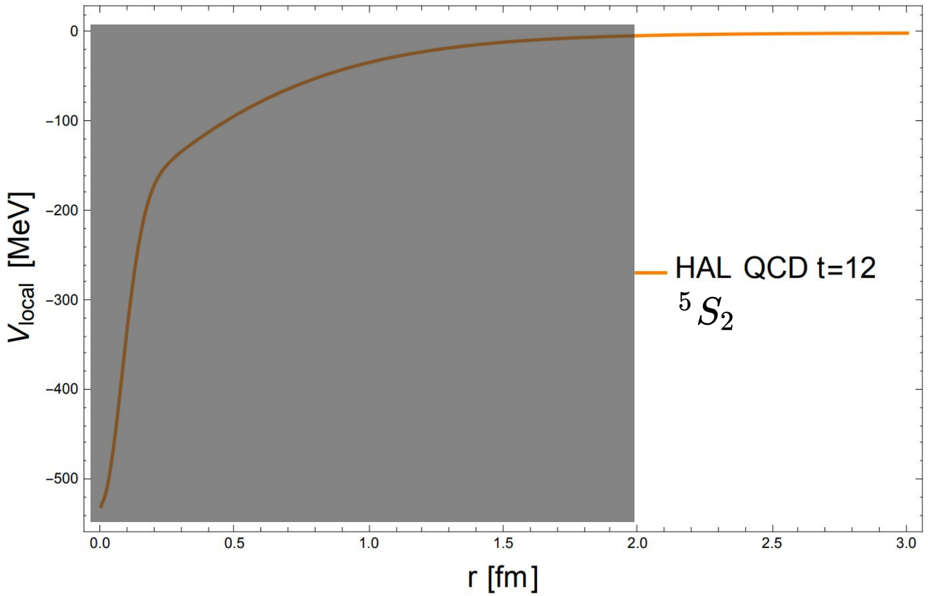
purity 75% (ALICE)



Correlation function ($^5S_2$) with distance cutoff

- Correlation function from $^5S_2$ channel with cutoff in r (for $r < r_{cutoff} \Rightarrow V = 0$)





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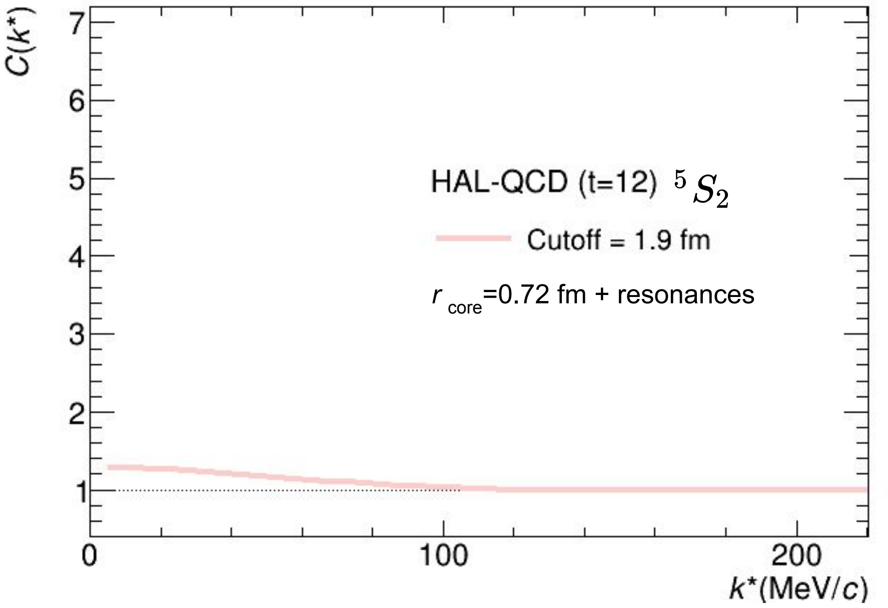

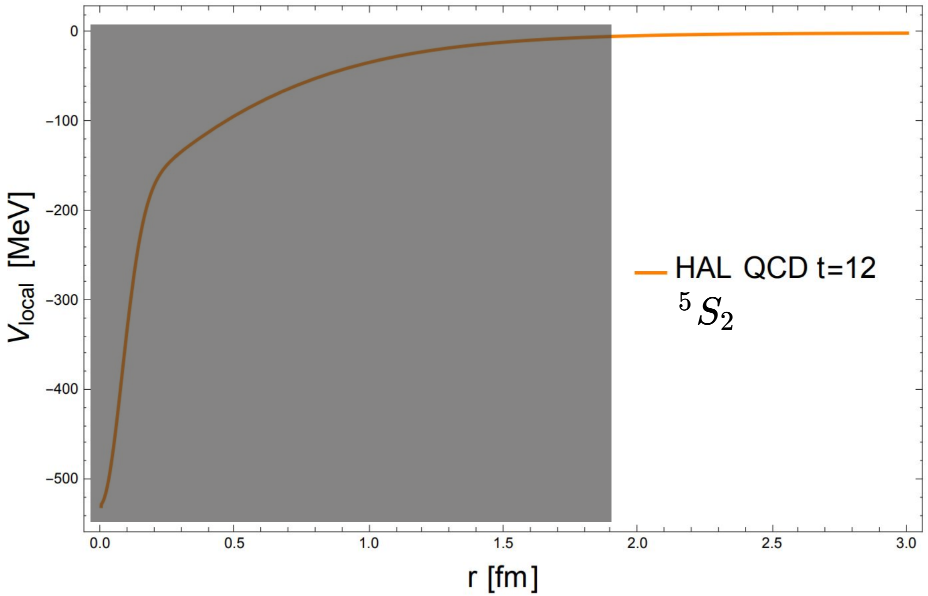

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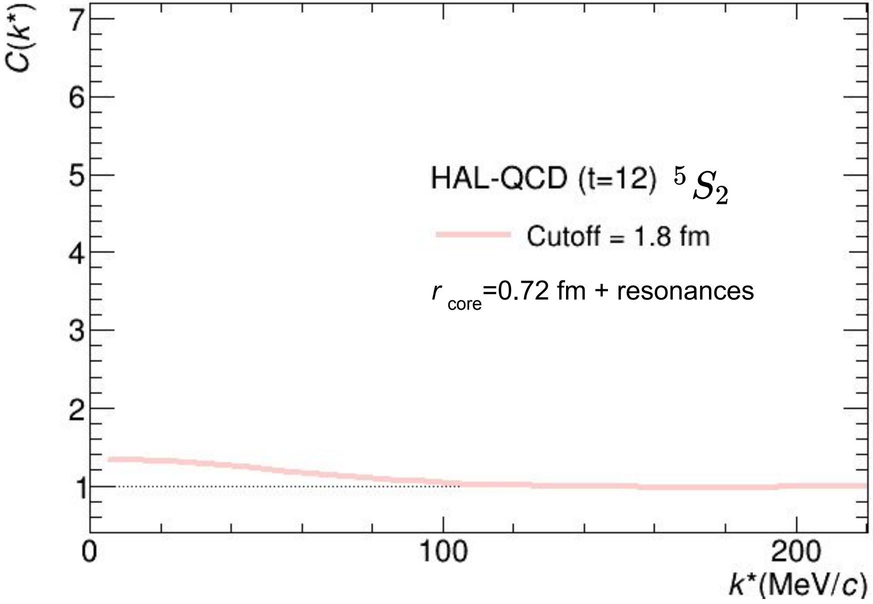

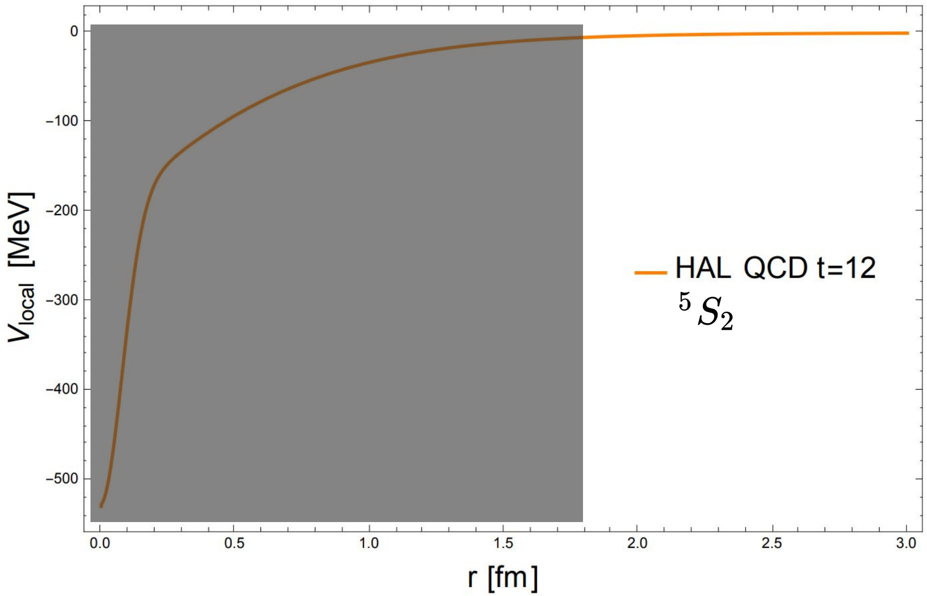

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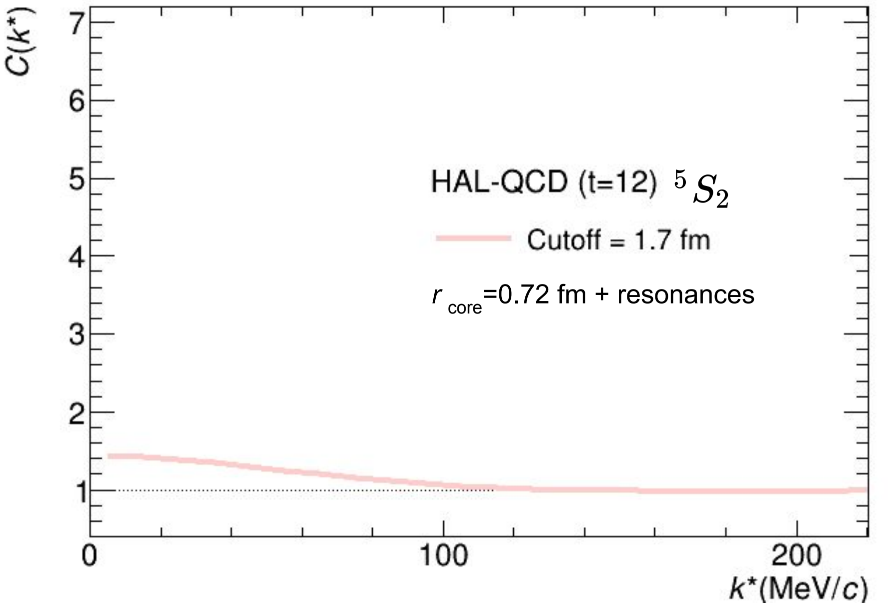

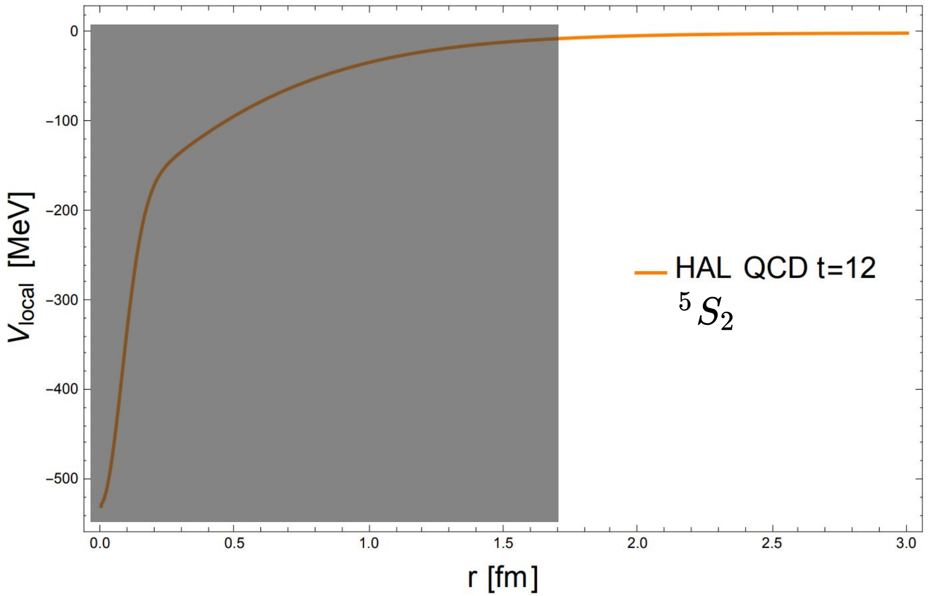

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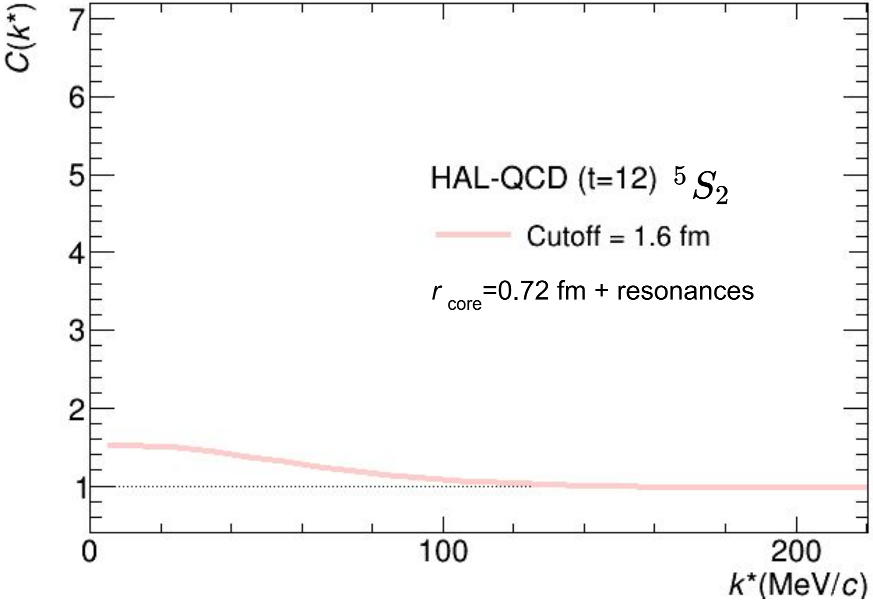

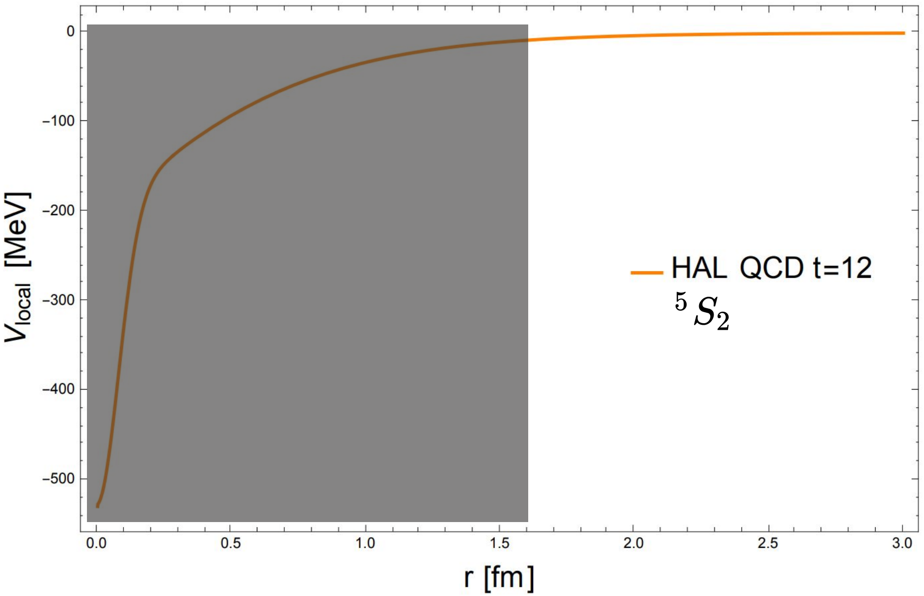

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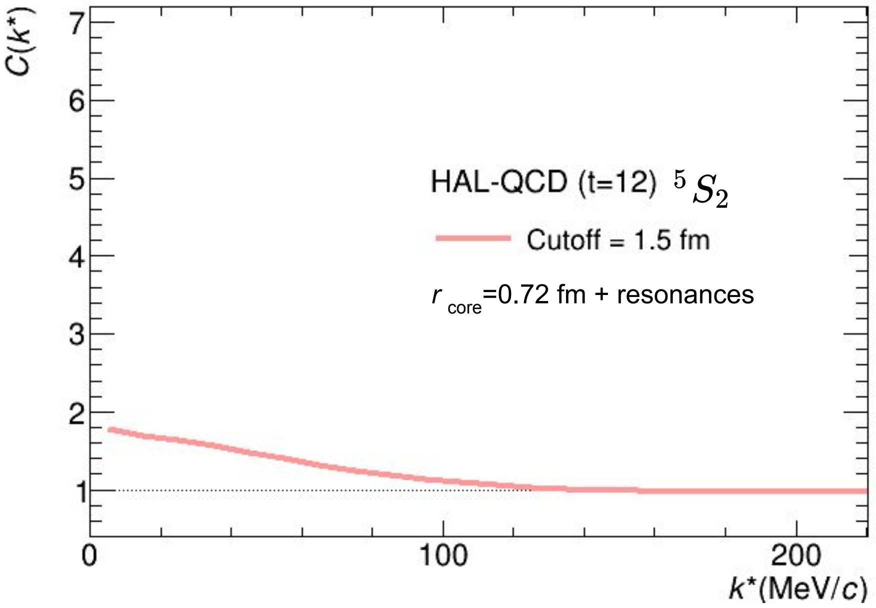

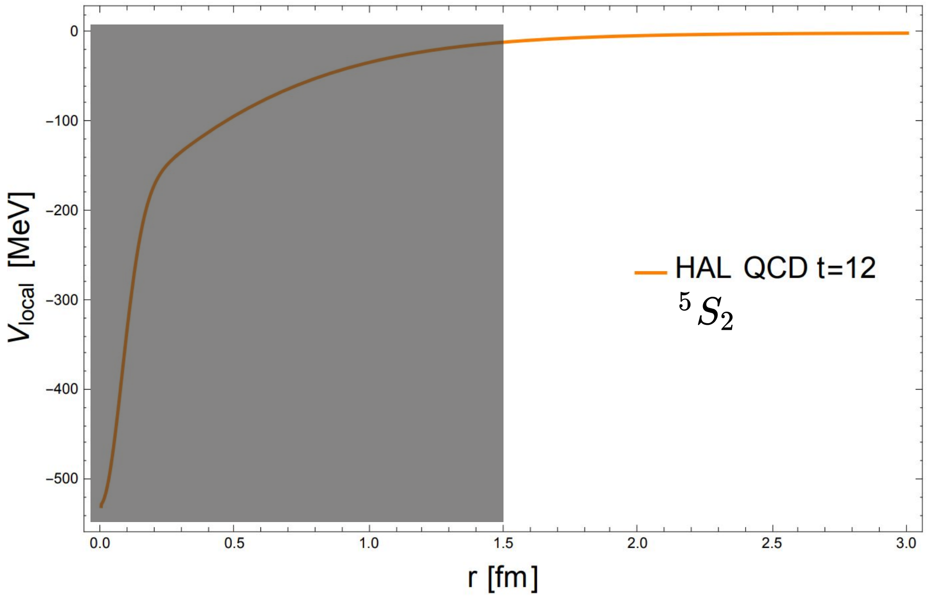

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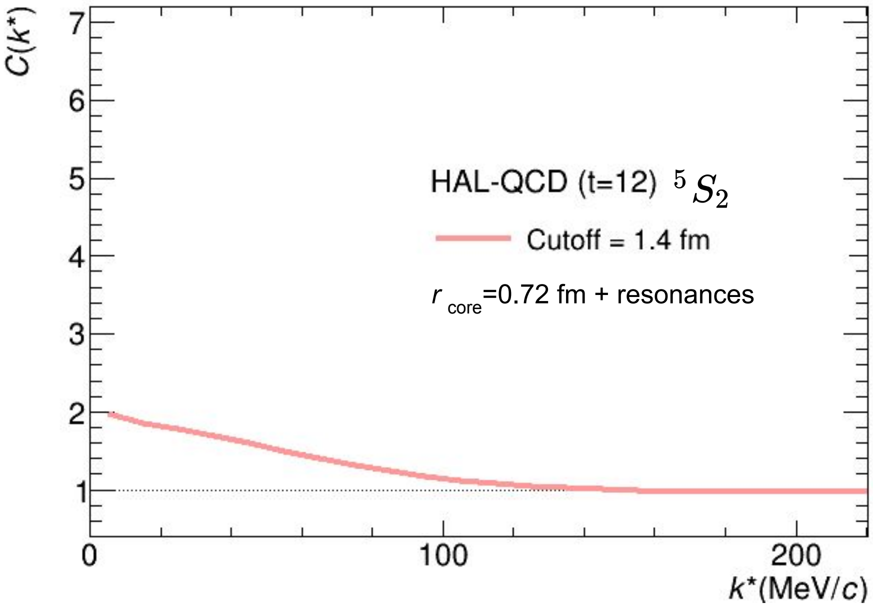

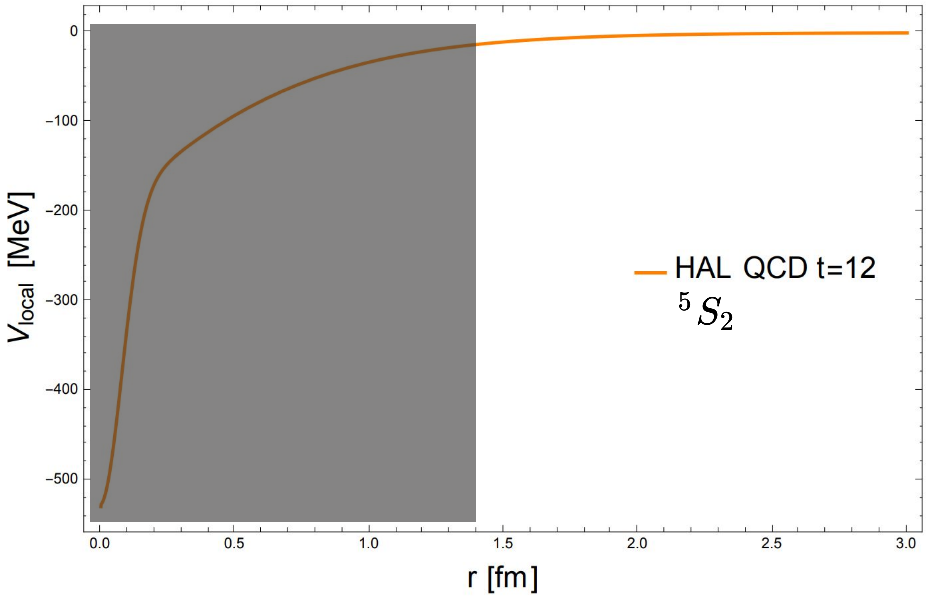

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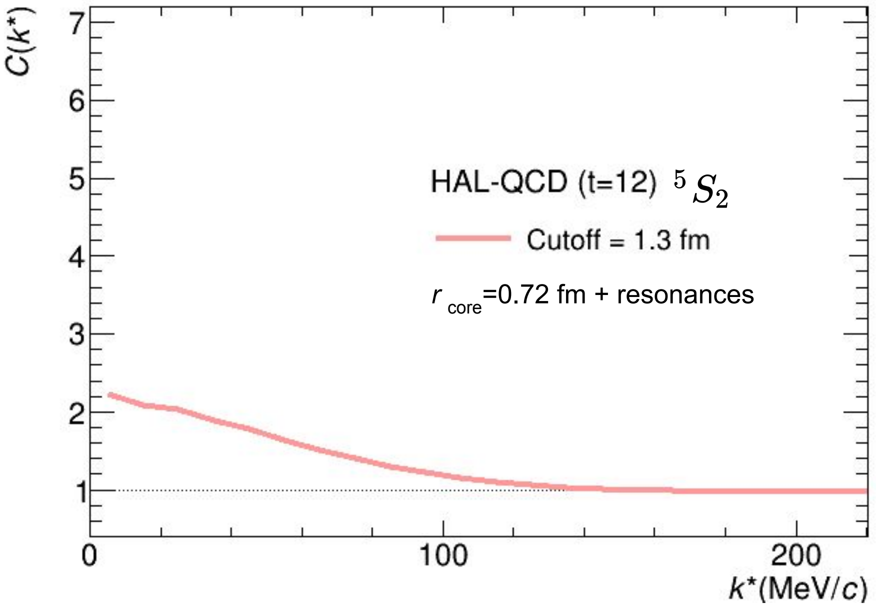

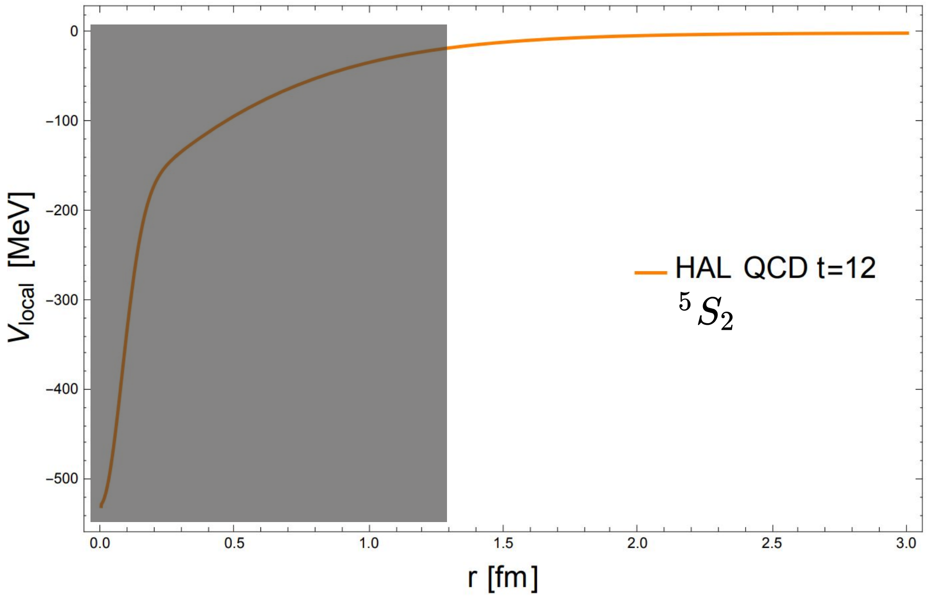

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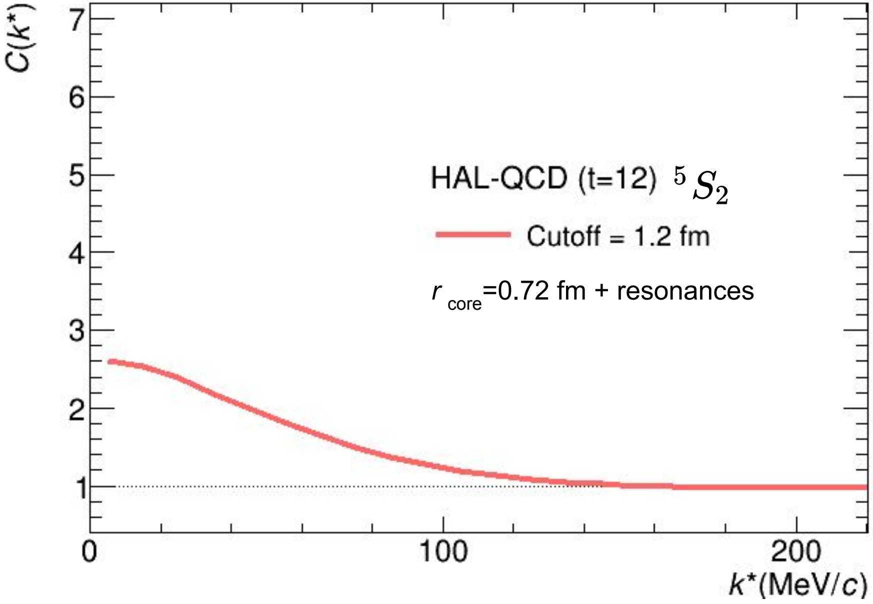

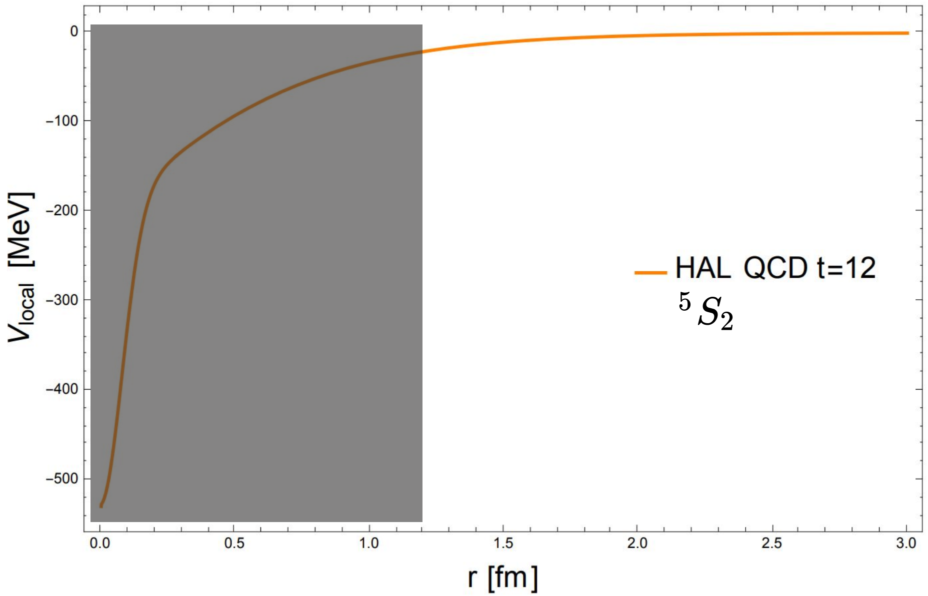

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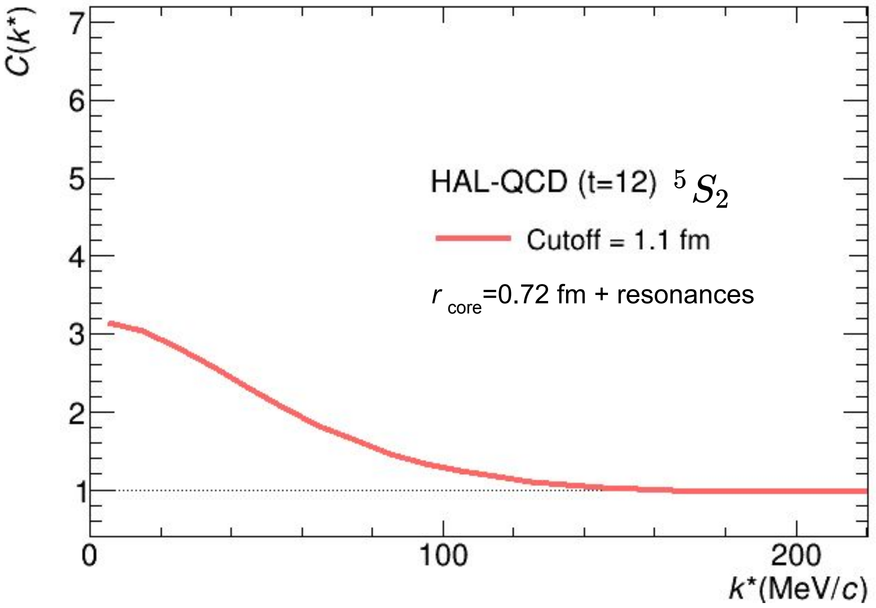

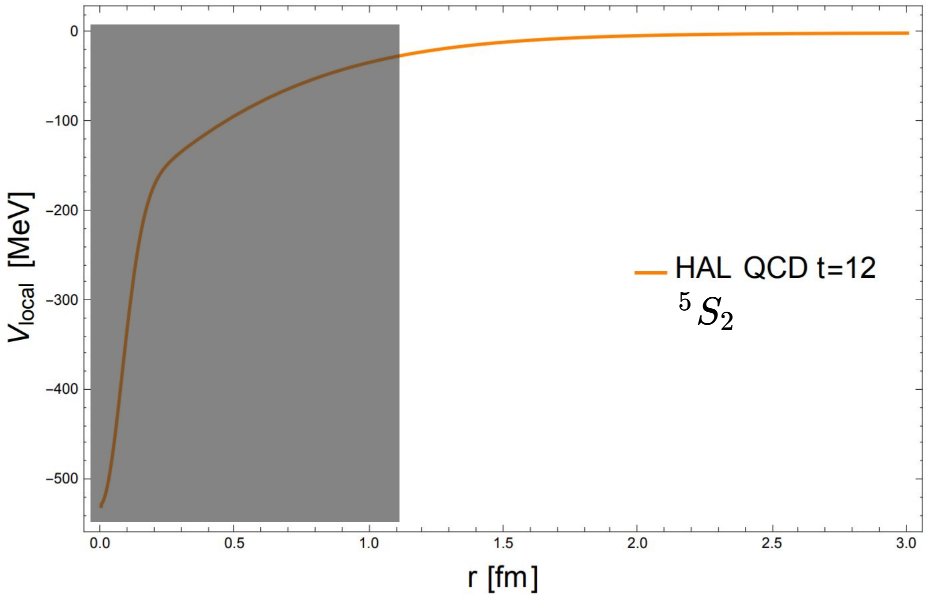

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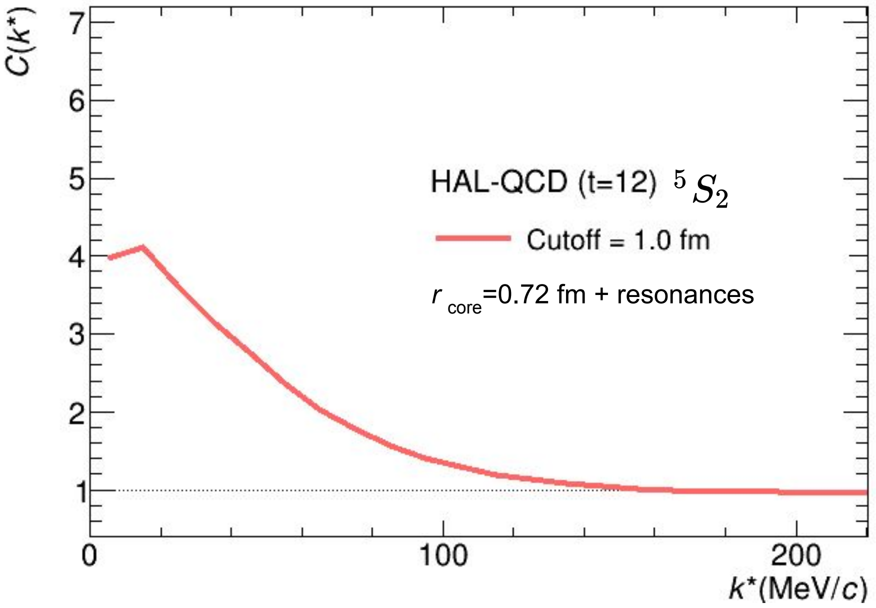

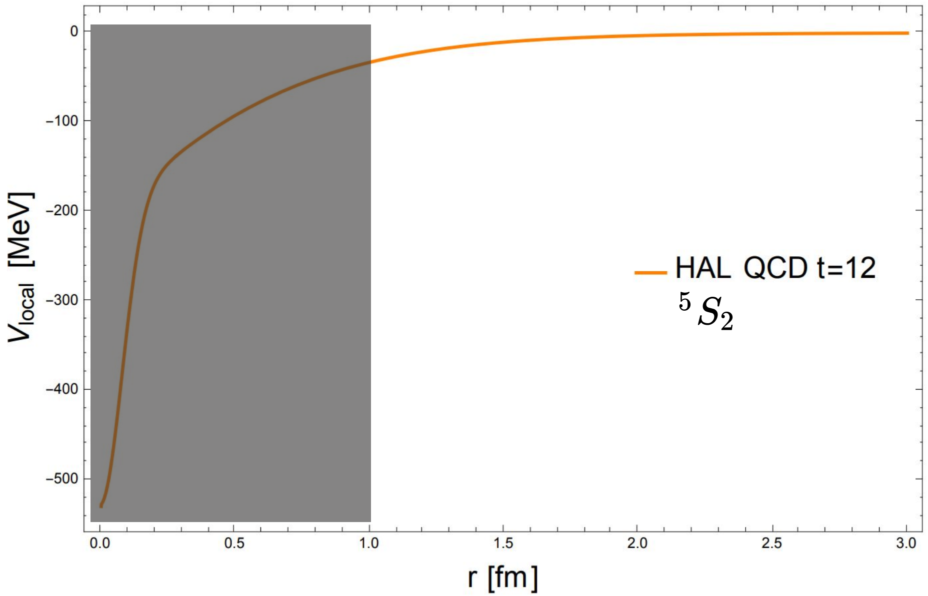

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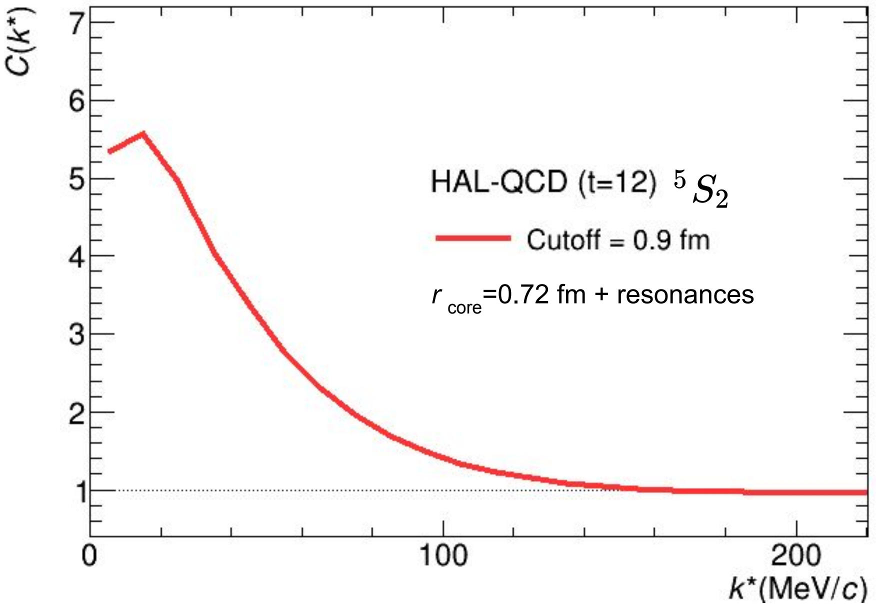

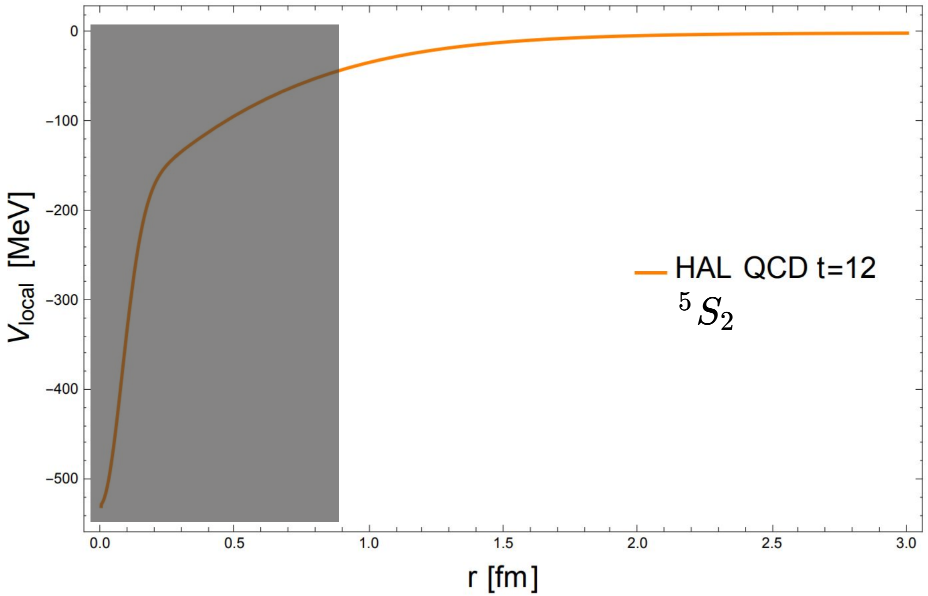

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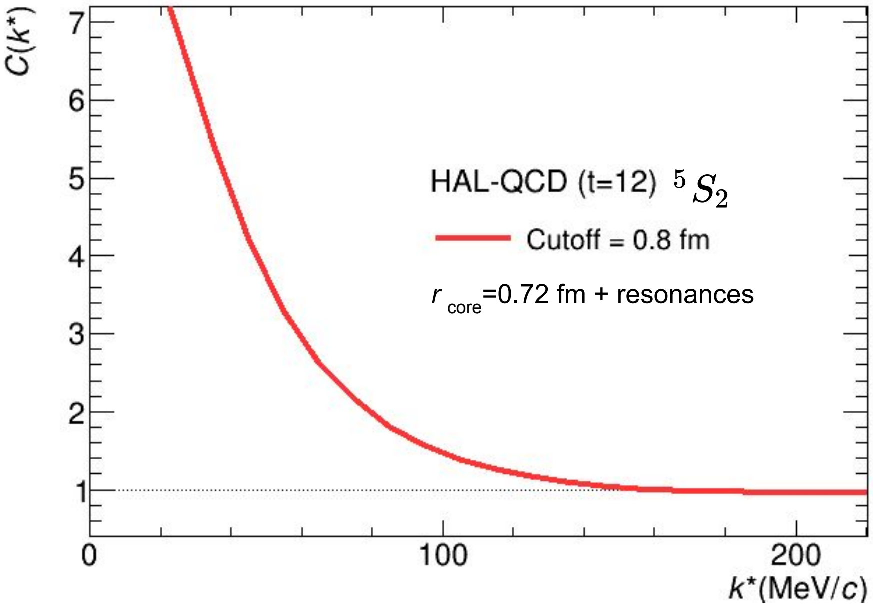

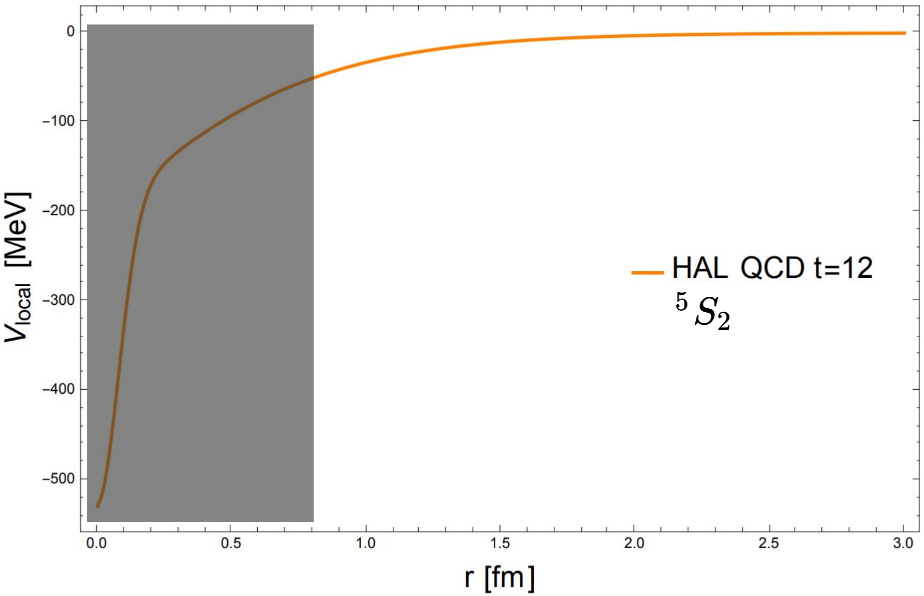

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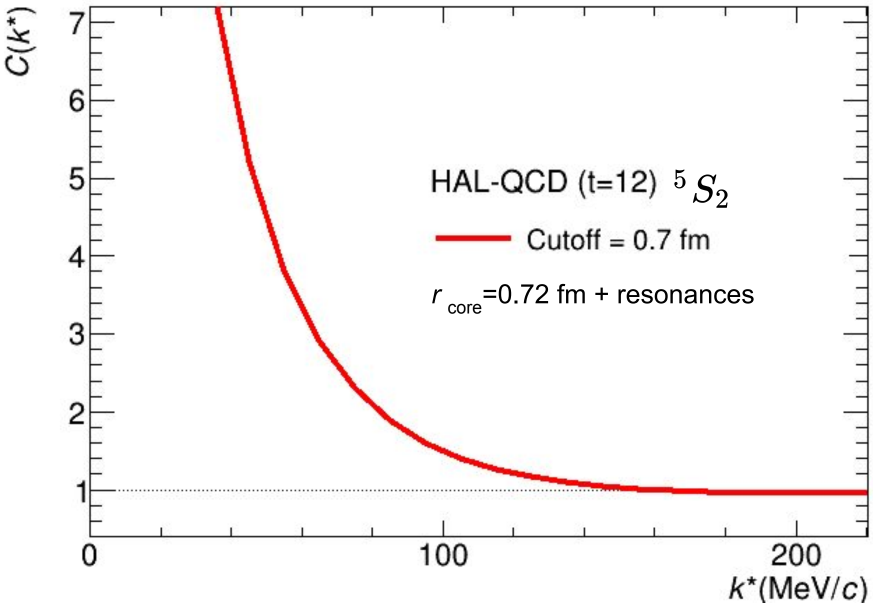

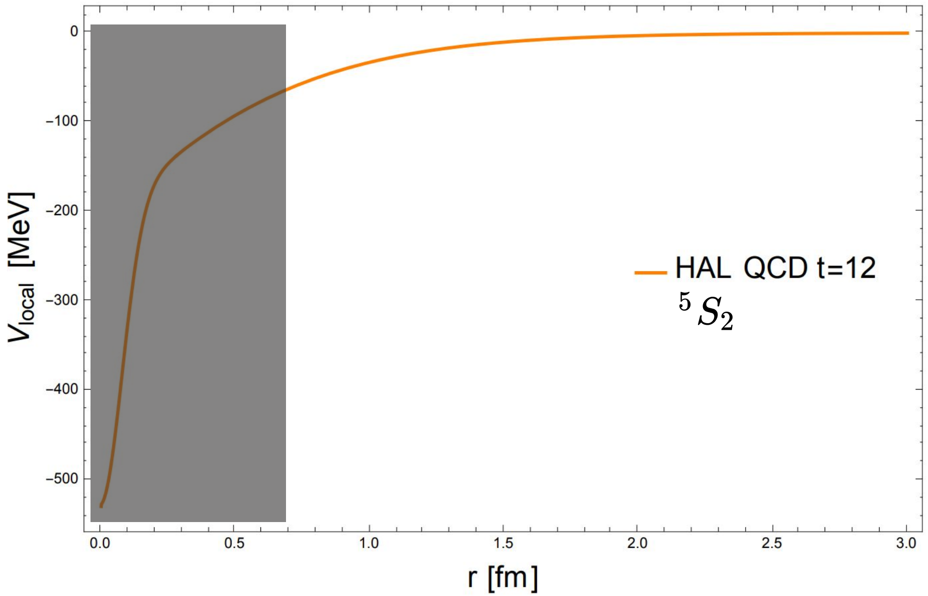

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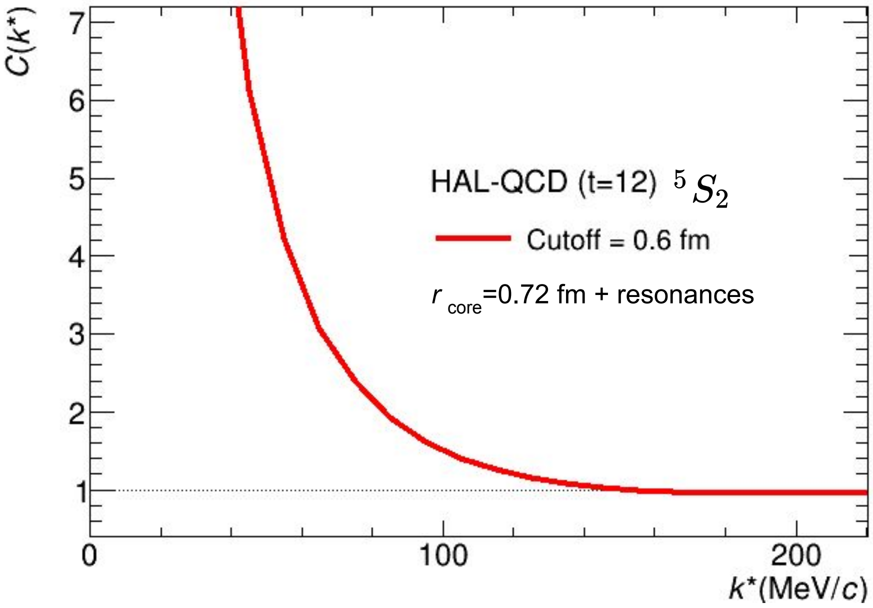

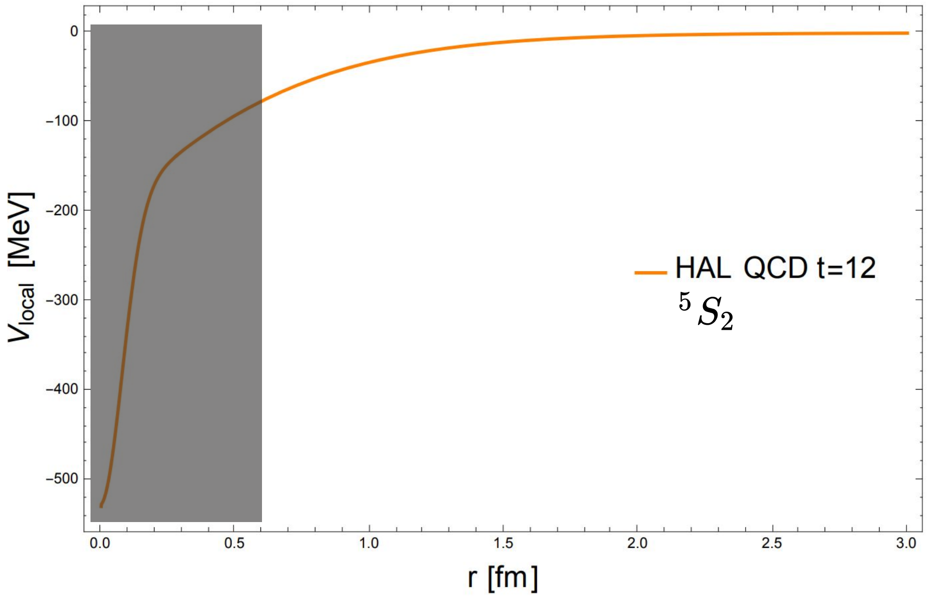

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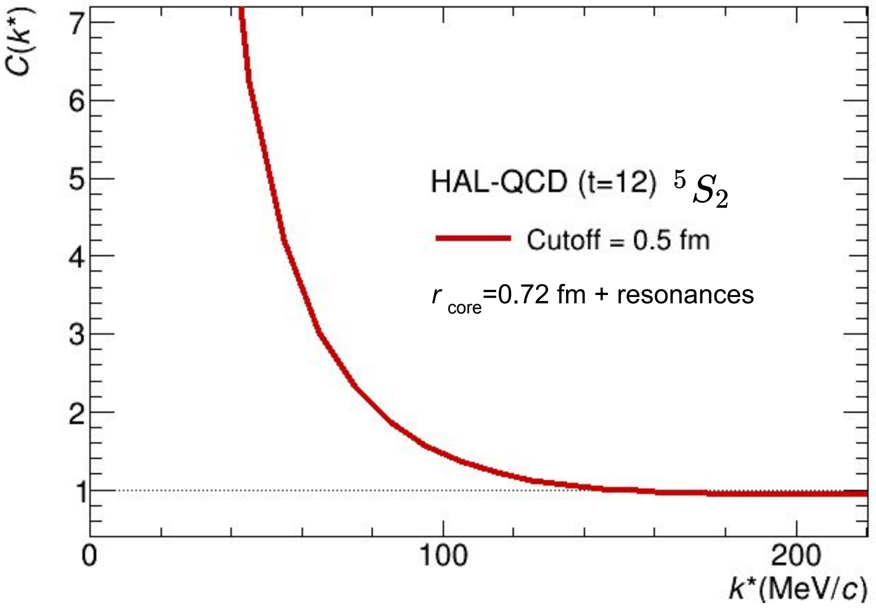
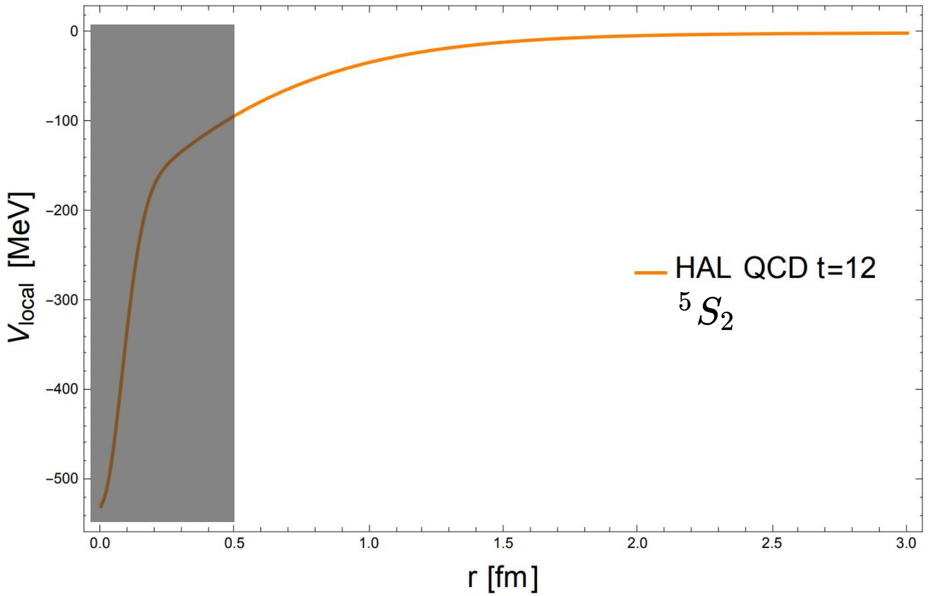
- HAL-QCD with physical quark masses (t=12): **maximum of the $C(k^*)$ for r_{cutoff} = 0.5 fm**





Correlation function ($^5S_2$) with distance cutoff

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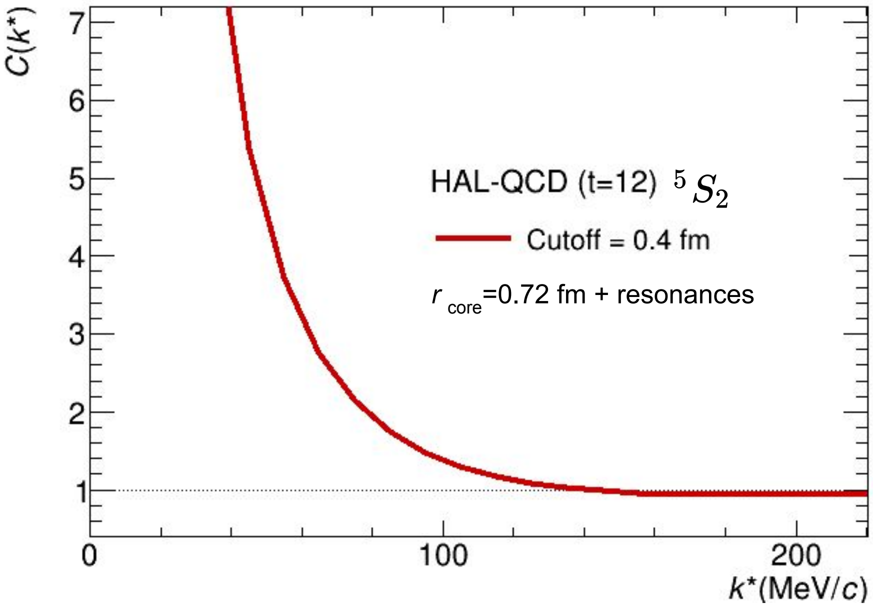

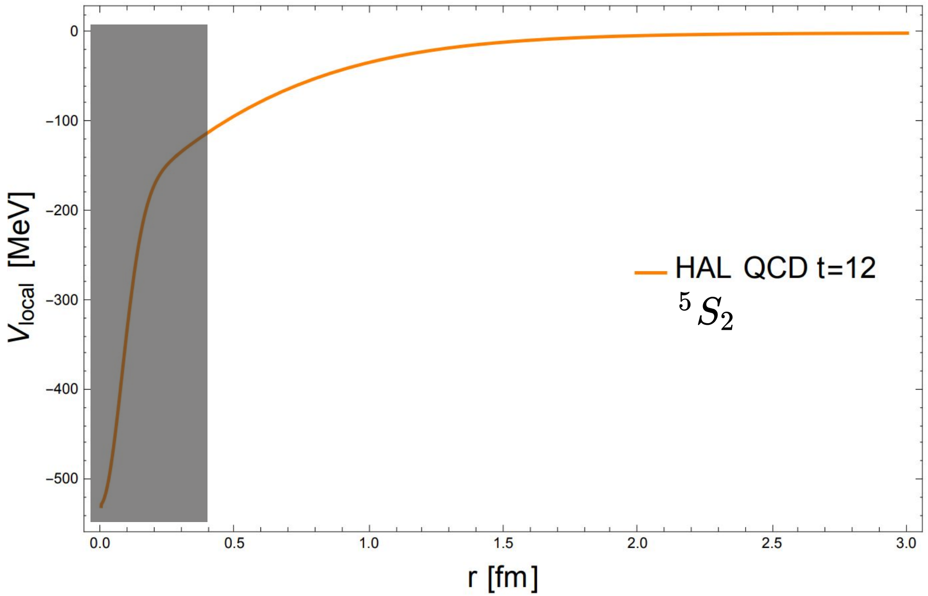

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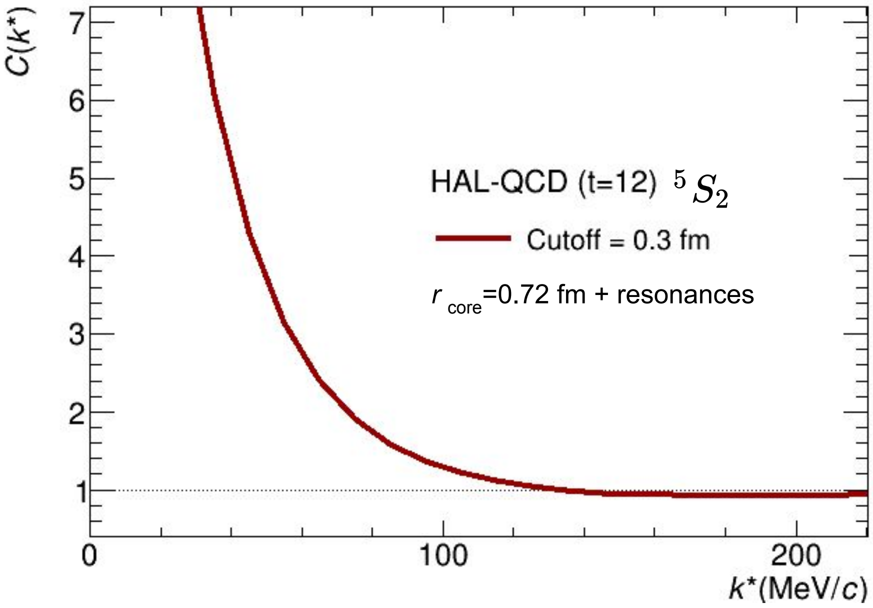

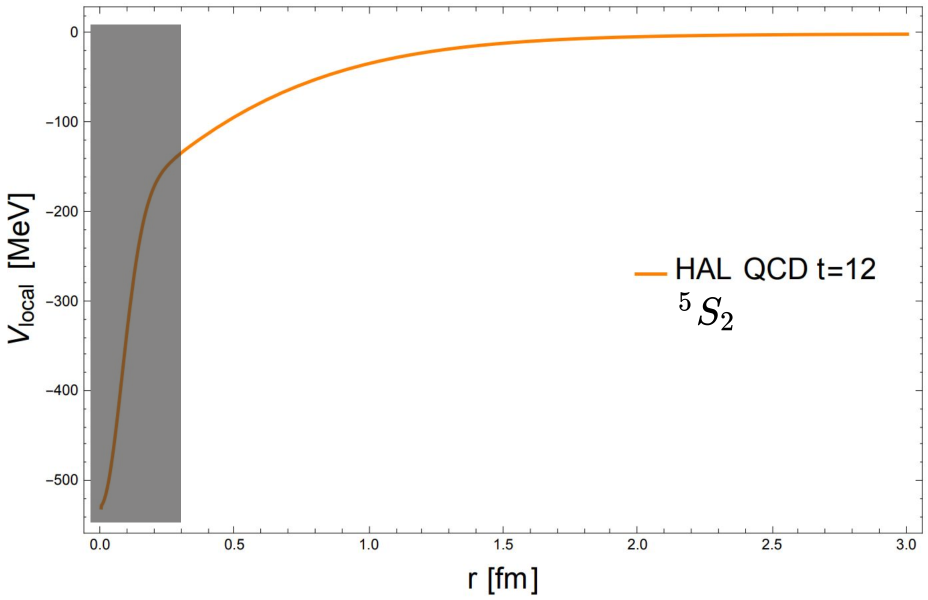

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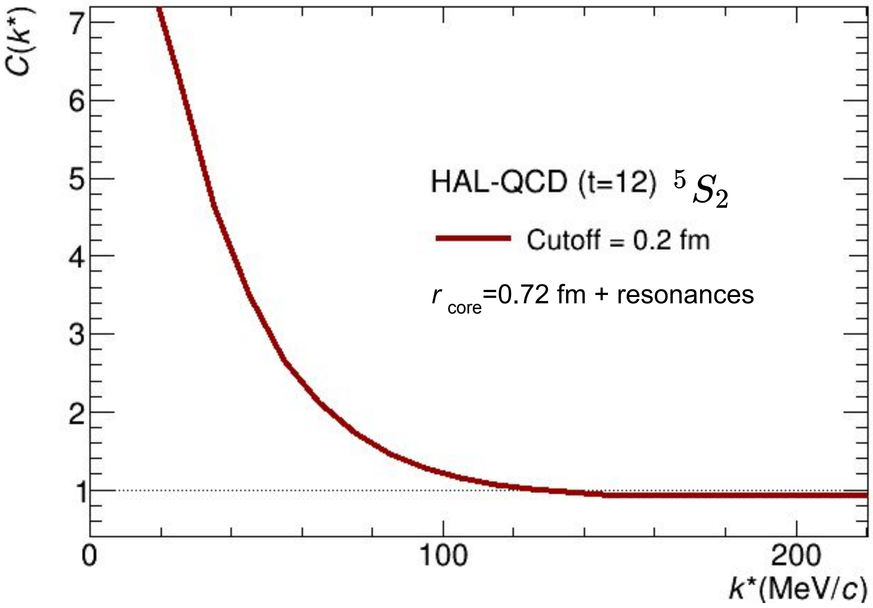

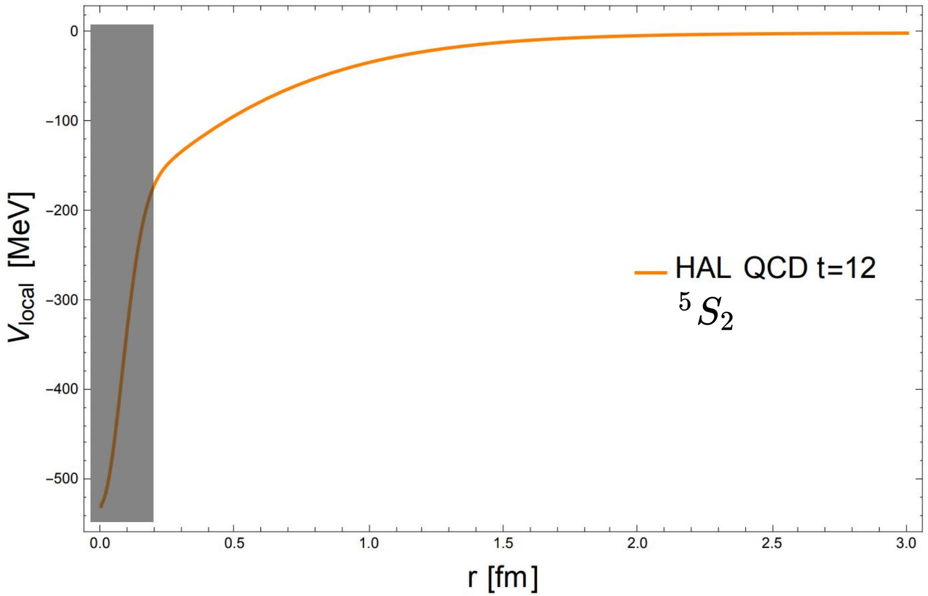

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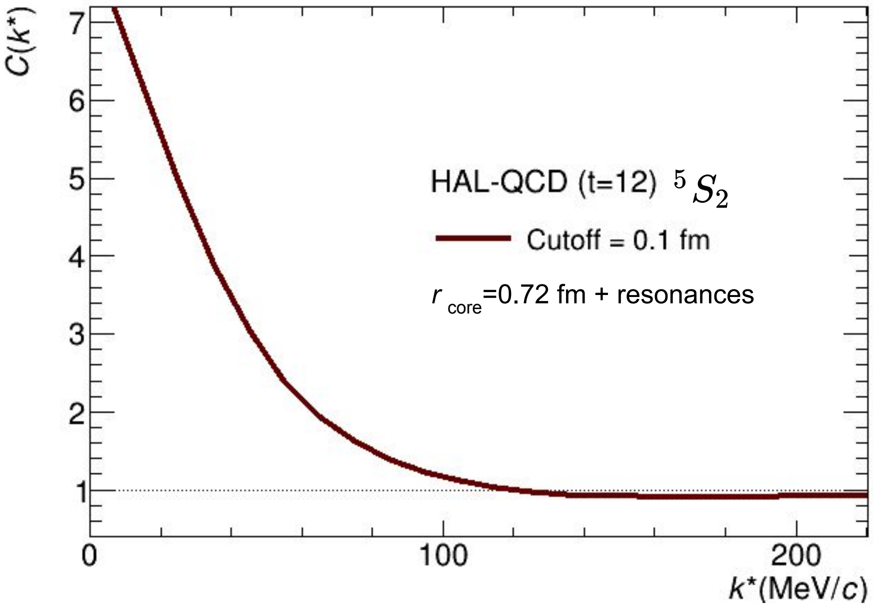

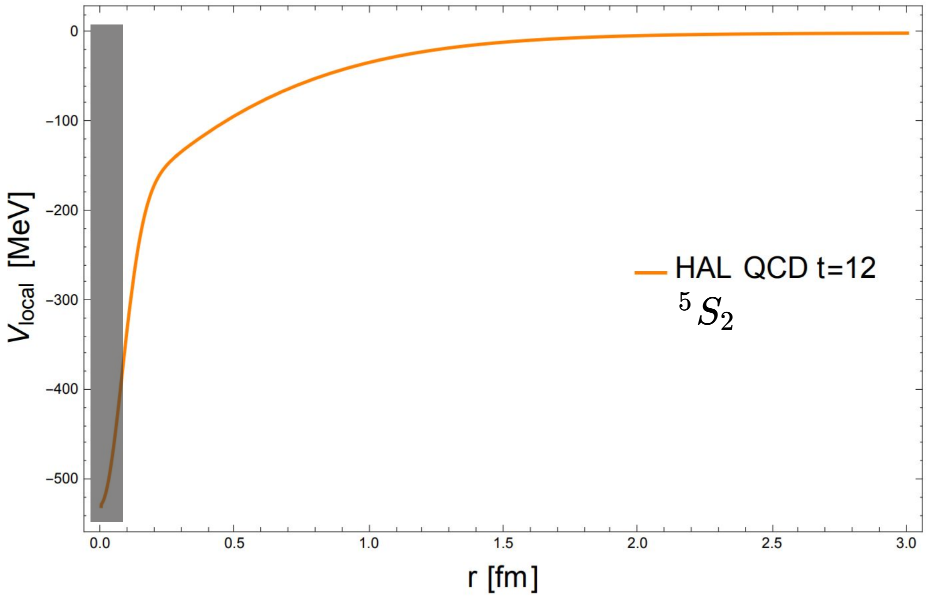

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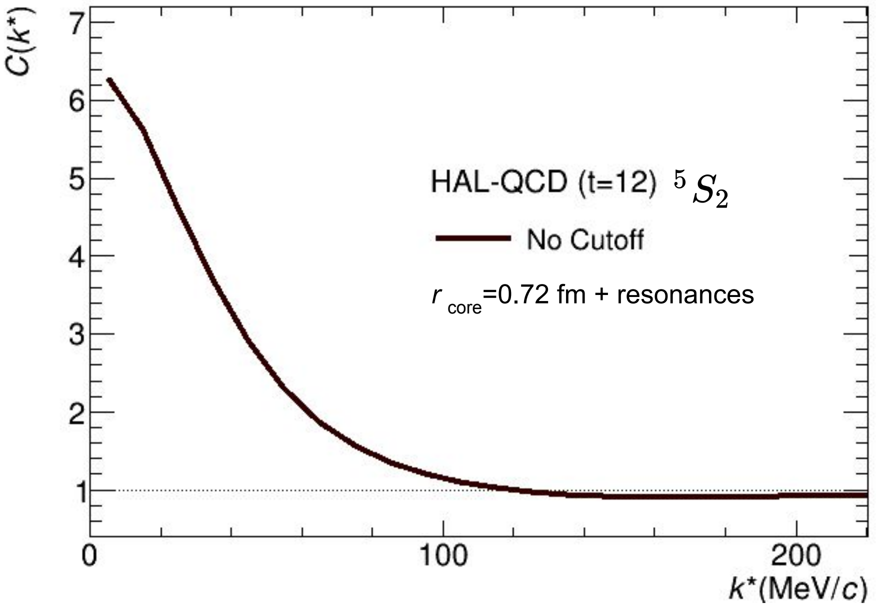

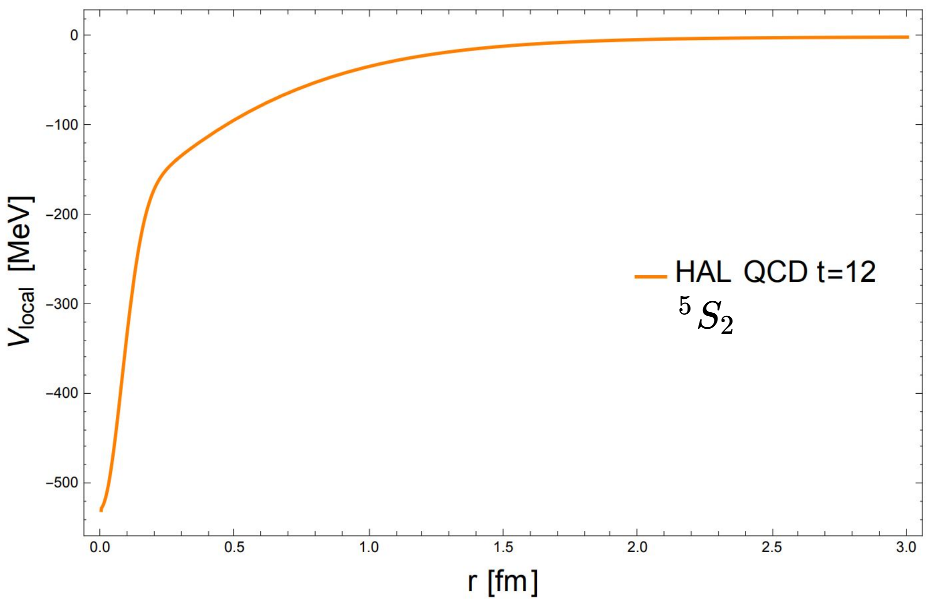

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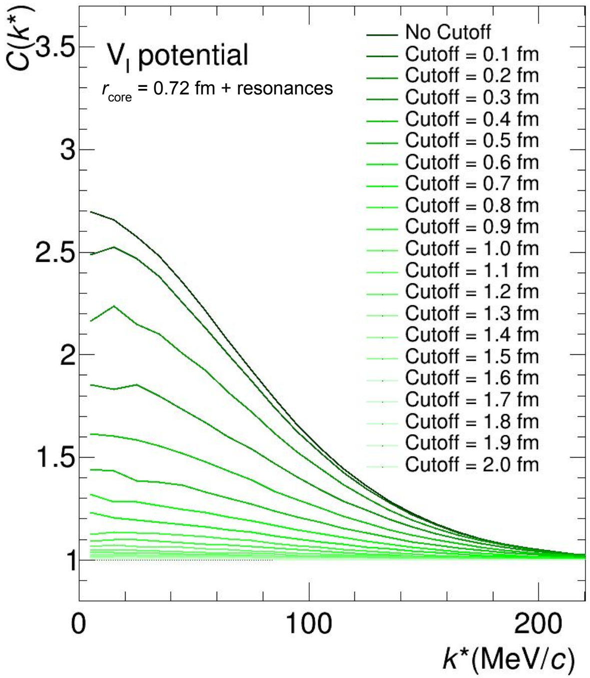
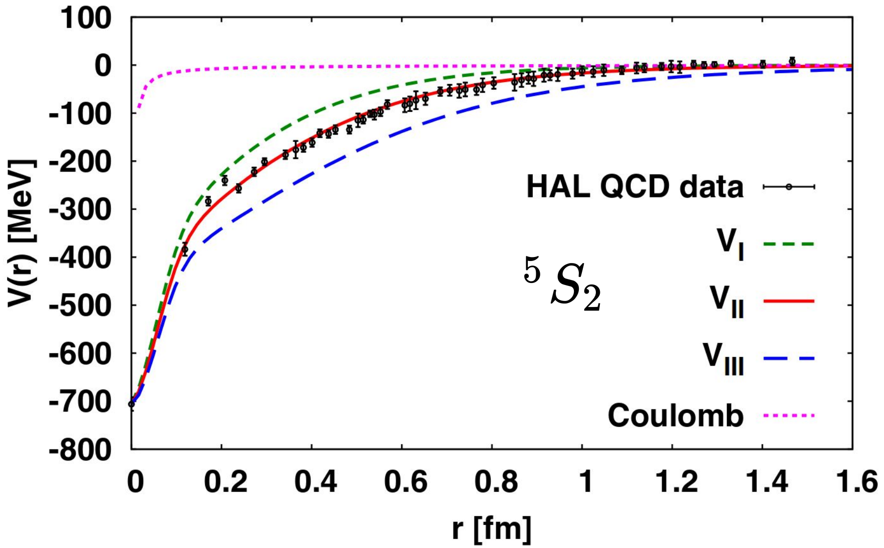
- For **VI potential (<u>no bound state</u>) *C*(*k**) always increases** with decreasing r_{cutoff}





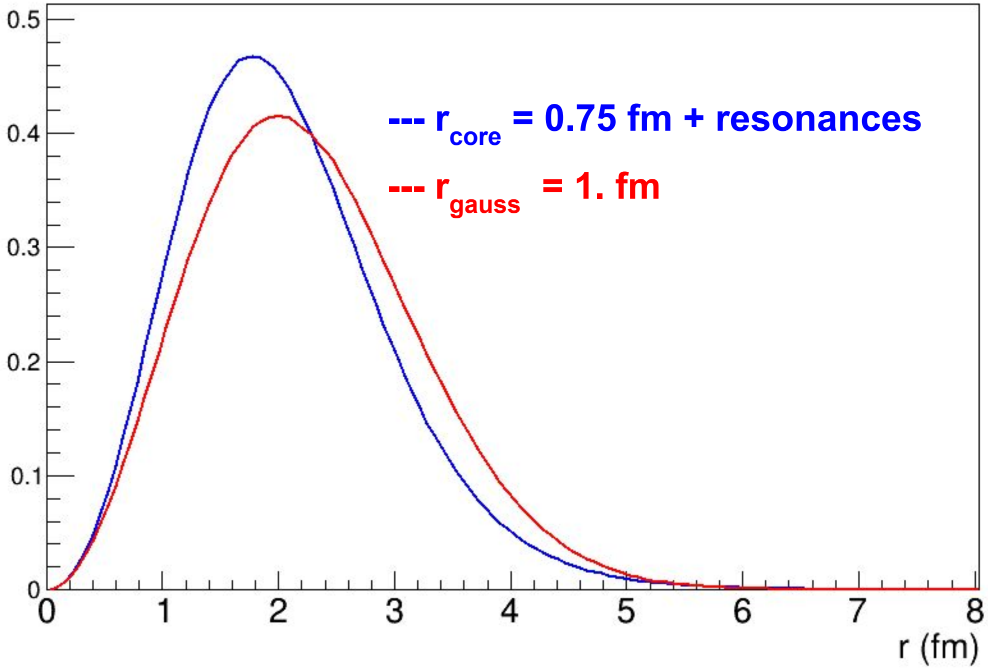
Summary

- ALICE delivers the first **precise data** to test the p-Ω interaction.
- The small source size of pp collisions and the high purity of the sample favor the sensitivity of ALICE data:
  - The comparison of the experimental C(k*) by ALICE with the expectation from the models is **very sensitive to the shape of the model potential**.
- The Coulomb-only hypothesis is excluded showing the **strong attractive character of the interaction.**
- Models predicting large binding energies for the NΩ di-baryon are **excluded** by ALICE data

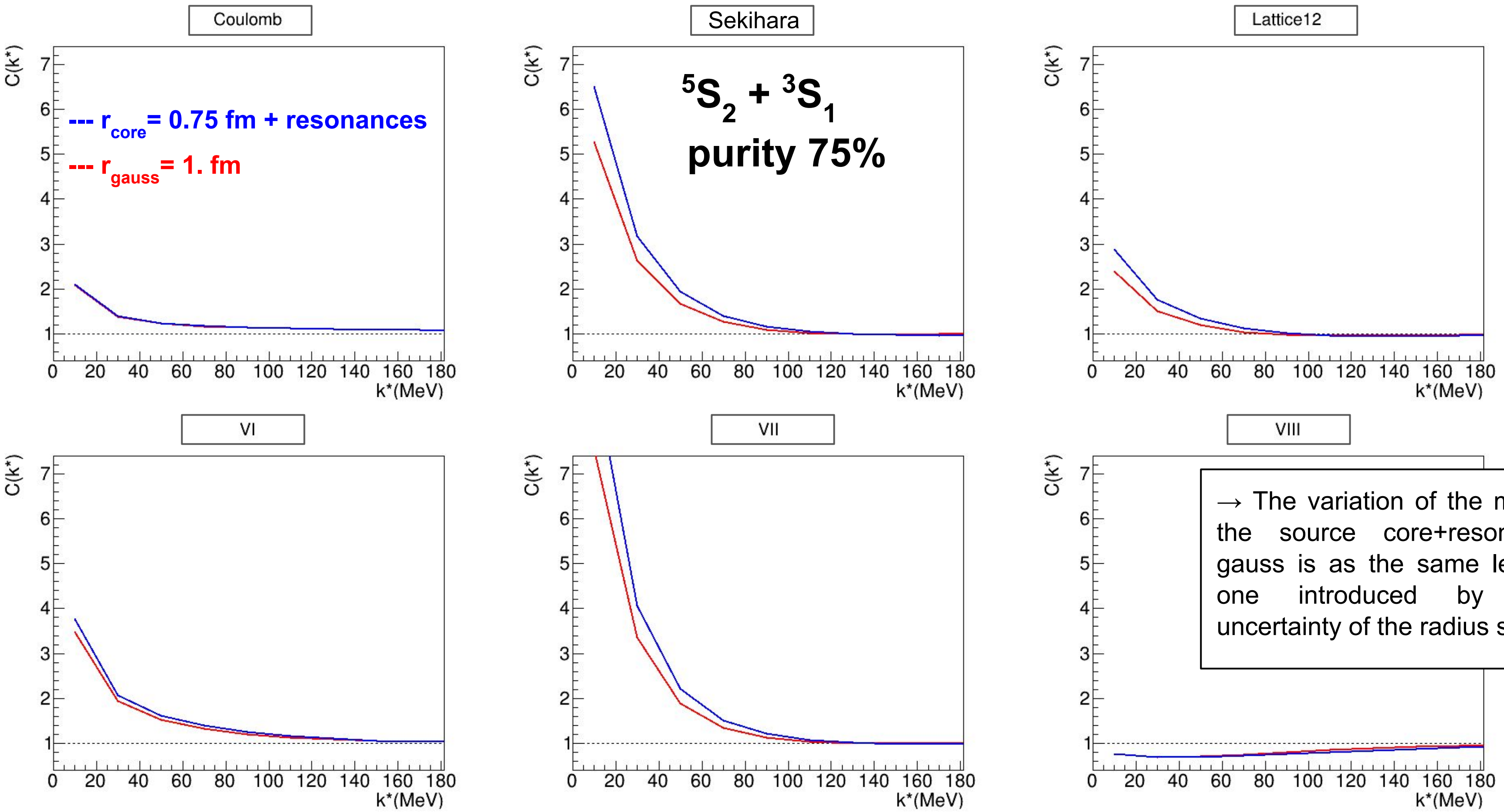
backup

p-Ω^- Correlation function: source dependence

- Comparison of the C(k*) for the different models for different source assumptions
- Size of the source determined from p-p fitted radius vs <m_T>
    - core gaussian source + resonances effects
    - pure gaussian source



p-Ω⁻ Correlation function: source dependence



→ The variation of the models with the source core+resonances vs gauss is as the same level as the one introduced by the the uncertainty of the radius size