First Experimental Evidence of an Attractive Proton-ϕ Interaction

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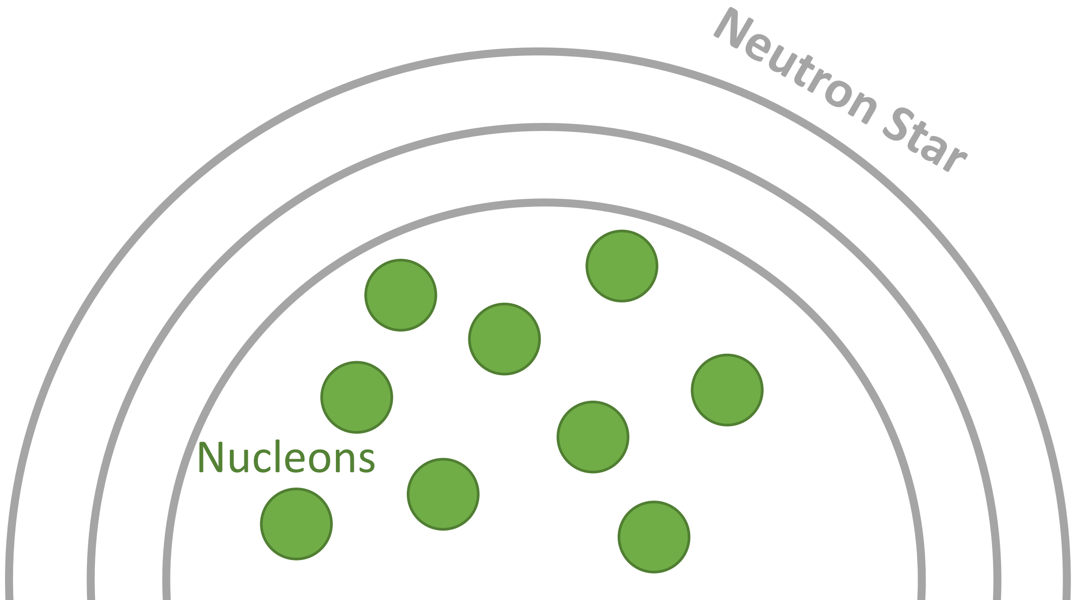
Technical University of Munich
IMPRS Recruiting Workshop
15/11/2021

Meson exchange

- Neutron stars
  - Equation of State (EoS) of dense hadronic matter depends on constituents and interactions among them



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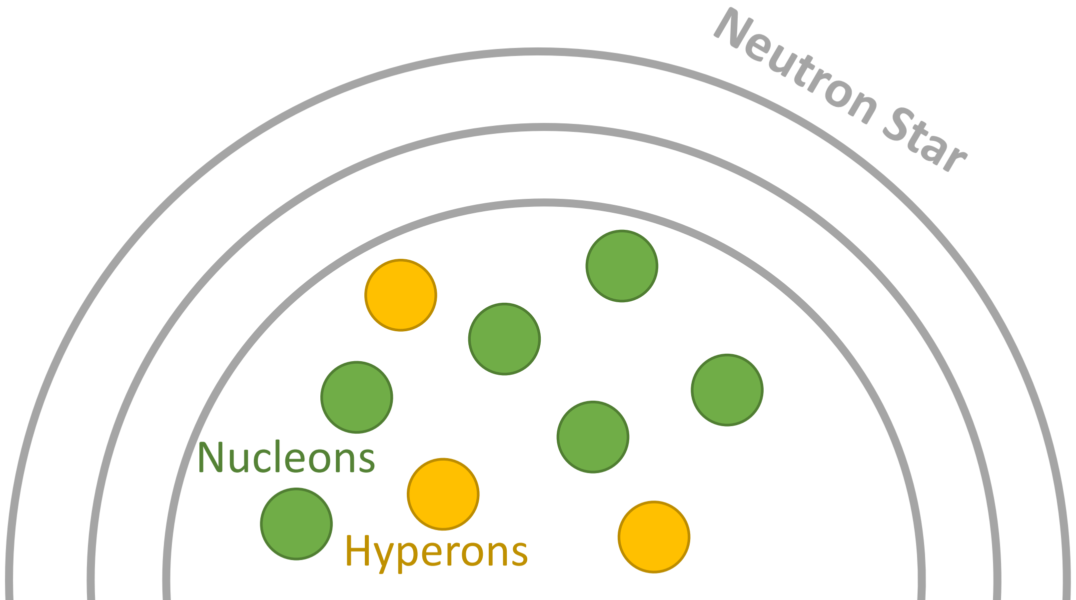
  - Hyperons might be present in core region (energetically favourable)



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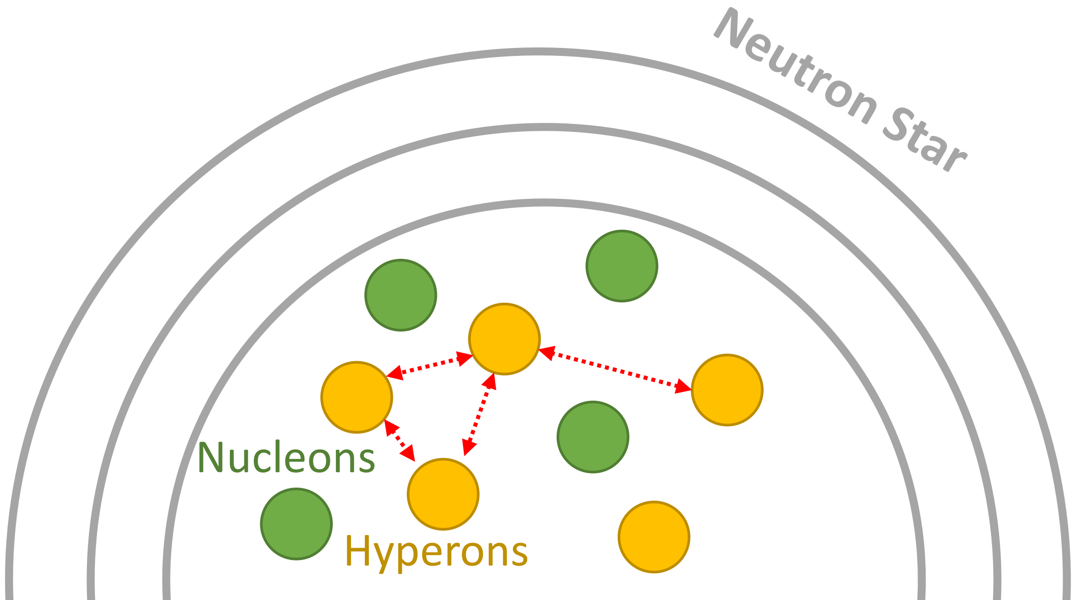
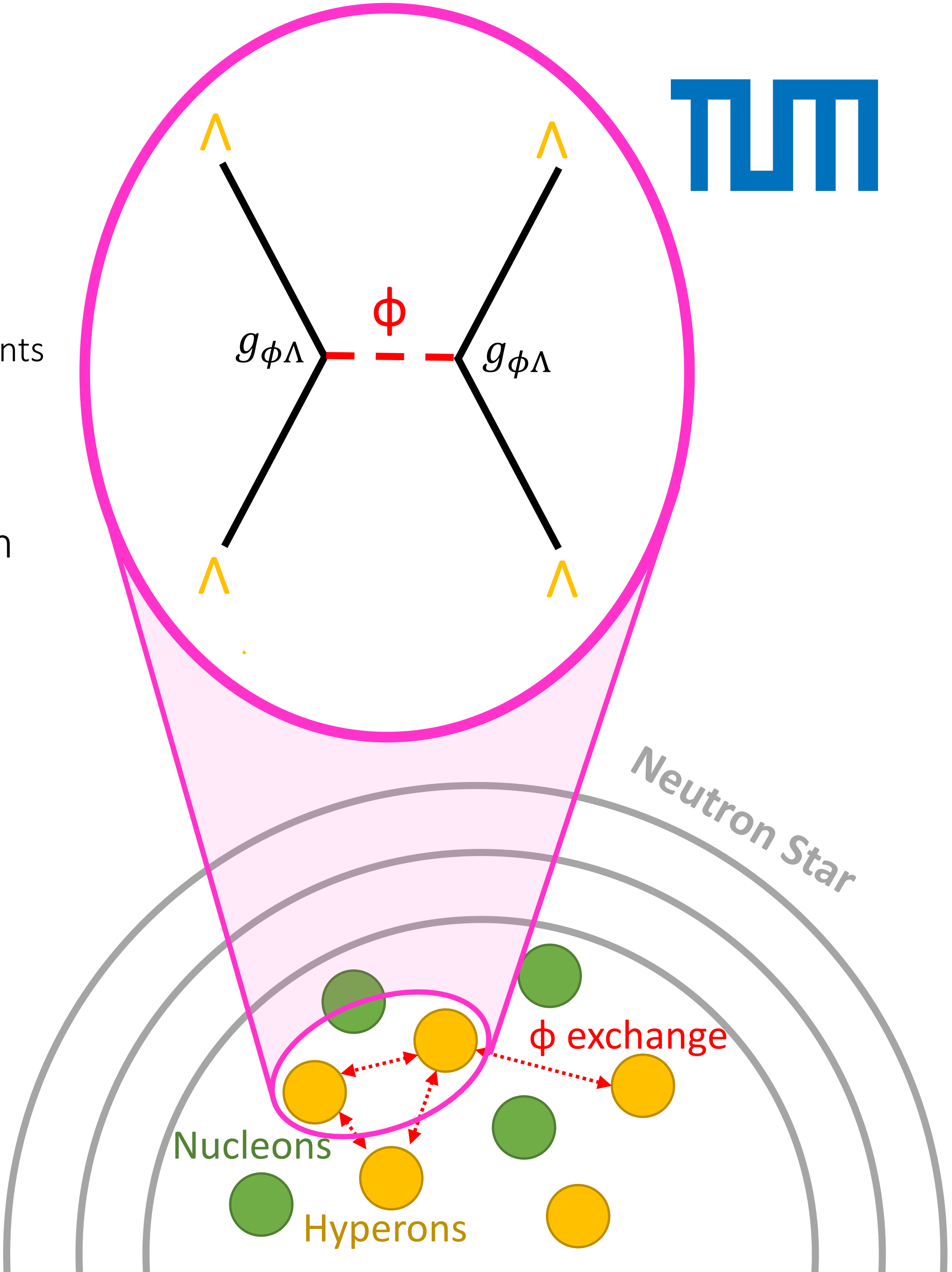


Meson exchange

- Neutron stars
  - Equation of State (EoS) of dense hadronic matter depends on constituents and interactions among them
  - Hyperons might be present in core region (energetically favourable)
- ϕ meson as mediator of the interaction among hyperons (Y) in neutron stars
- From theoretical calculations assuming SU(3) symmetry

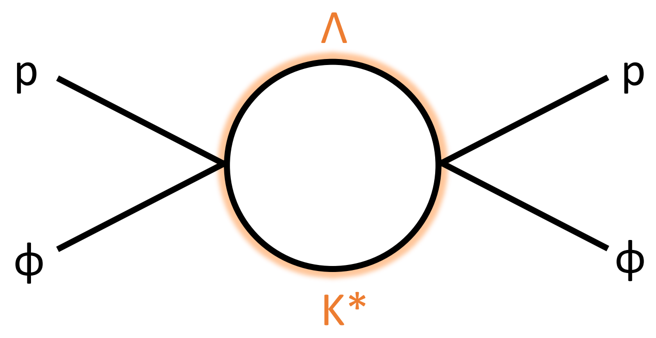
  $g_{\phi Y} \propto g_{\phi N}$

  S. Weissborn et al., *Nuclear Physics A*, **881** (2012) 62-77

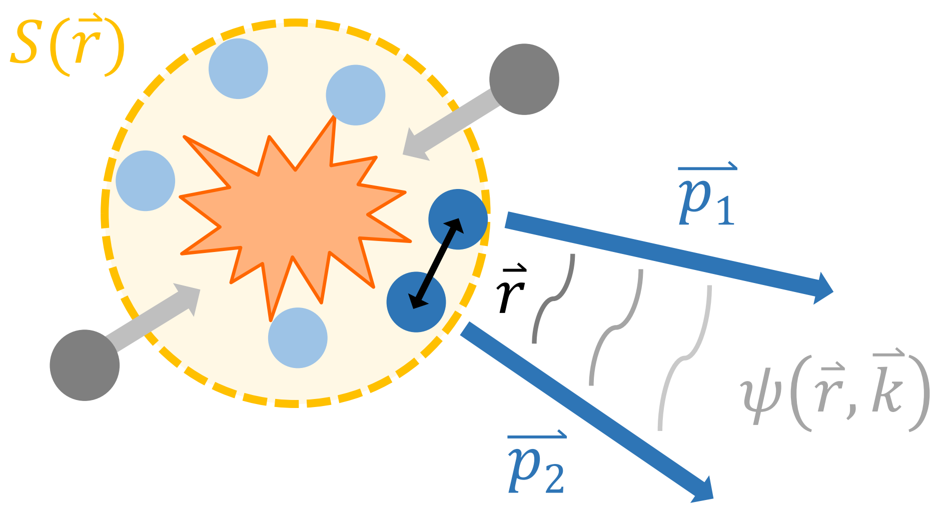


Genuine p–ϕ interaction

- Relevant for hadronic models used to describe ϕ-meson properties within nuclear medium
- Expected to be suppressed by OZI rule
  - Hinders processed with disconnected quark lines
- Interaction might be mediated via channel coupling
  Phys. Rev. C **96** (2019) 034618, *Phys. Rev. C* **95** (2017) 015201
- Experimental method needed to measure the interaction



Correlation function



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

experimental definition

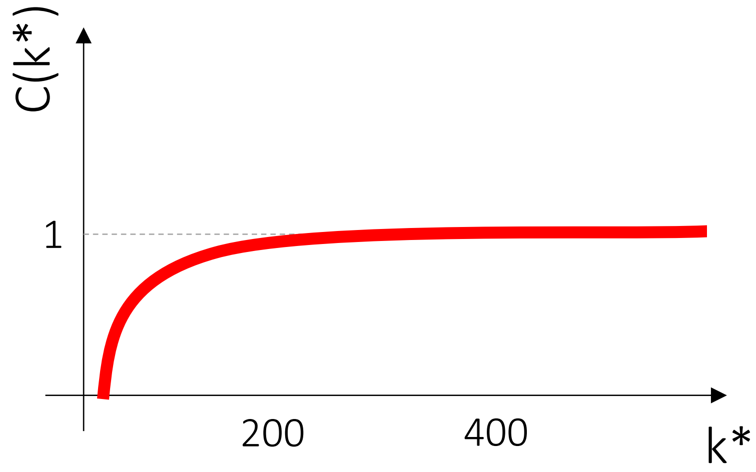
theoretical definition

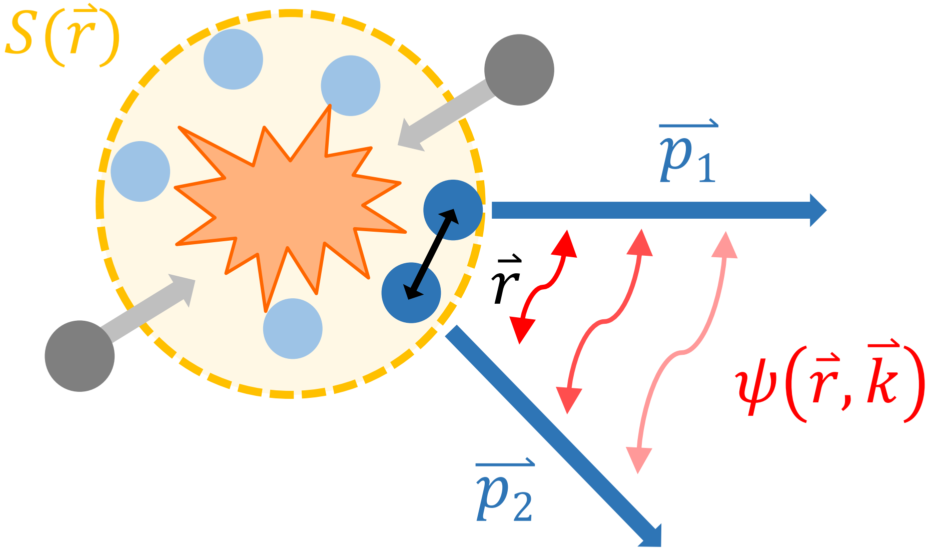
S. Pratt, *Phys. Rev. C* **56** (1997) 1095
S.E. Koonin, *Phys. Rev. B* **70** (1977) 43

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

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

Correlation function





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repulsion

experimental definition

theoretical definition

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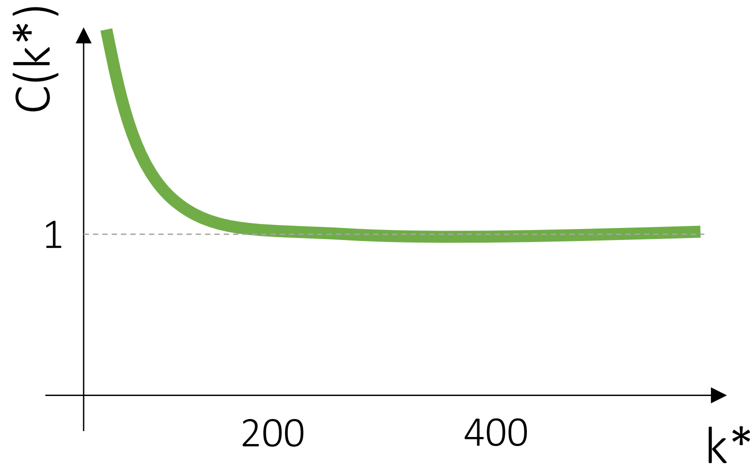
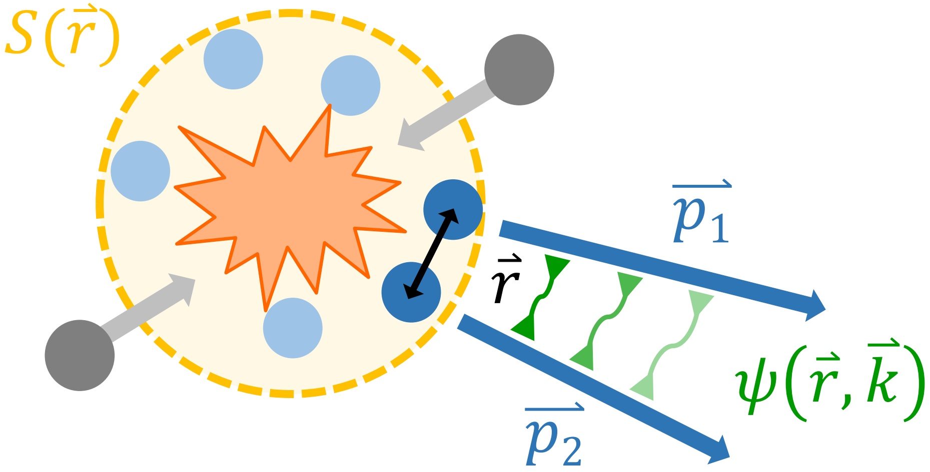
Correlation function





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attraction

experimental definition

theoretical definition

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S.E. Koonin, *Phys. Rev. B* **70** (1977) 43

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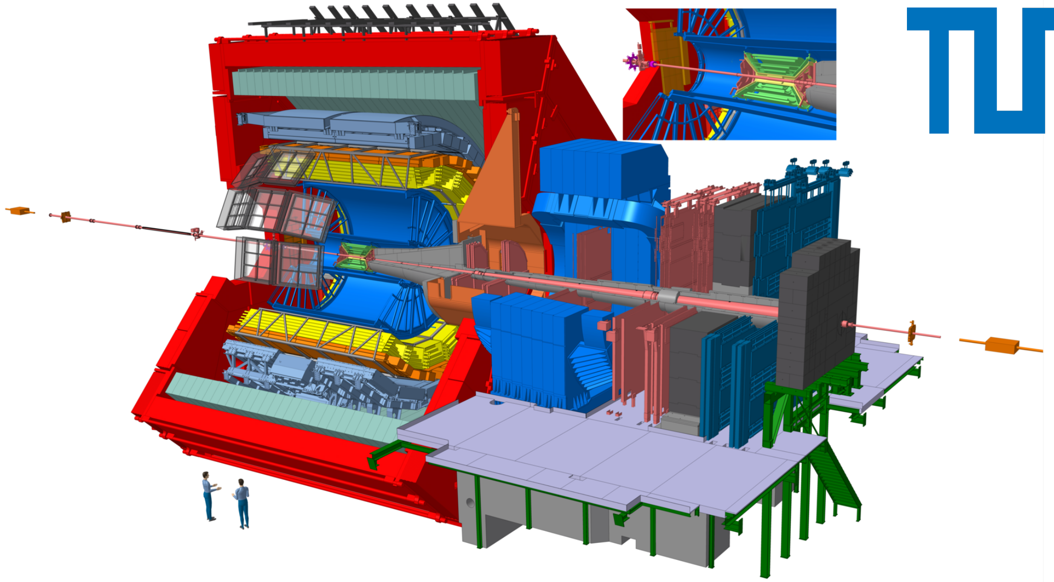
Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

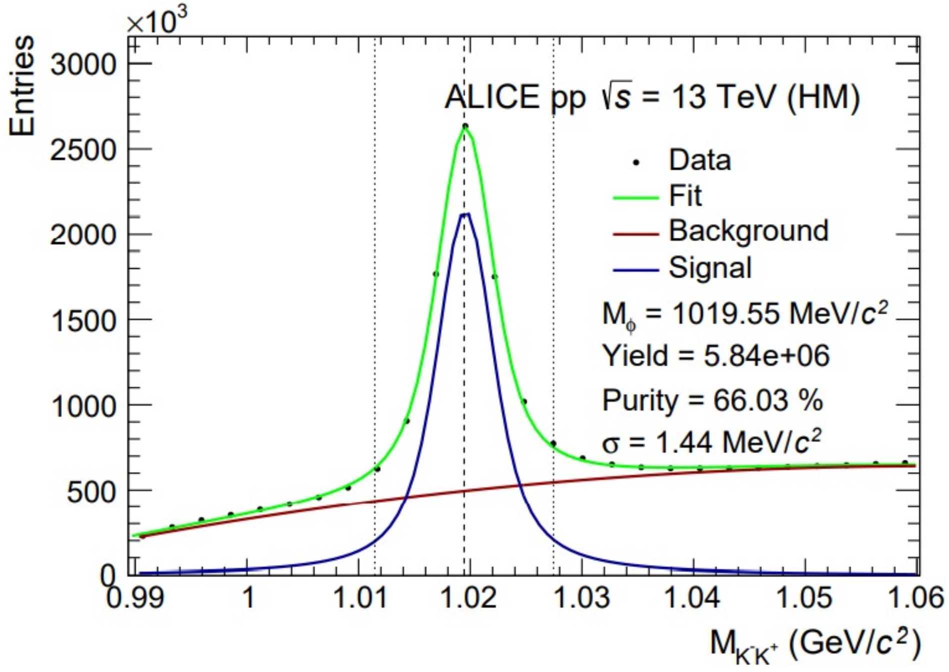
Analysis

- High-multiplicity (HM) pp collisions at √s = 13 TeV
- Particle identification with ALICE Detector
  - Proton detected directly
    - Proton purity of 99%

      ALICE Collab., *Phys. Lett B* **811** (2020) 135849
  - ϕ candidates reconstructed from $\phi \to K^+K^-$
    - Purity of 66%

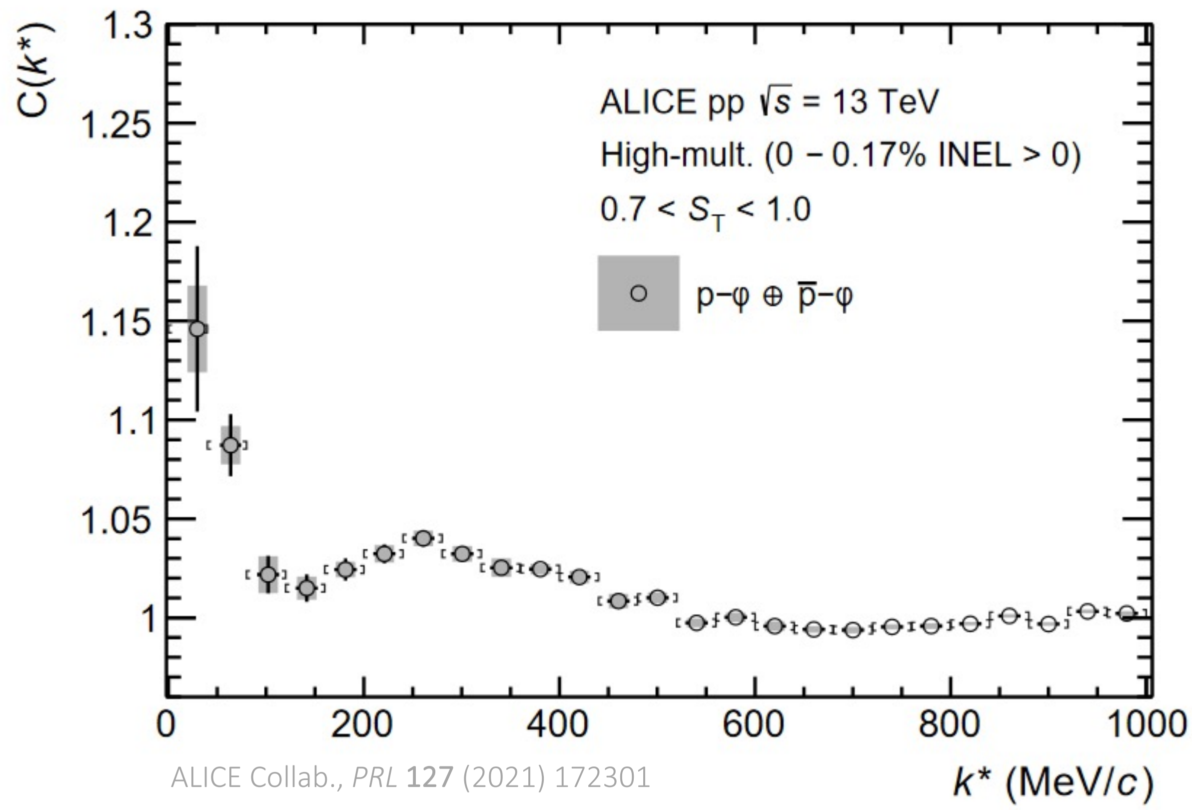


https://alice-figure.web.cern.ch/node/11219



CF model

$$C_{exp}(k^*) = C_{femto}(k^*) \cdot C_{non-femto}(k^*)$$



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

CF model

$$C_{femto}(k^*) = \sum \lambda_{ij} \cdot C_{ij}(k^*)$$

$$C_{exp}(k^*) = C_{femto}(k^*) \cdot C_{non-femto}(k^*)$$

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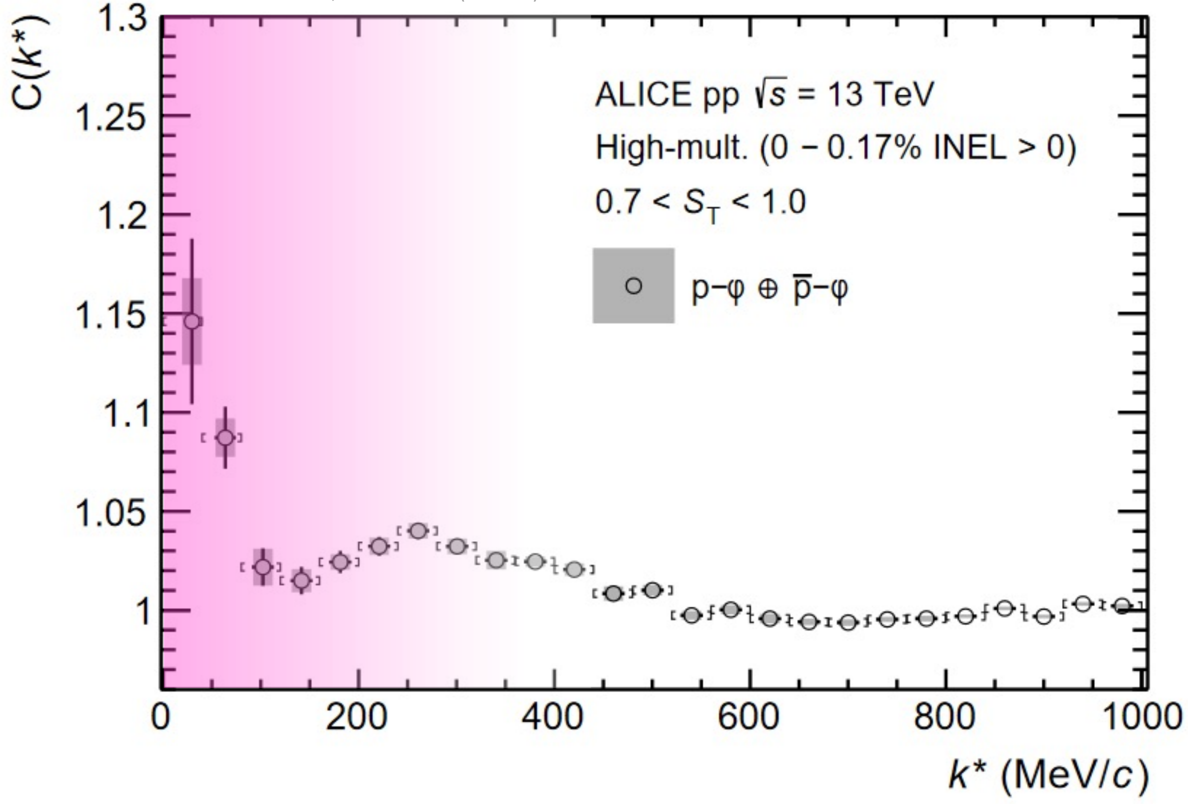

<u>Contributions from FSI</u> (femto) quantified by purity ($\mathcal{P}_i$) and feed-down fractions (f_i) via $\lambda_{ij} = \mathcal{P}_1 \cdot f_{i_1} \cdot \mathcal{P}_2 \cdot f_{j_2}$

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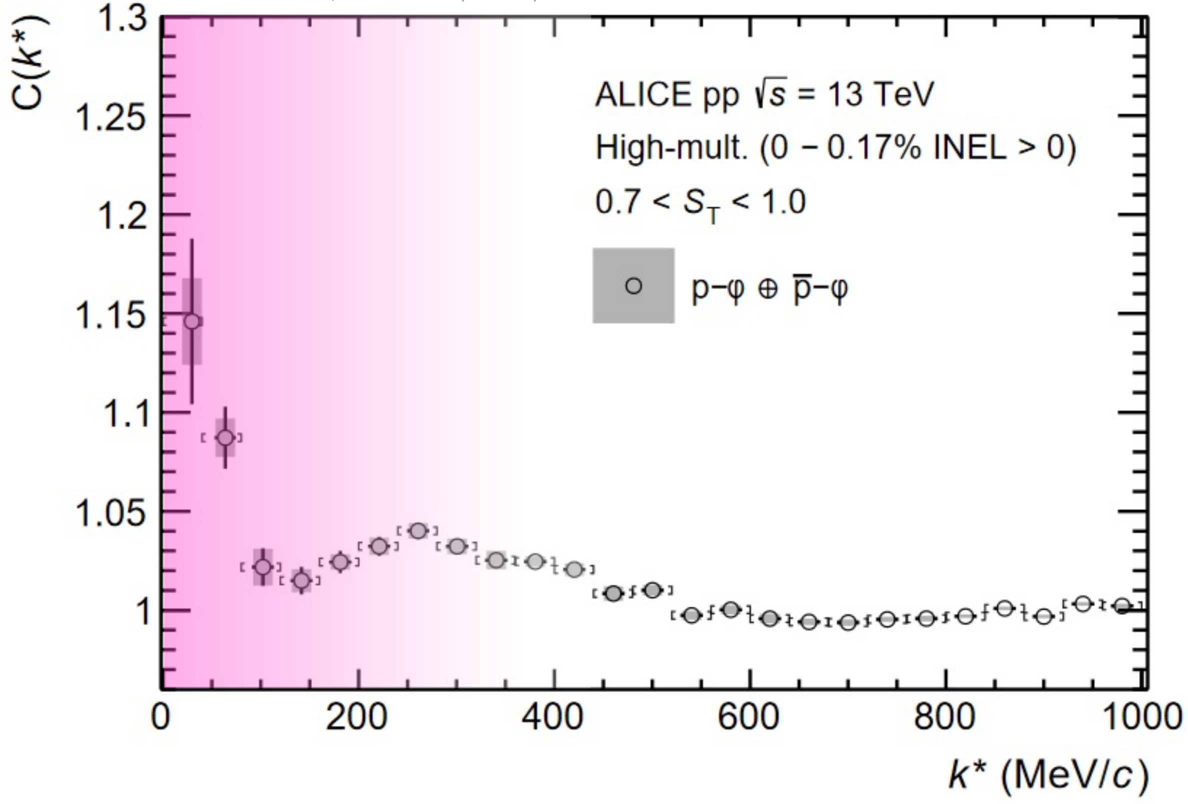

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- Genuine p–ϕ (46.3%)
- Flat contribution from misidentified and secondary protons (10.4%)
- Combinatorial background from misidentified ϕ mesons (43.3%)

CF model

$$C_{exp}(k^*) = C_{femto}(k^*) \cdot C_{non-femto}(k^*)$$

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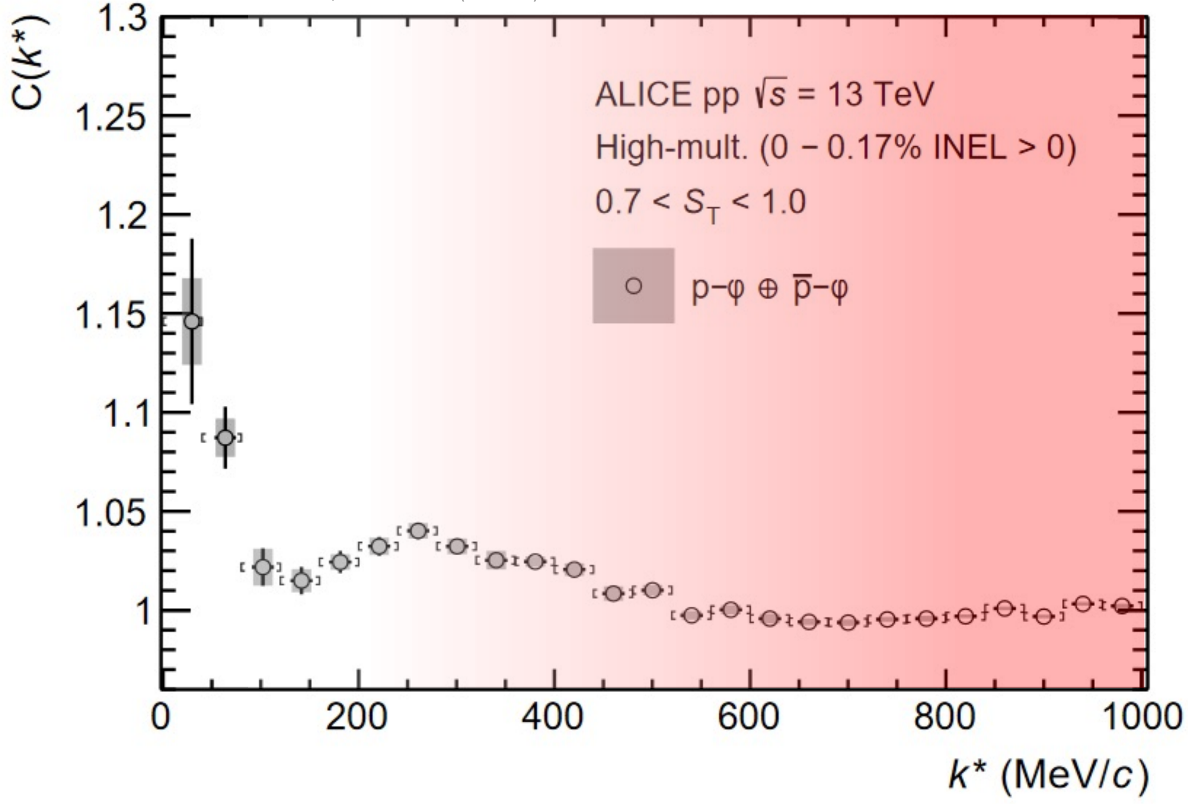
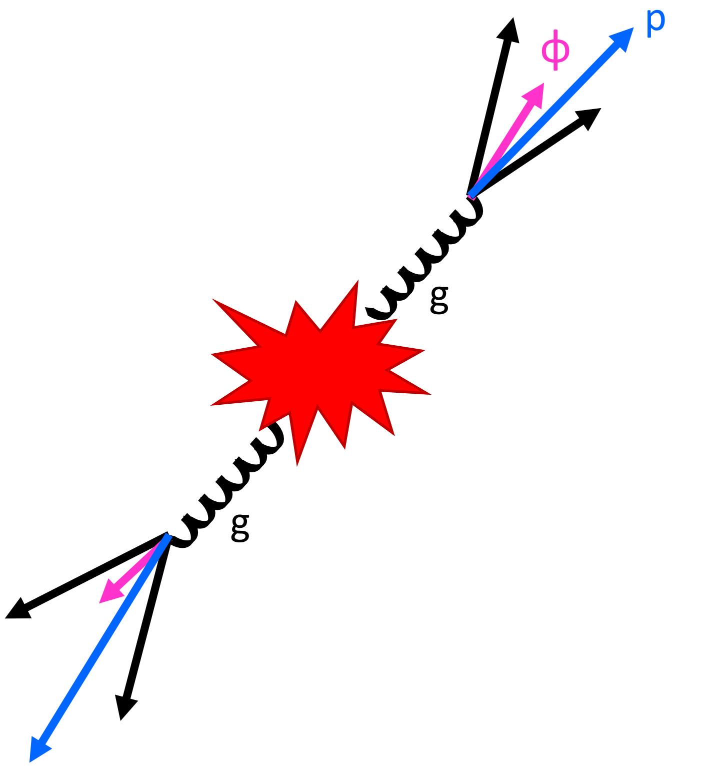


__Background__ (non-femto)

- auto-correlations (minijets)
- energy-momentum conservation effects

Minijets

- Present in previous meson-meson and meson-baryon analyses
  ALICE Collab. Phys. Rev. Lett. **124** (2020) 092301
- Auto-correlated p and ϕ emitted in jet-like structures
- Well described by Pythia 8
  ALICE Collab., *Phys. Rev. D* **84** (2011) 112004



Non-femtoscopic background

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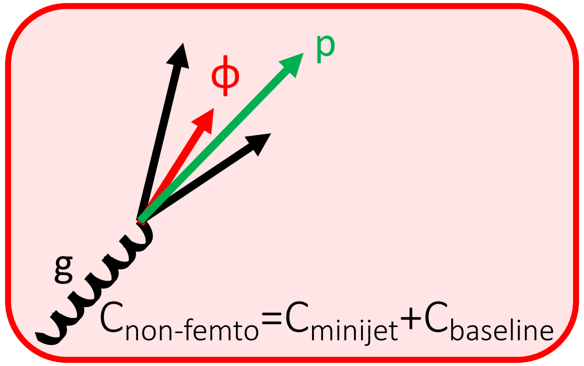
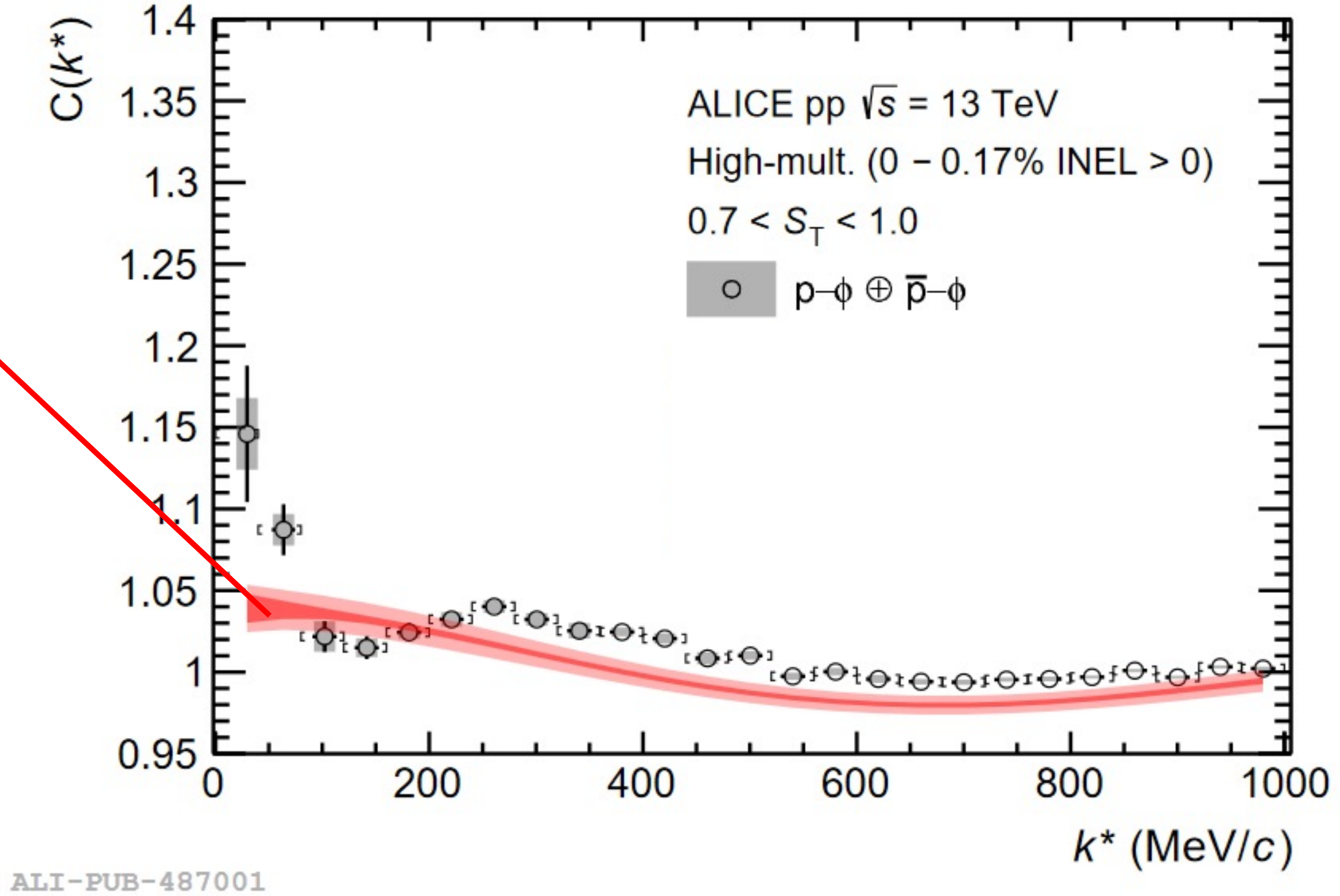
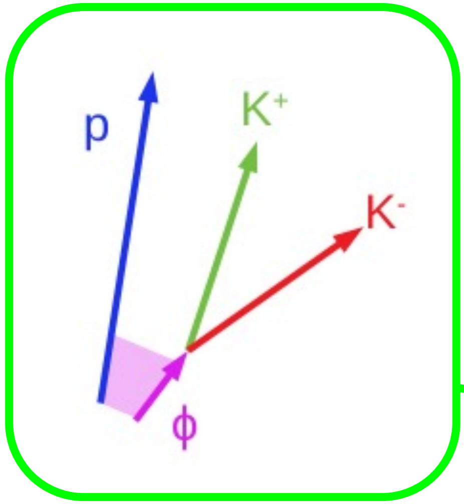
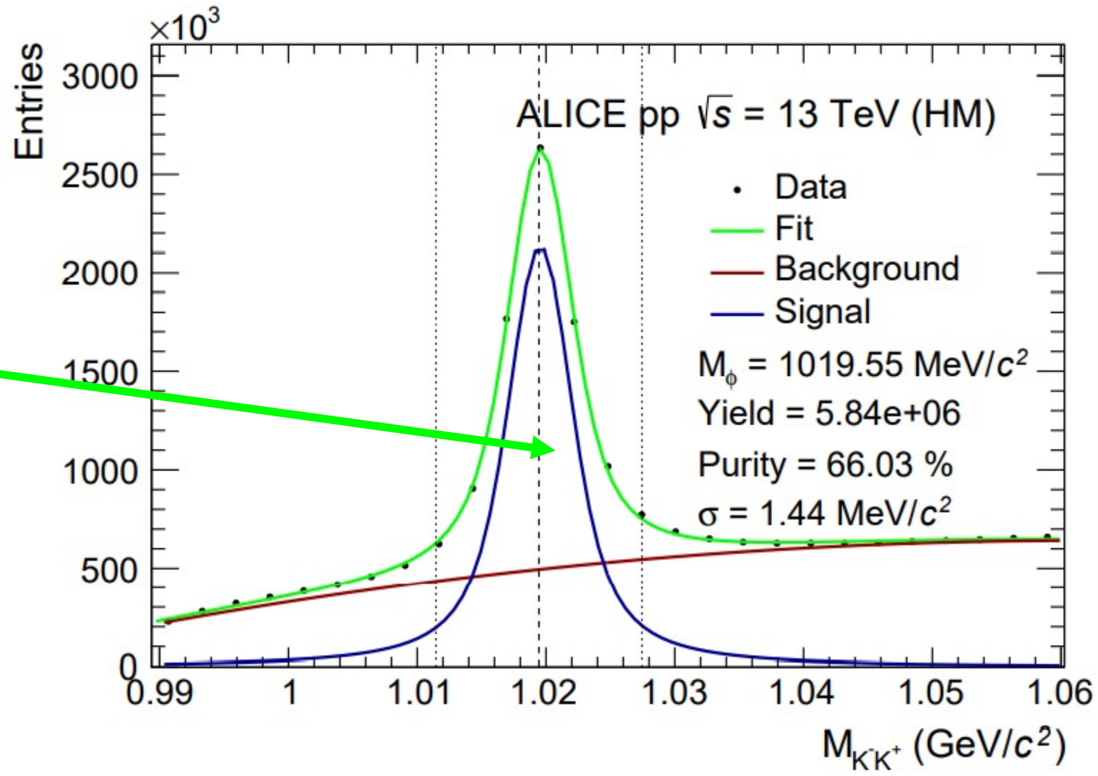




Combinatorial p-K^+K^- background

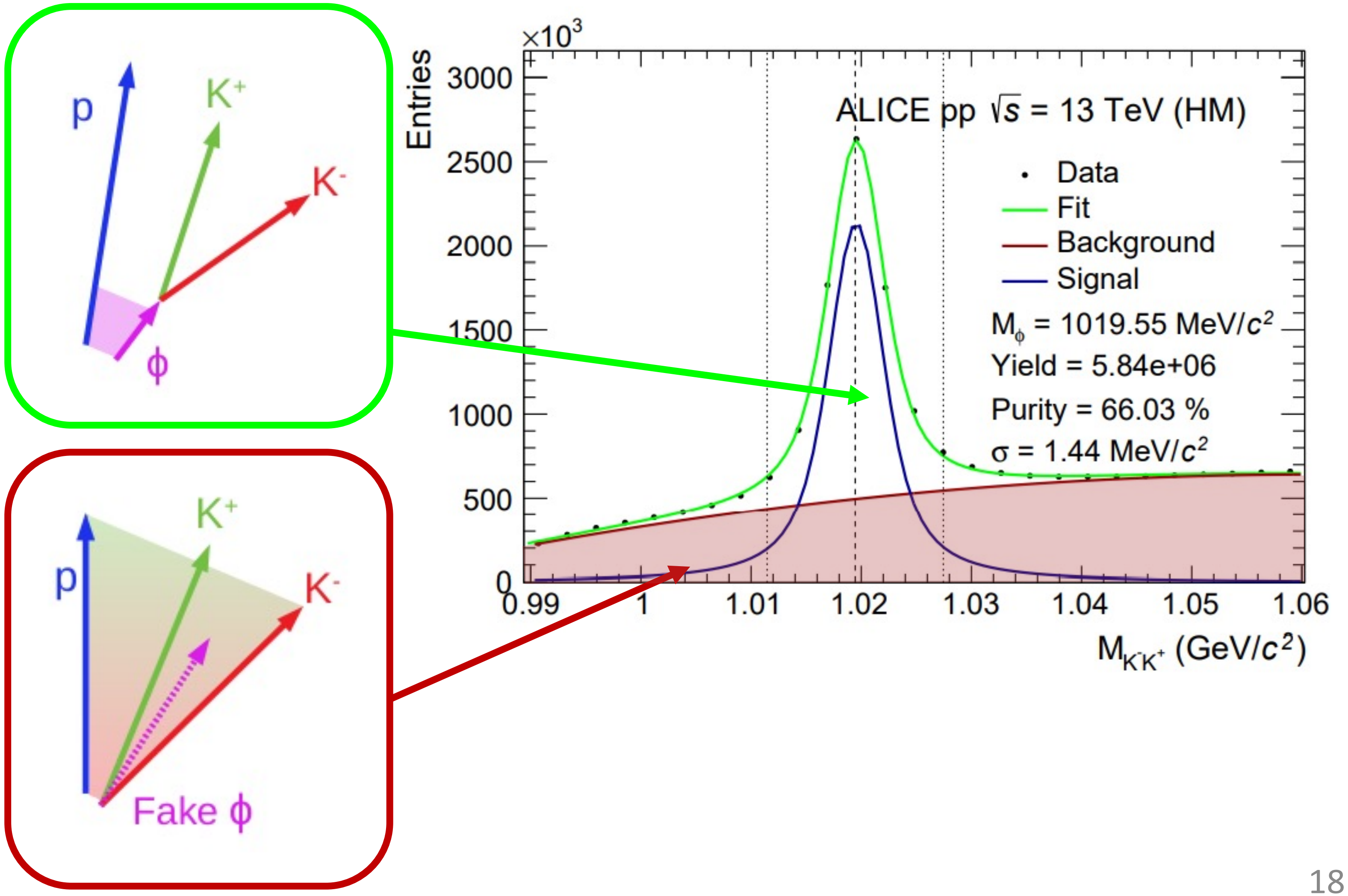
- ϕ candidates reconstructed via invariant mass of K^+K^-





Combinatorial p-K^+K^- background

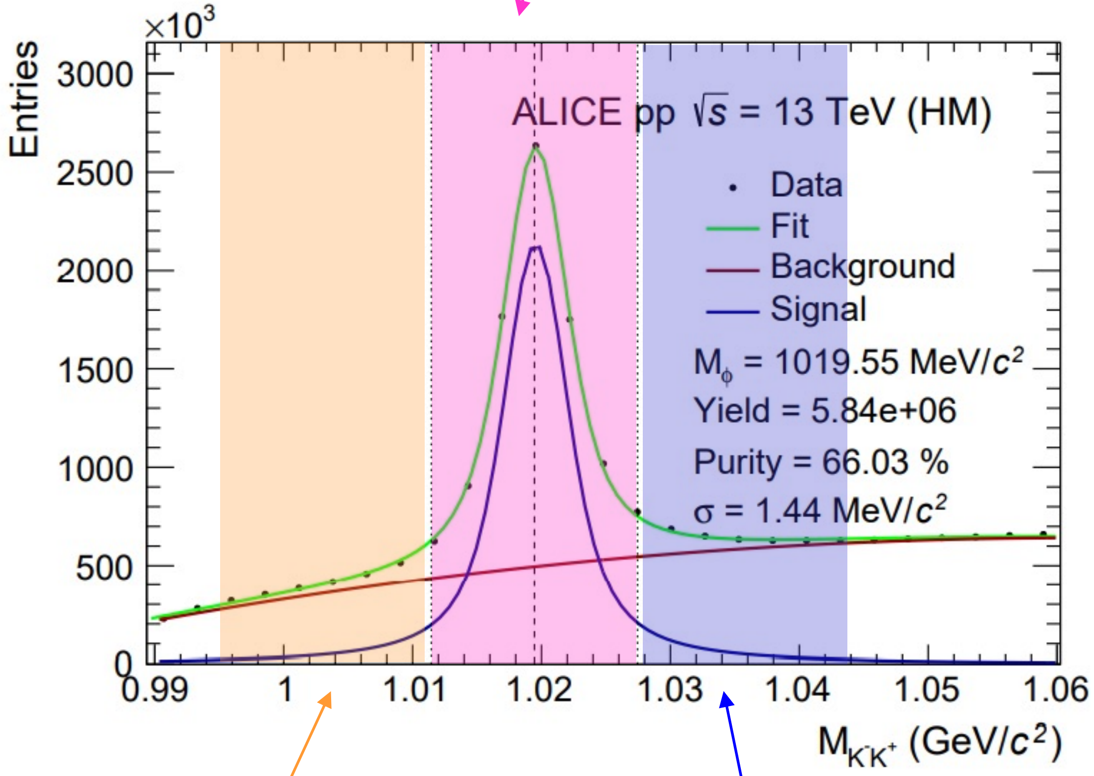
- ϕ candidates reconstructed via invariant mass of K^+K^-
- Finite purity of reconstructed ϕ → correlation signal from 2-body interaction between p, K^+ and K^-



Combinatorial p-K^+K^- background

- ϕ candidates reconstructed via invariant mass of K^+K^-
- Finite purity of reconstructed ϕ → correlation signal from 2-body interaction between p, K^+ and K^-
- Accessed by sideband analysis

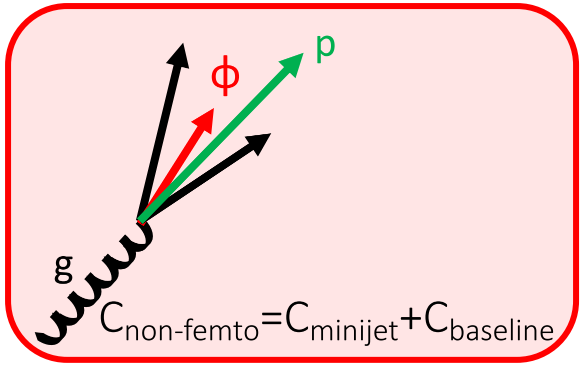
Phi Peak: $M_\phi \pm 8$ MeV/c^2

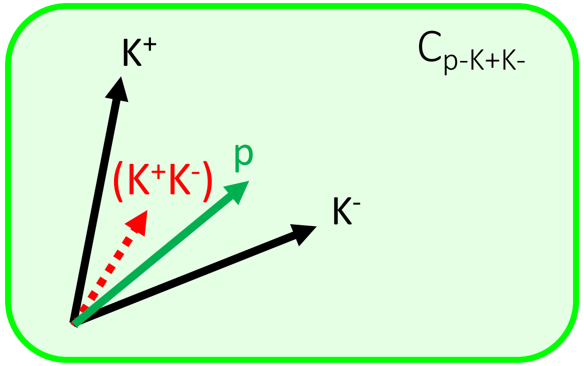


Left SB: 0.995-1.011 GeV/c^2

Right SB: 1.028-1.044 GeV/c^2

Combinatorial p-K⁺K⁻ background





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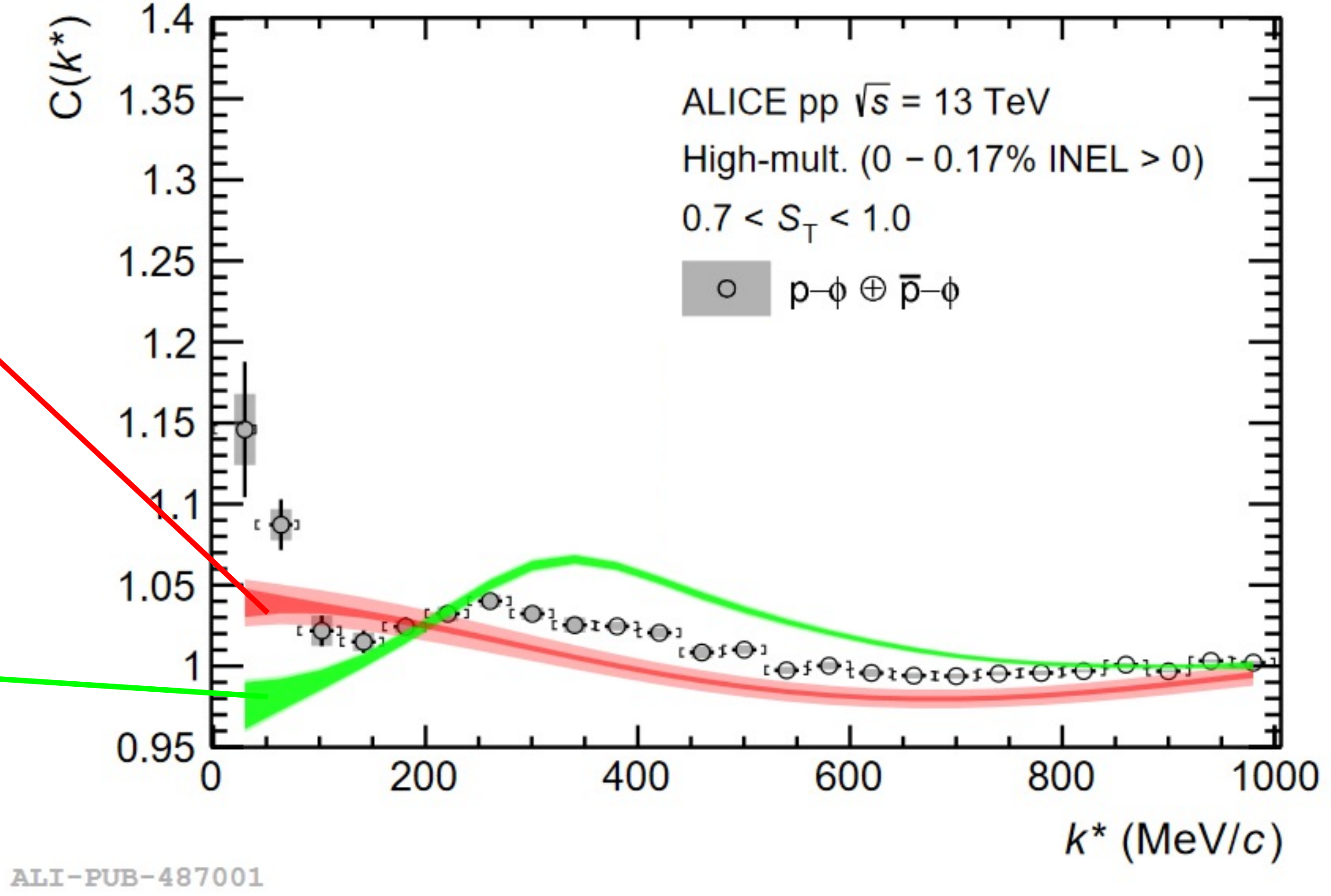
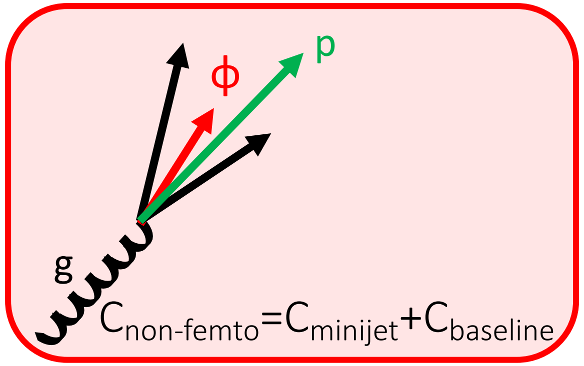
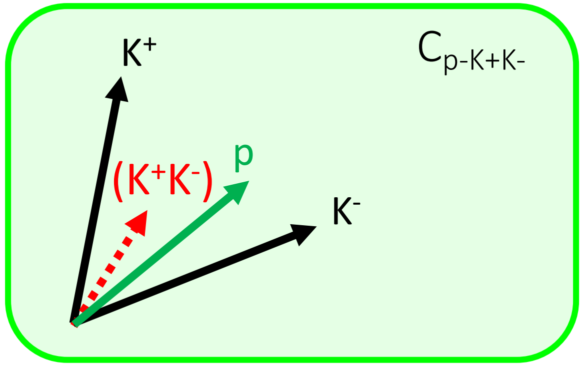


Total Background





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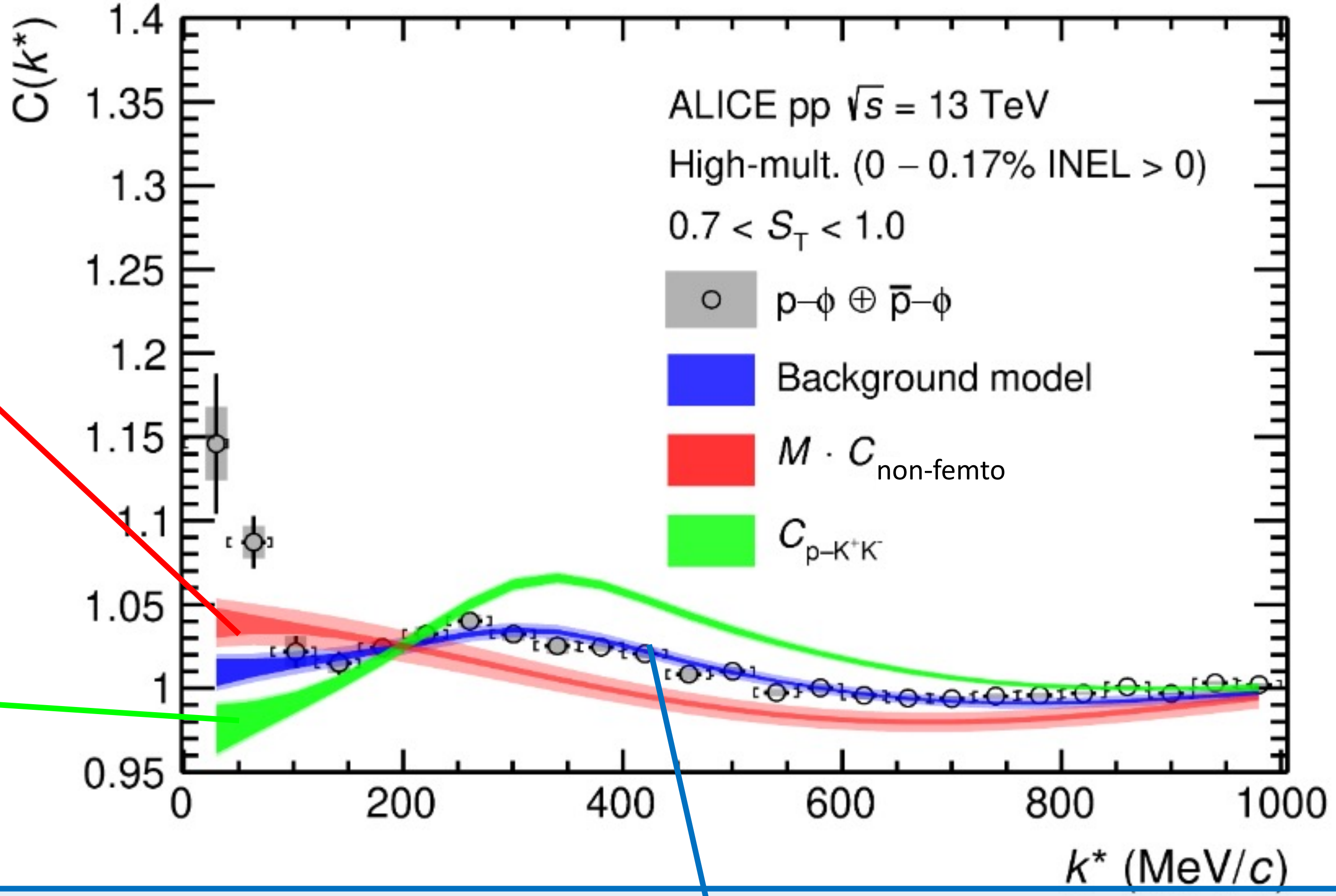

Combine contributions to get description of **total background**, used to derive genuine p–ϕ CF

Results p–ϕ

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

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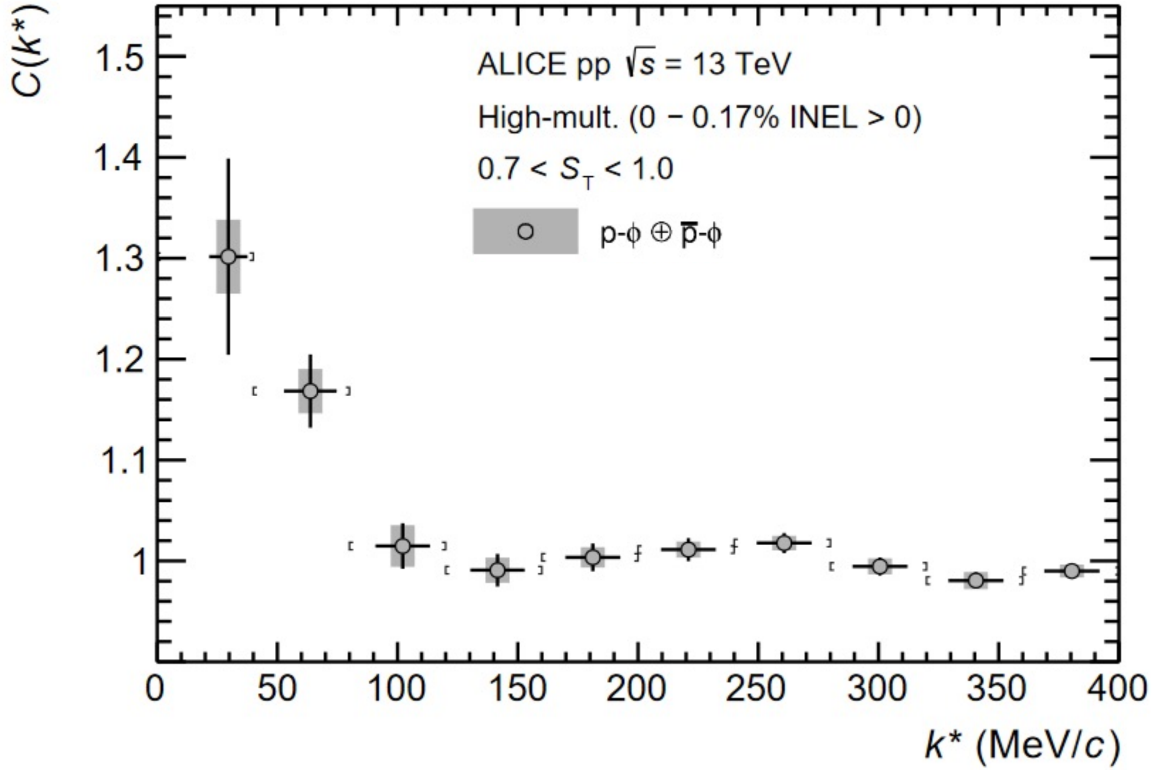

Results p–ϕ

- 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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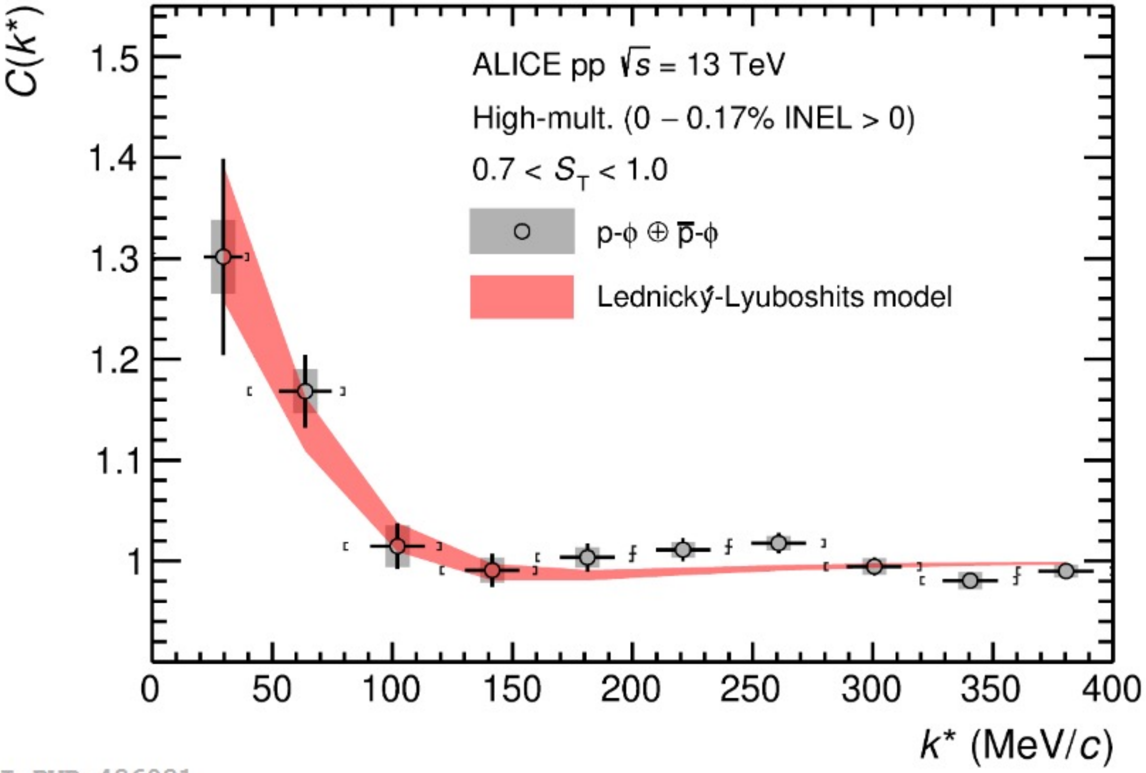


ALI-PUB-486981

Results p–ϕ

- 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

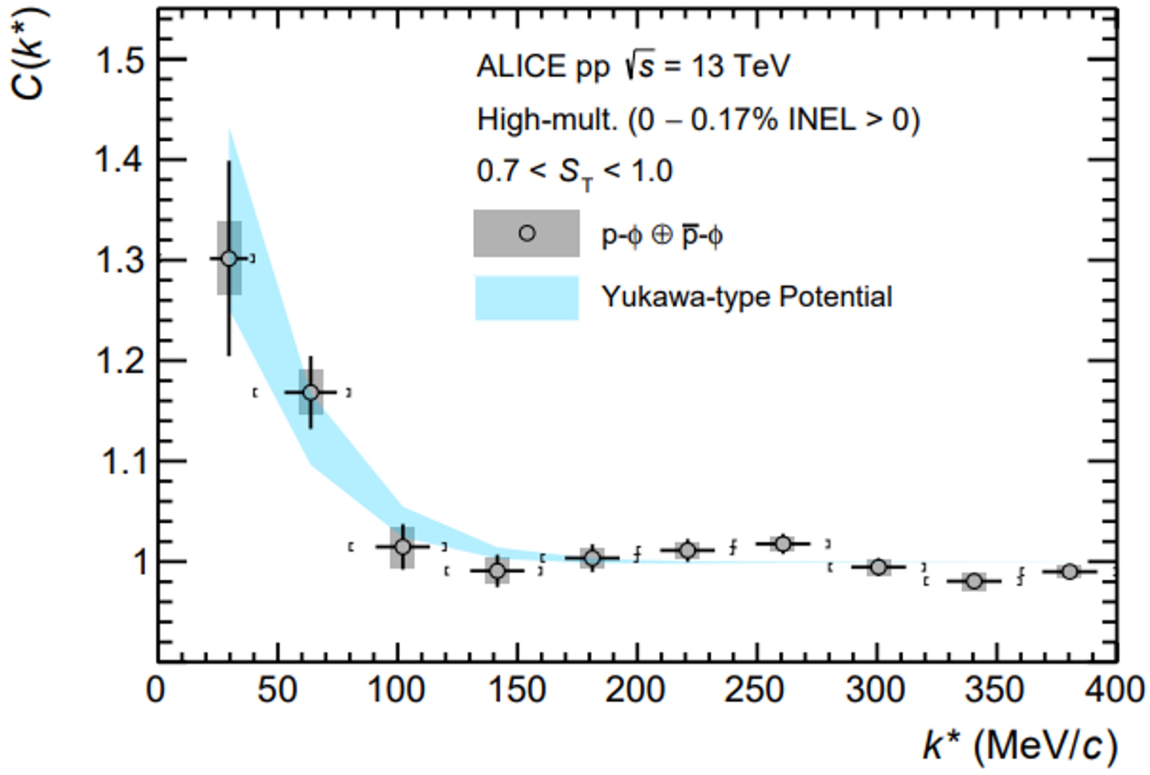
Strength A = 0.021 ± 0.009(stat.) ± 0.006(syst.)

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



Summary

- First measurement of the p–ϕ correlation function
- Attractive p–ϕ interaction dominated by elastic contributions in vacuum
- Extraction of $g_{\phi Y} \propto g_{\phi N}$ → Relevant for meson exchange between hyperons in Neutron Stars
- PRL Editor's selection
  ALICE Collab., *PRL* **127** (2021) 172301

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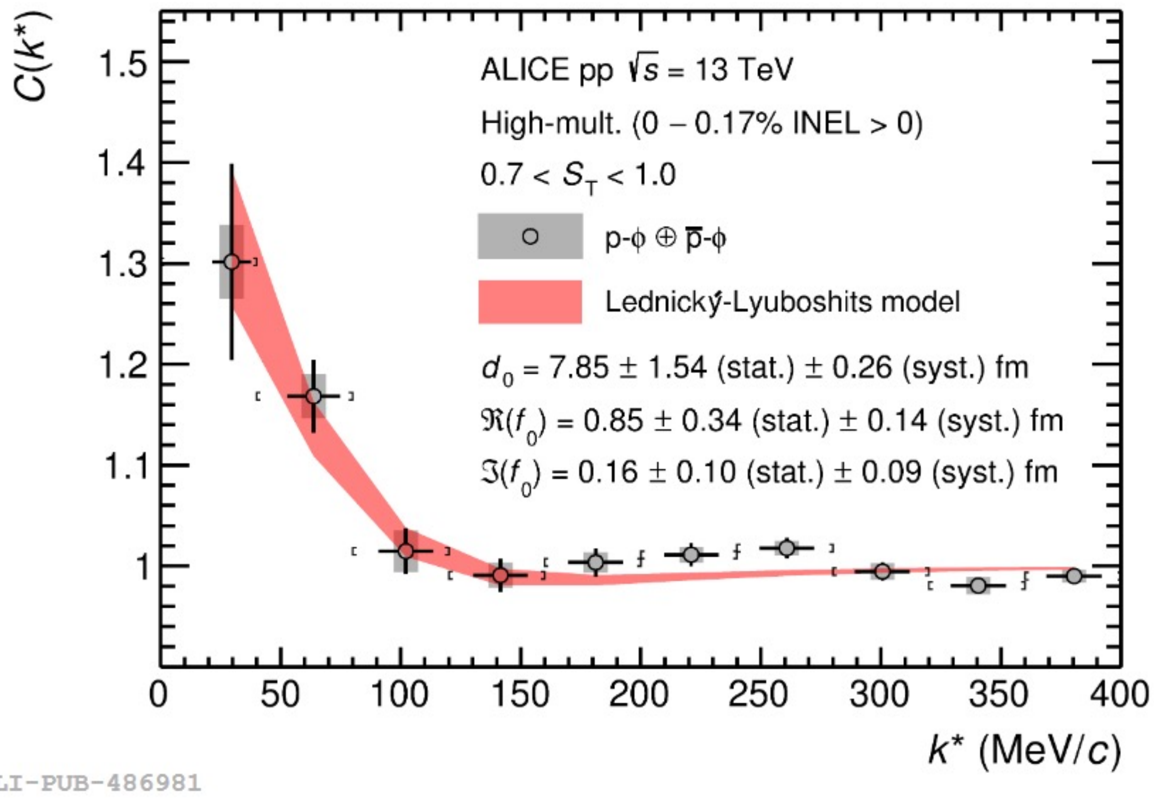


BACKUP

Correlation function model

Original:

femtoscopic contributions $C_{femto}(k^*)$

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

Non-femtoscopic background $C_{non\text{-}femto}(k^*)$

Combinatorial p–KK background (derivation data driven, includes non-femtoscopic contribution)

$$C_{p-KK,\boldsymbol{exp}}(k^*) = \mathcal{N} \cdot \left(MJ_{p-\phi}(k^*) + BL\right) \cdot C_{p-KK}(k^*)$$

Lednicky-Lyuboshits approach

$$C(k^*) = \sum_S \rho_S \left[\frac{1}{2} \left| \frac{f(k^*)}{r_0} \right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi} r_0} \right) + \frac{2\Re f(k^*)}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im f(k^*)}{r_0} F_2(2k^* r_0) \right]$$

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

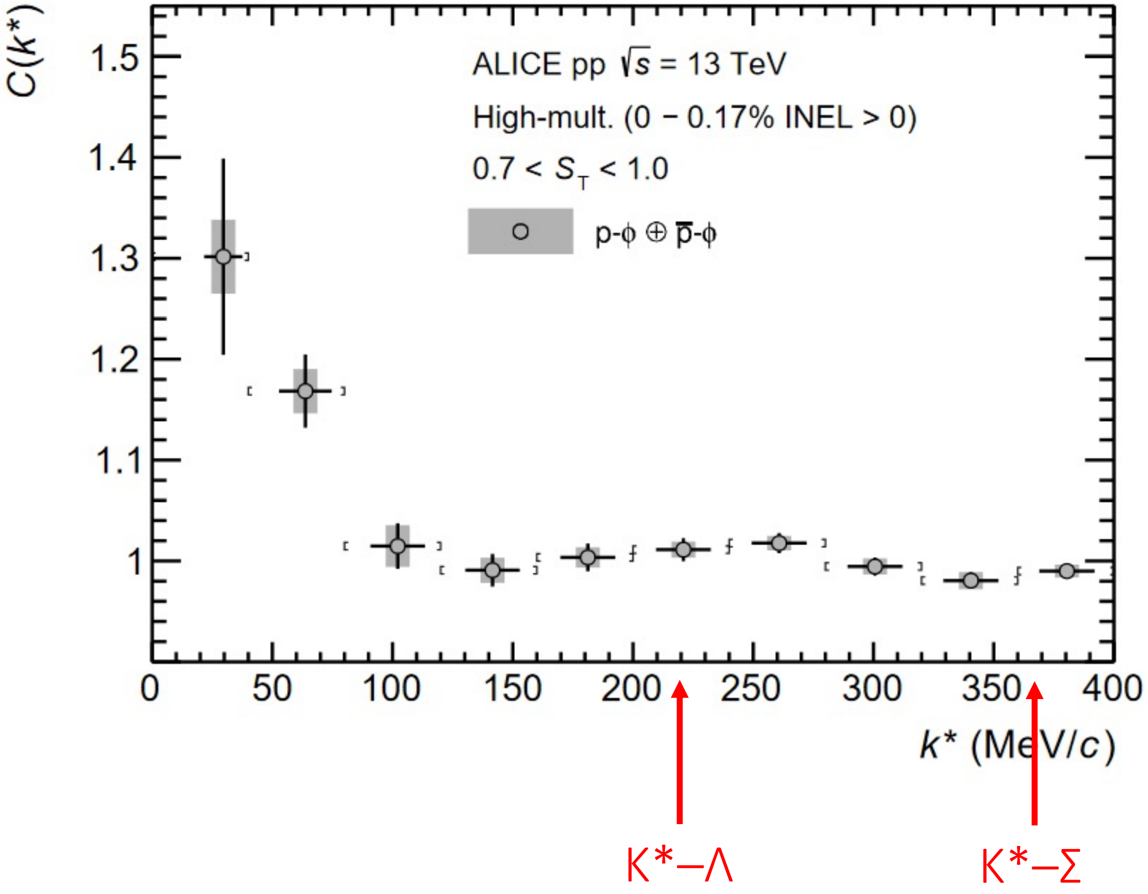
R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys*. **53** (1982) 770

- 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

Coupled channels

- CF tool to study coupled channels (CC)
  J. Haidenbauer, Nucl.Phys.A 981 (2019) 1
  Y. Kamiya et al., Phys.Rev.Lett. 124 (2020) 13
- Above-threshold channels ($m_{channel} > m_{pair}$) can lead to cusp structure at channel opening k* in p–ϕ system e.g. K*–Λ, K*–Σ

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



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  Y. Kamiya et al., Phys.Rev.Lett. 124 (2020) 13
- Above-threshold channels ($m_{channel} > m_{pair}$) can lead to cusp structure at channel opening k* in p–ϕ system e.g. K*–Λ, K*–Σ
- Below-threshold channels effectively increase CF e.g. K–Λ, K–Σ, K–Λ (1405)

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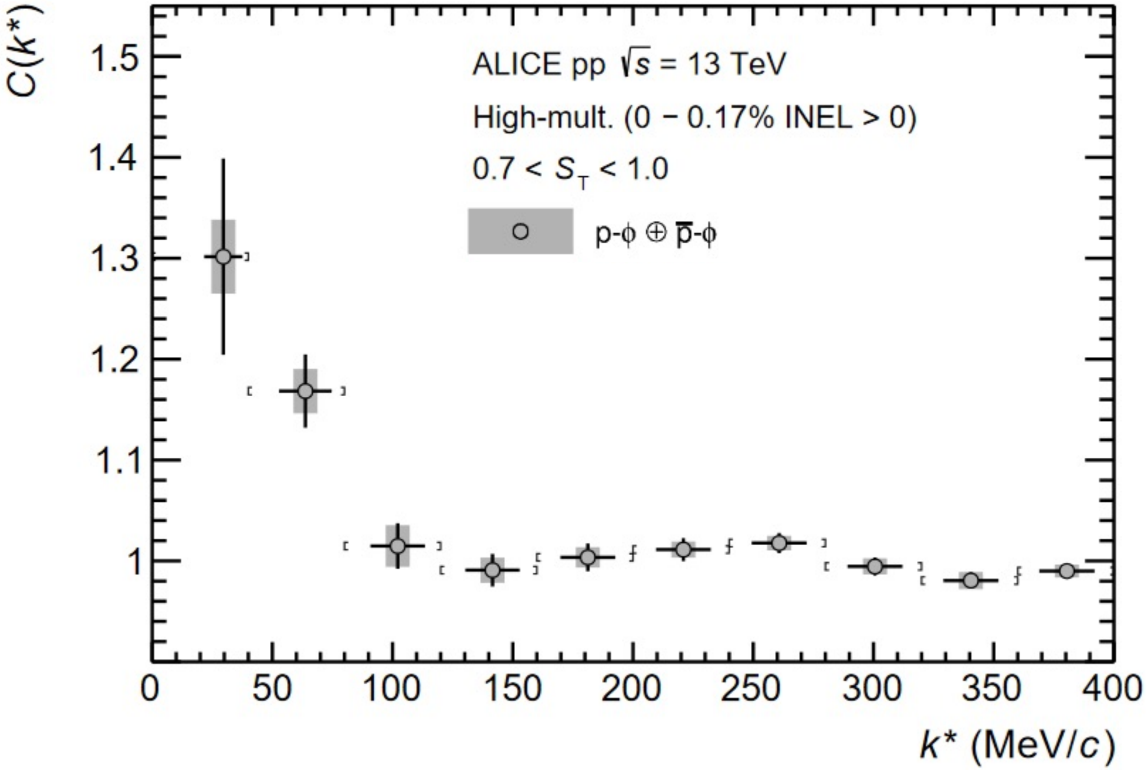


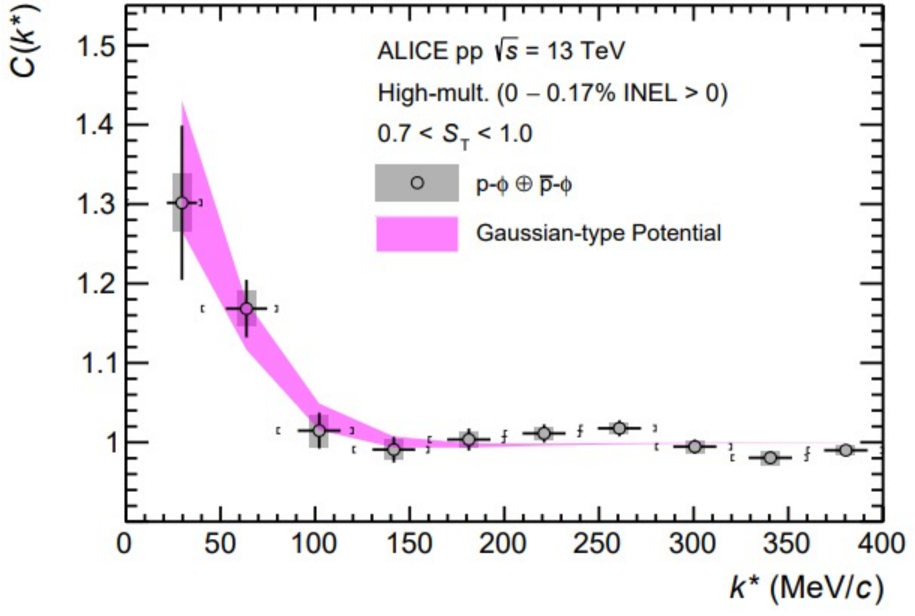
Results p–ϕ

- Gaussian-type potential with real parameters
  Phys. Rev. Lett. **98** (2007) 042501
    - $V(r) = -V_{eff} \cdot e^{-\mu r^2}$
- CF obtained **numerically** using CATS framework
  D.L. Mihaylov et al, *Eur. Phys. J.* **C78** (2018) no.5, 394

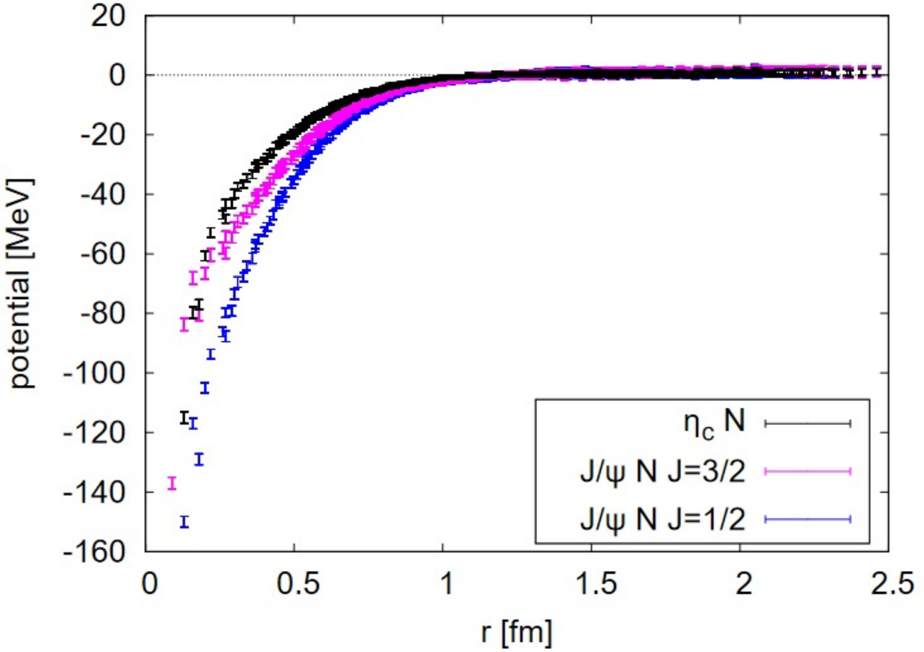
V_{eff} = 2.5±0.9(stat.) ± 1.4(syst.) MeV

μ = 0.14 ± 0.06(stat.) ± 0.09(syst.) fm−2

- Very shallow potential depth
- Much shallower than Lattice QCD potential for N–J/ψ strong interaction (indirect comparison)
  T. Sugiura, Y. Ikeda, and N. Ishii, *PoS* **LATTICE2018** (2019) 093

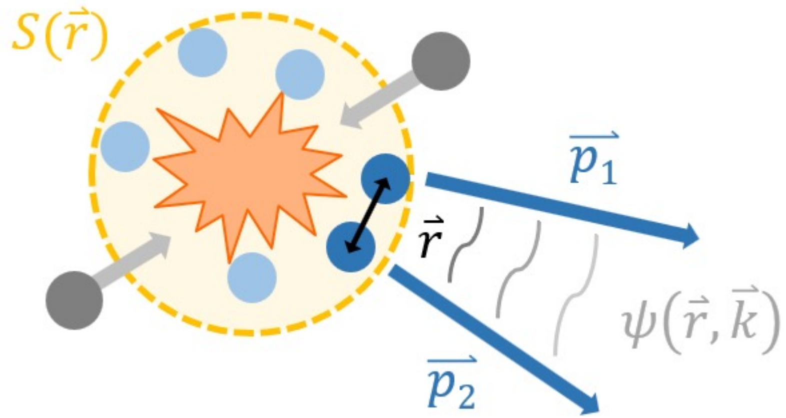


T. Sugiura, Y. Ikeda, and N. Ishii, *PoS* **LATTICE2018** (2019) 093



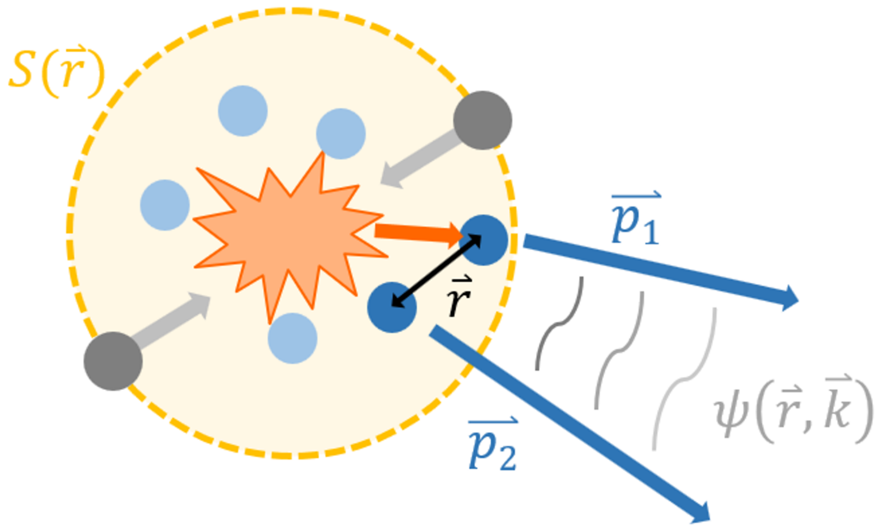
The source

- Particle emission from **Gaussian core** source



The source

- Particle emission from **Gaussian core** source
- Core radius effectively increased by short-lived strongly decaying **resonances** ($c\tau \approx r_{\mathrm{core}}$)



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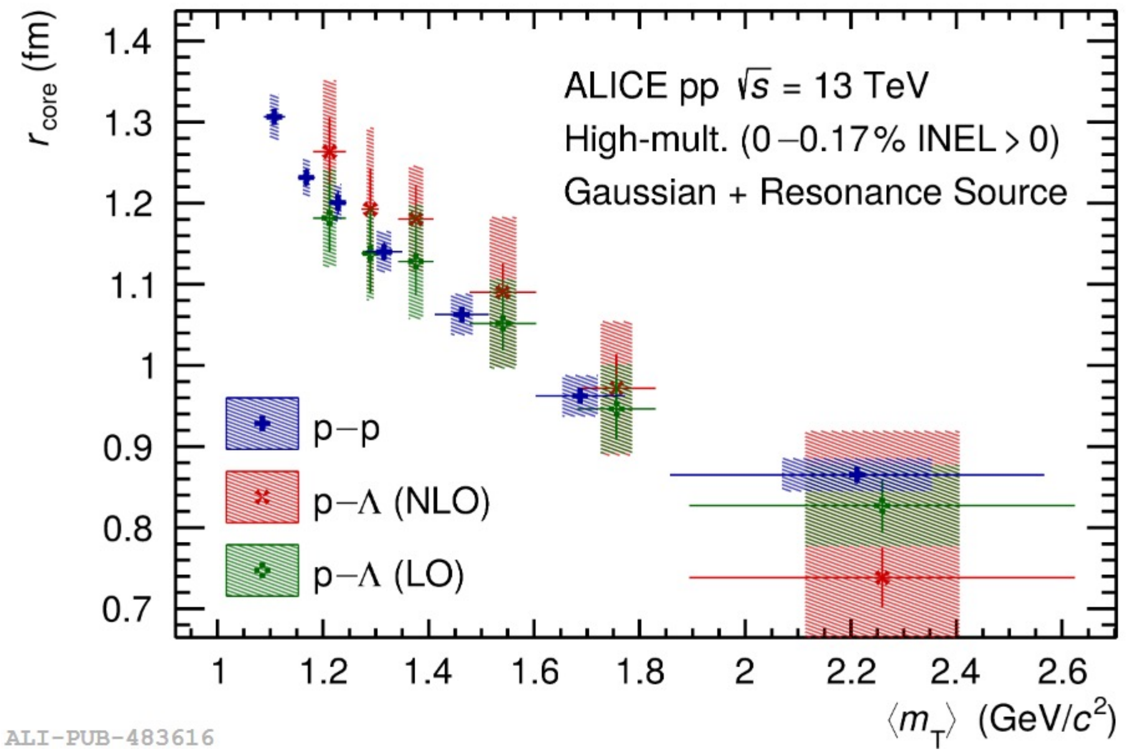
- Universal source model constrained from pp pairs (well-known interaction)

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



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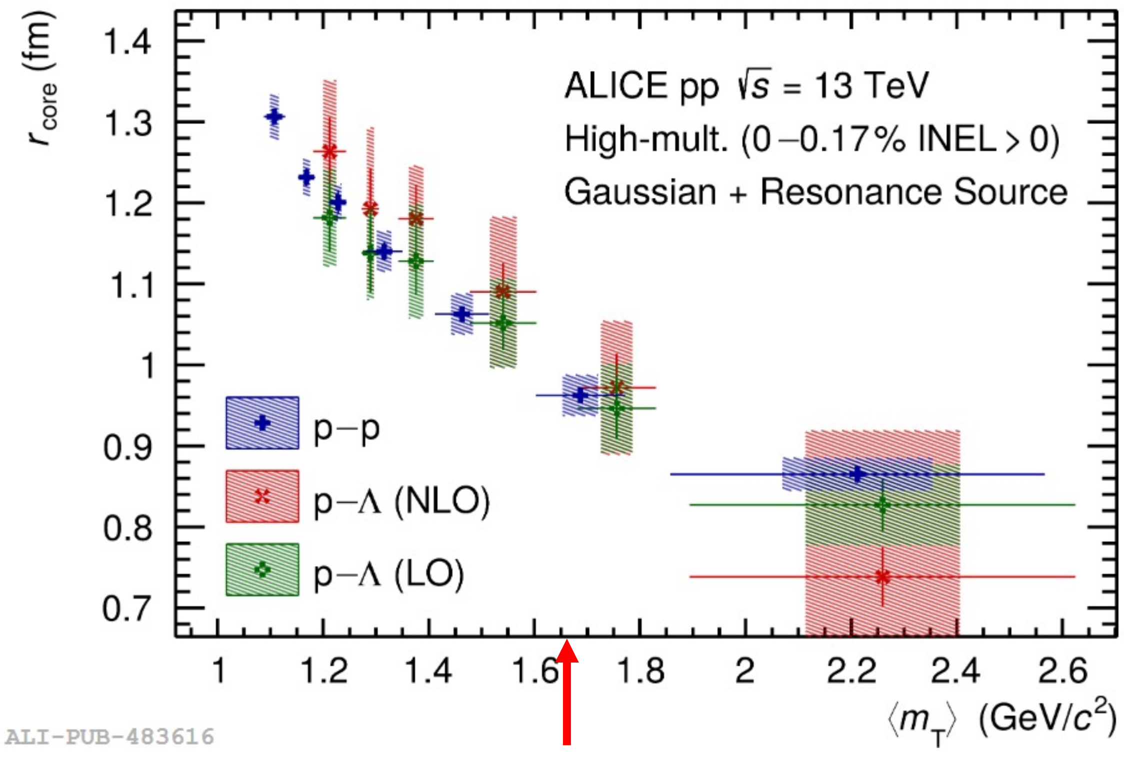
  ALICE Collab., *Physics Letters B*, **811** (2020) 135849
- Gaussian core source scales with $\langle m_T \rangle$
  - r_{core} = 0.98 ± 0.04 fm
- Effects from short-lived resonances
  - no relevant contribution from strongly decaying resonances feeding to the ϕ
  - Sizable amount of protons from decay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



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