Experimental Evidence for an Attractive Proton-ϕ Interaction

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IMPRS YSW
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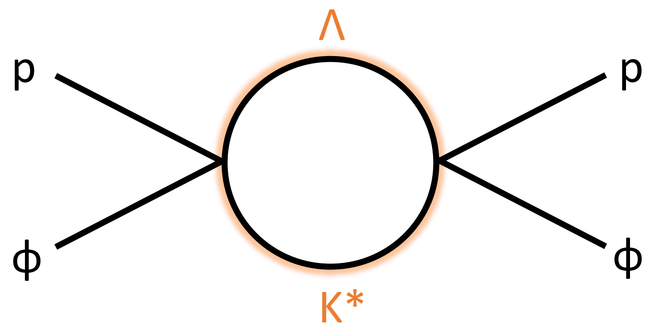
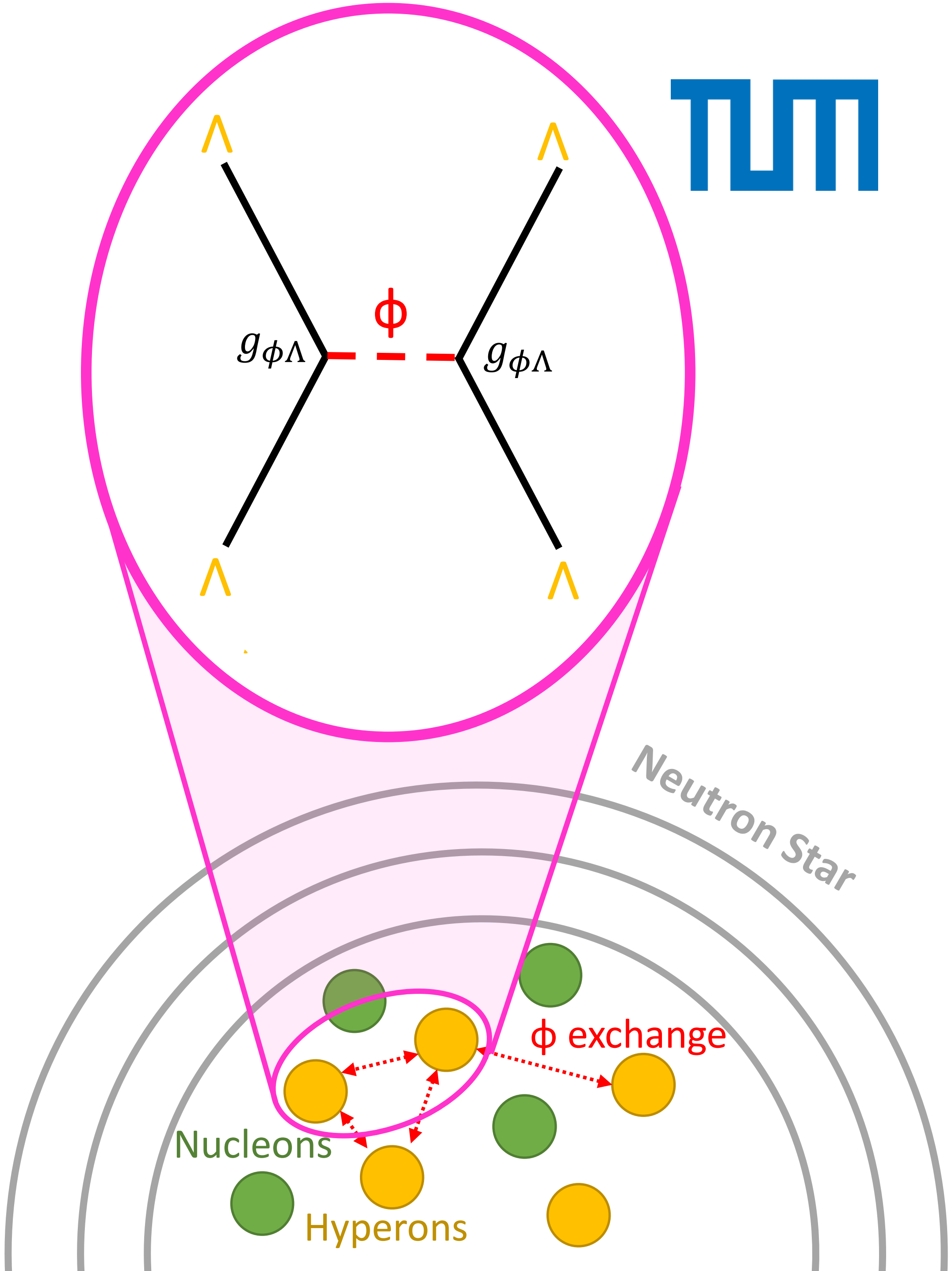
Based on ALICE Collab., *PRL* **127** (2021) 172301

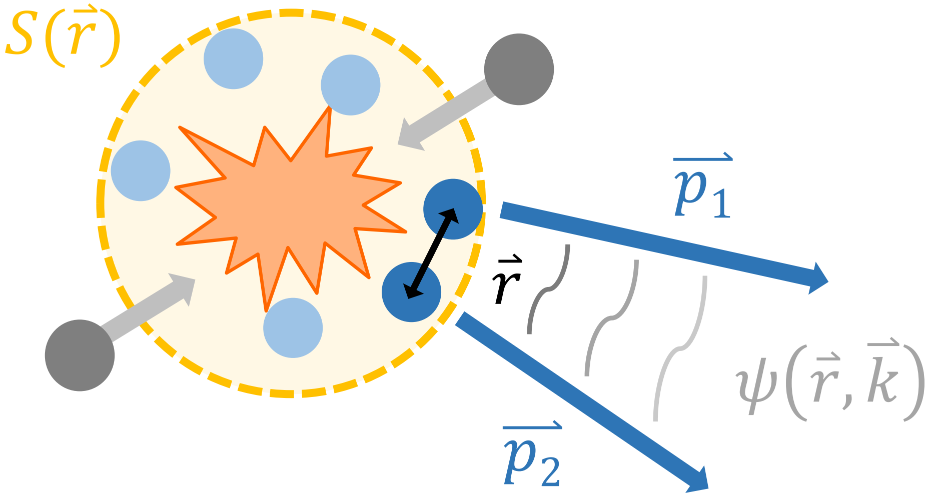
Genuine p–ϕ interaction

- Exchange meson within framework of relativistic mean field models → Access to interaction among hyperons
- 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



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

experimental definition — theoretical definition

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

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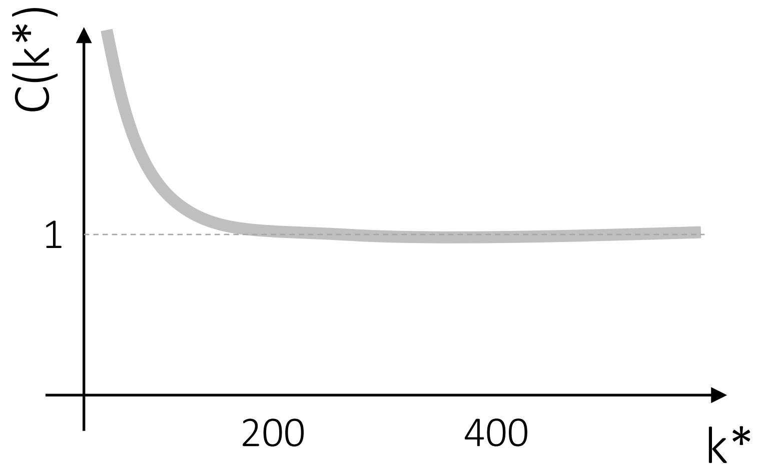

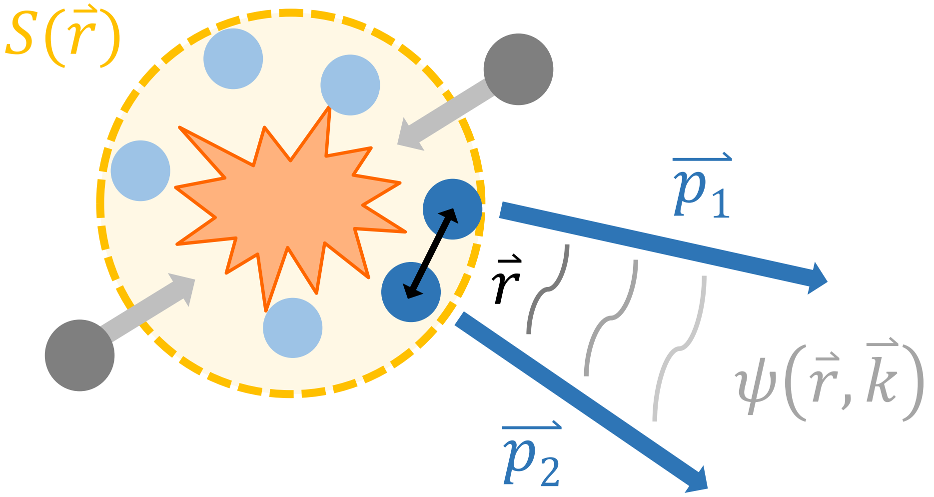

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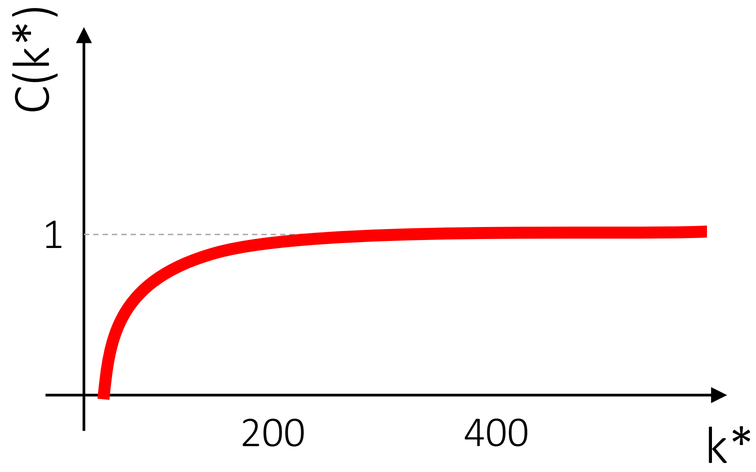

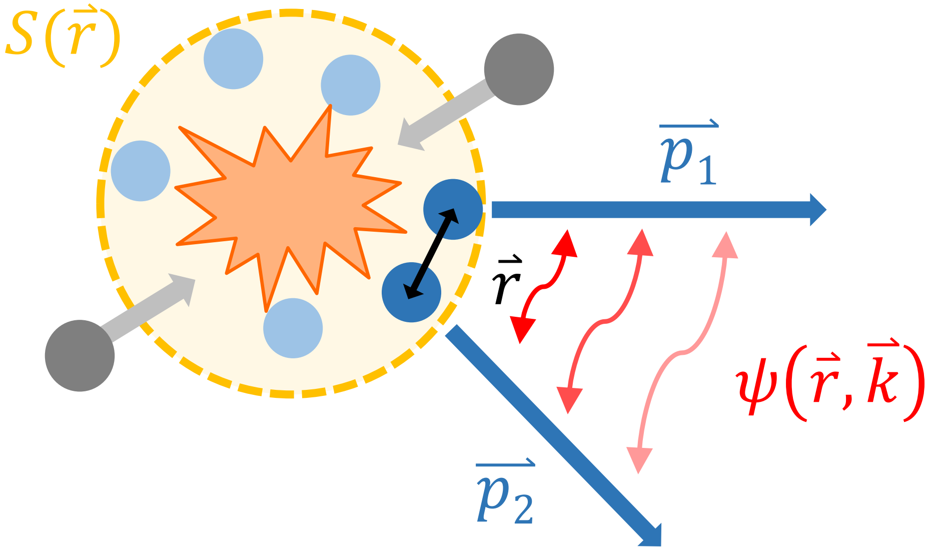

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repulsion

experimental definition — theoretical definition

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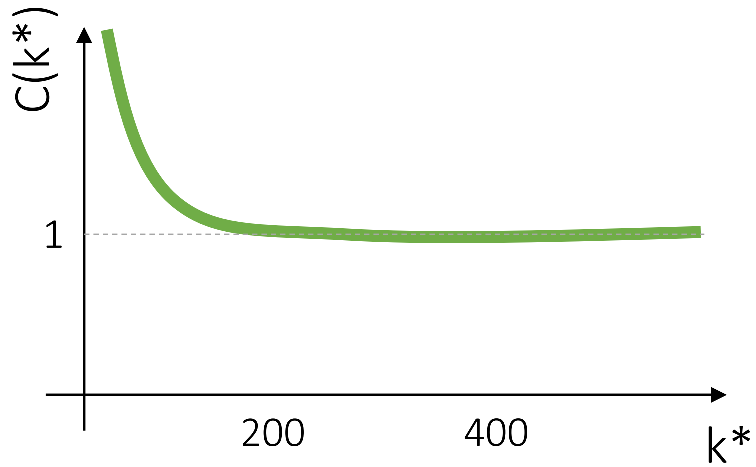
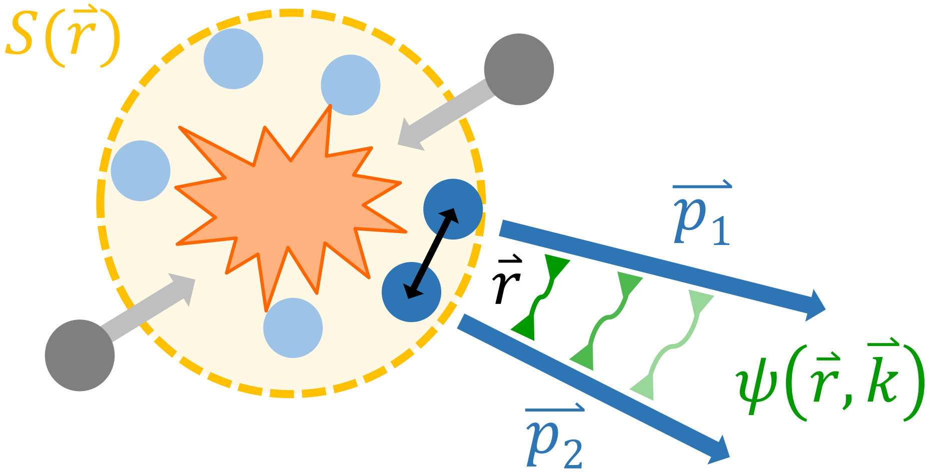
Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

Correlation function





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attraction

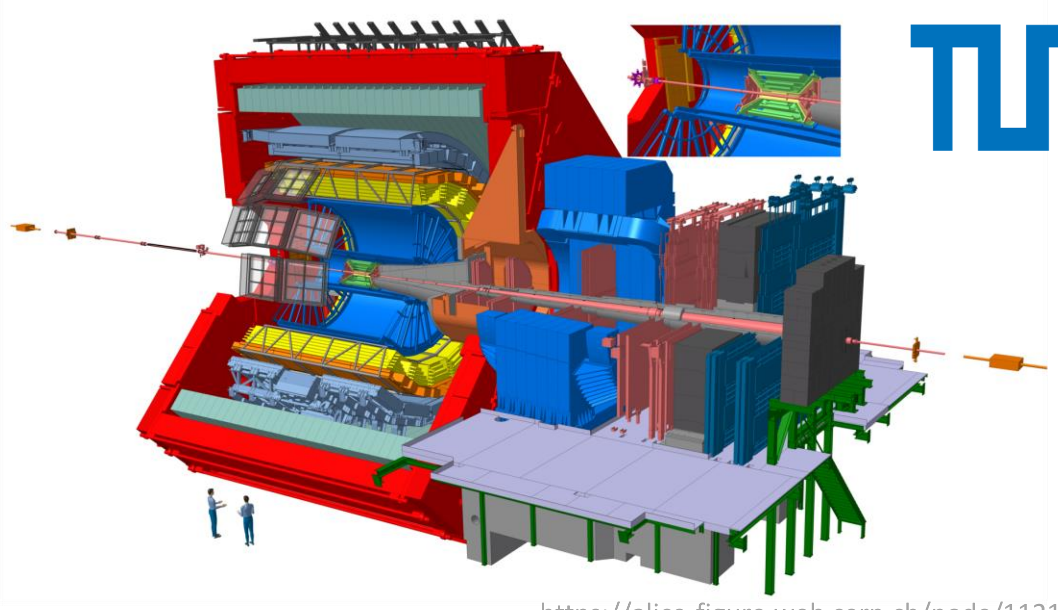
experimental definition — theoretical definition

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

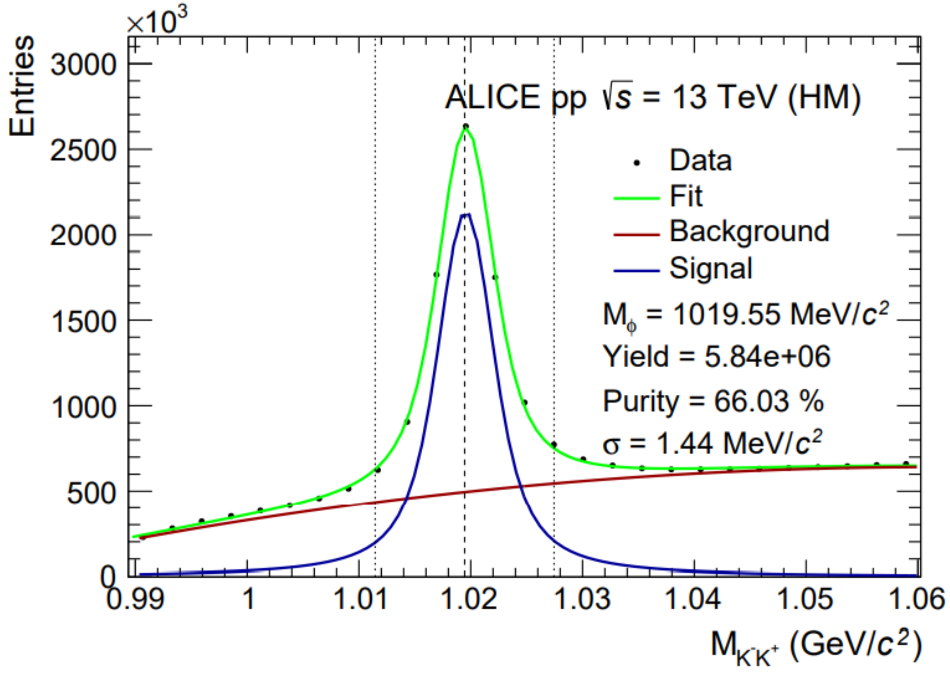
Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

Analysis

- LHC Run 2 data (2016-2018)
- **High-multiplicity** (HM) pp collisions at √s = 13 TeV
  - About 1 billion events
  - Enhanced production of particles with hidden and open strangeness
- ALICE provides excellent PID by means of TPC and TOF
  - Proton detected directly
    - Proton purity of 99% with primary fraction 82%
    ALICE Collab., *Phys. Lett B* **811** (2020) 135849
  - ϕ candidates reconstructed from $\phi \rightarrow K^+K^-$
    - p_T integrated purity of 66%

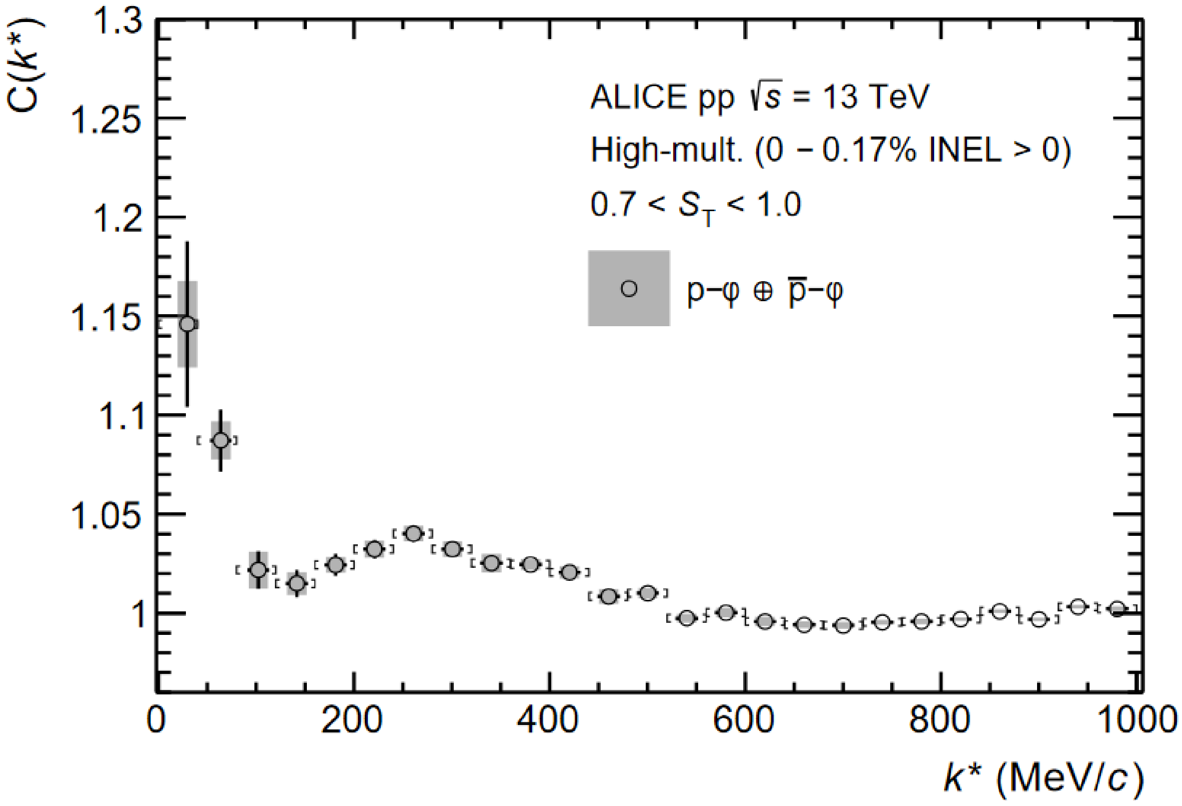


https://alice-figure.web.cern.ch/node/11219



CF model

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



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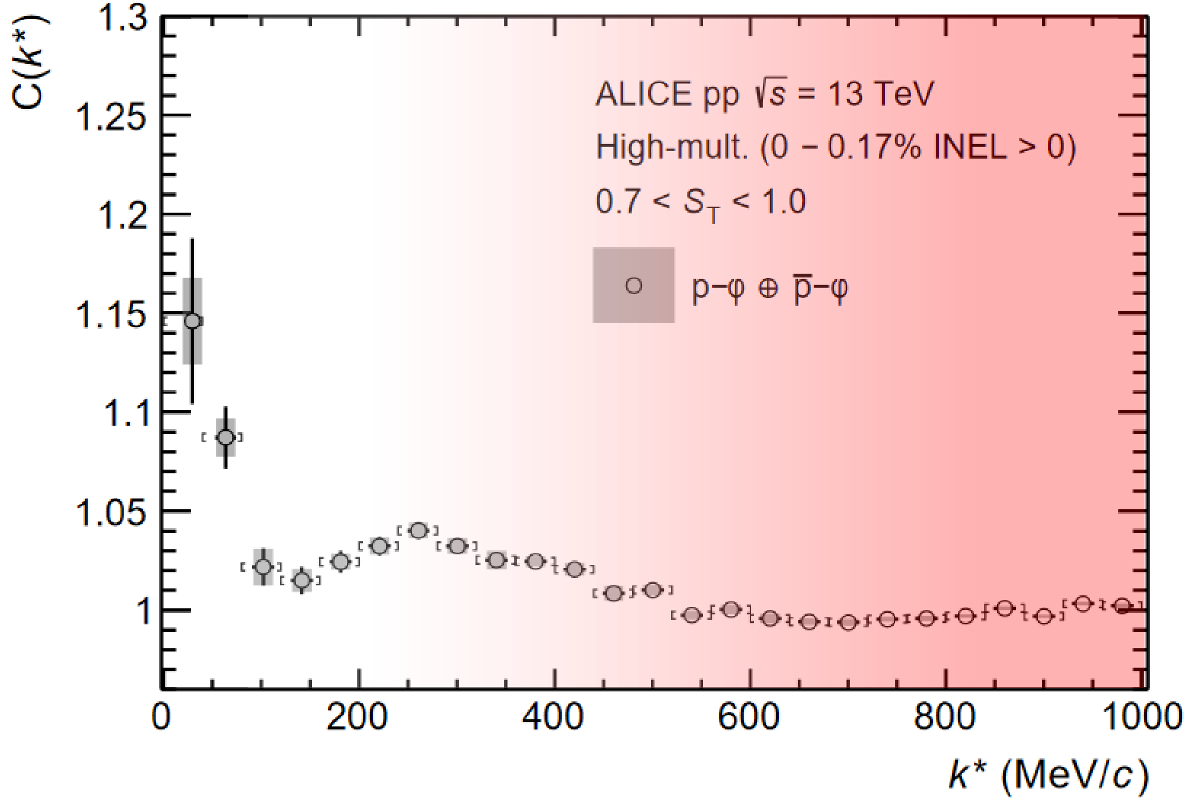
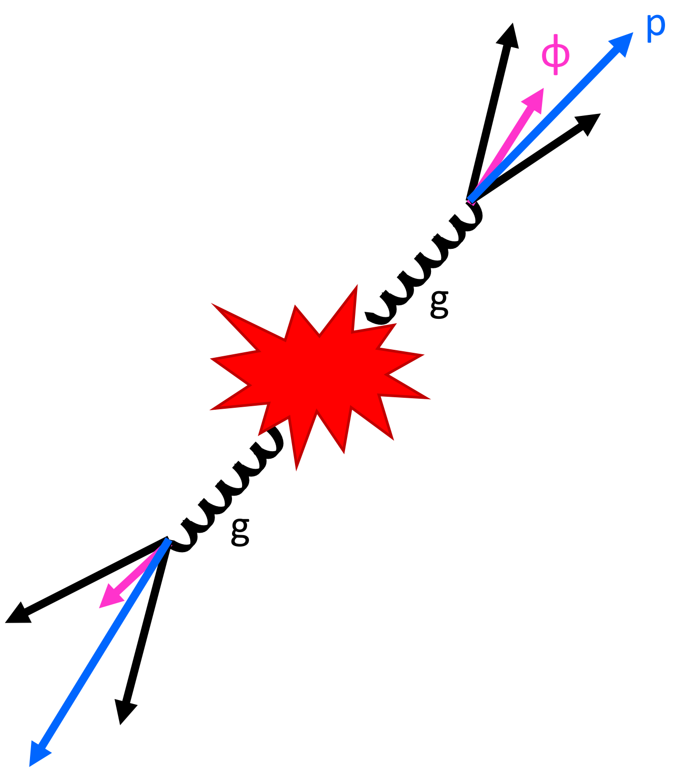


Background (non-femto)

- 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



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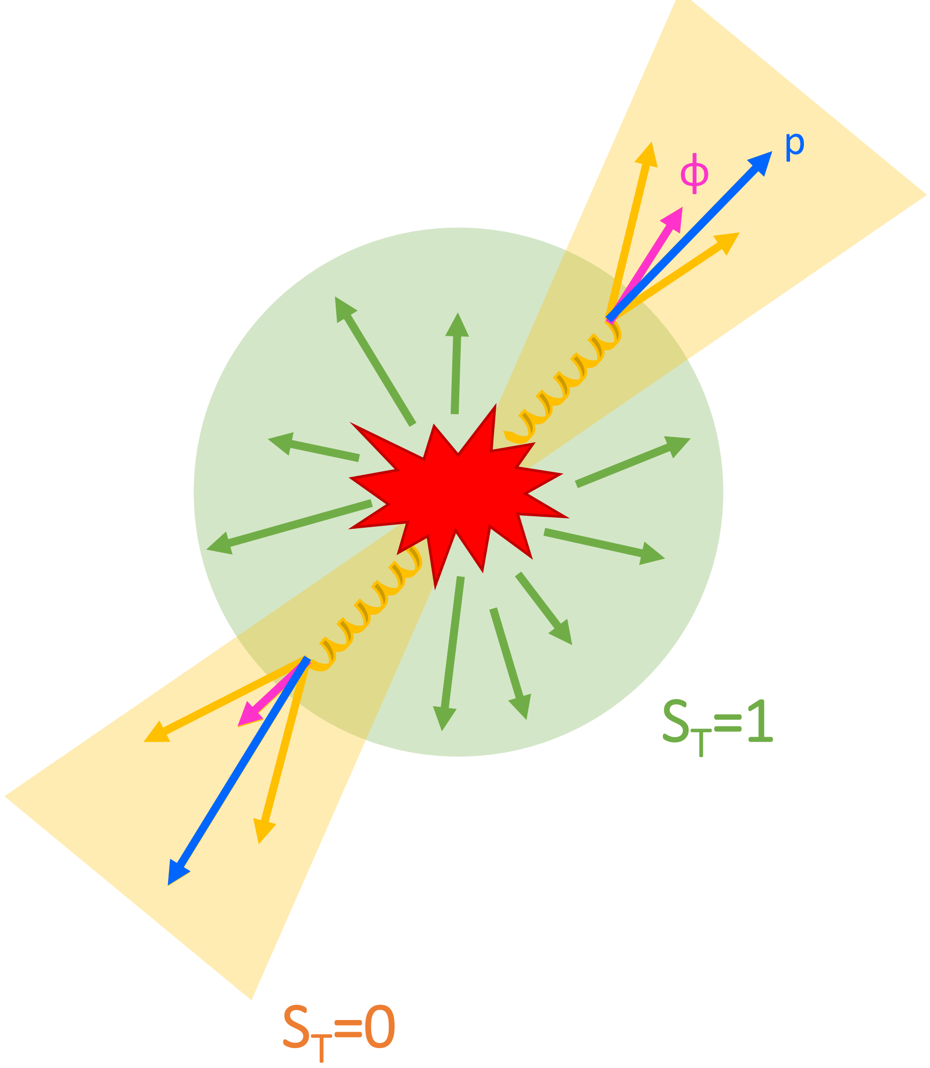
- Less pronounced in spherical events
  - Event shape classified by transverse Sphericity $S_T \in [0,1]$
    ALICE Collab., *JHEP* **09** (2019) 108
  - In this Analysis: 0.7< S_T <1.0



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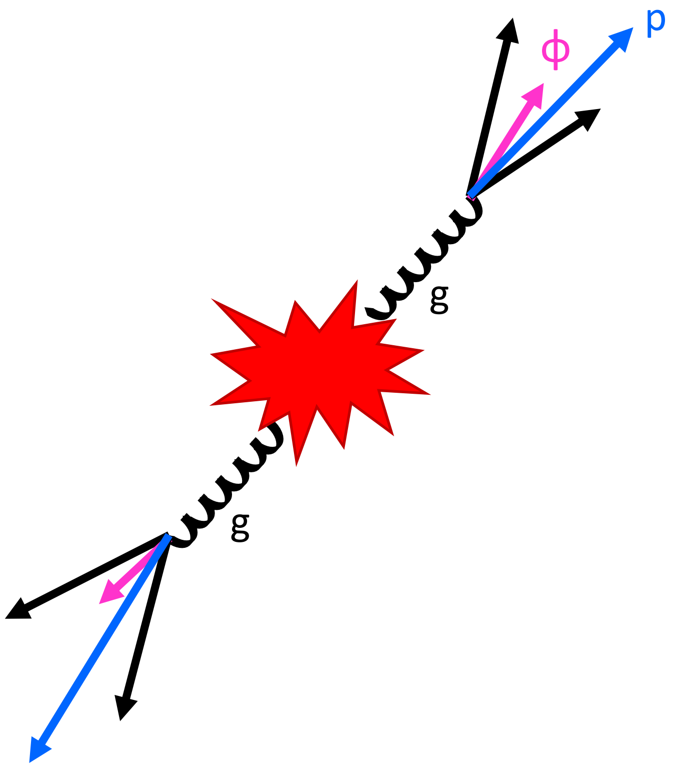
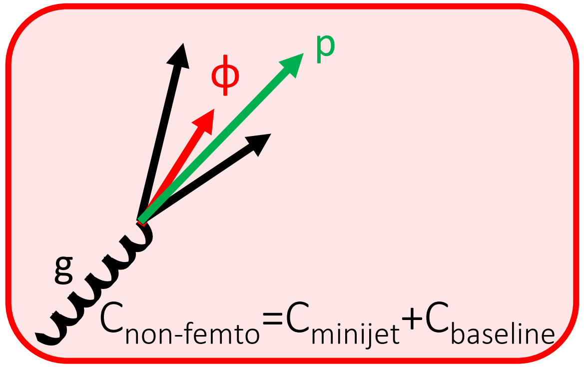
    ALICE Collab., *JHEP* **09** (2019) 108
  - In this Analysis: $0.7 < S_T < 1.0$
- Residual minijet background well described by Pythia 8
  ALICE Collab., *Phys. Rev. D* **84** (2011) 112004



Non-femtoscopic background



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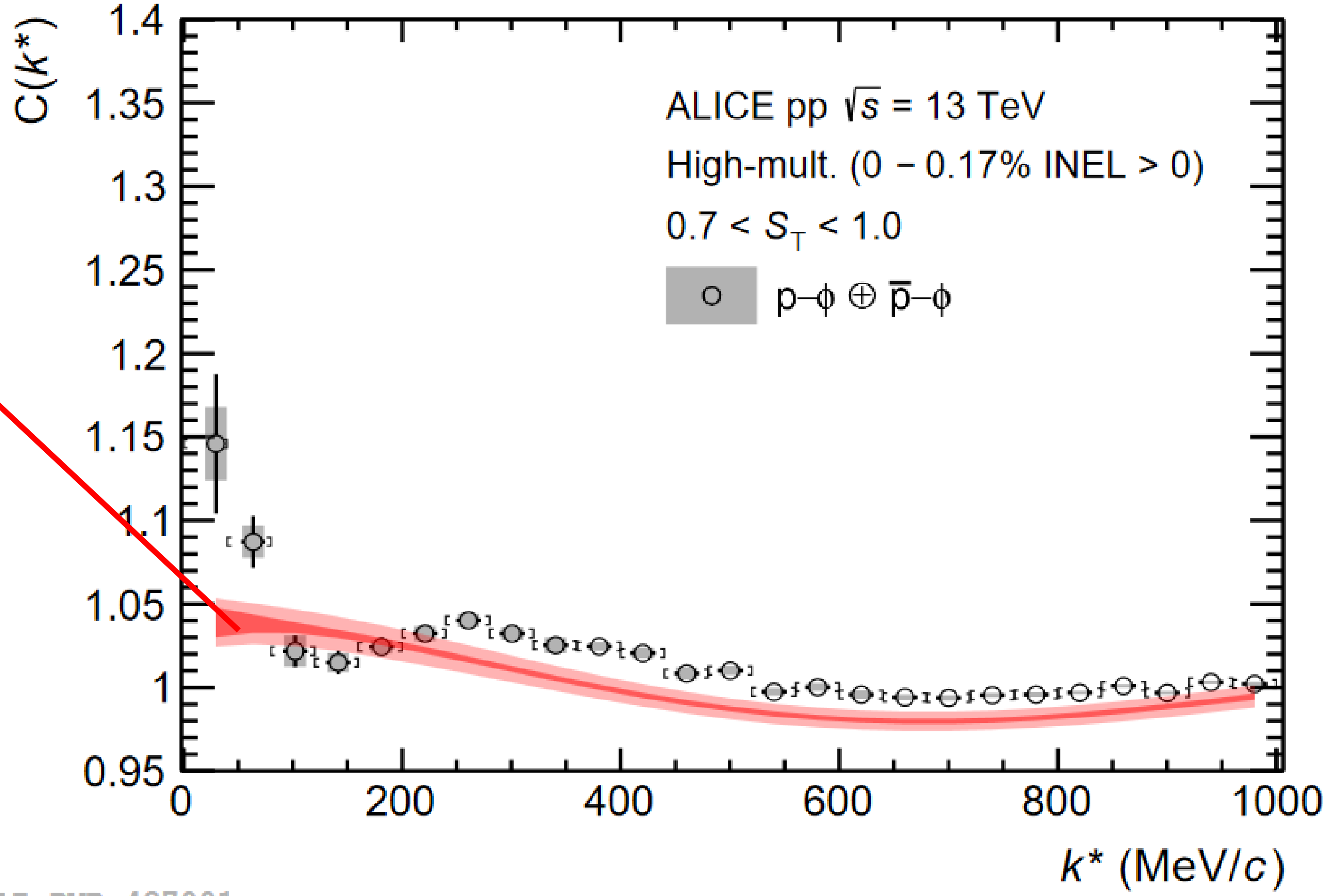

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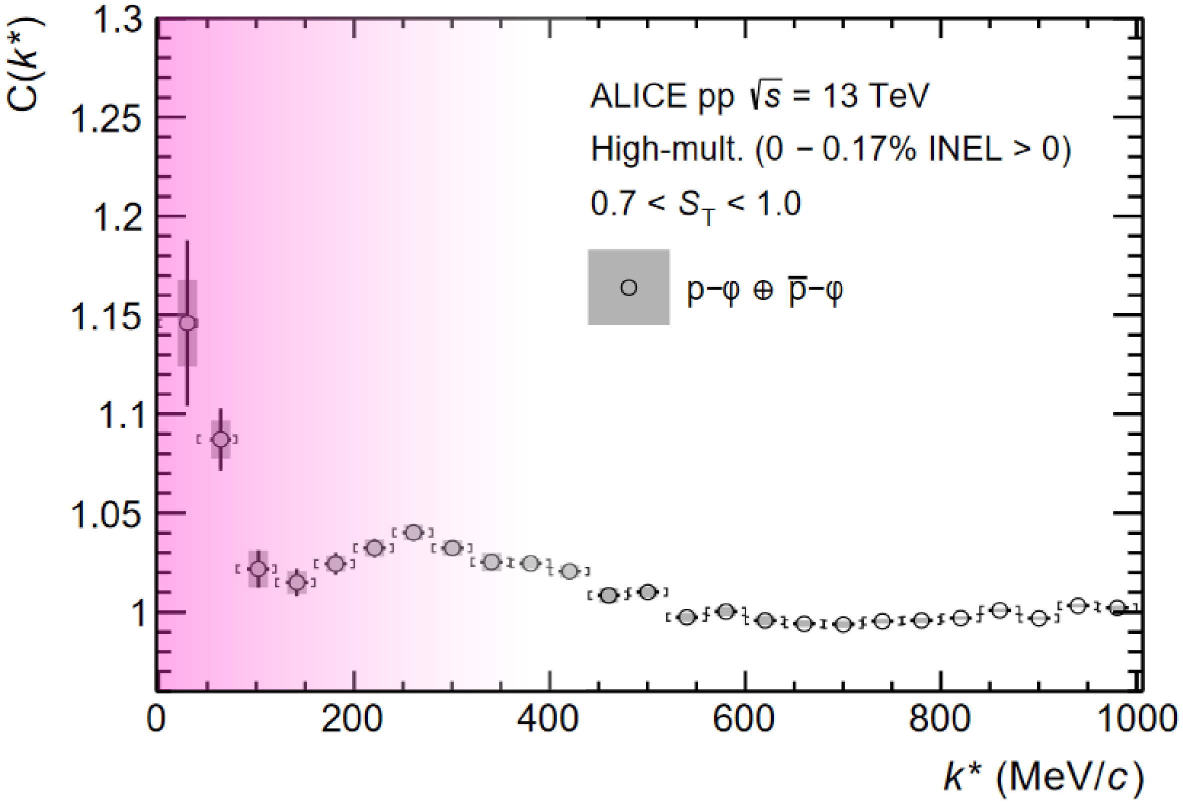
CF model

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

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



<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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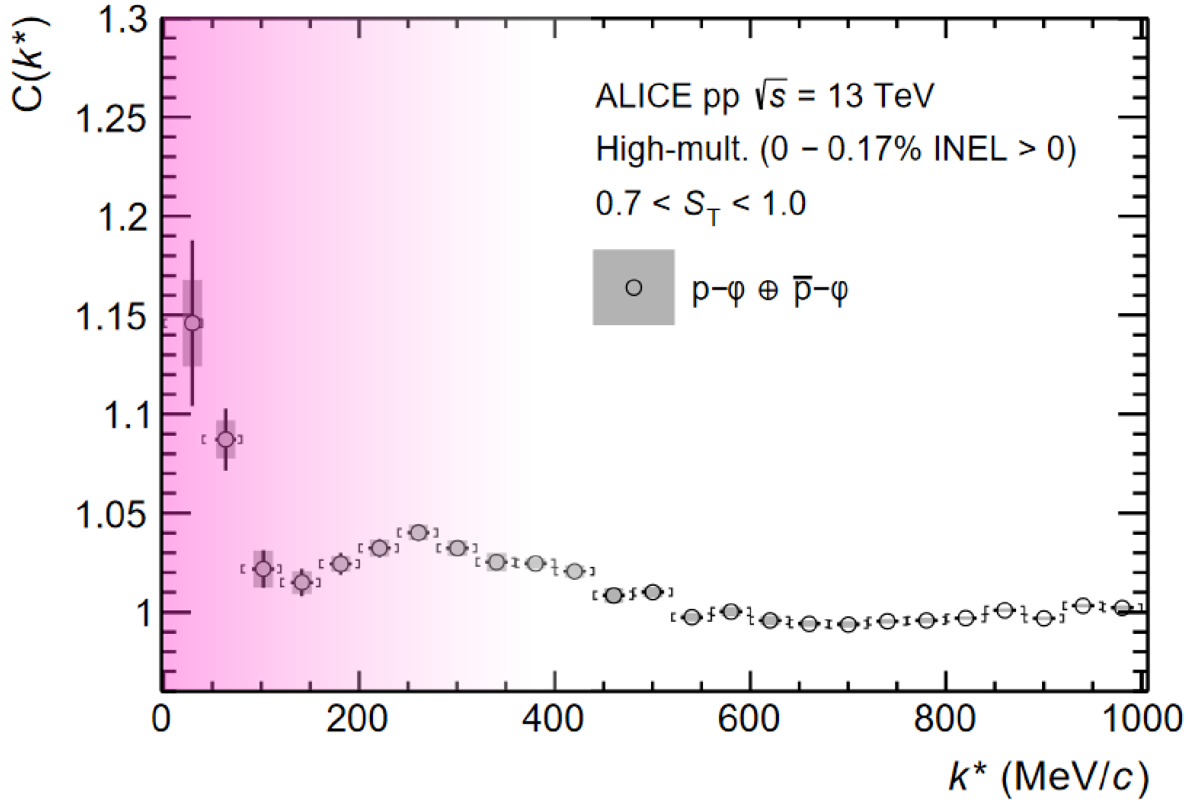

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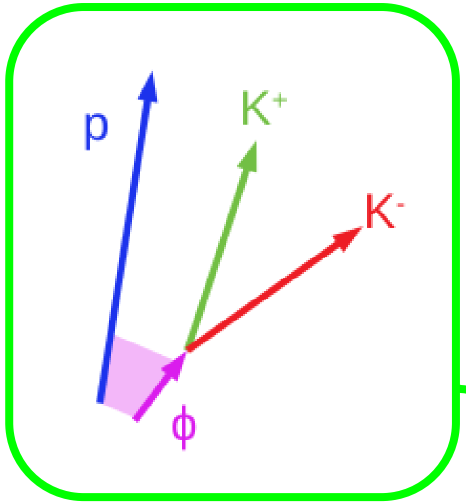
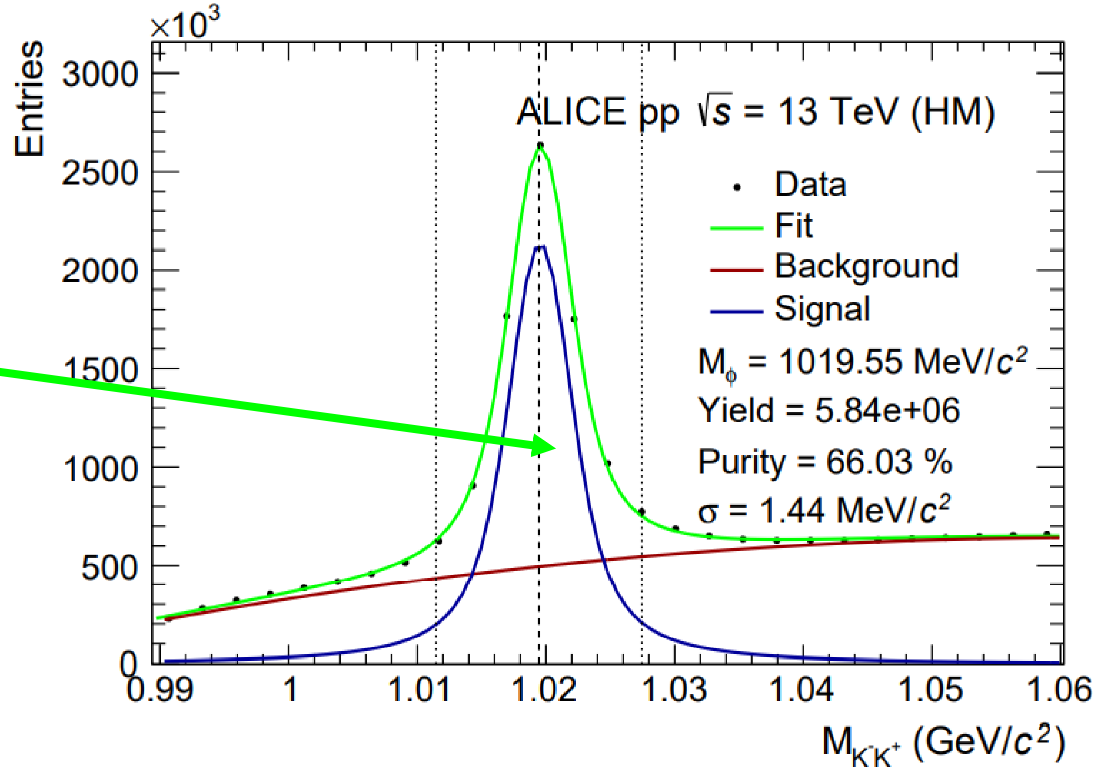
- Genuine p–ϕ (46.3%)
- Flat contribution from misidentified and secondary protons (10.4%)
- Combinatorial background from misidentified ϕ mesons (43.3%)

Combinatorial p-K^+K^- background

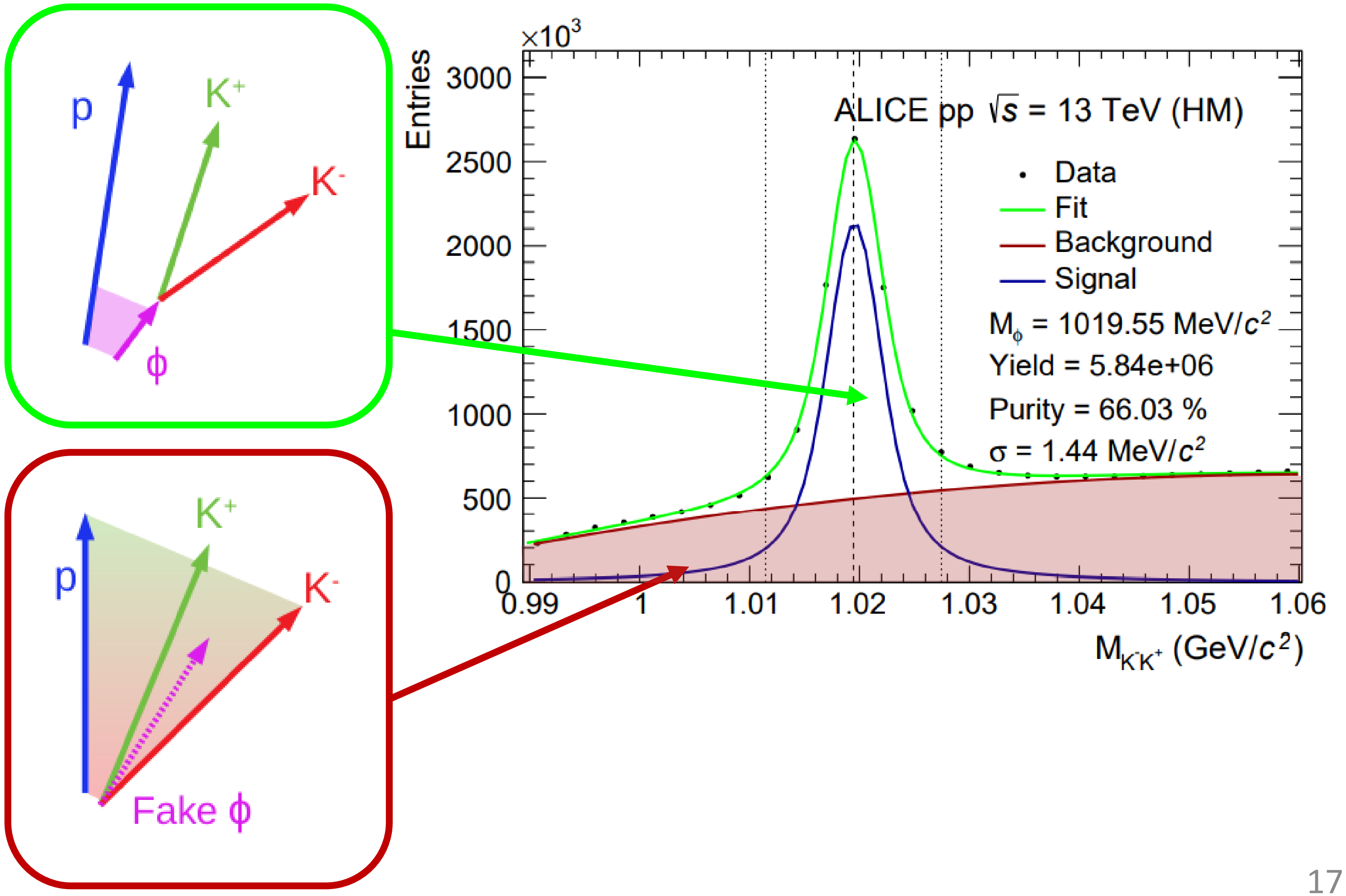
- ϕ candidates reconstructed via invariant mass of K^+K^-





Combinatorial p-K^+K^- background

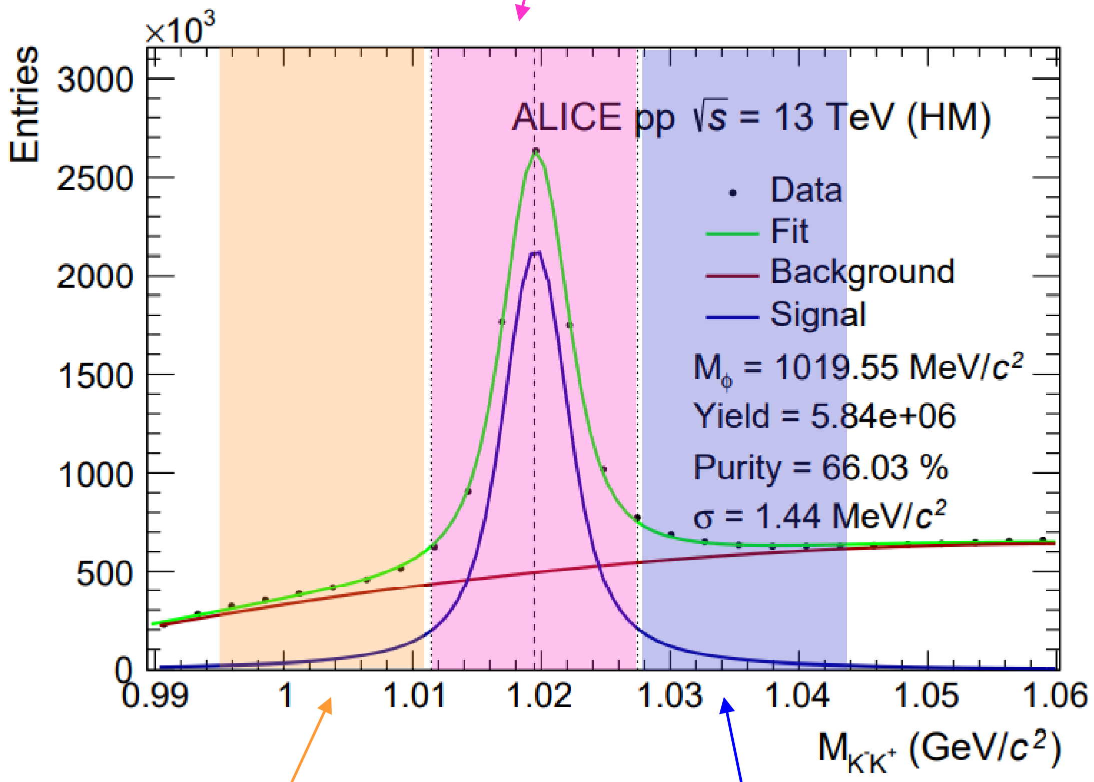
- ϕ candidates reconstructed via invariant mass of K^+K^-
- Finite purity of reconstructed ϕ → correlation signal from 2 and 3-body interaction between p, K^+ and K^-



Combinatorial p-K^+K^- background

- ϕ candidates reconstructed via invariant mass of K^+K^-
- Finite purity of reconstructed ϕ → correlation signal from 2 and 3-body interaction between p, K^+ and K^-
- Accessed by sideband analysis

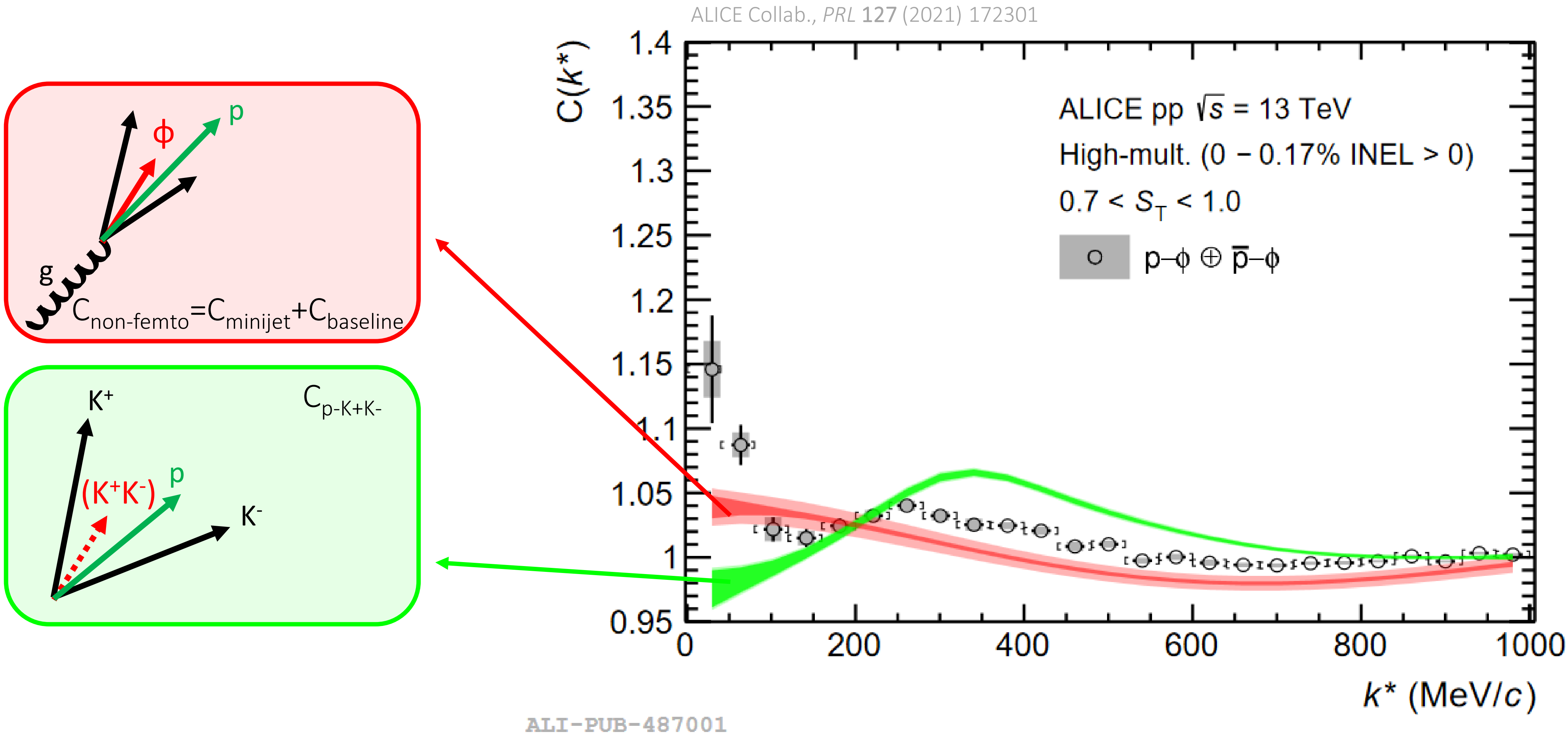
Phi Peak: M_ϕ±8 MeV/c^2



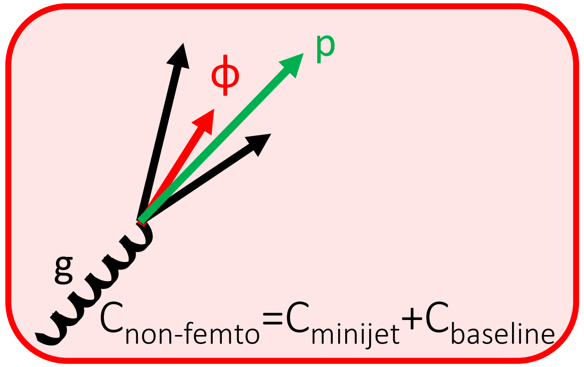
Left SB: 0.995-1.011 GeV/c^2

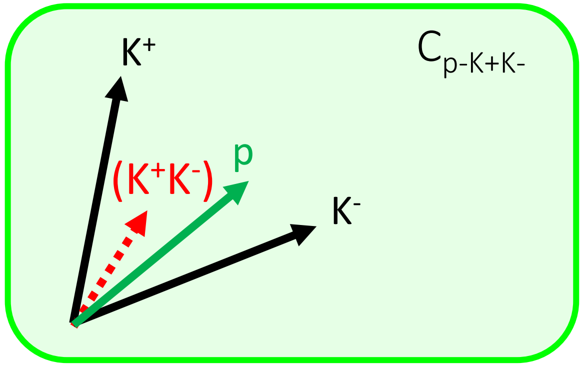
Right SB: 1.028-1.044 GeV/c^2

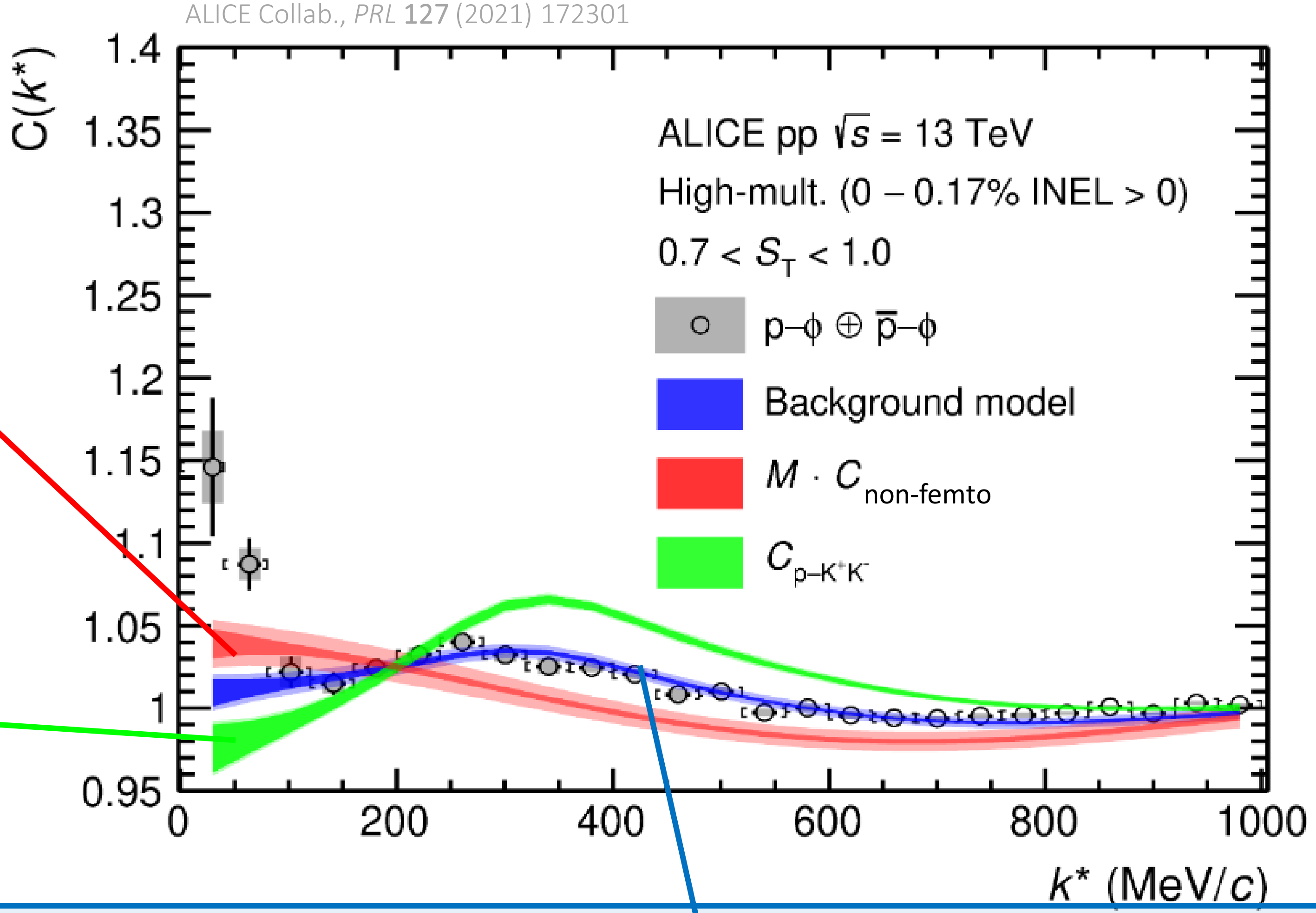
Combinatorial p-K$^+$K$^-$ background



Total Background







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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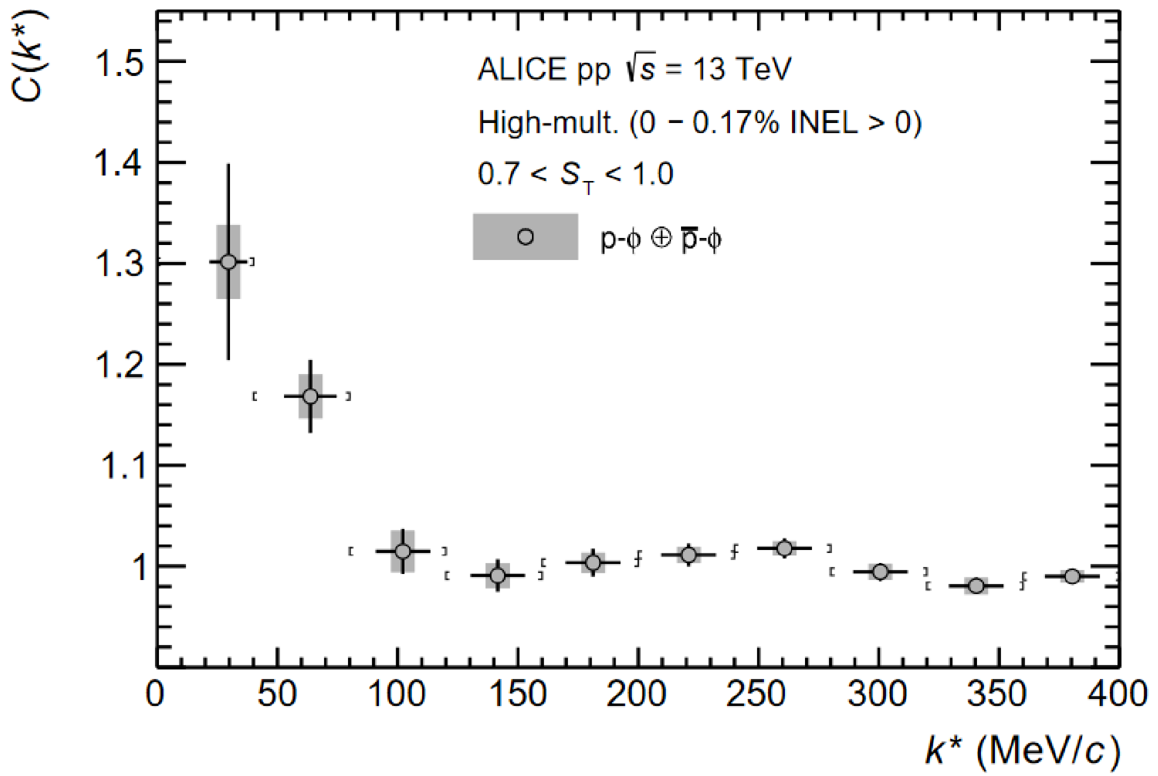

Results p–ϕ

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

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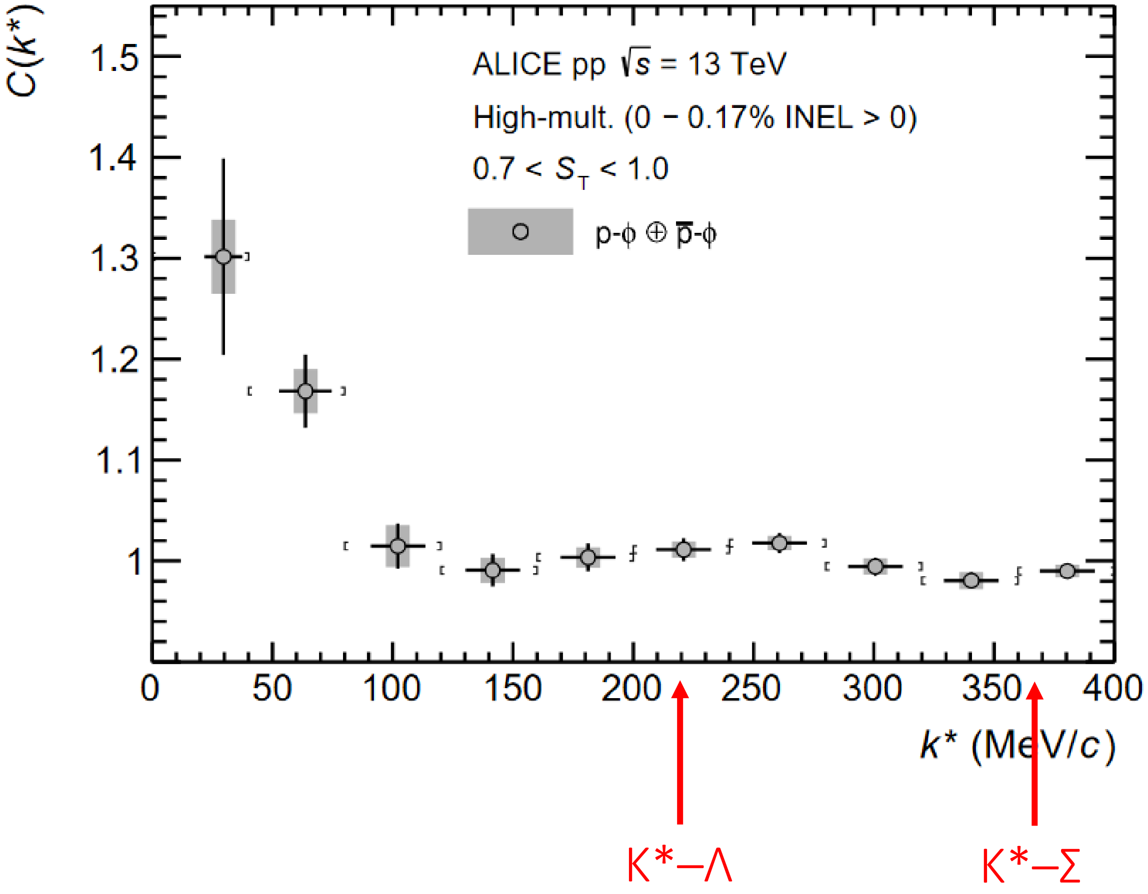

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- Above-threshold channels ($m_{channel} > m_{pair}$) can lead to cusp structure at channel opening k* in p–ϕ system e.g. K*–Λ, K*–Σ
- Below-threshold channels effectively increase CF e.g. K–Λ, K–Σ, K–Λ (1405)

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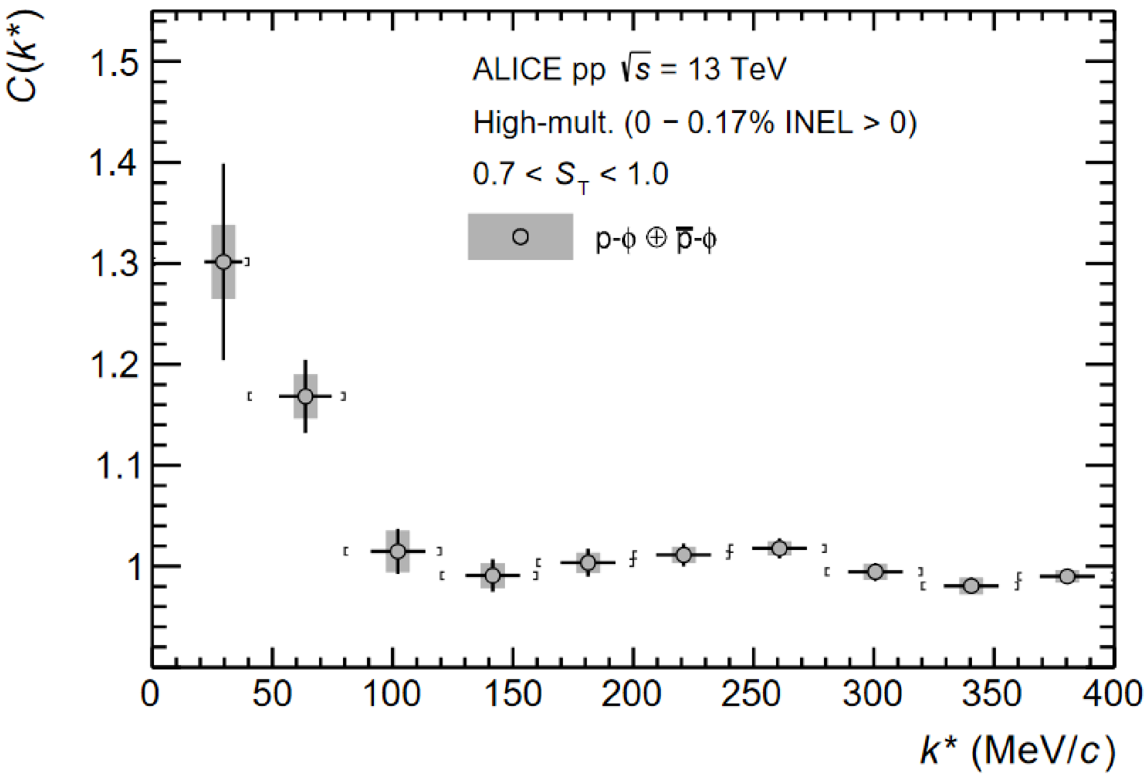

Scattering parameters

- 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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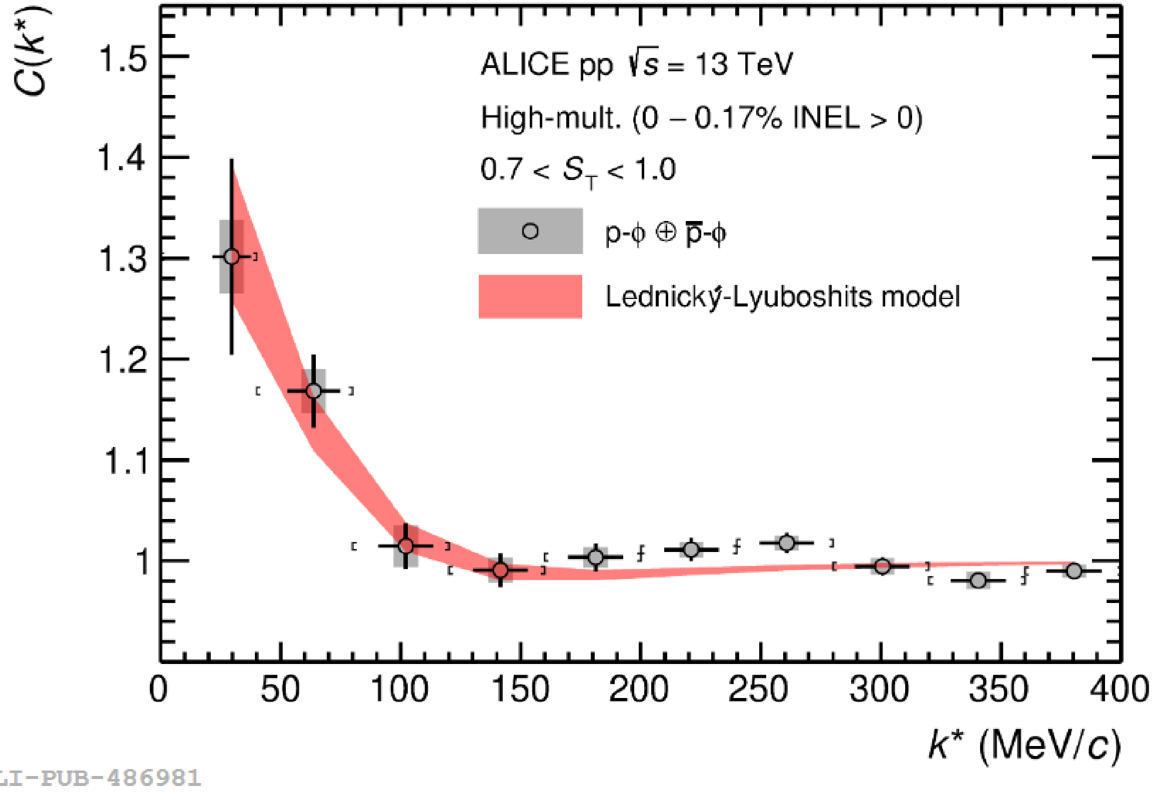

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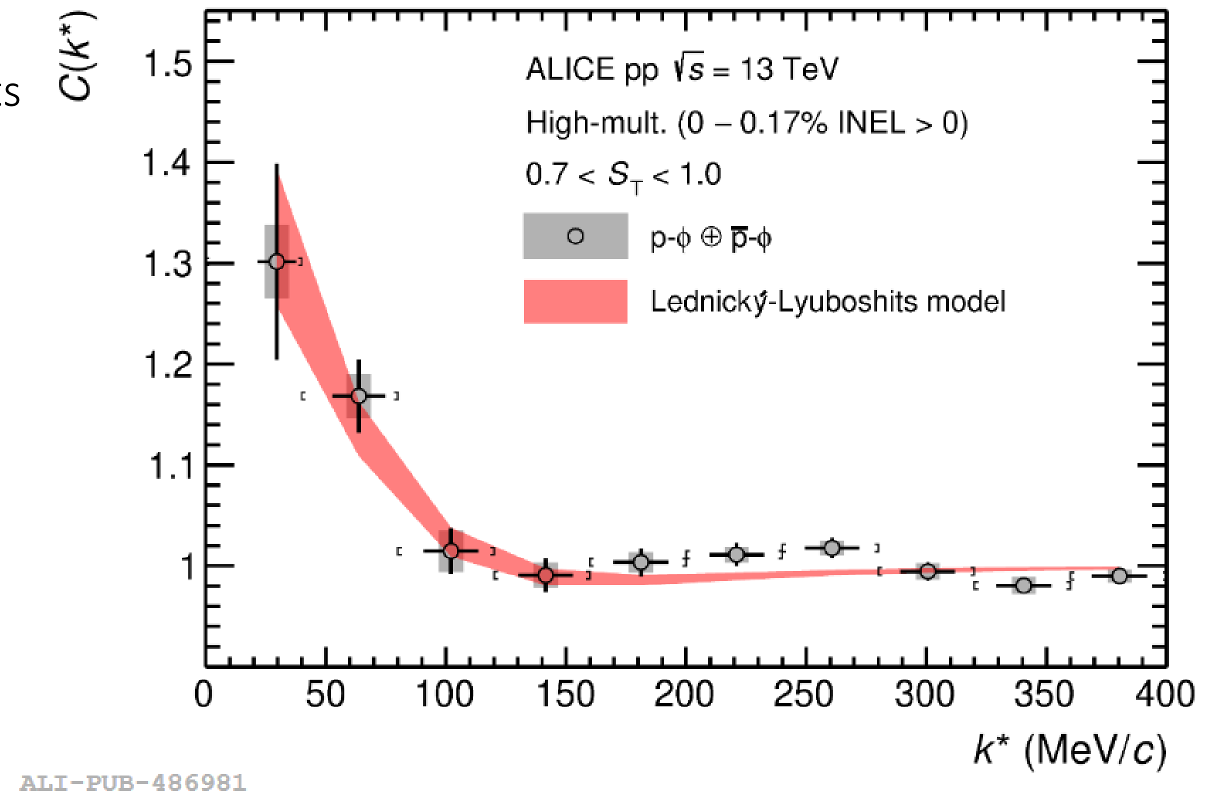
Im(f_0)=0.16±0.10(stat.) ±0.09(syst.) fm

- 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

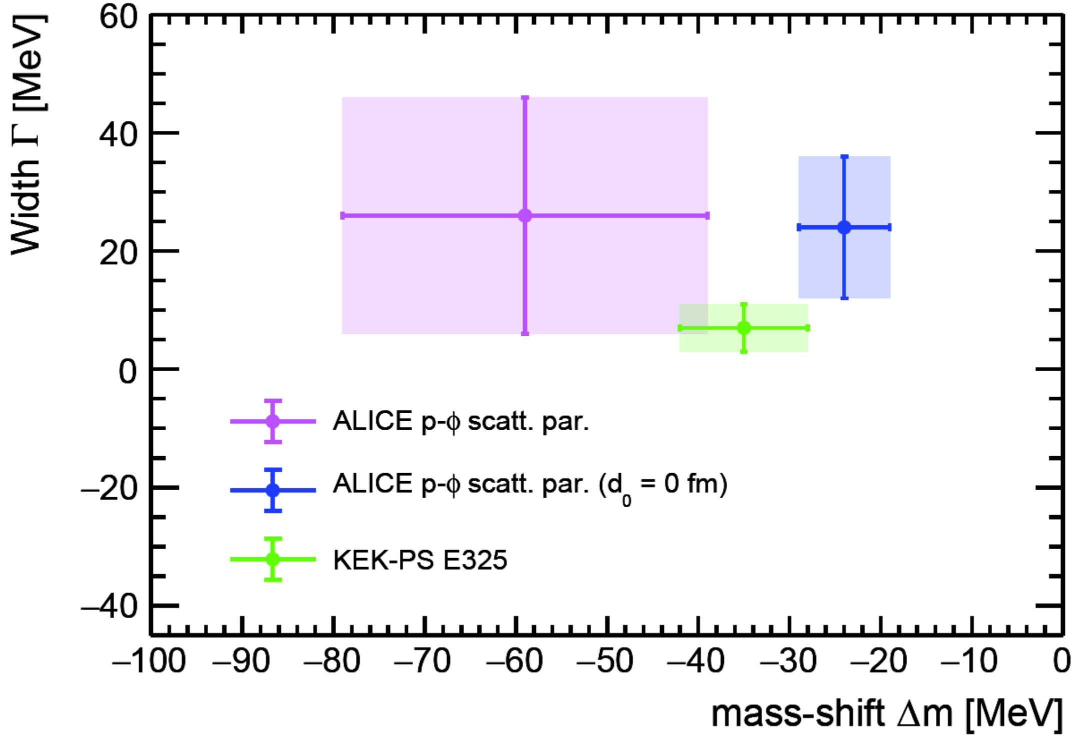
Im(f_0)=0.15±0.04(stat.) ±0.06(syst.) fm

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



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

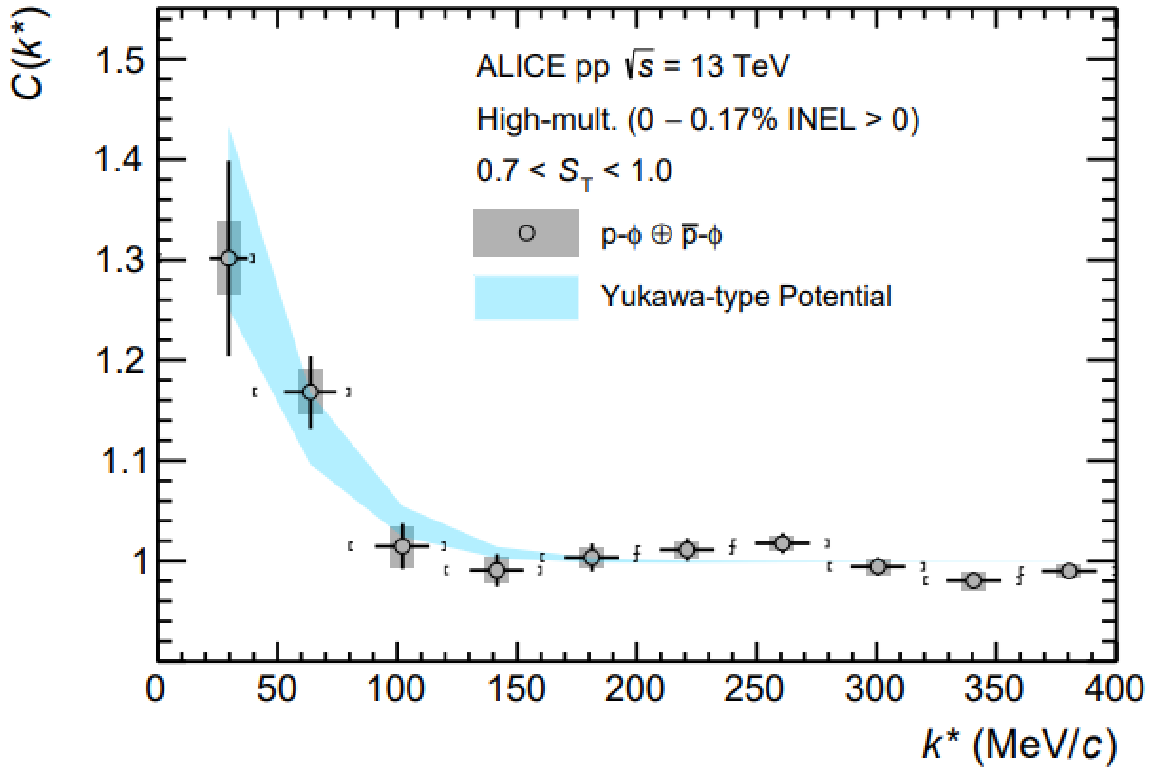
Strength A = 0.021 ± 0.009(stat.) ± 0.006(syst.)

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

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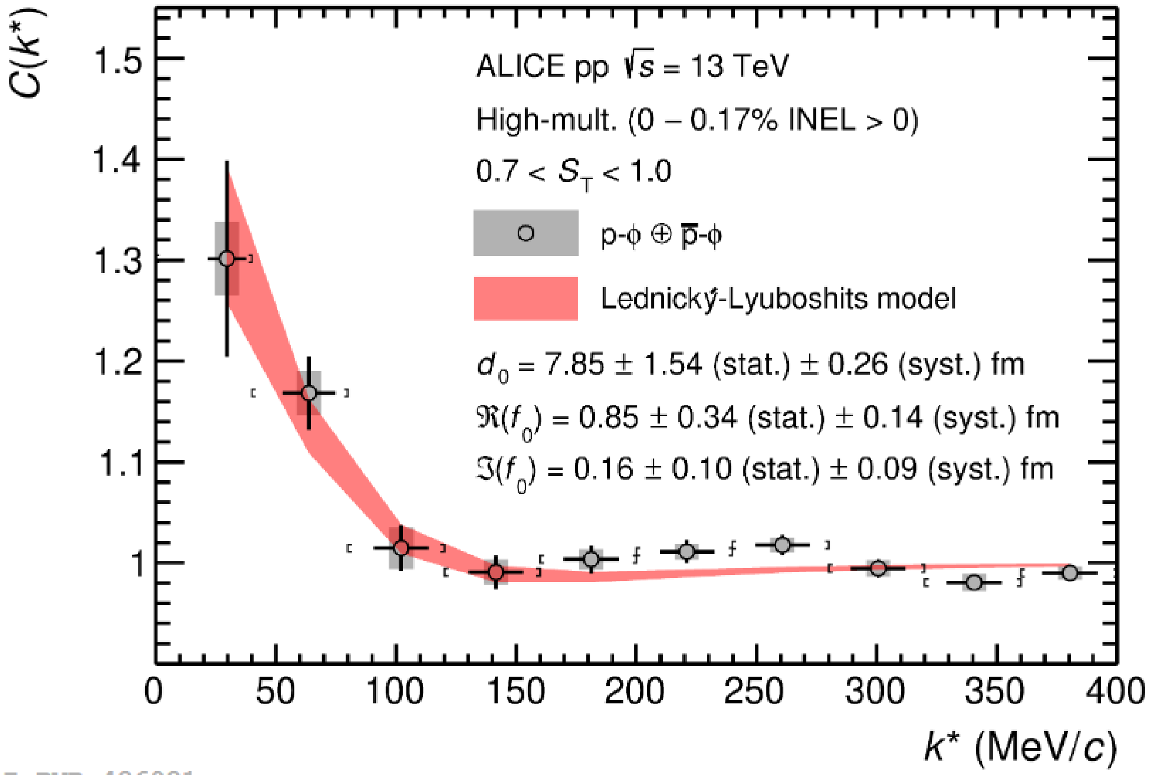
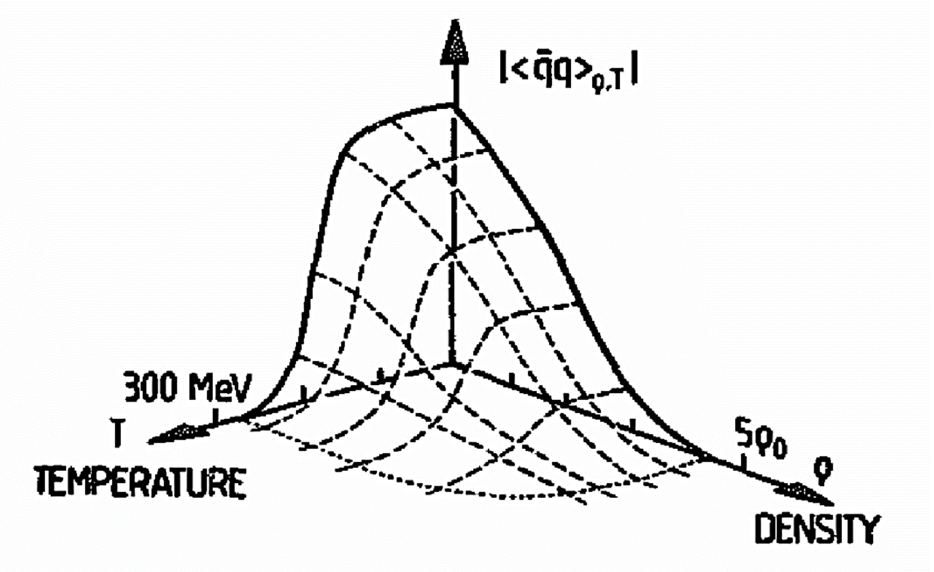


ALI-PUB-486981

BACKUP

Chiral symmetry

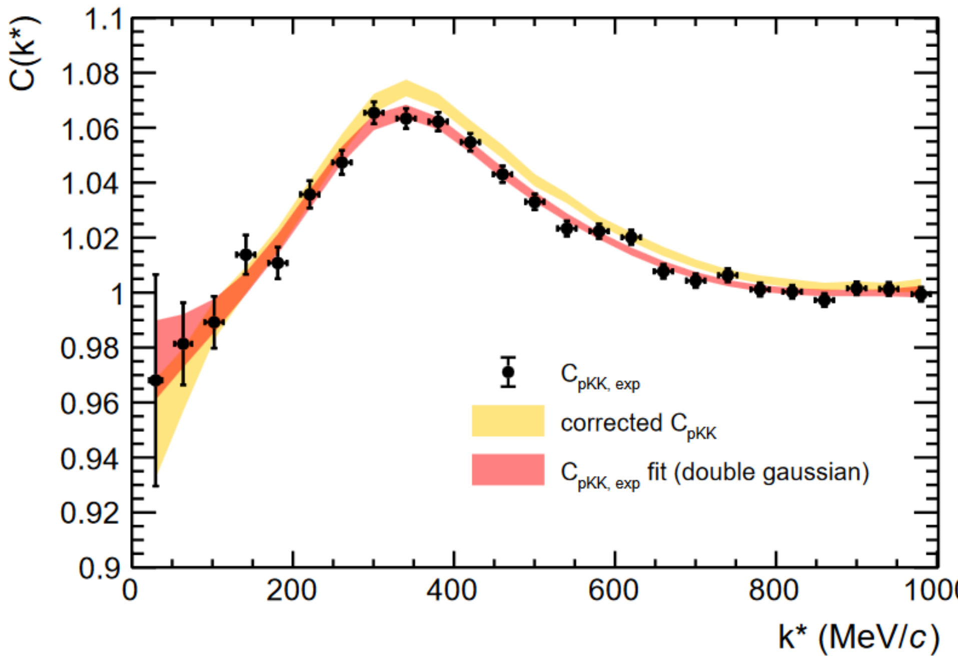
- Chiral symmetry spontaneously broken → non-zero vacuum expectation value $\langle q\bar{q} \rangle$
- Partial restoration expected ($\langle q\bar{q} \rangle \rightarrow 0$) in dense and/or hot strongly interacting medium → modification of $\langle q\bar{q} \rangle$ condensate reflected in spectral shape of hadrons
    - ϕ meson well-known probe, expected to exhibit in-medium broadening and mass shift
- Study of mesons-nucleon interaction **in vacuum** → constrain baseline for in-medium measurements



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

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

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 $C_{p-KK}(k^*)$:

$$C_{tot}(k^*) \\ = \mathcal{N} \cdot \left(MJ_{p-\phi}(k^*) + BL\right) \cdot \left[\left(\lambda_{gen} - \frac{\lambda_{p-KK} \cdot \alpha}{(1-\alpha)}\right) \cdot C_{gen}(k^*) + \lambda_{flat} \cdot C_{flat}(k^*)\right] + \frac{\lambda_{p-KK}}{(1-\alpha)} \cdot C_{p-KK,\boldsymbol{exp}}(k^*)$$

Data parametrized by a polynomial of fifth order

Data parametrized by a double Gaussian

Lednicky-Lyuboshits approach

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

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

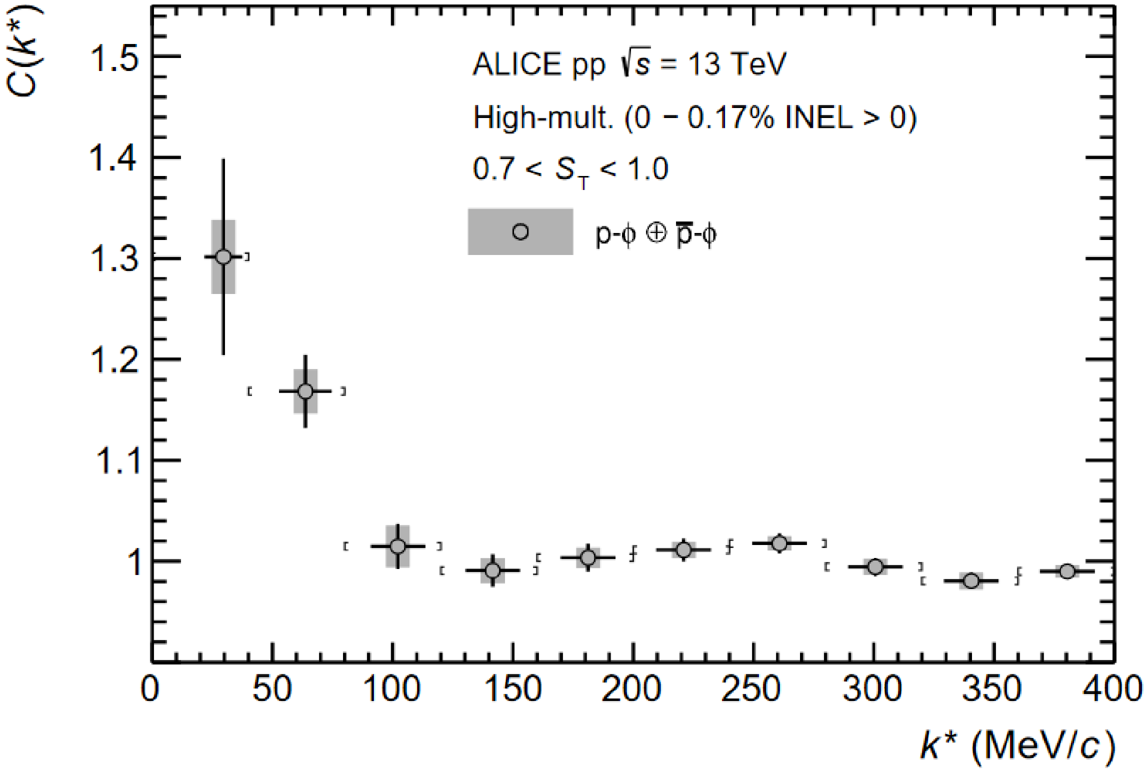
R. Lednicky and V.L. Lyuboshits, *Sov. J. Nucl. Phys*. **53** (1982) 770

- 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

Results p–ϕ

- Observation of **attractive** p–ϕ interaction
- 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
- Below-threshold channels effectively increase CF e.g. K–Λ, K–Σ, K–Λ (1405)

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



Relativistic mean field model

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

Meson-Baryon interaction | Scalar meson term | Vector meson term

Scattering length

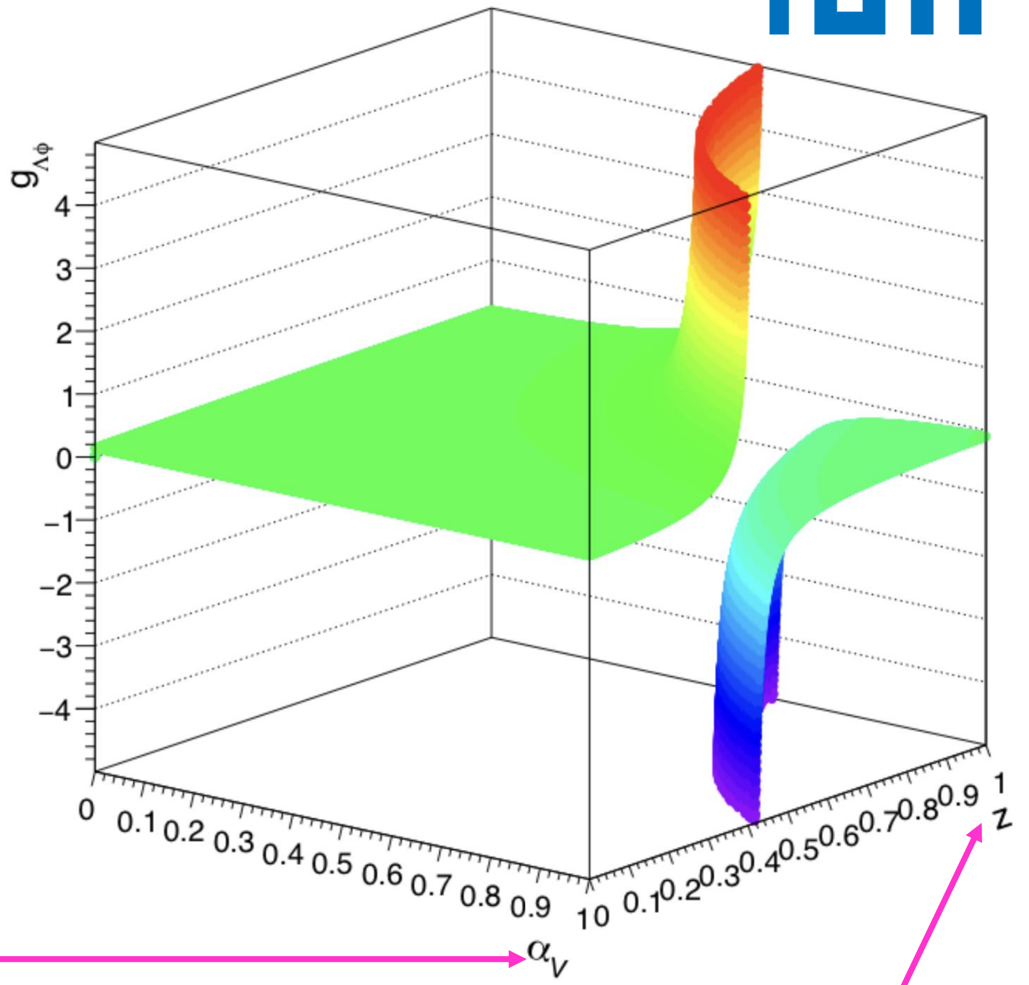
$$\frac{g_{N\phi}}{g_{N\omega}} = -\frac{\sqrt{3}-\sqrt{2}(4\alpha_V-1)z}{\sqrt{6}+(4\alpha_V-1)z},$$

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

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

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

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 $z=g_8/g_1$

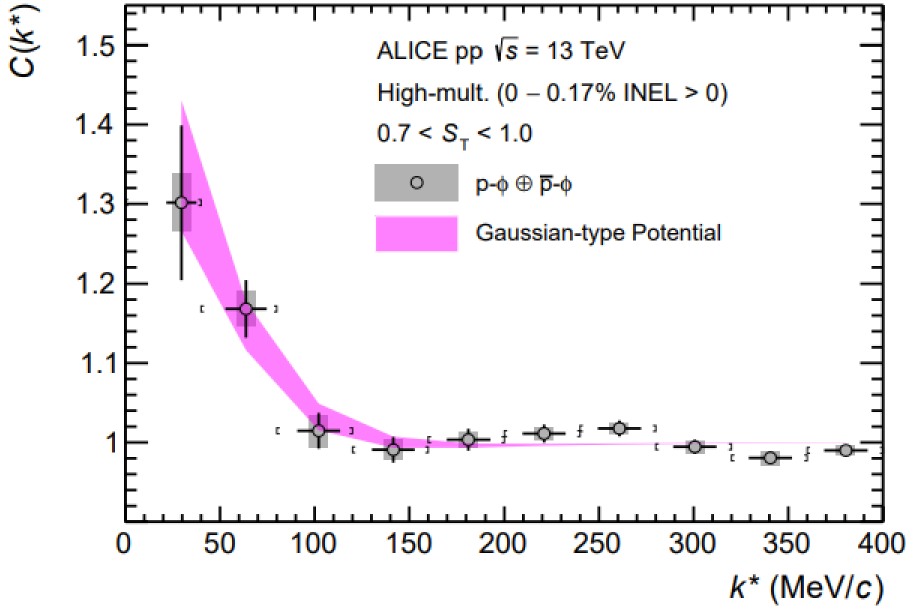
Results p–ϕ

- 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

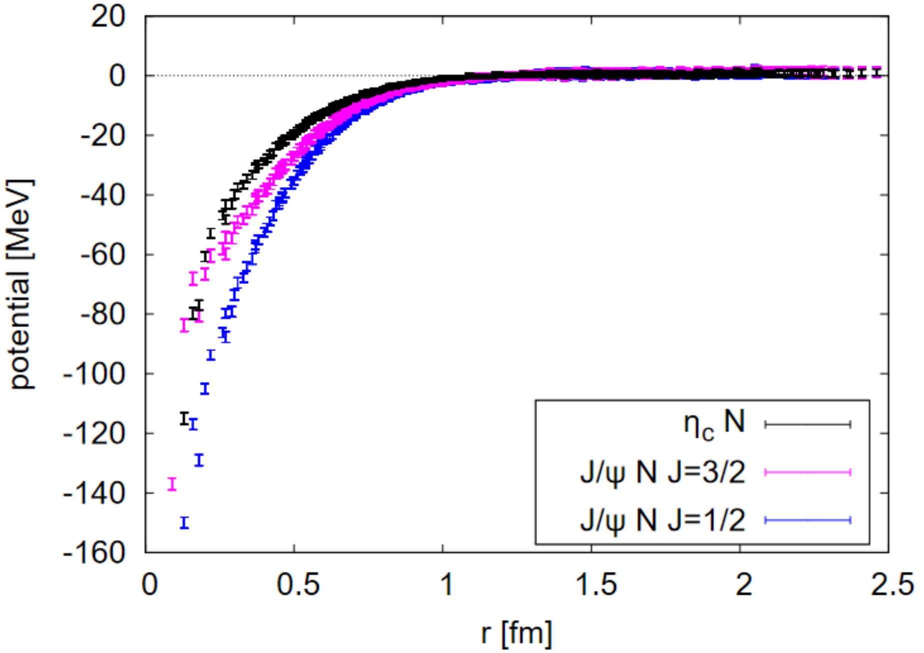
V_{eff} = 2.5±0.9(stat.) ± 1.4(syst.) MeV

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

- Very shallow potential depth found of
  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

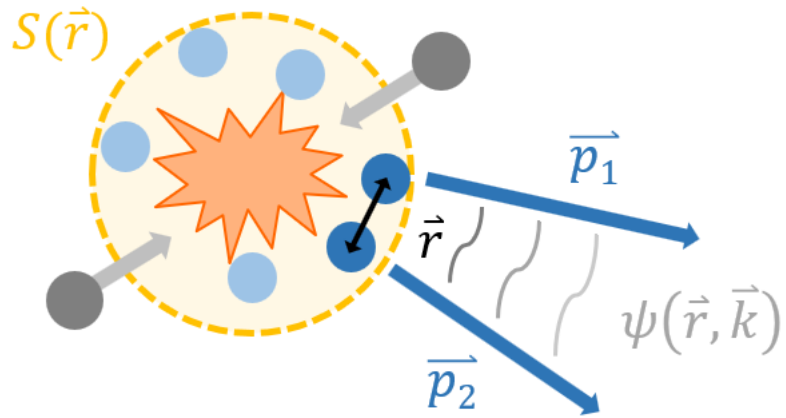


T. Sugiura, Y. Ikeda, and N. Ishii, *PoS* **LATTICE2018** (2019) 093



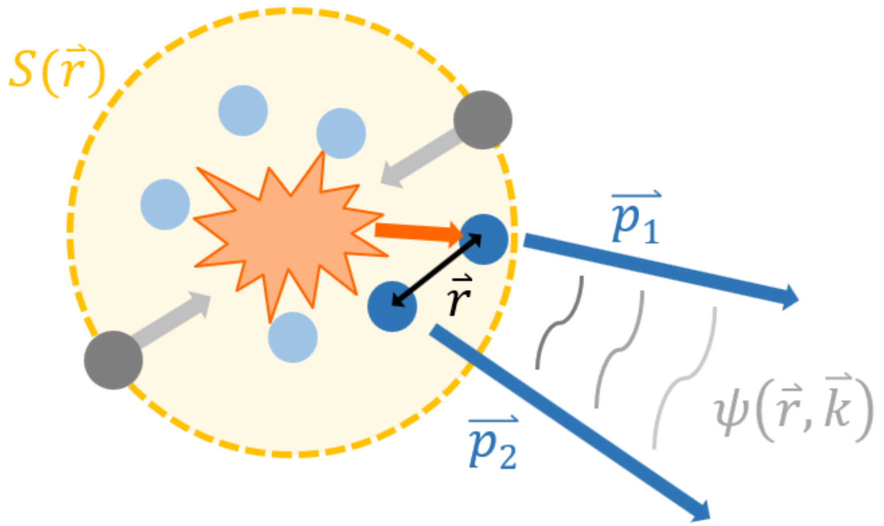
The source

- Particle emission from **Gaussian core** source



The source

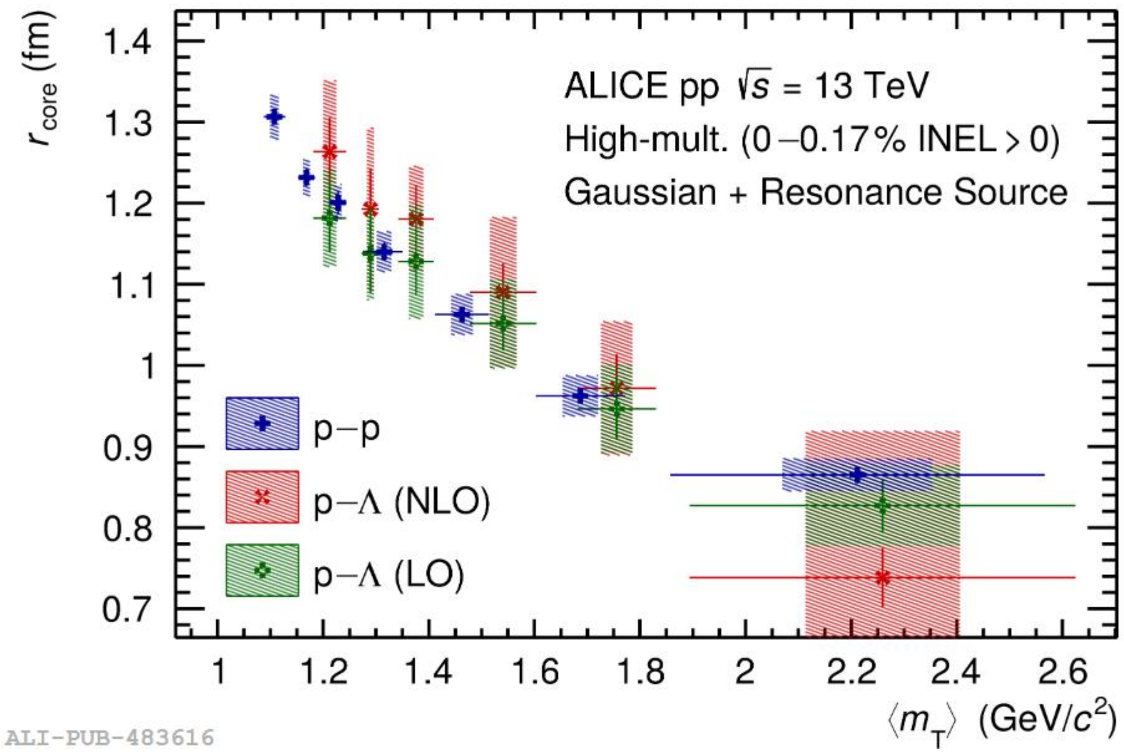
- Particle emission from **Gaussian core** source
- Core radius effectively increased by short-lived strongly decaying **resonances** (cτ ≈ r_{core})



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



The source

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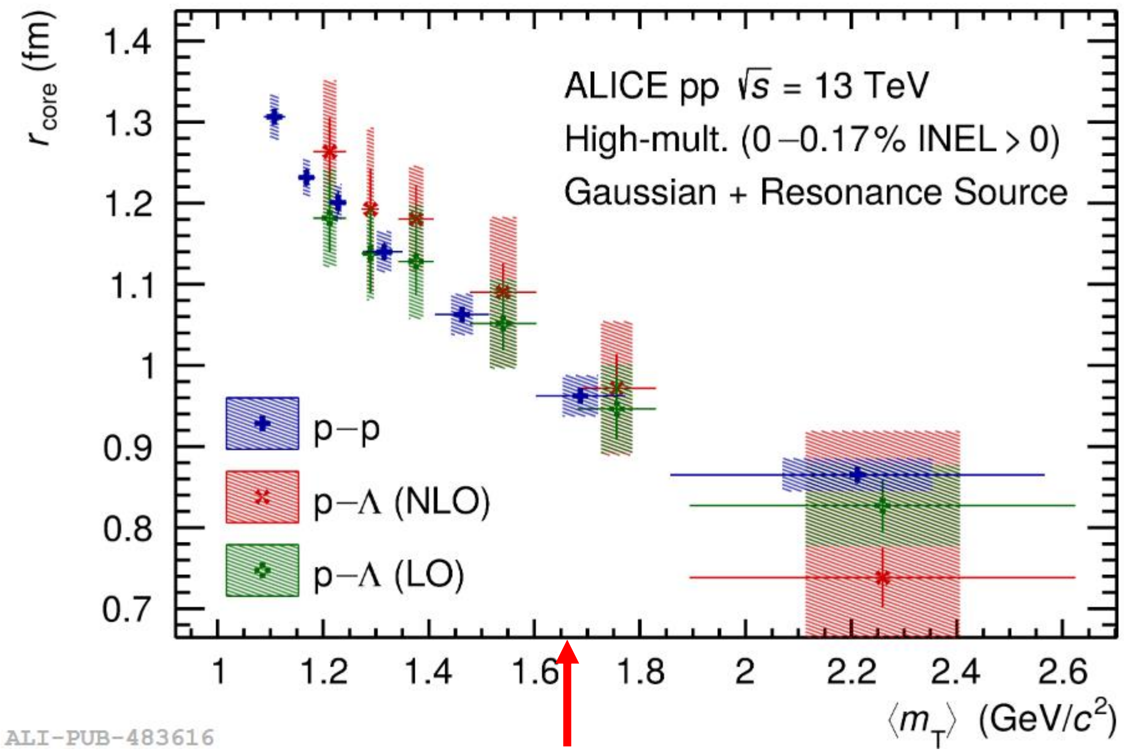
- Universal source model constrained from pp pairs (well-known interaction)
  ALICE Collab., *Physics Letters B*, **811** (2020) 135849
- Gaussian core source scales with $\langle m_T \rangle$
  - $r_{core} = 0.98 \pm 0.04$ fm
- Effects from short-lived resonances
  - no relevant contribution from strongly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



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