Proton-ϕ interaction studied in pp collisions with ALICE at the LHC

Emma Chizzali on behalf of the ALICE Collaboration
Technical University of Munich
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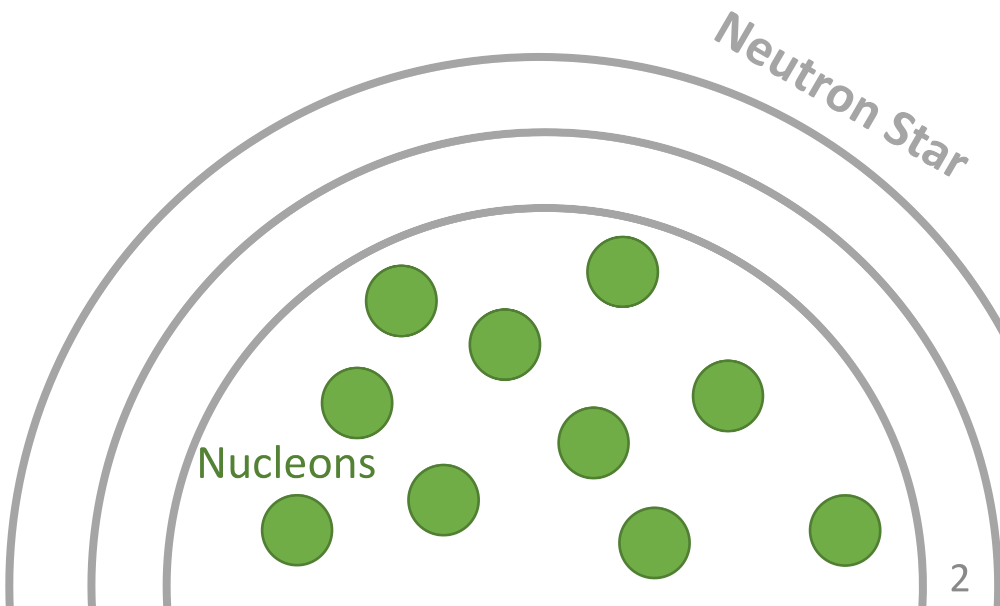
26/05/2021

Neutron Stars

- Neutron stars
  - Composition of the interior not well constrained (high densities)
  - Equation of State depends on constituents and interactions among them
- Possibility of hyperon star?



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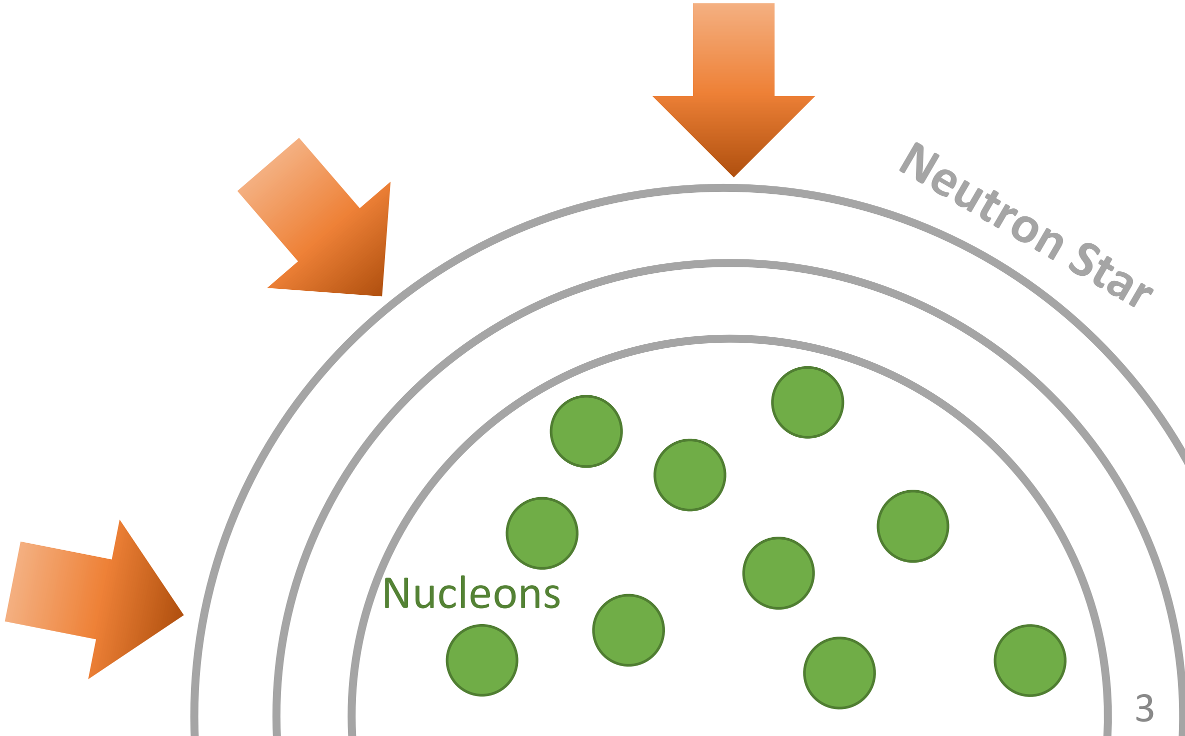

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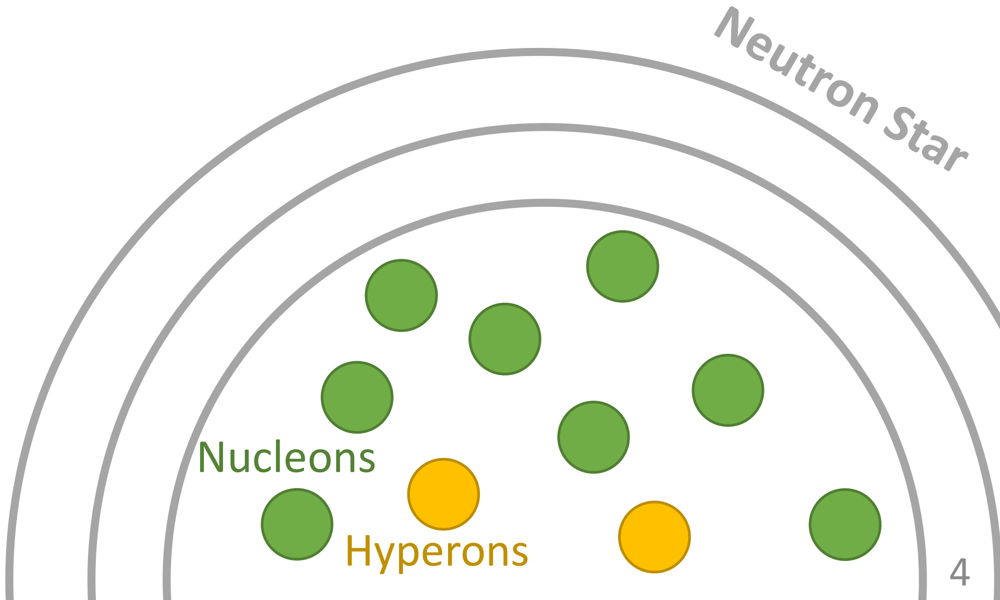

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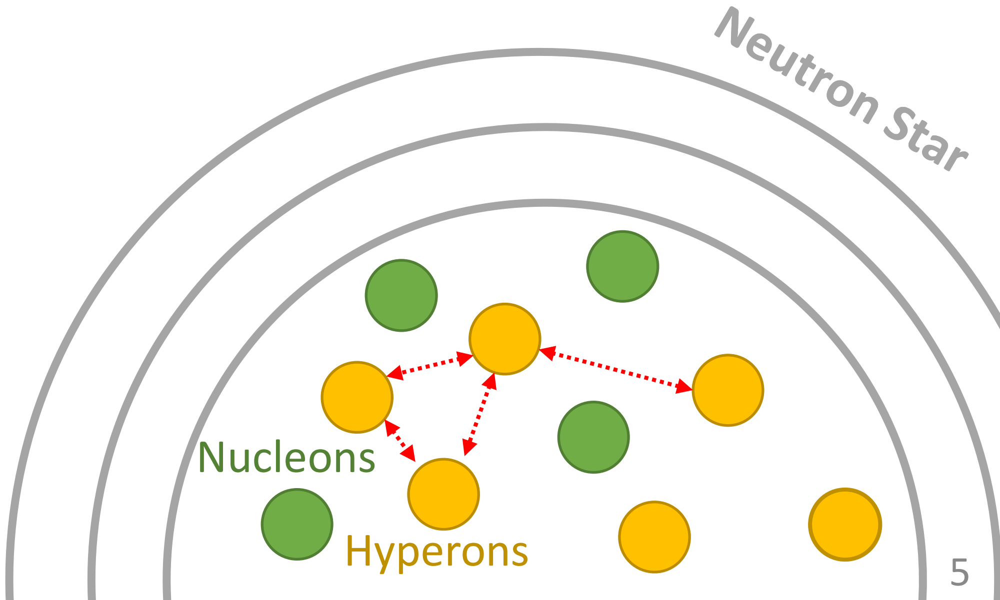

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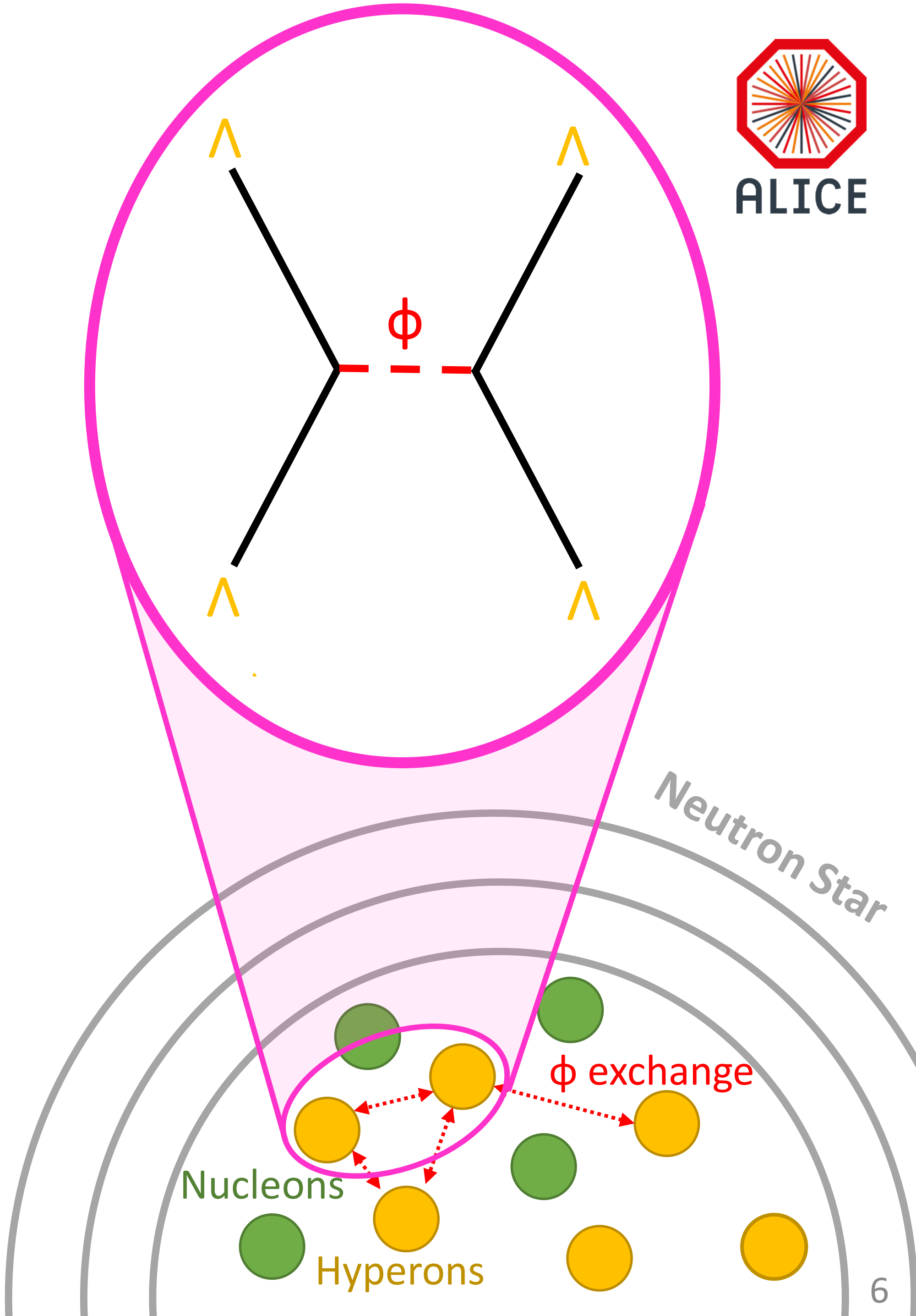
    - Can be modeled as effective ϕ meson exchange

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



Meson exchange

- ϕ meson as mediator of the strong repulsive force between hyperons
- Including repulsive Y–Y interaction leads to stiffening of the EoS

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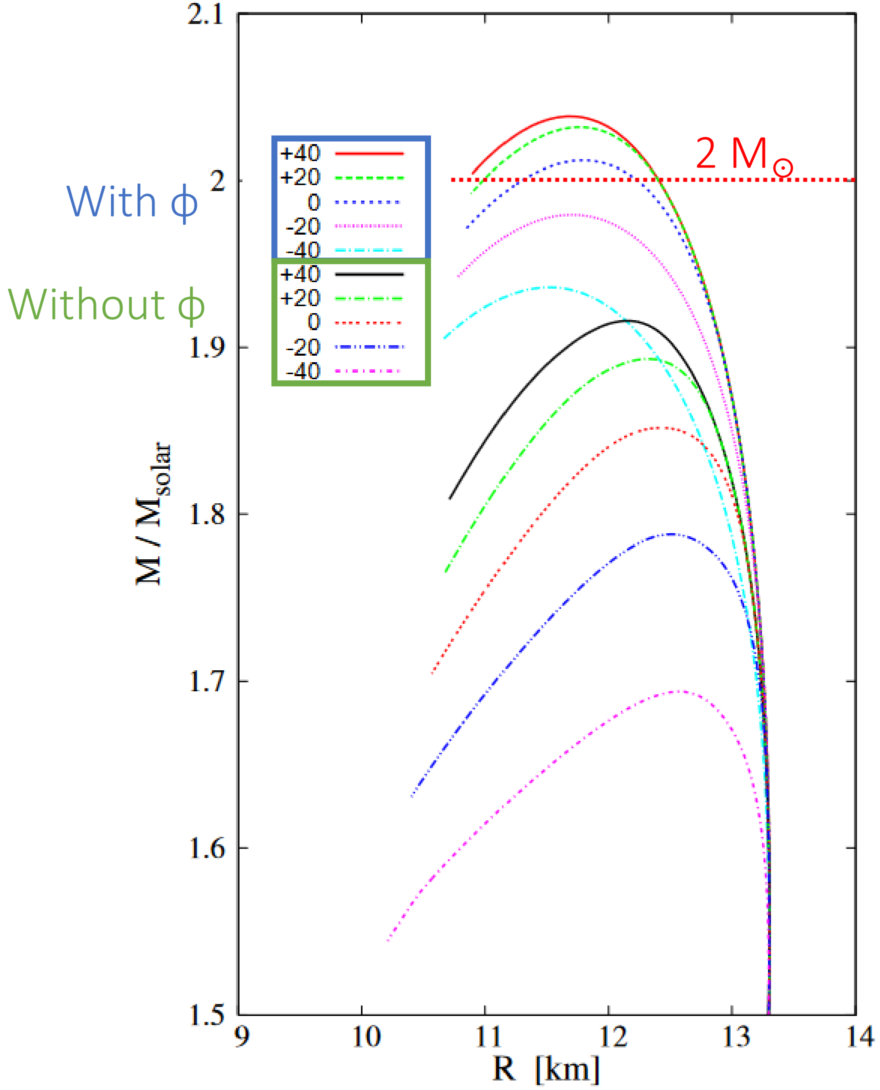

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    ALICE, Collab. *PRL* **123** (2019) 112002

    Takashi Inoue, *AIP Conference Proceedings* **2130** (2019) 020002

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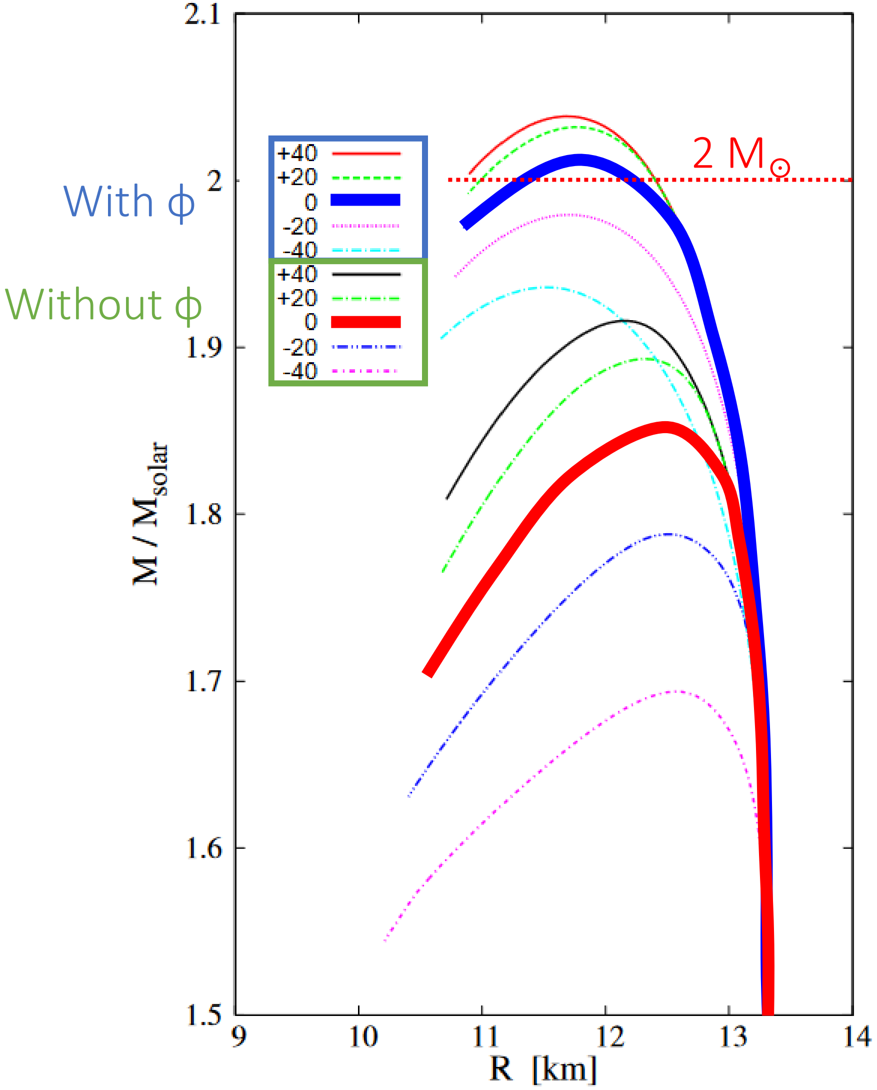

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- From theoretical calculations assuming SU(3) symmetry

$$2g_{\phi\Lambda} = -\frac{2\sqrt{2}}{3} g_{\omega N} \text{ and } g_{\omega N} \propto g_{\phi N} \rightarrow g_{\phi\Lambda} \propto g_{\phi N}$$

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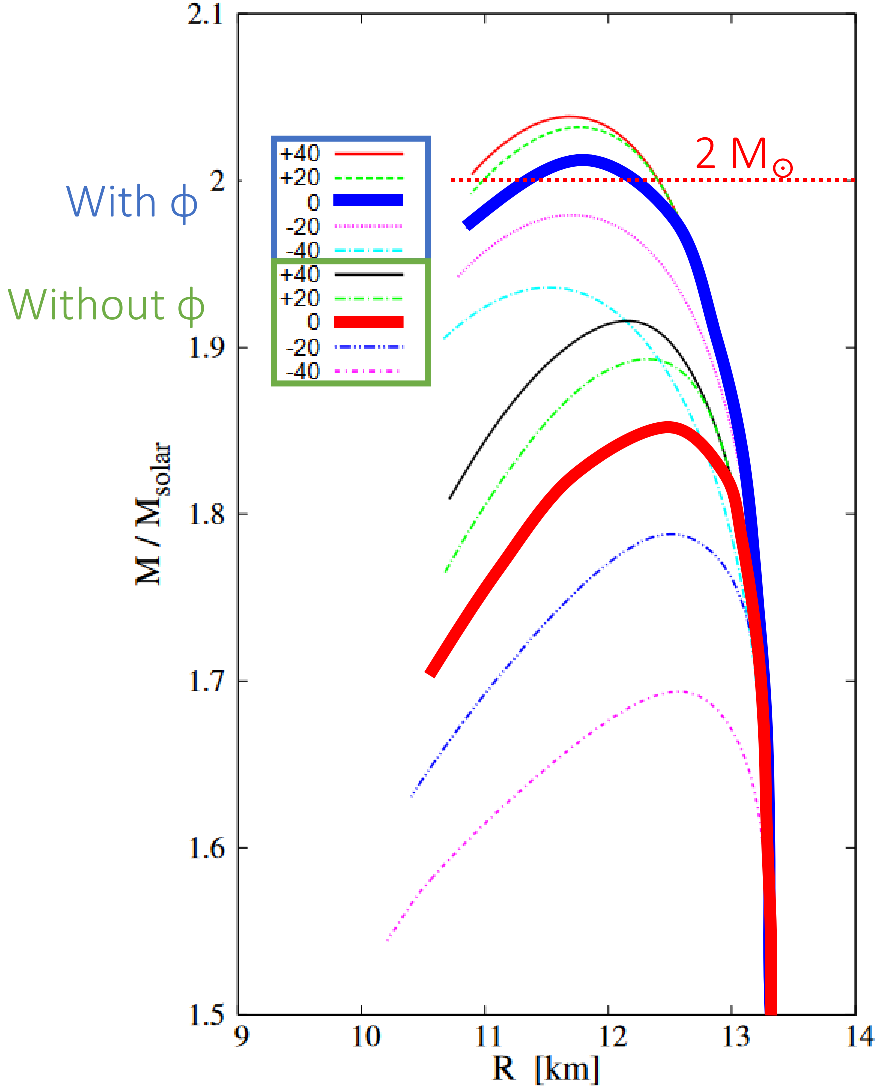
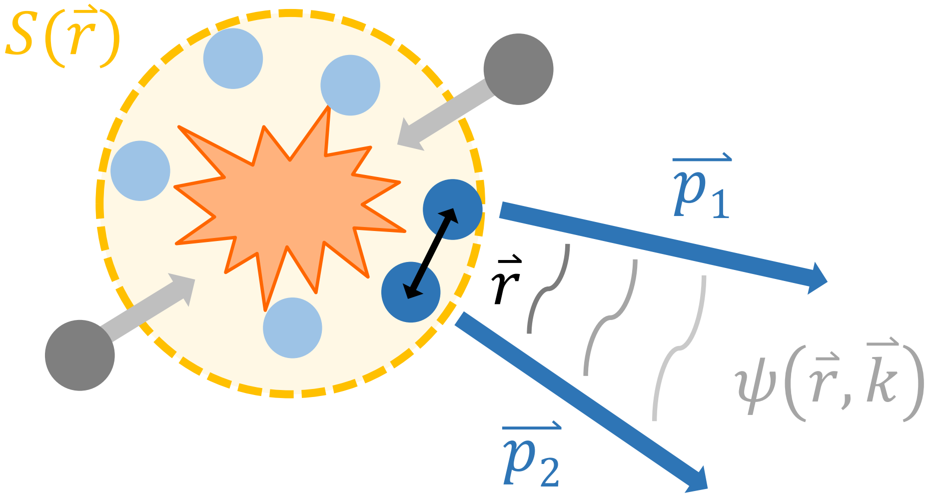


Correlation function



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

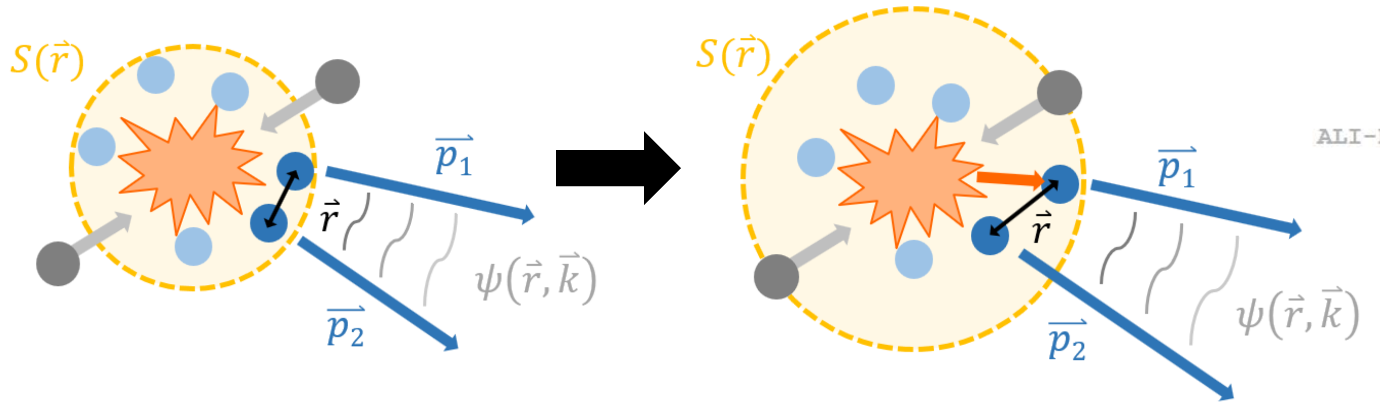
Relative momentum $k^* = \frac{1}{2}\,|\,\mathrm{p}_1^* - \mathrm{p}_2^*\,|$ and $\overrightarrow{\mathrm{p}_1^*} + \overrightarrow{\mathrm{p}_2^*} = 0$

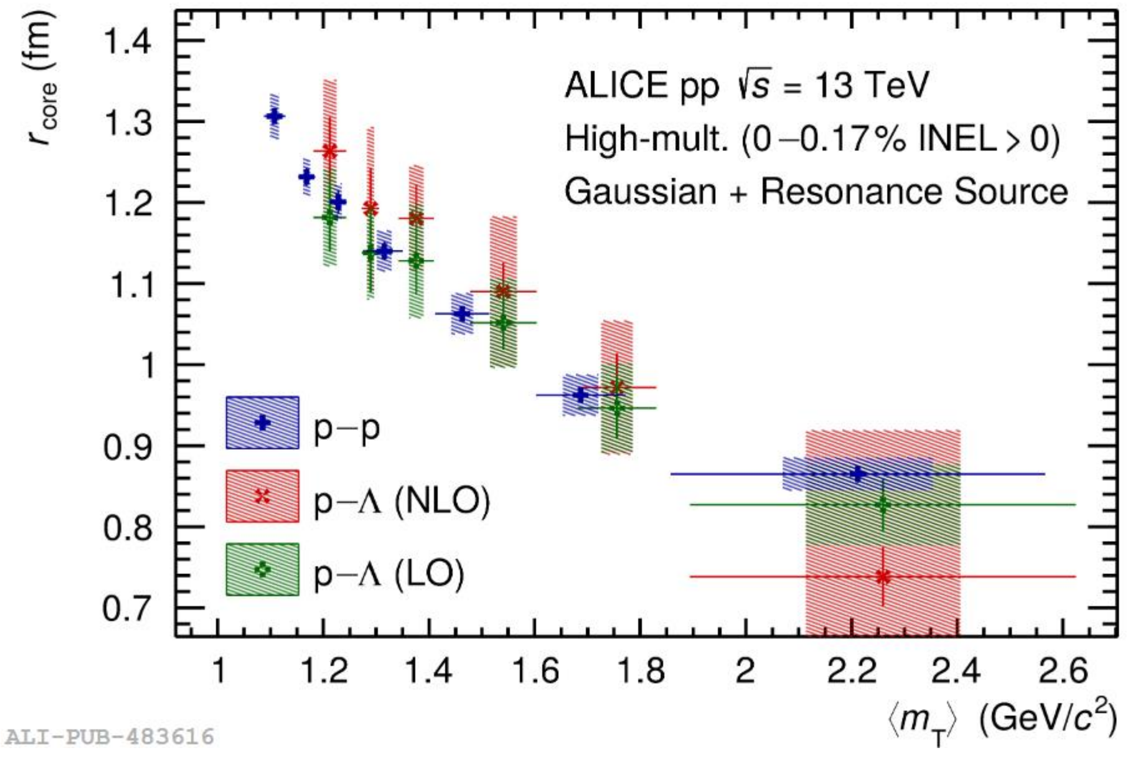
Relative distance $\vec{r}^* = \vec{r}_1^* - \vec{r}_2^*$

The source

- Source constrained from pp pairs (well known interaction)
  - **Gaussian core** from which particles are emitted is effectively increased by short-lived strongly decaying **resonances** ($c\tau \approx r_{core}$)
  - Use universal source model to get p- ϕ source

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





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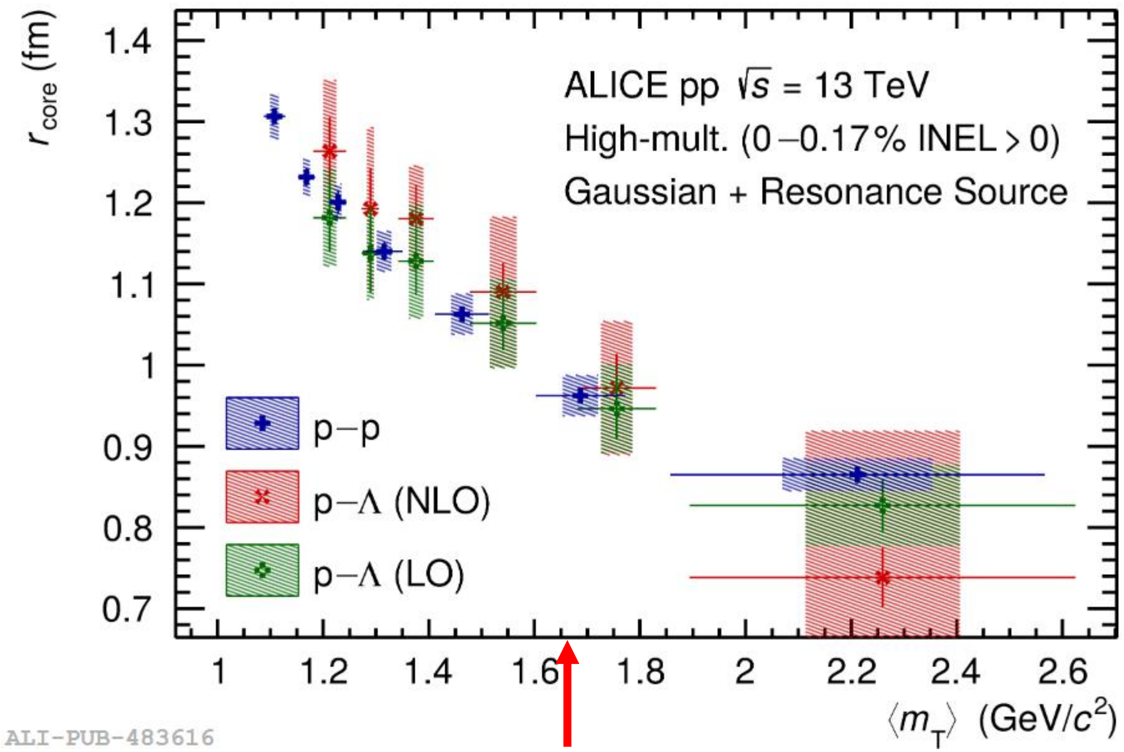
- Gaussian core source scales with $\langle m_T \rangle$
  - $r_{core} = 0.98 \pm 0.04$ fm
- Exponential tail from resonances
  - no relevant contribution from strongly decaying resonances feeding to the ϕ
  - Sizable amount of protons from decay of e.g. Delta resonances (only ~33% primordial protons)
  - effective Gaussian size: $\boldsymbol{r_{eff}} = 1.08 \pm 0.05$ fm



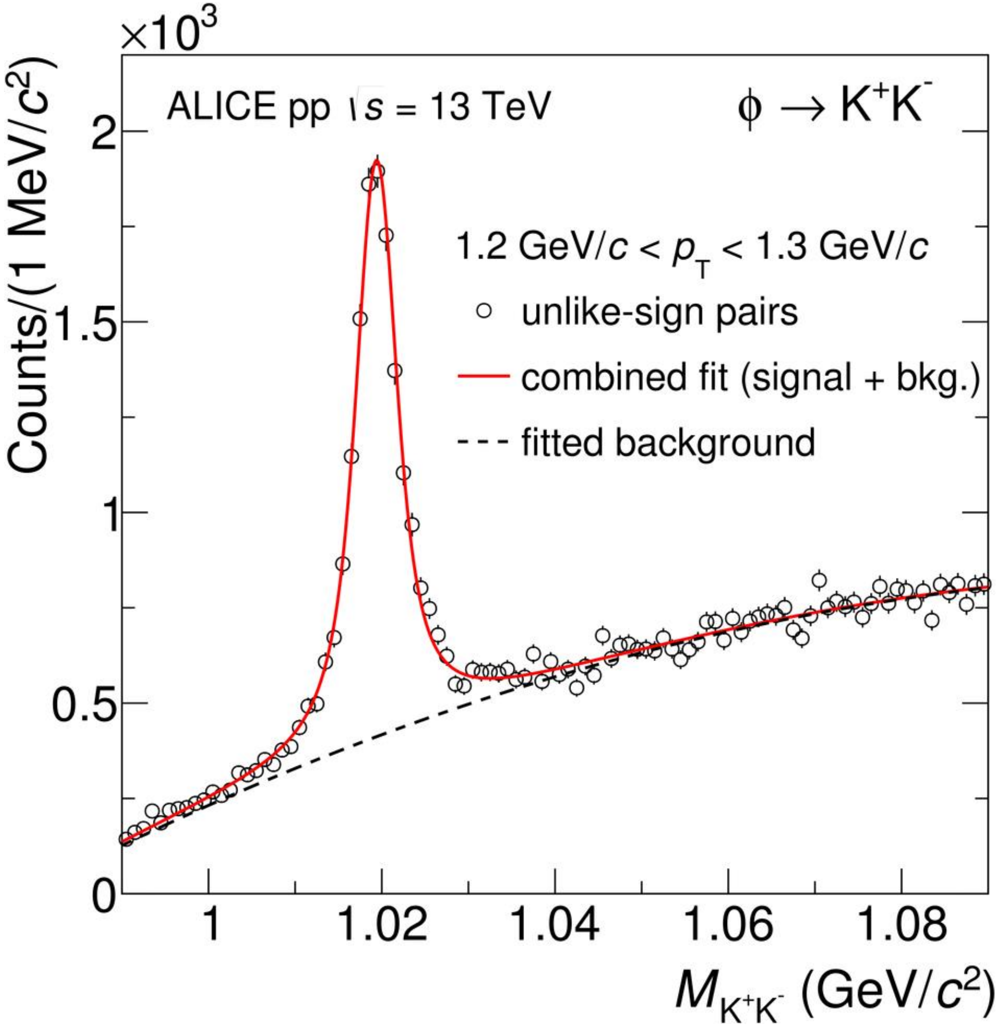
$\langle m_{T,\,p\phi} \rangle = 1.66$ GeV/c^2

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%

pair	yield with k*<200 MeV/c
$\bar{p}-\phi$	3.61 x 10^4
$p-\phi$	4.17 x 10^4

ALICE Collab., *Eur.Phys.J.C* **81** (2021) 3, 256

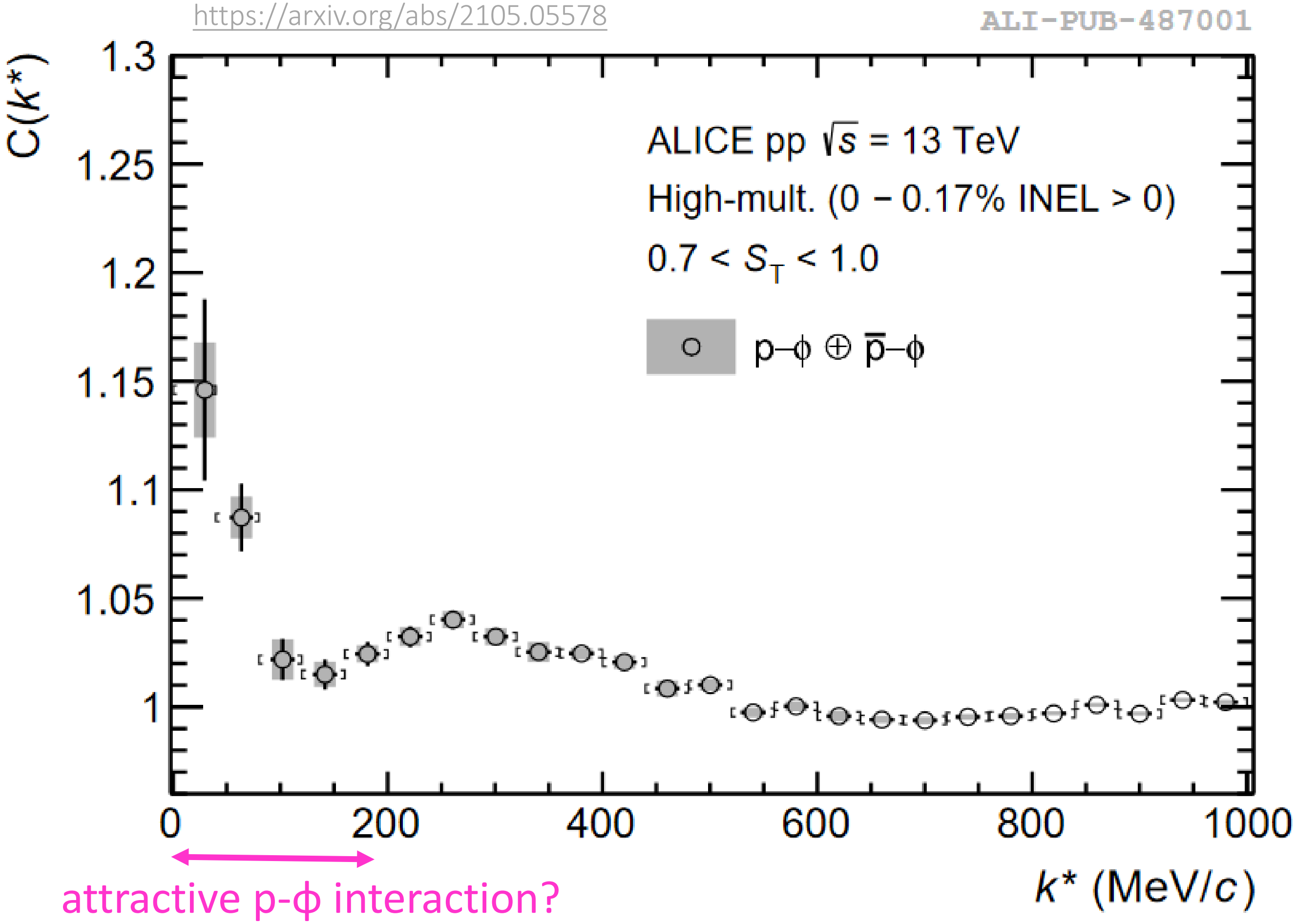


CF model

$$C_{exp}(k^*) = C_{p-\phi}(k^*)$$

Experimental p-ϕ correlation function

https://arxiv.org/abs/2105.05578



attractive p-ϕ interaction?

enhancement → additional contributions to CF besides genuine p-ϕ interaction

CF model

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CF model

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

CF model

ALICE

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

<u>Background</u> (non-femto)
- auto-correlations (minijets)
- energy-momentum conservation effects

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

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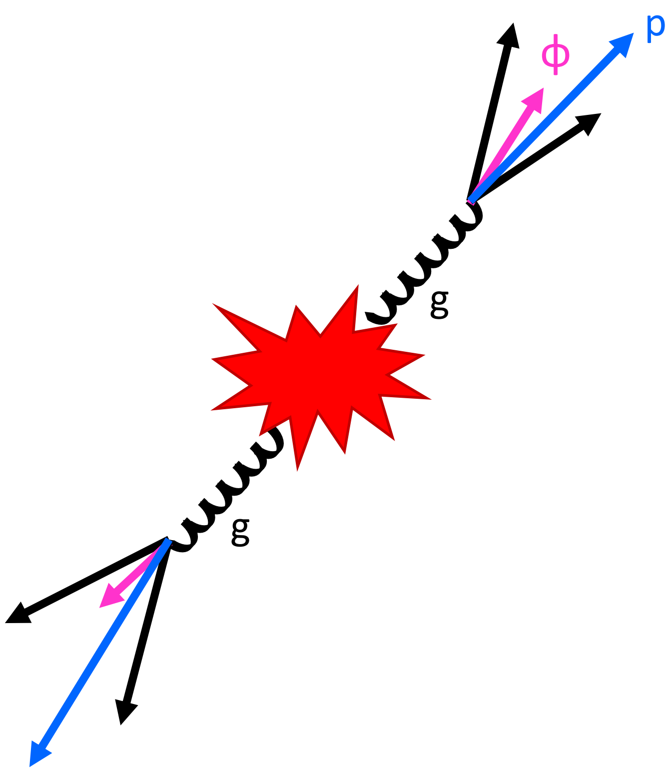
- Present in previous meson-meson and meson-baryon analyses
  ALICE Collab. Phys. Rev. Lett. **124** (2020) 092301
- Auto-correlated p and ϕ emitted in jet-like structures



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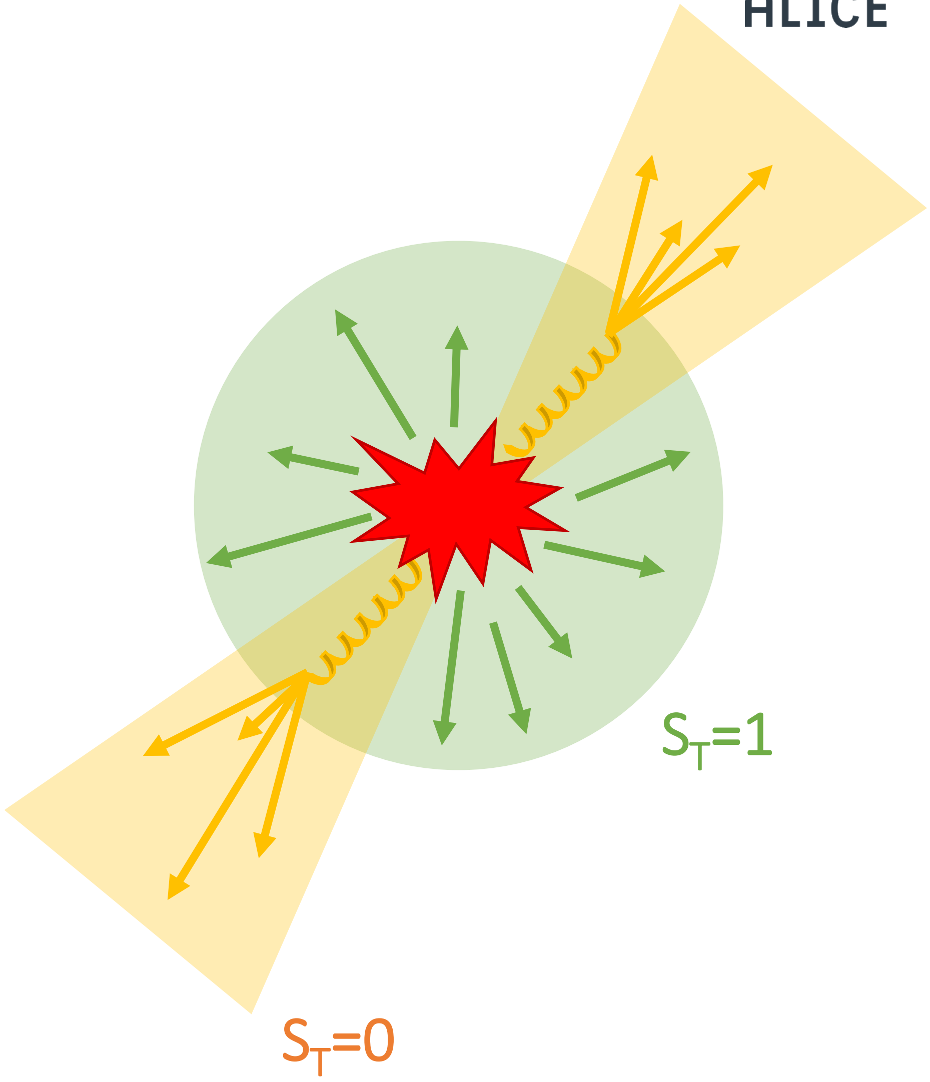
- Less pronounced in spherical events
  - Event shape classified by transverse Sphericity S_T
    ALICE Collab., *JHEP* **09** (2019) 108
  - Caluclation from eigenvalues $\lambda_1 \geq \lambda_2$ of Transverse Momentum Matrix:

$$M_{xy} = \frac{1}{\sum_j p_{Tj}} \sum_i \frac{1}{p_{Ti}} \begin{bmatrix} p_{xi}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & p_{yi}^2 \end{bmatrix} \rightarrow S_T = \frac{2\lambda_2}{\lambda_1+\lambda_2}, \; S_T \in [0,1]$$

  - In this Analysis: $0.7 < S_T < 1.0$



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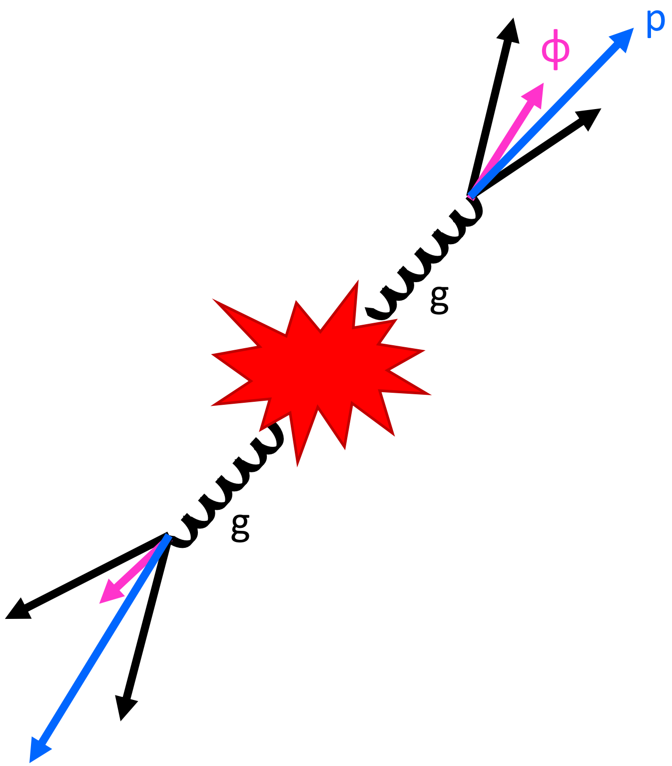
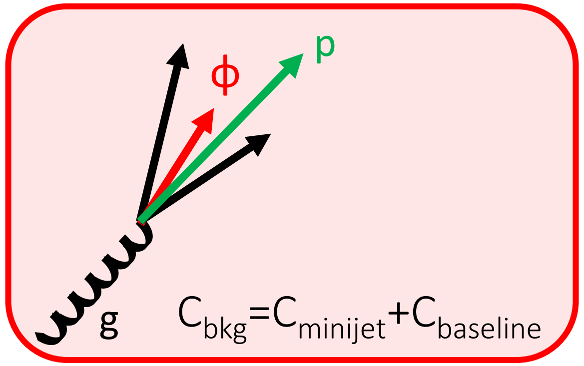
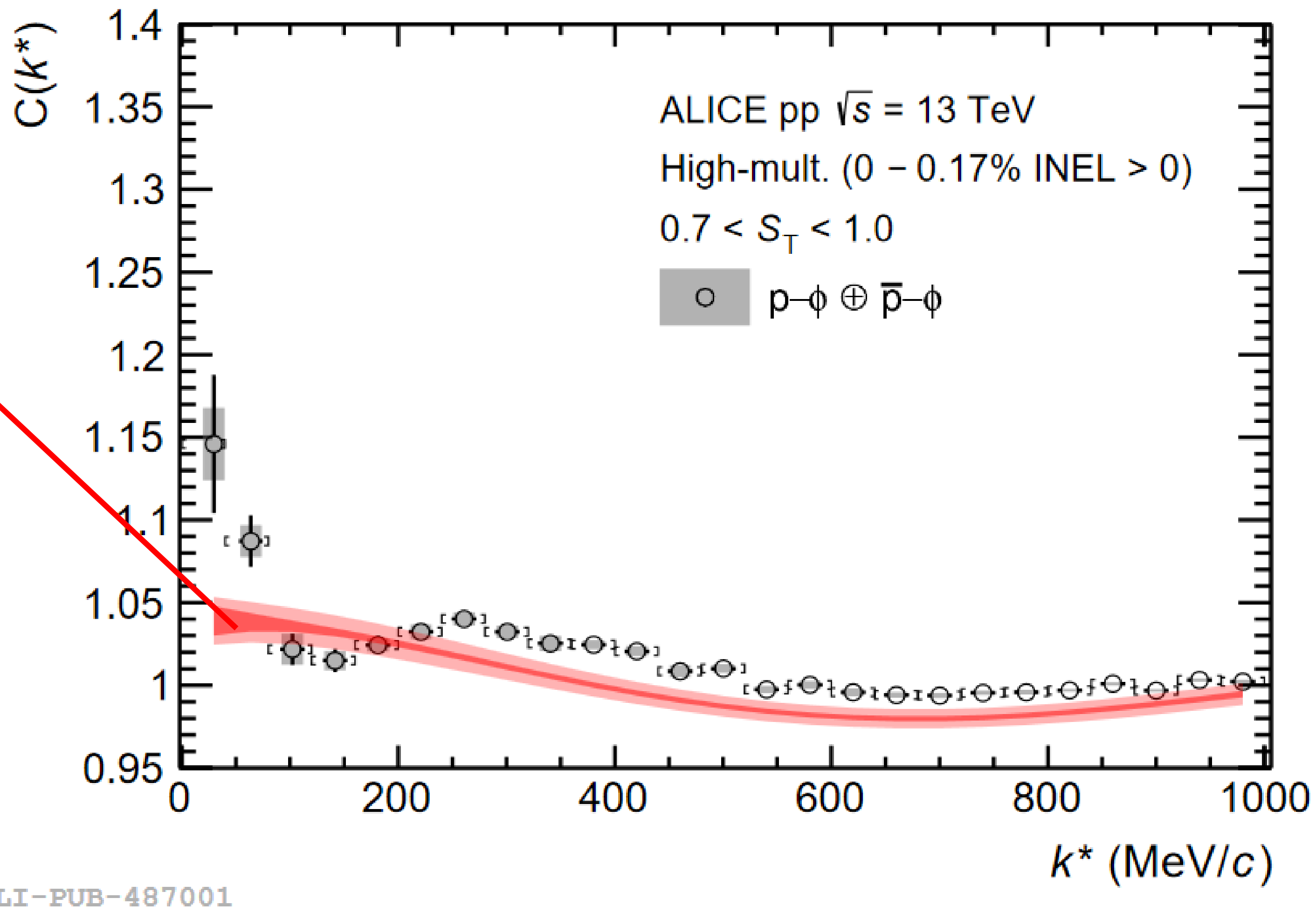
- Residual minijet background well described by Phytia 8
  ALICE Collab., *Phys. Rev. D* **84** (2011) 112004



Non-femtoscpic background

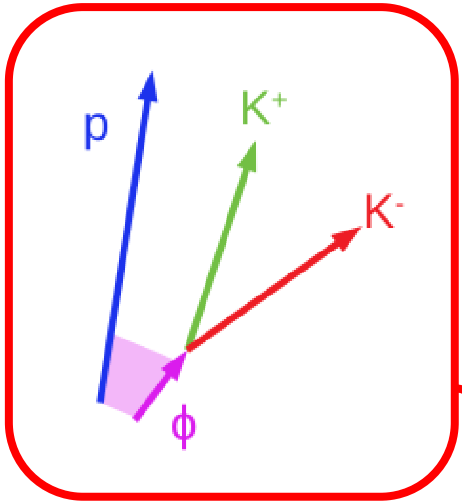


https://arxiv.org/abs/2105.05578

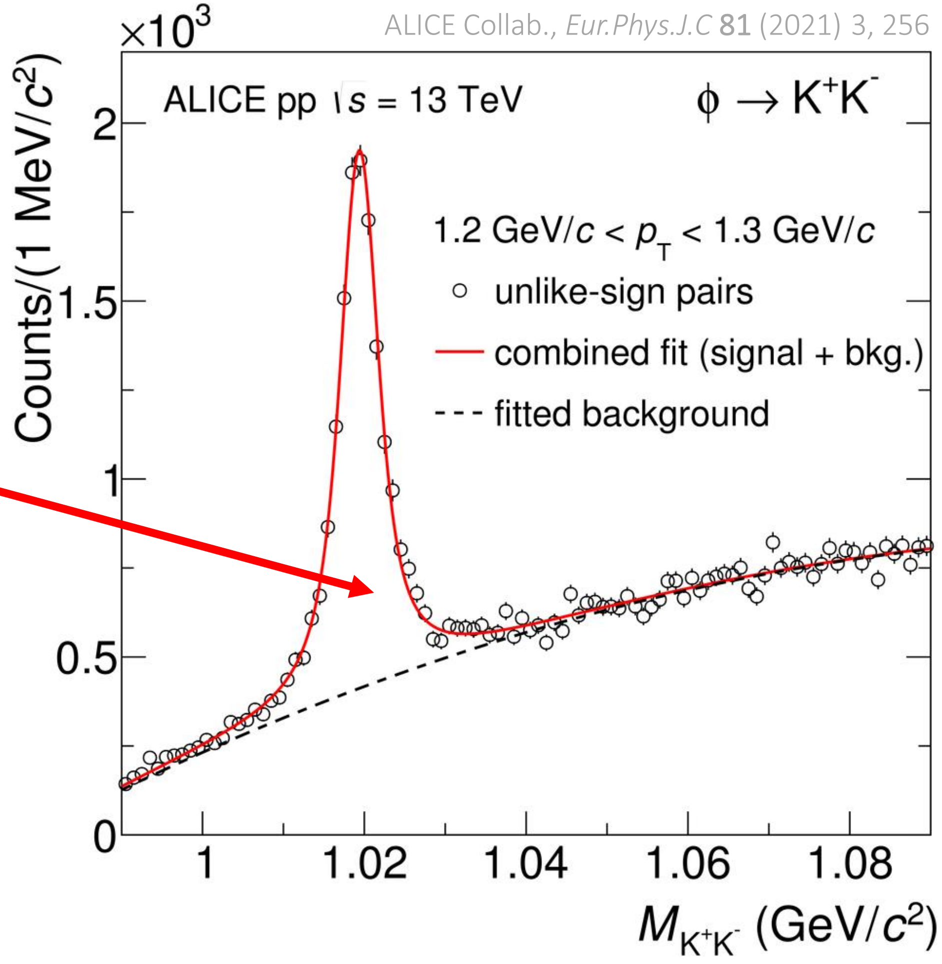


Combinatorial p-K$^+$K$^-$ background

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



ALICE Collab., *Eur.Phys.J.C* **81** (2021) 3, 256



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

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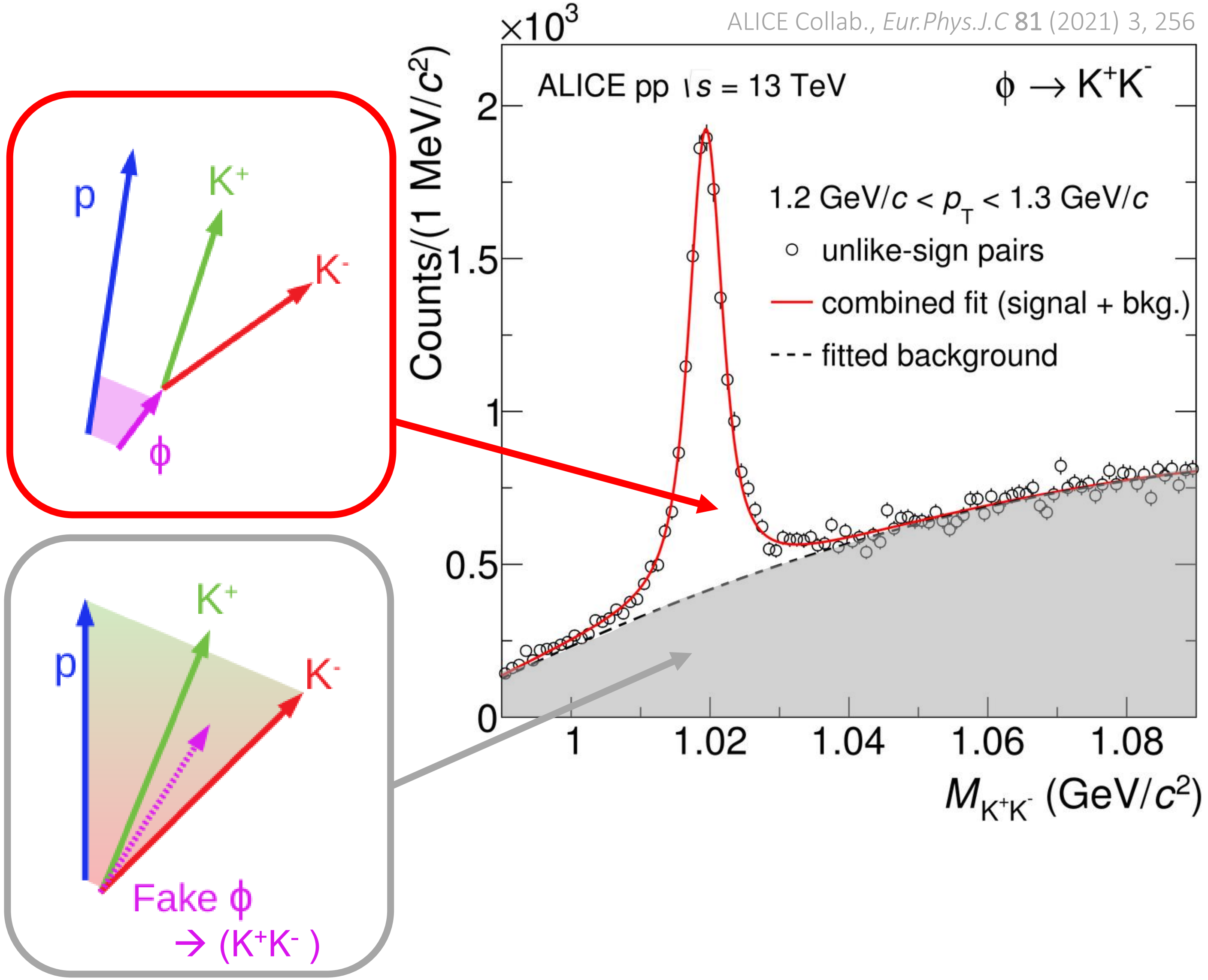
- purity of reconstructed ϕ mesons only ~57%
  → correlation signal from 2 and 3-body interaction between p, K$^+$ and K$^-$



Combinatorial p-K^+K^- background

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  → correlation signal from 2 and 3-body interaction between p, K^+ and K^-
- Sideband analysis

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

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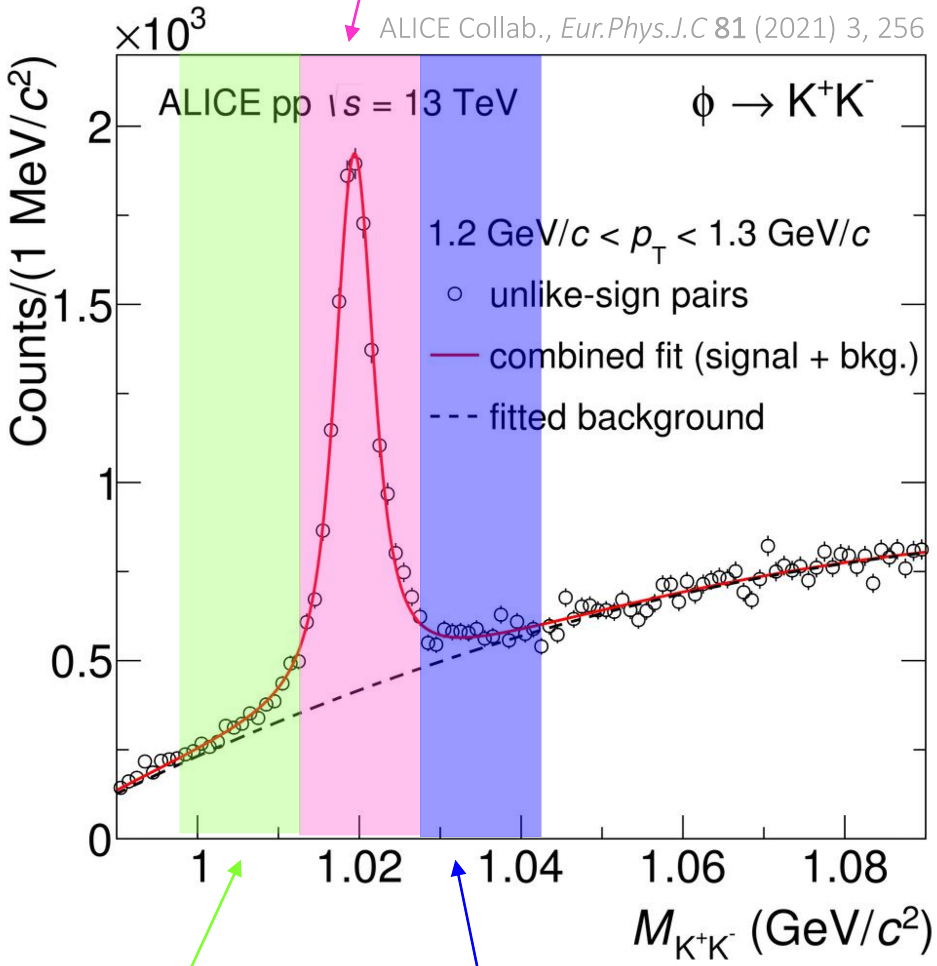
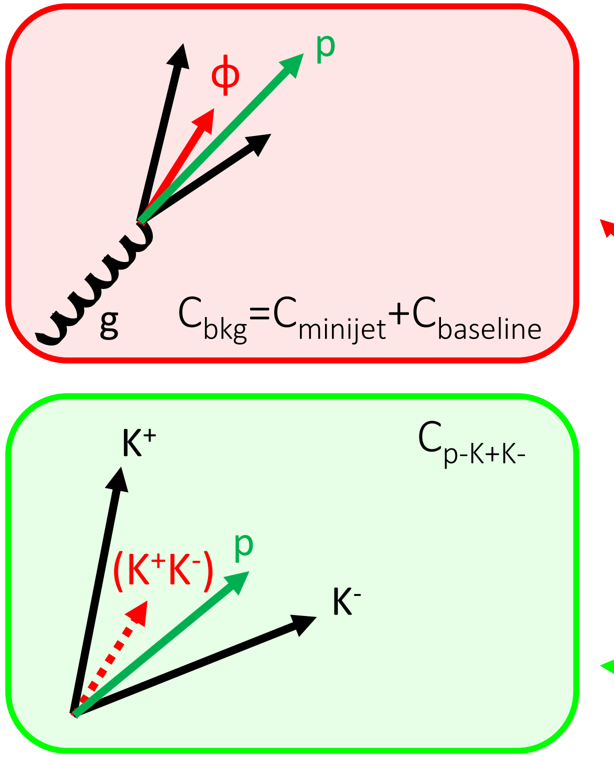


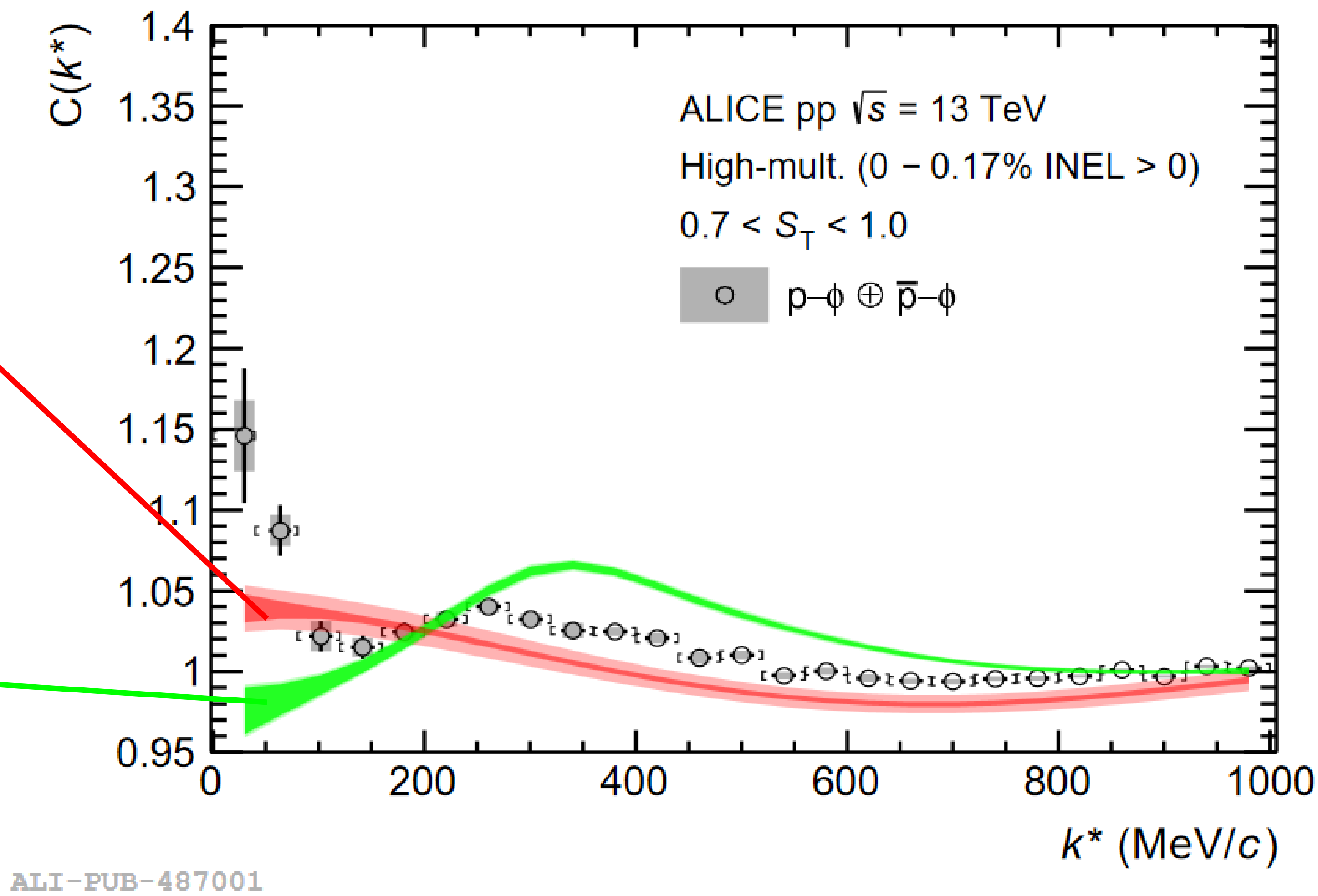
Left SB: 0.995-1.011 GeV/c^2

Right SB: 1.028-1.044 GeV/c^2

Non-femtoscpic background

https://arxiv.org/abs/2105.05578





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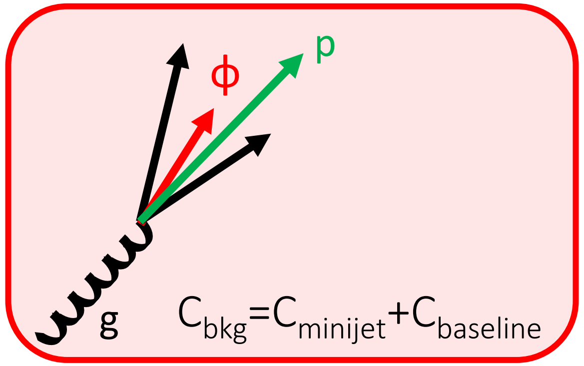
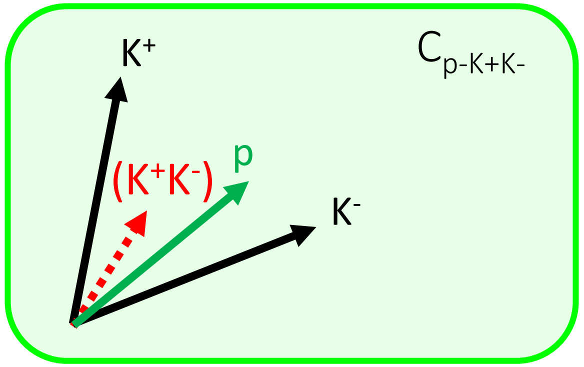
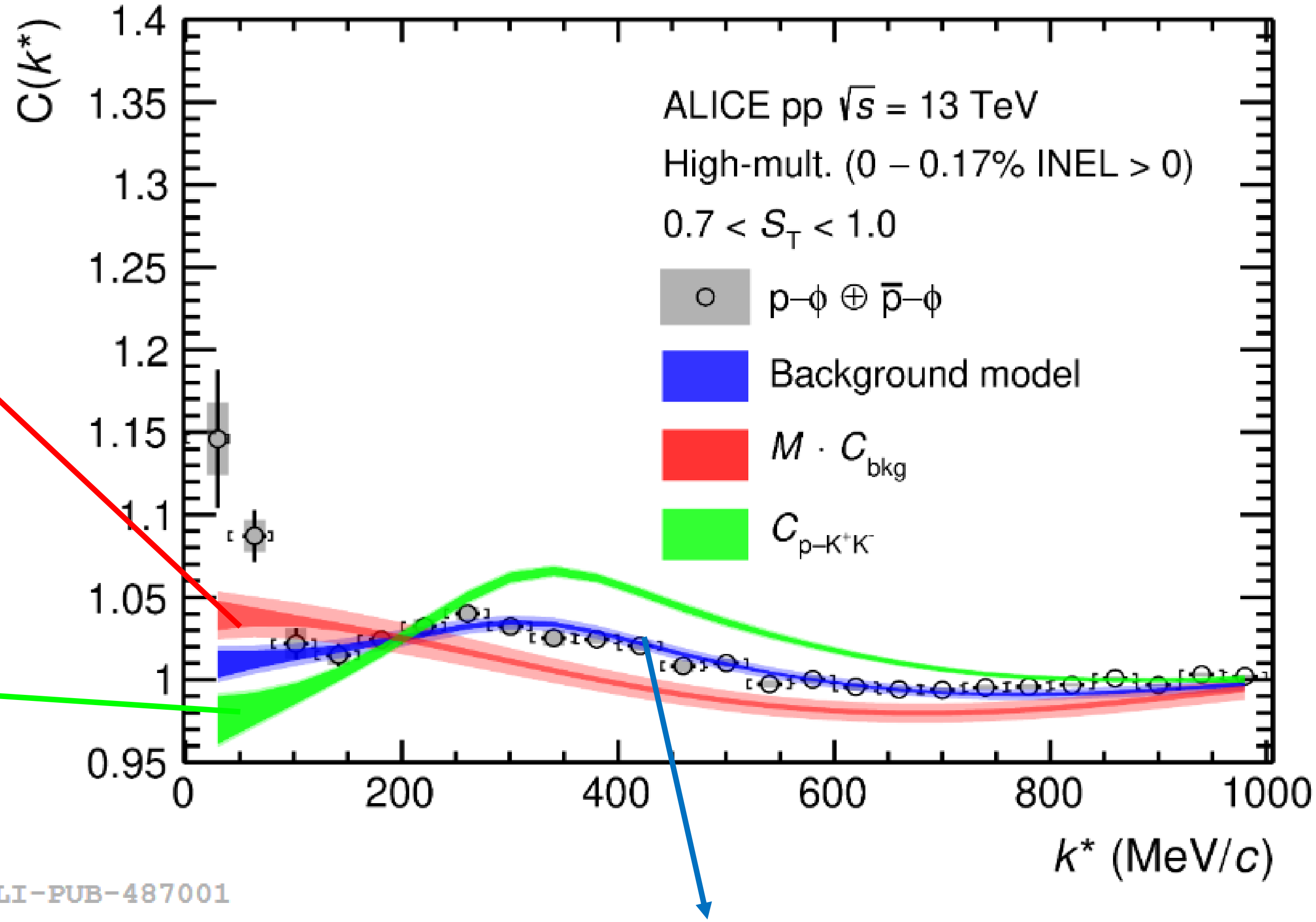




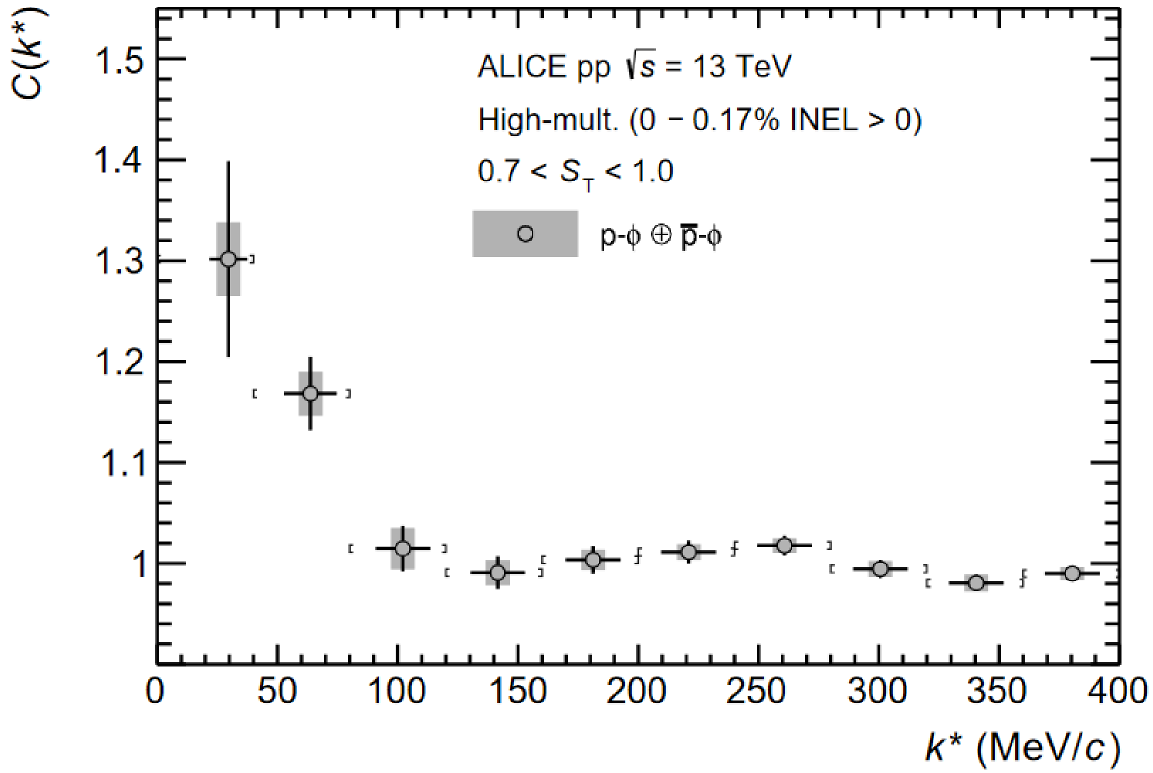


Combine contributions to get description of **total background**, used to derive genuine p–ϕ CF

Results p–ϕ

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

https://arxiv.org/abs/2105.05578



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- 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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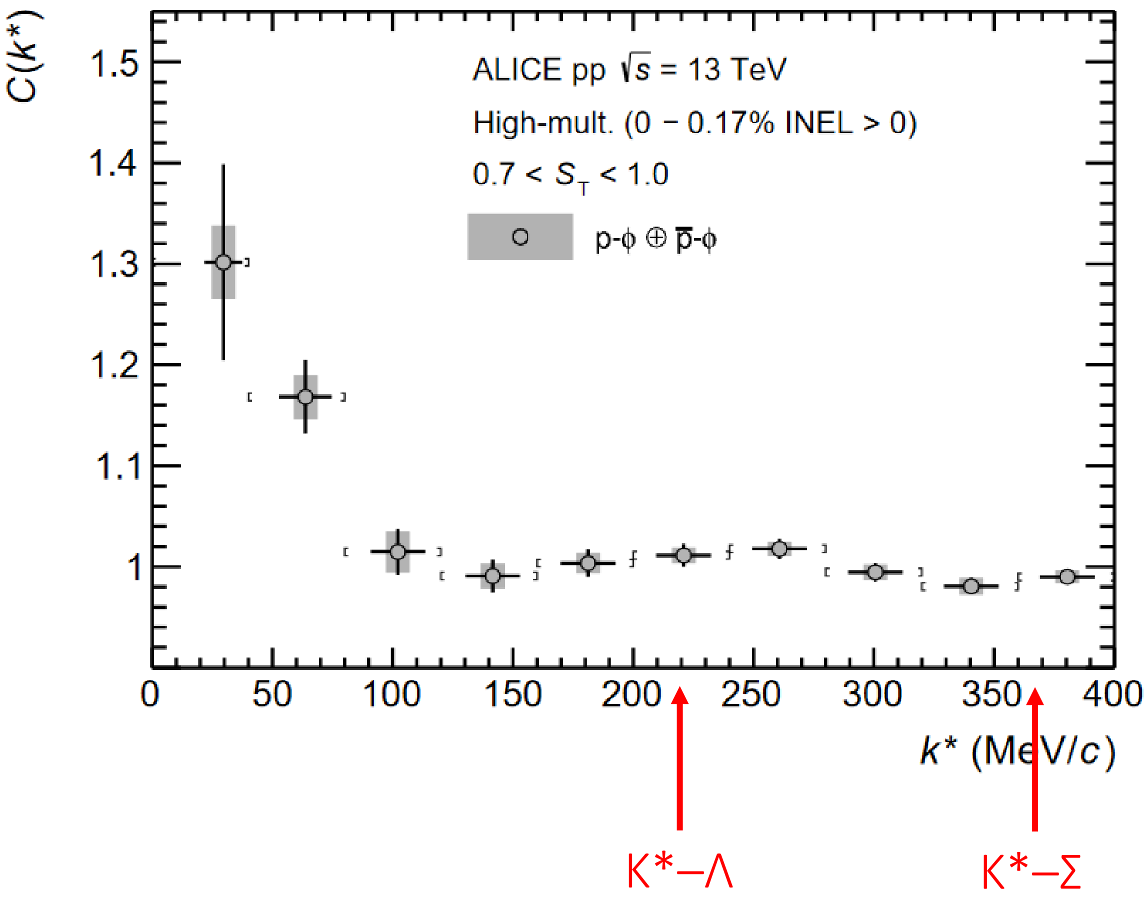

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- Above-threshold channels ($m_{channel} > m_{pair}$) can lead to cusp structure at channel opening k* in p–ϕ system e.g. K*–Λ, K*–Σ
- Below-threshold channels effectively increase CF e.g. K–Λ, K–Σ, K–Λ (1405)

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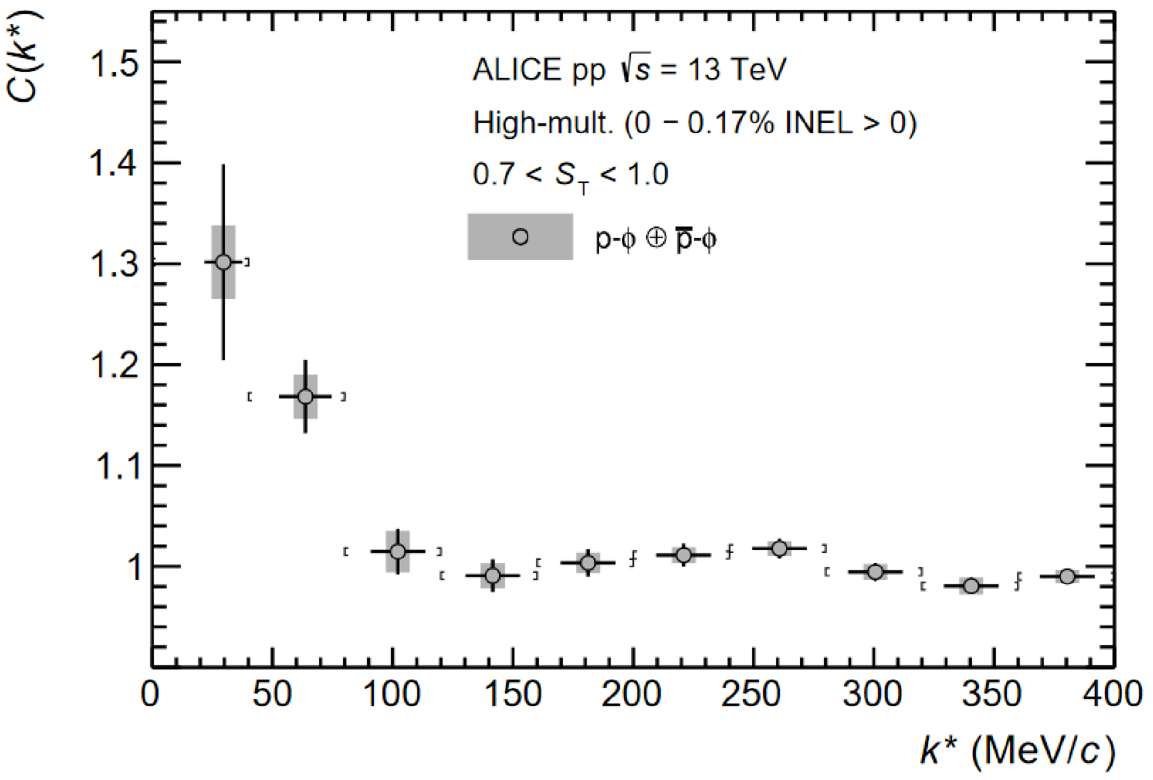

Lednicky-Lyuboshits approach

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

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

Results p–ϕ

- Scattering parameters extracted by employing the analytical Lednicky-Lyuboshits approach
- Imaginary contribution to the scattering length f_0 accounts for inelastic channels

$$d_0=7.85\pm1.54(\text{stat.})\pm0.26(\text{syst.})\ \text{fm}$$
$$\mathrm{Re}(f_0)=0.85\pm0.34(\text{stat.})\pm0.14(\text{syst.})\ \text{fm}$$
$$\mathrm{Im}(f_0)=0.16\pm0.10(\text{stat.})\pm0.09(\text{syst.})\ \text{fm}$$

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

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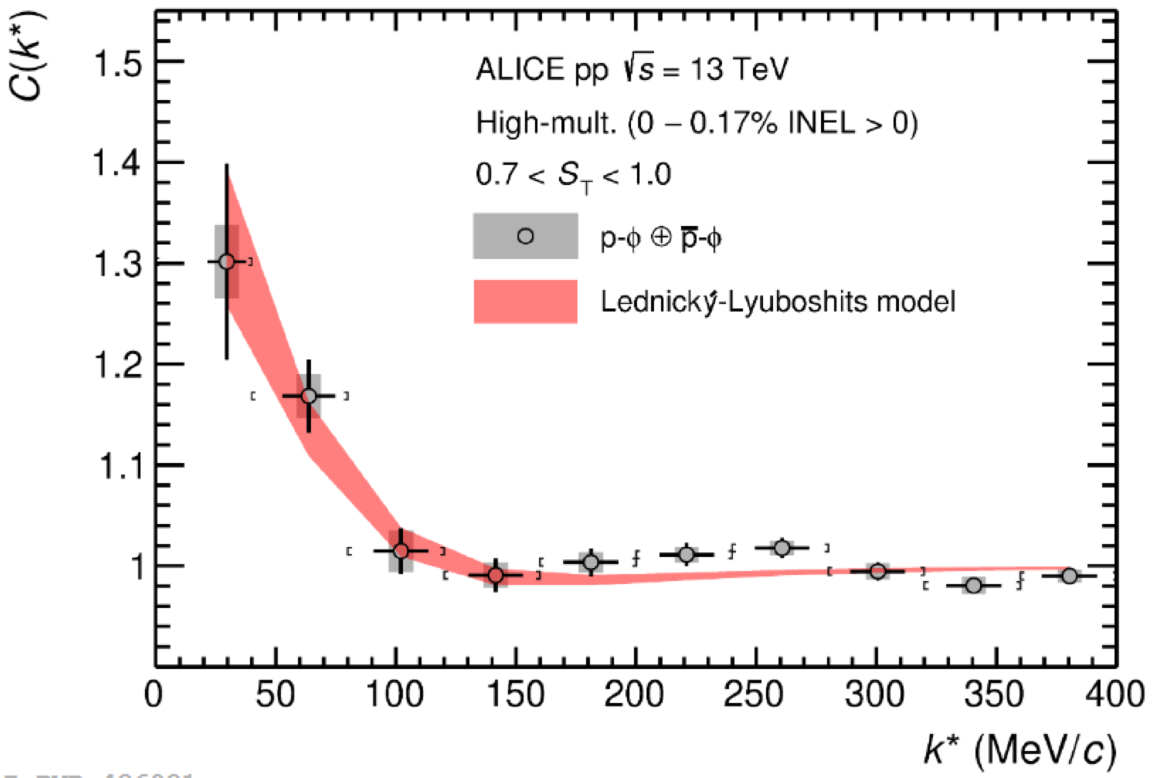

ALI-PUB-486981

Results p–ϕ

- Yukawa-type of potential with real parameters
  Phys. Rev. Lett. **98** (2007) 042501
  - $V(r) = -A \cdot \frac{e^{-\alpha r}}{r}$
  - Strenght A = 0.021 $\pm$ 0.009(stat.) $\pm$ 0.006(syst.)
    inverse range α = 65.9 $\pm$ 38.0(stat.) $\pm$ 17.5(syst.)MeV
- CF obtained **numerically** using CATS framework
  D.L. Mihaylov et al, *Eur. Phys. J.* **C78** (2018) no.5, 394
- Extraction of N–ϕ coupling constant as $\sqrt{A}$

$\boxed{g_{\phi N}=0.14\pm0.03(\text{stat.})\pm0.02(\text{syst.})}$

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

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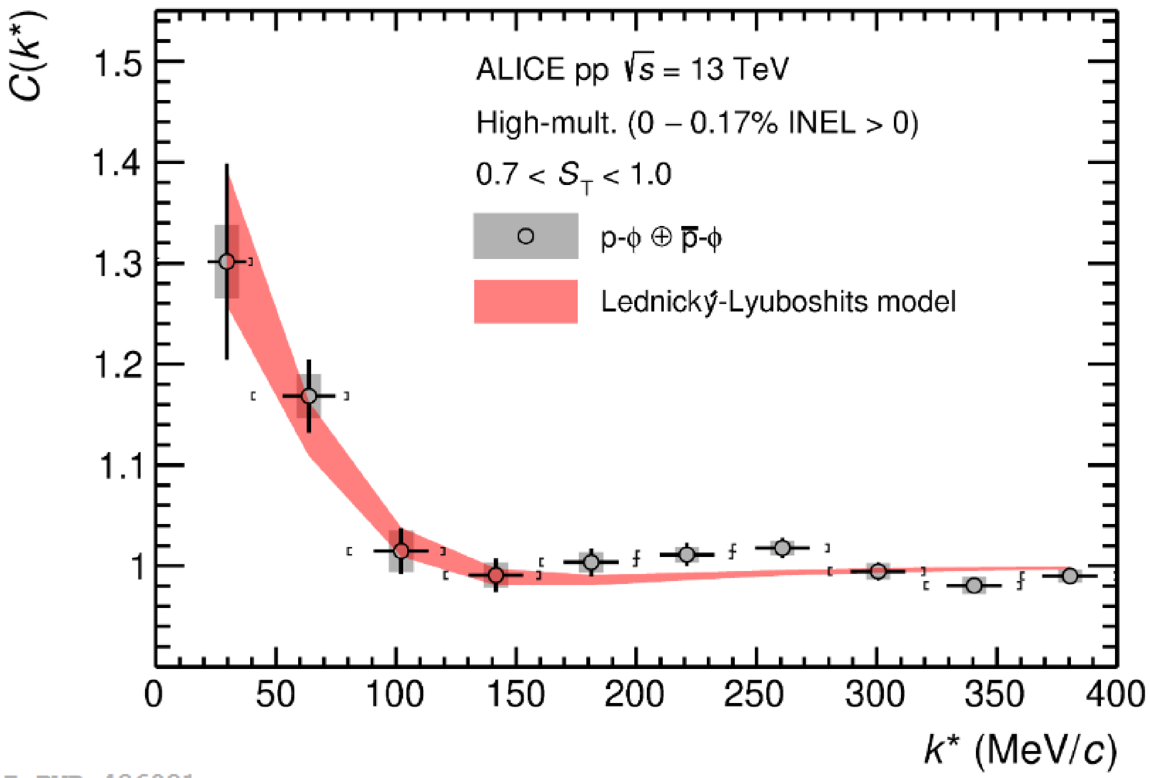
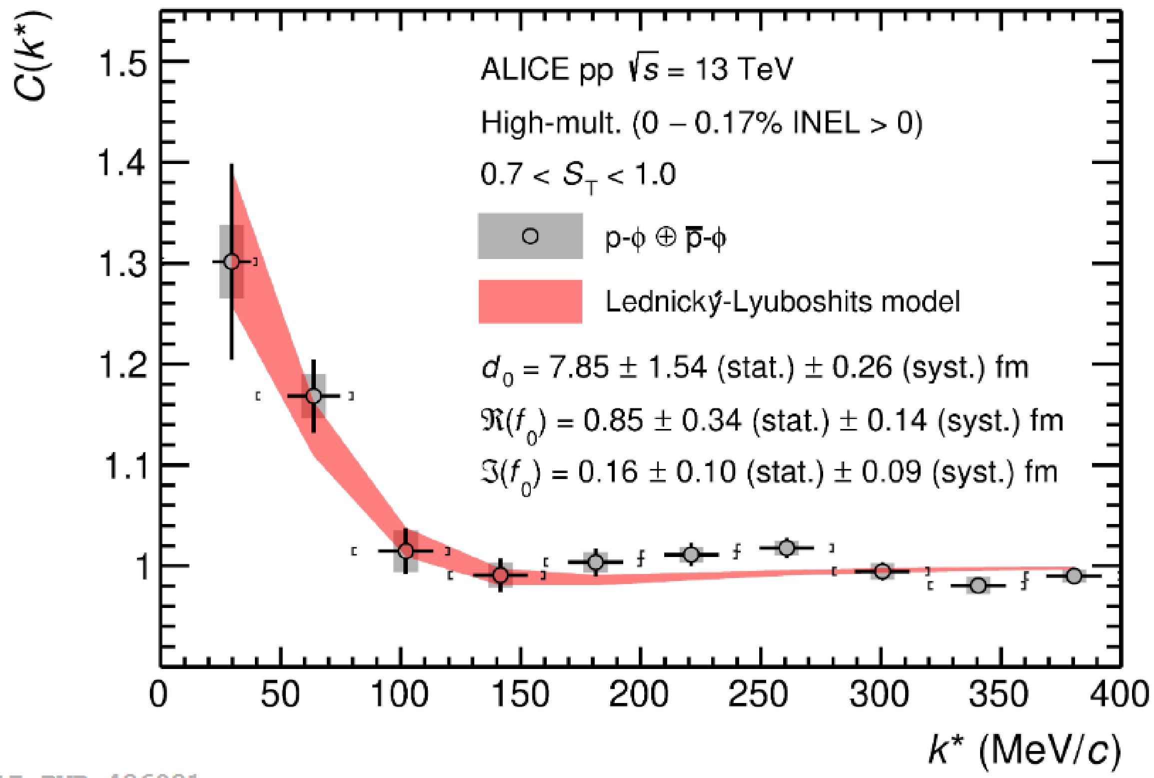


ALI-PUB-486981

Summary

- First measurement of the p–ϕ correlation function
- Attractive p–ϕ interaction dominated by elastic contributions
- Extraction of $g_{\phi\Lambda} \propto g_{\phi N}$ → Relevant for meson exchange between hyperons in Neutron Stars
- Published on https://arxiv.org/abs/2105.05578, submitted to PRL

https://arxiv.org/abs/2105.05578



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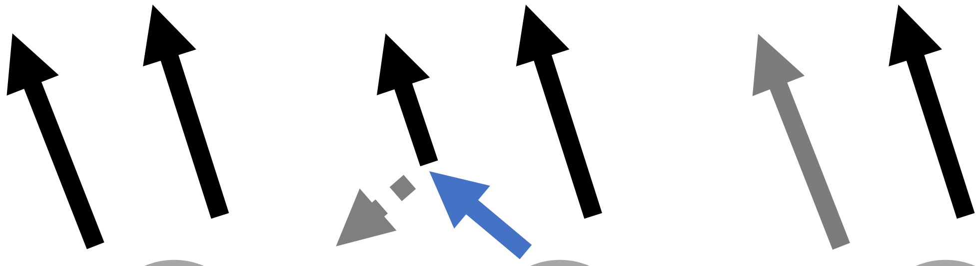
BACKUP

Contributions to CF



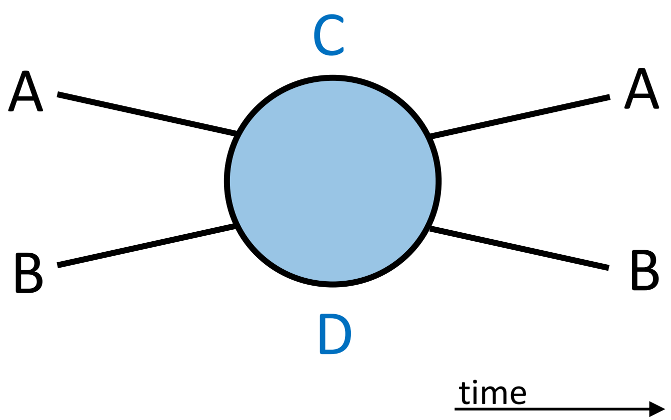
$$C_{femto}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

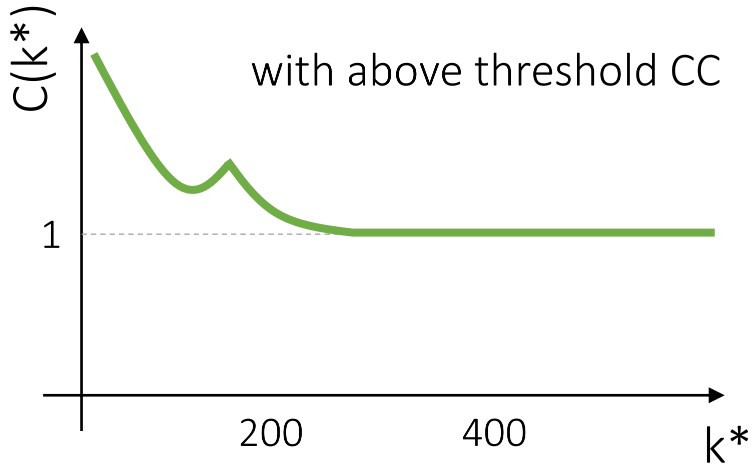
Contributions from: genuine feed-down misidentifications

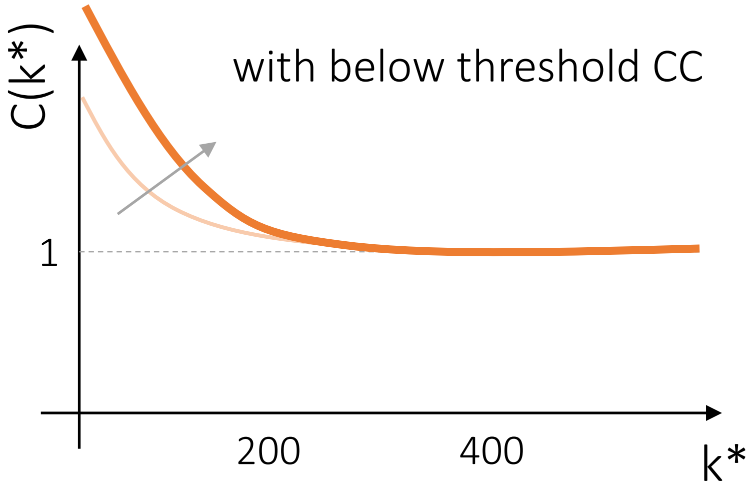
- Separation between contributions to FSI and general background
  $C_{exp}(k^*) = C_{non-femto}(k^*) \cdot C_{femto}(k^*)$
- contributions to FSI (femto) quantified by purity ($\mathcal{P}_i$) and feed-down fractions (f_i) :
  $\lambda_{ij} = \mathcal{P}_1 \cdot f_{i_1} \cdot \mathcal{P}_2 \cdot f_{j_2}$
- Additional background (non-femto) arises from auto-correlations (mini-jets) and energy-momentum conservation effects

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
- CC share same quantum numbers as particle pair
- Above-threshold channels ($m_{channel} > m_{pair}$) lead to cusp structure at channel opening k*
- Below-threshold channels ($m_{channel} < m_{pair}$) effectively increase CF

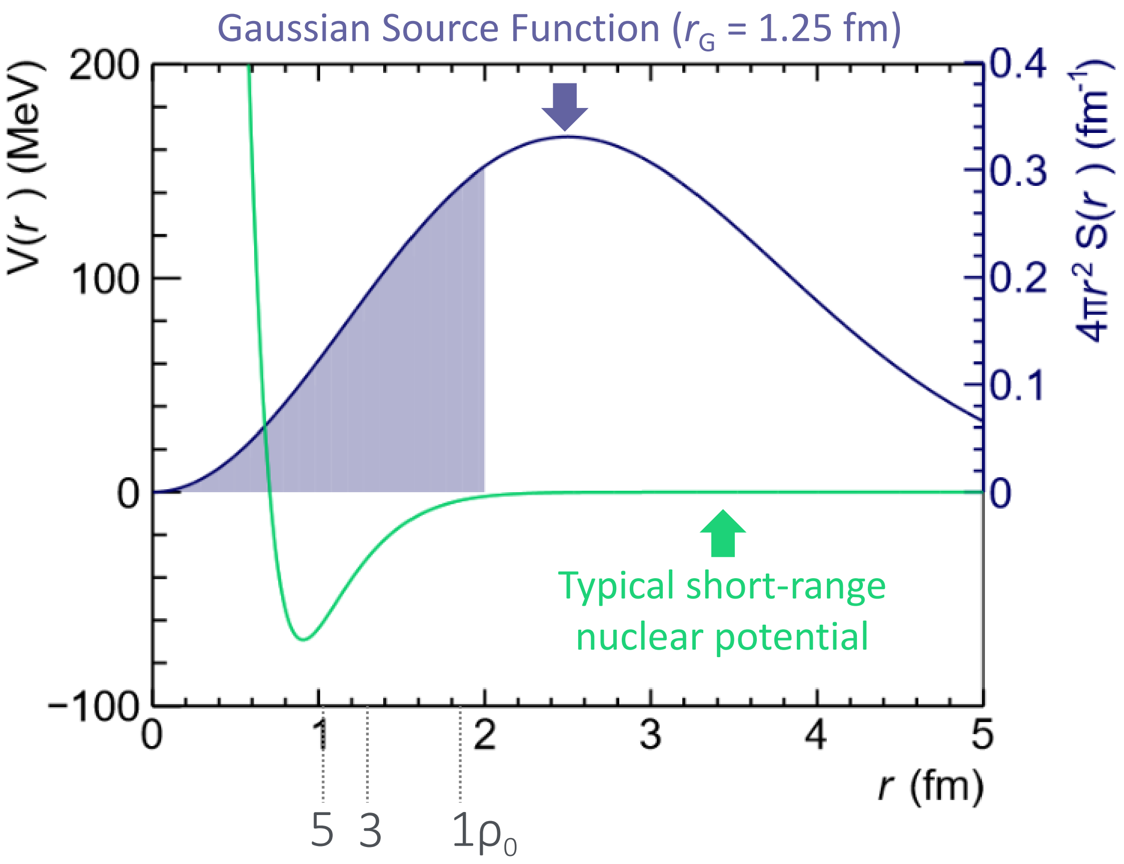






Accessing the short-range interaction

- Small particle-emitting source created in pp and p–Pb collisions at the LHC
  D. Mihaylov et al., *Eur. Phys. J.* **C78** (2018) 394
  - Gives rise to pronounced correlation signal
- Small interparticle distance → Doorway to study large densities



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
- Very shallow potential depth found of
  V_{eff} = 2.5±0.9(stat.) ± 1.4(syst.) MeV
  μ = 0.14 ± 0.06(stat.) ± 0.09(syst.) fm^{-2}
- 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