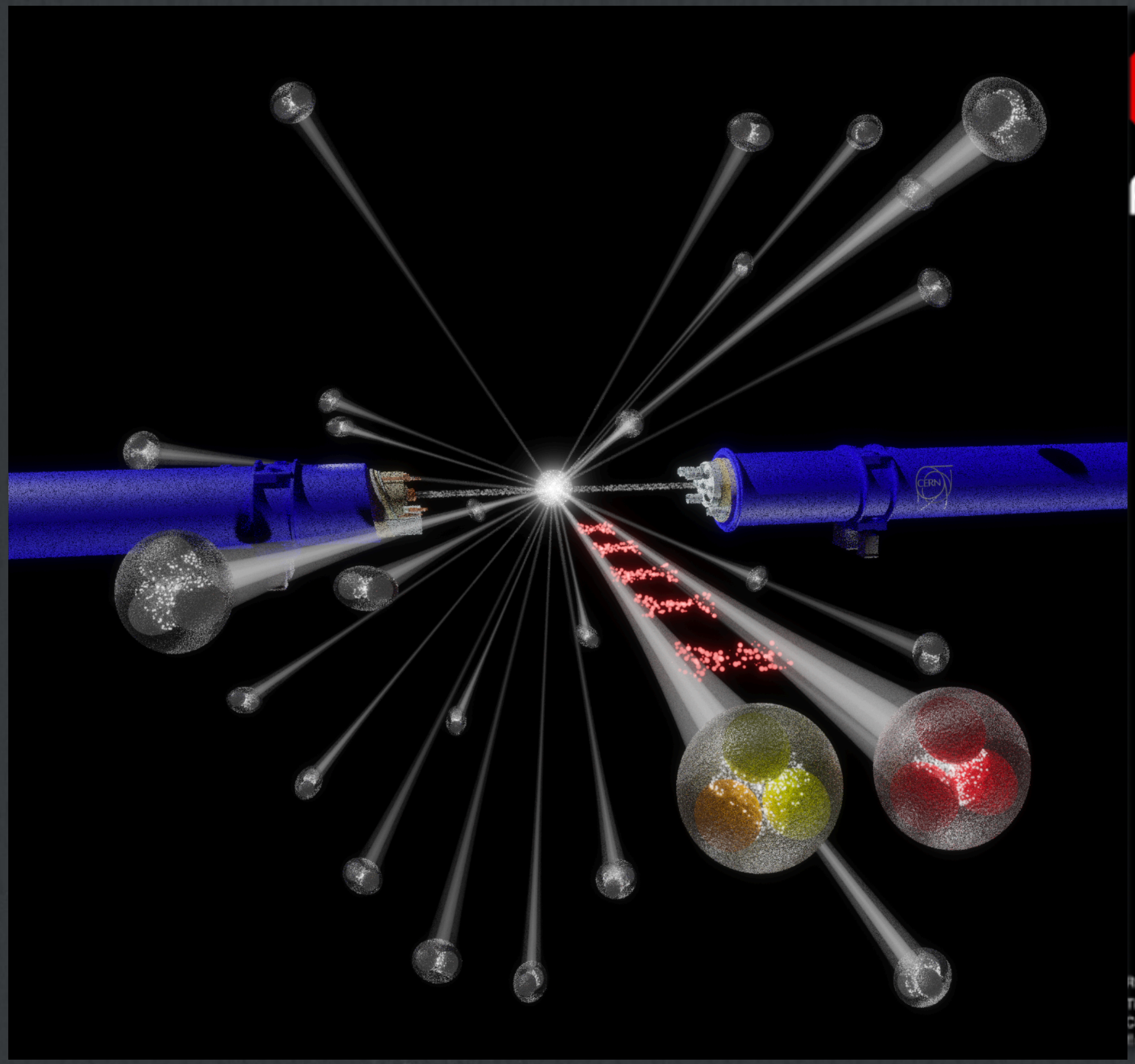
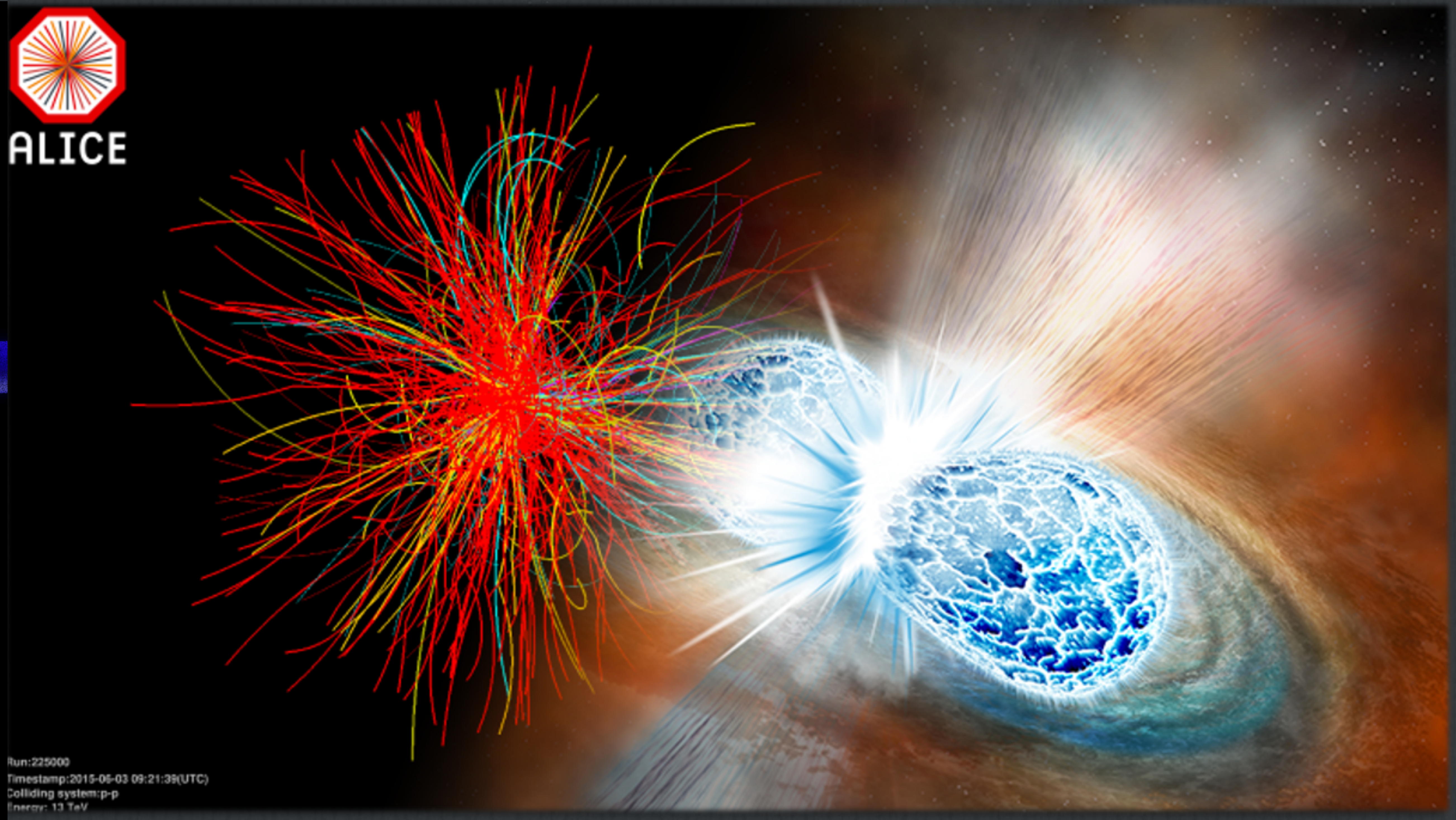
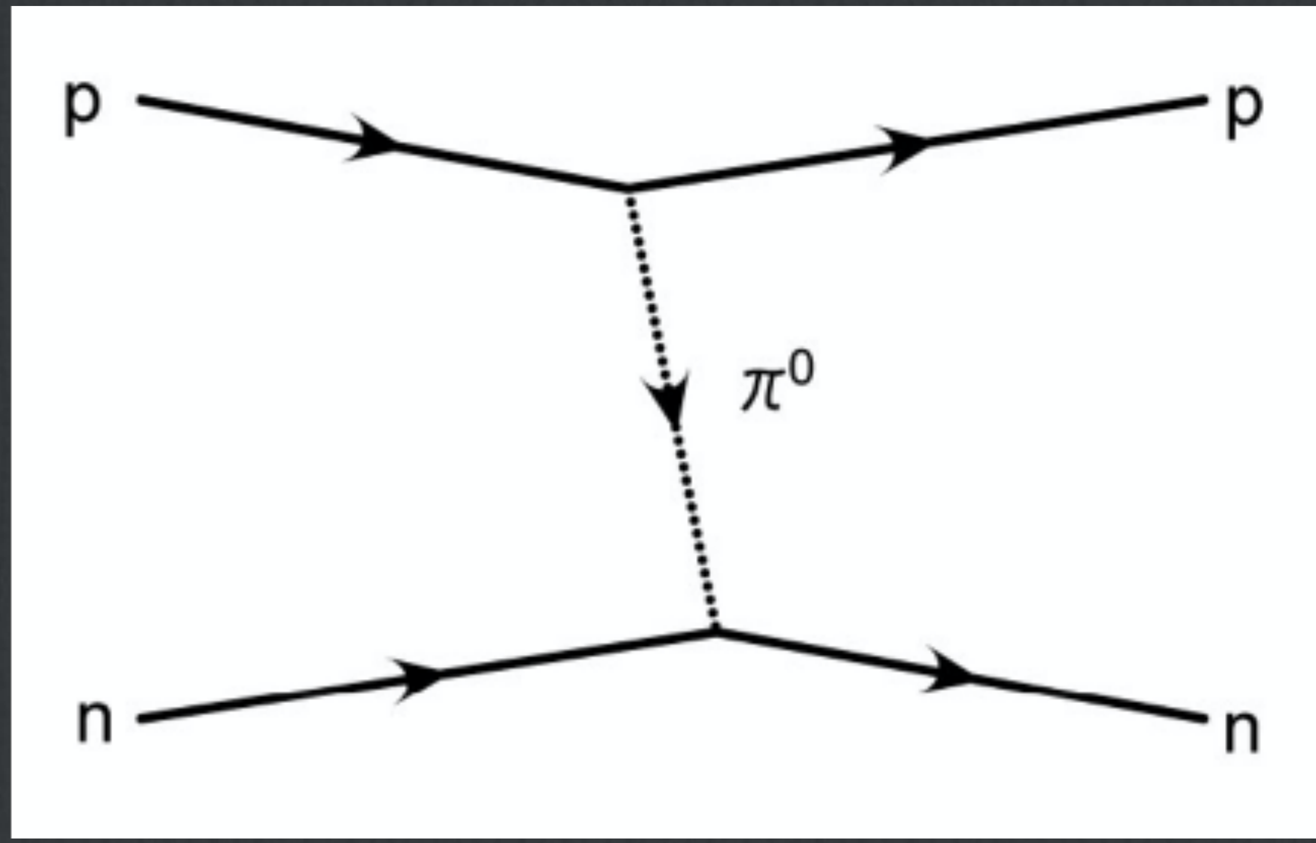
Femtoscopy with hyperons (and ϕ) and charm hadrons

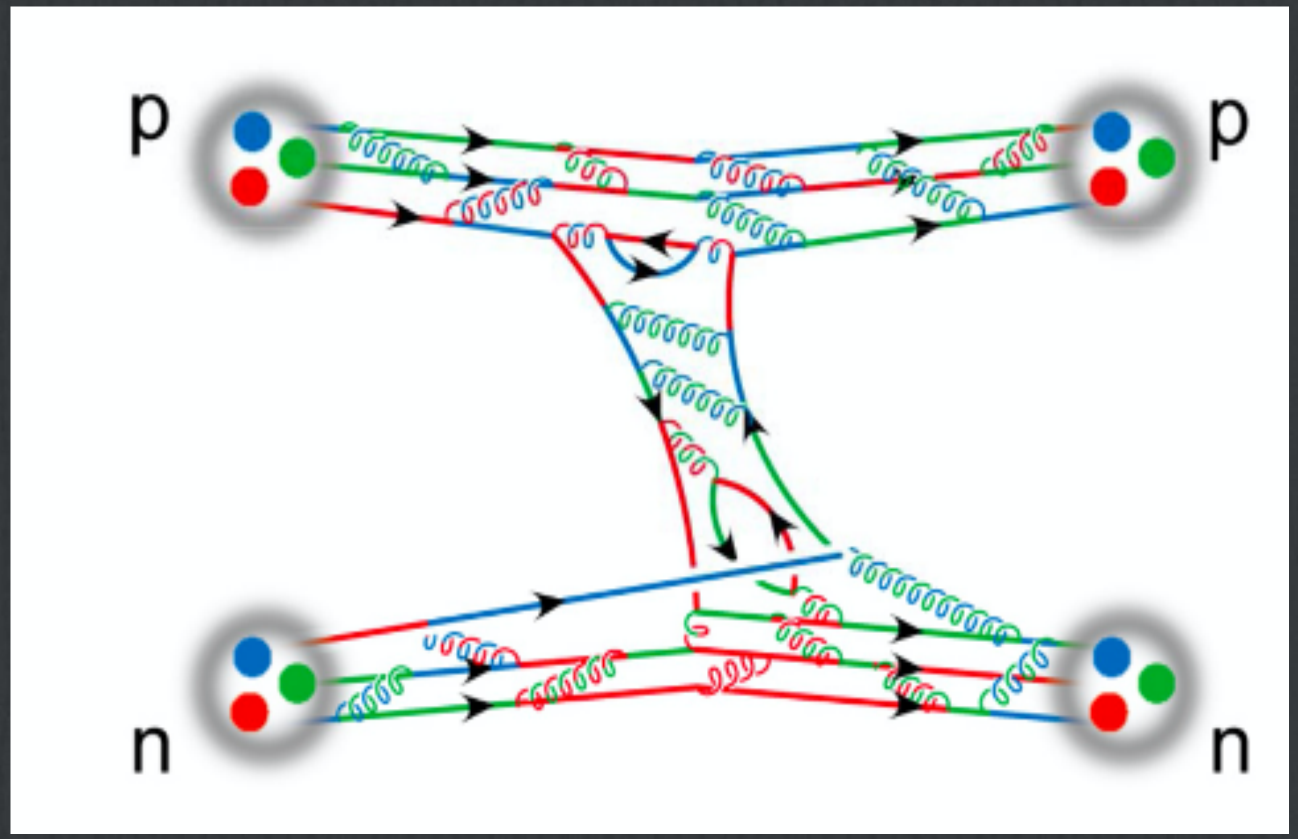
Prof. Dr. Laura Fabbietti (TUM)





What does progress in the field mean?



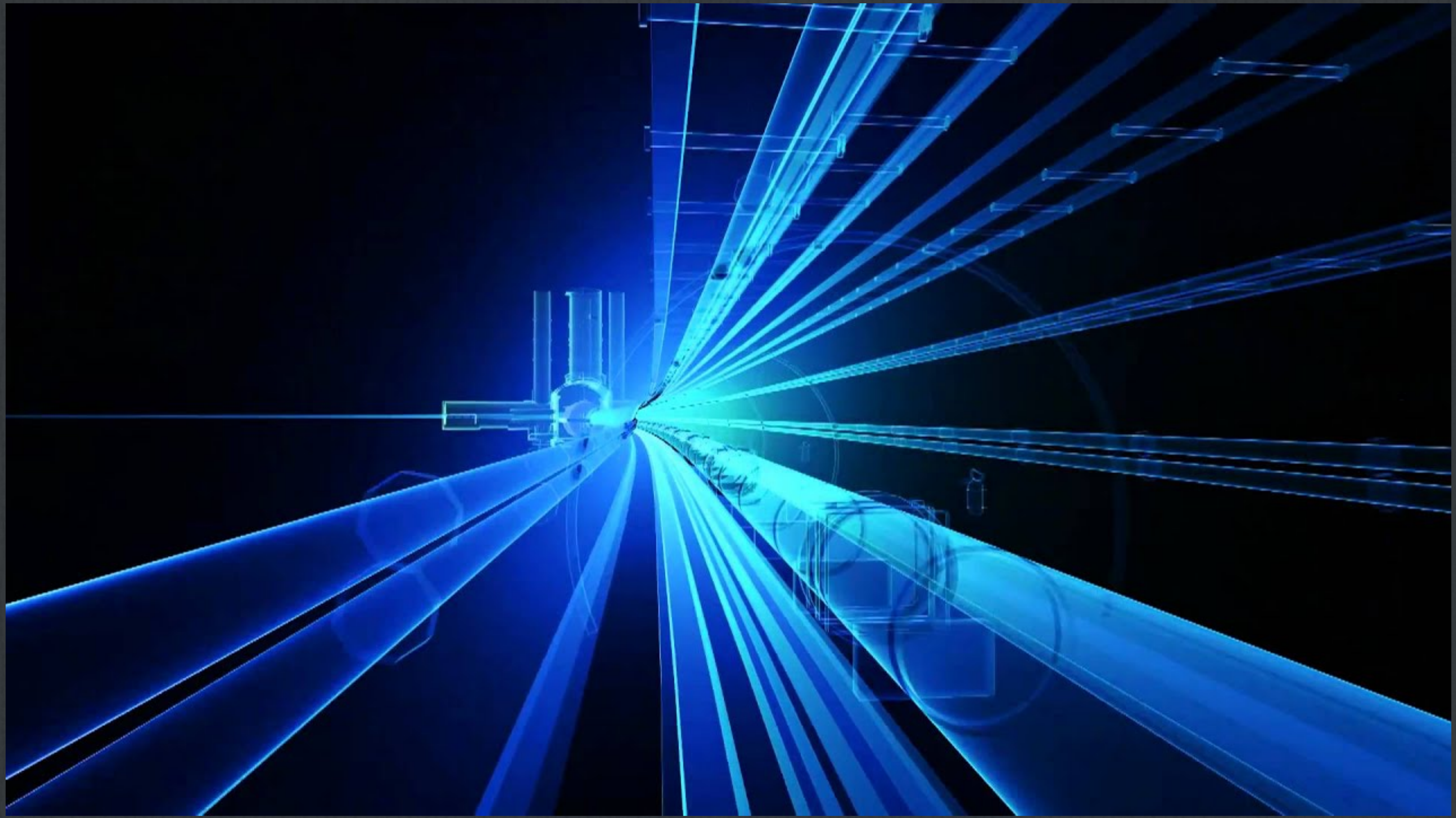


From effective field theory to first principle calculations

Particle production at the LHC accelerator

Large Hadron Collider LHC

Biggest accelerator worldwide where the highest energies are achieved : $\sqrt{s} =$ 13 TeV for pp collisions

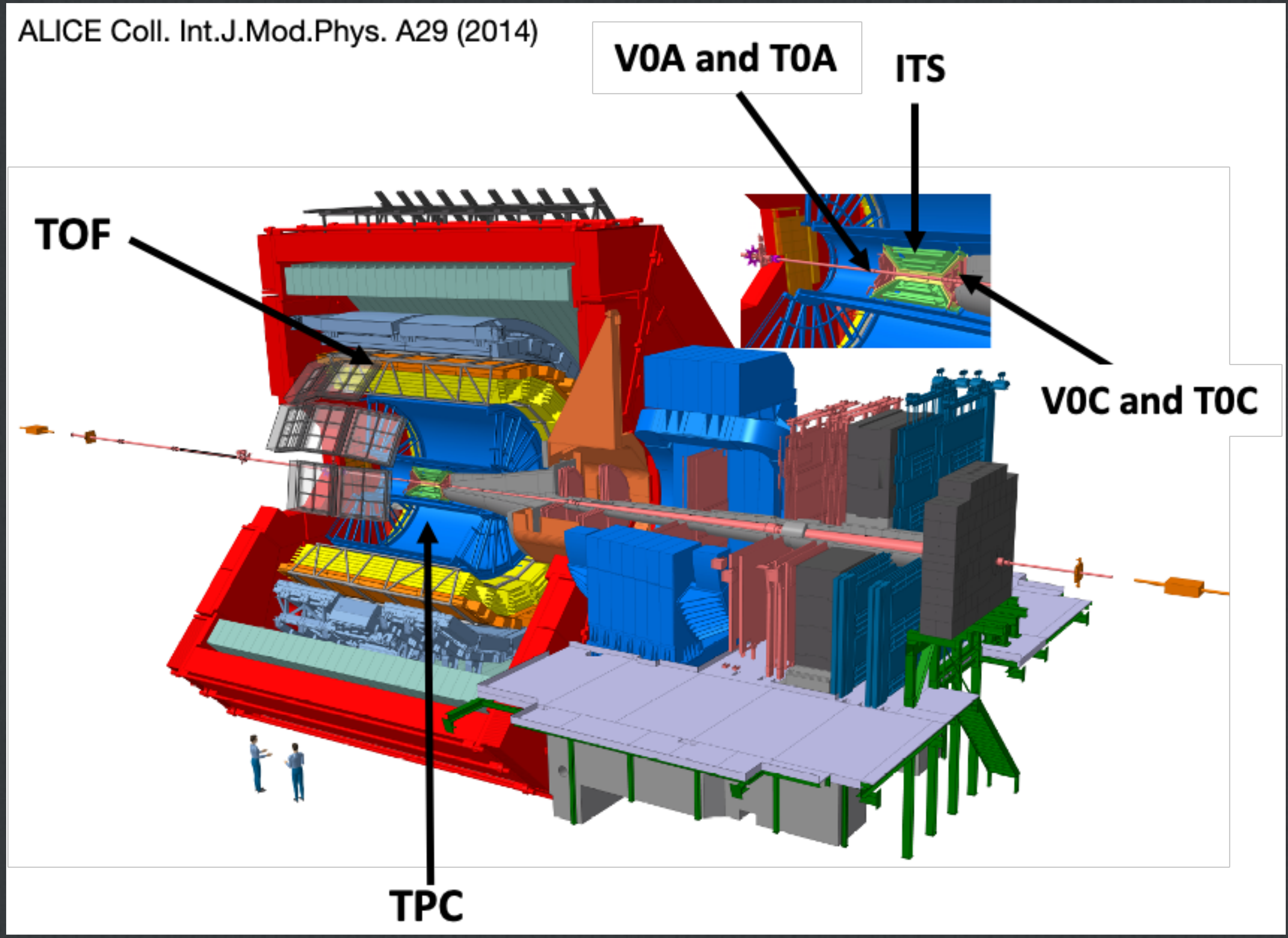


$$E = mc^2$$

Each pp collision leads to the creation of ~ 30 new particles

From 2022 we can record 500.000 collisions per second

Particle production and decays in ALICE



pp collisions at $\sqrt{s} = 13$ TeV
1.2 Billions high multiplicity events
<M> = 30 particles/event

$$\Lambda \rightarrow \pi^- + p$$

$$\Xi^- \rightarrow \Lambda + \pi^-$$

$$\Omega^- \rightarrow \Lambda + K^-$$

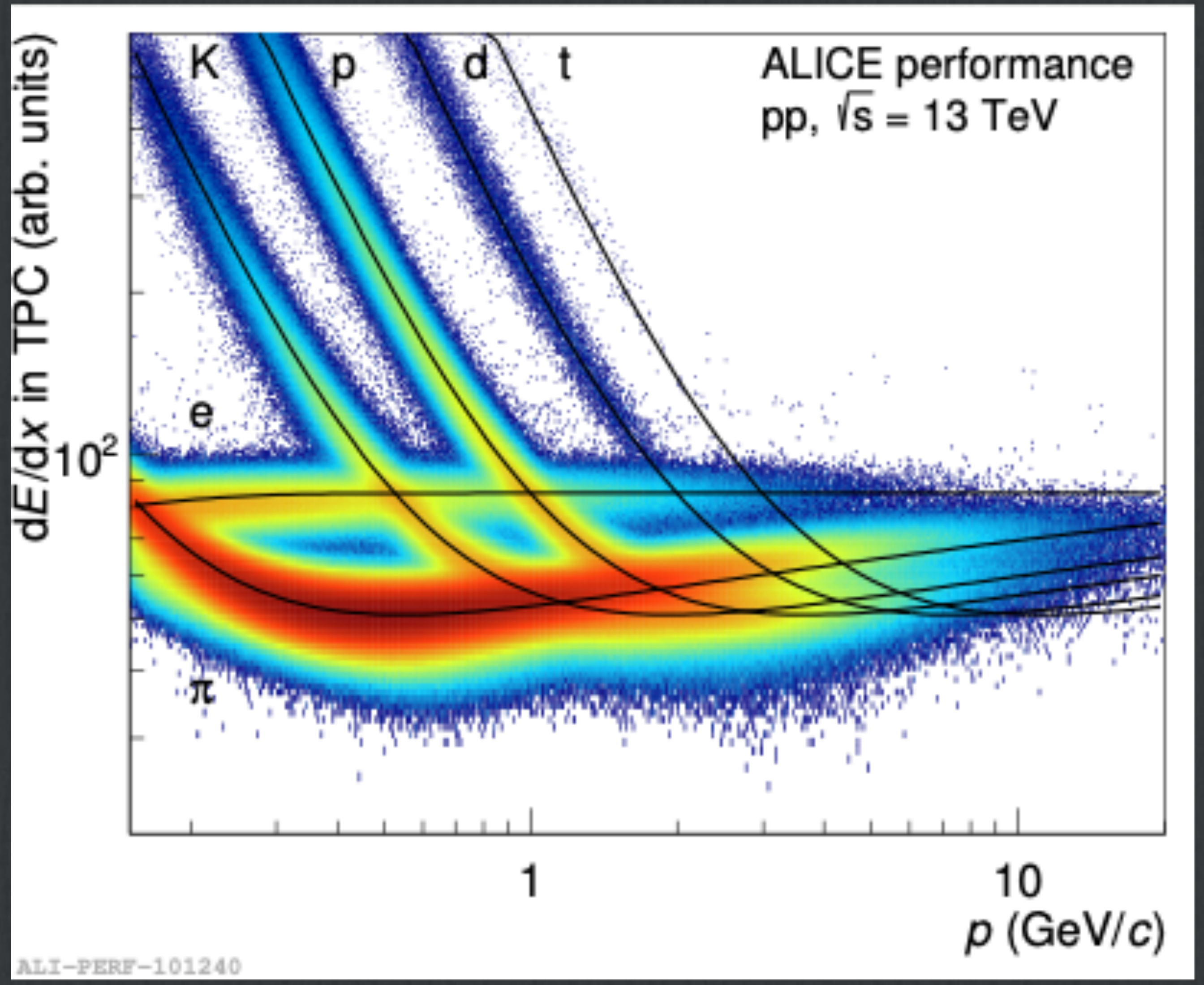
$$\Sigma^0 \rightarrow \Lambda + \gamma$$

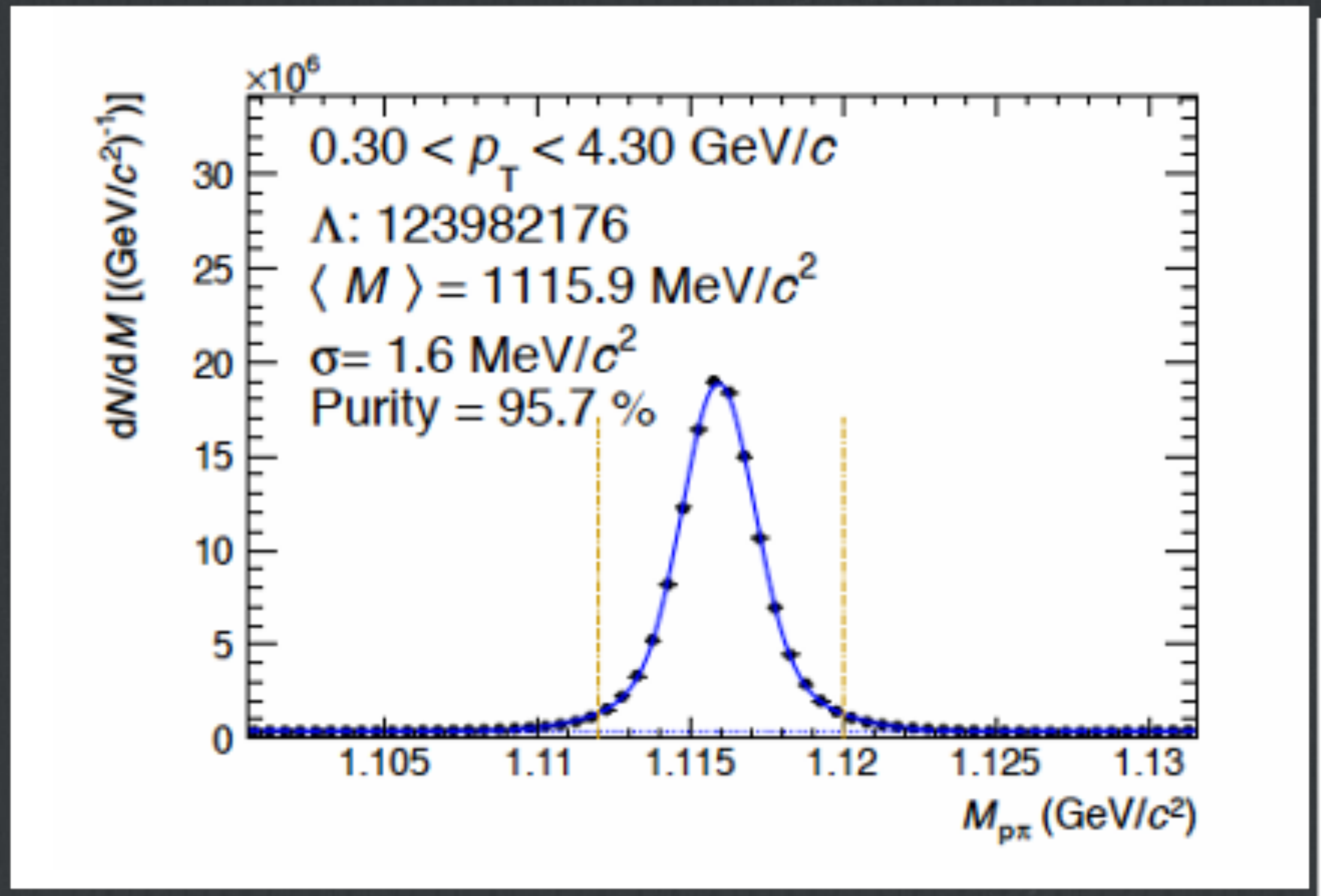
$$\varphi \rightarrow K^+ + K^-$$

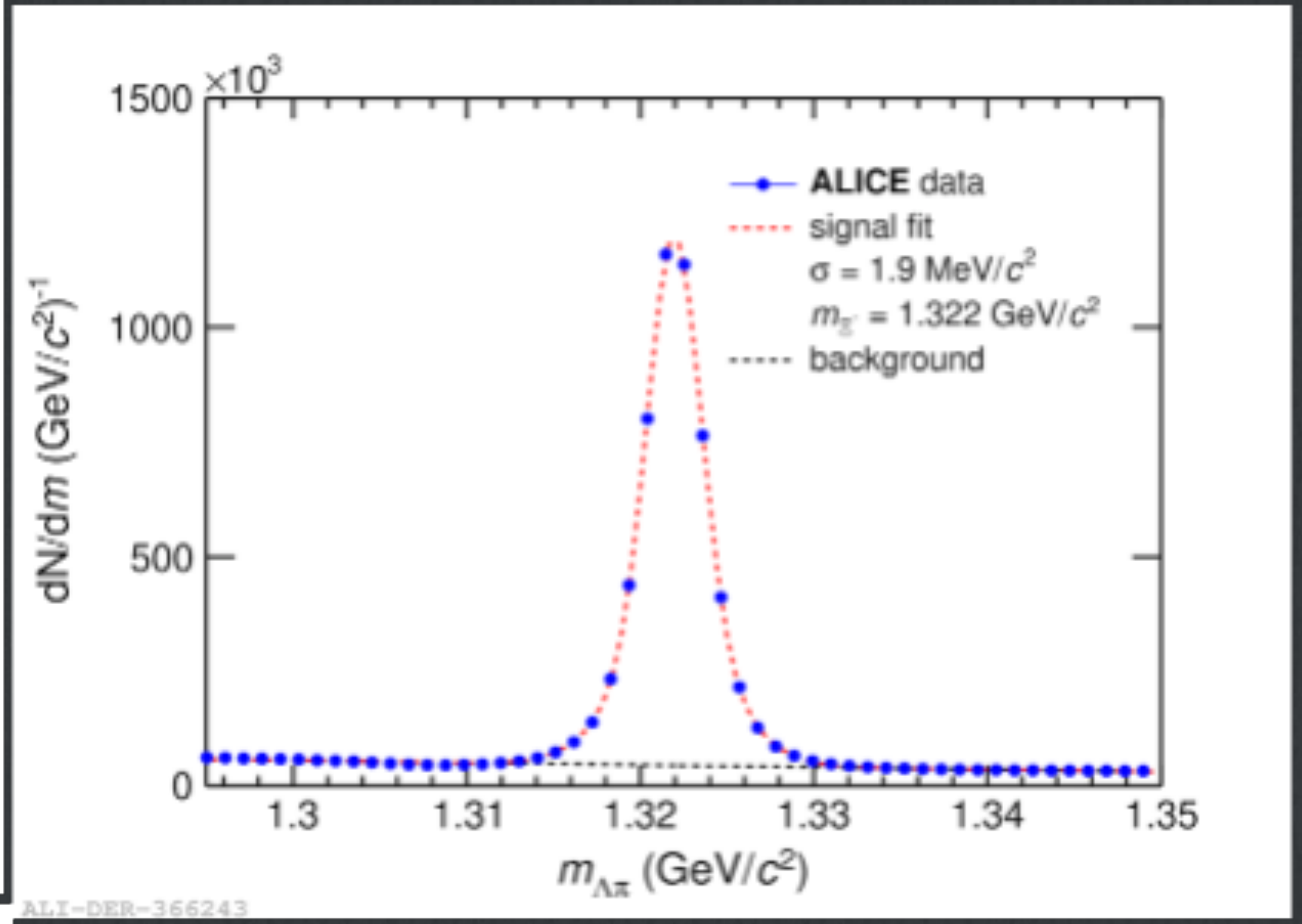
$$D \rightarrow K\pi\pi$$

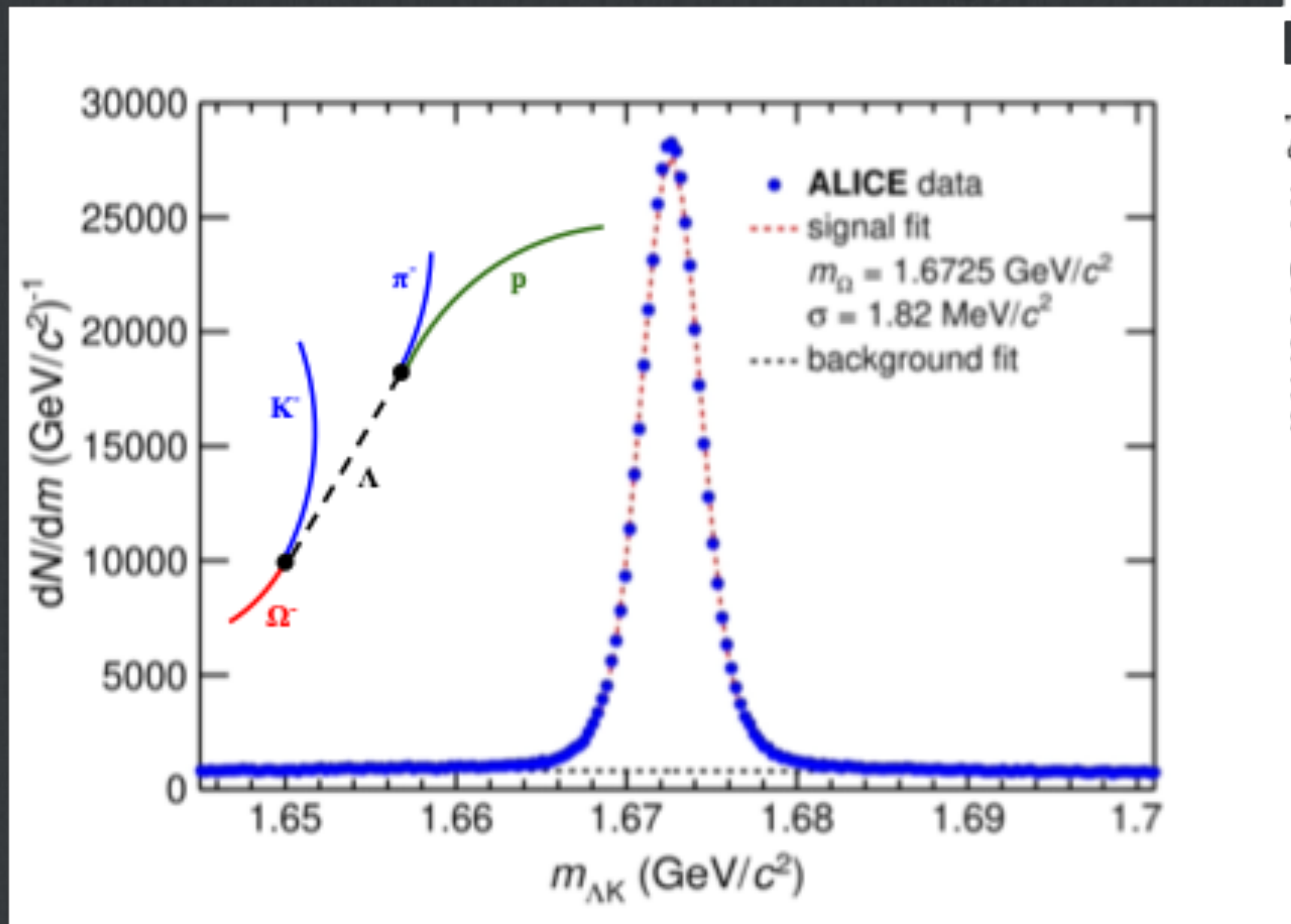
The very good PID capabilities of the detector result in very pure samples!

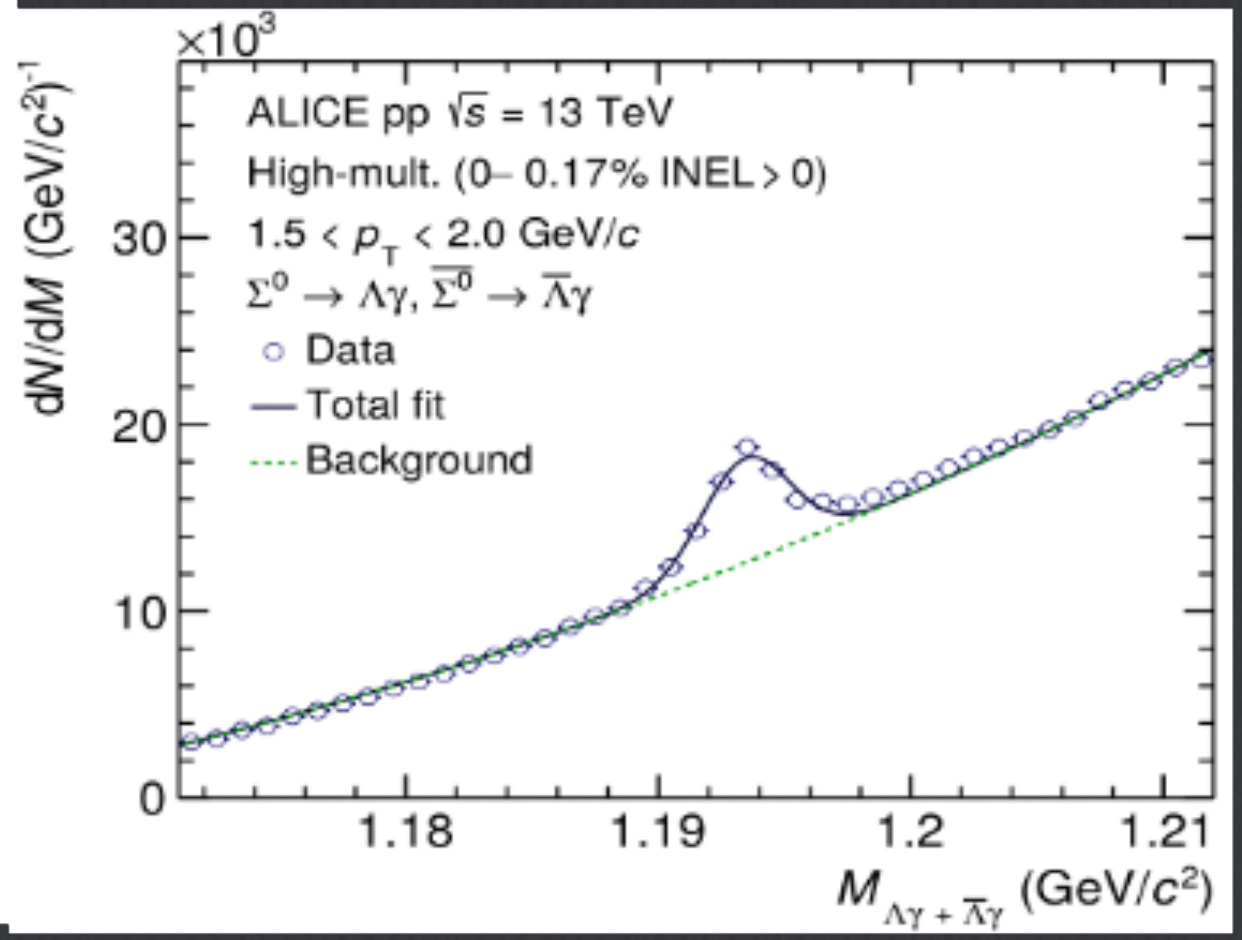
Hyperons reconstruction with ALICE











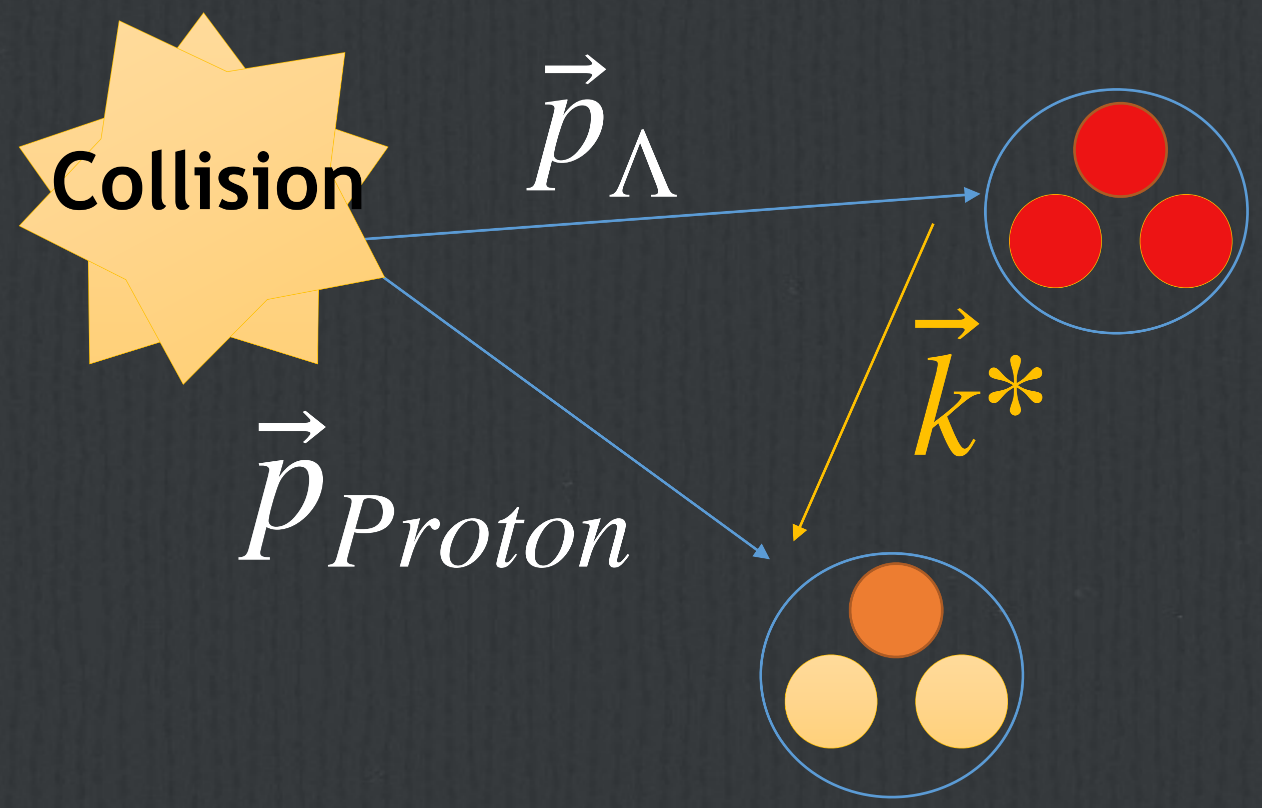
$$\Lambda \rightarrow \pi^- + p$$

$$\Xi^- \rightarrow \Lambda + \pi^-$$

$$\Omega^- \rightarrow \Lambda + K^-$$

$$\Sigma^0 \rightarrow \Lambda + \gamma$$

Measurement of the hyperon-nucleon interaction



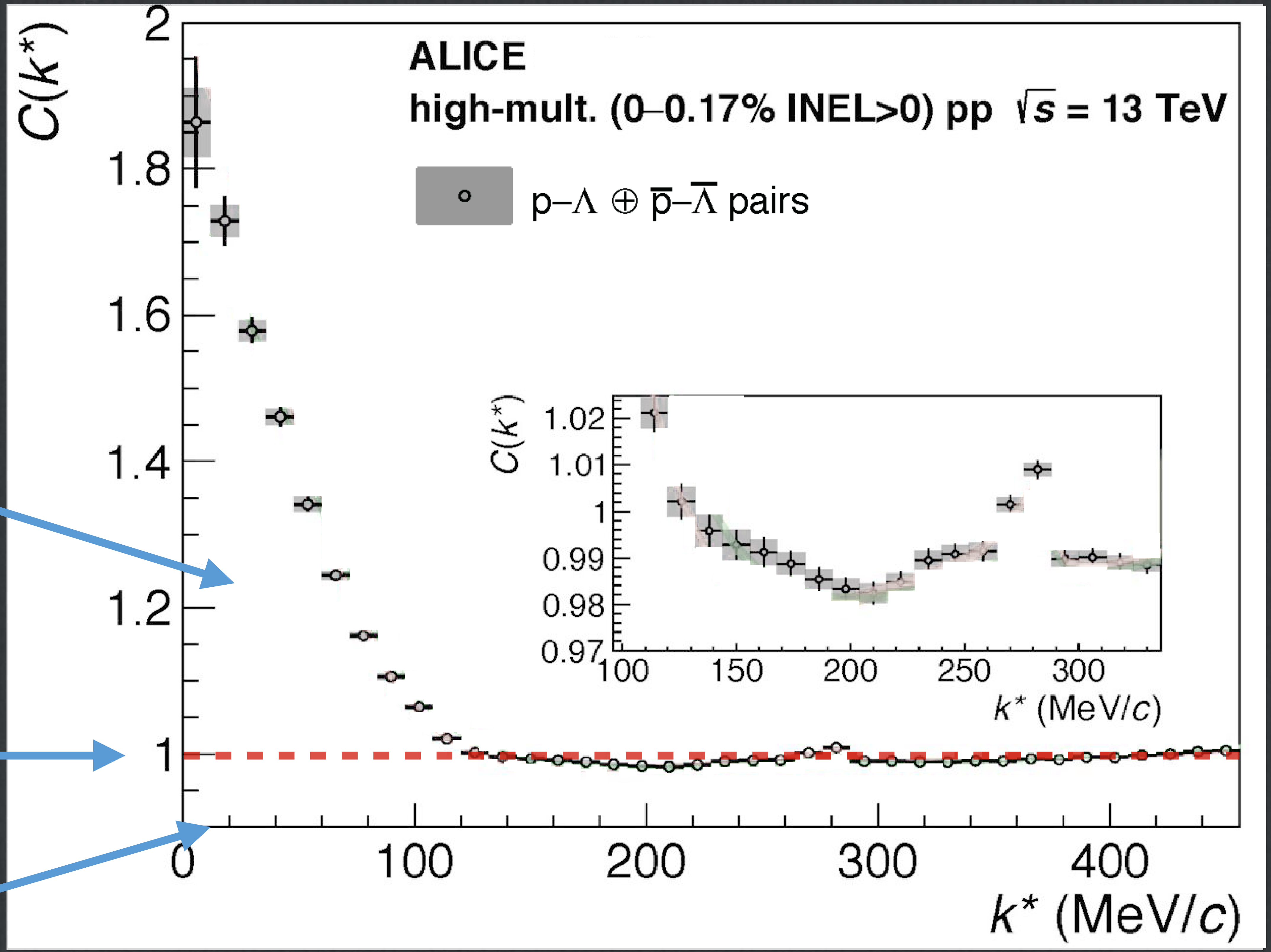
$$C(k^*) = \xi(k^*)\frac{SE}{ME}$$

C(k*)>1: attractive interaction

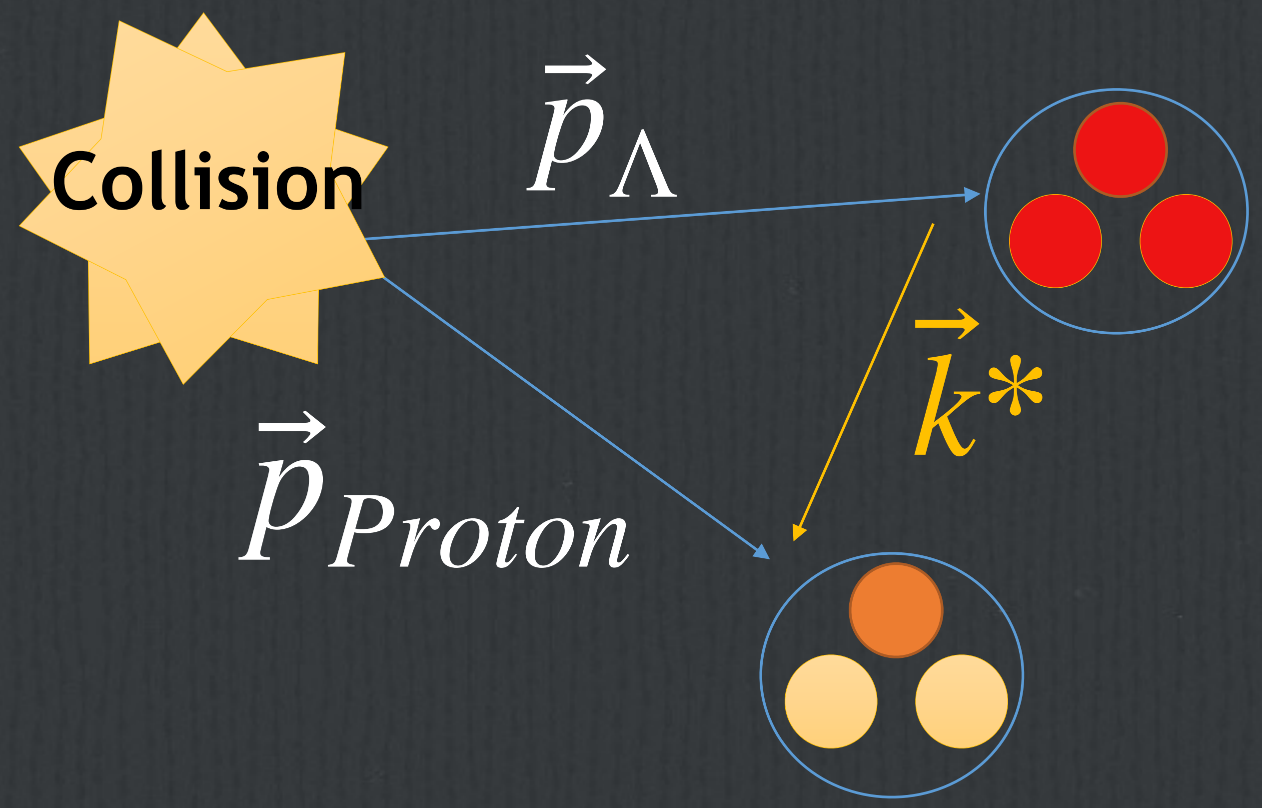
C(k*) = 1: no interaction

C(k*) <1: repulsive interaction

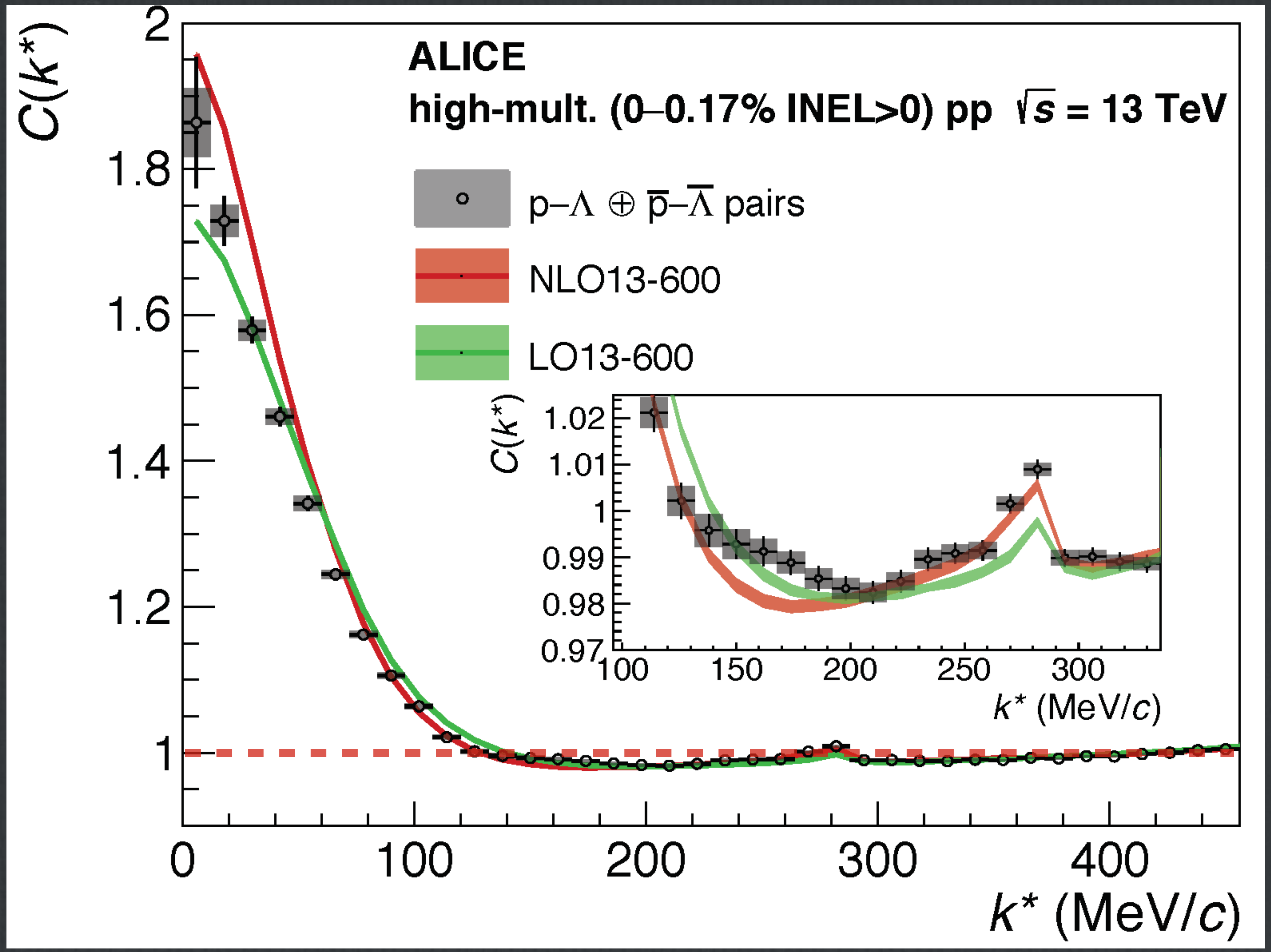
ALICE Coll. PLB 832 (2022) 137272



Measurement of the hyperon-nucleon interaction



ALICE Coll. PLB 832 (2022) 137272



S. E. Koonin et al. PLB 70 (1977)

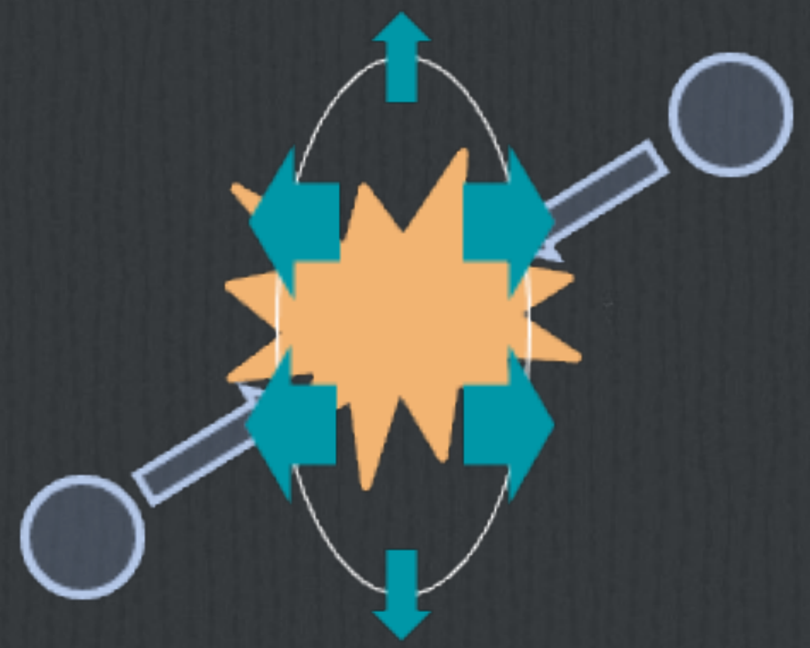
$$C(|\vec{k^*}|) = \xi(k^*)\frac{SE}{ME} = \int S(r)\,|\psi(\vec{r},\vec{k^*})|^2\, d\vec{r}^3$$

Particle emitting source

Relative wave function

CATS (Correlation Analysis Tool using the Schödinger equation)
D. Mihaylov, L. Fabbietti et al. EPJC 78 (2018)

Determination of the particle-emitting source



Anisotropic + Radial

Pressure gradients

Given the pair transverse mass $m_T = \sqrt{\frac{1}{4}(p_{1T} + p_{2T})^2 + (m_1 + m_2)^2}$

$$\rightarrow S(r) = G(r, r_{core}(m_T)) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(\frac{-r}{4r_{core}^2}\right)$$

Determination of the particle-emitting source

Anisotropic + Radial

Pressure gradients

Given the pair transverse mass $m_T = \sqrt{\frac{1}{4}(p_{2T}+p_{1T})^2 + (m_1+m_2)^2}$

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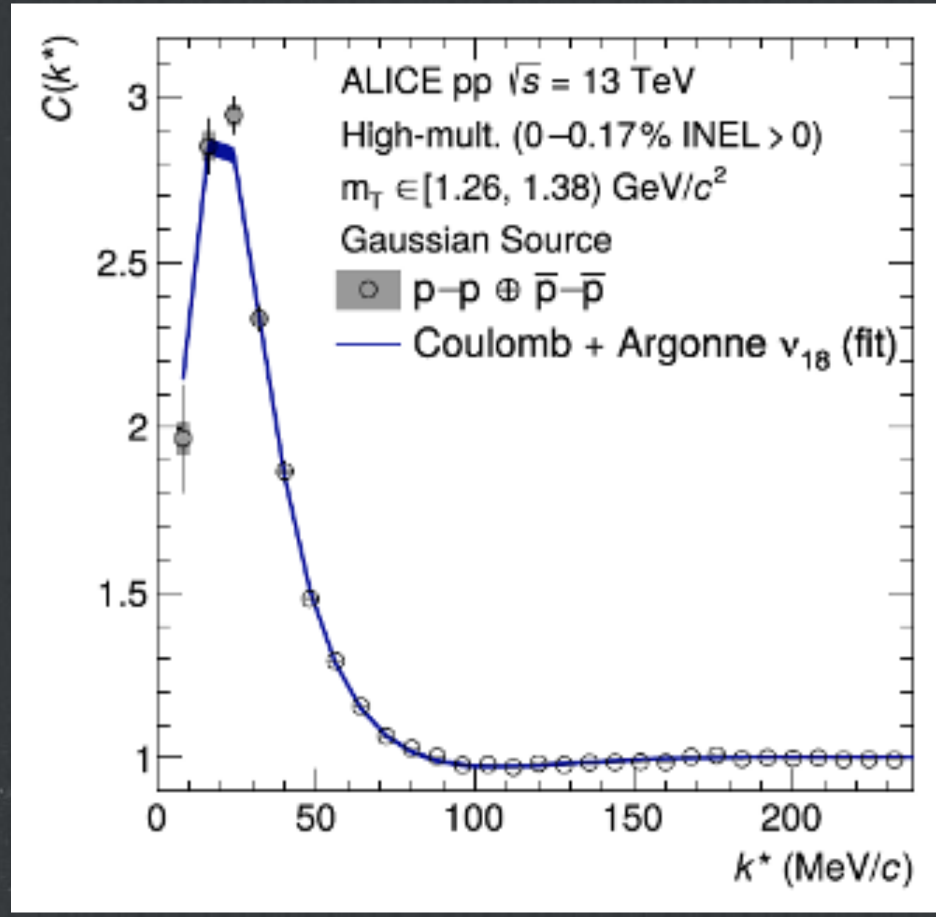
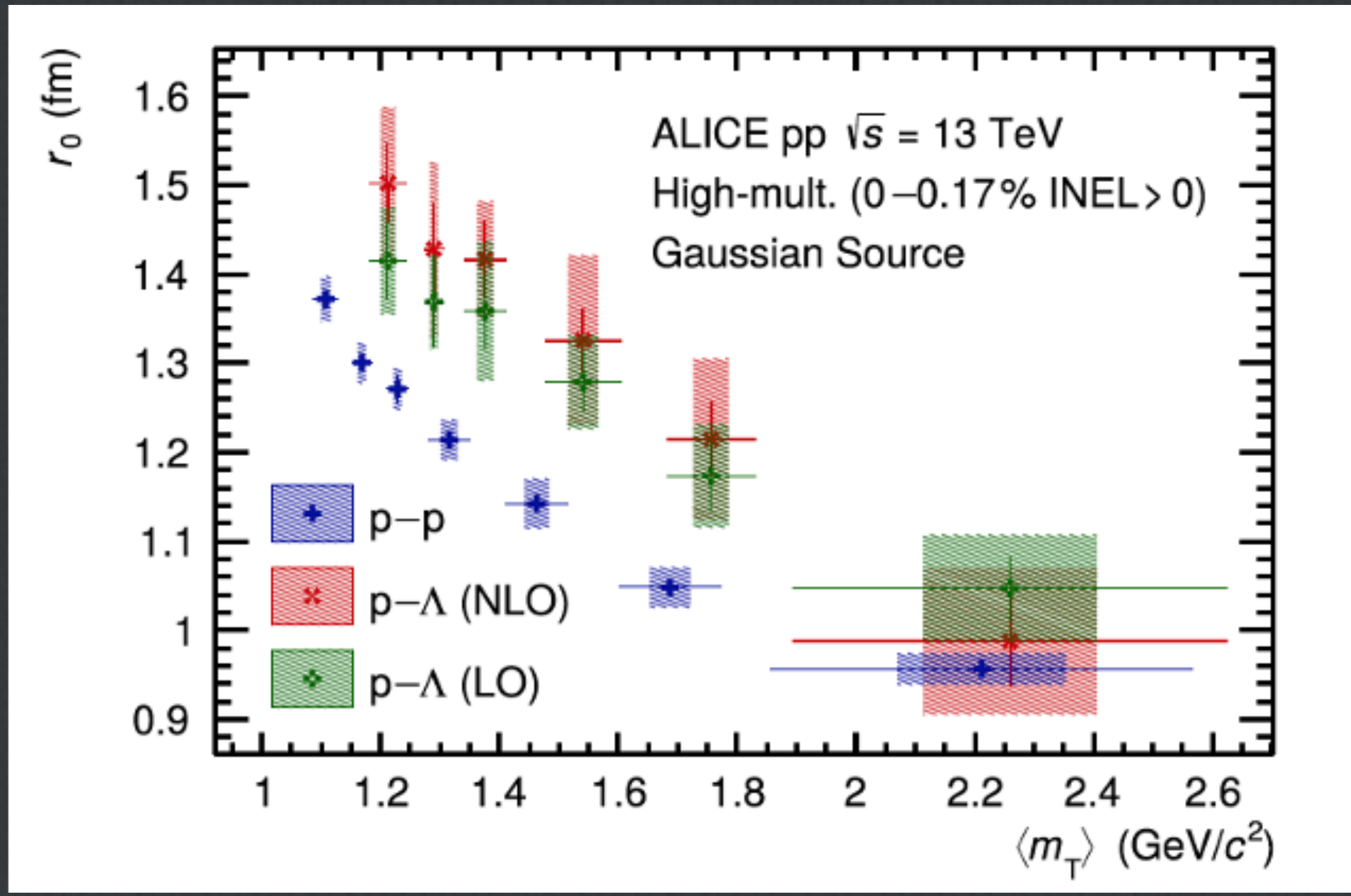
ALICE Coll., PLB, 811 (2020)

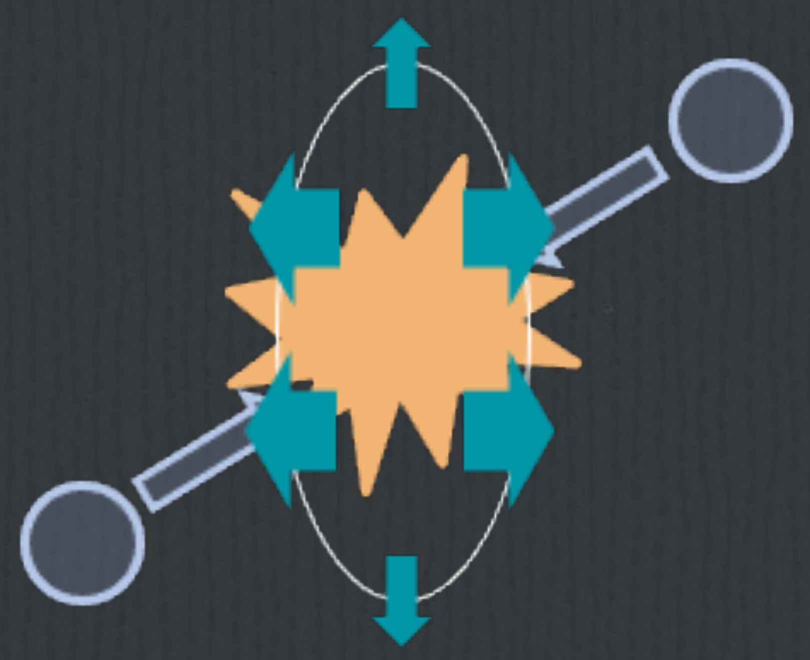


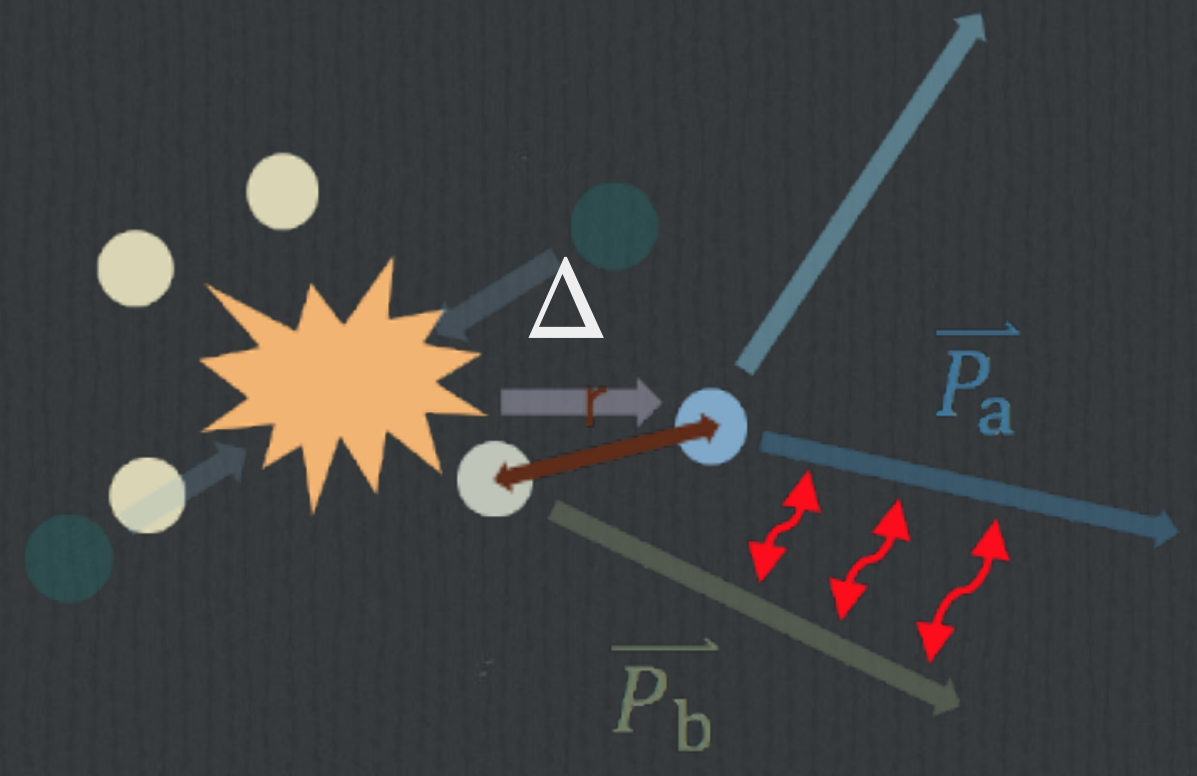
$$C(k^*) = \int S(r)\,|\psi(\vec{r},\vec{k^*})|^2\,d\vec{r}^3$$

pp Correlation: AV18 + Coulomb potentials used with CATS to calculate $\psi(\vec{k}^*, \vec{r})$



Determination of the particle-emitting source





Anisotropic + Radial

Pressure gradients

Resonances with cτ ~ r $_{core}$ ~ 1fm (Δ++, N*,Σ*)

Particle	Primordial fraction	Resonances <cτ>
Proton	33 %	1.6 fm
Lambda	34 %	4.7 fm

U. Wiedemann and U. Heinz PRC 56 (1997)

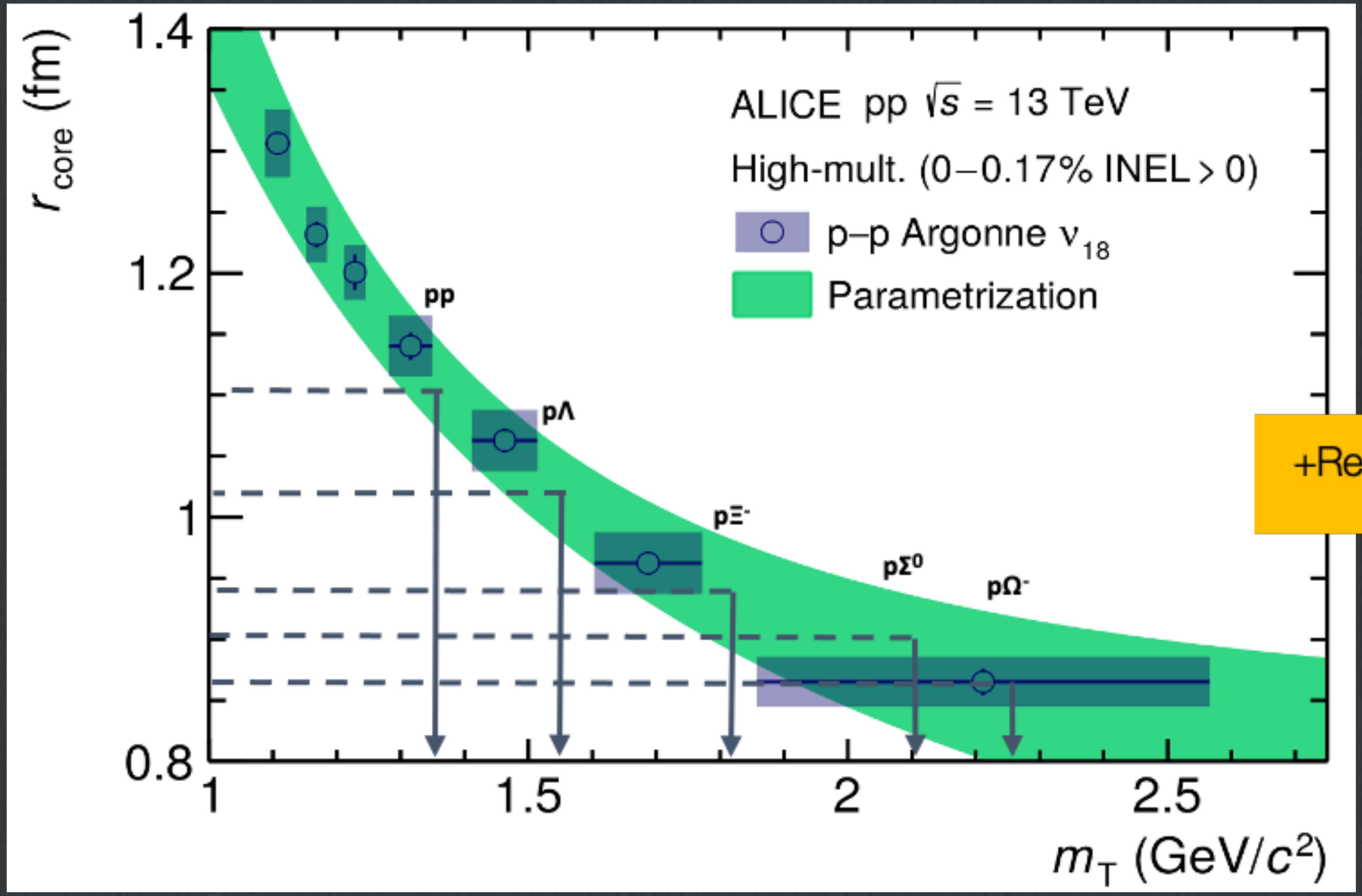
Given the pair transverse mass $m_T = \sqrt{\frac{1}{4}(p_{1T} + p_{2T})^2 + (m_1 + m_2)^2}$

$$\rightarrow S(r) = G(r, r_{core}(m_T)) = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(\frac{-r}{4r_{core}^2}\right) \otimes E(r,s) = \frac{1}{s}\exp\left(-\frac{r}{s}\right)$$

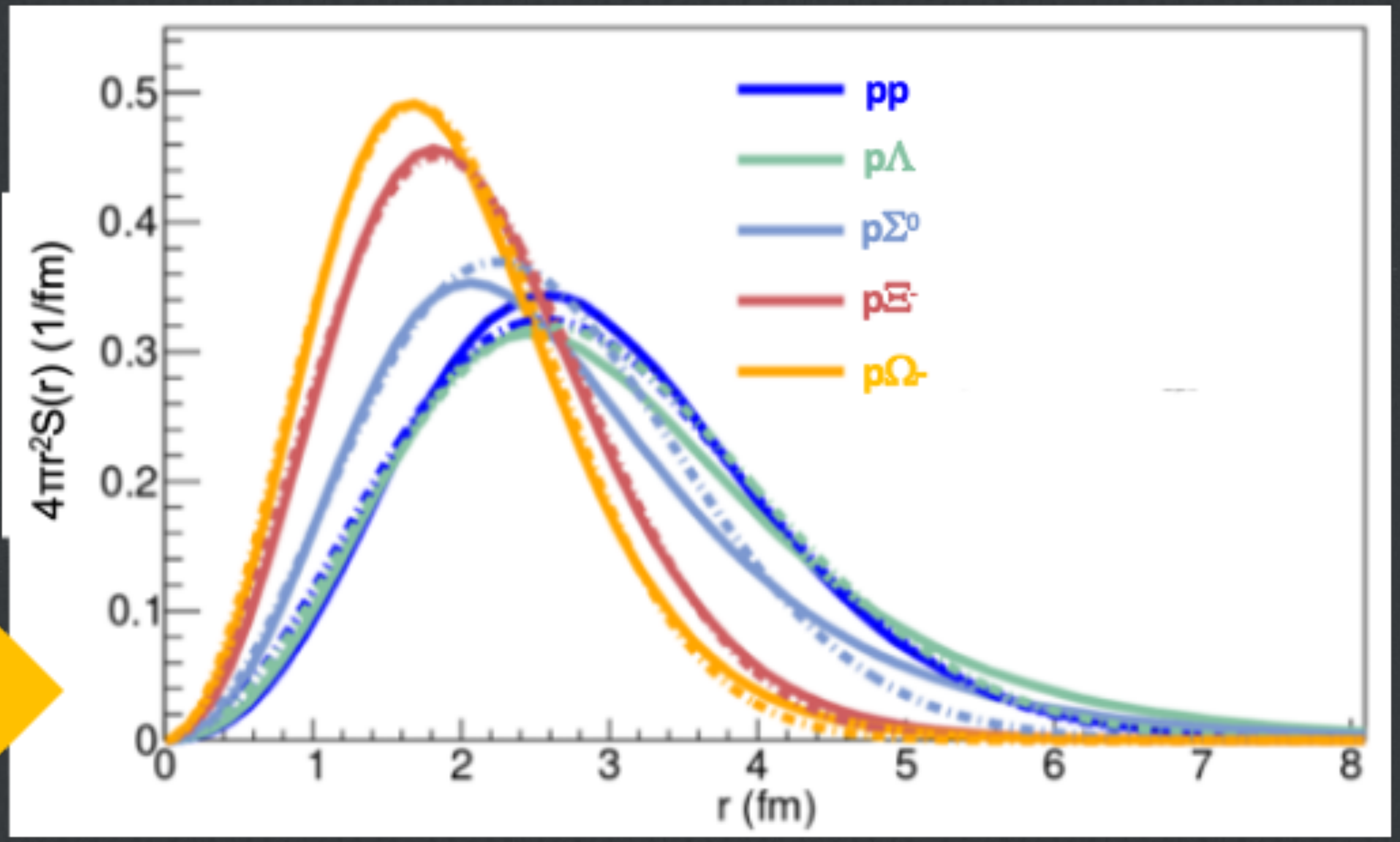
$$s = \beta\gamma\tau_{res}$$

One source to rule them all

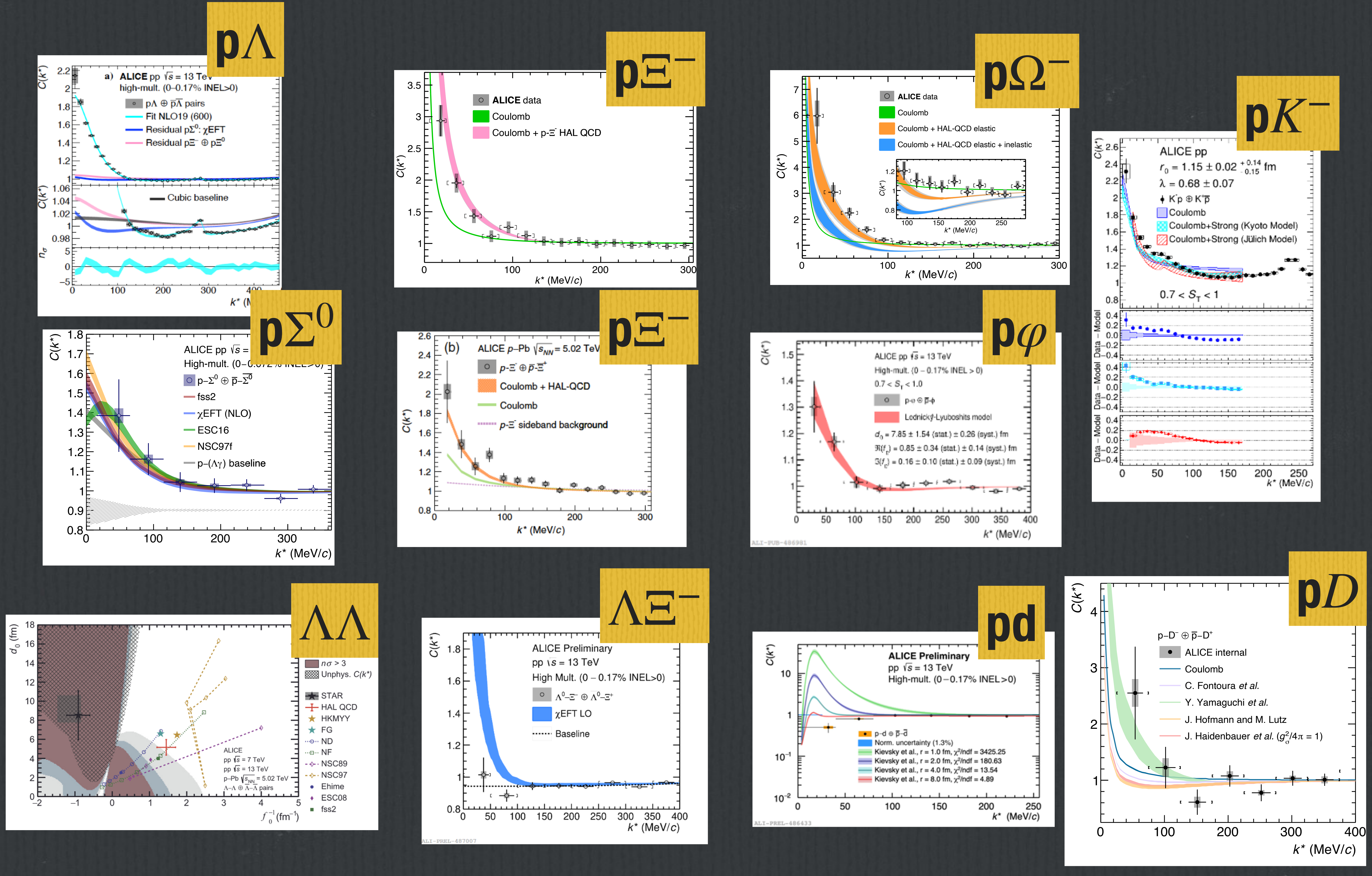
ALICE Coll., PLB, 811 (2020)



+Resonances



Two body interaction among many hadrons



Our recent papers:

CATS: EPJA 78 (2018)
Projector: EPJC 82 (2022)
Review 1: Prog.Part.Nucl.Phys. 112 (2020)
Review 2:Ann.Rev.Nucl.Part.Sci. 71 (2021)
p-ϕ bound state: arXiv:2212.12690

p-K: PRL 124 (2020) 092301
p-K: PLB 822 (2021), EPJC (2022)
p-p, p-Λ, Λ-Λ: PRC 99 (2019) 024001
Λ-Λ: PLB 797 (2019) 134822
p-Ξ⁻: PRL. 123 (2019)
p-Ξ⁻, p-Ω⁻: Nature 588 (2020) 232–238
p-Σ⁰: PLB 805 (2020) 135419
p-φ: PRL 127 (2021)
$p-\bar{p}, \Lambda-\bar{\Lambda}, p-\bar{\Lambda}$: PLB 829 (2022)
p-Λ: PLB 832 (2022) 137272
$\Lambda-\Xi$: PLB 137223 (2022)
D-p: PRD **106**, 052010 (2022)
ppp, ppΛ: arXiv:2206.03344

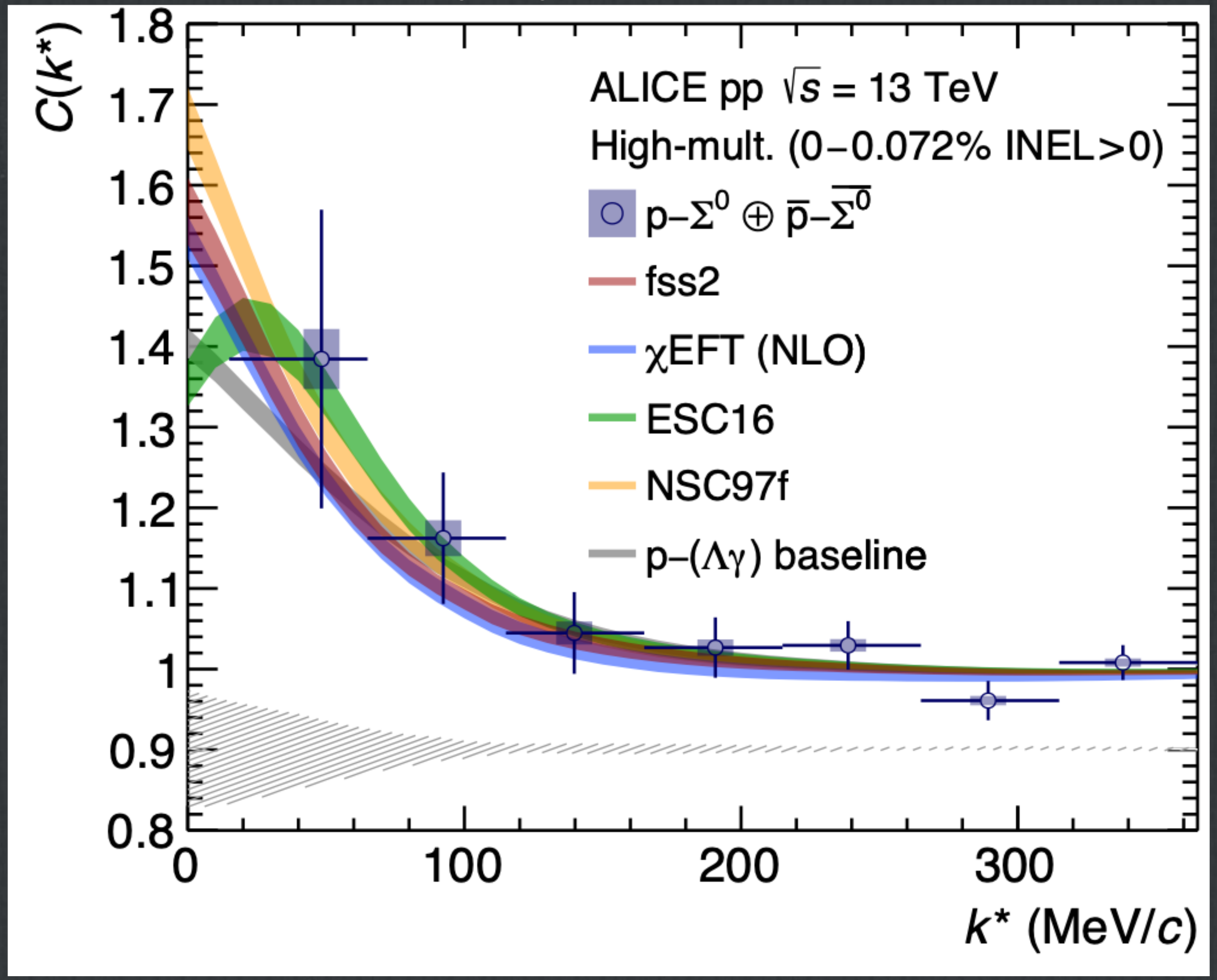
What can be done better elsewhere

- Reconstruction of Σ^0 via decay to $\Lambda+\gamma$
- γ reconstructed from conversion e+e-
- p Σ^0 compatible to the baseline

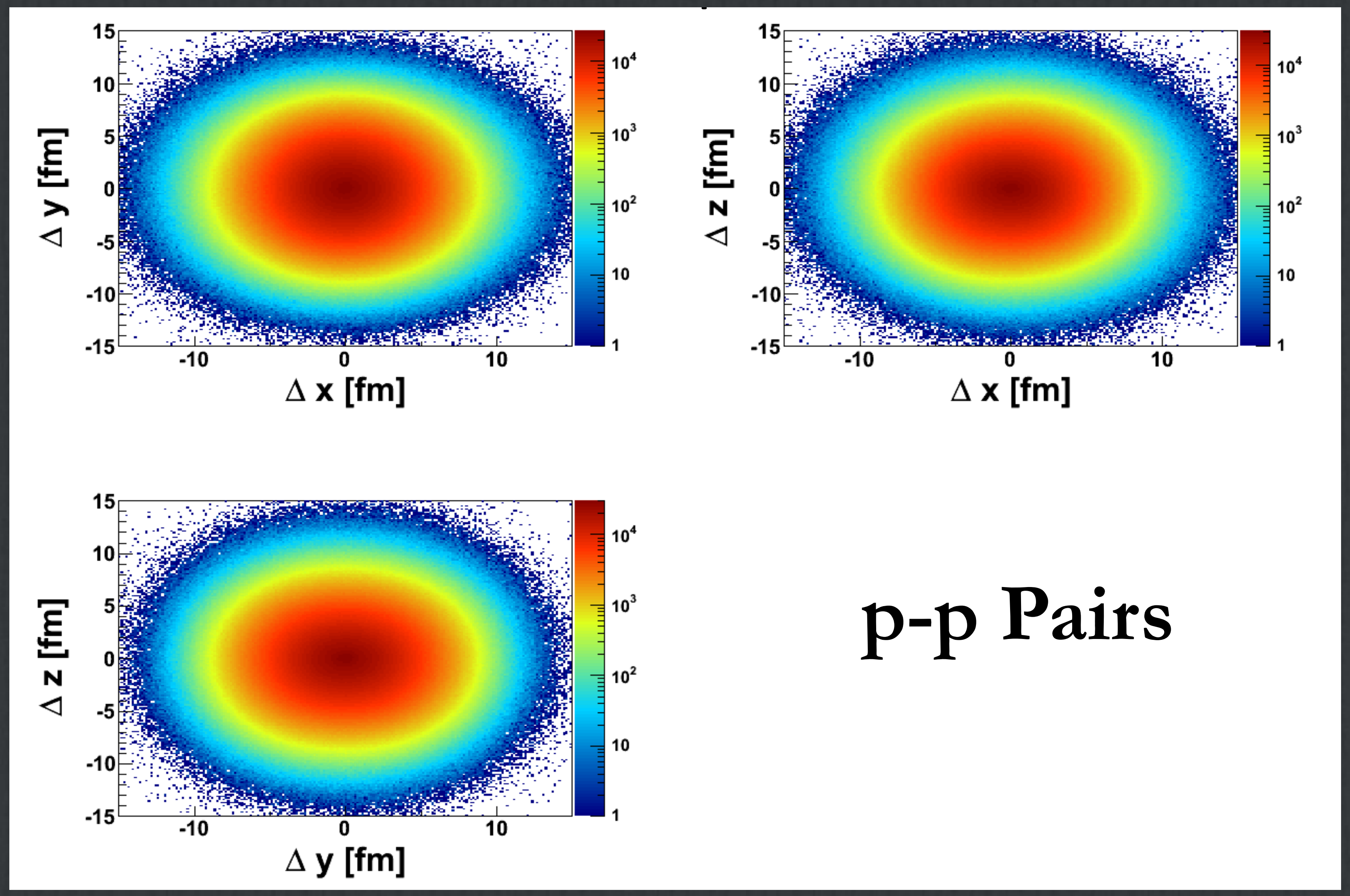
→ stay tuned for data of Run 3 for higher statistics!

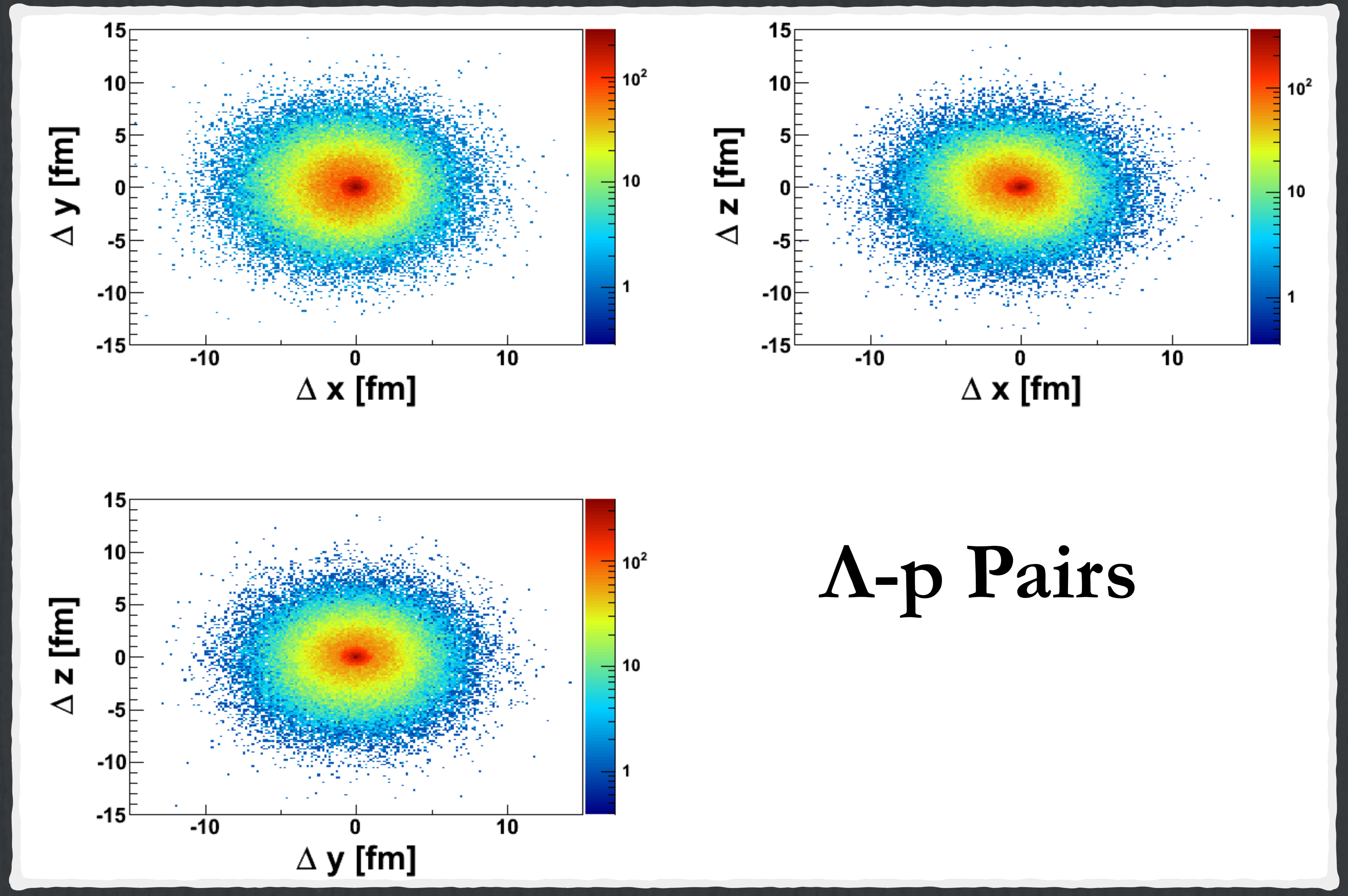
But a measurement in HADES with p+p collisions and the electromagnetic calorimeter could be competitive.
Same for Ξ^0

ALICE, PLB 805 (2020) 135419



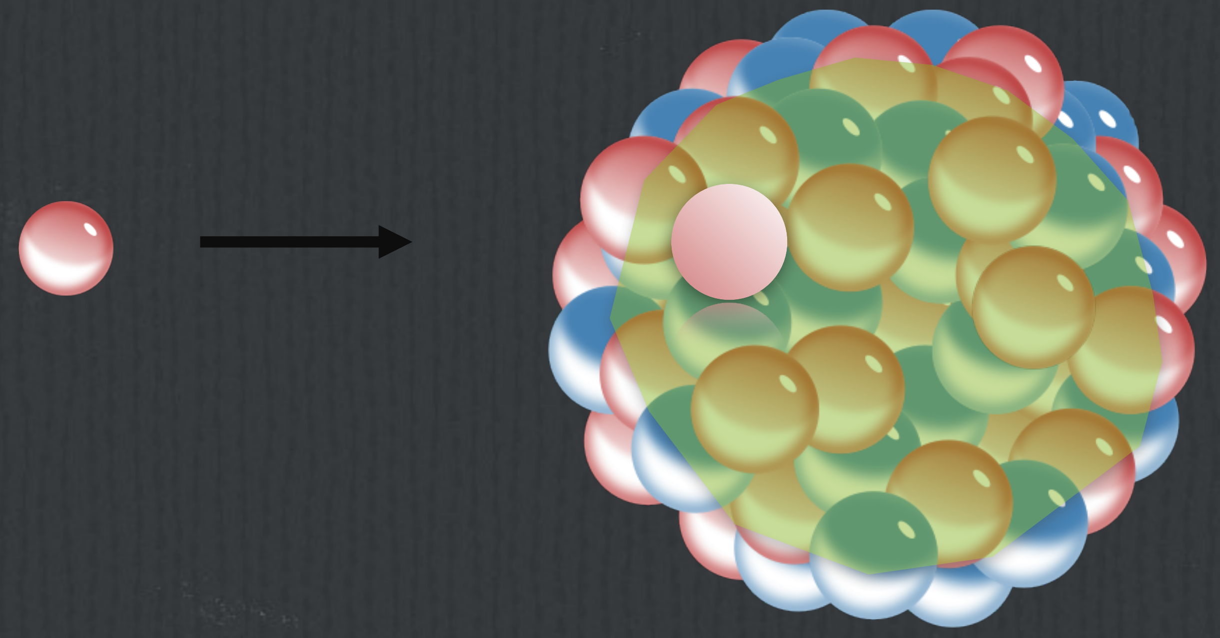
Scattering in nuclear matter



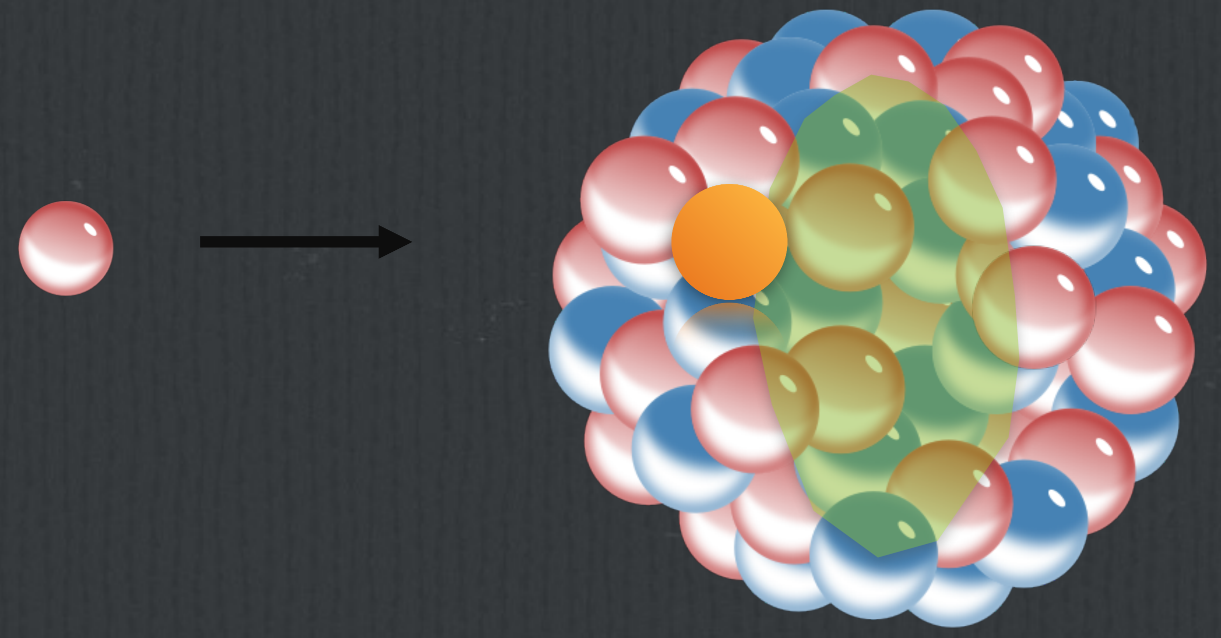


Λ-p source: 1.24 times smaller than p-p source (from UrQMD)

p-scattering in the nucleus

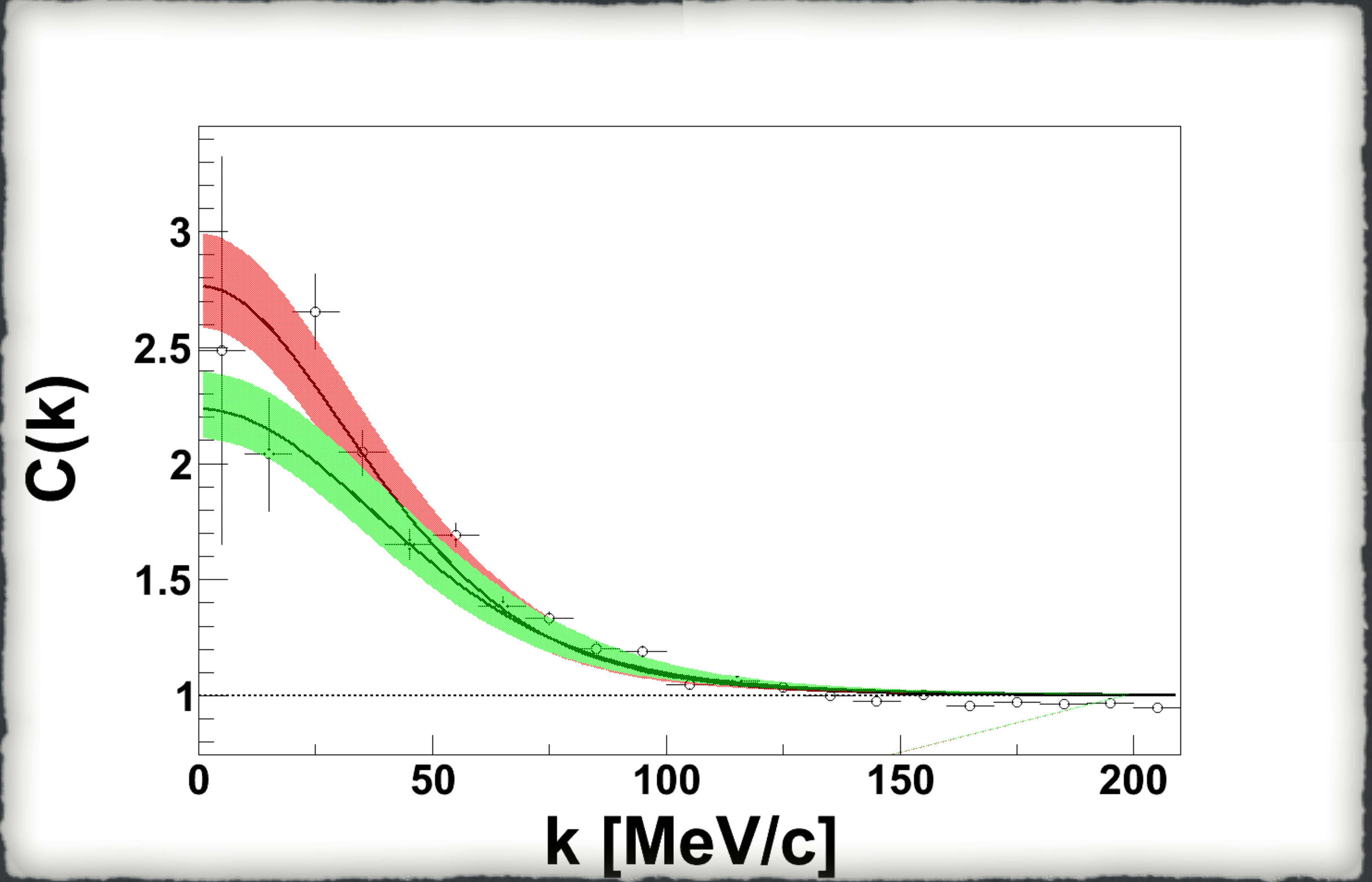


Λ-scattering in the nucleus



Λ-p Correlation in p+Nb collisions at $\sqrt{s}$ = 3.5 GeV

J. Adamczewski-Musch et al.,[HADES coll.] Phys. Rev. C. 94 (2016).

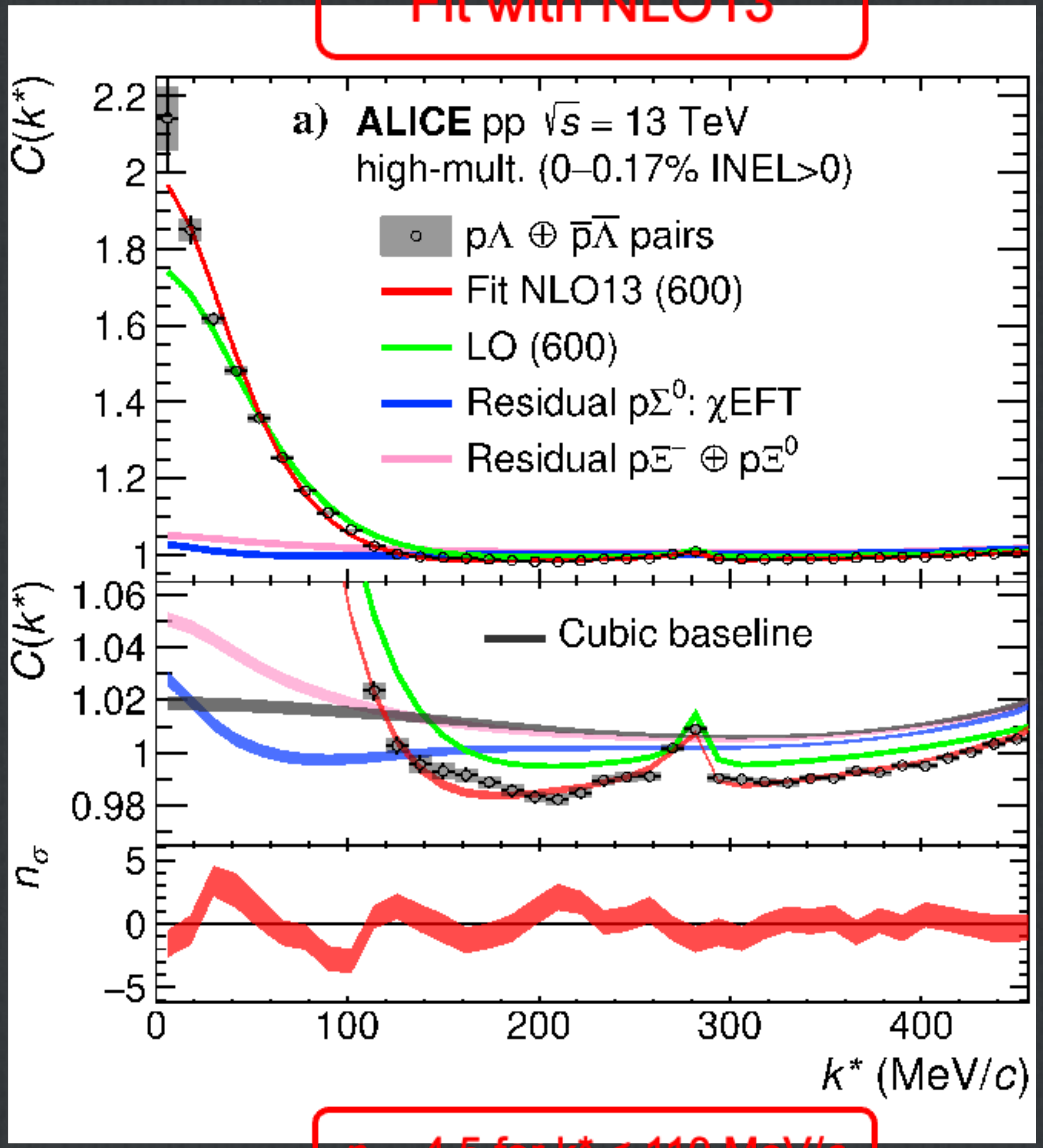


New data on p+p collisions at 3.5 GeV
Factor 100 (?) more statistics than this plot

Λ-p Correlation in p+p collisions at $\sqrt{s}$ = 13 TeV

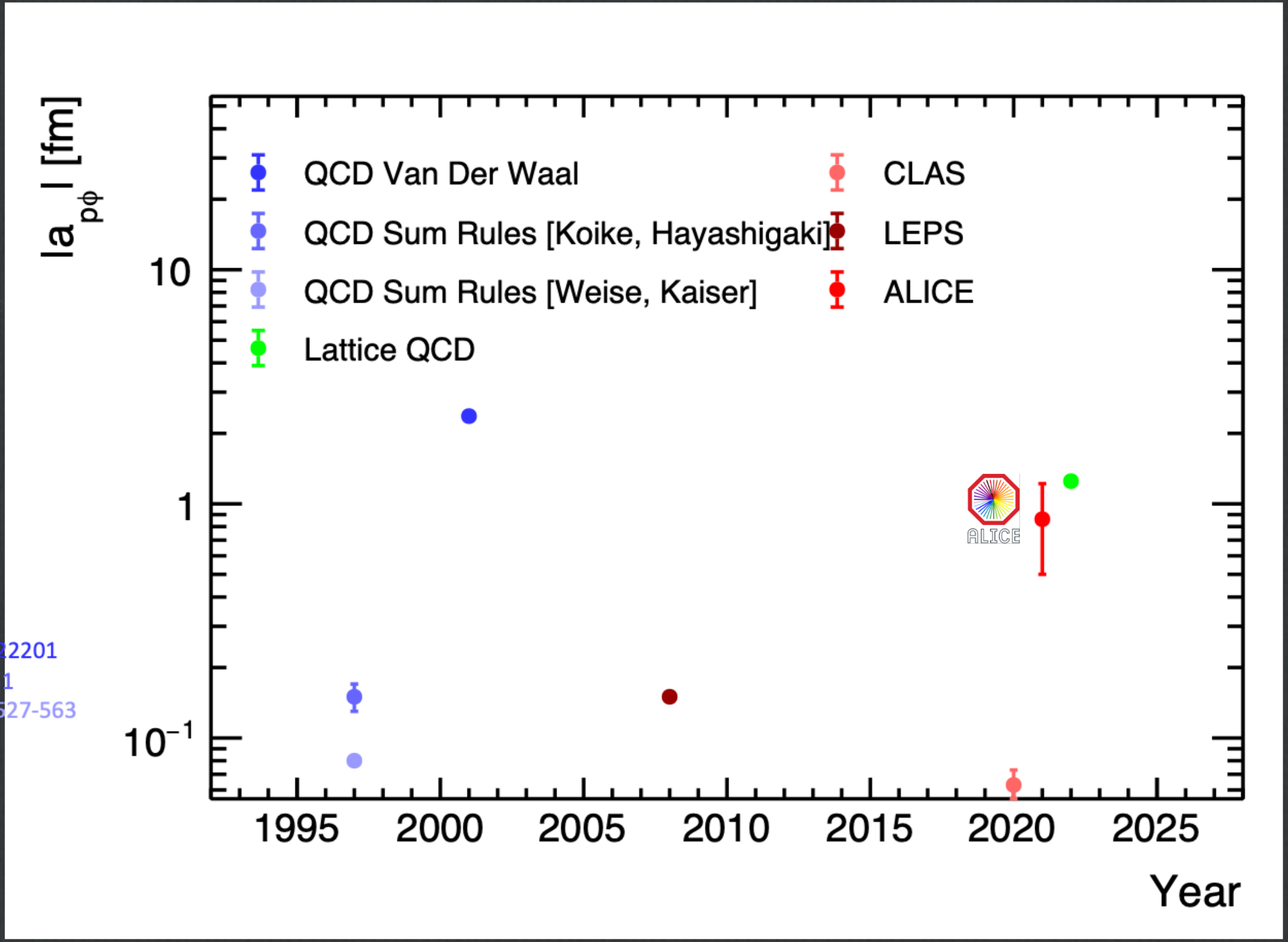
ALICE, PLB 833 (2022), 137272

Fit with NLO13



n_σ~ 4.5 for k* < 110 MeV/c

Vector Meson- Nucleon final state interaction



H. Gao, T.S.H. Lee & V. Marinov, Phys Rev C **63** (2001) 022201
Y. Koike & A. Hayashigaki, Prog Theor Phys **98** (1997) 631
F. Kling, N. Kaiser & W. Weise, Nucl.Phys. A **624** (1997) 527-563
IS, L. Pentchev, & A.I. Titov, Phys Rev C **101** (2020)
W.C. Chang *et al*, Phys Lett B **658**, 209 (2008)
S. Acharya *et al*, Phys. Rev. Lett. **127** (2021) 172301

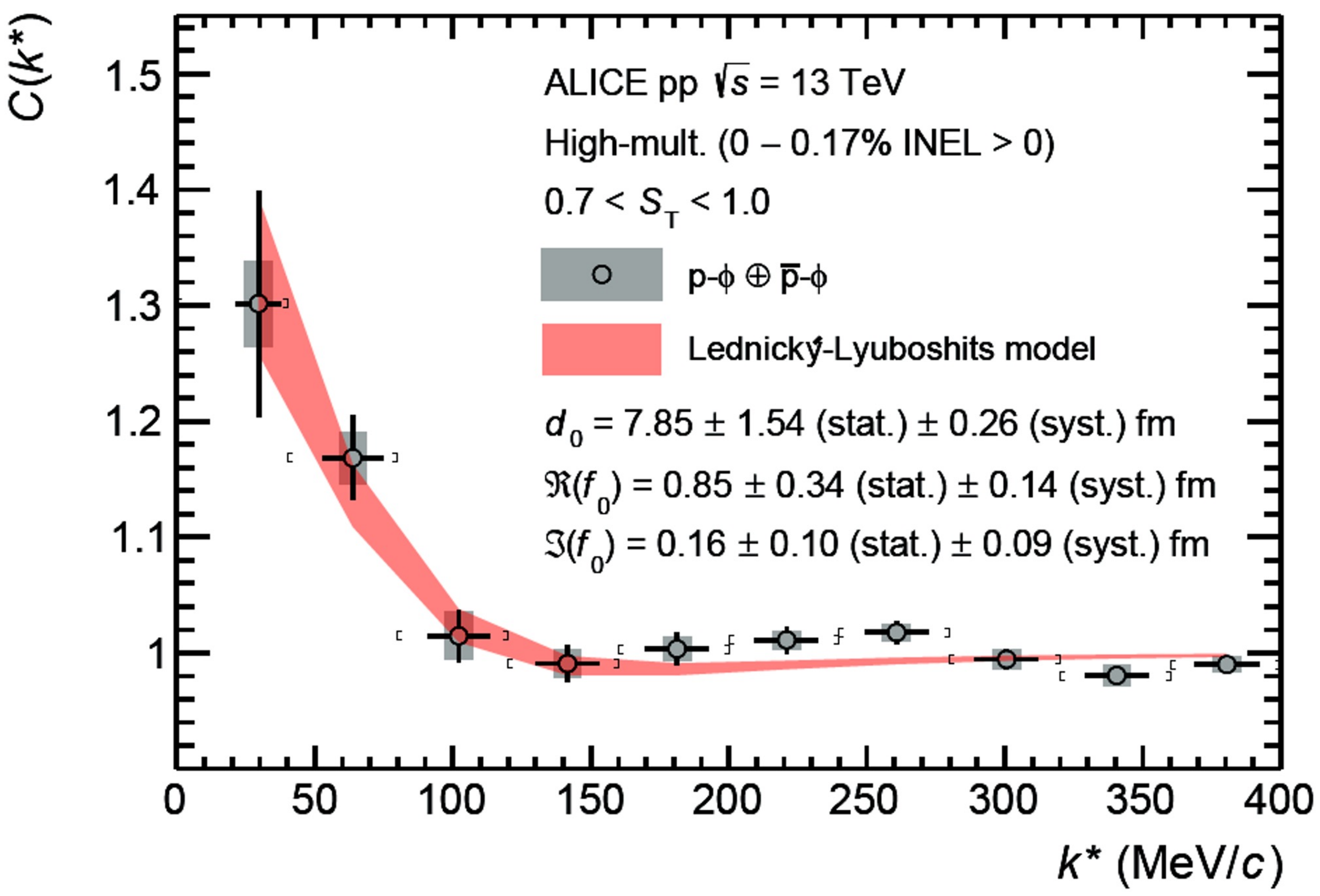
Spin averaged scattering parameters

- 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

$$\Re(f_0) = 0.85 \pm 0.34(stat.) \pm 0.14(syst.)\ \text{fm}$$
$$\Im(f_0) = 0.16 \pm 0.10(stat.) \pm 0.09(syst.)\ \text{fm}$$
$$d_0 = 7.85 \pm 1.54\ (stat.) \pm 0.26(syst.)\ \text{fm}$$

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

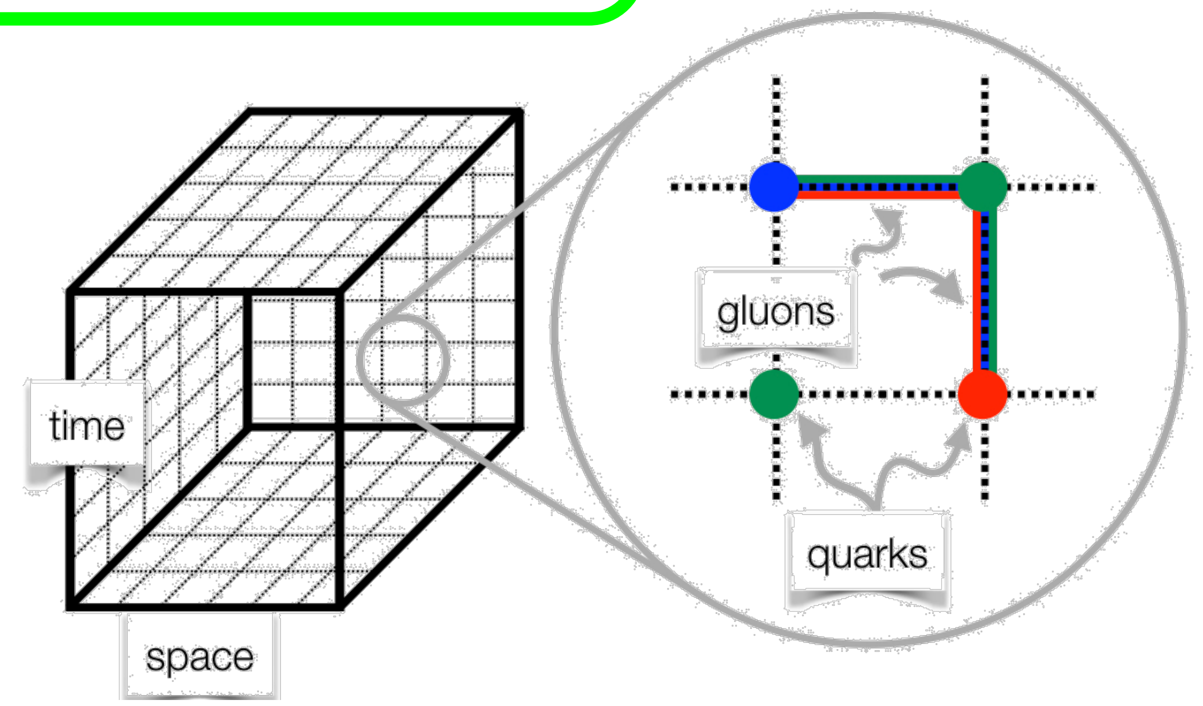
ALICE Collab., *PRL* **127** (2021) 172301

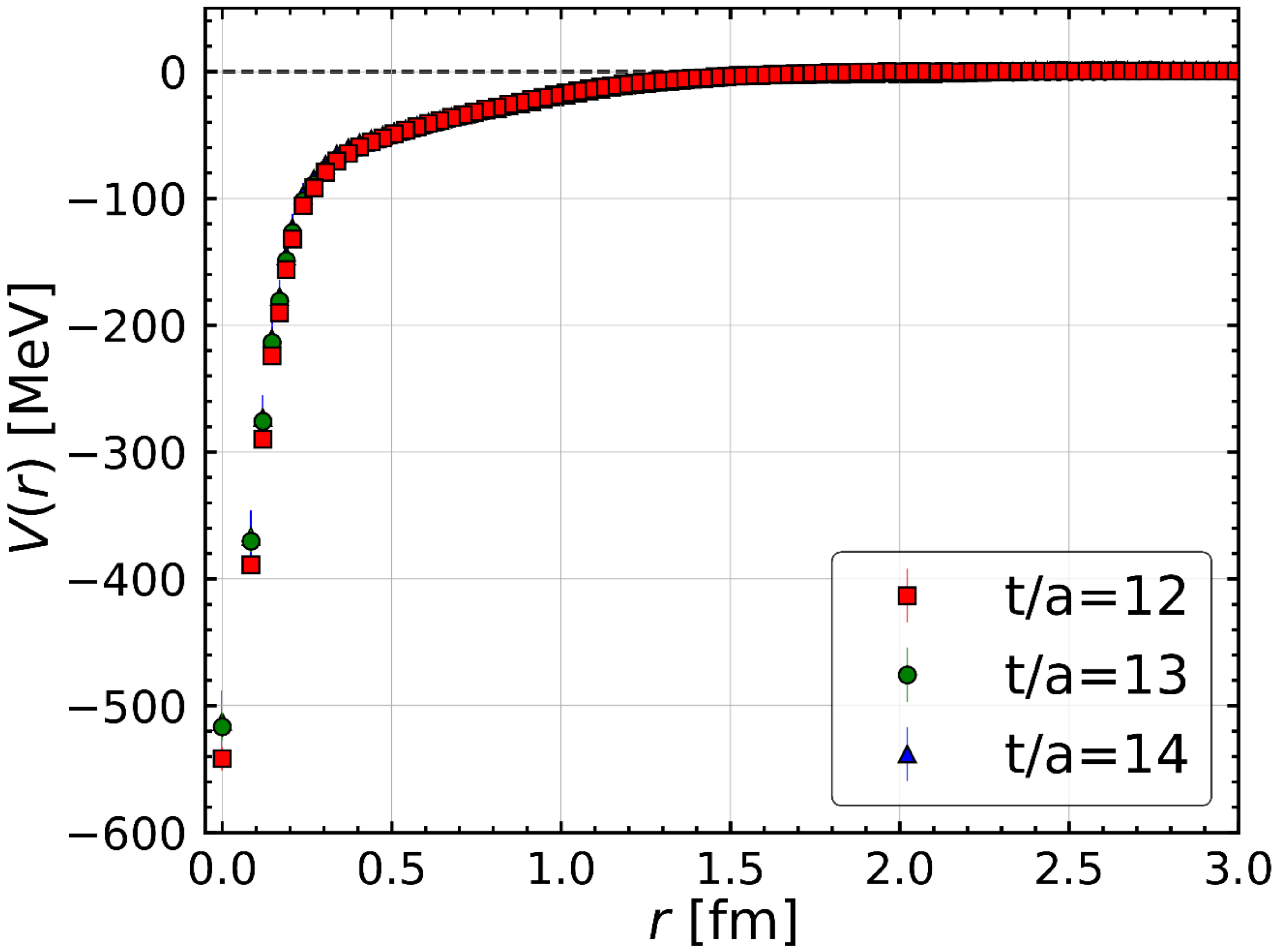


Lattice potential $^4S_{3/2}$

- First simulation of the N-ϕ system in large lattice volume $\simeq$ (8.1 fm)^3 and lattice spacing a $\simeq$ 0.08 fm
- Light dynamical quarks near the physical point (m_π = 146.4 MeV)
- Attractive core → Pauli exclusion does not operate due to no common quarks
- Long-ranged attractive tail, hints of pion dynamics

$$f_0 = 1.43^{+0.23}_{-0.23}(stat.)^{+0.06}_{-0.36}(syst.)\ \text{fm}\ ^*$$
$$d_0 = 2.36^{+0.10}_{-0.10}(stat.)^{+0.48}_{-0.02}(syst.)\ \text{fm}$$





Studying spin dependent interaction

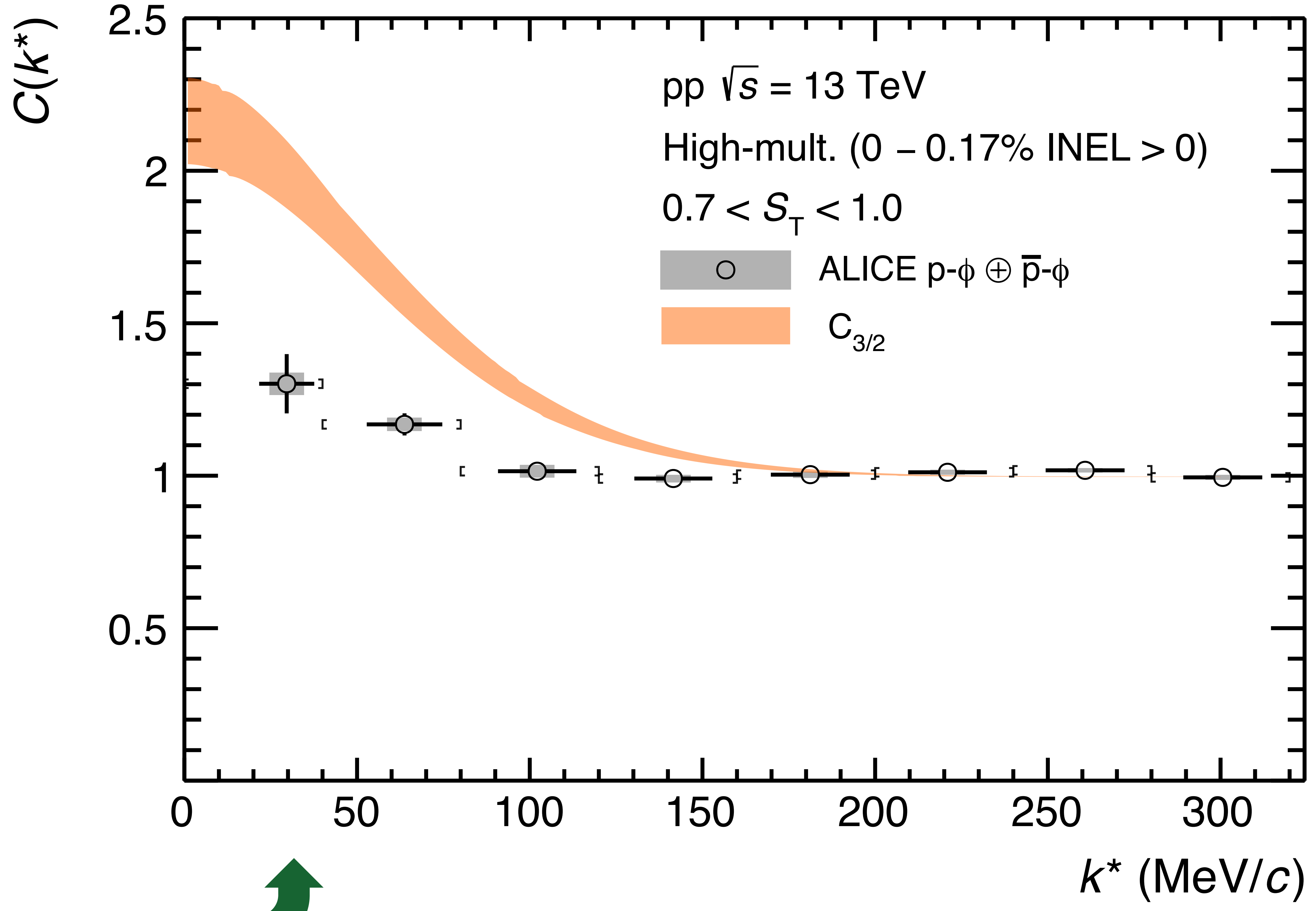
$^4S_{3/2}$ channel

- Dominated by elastic scattering states
- Modelled using HAL QCD potential
  Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
- Potential at physical-pion mass

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

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

Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507



$$C(k^*) = \int S(\vec{r}^*) \left|\psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3\vec{r}^*$$

CATS framework solves $\hat{\mathcal{H}}\psi(\vec{k}^*, \vec{r}^*) = E\psi(\vec{k}^*, \vec{r}^*)$

D.L. Mihaylov et al, *Eur. Phys. J.* **C78** (2018) no.5, 394

Studying spin dependent interaction

TECHNISCHE UNIVERSITÄT MÜNCHEN

ALICE

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  Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
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Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507

$^2S_{1/2}$ channel

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

$$V_{\frac{1}{2}}(r) = V_{LATTICE,\,MOD}(r) + \underbrace{i \cdot \sqrt{f(r;b_3)} \cdot \frac{\gamma}{r} e^{-m_K \cdot r}}_{\text{Imaginary Part of Pot}}$$

Imaginary Part of Pot

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

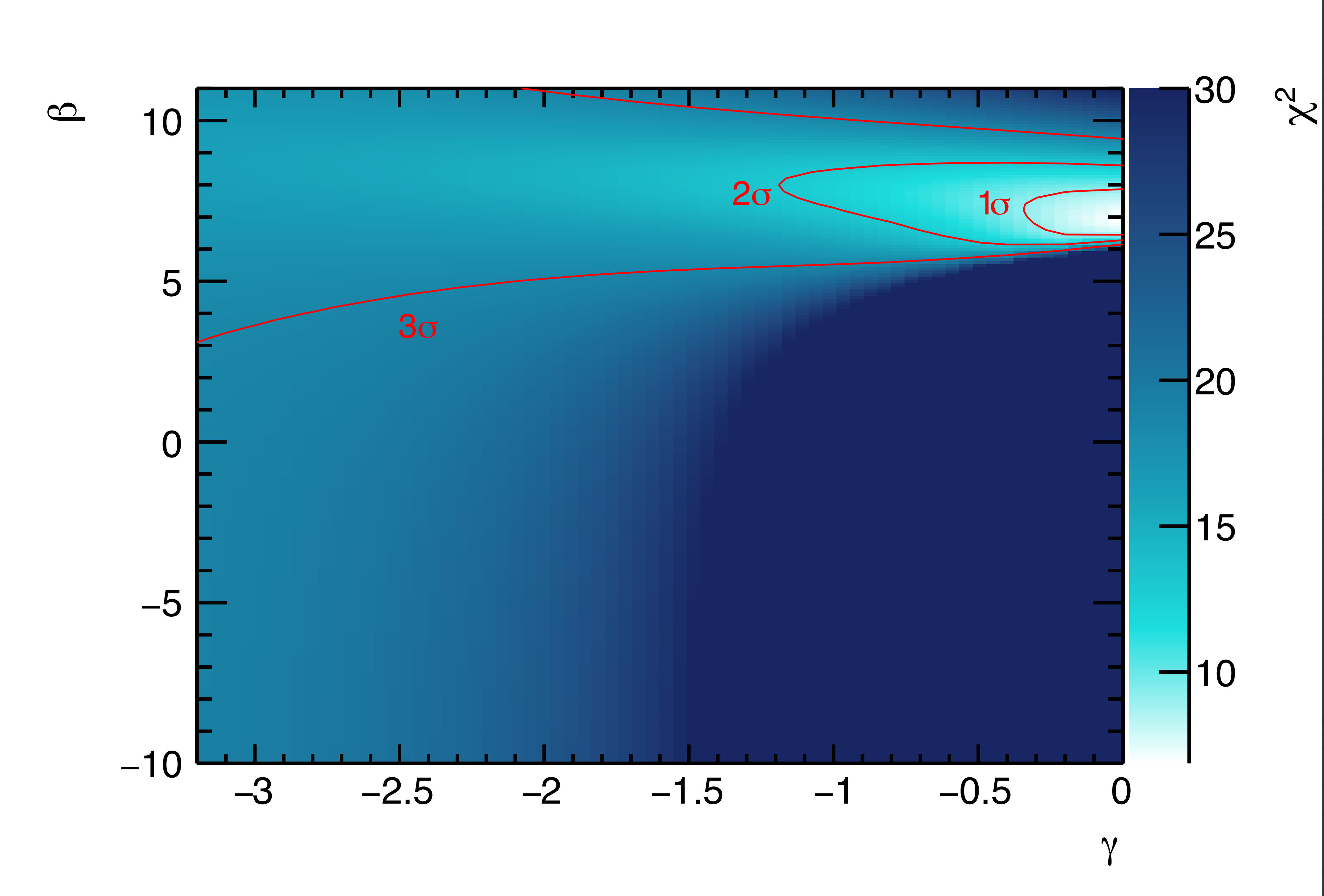
Real Part of Pot

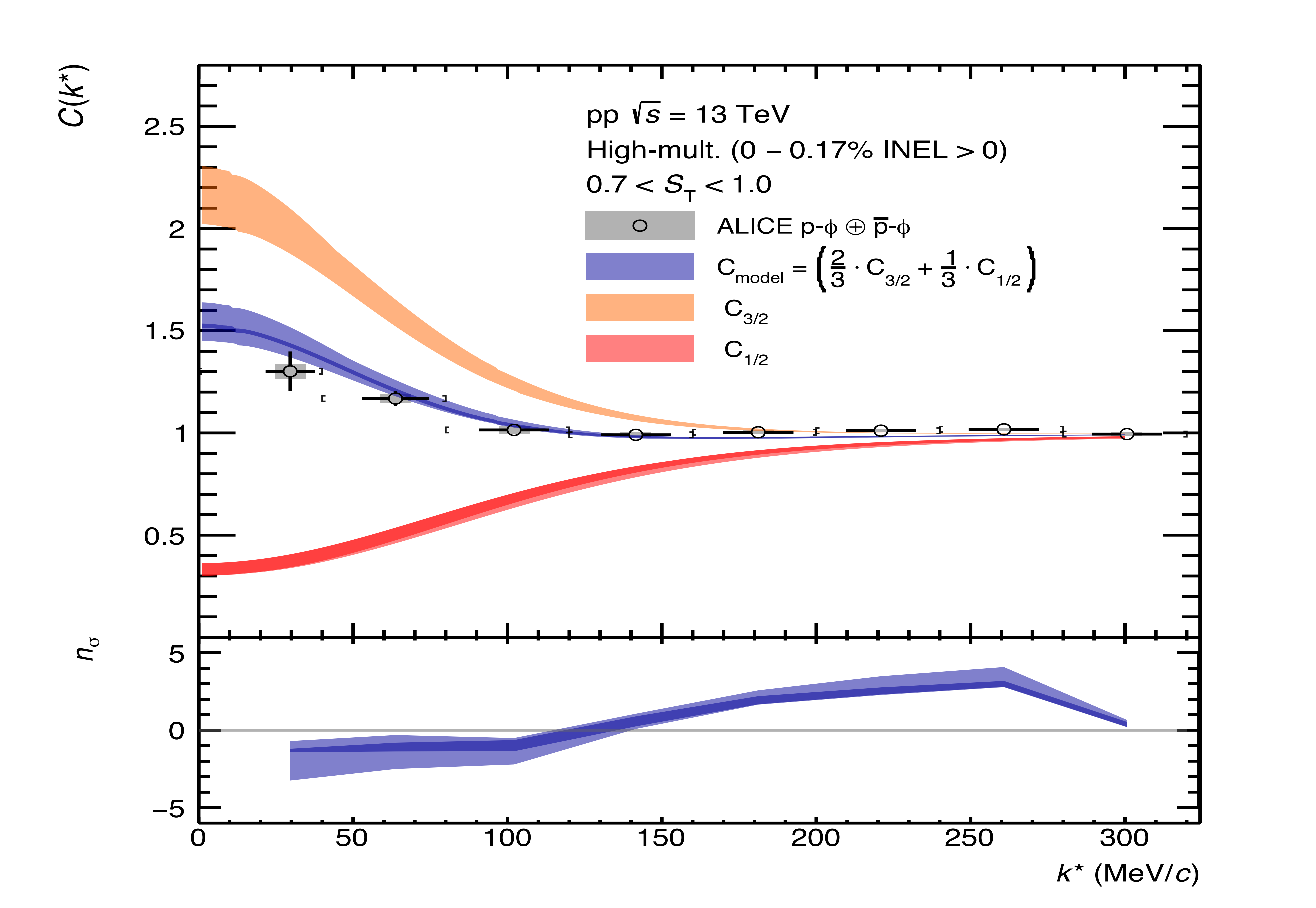
$$V_{LATTICE,\,MOD}(r) = \beta \cdot V_{short}(r) + V_{2\pi}(r)$$

$\rightarrow C_{1/2}^{(\beta,\gamma)}(k^*)$

Results on ϕ-proton

arXiv:2212.12690 [nucl-ex]





- Repulsive interaction in the S= 1/2 excluded by more than 3σ
- Attractive interaction AND bound state

$$\Re(f_0) = -1.47^{+0.44}_{-0.37}(stat.)^{+0.14}_{-0.17}(syst.)\text{ fm}$$
$$\Im(f_0) = 0.00^{+0.26}_{-0.00}(stat.)^{+0.15}_{-0.00}(syst.)\text{ fm}$$
a
$$\Re(d_0) = 0.37^{+0.07}_{-0.08}(stat.)^{+0.03}_{-0.03}(syst.)\text{ fm}$$
$$\Im(d_0) = 0.00^{+0.00}_{-0.02}(stat.)^{+0.00}_{-0.01}(syst.)\text{ fm}$$

E_B = 14.7 - 56.6 MeV

Scattering parameters of $^2S_{1/2}$

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

- Scattering parameters of S=1/2 extracted from phase-shift using effective range expansion

$$\Re(f_0) = -1.47^{+0.44}_{-0.37}(stat.)^{+0.14}_{-0.17}(syst.)\ \text{fm}$$
$$\Im(f_0) = 0.00^{+0.26}_{-0.00}(stat.)^{+0.15}_{-0.00}(syst.)\ \text{fm}$$
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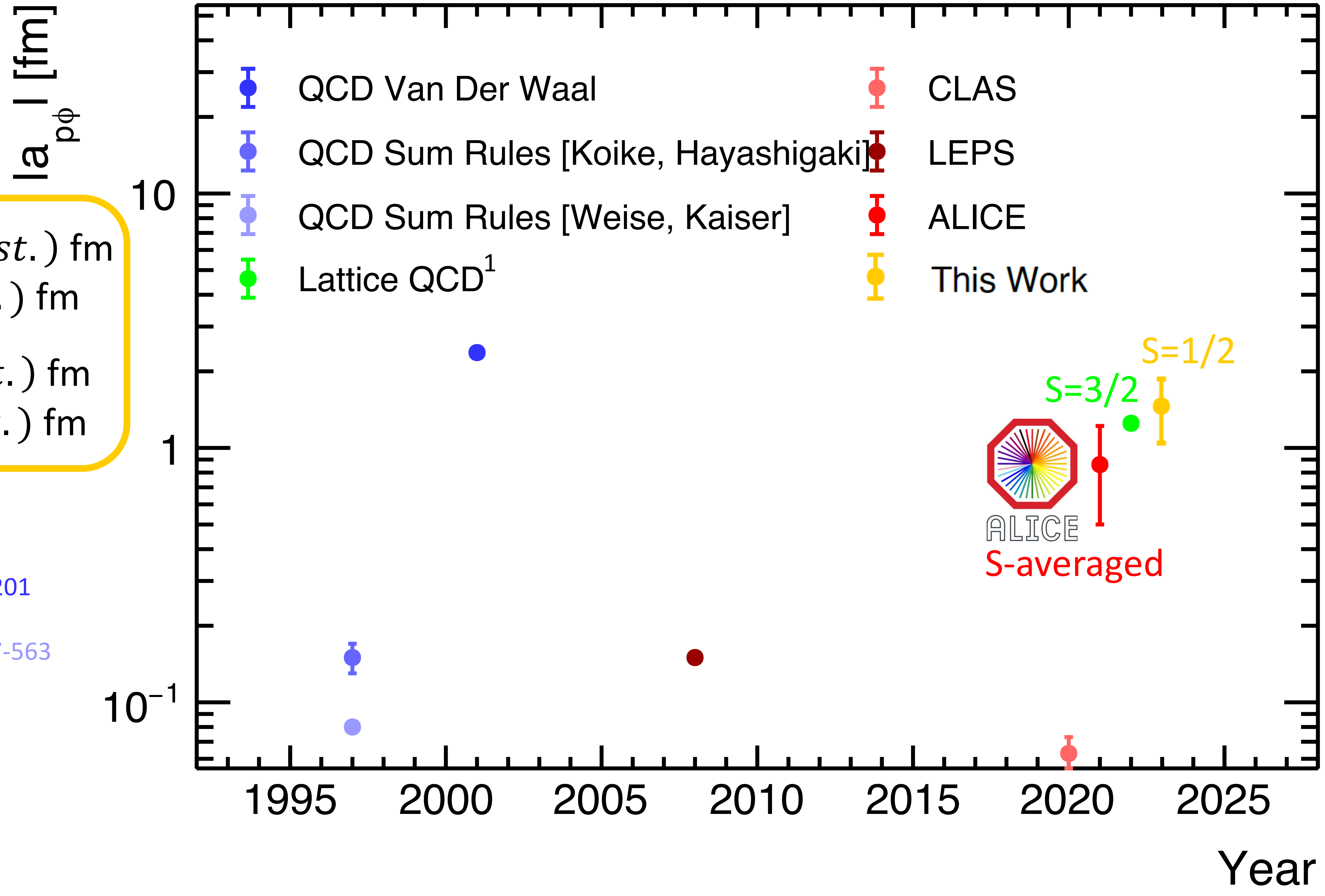

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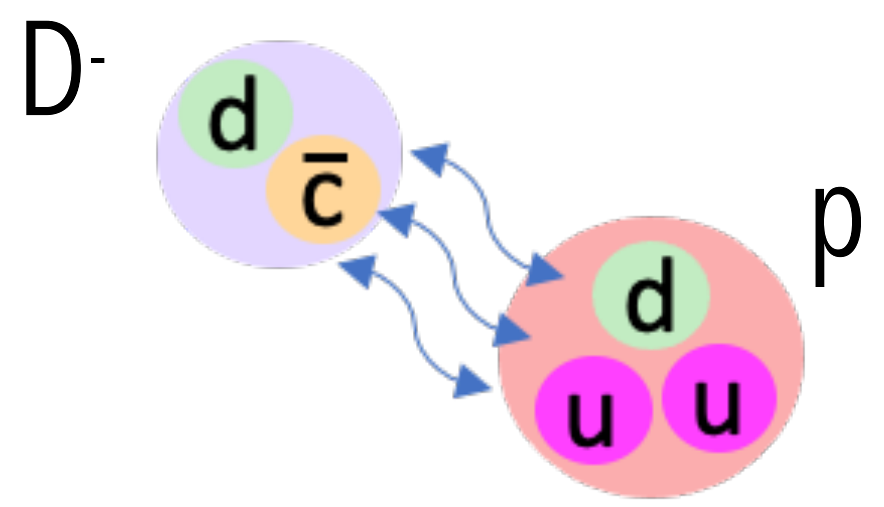
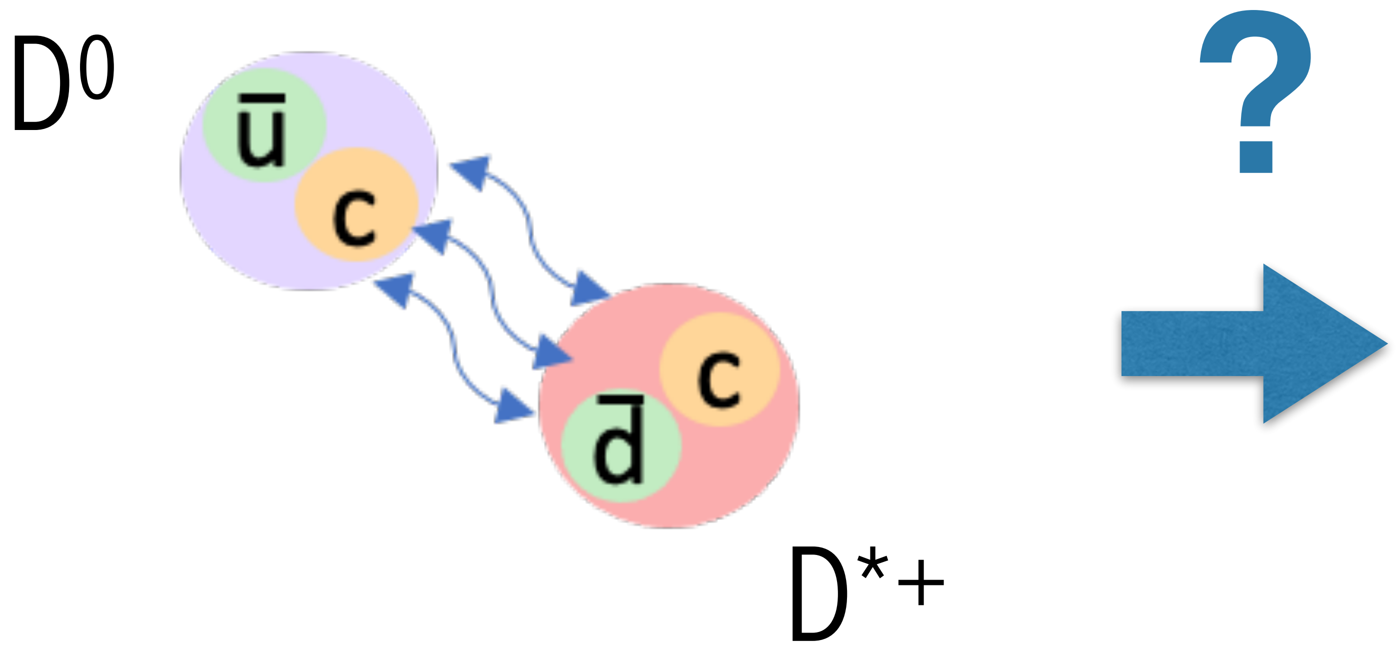
Yan Lyu et al., *Phys. Rev. D* **106** (2022) 074507
arXiv:2212.12690 [nucl-ex]

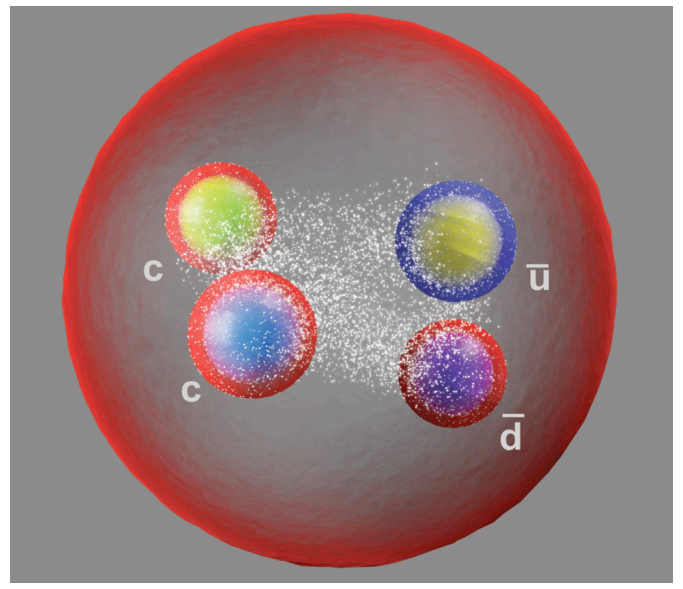
[1] estimated by extrapolating results to physical masses

Residual strong interaction among charmed hadrons

- The residual strong interaction among hadrons is rather well known for NN, less known for YN and barely known for Charmed hadrons-light hadrons combination

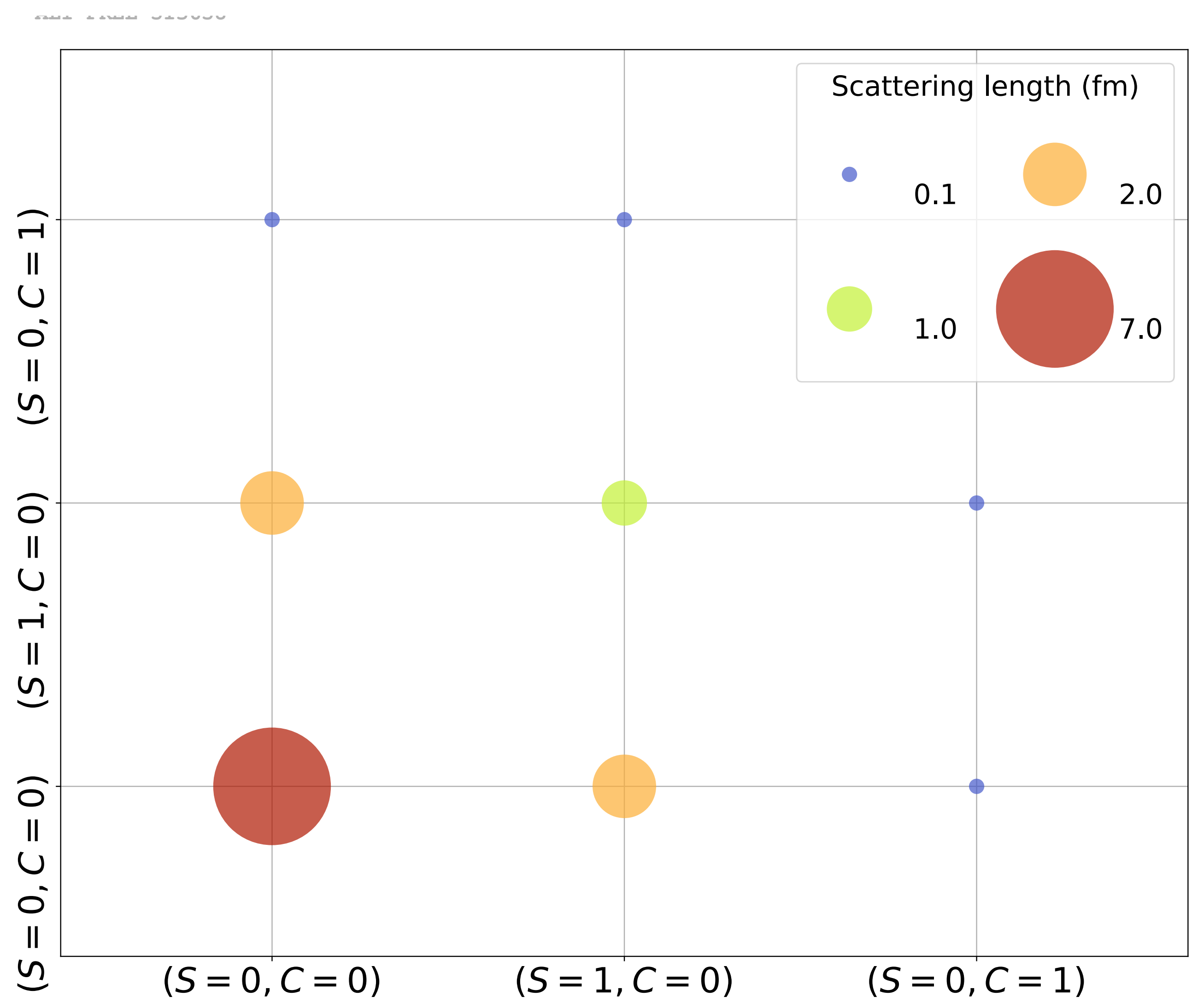






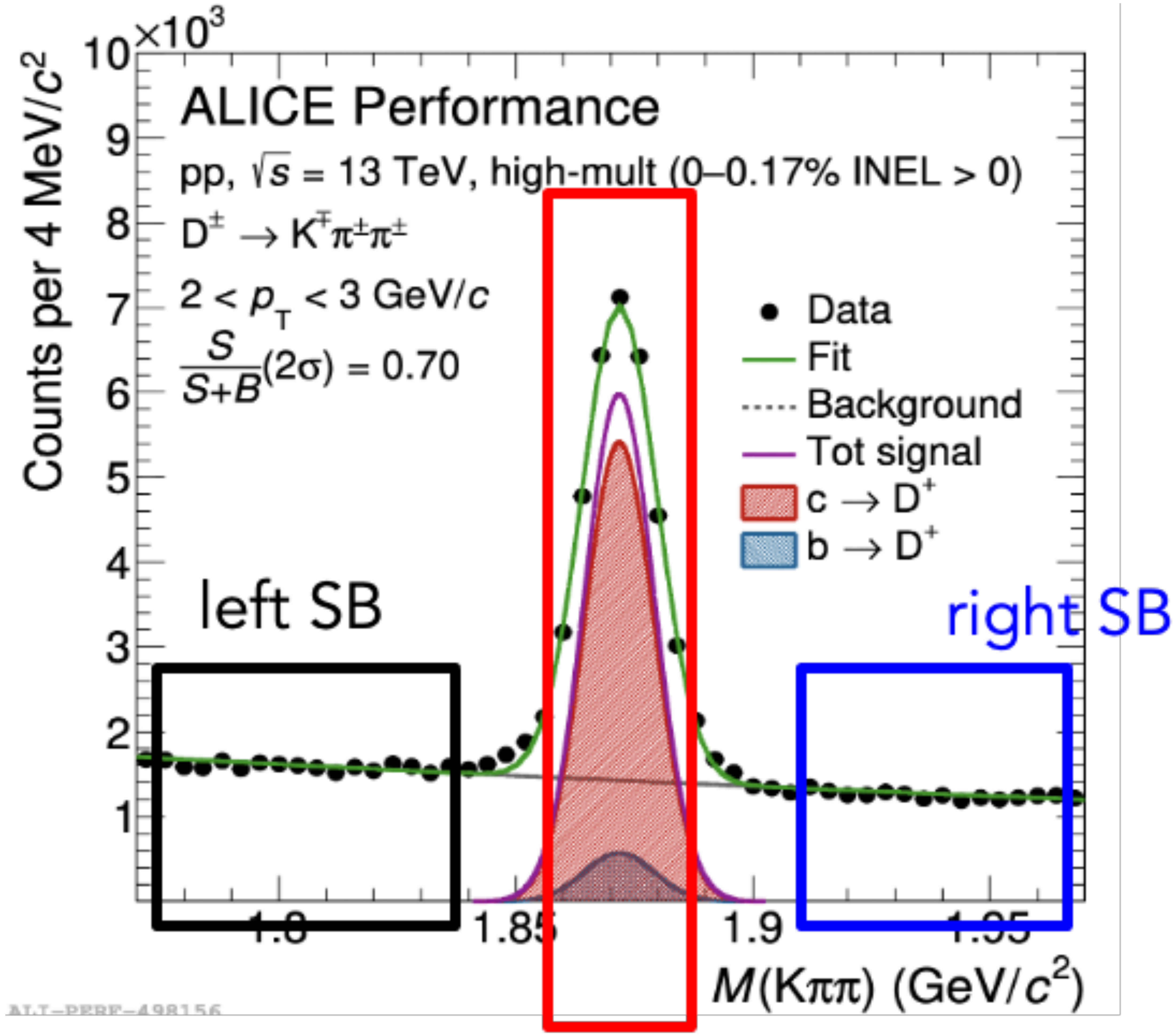
- Determine the hierarchy of the hadron-hadron coupling for all quark flavours

M. He et al, PLB 701 (2011) 445–450



- Determine the scattering parameters among charmed hadrons as a tool to study molecular states with charm content

D mesons in Run 2



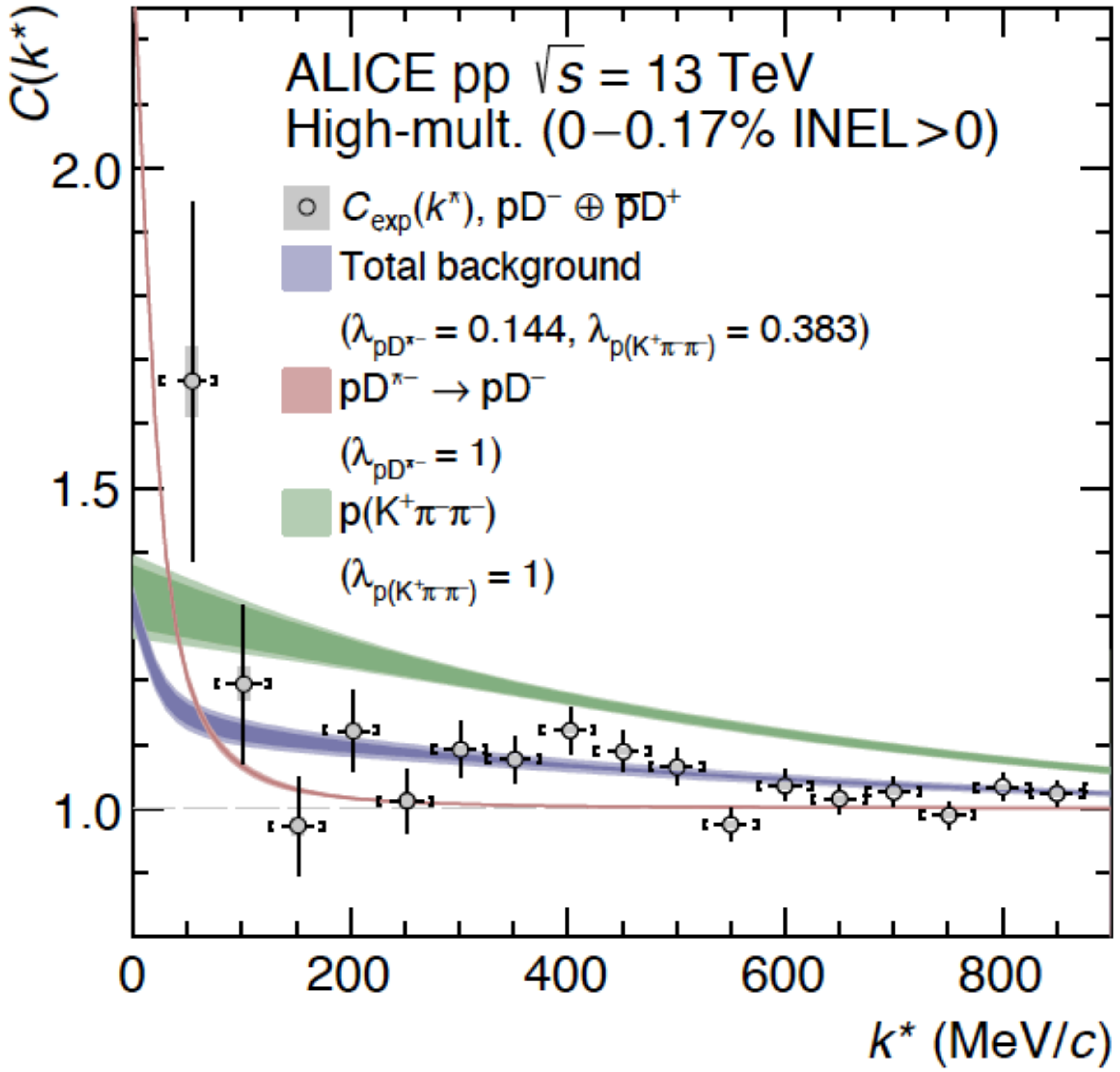
- Relevant sources of background
  1. Uncorrelated ($K^+ \pi^- \pi^-$) background candidates
     - ➡ Parametrised from the measured C(k*) computed with D^- candidates in the sidebands
  2. D^- from D^{*-} decays (~30% of D^-)
     - ➡ p– D^{*-} strong interaction not known, only Coulomb considered

- All these contributions must be considered for the interpretation of the correlation function

ND̄ raw correlation function

$$C_{\mathrm{exp}}(k^*) = \lambda_{\mathrm{pD^-}} \times C_{\mathrm{pD^-}}(k^*) + \lambda_{\mathrm{p(K^+\pi^-\pi^-)}} \times C_{\mathrm{p(K^+\pi^-\pi^-)}}(k^*) + \lambda_{\mathrm{pD^{*-}}} \times C_{\mathrm{pD^{*-}}}(k^*) + \lambda_{\mathrm{flat}} \times C_{\mathrm{flat}}.$$

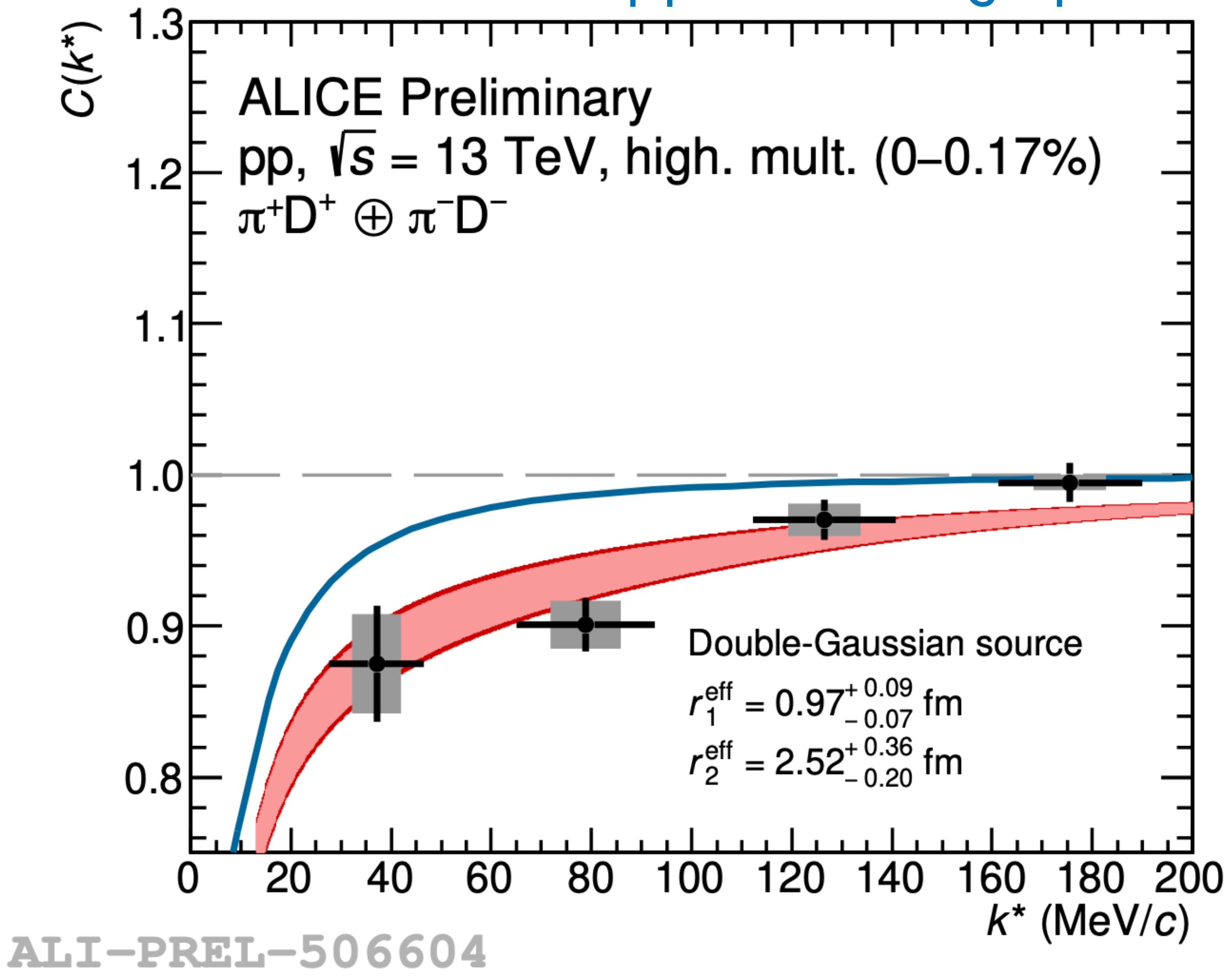
ALICE, arXiv: 2201.05352



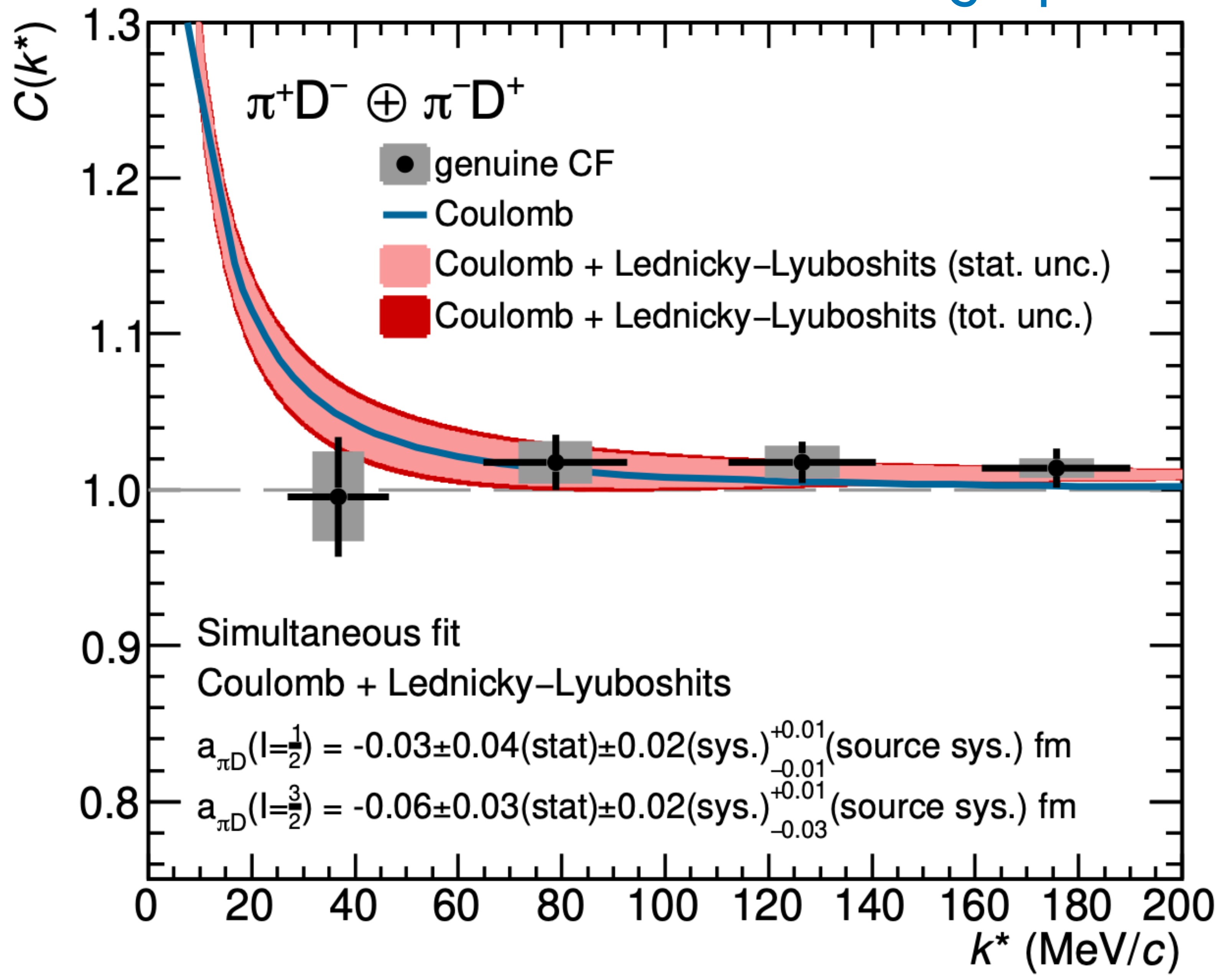
- The different λ parameters are extracted from the weight of the side-bands, the evaluated D* contribution and the purity for the D and p reconstruction
- There is no mini-jets background for the $\bar{\mathrm{D}}N$ correlation

πD interaction: fit with Lednický-Lyuboshits formula

Opposite-charge pairs

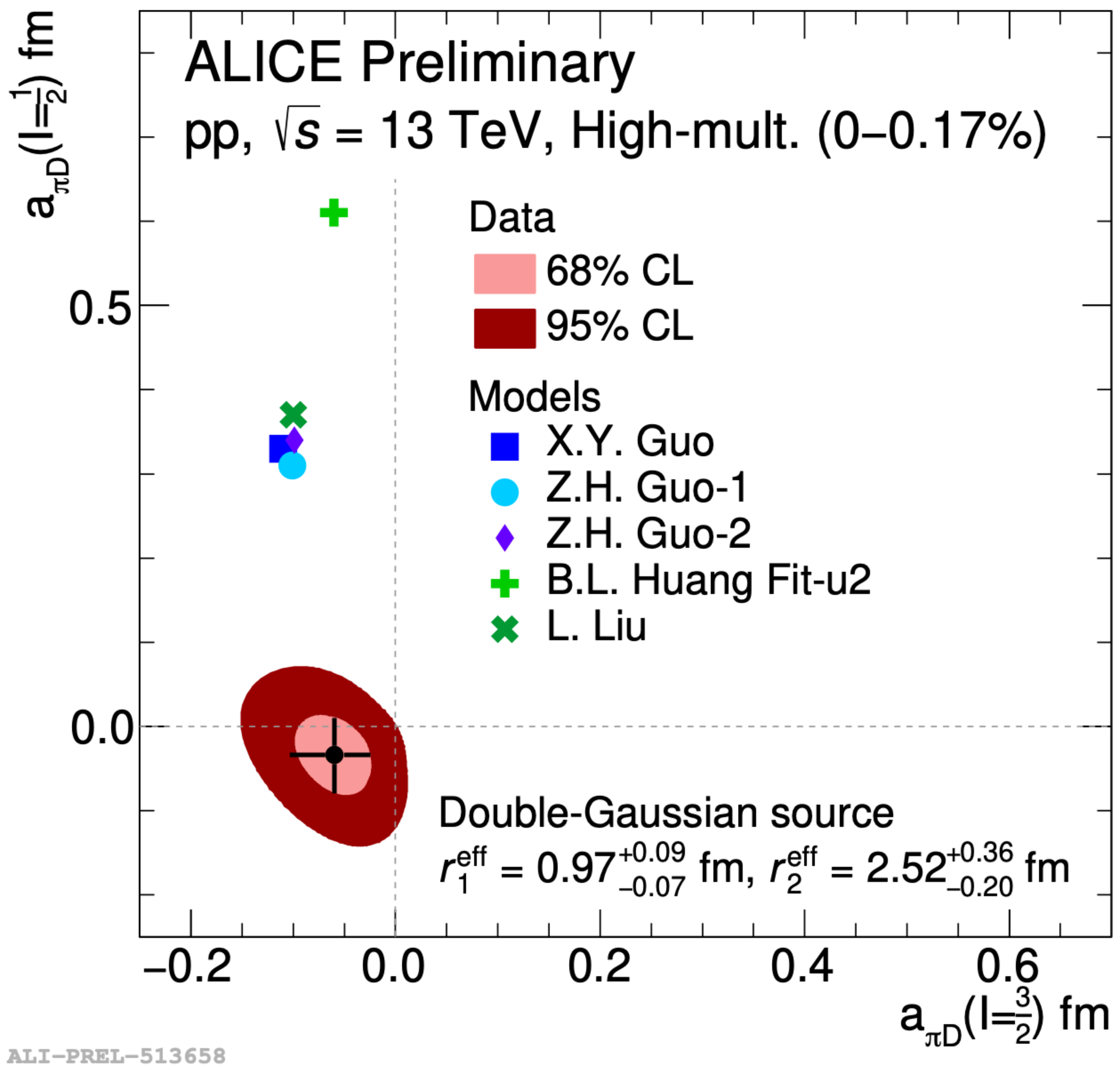


Same-charge pairs



[ALICE preliminary]

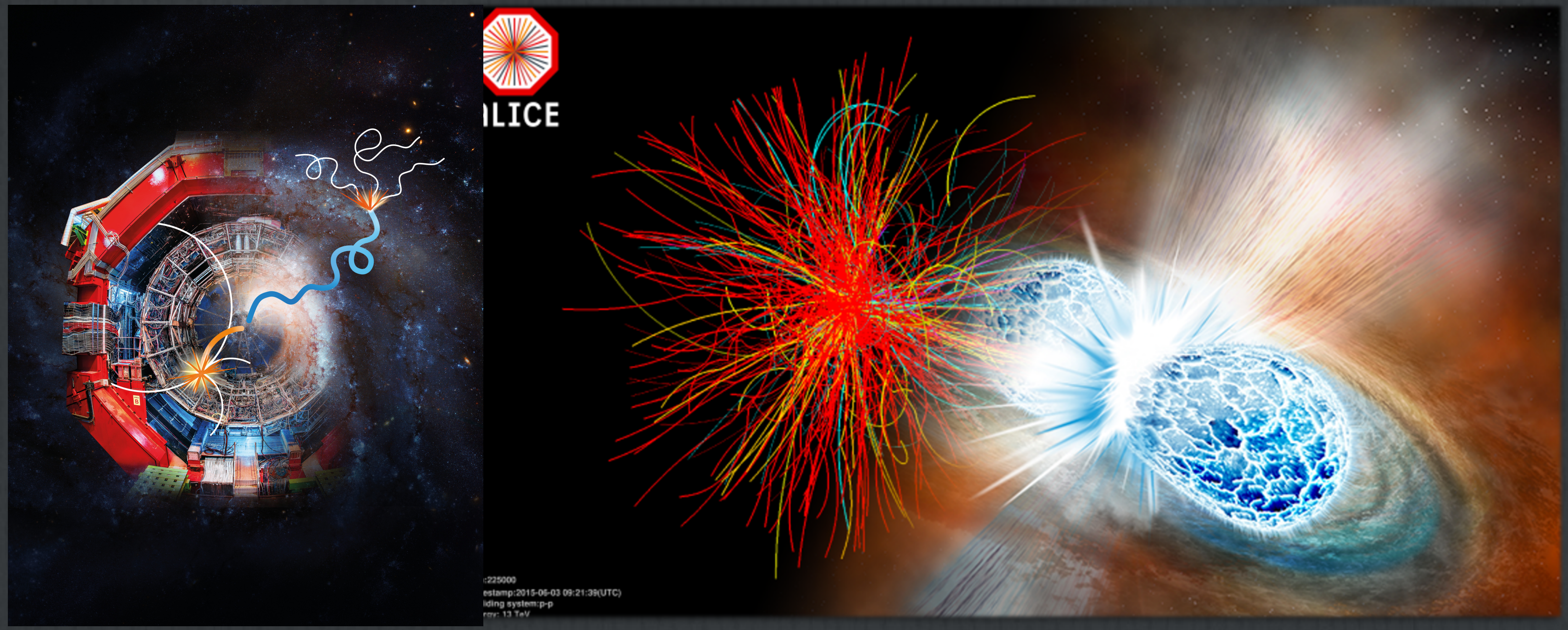
- π^+D^+
  - I=3/2 channel only
- π^+D^-
  - I=3/2 (33%), I=1/2 (66%)



- Scattering length for I=3/2 in agreement with models
- Scattering length for I=1/2 significantly smaller than models
- The values found indicate a **small rescattering of D mesons in the hadronic phase of heavy-ion collisions**

[ALICE preliminary]

Thank you for your attention



BMBF Forschungsschwerpunkt ALICE Experiment 202 ALICE

SFB 1258 Neutrinos Dark Matter Messengers

ORIGINS Excellence Cluster

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