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Benedict Heybeck
for the ALICE collaboration

Measurement of the p-Σ^+ correlation function in pp collisions with ALICE

Goethe-University Frankfurt
IKF

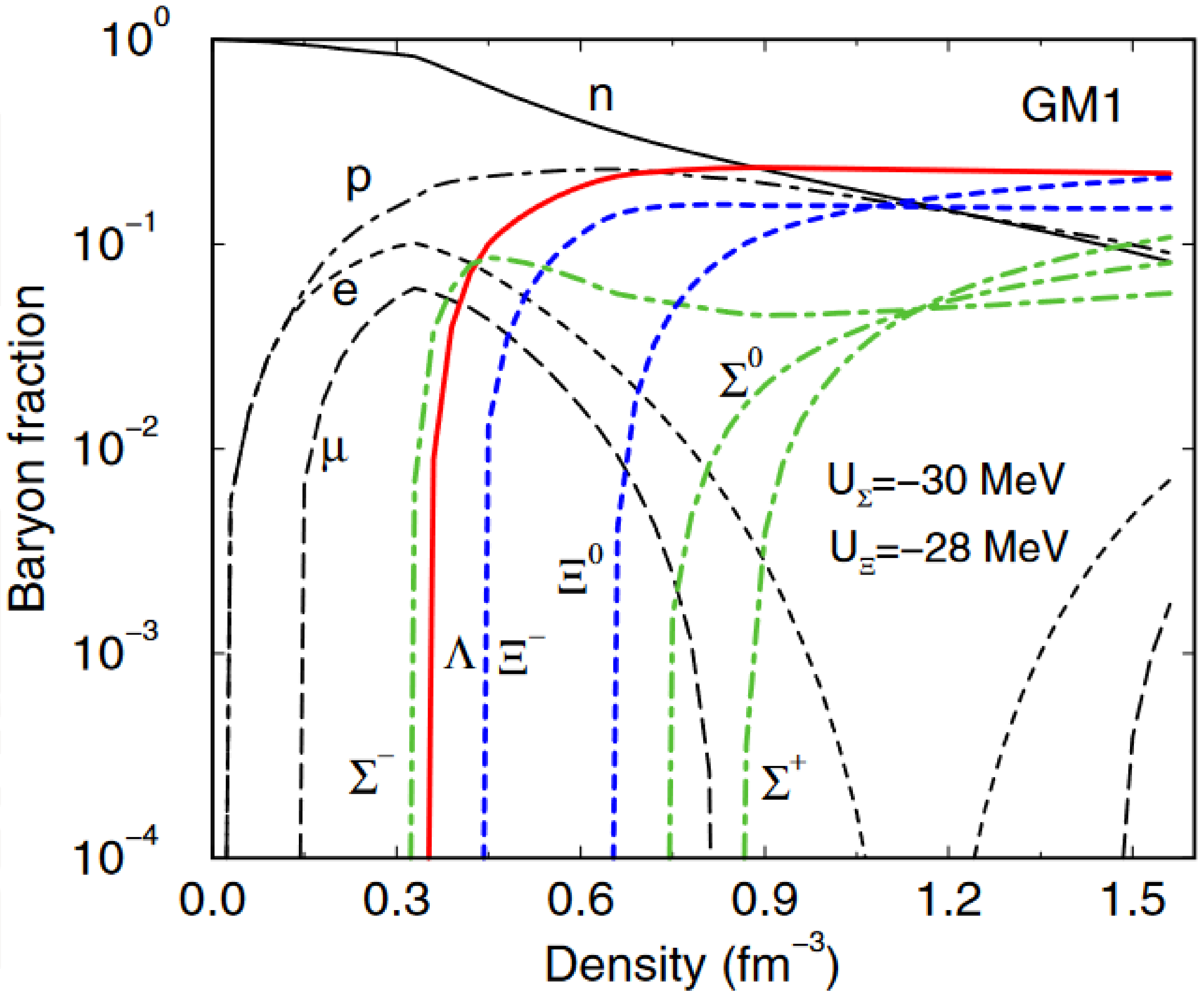
FSP ALICE

IKF Institut für Kernphysik Frankfurt

ALICE

Motivation

- Σ-nucleon interaction important to understand the composition and equation of state of dense astrophysical objects like neutron stars
- Depending on the potential, Σ baryons might be present in neutron stars



[1] J. Schaffner-Bielich, Nuc. Phys. A 835 (2010) 279

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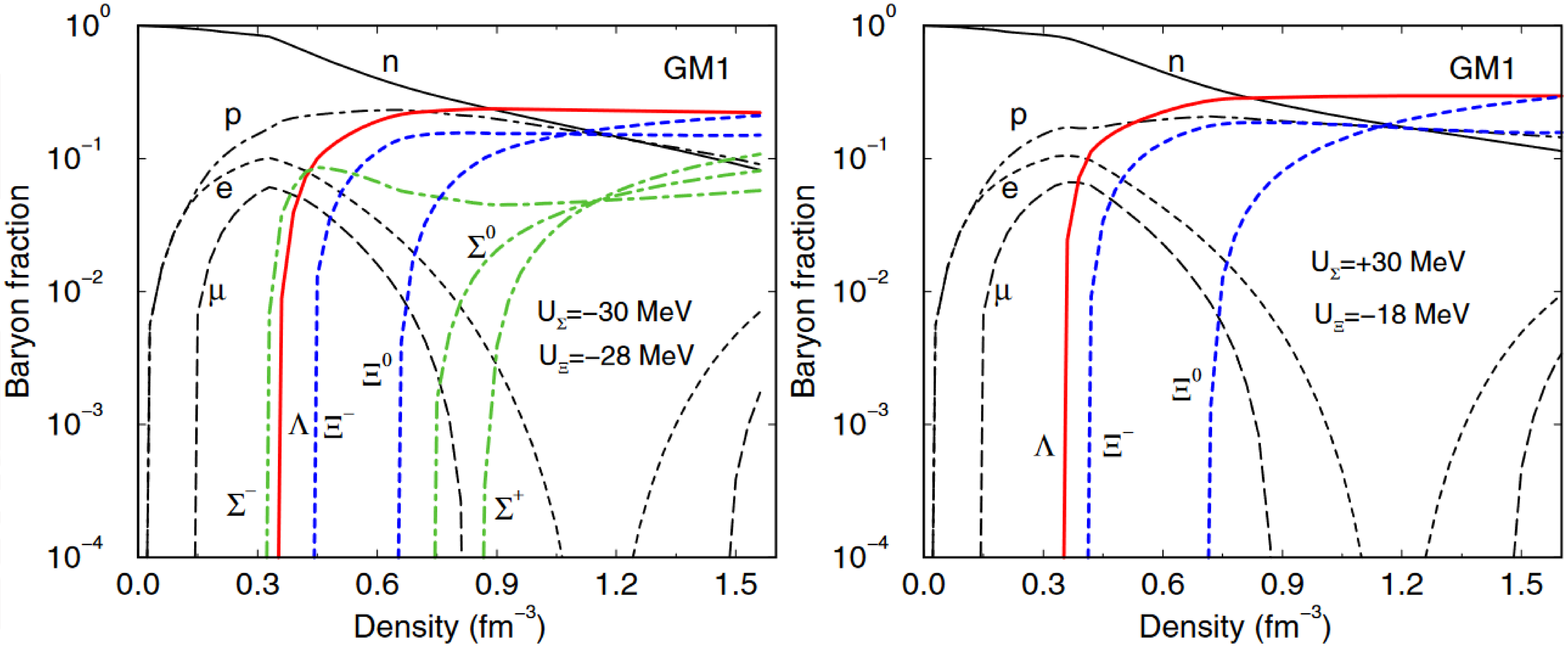

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- Baryon-baryon interactions representable by 6 distinct multiplets:

$$8 \otimes 8 = 27 \oplus 10 \oplus 10^* \oplus 8_s \oplus 8_a \oplus 1$$

channel			spin-parity	
baryon pair	strangeness	isospin	singlet-even/triplet-odd	triplet-even/singlet-odd
N–N	0	0	-	$(\overline{10})$
N–N	0	1	(27)	-
N–Λ	1	1/2	$\frac{1}{\sqrt{10}}[(8_s)+3(27)]$	$\frac{1}{\sqrt{2}}[-(8_a)+(\overline{10})]$
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- $^1S_0$ channel of p-Σ^+ interaction <u>rather well known</u> through NN $(I=1)$ interaction, but $^3S_1$ is <u>not accessible</u> through NN or ΛN interactions

- p-Σ^+ system well suited to study partially Pauli-forbidden decuplet

[2] J-PARC E40, Progress of Theoretical and Experimental Physics 9 (2022) 093D01

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- Experimental data is scarce, all data points obtained from scattering
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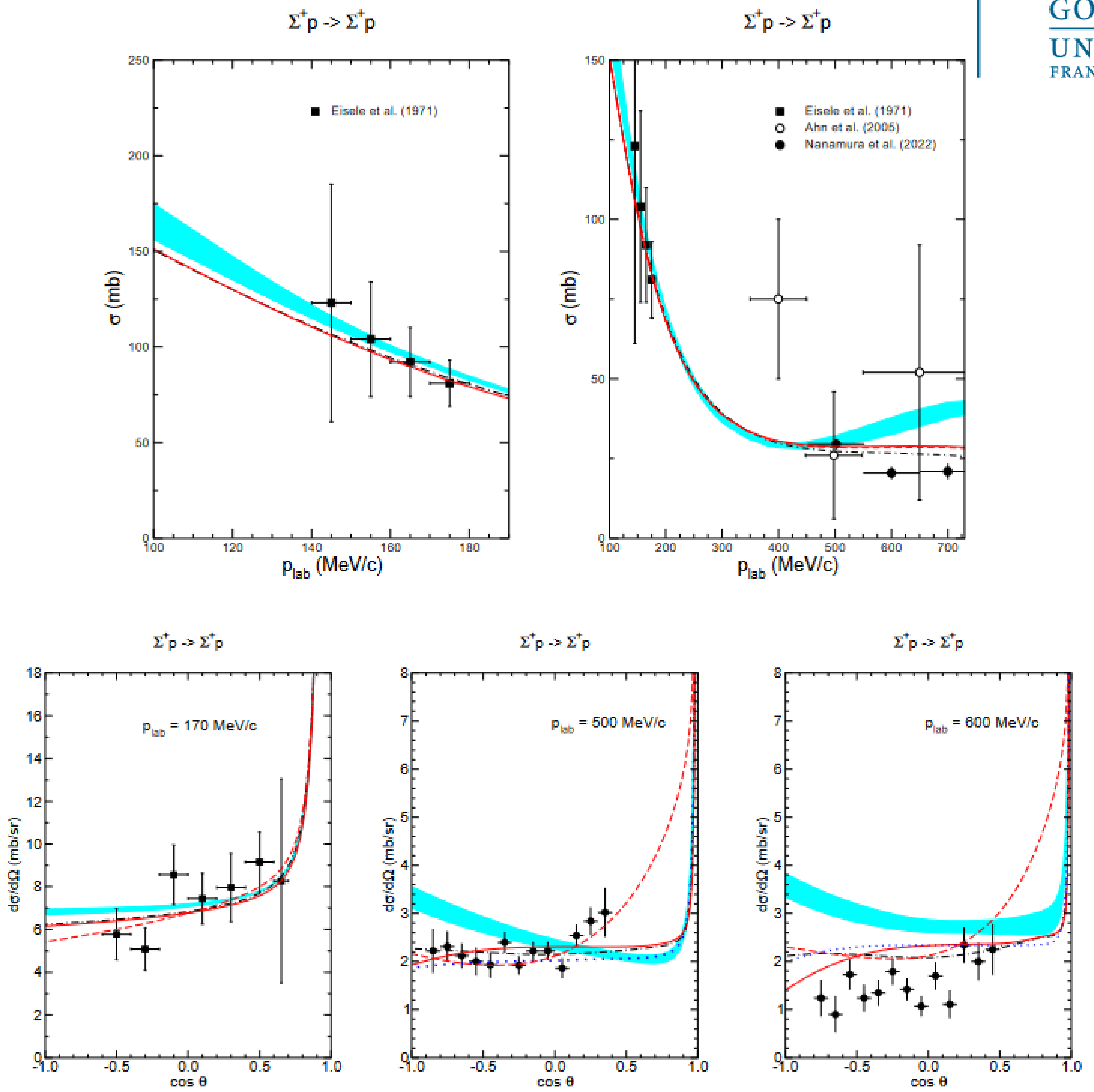
- Predictions for $^3S_1$ state of p-Σ^+ interaction range from strong repulsion (fss2) to moderate attraction (NSC97f)



[3] J. Haidenbauer et al., Eur. Phys. J. A 59 (2023) 63

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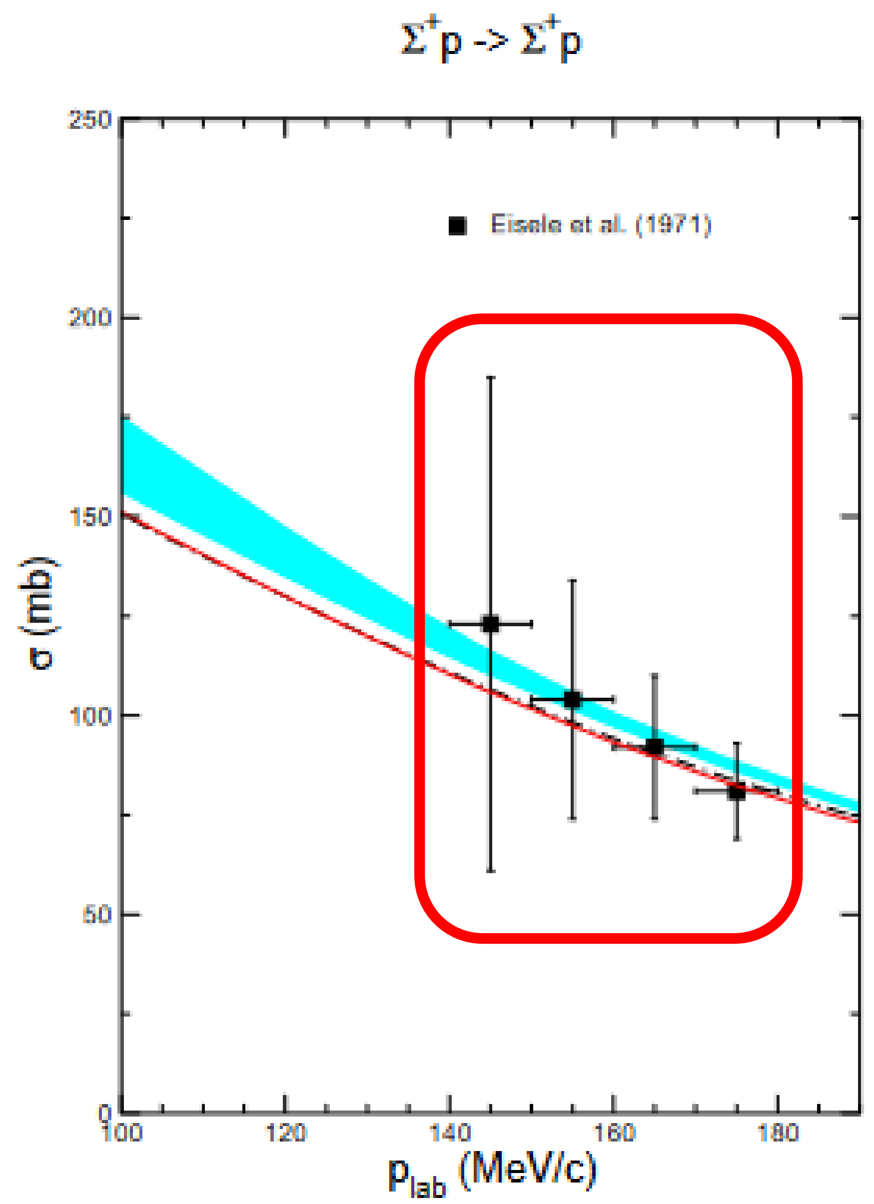
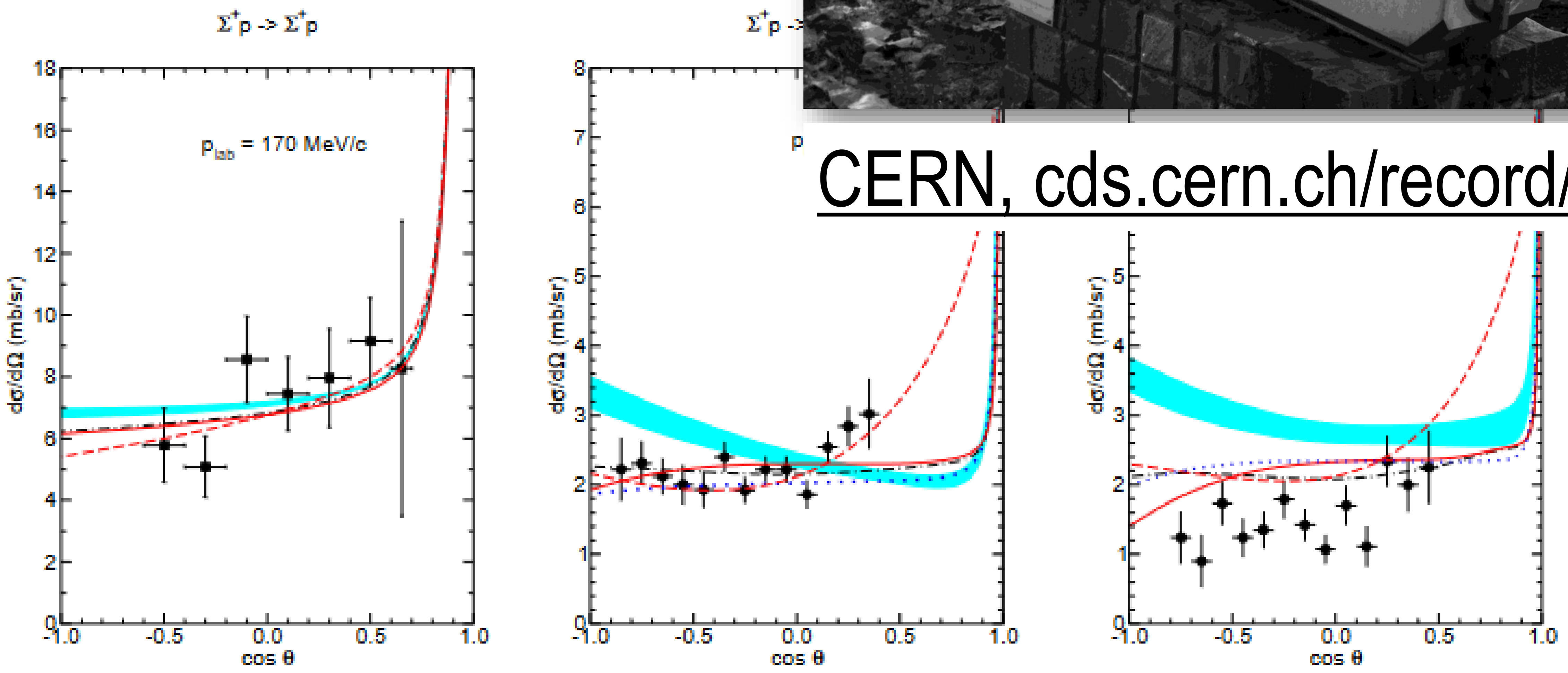




CERN, cds.cern.ch/record/969872

[3] J. Haidenbauer et al., Eur. Phys. J. A 59 (2023) 63

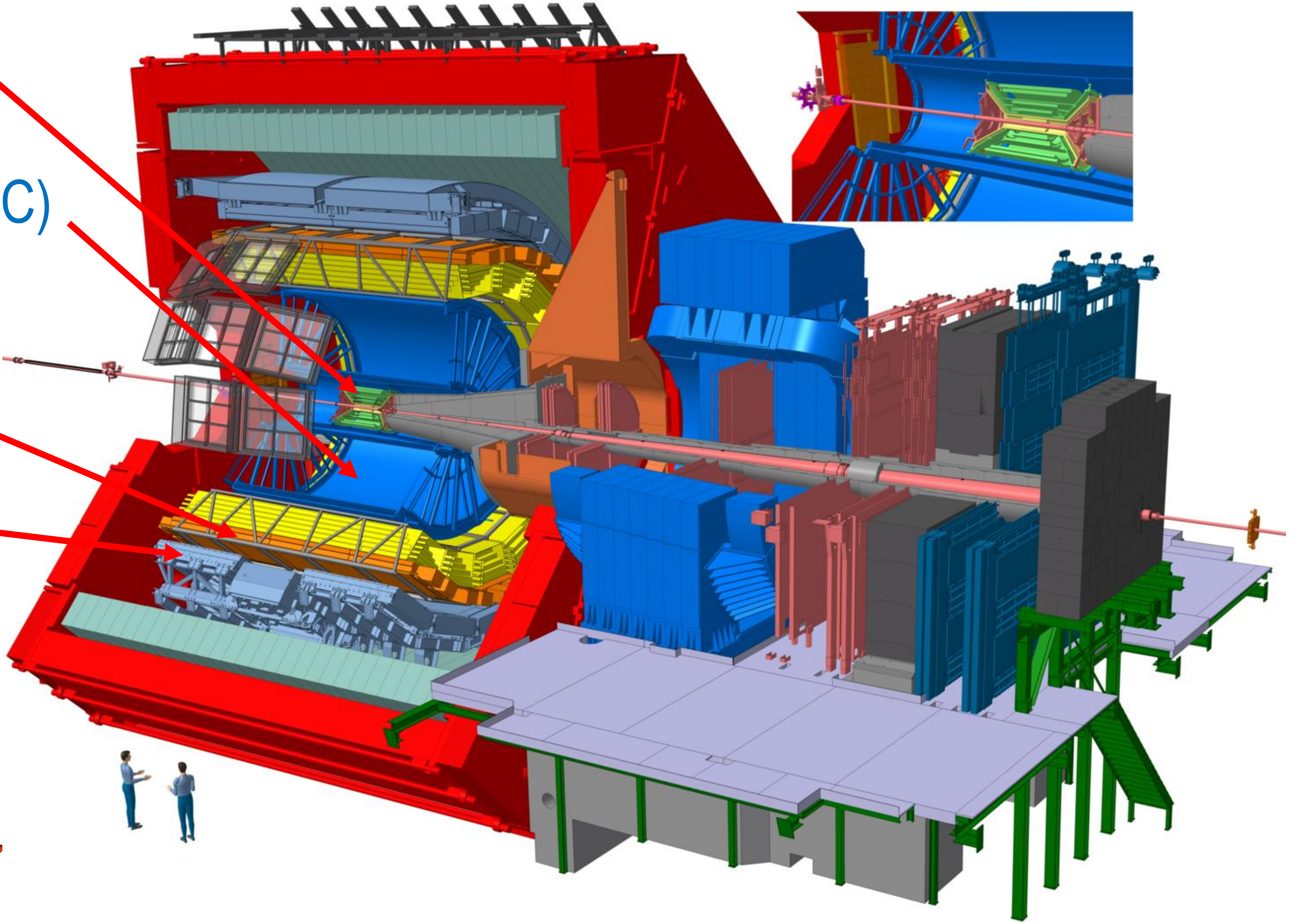
The ALICE Detector

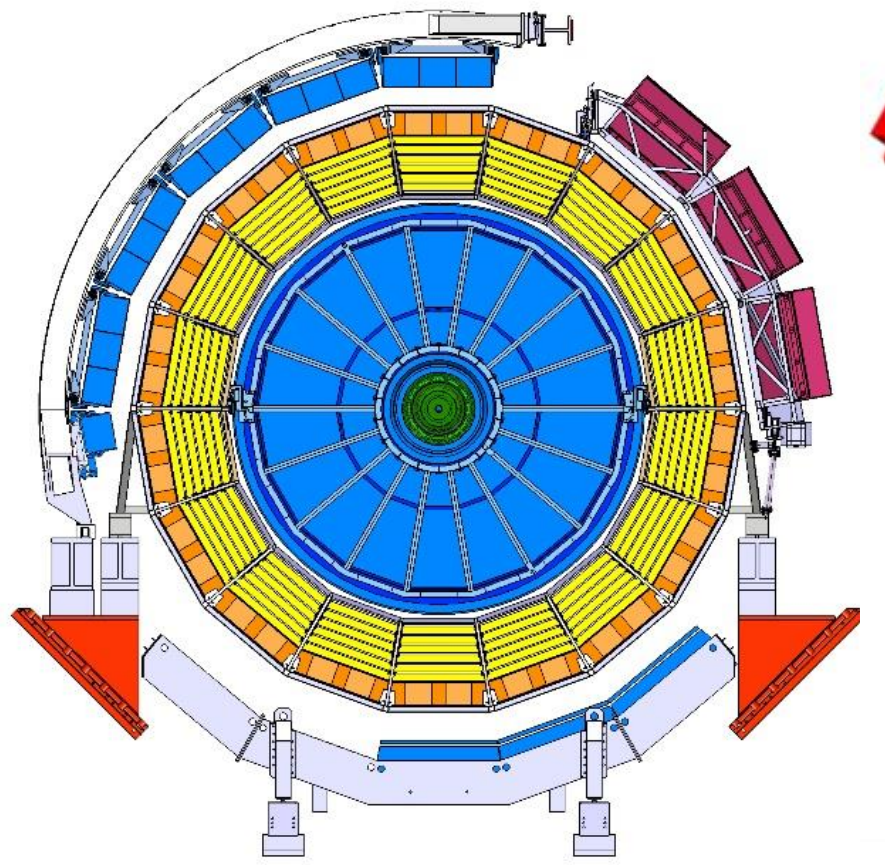
Inner Tracking System (ITS)
→ vertex reconstruction

Time Projection Chamber (TPC)
→ tracking + PID

Time Of Flight (TOF)
→ PID

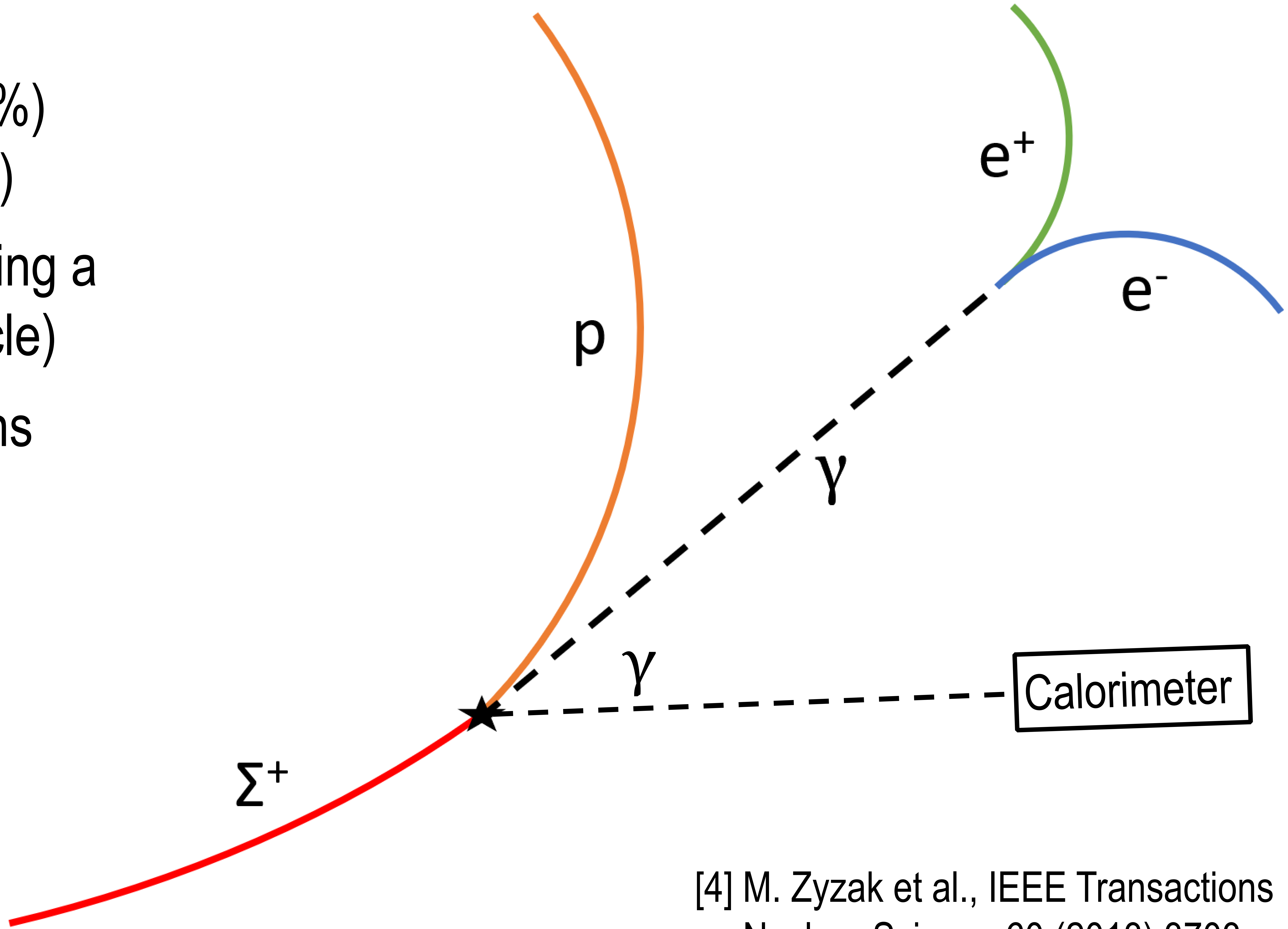
Calorimeters
→ Photon measurement





Σ^+ reconstruction in ALICE

- $\Sigma^+ \rightarrow \pi^0 + p$ (BR = 51.57%)
  $\pi^0 \rightarrow \gamma + \gamma$ (BR ≈ 100%)
- Reconstruct secondary vertex using a Kalman Filter approach (KFParticle)
- Measure photons with conversions and the calorimeters



[4] M. Zyzak et al., IEEE Transactions on Nuclear Science 60 (2013) 3703

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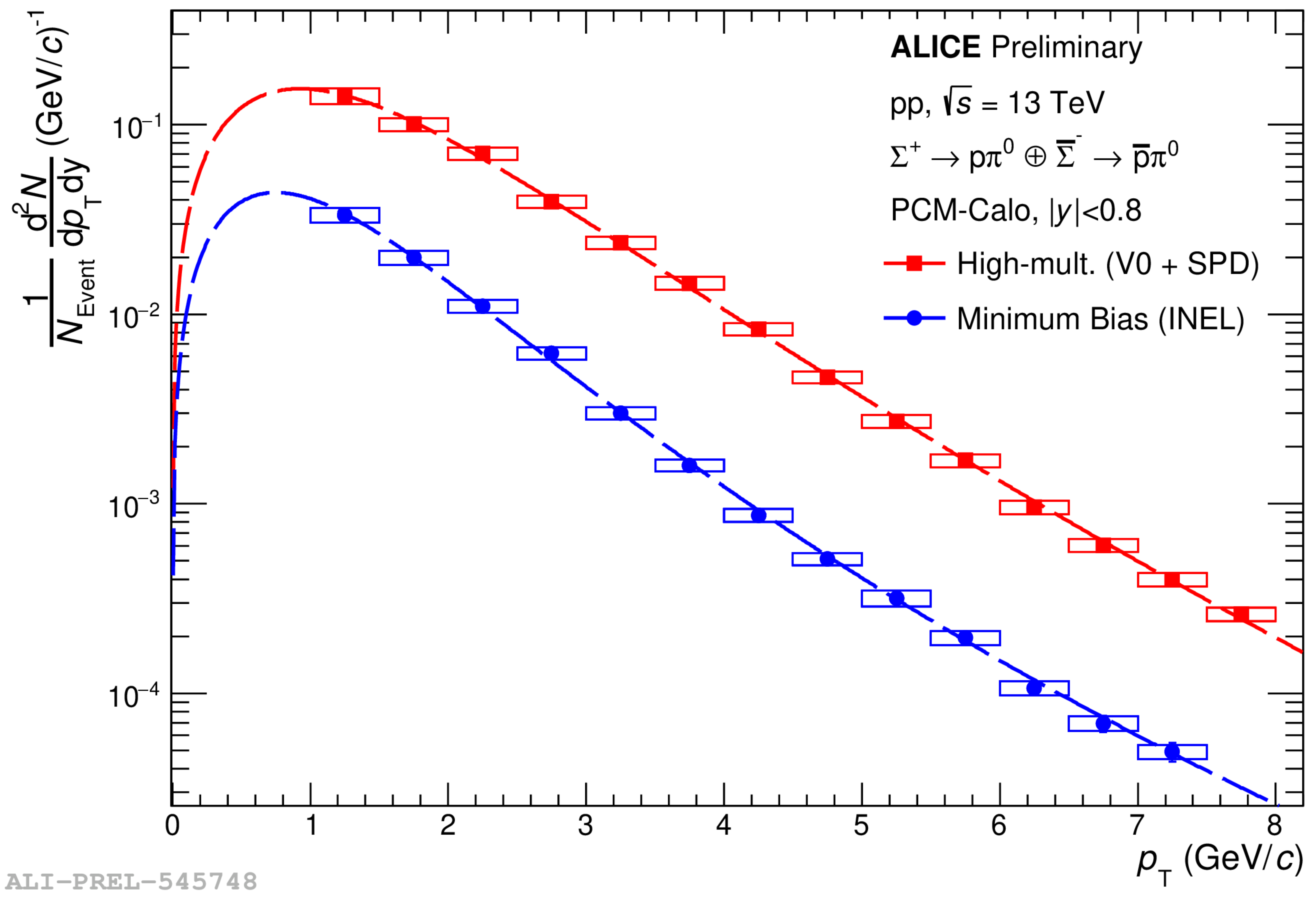
  → First Σ^+ spectra at the LHC

First measurement of Σ^+ at LHC energies!



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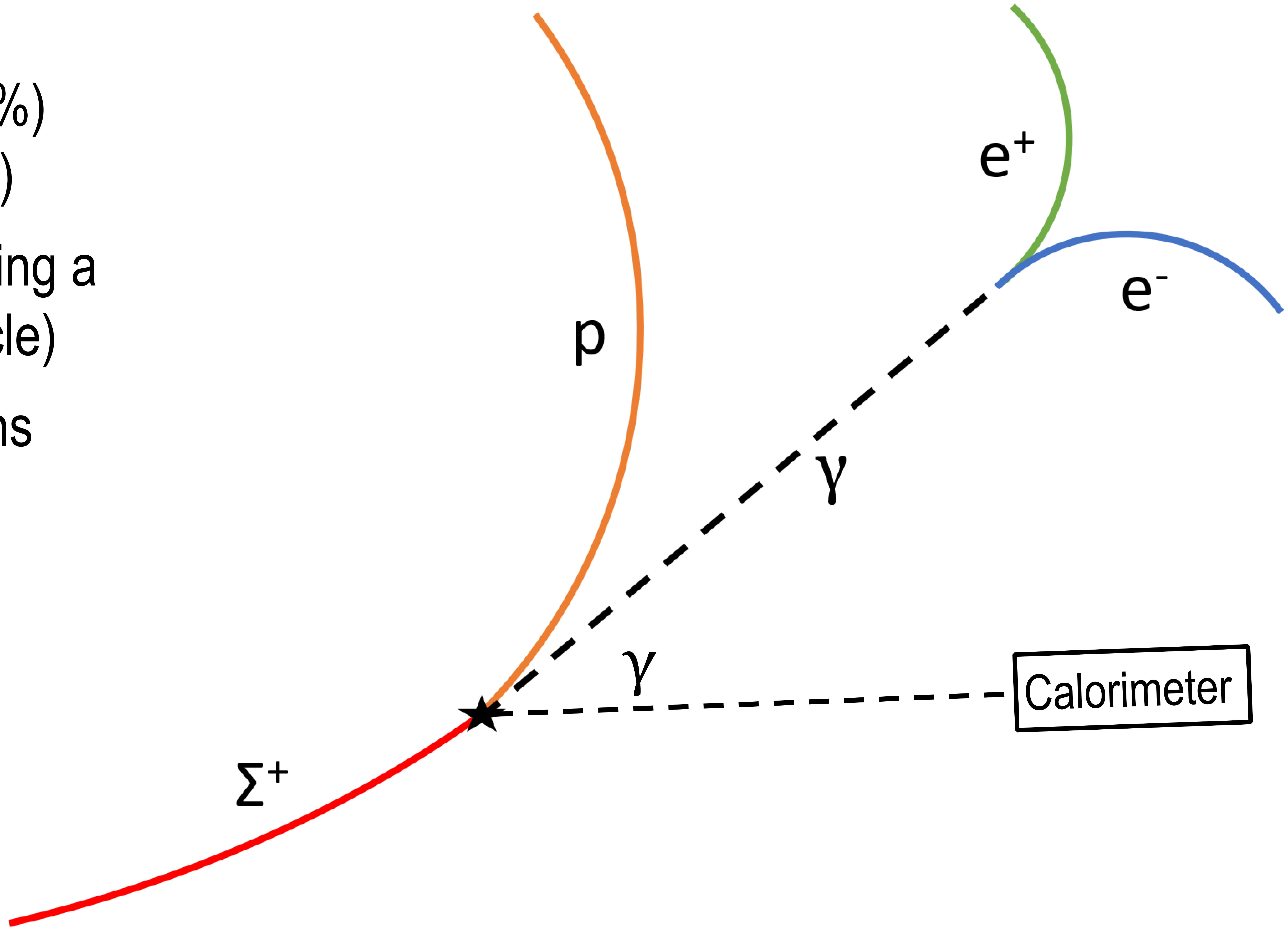
  → First Σ^+ spectra at the LHC
- Efficiency too low for femtoscopy



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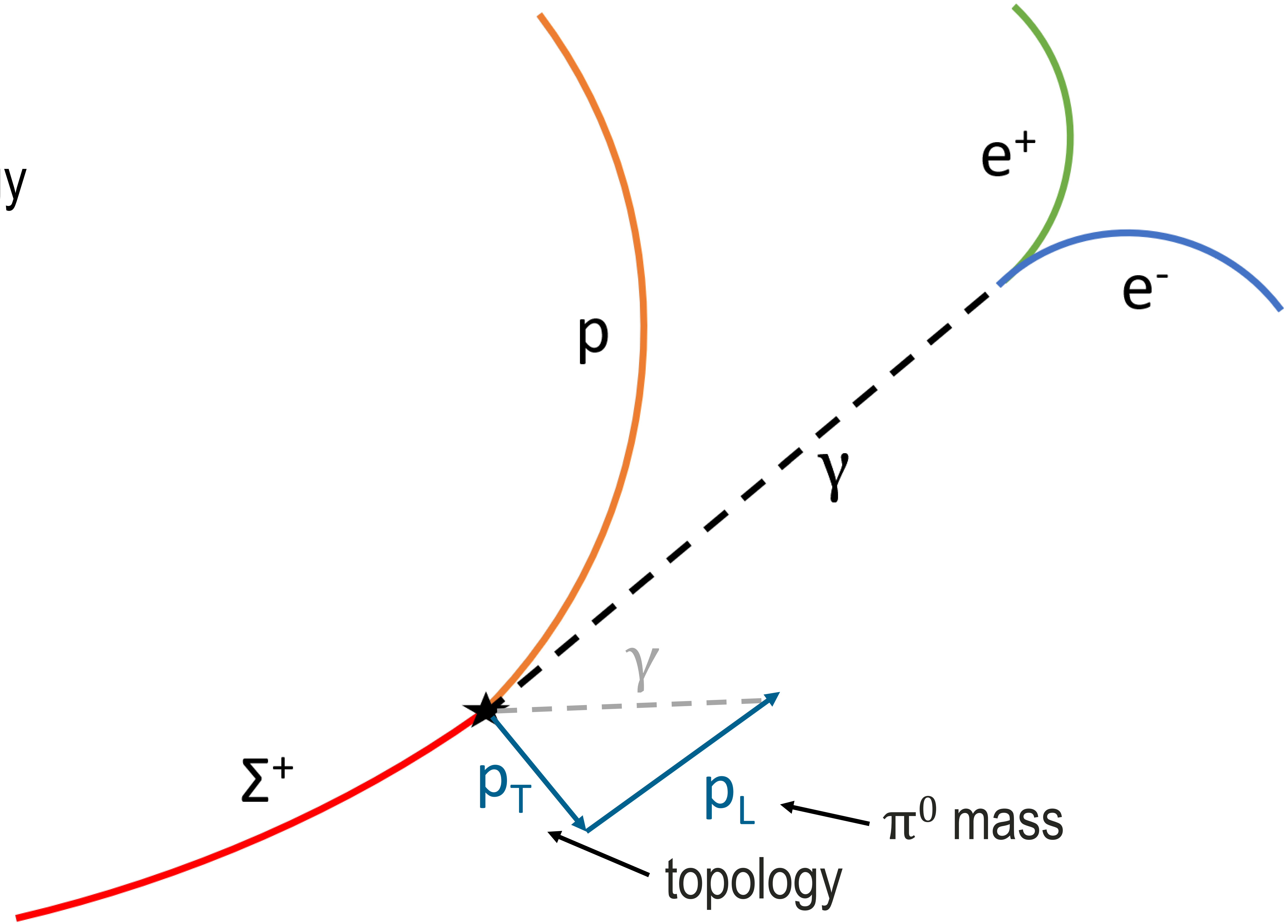
- Select particles using machine learning approach (XGBoost)



[5] T. Chen, C. Guestrin, arXiv:1603.02754 (2016)

Σ^+ reconstruction in ALICE

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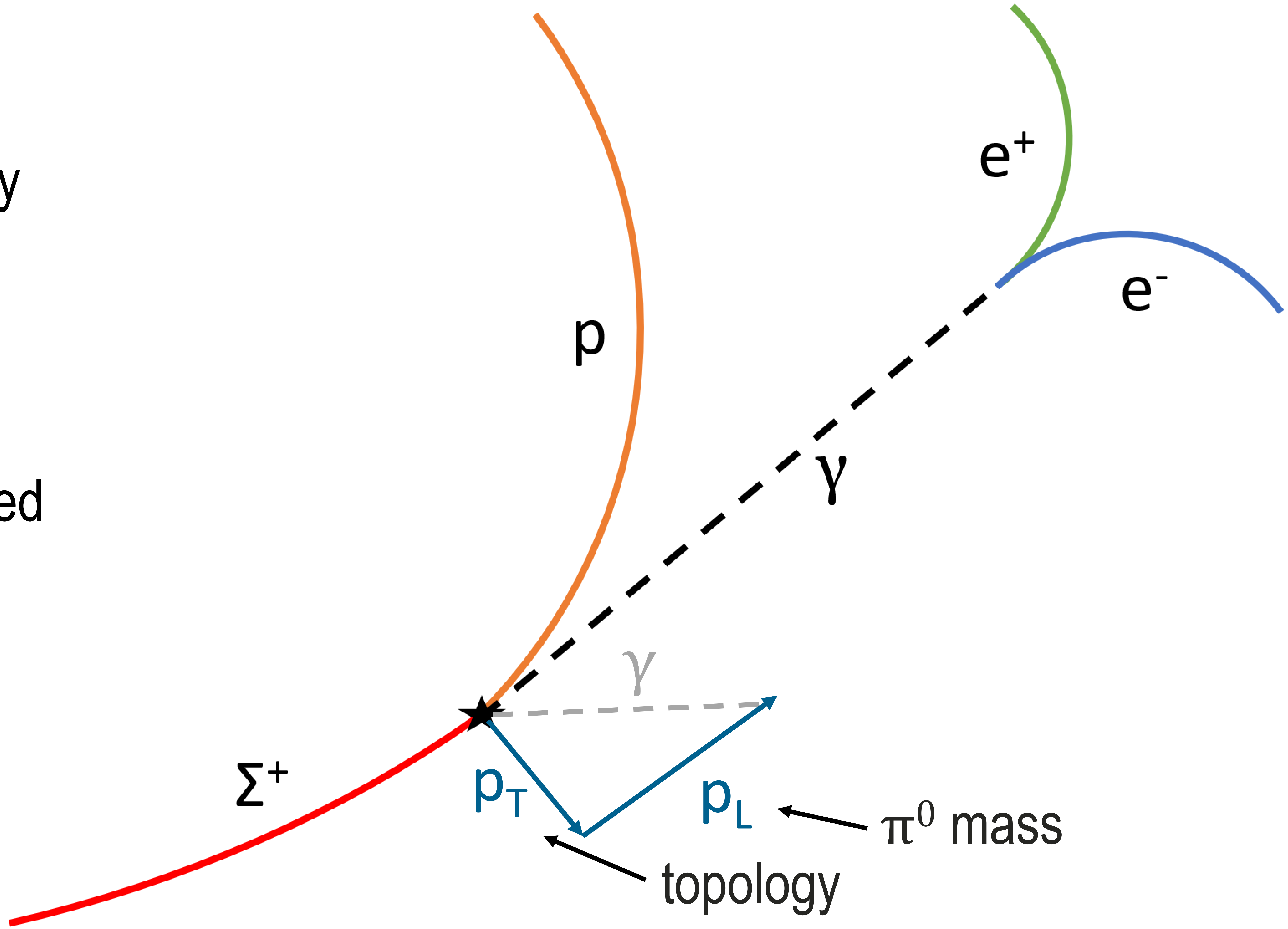
- Reconstruction efficiency improved by one order of magnitude
- Twofold improvement of purity



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- Reconstruct only one photon to improve efficiency and calculate missing momentum from topology and π^0 mass
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- Reconstruction efficiency improved by one order of magnitude
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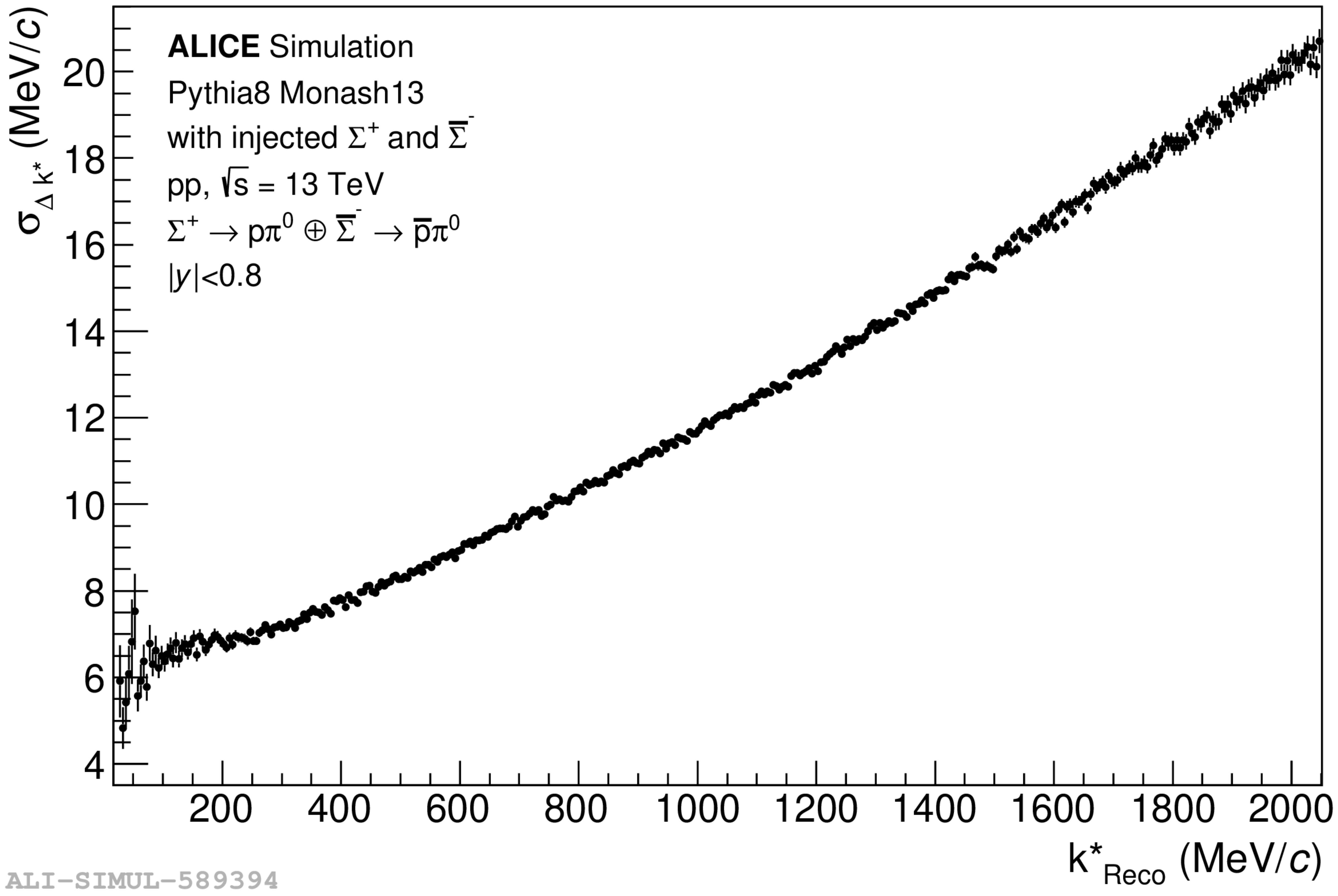
- Refit vertex using Σ^+ mass constraint → Very good k* resolution (~6 MeV/*c*)

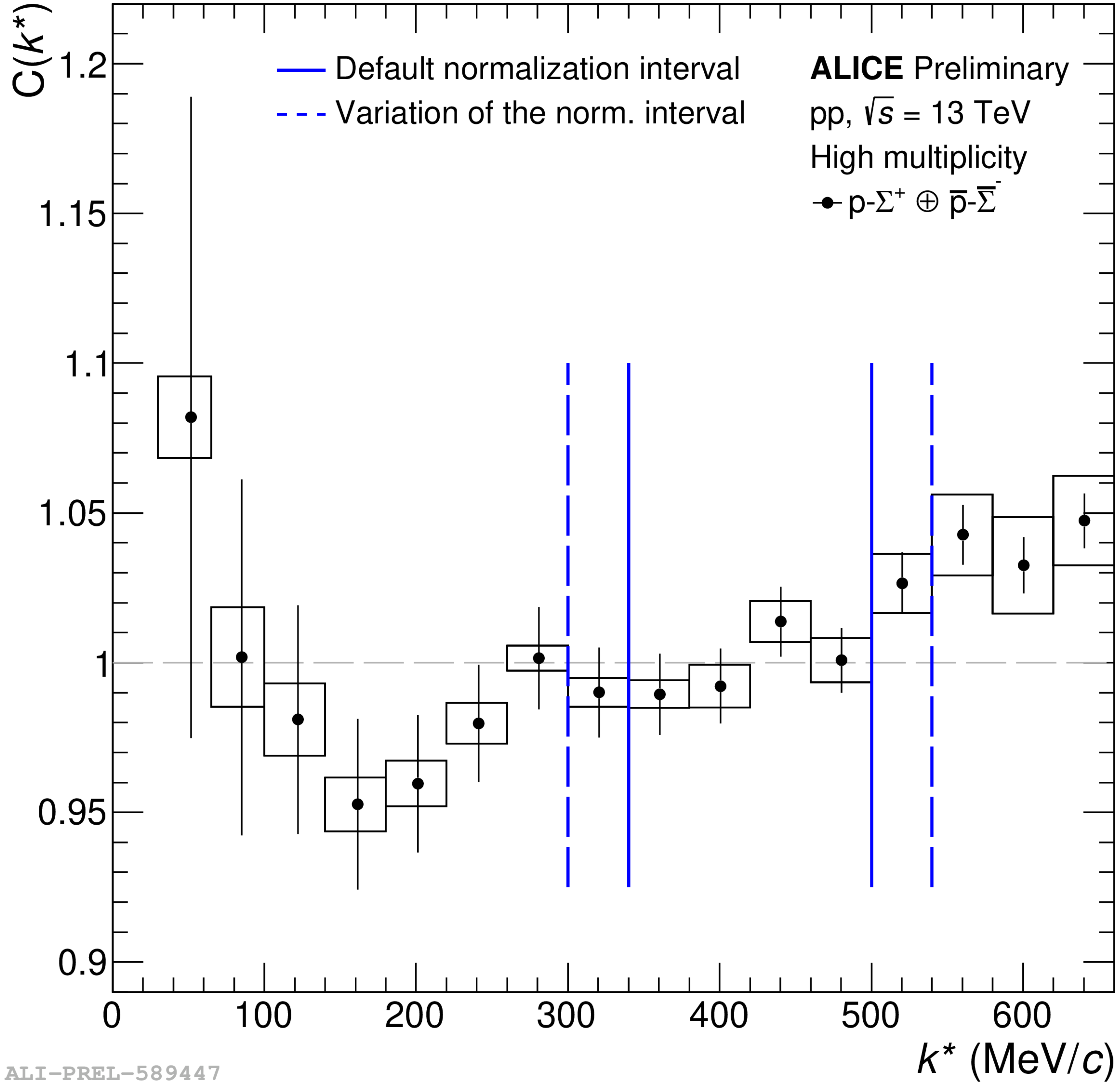
$$k^* = \frac{1}{2}|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|$$



Correlation function

- The experimental correlation function is defined as

$$C(k^*) = \boxed{\mathcal{N}} \times \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$



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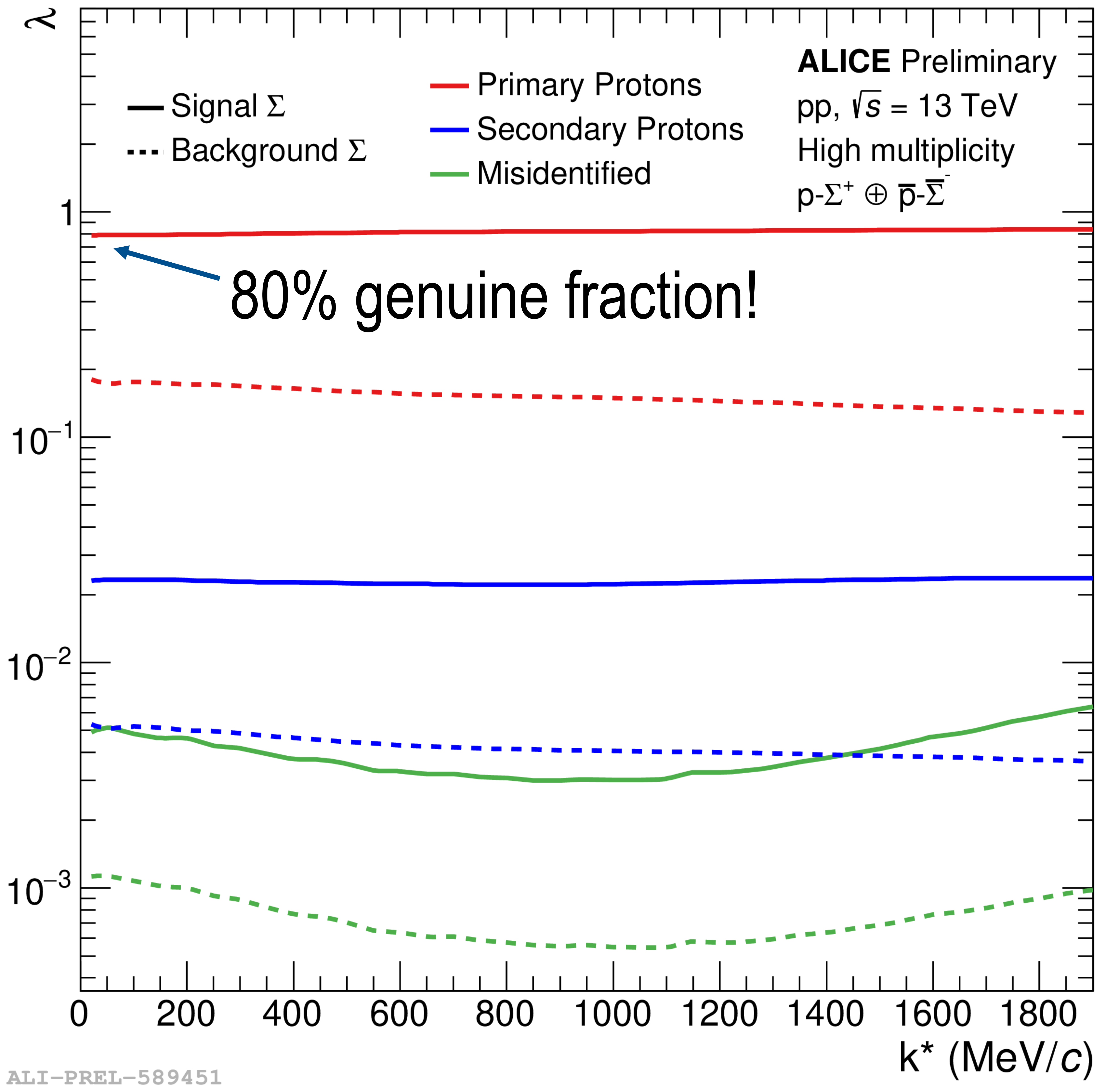
- Correlation function contains contributions from misidentification and feed-down quantified by λ parameters
- λ parameters determined using novel data-driven approach based of effective spectra



Femto theory (in a nutshell)

- Koonin-Pratt equation:

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

[6,7] S. Pratt, Phys. Rev. D 33 (1986) 1314; M. Lisa et al., Ann. Rev. Nucl. Part. Sci. 55 (2005) 357

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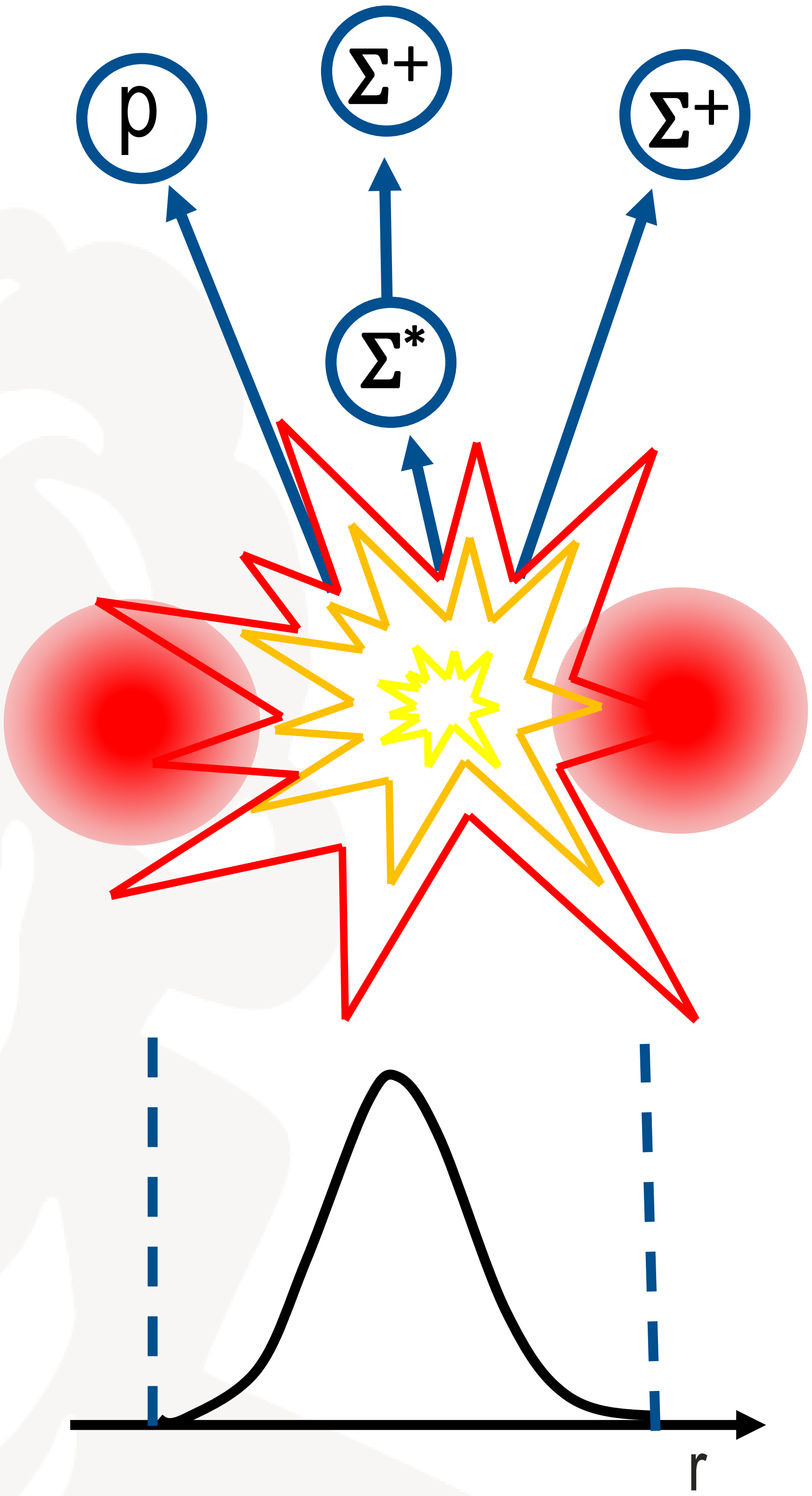

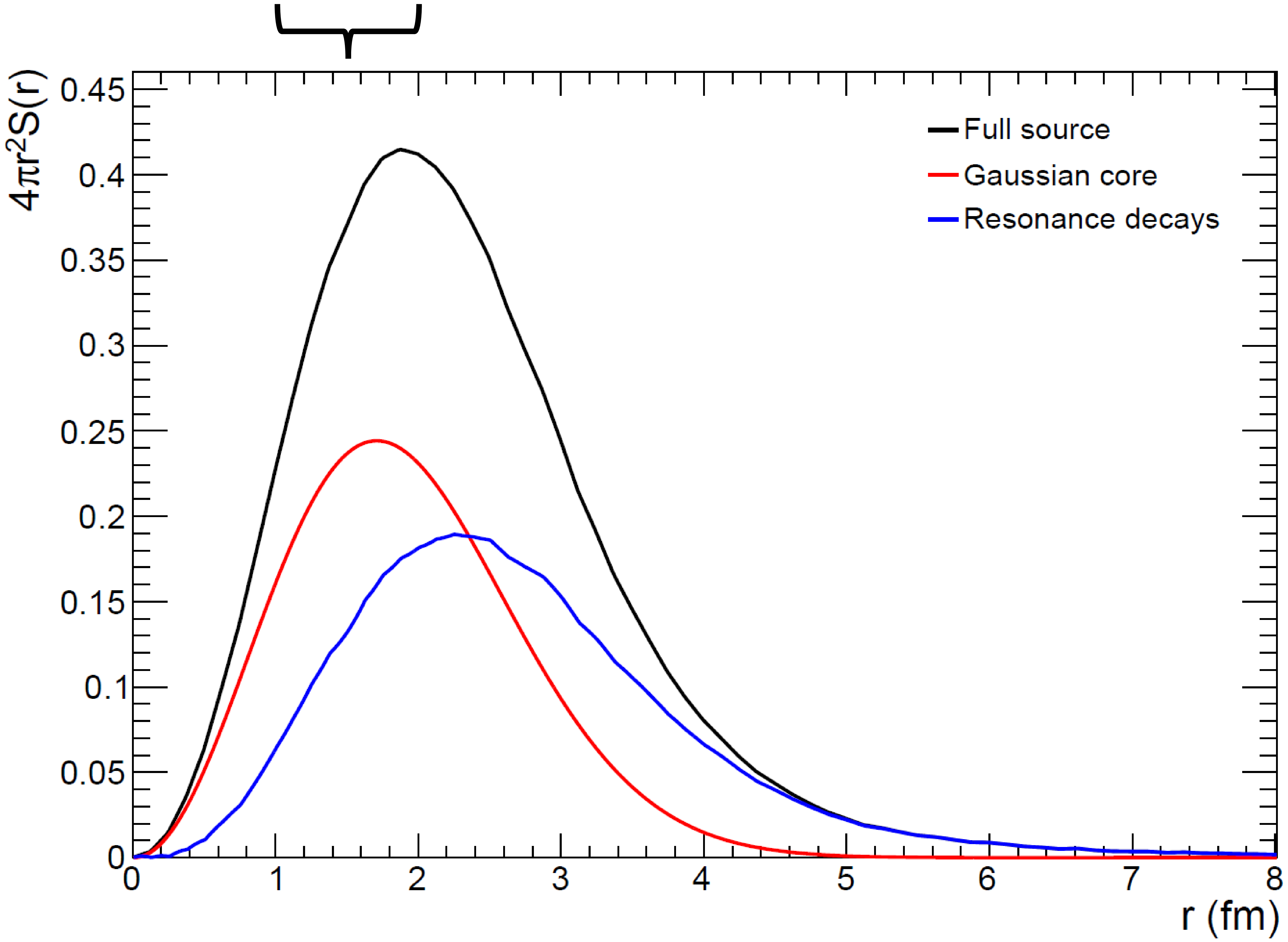

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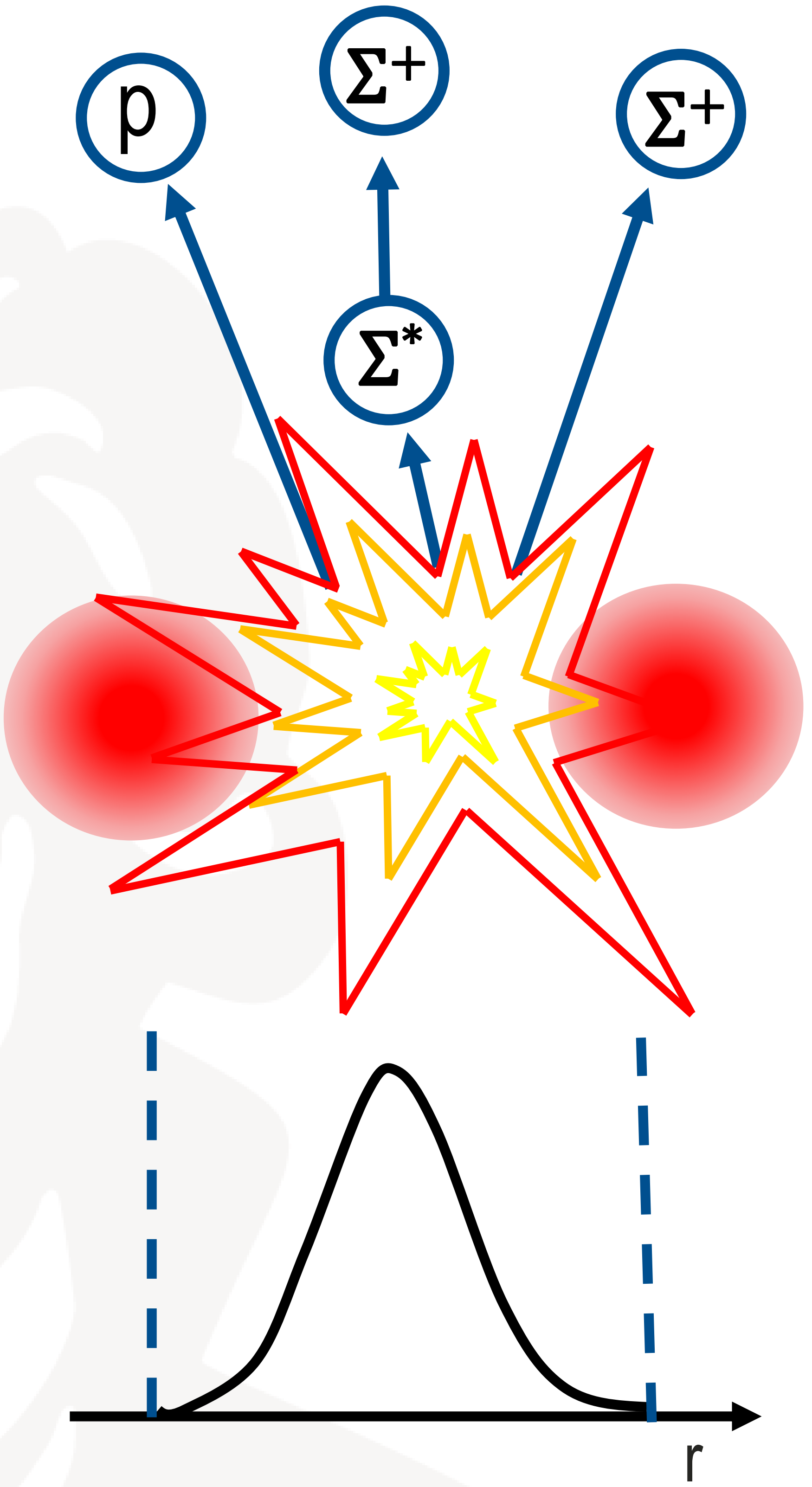

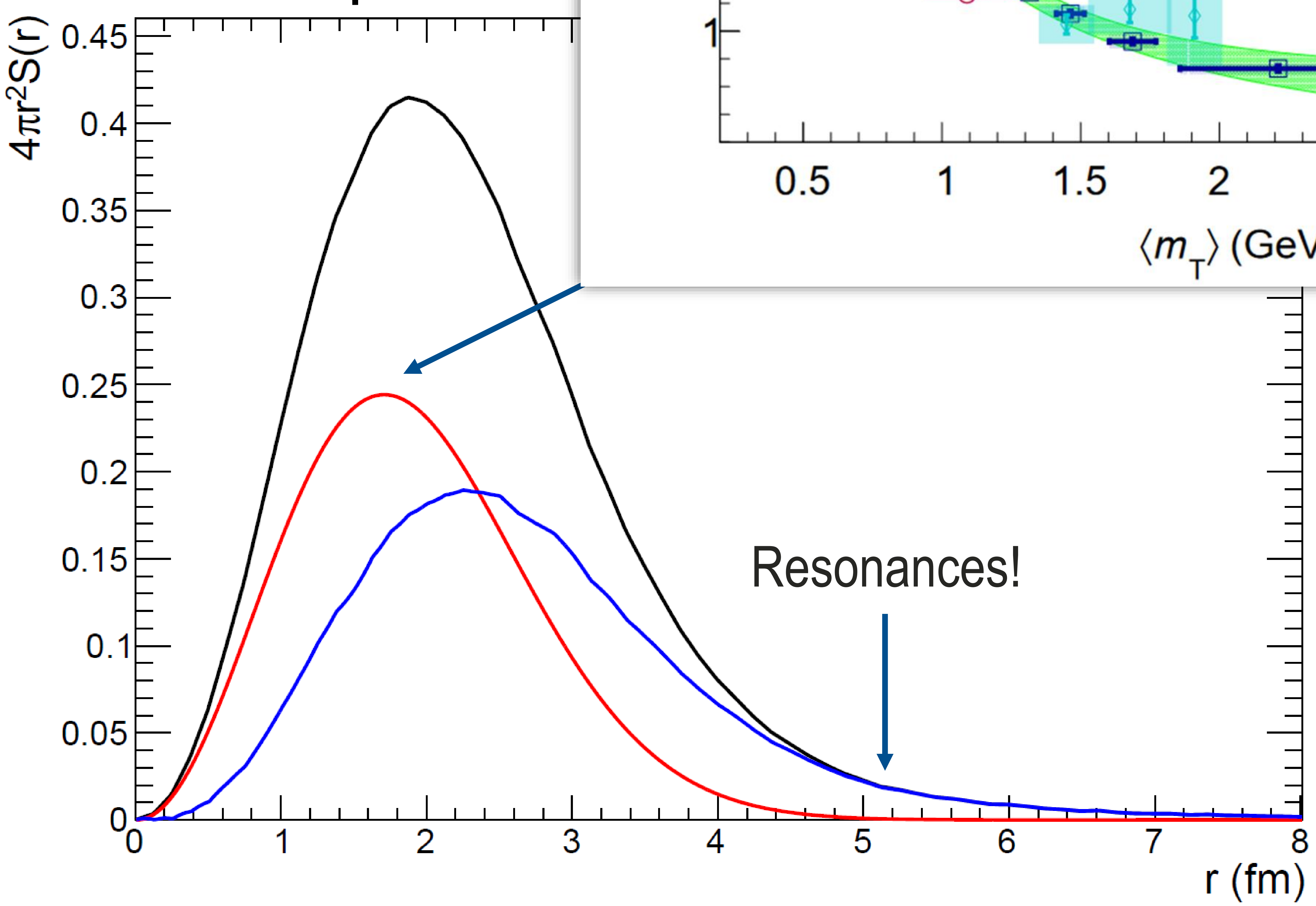

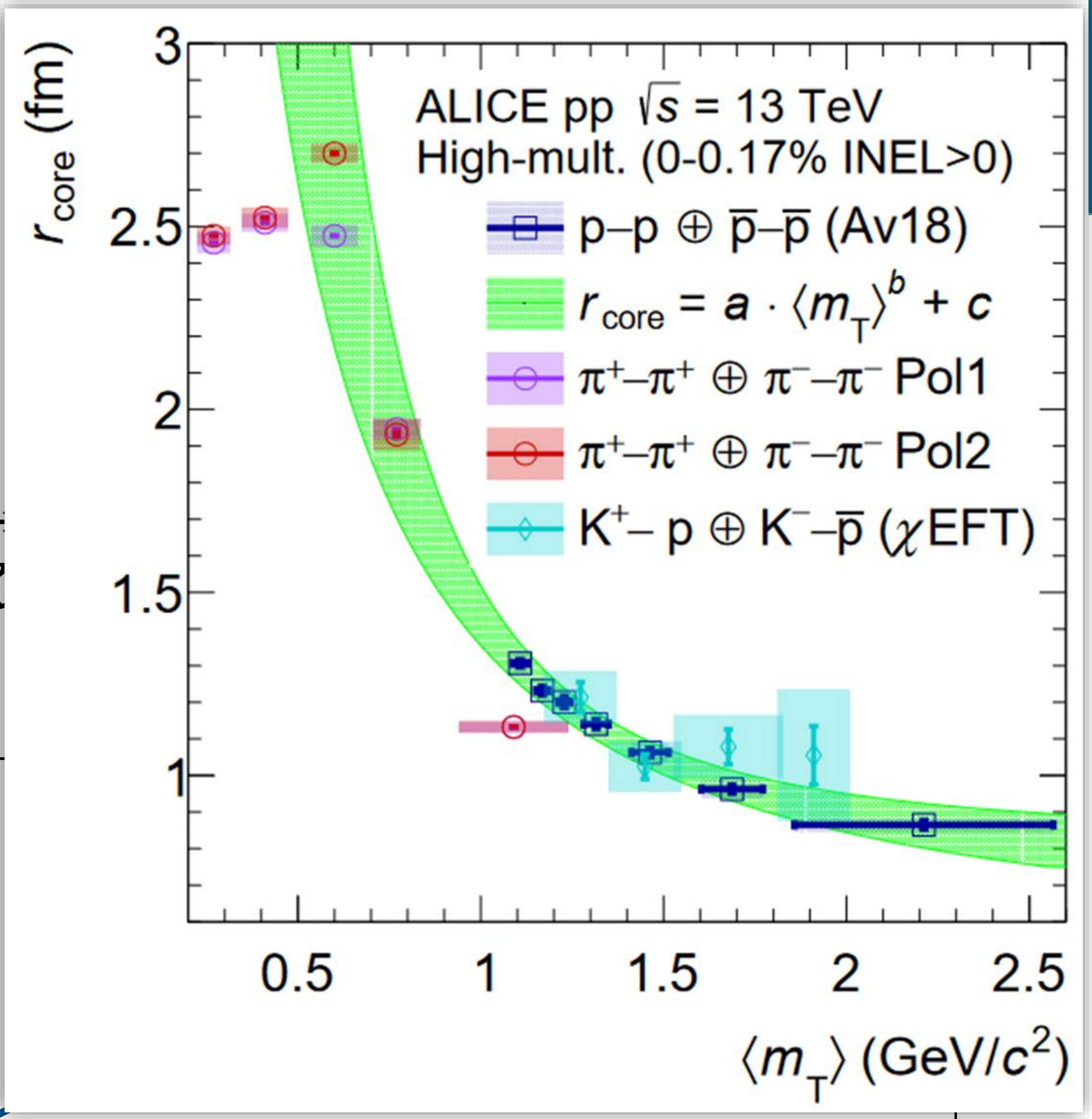

[8] arXiv:2311.14527

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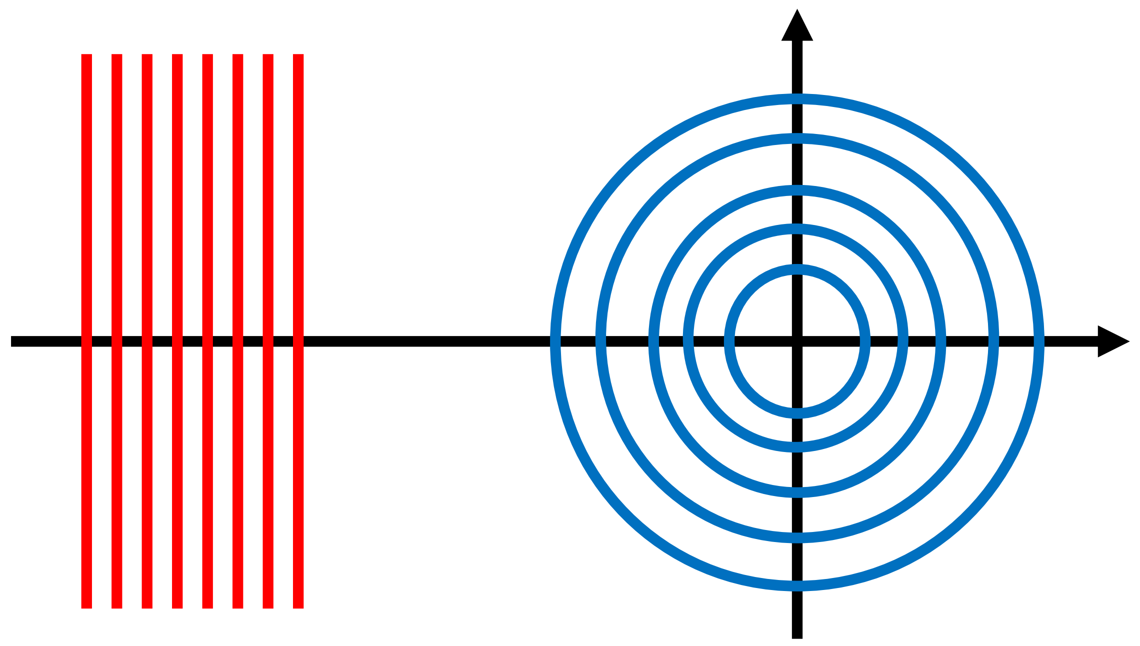

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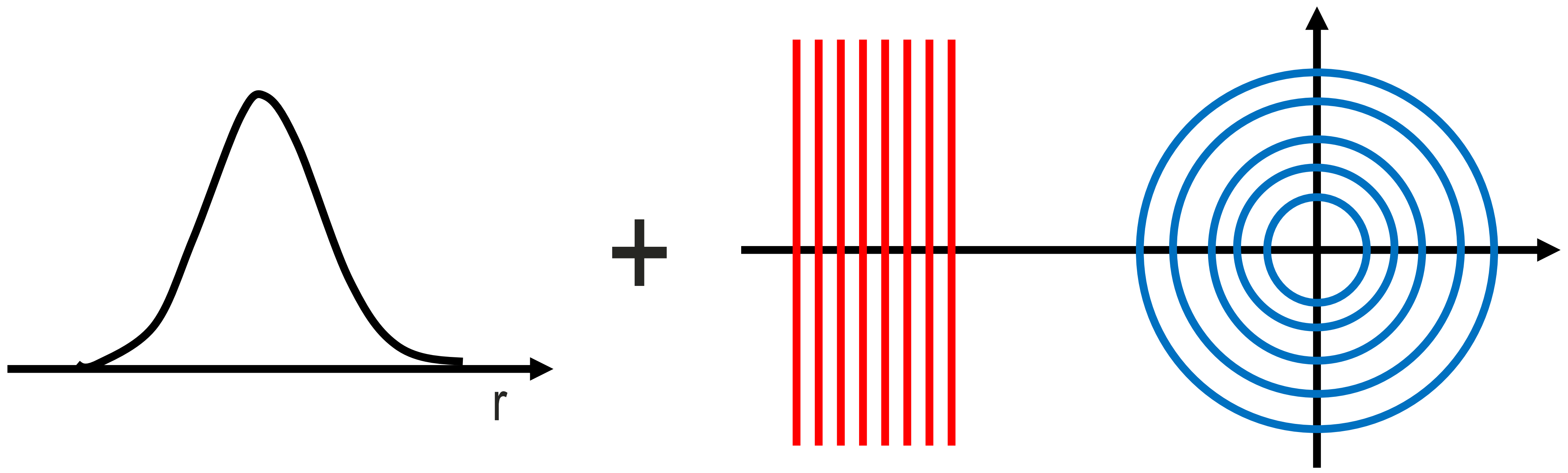

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$$C(k^*) = 1 + \frac{2\Re f(k^*)}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im f(k^*)}{r_0} F_2(2k^* r_0) + \frac{|f(k^*)|^2}{2r_0^2}\left(1 - \frac{d_0}{2\sqrt{\pi} r_0}\right)$$

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Effective range approximation: $f(k^*)^{-1} \approx -\frac{1}{a_0} + \frac{d_0}{2} {k^*}^2 - ik^* + O\left({k^*}^4\right)$

Effective range (d_0)

Scattering length (a_0)

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→ Lednický-Lyuboshits approach

[9] R. Lednicky, V. Lyuboshits, Yad. Fiz. 35 (1981) 1316

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Collaboration with Johann Haidenbauer

Solve Schrödinger equation in generic potential:

$$V(r) = V_0 \mathrm{e}^{-(m_{\pi^0} r)^2} + \frac{\alpha}{r}$$

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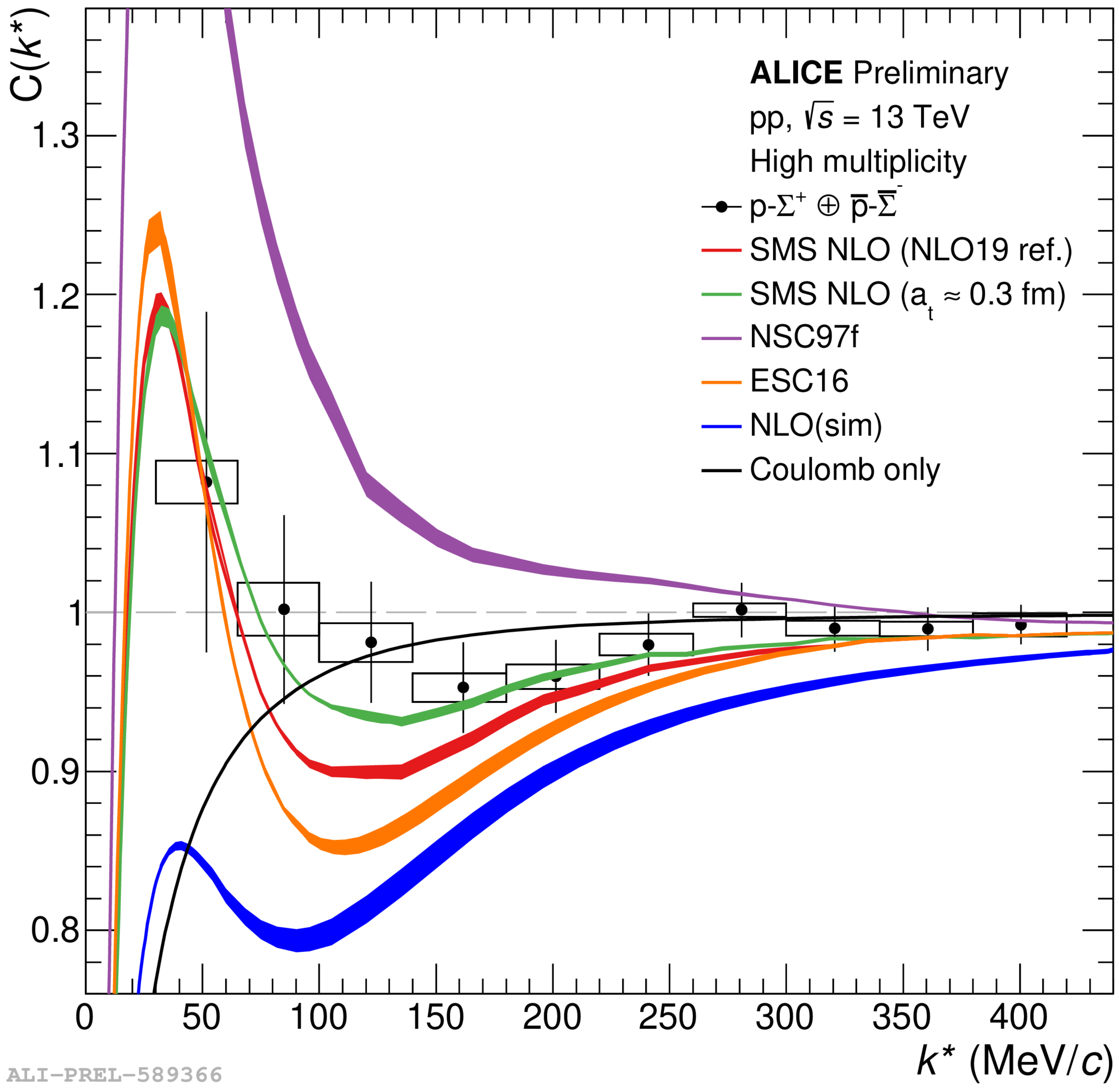
Comparison with data

- Calculations weighted by λ-parameters to account for impurities in the data
- Error bands arise from uncertainty of the source size
- Large spread in model predictions → Data very constraining despite sizeable uncertainties



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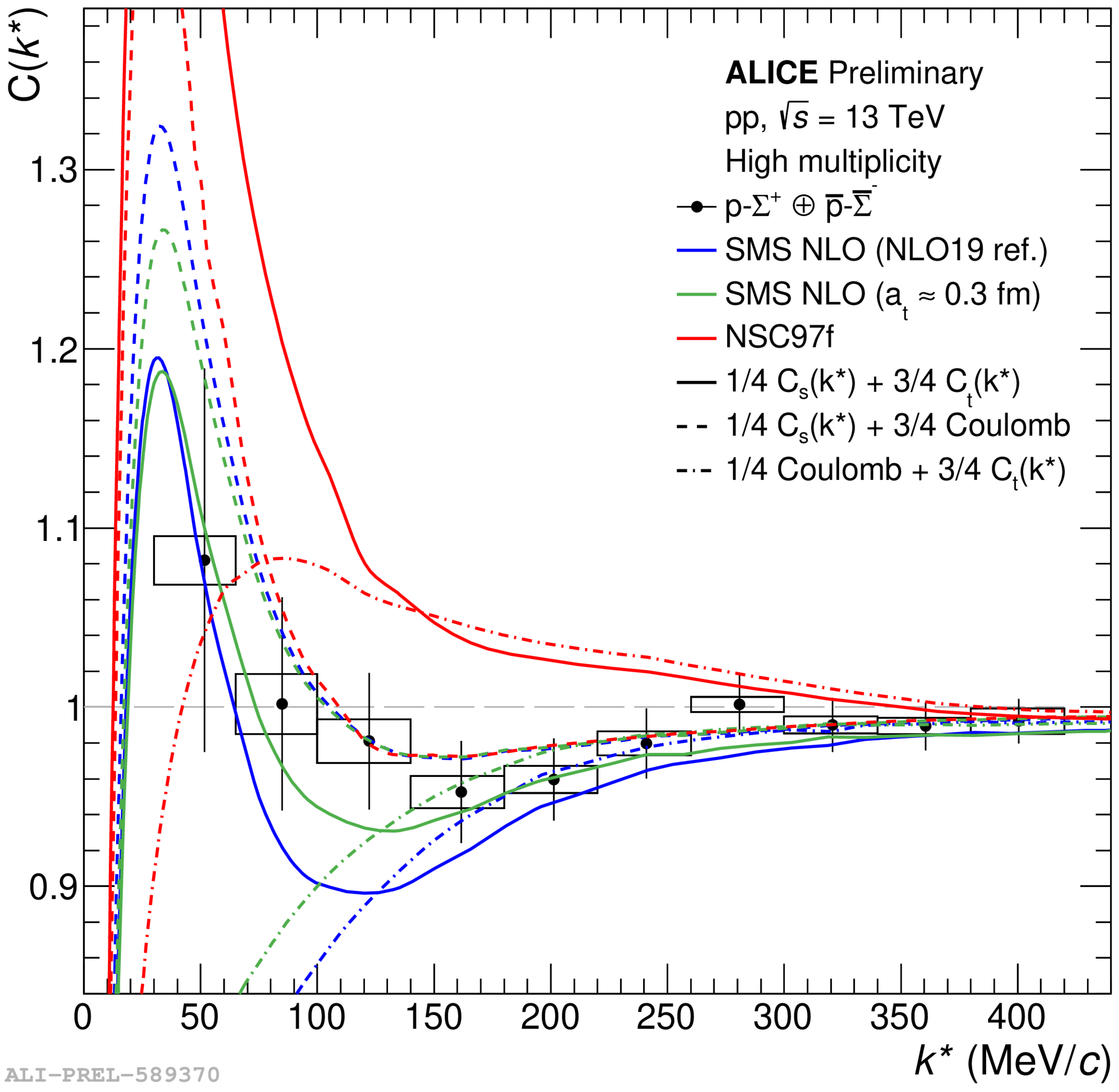
$^1S_0$ & $^3S_1$ channel

- ➢ Sensitivity to singlet strength only in the first bin



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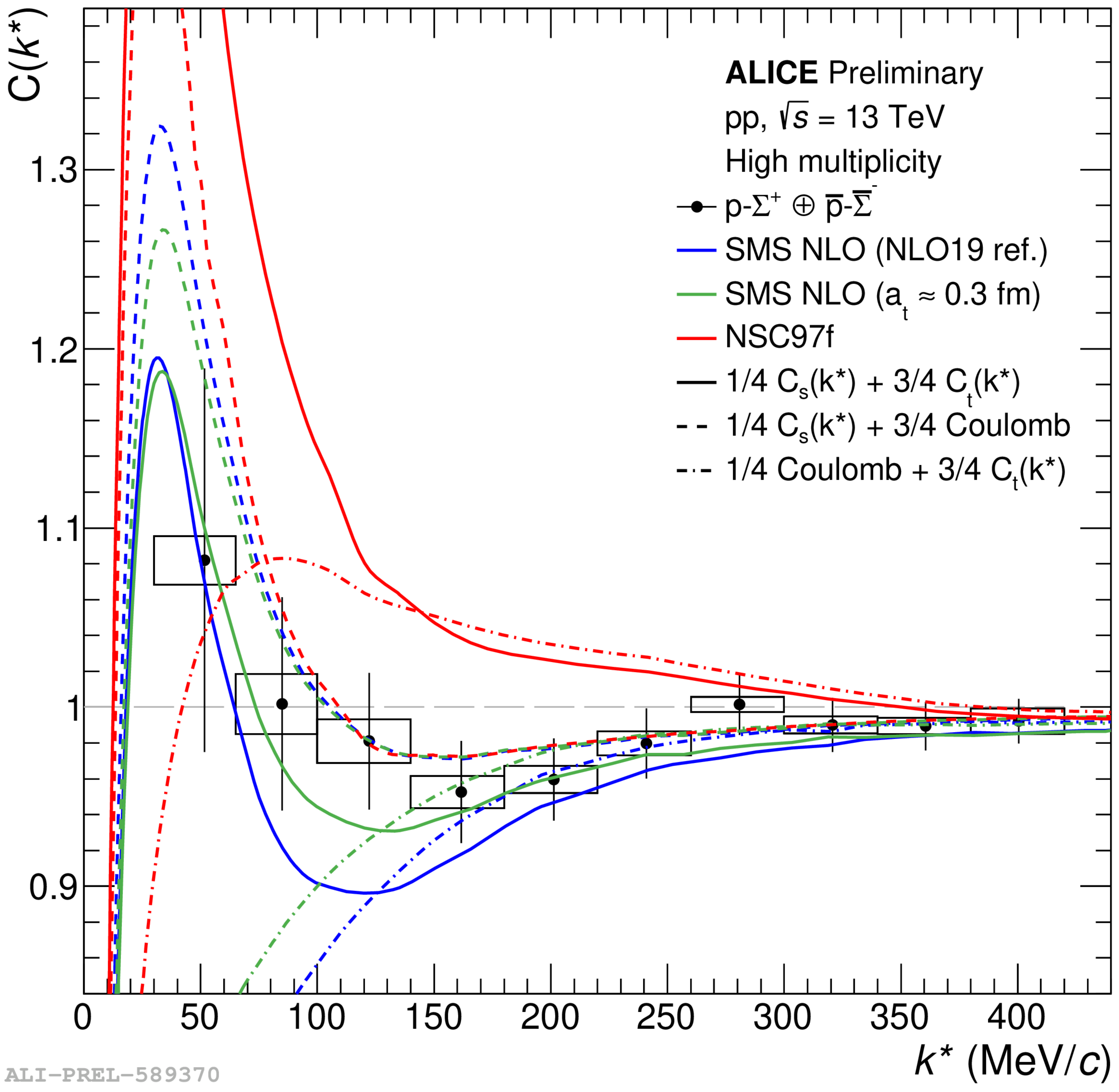

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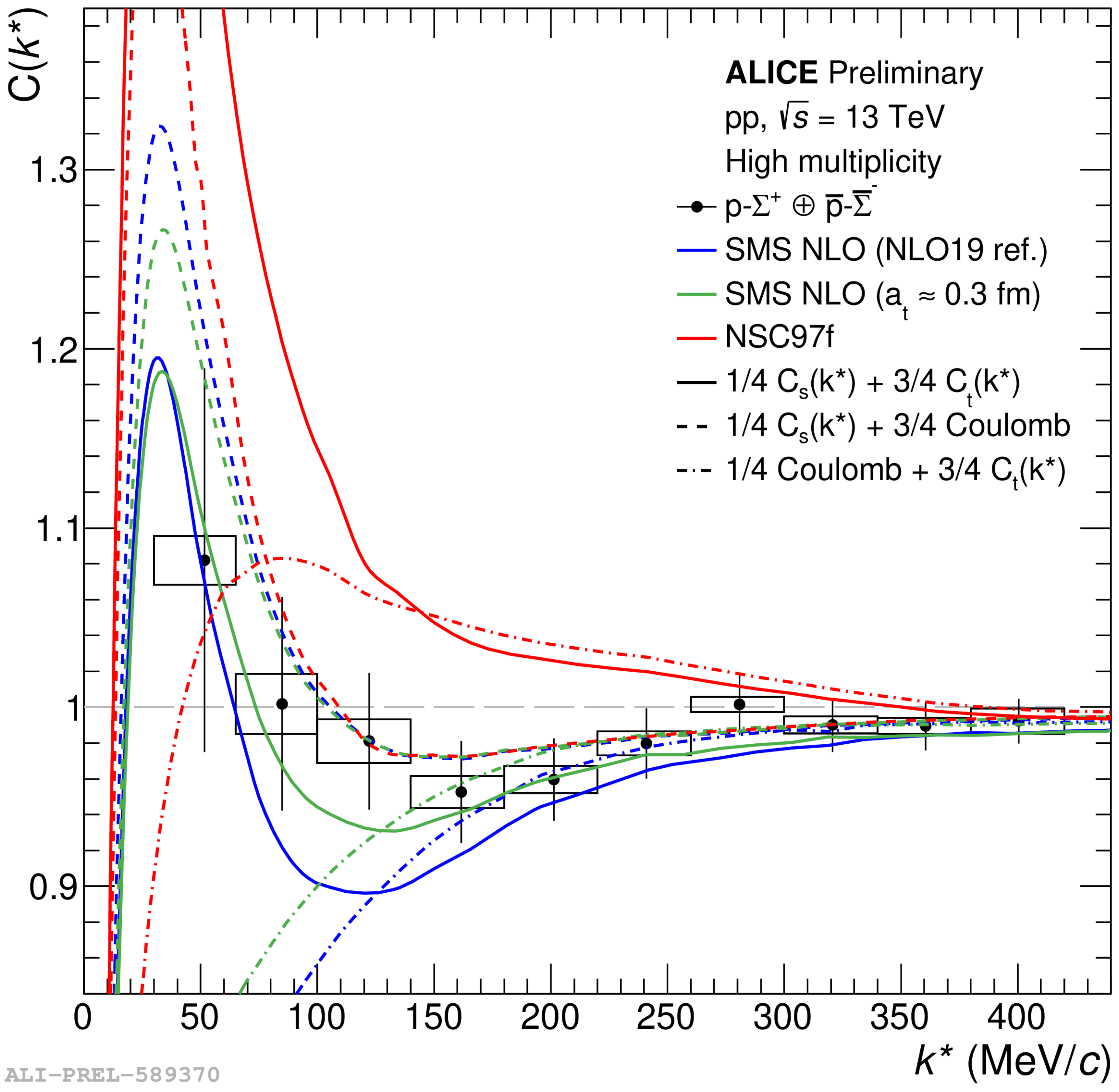
- Correlation function very sensitive to triplet strength at higher k*
- Good agreement with very shallow repulsion



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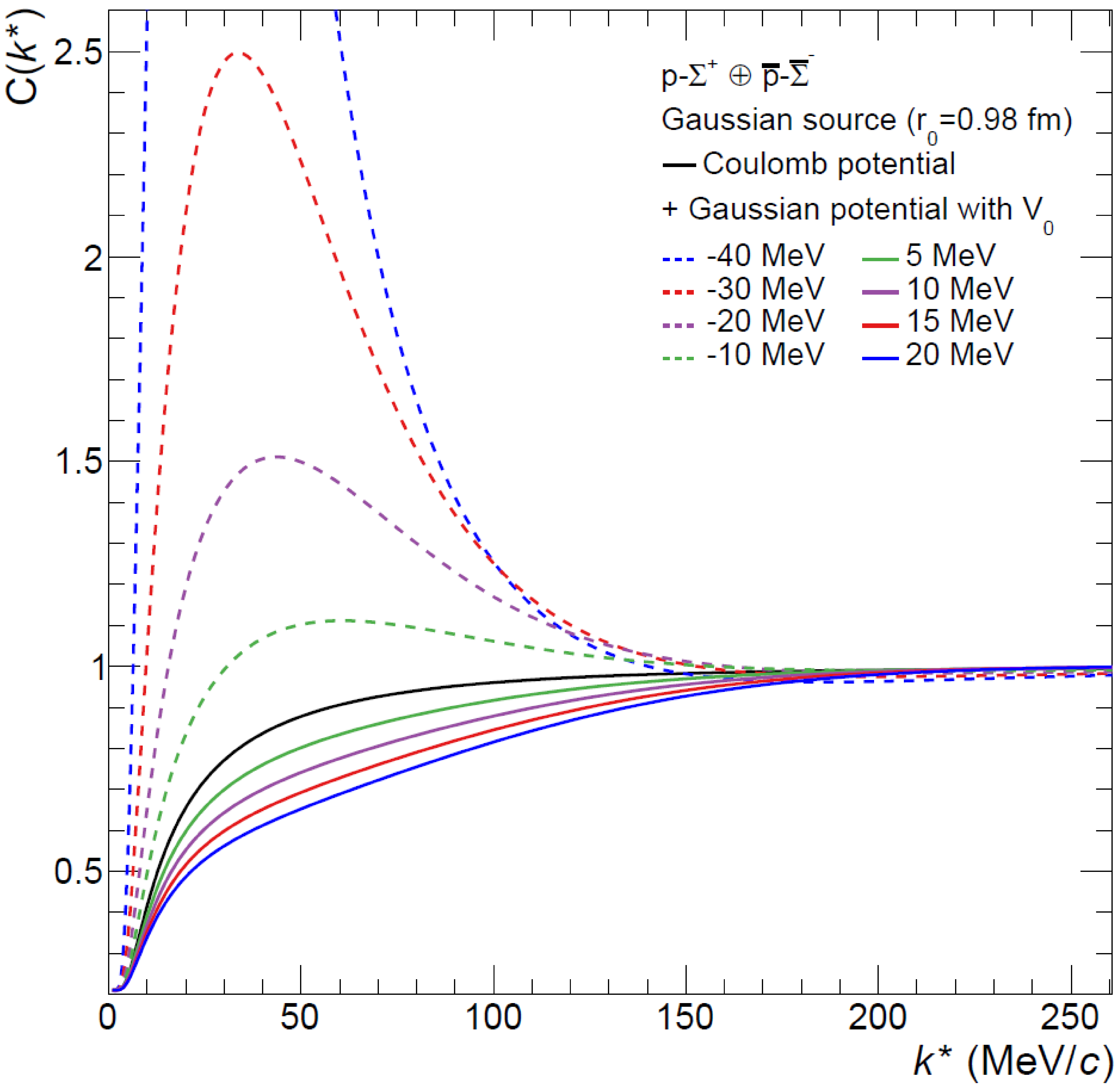
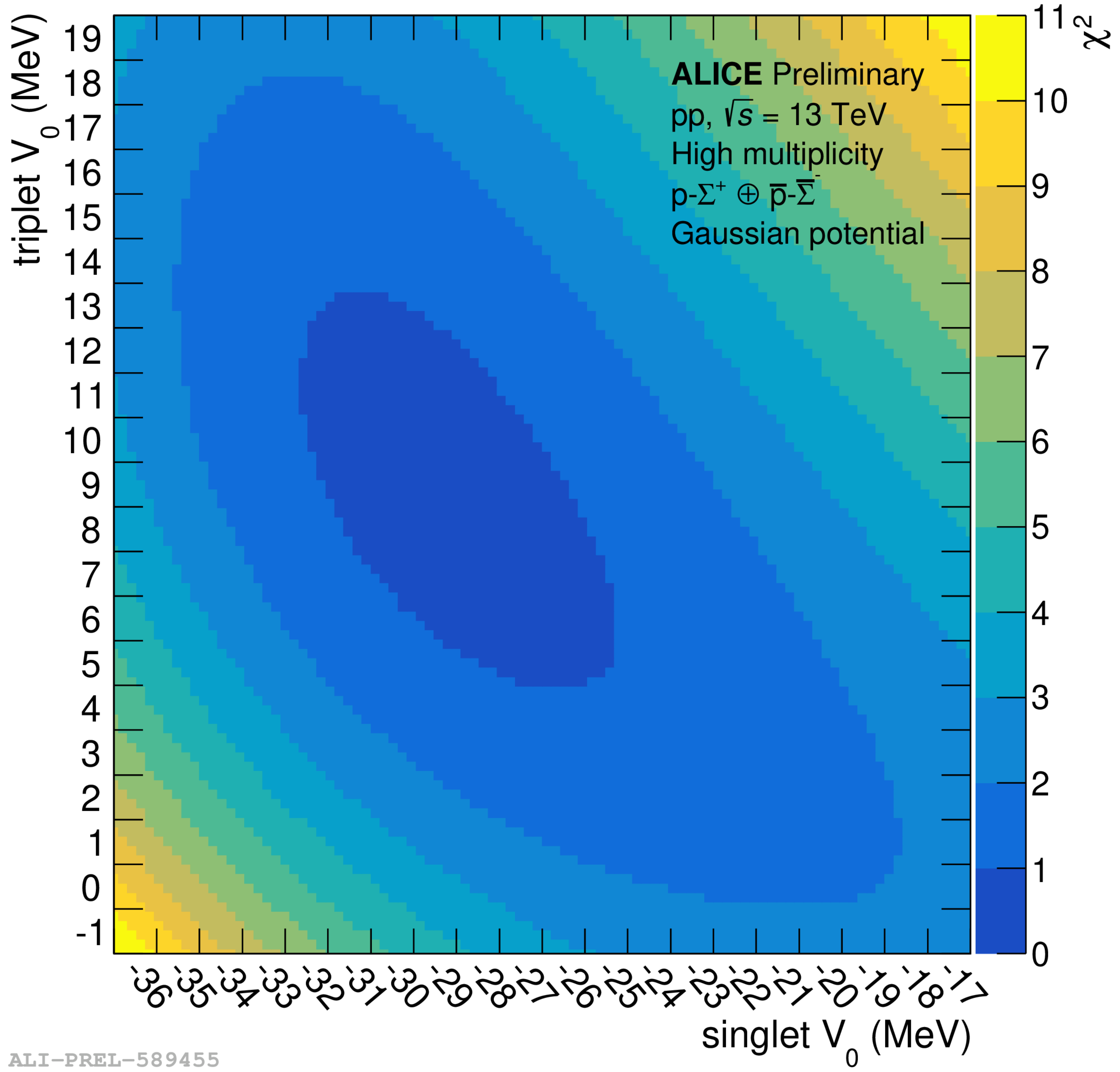
Gaussian potential

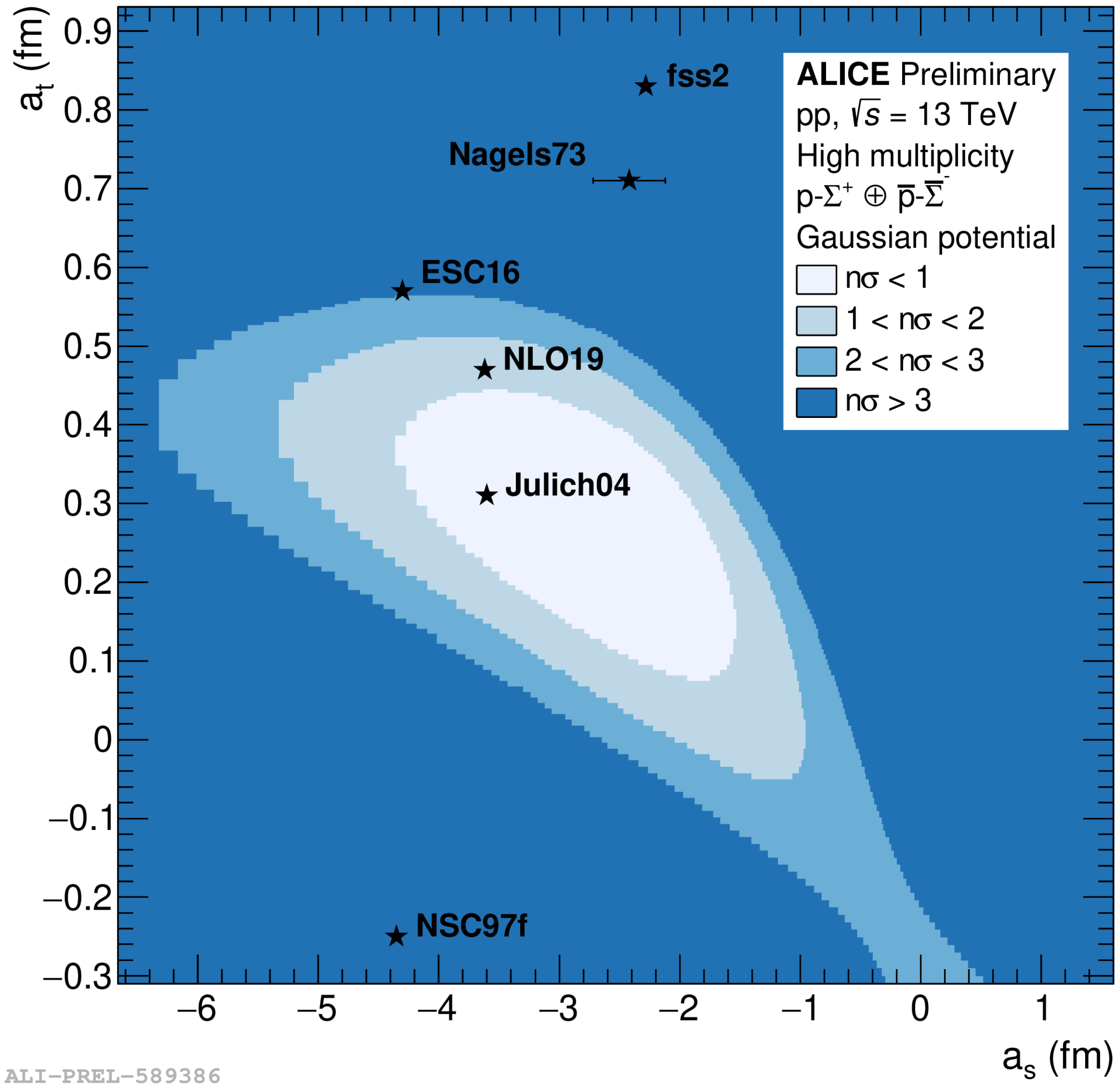
- Obtain correlation functions from Gauss + Coulomb potential and compare to data





Gaussian potential

- Singlet scattering length in agreement with all considered model predictions
- In the triplet again a shallow repulsion is found with $a_0 \approx 0.3$ fm.
- Best agreement with meson-exchange model Jülich04



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fss2: Y. Fujiwara et al., Phys. Rev. C 65 (2001) 014002
Nagels73: M. Nagels et al., Annals Phys. 79 (1973) 338
Jülich04: J. Haidenbauer et al., Phys. Rev. C 72 (2005) 044005

Conclusion

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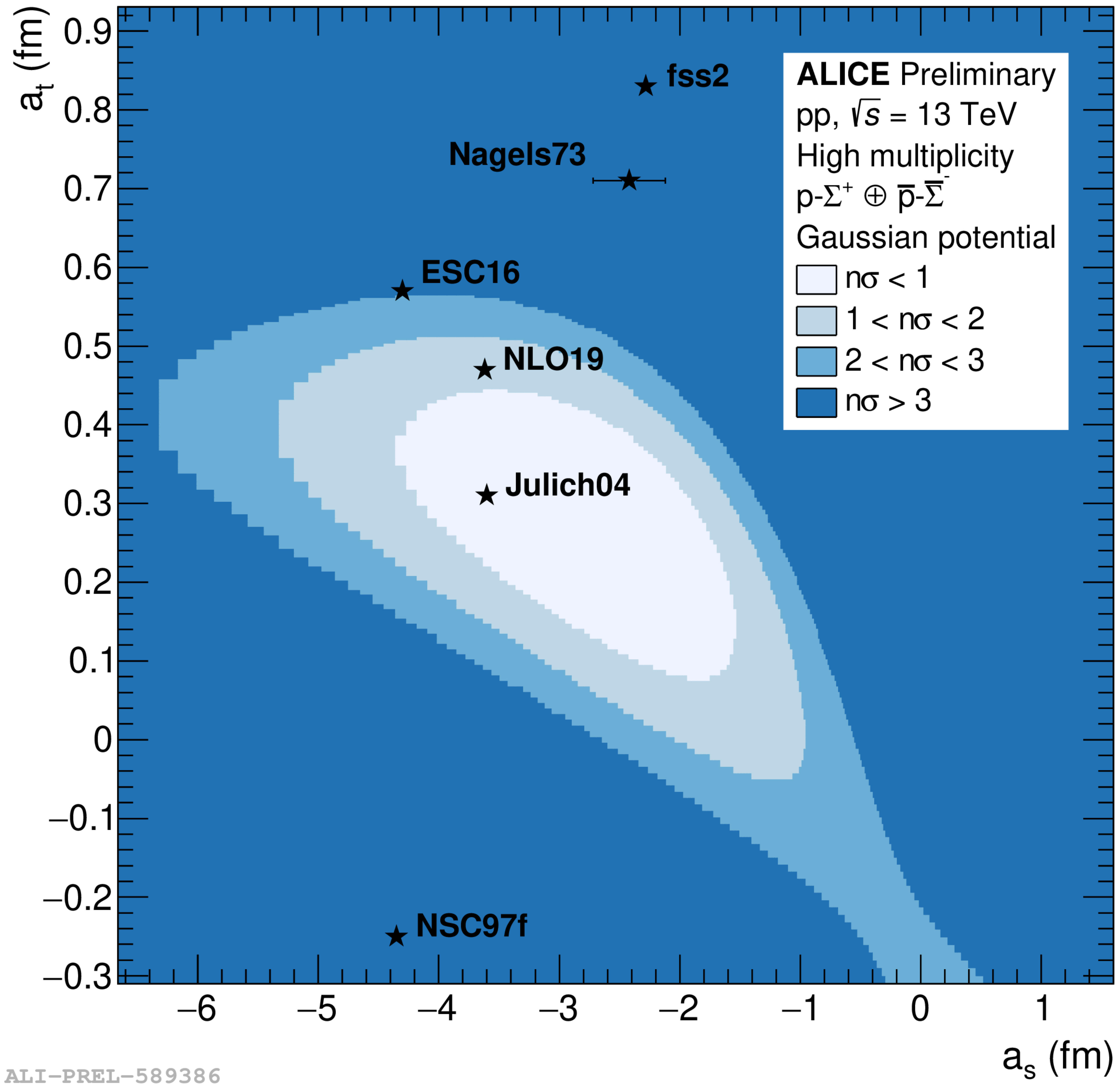

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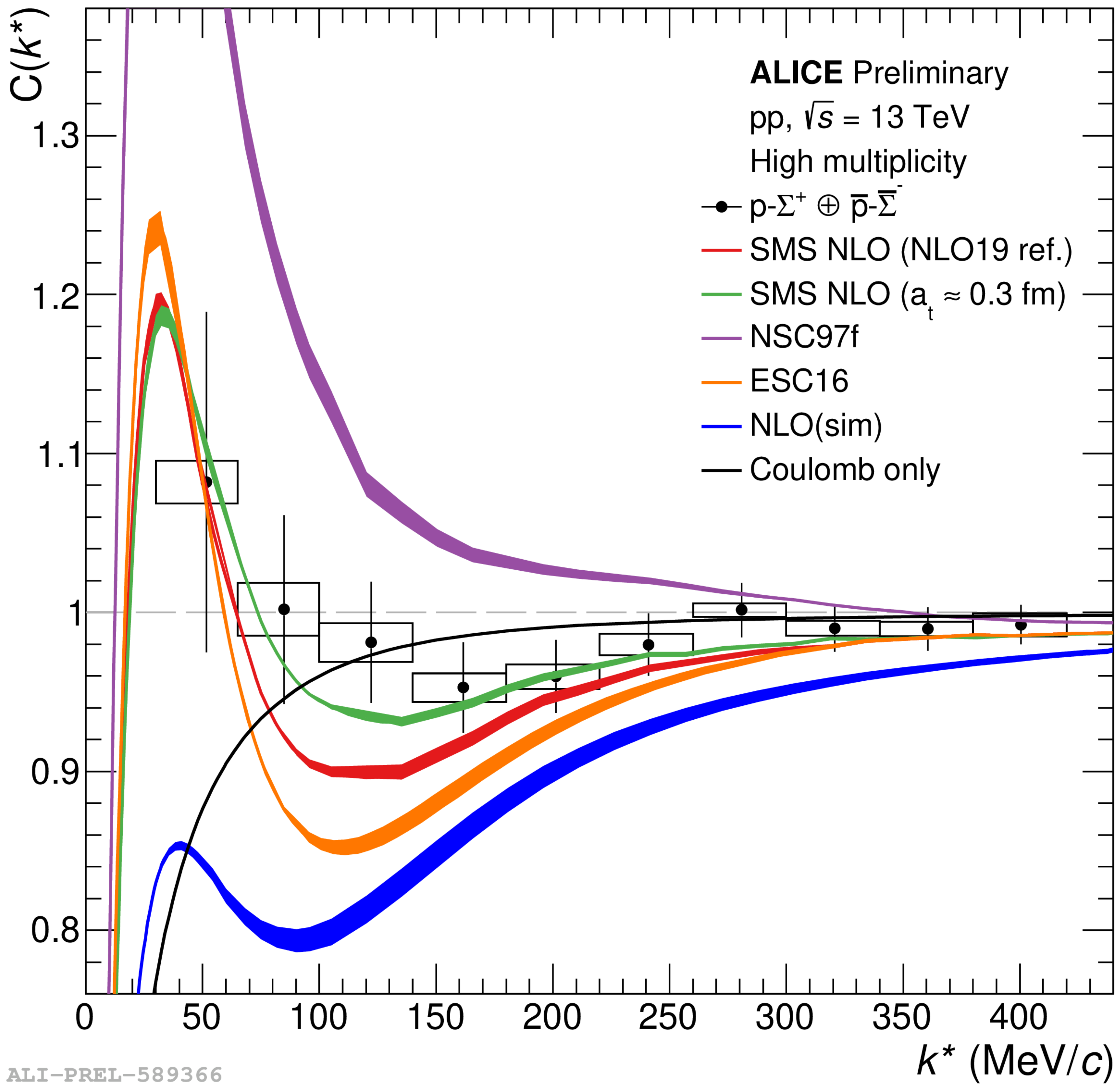

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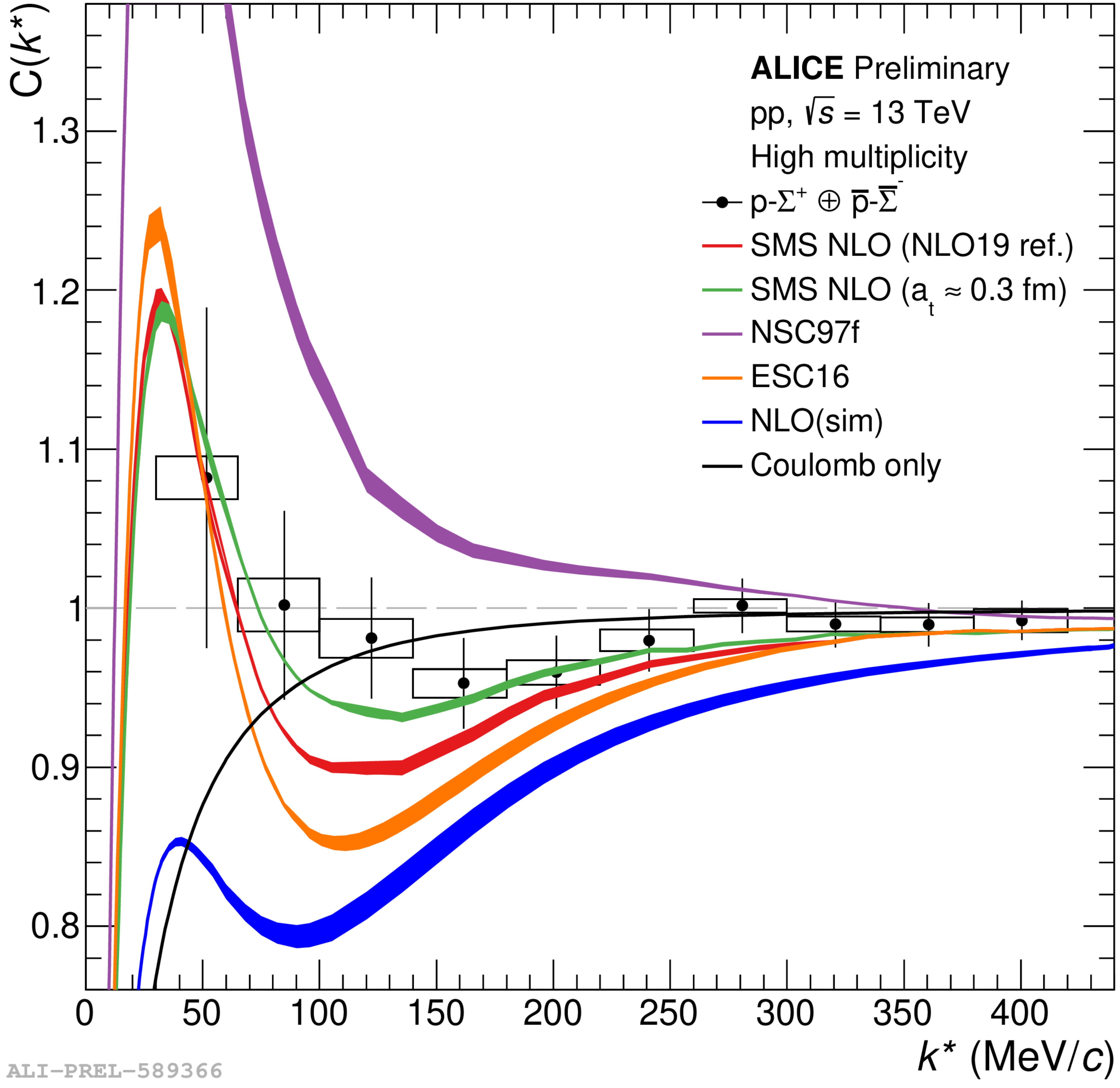
Thank you!



Backup

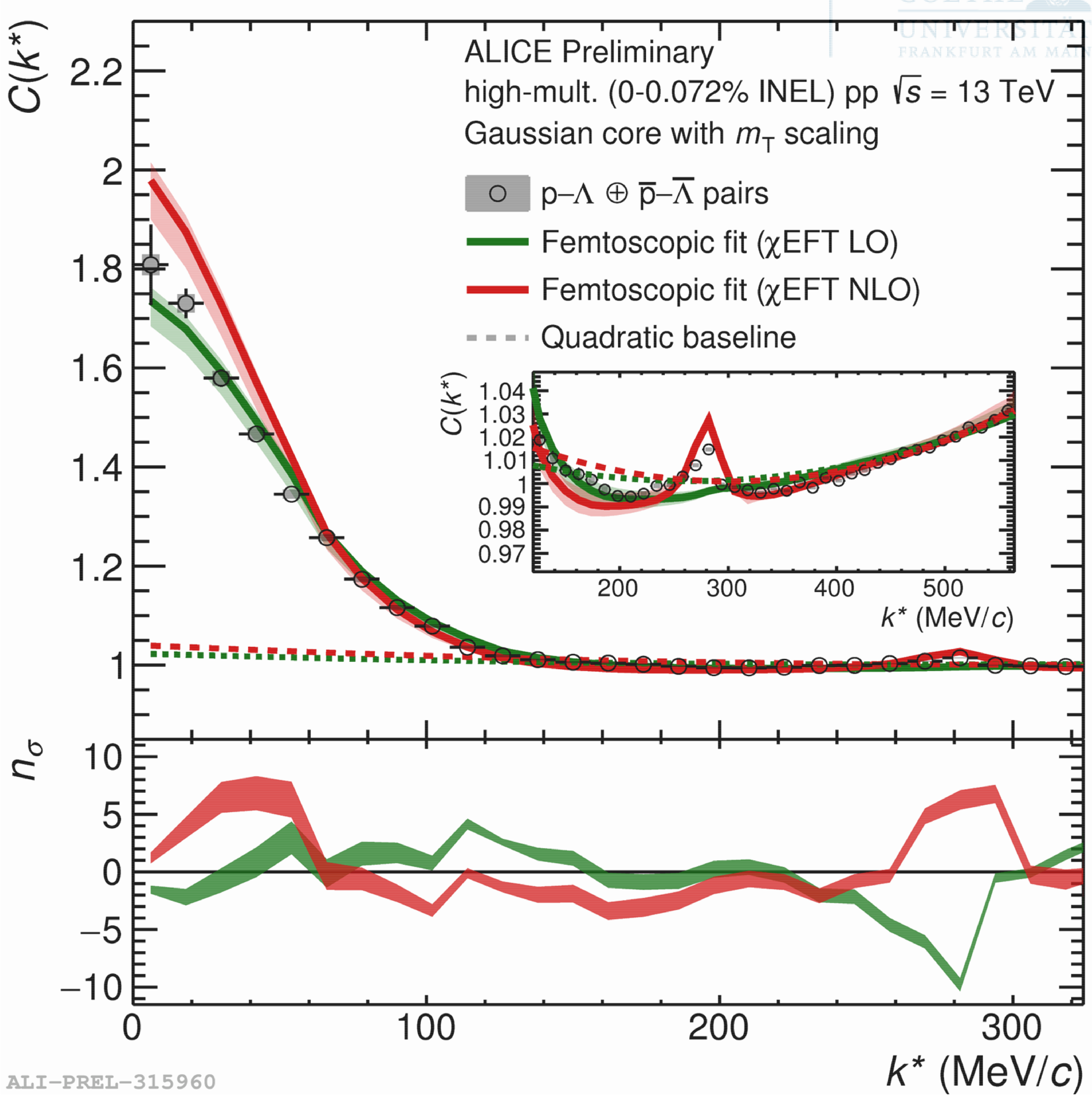
Motivation

- The observable of interest in femtoscopy is the relative momentum

$$k^* = \frac{1}{2}|\vec{p}_1^{\,*} - \vec{p}_2^{\,*}|$$

distribution of the particle pairs evaluated in their rest frame

- Contribution of Σ^0 decays to Λ is sizeable contamination of the p-Λ correlation function (~16%)
- Notable uncertainty on extracted p-Λ and p-p-Λ interactions



Femto theory (in a nutshell)

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- Koonin-Pratt equation:

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

$$\Psi(k^*,r) = e^{-ik^*r} + f(k^*)\frac{e^{ik^*r}}{r}$$

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

Effective range approximation: $f(k^*)^{-1} \approx -\frac{1}{a_0} + \frac{d_0}{2}k^{*2} - ik^* + O\left(k^{*4}\right)$

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Femto theory (in a nutshell)

Model	NLO13(600)	NLO19(600)	Julich04	ESC16	Nagels73	fss2	NLO(sim)	NSC97f
a_s [fm]	-3.56	-3.62	-3.6	-4.3	-2.42	-2.28	-2.39	-4.35
r_s [fm]	3.54	3.5	3.24	3.25	3.41	4.68	4.61	3.16
a_t [fm]	0.49	0.47	0.31	0.57	0.71	0.83	0.8	-0.25
r_t [fm]	-5.08	-5.77	-12.2	-3.11	-0.78	-1.52	-1.25	28.9

$d_0 = 29$ fm !

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[11] J. Haidenbauer, U.G. Meissner, Exploring the Σ^+ p interaction by measurements of the correlation function, Phys. Lett. B 829 (2022)

Gaussian potential

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➢ Use bootstrapping precedure to relate χ^2 and p-value