proton-deuteron femtoscopy in pp collisions

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EXOTICO workshop @ECT*, October 20th, 2022. Trento.

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 754496

Motivation

<u>proton-deuteron (p-d) interaction</u>

- p-d interaction is well constrained from the **scattering experiments**

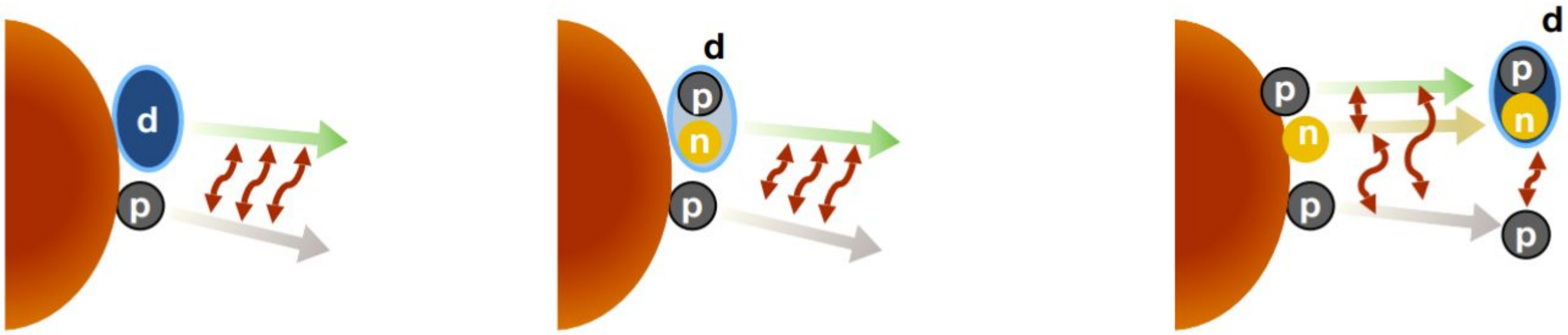
<u>Three body forces</u>

- Fundamental to **explain the nuclear structure**, might become more important at higher densities
- Fundamental **ingredient for the Equation of State (EoS) of dense nuclear matter**
- Theory currently anchored to properties of nuclei, hypernuclei and scattering data

⇒ p-d correlations in pp collisions at the LHC provide a new way to explore the interaction of a three body system at short distances

Production mechanism of light nuclei not understood:

- Models: Thermal emission or Coalescence   Stanislaw Mrowczynski @EXOTICO
- What can final-state interaction studies say about the formation of deuterons (antideuterons)?



ALICE data
pp collisions @13TeV, High-Multiplicity

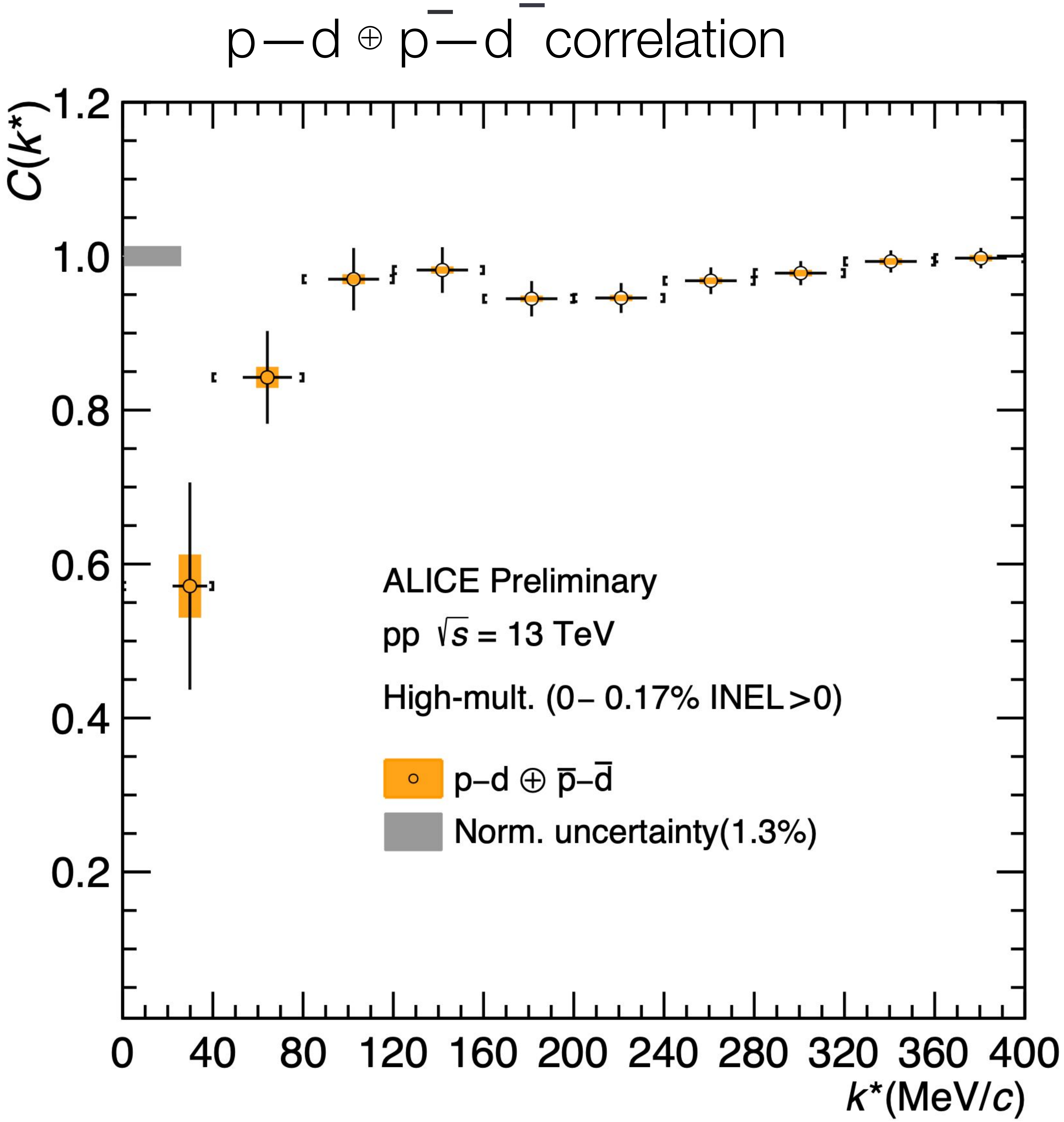
pp collisions @13TeV, High-Multiplicity

- Run 2 High-multiplicity data set with ~1x10^9 events
- Particles are selected in momentum range:
  - (anti)protons: $0.5 < p_T < 4$ GeV/c
  - (anti)deuterons: $0.4 < p_T < 2.3$ GeV/c

$p-d \oplus \bar{p}-\bar{d}$ correlation

⇒ All particles tracked and identified by TPC+TOF
purities >98%
⇒ High-Multiplicity sample enhances number of pairs
p-$d \oplus \bar{p}$-$\bar{d}$ pairs k*<200 MeV/c = 3851

p-d experimental correlation function



Data corrected for:

- Finite resolution
  - corrected using resolution matrices from MC

Theoretical correlation function corrected for:

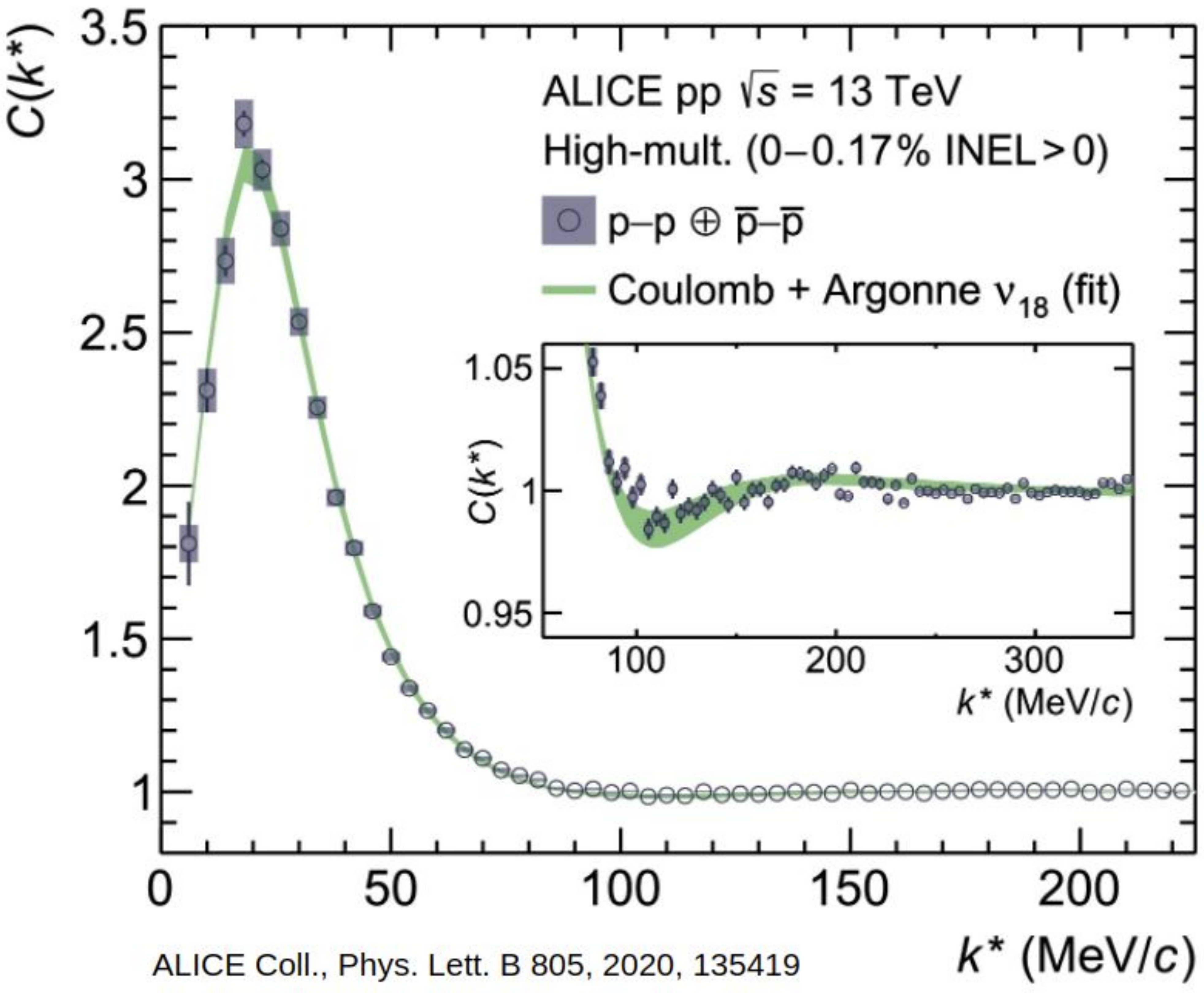
- Feed-down
  - Lambda parameters for genuine interaction: **λ_{pd}= 82%**
  - All contributions including feed-down to protons considered as C(k*) = 1.
- Non-Femtoscopy effects
  - Baseline fitted with pol-2 (flat at k*=0)

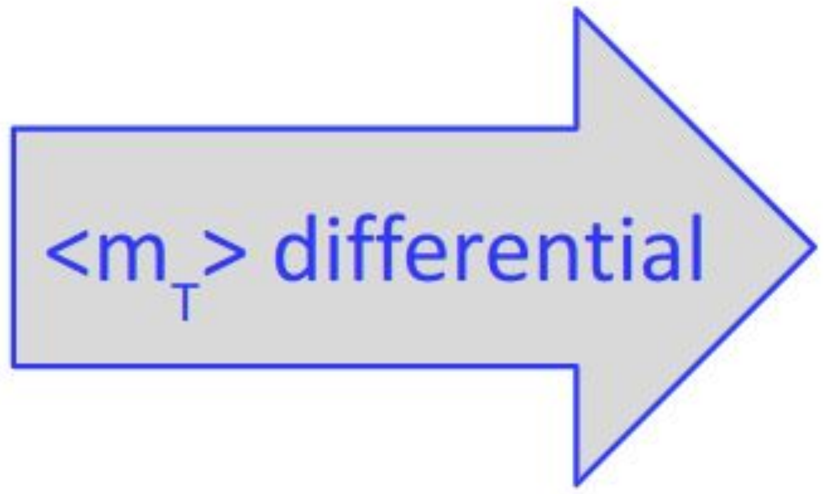
Determination of the source size via m_T scaling + effect of resonances

Common baryon source as a function of <m_T>

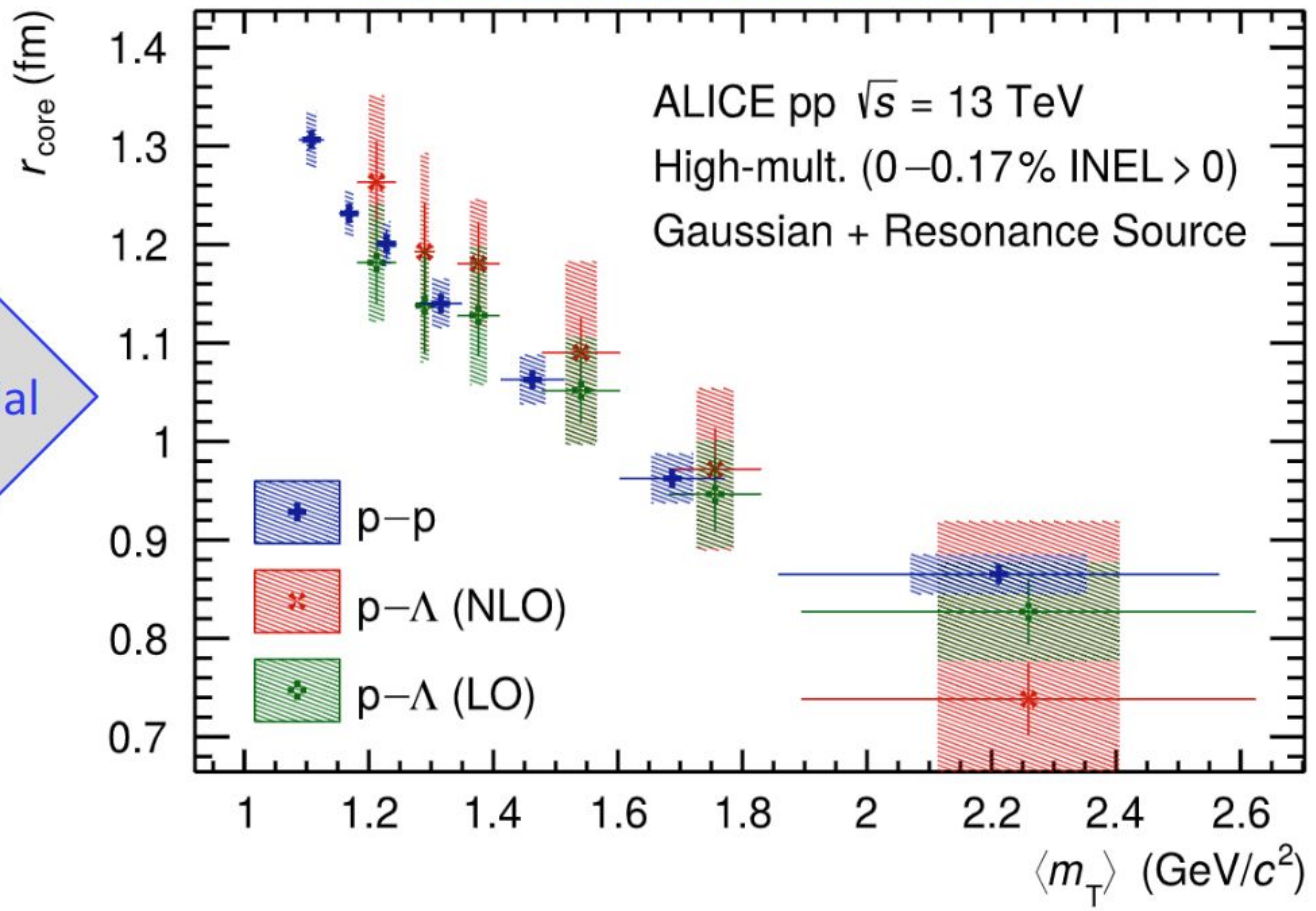
Source size is determined via traditional femtoscopy analysis (known interaction)

- **fit p-p correlation function ⇒ extract gaussian source radius**
- differential <m_T> fit ⇒ **“map” of source size**
- take into account effect of strong decaying resonances





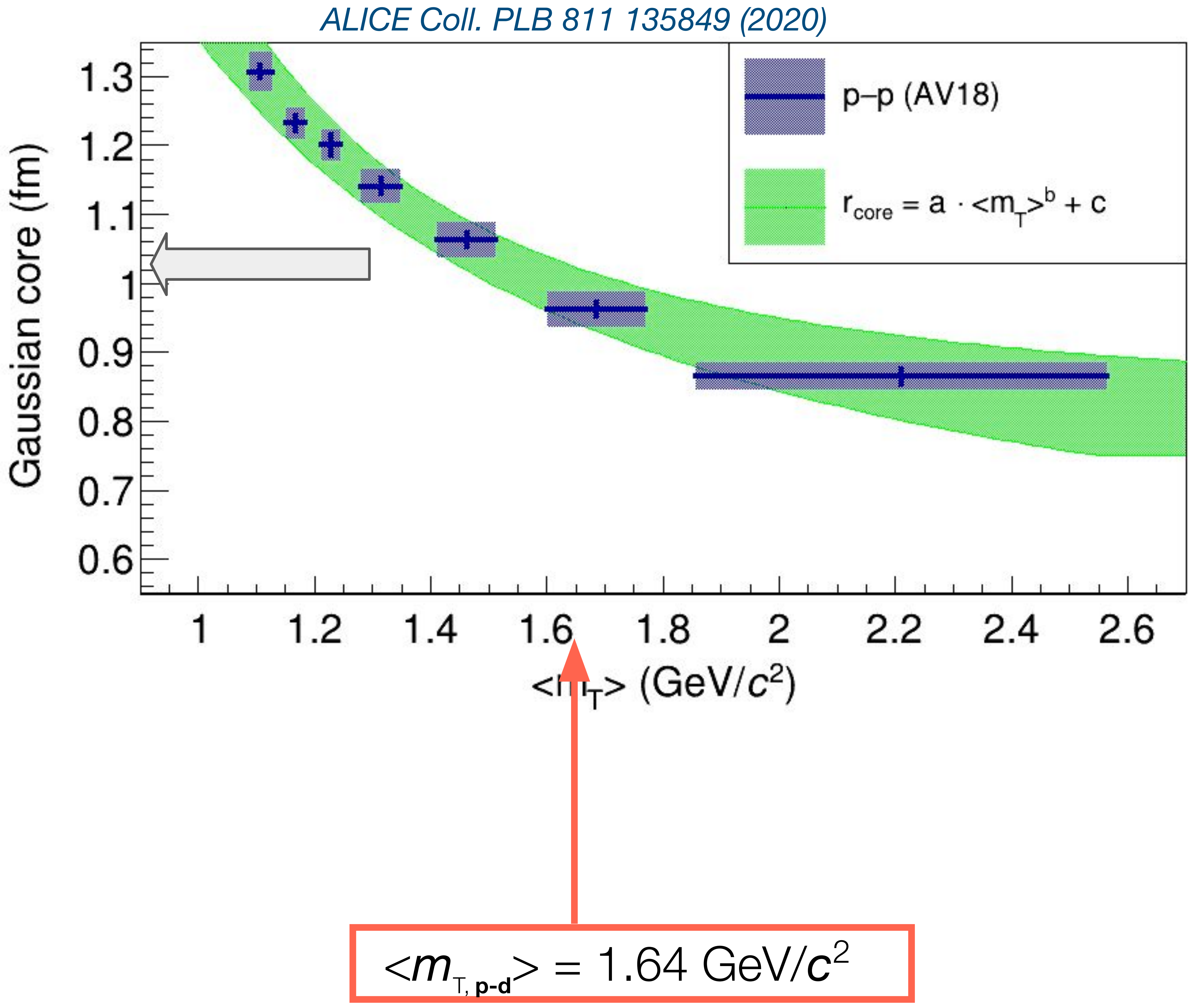
ALICE Coll., Phys. Lett. B 811 (2020) 135849



Source size for pd via m_T **scaling** + resonances

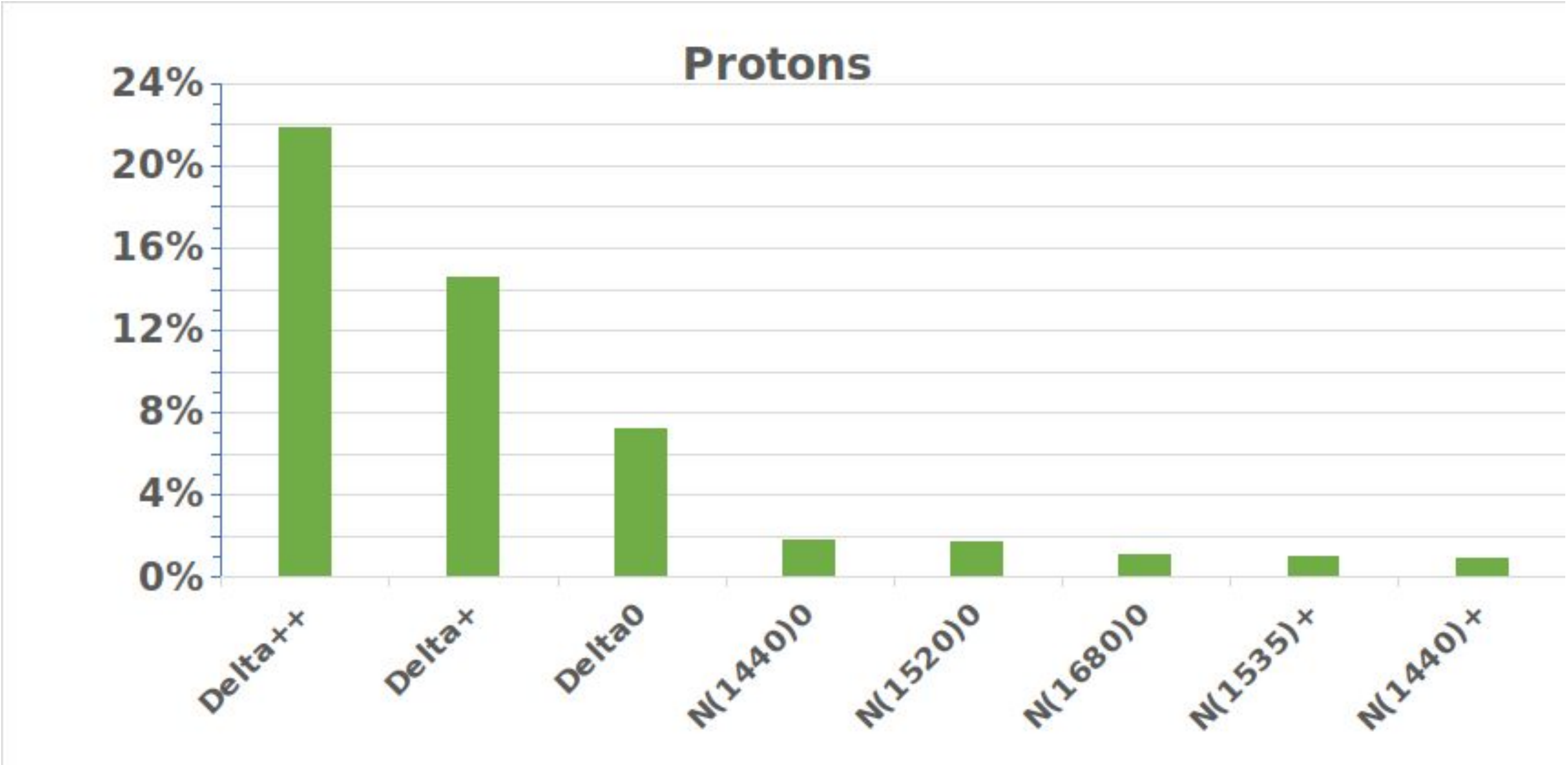
- Assume for pd the universal m_T scaling
- “Core” radius:

Source size	pd
r_{core}	0.99±0.05 fm



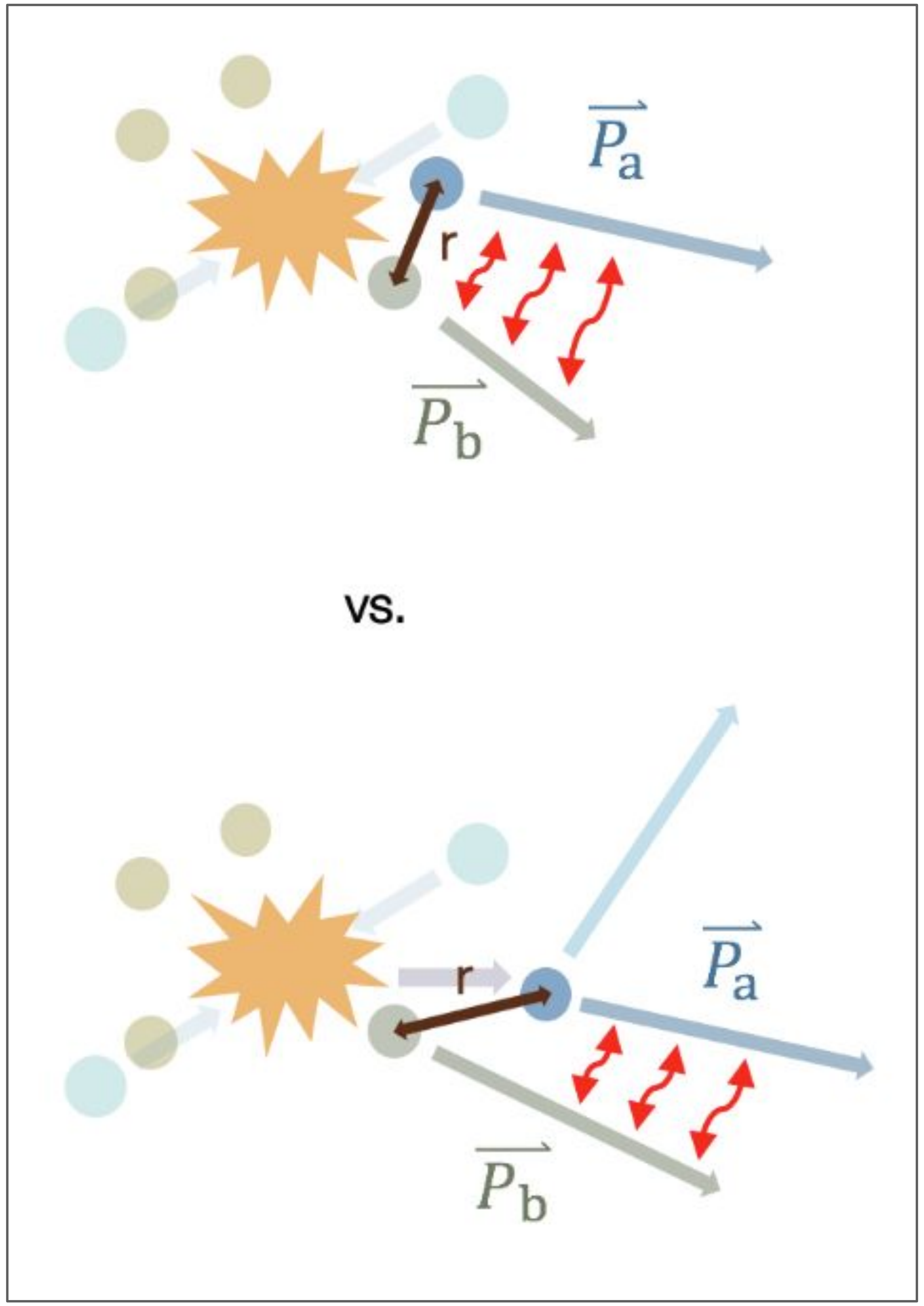
Source size for pd via m_T scaling + **resonances**

- The source radius is effectively increased by **short-lived strongly decaying resonances** ($c\tau \approx r_{core}$)



- Increase of the source size (long distance tails)

Source size	pd
r_{core}	0.99±0.05 fm
r_{eff}	**1.08±0.06 fm**



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Theoretical model comparison

Lednicky model: pointlike deuterons

Lednicky model

- **For distinguishable particles**
  - starting from the scattering parameters ⇒ define the s-wave two-particle relative wave function
  - considers Coulomb effects

- Coulomb-corrected wave function for final-state interactions (Lednicky): arxiv.org/abs/nucl-th/0501065

$$\psi_{-k^*}(r^*) = e^{i\delta_c}\sqrt{A_c(\eta)}\left[e^{-ik^*r^*}F\left(-i\eta, 1, i\zeta\right) + f_c(k^*)\frac{\tilde{G}(\rho,\eta)}{r^*}\right]$$

  - f_c : Coulomb normalised scattering amplitude for strong interaction
  - $F(-i\eta, 1, i\zeta)$: confluent hypergeometric function
  - $\tilde{G}(\rho,\eta)$: combination of singular and regular Coulomb function, describes asymptotic behaviour of wavefunction

⇒ to obtain two-particle correlation we can use Koonin-Pratt formula

Lednicky model: How accurate is it?🤔

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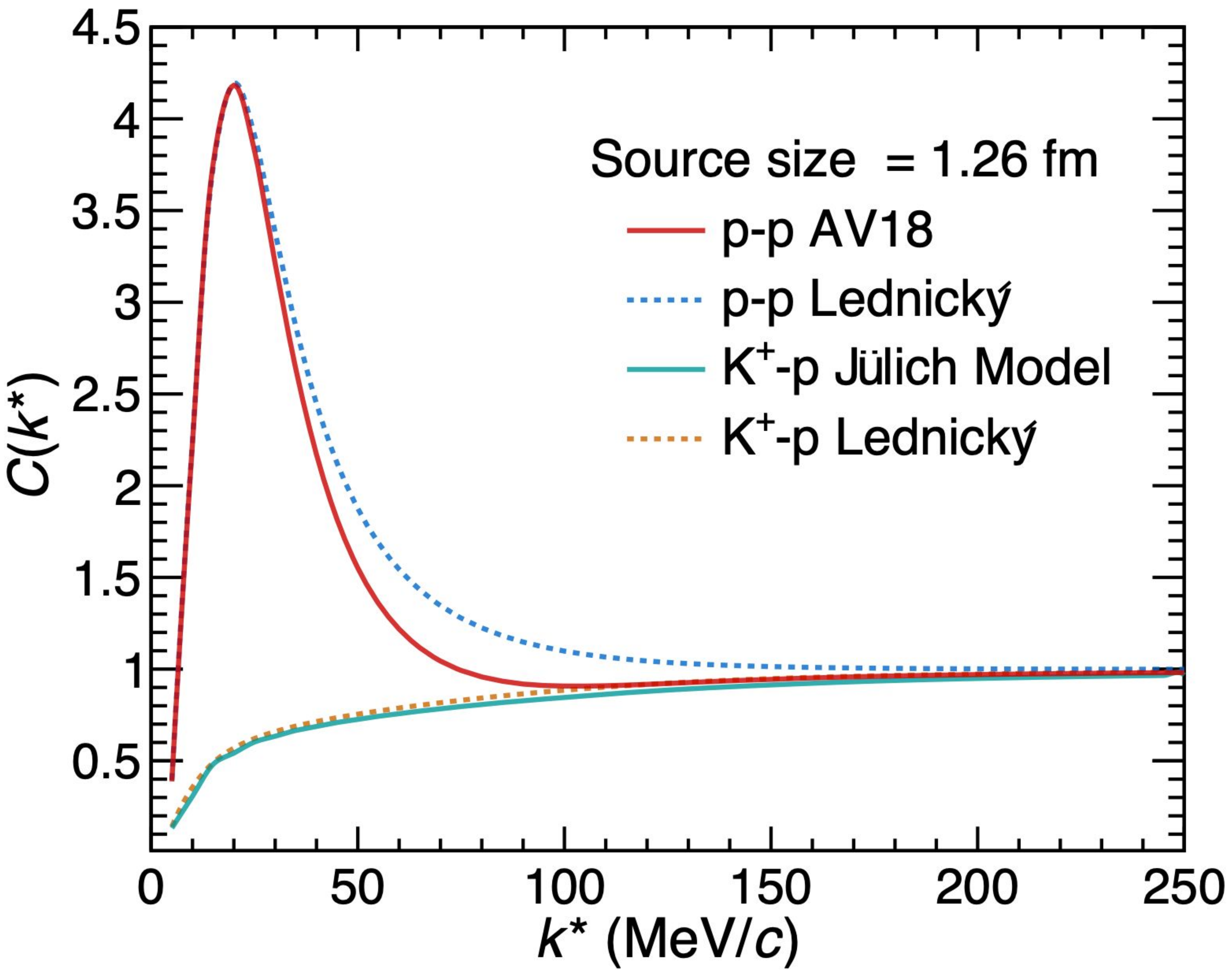
ALICE

- **Benchmark:** compare correlations with Lednicky model with calculations using
  - pp from AV18 potential
  - K^+p from Jülich model

System	f_0(fm)	r_0(fm)	References
pp (S=0)	7.806	2.788	R. Wiringa et al. [6]
K^+p (S=1/2)	−0.316	0.373	M. Hoffmann et al. [7]

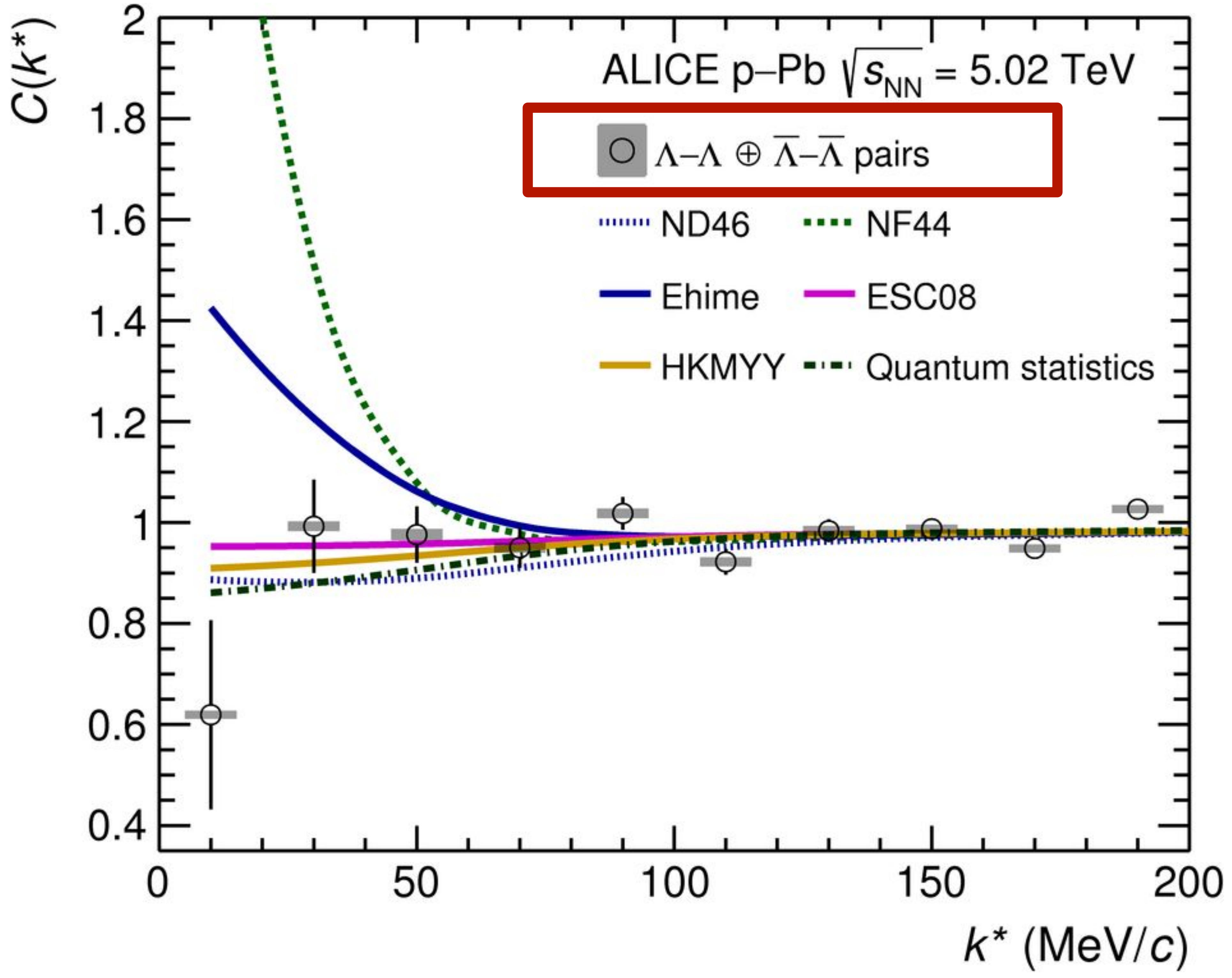
- **Correlations are well reproduced by Lednicky approach**
  - even with no anti-symmetrization for pp case!



Convention sign: In this presentation positive (negative) f_0 means attractive (repulsive) interaction

Lednicky model: How accurate is it? 🤔

- Some examples
  - Lednicky-Luboshits approach vs ALICE data



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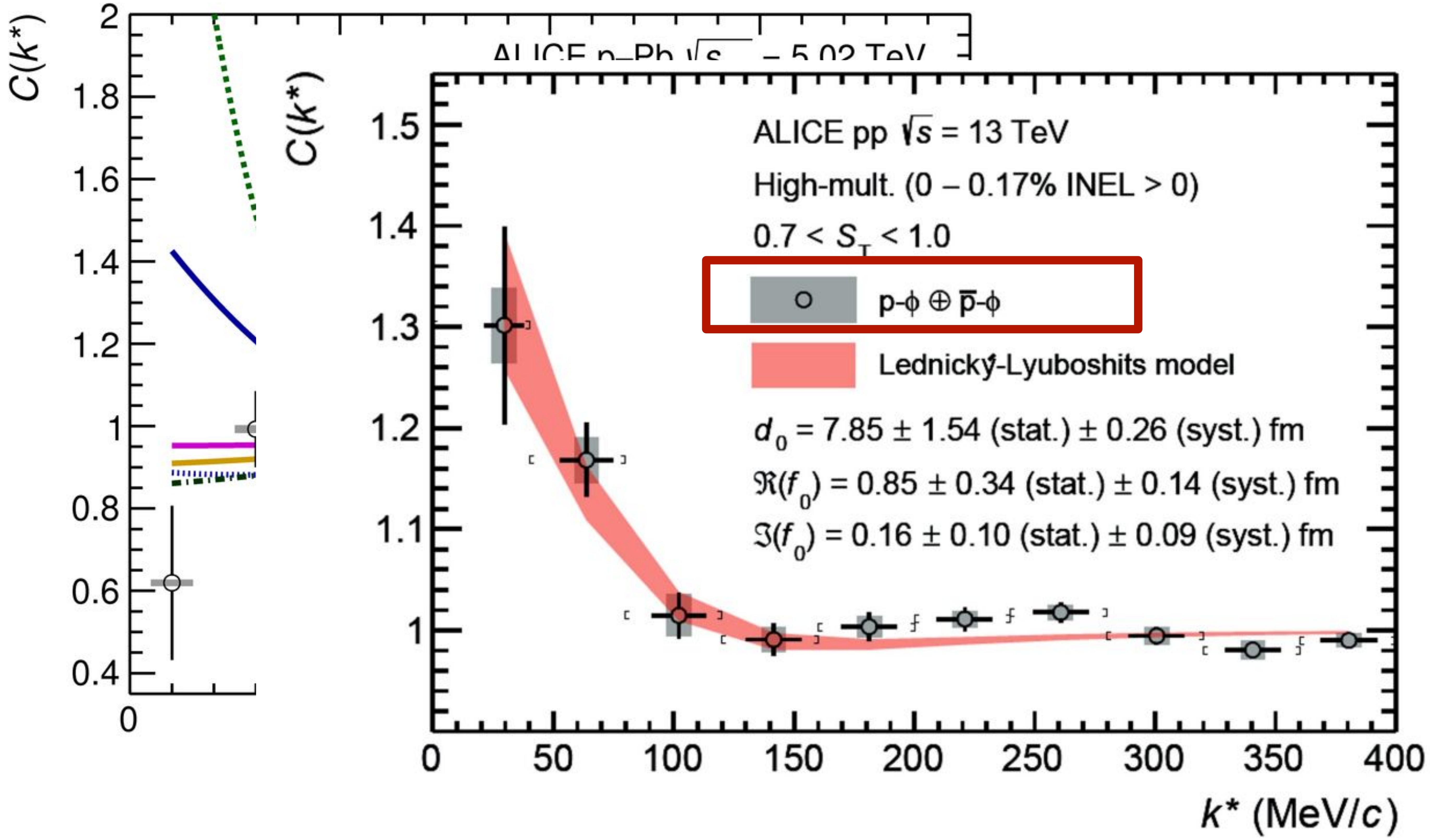

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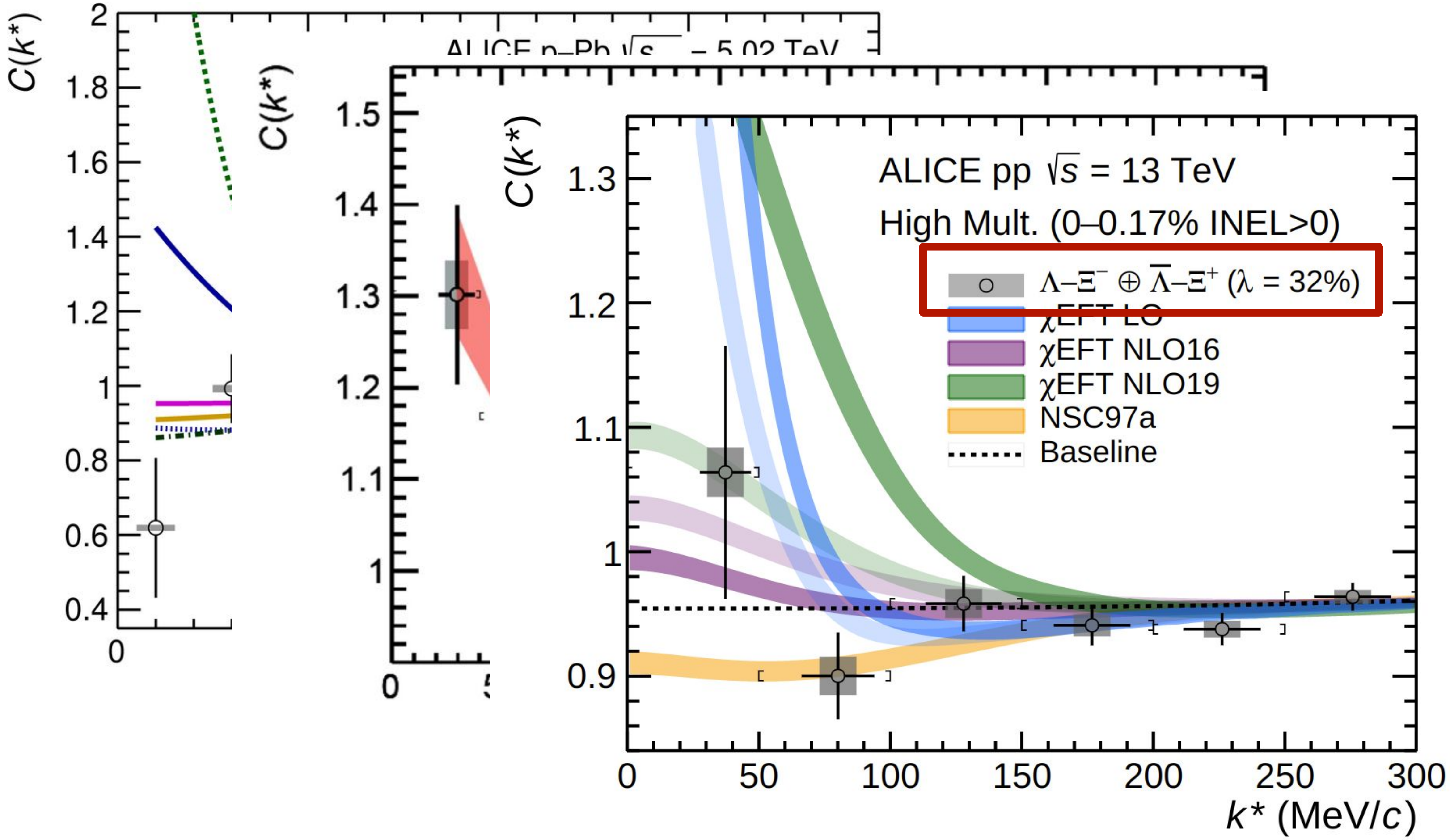

Lednicky model: How accurate is it? 🤔

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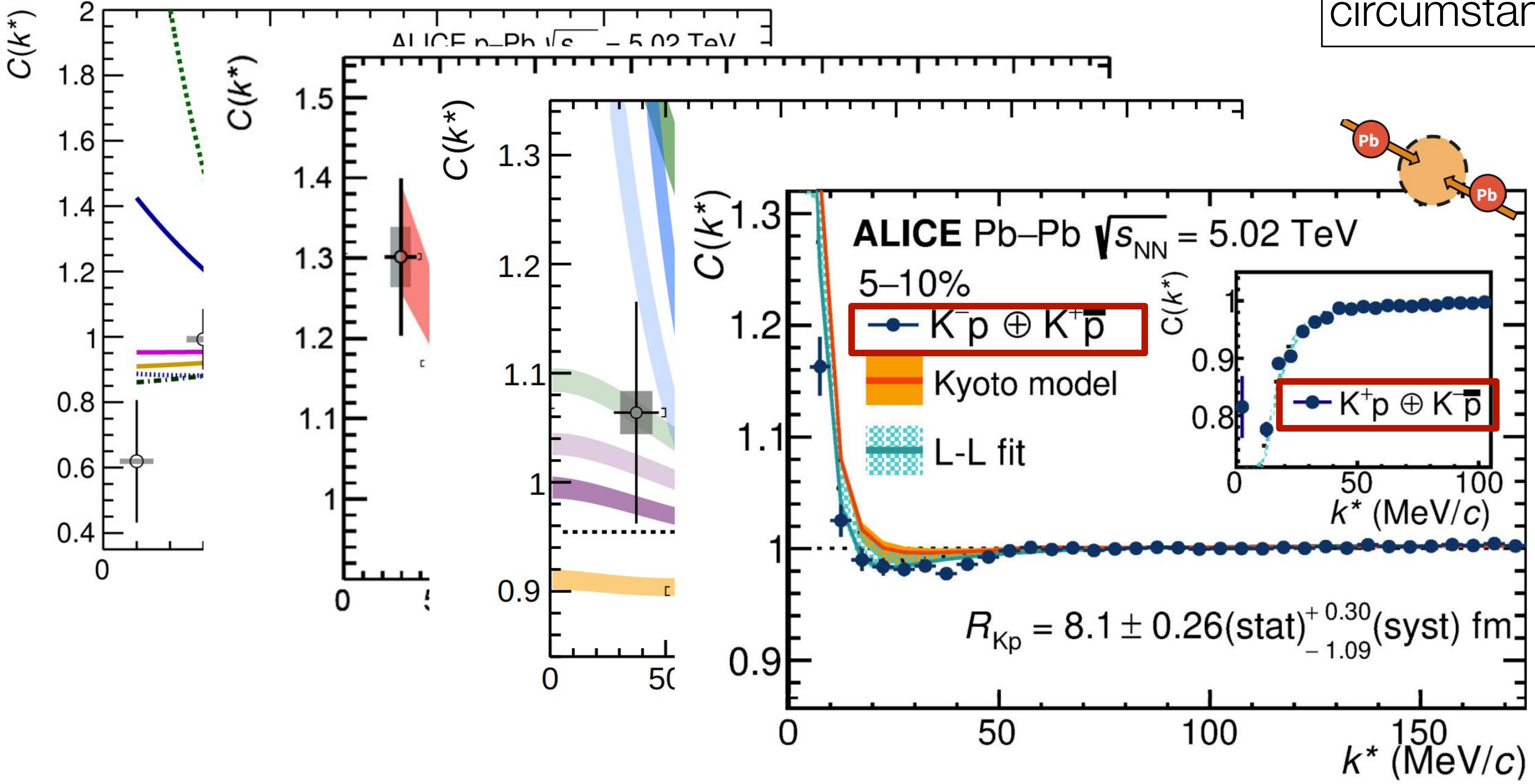
⇒ Useful tool (under the right circumstances)



Lednicky model: pointlike deuterons

⇒ **pd scattering parameters** from fits to pd scattering data

$S = 1/2$		$S = 3/2$		
$f_0(\text{fm})$	$r_0(\text{fm})$	$f_0(\text{fm})$	$r_0(\text{fm})$	
$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.80}_{-1.20}$	$2.05^{+0.25}_{-0.25}$	Van Oers et al. Nucl. Phys. A 561 (1967)
$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.40}_{-0.10}$	$2.63^{+0.01}_{-0.02}$	J.Arvieux et al. Nucl. Phys. A92 221 (1973)
-4.0	—	-11.1	—	E.Huttel et al. Nucl. Phys. A406 443 (1983)
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Assumption: Deuteron as point like particle

Lednicky model: pointlike deuterons

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Assumption: Deuteron as point like particle

pd data not described

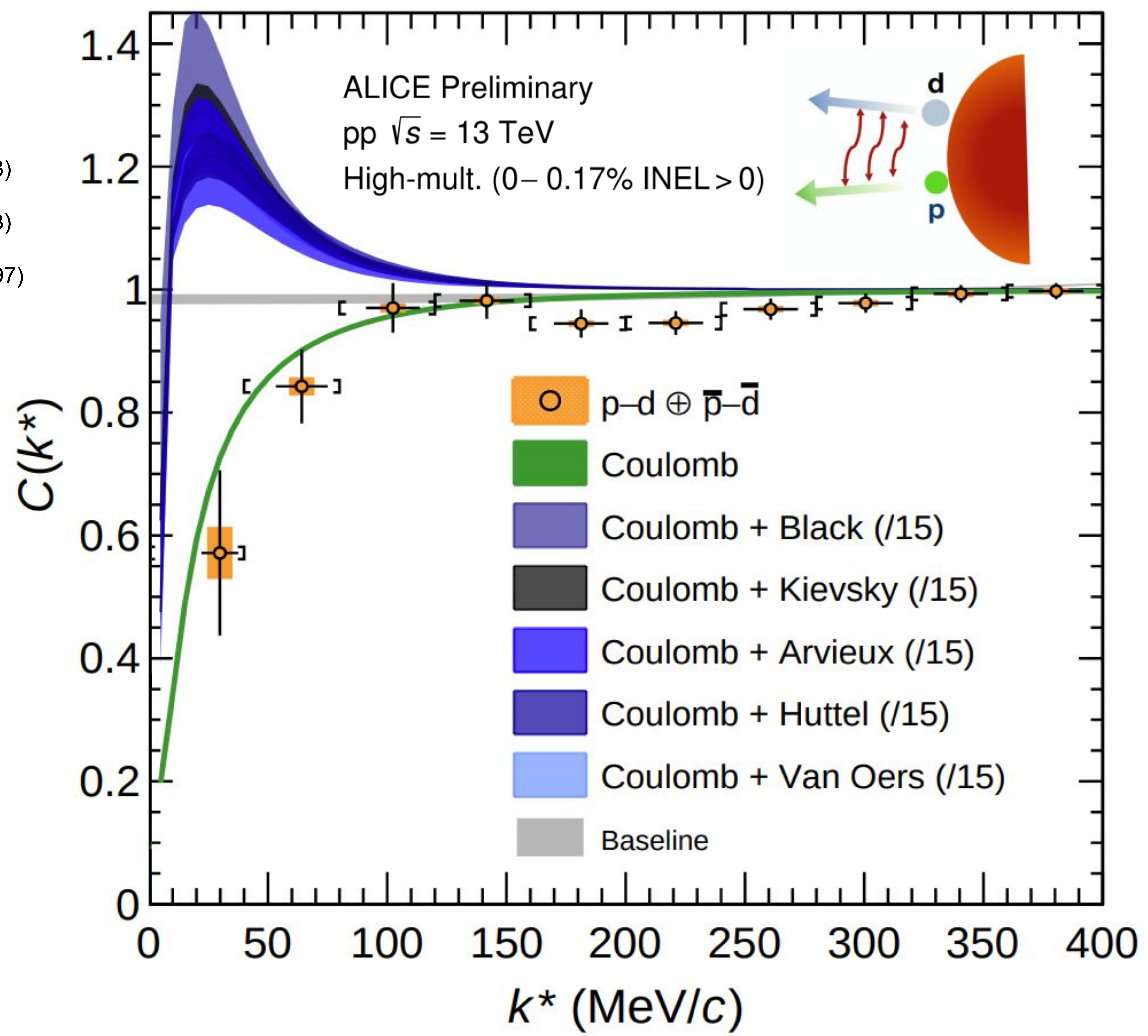
Model and data disagree for source size r = 1.08 fm

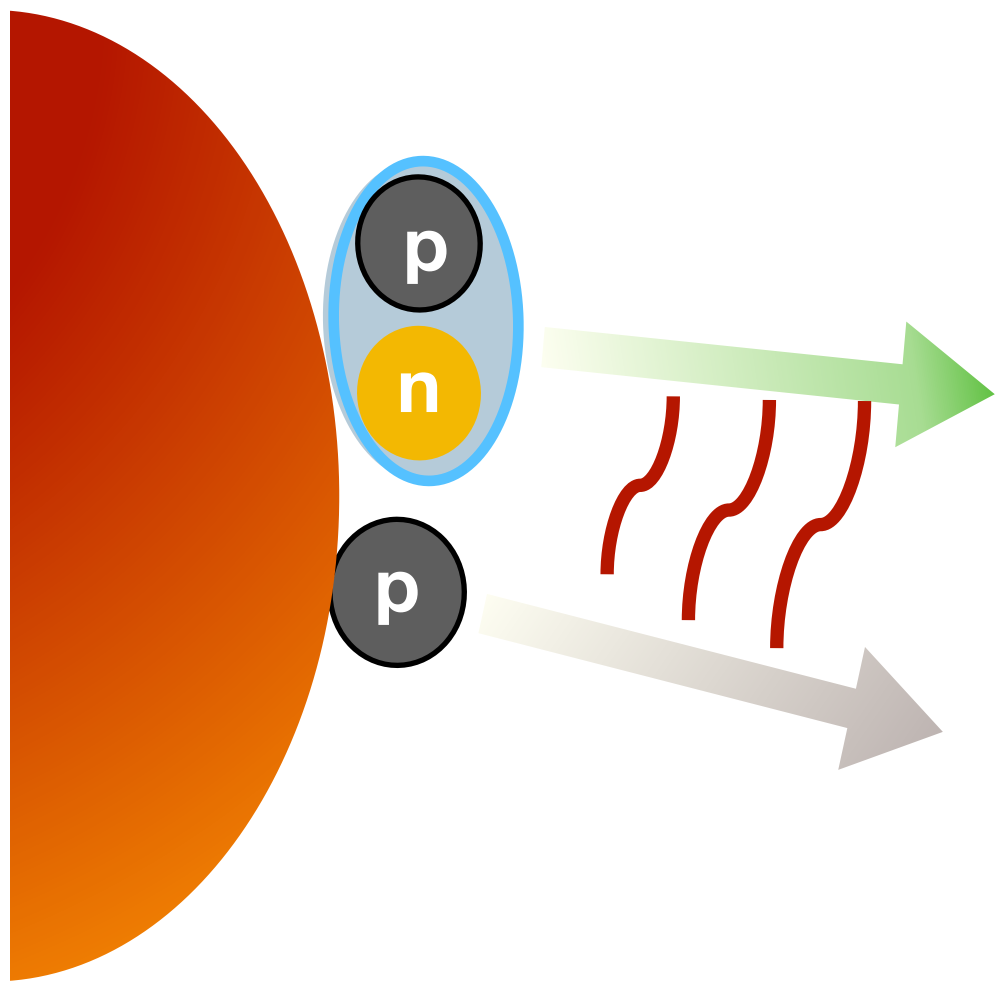
➡ Model does not account for p-(p-n) interaction

⇒ **pd can't be treated as effective two-body system**

r_{pd}=1.08±0.06 fm

pd model calculations scaled by 1/15





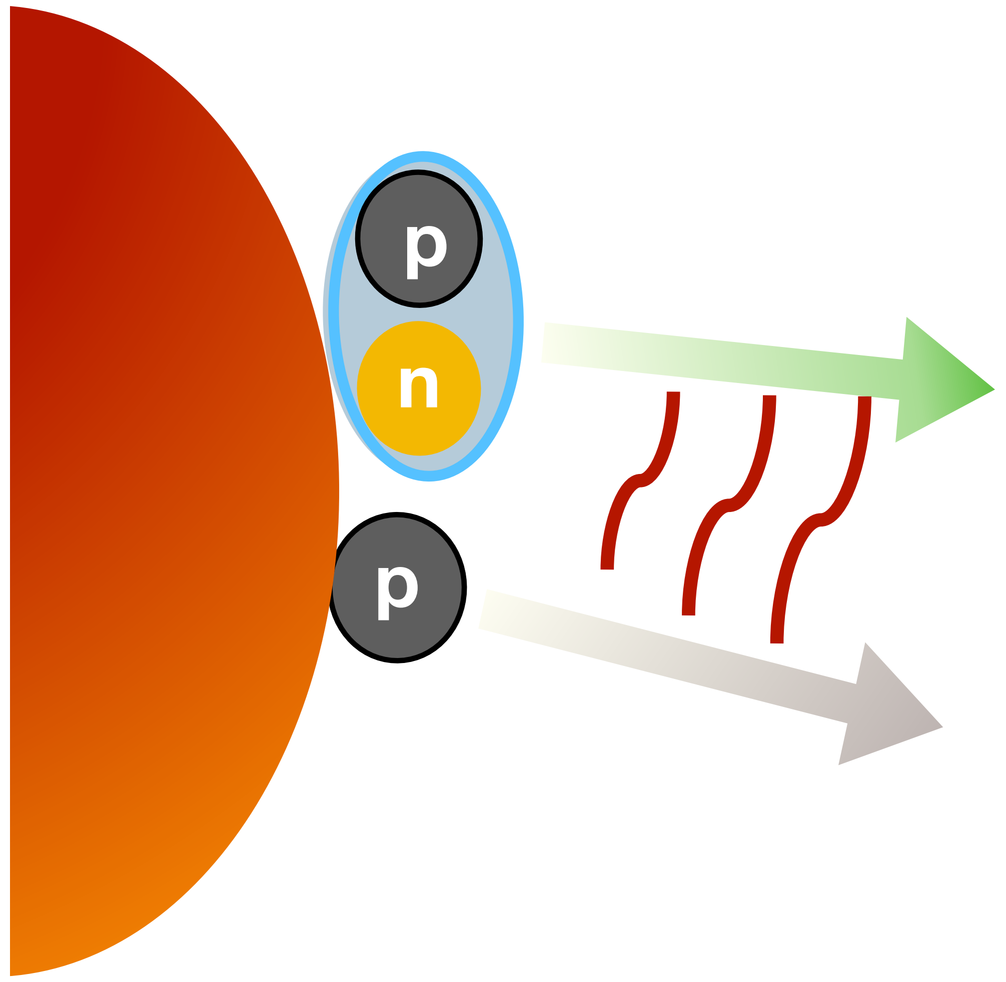
Pisa model: **pd as three-body system**

p-d correlation with d as composite object

Full calculation of a three-body p-p-n system projected into the p-d final state

Model under construction: Three-body dynamics calculation by PISA theory group: M. Viviani, A. Kievsky, L. Marcucci

- **Two-body interaction** Argonne V18 potential
- **Three-body interaction** Urbana XI potential
- **Deuteron wave-function** from AV18 NN interaction
- Deuteron is formed at the same time as the proton



p-d correlation with d as composite object

- **Three-body full p-d wave function** $\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y})$ describing three body dynamics, anchored to p–d scattering observables.
  - x = distance of p-n system within the deuteron
  - y = p-d distance
  - m_2 and m_1 deuteron and proton spin

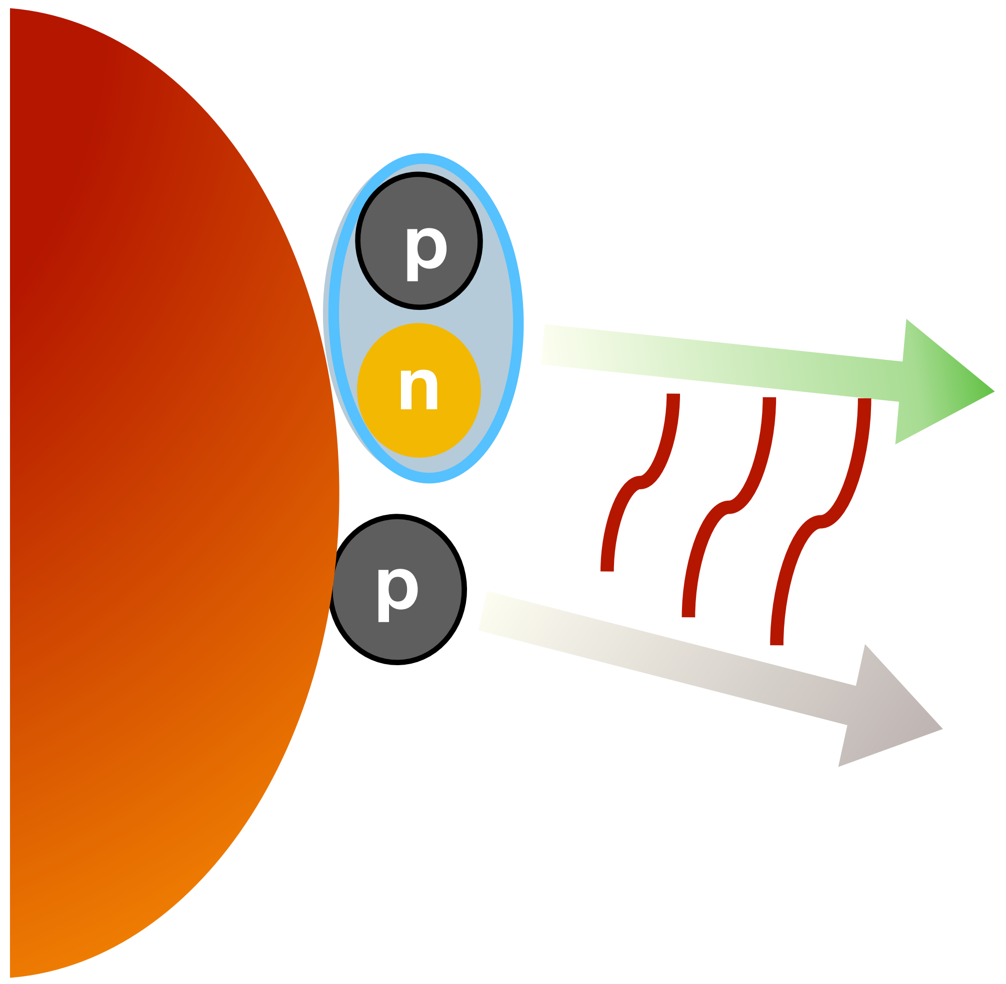
- $\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y})$ projected to obtain an effective proton-deuteron wave function:

$$\psi_{m_2',m_1',m_2,m_1}(k,\boldsymbol{y}) = \int d^3x \left[\phi_{m_2'}(1,2)(\boldsymbol{x})\chi_{m_1'}(3)\right]^\dagger \Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) .$$

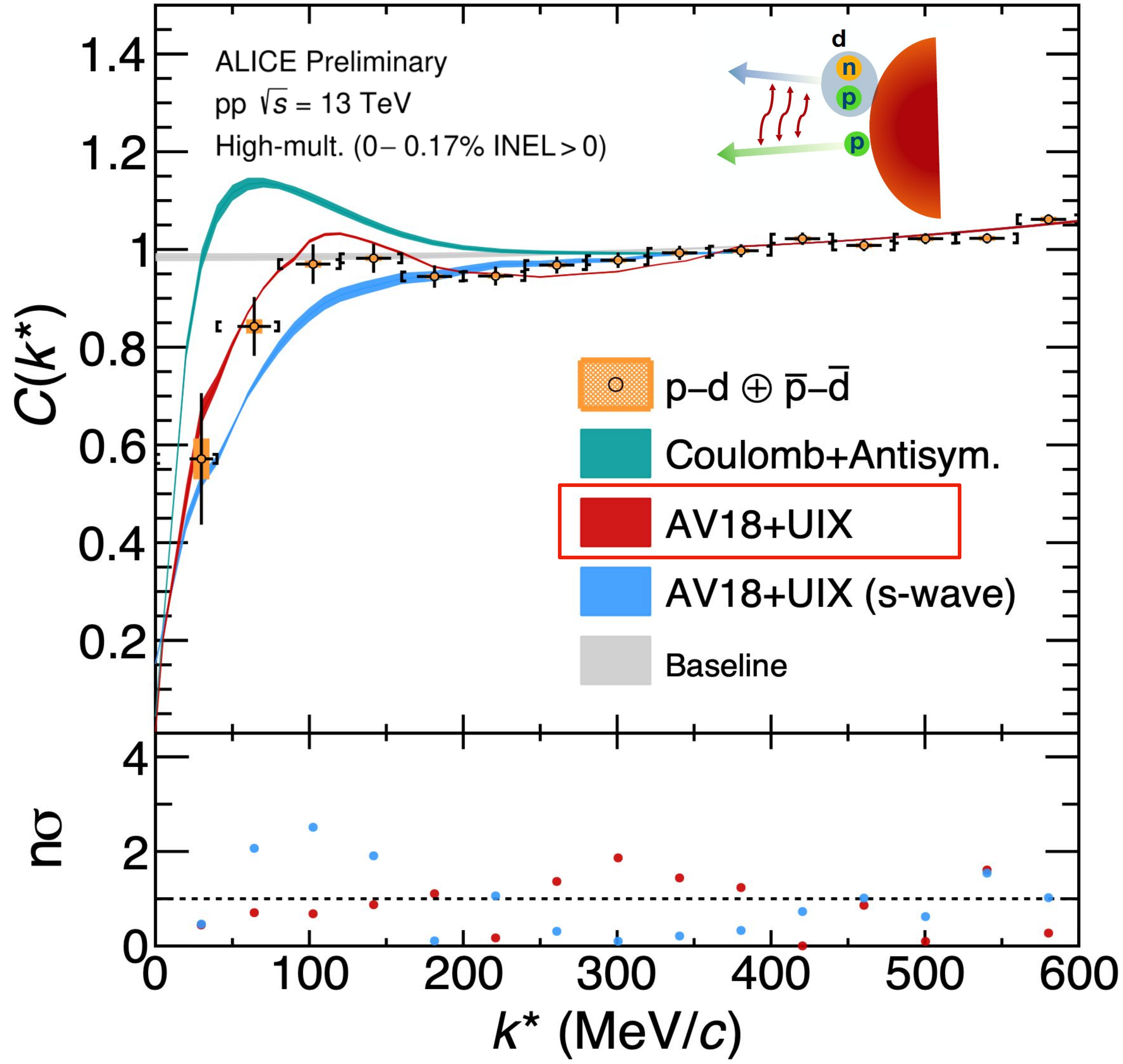
with $\phi_{m_2'}$, $\chi_{m_1'}$ the deuteron and proton wave-functions

- The correlation function is defined as

$$C_{pd}(k) = 3 \times \frac{1}{6} \sum_{m_2,m_1} \sum_{m_2',m_1'} \int d^3y S_R(y) |\psi_{m_2',m_1',m_2,m_1}(k,\boldsymbol{y})|^2 .$$



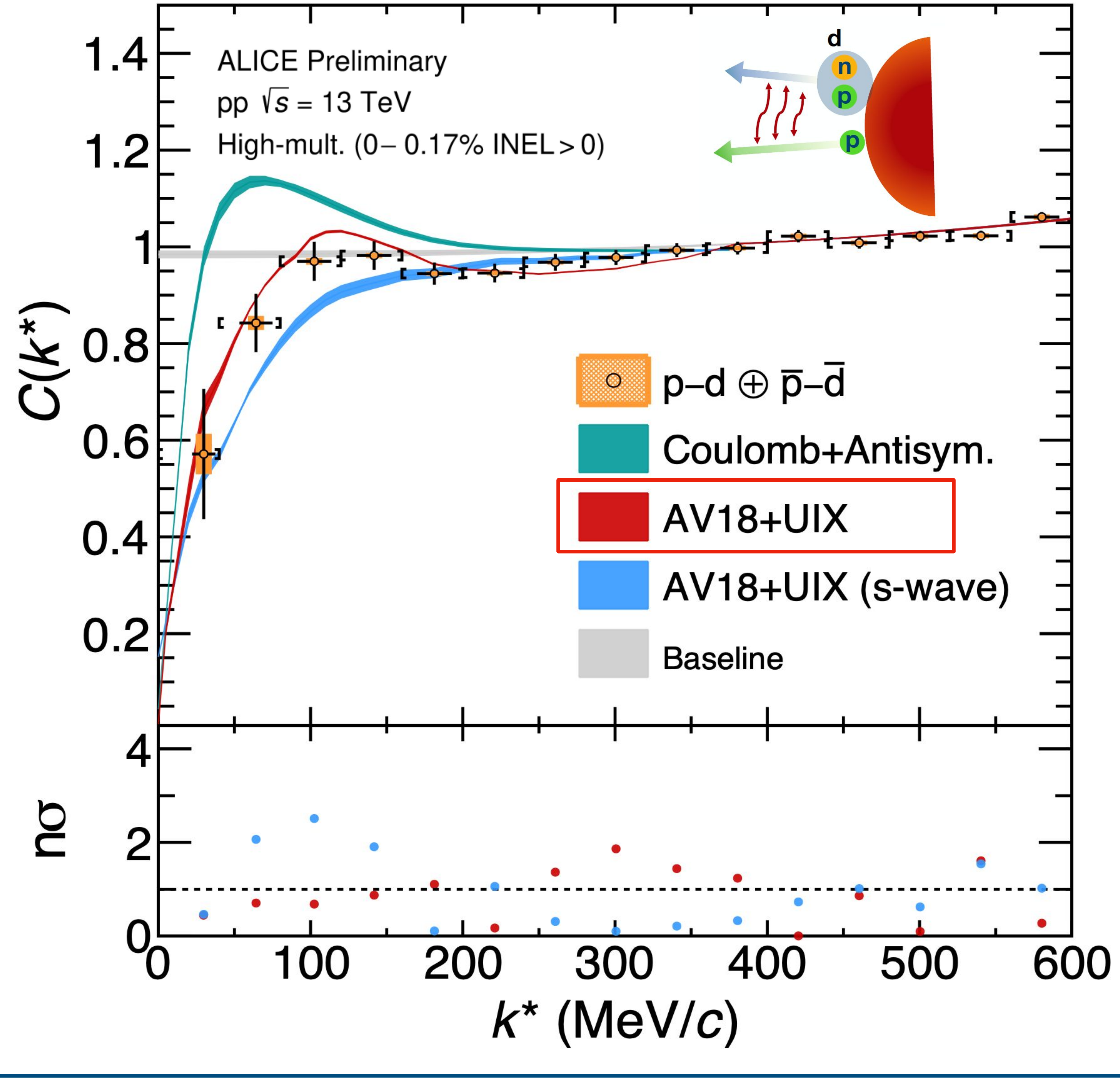
Pisa model vs ALICE data



WORK IN PROGRESS:

Preliminary Model including NN and NNN interactions in s+d-wave agrees much better with data

Pisa model vs ALICE data



WORK IN PROGRESS:

Preliminary Model including NN and NNN interactions in s+d-wave agrees much better with data

…everything seems to be "back to normal":

- **Coulomb interaction not strong enough** to describe the data
- Data **sensitive** to inclusion of **d-wave**
- Source size = 1.08±0.06 fm **⇒ fully formed deuteron present assuming small source**

Conclusions and outlook

Conclusions

Three-particle systems can be accessed and studied at the LHC in pp collisions with a novel technique

Proton-deuteron femtoscopy

➡ **Cannot be treated as effective two-body system:** assumption of pointlike and distinguishable particles does not work

➡ **Deuteron described as composite object interacting with a proton:** model considering p(pn) three-body dynamics **reproduce** the data

- Source size extracted from the 'universal' m_T scaling.
- Small distance probes short range NNN interaction
- Measured correlation function sensitive to inclusion of higher partial waves

- **More statistics = more physics:** A m_T dependent study would enable access to shorter distances for the three body system in the near future.