# New directions in the study of (hyper)nuclei formation and strong interaction in three-body systems in ALICE

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on behalf of the **ALICE Collaboration**

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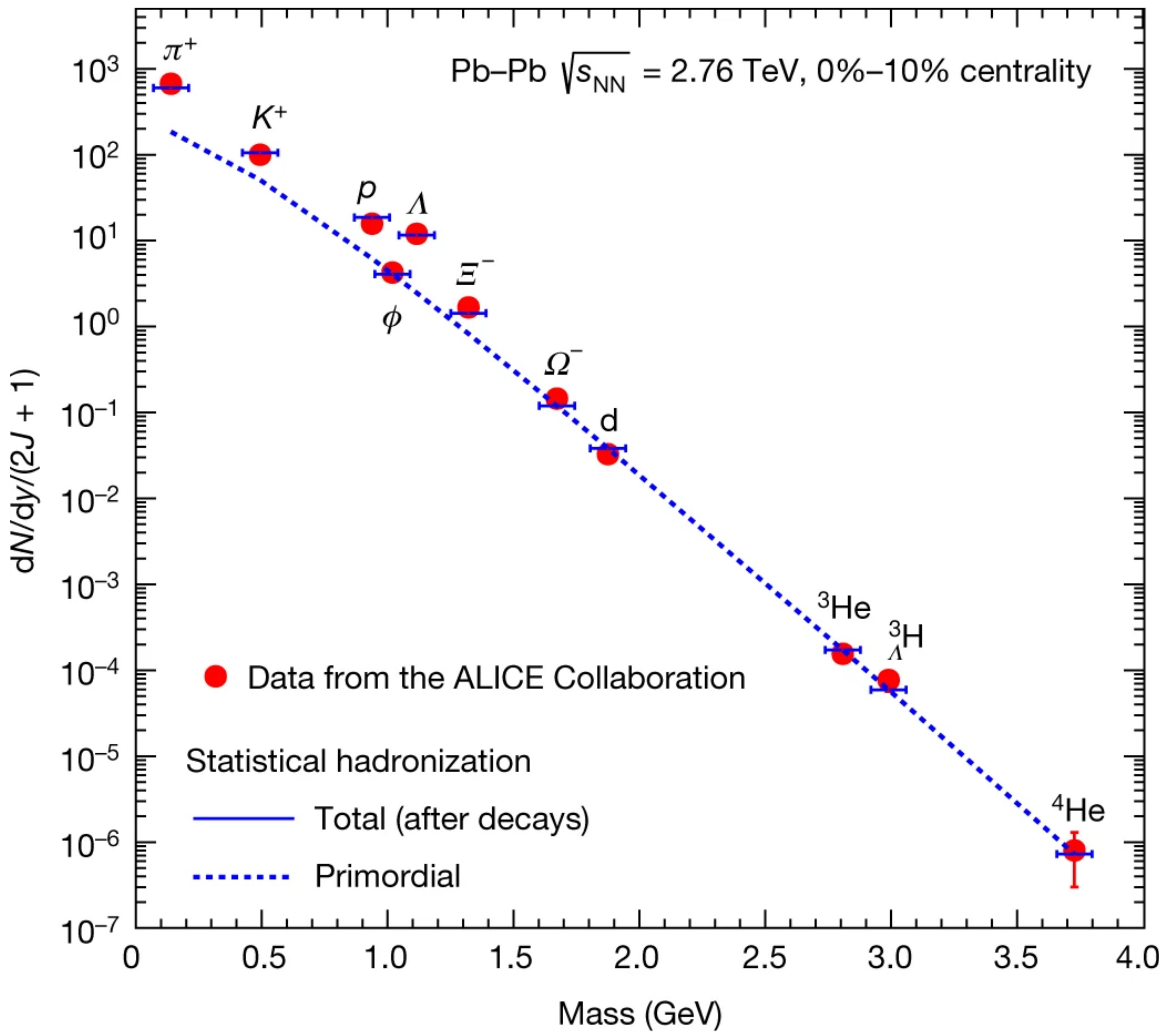
16 May, 2023

# Nucleosynthesis at the LHC

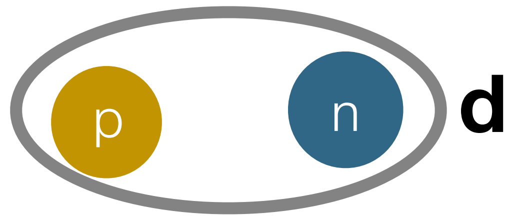
- **(Hyper)Nuclei:** unique probes to study the interactions between hadrons
    - Formation of light (hyper)nuclei occurs at extremely high temperatures (T ~ 100 MeV) at the LHC
- Production mechanism of light (hyper)nuclei not understood
    - **Statistical Hadronisation Models** (SHM): yields described by filling the available phase-space after the collision[1,2]

➡ Microscopic details are absent



[1] A. Andronic et al., Nature 561, (2018) 3210
[2] Vovchenko et al., Phys. Lett. B 785, (2018) 171

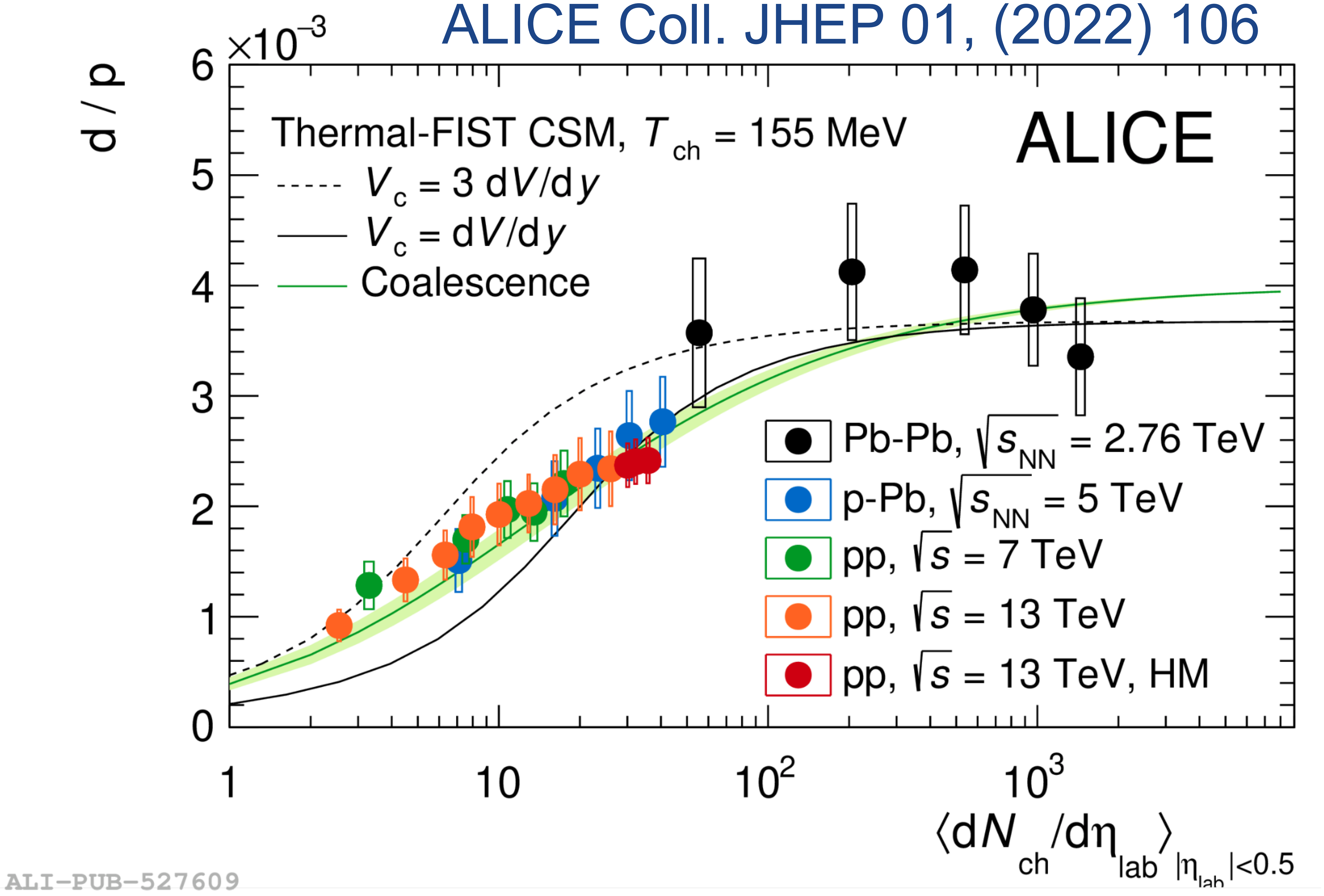
# Nucleosynthesis at the LHC



- **(Hyper)Nuclei:** unique probes to study the interactions between hadrons
  - Formation of light (hyper)nuclei occurs at extremely high temperatures (T ~ 100 MeV) at the LHC
- Production mechanism of light (hyper)nuclei not understood
  - **Coalescence**[1]: nuclei arise from the overlap of the nucleons in the phase space

    ➡ microscopic description

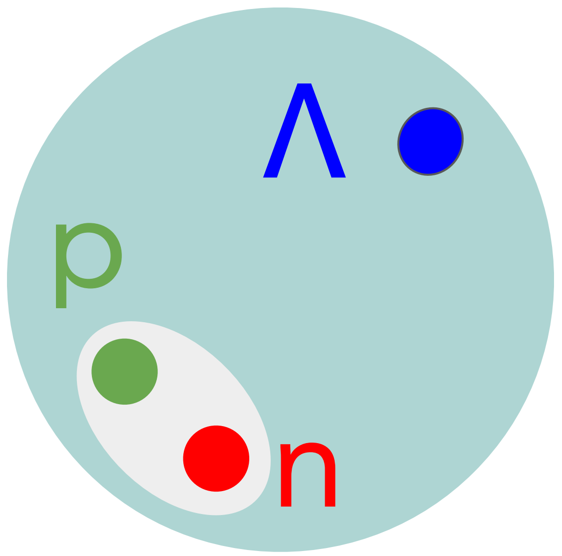
    ➡ yield predictions relative to the nucleon ones

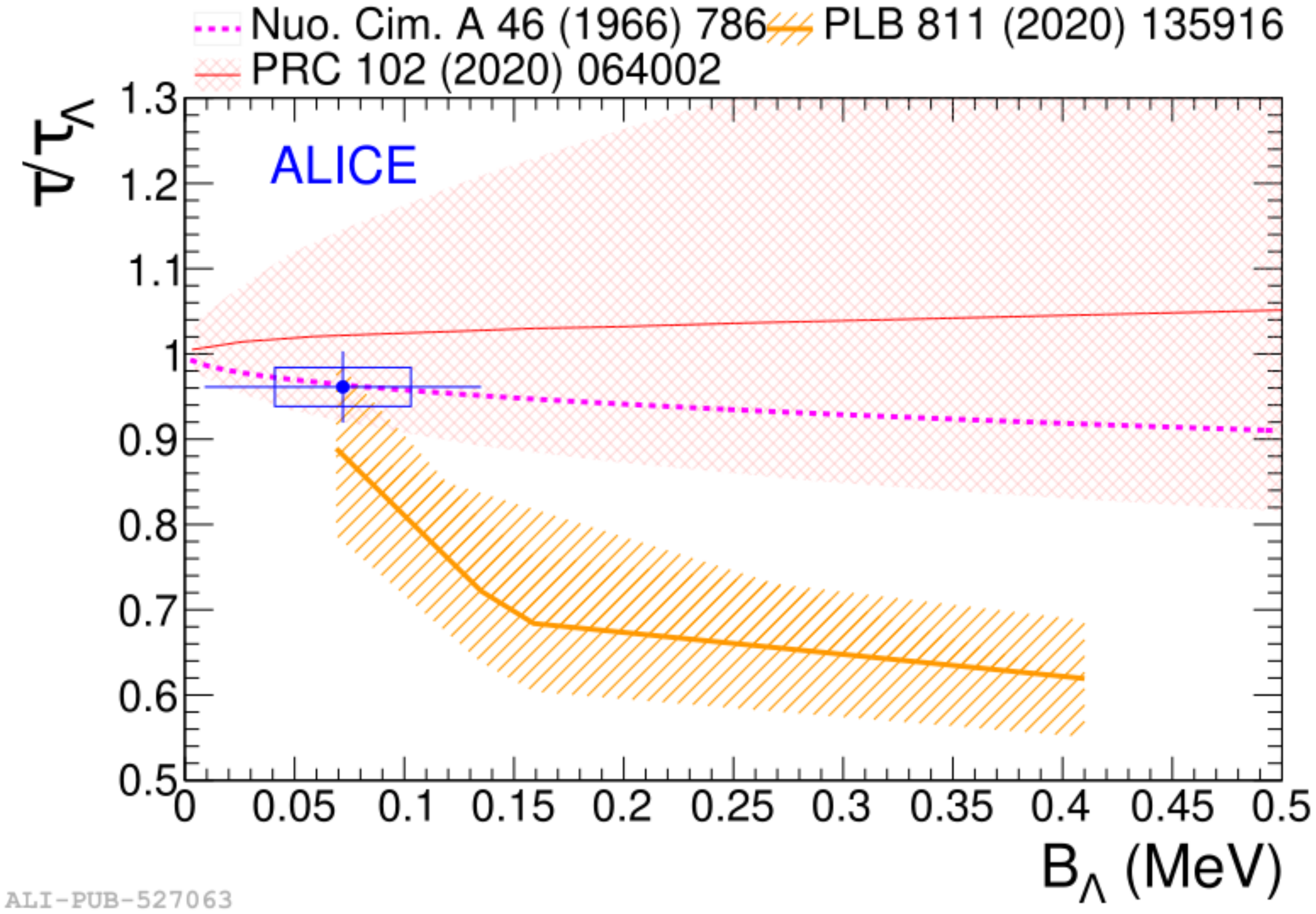

ALICE Coll. JHEP 01, (2022) 106

[1] Sun et al., Phys. Lett. B 792, (2019) 132

# $^{3}_{\Lambda}$H production

- Hypertriton ($^{3}_{\Lambda}$H): shallow bound state of a neutron, a proton and the hyperon Λ
  - Powerful probe for investigating the nucleon - Λ interaction
- Weakly bound state
  - ALICE measured with unprecedented precision the $^{3}_{\Lambda}$H lifetime and the energy required to separate the Λ from the deuteron ($B_{\Lambda}$)[1]
  - Low $B_{\Lambda}$ of ~ 100 keV corresponds to a **large radius of ~ 5 fm**[2]





ALI-PUB-527063

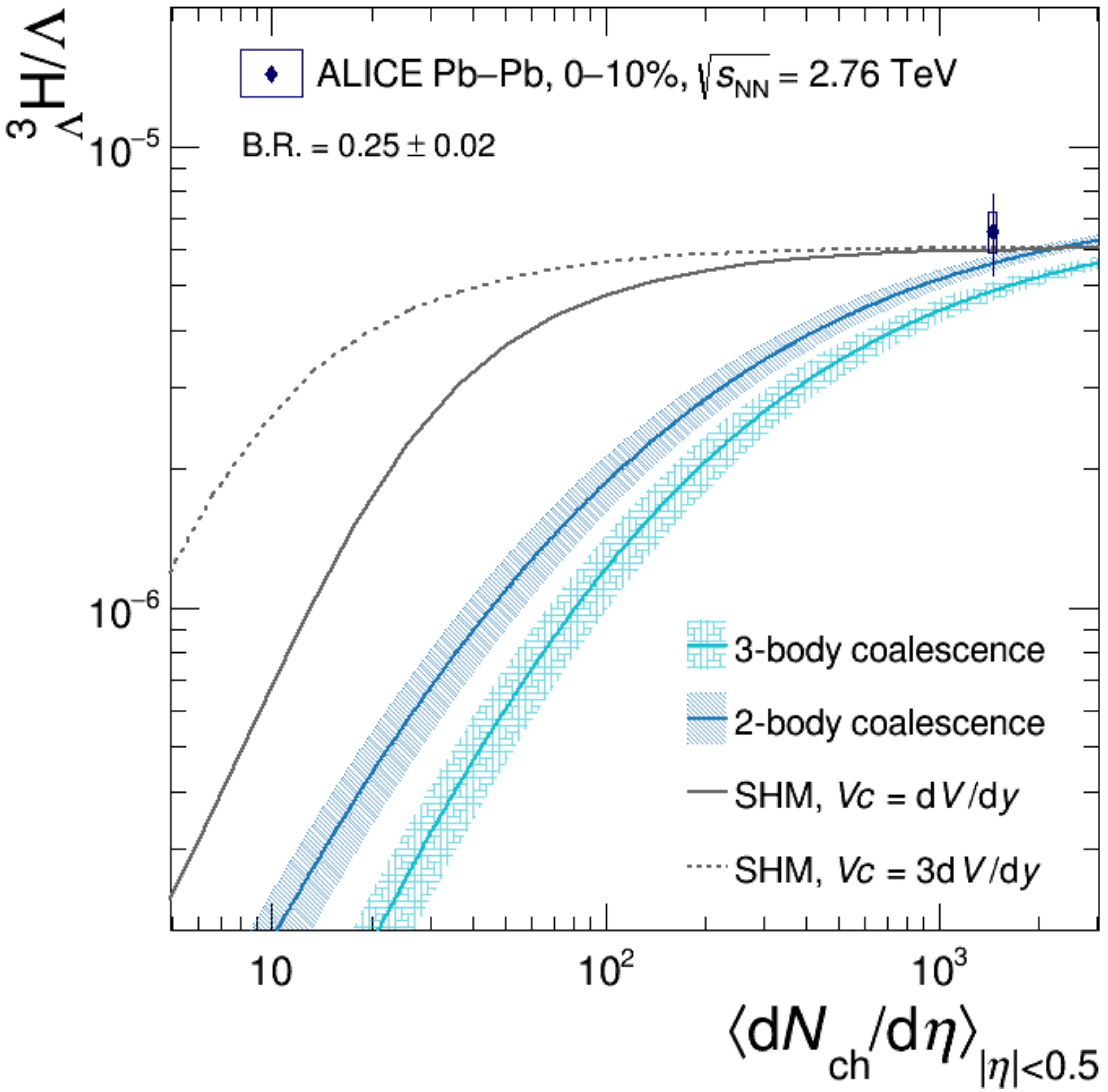
**Can shallow binding energy affect the production?**

[1] arXiv:2209.07360

[2] *Hildenbrand et al.*, Phys. Rev. C, 100(3), 034002 (2019)

# $^{3}_{\Lambda}$H production

- Weakly bound state ($B_{\Lambda}$ ~ 100 keV)
- Yield ratio $^{3}_{\Lambda}$H/Λ
  - ➡ Large separation between **SHM**[1] and **coalescence**[2] predictions at low charged-particle multiplicity density
  - ➡ Coalescence is sensitive to the interplay between the size of the collision system and the spatial extension of the nucleus wave function



[1] *Vovchenko, et al.*, Phys. Lett., B 785, 171-174, (2018)
[2] *Sun. et al.*, Phys. Lett. B 792, 132–137, (2019)
[3] Phys. Lett. B 754, 360–372, (2016)

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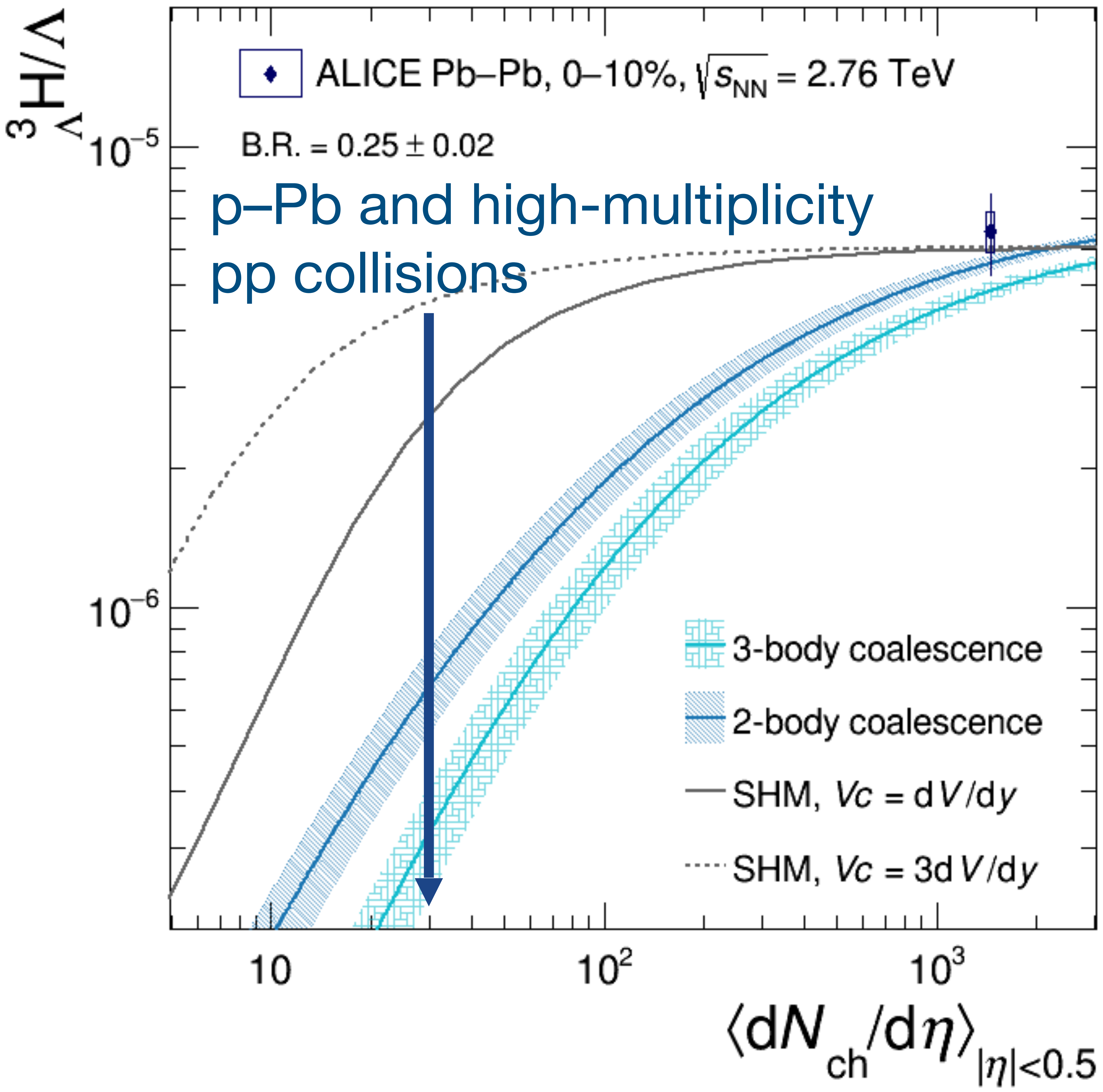
- $^{3}_{\Lambda}$H production in pp and p–Pb: a key to understand the nuclear production mechanism at the LHC

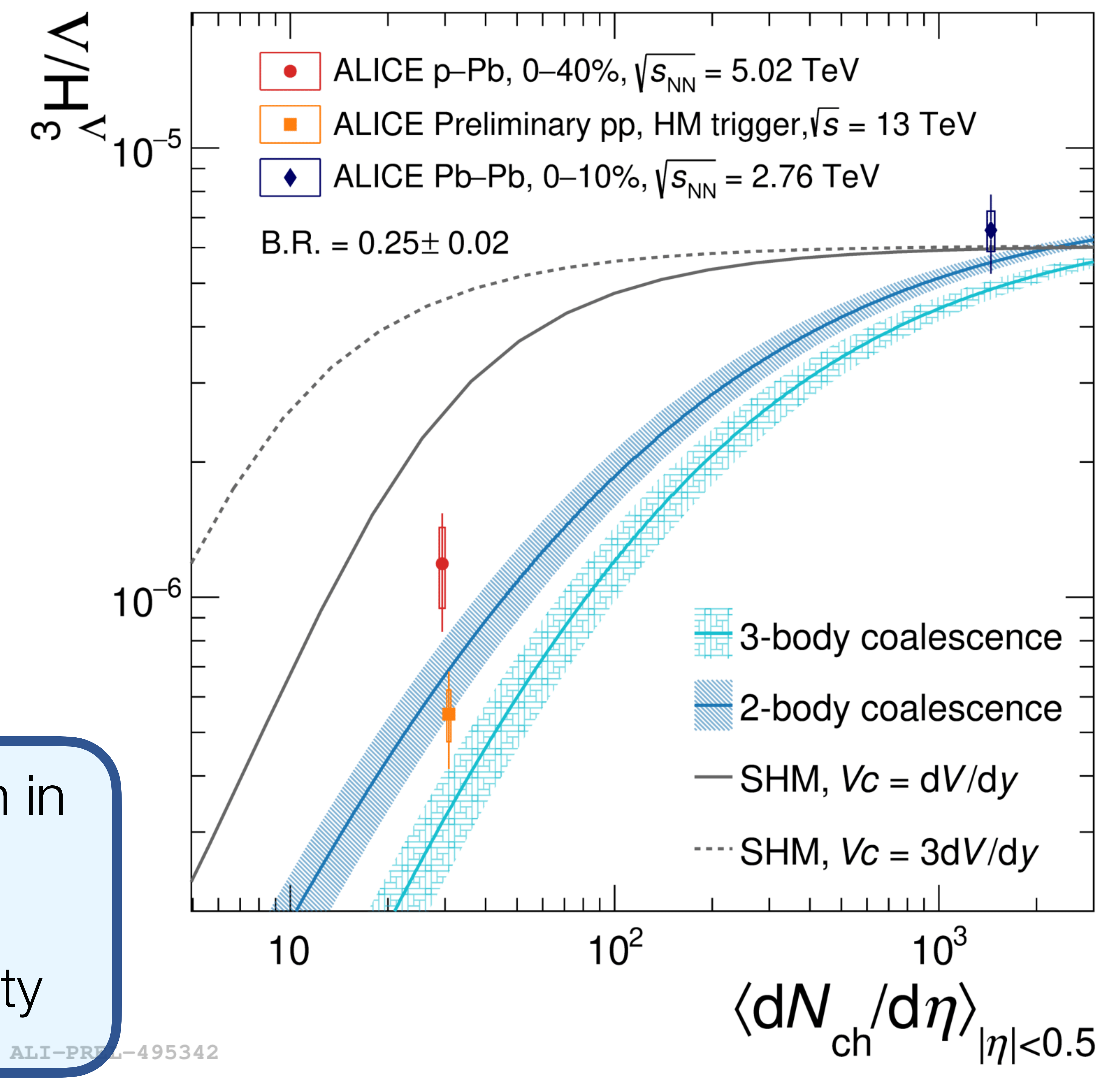


# $^{3}_{\Lambda}$H/Λ in pp and p–Pb collisions

- First measurements of $^{3}_{\Lambda}$H production in pp and p–Pb collisions
  - Good agreement with 2-body coalescence
  - Tension with SHM at low charged-particle multiplicity density
  - $V_C$ = 3 dV/dy excluded: deviation > 6σ
  - First significant constraint to SHM possible configurations

Coalescence quantitatively describes the $^{3}_{\Lambda}$H suppression in small systems

The nuclear size matters at low charged-particle multiplicity



Phys. Rev. Lett. 128, (2022) 252003

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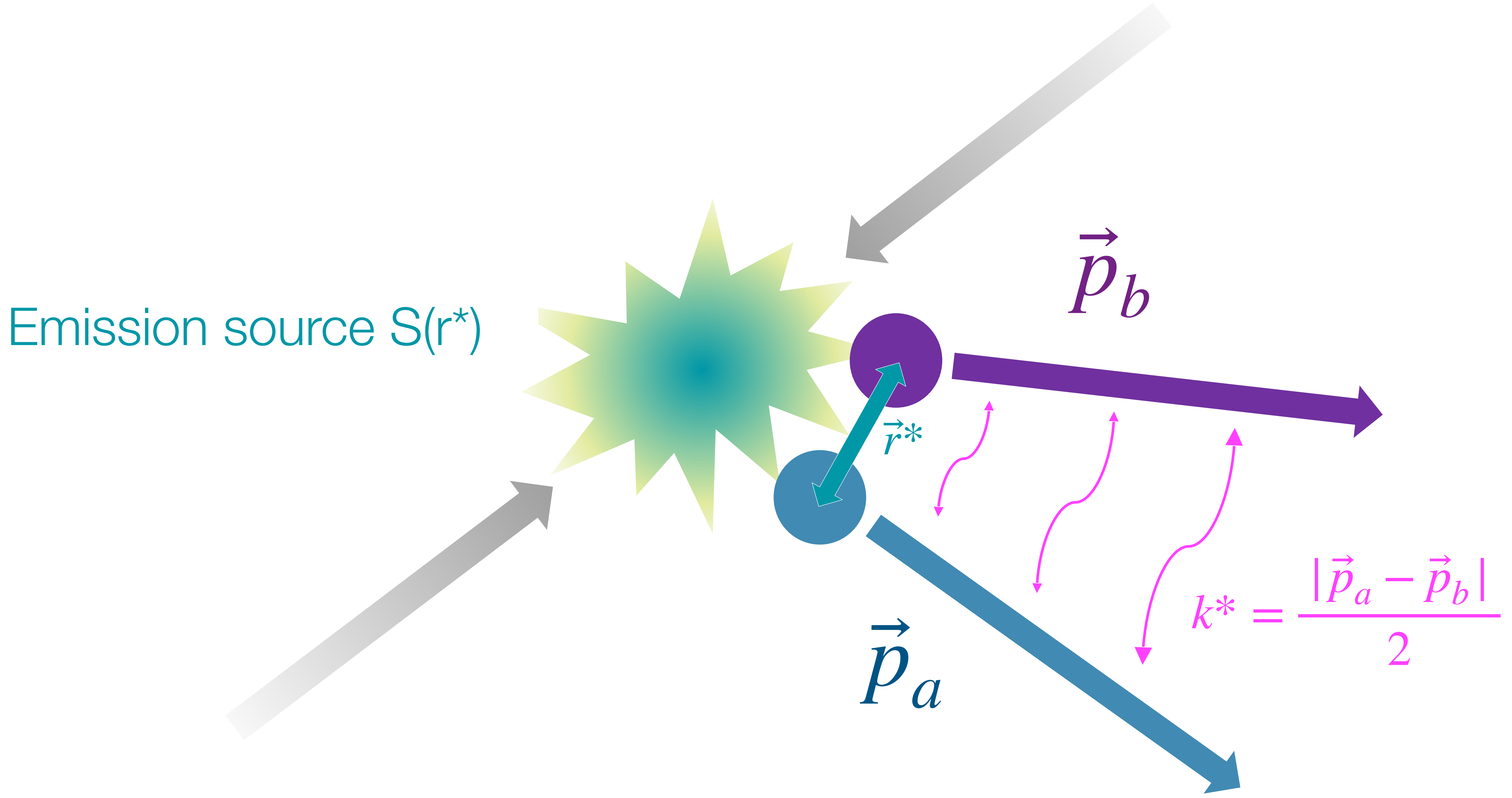
# Femtoscopy: a new era to study interaction in three-body sytems

# Femtoscopy

- **Main observable:** correlation in the relative momentum *k** of a particle pair
  - Emitting source: ~ 1 fm (Gaussian profile)
  - Two-particle relative wave function: expresses the interaction between particles



- Study the emission source if the interaction among the particle pair is known
- Or study the interaction among the particles if emission source is known

## Koonin-Pratt Equation

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

*CATS Framework: D. Mihaylov et al., EPJ. C78 (2018) 394*
*S.E. Koonin PLB 70 43 (1977)*

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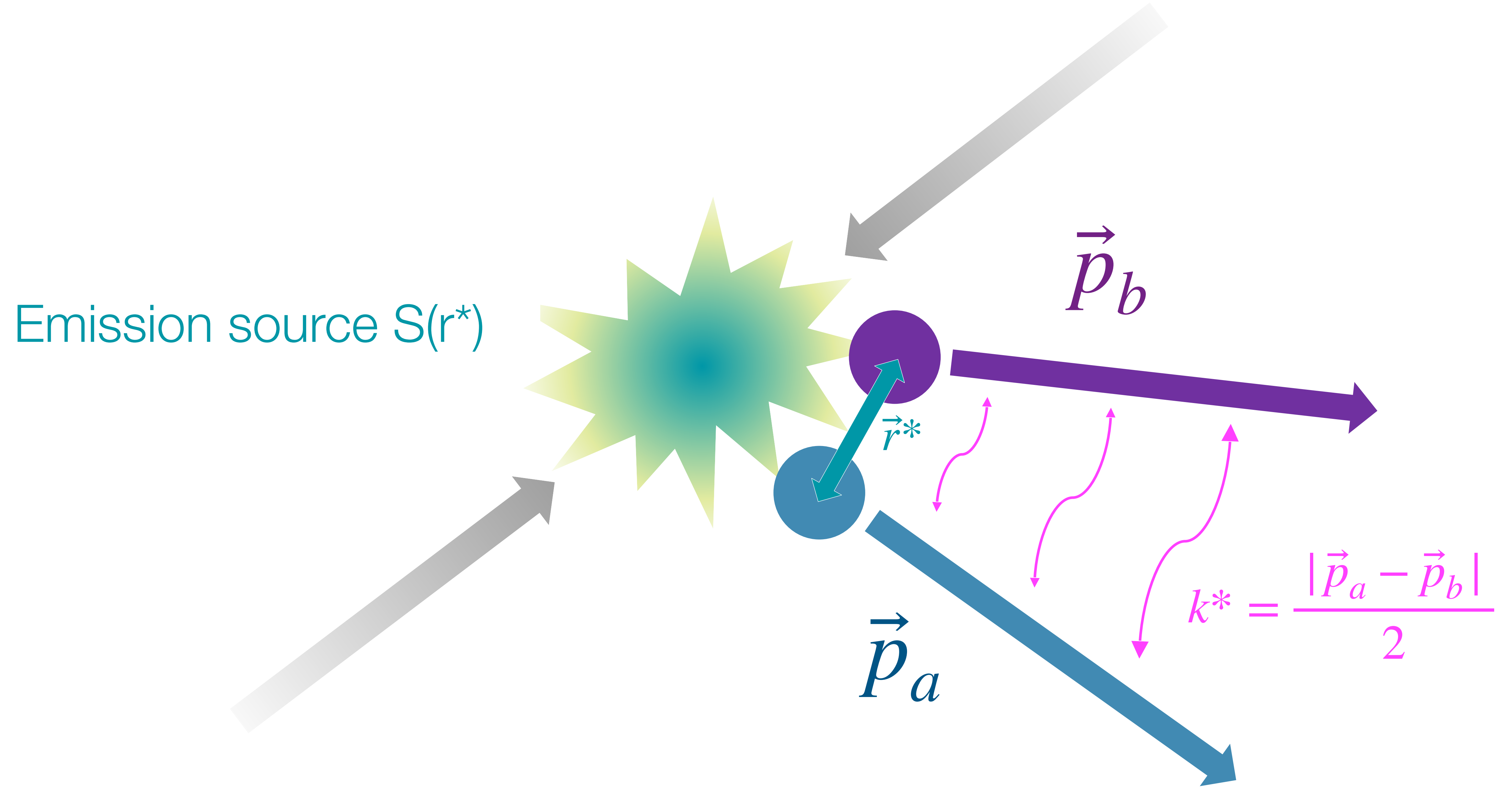
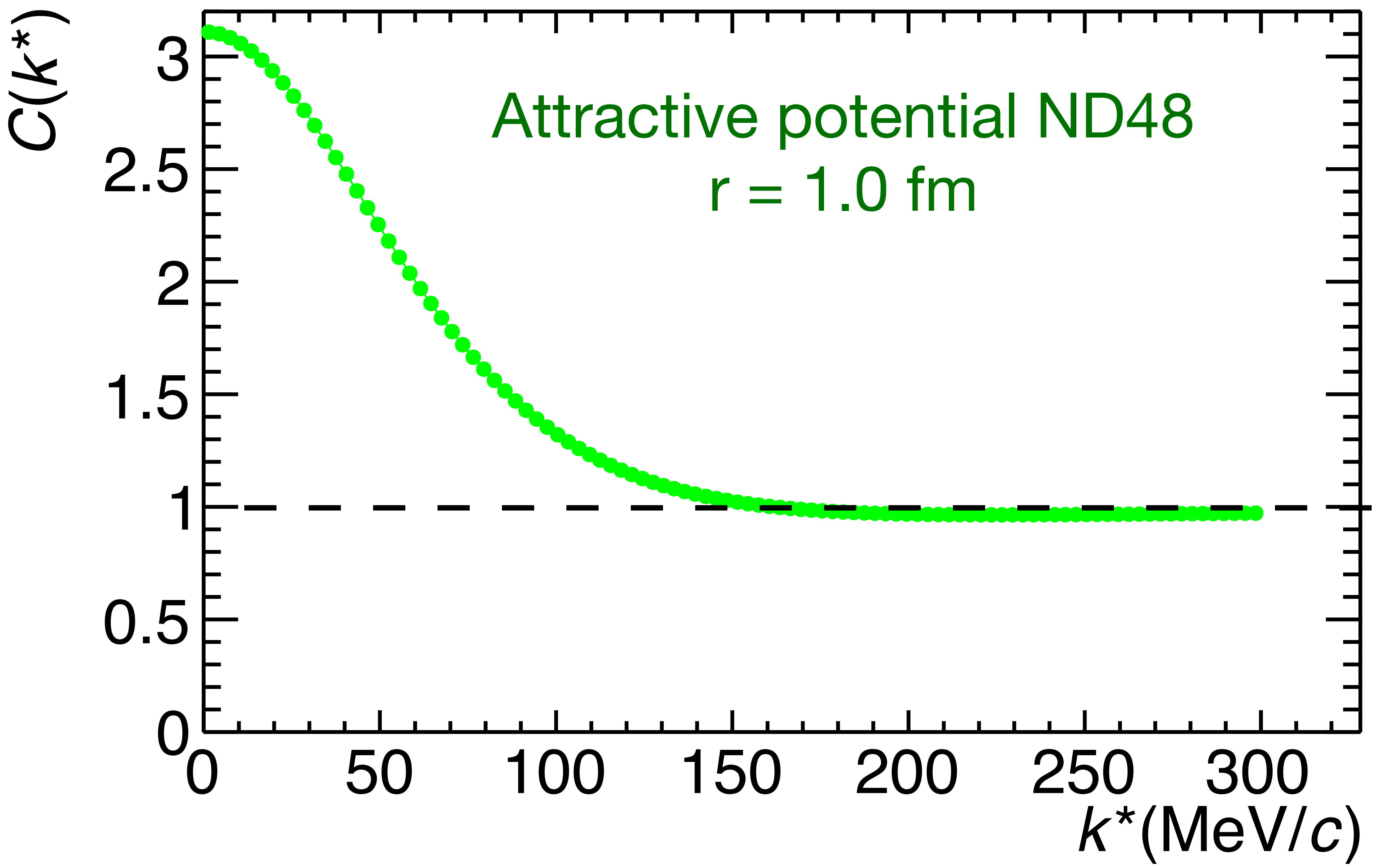
# Femtoscopy

- Correlation rises above 1 for attractive potentials





## Koonin-Pratt Equation

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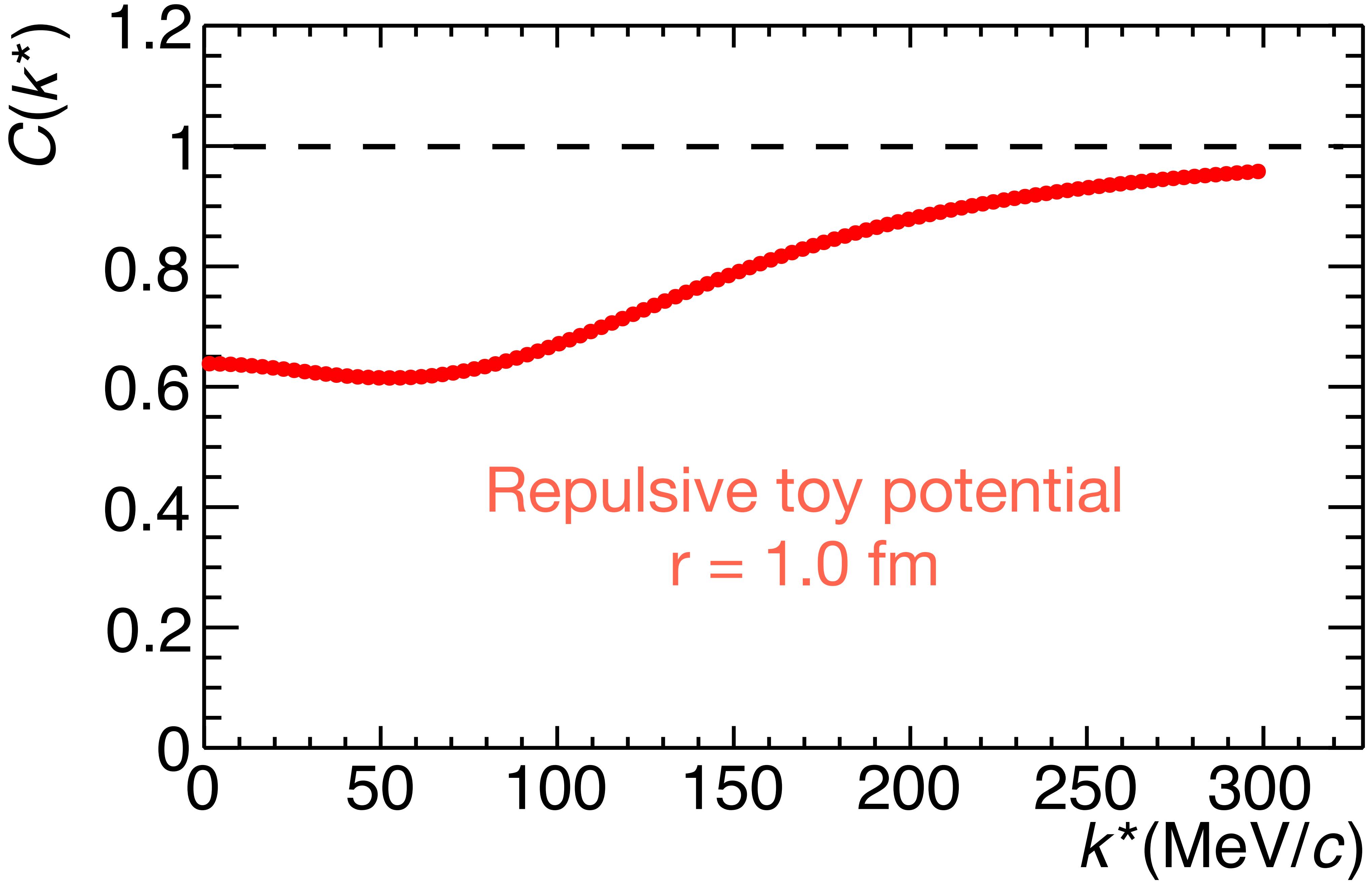
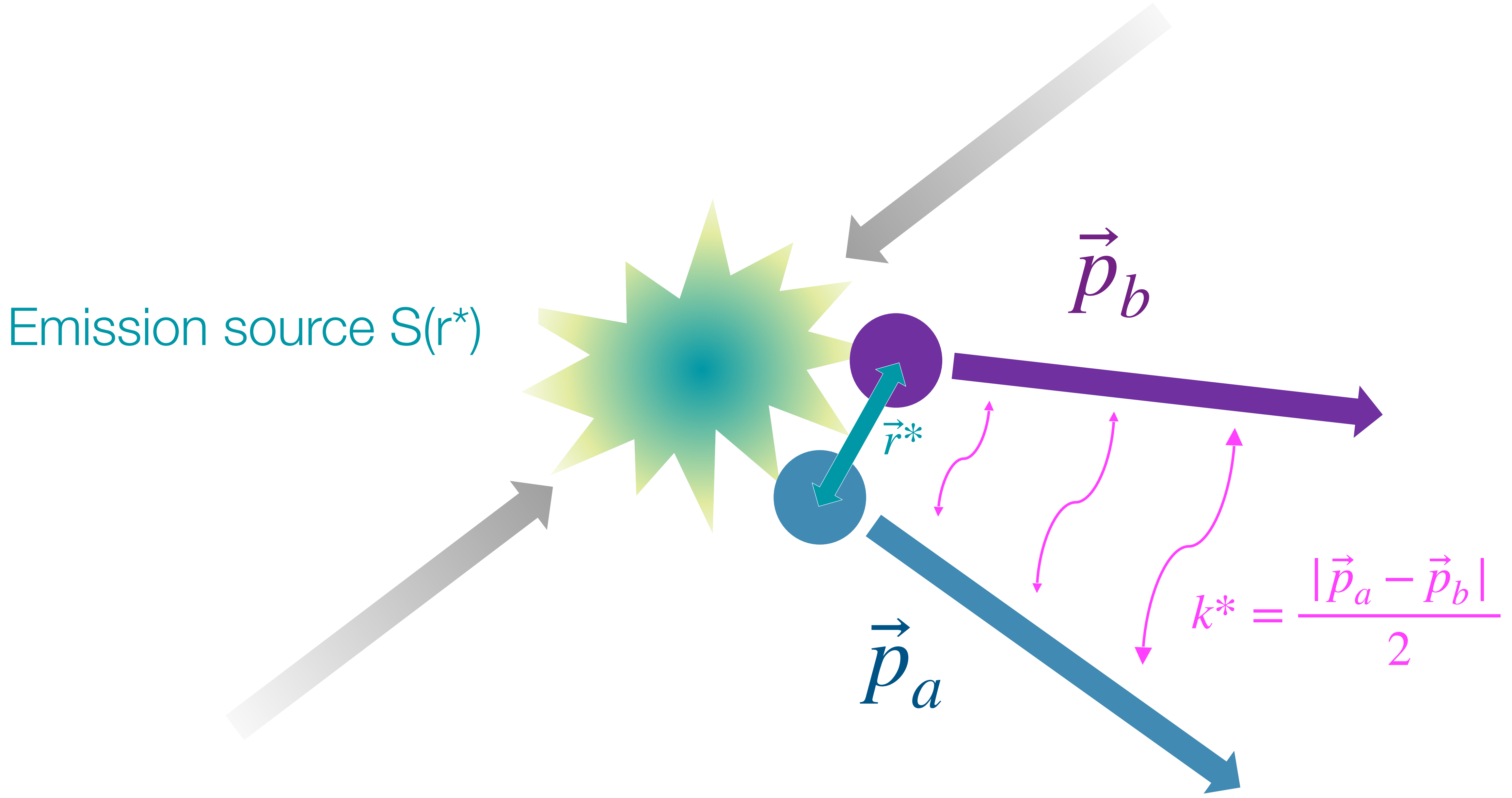
*S.E. Koonin PLB 70 43 (1977)*

# Femtoscopy

- Repulsive interaction brings correlation below 1





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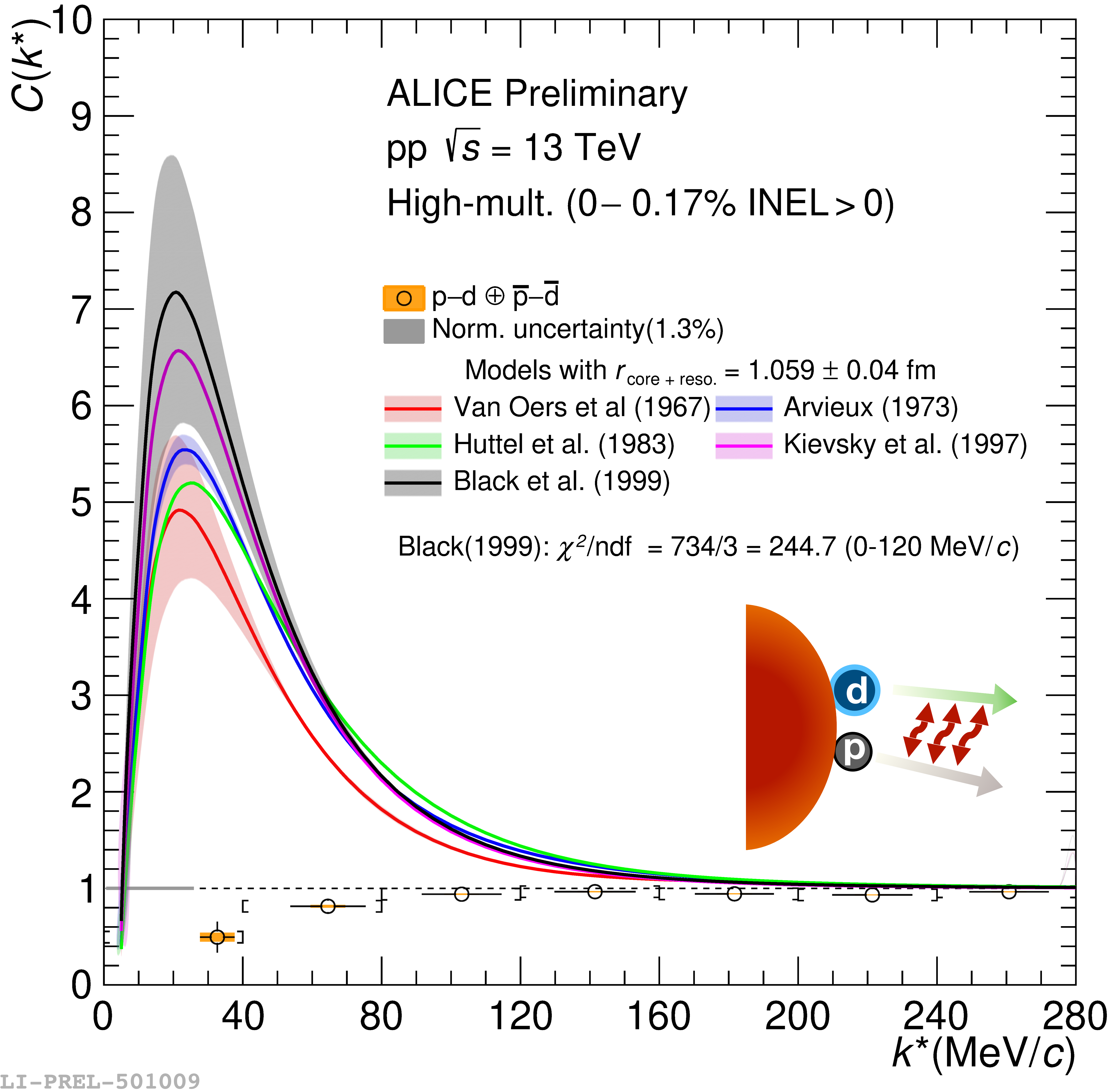
*CATS Framework: D. Mihaylov et al., EPJ. C78 (2018) 394*
*S.E. Koonin PLB 70 43 (1977)*

# proton-deuteron correlation in pp collisions



ALI-PREL-501009

$$r_{\text{eff}}^{\text{pd}} = 1.08^{+0.06}_{-0.06}\ \text{fm}$$

- Data are not described by the two-body calculations
  - p–d can't be treated as effective two-body system
  - Short-range interaction must be treated properly

Sensitivity to the dynamics of the three-body p-(p-n) system

*Van Oers,Brockmann et al. Nucl. Phys. A 561-583 (1967)*
*J.Arvieux et al. Nucl. Phys. A 221 253-268 (1973)*
*E.Huttel et al. Nucl. Phys. A 406 443-455 (1983)*
*A.Kievsky et al. PLB 406 292-296 (1997)*
*T.C.Black et al. PLB 471 103-107 (1999)*

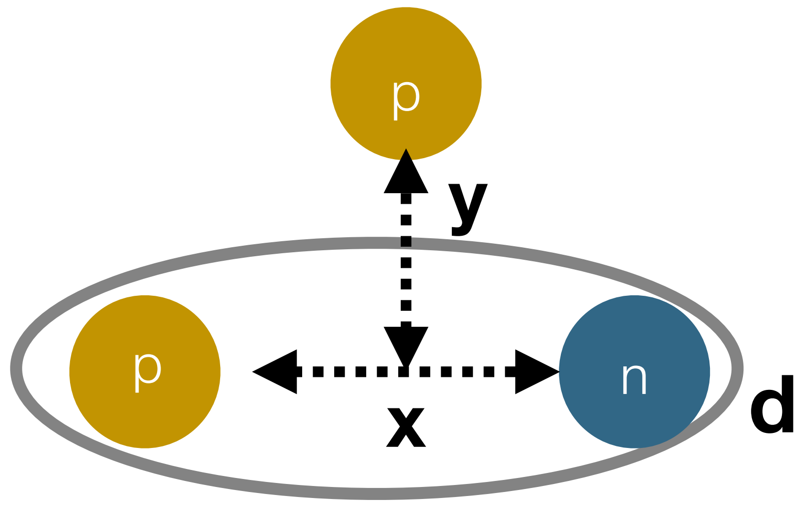
# Pisa model: p-d as three-body system

- **Starting with the p-p-n state that goes into p-d state**:
  - Nucleons with the Gaussian sources distributions

Single-particle Gaussian emission source

$$A_d C_{pd}(k) = \frac{1}{6}\sum_{m_2,m_1}\int d^3r_1 d^3r_2 d^3r_3\, S_1(r_1)S_1(r_2)S_1(r_3)|\Psi_{m_2,m_1}|^2 ,$$

- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state



Calculation done by PISA theory group: Michele Viviani, Alejandro Kievsky and Laura Marcucci

Mrówczyński et al *Eur. Phys. J. Special Topics 229, 3559 (2020)*

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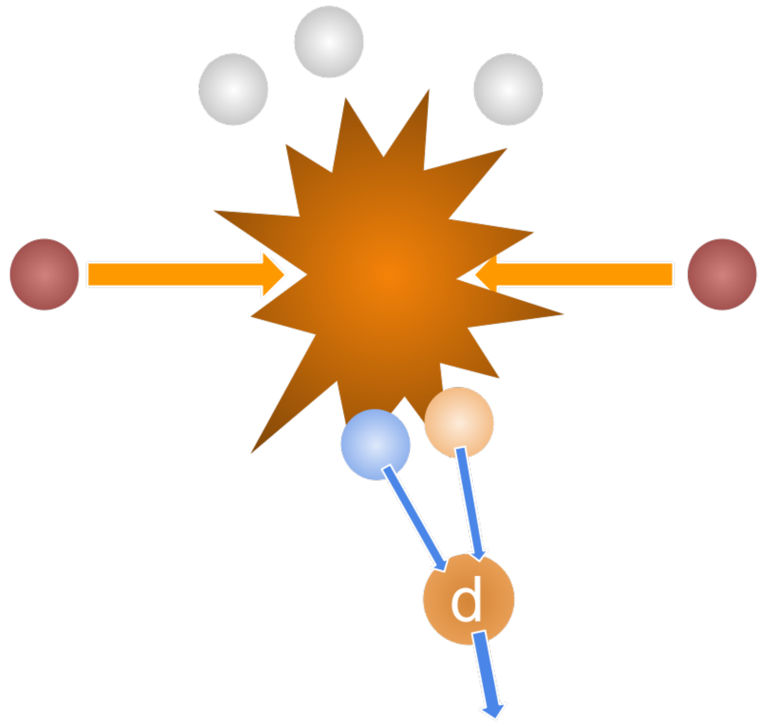
- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state
- $A_d$ is the deuteron formation probability using deuteron wavefunction



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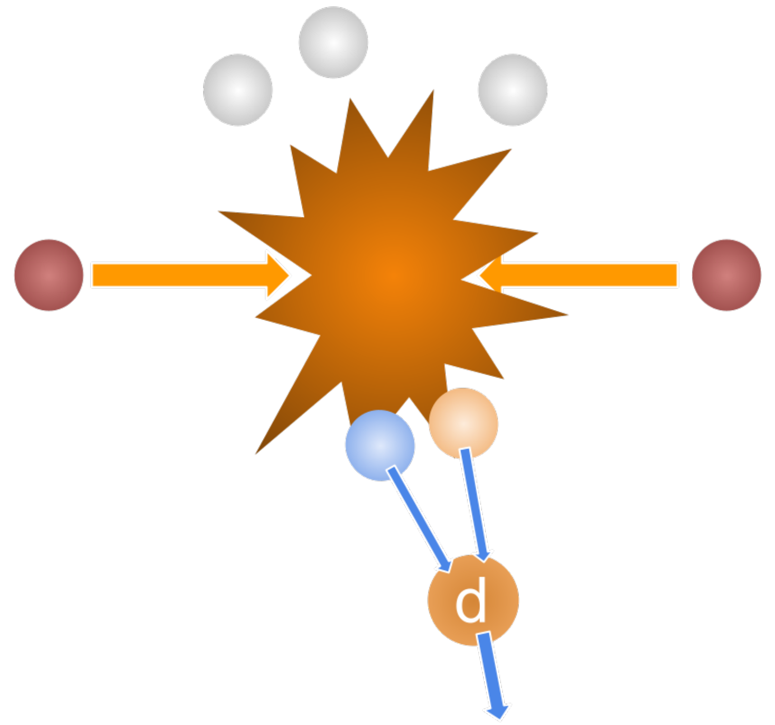
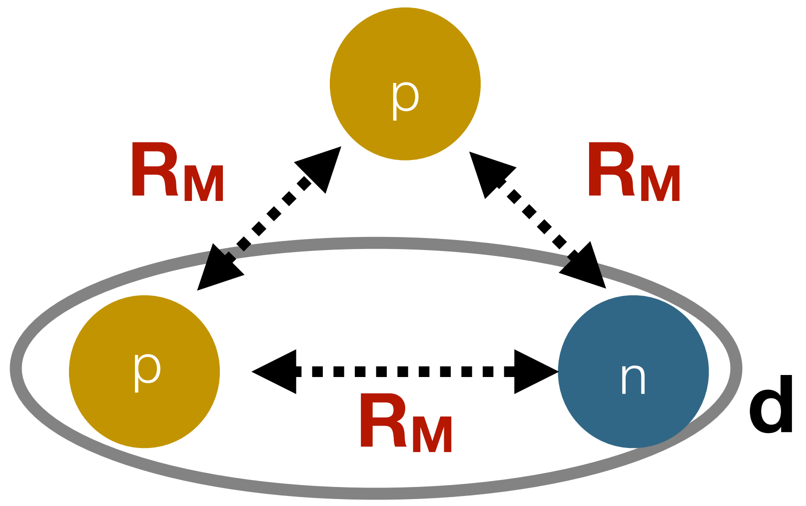
- $\Psi_{m_2,m_1}(x,y)$ three-nucleon wave function asymptotically behaves as p–d state
- $A_d$ is the deuteron formation probability using deuteron wavefunction
- Final definition of the correlation with p–p source size $R_M$ :



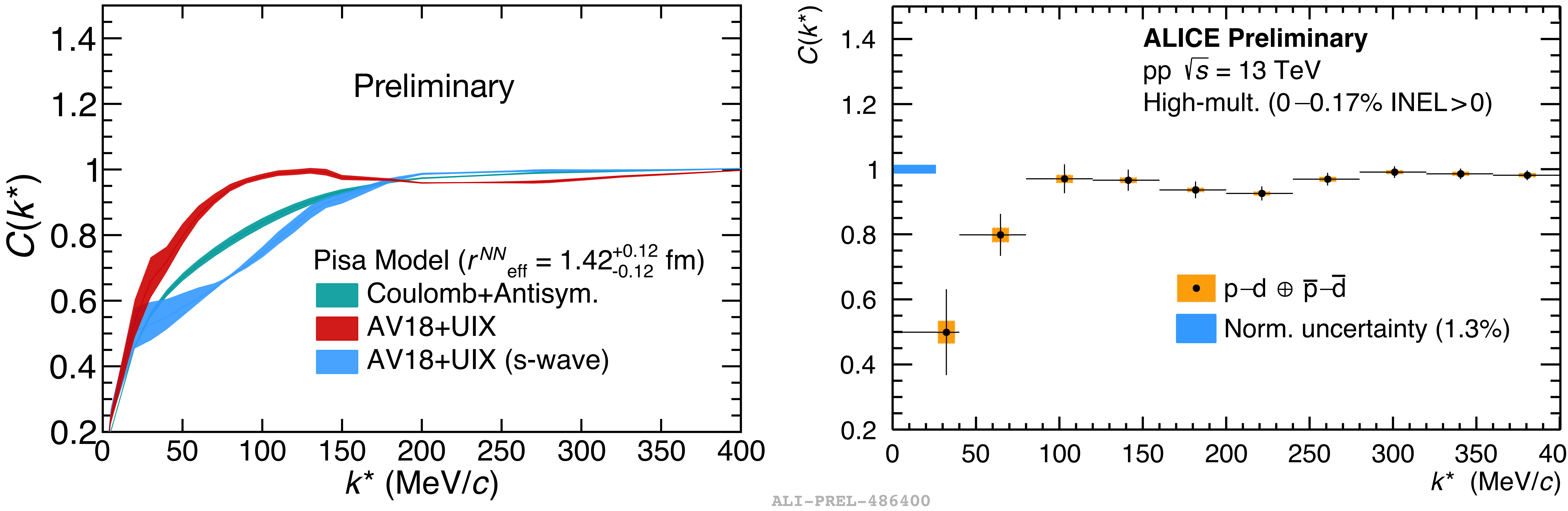
$$A_d C_{pd}(k) = \frac{1}{6}\sum_{m_2,m_1}\int \rho^5 d\rho d\Omega\, \frac{e^{-\rho^2/4R_M^2}}{(4\pi R_M^2)^3}|\Psi_{m_2,m_1}|^2 .$$



Mrówczyński et al *Eur. Phys. J. Special Topics 229, 3559 (2020)*

# Pisa model: theoretical p-d correlation

Calculation done by PISA theory group: Michele Viviani, Alejandro Kievsky and Laura Marcucci

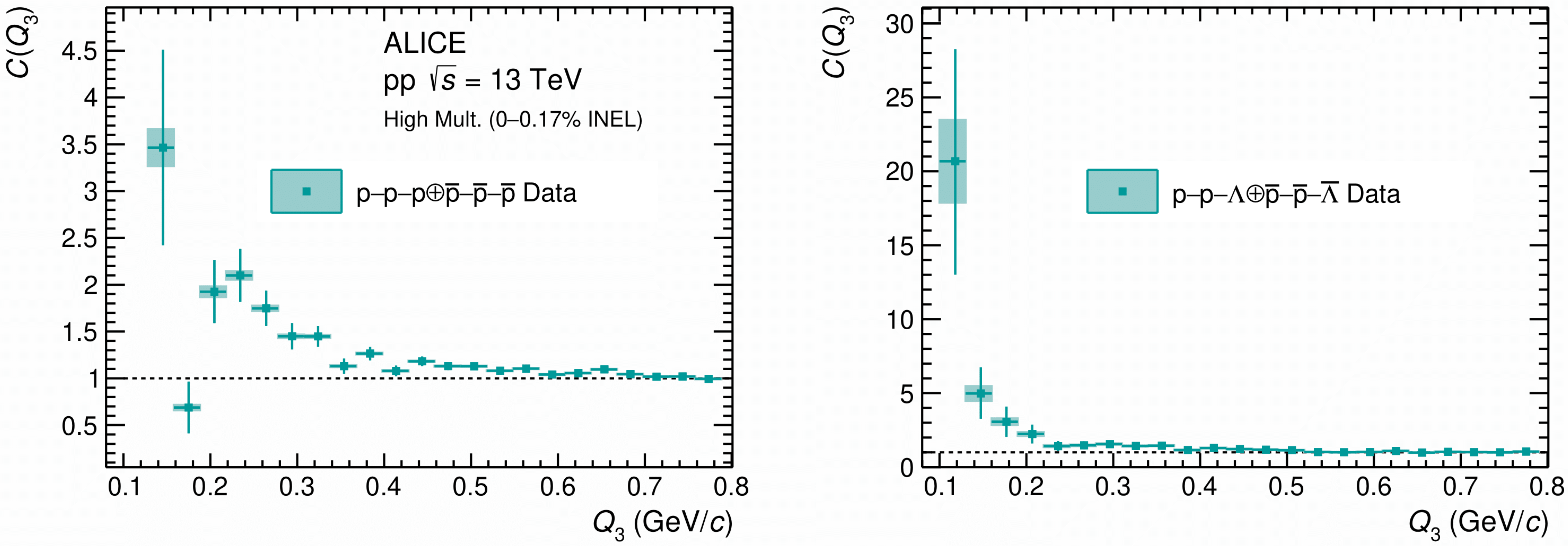


- ➡ **Model calculation qualitatively reproduces the data**
- ➡ **The p-d correlation is affected by two + three-body p-p-n interactions!**

# Three-body femtoscopy with ALICE

- Extending femtoscopy to three-particle correlations: p-p-p and p-p-Λ[1]
- New way to study interaction in hadron-triplets

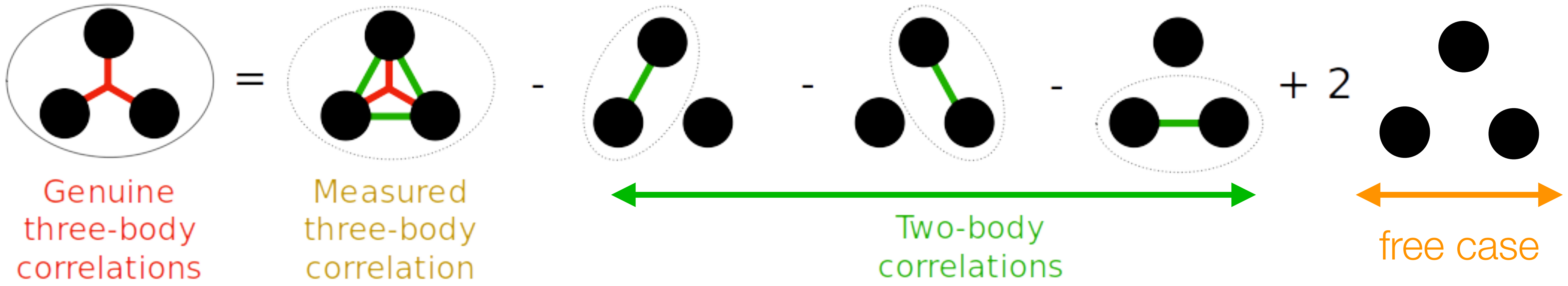
$$C(\mathbf{p_1},\mathbf{p_2},\mathbf{p_3}) = \frac{P(\mathbf{p_1},\mathbf{p_2},\mathbf{p_3})}{P(\mathbf{p_1})P(\mathbf{p_2})P(\mathbf{p_3})} = N\frac{N_{same}(Q_3)}{N_{mixed}(Q_3)} \qquad Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$



How to interpret the results? Interplay between 2-body and 3-body forces

[1] arXiv:2206.03344

# Steps to genuine three-body interaction



Genuine three-body correlations

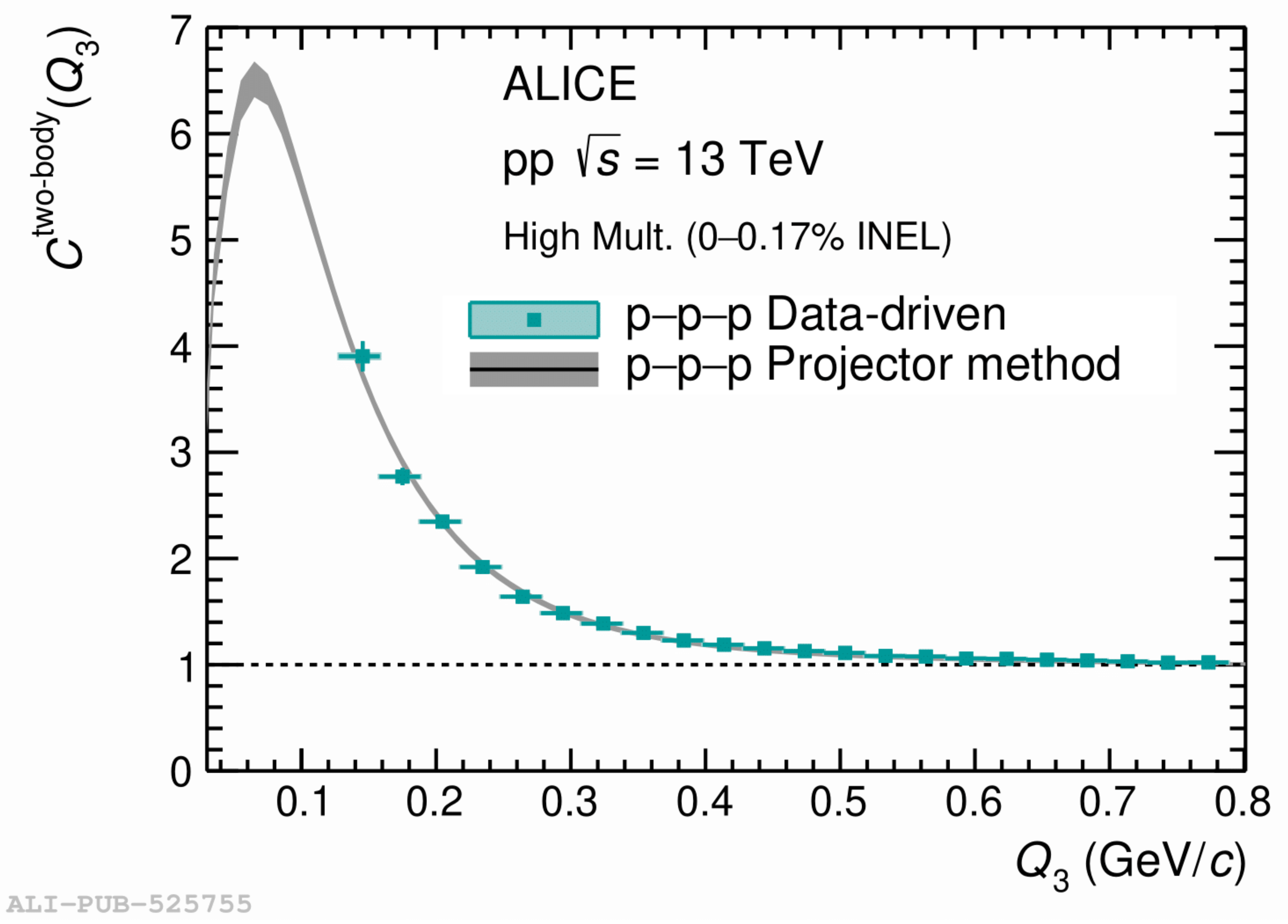
Measured three-body correlation

Two-body correlations

free case

Kubo, J. Phys. Soc. Jpn. 177 (1962)

- First study underlying two body correlations with a data driven and a phase-space projector methods



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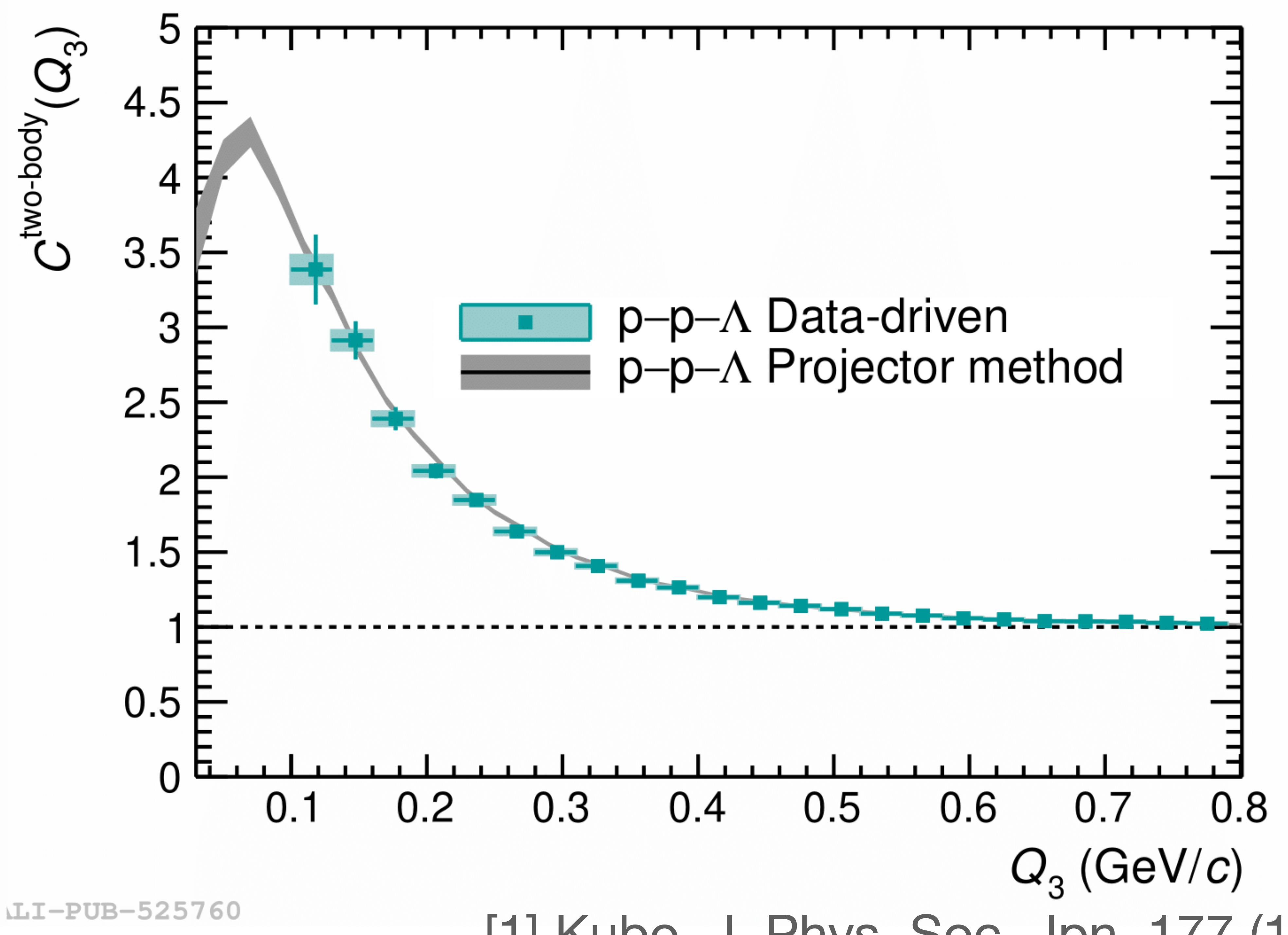
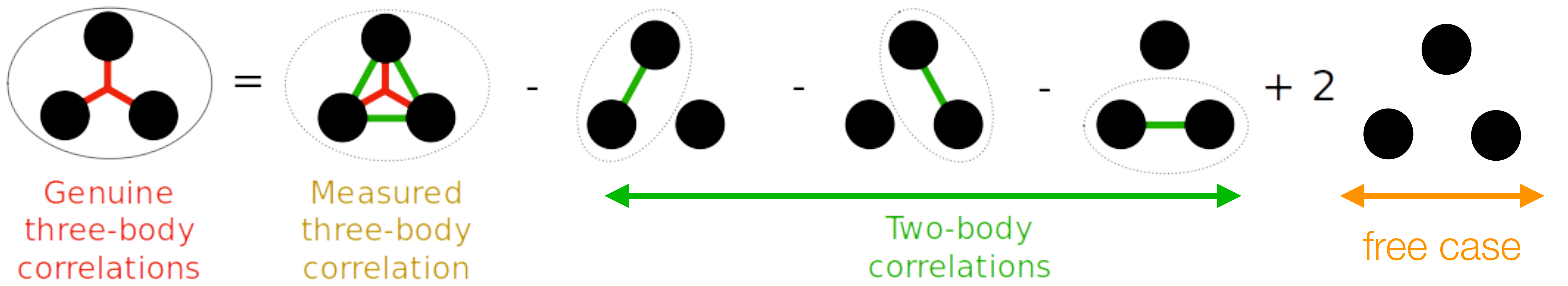


ALI-PUB-525760

[1] Kubo, J. Phys. Soc. Jpn. 177 (1962)
[2] arXiv:2206.03344
[3] R. Del Grande et al. EPJC 82 (2022)

# Cumulant: measure for three-body effects

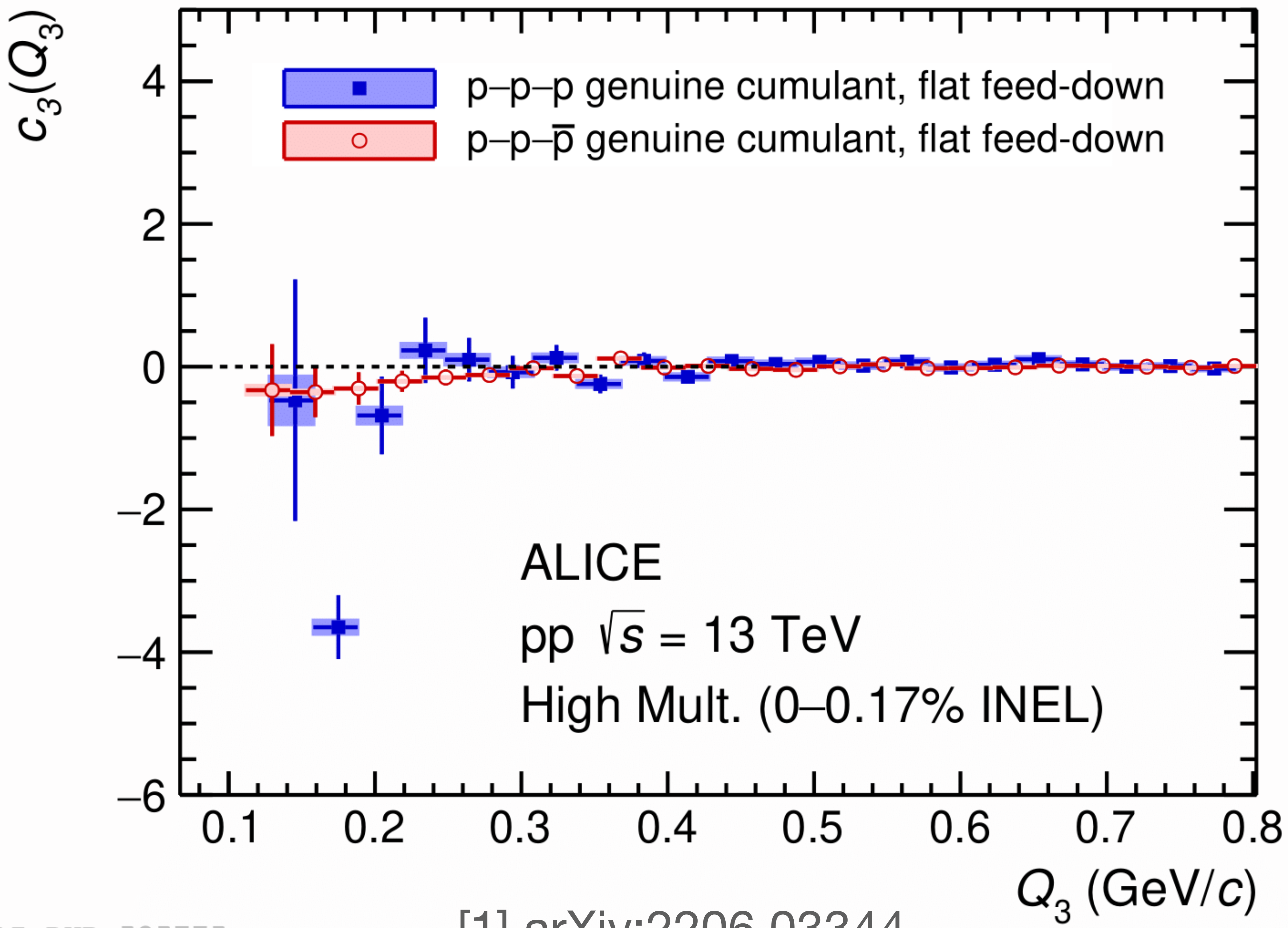
$c_3$ ($Q_3$)



Kubo, J. Phys. Soc. Jpn. 177 (1962)

$c_3$ ($Q_3$) allows to isolate effects associated with the genuine three-body interactions

- p-p-p and p-p-p̄ cumulants : nonzero
  - Hint of a genuine three-body effect
- Possible interpretations:
  - Pauli blocking at three-particle level
  - Three-body strong interaction



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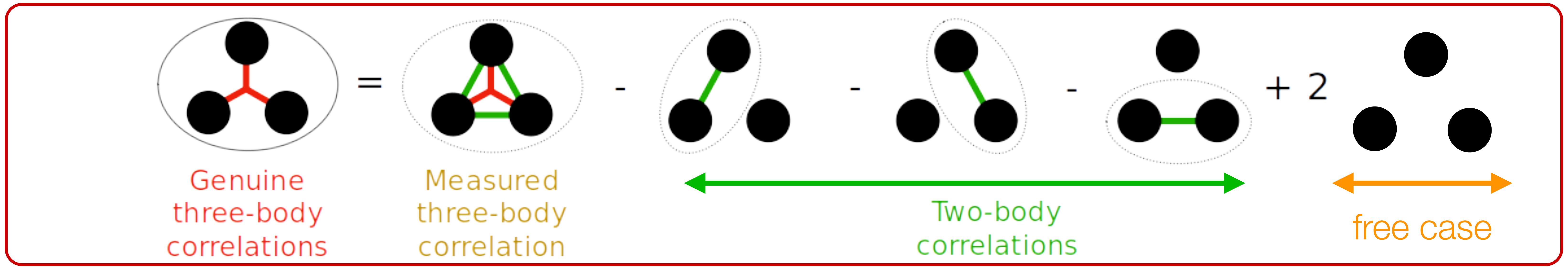
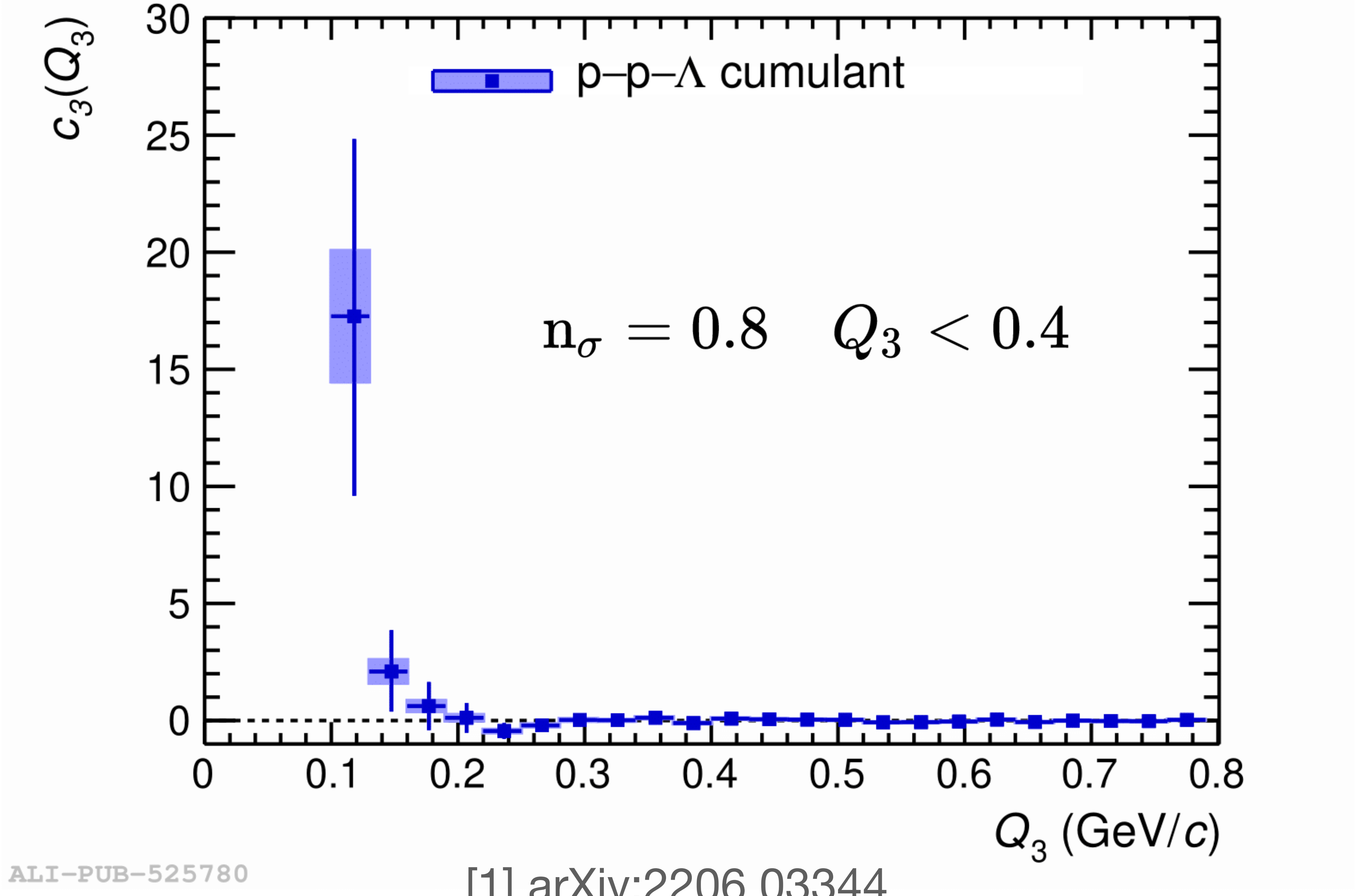


Kubo, J. Phys. Soc. Jpn. 177 (1962)

$c_3$ $(Q_3)$ allows to isolate effects associated with the genuine three-body interactions

- p-p-$\Lambda$ cumulants : compatible with zero
  - The ongoing Run 3 and future Run 4 at the LHC with a much larger data sample will allow for precise measurements

➡ p-p-$\Lambda$ interaction plays a crucial role in constrainig the equation of state of the neutron stars[1]



[1] arXiv:2206.03344

# Conclusions

**Summary:**

- $^{3}_{\Lambda}$H/Λ ratio in pp and p–Pb favours coalescence description
- Correlation of deuteron-proton: access to three-body system
- Three-body effects significant in p-p-p correlation
- p-p-Λ correlation exhibits no significant deviation from two-body correlation

**Outlook:**

- Deuterons can be combined to other hadrons to study many-body interaction
- Precise measurements to come in LHC Run 3 and Run 4!

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Thanks for your attention!

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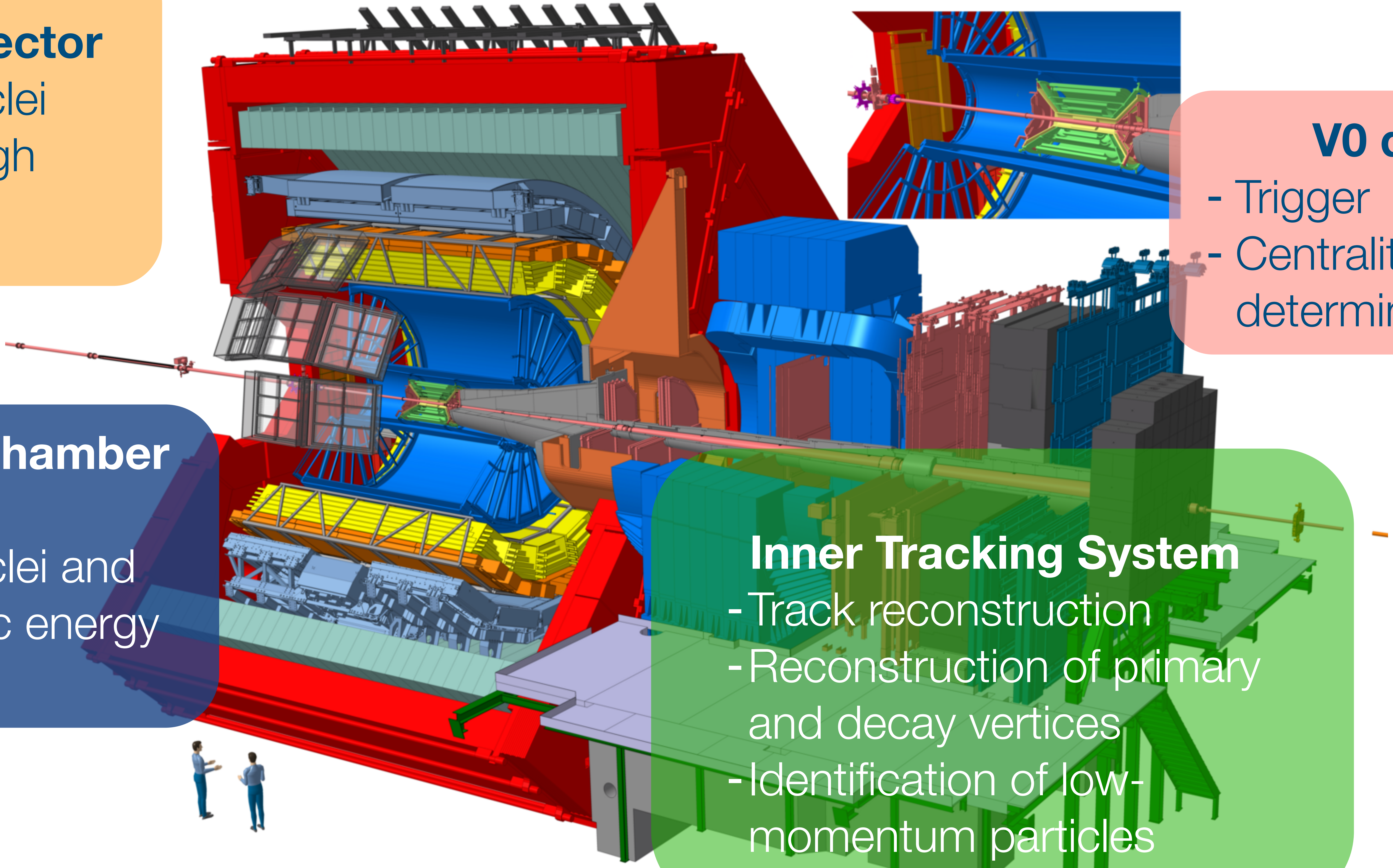
# additional slides

# ALICE detector: Run 2



**Time-Of-Flight detector**
- Identification of nuclei and hadrons through their time-of-flight

**V0 detectors**
- Trigger
- Centrality/multiplicity determination

**Time Projection Chamber**
- Tracking
- Identification of nuclei and hadrons via specific energy loss

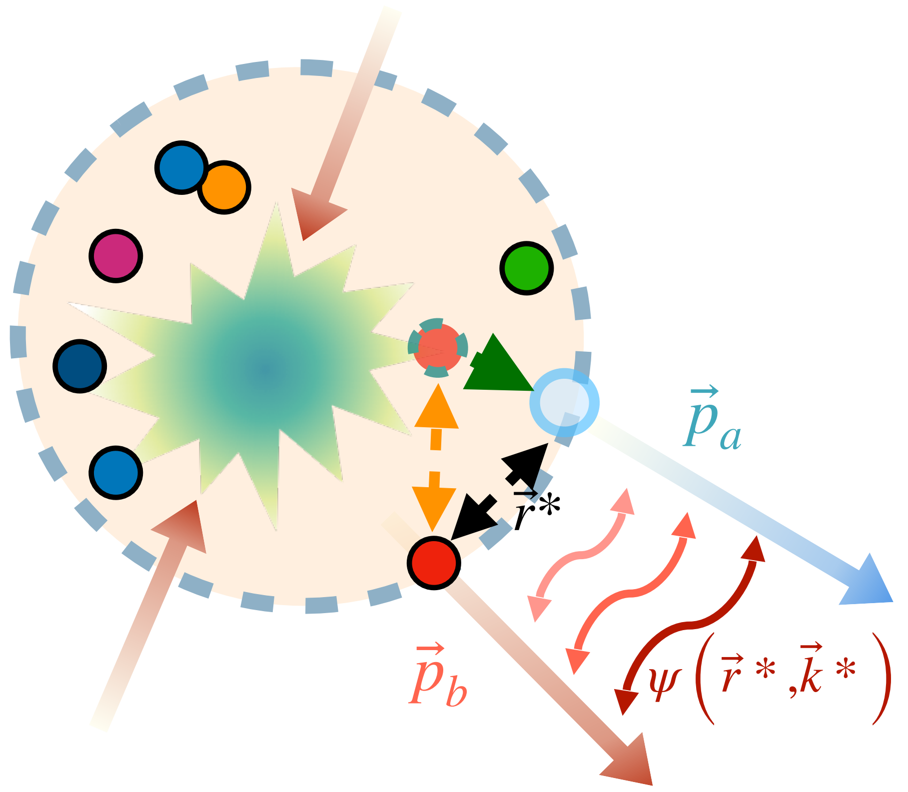
**Inner Tracking System**
- Track reconstruction
- Reconstruction of primary and decay vertices
- Identification of low-momentum particles

**ALICE : ITS and TPC upgrades**

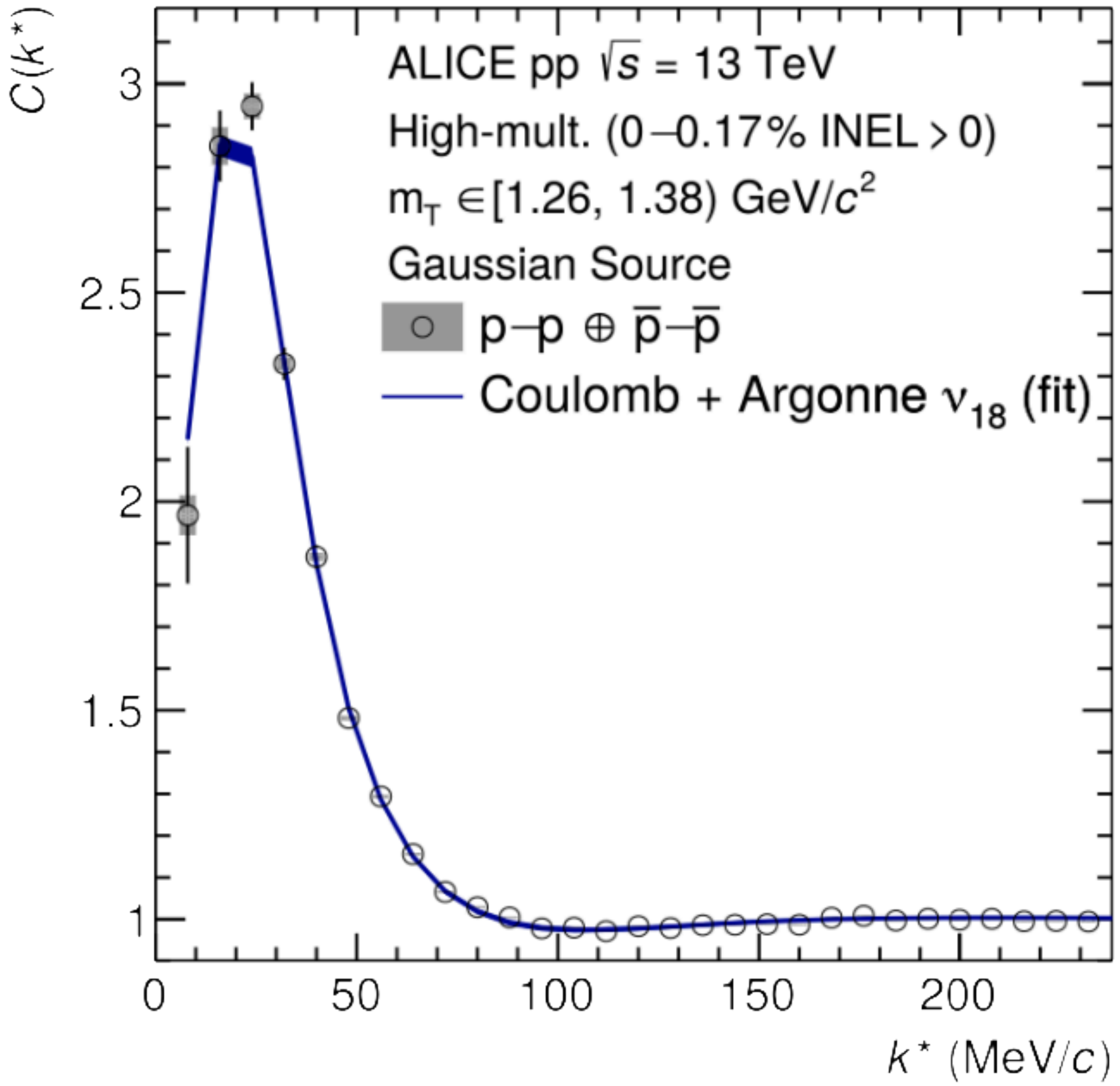
# The femtoscopic source

- Short distances in pp collisions
- Particle emission from **Gaussian core** source
- Well constrained theoretical p-p correlation with **AV18 interaction** with Fermi-Dirac statistics, Coulomb and strong interaction
- Extract: the source size as fit parameter in transverse mass ranges of pp pairs

**Include short-lived strongly decaying resonances** (cτ ≈ 1 fm) e.g. Δ-resonances in case of protons



PLB 811 (2020) 1358249



## Koonin-Pratt Equation

$$C(k^*) = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}$$

*ALICE Coll. PLB 811 135849 (2020)*

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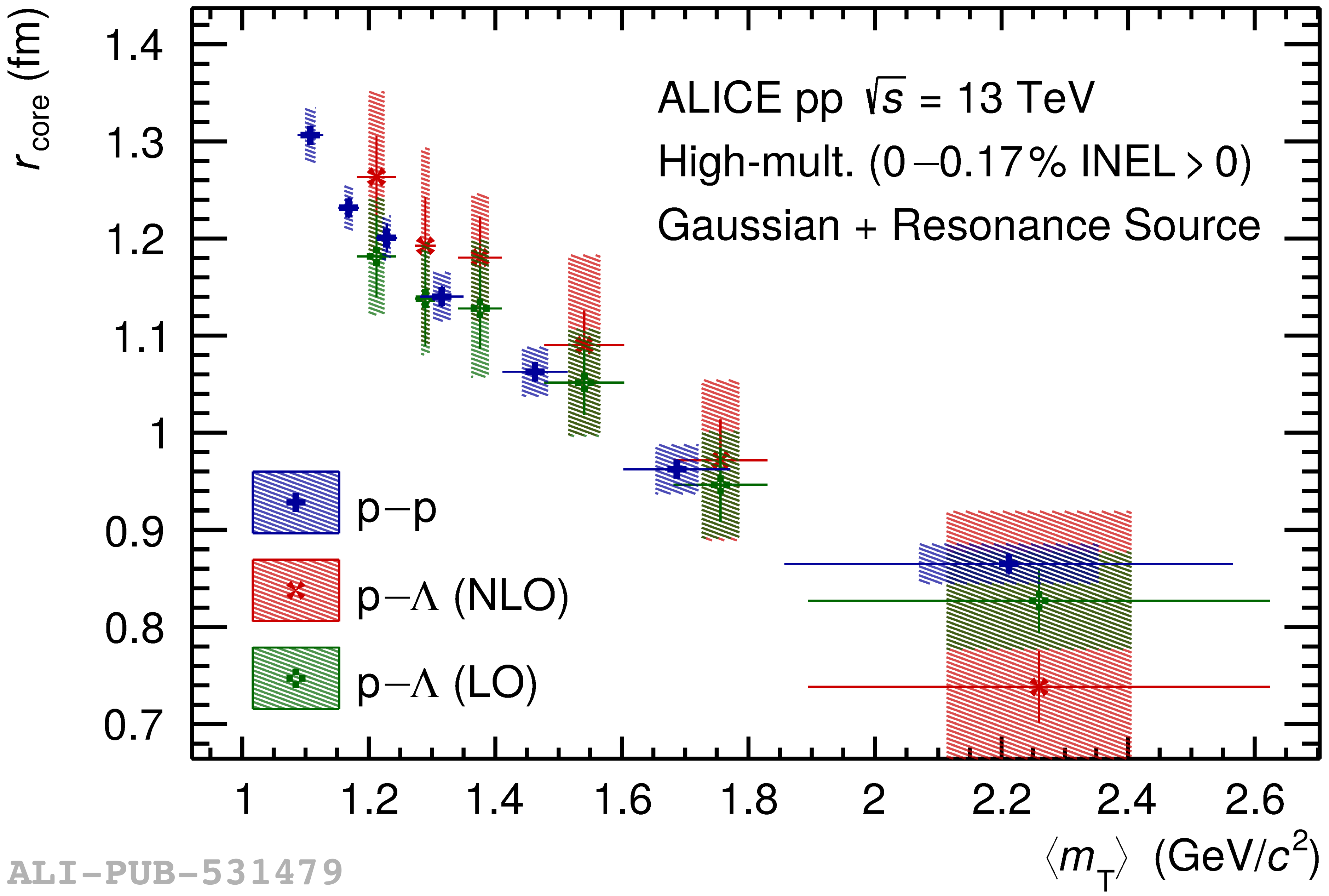

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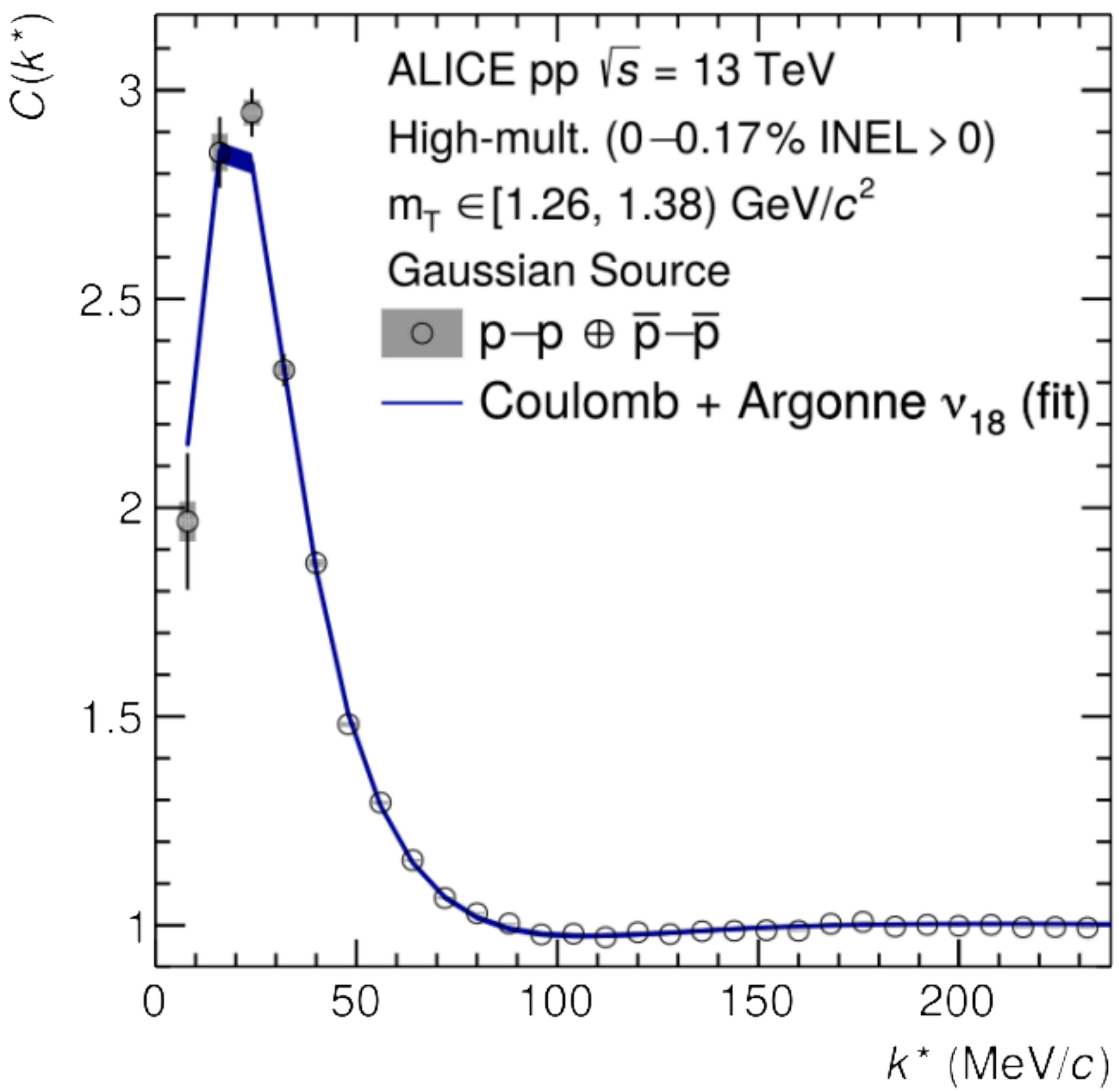

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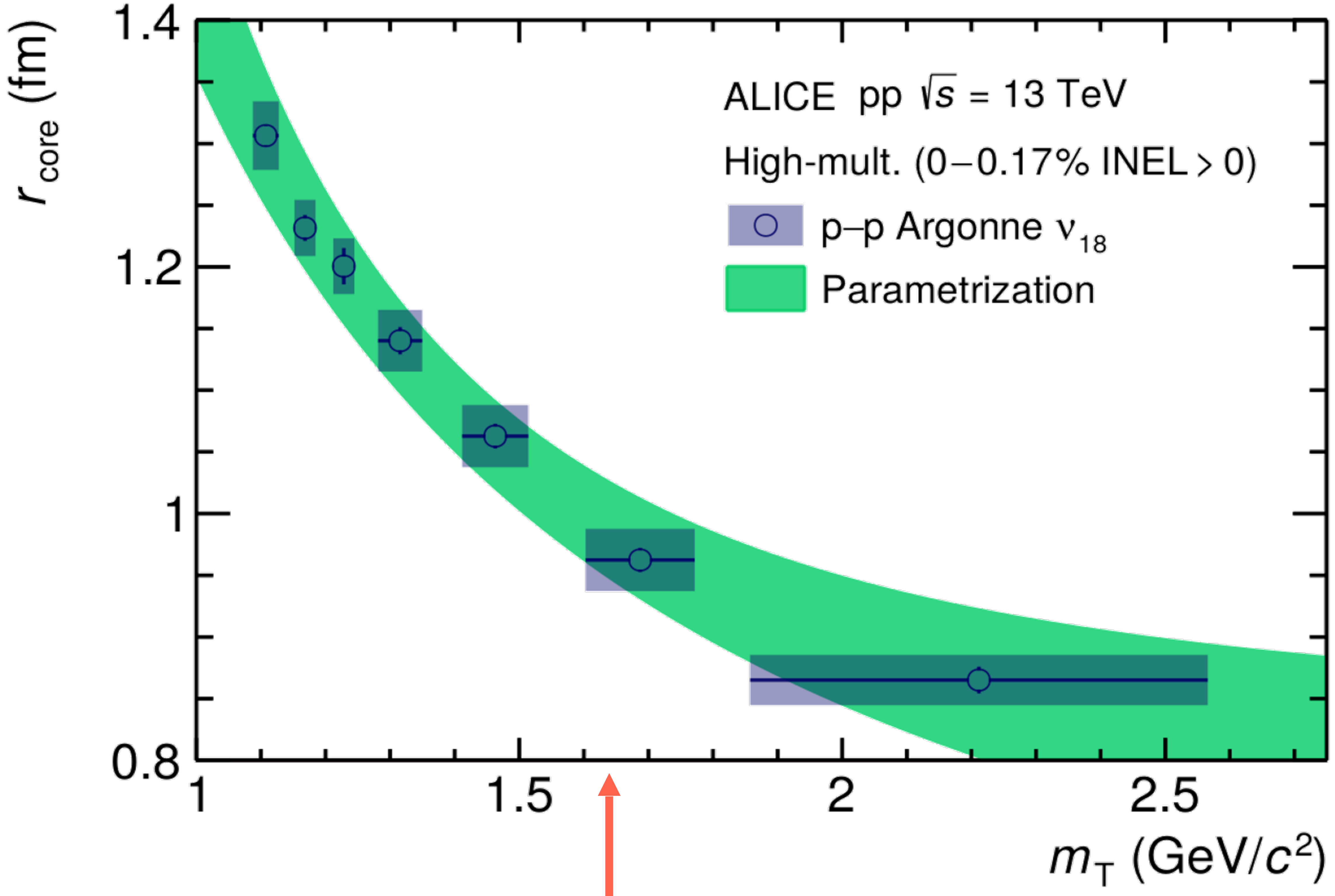
*ALICE Coll. PLB 811 135849 (2020)*

# The femtoscopic source

- p–d **Gaussian core** source($r_{core}$): using the $m_T$ -scalling

| Source size | mean value:pd |
|---|---|
| $r_{core}$ | 0.99±0.05 fm |



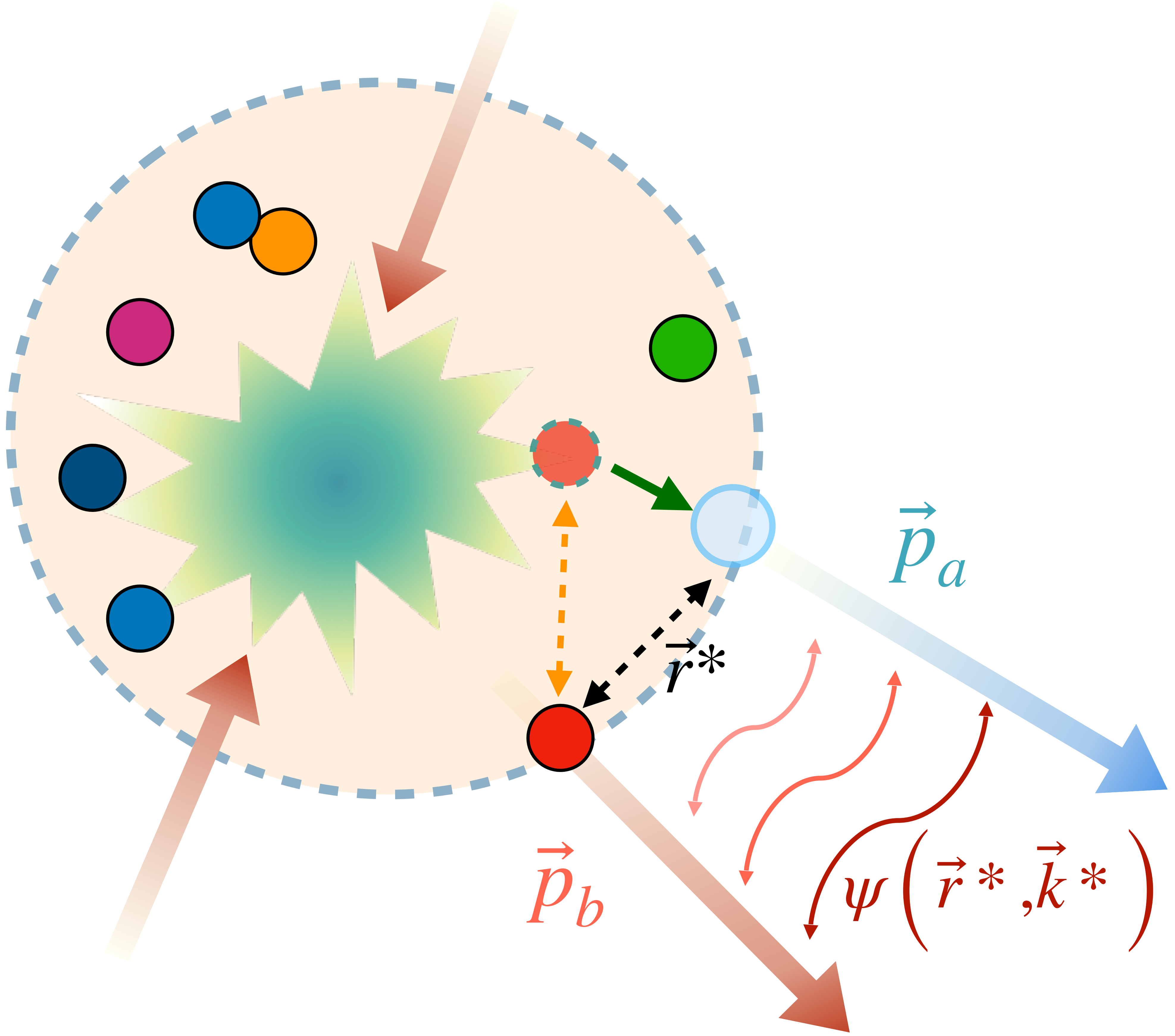
$<m_{T,\,p\text{-}d}> = 1.64$ GeV/$c^2$

*ALICE Coll. PLB 811 135849 (2020)*

# The femtoscopic source

- p–d **Gaussian core** source($r_{core}$): using the $m_T$ -scalling
- The source radius is effectively increased by **short-lived strongly decaying resonances** ($c\tau \approx r_{core}$) e.g. Δ-resonances in case of protons

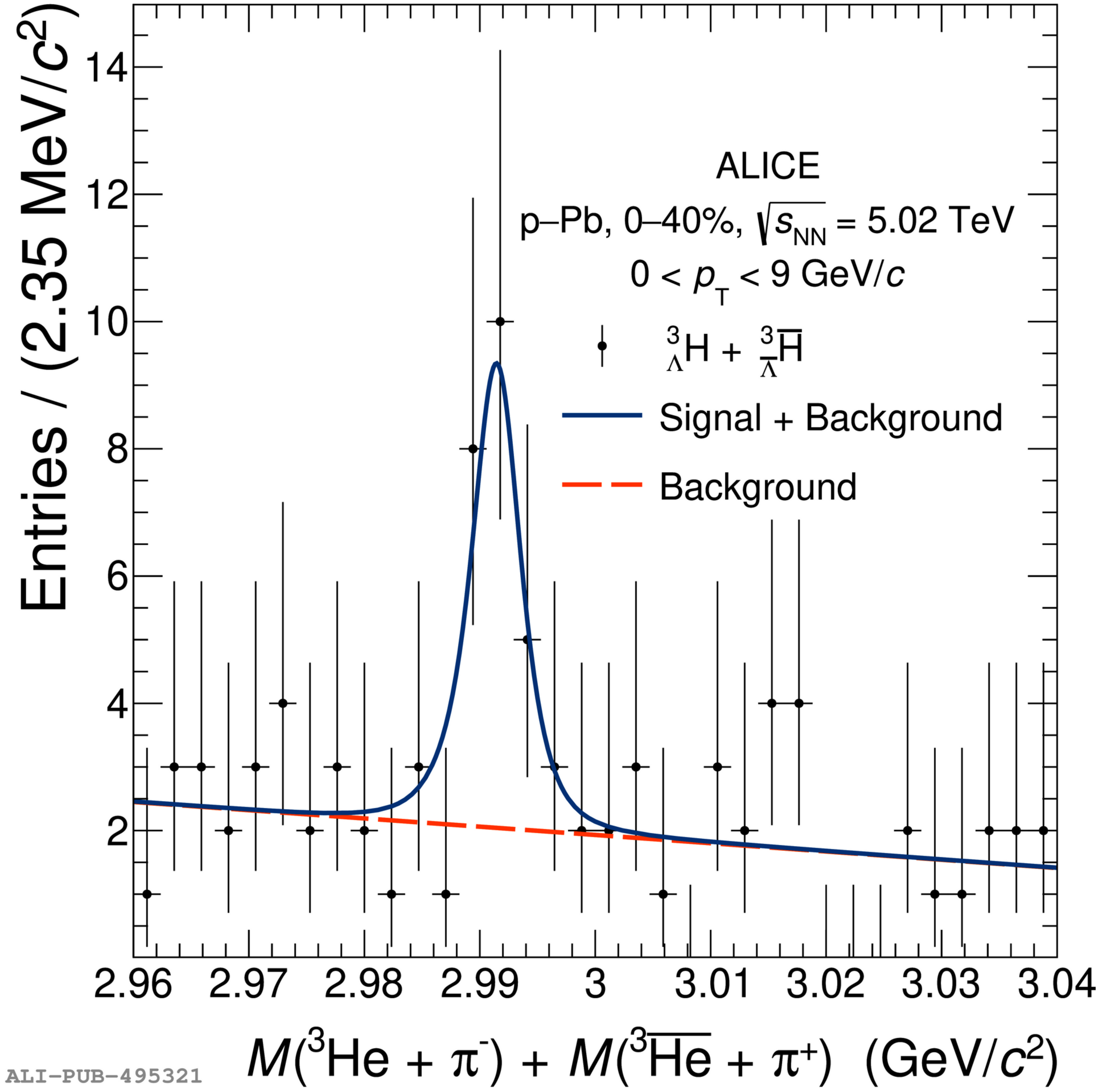
| Source size | mean value:pd |
|---|---|
| $r_{core}$ | 0.99±0.05 fm |
| $r_{eff}$ | 1.08±0.06 fm |



*ALICE Coll. PLB 811 135849 (2020)*

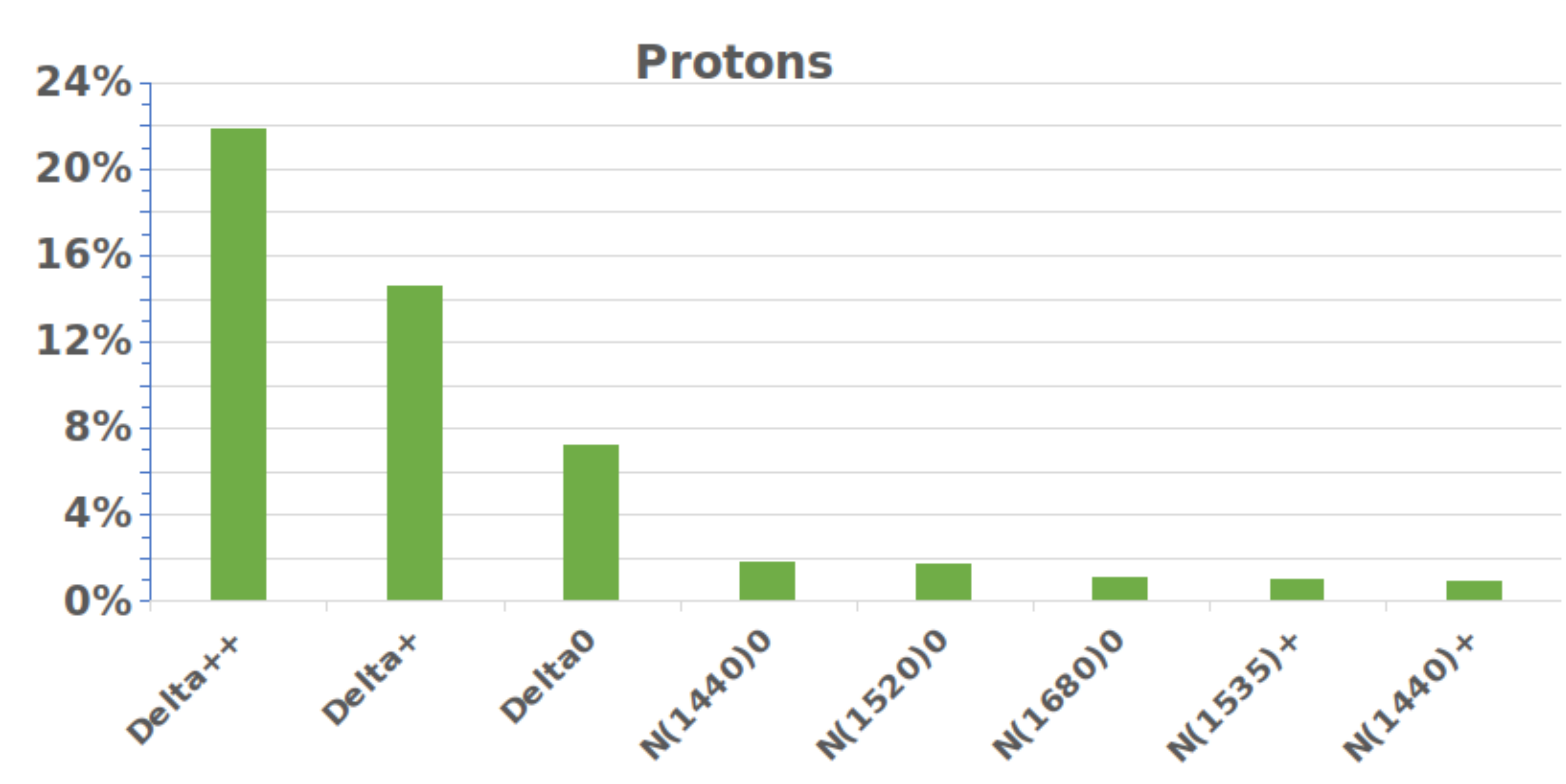
# ${}^{3}_{\Lambda}$H selection: pp and p–Pb collisions

- Data samples:
  - pp collisions at $\sqrt{s}$ = 13 TeV and p–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected during Run 2
- ${}^{3}_{\Lambda}$H selection in pp: trigger on high multiplicity events using V0 detectors
  - Topological selections on triggered events
- ${}^{3}_{\Lambda}$H selection in p–Pb: 40% most central collisions + BDT Classifier
- **Significance > 4σ both in pp and p–Pb**

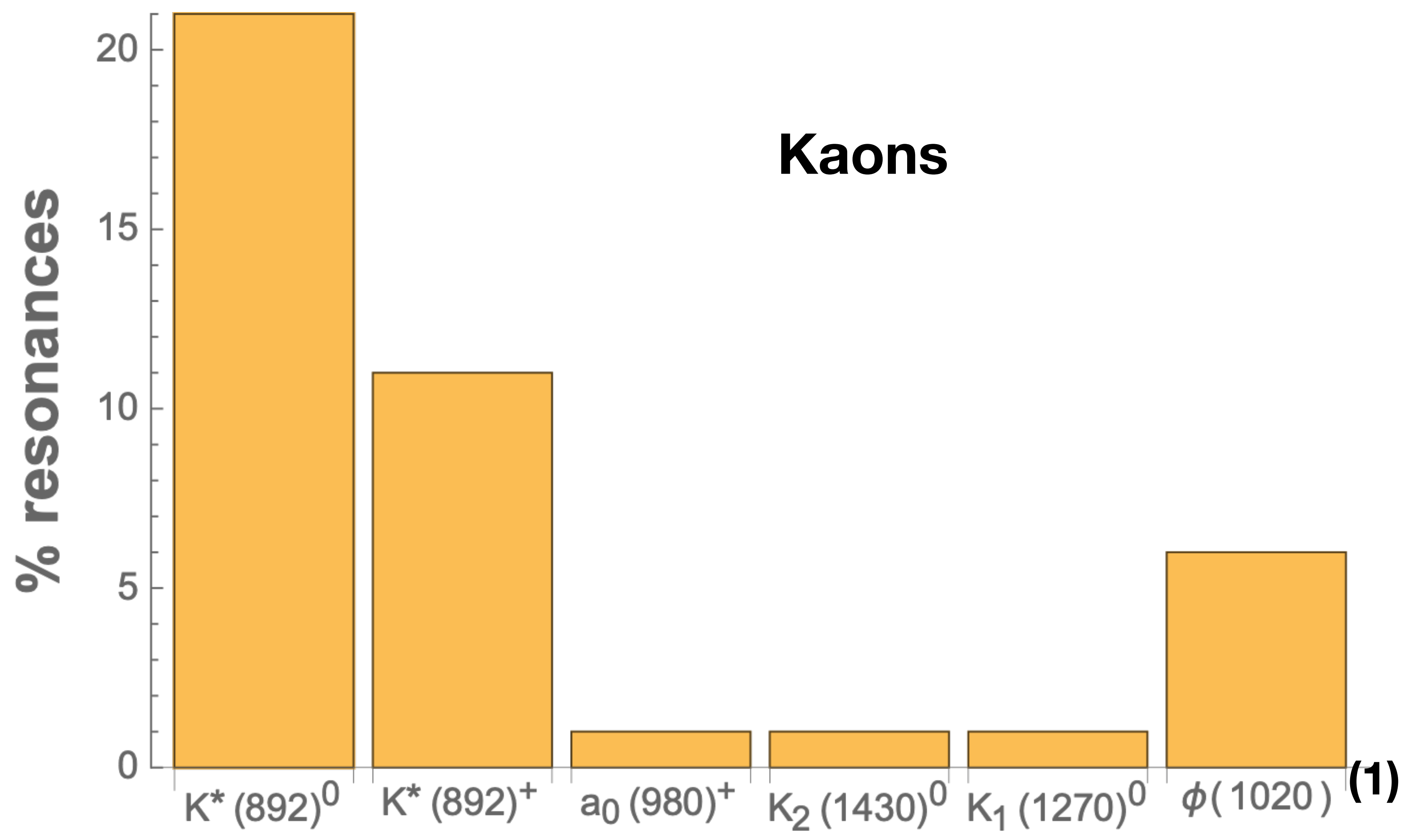


# The source for pd and K+d

- Short distances in pp and p—Pb collisions
- Particle emission from **Gaussian core** source
- The source radius is effectively increased by **short-lived strongly decaying resonances** ($c\tau \approx r_{\mathrm{core}}$) e.g. Δ-resonances in case of protons



| Source size | mean value:pd | mean value:k+d |
|---|---|---|
| $r_{\mathrm{core}}$ | 0.99±0.05 fm | 1.04±0.04 fm |
| $r_{\mathrm{eff}}$ | 1.08±0.06 fm | $1.41^{+0.03}_{-0.09}$ fm |

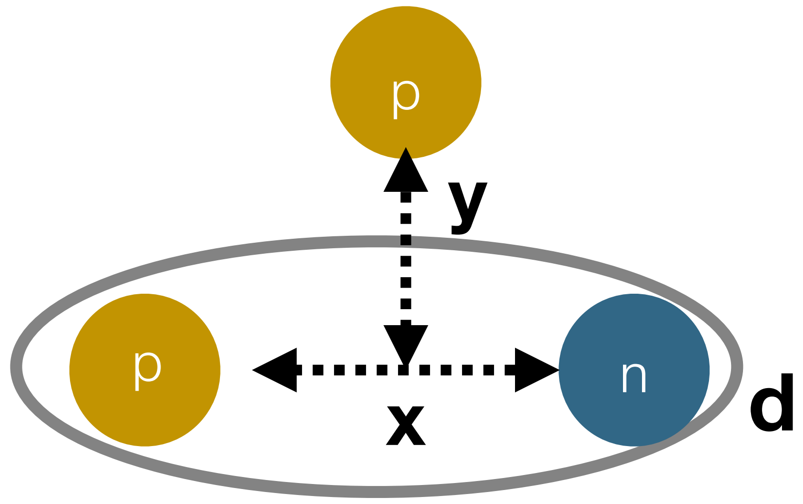


**(1) $\phi$(1020) corrected as feed-down**

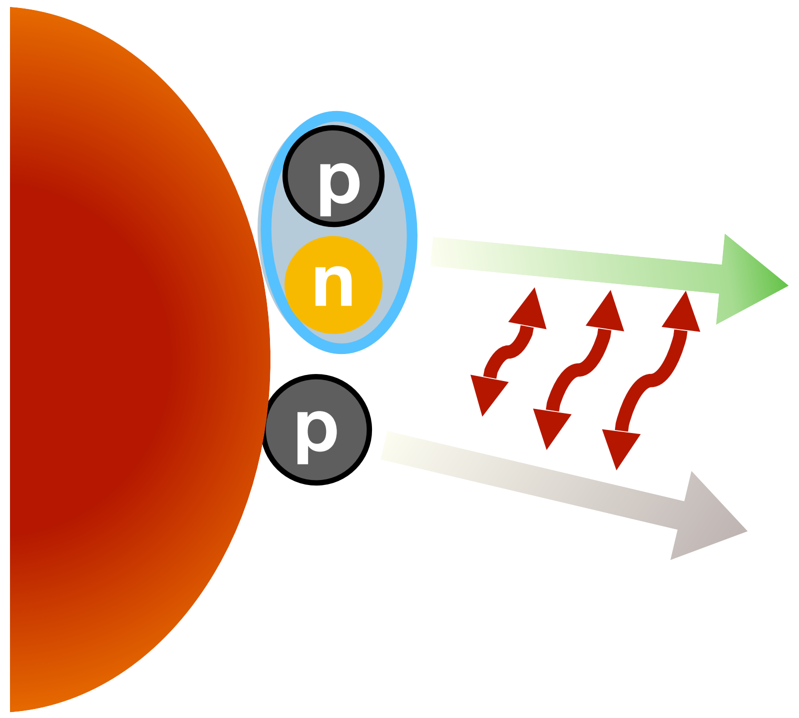
# p–d correlation with d as composite object

**The three body wave function with proper treatment of 2N and 3N interaction at very short distances goes to a p–d state.**

- **Three–body wavefunction for p–d:** $\Psi_{m_2, m_1}(x, y)$ 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
- $\Psi_{m_2, m_1}(x, y)$ three-nucleon wave function asymptotically behaves as p–d state:



$$\Psi_{m_2,m_1}(\boldsymbol{x},\boldsymbol{y}) = \underbrace{\Psi^{(\text{free})}_{m_2,m_1}}_{\text{Asymptotic form}} + \sum_{LSJ}^{J\leq\bar{J}} \sqrt{4\pi}\, i^L \sqrt{2L+1}\, e^{i\sigma_L} \underbrace{(1m_2\tfrac{1}{2}m_1|SJ_z)(L0SJ_z|JJ_z)\widetilde{\Psi}_{LSJJ_z}}_{\text{Strong three-body interaction}} \, .$$



➡ $\widetilde{\Psi}_{LSJJ_Z}$ describe the configurations where the three particles are close to each other

➡ $\Psi^{(\text{free})}_{m_1,m_2}$ an asymptotic form of p-d wave function

*Kievsky et al, Phys. Rev. C 64 (2001) 024002*
*Kievsky et al, Phys. Rev. C 69 (2004) 014002*
*Deltuva et al, Phys. Rev. C71 (2005) 064003*

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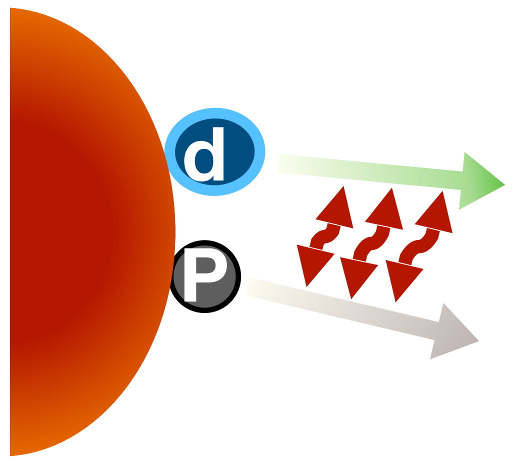


# Theoretical model comparison

# **Lednický model: pointlike deuterons**

R. Lednický, Phys. Part. Nuclei 40, 307–352 (2009)

# 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

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

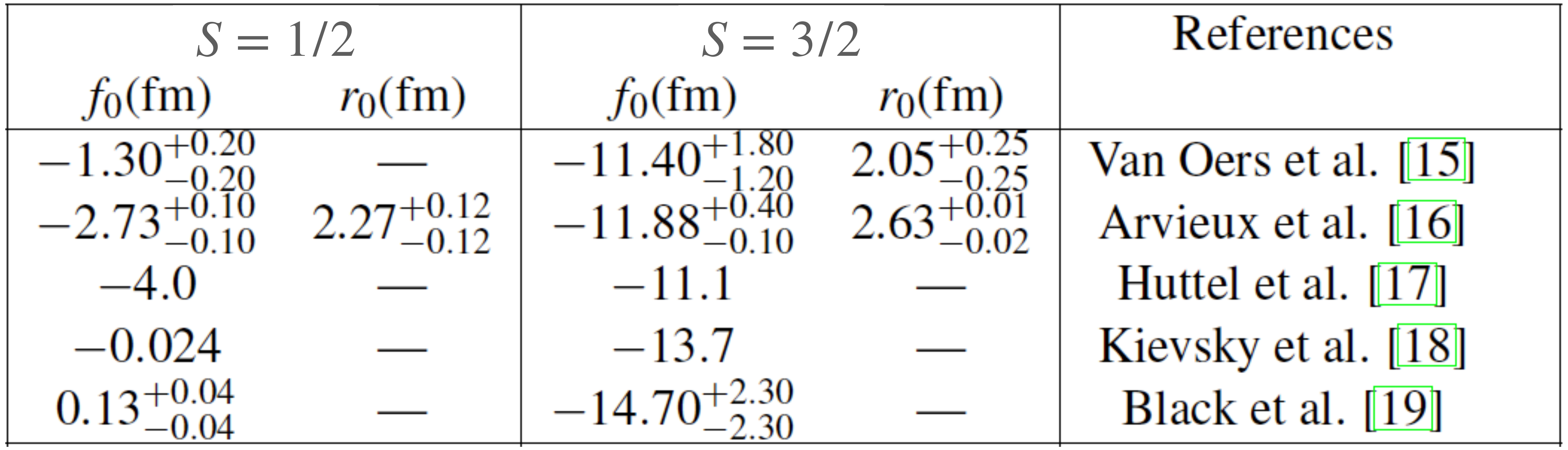
- $f_c$ : Coulomb normalised scattering amplitude for strong interaction
- $F(-i\eta, 1, i\zeta)$ : confluent hypergeometric function
- $\tilde{G}(\rho,\eta)$: combination of singular and regular Coulomb function, describes asymptotic behaviour of wavefunction

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

# Lednický model: pointlike deuterons

- **For distinguishable pointlike particles**
  - Starting from the scattering parameters ⇒ define the s-wave two-particle relative wave function
  - Considers Coulomb effects
  - Assumption: p and d are pointlike particles!

⇒ **p–d scattering parameters** from fits to p–d scattering data



| $S = 1/2$ | | $S = 3/2$ | | References |
|---|---|---|---|---|
| $f_0$(fm) | $r_0$(fm) | $f_0$(fm) | $r_0$(fm) | |
| $-1.30^{+0.20}_{-0.20}$ | — | $-11.40^{+1.80}_{-1.20}$ | $2.05^{+0.25}_{-0.25}$ | Van Oers et al. [15] |
| $-2.73^{+0.10}_{-0.10}$ | $2.27^{+0.12}_{-0.12}$ | $-11.88^{+0.40}_{-0.10}$ | $2.63^{+0.01}_{-0.02}$ | Arvieux et al. [16] |
| $-4.0$ | — | $-11.1$ | — | Huttel et al. [17] |
| $-0.024$ | — | $-13.7$ | — | Kievsky et al. [18] |
| $0.13^{+0.04}_{-0.04}$ | — | $-14.70^{+2.30}_{-2.30}$ | — | Black et al. [19] |

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

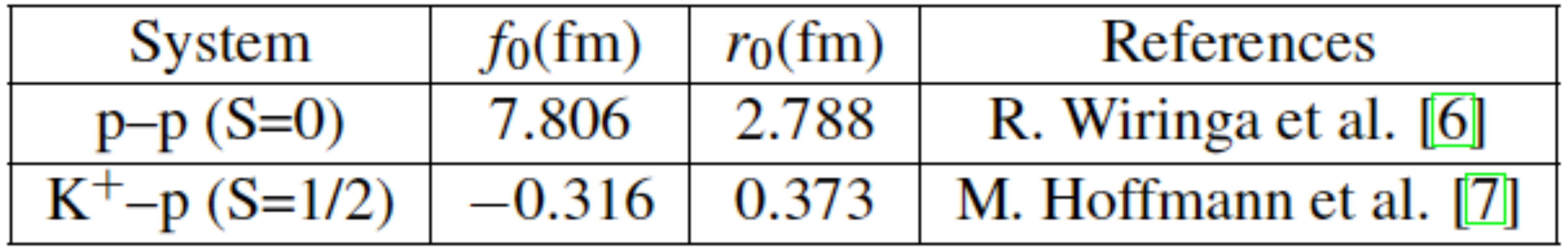
R. Lednicky, Phys. Part. Nuclei 40, 307–352 (2009)

# How accurate is the theory ?

- **Benchmark:** compare correlations with Lednicky model with calculations using

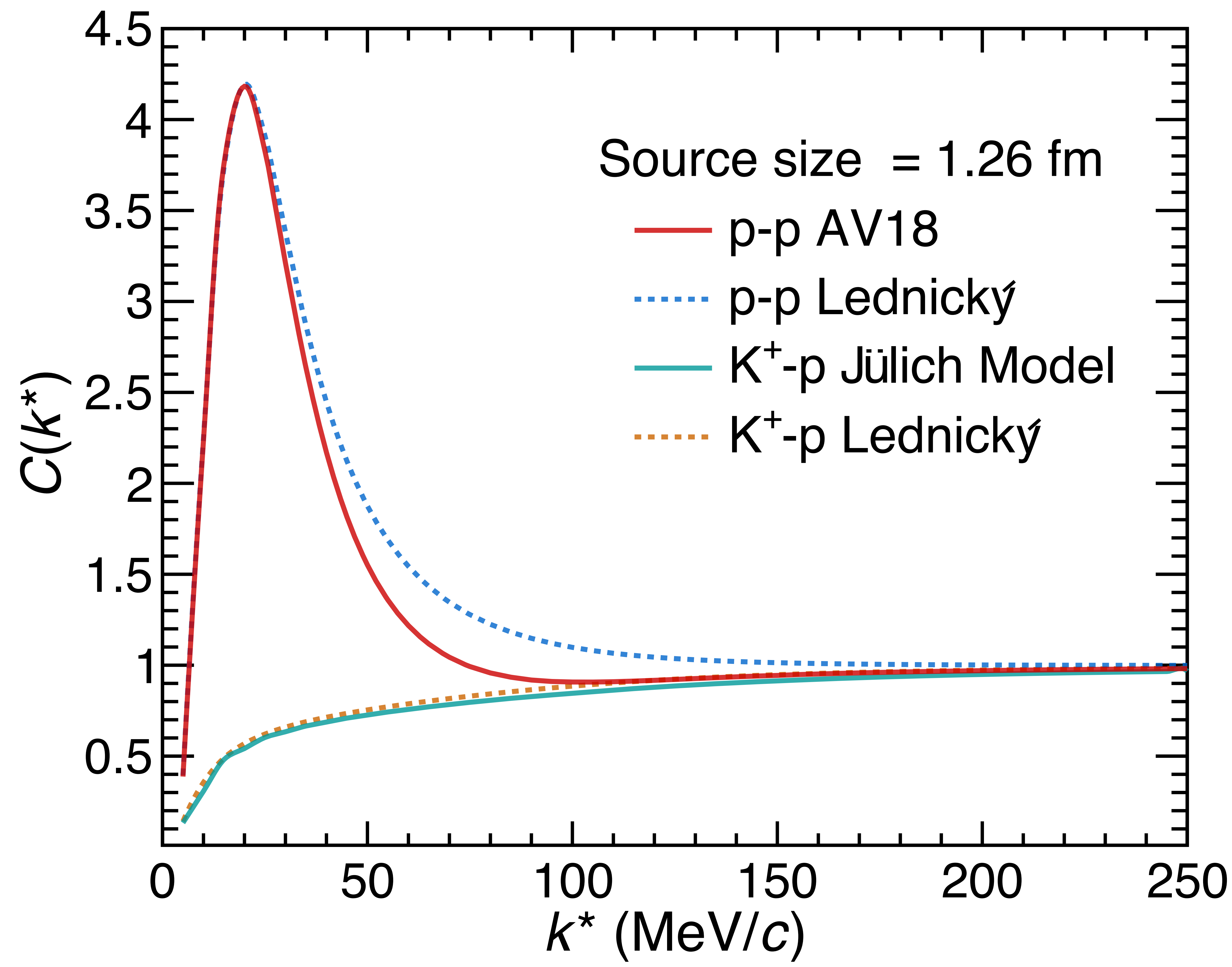
  - pp from AV18 potential

  - $K^+p$ from Jülich model



| System | $f_0$(fm) | $r_0$(fm) | References |
|---|---|---|---|
| p–p (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**



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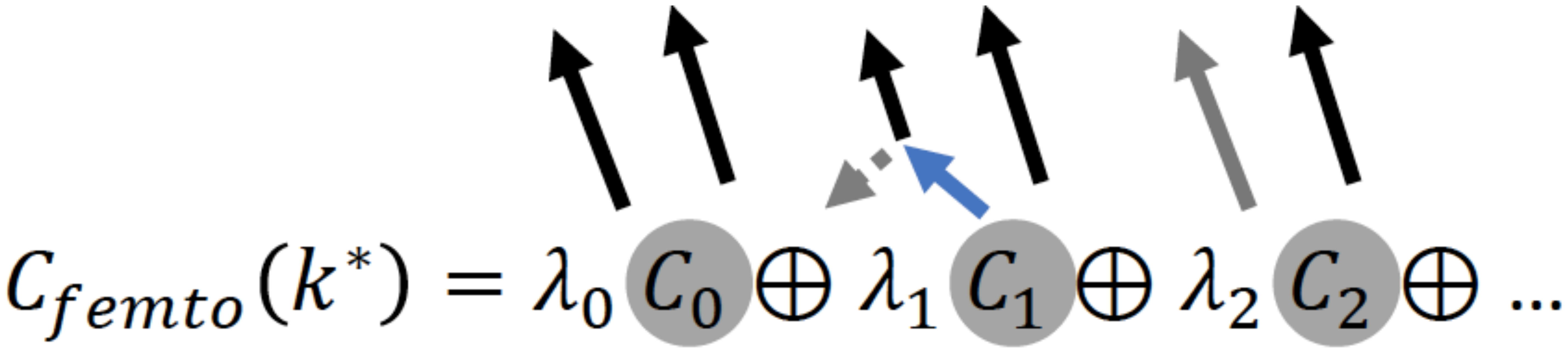
# Femtoscopic correlation

- The femtoscopic correlation may have background/contributions from
  - Particles from weak decays
  - Particles from material knock-outs
  - Misidentifications



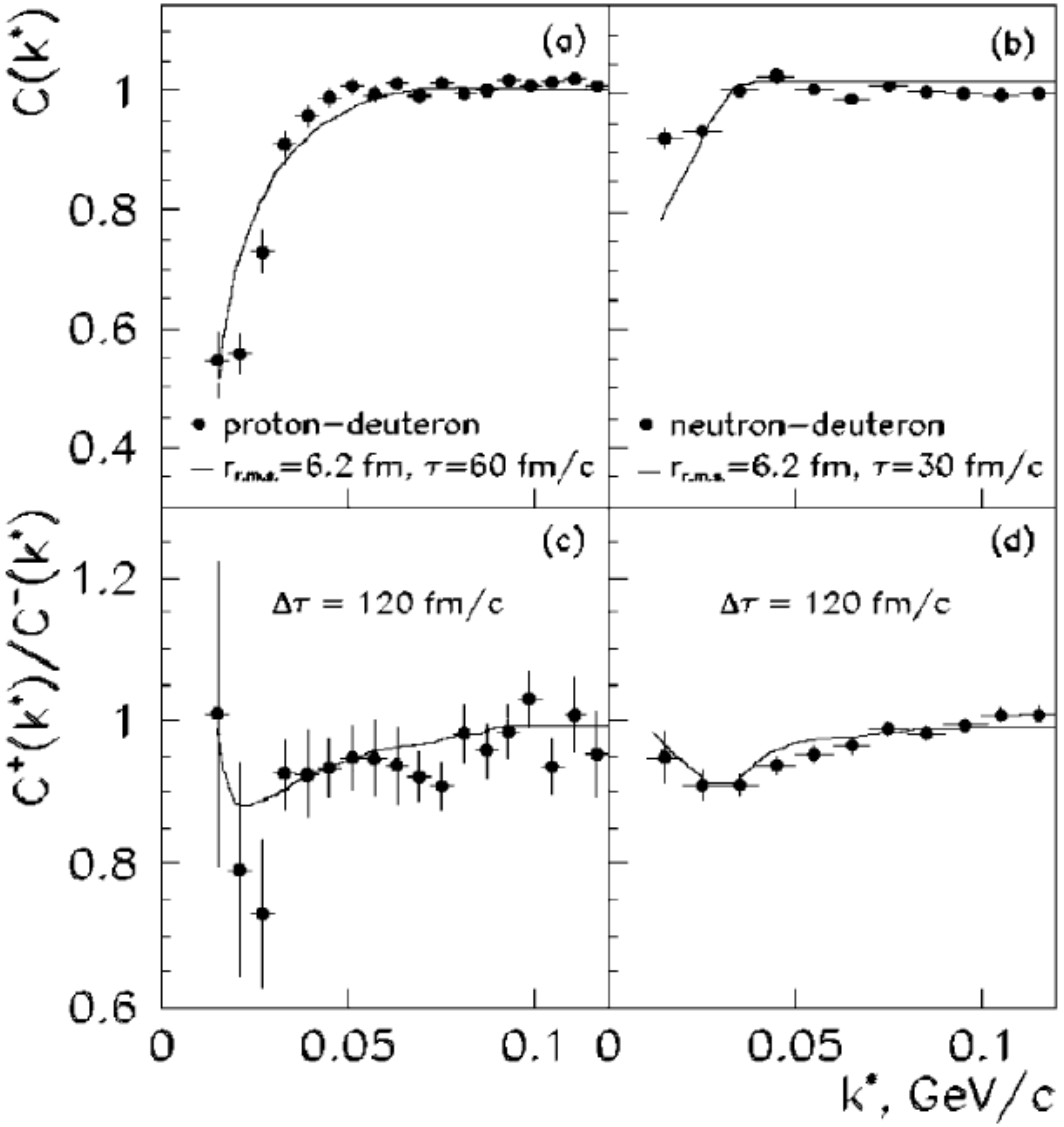
$$C_{femto}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 \oplus \ldots$$

Contributions from: genuine feed-down misidentifications

- Quantification of the contributions to the pairs done by the lambda parameters $\lambda_{ij} = \mathscr{P}_i . f_i \times \mathscr{P}_j . f_j$
  - Purity of the individual particles ($\mathscr{P}_i$)
  - Feed-down fractions ($f_i$)

# proton-deuteron correlation measurement so far

- **Status**:
  - p-d correlation function from 2006
  - GANIL(Grand Accélérateur National d'Ions Lourds):
    - $^{40}$Ar-$^{58}$Ni reaction at 77 MeV/u
    - Show a clear depletion
    - Only unto 100 MeV/c in relative momentum



[1] Wosińska, K., Pluta, J., Hanappe, F. *et al. Eur. Phys. J. A* 32, 55–59 (2007)

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# Another calculation at hand

- Hadron-Deuteron Correlations and Production of Light Nuclei in Relativistic Heavy-Ion Collisions: arxiv.org/abs/1904.08320
  - hadron-deuteron correlation function which carries information about the source of the deuterons
  - Allows one to determine whether a deuteron is directly emitted from the fireball or if it is formed afterwards
  - Conclusion:
    - The theoretical p-d correlation function is strongly dependent on the source size

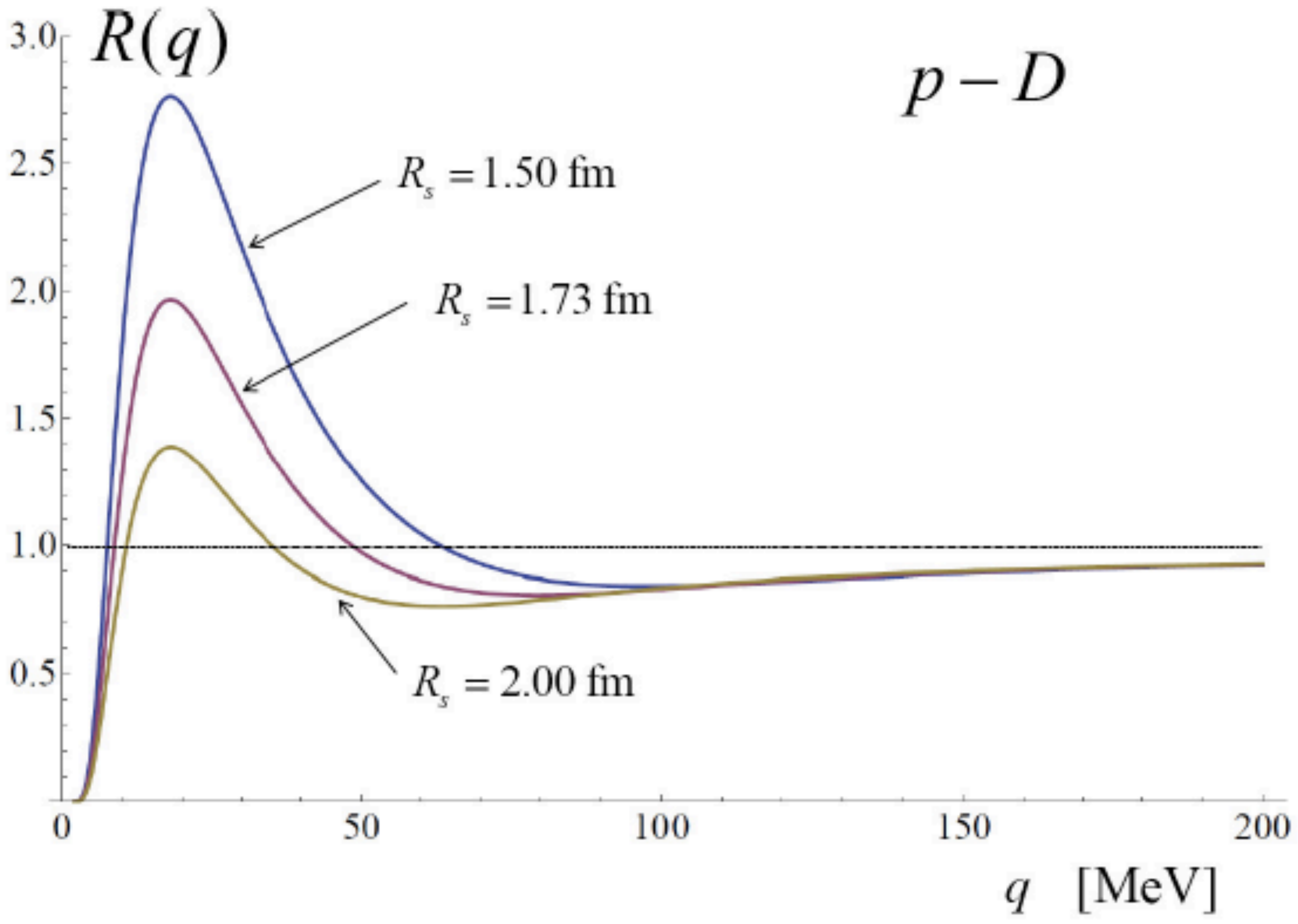

Fig. 2. $p-D$ correlation function