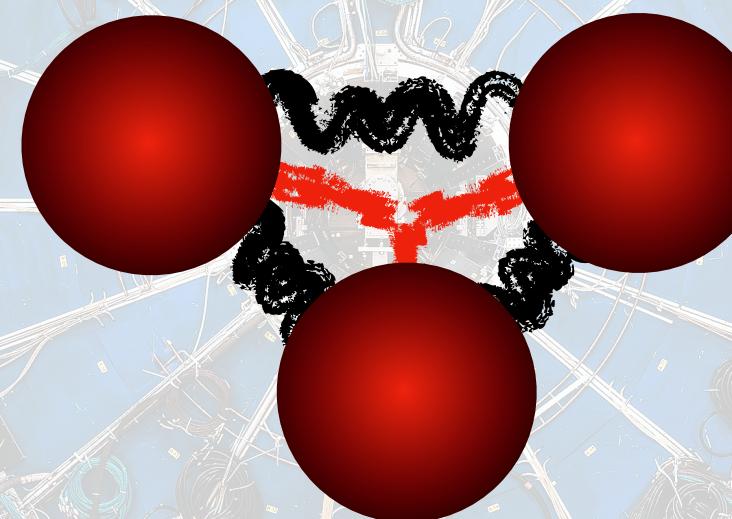
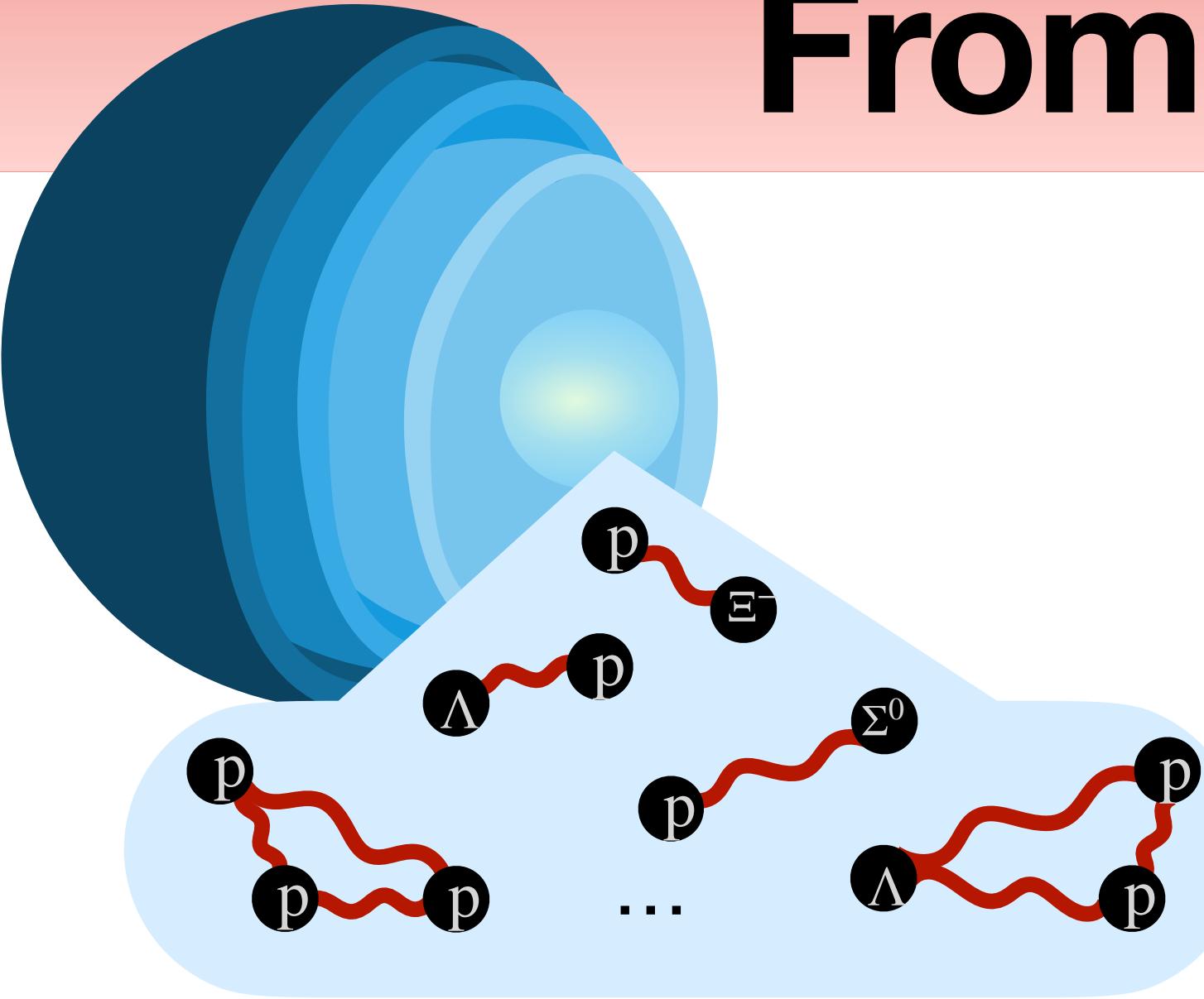


# 3-body interactions of hadrons in pp collisions with ALICE



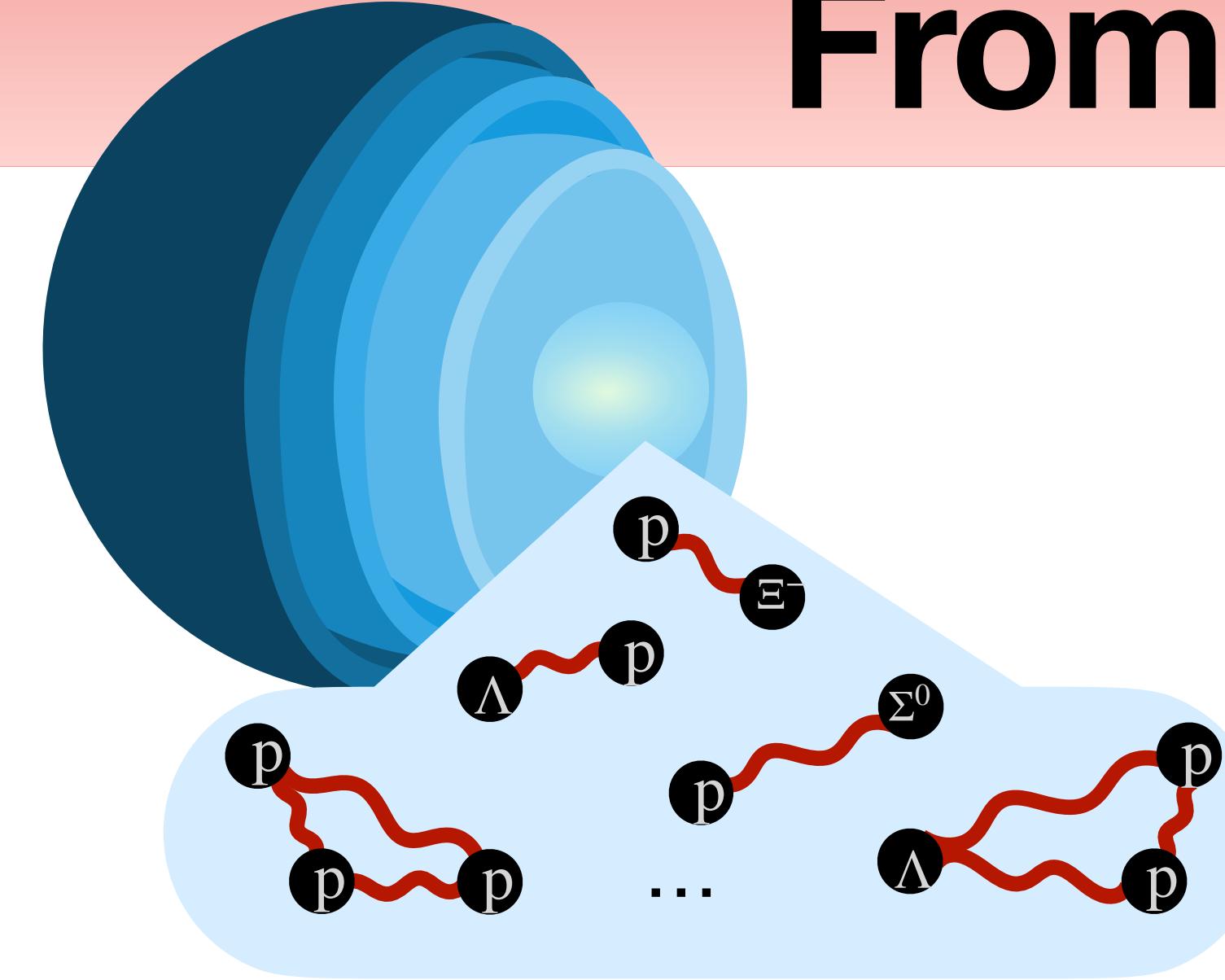
Laura Šerkšnytė  
Technical University of Munich  
On behalf of the ALICE Collaboration  
EMMI workshop  
Trieste 05.07.23

# From nuclear matter...



- Properties of nuclei and hypernuclei cannot be described satisfactorily with two-body forces only  
L.E. Marcucci et al., Front. Phys. 8:69 (2020)
- N-N-N and N-N-Lambda interactions: fundamental ingredients for the Equation of State (EoS) of neutron stars  
D. Lonardoni et al., PRL 114, 092301 (2015)

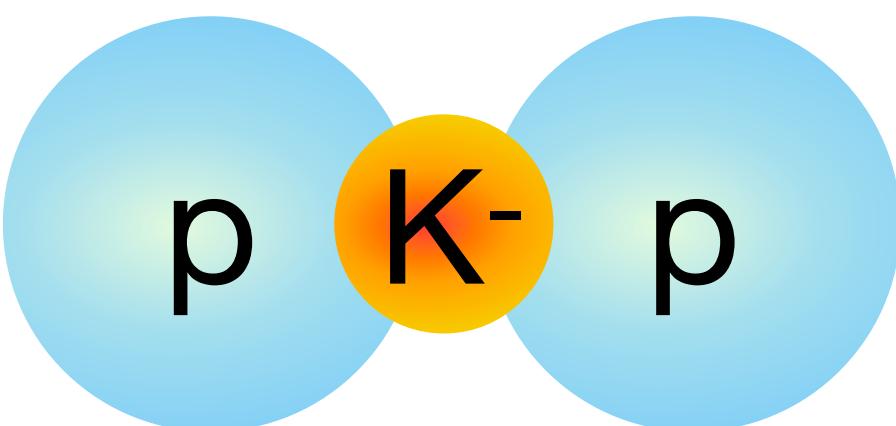
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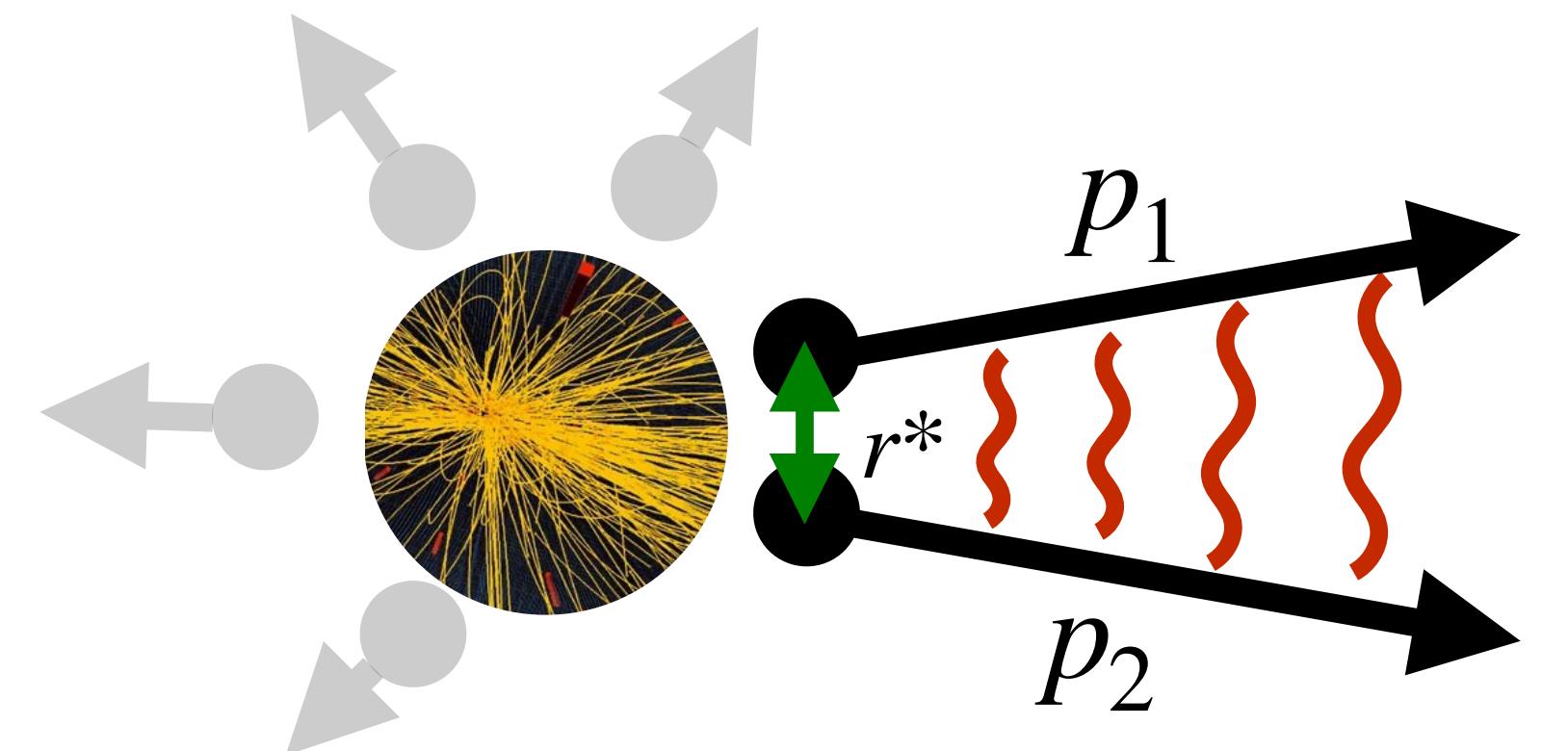
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D. Lonardoni et al., PRL 114, 092301 (2015)

## ... to kaonic bound states

- $\bar{K}$ -N-N: exotic bound states of antikaons with nucleons predicted twenty years ago  
S. Wycech, NPA 450 (1986) 399; Y. Akaishi, T. Yamazaki, PRC 65 (2002) 044005;  
Sekihara et. al., PTEP 2016 no. 12, (2016); N. V. Shevchenko et.al., PRL 98 (2007) 082301;  
S. Wycech, A. M. Green, PRC 79 (2009) 014001; Y. Ikeda, T. Sato, PRC 76 (2007) 035203;  
N. Barnea et. al., PLB 712 (2012) 132-137
- First solid experimental evidence of the p-p-K- bound state by the E15 Collaboration  
E15 Coll., PLB 789 (2019) 620

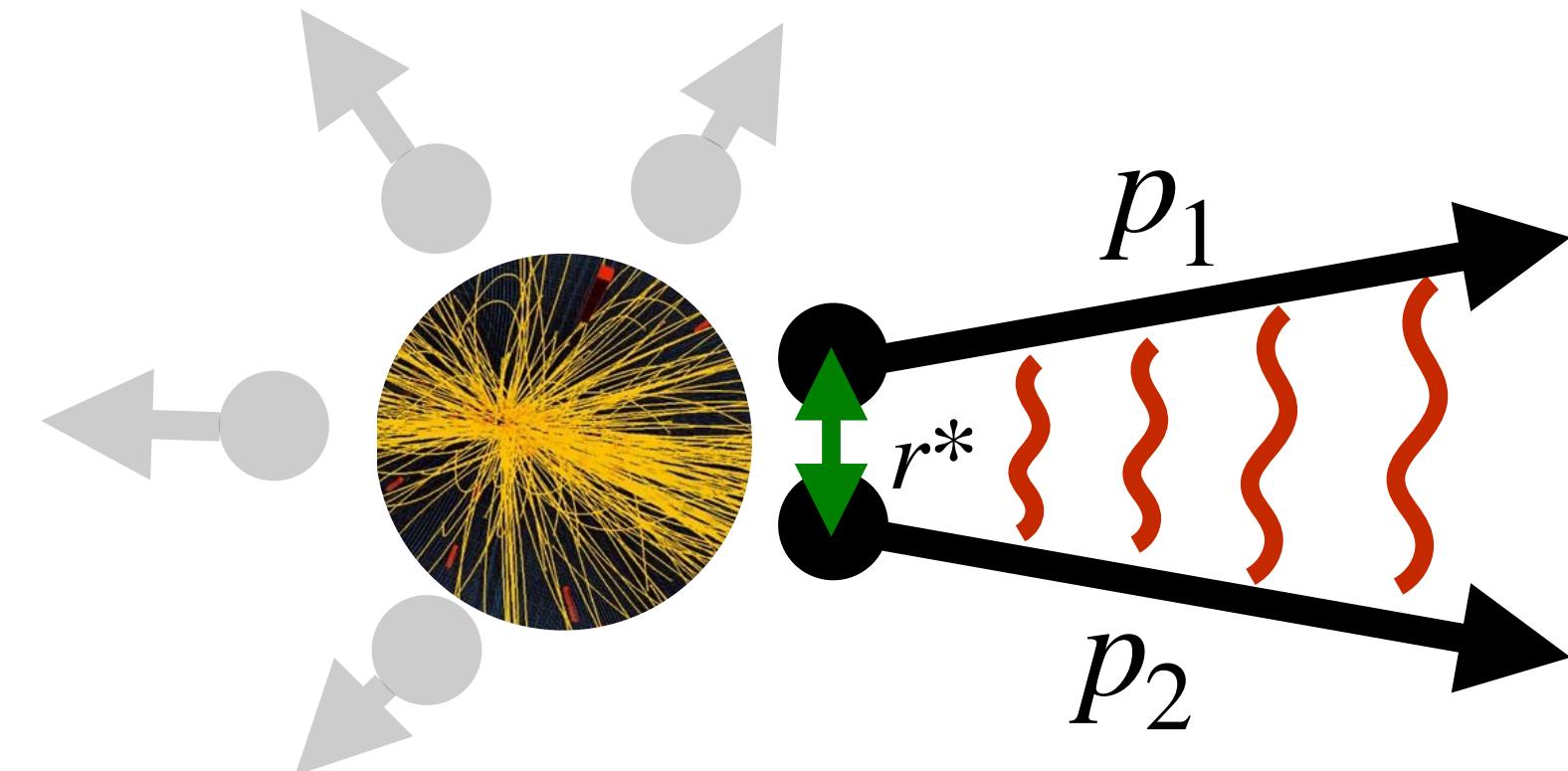


# Femtoscopy



Emission source  $S(r^*)$

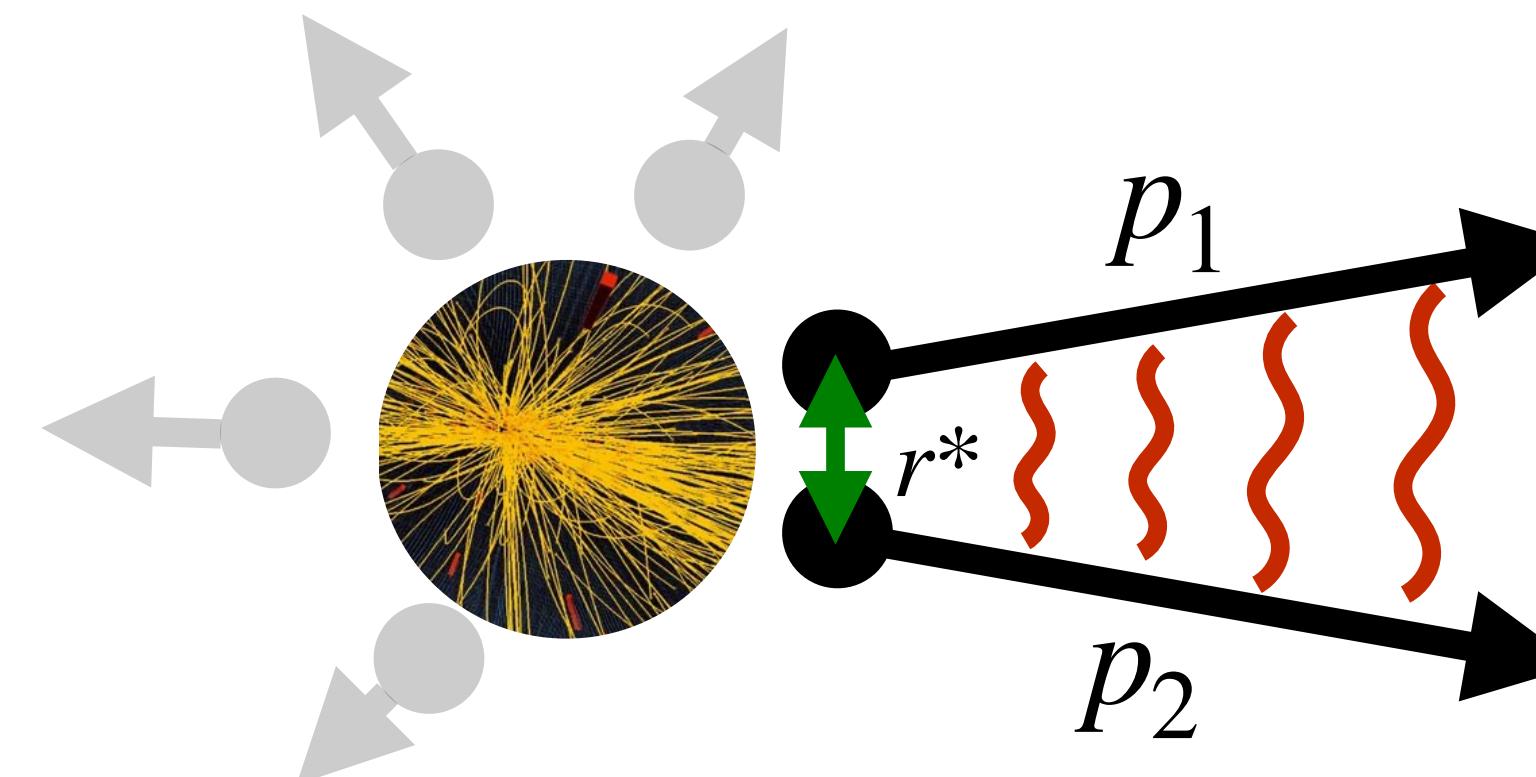
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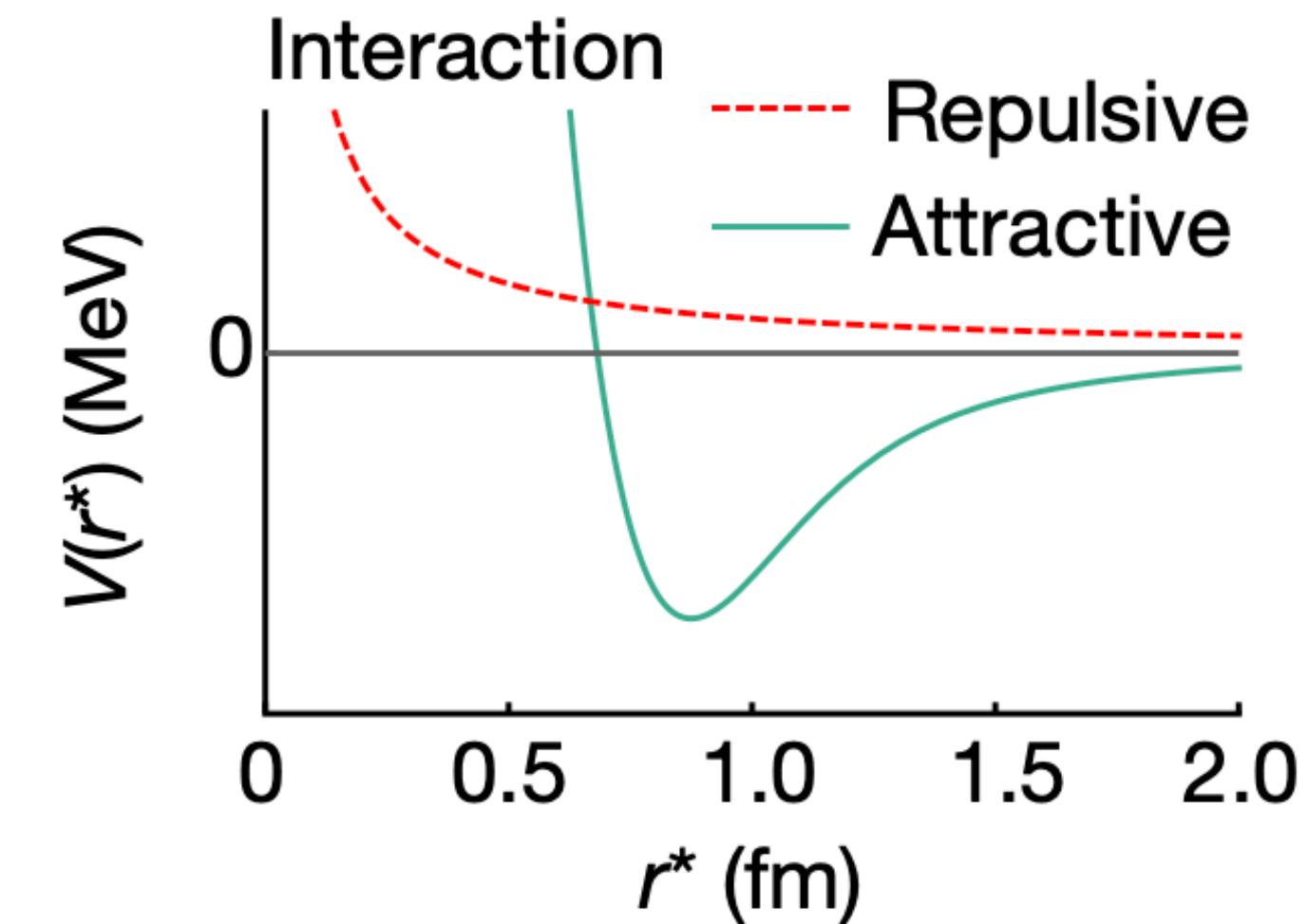
Emission source  $S(r^*)$

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

# Femtoscopy



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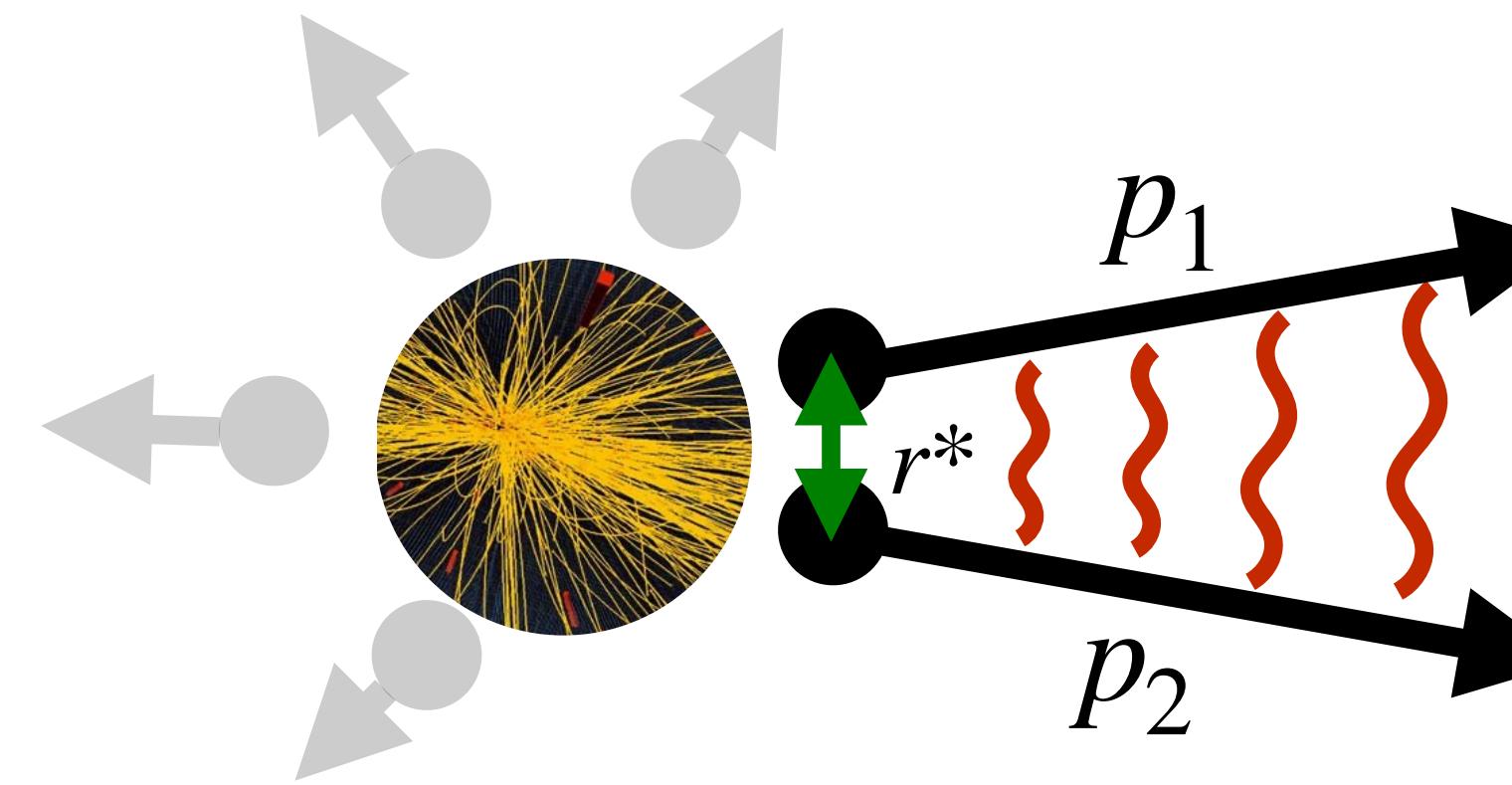


Interaction  
Schrödinger equation  
Two-particle wave function  
 $|\psi(\mathbf{k}^*, \mathbf{r}^*)|$

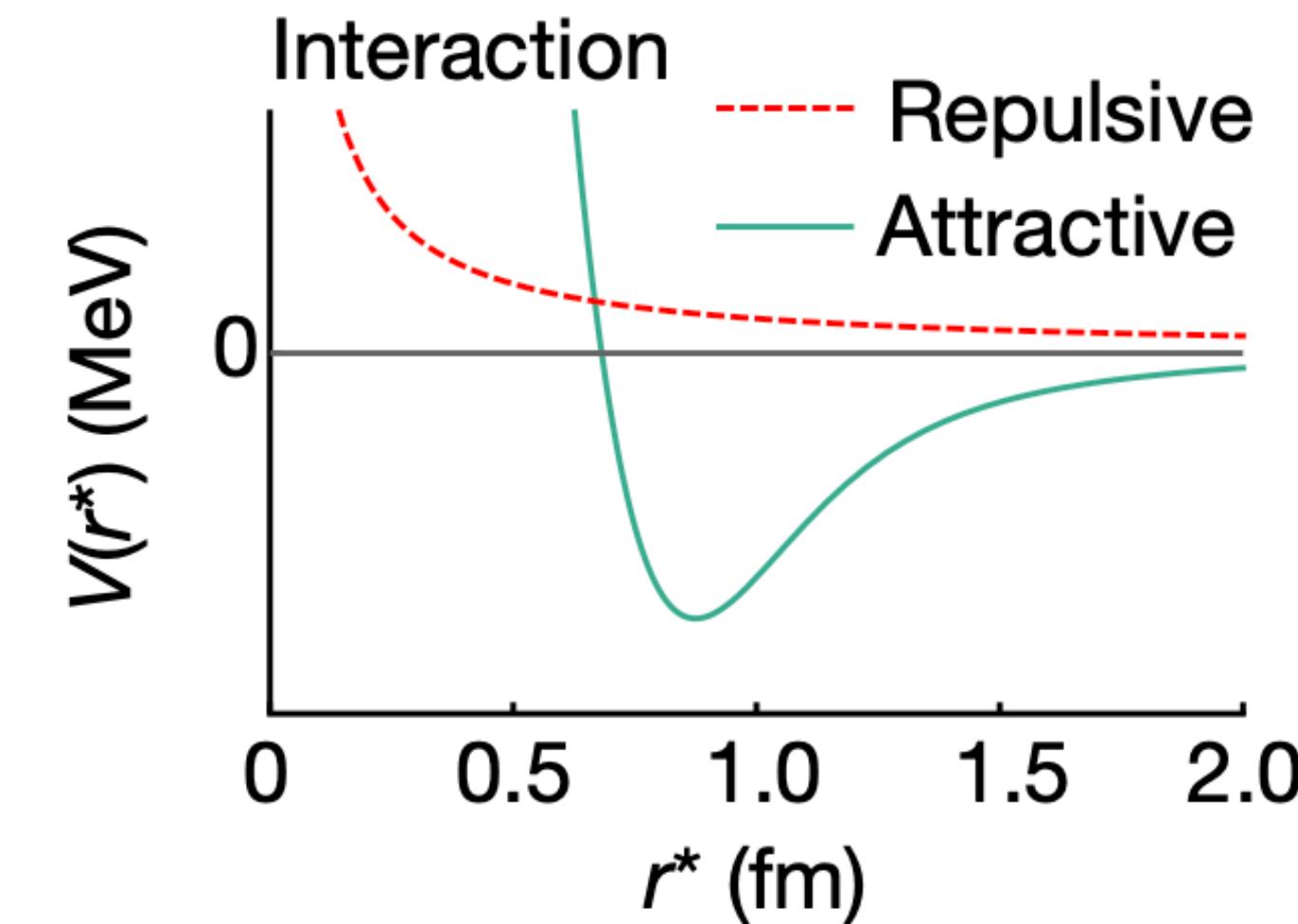
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ALICE, Nature 588, 232–238 (2020)

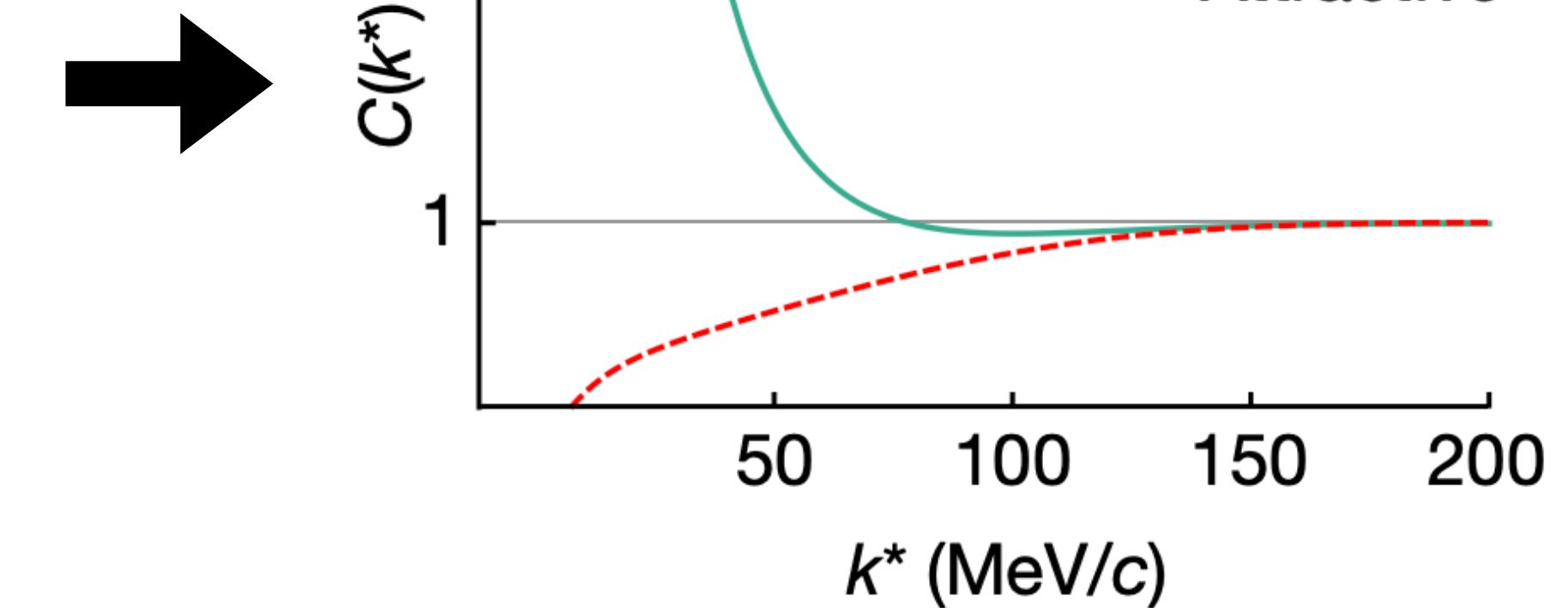
# Femtoscopy



Emission source  $S(r^*)$



Interaction  
Schrödinger equation  
Two-particle wave function  
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Correlation function  $C(k^*)$

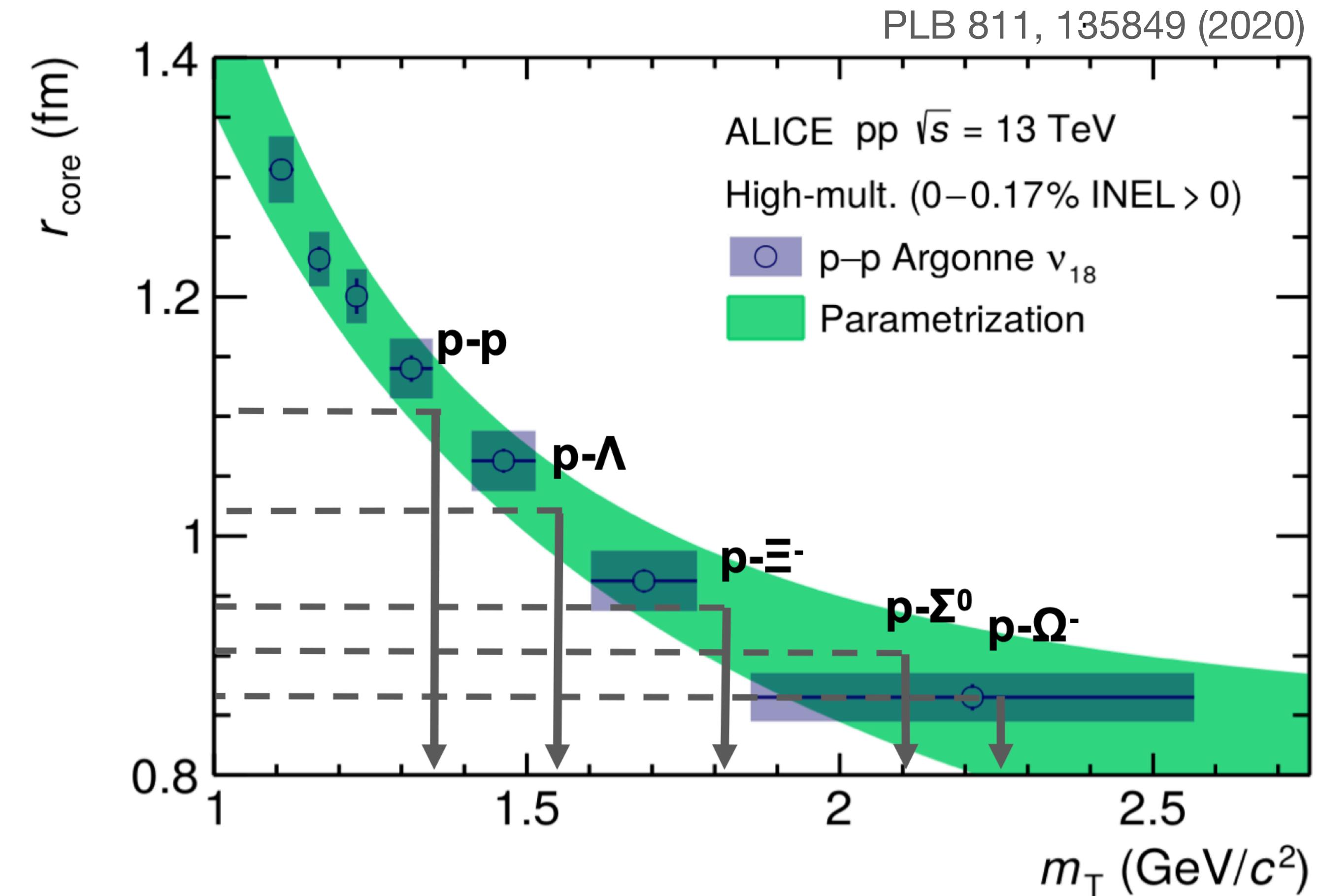
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# Emission source

- Two main contributions:
  - general: Collective effects result in Gaussian core
  - specific: Decaying resonances require source correction
- Access to very small distances in pp collisions at the LHC

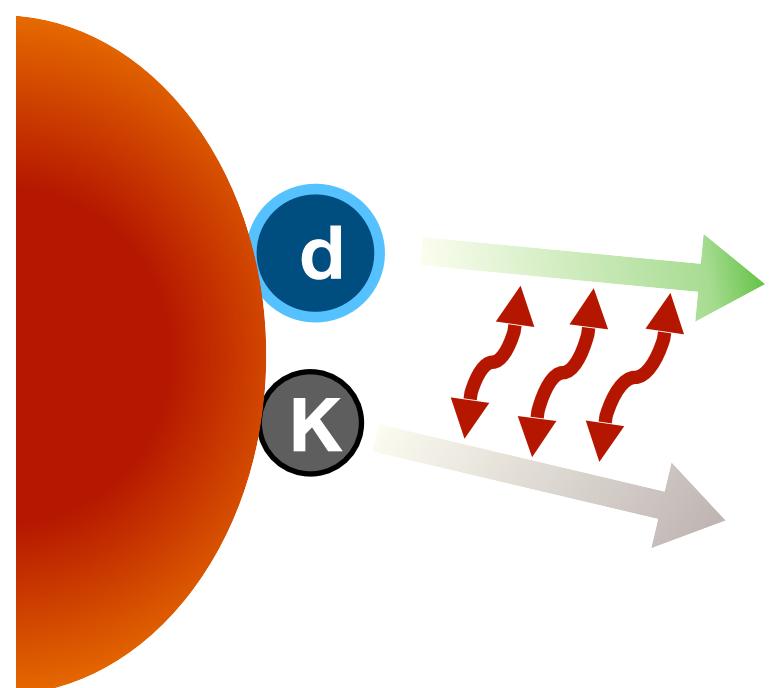
Talks by Dimitar Mihaylov and Maximilian Korwieser on Monday



# Kaon-deuteron correlation

- Effective two-body system
  - Coulomb + Strong interactions via Lednický model; only s-wave  
R. Lednický, Phys. Part. Nuclei 40, 307–352 (2009)
  - Anchored to scattering experiments
  - Emission source: from  $m_T$  scaling

$$r_{\text{eff}}^{\text{Kd}} = 1.41^{+0.03}_{-0.06} \text{ fm}$$

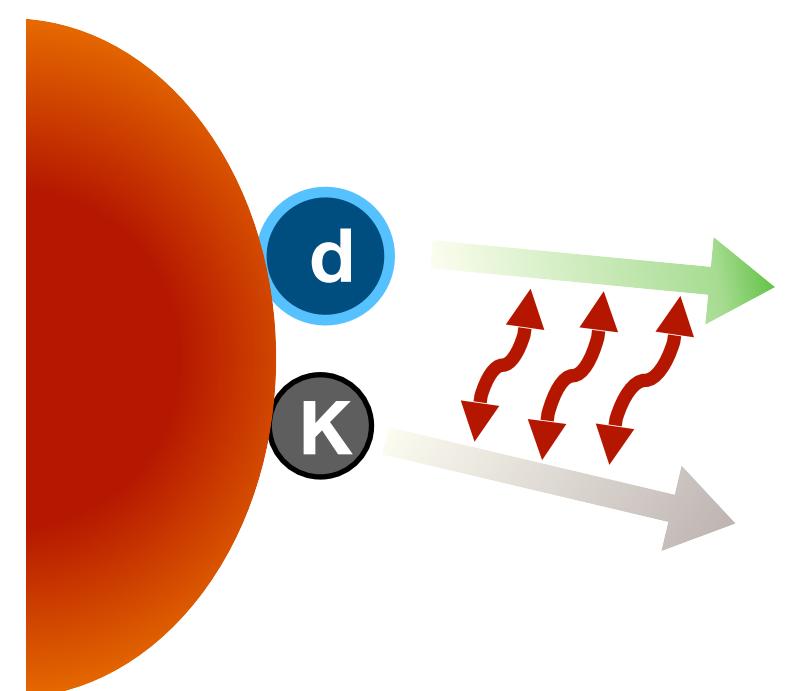


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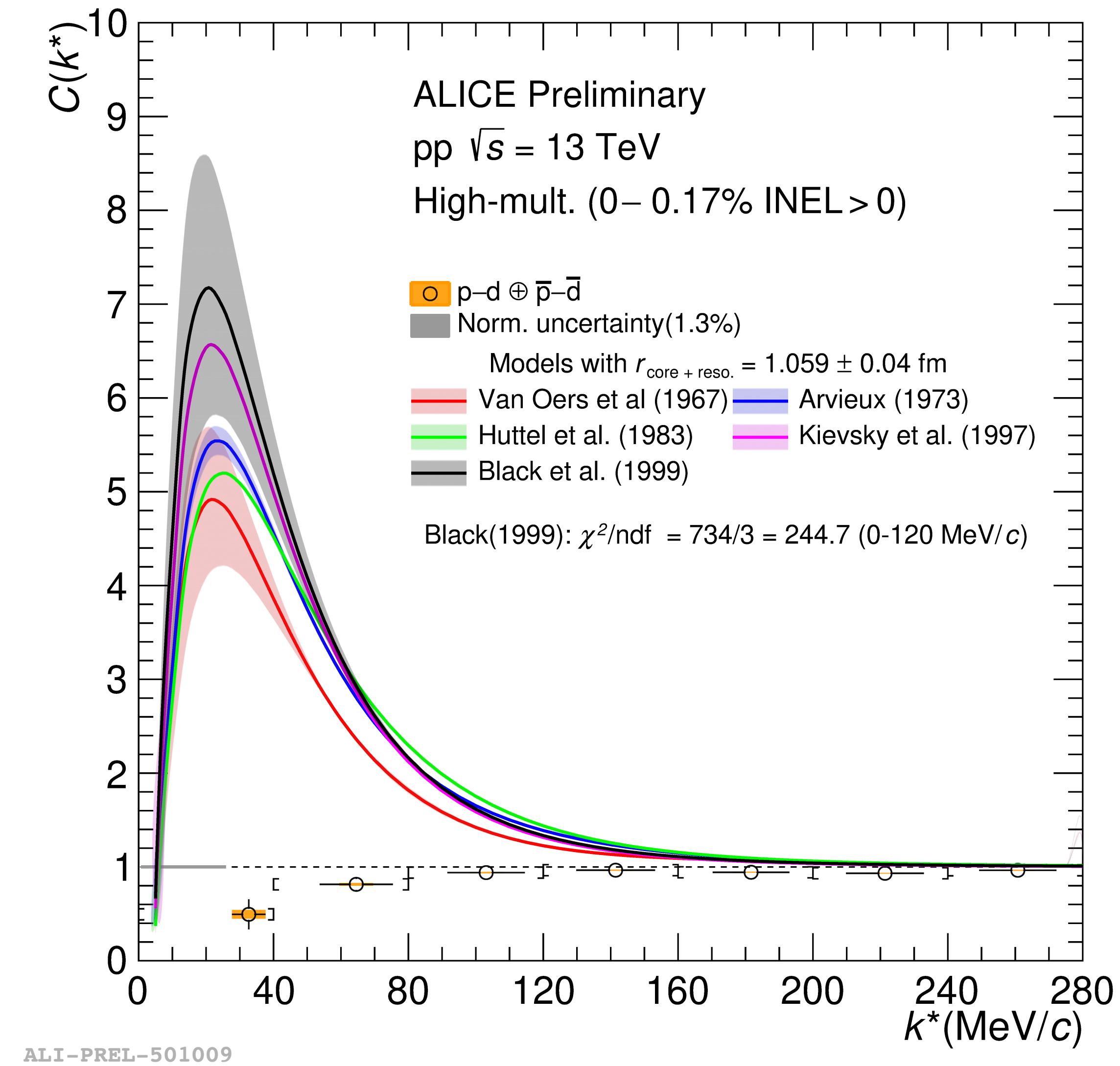
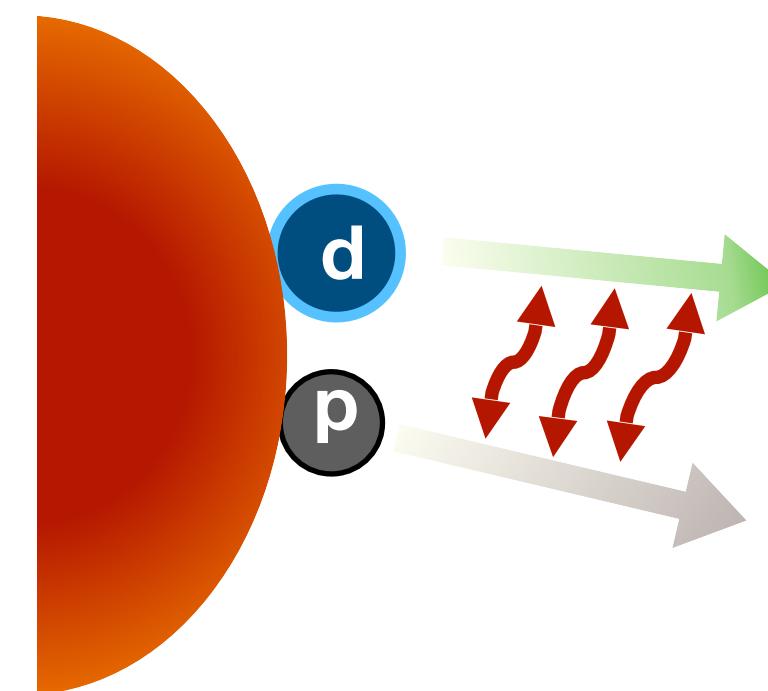
$\text{K}^+$  - d system can be described as two body!  
Source from universal scaling works!



# Proton-deuteron correlation

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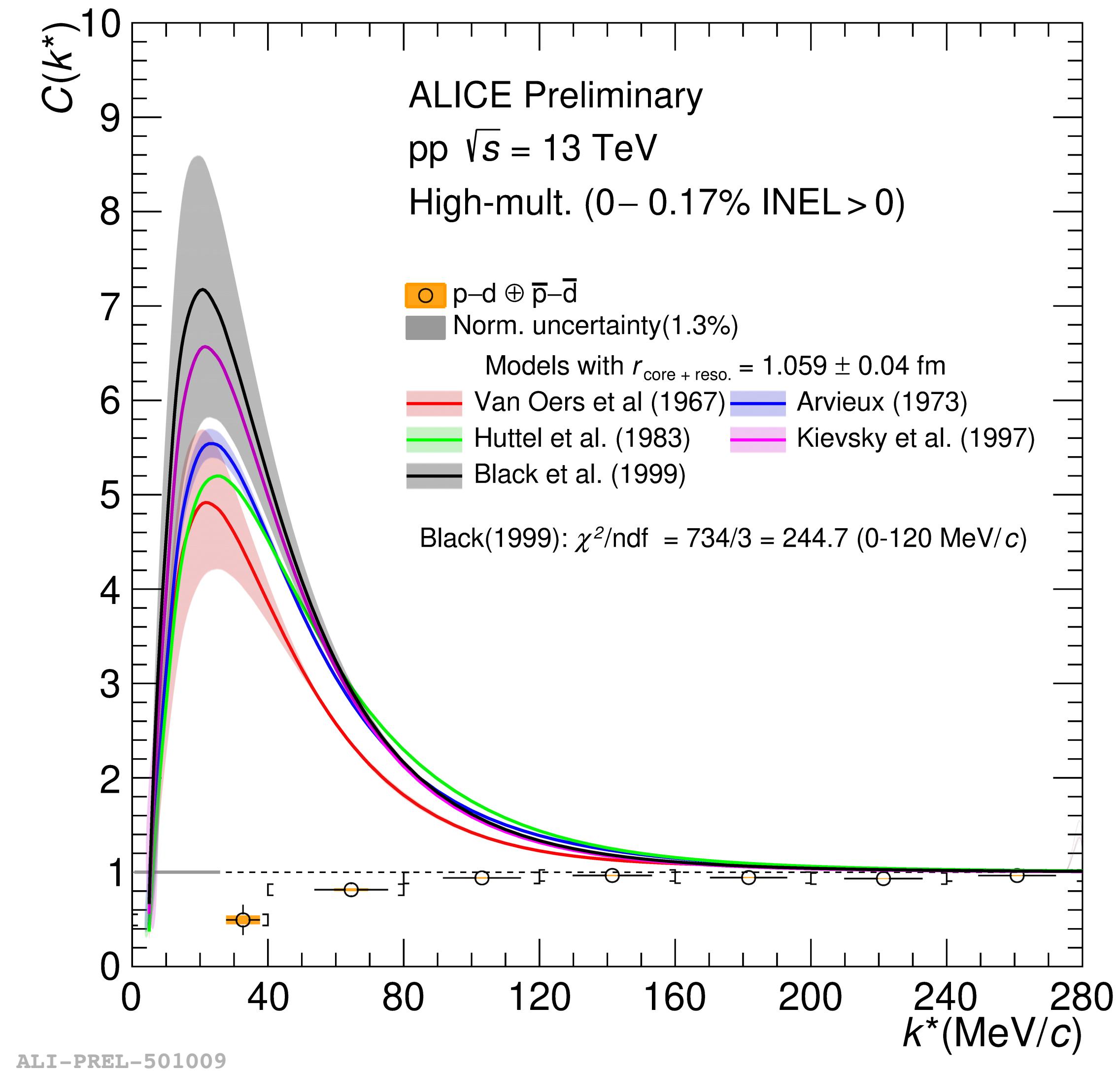
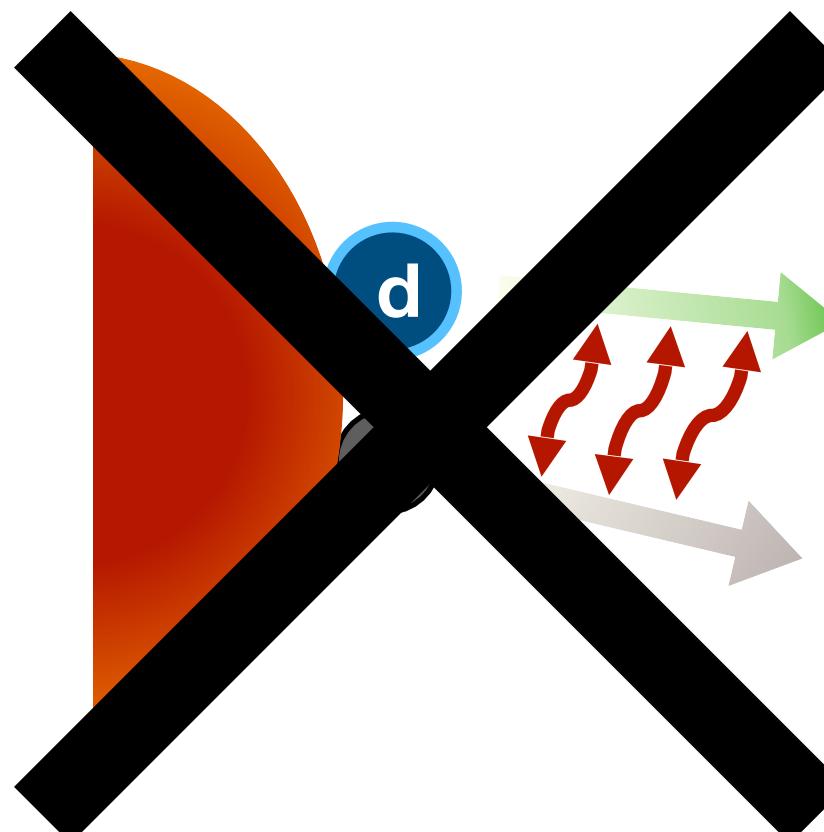
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Such model does not describe the data  
→ can't be modelled as effective two-body system!

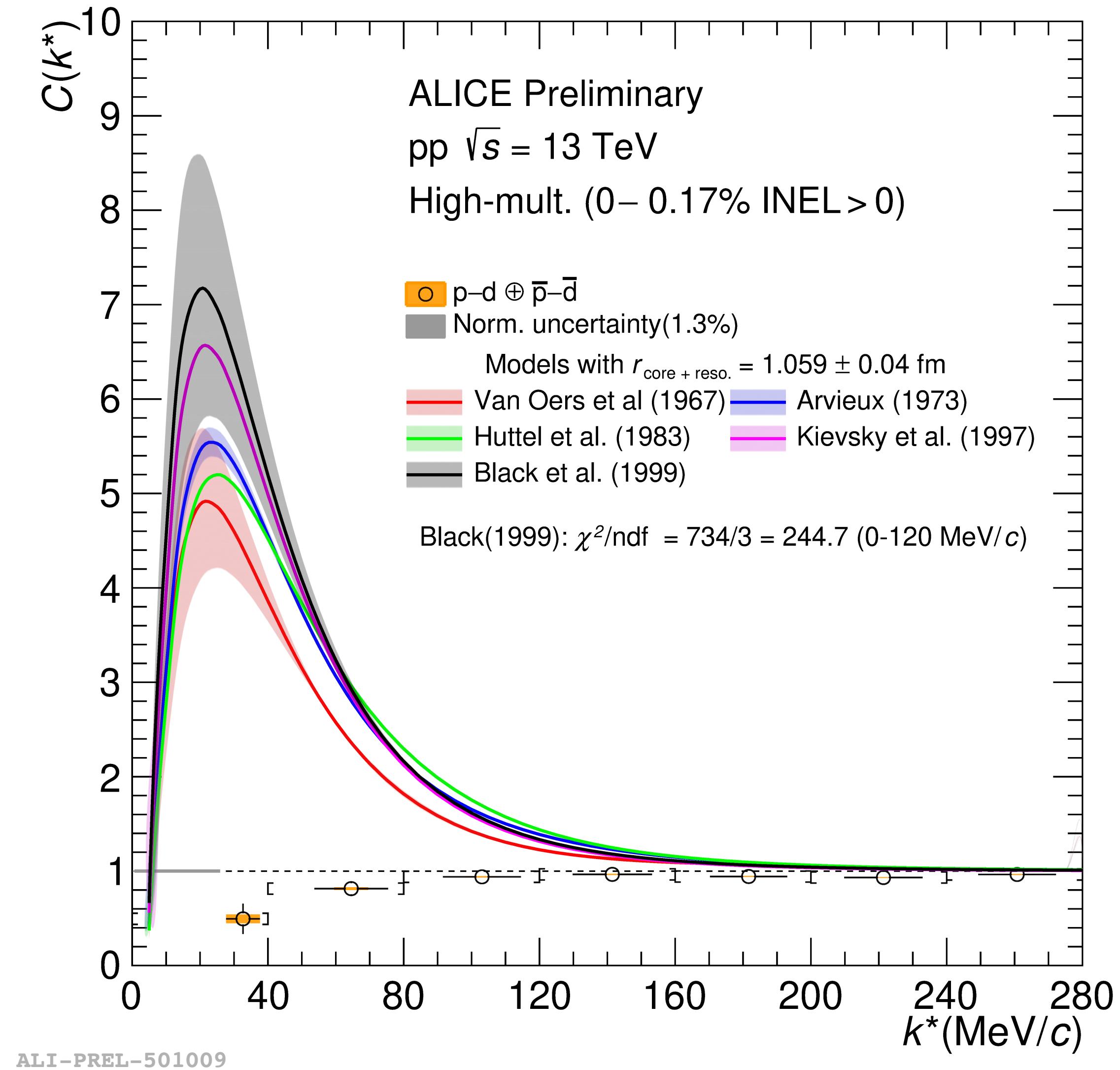
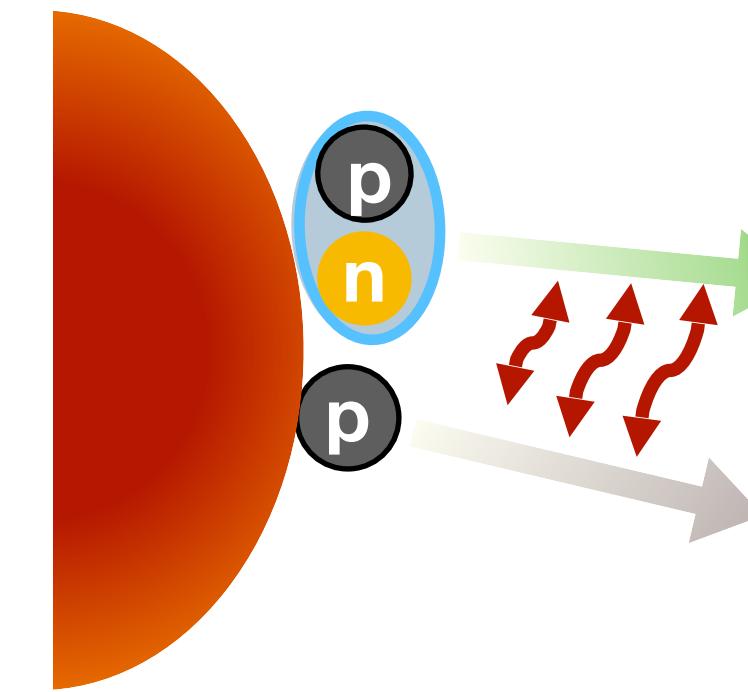
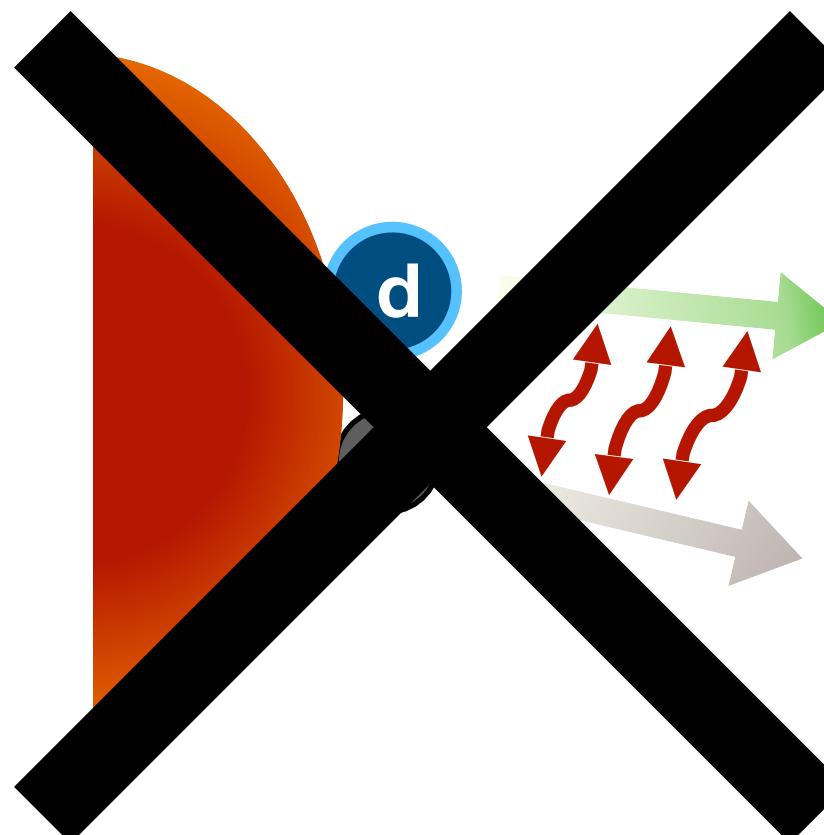


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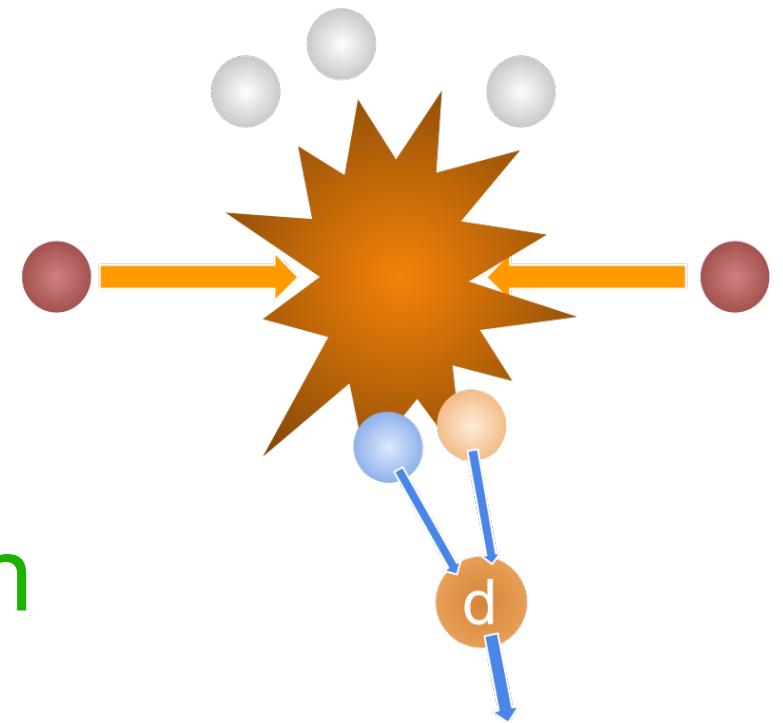
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# Three-body dynamics

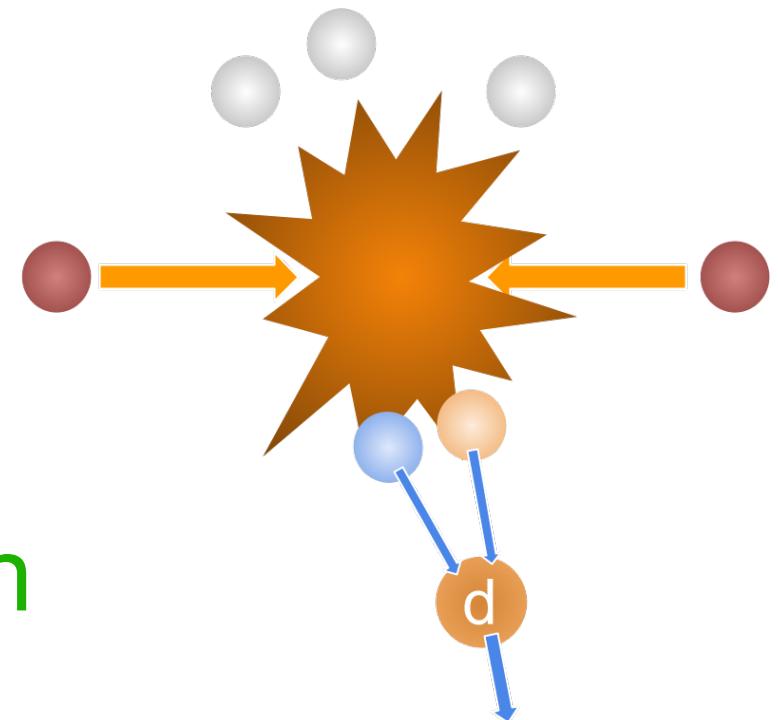
- Start with p-p-n state:
  - single-particle Gaussian emission source
  - three-nucleon wave function asymptotically behaves as p-d state
  - account for the probability to form deuteron employing deuteron wave function



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

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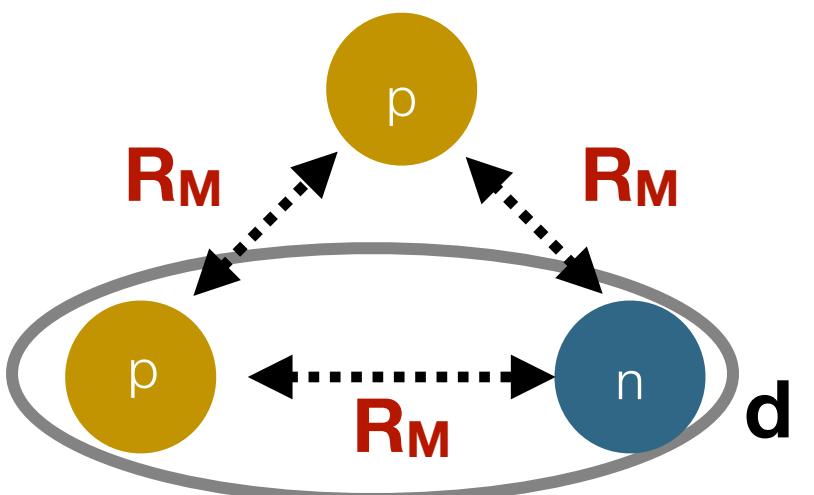
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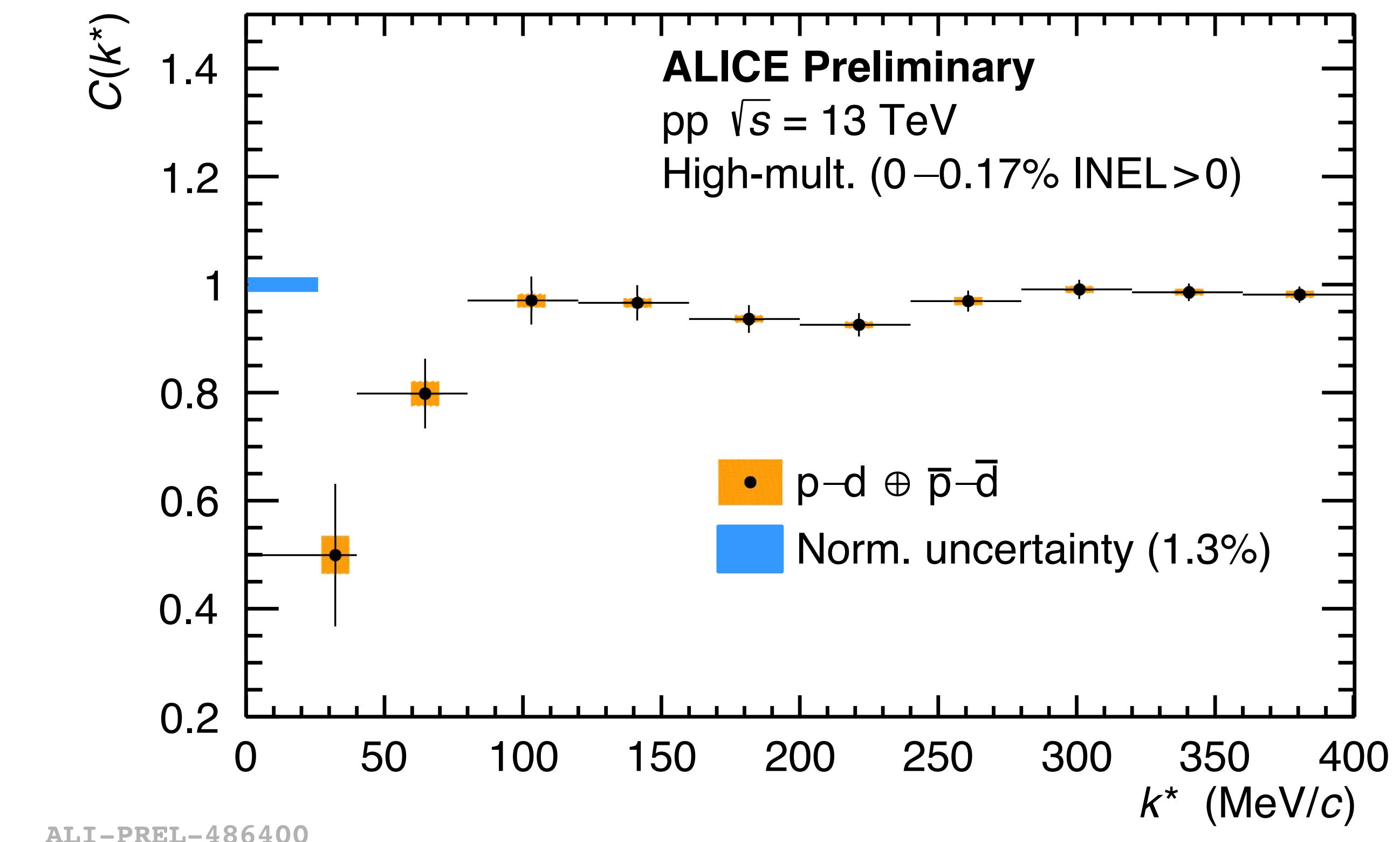
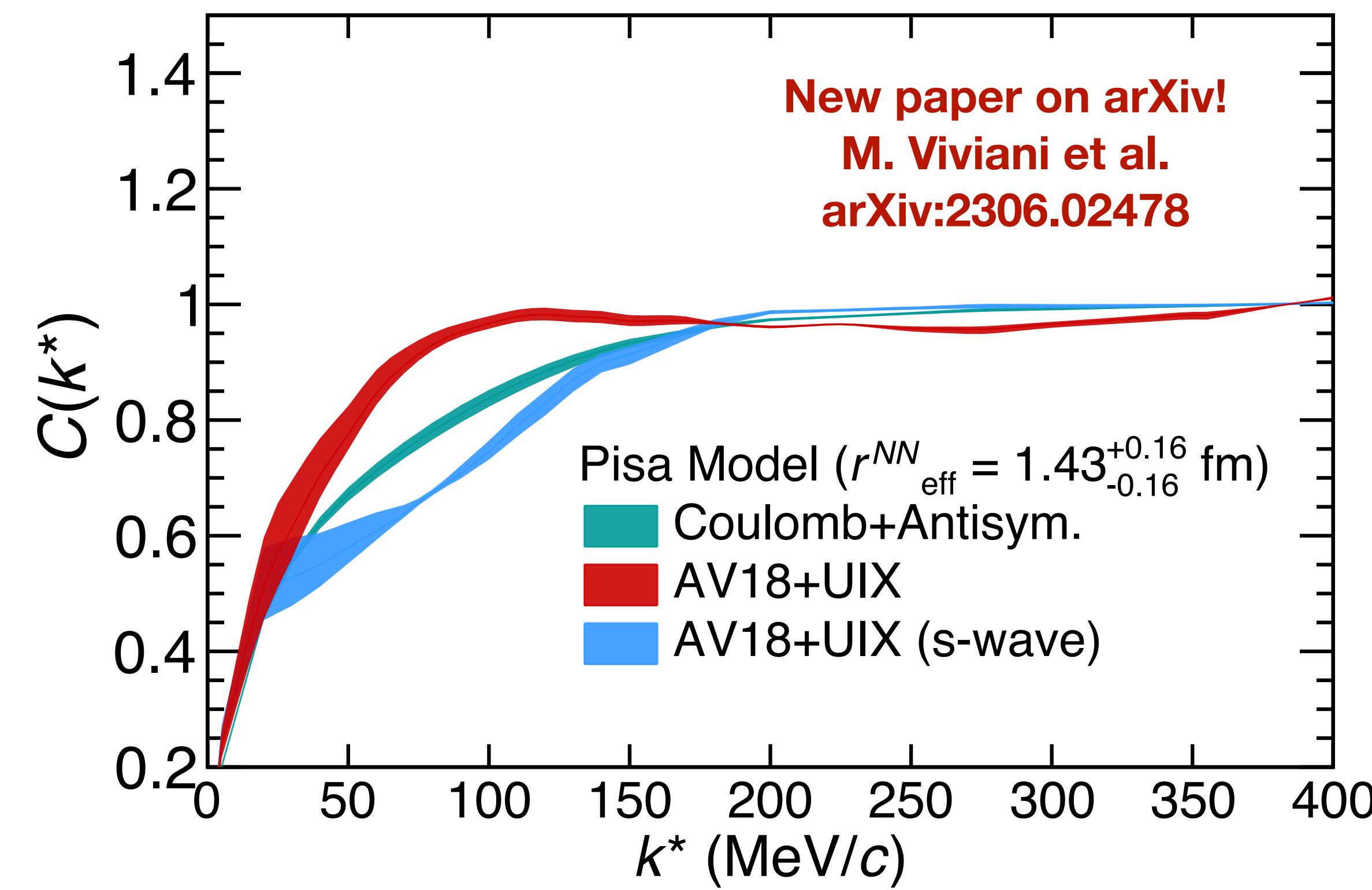
- Rewritten as a function of the known source size  $R_M$  constrained by p-p

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



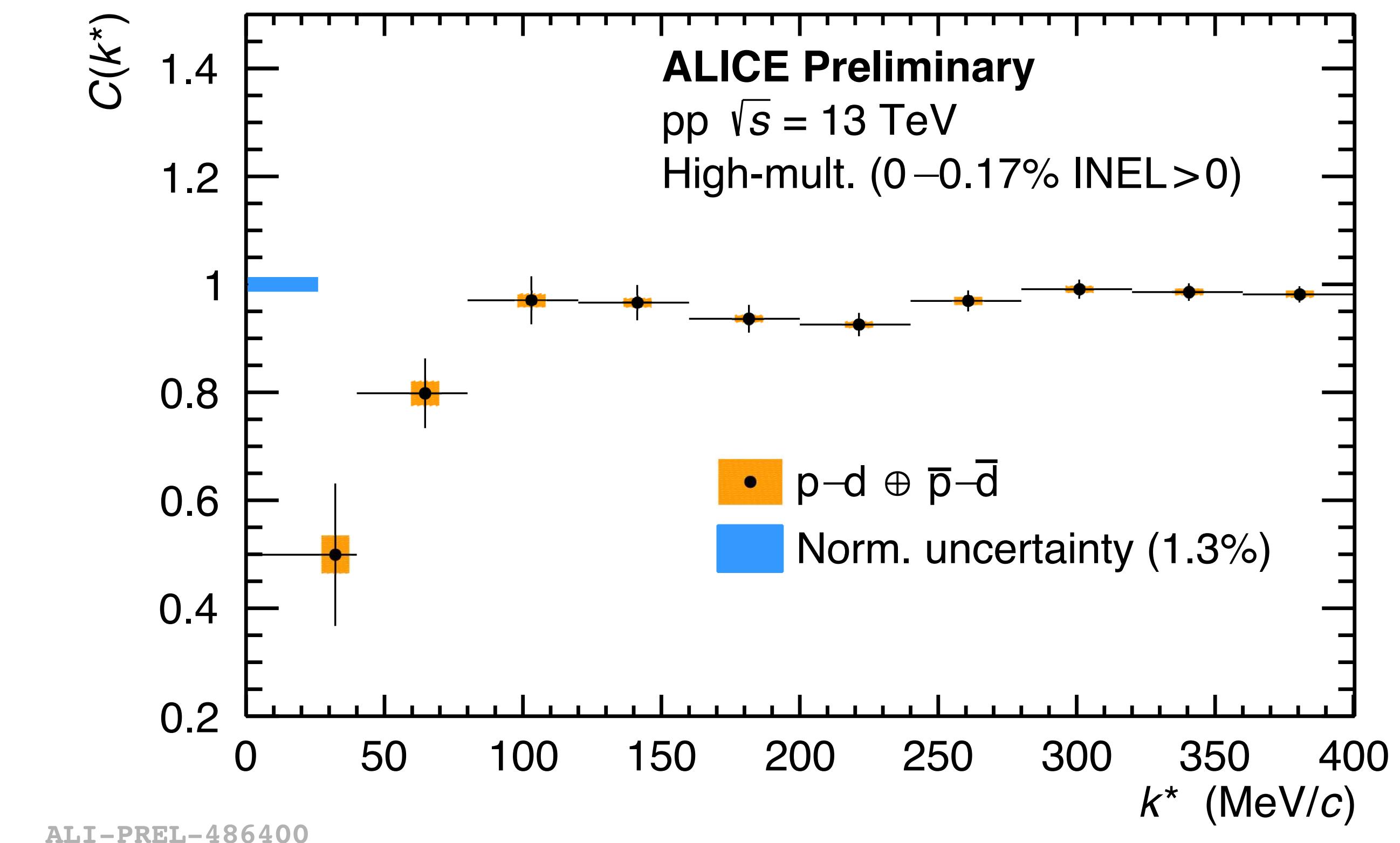
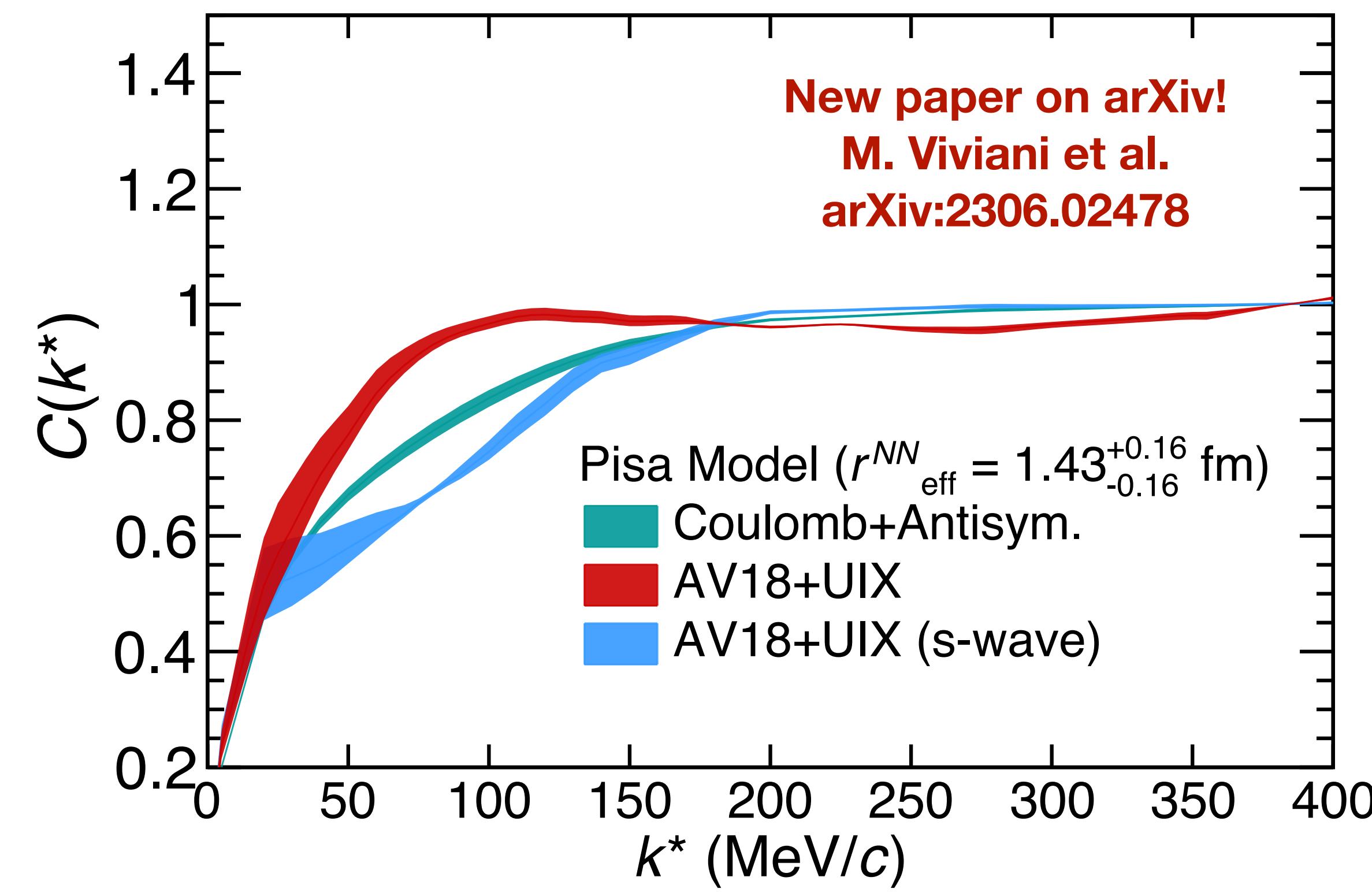
# Three-body dynamics in p-d system

- Modelling of the p-d correlation function as a three-body system can describe the data well  
→ Includes two-body (AV18) and three-body (UIX) interactions



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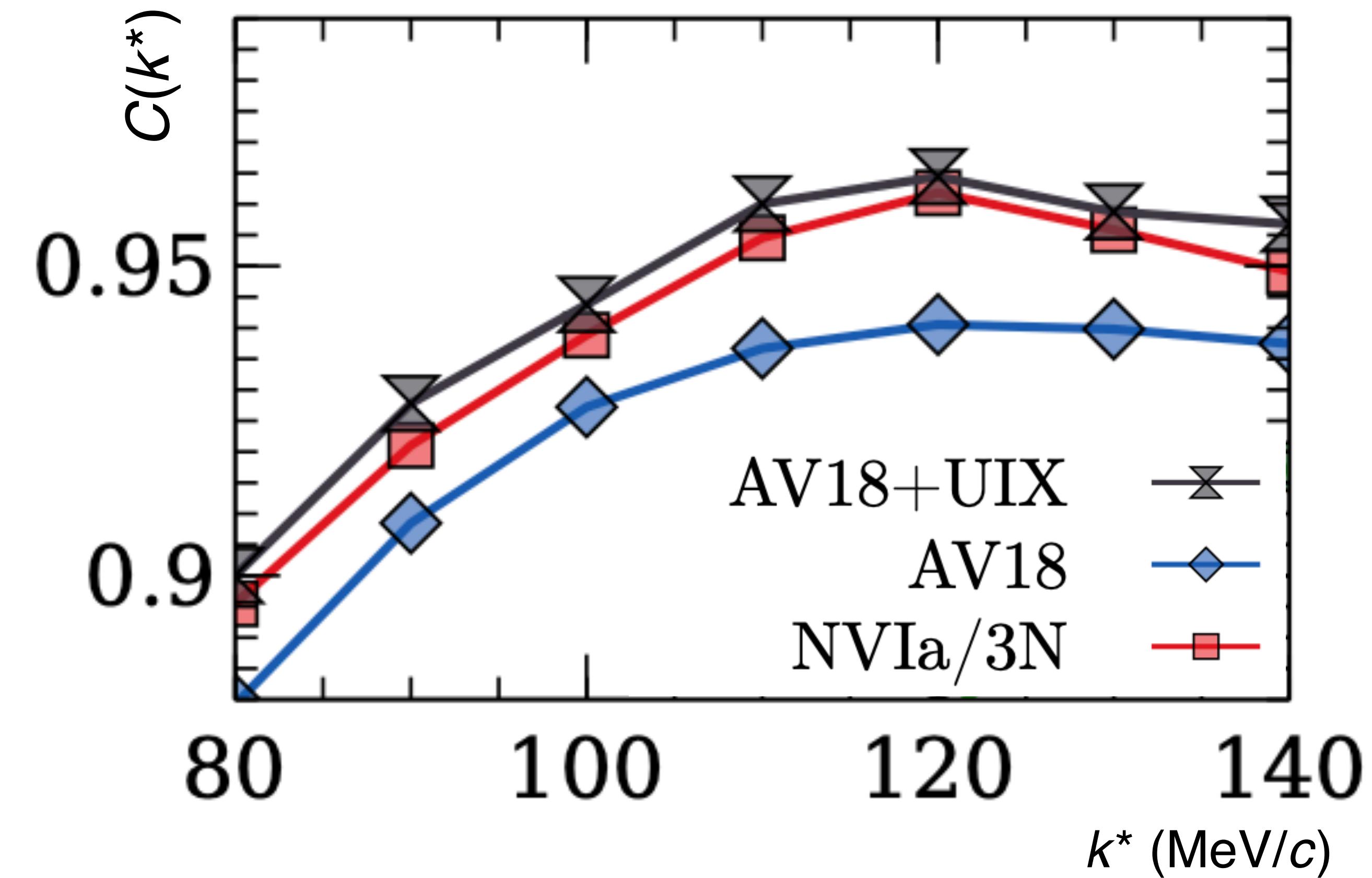
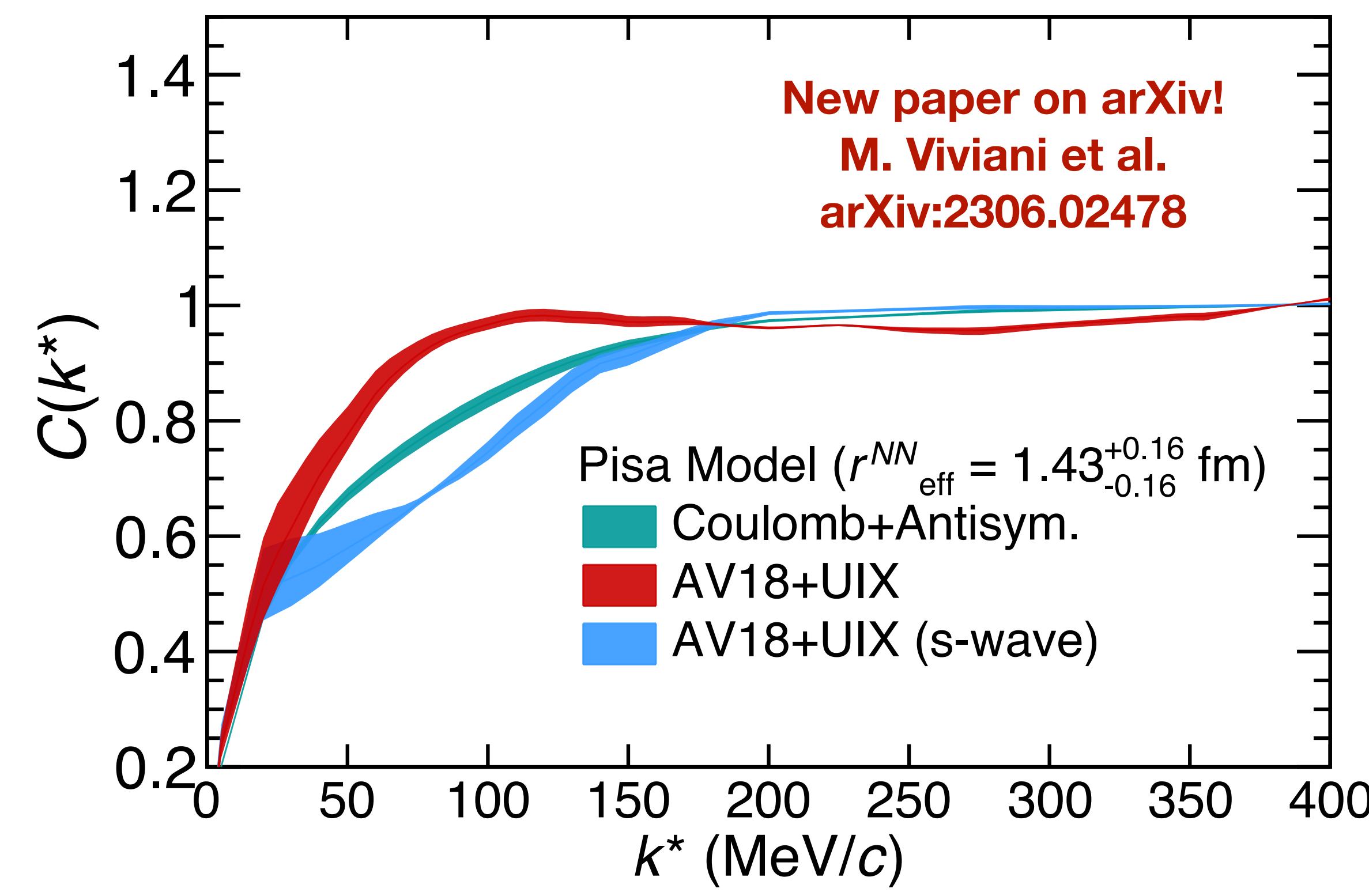
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System sensitive to the three-body dynamics and also the three-body interaction!

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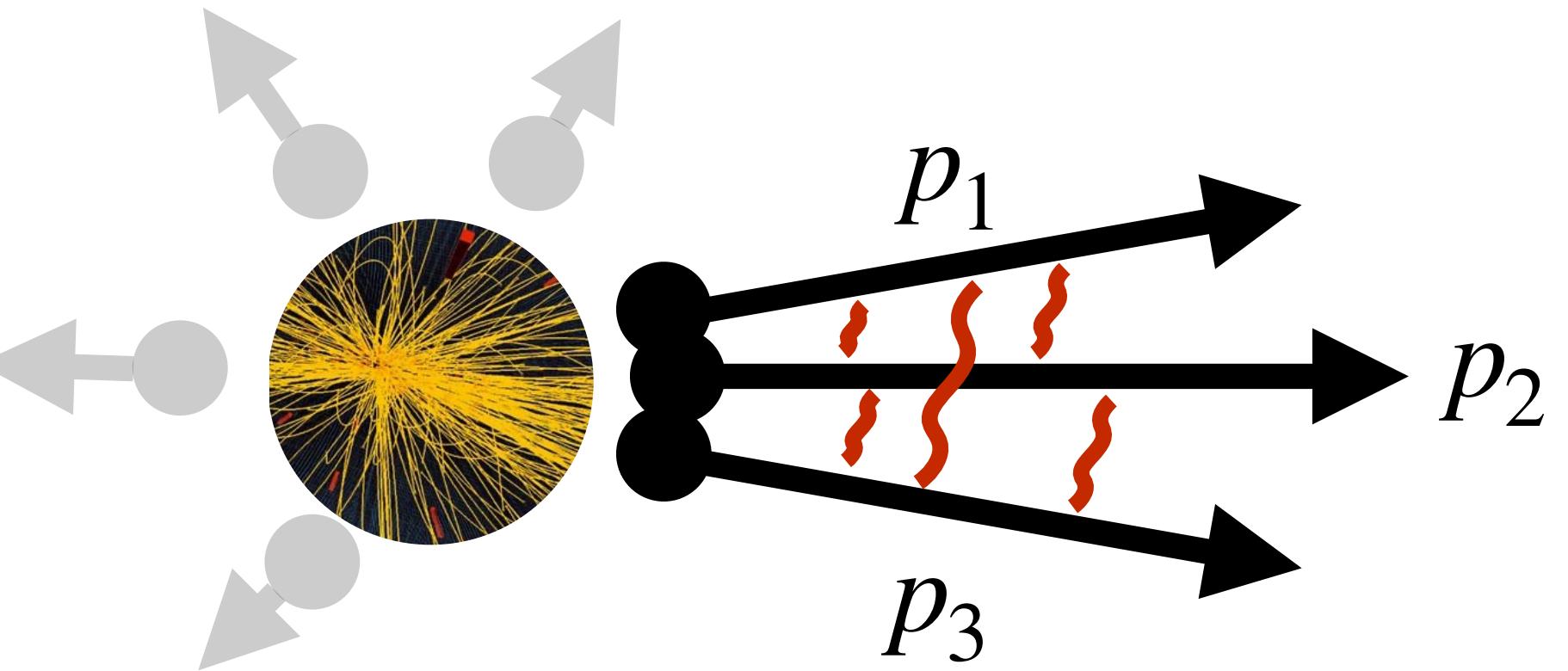
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# Three-particle femtoscopy

- Experimental three-particle correlation function

$$C(Q_3) = \mathcal{N} \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

$$Q_3 = \sqrt{-q_{ij}^2 - q_{jk}^2 - q_{ki}^2}$$

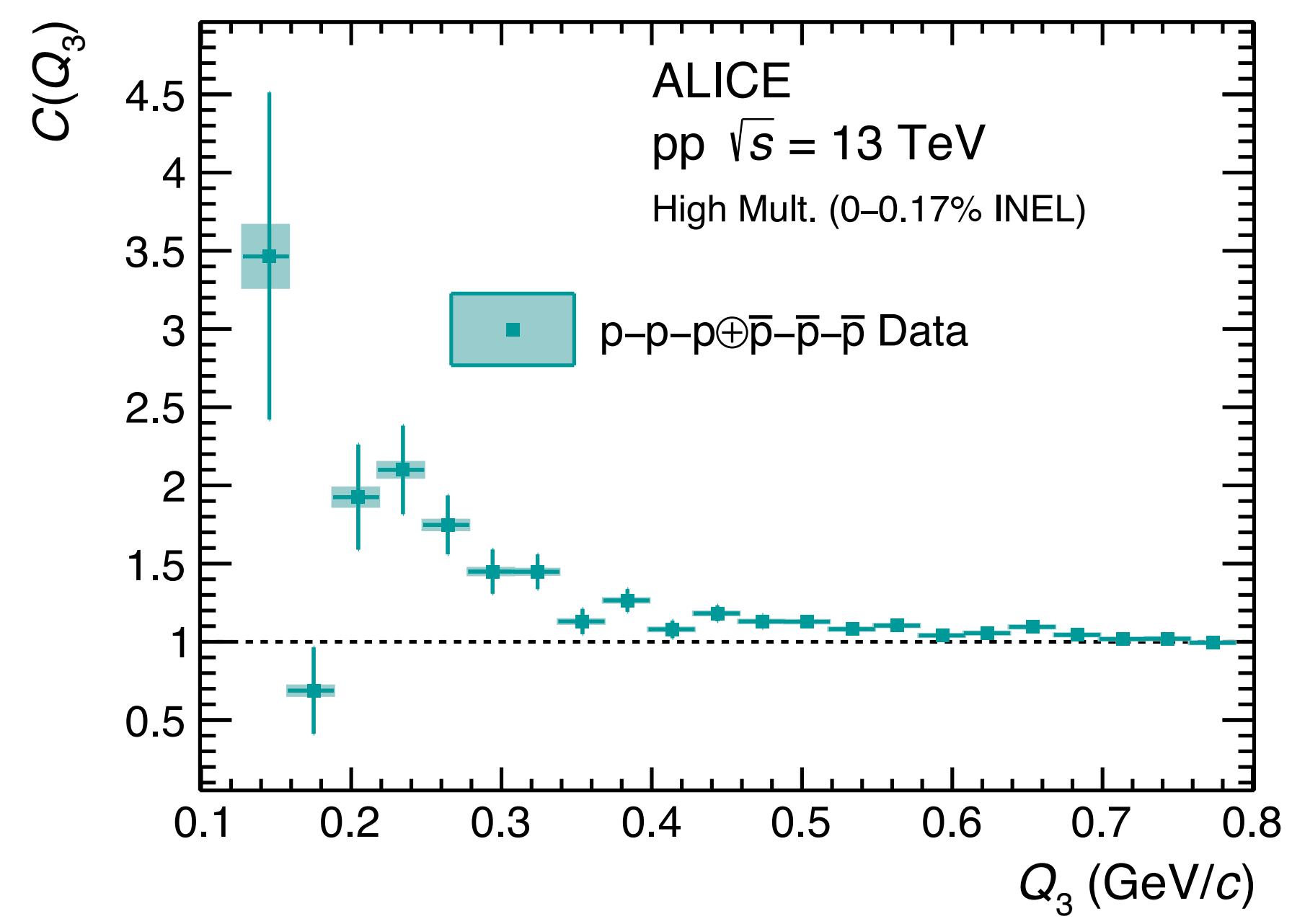
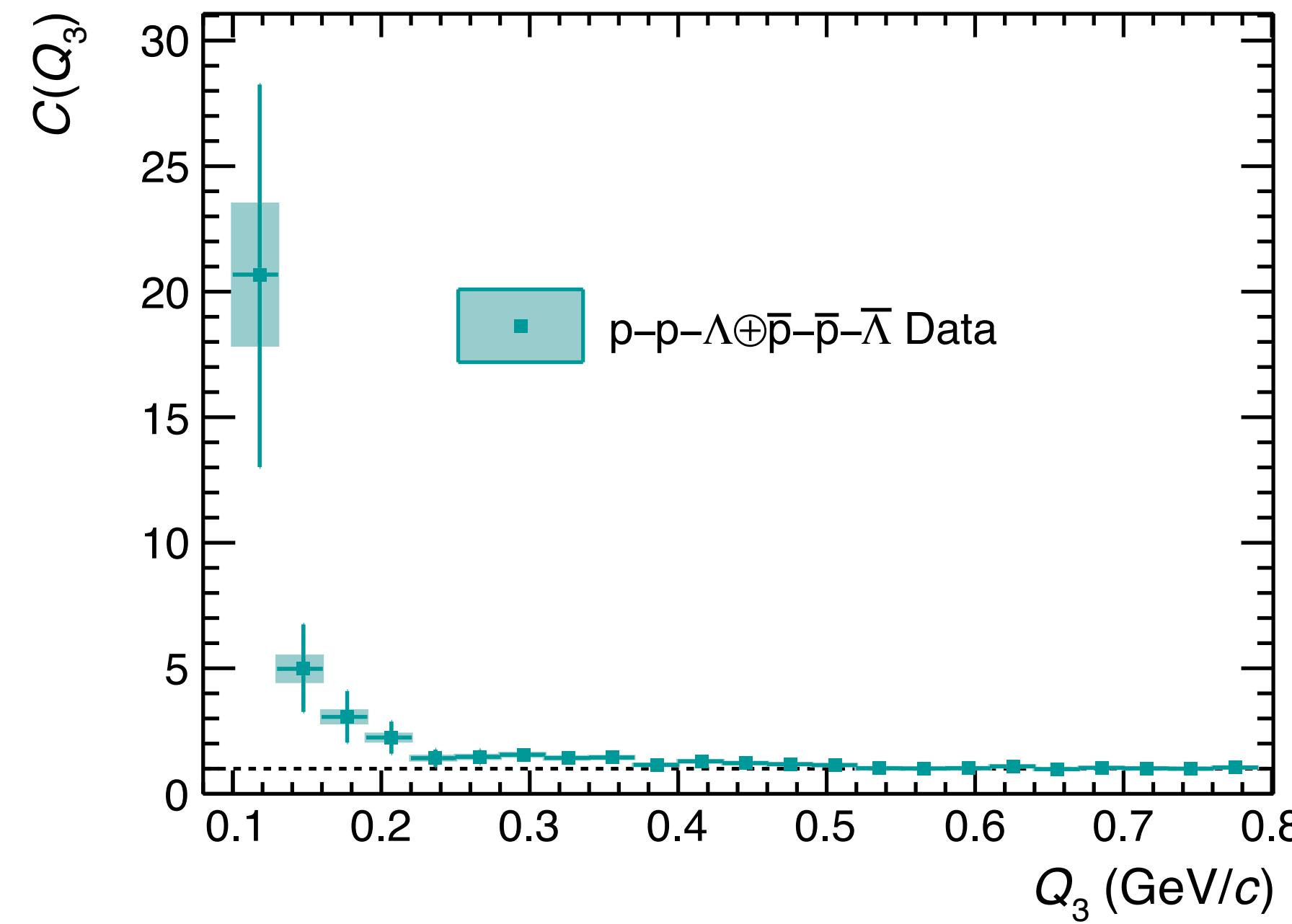
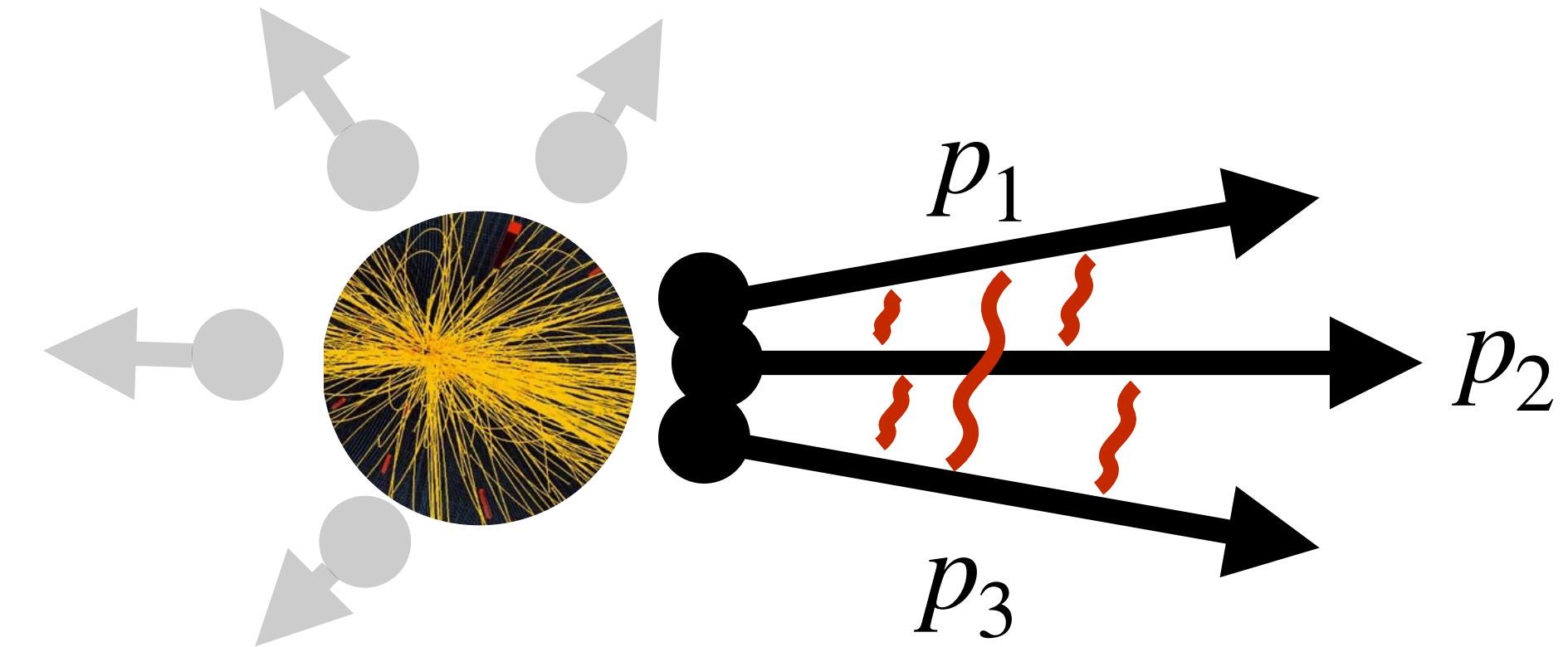


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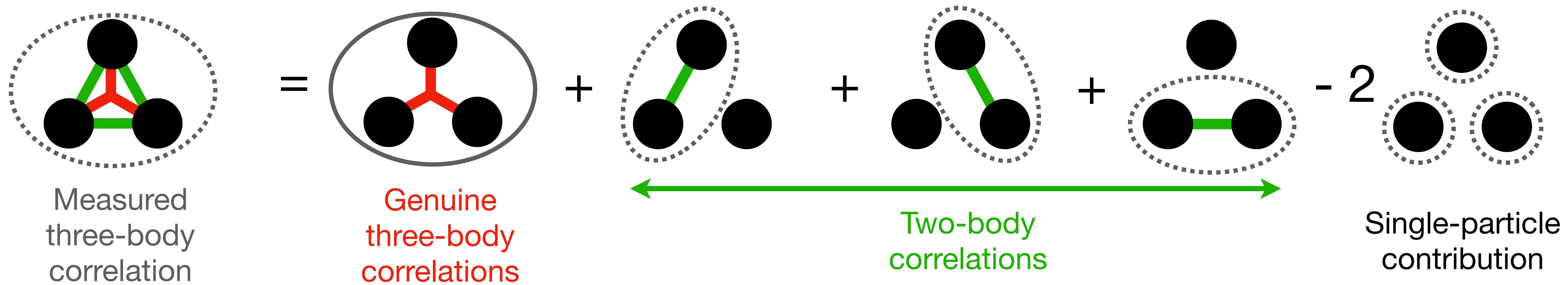
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# Cumulants in femtoscopy

The total three-particle correlations can be expressed as a sum of genuine three-body correlation and the lower-order contributions employing Kubo's cumulants [1]:



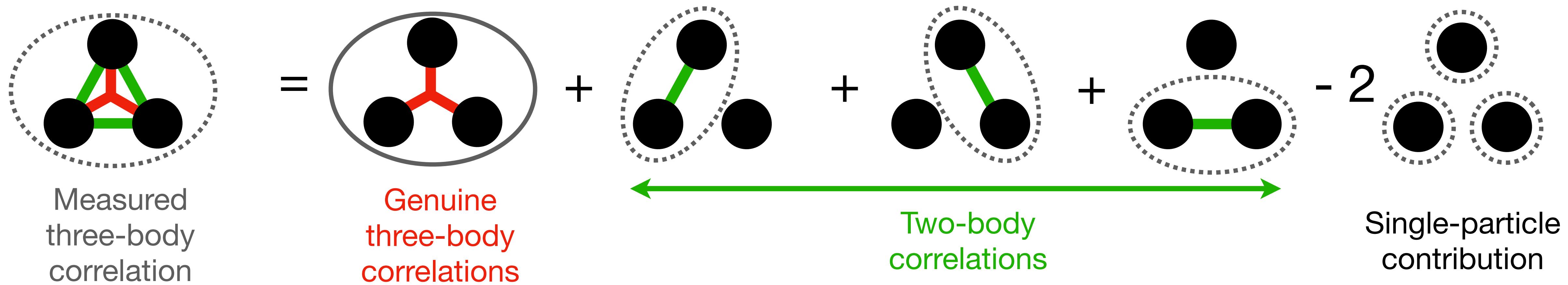
In terms of correlation functions:

$$c_3(Q_3) = C(Q_3) - C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2$$

[1] R. Kubo, J. Phys. Soc. Jpn. 17, 1100-1120 (1962)

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Lower-order  
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# Lower-order contributions

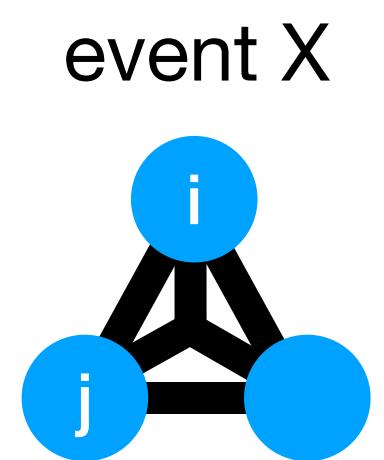
## Data-driven method

- Use event mixing
- Two particles from the same event and one particle from another:

# Lower-order contributions

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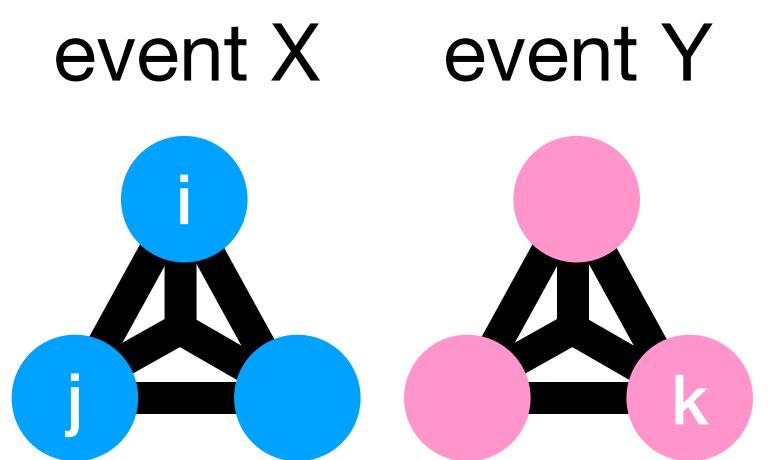
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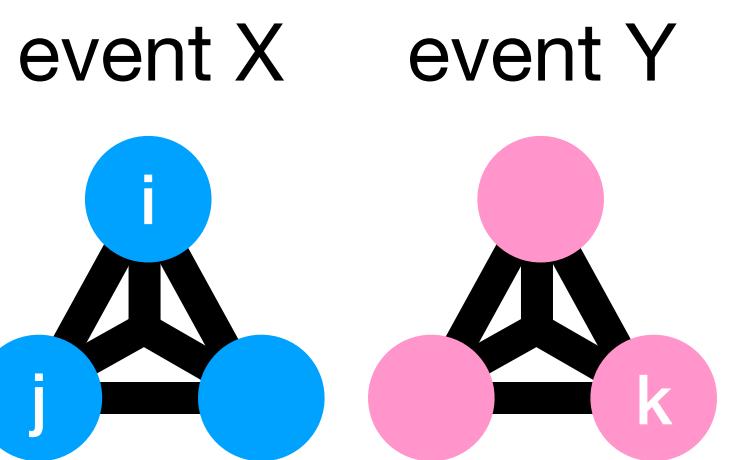
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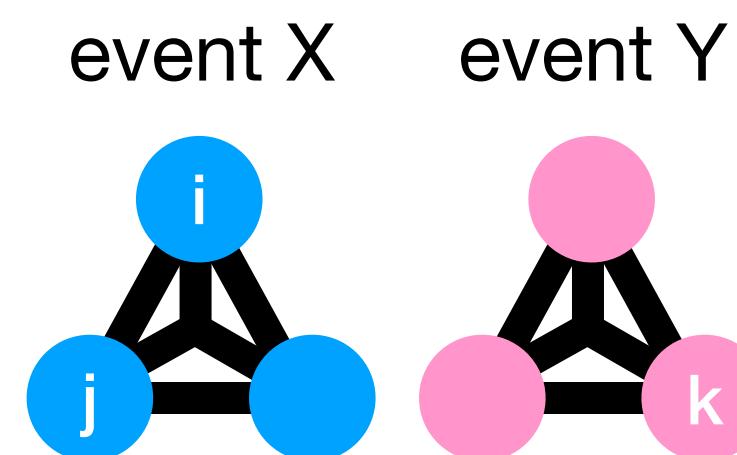
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- Calculate Lorentz-invariant scalar  $Q_3$  for every triplet  $\mathbf{p}_i, \mathbf{p}_j, \mathbf{p}_k$  to obtain  $C_{ij}(Q_3)$

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## Projector method

- Use two-particle measured or theoretical correlation function  $C([\mathbf{p}_i, \mathbf{p}_j])$
- Perform kinematic transformation:

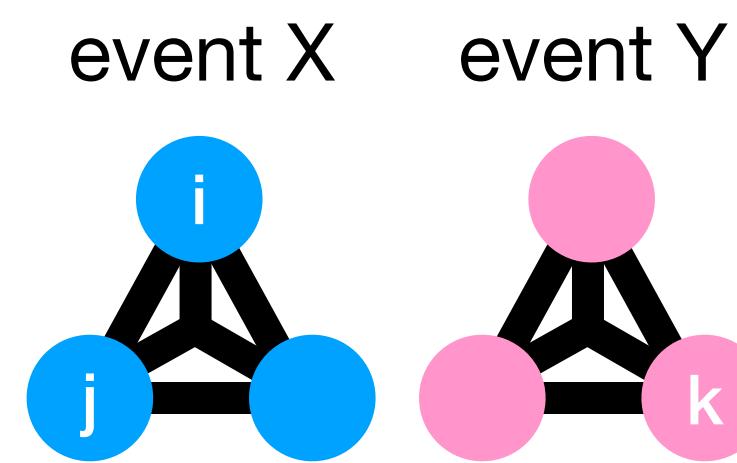
$$C_2 \left( k_{ij}^* \right) \rightarrow C_{ij} \left( Q_3 \right)$$

Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

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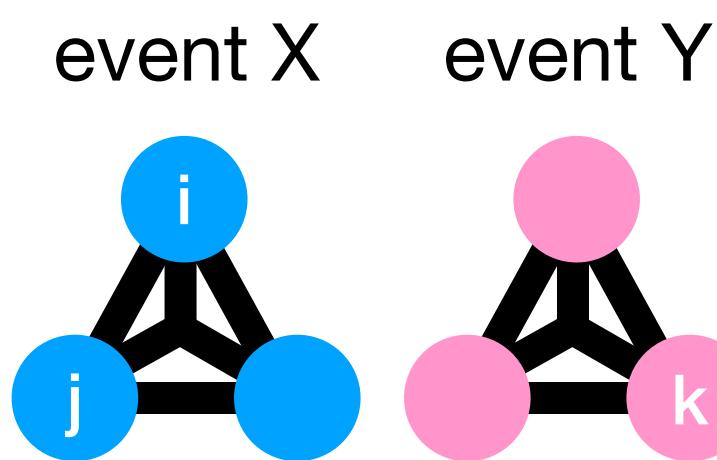
$$k_{ij}^* \text{ (pair)} \rightarrow Q_3 \text{ (triplet)}$$

For one  $Q_3$  value →

# Lower-order contributions

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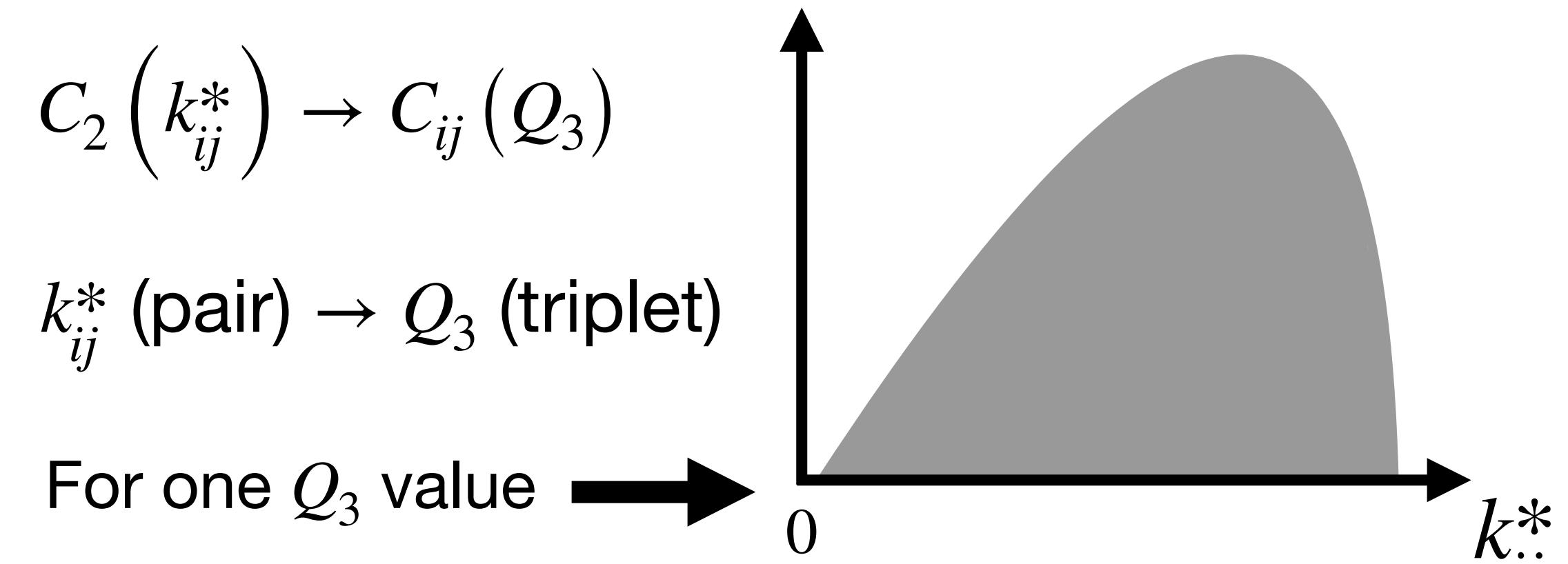
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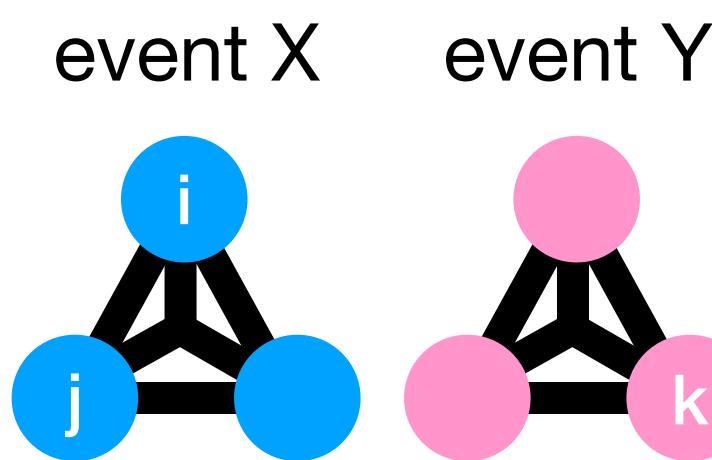
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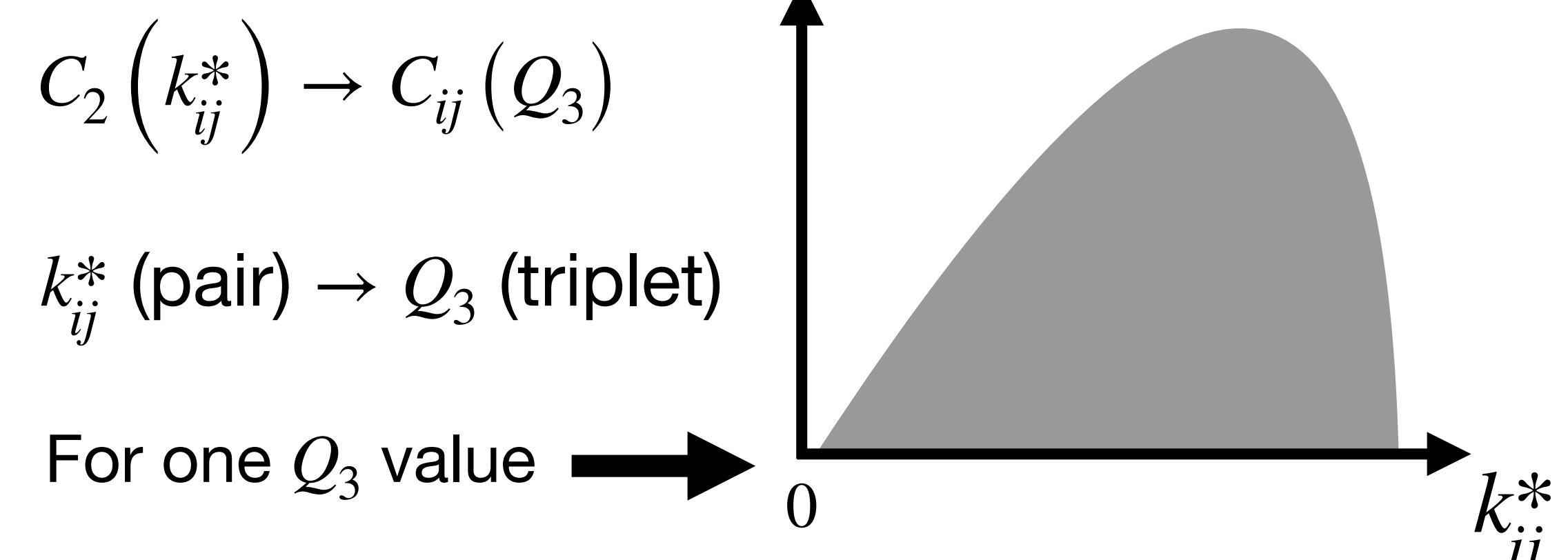


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- Perform kinematic transformation:



- To obtain the correlation function:

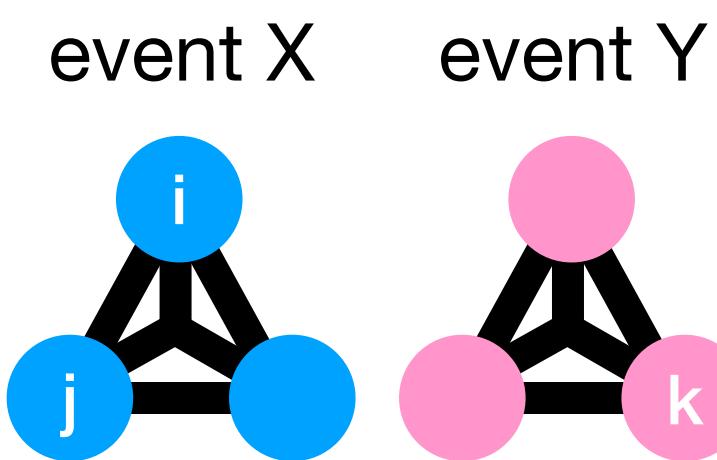
$$C_{ij}(Q_3) = \int C(k_{ij}^*) W_{ij}(k_{ij}^*, Q_3) dk_{ij}^*$$

Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

# Lower-order contributions

## Data-driven method

- Use event mixing
- Two particles from the same event and one particle from another:



$$C_{ij} \left( [\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k \right) = \frac{N_2(\mathbf{p}_i, \mathbf{p}_j) N_1(\mathbf{p}_k)}{N_1(\mathbf{p}_i) N_1(\mathbf{p}_j) N_1(\mathbf{p}_k)}$$

- Calculate Lorentz-invariant scalar  $Q_3$  for every triplet  $\mathbf{p}_i, \mathbf{p}_j, \mathbf{p}_k$  to obtain  $C_{ij}(Q_3)$

## Projector method

- Use two-particle measured or theoretical correlation function  $C([\mathbf{p}_i, \mathbf{p}_j])$
- Perform kinematic transformation:

$$C_2(k_{ij}^*) \rightarrow C_{ij}(Q_3)$$

$$k_{ij}^* \text{ (pair)} \rightarrow Q_3 \text{ (triplet)}$$

For one  $Q_3$  value

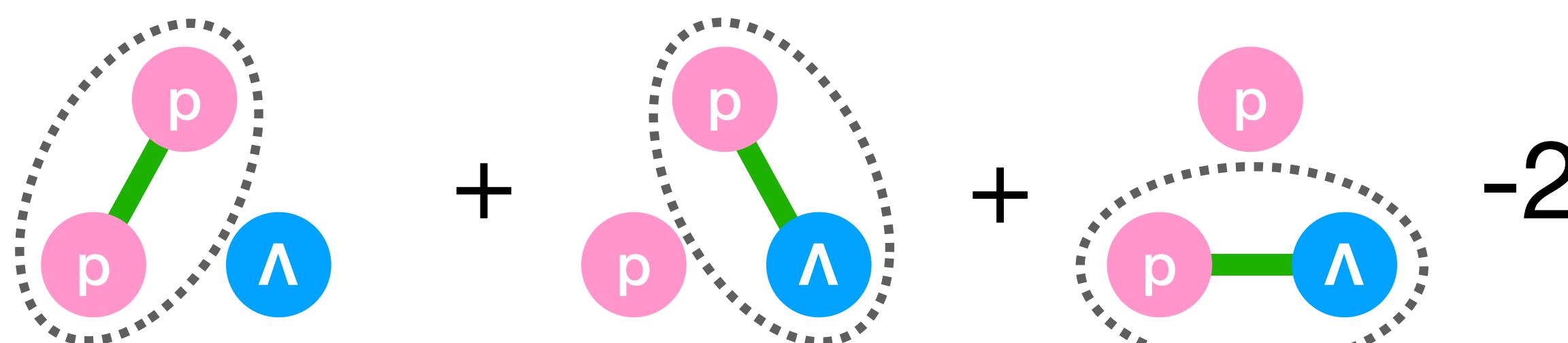
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Del Grande, Šerkšnytė et al. EPJC 82 (2022) 244

New Method!!!

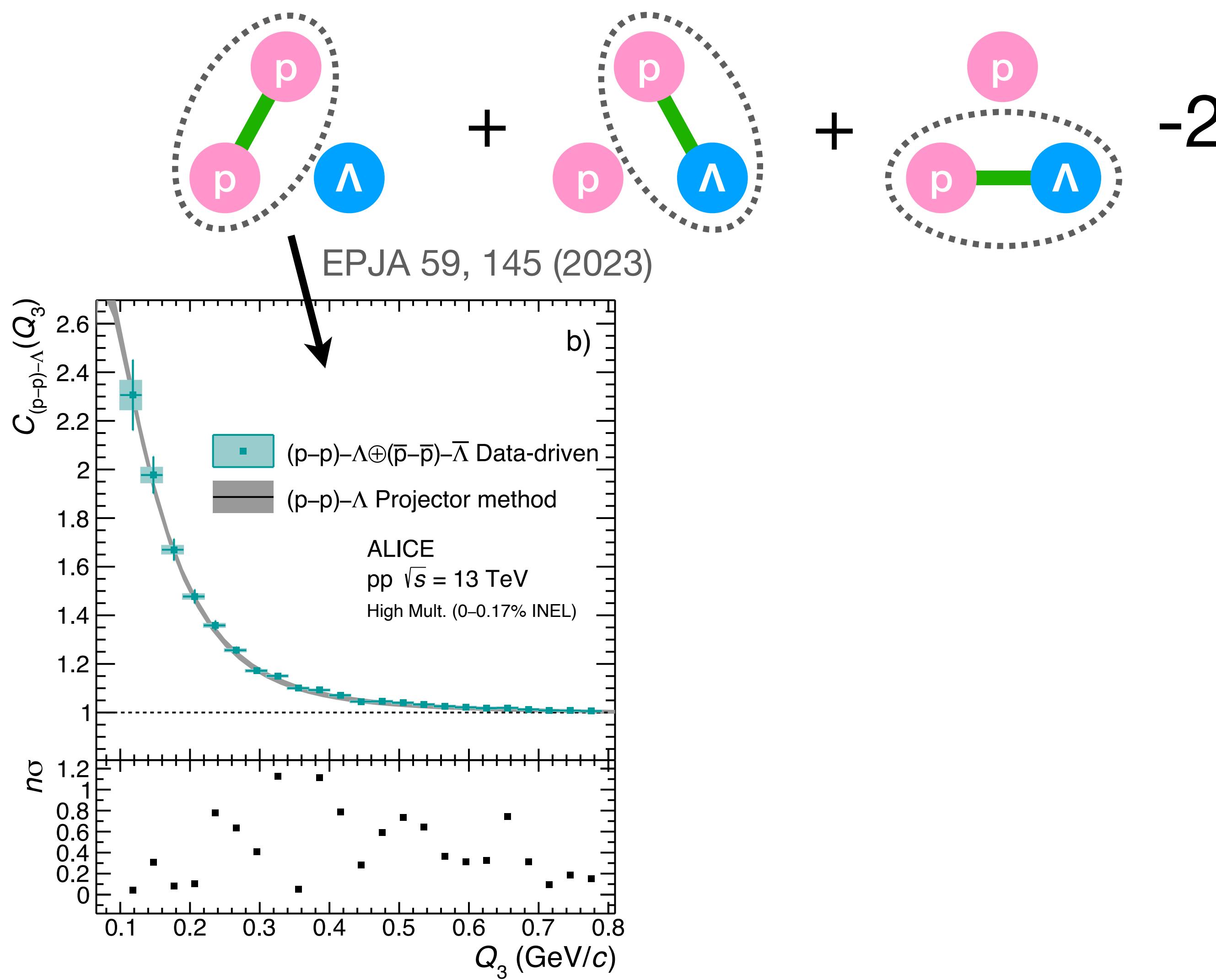
# Lower-order contributions: p-p- $\Lambda$



Already measured p-p [1] and p- $\Lambda$  [2] correlation functions used for projection

[1] PLB 805 (2020) 135419; [2] arXiv:2104.04427

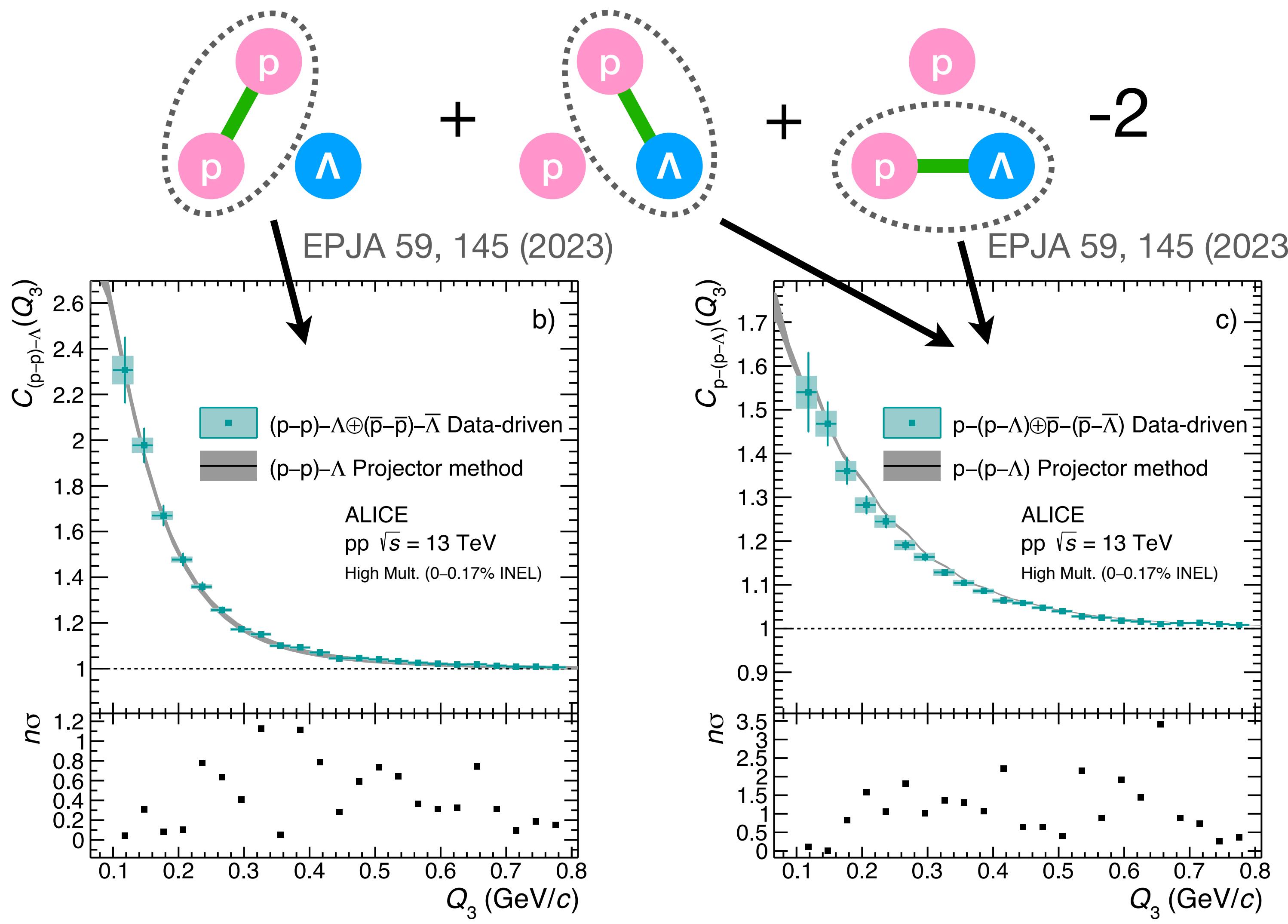
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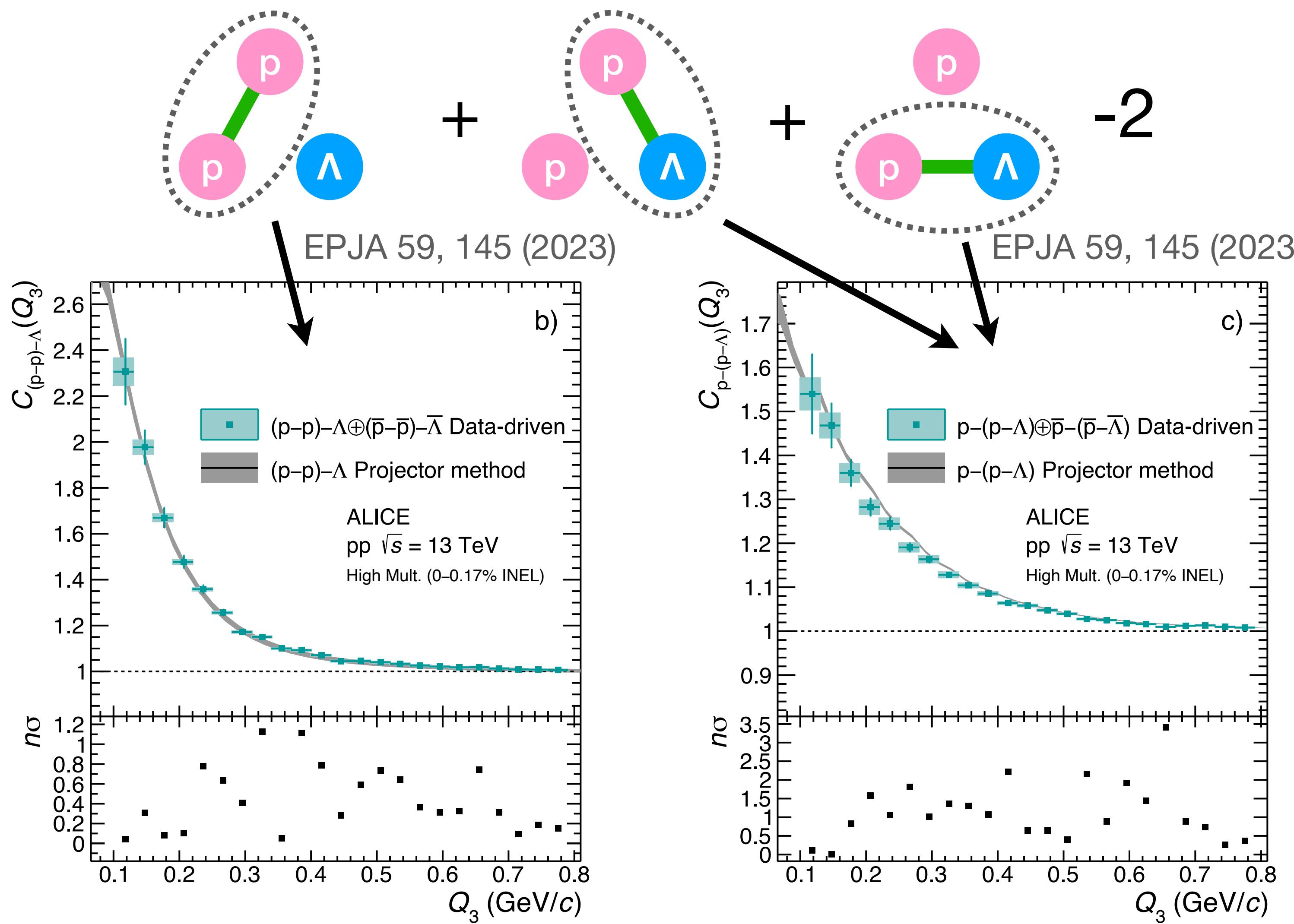
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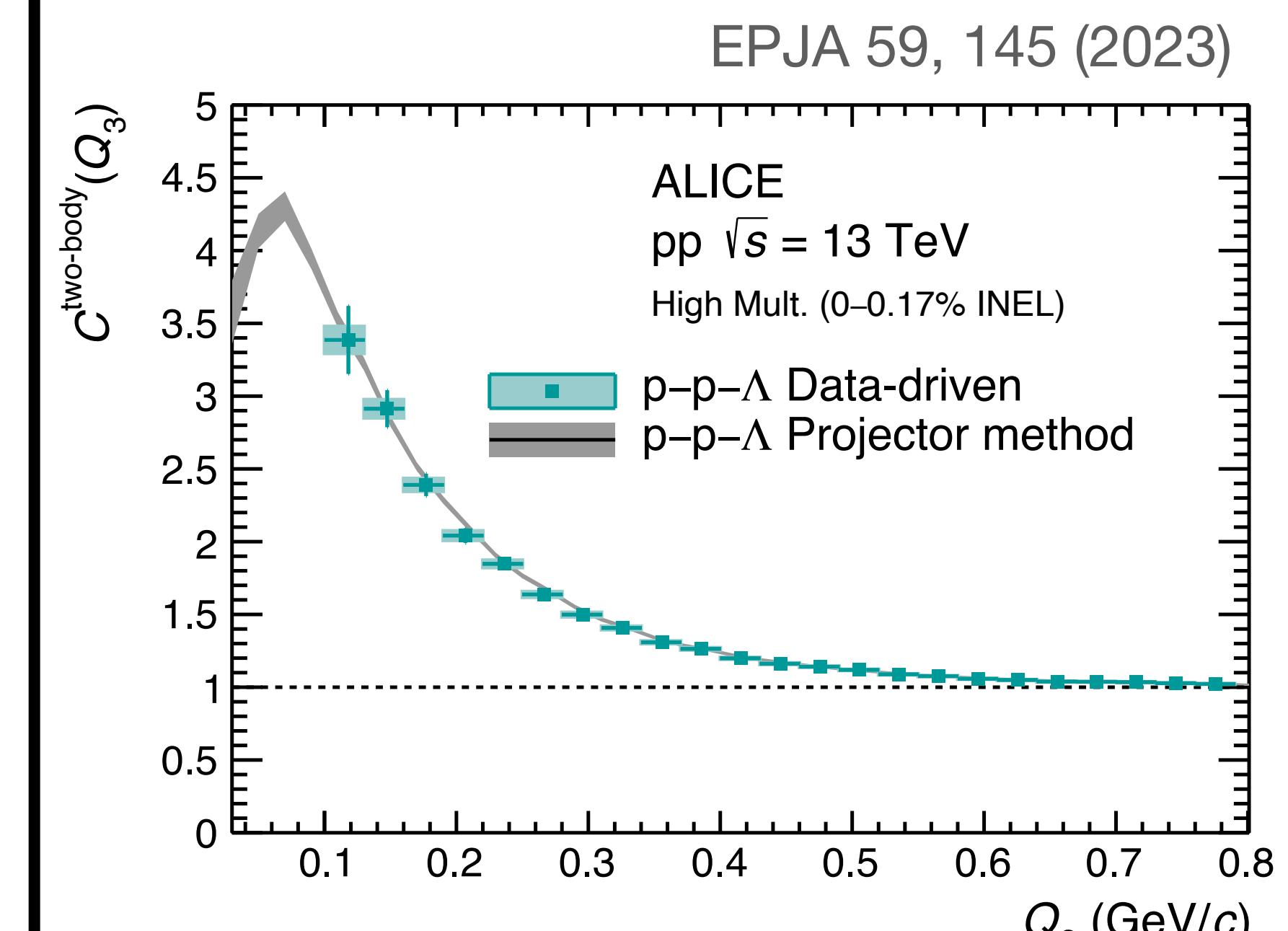
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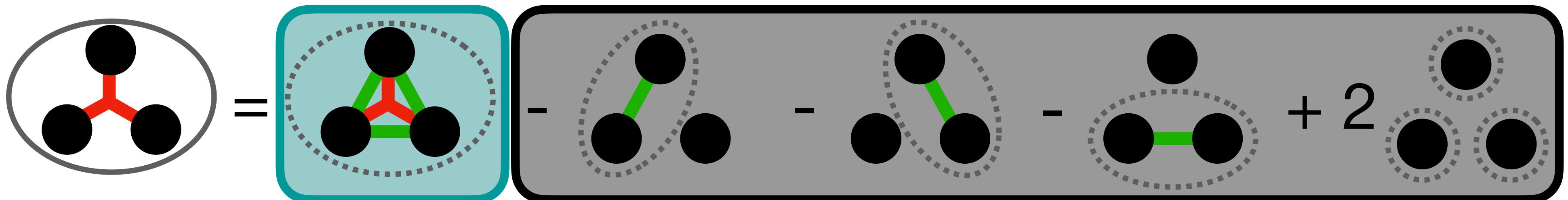
**Total lower-order contributions**



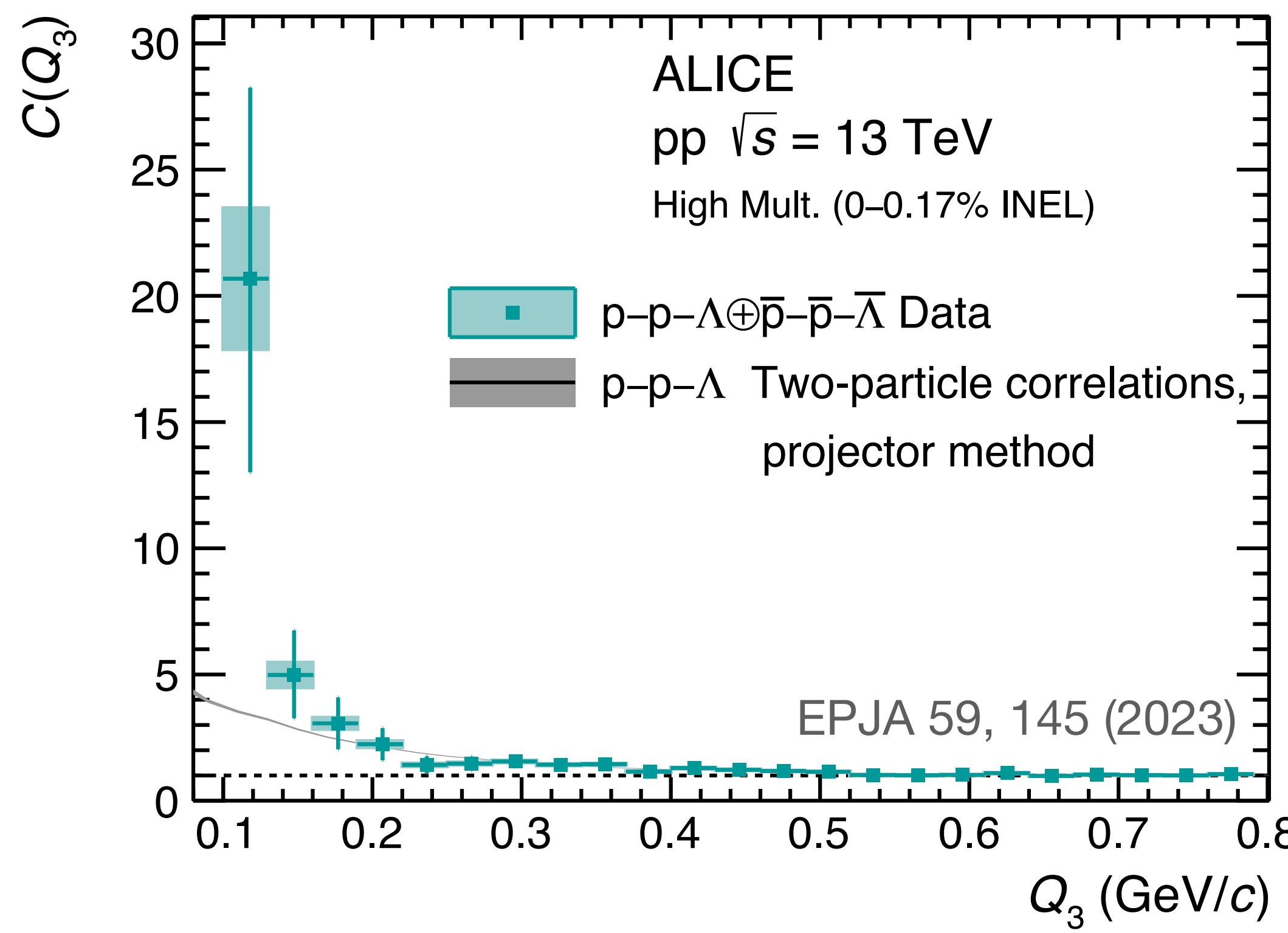
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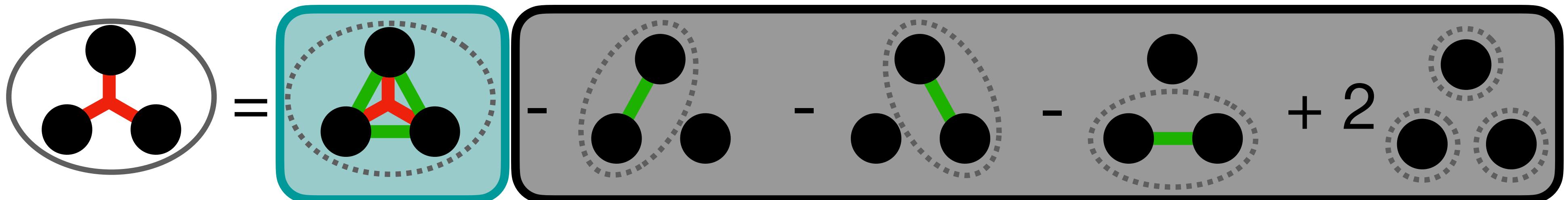
# p-p- $\Lambda$ and p-p-p correlation functions



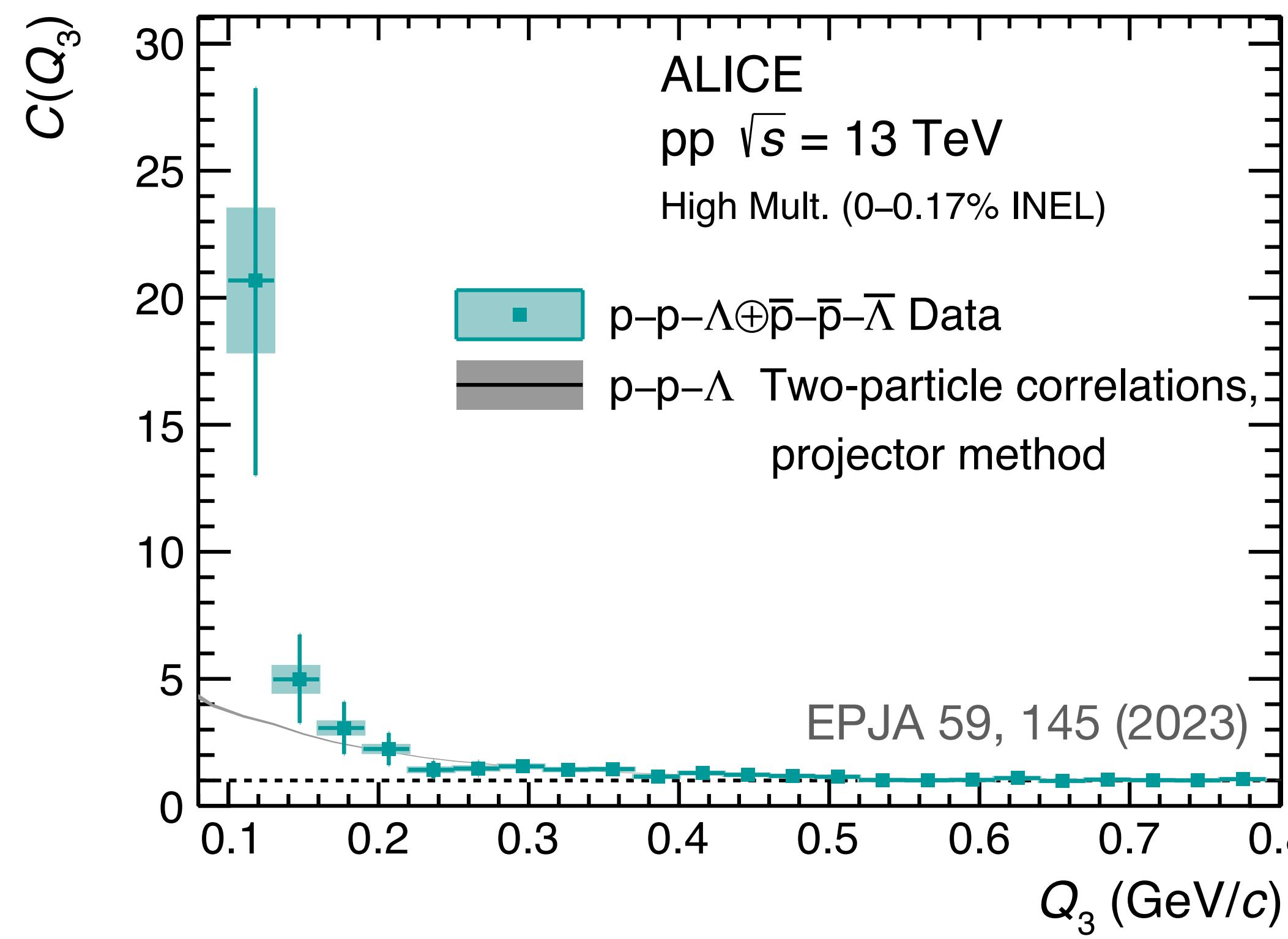
p-p- $\Lambda$



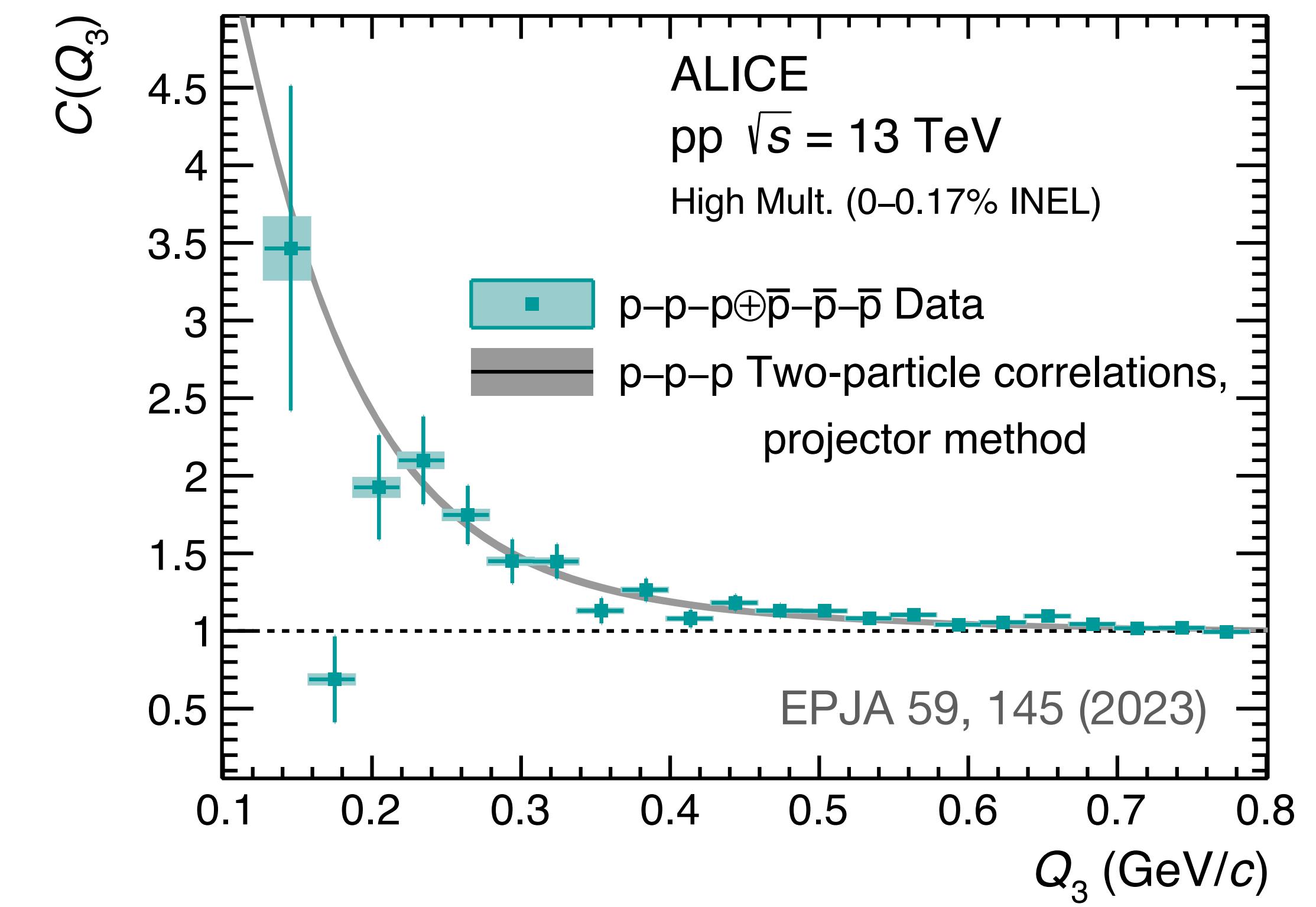
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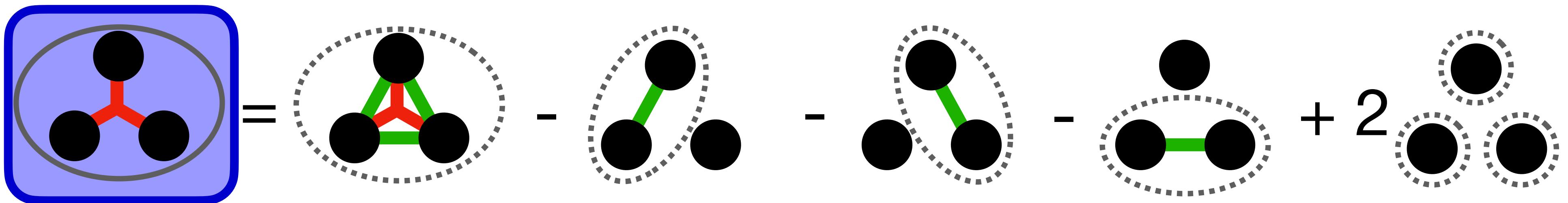
p-p- $\Lambda$



p-p-p

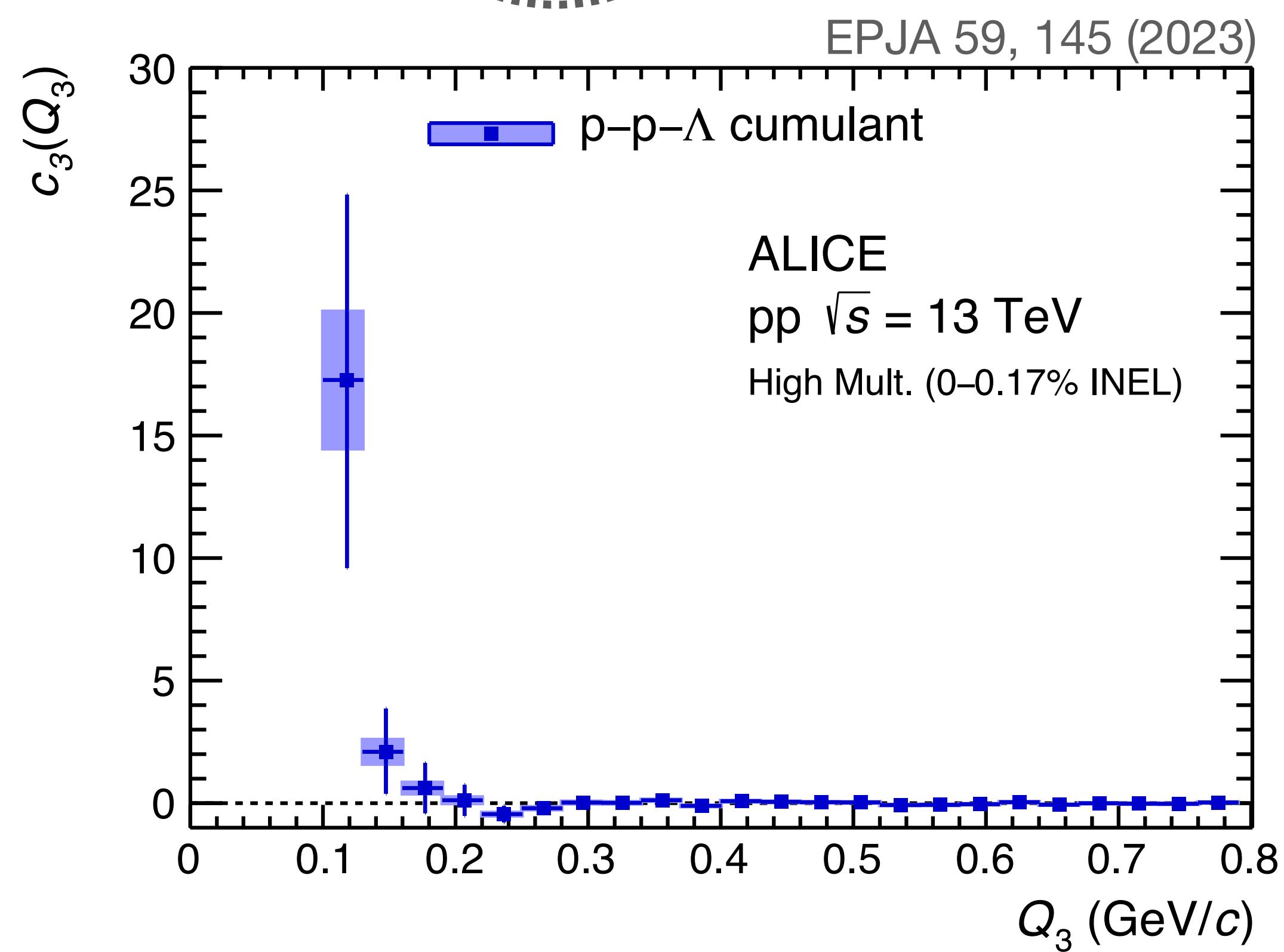


# p-p- $\Lambda$ cumulant

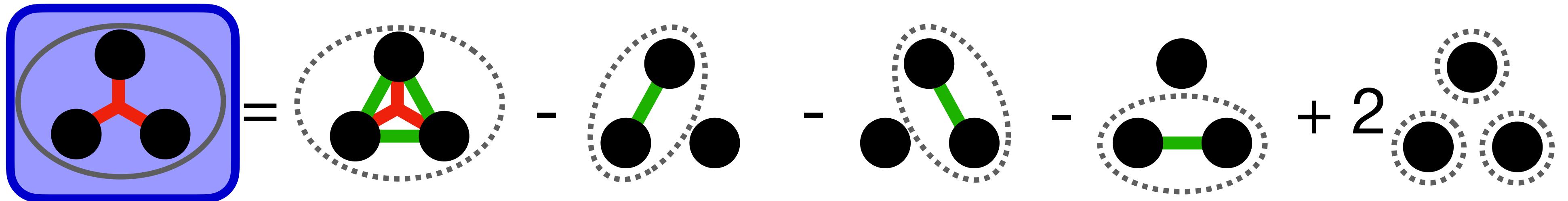


## Hint of a positive cumulant for p-p- $\Lambda$

- Only two identical and charged particles
- ✓ Main expected contribution from three-body strong interaction

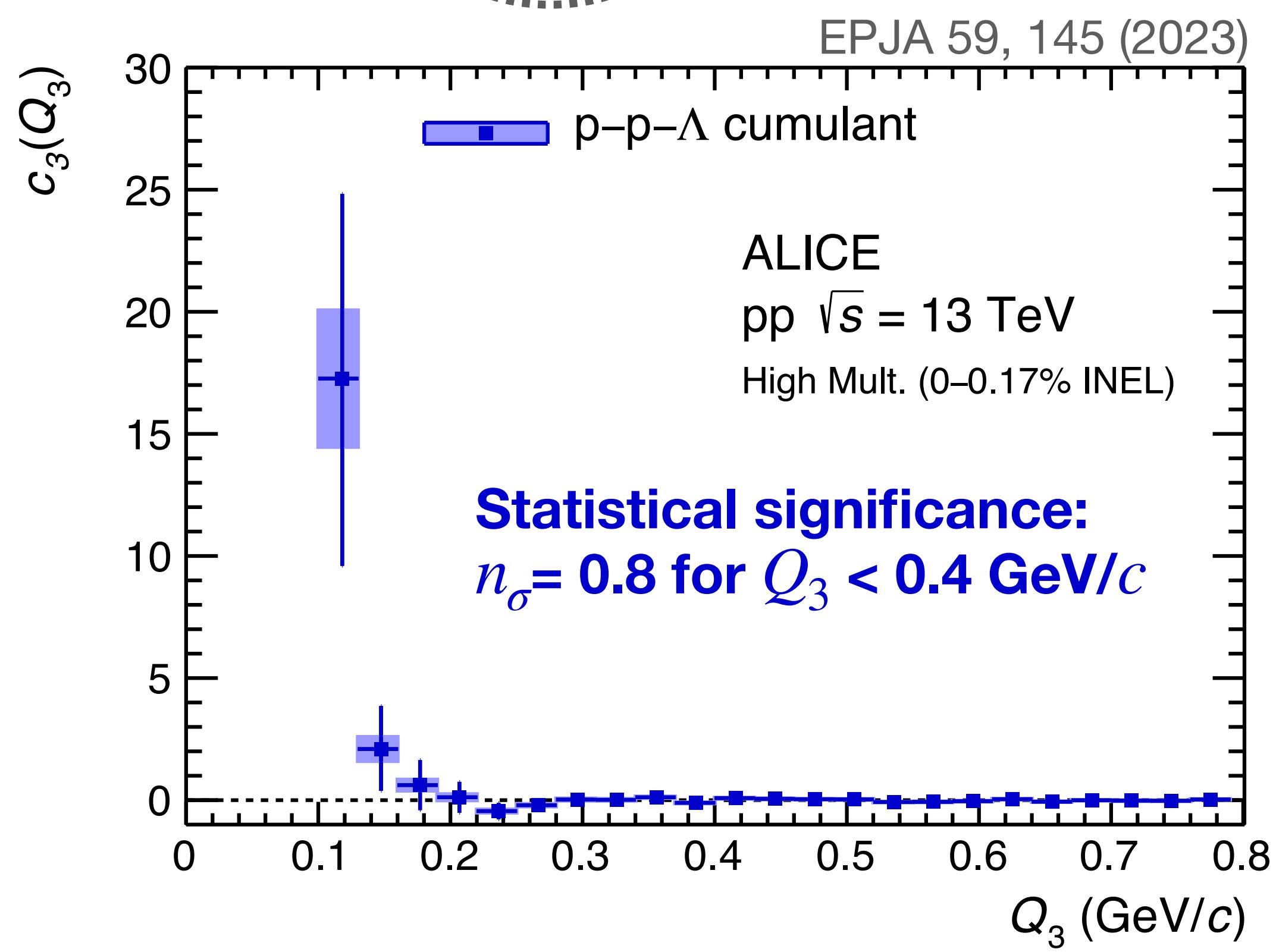


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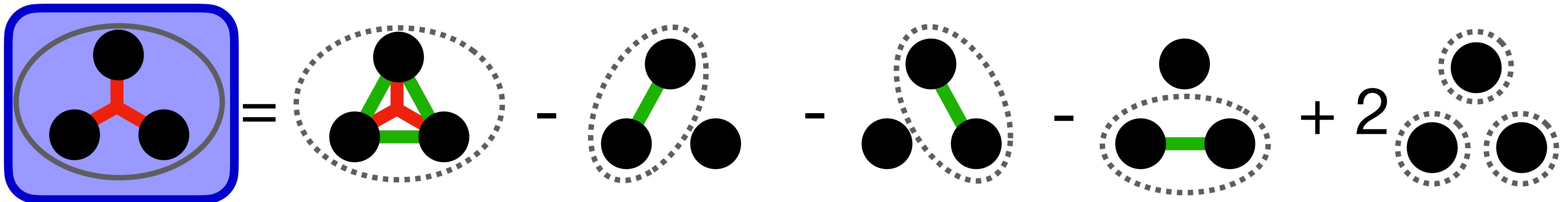


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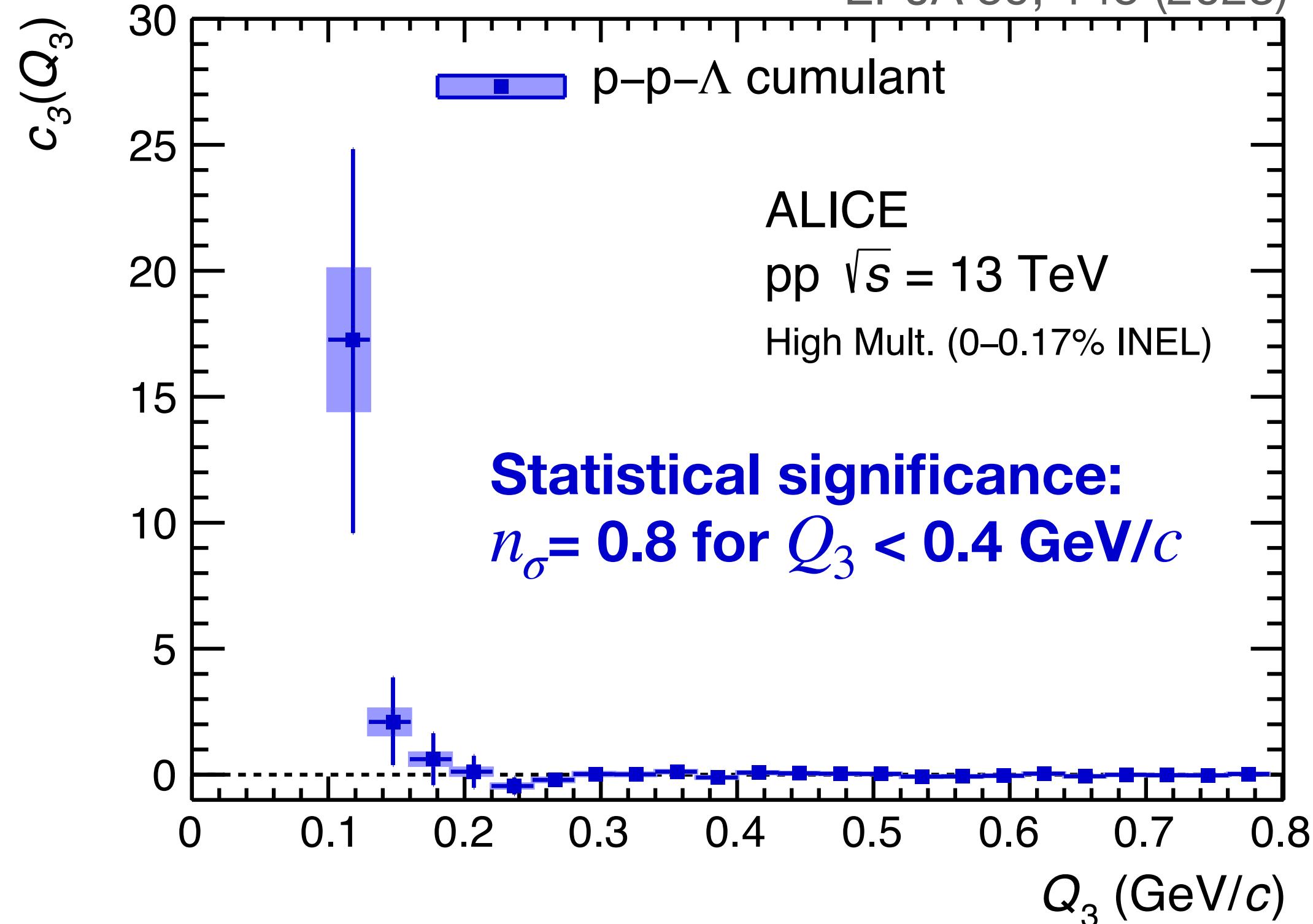
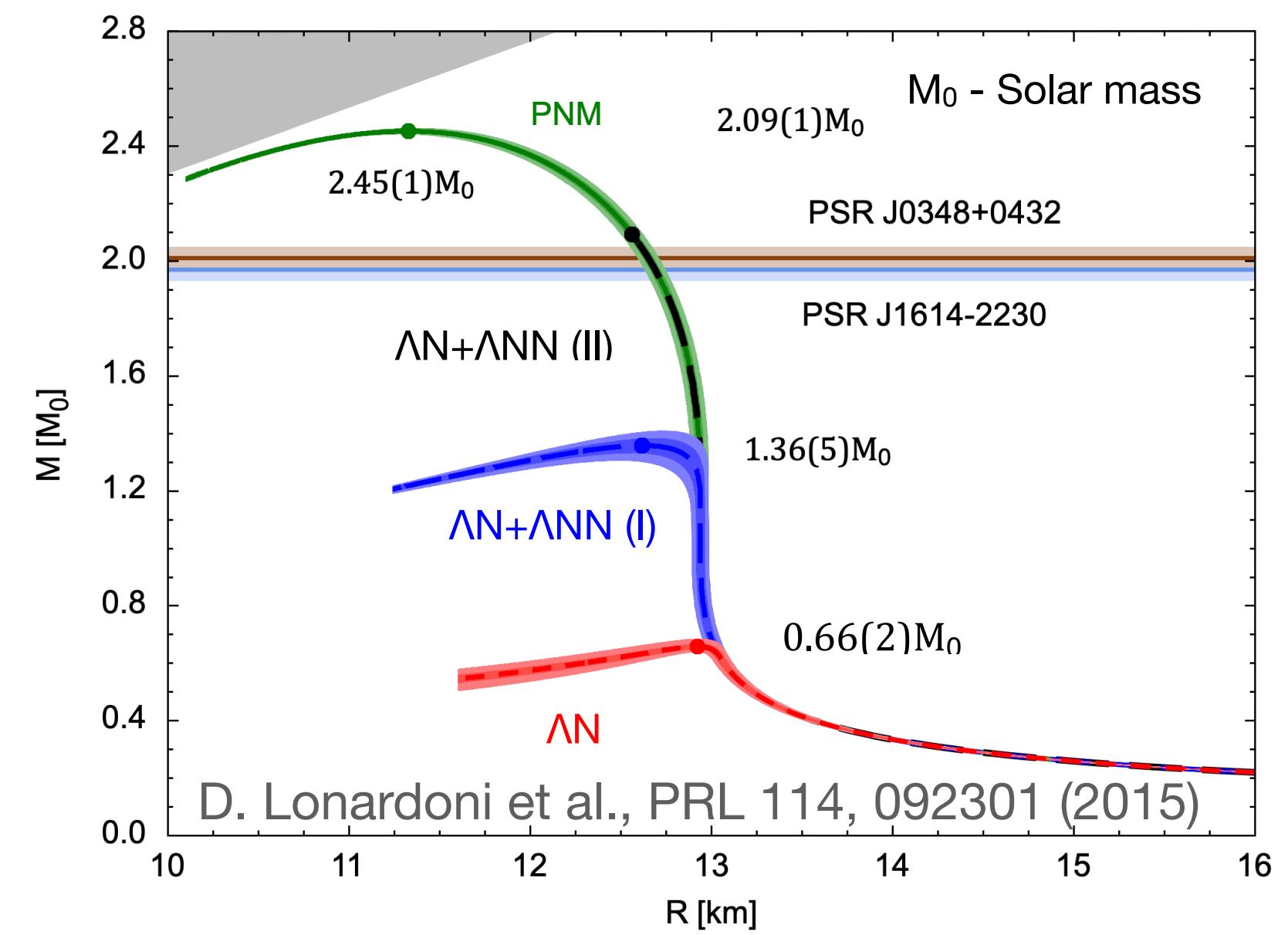
# p-p- $\Lambda$ cumulant



EPJA 59, 145 (2023)

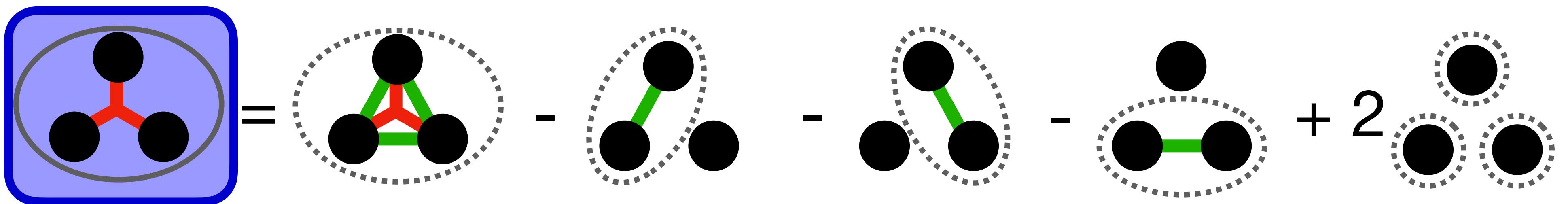
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**Statistical significance:**  
 $n_\sigma = 0.8$  for  $Q_3 < 0.4 \text{ GeV}/c$

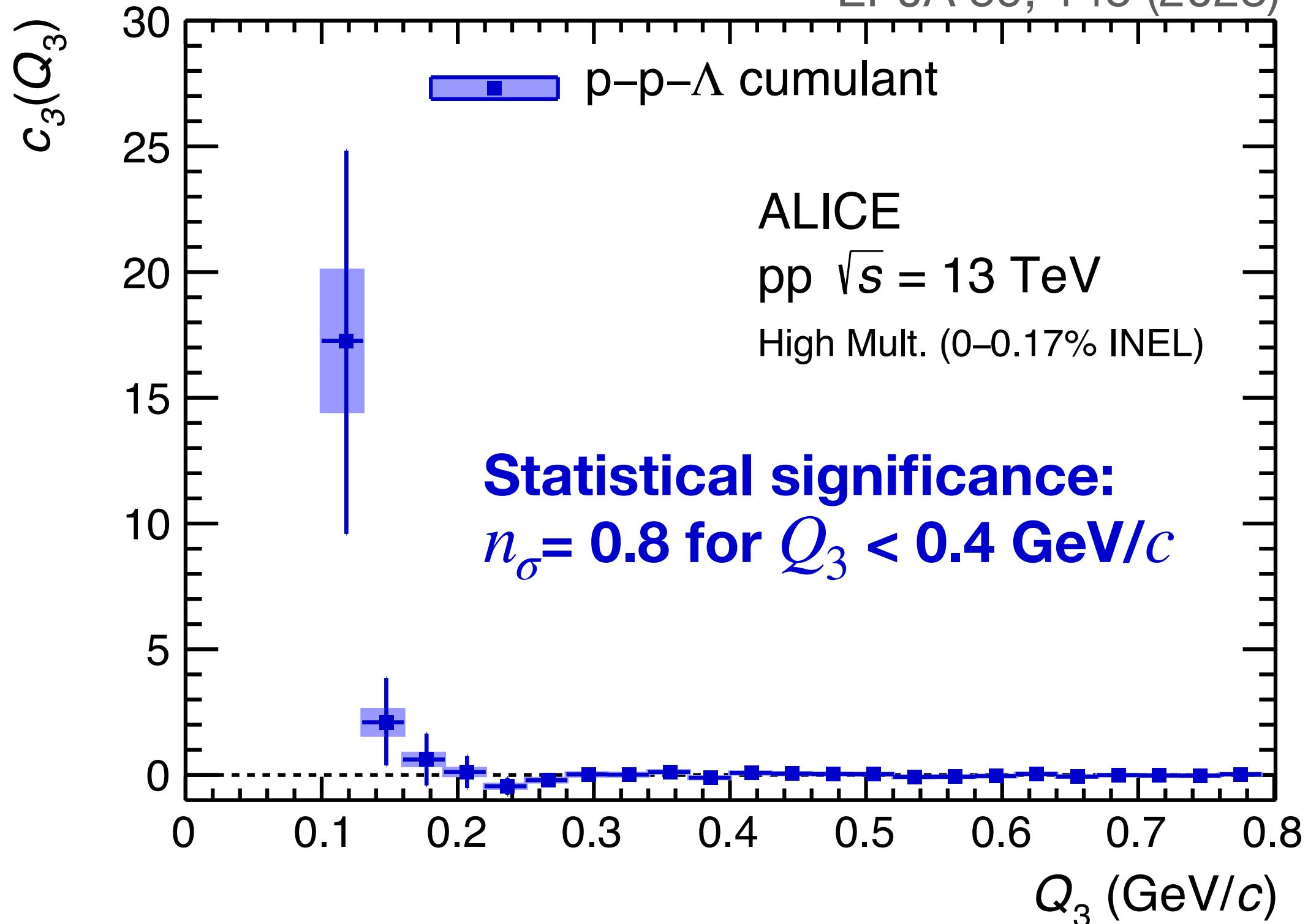
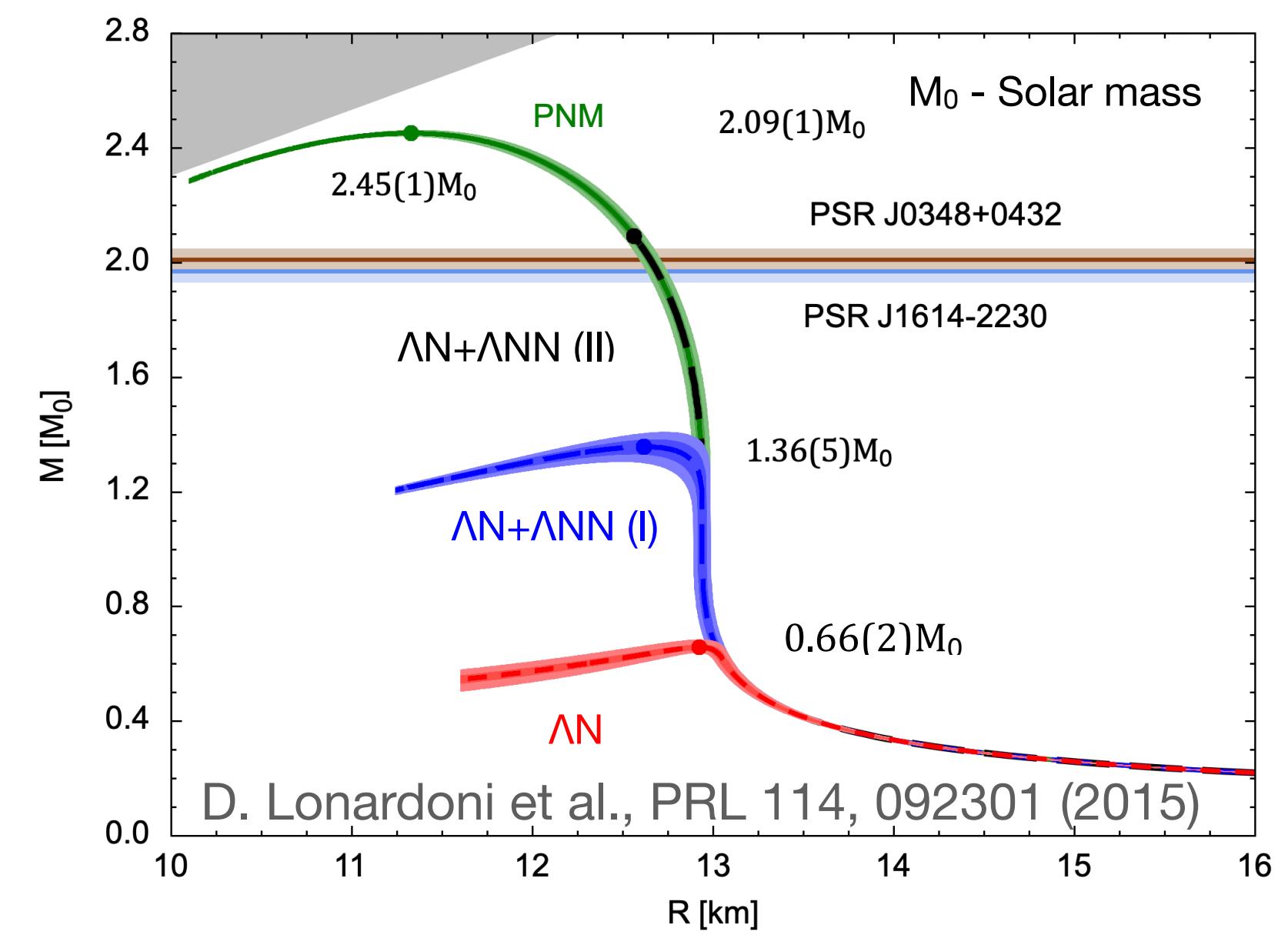
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EPJA 59, 145 (2023)

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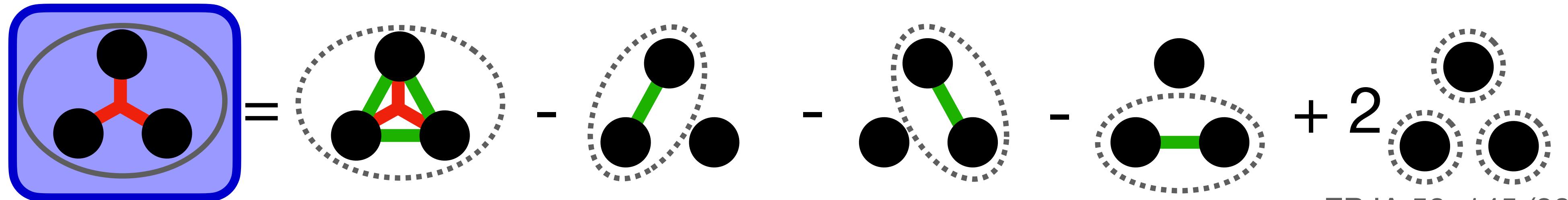
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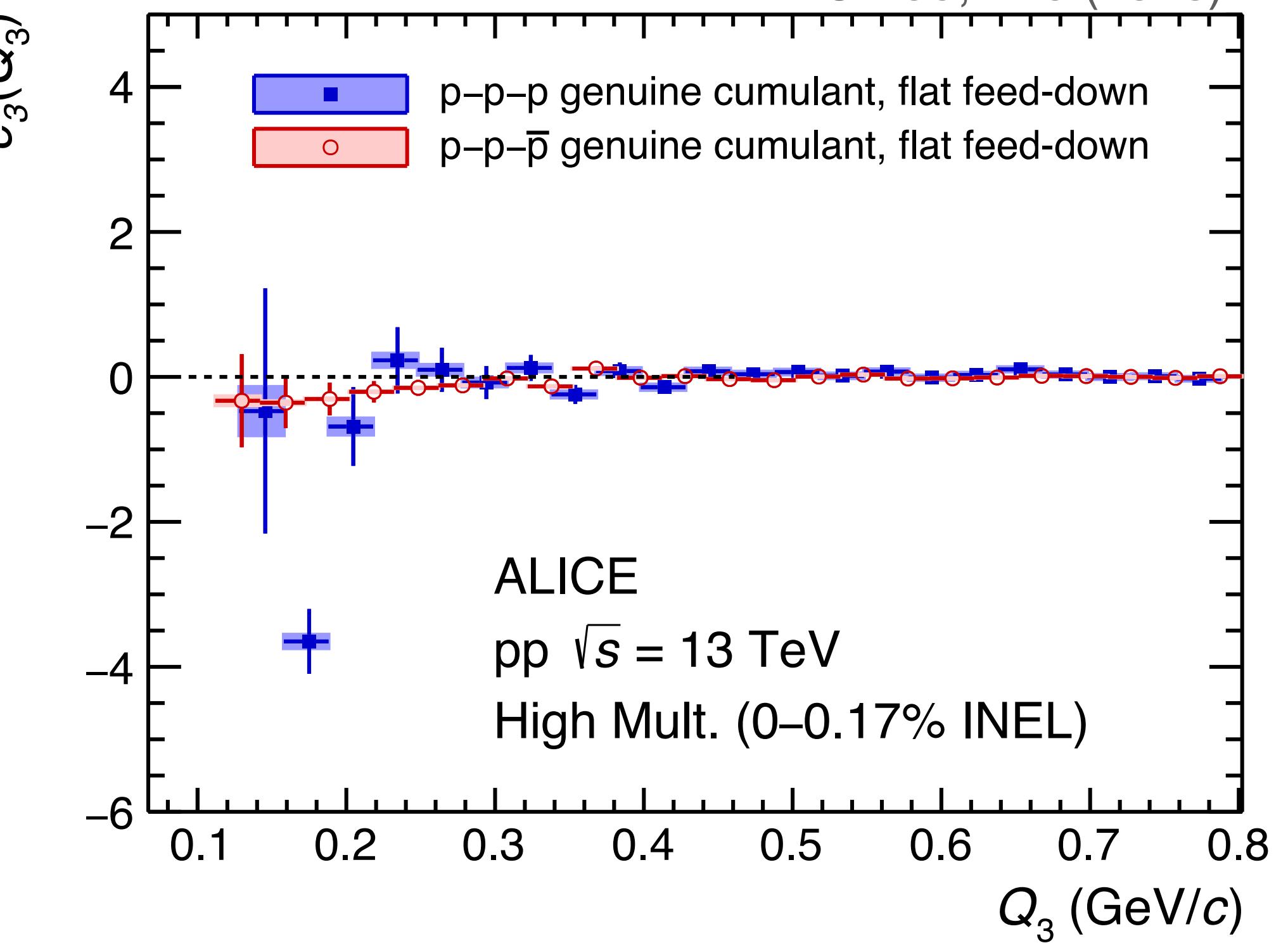
*In upcoming Run 3, two orders of magnitude gain in statistics expected!*

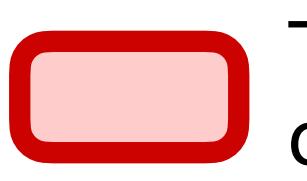
# p-p-p cumulant



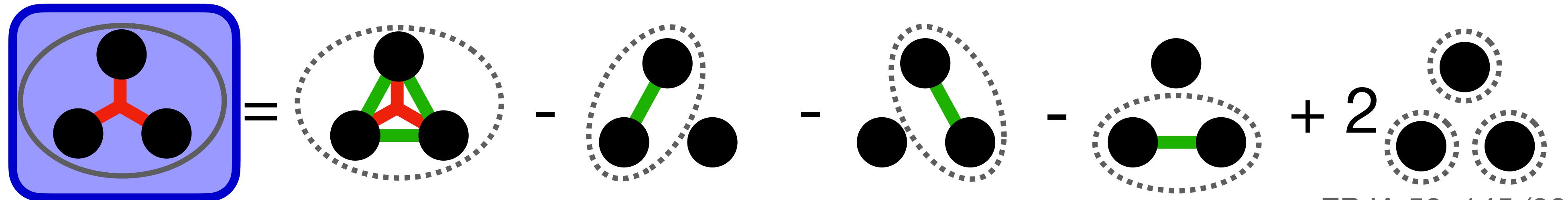
EPJA 59, 145 (2023)

**Negative cumulant for p-p-p**



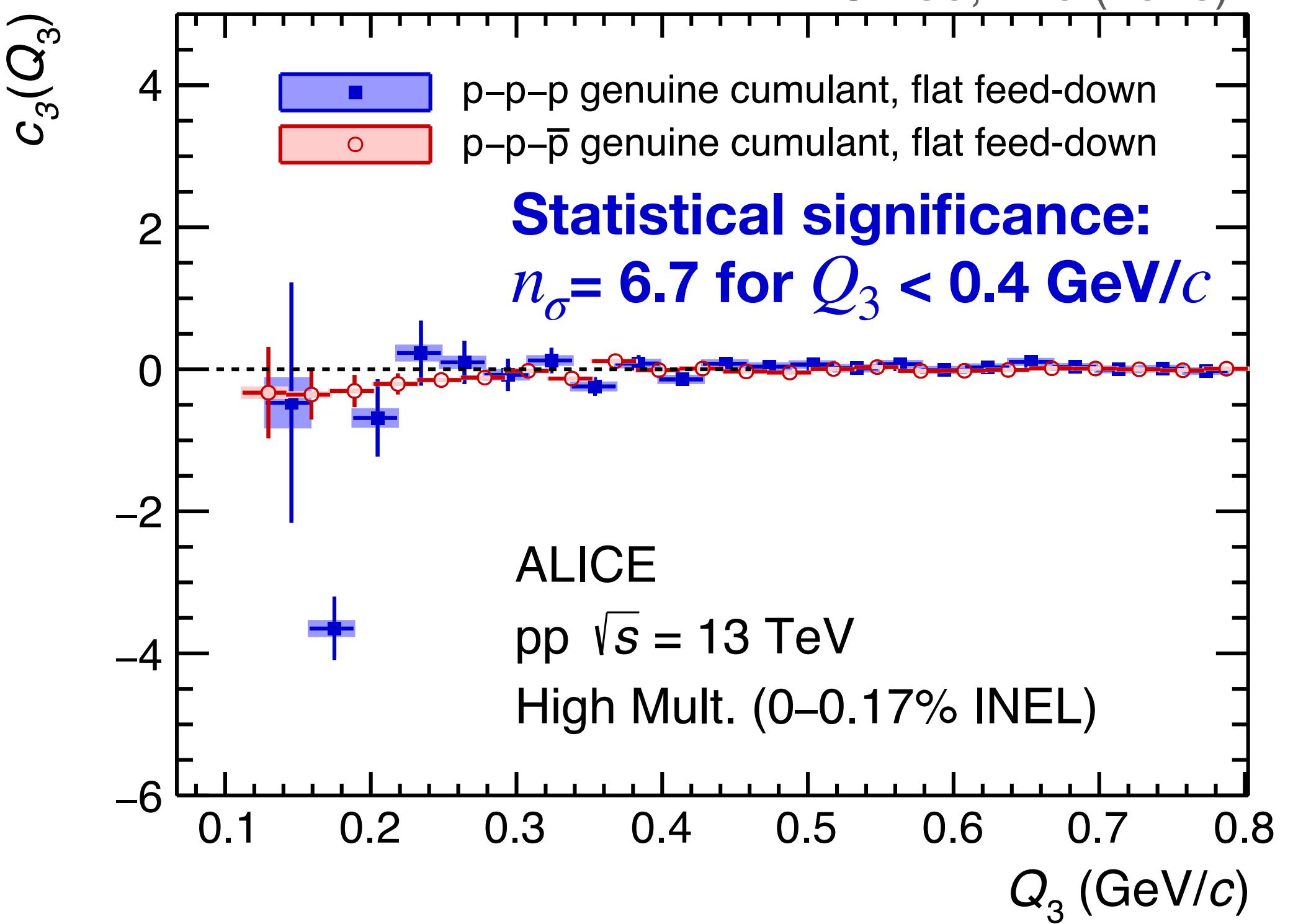
 Test with mixed-charge particles,  
cumulant negligible.

# p-p-p cumulant



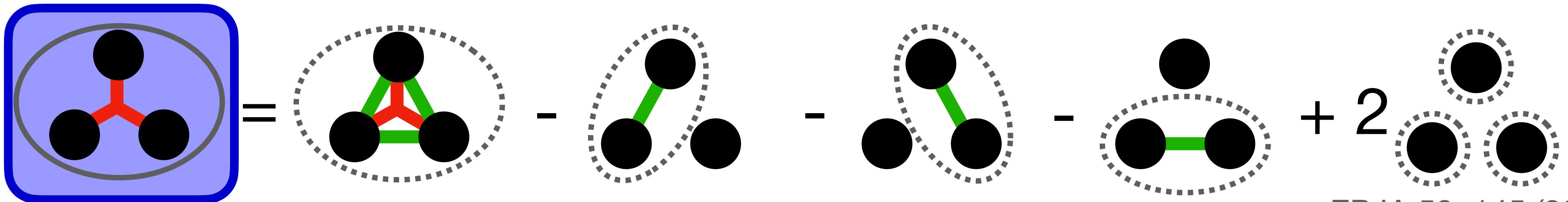
EPJA 59, 145 (2023)

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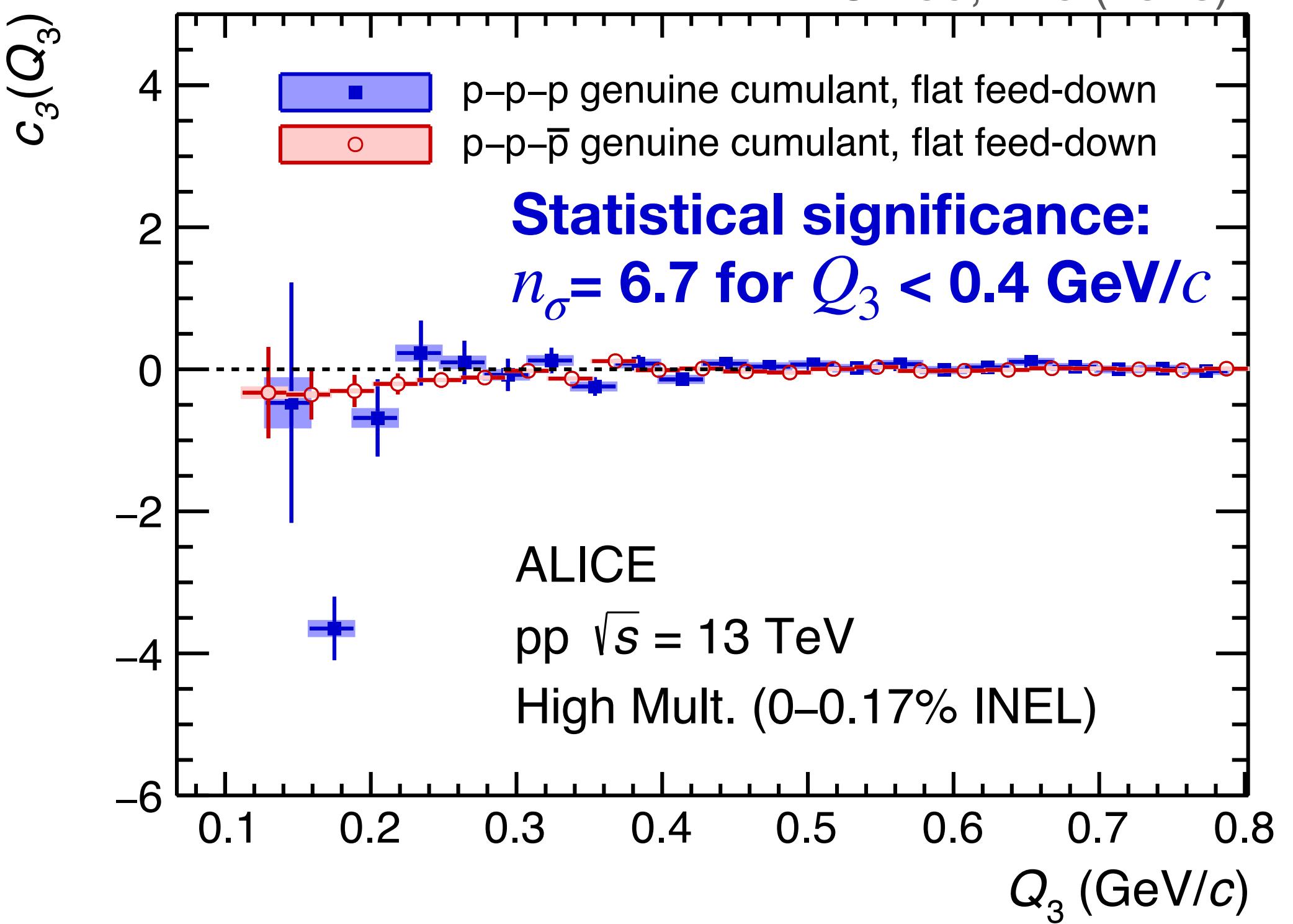
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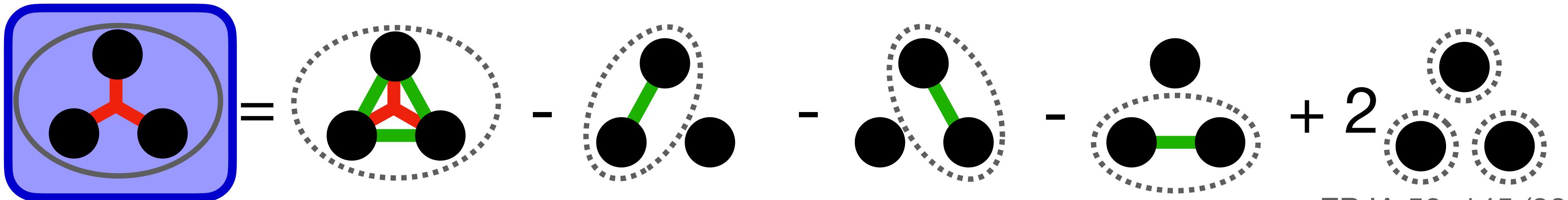
# Negative cumulant for p-p-p

- Possible forces at play:
    - *Quantum statistics at the three-particle level*
    - three-body strong interaction
    - long-range Coulomb



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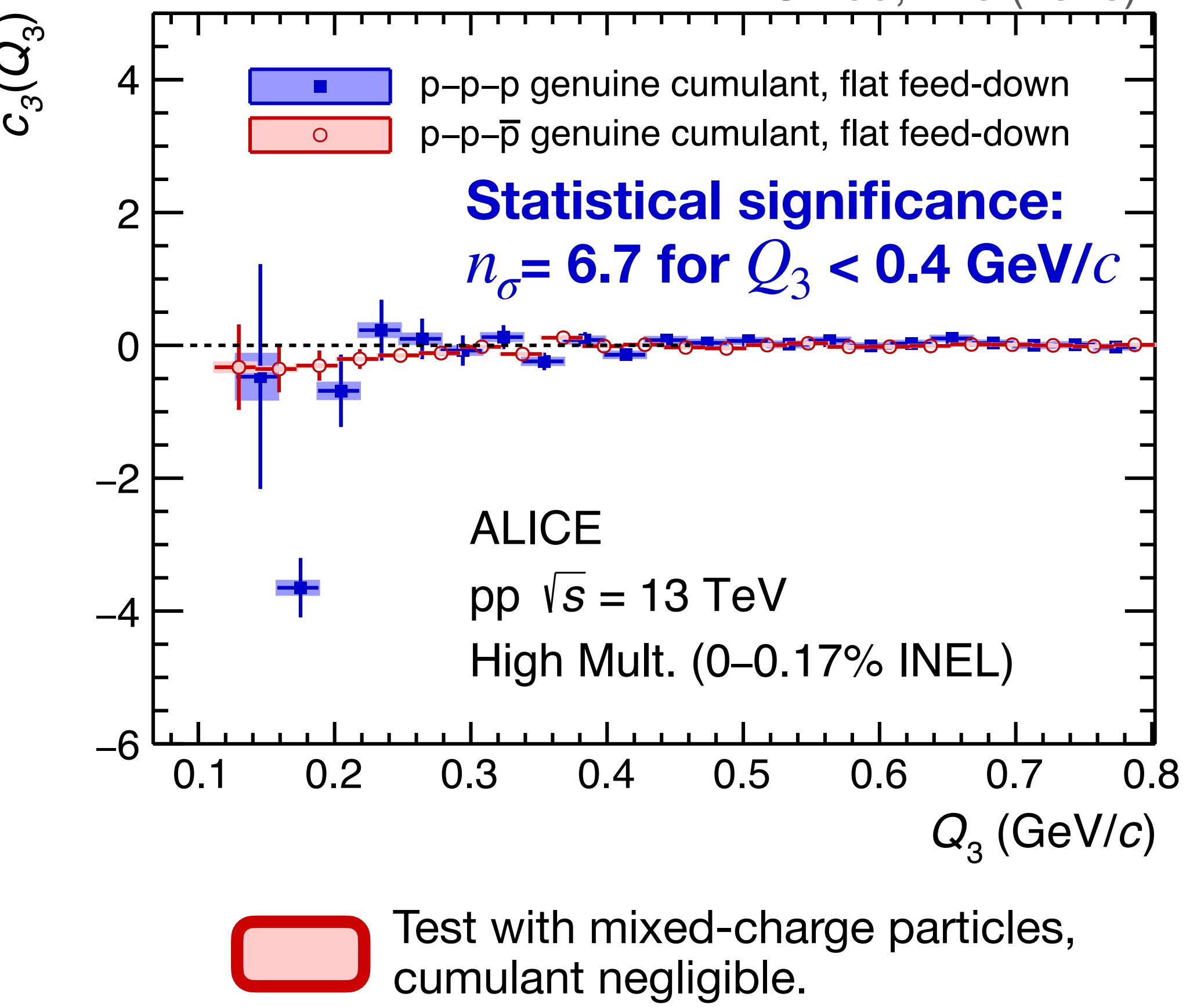


EPJA 59, 145 (2023)

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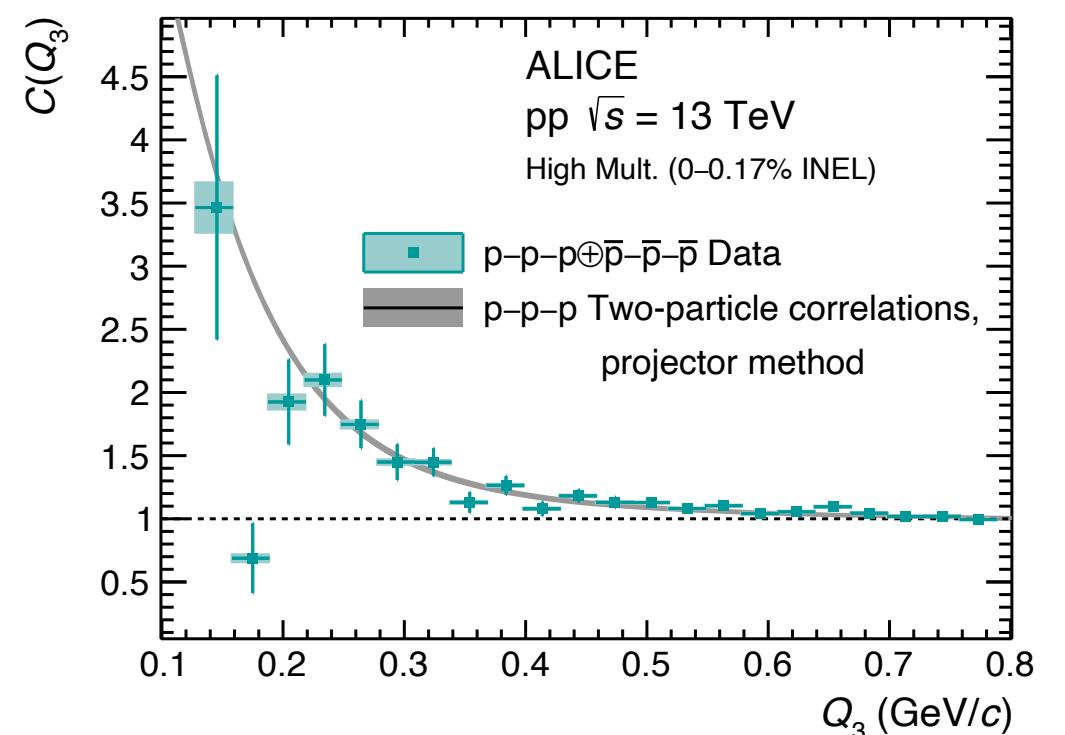
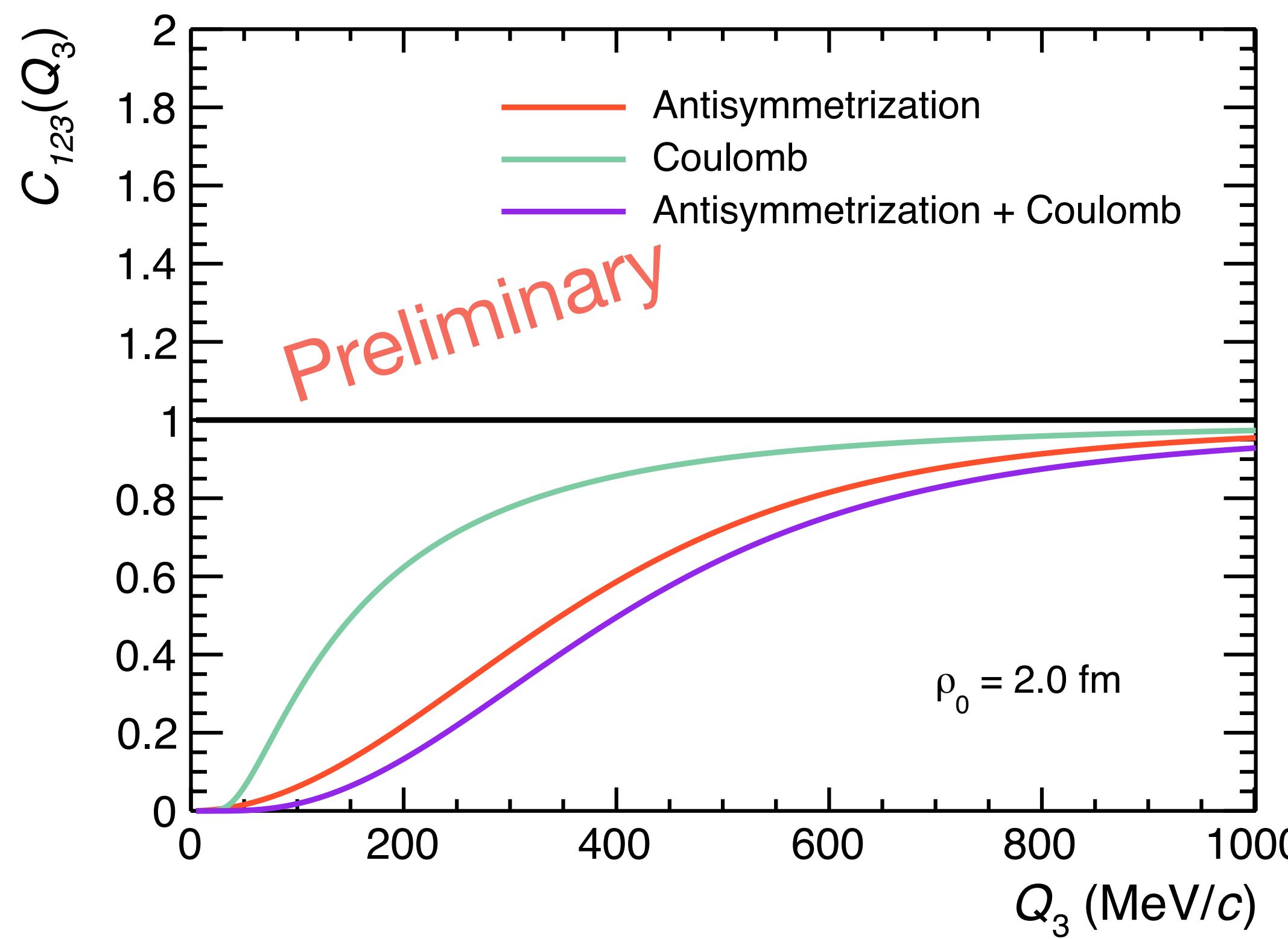
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Ongoing collaboration with A. Kievsky, L. Marcucci and M. Viviani (Pisa University - INFN) for the theoretical interpretation



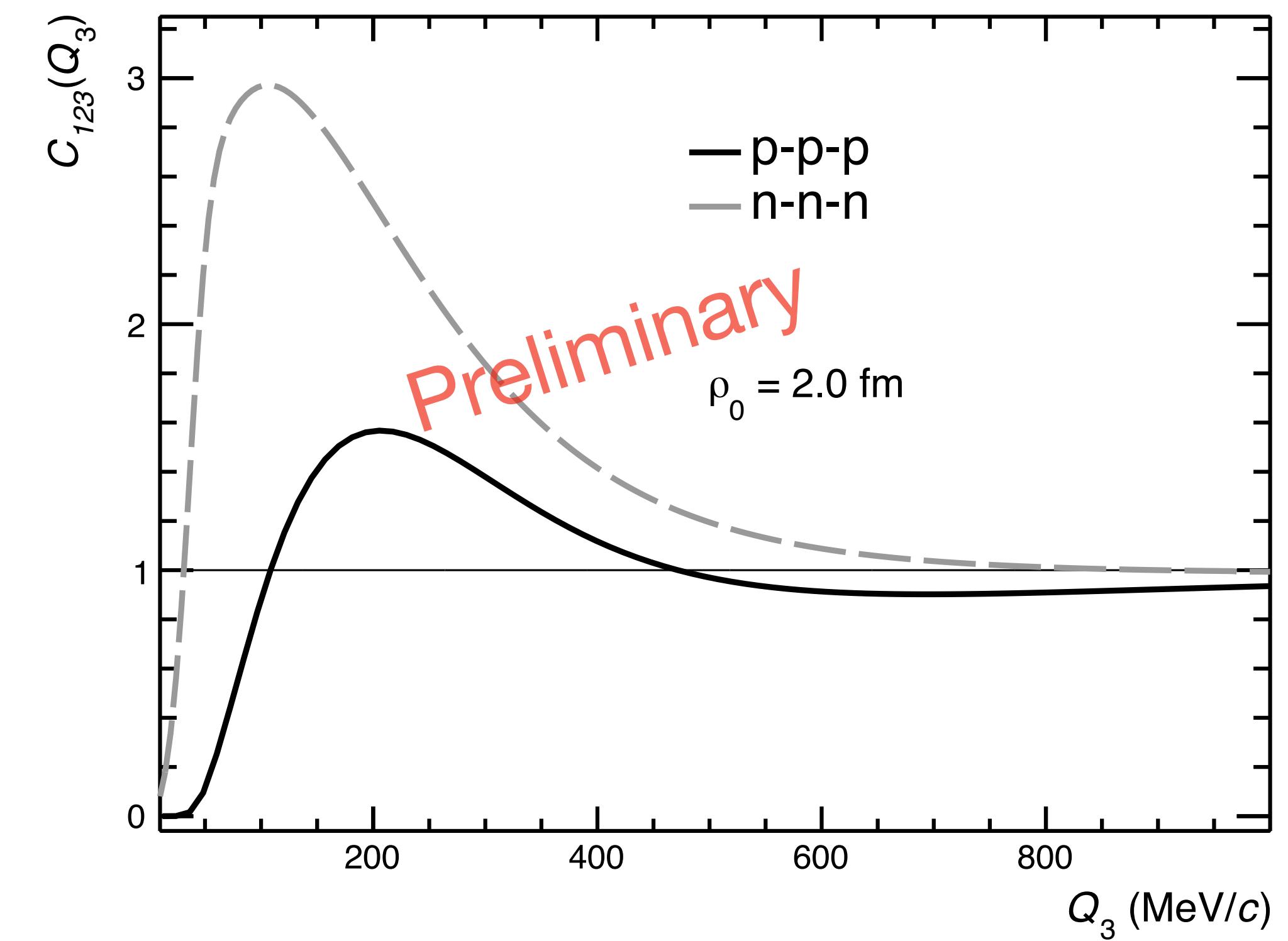
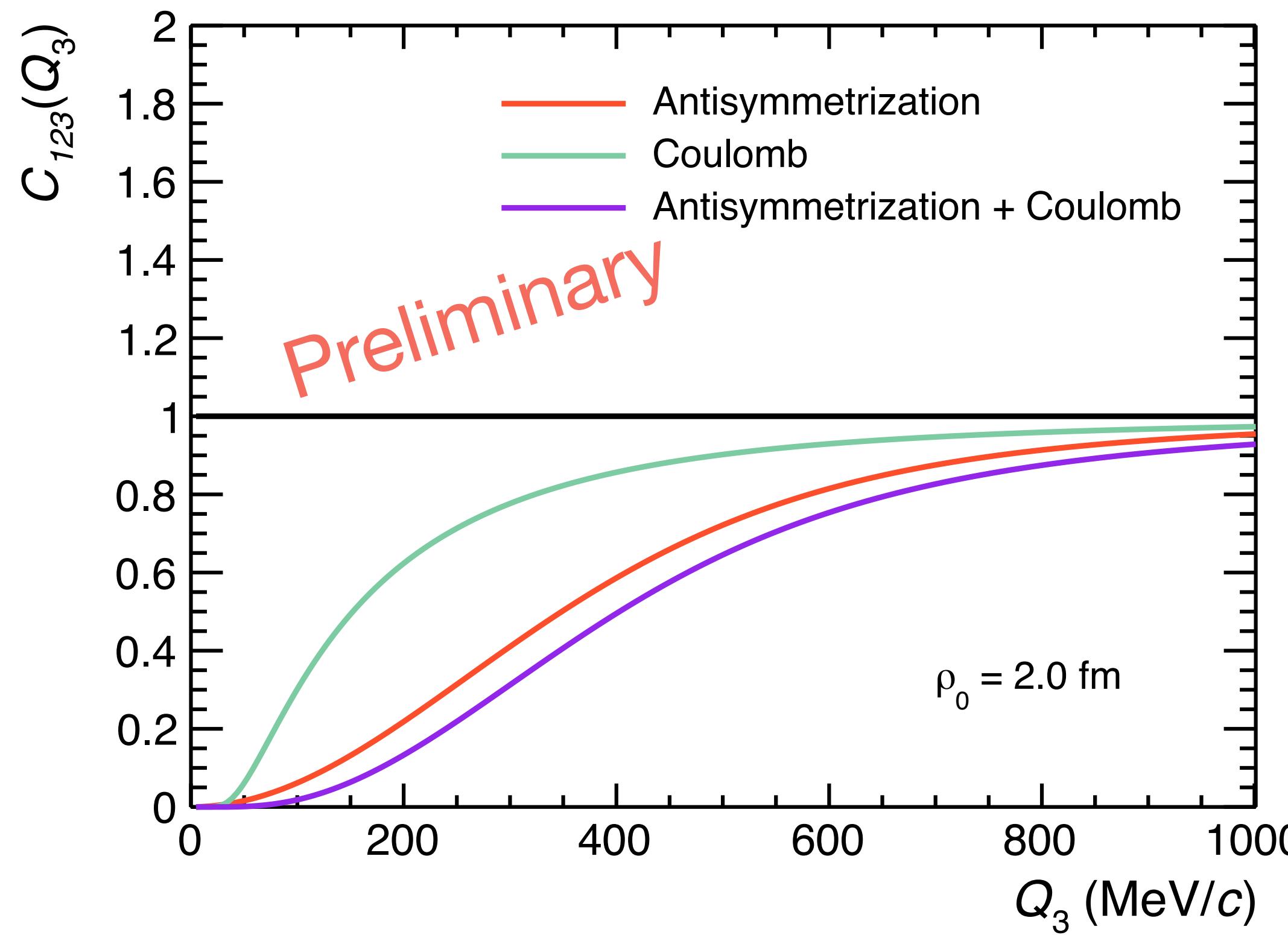
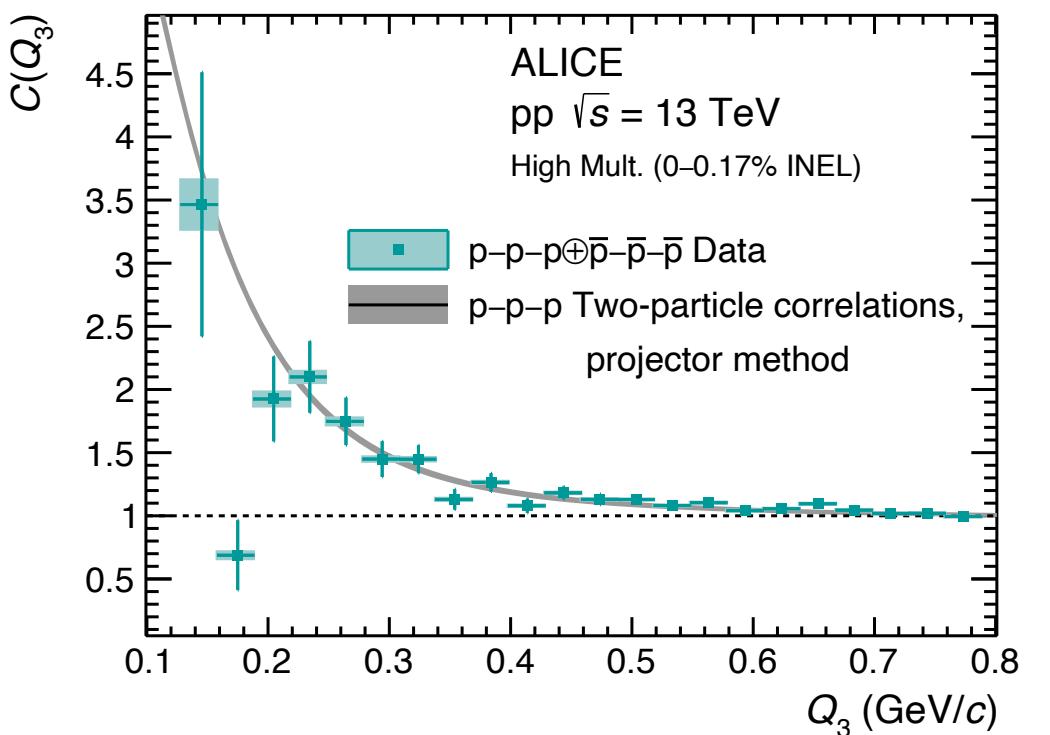
# p-p-p calculations (work in progress)

- Calculations performed by Alejandro Kievsky (PISA group)
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  - only two-body strong interaction included
  - approximate Coulomb interaction, as a function of hyper-radius only

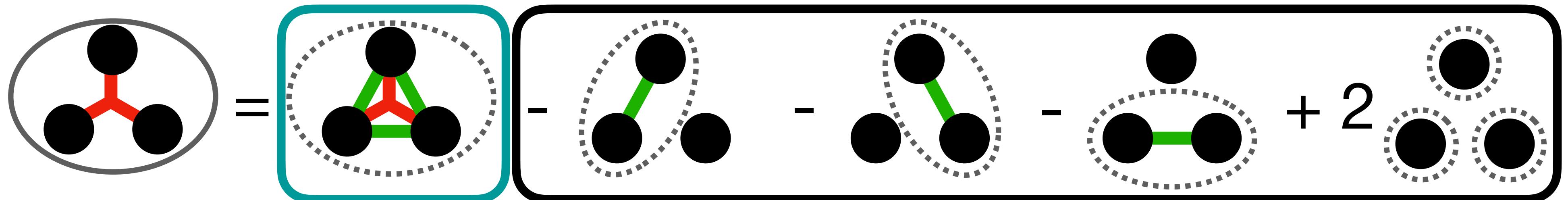


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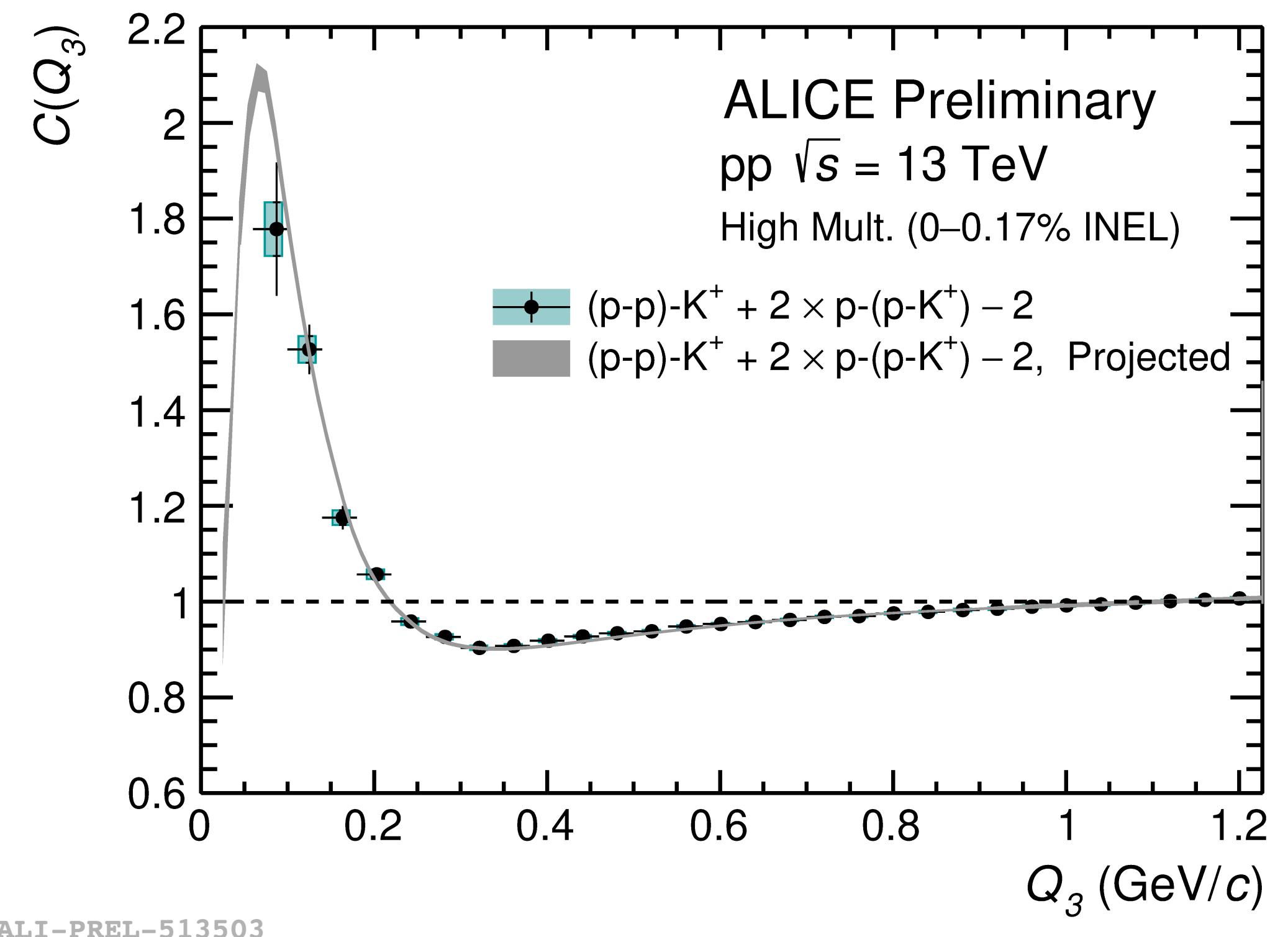
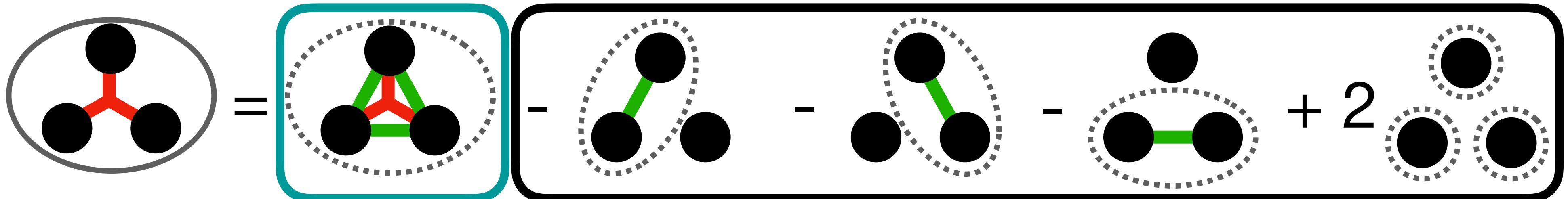


# p-p-K<sup>+</sup> correlation function



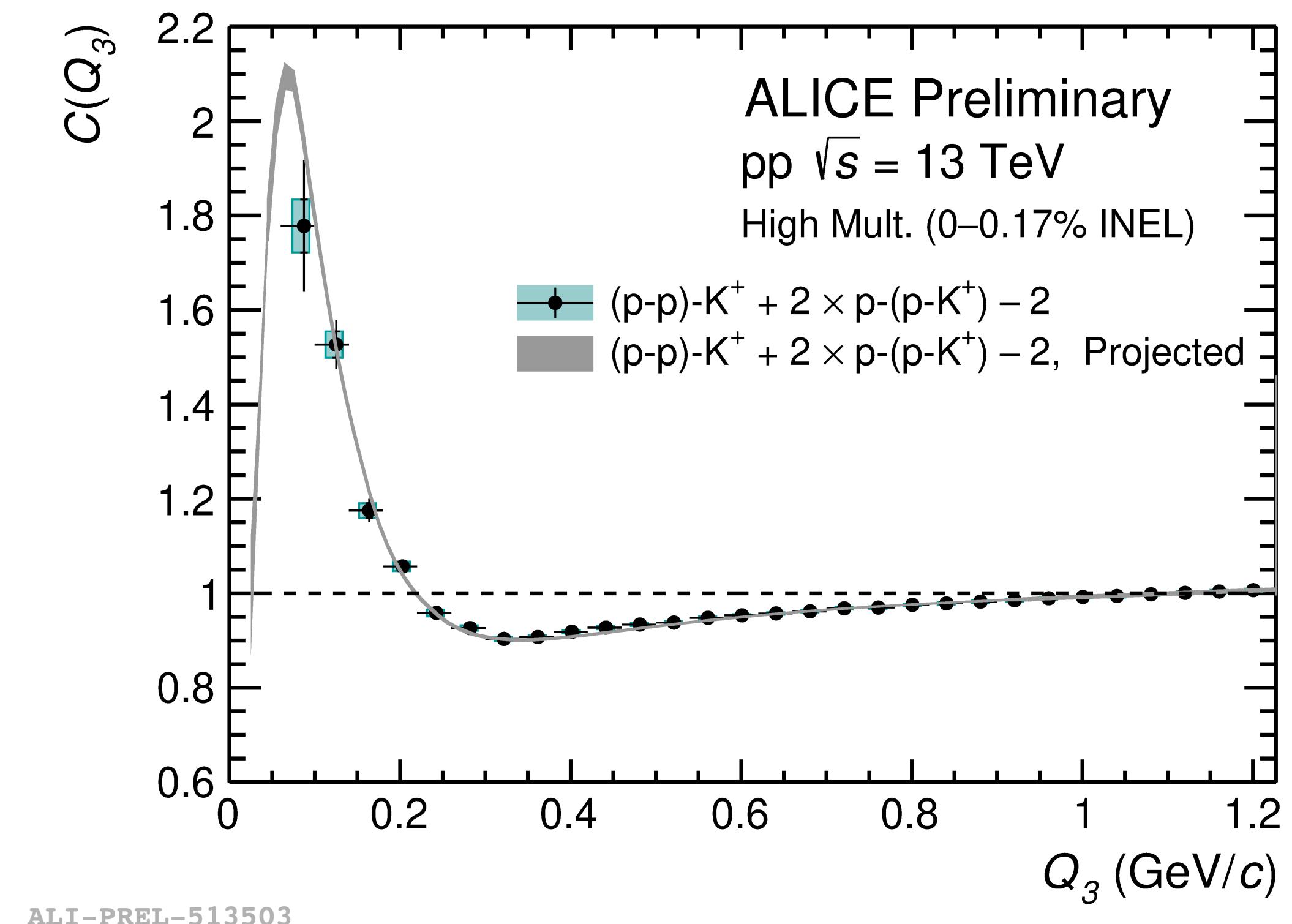
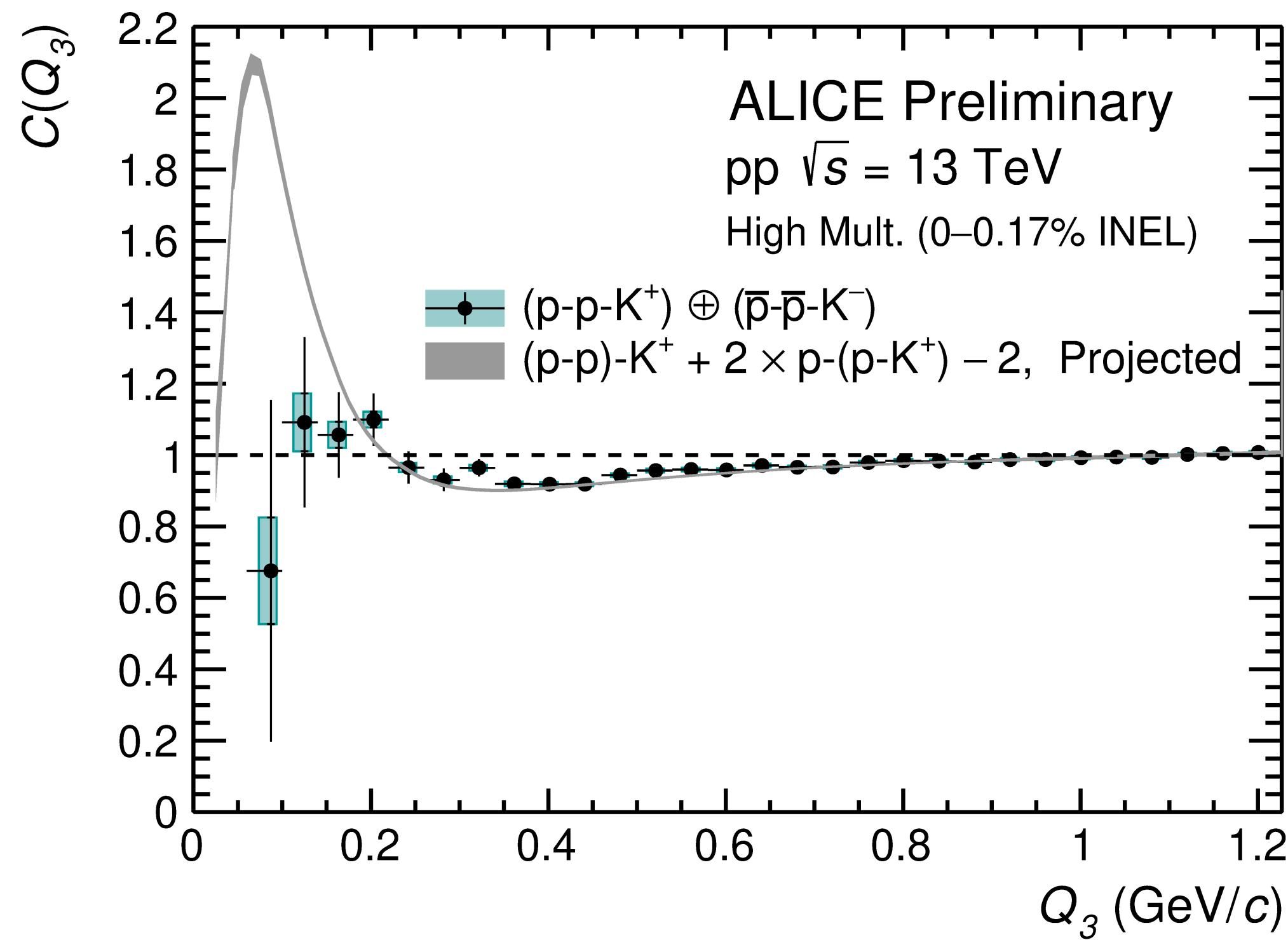
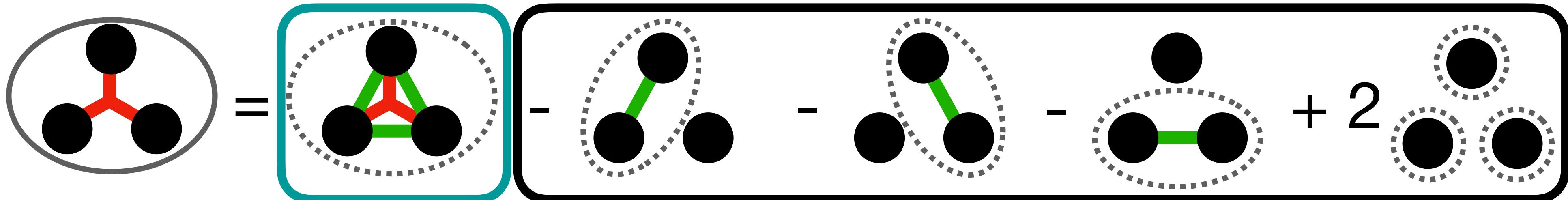
Already measured p-p [1] and newly obtained p-K<sup>+</sup> correlation functions used for projection.

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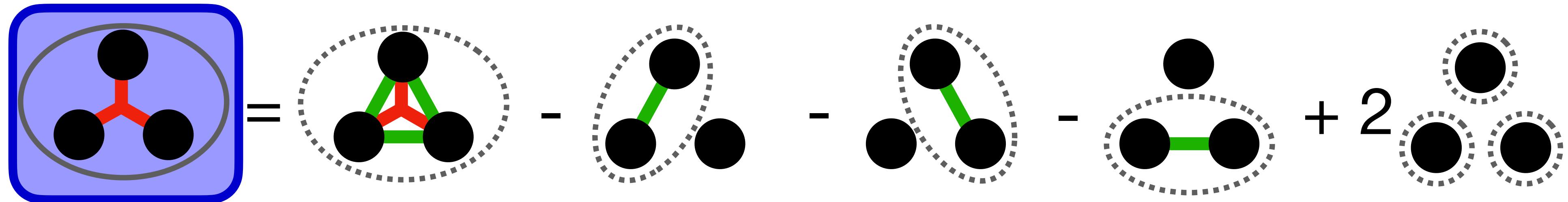
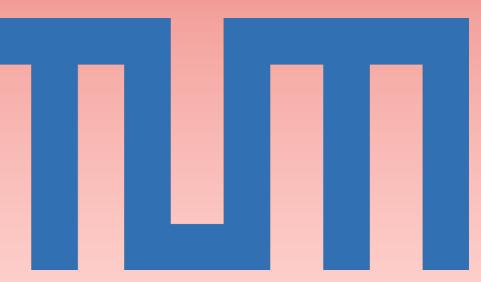
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# p-p-K<sup>+</sup> cumulant

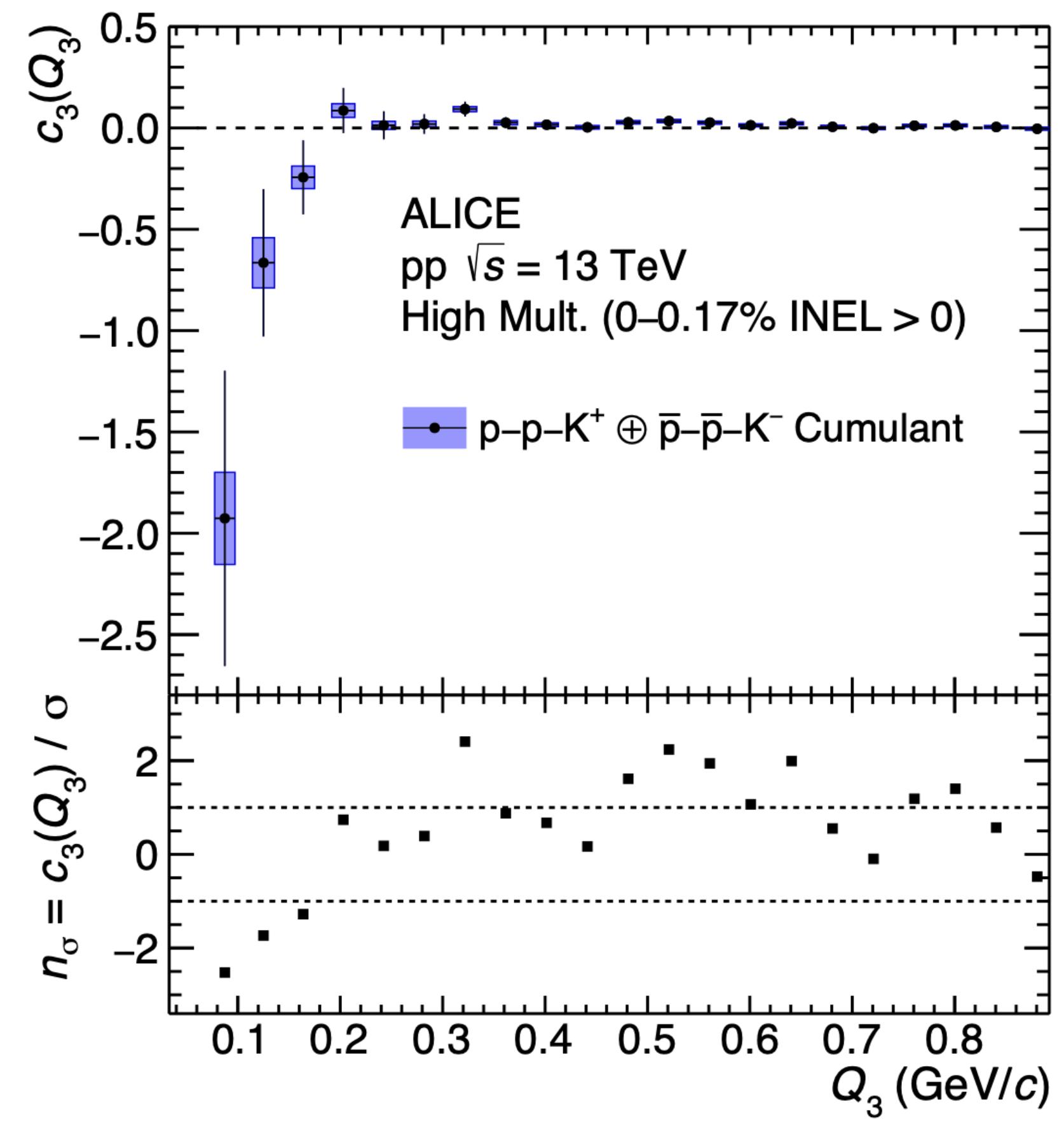
New paper: arXiv:2303.13448



**Negative cumulant for p-p-K<sup>+</sup>**

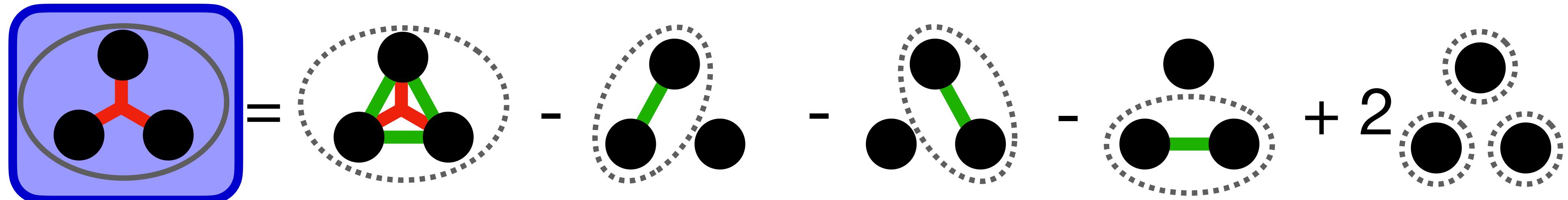
**Statistical significance:**

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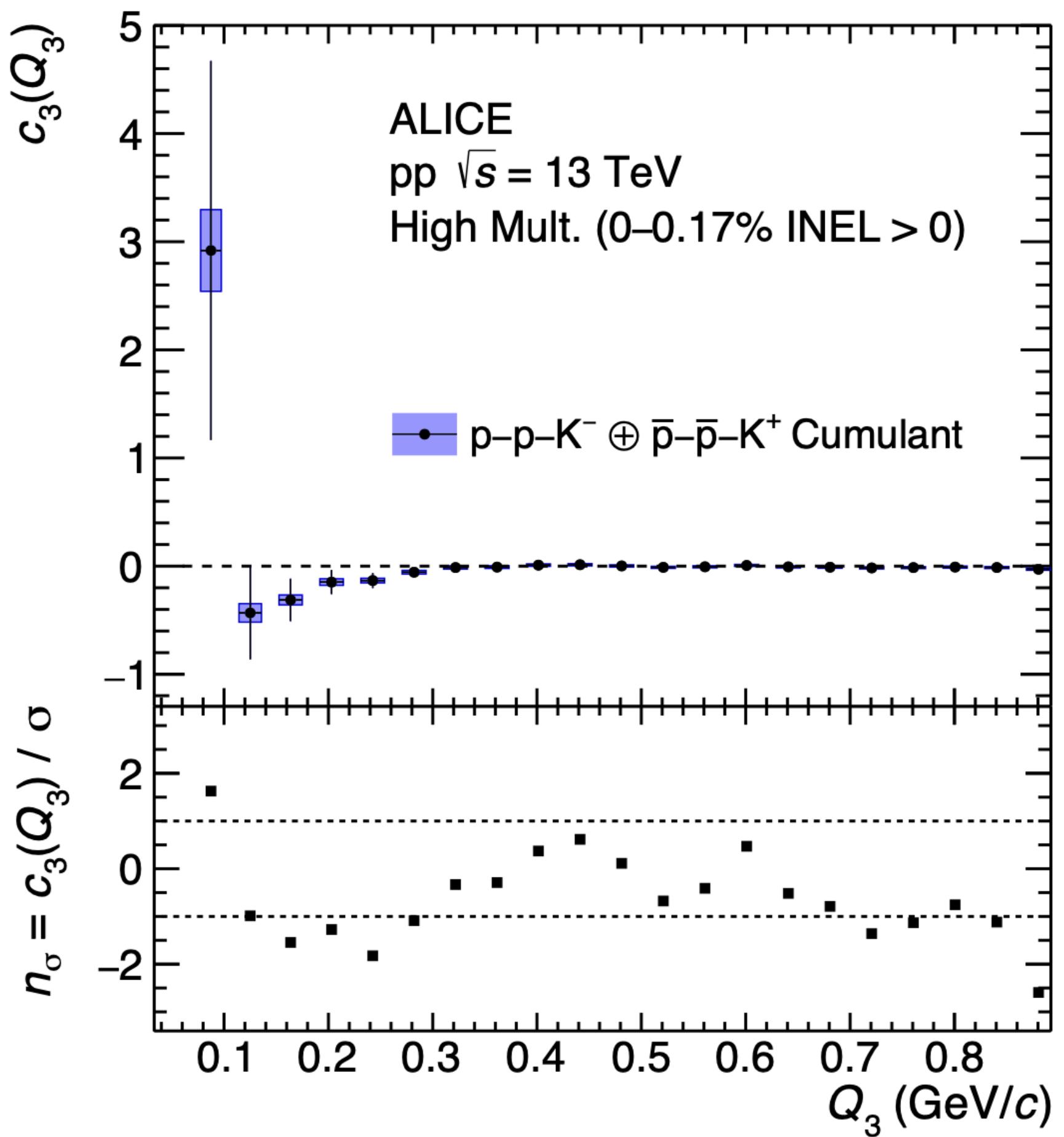


# p-p-K- cumulant

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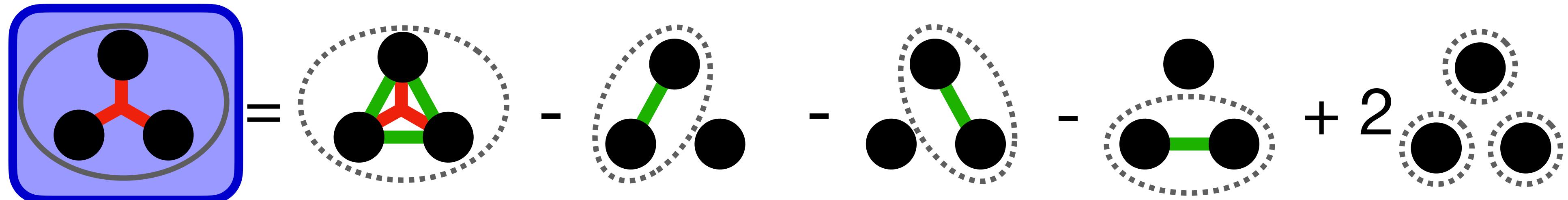
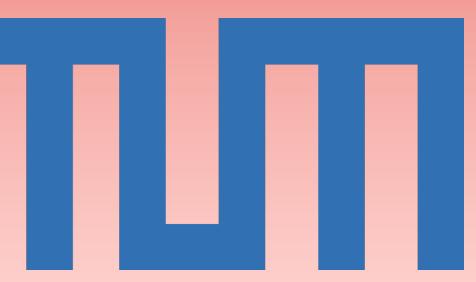


Zero cumulant for p-p-K-

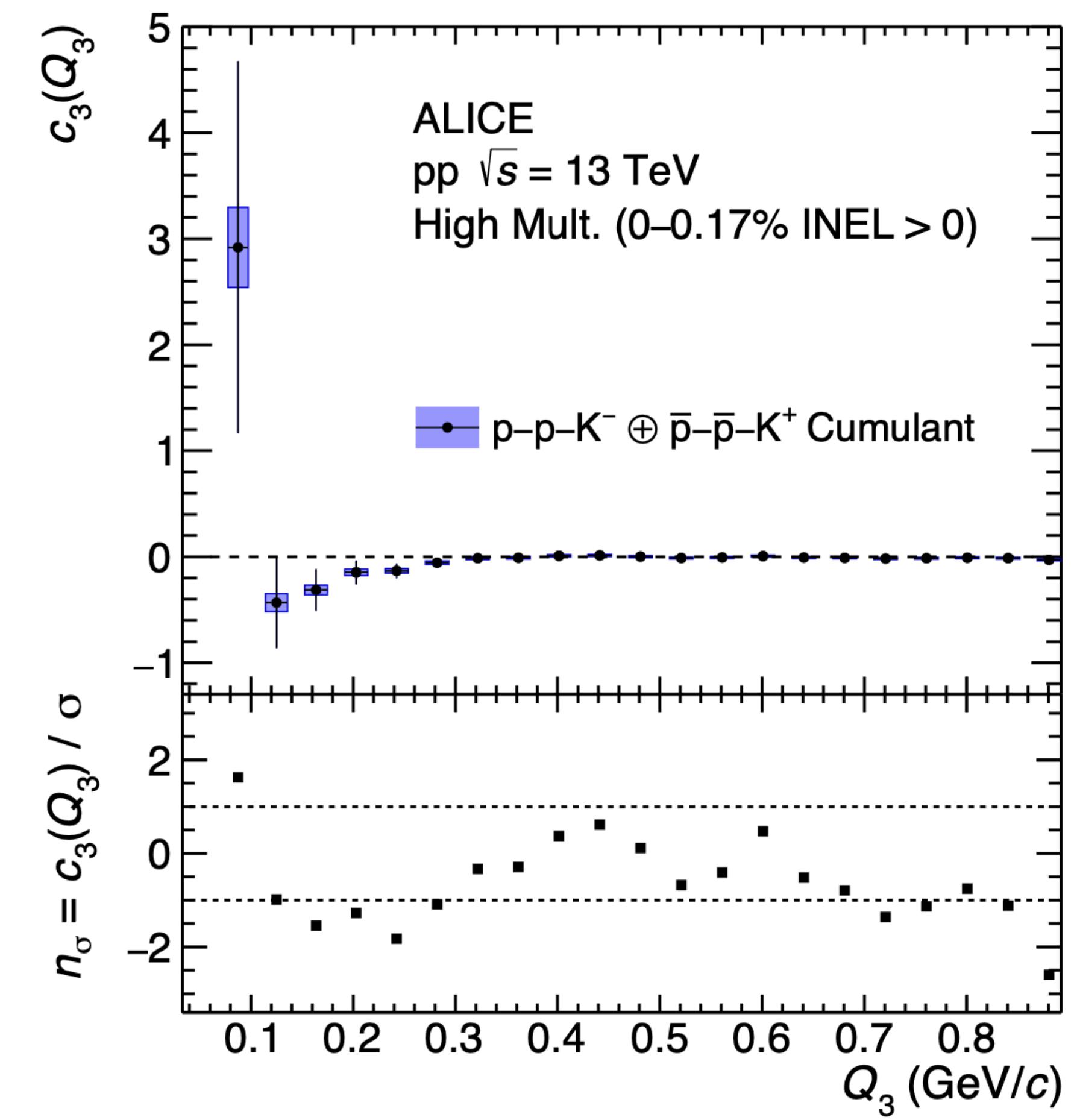
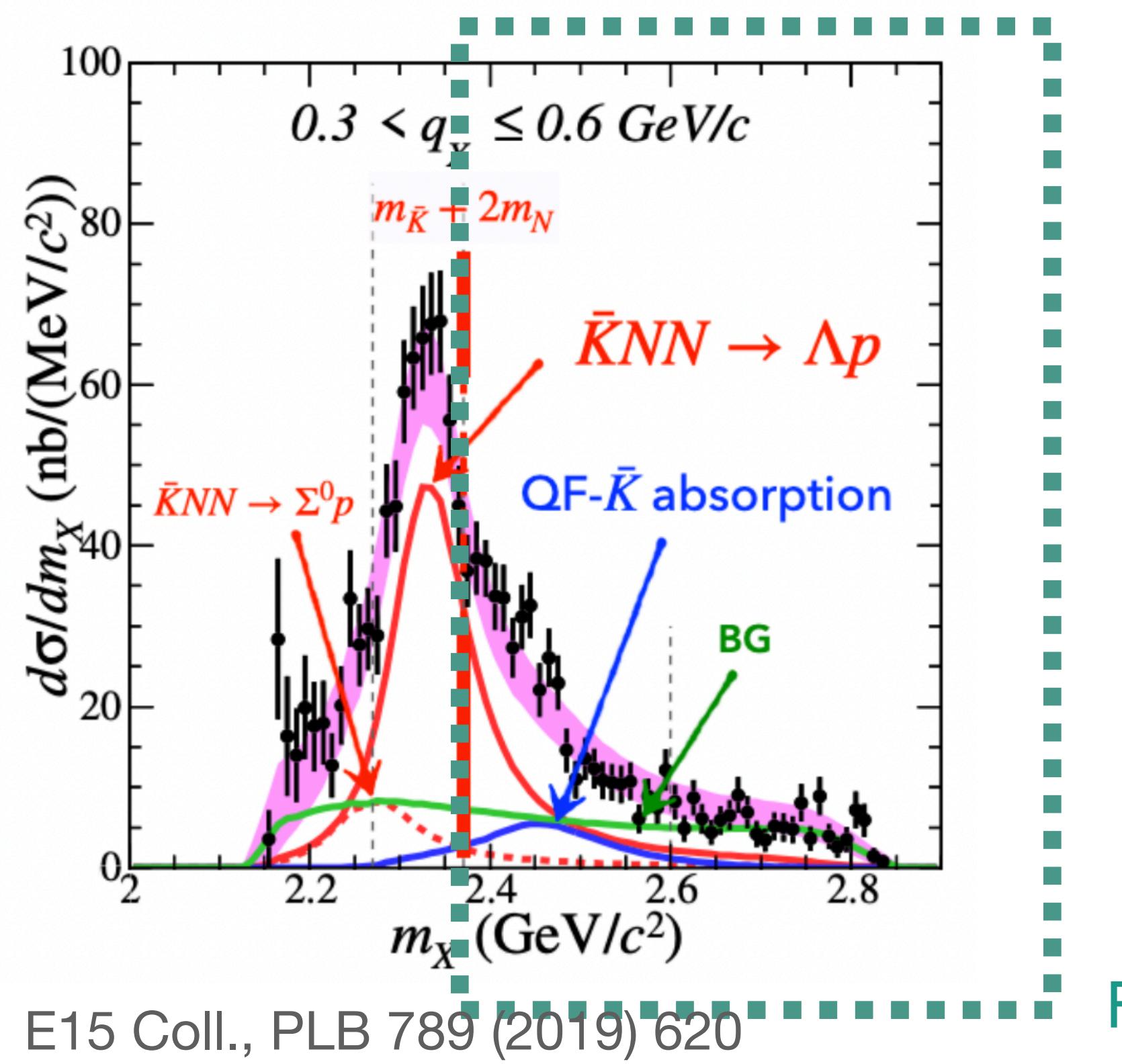


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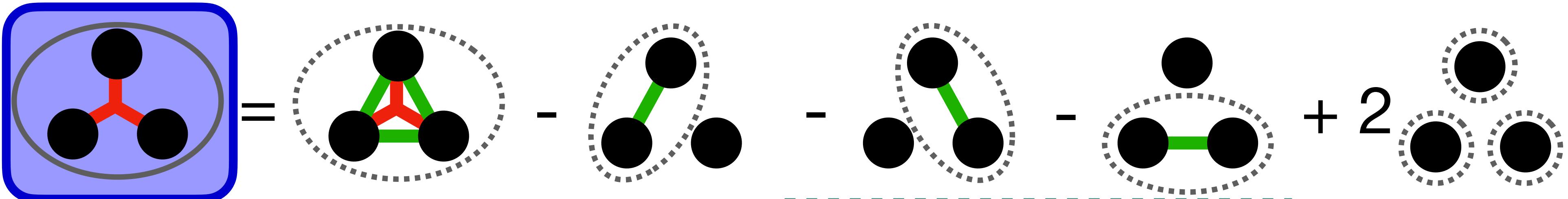


**Zero cumulant for p-p-K-**

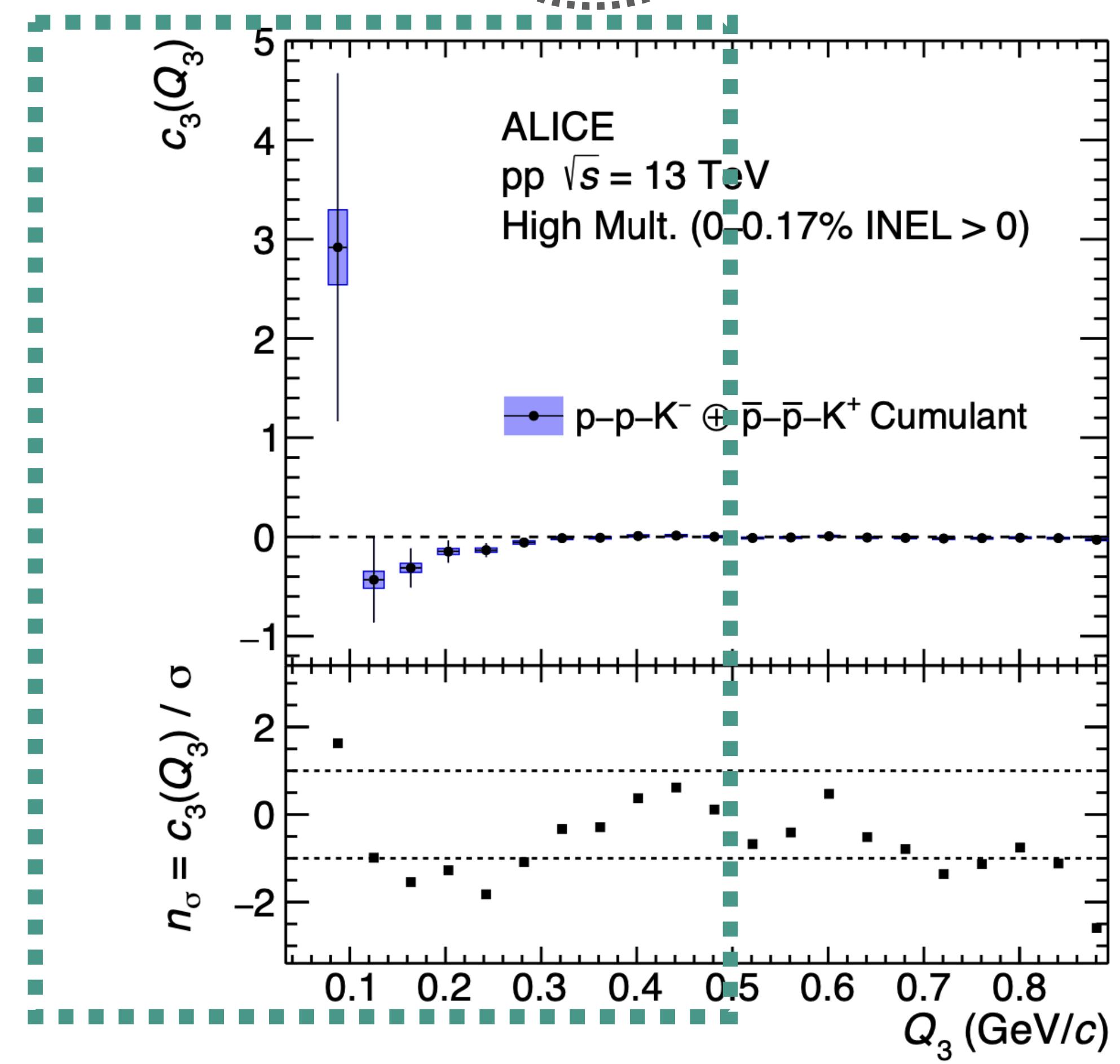
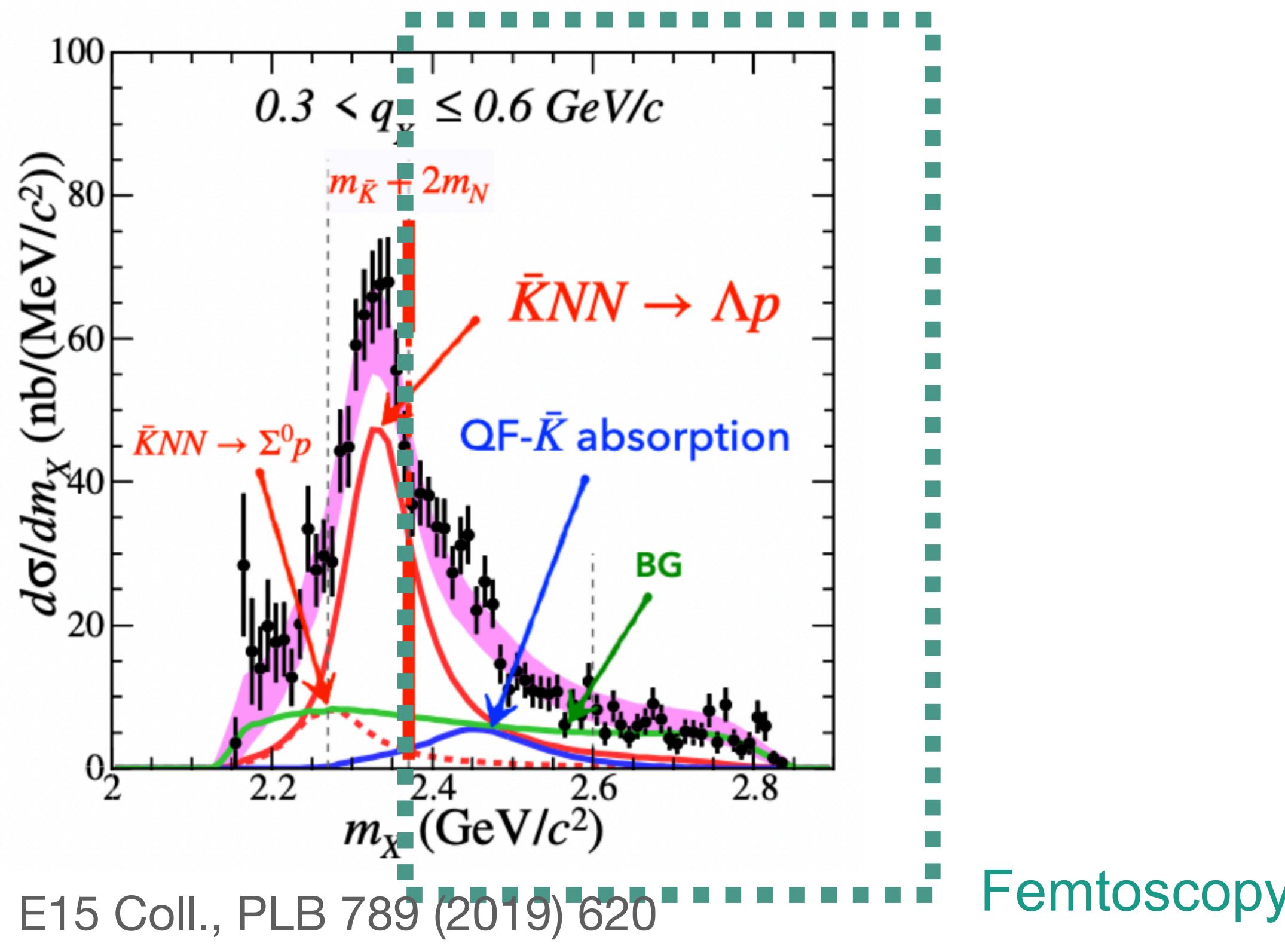


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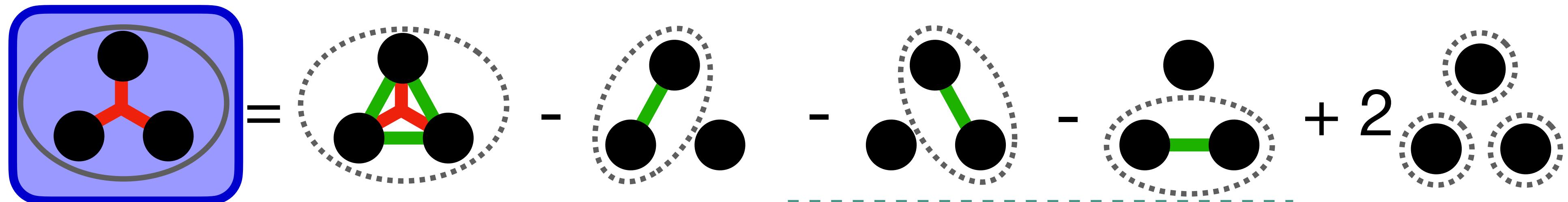


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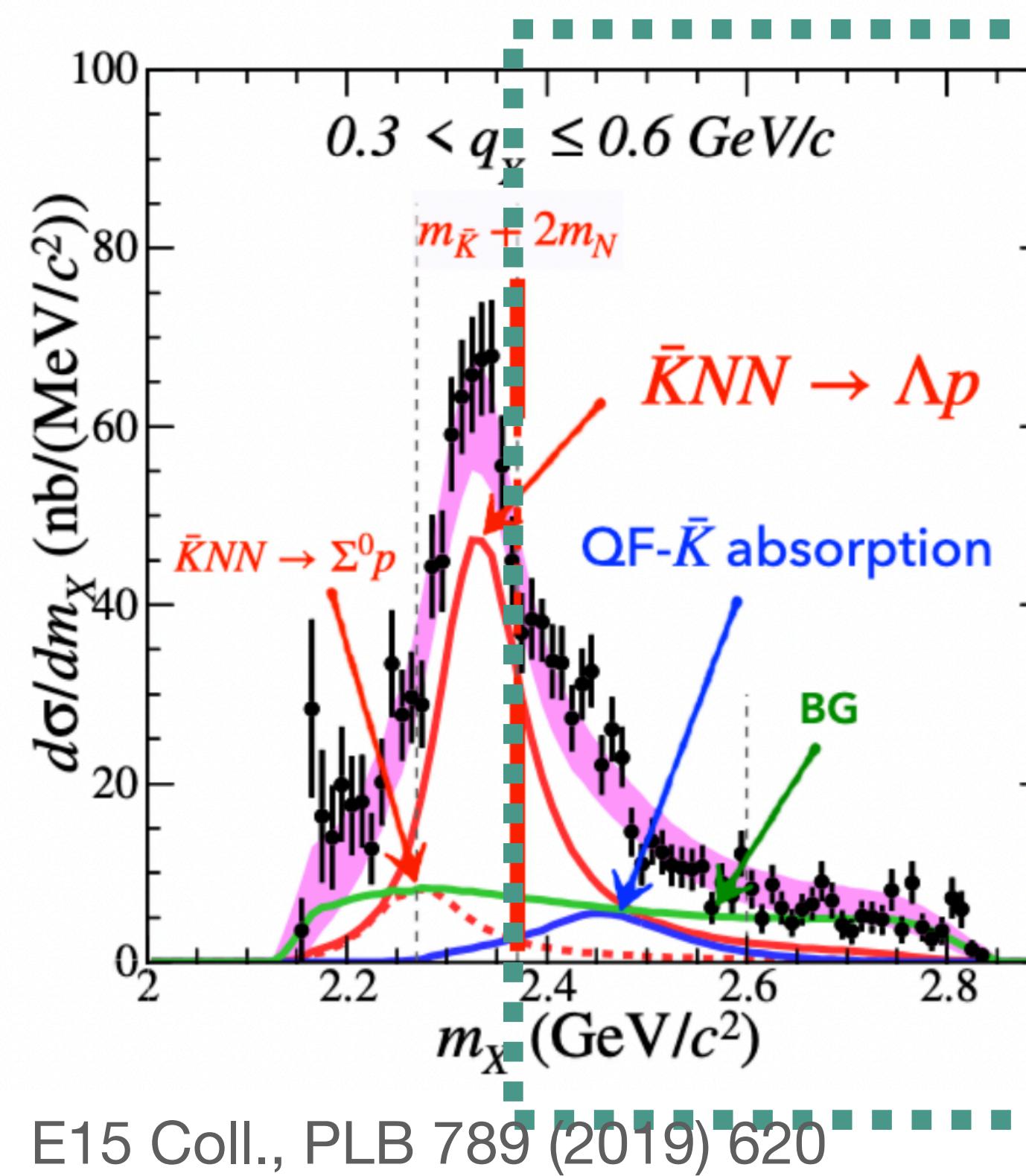


# p-p-K- cumulant

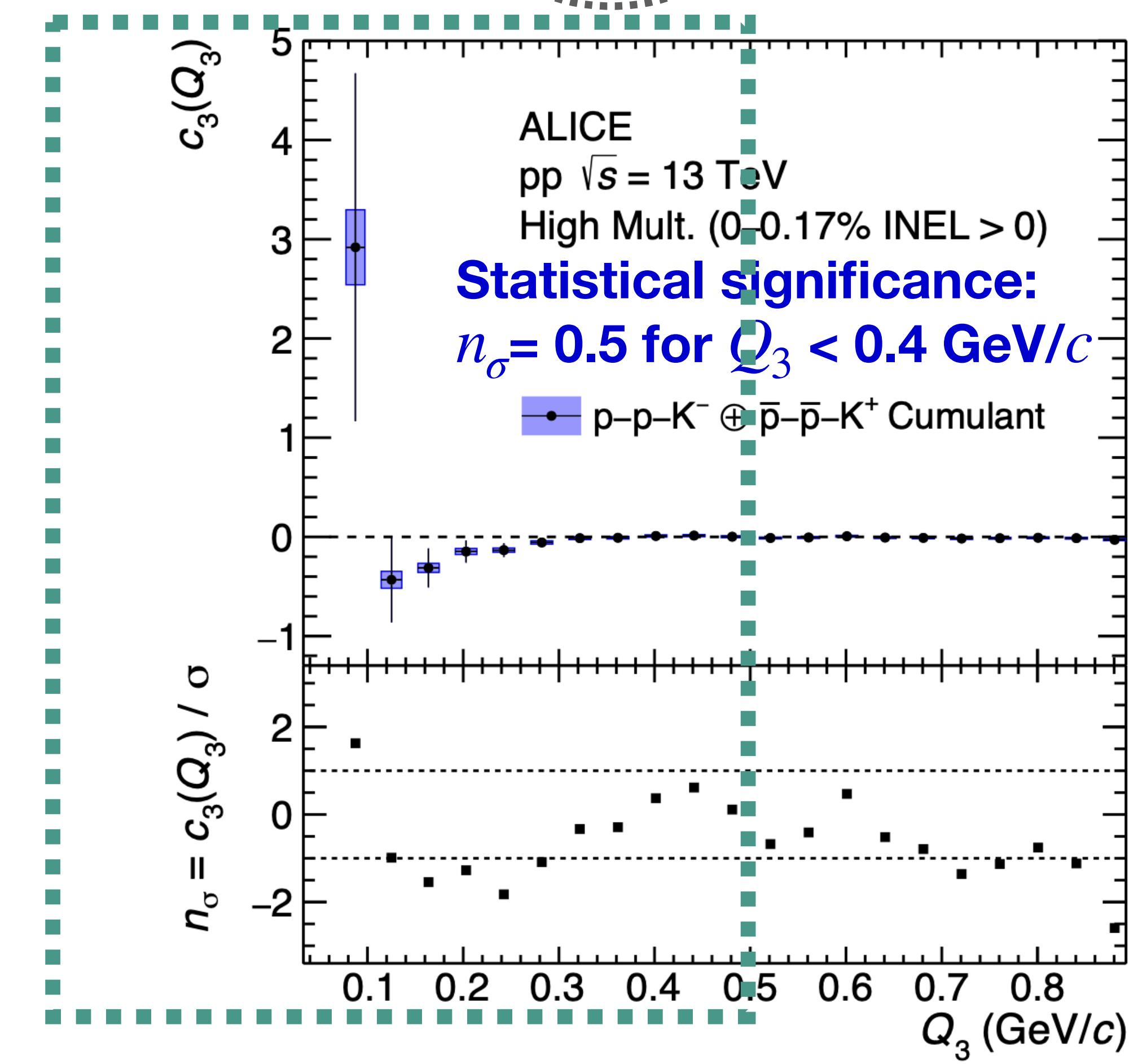
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Zero cumulant for p-p-K-



Femtoscopy

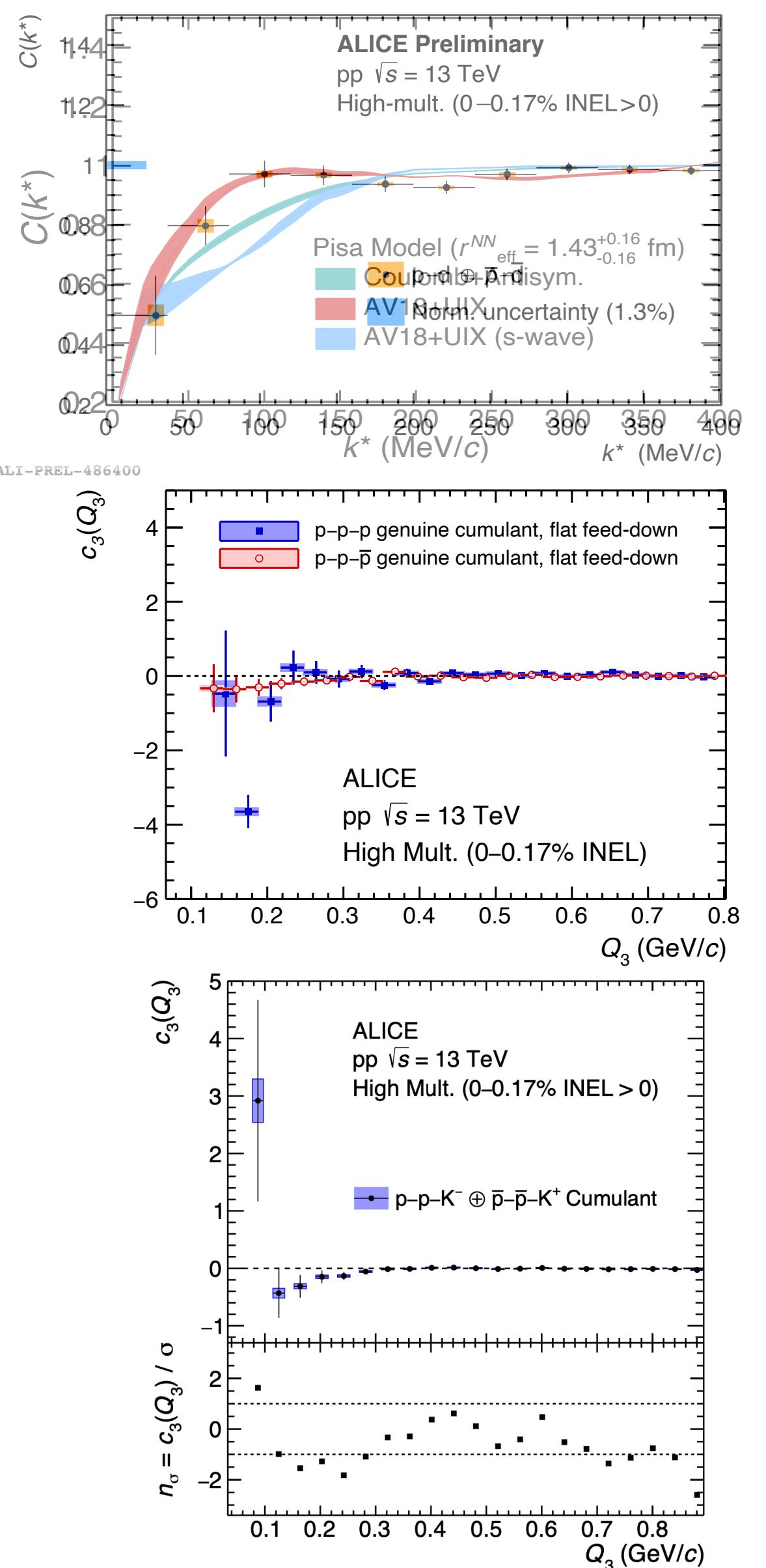
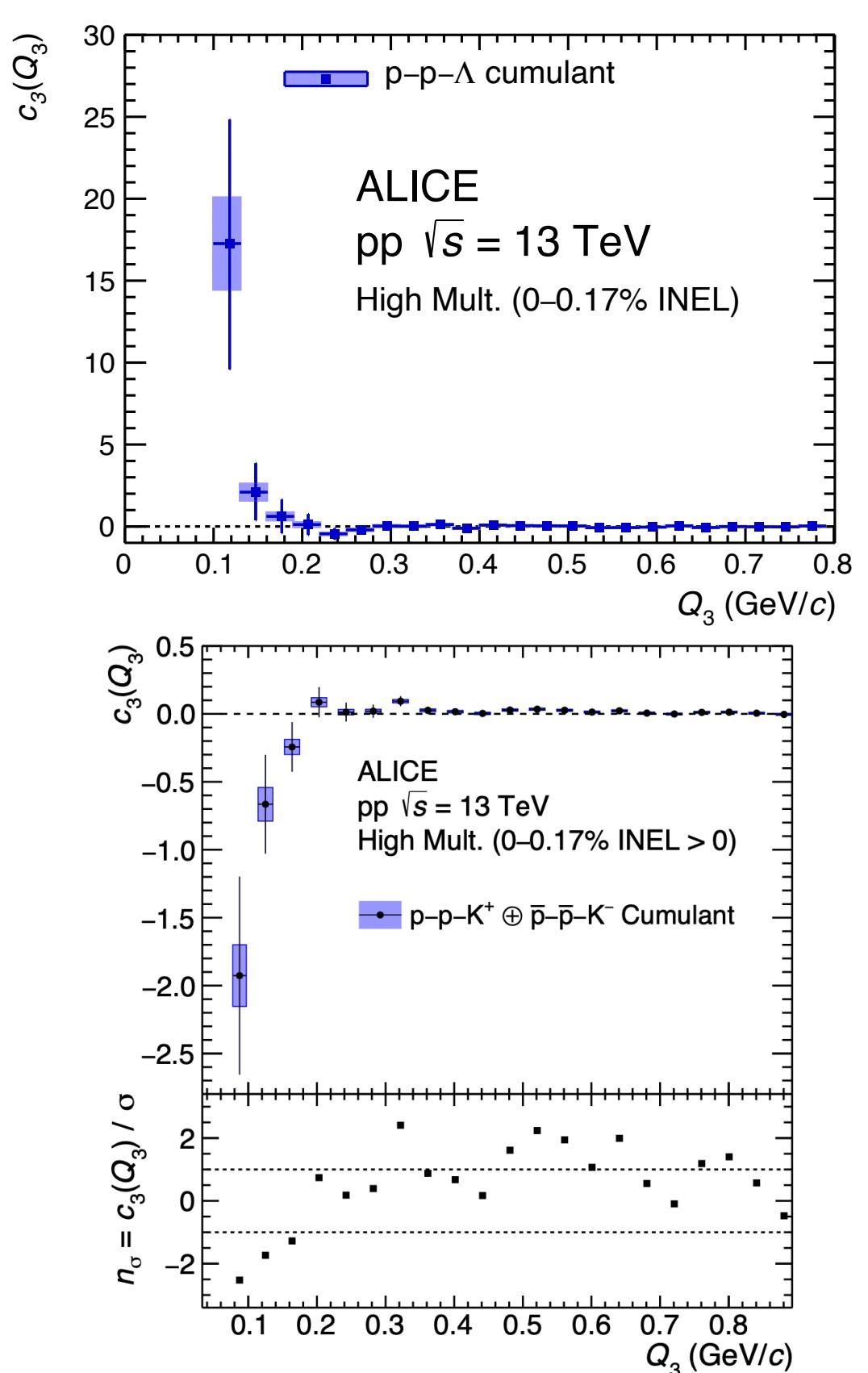


# Conclusions

**First measurements tackling the problem of genuine three-body interactions using femtoscopy!**

- **K<sup>+</sup>-d**: can be described as effective two-body system with source size from baryon analysis
- **p-d**: can be described with full three-body calculations
- **p-p-Λ**: no significant deviation from 0 in Run 2 data
- **p-p-p**: negative cumulant with a significance of  $6.7\sigma$
- **p-p-K<sup>+</sup>** and **p-p-K<sup>-</sup>**: cumulants compatible with 0, no evidence of a genuine three-body force

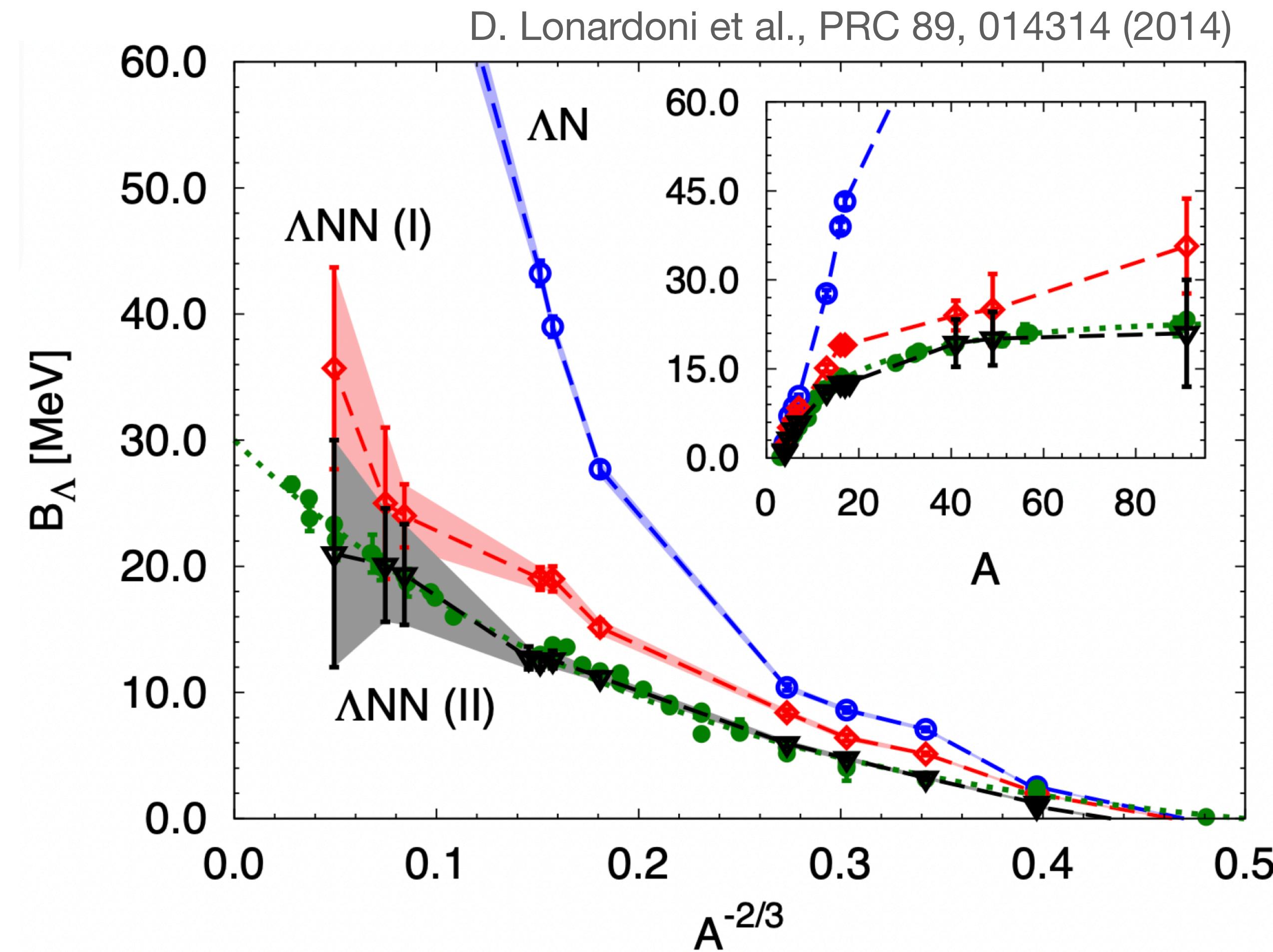
**Final constraints on three-body interactions will arrive with Run 3 data!**



# **Back-up**

# How to constrain three-body forces?

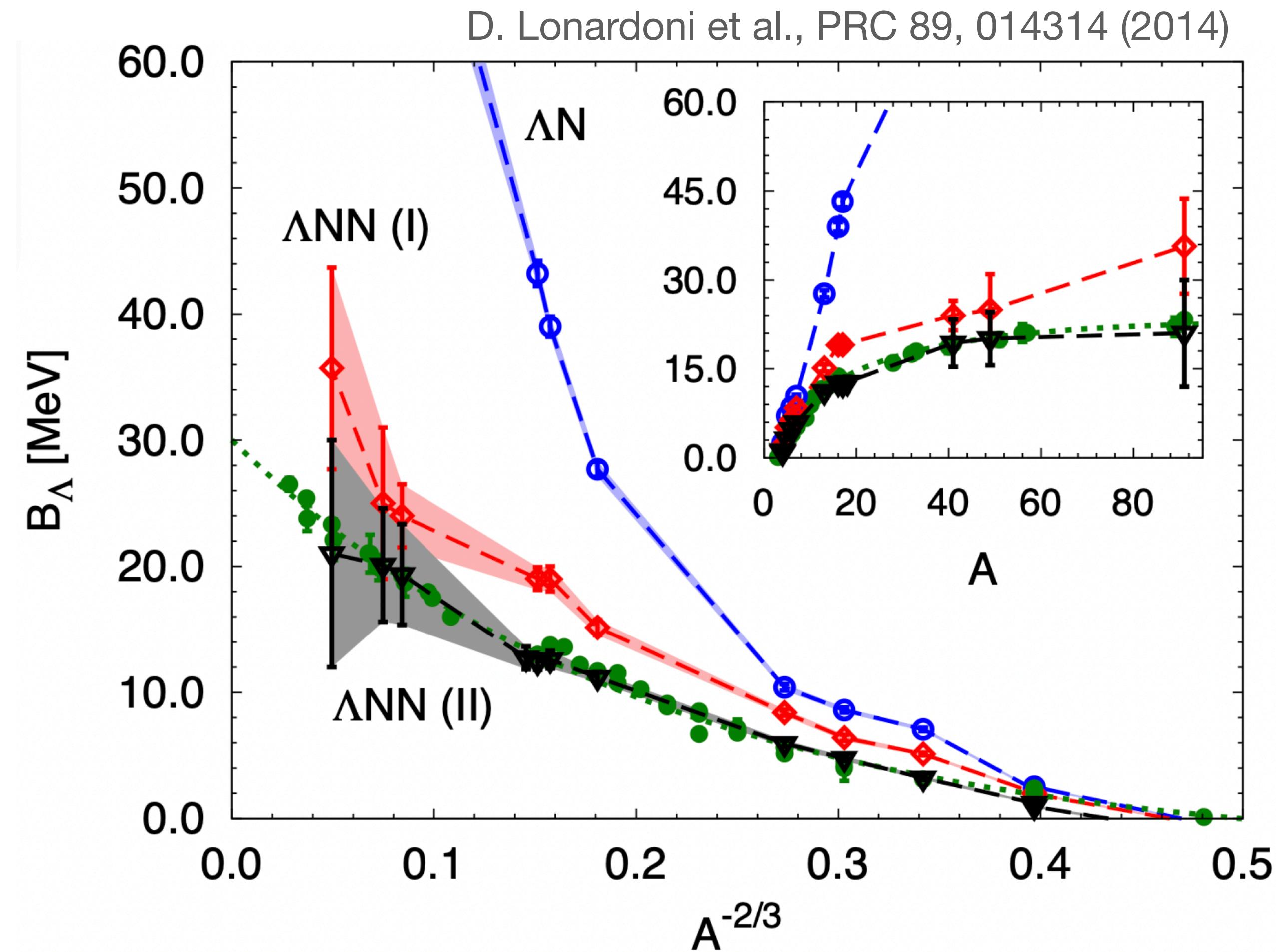
- Models are fitted to reproduce measured (hyper)nuclei properties
  - Access only to nuclear densities
  - Strongly dependent on the assumed two-body and many-body interactions
  - Different parametrisations of three-body forces describe better different nuclei



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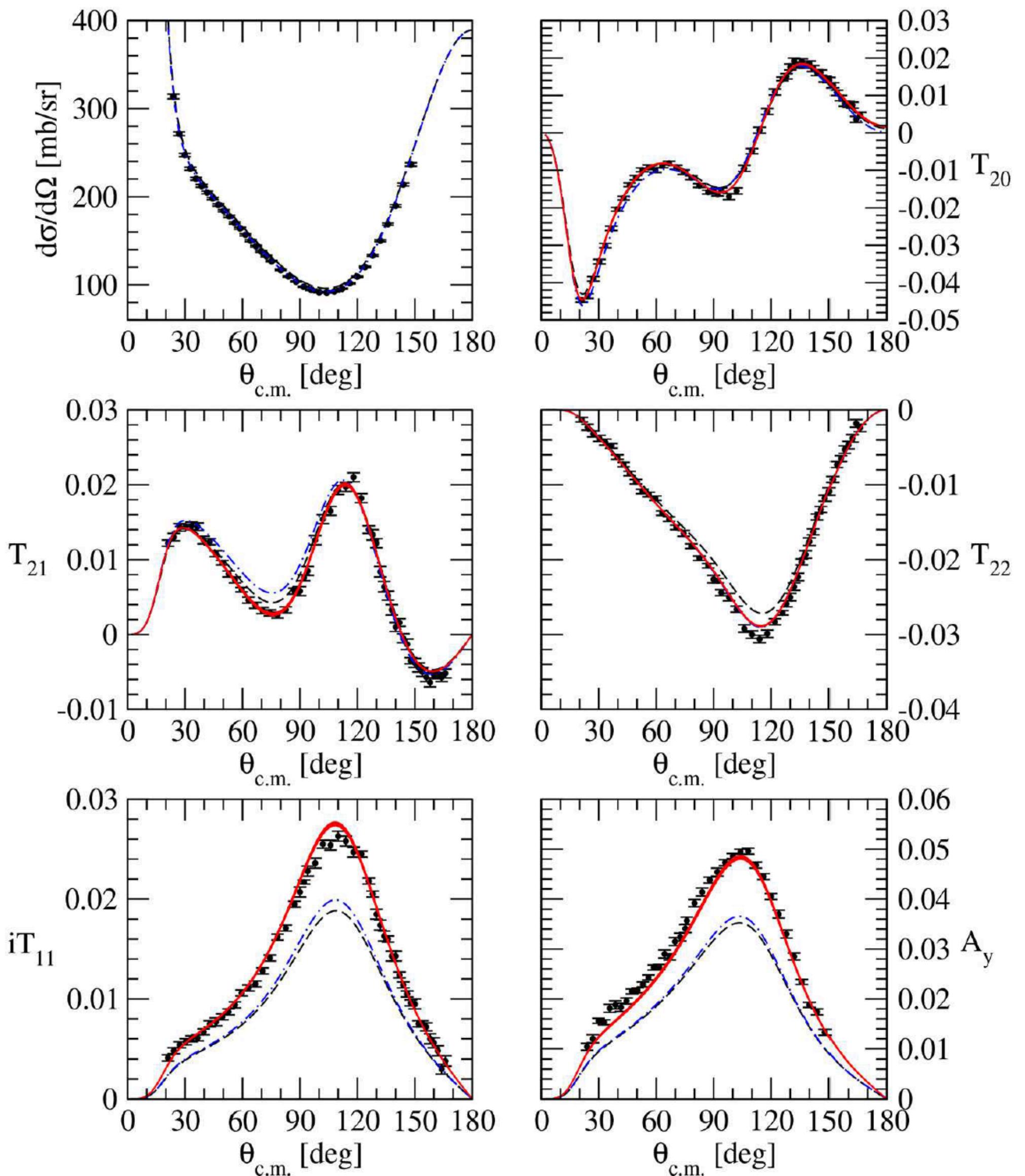
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  - Different parametrisations of three-body forces describe better different nuclei

Parameters	System	$B_{\Lambda}^{CSB}$
Set (I)	$^4_{\Lambda}\text{H}$	1.89(9)
	$^4_{\Lambda}\text{He}$	2.13(8)
Set (II)	$^4_{\Lambda}\text{H}$	0.95(9)
	$^4_{\Lambda}\text{He}$	1.22(9)
Expt. [12]	$^4_{\Lambda}\text{H}$	2.04(4)
	$^4_{\Lambda}\text{He}$	2.39(3)



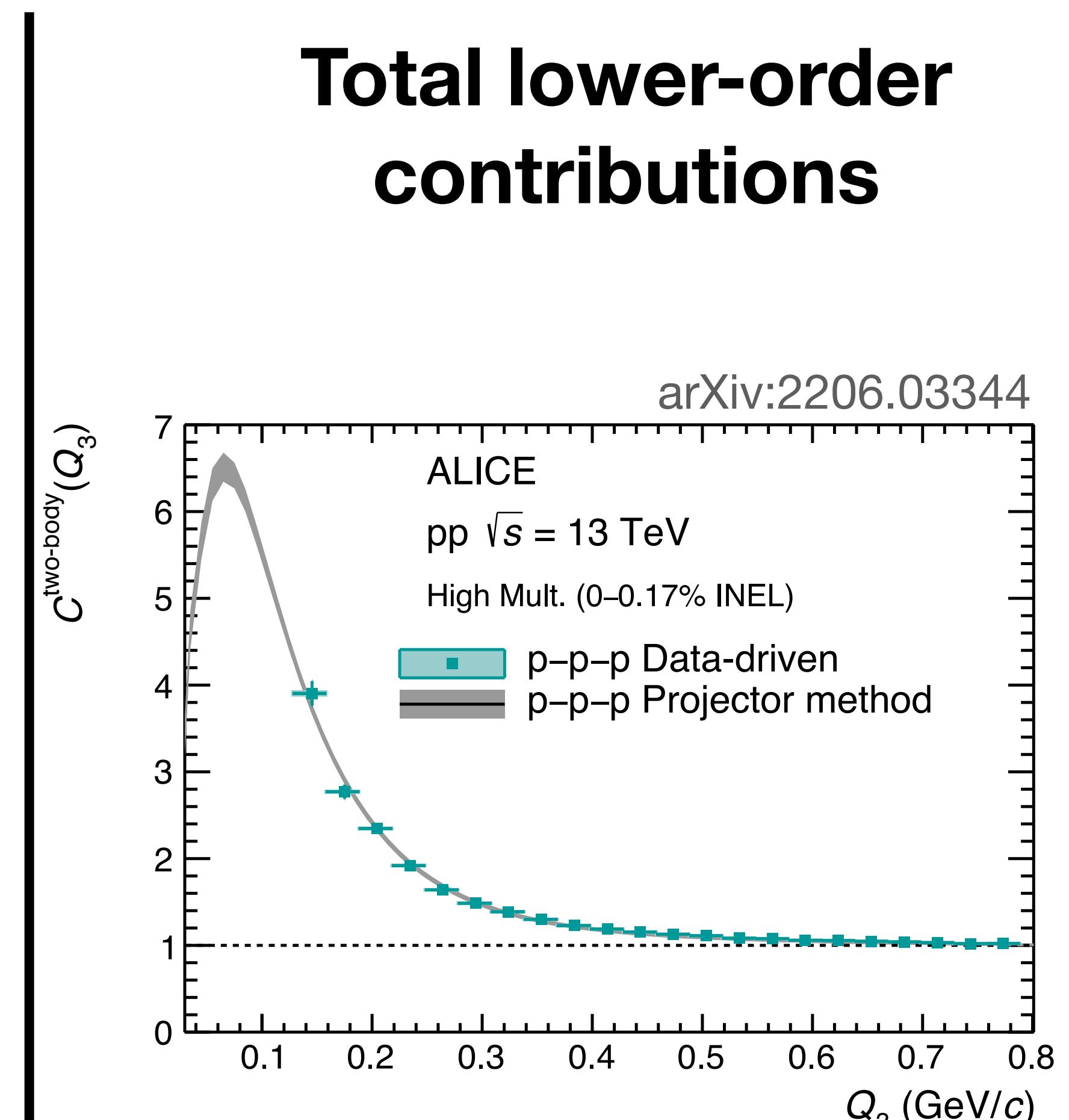
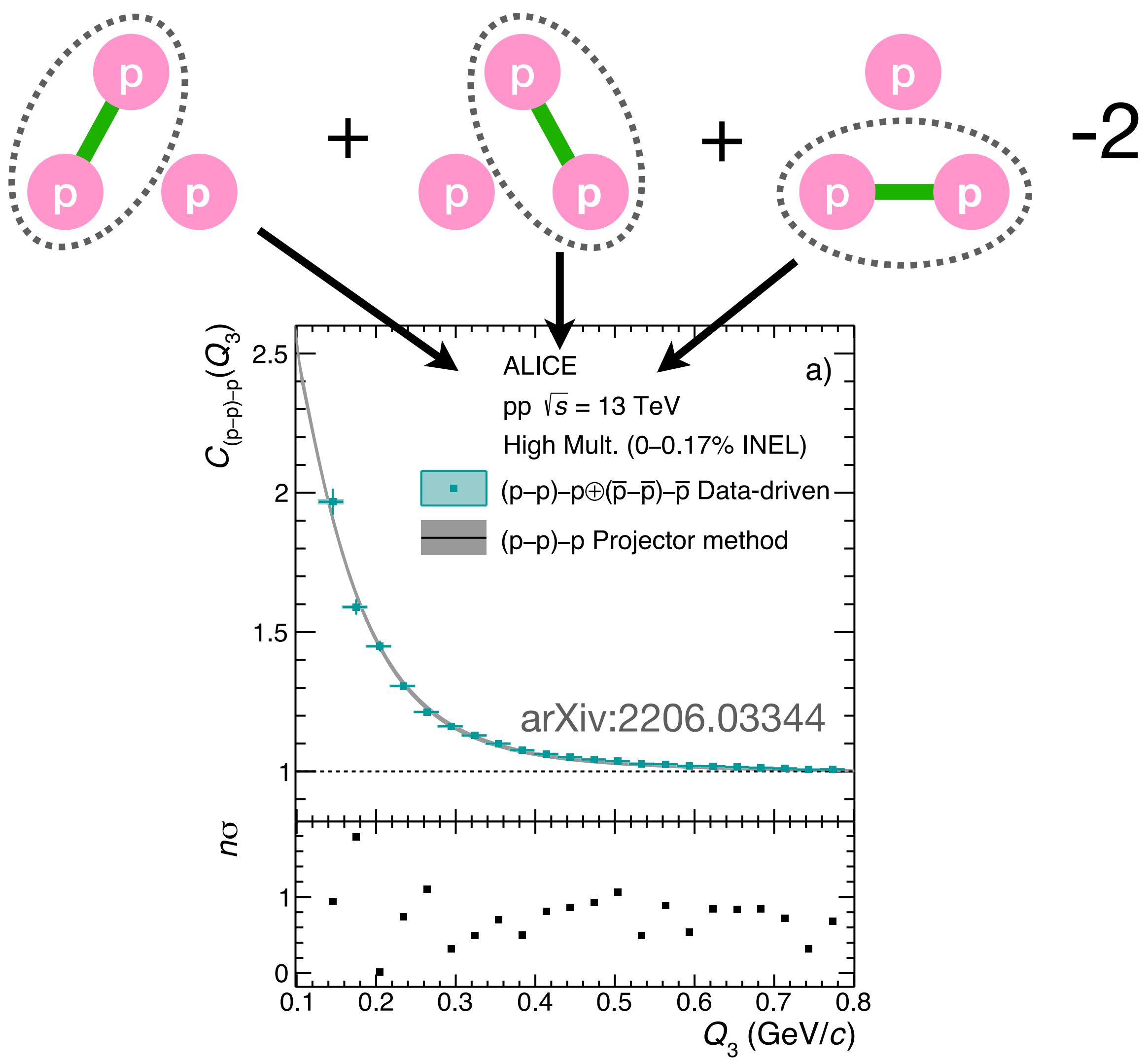
# p-d scattering

- Three body interactions are required to reproduce scattering data



L.E. Marcucci et al., Front. Phys. 8, 69 (2020)

# Lower-order contributions: p-p-p



Already measured p-p [1] correlation function used for projection.

[1] PLB 805 (2020) 135419

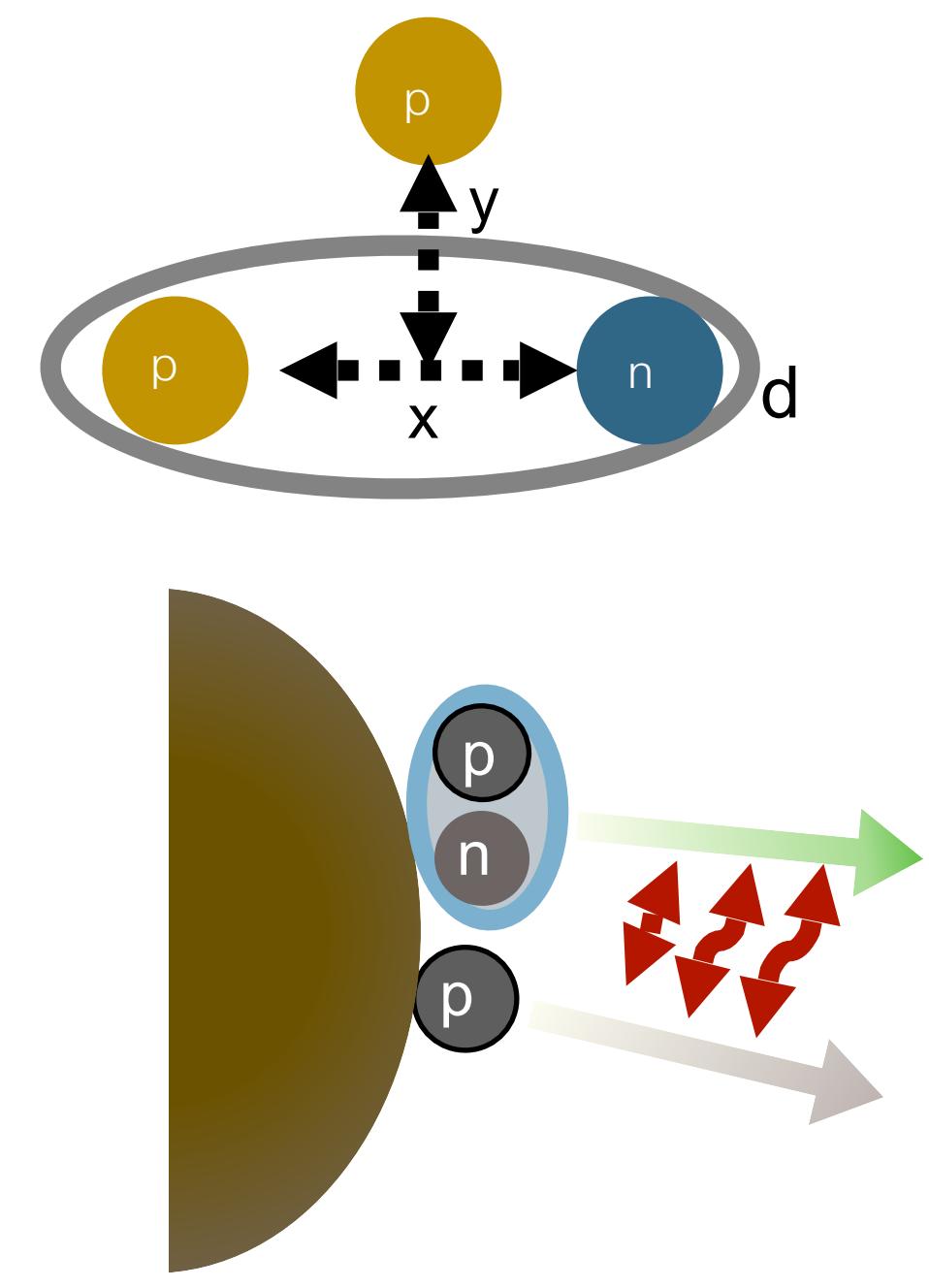
# Proton-deuteron wave function

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
  - m2 and m1 deuteron and proton spin
- $\Psi_{m_2, m_1}(x, y)$  three-nucleon wave function asymptotically behaves as p-d state:

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

- $\tilde{\Psi}_{LSJJ_z}$  describe the configurations where the three particles are close to each other
- $\Psi_{m_2, m_1}^{(\text{free})}$  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

# Proton-deuteron correlations

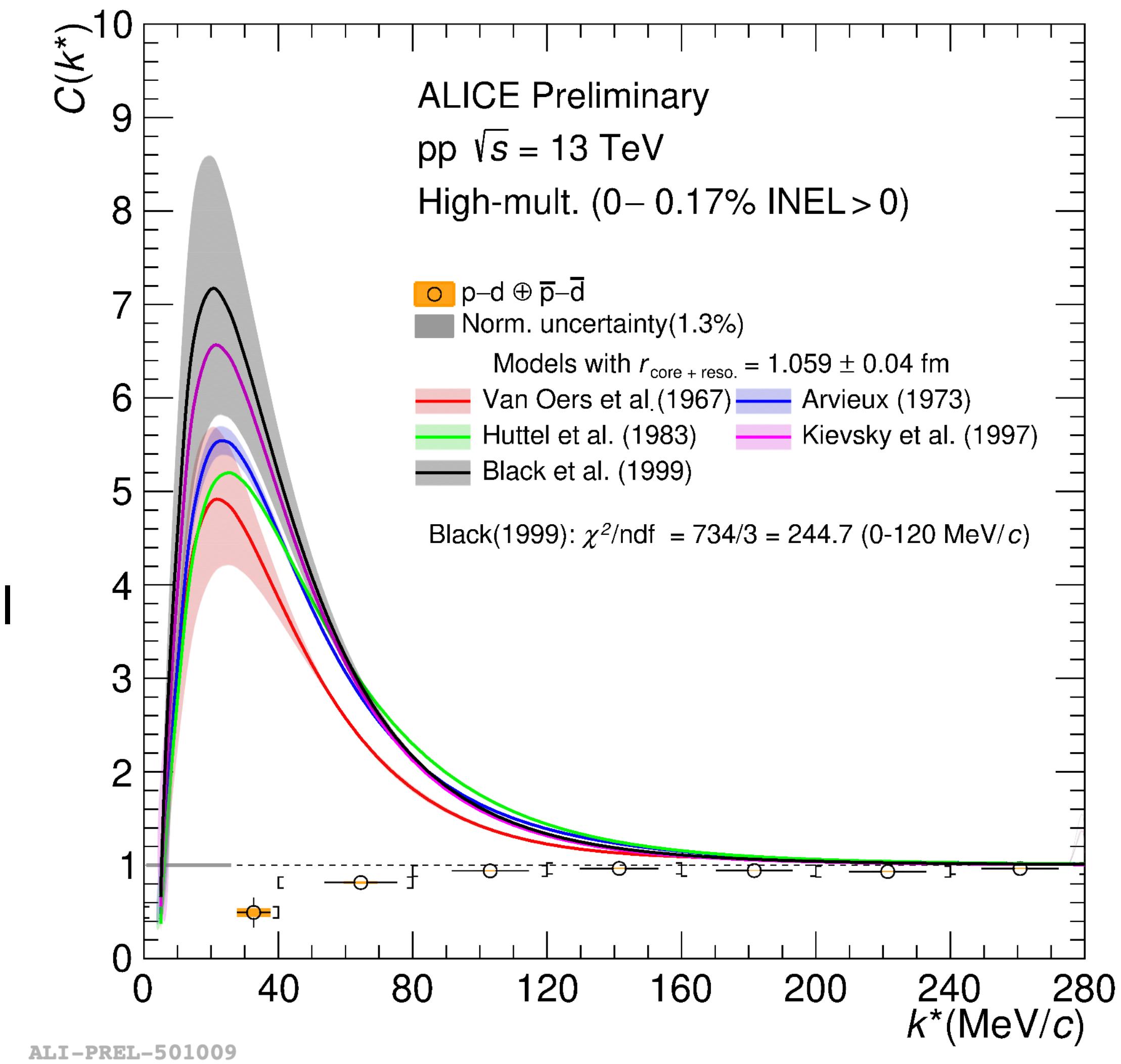
Point-like particle models anchored to scattering experiments

	$S = 1/2$		$S = 3/2$	
	$f_0(\text{fm})$	$d_0(\text{fm})$	$f_0(\text{fm})$	$d_0(\text{fm})$
Van Oers et al. (1967)	$-1.30^{+0.20}_{-0.20}$	—	$-11.40^{+1.20}_{-1.80}$	$2.05^{+0.25}_{-0.25}$
Arvieux (1973)	$-2.73^{+0.10}_{-0.10}$	$2.27^{+0.12}_{-0.12}$	$-11.88^{+0.10}_{-0.40}$	$2.63^{+0.01}_{-0.02}$
Huttel et al. (1983)	—	—	—	—
Kievsky et al. (1997)	—	—	—	—
Black et al. (1999)	$0.13^{+0.04}_{-0.04}$	—	$-14.70^{+2.30}_{-2.30}$	—

W. T. H. Van Oers, & K. W. Brockman Jr, NPA 561 (1967);  
 J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);  
 A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);

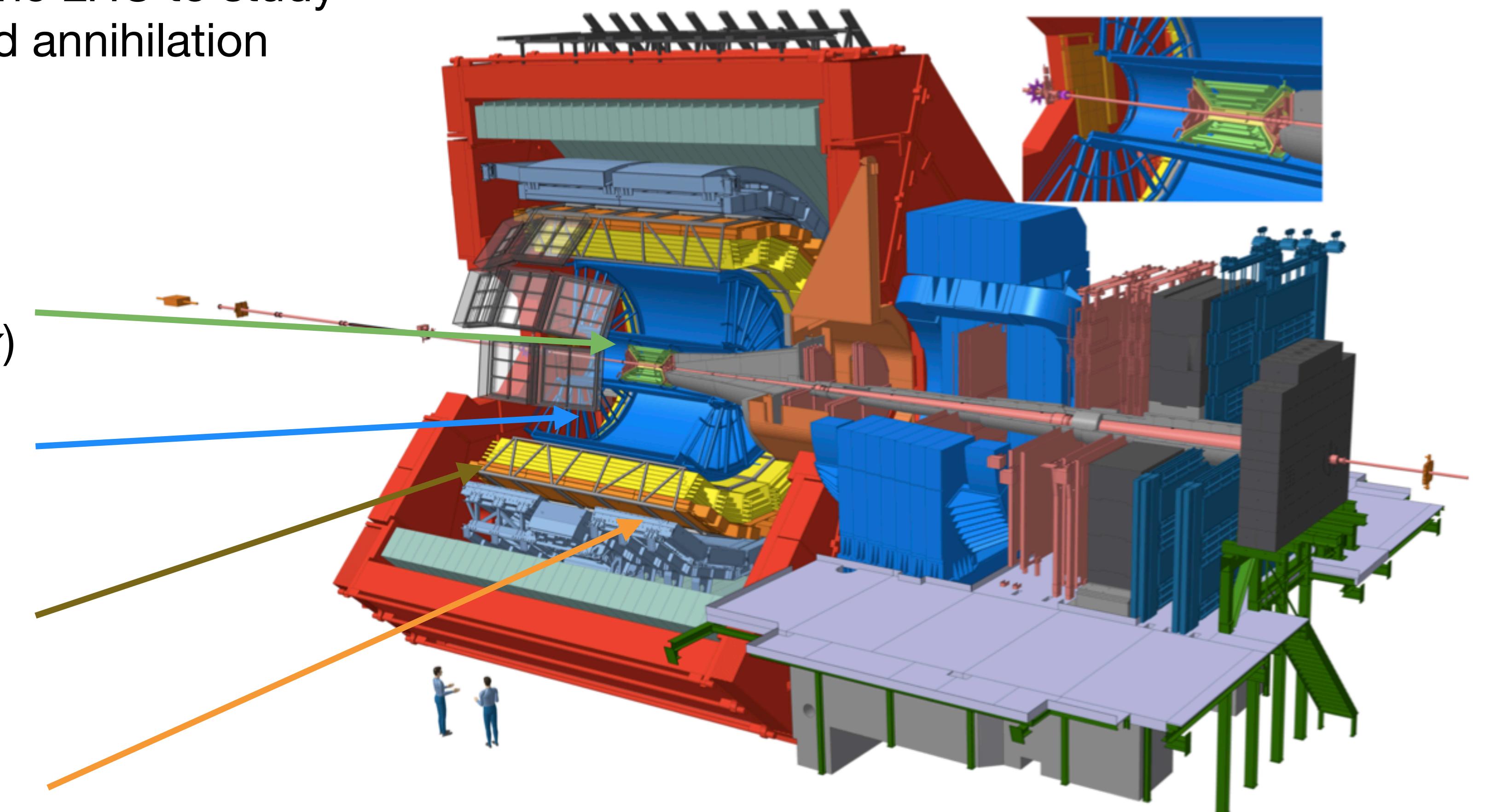
- Coulomb + strong interaction using the Lednický model  
*Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)*
- Only s-wave interaction
- Source radius evaluated using the hadron-hadron universal  $m_T$  scaling

Point-like particle description doesn't work for p-d



# ALICE detector

- Excellent tracking and particle identification (PID) capabilities
- Most suitable detector at the LHC to study (anti-)nuclei production and annihilation



Time Of Flight detector  
PID (TOF measurement)

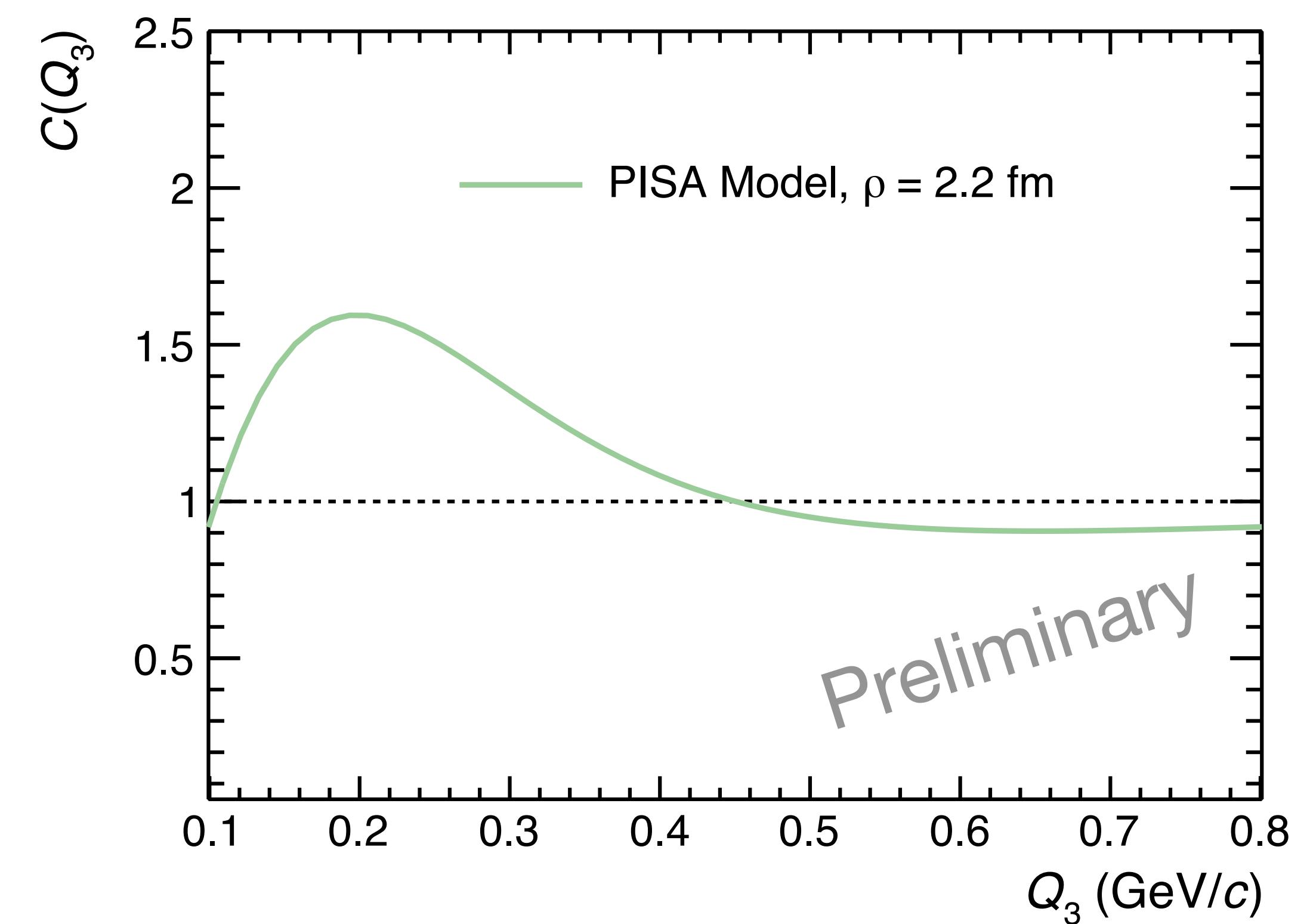
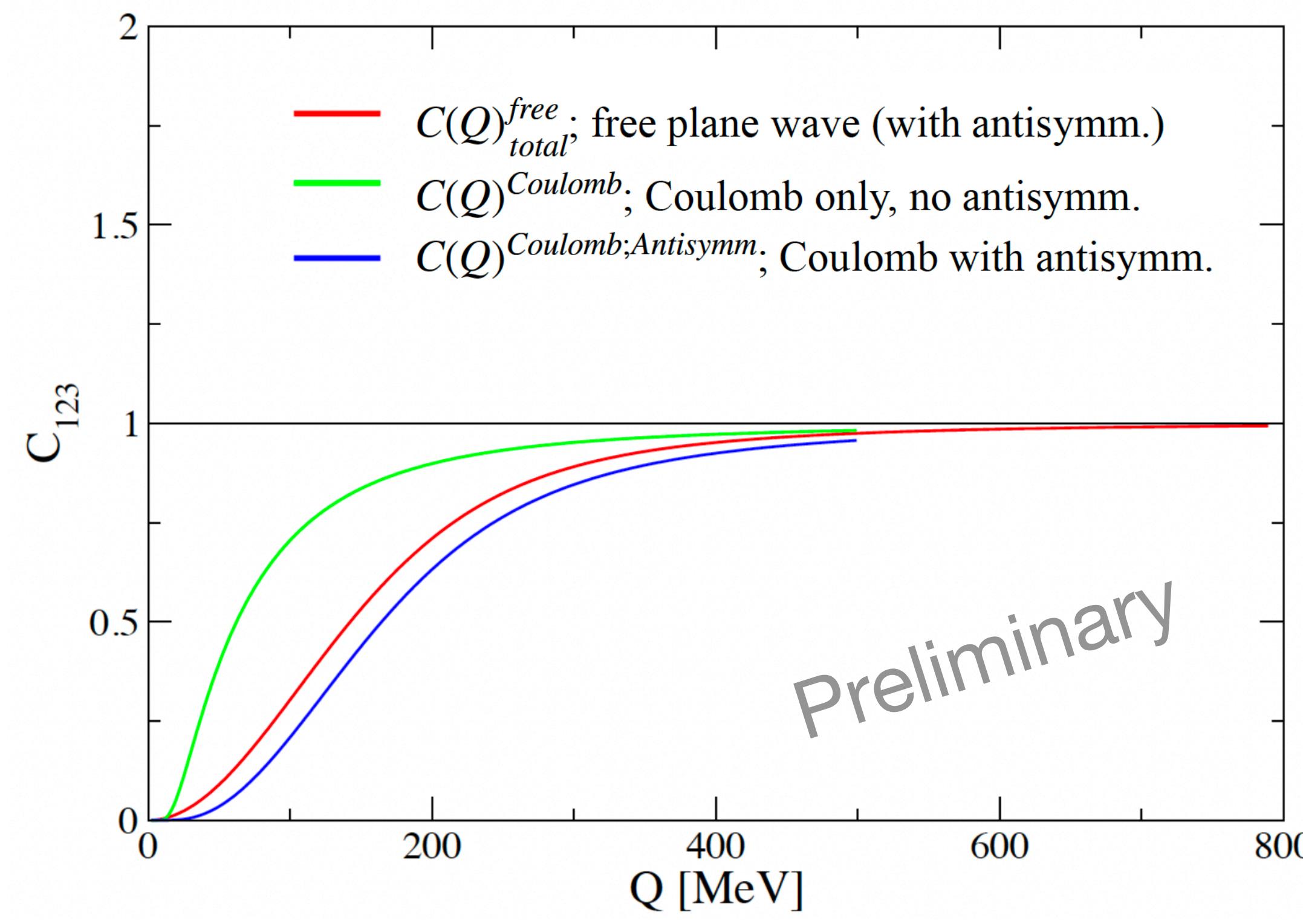
Transition Radiation Detector

Time Projection Chamber  
Tracking, PID ( $dE/dx$ )

Inner Tracking System  
Tracking, vertex, PID ( $dE/dx$ )

# p-p-p calculations (ongoing)

- Calculations performed by Alejandro Kievsky



# Projector

- Looking at 2-body correlation function in 3-body space requires to account for the phase-space of the particles.
- The projection onto  $Q_3$  is performed by integrating the correlation function over all the configurations in the momentum phase space having the same value of  $Q_3$

$$C(Q_3) = \iiint_{Q_3=\text{constant}} C([\mathbf{p}_i, \mathbf{p}_j], \mathbf{p}_k) d^3\mathbf{p}_i d^3\mathbf{p}_j d^3\mathbf{p}_k = \int C_2(k_{ij}^*) W_{ij}(k_{ij}^*, Q_3) dk_{ij}^*$$

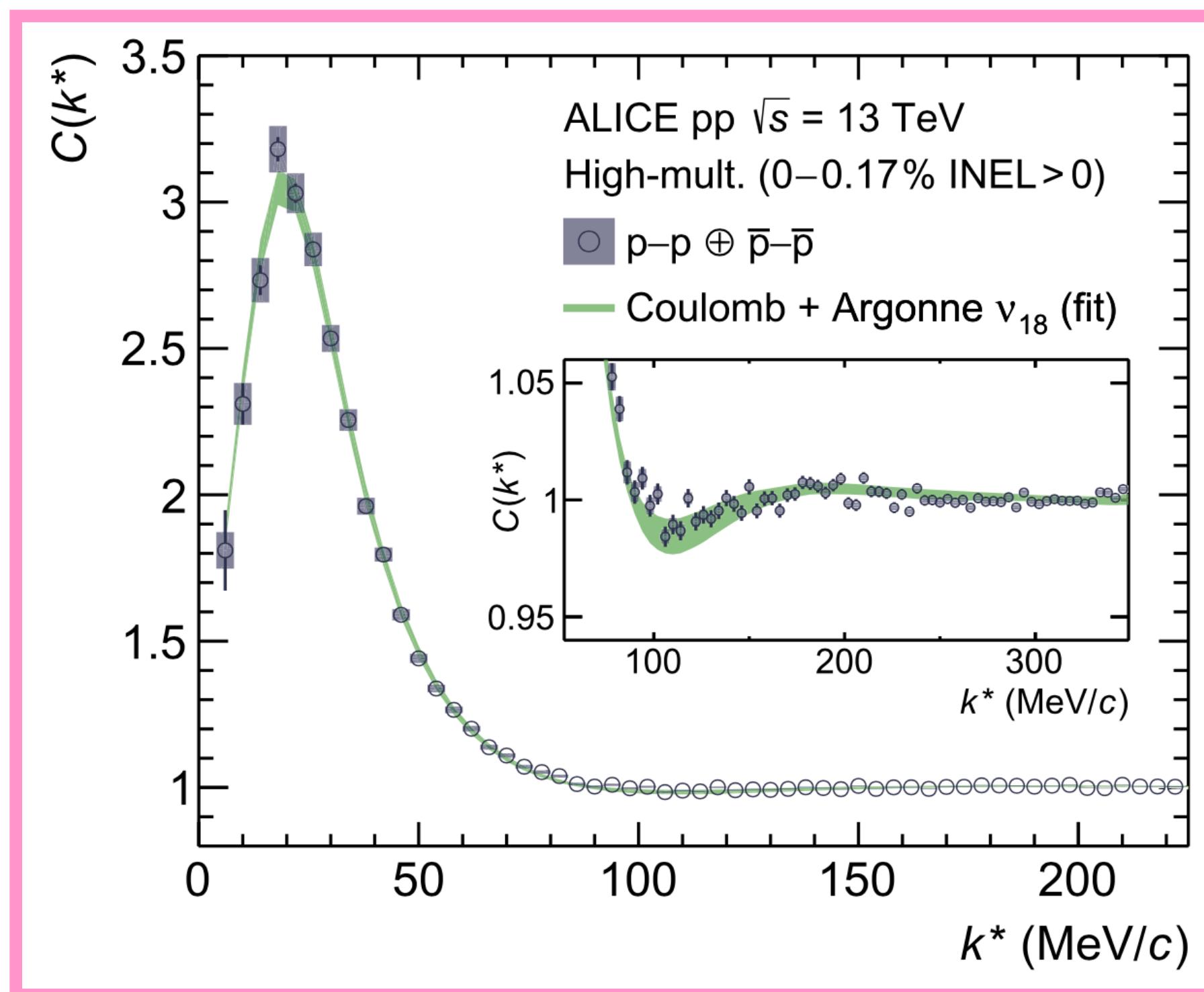
$$W_{ij}(k_{ij}^*, Q_3) = \frac{16(\alpha\gamma - \beta^2)^{3/2} k_{ij}^{*2}}{\pi\gamma^2 Q_3^4} \sqrt{\gamma Q_3^2 - (\alpha\gamma - \beta^2) k_{ij}^{*2}}$$

- The  $\alpha, \beta, \gamma$  depend only on the masses of the three particles.

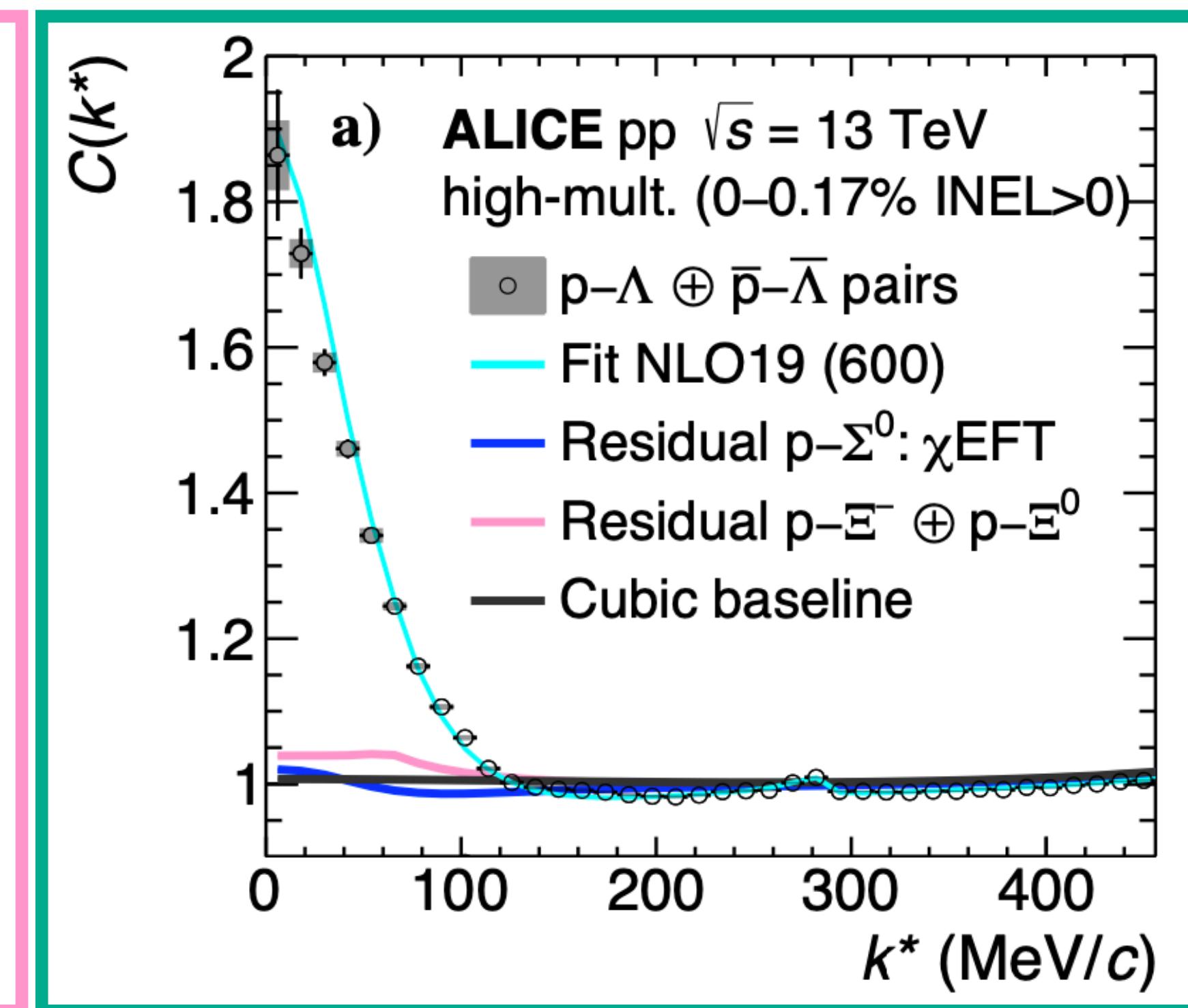
# Two-body measurements

- Many different two-body interactions measured successfully!

p ? p



p ?  $\Lambda$

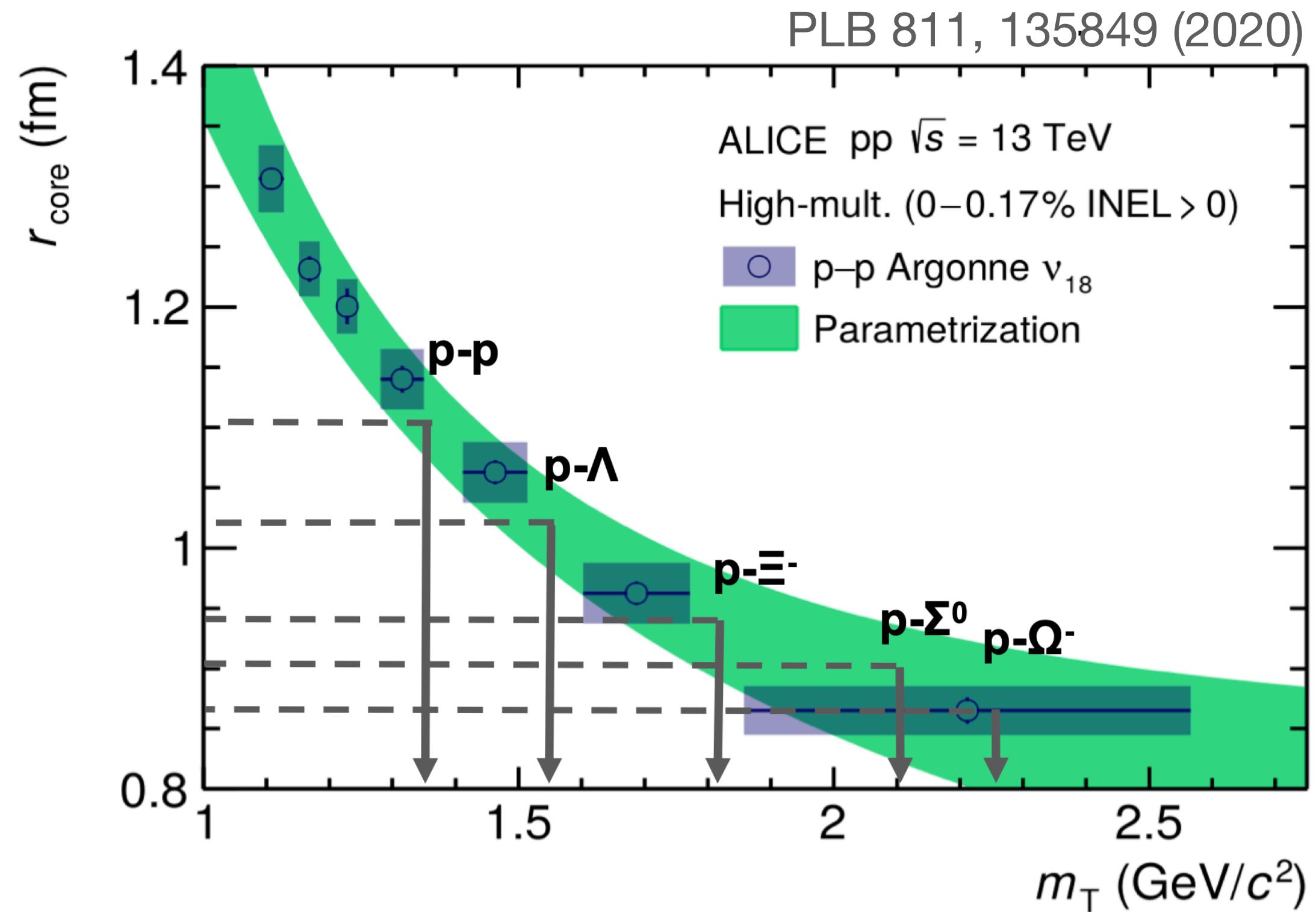


TUM Group:  
EPJC 78 (2018) 394  
arXiv:2107.10227

ALICE:  
PRC 99 (2019) 024001  
PLB 797 (2019) 134822  
PRL 123 (2019) 112002  
PRL 124 (2020) 09230  
PLB 805 (2020) 135419  
PLB 811 (2020) 135849  
Nature 588 (2020) 232-238  
arXiv:2104.04427  
arXiv:2105.05578  
arXiv:2105.05683  
arXiv:2105.05190

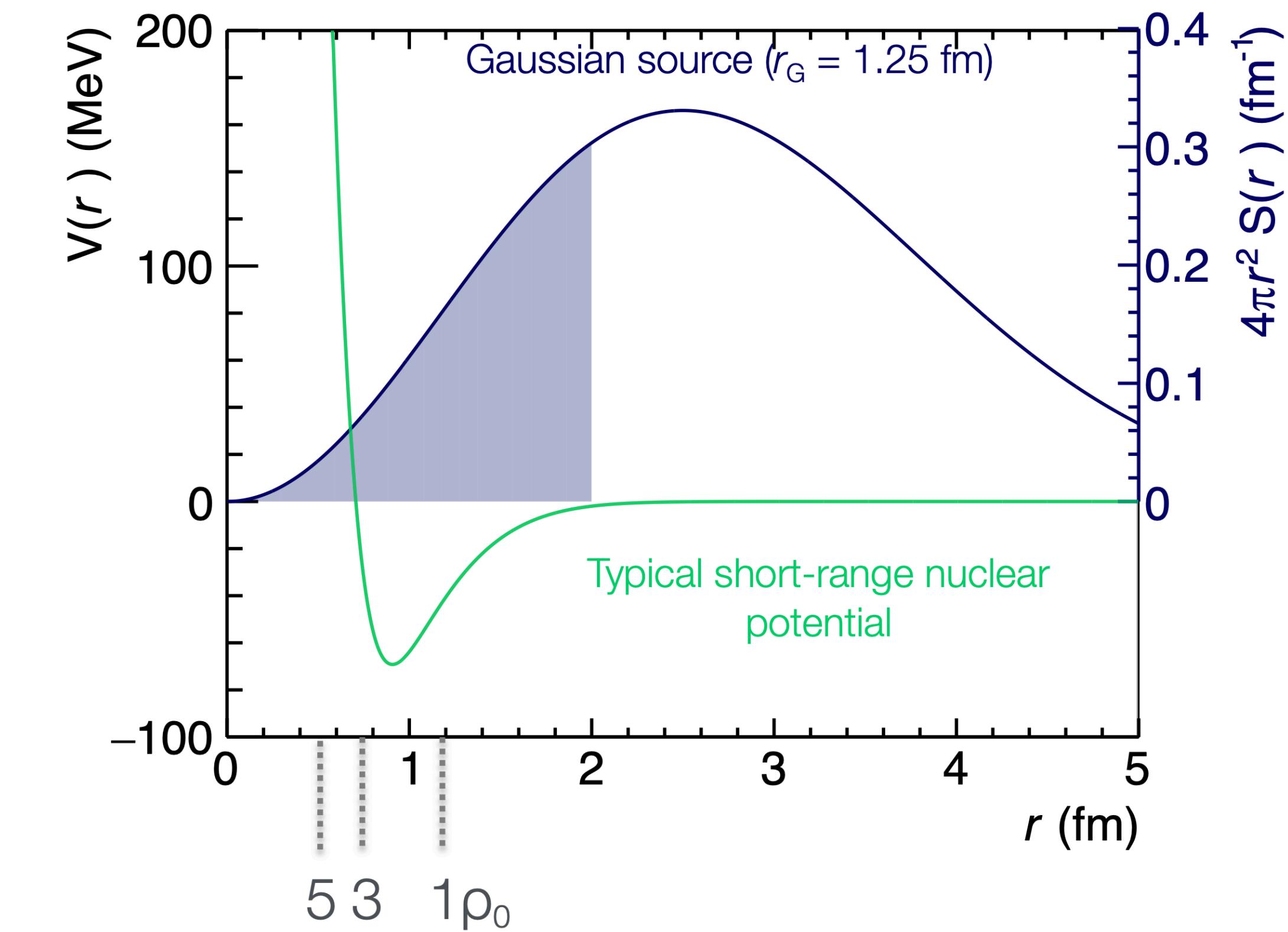
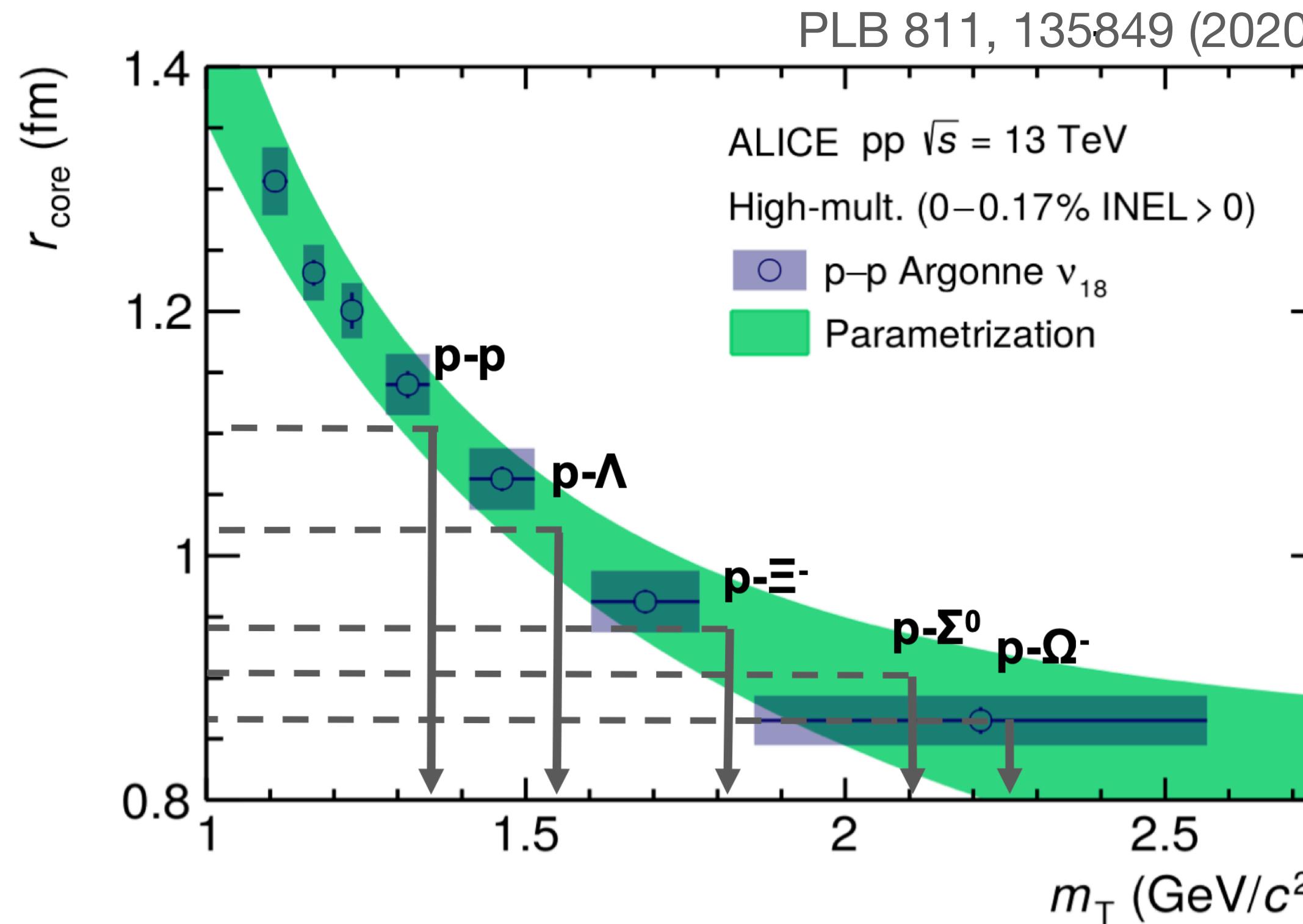
# Emission source

- Two main contributions:
  - general: Collective effects result in Gaussian core
  - specific: Decaying resonances require source correction



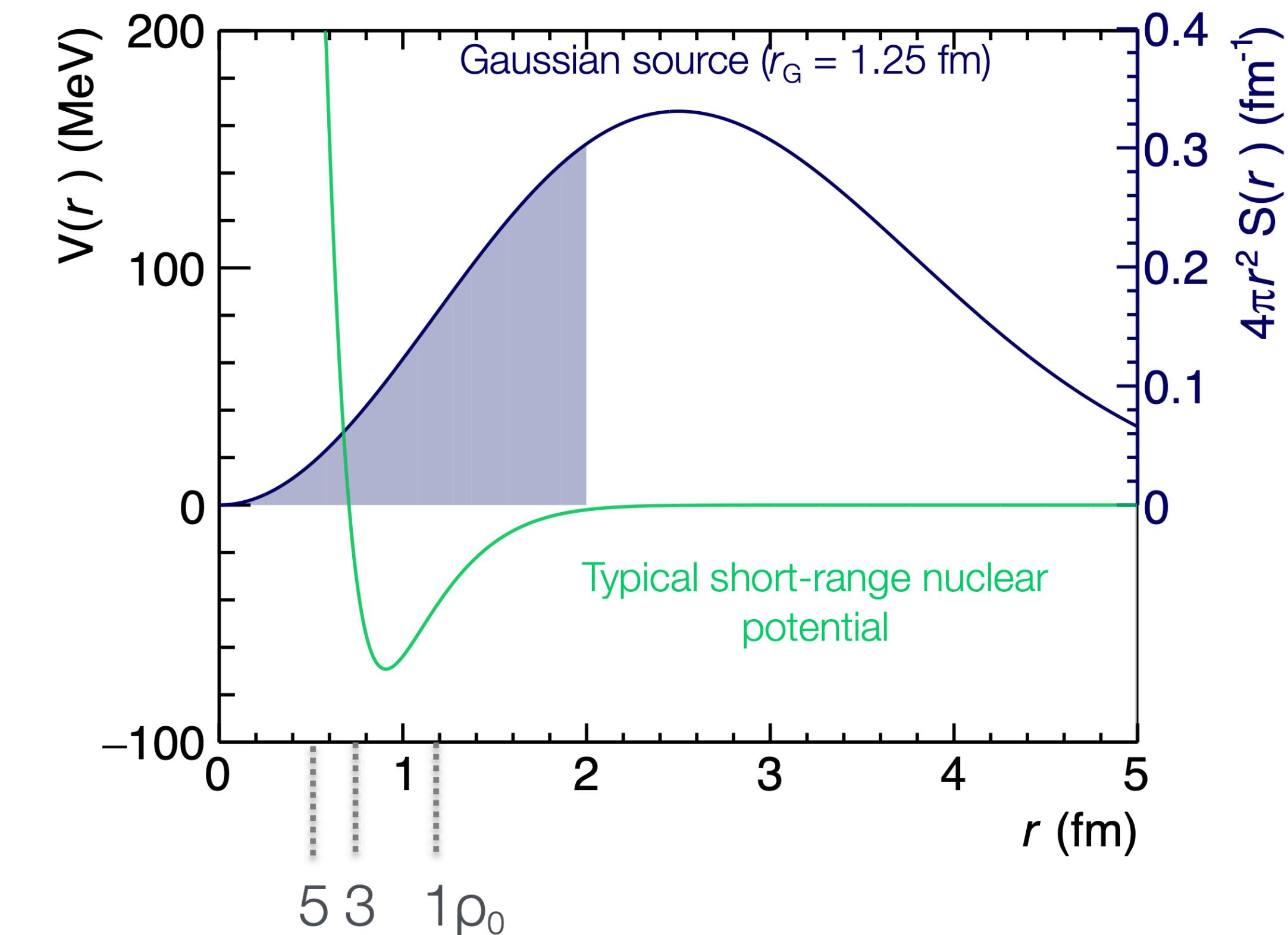
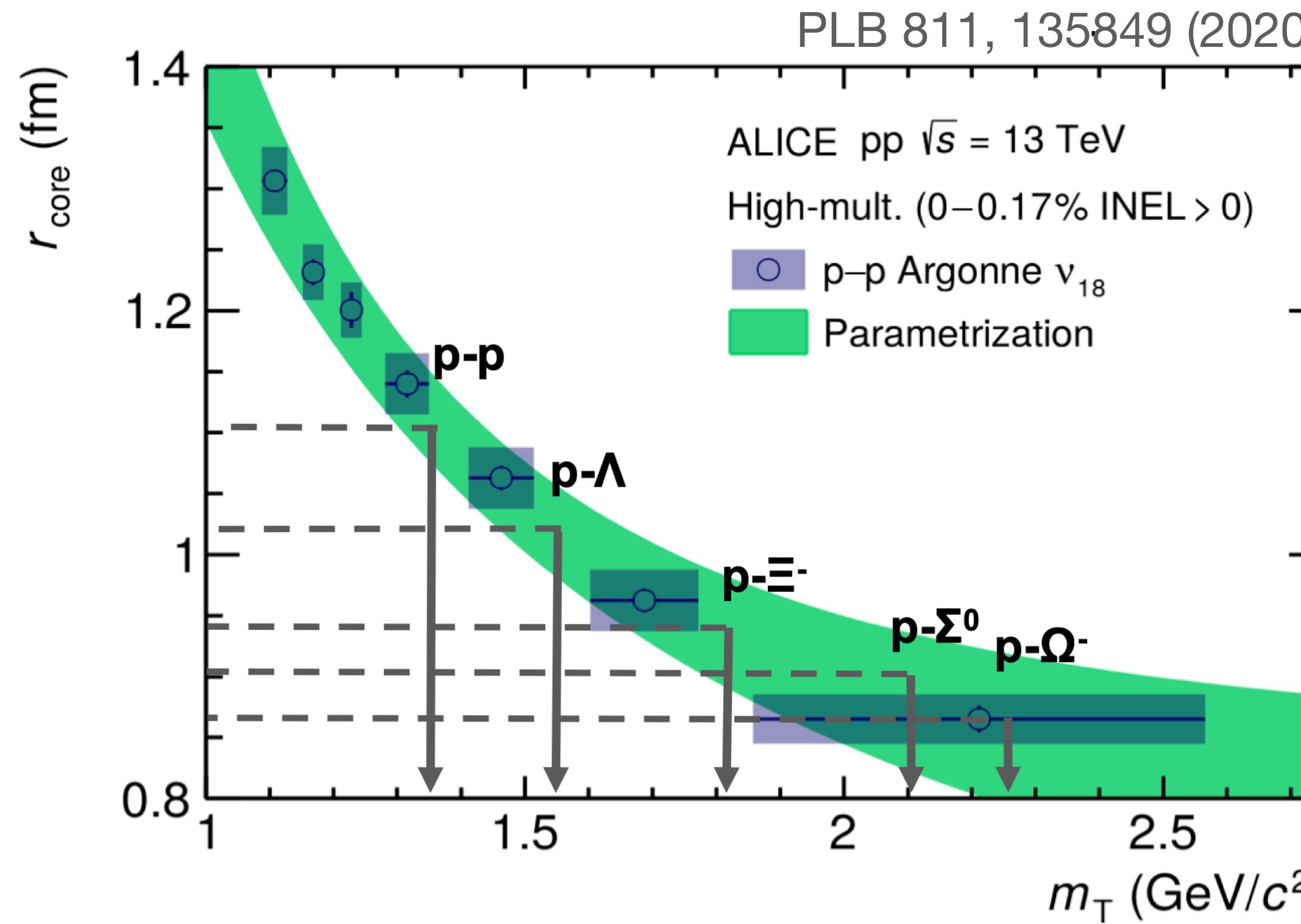
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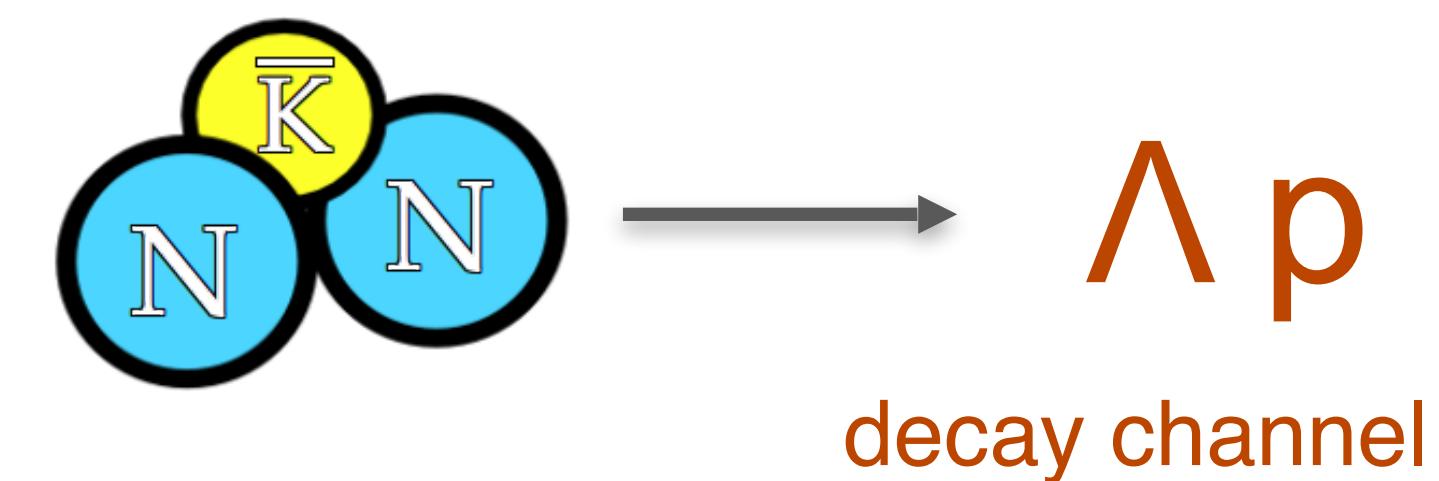
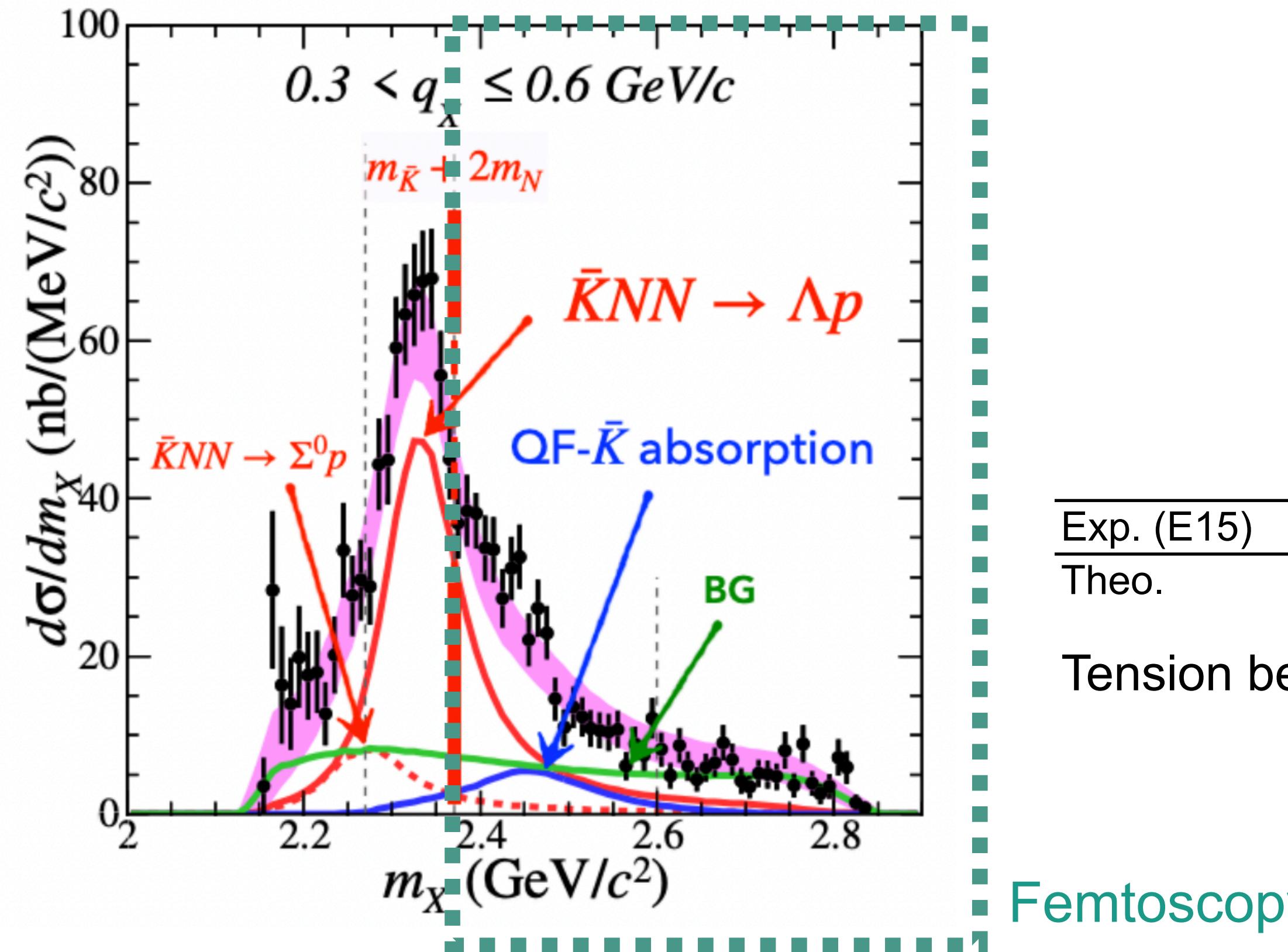


How to access three-body systems?

# Observed ppK- state

- First positive experimental evidence of the **p-p-K- bound state** by the E15 Collaboration.

E15 Coll., PLB 789 (2019) 620. Phys. Rev. C 102 (2020) 4, 044002



	B. E. (MeV)	Width (MeV)
Exp. (E15)	42	100
Theo.	16	72

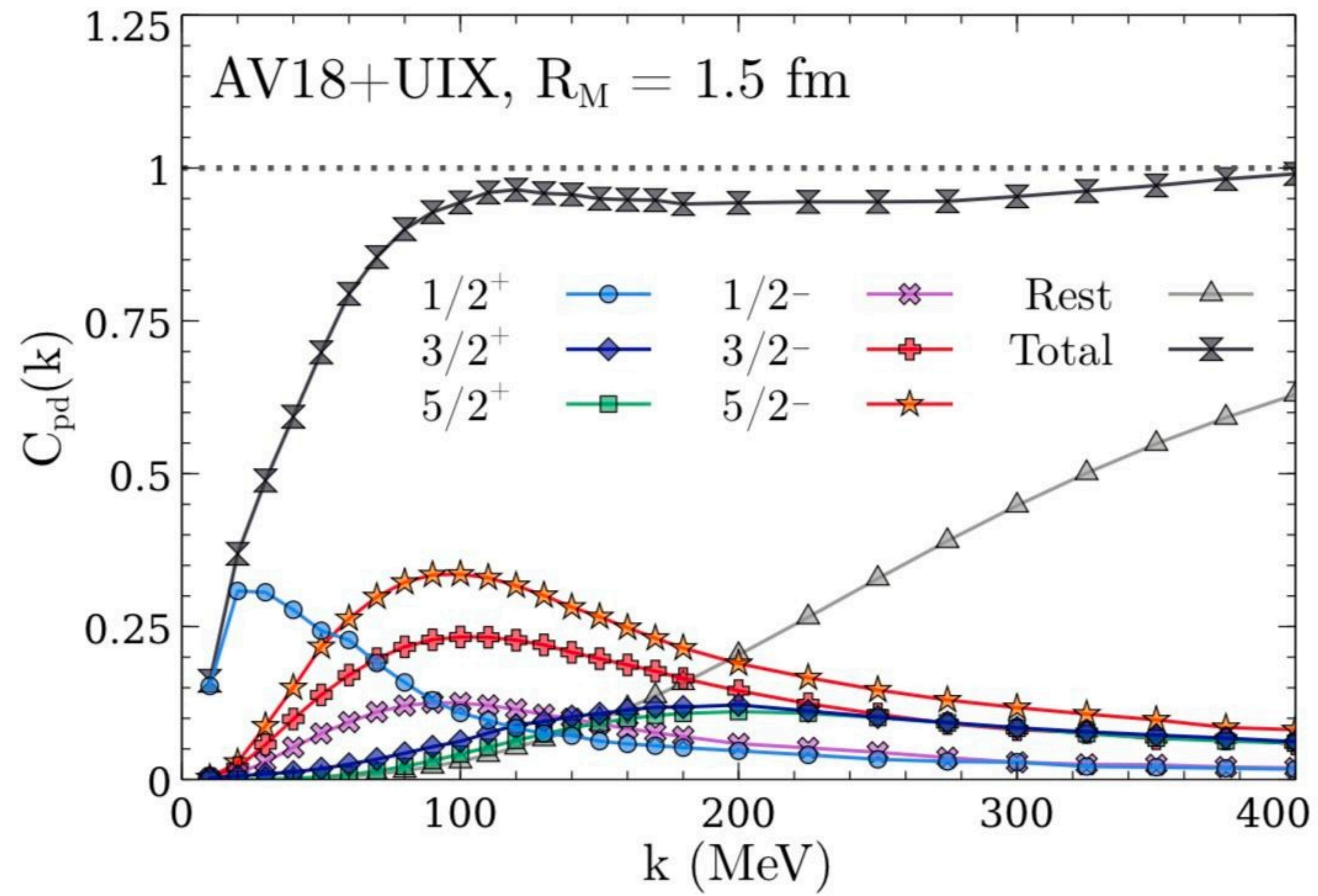
E15 Coll., Phys. Rev. C 102 (2020) 4, 044002

Sekihara et al., PTEP 2016 no. 12, (2016)

Tension between the theoretical models and experimental measurement

**Next challenge:** explore many-body systems dynamics using femtoscopy!

# p-d partial waves



$J^\pi$	Wave
$\frac{1}{2}^+$	$^2S_{\frac{1}{2}}$
	$^4D_{\frac{1}{2}}$
$\frac{1}{2}^-$	$^2P_{\frac{1}{2}}$
	$^4P_{\frac{1}{2}}$
$\frac{3}{2}^+$	$^4S_{\frac{3}{2}}$
	$^2D_{\frac{3}{2}}$
	$^4D_{\frac{3}{2}}$
$\frac{3}{2}^-$	$^2P_{\frac{3}{2}}$
	$^4P_{\frac{3}{2}}$
	$^4F_{\frac{3}{2}}$
$\frac{5}{2}^-$	$^4P_{\frac{5}{2}}$
	$^2F_{\frac{5}{2}}$
	$^4F_{\frac{5}{2}}$