Hyperon-nucleon interaction at NNLO in chiral EFT

Ulf-G. Meißner, Univ. Bonn & FZ Jülich

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by ERC, EXOTIC

CONTENTS

- Short introduction: Why chiral EFT?
- Short recap of the YN interaction at LO and NLO
- YN interaction at NNLO
- Summary & outlook

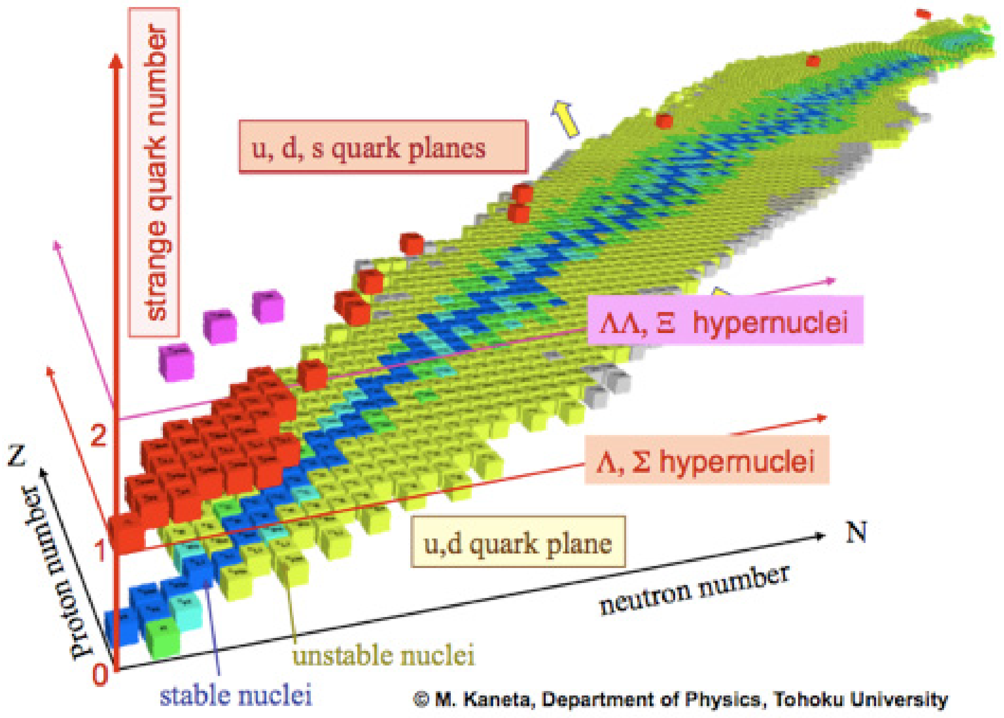
Haidenbauer, UGM, Nogga, Le, EPJ A (2023) [in print] [2301.00722 [nucl-th]]

STRANGENESS NUCLEAR PHYSICS

- Very few hyperon-nucleon scattering data (different to NN)

$\hookrightarrow$ improve the data base J-PARC, JLab, ...

$\hookrightarrow$ Hypernuclei play an important role to unravel the hyperon-nucleon or more generally the baryon-baryon (BB) interactions



- Best approach to YN/YY scattering: chiral EFT $\to$ this talk

- Apply chiral EFT forces in nuclei $\to$ Hoai Le's talk

$\hookrightarrow$ Further tests of the SU(3)$_f$ symmetry of QCD

BB INTERACTION in CHIRAL EFFECTIVE FIELD THEORY

- Original idea to use chiral EFT by Weinberg for the NN & NNN interactions

  Weinberg (1990,1991)

- Advantages of the chiral EFT approach:
  - Power counting $\to$ systematic improvement by going to higher orders
  - Two- and three-baryon forces and external currents in a consistent way
  - Degrees of freedom tied to the QCD symmetries & their realization

  $\hookrightarrow$ Goldstone bosons (π, K, η) coupled to matter fields $(N, \Lambda, \Sigma, \Xi)$

- Interaction given by
  - Pseudoscalar meson exchanges $(\pi, \pi\pi, K, \eta, \pi K, \ldots)$
  - Contact terms for the unresolved short-distance interactions $\to$ LECs

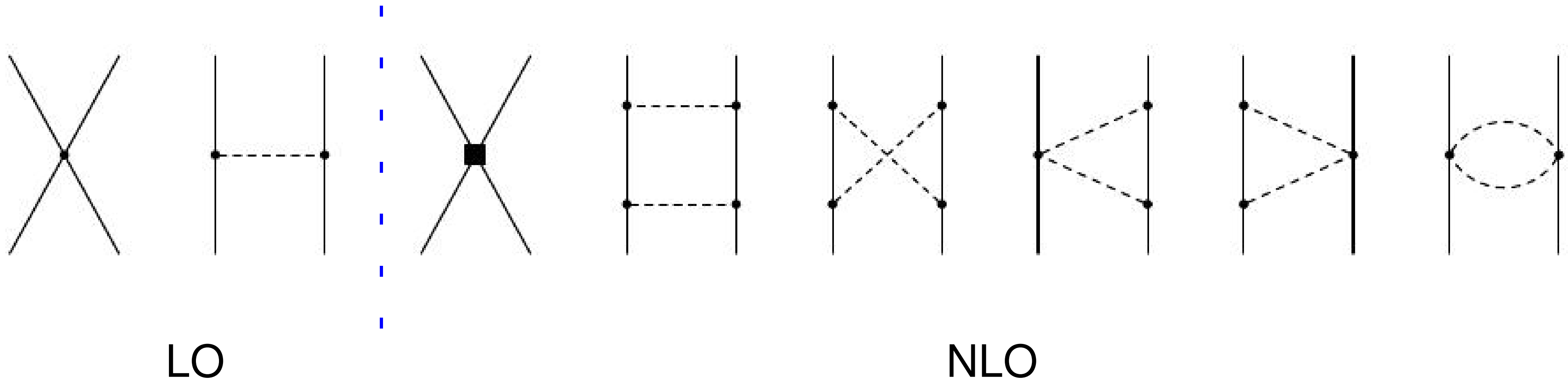
  $\hookrightarrow$ LECs to be determined from fits to data

CHIRAL EFT at LO and NLO

LO: Polinder, Haidenbauer, UGM, Nucl. Phys. A **779** (2006) 244 [initiated by UGM]

NLO13: Haidenbauer, Petschauer, Kaiser, UGM, Nogga, Weise, Nucl. Phys. A **915** (2013) 24

NLO19: Haidenbauer, UGM, Nogga, Eur. Phys. J. **A 56** (2020) 91

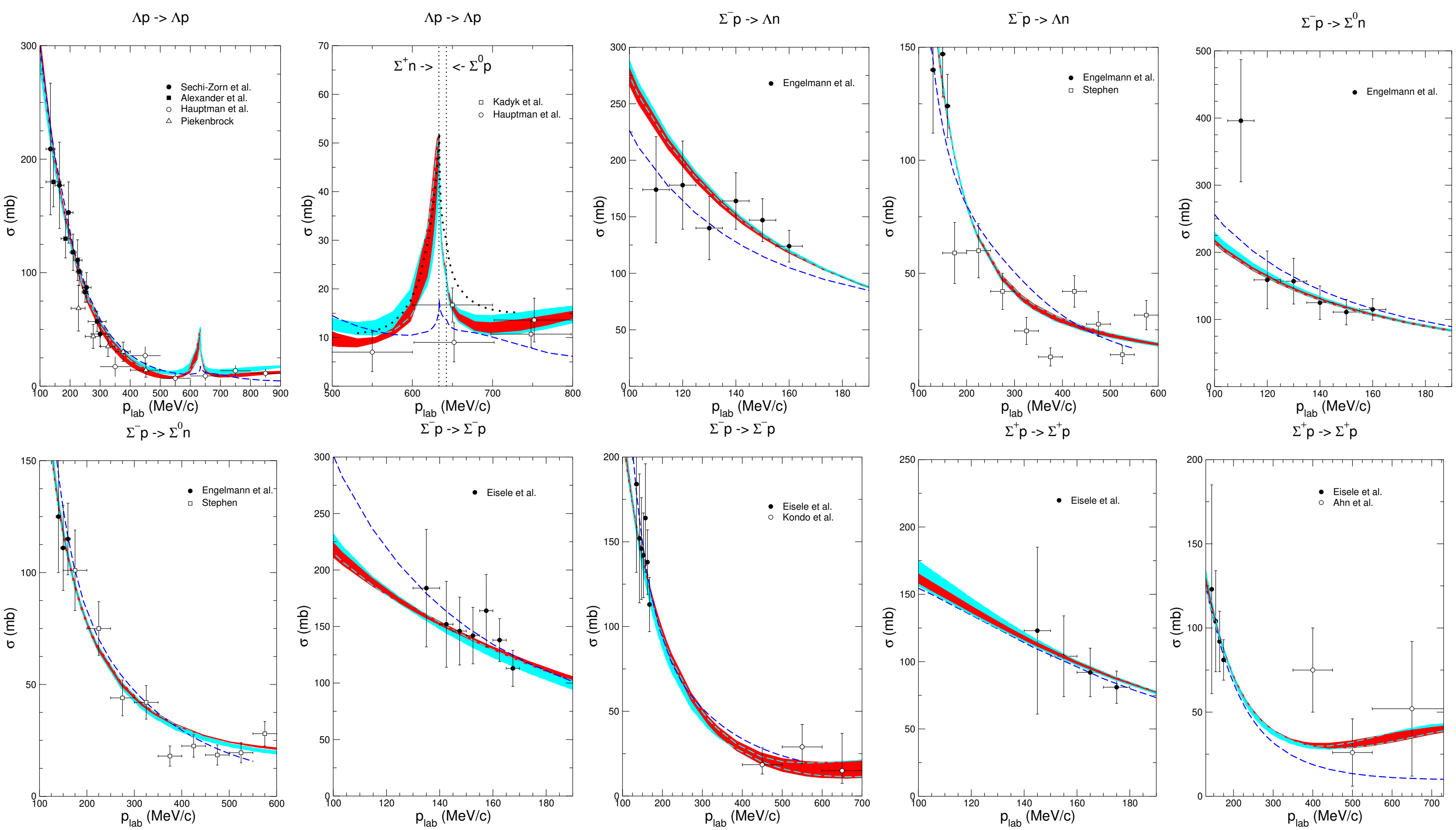


- Use SU(3) symmetry to relate MBB couplings and the various contact term LECs

- Need SU(3) breaking for a combined description of NN & YN interactions (NLO19)

YN INTERACTION at NLO

- Total XS results (fit to 36 low-energy data points + $E({}^3_\Lambda\mathrm{He})$, only cut-off variations) [better uncertainty estimate available for NLO19]



NLO13

NLO19

J'04

closed symbols: fit
open symbols: prediction

Jülich '04 potential: Haidenbauer and UGM, Phys. Rev. C **72** (2005) 044005

WHY NNLO?

Haidenbauer, UGM, Nogga, Le, EPJ A (2023) [in print] [2301.00722 [nucl-th]]

- New data from the J-PARC E40 experiment (also JLab)
  Miwa et al., Phys. Rev. C 104 (2012) 045204; Phys. Rev. Lett. 128 (2022) 072501
  Nanamura et al., PTEP 2022 (2022) 093D01

- in the NN case, NNLO corrections $\ll$ NLO ones, mostly in the P-waves

- no new short-distance LECs at this order, MB LECs known $\to$ extra slide

- at NNLO three-body forces appear $\to$ important for hyper-nuclei $\to$ H. Le's talk

- improved regularization (taken from NN) Reinert et al., EPJA 54 (2018) 86

$$V_{1P}^{\rm reg} \propto \frac{e^{-\frac{\vec{q}^{\,2}+M_P^2}{\Lambda^2}}}{\vec{q}^{\,2}+M_P^2} \to \frac{1}{\vec{q}^{\,2}+M_P^2} - \frac{1}{\Lambda^2} + \frac{\vec{q}^{\,2}+M_P^2}{\Lambda^4} + \ldots,\quad P=\pi,K,\eta$$

$\hookrightarrow$ does not affect the long-range physics at any oder in $1/\Lambda^2$

$\hookrightarrow$ also applicable to $2P$ exchanges (only 2π relevant)

FIT STRATEGY

- Incomplete angular coverage for $\Sigma^{\pm} p \to \Sigma^{\pm} p$, thus use

$$\sigma = \frac{2}{\cos\theta_{\max} - \cos\theta_{\min}} \int_{\cos\theta_{\min}}^{\cos\theta_{\max}} \frac{d\sigma(\theta)}{d\cos\theta} d\cos\theta$$

$\cos\theta_{\min} = -0.5$ and $\cos\theta_{\max} = 0.5$

- Fit to the same 36 data for Λp, $\Sigma^- p$, $\Sigma^+ p$ scattering at low energies as done for LO, NLO13 and NLO19

	SMS NLO			SMS NNLO			NLO13	NLO19
Λ (MeV)	500	550	600	500	550	600	600	600
total χ^2	15.5	15.7	16.2	15.8	15.6	15.7	16.8	16.3

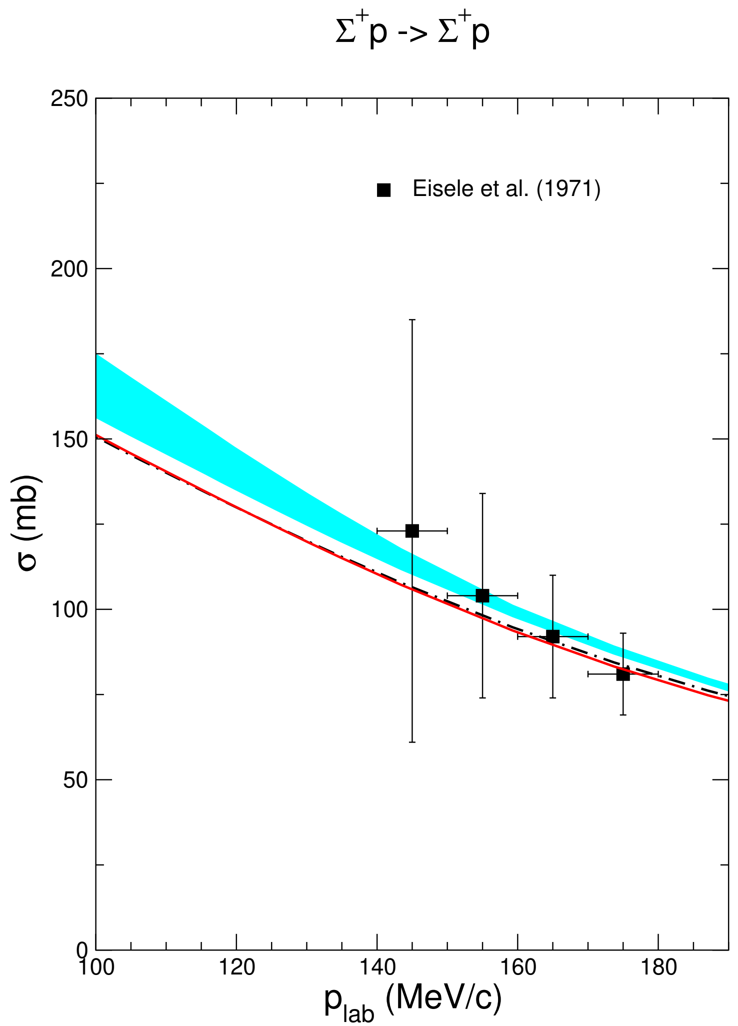
- Comments: S-wave LECs from the combined Λp, ΣN fits w/o E40 data

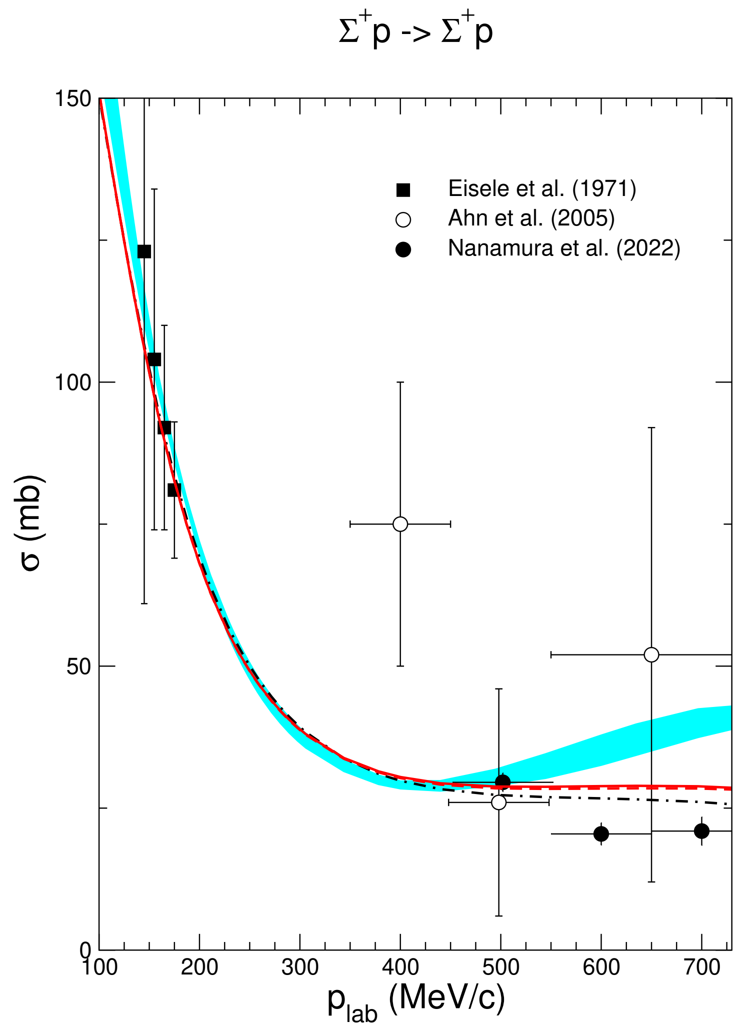
  P-wave LECs in ${}^3P_{0,1,2}$ at NLO from NN — Reinert et al. (2018)

  P-wave LECs at NNLO from the data (two scenarios)

The $\Sigma^+ p$ CHANNEL I

- total X sections:





solid SMS N2LO

dash-dotted SMS NLO

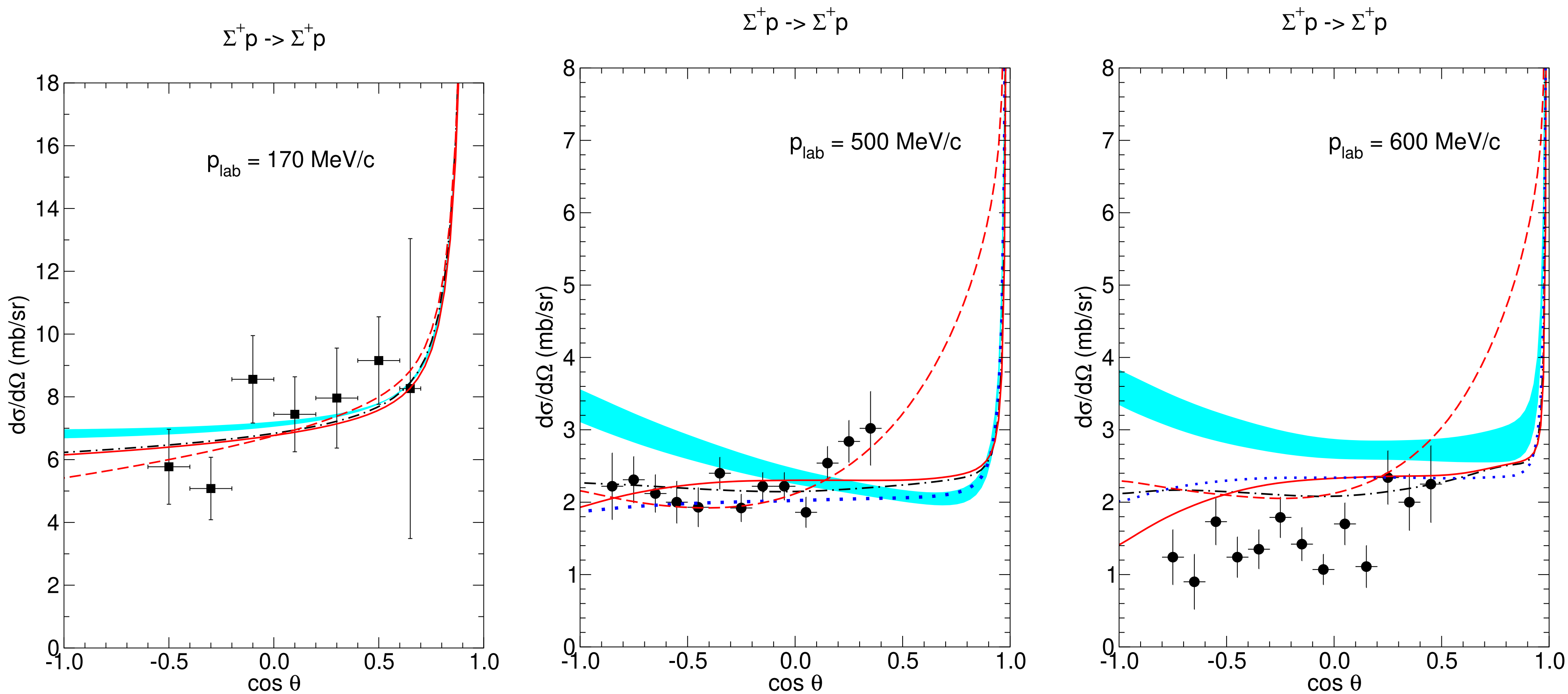
dashed SMS N2LO alt.

band NLO19

dotted NLO19 readj.

The $\Sigma^+ p$ CHANNEL II

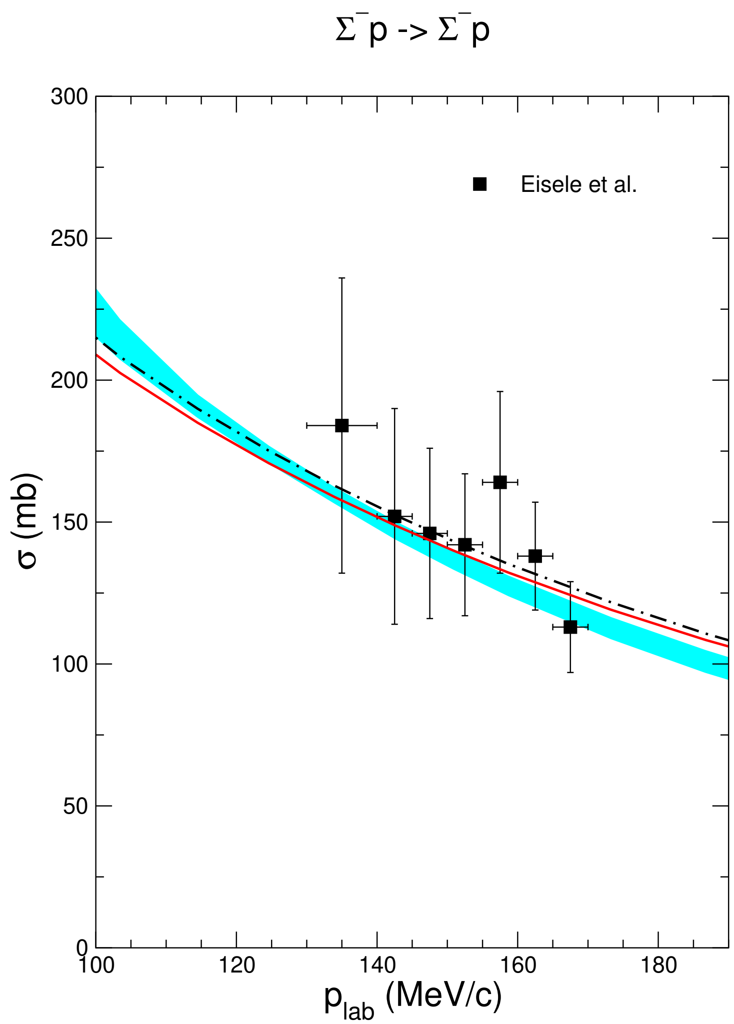
- differential X sections:

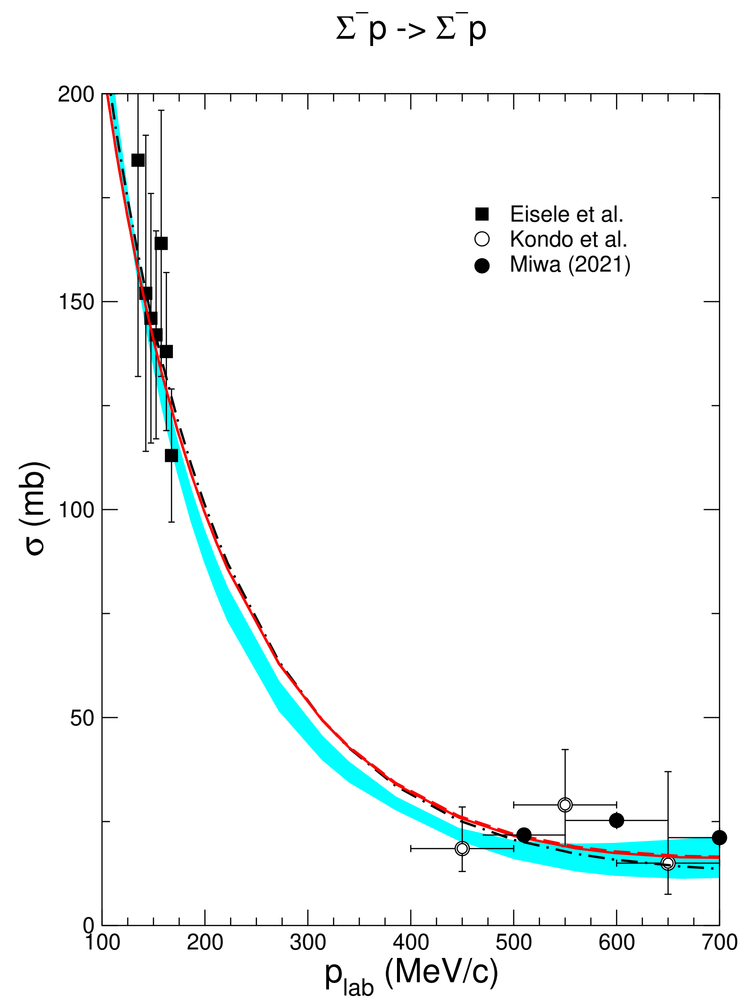


E40 data at $p_{\rm lab} = 500 {\rm MeV}/c$ can be described, problems at the higher energy

The $\Sigma^- p$ CHANNEL I

- total X sections:





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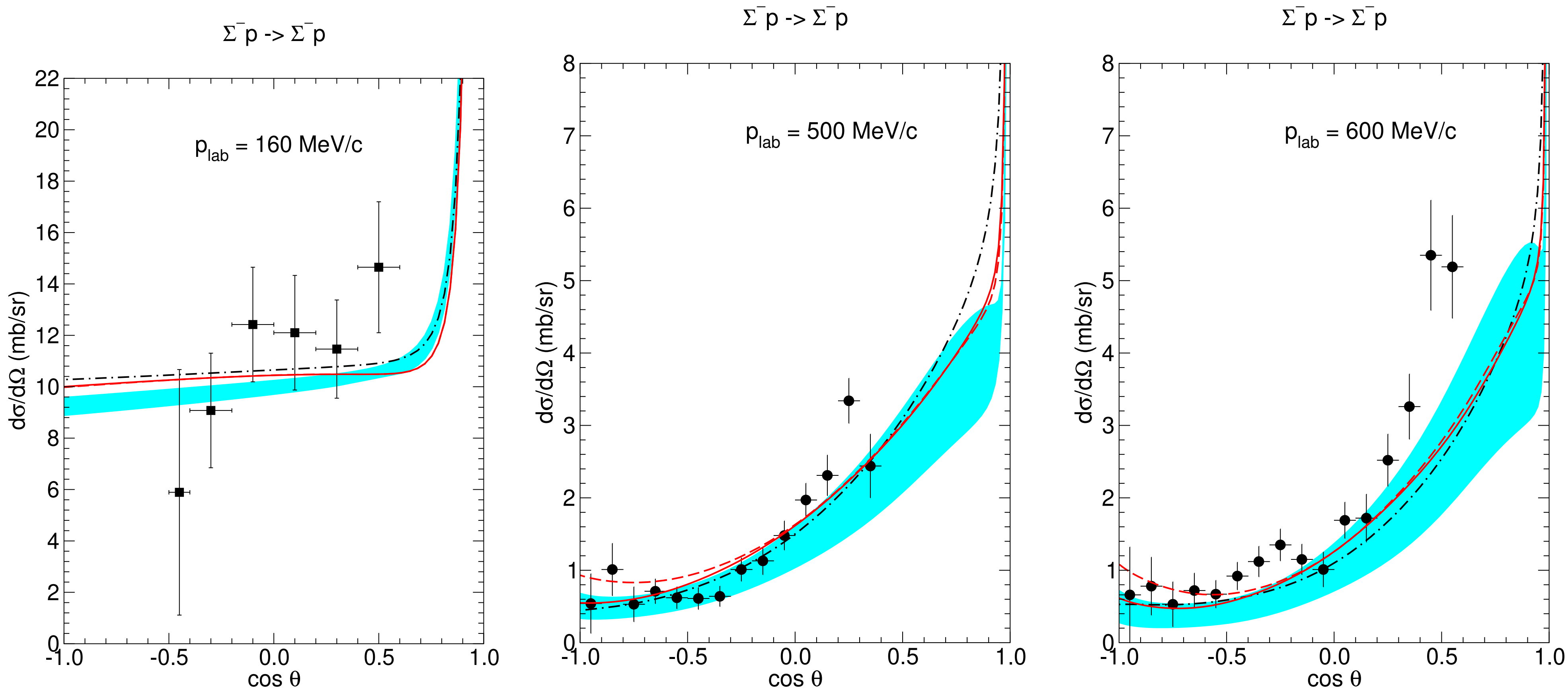
The $\Sigma^- p$ CHANNEL II

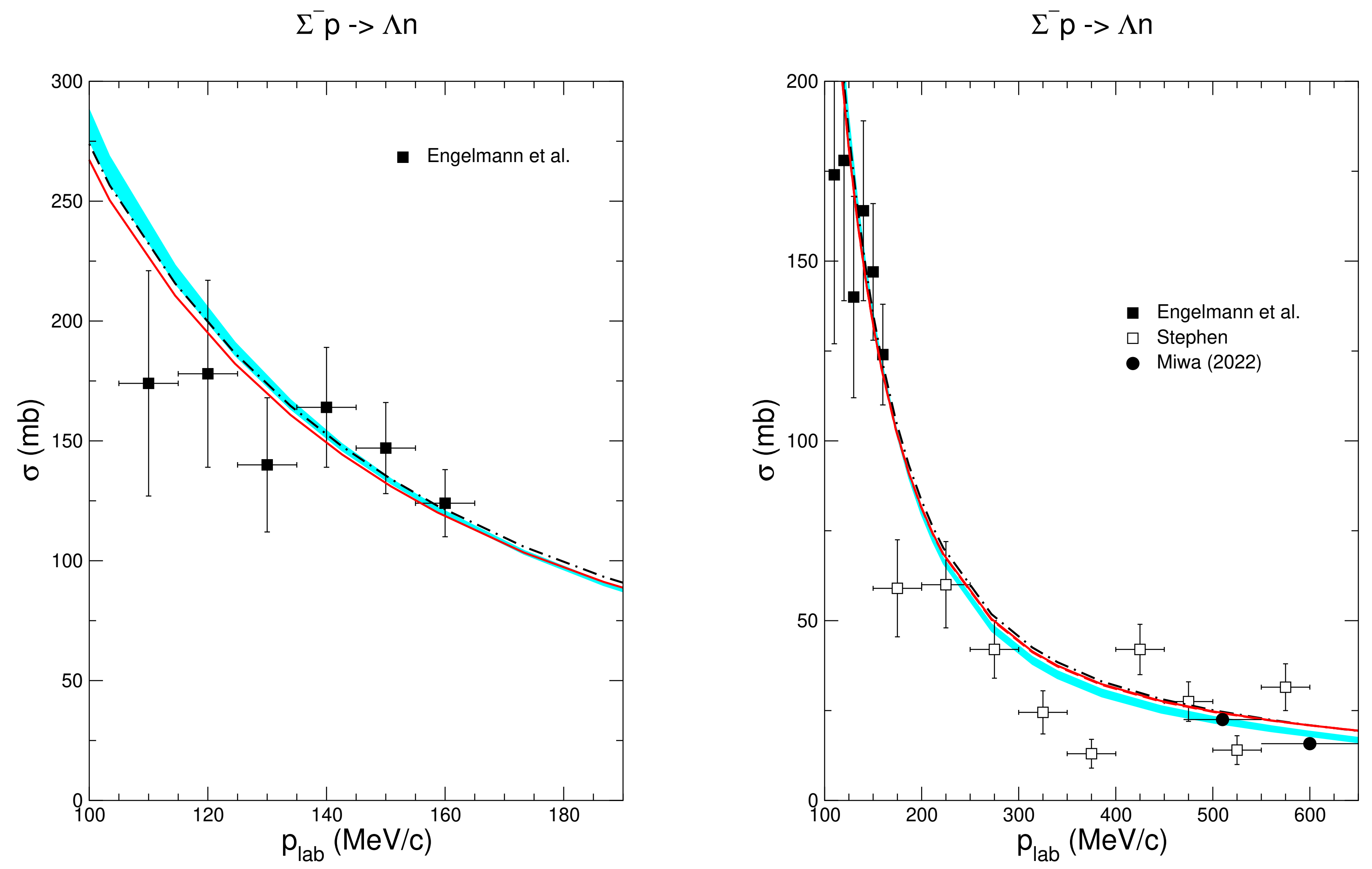
- differential X sections:



E40 data can be described, forward direction at the higher energy?

The $\Sigma^- p \to \Lambda n$ TRANSITION I

- total X sections:



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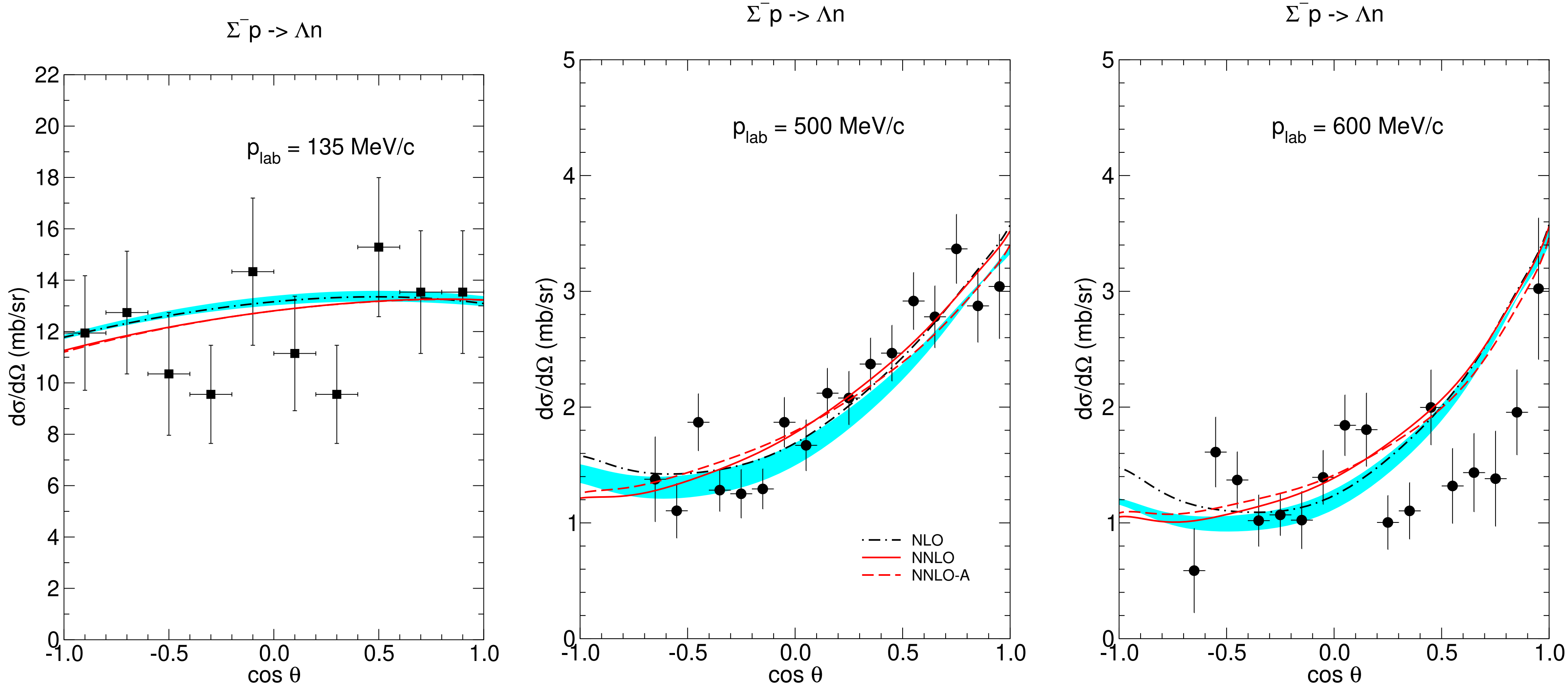
band NLO19

dotted NLO19 readj.

The $\Sigma^- p \to \Lambda n$ TRANSITION II

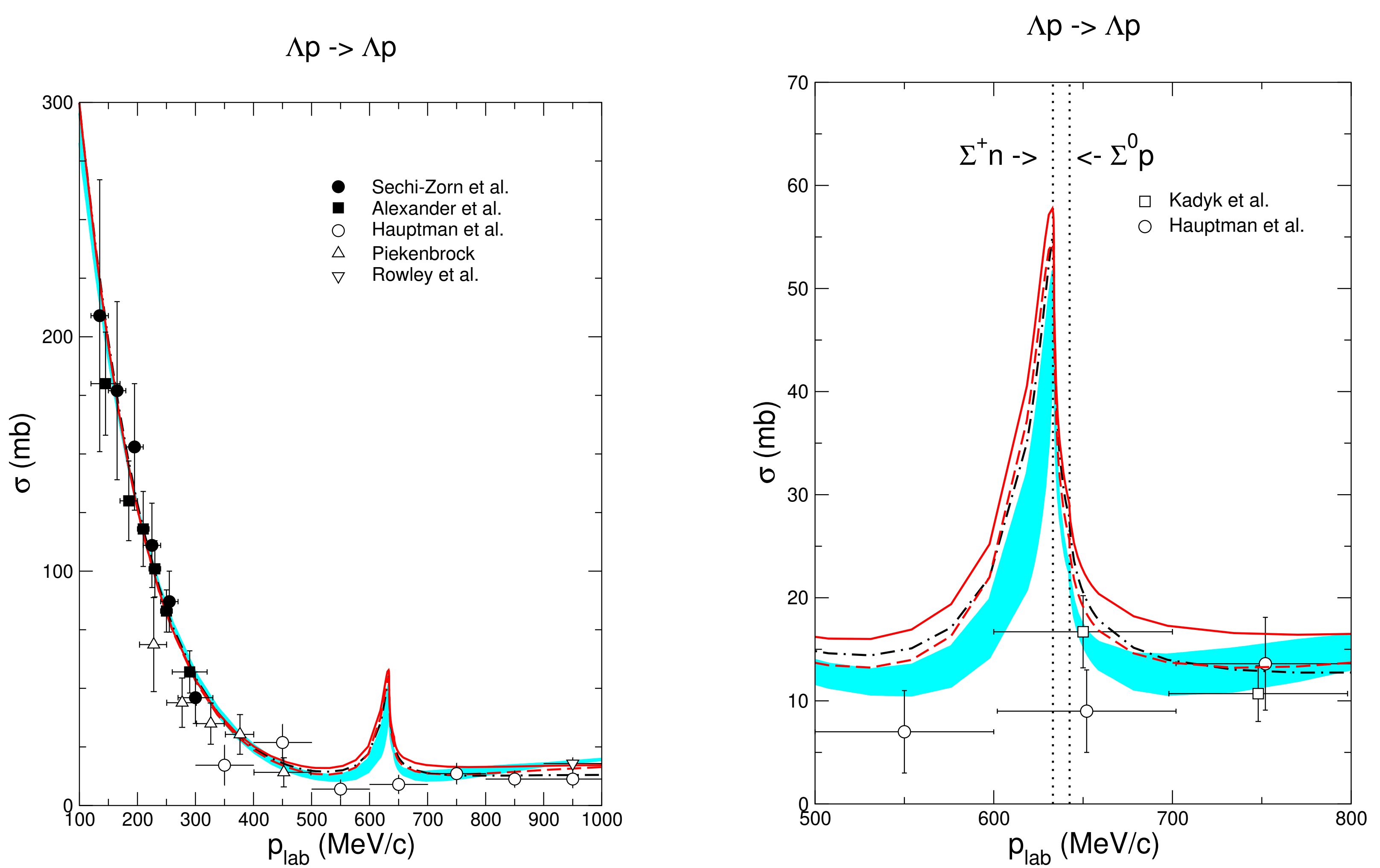
- differential X sections:



All interactions are in line with the data

The Λp CHANNEL I

- total X sections:



solid SMS N2LO

dash-dotted SMS NLO

dashed SMS N2LO alt.

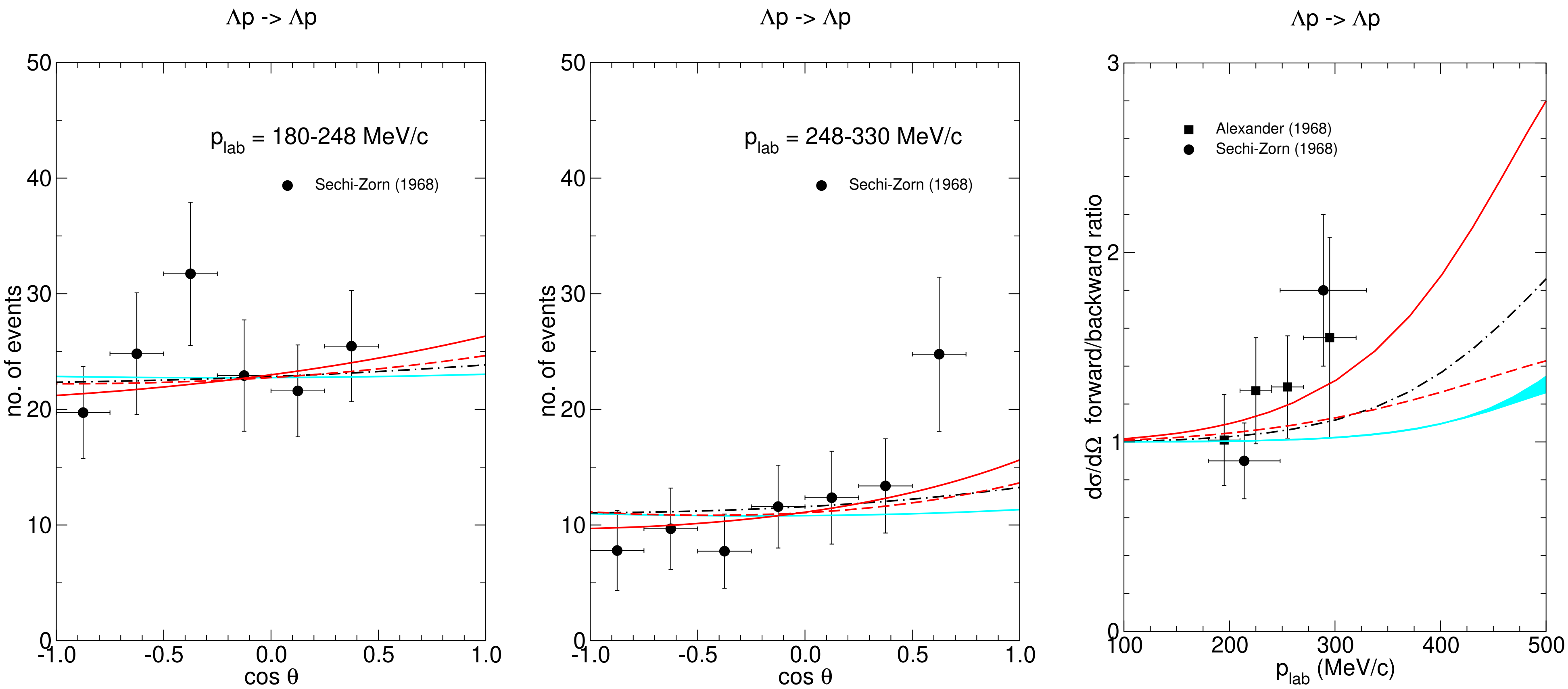
band NLO19

dotted NLO19 readj.

▽ Rowley et al., Phys. Rev. Lett. 127 (2021) 272303

The Λp CHANNEL II

- differential X sections:



all data can be described (incl. JLab), no E40 data so far

UNCERTAINTY ESTIMATES I

- Use the EKM formalism Epelbaum, Krebs, UGM, EPJA 51 (2015) 53

$$\Delta X^{\rm NNLO}(k)$$
$$= \max\left(Q^4 \cdot \left|X^{\rm LO}(k)\right|, Q^2 \cdot \left|X^{\rm LO}(k) - X^{\rm NLO}(k)\right|, Q \cdot \left|X^{\rm NLO}(k) - X^{\rm NNLO}(k)\right|\right)$$

- Expansion parameter Q defined by:

$$Q = \max\left(\frac{k}{\Lambda_b}, \frac{M_\pi}{\Lambda_b}\right)$$

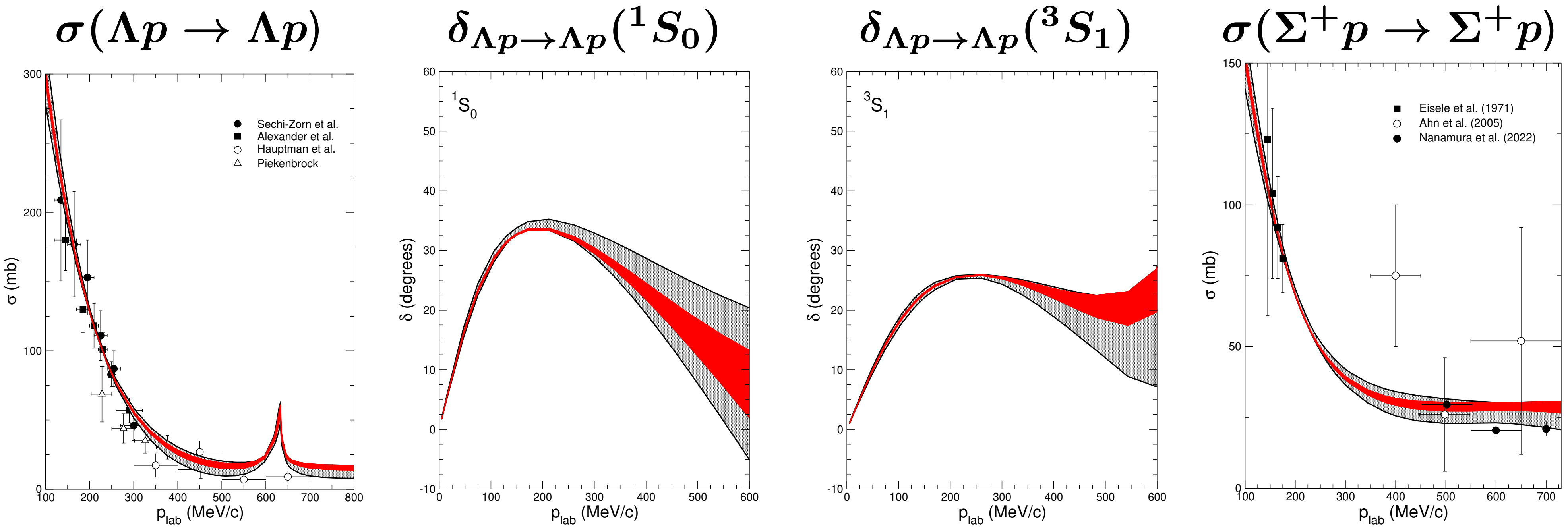
k = on-shell center-of-mass momentum

Λ_b = breakdown scale of the chiral EFT expansion, $\Lambda_b \simeq 600$ MeV

- for Bayesian methods, see e.g. Furnstahl et al., Phys. Rev. C 92 (2015) 024005

UNCERTAINTY ESTIMATES II

- Assorted results:



grey band = NLO   red band = NNLO

- Expected trend: uncertainties at NNLO visibly smaller than at NLO √

FURTHER RESULTS I

- Hyper-Triton BE no longer fitted exactly (due to conflicting exp's), kept to $\sim \mathbf{150}$ keV

Juric et al. (1973) $B_\Lambda = \mathbf{130 \pm 5}$ keV
STAR coll. (2020) $B_\Lambda = \mathbf{410 \pm 120 \pm 110}$ keV
ALICE coll. (2022) $B_\Lambda = \mathbf{72 \pm 63 \pm 36}$ keV
MAINZ 2022 average $B_\Lambda = \mathbf{148 \pm 40}$ keV

- ${}^4_\Lambda$He:

YN interaction	$J^\pi = 0^+$ B_Λ [MeV]	$J^\pi = 1^+$ B_Λ [MeV]
SMS NLO(550)	2.102	1.102
SMS NNLO(550)[a]	2.024	1.251
SMS NNLO(550)[b]	1.964	1.188
NLO13(600)	1.477	0.580
NLO19(600)	1.461	1.055
Exp.	$\mathbf{2.377 \pm 0.036}$	$\mathbf{0.942 \pm 0.036}$

⋆ marked improvement, but still slightly off

⋆ no 3BFs and no CSB → H. Le's talk

FURTHER RESULTS II

- Λ and Σ in nuclear matter $\rightarrow$ single-particle potentials at $k_F = 1.35$ fm^{-1}:

YN interaction	$U_\Lambda(0)$ [MeV]	$U_\Sigma(0)$ [MeV]
SMS NLO(550)	-32.1	-1.6
SMS NNLO(550)^a	-38.5	$+2.5$
SMS NNLO(550)^b	-35.9	$+2.5$
NLO13(600)	-21.6	$+17.1$
NLO19(600)	-32.6	$+16.9$

$\star$ Values for the Λ consistent with emp. findings $U_\Lambda(0) \sim -30 \ldots -27$ MeV

Gal, Hungerford, Millener, RMP 88 (2016) 035004

$\star$ U_Σ less repulsive than NLO13 & NLO19 and
below the range 10 - 50 MeV advocated by Gal et al.

$\hookrightarrow$ J-PARC data for $\Sigma^+ p$ difficult to reconcile with a strongly repulsive U_Σ

$\hookrightarrow$ more data needed!

SUMMARY & OUTLOOK

Haidenbauer, UGM, Nogga, Le, EPJ A (2023) [in print] [2301.00722 [nucl-th]]

- Worked out $\Lambda N - \Sigma N$ interactions in chiral EFT at NNLO

  $\rightarrow$ new & improved semilocal regularization

  $\rightarrow$ no new LECs (meson-baryon interaction known at that order)

- Number of results:

  $\rightarrow$ confirm previous YN results at NLO

  $\rightarrow$ new $\Sigma^{\pm}p$ scattering data at $p_{\rm lab} \simeq 500$ MeV/c can be described

  $\rightarrow$ unique determination of the P-waves not yet possible

  $\rightarrow$ improved description of the $J^{\pi} = 0^{+}, 1^{+}$ states in ${}^{4}_{\Lambda}$He

  $\rightarrow$ interesting results for in-medium single-particle potentials $U_{\Lambda,\Sigma}$

- Outlook:

  $\rightarrow$ need more precise differential Xsection data (in some case CFs) $\rightarrow$ slide

  $\rightarrow$ hypernuclei including three-body forces

  $\rightarrow$ hypernuclei including charge-symmetry breaking

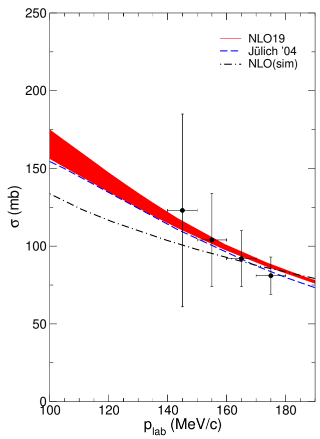
EXPLORING the $\Sigma^+ p$ INTERACTION

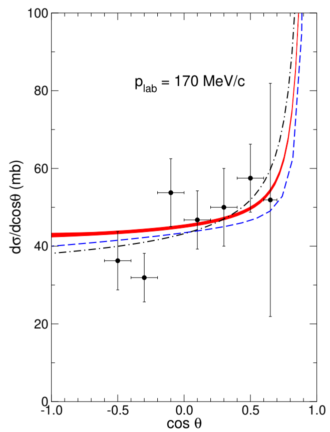
Haidenbauer, UGM, Phys. Lett. B 829 (2022) 137074 [arXiv:2109.11794]

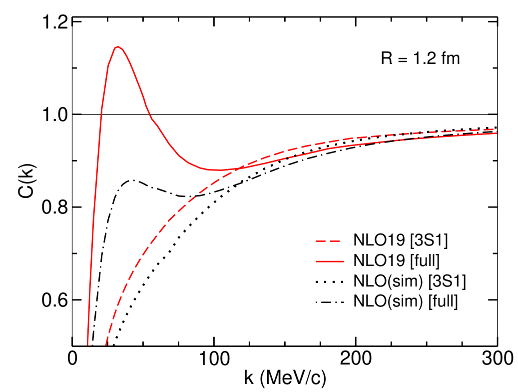
- Spin-dependent components of the YN interactions are largely unknown
- Correlation function (CF) for $\Sigma^+ p$ system: $C(k) = \underbrace{\frac{1}{4} C_s(k)}_{\text{attractive}} + \underbrace{\frac{3}{4} C_t(k)}_{\text{repulsive}}$

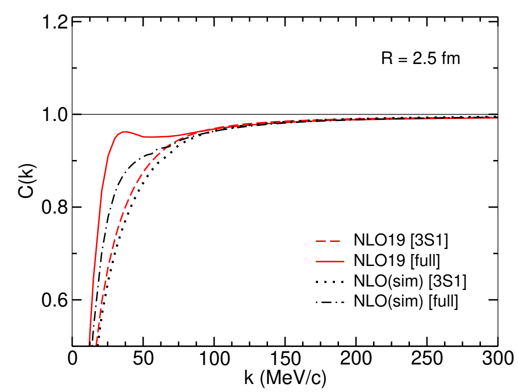
↪ combine with XS data to separate the singlet/triplet contributions by measuring the CF

- total XS
- diff. XS
- CF in pp collisions
- CF in HI collisions









- contributions add up

↪ separation not possible

- visible signal for $k > 25$ MeV/c

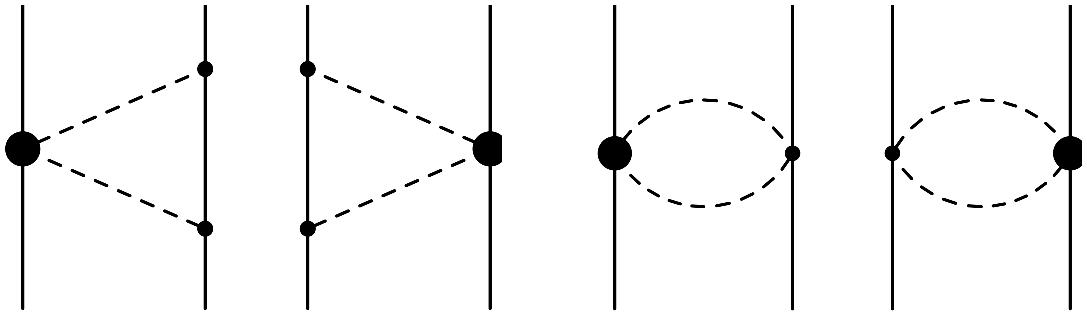
↪ separation possible (easier in pp)

⇑ singlet/triplet separation w/o spin-dependent measurement

SPARES

YN INTERACTION at NNLO

- Pertinent diagrams:



$\hookrightarrow$ vertices from $\mathcal{L}_{MB}^{(2)}$ ●

$\hookrightarrow$ LECs $\underbrace{b_{0,D,F}, b_{1,2,3,4}, d_{1,2,3}}_{\text{combinations thereof}}$

$\hookrightarrow$ no new contact interactions!

- $b_{0,D,F}$ fixed from baryon mass splittings and the πN sigma term

- use matching relations: $c_3 = b_1 + b_2 + b_3 + 2b_4, \ldots$ Frink, UGM (2004)

$\hookrightarrow$ the SU(2) c_i from Roy-Steiner equations and CHPT Hoferichter, de Elvira, Kubis, UGM (2015)

- combined w/ scattering data fixes all b_i LECs Mai, Bruns, Kubis, UGM (2015)

- LECs d_i from decuplet saturation Petschauer, Haidenbauer, Kaiser, UGM, Weise (2017)

$\hookrightarrow$ NNLO contribution to the YN interaction completely fixed!