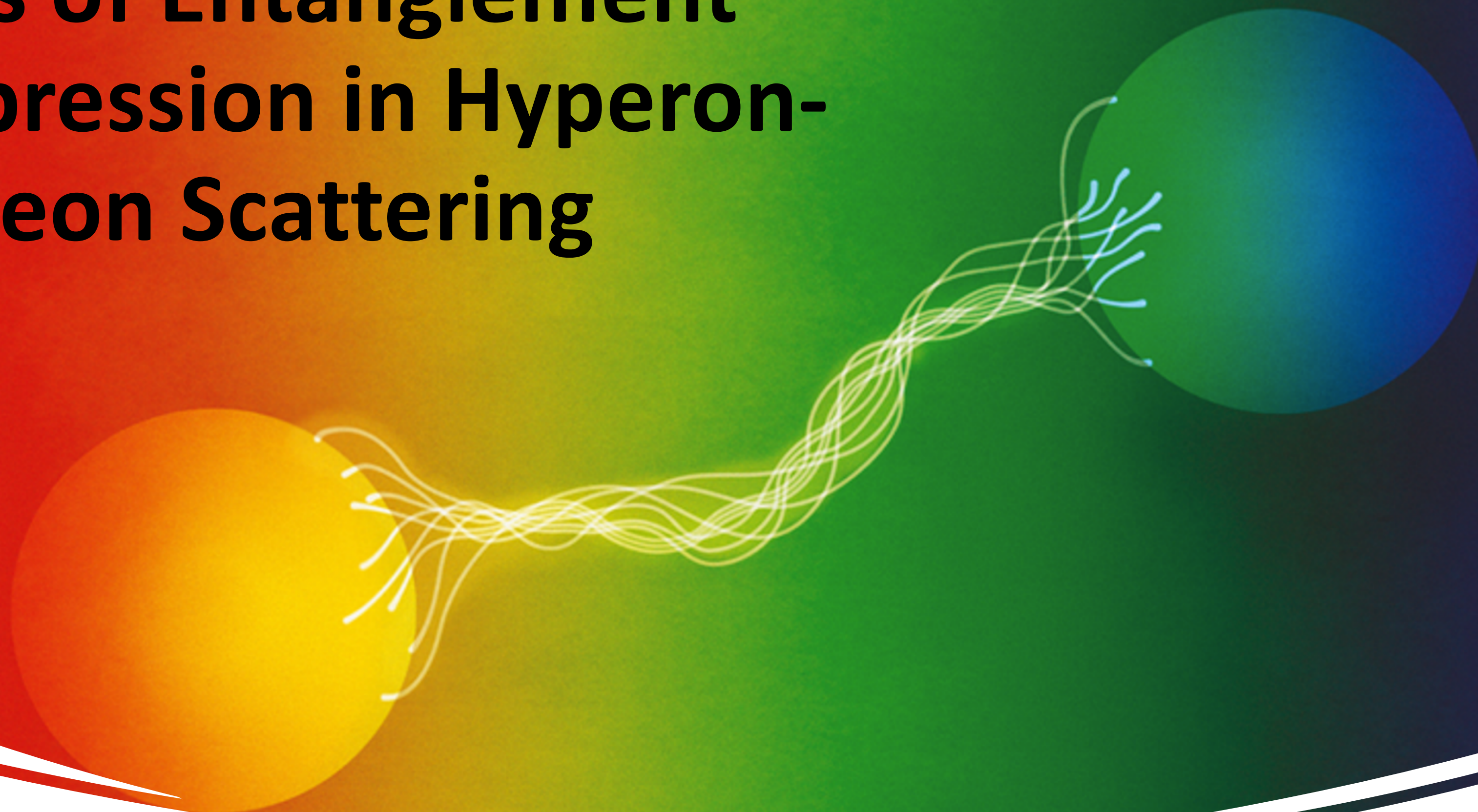
Hints of Entanglement Suppression in Hyperon-Nucleon Scattering



- **Ian Low**
- **Argonne/Northwestern**

- **The 39th Winter Workshop on Nuclear Dynamics, Feb. 13, 2024**

Acknowledgement:

U.S. DEPARTMENT OF ENERGY | Office of Science

Office of Nuclear Physics

Why study hyperon-nucleon interactions?

Understanding NN and YN interactions is essential for having a comprehensive picture of nuclear dynamics and strong interactions.

- Understand hypernuclear structures and hyperon matters
- NN and YN interactions together give a unified understanding of baryon-baryon interactions.
- The formation of heavy neutron star → The hyperon puzzle

Neutron stars offer a unique window into fundamental matters and interactions under extreme conditions.

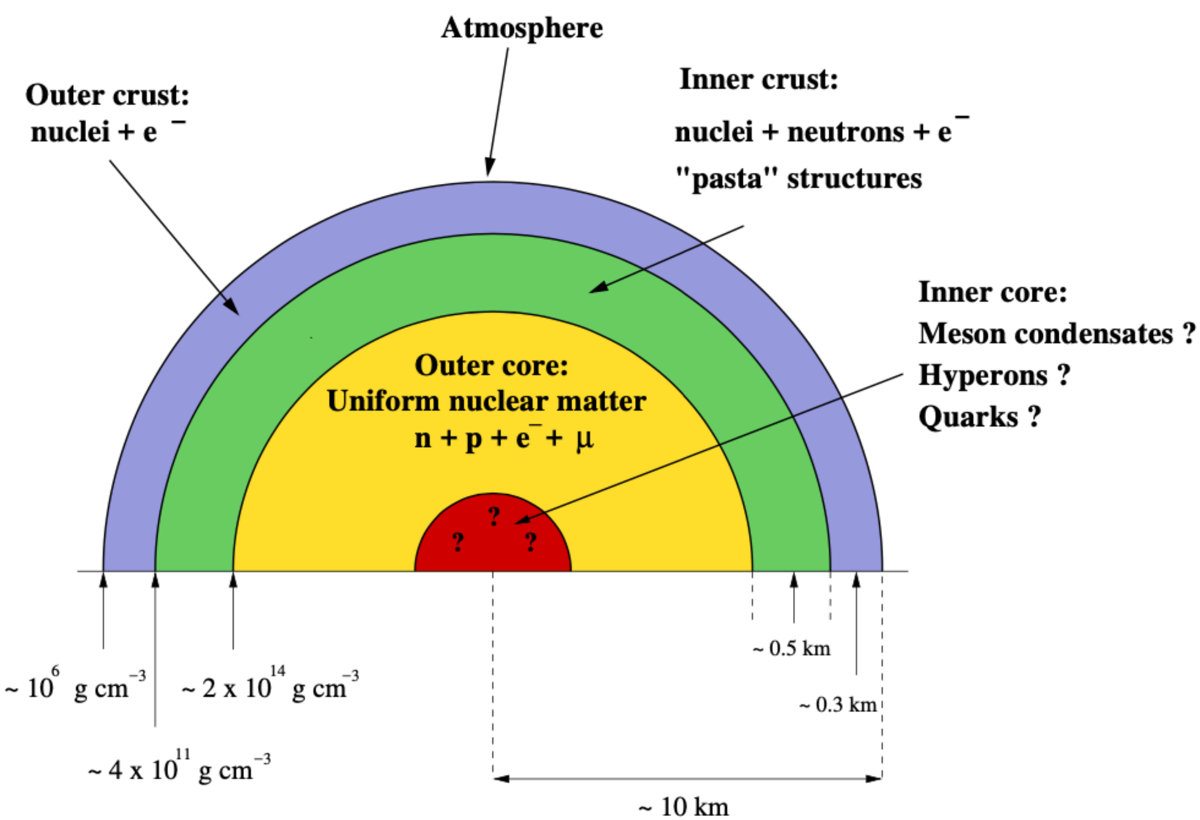


Figure from arXiv:1805.00837

Neutron stars offer a unique window into fundamental matters and interactions under extreme conditions.

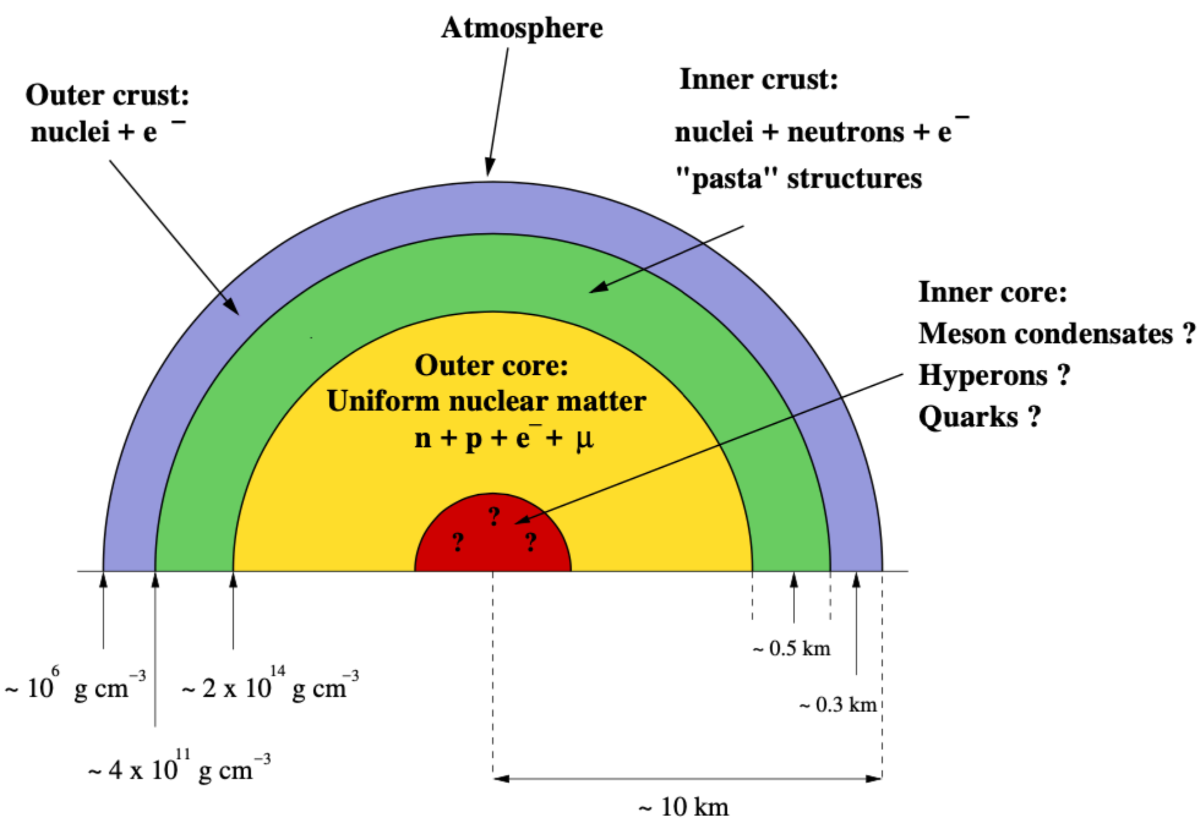
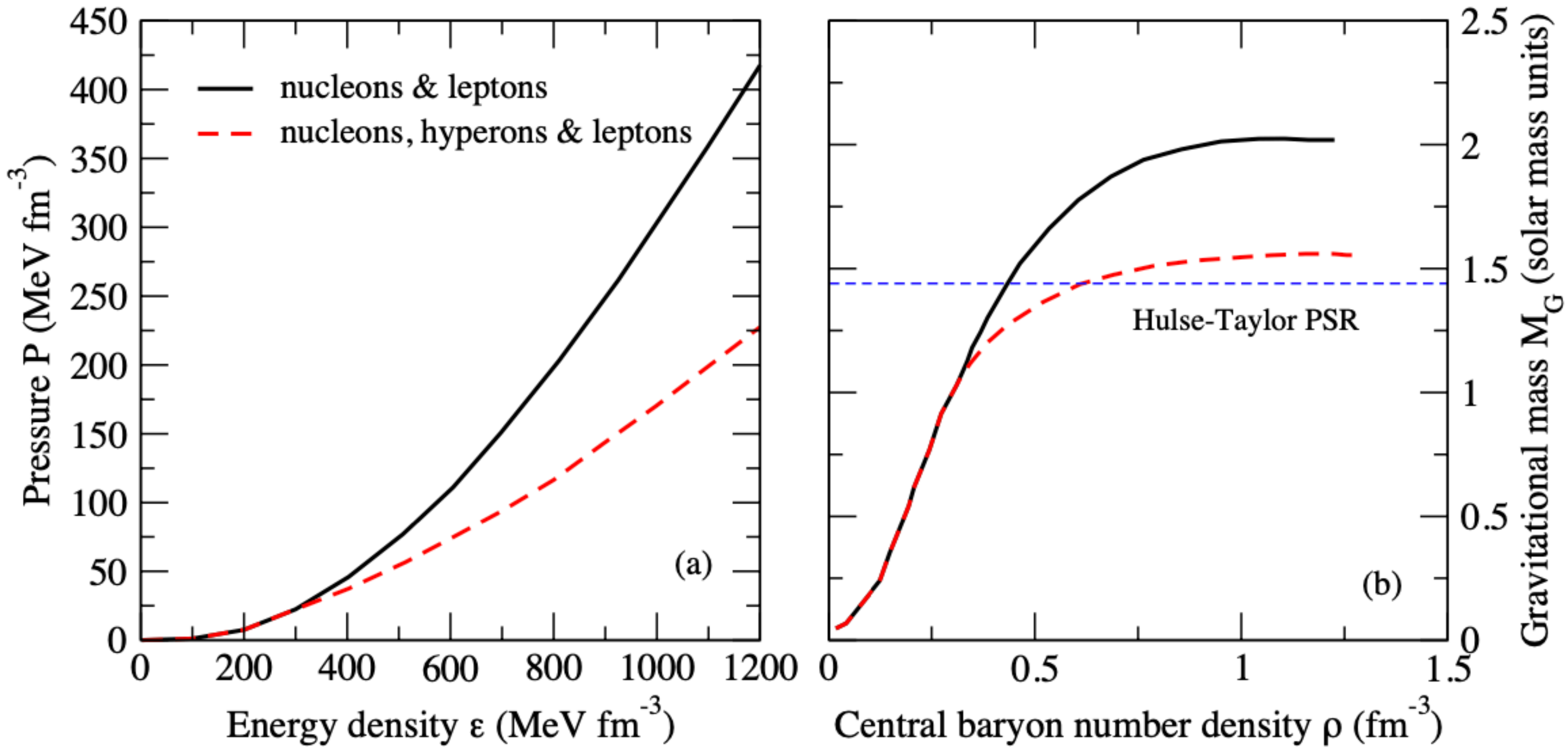


Figure from arXiv:1805.00837

- The inner core is modeled as a uniform liquid in equilibrium w.r.t. weak interactions.
- As a consequence, the inverse process of hyperon decaying into nucleons must also occur.
- The appearance of hyperons softens the equation of state (EOS) and reduces the mass of the neutron star.

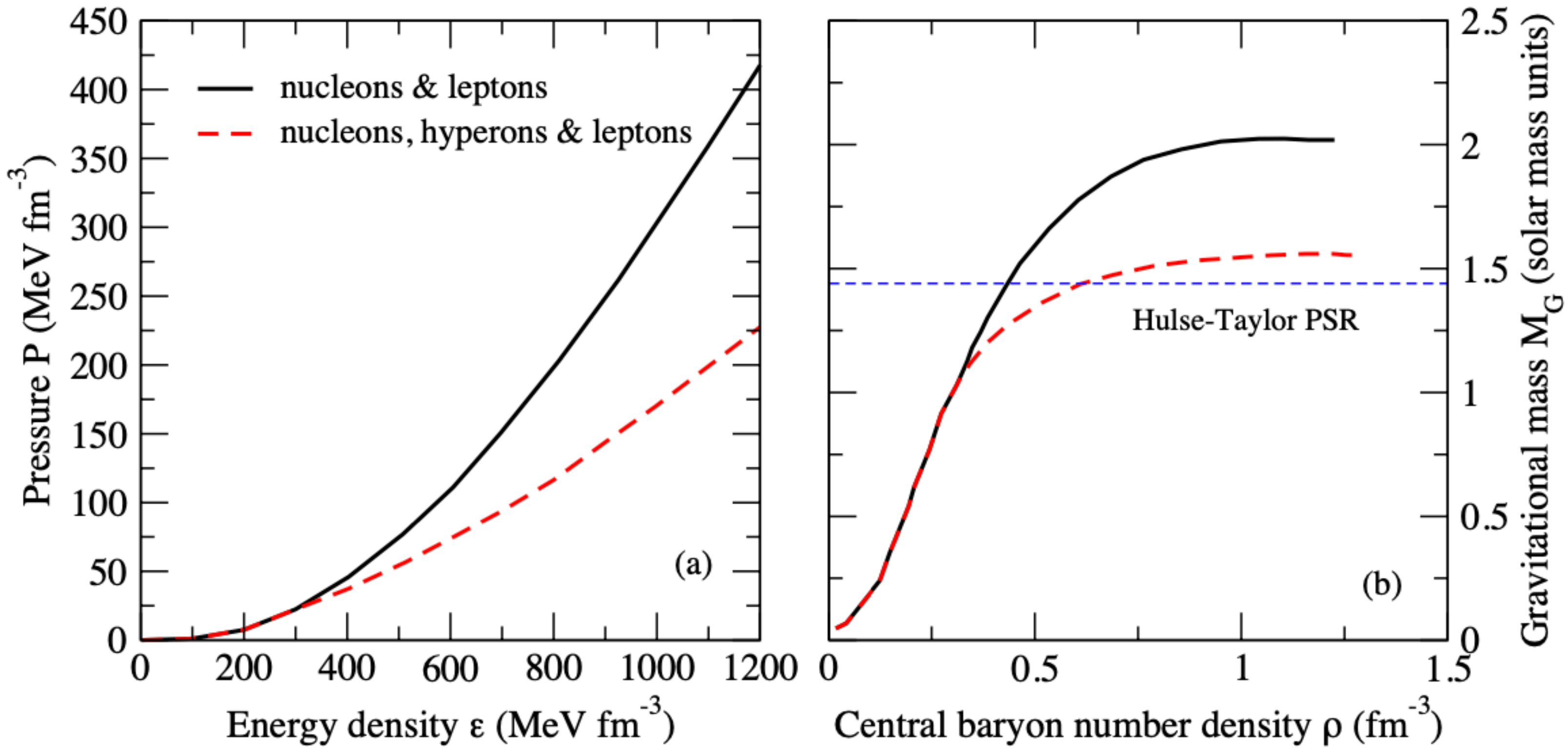
Under these assumptions, neutron stars are expected to be lighter than (1.5 – 2) Solar masses:

arXiv:1510.06306



Under these assumptions, neutron stars are expected to be lighter than (1.5 – 2) Solar masses:

arXiv:1510.06306



But we have observed neutron stars heavier than two solar masses. This is the hyerpon puzzle!

- So we don’t quite understand YN interactions, because there’s been very few measurements historically.

- So we don’t quite understand YN interactions, because there’s been very few measurements historically.

- But recently there are several renewed experimental efforts to study YN scattering more precisely:

PHYSICAL REVIEW LETTERS **128,** 072501 (2022)

Precise Measurement of Differential Cross Sections of the $\Sigma^- p \to \Lambda n$ Reaction in Momentum Range 470–650 MeV/c

K. Miwa,[1] J. K. Ahn,[2] Y. Akazawa,[3] T. Aramaki,[1] S. Ashikaga,[4] S. Callier,[5] N. Chiga,[1] S. W. Choi,[2] H. Ekawa,[6] P. Evtoukhovitch,[7] N. Fujioka,[1] M. Fujita,[8] T. Gogami,[4] T. Harada,[4] S. Hasegawa,[8] S. H. Hayakawa,[1] R. Honda,[3] S. Hoshino,[9] K. Hosomi,[8] M. Ichikawa,[4,14] Y. Ichikawa,[8] M. Ieiri,[3] M. Ikeda,[1] K. Imai,[8] Y. Ishikawa,[1] S. Ishimoto,[3] W. S. Jung,[2] S. Kajikawa,[1] H. Kanauchi,[1] H. Kanda,[10] T. Kitaoka,[1] B. M. Kang,[2] H. Kawai,[11] S. H. Kim,[2] K. Kobayashi,[9] T. Koike,[1] K. Matsuda,[1] Y. Matsumoto,[1] S. Nagao,[1] R. Nagatomi,[9] Y. Nakada,[9] M. Nakagawa,[6] I. Nakamura,[3] T. Nanamura,[4,8] M. Naruki,[4] S. Ozawa,[1] L. Raux,[5] T. G. Rogers,[1] A. Sakaguchi,[9] T. Sakao,[1] H. Sako,[8] S. Sato,[8] T. Shiozaki,[1] K. Shirotori,[10] K. N. Suzuki,[4] S. Suzuki,[3] M. Tabata,[11] C. d. L. Taille,[5] H. Takahashi,[3] T. Takahashi,[3] T. N. Takahashi,[15] H. Tamura,[1,8] M. Tanaka,[3] K. Tanida,[8] Z. Tsamalaidze,[7,12] M. Ukai,[3,1] H. Umetsu,[1] S. Wada,[1] T. O. Yamamoto,[8] J. Yoshida,[1] and K. Yoshimura[13]

(J-PARC E40 Collaboration)

- So we don’t quite understand YN interactions, because there’s been very few measurements historically.

- But recently there are several renewed experimental efforts to study YN scattering more precisely:

PHYSICAL REVIEW LETTERS **128,** 072501 (2022)

Precise Measurement of Differential Cross Sections of the $\Sigma^- p \rightarrow$
Momentum Range 470–650 MeV/*c*

K. Miwa,[1] J. K. Ahn,[2] Y. Akazawa,[3] T. Aramaki,[1] S. Ashikaga,[4] S. Callier,[5] N. Chiga,[1]
P. Evtoukhovitch,[7] N. Fujioka,[1] M. Fujita,[8] T. Gogami,[4] T. Harada,[4] S. Hasegawa,[8] S. H.
S. Hoshino,[9] K. Hosomi,[8] M. Ichikawa,[4,14] Y. Ichikawa,[8] M. Ieiri,[3] M. Ikeda,[1] K. Imai,[8] Y.
S. Jung,[2] S. Kajikawa,[1] H. Kanauchi,[1] H. Kanda,[10] T. Kitaoka,[1] B. M. Kang,[2] H. Kawai,[11]
T. Koike,[1] K. Matsuda,[1] Y. Matsumoto,[1] S. Nagao,[1] R. Nagatomi,[9] Y. Nakada,[9] M. Na
T. Nanamura,[4,8] M. Naruki,[4] S. Ozawa,[1] L. Raux,[5] T. G. Rogers,[1] A. Sakaguchi,[9] T. Sakao,[1] H.
K. Shirotori,[10] K. N. Suzuki,[4] S. Suzuki,[3] M. Tabata,[11] C. d. L. Taille,[5] H. Takahashi,[3] T. Ta
H. Tamura,[1,8] M. Tanaka,[3] K. Tanida,[8] Z. Tsamalaidze,[7,12] M. Ukai,[3,1] H. Umetsu,[1] S. V
J. Yoshida,[1] and K. Yoshimura[13]

(J-PARC E40 Collaboration)

PHYSICAL REVIEW LETTERS **127,** 272303 (2021)

Improved Λp Elastic Scattering Cross Sections between 0.9 and 2.0 GeV/*c*
as a Main Ingredient of the Neutron Star Equation of State

J. Rowley,[35] N. Compton,[35] C. Djalali,[35] K. Hicks,[35] J. Price,[2] N. Zachariou,[47] K. P. Adhikari,[36] W. R. Armstrong,[1] H. Atac,[41] L. Baashen,[13] L. Barion,[17] M. Bashkanov,[47] M. Battaglieri,[42,19] I. Bedlinskiy,[31] F. Benmokhtar,[10] A. Bianconi,[45,22] L. Biondo,[19,16,29] A. S. Biselli,[11] M. Bondi,[19] F. Bossù,[6] S. Boiarinov,[42] W. J. Briscoe,[15] W. K. Brooks,[43] D. Bulumulla,[36] V. D. Burkert,[42] D. S. Carman,[42] J. C. Carvajal,[13] A. Celentano,[19] P. Chatagnon,[23] V. Chesnokov,[39] T. Chetry,[30] G. Ciullo,[17,12] L. Clark,[46] P. L. Cole,[27] M. Contalbrigo,[17] G. Costantini,[45,22] V. Crede,[14] A. D’Angelo,[20,38] N. Dashyan,[51] R. De Vita,[19] M. Defurne,[6] A. Deur,[42] S. Diehl,[37,8,40] R. Dupré,[23] H. Egiyan,[42,32] M. Ehrhart,[1] A. El Alaoui,[43] L. El Fassi,[30,1] P. Eugenio,[14] G. Fedotov,[39] S. Fegan,[47] R. Fersch,[7,50] A. Filippi,[21] A. Fradi,[23] G. Gavalian,[42,36] F. X. Girod,[42,6] D. I. Glazier,[46] A. Golubenko,[39] R. W. Gothe,[40] K. Griffioen,[50] L. Guo,[13] K. Hafidi,[1] H. Hakobyan,[43,51] M. Hattawy,[36] T. B. Hayward,[8] D. Heddle,[7,42] A. Hobart,[23] M. Holtrop,[32] Y. Ilieva,[40] D. G. Ireland,[46] E. L. Isupov,[39] D. Jenkins,[48] H. S. Jo,[26] K. Joo,[8] D. Keller,[49,35] A. Khanal,[13] M. Khandaker,[34] A. Kim,[8] I. Korover,[28] A. Kripko,[37] V. Kubarovsky,[42] S. E. Kuhn,[36] L. Lanza,[20] M. Leali,[45,22] P. Lenisa,[17,12] K. Livingston,[46] I. J. D. MacGregor,[46] D. Marchand,[23] N. Markov,[42,8] L. Marsicano,[19] V. Mascagna,[44,22] M. E. McCracken,[4] B. McKinnon,[46] C. McLauchlin,[40] Z. E. Meziani,[1] S. Migliorati,[45,22] T. Mineeva,[43,8] M. Mirazita,[18] V. Mokeev,[42,39] E. Munevar,[15] C. Munoz Camacho,[23] P. Nadel-Turonski,[42,5] K. Neupane,[40] S. Niccolai,[23] G. Niculescu,[25] T. R. O’Connell,[8] M. Osipenko,[19] A. I. Ostrovidov,[14] P. Pandey,[36] M. Paolone,[33] L. L. Pappalardo,[17,12] E. Pasyuk,[42] O. Pogorelko,[31] Y. Prok,[36,49] T. Reed,[13] M. Ripani,[19] J. Ritman,[24] A. Rizzo,[20,38] G. Rosner,[46] F. Sabatie,[6] C. Salgado,[34] A. Schmidt,[15] R. A. Schumacher,[4] Y. G. Sharabian,[42] U. Shrestha,[8] D. Sokhan,[46] O. Soto,[18] N. Sparveris,[41] I. I. Strakovsky,[15] S. Strauch,[40] R. Tyson,[46] M. Ungaro,[42,8] L. Venturelli,[45,22] H. Voskanyan,[51] A. Vossen,[9,42] E. Voutier,[23] D. P. Watts,[47] K. Wei,[8] X. Wei,[42] R. Wishart,[46] M. H. Wood,[3,40] B. Yale,[50] M. Yurov,[26] J. Zhang,[49,36] and Z. W. Zhao[9,40]

(CLAS Collaboration)

- So we don’t quite understand YN interactions, because there’s been very few measurements historically.

- But recently there are several renewed experimental efforts to study YN scattering more precisely:

PHYSICAL REVIEW LETTERS **128,** 072501 (2022)

Precise Measurement of Differential Cross Sections of the $\Sigma^- p \to$
Momentum Range 470–650 MeV/c

K. Miwa,[1] J. K. Ahn,[2] Y. Akazawa,[3] T. Aramaki,[1] S. Ashikaga,[4] S. Callier,[5] N. Chiga,[1]
P. Evtoukhovitch,[7] N. Fujioka,[1] M. Fujita,[8] T. Gogami,[4] T. Harada,[4] S. Hasegawa,[8] S. H.
S. Hoshino,[9] K. Hosomi,[8] M. Ichikawa,[4,14] Y. Ichikawa,[8] M. Ieiri,[3] M. Ikeda,[1] K. Imai,[8] Y.
S. Jung,[2] S. Kajikawa,[1] H. Kanauchi,[1] H. Kanda,[10] T. Kitaoka,[1] B. M. Kang,[2] H. Kawai,[11]
T. Koike,[1] K. Matsuda,[1] Y. Matsumoto,[1] S. Nagao,[1] R. Nagatomi,[9] Y. Nakada,[9] M. Na
T. Nanamura,[4,8] M. Naruki,[4] S. Ozawa,[1] L. Raux,[5] T. G. Rogers,[1] A. Sakaguchi,[9] T. Sakao,[1] H.
K. Shirotori,[10] K. N. Suzuki,[4] S. Suzuki,[3] M. Tabata,[11] C. d. L. Taille,[5] H. Takahashi,[3] T. Ta
H. Tamura,[1,8]

PHYSICAL REVIEW LETTERS **127,** 272303 (2021)

Improved Λp Elastic Scattering Cross Sections between 0.9 and 2.0 GeV/c as a Main Ingredient of the Neutron Star Equation of State

J. Rowley,[35] N. Compton,[35] C. Djalali,[35] K. Hicks,[35] J. Price,[2] N. Zachariou,[47] K. P. Adhikari,[36] W. R. Armstrong,[1]
H. Atac,[41] L. Baashen,[13] L. Barion,[17] M. Bashkanov,[47] M. Battaglieri,[42,19] I. Bedlinskiy,[31] F. Benmokhtar,[10]
A. Bianconi,[45,22] L. Biondo,[19,16,29] A. S. Biselli,[11] M. Bondi,[19] F. Bossù,[6] S. Boiarinov,[42] W. J. Briscoe,[15] W. K. Brooks,[43]
D. Bulumulla,[36] V. D. Burkert,[42] D. S. Carman,[42] J. C. Carvajal,[13] A. Celentano,[19] P. Chatagnon,[23] V. Chesnokov,[39]
T. Chetry,[30] G. Ciullo,[17,12] L. Clark,[46] P. L. Cole,[27] M. Contalbrigo,[17] G. Costantini,[45,22] V. Crede,[14] A. D’Angelo,[20,38]
N. Dashyan,[51] R. De Vita,[19] M. Defurne,[6] A. Deur,[42] S. Diehl,[37,8,40] R. Dupré,[23] H. Egiyan,[42,32] M. Ehrhart,[1] A. El Alaoui,[43]
L. El Fassi,[30,1] P. Eugenio,[14] G. Fedotov,[39] S. Fegan,[47] R. Fersch,[7,50] A. Filippi,[21] A. Fradi,[23] G. Gavalian,[42,36]
F. X. Girod,[42,6] D. I. Glazier,[46] A. Golubenko,[39] R. W. Gothe,[40] K. Griffioen,[50] L. Guo,[13] K. Hafidi,[1] H. Hakobyan,[43,51]
M. Hattawy,[36] T. B. Hayward,[8] D. Heddle,[7,42] A. Hobart,[23] M. Holtrop,[32] Y. Ilieva,[40] D. G. Ireland,[46] E. L. Isupov,[39]
D. Jenkins,[48] H. S. Jo,[26] K. Joo,[8] D. Keller,[49,35] A. Khanal,[13] M. Khandaker,[34] A. Kim,[8] I. Korover,[28] A. Kripko,[37]
V. Kubarovsky,[42] S. E. Kuhn,[36] L. Lanza,[20] M. Leali,[45,22] P. Lenisa,[17,12] K. Livingston,[46] I. J. D. MacGregor,[46]
D. Marchand,[23] N. Markov,[42,8] L. Marsicano,[19] V. Mascagna,[44,22] M. E. McCracken,[4] B. McKinnon,[46] C. McLauchlin,[40]
cho,[23]
idov,[14]
ni,[19]
bian,[42]

Physics Letters B 805 (2020) 135419

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

PHYSICS LETTERS B

Investigation of the p–Σ^0 interaction via femtoscopy in pp collisions

ALICE Collaboration *

Check for updates

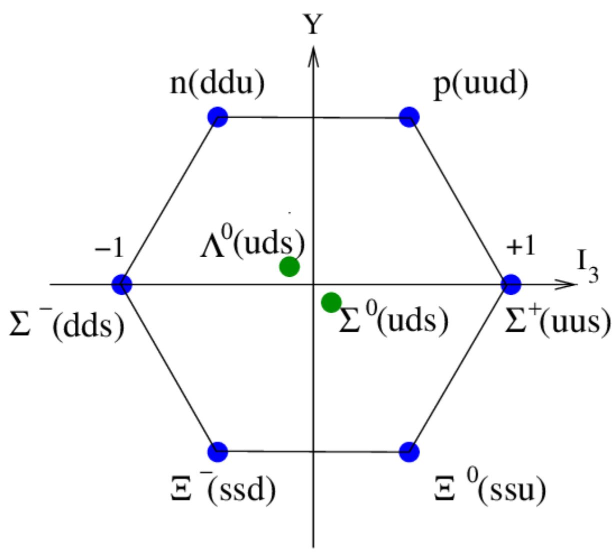
On the theoretical side, there's been continuous efforts to understand NN, YN and YY interactions. Three major approaches are

- Meson-exchange Potential models (Nijmegen and Julich potentials)
- the Chiral Effective Field Theory (xEFT)
- Lattice QCD simulations

On the theoretical side, there's been continuous efforts to understand NN, YN and YY interactions. Three major approaches are

- Meson-exchange Potential models (Nijmegen and Julich potentials)
- the Chiral Effective Field Theory (xEFT)
- Lattice QCD simulations

The underlying organizing principle is the SU(3) flavor symmetry:

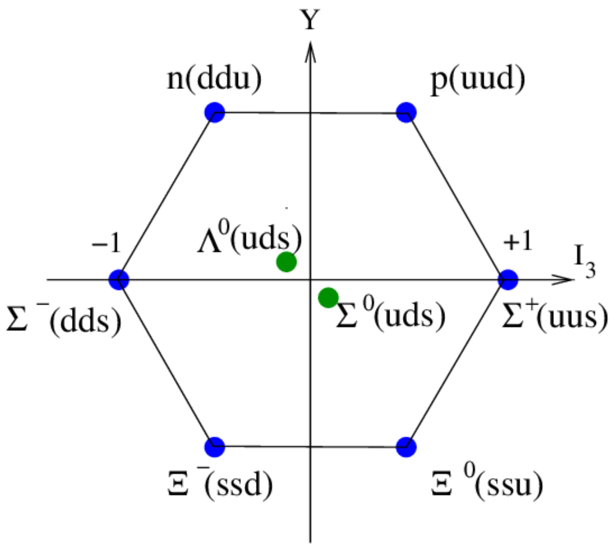


Particle	Experimental mass (MeV)
P	938.26
N	939.55
Λ	1115.6
Σ^+	1189.4
Σ^0	1192.5
Σ^-	1197.3
Ξ^0	1314.7
Ξ^-	1321.3

On the theoretical side, there's been continuous efforts to understand NN, YN and YY interactions. Three major approaches are

- Meson-exchange Potential models (Nijmegen and Julich potentials)
- the Chiral Effective Field Theory (xEFT)
- Lattice QCD simulations

The underlying organizing principle is the SU(3) flavor symmetry:



Particle	Experimental mass (MeV)
P	938.26
N	939.55
Λ	1115.6
Σ^+	1189.4
Σ^0	1192.5
Σ^-	1197.3
Ξ^0	1314.7
Ξ^-	1321.3

A major challenge: How to best incorporate SU(3) breaking effects amid constraints from the NN sector?

Parallel to the new experimental efforts, there's a new approach to understand nuclear dynamics from the quantum information-theoretic perspective:

PHYSICAL REVIEW LETTERS **122,** 102001 (2019)

Entanglement Suppression and Emergent Symmetries of Strong Interactions

Silas R. Beane,[1] David B. Kaplan,[2] Natalie Klco,[1,2] and Martin J. Savage[2]
[1] *Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA*
[2] *Institute for Nuclear Theory, University of Washington, Seattle, Washington 98195-1550, USA*

(Received 20 December 2018; published 14 March 2019)

Entanglement suppression in the strong-interaction S matrix is shown to be correlated with approximate spin-flavor symmetries that are observed in low-energy baryon interactions, the Wigner $SU(4)$ symmetry for two flavors and an $SU(16)$ symmetry for three flavors. We conjecture that

This raises the intriguing possibility of understanding nuclear interactions and the associated emergent symmetries from quantum entanglement!

arXiv:1812.03138

Entanglement is quantum world's most prominent feature:

- It refers to the situation where a measurement on a subsystem will improve our knowledge on the rest of the system.

- A quantum state of a system is entangled if it cannot be written as a tensor-product state of its subsystems.

- Consider a bipartite system $\mathcal{H}_{12} = \mathcal{H}_1 \otimes \mathcal{H}_2$, a state vector $|\psi\rangle \in \mathcal{H}_{12}$ is *entangled* if there is NO $|\psi_1\rangle \in \mathcal{H}_1$ and $|\psi_2\rangle \in \mathcal{H}_2$ such that

$$|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$$

To quantify the amount of entanglement, we need entanglement measure.

Many possibilities for Entanglement Measure. For bipartite systems:

von Neumann entropy: $E(\rho) = -\mathrm{Tr}(\rho_1 \ln \rho_1) = -\mathrm{Tr}(\rho_2 \ln \rho_2)$

Linear entropy: $E(\rho) = -\mathrm{Tr}(\rho_1(\rho_1 - 1)) = 1 - \mathrm{Tr}\rho_1^2$

$$\rho = |\psi\rangle\langle\psi| \qquad\qquad \rho_{1/2} = \mathrm{Tr}_{2/1}(\rho)$$

The common property is that the entanglement measure vanishes for a product state $|\psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle$, but attains the maximum for maximally entangled states (such as the Bell states.)

Entanglement is a property of the quantum state. But we are more interested in the ability of a *quantum-mechanical operator* (i.e. the S-matrix) to entangle.

Entanglement is a property of the quantum state. But we are more interested in the ability of a *quantum-mechanical operator* (i.e. the S-matrix) to entangle.

The “entanglement power” deals with this issue is by averaging over the initial states:

$$E(U) = \overline{E(U\,|\psi_1\rangle \otimes |\psi_2\rangle)},$$

It is a measure of the ability of an operator *U* to generate entanglement on product states.

Entanglement is a property of the quantum state. But we are more interested in the ability of a *quantum-mechanical operator* (i.e. the S-matrix) to entangle.

The "entanglement power" deals with this issue is by averaging over the initial states:

$$E(U) = \overline{E(U\,|\psi_1\rangle \otimes |\psi_2\rangle)},$$

It is a measure of the ability of an operator *U* to generate entanglement on product states.

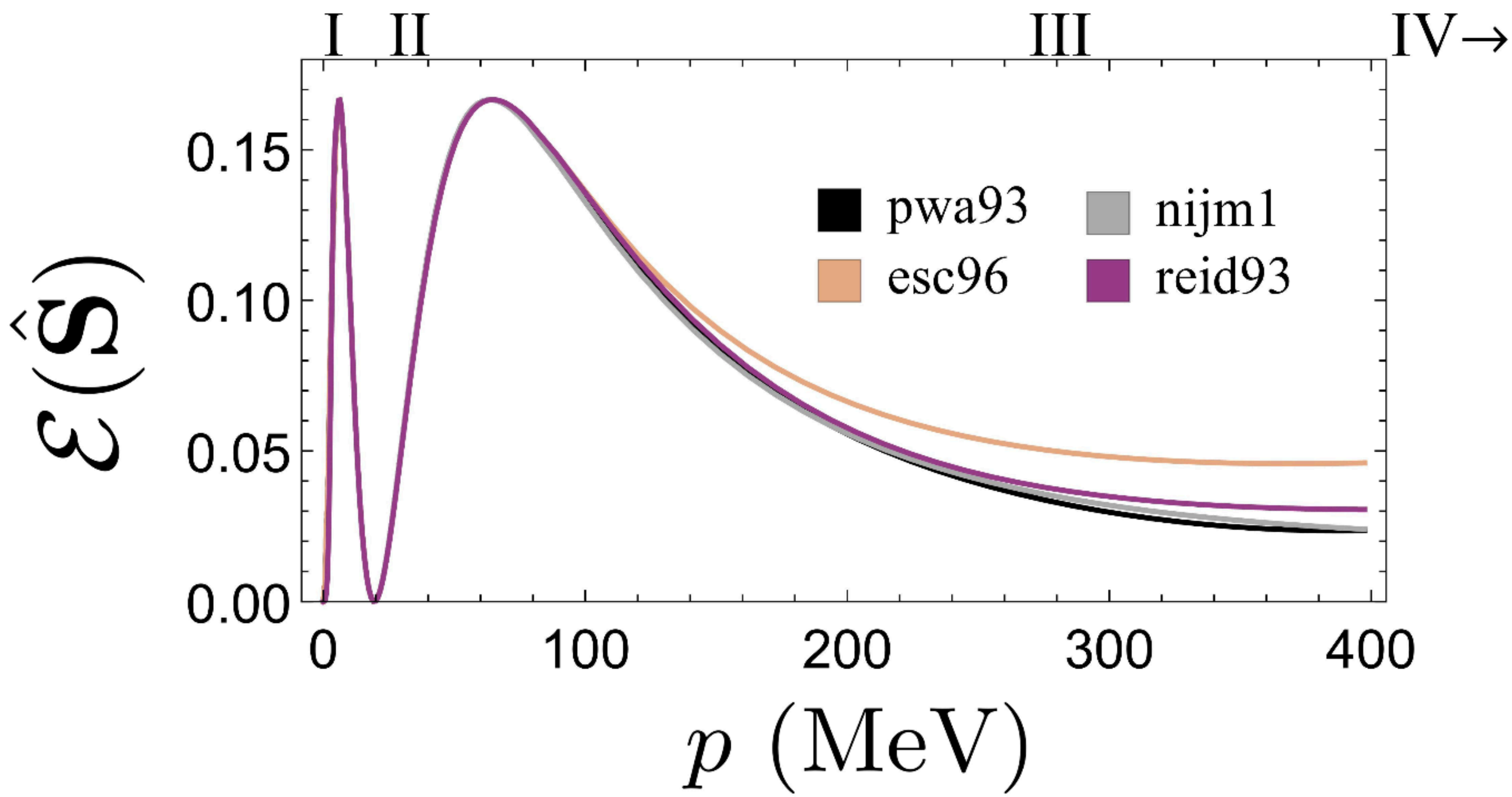
A minimally entangling operator has *E*(*U*) = 0, i.e.,

$$|\ \ \rangle \otimes |\ \ \rangle \xrightarrow{U} |\ \ \rangle \otimes |\ \ \rangle$$

Two operators have the same entanglement power if they differ by single-qubit operations:

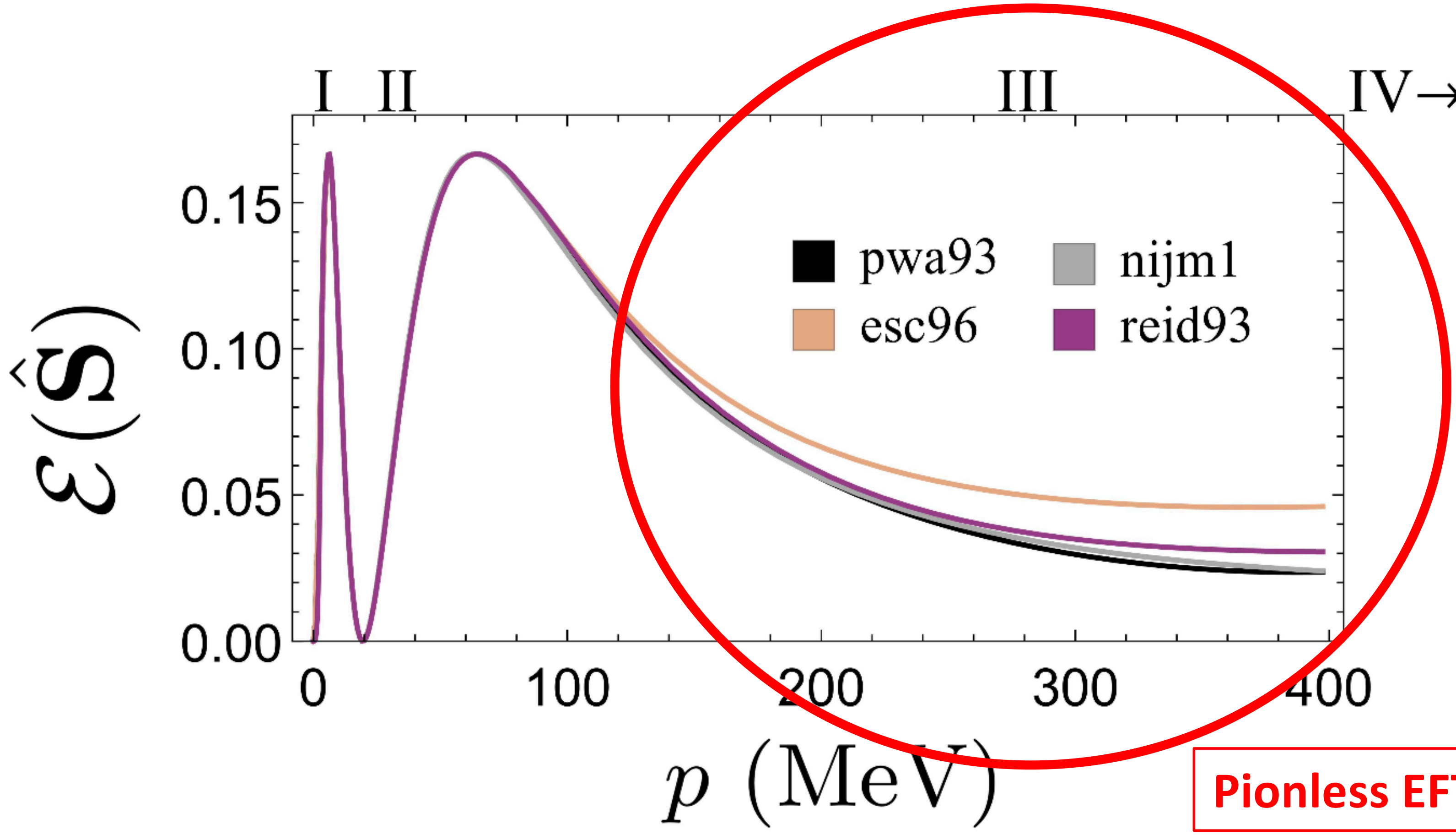
$$U \sim U' \qquad \text{if} \qquad U = (U_1 \otimes U_2)U'(V_1 \otimes V_2)$$

Using these tools, the Seattle group found the S-matrix in NN scattering tends to minimize entanglement in the far infrared region with the nucleons as fundamental degrees of freedom:



arXiv:1812.03138

Using these tools, the Seattle group found the S-matrix in NN scattering tends to minimize entanglement in the far infrared region with the nucleons as fundamental degrees of freedom:



Pionless EFT!

arXiv:1812.03138

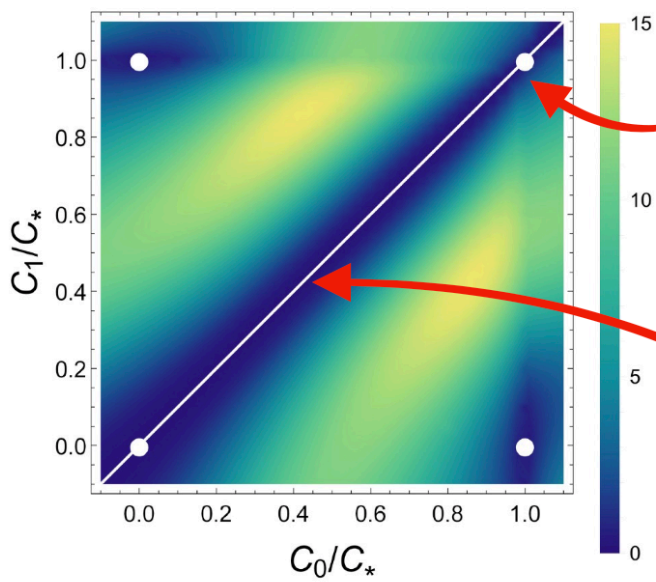
Moreover, regions of entanglement suppression coincides with the appearance of emergent symmetries such as the spin-flavor symmetry and the non-relativistic conformal invariance:

$$\mathcal{L}_6 = -\tfrac{1}{2}C_S(N^\dagger N)^2 - \tfrac{1}{2}C_T(N^\dagger \vec{\sigma} N)^2$$

$$^1S_0: \qquad \bar{C}_0 = (C_S - 3C_T)$$

$$^3S_1: \qquad \bar{C}_1 = (C_S + C_T)$$

$$\mathcal{E}(\hat{\mathbf{S}}) = \frac{1}{6}\,\sin^2\left(2(\delta_1 - \delta_0)\right)$$



Conformal fixed points (zero or infinite scattering lengths, $\delta_i = 0, \pi/2$)

SU(4)$_{\text{Wigner}}$ symmetry line ($\delta_0 = \delta_1$)

Slide by D.B. Kaplan

Emergent symmetries in NN scattering:

- Schrodinger symmetry (non-relativistic conformal invariance)

The largest symmetry group preserved by the Schrodinger equation, which includes Galilean boosts, scale and special conformal transformations.

- Spin-flavor symmetries

Symmetries mixing flavor (internal) with spin (spacetime).
Examples: SU($2N_f$) quark spin-flavor symmetries;
Wigner's ''supermultiplet'' SU(4) spin-flavor symmetry:

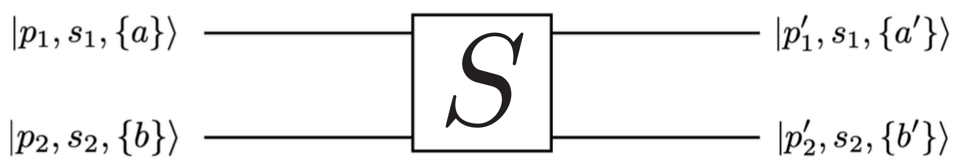
$$N = \begin{pmatrix} p\uparrow \\ p\downarrow \\ n\uparrow \\ n\downarrow \end{pmatrix}$$

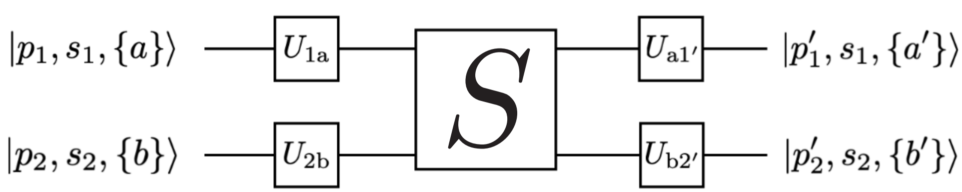
We would like to stuy the information-theoretic property of the S-matrix.

In the scattering process the S-matrix acts on the IN-state:

$$|\text{out}\rangle = S\;|\text{in}\rangle$$

For 2-to-2 scattering of spin-1/2 fermions, the S-matrix can be viewed as a quantum logic gate acting on the spin-space:





Low, Mehen: 2104.10835

It turns out that, modulo the equivalent class, there are two and only two minimally entangling operators,

$$\mathbf{1} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} , \qquad \mathrm{SWAP} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} .$$

Identity gate: do nothing.
SWAP gate: interchange the qubits.

$$\mathrm{SWAP} \sim -1 \quad \text{as} \quad [\mathrm{SWAP}]^2 = 1$$

In terms of Pauli matrices,

$$\mathrm{SWAP} = (1 + \boldsymbol{\sigma} \cdot \boldsymbol{\sigma})/2 \ , \qquad \boldsymbol{\sigma} \cdot \boldsymbol{\sigma} \equiv \sum_a \boldsymbol{\sigma}^a \otimes \boldsymbol{\sigma}^a \ .$$

Low, Mehen: 2104.10835

Consider the scattering of two qubits, Alice and Bob, in the low-energy:

- Only the s-wave channel dominates.

- The S-matrix can be decomposed into ${}^1S_0$ and ${}^3S_1$ channels → there are two phase shifts: δ_0 and δ_1 , respectively.

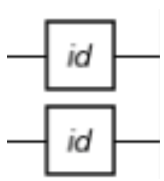
- Rotational invariance and Unitarity then uniquely fix the S-matrix:

$$S = e^{2i\delta_0}\,\frac{(1-\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})}{4} + e^{2i\delta_1}\,\frac{(3+\boldsymbol{\sigma}\cdot\boldsymbol{\sigma})}{4}$$

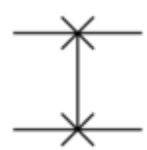
Spin-projector into ${}^1S_0$ channel

Spin-projector into ${}^3S_1$ channel

$S =$



$+$



In terms of quantum logic gates,

$$S = \frac{1}{2}\left(e^{2i\delta_1} + e^{2i\delta_0}\right)\mathbf{1} + \frac{1}{2}\left(e^{2i\delta_1} - e^{2i\delta_0}\right)\ \mathrm{SWAP},$$

Conditions for the S-matrix to minimize entanglement:

1. $S = 1$ if $\delta_0 = \delta_1$ ⇒ SU(4) or SU(16) spin-flavor sym.
2. S = SWAP if $|\delta_0 - \delta_1| = \pi/2$ ⇒ Schrodinger sym.

Low, Mehen: 2104.10835

In terms of quantum logic gates,

$$S = \frac{1}{2}\left(e^{2i\delta_1} + e^{2i\delta_0}\right)\mathbf{1} + \frac{1}{2}\left(e^{2i\delta_1} - e^{2i\delta_0}\right)\ \mathrm{SWAP},$$

Conditions for the S-matrix to minimize entanglement:

1. $S = 1$ if $\delta_0 = \delta_1$ ⇨ SU(4) or SU(16) spin-flavor sym.
2. S = SWAP if $|\delta_0 - \delta_1| = \pi/2$ ⇨ Schrodinger sym.

The appearance of emergent symmetries in NN scattering is a consequence of the S-matrix minimizing entanglement!

Low, Mehen: 2104.10835

- Nucleons are part of spin-1/2 octet baryons:

In the SU(3) flavor-symmetric limit :

$$B = \begin{pmatrix} \Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & \Sigma^+ & p \\ \Sigma^- & -\Sigma^0/\sqrt{2} + \Lambda/\sqrt{6} & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

A low-energy effective field theory:

$$\langle \cdot \rangle \equiv \mathrm{Tr}(\ \cdot\ )$$

$$\mathcal{L}_{\mathrm{LO}}^{n_f=3} = -\frac{c_1}{f^2}\langle B_i^\dagger B_i B_j^\dagger B_j\rangle - \frac{c_2}{f^2}\langle B_i^\dagger B_j B_j^\dagger B_i\rangle - \frac{c_3}{f^2}\langle B_i^\dagger B_j^\dagger B_i B_j\rangle - \frac{c_4}{f^2}\langle B_i^\dagger B_j^\dagger B_j B_i\rangle$$
$$- \frac{c_5}{f^2}\langle B_i^\dagger B_i\rangle\langle B_j^\dagger B_j\rangle - \frac{c_6}{f^2}\langle B_i^\dagger B_j\rangle\langle B_j^\dagger B_i\rangle, \quad i,j = \uparrow,\downarrow$$

Savage, Wise (1995)

Lattice QCD could compute the six Wilson coefficients under some special circumstances:

INT-PUB-17-017, MIT-CTP-4912, NSF-ITP-17-076

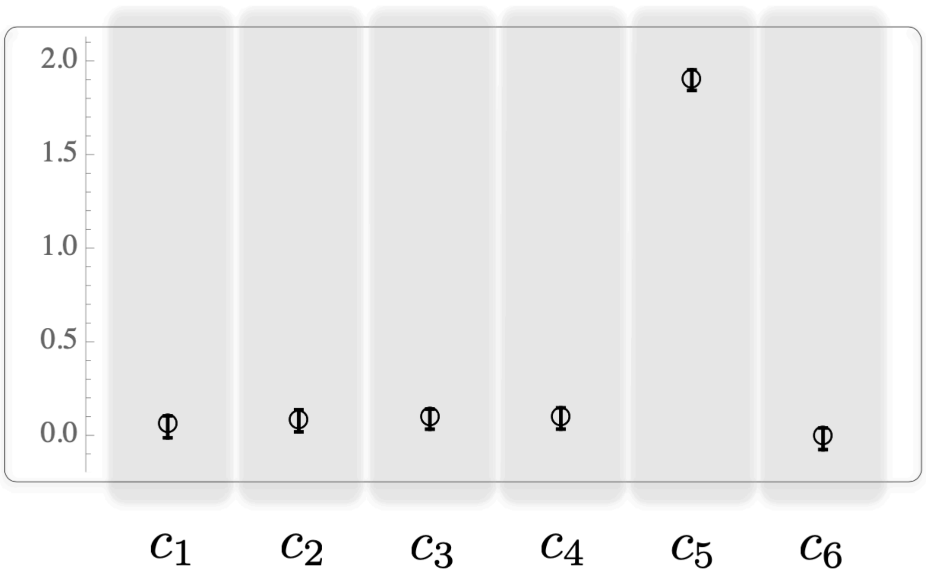
Baryon-Baryon Interactions and Spin-Flavor Symmetry from Lattice Quantum Chromodynamics

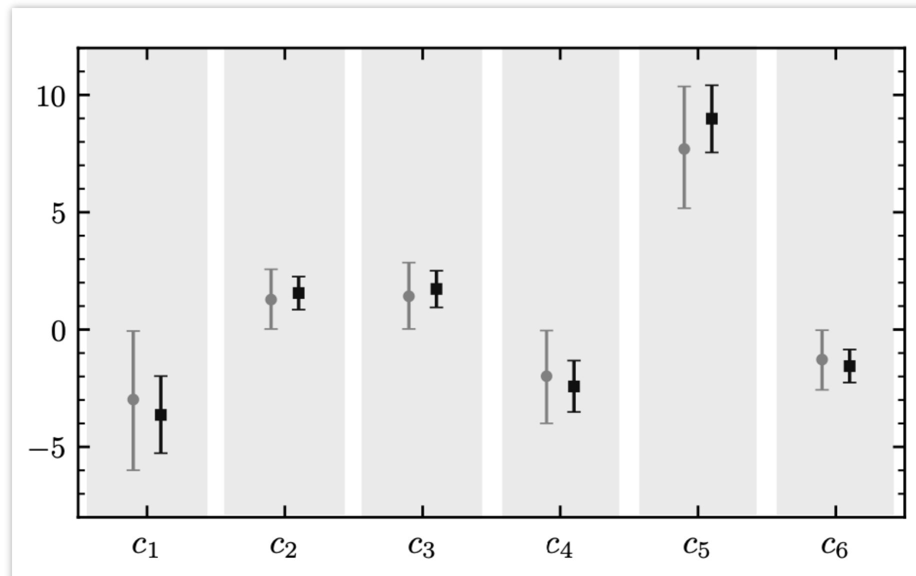
Michael L. Wagman,[1,2] Frank Winter,[3] Emmanuel Chang, Zohreh Davoudi,[4] William Detmold,[4] Kostas Orginos,[5,3] Martin J. Savage,[1,2] and Phiala E. Shanahan[4]
(NPLQCD Collaboration)

ICCUB-20-020, UMD-PP-020-7, MIT-CTP/5238, INT-PUB-20-038
FERMILAB-PUB-20-498-T

Low-energy Scattering and Effective Interactions of Two Baryons at $m_\pi \sim 450$ MeV from Lattice Quantum Chromodynamics

Marc Illa,[1] Silas R. Beane,[2] Emmanuel Chang, Zohreh Davoudi,[3,4] William Detmold,[5] David J. Murphy,[5] Kostas Orginos,[6,7] Assumpta Parreño,[1] Martin J. Savage,[8] Phiala E. Shanahan,[5] Michael L. Wagman,[9] and Frank Winter[7]
(NPLQCD Collaboration)





m_π = 804 MeV

m_π = 450 MeV

m_π = 150 MeV in reality

In the limit where all coefficients but c_5 are vanishing:

$$\begin{aligned}\mathcal{L}_{\mathrm{LO}}^{n_f=3} = &-\frac{c_1}{f^2}\langle B_i^\dagger \cancel{B_i B_j^\dagger} B_j\rangle - \frac{c_2}{f^2}\langle B_i^\dagger B_j \cancel{B_j^\dagger B_i}\rangle - \frac{c_3}{f^2}\langle B_i^\dagger \cancel{B_j^\dagger B_i} B_j\rangle - \frac{c_4}{f^2}\langle \cancel{B_i^\dagger B_j^\dagger} B_j B_i\rangle \\ &- \frac{c_5}{f^2}\langle B_i^\dagger B_i\rangle\langle B_j^\dagger B_j\rangle - \frac{c_6}{f^2}\langle B_i^\dagger \cancel{B_j\rangle\langle} B_j^\dagger B_i\rangle, \qquad i,j = \uparrow,\downarrow\end{aligned}$$

The remaining operator can be re-written,

$$\mathcal{B} = (n_\uparrow, n_\downarrow, p_\uparrow, p_\downarrow, \dots) \ , \qquad \mathcal{L} = -c_5 \left(\mathcal{B}^\dagger \mathcal{B}\right)^2$$

which is invariant under an SU(16) spin-flavor symmetry

$$\mathcal{B} \to U\mathcal{B} \ , \qquad U^\dagger U = 1$$

U = 16x16
unitary matrix!

There is no large N_c explanation!

Let's extend the analysis to other spin-1/2 baryons, which have a rich theoretical structure and phenomenology:

-- A total 8x8 = 64 scattering channels. Assuming SU(3) flavor:

$$\mathbf{8} \otimes \mathbf{8} = \mathbf{27} \oplus \mathbf{8}_S \oplus \mathbf{1} \oplus \mathbf{10} \oplus \overline{\mathbf{10}} \oplus \mathbf{8}_A$$

-- Strong interaction preserves charge (Q) and strangeness (S)

→ Classify the scattering channel into sectors with definitive (Q, S).

	Q	S
nn	0	0
np	1	0
pp	2	0
$n\Sigma^-$	-1	-1
$n\Lambda$		
$n\Sigma^0$	0	-1
$p\Sigma^-$		
$p\Lambda$		
$p\Sigma^0$	1	-1
$n\Sigma^+$		
$p\Sigma^+$	2	-1

	Q	S
$\Sigma^-\Sigma^-$	-2	-2
$\Sigma^-\Lambda$		
$\Sigma^-\Sigma^0$	-1	-2
$n\,\Xi^-$		
$\Sigma^+\Sigma^-$		
$\Sigma^0\Sigma^0$		
$\Lambda\Sigma^0$		
$\Lambda\Lambda$	0	-2
$n\,\Xi^0$		
$p\,\Xi^-$		
$\Sigma^+\Lambda$		
$\Sigma^+\Sigma^0$	1	-2
$p\,\Xi^0$		
$\Sigma^+\Sigma^+$	2	-2

	Q	S
$\Sigma^-\Xi^-$	-2	-3
$\Sigma^-\Xi^0$		
$\Xi^-\Sigma^0$	-1	-3
$\Xi^-\Lambda$		
$\Xi^-\Sigma^+$		
$\Xi^0\Lambda$	0	-3
$\Xi^0\Sigma^0$		
$\Xi^0\Sigma^+$	1	-3
$\Xi^-\Xi^-$	-2	-4
$\Xi^-\Xi^0$	-1	-4
$\Xi^0\Xi^0$	0	-4

The S-matrix is block-diagonal among different (Q,S) sectors.

Liu, Low, Mehen: 2210.12085

1-d sector

	Q	S
nn	0	0
np	1	0
pp	2	0
$n\Sigma^-$	-1	-1
$n\Lambda$ $n\Sigma^0$ $p\Sigma^-$	0	-1
$p\Lambda$ $p\Sigma^0$ $n\Sigma^+$	1	-1
$p\Sigma^+$	2	-1

	Q	S
$\Sigma^-\Sigma^-$	-2	-2
$\Sigma^-\Lambda$ $\Sigma^-\Sigma^0$ $n\,\Xi^-$	-1	-2
$\Sigma^+\Sigma^-$ $\Sigma^0\Sigma^0$ $\Lambda\Sigma^0$ $\Lambda\Lambda$ $n\,\Xi^0$ $p\,\Xi^-$	0	-2
$\Sigma^+\Lambda$ $\Sigma^+\Sigma^0$ $p\,\Xi^0$	1	-2
$\Sigma^+\Sigma^+$	2	-2

	Q	S
$\Sigma^-\Xi^-$	-2	-3
$\Sigma^-\Xi^0$ $\Xi^-\Sigma^0$ $\Xi^-\Lambda$	-1	-3
$\Xi^-\Sigma^+$ $\Xi^0\Lambda$ $\Xi^0\Sigma^0$	0	-3
$\Xi^0\Sigma^+$	1	-3
$\Xi^-\Xi^-$	-2	-4
$\Xi^-\Xi^0$	-1	-4
$\Xi^0\Xi^0$	0	-4

The S-matrix is block-diagonal among different (Q,S) sectors.

Liu, Low, Mehen: 2210.12085

3-d sector

	Q	S
nn	0	0
np	1	0
pp	2	0
$n\Sigma^-$	-1	-1
$n\Lambda$ $n\Sigma^0$ $p\Sigma^-$	0	-1
$p\Lambda$ $p\Sigma^0$ $n\Sigma^+$	1	-1
$p\Sigma^+$	2	-1

	Q	S
$\Sigma^-\Sigma^-$	-2	-2
$\Sigma^-\Lambda$ $\Sigma^-\Sigma^0$ $n\,\Xi^-$	-1	-2
$\Sigma^+\Sigma^-$ $\Sigma^0\Sigma^0$ $\Lambda\Sigma^0$ $\Lambda\Lambda$ $n\,\Xi^0$ $p\,\Xi^-$	0	-2
$\Sigma^+\Lambda$ $\Sigma^+\Sigma^0$ $p\,\Xi^0$	1	-2
$\Sigma^+\Sigma^+$	2	-2

	Q	S
$\Sigma^-\Xi^-$	-2	-3
$\Sigma^-\Xi^0$ $\Xi^-\Sigma^0$ $\Xi^-\Lambda$	-1	-3
$\Xi^-\Sigma^+$ $\Xi^0\Lambda$ $\Xi^0\Sigma^0$	0	-3
$\Xi^0\Sigma^+$	1	-3
$\Xi^-\Xi^-$	-2	-4
$\Xi^-\Xi^0$	-1	-4
$\Xi^0\Xi^0$	0	-4

The S-matrix is block-diagonal among different (Q,S) sectors.

Liu, Low, Mehen: 2210.12085

6-d sector

	Q	S
nn	0	0
np	1	0
pp	2	0
$n\Sigma^-$	-1	-1
$n\Lambda$ $n\Sigma^0$ $p\Sigma^-$	0	-1
$p\Lambda$ $p\Sigma^0$ $n\Sigma^+$	1	-1
$p\Sigma^+$	2	-1

	Q	S
$\Sigma^-\Sigma^-$	-2	-2
$\Sigma^-\Lambda$ $\Sigma^-\Sigma^0$ $n\,\Xi^-$	-1	-2
$\Sigma^+\Sigma^-$ $\Sigma^0\Sigma^0$ $\Lambda\Sigma^0$ $\Lambda\Lambda$ $n\,\Xi^0$ $p\,\Xi^-$	0	-2
$\Sigma^+\Lambda$ $\Sigma^+\Sigma^0$ $p\,\Xi^0$	1	-2
$\Sigma^+\Sigma^+$	2	-2

	Q	S
$\Sigma^-\Xi^-$	-2	-3
$\Sigma^-\Xi^0$ $\Xi^-\Sigma^0$ $\Xi^-\Lambda$	-1	-3
$\Xi^-\Sigma^+$ $\Xi^0\Lambda$ $\Xi^0\Sigma^0$	0	-3
$\Xi^0\Sigma^+$	1	-3
$\Xi^-\Xi^-$	-2	-4
$\Xi^-\Xi^0$	-1	-4
$\Xi^0\Xi^0$	0	-4

The S-matrix is block-diagonal among different (Q,S) sectors.

Liu, Low, Mehen: 2210.12085

We are able to obtain conditions on the scattering phases under which each (Q, S) sector is minimally entangled:

(Q, S) sectors	Minimal Entanglement Conditions
np $\Sigma^-\Xi^-$ $\Sigma^+\Xi^0$	$\delta_{27} = \delta_{\overline{10}}$ or $\delta_{27} = \delta_{\overline{10}} \pm \frac{\pi}{2}$
$n\Sigma^-$ $p\Sigma^+$ $\Xi^-\Xi^0$	$\delta_{27} = \delta_{10}$ or $\delta_{27} = \delta_{10} \pm \frac{\pi}{2}$
$(p\Lambda,\ p\Sigma^0,\ n\Sigma^+)$ $(n\Lambda,\ n\Sigma^0,\ p\Sigma^-)$ $(\Sigma^-\Lambda,\ \Sigma^-\Sigma^0,\ n\,\Xi^-)$ $(\Sigma^+\Lambda,\ \Sigma^+\Sigma^0,\ p\,\Xi^0)$ $(\Sigma^-\Xi^0, \Xi^-\Sigma^0, \Xi^-\Sigma^0)$ $(\Xi^-\Sigma^+, \Xi^0\Lambda, \Xi^0\Sigma^0)$	$\delta_{27} = \delta_{8_S} = \delta_{10} \pm \frac{\pi}{2} = \delta_{\overline{10}} \pm \frac{\pi}{2} = \delta_{8_A} \pm \frac{\pi}{2}$ or $\delta_{27} = \delta_{8_S} = \delta_{10} = \delta_{\overline{10}} = \delta_{8_A}$
$(\Sigma^+\Sigma^-,\ \Sigma^0\Sigma^0,\ \Lambda\Sigma^0,\ \Xi^-p,\ \Xi^0n,\ \Lambda\Lambda)$	$\delta_{27} = \delta_{8_S} = \delta_1 = \delta_{10} = \delta_{\overline{10}} = \delta_{8_A}$ or $\delta_{27} = \delta_{8_S} = \delta_1 = \delta_{10} \pm \frac{\pi}{2} = \delta_{\overline{10}} \pm \frac{\pi}{2} = \delta_{8_A} \pm \frac{\pi}{2}$

TABLE III. Conditions in each flavor sector for the S-matrix to be minimally entangling. An Identity gate is achieved when all the phases are equal, while a SWAP gate is when the phases differ by $\pi/2$.

Liu, Low, Mehen: 2210.12085

A summary table on possible emerging symmetries:

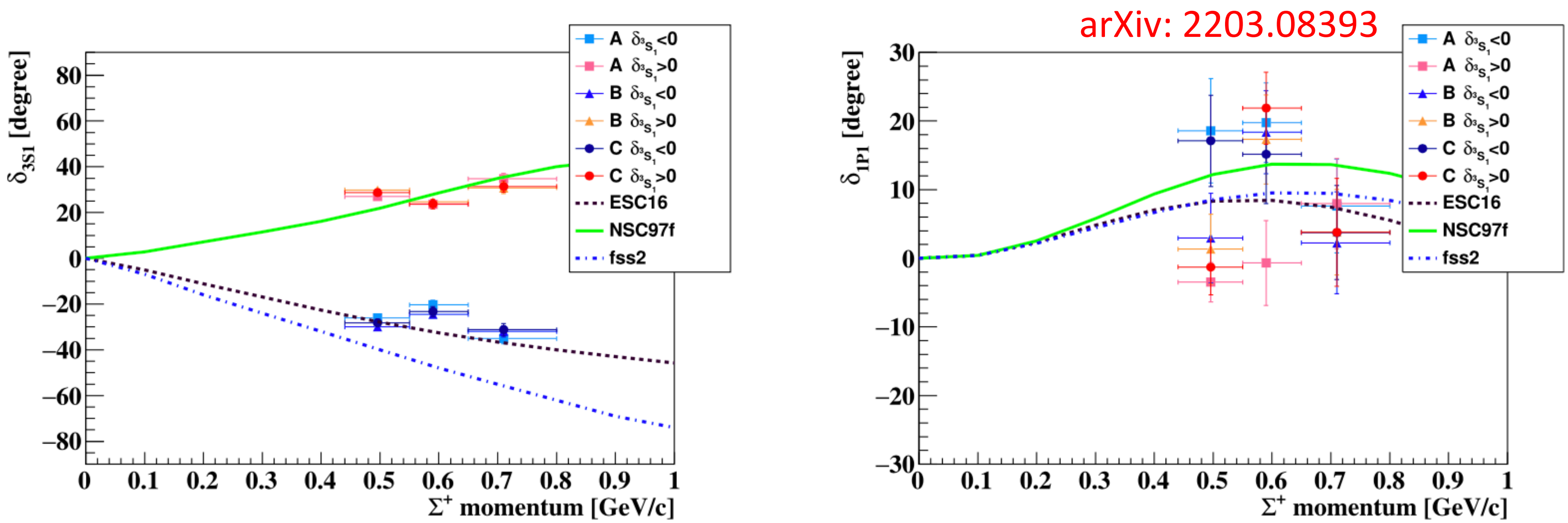
Flavor Subspace	Symmetry of Lagrangian
np $\Sigma^-\Xi^-$ $\Sigma^+\Xi^0$	$SU(6)$ spin-flavor symmetry or conformal symmetry in $\mathbf{27}$ and $\overline{\mathbf{10}}$ irrep channels
$n\Sigma^-$ $p\Sigma^+$ $\Xi^-\Xi^0$	conjugate of $SU(6)$ spin-flavor symmetry or conformal symmetry in $\mathbf{27}$ and $\mathbf{10}$ irrep channels
$(p\Lambda,\ p\Sigma^0,\ n\Sigma^+)$ $(n\Lambda,\ n\Sigma^0,\ p\Sigma^-)$ $(\Sigma^-\Lambda,\ \Sigma^-\Sigma^0,\ n\,\Xi^-)$ $(\Sigma^+\Lambda,\ \Sigma^+\Sigma^0,\ p\,\Xi^0)$ $(\Sigma^-\Xi^0, \Xi^-\Sigma^0, \Xi^-\Sigma^0)$ $(\Xi^-\Sigma^+, \Xi^0\Lambda, \Xi^0\Sigma^0)$	$SO(8)$ flavor symmetry or conformal symmetry in $\mathbf{27}$, $\mathbf{8}_{\boldsymbol{S}}$, $\mathbf{8}_{\boldsymbol{A}}$, $\mathbf{10}$ and $\overline{\mathbf{10}}$ irrep channels
$(\Sigma^+\Sigma^-,\ \Sigma^0\Sigma^0,\ \Lambda\Sigma^0,\ \Xi^-p,\ \Xi^0n,\ \Lambda\Lambda)$	$SU(16)$ symmetry or $SU(8)$ and conformal symmetry

TABLE V. Symmetries predicted by entanglement minimization in each flavor sector.

What does the data say?

- It turns out there are global fits of scattering phases using YN data, based on the meson-exchange potential models and xEFT.

- E40 collaboration at J-PARC also fitted the scattering phases in (Sigma+, p) scattering:



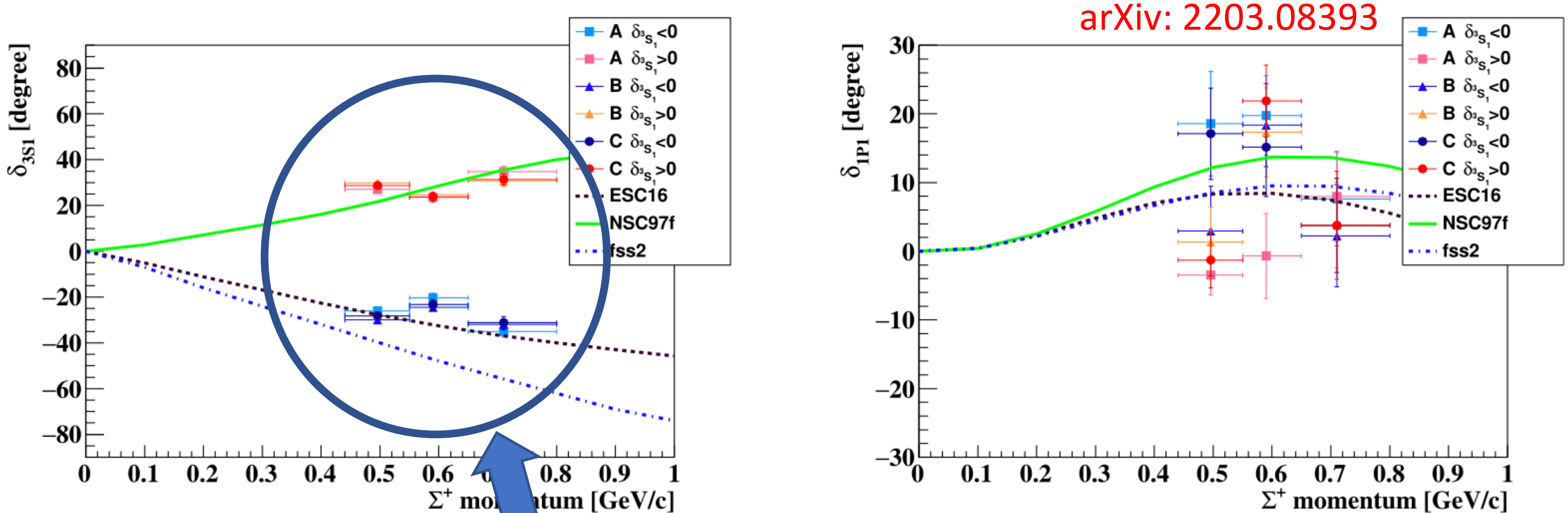
(a) $\delta_{^3S_1}$ (b) $\delta_{^1P_1}$

Fig. 28. Obtained phase shifts $\delta_{^3S_1}$ and $\delta_{^1P_1}$ as a function of the incident momentum. The black dashed, green solid, and blue dotted lines represent the calculated phase shifts of ESC16 [16], NSC97f [8], and fss2 [6], respectively.

- It turns out there are global fits of scattering phases using YN data, based on the meson-exchange potential models and xEFT.

- E40 collaboration at J-PARC also fitted the scattering phases in (Sigma+, p) scattering:

arXiv: 2203.08393



(a) $\delta_{^3S_1}$ (b) $\delta_{^1P_1}$

Fig. 28. Obtained phase shifts $\delta_{^3S_1}$ and $\delta_{^1P_1}$ as a function of the incident momentum. The black dashed, green solid, and blue dotted lines represent the calculated phase shifts of ESC16 [16], NSC97f [8], and fss2 [6], respectively.

Data do not yet have the discriminating power to break the sign degeneracy in 3S1 channel, which is crucial for understanding the hyperon puzzle!

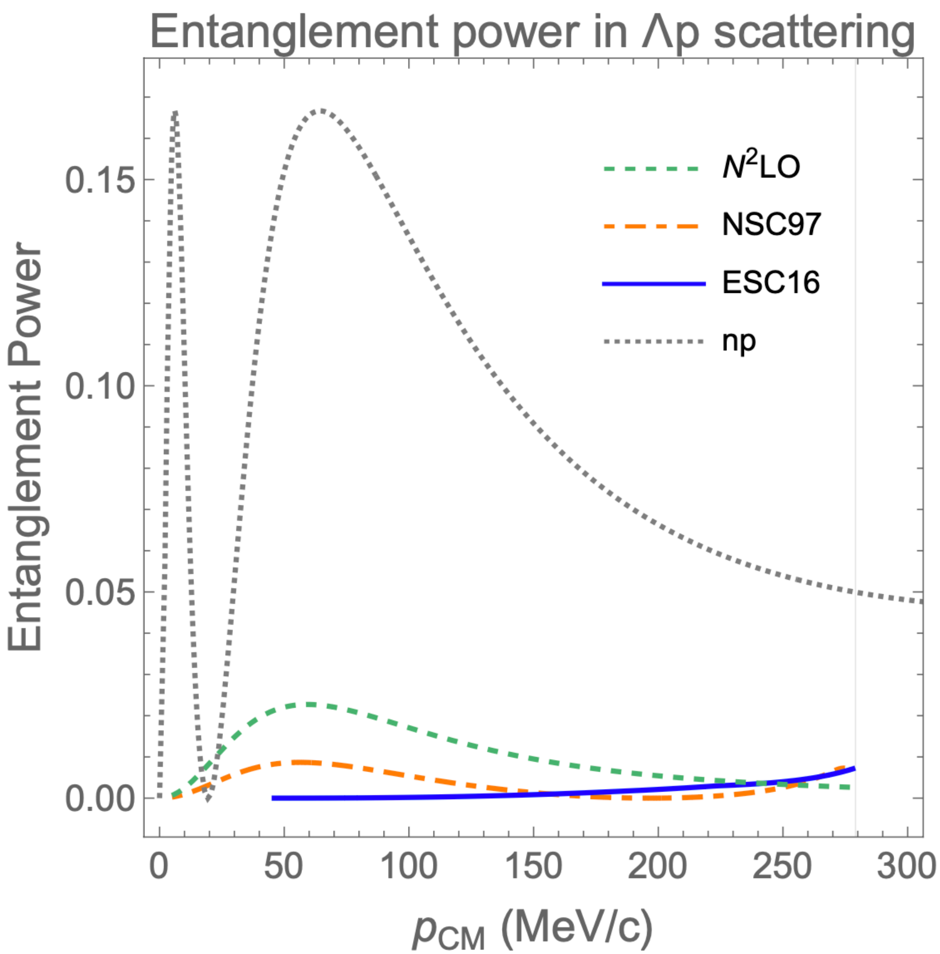
We considered the S=-1 hyperons:

Q	-1	0	1	2
Flavor	$\Sigma^- n$	$\Lambda n, \Sigma^0 n, \Sigma^- p$	$\Lambda p, \Sigma^0 p, \Sigma^+ n$	$\Sigma^+ p$
Total Mass (MeV)	2137	Λn : 2055 $\Sigma^0 n$: 2132 $\Sigma^- p$: 2136	Λp : 2054 $\Sigma^+ n$: 2129 $\Sigma^0 p$: 2131	2128

Q. Liu and IL: 2312.02289

We considered the S=-1 hyperons:

Q	-1	0	1	2
Flavor	$\Sigma^- n$	$\Lambda n, \Sigma^0 n, \Sigma^- p$	$\Lambda p, \Sigma^0 p, \Sigma^+ n$	$\Sigma^+ p$
Total Mass (MeV)	2137	Λn : 2055 $\Sigma^0 n$: 2132 $\Sigma^- p$: 2136	Λp : 2054 $\Sigma^+ n$: 2129 $\Sigma^0 p$: 2131	2128



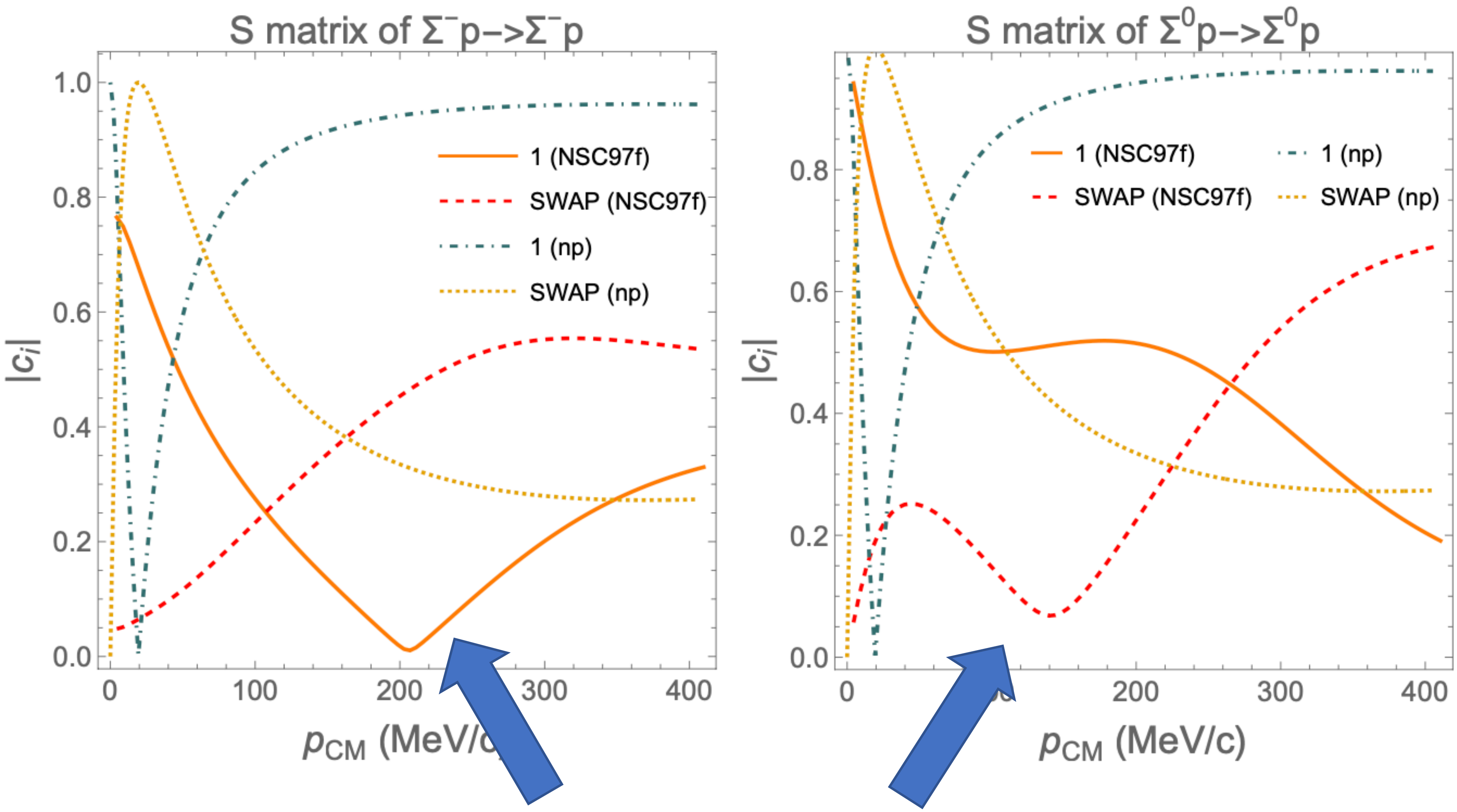
We stay below the pion production Threshold:

Pion production process	p_{CM} (MeV/c)	p_{lab} (MeV/c)
$\Lambda n \to \Lambda p \pi^-$	382.8	893.9
$\Sigma^+ p \to \Sigma^+ n \pi^+$	390.3	943.4

Reall (Lambda, p) and (Lambda, n) are related by isospin invariance. They share similar features.

Q. Liu and IL: 2312.02289

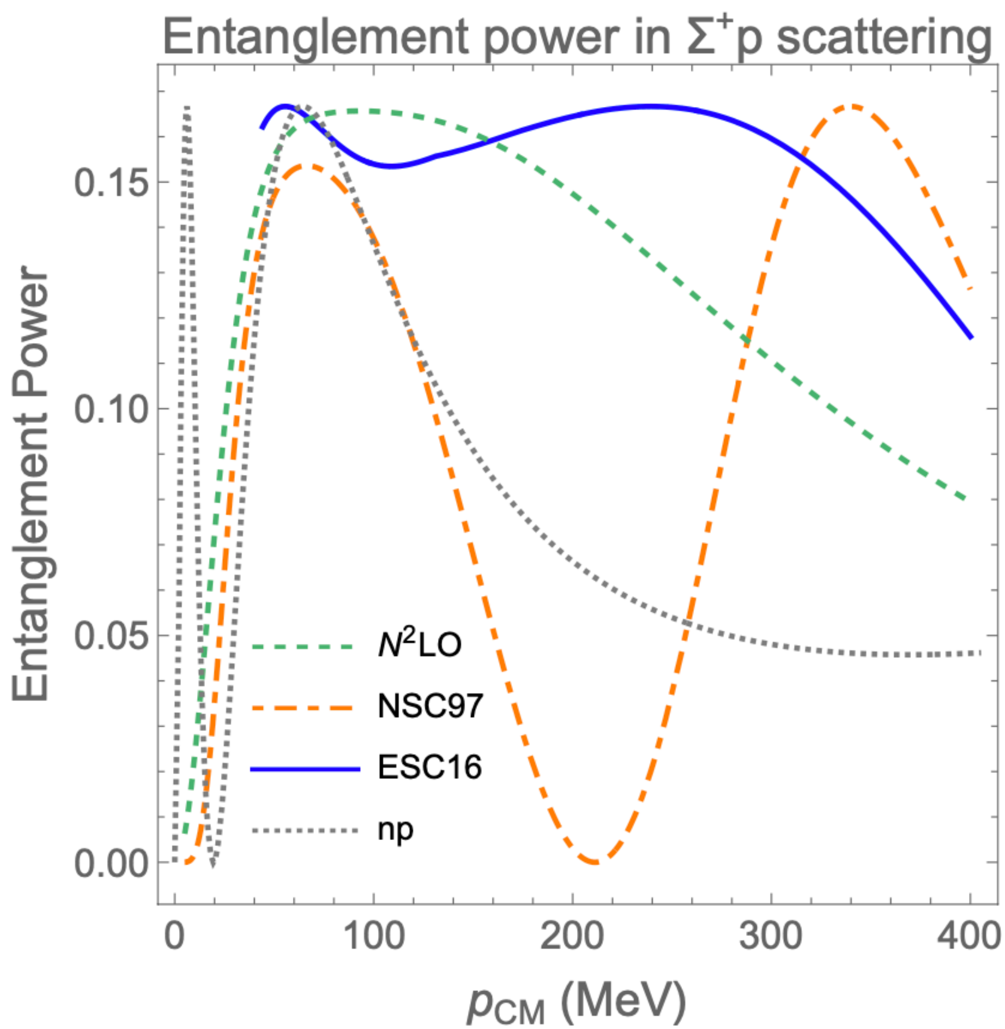
The same observation apply to (Sigma-,p), (Sigma0, p) as well as their isospin partners (Sigma+,n) and(Sigma0,n):



Entanglement suppression!

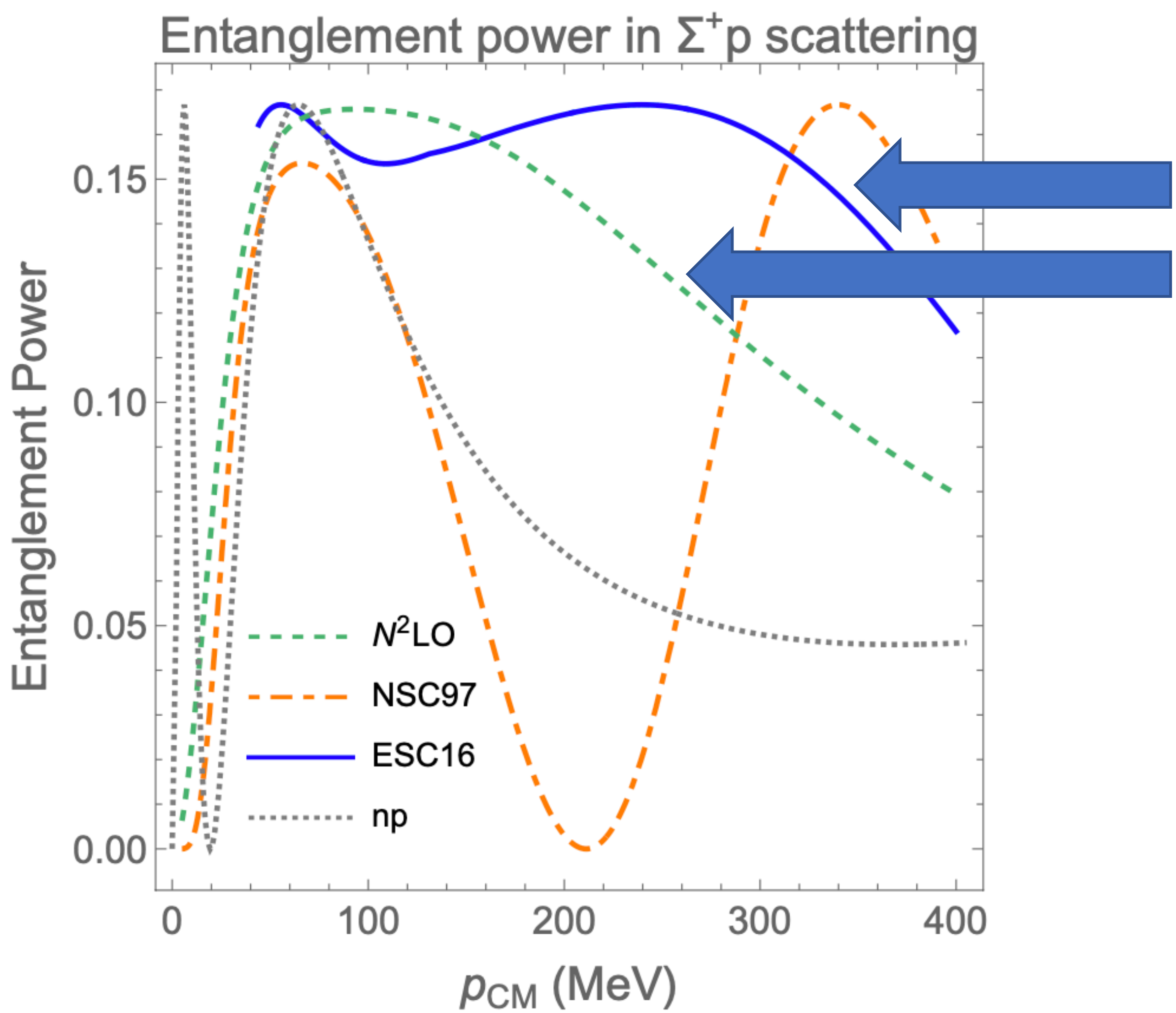
Q. Liu and IL: 2312.02289

One outlier is (Sigma+, p) channel, where differing global fits give different results:



Q. Liu and IL: 2312.02289

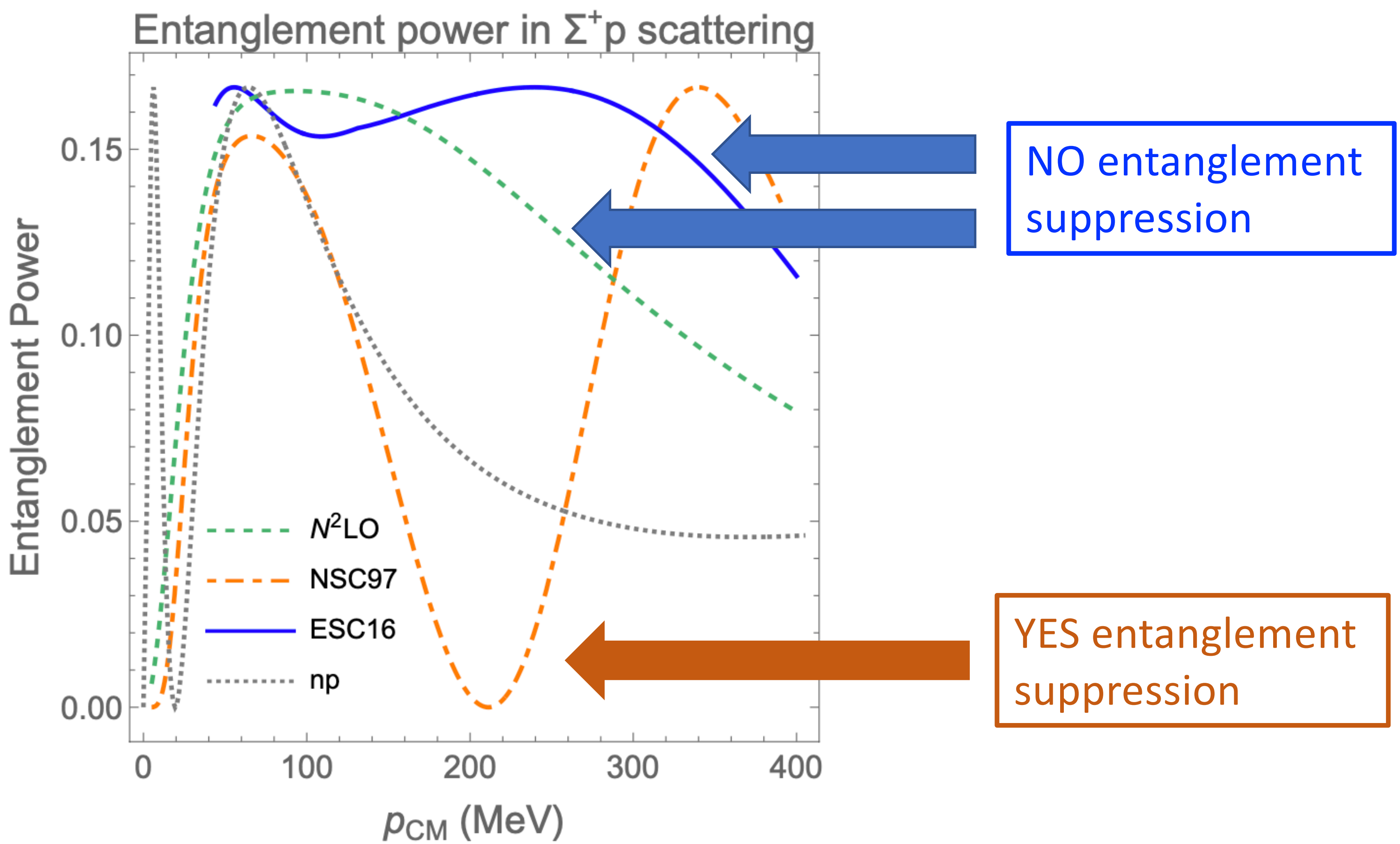
One outlier is (Sigma+, p) channel, where differing global fits give different results:



NO entanglement suppression

Q. Liu and IL: 2312.02289

One outlier is (Sigma+, p) channel, where differing global fits give different results:



Q. Liu and IL: 2312.02289

For (Lambda+, p), we proposed a "quantum observable" which could break the degeneracy among different global fits:

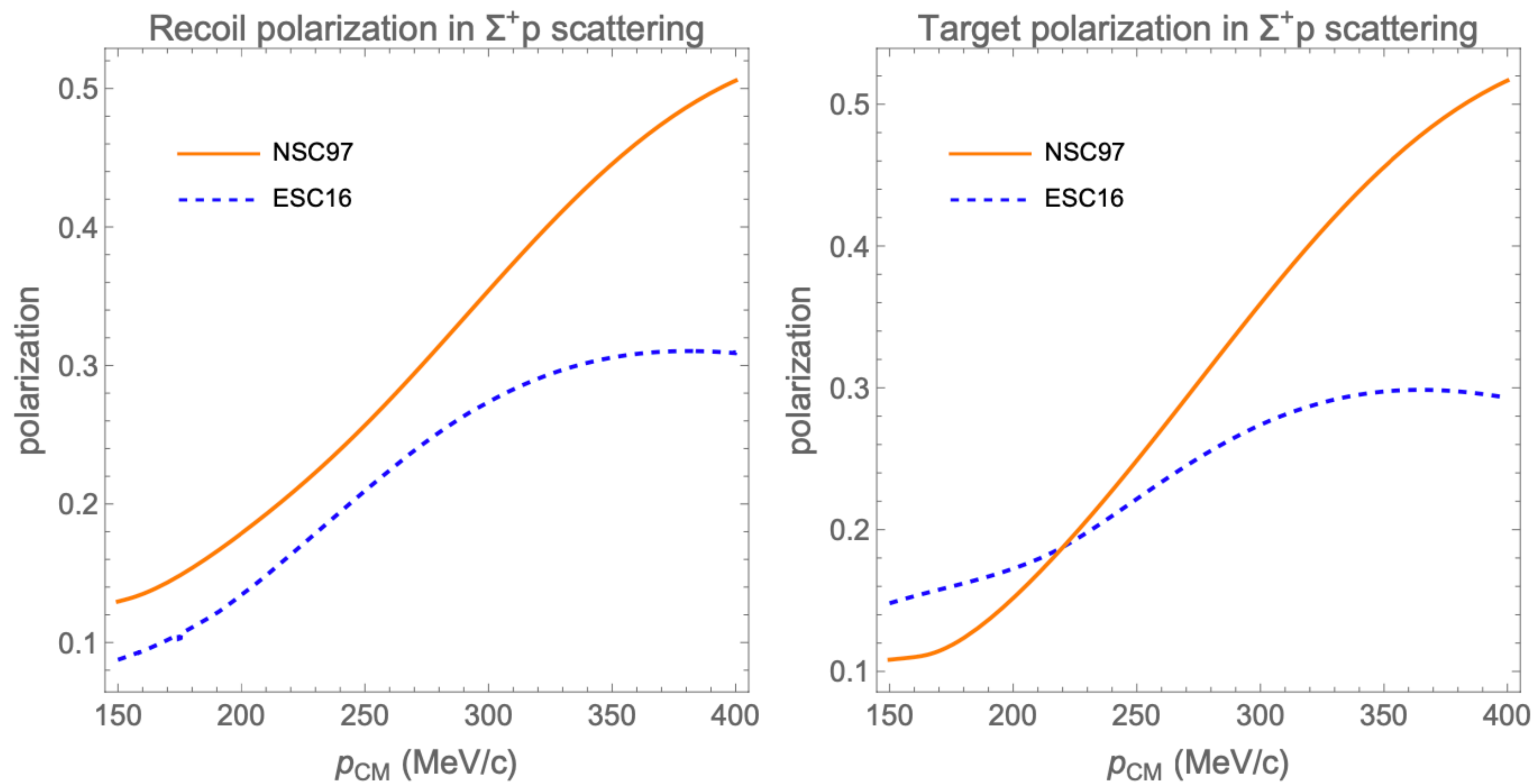


FIG. 4. *Predicted polarizations of the recoiling Σ^+ (recoil) and the recoiling p (target) in Σ^+p scattering, assuming an unpolarized proton target and a 25% polarized hyperon beam.*

Q. Liu and IL: 2312.02289

Outlook

- QIS provides new tools and perspectives to understand nuclear dynamics.
- In the NN sector, emergent symmetries can be viewed as consequences of entanglement suppression.
- Existing global fits on YN scattering provide hints of entanglement suppression. Need more data!
- New “Quantum Observables” could provide insights into the long-standing hyperon puzzle.