

# **MeV-Scale Spin Teleportation with a Polarized Proton Target**

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# Entanglement

A classically forbidden form of correlation shared between separate local subsystems.

- **Unentangled** state: a product pure state with  $N$  parts (the wave function is made of  $N$  parts; not necessarily  $N$  particles)

$$|\Psi_N\rangle = |\phi_1\rangle \otimes |\phi_2\rangle \otimes \cdots \otimes |\phi_N\rangle$$

with  $|\phi_i\rangle$  being the wave function of the  $i$ th part.

- **Entangled** state: not unentangled.
- **Qubit** : **two-level** quantum system, with basis vectors given

by  $|0\rangle$  and  $|1\rangle$  mapped into a **sphere**.

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$\text{Bell's state: } |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

$$|\Phi^\pm\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

$\neq (a|0\rangle + b|1\rangle) \otimes (c|0\rangle + d|1\rangle) \rightarrow$  **entangled**

# Entanglement in nuclear experiments

- **Existence (1976-2006)  $\Rightarrow$  Properties (2025-)  $\Rightarrow$  Applications?**
- **Existence of nuclear entanglement: nuclear Bell test**

1976



## Wolfgang Mittig

- M. Laméhi-Rachti and **W. Mittig**, *Quantum mechanics and hidden variables: A test of Bell's inequality by the measurement of the spin correlation in low-energy proton-proton scattering*, Phys. Rev. D **14**, 2543 (1976).

2006

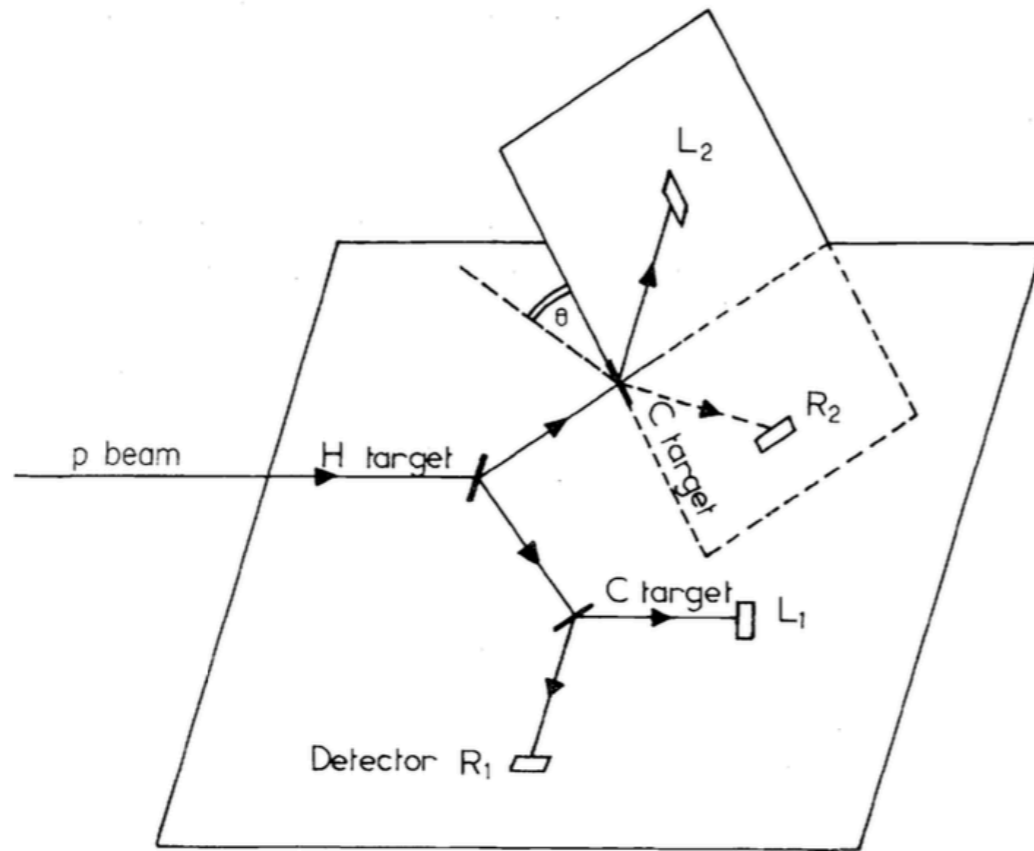


## Hideyuki Sakai

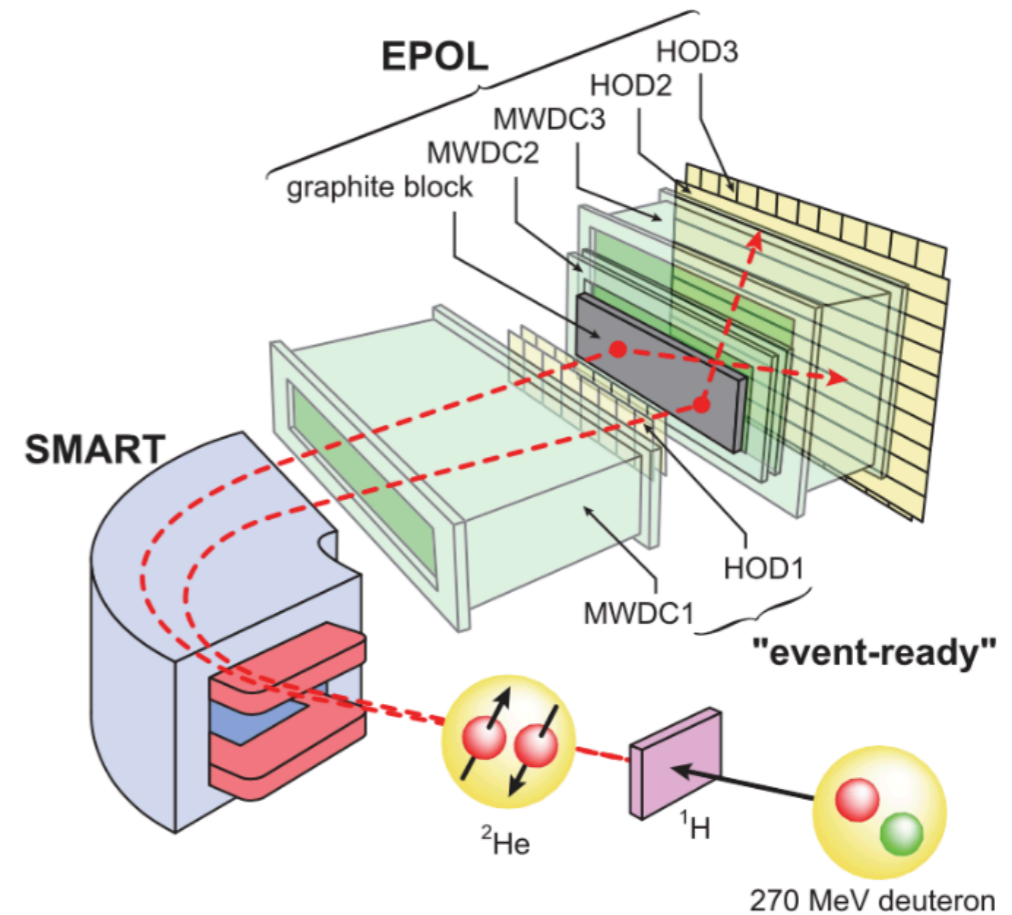
- **H. Sakai**, T. Saito, T. Ikeda, K. Itoh, T. Kawabata, H. Kuboki, Y. Maeda, N. Matsui, C. Rangacharyulu, M. Sasano, Y. Satou, K. Sekiguchi, K. Suda, A. Tamii, T. Uesaka, and K. Yako, *Spin Correlations of Strongly Interacting Massive Fermion Pairs as a Test of Bell's Inequality*, Phys. Rev. Lett. **97**, 150405 (2006).

Spin-entangled (spin-singlet) proton pairs were generated in **two** different ways.

# Experimental setups for nuclear Bell tests



Mittig (1976)



Sakai (2006)

Sakai (2006): “It is to be noted that the entanglement of the spin- singlet state was retained even when the two protons traversed through large amounts of material media (50 cm thick argon ethane gas in wire chambers, 1 cm thick plastic scintillators, and up to 5 cm thick graphite slab). It is indeed remarkable that the strongly interacting pairs maintain the correlations for distances greater than  $10^{13}$ – $10^{14}$  times their coherence length, which was estimated to be  $10^{-14}$  m (the size of a wave packet of two protons at production).”

# • Properties of nuclear entanglement (2025-)

Letter of Intent submitted to GSI (Nov, 2025)

## Entanglement: A possible source of information on nuclear structure

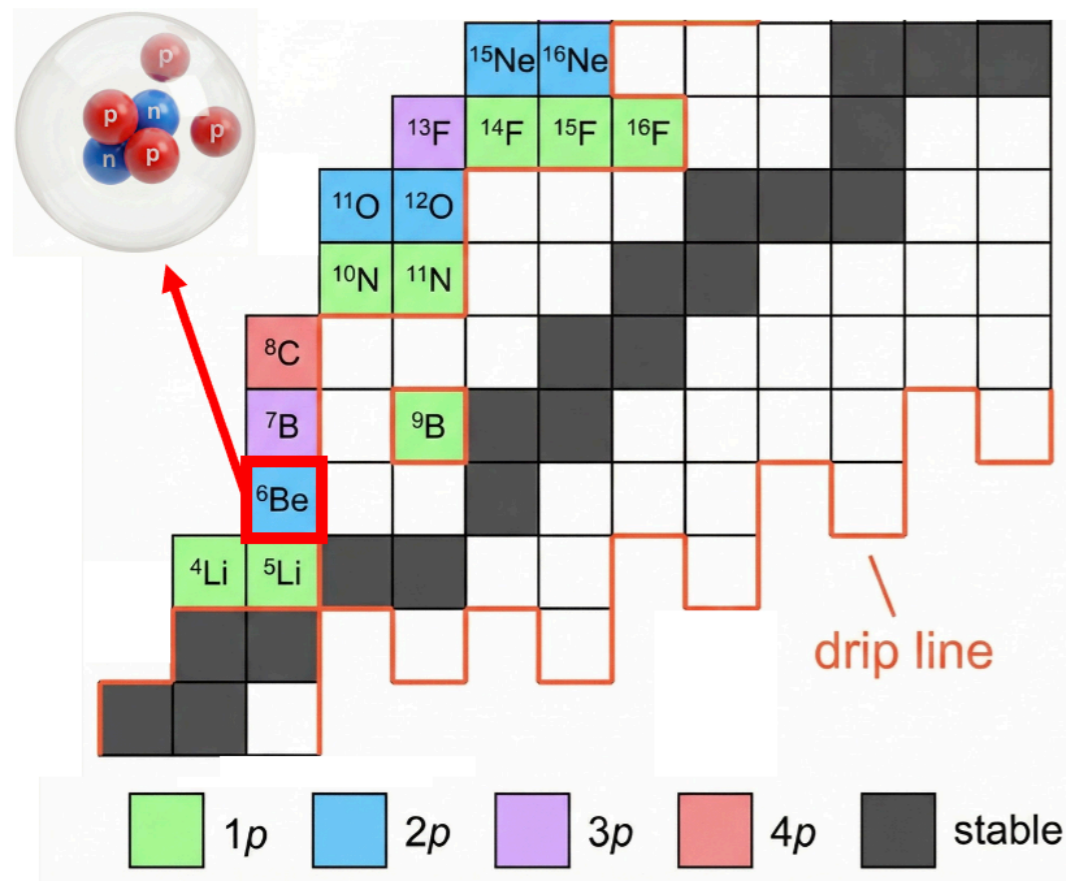
H. Alvarez-Pol<sup>1</sup>, Y. Ayyad<sup>1</sup>, Y. Khelifi<sup>1</sup>, W. Mittig<sup>2</sup>, D. Bazin<sup>2</sup>, D. Lee<sup>2</sup>, **D. Bai<sup>3</sup>**, and A. Macchiavelli<sup>4</sup>

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<sup>2</sup>Facility for Rare Isotope Beams, Michigan State University, East Lansing, Michigan 48824, USA

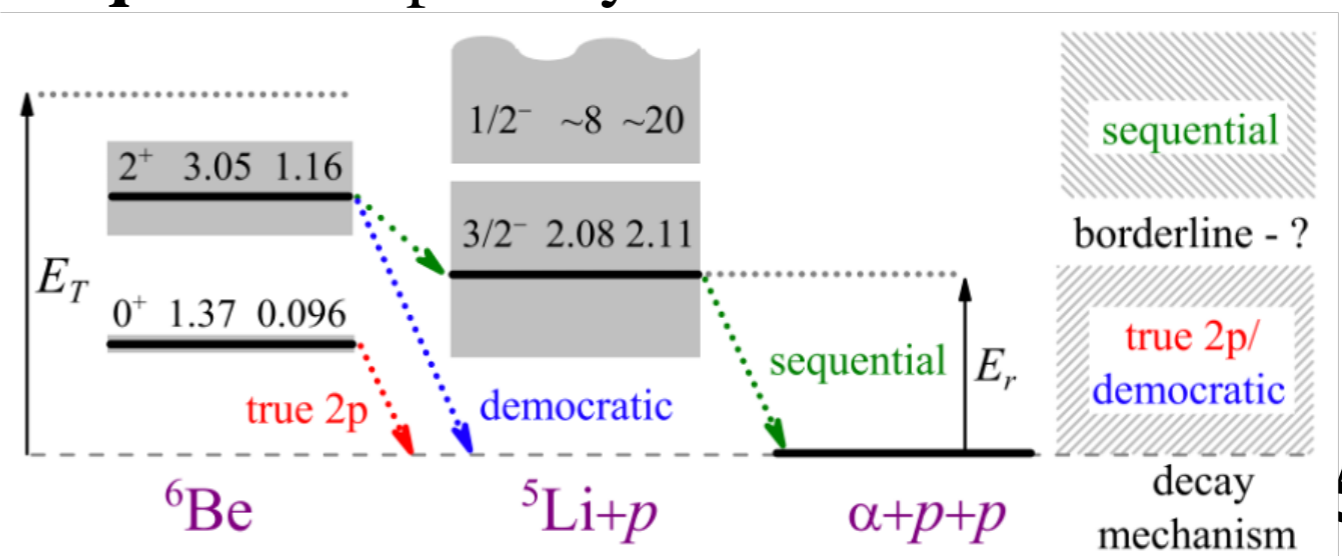
**<sup>3</sup>College of Mechanics and Engineering Science, Hohai University, Nanjing 211100, China**

<sup>4</sup>Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA



**<sup>6</sup>Be**: the lightest 2p emitter,  $\alpha+p+p$ .

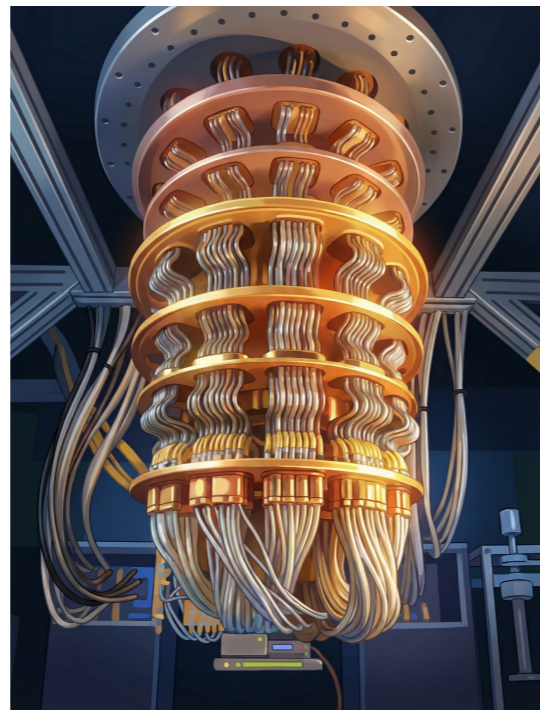
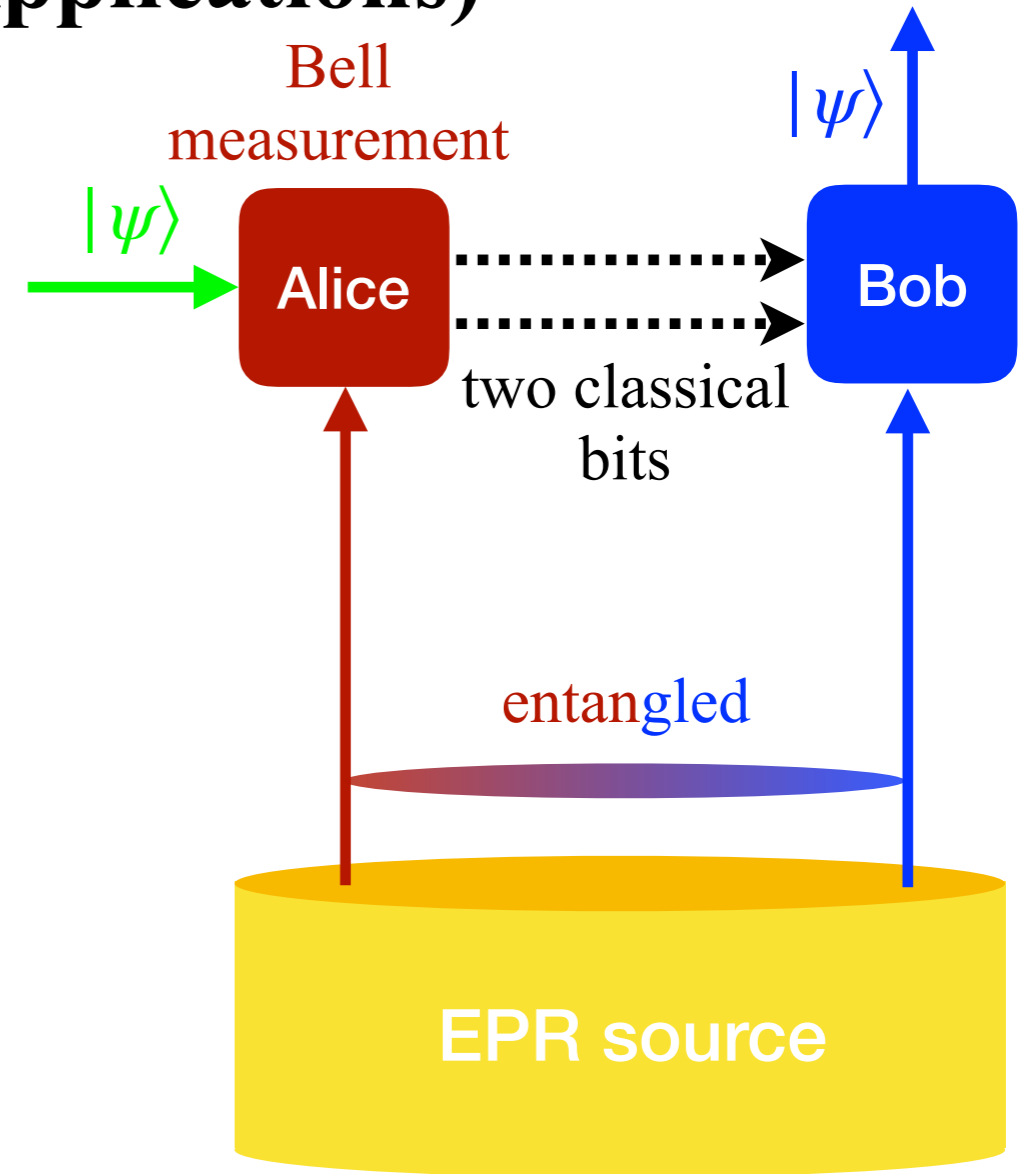
Its ground state and the first 2<sup>+</sup> excited state show a rich mix of **true**, **democratic**, and **sequential** 2p decays.



# Quantum teleportation (Applications)

Quantum Teleportation (QT) enables the transfer of an **unknown quantum state** between distant qubits using entanglement.

Demonstrated in, e.g., **photons** and **superconducting circuits**.



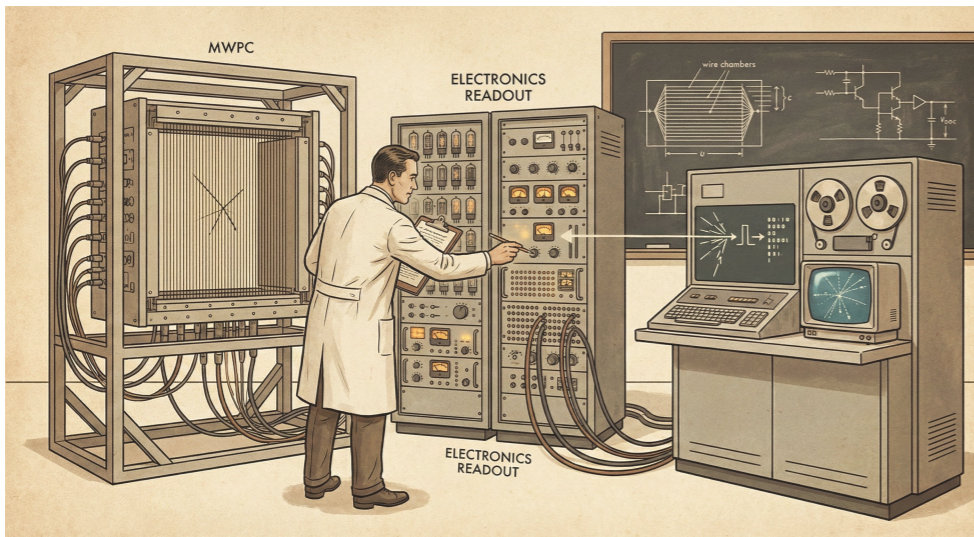
The quantum state carried by the **data qubit** transmitted intactly to the **target qubit** with the help of an entangled **ancilla qubit**.

# QT in nuclear physics?

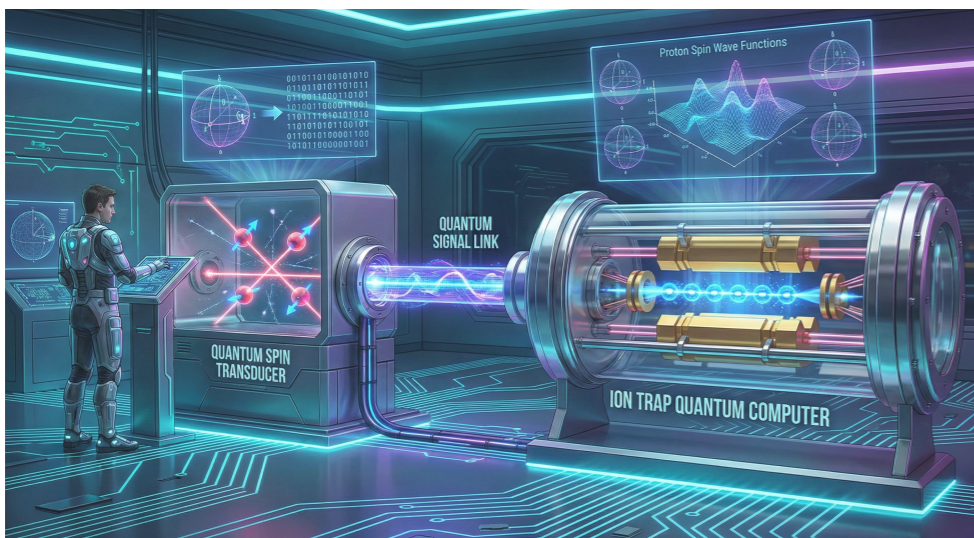
- A quantum effect rarely demonstrated in nuclear physics at MeV energies.
- **INTACT** transmission of quantum states from the target nucleus. *In comparison, although traditional nuclear reactions do transfer quantum information, they typically transform quantum states, with details depending on reaction mechanism (often model dependent).*
- Paving the way to teleport quantum states of atomic nuclei to other platforms (trapped ions, superconducting circuits, etc)? *Performing quantum tasks (e.g., quantum state tomography) is very difficult for atomic nuclei, but can be quite easy for, e.g., trapped ions and superconducting circuits.*



- Pre-WWII ~ 1960s: **The era of vision & "scanning girls"**



- 1968~present: **The Charpak revolution & the classical computer takeover**



- 20XX~?: **The era of quantum devices?**
1. Teleport unknown quantum states between particles of **the same species**; ← **We are here.**
  2. Teleport unknown quantum states between particles of **different species**;
  3. Teleport unknown quantum states **across different energy scales.**

# Mathematics of QT

- Alice has **an unknown quantum state** to be transferred to Bob

$$|\psi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1.$$

- Alice and Bob share **a pair of maximally entangled qubits** (in one of the Bell states: **Alice: 2nd, Bob: 3rd**)

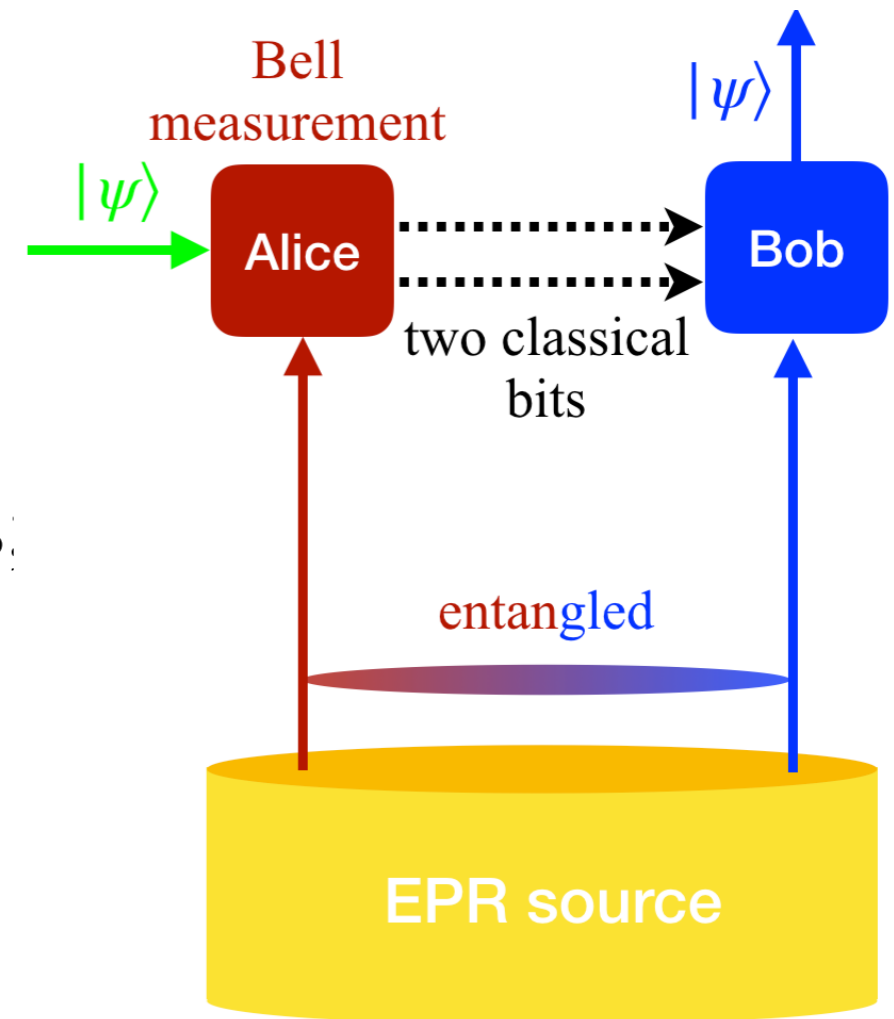
$$|\Psi^-\rangle_{23} = \frac{1}{\sqrt{2}}(|01\rangle_{23} - |10\rangle_{23}).$$

- For late convenience, the other three Bell states are given by

$$|\Psi^+\rangle_{23} = \frac{1}{\sqrt{2}}(|01\rangle_{23} + |10\rangle_{23}),$$

$$|\Phi^+\rangle_{23} = \frac{1}{\sqrt{2}}(|00\rangle_{23} + |11\rangle_{23}), \quad |\Phi^-\rangle_{23} = \frac{1}{\sqrt{2}}(|00\rangle_{23} - |11\rangle_{23}).$$

The Bell states are mutually orthogonal.



- The quantum state of three qubits is given by

$$\begin{aligned}
& |\psi\rangle_1 \otimes |\Psi^-\rangle_{23} \\
&= (\alpha|0\rangle_1 + \beta|1\rangle_1) \otimes \frac{1}{\sqrt{2}}(|01\rangle_{23} - |10\rangle_{23}) \\
&= \frac{1}{\sqrt{2}}(\alpha|001\rangle_{123} - \alpha|010\rangle_{123} + \beta|101\rangle_{123} - \beta|110\rangle_{123}) \\
&= \frac{1}{2} [ |\Phi^+\rangle_{12} \otimes (\alpha|1\rangle_3 - \beta|0\rangle_3) \\
&\quad + |\Phi^-\rangle_{12} \otimes (\alpha|1\rangle_3 + \beta|0\rangle_3) \\
&\quad + |\Psi^+\rangle_{12} \otimes (-\alpha|0\rangle_3 + \beta|1\rangle_3) \\
&\quad + |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3) ]
\end{aligned}$$

- Alice** does quantum measurement for the 1st and 2nd qubits in Bell basis, aka **Bell measurement**.

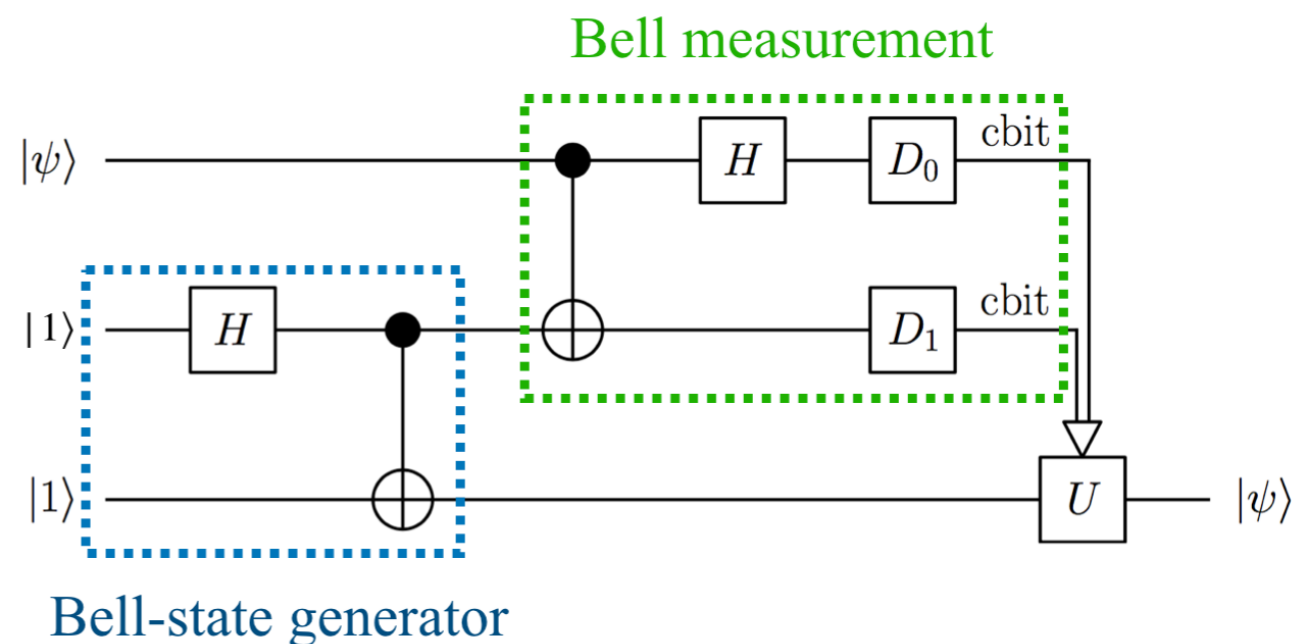
- After **Bell measurement**, there are four possibilities, each with a probability of 1/4.

$$|\Phi^+\rangle_{12} \otimes (\alpha |1\rangle_3 - \beta |0\rangle_3),$$

$$|\Phi^-\rangle_{12} \otimes (\alpha |1\rangle_3 + \beta |0\rangle_3),$$

$$|\Psi^+\rangle_{12} \otimes (-\alpha |0\rangle_3 + \beta |1\rangle_3),$$

$$|\Psi^-\rangle_{12} \otimes (-\alpha |0\rangle_3 - \beta |1\rangle_3).$$



- Depending on the result of **Bell measurement** (encoded by **two** classical bits), **Bob** transforms his qubit (the **3rd** qubit) accordingly

$$\text{Alice: } |\Phi^+\rangle_{12} \Rightarrow \text{Bob: } ZX(\alpha |1\rangle_3 - \beta |0\rangle_3) = \alpha |0\rangle_3 + \beta |1\rangle_3,$$

$$\text{Alice: } |\Phi^-\rangle_{12} \Rightarrow \text{Bob: } X(\alpha |1\rangle_3 + \beta |0\rangle_3) = \alpha |0\rangle_3 + \beta |1\rangle_3,$$

$$\text{Alice: } |\Psi^+\rangle_{12} \Rightarrow \text{Bob: } Z(-\alpha |0\rangle_3 + \beta |1\rangle_3) = -(\alpha |0\rangle_3 + \beta |1\rangle_3),$$

$$\text{Alice: } |\Psi^-\rangle_{12} \Rightarrow \text{Bob: } -(\alpha |0\rangle_3 + \beta |1\rangle_3).$$

# Three ingredients of QT

- *Sources of entangled pairs*

- ➔ **How to generate entangled proton pairs?**

1. Elastic proton-proton scattering [W. Mittig (1976)];
2.  $p(d,2p)n$  [H. Sakai (2006)];
3.  $2p$  radioactivity from, e.g.,  ${}^6\text{Be}$ ;
4. ...

- *Bell measurement*

- ➔ **How to do Bell measurement for protons?**

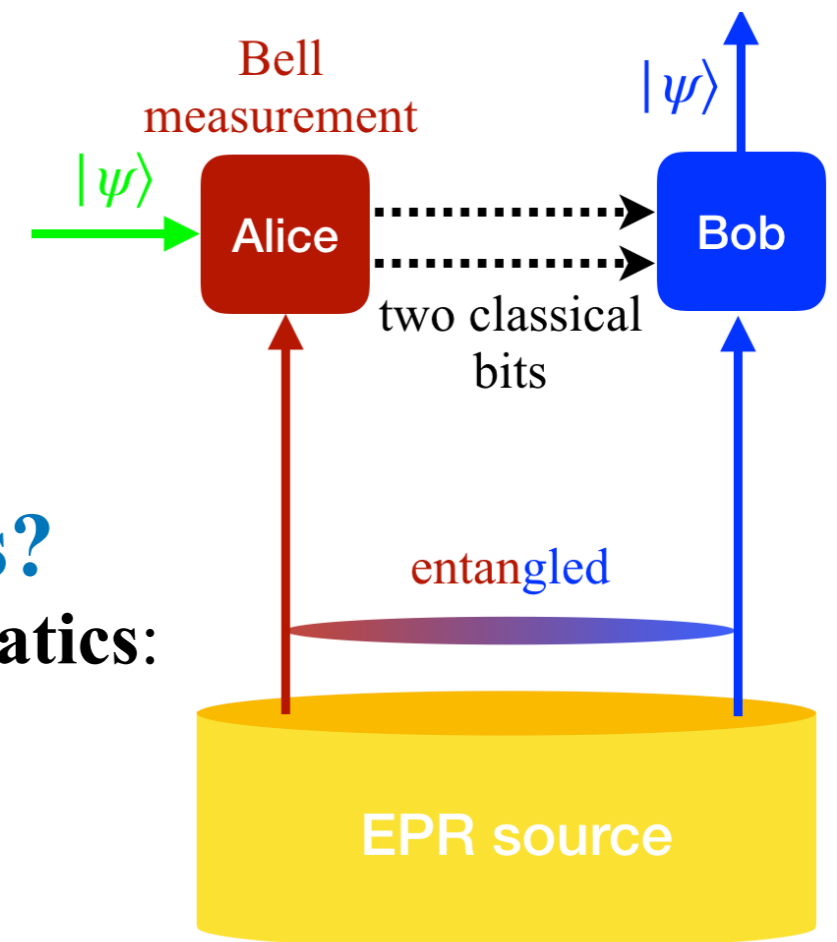
Make use of proton-proton scattering at **specific kinematics**:

1.  $T_{\text{lab}} < 10$  MeV
2.  $(T_{\text{lab}}, \theta_{\text{CM}}) = (151 \text{ MeV}, 90^\circ)$

- *Classical information transmission*

- ➔ **What classical information is needed to be transmitted?**

One classical bit to tell whether the wanted proton-proton scattering happens or not.



# Spin entanglement in NN scattering

- S. R. Beane, D. B. Kaplan, N. Klco, M. J. Savage, PRL 122, 102001 (2019) (np)
- DB, PLB 845, 138162 (2023) (np)
- G. A. Miller, PRC 108, L031002 (2023) (np)
- A. L. Cavallin, O. Thim, C. Forssen, PRC 113, 014005 (2026) (np, nn)
- **Z. X. Shen, H. Y. Shang, Y. G. Ma, DB, S. M. Wang, Z. C. Xu, Y. Ayyad, C. Filgueira, arXiv:2510.24325 (pp)**

## Key takeaways of arXiv:2510.24325:

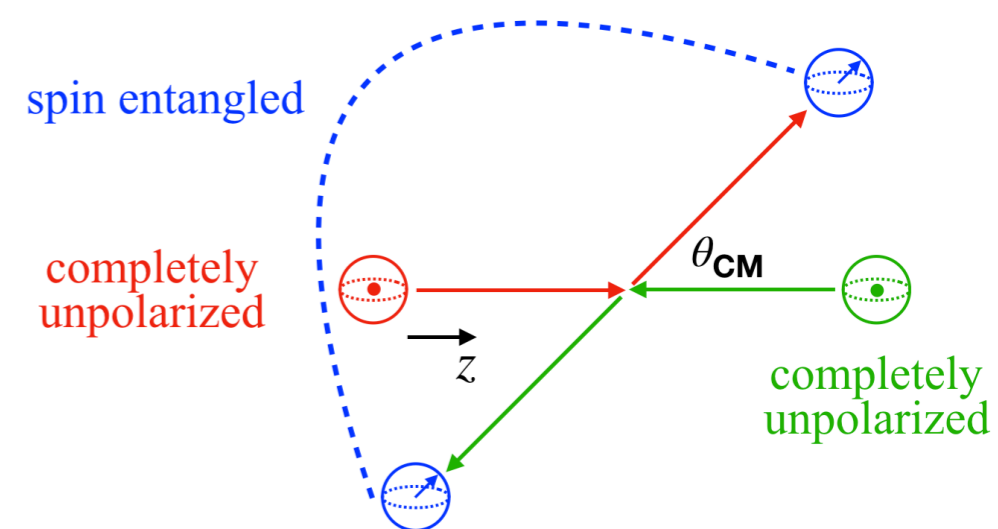
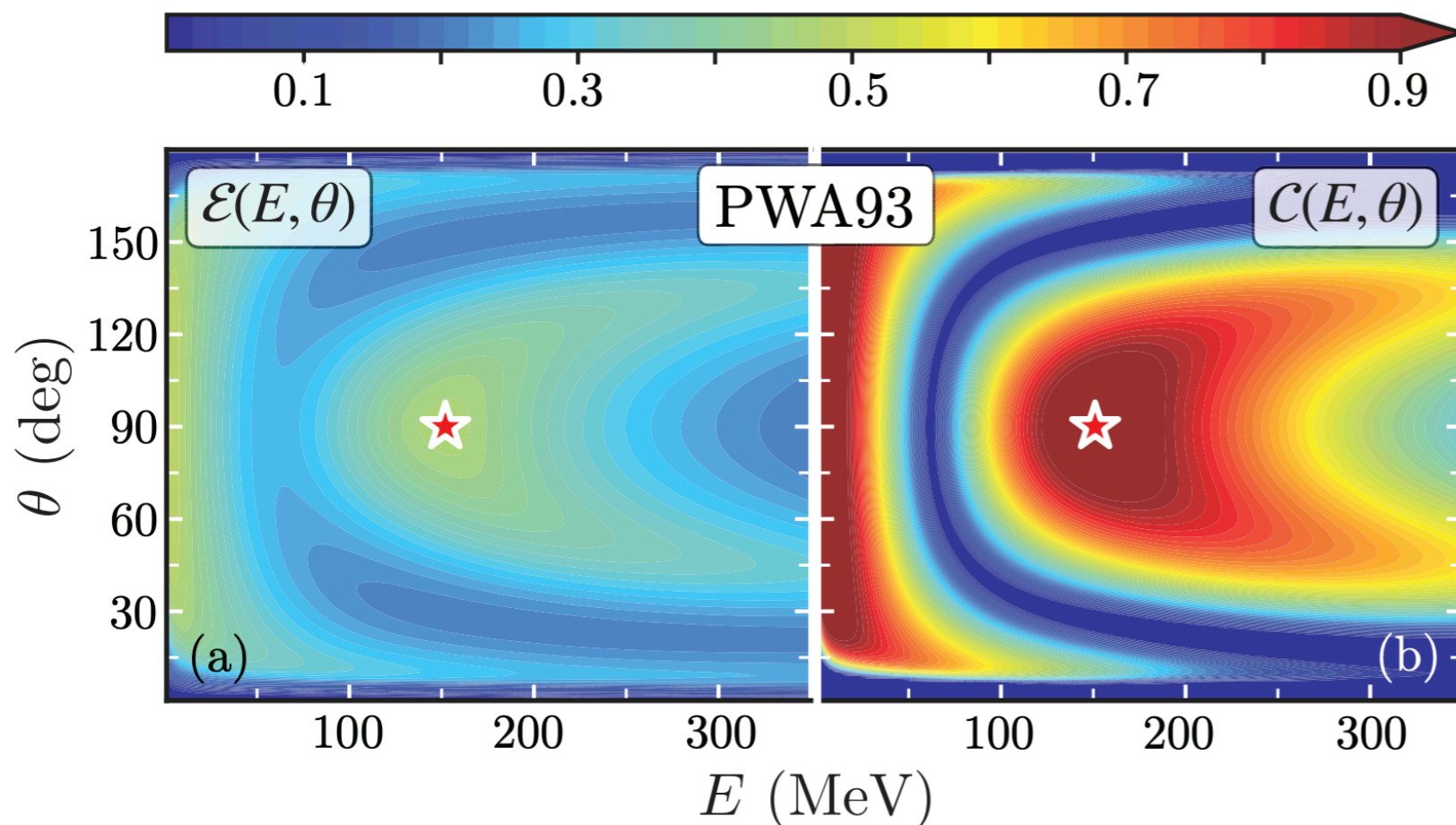
- Spin entanglement reveals the emergence of a **Bell transition operator**  $|\Psi^+\rangle\langle\Phi^-|$  at intermediate energy
- Realizing **spin teleportation** at **MeV** scale

# Proton-proton scattering

Information of proton-proton scattering is encoded by **spin amplitude**  $M(E, \theta)$

$$\rho_{\text{fin}} = M\rho_{\text{init}}M^\dagger \Rightarrow \text{entanglement measures}$$

**Concurrence:**  $C(\rho_{\text{fin}}) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\} \in [0, 1]$ , with  $\lambda_i$  the eigenvalue of  $R = [\sqrt{\rho}(\sigma_y \otimes \sigma_y)\rho_{\text{fin}}^*(\sigma_y \otimes \sigma_y)\sqrt{\rho}]^{1/2}$  in decreasing order.



**Two** special regions support large spin entanglement.

- At  $E < 10$  MeV, **Bell projection operator**

$$M \propto |\Psi^-\rangle\langle\Psi^-|$$

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

$S$ -wave dominance at low energy.

- At  $(E, \theta) = (151 \text{ MeV}, 90^\circ)$ ,

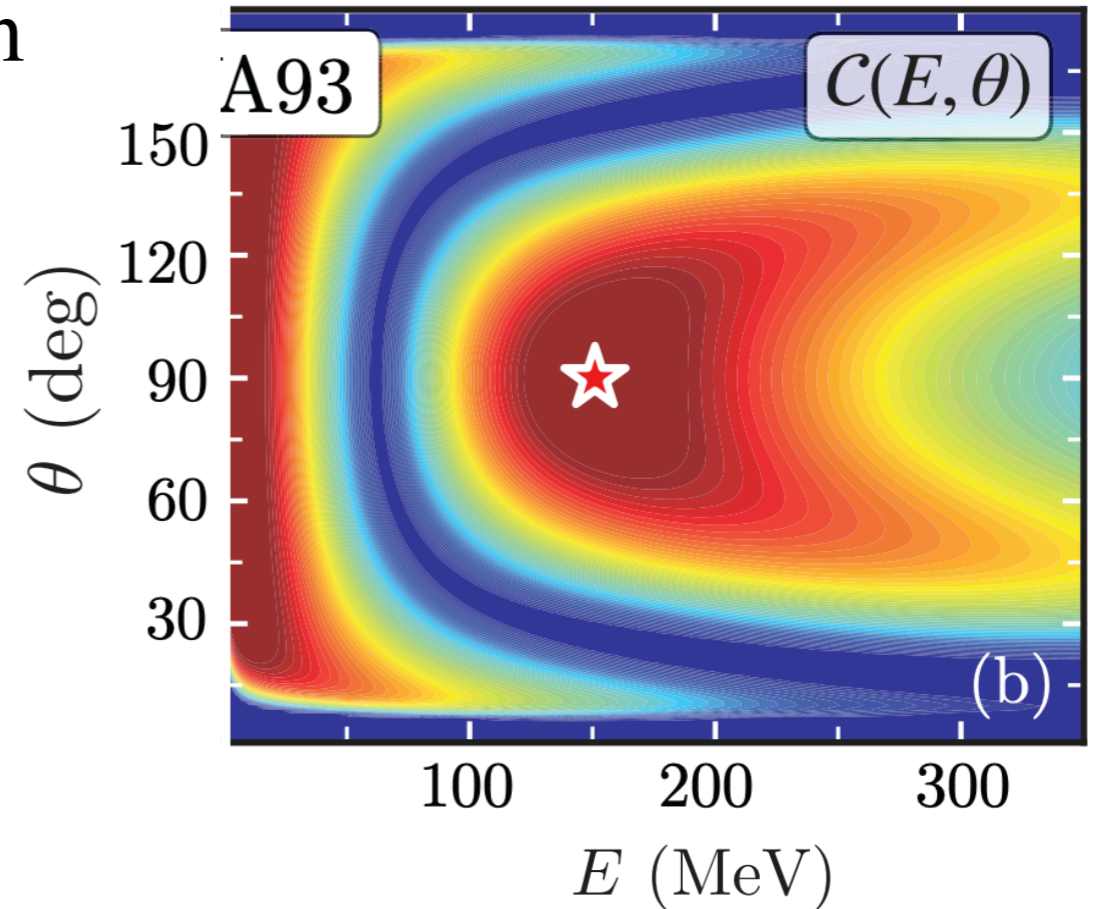
$$M \propto |\Psi^+\rangle\langle\Phi^-| \quad \text{Bell transition operator}$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \quad |\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

Explicitly,  $M =$

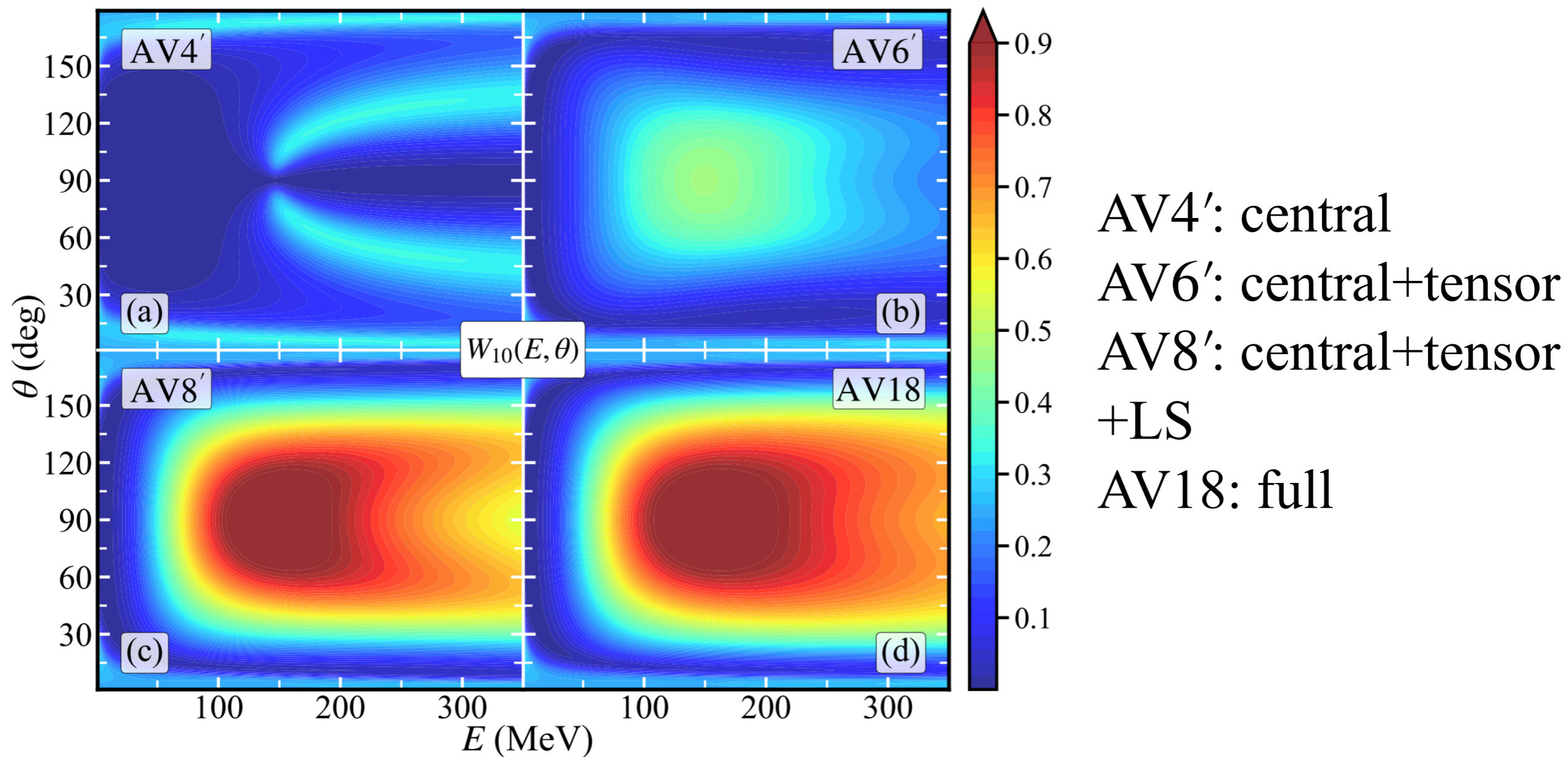
$$\begin{pmatrix} 0 & 0.17199 + 0.066145 i & 0.17199 + 0.066145 i & 0 \\ -1.92264 - 0.029195 i & 0.0671124 + 0.0728236 i & -0.0671124 - 0.0728236 i & 1.92264 + 0.029195 i \\ -1.92264 - 0.029195 i & -0.0671124 - 0.0728236 i & 0.0671124 + 0.0728236 i & 1.92264 + 0.029195 i \\ 0 & -0.17199 - 0.066145 i & -0.17199 - 0.066145 i & 0 \end{pmatrix}$$

small



# Physical origins

**Bell-triplet fraction  $W_{10}$  in AV series of nuclear forces.**



A joint contribution from tensor and LS forces.

## Saclay amplitude

$$M = \frac{1}{2} \left[ (a+b) \mathbf{1}_4 + (a-b) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{n}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{n}}) + (c+d) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{m}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{m}}) + (c-d) (\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{l}}) (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{l}}) \right. \\ \left. + e [(\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{n}}) + (\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{n}})] \right]$$

For identical particles

$$a = 0, \quad c = -b.$$

Write  $M$  at  $90^\circ$  in Bell basis  $\{|\Psi^-\rangle, |\Psi^+\rangle, |\Phi^+\rangle, |\Phi^-\rangle\}$

$$M_{\text{Bell}}^{pp} = \begin{pmatrix} 2b & 0 & 0 & 0 \\ 0 & 0 & 0 & -(d - ie) \\ 0 & 0 & 0 & 0 \\ 0 & -(d + ie) & 0 & 0 \end{pmatrix} \begin{matrix} |\Psi^-\rangle \\ |\Psi^+\rangle \\ |\Phi^+\rangle \\ |\Phi^-\rangle \end{matrix}$$

$$\begin{matrix} |\Psi^-\rangle & |\Psi^+\rangle & |\Phi^+\rangle & |\Phi^-\rangle \end{matrix}$$

In the limit of  $b \rightarrow 0$  and  $d + ie \rightarrow 0$ ,  $M_{\text{Bell}}^{pp} = -(d - ie) |\Psi^+\rangle \langle \Phi^-|$ .

# Saclay amplitude and $W_{10}$

Potential	$ d - ie $	$ d + ie $	$2 b $	$W_{10}$
AV4'	0.002	0.002	0.200	0.0001
AV6'	2.011	2.155	0.200	0.463
AV8'	3.779	0.362	0.200	0.988
AV18	3.862	0.383	0.164	0.989

## Translation to partial-wave conditions

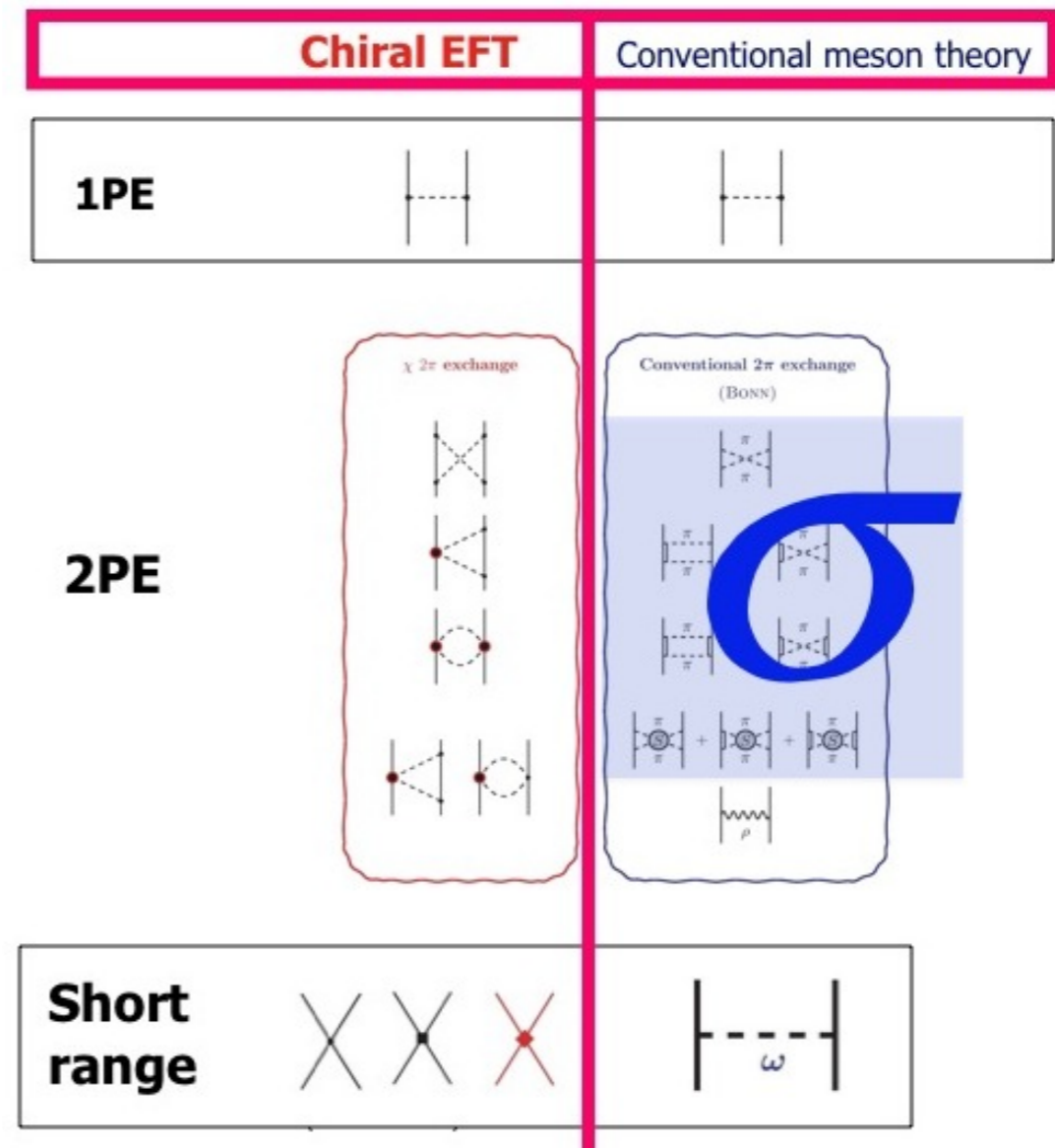
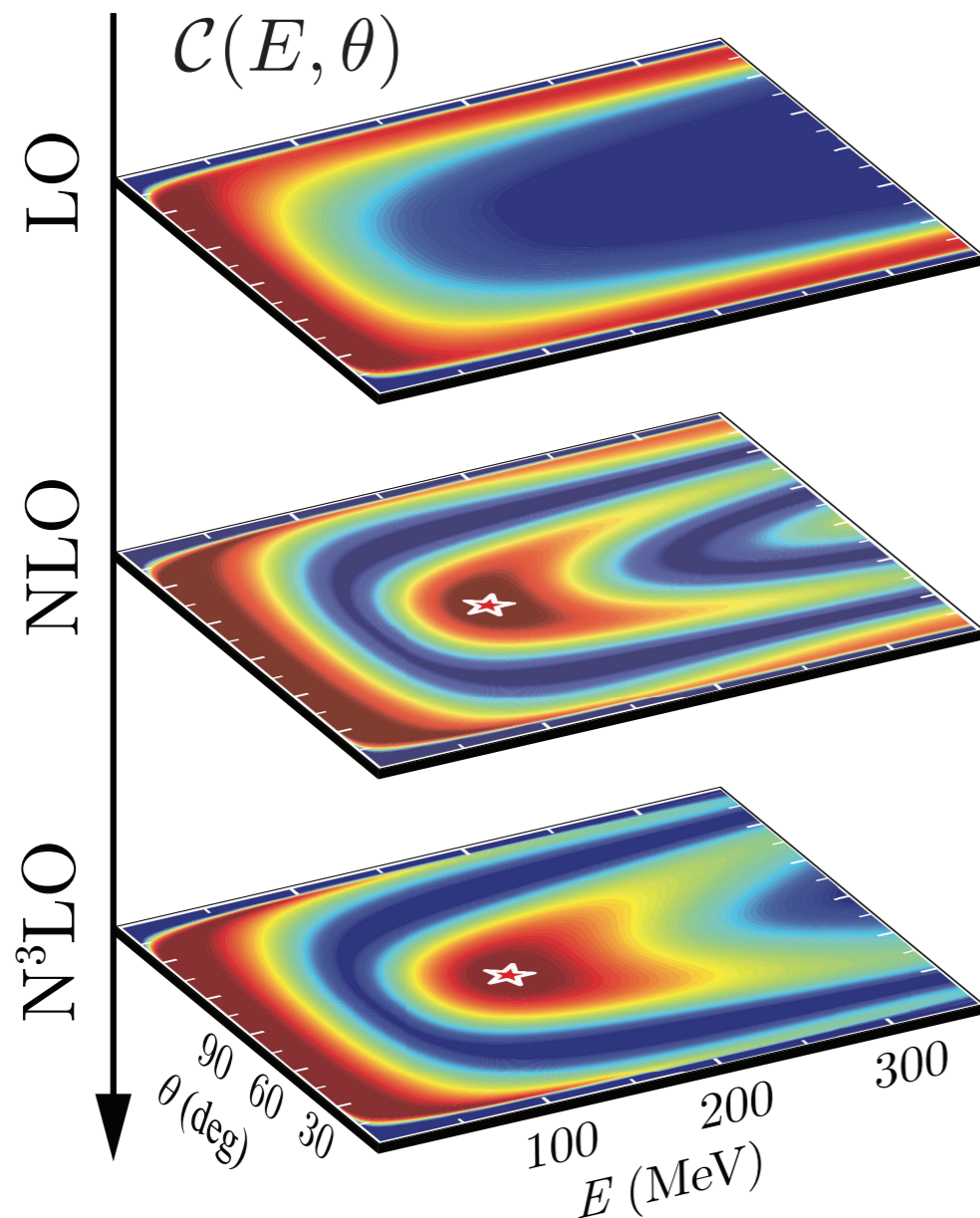
Condition	Saclay form	Partial-wave form	Physical meaning
$d + ie \rightarrow 0$	$M_{10} \rightarrow 0$	$T_2 = T_0$ , i.e., $\delta_{3P_2} = \delta_{3P_0}$	Accidental $J$ -degeneracy
$b \rightarrow 0$	$^1S_0$ amplitude vanishes	$\delta_{1S_0} \rightarrow 0$	$S$ -wave Ramsauer transparency

## Phase shifts patterns at 151 MeV.

Potential	$\delta_{3P_0}$	$\delta_{3P_1}$	$\delta_{3P_2}$	Pattern
AV4'	$-3.1^\circ$	$-3.1^\circ$	$-3.1^\circ$	All degenerate
AV6'	$+22.6^\circ$	$-13.1^\circ$	$+0.6^\circ$	Tensor splits $J = 0$ upward
AV8'	$+4.4^\circ$	$-17.3^\circ$	$+13.8^\circ$	LS reshapes: $J = 2$ up, $J = 0$ down
AV18	$+4.4^\circ$	$-17.4^\circ$	$+14.3^\circ$	Nearly identical to AV8'

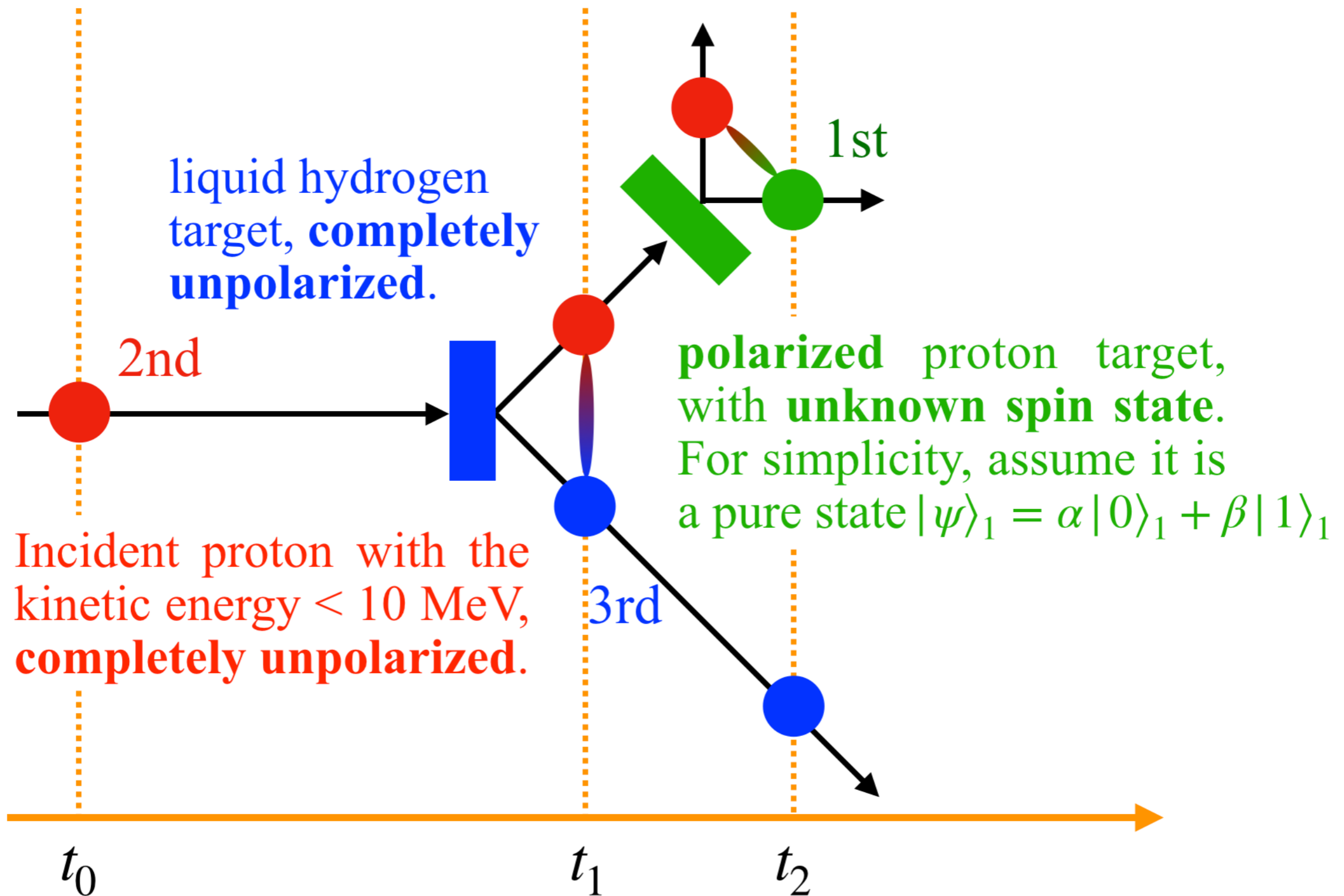
# Chiral EFT

Bell transition operator emerges only at NLO and beyond. LS force appears as contact terms at NLO (integrating out heavy mesons).



Machleidt (2014)

# Spin teleportation < 10 MeV



$$\mathbf{t}_0 : |\psi\rangle_1 \langle\psi|_1 \otimes \frac{I}{2} \otimes \frac{I}{2}$$

$$\mathbf{t}_1 : |\psi\rangle_1 \langle\psi|_1 \otimes \left[ M_{23} \left( \frac{I}{2} \otimes \frac{I}{2} \right) M_{23}^\dagger \right]$$

$$\Rightarrow |\psi\rangle_1 \otimes |\Psi^-\rangle_{23} \text{ pure state}$$

$$= \frac{1}{2} [ |\Phi^+\rangle_{12} \otimes (\alpha|1\rangle_3 - \beta|0\rangle_3) + |\Phi^-\rangle_{12} \otimes (\alpha|1\rangle_3 + \beta|0\rangle_3) \\ + |\Psi^+\rangle_{12} \otimes (-\alpha|0\rangle_3 + \beta|1\rangle_3) + |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3) ]$$

$$\mathbf{t}_2 : (M_{12} \otimes I) \frac{1}{2} [\dots + |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3)]$$

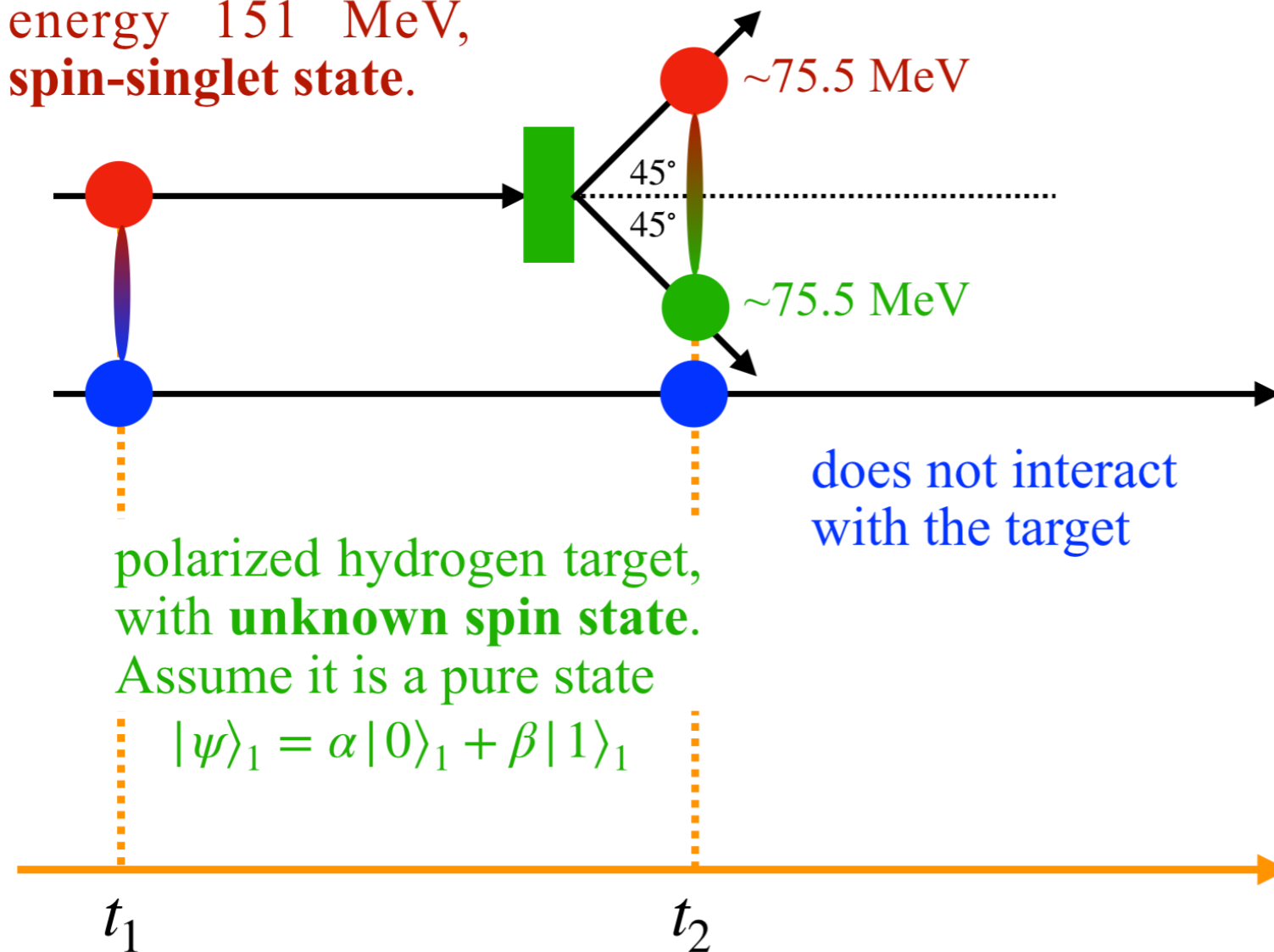
$$\rightarrow |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3) \quad \downarrow$$

- The unknown spin state of the polarized hydrogen target is teleported to the 3rd proton some distance away.
- The polarization of the 3rd proton can be measured and compared to that provided by the producer of the polarized target.

# Spin teleportation at 151 MeV

- Produce spin-entangled proton pairs by, e.g.,  $p(d,2p)n$  following Sakai (2006) and select two-proton events with relative energies  $< 1$  MeV; deuteron at 302 MeV  $\rightarrow$  two protons at 151 MeV.

Incident two protons with the kinetic energy 151 MeV, spin-singlet state.



$$\begin{aligned}
 t_1: & |\psi\rangle_1 \otimes |\Psi^-\rangle_{23} \\
 &= \frac{1}{2} [ |\Phi^+\rangle_{12} \otimes (\alpha|1\rangle_3 - \beta|0\rangle_3) \\
 &+ |\Phi^-\rangle_{12} \otimes (\alpha|1\rangle_3 + \beta|0\rangle_3) \\
 &+ |\Psi^+\rangle_{12} \otimes (-\alpha|0\rangle_3 + \beta|1\rangle_3) \\
 &+ |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3) ]
 \end{aligned}$$

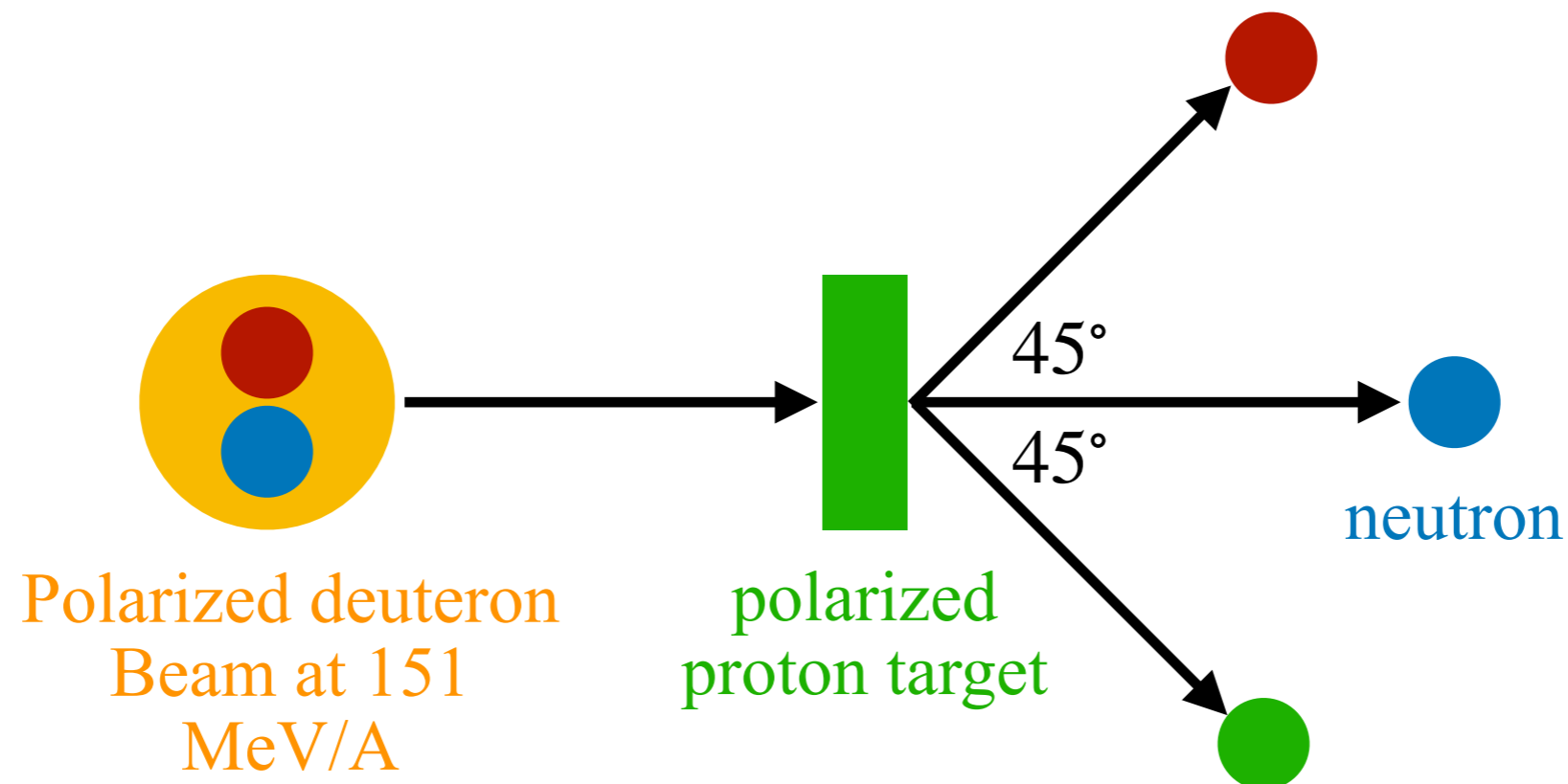
$$\begin{aligned}
 t_2: & (M_{12} \otimes I) |\psi\rangle_1 \otimes |\Psi^-\rangle_{23} \\
 & \rightarrow |\Psi^+\rangle_{12} \otimes (\alpha|1\rangle_3 + \beta|0\rangle_3)
 \end{aligned}$$

$$M_{12} \propto |\Psi^+\rangle_{12} \langle \Phi^-|_{12}$$

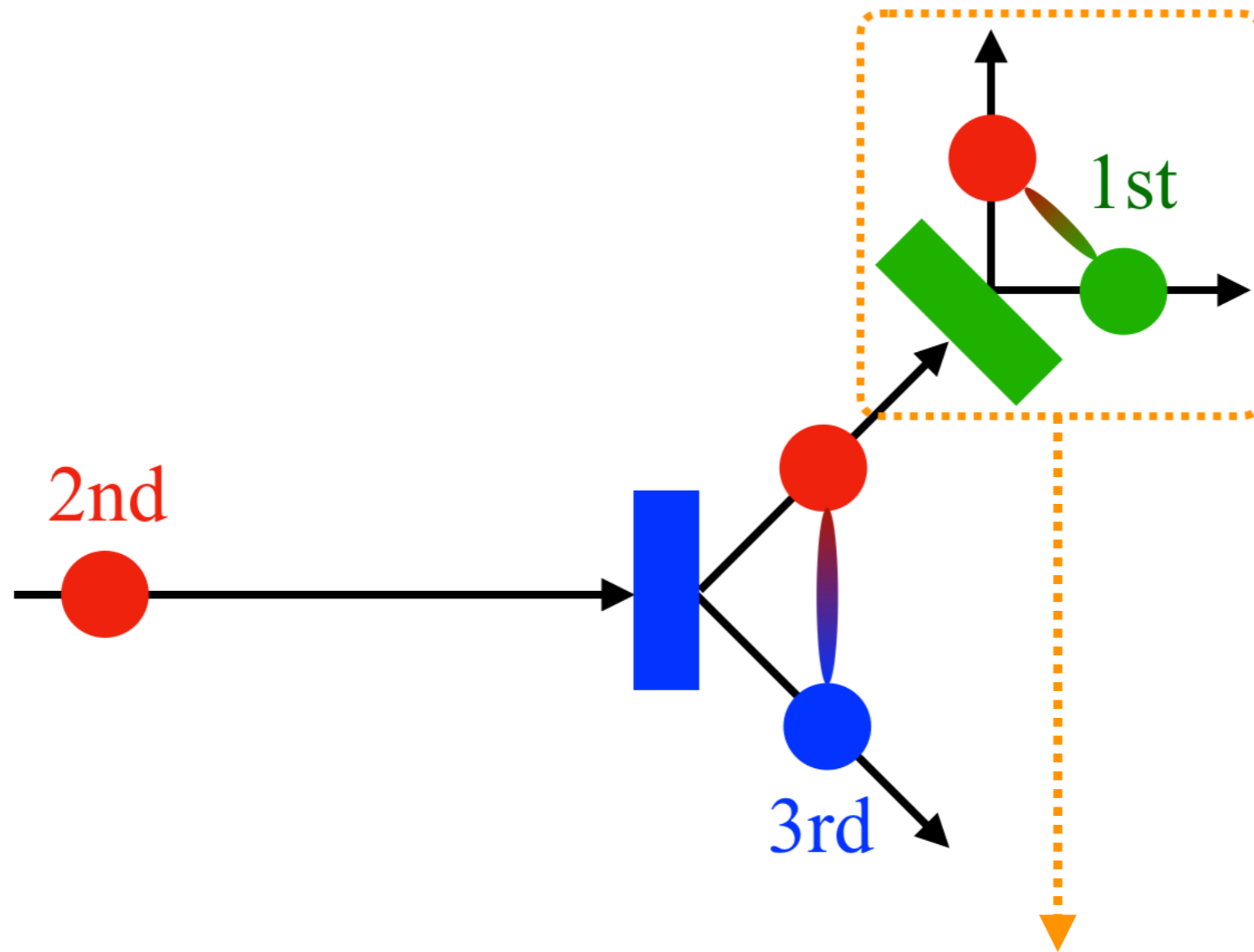
equal to  $|\psi\rangle_1 = \alpha|0\rangle_1 + \beta|1\rangle_1$  up to the inversion of the z-axis.

# Spin teleportation with polarized deuteron beams

- A polarized deuteron beam in the  $m_S = 0$  state onto a polarized proton target; a proton-neutron pair in Bell-triplet state.
- In quasi-free scattering (QFS) at  $\sim 151$  MeV/A, the proton inside the deuteron scatters off the target proton as if in free space, leaving the neutron as a spectator. Then, the spin state of the target proton would then be teleported to the spectator neutron.



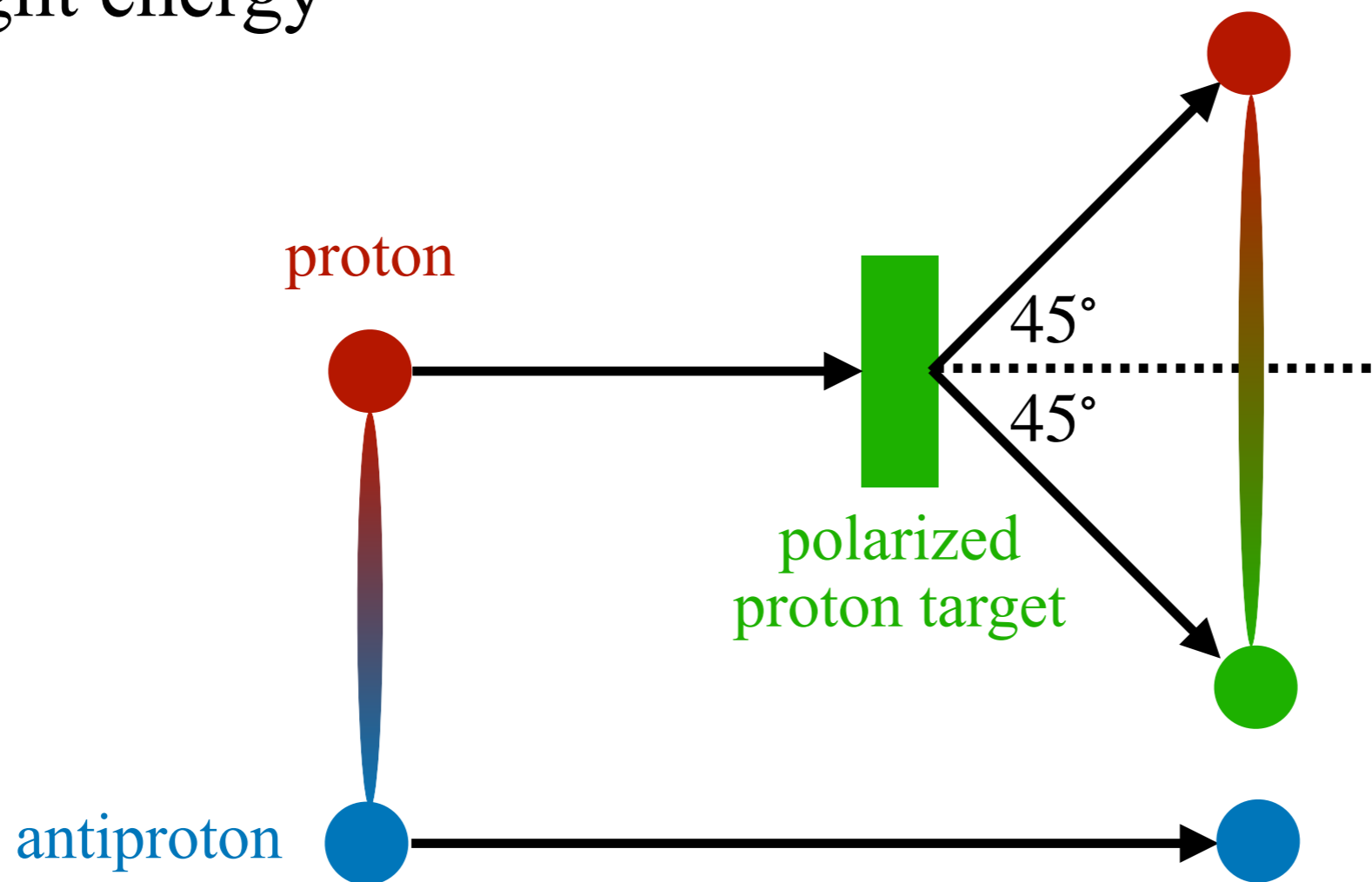
# Classical information transmission



The second proton-proton scattering happens **probabilistically**. **NOT every 3rd proton** teleports **the unknown spin state**. **Classical information** is needed to help select the right events.

# Towards spin teleportation between protons and antiprotons

- Suppose a maximally spin-entangled proton-antiproton pair at the right energy



- Alternative to spin-filter approach for producing polarized antiproton?

# Proposal for testing Bell transition operator

Submitted to RCNP (Feb, 2026)

RCNP EXPERIMENT E

## PROPOSAL FOR EXPERIMENT AT RCNP

27 Feb 2026

### TITLE:

**Emergence of Strong Nuclear Entanglement by Proton-Proton Scattering**

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T. Kawabata	Department of Physics, The University of Osaka	Professor
A. Sakaue	Department of Physics, The University of Osaka	Assistant Professor
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Y. Lin	Department of Physics, The University of Osaka	D1
S. Sakajo	Department of Physics, The University of Osaka	D1
S. Maesato	Department of Physics, The University of Osaka	M2
T. Okamura	Department of Physics, The University of Osaka	M2
H. Shimojo	Department of Physics, The University of Osaka	M2
R. Tanaka	Department of Physics, The University of Osaka	M1
S. Yamamoto	Department of Physics, The University of Osaka	M1
M. Yabumoto	Department of Physics, The University of Osaka	B4
T. Watanabe	Department of Physics, The University of Osaka	B4
Y. Matsuda	RCNP, The University of Osaka	Professor
E. Ideguchi	RCNP, The University of Osaka	Associate Professor
H. J. Ong	IMP, Chinese Academy of Science	Senior Researcher
D. T. Tran	Vietnam Academy of Science and Technology	Researcher
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S. Okamoto	Department of Physics, Kyoto University	D3
M. Itoh	RARiS, Tohoku University	Professor
S. Adachi	RARiS, Tohoku University	Assistant Professor
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# Conclusions

- Quantum teleportation for protons at MeV, making use of Bell projection and transition operators realized naturally in proton-proton scattering.
- Future directions:
  1. Numerical simulations of experimental details;
  2. Understanding quantum decoherence effects in detectors;
  3. Quantum teleportation between different species and across energy scales.
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