Spin Teleportation of Protons at the MeV Scale

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Z. X. Shen et al., PRL 137, 142501 (2026)

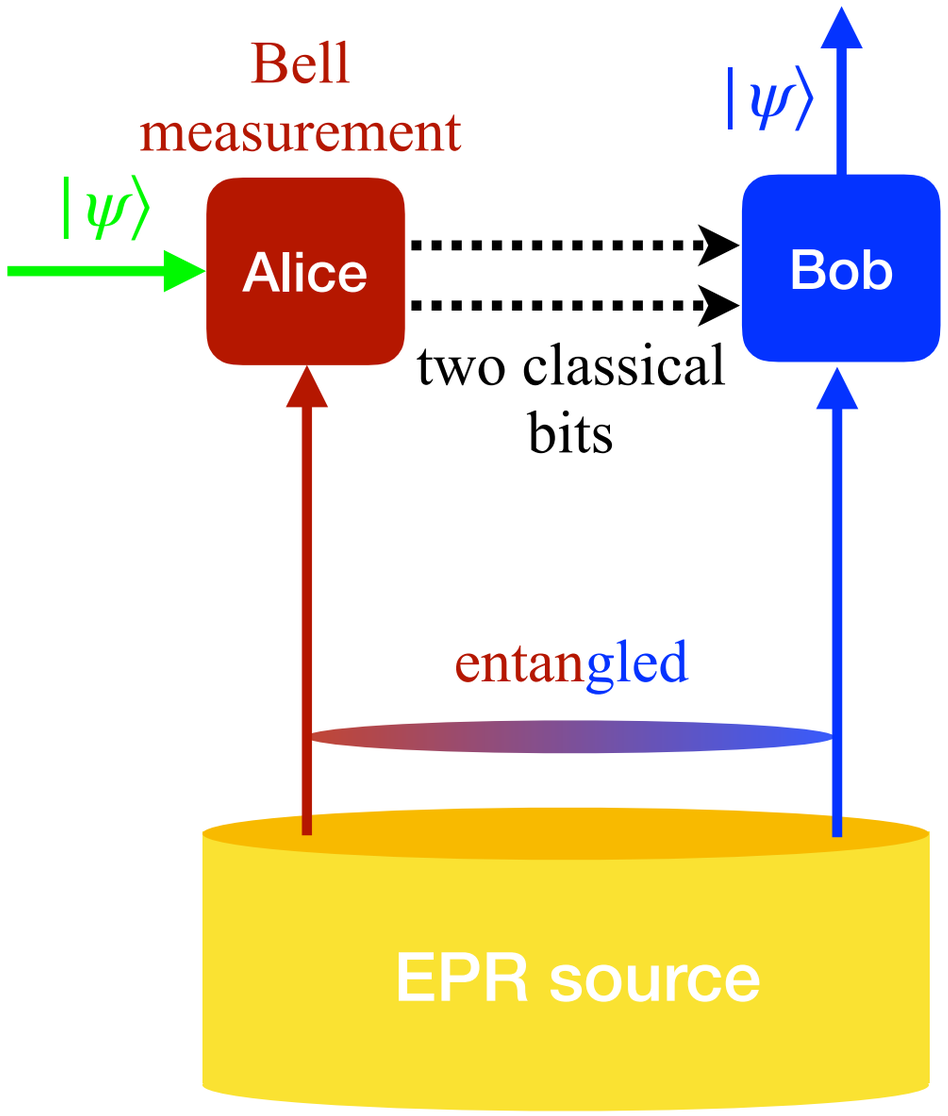
14th ITP/CAS-BLTP/JINR Joint Workshop on Physics of Strong Interacting Systems

Oct 19, 2026

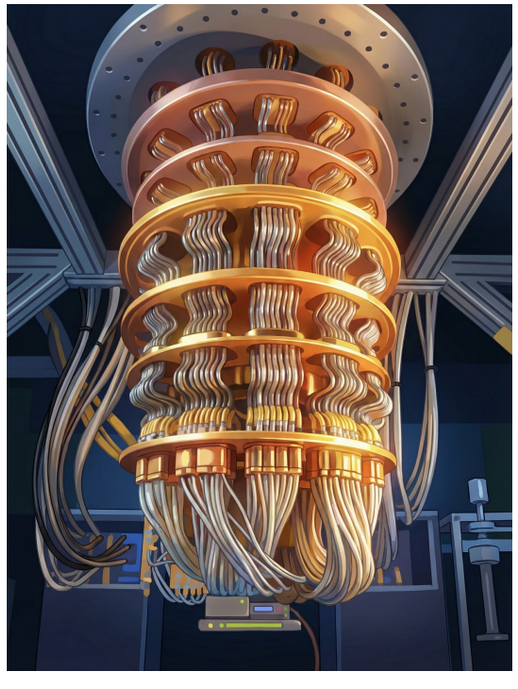
Quantum teleportation

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 the MeV scale; pioneered by B. F. Kostenko *et al.* (2000); push the frontiers of quantum control over the strong interaction.
- New opportunities for nuclear instrumentation: **nuclear quantum engineering** *vs* quantum engineering, analogous to nuclear electronics *vs* electronics.

A stark imbalance exists between nuclear physics and quantum information science: quantum state tomography of spin wave functions is very difficult in nuclear experiments even for two protons, but is elementary for modern quantum hardware based on trapped ions, neutral atoms, superconducting circuits, etc.

Teleporting quantum states of atomic nuclei to more manipulable quantum hardware?

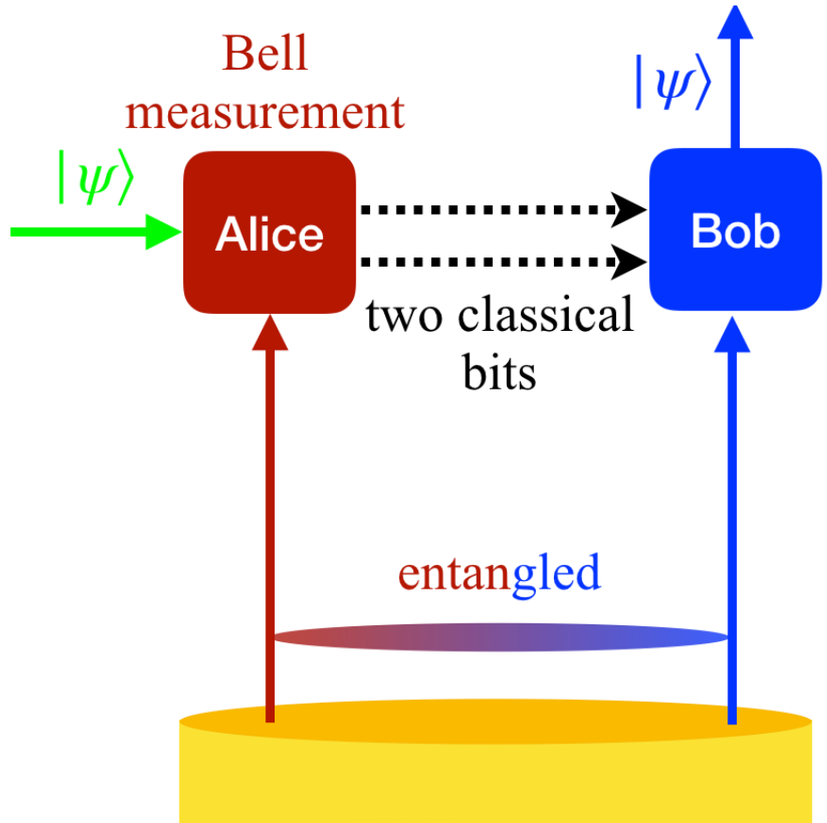
Mathematics of QT

- 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

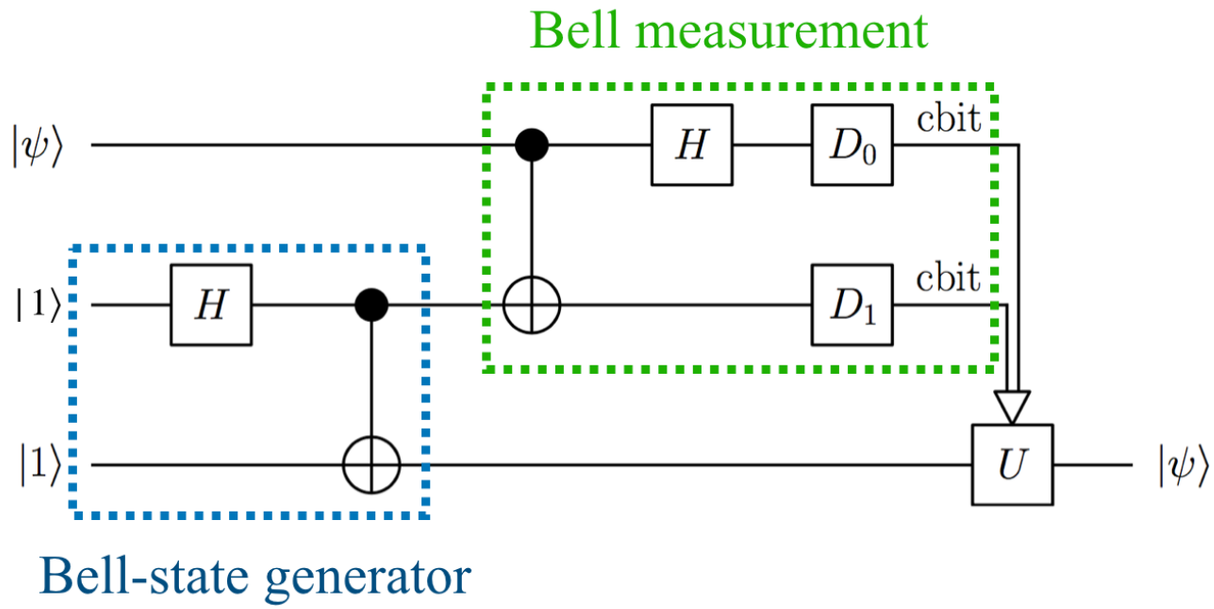
$$|\Psi^+\rangle_{23} = \frac{1}{\sqrt{2}}(|01\rangle_{23} + |10\rangle_{23}),$$

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

The Bell states are mutually orthogonal.

- 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}Be;
4. …

- *Bell measurement*

➡ **How to do Bell measurement for protons?**

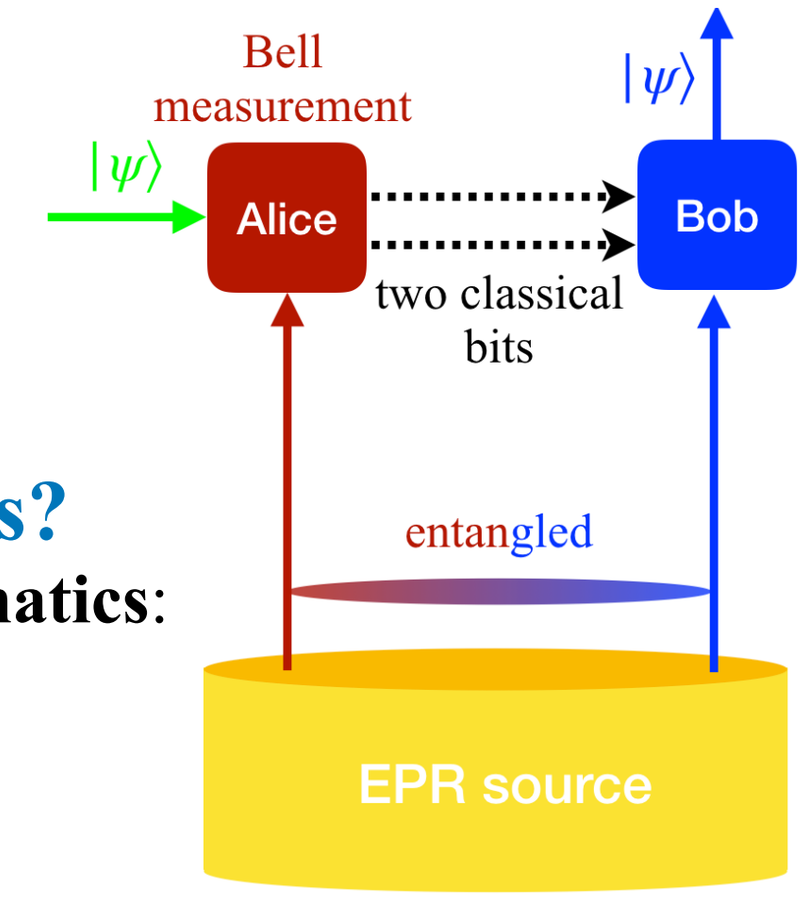
Make use of proton-proton scattering at **specific kinematics**:

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

- *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.

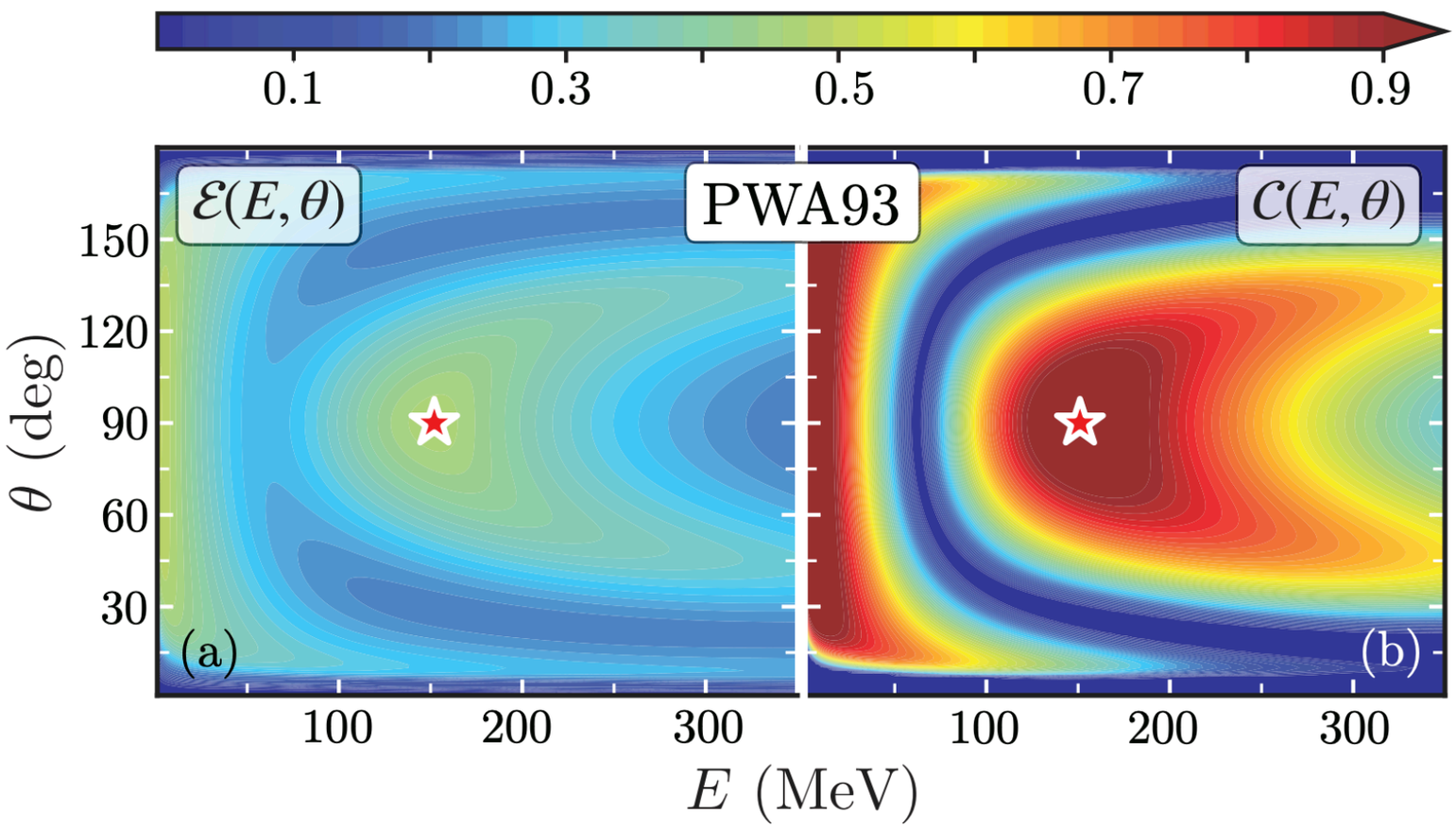


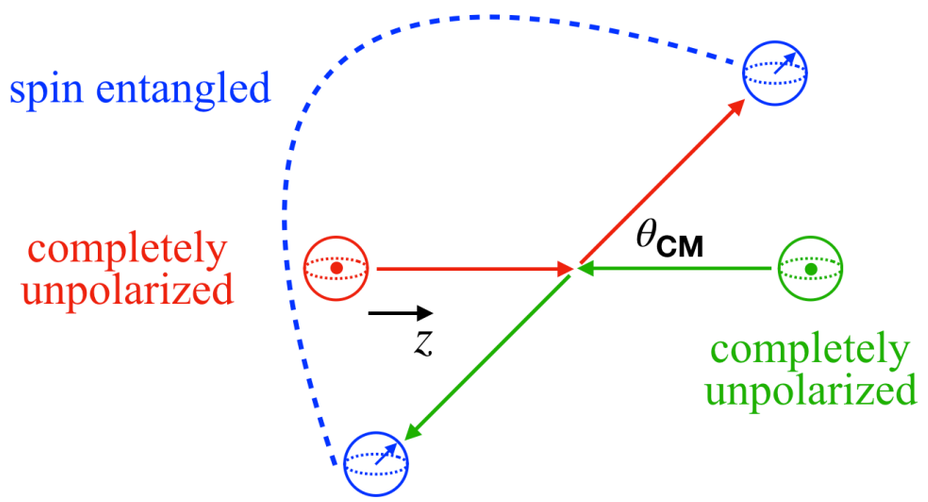
Proton-proton scattering

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 λ_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.





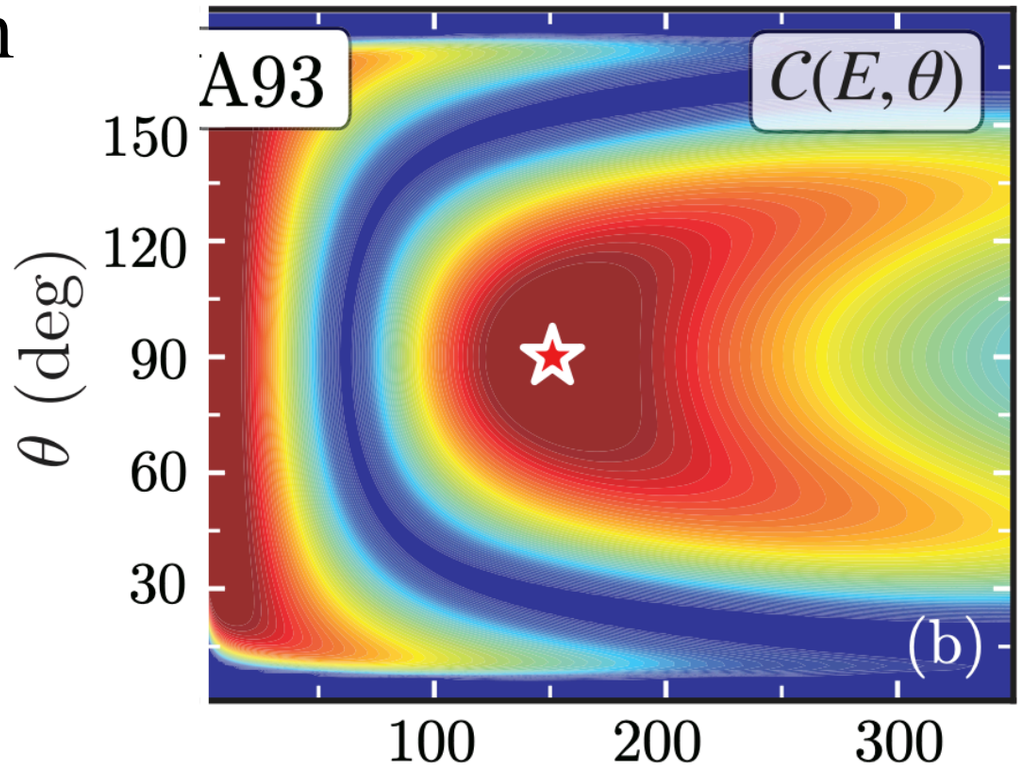
Two special regions support large spin entanglement.

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

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

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

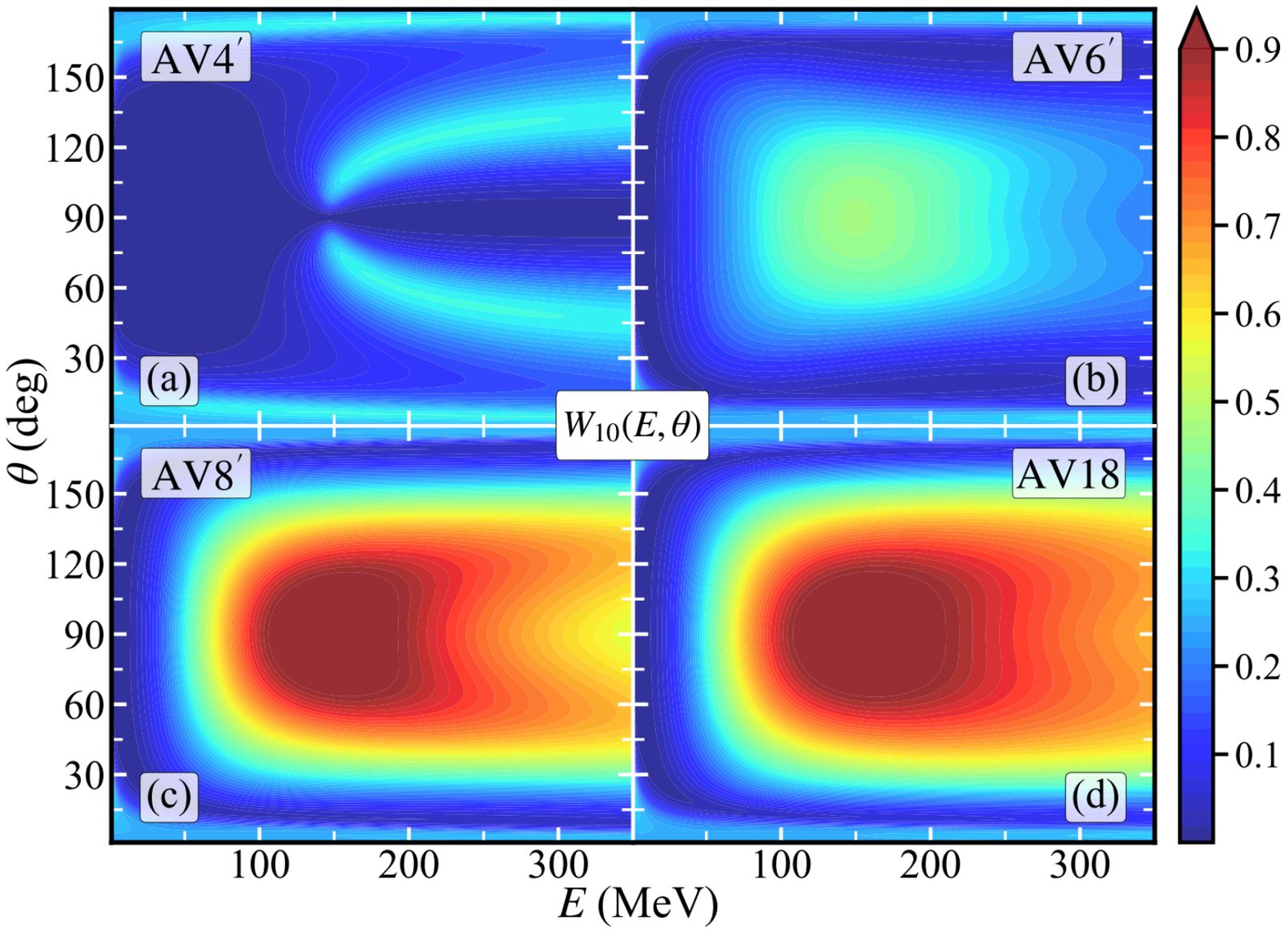
Explicitly, $M =$

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

small

Physical origins

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



AV4′: central

AV6′: central+tensor

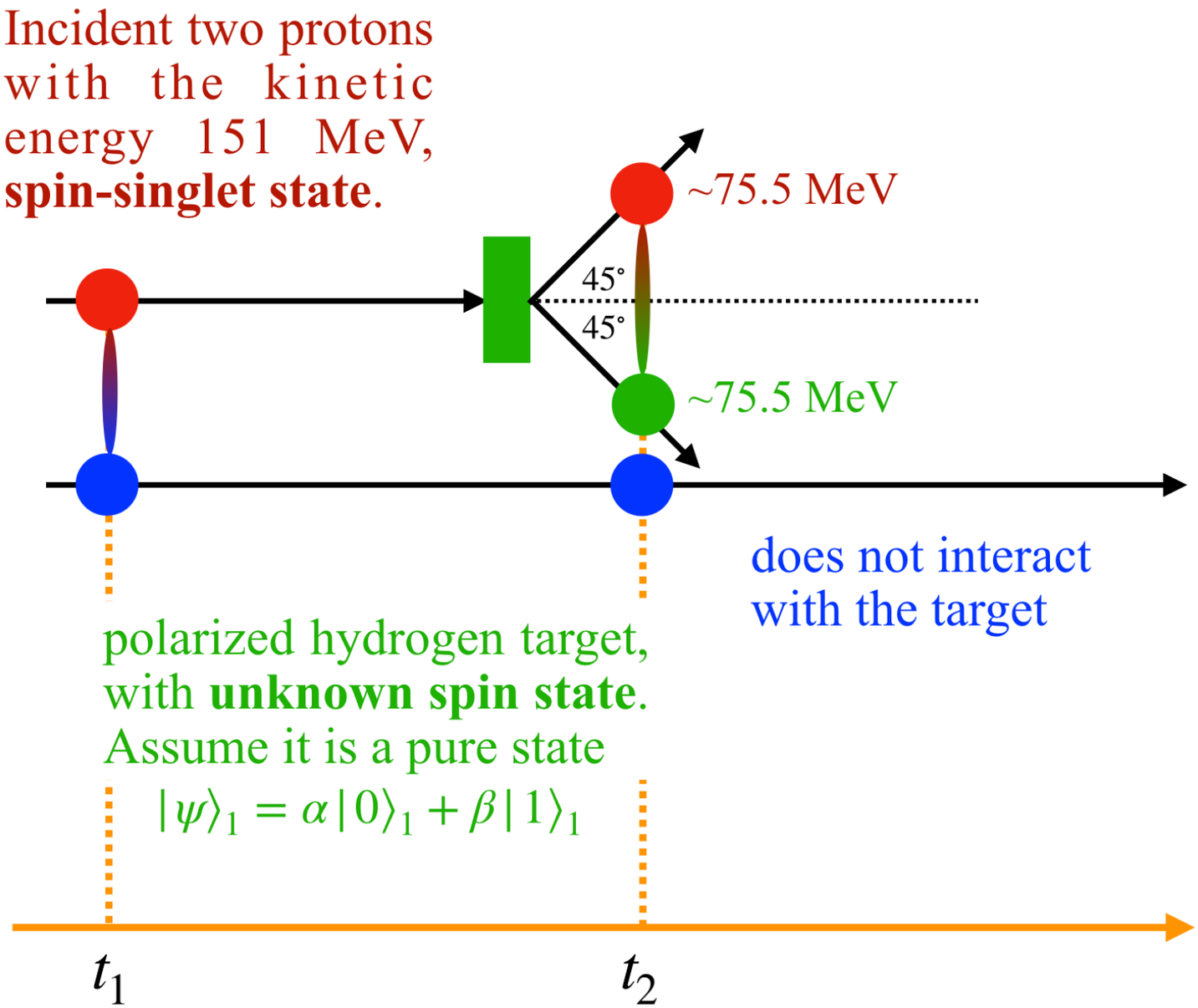
AV8′: central+tensor +LS

AV18: full

A joint contribution from tensor and LS forces.

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 → two protons at 151 MeV.



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

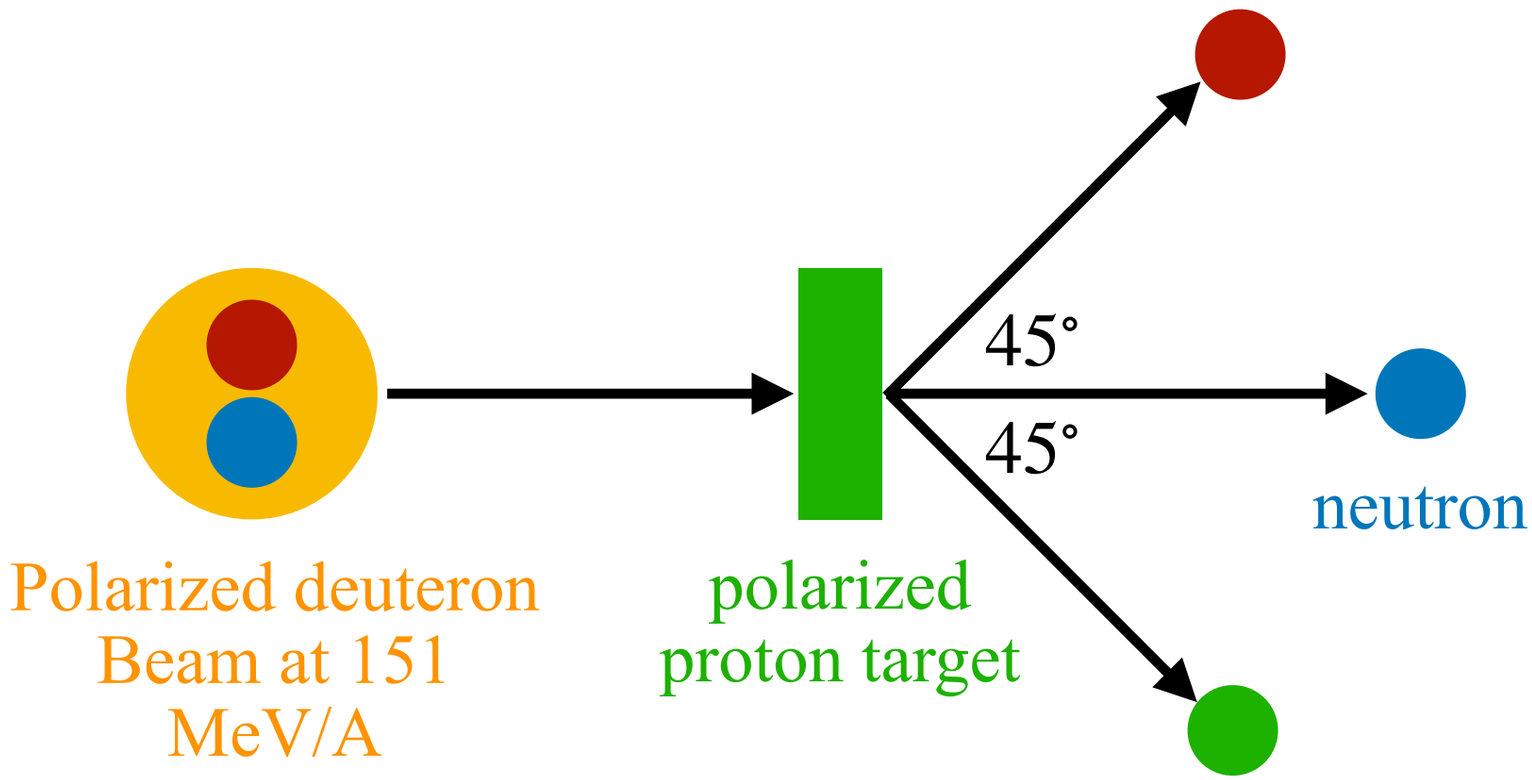
$$t_2 : (M_{12} \otimes I)|\psi\rangle_1 \otimes |\Psi^-\rangle_{23}$$
$$\rightarrow |\Psi^+\rangle_{12} \otimes (\alpha|1\rangle_3 + \beta|0\rangle_3)$$

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

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

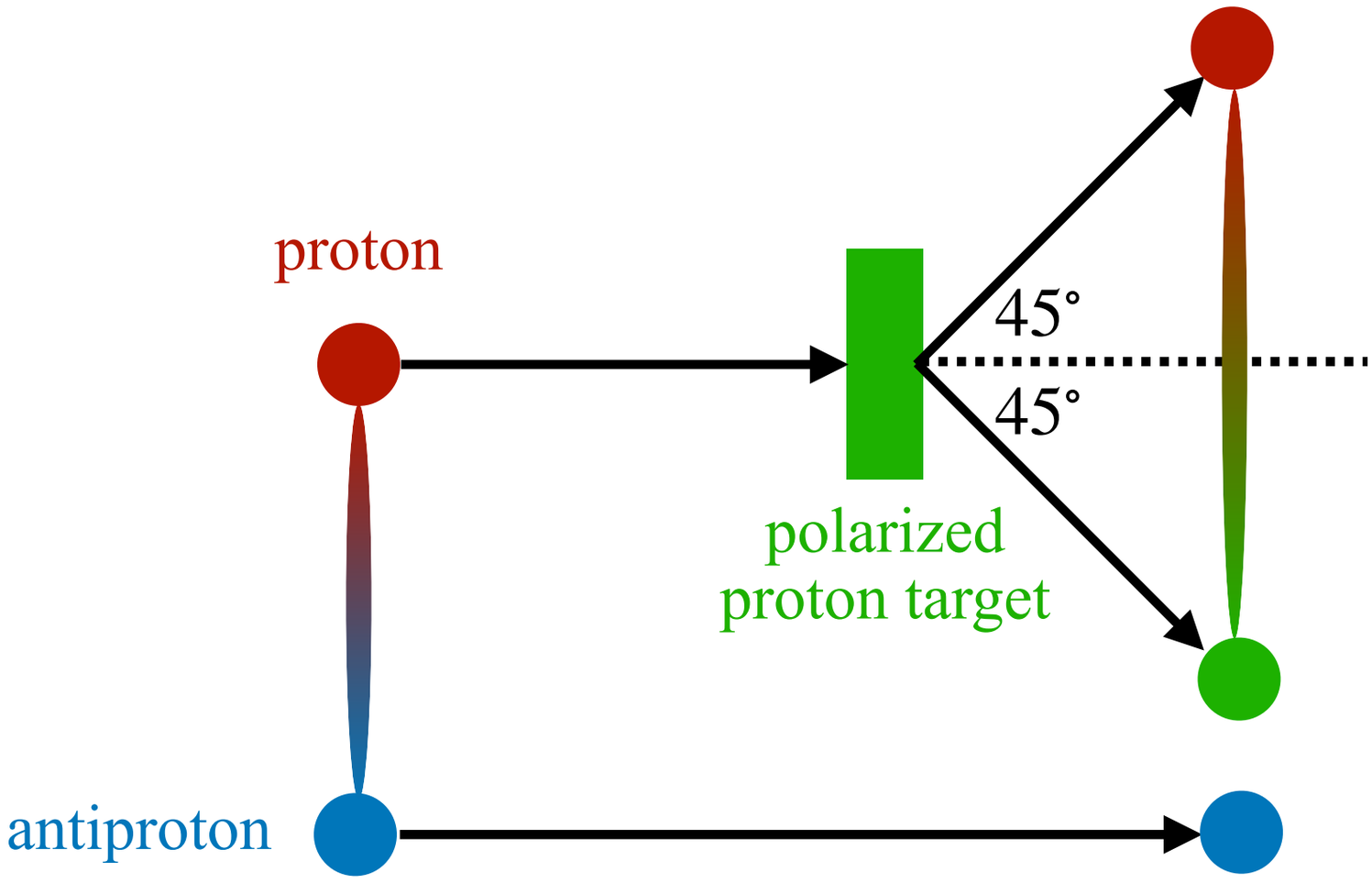
Spin teleportation with polarized deuteron beams

- 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 ~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.



Towards spin teleportation between protons and antiprotons?

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



Proposal for testing Bell transition operator

Approved by RCNP (April, 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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Conclusions

- Quantum teleportation for protons at MeV, making use of Bell projection and transition operators realized naturally in proton-proton scattering.
- Future directions: Make it a reality in experiments.
- Special thanks to:

Fudan U.: Zhaoxin Sheng, Haoyu Shang, Yugang Ma, Simin Wang, Zhicheng Xu

IGFAE: Yassid Ayyad, Hector Alvarez-Pol, Youssef Khlifi, Carolina Filgueira

FRIB: Wolfgang Mittig, Daniel Bazin, Dean Lee

Fukui U.: Tatsuya Furuno


Thank you!
河海大学

- The quantum state of three qubits is given by

$$|\psi\rangle_1 \otimes |\Psi^-\rangle_{23}$$

$$= (\alpha|0\rangle_1 + \beta|1\rangle_1) \otimes \frac{1}{\sqrt{2}}(|01\rangle_{23} - |10\rangle_{23})$$

$$= \frac{1}{\sqrt{2}}(\alpha|001\rangle_{123} - \alpha|010\rangle_{123} + \beta|101\rangle_{123} - \beta|110\rangle_{123}$$

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

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

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

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

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

Saclay amplitude

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

For identical particles

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

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

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

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

Saclay amplitude and W_{10}

Potential	$\lvert d-ie\rvert$	$\lvert d+ie\rvert$	$2\lvert b\rvert$	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

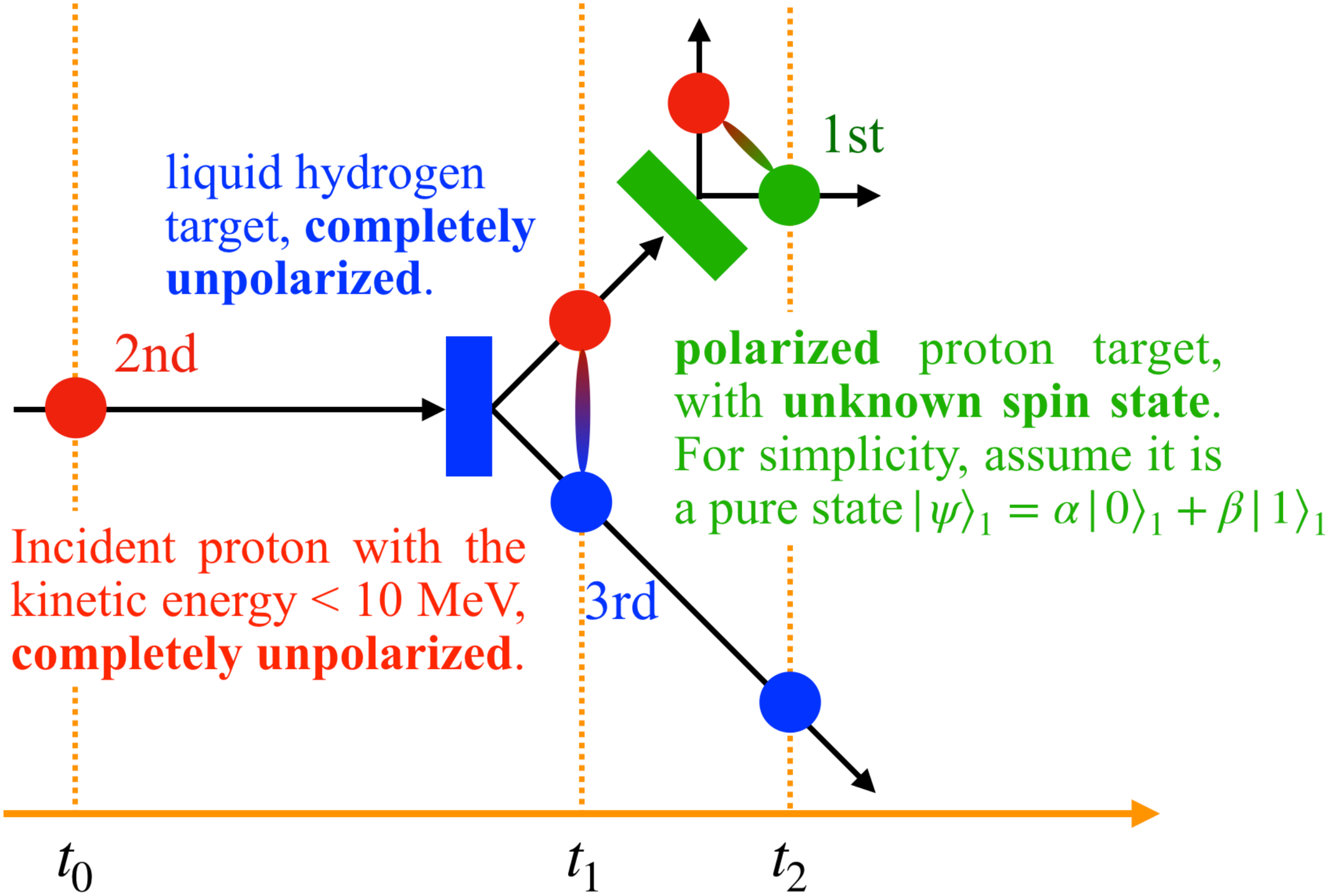
Translation to partial-wave conditions

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

Phase shifts patterns at 151 MeV.

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

Spin teleportation < 10 MeV



$$\mathbf{t_0}: |\psi\rangle_1\langle\psi|_1 \otimes \frac{I}{2} \otimes \frac{I}{2}$$

$$\mathbf{t_1}: |\psi\rangle_1\langle\psi|_1 \otimes \left[M_{23}\left(\frac{I}{2} \otimes \frac{I}{2}\right)M_{23}^{\dagger}\right]$$

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

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

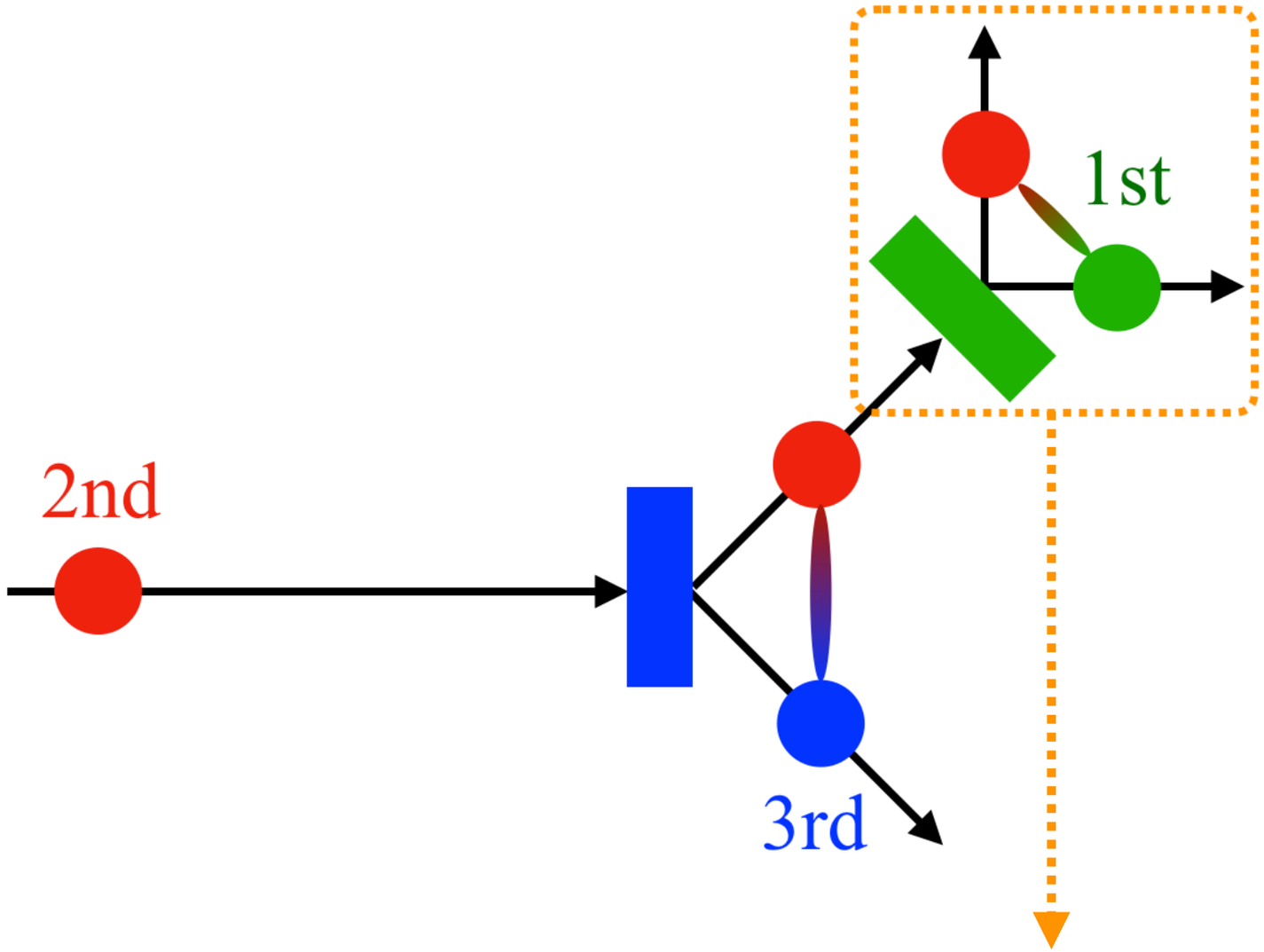
$$+ |\Psi^+\rangle_{12} \otimes (-\alpha|0\rangle_3 + \beta|1\rangle_3) + |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3)]$$

$$\mathbf{t_2}: (M_{12} \otimes I)\frac{1}{2}[\cdots + |\Psi^-\rangle_{12} \otimes (-\alpha|0\rangle_3 - \beta|1\rangle_3)]$$

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

- 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.

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.