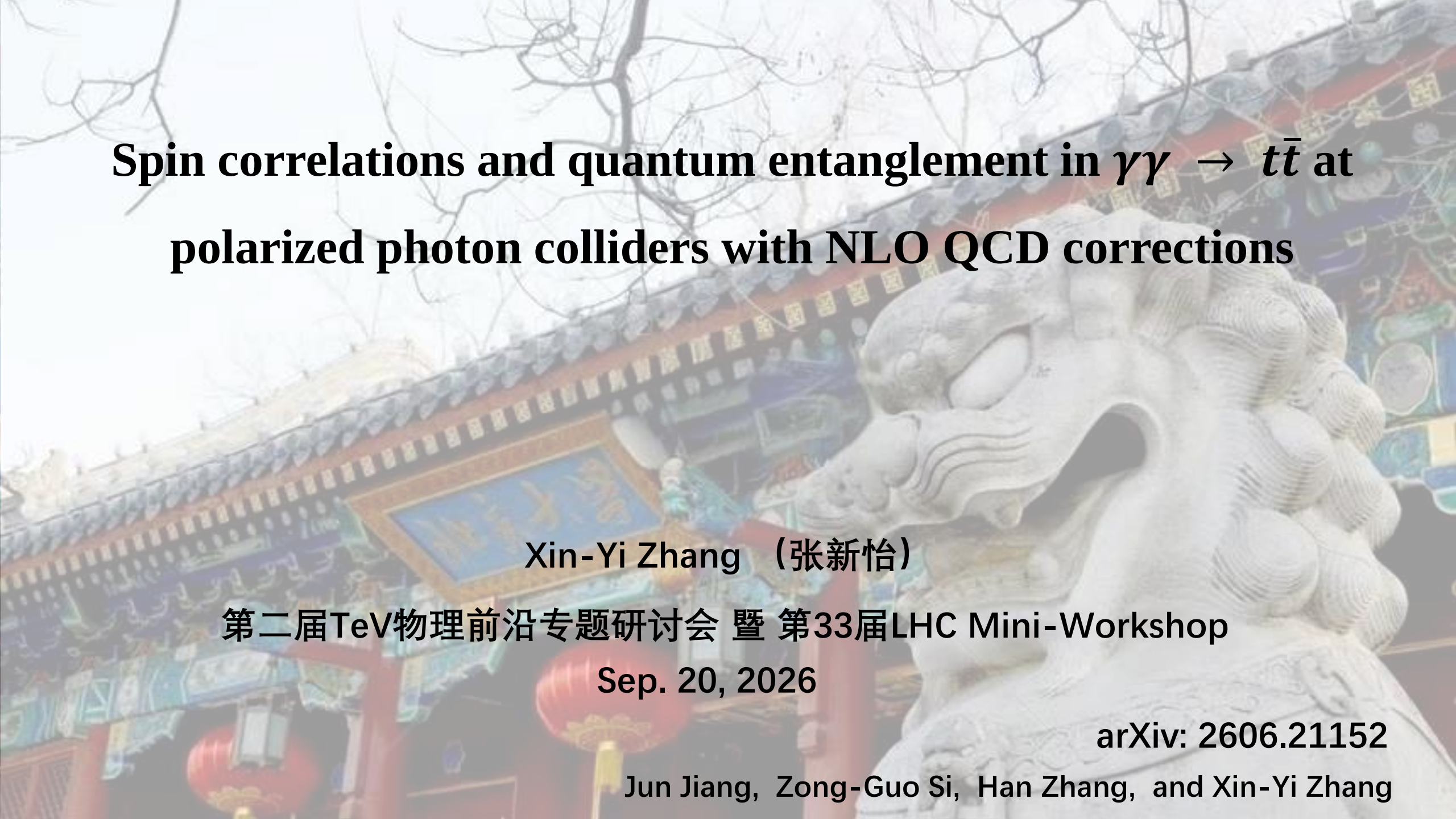




Spin correlations and quantum entanglement in $\gamma\gamma \rightarrow t\bar{t}$ at polarized photon colliders with NLO QCD corrections

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Introduction



Theoretical Framework



Numerical results & analysis

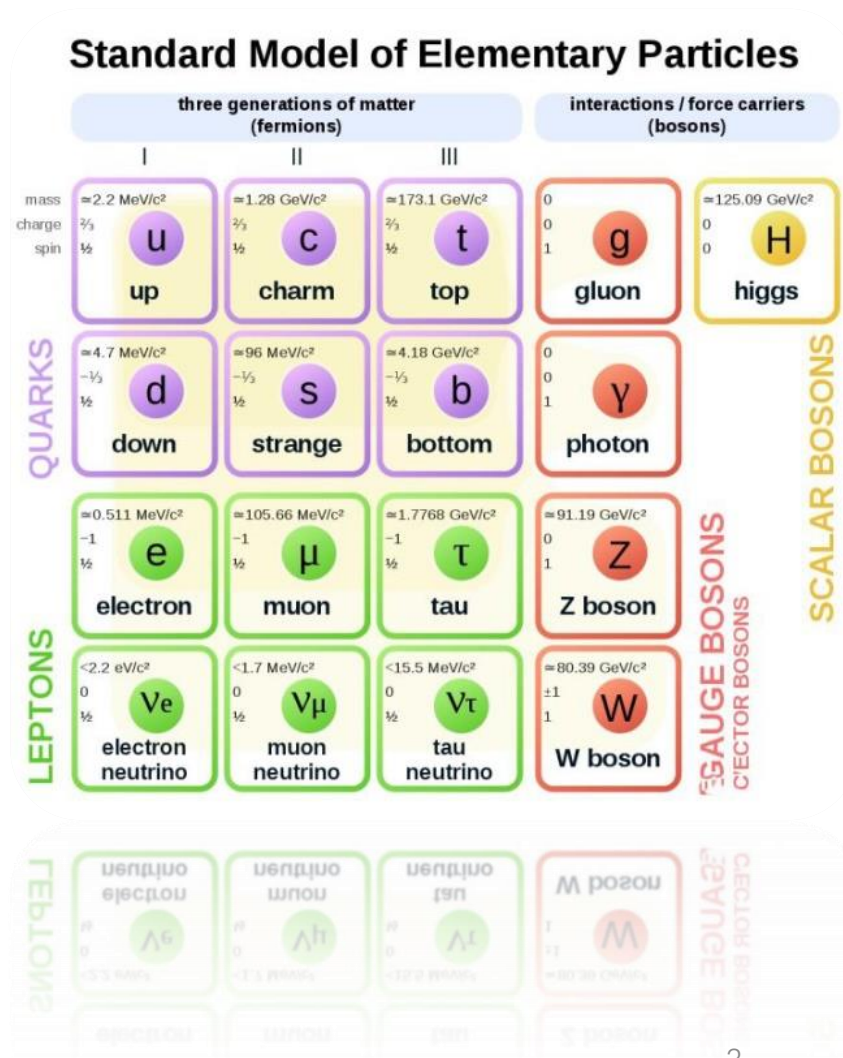


Summary



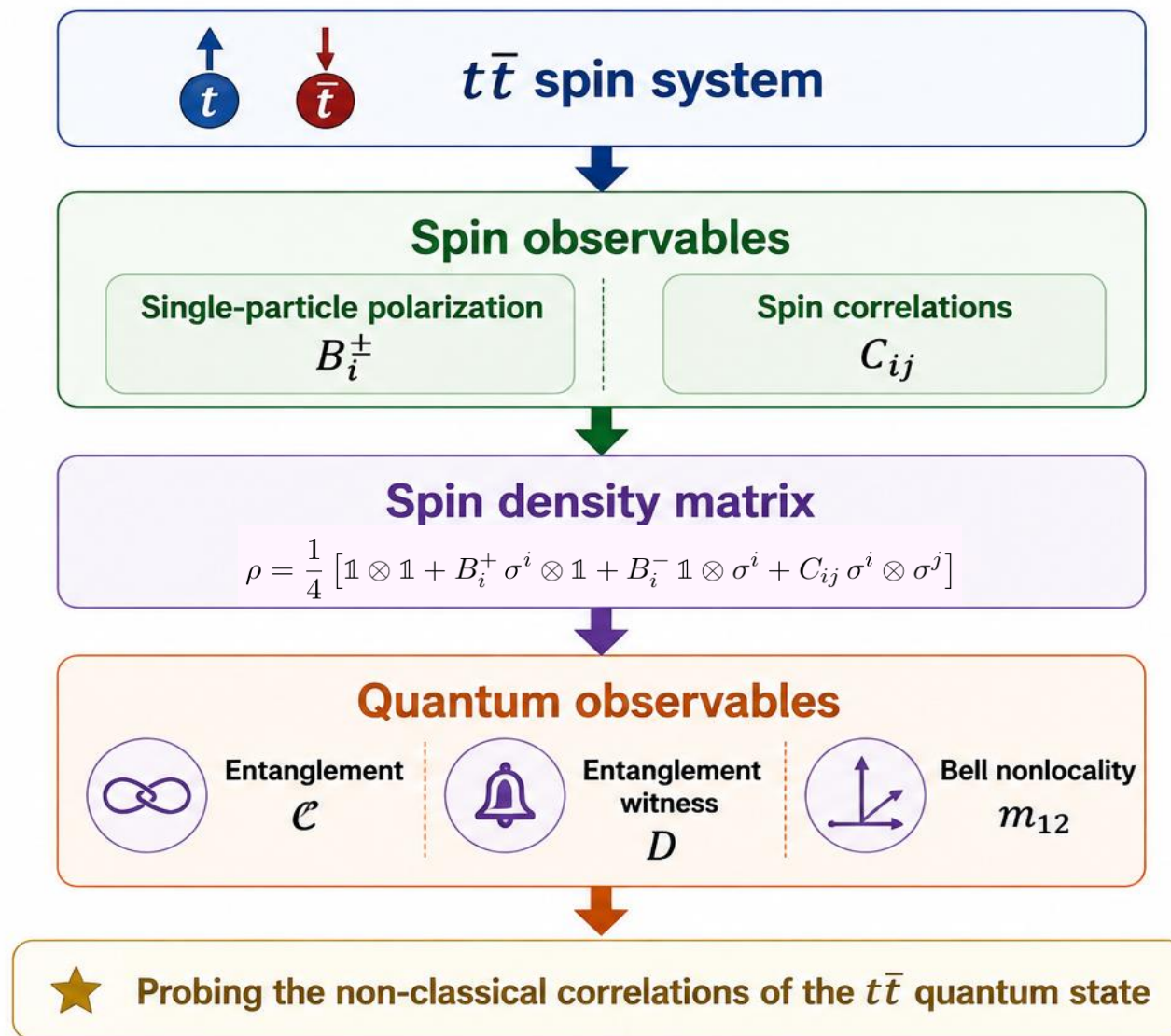
Introduction

- SM has achieved great success;
- There are still many unresolved issues;
- Top quark with a large Yukawa coupling.



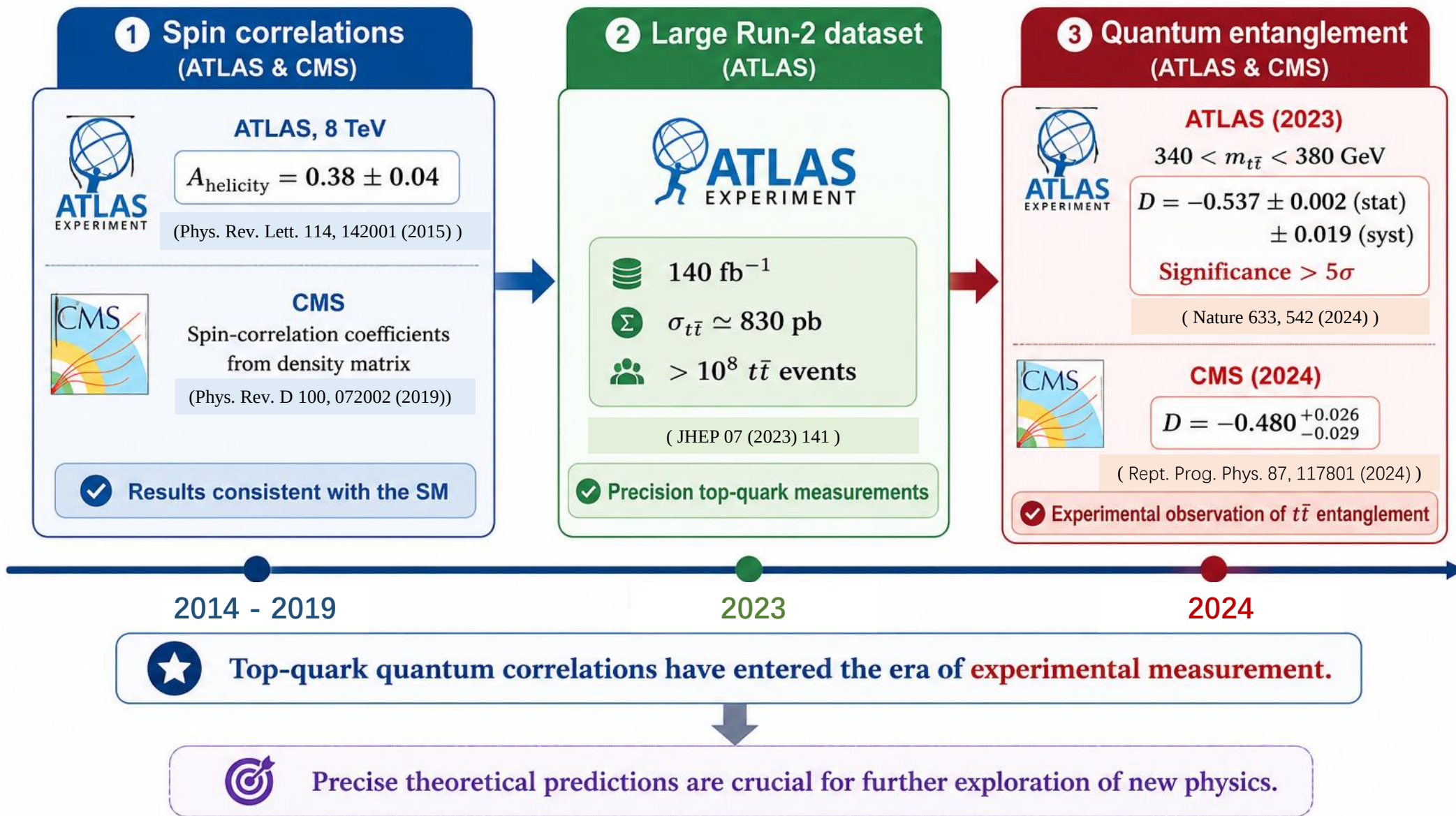


- top quark decays before hadronization;
- Decay products probe the top-quark spin;
- The $t\bar{t}$ pair forms a bipartite spin system.



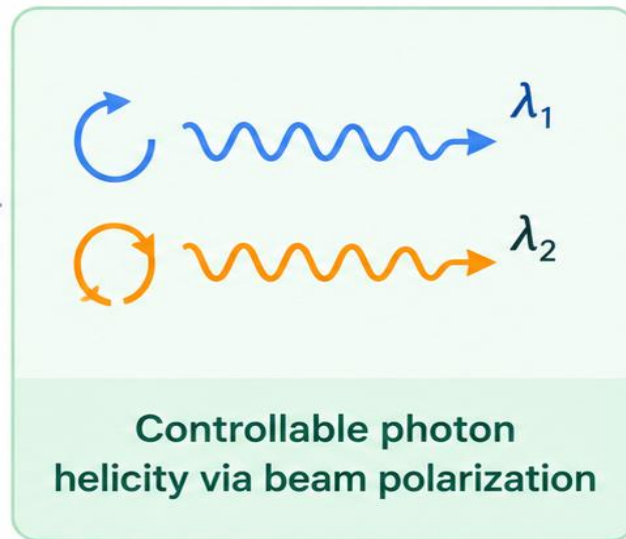
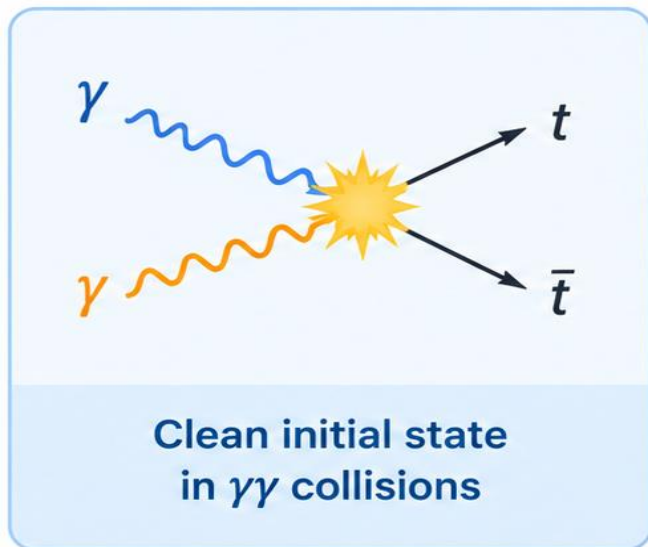


Experiments





polarized photon collider



An ideal laboratory for studying top-quark spin correlations
and quantum correlations

Top-quark spin physics

- ✓ Phys. Rev. D 53, 4886 (1996)
- ✓ Phys. Lett. B 411, 173 (1997)
- ✓ Nucl. Phys. B 690, 81 (2004)
- ✓ Phys. Rev. D 74, 113005 (2006)

Higher-order corrections

- ✓ Phys. Rev. D 54, 2030 (1996)
- ✓ Eur. Phys. J. C 9, 101 (1999)
- ✓ Phys. Atom. Nucl. 64, 275 (2001)
- ✓ JHEP 03 (2026) 068

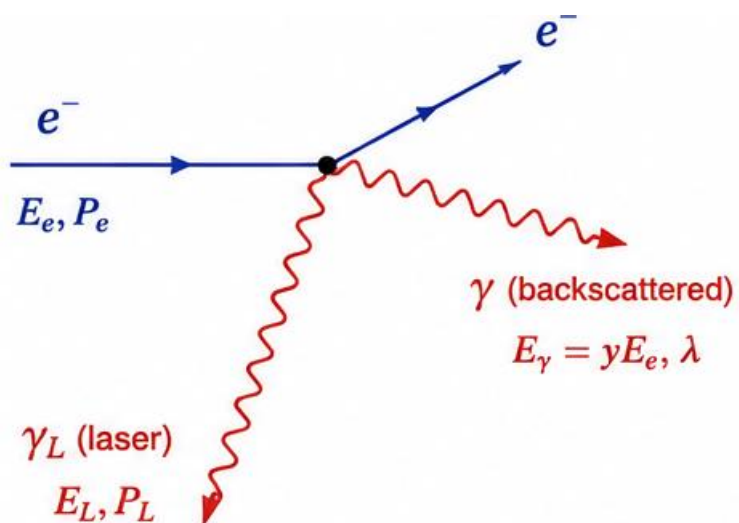
Quantum correlations

- Quantum 6, 820 (2022)
- Prog. Part. Nucl. Phys. 139, 104134 (2024)
- S. Y. Choi, D. W. Kang, J. S. Lee, and C. B. Park, (2026), arXiv:2603.12830



Part 02

Theoretical Framework



$$\sigma_{t\bar{t}} = \int_0^{y_{\max}} dy_1 \int_0^{y_{\max}} dy_2 f_\gamma^e(y_1, P_e^{(1)}, P_L^{(1)}) f_\gamma^e(y_2, P_e^{(2)}, P_L^{(2)}) \hat{\sigma}_{\gamma\gamma \rightarrow t\bar{t}X}(\hat{s}, \lambda_1, \lambda_2)$$

$$\lambda_i = P_\gamma(y_i, P_e^{(i)}, P_L^{(i)}), \quad i = 1, 2,$$

$$P_\gamma(y, P_e, P_L) = \frac{1}{\mathcal{N} f_\gamma^e(y, P_e, P_L)} \left\{ x \xi P_e [1 + (1 - y)(2\xi - 1)^2] - (2\xi - 1) P_L \left[\frac{1}{1 - y} + 1 - y \right] \right\}$$

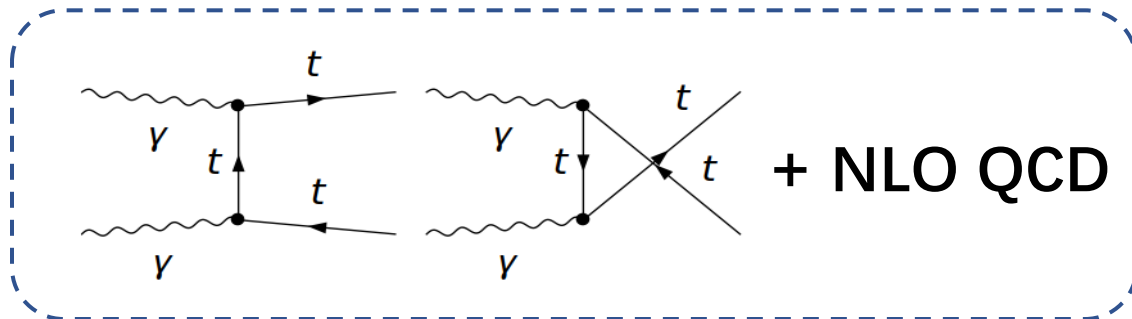
$$\xi = \frac{y}{x(1 - y)}, \quad x = \frac{4E_L E_e}{m_e^2} \quad 0 \leq y \leq x/(x + 1)$$

Collider setup: $E_L \simeq 1.26 \text{ eV}$ for $E_e = 250 \text{ GeV}$ $x_{\max} = 2(1 + \sqrt{2})$



Theoretical Framework

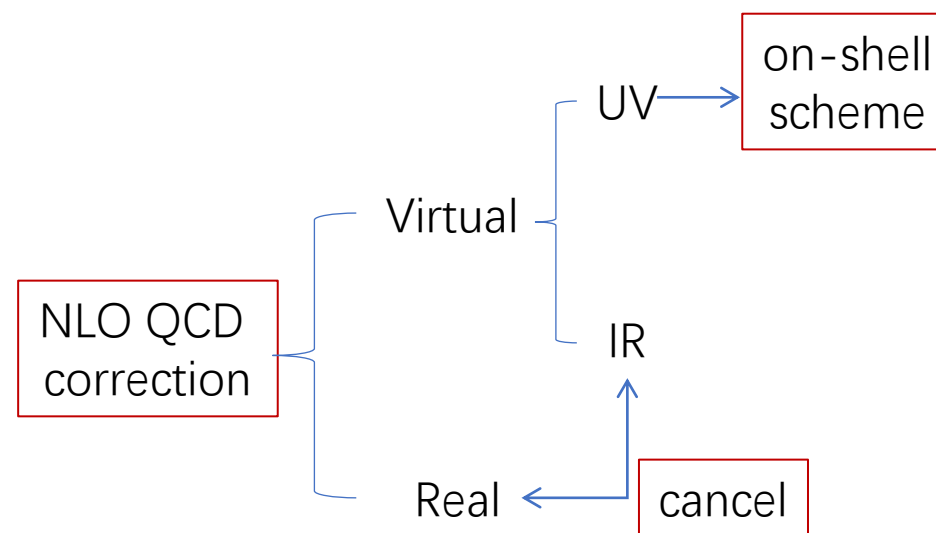
$$\gamma(p_1, \lambda_1) + \gamma(p_2, \lambda_2) \rightarrow t(k_1, s_t) + \bar{t}(k_2, s_{\bar{t}})$$



$$d\hat{\sigma}(\lambda_1, \lambda_2, s_t, s_{\bar{t}}) = \frac{N_c}{2\hat{s}} |M|^2 d\Phi$$

$$|M|^2 = \frac{16\alpha^2 Q_t^4 \pi^2}{(1 - \beta^2 z^2)^2} \left\{ A_0 + B_0[p_1 \cdot (s_t + s_{\bar{t}})] + B_0|_{\lambda_1 \leftrightarrow \lambda_2}[p_2 \cdot (s_t + s_{\bar{t}})] + C_0(s_t \cdot s_{\bar{t}}) + D_0(p_1 \cdot s_t)(p_2 \cdot s_{\bar{t}}) \right. \\ \left. + D_0|_{z \rightarrow -z}(p_2 \cdot s_t)(p_1 \cdot s_{\bar{t}}) \right\},$$

dimensional regularization with $D = 4 - 2\varepsilon$





Theoretical Framework

$$R = \tilde{A} \mathbb{1} \otimes \mathbb{1} + \tilde{B}_i^+ \sigma^i \otimes \mathbb{1} + \tilde{B}_i^- \mathbb{1} \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j$$



normalized

$$\rho = \frac{1}{4} [\mathbb{1} \otimes \mathbb{1} + B_i^+ \sigma^i \otimes \mathbb{1} + B_i^- \mathbb{1} \otimes \sigma^i + C_{ij} \sigma^i \otimes \sigma^j]$$

- $B_i^\pm$: Single particle polarization
- C_{ij} : Spin correlations between t and $\bar{t}$

$$B_a^\pm = 2 \langle \hat{\mathbf{a}} \cdot \vec{s}_{t,\bar{t}} \rangle$$

$$C_{ab} = 4 \langle (\hat{\mathbf{a}} \cdot \vec{s}_t)(\hat{\mathbf{b}} \cdot \vec{s}_{\bar{t}}) \rangle$$

Project

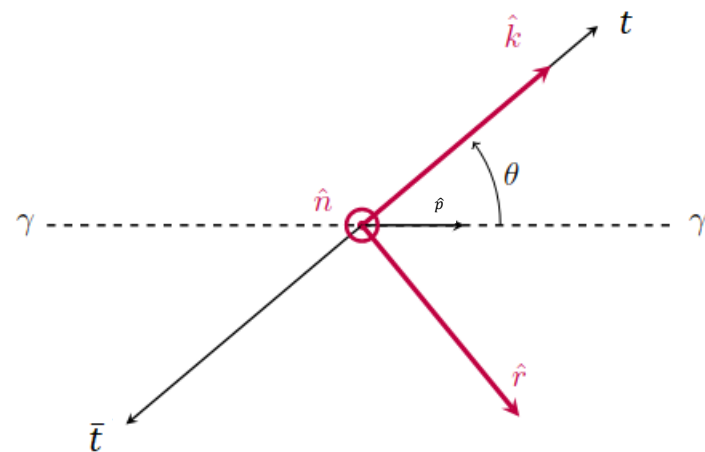
- $\hat{\mathbf{k}}$: the direction of flight of top quark

$$\hat{\mathbf{r}} = \frac{1}{r} (\hat{\mathbf{p}} - z \hat{\mathbf{k}})$$

$$\hat{\mathbf{n}} = \frac{1}{r} (\hat{\mathbf{p}} \times \hat{\mathbf{k}})$$

$$z = \hat{\mathbf{p}} \cdot \hat{\mathbf{k}}$$

$$r = \sqrt{1 - z^2}$$





Concurrence

$$C[\rho] = \max(0, \zeta_1 - \zeta_2 - \zeta_3 - \zeta_4)$$

$\zeta_1 > \zeta_2 > \zeta_3 > \zeta_4$, ζ_i are the square roots of the eigenvalues of $R = \rho (\sigma_2 \otimes \sigma_2) \rho^* (\sigma_2 \otimes \sigma_2)$

- $0 < C[\rho] \leq 1$, Quantum entanglement exists
- $C[\rho] = 0$, No quantum entanglement

Bell inequality

$$M = CC^T$$

C is the 3×3 correlation, let $m_1 \geq m_2 \geq m_3$ be the eigenvalues of M , the Bell inequality is violated when

$$m_{12} \equiv m_1 + m_2 > 1$$

Part 03

NUMERICAL RESULTS & ANALYSIS

	Unpolarized	$(0.85, 0.85; 1, 1)$	$(0.85, 0.85; -1, -1)$	$(0.85, -0.85; 1, -1)$	$(0.85, -0.85; -1, 1)$
σ_{LO} [fb]	71.29	27.65	223.99	20.53	75.64
σ_{NLO} [fb]	105.25	44.70	318.52	31.63	107.53
$K = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$	1.48	1.62	1.42	1.54	1.42

- The production cross section is **sensitive** to the initial state photon polarization;
- NLO QCD corrections **enhance** the production rate.

	Unpolarized	(0.85, 0.85; 1, 1)	(0.85, 0.85; -1, -1)	(0.85, -0.85; 1, -1)	(0.85, -0.85; -1, 1)
$ B_k^\pm $	0	0.396	0.699	0	0
$ B_r^\pm $	0	0	0	0.107	0.562
$ B_n^\pm $	0	0	0	0	0

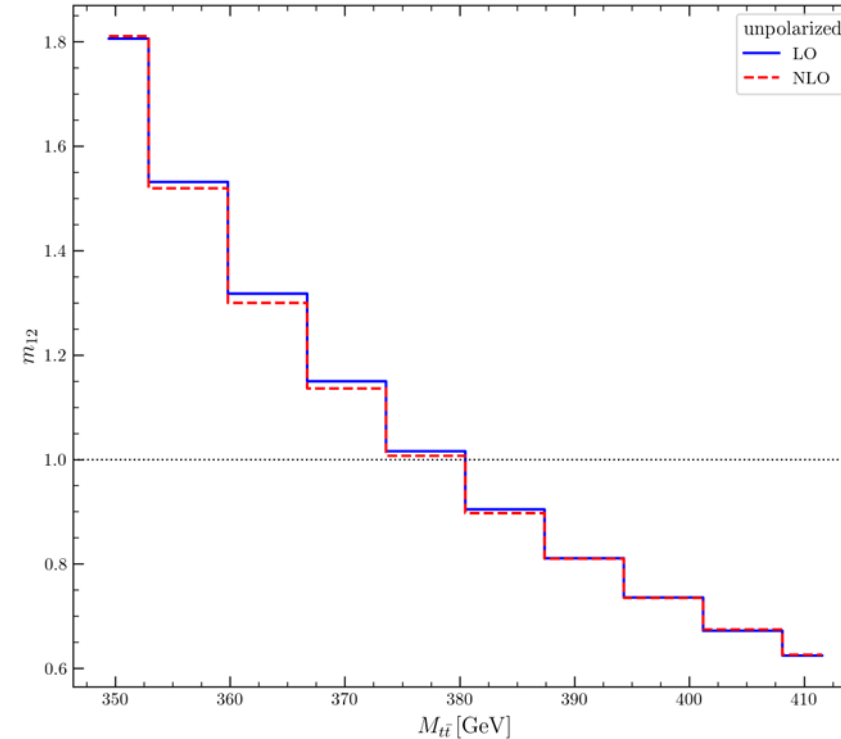
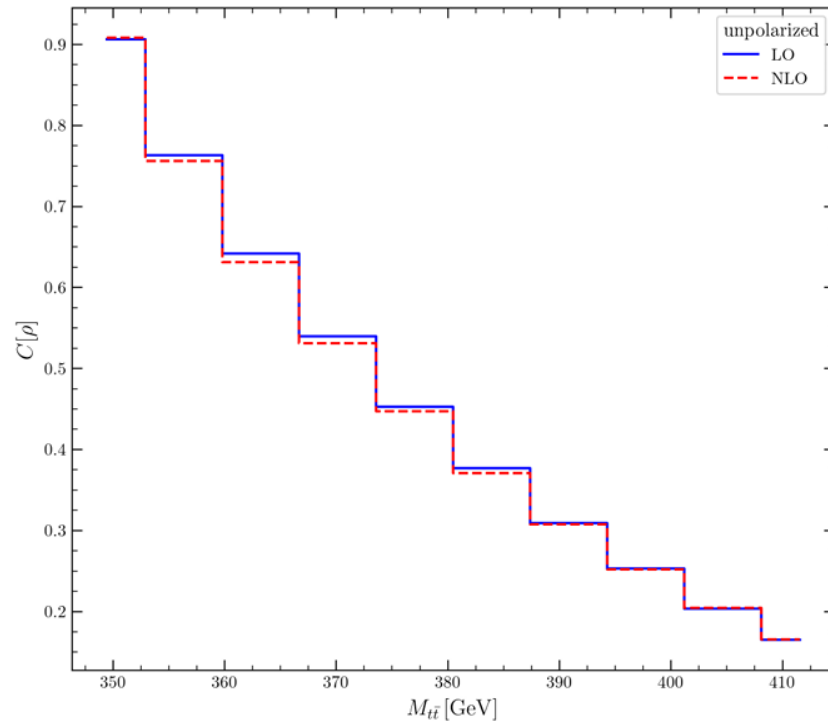
- **Unpolarized** initial state gives $B_i^\pm = 0$ at LO, with negligible NLO QCD effects.
- **Symmetric** polarization configurations induce dominant **k -axis** polarization.
- **Asymmetric** polarization configurations induce dominant **r -axis** polarization.

	Unpolarized		(0.85,0.85;1,1)		(0.85,0.85;-1,-1)		(0.85,-0.85;1,-1)		(0.85,-0.85;-1,1)	
	LO	NLO	LO	NLO	LO	NLO	LO	NLO	LO	NLO
C_{kk}	-0.781	-0.793	-0.864	-0.878	-0.977	-0.975	-0.769	-0.780	-0.104	-0.158
C_{rr}	-0.478	-0.492	-0.628	-0.653	-0.657	-0.649	-0.487	-0.502	0.252	0.202
C_{nn}	-0.618	-0.626	-0.716	-0.731	-0.672	-0.666	-0.636	-0.645	-0.317	-0.350

- Initial state polarization affects the spin-correlation structure, off-diagonal components negligible;
- NLO QCD corrections are **moderate**, at the few-percent level;
- Most configurations are **dominated by C_{kk}** , while (0.85,-0.85;-1,1) modifies the spin structure;



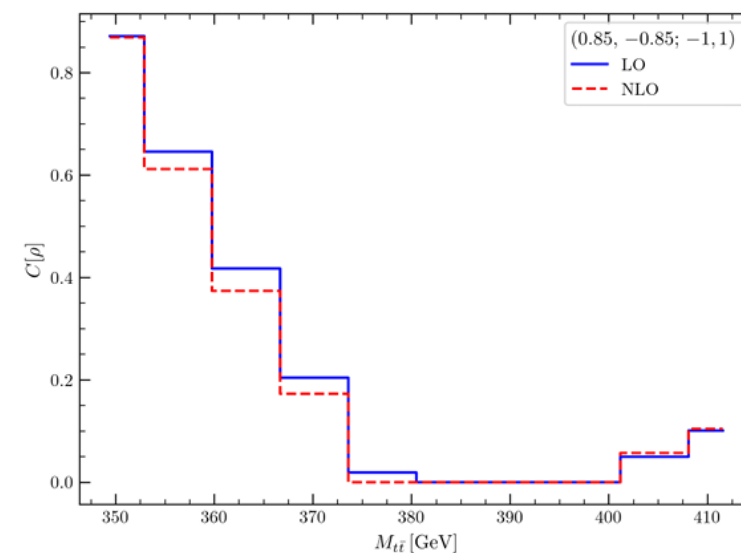
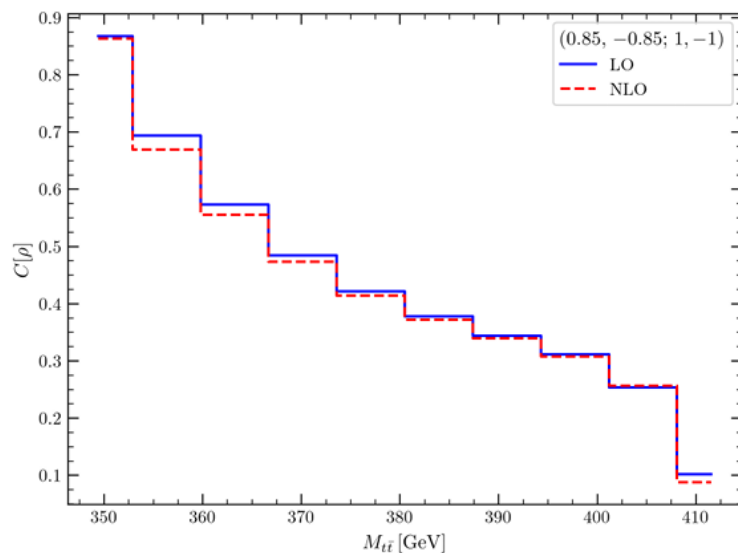
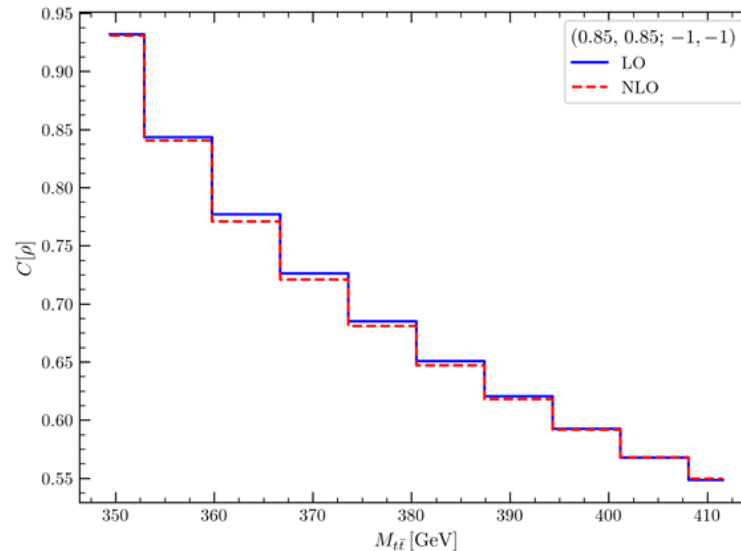
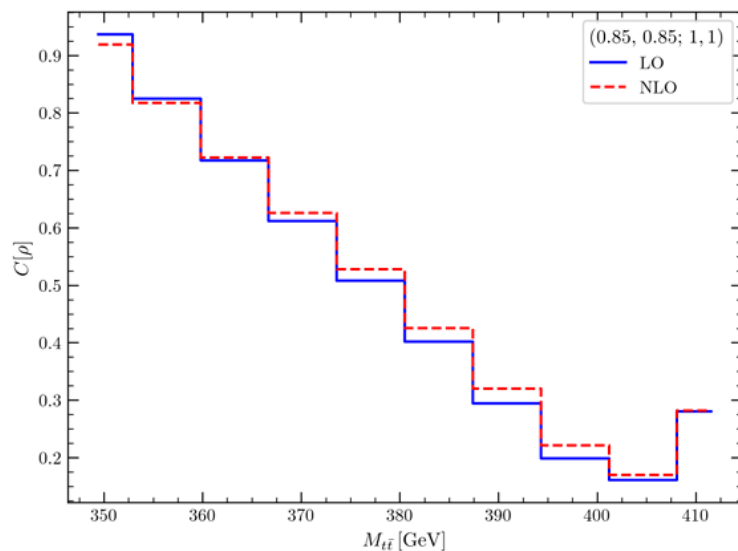
Entanglement Observables



- The concurrence is maximal near the production threshold;
- Bell nonlocality is present at low $M_{t\bar{t}}$ with $m_{12} > 1$;



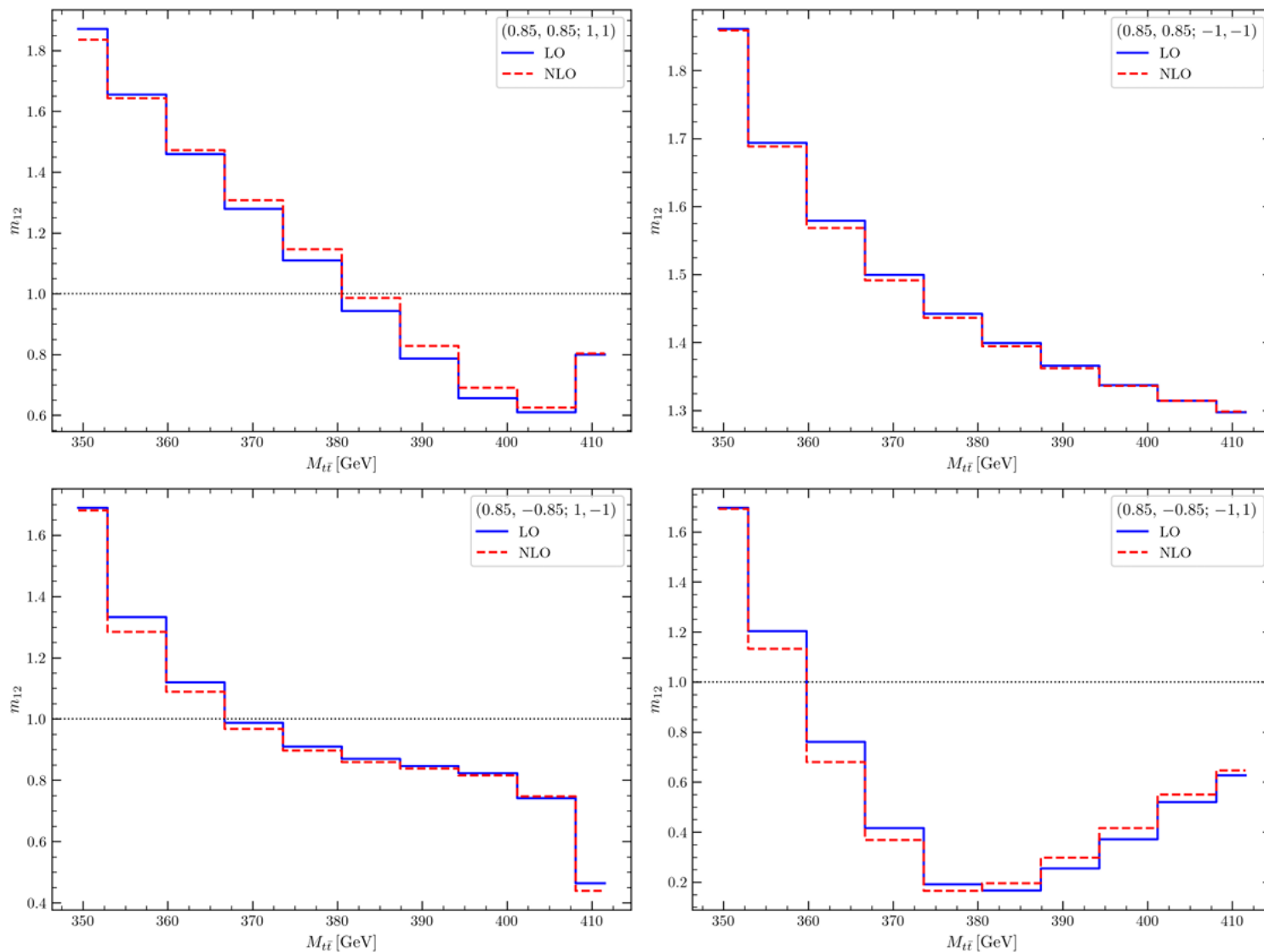
Entanglement Observables



- The concurrence strongly depends on the initial-state polarization.
- $(0.85, -0.85; -1, 1)$ configuration exhibits a **nonmonotonic behavior**.
- NLO QCD corrections are small, producing only minor quantitative changes.



Entanglement Observables



- Bell nonlocality strongly depends on the initial-state polarization.
- The $(0.85, 0.85; -1, -1)$ configuration maintains $m_{12} > 1$ over the full $M_{t\bar{t}}$ range.
- NLO QCD corrections do not alter the qualitative behavior of m_{12} .



Part 04

SUMMARY

1. We present **NLO QCD** corrections on $t\bar{t}$ spin correlations and **quantum entanglement** at a polarized photon collider.
2. Initial-state polarization **significantly affects** the total cross section, spin observables, and quantum entanglement.
3. **NLO QCD** corrections affect cross sections more than spin and quantum-entanglement observables.

Thanks !