Disentangling new physics with quantum entanglement in top-pair production at future lepton colliders

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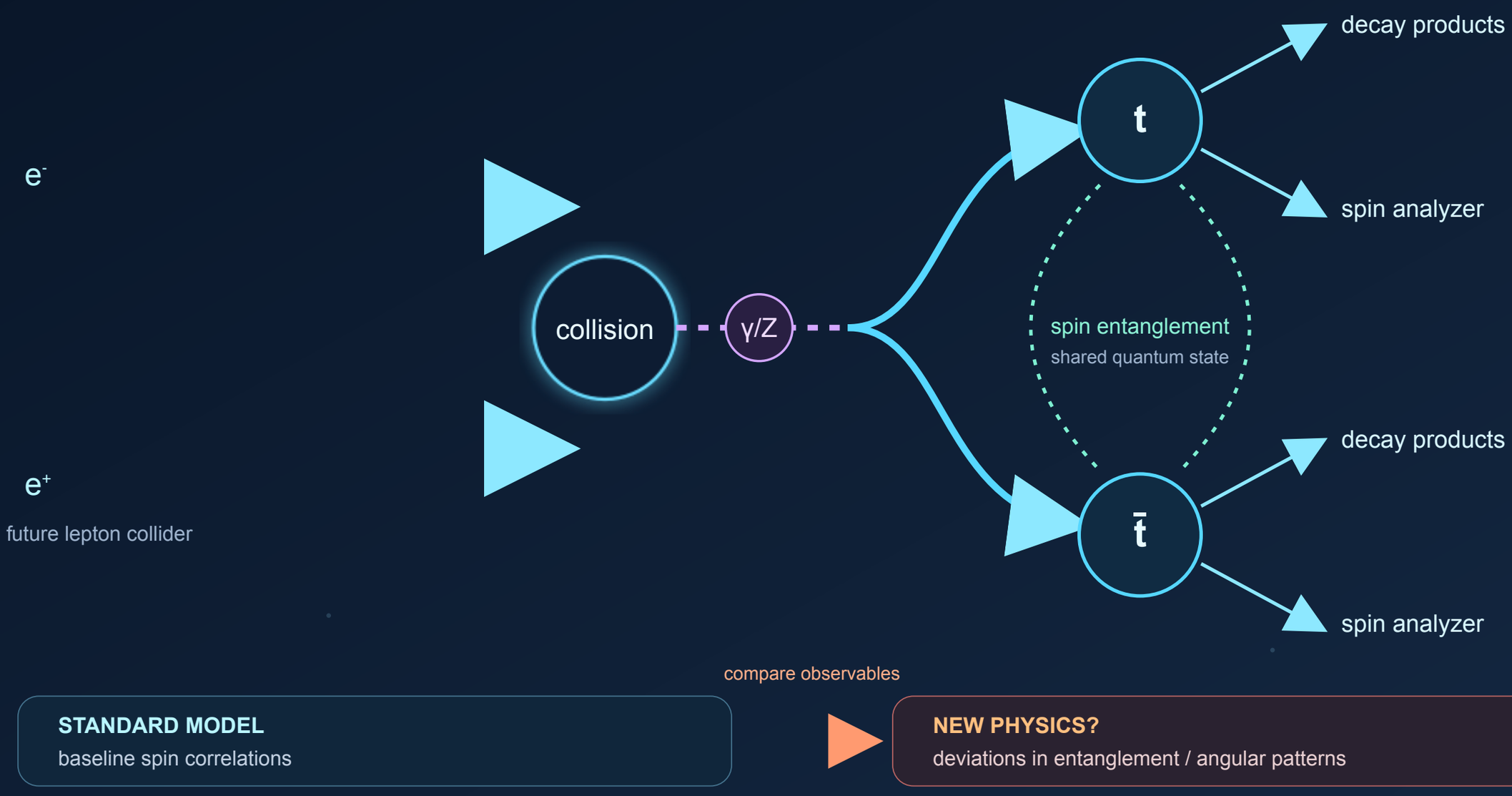
LCWS2026@KEK, 2026/11/11



by ChatGPT with the title only

Disentangling new physics with quantum entanglement

$t\bar{t}$ production at future lepton colliders



compare observables

STANDARD MODEL
baseline spin correlations

NEW PHYSICS?
deviations in entanglement / angular patterns

Top quark
an ideal quantum bit (qubit)

- The heaviest elementary particle (173 GeV)
- Decays (almost) 100% into a bottom quark and a W boson
- Life time (10^{-25} s) < Timescale of hadronization (10^{-24} s)
  ⟹ Top spin information is transferred to its decay products.
- Especially, the distribution of the lepton from top decays is 100% correlated with the spin of the top quark.
  ⟹ We can reconstruct the top-antitop spin quantum state in the dilepton top-pair decays.

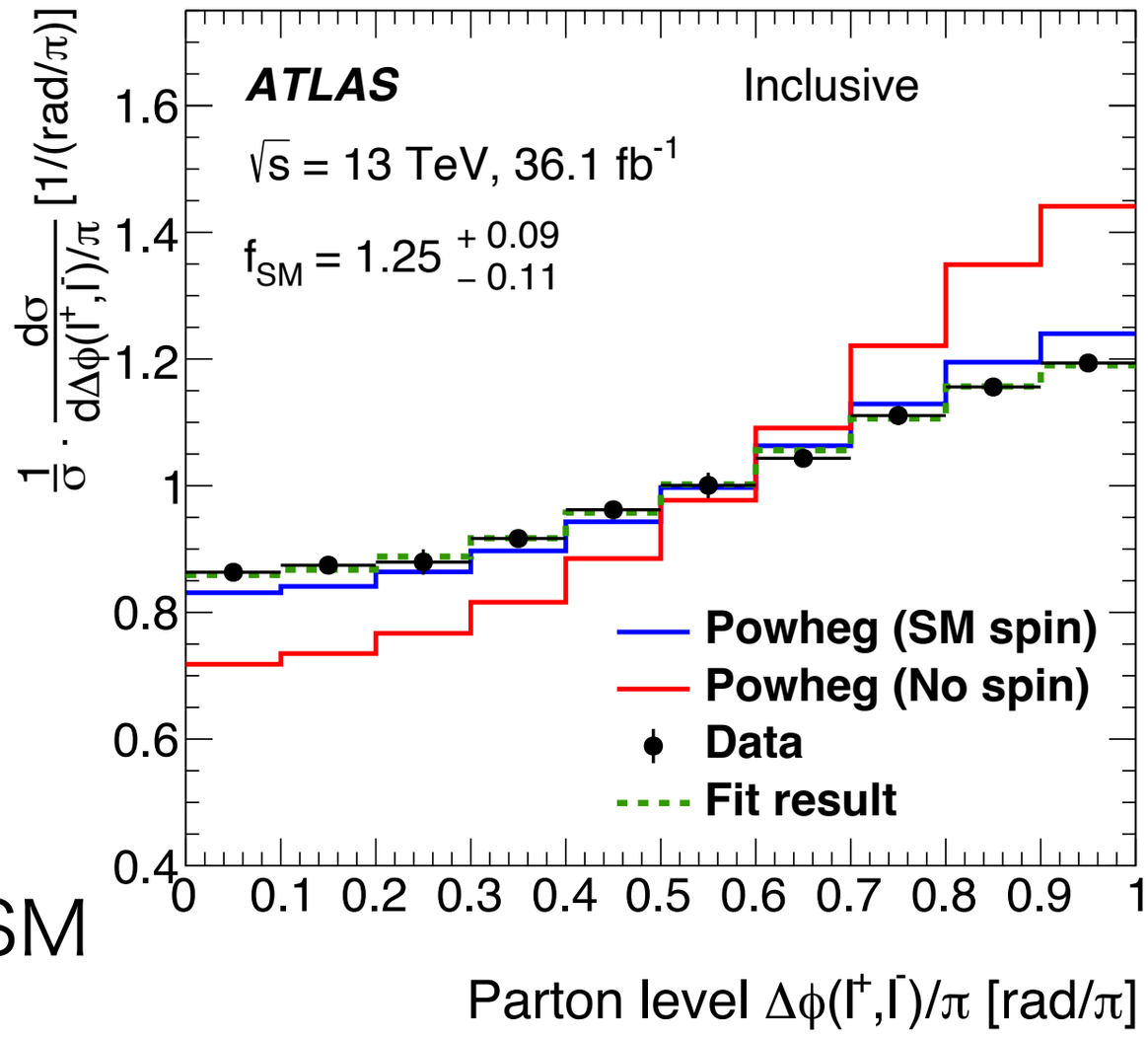
Spin correlations of top-quark pair at the LHC (before quantum fever…)

- The degree of correlation

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}.$$

- $A = 0$: no spin correlation
- $A \neq 0$: spin correlation
  e.g. $A = 3.2$ at LHC14 in the SM

EPJC2020



Quantum entanglement with top quarks at the LHC

(quantum fever!)

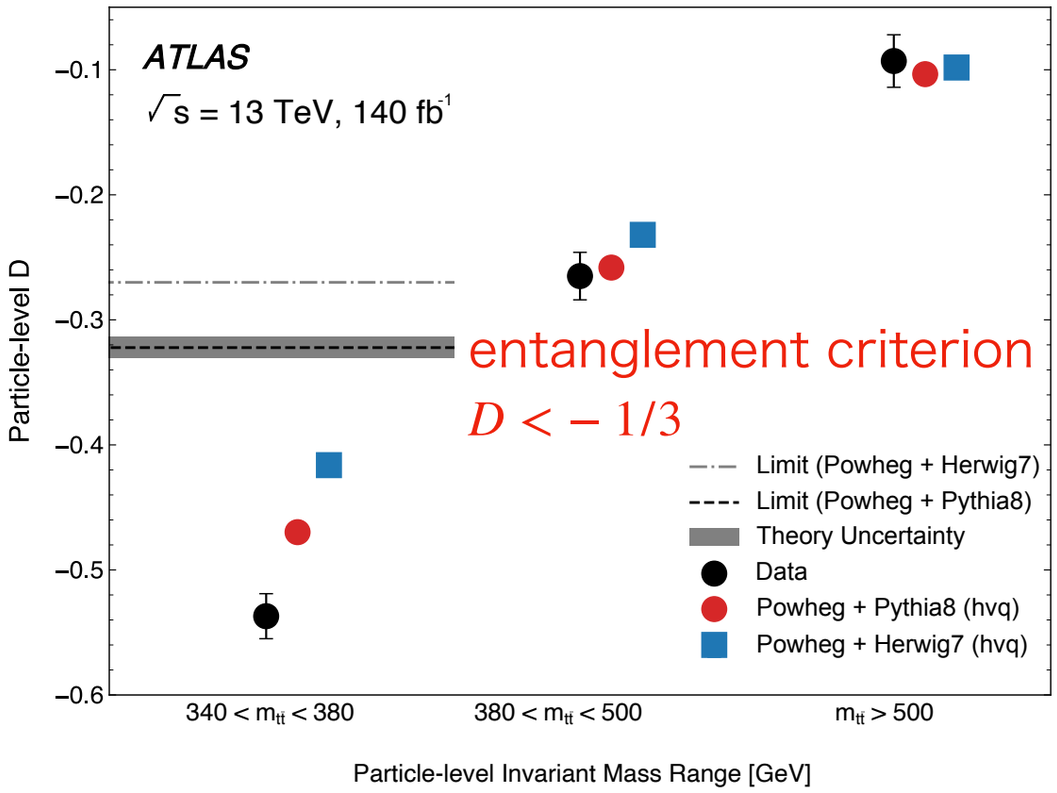
Afik, de Nova (2021)
Fabbrichesi, Floreanini, Panizzo (2021)
Severi, Boschi, Maltoni, Sioli (2022)
Aguilar-Saavedra, Casas (2022)
Maltoni, Severi, Tentori, Vryonidou (2024)
…

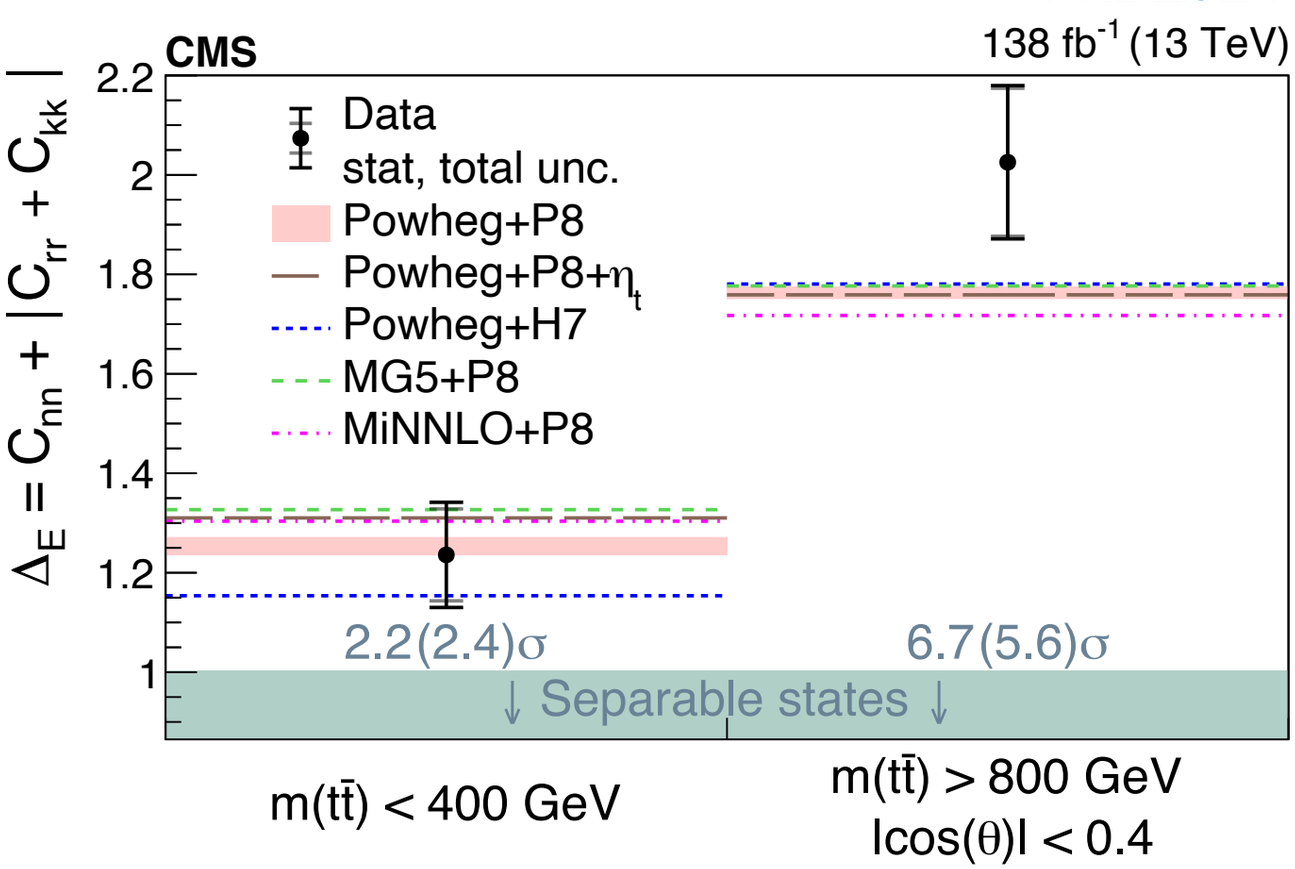
[Lepton colliders]
Maltoni, Severi, Tentori, Vryonidou (2024)
Durupt, Maltoni, Mattelaer (2026)
Altakach, Lamba, Maltoni, Sakurai (2026)
Guo, Han, Low, Su (2026)
…

see also the review paper by Barr, Fabbrichesi, Floreanini, Gabrielli (2024)

PRD2024

Nature2024





Spin density matrix of a two-qubit system

$l^- l^+ \to t\bar{t}$

$$\rho_{\lambda_t \lambda_{\bar{t}}, \lambda'_t \lambda'_{\bar{t}}} = \frac{R_{\lambda_t \lambda_{\bar{t}}, \lambda'_t \lambda'_{\bar{t}}}}{\sum_{\lambda_t, \lambda_{\bar{t}}} R_{\lambda_t \lambda_{\bar{t}}, \lambda_t \lambda_{\bar{t}}}}$$

$$R_{\lambda_t \lambda_{\bar{t}}, \lambda'_t \lambda'_{\bar{t}}} \equiv \frac{1}{4} \sum_{\lambda_{l-}, \lambda_{l+}} \mathcal{M}(\lambda_{l-}, \lambda_{l+}; \lambda_t, \lambda_{\bar{t}}) \, \mathcal{M}^*(\lambda_{l-}, \lambda_{l+}; \lambda'_t, \lambda'_{\bar{t}})$$

unpolarized initial state

- Spin density matrix can be decomposed as

$$\rho = \frac{1}{4} \left(\mathbf{1} \otimes \mathbf{1} + \mathcal{B}_1 \cdot \boldsymbol{\sigma} \otimes \mathbf{1} + \mathcal{B}_2 \cdot \mathbf{1} \otimes \boldsymbol{\sigma} + \mathcal{C} \cdot \boldsymbol{\sigma} \otimes \boldsymbol{\sigma} \right)$$

top-polarization antitop-polarization spin-correlation

$$C_{ij} = \mathrm{Tr}[\rho \, (\sigma_i \otimes \sigma_j)]$$

Entanglement markers

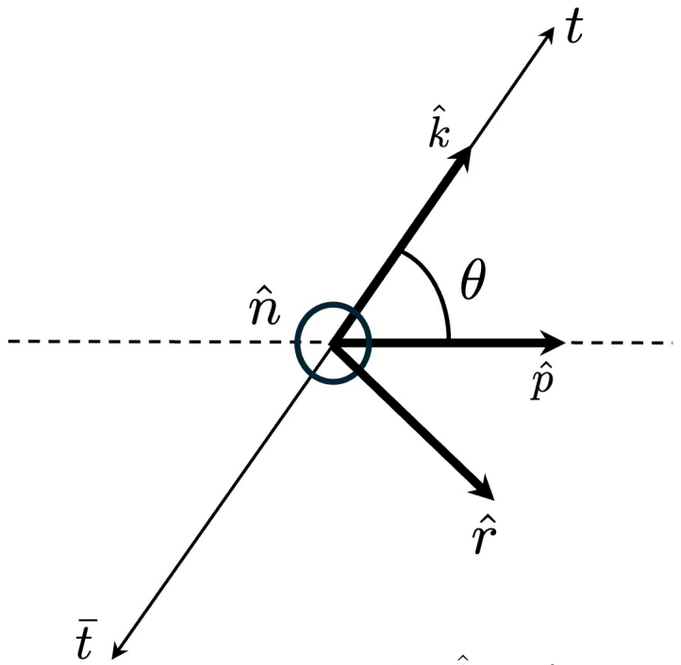
diagonal elements of the correlation matrix C_{ij}

$$D^{(1)} = \frac{1}{3}(C_{kk} + C_{rr} + C_{nn}),$$

$$D^{(k)} = \frac{1}{3}(C_{kk} - C_{rr} - C_{nn}),$$

$$D^{(r)} = \frac{1}{3}(-C_{kk} + C_{rr} - C_{nn}),$$

$$D^{(n)} = \frac{1}{3}(-C_{kk} - C_{rr} + C_{nn}).$$



$\hat{k}$ = top direction, i=3,

$\hat{r} = \frac{\hat{p} - \hat{k}\cos\theta}{\sin\theta}$, i=1,

$\hat{n} = \frac{\hat{p} \times \hat{k}}{\sin\theta}$, i=2

- The sufficient condition for entanglement form the Peres-Horodecki criterion:

$$D_{\min} \equiv \min\{D^{(1)}, D^{(k)}, D^{(r)}, D^{(n)}\} < -\frac{1}{3}$$

Helicity amplitudes to quantum observables

1. Define the model (Lagrangian)

2. Compute the helicity amplitudes

3. Construct the spin density matrix

4. Derive the correlation matrix C

5. Compute the quantum observables, such as entanglement marker, concurrence, CHSH (Clauser-Horne-Shimony-Holt) Bell inequality, …

Helicity amplitudes

in the SM (γ/Z mediated) and beyond (X)

$$\mathcal{M}(\lambda_{l^-},\lambda_{l^+};\lambda_t,\lambda_{\bar{t}}) = \mathcal{M}^{(\mathrm{SM})}(\lambda_{l^-},\lambda_{l^+};\lambda_t,\lambda_{\bar{t}}) + \mathcal{M}^{(X)}(\lambda_{l^-},\lambda_{l^+};\lambda_t,\lambda_{\bar{t}})$$

$$\mathcal{M}^{(\mathrm{SM})}(+,-;\pm,\pm) = \sqrt{1-\beta^2}\,\sin\theta\,\left[e^2Q_lQ_t + \frac{s\,g_Z^{Rl}}{2}\frac{g_Z^{Lt}+g_Z^{Rt}}{s-m_Z^2+im_Z\Gamma_Z}\right],$$

$$\mathcal{M}^{(\mathrm{SM})}(-,+;\pm,\pm) = -\sqrt{1-\beta^2}\,\sin\theta\,\left[e^2Q_lQ_t + \frac{s\,g_Z^{Ll}}{2}\frac{g_Z^{Lt}+g_Z^{Rt}}{s-m_Z^2+im_Z\Gamma_Z}\right],$$

$$\mathcal{M}^{(\mathrm{SM})}(+,-;\pm,\mp) = (1\pm\cos\theta)\left[e^2Q_lQ_t + \frac{s\,g_Z^{Rl}}{2}\frac{g_Z^{Lt}(1\mp\beta)+g_Z^{Rt}(1\pm\beta)}{s-m_Z^2+im_Z\Gamma_Z}\right],$$

$$\mathcal{M}^{(\mathrm{SM})}(-,+;\pm,\mp) = (1\mp\cos\theta)\left[e^2Q_lQ_t + \frac{s\,g_Z^{Ll}}{2}\frac{g_Z^{Lt}(1\mp\beta)+g_Z^{Rt}(1\pm\beta)}{s-m_Z^2+im_Z\Gamma_Z}\right],$$

Helicity amplitudes

in the spin-0, 1, and 2 scenarios

- Spin-0 (Scalar extension)

$$\mathcal{L} \supset -m_\Phi^2 \Phi^\dagger \Phi + \left\{ -Y_l\, \bar{l}_L \Phi l_R - Y_t\, \bar{q}_L \tilde{\Phi} t_R + h.c. \right\}$$

- Spin-1 ($U(1)_{B-L}$)

$$\mathcal{L} \supset -g_{B-L} Q^l_{B-L}\, \bar{l} \gamma^\mu l\, Z'_\mu - g_{B-L} Q^t_{B-L}\, \bar{t} \gamma^\mu t\, Z'_\mu$$

- Spin-2 (Randall-Sundrum)

$$\mathcal{L}_{\rm int} = -\frac{1}{\bar{M}_{\rm Pl}} T^{\mu\nu}(x)\, h^{(0)}_{\mu\nu}(x) - \frac{1}{\Lambda_\pi} T^{\mu\nu}(x) \sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}(x)$$

$$\mathcal{M}^{(\Phi)}(\pm,\pm;\pm,\pm) = -\frac{s}{2}\frac{Y_l Y_t\,(1-\beta)}{s - m_\Phi^2 + i m_\Phi \Gamma_\Phi},$$
$$\mathcal{M}^{(\Phi)}(\pm,\pm;\mp,\mp) = \frac{s}{2}\frac{Y_l Y_t\,(1+\beta)}{s - m_\Phi^2 + i m_\Phi \Gamma_\Phi},$$

$$\mathcal{M}^{(Z')}(\pm,\mp;+,+) = \pm\sqrt{1-\beta^2}\sin\theta \frac{s\, g^2_{B-L} Q^l_{B-L} Q^t_{B-L}}{s - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}},$$
$$\mathcal{M}^{(Z')}(\pm,\mp;-,-) = \pm\sqrt{1-\beta^2}\sin\theta \frac{s\, g^2_{B-L} Q^l_{B-L} Q^t_{B-L}}{s - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}},$$
$$\mathcal{M}^{(Z')}(\pm,\mp;+,-) = (1 \pm \cos\theta)\frac{s\, g^2_{B-L} Q^l_{B-L} Q^t_{B-L}}{s - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}},$$
$$\mathcal{M}^{(Z')}(\pm,\mp;-,+) = (1 \mp \cos\theta)\frac{s\, g^2_{B-L} Q^l_{B-L} Q^t_{B-L}}{s - m^2_{Z'} + i m_{Z'}\Gamma_{Z'}},$$

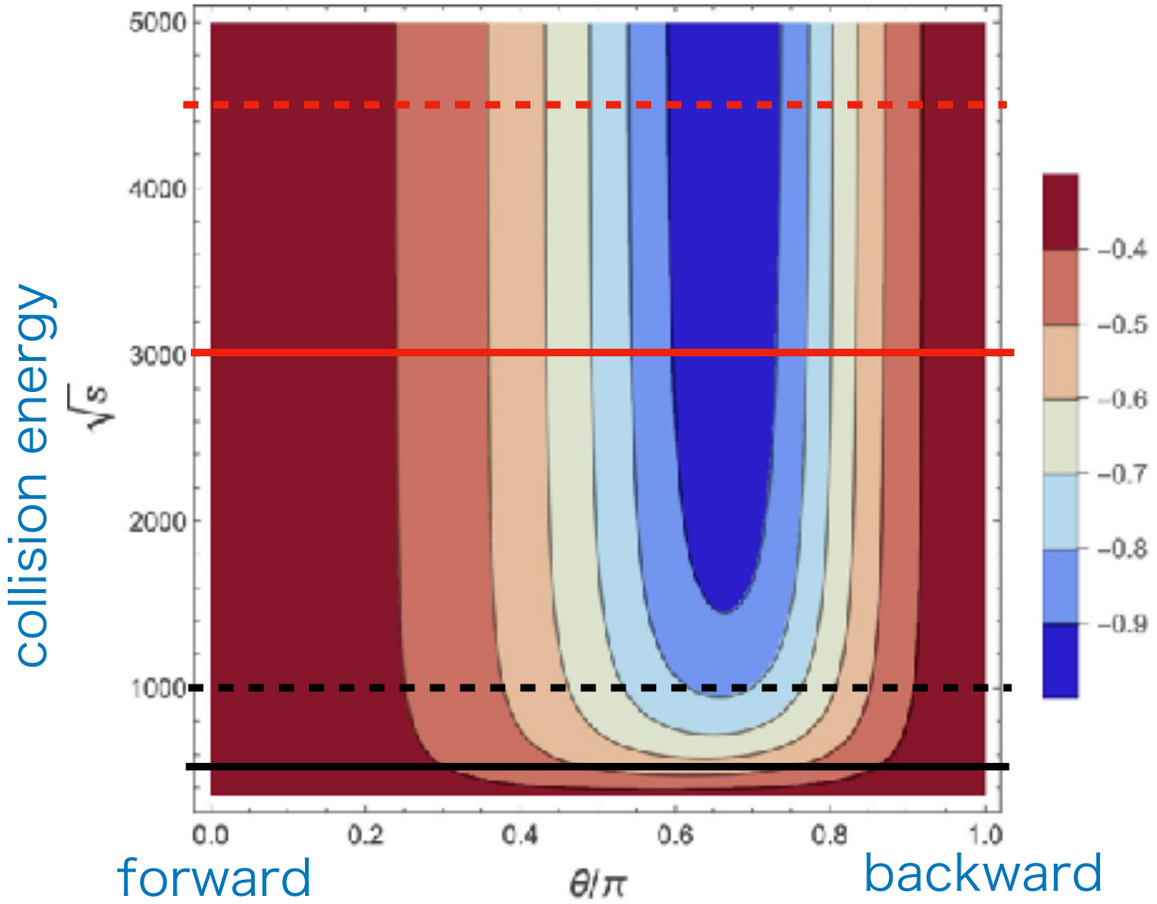
$$\mathcal{M}^{(G)}(\pm,\mp;+,+) = \mp\frac{s^2\beta}{4} A(s)\sqrt{1-\beta^2}\,\sin\theta\cos\theta,$$
$$\mathcal{M}^{(G)}(\pm,\mp;-,-) = \mp\frac{s^2\beta}{4} A(s)\sqrt{1-\beta^2}\,\sin\theta\cos\theta,$$
$$\mathcal{M}^{(G)}(\pm,\mp;+,-) = \mp\frac{s^2\beta}{8} A(s)\,(2\cos^2\theta \pm \cos\theta - 1),$$
$$\mathcal{M}^{(G)}(\pm,\mp;-,+) = \pm\frac{s^2\beta}{8} A(s)\,(2\cos^2\theta \mp \cos\theta - 1).$$

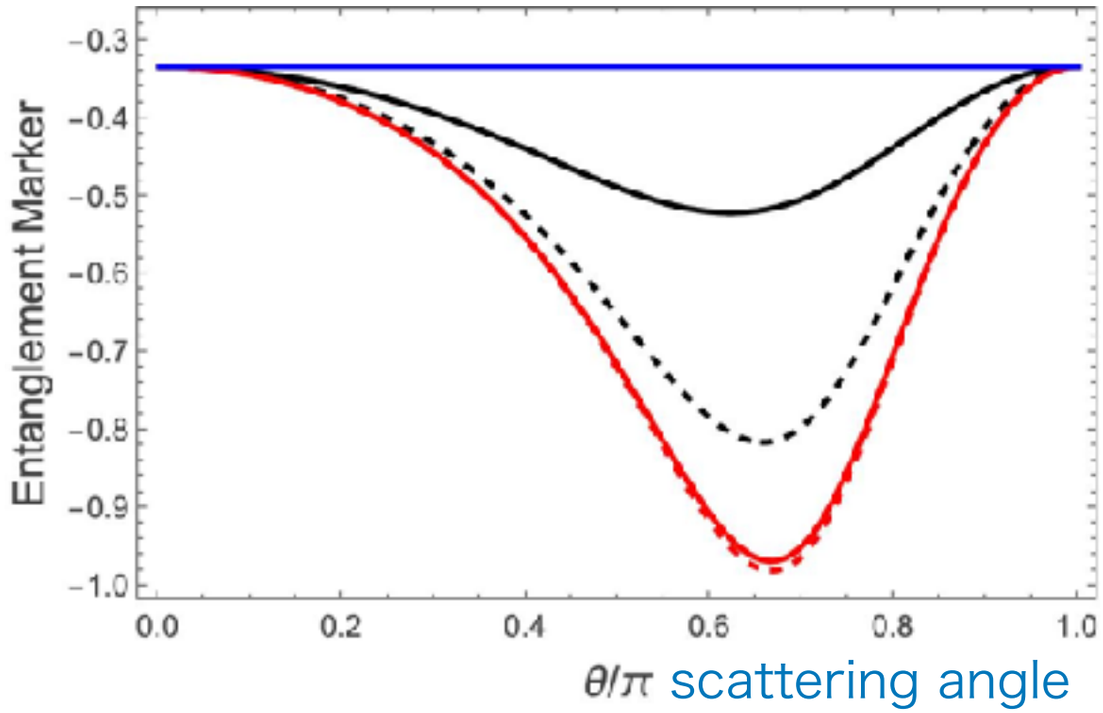
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model	mediated particle	masses [TeV]	coupling parameters
scalar-mediator	Φ (spin-0)	0.2	$Y_l = Y_t = 0.2$
$U(1)_{B-L}$	Z' (spin-1)	5.0	$g_{B-L} = 0.4$
RS	G (spin-2)	5.5, 10.1, 14.6, 19.1	$\kappa/\bar{M}_{\rm Pl} = 0.2$

Entanglement markar D_{min}

in the SM (photon and Z mediated)

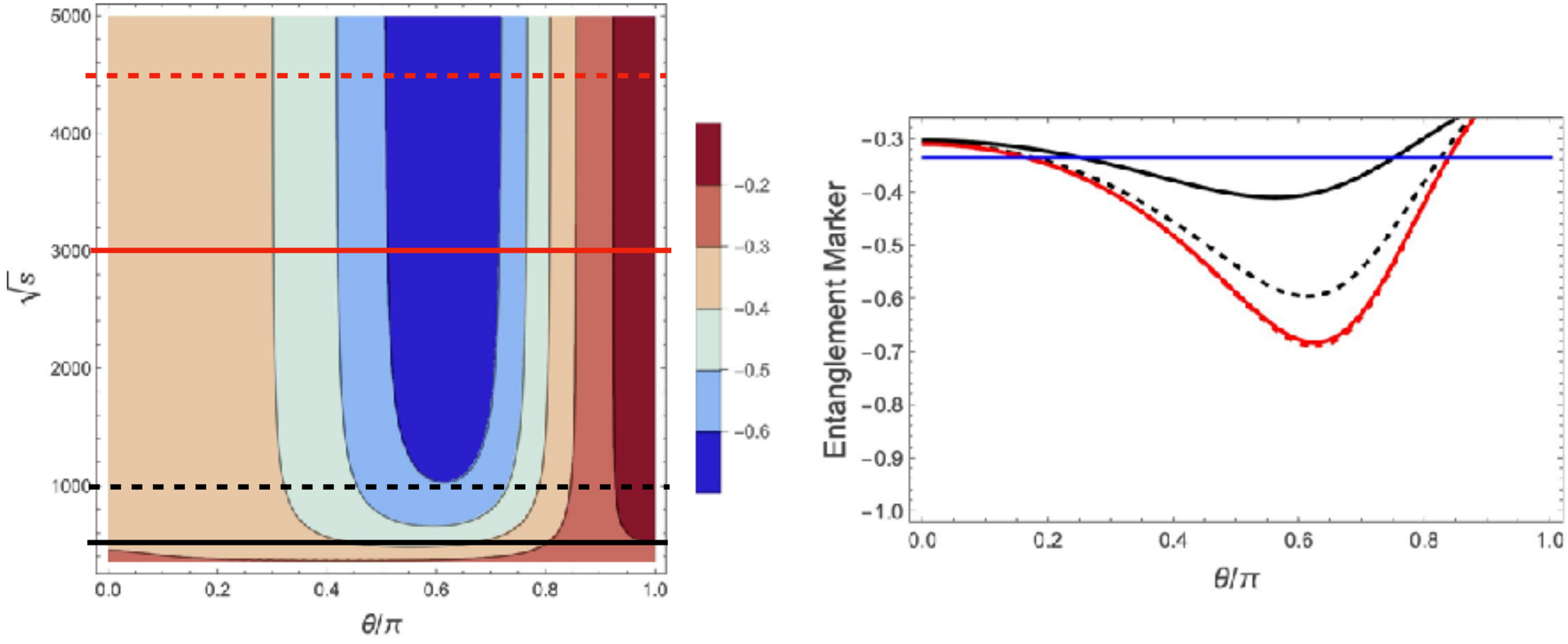




- The correlation is strongest in the backward region, $\theta/\pi \sim 0.7$, and increases gradually with energy.
- This asymmetry is due to the chiral structure of the couplings between the Z boson and the fermions.

Entanglement markar D_{min}

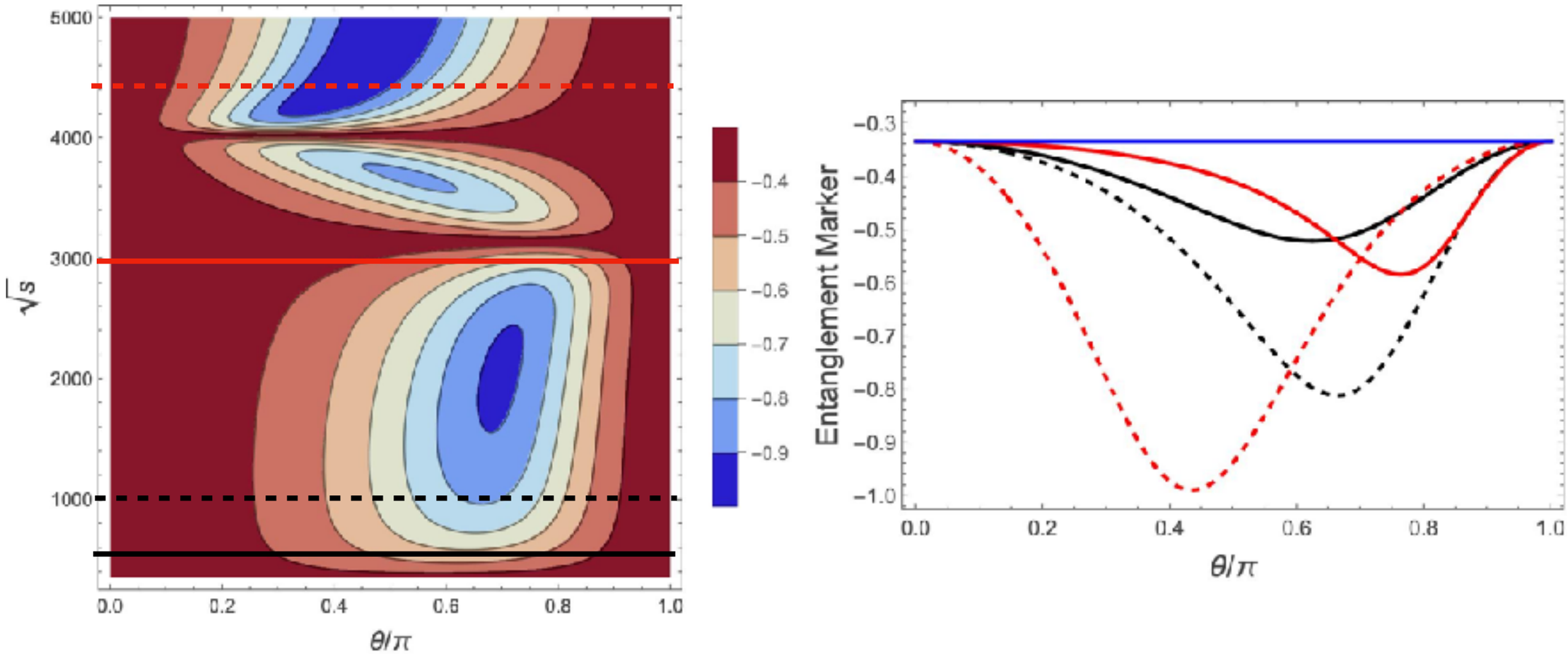
in the spin-0 mediated scenario



- Overall behaviors remain unchanged due to the absence of strong interference with the SM amplitudes.

- Reduction of the entanglement is observed, since, unlike the SM vector interactions, scalar exchange enhances like-helicity top-pair configurations, which dilute the opposite-helicity correlations in the SM.

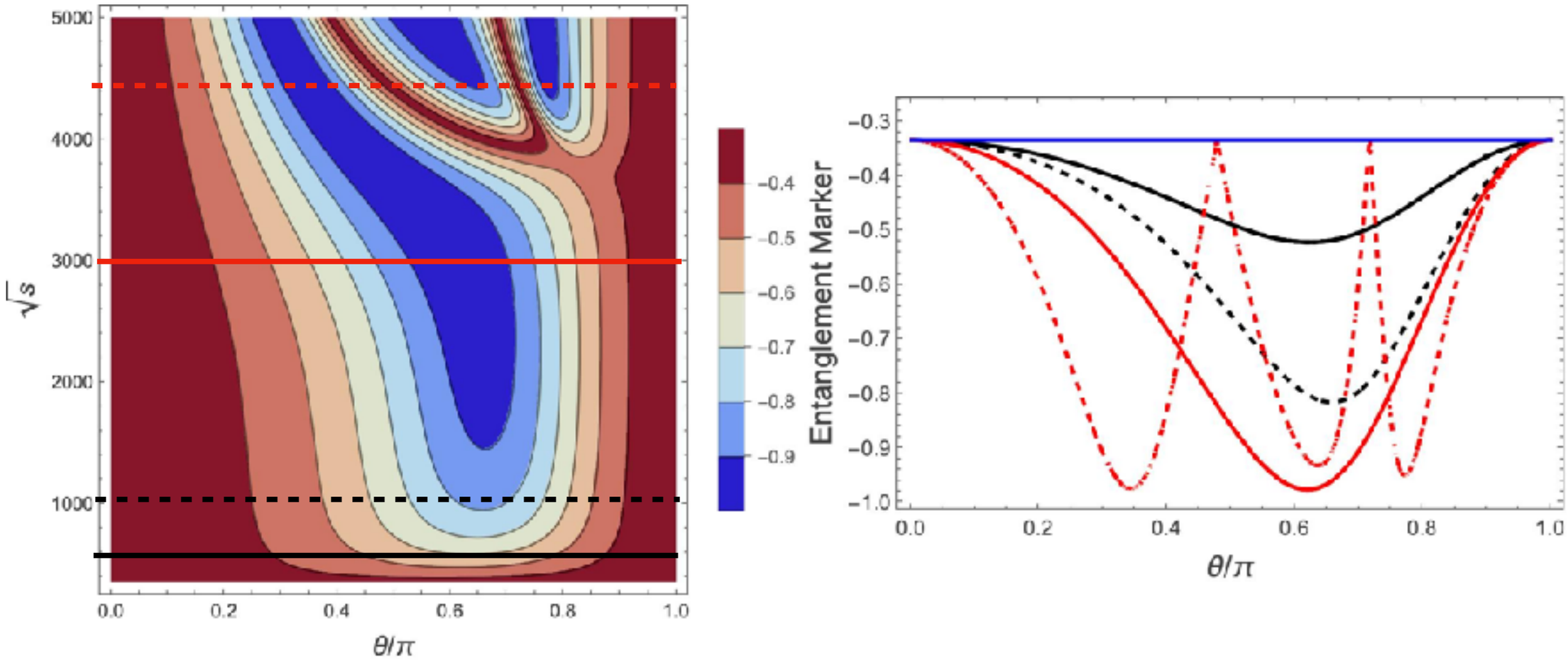
Entanglement markar D_{min}
in the spin-1 mediated scenario



- Characteristic reshaping of the entanglement pattern is observed.
- This is due to the interference between the chiral SM interaction and the vector-like Z' interaction.

Entanglement markar D_{min}

in the spin-2 mediated scenario



- Characteristic angular structures associated with spin-2 massive graviton exchange in higher energies.
- All the behaviors can be explained by the interference between the SM contribution and the KK-graviton contribution.

Automated computation of spin-density matrices and quantum observables in MadGraph

by V. Durupt, F. Maltoni, O. Mattelaer [JHEP04(2026)103]

Model	$D^{(1)}$		$D^{(k)}$		$D^{(r)}$		$D^{(n)}$	
	Theory	`MadGraph`	Theory	`MadGraph`	Theory	`MadGraph`	Theory	`MadGraph`
SM	0.333	0.333	0.326	0.326	−0.133	−0.135	−0.526	−0.525
scalar-mediator	−0.338	−0.338	−0.329	−0.329	0.333	0.333	0.333	0.333
$U(1)_{B-L}$	0.333	0.333	0.325	0.325	0.002	0.002	−0.660	−0.660
RS	0.333	0.333	0.322	0.322	−0.438	−0.439	−0.217	−0.216

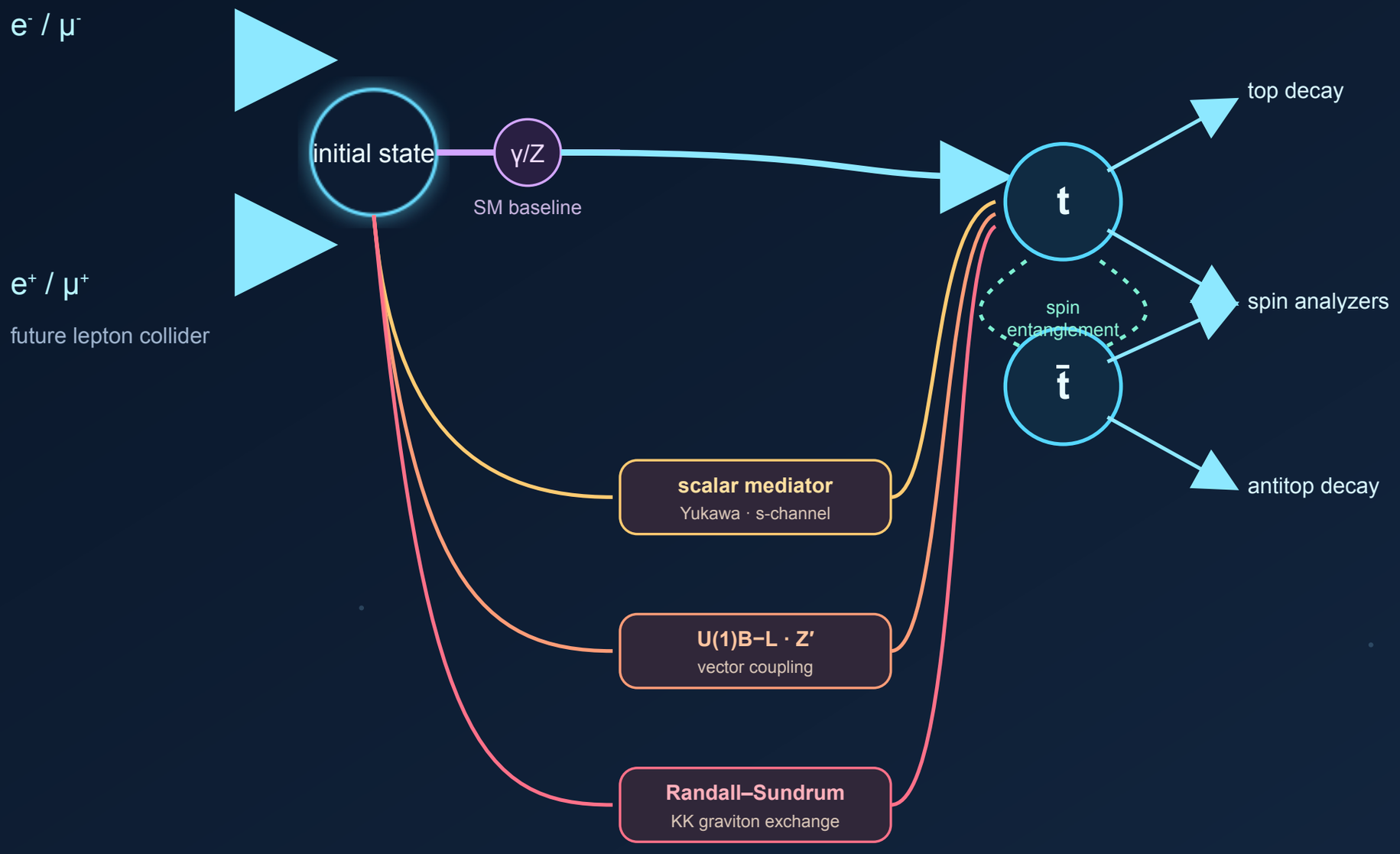
Table 3: Comparison of the entanglement markers $D^{(i)}$ obtained from the analytical calculation (Theory) and the numerical simulation by `MadGraph`.

- We confirmed all the numerical results based on analytical formula by automated computation of event-by-event spin-density matrices in MadGraph;
  spin-0, 2: `HiggsCharacterisation` (`HC`) model [Artoisenet et al. JHEP2013]
  spin-1: `U1XGeneric` model [Das et al. PRD2022]

- We would like to thank Valentin Durupt, Fabio Maltoni, and Olivier Mattelaer for technical help in numerical computation of spin density matrices in MadGraph.

Disentangling new physics with quantum entanglement

$t\bar{t}$ production at future lepton colliders · ILC and multi-TeV $\mu^+\mu^-$ colliders



Quantum observables

- entanglement marker
- concurrence
- maximal CHSH parameter

Scan dependence on:

√s · scattering angle θ

model parameters

spin correlations → new physics

SM: characteristic spin correlations

Scalar: typically reduced entanglement

Z′ / KK graviton: sizable deviations possible

Summary and outlook

- We performed a systematic study of **quantum entanglement for top-pair production at future lepton colliders** within the SM and three representative BSM scenarios, additional spin-0, 1, and 2 mediated interactions.
- We found that each scenario produces **qualitatively distinct patterns in the QI observables**, reflecting the properties of the underlying new particle and its interactions.
- Incorporating realistic reconstruction and detector effects will be essential for accessing the experimental feasibility of measuring these QI observables in practice.

6th Iwate Collider School

ICS2027

23-27 February, 2027

Appi highland, Iwate, Japan

Registration fee

FREE and local expenses will be supported.
(No support for travel fees.)

Eligibility

Mainly for graduate students and postdoc fellows
(Max. 25 participants in person)

Venue

ANA Holiday INN Resort Appi Kogen

Application submission deadline

6 December, 2026

Website

https://ics.sgk.iwate-u.ac.jp/

Contact

Overview

Students will learn a variety of topics in collider physics via lectures and tutorials. Long lunch break for skiing and discussions are planned.

Lecturers:

- Shion Chen (Kyoto, Japan)
- Benjamin Fuks (Paris, France)
- Tao Han (Pittsburgh, USA)
- Theo Heimel (Louvain, Belgium)
- Fabio Maltoni (Louvain / Bologna, Italy)
- Daniele Massaro (CERN, Switzerland)
- Olivier Mattelaer (Louvain, Belgium) etc.

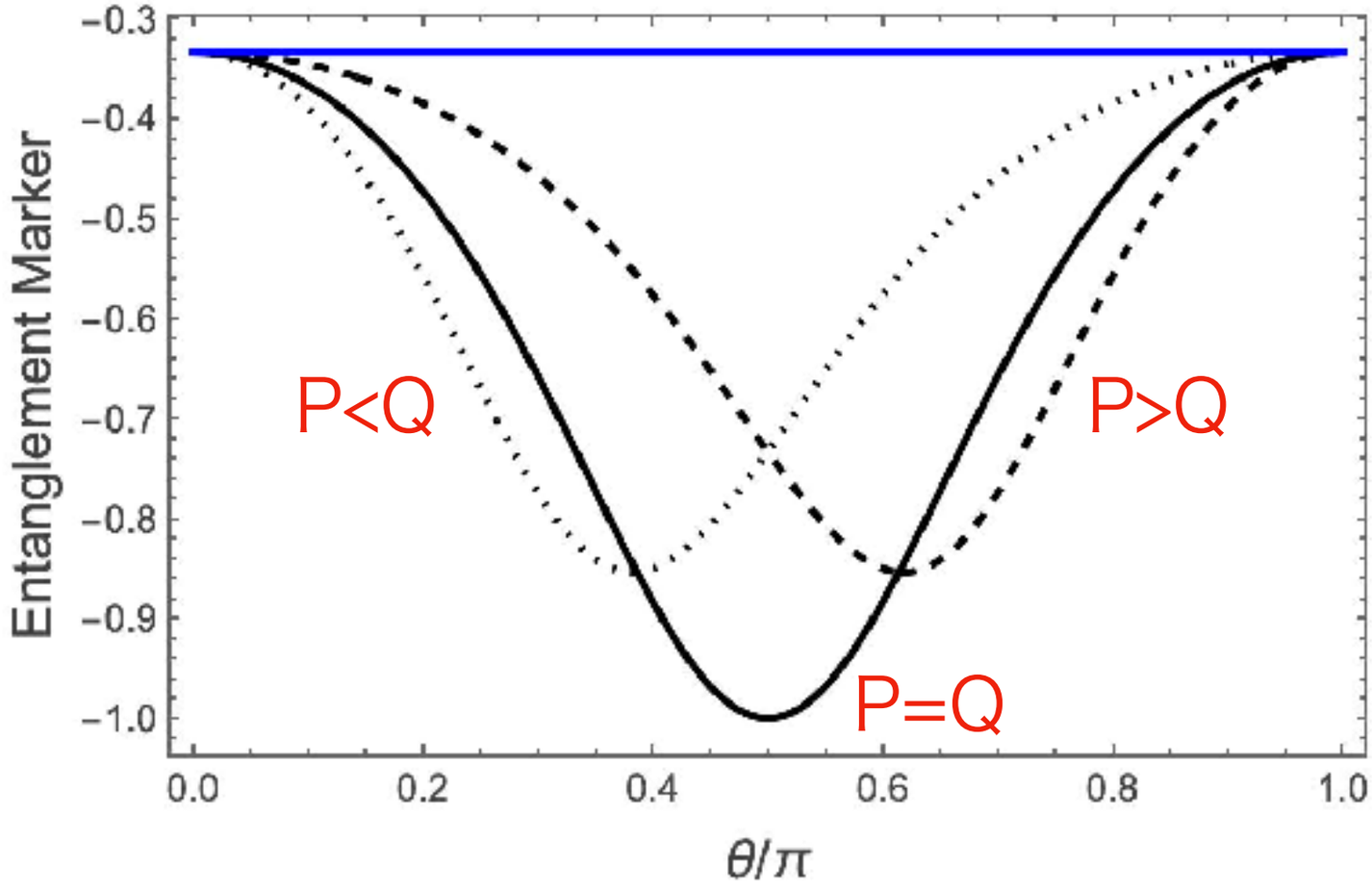
Organizers:

- Kaoru Hagiwara (KEK)
- Junichi Kanzaki (Iwate U.)

supplement

Entanglement marker

a toy chiral spin-1 coupling model



$$\cos\theta_{\rm ext} = \frac{\sqrt{Q}-\sqrt{P}}{\sqrt{P}+\sqrt{Q}}$$

$$P = \left(g_R^t g_R^e\right)^2 + \left(g_L^t g_L^e\right)^2$$
$$Q = \left(g_R^t g_L^e\right)^2 + \left(g_L^t g_R^e\right)^2$$

Entanglement markar

a toy chiral + heavy vectorlike coupling model

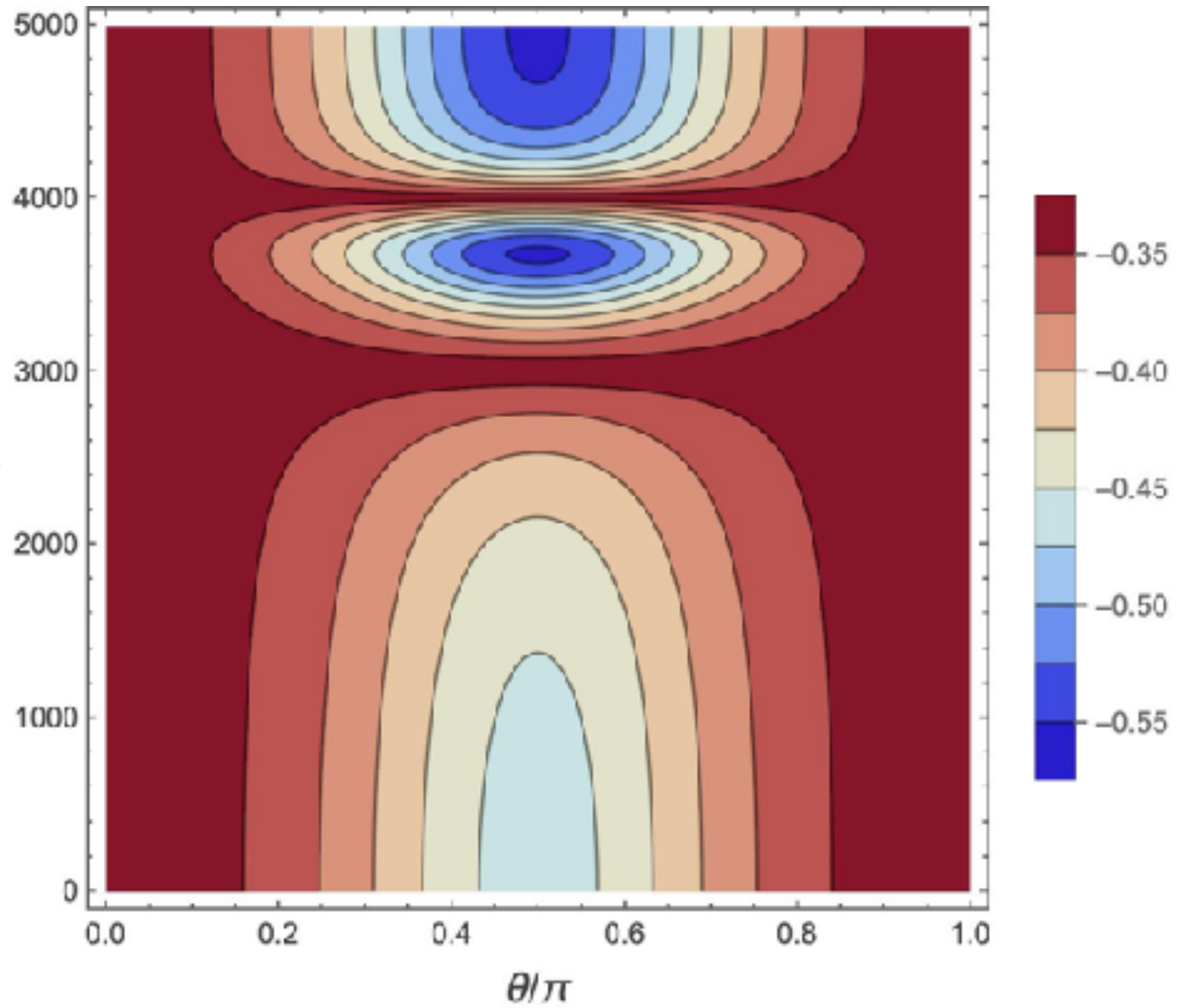
$$\mathcal{L}_{\rm int} = A_\mu \left[\bar{e}\gamma^\mu \left(g_L^l P_L + g_R^l P_R\right) e + \bar{t}\gamma^\mu \left(g_L^t P_L + g_R^t P_R\right) t\right] + g_{B-L} X_\mu \left(Q_{B-L}^l\, \bar{e}\gamma^\mu e + Q_{B-L}^t\, \bar{t}\gamma^\mu t\right).$$

$$\rho(s,\theta) = \frac{1}{N(s,\theta)} \begin{pmatrix} A(s,\theta) & 0 & 0 & B(s,\theta) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ B(s,\theta) & 0 & 0 & D(s,\theta) \end{pmatrix}$$

$$B(s,\theta) = [G_{RR}(s)G_{RL}(s) + G_{LR}(s)G_{LL}(s)]\sin^2\theta$$

$$G_{RR}(s) = g_R^l g_R^t - \chi(s), \qquad G_{LR}(s) = g_L^l g_R^t - \chi(s),$$
$$G_{LL}(s) = g_L^l g_L^t - \chi(s), \qquad G_{RL}(s) = g_R^l g_L^t - \chi(s),$$

$$\chi(s) = \frac{g_{B-L}^2}{3}\frac{s}{s - M_X^2}$$



- The entanglement marker reaches the separability bound when the off-diagonal element vanishes, i.e.

$$G_{RR}(s)G_{RL}(s) + G_{LR}(s)G_{LL}(s) = 0$$

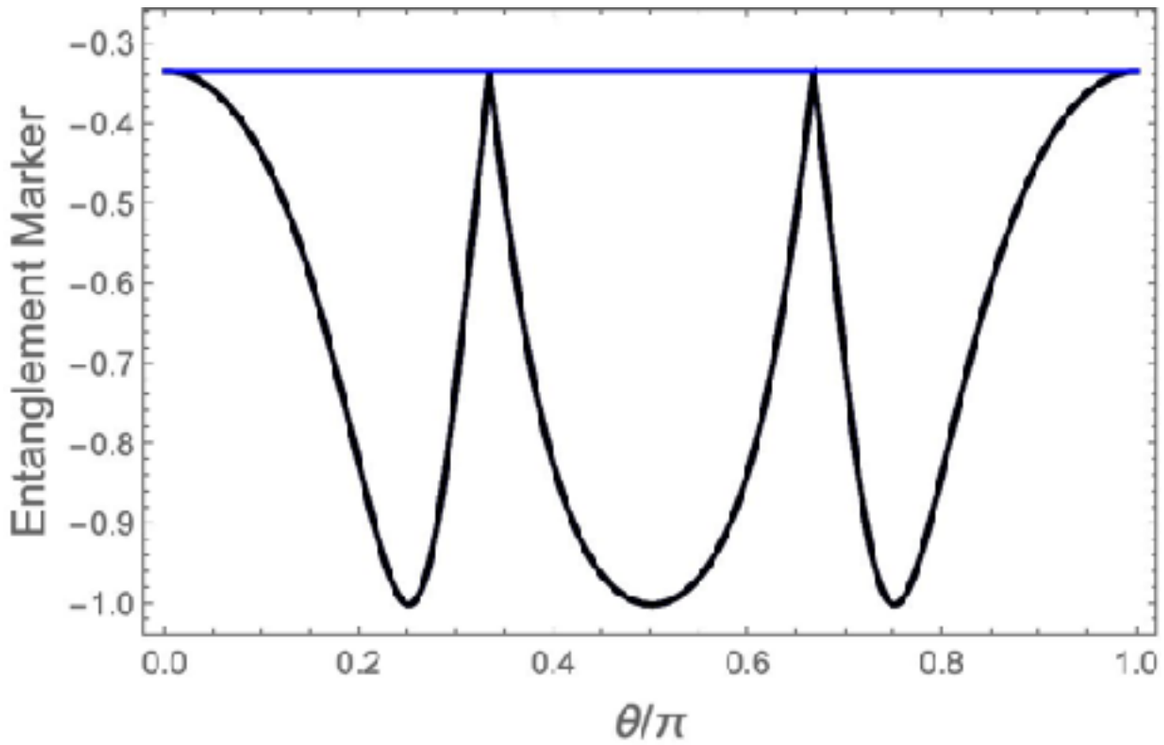
Entanglement markar

only first KK graviton with the massless top limit

$$\rho = \frac{1}{2}\begin{pmatrix} 1 & 0 & 0 & r(\theta) \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ r(\theta) & 0 & 0 & 1 \end{pmatrix}$$

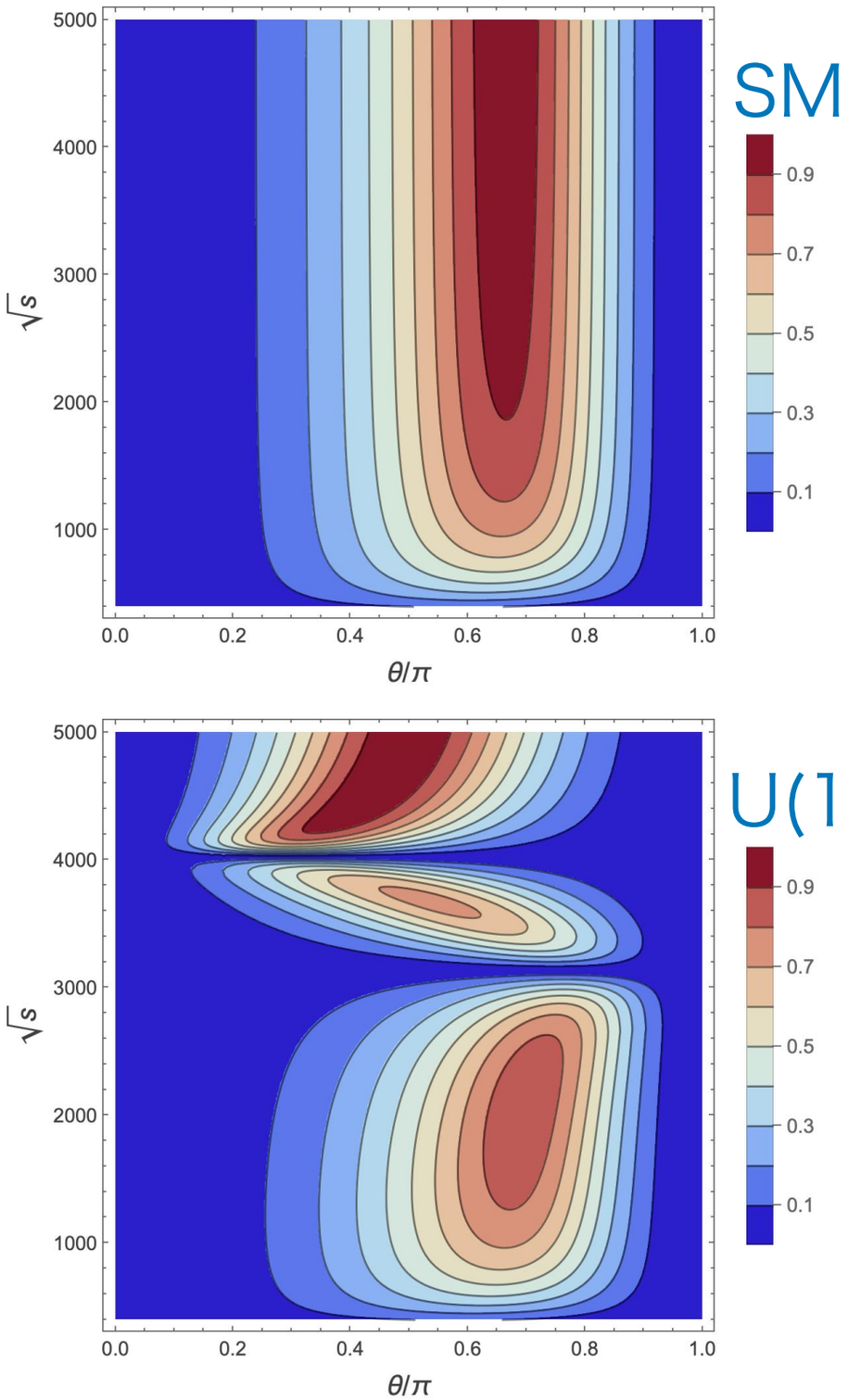
$$r(\theta) = \frac{2\sin\theta\sin 3\theta}{2+\cos 2\theta+\cos 4\theta}$$

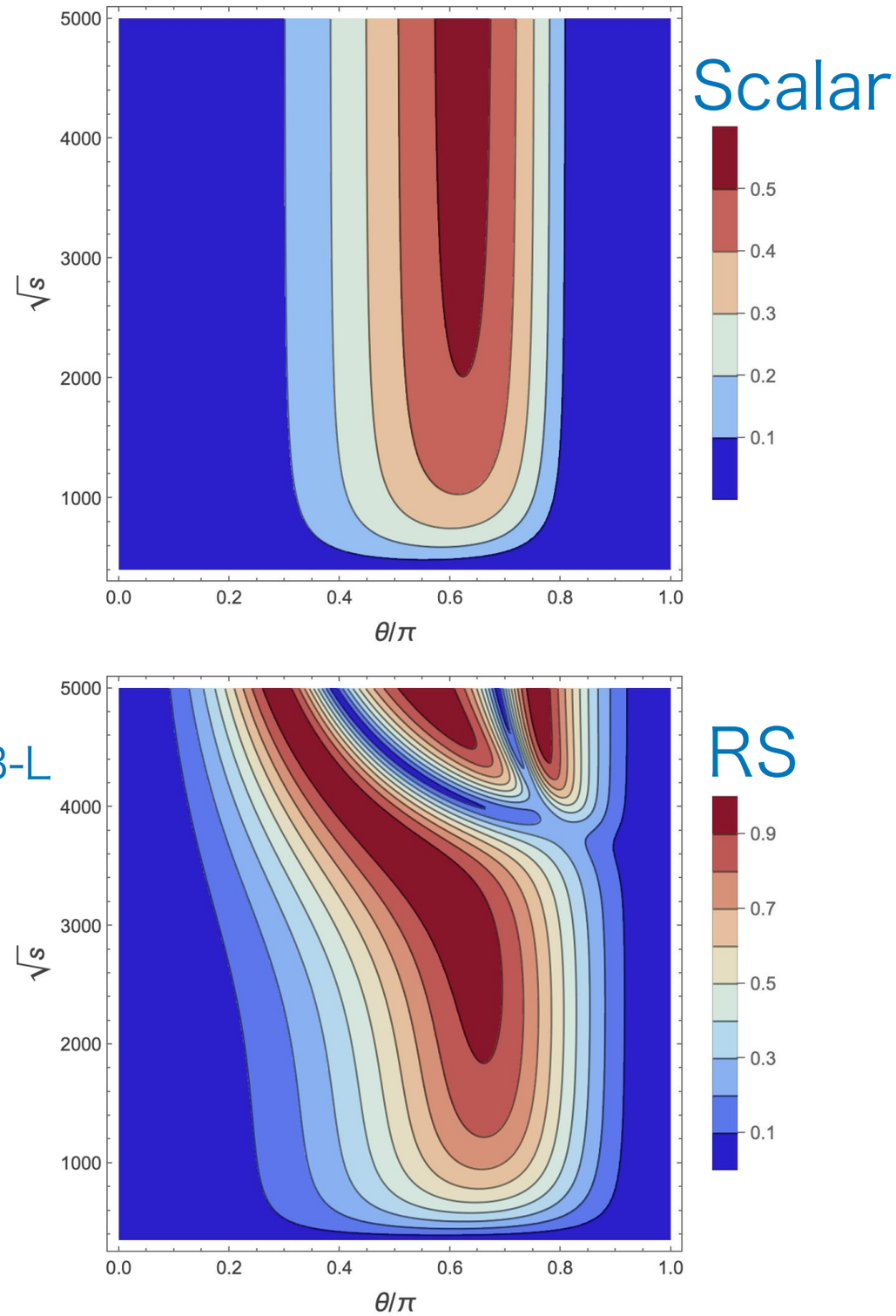
$$D_{\min}(\theta) = -\frac{1}{3}\left(1+2\left|r(\theta)\right|\right)$$



- The entanglement marker becomes its boundary value whenever $r(\theta) = 0$, i.e. $\theta = n\pi/3$.

Concurrence





CHSH Bell parameter

