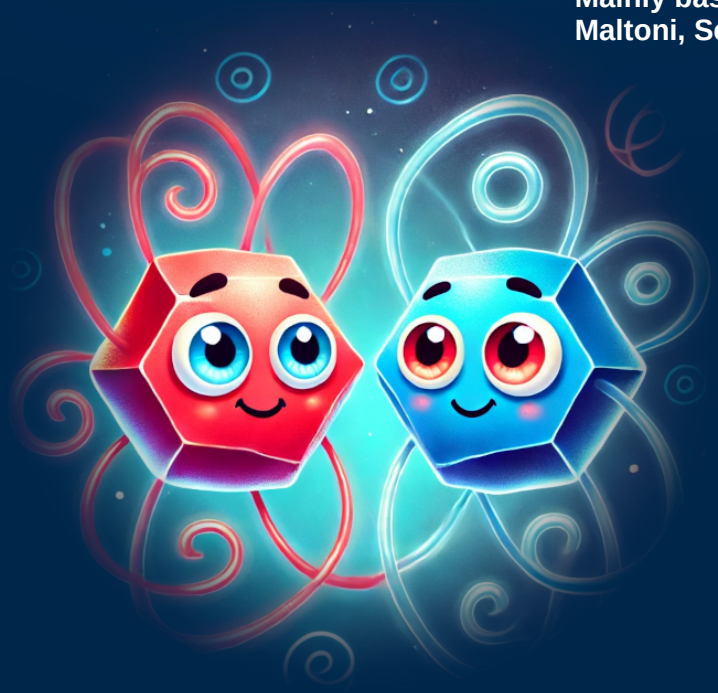
Quantum tops at circular lepton colliders

Mainly based on:
Maltoni, Severi, ST, Vryonidou: 2404.08049



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fnrs
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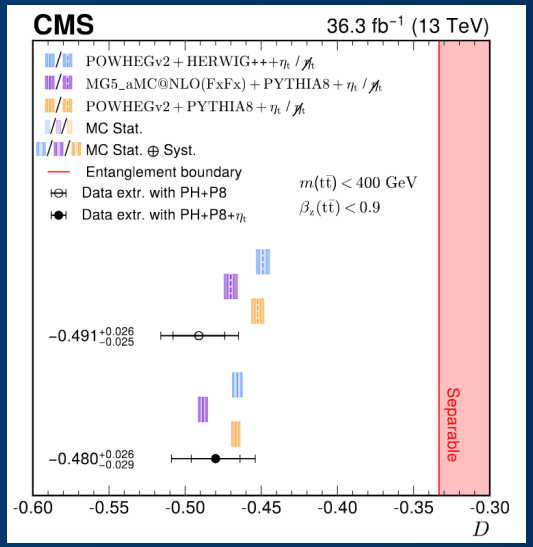
UCLouvain

Quantum Tops at the LHC

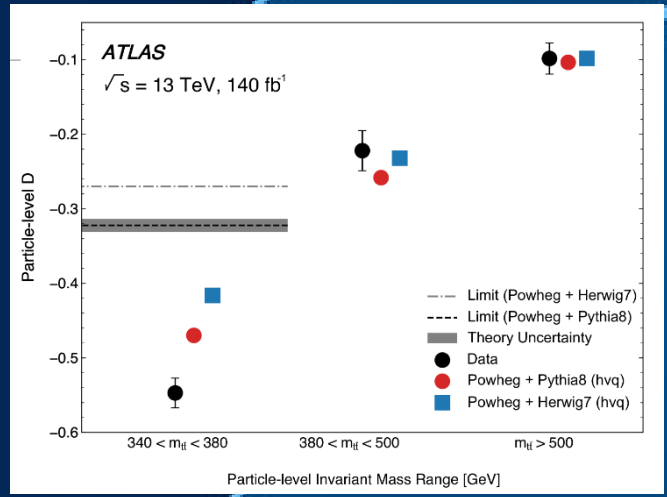
Article | Open access | Published: 18 September 2024

Observation of quantum entanglement with top quarks at the ATLAS detector

The ATLAS Collaboration



ATLAS AND CMS OBSERVATION OF TOP QUANTUM ENTANGLEMENT AT LHC



Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*

WHAT'S NEXT?

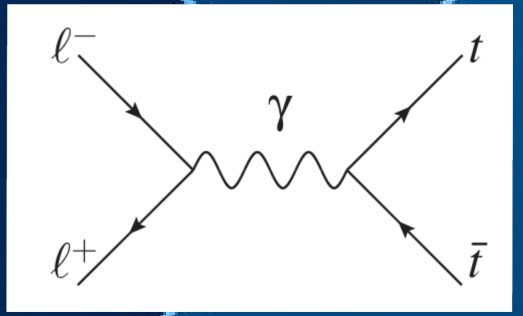
WHAT'S NEXT?

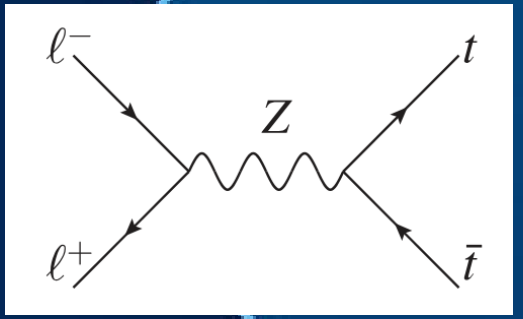
Quantum Tops as New Physics Probe

[Maltoni, Severi, ST, Vryonidou 2401.08751]

WHAT'S NEXT?

Quantum Tops as New Physics Probe [Maltoni, Severi, ST, Vryonidou 2401.08751]





Quantum Tops at Future Lepton Colliders

THIS TALK!

Simone Tentori

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Tops as Qubits

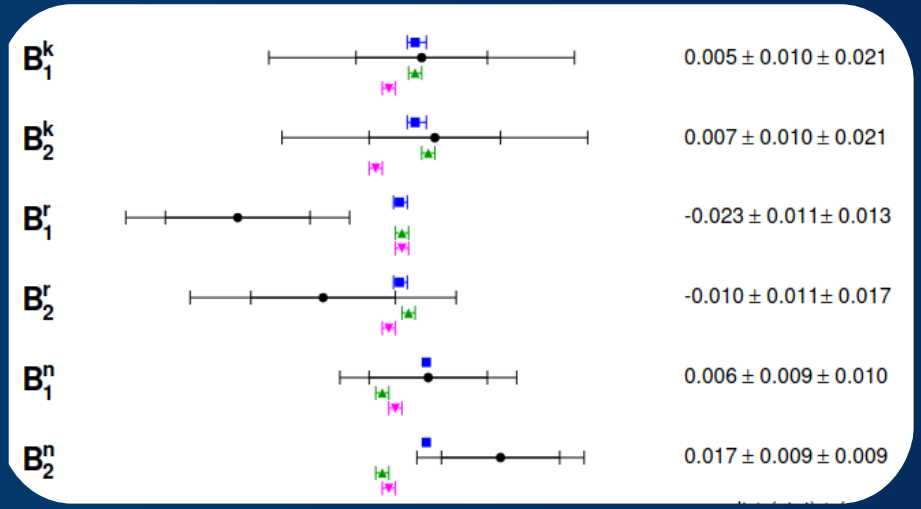
$$\rho = {}^1\!/_4\big(\mathbf{1}\otimes\mathbf{1} + \mathcal{B}_1\cdot\boldsymbol{\sigma}\otimes\mathbf{1} + \mathcal{B}_2\cdot\mathbf{1}\otimes\boldsymbol{\sigma} + \mathcal{C}\cdot\boldsymbol{\sigma}\otimes\boldsymbol{\sigma}\big),$$

Quantum Info

Tops as Qubits

$$\rho = {}^1/_4\left(1 \otimes 1 + \mathcal{B}_1 \cdot \boldsymbol{\sigma} \otimes 1 + \mathcal{B}_2 \cdot 1 \otimes \boldsymbol{\sigma} + \mathcal{C} \cdot \boldsymbol{\sigma} \otimes \boldsymbol{\sigma}\right),$$

Quantum Info



POLARISATION

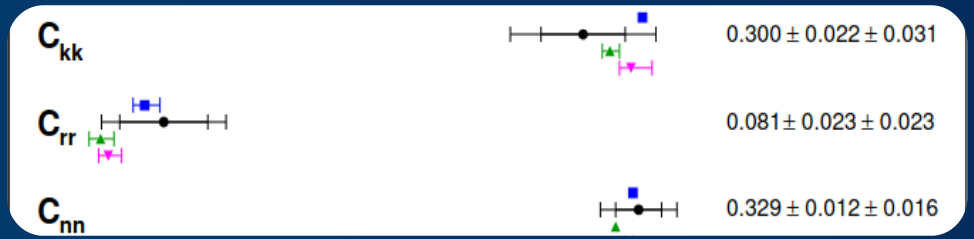
Physical Observables

[CMS: 1907.03729]

Tops as Qubits

$$\rho = {}^1\!/_4\left(1 \otimes 1 + \mathcal{B}_1 \cdot \boldsymbol{\sigma} \otimes 1 + \mathcal{B}_2 \cdot 1 \otimes \boldsymbol{\sigma} + \mathcal{C} \cdot \boldsymbol{\sigma} \otimes \boldsymbol{\sigma}\right),$$

Quantum Info

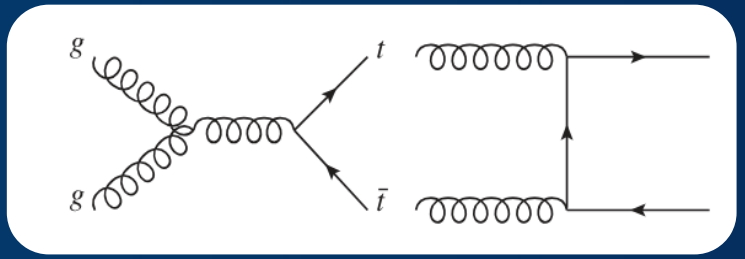


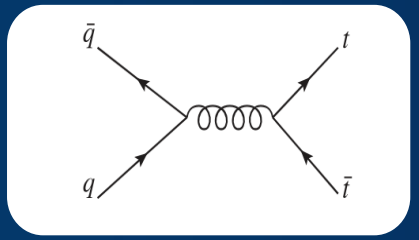
[CMS: 1907.03729]

SPIN CORRELATIONS

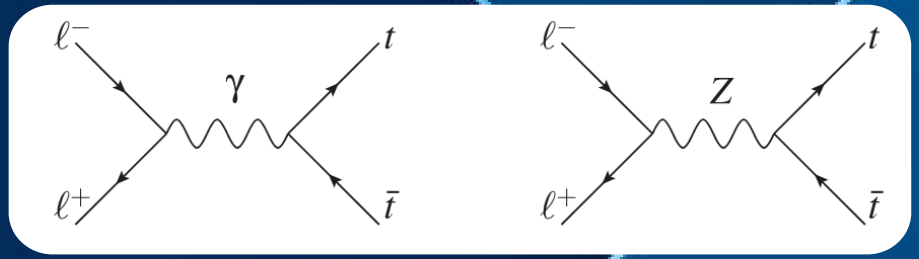
Physical Observables

QCD VS QED



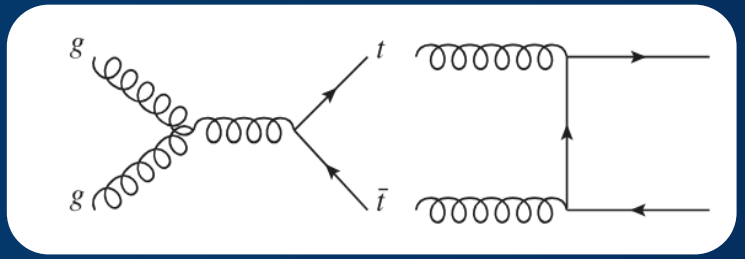


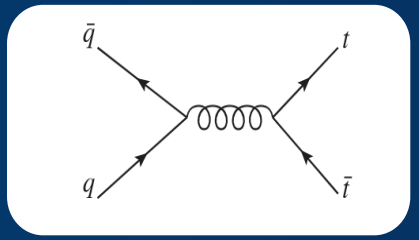
s-channel and t-channel



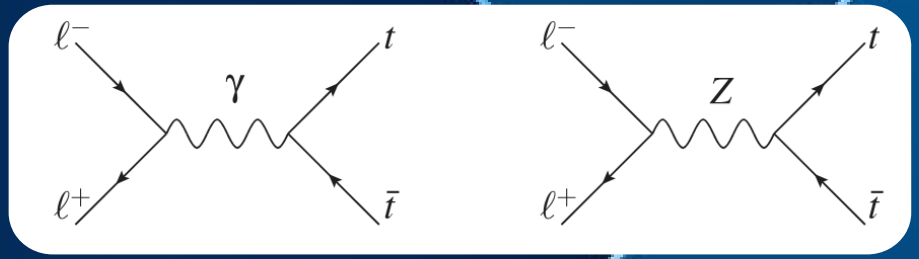
s-channel only

QCD VS QED



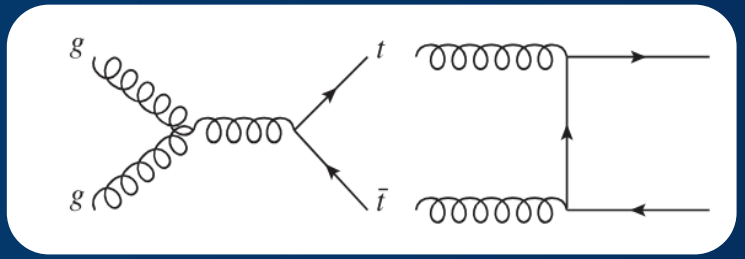


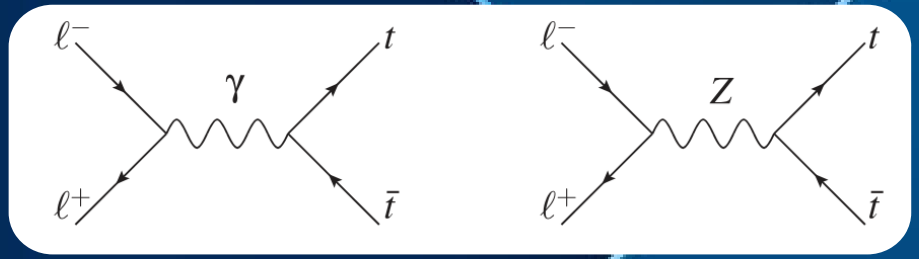
Parity preserving

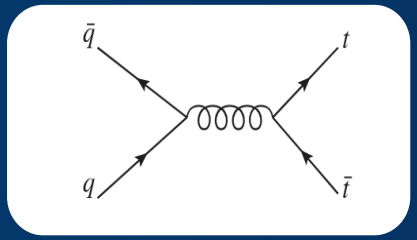


Parity breaking

QCD VS QED

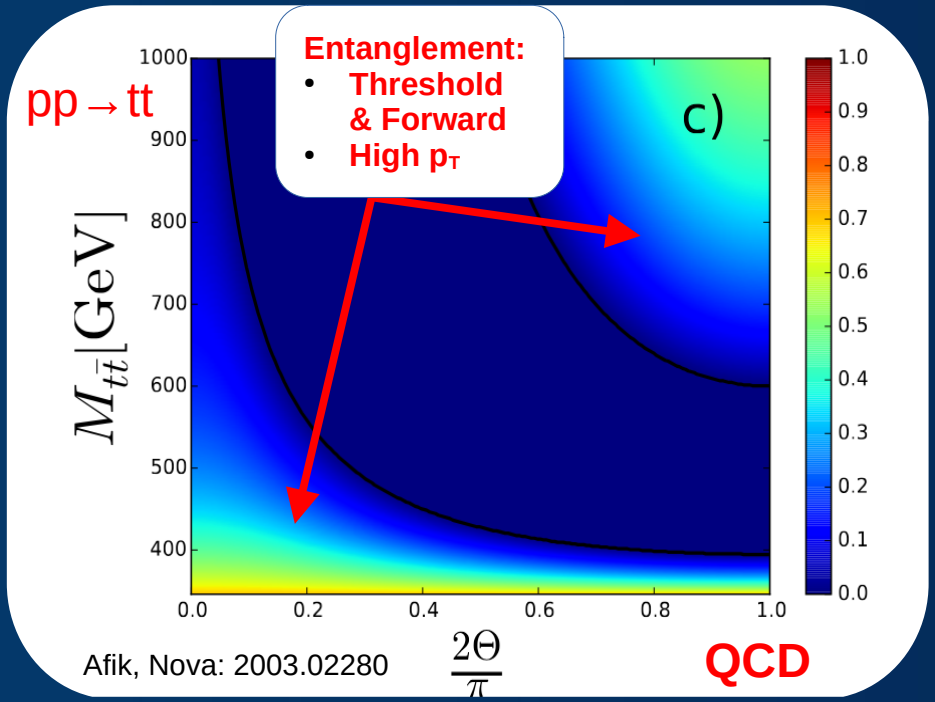






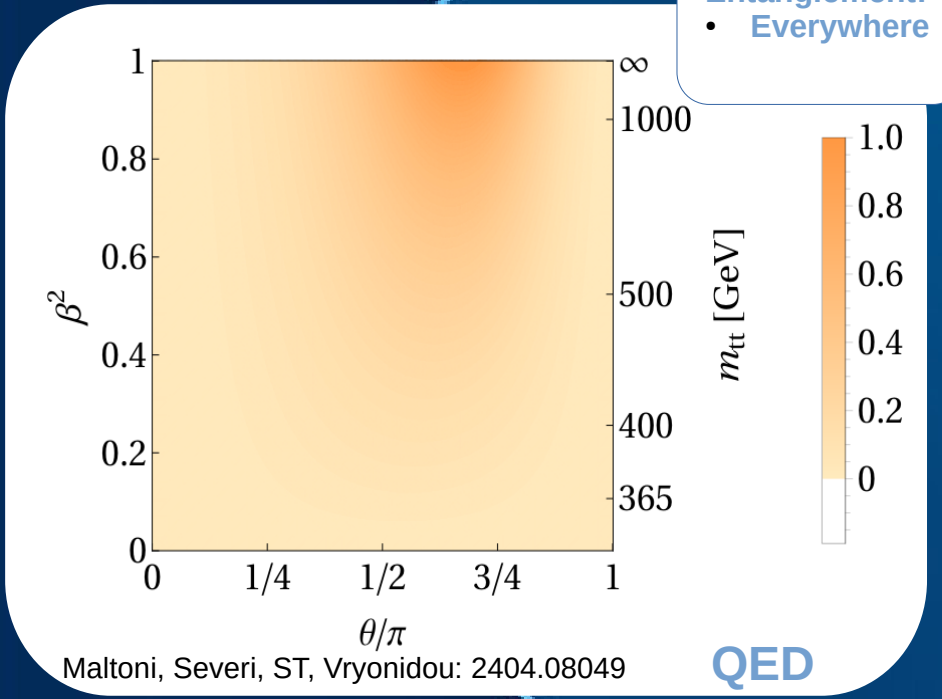
- **Different Entanglement Regions**
- **Different Threshold Effects**

Entanglement - I



Afik, Nova: 2003.02280

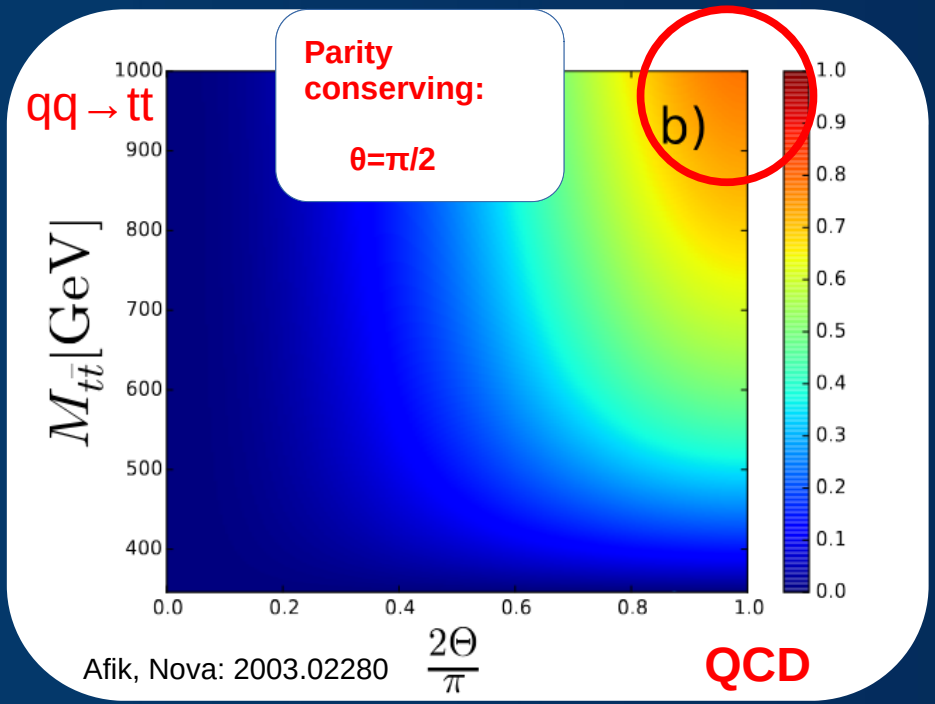
QCD



Maltoni, Severi, ST, Vryonidou: 2404.08049

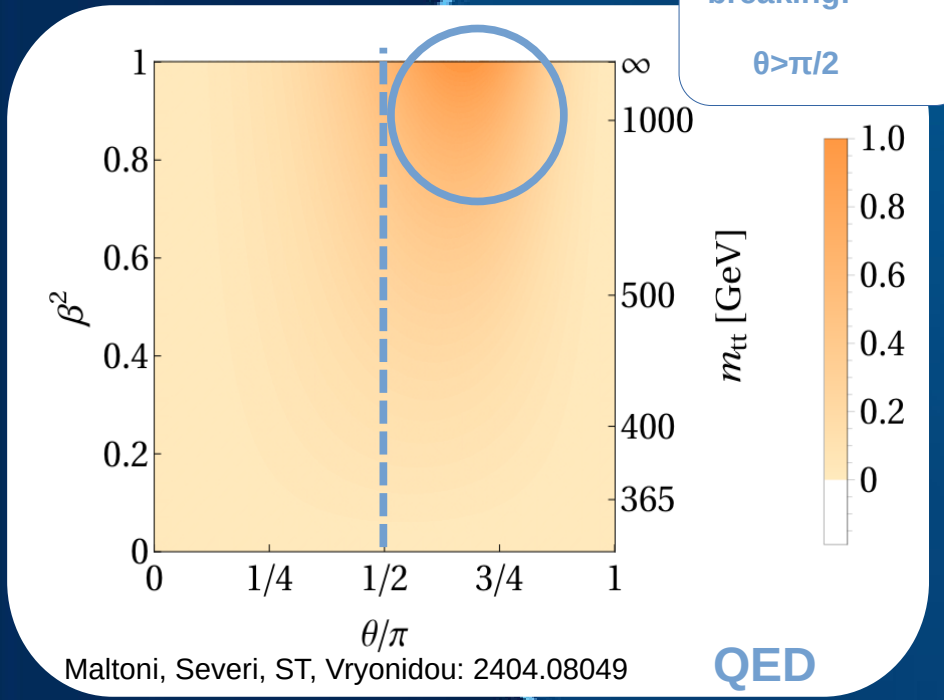
QED

Entanglement - II



Afik, Nova: 2003.02280

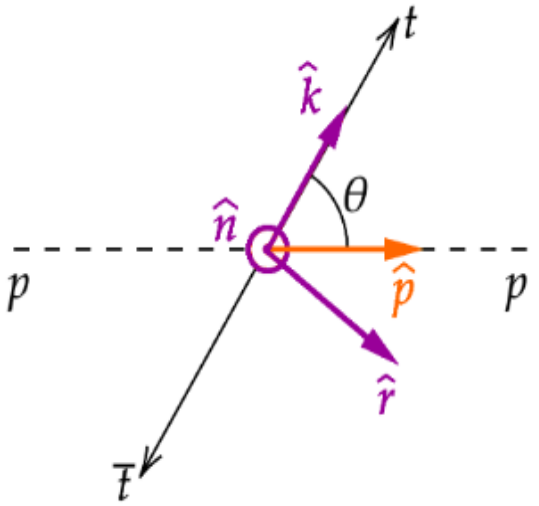
QCD



Maltoni, Severi, ST, Vryonidou: 2404.08049

QED

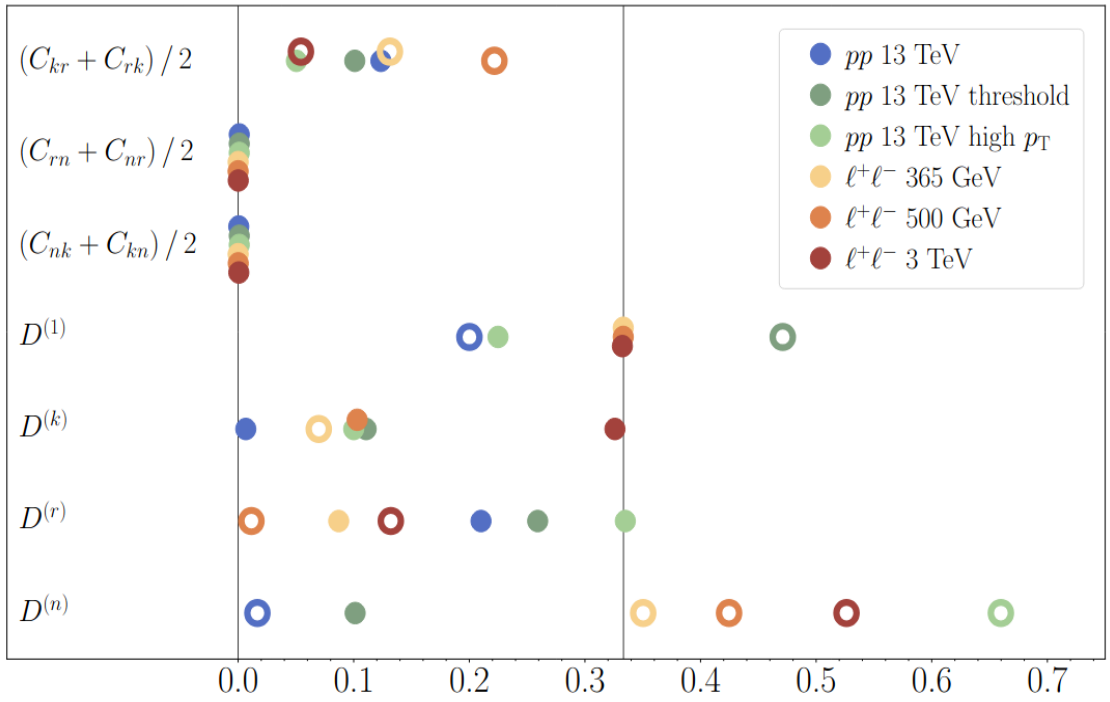
Entanglement III



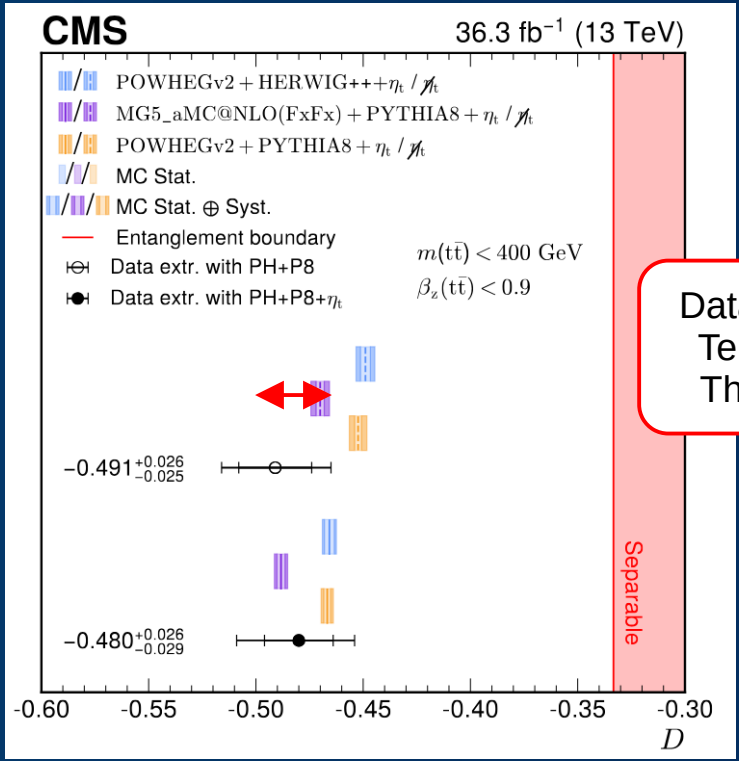
$$D^{(1)} = 1/3(+C_{kk} + C_{rr} + C_{nn}),$$
$$D^{(k)} = 1/3(+C_{kk} - C_{rr} - C_{nn}),$$
$$D^{(r)} = 1/3(-C_{kk} + C_{rr} - C_{nn}),$$
$$D^{(n)} = 1/3(-C_{kk} - C_{rr} + C_{nn}).$$

$$D_{\min} < -1/3$$

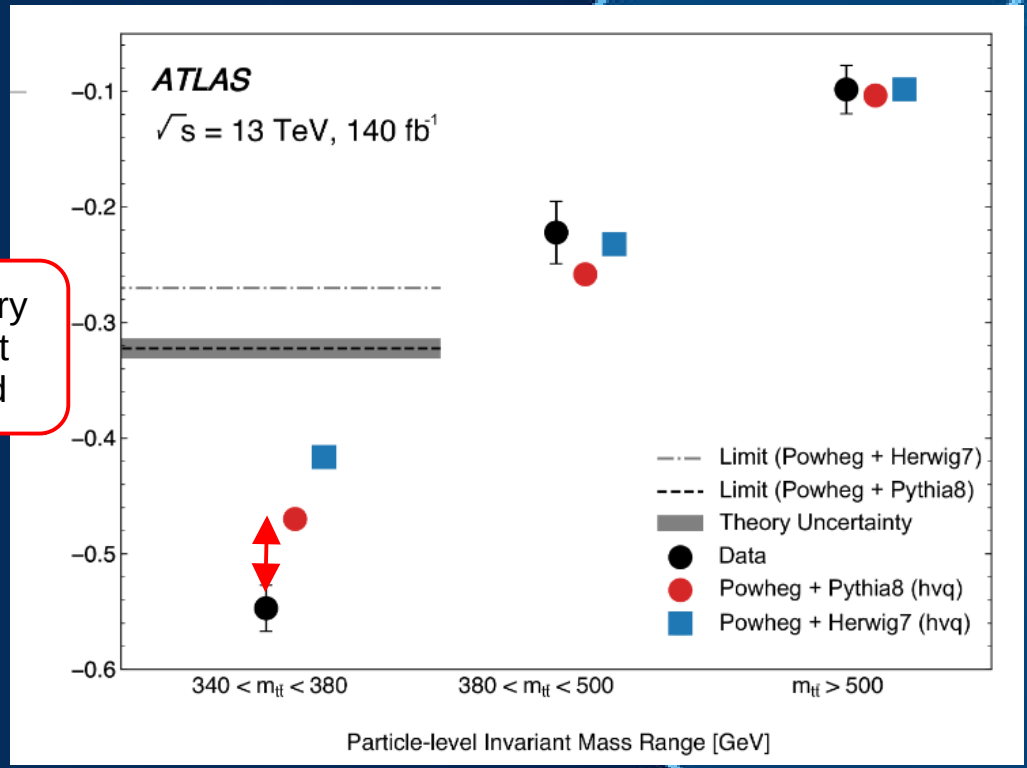
Entanglement - IV



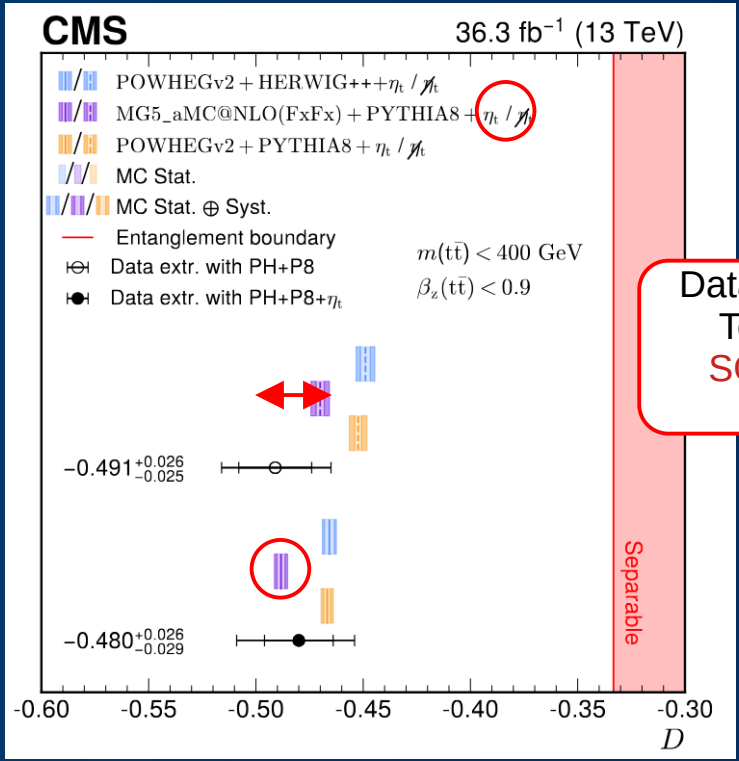
Threshold Effects I



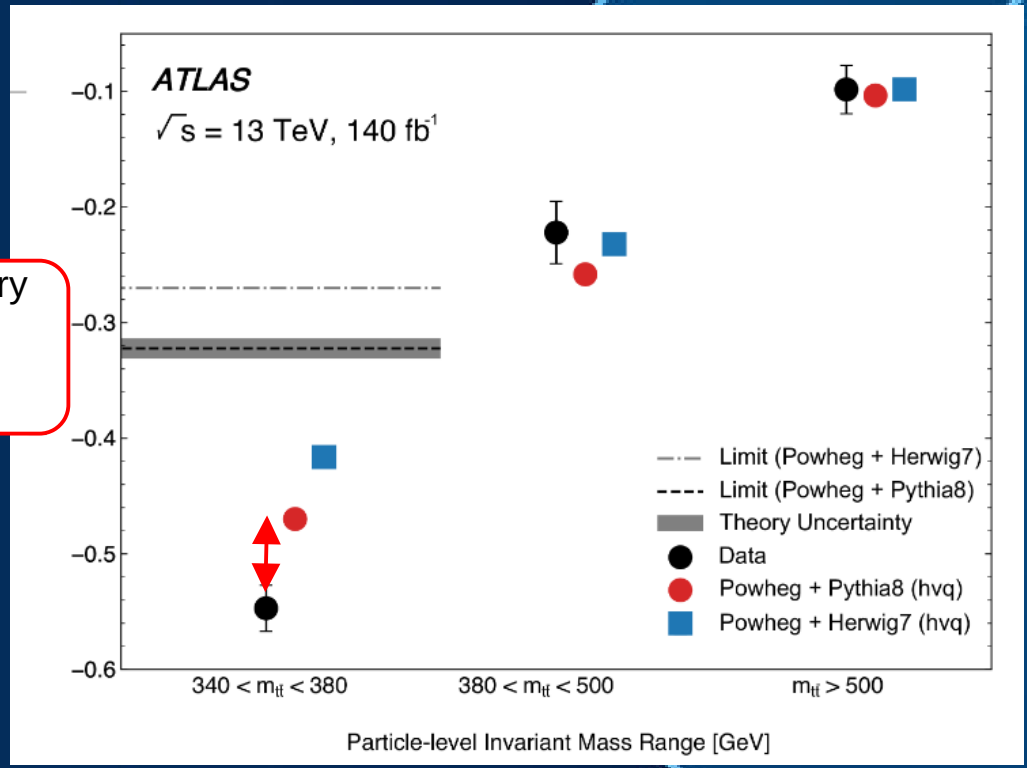
Data-Theory Tension at Threshold



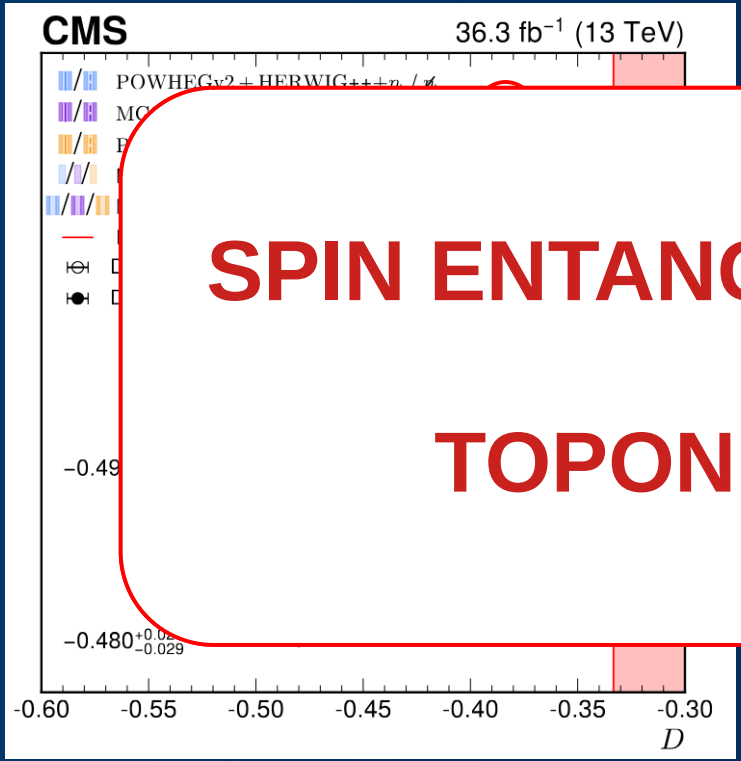
Threshold Effects I

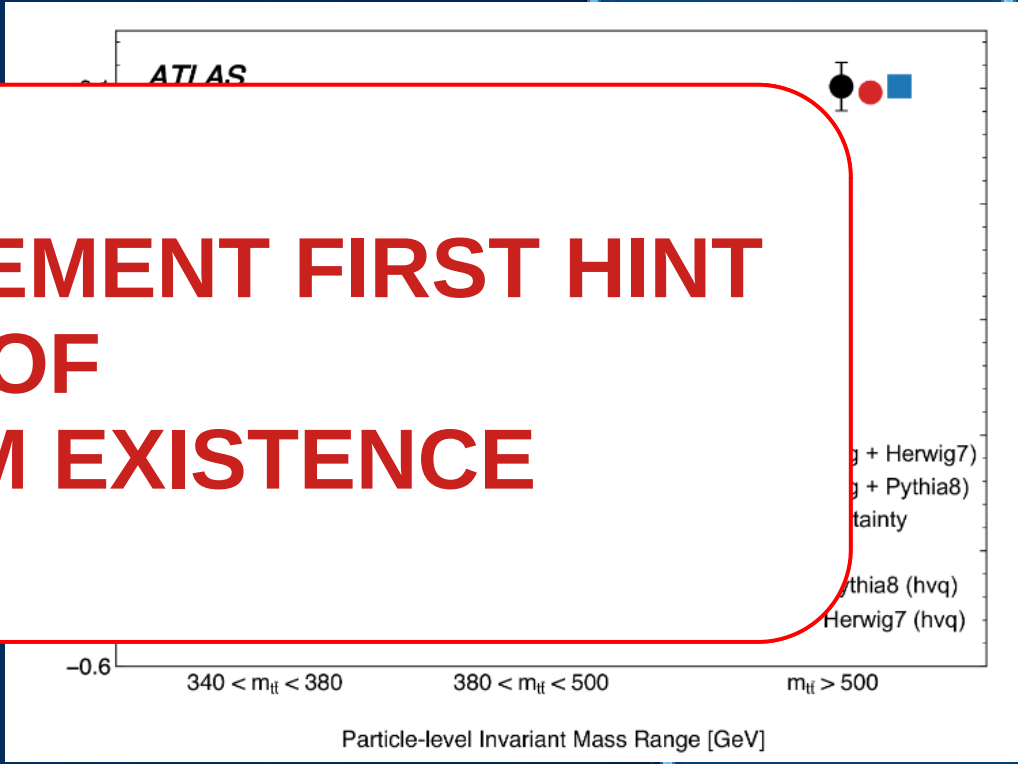


Data-Theory Tension SOLVED by η_t



Threshold Effects I





SPIN ENTANGLEMENT FIRST HINT OF TOPONIUM EXISTENCE

Threshold Effects II

η_t

QUANTUM STATE

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \right)$$

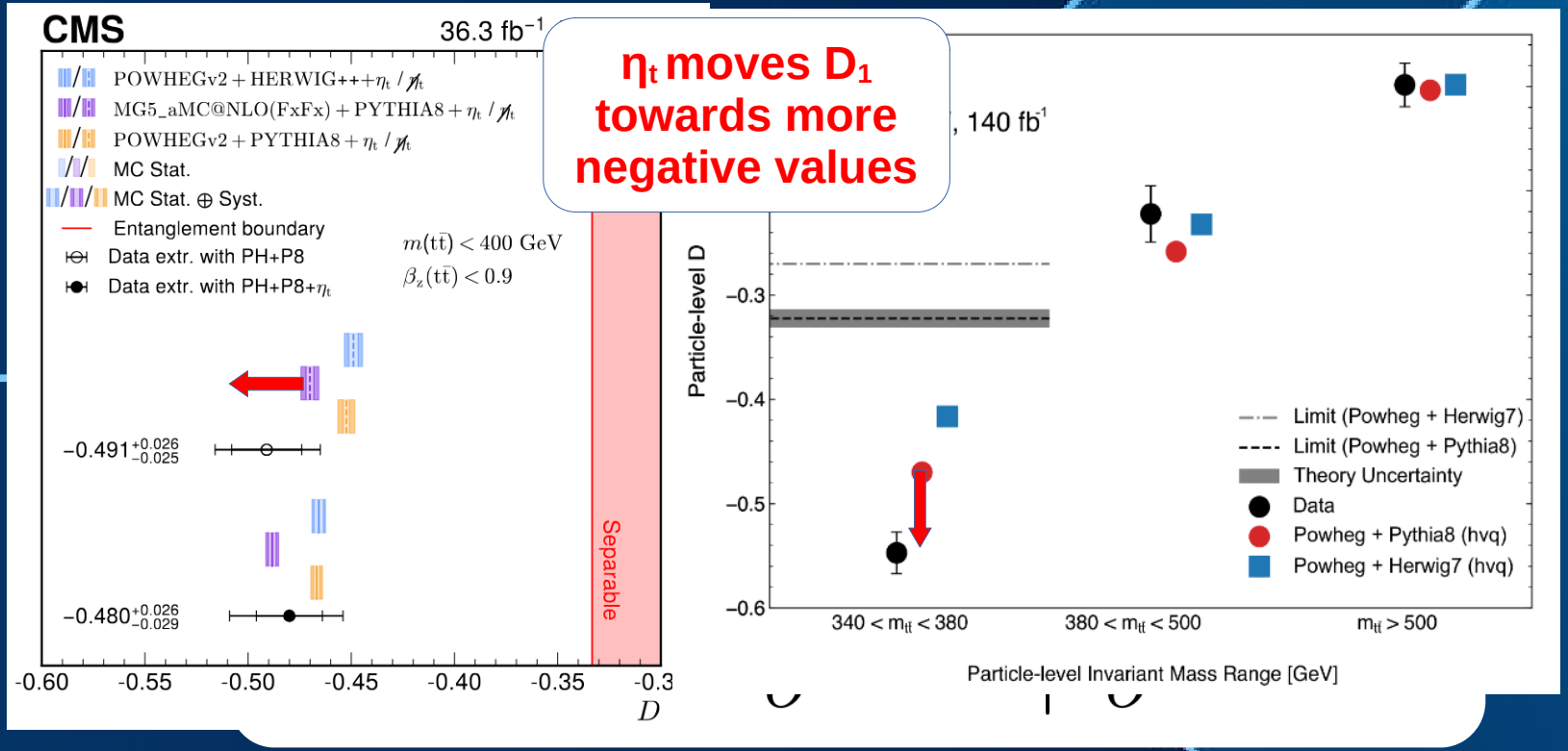
$D_1^{\eta t}=-1$

$$D_1^{\mathrm{tot}} = \frac{D_1^{\mathrm{QCD}}\sigma^{\mathrm{QCD}} + D_1^{\eta_t}\sigma^{\eta_t}}{\sigma^{\mathrm{QCD}} + \sigma^{\eta_t}}$$

Threshold Effects II

η_t

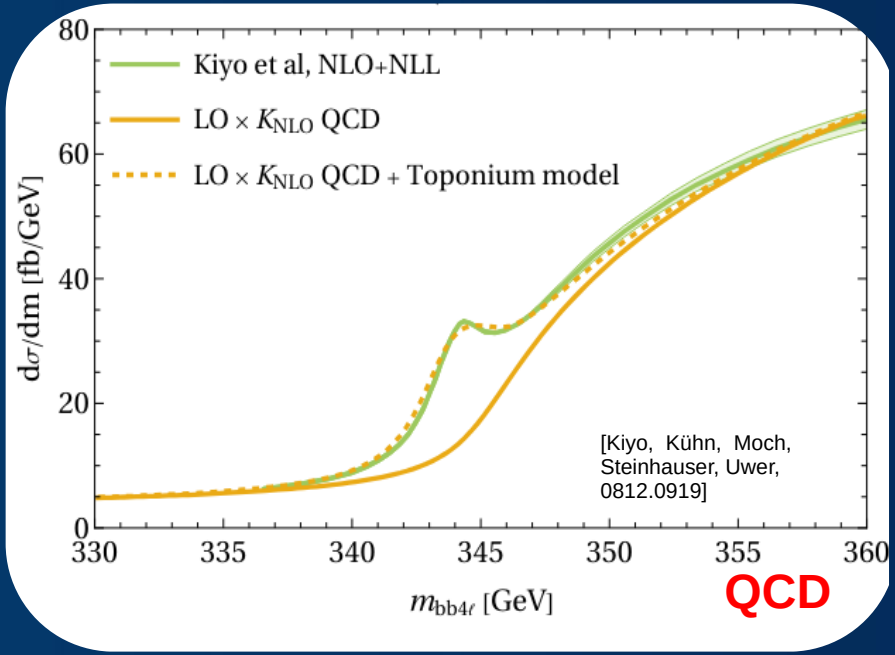
$D_1^{\eta t}=-1$

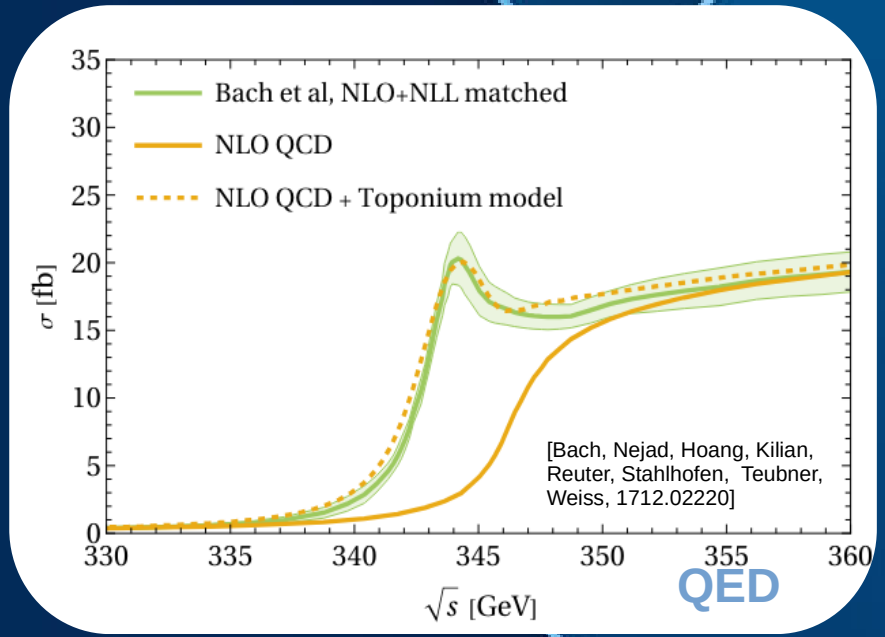


η_t moves D_1 towards more negative values

Threshold Effects III

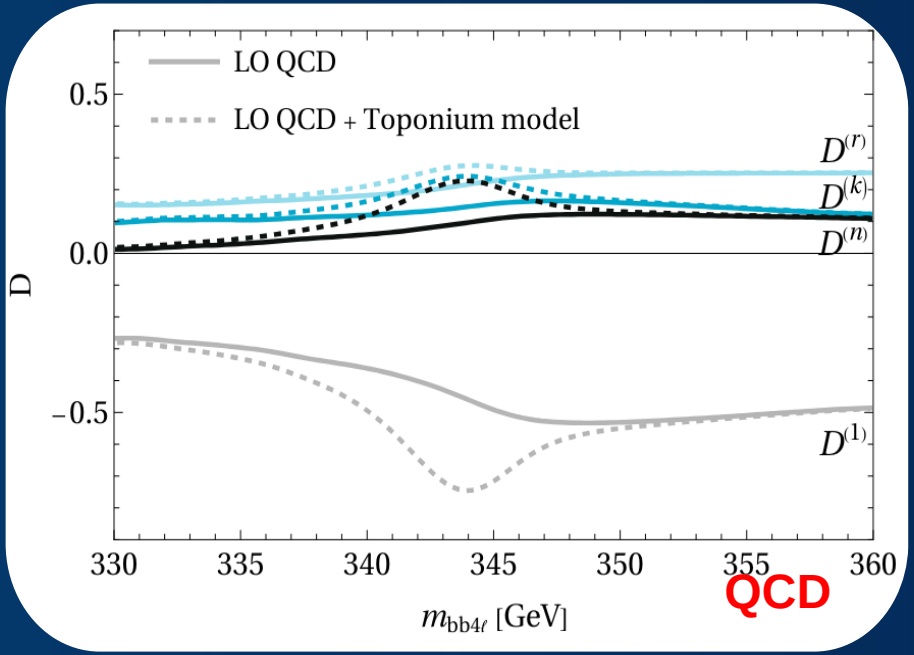
WHAT ABOUT LEPTON COLLIDERS?

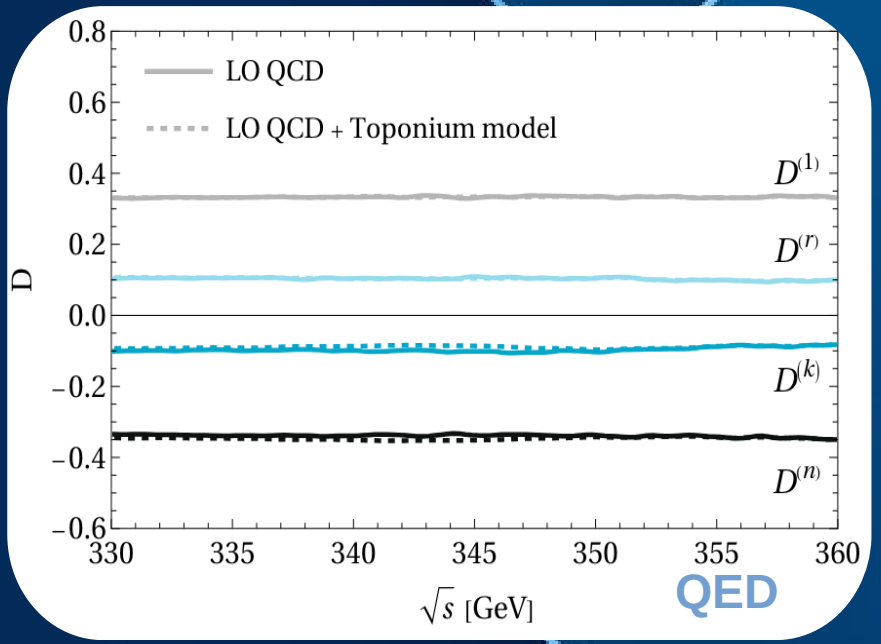




Threshold Effects III

WHAT ABOUT LEPTON COLLIDERS?



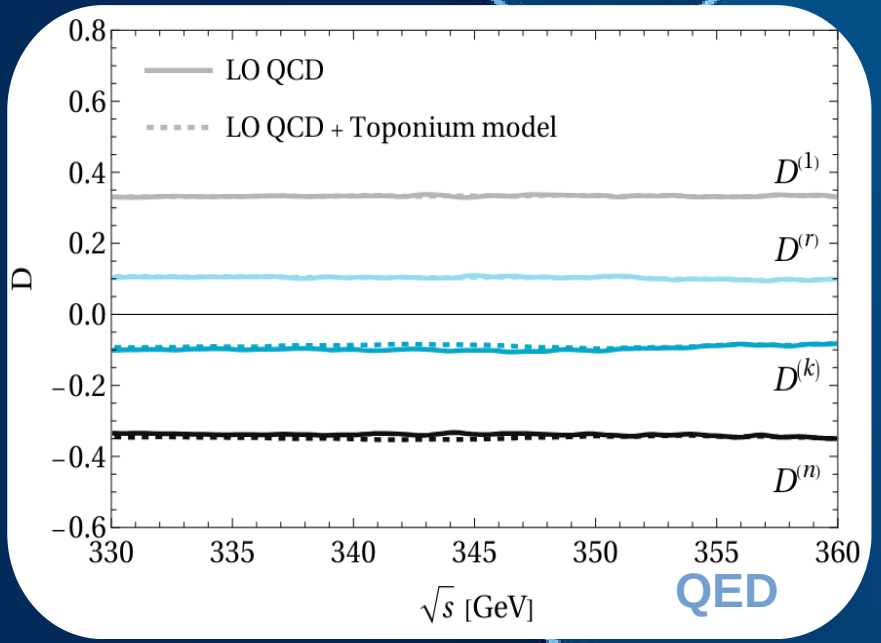


Threshold Effects III

WHAT ABOUT LEPTON COLLIDERS?

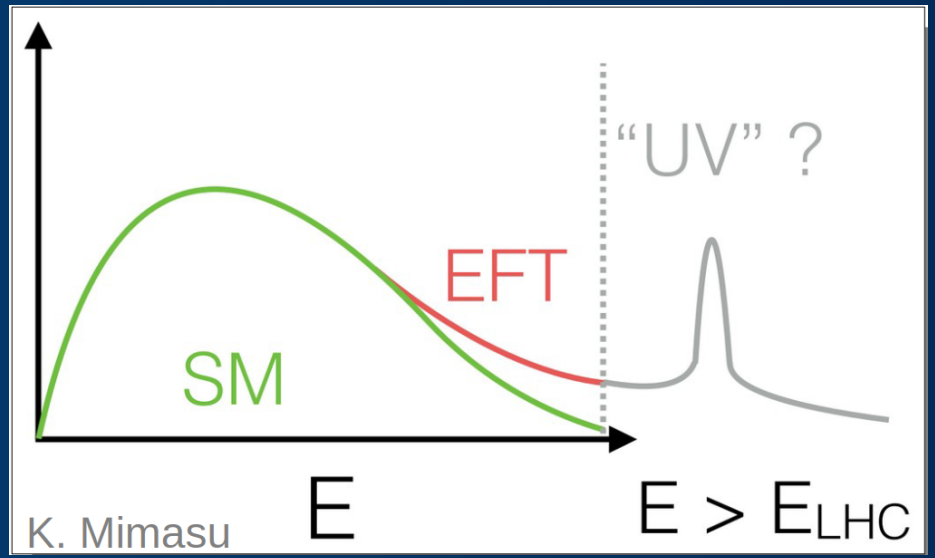
T quantum state same of QED production

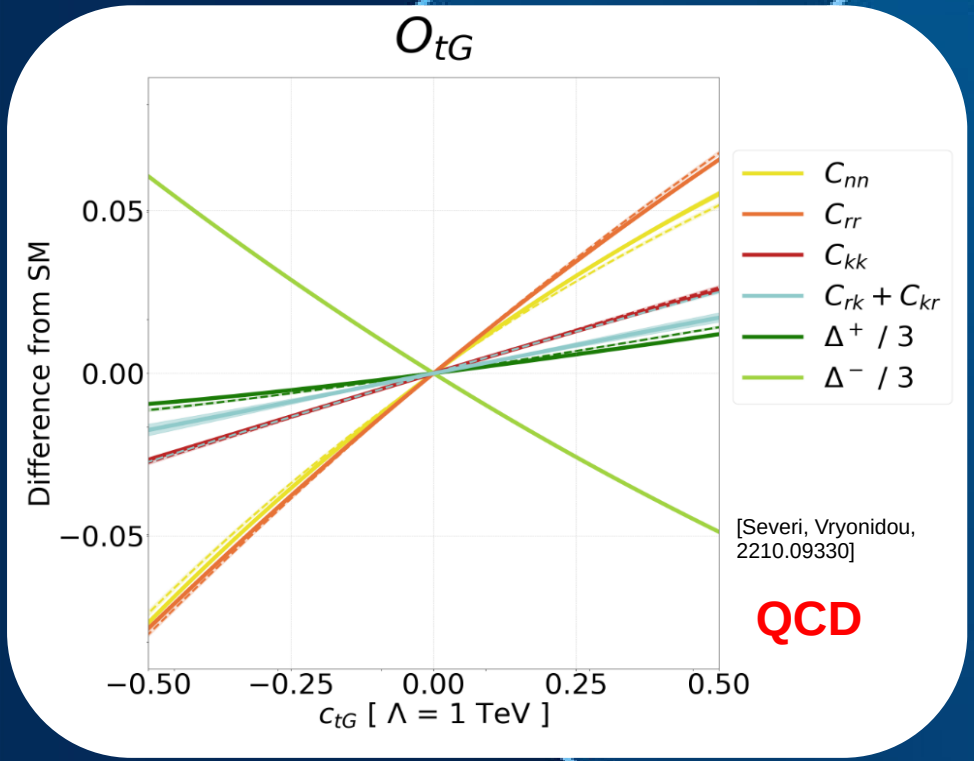
No Gain



SMEFT and QUANTUM - I

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{1}{\Lambda^2} c_i \mathcal{O}_i^{(6)} + \sum_i \frac{1}{\Lambda^4} c_i \mathcal{O}_i^{(8)}$$

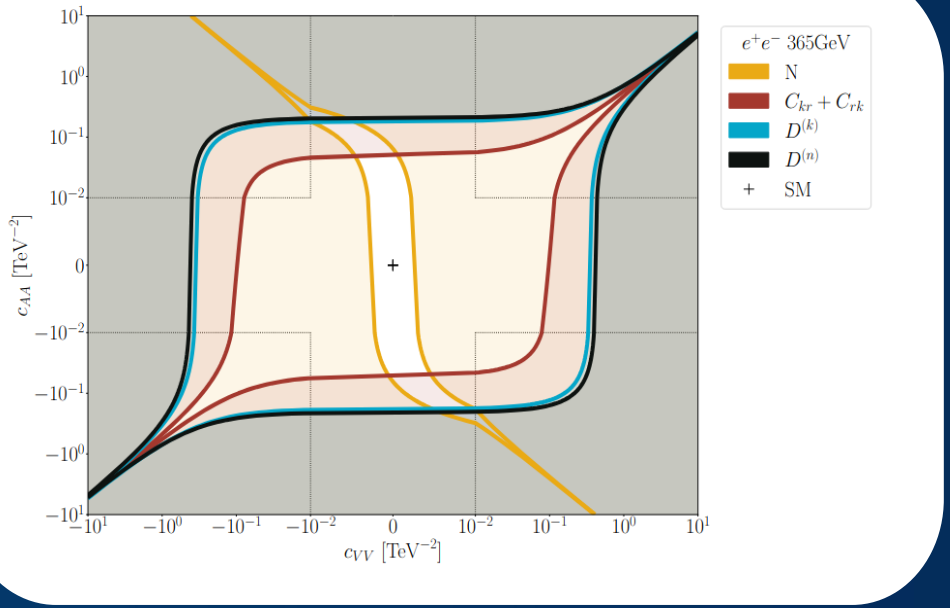


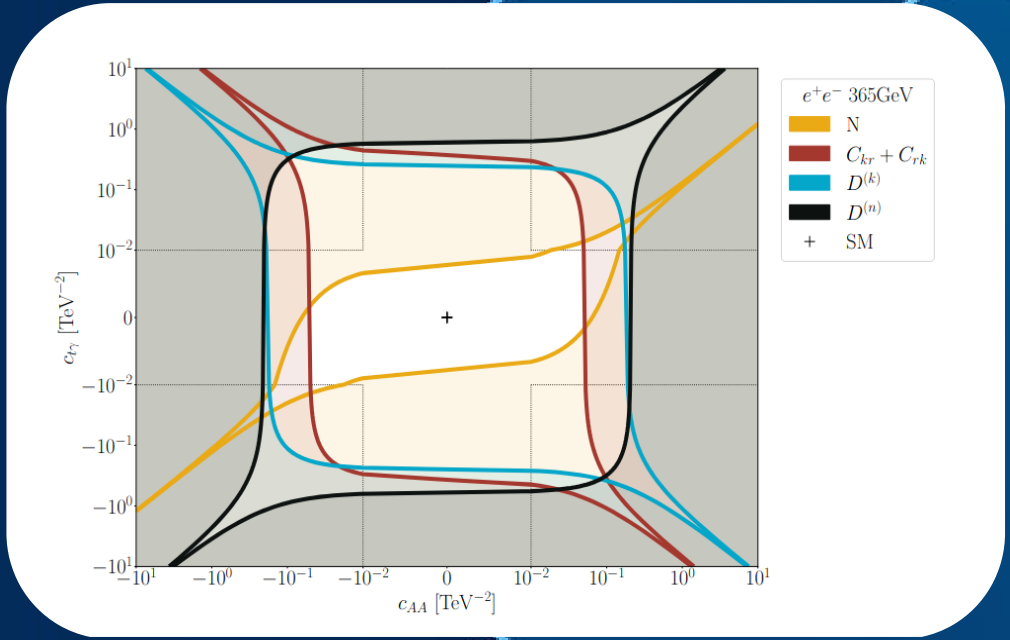


[Severi, Vryonidou, 2210.09330]

QCD

SMEFT and QUANTUM - II





SMEFT and QUANTUM - III

N Events best observable

$$\Delta\sigma = c_1\, A^{[1]} + c_2\, A^{[2]}.$$

$$\tan\alpha_N = -\frac{A^{[1]}}{A^{[2]}},$$

FLAT DIRECTIONS

SMEFT and QUANTUM - III

N Events best observable

$$\Delta\sigma = c_1\, A^{[1]} + c_2\, A^{[2]}.$$

$$\tan\alpha_N = -\frac{A^{[1]}}{A^{[2]}},$$

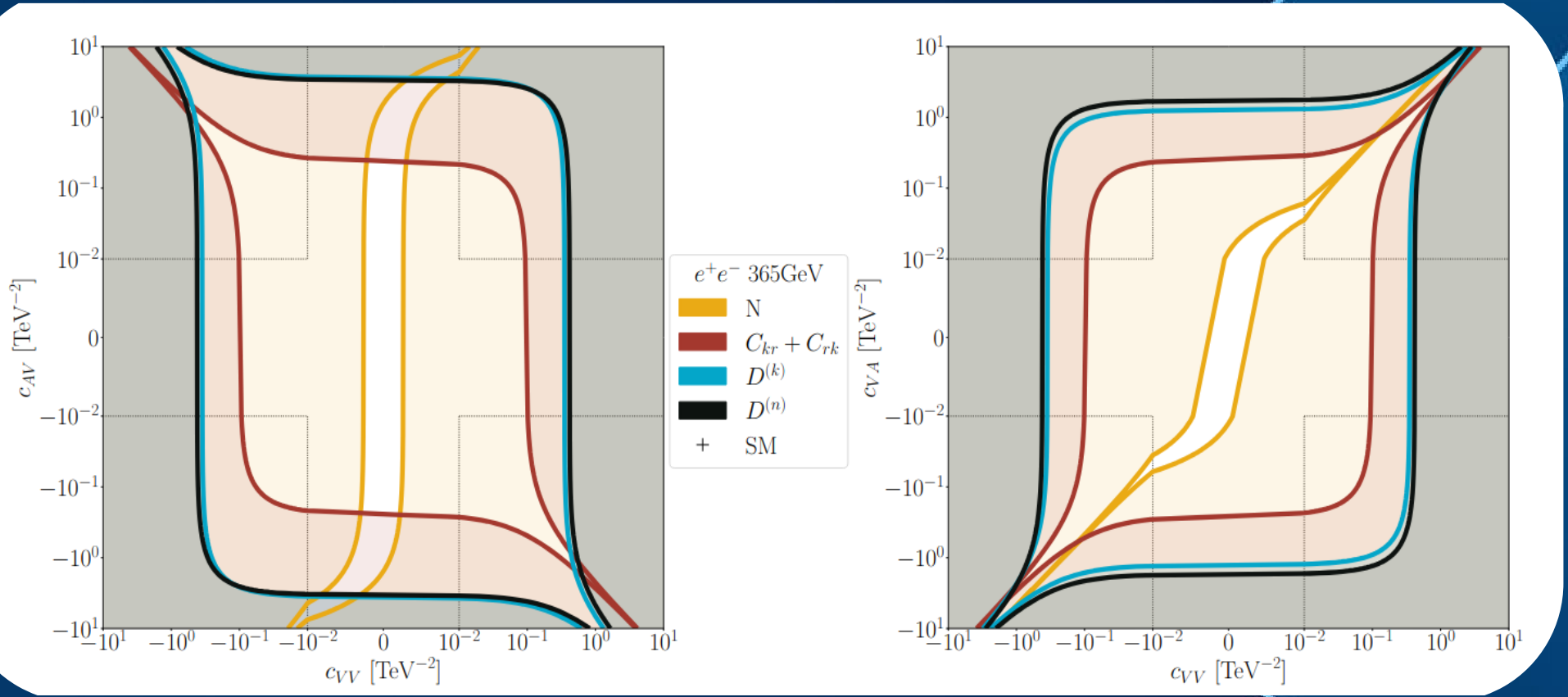
FLAT DIRECTIONS

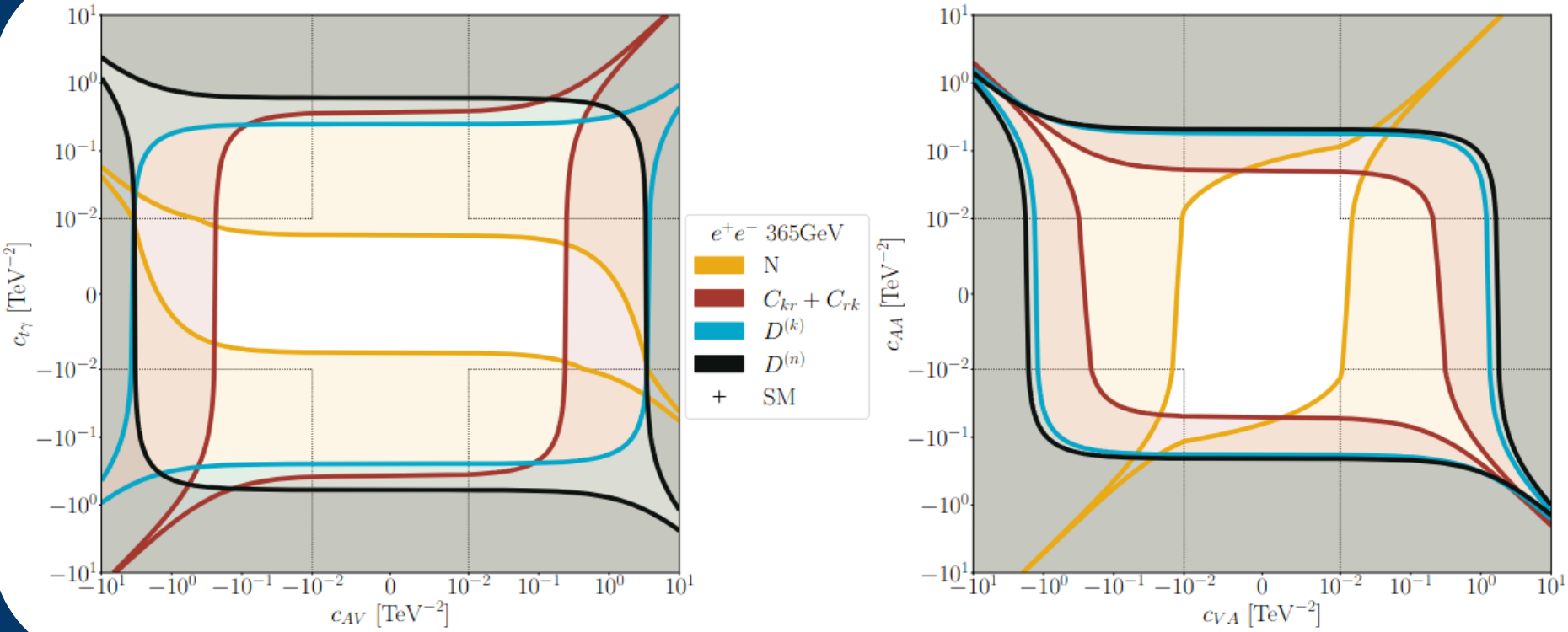
Quantum observables

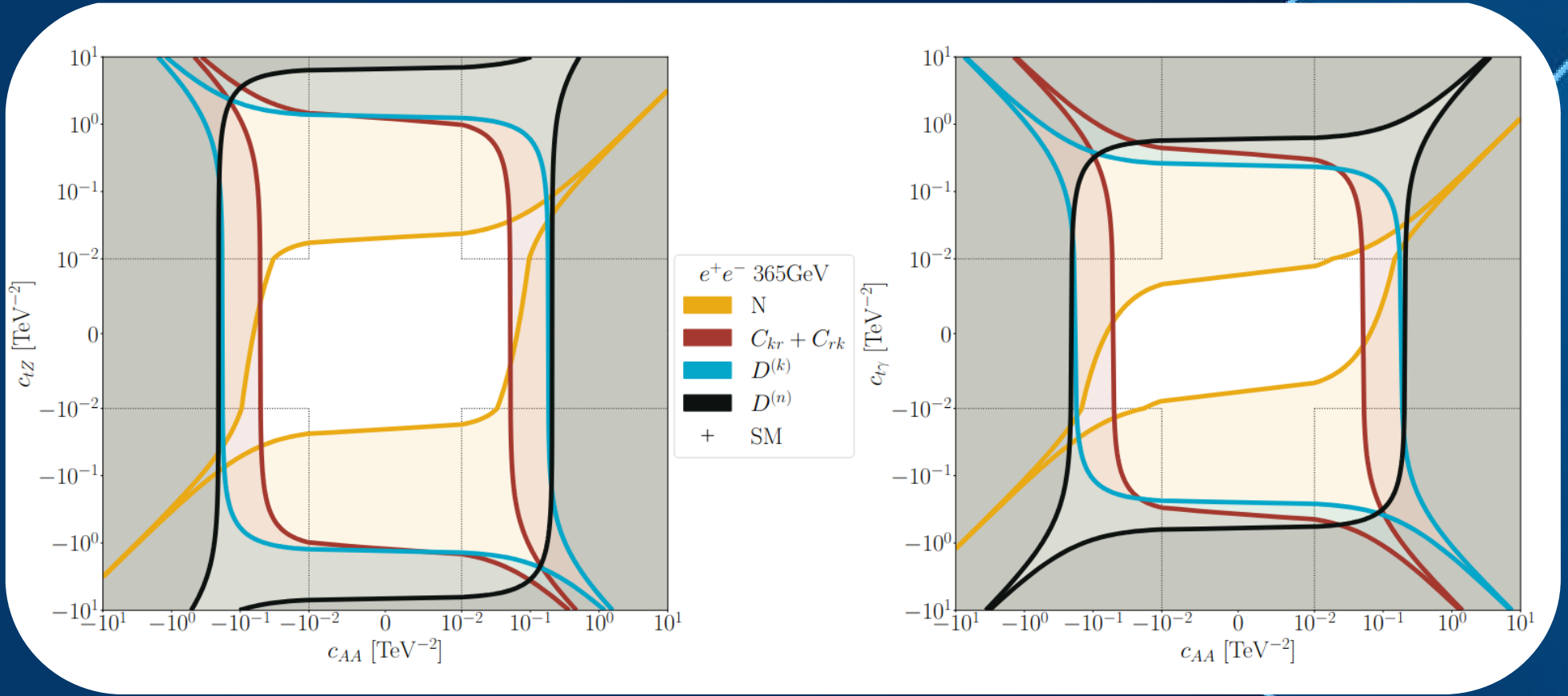
$$\Delta D_{\rm SMEFT} = \frac{\widetilde{D}^{[\rm SM]} + c_1\widetilde{D}^{[1]} + c_2\widetilde{D}^{[2]}}{A^{[\rm SM]} + c_1 A^{[1]} + c_2 A^{[2]}} - \frac{\widetilde{D}^{[\rm SM]}}{A^{[\rm SM]}}.$$

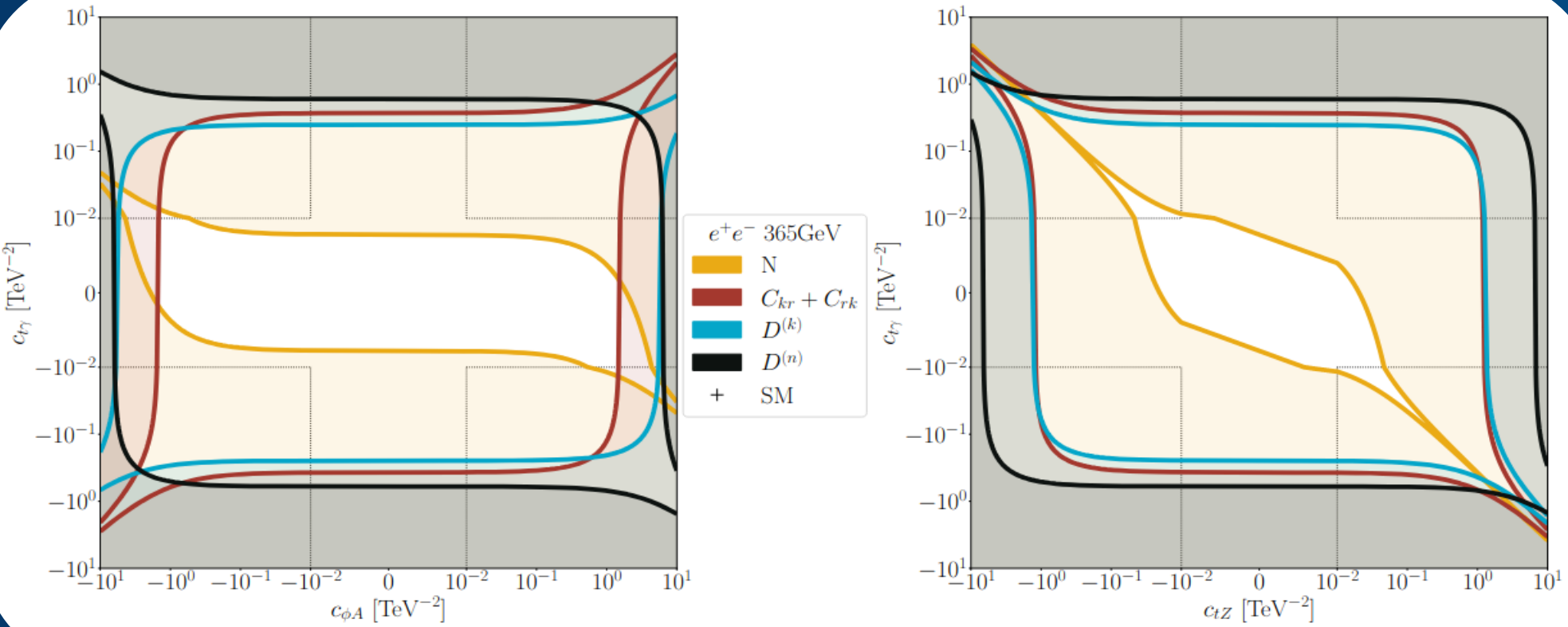
$$\tan\alpha_N \cdot \frac{D^{[1]} - D^{[\rm SM]}}{D^{[2]} - D^{[\rm SM]}}.$$

DIFFERENT DIRECTIONS

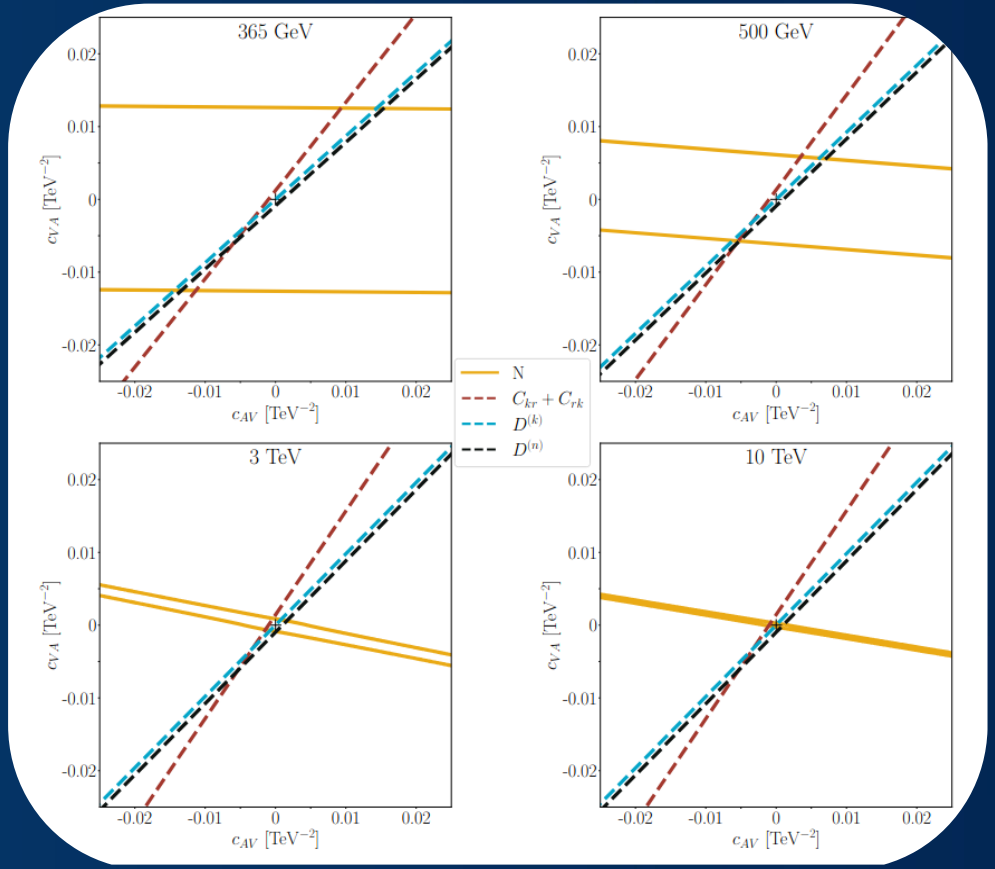

e^+e^- 365GeV
N
$C_{kr} + C_{rk}$
$D^{(k)}$
$D^{(n)}$
SM
c_{AV} [TeV^{-2}]
c_{VV} [TeV^{-2}]
c_{VA} [TeV^{-2}]
c_{VV} [TeV^{-2}]

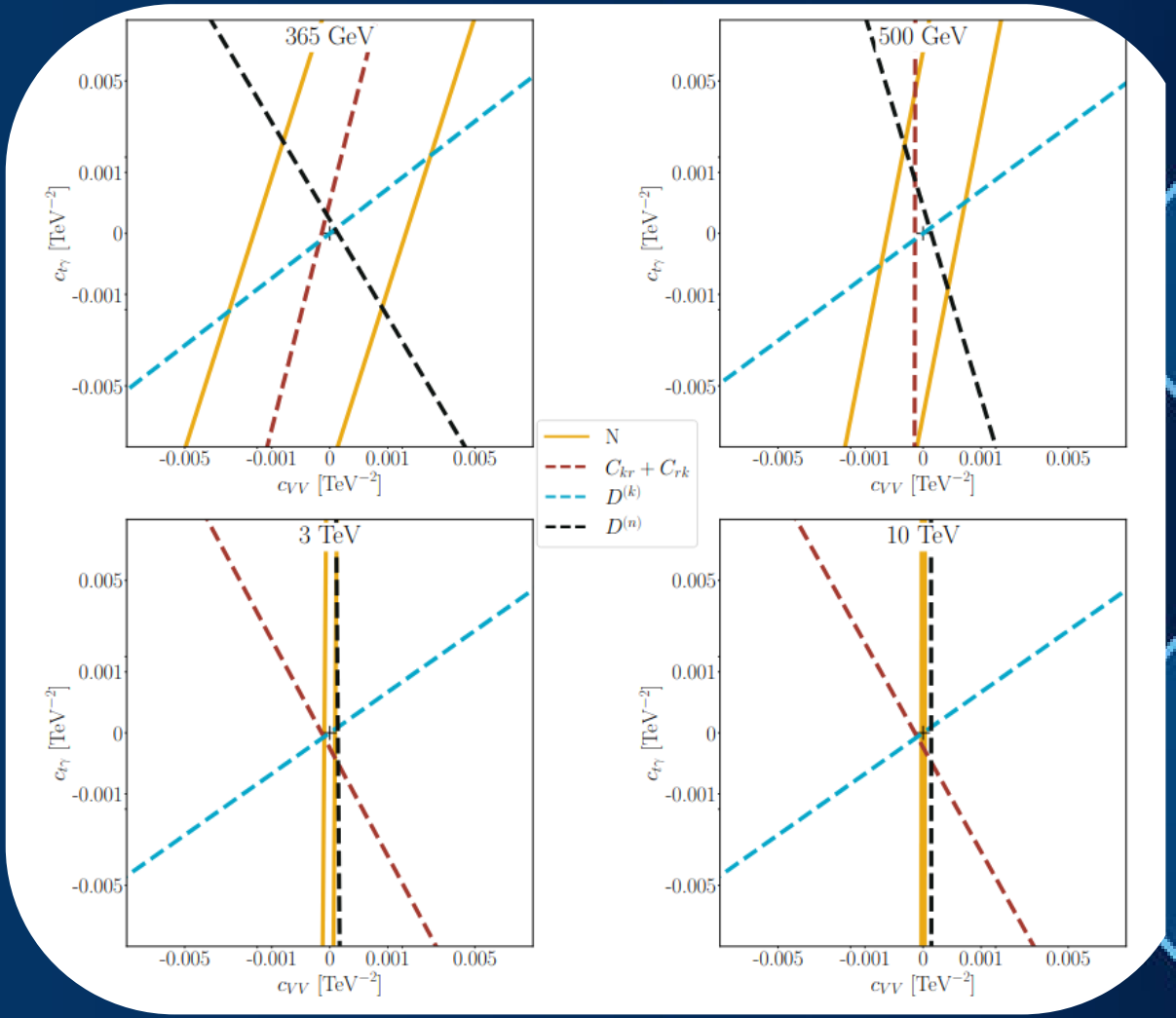

e^+e^- 365GeV
N
$C_{kr} + C_{rk}$
$D^{(k)}$
$D^{(n)}$
+ SM
$c_{t\gamma}$ [TeV^{-2}]
c_{AV} [TeV^{-2}]
c_{AA} [TeV^{-2}]
c_{VA} [TeV^{-2}]

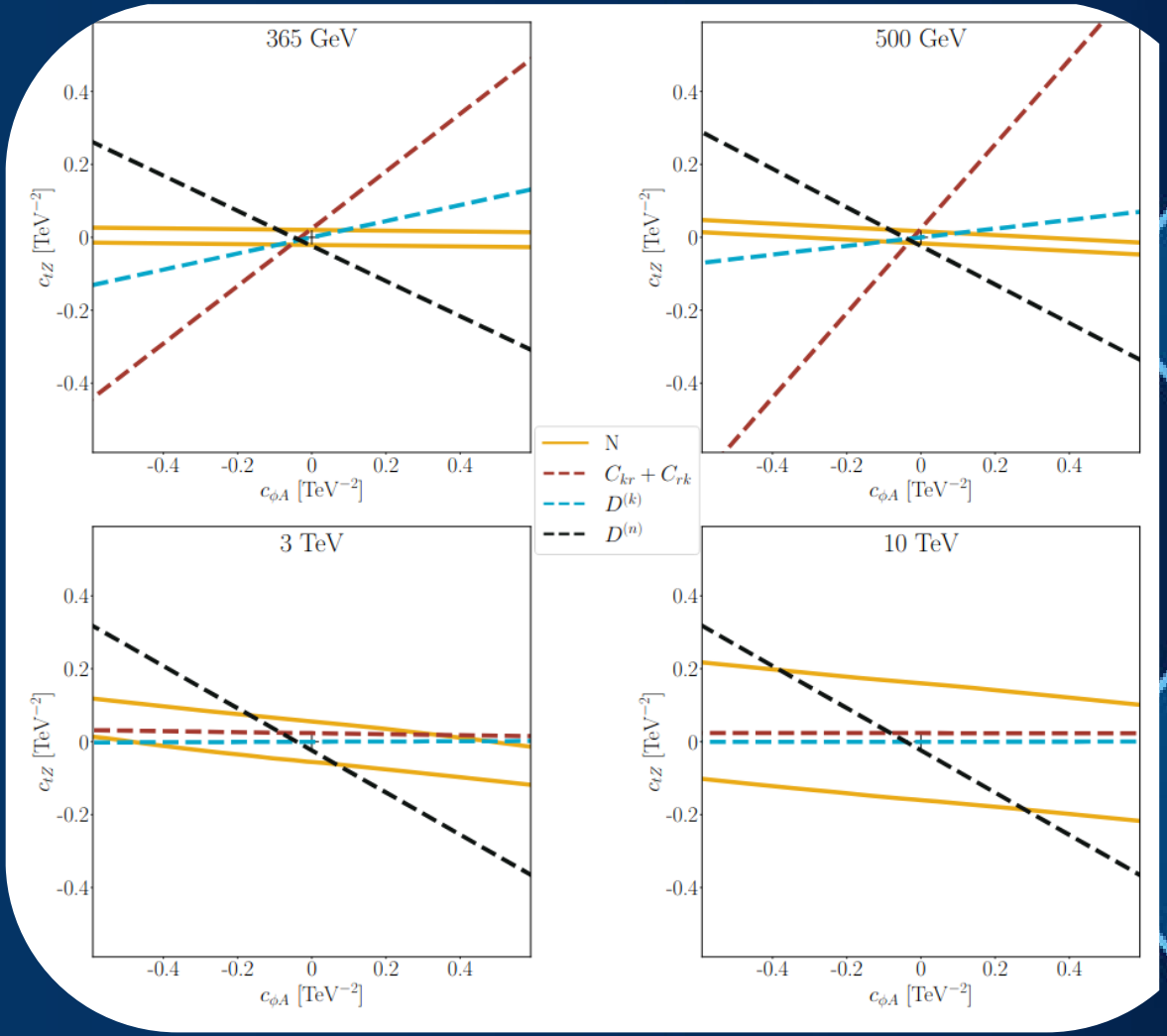

e^+e^- 365GeV
N
$C_{kr} + C_{rk}$
$D^{(k)}$
$D^{(n)}$
+ SM
c_{tZ} [TeV^{-2}]
c_{AA} [TeV^{-2}]
$c_{t\gamma}$ [TeV^{-2}]
c_{AA} [TeV^{-2}]


e^+e^- 365GeV
N
$C_{kr} + C_{rk}$
$D^{(k)}$
$D^{(n)}$
+ SM
$c_{t\gamma}$ [TeV^{-2}]
$c_{\phi A}$ [TeV^{-2}]
c_{tZ} [TeV^{-2}]

SMEFT and QUANTUM - IV




365 GeV
500 GeV
3 TeV
10 TeV
$c_{t\gamma}$ [TeV^{-2}]
c_{VV} [TeV^{-2}]
0.005
0.001
0
-0.001
-0.005
N
$C_{kr} + C_{rk}$
$D^{(k)}$
$D^{(n)}$

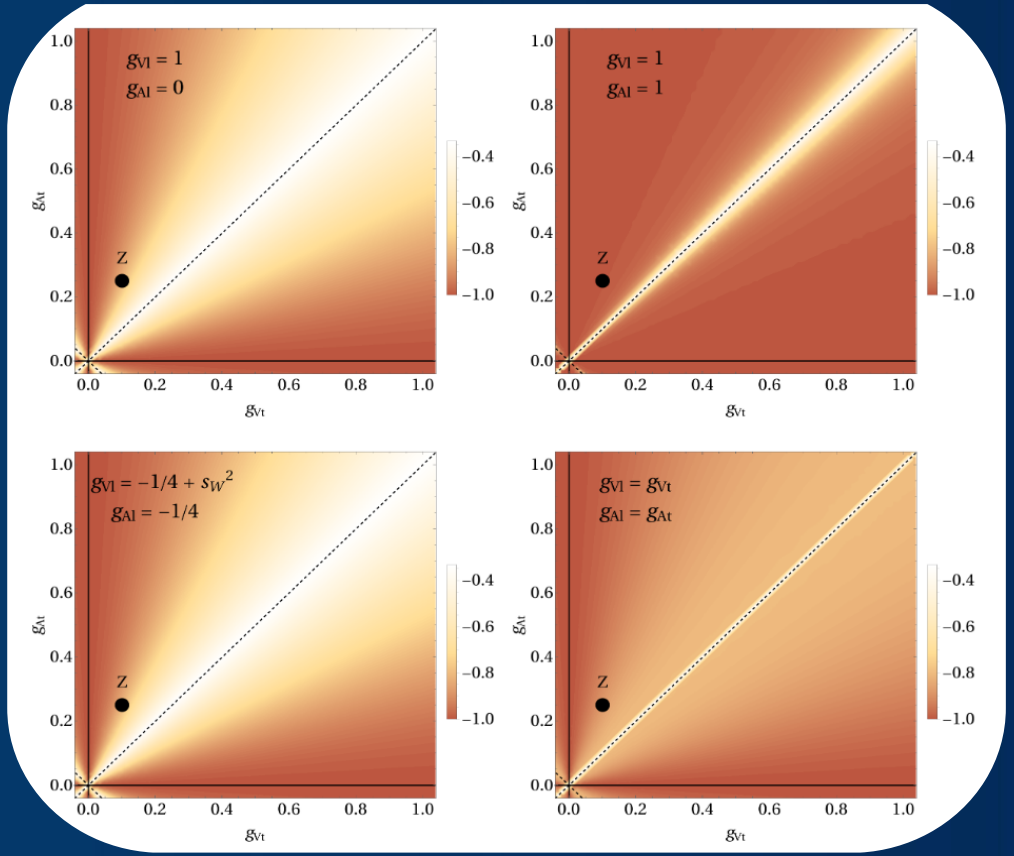

365 GeV
500 GeV
3 TeV
10 TeV
c_{tZ} [TeV^{-2}]
$c_{\phi A}$ [TeV^{-2}]
0.4
0.2
0
-0.2
-0.4
N
$C_{kr} + C_{rk}$
$D^{(k)}$
$D^{(n)}$

CONCLUSIONS

- Entanglement as a parity probe for Future Lepton Collider
- Distinct Phenomenology from Hadron Colliders
- Good observables to lift degeneracy in NP Physics Fits

BACKUP

More on Parity



$$g_{At} = 0 \quad \text{or} \quad g_{Vt} = 0 \implies \text{conservation of } P,$$
$$g_{At} = g_{Vt} \quad \text{or} \quad g_{At} = -g_{Vt} \implies \text{maximal violation of } P.$$

SMEFT COEFFICIENTS

4 FERMIONS

$$
\begin{aligned}
\mathcal{O}_{Q\ell}^{(1)} &= (\overline{Q}_L\gamma^\mu Q_L)(\overline{\ell}_L\gamma_\mu \ell_L),\\
\mathcal{O}_{Q\ell}^{(3)} &= (\overline{Q}_L\gamma^\mu \sigma_I Q_L)(\overline{\ell}_L\gamma_\mu \sigma^I \ell_L),\\
\mathcal{O}_{Qe} &= (\overline{Q}_L\gamma^\mu Q_L)(\overline{\ell}_R\gamma_\mu \ell_R),\\
\mathcal{O}_{t\ell} &= (\overline{t}_R\gamma^\mu t_R)(\overline{\ell}_L\gamma_\mu \ell_L),\\
\mathcal{O}_{te} &= (\overline{t}_R\gamma^\mu t_R)(\overline{\ell}_R\gamma_\mu \ell_R).
\end{aligned}
$$

$$
\begin{aligned}
& c_{Q\ell}^{(3)} + c_{Q\ell}^{(1)},\\
c_{\mathrm{VV}} &= \frac{1}{4}\left(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} + c_{Qe}\right),\\
c_{\mathrm{AV}} &= \frac{1}{4}\left(-c_{Q\ell}^{(1)} + c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} - c_{Qe}\right),\\
c_{\mathrm{VA}} &= \frac{1}{4}\left(-c_{Q\ell}^{(1)} + c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} + c_{Qe}\right),\\
c_{\mathrm{AA}} &= \frac{1}{4}\left(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} - c_{Qe}\right).
\end{aligned}
$$

SMEFT COEFFICIENTS

Current current

$$\mathcal{O}_{\phi Q}^{(1)} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\overline{Q}_L \gamma^\mu Q_L),$$
$$\mathcal{O}_{\phi Q}^{(3)} = i(\phi^\dagger \overleftrightarrow{D}_{\mu\, I} \phi)(\overline{Q}_L \gamma^\mu \sigma^I Q_L),$$
$$\mathcal{O}_{\phi t} = i(\phi^\dagger \overleftrightarrow{D}_\mu \phi)(\bar{t}_R \gamma^\mu t_R),$$

$$c_{\phi Q}^{(3)} + c_{\phi Q}^{(1)},$$
$$c_{\phi \mathrm{V}} = \frac{1}{2}\left(c_{\phi t} + c_{\phi Q}^{(1)} - c_{\phi Q}^{(3)}\right),$$
$$c_{\phi \mathrm{A}} = \frac{1}{2}\left(c_{\phi t} - c_{\phi Q}^{(1)} + c_{\phi Q}^{(3)}\right).$$

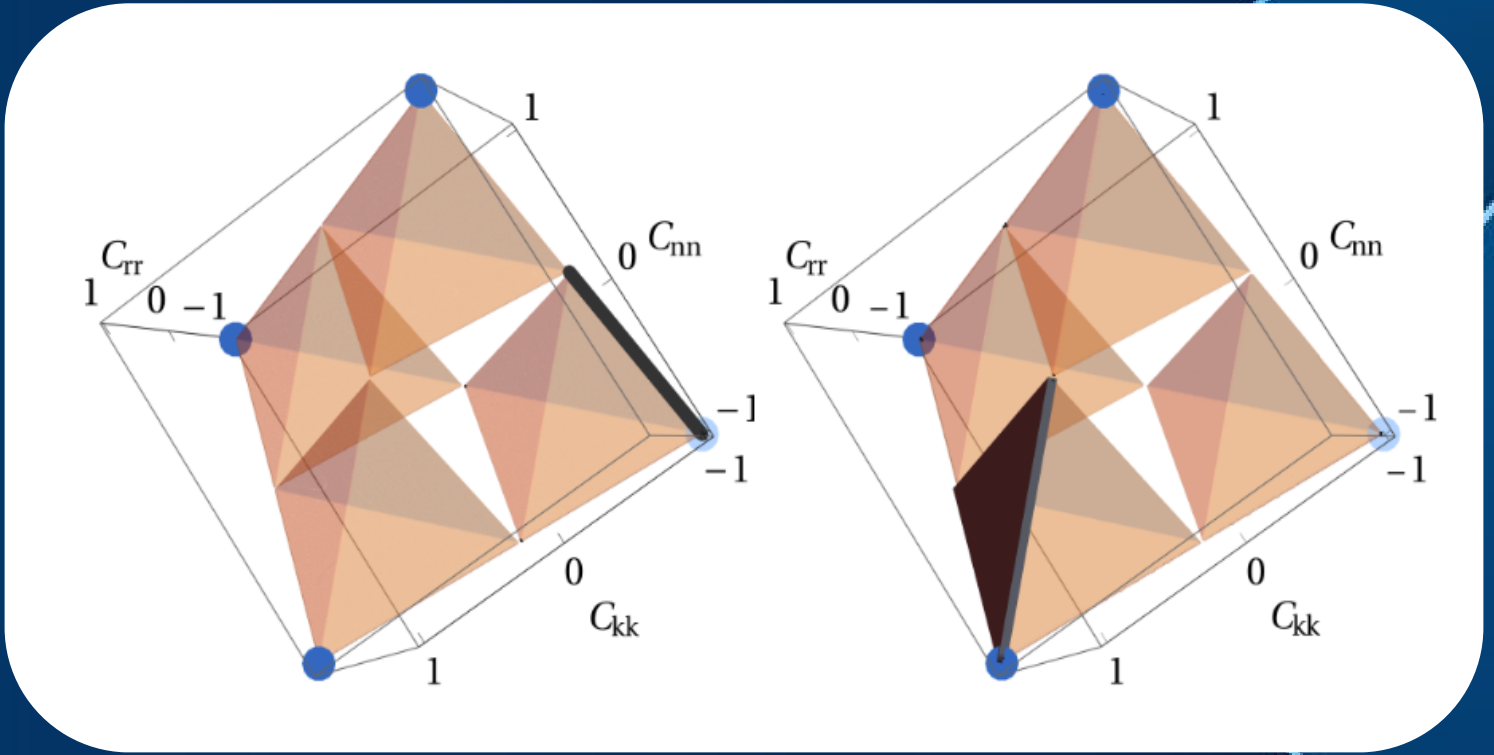
SMEFT COEFFICIENTS

Dipoles

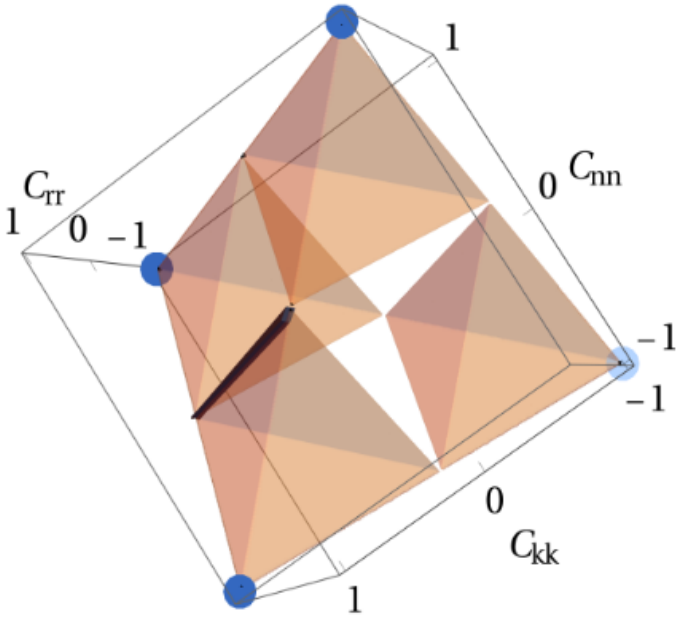
$$\mathcal{O}_{tW} = (\overline{Q}_L \gamma^{\mu\nu} \sigma_I t_R)\, \widetilde{\phi}\, W^I_{\mu\nu},$$
$$\mathcal{O}_{tB} = (\overline{Q}_L \gamma^{\mu\nu} t_R)\, \widetilde{\phi}\, B_{\mu\nu}.$$

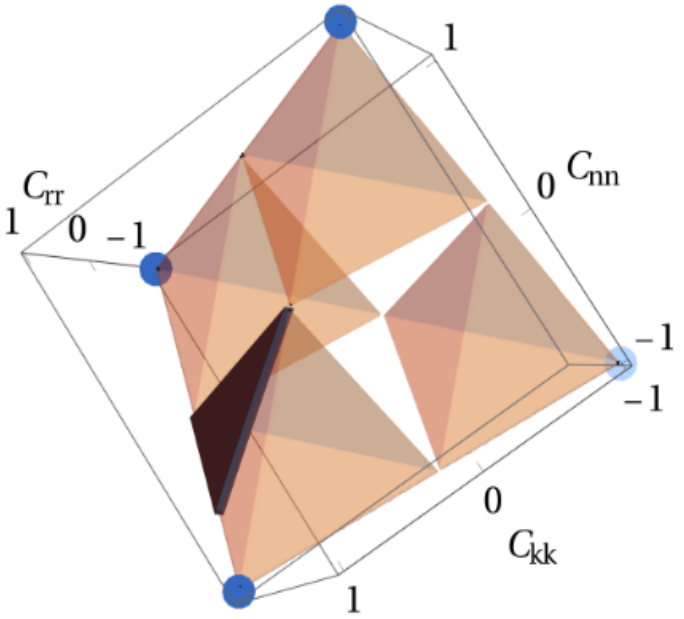
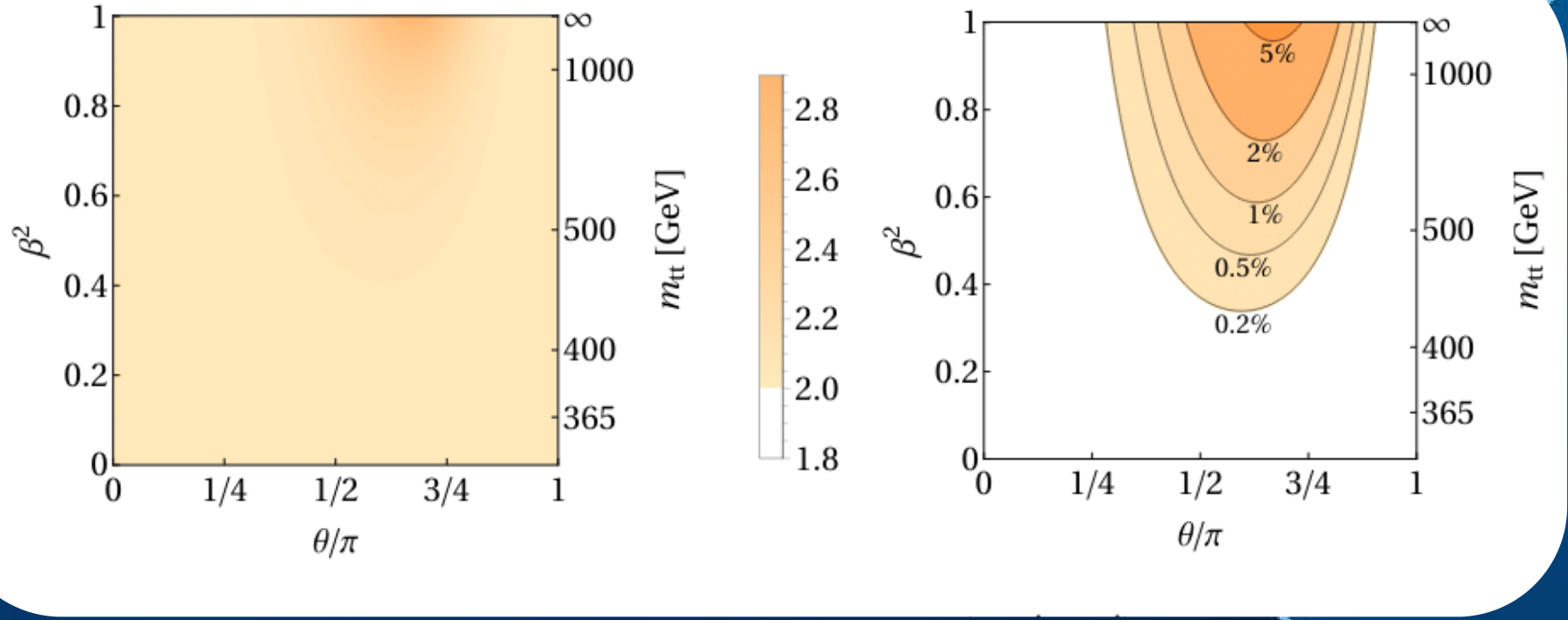
$$c_{tZ} = c_W\, c_{tW} - s_W\, c_{tB},$$
$$c_{t\gamma} = s_W c_{tW} + c_W c_{tB},$$

Reachable states: QCD vs QED



Reachable states QED





Bell Violations