Top Entanglement for searches of new physics

Drawings by Gaia Fontana @QFToons

24/04/24

Claudio Severi - U. Manchester

Top Entanglement for searches of new physics

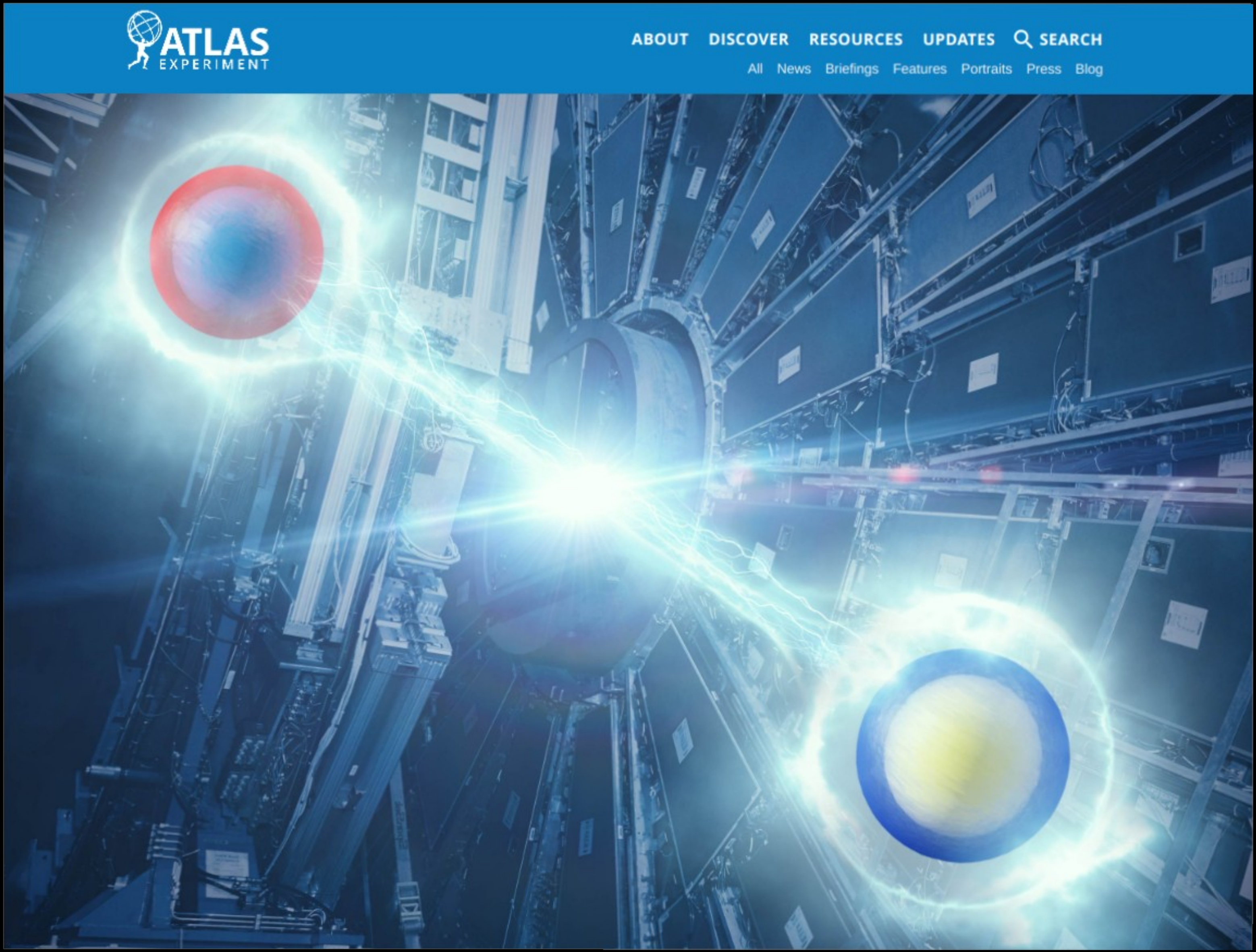
2210.09330 (hep-ph)
with E.Vryonidou

2401.08751 (hep-ph)
2404.08049 (hep-ph)
with F.Maltoni, S.Tentori, E.Vryonidou

MANCHESTER 1824
The University of Manchester

Funded by
the European Union

24/04/24 Claudio Severi - U. Manchester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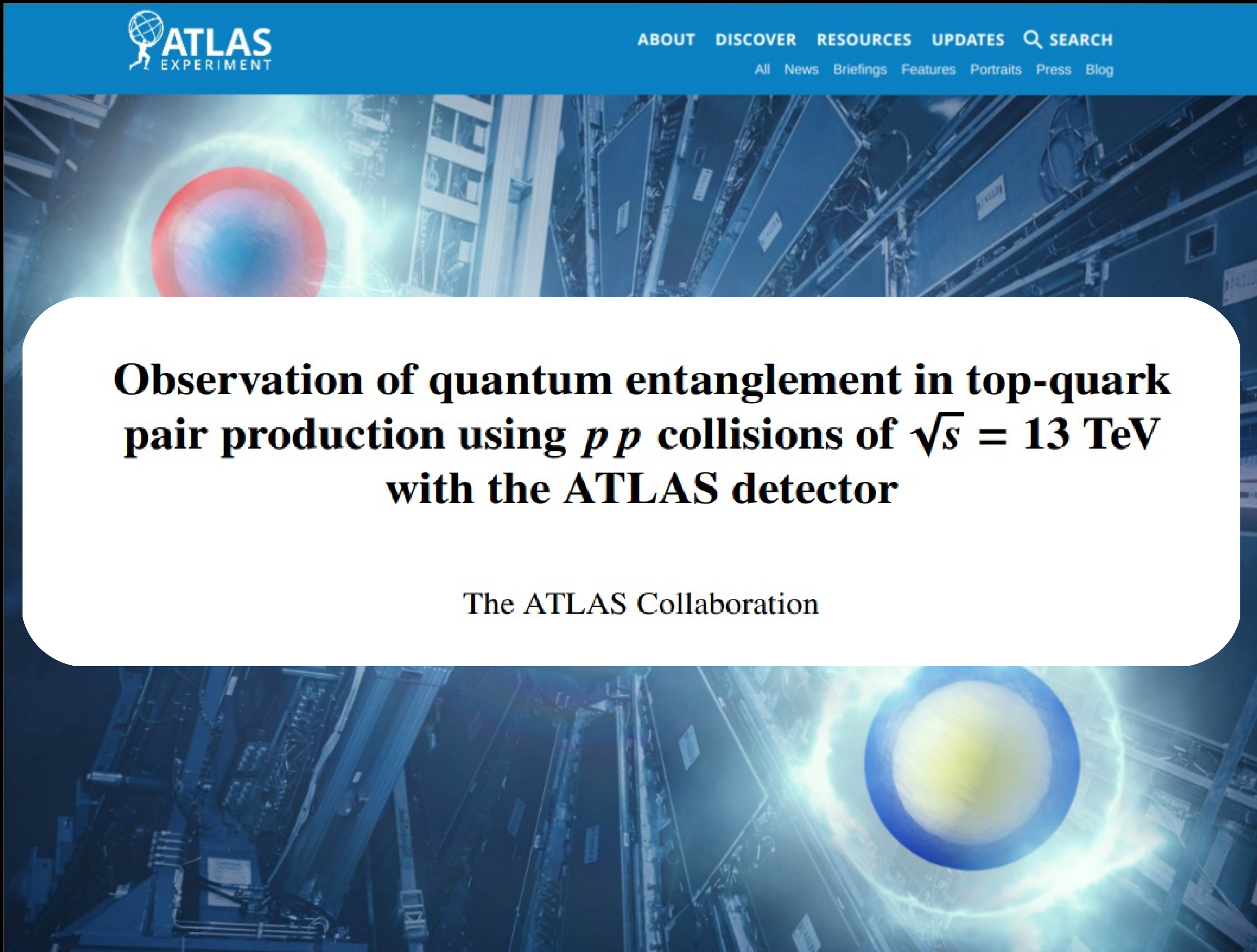
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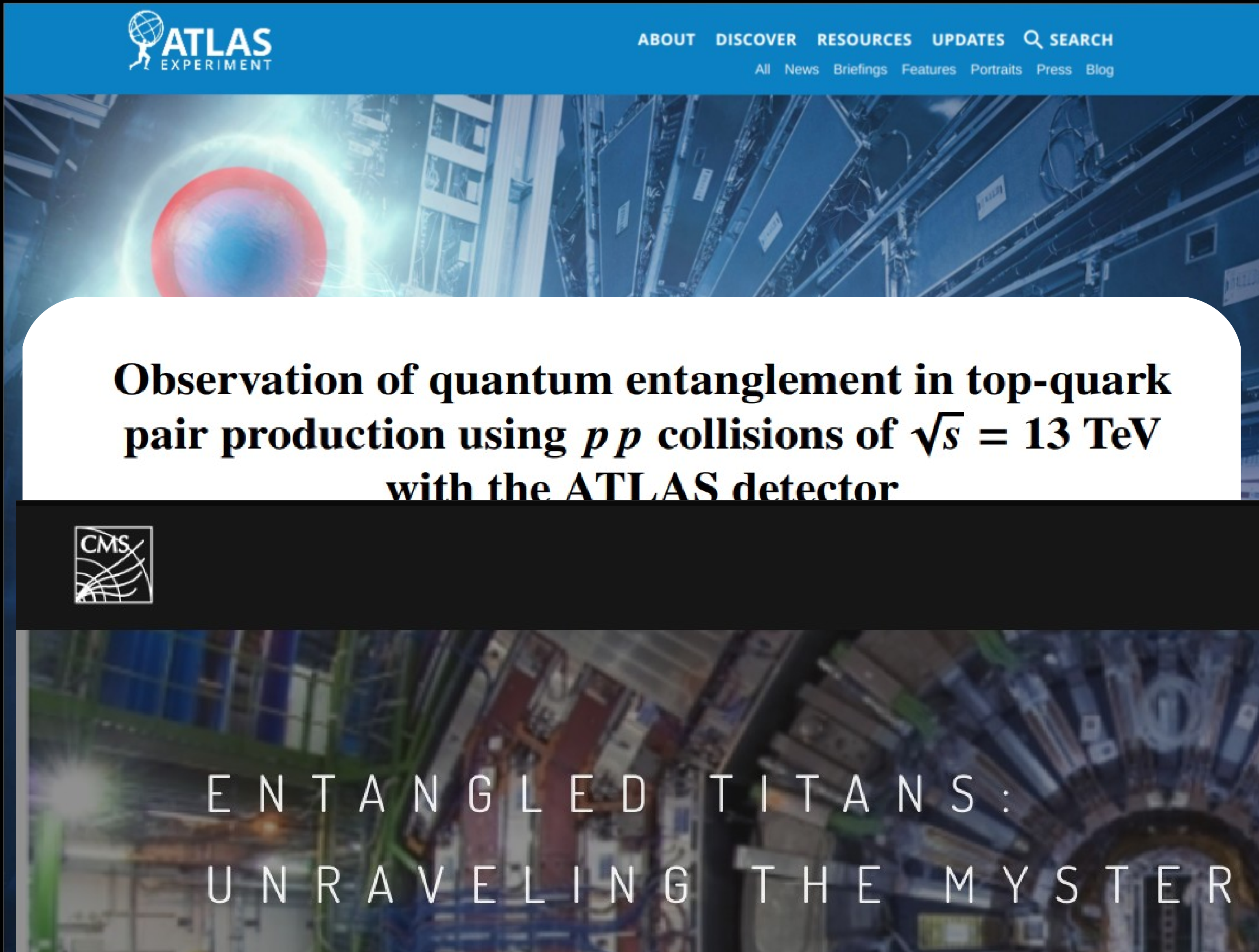
The ATLAS Collaboration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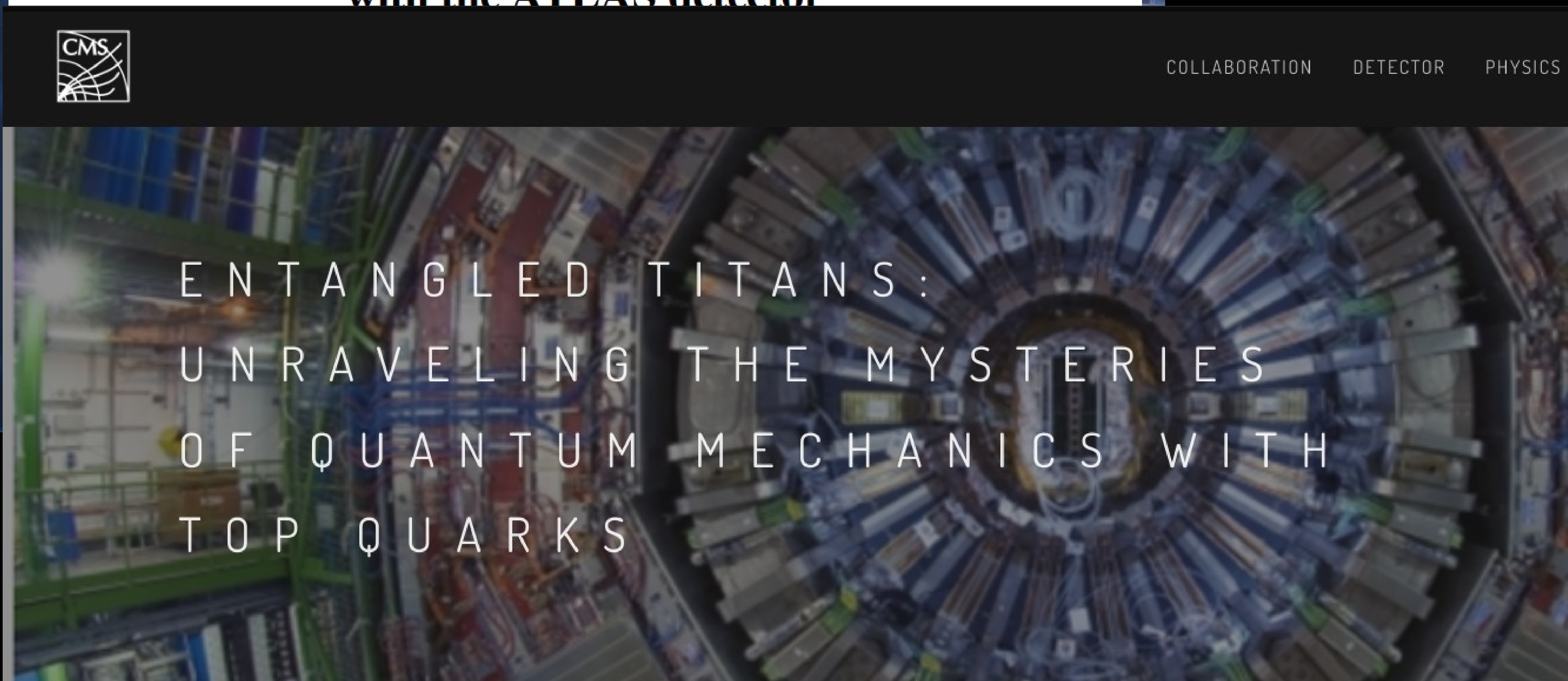
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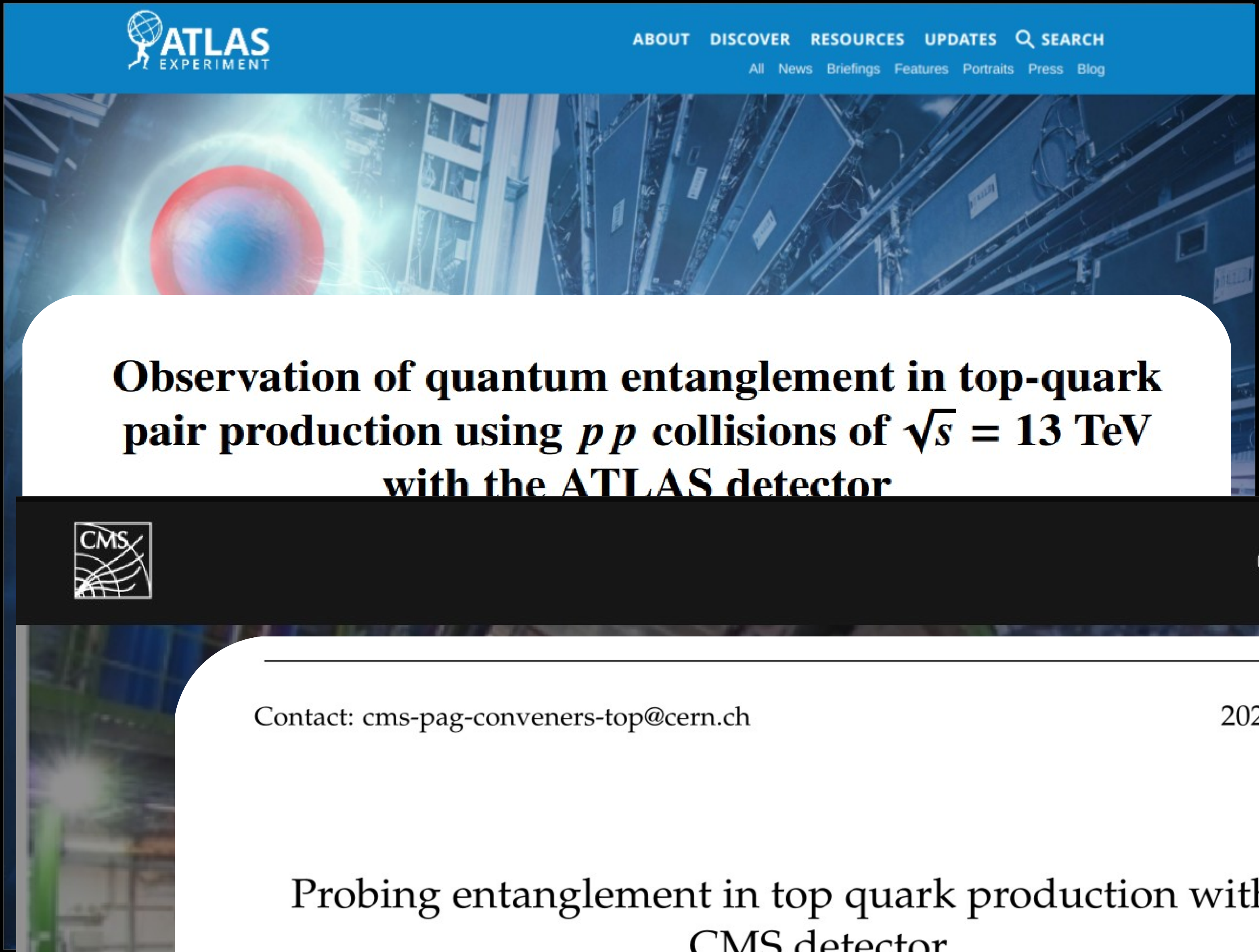
PHYSICS
ENTANGLED TITANS:
UNRAVELING THE MYSTERIES
OF QUANTUM MECHANICS WITH
TOP QUARKS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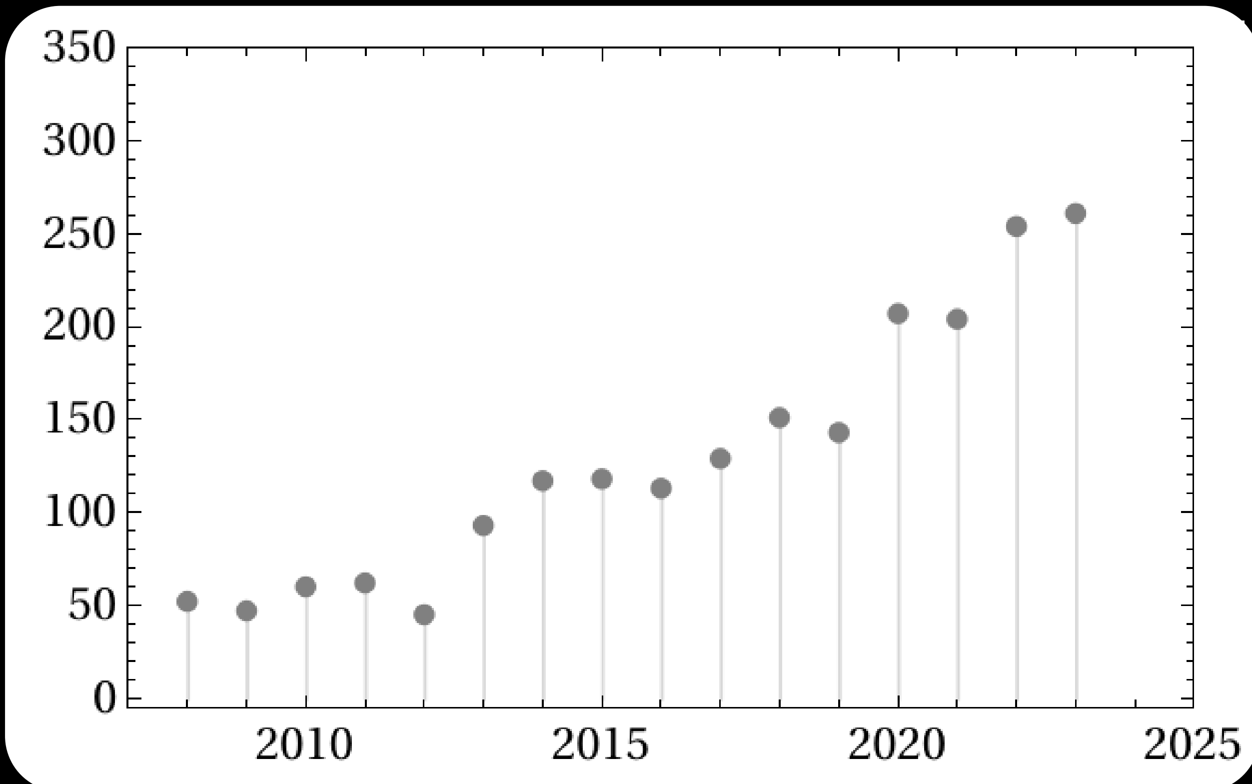
CMS
COLLABORATION DETECTOR PHYSICS
Contact: cms-pag-conveners-top@cern.ch
2024/03/27
Probing entanglement in top quark production with the CMS detector
The CMS Collaboration

Number of papers in hep-ph with “entanglement” or “quantum” or “Bell” in the title



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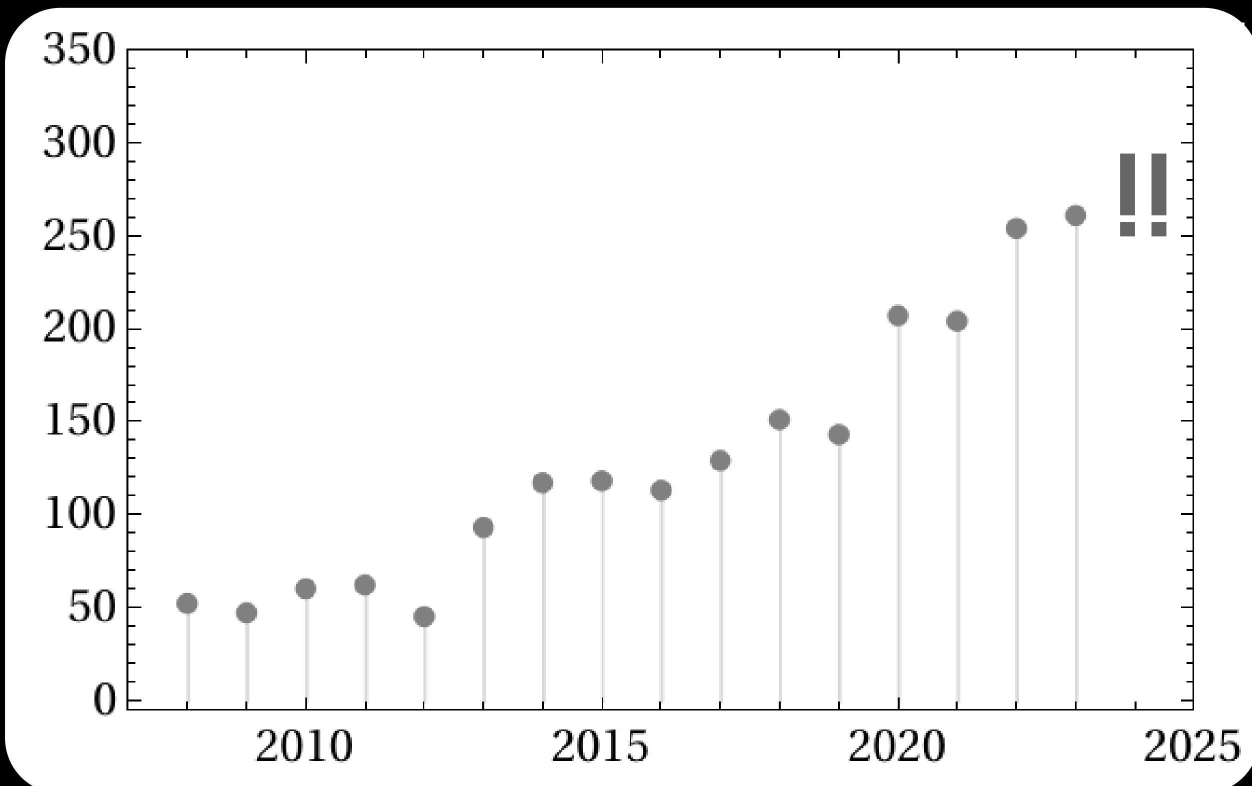

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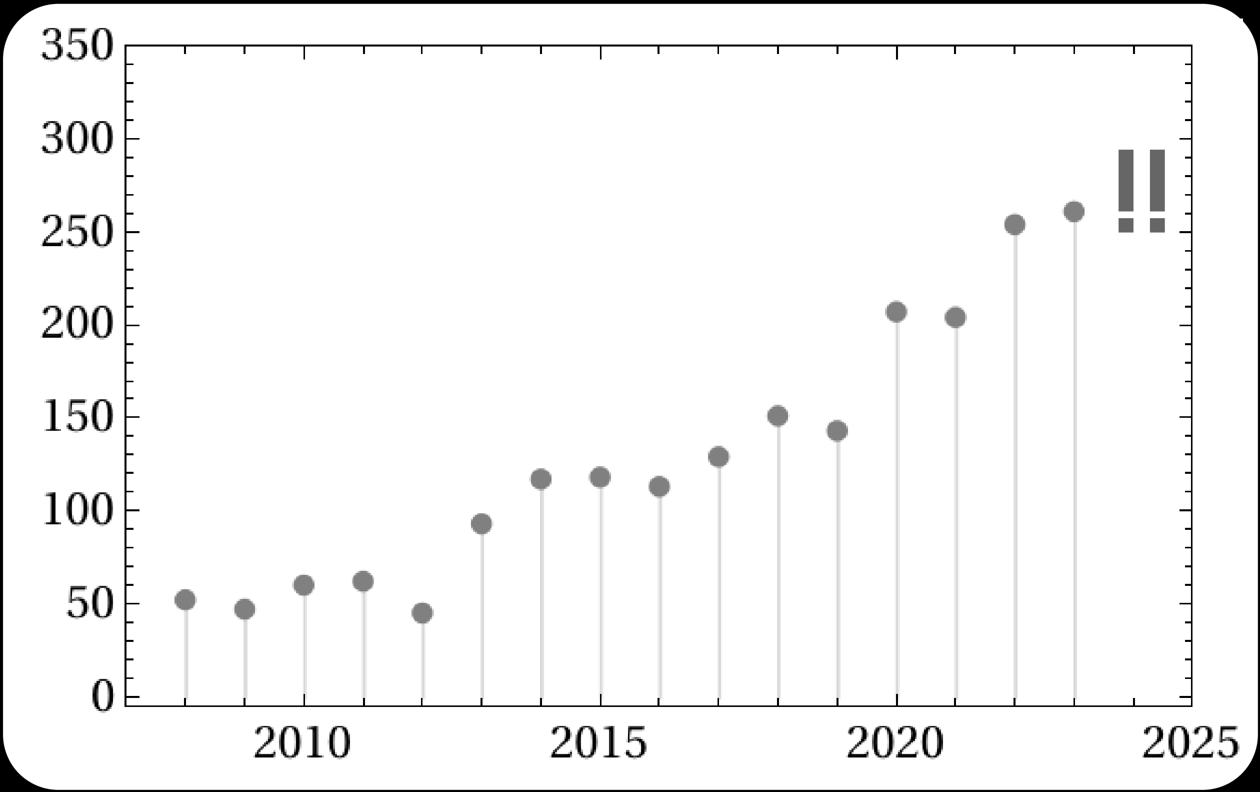
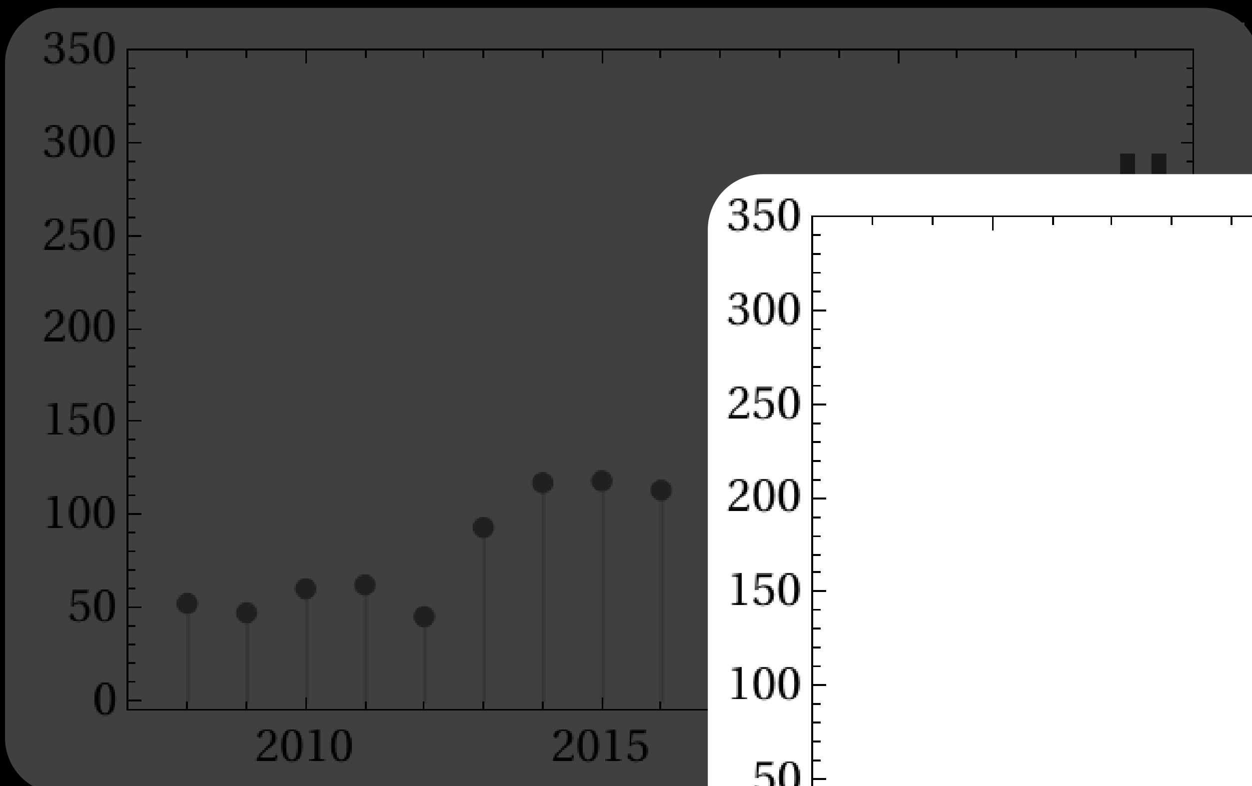
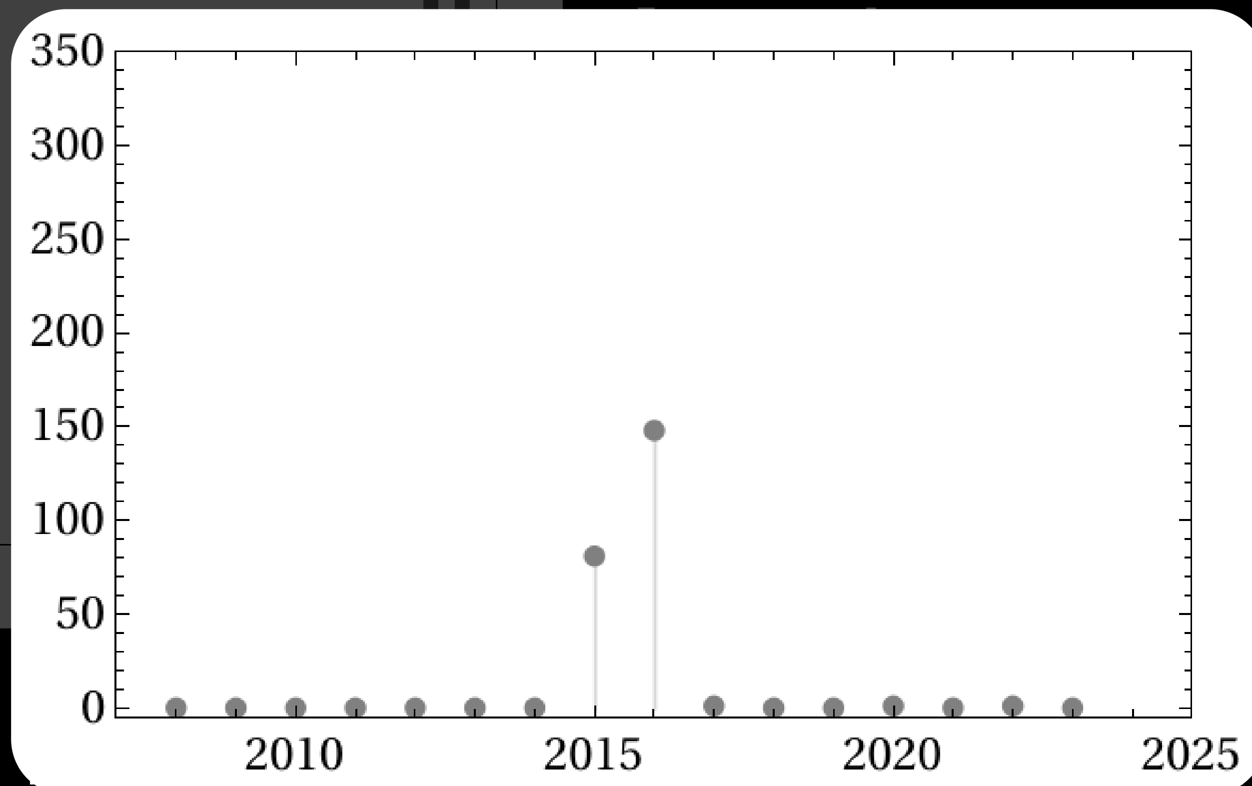


>1 per day
6x the rate in 2008-11

Number of papers in hep-ph with “entanglement” or “quantum” or “Bell” in the title





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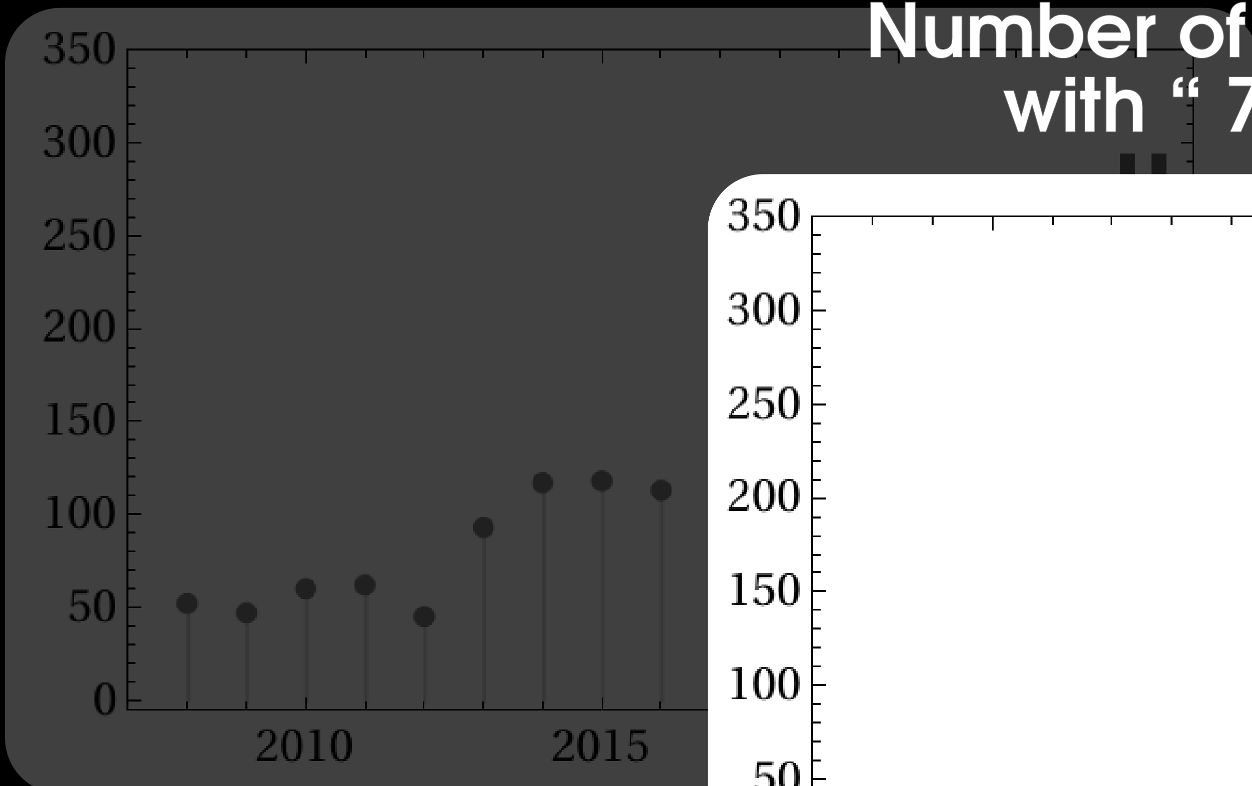
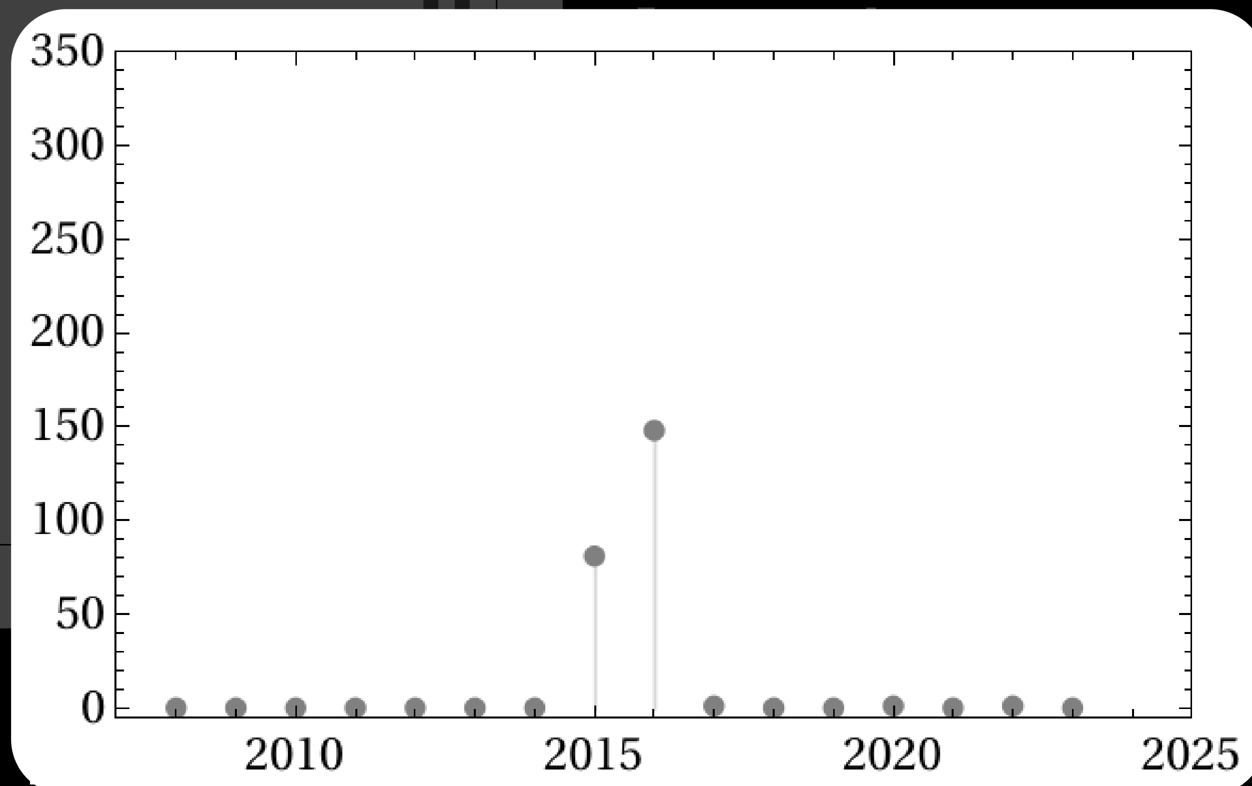


Number of papers in hep-ph
with “ 750 ” in the title



Is the field of Quantum Information in colliders here to stay?

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Yes!

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Yes! … for a very precise reason

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Not because it's cool (which it is)

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Yes! … for a very precise reason

Not because it's cool (which it is)
Not because it will disprove QM (which it won't)

Is the field of Quantum Information in colliders here to stay?

Yes! … for a very precise reason

Not because it's cool (which it is)

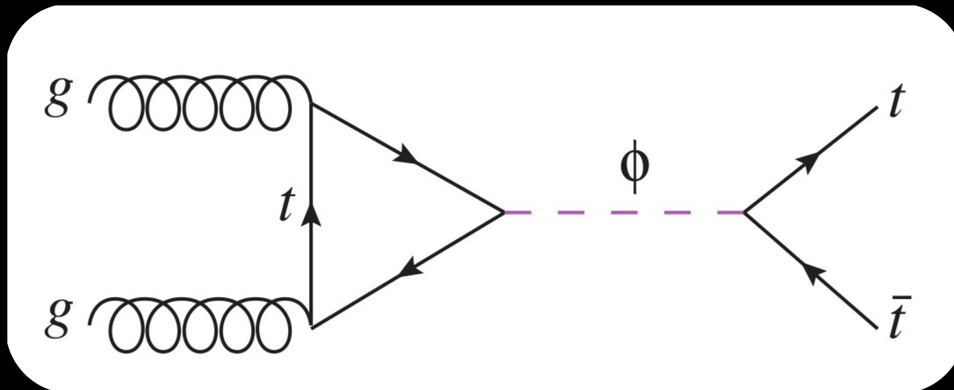
Not because it will disprove QM (which it won't)

Because it is useful for our jobs as particle physicists

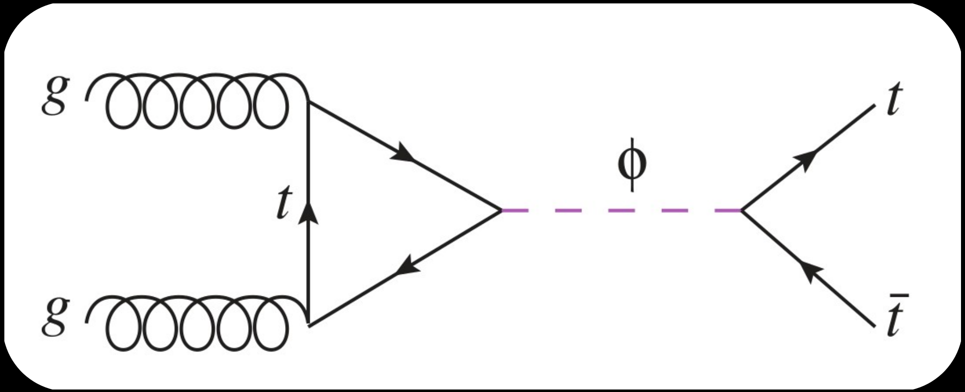
I will show it with three examples:

1. Heavy scalars
2. SMEFT at the LHC
3. SMEFT in an e^+e^- collider

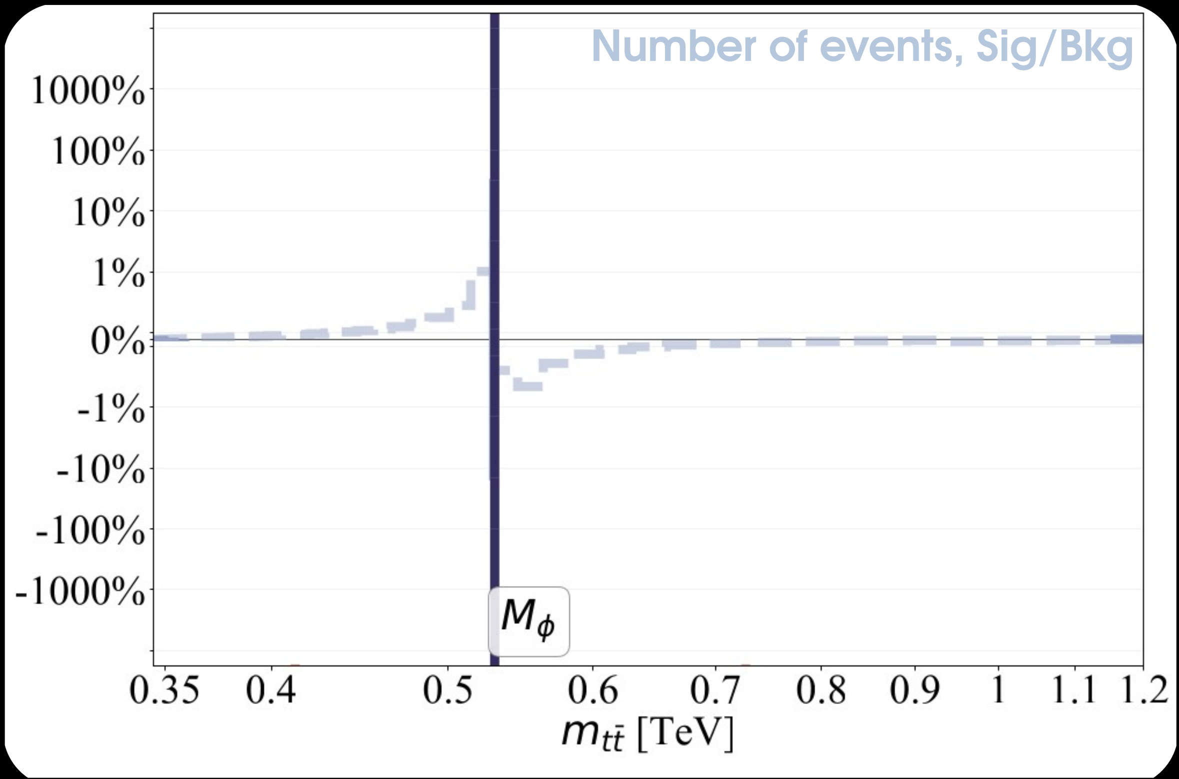
Heavy scalars



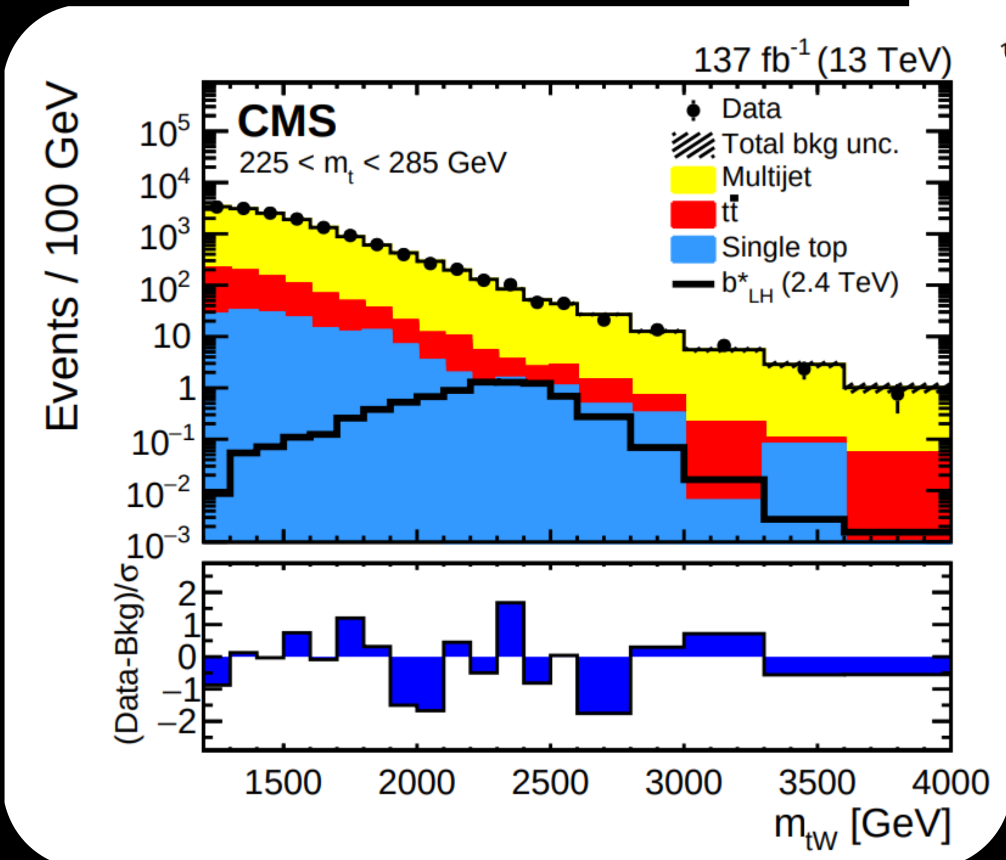
Heavy scalars

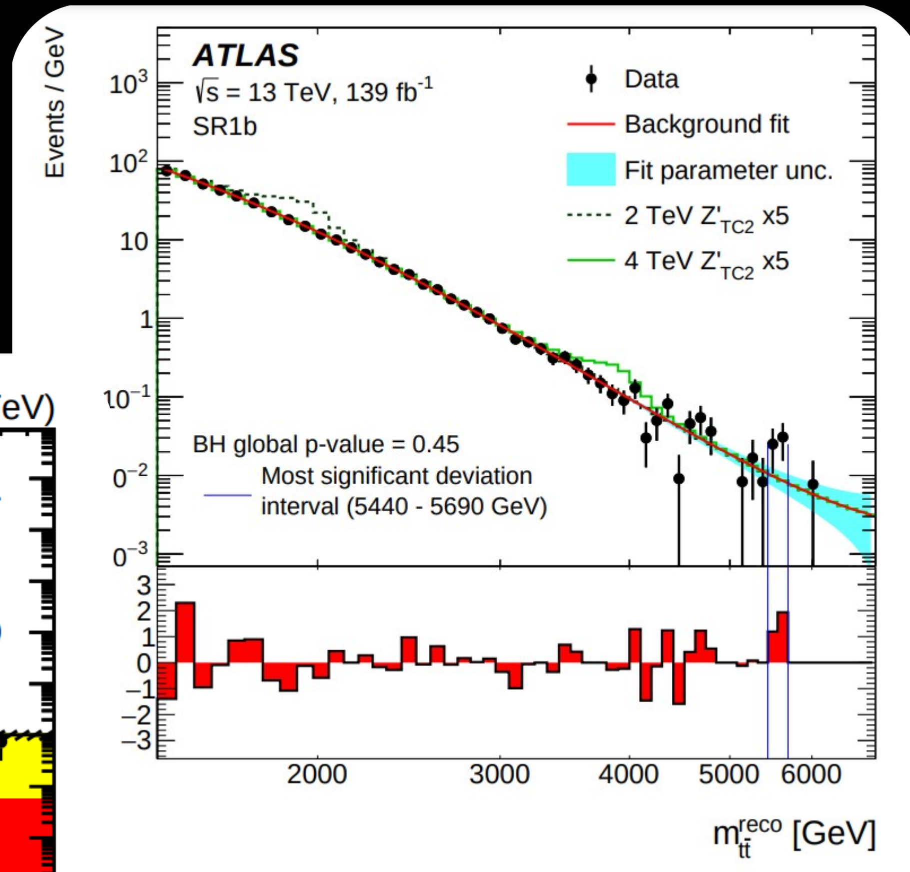


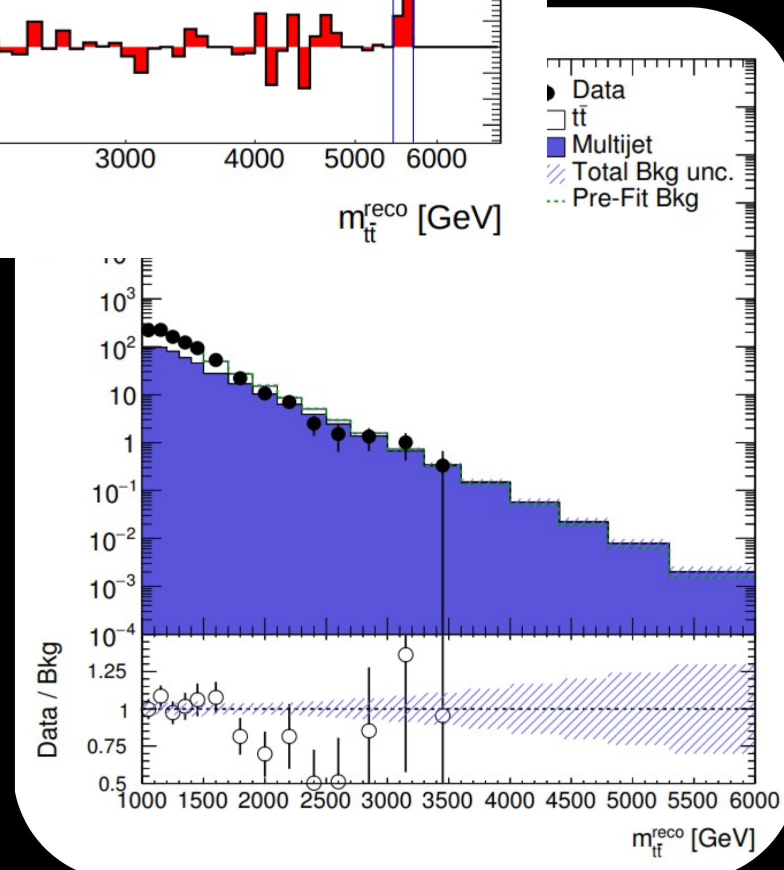
If the coupling to tops is still O(1) but M > $2m_t$ the width can be tens/hundreds of GeV



Searches for heavy scalars







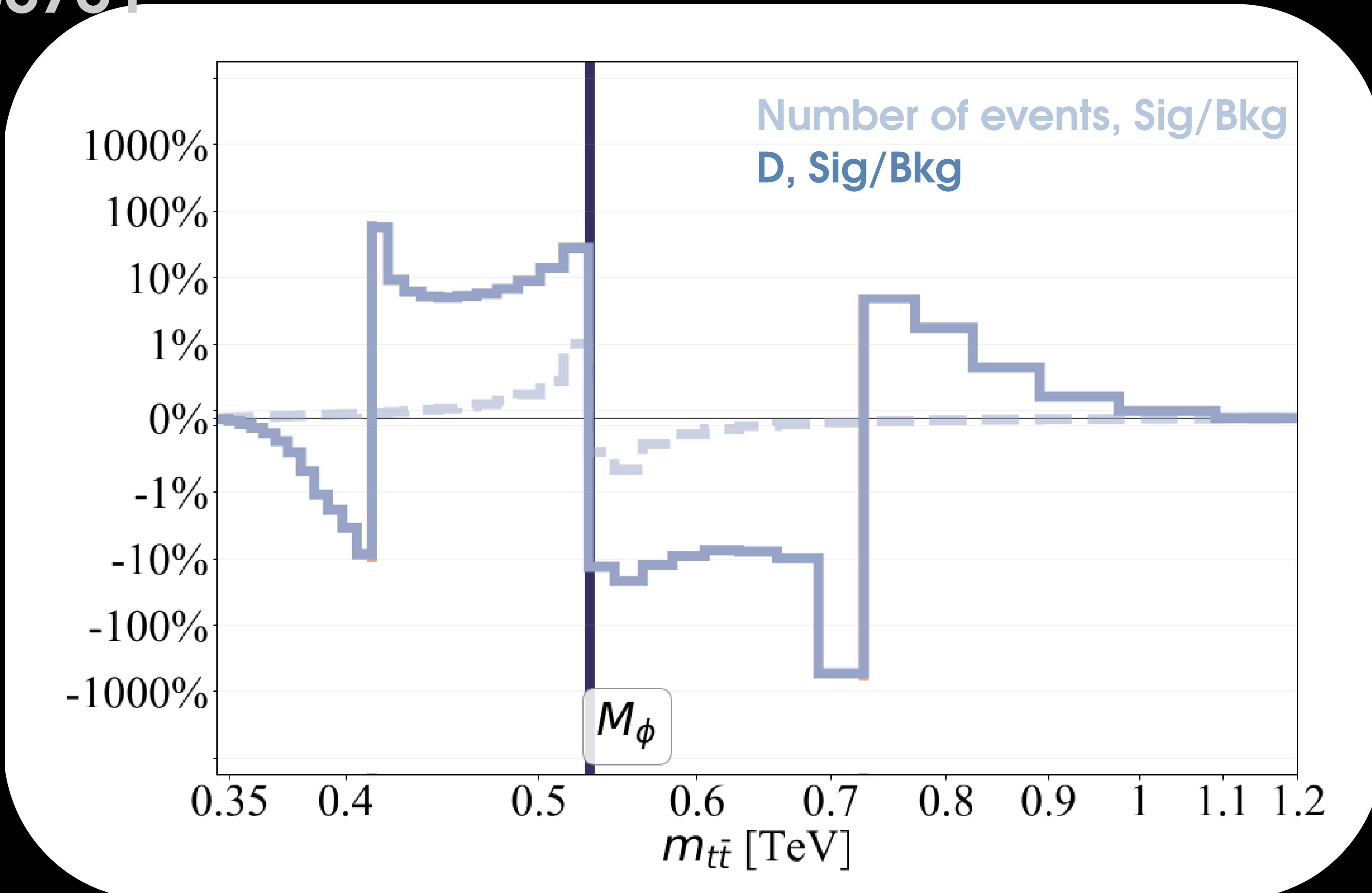
Heavy scalars

But… tops produced by ϕ decays have total spin 0,
The QCD background is very different.

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

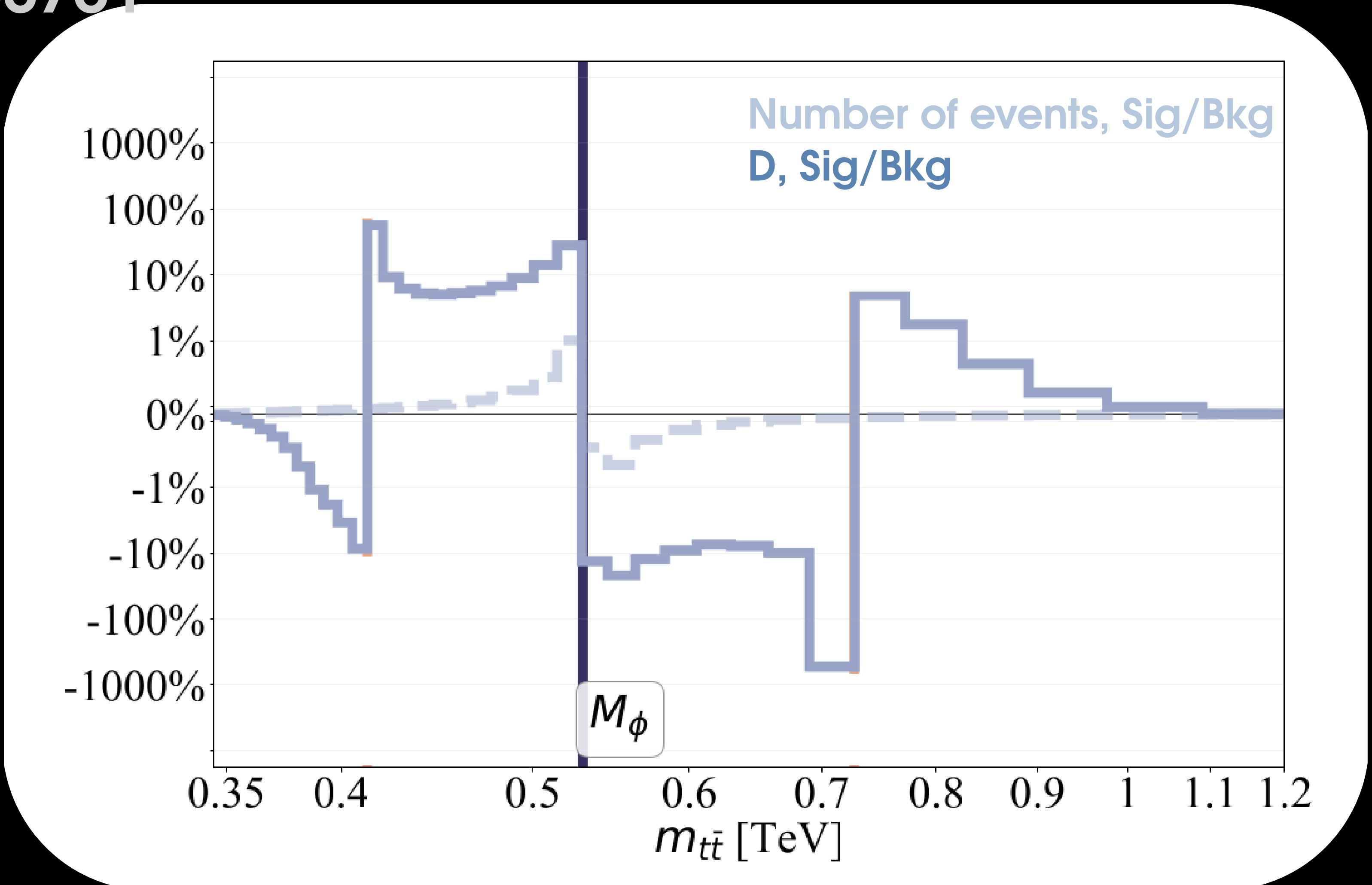
Specific combinations of C_{ij} are sensitive to specific spin states.

For a scalar $\phi \to tt$ we want D^k, for a pseudoscalar D^1



The effect on D can be 10-100x larger than the effect on the total rate

2401.08751



The effect on D can be 10-100x larger than the effect on the total rate

<u>Quantum observables outperform the others</u>

SMEFT at the LHC

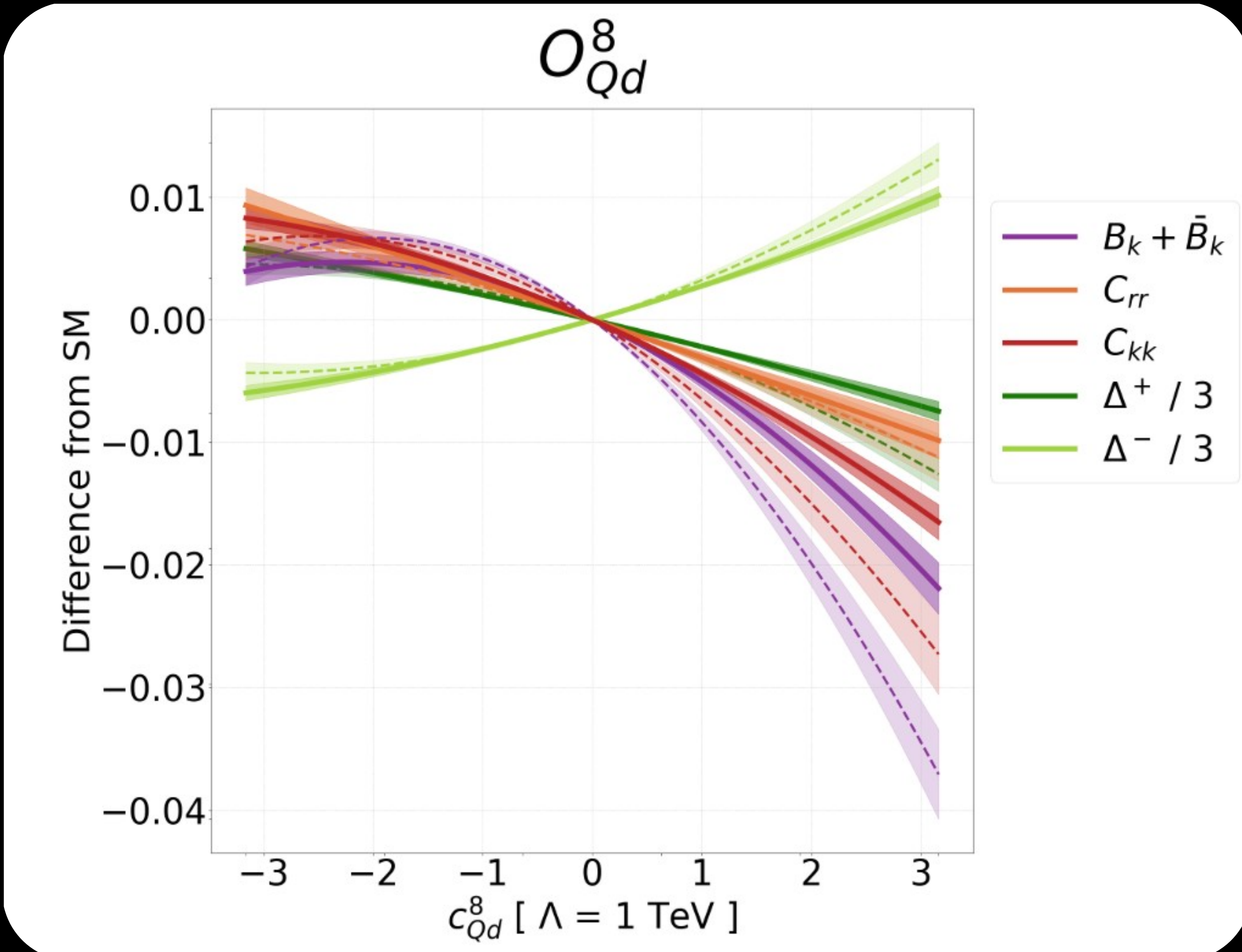
A lot more degrees of freedom…

$$\mathcal{O}_{tu}^{8} = \sum_{\mathrm{f}=1}^{2}(\bar{t}\gamma_\mu T^A t)(\overline{u}_{\mathrm{f}}\gamma^\mu T_A u_{\mathrm{f}})$$
$$\mathcal{O}_{td}^{8} = \sum_{\mathrm{f}=1}^{3}(\bar{t}\gamma_\mu T_A t)(\overline{d}_{\mathrm{f}}\gamma^\mu T^A d_{\mathrm{f}})$$
$$\mathcal{O}_{tq}^{8} = \sum_{\mathrm{f}=1}^{2}(\overline{q}_{\mathrm{f}}\gamma_\mu T_A q_{\mathrm{f}})(\bar{t}\gamma^\mu T^A t)$$
$$\mathcal{O}_{Qu}^{8} = \sum_{\mathrm{f}=1}^{2}(\overline{Q}\gamma_\mu T_A Q)(\overline{u}_{\mathrm{f}}\gamma^\mu T^A u_{\mathrm{f}})$$
$$\mathcal{O}_{Qd}^{8} = \sum_{\mathrm{f}=1}^{3}(\overline{Q}\gamma_\mu T_A Q)(\overline{d}_{\mathrm{f}}\gamma^\mu T^A d_{\mathrm{f}})$$
$$\mathcal{O}_{Qq}^{1,8} = \sum_{\mathrm{f}=1}^{2}(\overline{Q}\gamma_\mu T^A Q)(\overline{q}_{\mathrm{f}}\gamma^\mu T_A q_{\mathrm{f}})$$
$$\mathcal{O}_{Qq}^{3,8} = \sum_{\mathrm{f}=1}^{2}(\overline{Q}\gamma_\mu T^A \sigma_I Q)(\overline{q}_{\mathrm{f}}\gamma^\mu T_A \sigma^I q_{\mathrm{f}})$$

+ color singlets (at higher order)

$$\mathcal{O}_{gt} = \bar{t}\, T_A \gamma^\mu D^\nu t\, G_{\mu\nu}^A,$$
$$\mathcal{O}_{gQ} = \overline{Q} T_A \gamma^\mu D^\nu Q G_{\mu\nu}^A,$$
$$\mathcal{O}_{tG} = g_S\, \overline{Q} T_A \tilde{\varphi} \sigma^{\mu\nu} t\, G_{\mu\nu}^A$$

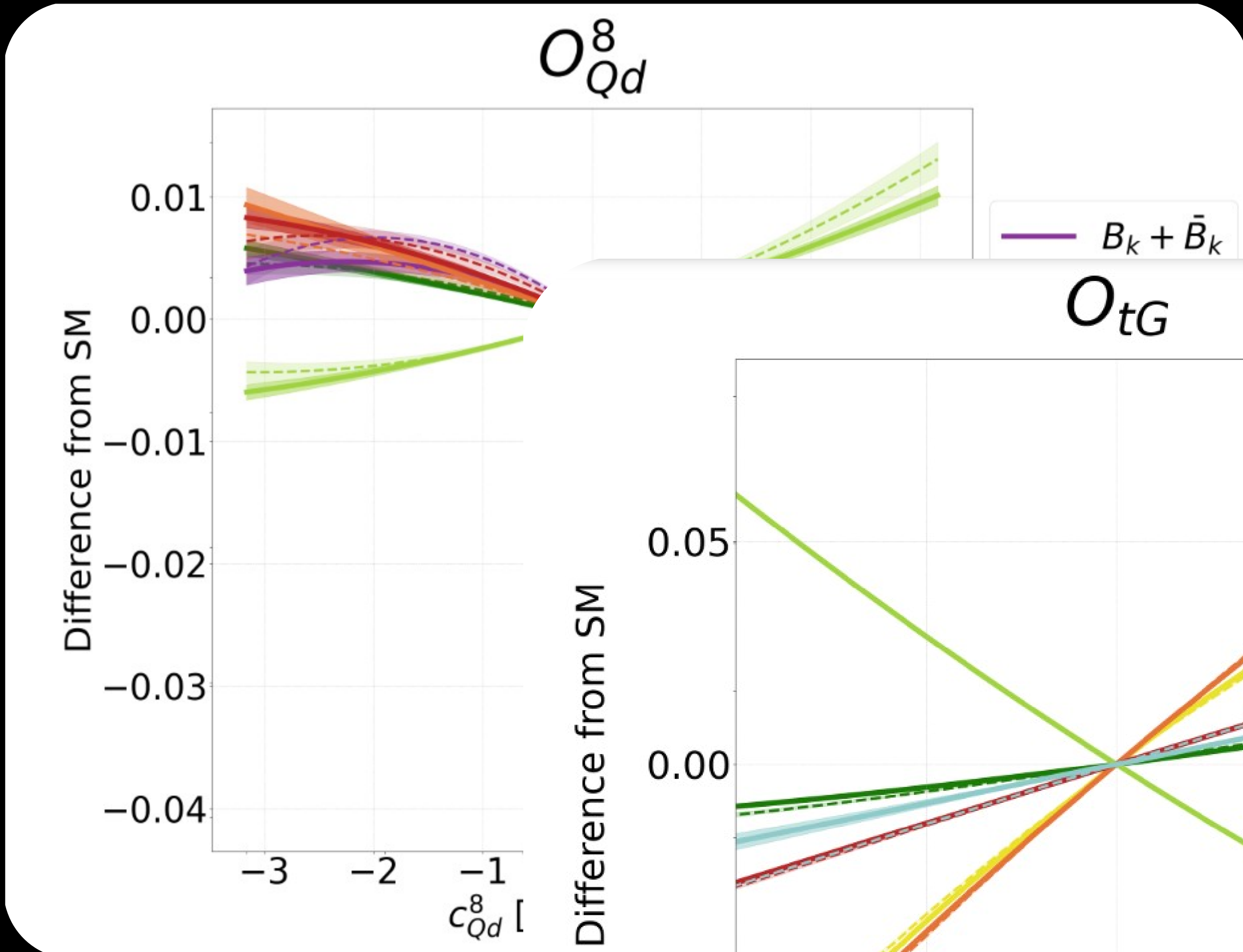
"Quantum" observables may:
- improve the overall discovery power
- lift flat directions

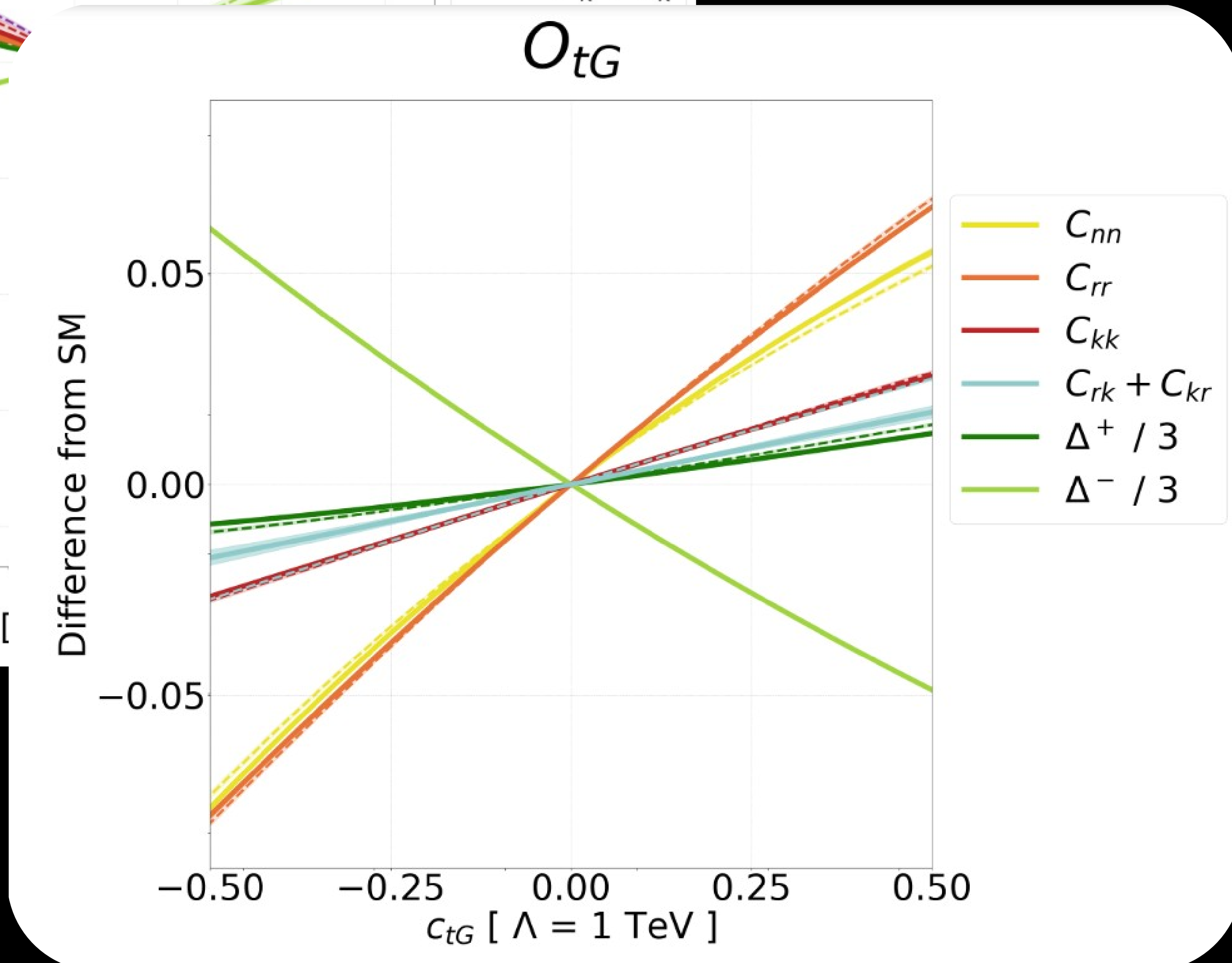


Shift in tt spin observables due to sample 4f operators

2210.09330

Shift in tt spin observables due to sample 4f operators





Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

Coupling	95% CL	Theoretical unc.	χ^2	Coefficients
$\hat{\mu}_t$	$-0.014 < \hat{\mu}_t < 0.004$	± 0.001	7	$C_{kk}, C_{nn}, C_{rk}+C_{kr}, D$
$\hat{d}_t$	$-0.020 < \hat{d}_t < 0.012$	—	9	$B_2^r, B_1^n, C_{nr}-C_{rn}, C_{nk}-C_{kn}$
$\hat{c}_{--}$	$-0.040 < \hat{c}_{--} < 0.006$	± 0.001	7	$B_2^r, B_1^n, C_{nr}-C_{rn}, C_{nk}-C_{kn}$
$\hat{c}_{-+}$	$-0.009 < \hat{c}_{-+} < 0.005$	—	11	$B_1^n, B_2^n, B_1^{r*}, C_{nk}+C_{kn}$
$\hat{c}_{VV}$	$-0.011 < \hat{c}_{VV} < 0.042$	± 0.004	7	$C_{kk}, C_{nn}, C_{rk}+C_{kr}, D$
$\hat{c}_{VA}$	$-0.044 < \hat{c}_{VA} < 0.027$	± 0.003	9	$B_2^k, B_2^r, C_{kk}, C_{nr}+C_{rn}$
$\hat{c}_{AV}$	$-0.035 < \hat{c}_{AV} < 0.032$	± 0.001	6	$B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}$
$\hat{c}_1$	$-0.09 < \hat{c}_1 < 0.34$	± 0.04	7	$C_{kk}, C_{nn}, C_{rk}+C_{kr}, D$
$\hat{c}_3$	$-0.35 < \hat{c}_3 < 0.21$	± 0.02	9	$B_2^k, B_2^r, C_{kk}, C_{nr}+C_{rn}$
$\hat{c}_1-\hat{c}_2+\hat{c}_3$	$-0.17 < \hat{c}_1-\hat{c}_2+\hat{c}_3 < 0.15$	± 0.01	6	$B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}$

Constraints competitive with global fits (at the time of publication)

Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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$\hat{c}_{VA}$	$-0.044 < \hat{c}_{VA} < 0.027$	± 0.003	9	B_2^k, B_2^r, C_{kk}, $C_{nr} + C_{rn}$
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$\hat{c}_1 - \hat{c}_2 + \hat{c}_3$	$-0.17 < \hat{c}_1 - \hat{c}_2 + \hat{c}_3 < 0.15$	± 0.01	6	B_1^{k*}, B_2^{k*}, B_1^{r*}, B_2^{r*}

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Measurement of the top quark polarization and $t\bar{t}$ spin correlations using dilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV

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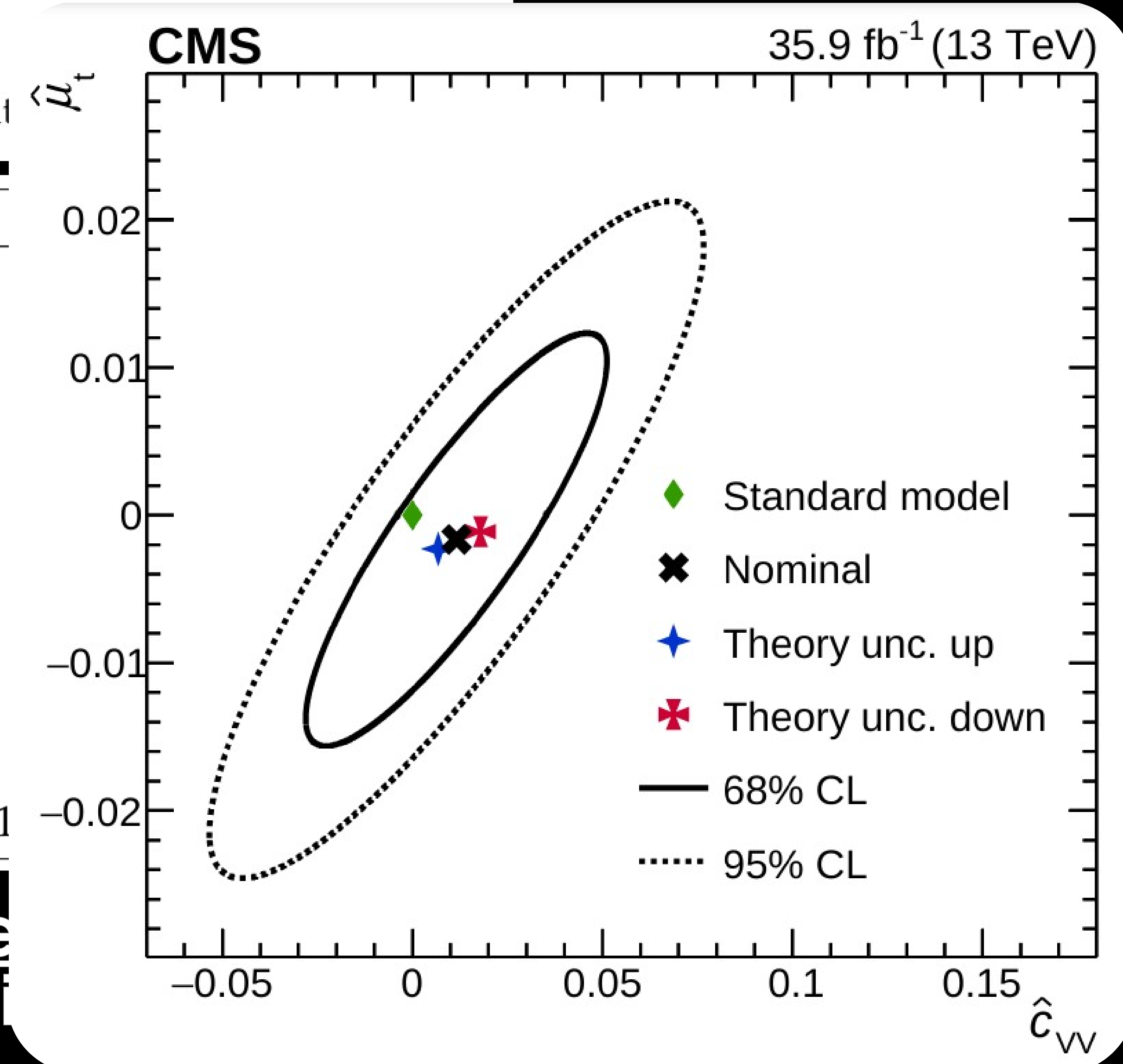
$\hat{c}_1 - \hat{c}_2 + \hat{c}_3$	$-0.17 < \hat{c}_1 - \hat{c}_2 + \hat{c}_3 < 0.1$



Constraints <u>competitive</u>
(at the time of publicati

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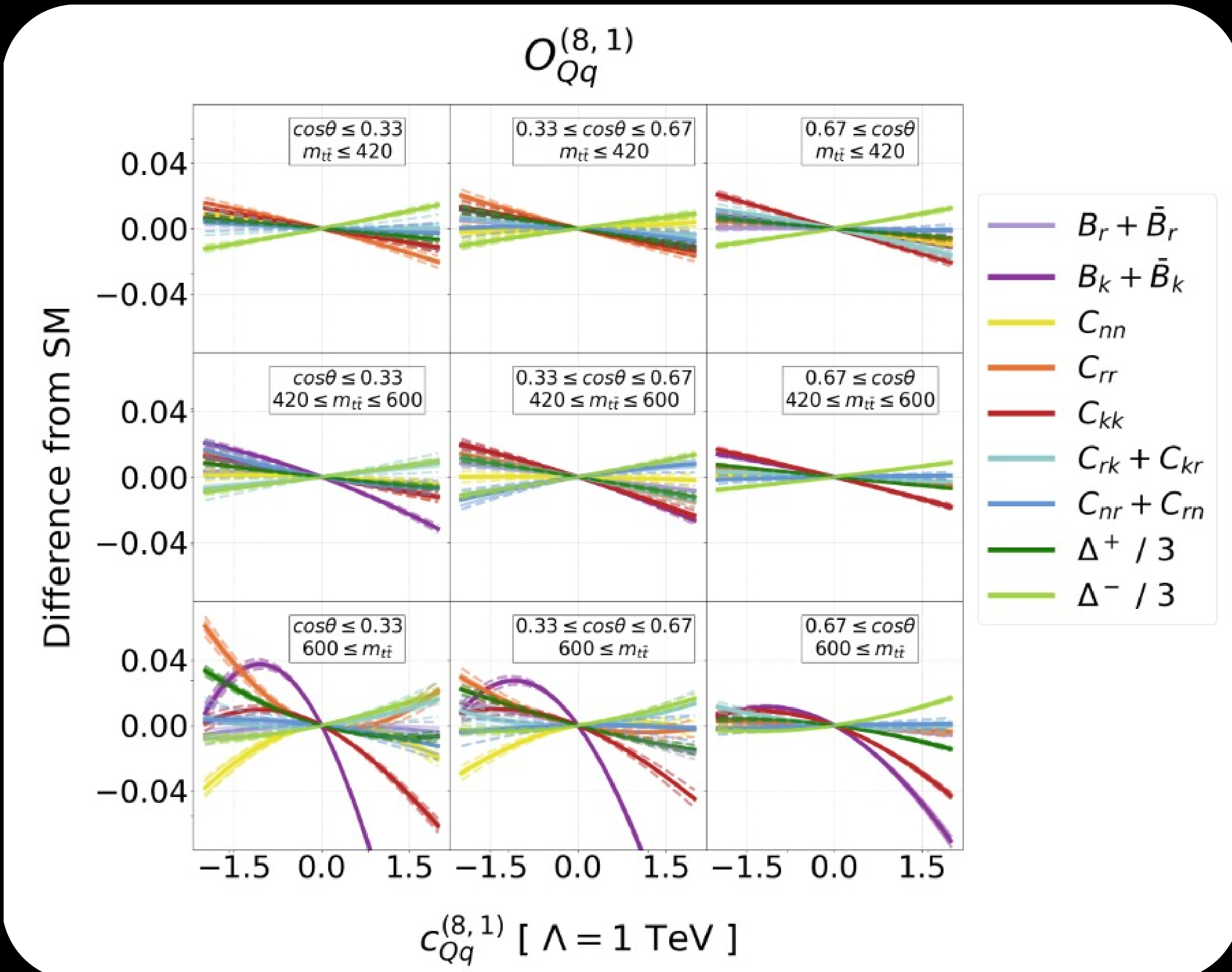


p_T^2 dependence makes differential measurements particularly powerful

Spin/entanglement measurements may come to dominate global fits in the top sector

Operator	CMS [12] 36 fb^{-1} Inclusive	Run III Projection 300 fb^{-1} Differential	Current Global Fit
$\mathcal{O}_{tG}$	$[-0.18, 0.18]$	$[-0.03, 0.04]$	$[0.00, 0.11]$
$\mathcal{O}_{tu}^{8}$	$[-5.8, 3.6]$	$[-1.0, 0.7]$	$[-0.9, 0.3]$
$\mathcal{O}_{td}^{8}$	$[-7.9, 5.2]$	$[-1.3, 1.0]$	$[-1.3, 0.6]$
$\mathcal{O}_{tq}^{8}$	$[-4.2, 3.1]$	$[-0.7, 0.5]$	$[-0.5, 0.4]$
$\mathcal{O}_{Qu}^{8}$	$[-9.4, 4.6]$	$[-0.7, 0.6]$	$[-1.0, 0.5]$
$\mathcal{O}_{Qd}^{8}$	$[-11.7, 5.8]$	$[-0.9, 0.8]$	$[-1.6, 0.9]$
$\mathcal{O}_{Qq}^{(1,8)}$	$[-5.8, -4.6] \cup [-1.7, 2.5]$	$[-0.4, 0.3]$	$[-0.4, 0.3]$
$\mathcal{O}_{Qq}^{(3,8)}$	$[-5.0, 4.2]$	$[-1.1, 0.8]$	$[-0.5, 0.4]$
$\mathcal{O}_{tu}^{1}$	$[-2.1, 2.1]$	$[-0.5, 0.5]$	$[-0.4, 0.3]$
$\mathcal{O}_{td}^{1}$	$[-2.7, 2.6]$	$[-0.6, 0.6]$	$[-0.4, 0.4]$
$\mathcal{O}_{tq}^{1}$	$[-1.7, 1.8]$	$[-0.4, 0.4]$	$[-0.2, 0.3]$
$\mathcal{O}_{Qu}^{1}$	$[-2.1, 2.4]$	$[-0.4, 0.5]$	$[-0.3, 0.4]$
$\mathcal{O}_{Qd}^{1}$	$[-2.8, 3.0]$	$[-0.6, 0.6]$	$[-0.3, 0.4]$
$\mathcal{O}_{Qq}^{(1,1)}$	$[-1.8, 1.8]$	$[-0.4, 0.4]$	$[-0.3, 0.2]$
$\mathcal{O}_{Qq}^{(3,1)}$	$[-1.8, 1.8]$	$[-0.4, 0.4]$	$[-0.1, 0.2]$

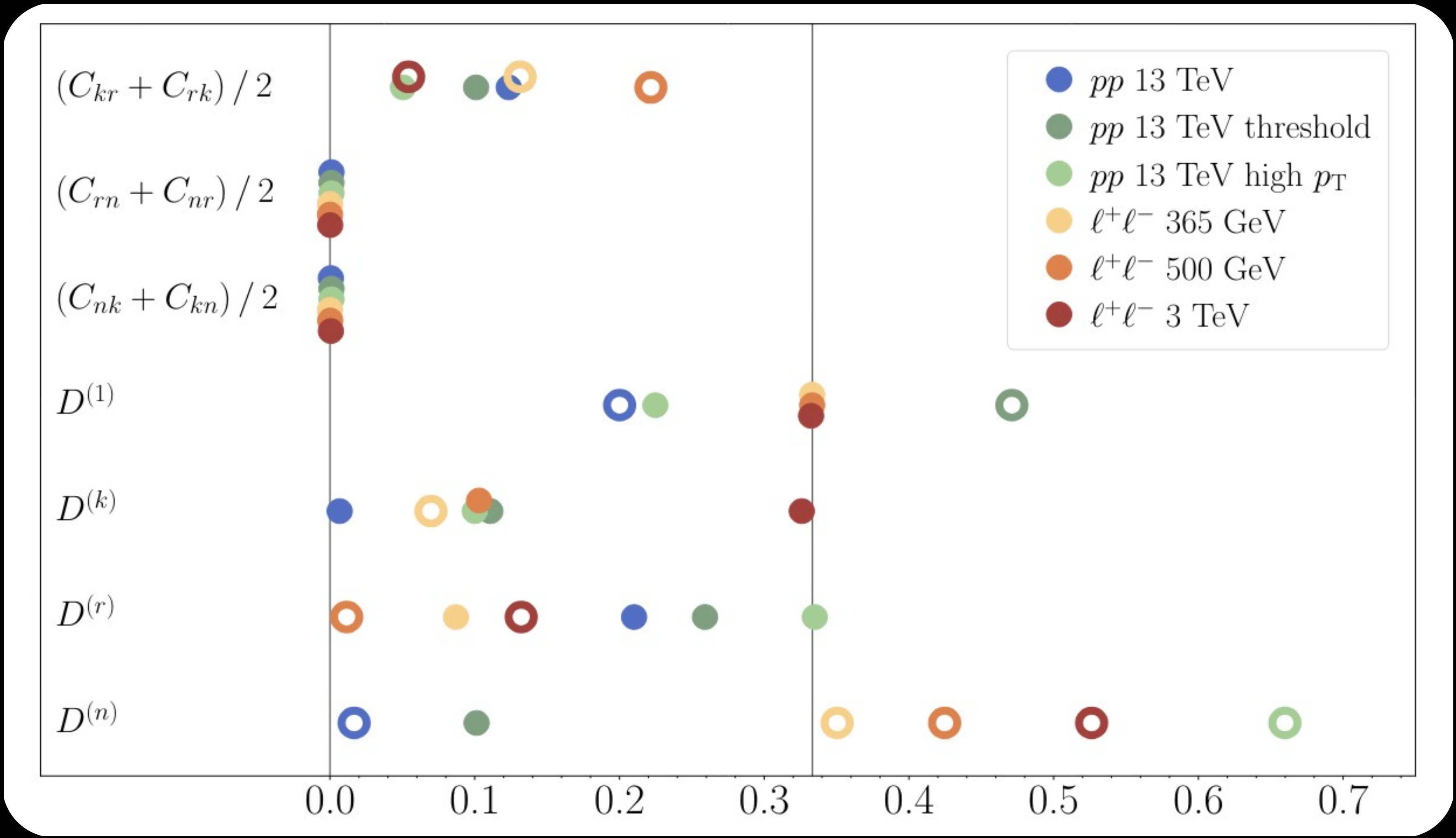
our projections suggest they will

Spin/entanglement measurements may come to dominate global fits in the top sector

2404.08049

SMEFT in an e+e-

- Unique environment -- EW dominated ttbar production
- Incredibly precise
- Fixed √(s hat)



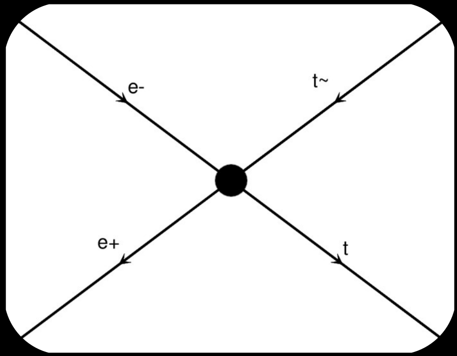
The SMEFT degrees of freedom are similar to the LHC case,

$$c_{\mathrm{VV}} = \frac{1}{4}\big(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} + c_{Qe}\big),$$

$$c_{\mathrm{AV}} = \frac{1}{4}\big(-c_{Q\ell}^{(1)} + c_{Q\ell}^{(3)} + c_{te} + c_{t\ell} - c_{Qe}\big),$$

$$c_{\mathrm{VA}} = \frac{1}{4}\big(-c_{Q\ell}^{(1)} + c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} + c_{Qe}\big),$$

$$c_{\mathrm{AA}} = \frac{1}{4}\big(c_{Q\ell}^{(1)} - c_{Q\ell}^{(3)} + c_{te} - c_{t\ell} - c_{Qe}\big).$$



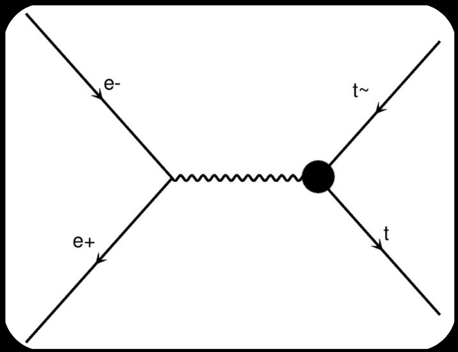
with the addition of current and dipole operators:

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

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

$$c_{\mathrm{t}Z} = c_{\mathrm{W}}\, c_{tW} - s_{\mathrm{W}}\, c_{tB},$$

$$c_{\mathrm{t}\gamma} = s_{\mathrm{W}} c_{tW} + c_{\mathrm{W}} c_{tB},$$



Surprisingly, there are only *six* quantum states available to the system,

		$\mathcal{M}_1$		
		$Q_{\rm t}$, $g_{\rm Vt}$, $c_{\rm VV}$, $c_{\rm VA}$, $c_{\phi \rm V}$	$g_{\rm At}$, $c_{\rm AV}$, $c_{\rm AA}$, $c_{\phi \rm A}$	$c_{{\rm t}Z}$, $c_{{\rm t}\gamma}$
$\mathcal{M}_2$	$Q_{\rm t}$, $g_{\rm Vt}$ $c_{\rm VV}$, $c_{\rm VA}$, $c_{\phi \rm V}$	$A^{[0]}$	$A^{[1]}$	$A^{[6,0,D]}$
	$g_{\rm At}$ $c_{\rm AV}$, $c_{\rm AA}$, $c_{\phi \rm A}$	$A^{[1]}$	$A^{[2]}$	$A^{[6,1,D]}$
	$c_{{\rm t}Z}$, $c_{{\rm t}\gamma}$	$A^{[6,0,D]}$	$A^{[6,1,D]}$	$A^{[8,{\rm DD}]}$

The final spin state is a combination of these 6, weighted by SM and SMEFT couplings.

Surprisingly, there are only *six* quantum states available to the system,

		$\mathcal{M}_1$		
		$Q_{\rm t}$, $g_{\rm Vt}$, $c_{\rm VV}$, $c_{\rm VA}$, $c_{\phi \rm V}$	$g_{\rm At}$, $c_{\rm AV}$, $c_{\rm AA}$, $c_{\phi \rm A}$	$c_{{\rm t}Z}$, $c_{{\rm t}\gamma}$
$\mathcal{M}_2$	$Q_{\rm t}$, $g_{\rm Vt}$ $c_{\rm VV}$, $c_{\rm VA}$, $c_{\phi \rm V}$	$A^{[0]}$	$A^{[1]}$	$A^{[6,0,D]}$
	$g_{\rm At}$ $c_{\rm AV}$, $c_{\rm AA}$, $c_{\phi \rm A}$	$A^{[1]}$	$A^{[2]}$	$A^{[6,1,D]}$
	$c_{{\rm t}Z}$, $c_{{\rm t}\gamma}$	$A^{[6,0,D]}$	$A^{[6,1,D]}$	$A^{[8,\rm DD]}$

The final spin state is a combination of these 6, weighted by SM and SMEFT couplings.

Not all spin states are reachable via SMEFT

Surprisingly, there are only *six* quantum states available to the system,

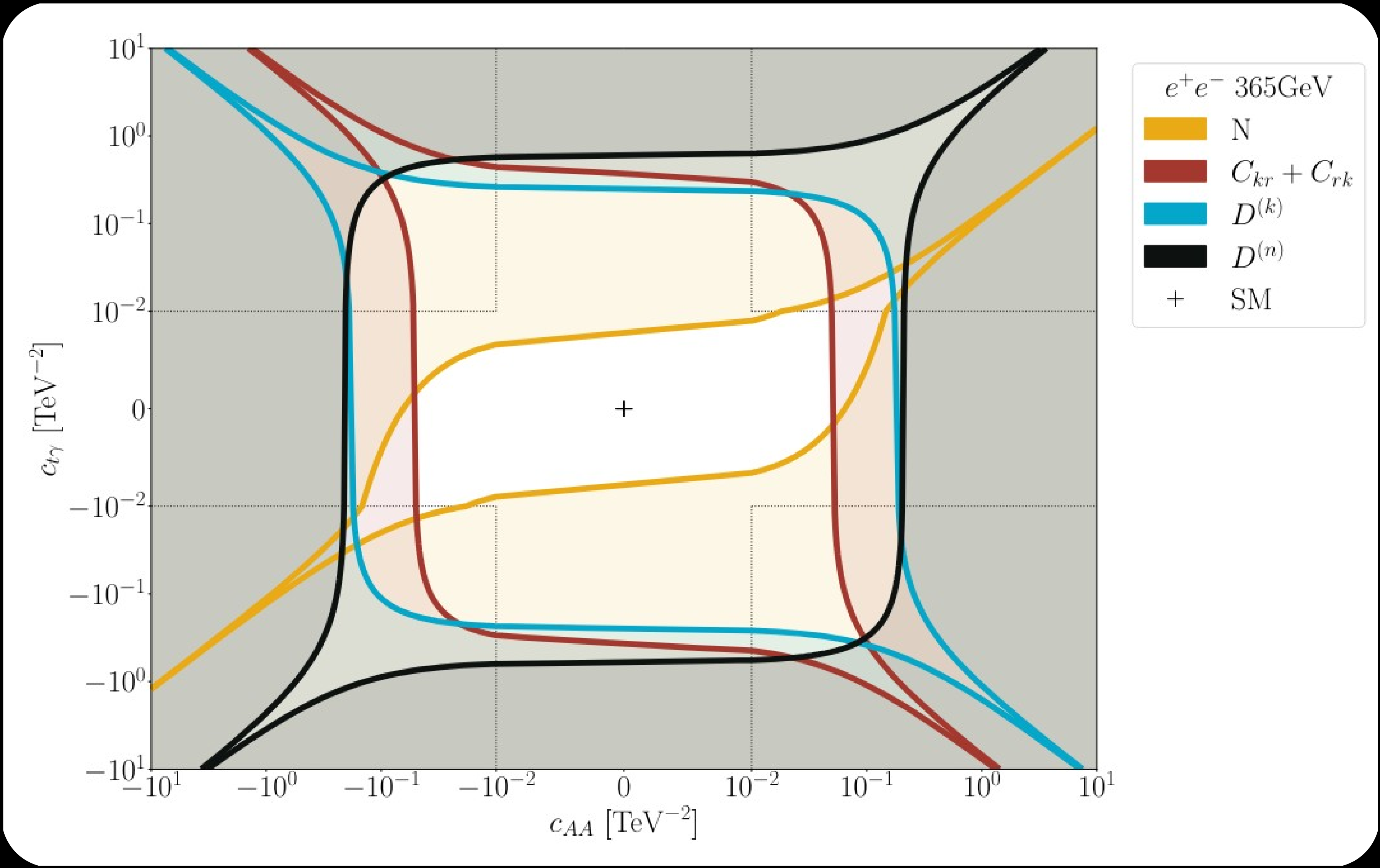
		$\mathcal{M}_1$		
		$Q_{\rm t},\ g_{\rm Vt},$ $c_{\rm VV},\ c_{\rm VA},\ c_{\phi \rm V}$	$g_{\rm At},$ $c_{\rm AV},\ c_{\rm AA},\ c_{\phi \rm A}$	$c_{{\rm t}Z},\ c_{{\rm t}\gamma}$
$\mathcal{M}_2$	$Q_{\rm t},\ g_{\rm Vt}$ $c_{\rm VV},\ c_{\rm VA},\ c_{\phi \rm V}$	$A^{[0]}$	$A^{[1]}$	$A^{[6,0,D]}$
	$g_{\rm At}$ $c_{\rm AV},\ c_{\rm AA},\ c_{\phi \rm A}$	$A^{[1]}$	$A^{[2]}$	$A^{[6,1,D]}$
	$c_{{\rm t}Z},\ c_{{\rm t}\gamma}$	$A^{[6,0,D]}$	$A^{[6,1,D]}$	$A^{[8,{\rm DD}]}$

The final spin state is a combination of these 6, weighted by SM and SMEFT couplings.

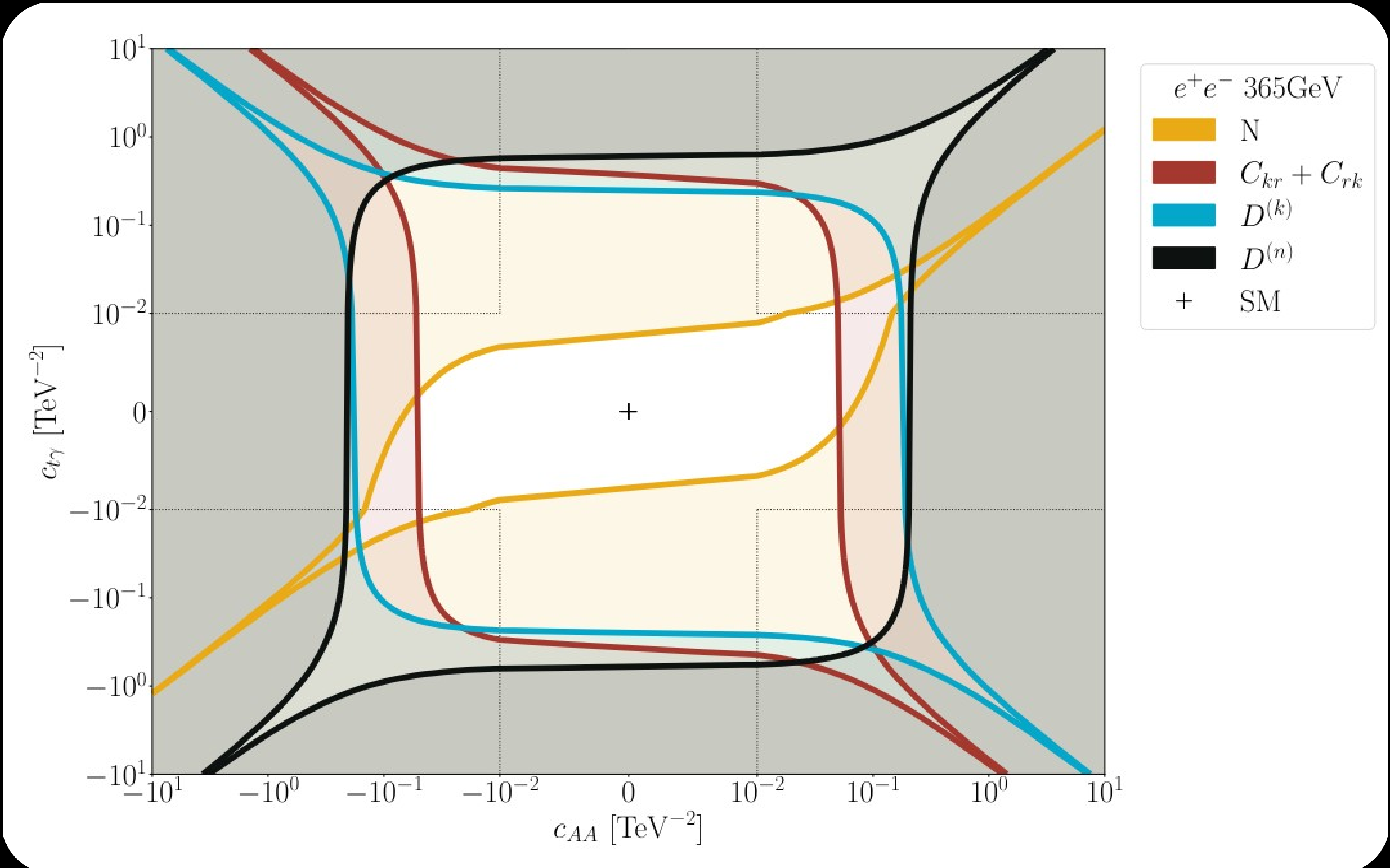
<u>Not all spin states are reachable via SMEFT</u>

(Not all spin states are reachabe via QFT)

FCC-ee 365GeV 1.5/ab



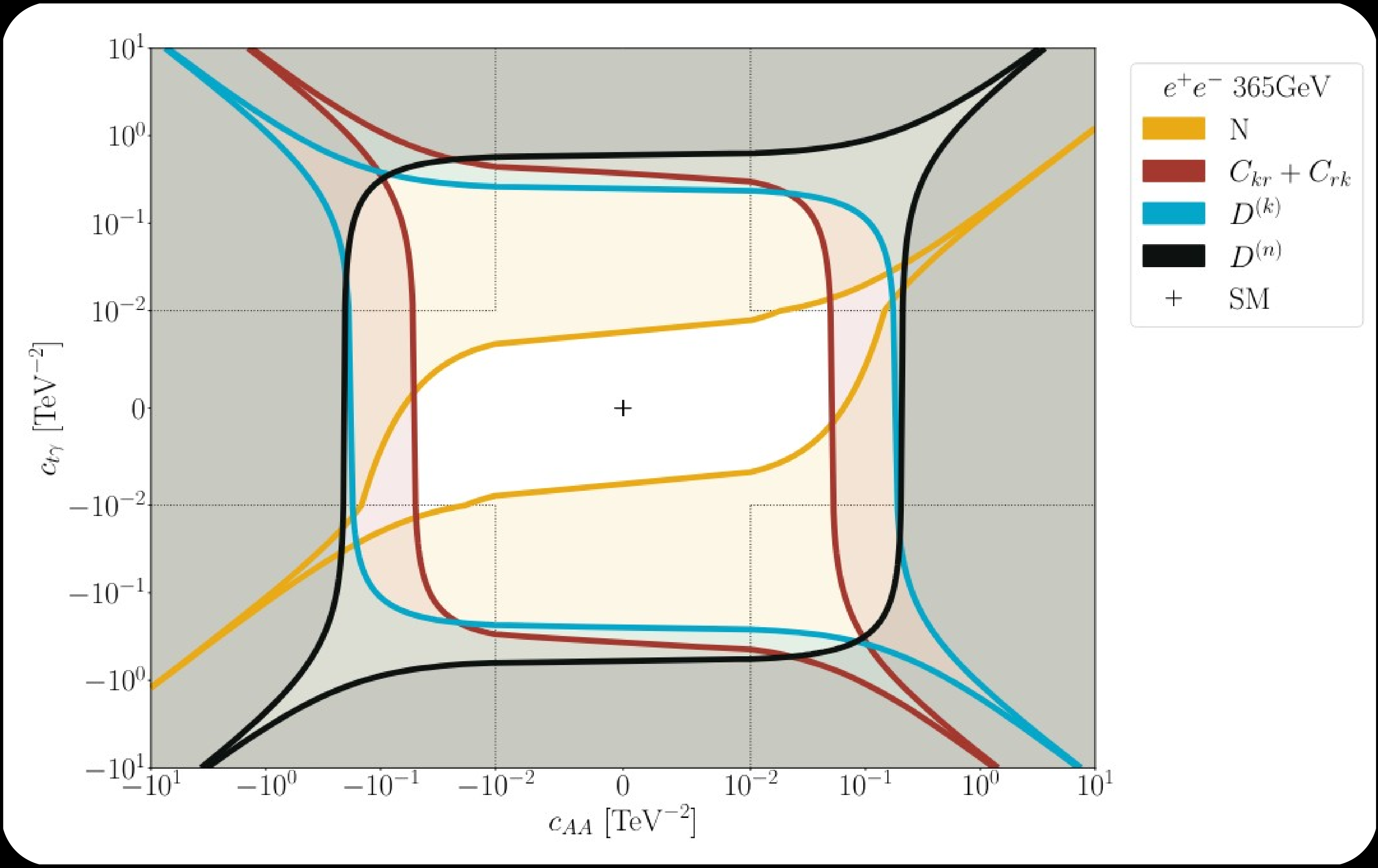
FCC-ee 365GeV 1.5/ab



Simulations show spin/entanglement measurements are probably not competitive with “standard” observables

2404.08049

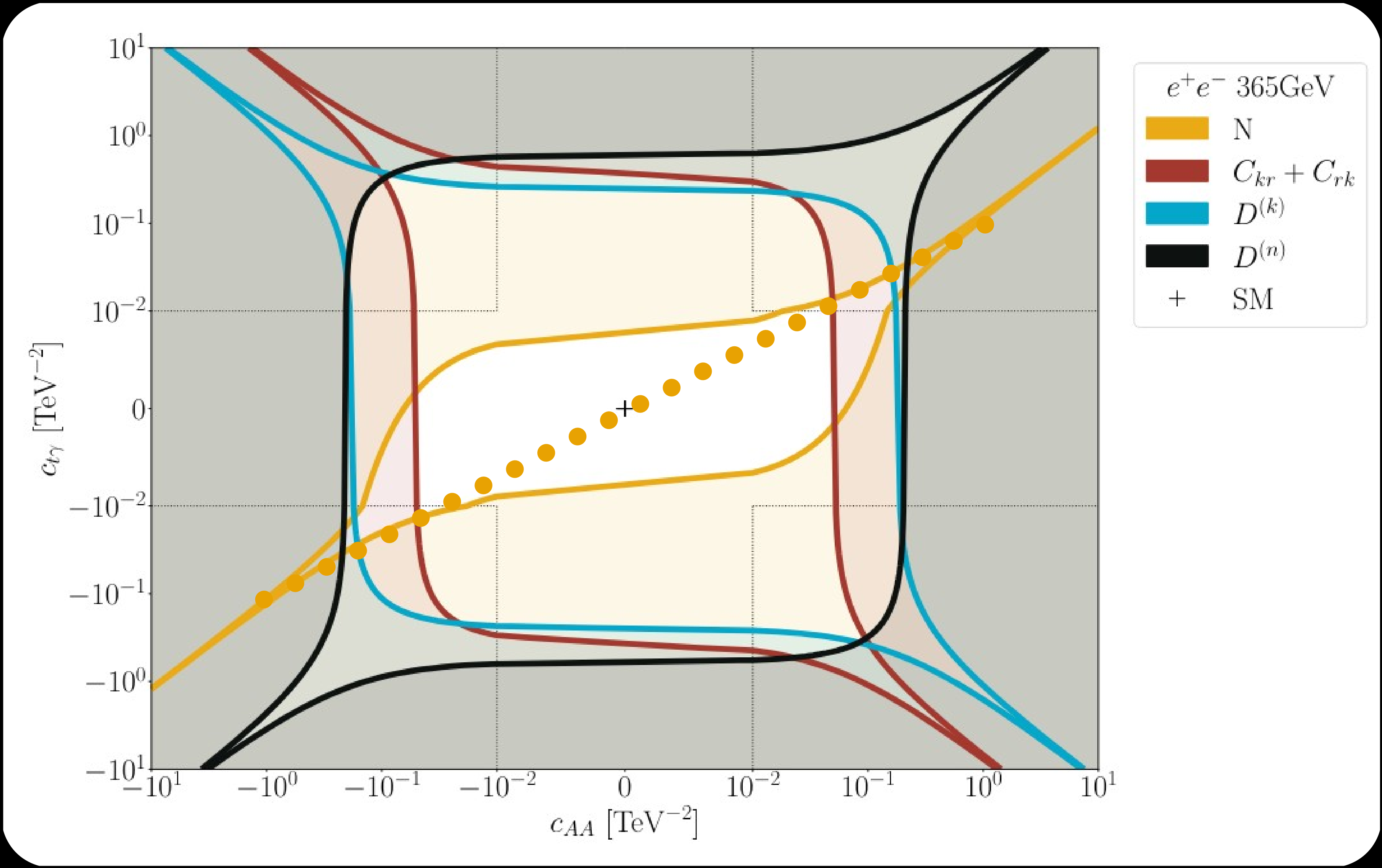
FCC-ee 365GeV 1.5/ab



Simulations show spin/entanglement measurements are probably not competitive with "standard" observables

However...

FCC-ee 365GeV 1.5/ab



Simulations show spin/entanglement measurements are probably not competitive with "standard" observables

However...

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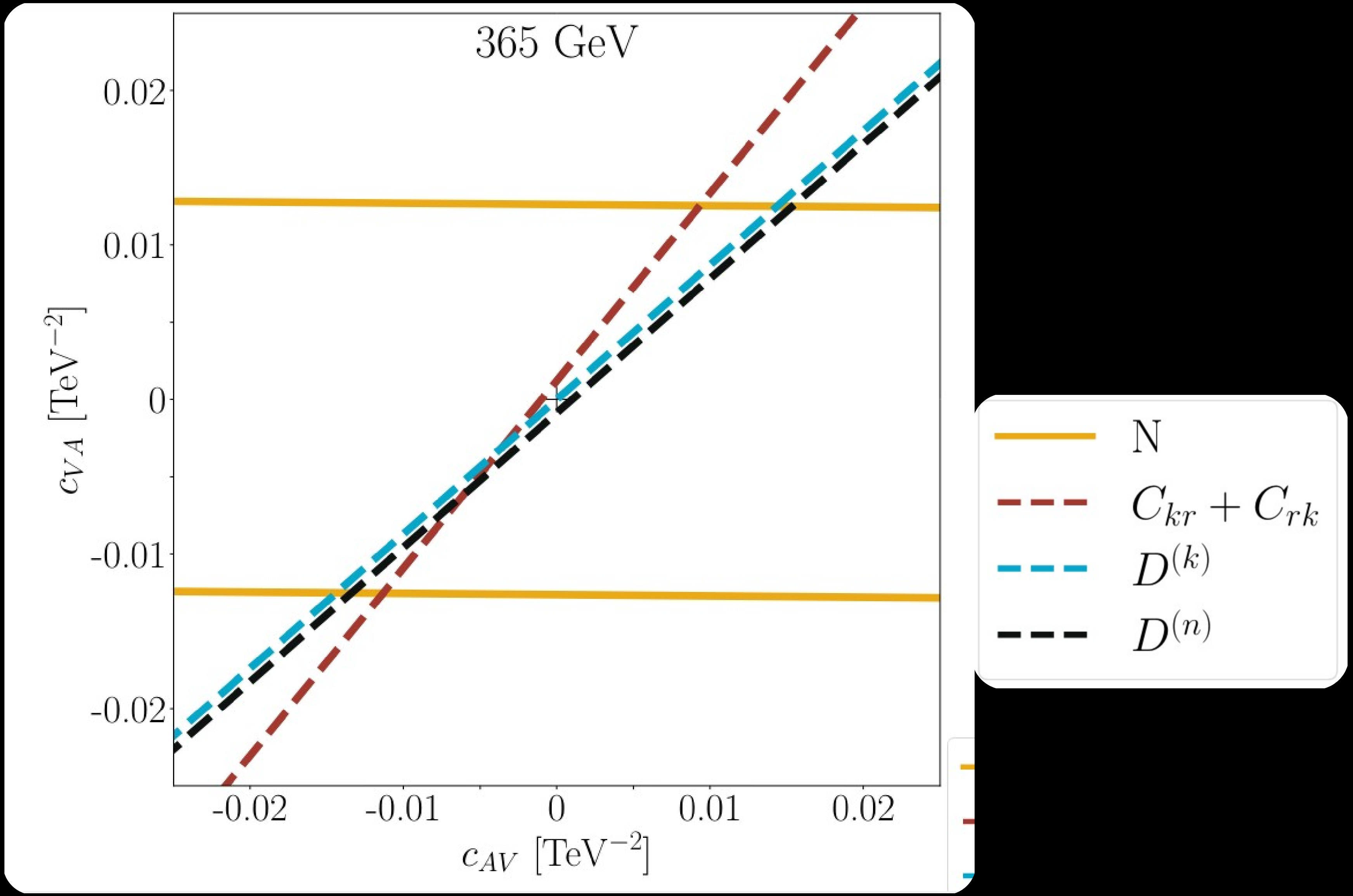
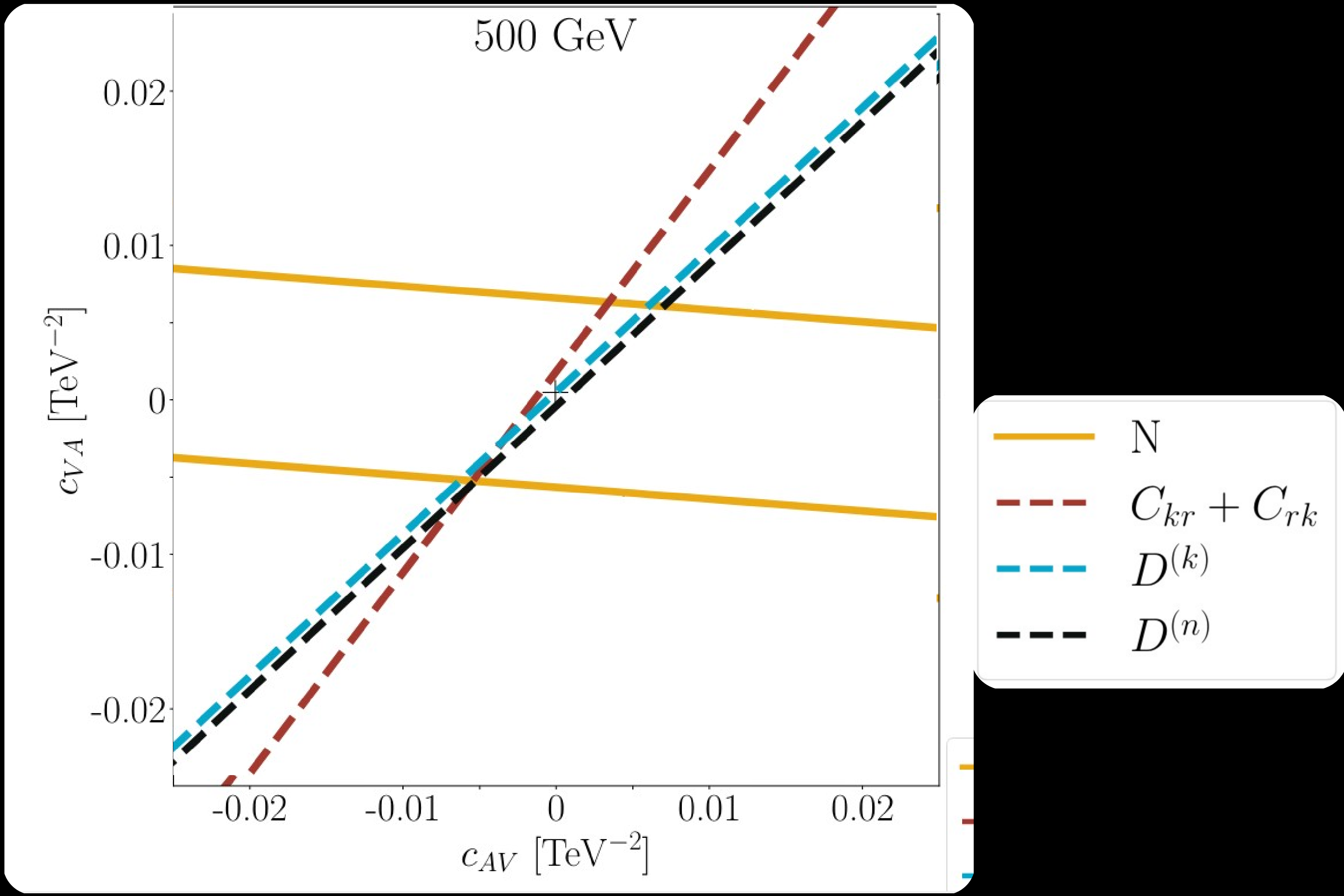
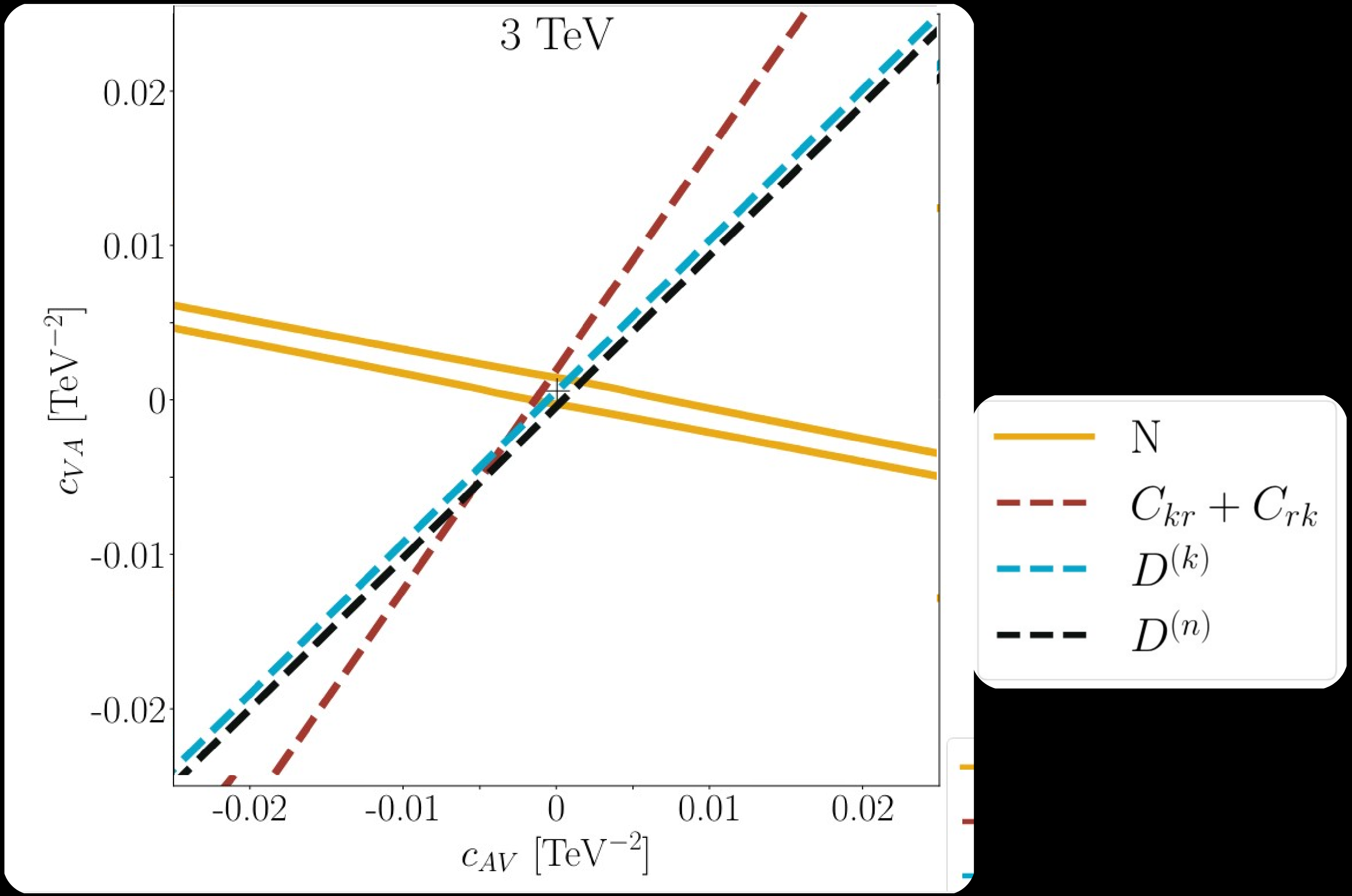


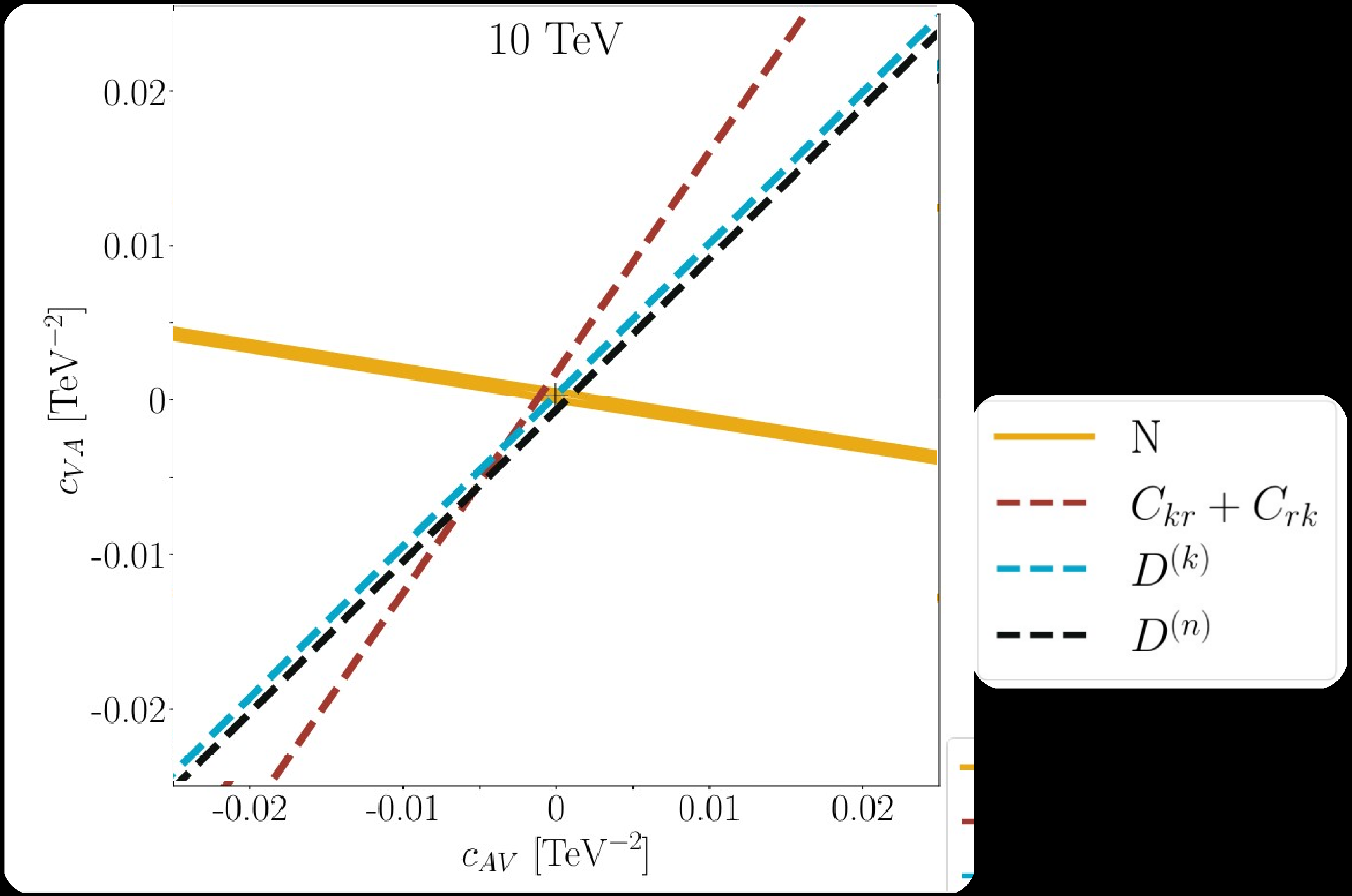
Kinematical and spin observables probe different physical properties, and their flat directions are ~ orthogonal



Kinematical and spin observables probe different physical properties, and their flat directions are ~ orthogonal



Kinematical and spin observables probe different physical properties, and their flat directions are ~ orthogonal



Kinematical and spin observables probe different physical properties, and their flat directions are ~ orthogonal

A few final remarks...

The field of Quantum Information in collider physics is here to stay: in the next decade we will study foundations of QM at the TeV scale.

- entanglement in brand new processes
- Bell violations at the TeV scale
- testing QM in new regimes of temperature/density/...

The interest is *not just academic*: there are concrete and present applications to our day-to-day activities.

Thank you :)