Quantum entanglement and top spin correlations in the SM Effective Field Theory

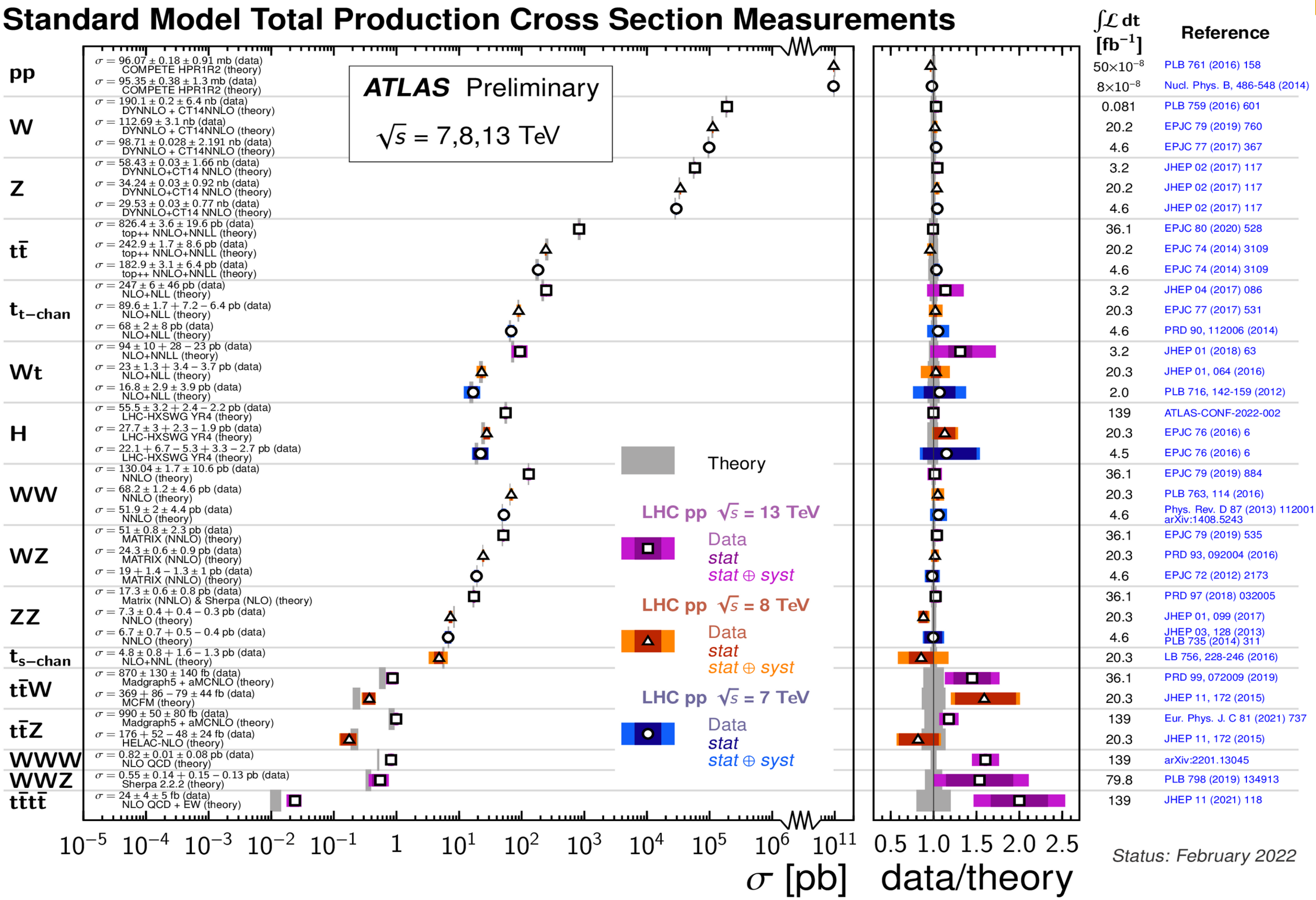
with Eleni Vryonidou, 2210.09330

21/3/23

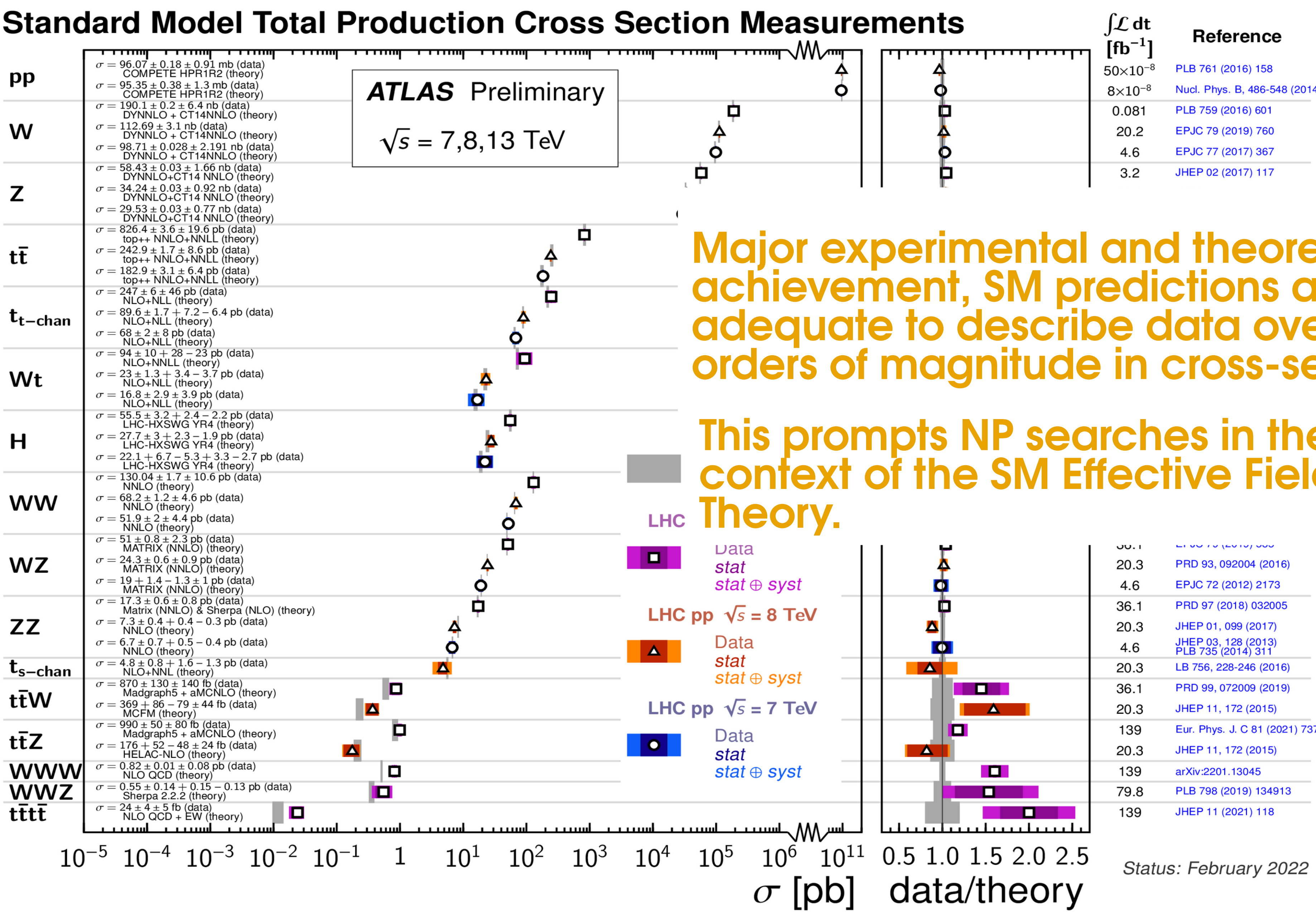
Claudio Severi - University of Manchester

Where do we stand?

Where do we stand?



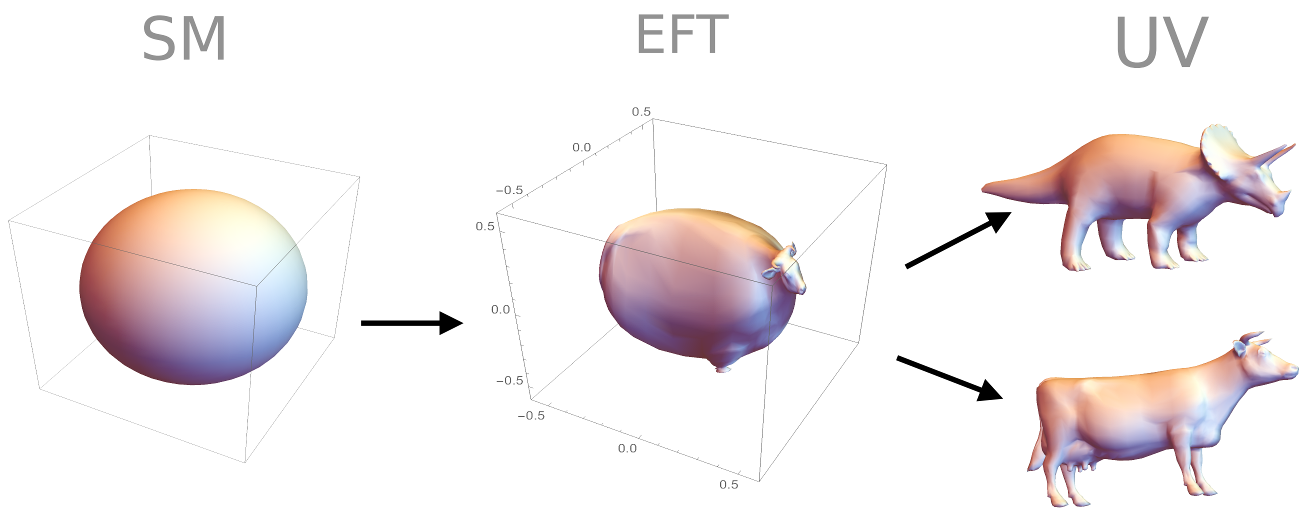
Where do we stand?



Major experimental and theoretical achievement, SM predictions are adequate to describe data over 12 orders of magnitude in cross-section.

This prompts NP searches in the context of the SM Effective Field Theory.

The SM Effective Field Theory



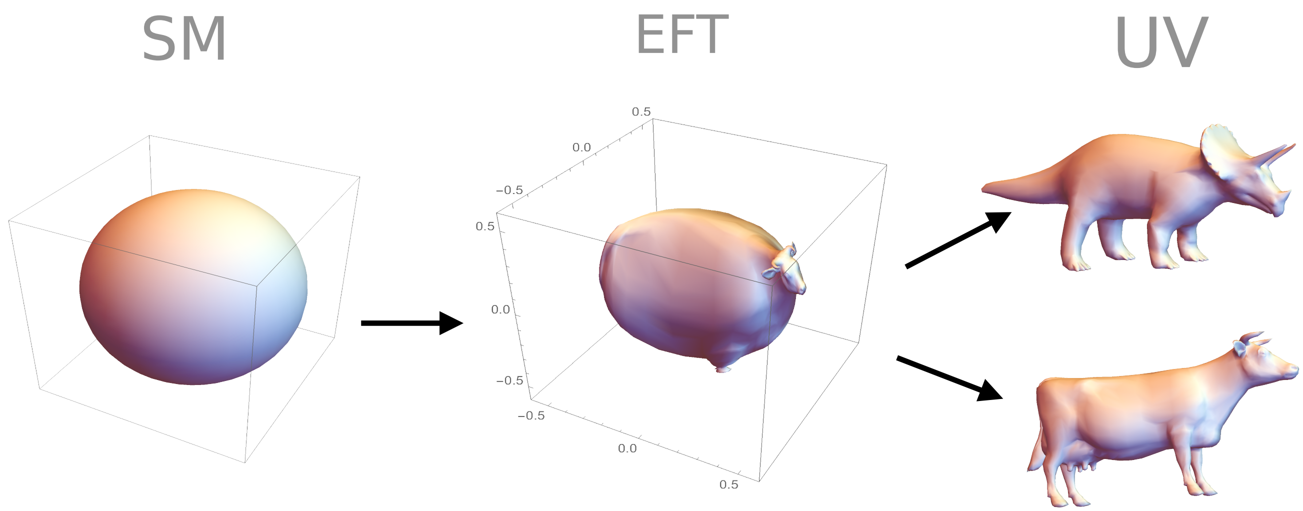
Energy

UV physics (heavy particles) $\mathcal{L}_{NP}(?)$

Effective Field Theory $\mathcal{L}_{\mathrm{SMEFT}}(\phi)$

Standard Model $\mathcal{L}_{SM}(\phi)$

The SM Effective Field Theory



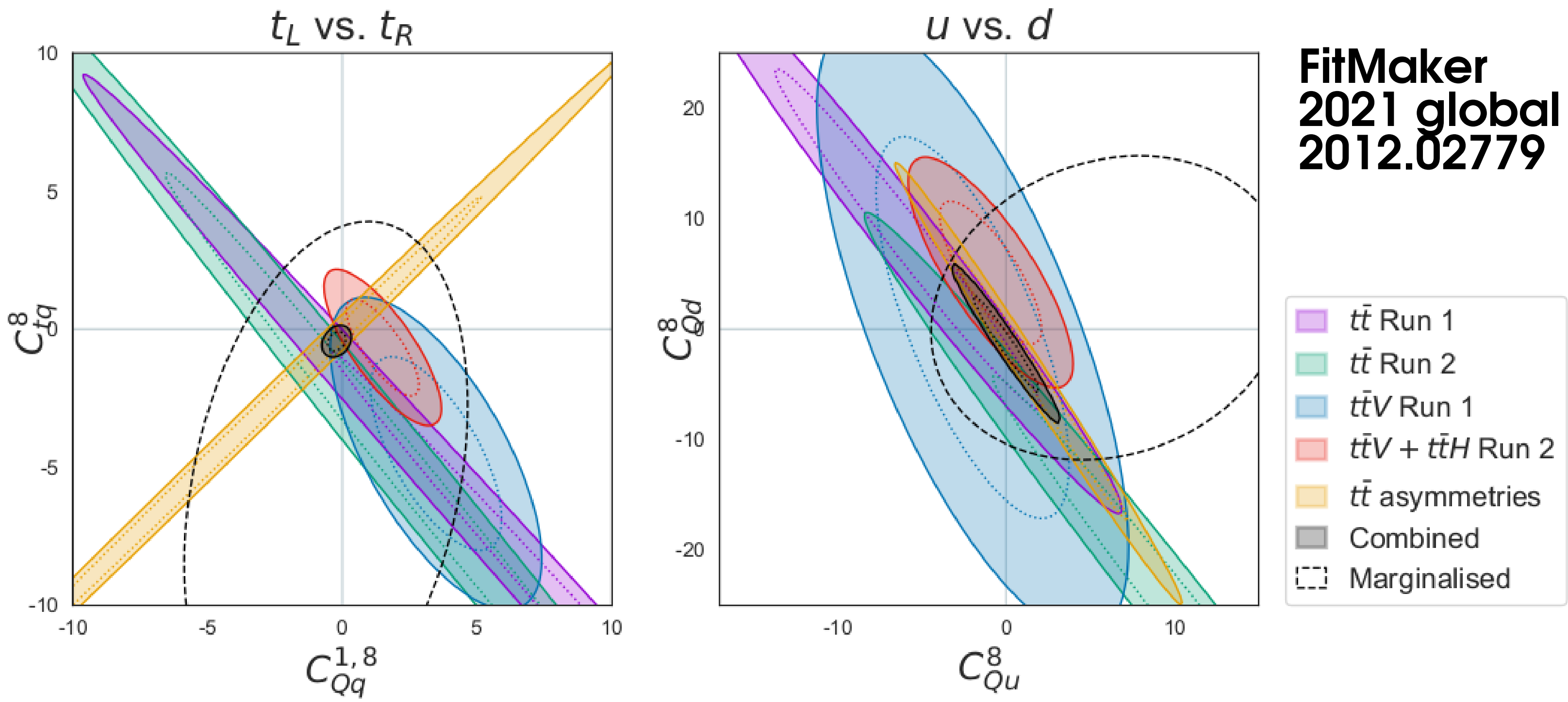
The SM Lagrangian is extended with a stack of higher dimensional operators,

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d=5}^{\infty} \sum_{k} \frac{c_k}{\Lambda^{d-4}} \mathcal{O}_k,$$

that describe heavy new physics in the "most model independent way" possible.

Need for "unconventional" measurements

Global SMEFT fits are plagued by the presence of flat directions. A well known example is four-fermion operators in the top sector:



FitMaker 2021 global fit 2012.02779

The sheer number of operators, and the need to break the degeneracies that arise, demands the consideration of the largest possible set of observables.

New physics in spin correlations

Top spin correlation measurements are sensitive to all four-fermion operators in the top sector,

$$\mathcal{O}^8_{tu} = \sum_{\mathrm{f}=1}^2 (\bar{t}\gamma_\mu T^A t)(\overline{u}_\mathrm{f}\gamma^\mu T_A u_\mathrm{f})$$

$$\mathcal{O}^8_{td} = \sum_{\mathrm{f}=1}^3 (\bar{t}\gamma_\mu T_A t)(\bar{d}_\mathrm{f}\gamma^\mu T^A d_\mathrm{f})$$

$$\mathcal{O}^8_{tq} = \sum_{\mathrm{f}=1}^2 (\overline{q}_\mathrm{f}\gamma_\mu T_A q_\mathrm{f})(\bar{t}\gamma^\mu T^A t)$$

$$\mathcal{O}^8_{Qu} = \sum_{\mathrm{f}=1}^2 (\overline{Q}\gamma_\mu T_A Q)(\overline{u}_\mathrm{f}\gamma^\mu T^A u_\mathrm{f})$$

$$\mathcal{O}^8_{Qd} = \sum_{\mathrm{f}=1}^3 (\overline{Q}\gamma_\mu T_A Q)(\bar{d}_\mathrm{f}\gamma^\mu T^A d_\mathrm{f})$$

$$\mathcal{O}^{1,8}_{Qq} = \sum_{\mathrm{f}=1}^2 (\overline{Q}\gamma_\mu T^A Q)(\overline{q}_\mathrm{f}\gamma^\mu T_A q_\mathrm{f})$$

$$\mathcal{O}^{3,8}_{Qq} = \sum_{\mathrm{f}=1}^2 (\overline{Q}\gamma_\mu T^A \sigma_I Q)(\overline{q}_\mathrm{f}\gamma^\mu T_A \sigma^I q_\mathrm{f})$$

$$\mathcal{O}^1_{tu} = \sum_{\mathrm{f}=1}^2 (\bar{t}\gamma_\mu t)(\overline{u}_\mathrm{f}\gamma^\mu u_\mathrm{f})$$

$$\mathcal{O}^1_{td} = \sum_{\mathrm{f}=1}^3 (\bar{t}\gamma_\mu t)(\bar{d}_\mathrm{f}\gamma^\mu d_\mathrm{f})$$

$$\mathcal{O}^1_{tq} = \sum_{\mathrm{f}=1}^2 (\overline{q}_\mathrm{f}\gamma_\mu q_\mathrm{f})(\bar{t}\gamma^\mu t)$$

$$\mathcal{O}^1_{Qu} = \sum_{\mathrm{f}=1}^2 (\overline{Q}\gamma_\mu Q)(\overline{u}_\mathrm{f}\gamma^\mu u_\mathrm{f})$$

$$\mathcal{O}^1_{Qd} = \sum_{\mathrm{f}=1}^3 (\overline{Q}\gamma_\mu Q)(\bar{d}_\mathrm{f}\gamma^\mu d_\mathrm{f})$$

$$\mathcal{O}^{1,1}_{Qq} = \sum_{\mathrm{f}=1}^2 (\overline{Q}\gamma_\mu Q)(\overline{q}_\mathrm{f}\gamma^\mu q_\mathrm{f})$$

$$\mathcal{O}^{3,1}_{Qq} = \sum_{\mathrm{f}=1}^2 (\overline{Q}\gamma_\mu \sigma_I Q)(\overline{q}_\mathrm{f}\gamma^\mu \sigma^I q_\mathrm{f})$$

and to the top chromomagnetic moment,

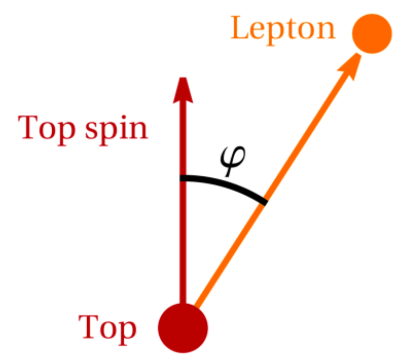
$$\mathcal{O}_{tG} = g_S\, \overline{Q} T_A \tilde{\varphi} \sigma^{\mu\nu} t\, G^A_{\mu\nu}$$

New physics in spin correlations

Top spin correlation measurements probe both top production and decay.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1+\alpha_a B_i \cos\theta_i}{2}, \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\bar{\theta}_i} = \frac{1+\alpha_b \bar{B}_i \cos\bar{\theta}_i}{2}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_i\cos\bar{\theta}_j)} = -\frac{1+C_{ij}\alpha_a\alpha_b\ \cos\theta_i\cos\bar{\theta}_j}{2}\log\left|\cos\theta_i\cos\bar{\theta}_j\right|,$$

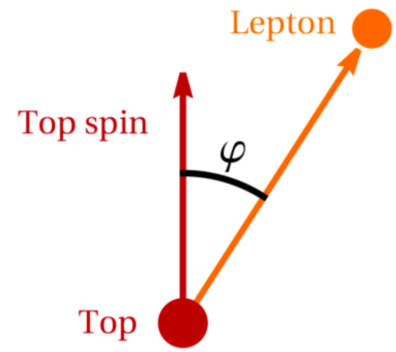


New physics in spin correlations

Top spin correlation measurements probe both top production and decay.

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_i} = \frac{1+\alpha_a B_i \cos\theta_i}{2}, \quad \frac{1}{\sigma}\frac{d\sigma}{d\cos\bar{\theta}_i} = \frac{1+\alpha_b \bar{B}_i \cos\bar{\theta}_i}{2}$$

$$\frac{1}{\sigma}\frac{d\sigma}{d(\cos\theta_i\cos\bar{\theta}_j)} = -\frac{1+C_{ij}\alpha_a\alpha_b\,\cos\theta_i\cos\bar{\theta}_j}{2}\log\left|\cos\theta_i\cos\bar{\theta}_j\right|,$$



However, in the dilepton channel,
all O(1/Λ²) effects in top decay cancel out

$$\alpha_\ell = 1 - \frac{c^2_{uW,33}v^4}{\Lambda^4}\frac{4(2m_t^6+3m_t^4m_W^2-6m_t^2m_W^4+m_W^6+12m_t^4m_W^2\log m_W/m_t)}{(m_W^2-m_t^2)^2(m_t^2+2m_W^2)}$$

the measurement is a clean discovery channel for NP in top production.

Observables

There are 15 spin degrees of freedom in tt~:

CP even		CP odd	
$B_k + \overline{B}_k$	P-odd	$B_k - \overline{B}_k$	P-odd
$B_r + \overline{B}_r$	P-odd	$B_r - \overline{B}_r$	P-odd
$B_n + \overline{B}_n$	P-even	$B_n - \overline{B}_n$	P-even
C_{kk}	P-even		
C_{rr}	P-even		
C_{nn}	P-even		
$C_{kr} + C_{rk}$	P-even	$C_{kr} - C_{rk}$	P-even
$C_{kn} + C_{rn}$	P-odd	$C_{kn} - C_{rn}$	P-odd
$C_{rn} + C_{rn}$	P-odd	$C_{rn} - C_{rn}$	P-odd

Specific combinations are sensitive to CPV,

(table)

entanglement,

$$\Delta^{\pm} = \pm(C_{kk} + C_{rr}) - C_{nn} - 1$$

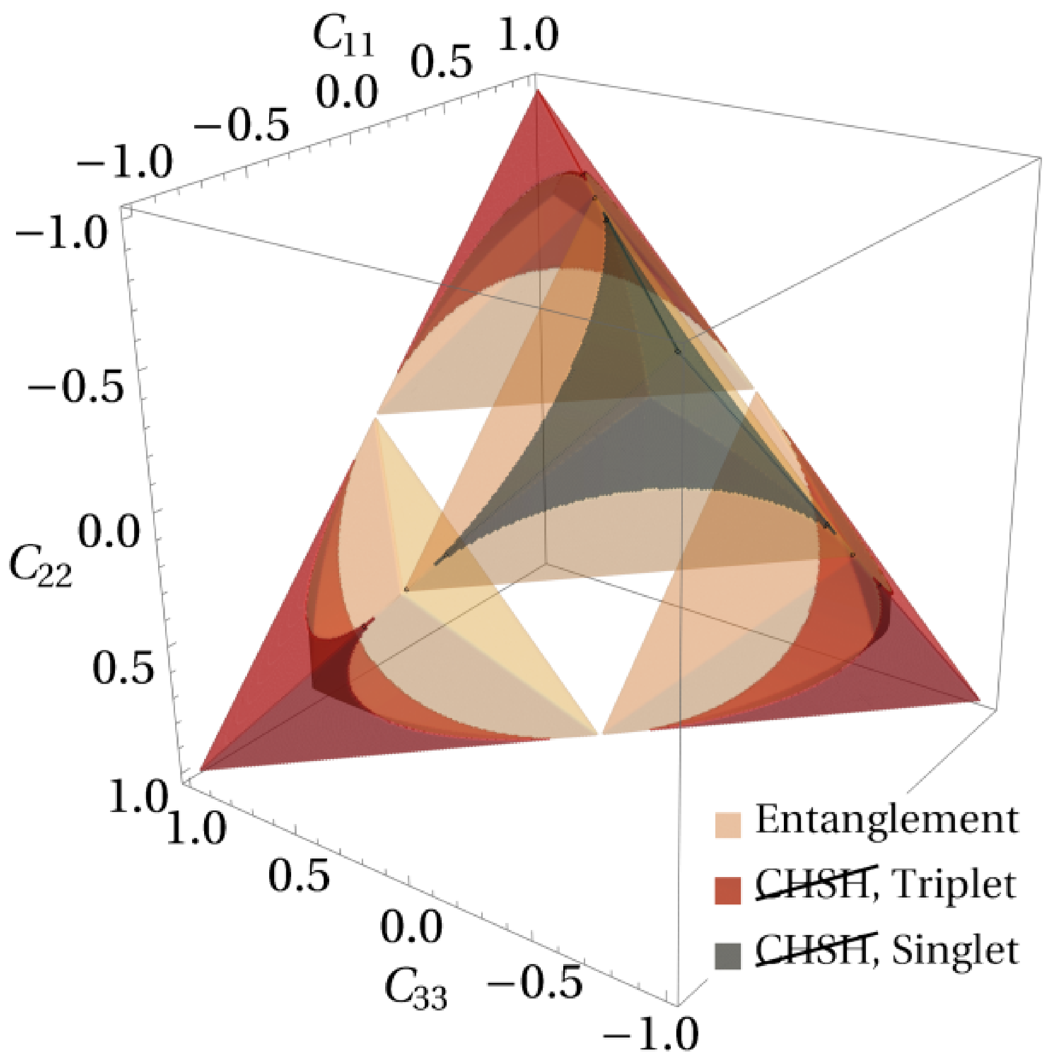
and Bell Inequalities,

$$\sqrt{2}\,\big| - C_{rr} + C_{nn}\big| \leq 2,$$

Observables

There are 15 spin degrees of freedom in tt~:

CP even	
$B_k + \overline{B}_k$	P-odd
$B_r + \overline{B}_r$	P-odd
$B_n + \overline{B}_n$	P-even
C_{kk}	P-even
C_{rr}	P-even
C_{nn}	P-even
$C_{kr} + C_{rk}$	P-even
$C_{kn} + C_{rn}$	P-odd
$C_{rn} + C_{rn}$	P-odd



1

Aside: calculating spin correlations (is hard)

A proper computation requires the full production+decay matrix element, p p → t t → l+ l- b b ν ν, or the production matrix element p p → t t helicity by helicity.

At LO in the SMEFT analytical results are available [2203.05619]

$$\begin{aligned}\tilde{C}^{gg,(2)}_{kk} = \frac{m_t^4}{\Lambda^4}\frac{1}{1-\beta^2}\Bigg[&\frac{g_s^4 v^2}{24 m_t^2}\frac{1}{(1-\beta^2 z^2)^2}\Big(9\beta^6 z^2\left(z^4-2\right)+\beta^4\left(-18z^6+25z^4-12z^2-14\right)\\ &+\beta^2\left(-28z^4+81z^2+12\right)-18z^2-19\Big)c_{tG}^2-\frac{24\beta^2 m_t^4}{\left(4m_t^2-m_h^2\left(1-\beta^2\right)\right)^2}c_{\varphi G}^2\\ &+\frac{27 g_s^4\left(1-\left(2-\beta^2\right)z^2\right)}{4\left(1-\beta^2\right)}c_G^2-\frac{2\sqrt{2}g_s^2 v m_t\beta^2\left(1-z^2\right)}{\left(1-\beta^2 z^2\right)\left(4m_t^2-m_h^2\left(1-\beta^2\right)\right)}c_{tG}c_{\varphi G}\\ &+\frac{9 g_s^4 v\left(1-\left(2-\beta^2\right)z^2\right)}{2\sqrt{2}m_t\left(1-\beta^2 z^2\right)}c_{tG}c_G\Bigg],\end{aligned}\qquad\text{(A11c)}$$

$$\begin{aligned}\tilde{C}^{gg,(2)}_{rr} = \frac{m_t^4}{\Lambda^4}\frac{1}{1-\beta^2}\Bigg[&\frac{g_s^4 v^2}{24 m_t^2}\frac{1}{(1-\beta^2 z^2)^2}\Big(-9\beta^6 z^2\left(z^4-2z^2+2\right)+\beta^4\left(18z^6-57z^4+52z^2-14\right)\\ &+\beta^2\left(28z^4-57z^2+58\right)+18z^2-37\Big)c_{tG}^2+\frac{24\beta^2 m_t^4}{\left(4m_t^2-m_h^2\left(1-\beta^2\right)\right)^2}c_{\varphi G}^2\\ &-\frac{27 g_s^4\left(1-\left(2-\beta^2\right)z^2\right)}{4\left(1-\beta^2\right)}c_G^2+\frac{2\sqrt{2}g_s^2 v m_t\beta^2\left(1-z^2\right)}{\left(1-\beta^2 z^2\right)\left(4m_t^2-m_h^2\left(1-\beta^2\right)\right)}c_{tG}c_{\varphi G}\\ &-\frac{9 g_s^4 v\left(1-\left(2-\beta^2\right)z^2\right)}{2\sqrt{2}m_t\left(1-\beta^2 z^2\right)}c_{tG}c_G\Bigg],\end{aligned}\qquad\text{(A11d)}$$

$$\begin{aligned}\tilde{C}^{gg,(2)}_{rk} = \frac{m_t^4}{\Lambda^4}\frac{1}{\sqrt{1-\beta^2}}\Bigg[&\frac{g_s^4 v^2}{192 m_t^2}\frac{1}{(1-\beta^2 z^2)^2}\Big(-144\beta^4 z^3\left(1-z^2\right)^{3/2}+16\beta^2 z\sqrt{1-z^2}\left(14z^2-23\right)\\ &+144z\sqrt{1-z^2}\Big)c_{tG}^2+\frac{27}{2}g_s^4 z\frac{\sqrt{1-z^2}}{1-\beta^2}c_G^2-\frac{2\sqrt{2}g_s^2 v m_t\beta^2 z\sqrt{1-z^2}}{\left(1-\beta^2 z^2\right)\left(4m_t^2-m_h^2\left(1-\beta^2\right)\right)}c_{tG}c_{\varphi G}\\ &+\frac{9 g_s^4 v z\sqrt{1-z^2}}{\sqrt{2}m_t\left(1-\beta^2 z^2\right)}c_{tG}c_G\Bigg],\end{aligned}\qquad\text{(A11e)}$$

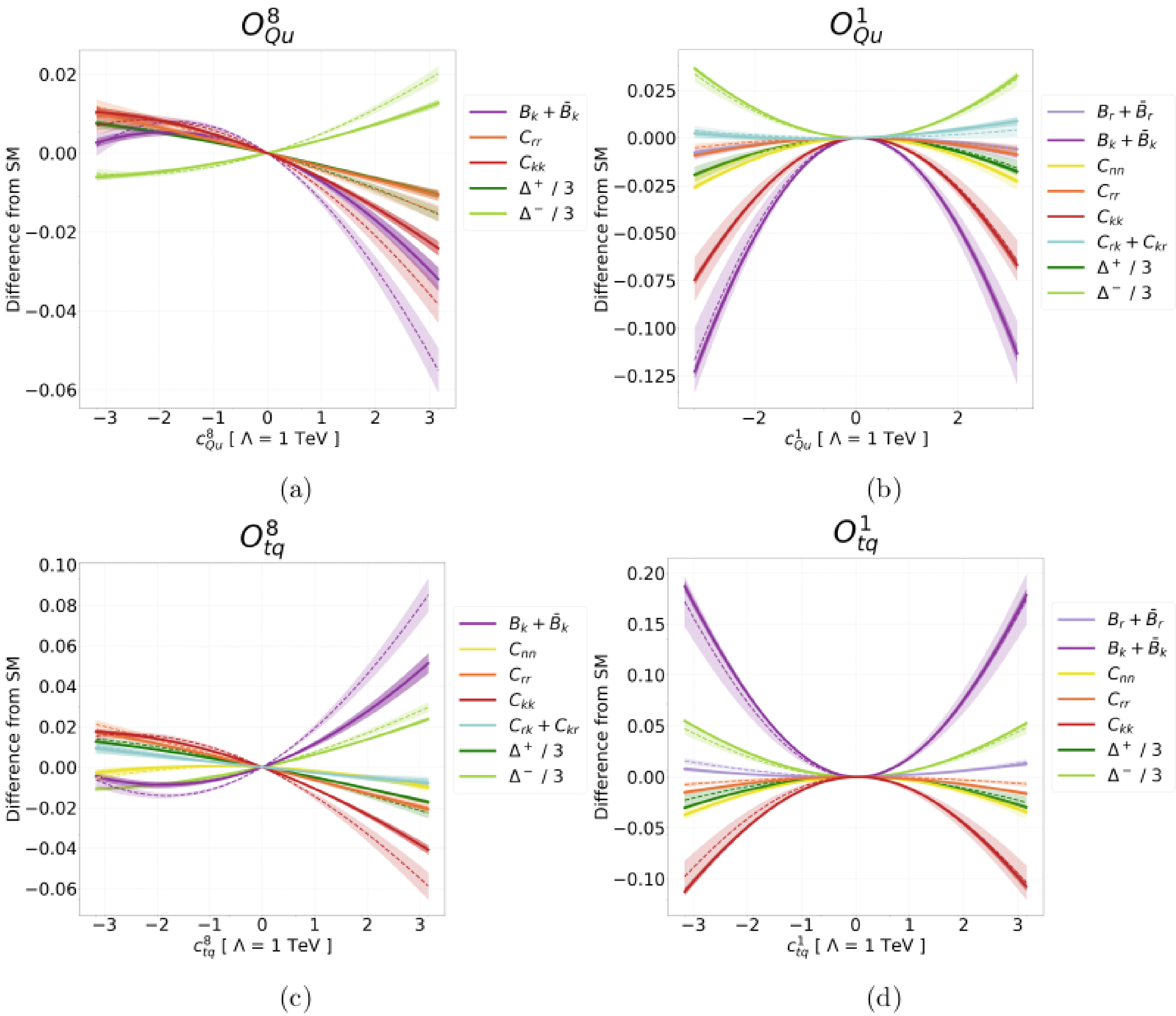
Aside: calculating spin correlations (is hard)

At NLO in the SMEFT this seems beyond the current technology.

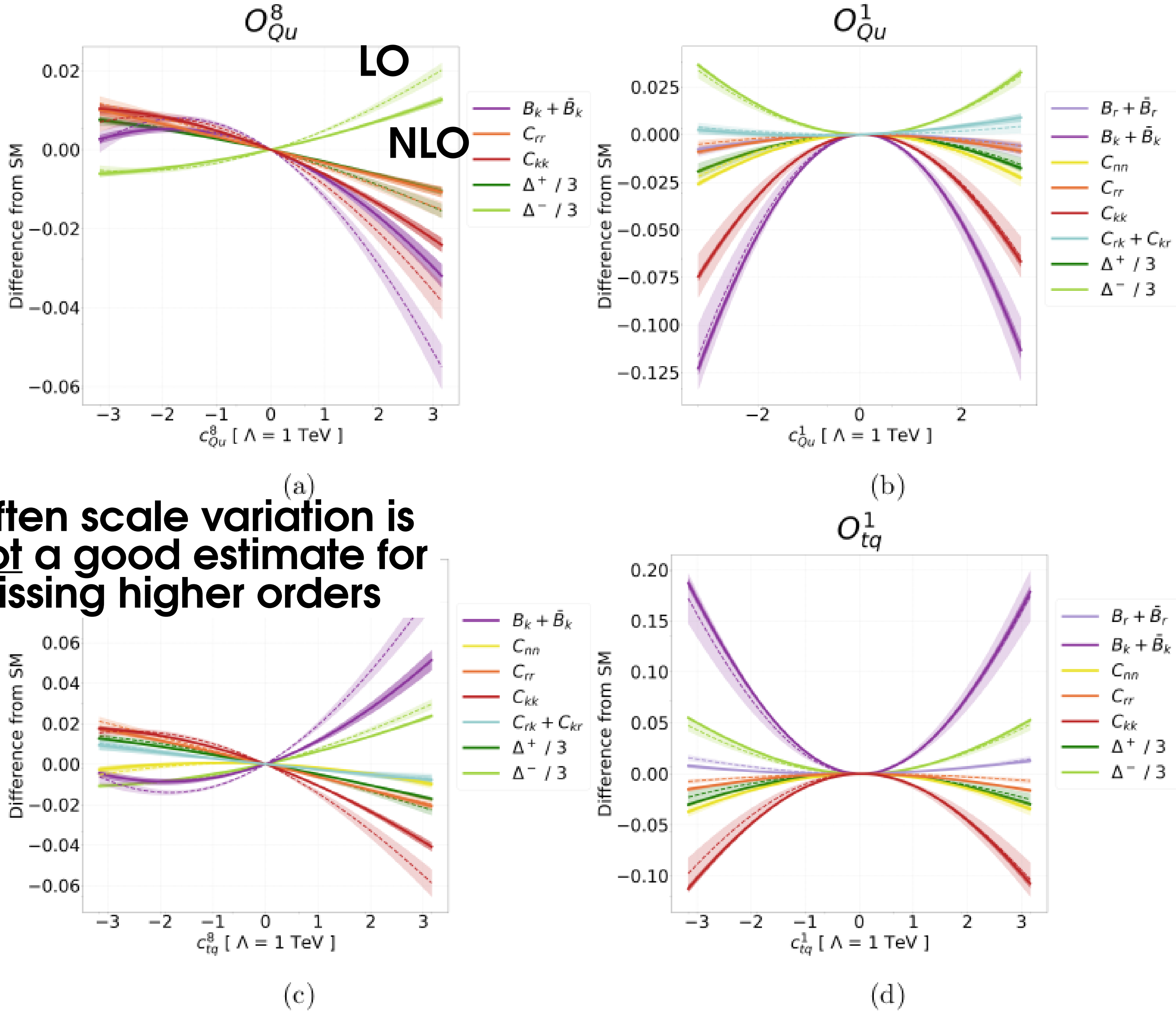
Our calculation is at NLO on all aspects except for virtual corrections to the spin state, where the accuracy is better than LO, but not yet full NLO.

	LO QCD	NLO QCD	
		Real emission	Virtual corrections
$t\,\bar{t}$ kinematics	✓	✓	✓
$t\,\bar{t}$ spin state	✓	✓	Approximate

Inclusive calculation



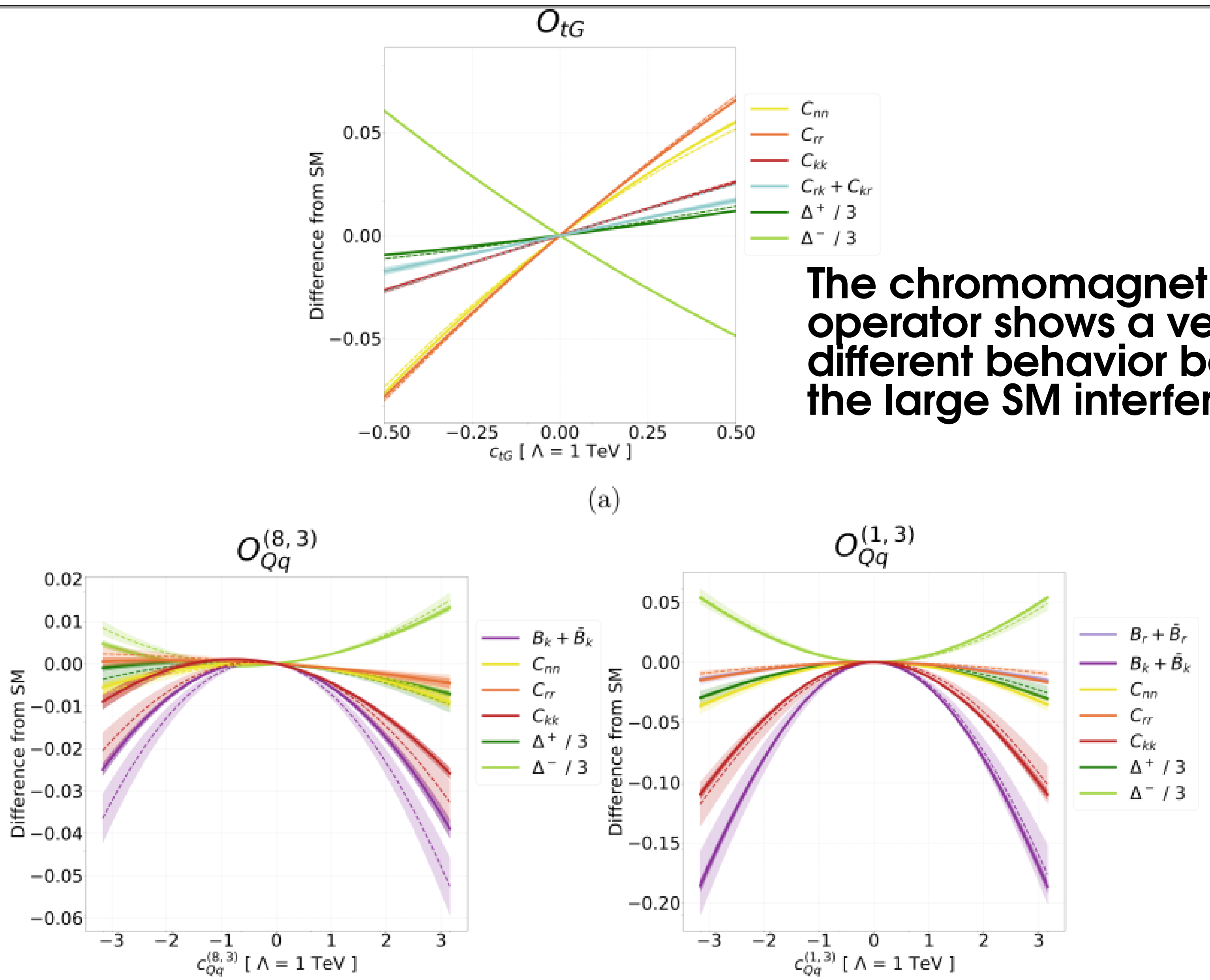
Inclusive calculation



(a) (b) (c) (d)

Often scale variation is <u>not</u> a good estimate for missing higher orders

Inclusive calculation



(a)

(b)

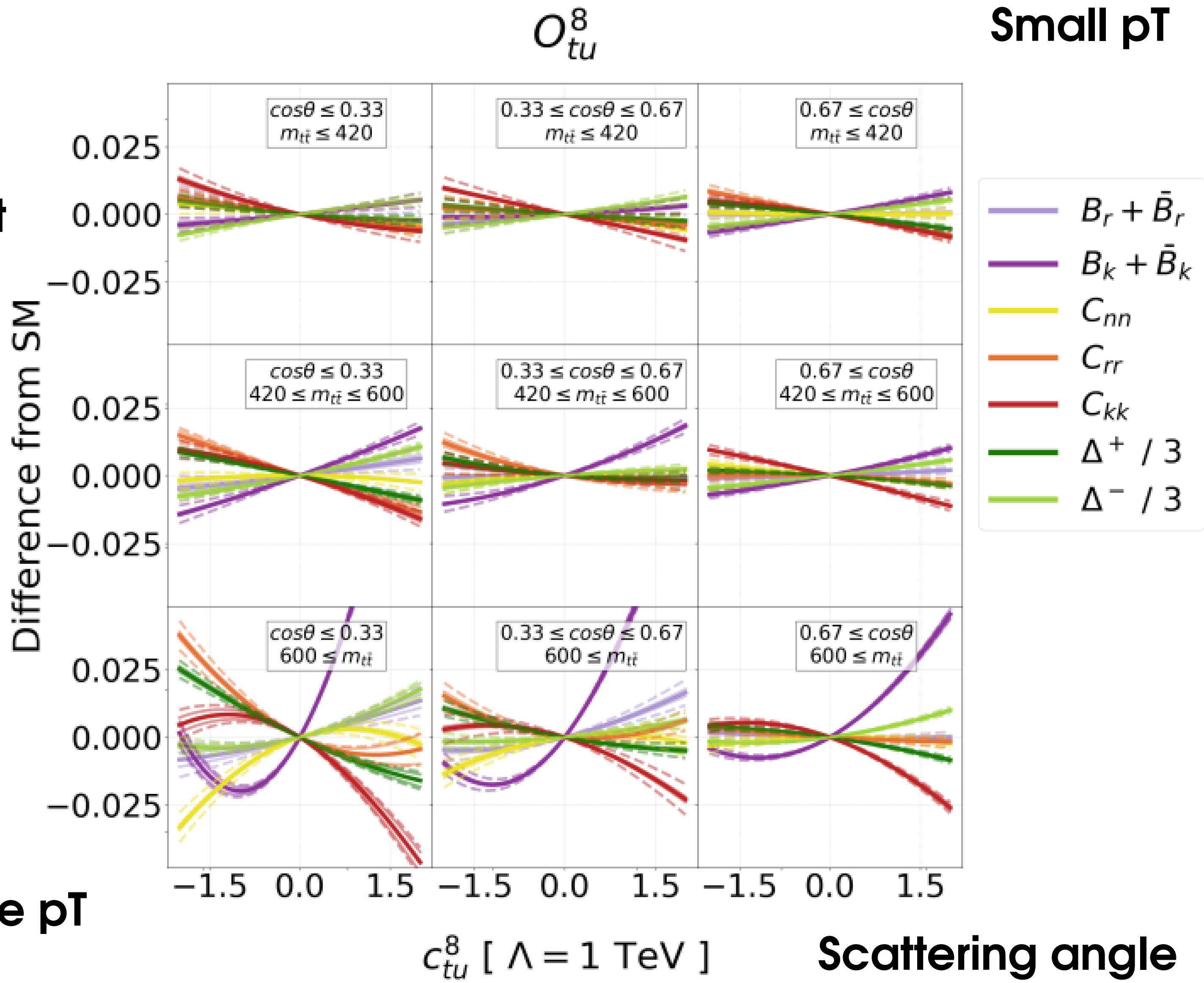
(c)

The chromomagnetic operator shows a very different behavior because of the large SM interference

Differential calculation

Small pT

Pair invariant mass

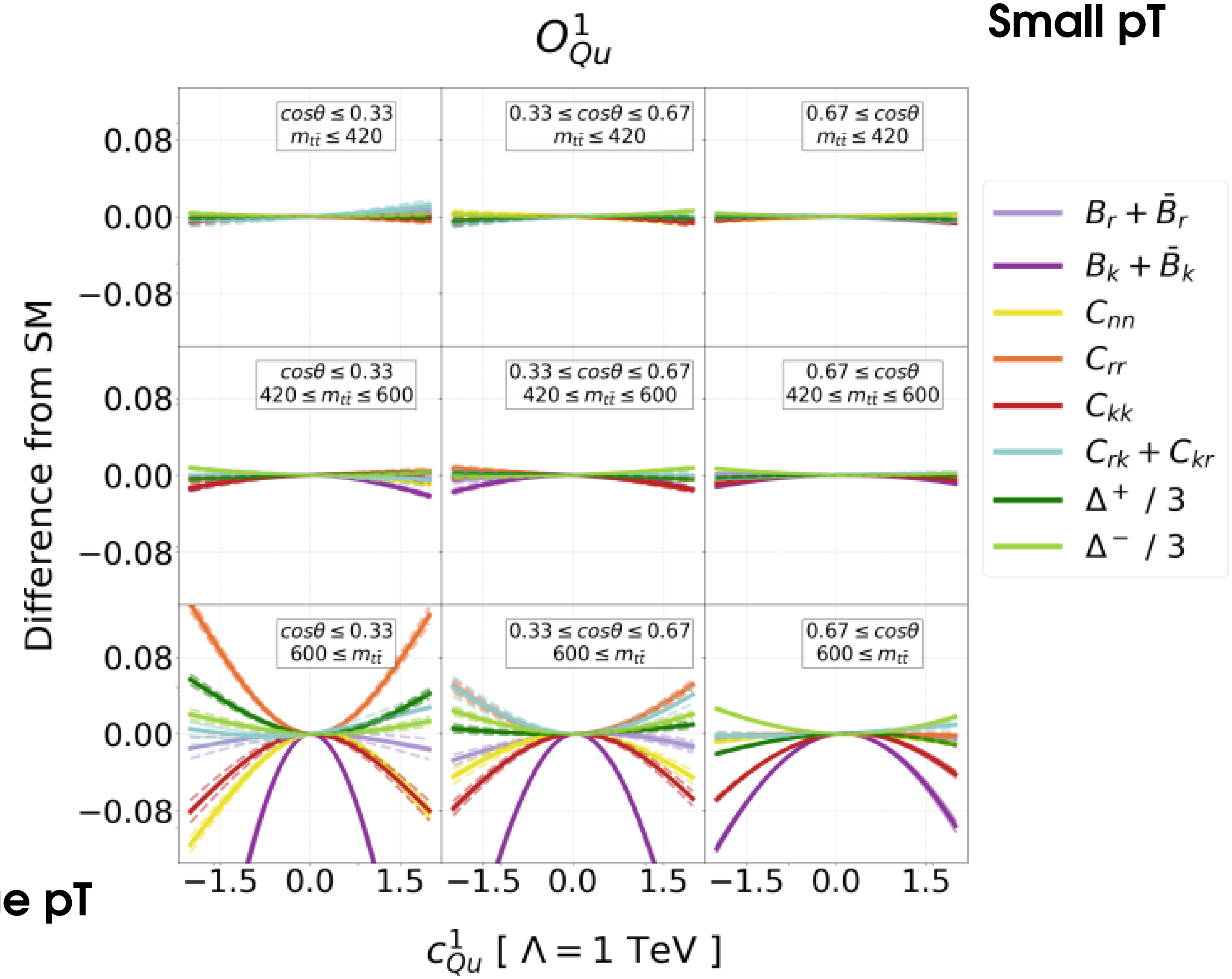


Large pT

Scattering angle

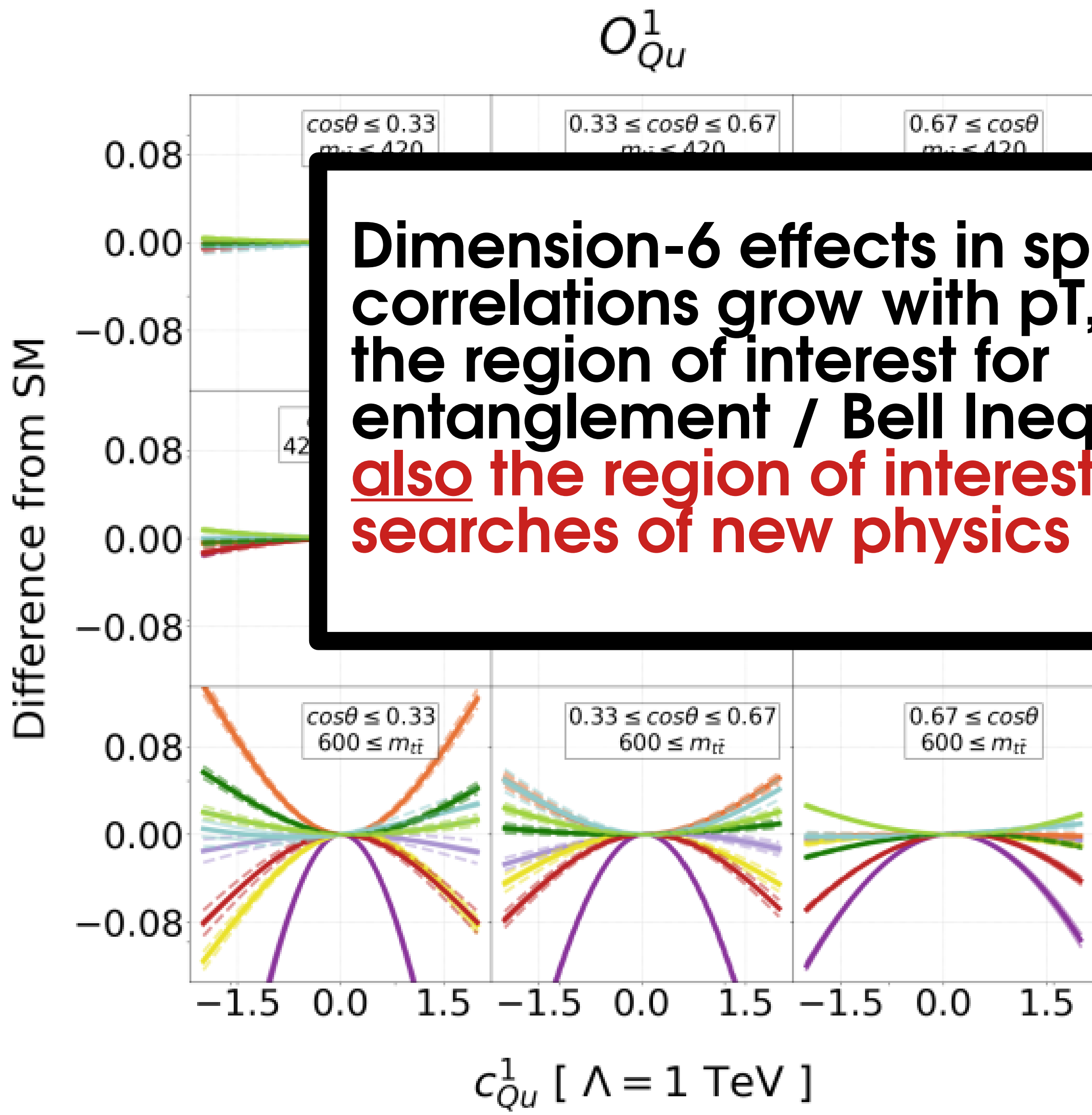
Differential calculation

Small pT



Large pT

Differential calculation



Dimension-6 effects in spin correlations grow with pT, making the region of interest for entanglement / Bell Inequalities <u>also</u> the region of interest for searches of new physics

Impact on SMEFT searches

The lack of experimental data makes the possible impact of spin correlation measurements hard to estimate.

However, our preliminary projection from the 2019 CMS measurement to Run 3 found that <u>one</u> differential measurement of the top spin density matrix would yield constraints competitive with the current <u>full global fit</u> to top LHC data.

New physics affecting top spin would be discovered/constrained into the multi-TeV region.

Conclusions

Entanglement/Bell observables and top spin measurements in general offer a unique view on new physics in the top sector.

The most promising kinematical region is the one at large pT, already considered for the exploration of quantum effects, such as entanglement and BIs.

The intricate pattern of NP effects calls for differential measurements, which will yield a remarkable discovery potential.