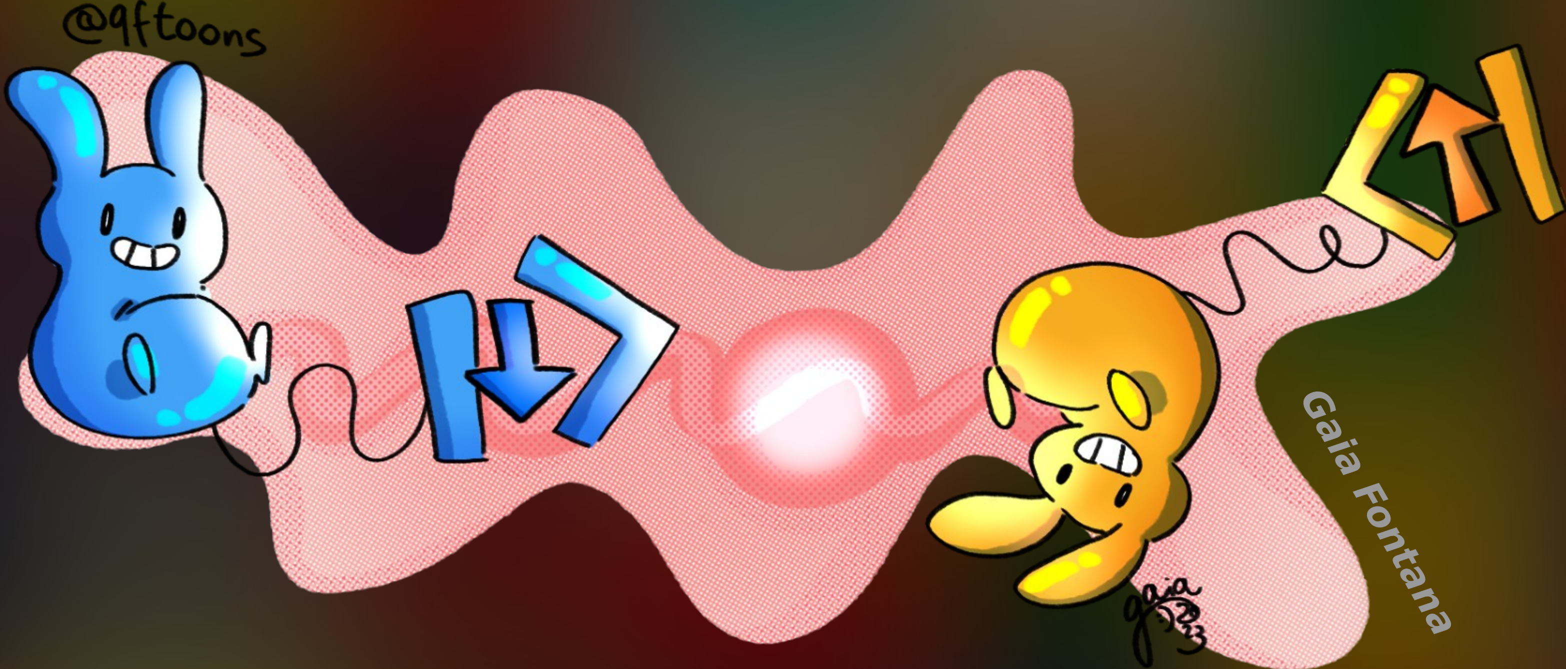
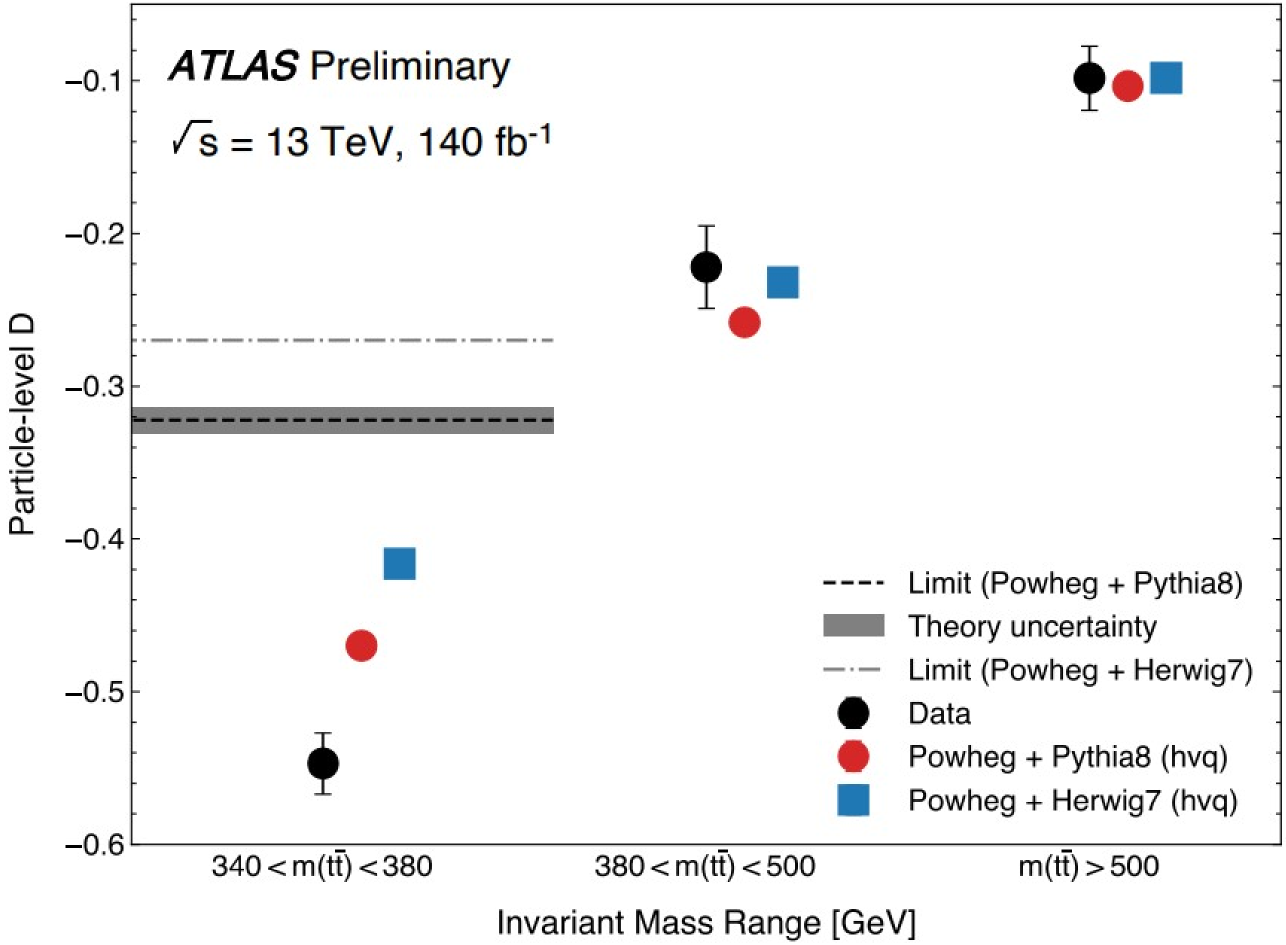
Searches of New Physics with entangled tops

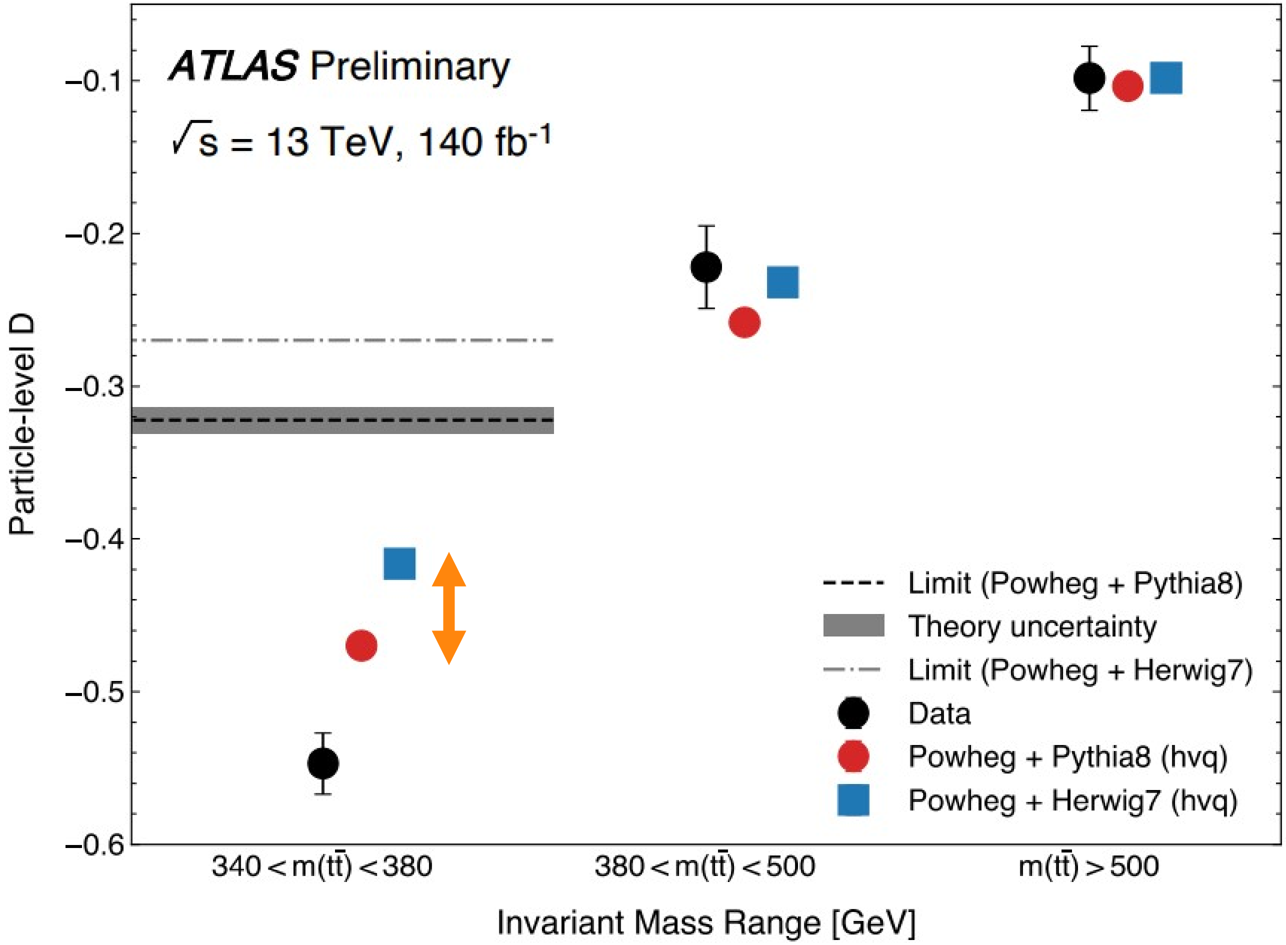


7/11/23 Claudio Severi - Quantum Observables for Collider Physics

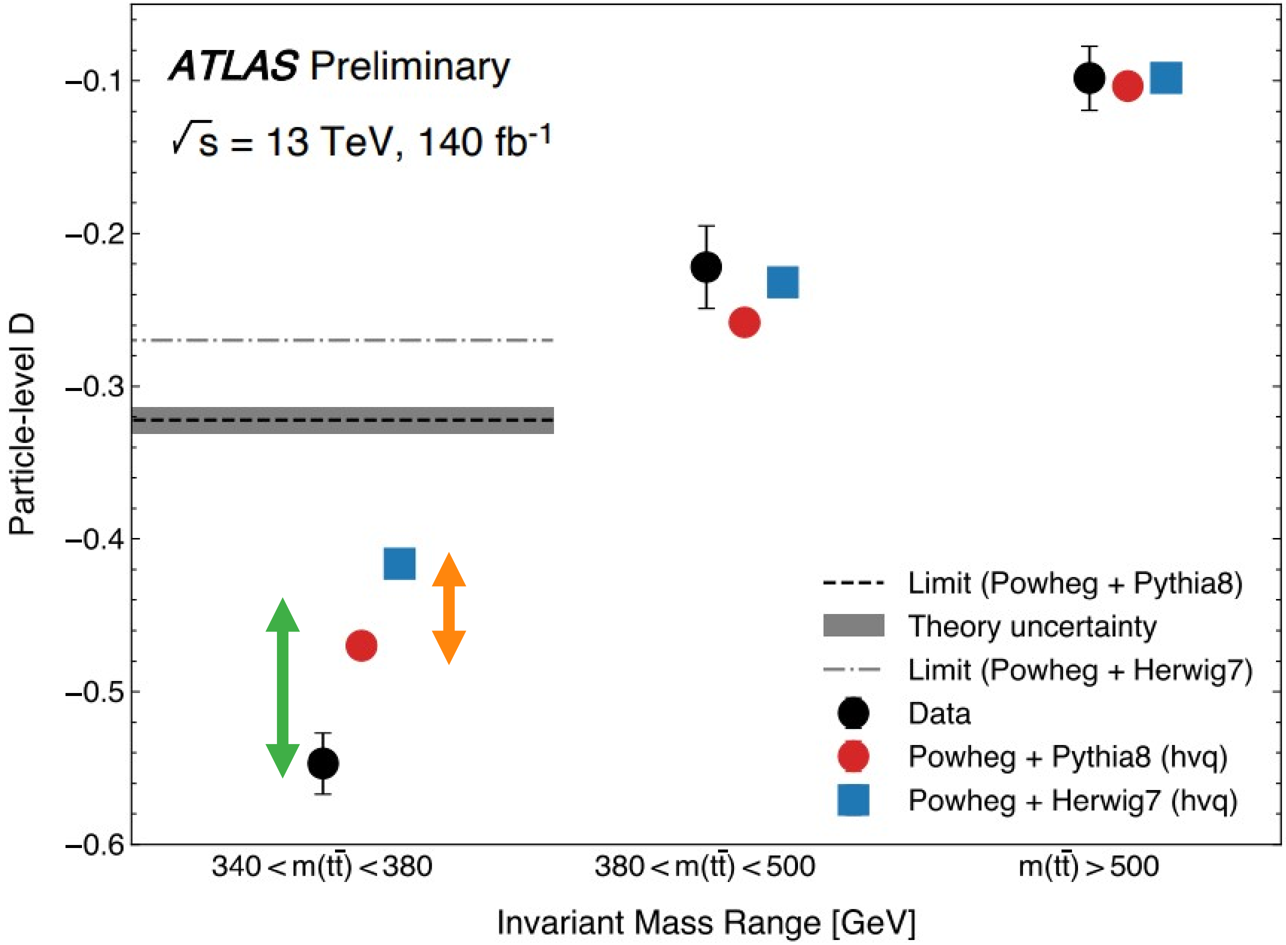
ATLAS-CONF-2023-069

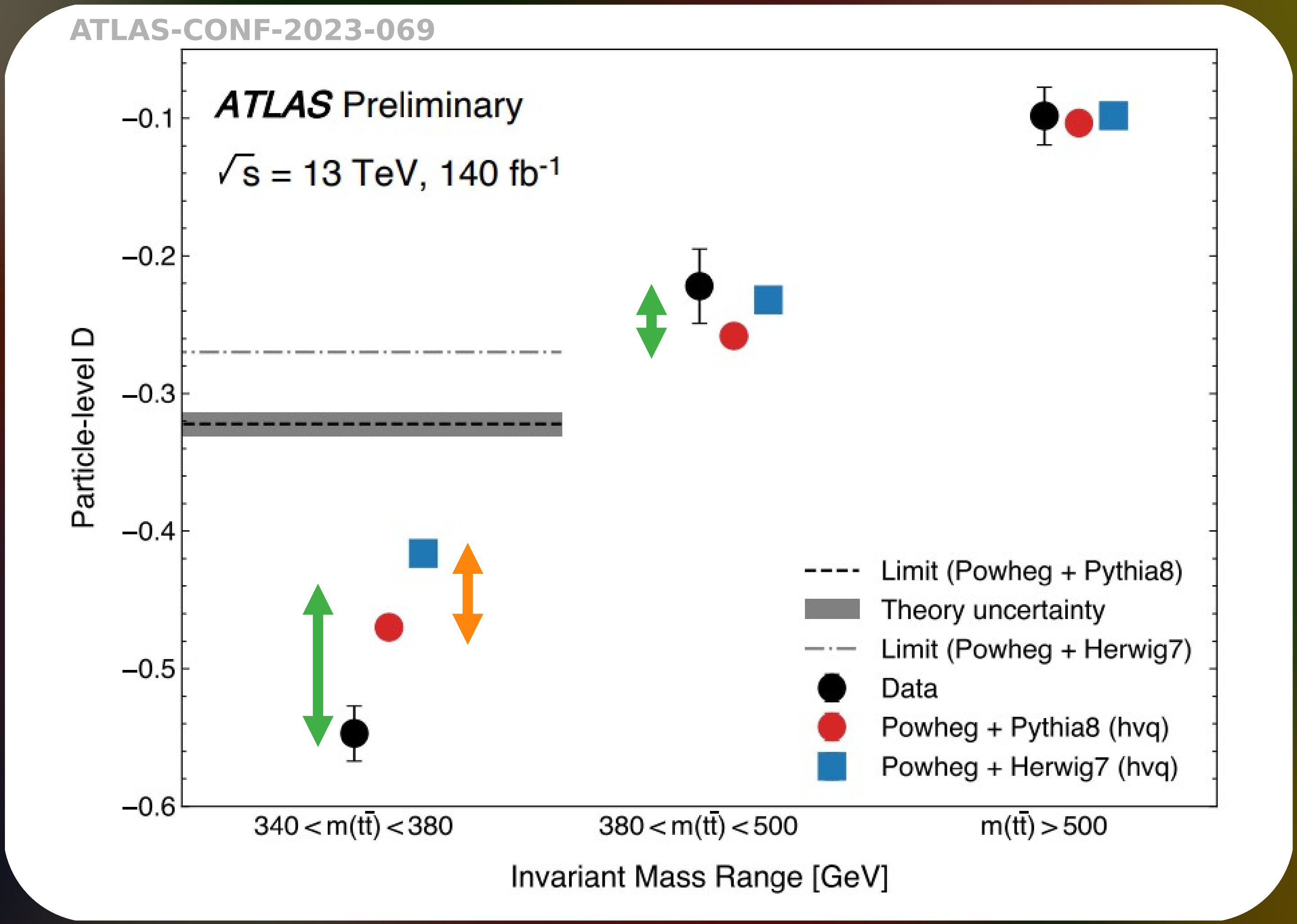


ATLAS-CONF-2023-069

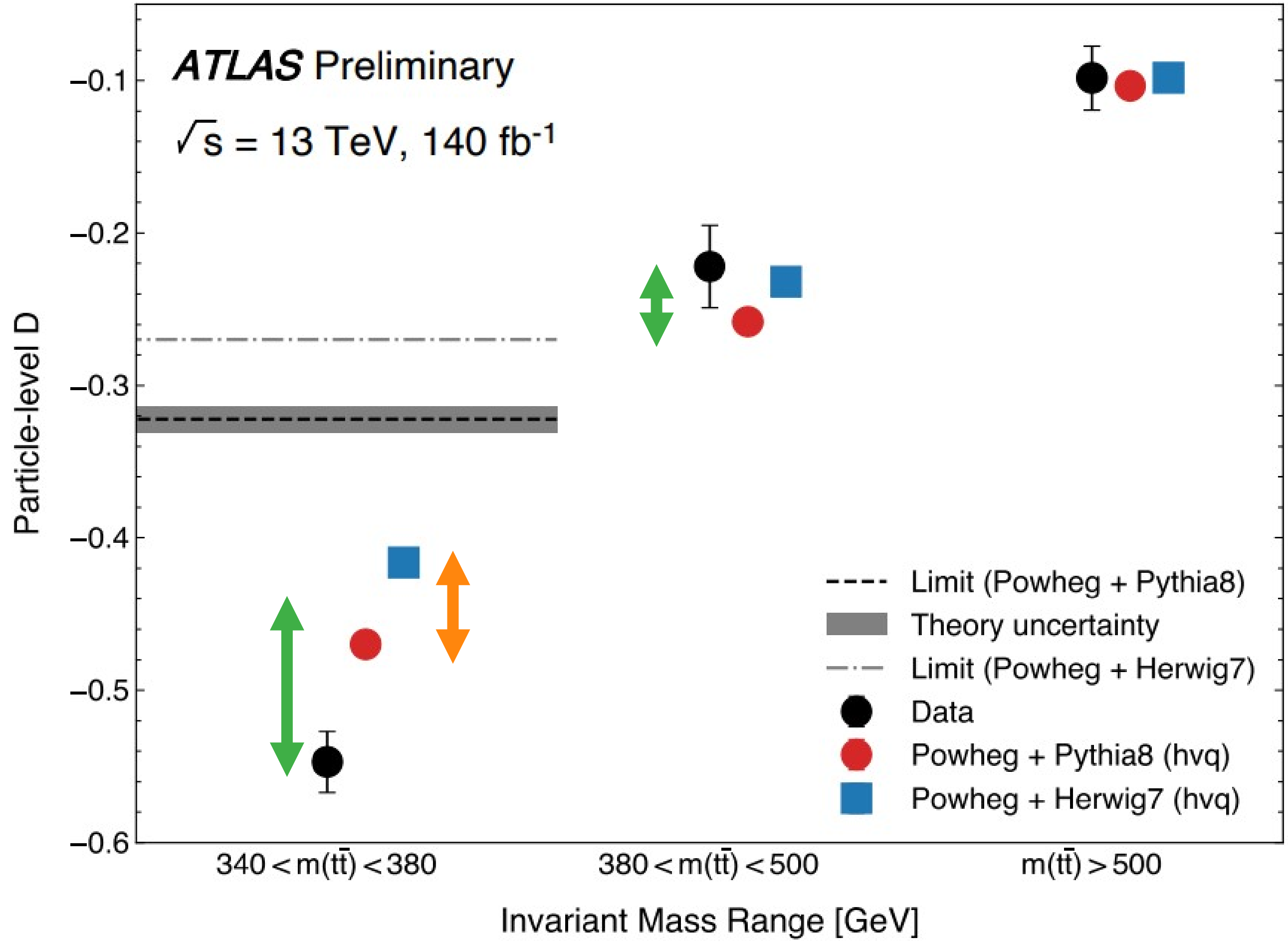


ATLAS-CONF-2023-069



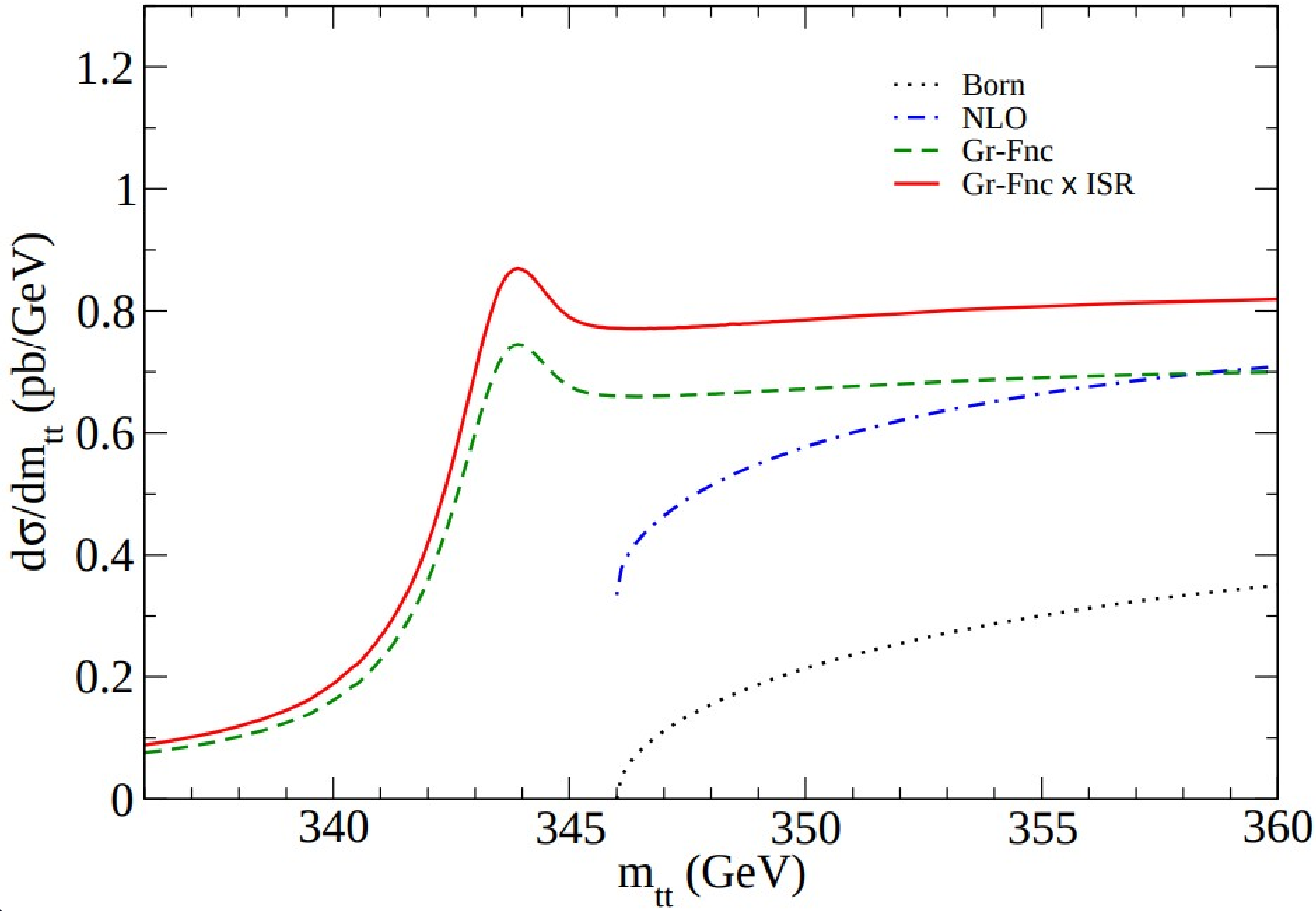

ATLAS-CONF-2023-069
ATLAS Preliminary
√s = 13 TeV, 140 fb-1
Particle-level D
−0.1
−0.2
−0.3
−0.4
−0.5
−0.6
Limit (Powheg + Pythia8)
Theory uncertainty
Limit (Powheg + Herwig7)
Data
Powheg + Pythia8 (hvq)
Powheg + Herwig7 (hvq)
340 < m(tt̄) < 380
380 < m(tt̄) < 500
m(tt̄) > 500
Invariant Mass Range [GeV]

ATLAS-CONF-2023-069



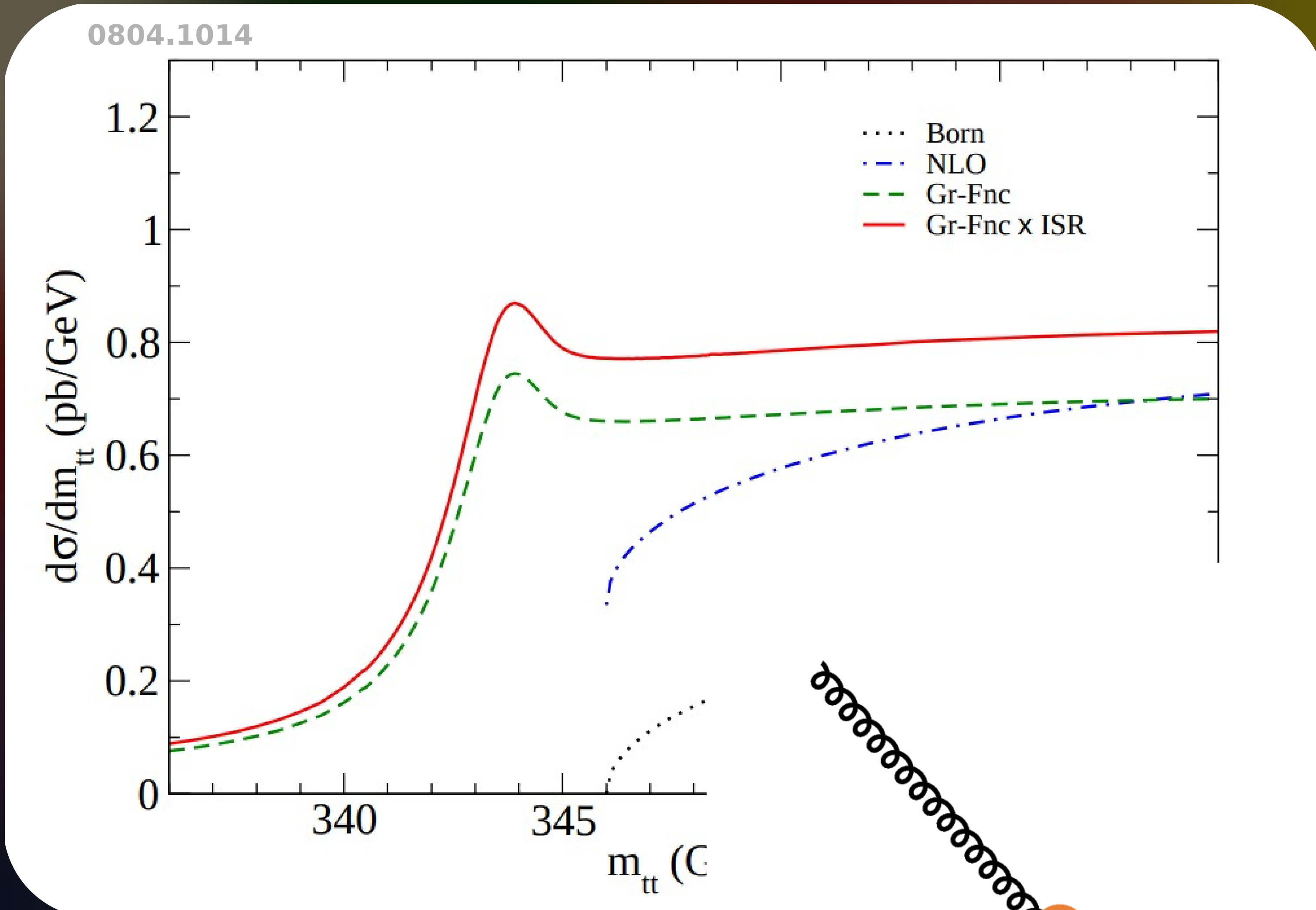
This is probably mismodelling, but what if...

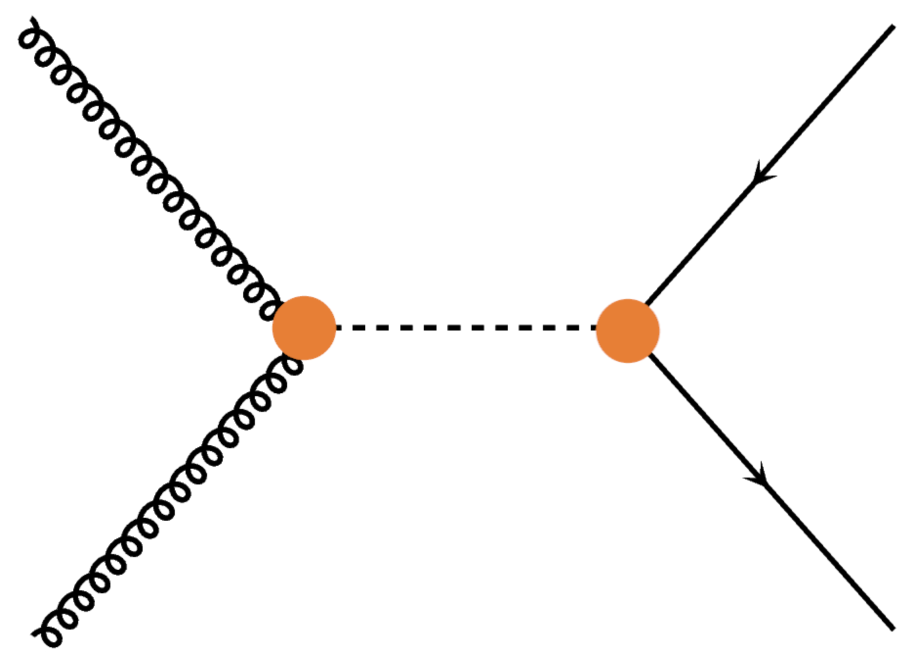
0804.1014

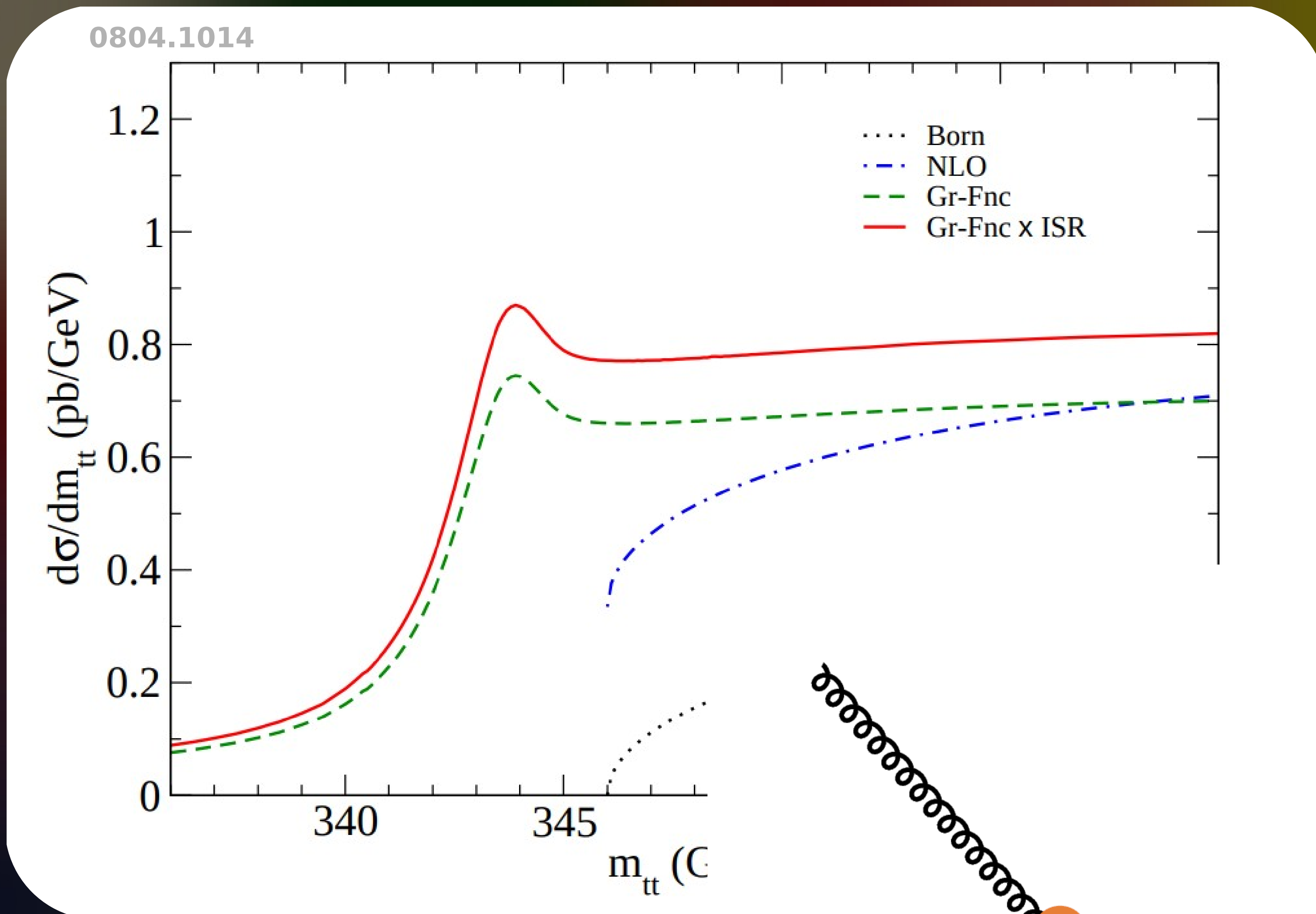


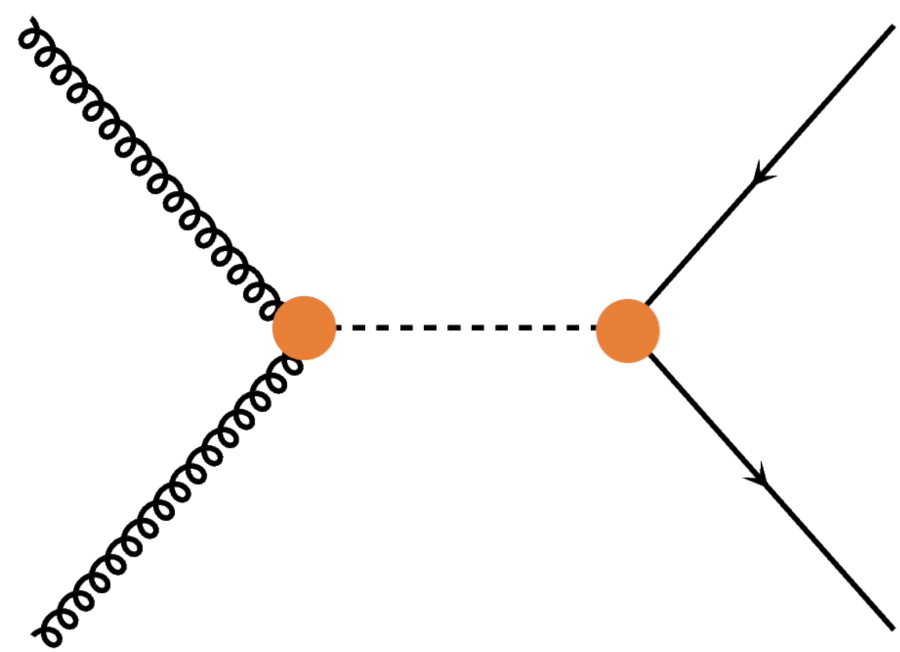
Born
NLO
Gr-Fnc
Gr-Fnc x ISR
dσ/dm_tt (pb/GeV)
m_tt (GeV)
1.2
1
0.8
0.6
0.4
0.2
0
340
345
350
355
360

0804.1014


Born
NLO
Gr-Fnc
Gr-Fnc x ISR
dσ/dm_tt (pb/GeV)
1.2
1
0.8
0.6
0.4
0.2
0
340
345
m_tt (G



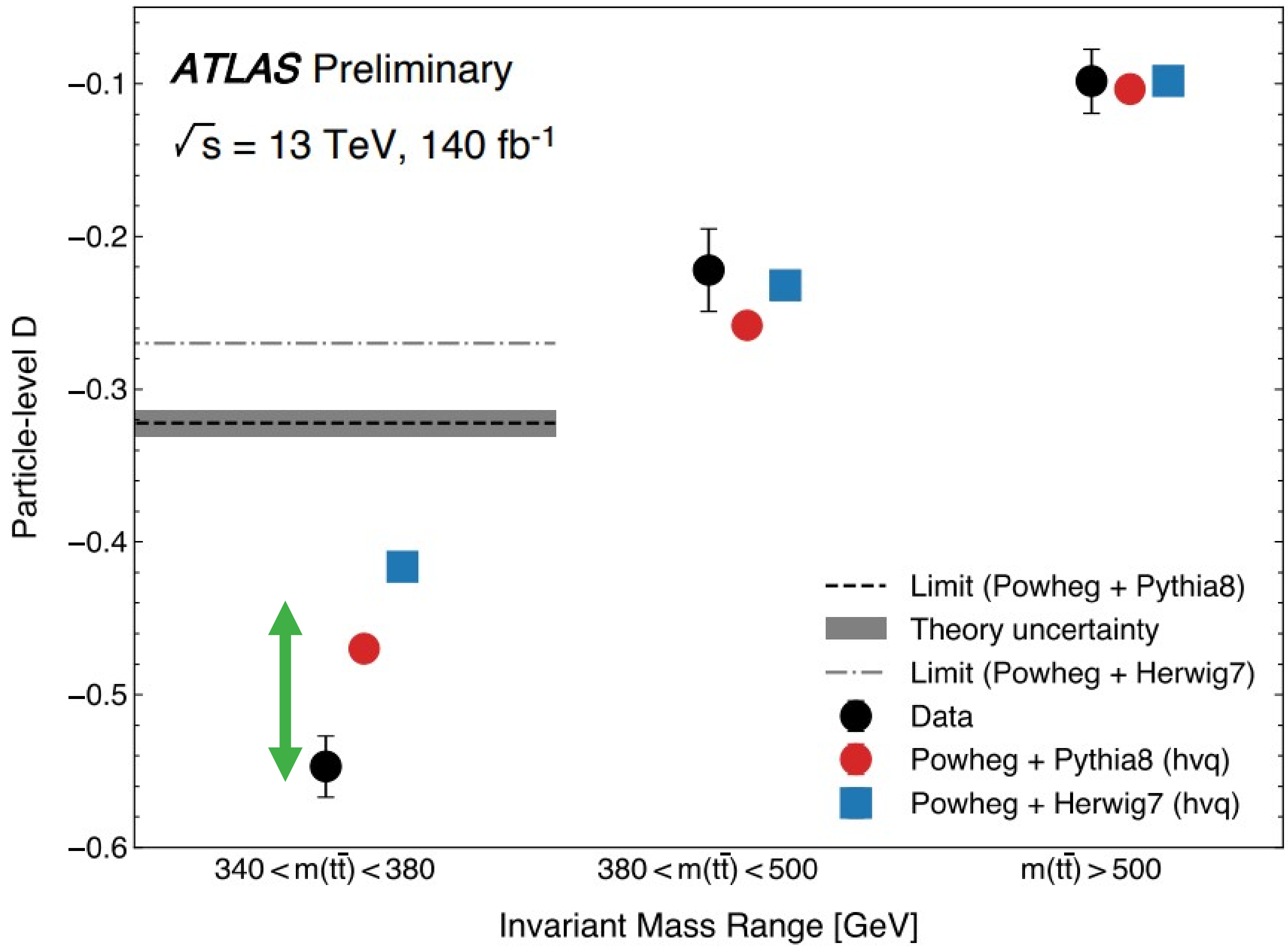




$D_{Obs} = x\, D_{NP} + (1\text{-}x)\, D_{SM}$

Most favourable case:
$D_{NP} = -1$

ATLAS-CONF-2023-069

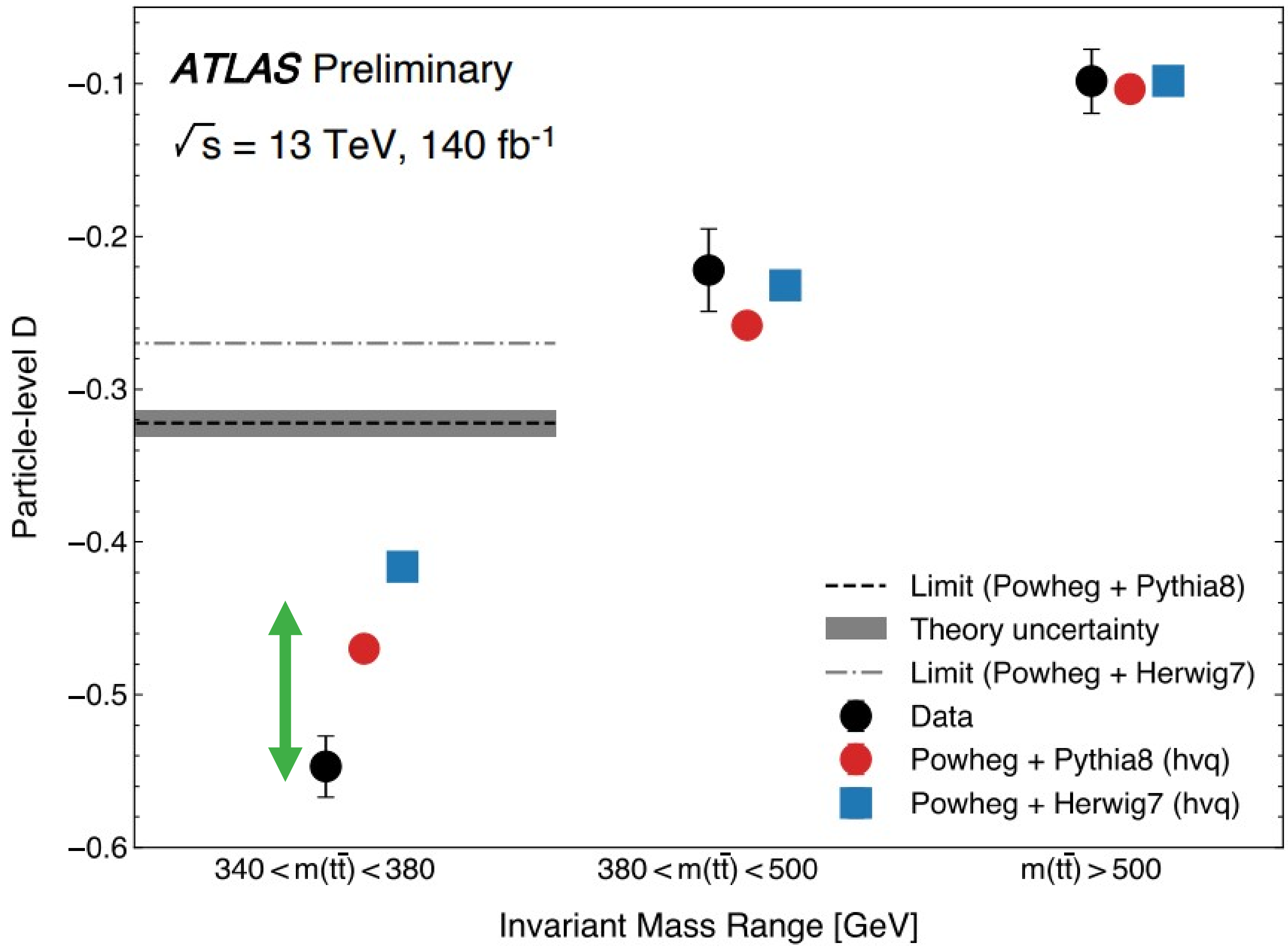


$D_{Obs} = x\, D_{NP} + (1-x)\, D_{SM}$

Most favourable case:

$D_{NP} = -1 \quad \rightarrow \quad x \simeq 0.15$

ATLAS-CONF-2023-069



$D_{Obs} = x\, D_{NP} + (1-x)\, D_{SM}$

Most favourable case:

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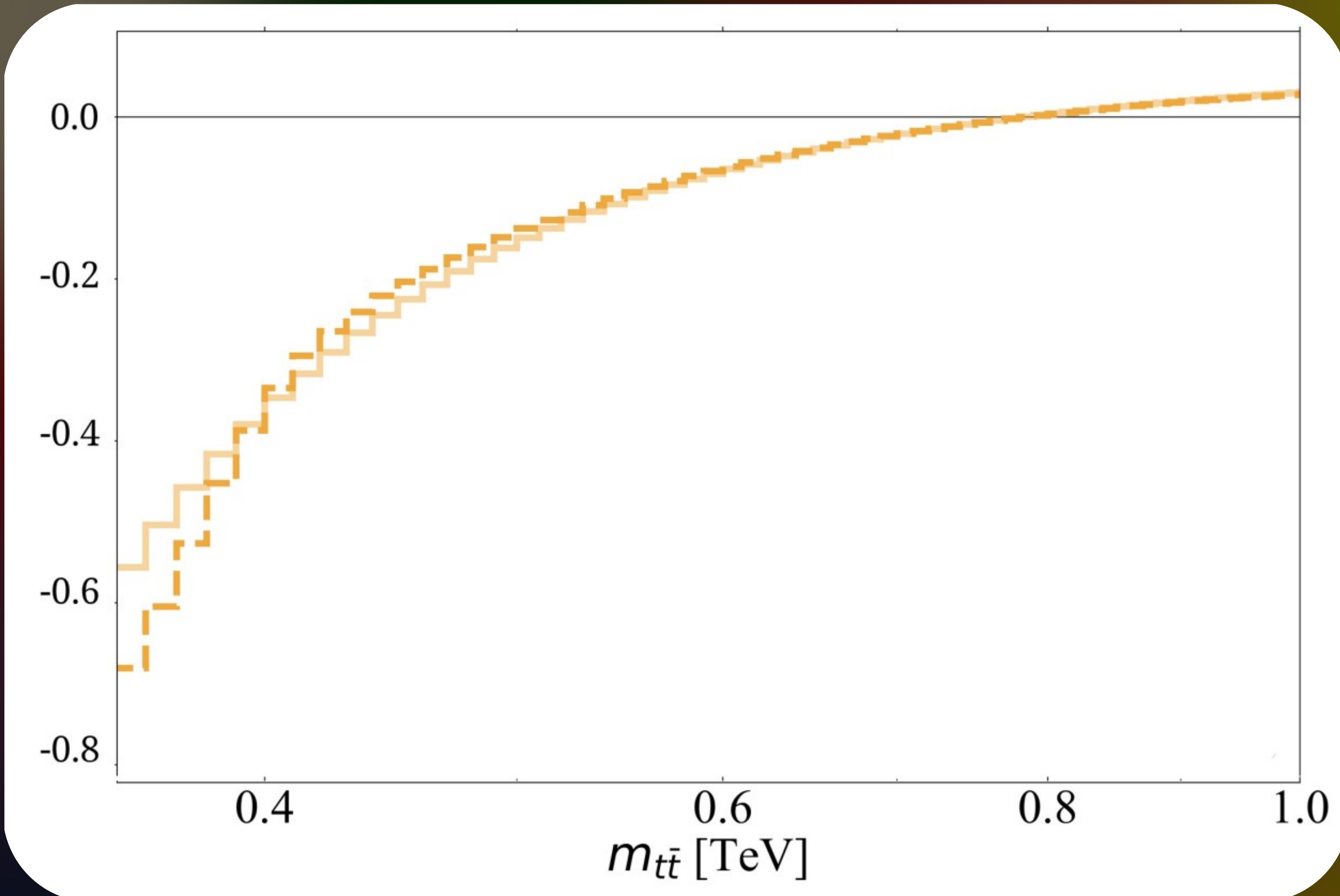
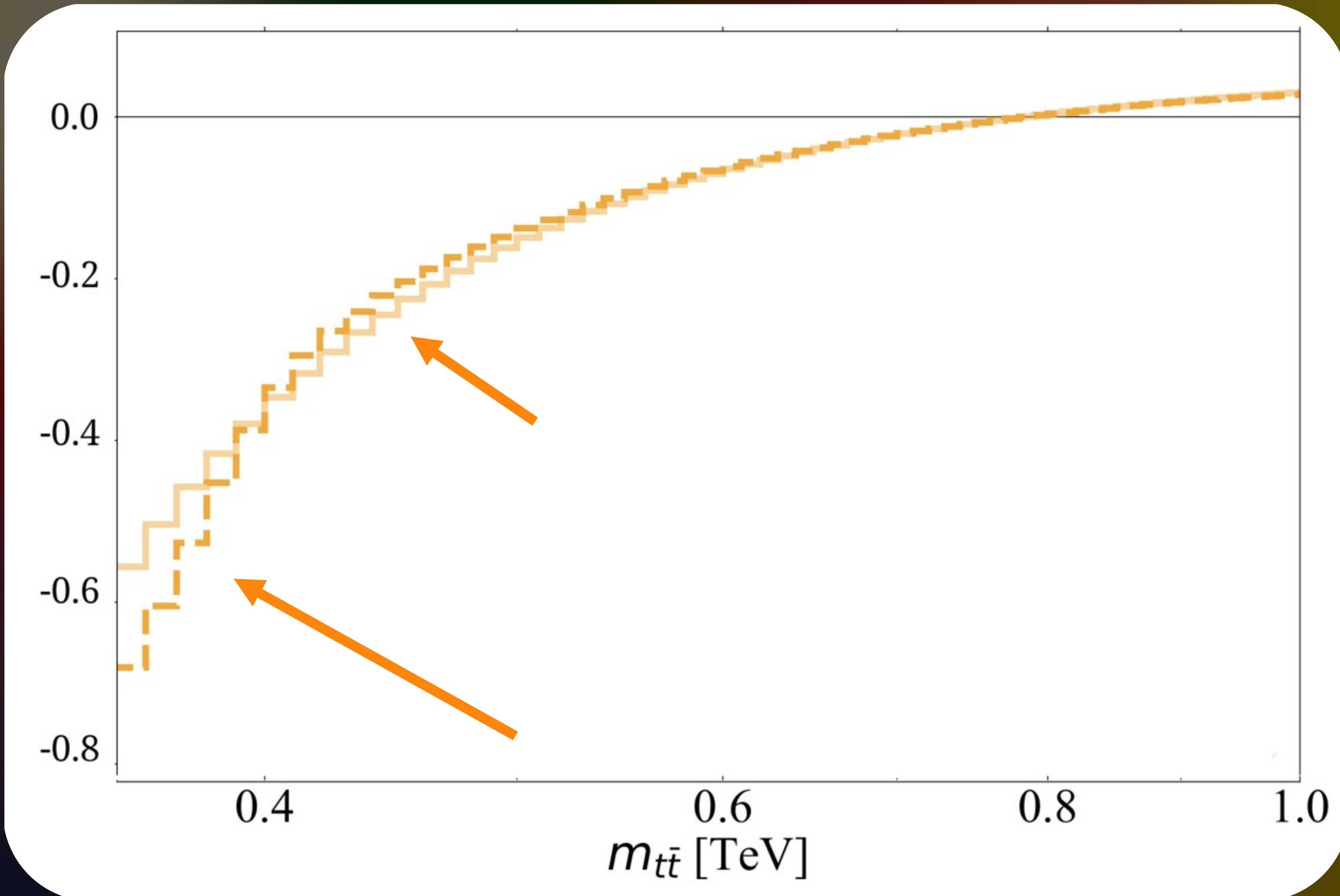
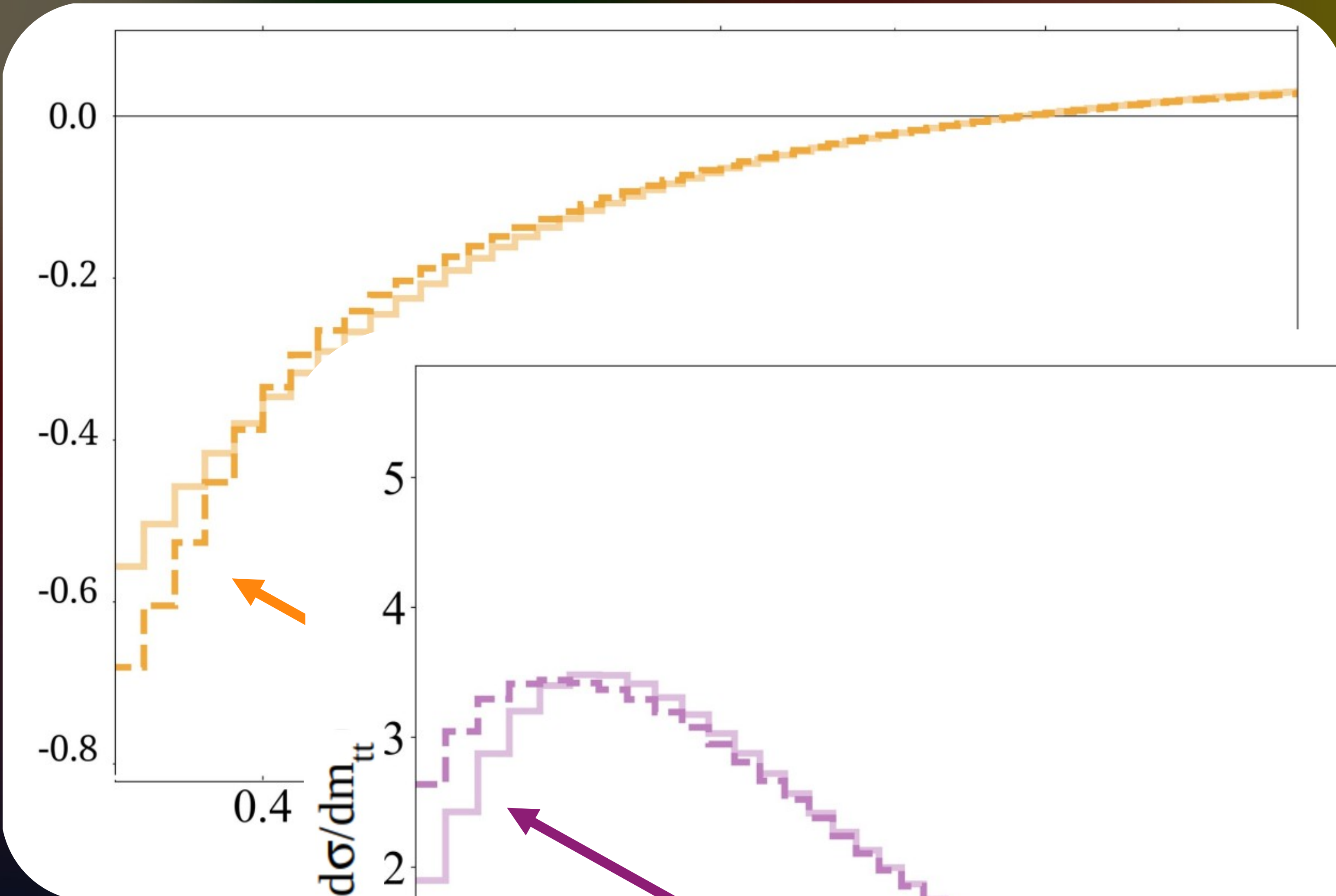
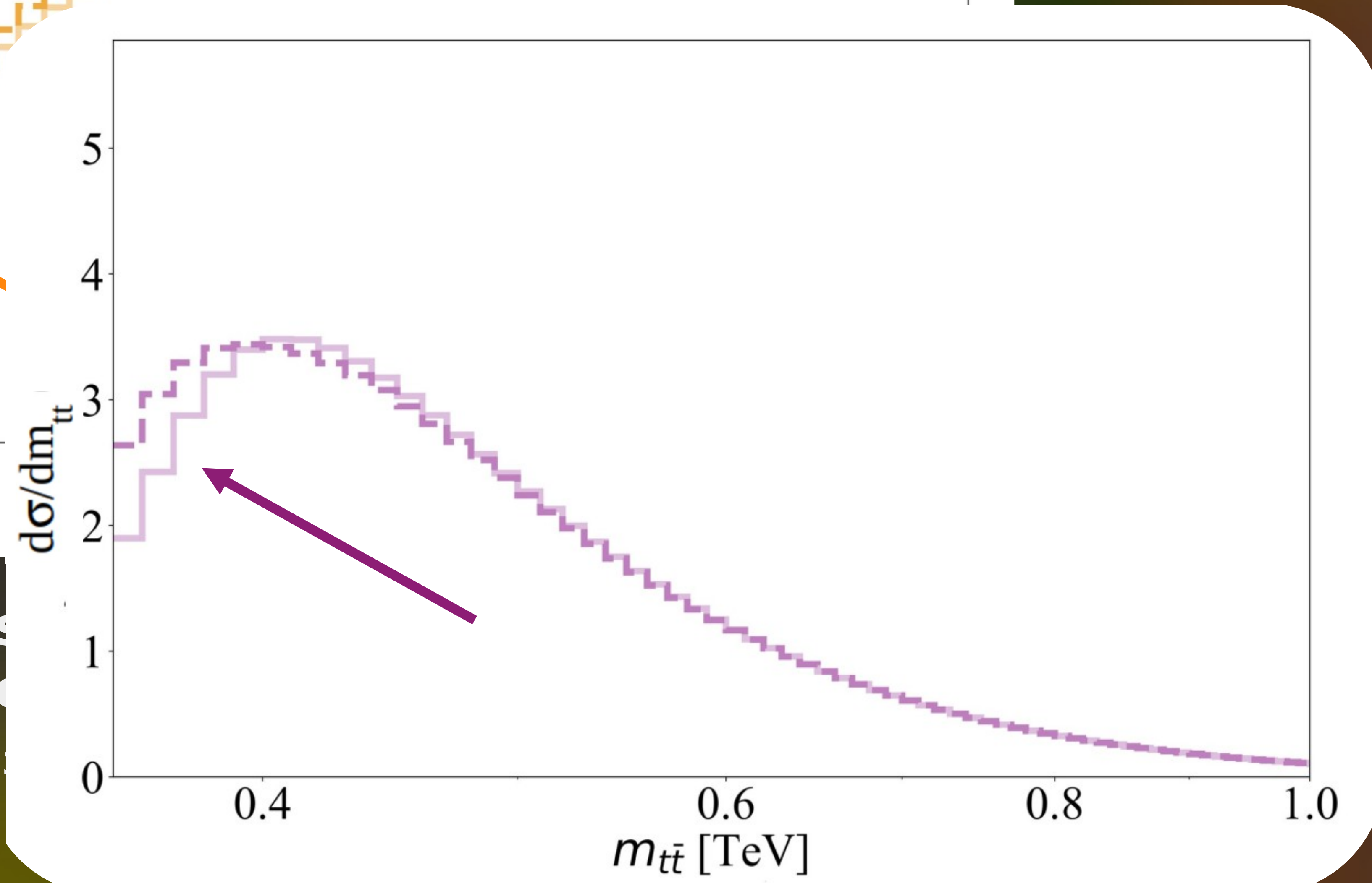


Inject resonant pseudoscalar signal with $\chi_{340\text{-}380\ \mathrm{GeV}} \simeq 0.15$



Inject resonant pseudoscalar signal with $\chi_{340\text{-}380\ \mathrm{GeV}} \simeq 0.15$





Inject res
pseudosc
with X_{340-}

There is a variety of spin/entanglement observables, apart from D...

Observable	Coefficient	Coefficient function
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-
$\cos\theta_1^k \cos\theta_2^k$	C_{kk}	c_{kk}
$\cos\theta_1^r \cos\theta_2^r$	C_{rr}	c_{rr}
$\cos\theta_1^n \cos\theta_2^n$	C_{nn}	c_{nn}
$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$	$C_{rk} + C_{kr}$	c_{rk}
$\cos\theta_1^r \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^r$	$C_{rk} - C_{kr}$	c_n
$\cos\theta_1^n \cos\theta_2^r + \cos\theta_1^r \cos\theta_2^n$	$C_{nr} + C_{rn}$	c_{nr}
$\cos\theta_1^n \cos\theta_2^r - \cos\theta_1^r \cos\theta_2^n$	$C_{nr} - C_{rn}$	c_k
$\cos\theta_1^n \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^n$	$C_{nk} + C_{kn}$	c_{kn}
$\cos\theta_1^n \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^n$	$C_{nk} - C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$
$\cos\varphi_{\text{lab}}$	$A_{\cos\varphi}^{\text{lab}}$	—
$\lvert\Delta\phi_{\ell\ell}\rvert$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	—
$\lvert\Delta\eta_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$	—

CMS-PAS-FTR-18-034

There is a variety of spin/entanglement observables, apart from D...

Observable	Coefficient	Coefficient function
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-
$\cos\theta_1^k \cos\theta_2^k$	C_{kk}	c_{kk}
$\cos\theta_1^r \cos\theta_2^r$	C_{rr}	c_{rr}
$\cos\theta_1^n \cos\theta_2^n$	C_{nn}	c_{nn}
$\cos\theta_1^r \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^r$	$C_{rk} + C_{kr}$	c_{rk}
$\cos\theta_1^r \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^r$	$C_{rk} - C_{kr}$	c_n
$\cos\theta_1^n \cos\theta_2^r + \cos\theta_1^r \cos\theta_2^n$	$C_{nr} + C_{rn}$	c_{nr}
$\cos\theta_1^n \cos\theta_2^r - \cos\theta_1^r \cos\theta_2^n$	$C_{nr} - C_{rn}$	c_k
$\cos\theta_1^n \cos\theta_2^k + \cos\theta_1^k \cos\theta_2^n$	$C_{nk} + C_{kn}$	c_{kn}
$\cos\theta_1^n \cos\theta_2^k - \cos\theta_1^k \cos\theta_2^n$	$C_{nk} - C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk} + c_{rr} + c_{nn})/3$
$\cos\varphi_{\text{lab}}$	$A_{\cos\varphi}^{\text{lab}}$	—
$\lvert\Delta\phi_{\ell\ell}\rvert$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	—
$\lvert\Delta\eta_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$	—

Leptons in the laboratory frame

CMS-PAS-FTR-18-034

There is a variety of spin/entanglement observables, apart from D...

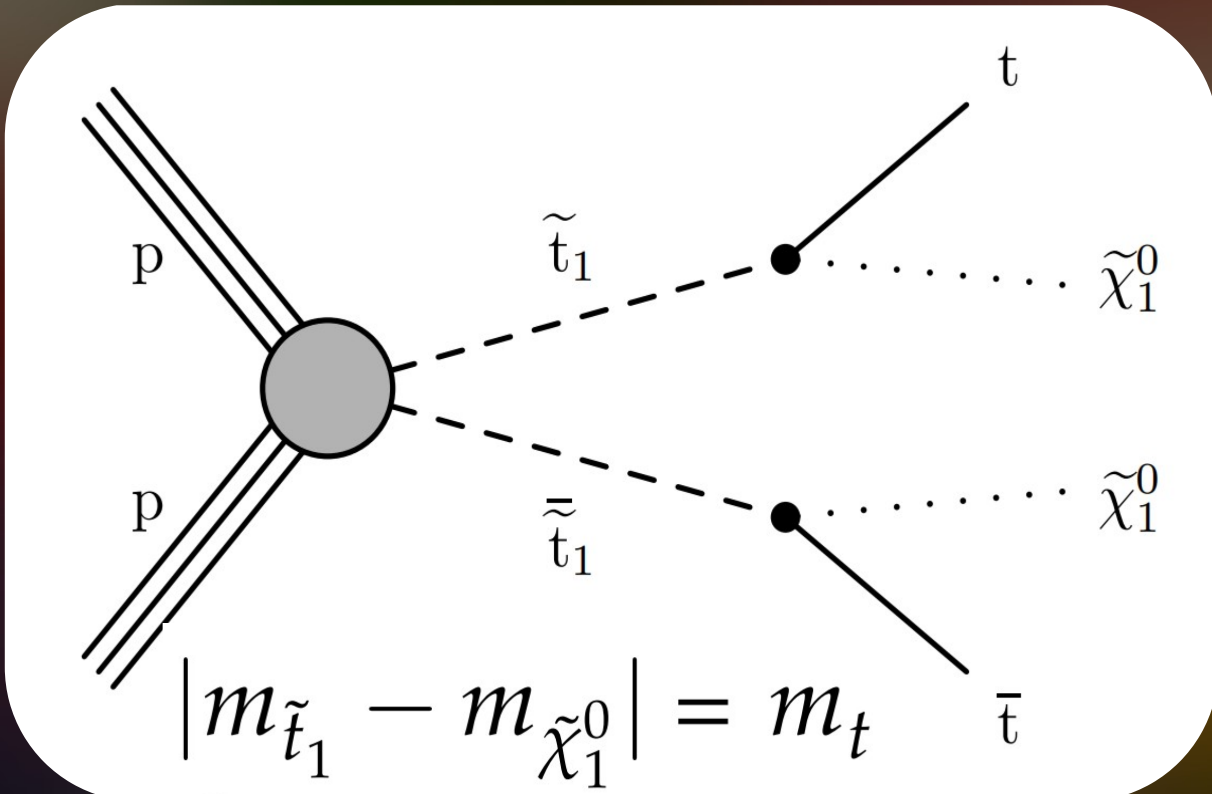
Observable	Coefficient	Coefficient function
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-
$\cos\theta_1^k\cos\theta_2^k$	C_{kk}	c_{kk}
$\cos\theta_1^r\cos\theta_2^r$	C_{rr}	c_{rr}
$\cos\theta_1^n\cos\theta_2^n$	C_{nn}	c_{nn}
$\cos\theta_1^r\cos\theta_2^k+\cos\theta_1^k\cos\theta_2^r$	$C_{rk}+C_{kr}$	c_{rk}
$\cos\theta_1^r\cos\theta_2^k-\cos\theta_1^k\cos\theta_2^r$	$C_{rk}-C_{kr}$	c_n
$\cos\theta_1^n\cos\theta_2^r+\cos\theta_1^r\cos\theta_2^n$	$C_{nr}+C_{rn}$	c_{nr}
$\cos\theta_1^n\cos\theta_2^r-\cos\theta_1^r\cos\theta_2^n$	$C_{nr}-C_{rn}$	c_k
$\cos\theta_1^n\cos\theta_2^k+\cos\theta_1^k\cos\theta_2^n$	$C_{nk}+C_{kn}$	c_{kn}
$\cos\theta_1^n\cos\theta_2^k-\cos\theta_1^k\cos\theta_2^n$	$C_{nk}-C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk}+c_{rr}+c_{nn})/3$
$\cos\varphi_{\text{lab}}$	$A^{\text{lab}}_{\cos\varphi}$	—
$\lvert\Delta\phi_{\ell\ell}\rvert$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	—
$\lvert\Delta\eta_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$	—

Leptons in the laboratory frame

CMS-PAS-FTR-18-034

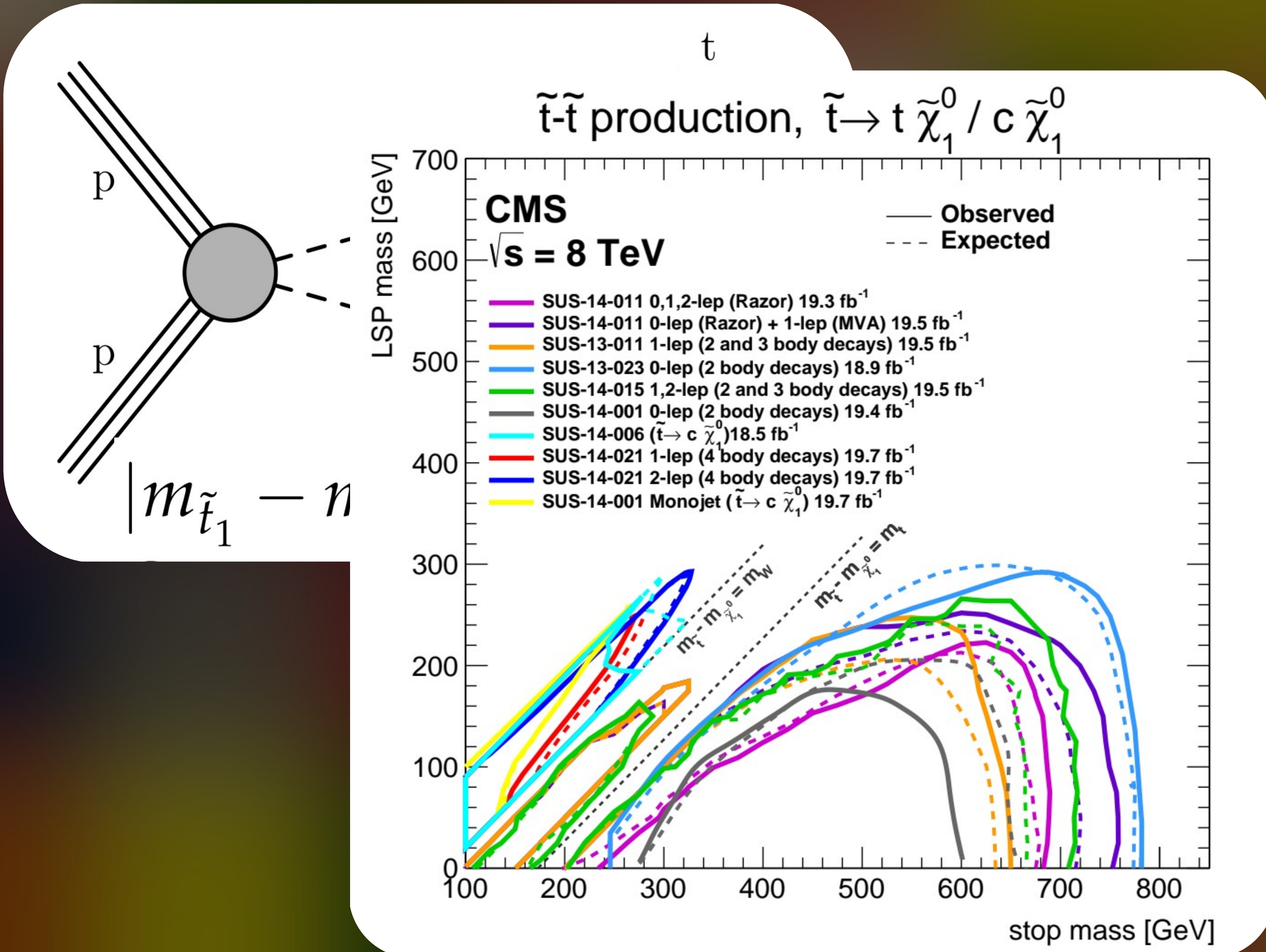
The motivation for using some of these variables can be found in [25]. The highest ranked variables are the angular variables $\Delta\eta_{\ell\ell}$, $\cos\varphi_{\text{lab}}$, and $\Delta\phi_{\ell\ell}$. In principle, adding additional kinematic variables to the DNN will improve the sensitivity further. However, by adding basic

Example: SUSY in the top mass corridor

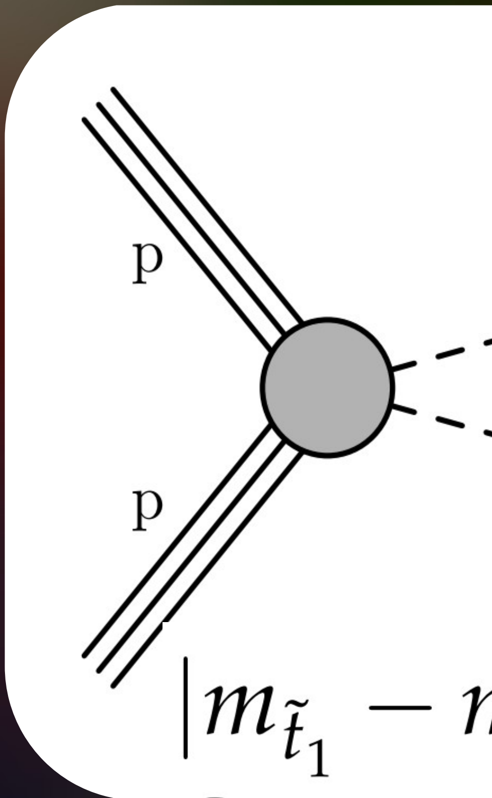


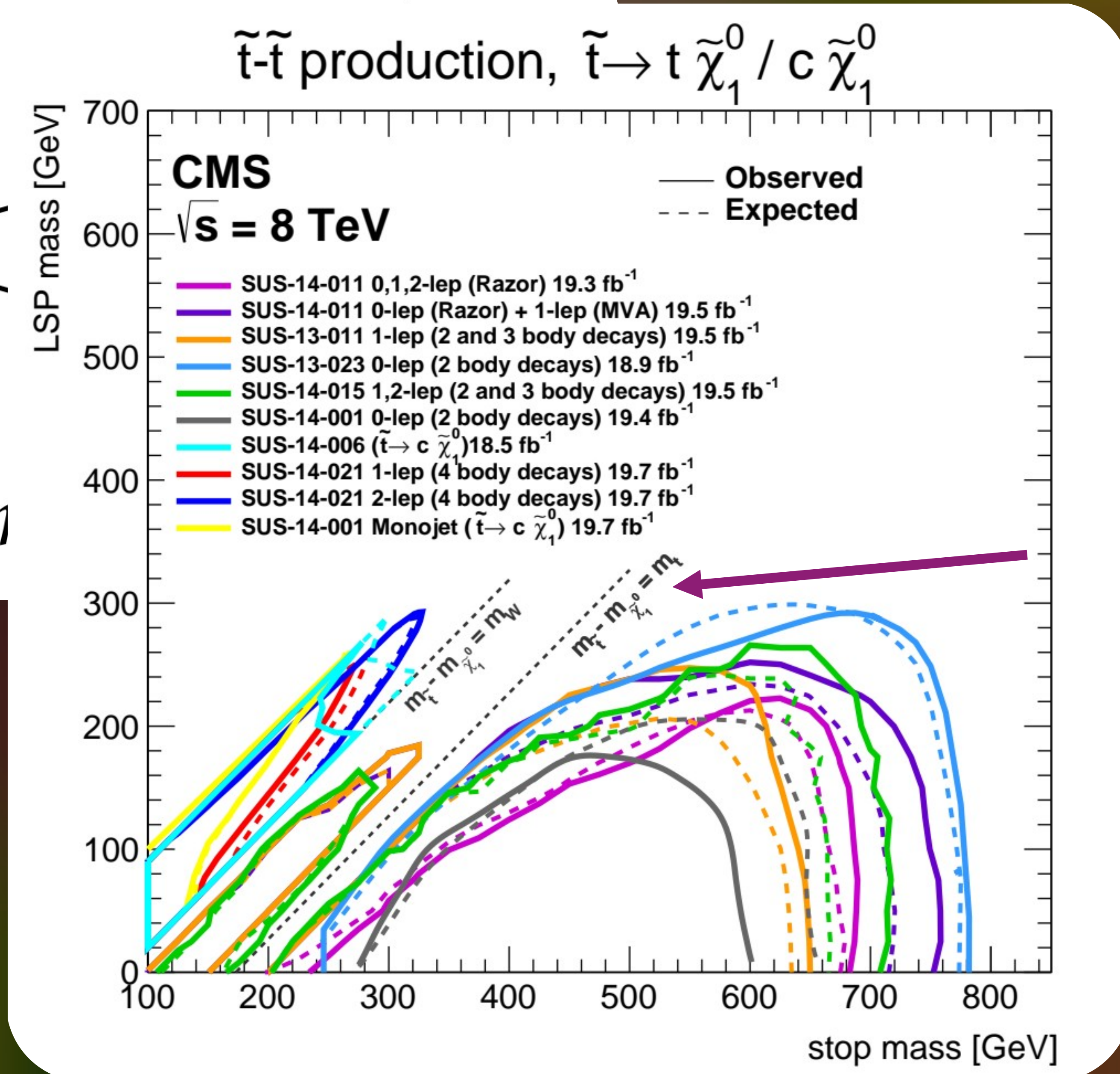
$$\left| m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \right| = m_t$$

Example: SUSY in the top mass corridor

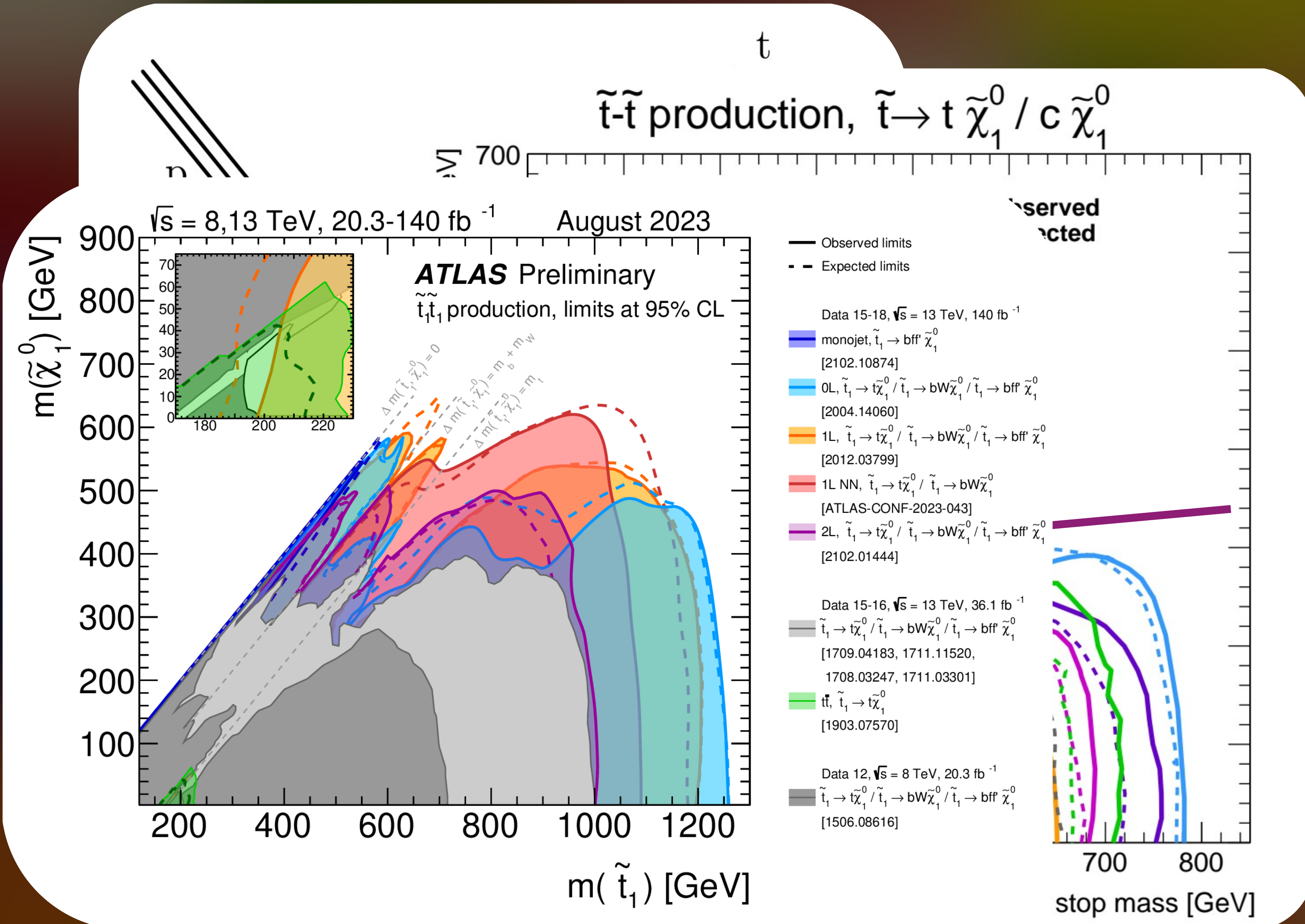


Example: SUSY in the top mass corridor



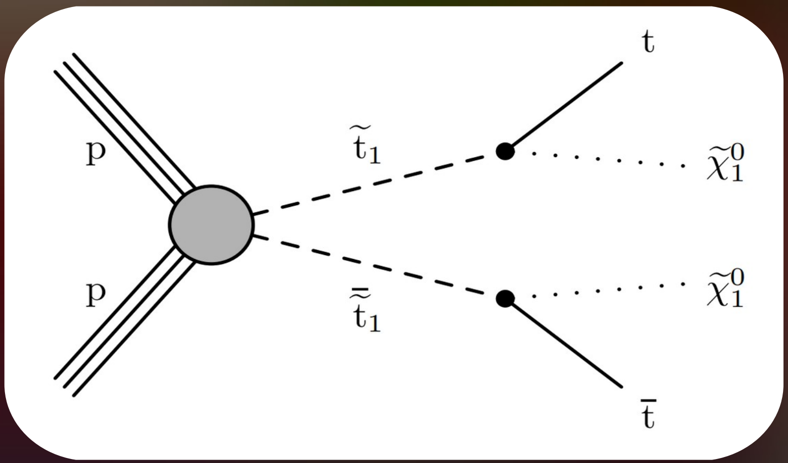


Example: SUSY in the top mass corridor



Example: SUSY in the top mass corridor

Spin correlations on the other hand...

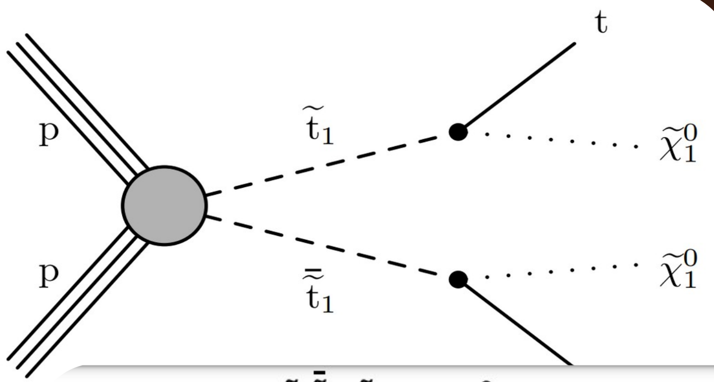


$$C_{ij} = (1-\mathsf{x})\, C_{ij\,\mathrm{SM}} + \mathsf{x}\, C_{ij\,\mathrm{SUSY}} < C_{ij\,\mathrm{SM}}.$$

$$B_i = (1-\mathsf{x})\, B_{i\,\mathrm{SM}} + \mathsf{x}\, B_{i\,\mathrm{SUSY}} > B_{i\,\mathrm{SM}}.$$

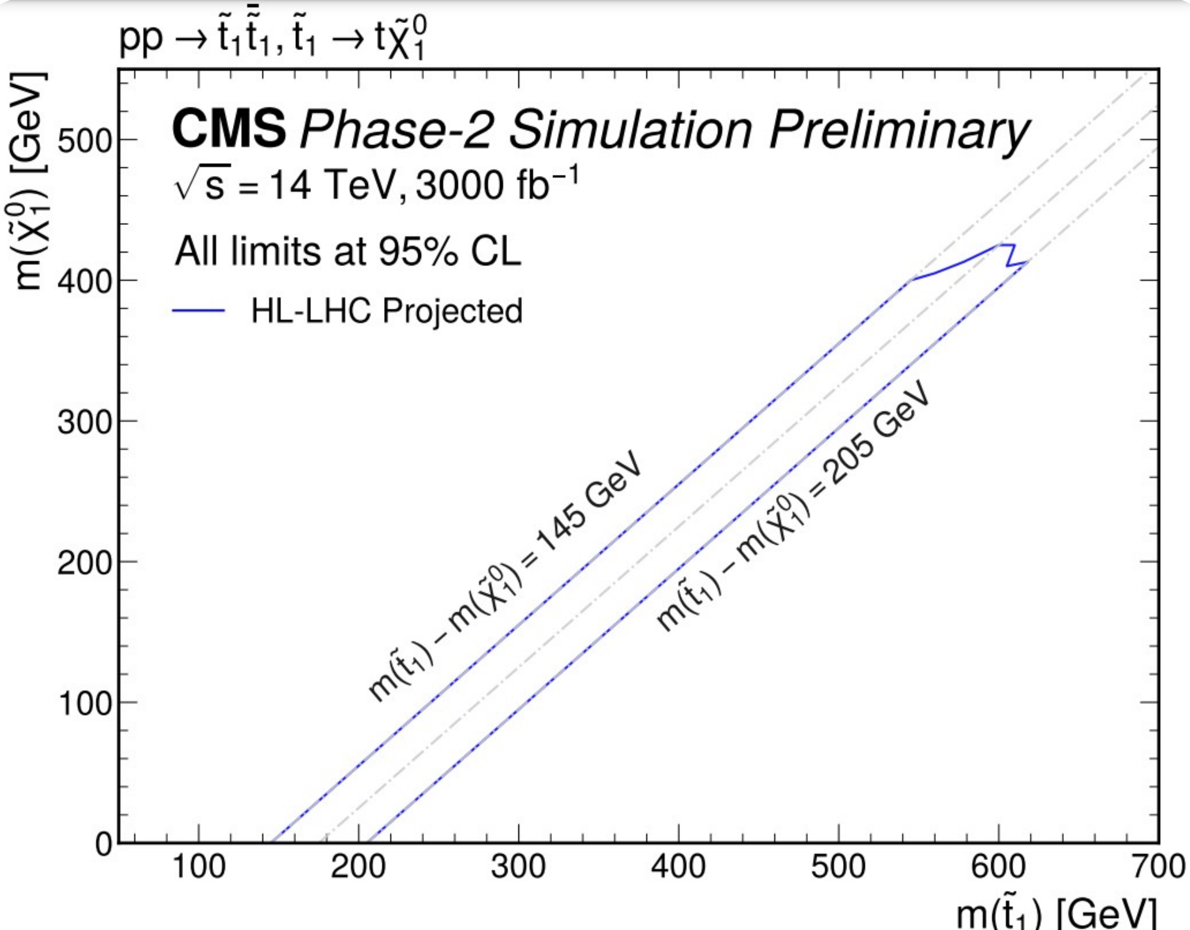
Example: SUSY in the top mass corridor

Spin correlations on the other hand...



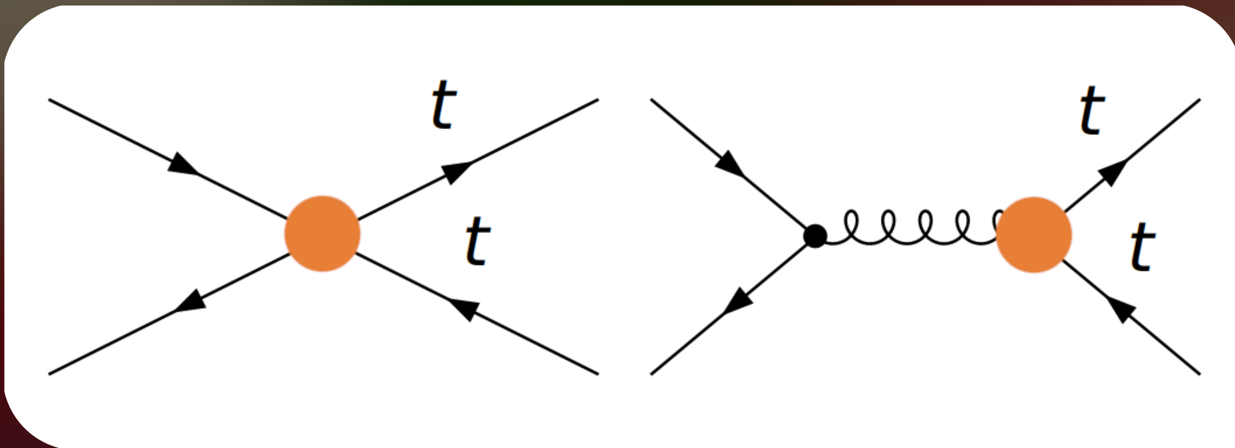
$$C_{ij} = (1 - \mathrm{x})\, C_{ij\,\mathrm{SM}} + \mathrm{x}\, C_{ij\,\mathrm{SUSY}} < C_{ij\,\mathrm{SM}}.$$

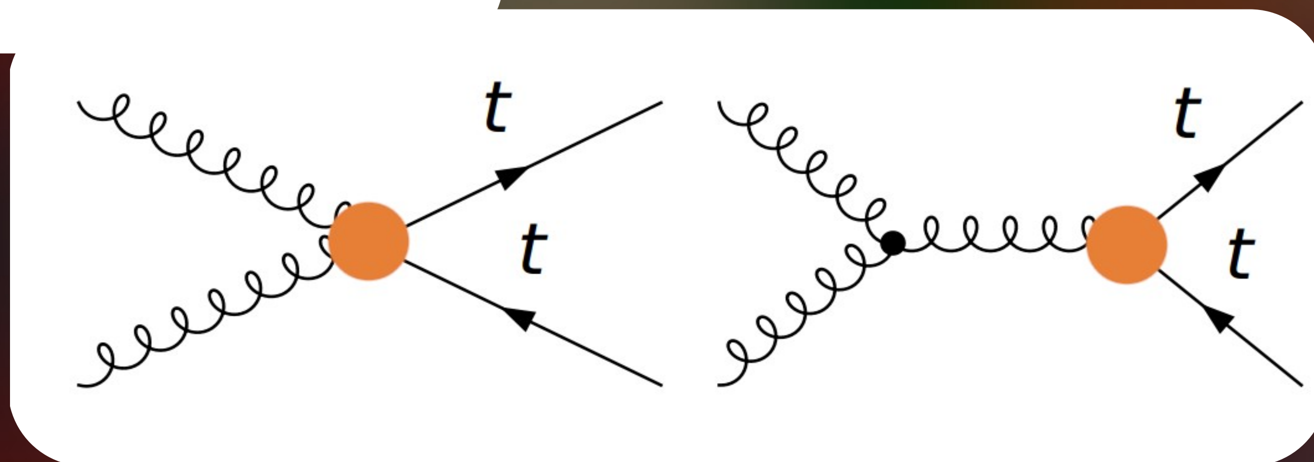
$$B_i = (1 - \mathrm{x})\, B_{i\,\mathrm{SM}} + \mathrm{x}\, B_{i\,\mathrm{SUSY}} > B_{i\,\mathrm{SM}}.$$



B_{1i}, B_{2j}, C_{ij} + lab. observables

Example: Heavy non-resonant new physics





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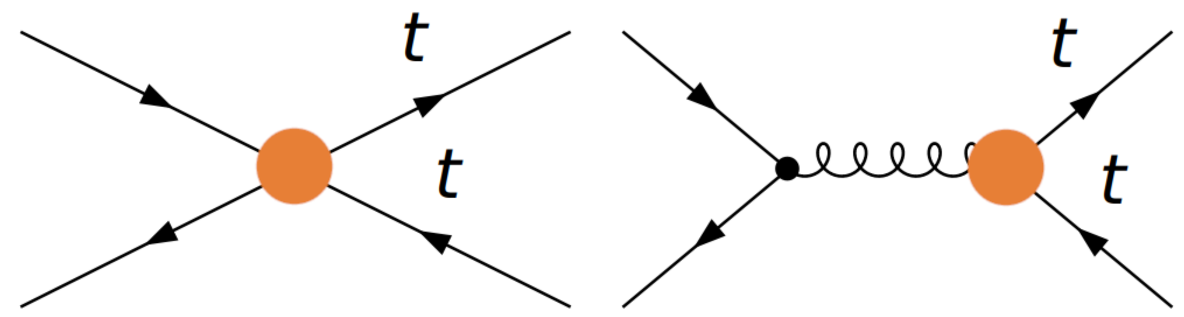


$$\mathcal{O}_{tu}^{8} = \sum_{\mathrm{f}=1}^{2} (\bar{t}\gamma_\mu T^A t)(\overline{u}_{\mathrm{f}}\gamma^\mu T_A u_{\mathrm{f}})$$

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

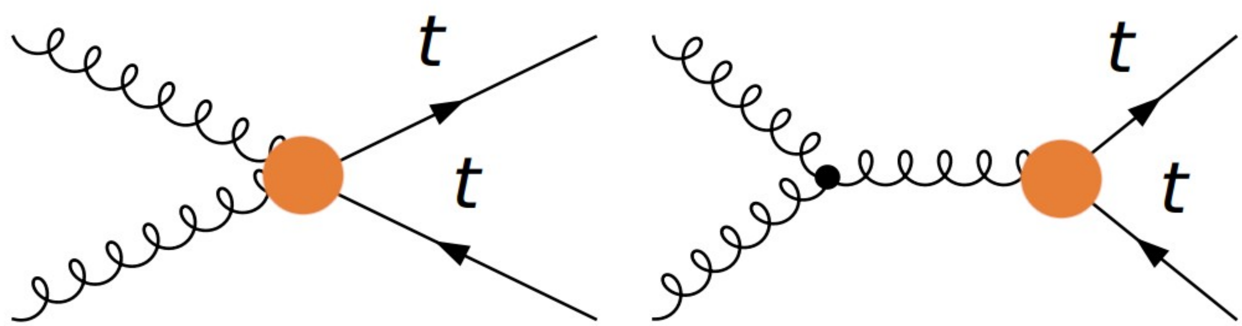
$$\mathcal{O}_{tq}^{8} = \sum_{\mathrm{f}=1}^{2} (\overline{q}_{\mathrm{f}}\gamma_\mu T_A q_{\mathrm{f}})(\bar{t}\gamma^\mu T^A t)$$

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

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

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

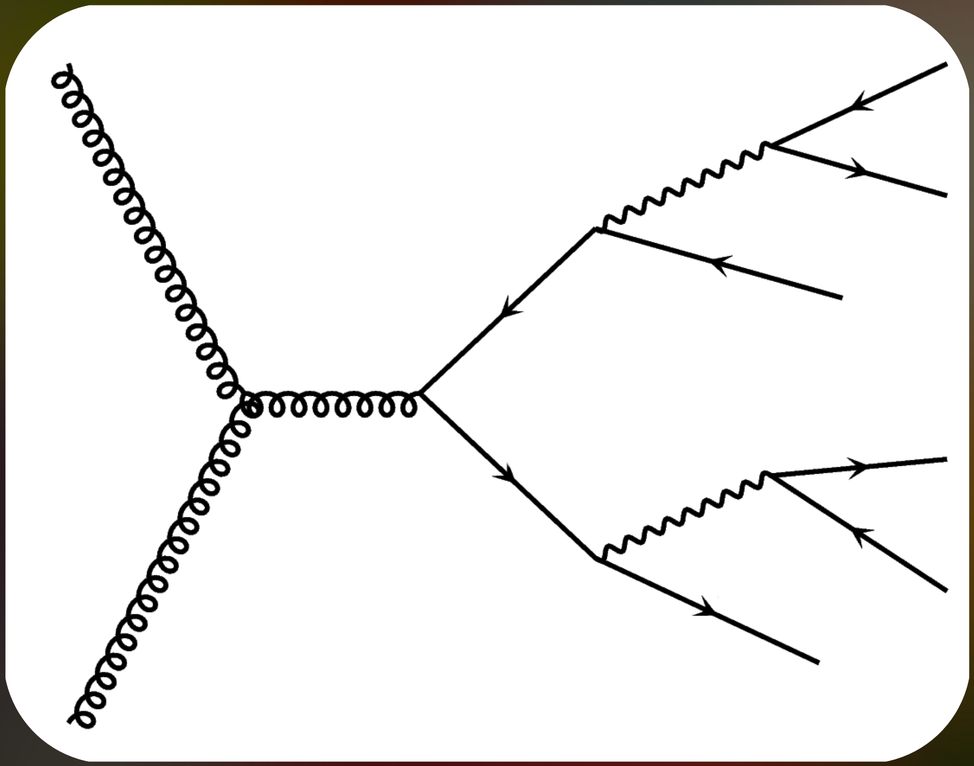
$$\mathcal{O}_{Qq}^{3,8} = \sum_{\mathrm{f}=1}^{2} (\overline{Q}\gamma_\mu T^A \sigma_I Q)(\overline{q}_{\mathrm{f}}\gamma^\mu T_A \sigma^I q_{\mathrm{f}})$$



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

Example: Heavy non-resonant new physics

Aside: are we still measuring spin?



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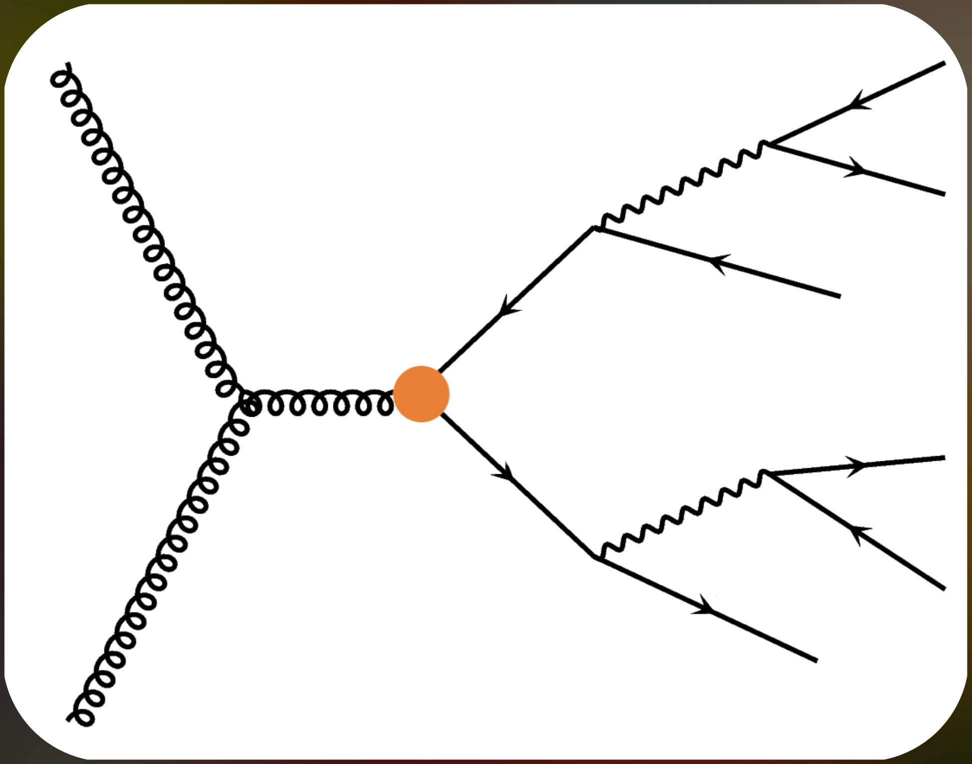

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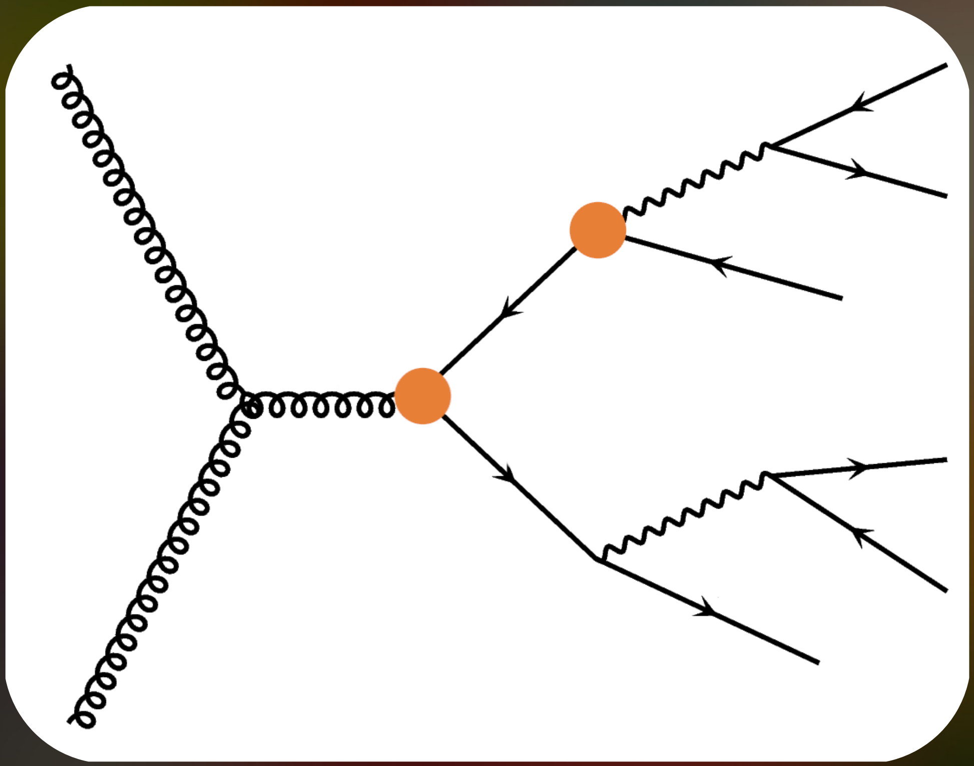

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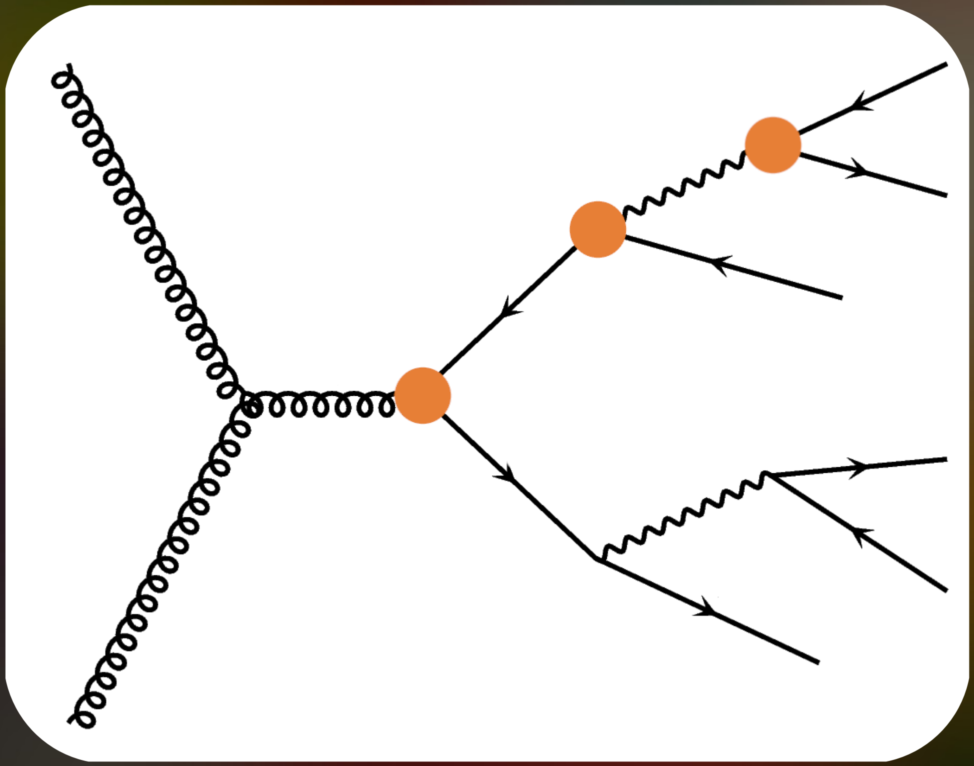

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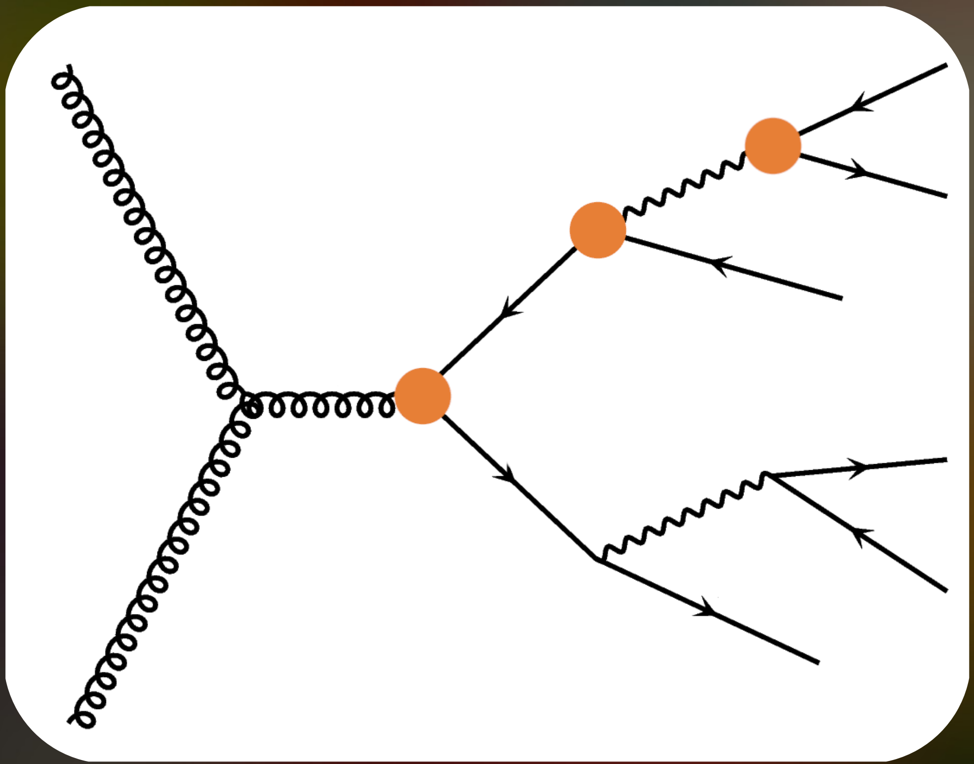
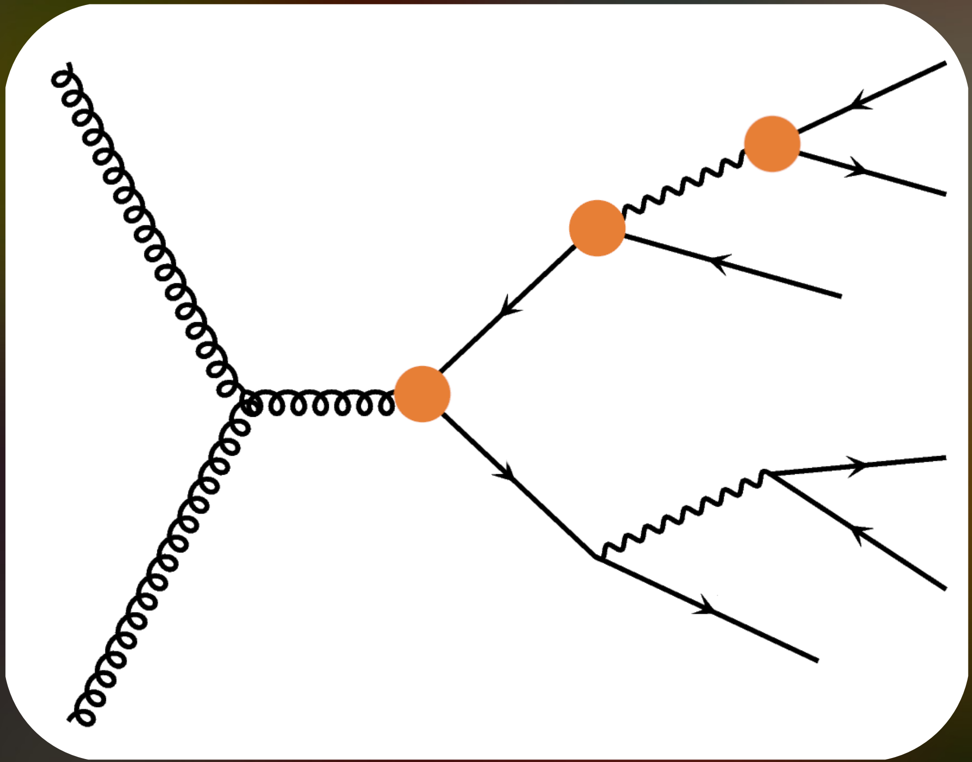


1. There is still such a thing as *spin analyzing power*

Example: Heavy non-resonant new physics

Aside: are we still measuring spin?

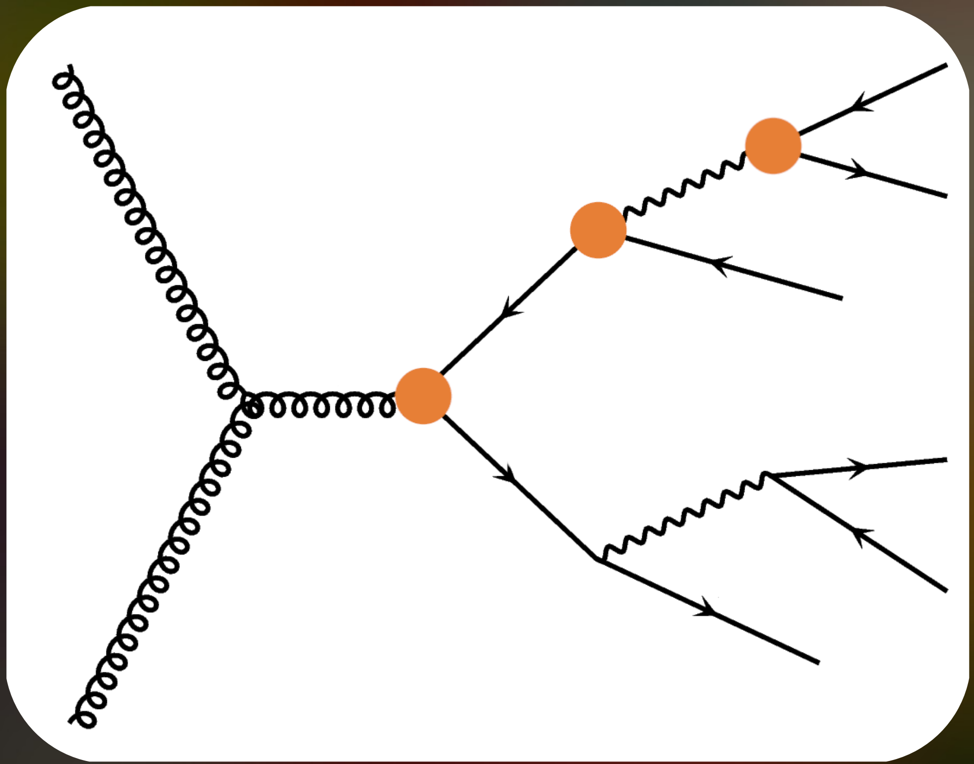


1. There is still such a thing as *spin analyzing power*
2. The analyzing power of leptons is

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

Example: Heavy non-resonant new physics

Aside: are we still measuring spin?



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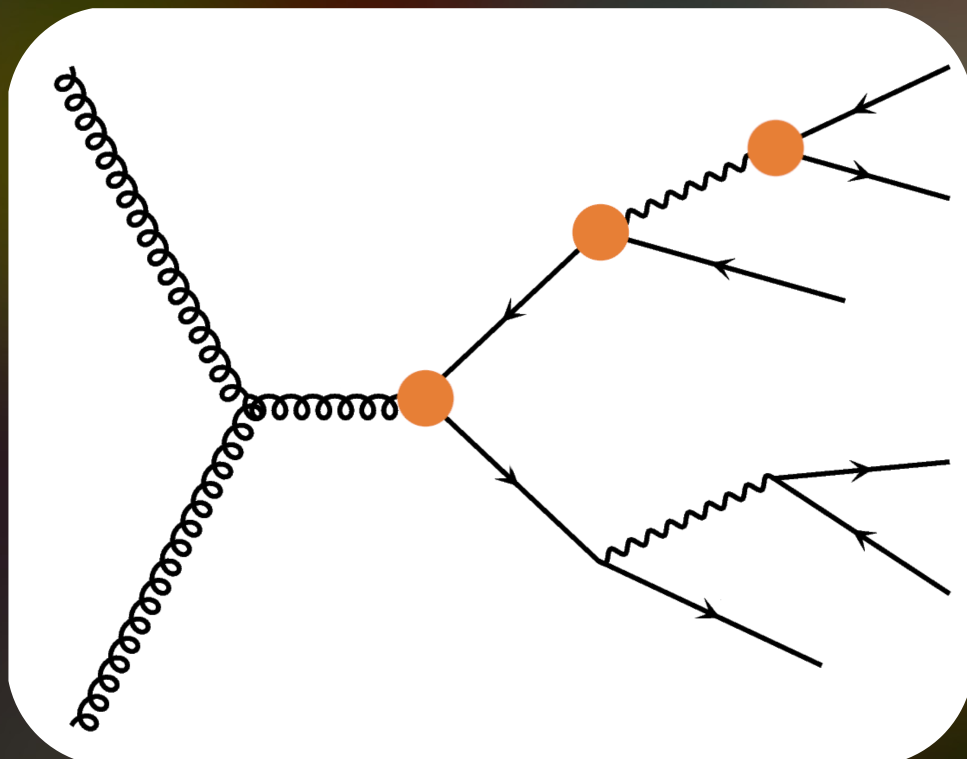
$\alpha_\ell = 1 -$ **(< 10^{-4})**

Example: Heavy non-resonant new physics

Aside: are we still measuring spin?



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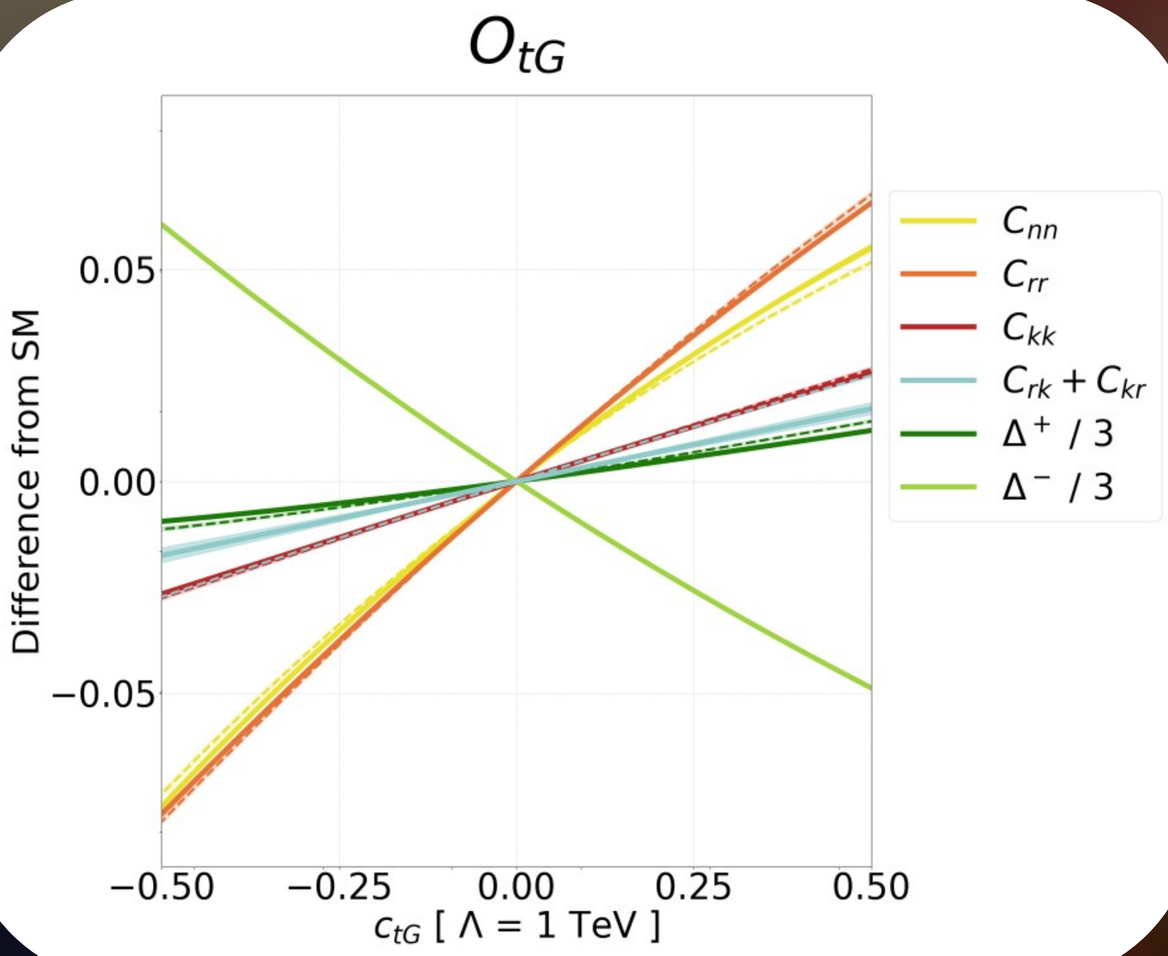
$$\alpha_\ell = 1 - (< 10^{-4}) \quad !$$

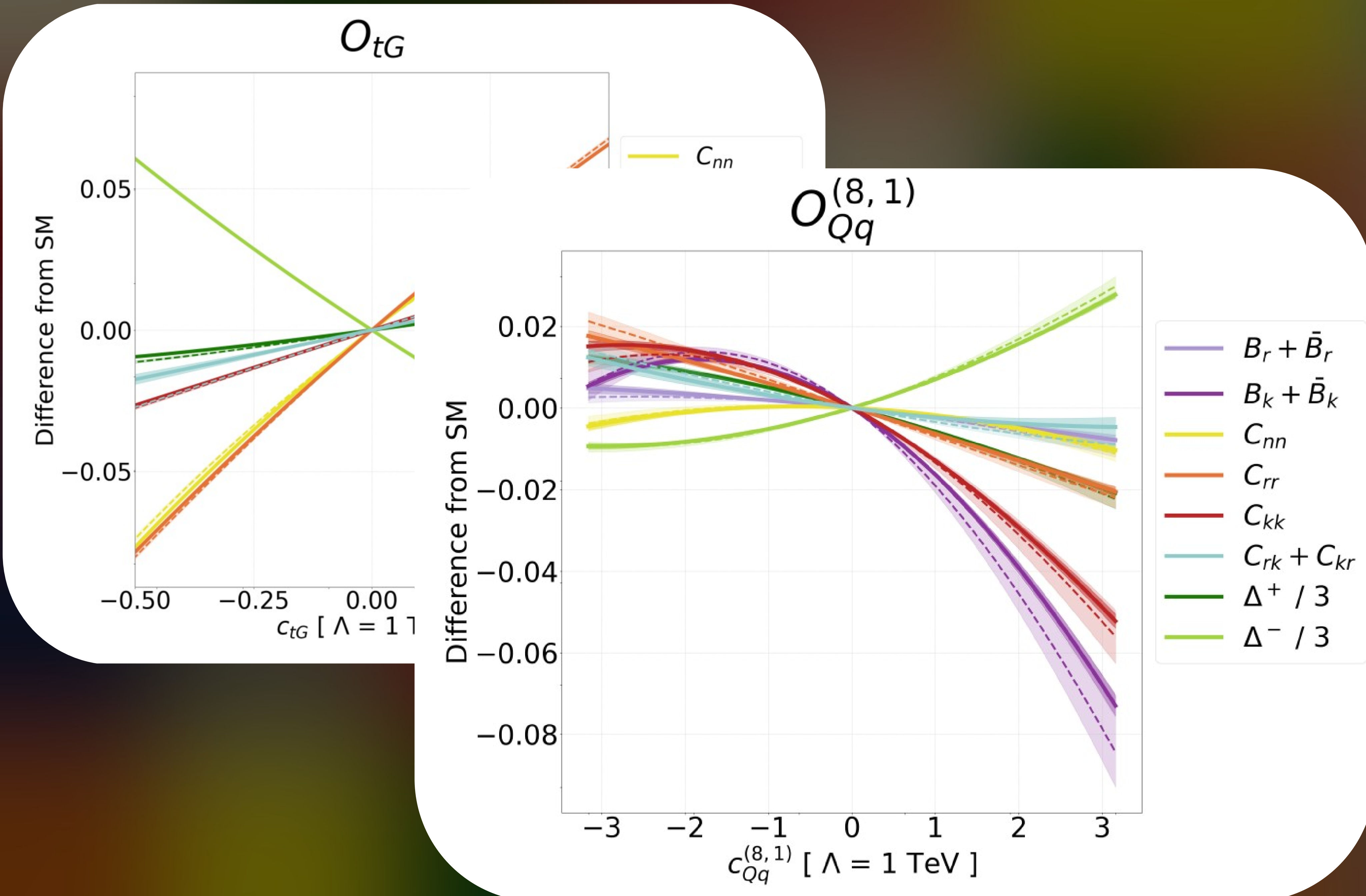
Example: Heavy non-resonant new physics



Usual spin correlation coefficients

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

Example: Heavy non-resonant new physics



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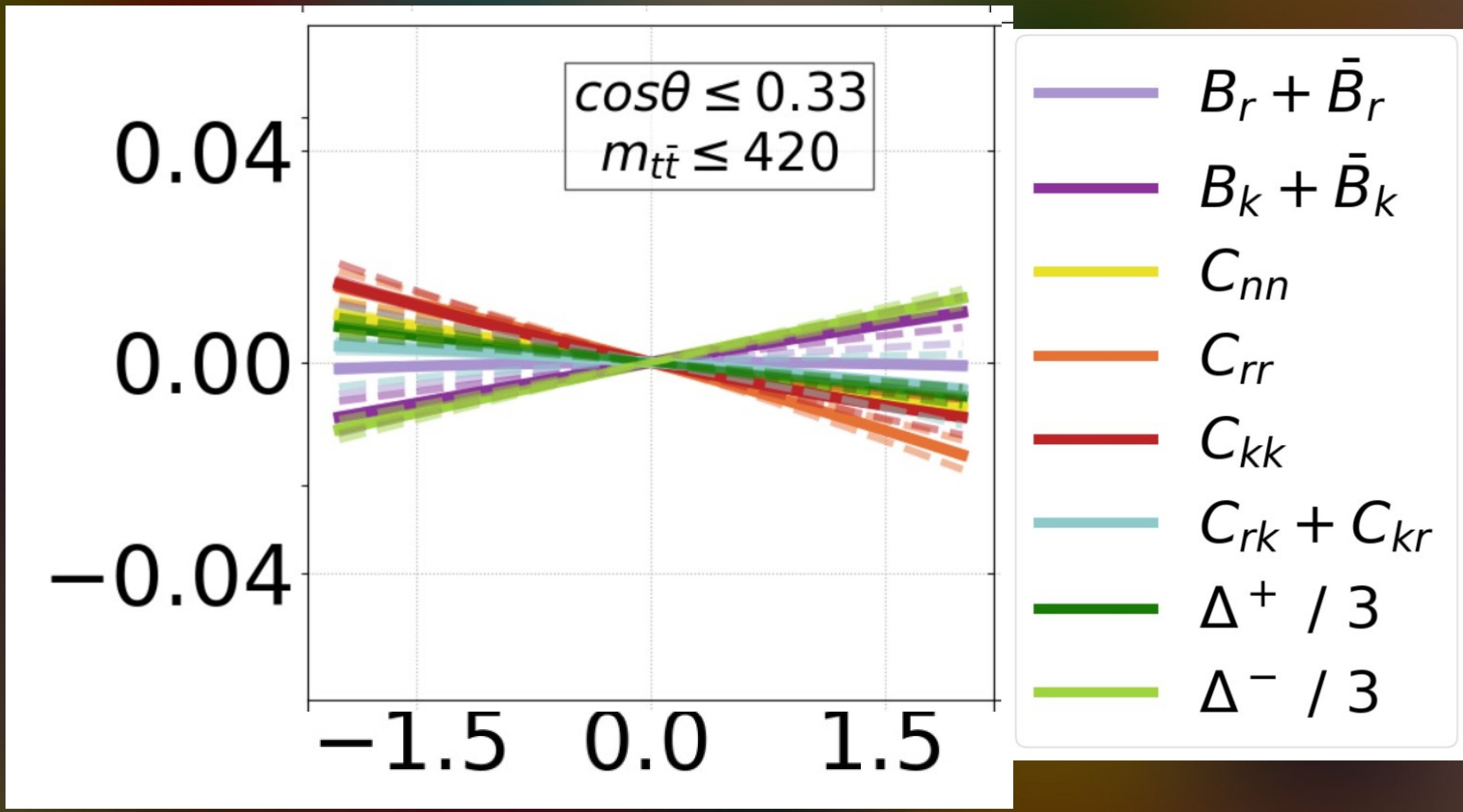
As usual differential measurements enhance sensitivity

O_{tq}^{8}

Difference from SM



c_{tq}^{8} [TeV^{-2}]

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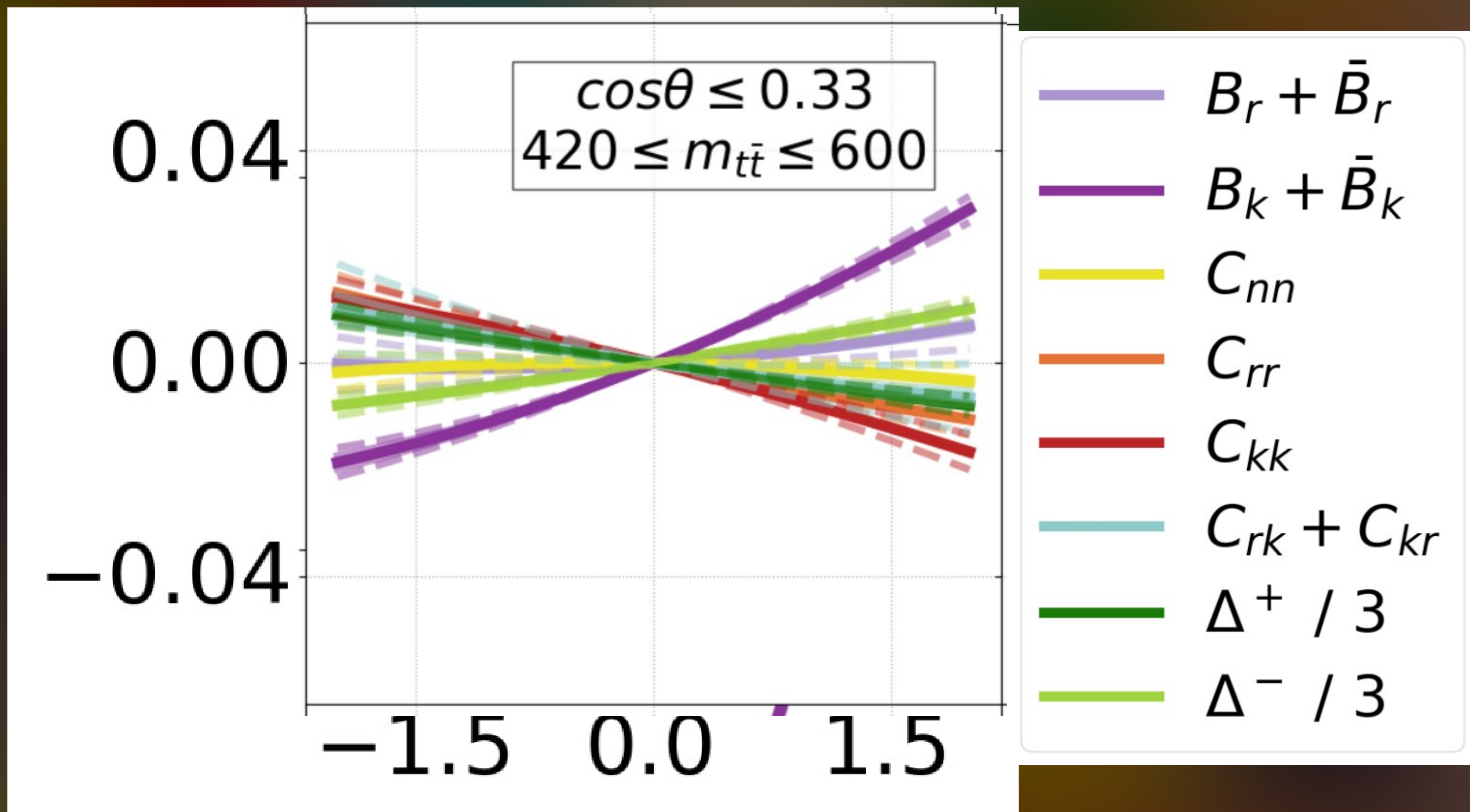

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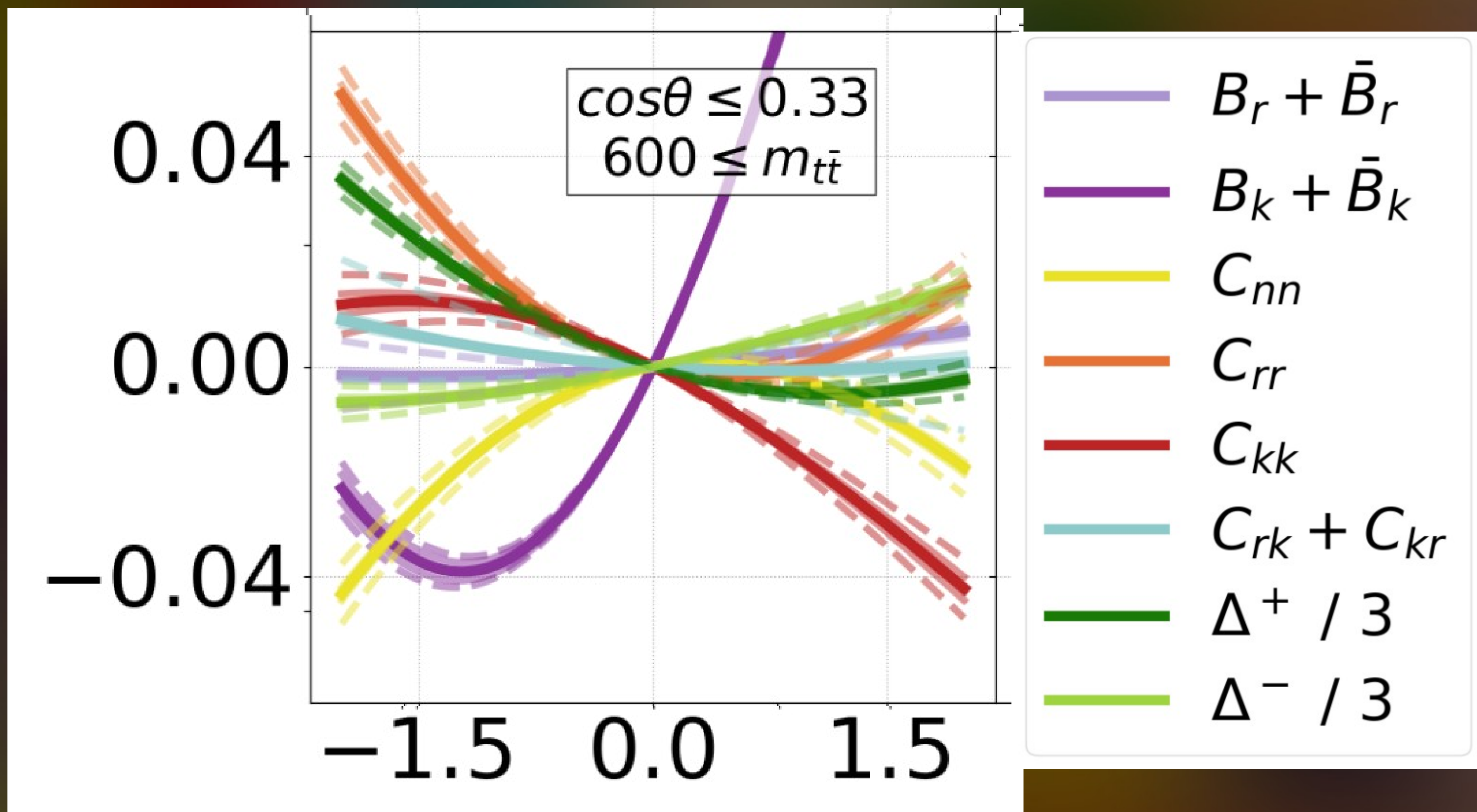

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Operator	CMS [12] $36\,\mathrm{fb}^{-1}$ Inclusive	Run III Projection $300\,\mathrm{fb}^{-1}$ Differential	Current Global Fit
$\mathcal{O}_{tG}$	$[-0.18, 0.18]$	$[-0.03, 0.04]$	$[0.00, 0.11]$
$\mathcal{O}^8_{tu}$	$[-5.8, 3.6]$	$[-1.0, 0.7]$	$[-0.9,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

Thank you :D