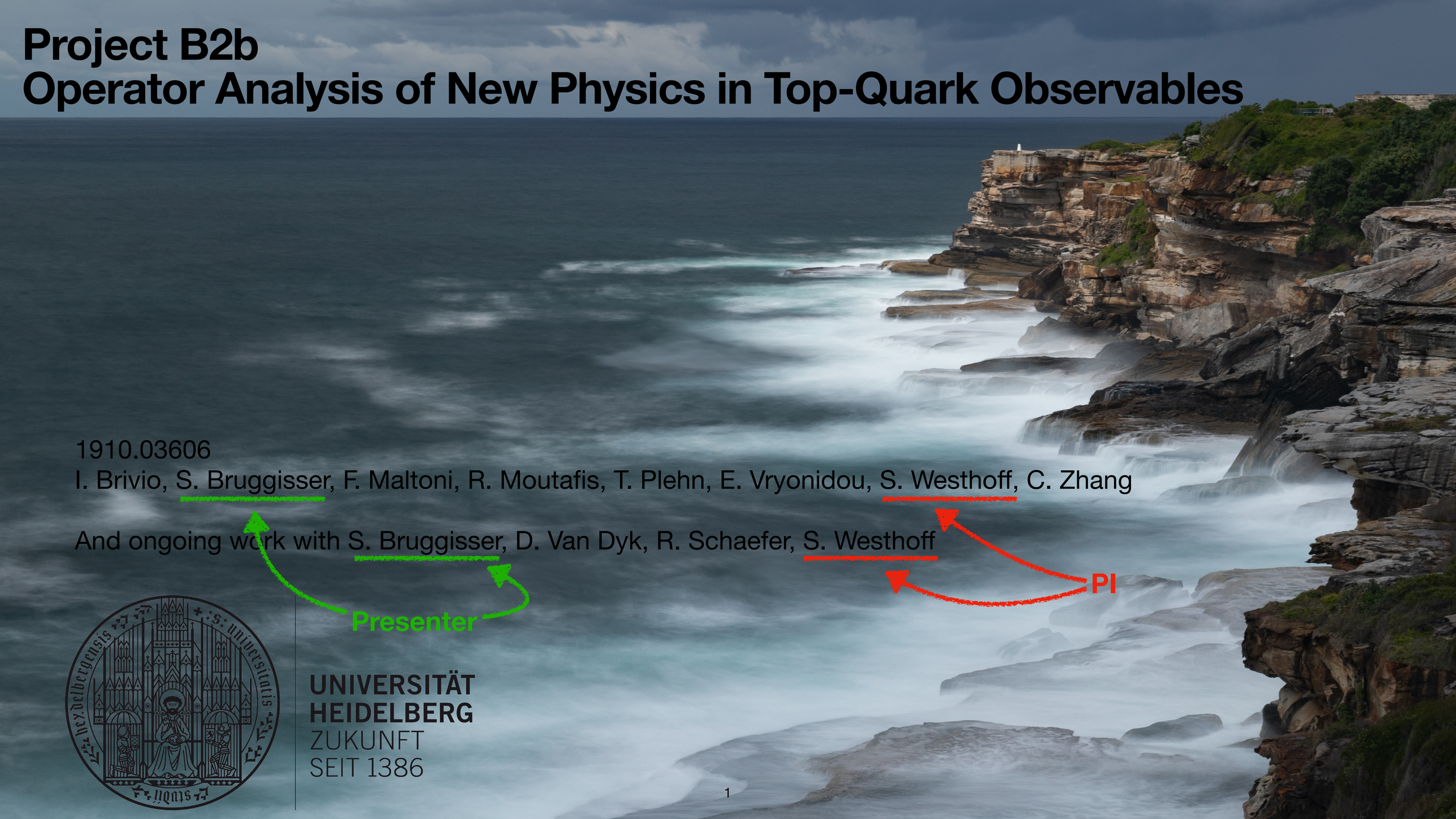
Project B2b
Operator Analysis of New Physics in Top-Quark Observables



1910.03606

I. Brivio, S. Bruggisser, F. Maltoni, R. Moutafis, T. Plehn, E. Vryonidou, S. Westhoff, C. Zhang

And ongoing work with S. Bruggisser, D. Van Dyk, R. Schaefer, S. Westhoff

Presenter

PI

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

Why the Top-Sector?

- Couples the strongest to the Higgs → Top-sector influences Higgs-sector and vice-versa → part of EW symmetry breaking?
- Many BSM models modify the Top-sector: Light Top partners in SUSY/Composite Higgs, etc.
- The LHC is a Top-factory → wealth of data to be explored.

Why now?

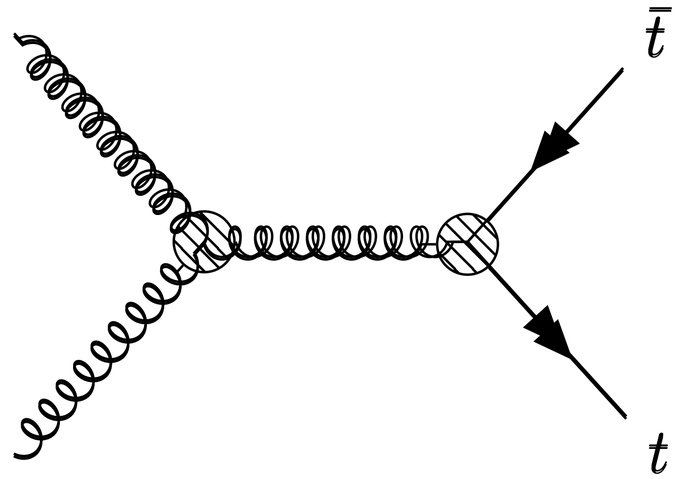
- Existing top-fits:
  - TopFitter collaboration: 1512.03360, 1612.02294, 1901.03164
  - SMEFiT collaboration: 1901.05965

- What we can do:
  - Including ATLAS and CMS 13 TeV differential measurements
  - Studying the impact of NLO predictions
  - Detailed study of degeneracies
  - More honest treatment of theoretical uncertainties
  - Systematic study of the impact of uncertainties

The EFT

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{d=6} + \sum_j \frac{c_j}{\Lambda^4}\mathcal{O}_j^{d=8} + \dots$$

- All relevant (including at least one Top) operators up to d=6
- Assumptions:
  - $U(2)_u \times U(2)_d \times U(2)_Q$ flavour symmetry
  - Light quarks considered massless (Yukawa=0)
  - Diagonal CKM
  - CP conserving
  - Warsaw-basis operators or linear combinations thereof
  - Total of 22 operators considered



The Operators

- Four-fermion vs. Two-fermion
- Gauge structure or Up vs. Down
- Chirality of the top
- …

parameter	$t\bar{t}$	single t	tW	tZ	t decay	$t\bar{t}Z$	$t\bar{t}W$
$C_{Qq}^{1,8}$	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
$C_{Qq}^{3,8}$	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}
C_{tu}^{8}, C_{td}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
$C_{Qq}^{1,1}$	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{Qq}^{3,1}$	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-2}	–	Λ^{-2}	Λ^{-2}	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
C_{tu}^{1}, C_{td}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{Qu}^{8}, C_{Qd}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	–
C_{tq}^{8}	Λ^{-2}	–	–	–	–	Λ^{-2}	Λ^{-2}
C_{Qu}^{1}, C_{Qd}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	–
C_{tq}^{1}	Λ^{-4} $[\Lambda^{-2}]$	–	–	–	–	Λ^{-4} $[\Lambda^{-2}]$	Λ^{-4} $[\Lambda^{-2}]$
$C_{\phi Q}^{-}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi Q}^{3}$	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–
$C_{\phi t}$	–	–	–	Λ^{-2}	–	Λ^{-2}	–
$C_{\phi tb}$	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tZ}	–	–	–	Λ^{-2}	–	Λ^{-2}	–
C_{tW}	–	Λ^{-2}	Λ^{-2}	Λ^{-2}	Λ^{-2}	–	–
C_{bW}	–	Λ^{-4}	Λ^{-4}	Λ^{-4}	Λ^{-4}	–	–
C_{tG}	Λ^{-2}	$[\Lambda^{-2}]$	Λ^{-2}	–	$[\Lambda^{-2}]$	Λ^{-2}	Λ^{-2}

Event Kinematics

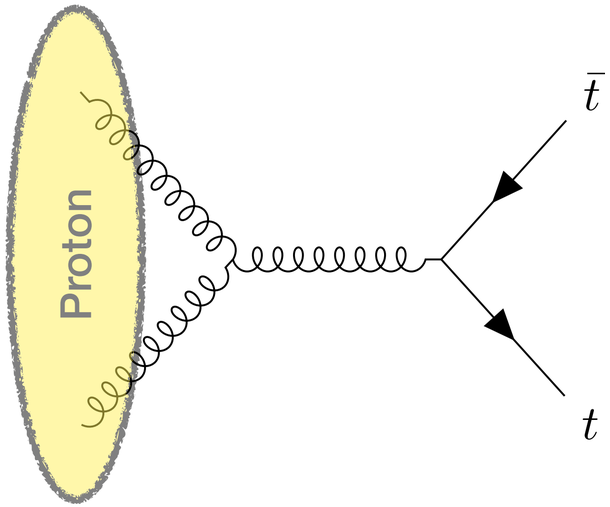
Or Rates vs. Tails

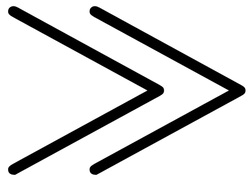
$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu} \qquad O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$

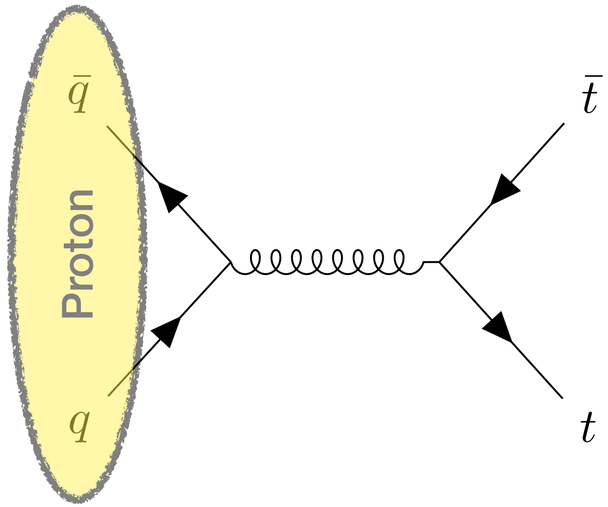
$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

Very small

Very large
For high bins







Event Kinematics

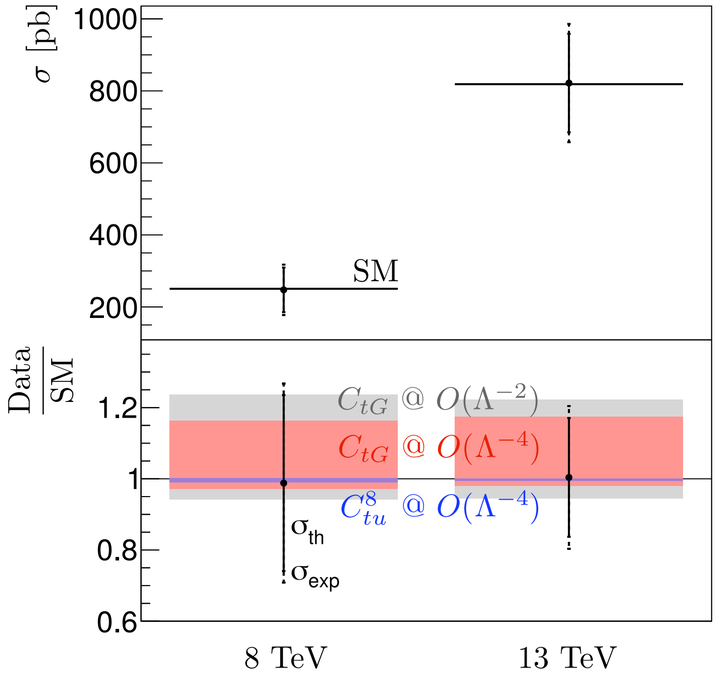
Or Rates vs. Tails

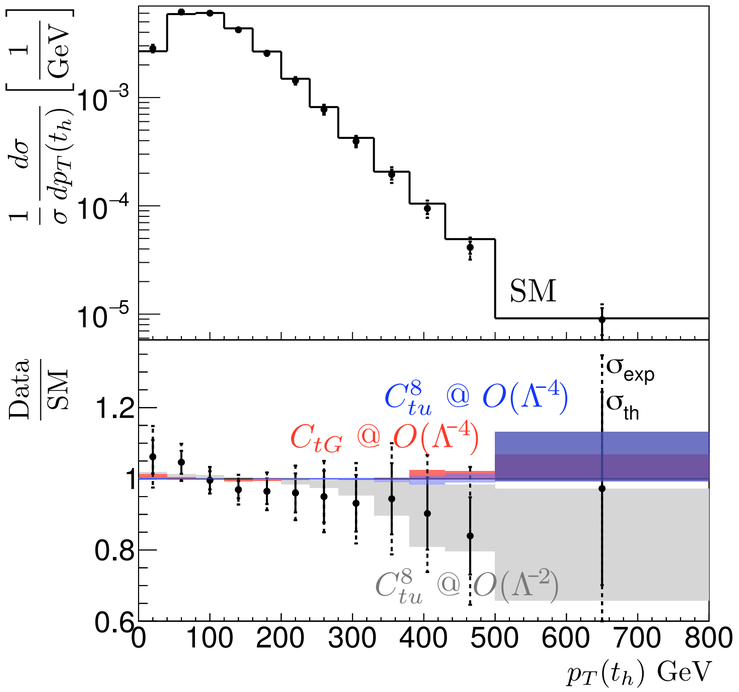
$$O_{tG} = C_{tG}(\bar{q}_3\sigma^{\mu\nu}T^A u_3)\tilde{\phi}G^A_{\mu\nu} \qquad O^8_{tu} = C^8_{tu}(\bar{u}_3\gamma^\mu T^A u_3)(\bar{u}_i\gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

Very small

Very large
For high bins





Up vs. Down

And Gauge Structure

$$O_{Qq}^{1,8} = C_{Qq}^{1,8}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i)$$

$$O_{Qq}^{3,8} = C_{Qq}^{3,8}(\bar{q}_3\gamma^\mu T^A \tau^I q_3)(\bar{q}_i\gamma_\mu T^A \tau^I q_i)$$

SU(2) Singlet
Sensitive to u+d initial state

SU(2) Tripplet
Sensitive to u-d initial state

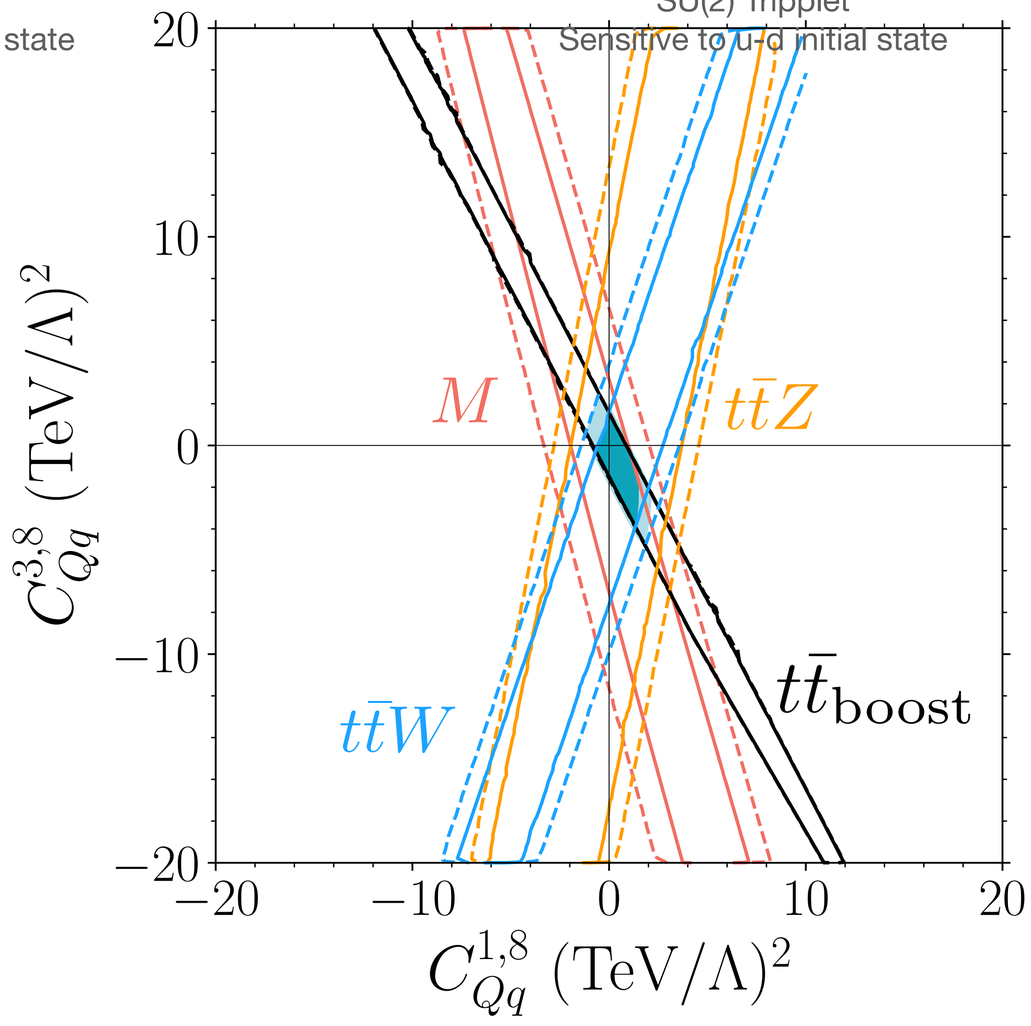
$$r(x) = \frac{f_u(x) f_{\bar{u}}(s/xS)}{f_d(x) f_{\bar{d}}(s/xS)}$$

Valence quark maximum

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP}\left[\quad 3 C_{Qq}^{1,8} + \quad 1 C_{Qq}^{3,8}\right]$$

Probe different r(x) in boosted regime

Include ttZ and ttW measurements



Chirality
Or Left vs. Right

$$O_{tq}^{8} = C_{tq}^{8}(\bar{u}_3\gamma^\mu T^A u_3)(\bar{q}_i\gamma_\mu T^A q_i)$$

Right handed Top
in final state

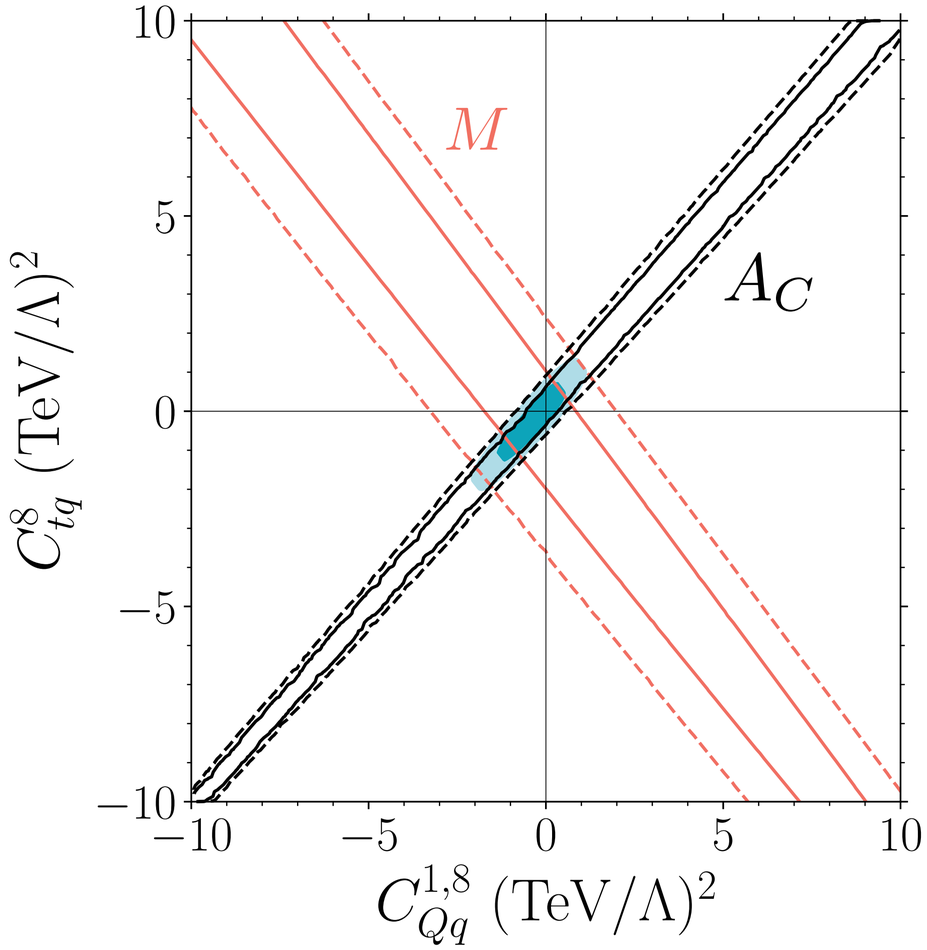
$$O_{Qq}^{1,8} = C_{Qq}^{1,8}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{q}_i\gamma_\mu T^A q_i)$$

Left handed Top
in final state

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(\frac{C_{tq}^{8}}{\Lambda^2} + \frac{C_{Qq}^{1,8}}{\Lambda^2}\right)$$

$$A_C = \frac{\sigma\left(\Delta|y| > 0\right) - \sigma\left(\Delta|y| > 0\right)}{\sigma\left(\Delta|y| > 0\right) + \sigma\left(\Delta|y| > 0\right)} \quad \text{with} \quad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

$$A_C = \frac{\sigma_{t\bar{t}}^{SM,A} + \sigma_{t\bar{t}}^{NP,A}\left(\frac{C_{Qq}^{1,8}}{\Lambda^2} - \frac{C_{tq}^{8}}{\Lambda^2}\right)}{\sigma_{t\bar{t}}}$$



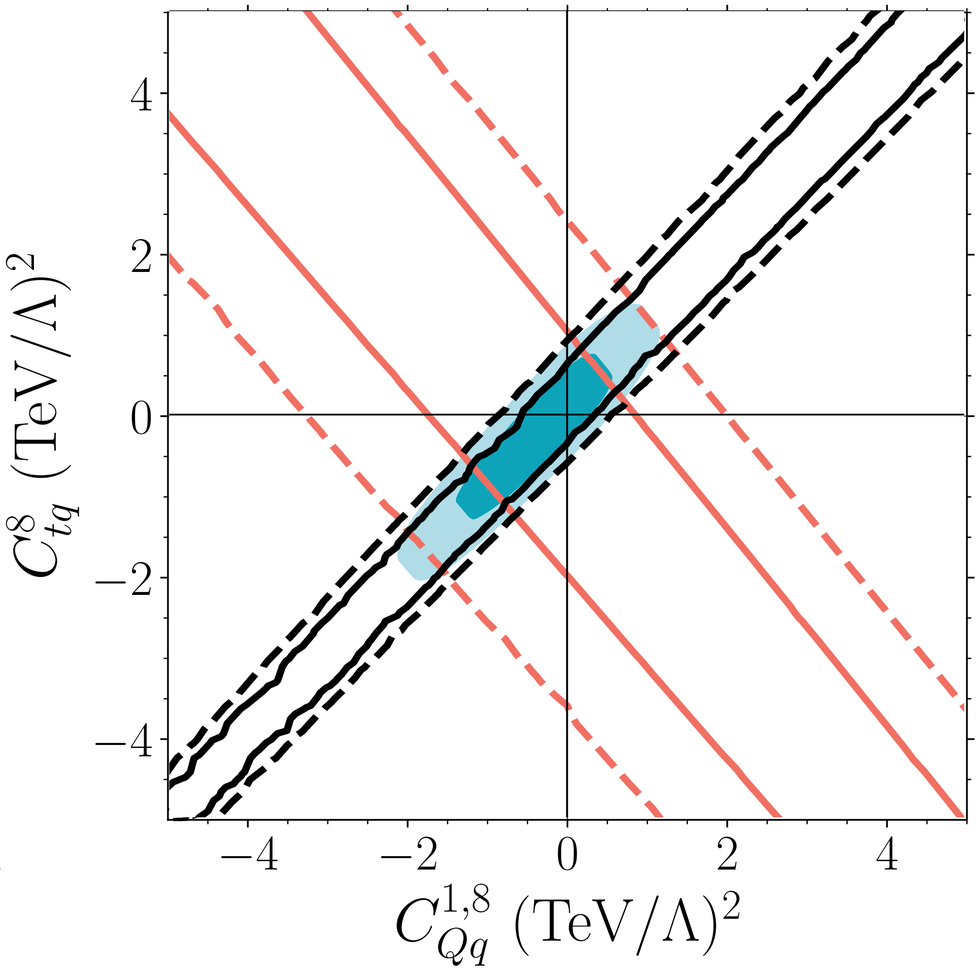
NLO Corrections can also help to resolve this degeneracy

Quadratic Terms

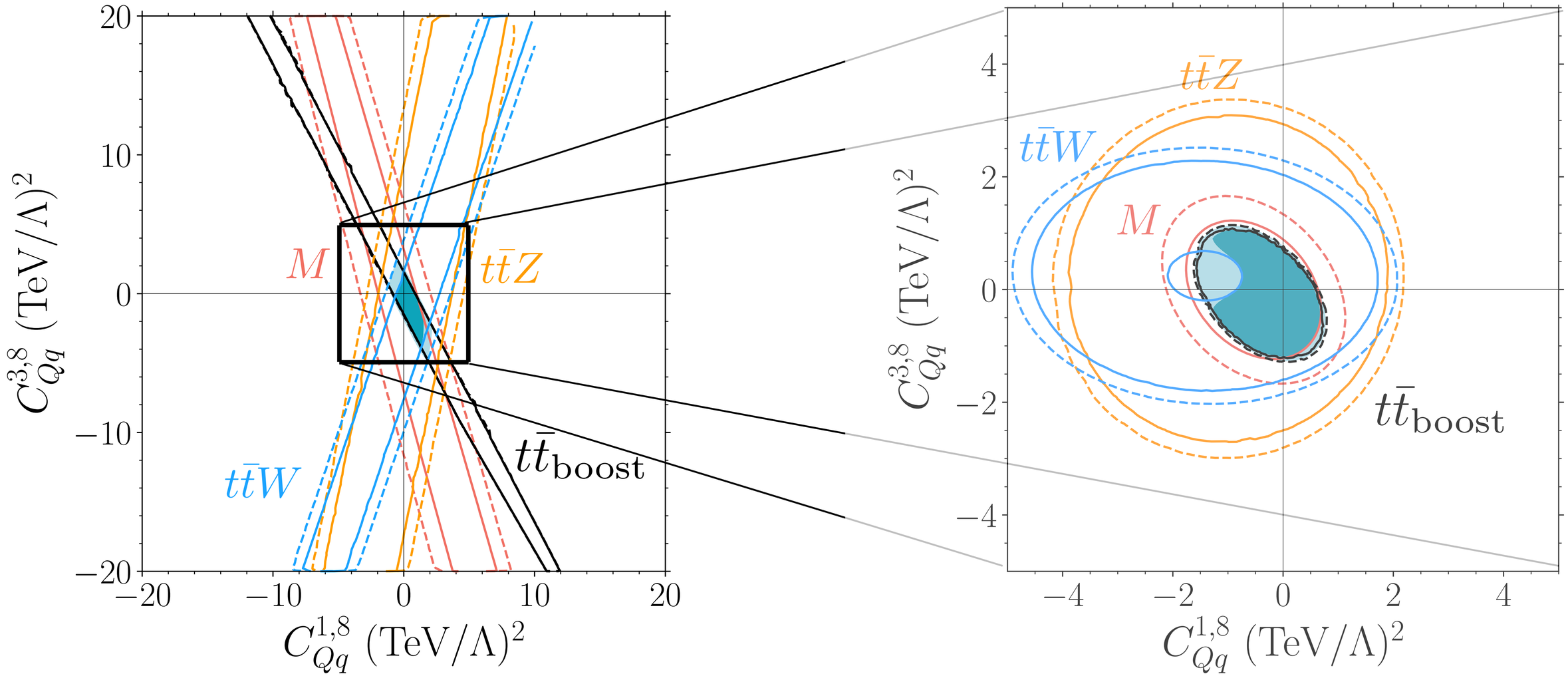
$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

$$\sigma_{t\bar{t}} = \sigma_{t\bar{t}}^{SM} + \sigma_{t\bar{t}}^{NP,int}\left(C_{tq}^{8} + C_{Qq}^{1,8}\right) + \sigma_{t\bar{t}}^{NP,quad,1}\left(\left(C_{tq}^{8}\right)^2 + \left(C_{Qq}^{1,8}\right)^2\right) + \dots$$

$$A_C = \frac{\sigma_{t\bar{t}}^{SM,A} + \sigma_{t\bar{t}}^{NP,A}\left(C_{Qq}^{1,8} - C_{tq}^{8}\right) + \sigma_{t\bar{t}}^{NP^2,A}\left(\left(C_{Qq}^{1,8}\right)^2 - \left(C_{tq}^{8}\right)^2\right)}{\sigma_{t\bar{t}}}$$

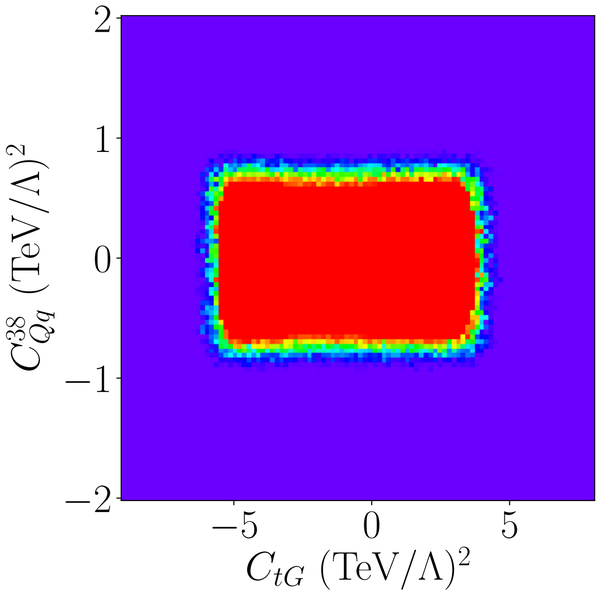


Quadratic Terms

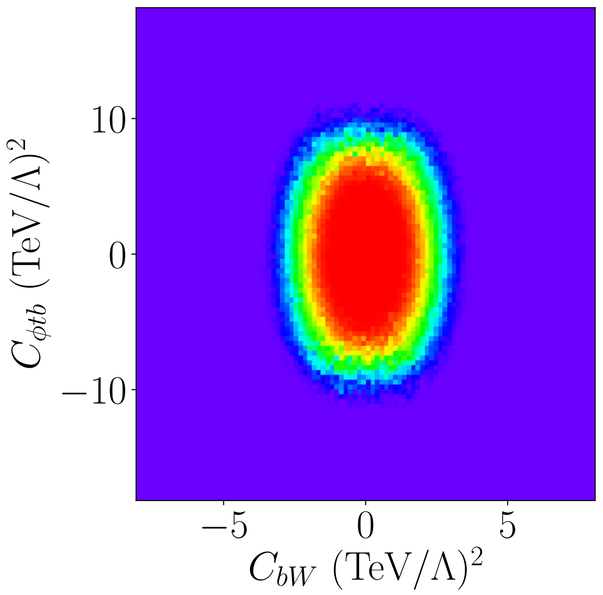


Single Top

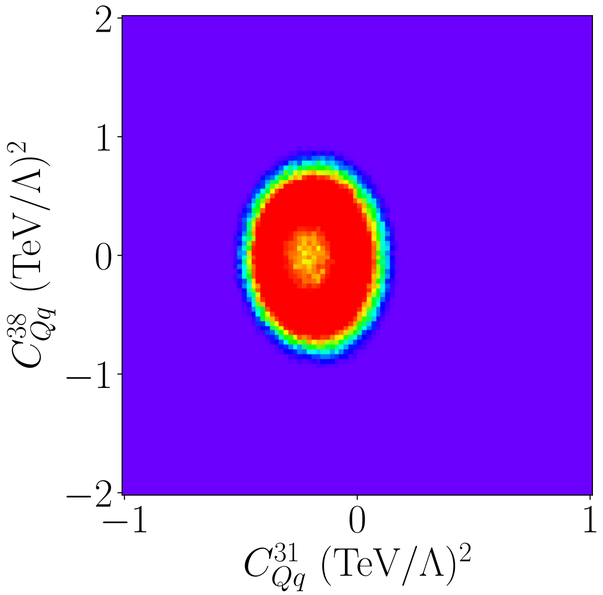
Some aspects



- Constrained by independent measurements

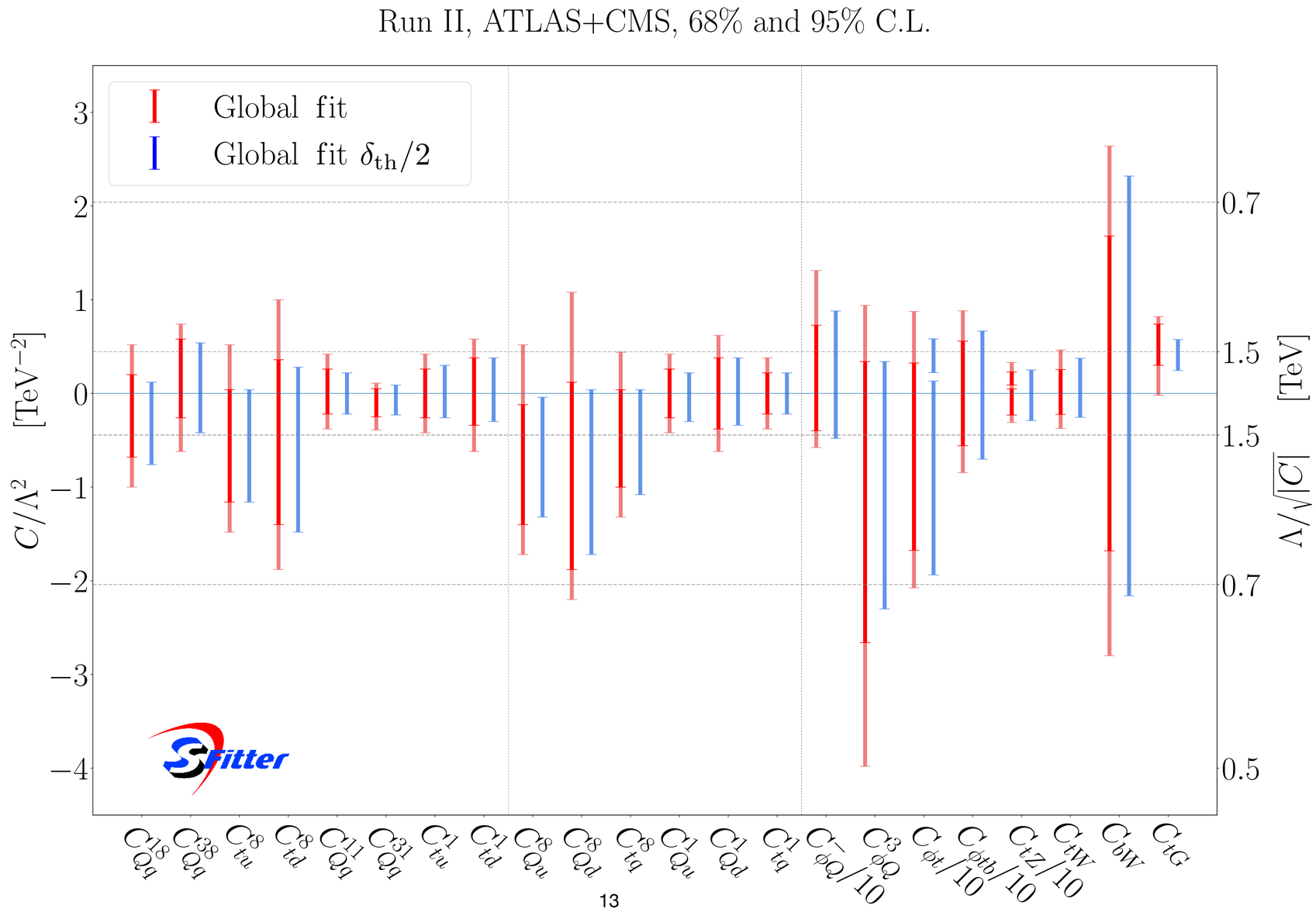


- Both contribute quadratically



- One linear and one quadratic contribution

Results


Run II, ATLAS+CMS, 68% and 95% C.L.
Global fit
Global fit $\delta_{\rm th}/2$
C/Λ^2 [TeV^{-2}]
$\Lambda/\sqrt{|C|}$ [TeV]
3
2
1
0
−1
−2
−3
−4
0.7
1.5
1.5
0.7
0.5
SFitter
C_{Qq}^{18}
C_{Qq}^{38}
C_{tu}^{8}
C_{td}^{8}
C_{Qq}^{11}
C_{Qq}^{31}
C_{tu}^{1}
C_{td}^{1}
C_{Qu}^{8}
C_{Qd}^{8}
C_{tq}^{8}
C_{Qu}^{1}
C_{Qd}^{1}
C_{tq}^{1}
$C_{\phi Q}^{-}/10$
$C_{\phi Q}^{3}/10$
$C_{\phi t}/10$
$C_{\phi tb}/10$
$C_{tZ}/10$
C_{tW}
C_{bW}
C_{tG}

New Directions

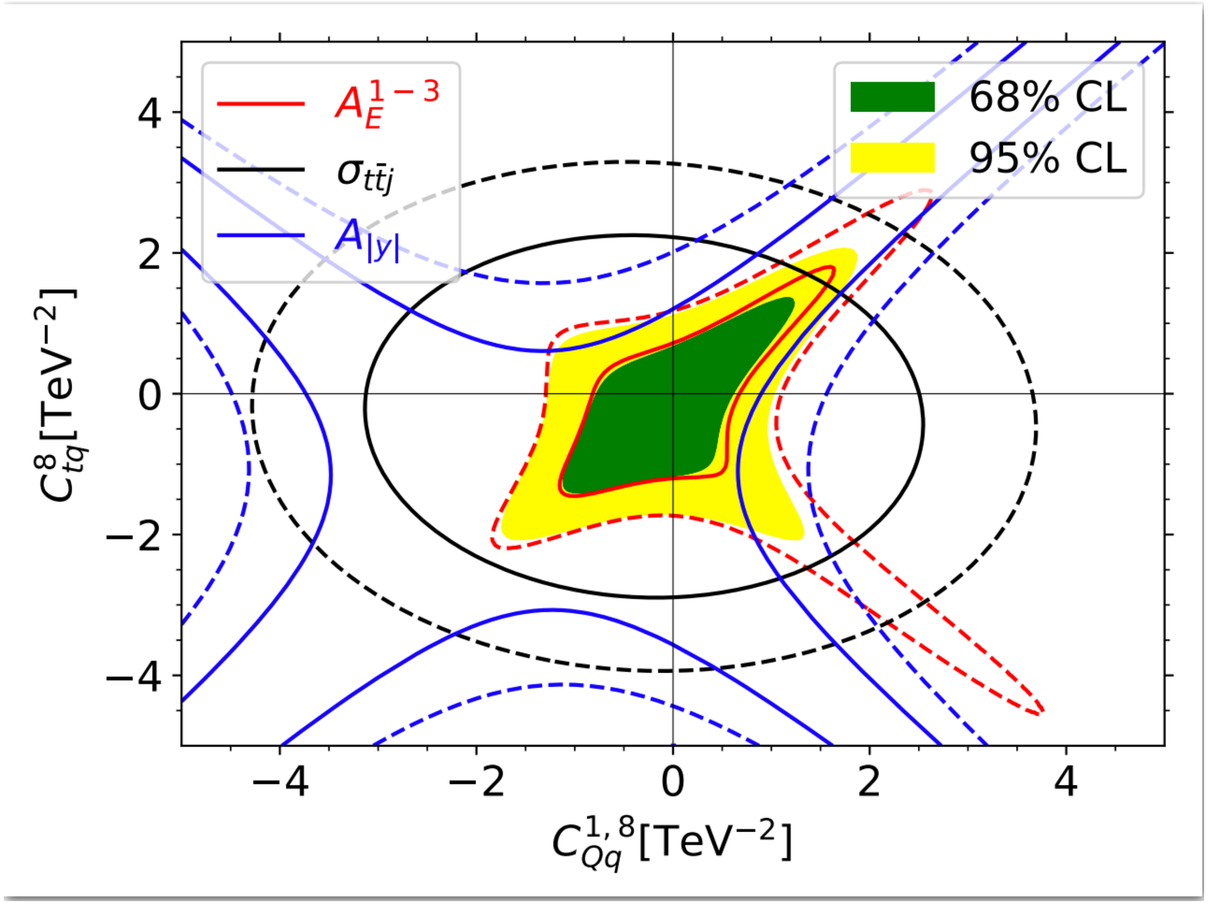
New Observables (e.g. Energy asymmetry)

$$A_E(\theta_j) = \frac{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) - \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}{\sigma_{t\bar{t}j}(\theta_j, \Delta E > 0) + \sigma_{t\bar{t}j}(\theta_j, \Delta E < 0)}$$

$$\Delta E = E_t - E_{\bar{t}}$$

	$A_{\lvert y\rvert}$	A_E
Order	NLO	LO
Process	tt	ttj

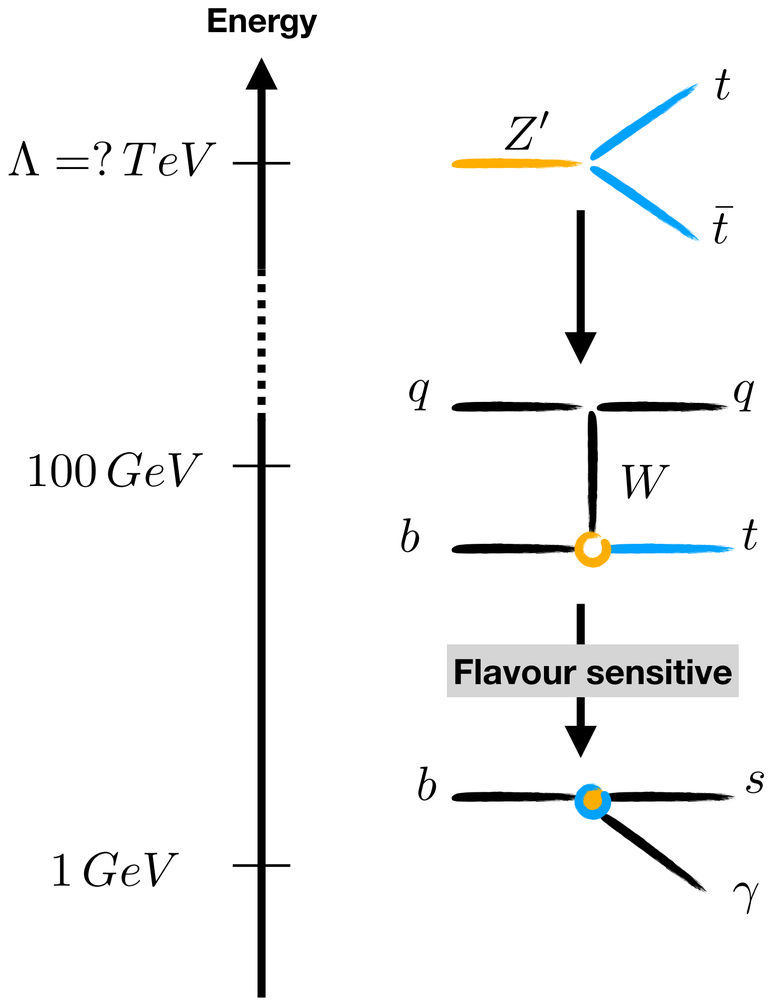
Resolve new directions in parameter space!

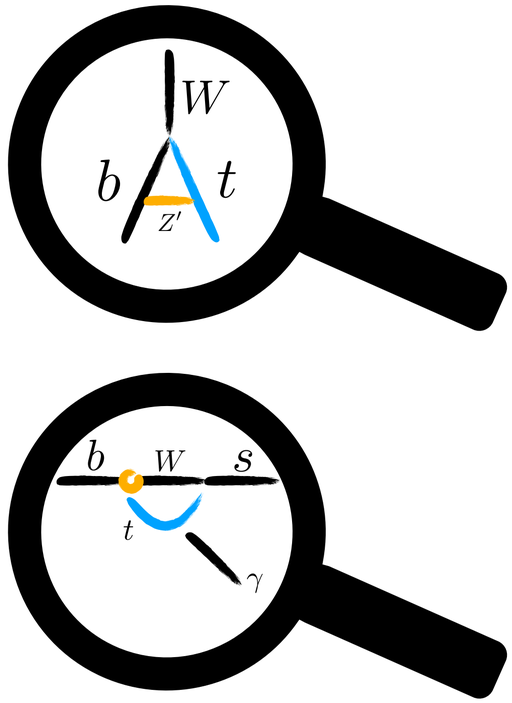


Basan, Berta, Masetti, Vryonidou, Westhoff: 2001.07225

New Directions

Flavour (Work in Progress)



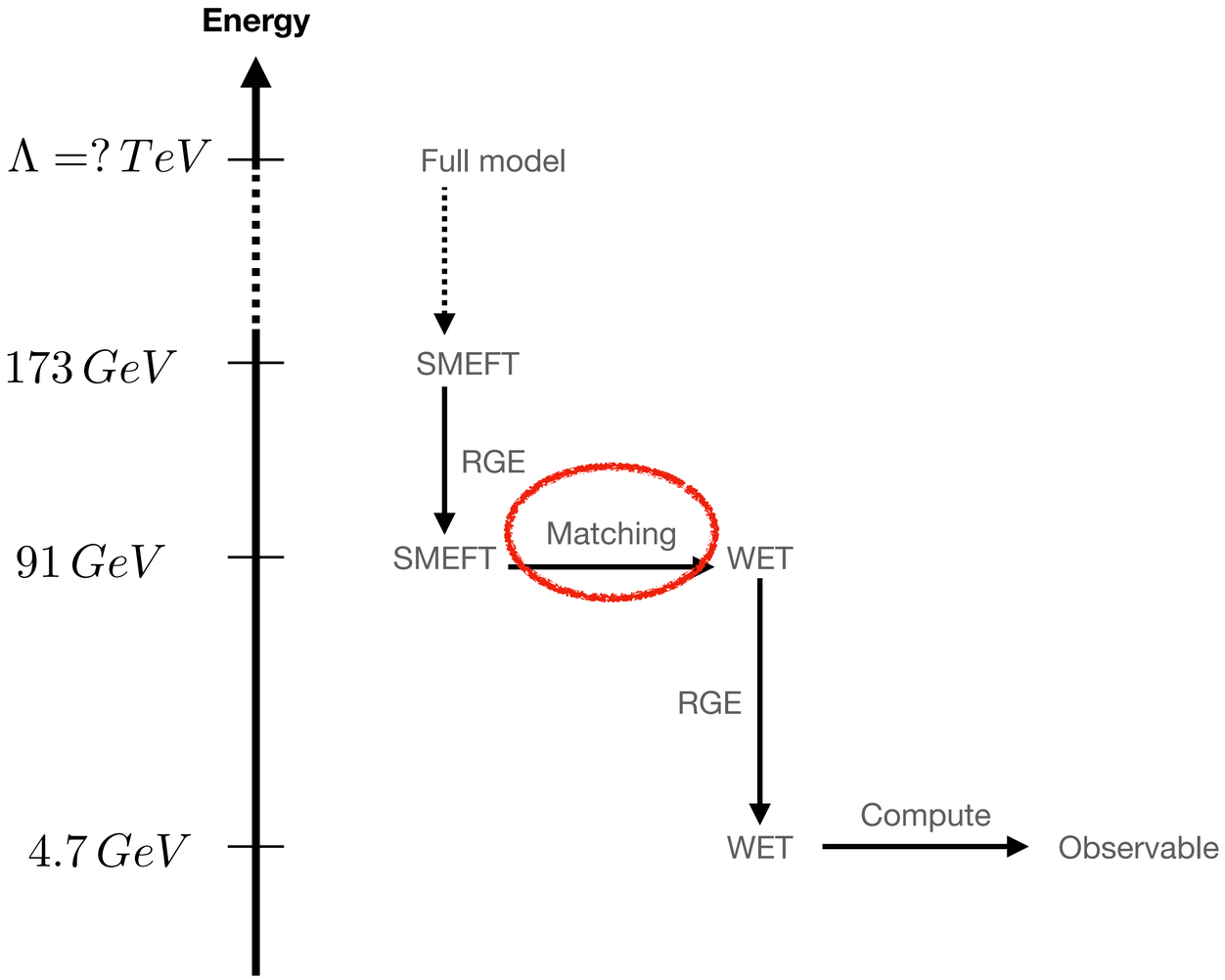


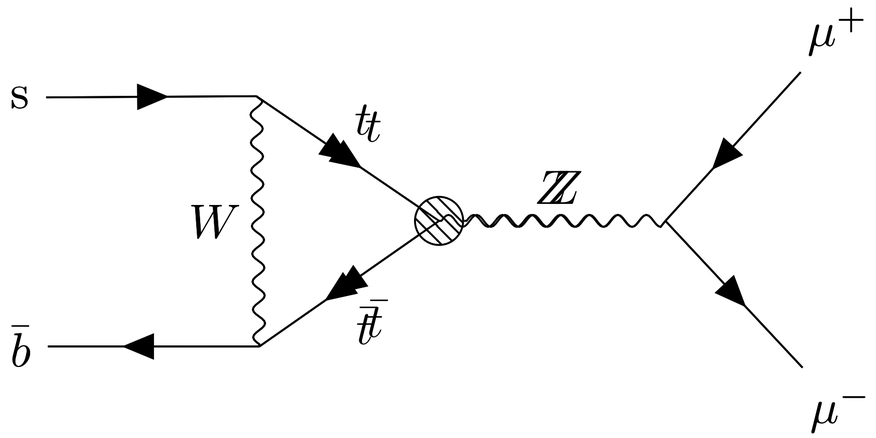
$$^{\ddagger}\mathcal{O}_{uW}^{ij} = \left(\bar{q}^i \sigma^{\mu\nu} u^j\right) \tau^I \tilde{\phi} W_{\mu\nu}^I$$

MFV	C_{uW}^{ij}
ii	0
33	$(a + y_t^2 b) y_t$
kj	0
$k3$	$c y_b^2 y_t V_{kb} V_{tb}^*$

New Directions

Flavour (Work in Progress)



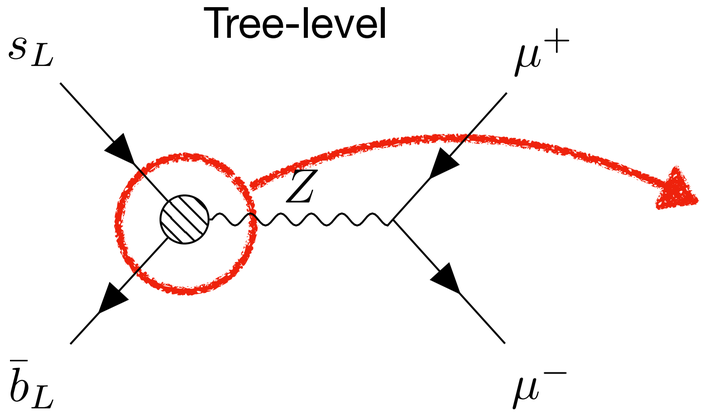


$$\left[\mathcal{O}^1_{\phi q}\right]_{ij} = \left(\phi^\dagger\, i \overleftrightarrow{D_\mu}\, \phi\right)(\bar{q}_i \gamma^\mu q_j)$$

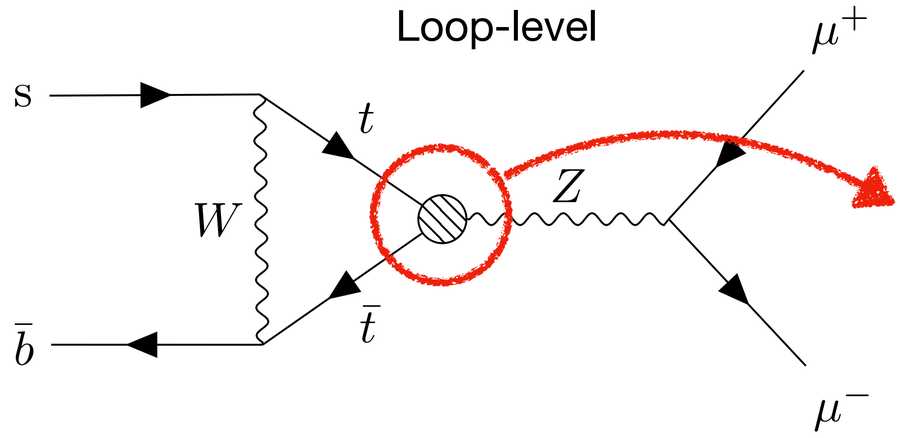
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

New Directions

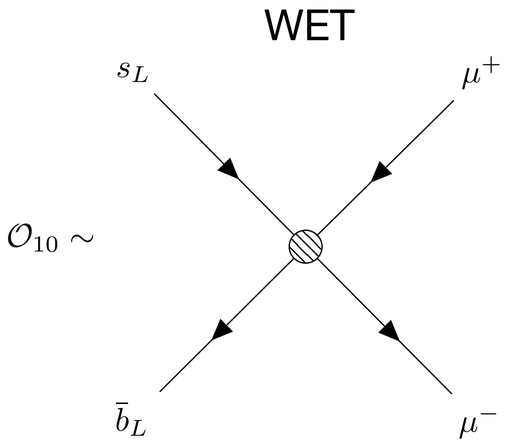
Flavour (Work in Progress)

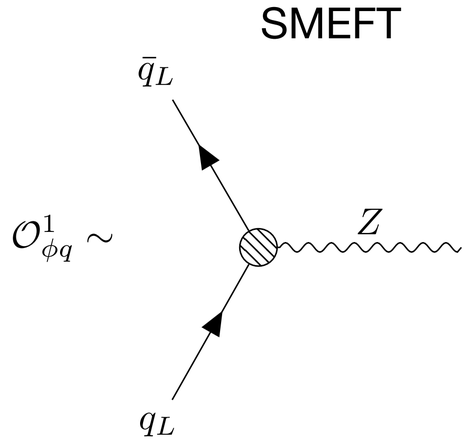


$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$





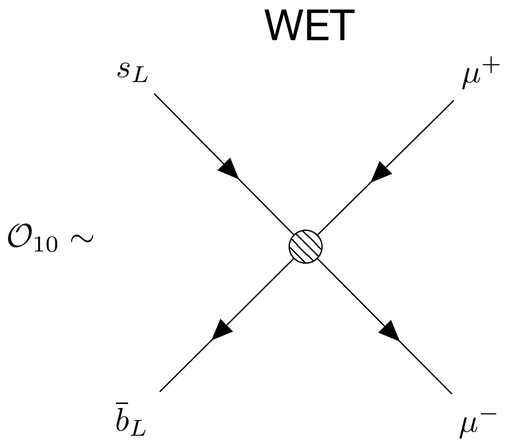
$$\mathcal{C}_{10} \quad b$$

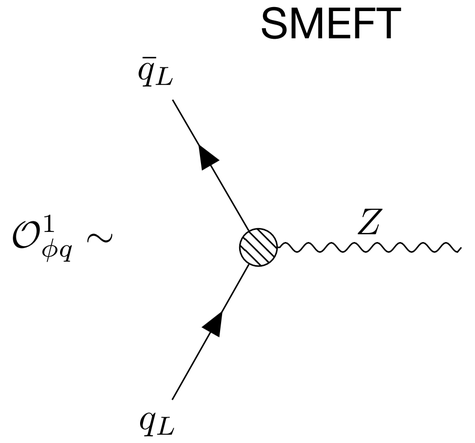
$$\mathcal{C}^1_{\phi q} \begin{cases} \text{Tree-level} & b \\ \text{Loop-level} & a + y_t^2 b \end{cases}$$

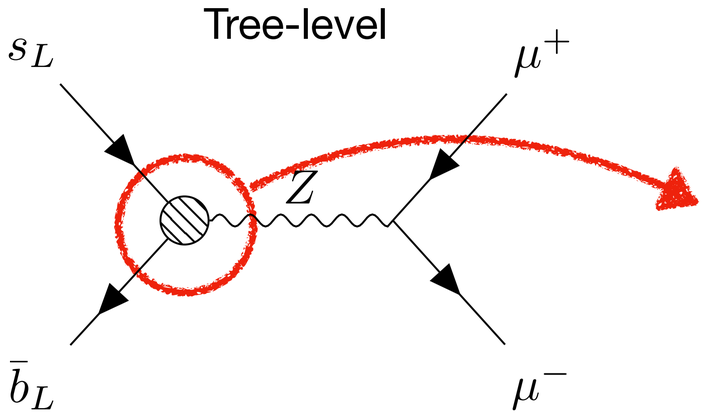
MFV	$\mathcal{C}^1_{\phi q}$
ii	a
33	$(a + y_t^2 b) y_t$

New Directions

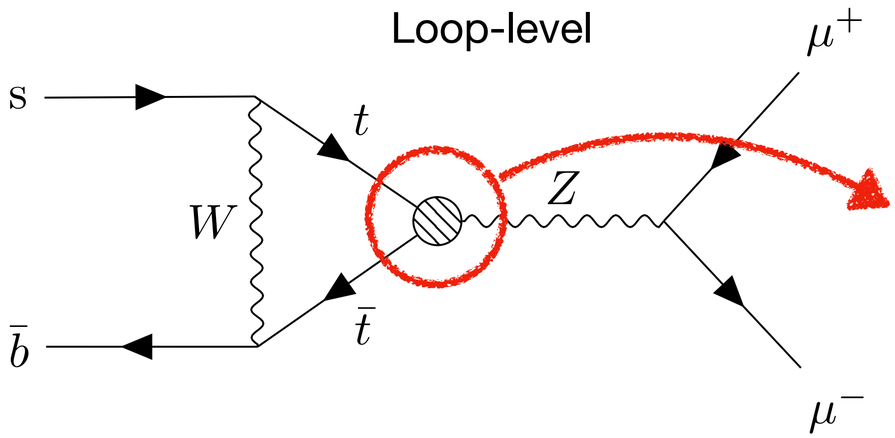
Flavour (Work in Progress)







$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{ij} V^*_{is} V_{jb} \left(\bar{s}_L \gamma_\mu b_L\right) Z^\mu$$



$$\sim \left[\mathcal{C}^1_{\phi q}\right]_{33} V^*_{ts} V_{tb} \left(\bar{t}_L \gamma_\mu t_L\right) Z^\mu$$

Matching & Running	$\mathcal{C}_{10}$
$a^1_{\phi q}$	0.1
$b^1_{\phi q}$	24.73

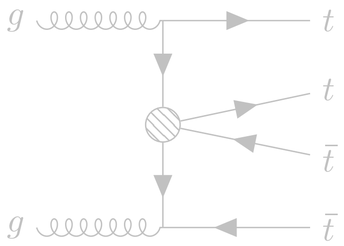
Conclusion

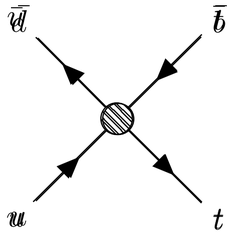
- Now is the time for Top-BSM
- Resolve degeneracies with different measurements
- Theorists can achieve allot by lowering the uncertainties
- Still opportunities for new observables
- Interesting playground for connecting high- and low-energy physics

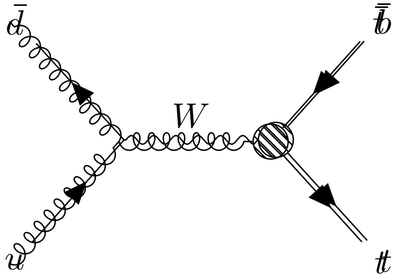
The Operators

For full list see 1910.03606

	4 heavy fermions	2 heavy - 2 light fermions	2 heavy fermions - boson
Examples	$C_{qu}^{8(3333)}(\bar{q}_3\gamma^\mu T^A q_3)(\bar{u}_3\gamma_\mu T^A u_3)$	$Oqt8 = C_{qu}^{8(ii33)}(\bar{q}_i\gamma^\mu T^A q_i)(\bar{u}_3\gamma_\mu T^A u_3)$ $Oqt1 = C_{qu}^{1(ii33)}(\bar{q}_i\gamma^\mu q_i)(\bar{u}_3\gamma_\mu u_3)$	$OtG = \mathrm{Re}\left\{C_{uG}^{(33)}\right\}(\bar{q}_3\sigma^{\mu\nu}T^A u_3)\tilde{\phi}G^A_{\mu\nu}$ $OtW = \mathrm{Re}\left\{C_{uW}^{(33)}\right\}(\bar{q}_3\sigma^{\mu\nu}\tau^{\mathcal{I}} u_3)\tilde{\phi}W^{\mathcal{I}}_{\mu\nu}$
Processes	$t\bar{t}t\bar{t}$ $t\bar{t}b\bar{b}$	$t\bar{t}$ production single t production tZ $t\bar{t}Z/W/H$	$t\bar{t}$ production single t production tZ/W $t\bar{t}Z/W/H$







Event Kinematics

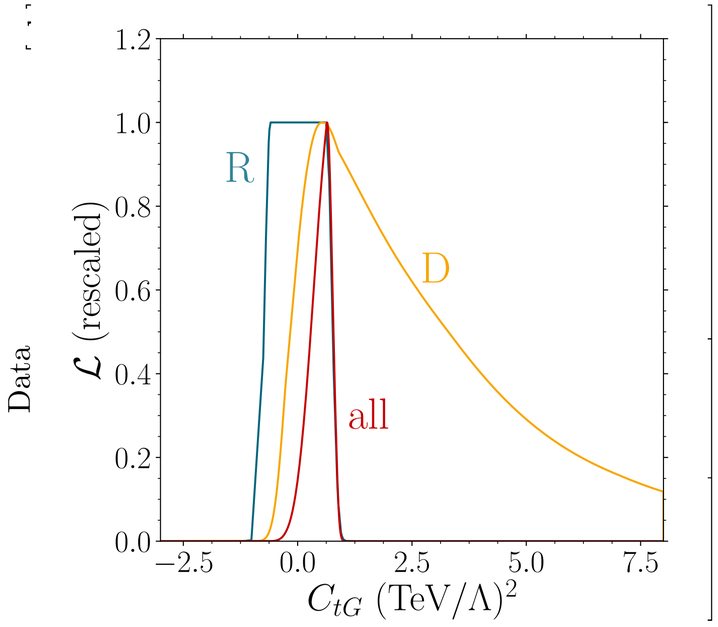
Or Rates vs. Tails

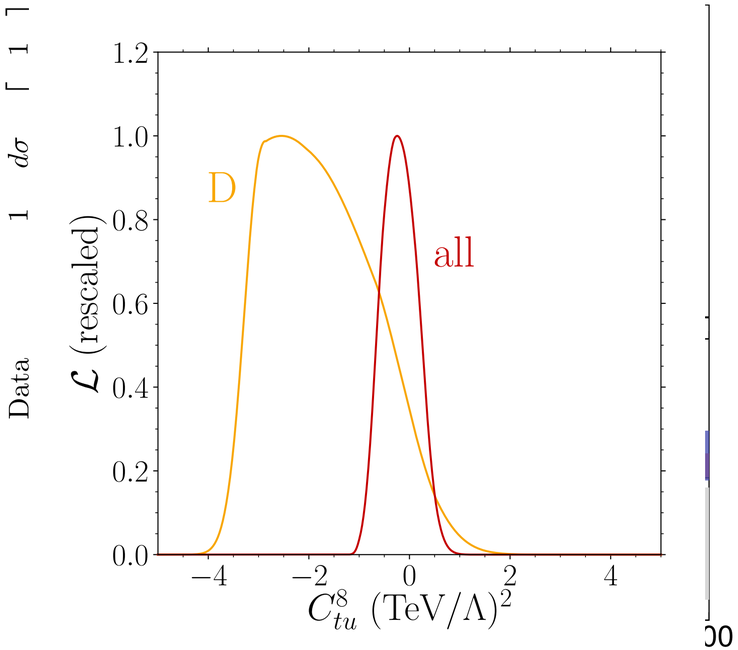
$$O_{tG} = C_{tG}(\bar{q}_3 \sigma^{\mu\nu} T^A u_3)\tilde{\phi} G^A_{\mu\nu} \qquad O^8_{tu} = C^8_{tu}(\bar{u}_3 \gamma^\mu T^A u_3)(\bar{u}_i \gamma_\mu T^A u_i)$$

$$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}} \approx \frac{\sigma_{SM}(m_{t\bar{t}})}{\sigma_{SM}(2m_t)}\left(1 + \mathcal{O}(1)\frac{C_{tG}}{\Lambda^2} + \mathcal{O}(m^2_{t\bar{t}})\frac{|C_{tG}|^2}{\Lambda^4} + \mathcal{O}(m^2_{t\bar{t}})\frac{C^8_{tu}}{\Lambda^2} + \mathcal{O}(m^4_{t\bar{t}})\frac{|C^8_{tu}|^2}{\Lambda^4}\right)$$

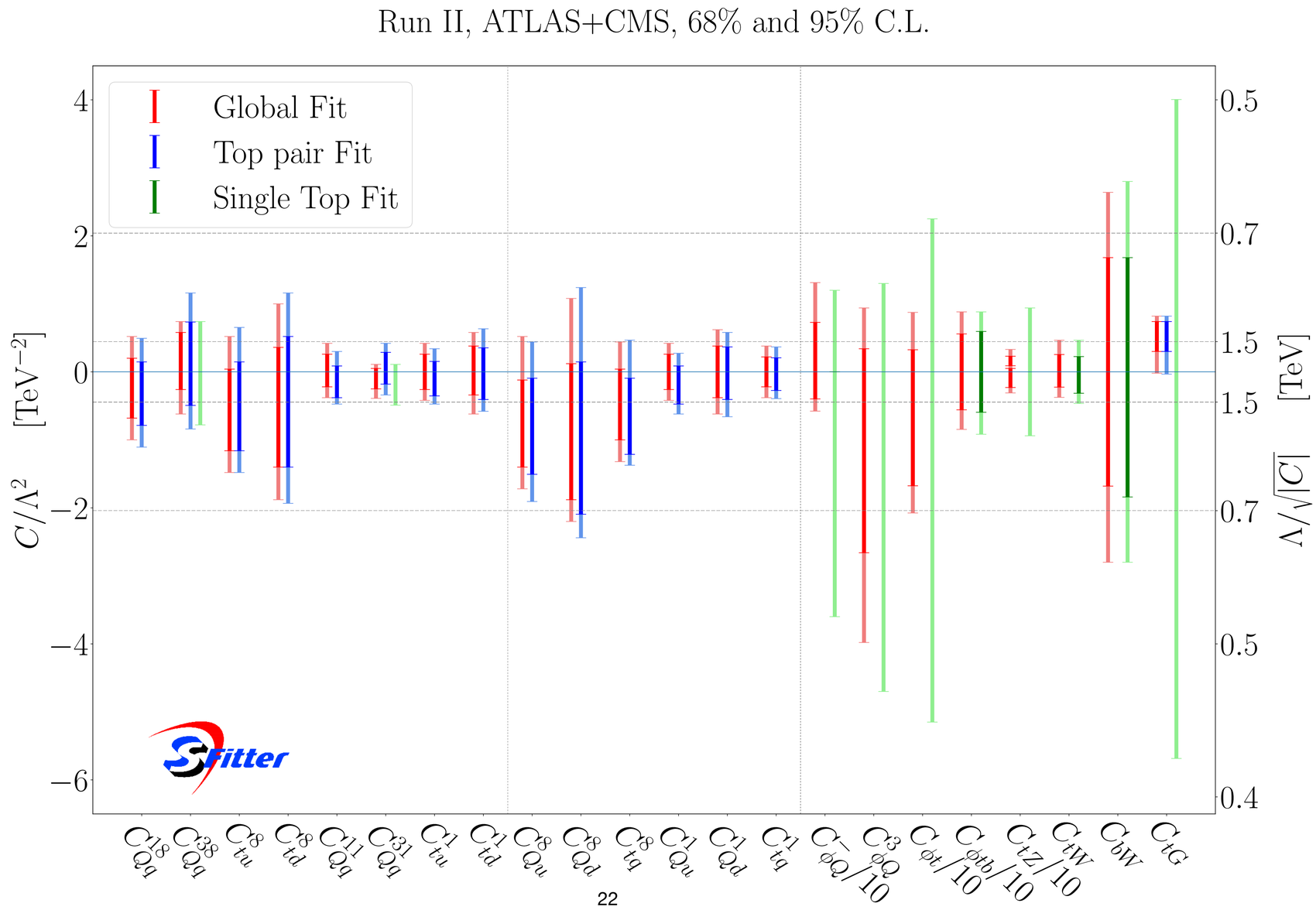
Very small

Very large
For high bins





Results


Run II, ATLAS+CMS, 68% and 95% C.L.
Global Fit
Top pair Fit
Single Top Fit
C/Λ^2 [TeV^{-2}]
$\Lambda/\sqrt{|C|}$ [TeV]
4
2
0
−2
−4
−6
0.5
0.7
1.5
1.5
0.7
0.5
0.4
SFitter
C_{Qq}^{18}
C_{Qq}^{38}
C_{tu}^{8}
C_{td}^{8}
C_{Qq}^{11}
C_{Qq}^{31}
C_{tu}^{1}
C_{td}^{1}
C_{Qu}^{8}
C_{Qd}^{8}
C_{tq}^{8}
C_{Qu}^{1}
C_{Qd}^{1}
C_{tq}^{1}
$C_{\phi Q}^{-}/10$
$C_{\phi Q}^{3}/10$
$C_{\phi t}/10$
$C_{\phi tb}/10$
$C_{tZ}/10$
C_{tW}
C_{bW}
C_{tG}

NLO Effects for chirality