CRC-TRR-257

A GLOBAL SEARCH FOR NEW PHYSICS WITH TOPS

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New physics at a distance

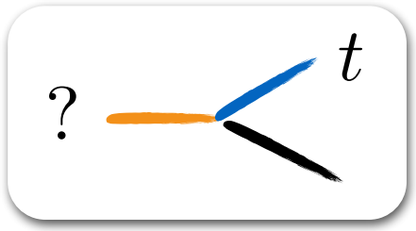
energy [GeV]

Λ

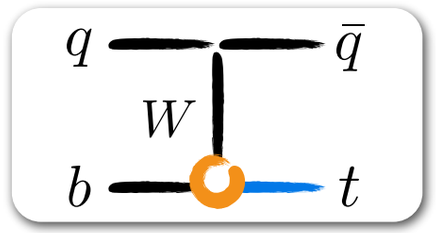
100

1

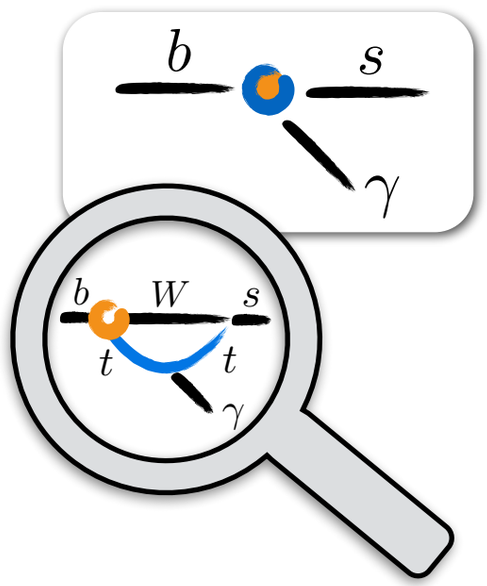
$$\mathcal{L}_f = ???$$



$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} O_i + \dots$$



$$\mathcal{L}_{\text{WET}} = \sum_i \mathcal{C}_i \mathcal{O}_i + \dots$$

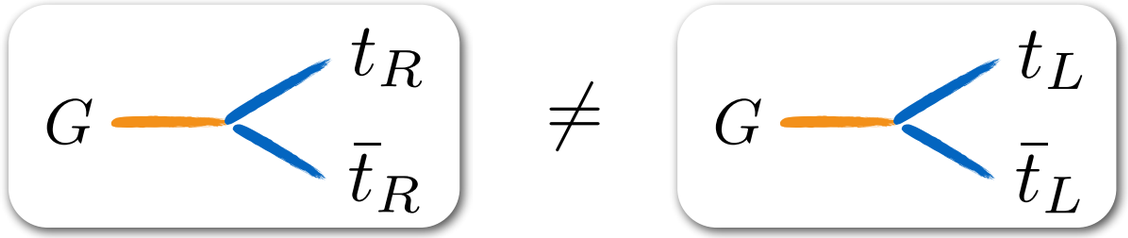


Here: effective interactions with top quarks.

Effects in top observables

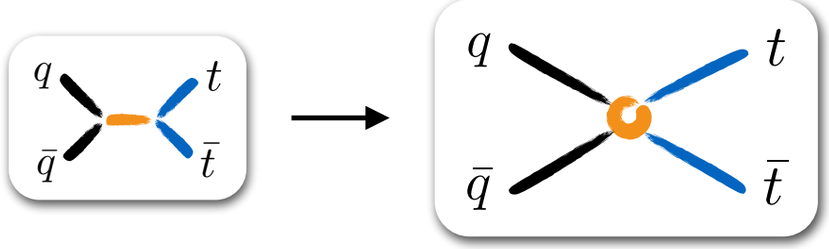
Example: heavy color-octet boson

$\Lambda \sim M_G$:



At the LHC:

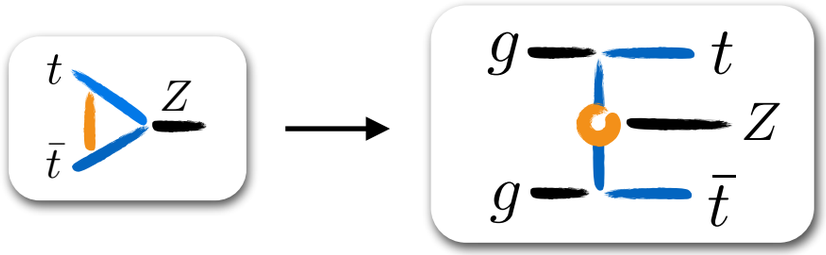
- $t\bar{t}$ production



$$O_{tq}^{8} = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{q}_L \gamma^\mu T^A q_L)$$

$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L)$$

- $t\bar{t}Z$ production



$$O_{\phi Q}^{1} = i(\phi^\dagger \overset{\leftrightarrow}{D}_\mu \phi)(\bar{Q}_L \gamma^\mu Q_L)$$

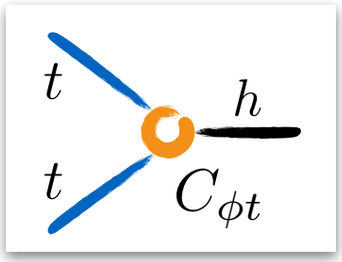
Goal: resolve effective top couplings in a global analysis.

new vectors (e.g.): Bauer, SW et al. 1008.0742; Haisch, SW 1106.0529

new scalars, fermions: Dawson, Homiller, Lane 2007.01296

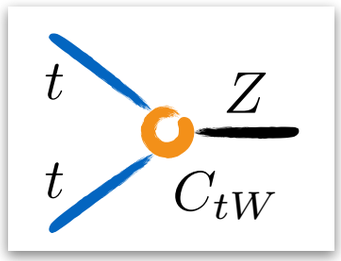
Top effective theory

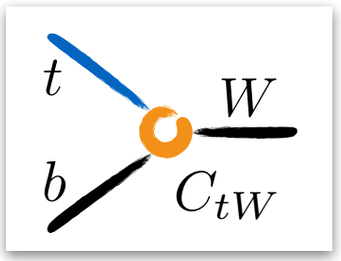
Higgs



$$O_{t\phi} = (\overline{Q}\, t\, \widetilde{\phi})(\phi^\dagger \phi)$$

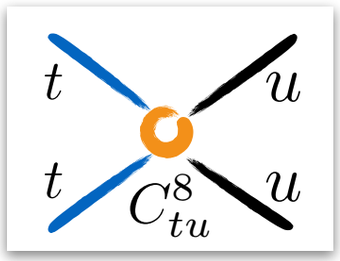
gauge bosons





$$^\ddagger O_{tW} = (\bar{Q}\sigma^{\mu\nu} t)\, \tau^I \widetilde{\phi}\, W^I_{\mu\nu}$$

light quarks



$$O^8_{tu} = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

Observables:

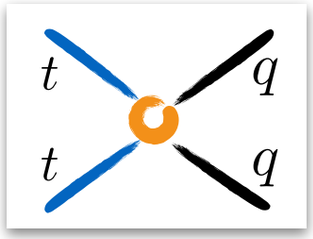
$$\sigma = \sigma_{\rm SM} + \sum_i \frac{C_i}{\Lambda^2}\sigma_i + \sum_{i,j} \frac{C_i C_j}{\Lambda^4}\sigma_{ij}$$

- dimension-6 operators with tops, NLO QCD precision
- flavor symmetry $U(2)_q \times U(2)_u \times U(2)_d$
- O(20) operators in top-pair, single top, ttV, tV production

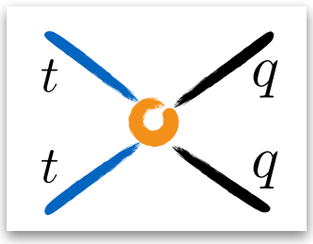
automated simulations with SMEFT@NLO: Degrande et al. 2008.11743

analysis framework (LHC Top WG): Aguilar Saavedra, SW et al. 1802.07237

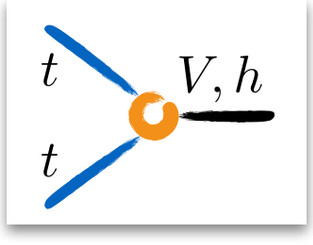
LHC processes in top EFT



LL, RR



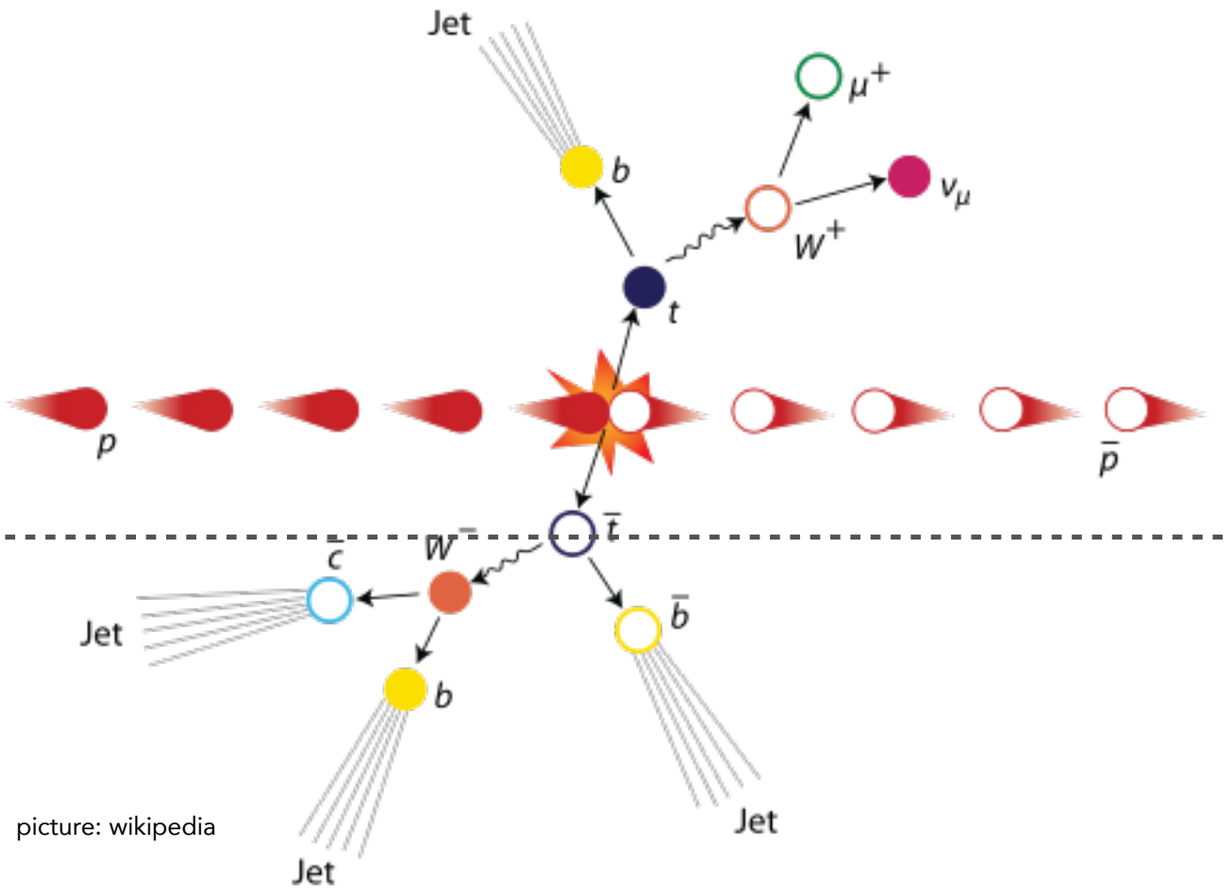
LR, RL



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}	–	–
$C_{\phi t}$	–	–	–	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}

Hartland et al. 1901.05965; Brivio, SW et al. 1910.03606

Global analysis of the top sector



picture: wikipedia

top EFT prediction

parton level

measurement unfolded

Global fit using SFitter

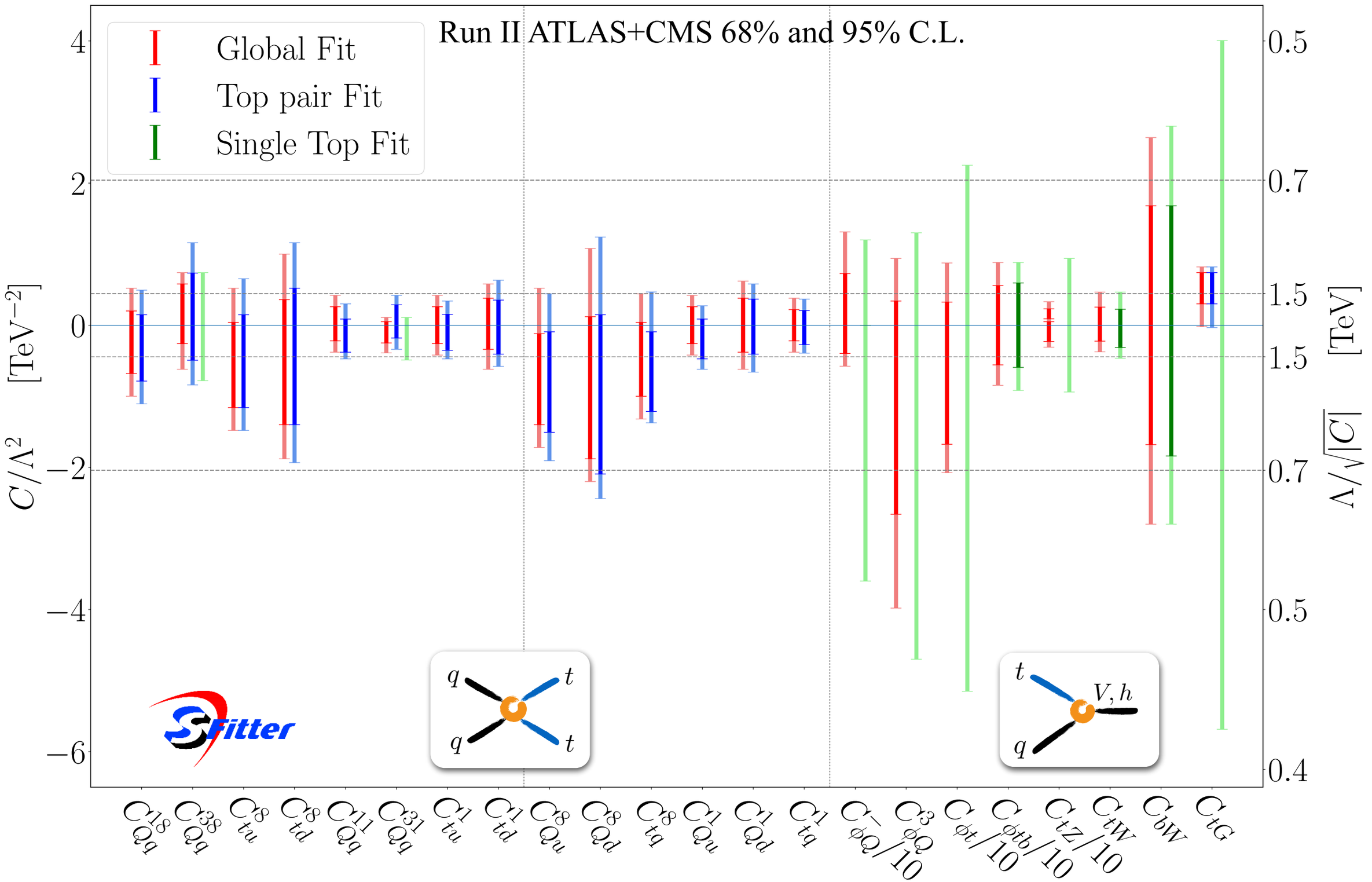
SFitter: Lafaye, Plehn, Zerwas hep-ph/0404282

- LHC top observables measured in Run 2 data
- cross sections and kinematic distributions
- accounts for correlated uncertainties

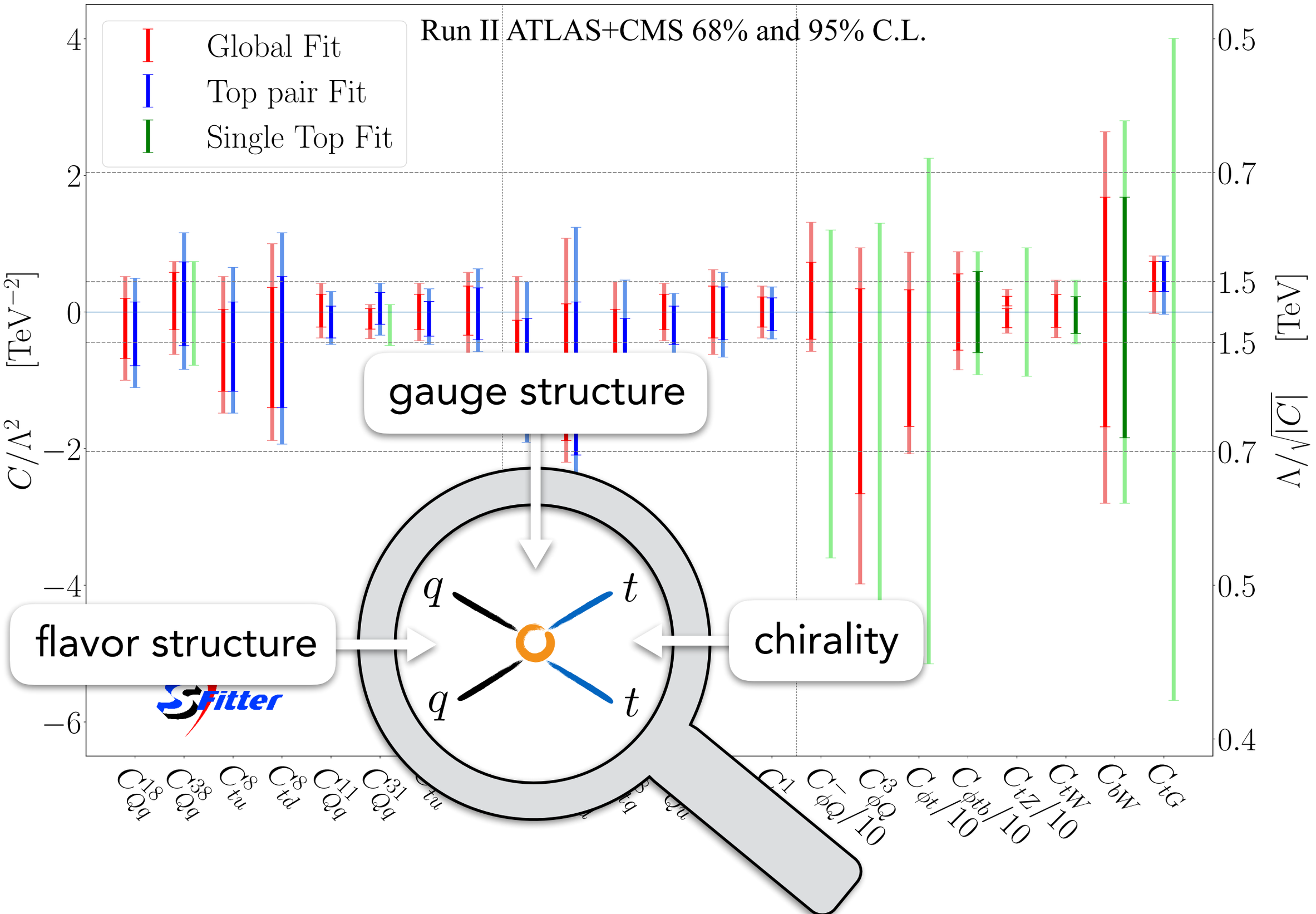
Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, SW, Zhang 1910.03606

other global top fits: Buckley et al. 2016+; Hartland et al. 2019; Durieux et al. 2019

Bounds on effective top couplings



Bounds on effective top couplings



Disentangling operator contributions

- 4-quark versus gluon operators

  → boosted tops

- chirality

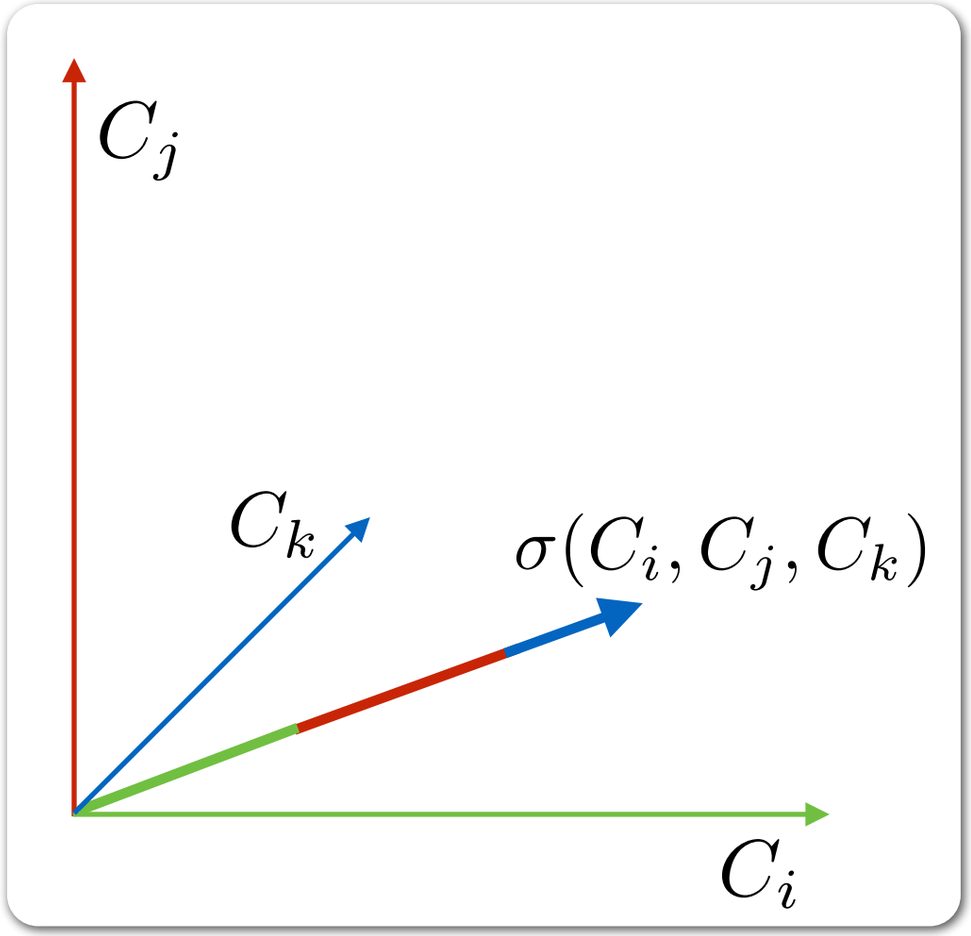
  → charge asymmetry
  spin correlations

- gauge structure (weak isospin)

  → boosted top, ttW, ttZ

- flavor structure

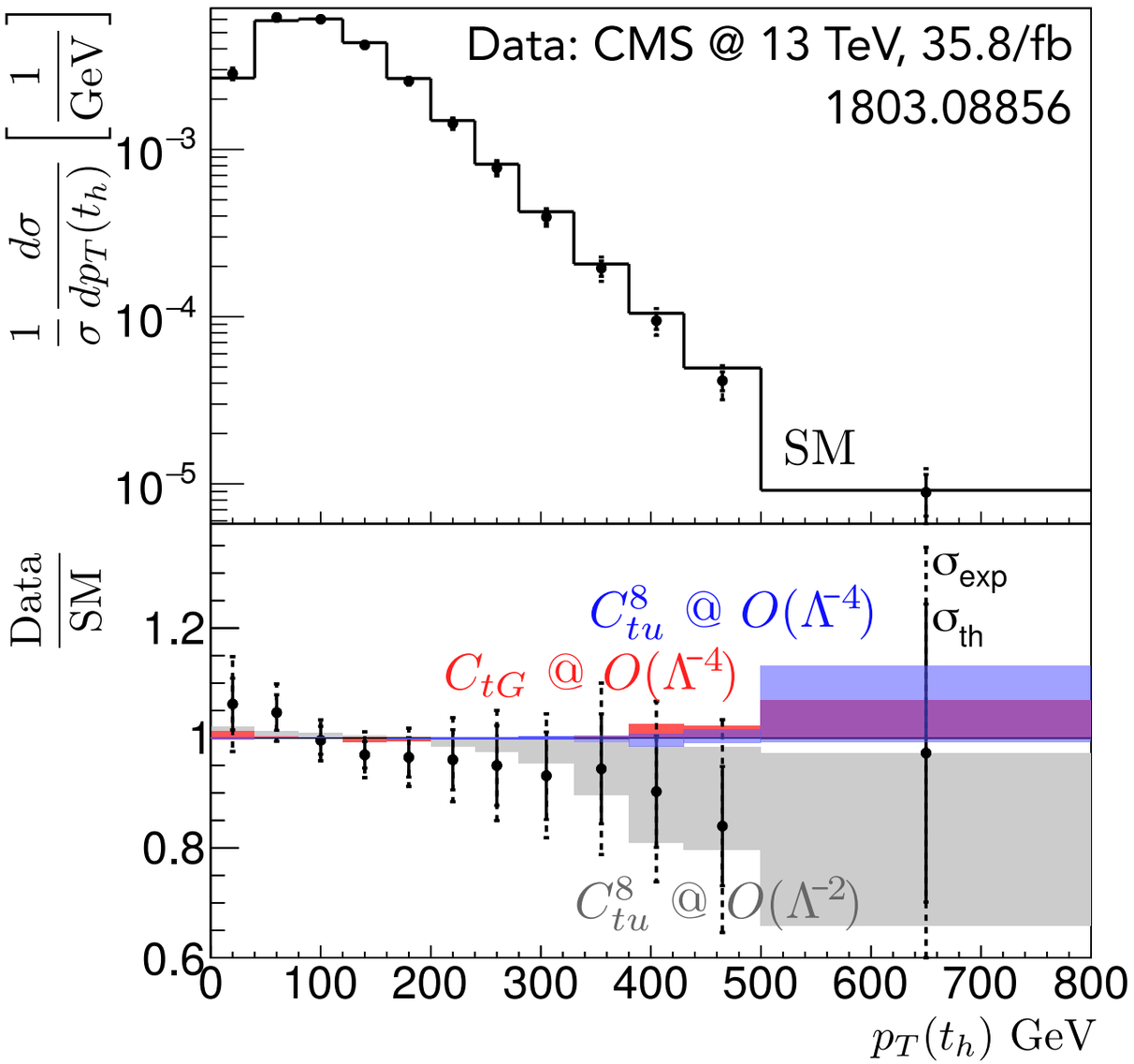
  → B and K physics



4-quark versus gluon operators

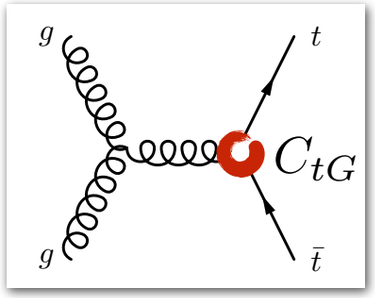
Sensitivity to 4-quark operators grows with energy:

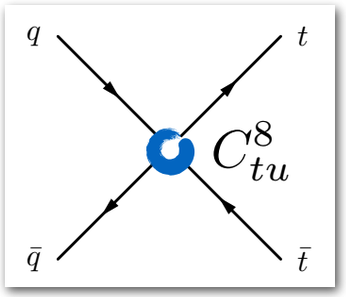
$$s \gg m_t^2 : \ \sigma_{t\bar{t}}(s) \sim \sigma_{\rm SM} \left(1 + \frac{m_t v}{\Lambda^2} C_{tG} + \frac{s}{\Lambda^2} C_{tu}^8 + \mathcal{O}\left(\frac{s^2}{\Lambda^4}\right) C_i C_j\right)$$



$$O_{tG} = (\bar{Q}\sigma^{\mu\nu} T^A t)\, \widetilde{\phi}\, G^A_{\mu\nu}$$

$$O_{tu}^8 = (\bar{t}\gamma_\mu T^A t)(\bar{u}_i \gamma^\mu T^A u_i)$$

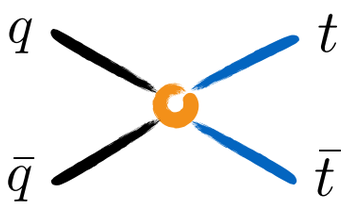




Search with boosted tops in tails of distributions.

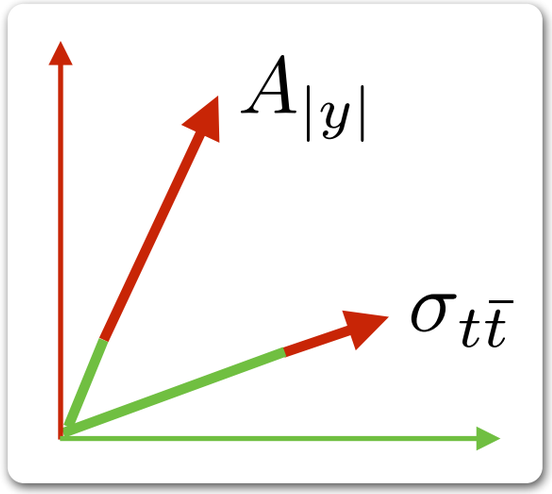
Brivio, SW et al. 1910.03606; see also Englert et al. 1607.04304

Top chirality

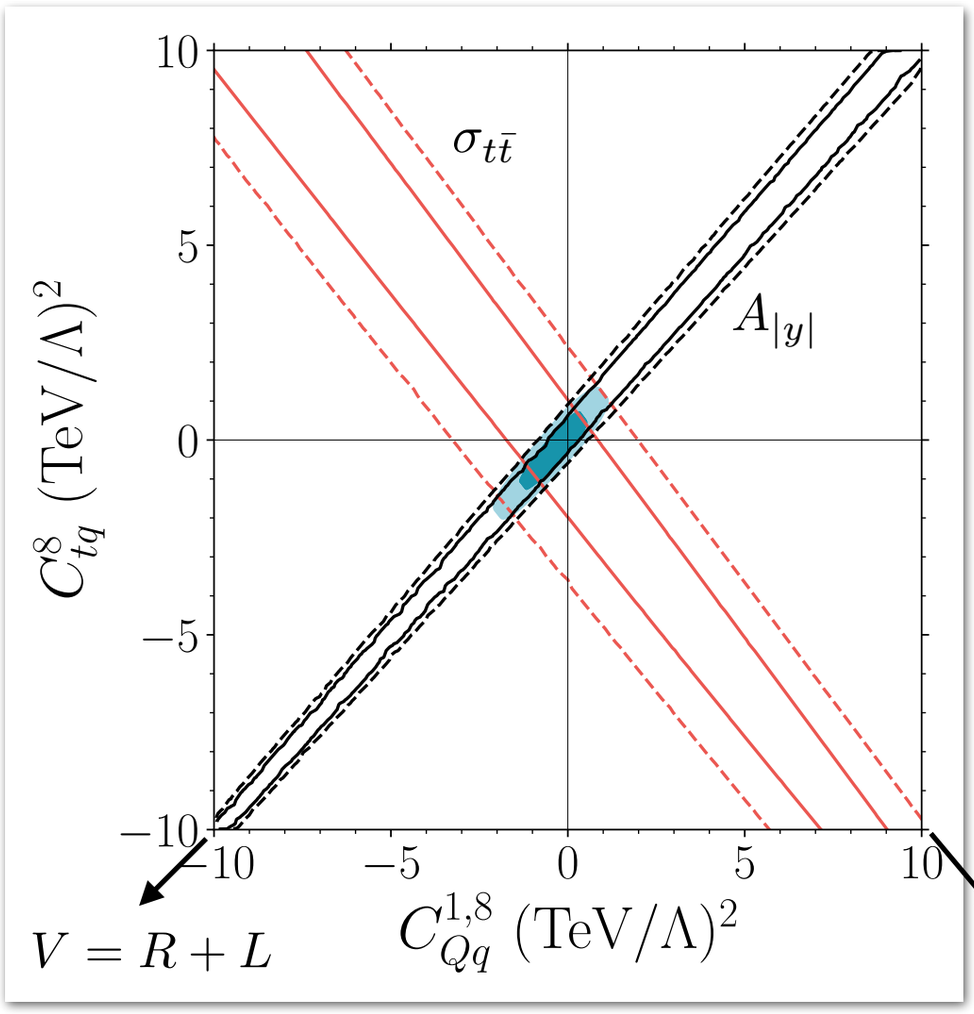


$$O_{tq}^{8} = (\bar{t}_R \gamma_\mu T^A t_R)(\bar{q}_L \gamma^\mu T^A q_L) \sim RL$$

$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L) \sim LL$$



- linear Wilson contributions $O(C/\Lambda^2)$



top-antitop cross section:

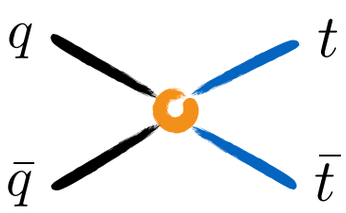
$$\sigma_{t\bar{t}} = \sigma_{\mathrm{SM}} + \sigma_{VV}\left(C_{Qq}^{1,8} + C_{tq}^{8}\right)$$

charge asymmetry:

$$A_{|y|} = \frac{\sigma_{\mathrm{SM}}^{A} + \sigma_{AA}\left(C_{Qq}^{1,8} - C_{tq}^{8}\right)}{\sigma_{t\bar{t}}}$$

Brivio, SW et al. 1910.03606

Top chirality



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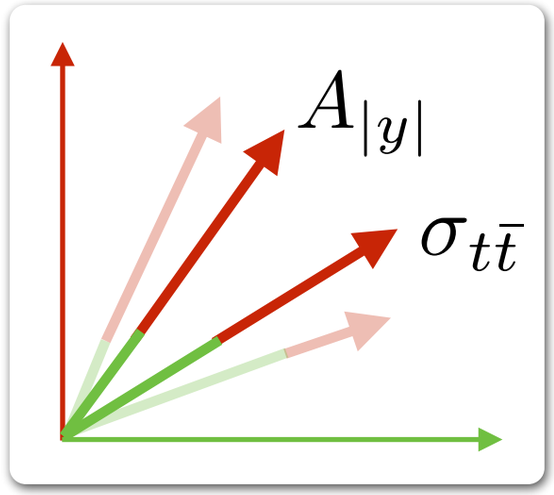
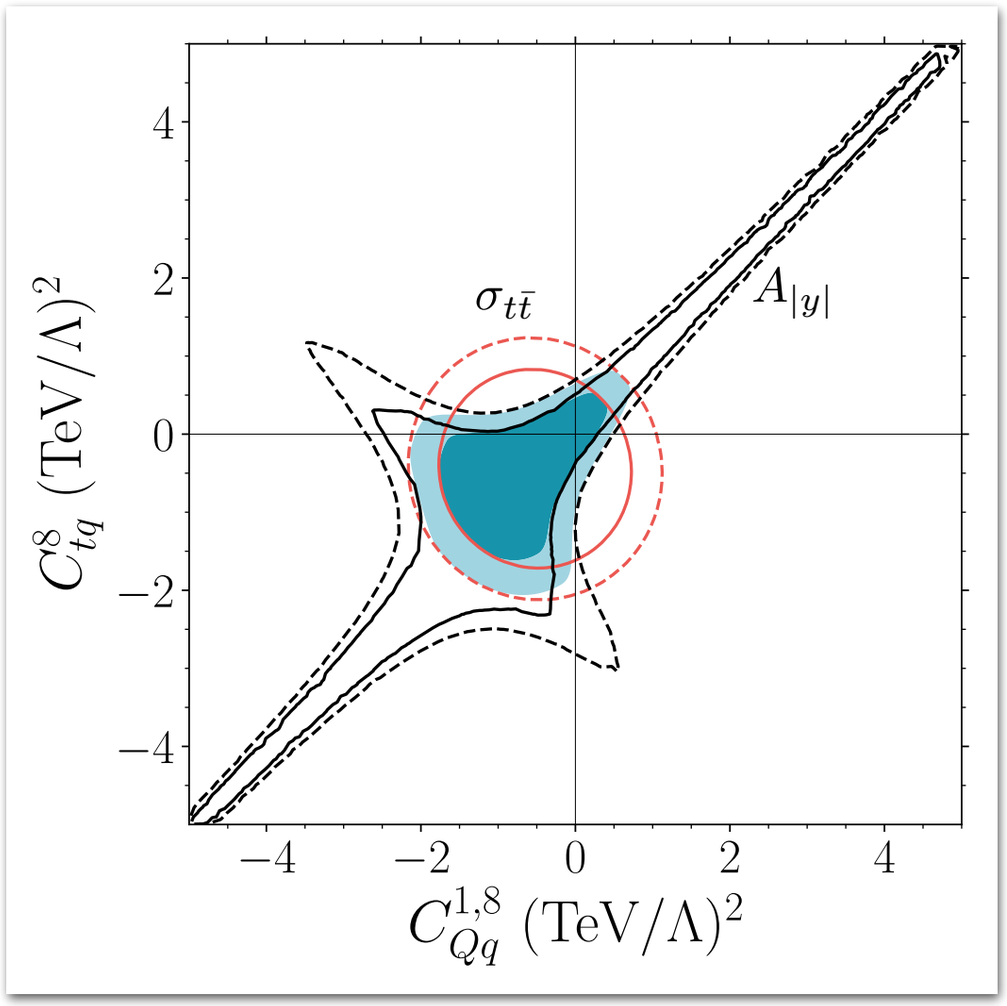


- quadratic Wilson contributions $O(C^2/\Lambda^4)$



top-antitop cross section:

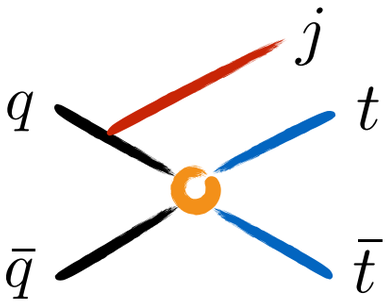
$$\sigma_{t\bar{t}} = \sigma_{\mathrm{SM}} + \sigma_{VV}\left(C_{Qq}^{1,8} + C_{tq}^{8}\right) + \sigma_{V+A}\left(|C_{Qq}^{1,8}|^2 + |C_{tq}^{8}|^2\right) + \sigma_{V-A}\, C_{Qq}^{1,8} C_{tq}^{8}$$

charge asymmetry:

$$A_{|y|} = \frac{\sigma_{\mathrm{SM}}^{A} + \sigma_{AA}\left(C_{Qq}^{1,8} - C_{tq}^{8}\right)}{\sigma_{t\bar{t}}} + \sigma_{VVAA}\left(|C_{Qq}^{1,8}|^2 - |C_{tq}^{8}|^2\right)/\sigma_{t\bar{t}}$$

Brivio, SW et al. 1910.03606

Resolving blind directions



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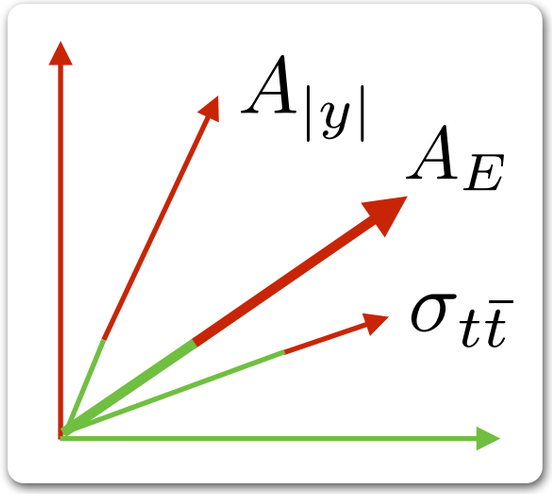
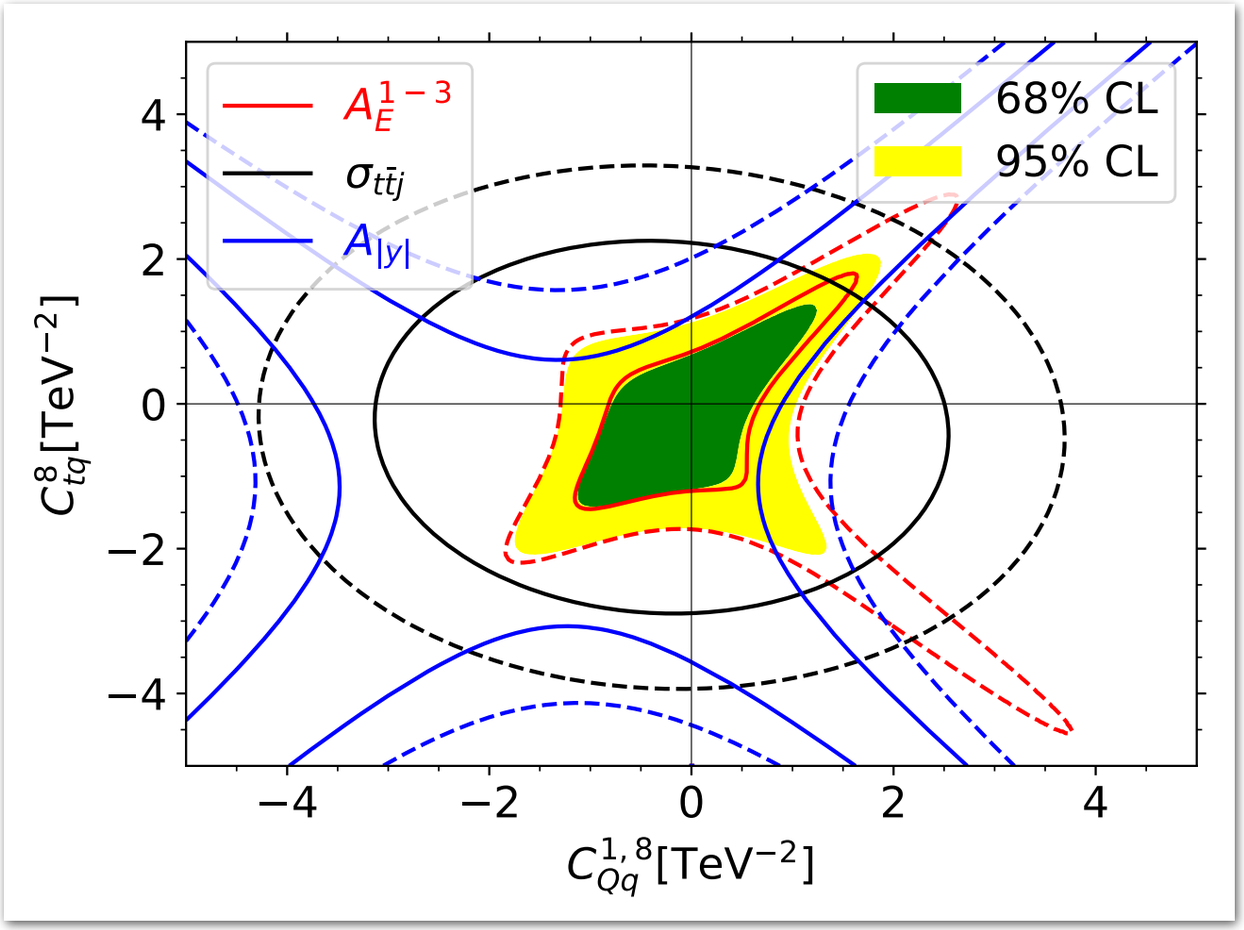
$$O_{Qq}^{1,8} = (\bar{Q}_L \gamma_\mu T^A Q_L)(\bar{q}_L \gamma^\mu T^A q_L) \sim LL$$



Jet probes new directions in EFT space:



measured: ATLAS-CONF-2019-026

rapidity asymmetry $A_{|y|}\,(t\bar{t})$

projected:

energy asymmetry $A_E\,(t\bar{t}j)$

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

Basan, Berta, Masetti, Vryonidou, SW 2001.07225

Gauge structure

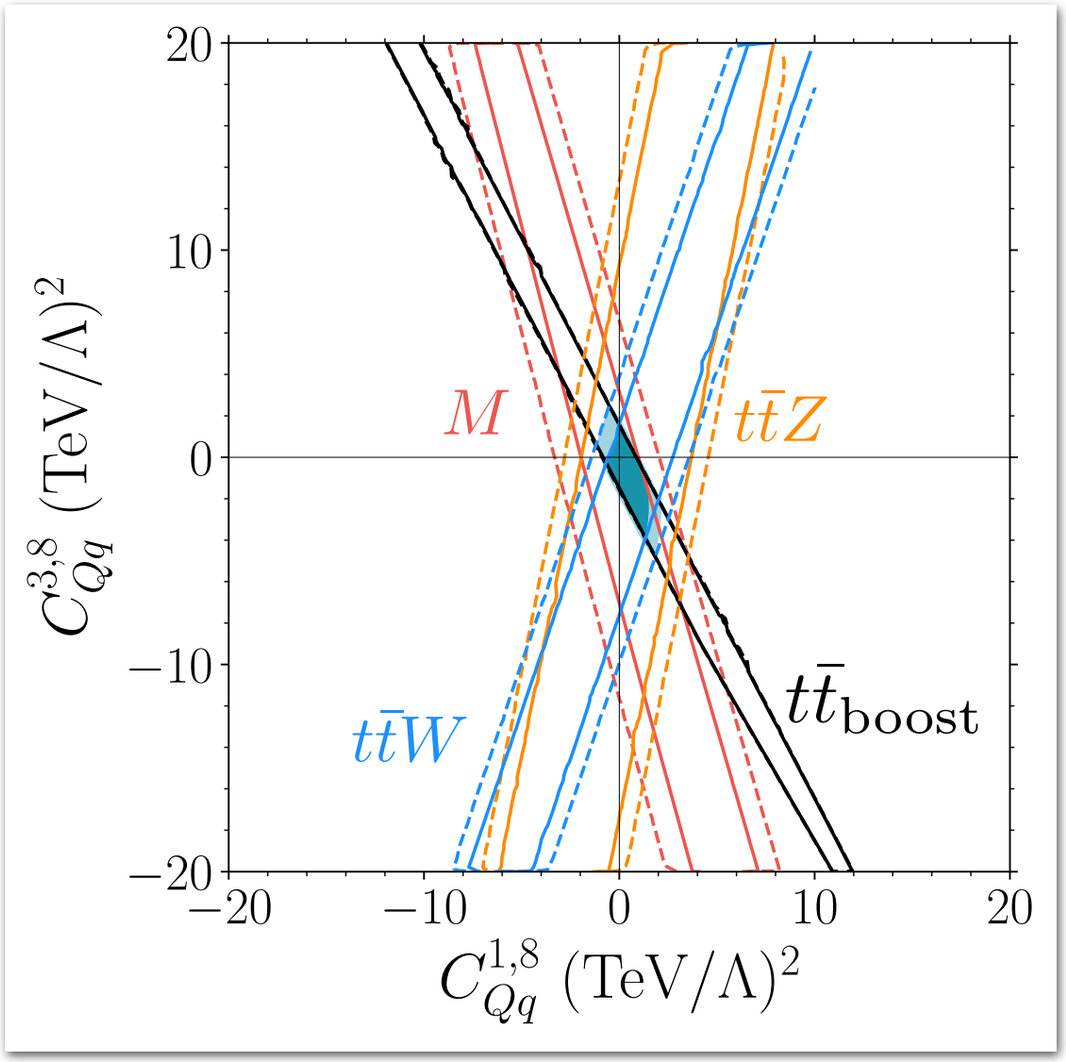
weak singlet: $O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$

weak triplet: $O_{Qq}^{3,8} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$

key: parton distributions

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

- linear Wilson contributions $O(C/\Lambda^2)$



top-antitop cross section:

$$\sigma_{t\bar{t}} \sim (r+1) C_{Qq}^{1,8} + (r-1) C_{Qq}^{3,8}$$

$$\approx 3 C_{Qq}^{1,8} + C_{Qq}^{3,8}$$

ttW associated production:

$$\sigma_{t\bar{t}W} \sim C_{Qq}^{1,8} (\sigma_{uu} + \sigma_{dd}) + C_{Qq}^{3,8} \sigma_{ud}$$

Brivio, SW et al. 1910.03606

Gauge structure

weak singlet: $O_{Qq}^{1,8} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$

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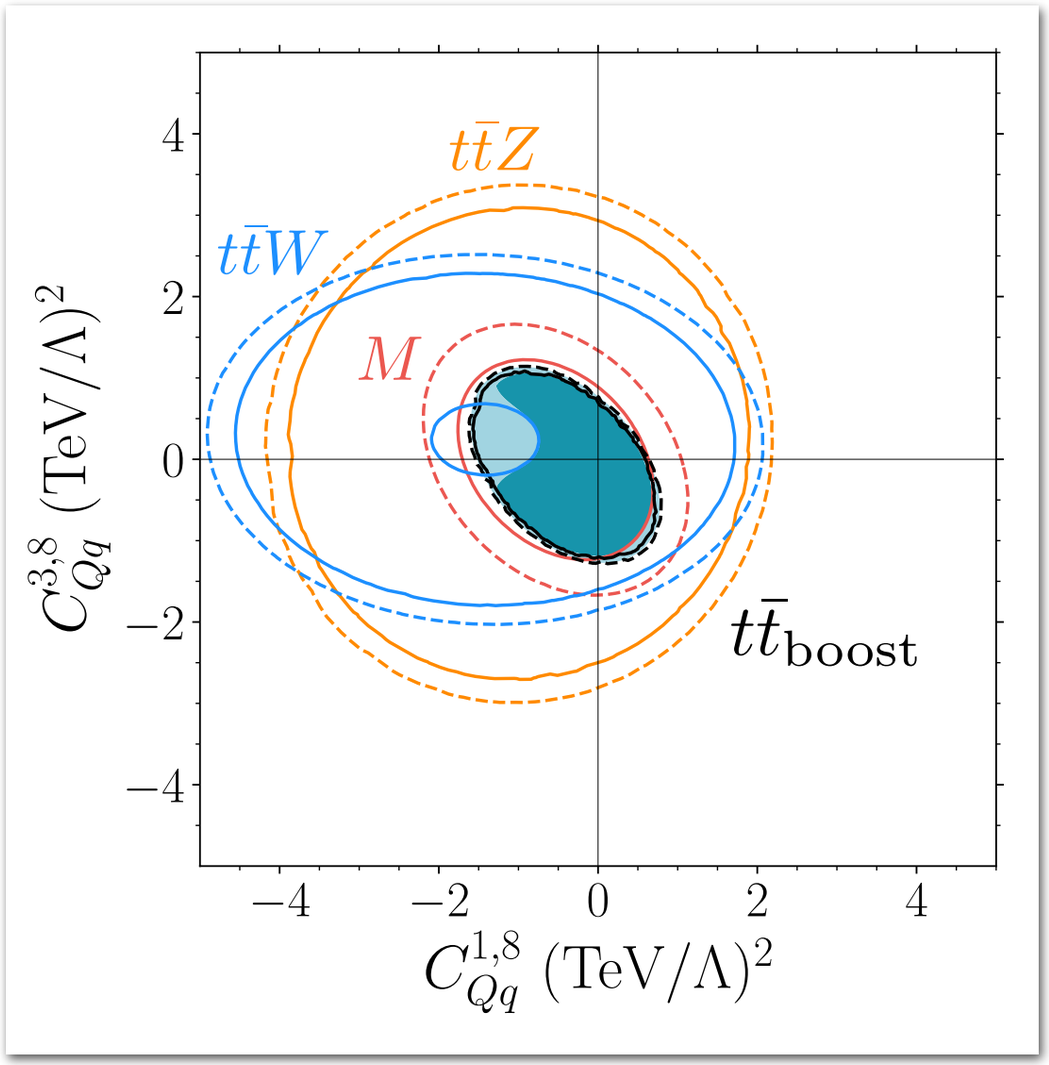
key: parton distributions

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

- quadratic Wilson contributions $O(C^2/\Lambda^4)$



All Wilson coefficients bounded.
Remaining blind directions in fit.

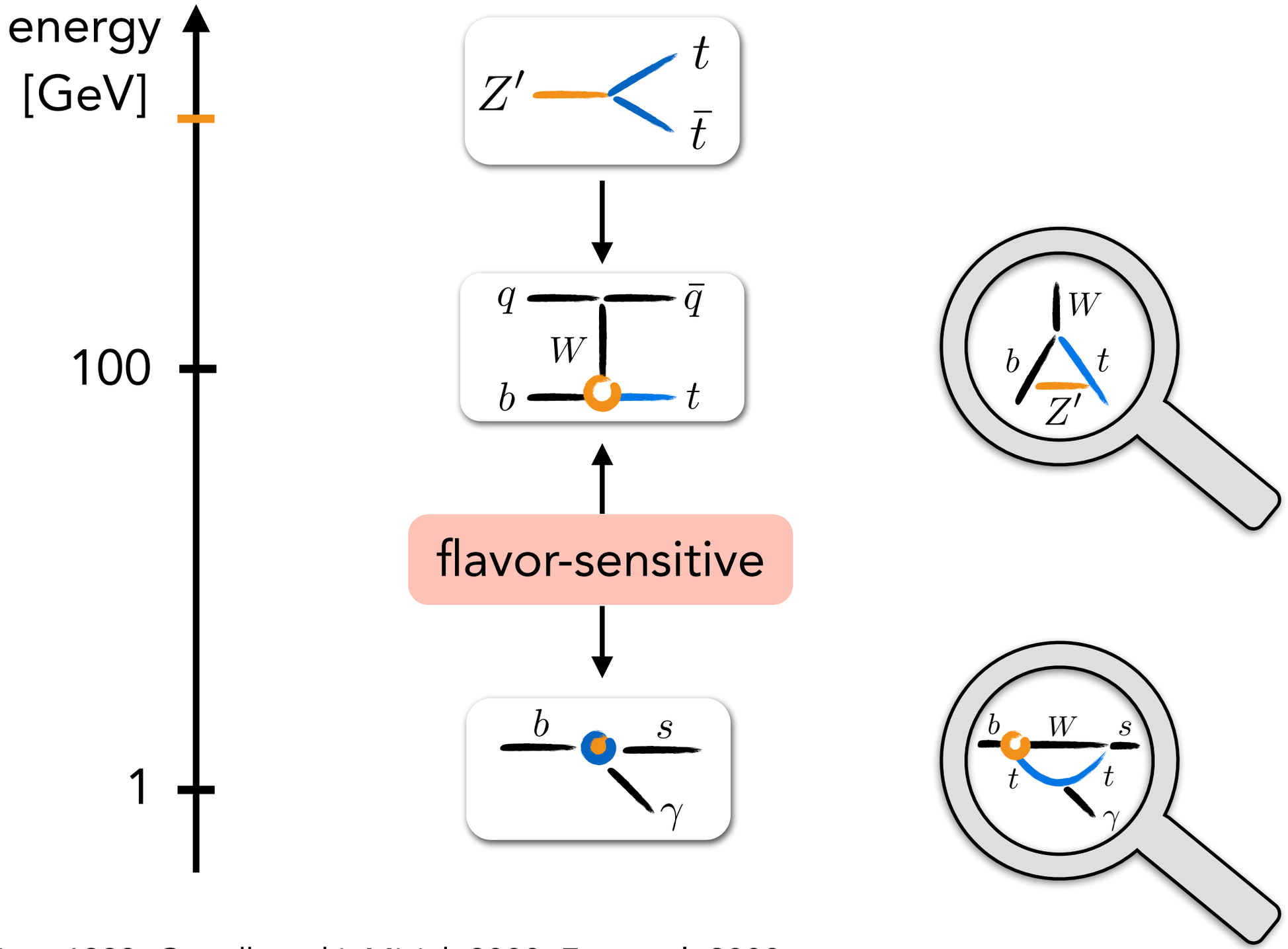
Brivio, SW et al. 1910.03606

Key to better resolution

- correlations between measurements — Bissmann et al. 1912.06090
- precision in high-energy tails ($t\bar{t}$, single top) — Englert et al. 1607.04304
- top properties including lepton observables — Basan et al. 2001.07225
- SM-rare processes (tZj, thj, tZW) — Degrande et al. 1804.07773; Maltoni et al. 1904.05637
- comparing predictions to data at parton/particle/detector level?

New physics could first show up in small, **connected** deviations.

Top and flavor

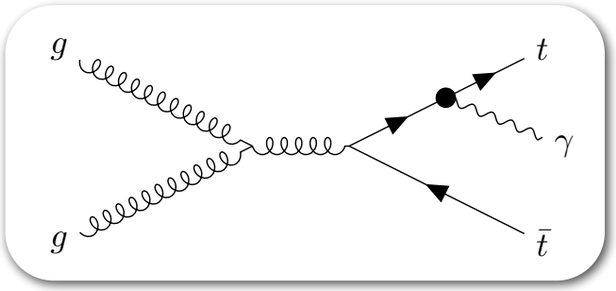


Hewett, Rizzo 1993; Grzadkowski, Misiak 2008; Fox et al. 2008

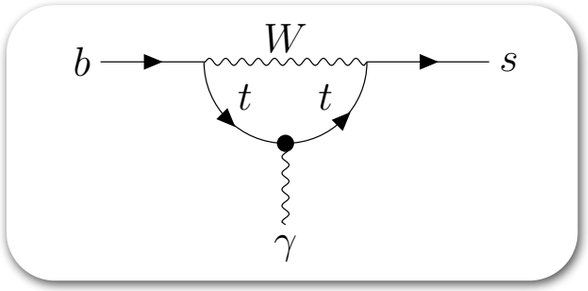
Brod et al. 2014; Cirigliano et al. 2016; Bissmann et al. 2019; Aoude et al. 2020

Combining top and flavor observables

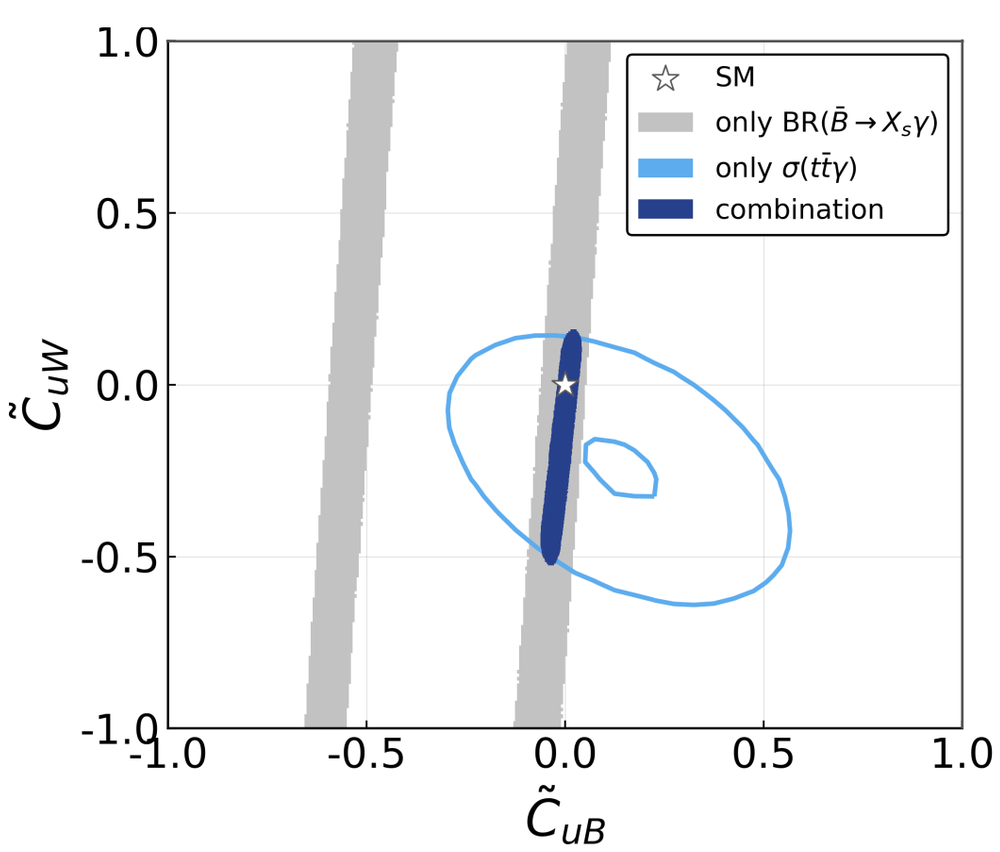
Top: $pp \to t\bar{t}\gamma$



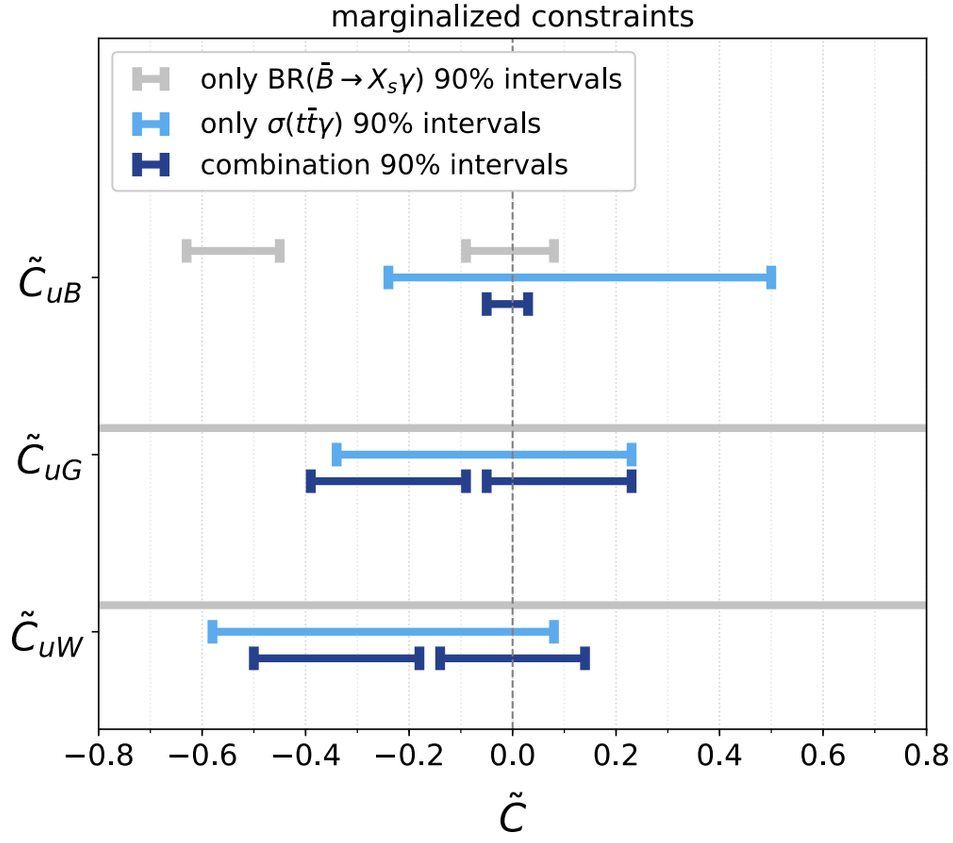
Flavor: $B \to X_s\gamma$



Breaking blind directions



… and gaining sensitivity.

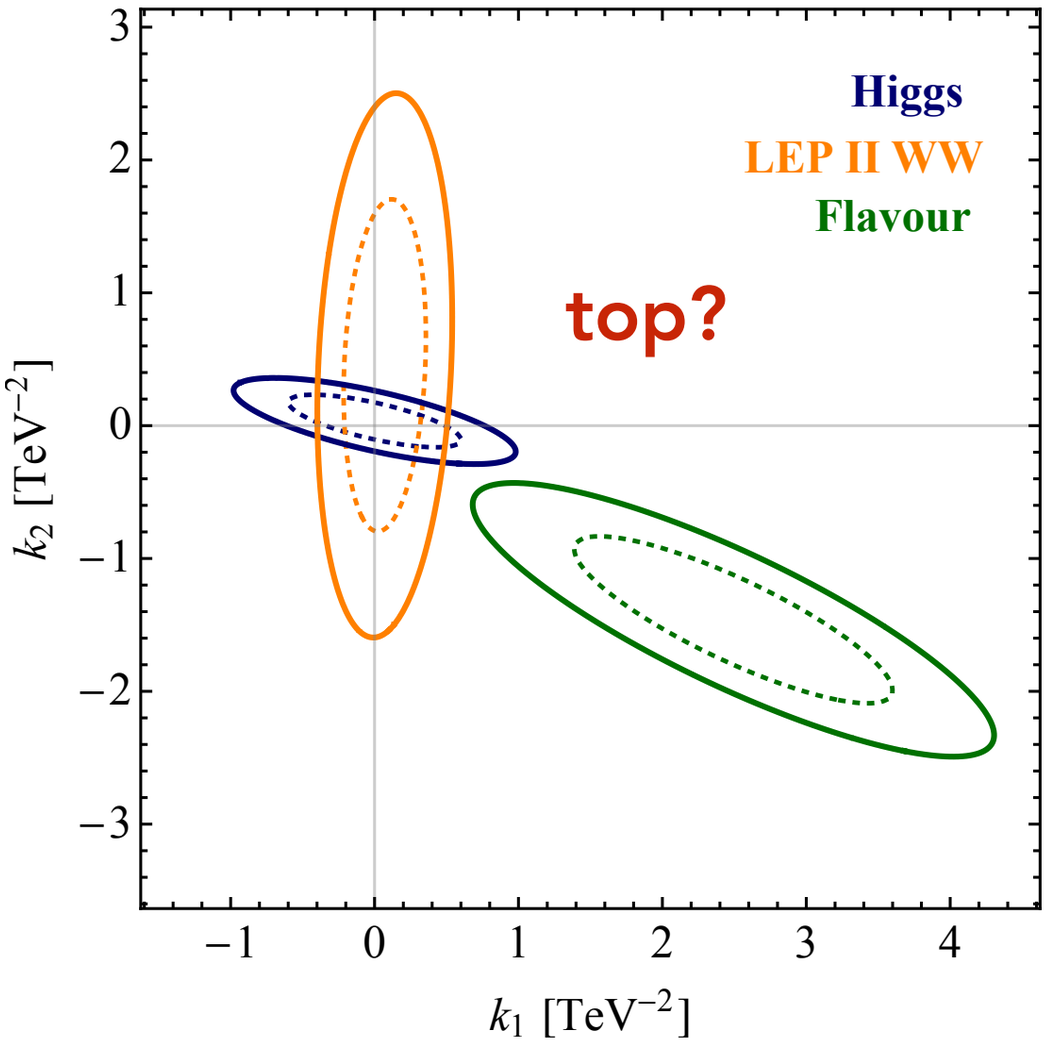


Bissmann, Erdmann, Grunwald, Hiller, Kroeninger 1909.13632

Top - Flavor - Higgs - Electroweak

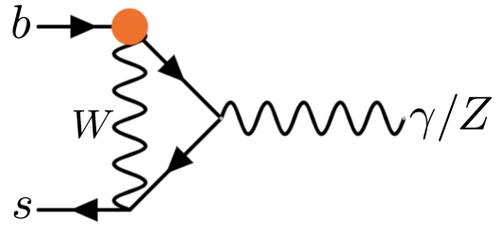
Connecting Flavor - Higgs - EW

Aoude, Hurth, Renner, Shepherd 2003.05432

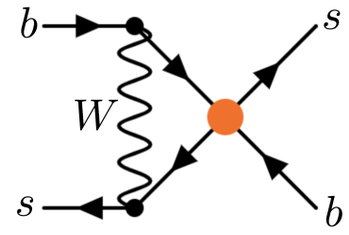


$b \to s\gamma$

$b \to s\ell^+\ell^-$



B_s mixing



assuming minimal flavor violation

k_1, k_2 : blind directions in Z-pole obs.

Connecting Top and Flavor

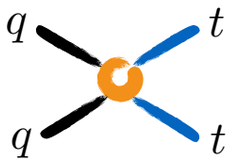
Bruggisser, van Dyk, Schaefer, SW - work in progress

Connecting Top and Higgs

Ethier et al. - work in progress (Maltoni at ICHEP 2020)

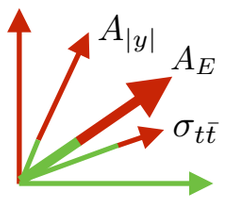
global Higgs + EW fits: Ellis et al. 1803.03252, Biekoetter et al. 1812.07587, Almeida et al. 1812.01009

Summary: new physics search with tops

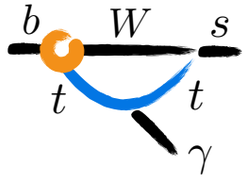


- Probe effective couplings with precise observables.

- Use kinematics to decipher gauge and chiral structure.



- New observables resolve blind directions.



- Combine top with flavor, Higgs, EW for new insights.

Thank you!