EFFECTIVE FIELD THEORIES in PARTICLE PHYSICS

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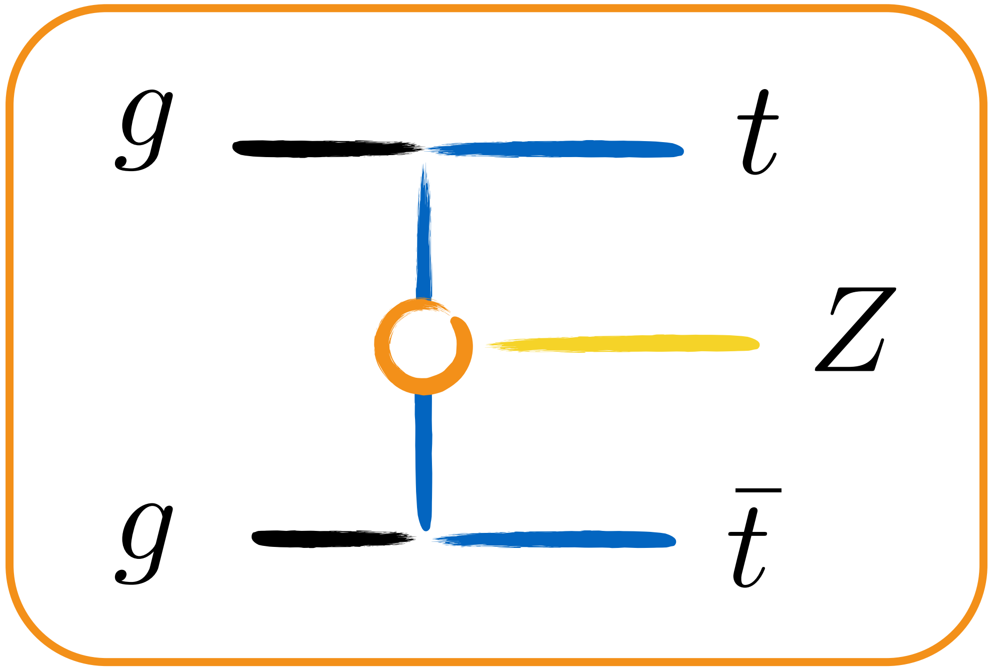
jDPG Theory Workshop • Jan 6-9, 2022 • Grafenschloss Diez

Part III

Standard Model Effective Field Theory



Multi-scale physics

Standard Model $\{q, t, \ell, g, \gamma, Z, W^{\pm}, h\}$

$\Lambda = m_W$

Weak Effective Theory

$$\mathcal{L}_{\mathrm{WET}} = \mathcal{L}_{\mathrm{QCD+QED}} - \frac{4G_F}{\sqrt{2}} \sum_i \mathcal{C}_i \, \mathcal{O}_i^{(6)} + \ldots$$

$\{q, \ell, g, \gamma\}$

m_b

A new scale

fundamental theory

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

$\{\mathrm{SM} + X\}$

$\Lambda = m_X$

Standard Model Effective Field Theory

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i}{\Lambda^{\gamma_i}} O_i$$

$\{\mathrm{SM}\}$

m_W

Weak Effective Theory

$$\mathcal{L}_{\mathrm{WET}} = \mathcal{L}_{\mathrm{QCD+QED}} - \frac{4G_F}{\sqrt{2}} \sum_i \mathcal{C}_i\, \mathcal{O}_i^{(6)} + \ldots$$

$\{q, \ell, g, \gamma\}$

m_b

SMEFT versus WET

WET: $$\mathcal{L}_{\text{WET}} = \mathcal{L}_{\text{QCD+QED}} - \frac{4G_F}{\sqrt{2}} \sum_a \mathcal{C}_a \, \mathcal{O}_a^{(6)}$$ $$\mathcal{O} = \{\mathcal{O}_{\text{SM}}, \mathcal{O}_{\text{NP}}\}$$

- Purpose: precise low-energy description of **weak interactions**

SMEFT: $$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C_5}{\Lambda} O^{(5)} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)} + \ldots$$ $$O = \{O_{\text{NP}}\}$$

- Purpose: general low-energy description of **new physics effects**

SMEFT versus WET

WET: $$\mathcal{L}_{\rm WET} = \mathcal{L}_{\rm QCD+QED} - \frac{4G_F}{\sqrt{2}} \sum_a \mathcal{C}_a\, \mathcal{O}_a^{(6)}$$ $\mathcal{O} = \{\mathcal{O}_{\rm SM}, \mathcal{O}_{\rm NP}\}$

- Purpose: precise low-energy description of **weak interactions**
- UV completion: **Standard Model** (plus new physics)
- Wilson coefficients: **matching**.

SMEFT: $$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{C_5}{\Lambda} O^{(5)} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)} + \ldots$$ $O = \{O_{\rm NP}\}$

- Purpose: general low-energy description of **new physics effects**
- UV completion: **unknown** (new physics)
- Wilson coefficients: respect SM **symmetries**.

Standard Model Effective Theory

Goal: describe effects of new physics in SM particle interactions.

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C_5}{\Lambda} O^{(5)} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)} + \ldots$$

review: Brivio, Trott 2017

- model-independent
- complete
- renormalizable

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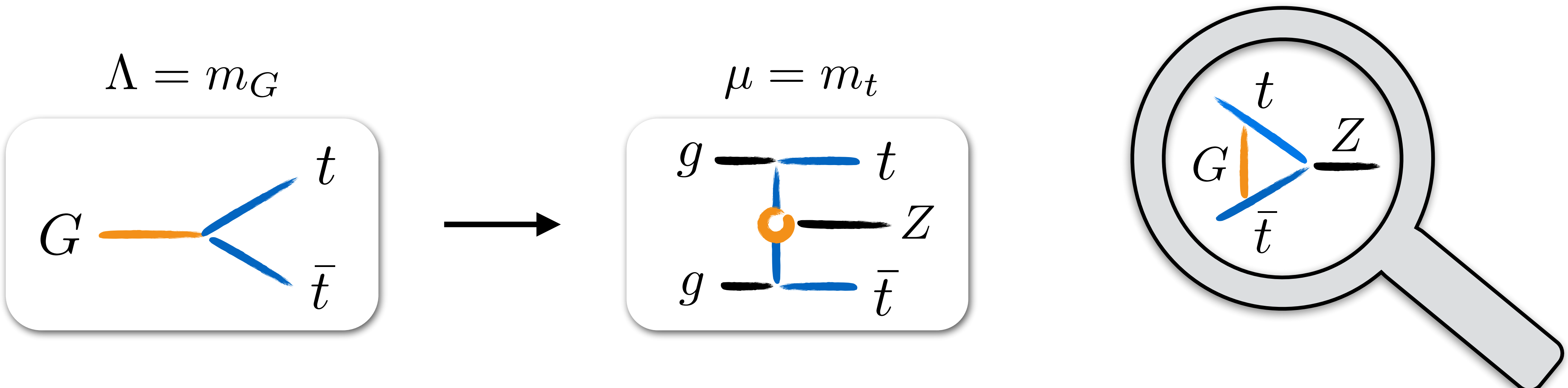
Example: new gauge boson coupling to top quarks

$\Lambda = m_G$ $\mu = m_t$



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

SMEFT operators

- complete set of all possible operators
- respect SM symmetries
- running similar to WET

Warsaw basis:
Grzadkowski et al. 2010

Jenkins, Manohar, Trott 2013

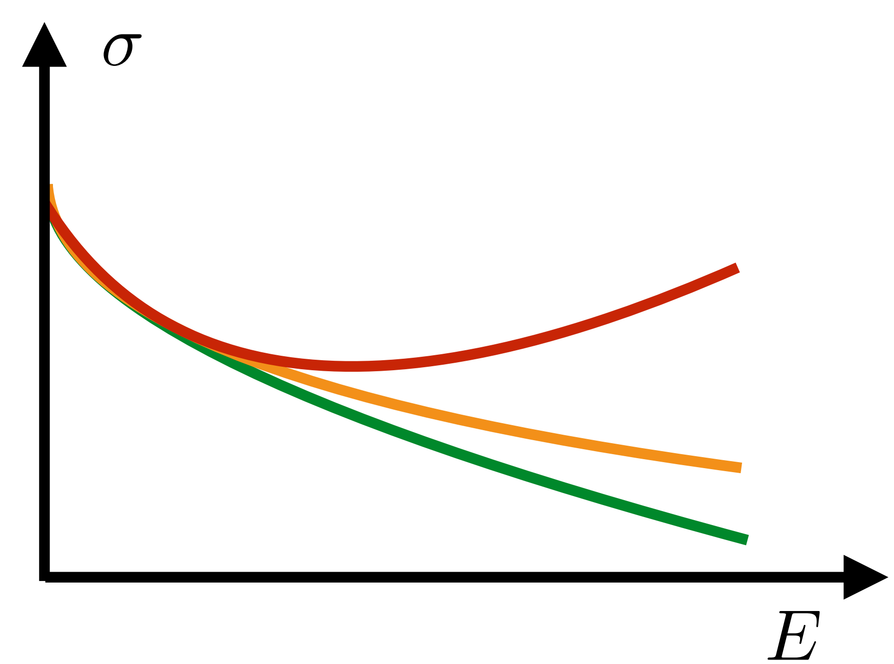
Operator effects in 2-2 scattering (dim. 6):

$$\mathcal{M} \sim \frac{v^m}{\Lambda^2}\frac{E^{2-m+n}}{m_V^n}$$

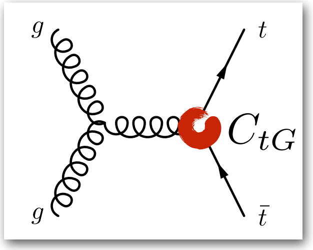
m vevs; *n* Goldstones

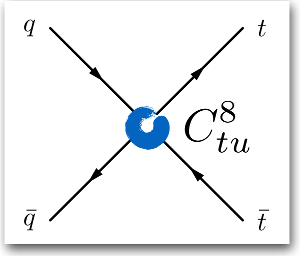
Maltoni, Mantani, Mimasu 2019

- $O_{4f} = (\bar{f}\gamma_\mu f)(\bar{f}\gamma^\mu f) \rightarrow \frac{E^2}{\Lambda^2}$
- $O_{Hf} = (H^\dagger i D_\mu H)(\bar{f}\gamma^\mu f) \rightarrow \frac{vE}{\Lambda^2}$
- $O_{fV} = (\bar{F}_L \sigma^{\mu\nu} f_R) H V_{\mu\nu} \rightarrow \frac{m_f v}{\Lambda^2}$



Top-antitop production at high energies



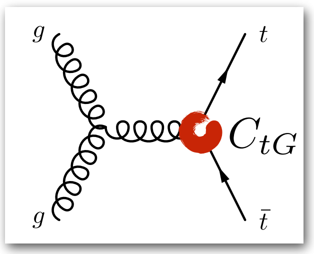


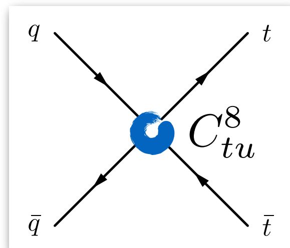
$$O_{tG} = (\overline{Q}_L \sigma^{\mu\nu} T^A t_R) \widetilde{H} G^A_{\mu\nu}$$

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

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

Top-antitop production at high energies





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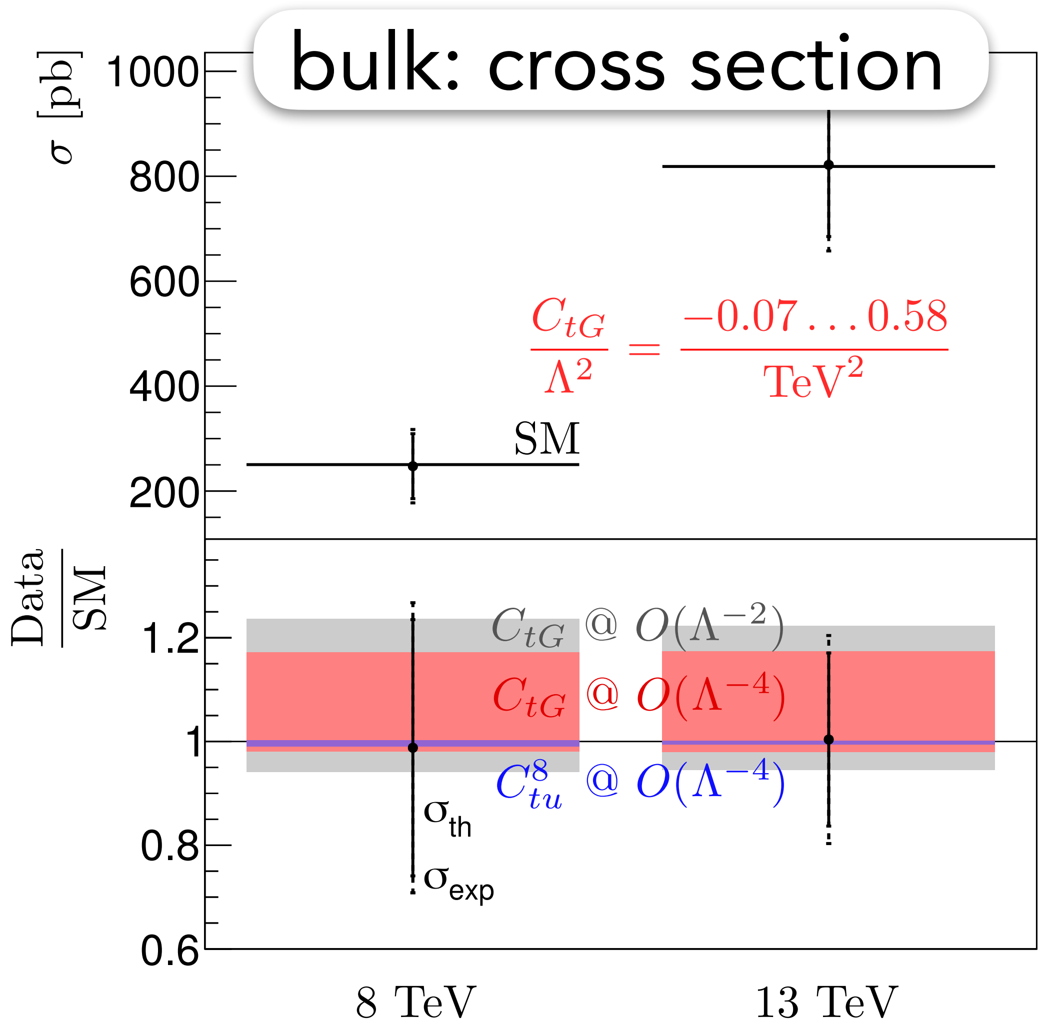
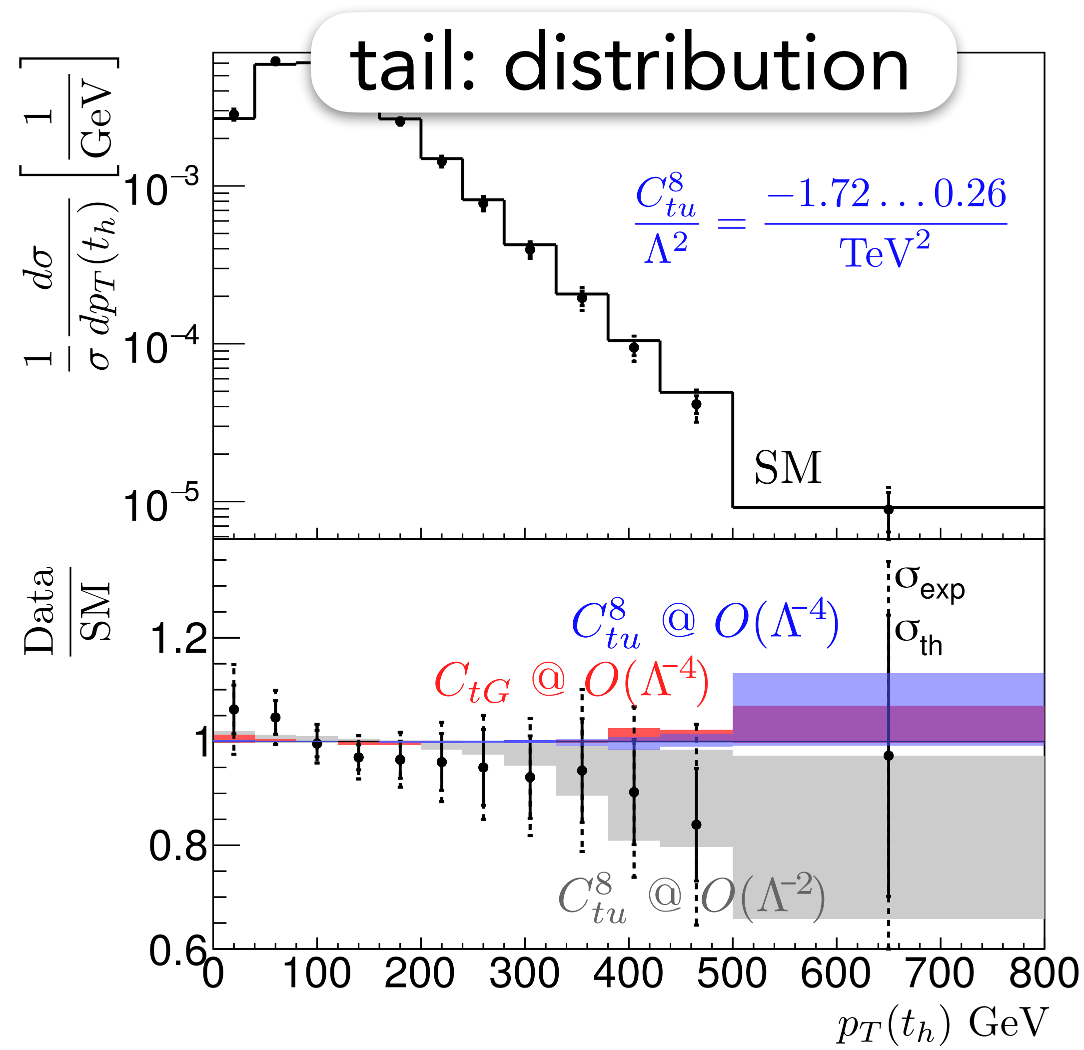
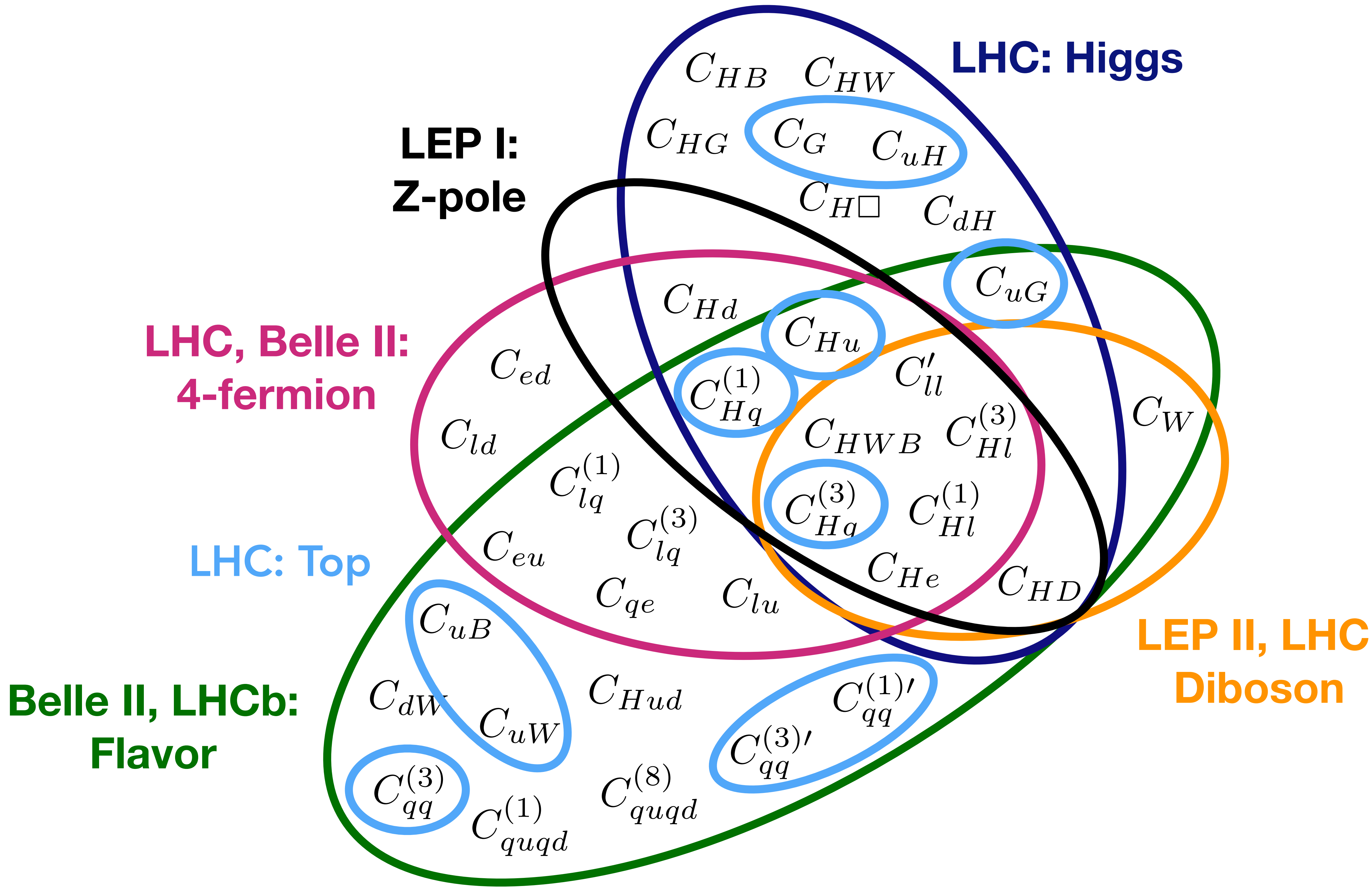




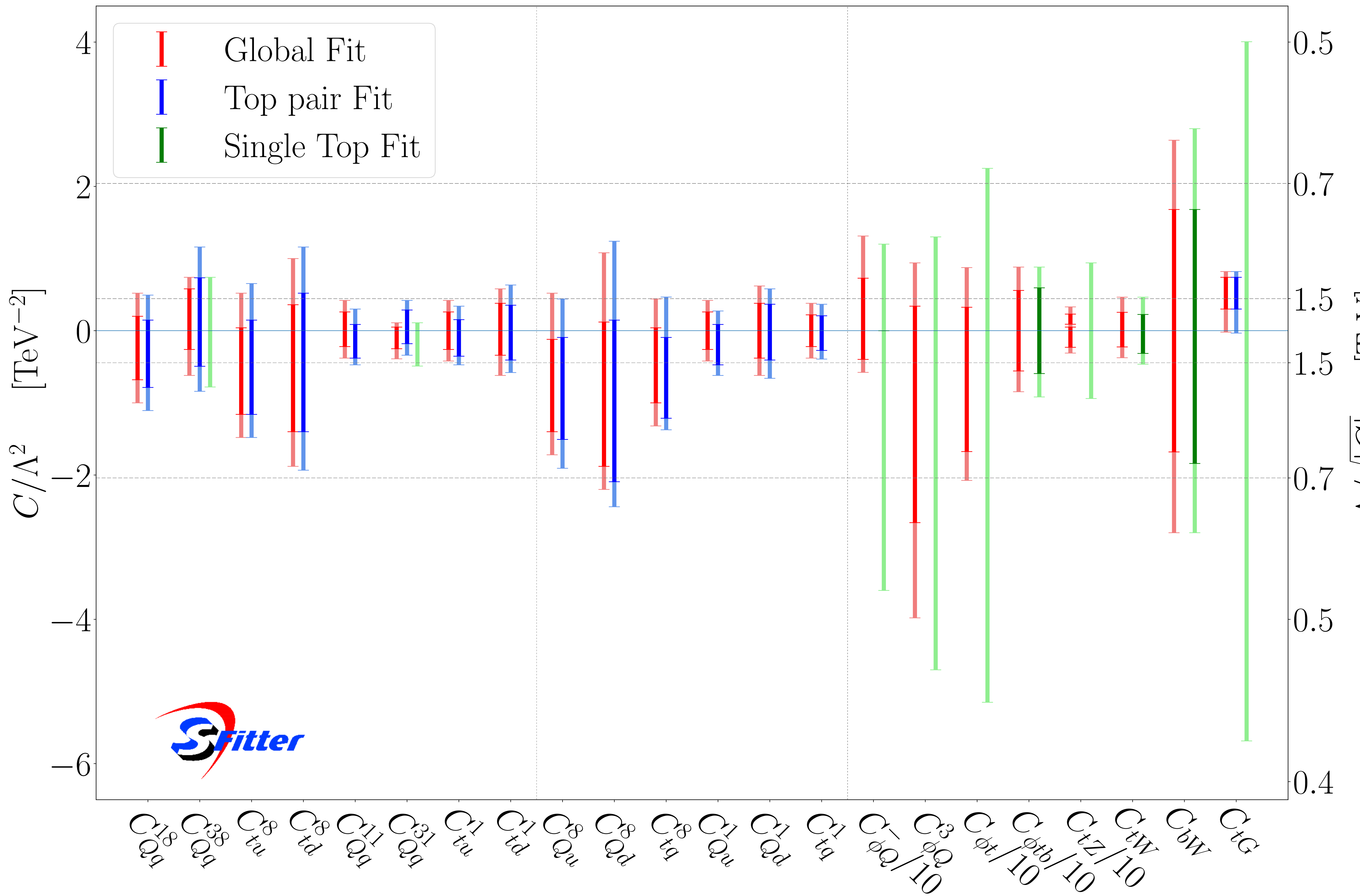
Brivio, Westhoff et al. 2019

Probing the SMEFT space



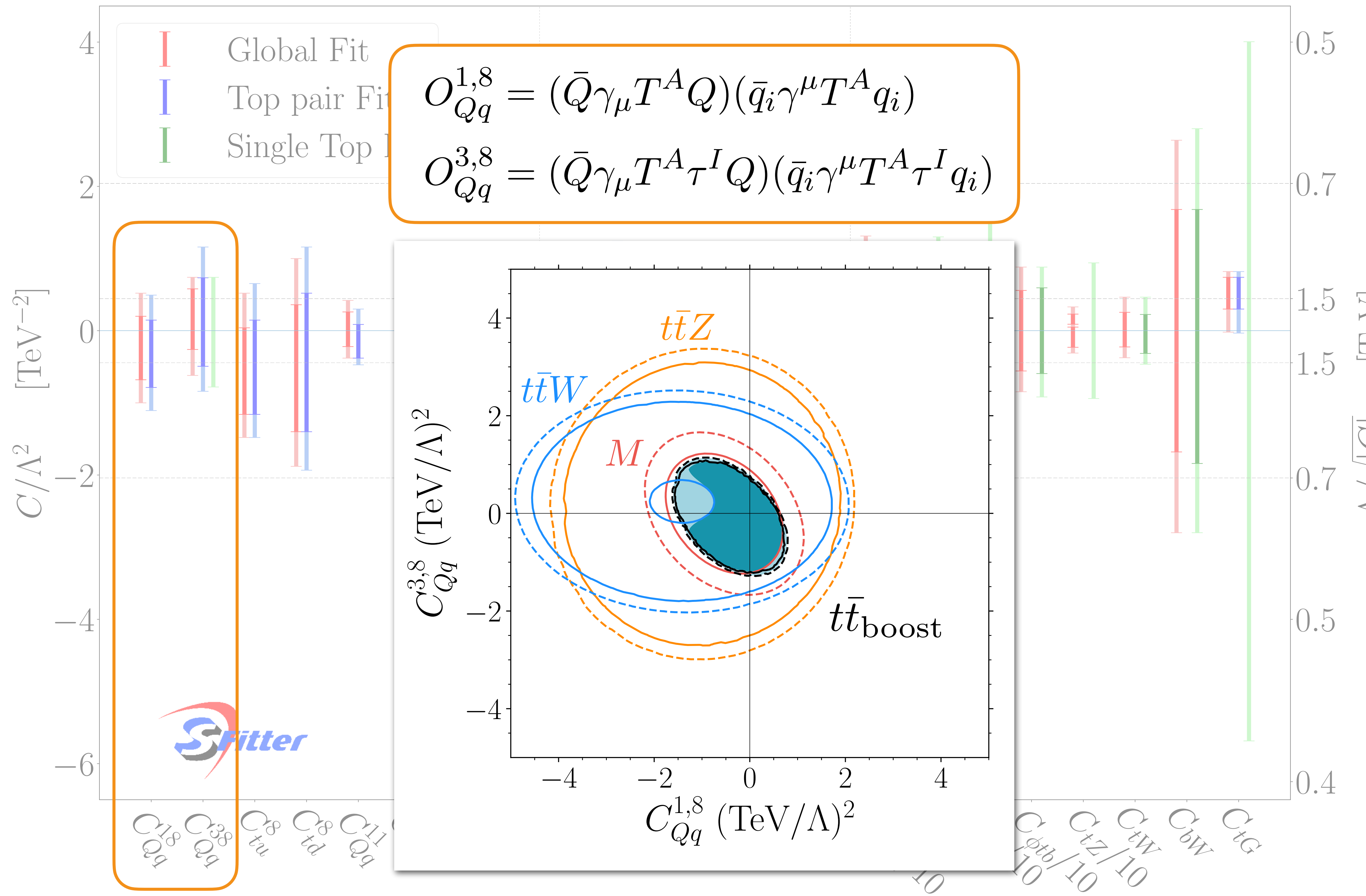
adapted from Aoude et al. 2020

Global fit of LHC top data



Brivio, Westhoff et al. 2019

Resolving directions in SMEFT space



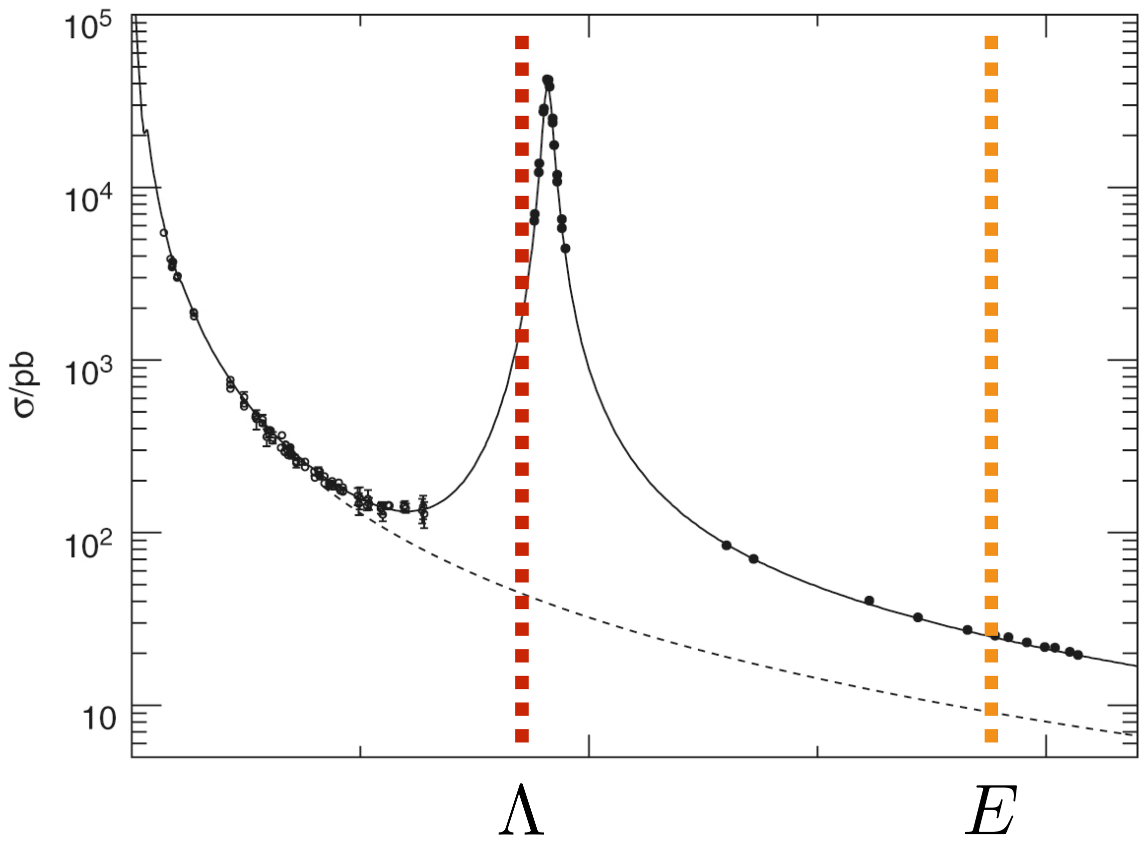
$$O^{1,8}_{Qq} = (\bar{Q}\gamma_\mu T^A Q)(\bar{q}_i \gamma^\mu T^A q_i)$$

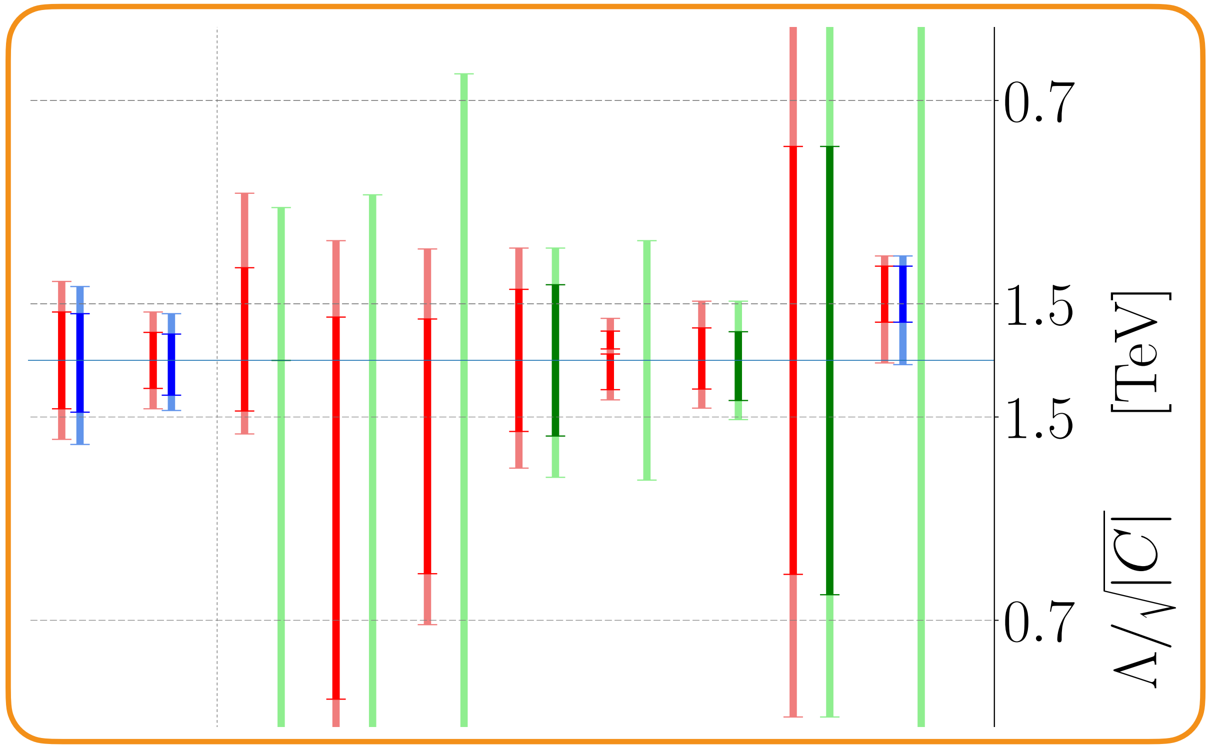
$$O^{3,8}_{Qq} = (\bar{Q}\gamma_\mu T^A \tau^I Q)(\bar{q}_i \gamma^\mu T^A \tau^I q_i)$$

Brivio, Westhoff et al. 2019

SMEFT at its limits

- LHC probes energies up to $E \sim 5\,\mathrm{TeV}$
- constrains SMEFT effects up to $\Lambda/\sqrt{C} \sim 1.5\,\mathrm{TeV}$





Caution: SMEFT interpretation not always valid at high energies.

Summary Part III

Standard Model Effective Theory:

- general description of new physics effects for $E \ll \Lambda$
- effective Lagrangian:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C_5}{\Lambda} O^{(5)} + \sum_i \frac{C_i}{\Lambda^2} O_i^{(6)} + \ldots$$

SMEFT amplitude parametrizes effects of heavy new physics:

- model-independent, SM-invariant, complete
- combine observables in global fits

SMEFT can help to discover subtle NP effects via correlations.

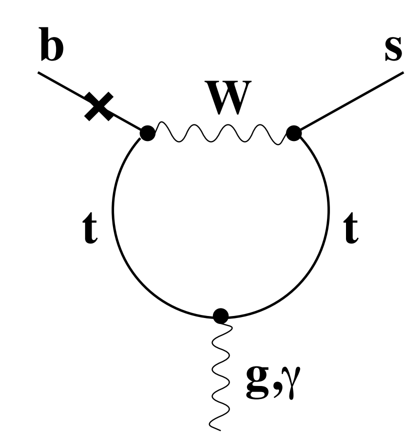
Your turn

1) Consider Higgs production and decay into photons at the LHC:

$$pp \to h \to \gamma\gamma$$

- Write down the Feynman diagram for this process.
- What SMEFT operators can be probed?

2) Consider the rare *B* meson decay $B \to X_s\gamma$.



- What SMEFT operators contribute?
- Can they be probed in other processes?

Combining LHC and flavor observables

$\Lambda = m_X$

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

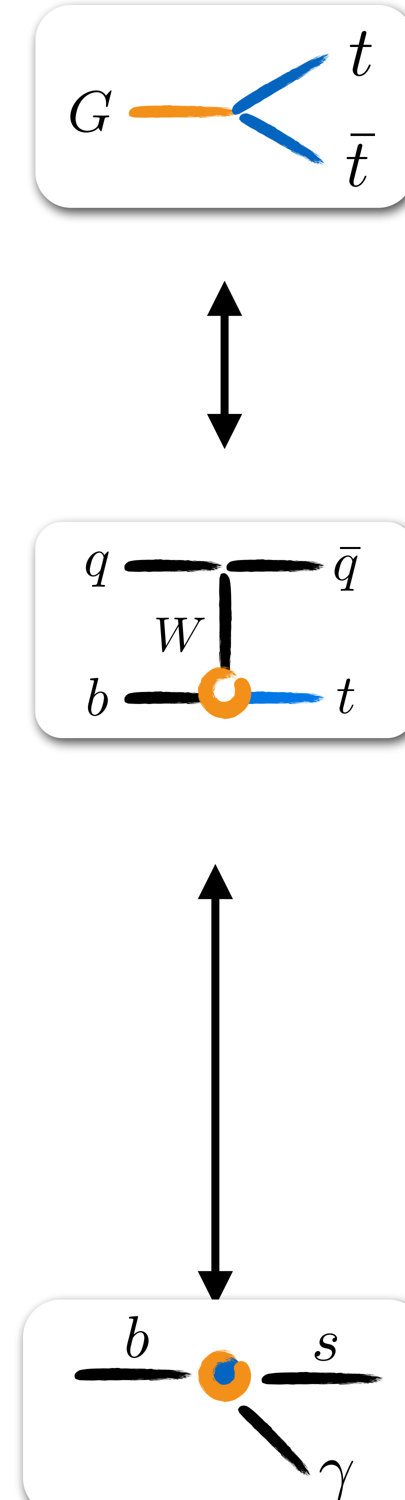
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^{\gamma_i}} O_i$$

m_W

$$\mathcal{C}_i(m_W) = F(C_i(m_W))$$

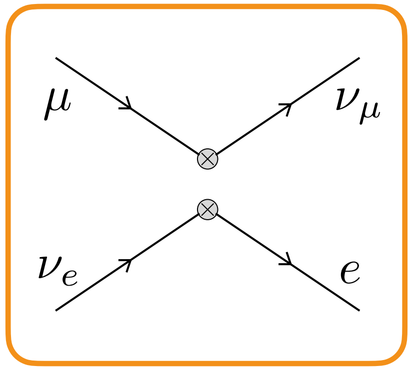
$$\mathcal{L}_{\text{WET}} = \mathcal{L}_{\text{QCD+QED}} - \frac{4G_F}{\sqrt{2}} \sum_i \mathcal{C}_i\, \mathcal{O}_i^{(6)}$$

m_b



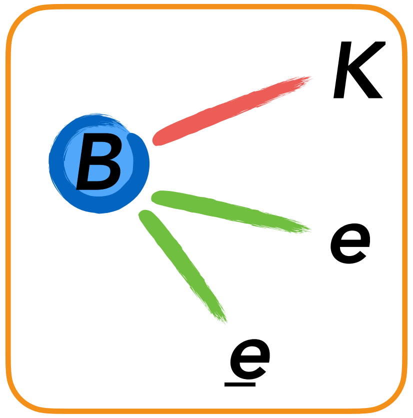
Bruggisser, van Dyk, Schaefer, Westhoff 2021

Take home: Most powerful tools



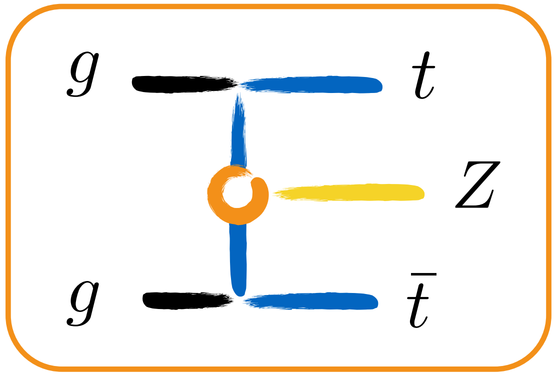
Basics:

- effective Lagrangian
- operator expansion



Weak EFT:

- meson decays through weak interactions
- running effective couplings



Standard Model EFT:

- particle collisions above the weak scale
- model-independent search for heavy new physics

Literature

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A. Manohar 2018: Introduction to Effective Field Theories

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I. Brivio, M. Trott, 2017: The Standard Model as an Effective Field Theory