Funded by DFG Deutsche Forschungsgemeinschaft German Research Foundation

Collaborative Research Center TRR 257 P H Particle Physics Phenomenology after the Higgs Discovery

TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Running and Matching in the SMEFT

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Vast Range of BSM Scenarios

- **Deficits of the Standard Model:**
  - Not accounting for several cosmological observations (dark matter, baryon asymmetry, dark energy, gravity, ...)
  - Theoretical shortcomings:
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    - No explanation of neutrino masses
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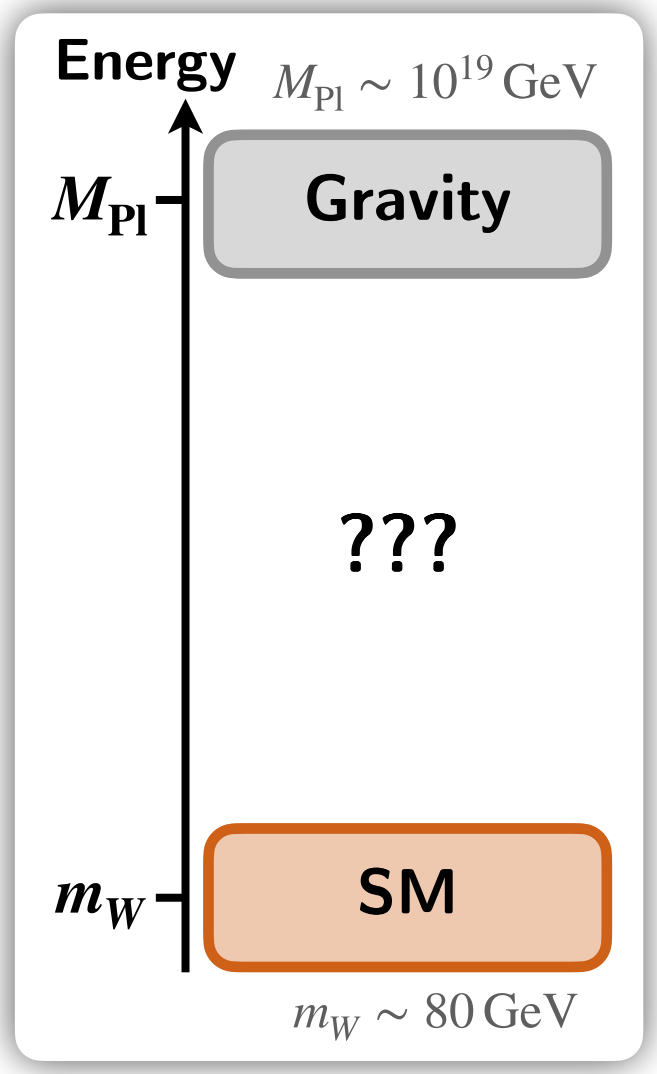

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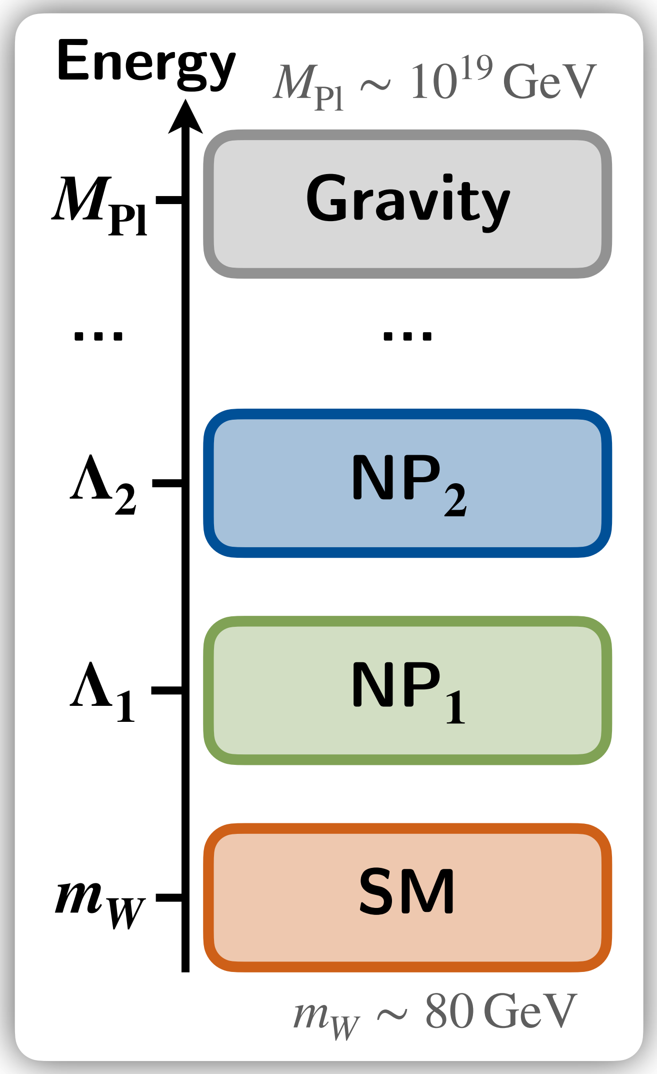
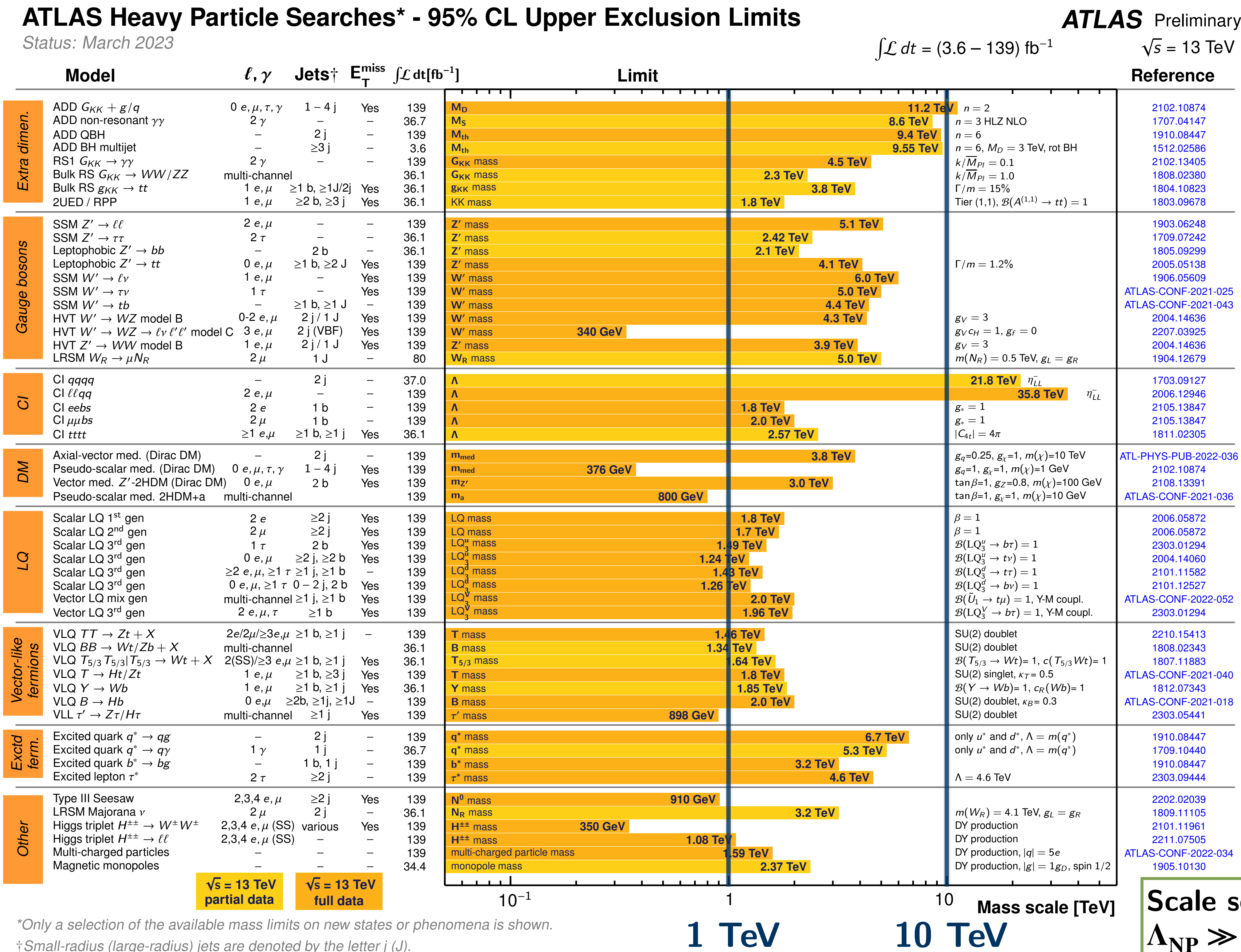


- Resolved by NP beyond the SM at higher energies? → out of reach of current experiments
- Wide range of possible BSM theories (SUSY, composite Higgs, Pati-Salam,...)
- Not all SM shortcomings necessarily solved in single theory → **multi-layer structure**

➡ Determining the next layer is the principal challenge of HEP

Collider Limits on the New Physics Scale



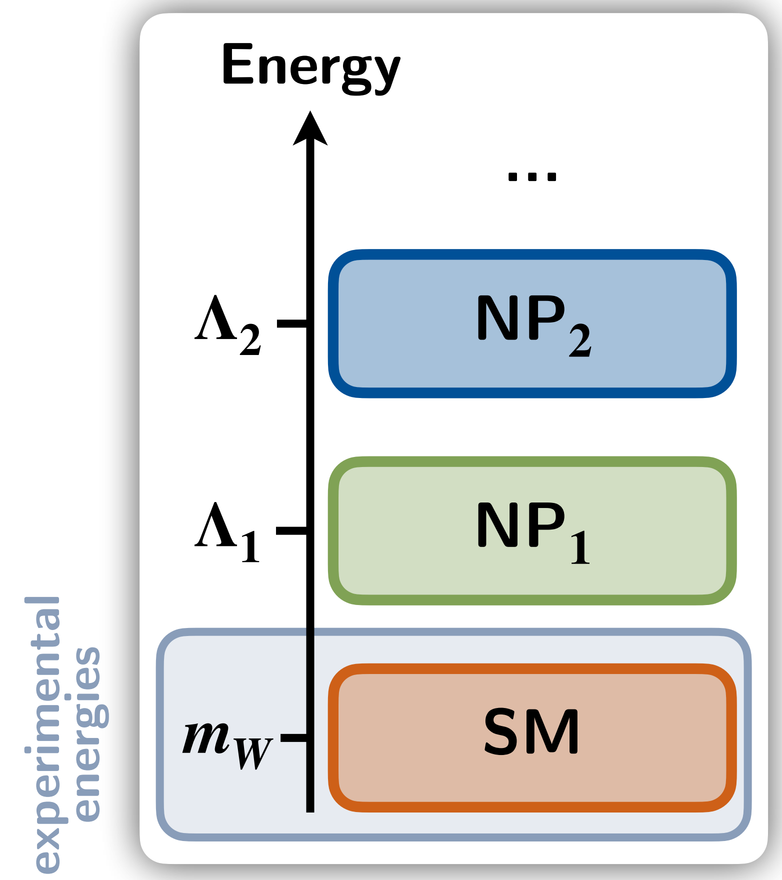
ATL-PHYS-PUB-2023-008

1 TeV **10 TeV**

Scale separation: $\Lambda_{NP} \gg v_{EW}$

Benefits of Effective Field Theory

- Heavy BSM particles not directly produced in experiments
- Probe heavy states indirectly through imprints on low-energy observables $\mathcal{O}_{\text{exp}} \simeq \mathcal{O}_{\text{SM}} + \delta\mathcal{O}_{\text{NP}}$



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  - Consider $\mathscr{L}_{\text{NP}}(\eta_H, \eta_L)$ with fields η_H and η_L with masses $\Lambda_1 \sim m_H \gg m_L \sim m_W$
  - Construct effective description $\mathscr{L}_{\text{EFT}}(\eta_L)$ containing only SM particles η_L
  - Effects η_H incorporated through new small interactions Q_i

$$\mathscr{L}_{\text{EFT}}(\eta_L) = \mathscr{L}_{d=4}(\eta_L) + \sum_{d=5}^{\infty} \frac{1}{m_H^{d-4}} \sum_i C_i^{(d)} Q_i^{(d)}(\eta_L)$$

  - Only finite number of operators Q_i allowed (for fixed d)

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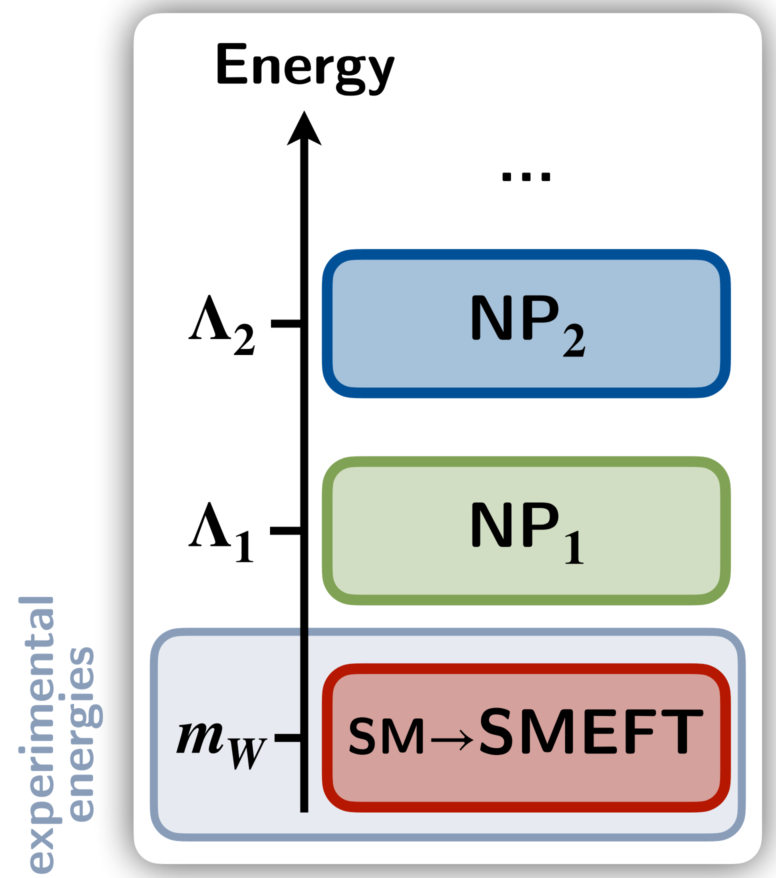

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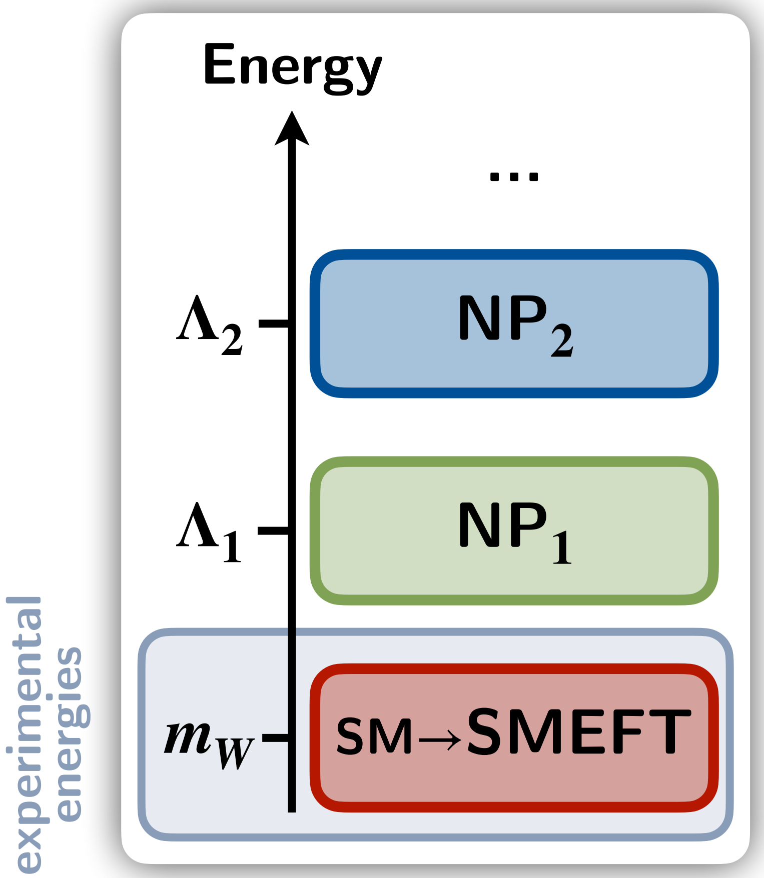
  - ➡ Resummation of large logarithmic corrections



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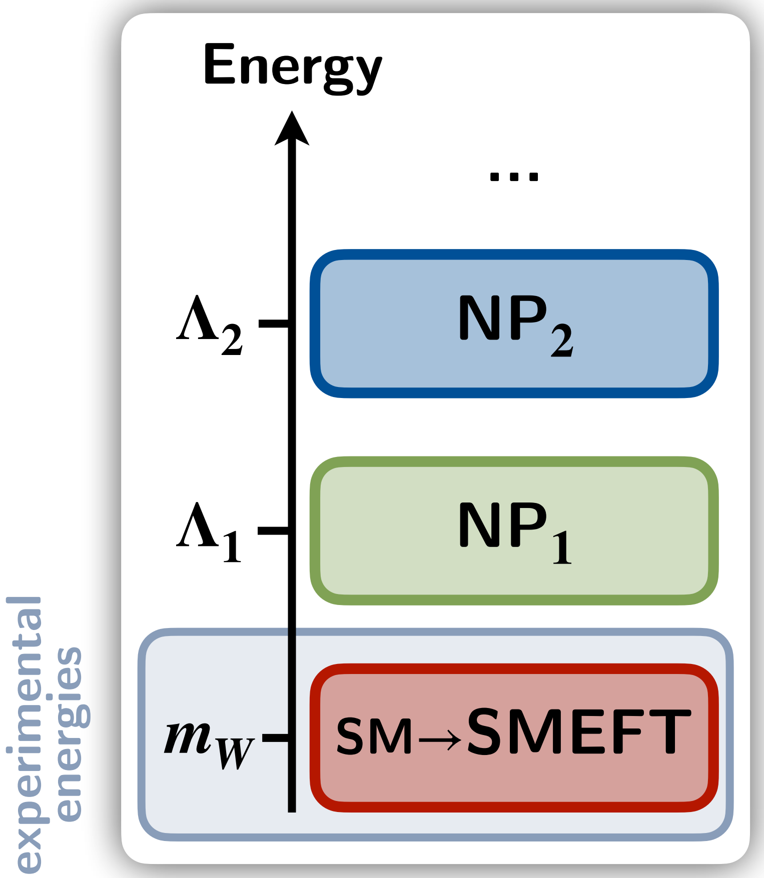

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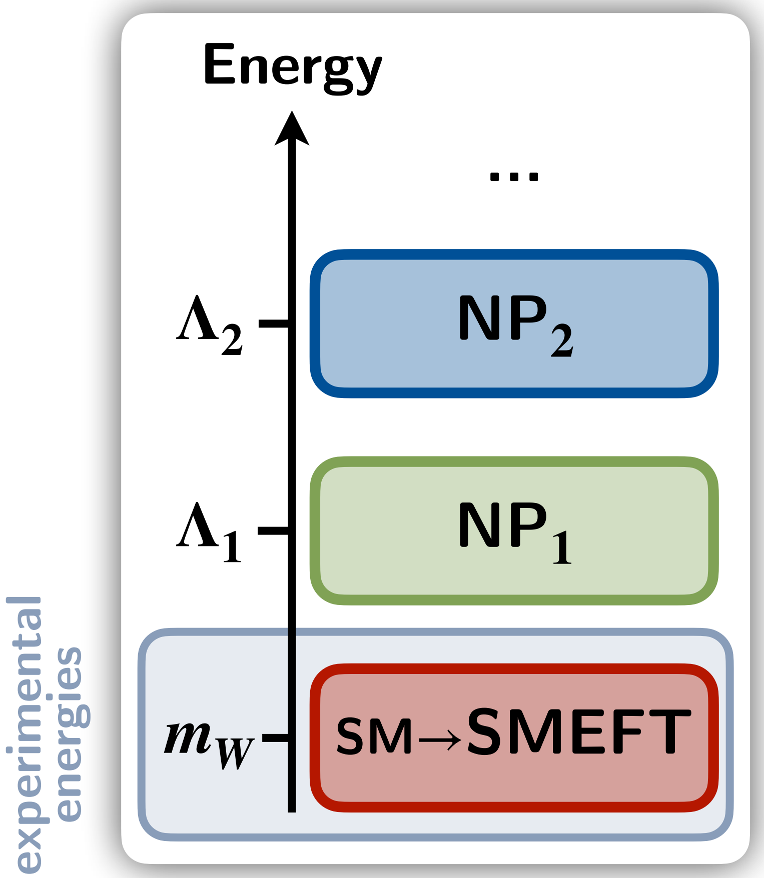

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- Challenge:
  - Relate Wilson coefficients C_i to parameters of explicit BSM theories

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- Physics described by tower of EFTs valid at different energy scales (every QFT is an EFT)
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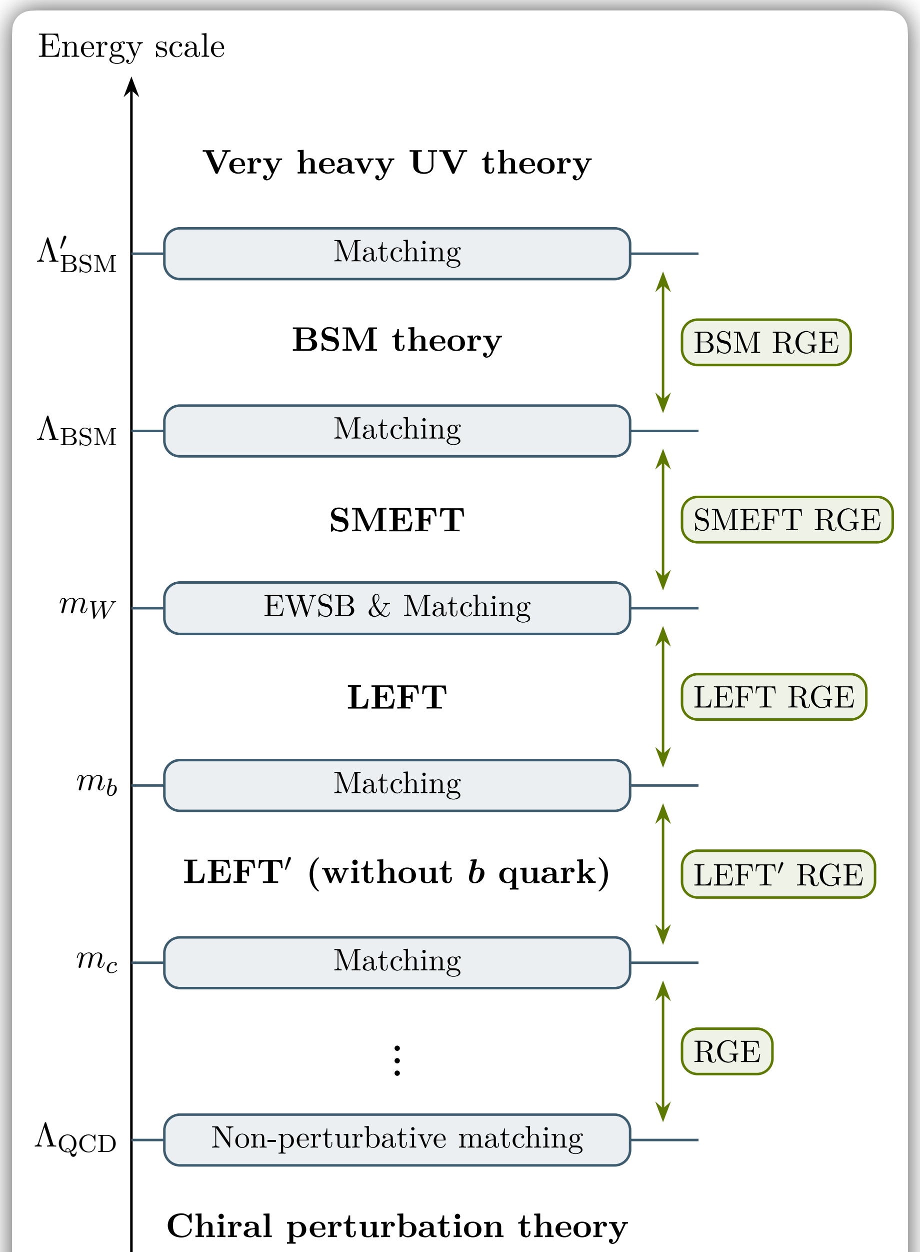

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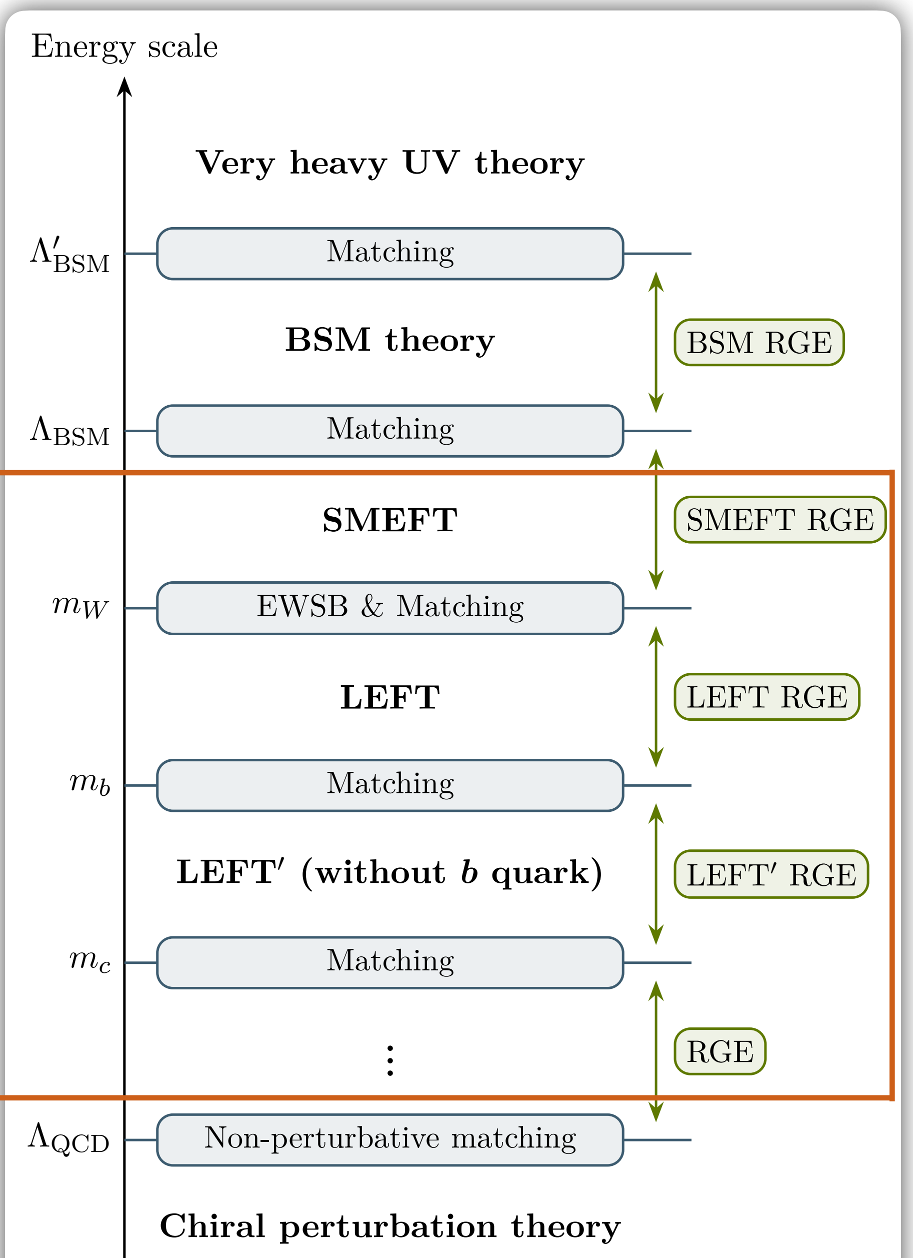

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SMEFT-to-LEFT matching:
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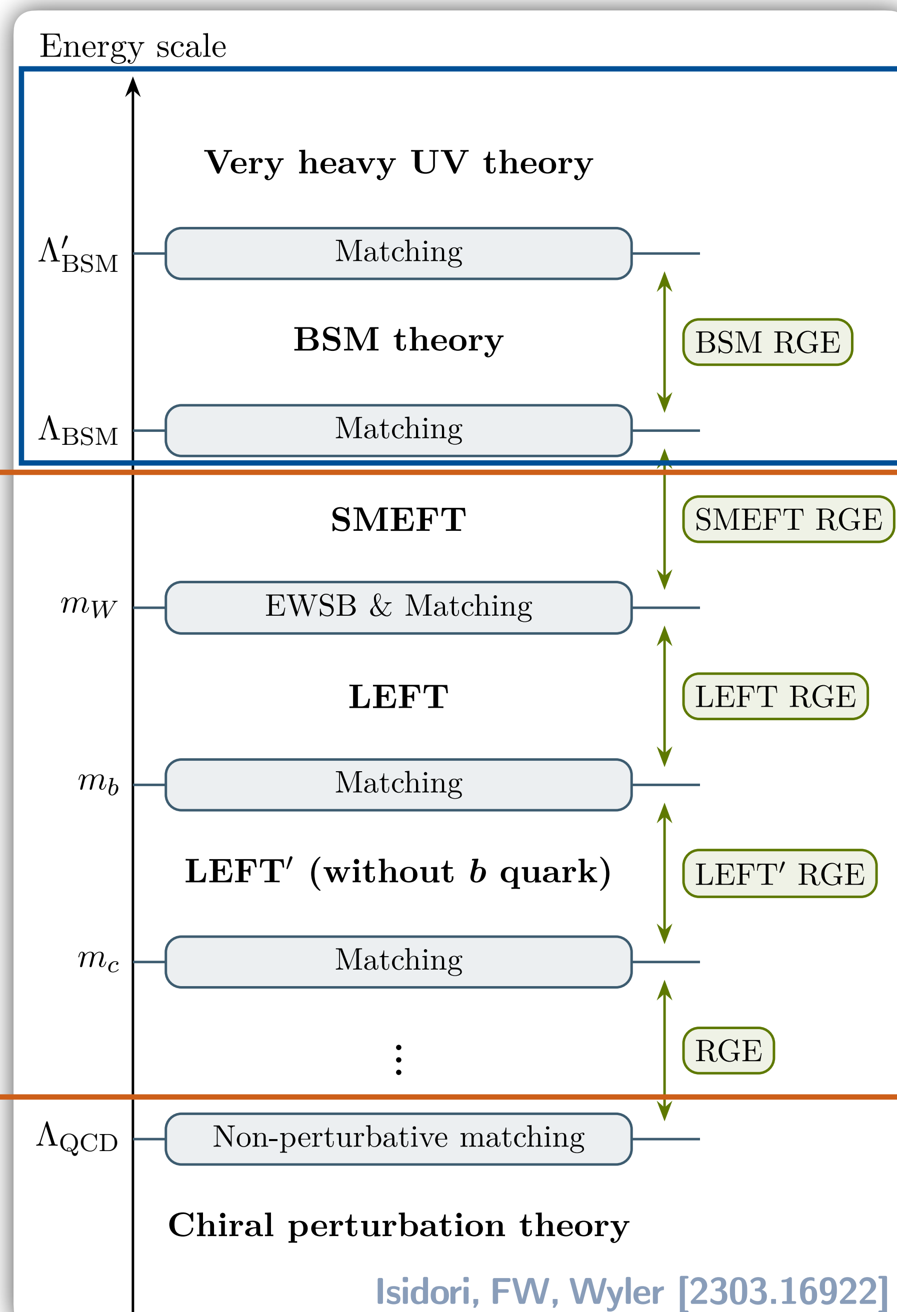

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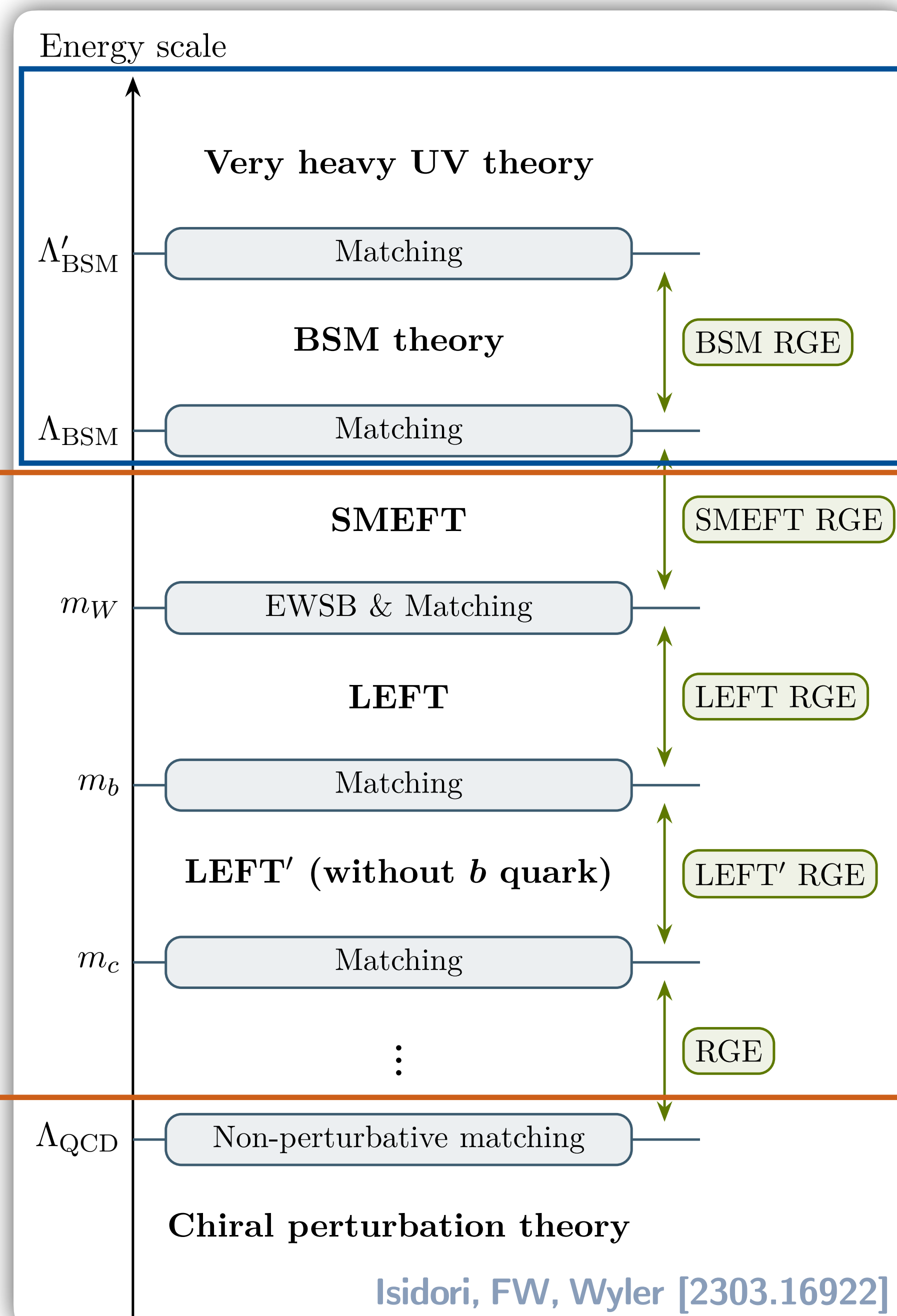

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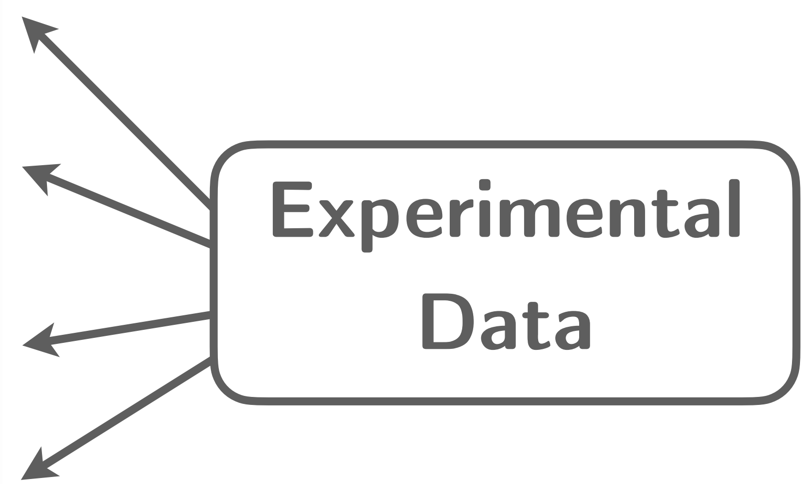

Scale Evolution in EFTs

Running and Matching in SMEFT and LEFT

Renormalization Group Evolution in SMEFT and LEFT

- RG evolution from one particle threshold to the next
- Resummation of large logarithmic corrections:
  - SMEFT: $\log\left(\frac{\Lambda_{\text{BSM}}^2}{m_W^2}\right)$, LEFT: $\log\left(\frac{m_W^2}{m_b^2}\right)$, ...
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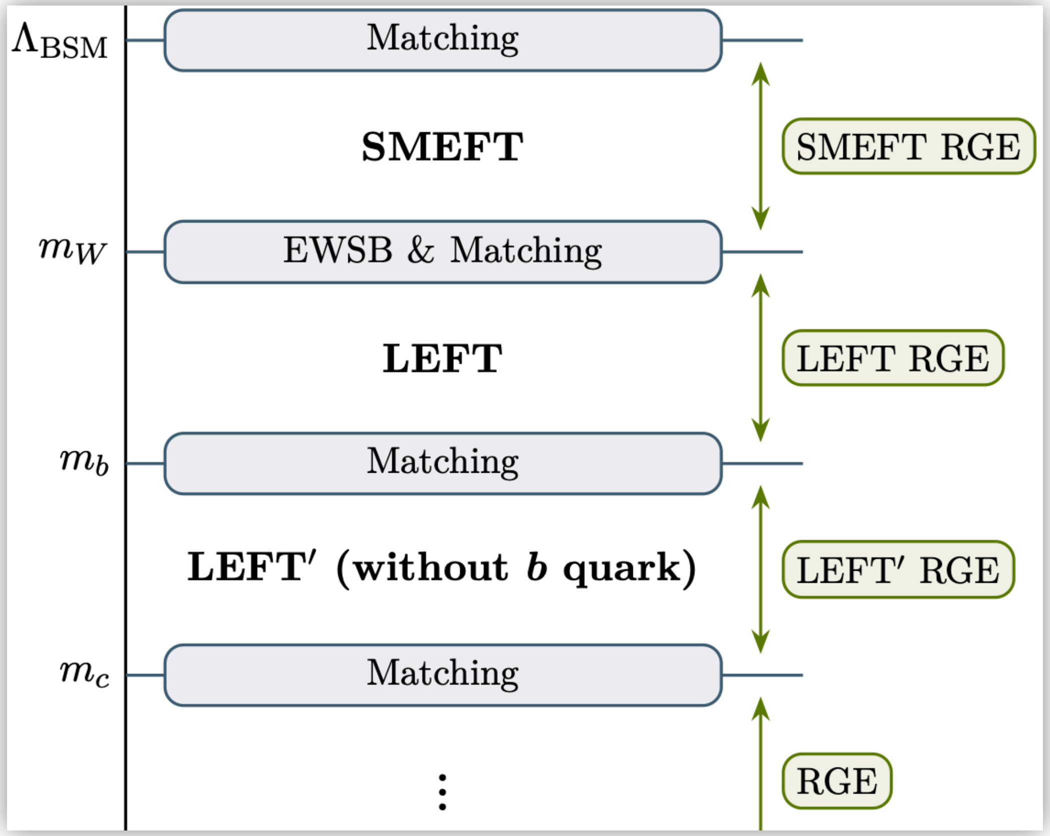

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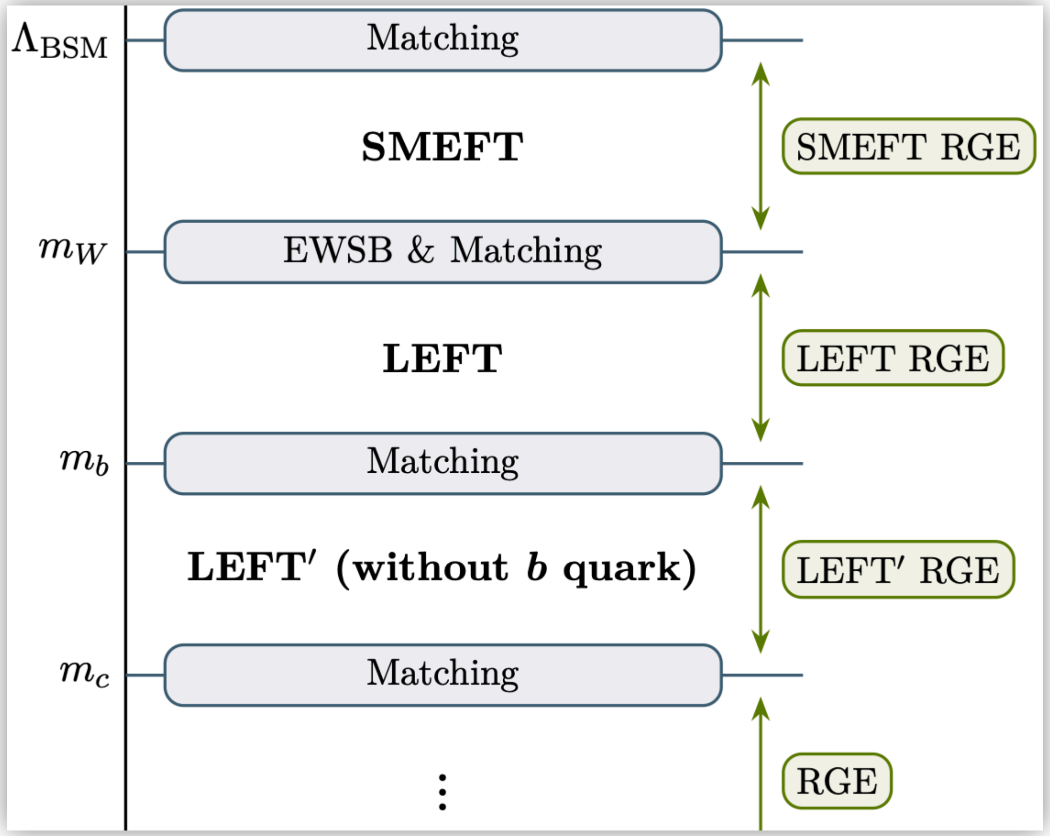

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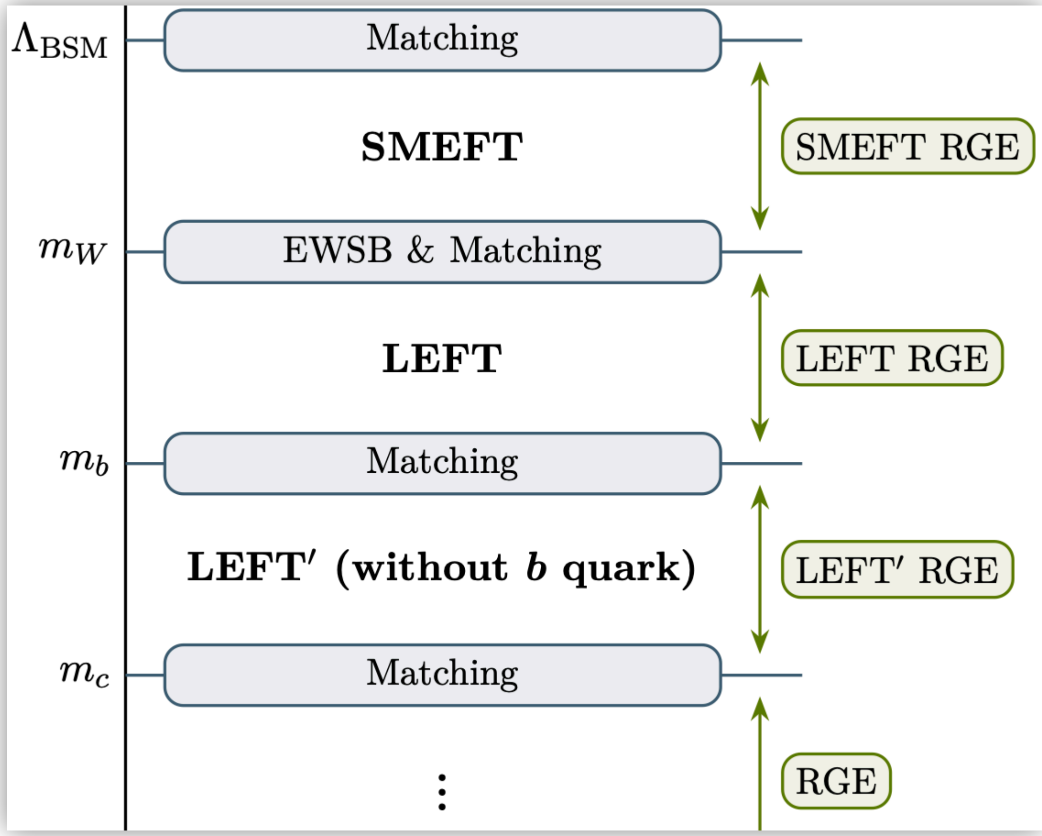

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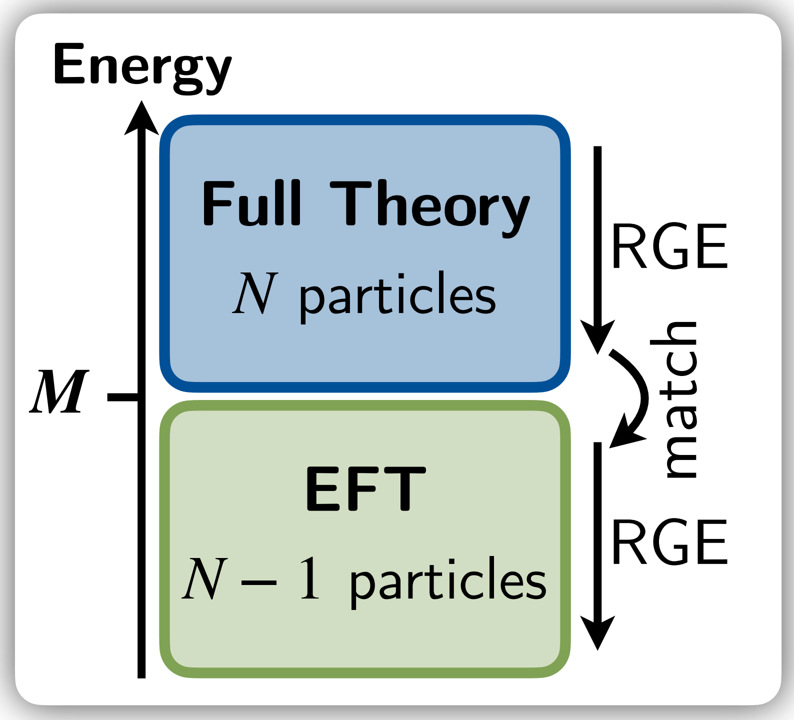
- **Two-loop RGE**: significant progress
  Naterop, Stoffer [2412.13251]
  Born, Fuentes-Martín, Kvedaraitė, Thomsen [2410.07320]
  Di Noi, Gröber, Mandal [2408.03252]
  Jenkins, Manohar, Naterop, Pagès [2310.19883]
  Aebischer, Buras, Kumar [2203.11224]
  Bern, Parra-Martinez, Sawyer [2005.12917]

RG Evolution Across Particle Thresholds: Matching

- RGE across the mass threshold: particle becomes non-dynamical
- The particle should be integrated out of the spectrum
  - Obtaining new EFT with fewer particles
- **Matching:** determining the operators and coefficient of this EFT



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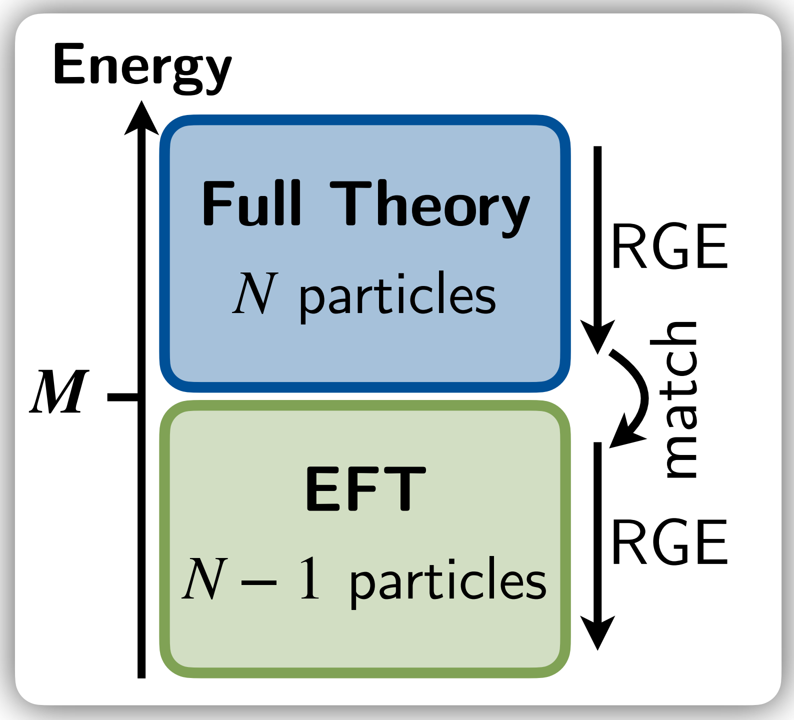

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  As function of light fields η_L only

  ➡ Expand UV contribution in powers of m_H^{-1}

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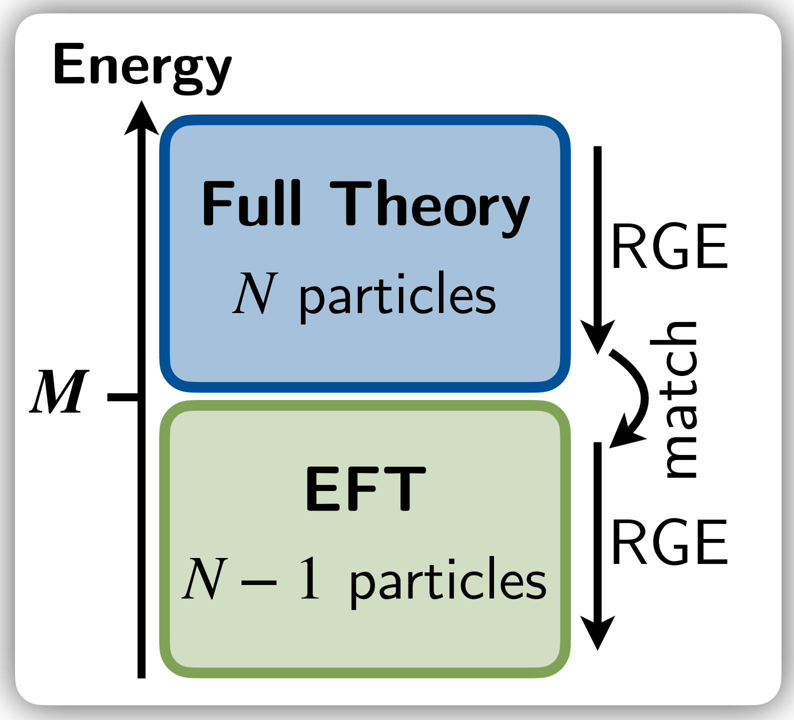

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- Matching conditions can be seen as RG equations when decoupling a particle while crossing its mass threshold
  - Log terms of matching conditions provide difference between RGE of UV and IR theory

Diagrammatic Matching: off-shell vs. on-shell

- **Diagrammatic on-shell matching:**
  - Compute all Feynman diagrams contributing to S-matrix, i.e.,
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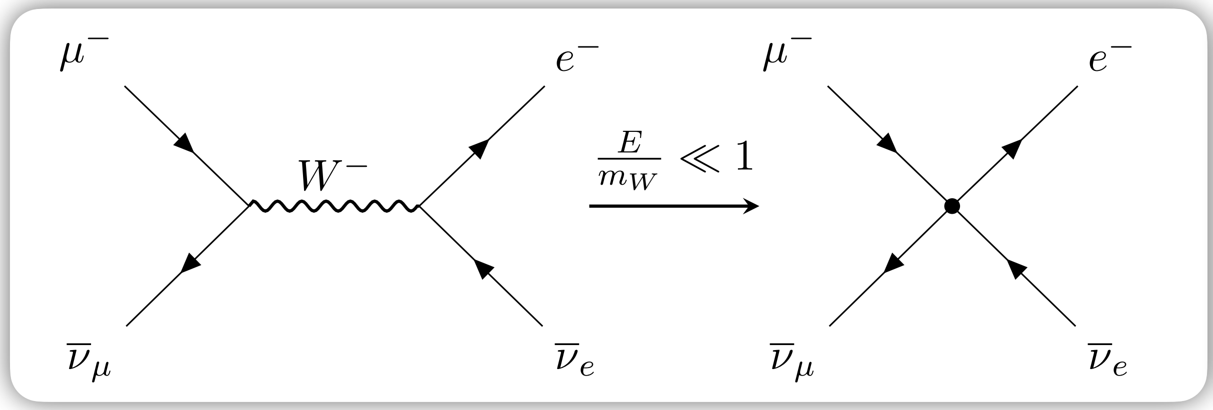
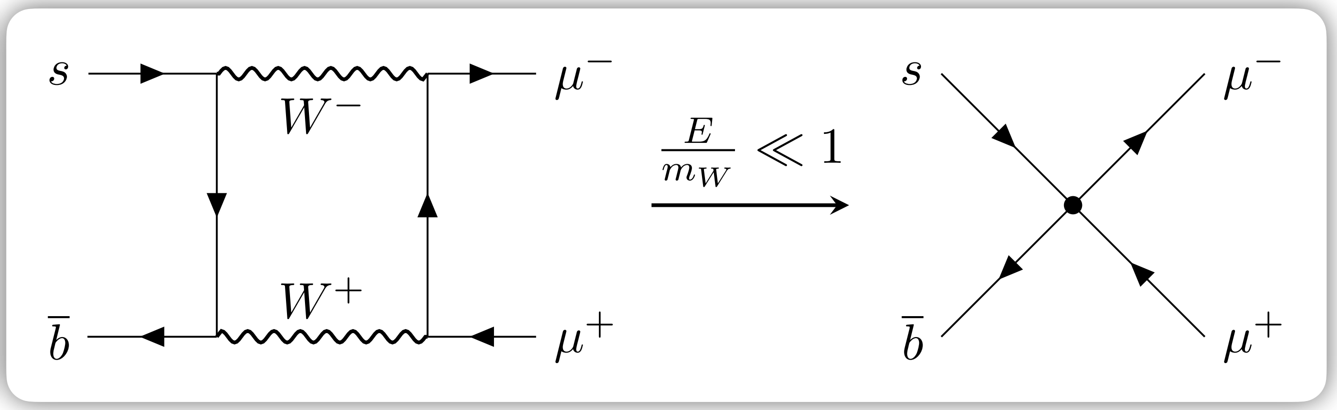


Tree-level matching $G_F = \frac{\sqrt{2}}{8}\frac{g^2}{M_W^2}$



One-loop matching

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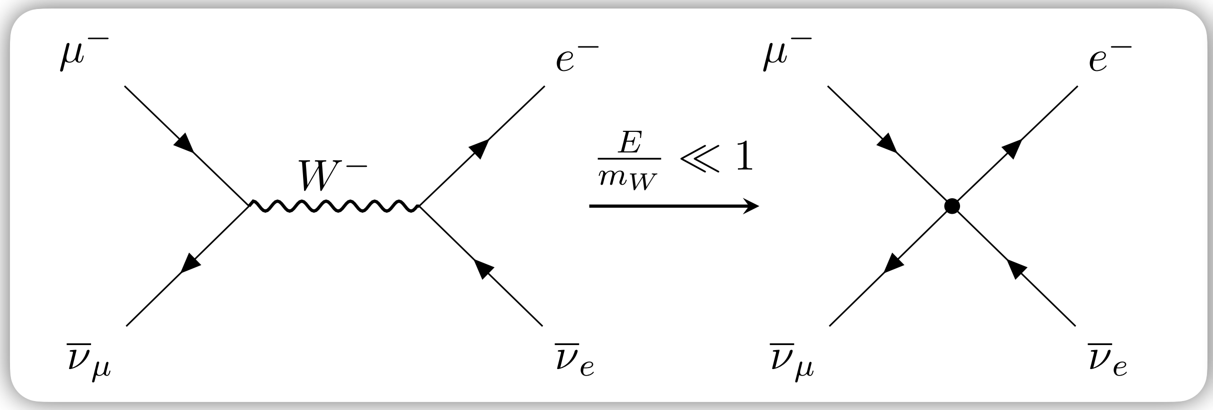
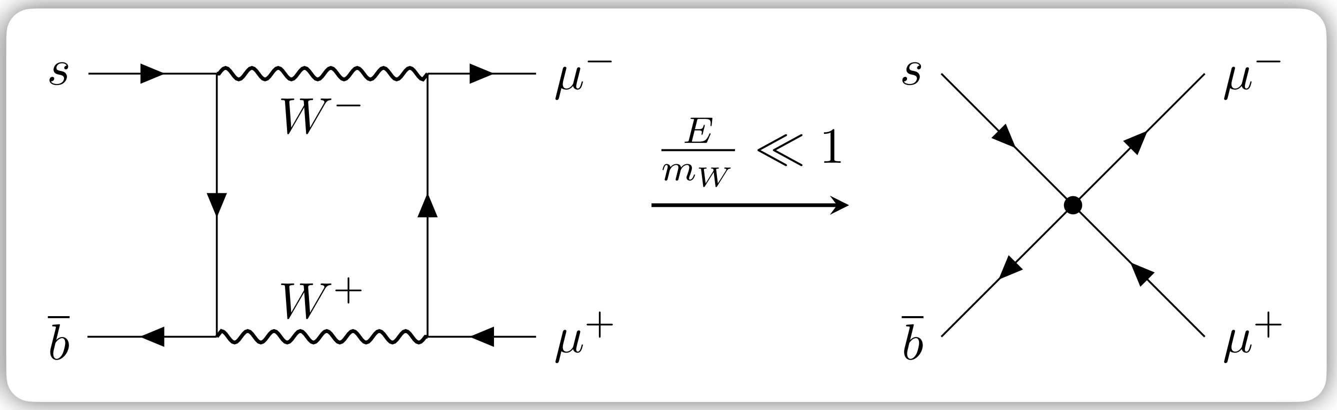
Note: need to know EFT operators in advance





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Functional Matching

- **Lagrangian:** $\mathscr{L}_{\mathrm{UV}}(\eta)$ with fields $\eta = \left(\eta_H, \eta_L\right)^{\intercal}$ and hierarchy $m_H \gg m_L$

- **Background field method:** shift all fields $\eta \to \hat{\eta} + \eta$
  $\hat{\eta}$: background fields (satisfy classical EOM)
  η: pure quantum fluctuation

- **Path integral representation of effective quantum action:**

$$\exp\left(i\Gamma_{\mathrm{UV}}(\hat{\eta})\right) = \int \mathscr{D}\eta \, \exp\left(i \int \mathrm{d}^D x \, \mathscr{L}_{\mathrm{UV}}(\eta + \hat{\eta})\right)$$

  - Perform path integral over η_H (*"integrating out"* the heavy states)
  - Expand in powers of m_H^{-1}

- **Produces effective quantum action of EFT:**
  - Γ_{EFT} containing all higher-dimensional operators and coefficients

Gaillard [*Nucl. Phys. B* 268 (1986) 669-692];

Cheyette [*Nucl. Phys. B* 297 (1988) 183-204];

Dittmaier, Grosse-Knetter [hep-ph/9501285] [hep-ph/9505266];

Henning, Lu, Murayama [1412.1837];

Drozd, Ellis, Quevillon, You [1512.03003];

del Aguila, Kunszt, Santiago [1602.00126];

Fuentes-Martin, Portoles, Ruiz-Femenia [1607.02142];

Henning, Lu, Murayama [1604.01019];

Zhang [1610.00710];

Krämer, Summ, Voigt [1908.04798];

Cohen, Lu, Zhang [2011.02484] [2012.07851];

Fuentes-Martín, König, Pagès, Thomsen, FW [2012.08506] [2212.04510];

& many more

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- **Saddle point approximation of the action:**

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higher loop orders
Fuentes-Martín, (Moreno-Sánchez,) Palavrić, Thomsen [2311.13630], [2412.12270]

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- Missing pieces:
  - Integrating out vector bosons
  - Linking to the phenomenological EFT toolchain

Eliminating Redundant Operators (when matching off-shell)

- $\Gamma^{(1)}_{\text{UV}}\Big|_{\text{hard}} = \int \mathrm{d}^D x\, \mathscr{L}^{(1)}_{\text{EFT}}$ directly provides **EFT operators & coefficients**, but $\mathscr{L}_{\text{EFT}}$ contains **redundancies** among the operators and is in a $\boldsymbol{D}$**-dimensional** space

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  - Reduction of Dirac algebra
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(Reduction of Dirac algebra, Fierz identities) → **evanescent operators**

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Required for:
matching & running

- Some identities for the reduction of redundant operator structures are **intrinsically 4-dimensional** and do not hold in $D = 4 - 2\epsilon$ dimensions:

  - Projections onto 4-dimensional Dirac basis $\{\Gamma_N\} = \{P_L, P_R, \gamma^\mu P_L, \gamma^\mu P_R, \sigma^{\mu\nu}\}$
    - Dirac reduction $$X \otimes Y = \sum_n b_n(X, Y)\Gamma^n \otimes \tilde{\Gamma}_n$$
    - Fierz identities $$(X) \otimes [Y] = \frac{1}{4}\mathrm{tr}\{X\tilde{\Gamma}_n Y \tilde{\Gamma}_m\}\, (\Gamma^m] \otimes [\Gamma^n)$$
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Physical Contributions by Evanescent Operators

Buras, Weisz [Nucl.Phys.B 333 (1990) 66-99]; Dugan and Grinstein [PLB 256 (1991) 239]; Herrlich, Nierste [hep-ph/9412375]

- Evanescent operators $E \equiv R - Q$ formally of rank ϵ
  - Tree level: no physical contributions
  - One loop: contributions from (local) UV poles $\Rightarrow$ finite contribution to matrix elements
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- For one-loop EFT action $S^{(1)}$ we find ($\mathscr{P}$ projection $R \to Q$ using $D = 4$ identities)

$$\mathscr{P} S_Q^{(1)} = \mathscr{P} S_R^{(1)} + \Delta S^{(1)}, \qquad \text{where} \qquad \Delta S^{(1)} \equiv \mathscr{P}\left(\overline{\Gamma}_R^{(1)} - \overline{\Gamma}_Q^{(1)}\right)$$

  - $\overline{\Gamma}_X^{(1)}$: sum of one-loop diagrams with vertices from X contributing to effective action
  - $\Delta S^{(1)}$: sum of one-loop diagrams with insertions of evanescent operators $E = R - Q$

- **Resulting renormalization scheme is an evanescent-free version of $\overline{\text{MS}}$**

Aebischer, Buras, Kumar [2202.01225]; Aebischer, Pesut [2208.10513]; Aebischer, Pesut, Polonsky [2211.01379]; Fuentes-Martin, König, Pages, Thomsen, FW [2211.09144];

Example

- Example term from tree-level EFT Lagrangian requiring Fierzing to map onto Warsaw basis
- Fierz identity: $(\overline{q}_p u_r)(\overline{u}_s q_t) = -\frac{1}{6}(\overline{q}_p \gamma_\mu q_t)(\overline{u}_s \gamma^\mu u_r) - (\overline{q}_p \gamma_\mu T^A q_t)(\overline{u}_s \gamma^\mu T^A u_r)$
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$$
\begin{aligned}
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& + \frac{1}{4}\overline{y_u^{uv}}\, y_u^{ts} Q_{qu}^{(1)puvr} + \frac{1}{4}\overline{y_u^{pr}}\, y_u^{uv} Q_{qu}^{(1)utsv} + \frac{1}{2} y_d^{tu} y_u^{vs} Q_{quqd}^{(8)vrpu} \\
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& + Q_{uH}^{pr}\left(3\overline{y_u^{uv}}\, y_u^{tv} y_u^{us} - \frac{3}{2}\lambda y_u^{ts}\right) + \frac{3}{2}\overline{y_e^{uv}}\, \overline{y_u^{pr}}\, \overline{Q_{\ell equ}^{(1)uvts}} \\
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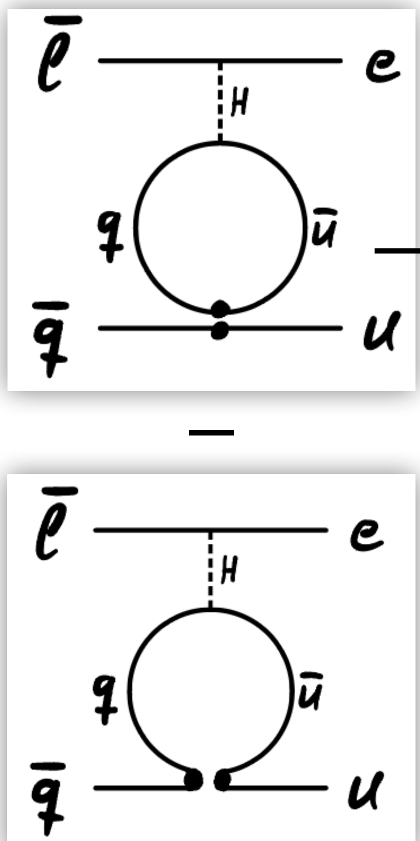

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- Finite renormalization to compensate for evanescent operator
  (loop suppressed → only relevant for tree-level EFT Lagrangian)
- Renormalization scheme: **evanescent-free version of $\overline{\text{MS}}$**
- All finite renormalization constants required for SMEFT computed in
  Fuentes-Martín, König, Pagès, Thomsen, FW [2211.09144]

Phenomenology

From High to Low Energies

Combining Data at Different Energies with EFTs

- Low-energy BSM analyses often performed directly in EFT setup (LEFT)
  - EFT validity $E \ll \Lambda_{\text{NP}}$ ✓
  - Pheno tools with large sets of experimental observables available
    - e.g. `flavio` Straub (Stangl) [1810.08132] , `EOS` van Dyk *et al.* [2111.15428]

- High-energy BSM searches at LHC mostly performed for explicit BSM theories
  - EFT validity $E \lesssim \Lambda_{\text{NP}}$? → has to be assessed case by case
  - Have to be recast/reinterpreted in EFT framework
  - Some tools for certain observables
    - e.g. `SMEFiT` Giani *et al.* [2302.06660], `HEPfit` De Blas *et al.* [1910.14012], `HighPT` Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10756]

- Some results now directly provided in EFT framework
  - More hopefully in the future

➡ Advantageous for EFT program

Example:

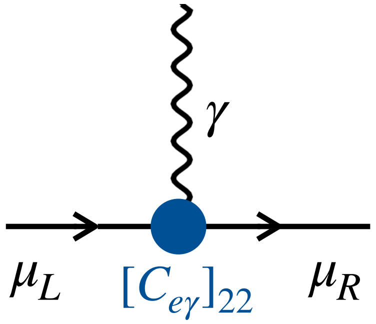
Importance of RG Mixing for $(g-2)_\mu$ and $\mathcal{B}(\mu \to e\gamma)$

Flavor Patterns of the Anomalous Magnetic Moment of the Muon

Measurements of $(g-2)_\mu$ and $\mathcal{B}(\mu \to e\gamma)$

- We work in the SMEFT/LEFT with the hypothesis of heavy NP: $\Lambda_{\text{NP}} \gg v$
- Electromagnetic dipole operator in LEFT: $[Q_{e\gamma}]_{\alpha\beta} = (v/\sqrt{2})\left(\bar{e}^L_\alpha \sigma^{\mu\nu} e^R_\beta\right) F_{\mu\nu}$

$(g-2)_\mu$



$\Delta a_\mu = a_\mu^{\text{Exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}$

[hep-ex/0602035, 2104.03281, 2006.04822]

Hints at non-vanishing dipole operator $[C'_{e\gamma}]_{22}$

$[C'_{e\gamma}]_{22} = 1.0 \times 10^{-5}\,\text{TeV}^{-2}$

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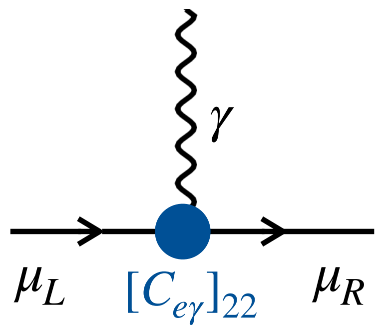

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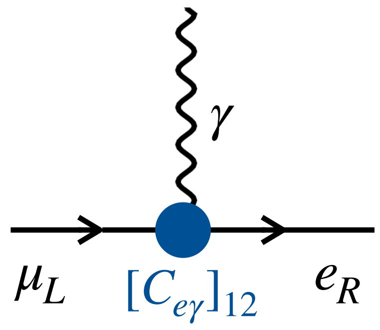
$\mu \to e\gamma$



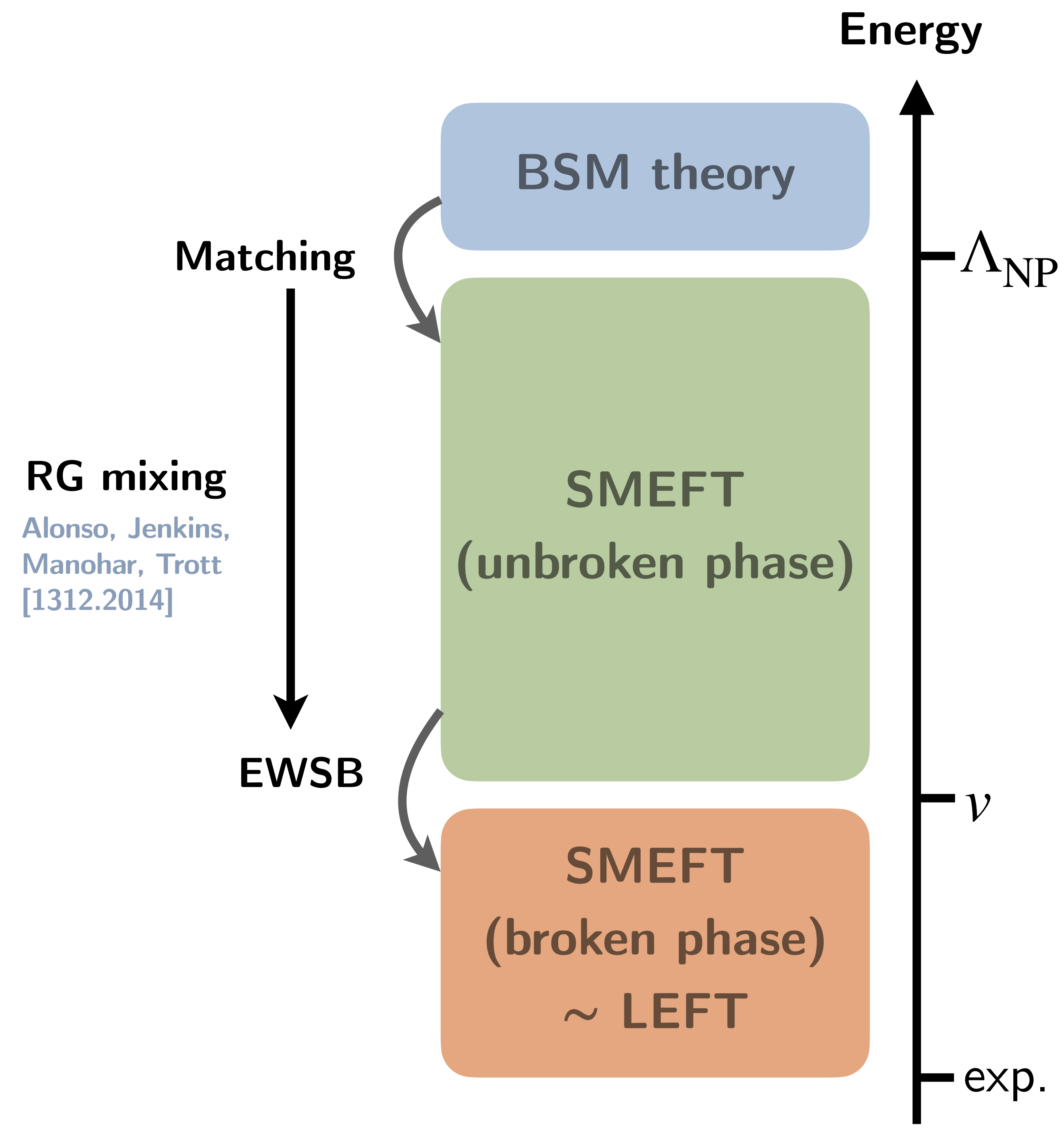
Non-observation of radiative LFV decays
$\mathscr{B}(\mu^+ \to e^+\gamma) \leq 4.2 \times 10^{-13}$ (90% C.L.)
MEG [1605.05081]

Implies strongly suppressed off-diagonal couplings $[C'_{e\gamma}]_{12(21)} \ll [C'_{e\gamma}]_{22}$

$|[C'_{e\gamma}]_{12(21)}| \leq 2.1 \times 10^{-10}\,{\rm TeV}^{-2}$

Misalignment: $\epsilon_{12}^{L(R)} \equiv \left| [C'_{e\gamma}]_{12(21)} / [C'_{e\gamma}]_{22} \right| \leq 2 \times 10^{-5}$

Renormalization Group Mixing of the Dipole Operators



Renormalization Group Mixing of the Dipole Operators

The broken phase

$$\begin{pmatrix} C_{\underset{rs}{e\gamma}} \\ C_{\underset{rs}{eZ}} \end{pmatrix} = \begin{pmatrix} c_\theta & -s_\theta \\ -s_\theta & -c_\theta \end{pmatrix} \begin{pmatrix} C_{\underset{rs}{eB}} \\ C_{\underset{rs}{eW}} \end{pmatrix}$$

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$$c_\theta = \frac{g_2}{\sqrt{g_1^2 + g_2^2}} = \frac{e}{g_1}$$

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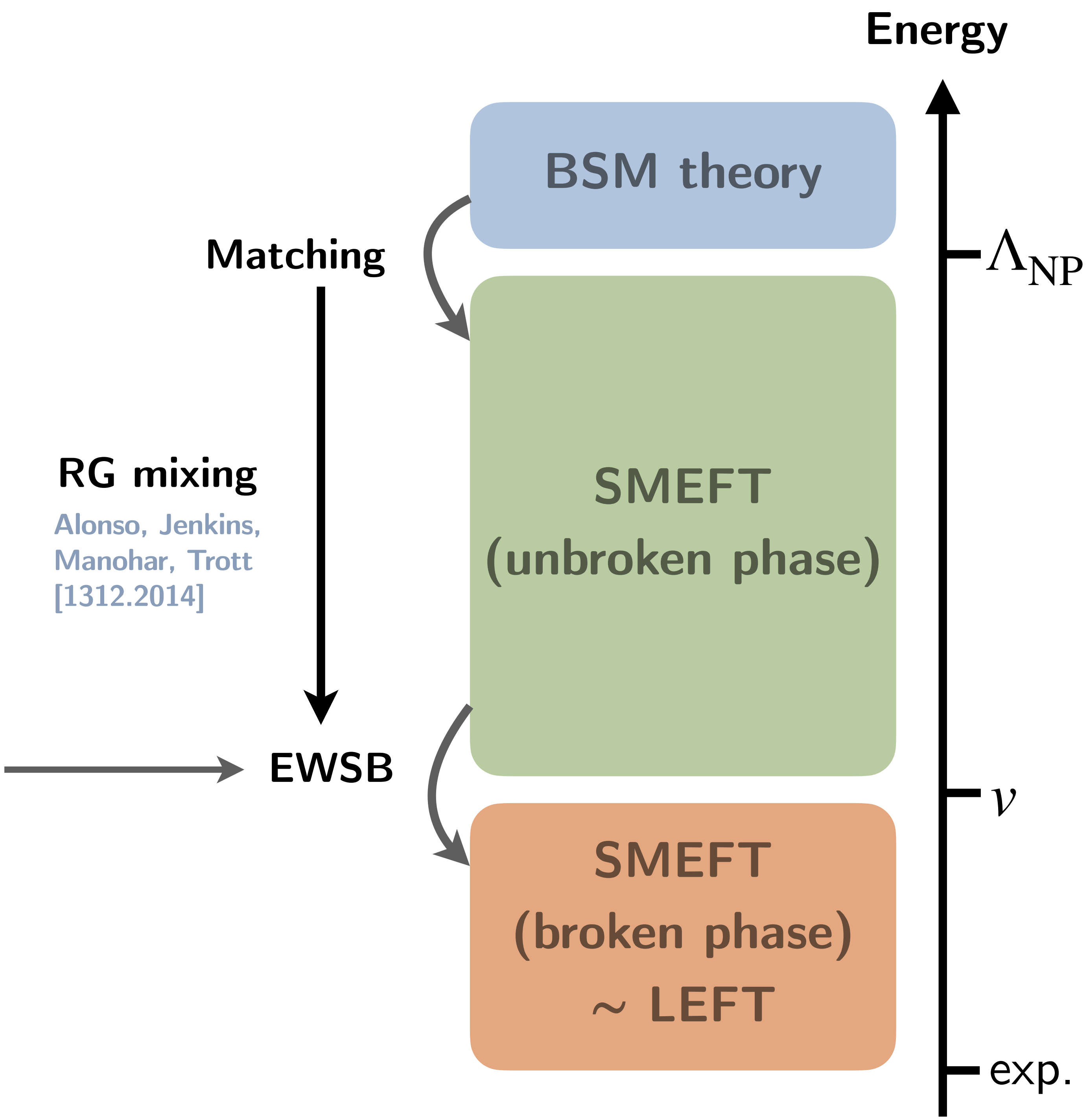

Renormalization Group Mixing of the Dipole Operators

SMEFT operators with $(\bar{\ell}_\alpha \Gamma e_\beta)$ structure:

$$[Q^{(1)}_{lequ}]_{\alpha\beta ij} = (\bar{\ell}^n_\alpha e_\beta)\epsilon_{nm}(\bar{q}^m_i u_j)$$

$$[Q^{(3)}_{lequ}]_{\alpha\beta ij} = (\bar{\ell}^n_\alpha \sigma_{\mu\nu} e_\beta)\epsilon_{nm}(\bar{q}^m_i \sigma^{\mu\nu} u_j)$$

$$[Q_{ledq}]_{\alpha\beta ij} = (\bar{\ell}^n_\alpha e_\beta)(\bar{d}_i q^n_j)$$

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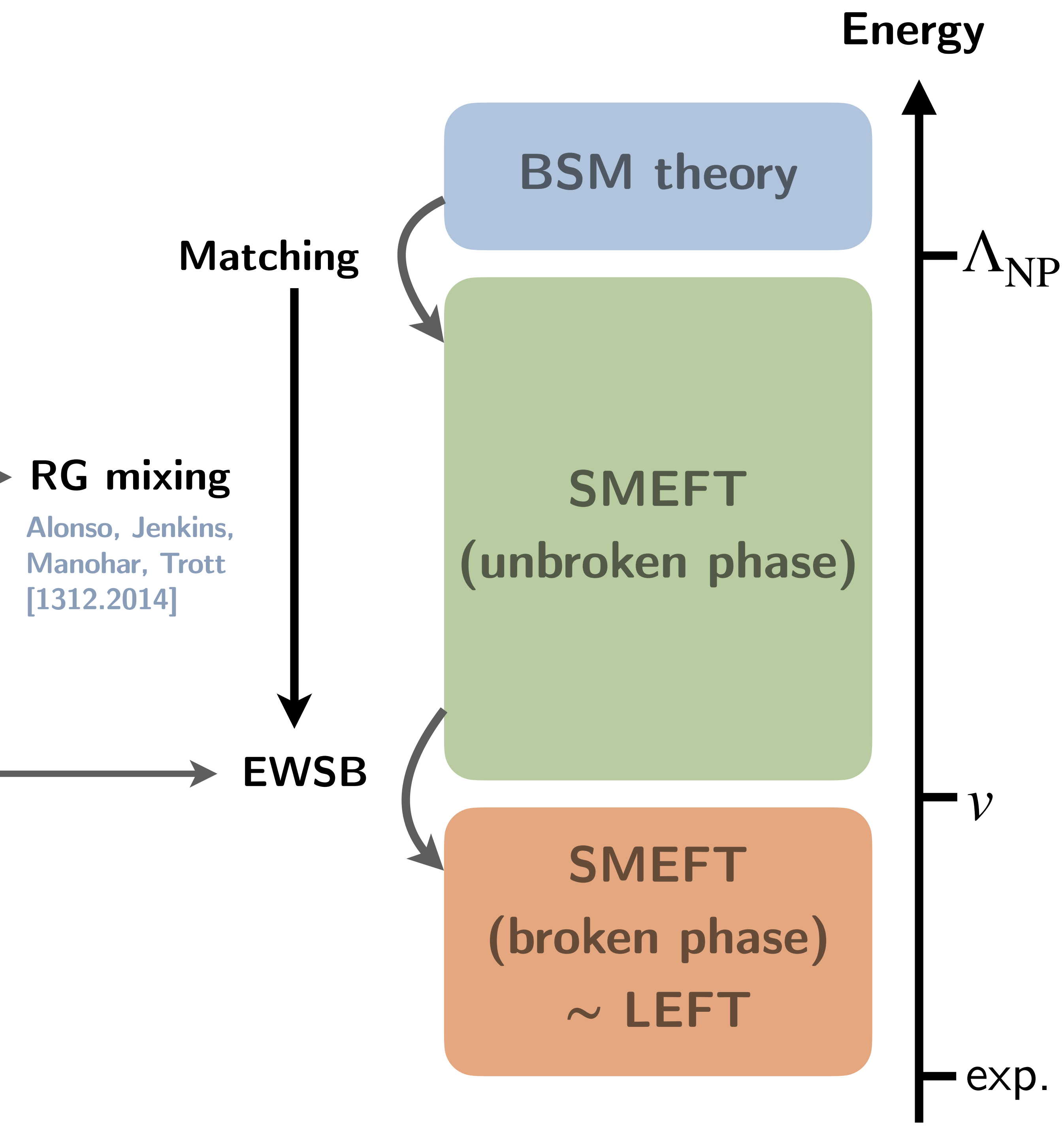

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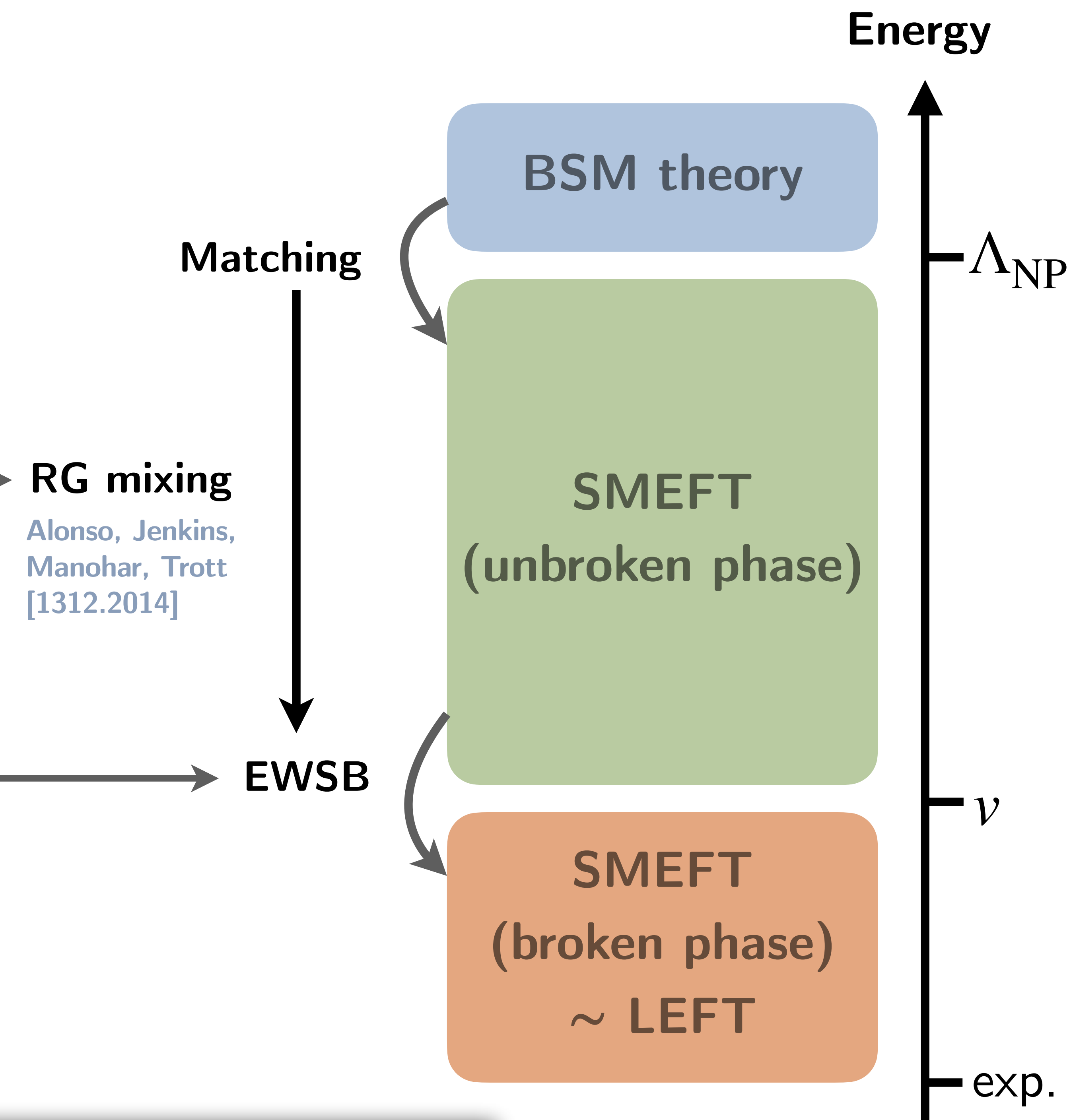


y_t and y_b Yukawa enhanced running:

$$C_{\underset{\alpha\beta}{e\gamma}}(\mu_L) = \left[1 - 3L\left(y_t^2 + y_b^2\right)\right] C_{\underset{\alpha\beta}{e\gamma}}(\mu_H) - \left[16 L y_t e\right] C^{(3)}_{\underset{\alpha\beta 33}{lequ}}(\mu_H)$$

$$[\mathcal{Y}_e]_{\alpha\beta}(\mu_L) = [Y_e]_{\alpha\beta}(\mu_H) - \frac{v^2}{2} C_{\underset{\alpha\beta}{eH}}(\mu_H) + 6 v^2 L \left[y_t^3 C^{(1)}_{\underset{\alpha\beta 33}{lequ}} - y_b^3 C_{\underset{\alpha\beta 33}{ledq}} + \frac{3}{4}(y_t^2 + y_b^2) C_{\underset{\alpha\beta}{eH}} \right]_{\mu_H}$$

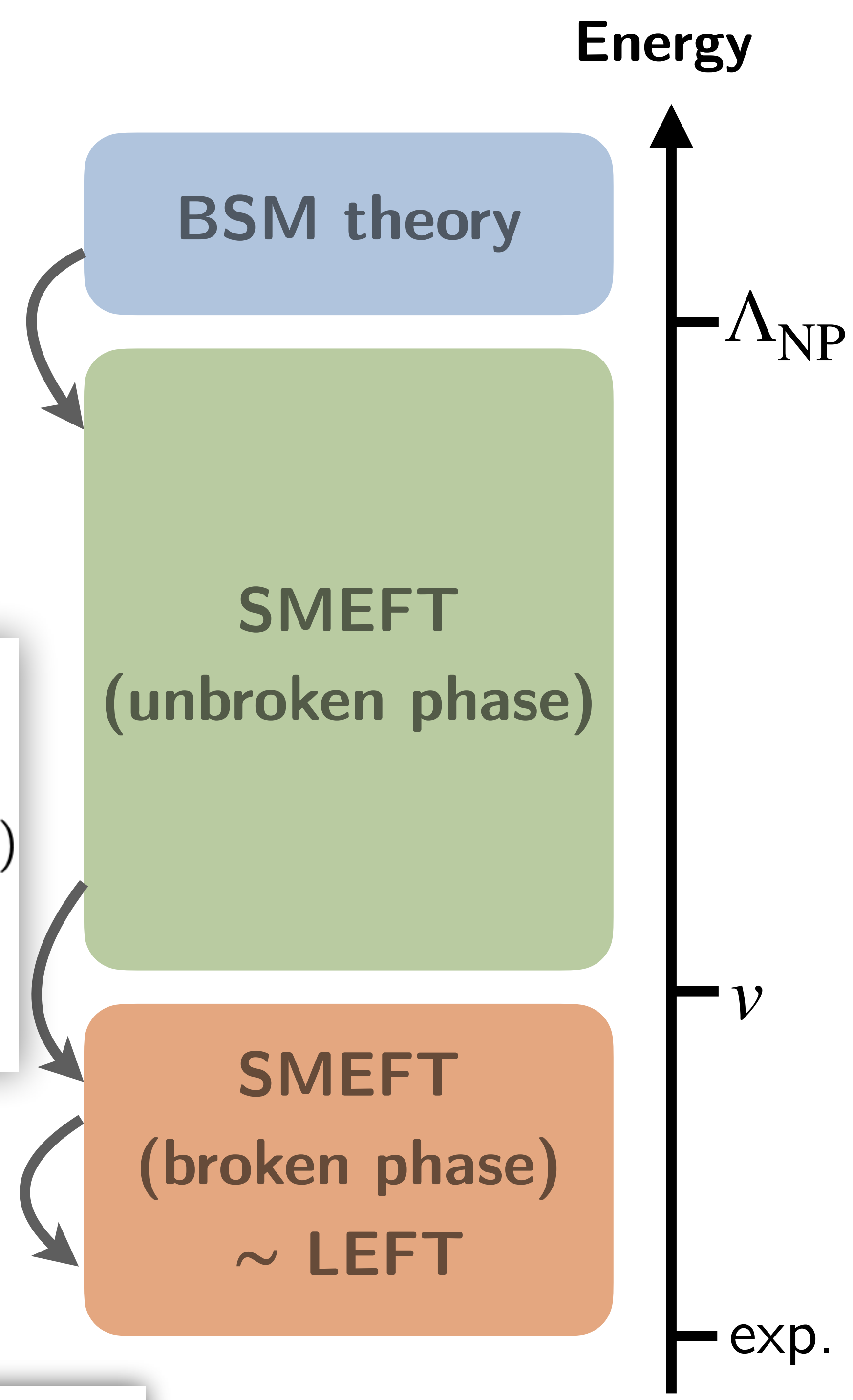
Renormalization Group Mixing of the Dipole Operators

$$\theta_L^Y = \frac{[Y_e]_{12}}{[Y_e]_{22}}\bigg|_{\mu_H}\,,\quad \theta_L^{e\gamma} = \frac{C_{\underset{12}{e\gamma}}}{C_{\underset{22}{e\gamma}}}\bigg|_{\mu_H}\,,\quad \theta_L^{eH} = \frac{C_{\underset{12}{eH}}}{C_{\underset{22}{eH}}}\bigg|_{\mu_H}\,,\quad \theta_L^{u_i} = \frac{C^{(i)}_{\underset{1233}{lequ}}}{C^{(i)}_{\underset{2233}{lequ}}}\bigg|_{\mu_H}\,,\quad \theta_L^{d} = \frac{C_{\underset{1233}{ledq}}}{C_{\underset{2233}{ledq}}}\bigg|_{\mu_H}$$

Matching

RG mixing

$$\begin{aligned} C'_{\underset{12}{e\gamma}}(\mu_L) &= (\theta_L^{e\gamma} - \theta_L^{Y}) C'_{\underset{22}{e\gamma}}(\mu_L) + (\theta_L^{e\gamma} - \theta_L^{u_3})(16 L e y_t) C^{(3)}_{\underset{2233}{lequ}}(\mu_H) \\ &+ \left[(\theta_L^{Y} - \theta_L^{u_1}) C^{(1)}_{\underset{2233}{lequ}}(\mu_H) + (\theta_L^{d} - \theta_L^{Y}) \frac{y_b^3}{y_t^3} C_{\underset{2233}{ledq}}(\mu_H) \right] 6 L v^2 y_t^3 \frac{1}{y_\mu} C'_{\underset{22}{e\gamma}}(\mu_L) \\ &+ (\theta_L^{eH} - \theta_L^{Y}) \frac{1 - 9L(y_t^2 + y_b^2)}{2} C_{\underset{22}{eH}}(\mu_H) v^2 \frac{1}{y_\mu} C'_{\underset{22}{e\gamma}}(\mu_L)\,. \end{aligned}$$



<u>**rotate to mass basis**</u>

y_t and y_b Yukawa enhanced running:

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Matching to a BSM Model

Defining the $S_1 \sim (\bar{3},1)_{1/3}$ leptoquark model:

$$\mathscr{L}_{\rm UV} = \mathscr{L}_{\rm SM} + (D_\mu S_1)^\dagger (D^\mu S_1) - M^2 S_1^\dagger S_1 - \Big[\lambda^L_{pr} \, (\bar{q}^c_p \varepsilon \ell_r) \, S_1 + \lambda^R_{pr} \, (\bar{u}^c_p e_r) \, S_1 + \mathrm{h.c.} \Big]$$

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Matching at tree level & one loop:

$$\begin{aligned}
Q^{(1)}_{lq} &= (\bar{\ell}_p \gamma_\mu \ell_r)(\bar{q}_s \gamma^\mu q_t) &\to&\quad C^{(1)}_{lq} = \tfrac{1}{4}\lambda^L_{pr}\lambda^{L*}_{ts} \\
Q^{(3)}_{lq} &= (\bar{\ell}_p \gamma_\mu \tau^I \ell_r)(\bar{q}_s \gamma^\mu \tau^I q_t) &\to&\quad C^{(3)}_{lq} = -\tfrac{1}{4}\lambda^L_{pr}\lambda^{L*}_{ts} \\
Q_{eu} &= (\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t) &\to&\quad C_{eq} = \tfrac{1}{2}\lambda^R_{rp}\lambda^{R*}_{st} \\
Q^{(1)}_{lequ} &= (\bar{\ell}^i_p e_r)\varepsilon_{ij}(\bar{q}^j_s u_t) &\to&\quad C^{(1)}_{lequ} = \tfrac{1}{2}\lambda^R_{pr}\lambda^{L*}_{ts} \\
Q^{(3)}_{lequ} &= (\bar{\ell}^i_p \sigma_{\mu\nu} e_r)\varepsilon_{ij}(\bar{q}^j_s \sigma^{\mu\nu} u_t) &\to&\quad C^{(3)}_{lequ} = -2\lambda^R_{pr}\lambda^{L*}_{ts}
\end{aligned}$$

$$[Q_{eW}]_{pr} = (\bar{\ell}_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$$

$$[Q_{eB}]_{pr} = (\bar{\ell}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$$

$$[C_{eW}]_{pr} = \frac{1}{16\pi^2}\frac{g_2}{8}\left\{ \lambda^{L*}_{sp}\lambda^L_{st}[Y_e]_{tr} - 3\lambda^{L*}_{sp}[Y^*_u]_{st}\lambda^R_{tr}\left[\frac{3}{2} + \log\left(\frac{\mu^2_M}{M^2_S}\right)\right]\right\}$$

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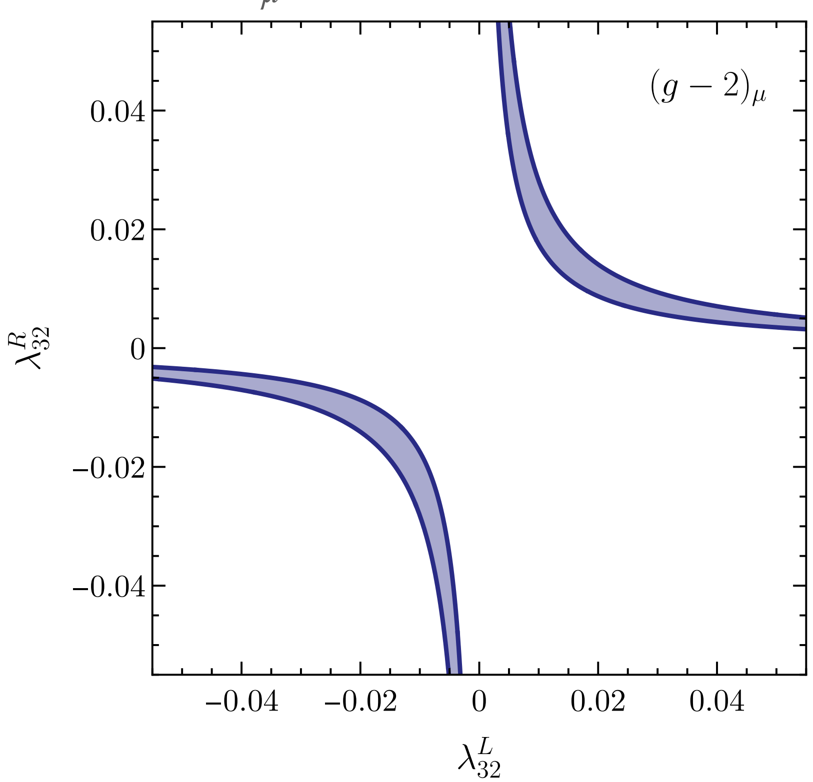
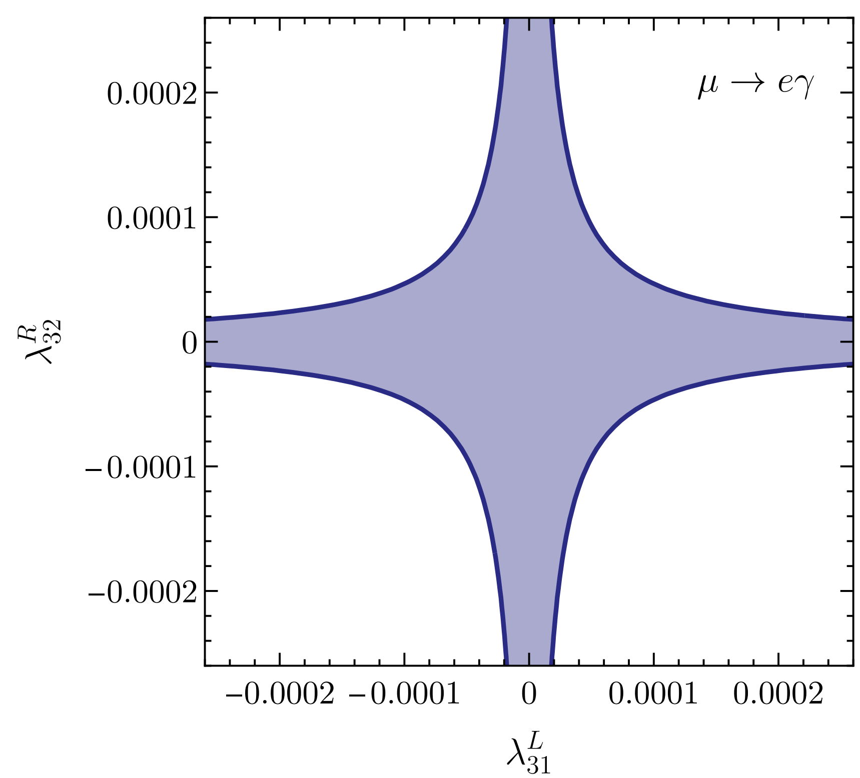
Results:

$\Delta a_\mu = (251 \pm 59) \times 10^{-11}$



$\mathscr{B}(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$



➡ Peculiar flavor structure implied: Isidori, Pagès, FW [2111.13724]; Aebischer, Dekens, Jenkins, Manohar, Sengupta, Stoffer [2102.08954]

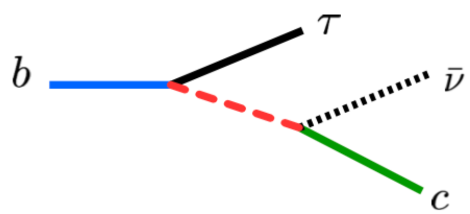
Example:
Complementarity of Low- and High-Energy Data

Linking High-p_T Drell-Yan Tails to $R_{D^{(*)}}$ Anomalies in a Leptoquark Model

New Physics in $b \to c\,\tau\,\nu$ Transitions?

Hints for NP in $b \to c\,\tau\,\nu$ transitions:

$$R_{D^{(*)}} = \frac{\mathscr{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathscr{B}\left(B \to D^{(*)}\ell\nu\right)}$$

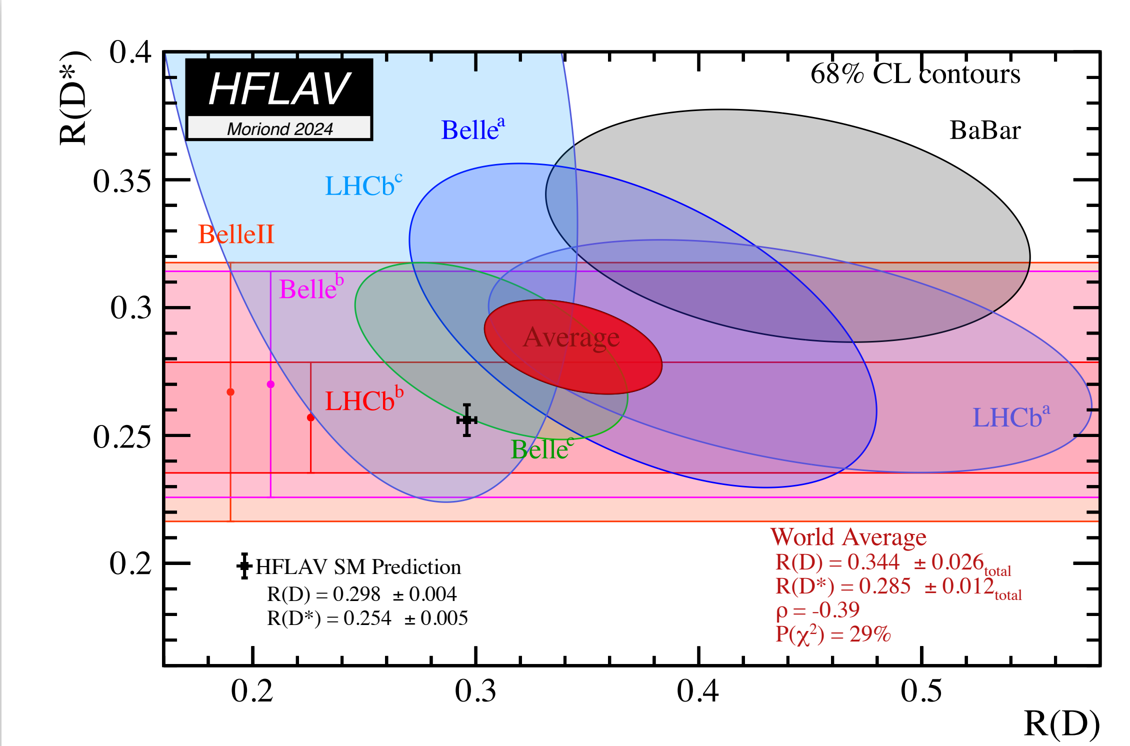


World average:

- $R_D = 0.344 \pm 0.026$
- $R_{D*} = 0.285 \pm 0.012$

SM prediction:

- $R_D^{\mathrm{SM}} = 0.298 \pm 0.004$
- $R_{D*}^{\mathrm{SM}} = 0.254 \pm 0.005$



https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

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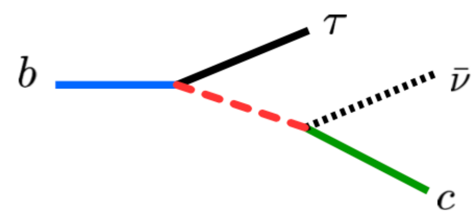

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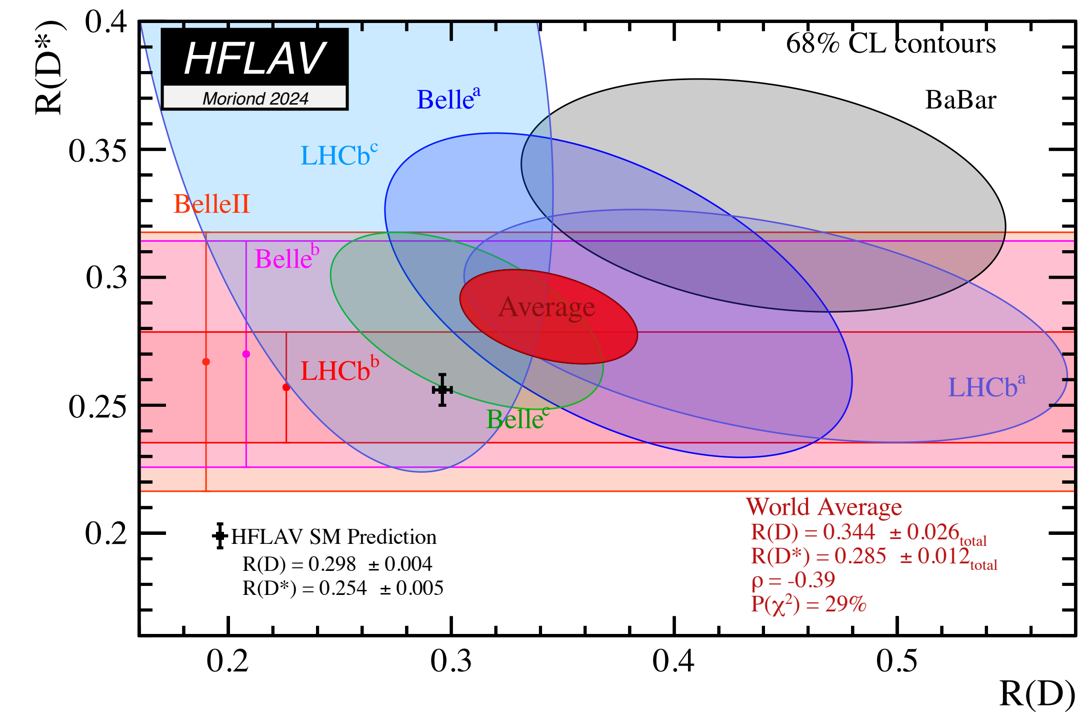

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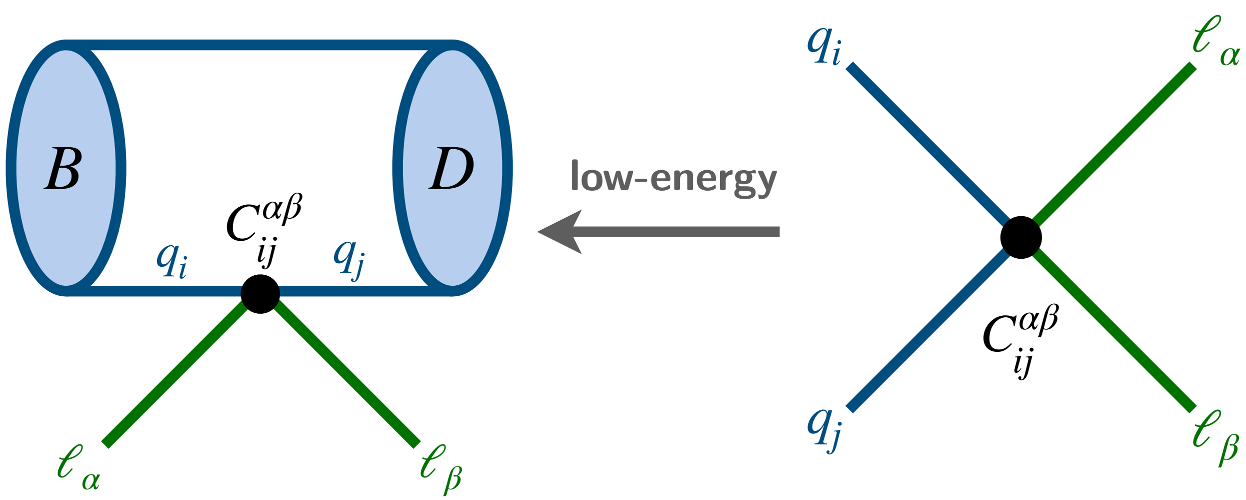
Probing semileptonic operators at different scales:



$b \to c\tau\bar{\nu}$

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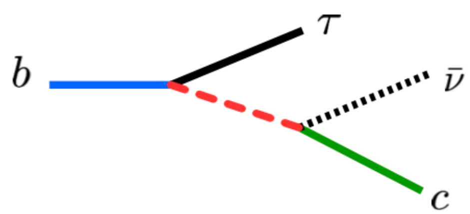

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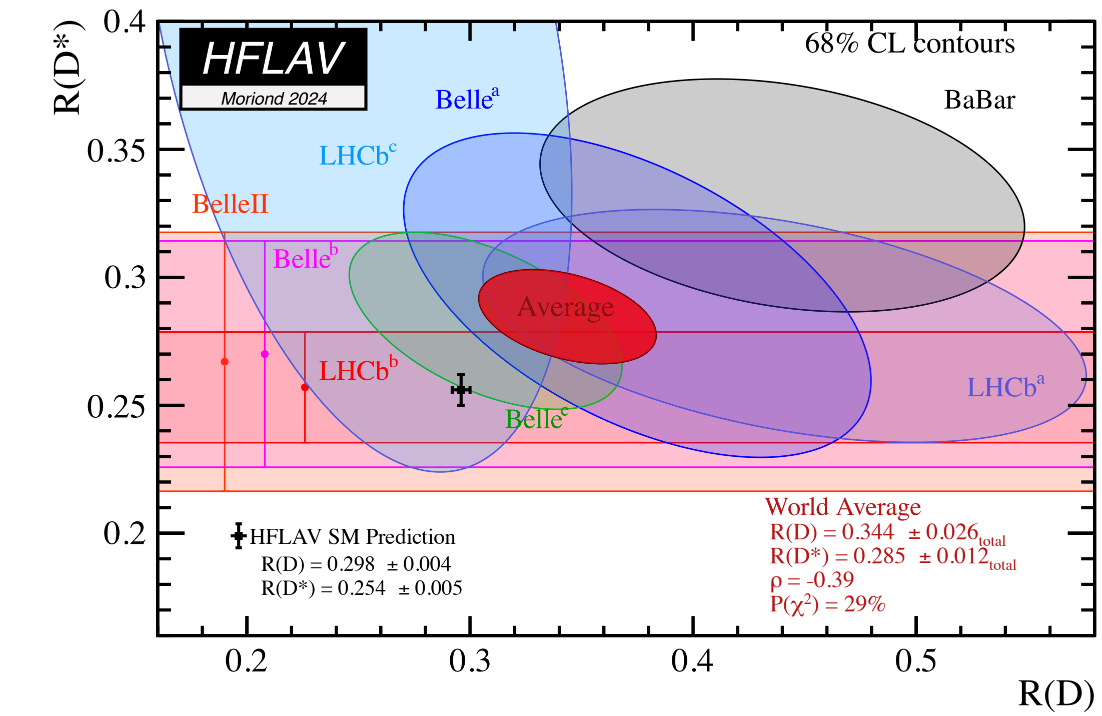

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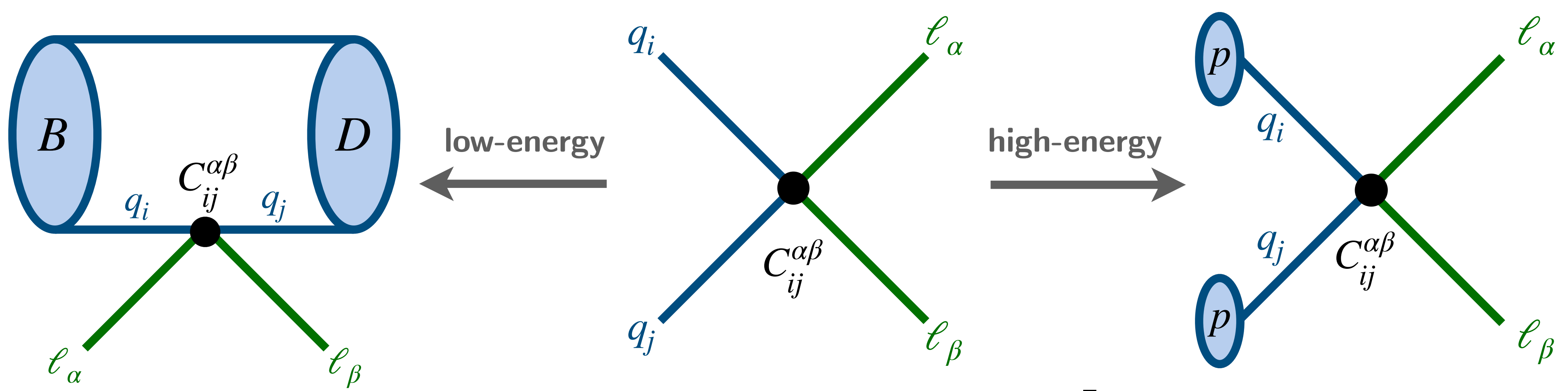
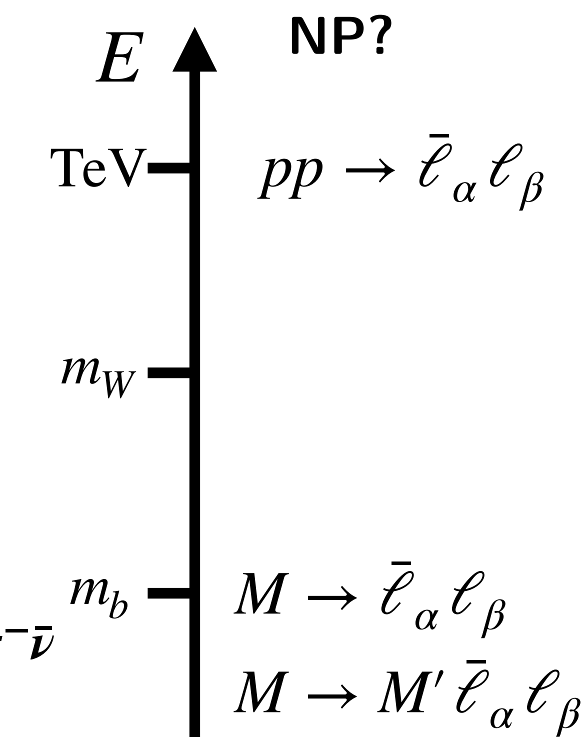


$b \to c\tau\bar{\nu}$

$b\bar{b} \to \tau^+\tau^-$, $b\bar{s} \to \tau^+\tau^-$, $b\bar{c} \to \tau^-\bar{\nu}$

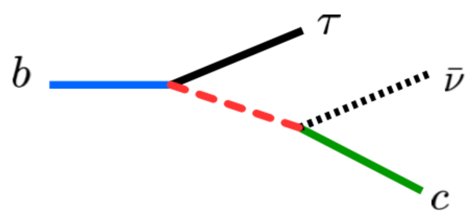


➡ **Possible NP explanations: S_1, U_1, R_2 leptoquarks**

New Physics in $b \to c\,\tau\,\nu$ Transitions?

Hints for NP in $b \to c\,\tau\,\nu$ transitions:

$$R_{D^{(*)}} = \frac{\mathscr{B}\left(B \to D^{(*)}\tau\nu\right)}{\mathscr{B}\left(B \to D^{(*)}\ell\nu\right)}$$

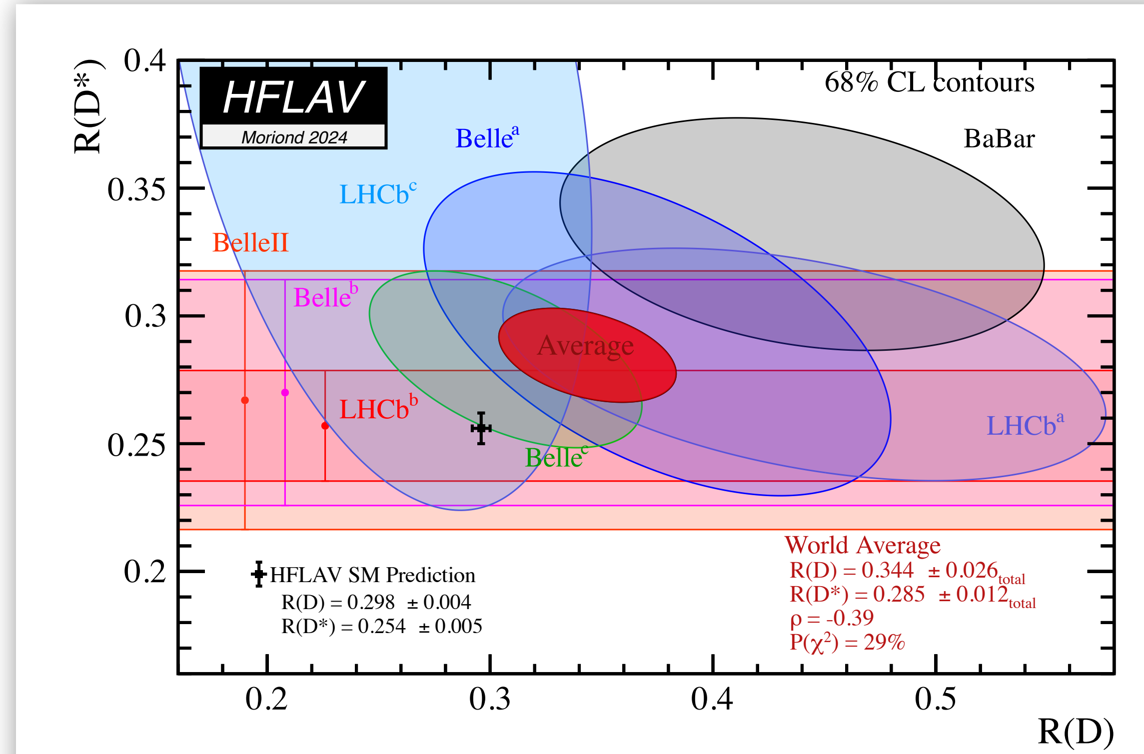


World average:

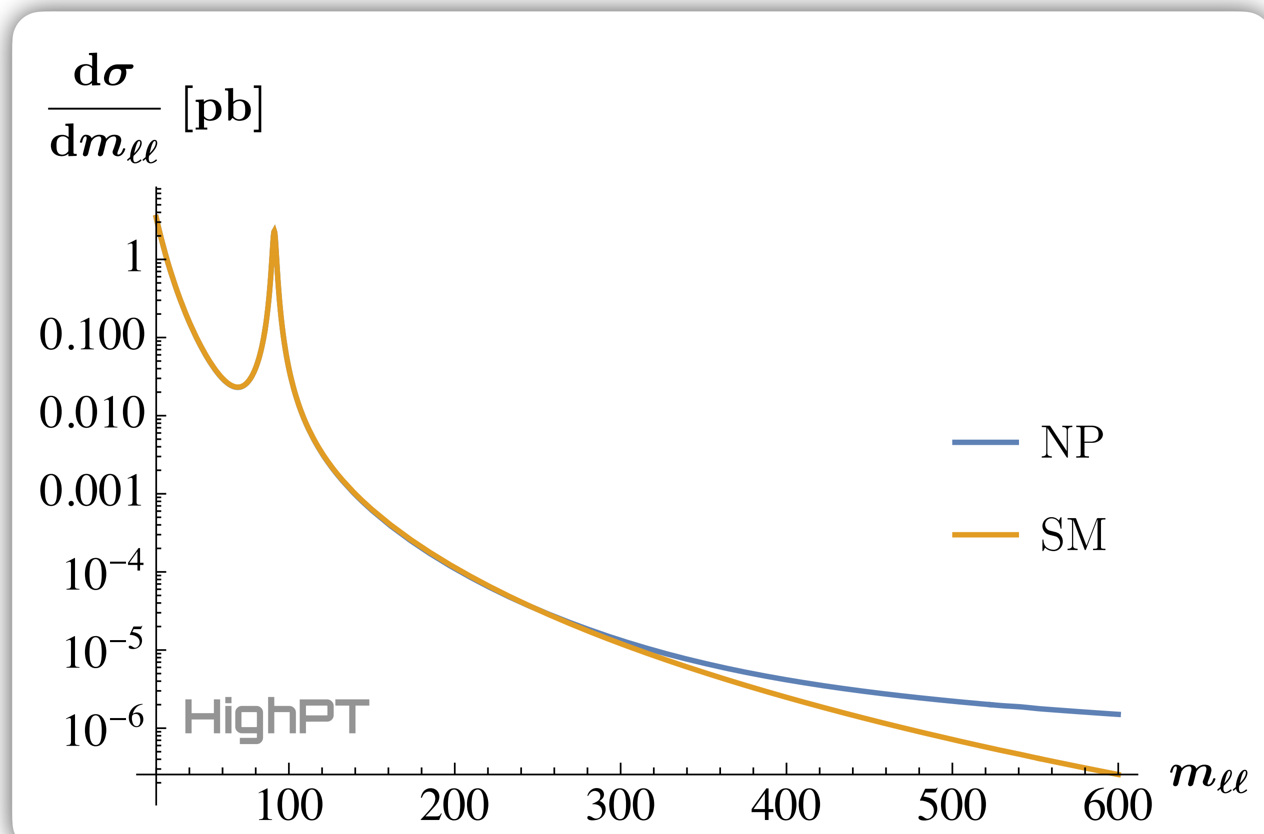
- $R_D = 0.344 \pm 0.026$
- $R_{D^*} = 0.285 \pm 0.012$

SM prediction:

- $R_D^{SM} = 0.298 \pm 0.004$
- $R_{D^*}^{SM} = 0.254 \pm 0.005$

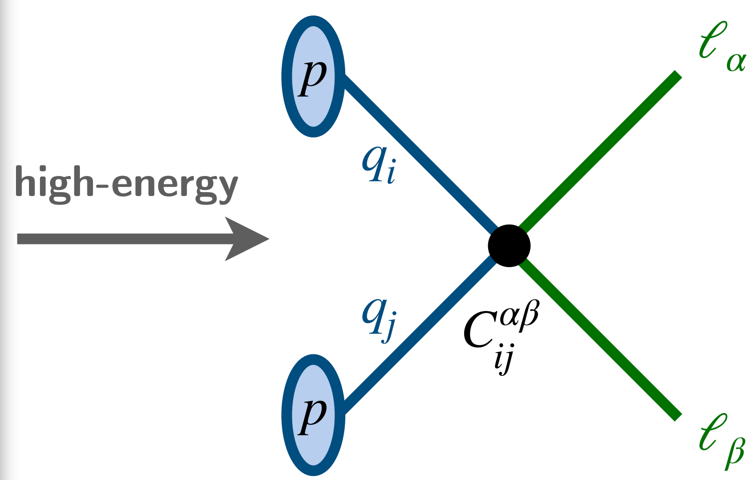


https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

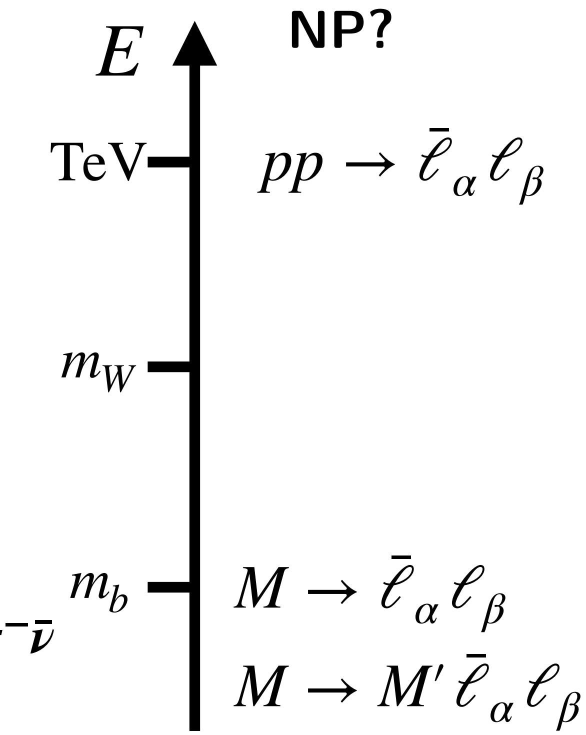


...rent scales:

high-energy



$b\bar{b} \to \tau^+\tau^-$, $b\bar{s} \to \tau^+\tau^-$, $b\bar{c} \to \tau^-\bar{\nu}$



➡ **Possible NP explanations: S_1, U_1, R_2 leptoquarks**

Example: Matching the U_1 Vector Leptoquark onto SMEFT

- The U_1 vector leptoquark $(\mathbf{3},\mathbf{1})_{2/3}$

$$\mathcal{L}_{U_1} = \mathcal{L}_{\text{SM}} - \frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U^\mu + (U_\mu J^\mu + \text{h.c.})$$

$$J_U^\mu = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma^\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma^\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\,\bar{q}_L^k\gamma^\mu\ell_L^3\right]$$

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- Integrating out the U_1

$$\begin{aligned} Q_{LL}^{ij\alpha\beta} &= (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{\ell}_L^\beta\gamma^\mu q_L^j)\,,\\ Q_{LR}^{ij\alpha\beta} &= (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)\,,\\ Q_{RR}^{ij\alpha\beta} &= (\bar{d}_R^i\gamma_\mu e_R^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)\,. \end{aligned}$$

$$\begin{aligned} \mathcal{L}_{\rm EFT} &= \mathcal{L}_{\rm SM} - \frac{1}{M_U^2}J_\mu^\dagger J^\mu \\ &= \mathcal{L}_{\rm SM} - \frac{2}{v^2}\left[C_{LL}^{ij\alpha\beta}\,Q_{LL}^{ij\alpha\beta} + C_{RR}^{ij\alpha\beta}\,Q_{RR}^{ij\alpha\beta} + \left(C_{LR}^{ij\alpha\beta}\,Q_{LR}^{ij\alpha\beta} + \text{h.c.}\right)\right] \end{aligned}$$

- Mapping onto Warsaw basis

$$\begin{aligned} \mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} - \frac{g_U^2}{2M_U^2}\Bigg\{&\frac{1}{2}\kappa_p^L\kappa_r^{L*}\left([Q_{lq}^{(1)}]_{33pr} + [Q_{lq}^{(3)}]_{33pr}\right) \\ &+ |\beta_R|^2\,[Q_{ed}]_{3333} - \left(2\beta_R\kappa_p^{L*}[Q_{ledq}]_{333p} + \text{h.c.}\right)\Bigg\} \end{aligned}$$

→ $b \to c\tau\nu$ transitions at low energies

Example: Matching the U_1 Vector Leptoquark onto SMEFT

- The U_1 vector leptoquark $(\mathbf{3},\mathbf{1})_{2/3}$

$$\mathcal{L}_{U_1} = \mathcal{L}_{\rm SM} - \frac{1}{2}U^\dagger_{\mu\nu}U^{\mu\nu} + M_U^2 U^\dagger_\mu U^\mu + (U_\mu J^\mu + \text{h.c.})$$

$$J_U^\mu = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma^\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma^\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\,\bar{q}_L^k\gamma^\mu\ell_L^3\right]$$

- Integrating out the U_1

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} - \frac{1}{M_U^2}J^\dagger_\mu J^\mu$$
$$= \mathcal{L}_{\rm SM} - \frac{2}{v^2}\left[C_{LL}^{ij\alpha\beta}\,Q_{LL}^{ij\alpha\beta} + C_{RR}^{ij\alpha\beta}\,Q_{RR}^{ij\alpha\beta} + \left(C_{LR}^{ij\alpha\beta}\,Q_{LR}^{ij\alpha\beta} + \text{h.c.}\right)\right]$$

$$Q_{LL}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{\ell}_L^\beta\gamma^\mu q_L^j)\,,$$
$$Q_{LR}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)\,,$$
$$Q_{RR}^{ij\alpha\beta} = (\bar{d}_R^i\gamma_\mu e_R^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)\,.$$

- Mapping onto Warsaw basis

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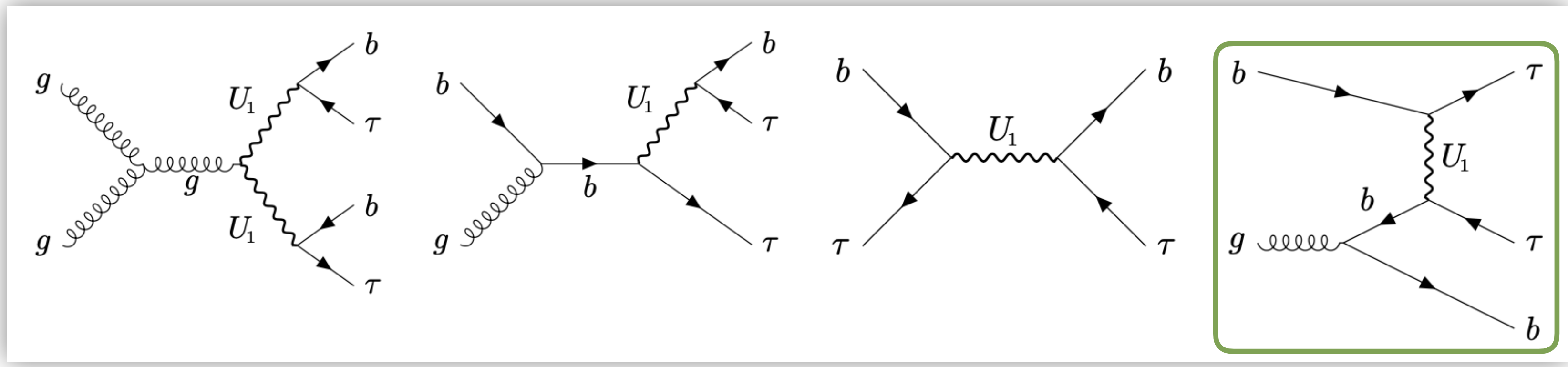
→ $b \to c\tau\nu$ transitions at low energies

Collider signatures:



⇒ focus on Drell-Yan here
(can be analyzed in full model or EFT)

Drell-Yan in Light of the $R_{D^{(*)}}$ Anomalies: U_1 Leptoquark

LQ with $m_{U_1} = 2\,\mathrm{TeV}$: $\mathscr{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\overline{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\overline{d}_i \gamma_\mu e_\alpha) + \mathrm{H.c.} \rightarrow [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}}{2}$

- Electroweak and flavor limits run up to 2 TeV using SMEFT/LEFT RGE

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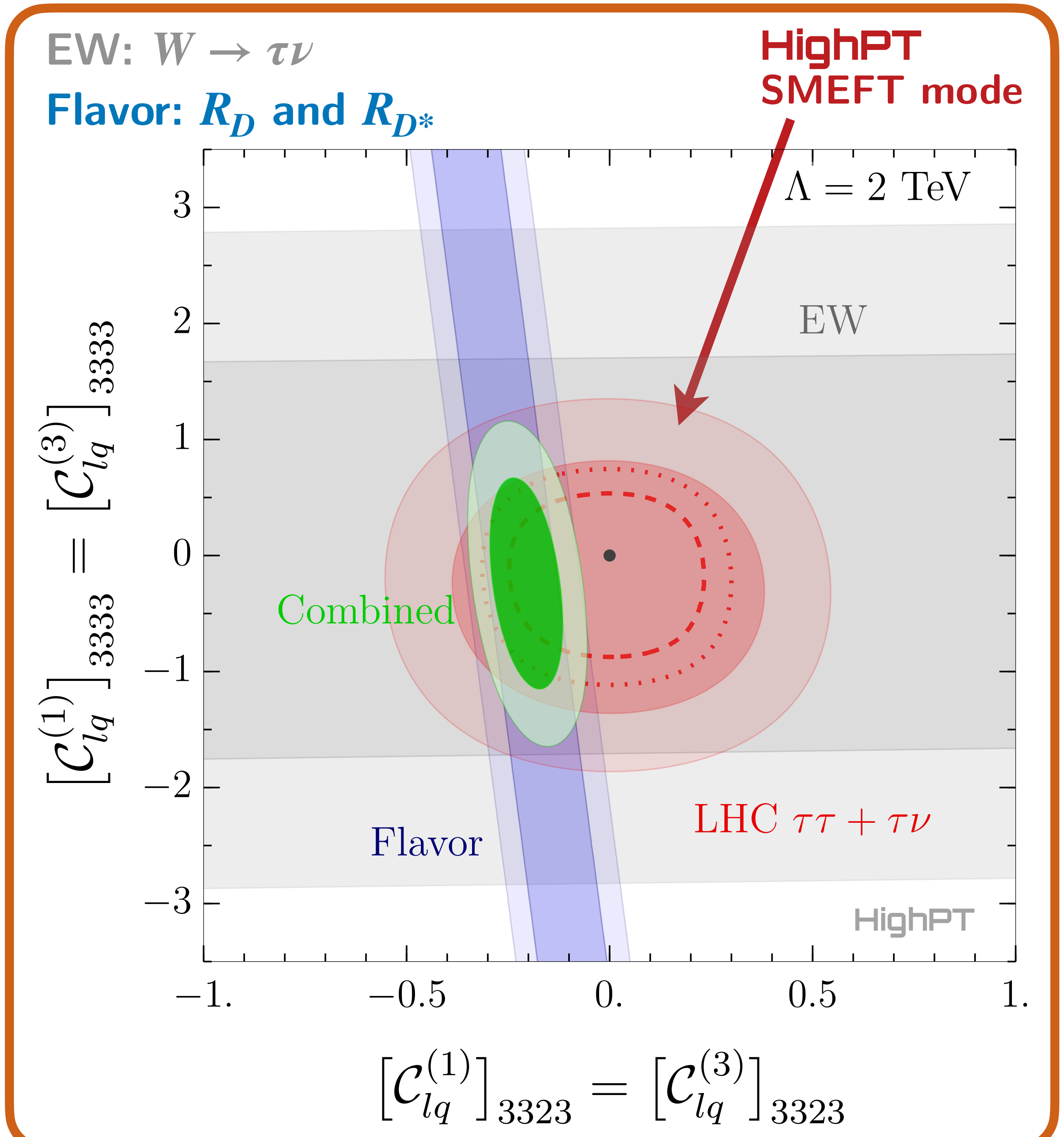
- Electroweak and flavor limits run up to 2 TeV using SMEFT/LEFT RGE

SMEFT fit



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LQ with $m_{U_1} = 2\,\mathrm{TeV}$: $\mathscr{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\bar{d}_i \gamma_\mu e_\alpha) + \mathrm{H.c.} \to [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}}{2}$

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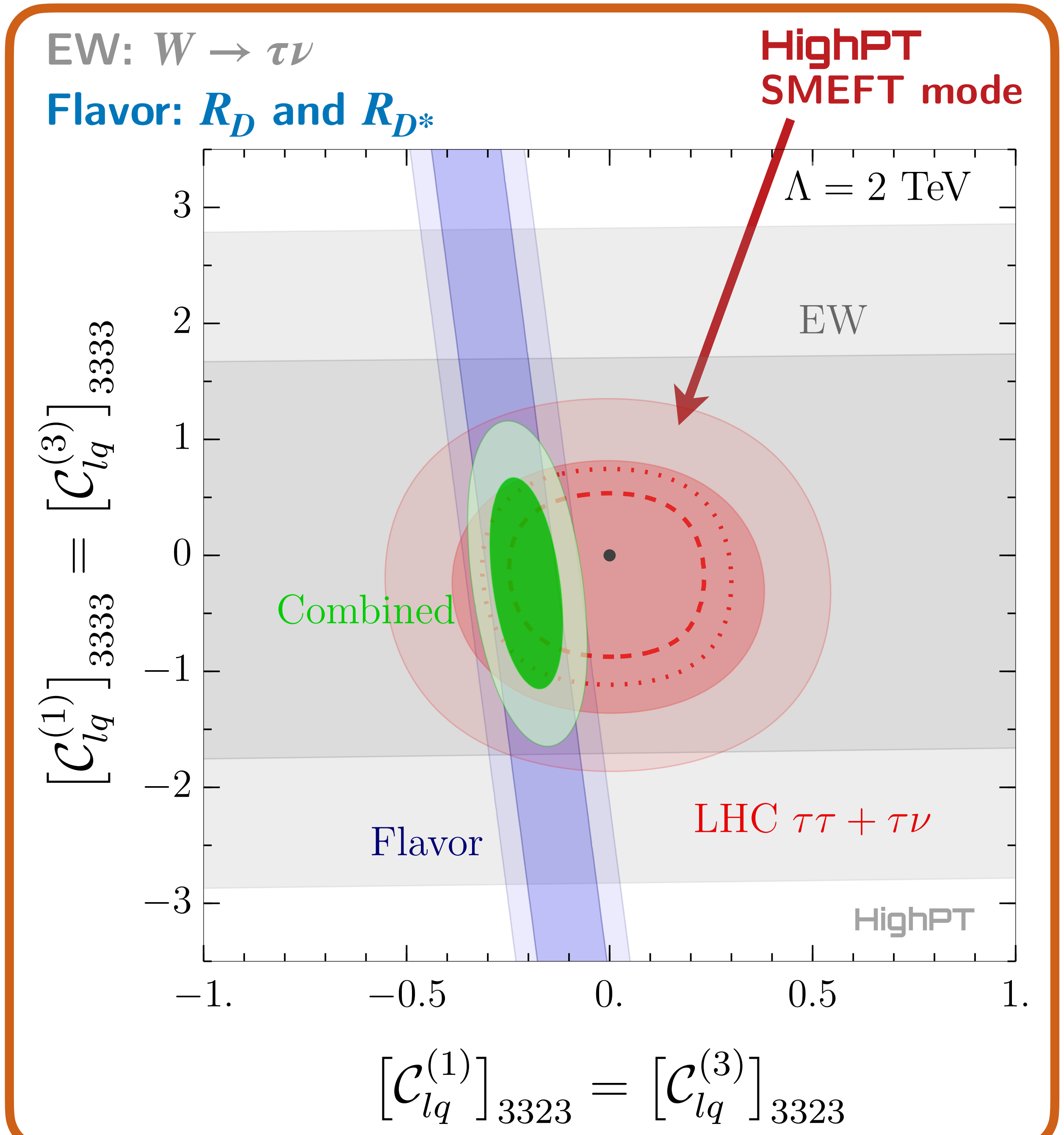
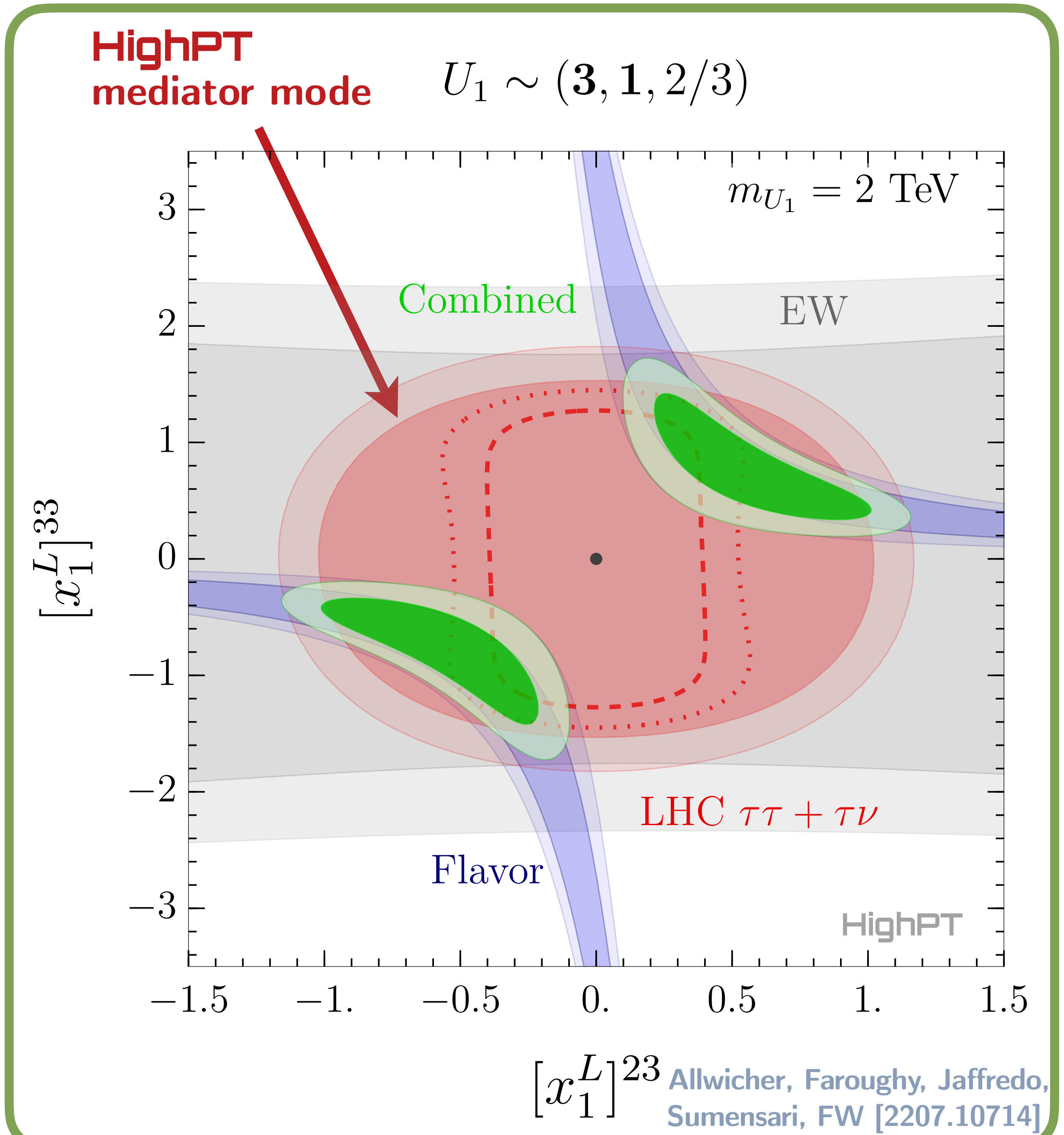
SMEFT fit



LQ mediator fit



Allwicher, Faroughy, Jaffredo, Sumensari, FW [2207.10714]

Drell-Yan in Light of the $R_{D^{(*)}}$ Anomalies: U_1 Leptoquark

LQ with $m_{U_1} = 2\,\mathrm{TeV}$: $\mathscr{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\bar{d}_i \gamma_\mu e_\alpha) + \mathrm{H.c.} \to [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}}{2}$

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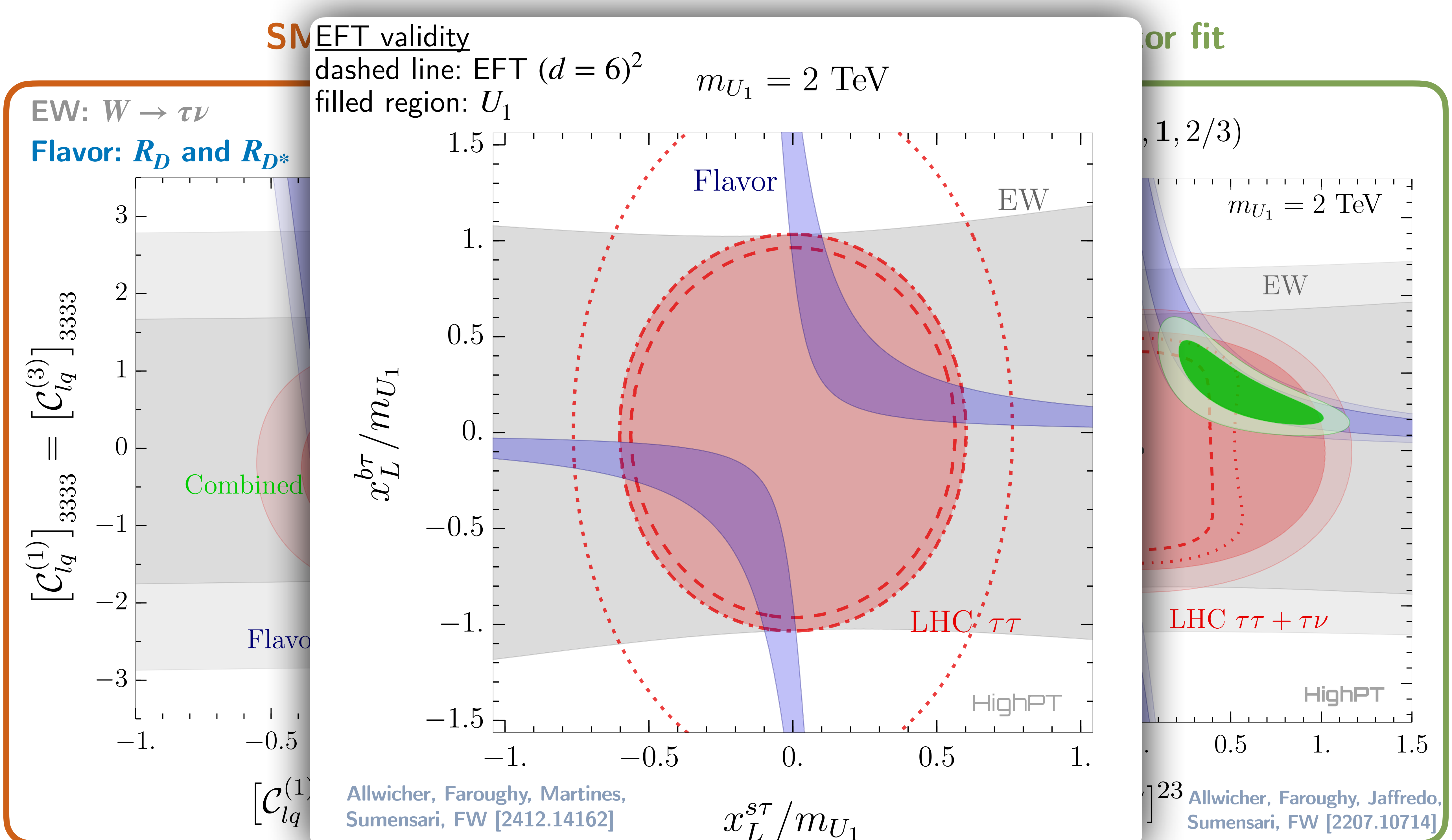
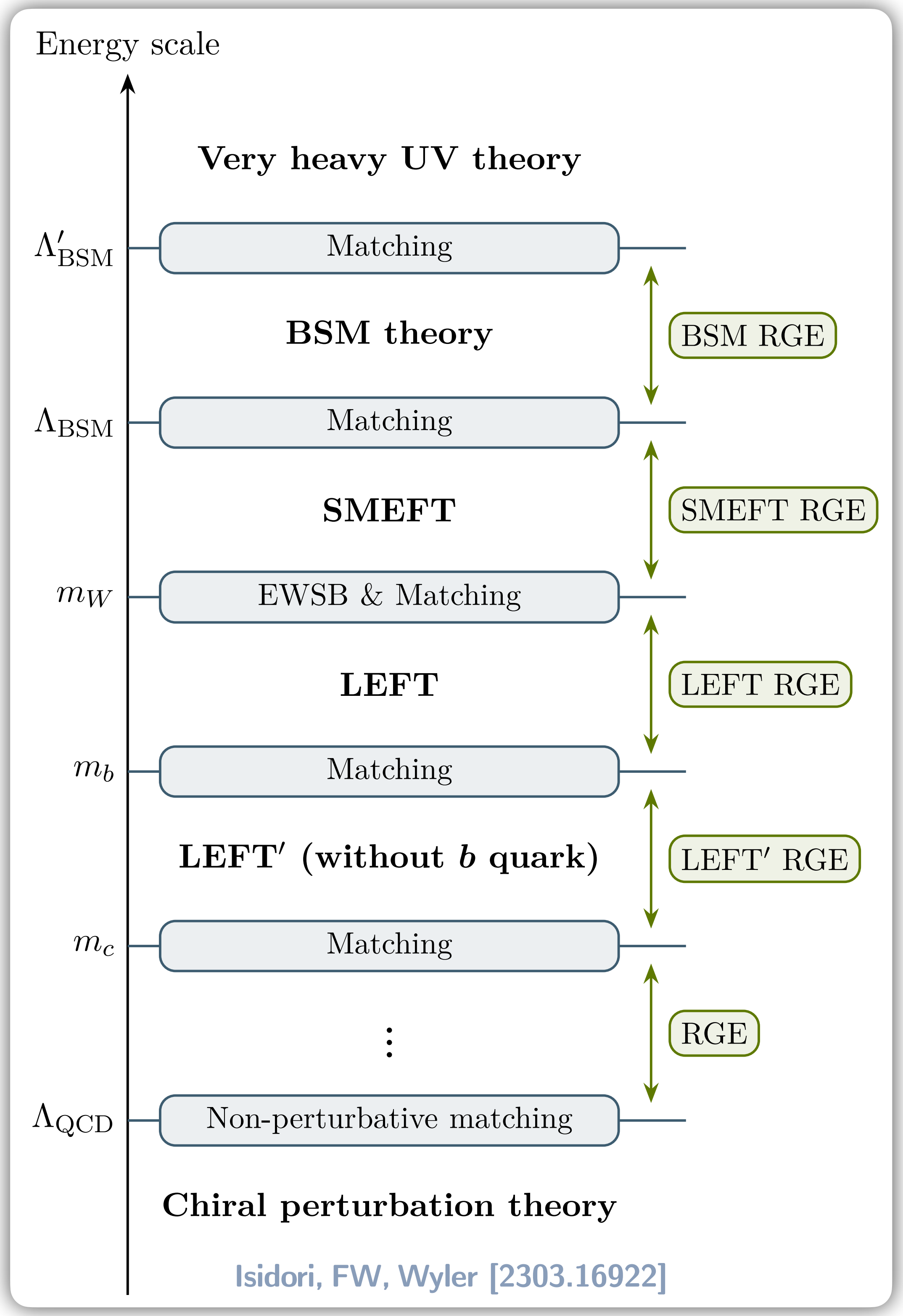


Conclusions and Future Directions

- Plethora of BSM theories w/o clear preferences
- Wide range of complementary measurements from:
  high-p_T tails at LHC, EWPO, Higgs decays, flavor, ...
- Complicated analyses involving many energy scales
- EFTs are ideal tool:
  - Model independent
  - Separates problems by involved energy scales
  - Linking of EFTs by running and matching
  - Reduction of parameters by matching onto BSM
  - Most steps automatized in various tool
- Future:
  - Linking of various EFT tools for *matching*, *running*, and obtaining the *likelihoods*
  - Investigating more complex NP scenarios (e.g. MSSM)



Thank you!