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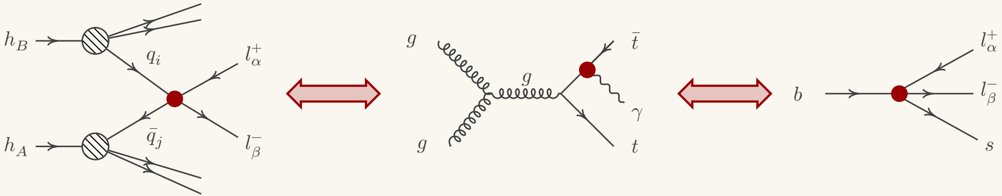
Studienstiftung des deutschen Volkes



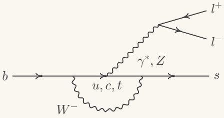
Synergies between flavour and high-pT observables

Global fits in the Standard Model Effective Field Theory

Lara Nollen

Standard Model at the LHC 2024 8th May 2024

EFT Approach to Flavour Observables



- Low background and high precision $\rightarrow$ ideal to search for **new physics**

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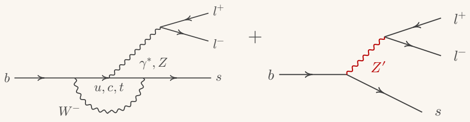

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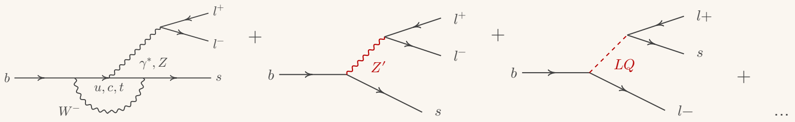

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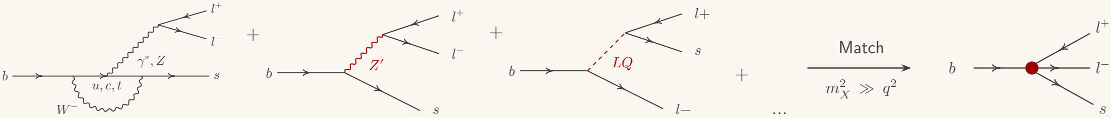

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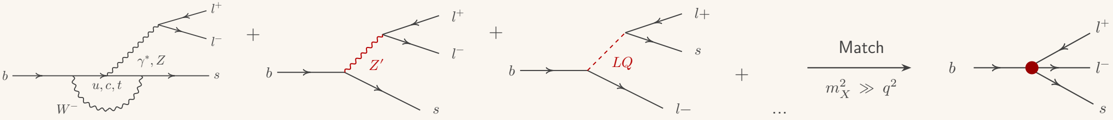

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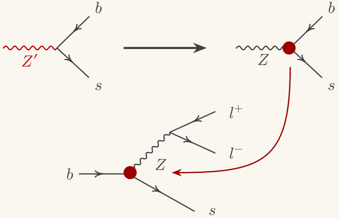

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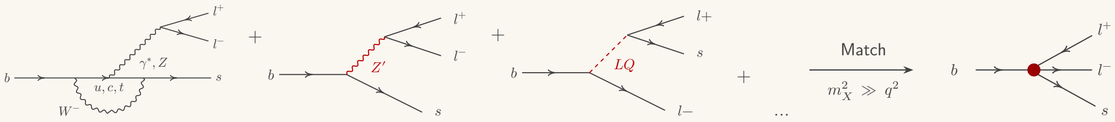

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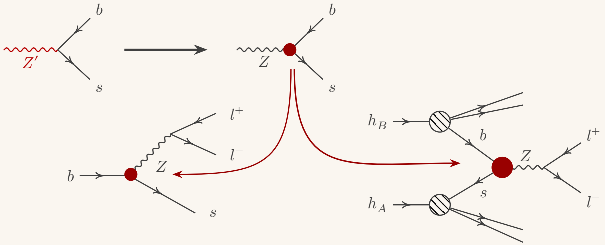
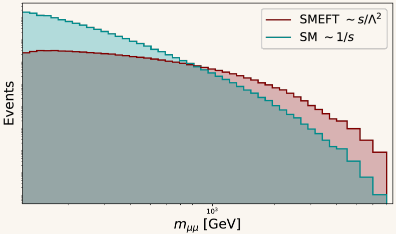
- Combined fit of observables

  $\Longrightarrow$ **Correlations**

  and breaking of flat directions



Collider observables in the SMEFT



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  $\Longrightarrow$ Very sensitive to NP, especially in high-p_T tails

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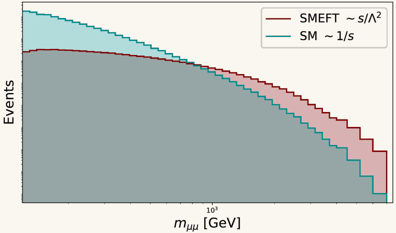

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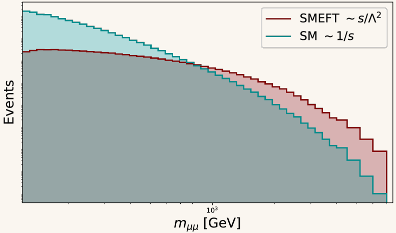

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- Many measurements not unfolded

- Initial state dependent on PDFs

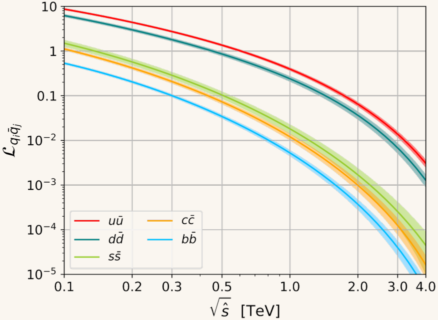
  (see e.g. talk by Thomas Cridge)

- Parton-parton luminosities

$$\mathcal{L}_{q_i\bar{q}_j} = \tau \int_\tau^1 \frac{\mathrm{d}x}{x} \left[f_{q_i}(x,\mu_F) f_{\bar{q}_j}(\tau/x,\mu_F) + f_{\bar{q}_j}(x,\mu_F) f_{q_i}(\tau/x,\mu_F) \right]$$

$$\sigma = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(\tau s)$$

- Suppresses heavy flavour initial states



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- SMEFT is constructed from all SM fields with the full SM symmetry

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)}$$

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- Dimension-6 operators: Warsaw basis, 59 operators $\Longrightarrow$ **2499** Wilson coefficients

Flavour patterns in the SMEFT

- One four-fermion operator $\implies$ up to **81** Wilson coefficients due to flavour indices

$$O^{(1)}_{\substack{lq\\ijkl}} = \left(\bar{l}_i \gamma_\mu l_j\right)\left(\bar{q}_k \gamma^\mu q_l\right) \implies C^{(1)}_{\substack{lq\\ijkl}} \sim \begin{pmatrix} C_{ee} & C_{e\mu} & C_{e\tau} \\ C_{\mu e} & C_{\mu\mu} & C_{\mu\tau} \\ C_{\tau e} & C_{\tau\mu} & C_{\tau\tau} \end{pmatrix} \otimes \begin{pmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{pmatrix}$$

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- **Flavour assumptions** are a powerful tool to reduce the number of free parameters
- $\Lambda_{\text{FCNC}} \gg 1\,\text{TeV} \implies$ assume suppression of FCNC processes
- **Minimal Flavour Violation** (MFV) $\rightarrow$ U$(3)^5$ symmetry breaking only by Yukawas
- The SM Yukawa matrices are treated as spurions

$$Y_u : \; (3, \bar{3}, 1, 1, 1) \quad Y_d : \; (3, 1, \bar{3}, 1, 1) \quad Y_e : \; (1, 1, 1, 3, \bar{3})$$

$\implies$ Symmetry is formally restored $\quad \mathcal{L}_{\text{Yuk}} = -\bar{\ell}\, Y_e\, e_R \varphi - \bar{q}\, Y_d\, d_R \varphi - \bar{q}\, Y_u\, u_R \tilde{\varphi} + \text{h.c.}$ ✓

Minimal Flavour Violation in SMEFT

- Expand the quark bilinears

$$\bar{q}_L q_L :\sim a_1 \mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots \quad \bar{u}_R u_R :\sim b_1 \mathbb{1} + b_2 Y_u^\dagger Y_u + \ldots \quad \bar{d}_R d_R :\sim e_1 \mathbb{1} + e_2 Y_d^\dagger Y_d + \ldots$$

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See also e.g. Bruggisser et al. [JHEP 02 (2023) 225] or Greljo et al. [JHEP 05 (2023) 087] for MFV in SMEFT

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- Assumptions:
  - $Y_u \sim \text{diag}\,(0, 0, y_t)$
  - $Y_l \sim 0 \rightarrow$ Lepton-flavour universality
  - $Y_d \sim 0 \rightarrow$ No up-type FCNCs, no chirality flipping down-type operators

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- Rotating to the mass basis yields:

$$C\,\bar{q}_L q_L \supset \left[\bar{u}_L \begin{pmatrix} a_1 & 0 & 0 \\ 0 & a_1 & 0 \\ 0 & 0 & a_1 + a_2\, y_t^2 \end{pmatrix} u_L + \bar{d}_L \begin{pmatrix} a_1 + a_2\, |V_{td}|^2\, y_t^2 & a_2\, V_{td}^* V_{ts}\, y_t^2 & a_2\, V_{td}^* V_{tb}\, y_t^2 \\ a_2\, V_{ts}^* V_{td}\, y_t^2 & a_1 + a_2\, |V_{ts}|^2\, y_t^2 & a_2\, V_{ts}^* V_{tb}\, y_t^2 \\ a_2\, V_{tb}^* V_{td}\, y_t^2 & a_2\, V_{tb}^* V_{ts}\, y_t^2 & a_1 + a_2\, |V_{tb}|^2\, y_t^2 \end{pmatrix} d_L \right]$$

$t\bar{t}$ Drell-Yan $b \to s$

- Imposes **correlations** among flavour entries and allows for **down-type FCNCs**

See also e.g. Bruggisser et al. [JHEP 02 (2023) 225] or Greljo et al. [JHEP 05 (2023) 087] for MFV in SMEFT

Probing flavour with global MFV SMEFT Fits

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- Parameterization (all higher-order insertions of $Y_u Y_u^\dagger$ give rise to the same structure)

$$\tilde{C}_{q\bar{q}} = \frac{v^2}{\Lambda^2}\, a_1 \qquad \gamma_a = \sum_{n\geq 1} y_t^{2n}\, a_{2n}/a_1$$

- γ_a probes the ratio of the MFV coefficients $\to$ constrained by combining at least two sectors

$$u_L^i \bar{u}_L^i \sim \tilde{C}_i \qquad d_L^i \bar{d}_L^i \sim \tilde{C}_i(1+\gamma_A|V_{ti}|^2) \qquad \bar{u}_L^i d_L^j \sim \tilde{C}_i\, V_{ij}$$

$$t_L \bar{t}_L \sim \tilde{C}_i(1+\gamma_a) \qquad b_L \bar{s}_L \sim \tilde{C}_i \gamma_a\, V_{ts}^* V_{tb} \qquad \bar{t}_L d_L^j \sim \tilde{C}_i\,(1+\gamma_A) V_{tj}$$

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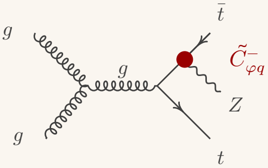
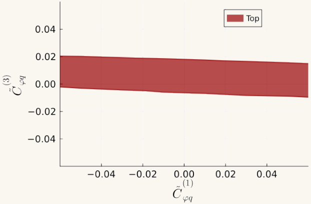
Flat directions and global Fits

- Individual observables always leave unconstrained (flat) directions in parameter space

$$\tilde{C}^{\pm}_{\varphi q} = \tilde{C}^{1}_{\varphi q} \pm \tilde{C}^{3}_{\varphi q}$$





See also e.g. Greljo et al. [JHEP 11 (2020) 080] or Hiller et al. [JHEP 06 (2021) 010] or Allwicher et al. [JHEP 03 (2024) 049] for global SMEFT Fits

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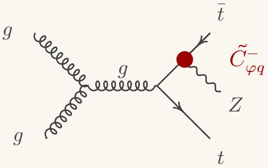

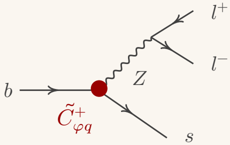

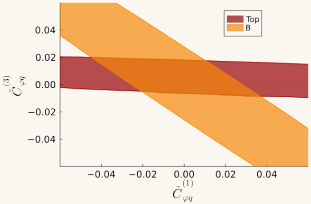

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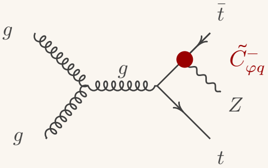

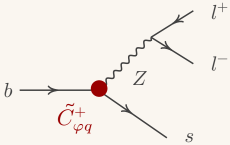

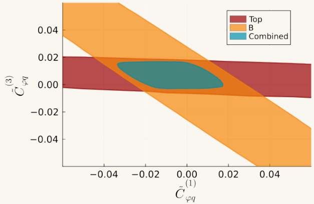

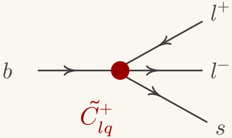

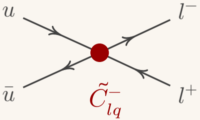

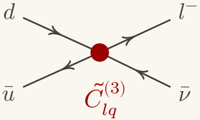

- Different observables probe different linear combinations

  $\rightarrow$ Combination breaks flat directions and thus strongly improves the fit

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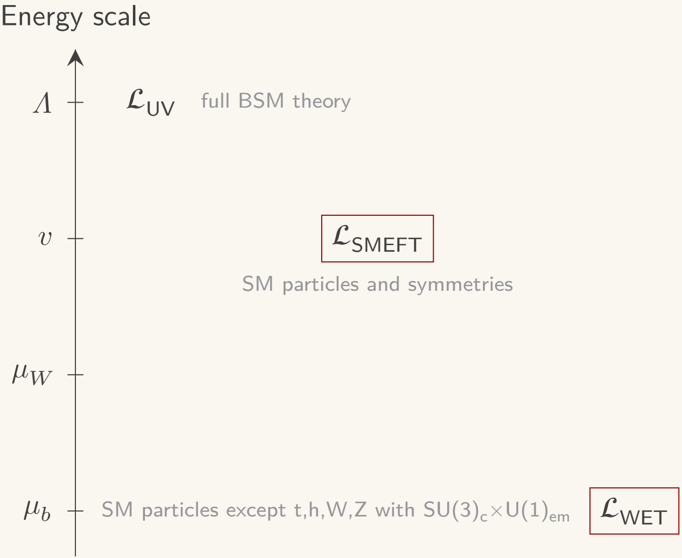
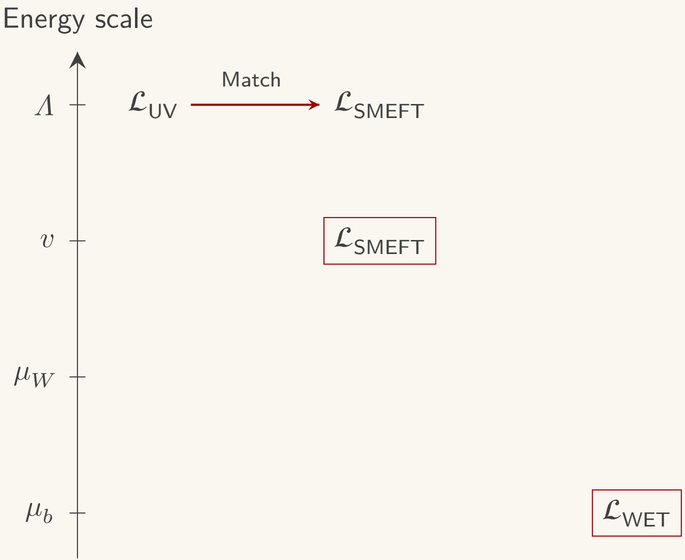
Running and Matching

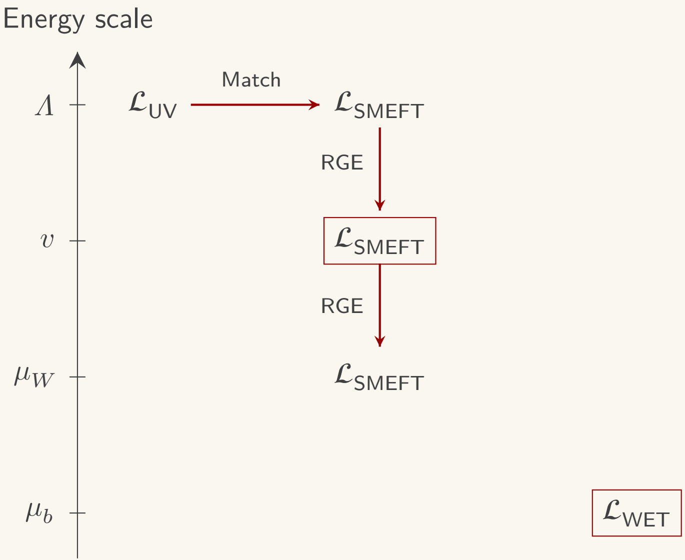


Running and Matching



- Match a potential UV theory onto the SMEFT at the matching scale Λ (see e.g. talk by Javier Fuentes-Martin)

Running and Matching



- Match a potential UV theory onto the SMEFT at the matching scale Λ (see e.g. talk by Javier Fuentes-Martin)
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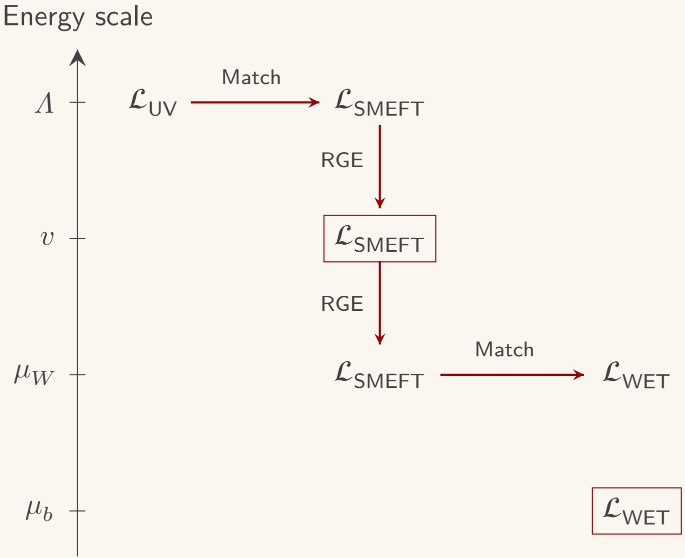
Running and Matching



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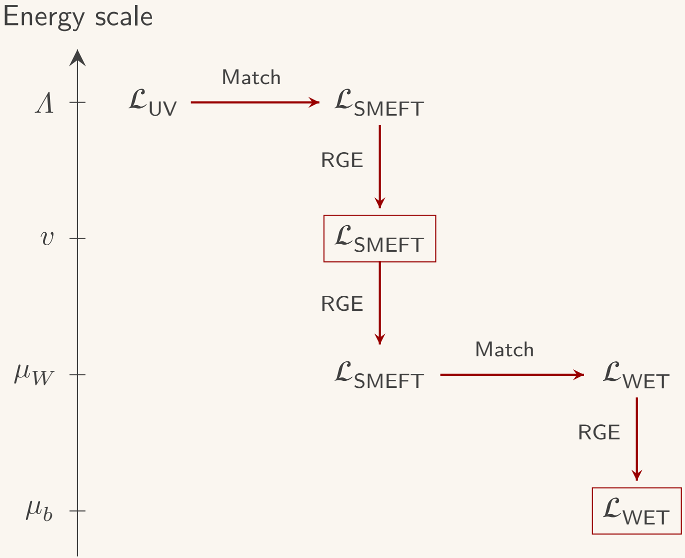
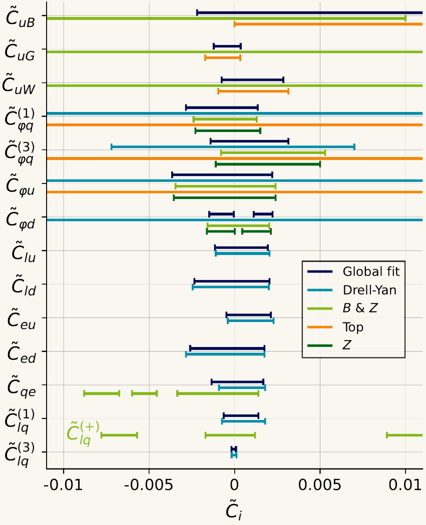
- Match the SMEFT onto the WET at the scale μ_W

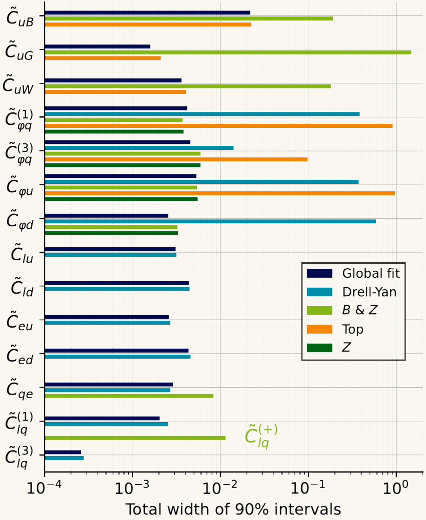
Running and Matching



- Match a potential UV theory onto the SMEFT at the matching scale Λ (see e.g. talk by Javier Fuentes-Martin)
- Apply the SMEFT RGE to evolve the Wilson coefficients to lower energy scales
- Compute collider observables at the electroweak scale
- Match the SMEFT onto the WET at the scale μ_W
- Use the WET RGE to compute the Wilson coefficients at the scale μ_b of flavour-observables

Synergies between flavour and high-pT observables

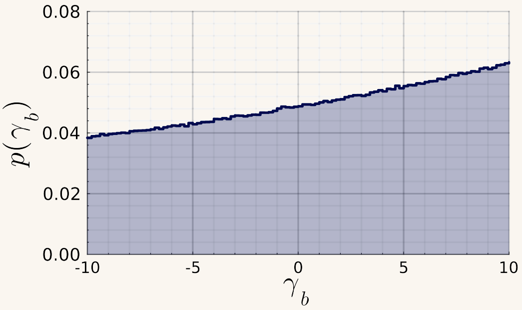




Grunwald, Hiller, Kröninger, LN, [JHEP 11 (2023) 110]

Probing the MFV parameters

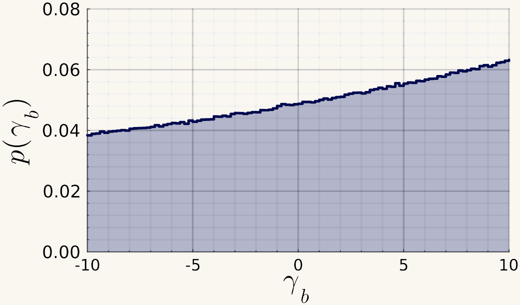
$$\gamma_b = \sum_{n\geq 1} y_t^{2n} \frac{b_{2n}}{b_1}$$ right-handed up-type quarks

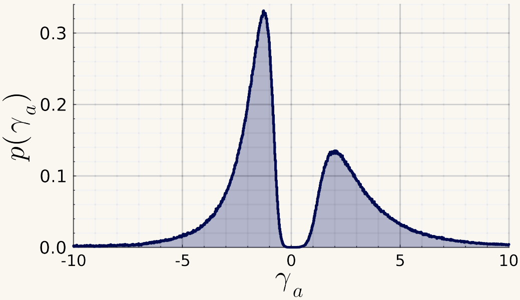


Probing the MFV parameters

$$\gamma_b = \sum_{n\geq 1} y_t^{2n} \frac{b_{2n}}{b_1}$$ right-handed up-type quarks

$$\gamma_a = \sum_{n\geq 1} y_t^{2n} \frac{a_{2n}}{a_1}$$ left-handed doublets

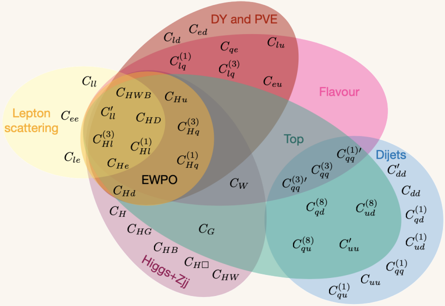




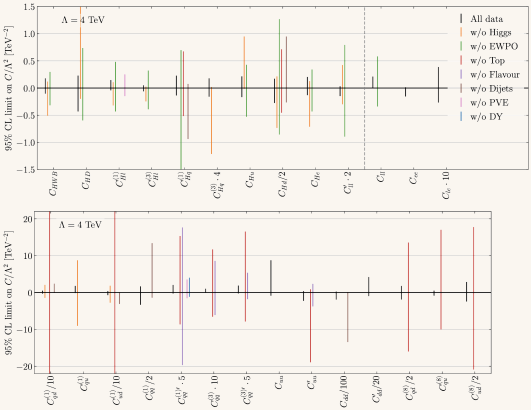
- The ratio γ_a peaks at -1.2 and 1.9 $\rightarrow$ **favors large corrections in the MFV expansion**

Caveats and future prospects

- Ideally inclusion of all relevant operators $\rightarrow$ even larger parameter space



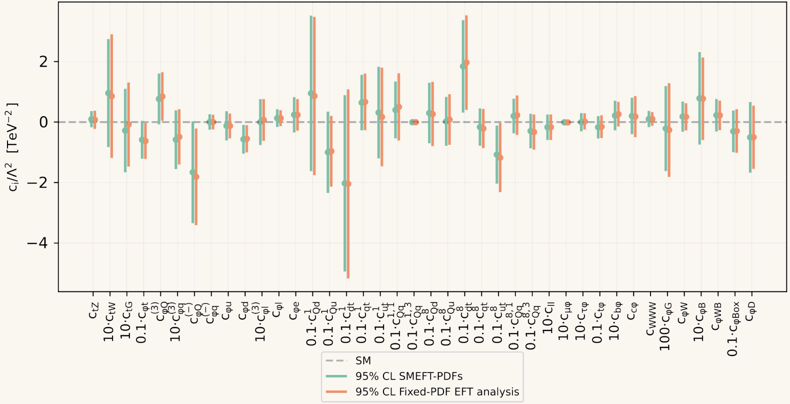
Bartocci, Biekötter, Hurth, [arXiv:2311.04963]



Bartocci, Biekötter, Hurth, [arXiv:2311.04963]

Caveats and future prospects

- Ideally inclusion of all relevant operators → even larger parameter space
- PDFs can mask new physics effects → ideally a joint fit of PDFs and Wilson coefficients



Costantini, Hammou, Kassabov, Madigan, Mantani, Morales Alvarado, Moore, Ubiali [arXiv:2402.03308]

Caveats and future prospects

- Ideally inclusion of all relevant operators → even larger parameter space
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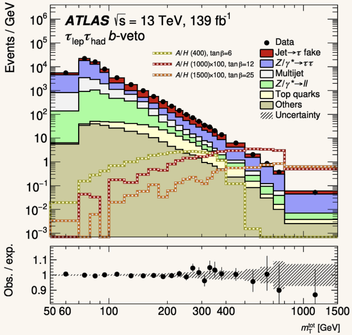
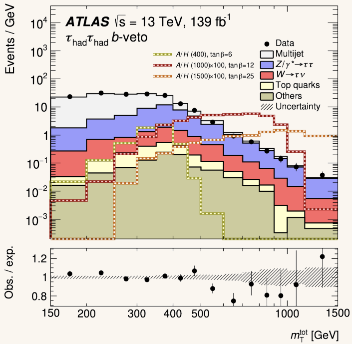
- SMEFT oftentimes not accounted for in background and detector efficiencies

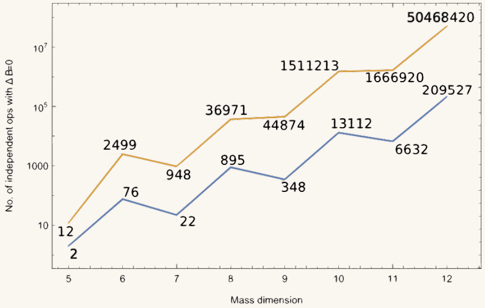




ATLAS Collaboration, [Phys.Rev.Lett. 125 (2020) 5, 051801]

Caveats and future prospects

- Ideally inclusion of all relevant operators $\rightarrow$ even larger parameter space
- PDFs can mask new physics effects $\rightarrow$ ideally a joint fit of PDFs and Wilson coefficients
- SMEFT oftentimes not accounted for in background and detector efficiencies
- Dimension-8 operators formally of same order as dimension-6 squared terms



Henning, Lu, Melia, Murayama, [JHEP 08 (2017) 016], Figure by Ilaria Brivio

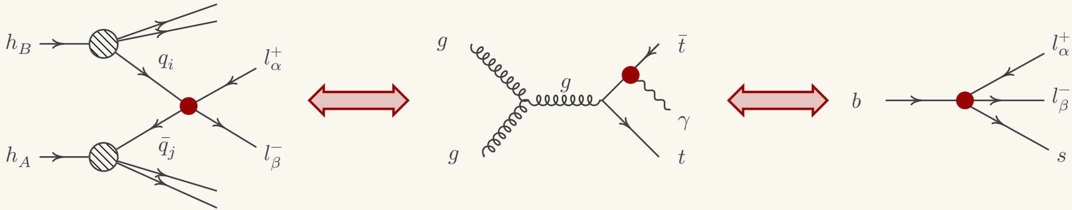
$$\mathcal{M} = \mathcal{M}^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{M}_i^{\text{BSM}}$$

$$\sigma \propto |\mathcal{M}|^2$$

$$\sigma = \sigma^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{\text{int}} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_i C_j \sigma_{ij}^{\text{sq}}$$

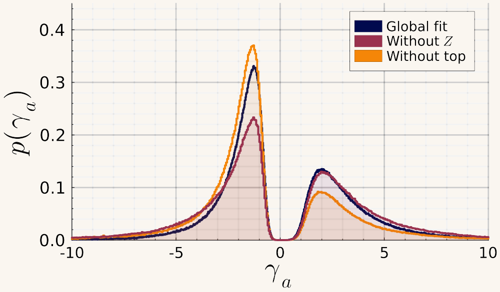
Conclusions

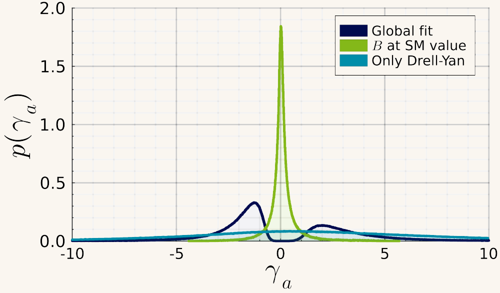
- EFTs allow to **largely model-independently** connect flavour and collider observables
- Global fits **break flat directions** and exploit synergies between different observables
- **Flavour assumptions** are a powerful tool to reduce the number of free parameters
- Potential to **test the flavour** structure of possible BSM physics



Supplementary Slides

Impact of Z, top and the B-anomalies

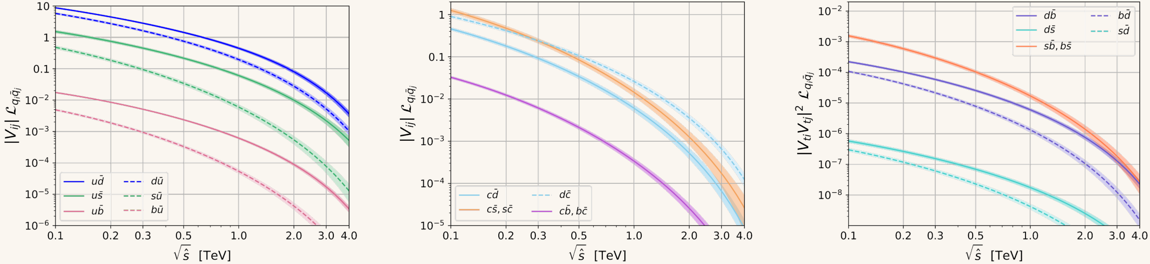




- Only a small impact of the top quark sector and Z pole measurements on γ_a
- $b \to s$ sector directly proportional to higher order MFV correction

  $\Longrightarrow$ B-**anomalies** seem to be the origin of the shape of γ_a

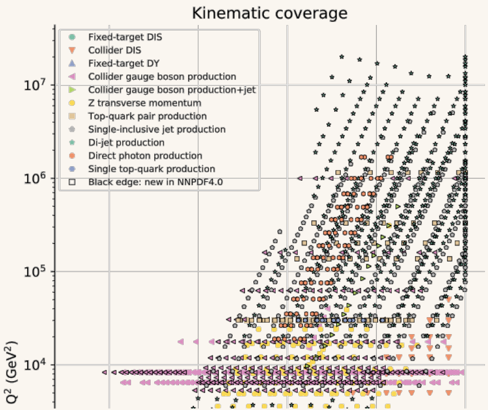
Parton-Parton Luminosities



$$\mathcal{L}_{q_i\bar{q}_j} = \tau \int_\tau^1 \frac{\mathrm{d}x}{x}\left[f_{q_i}(x,\mu_F) f_{\bar{q}_j}(\tau/x,\mu_F) + f_{\bar{q}_j}(x,\mu_F) f_{q_i}(\tau/x,\mu_F)\right]$$

$$\sigma = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau}\,\mathcal{L}_{q_i\bar{q}_j}(\tau)\,\hat{\sigma}(\tau s)$$

Kinematic coverage NNPDF4.0



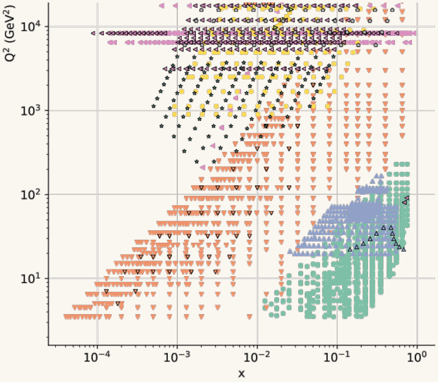


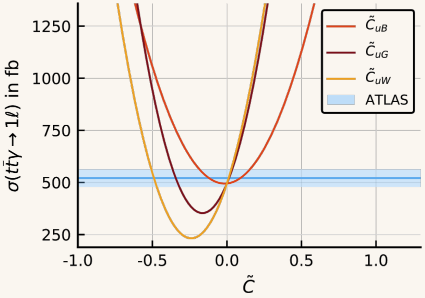
Figure 2.1. The kinematic coverage of the NNPDF4.0 dataset in the (x, Q^2) plane.

NNPDF Collaboration, [Eur.Phys.J.C 82 (2022) 5, 428]

The EFT cross section

MC Computation

$$\mathcal{M} = \mathcal{M}^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{M}_i^{\text{BSM}} \xrightarrow{\sigma \propto |\mathcal{M}|^2} \sigma = \sigma^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i\, \sigma_i^{\text{int}} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_i C_j \sigma_{ij}^{\text{BSM}}$$



[aEur.Phys.J.C 80 (2020) 2, 136]

model definition	SMEFTSIM [arXiv:2012.11343]
parton level Monte Carlo	MADGRAPH5 [arXiv:1405.0301]
hadronisation and parton shower	PYTHIA8 [arXiv:1410.3012]
detector simulation	DELPHES3 [arXiv:1307.6346]

SMEFT Operators in Warsaw basis

$$O_{uG} = (\bar{q}_L \sigma^{\mu\nu} T^A u_R)\, \tilde{\varphi} G^A_{\mu\nu}\,, \qquad O_{uW} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tau^I \tilde{\varphi} W^I_{\mu\nu}\,,$$

$$O_{uB} = (\bar{q}_L \sigma^{\mu\nu} u_R)\, \tilde{\varphi} B_{\mu\nu}\,, \qquad O_{qe} = \left(\bar{q}_L \gamma_\mu q_L\right)\left(\bar{e}_R \gamma^\mu e_R\right)\,,$$

$$O^{(1)}_{lq} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{q}_L \gamma^\mu q_L\right)\,, \qquad O^{(3)}_{lq} = \left(\bar{l}_L \gamma_\mu \tau^I l_L\right)\left(\bar{q}_L \gamma^\mu \tau^I q_L\right)\,,$$

$$O_{eu} = \left(\bar{e}_R \gamma_\mu e_R\right)\left(\bar{u}_R \gamma^\mu u_R\right)\,, \qquad O_{ed} = \left(\bar{e}_R \gamma_\mu e_R\right)\left(\bar{d}_R \gamma^\mu d_R\right)\,,$$

$$O_{lu} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{u}_R \gamma^\mu u_R\right)\,, \qquad O_{ld} = \left(\bar{l}_L \gamma_\mu l_L\right)\left(\bar{d}_R \gamma^\mu d_R\right)\,,$$

$$O^{(1)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{q}_L \gamma^\mu q_L\right)\,, \qquad O^{(3)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{q}_L \tau^I \gamma^\mu q_L\right)\,,$$

$$O_{\varphi u} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{u}_R \gamma^\mu u_R\right)\,, \qquad O_{\varphi d} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{d}_R \gamma^\mu d_R\right)\,,$$

Weak Effective Theory

Effective Lagrangian for $b \to sll$

$$\mathcal{L}_{\mathsf{WET}}^{bs} = \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) Q_i(\mu)$$

$$Q_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} \qquad Q_8 = \frac{g_s}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}$$

$$Q_9 = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell) \qquad Q_{10} = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \gamma_5 \ell)$$

$$Q_L = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{\nu} \gamma^\mu (1 - \gamma_5) \nu)$$

Weak Effective Theory for Meson mixing

Effective Lagrangian for $B_s\bar{B}_s$

$$\mathcal{L}_{\text{WET}}^{\text{mix}} = \frac{G_F^2 m_W^2}{16\pi^2} \left|V_{tb}V_{ts}^*\right|^2 \sum_i Q_i^{\text{mix}}(\mu) C_i^{\text{mix}}(\mu)\,,$$

$$Q_{V,LL}^{\text{mix}} = \left(\bar{s}_L \gamma_\mu b_L\right)\left(\bar{s}_L \gamma^\mu b_L\right)$$

Tree-level Matching

$$\Delta C_9^{\text{tree}} = \frac{\pi}{\alpha}\,\gamma_a\,\left[\tilde{C}_{lq}^{+} + \tilde{C}_{qe} + \left(-1 + 4\sin^2\theta_w\right)\tilde{C}_{\varphi q}^{+}\right]$$
$$= \gamma_a \cdot \left(430.511\,\left(\tilde{C}_{qe} + \tilde{C}_{lq}^{+}\right) - 45.858\tilde{C}_{\varphi q}^{+}\right)\,,$$

$$\Delta C_{10}^{\text{tree}} = \frac{\pi}{\alpha}\,\gamma_a\,\left[-\tilde{C}_{lq}^{+} + \tilde{C}_{qe} + \tilde{C}_{\varphi q}^{+}\right]$$
$$= \gamma_a \cdot 430.511\left(\tilde{C}_{\varphi q}^{+} + \tilde{C}_{qe} - \tilde{C}_{lq}^{+}\right)\,,$$

$$\Delta C_L^{\text{tree}} = \frac{\pi}{\alpha}\,\gamma_a\,\left[\tilde{C}_{lq}^{-} + \tilde{C}_{\varphi q}^{+}\right]$$
$$= \gamma_a \cdot 430.511\,\left(\tilde{C}_{\varphi q}^{+} + \tilde{C}_{lq}^{-}\right)$$

One-Loop Matching

$$C_7 = -2.351\,\tilde{C}_{uB} + 0.093\,\tilde{C}_{uW} + \gamma_a \cdot \left(-0.095\,\tilde{C}^{+}_{\varphi q} + 1.278\,\tilde{C}^{(3)}_{\varphi q}\right) + (1+\gamma_a) \cdot \left(-0.388\,\tilde{C}^{(3)}_{\varphi q}\right)$$

$$C_8 = -0.664\,\tilde{C}_{uG} + 0.271\,\tilde{C}_{uW} + \gamma_a \cdot \left(0.284\,\tilde{C}^{+}_{\varphi q} + 0.667\,\tilde{C}^{(3)}_{\varphi q}\right) + (1+\gamma_a) \cdot \left(-0.194\,\tilde{C}^{(3)}_{\varphi q}\right)$$

$$\begin{aligned} C_9 = {} & 2.506\,\tilde{C}_{uB} + 2.137\,\tilde{C}_{uW} + (1+\gamma_b)\left(0.213\,\tilde{C}_{\varphi u} + 2.003\left(-\tilde{C}_{lu} - \tilde{C}_{eu}\right)\right) \\ & + (1+\gamma_a) \cdot \left(-0.213\,\tilde{C}^{(1)}_{\varphi q} + 4.374\,\tilde{C}^{(3)}_{\varphi q} + 2.003\left(\tilde{C}_{qe} + \tilde{C}^{(1)}_{lq}\right) - 3.163\,\tilde{C}^{(3)}_{lq}\right) \end{aligned}$$

$$\begin{aligned} C_{10} = {} & -7.515\,\tilde{C}_{uW} + (1+\gamma_b) \cdot \left(2.003\left(-\tilde{C}_{\varphi u} - \tilde{C}_{eu} + \tilde{C}_{lu}\right)\right) \\ & + (1+\gamma_a) \cdot \left(2.003\left(\tilde{C}^{(1)}_{\varphi q} + \tilde{C}_{qe} - \tilde{C}^{(1)}_{lq}\right) - 17.884\,\tilde{C}^{(3)}_{\varphi q} + 3.163\,\tilde{C}^{(3)}_{lq}\right) \end{aligned}$$

$$\begin{aligned} C_L = {} & 12.889\,\tilde{C}_{uW} + (1+\gamma_a) \cdot \left(2.003\left(\tilde{C}^{(1)}_{\varphi q} + \tilde{C}^{(1)}_{lq}\right) - 22.830\tilde{C}^{(3)}_{\varphi q} - 16.275\tilde{C}^{(3)}_{lq}\right) \\ & + (1+\gamma_b) \cdot 2.003\left(-\tilde{C}_{\varphi u} - \tilde{C}_{lu}\right) \end{aligned}$$

$$C^{\text{mix}}_{V,LL} = -22.023\,\tilde{C}_{uW} + \gamma_a \cdot \left(14.317\,\tilde{C}^{(1)}_{\varphi q} + 11.395\,\tilde{C}^{(3)}_{\varphi q}\right) .$$

MFV Spurion Expansion

MFV Spurion expansion of quark bilinears:

$$\bar{q}_L q_L :\sim a_1 \mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \dots$$

$$\bar{u}_R u_R :\sim b_1 \mathbb{1} + b_2 Y_u^\dagger Y_u + \dots \qquad \bar{q}_L u_R :\sim (c_1 \mathbb{1} + c_2 Y_u Y_u^\dagger + c_3 Y_d Y_d^\dagger + \dots) Y_u$$

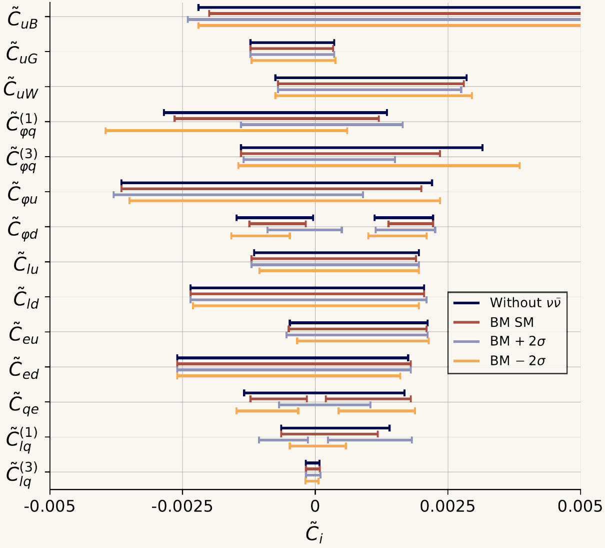
$$\bar{d}_R d_R :\sim e_1 \mathbb{1} + e_2 Y_d^\dagger Y_d + \dots \qquad \bar{q}_L d_R :\sim (d_1 \mathbb{1} + d_2 Y_u Y_u^\dagger + d_3 Y_d Y_d^\dagger + \dots) Y_d$$

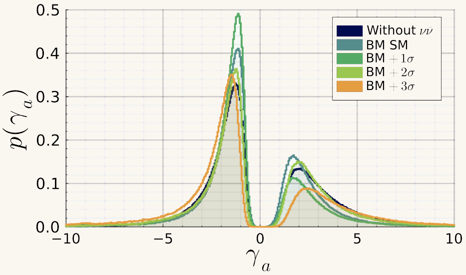
After the rotation to the mass basis:

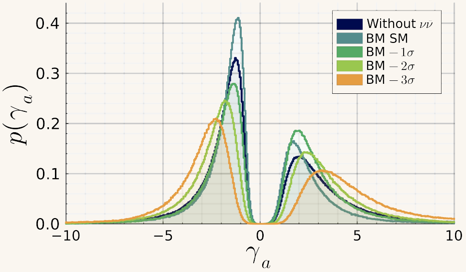
$$\begin{aligned} \bar{q}_L q_L :\ & \bar{d}_{Li} d_{Lj} \to a_1 \delta_{ij} + a_2 y_t^2 V_{ti}^* V_{tj} \\ & \bar{u}_{Li} u_{Lj} \to a_1 \delta_{ij} + a_2 y_t^2 \delta_{3i} \delta_{3j} \\ & \bar{u}_{Li} d_{Lj} \to a_1 V_{ij} + a_2 y_t^2 \delta_{3i} V_{tj} \\ & \bar{d}_{Li} u_{Lj} \to a_1 V_{ji}^* + a_2 y_t^2 V_{ti}^* \delta_{3j} \end{aligned}$$

$$\begin{aligned} \bar{q}_L u_L :\ & \bar{u}_{Li} u_{Rj} \to (c_1 + c_2 y_t^2) y_t \delta_{3i} \delta_{3j} \,, \\ & \bar{d}_{Li} u_{Rj} \to (c_1 + c_2 y_t^2) y_t V_{ti}^* \delta_{3j} \,, \\ \bar{q}_L d_R :\ & \simeq 0 \\ \bar{u}_R u_R :\ & \bar{u}_{Ri} u_{Rj} \to b_1 \delta_{ij} + b_2 y_t^2 \delta_{3i} \delta_{3j} \\ \bar{d}_R d_R :\ & \bar{d}_{Ri} d_{Rj} \to e_1 \delta_{ij} \end{aligned}$$

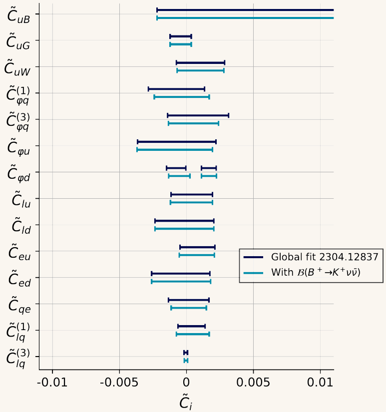
Impact of $\mathcal{B}(B^{0/+} \to K^{*0/+}\nu\bar{\nu})$

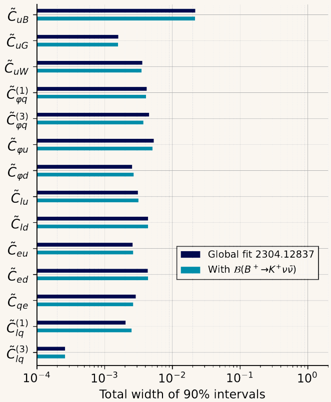


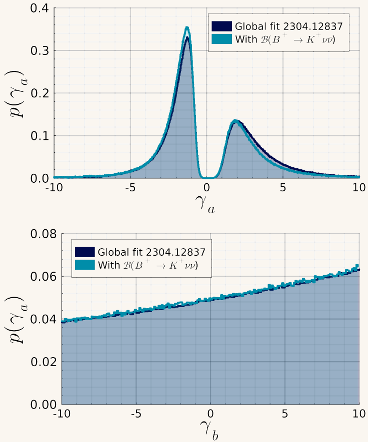




The impact of the $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})$ measurement



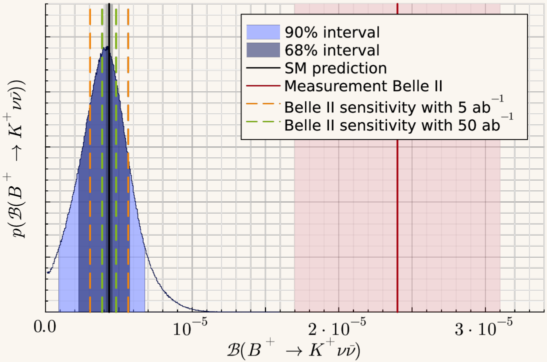


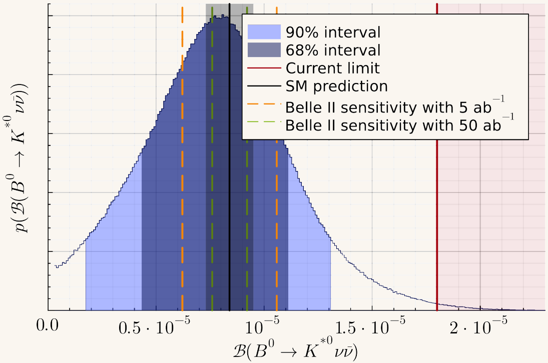


- Recent measurement by Belle II: $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) = (2.4 \pm 0.7) \cdot 10^{-5}$ [EPS-HEP, 2023]
- SM prediction: $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\text{SM}} = (4.34 \pm 0.23) \cdot 10^{-6}$ (resonant τ contribution $\sim 5 \cdot 10^{-7}$ not included)

Predictions of dineutrino branching ratios

- Posterior probability distributions can be used to predict the branching ratios within MFV





- Only left handed currents are generated in MFV $\to$ **Dineutrino branching ratios are correlated**

$$\frac{\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})}{\mathcal{B}(B^0 \to K^{*0} \nu\bar{\nu})} = 0.52 \pm 0.06$$

$B \to K$ Form Factors

- BSZ parameterization

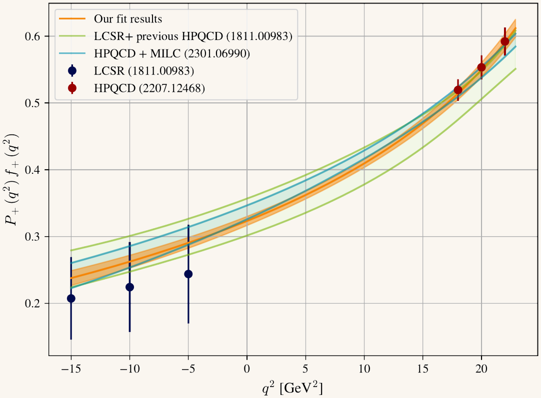
$$f_i(q^2) = \frac{1}{P_i(q^2)} \sum_{n=0}^{K-1} a_n^i \left[z(q^2) - z(0)\right]^n$$

- Pole factors

$$P_i(q^2) = 1 - q^2/M_{B_i}^2$$

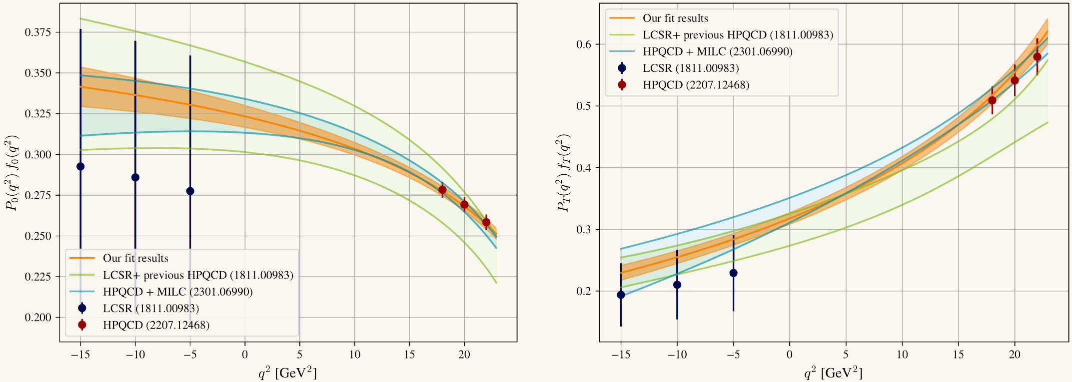
- Conformal mapping

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$



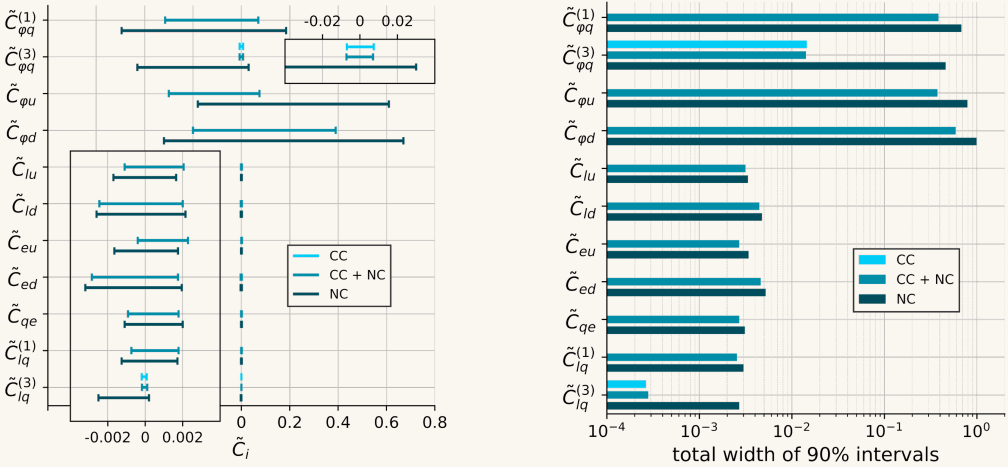
with $t_+ = (M_{B^+} + M_{K^+})^2$ and $t_0 = (M_{B^+} + M_{K^+})(\sqrt{M_{B^+}} - \sqrt{M_{K^+}})^2 \implies |z| < 0.15$

$B \to K$ Form Factor Fit results

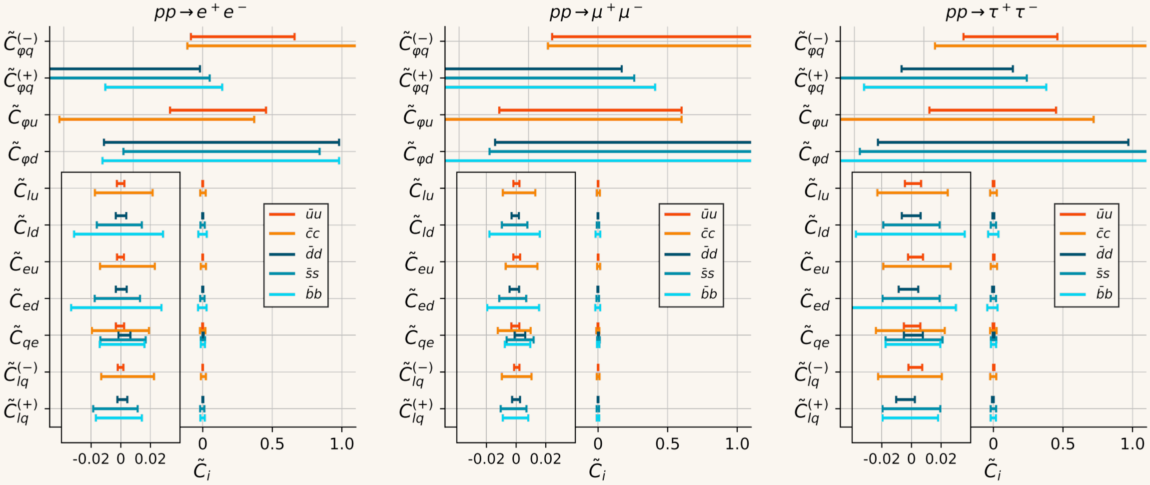


Grunwald, Hiller, Kröninger, LN, [JHEP 11 (2023) 110]

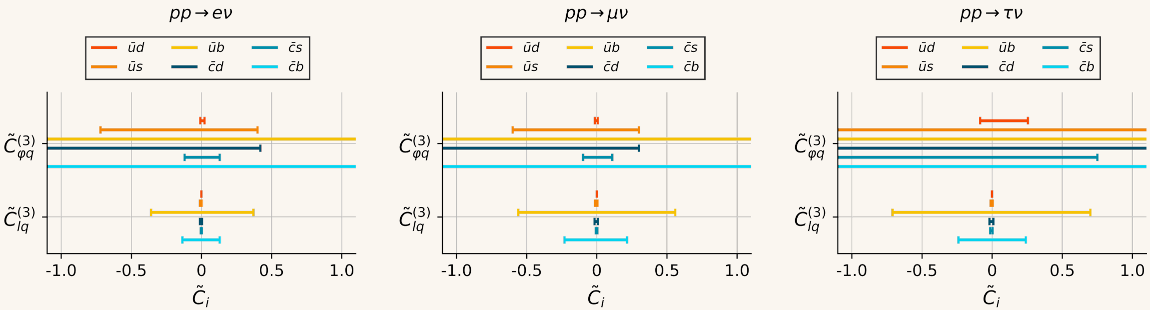
MFV Drell-Yan Fits



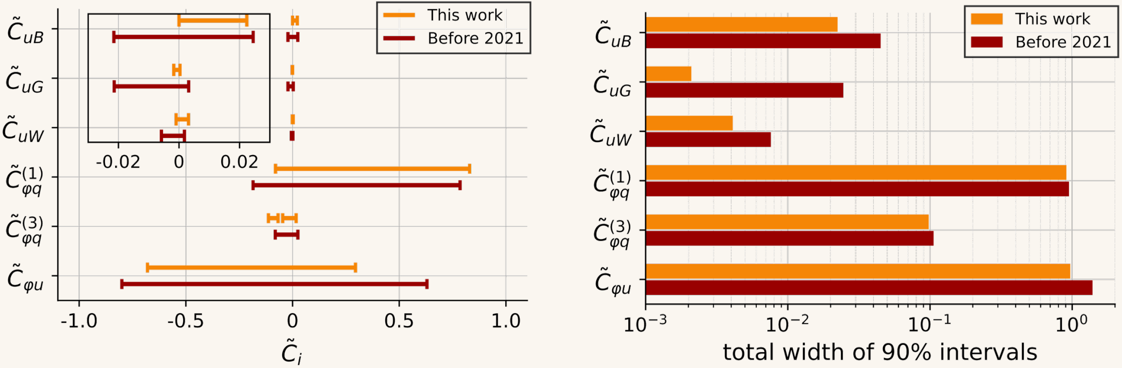
Flavour-Specific NC Drell-Yan Fits



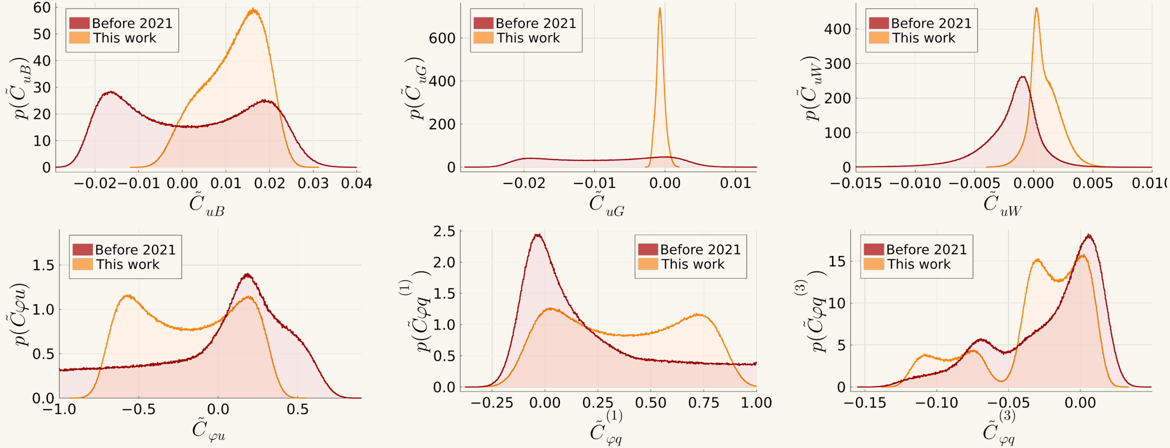
Flavour-Specific CC Drell-Yan Fits



Top Fits


This work
Before 2021
$\tilde{C}_{uB}$
$\tilde{C}_{uG}$
$\tilde{C}_{uW}$
$\tilde{C}^{(1)}_{\varphi q}$
$\tilde{C}^{(3)}_{\varphi q}$
$\tilde{C}_{\varphi u}$
-0.02
0
0.02
-1.0
-0.5
0
0.5
1.0
$\tilde{C}_i$
10^{-3}
10^{-2}
10^{-1}
10^{0}
total width of 90% intervals

Top Fit Posterior Probability Distributions



Top quark measurements included in the fit

Process	Observable	SMEFT operators	Experiment
$t\bar{t}$	$\frac{\mathrm{d}\sigma}{\mathrm{dm}(t\bar{t})}$	$\tilde{C}_{uG}$	CMS
$t\bar{t}Z$	$\frac{\mathrm{d}\sigma}{\mathrm{dp_T}(Z)}$	$\tilde{C}_{uG}$ $\tilde{C}_{uZ}$ $\tilde{C}_{\varphi u}$ $\tilde{C}^{-}_{\varphi q}$	ATLAS
$t\bar{t}\gamma$	$\frac{\mathrm{d}\sigma}{\mathrm{dp_T}(\gamma)}$	$\tilde{C}_{uG}$ $\tilde{C}_{u\gamma}$	ATLAS
$t\bar{t}W$	$\sigma_{t\bar{t}W}$	$\tilde{C}_{uG}$	ATLAS
$t\bar{t}H$	$\sigma_{t\bar{t}H} \times \mathcal{B}_{\gamma\gamma}$	$\tilde{C}_{uG}$	ATLAS
$t \to Wb$	f_0, f_L	$\tilde{C}_{uW}$	ATLAS
$t \to Wb$	Γ_t	$\tilde{C}_{uW}$ $\tilde{C}^{3}_{\varphi q}$	ATLAS

Drell-Yan measurements included in the fit

Process	Observable	Experiment	$\sqrt{s}$	Int. luminosity
$pp \to e^+e^-$	Events, 68 bins	CMS	13 TeV	137 fb^{-1}
$pp \to \mu^+\mu^-$	Events, 36 bins	CMS	13 TeV	140 fb^{-1}
$pp \to \tau^+\tau^-$	Events, 17 bins	ATLAS	13 TeV	139 fb^{-1}
$pp \to e\nu$	Events, 40 bins	ATLAS	13 TeV	139 fb^{-1}
$pp \to \mu\nu$	Events, 35 bins	ATLAS	13 TeV	139 fb^{-1}
$pp \to \tau\nu$	Events, 10 bins	ATLAS	13 TeV	139 fb^{-1}

Flavour measurements included in the fit

Process	Observable	Experiment	q^2 bin [GeV^2]
$\bar{B} \to X_s \gamma$	$\mathcal{B}_{E_\gamma > 1.6\ \text{GeV}}$	HFLAV	/
$B^0 \to K^* \gamma$	$\mathcal{B}$	HFLAV	/
$B^+ \to K^{*+} \gamma$	$\mathcal{B}$	HFLAV	/
$\bar{B} \to X_s \ell^+ \ell^-$	$\mathcal{B}$	BaBar	$[1, 6]$
	$A_{\mathsf{F}\mathcal{B}}$	Belle	$[1, 6]$
$B_s \to \mu^+ \mu^-$	$\mathcal{B}$	CMS	/
$B^0 \to K^* \mu^+ \mu^-$	$F_L,\ P_1,\ P_2,\ P_3,$ $P'_4,\ P'_5,\ P'_6,\ P'_8$	LHCb	$[1.1, 6]$
$B^0 \to K \mu^+ \mu^-$	$\text{d}\mathcal{B}/\text{d}q^2$	LHCb	$[1, 6]$
$B^+ \to K^+ \mu^+ \mu^-$	$\text{d}\mathcal{B}/\text{d}q^2$	LHCb	$[1, 6]$
$B^+ \to K^{+*} \mu^+ \mu^-$	$\text{d}\mathcal{B}/\text{d}q^2$	LHCb	$[1, 6]$
$B_s \to \phi \mu^+ \mu^-$	$F_L,\ S_3,\ S_4,\ S_7$	LHCb	$[1, 6]$
$\Lambda_b \to \Lambda \mu^+ \mu^-$	$\text{d}\mathcal{B}/\text{d}q^2$	LHCb	$[15, 20]$
$B_s - \bar{B}_s$ mixing	ΔM_s	HFLAV	/