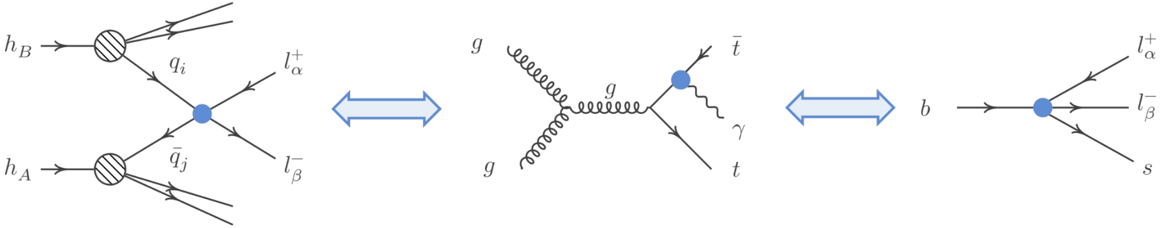
tu dortmund university

Department of Physics

Synergies from Beauty, Top, Z and Drell-Yan Measurements in SMEFT

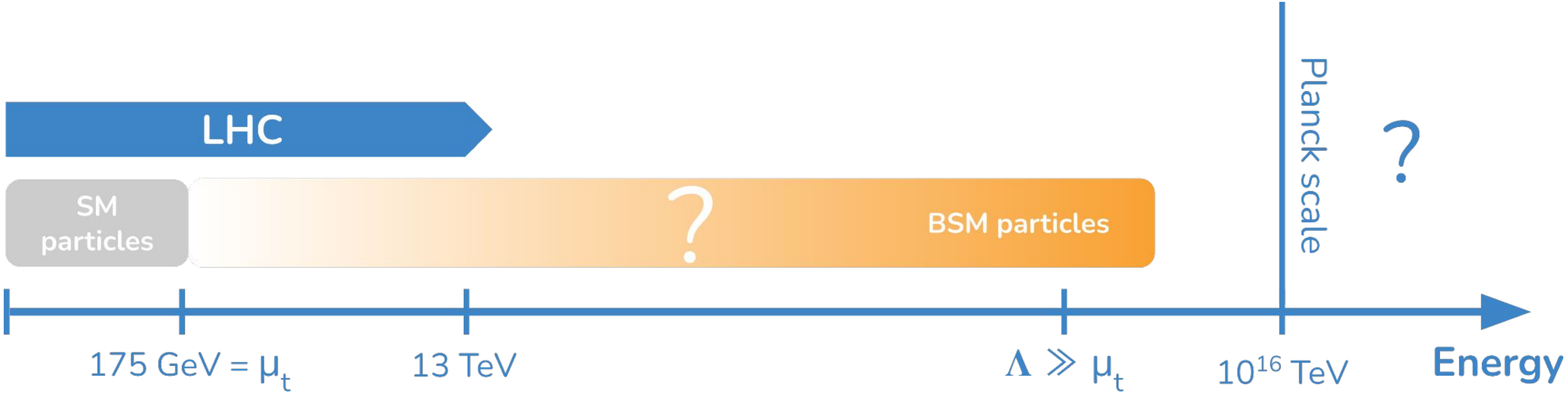


Cornelius Grunwald, Gudrun Hiller, Lara Nollen, Kevin Kröninger

LHC EFT WG Meeting

February 19, 2024

Standard Model effective field theory (SMEFT)



effective extension of the SM Lagrangian for energies much higher than the SM scale:

$$\mathcal{L}_{\mathrm{SMEFT}} = \underset{\text{mass dimension = 4}}{\mathcal{L}_{\mathrm{SM}}} + \underbrace{\frac{1}{\Lambda^2} \sum_i C_i^{(6)} O_i^{(6)}}_{\text{BSM physics}} + \ldots$$

Λ : energy scale

O_i : higher dimensional operators

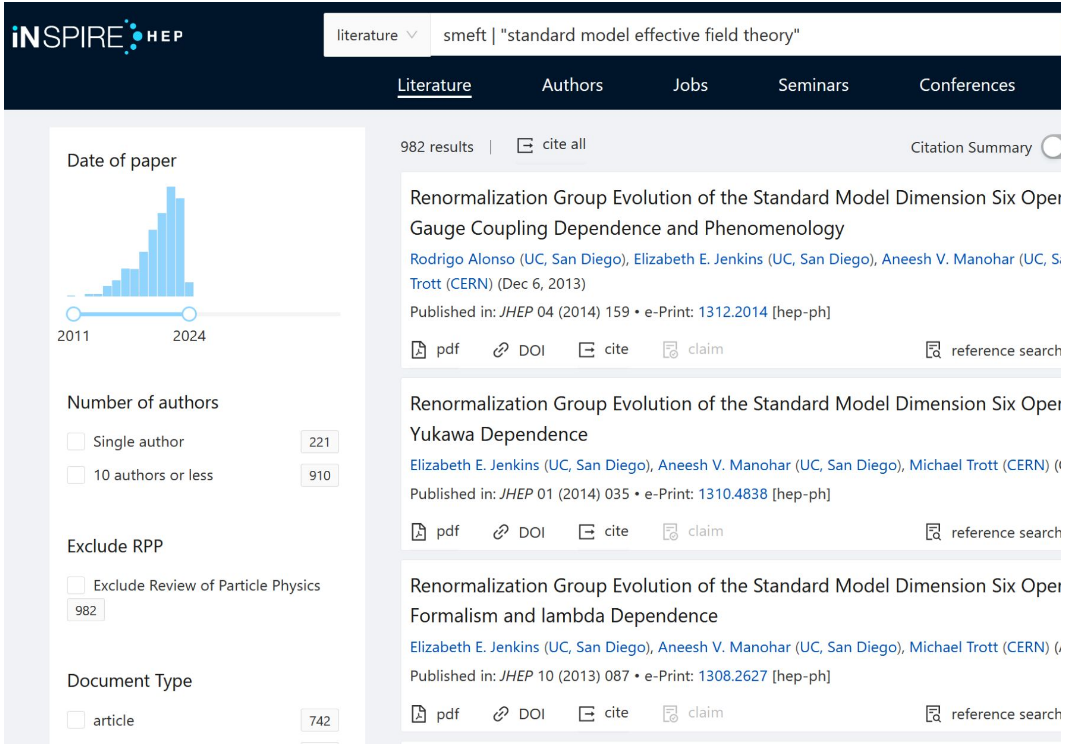
C_i : Wilson coefficients $\tilde{C}_i = \frac{v^2}{\Lambda^2} C_i$

➡ model-independent probes of BSM phenomena by constraining values of the Wilson coefficients

Global SMEFT fits

- SMEFT gained a lot of popularity in recent years
- 59 dimension-six operators
  (2499 when considering flavor structure)
- EFT interpretations of single measurements can only constrain a small number of Wilson coefficients

➡ global fits combining measurements from different physics sectors



smeft | "standard model effective field theory"

982 results

Date of paper

Number of authors

☐ Single author	221
☐ 10 authors or less	910

Exclude RPP

☐ Exclude Review of Particle Physics 982

Document Type

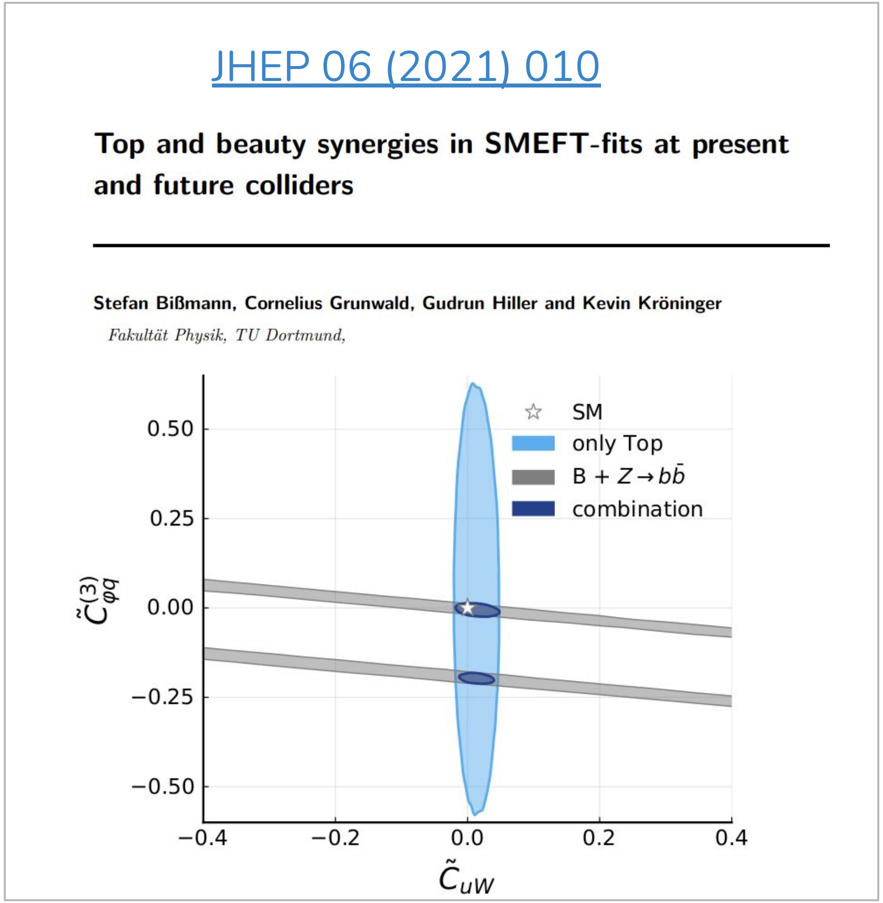
☐ article	742

Renormalization Group Evolution of the Standard Model Dimension Six Oper
Gauge Coupling Dependence and Phenomenology
Rodrigo Alonso (UC, San Diego), Elizabeth E. Jenkins (UC, San Diego), Aneesh V. Manohar (UC, S
Trott (CERN) (Dec 6, 2013)
Published in: *JHEP* 04 (2014) 159 • e-Print: 1312.2014 [hep-ph]

Renormalization Group Evolution of the Standard Model Dimension Six Oper
Yukawa Dependence
Elizabeth E. Jenkins (UC, San Diego), Aneesh V. Manohar (UC, San Diego), Michael Trott (CERN) (
Published in: *JHEP* 01 (2014) 035 • e-Print: 1310.4838 [hep-ph]

Renormalization Group Evolution of the Standard Model Dimension Six Oper
Formalism and lambda Dependence
Elizabeth E. Jenkins (UC, San Diego), Aneesh V. Manohar (UC, San Diego), Michael Trott (CERN) (
Published in: *JHEP* 10 (2013) 087 • e-Print: 1308.2627 [hep-ph]

Synergies in SMEFT fits



JHEP 06 (2021) 010

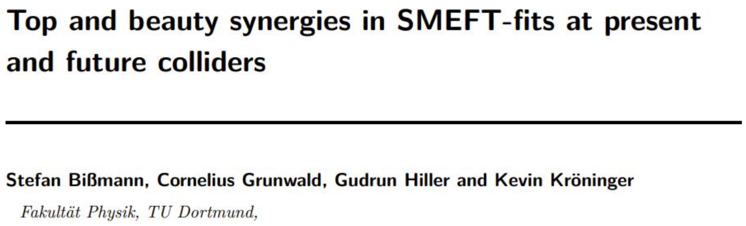
Top and beauty synergies in SMEFT-fits at present and future colliders

Stefan Bißmann, Cornelius Grunwald, Gudrun Hiller and Kevin Kröninger

Fakultät Physik, TU Dortmund,

Synergies in SMEFT fits

JHEP 06 (2021) 010



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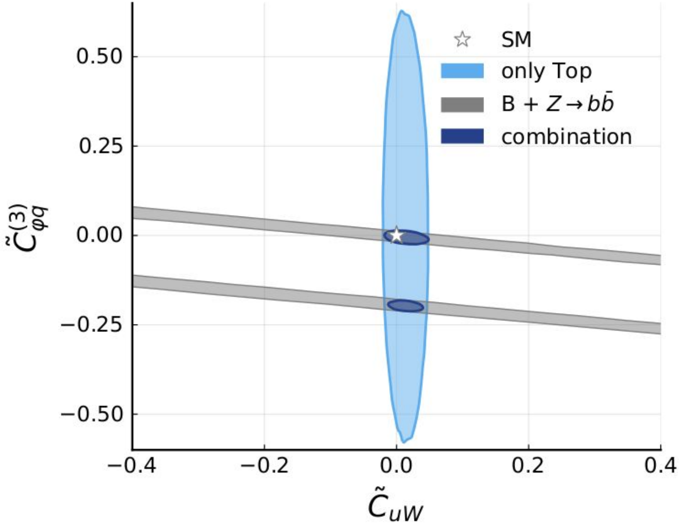
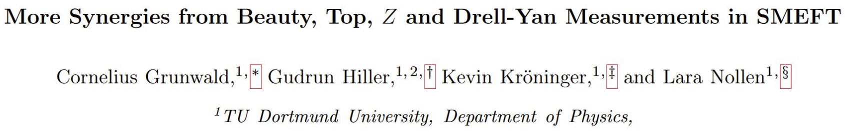


NEW!

arXiv: 2304.12837



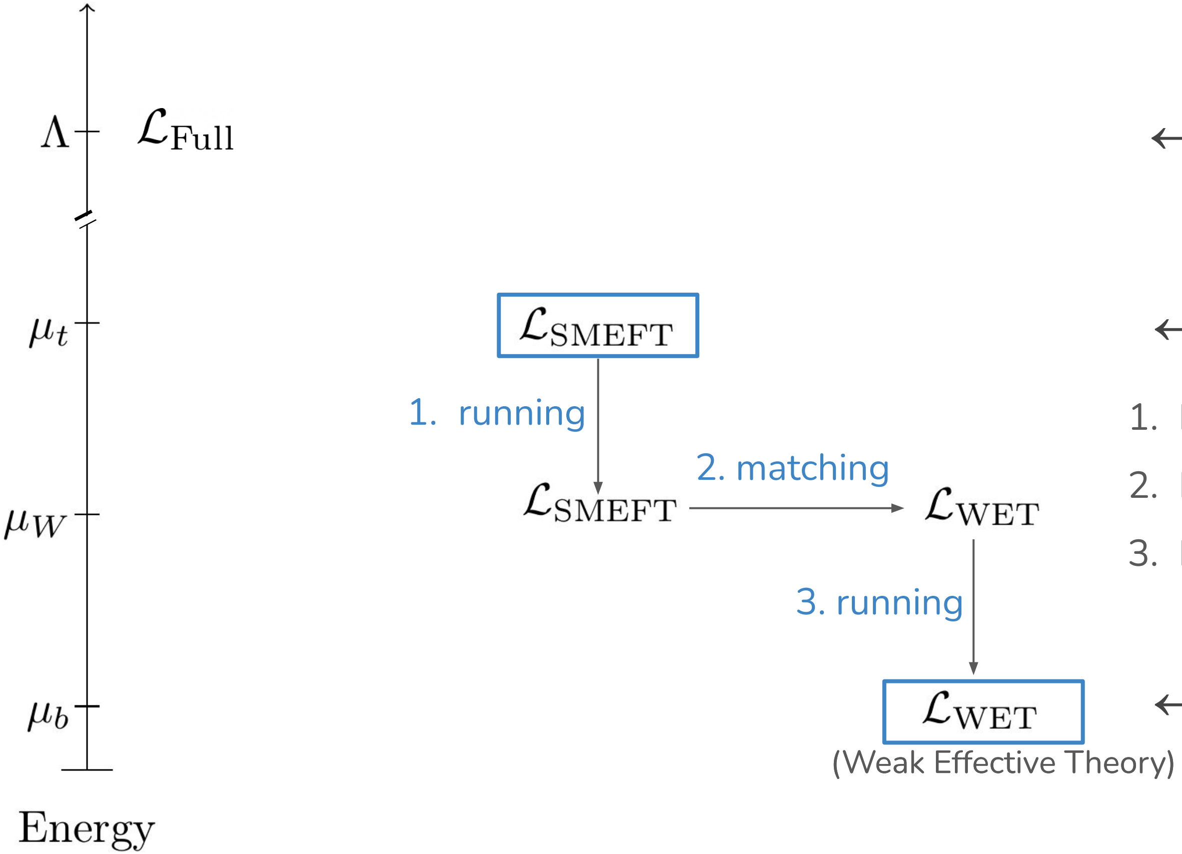
More Synergies from Beauty, Top, Z and Drell-Yan Measurements in SMEFT

Cornelius Grunwald,[1,*] Gudrun Hiller,[1,2,†] Kevin Kröninger,[1,‡] and Lara Nollen[1,§]

[1] *TU Dortmund University, Department of Physics,*

- \+ updated top-quark measurements
- \+ include Drell-Yan data
- \+ impose MFV flavor pattern to couple different sectors

Combining different energy scales & EFT formalisms



$\mathcal{L}_{\text{Full}}$

$\boxed{\mathcal{L}_{\text{SMEFT}}}$

1. running

$\mathcal{L}_{\text{SMEFT}}$ $\xrightarrow{\text{2. matching}}$ $\mathcal{L}_{\text{WET}}$

3. running

$\boxed{\mathcal{L}_{\text{WET}}}$

(Weak Effective Theory)

← **Full theory of SM + BSM particles**

Top-quark measurements

← **SM particles**

1. Running in SMEFT (RGE)
2. Matching SMEFT onto WET at scale μ_W
3. Running in WET (RGE)

B physics measurements

← **SM particles without t, h, W, Z**

MFV Flavor Structure

- impose Minimal Flavor Violation (MFV) to couple different sectors
- MFV requires spurion expansion with Yukawa matrices:

example for quark bilinears: $\bar q_L q_L :\sim a_1 \mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots$

left-handed quarks

$\bar u_R u_R :\sim b_1 \mathbb{1} + b_2 Y_u^\dagger Y_u + \ldots$

right-handed up-type quarks

- rotation into mass basis & keeping only y_t imposes correlations between sectors:

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

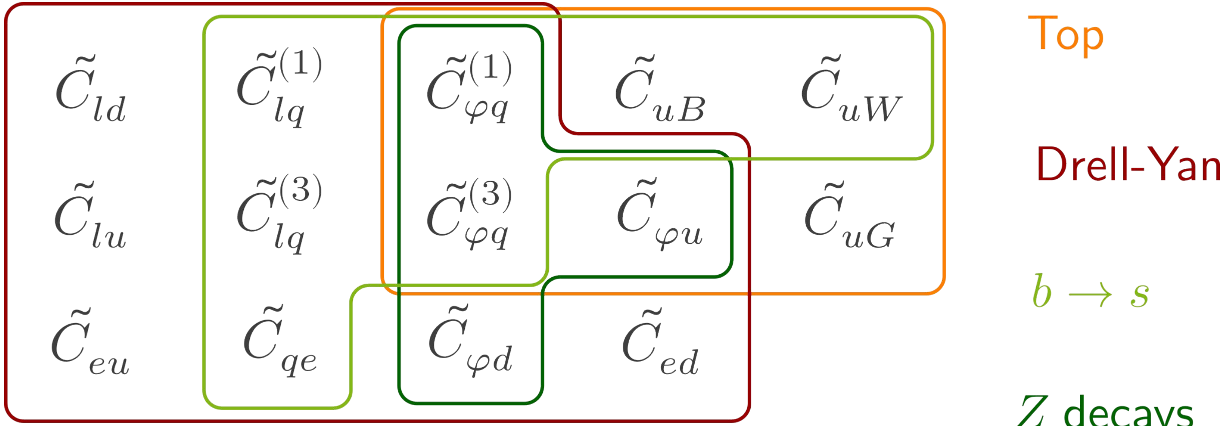
$t\bar t$ Drell-Yan $b \to s$

- re-parametrization:

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

"ratio of higher-order corrections to leading terms"

Free Parameters



$\tilde{C}_{ld}$	$\tilde{C}_{lq}^{(1)}$	$\tilde{C}_{\varphi q}^{(1)}$	$\tilde{C}_{uB}$	$\tilde{C}_{uW}$
$\tilde{C}_{lu}$	$\tilde{C}_{lq}^{(3)}$	$\tilde{C}_{\varphi q}^{(3)}$	$\tilde{C}_{\varphi u}$	$\tilde{C}_{uG}$
$\tilde{C}_{eu}$	$\tilde{C}_{qe}$	$\tilde{C}_{\varphi d}$	$\tilde{C}_{ed}$	

Top

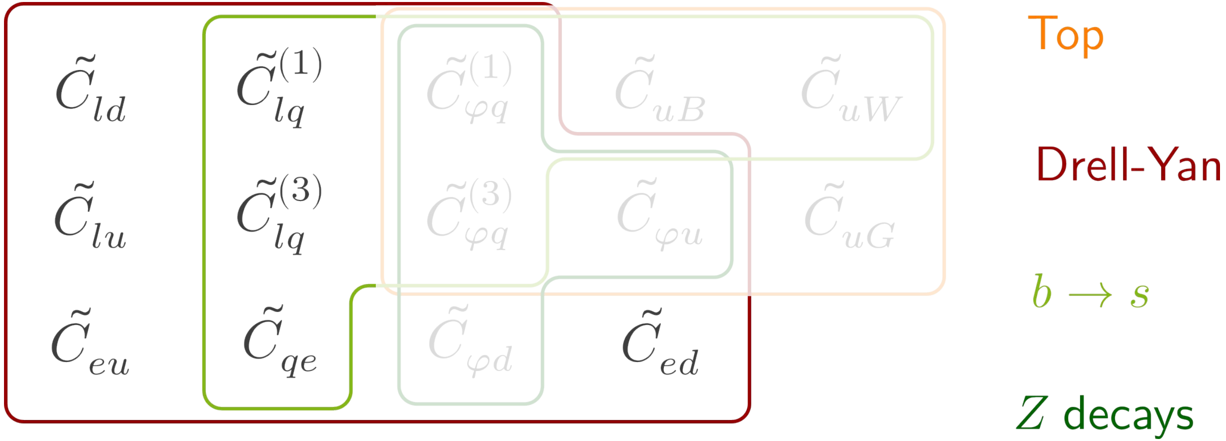
Drell-Yan

$b \to s$

Z decays

14 Wilson coefficients:

Free Parameters



$\tilde{C}_{ld}$ $\tilde{C}^{(1)}_{lq}$ $\tilde{C}^{(1)}_{\varphi q}$ $\tilde{C}_{uB}$ $\tilde{C}_{uW}$

$\tilde{C}_{lu}$ $\tilde{C}^{(3)}_{lq}$ $\tilde{C}^{(3)}_{\varphi q}$ $\tilde{C}_{\varphi u}$ $\tilde{C}_{uG}$

$\tilde{C}_{eu}$ $\tilde{C}_{qe}$ $\tilde{C}_{\varphi d}$ $\tilde{C}_{ed}$

Top

Drell-Yan

$b \to s$

Z decays

14 Wilson coefficients:

- 7 semileptonic four-fermion operators

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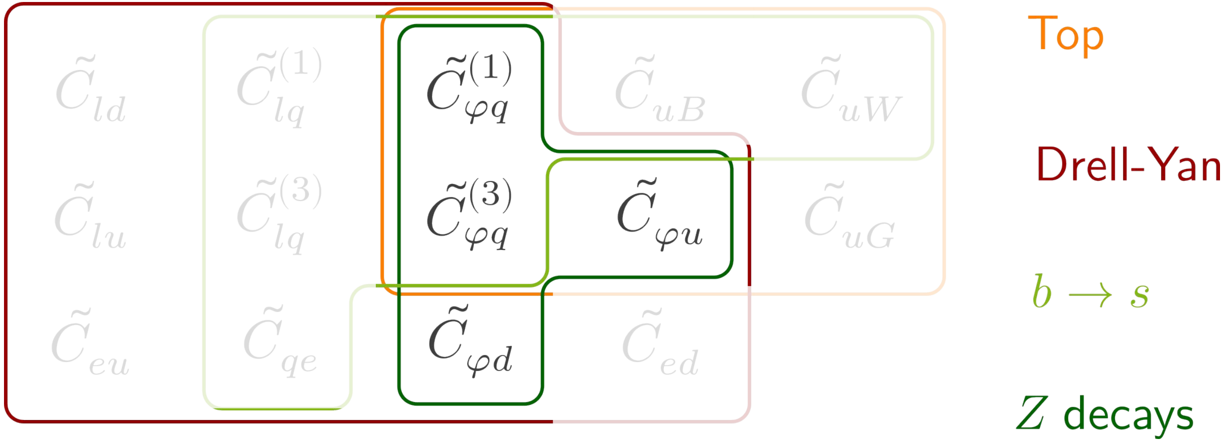
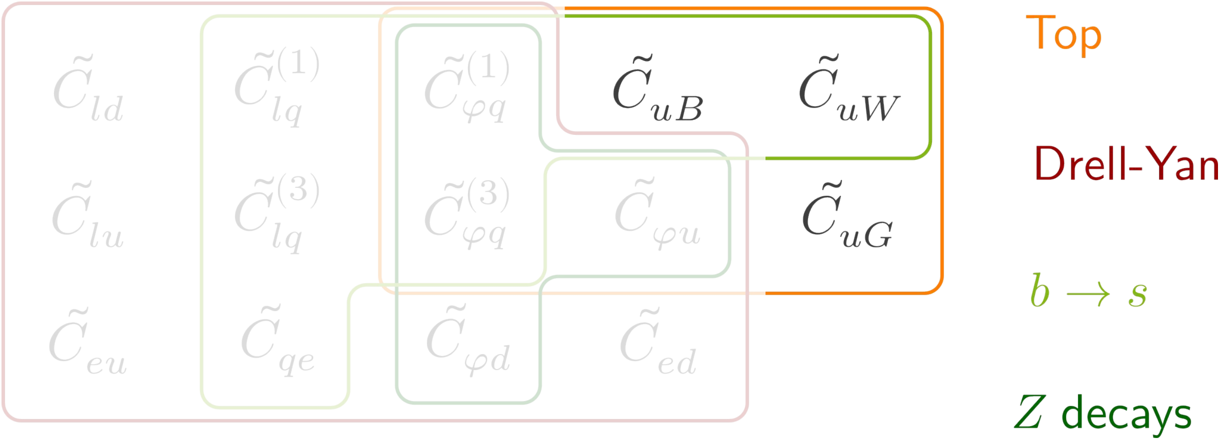


14 Wilson coefficients:

- 7 semileptonic four-fermion operators
- 4 penguin operators

Free Parameters



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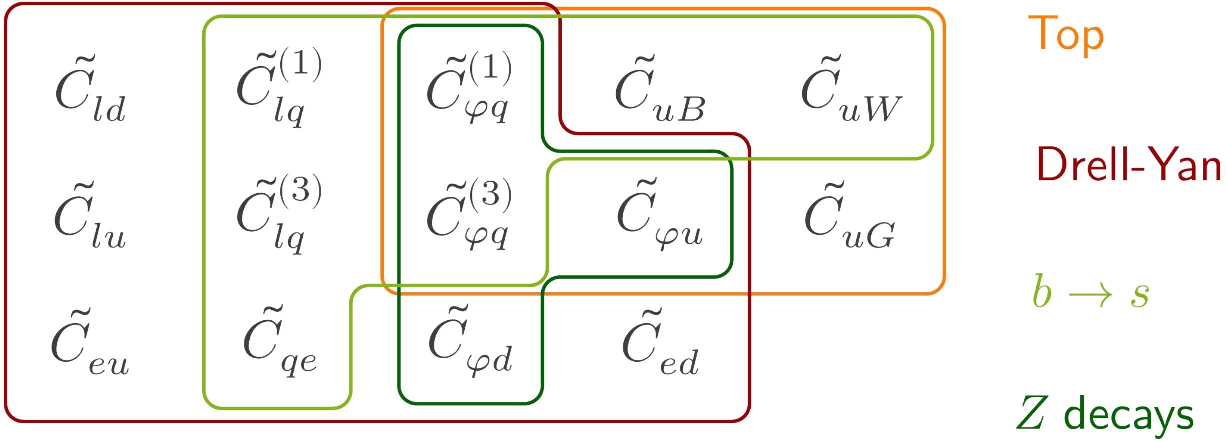


14 Wilson coefficients:

- 7 semileptonic four-fermion operators
- 4 penguin operators
- 3 up-type dipole operators

2 ratios from MFV expansion:

- γ_a for left-handed quark doublets
- γ_b for right-handed up-quark singlets

➡ total of 16 degrees of freedom

Observables & Measurements

Top

$\sigma_{t\bar{t}}$ (diff.) $\sigma_{t\bar{t}Z}$ (diff.) $\sigma_{t\bar{t}\gamma}$ (diff.) Γ_t

$\sigma_{t\bar{t}H}$ (incl.) $\sigma_{t\bar{t}W}$ (incl.) f_0 f_L

Drell-Yan

e^+e^- $e\nu$

$\mu^+\mu^-$ $\mu\nu$

$\tau^+\tau^-$ $\tau\nu$

Z decays

R_b A^b_{FB} R_c A^c_{FB}

b → s

$\mathcal{B}_{\bar{B}\to X_s\gamma}$ $\mathcal{B}_{B_s\to\mu^+\mu^-}$ $\mathcal{B}_{\bar{B}\to X_s l^+l^-}$ $F_{L\ B^0\to K^*\mu^+\mu^-}$

$P^{(\prime)}_{i\ B^0\to K^*\mu^+\mu^-}$ $\mathcal{B}_{B^{0/+}\to K^{0/+}\mu^+\mu^-}$ $\mathcal{B}_{B^{0/+}\to K^{*0/+}\gamma}$

$\mathcal{B}_{B^+\to K^{+*}\mu^+\mu^-}$ $S_{i\ B_s\to\phi\mu^+\mu^-}$ $\mathcal{B}_{\Lambda_b\to\Lambda\mu^+\mu^-}$ $\Delta M_{s\ B_s/\bar{B}_s}$

CMS

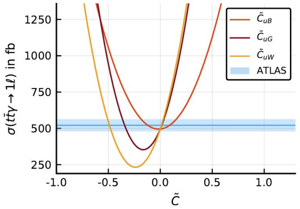
ATLAS EXPERIMENT

LHCb

BELLE

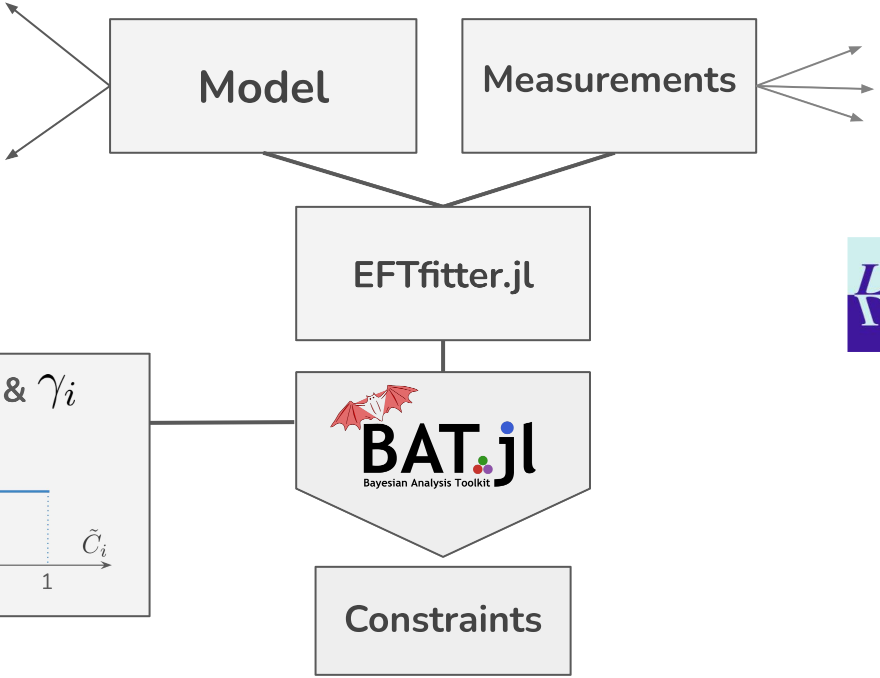
HFLAV

BABAR



MC simulations + interpolations

matching + running + theory calculations



Model

Measurements

Top-quark, B, Z, Drell-Yan

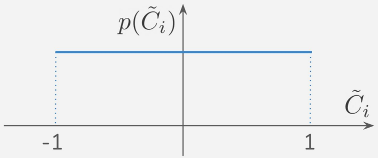
nominal values

uncertainties

correlations

EFTfitter.jl

Prior on $\tilde{C}_i$ & γ_i



BAT.jl

Bayesian Analysis Toolkit

Constraints

LHCb

BELLE

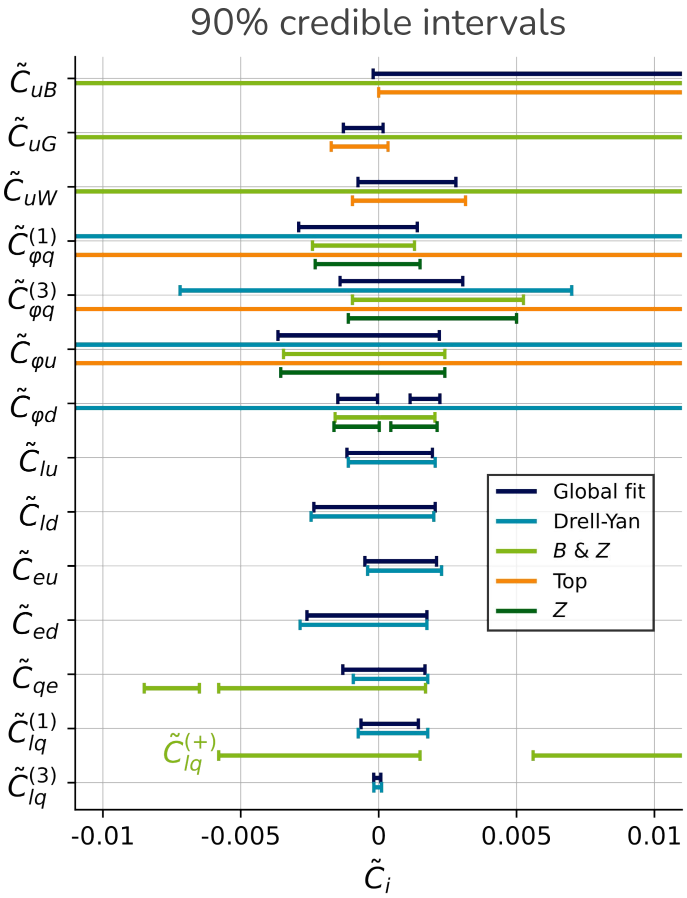
BABAR

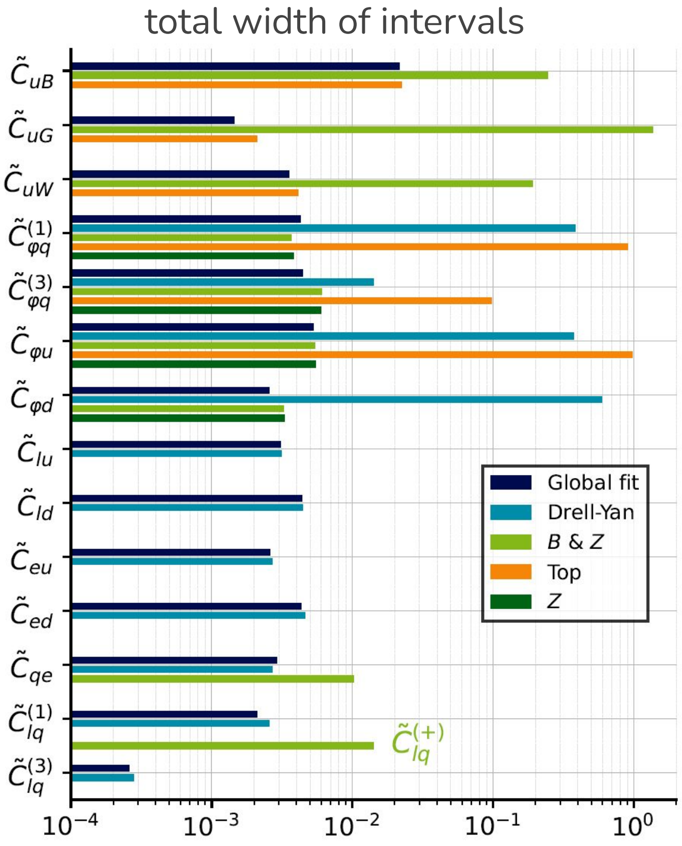
HFLAV

CMS

ATLAS EXPERIMENT

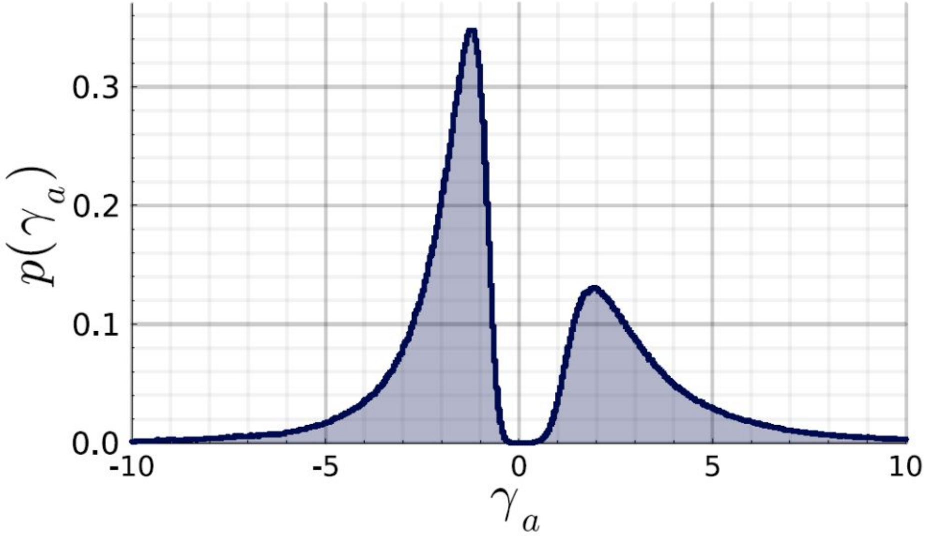
Results of the combined fit


90% credible intervals


total width of intervals

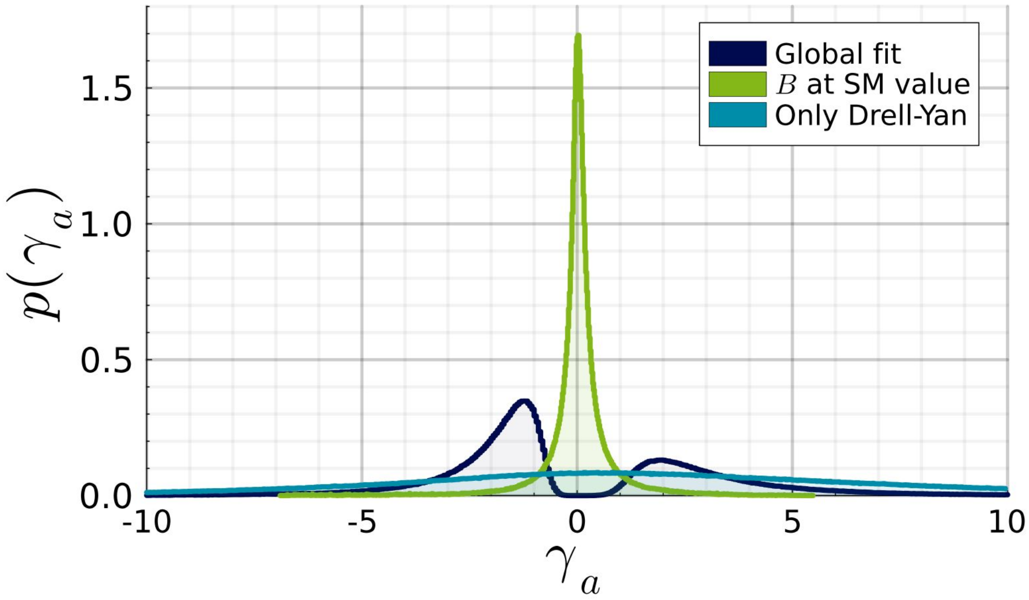
Constraints on the MFV parameters

$$\gamma_a = \sum_{n\geq 1} y_t^{2n}\, a_{2n}/a_1$$ left-handed quarks



- posterior of γ_a peaks at -1.2 & 1.9
- expected: within [-1, 1] & centered around 0
- fit favors large higher-order corrections in the MFV expansion

Where is this pattern in γ_a coming from?



- $b \rightarrow s$ sector directly proportional to higher-order MFV corrections: very sensitive on γ_a
- $\gamma_a = 0$ would not allow for NP in this sector, which is contradicting the measurements

➡ *B* anomalies seem to be origin of the shape of γ_a

Impact of $b \longrightarrow s\nu\nu$ transitions

- $b \rightarrow s$ transitions only probe linear combinations of Wilson coefficients:

$$b \rightarrow s\ell^+\ell^- \qquad \tilde{C}^{(+)}{}_{lq} = \tilde{C}^{(1)}_{lq} + \tilde{C}^{(3)}_{lq}$$

$$b \rightarrow s\nu\bar{\nu} \qquad \tilde{C}^{(-)}{}_{lq} = \tilde{C}^{(1)}_{lq} - \tilde{C}^{(3)}_{lq}$$

- only upper bounds on $b \longrightarrow s\nu\nu$ branching ratios available
- hypothetical BELLE II measurements:
  (SM value + expected uncertainties)

$$B(B^0 \rightarrow K^{*0}\nu\bar{\nu})_{\text{BM SM}} = (9.5 \pm 2.5) \cdot 10^{-6}$$
$$B(B^+ \rightarrow K^+\nu\bar{\nu})_{\text{BM SM}} = (4.4 \pm 1.3) \cdot 10^{-6}$$

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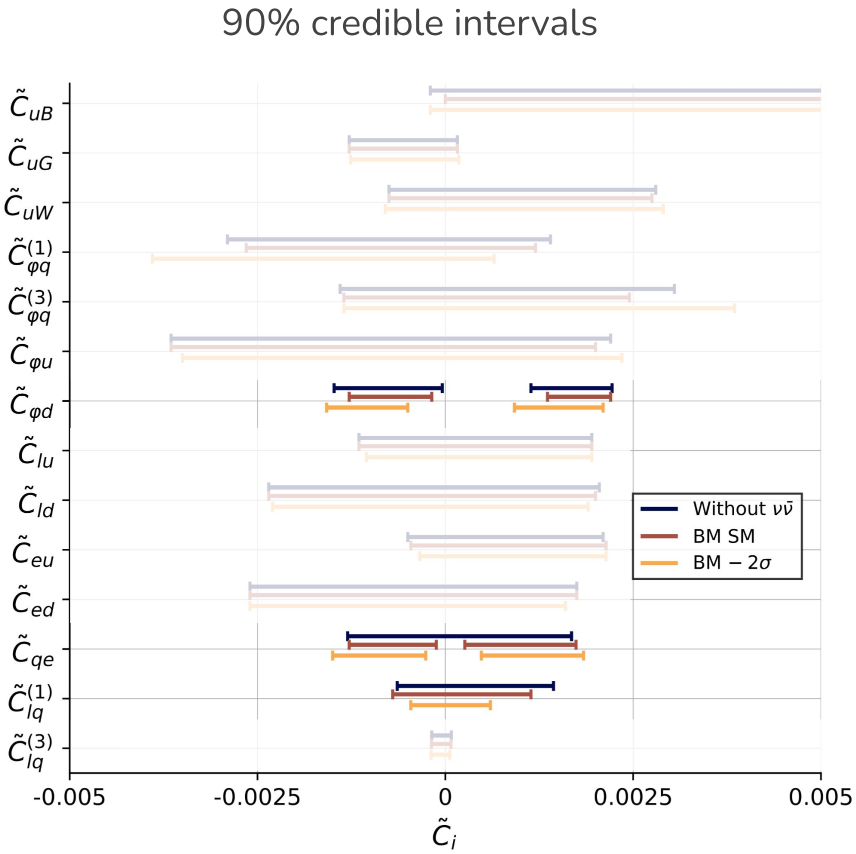
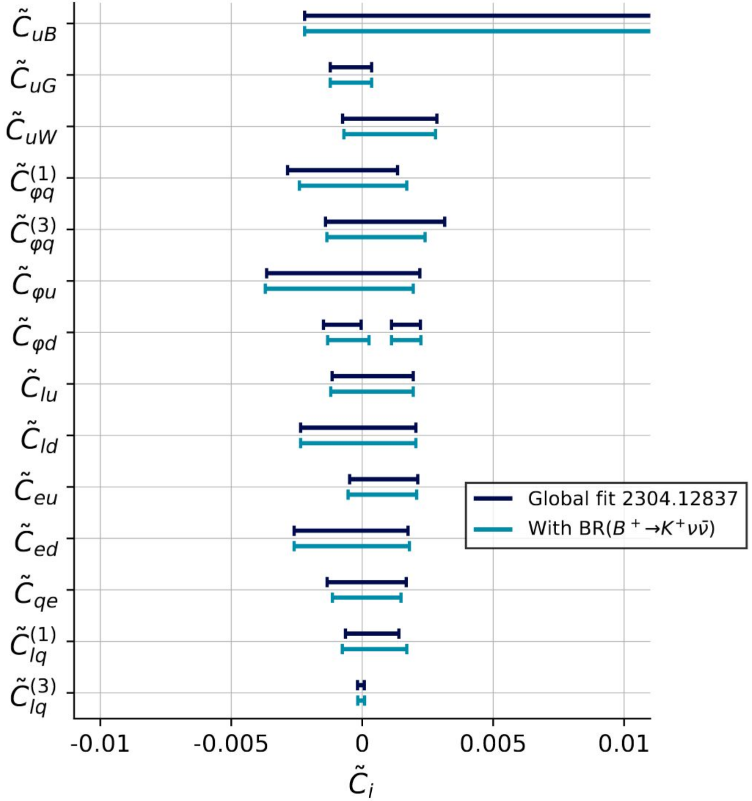


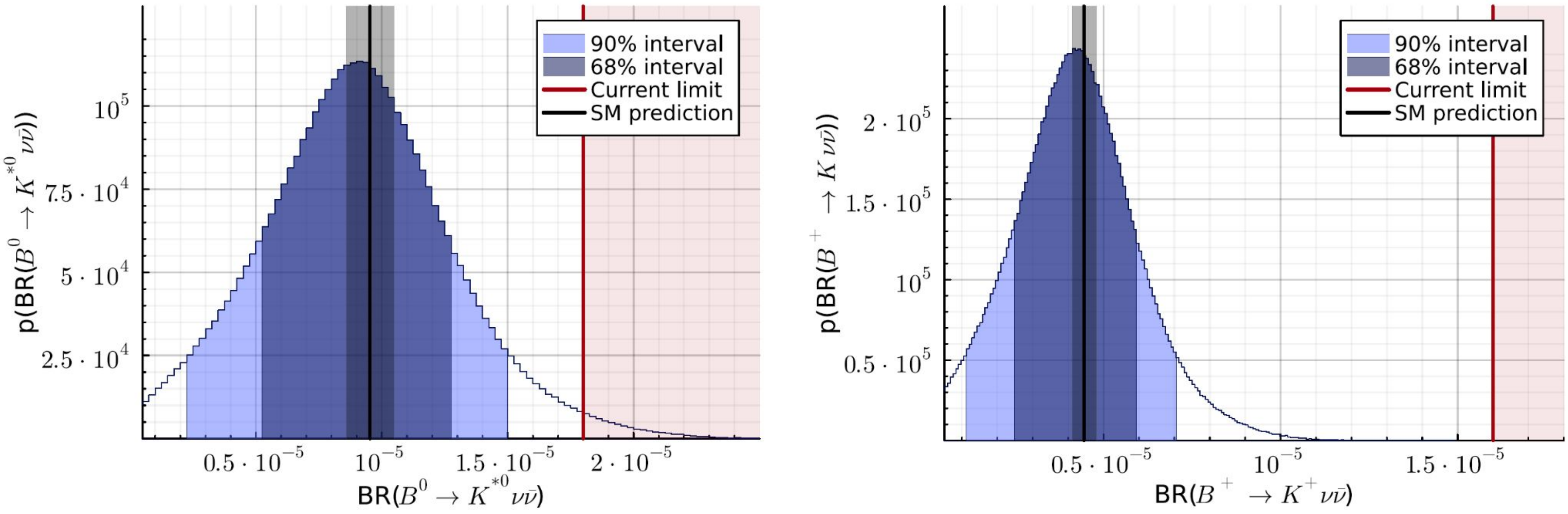
Impact of $b \rightarrow s\nu\nu$ transitions

- recent evidence (3.5σ) on $B^+ \rightarrow K^+\nu\bar{\nu}$ decays by BELLE II (2311.14647)

90% credible intervals



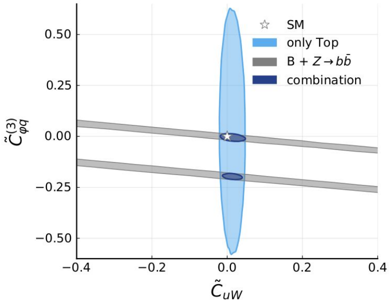
Prediction of $B \to K\nu\nu$ branching ratios



- idea: use posterior distribution to predict new observables not included in the fit
- here: branching ratios of $B^0 \to K^{*0}\nu\nu$ & $B^+ \to K^+\nu\nu$
- as expected: in agreement with SM & in reach of BELLE II

Summary & Conclusion

- **SMEFT** is a **powerful tool** to **search** for **BSM** physics at current experiments
- probing **many operators** at the same time requires **global fits** combining measurements from **different sectors**



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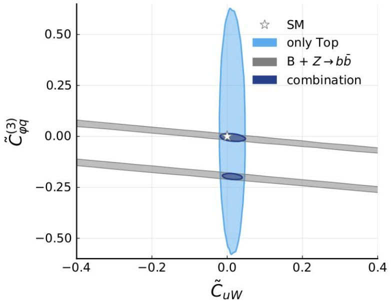

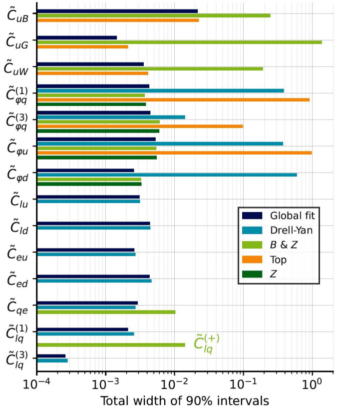

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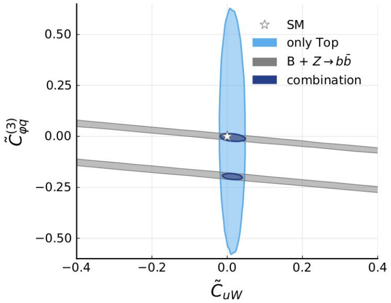

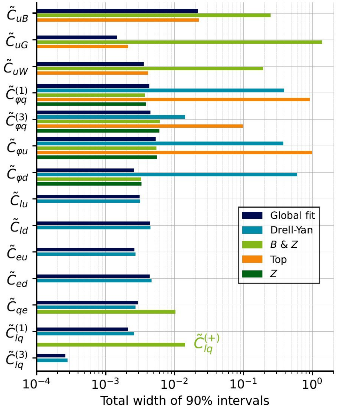

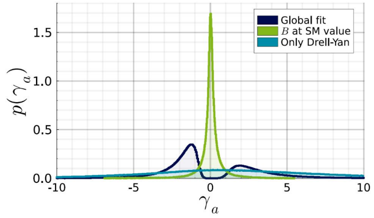

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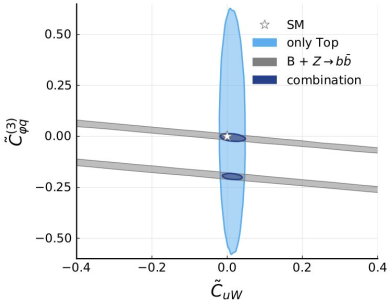

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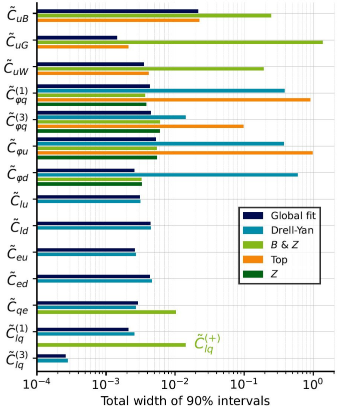

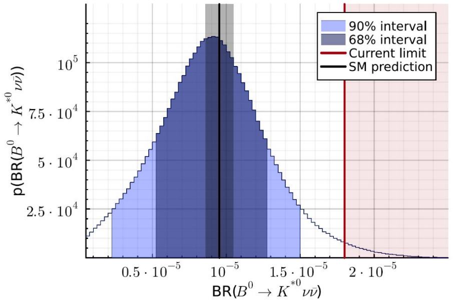

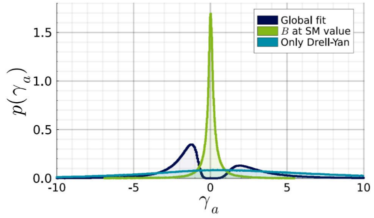

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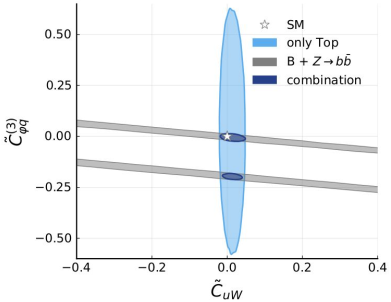
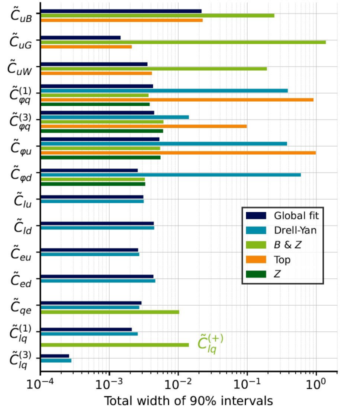
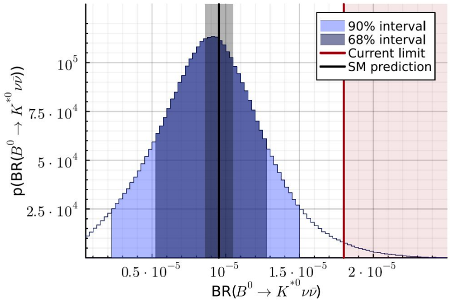
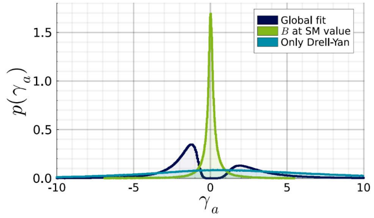






[arXiv: 2304.12837](https://arxiv.org/abs/2304.12837)

Thank you for your attention!



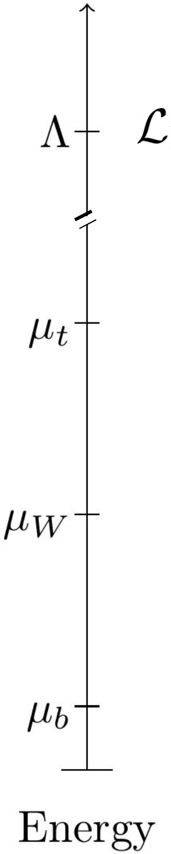
Backup Slides

Dimension-Six Operators in Warsaw Basis

$$O_{uG} = \left(\bar{q}_L \sigma^{\mu\nu} T^A u_R\right) \tilde{\varphi} G^A_{\mu\nu} \,,$$
$$O_{uB} = \left(\bar{q}_L \sigma^{\mu\nu} u_R\right) \tilde{\varphi} B_{\mu\nu} \,,$$
$$O^{(1)}_{lq} = \left(\bar{l}_L \gamma_\mu l_L\right) \left(\bar{q}_L \gamma^\mu q_L\right) \,,$$
$$O_{eu} = \left(\bar{e}_R \gamma_\mu e_R\right) \left(\bar{u}_R \gamma^\mu u_R\right) \,,$$
$$O_{lu} = \left(\bar{l}_L \gamma_\mu l_L\right) \left(\bar{u}_R \gamma^\mu u_R\right) \,,$$
$$O^{(1)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{q}_L \gamma^\mu q_L\right) \,,$$
$$O_{\varphi u} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{u}_R \gamma^\mu u_R\right) \,,$$

$$O_{uW} = \left(\bar{q}_L \sigma^{\mu\nu} u_R\right) \tau^I \tilde{\varphi} W^I_{\mu\nu} \,,$$
$$O_{qe} = \left(\bar{q}_L \gamma_\mu q_L\right) \left(\bar{e}_R \gamma^\mu e_R\right) \,,$$
$$O^{(3)}_{lq} = \left(\bar{l}_L \gamma_\mu \tau^I l_L\right) \left(\bar{q}_L \gamma^\mu \tau^I q_L\right) \,,$$
$$O_{ed} = \left(\bar{e}_R \gamma_\mu e_R\right) \left(\bar{d}_R \gamma^\mu d_R\right) \,,$$
$$O_{ld} = \left(\bar{l}_L \gamma_\mu l_L\right) \left(\bar{d}_R \gamma^\mu d_R\right) \,,$$
$$O^{(3)}_{\varphi q} = \left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right) \left(\bar{q}_L \tau^I \gamma^\mu q_L\right) \,,$$
$$O_{\varphi d} = \left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right) \left(\bar{d}_R \gamma^\mu d_R\right) \,,$$

Combining different energy scales & EFT formalisms



$\mathcal{L}_{\text{Full}}$ ← **Full theory of SM + BSM particles**

Top-quark measurements

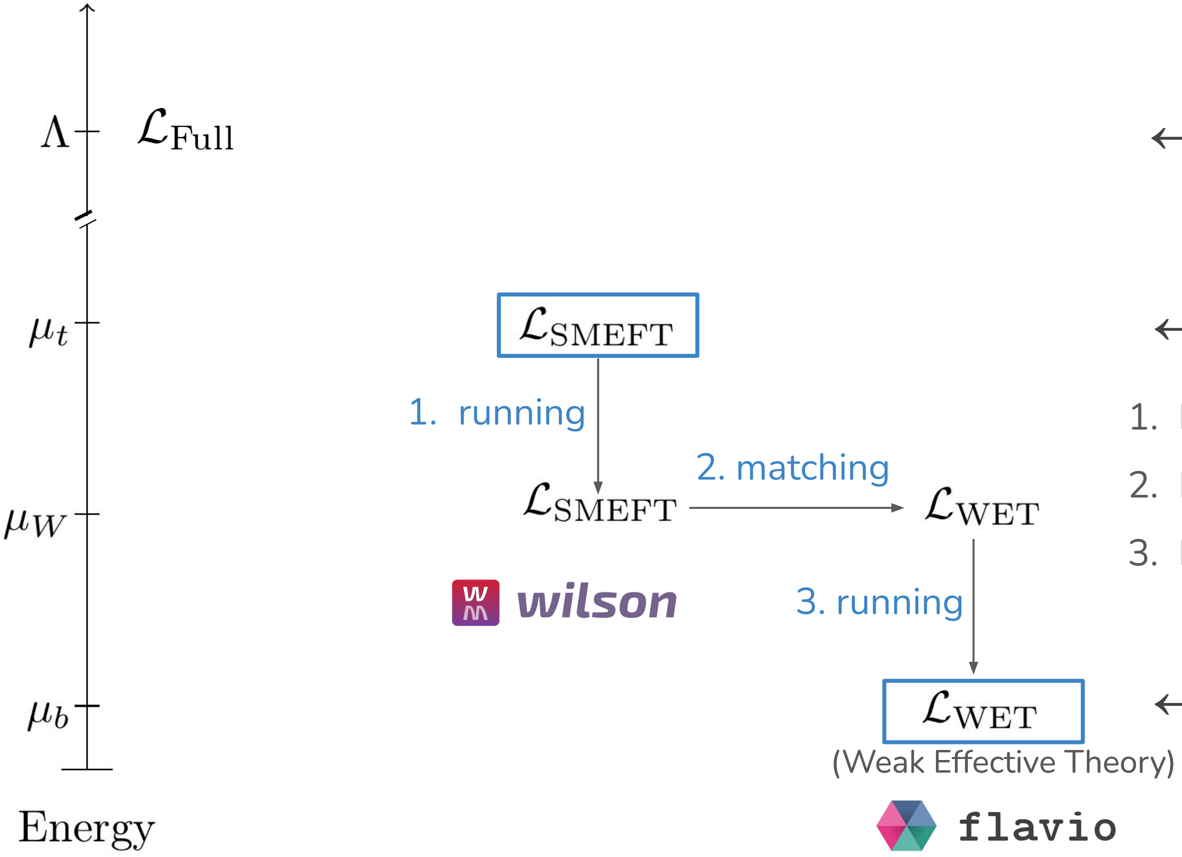
$\mathcal{L}_{\text{SMEFT}}$ ← **SM particles**

B physics measurements

$\mathcal{L}_{\text{WET}}$ ← **SM particles without t, h, W, Z**

(Weak Effective Theory)

Combining different energy scales & EFT formalisms



Λ $\mathcal{L}_{\text{Full}}$

μ_t $\mathcal{L}_{\text{SMEFT}}$

1. running

μ_W $\mathcal{L}_{\text{SMEFT}}$ 2. matching $\mathcal{L}_{\text{WET}}$

wilson

3. running

μ_b $\mathcal{L}_{\text{WET}}$

(Weak Effective Theory)

flavio

Energy

← **Full theory of SM + BSM particles**

Top-quark measurements

← **SM particles**

1. Running in SMEFT (RGE)
2. Matching SMEFT onto WET at scale μ_W
3. Running in WET (RGE)

B physics measurements

← **SM particles without t, h, W, Z**

Weak Effective Theory - WET

Effective Lagrangian for $b \to sll$

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

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

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

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

Tree-Level Matching

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

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

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

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 in SMEFT

- Expand the quark bilinears

$$\bar q_L q_L :\sim a_1 \mathbb{1} + a_2 Y_u Y_u^\dagger + a_3 Y_d Y_d^\dagger + \ldots \qquad \bar u_R u_R :\sim b_1 \mathbb{1} + b_2 Y_u^\dagger Y_u + \ldots \qquad \bar d_R d_R :\sim e_1 \mathbb{1} + e_2 Y_d^\dagger Y_d + \ldots$$

$$\bar q_L u_R :\sim (c_1 \mathbb{1} + c_2 Y_u Y_u^\dagger + c_3 Y_d Y_d^\dagger + \ldots) Y_u \qquad \bar q_L d_R :\sim (d_1 \mathbb{1} + d_2 Y_u Y_u^\dagger + d_3 Y_d Y_d^\dagger + \ldots) Y_d$$

- Rotating to the mass basis and retaining only y_t yields:

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

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

- Imposes **correlations** among flavor entries and allows for **down-type FCNCs**
- $Y_d \sim 0 \to$ No up-type FCNCs and no chirality flipping down-type operators
- $Y_l \sim 0 \to$ Lepton-flavor universality

See also e.g. Bruggisser et al. [arXiv:2212.02532] or Greljo et al. [arXiv:2212.10497] for MFV in SMEFT

MFV Flavor Structure

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

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

- re-parametrization:

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

"ratio of higher-order corrections to leading terms"

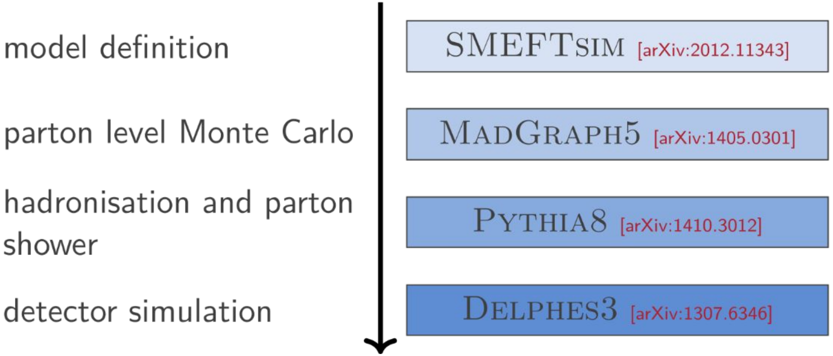
- sensitivities to γ_a :

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

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

MC Simulation Chain

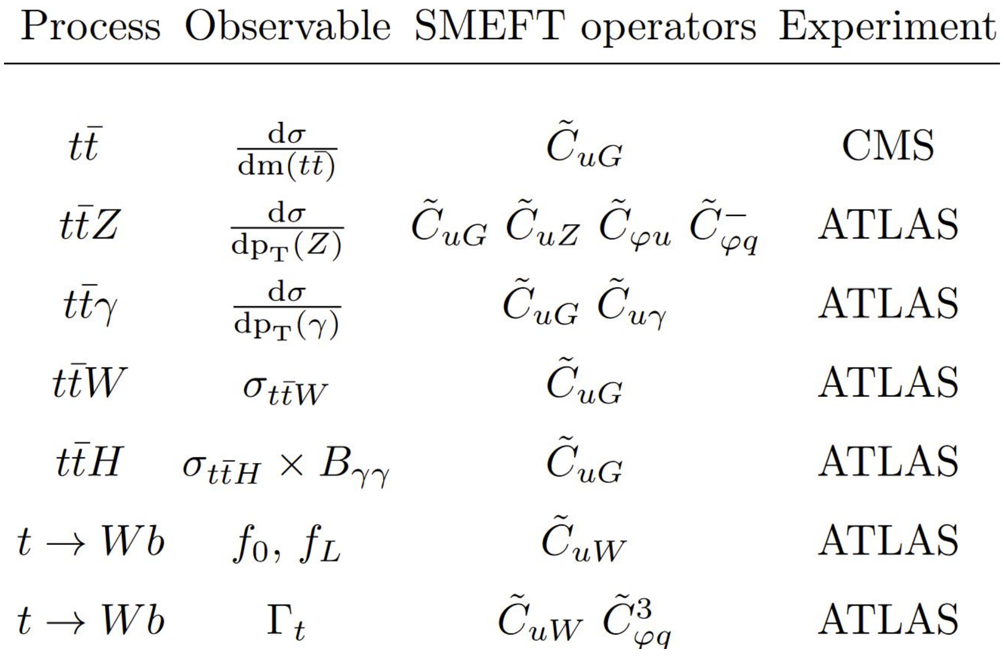
$$\mathcal{M} = \mathcal{M}^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \mathcal{M}_i^{\text{BSM}} \xrightarrow{\sigma \propto |\mathcal{M}|^2} \sigma = \sigma^{\text{SM}} + \frac{1}{\Lambda^2}\sum_i C_i \sigma_i^{\text{int}} + \frac{1}{\Lambda^4}\sum_{i\leq j} C_i C_j \sigma_{ij}^{\text{BSM}}$$



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]

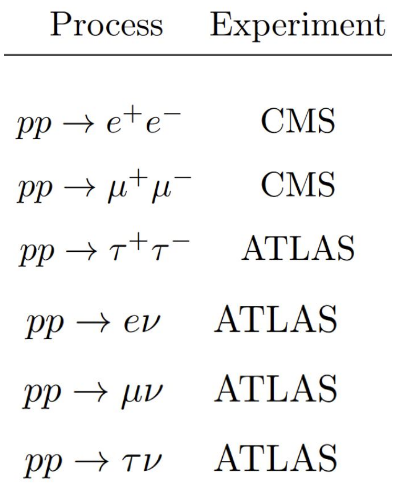
Top-Quark & Drell-Yan Observables

Top-Quark



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
$t\bar{t}H$	$\sigma_{t\bar{t}H} \times B_{\gamma\gamma}$	$\tilde{C}_{uG}$	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

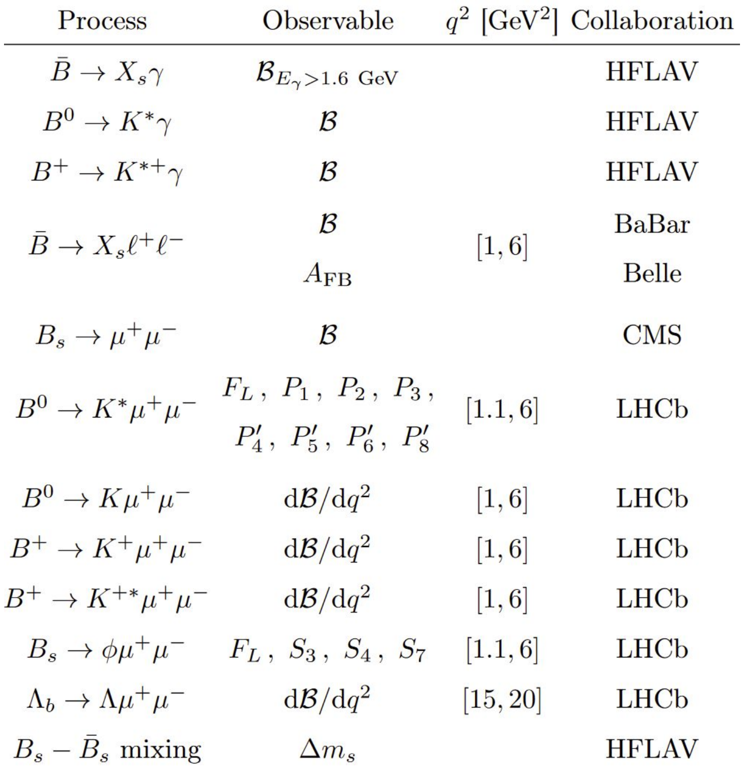
Drell-Yan



Process	Experiment
$pp \to e^+e^-$	CMS
$pp \to \mu^+\mu^-$	CMS
$pp \to \tau^+\tau^-$	ATLAS
$pp \to e\nu$	ATLAS
$pp \to \mu\nu$	ATLAS
$pp \to \tau\nu$	ATLAS

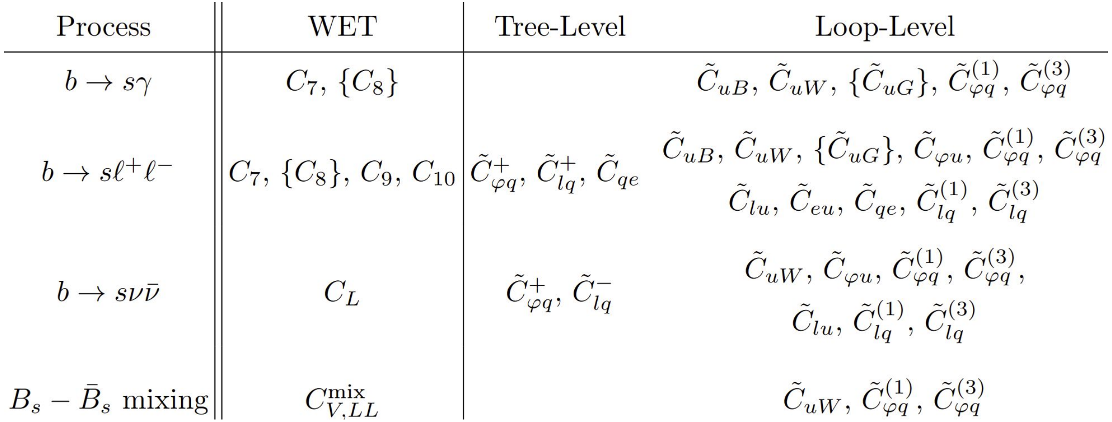
B Observables & Sensitivities

Observables



Process	Observable	q^2 [GeV^2]	Collaboration
$\bar{B} \to X_s \gamma$	$\mathcal{B}_{E_\gamma > 1.6\ \text{GeV}}$		HFLAV
$B^0 \to K^* \gamma$	$\mathcal{B}$		HFLAV
$B^+ \to K^{*+} \gamma$	$\mathcal{B}$		HFLAV
$\bar{B} \to X_s \ell^+ \ell^-$	$\mathcal{B}$ A_{FB}	$[1, 6]$	BaBar Belle
$B_s \to \mu^+ \mu^-$	$\mathcal{B}$		CMS
$B^0 \to K^* \mu^+ \mu^-$	$F_L\,,\ P_1\,,\ P_2\,,\ P_3\,,$ $P_4'\,,\ P_5'\,,\ P_6'\,,\ P_8'$	$[1.1, 6]$	LHCb
$B^0 \to K \mu^+ \mu^-$	$\mathrm{d}\mathcal{B}/\mathrm{d}q^2$	$[1, 6]$	LHCb
$B^+ \to K^+ \mu^+ \mu^-$	$\mathrm{d}\mathcal{B}/\mathrm{d}q^2$	$[1, 6]$	LHCb
$B^+ \to K^{+*} \mu^+ \mu^-$	$\mathrm{d}\mathcal{B}/\mathrm{d}q^2$	$[1, 6]$	LHCb
$B_s \to \phi \mu^+ \mu^-$	$F_L\,,\ S_3\,,\ S_4\,,\ S_7$	$[1.1, 6]$	LHCb
$\Lambda_b \to \Lambda \mu^+ \mu^-$	$\mathrm{d}\mathcal{B}/\mathrm{d}q^2$	$[15, 20]$	LHCb
$B_s - \bar{B}_s$ mixing	Δm_s		HFLAV

Sensitivities



Process	WET	Tree-Level	Loop-Level
$b \to s\gamma$	$C_7,\ \{C_8\}$		$\tilde{C}_{uB},\ \tilde{C}_{uW},\ \{\tilde{C}_{uG}\},\ \tilde{C}_{\varphi q}^{(1)},\ \tilde{C}_{\varphi q}^{(3)}$
$b \to s\ell^+\ell^-$	$C_7,\ \{C_8\},\ C_9,\ C_{10}$	$\tilde{C}_{\varphi q}^{+},\ \tilde{C}_{lq}^{+},\ \tilde{C}_{qe}$	$\tilde{C}_{uB},\ \tilde{C}_{uW},\ \{\tilde{C}_{uG}\},\ \tilde{C}_{\varphi u},\ \tilde{C}_{\varphi q}^{(1)},\ \tilde{C}_{\varphi q}^{(3)}$ $\tilde{C}_{lu},\ \tilde{C}_{eu},\ \tilde{C}_{qe},\ \tilde{C}_{lq}^{(1)},\ \tilde{C}_{lq}^{(3)}$
$b \to s\nu\bar{\nu}$	C_L	$\tilde{C}_{\varphi q}^{+},\ \tilde{C}_{lq}^{-}$	$\tilde{C}_{uW},\ \tilde{C}_{\varphi u},\ \tilde{C}_{\varphi q}^{(1)},\ \tilde{C}_{\varphi q}^{(3)},$ $\tilde{C}_{lu},\ \tilde{C}_{lq}^{(1)},\ \tilde{C}_{lq}^{(3)}$
$B_s - \bar{B}_s$ mixing	$C_{V,LL}^{\text{mix}}$		$\tilde{C}_{uW},\ \tilde{C}_{\varphi q}^{(1)},\ \tilde{C}_{\varphi q}^{(3)}$

$B \to K\nu\nu$ benchmark scenarios

- Experimental upper limits [Phys. Rev. D 96, 091101 (2017)]

$$B(B^0 \to K^{*0}\nu\bar{\nu})_{\text{exp}} < 1.8 \cdot 10^{-5} \qquad B(B^+ \to K^+\nu\bar{\nu})_{\text{exp}} < 1.6 \cdot 10^{-5}$$

- SM prediction [arXiv:1810.08132]

$$B(B^0 \to K^{*0}\nu\bar{\nu})_{\text{SM}} = (9.53 \pm 0.95) \cdot 10^{-6} \quad B(B^+ \to K^+\nu\bar{\nu})_{\text{SM}} = (4.39 \pm 0.60) \cdot 10^{-6}$$

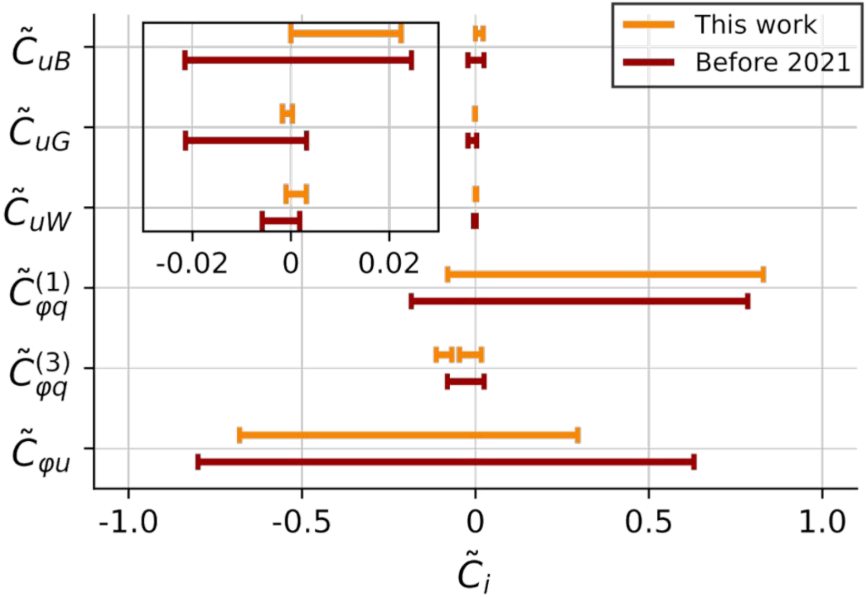
- Benchmark measurements

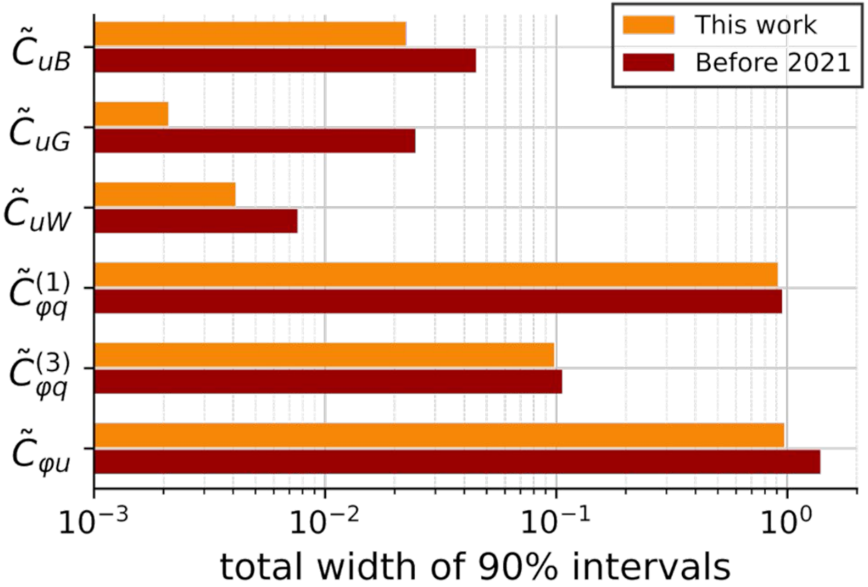
$$B(B^0 \to K^{*0}\nu\bar{\nu})_{\text{BM SM}} = (9.5 \pm 2.5) \cdot 10^{-6} \quad B(B^+ \to K^+\nu\bar{\nu})_{\text{BM SM}} = (4.4 \pm 1.3) \cdot 10^{-6}$$

$$B(B^0 \to K^{*0}\nu\bar{\nu})_{\text{BM}+2\sigma} = (14.5 \pm 2.5) \cdot 10^{-6} \quad B(B^+ \to K^+\nu\bar{\nu})_{\text{BM}+2\sigma} = (7.0 \pm 1.3) \cdot 10^{-6}$$

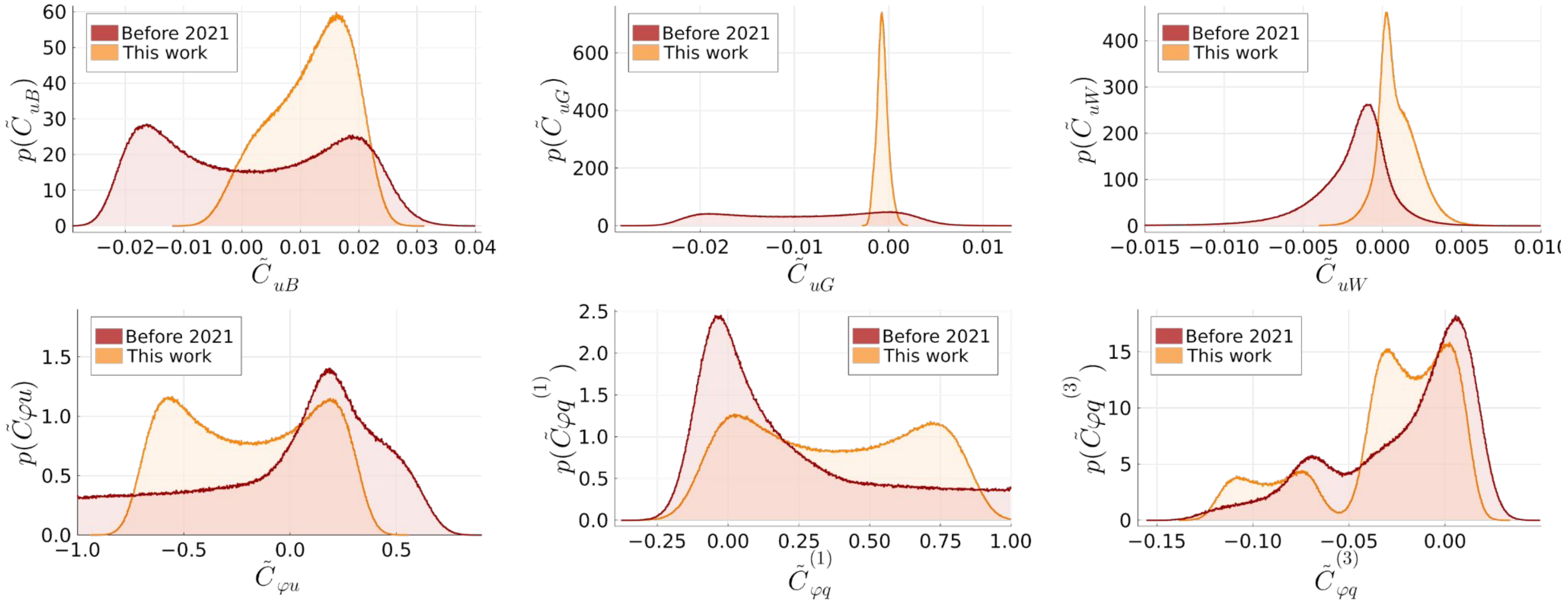
$$B(B^0 \to K^{*0}\nu\bar{\nu})_{\text{BM}-2\sigma} = (4.6 \pm 2.5) \cdot 10^{-6} \quad B(B^+ \to K^+\nu\bar{\nu})_{\text{BM}-2\sigma} = (1.8 \pm 1.3) \cdot 10^{-6}$$

Top-quark Fit

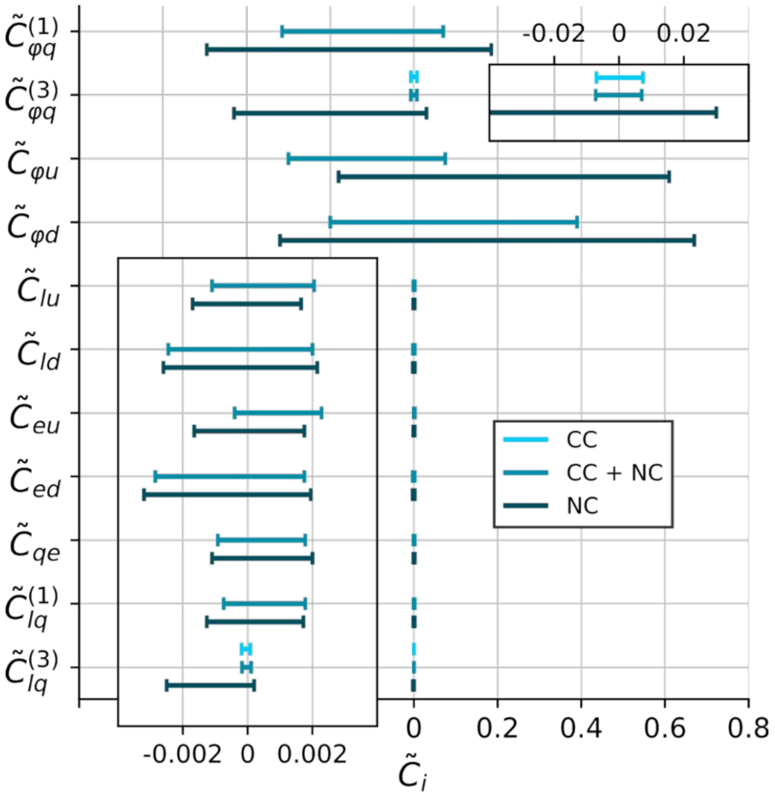


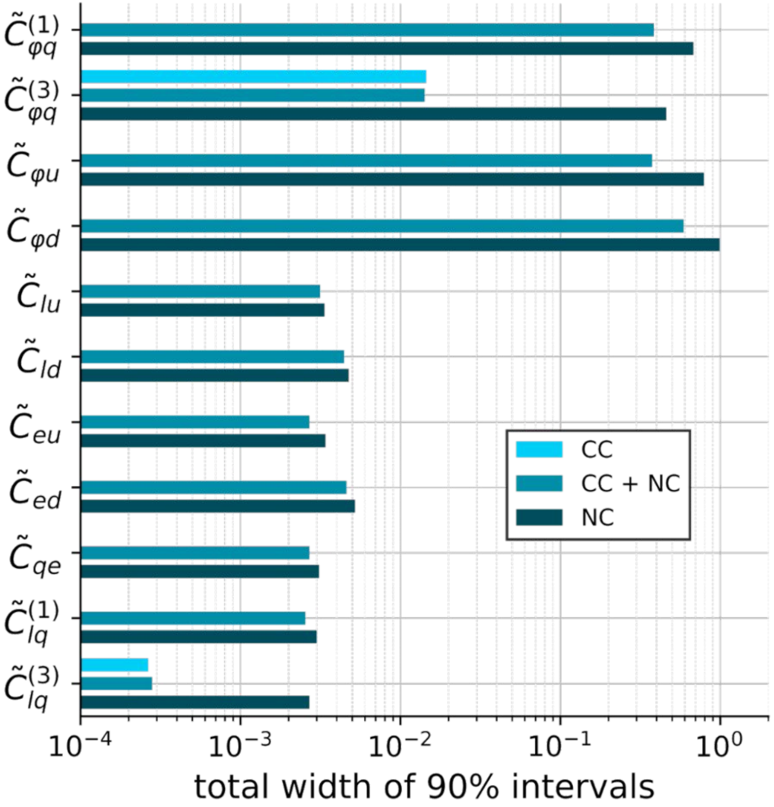


Top-quark Fit

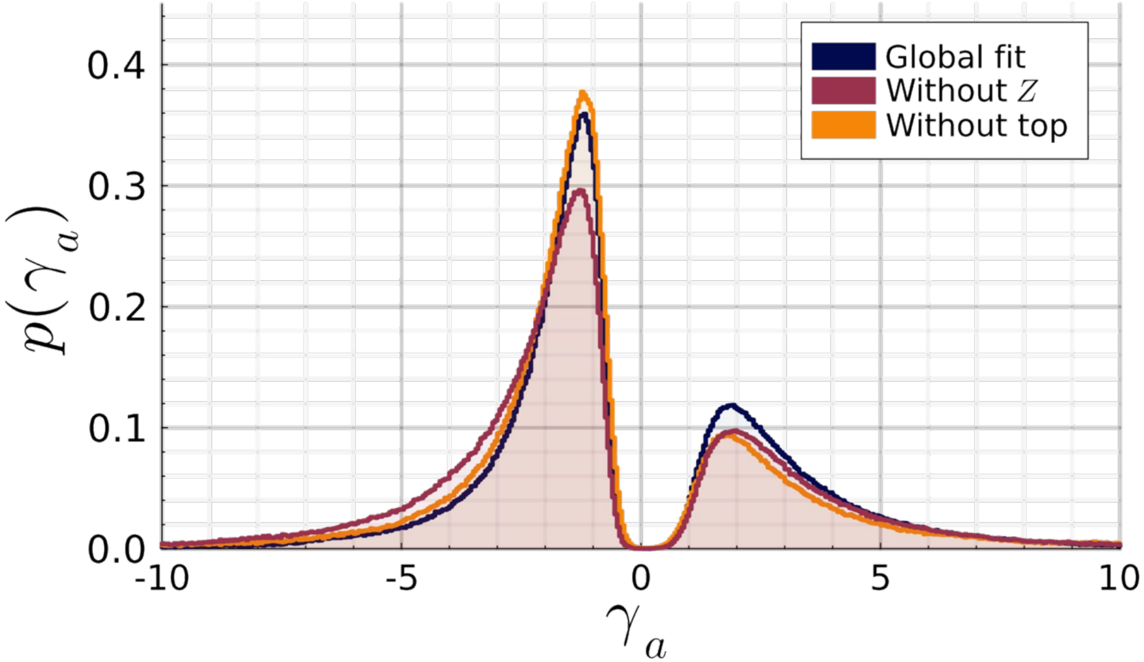


Drell-Yan Fits





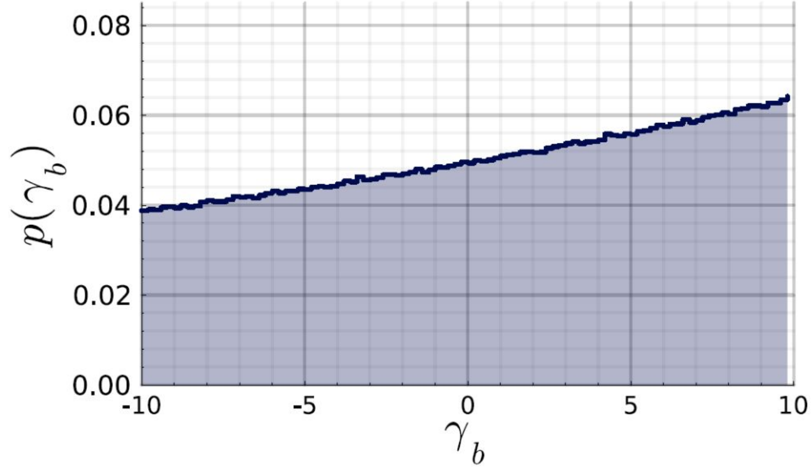
Impact of Top & Z on γ_a



$\Longrightarrow$ No large impact of top and Z measurements on γ_a

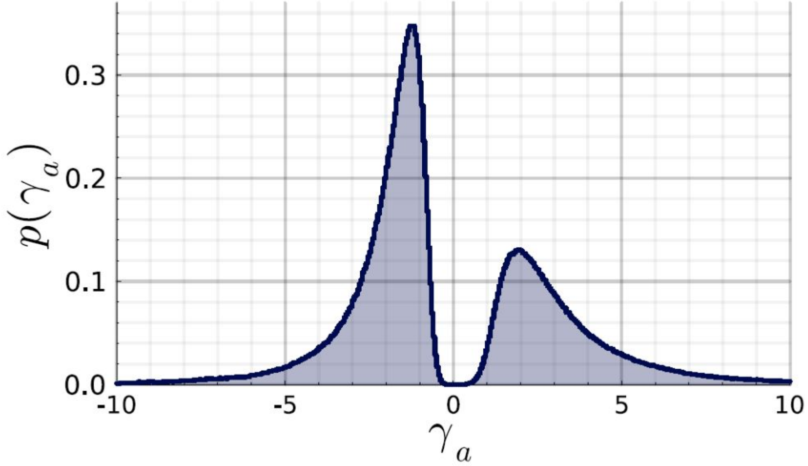
Constraints on the MFV parameters

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



- basically no constraints on γ_b
- expected as observables not very sensitive to γ_b

$\gamma_a = \sum_{n\geq 1} y_t^{2n}\, a_{2n}/a_1$ left-handed quarks



- posterior of γ_a peaks at -1.2 & 1.9
- expected: within [-1, 1] & centered around 0
- fit favors large higher-order corrections in the MFV expansion