Constraints on SMEFT operators using the missing energy + jet signature

Based on my master thesis supervised under Gudrun Hiller

Daniel Wendler

29.09.2022

HIGGS, FLAVOR AND BEYOND

Standard model effective field theory (SMEFT)

- Constructed using SM DOFs and gauge invariance under $SU(3)_c \times SU(2)_L \times U(1)_Y$
- Scale separation between the process and the NP scale Λ
- Linearly realized EWSB

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

$C_i^{(d)}$: Wilson coefficients capture the UV physics

$Q_i^{(d)}$: Local operators build out of SM DOFs

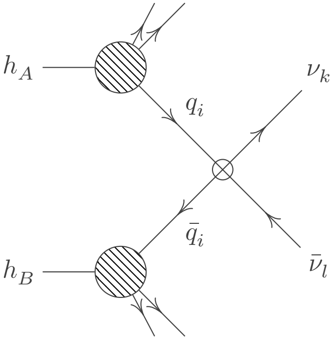
Semileptonic four-fermion operators

- Focus on four-fermion operators coupling quarks and leptons

$$\mathcal{L}^6_{FF} = \frac{C^{(1)}_{lq,klij}}{\Lambda^2}\left(\bar{l}_k\gamma_\mu l_l\right)\left(\bar{q}_i\gamma^\mu q_j\right) + \frac{C^{(3)}_{lq,klij}}{\Lambda^2}\left(\bar{l}_k\gamma_\mu\tau^I l_l\right)\left(\bar{q}_i\gamma^\mu\tau^I q_j\right) + \frac{C_{lu,klij}}{\Lambda^2}\left(\bar{l}_k\gamma_\mu l_l\right)\left(\bar{u}_i\gamma^\mu u_j\right) + \frac{C_{ld,klij}}{\Lambda^2}\left(\bar{l}_k\gamma_\mu l_l\right)\left(\bar{d}_i\gamma^\mu d_j\right) \quad .$$

- Related to B-Anomalies and LFU

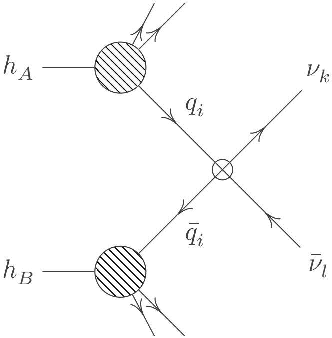
LO Drell-Yan in the SMEFT



$$\sigma_{BSM}(pp \to \nu_k \bar{\nu}_l) = \sum_{i,j} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{ij}(\tau) \hat{\sigma}(\tau s)$$

- Scaling variable: $\tau = \hat{s}/s$
- Hard cross section : $\hat{\sigma}(\hat{s})$
- Parton luminosity functions: $\mathcal{L}_{ij}(\tau)$

LO Drell-Yan in the SMEFT

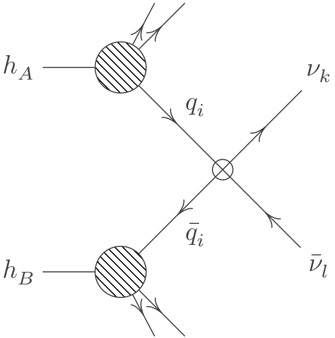


$$\sigma_{BSM}(pp \to \nu_k \bar{\nu}_l) = \sum_{i,j} \int \frac{d\tau}{\tau} \mathcal{L}_{ij}(\tau) \hat{\sigma}(\tau s)$$

- Scaling variable: $\tau = \hat{s}/s$
- Hard cross section : $\hat{\sigma}(\hat{s})$
- Parton luminosity functions: $\mathcal{L}_{ij}(\tau)$

Dineutrino pair not detectable at the LHC

LO Drell-Yan in the SMEFT



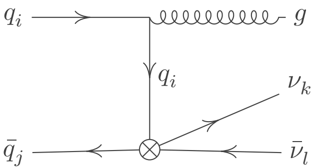
$$\sigma_{BSM}(pp \to \nu_k \bar{\nu}_l) = \sum_{i,j} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{ij}(\tau) \hat{\sigma}(\tau s)$$

- Scaling variable: $\tau = {}^{\hat{s}}/_{s}$
- Hard cross section : $\hat{\sigma}(\hat{s})$
- Parton luminosity functions: $\mathcal{L}_{ij}(\tau)$

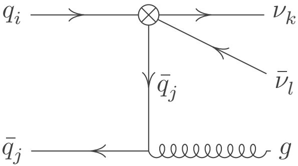
Dineutrino pair not detectable at the LHC

$\Rightarrow$ extra radiation of a jet

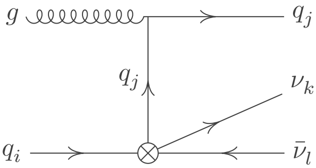
Drell-Yan NLO



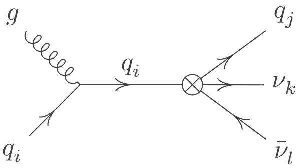
(a)



(b)



(c)



(d)

Missing energy spectrum

- Final cross section will be incoherently summed over neutrino flavors

BSM differential cross section

$$\frac{\mathrm{d}\sigma(s, E_T^{miss})}{\mathrm{d}E_T^{miss}} = \sum_{i,j=q} C^2_{ij,eff} \int \frac{\mathrm{d}\tau}{\tau} \left(f_1(\tau, E_T^{miss}) \mathcal{L}_{ij}(\tau) + f_2(\tau, E_T^{miss}) \mathcal{L}_{ig}(\tau) \right)$$

- Limits can be calculated on effective WC

$$C^2_{ij,eff} = \sum_{k,l=\nu} |C^{\pm}_{lq,klij}|^2 + |C_{lu/d,klij}|^2$$

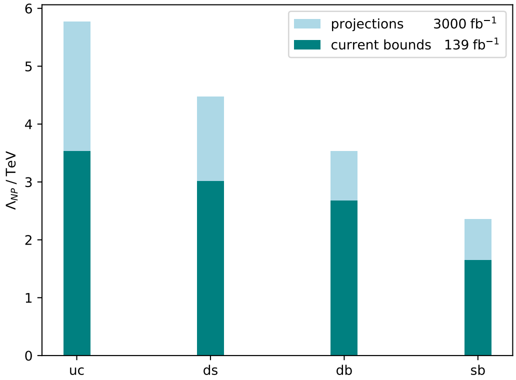
- Focus on offdiagonal quark WCs ($i \neq j$), where interference can be neglected.

Limits within the SMEFT

$C_{ij,eff}$	limits (139 fb^{-1})	projections (3000 fb^{-1})
uc	0.08	0.03
ds	0.11	0.05
db	0.14	0.07
sb	0.37	0.18

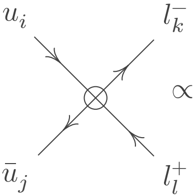
$$C^2_{ij,eff} = \sum_{k,l=\nu} |C^{\pm}_{lq,klij}|^2 + |C_{lu/d,klij}|^2$$

NP scales constrained ($C = 1$)

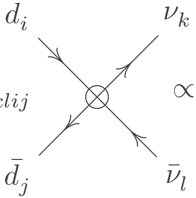


Connections to charged dilepton WCs

Left-chiral quark coefficients

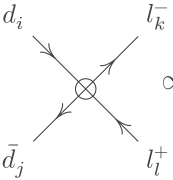


$$\propto C^{(1)}_{lq,klij} - C^{(3)}_{lq,klij}$$

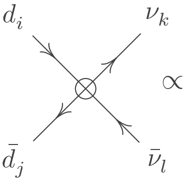


$$\propto C^{(1)}_{lq,klij} - C^{(3)}_{lq,klij}$$

Right-chiral quark coefficients



$$\propto C_{ld,klij}$$



$$\propto C_{ld,klij}$$

Limits within the WET: uc

$cull'$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$\lvert\mathcal{K}_{L,R}^{cull'}\rvert_{DY}$	2.9	1.6	5.6	1.6	4.7	5.1
$\lvert\mathcal{K}_{L,R}^{cull'}\rvert_{D}$	4.0	0.9	-	2.2	-	-
$\lvert\mathcal{K}_{L}^{cull'}\rvert_{\nu\bar{\nu}} \cdot 10^2$	[-1.9,0.7]	[-1.9,0.7]	[-1.9,0.7]	1.1	1.1	1.1
$\lvert\mathcal{K}_{L}^{cull'}\rvert_{\nu\bar{\nu}}^{pp}$	5.7	5.7	5.7	4.1	4.1	4.1
$\lvert\mathcal{K}_{R}^{cull'}\rvert_{\nu\bar{\nu}}^{pp}$	4.2	4.2	4.2	2.9	2.9	2.9

- Limits on the down sector (ds,db,sb) also possible
- Additionally left-chiral top couplings can be constrained

Summary

- The basic idea and potential of missing energy signatures was explained
- Constraints on semileptonic four-fermion operators were presented and compared to existing ones
- Overall they are of equal size compared to conventional Drell-Yan, but some constraints from decays are more stringent
- Models: Leptoquarks, Z'

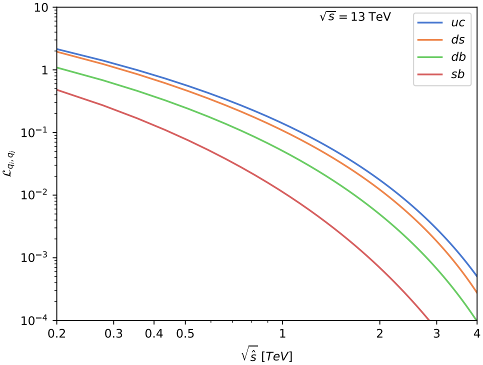
Summary

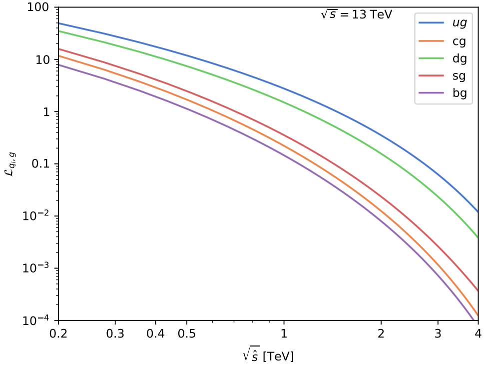
- The basic idea and potential of missing energy signatures was explained
- Constraints on semileptonic four-fermion operators were presented and compared to existing ones
- Overall they are of equal size compared to conventional Drell-Yan, but some constraints from decays are more stringent
- Models: Leptoquarks, Z'

Thank you for your attention !

BACKUP

Parton luminosity functions

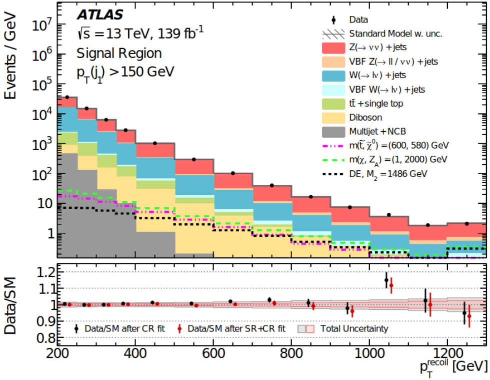




$$\mathcal{L}_{ij}(\tau) = \tau \int_\tau^1 \frac{\mathrm{d}x}{x} \left[f_i(x, \mu_F) f_{\bar{j}}(\tau/x, \mu_F) + i \Leftrightarrow j \right] .$$

Dataset arXiv: 2102.10874

- The dataset considered was published by the ATLAS collaboration
- Run 2 data: $\mathcal{L}_{int} = 139\ \text{fb}^{-1}$
- Projections assuming naive statical scaling of the data and uncertainties to $\mathcal{L}_{int} = 3000\ \text{fb}^{-1}$
- The observable is a missing energy E^T_{miss} spectrum



Limits within the WET: down-sector

$sdll'$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$\lvert\mathcal{K}^{sdll'}_{L,R}\rvert_{DY}$	3.5	1.9	6.7	2.0	6.1	6.6
$\lvert\mathcal{K}^{sdll'}_{L,R}\rvert_{K} \cdot 10^2$	5	1.6	-	6.6	-	-
$\lvert\mathcal{K}^{sdll'}_{R}\rvert_{\nu\bar{\nu}} \cdot 10^2$	[-1.9,0.7]	[-1.9,0.7]	[-1.9,0.7]	1.1	1.1	1.1
$\lvert\mathcal{K}^{sdll'}_{L}\rvert^{pp}_{\nu\bar{\nu}}$	4.2	4.2	4.2	2.9	2.9	2.9
$\lvert\mathcal{K}^{sdll'}_{R}\rvert^{pp}_{\nu\bar{\nu}}$	5.7	5.7	5.7	4.1	4.1	4.1

$bdll'$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$\lvert\mathcal{K}^{bdll'}_{L,R}\rvert_{DY}$	5.0	2.7	9.6	3.1	9.6	11
$\lvert\mathcal{K}^{bdll'}_{R}\rvert_{B}$	0.09	[-0.03, 0.03]	21	0.2	3.4	2.4
$\lvert\mathcal{K}^{bdll'}_{L}\rvert_{B}$	0.09	[-0.07,-0.02]	21	0.2	3.4	2.4
$\lvert\mathcal{K}^{bdll'}_{R}\rvert_{\nu\bar{\nu}}$	1.8	1.8	1.8	2.5	2.5	2.5
$\lvert\mathcal{K}^{bdll'}_{R}\rvert^{pp}_{\nu\bar{\nu}}$	7.3	7.3	7.3	5.2	5.2	5.2

$bsll'$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$\lvert\mathcal{K}^{bsll'}_{L,R}\rvert_{DY}$	13	7.1	25	8.0	27	30
$\lvert\mathcal{K}^{bsll'}_{R}\rvert_{B_s}$	0.04	[-0.03,-0.01]	32	0.1	2.8	3.4
$\lvert\mathcal{K}^{bsll'}_{L}\rvert_{B_s}$	0.04	[-0.07,-0.04]	32	0.1	2.8	3.4
$\lvert\mathcal{K}^{bsll'}_{R}\rvert_{\nu\bar{\nu}}$	1.4	1.4	1.4	1.8	1.8	1.8
$\lvert\mathcal{K}^{bsll'}_{R}\rvert^{pp}_{\nu\bar{\nu}}$	19.3	19.3	19.3	13.6	13.6	13.6

Limits within the WET: top

$tull'$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$\lvert\mathcal{K}^{tull'}_{L,R}\rvert$	~ 200	~ 200	n.a.	12	136	136
$\lvert\mathcal{K}^{tull'}_{L}\rvert^{a}_{\nu\bar{\nu}}$	[-1.6,1.8]	[-1.6,1.8]	[-1.6,1.8]	2.4	2.4	2.4
$\lvert\mathcal{K}^{tull'}_{L}\rvert^{pp}_{\nu\bar{\nu}}$	7.3	7.3	7.3	5.2	5.2	5.2

$tcll'$	ee	$\mu\mu$	$\tau\tau$	$e\mu$	$e\tau$	$\mu\tau$
$\lvert\mathcal{K}^{tcll'}_{L,R}\rvert$	~ 200	~ 200	n.a.	12	136	136
$\lvert\mathcal{K}^{tcll'}_{L}\rvert^{a}_{\nu\bar{\nu}}$	[-1.9,0.9]	[-1.9,0.9]	[-1.9,0.9]	1.8	1.8	1.8
$\lvert\mathcal{K}^{tcll'}_{L}\rvert^{pp}_{\nu\bar{\nu}}$	19.3	19.3	19.3	13.6	13.6	13.6

Cross section parametrization for dimension 6

- $\mathcal{M} = \mathcal{M}_{SM} + \sum_i \mathcal{M}_{BSM,i}$
- $\mathcal{M}_{BSM,i} \propto \frac{C_i}{\Lambda^2}$
- $\sigma \propto |\mathcal{M}|^2$

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

Operators in the Warsaw basis

LLLL		LLRR	
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)\,(\bar{q}_s \gamma^\mu l_r)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)\,(\bar{q}_s \gamma^\mu \tau^I q_r)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r \tilde{\varphi} G^A_{\mu\nu})$	$Q_{\varphi l}^{(1)}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{l}_p \gamma^\mu l_r)$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r \varphi G^A_{\mu\nu})$	$Q_{\varphi l}^{(3)}$	$\left(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{uW}	$\bar{q}_p \sigma^{\mu\nu} u_r \tau^I \tilde{\varphi} W^I_{\mu\nu}$	$Q_{\varphi u}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_p \gamma^\mu u_r)$
Q_{dW}	$\bar{q}_p \sigma^{\mu\nu} d_r \tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi d}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{d}_p \gamma^\mu d_r)$
Q_{uB}	$\bar{q}_p \sigma^{\mu\nu} u_r \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_p \gamma^\mu q_r)$
Q_{dB}	$\bar{q}_p \sigma^{\mu\nu} d_r \varphi B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$\left(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_p \gamma^\mu q_r)$

Simulation chain

Model Implementation: `Feynrules: Smeftsim UFO model` (arXiv:1310.1921)

$\Downarrow$

Parton level Monte Carlo: `MadGraph5` (arXiv:1106.0522)

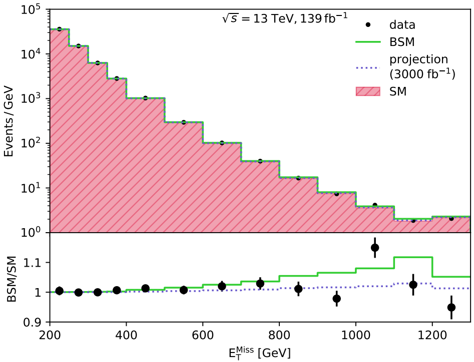
$\Downarrow$

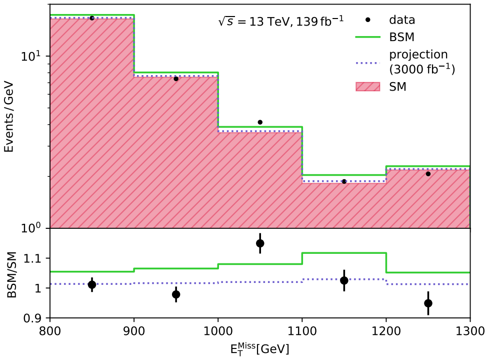
Hadronisation: `Pythia8` (arXiv:1410.3012)

$\Downarrow$

Detector Simulation: `Delphes` (arXiv:1307.6346)

Simulated spectrum





Charge averaging

- The Couplings that couple different lepton flavor are charge averaged

$$\overline{\mathcal{K}^{l+l'-}} = \sqrt{|\mathcal{K}^{l+l'-}|^2 + |\mathcal{K}^{l-l'+}|^2},$$

- Based on 2007.05001

Hard cross sections

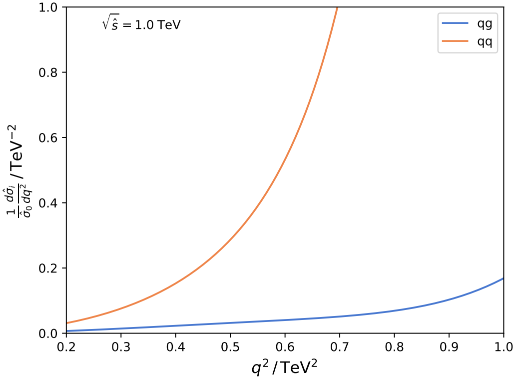
$q_i\bar{q}_j \to \nu\bar{\nu} + g$

$$\frac{\mathrm{d}\hat{\sigma}_{q_i\bar{q}_j}}{\mathrm{d}q^2} = \frac{\alpha_s C_{ij,eff}^2 q^2}{108\pi^2\hat{s}^2(\hat{s}-q^2)}\left(4\tanh^{-1}(1-\delta)(q^4+\hat{s}^2)+2(\delta-1)(q^2-\hat{s})^2\right)$$

$q_i g \to \nu\bar{\nu} + q_j$

$$\frac{\mathrm{d}\hat{\sigma}_{q_i g}}{\mathrm{d}q^2} = \frac{\alpha_s C_{ij,eff}^2 q^2}{288\pi\hat{s}^3}\left(\frac{\delta-1}{2}(q^2-\hat{s})(3q^2+\hat{s})+2\tanh^{-1}(1-\delta)(q^4+(q^2-\hat{s})^2)\right)$$

Parton level cross sections

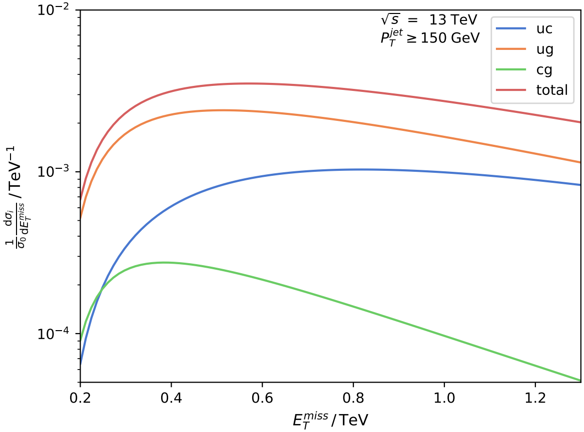


Total cross section

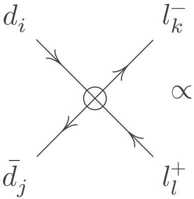
$pp \to \nu\bar{\nu} + jet$

$$\frac{\mathrm{d}\sigma(s, E_T^{miss})}{\mathrm{d}E_T^{miss}} = \sum_{i,j} \int \mathrm{d}\tau\, 2\sqrt{\frac{s}{\tau}} \left\{ \frac{\mathrm{d}\hat{\sigma}_{q_i\bar{q}_j}(\tau s, E_T^{miss})}{\mathrm{d}q^2} \mathcal{L}_{ij}(\tau) + \frac{\mathrm{d}\hat{\sigma}_{q_i g}(\tau s, E_T^{miss})}{\mathrm{d}q^2} 2\mathcal{L}_{ig}(\tau) \right\}.$$

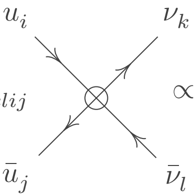
Hadronic cross section for $C_{uc,eff} = 1$



Left-chiral quark coefficients

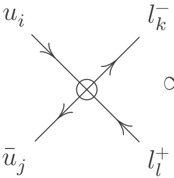


$$\propto C^{(1)}_{lq,klij} + C^{(3)}_{lq,klij}$$

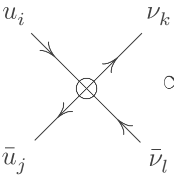


$$\propto C^{(1)}_{lq,klij} + C^{(3)}_{lq,klij}$$

Right-chiral quark coefficients



$$\propto C_{lu,klij}$$



$$\propto C_{lu,klij}$$

Matching

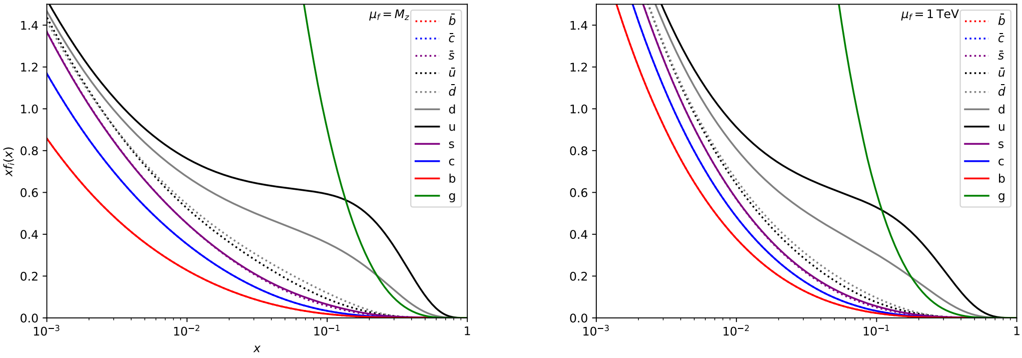
$$C_L^{U_{ijkl}} = K_L^{D_{ijkl}} = \frac{2\pi v^2}{\alpha_e \Lambda_{NP}^2} \left(C_{lq_{klij}}^{(1)} + C_{lq_{klij}}^{(3)} \right)$$

$$C_L^{D_{ijkl}} = K_L^{U_{ijkl}} = \frac{2\pi v^2}{\alpha_e \Lambda_{NP}^2} \left(C_{lq_{klpr}}^{(1)} - C_{lq_{ijpr}}^{(3)} \right)$$

$$C_R^{U_{ijkl}} = K_R^{U_{ijkl}} = \frac{2\pi v^2}{\alpha_e \Lambda_{NP}^2} C_{lu_{klij}}$$

$$C_R^{D_{ijkl}} = K_R^{D_{ijkl}} = \frac{2\pi v^2}{\alpha_e \Lambda_{NP}^2} C_{ld_{klij}},$$

PDFs


$\mu_f = M_z$
$\bar{b}$
$\bar{c}$
$\bar{s}$
$\bar{u}$
$\bar{d}$
d
u
s
c
b
g
$xf_i(x)$
x
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10^{-3}
10^{-2}
10^{-1}
1
$\mu_f = 1\,\mathrm{TeV}$