technische universität
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Missing Energy plus Jet in the SMEFT

2403.17063: In collaboration with Gudrun Hiller

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Higgs and Effective Field Theory 2024

Standard Model Effective Field Theory

- EFT constructed from the SM fields with the full SM gauge group

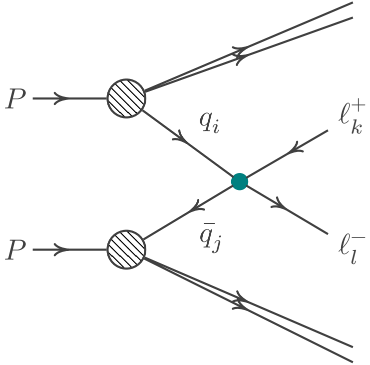
$$\mathcal{L}_{\mathsf{SMEFT}} = \mathcal{L}_{\mathsf{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda_{NP}^{d-4}} \mathcal{O}_i^{(d)}$$

- $C_i^{(d)}$: WC capturing the short distance physics
- $\mathcal{O}_i^{(d)}$: Effective operators encoding the long distance physics
- Λ_{NP} : NP scale
- Focus only on dimension 6 operators with vanishing SM interference

Drell-Yan within the SMEFT

- Several works[1] on high energy Drell-Yan tails in the SMEFT
- Constraining mainly four-fermion operators
- Energy enhancement relative to SM cross section

$$\frac{\mathrm{d}\hat{\sigma}_{SMEFT}}{\mathrm{d}q^2}\Bigg/\frac{\mathrm{d}\hat{\sigma}_{SM}}{\mathrm{d}q^2}\sim\frac{C^2}{\Lambda_{NP}^4}q^4$$



[1] 2207.10756, 2002.05684, 2003.12421 ...

What about neutrinos ?

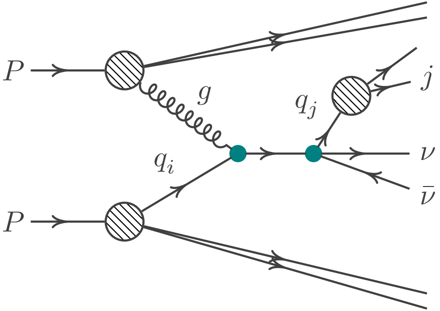
Drell-Yan to dineutrinos

- neutrinos and charged leptons are part of the same SU(2)-doublet
  $\Rightarrow$ correlations between the WCs
- However the q^2-Spectrum is not measurable at the LHC

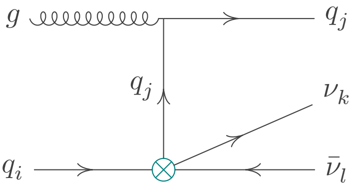
Drell-Yan to dineutrinos

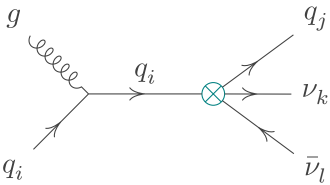
- neutrinos and charged leptons are part of the same SU(2)-doublet
  $\Rightarrow$ correlations between the WCs
- However the q^2-Spectrum is not measurable at the LHC
- Analyze $\Rightarrow P_T$-Spectrum
- Consider $pp \to \nu\bar{\nu} + \text{jet}$
- Partonic process:

$$q_i g \to \nu\bar{\nu} q_j$$
$$\bar{q}_i g \to \nu\bar{\nu} \bar{q}_j$$
$$q_i \bar{q}_j \to \nu\bar{\nu} g$$

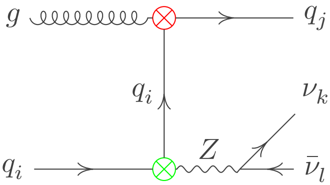


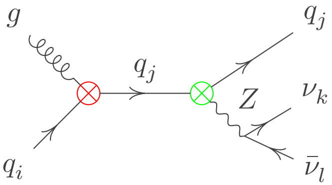
Parton process: $q_i g \to q_j \nu_k \bar{\nu}_l$





$$\underbrace{Q_{lq}^{(3)}, Q_{lq}^{(1)}, Q_{lu}, Q_{ld}}_{4F}$$





$$\underbrace{Q_{\varphi q}^{(3)}, Q_{\varphi q}^{(1)}, Q_{\varphi u}, Q_{\varphi d}}_{ZP}, \underbrace{Q_{uW}, Q_{dW}, Q_{uB}, Q_{dB}}_{EW}, \underbrace{Q_{uG}, Q_{dG}}_{G}$$

- Analyze ratios of cross section in the high energy regime ($q^2 \approx M_Z^2 \ll P_T^2, \hat{s}$)

$$R_I = \frac{\mathrm{d}\hat{\sigma}_I}{\mathrm{d}P_T} \Big/ \frac{\mathrm{d}\hat{\sigma}_{SM}}{\mathrm{d}P_T}$$

- four-fermion contact terms

$$R_{4F} \propto \sum_{k,l=\nu_e,\nu_\mu,\nu_\tau} \left(|C^{(1)}_{lq,klij} \pm C^{(3)}_{lq,klij}|^2 + |C_{lu/d,klij}|^2 \right) \frac{\hat{s}^2}{\Lambda_{NP}^4}$$

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- gluonic dipole operators

$$R_G \propto \left(|C_{u/dG,ij}|^2 + |C_{u/dG,ji}|^2 \right) \frac{\hat{s}^2}{\Lambda^4_{NP}}$$

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Fully energy enhanced

- EW dipole operators ($c_W = \cos\theta_W, s_W = \sin\theta_W$)

$$R_{EW} \propto \left(|c_W C_{u/dW,ij} - s_W C_{u/dB,ij}|^2 + |c_W C_{u/dW,ji} - s_W C_{u/dB,ji}|^2\right) \frac{\hat{s} v^2}{\Lambda_{NP}^4}$$

$\Rightarrow$ Partial energy enhancement

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$\Rightarrow$ Partial energy enhancement

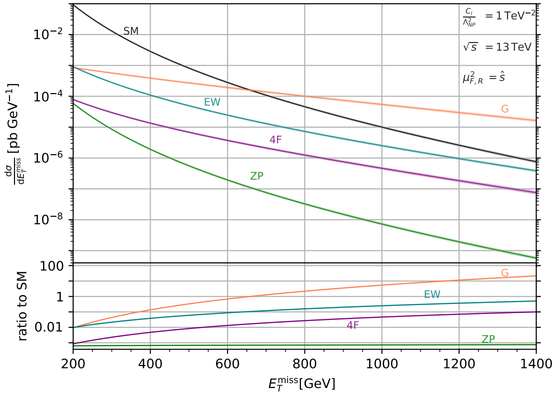
- EW penguin operators

$$R_{ZP} \propto \left(|C^{(1)}_{\varphi q,ij} \mp C^{(3)}_{\varphi q,ij}|^2 + |C_{\varphi u/d,ij}|^2\right) \frac{v^4}{\Lambda_{NP}^4} \sim \text{const}$$

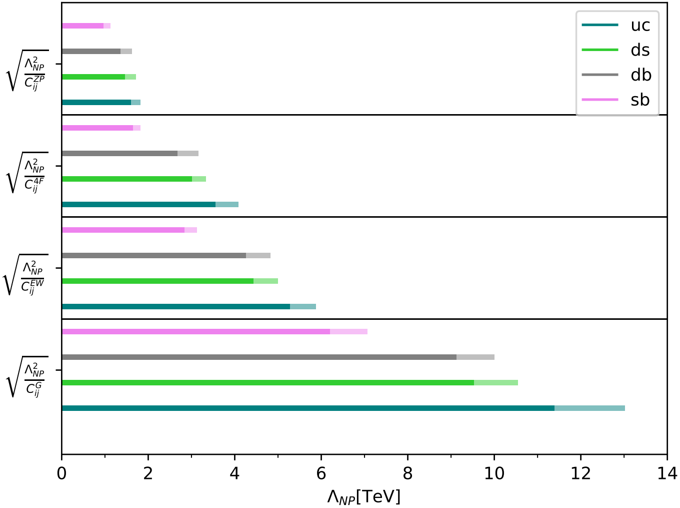
$\Rightarrow$ No energy enhancement

Total contribution of different operators

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



NP Scales probed



Bounds on four-fermion operators

- Bounds ($139\,\text{fb}^{-1}$) and HL-LHC projections ($3000\,\text{fb}^{-1}$)
- Recast of ATLAS analysis[1]
- Bounds derived on effective WC ($\Lambda_{NP} = 1\,\text{TeV}$)

$C_{ij,eff}$	limits	projections
uc	0.08	0.06
ds	0.11	0.09
db	0.14	0.10
sb	0.37	0.30

$$C^2_{ij,eff} = \sum_{k,l} |C^{(1)}_{lq,klij} \pm C^{(3)}_{lq,klij}|^2 + |C_{lu/d,klij}|^2$$

[1] arXiv:2102.10874

Comparision with existing bounds

- SU(2) allows connection with charged dilepton results
- Bounds on τ couplings are generally stronger using $pp \to \nu\bar{\nu} +$ jet than charged dilepton Drell-Yan (q^2-Spectrum)

process	$cull'$	$\tau\tau$	$e\tau$	$\mu\tau$	
$pp \to \ell^+\ell^-$	$\mathcal{K}_{L,R}^{cull'}$	5.6	4.7	5.1	
$K \to \nu\bar{\nu} + \pi$	$\mathcal{K}_{L}^{cu\ell\ell'}$	$[-1.9, 0.7] \cdot 10^{-2}$	1.1×10^{-2}	1.1×10^{-2}	
$pp \to \nu\bar{\nu} + X$	$\mathcal{K}_{L}^{cull'}$	5.7 (4.6)	4.1 (3.3)	4.1 (3.3)	[1]
$pp \to \nu\bar{\nu} + X$	$\mathcal{K}_{R}^{cull'}$	4.2 (3.3)	2.9 (2.2)	2.9 (2.2)	[1]

- Bounds on other couplings (e or μ) are generally weaker

[1] New results derived form MET$+$ jet

Summary

- The signature missing energy $+$ jet can be used to extract bounds on several SMEFT operators
- Overall 14 operators can be constrained
- Bounds from $pp \to \nu\bar{\nu} +$ jet on four-fermion operators involving τ-leptons and cu dipole couplings are found to be complementary and competitive
- Caveat: New ATLAS analysis[1] on differential cross section seems to not yield consistent results so far (Work in Progress)
- Outlook: Combine different sectors, such as charged dilepton DY, low energy observables, flavor and more

[1] arXiv:2403.02793

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Thank you for listening to my Talk !

[1] arXiv:2403.02793

Backup

Effective coefficients

- Cross section is only sensitive to certain combinations of WCs
- four-fermion contact terms

$$C_{ij}^{4F} = \sqrt{\sum_{k,l=e,\mu,\tau} |C_{lq,ijkl}^{1} \pm C_{lq,ijkl}^{3}|^2 + |C_{lu/d,klij}|^2}$$

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- Gluonic dipole operators

$$C_{ij}^{G} = \sqrt{|C_{u/dG,ij}|^2 + |C_{u/dG,ji}|^2}$$

- Electroweak dipole operators

$$C_{ij}^{EW} = \sqrt{|\cos\theta_W C_{qW,ij} - \sin\theta_W C_{qB,ij}|^2 + |\cos\theta_W C_{qW,ji} - \sin\theta_W C_{qB,ji}|^2}$$

- Penguin dipole operators

$$C_{ij}^{ZP} = \sqrt{|C_{\varphi q,ij}^{(\mp)}|^2 + |C_{\varphi u/d,ij}|^2}$$

$$x = \frac{2P_T}{\sqrt{\hat{s}}}$$

$$\frac{\mathrm{d}\hat{\sigma}_{SM}(q_i g \to \nu\bar{\nu} q_j)}{\mathrm{d}P_T} \approx \frac{\alpha_s \mathsf{Br}(Z \to \nu\bar{\nu}) \left(\epsilon_L^{i,j2} + \epsilon_R^{i,j2}\right)}{12\sqrt{2}} \frac{1}{\hat{s}^{3/2}} \frac{x^2+4}{x\sqrt{1-x^2}},$$

$$\frac{\mathrm{d}\hat{\sigma}_{ZP}(q_i g \to \nu\bar{\nu} q_j)}{\mathrm{d}P_T} \approx \frac{\alpha_s C_{ij}^{ZP2} \mathsf{Br}\,(Z \to \nu\bar{\nu})}{24} \frac{M_Z^2 v^2}{\Lambda_{NP}^4} \frac{1}{\hat{s}^{3/2}} \frac{x^2+4}{x\sqrt{1-x^2}},$$

$$\frac{\mathrm{d}\hat{\sigma}_{4F}(q_i g \to \nu\bar{\nu} q_j)}{\mathrm{d}P_T} \approx \frac{5\alpha_s C_{ij}^{4F2}}{432\sqrt{2}\pi^2} \frac{1}{\Lambda_{NP}^4} \sqrt{\hat{s}}(1-x)^{3/2},$$

$$\frac{\mathrm{d}\hat{\sigma}_{EW}(q_i g \to \nu\bar{\nu} q_j)}{\mathrm{d}P_T} \approx \frac{\alpha_s (C_{ij}^{EW})^2 \mathsf{Br}\,(Z \to \nu\bar{\nu})}{6\sqrt{2}} \frac{v^2}{\Lambda_{NP}^4} \frac{1}{\sqrt{\hat{s}}} \frac{x}{\sqrt{1-x^2}},$$

$$\frac{\mathrm{d}\hat{\sigma}_{G}(q_i g \to \nu\bar{\nu} q_j)}{\mathrm{d}P_T} \approx \frac{C_{ij}^{G2} \mathsf{Br}\,(Z \to \nu\bar{\nu})}{96\pi} \frac{1}{\Lambda_{NP}^4} \sqrt{\hat{s}} \frac{x}{\sqrt{1-x^2}},$$

Comparision with existing bounds

- Bounds on τ couplings are generally stronger using $pp \to \nu\bar{\nu} + \text{jet}$ than charged dilepton Drell-Yan (q^2-Spectrum)
- Comparing rescaled coefficients[1]

process	$cull'$	$\tau\tau$	$e\tau$	$\mu\tau$
$pp \to \ell^+\ell^-$	$\lvert\mathcal{K}_{L,R}^{cull'}\rvert_{DY}$	5.6	4.7	5.1
$pp \to \nu\bar{\nu} + X$	$\lvert\mathcal{K}_{L}^{cull'}\rvert_{\nu\bar{\nu}j}^{pp}$	5.7 (4.6)	4.1 (3.3)	4.1 (3.3)
$pp \to \nu\bar{\nu} + X$	$\lvert\mathcal{K}_{R}^{cull'}\rvert_{\nu\bar{\nu}j}^{pp}$	4.2 (3.3)	2.9 (2.2)	2.9 (2.2)

- Bounds on other couplings(i.e. e or μ) are generally weaker

[1] arXiv:2007.05001

Gluonic dipole operators: uc-coupling

- Comparison with bounds[1] derived from rare charm decays

$$|C_{uG,12}| = |C_{uG,21}| \lesssim 1.3 \times 10^{-3}$$

- Bounds derived from $pp \to \nu\bar{\nu} + \text{jet}$

$$|C_{uG,12}| = |C_{uG,21}| \lesssim 8 \times 10^{-3}$$

[1] arXiv:1701.06392

Four-fermion operators

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

Gluonic dipole operators

$$\mathcal{L}^6 \supset \frac{C_{ug,ij}}{\Lambda_{NP}^2}(\bar{q}_i \sigma^{\mu\nu} T^A u_j \tilde{\varphi} G^A_{\mu\nu}) + \frac{C_{dg,ij}}{\Lambda_{NP}^2}(\bar{q}_i \sigma^{\mu\nu} T^A d_j \varphi G^A_{\mu\nu})$$

Z-vertex corrections

$$
\begin{aligned}
\mathcal{L}^6 \supset & \frac{C_{uW,ij}}{\Lambda_{NP}^2}(\bar{q}_i \sigma^{\mu\nu} u_j \tau^I \tilde{\varphi} W_{\mu\nu}^I) + \frac{C_{dW,ij}}{\Lambda_{NP}^2}(\bar{q}_i \sigma^{\mu\nu} d_j \tau^I \varphi W_{\mu\nu}^I) \\
& + \frac{C_{uB,ij}}{\Lambda_{NP}^2}(\bar{q}_i \sigma^{\mu\nu} u_j \tilde{\varphi} B_{\mu\nu}) + \frac{C_{dB,ij}}{\Lambda_{NP}^2}(\bar{q}_i \sigma^{\mu\nu} d_j \varphi B_{\mu\nu}) \\
& + \frac{C_{\varphi q,ij}^{(1)}}{\Lambda_{NP}^2}\left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi\right)(\bar{q}_i \gamma^\mu q_j) + \frac{C_{\varphi q,ij}^{(3)}}{\Lambda_{NP}^2}\left(\varphi^\dagger i \overset{\leftrightarrow}{D}{}_\mu^I \varphi\right)(\bar{q}_i \tau^I \gamma^\mu q_j) \\
& + \frac{C_{\varphi u,ij}}{\Lambda_{NP}^2}\left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi\right)(\bar{u}_i \gamma^\mu u_j) + \frac{C_{\varphi d,ij}}{\Lambda_{NP}^2}\left(\varphi^\dagger i \overset{\leftrightarrow}{D}_\mu \varphi\right)(\bar{d}_i \gamma^\mu d_j)
\end{aligned}
$$

Recast

$$\sigma_{\text{SMEFT}} = \sigma_{\text{SM}} + \sum_i \frac{C_i}{\Lambda_{NP}^2}\sigma_i^{int} + \sum_{i,j} \frac{C_i C_j^*}{\Lambda_{NP}^4}\sigma_{ij}^{BSM}$$

- UFO model: SMEFTsim(arxiv:2012.11343)
- Cross section : MadGraph5 (arxiv:1804.10017)
- Showering and hadronization: Pythia8 (arxiv:2203.11601)
- Detector simulation: Delphes3 (arxiv:1307.6346)