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Teaming up MET plus jet with Drell-Yan in the SMEFT

In collaboration with G.Hiller and L.Nollen
Based on 2403.17063 and Work in preparation

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Standard Model Effective Field Theory

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

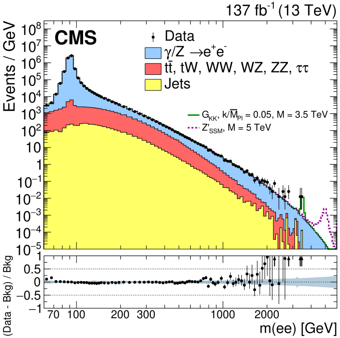
$$\mathcal{L}_{\mathsf{SMEFT}} = \mathcal{L}_{\mathsf{SM}} + \sum_{d=5}^{\infty} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

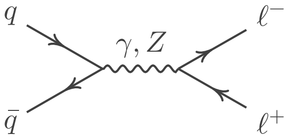
- $C_i^{(d)}$: WC capturing the short distance physics
- $\mathcal{O}_i^{(d)}$: Effective operators encoding the long distance physics
- Λ: New Physics scale or power counting parameter
- Focus on dimension 6 operators

Neutral-current DY in the SMEFT

- Drell-Yan (DY) studied extensively in the SMEFT
  [arxiv:2207.10756,arxiv:2304.12837, arXiv:2003.12421,...]

- Four-fermion and electroweak (EW) dipole operators are energy enhanced relative to the SM
- Flavor sensitivities through parton distribution functions (PDFs)
- Measurement of $m_{\ell\ell}$





SM contribution to NC DY

Drell-Yan to dineutrinos

- In the SMEFT charged leptons and neutrinos are part of an doublet

$$l = \begin{pmatrix} \nu \\ \ell \end{pmatrix}$$

So what about neutrinos ?

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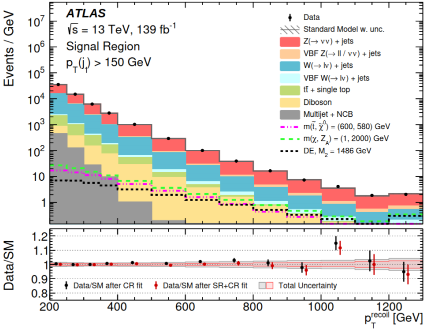


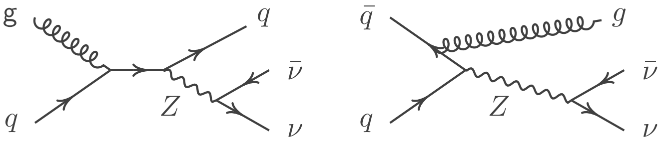
$$\mathbf{E}_\mathbf{T}^{\text{miss}} = -\sum_i \mathbf{P}_\mathbf{T}^\mathbf{i} \qquad i : \text{visible final state}$$

$$E_T^{\text{miss}} = |\mathbf{E}_\mathbf{T}^{\text{miss}}|$$

$\Rightarrow$ missing energy observables

E_T^{miss}-spectrum

- At LO $E_T^{\text{miss}} = P_T \gtrsim 100\,\text{GeV}$, separation from soft radiation
- The leading contribution will be through $\mathcal{O}(\alpha_s)$ contribution in the SM
- Multiple partonic channels contribute in the SM and SMEFT
- Gluon PDFs are dominant in the high energy regime



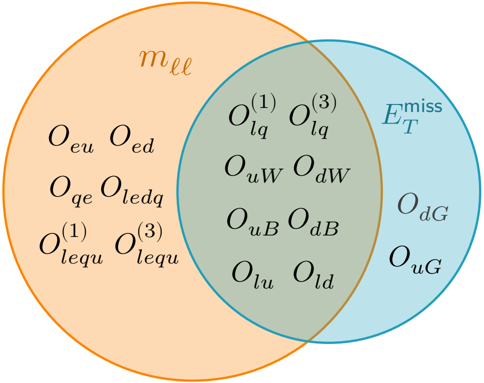
SM contributions to $pp \to \nu\bar{\nu} + \text{jet}$

Comparision between the observables

Observable	$m_{\ell\ell}$	$E_T^{\textsf{miss}}$
QCD order (LO)	1	α_s
Processes (LO)	$2 \to 2$	$2 \to 3$
Partonic channels (LO)	$q\bar{q}$	$q\bar{q},\ qg,\ \bar{q}g$
Leptons	charged leptons	neutrinos
Vector couplings	Z, γ	Z, g
Z resonance	within spectrum	integrated over
Lepton tagging	$\checkmark$	$\times$

Back to SMEFT

Operators considered



Semileptonic Four-Fermion					
$O^{(1)}_{\underset{\alpha\beta ij}{lq}}$	$(\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{q}_i\gamma^\mu q_j)$	$O^{(3)}_{\underset{\alpha\beta ij}{lq}}$	$(\bar{l}_\alpha\gamma_\mu\tau^I l_\beta)(\bar{q}_i\gamma^\mu\tau^I q_j)$	$O_{\underset{\alpha\beta ij}{qe}}$	$(\bar{q}_i\gamma_\mu q_j)(\bar{e}_\alpha\gamma^\mu e_\beta)$
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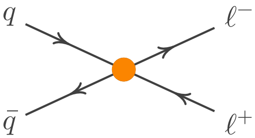
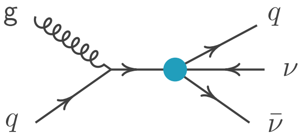
$O^{(3)}_{\underset{\alpha\beta ij}{lequ}}$	$(\bar{l}^k_\alpha\sigma_{\mu\nu}e_\beta)\epsilon_{km}(\bar{q}^m_i\sigma^{\mu\nu}u_j)$				

- Contact interaction $\Rightarrow$ fully energy enhanced
- Observables are proportional to linear combinations of several WCs
- Interference term with the SM for diagonal flavor combinations only
- WCs with SU(2) doublets can not absorb mass rotation matrices fully $\Rightarrow$ alignment dependence

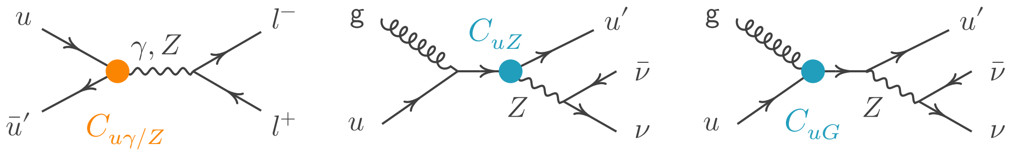




Dipole operators

$$\mathcal{L}^{\text{Dip}} = C_{uX}^{ij}\bar{q}_i\sigma^{\mu\nu}\tau^A u_j X_{\mu\nu}^A\tilde{\varphi} + C_{dX}^{ij}\bar{q}_i\sigma^{\mu\nu}\tau^A d_j X_{\mu\nu}^A\varphi + \text{h.c.} \qquad X = G^A, W^I, B$$

- Chirality flip $\Rightarrow$ interference term with SM strongly suppressed
- Proportional to $v \Rightarrow$ partial energy enhancement for EW Dipole
- Gluon dipoles are fully energy enhanced, due to the longitudinal modes of the Z



$C_{u\gamma}, C_{uZ}$ are related by rotations

High energy behaviour of C_{uG} and C_{dG}

- Longitudinal vector boson modes are equivalent to the goldstone modes π in the high energy limit [Nuclear Physics B 261 (1985) 379, arxiv:1911.12366]

$$\mathcal{M}(u_i g \to u_j Z_L) \overset{\hat{s} \gg v^2}{=} \mathcal{M}(u_i g \to u_j \pi^0)$$

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$$\mathcal{M}(u_i g \to u_j Z_L) \overset{\hat{s} \gg v^2}{=} \mathcal{M}(u_i g \to u_j \pi^0)$$

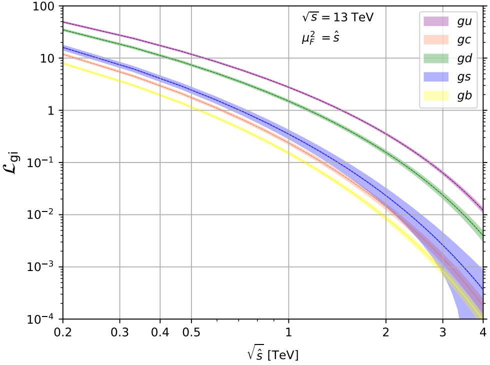
- Expansion of the higgs doublet

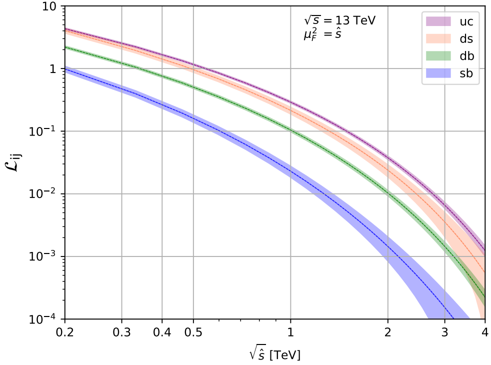
$$\phi = \begin{pmatrix} \pi^+ \\ \frac{v + h + i\pi^0}{\sqrt{2}} \end{pmatrix}$$

$$\Rightarrow \mathcal{L}^{\text{Dip}} \supset -i \frac{C_{uG}^{ij}}{\Lambda^2} \bar{u}_i \sigma^{\mu\nu} T^A P_R u_j G^A_{\mu\nu} \frac{\pi^0}{\sqrt{2}} + \text{h.c.}$$

- Describes a contact term $\Rightarrow$ fully energy enhanced

Quark flavor through PDFs

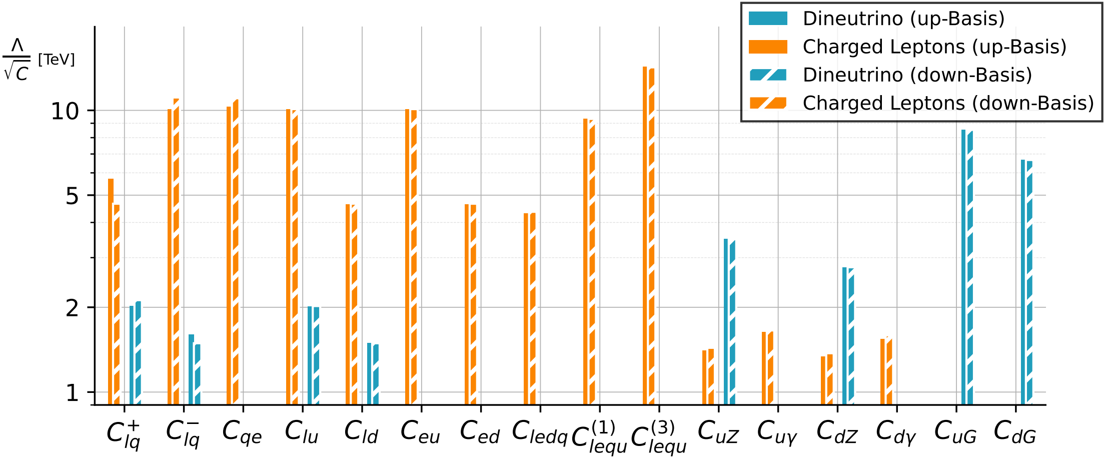




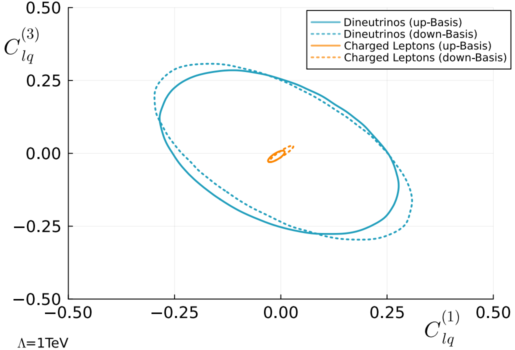
$$\mathrm{d}\sigma = \sum_{i,j=\text{partons}} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{ij}(\tau, \mu_F)\, d\hat{\sigma}_{ij}(\tau, P_T, \eta, \ldots) \quad \tau = \frac{\hat{s}}{s}$$

(preliminary) Results

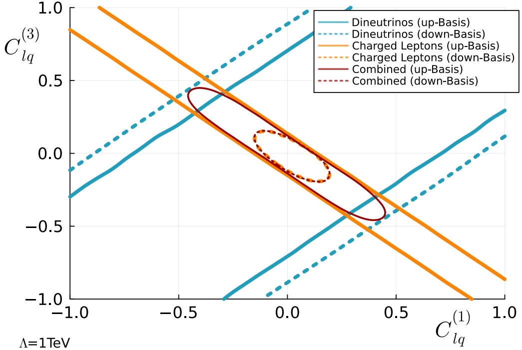
Single operator results: $(ij) = (12)$



Four-fermion operators with doublets

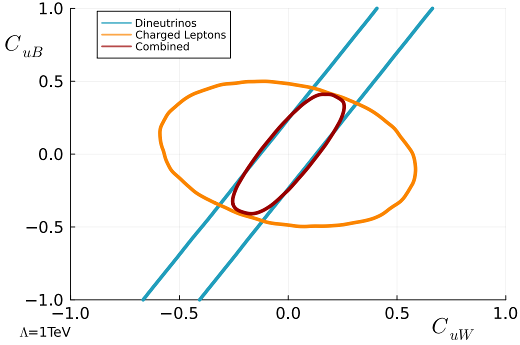


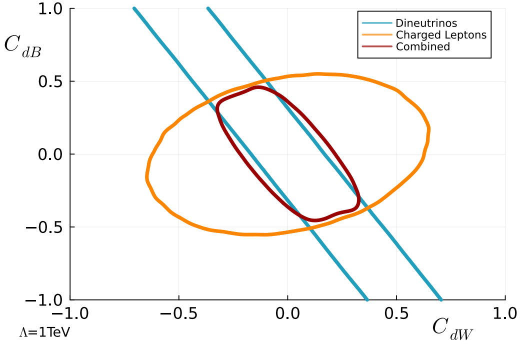
$(ij) = (12)$



$(ij) = (13)$

EW Dipoles: $(ij) = (12)$





Comparison in a larger context

- Bounds derived constrain the multi TeV region
- Flavor observables are usually more constraining than high-P_T, however processes involving τ-leptons are generally not measured
- $m_{\ell\ell}$ and E_T^{miss} complement this by constraining all lepton flavors
- Charm Physics: Gluon Dipoles give bounds $C_7^{(\prime)} \lesssim 2.8$ and $C_8^{(\prime)} \lesssim 4.4$, which are about one order of magnitude weaker than charm decays
- E_T^{miss} bounds on four-fermion operators can be extended to light sterile neutrinos

Summary

- $m_{\ell\ell}$ and E_T^{miss} probe different combination of WCs $\Rightarrow$ Synergies
- Full energy enhancement for four-fermion and gluon dipoles, partial energy enhancement for EW dipoles
- Generally $m_{\ell\ell}$ is more constraining for the four-fermion operators, but E_T^{miss} constraints the dipole operators better
- SMEFT is a tool to study correlations between different observables from different energy scales and experiments, to test the SM and check consistency

Backup

Operators

Dipole					
$O_{\underset{ij}{uB}}$	$(\bar{q}_i\sigma^{\mu\nu}u_j)\tilde{\varphi}B_{\mu\nu}$	$O_{\underset{ij}{uW}}$	$(\bar{q}_i\sigma^{\mu\nu}u_j)\tau^I\tilde{\varphi}W^I_{\mu\nu}$	$O_{\underset{ij}{uG}}$	$(\bar{q}_i\sigma^{\mu\nu}T^Au_j)\tilde{\varphi}G^A_{\mu\nu}$
$O_{\underset{ij}{dB}}$	$(\bar{q}_i\sigma^{\mu\nu}d_j)\varphi B_{\mu\nu}$	$O_{\underset{ij}{dW}}$	$(\bar{q}_i\sigma^{\mu\nu}d_j)\tau^I\varphi W^I_{\mu\nu}$	$O_{\underset{ij}{dG}}$	$(\bar{q}_i\sigma^{\mu\nu}T^Ad_j)\varphi G^A_{\mu\nu}$
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Lepton flavor for four-fermion operators

- Lepton rotation matrices can always be aligned with charged leptons
- Dineutrinos not tagged
  $\Rightarrow$ PMNS matrix drops out of E_T^{miss}-spectrum
- $m_{\ell\ell}$ measurements tag the leptons ($e^+e^-, \mu^+\mu^-, e^-\mu^+$etc.)
- Different lepton flavor scenarios

$$C_{ijkl} = C_{ij}^{\text{LU}} \delta_{kl}$$
$$C_{ijkl} = C_{ij}^{\text{cLFC}} \delta_{kl} + C_{ij}^{\text{LFV}} \delta_{k \neq l}$$

Four fermion: SU(2)-doublets

- Rotating to mass basis for left handed quarks $q = U^q q'$
- Up- or down-alignment
- Consider $C^{+}_{lq,ijkl}$ in matrix form for fixed k, l:

$$\mathcal{L}^{4\mathrm{F}} \supset \mathrm{Tr}\left[\bar{u}'\,(U^u)^\dagger\,\gamma^\mu C^{+}_{lq} U^u u'\,\left(\bar{\nu}\gamma_\mu \nu\right) + \bar{d}'\,(U^d)^\dagger\,\gamma^\mu C^{+}_{lq} U^d d'\,\left(\bar{\ell}\gamma_\mu \ell\right)\right]$$

$$= \mathrm{Tr}\left[\bar{u}'\gamma^\mu\,\underbrace{(U^u)^\dagger\,C^{+}_{lq} U^u}_{\tilde{C}^{+}_{lq}}\,u'\,\left(\bar{\nu}\gamma_\mu \nu\right) + \bar{d}'\,\underbrace{(U^d)^\dagger\,U^u}_{V_{\mathrm{CKM}}}\,\gamma^\mu\,\underbrace{(U^u)^\dagger\,C^{+}_{lq} U^u}_{\tilde{C}^{+}_{lq}}\,\underbrace{(U^u)^\dagger\,U^d}_{V_{\mathrm{CKM}}{}^\dagger}\,d'\,\left(\bar{\ell}\gamma_\mu \ell\right)\right]$$

- $(i,j) = (1,2)$ and expanding in $\lambda = \sin\theta_{\text{cab}}$

$$\tilde{C}^{+}_{lq,12kl}\left(\underbrace{\bar{u}'\gamma^{\mu}c'\bar{\nu}_k\gamma_{\mu}\nu_l}_{E_T^{\text{miss}}} + \underbrace{\bar{d}'\gamma^{\mu}s'\ell_k\gamma_{\mu}\ell_l + \lambda\left(\bar{d}'\gamma^{\mu}d' - \bar{s}'\gamma^{\mu}s'\right)\ell_k\gamma_{\mu}\ell_l}_{m_{\ell\ell}}\right) + \mathcal{O}(\lambda^2)$$

- Analogously for down alignment and (or) $C^{-}_{lq,ijkl}$
- Inclusivity of observables leads to the bound being dominated by one observable