Exploring the muon-Higgs coupling at a multi-TeV muon collider

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based on a work with
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What do we know about particle physics?

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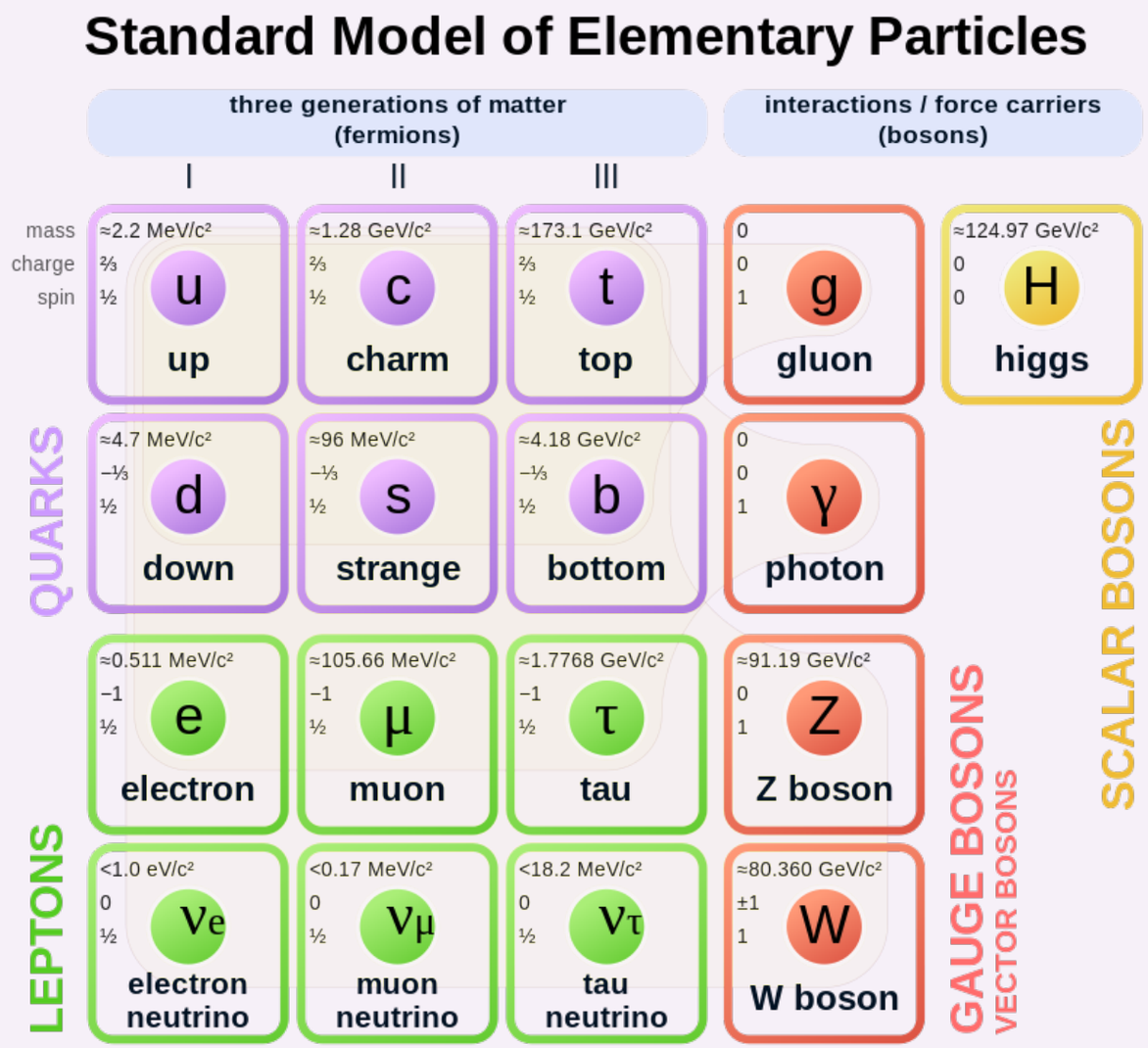

So this is it?

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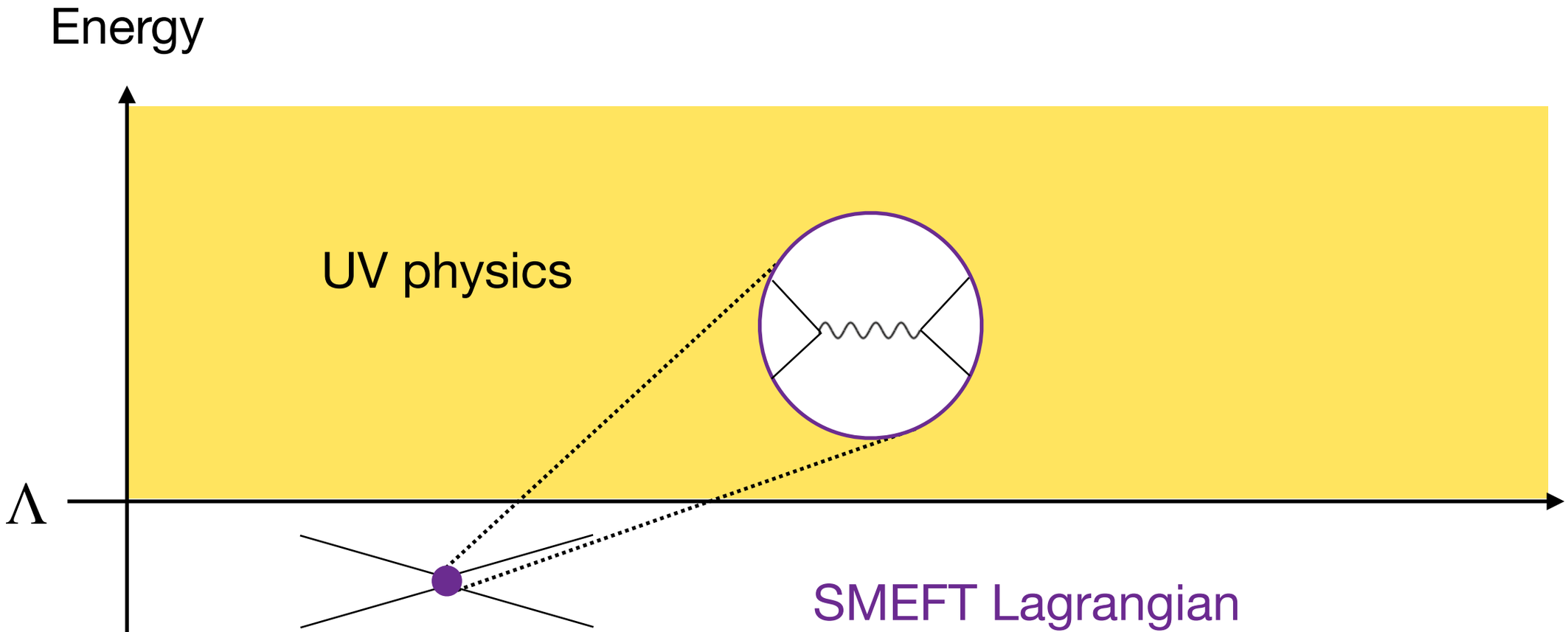
No

- dark matter
- neutrino mass
- matter/antimatter asymmetry
- …

We need a **model independent** description for new physics

SMEFT



SMEFT Lagrangian

$$\mathcal{L}_{\text{EFT}} = \sum_i \frac{c_i}{\Lambda^{d-4}} \mathcal{O}_i^{(d)} = \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \ldots$$

- Λ above the experimental energy
- the new operators preserve the fundamental gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$
- operators automatically ordered by the series expansion in Λ

Muon Yukawa in the SM

Can we increase the sensitivity on the **muon-Higgs coupling** at a high energy (3-30TeV) muon collider?

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$$\mathcal{L}_{\text{EW}} = -\frac{1}{2}\,\text{tr}\,W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + (D_\mu\varphi)^\dagger(D^\mu\varphi) + \mu^2\varphi^\dagger\varphi - \frac{\lambda}{2}(\varphi^\dagger\varphi)^2$$

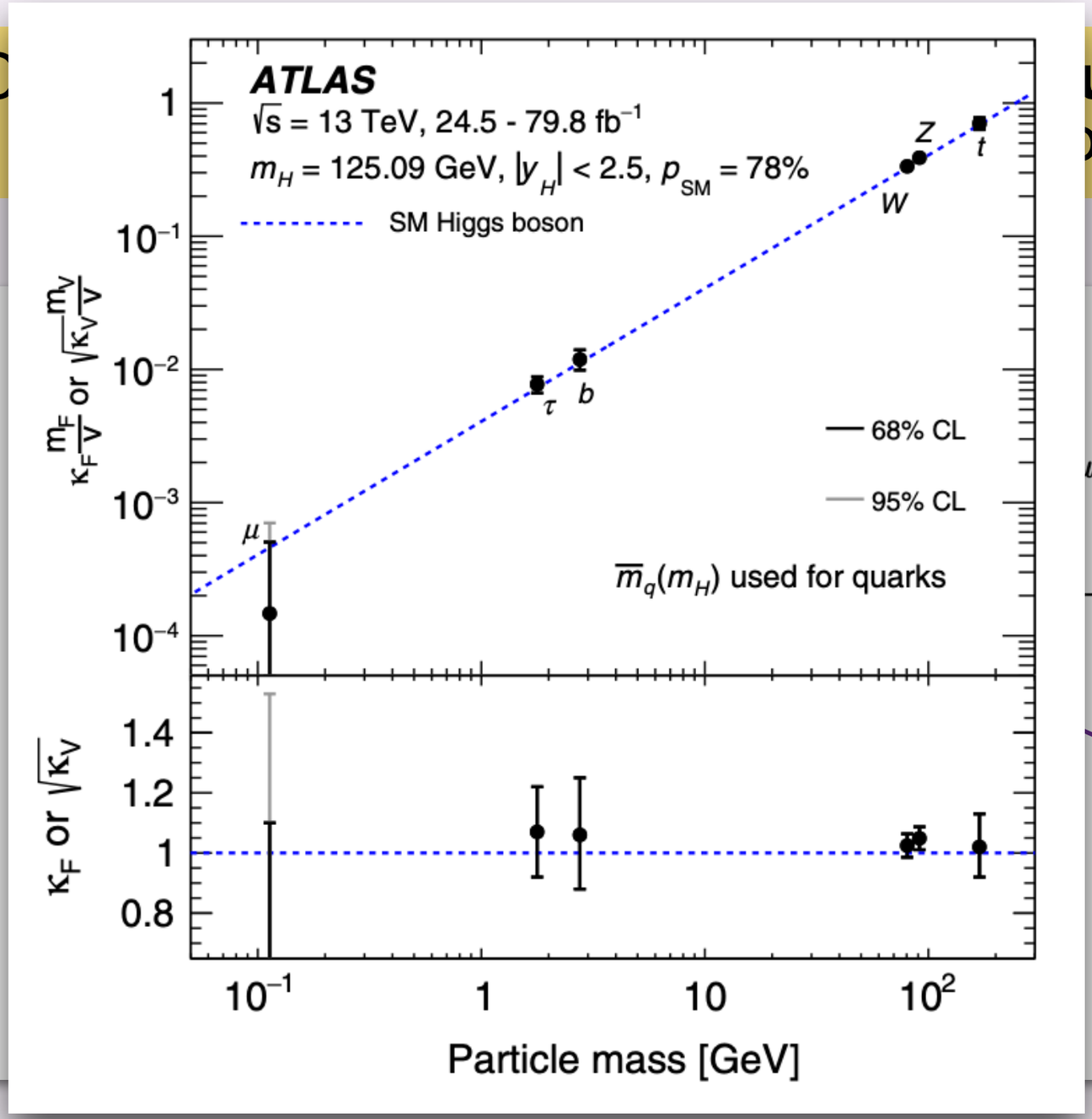
$$+ \sum_{f\in\{\ell_L,e_R\}} i\bar{f}^i \not{D} f^i - \left(\bar{\ell}_L^i \tilde{Y}_\ell^{ij} \varphi e_R^j + \text{h.c.}\right) + \mathcal{L}_{\text{gauge-fix}}$$

Yukawa sector

$$m_f = \frac{y_f v}{\sqrt{2}}$$

Muon Yukawa in the SM

C **uon-Higgs coupling**
on collider?



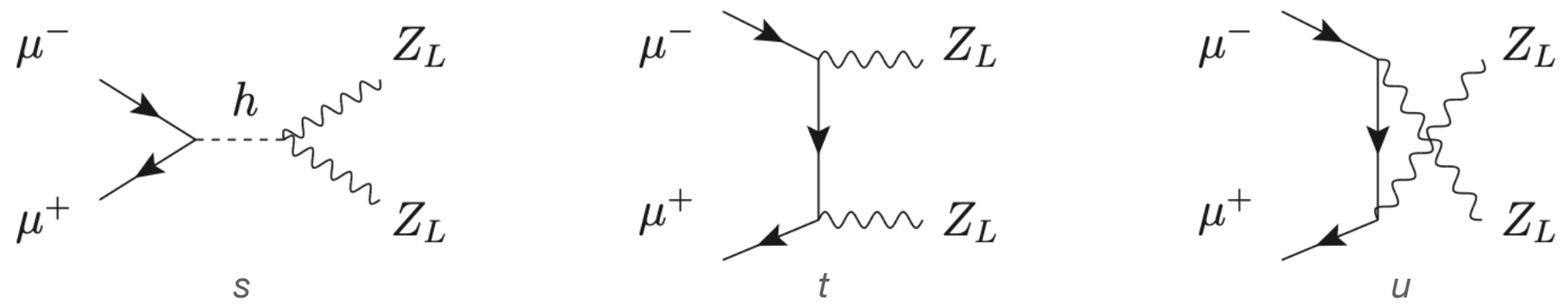
$$\varphi) + \mu^2 \varphi^\dagger \varphi - \frac{\lambda}{2} (\varphi^\dagger \varphi)^2$$

$$- \mathcal{L}_{\text{gauge-fix}}$$

$$m_f = \frac{y_f v}{\sqrt{2}}$$

Cancellations and unitarity in the SM

Example: simple EW process: $\mu^-\mu^+ \to ZZ$



- energy dependence induced by the longitudinal polarizations…

$$\epsilon_+ = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\i\\0\end{pmatrix}, \quad \epsilon_- = \frac{1}{\sqrt{2}}\begin{pmatrix}0\\1\\-i\\0\end{pmatrix}, \quad \epsilon_L = \frac{1}{m}\begin{pmatrix}p\\0\\0\\E\end{pmatrix}$$

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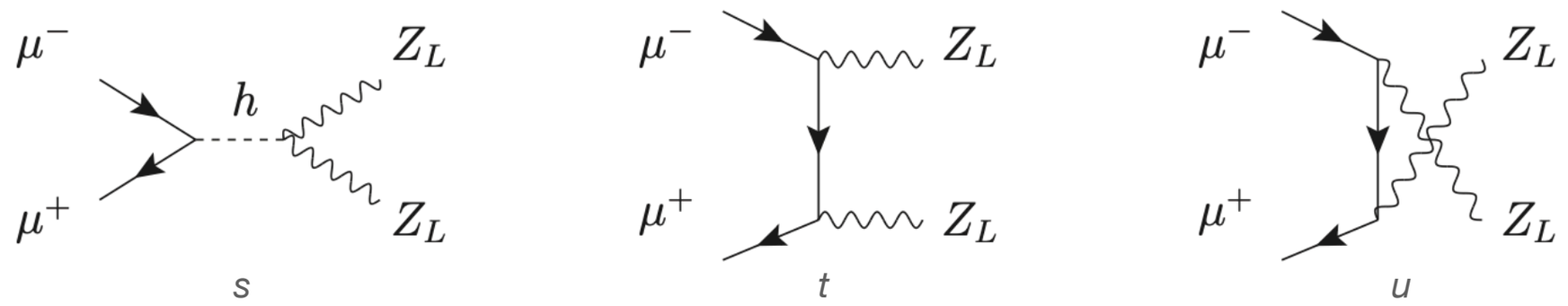

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- … but thanks to the Higgs mechanism…

$$\left.\begin{array}{l}\mathcal{M}_s(\mu_R^+\mu_L^- \to Z_L Z_L)\\ \mathcal{M}_s(\mu_L^+\mu_R^- \to Z_L Z_L)\end{array}\right\} \xrightarrow{E\gg m_Z} 0$$

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from the Yukawa coupling

$$\left.\begin{array}{l}\mathcal{M}_{t+u}(\mu_R^+\mu_L^- \to Z_L Z_L)\\ \mathcal{M}_{t+u}(\mu_L^+\mu_R^- \to Z_L Z_L)\end{array}\right\} \xrightarrow{E\gg m_Z} 0$$

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from kinematics

$$m_f = \frac{y_f v}{\sqrt{2}}$$

- Unitarity is restored! $\mathcal{M}_s + \mathcal{M}_{t+u} \xrightarrow{E\gg m_Z} 0$

Anomalous muon Yukawa

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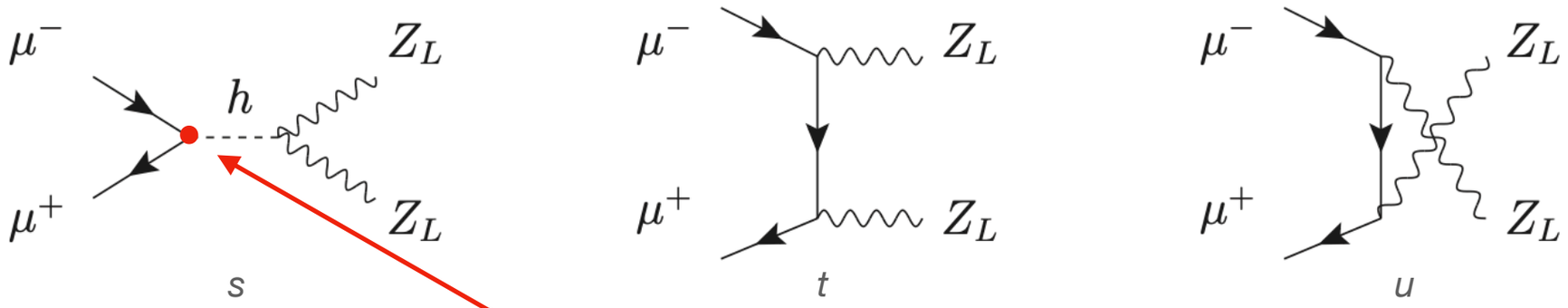
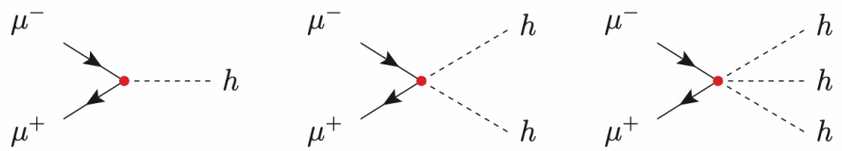


Effective operator that affects y_μ

$$\mathcal{L}^{(6)} = -\frac{c_{l\varphi}^{(6)}}{\Lambda^2}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)(\bar{l}_L\varphi\mu_R + \text{h. c.})$$



$$\mathscr{M}_s + \mathscr{M}_t + \mathscr{M}_u \xrightarrow{E \gg m_Z} \sim \sqrt{s}$$

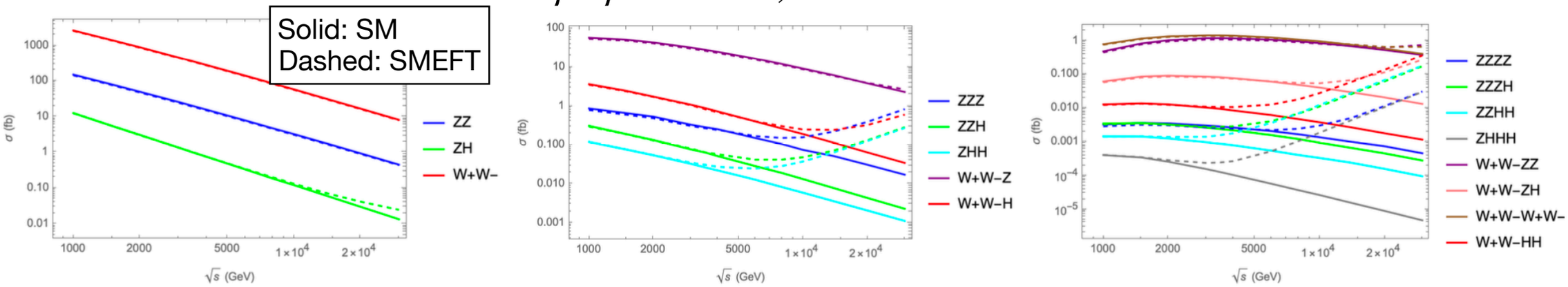
New physics induces an energy growth in the cross-section

Multiboson production

Anomalous y_μ in multiboson production at $1 < \sqrt{s} < 30$ TeV

$$\mathcal{L}^{(6)} = -\frac{c_{l\varphi}^{(6)}}{\Lambda^2}\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)(\bar{l}_L\varphi\mu_R + \text{h. c.})$$

$$\mu^-\mu^+ \to nV, nV + mH$$



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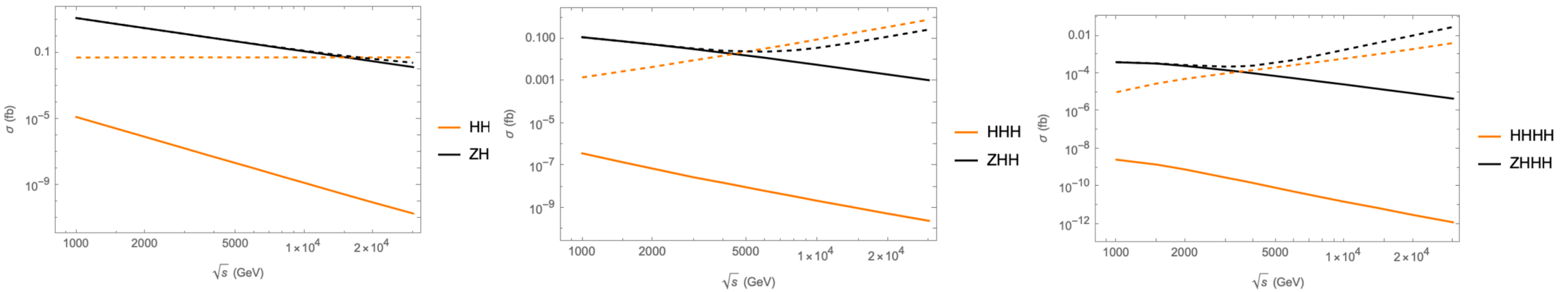

MadGraph5_aMC@NLO

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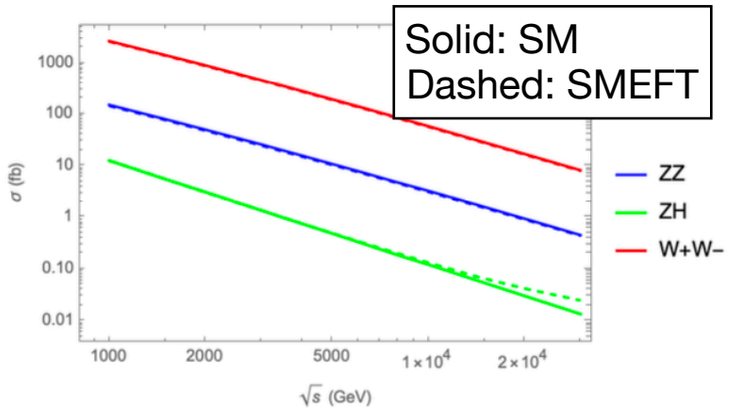

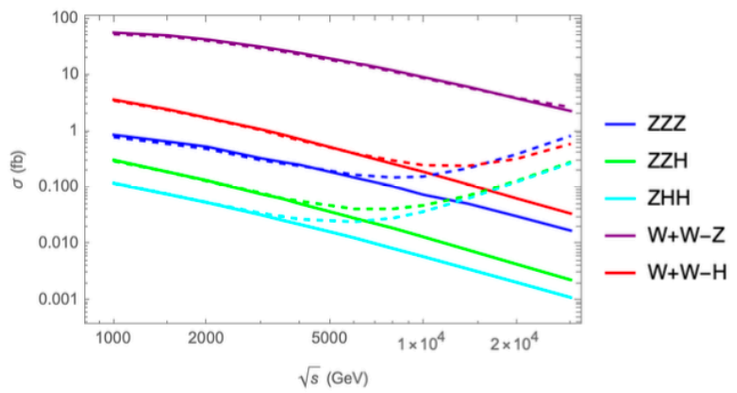

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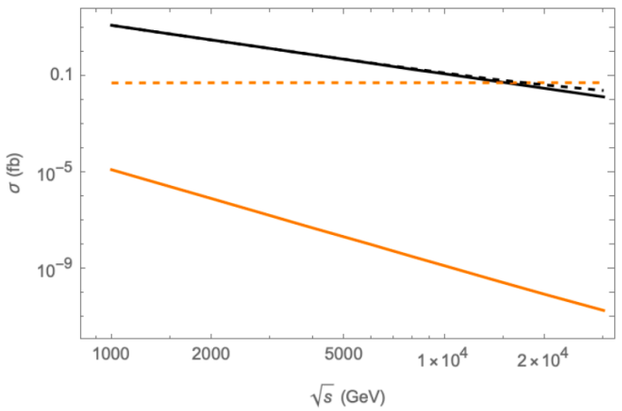
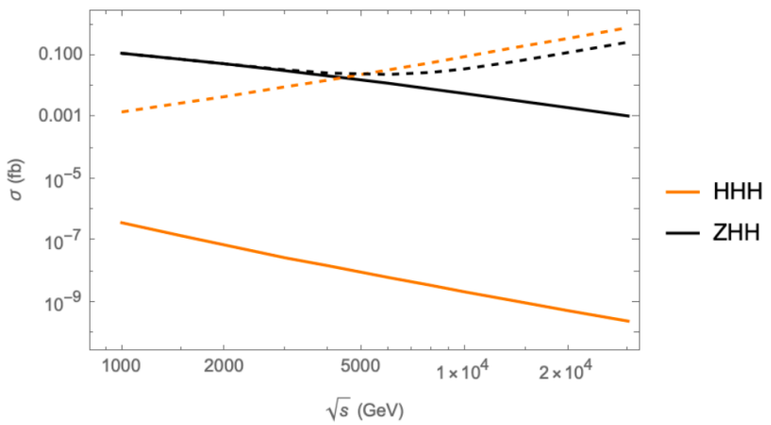
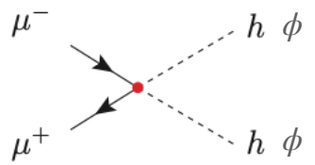




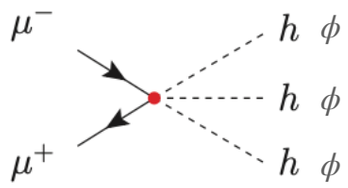
MadGraph5_aMC@NLO

High-energy behaviour

Goldstone Boson Equivalence Theorem



$$\sigma^{(2)} = I_2|V|^2, \quad I_2 = \frac{1}{32\pi}$$



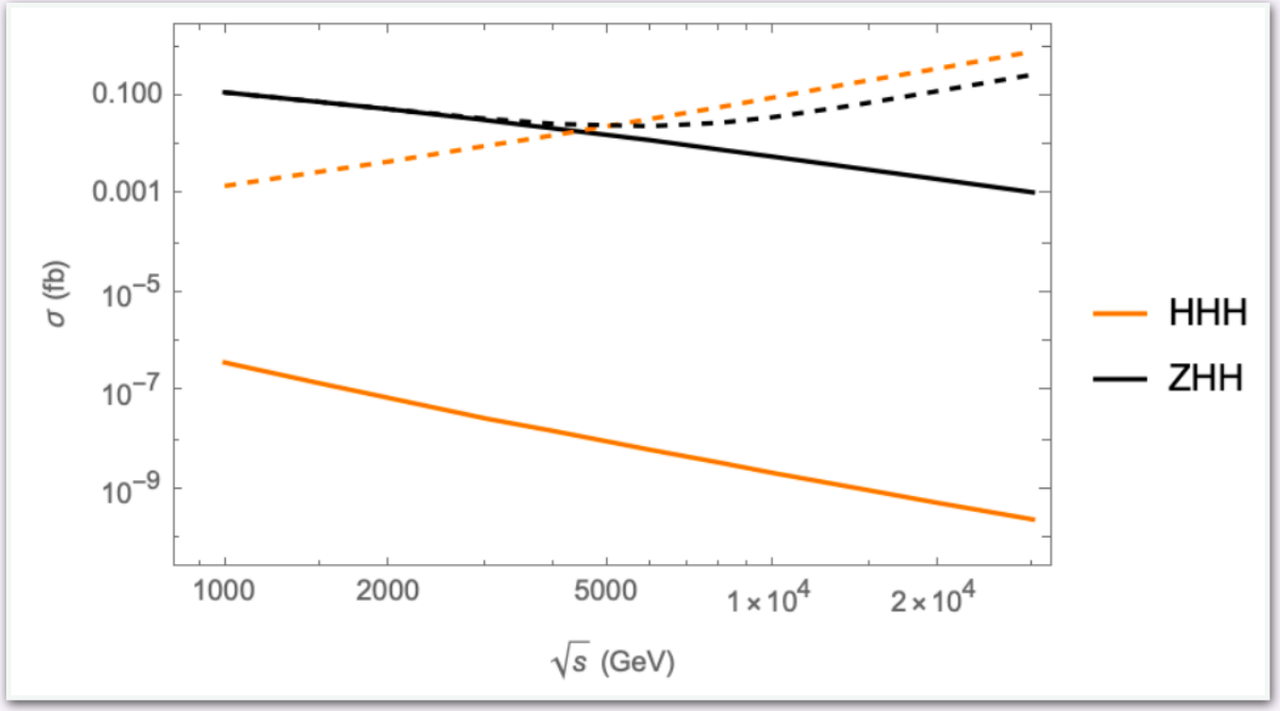
$$\sigma^{(3)} = I_3(s)|V|^2, \quad I_3(s) = \frac{s}{1024\pi^3}$$

Results

Conclusions:

- purely multi-Higgs production is suppressed in the SM, so it is more sensitive to deviations in y_μ
- the energy growth in three-boson production is quadratic in the c.o.m. energy

$$\sigma^{(3)} = I_3(s)|V|^2\,, \quad I_3(s) = \frac{s}{1024\pi^3}$$



HHH production is the most sensitive process to an anomalous y_μ

… work in progress!

EC, T. Han, W. Kilian, N. Kreher, Y. Ma, F. Maltoni, D. Pagani, J. Reuter, T. Striegl, K. Xie; to appear

Thanks for your attention!