EFT Measurements at the LHC

Markus Luty

UC Davis/QMAP

S. Chang, M. Chen, D. Liu, ML, arXiv:2212.06215

+ work in progress with S. Chang, T. Ma, A. Wulzer

Big Picture

- The Standard Model is the most general UV complete theory with the observed elementary particle content
- All parameters of the SM have been determined at the percent level or better
- Any observed deviation from the SM

$$\Rightarrow \begin{cases} \text{new light particles} & \leftarrow \text{ direct searches} \\ \text{new physics at high scales} & \leftarrow \text{ precision measurement} \end{cases}$$

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This talk:

- What are the observables that we want to measure?
- How should we measure/report them?

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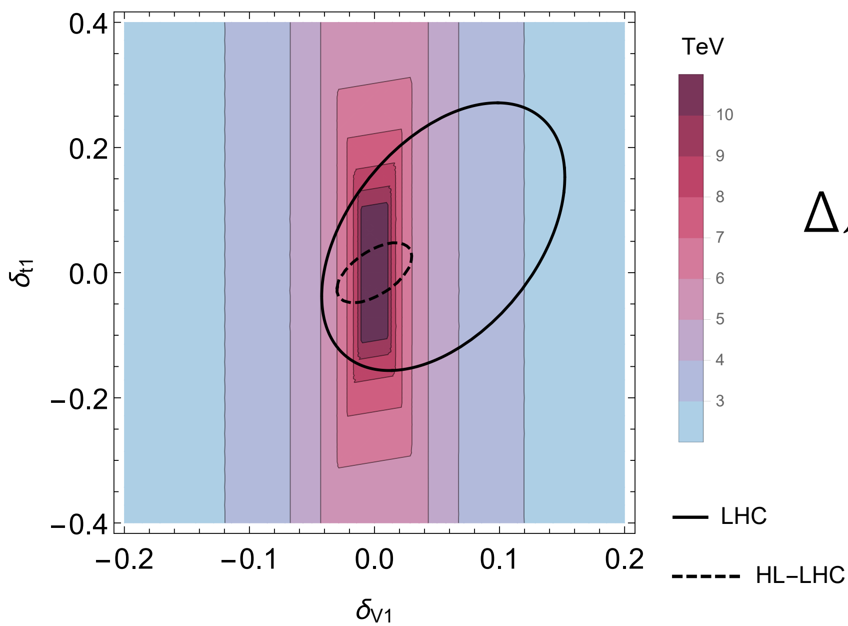

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Abu-Ajamieh, Chang, Chen, ML (2020)

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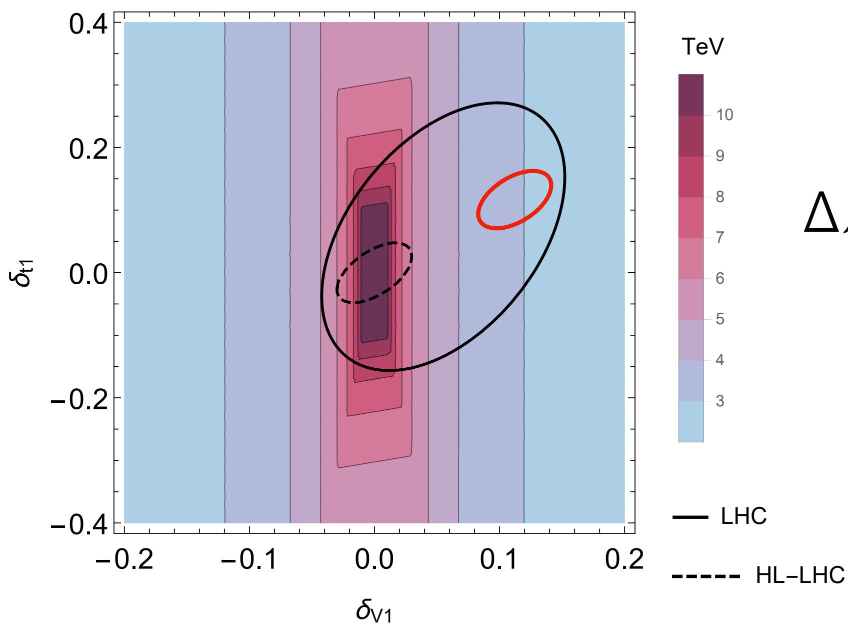

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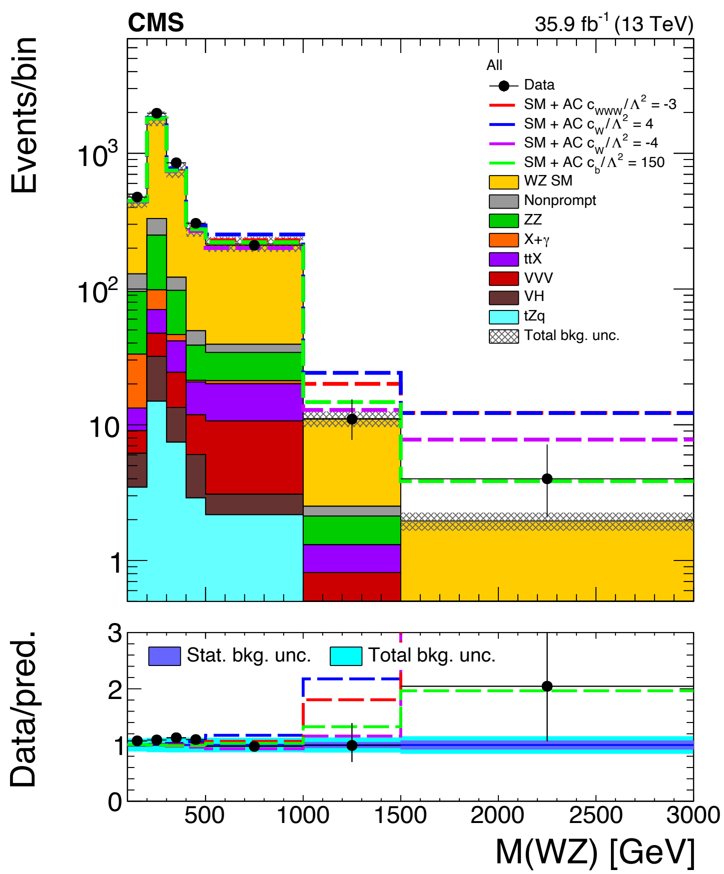
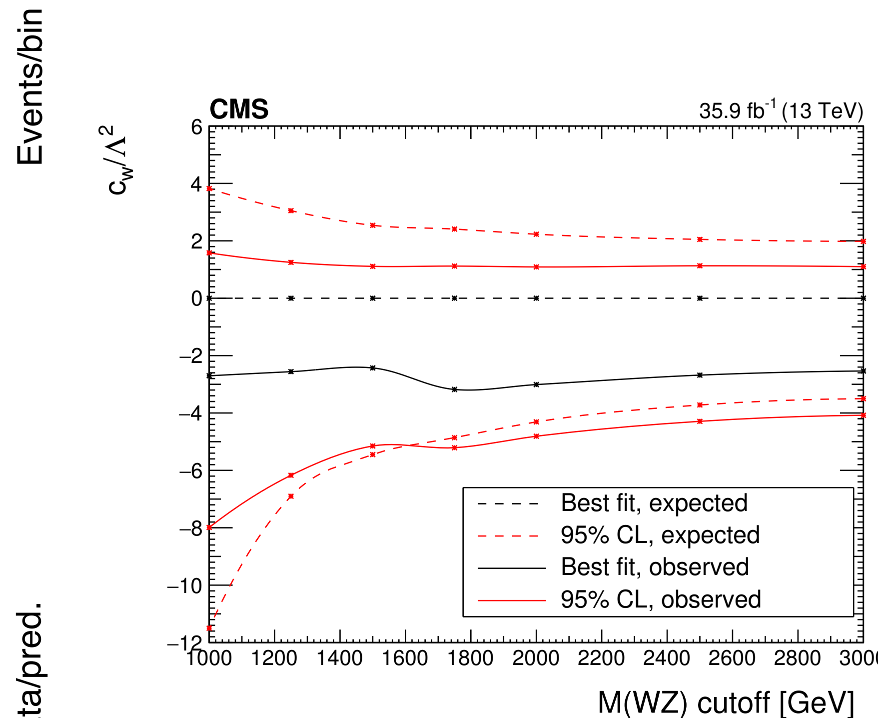
High Energy Signals

Exploit hardness of BSM contribution...

...but beware of breakdown of EFT

CMS-SMP-18-002





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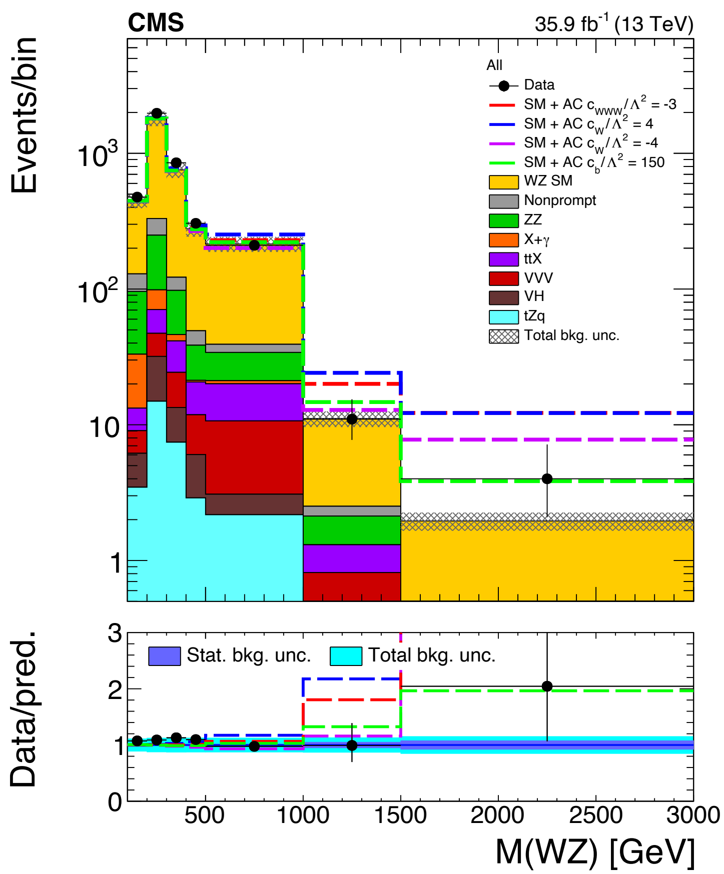
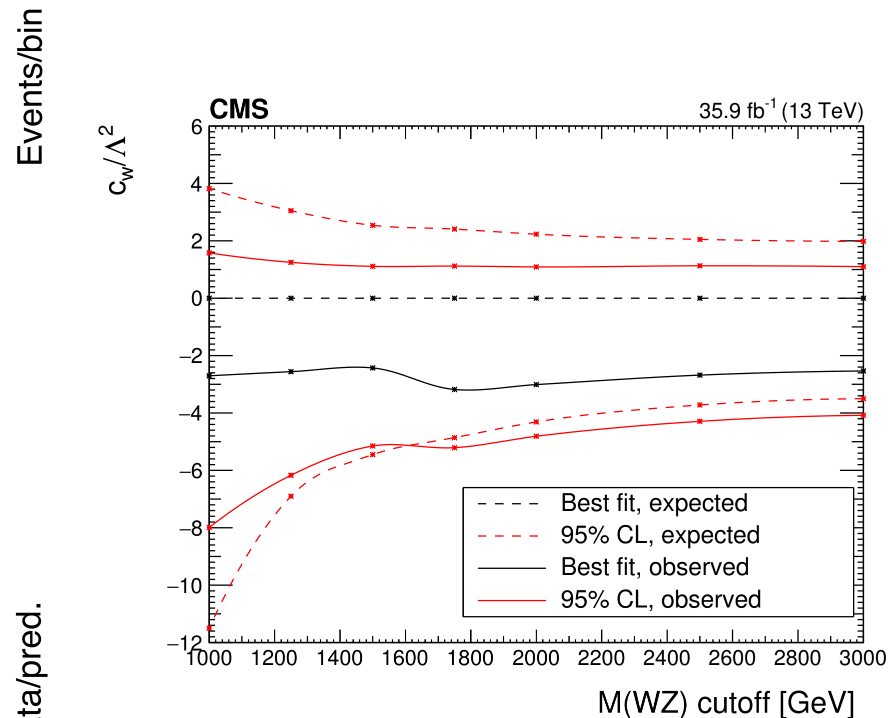
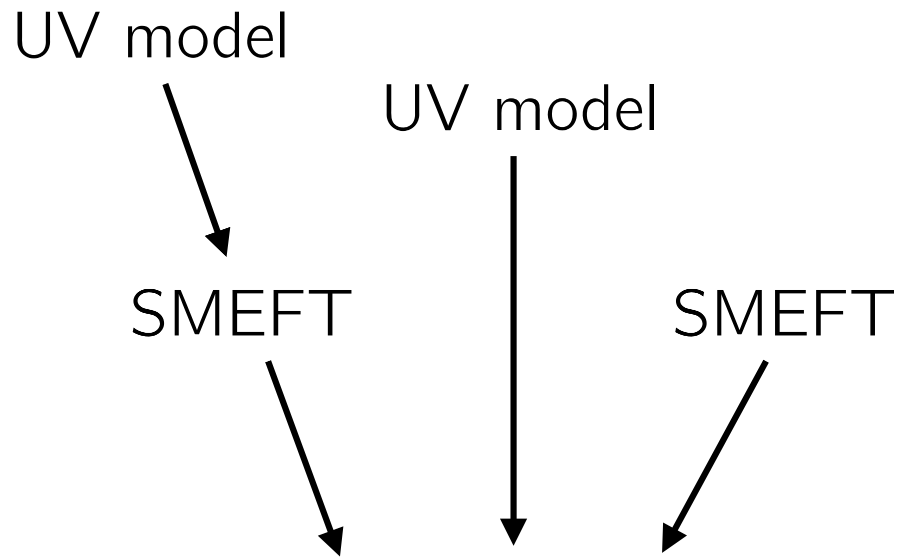




Can we be more systematic?

On-Shell Approach



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}}(\mu = E_{\text{exp}}) + \sum_i g_i(\mu = E_{\text{exp}})\mathcal{O}_i$$

$$\mathcal{O}_i = \text{function of physical fields } W_\mu^\pm, Z_\mu, h, \ldots$$

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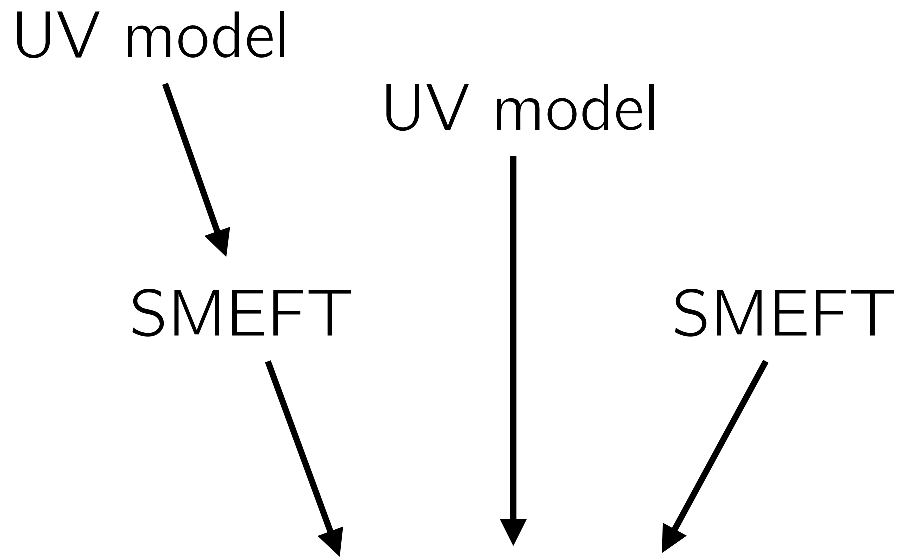

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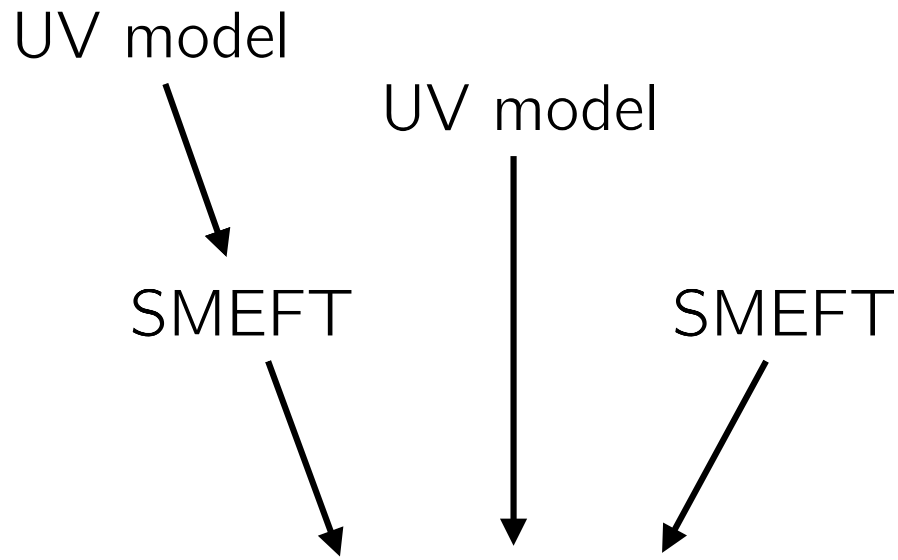

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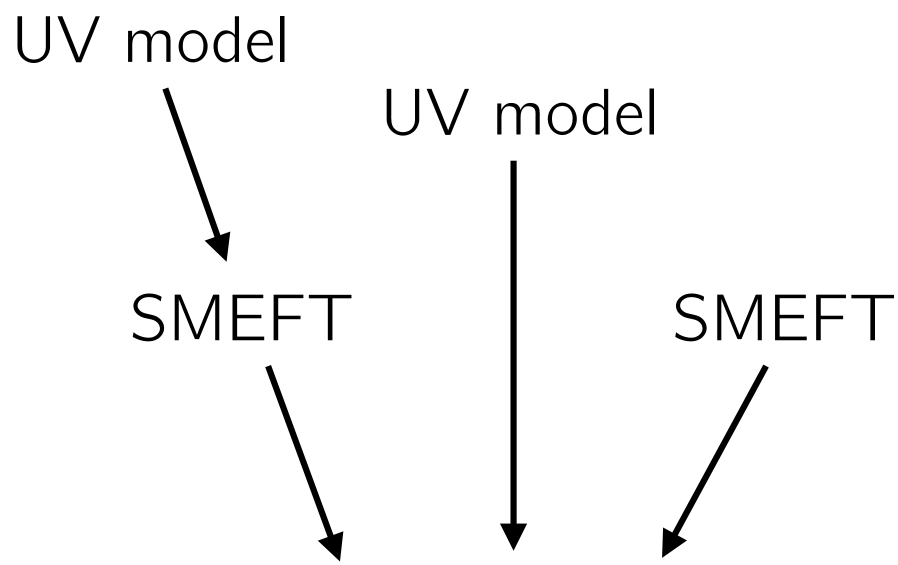

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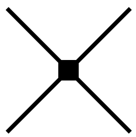
Classify: $\mathcal{O}_i \leftrightarrow$ Feynman rules for on-shell particles

Primary Observables



$$\sum_i g_i \mathcal{O}_i^{(4)} = \sum_\alpha g_\alpha \mathcal{O}_\alpha^{(4)} \left[1 + \frac{c_1}{M^2} s + \frac{c_2}{M^2} t + \frac{c_3}{M^4} s t + \cdots \right]$$

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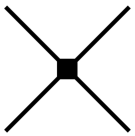

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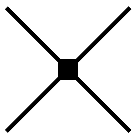

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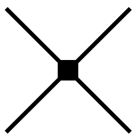

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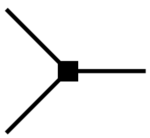

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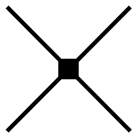

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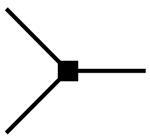

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- There are finitely many primary operators

  G. Durieux, T. Kitahara, C. S. Machado, Y. Shadmi, Y. Weiss, arXiv:2008.09652

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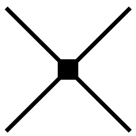

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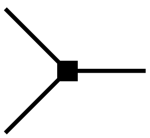

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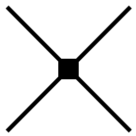

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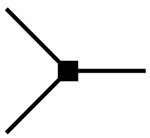

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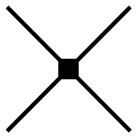

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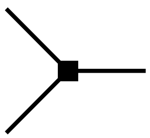

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  In such cases, define “physical primary” to be leading operator

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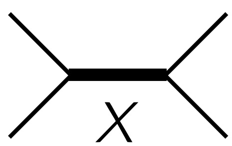

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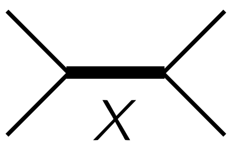

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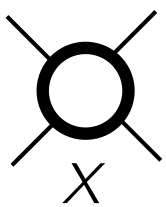

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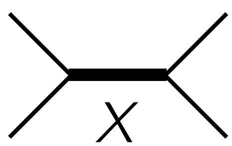

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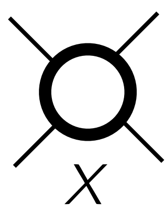

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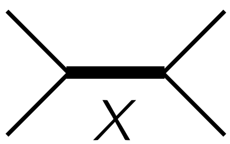

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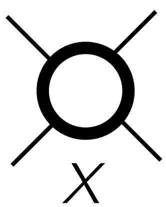

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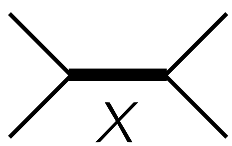

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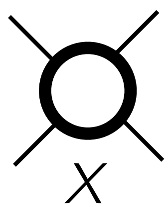

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$M \lesssim E_{\max}(g_\alpha)$

Primary Observables

i	$\mathcal{O}_i^{hZ\bar{f}f}$	CP	$d_{\mathcal{O}_i}$	SMEFT Operator	c Unitarity Bound
1	$hZ^\mu\bar{\psi}_L\gamma_\mu\psi_L$	$+$	5	$i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{Q}_L\gamma^\mu Q_L$	$\frac{0.6}{E_{\rm TeV}^2}, \frac{5}{E_{\rm TeV}^4}$
2	$hZ^\mu\bar{\psi}_R\gamma_\mu\psi_R$	$+$		$i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\bar{u}_R\gamma^\mu u_R$	
3	$hZ^{\mu\nu}\bar{\psi}_L\sigma_{\mu\nu}\psi_R + \text{h.c.}$	$+$	6	$\bar{Q}_L\sigma^{\mu\nu}u_R\sigma^a\widetilde{H}W^a_{\mu\nu} + \text{h.c.}$	$\frac{2}{E_{\rm TeV}^2}, \frac{10}{E_{\rm TeV}^4}$
4	$ih\widetilde{Z}_{\mu\nu}\bar{\psi}_L\sigma^{\mu\nu}\psi_R + \text{h.c.}$	$-$		$i\bar{Q}_L\sigma^{\mu\nu}u_R\sigma^a\widetilde{H}\widetilde{W}^a_{\mu\nu} + \text{h.c.}$	
5	$ihZ^\mu\left(\bar{\psi}_L\overleftrightarrow{\partial}_\mu\psi_R\right) + \text{h.c.}$	$+$	6	$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{Q}_L\overleftrightarrow{D}^\mu u_R\right)\widetilde{H} + \text{h.c.}$	$\frac{0.1}{E_{\rm TeV}^3}, \frac{4}{E_{\rm TeV}^6}$
6	$hZ^\mu\partial_\mu\left(\bar{\psi}_L\psi_R\right) + \text{h.c.}$	$-$		$i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)D^\mu\left(\bar{Q}_L u_R\right)\widetilde{H} + \text{h.c.}$	
7	$ihZ^\mu\partial_\mu\left(\bar{\psi}_L\psi_R\right) + \text{h.c.}$	$+$		$\left(H^\dagger \overleftrightarrow{D}_\mu H\right)D^\mu\left(\bar{Q}_L u_R\right)\widetilde{H} + \text{h.c.}$	
8	$hZ^\mu\left(\bar{\psi}_L\overleftrightarrow{\partial}_\mu\psi_R\right) + \text{h.c.}$	$-$		$i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{Q}_L\overleftrightarrow{D}^\mu u_R\right)\widetilde{H} + \text{h.c.}$	
9	$ih\widetilde{Z}_{\mu\nu}\left(\bar{\psi}_L\gamma^\mu\overleftrightarrow{\partial}^\nu\psi_L\right)$	$+$	7	$i\lvert H\rvert^2\widetilde{W}^{a\mu\nu}\left(\bar{Q}_L\gamma_\mu\sigma^a\overleftrightarrow{D}_\nu Q_L\right)$	$\frac{0.4}{E_{\rm TeV}^3}, \frac{1}{E_{\rm TeV}^4}$
10	$h\widetilde{Z}_{\mu\nu}\partial^\mu\left(\bar{\psi}_L\gamma^\nu\psi_L\right)$	$-$		$\lvert H\rvert^2\widetilde{W}^{a\mu\nu}D_\mu\left(\bar{Q}_L\gamma_\nu\sigma^a Q_L\right)$	
11	$ih\widetilde{Z}_{\mu\nu}\left(\bar{\psi}_R\gamma^\mu\overleftrightarrow{\partial}^\nu\psi_R\right)$	$+$		$i\lvert H\rvert^2\widetilde{B}^{\mu\nu}\left(\bar{u}_R\gamma_\mu\overleftrightarrow{D}_\nu u_R\right)$	
12	$h\widetilde{Z}_{\mu\nu}\partial^\mu\left(\bar{\psi}_R\gamma^\nu\psi_R\right)$	$-$		$\lvert H\rvert^2\widetilde{B}^{\mu\nu}D_\mu\left(\bar{u}_R\gamma_\nu u_R\right)$	

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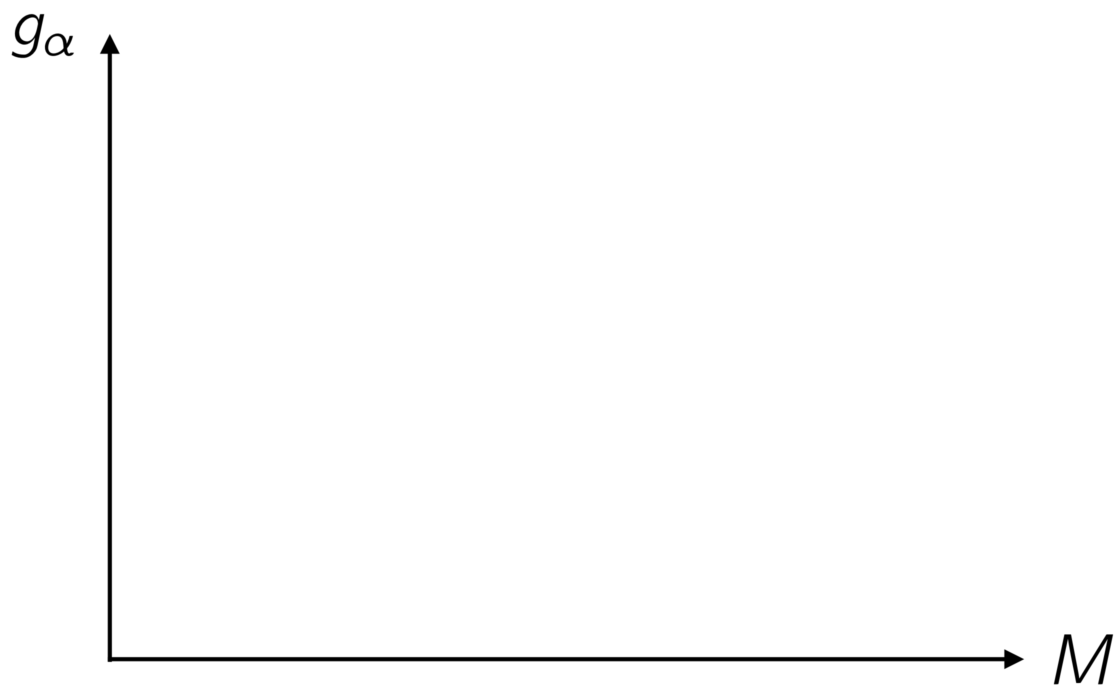
- Statistical error model

$$f_\alpha(x,y) = \sum_{i=1}^{N} c_{\alpha i}\, e_i(x,y)$$

$c_{\alpha i}$ = nuisance parameters $\qquad \langle c_{\alpha i} \rangle = 0, \quad \delta c_{\alpha i} = 1$

$e_i(x,y)$ = basis of shape functions

Constraining Primary Observables



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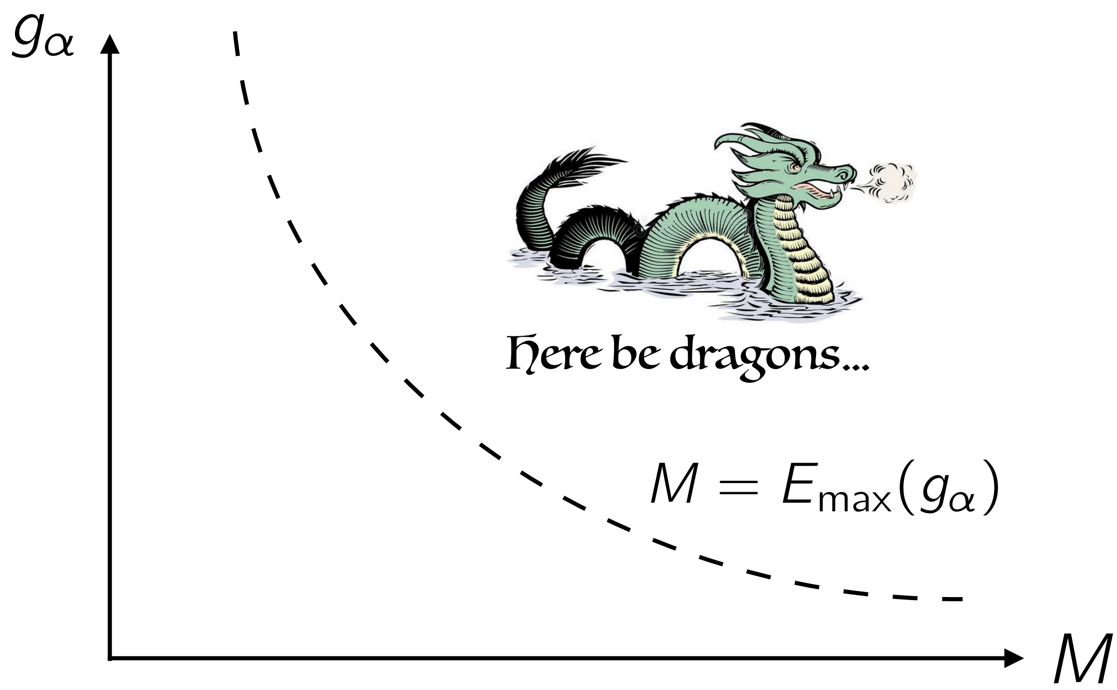

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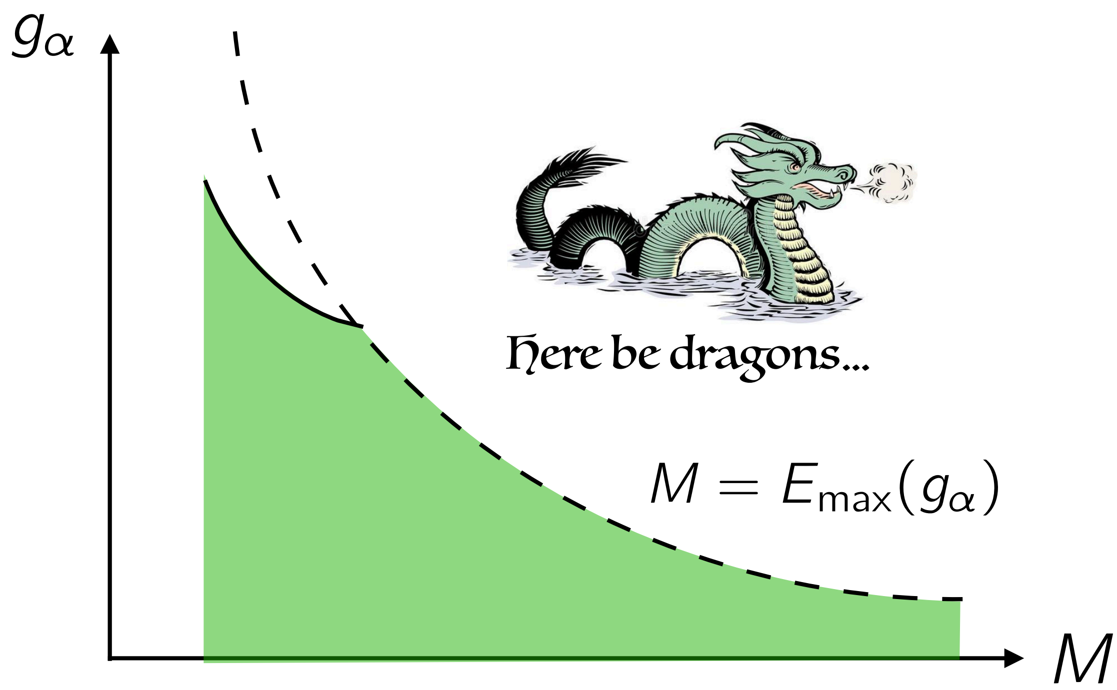

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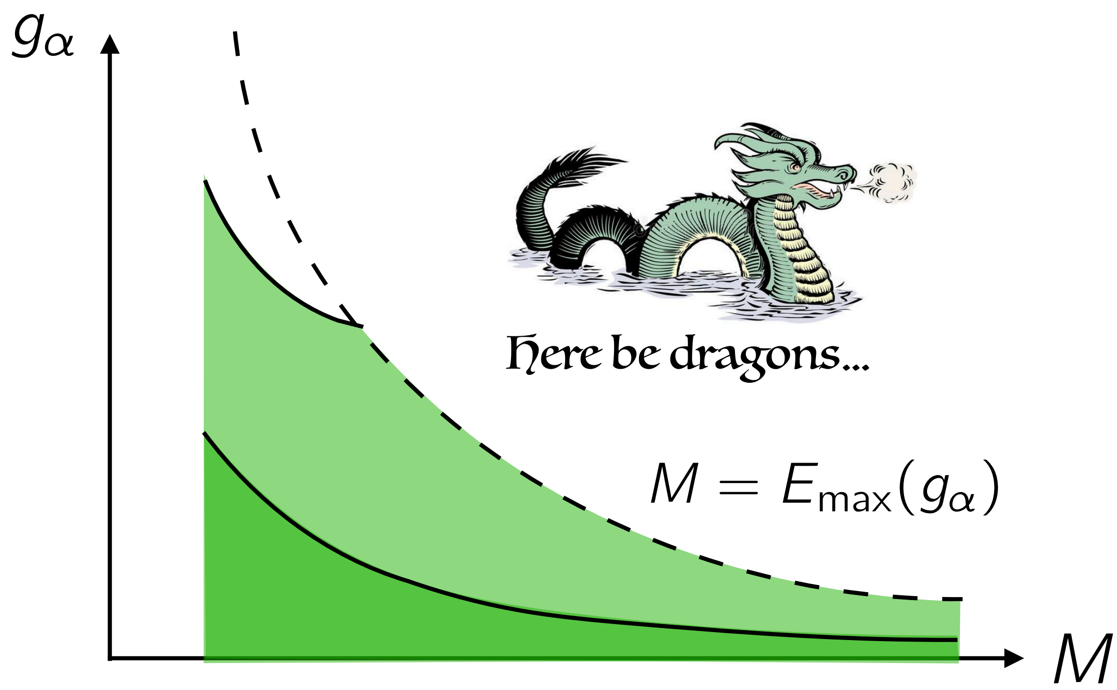

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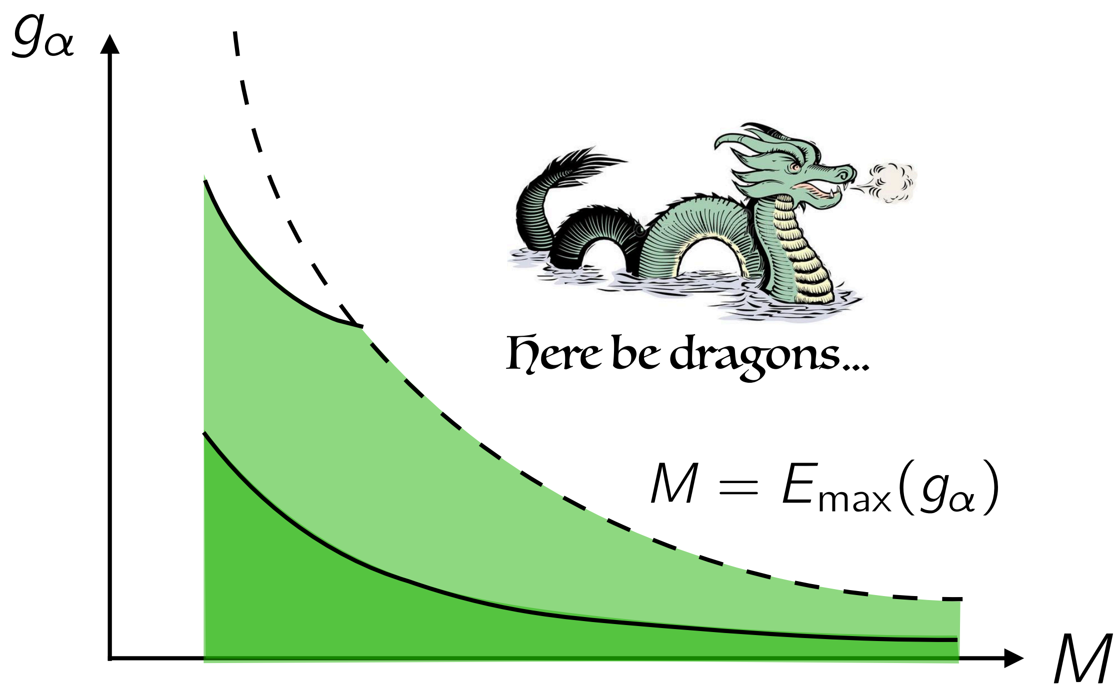

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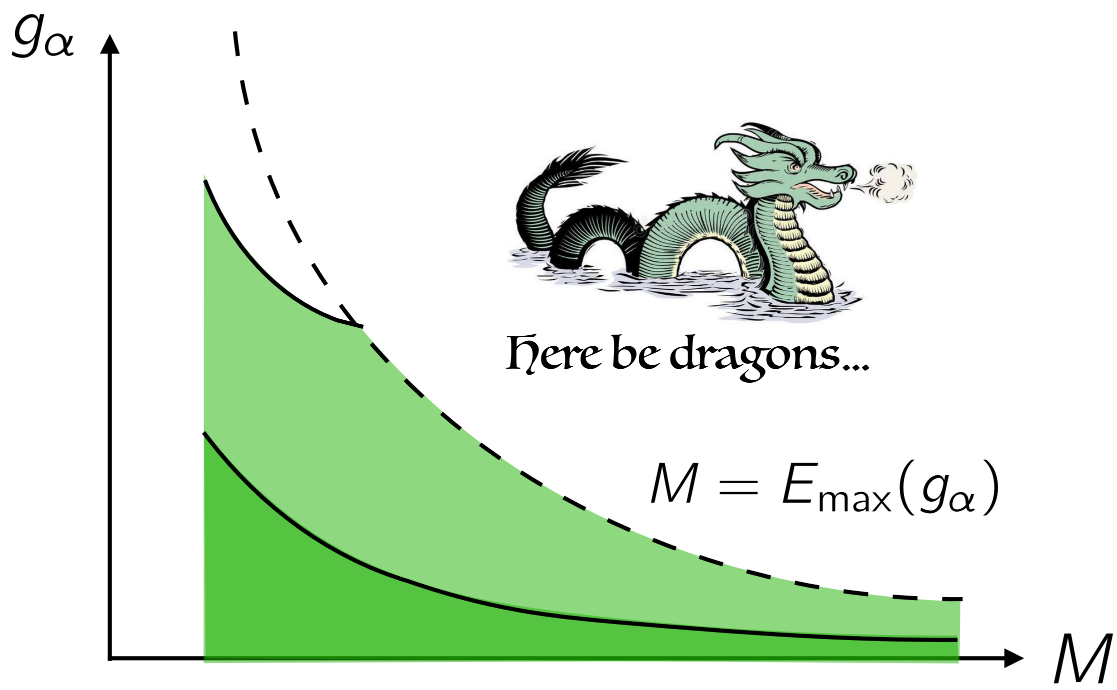

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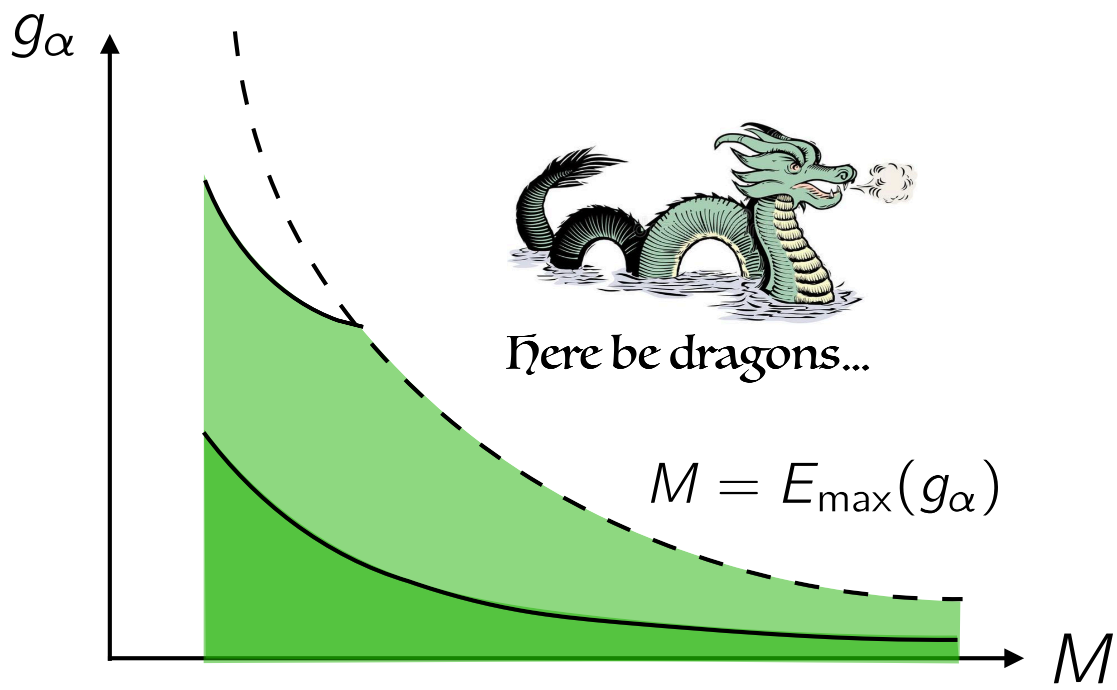

- Allows analyses to be optimized for sensitivity to EFTs
- Can compare/combine different channels
- Constraints can be directly compared to UV models

A Simple Analysis

Work in progress...

$$\Delta\mathcal{L} = i\delta g W_\mu^- \overleftrightarrow{\partial}_\nu W_\mu^+ Z_\nu$$

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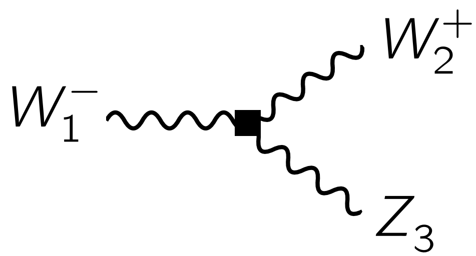

$$= \delta g(\epsilon_1 \cdot \epsilon_2)(p_1 - p_2) \cdot \epsilon_3$$

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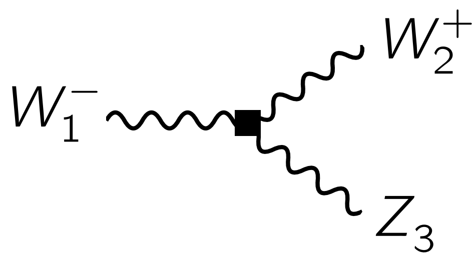

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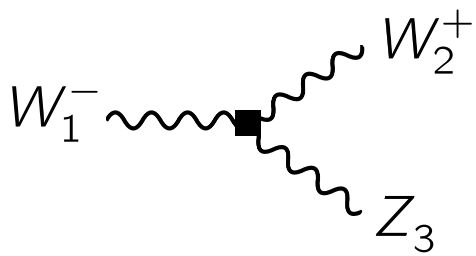

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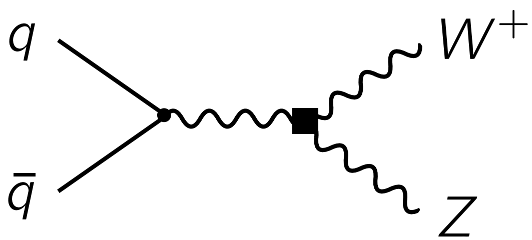

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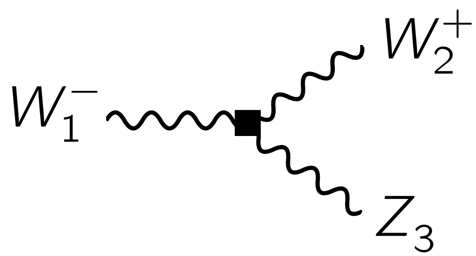

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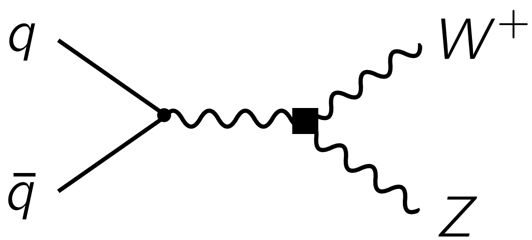

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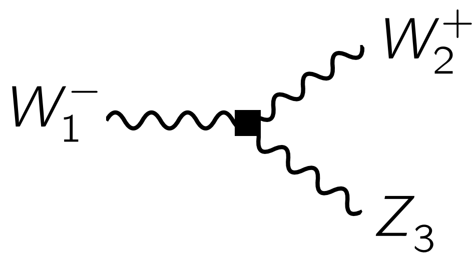

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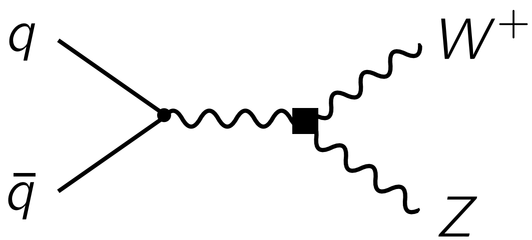

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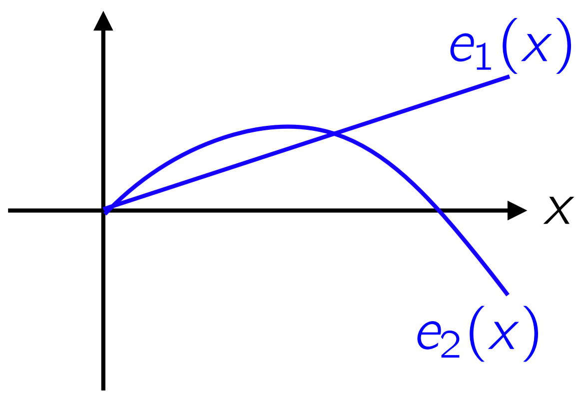

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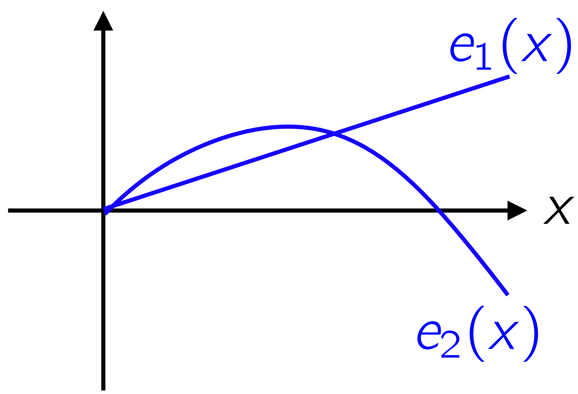

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c_i = nuisance parameters

$$L(\delta g, c) = L_{\rm data}(\delta g)\, L_{\rm prior}(c)$$

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