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QMAP

Matching EFT to LHC

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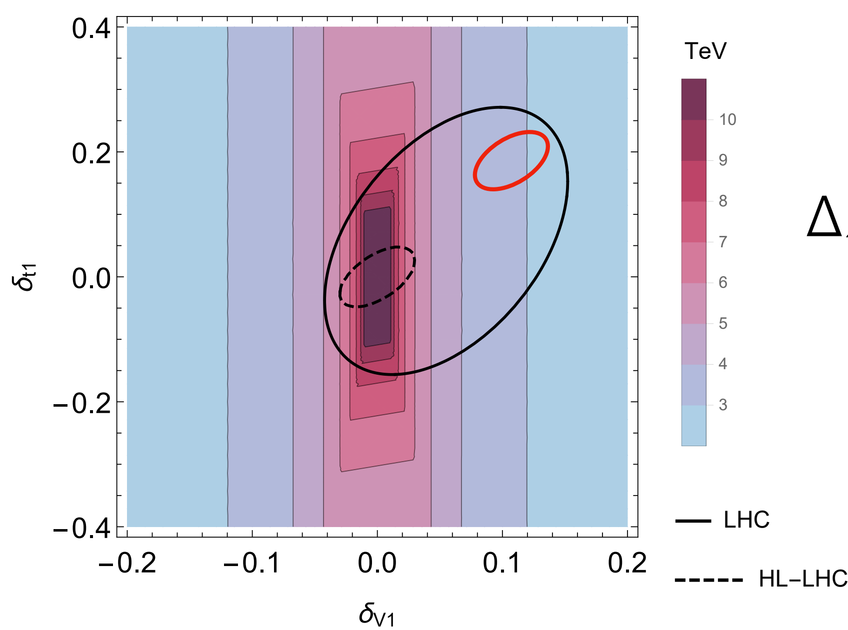
Measurement = Search

- All SM parameters known to 1% (or better)
  $\Rightarrow$ LHC measurement program = search for new physics
- New "no lose" theorem: Any observed deviation from the SM
  $\Rightarrow$ new physics at a known scale (unitarity)
- Scale of new physics is low even for most precise LHC measurements
  $E \lesssim 3$ TeV, precision $\gtrsim 10^{-2}$ (LEP : $E \simeq M_Z$, precision $\sim 10^{-3}$)



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

$$\Delta\mathcal{L} = \delta_{V1}\left(\frac{m_Z^2}{v} hZ^\mu Z_\mu + \frac{2m_W^2}{v} hW^{\mu+}W_\mu^-\right) + \delta_{t1}\frac{m_t}{v} h\bar{t}t$$

Measurement = EFT

- EFT is the natural language for reporting precision measurements
- No ~~sensible~~ agreed-upon methodology for performing measurements when higher-dimension operators are important

CERN-LPCC-2022-01
CERN-LHCEFTWG-2021-002

LHC EFT WG note
Truncation, validity, uncertainties

The truncation of the standard-model effective field theory (SMEFT), its validity and the associated uncertainties have been discussed in a dedicated meeting on January 19, 2021. Answering a call issued beforehand, three proposals were presented: *A*, *B*, and *C*. A preliminary version of the present note summarizing them was written by the editors, submitted for feedback to the proponents, and presented at the May 3 general meeting. Comments from the wider community were collected in an online document. Experimental collaborations provided formal feedback during a second dedicated meeting on June 28. The first version of this summary note was released on January 12, 2022. Proposal D was circulated on May 18 and comments collected, ahead of the May 23 general meeting. Extensive discussions took place with the whole community but no consensus emerged. None of the proposals has been approved or validated. No recommendation is therefore put forward at this time and this note only aims at summarizing the different points raised at meetings. Further work is needed to establish a prescription. In particular, the benchmarking of the different proposals on the working-group fitting exercise has been proposed and discussed.

Framework

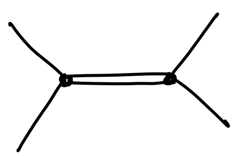
$$\mathcal{M} = \mathcal{M}_{\text{SM}} + \mathcal{M}_{\text{BSM}}$$

Search for one BSM operator at a time

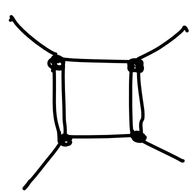
$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + g_{\text{EFT}} \mathcal{O}_{\text{BSM}}$$

EFT breaks down at scale M

$$\mathcal{M}_{\text{BSM}} = g_{\text{EFT}} \hat{\mathcal{M}}_{\text{BSM}} \left[1 + \underbrace{c_1 \frac{s}{M^2} + c_2 \frac{t}{M^2} + \cdots}_{\text{“universal” corrections}} \right]$$



$$= -\frac{g^2}{M^2} \left[1 + \frac{s}{M^2} + \frac{s^2}{M^4} + \cdots \right]$$



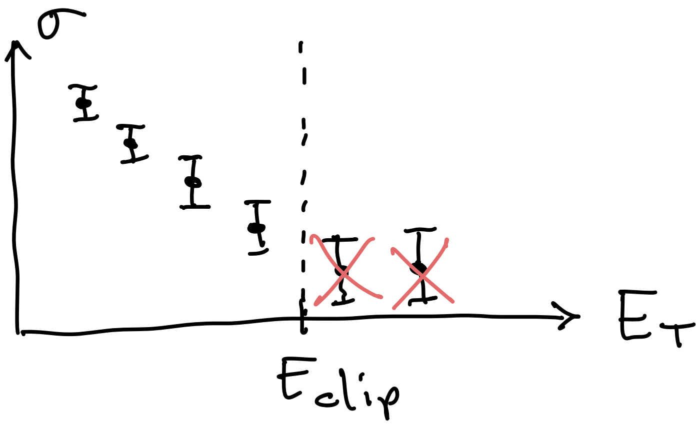
$$= \frac{g^2}{16\pi^2 M^2} \left[1 + c_1 \frac{s}{M^2} + c_2 \frac{t}{M^2} + \cdots \right]$$

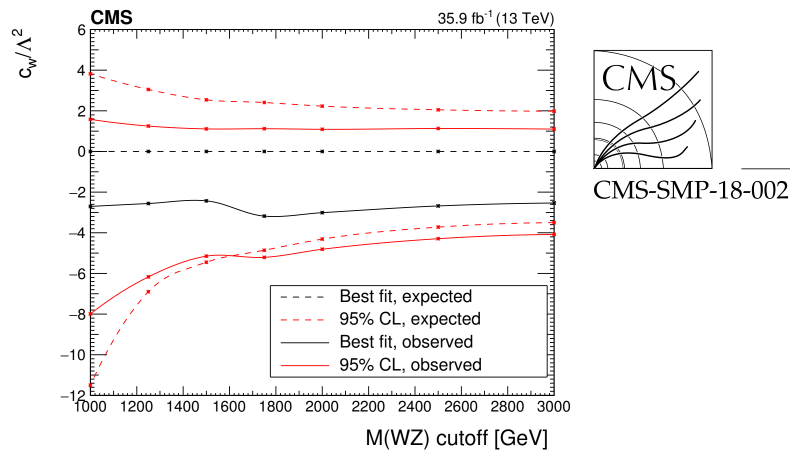
M = mass of heavy particle ⇒ expect $c_1, c_2, \ldots \sim 1$

Data Clipping

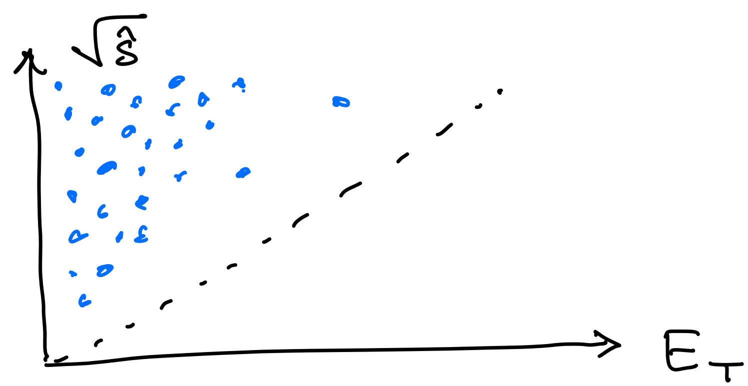
Search must be restricted to the kinematic regime where the EFT is valid

Impose experimental cut, *e.g.* $E_T > E_{\text{clip}}$





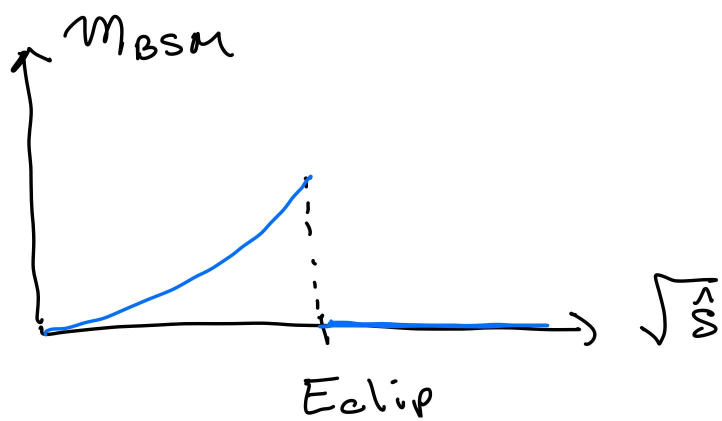
Constraint stable for large E_{clip} $\Rightarrow$ evidence that it is coming from low energy events



- Poor correlation between E_T and $\sqrt{\hat{s}}$
- Relation between E_{clip} and M?
- Treat theory error with experimental cut?

Model Clipping

Turn off BSM amplitude for $\sqrt{\hat{s}} > E_{\text{clip}}$

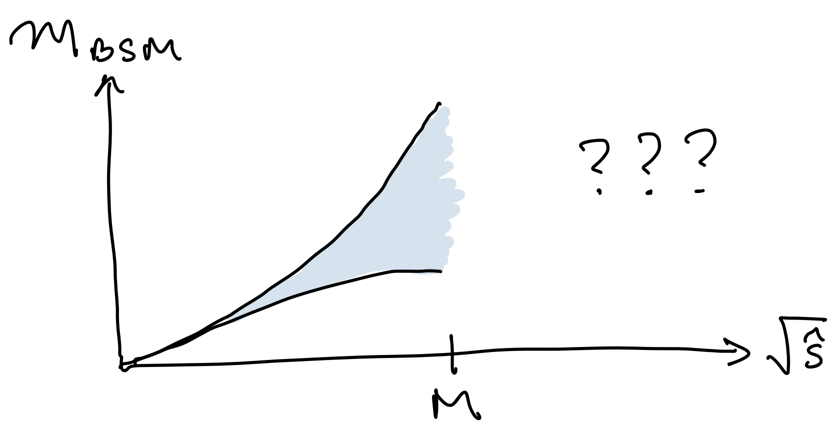


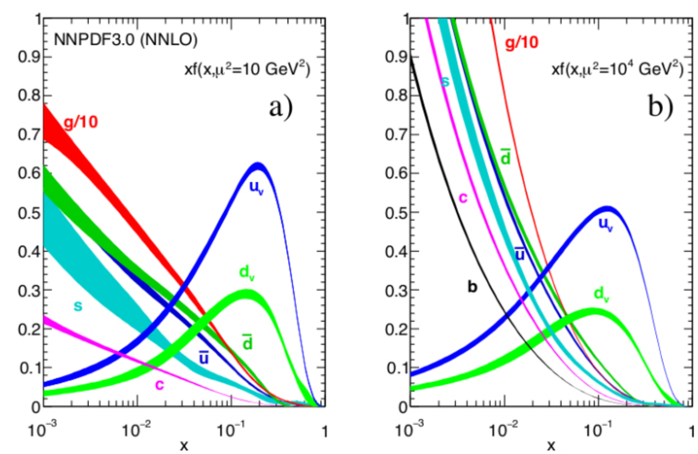
- Unphysical sharp feature at $\sqrt{\hat{s}} = E_{\text{clip}}$
- Relation between E_{clip} and M?

Our Proposal

Perform search in (g_{EFT}, M) plane

Treat higher order corrections as theory uncertainty (nuisance parameters)

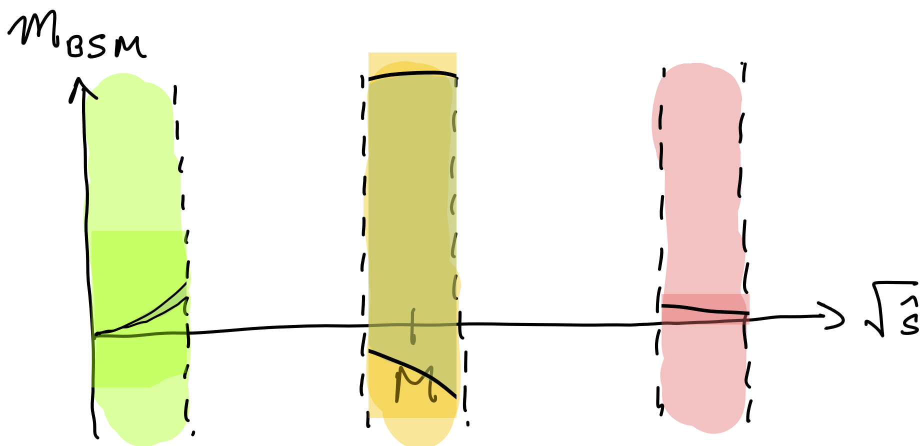




What about events with $\sqrt{\hat{s}} > M$?

A Tale of Three Bins

What should EFT signal model predict?



Predictive new physics | Not predictive | Predictive no new physics

Confidence interval for g_{EFT} from $\mathcal{R} = \dfrac{\mathcal{L}_{\mathrm{SM+BSM}}}{\mathcal{L}_{\mathrm{SM}}}$

$$\mathcal{L}_{\mathrm{SM+BSM}}(\sqrt{\hat{s}} \gg M) \simeq \mathcal{L}_{\mathrm{SM}}(\sqrt{\hat{s}} \gg M)$$

$\Rightarrow$ high energy bin cancels in $\mathcal{R}$

$\Rightarrow$ constraint (or discovery!) of g_{EFT} independent of high energy bin

But Wait…

If there is new physics in the data, the model prediction for the high energy bin is surely wrong.

This will show up in the statistical analysis as a bad fit.

The standard statistical interpretation of excluding $g_{\mathrm{EFT}} = 0$ with poor goodness of fit is that the SM has been ruled out, but the EFT does not describe the data well.

This is indeed the correct interpretation.

If there is significant data in the high energy bin, data clipping may reduce the dependence on the high energy bin, giving a better fit.

In fact, an analysis optimized for our EFT model would throw away the high energy bin.

Form Factors

$$\mathcal{M}_{\text{BSM}} = g_{\text{eff}} \hat{\mathcal{M}}_{\text{BSM}} \frac{f(s/M^2)}{s/M^2} \left[1 + c_1 f(s/M^2) + c_2 f(t/M^2) + \cdots \right]$$

$$x \ll 1 \,:\, f(x) \simeq x \qquad\qquad x \gg 1 \,:\, f(x) \sim \begin{cases} \text{constant} \\ x^{-\alpha} \\ e^{-\alpha x} \end{cases}$$

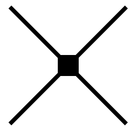
$c_1, c_2, \ldots =$ order 1 niusance parameters

(*e.g* Gaussian with $\langle c_i \rangle = 0$, $\langle c_i^2 \rangle = 1$)

- Generates most general series expansion in Mandelstam variables for $E \ll M$ ☑
- Prediction is 100% uncertain for $E \simeq M$ ☑
- New physics suppressed for $E \gg M$ ☑

How To

- Pick an operator to add to the SM

$\mathcal{O}_{\text{EFT}} \quad \longleftrightarrow \quad$  $= \mathcal{M}_{\text{BSM}}$

$$\mathcal{M}_{\text{BSM}} = g_{\text{EFT}} \underbrace{\hat{\mathcal{M}}_{\text{BSM}}}_{\text{Primary}} \left[1 + \underbrace{c_1 \frac{s}{M^2} + c_2 \frac{t}{M^2} + \cdots}_{\text{Mandelstam descendants}} \right]$$

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

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

Primary Operators

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

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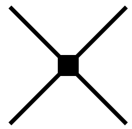
$\mathcal{O}_{\text{EFT}} \quad \longleftrightarrow$  $= \mathcal{M}_{\text{BSM}}$

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Note: space of $c_1, c_2, \ldots$ can be explored by reweighting events

- Design optimized search strategy for EFT model

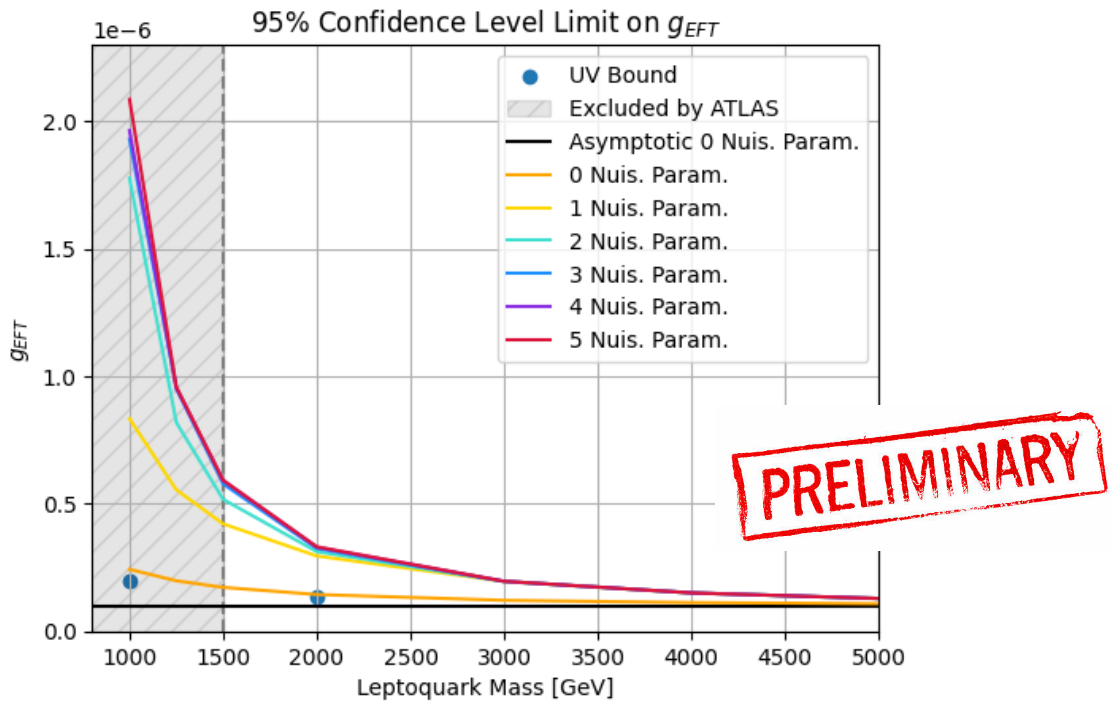
Optimized search for given (g_{EFT}, M) will minimize sensitivity to high energy bin because there is no signal there

Case Study

EFT operator $\bar{b}b\tau^+\tau^-$ motivated by flavor anomalies

Compare to CMS search for UV complete leptoquark model

t-channel resonance $\Rightarrow$ no dramatic feature for $\sqrt{s} > M$



- Convergence for ~ 3 nuisance parameters
- Identify $M = M_{\text{leptoquark}} \Rightarrow$ EFT search is conservative
- EFT constraints $\simeq$ full model for $M \gtrsim 3$ TeV

Conclusions

Proposal for EFT searches that gives a quantitative estimate of theory uncertainty due to higher dimension operators

- Treat as theory uncertainty (nuisance parameters)
- Clear physical interpretation of results in (g_{EFT}, M) plane
- Local in signal space
- Practical
- Let experimentalists be experimentalists!
- Precision measurements are an important part of the LHC legacy

EFT + form factors =