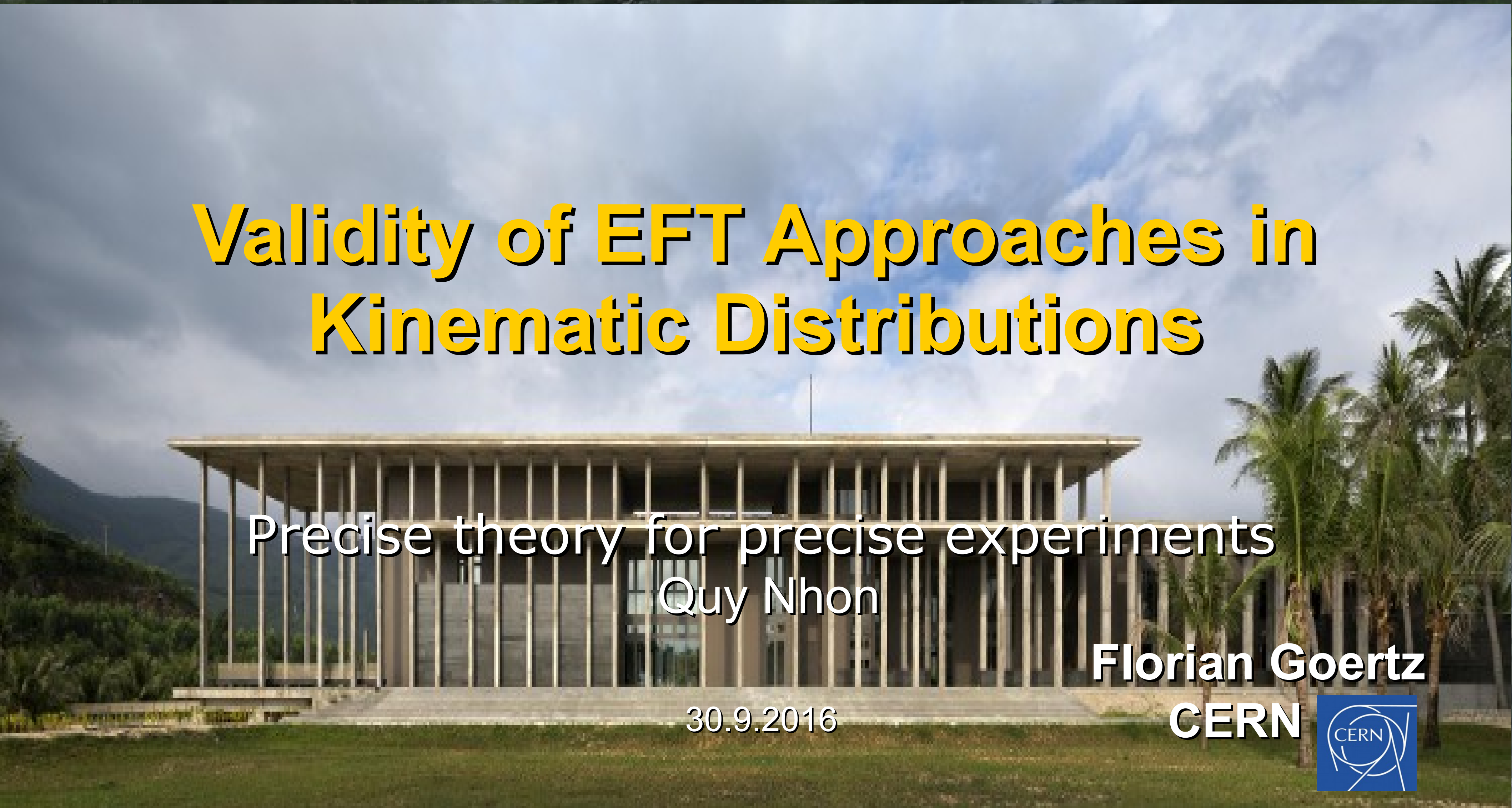


Validity of EFT Approaches in Kinematic Distributions

Precise theory for precise experiments

Quy Nhon

Florian Goertz

CERN

30.9.2016

Contino, Falkowski, FG, Grojean, Riva, JHEP07(2016)144

Effective Field Theory (EFT) Approach to NP

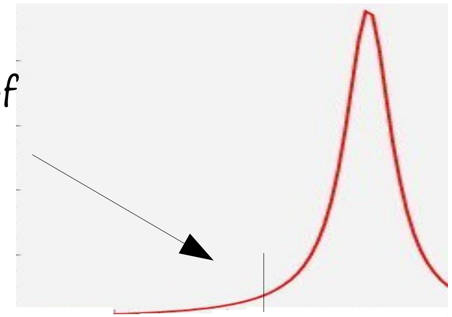
- NP at $\Lambda >> M_{EW}$, not directly accessible → well described by operators with $d[\mathcal{O}] > 4$ {See talks by S. Davidson and D. Marzocca}

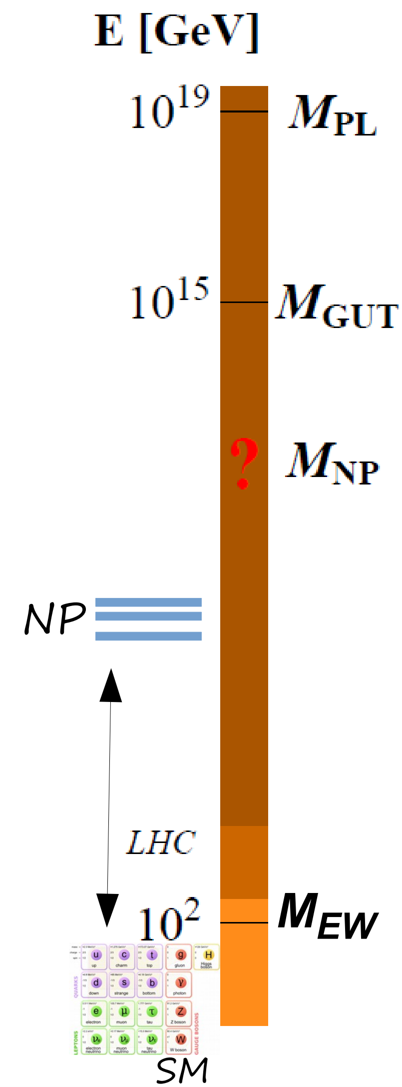
$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{D=6} + \mathcal{O}(E^4/\Lambda^4)$$

local operators = New Physics
SM field content + gauge symmetries

Effects scale like E^2/Λ^2
→ suppressed by mass scale of heavy new physics
[leading: D=6, D=8 in gen. further suppressed → see later]

Probe effects of NP in the tail





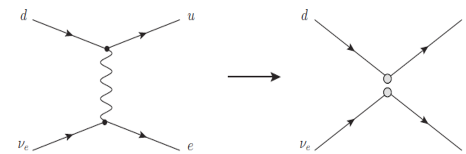
Weinberg, Wilson, Callen, Coleman, Wess, Zumino, ...

SM as IR limit, *expected* to work perfectly well at low E – new fundamental theory takes over at large E

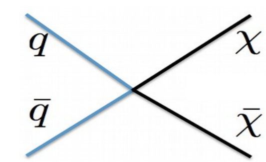
EFT Descriptions in Various Contexts

- *Physics at different scales → EFT description (universal concept): integrate out microscopic dof*

  - SM $\xrightarrow{\int [W, Z \text{ bosons}]}$ Fermi Theory of Weak Interactions

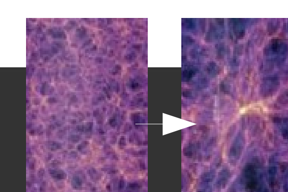


  - Dark Matter Model $\xrightarrow{\int [\text{heavy mediator}]}$ EFT for Dark Matter



  - χPT, SCET, HQET, ...
  - Condensed Matter: BCS Theory $\xrightarrow{\int [e^- \text{exch. phonons}]}$ Ginzburg-Landau , ...
  - Quantum Gravity → GR → Non-Relativistic GR

...



➔ *allows for gradual progress:* Fermi Theory → SM → 'New SM'

Bottom-Up: SM EFT

- Write down full set of non-redundant operators (i.e., basis):

  59 D=6 operators (2499 including full flavor structure)

[assuming B&L conservation]

Buchmuller, Wyler, NPB 268(1986)621–653,
Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884,
Alonso, Jenkins, Manohar, Trott, 1312.2014

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
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$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
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Table 2: Dimension-six operators other than the four-fermion ones.

$L)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
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	$\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
	$\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
	$\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
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	$T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
Q_{lequ}	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
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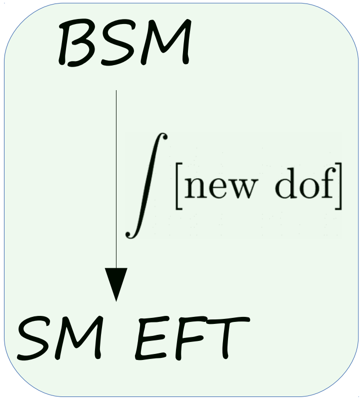

↳ Constrain coefficients: Amplitudes $\mathcal{A} = \mathcal{A}(c_i/\Lambda) \rightarrow$ cross sections, distributions

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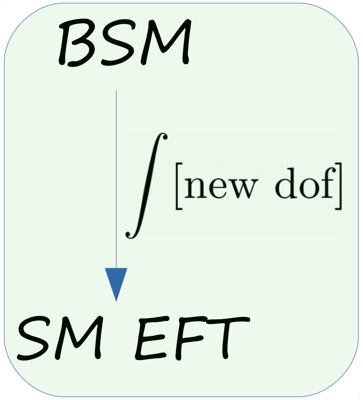

↳ Constrain coefficients: Amplitudes $\mathcal{A} = \mathcal{A}(c_i/\Lambda) \rightarrow$ cross sections, distributions

- In general only a limited subset relevant to leading approx. (e.g. Higgs observables at the LHC)

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_H}{2\Lambda^2}(\partial^\mu |H|^2)^2 - \frac{c_6}{\Lambda^2}\lambda_{\rm SM}|H|^6 - \left(\frac{c_t}{\Lambda^2} y_t |H|^2 \bar Q_L H^c t_R + \frac{c_b}{\Lambda^2} y_b |H|^2 \bar Q_L H b_R + \frac{c_\tau}{\Lambda^2} y_\tau |H|^2 \bar L_L H \tau_R + \text{h.c.}\right) + \frac{\alpha_s c_g}{4\pi\Lambda^2}|H|^2 G^a_{\mu\nu} G_a^{\mu\nu} + \frac{\alpha' c_\gamma}{4\pi\Lambda^2}|H|^2 B_{\mu\nu} B^{\mu\nu}$$

$+\kappa_{WW}$

CP even

For non-linear realization, see Grinstein, Trott 0704.1505
Contino, Grojean, Moretti, Piccinini, Rattazzi 1002.1011

Validity of EFT Description?

- Do not know the (more) fundamental theory (absence of clear s-channel resonance)

→ EFT approach to NP: parametrize BSM physics via coefficients of D>4 operators and constrain them from experimental data

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8} + \ldots$$

→ provide guidance for constructing UV completion

→ EFT Limits can be translated to various models

→ RG Evolution

Elias-Miro, Grojean, Gupta, Marzocca, 1312.2928; Grojean, Jenkins, Manohar, Trott, 1301.2588;
Elias-Miro, Espinosa, Masso, Pomarol, 1302.5661, 1308.1879; Jenkins, Manohar, Trott, 1308.2627, 1310.4838;
Alonso, Jenkins, Manohar, Trott, 1312.2014, 1409.0868;

Could have several heavy masses M_k, actually $c_i/\Lambda^2 \to C_i(M_k, g_k)$

Validity of EFT Description?

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8} + \ldots$$

→ constraints on $C_i^{(D)}$ can be set 'without further assumptions'

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→ constraints on $C_i^{(D)}$ can be set 'without further assumptions'

- When is such a constraint meaningful/consistent in general?
- When is it appropriate to truncate at D=6? When can higher terms (D=8) affect limits on D=6 coefficients?

➡ *Interpretation requires assumptions*

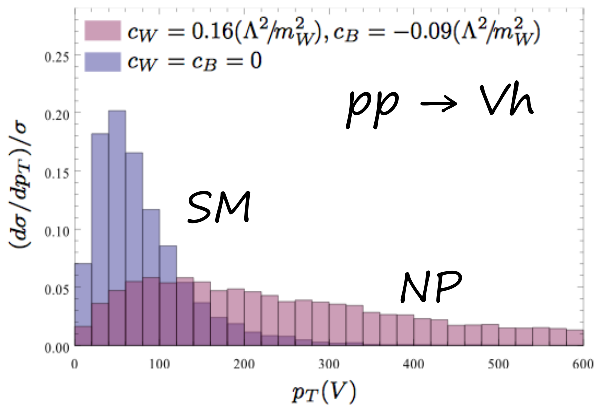
Validity of EFT Description?

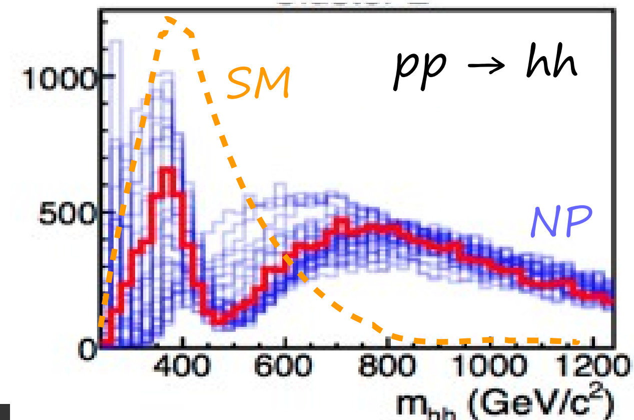
Experimental constraints: $C_i < \delta_i^{\exp}(M_{\rm cut})$

- Depend on upper value allowed for kinematic variables that set scale of process = $M_{\rm cut}$
- In some cases fixed by kinematics: on-shell Higgs decays, e+e- collisions

2→2 at LHC (WW, hV, hj, hh, ...): $M_{\rm cut}$ in general not fixed!

- Large E is just interesting range where pronounced sensitivity to NP is expected





Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320, ...

Kinematic distributions

Carvalho, Dall''Osso, Dorigo, FG, Gottardo, Tosi, 1507.02245

Azatov, Contino, Panico, Son, 1502.00539

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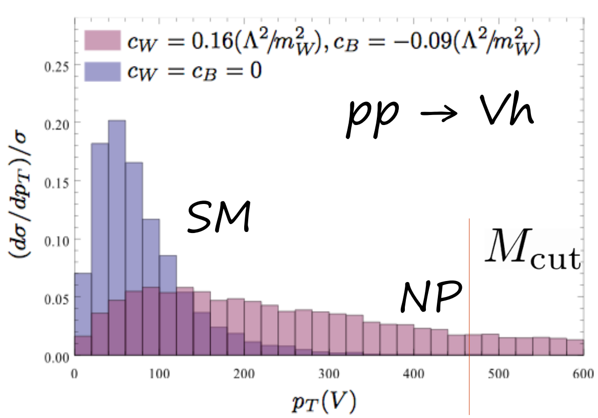

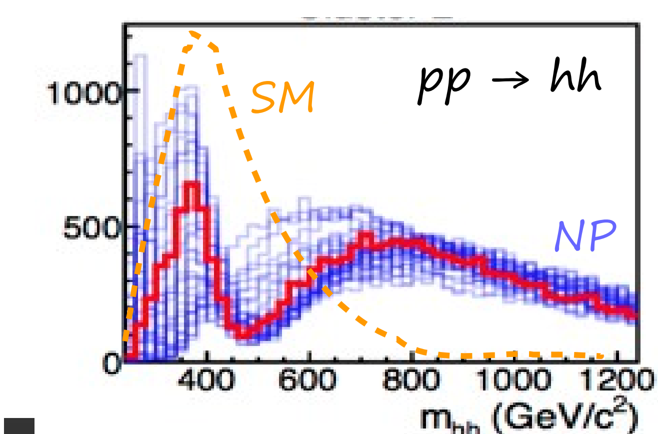

Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320, ...

Kinematic distributions

Carvalho, Dall''Osso, Dorigo, FG, Gottardo, Tosi, 1507.02245

Azatov, Contino, Panico, Son, 1502.00539

Validity of EFT Description?

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i \mathcal{O}_i^{D=6} + \mathcal{O}(E^4/\Lambda^4)$$

- Expansion only valid if scales E probed are smaller than mass of heavy states – if denoted collectively by Λ: $C_i \to c_i/\Lambda^2$ → E<<Λ
- Measurements only constrain $C_i(M_k, g_k)$, not NP scale Λ itself

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↳ Assessing validity requires (broad) assumptions about underlying UV theory → some degree of model dependence:

Since don't know Λ (i.e. heavy masses) → Experiments should allow for broadest range of interpretations → give results for various cutoffs $E < M_{\rm cut}$

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↓

Quantify EFT uncertainty: missing terms of $O(E^4/\Lambda^4)$

[here and in following truncate at D=6]

Necessity of Power Counting

$$\mathcal{L} = \mathcal{L}_{\rm SM}^{D\,\leq\,4} + \sum C_i^{(6)} \mathcal{O}_i^{D=6} + \sum C_i^{(8)} \mathcal{O}_i^{D=8} + \ldots$$

* Note that $\mathrm{C}_i^{(D)} \sim \frac{(\text{coupling})^{n_i - 2}}{(\text{high mass scale})^{D-4}}$, n_i = #fields

$$\mathcal{O}_1 = \bar{e}_L \gamma_\rho \nu_L^e \; \bar{\nu}_L^\mu \gamma_\rho \mu_L$$

↓ n=4

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* Assume power counting:
  one scale Λ + one coupling g_* → $C_i^{(6)} \sim g_*^{n_i-2}/\Lambda^2$

→ Bounds $\frac{c_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(M_{\rm cut})$ → bound on Λ depends on coupling strength g_* → validity

→ can assess their validity

Luty, ph/9706235
Cohen, Kaplan, Nelson, ph/9706275
Giudice, Grojean, Pomarol, Rattazzi, ph/0703164

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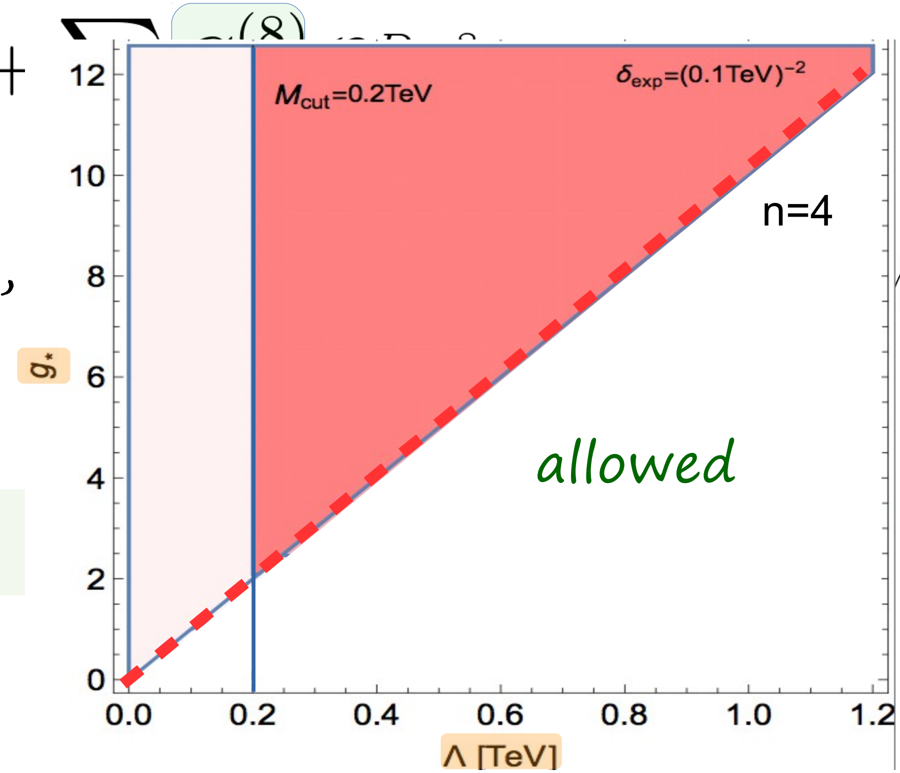

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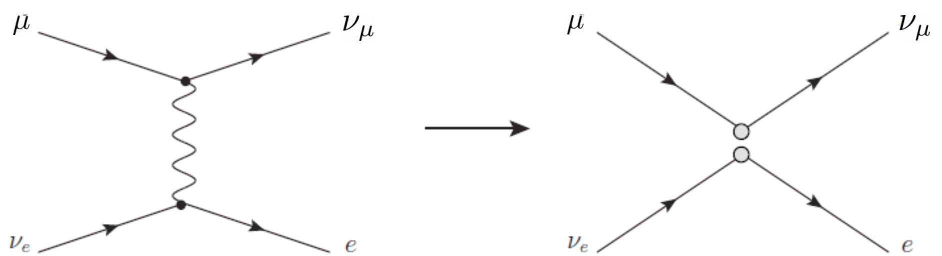
Well-Known Example: Fermi Theory of Weak Interactions



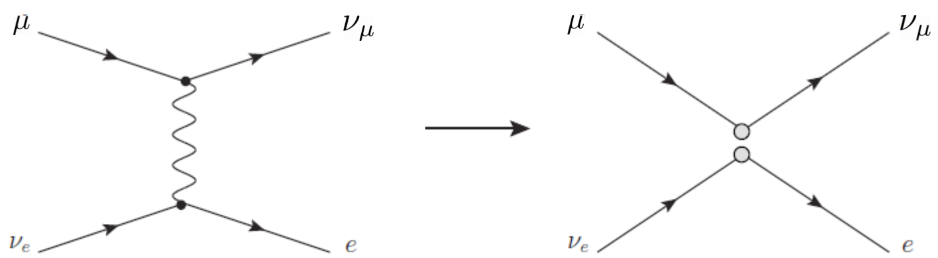
$$\mathcal{L}_{\rm eff} \supset \frac{c_1}{\Lambda^2} \underbrace{(\bar{e}\gamma_\rho P_L \nu_e)(\bar{\nu}_\mu \gamma_\rho P_L \mu)}_{\mathcal{O}_1} + \text{h.c.}\,, \qquad \frac{c_1}{\Lambda^2} = -\frac{g^2/2}{m_W^2} = -\frac{2}{v^2}$$

↳ Describes muon decay $\mu \to e\nu\nu$, inelastic scattering $\nu e \to \nu\mu$, ...

- From low energy measurement (muon decay) no identification $c_1 = -g^2/2 \sim -0.2; \quad \Lambda = m_W \sim 80\,\text{GeV}$ possible, only constrain ratio

$$c_1/\Lambda^2 = -2\sqrt{2}G_F \sim -3.3 \times 10^{-5}\,\text{GeV}^{-2}$$

Well-Known Example: Fermi Theory of Weak Interactions



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$$c_1/\Lambda^2 = -g^2/2m_W^2 \sim -3.3 \times 10^{-5}\,\text{GeV}^{-2}$$

Assumption for g	$\Lambda = m_W$
4π	1.5 TeV
1	123 GeV
10^{-3}	123 MeV

$\sim m_\mu \rightarrow$ EFT validity

Power Counting $\rightarrow$ Validity of Bounds

* Chosing $M_{\rm cut} = \kappa\Lambda;\ \kappa \in [0,1]$ allows to set bounds in (g_*, Λ) plane, automatically consistent with the EFT:

$$\frac{c_i^{(6)}(g_*)}{\Lambda^2} < \delta_i^{\rm exp}(\kappa\Lambda)$$

For each Λ derive bound on $c_i^{(6)}(g_*)$, employing only data below $M_{\rm cut} = \kappa\Lambda;\ \kappa \in [0,1]$

* $\kappa^2 = \dfrac{M_{\rm cut}^2}{\Lambda^2}$: tolerated (naive) error due to neglecting higher-derivative operators $\longrightarrow$ see later

See also Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320; Greljo, Isidori, Lindert, Marzocca, 1512.06135; Azatov, Contino, Panico, Son, 1502.00539; Berthier,Trott, 1502.02570, 1508.05060; Aguilar-Saavedra, Perez-Victoria, 1103.2765; Englert, Spannowsky, 1408.5147 Abdallah et al., 1409.2893; Racco, Wulzer, Zwirner, 1502.04701

Power Counting → EFT Error

* In general: (neglected) D=8 operators contributing to the same vertex as D=6 operators need to have same field content after EWSB

.

→ additional derivatives or Higgs fields → suppressed by

$$\kappa_E^2 = \left(\frac{E}{\Lambda}\right)^2 \quad \text{or} \quad \kappa_v^2 = \left(\frac{g_* v}{\Lambda}\right)^2$$

e.g. : $|H|^2 \bar{Q}_L H d_R$

→ relative error in determination of $C_i^{(6)}$ $(E \to M_{\mathrm{cut}})$

model dependent and should be reported separately from standard perturbative errors (scale variation) and pdf errors

Power Counting → EFT Error

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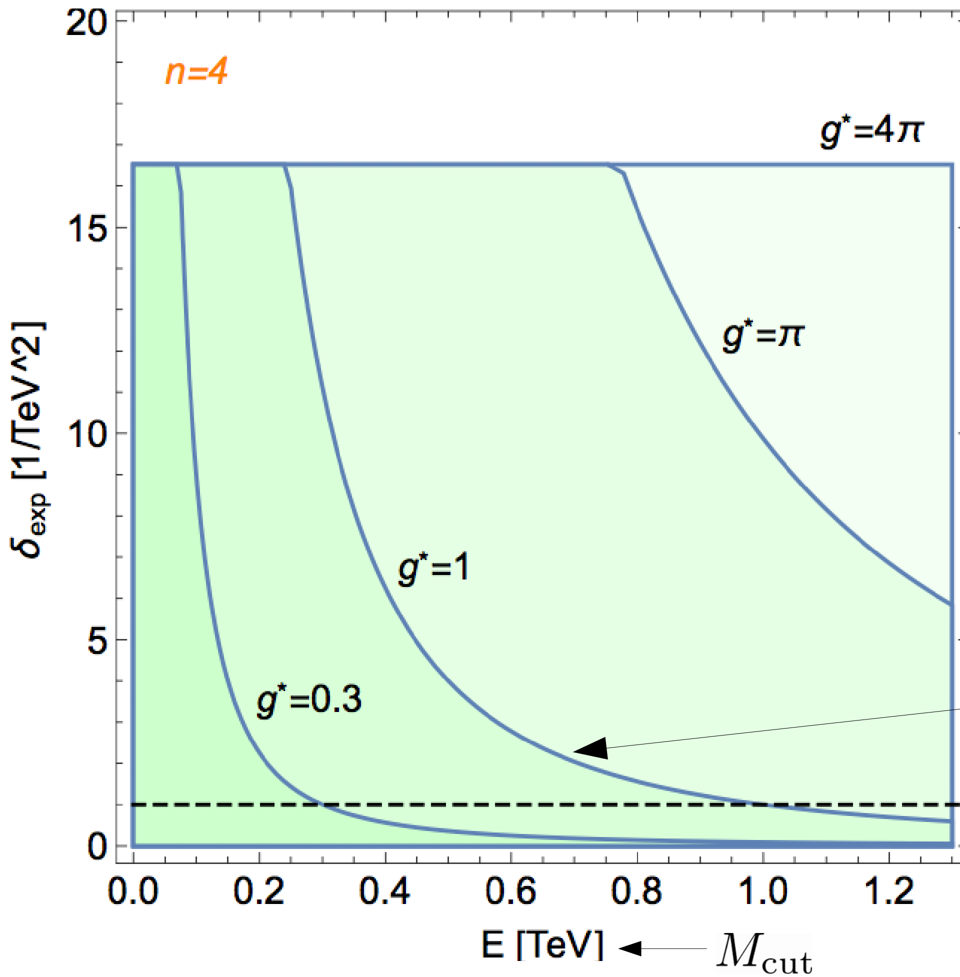
$$\kappa_E^2 = \left(\frac{E}{\Lambda}\right)^2 \quad \text{or} \quad \kappa_v^2 = \left(\frac{g_* v}{\Lambda}\right)^2$$

- Can trade $\Lambda \to \delta_i^{\text{exp}}(M_{\text{cut}})$ and address how accurate $C_i^{(6)}$ needs to be constrained (for given M_{cut}) in order for the bound to be consistent within the EFT $(\to \kappa_i < 1)$

$$\kappa_E^2 \lesssim \frac{M_{\text{cut}}^2}{g_*^2}\,\delta^{\text{exp}}(M_{\text{cut}})\,,\ \kappa_v^2 \lesssim v^2\,\delta^{\text{exp}}(M_{\text{cut}}) \quad \to \quad \delta^{\text{exp}} < \min(g_*^2/M_{\text{cut}}^2, 1/v^2)$$

Assume n_i=4

Accuracy Required for Consistent Bound



$\delta^{\rm exp} < \min(g_*^2/M_{\rm cut}^2, 1/v^2)$

$M_{\rm cut}$

Stronger constraints at fixed $M_{\rm cut}$ → validity range extended to smaller g*

'Illustrative' plot: for large $M_{\rm cut}$, $\delta^{\rm exp}$ (neglected) quadratic D=6 terms become relevant

Remark on Importance of D=8 Operators

- In general D=8 contributions suppressed, as discussed before, however can become important (while still EFT converges) in case

  1) Symmetry suppressing D=6 operator but not D=8 contribution
  (e.g. shift symmetry suppressing $|H|^2 G^a_{\mu\nu} G^{a,\mu\nu}$)

  2) Zero at leading order:
  Corrections appearing first at D=8 level without symmetry reason
  (e.g. s-channel production of neutral gauge-boson pairs)

  3) Selection Rules inherited from UV dynamics
  (e.g. light Dilaton coupling to D=4 stress-energy tensor)

  4) Fine Tuning

* Loop/NLO corrections including D=6 operators? Important in case weakly constrained coefficient enters beyond LO in well-measured quantity (while tree-level correction small), or where large SM k-factors!

See also: Giudice, Grojean, Pomarol, Rattazzi, ph/0703164; Liu, Pomarol, Rattazzi, Riva, 1603.03064;
Azatov, Contino, Panico, Son, 1502.00539; Degrande, 1308.6323; Azatov, Contino, Machado, Riva, 1607.05236

Explicit Example of Limit-Setting Procedure

- Consider $q\bar{q} \to Vh$ in Vector-Triplet Model

$$\mathcal{L} \supset i g_H \tilde{V}^i_\mu H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q \tilde{V}^i_\mu \bar{q}_L \gamma_\mu \sigma^i q_L$$

Integrate out $\tilde{V}$

$$\mathcal{L} \supset -\frac{1}{2M_V^2}\left(i g_H H^\dagger \sigma^i \overleftrightarrow{D}_\mu H + g_q \bar{q}_L \gamma_\mu \sigma^i q_L\right)^2$$

EWSB

$$\mathcal{L} \supset \frac{h}{v}\left(\delta c_z m_Z^2 Z_\mu Z_\mu + 2\sqrt{g_L^2 + g_Y^2} Z_\mu \sum_{f=u,d,e,\nu} \delta g_L^{Zf} \bar{f}\bar{\sigma}_\mu f\right) \quad \delta c_z = -\frac{3v^2}{2M_V^2} g_H^2, \quad [\delta g_L^{Zu}]_{11} = -[\delta g_L^{Zd}]_{11} = -\frac{v^2}{2M_V^2} g_H g_q .$$

- Corrects $q\bar{q} \to Zh$ (as well as $q\bar{q} \to Wh$)
- Amplitude for longitudinal V grows as square of partonic COM energy

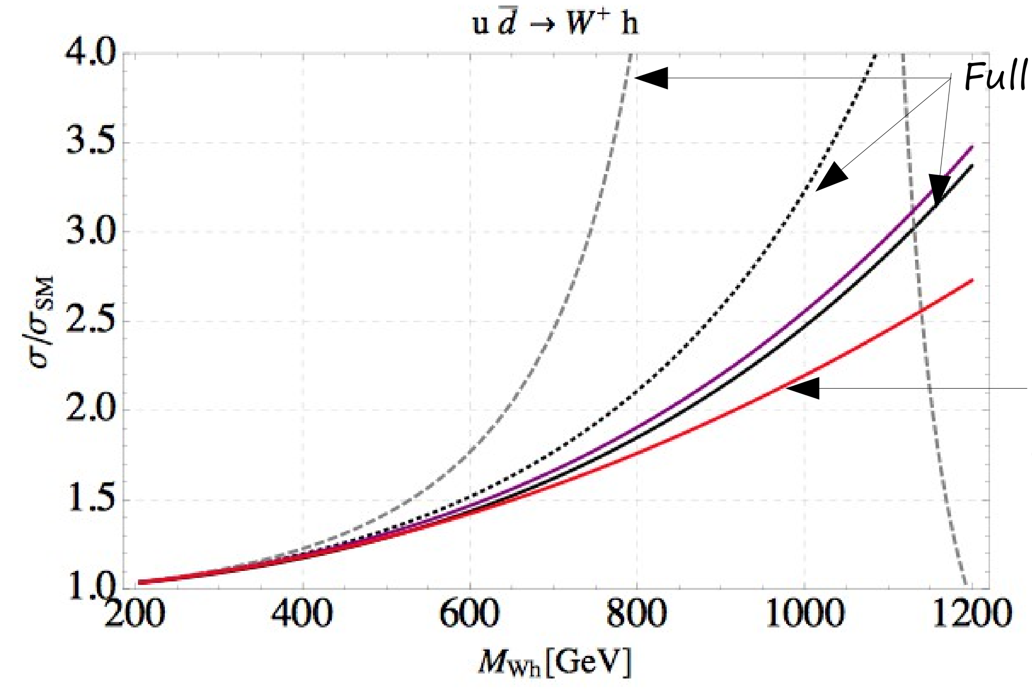
→ important effects at large $s = M_{Wh}^2$ ➡ EFT validity?

See also Biekotter, Knochel, Kramer, Liu. Riva, 1406.7320

Consider 3 Scenarios

- **Strongly coupled:** $M_V = 7$ TeV, $g_H = -g_q = 1.75$
- **Moderately coupled:** $M_V = 2$ TeV, $g_H = -g_q = 0.5$
- **Weakly coupled:** $M_V = 1$ TeV, $g_H = -g_q = 0.25$

- Lead to same effective coefficients, however vastly different range of EFT validity



Full model (weakly → strongly)

Starts to deviate later!

Linear EFT
(+quadratic terms: purple)

Hypothetical Measurement of $\sigma(pp \to W^+ h)$

M_{Wh}[TeV]	0.5	1	1.5	2	2.5	3
$\sigma/\sigma_{\rm SM}$	1 ± 1.2	1 ± 1.0	1 ± 0.8	1 ± 1.2	1 ± 1.6	1 ± 3.0

95% CL bounds

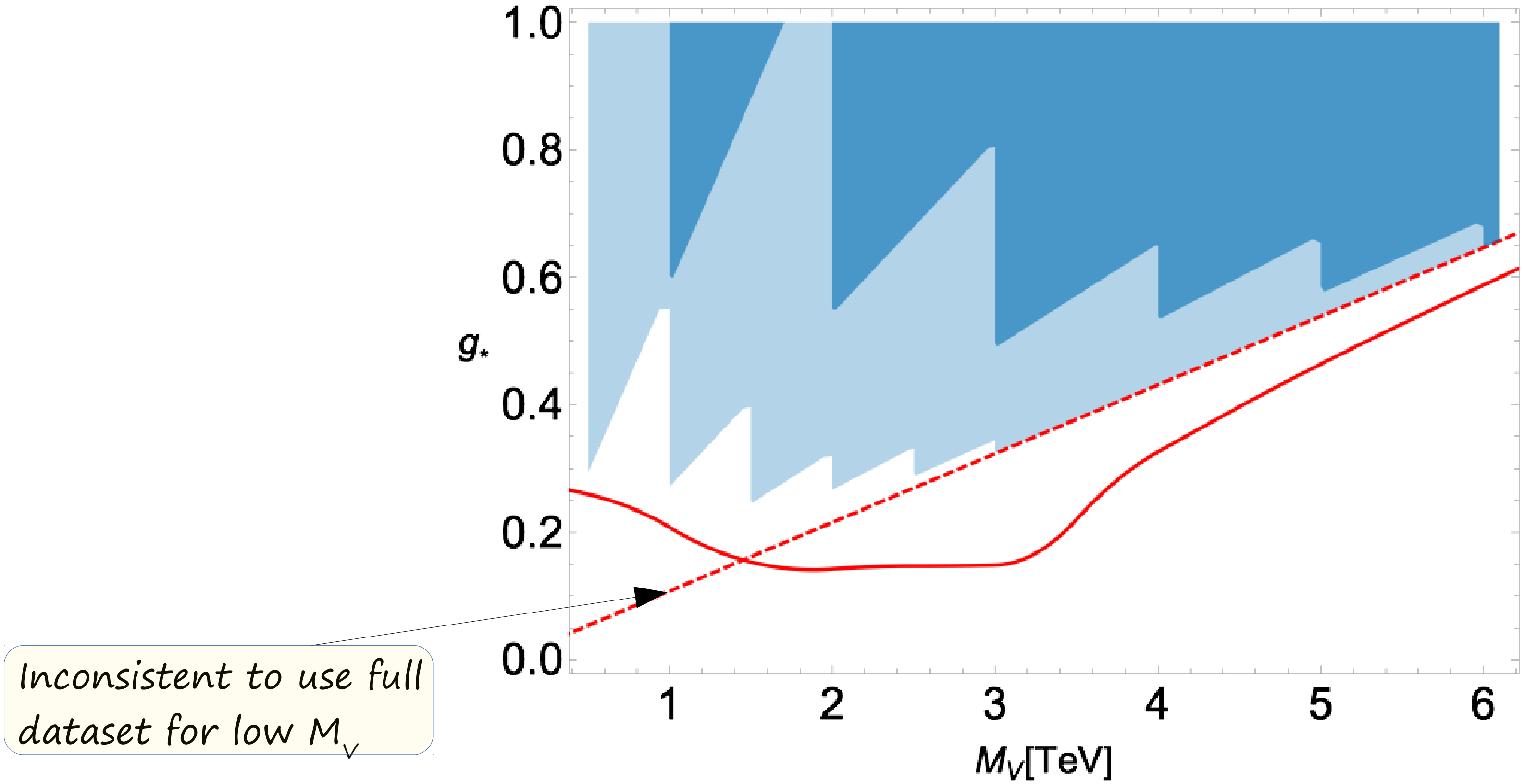
$M_{\rm cut}$[TeV]	0.5	1	1.5	2	2.5	3
$\delta g_L^{Wq} \times 10^3$	[-70, 20]	[-16,4]	[-7,1.6]	[-4.1,1.1]	[-2.7,0.8]	[-2.2,0.7]

Combine bins up to M_{cut}

$$\frac{\sigma}{\sigma_{SM}} \approx \left(1 + 160\,\delta g_L^{Wq} \frac{M_{Wh}^2}{\mathrm{TeV}^2}\right)^2$$

consider only $\delta g_L^{Wq} \equiv [\delta g_L^{Zu}]_{11} - [\delta g_L^{Zd}]_{11}$

Consistent Procedure of Setting Limits

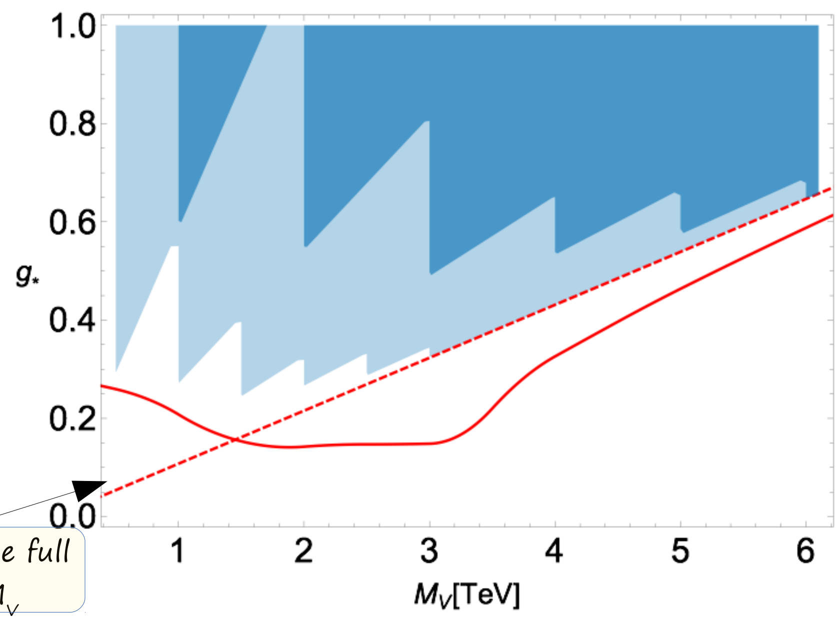


$$g_* \equiv -g_H = g_q$$

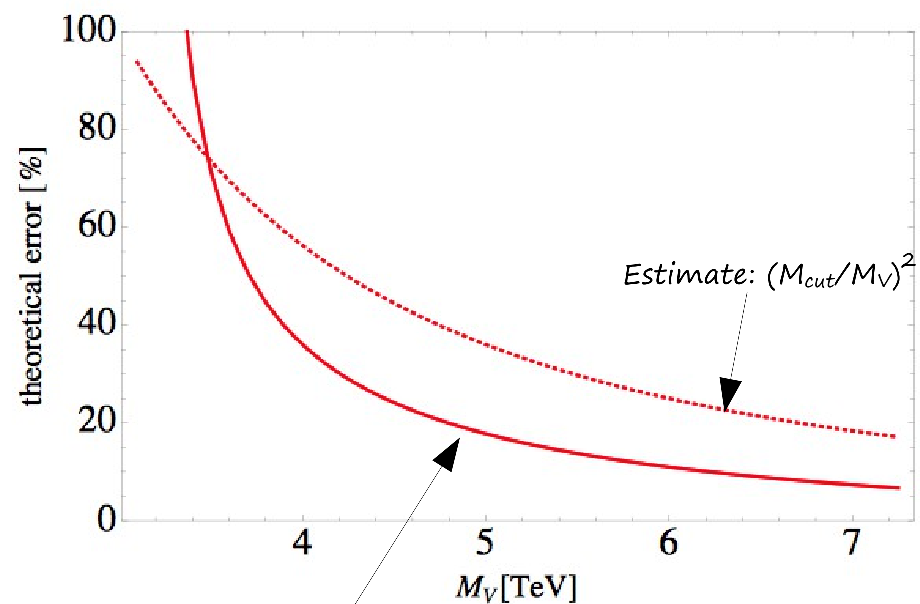
- red: Limits from full resonance model
- red, dashed: Limits from EFT using full dataset
- dark (light) blue: consistent EFT analysis using only data with $\mathrm{M}_{Wh} < M_{\mathrm{cut}} = \kappa M_V$, κ=0.5 (1)

→ Experimental results should be reported as function of M_{cut}

Consistent Procedure of Setting Limits



Inconsistent to use full dataset for low M_V



Difference between limit in EFT and full model for M_{cut}=3TeV

- dark (light) blue: consistent EFT analysis using only data with $\mathrm{M}_{Wh} < M_{\rm cut} = \kappa M_V$, κ=0.5 (1)
- Error explodes once M_V=M_{cut} is reached

Conclusions

- EFTs are a valuable tool to explore UV completion of the SM
- Coefficients can be measured in an agnostic way, however Interpretation requires assumptions on UV physics
- Power counting scheme allows to asses error in determination of D=6 coefficients
- Experimental results should be presented for different kinematic cuts, M_{cut}, to allow broadest range of interpretations