The Standard Model Effective Field Theory in a nutshell

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Motivation

Searching for new physics: two main strategies

direct searches

produce new particles at a collider
$\rightarrow$ leads to actual **discoveries**

indirect searches

look for **the effect** of new particles
without necessarily producing them

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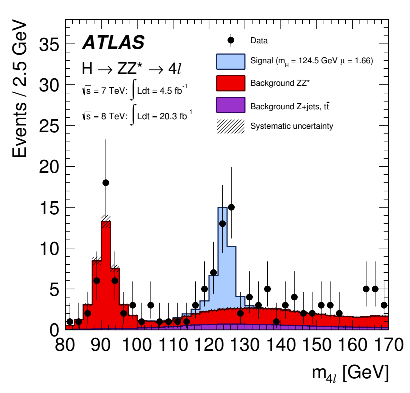

Searching for new physics: two main strategies

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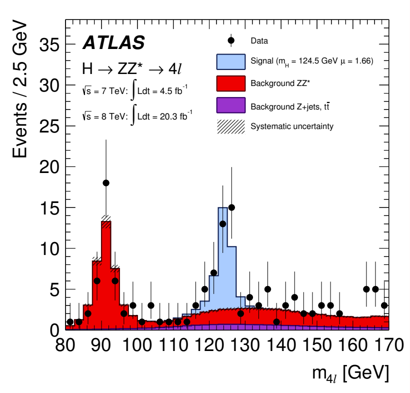

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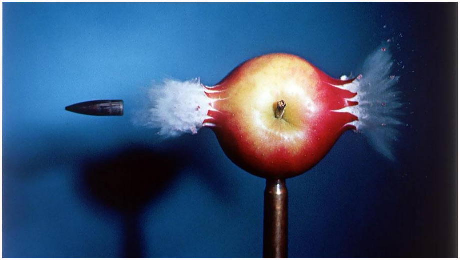

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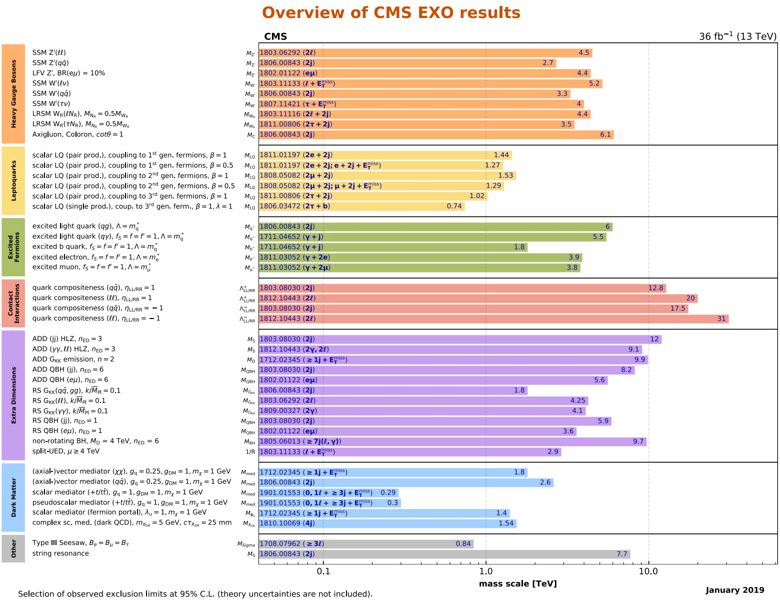
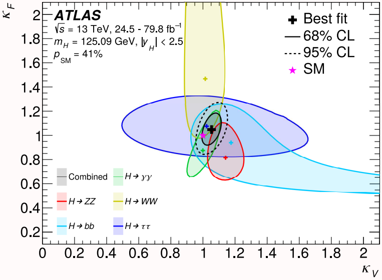
Searching for new physics: two main strategies

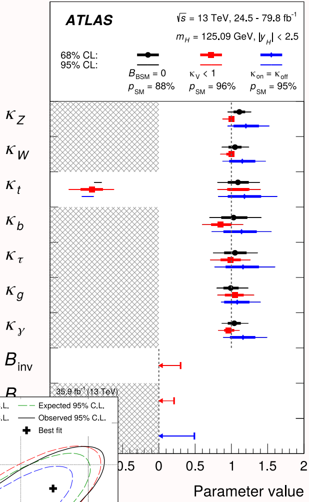
direct searches	**indirect searches**
produce new particles at a collider $\rightarrow$ leads to actual **discoveries**	look for **the effect** of new particles without necessarily producing them
we **need to know** beforehand what the new particle looks like	we **don't need to specify** in detail what we are looking for
only works if new particles are **within the energy reach** of the collider	gives valuable information even if the new particles are **out of the energy reach**
requires **high energy**	requires **precise measurements**

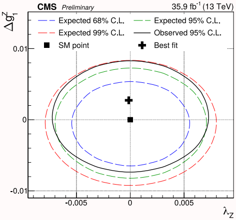
Direct searches of new physics at the LHC

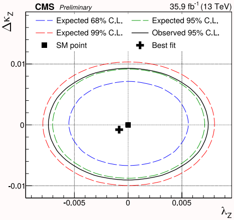


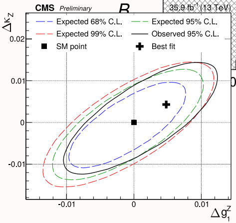
Historically: constraints on anomalous couplings



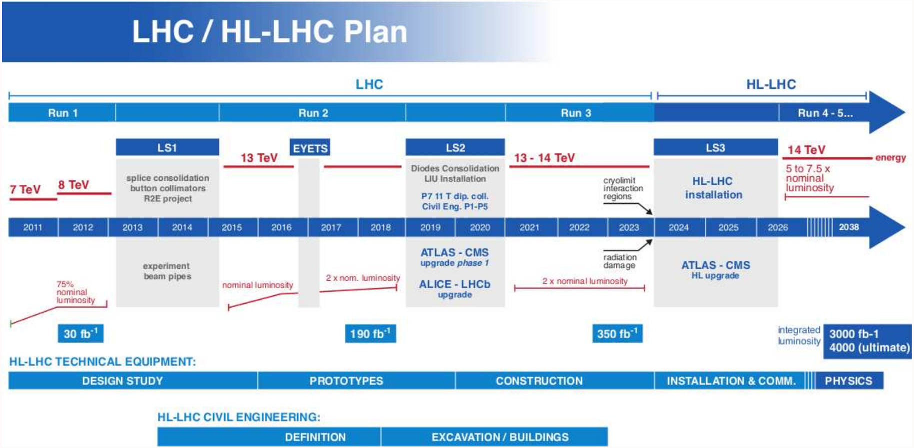








LHC: plans for the future



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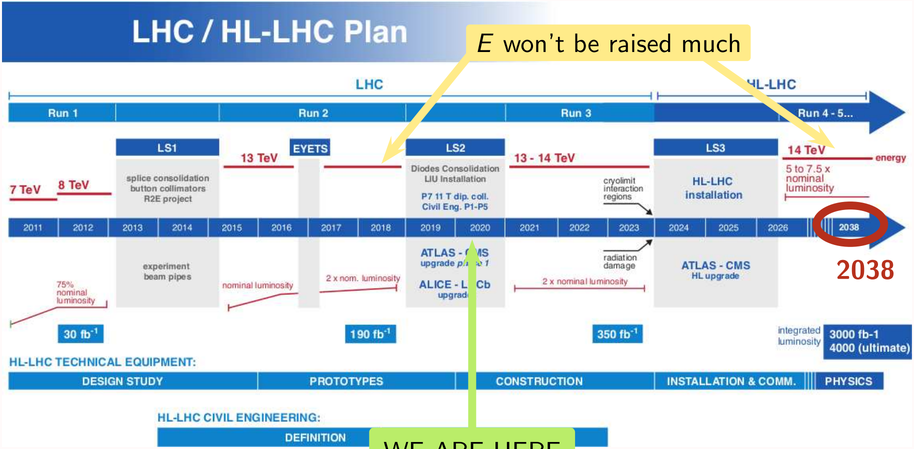

E won't be raised much

2038

WE ARE HERE

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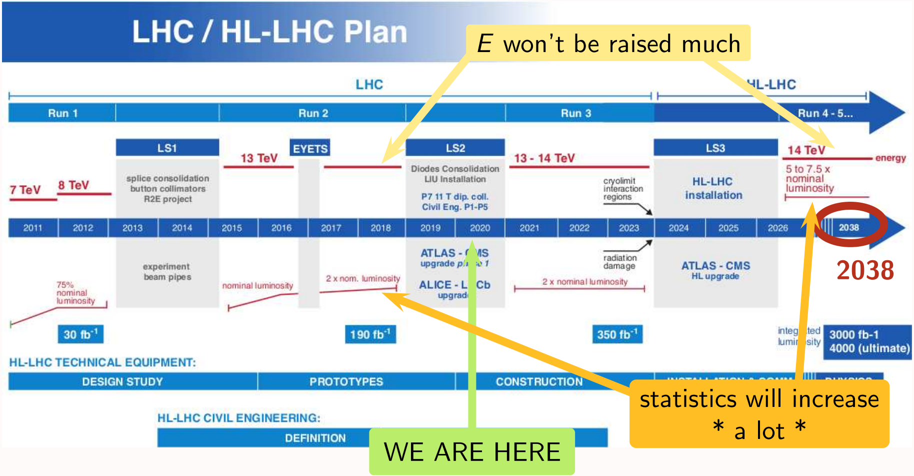

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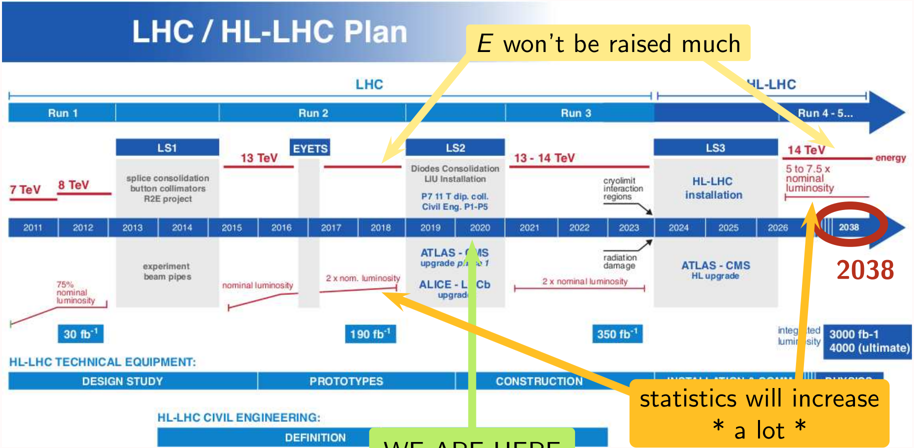

E won't be raised much

2038

statistics will increase
* a lot *

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precision will improve significantly

indirect searches will become more and more important!

worth having a systematic program

Theory tools

Standard Model recap

symmetries color $SU(3)$ isospin $SU(2)$ hypercharge $U(1)$

	color $SU(3)$	isospin $SU(2)$	hypercharge $U(1)$
	$T^a = \lambda^a/2$, $a = 1...8$	$t^i = \sigma^i/2$, $i = 1,2,3$	

fields

$\alpha = 1,2,3$

G_μ^a	**8**	-	-
W_μ^i	-	**3**	-
B_μ	-	-	0
l_α	-	$\mathbf{2} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	1/2
e_α	-	-	-1
q_α	**3**	$\mathbf{2} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	1/6
u_α	**3**	-	2/3
d_α	**3**	-	-1/3
H	-	$\mathbf{2} = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$	1/2

Standard Model recap

SM Lagrangian

all terms
– made of SM fields
– invariant under symmetries (+ Lorentz!)
– up to canonical dimension 4

$$\mathcal{L}_{SM} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} - \frac{1}{4} W^i_{\mu\nu} W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{\theta}{16\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$
$$+ \sum_{\psi=\{l,e,u,d,q\}} \bar{\psi} i \not{D} \psi - \left[\bar{l} H Y_l e + \bar{q} H Y_d d + \bar{q} \tilde{H} Y_u u + \text{hc.} \right]$$
$$+ D_\mu H^\dagger D^\mu H + \frac{m_h^2}{2} (H^\dagger H) - \lambda (H^\dagger H)^2$$

$$D_\mu \sim \partial_\mu + i g_s G^a_\mu T^a + i g \, W^i_\mu t^i + i g' B_\mu$$

- redundant terms were removed ($(D_\mu \bar{\psi}) i \gamma^\mu \psi, \;\; H^\dagger D_\mu D^\mu H \ldots$)
- 19 free parameters, fixed by measurements

The SM Effective Field Theory

symmetries & fields as in SM

Lagrangian includes invariant terms up to $d > 4$
$\rightarrow$ weighted by Λ^{4-d}

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$$\mathcal{L}_n = \sum_k C_k\, O_k^{(d=n)}$$

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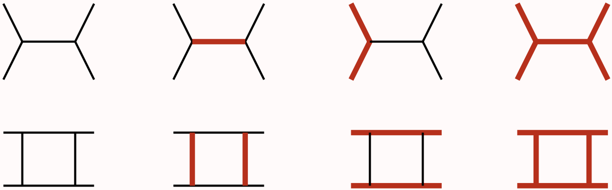
The SMEFT describes
the effects of new physics with scale $\boldsymbol{\Lambda} \gg \mathbf{v}$
onto processes that happen at the LHC or at lower energies

Effective Field Theories

$M \gg m$

Φ M φ m

$E \simeq M$



Effective Field Theories

$M \gg m$

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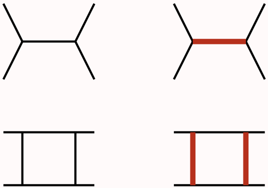
$m \lesssim E \ll M$



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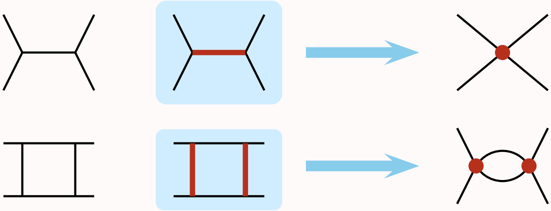

$$\sim \frac{1}{M^2}$$

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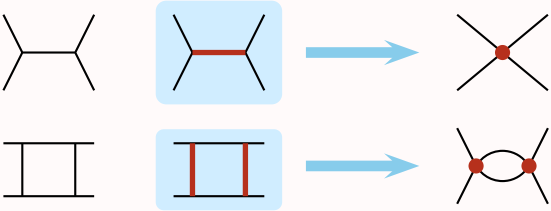

$\sim \dfrac{1}{M^2}$

$\sim \dfrac{1}{M^4}$

The effects of Φ at $E \ll M$ are described by

local, analytic operators $\propto \dfrac{1}{M^n}$

uncertainty principle

internal lines never on-shell

Decoupling Theorem

Appelquist, Carrazzone
PRD11 (1975) 2856

The SMEFT: a closer look

in practice: a Taylor expansion in $\left(\frac{E, v}{\Lambda}\right)$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \frac{1}{\Lambda^4}\mathcal{L}_8 + \dots$$

$$\mathcal{L}_n = \sum_k C_k\, O_k^{(d=n)}$$

<u>at each order d</u>: $\{O_k\}$ form a complete, non redundant set = a basis

O_k: *operators*
C_k: *Wilson coefficients*. encode all the UV information

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at each order d: $\{O_k\}$ form a complete, non redundant set = a **basis**

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$\mathcal{L}_5$ contains only 1 operator (Weinberg) → Majorana neutrino masses.

$\mathcal{L}_6$ leading deviations from SM → interesting for LHC, flavor ...

$\mathcal{L}_6$: the Warsaw basis

Grzadkowski,Iskrzynski,Misiak,Rosiek 1008.4884

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

$\mathcal{L}_6$: how many parameters?

counting - real and imaginary parts $\longrightarrow$ **2499** independent of the basis!
- all flavor combinations
- B-conserving only

Henning,Lu,Melia,Murayama 1512.03433

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2200+ come from 4-fermion operators. 279 from 2-fermion operators.

eg.

$O_{He,pr} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$ has $3 + (3\times 2) = \mathbf{9}$ independent par.

$O_{ledq,prst} = (\bar{l}_p^i e_r)(\bar{d}_s q_t^i)$ has $3\times 3\times 3\times 3\times 2 = \mathbf{162}$

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Flavor symmetries reduce the freedom $\rightarrow$ <u>much fewer</u> parameters

simplest: $\boxed{U(3)^5} = U(3)_l \times U(3)_e \times U(3)_q \times U(3)_u \times U(3)_d$

$\rightarrow$ only invariant contractions of the flavor indices are allowed.

e.g $O_{He,pr} \times \delta_{pr} \rightarrow \mathbf{1}$ parameter
$O_{ledq,prst} \times (Y_l)_{pr}(Y_d)_{st} \rightarrow \mathbf{2}$ parameters

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$O_{ledq,prst} \times (Y_l)_{pr}(Y_d)_{st} \rightarrow$ **2** parameters

tot $\mathcal{L}_6$ with $U(3)^5$: **81** param.

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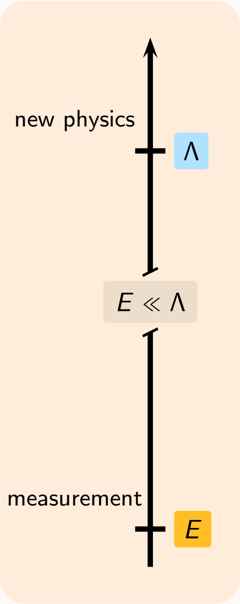
- **model independent**, within low-energy assumption

Physics with EFTs: Top-down & Bottom-up



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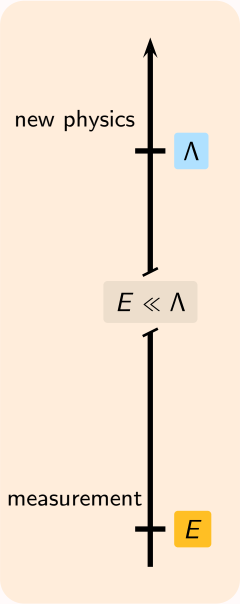

the UV theory is **known**

top-down

the EFT reproduces the full theory at $E \ll \Lambda$

makes the calculation easier

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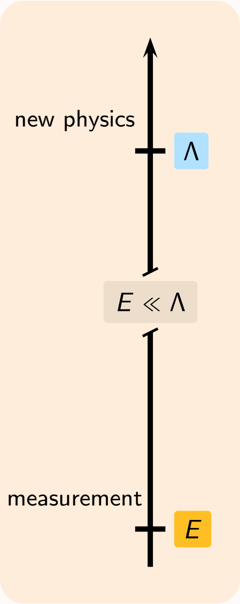

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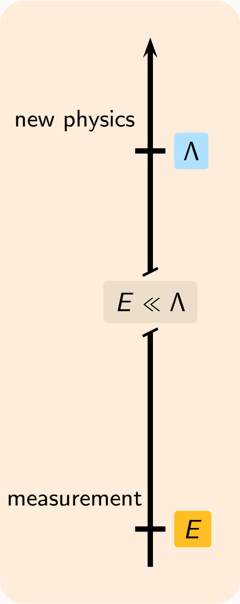
the EFT is built knowing <u>only</u> fields and symmetries at E

Physics with EFTs: Top-down & Bottom-up



the same EFT can match many models!

the UV theory is **known**

top-down

the EFT reproduces the full theory at $E \ll \Lambda$

makes the calculation easier

the UV theory is **unknown**

but its properties can be inferred from measurements

bottom-up

the EFT is built knowing only fields and symmetries at E

Top-down

Example: Z' model

SM + a neutral, massive vector boson.

$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \frac{M_{Z'}^2}{2} Z'_\mu Z'^\mu + Z'_\mu J^\mu$$

$$J^\mu = \kappa_q \, \bar{q}_L \gamma^\mu q_L + \kappa_u \, \bar{u}_R \gamma^\mu u_R + \kappa_d \, \bar{d}_R \gamma^\mu d_R + \kappa_l \, \bar{l}_L \gamma^\mu l_L + \kappa_e \, \bar{e}_R \gamma^\mu e_R$$

and we assume a $U(3)$ symmetry for each fermion field and $\kappa_q = 0 = \kappa_l$.

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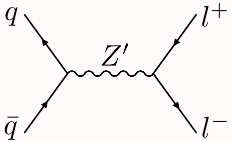
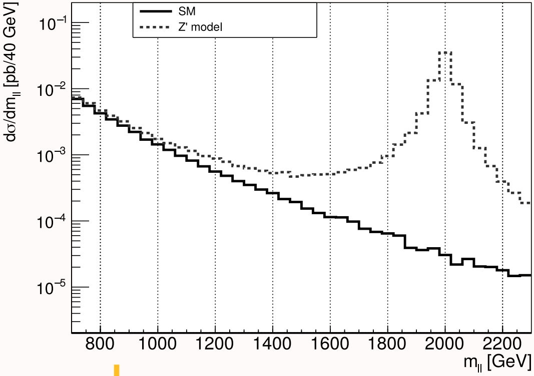
at the LHC, for instance dilepton signal



Dilepton with a heavy Z'

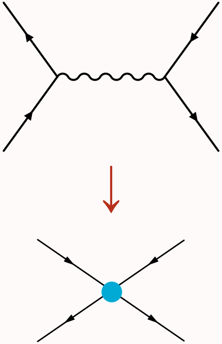
Let's assume $m_{Z'} = 2$ TeV



at $m_{ll} \ll m_{Z'}$ the SMEFT description applies

From Z' to SMEFT

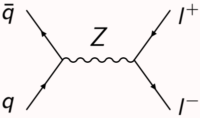
We can **integrate out** the Z'

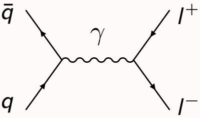


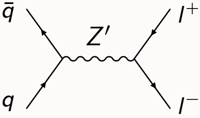
matching to the Warsaw basis:

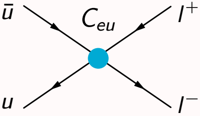
$$\boxed{C_{ij} = -\frac{(2-\delta_{ij})}{2m_{Z'}^2}\kappa_i\kappa_j}\ , \ i,j = \{l,e,q,u,d\}$$

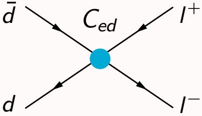
Dilepton with a heavy Z' - matrix elements

$\mathcal{A}_{SM} =$ 

$+$ 

$\mathcal{A}_{Z'} =$ 

$\mathcal{A}_{Z',SMEFT} =$ 

$+$ 

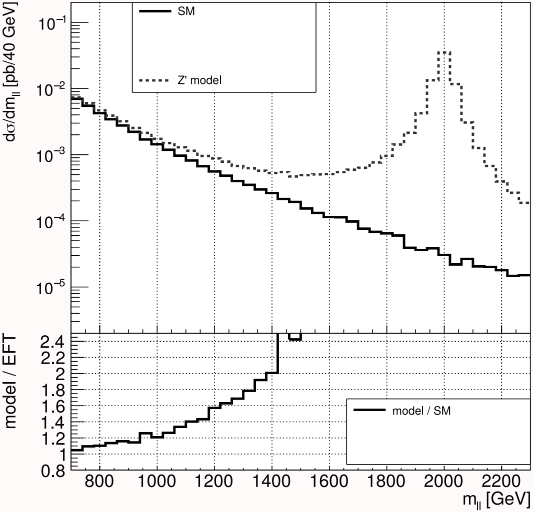
(remember $\kappa_q = 0 = \kappa_l$)

in the SMEFT: $\boxed{|\mathcal{A}|^2 = |\mathcal{A}_{SM}|^2 + 2\mathrm{Re}\mathcal{A}_{SM}\mathcal{A}^\dagger_{Z',SMEFT} + |\mathcal{A}_{Z',SMEFT}|^2}$

$\propto C_{ie} = -\kappa_i\kappa_e/m^2_{Z'}$ $\qquad$ $\propto C^2_{ie} = \kappa_i^2\kappa_e^2/m^4_{Z'}$

Dilepton with a heavy Z' - model vs SMEFT

Let's assume $m_{Z'} = 2$ TeV



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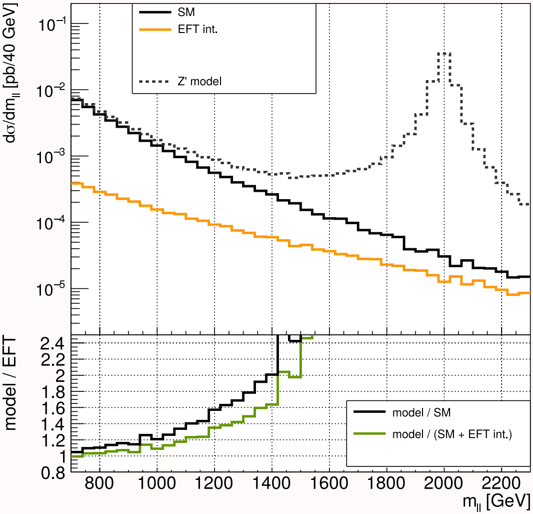

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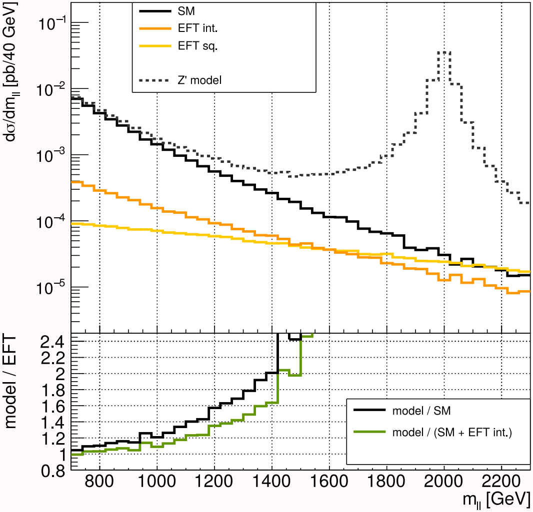

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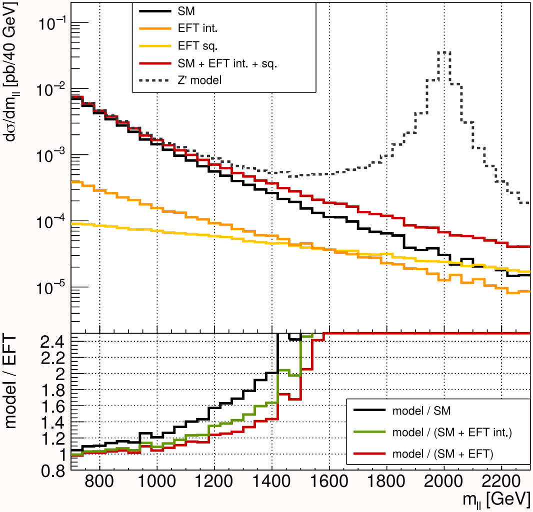


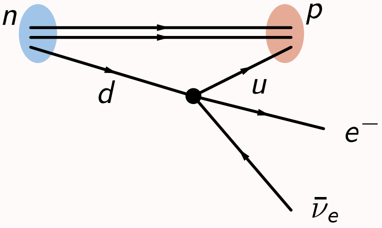
Bottom-up

An historic example: Fermi interactions

Fermi formulated a theory of β-decays in 1933, well before electroweak interactions were understood. Neutrinos were only an hypothesis at that time.

In modern QFT notation:

$$G_F(\bar{p}\gamma_\mu n)(\bar{e}\gamma_\mu \nu)$$



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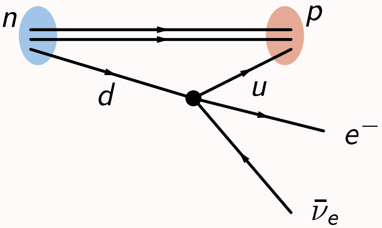

- G_F could be measured eg. fitting the energy spectra of the e^-

$\rightarrow$ $\boxed{G_F \simeq (290\,\mathrm{GeV})^{-2}}$ $\sim$ (typical scale of the underlying physics)$^{-2}$ $\sim v^{-2}$!

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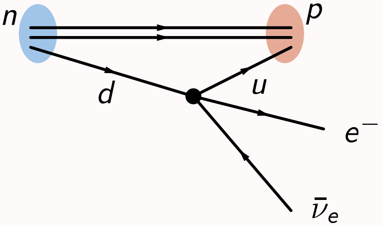

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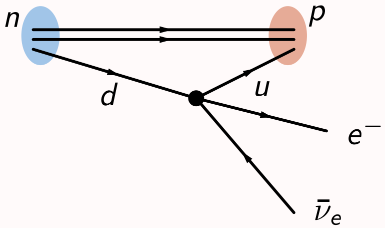

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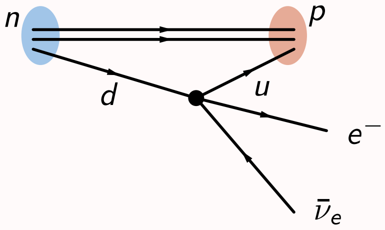

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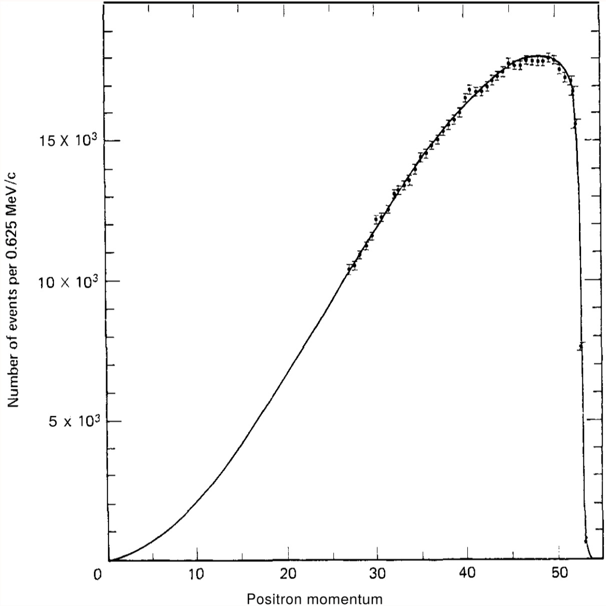
- fitting angular distributions $\rightarrow$ the currents have *left-handed* chirality

$\rightarrow$ very strong hints at the nature of EW interactions

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

Bardon et al. PRL 14 (1965) 449



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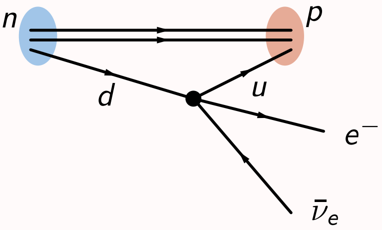
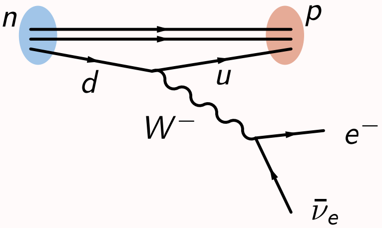


today we know

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2} = \frac{1}{\sqrt{2}v^2}$$

from integrating out the W



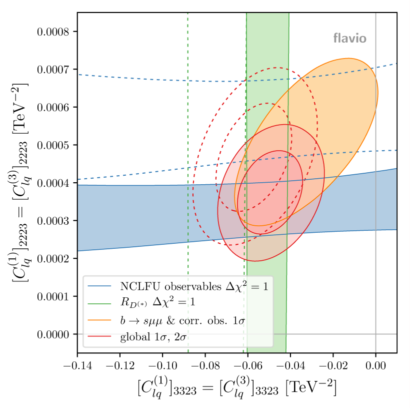
- the EFT worked very well as $\left(\frac{m_n}{m_W}\right)^2 \simeq \boxed{10^{-4}}$, $\left(\frac{m_\mu}{m_W}\right)^2 \simeq \boxed{10^{-6}}$

The SM is the new Fermi theory

. . . so what is the new SM?

An ambitious plan:

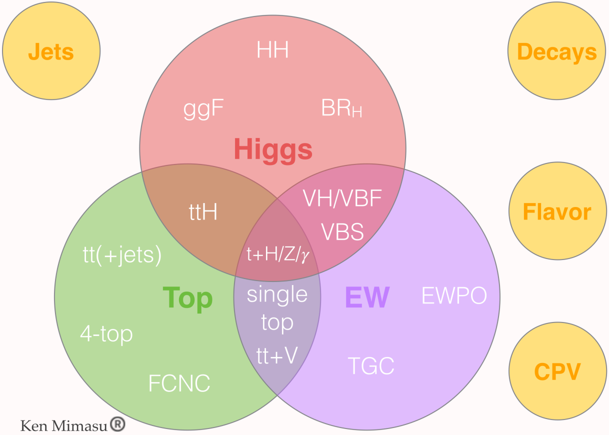
- compute processes in the SMEFT including *all* the relevant Wilson coefficients in $\mathcal{L}_6$
- make a fit to determine their values → who's **not zero**?
- infer hints about the possible UV sector



Aebischer,Altmannshofer,Guadagnoli, Reboud,Stangl,Straub 1903.10434

Global SMEFT analyses

- individual processes necessarily have **blind directions**
- combination of different processes / sectors required



Real example: fit to top quark processes

- $U(2)_q \times U(2)_u \times U(2)_d$
- top interactions only for now
- up to NLO QCD, quadratic SMEFT

Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606

22 relevant operators

also: Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, Zhang 1901.05965

34

---

tZ

$t\bar{t}Z, t\bar{t}W$

$$\mathcal{Q}_{tB} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}t)B_{\mu\nu}$$
$$\mathcal{Q}_{Ht} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}\gamma^\mu t)$$

single t

$$\mathcal{Q}_{bW} = (\bar{Q}H\sigma^{\mu\nu}\sigma^k b)W^k_{\mu\nu}$$
$$\mathcal{Q}_{Htb} = (i\tilde{H}^\dagger D_\mu H)(\bar{t}\gamma^\mu b)$$

$t\bar{t}$

$$\mathcal{Q}_{tG} = (\bar{Q}\tilde{H}\sigma^{\mu\nu}T^A t)G^A_{\mu\nu}$$

$$\begin{aligned}
\mathcal{Q}^1_{Qu} &= (\bar{Q}\gamma_\mu Q)(\bar{u}\gamma^\mu u) & \mathcal{Q}^8_{Qu} &= (\bar{Q}\gamma_\mu T^A Q)(\bar{u}\gamma^\mu T^A u)\\
\mathcal{Q}^1_{Qd} &= (\bar{Q}\gamma_\mu Q)(\bar{d}\gamma^\mu d) & \mathcal{Q}^8_{Qd} &= (\bar{Q}\gamma_\mu T^A Q)(\bar{d}\gamma^\mu T^A d)\\
\mathcal{Q}^1_{tu} &= (\bar{t}\gamma_\mu t)(\bar{u}\gamma^\mu u) & \mathcal{Q}^8_{tu} &= (\bar{t}\gamma_\mu T^A t)(\bar{u}\gamma^\mu T^A u)\\
\mathcal{Q}^1_{td} &= (\bar{t}\gamma_\mu t)(\bar{d}\gamma^\mu d) & \mathcal{Q}^8_{td} &= (\bar{t}\gamma_\mu T^A t)(\bar{d}\gamma^\mu T^A d)\\
\mathcal{Q}^{1,1}_{Qq} &= (\bar{Q}\gamma_\mu Q)(\bar{q}\gamma^\mu q) & \mathcal{Q}^{1,8}_{Qq} &= (\bar{Q}\gamma_\mu T^A Q)(\bar{q}\gamma^\mu T^A q)\\
\mathcal{Q}^1_{tq} &= (\bar{t}\gamma_\mu t)(\bar{q}\gamma^\mu q) & \mathcal{Q}^8_{tq} &= (\bar{t}\gamma_\mu T^A t)(\bar{q}\gamma^\mu T^A q)
\end{aligned}$$

$$\mathcal{Q}^3_{HQ} = (iH^\dagger \overleftrightarrow{D}^i_\mu H)(\bar{Q}\sigma^i\gamma^\mu Q)$$
$$\mathcal{Q}^1_{HQ} = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}\gamma^\mu Q)$$
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$$\mathcal{Q}^{3,8}_{Qq} = (\bar{Q}\gamma_\mu\sigma^k T^A Q)(\bar{q}\gamma^\mu\sigma^k T^A q)$$
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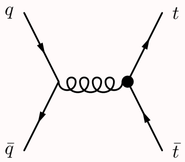
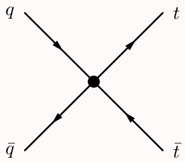
A typical issue: flat directions

e.g. $q\bar{q} \to t\bar{t}$ at tree-level:



C_{tG}



8 terms: 2 $\chi_q \times 2\chi_t \times$ 2 color contractions
+ singlet/triplet isospin for LL currents

$\updownarrow$

10 operators for <u>each</u> initial state (u/d)

restricting to those with **non-zero interference**:
7 4-fermion operators
(5 / initial state)

LL: $C_{Qq}^{(1,8)}$, $C_{Qq}^{(3,8)}$
LR: C_{tq}^{8}
RL: C_{Qu}^{8}, C_{Qd}^{8}
RR: C_{tu}^{8}, C_{td}^{8}

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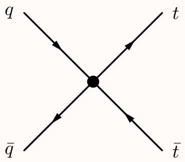

<u>notation</u>:

$C^{color}_{\chi_q \chi_t}$
$\beta_t^2 = 1 - 4m_t^2/s$
$c_t = \cos\theta(\vec{p}_t, \vec{p}_q)$ in c.m. frame

$$\Delta\sigma^{int}_{t\bar{t}} \propto \left[C^8_{LL} + C^8_{RR} + C^8_{LR} + C^8_{RL} \right] \left(1 + \beta_t^2 c_t^2 + \frac{2m_t^2}{s} \right) + \left[C^8_{LL} + C^8_{RR} - C^8_{LR} - C^8_{RL} \right] 2\beta_t c_t$$

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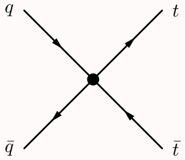

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LO, interference only can *never* distinguish $LL \leftrightarrow RR$ or $LR \leftrightarrow RL$

$\to$ breaking: NLO QCD
$(C_i C_j)$ terms
other processes in the fit (e.g. single-top)

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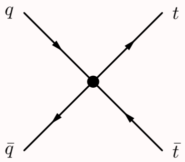

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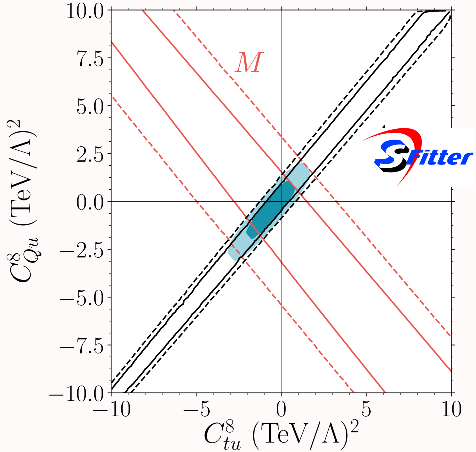
LO, interference only *can* distinguish $(LL + RR) \leftrightarrow (LR + RL)$

Same vs. different chiralities in $t\bar{t}$

$$\Delta\sigma^{int}_{t\bar{t}} \propto \left[C^8_{LL} \boxed{+C^8_{RR}} + C^8_{LR} \boxed{+C^8_{RL}}\right]\left(1+\beta_t^2 c_t^2 + \frac{2m_t^2}{s}\right) + \left[C^8_{LL} \boxed{+C^8_{RR}} - C^8_{LR} \boxed{-C^8_{RL}}\right] 2\beta_t c_t$$



likelihood contours:

$\ln L_{\max} - \ln L =$ 1/2 ———
2 - - - - -

($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

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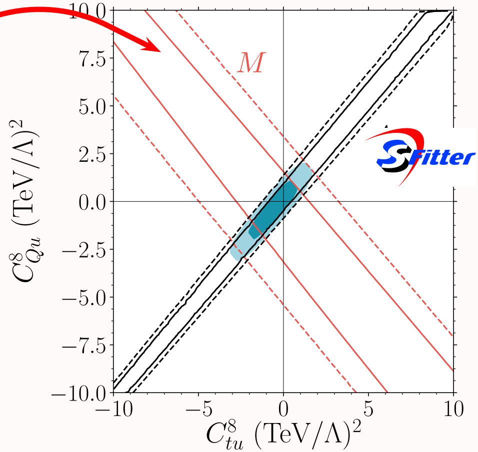
$\sigma_{t\bar t} + m_{t\bar t}$ dist



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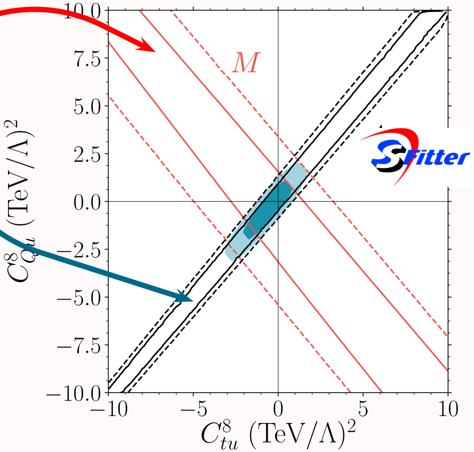
2 - - - - -

($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

$$\Delta\sigma^{int}_{t\bar t} \propto \left[C^8_{LL} + C^8_{RR} + C^8_{LR} + C^8_{RL}\right] \boxed{\left(1+\beta_t^2 c_t^2 + \frac{2m_t^2}{s}\right)} + \left[C^8_{LL} + C^8_{RR} - C^8_{LR} - C^8_{RL}\right] \boxed{2\beta_t c_t}$$

$\sigma_{t\bar t} + m_{t\bar t}$ dist

charge asymmetry
A_C



likelihood contours:

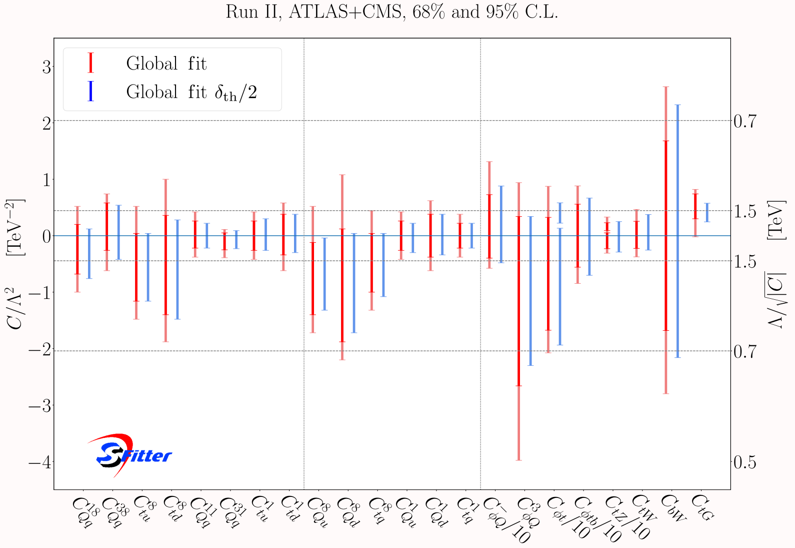
$\ln L_{\max} - \ln L =$ 1/2 ———
2 - - - - -

($\sim \Delta\chi^2 = 1, 4$ in Gaussian limit)

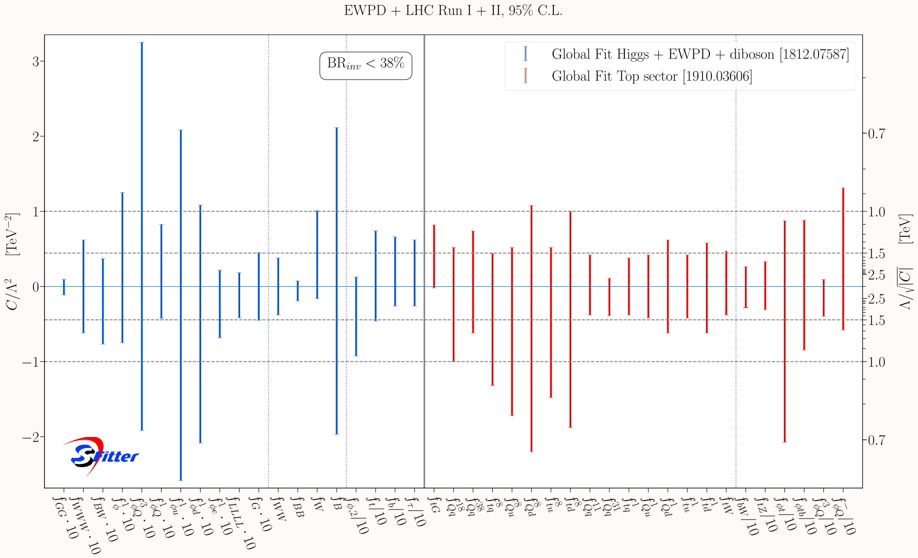
Global fit to top processes: results

fit to $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}W$, single-t, W helicity in t decays

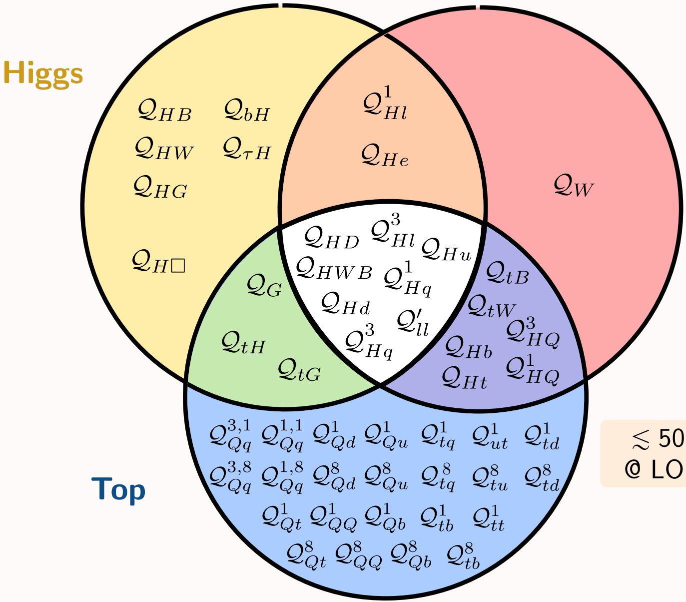
Brivio, Bruggisser, Maltoni, Moutafis, Plehn, Vryonidou, Westhoff, Zhang 1910.03606



Top fit vs EW+Higgs fit results



Next step: top + EW + Higgs



$\lesssim$ 50 parameters
@ LO interference

Recap & take-home

- Indirect searches of BSM physics @LHC will become more and more significant in the next runs
- The **SMEFT** is a well-defined and general theory framework to do this systematically
- It describes possible effects from *nearly-decoupled* new physics
  $\rightarrow$ complement direct searches
  $\rightarrow$ minimal model dependence
- Added value:
  - a full-fledged QFT
  - a universal language: allows combination with other experiments
  - allows an agnostic bottom-up approach
    $\rightarrow$ requires **global fits**

Backup slides

Top fit – observables

$pp \to t\bar{t}$

- 5 $\sigma_{t\bar{t}}$ measurements at 8 and 13 TeV
- 5 A_C measurements at 8 and 13 TeV
- 2 $d\sigma/dm_{t\bar{t}}$ dist. at 8 and 13 TeV (15 bins tot)
- 4 $d\sigma/dp_T^t(p_T^1, p_T^h)$ dist. at 8 and 13 TeV (30 bins tot)
- 1 $d^2\sigma/dm_{t\bar{t}}dt_{t\bar{t}}$ dist at 8 TeV (16 bins)
- 2 dist in high-p_T region $(p_T^t, m_{t\bar{t}})$ at 8 and 13 TeV (13 bins tot)

$pp \to t\bar{t}Z, pp \to t\bar{t}W$

- 2 $\sigma_{t\bar{t}V}$ measurements for each V at 8 and 13 TeV

Single-top

- 6 $\sigma_{tq,\bar{t}q}$ measurements in t-channel at 7, 8, 13 TeV
- 3 $\sigma_{t\bar{b},\bar{t}b}$ measurements in s-channel at 7, 8 TeV
- 6 $\sigma_{tW,\bar{t}W}$ measurements in tW channel at 7, 8, 13 TeV
- 1 σ_{tZq} measurement in tZq at 13 TeV

Top decays

- 4 measurements of W helicity at 7, 8, 13 TeV