LHC-EFT(S) IN RUN 3 AND BEYOND

- MY PERSONAL VIEWS -

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Christmas Workshop
Milano 21/12/2021

Is LHC Enough? - LHC, HL-LHC and what we can expect from the coming rounds

In this talk I will revisit the latest progress of the LHC collaborations in the analysis of the run-2 data and the prospects for run-3 and HL-LHC. In this period, the measurement of double Higgs production will play a crucial role to extract some intel on the shape of the Higgs potential. The theory community has already proposed different interpretations for this process in terms of HEFT and SMEFT and now waits patiently for the experimental results. In the meantime, limitations on computing resources and delays on the experimental upgrades are urging us to look for innovative methods and creative solutions to try and make the most of the data that we currently have.

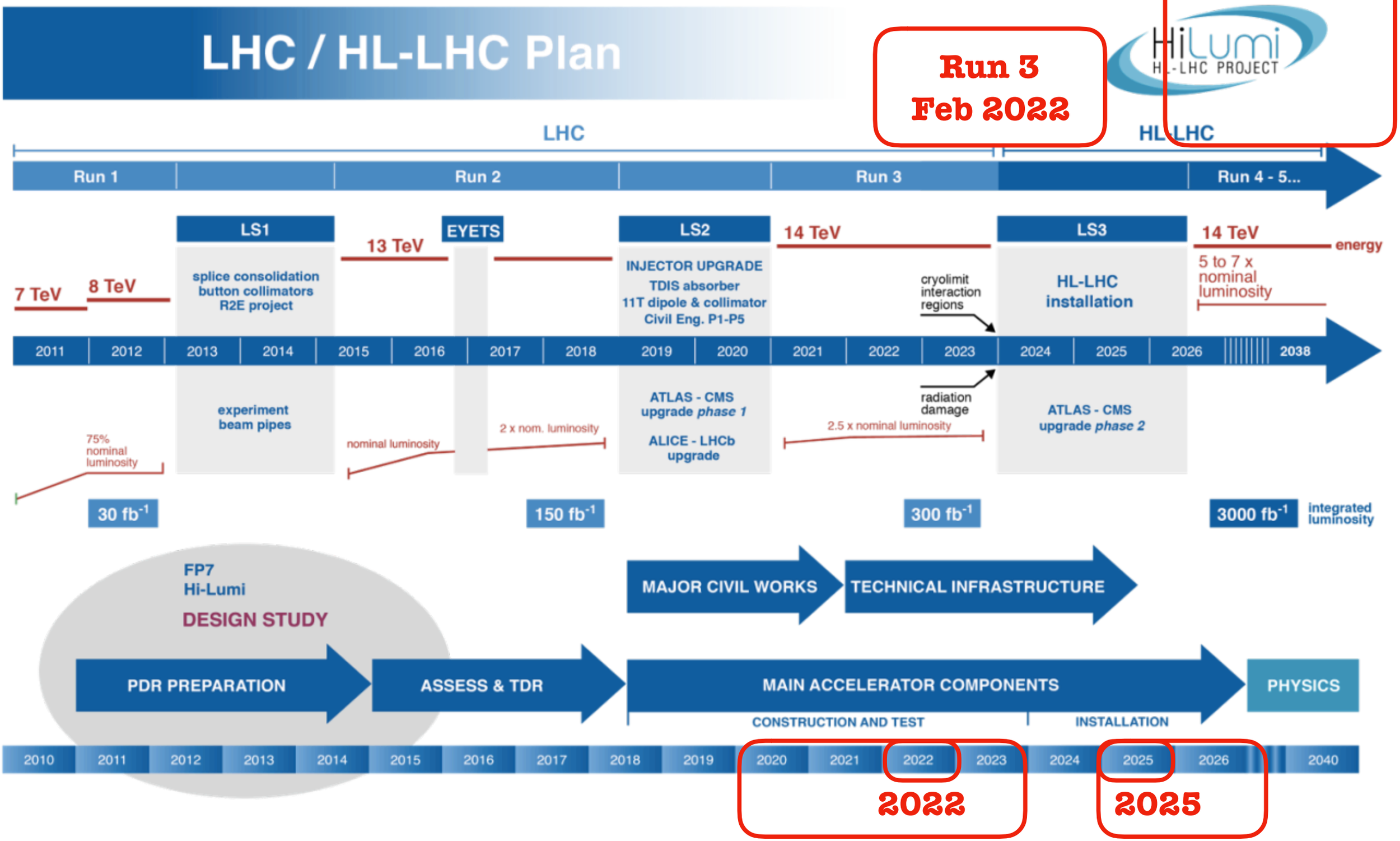
Outline

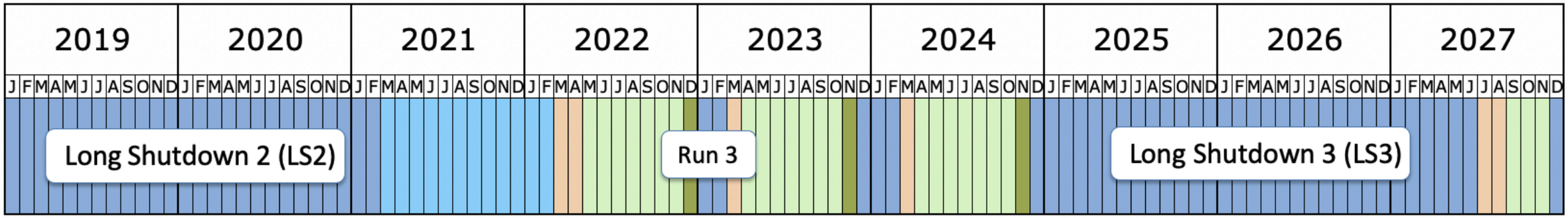
What are the problems/tasks that we have to address in LHC in the near future?

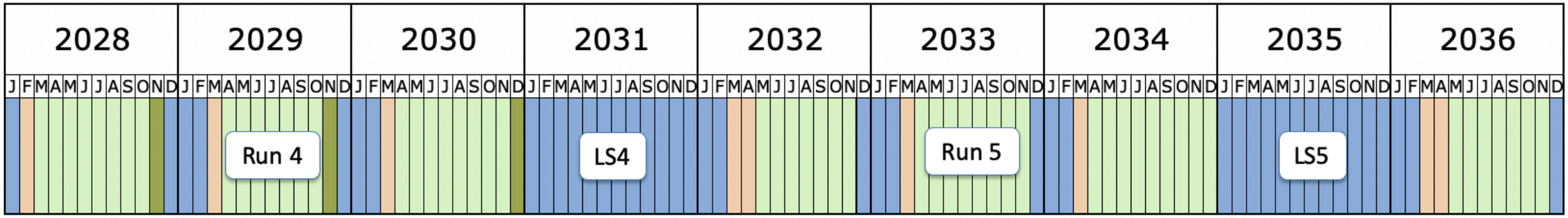
1. LHC news: Run-3 around the corner
2. News from the SMEFT side: fit status
3. Technical challenges
4. HEFT: The quest for the Higgs' shape
5. What next?

LHC technical news

Upgrade (from 2025)

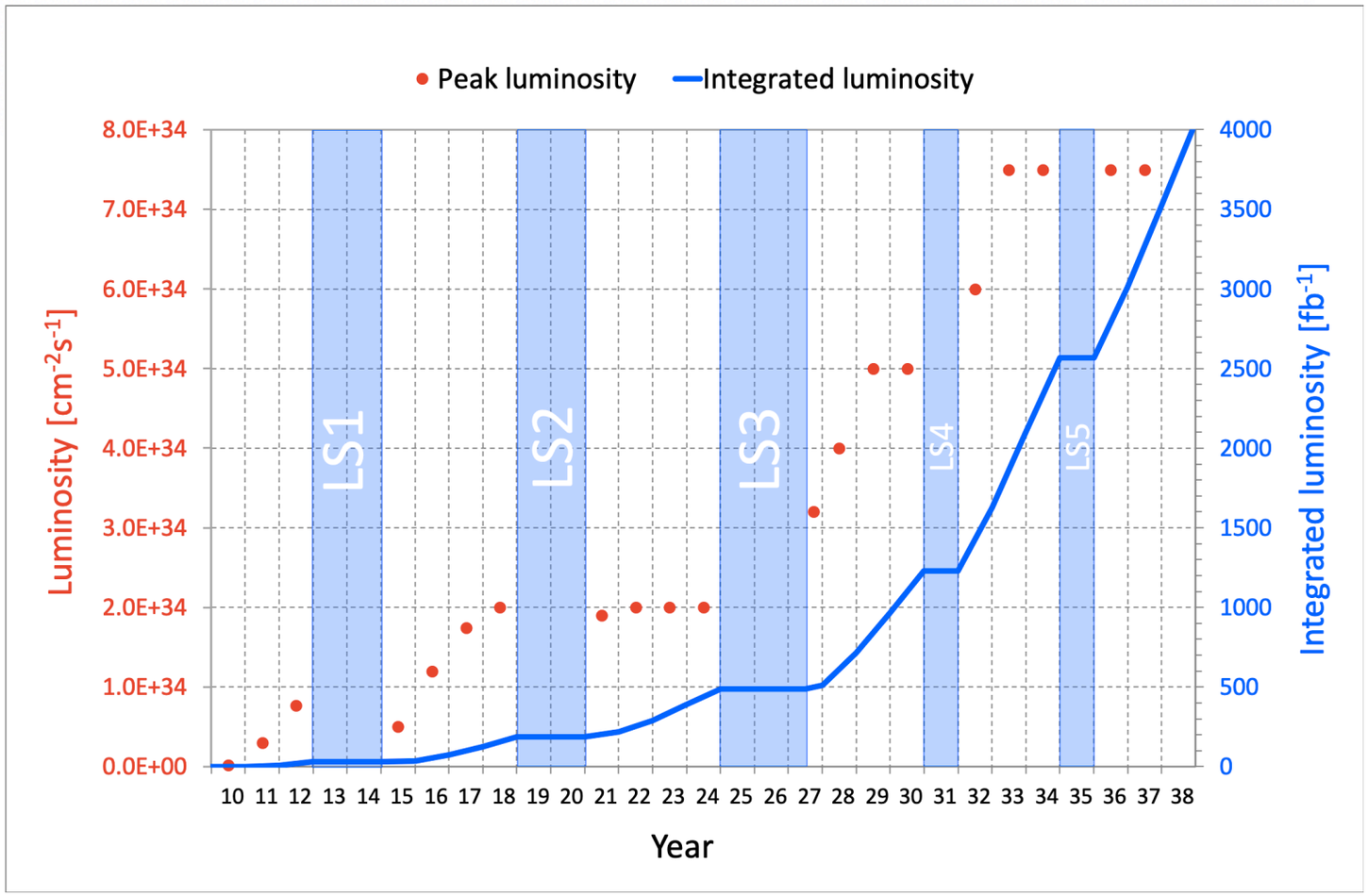






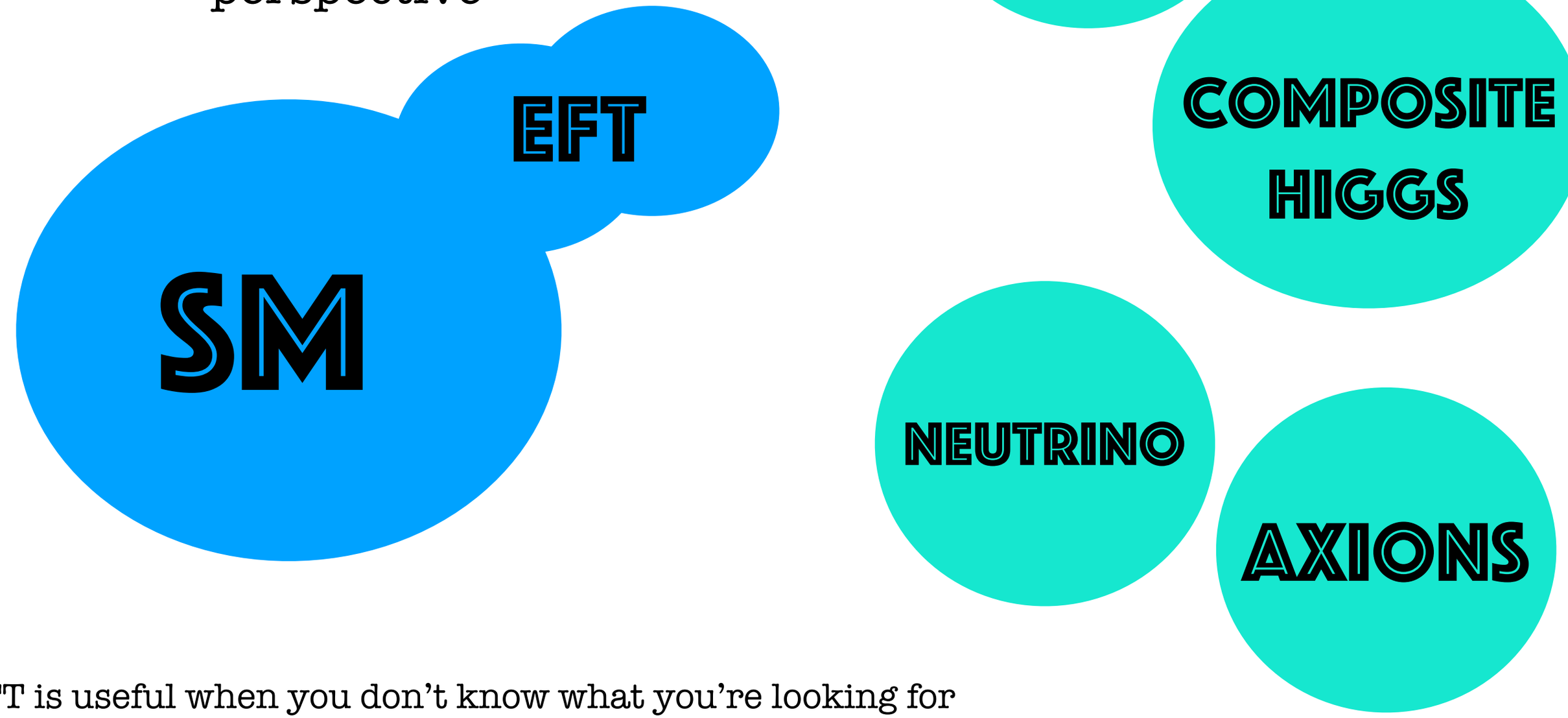
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning/magnet training

Updated plans as of July 2021



Theorist point of view

On option is to start from the SM perspective



EFT is useful when you don't know what you're looking for

Effective Field Theory(ies): SMEFT

$$\mathscr{L}_{EFT} = \mathscr{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_6^{(i)} + \sum_i \frac{d_j}{\Lambda^3}\mathcal{O}_7^{(i)} + \sum_i \frac{f_i}{\Lambda^4}\mathcal{O}_8^{(i)} + \ldots$$

- “O” are the operators and c/d/f their Wilson Coefficients
- We **usually** don’t look at odd-dimension operators within the gauge sectors (but they are relevant for neutrinos)
- Wilson coefficients are **not** measurable **(observables)**

An EFT: SMEFT

$$\sigma_{EFT} = \sigma_{SM} + \underbrace{\sigma_{int,6}}_{linear} + \underbrace{\sigma_{pure,6} + \sigma_{int,8}}_{quadratic} + \dots$$

- The leading contribution comes from the dim6 x SM interference
- The next contribution should include both dim6 squared terms (pure EFT) and dim8 x SM interference
- LHC fits available with dim. 6 linear + quadratic.
- No dim. 6 + 8 results available as of today

If I have a basis*, I can implement the EFT in the computing tools and compare my predictions with the exp. data

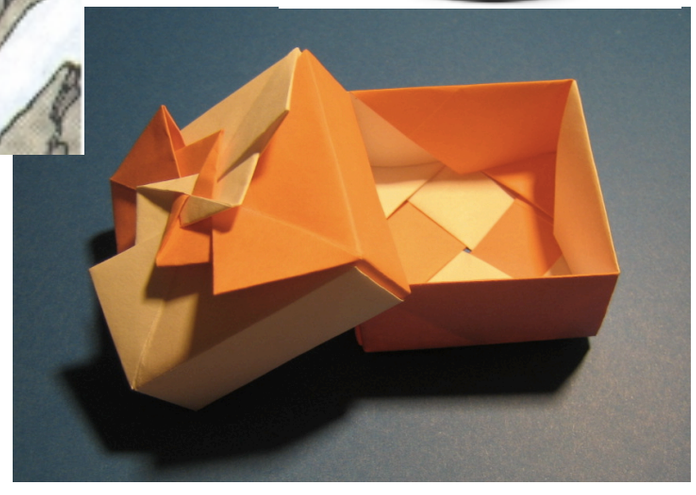
(This is one of the bottlenecks of HEFT)

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}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		



HEPData

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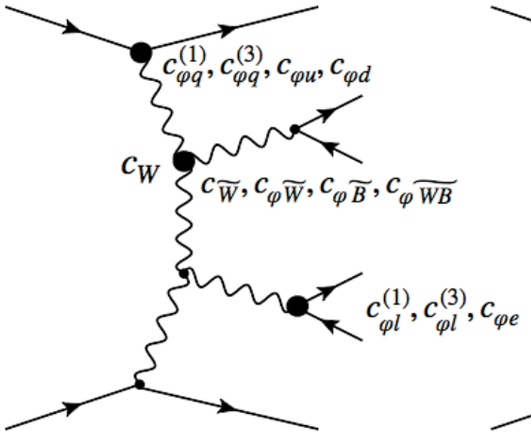

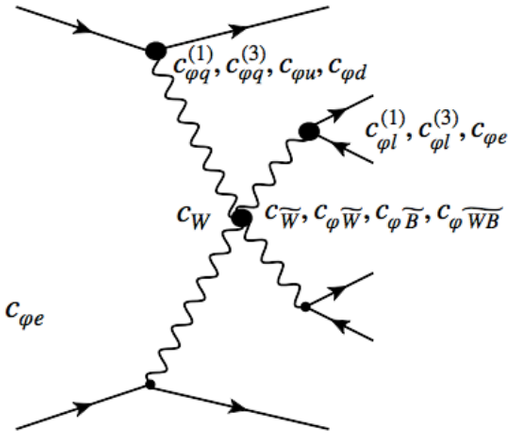

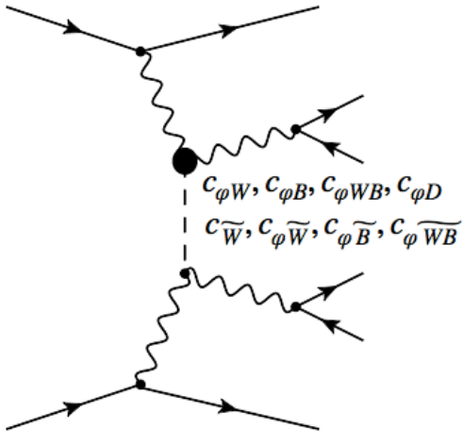

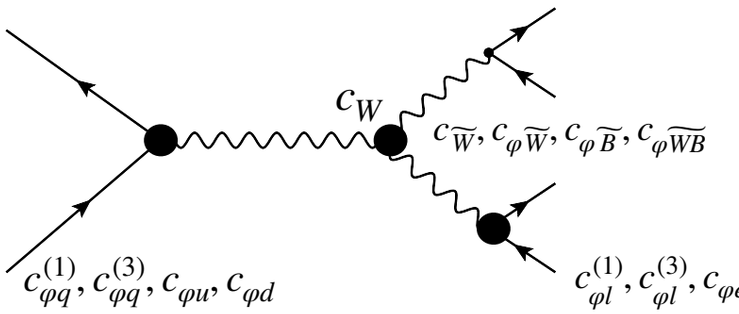

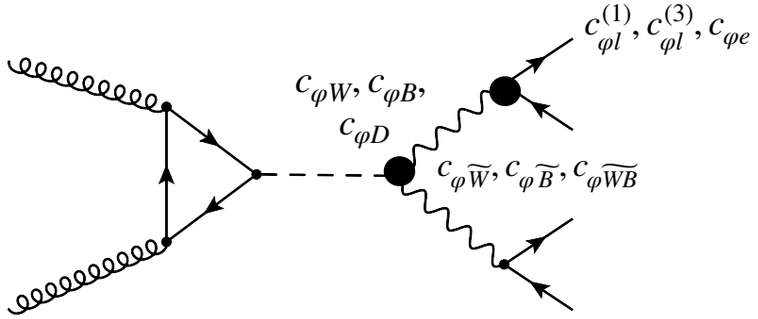

SMEFT analysis of vector boson scattering and diboson data from the LHC Run II

Jacob J. Ethier,[1,2] Raquel Gomez-Ambrosio,[3,4,†] Giacomo Magni,[1,2] Juan Rojo,[1,2]

EFT Fits, case 1: The electroweak sector

Final state	Selection	Observable	n_{dat}	$\mathcal{L}$ (fb^{-1})	Label
$W^\pm W^\pm jj$	EW-only	σ_{fid}	1	36.1	`ATLAS_WWjj_fid`
	EW-only	σ_{fid}	4	137	`CMS_WWjj_fid`
	EW+QCD	$\mathrm{d}\sigma/\mathrm{d}m_{ll}$ (*)			`CMS_WWjj_mll`
$ZW^\pm jj$	EW+QCD	$\mathrm{d}\sigma/\mathrm{d}m_{T_{WZ}}$	5	36.1	`ATLAS_WZjj_mwz`
	EW-only	σ_{fid}	4	137	`CMS_WZjj_fid`
	EW+QCD	$\mathrm{d}\sigma/\mathrm{d}m_{jj}$ (*)			`CMS_WZjj_mjj`
$ZZjj$	EW+QCD	σ_{fid}	1	139	`ATLAS_ZZjj_fid`
	EW-only	σ_{fid}	1	139	`CMS_ZZjj_fid`
γZjj	EW-only	σ_{fid}	1	36.1	`ATLAS_AZjj_fid`
	EW-only	σ_{fid}	1	35.9	`CMS_AZjj_fid`
VBS total (unfolded)			**18**		
$ZZjj$	EW+QCD+Bkg	Events/m_{ZZ}	4	139	`CMS_ZZjj_mzz`
γZjj	EW+QCD+Bkg	Events/$p_{T_{\ell\ell\gamma}}$	11	36.1	`ATLAS_AZjj_ptlla`
VBS total (detector-level)			**15**		

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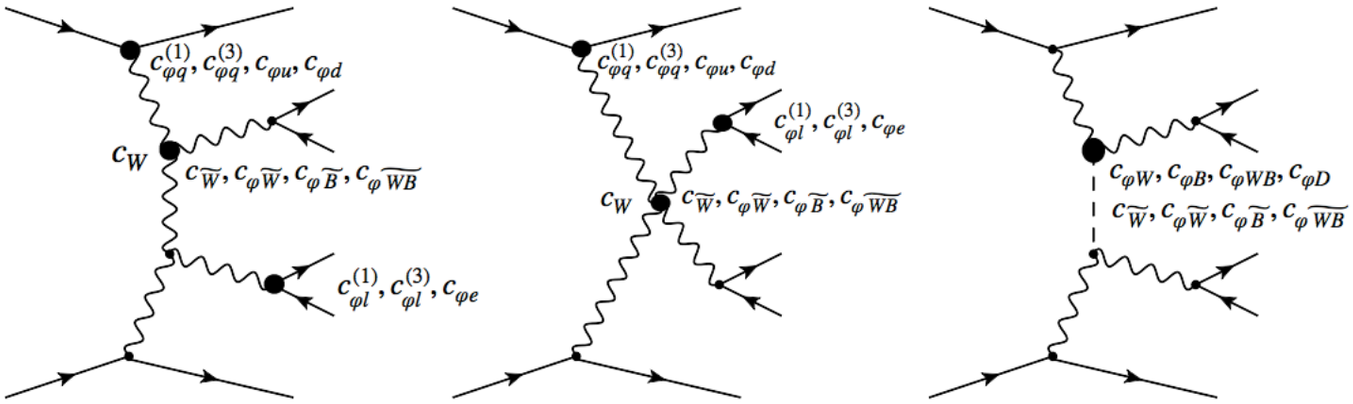
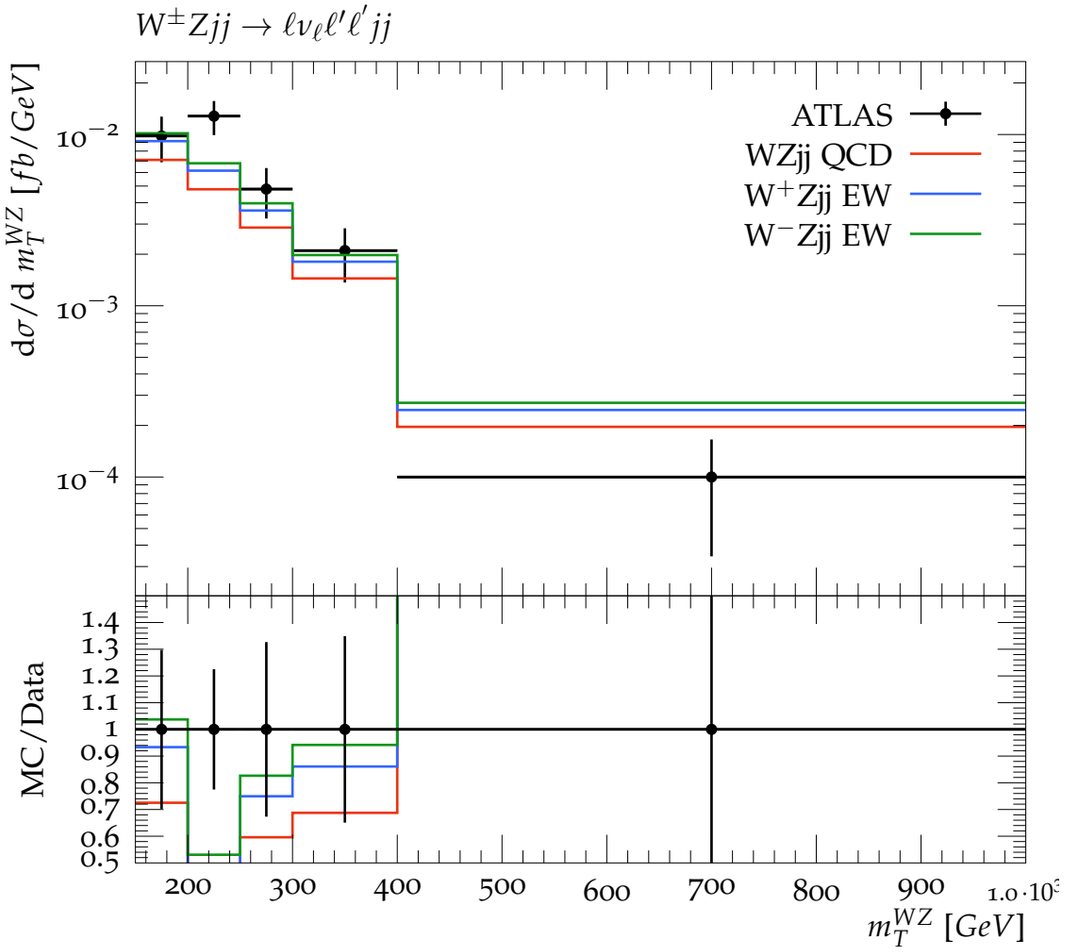
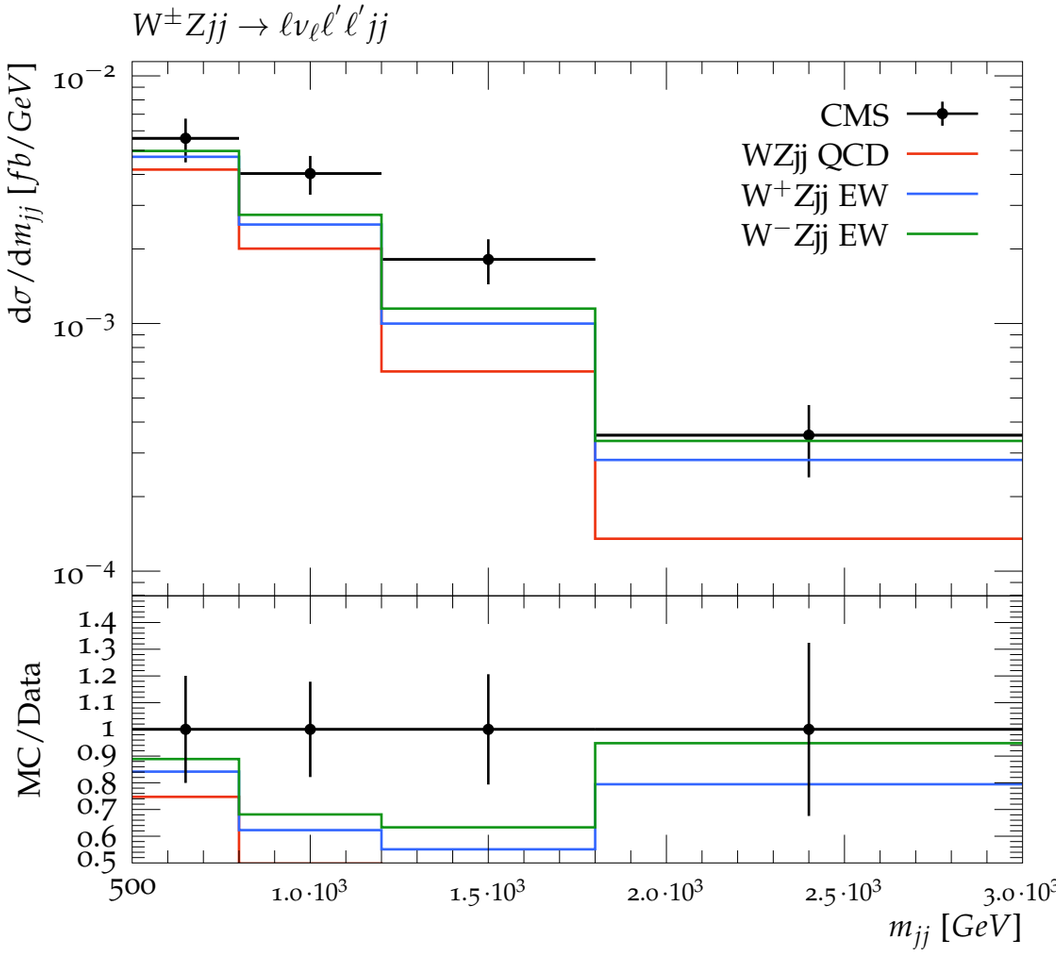
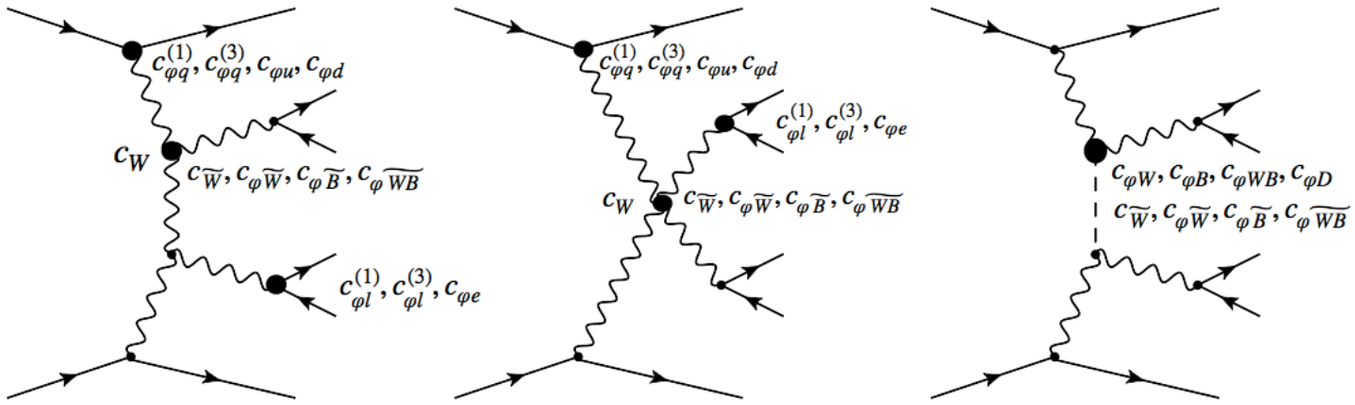


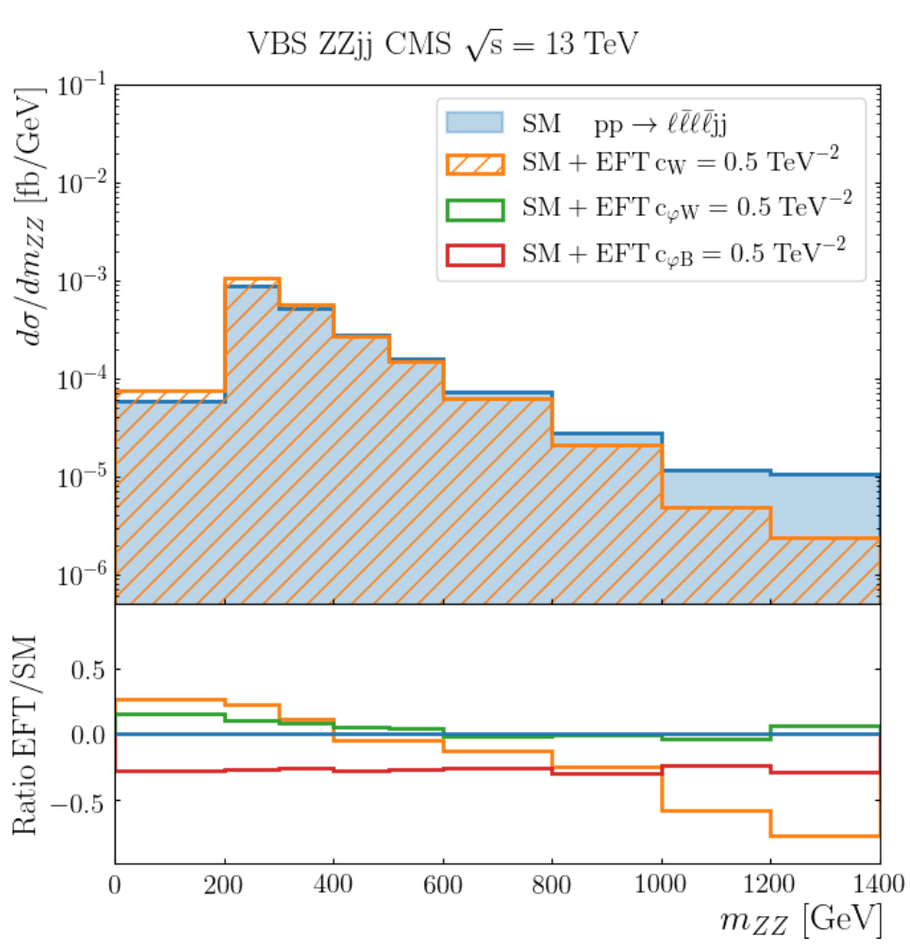
HEPData

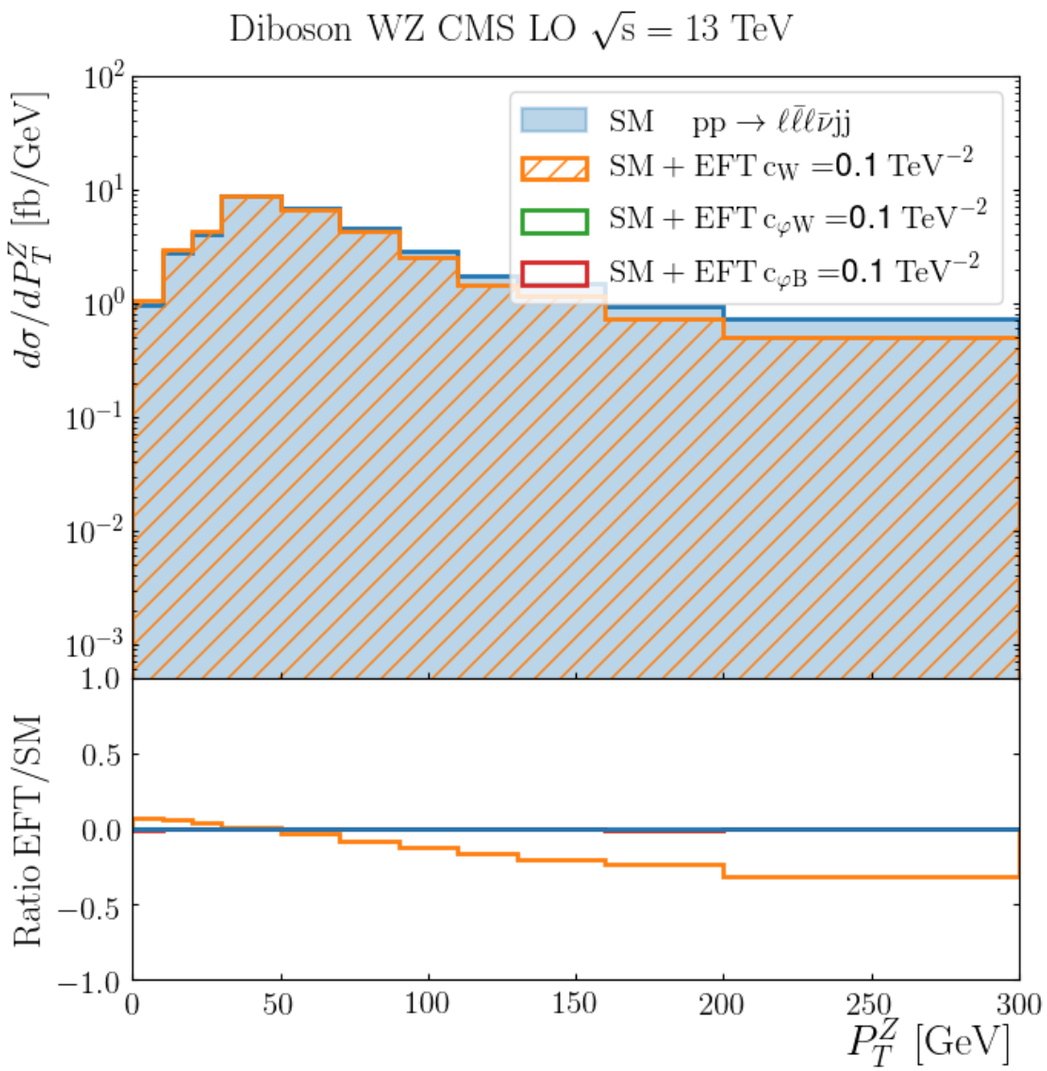


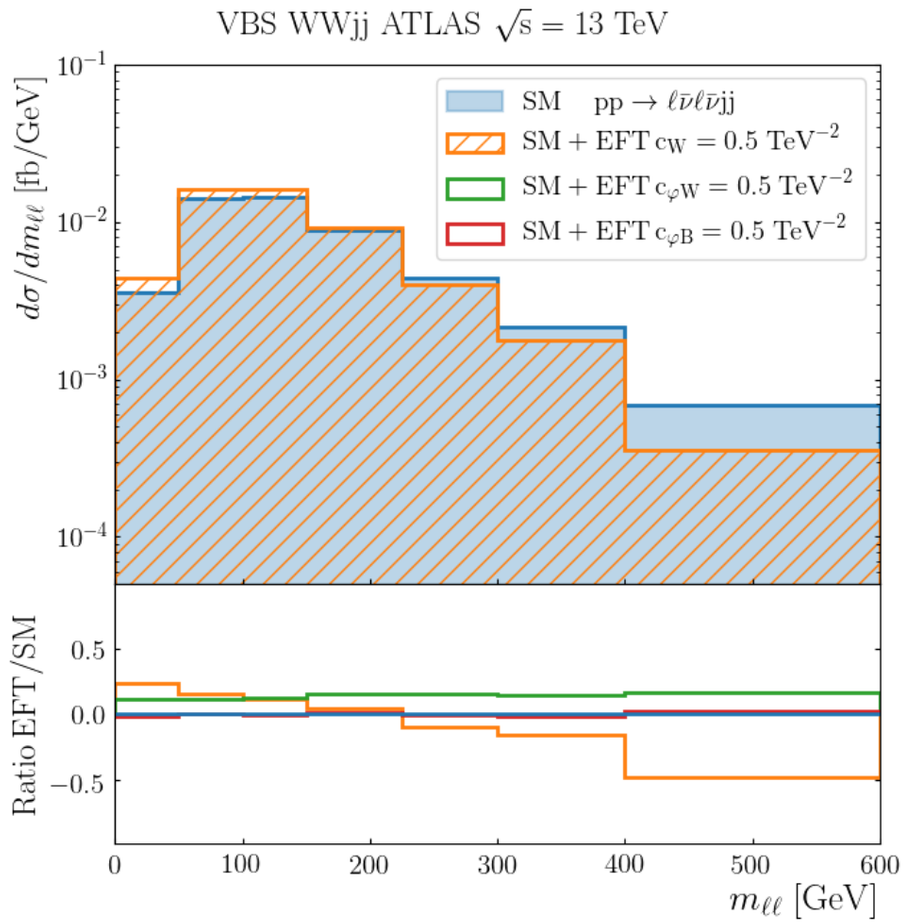


*In practise it is questionable if the amount of effort needed for this is worth it


c_W
$c_{\varphi q}^{(1)}, c_{\varphi q}^{(3)}, c_{\varphi u}, c_{\varphi d}$
$c_{\widetilde{W}}, c_{\varphi\widetilde{W}}, c_{\varphi\widetilde{B}}, c_{\varphi\widetilde{WB}}$
$c_{\varphi l}^{(1)}, c_{\varphi l}^{(3)}, c_{\varphi e}$
$c_{\varphi W}, c_{\varphi B}, c_{\varphi WB}, c_{\varphi D}$


VBS ZZjj CMS $\sqrt{s} = 13$ TeV
SM $pp \to \ell\bar{\ell}\ell\bar{\ell}jj$
SM + EFT $c_W = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.5$ TeV^{-2}
$d\sigma/dm_{ZZ}$ [fb/GeV]
Ratio EFT/SM
m_{ZZ} [GeV]


Diboson WZ CMS LO $\sqrt{s} = 13$ TeV
SM $pp \to \ell\bar{\ell}\ell\bar{\nu}jj$
SM + EFT $c_W = 0.1$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.1$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.1$ TeV^{-2}
$d\sigma/dP_T^Z$ [fb/GeV]
Ratio EFT/SM
P_T^Z [GeV]


VBS WWjj ATLAS $\sqrt{s} = 13$ TeV
SM $pp \to \ell\bar{\nu}\ell\bar{\nu}jj$
SM + EFT $c_W = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi W} = 0.5$ TeV^{-2}
SM + EFT $c_{\varphi B} = 0.5$ TeV^{-2}
$d\sigma/dm_{\ell\ell}$ [fb/GeV]
Ratio EFT/SM
$m_{\ell\ell}$ [GeV]

FITTING STRATEGY

- Define the figure of merit to minimise as:

$$\chi^2(c_k) = \frac{1}{N_{data}} \sum (O_{exp,i} - O_{th,i})(cov^{-1})_{ij} O_{exp,j} - O_{th,j})$$

- Include available experimental uncertainties, correlations and theory uncertainties (*from MC and pdfs*).
- Use **NESTED SAMPLING.** Sampling the posterior as:

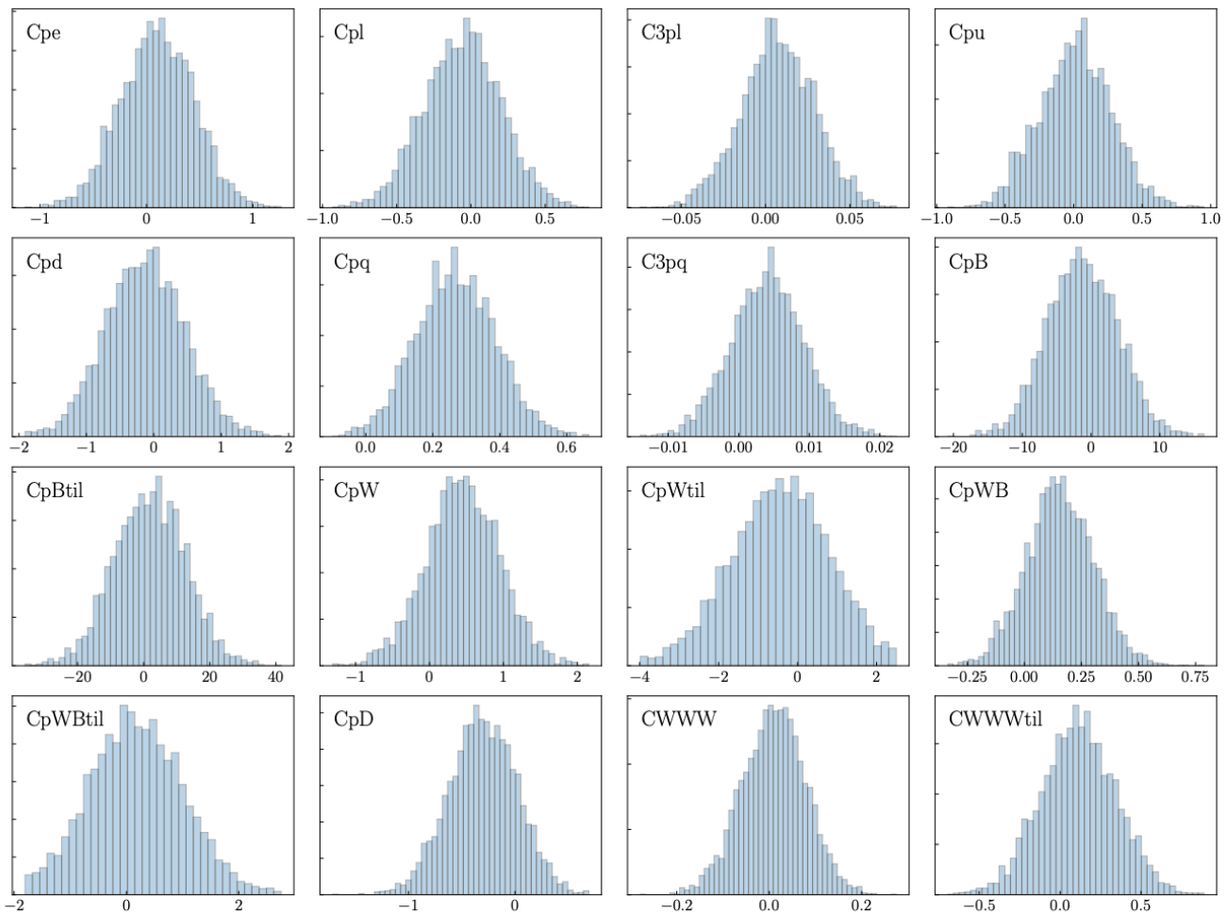
$$p(c_k \,|\, data) = \frac{1}{Z} \mathscr{L}(data \,|\, c_k) \Pi(c_k)$$

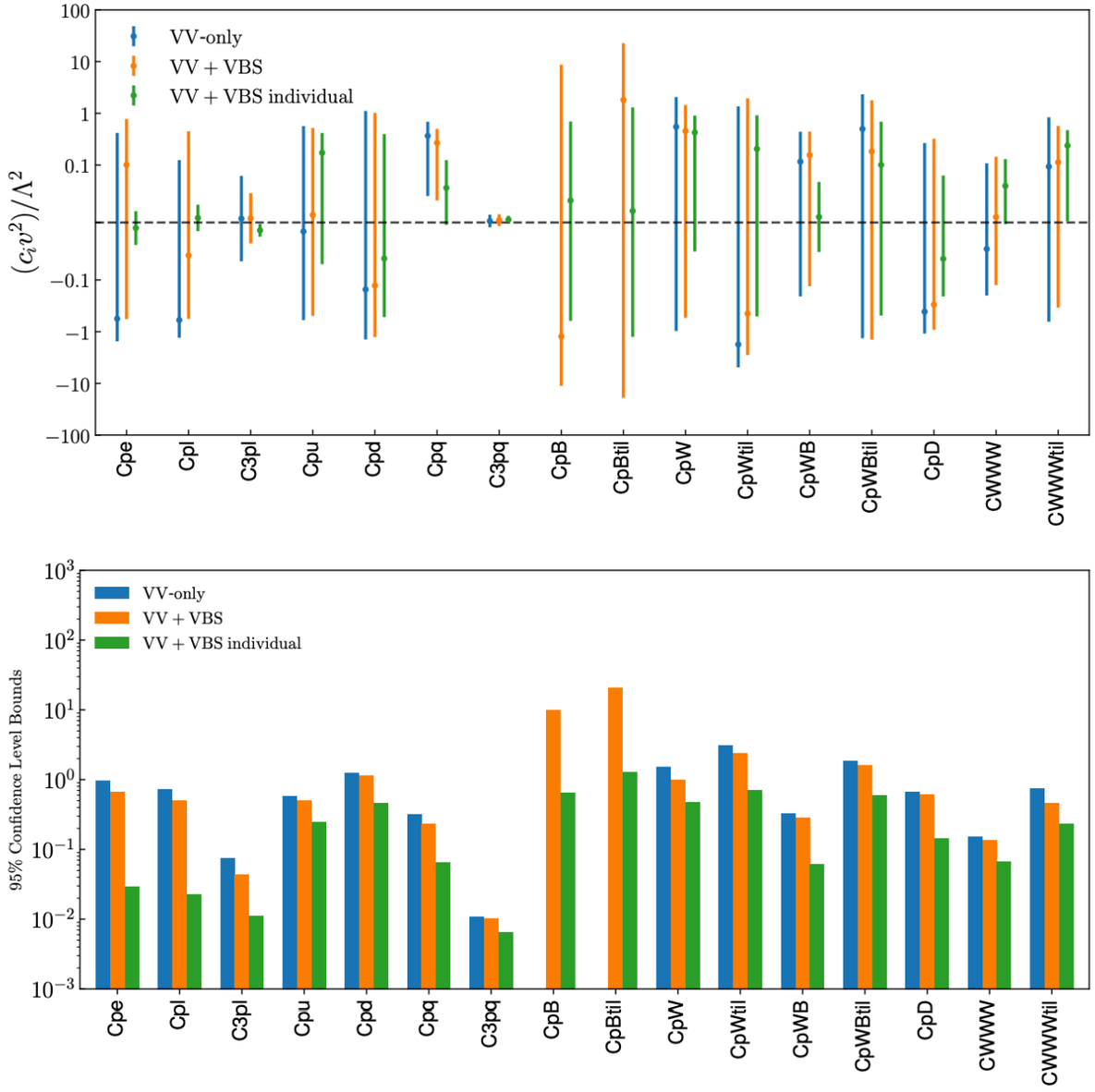
Multi Gaussian Likelihood

Prior, assumed flat

Fit output

VV+VBS fit



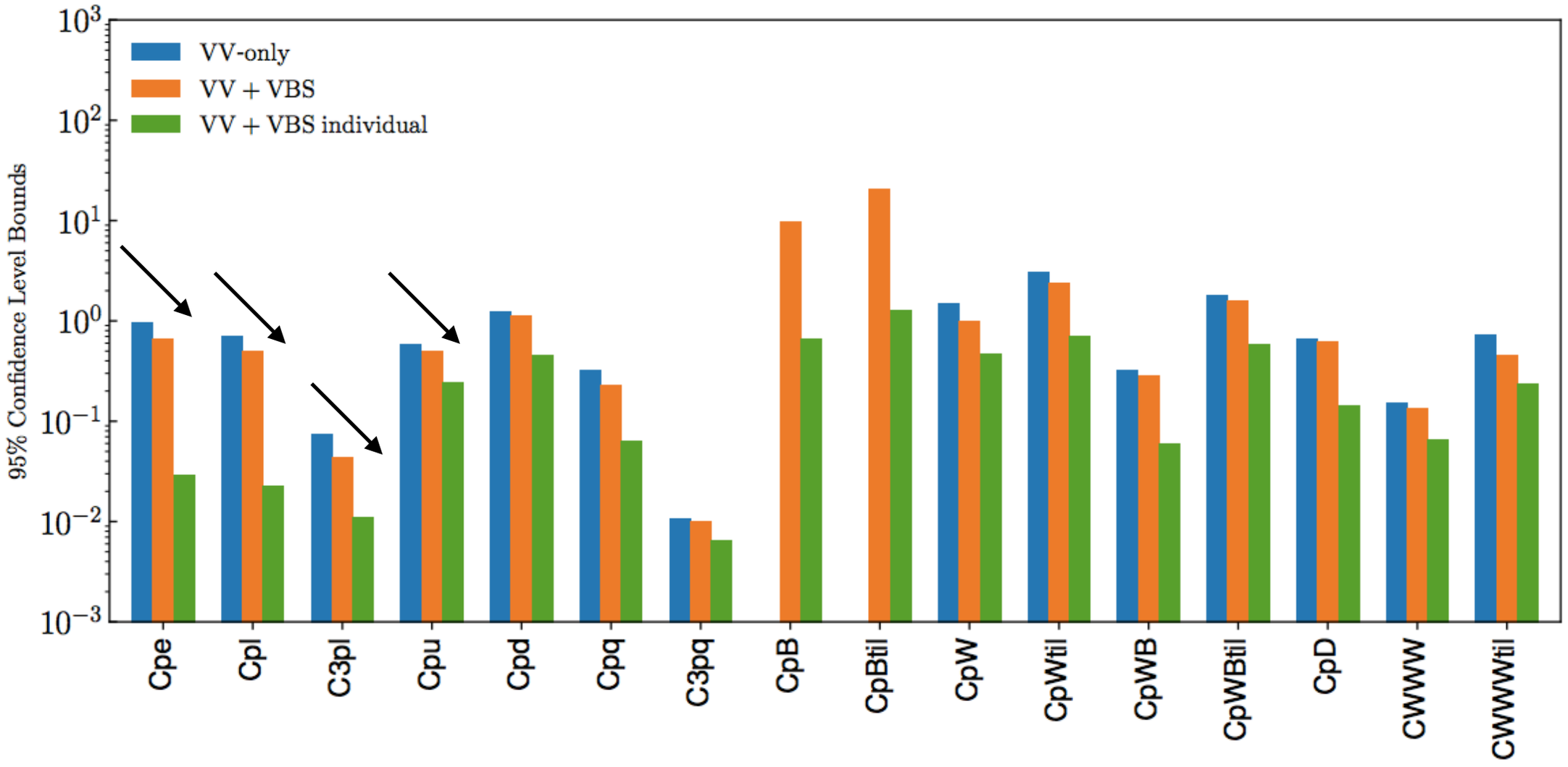


Posterior distribution VV+VBS

Central values and 95 % CL

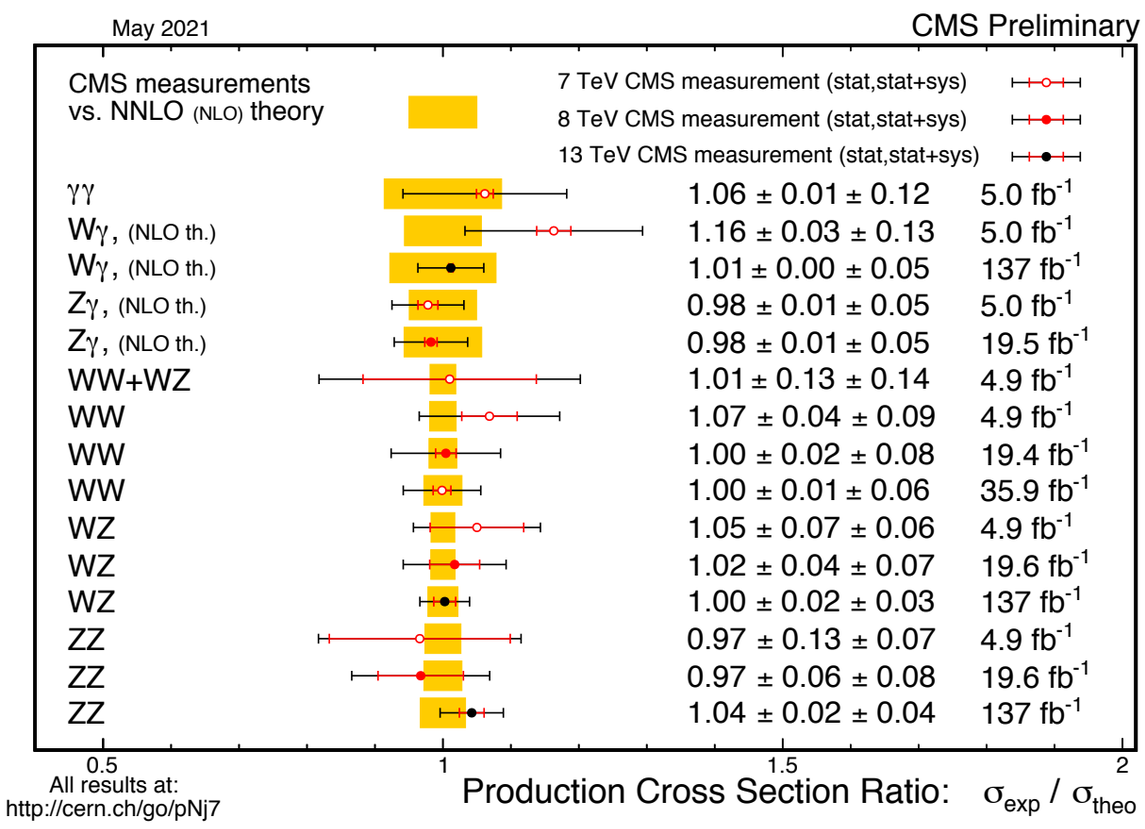
ph-hep/2101.03180

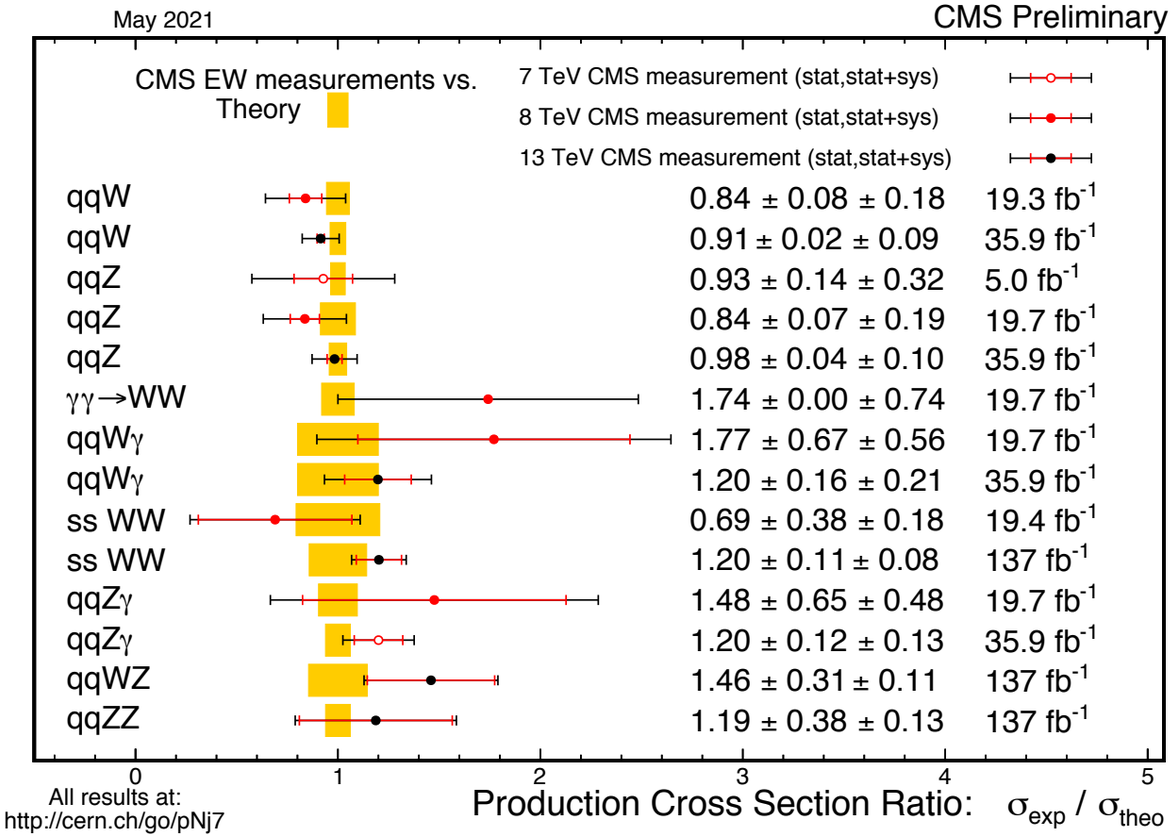
- Very satisfactory results but:
  - Difficult to scale up
  - Don’t teach much about the Higgs potential (however, stress test of the EWSB)



Next Steps

- Many extra channels/distributions became available in 2021 and more are expected to come in 2022
- Add quadratic terms and dimension 8 operators
- Global fit including LEP + LHC Higgs/top/EW data





Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC

The SMEFiT Collaboration:

Jacob J. Ethier,[1,2] Giacomo Magni,[1,2] Fabio Maltoni,[3,4] Luca Mantani,[3]
Emanuele R. Nocera,[2,5] Juan Rojo,[1,2], Emma Slade,[6] Eleni Vryonidou,[7] and Cen Zhang[8,9]

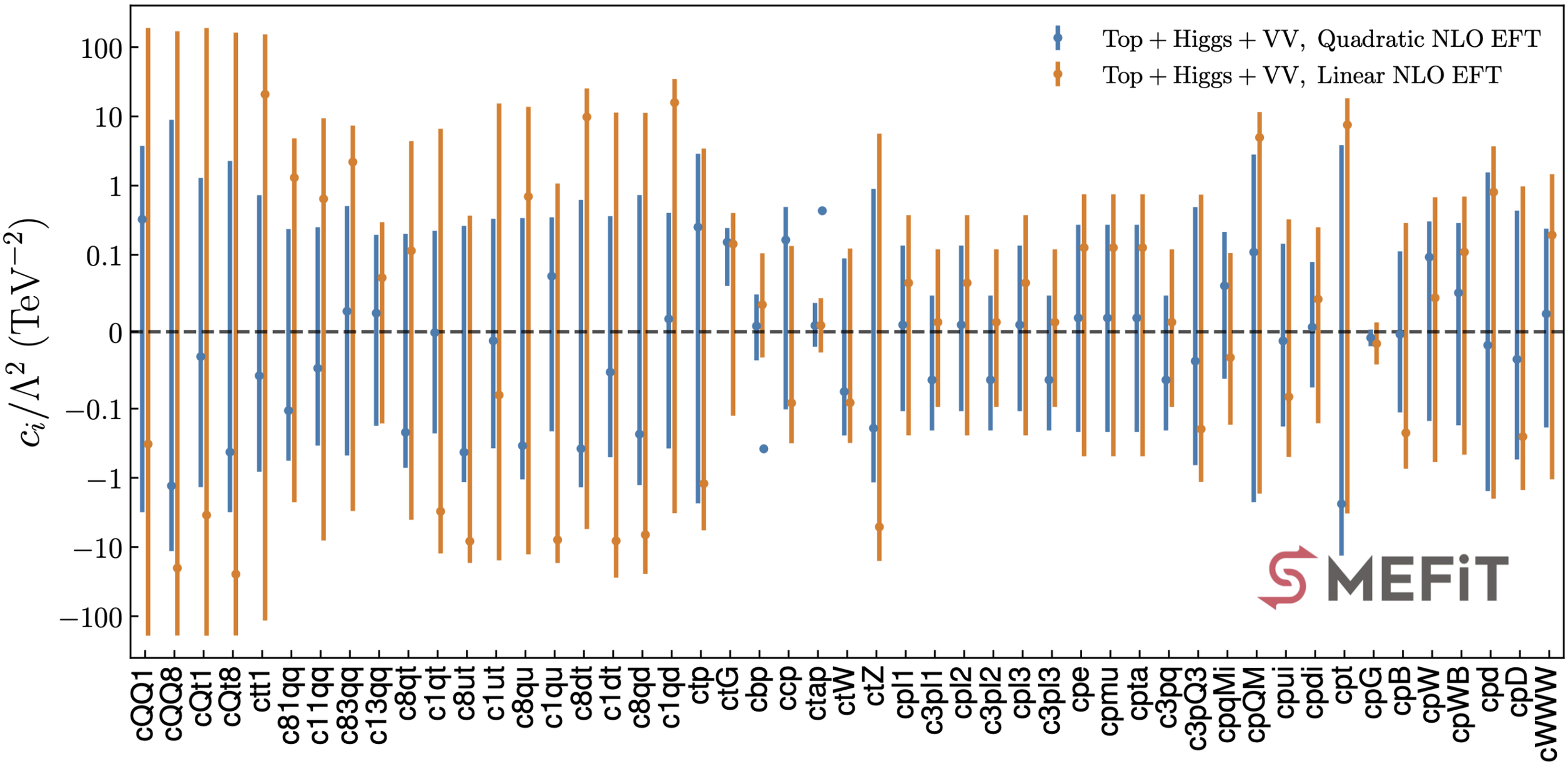
Include linear + quadratic terms
Not full PS + hepdata approach (partonic approx.)

ph-hep/ 2105.00006

Category	Processes	$n_{\rm dat}$
Top quark production	$t\bar{t}$ (inclusive)	94
	$t\bar{t}Z$, $t\bar{t}W$	14
	single top (inclusive)	27
	tZ, tW	9
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6
	Total	**150**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	40
	Run II, differential distributions & STXS	35
	Total	**97**
Diboson production	LEP-2	40
	LHC	30
	Total	**70**
Baseline dataset	**Total**	**317**

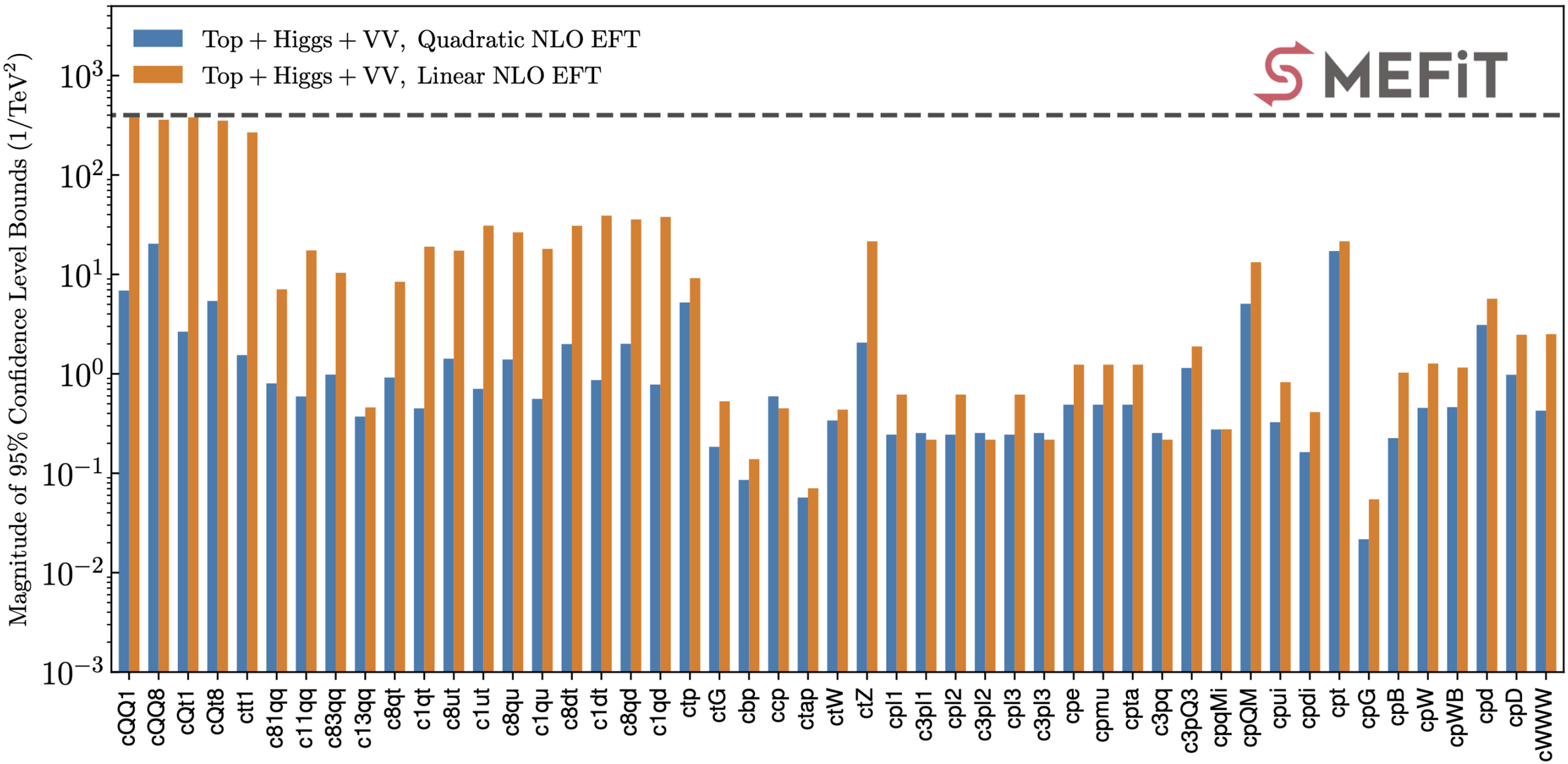
EFT fits:

$$\sigma_{EFT} = \sigma_{SM} + \underbrace{\sigma_{int,6}}_{linear} + \underbrace{\sigma_{pure,6} + \sigma_{int,8}}_{quadratic} + \ldots$$



ph-hep/2105.00006

EFT fits:



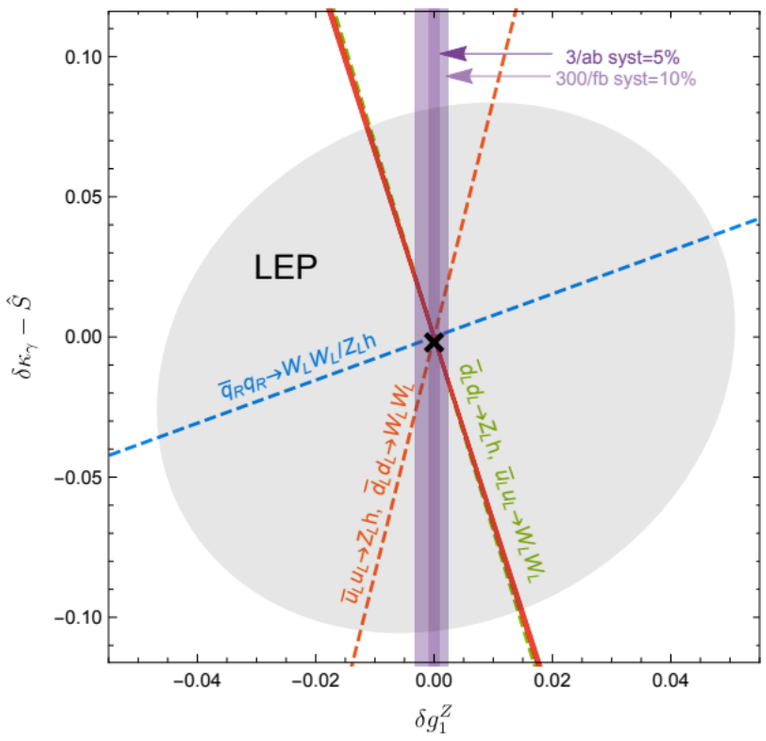
It seems that we can claim no new physics at LHC...
& Best constraints come from Higgs data

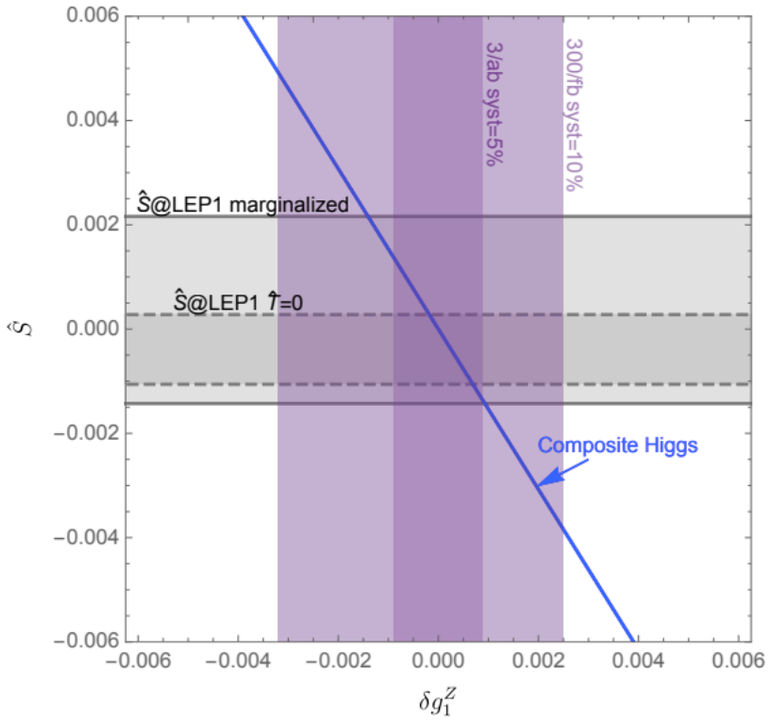
Worth checking: EWPD at LHC

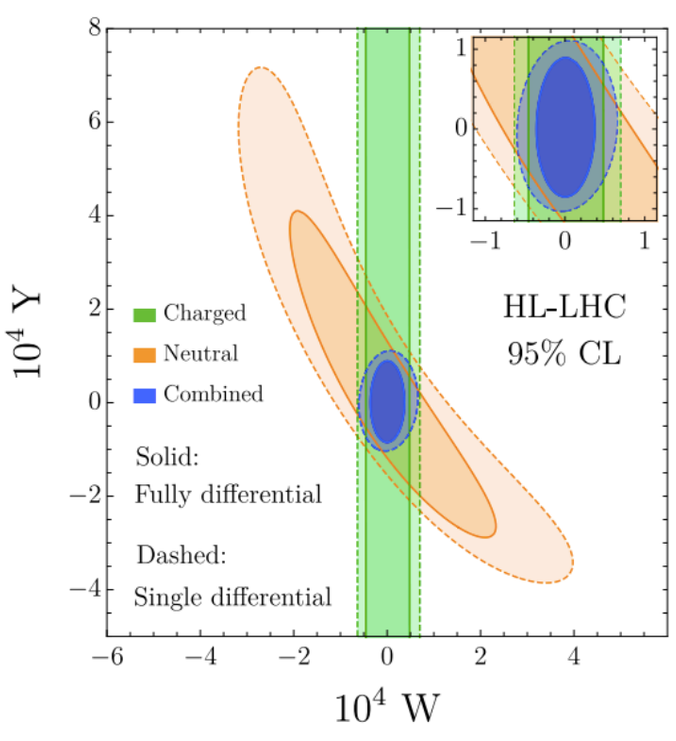
High-energy EFT probes with fully differential Drell–Yan measurements

Giuliano Panico[1,2], Lorenzo Ricci[3], and Andrea Wulzer[3,4,5]

https://arxiv.org/abs/2103.10532







https://arxiv.org/abs/1712.01310

Bottlenecks

- There are some bottlenecks on the path towards a global fit goal of the full LHC dataset at dim 6 + 8

- Technical: CPU resources

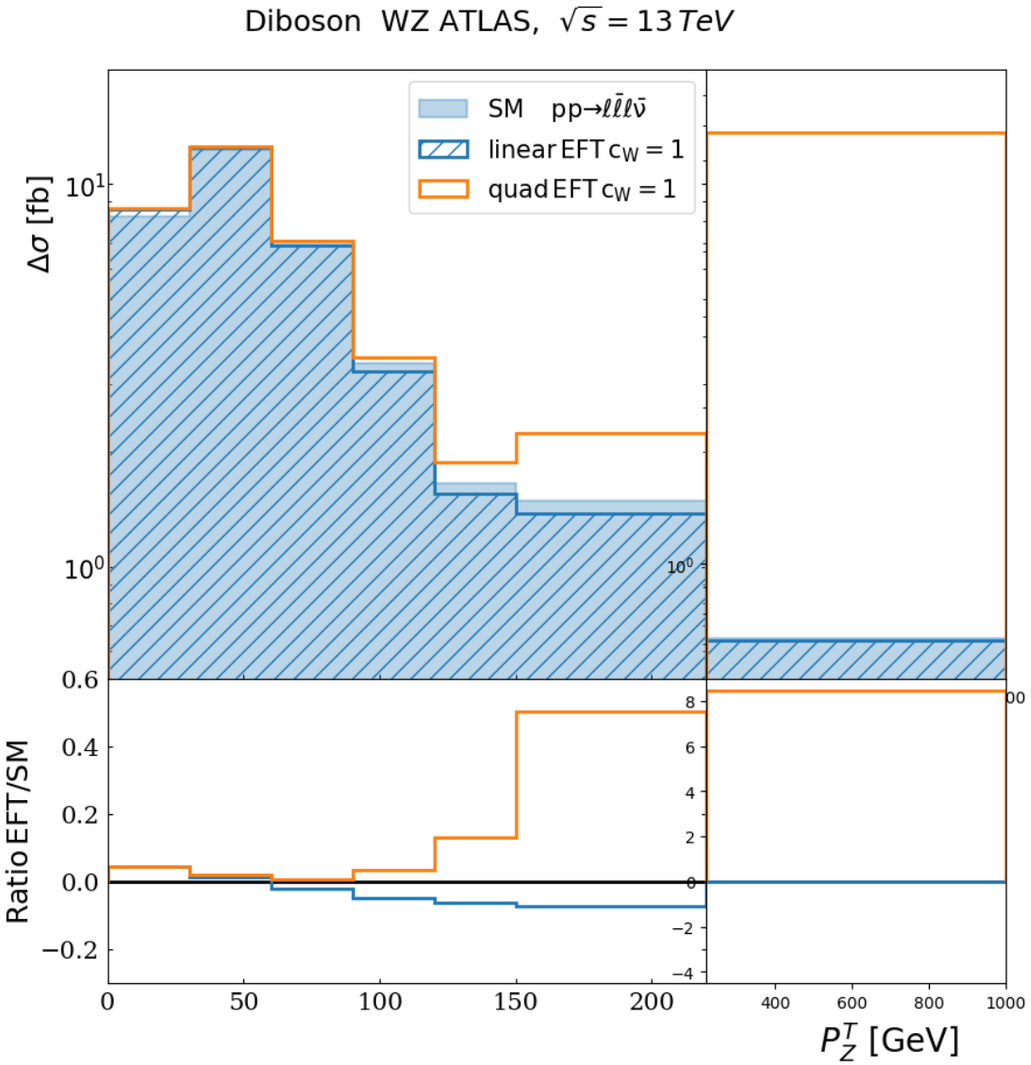
- Fundamental: effectiveness of the differential distribution approach

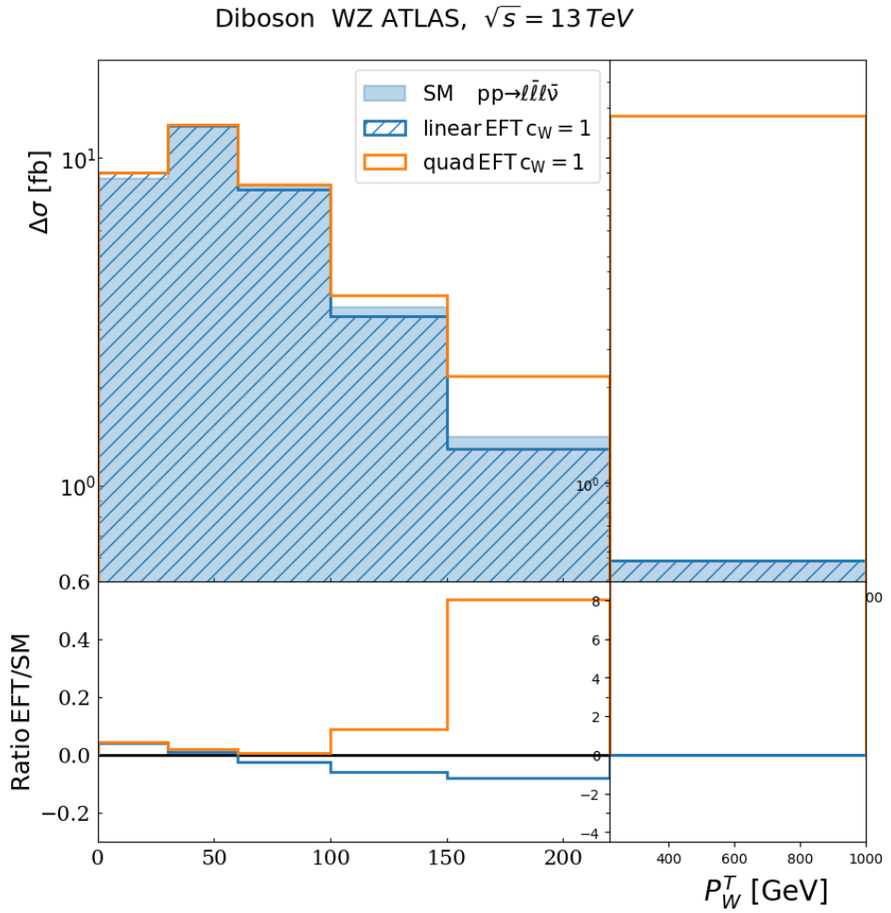
Possible solutions

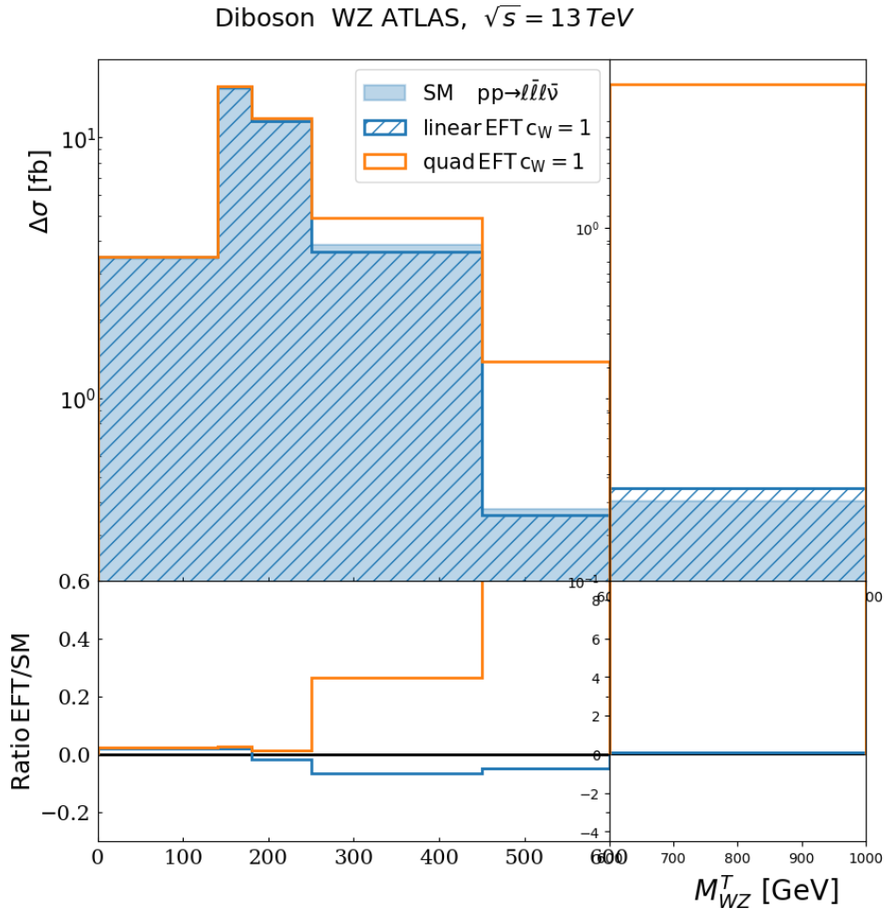
- Unbinned cross sections/ Pseudo Observables
- Machine Learning: supervised/unsupervised
- GPU acceleration/Quantum Computing

- Differential distributions for linear + quadratic dimension 6 EFT

- In general I have to guess what the optimal observable for the fit is







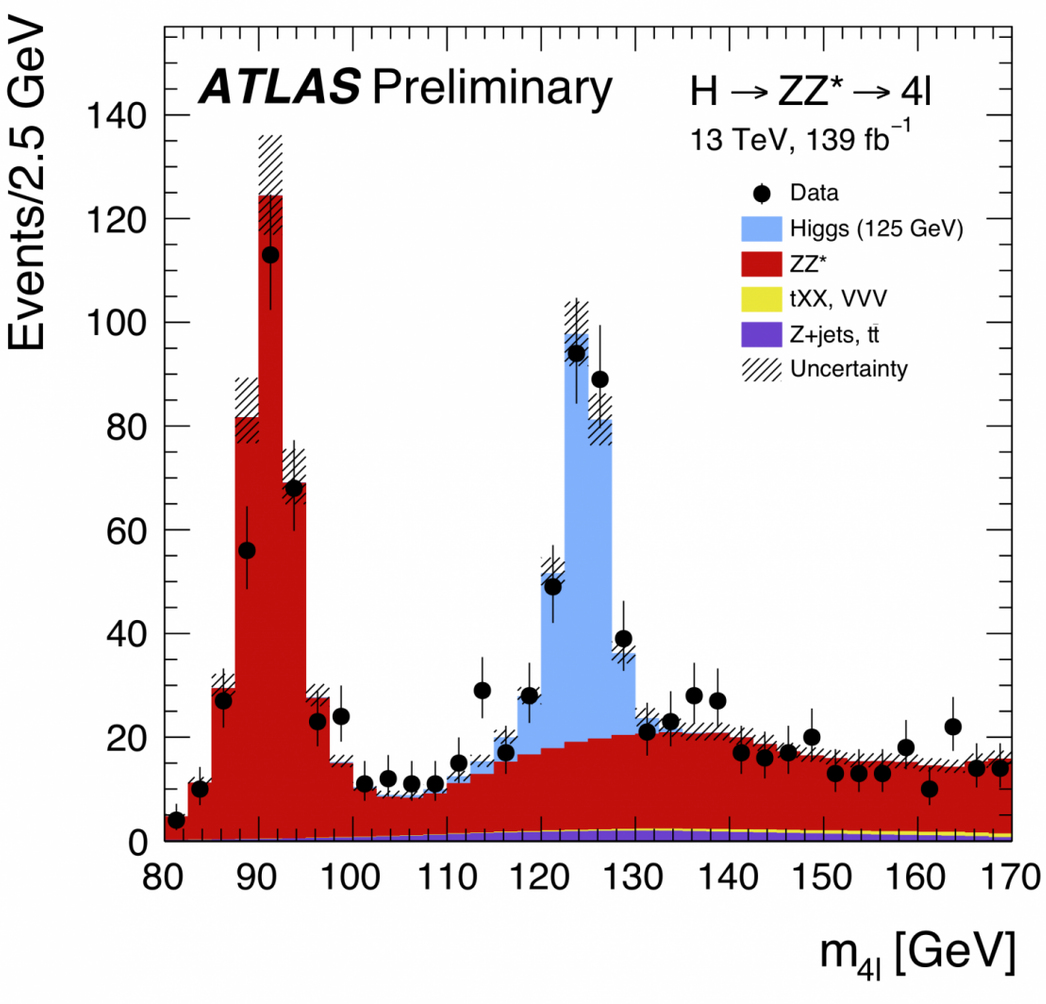
Work in progress with K. Lohwasser et al.

An added problem (or not?):

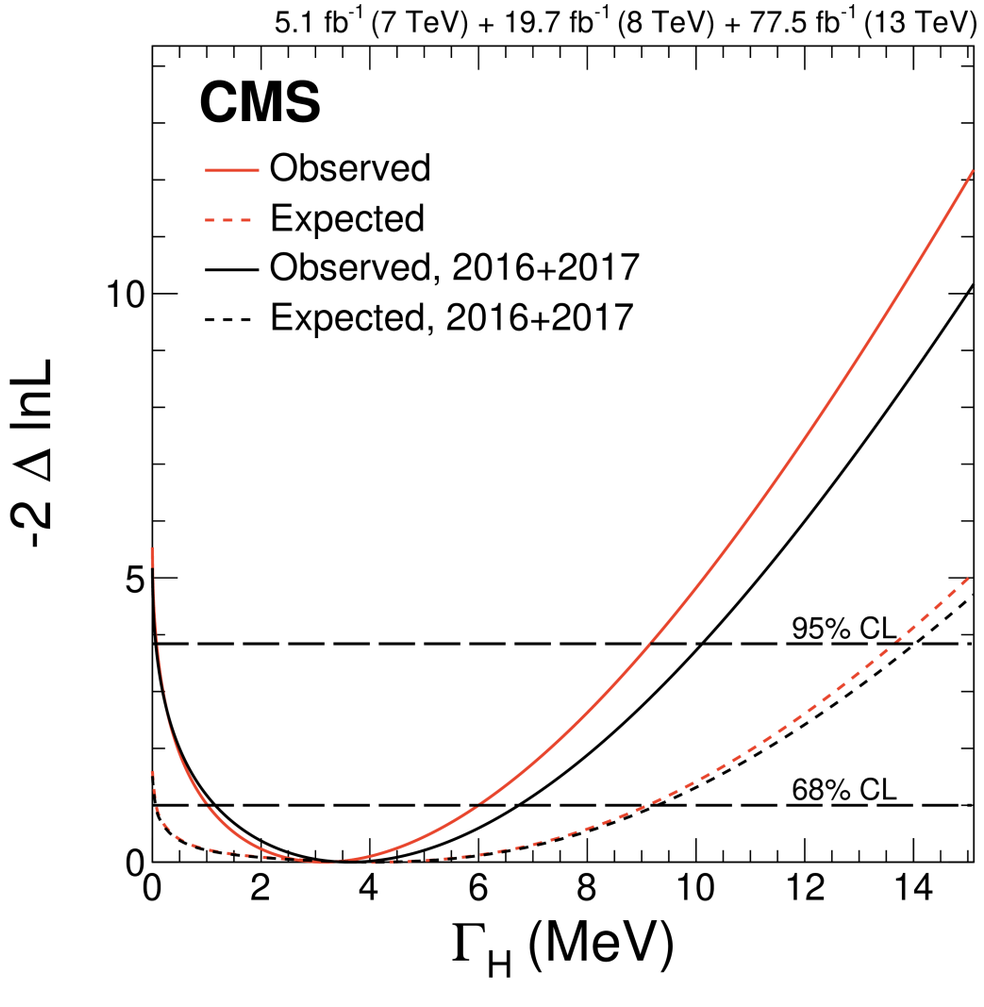
New physics doesn't show up at the level of the screen
(I didn't understand this sentence for much of my PhD)

How relevant is the unfolding procedure then? Can we circumvent it?

2012



202x



The elephant in the room: CPU resources

$$\sigma_{EFT} = \sigma_{SM} + \underbrace{\sigma_{int,6}}_{linear} + \underbrace{\sigma_{pure,6} + \sigma_{int,8}}_{quadratic} + \dots$$

1 prediction
(f.ex.500k events)

50 predictions
(25M events)

$$50 + \binom{50}{2} = 50 + 1225 = 1275$$

1275 predictions
(637M events)

"days" of CPU

100K = 500 MB
500K = 2.5GB

Example: 1 analysis, 50 EFT operators

The elephant in the room: CPU resources

If we restrict ourselves to only 10 operators...

$$\sigma_{EFT} = \sigma_{SM} + \underbrace{\sigma_{int,6}}_{linear} + \underbrace{\sigma_{pure,6} + \sigma_{int,8}}_{quadratic} + \dots$$

1 prediction
(500k events)

10 predictions
(5M events)

1275 predictions
(27.5M events)

$$10 + \binom{10}{2} = 10 + 45 = 55$$

If phase space cuts change in Run 3, we need to restart all the process

The elephant in the room: CPU* resources

LHC fits, as we know them, are - apparently - neither scalable nor sustainable

*

MadFlow: automating Monte Carlo simulation on GPU for particle physics processes

Stefano Carrazza[1,2,3], Juan Cruz-Martinez[1], Marco Rossi[1,2], Marco Zaro[1]

[1] TIF Lab, Dipartimento di Fisica, Università degli Studi di Milano and INFN Sezione di Milano.
[2] CERN Theoretical Physics Department and OpenLab, CH-1211 Geneva 23, Switzerland.
[3] Quantum Research Centre, Technology Innovation Institute, Abu Dhabi, UAE.

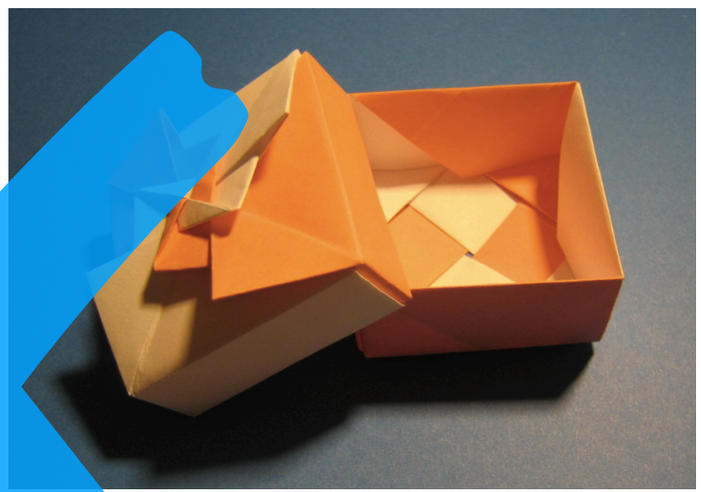
Pseudo Observables

A quantity I can calculate on an envelope (almost)

d1_squared_v4.frm

```
Global D1 =
*
* H to ZZ couplings
*
(
d_(mu1,mu3)*(chzz1sm+g6*chzzeft0) +
   g6*chzzeft1*(1/2)*g_(87,6_,mu1,p2,mu3,p3) +
   g6*chzzeft2*(1/2)*g_(88,7_,mu1,p2,mu3,p3)
)*
*
*Propagators
*
( d_(mu1,mu2)  + p2(mu1)*p2(mu2)/(M0^2) )*
( d_(mu3,mu4)  + p3(mu3)*p3(mu4)/(M0^2) )*
PropZ1*PropZ2*
*
* Traces
*
(
g_(1,6_,mu2)/2*(czll1sm + g6*czll1eft) +
g_(1,7_,mu2)/2*(czll2sm + g6*czll2eft) +
(1/2)*(g_(1,mu2,p2,6_)-g_(1,p2,mu2,6_))*g6*czll3eft +
(1/2)*(g_(1,mu2,p2,7_)-g_(1,p2,mu2,7_))*g6*czll4eft
```

Unbinned
Fiducial



STXS?

Unbinned Xsecs

Presenting Unbinned Differential Cross Section Results

Miguel Arratia,[a,b] Anja Butter,[c] Mario Campanelli,[d] Vincent Croft,[e] Dag Gillberg,[f] Kristin Lohwasser,[g] Bogdan Malaescu,[h] Vinicius Mikuni,[i] Benjamin Nachman,[j,k] Juan Rojo,[l,m] Jesse Thaler,[n,o] Ramon Winterhalder[p]

https://arxiv.org/abs/2109.13243

Machine learning + Matrix element

https://arxiv.org/abs/2109.10414

Back to the Formula — LHC Edition

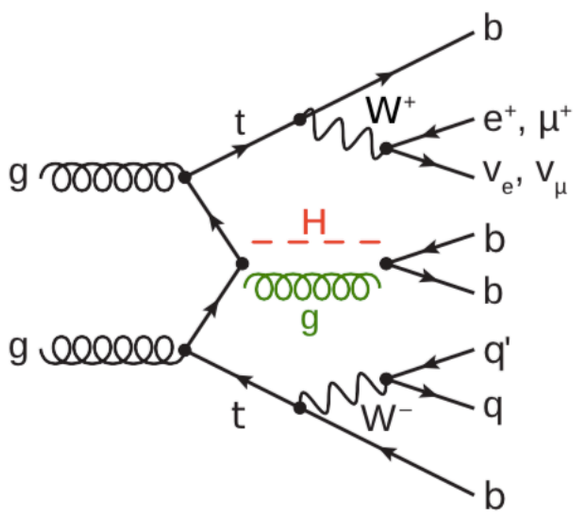
Anja Butter, Tilman Plehn, and Nathalie Soybelman

AND THE (NEAR) FUTURE?

Quantum Sensing/ Quantum Computing

- Many advantages to a quantum computer:
  - + Efficient
  - - Energy
  - ++++ Supremacy

Quantum Computing for the Higgs



6 qubits -> 64 variables

Hybrid algorithm: classic + quantum

Reproduce classic results!

Higgs analysis with quantum classifiers

Vasilis Belis[1,*], *Samuel* González-Castillo[2], *Christina* Reissel[1], *Sofia* Vallecorsa[3], *Elías* F. Combarro[4], *Günther* Dissertori[1], and *Florentin* Reiter[5]

[1]Institute of Particle Physics and Astrophysics, ETH Zürich, Zürich, Switzerland
[2]Faculty of Sciences, University of Oviedo, Oviedo, Spain
[3]CERN, 1, Esplanade des Particules, Geneva, CH 1211
[4]Department of Computer Science, University of Oviedo, Oviedo, Spain
[5]Institute for Quantum Electronics, ETH Zürich, Zürich, Switzerland

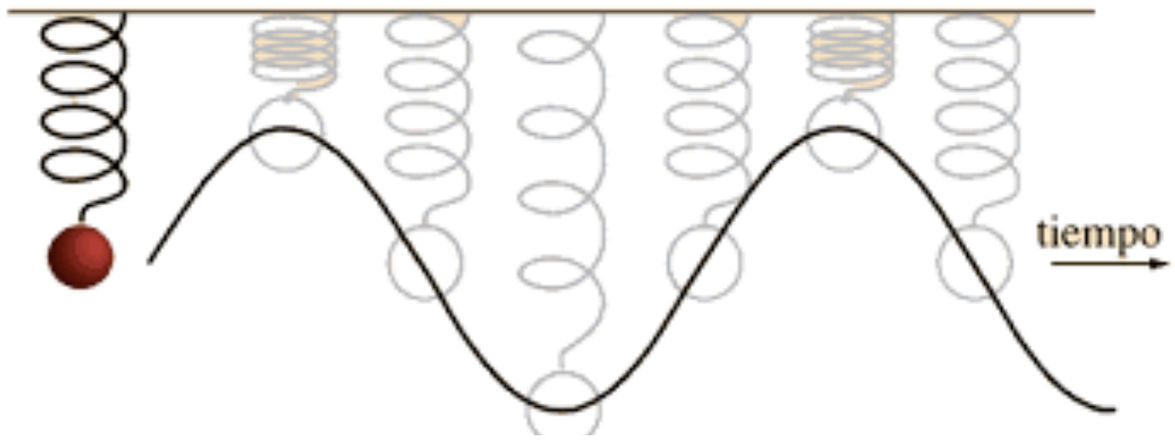
QC seems to be an optimal tool for the study of multidimensional problems

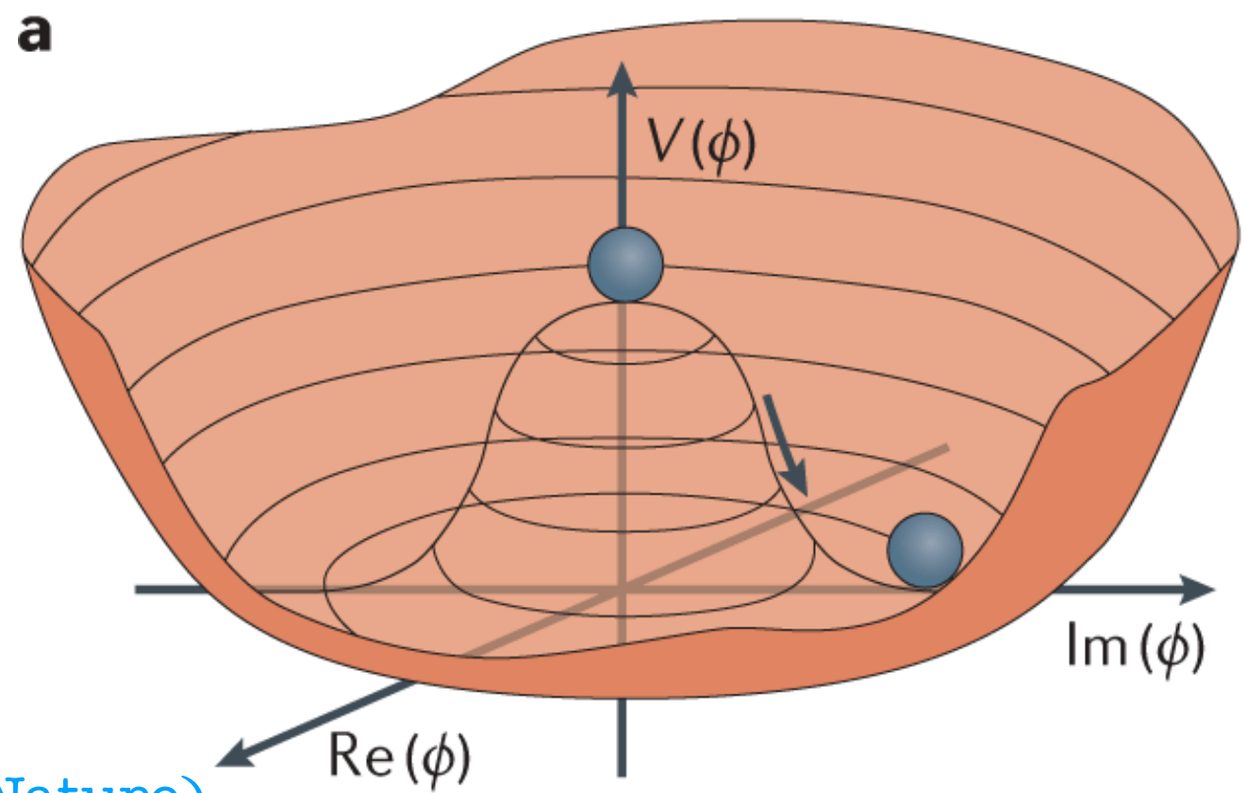
https://inspirehep.net/literature/1858884

LAST BUT NOT LEAST...

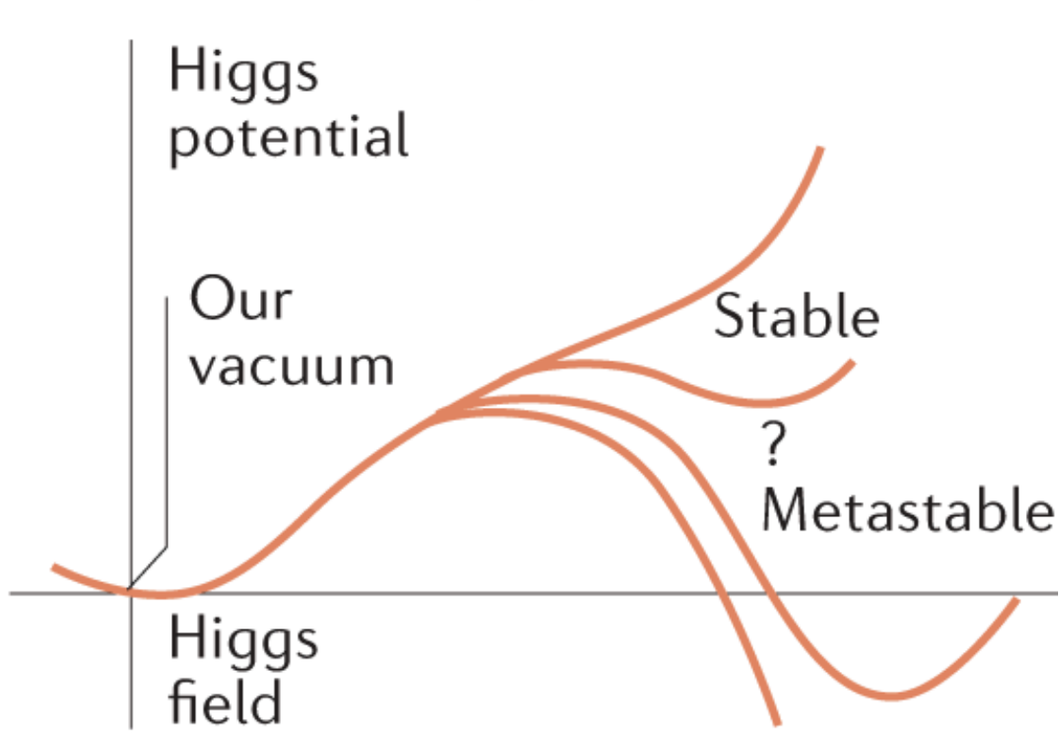
(The main challenge that LHC faces in the next 2 decades)

We still don't know much about the Higgs potential

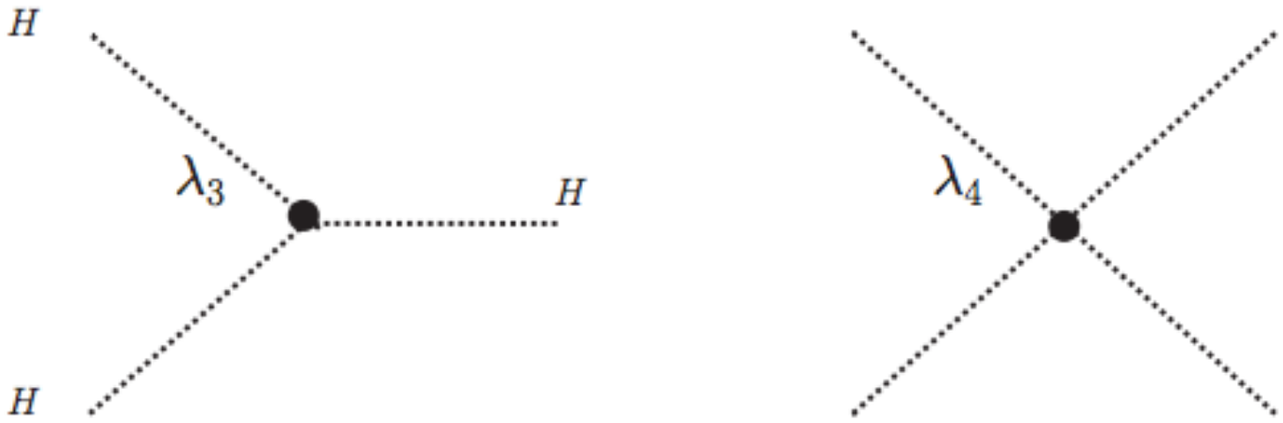




(Nature)

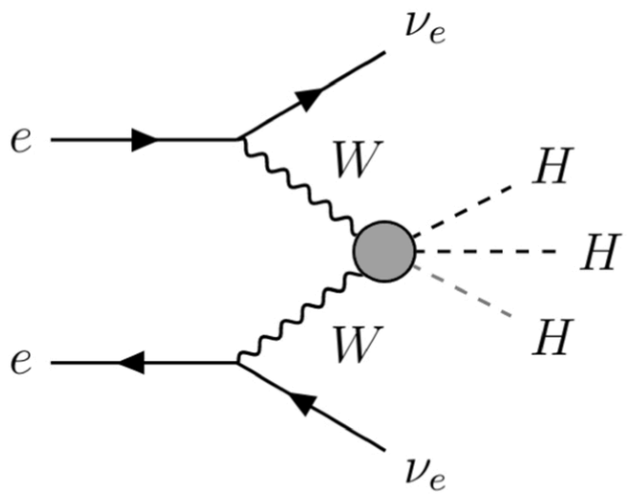


In the SM: $\lambda_3 = \lambda_4$

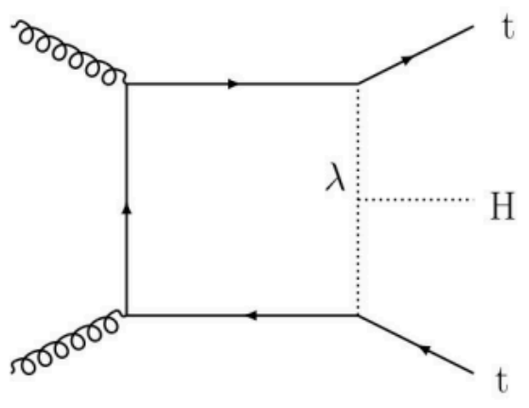


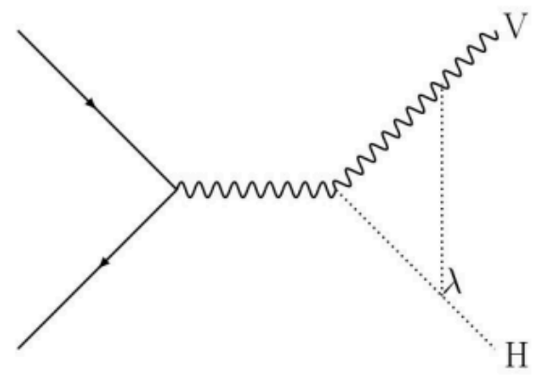
Yet, we have no experimental evidence for this.

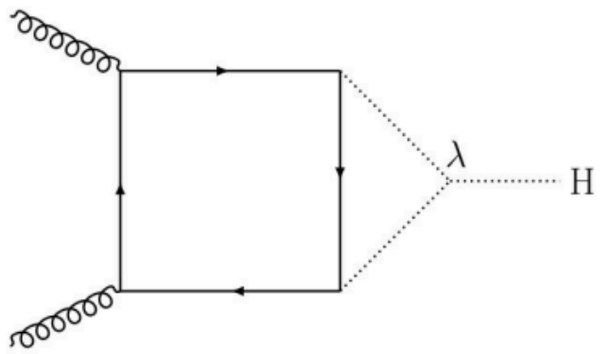
The H self coupling is accesible through multi Higgs production at leading order, or through loop processes in Higgs production and decay

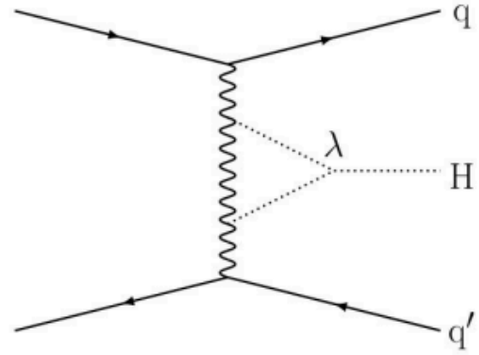


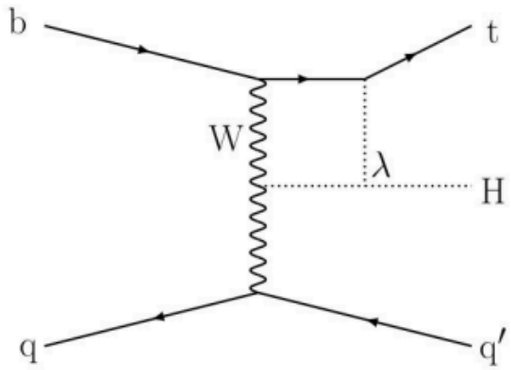
Multi Higgs production not accesible before HL-LHC











In the meantime...

- We can look at geometric (re)interpreations of the SM and its extensions

Geometry of the Scalar Sector

Rodrigo Alonso,[1] Elizabeth E. Jenkins,[1,2] Aneesh V. Manohar[1,2]

1. *Department of Physics, University of California at San Diego, La Jolla, CA 92093, USA*
2. *CERN TH Division, CH-1211 Geneva 23, Switzerland*

1605.03602

Is SMEFT Enough?

Timothy Cohen,[a] Nathaniel Craig,[b] Xiaochuan Lu,[a] and Dave Sutherland[c]

[a] *Institute for Fundamental Science, University of Oregon, Eugene, Oregon 97403, USA*
[b] *Department of Physics, University of California, Santa Barbara, CA 93106, USA*
[c] *INFN Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy*

2008.08597

SMEFT

$$\vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_4 + i\phi_3 \end{pmatrix}$$

HEFT

$$h \qquad \text{and} \qquad \vec{n} = \begin{pmatrix} n_1 = \pi_1/v \\ n_2 = \pi_2/v \\ n_3 = \pi_3/v \\ n_4 = \sqrt{1 - n_1^2 - n_2^2 - n_3^2} \end{pmatrix}$$

- SMEFT scalar sector —> Linear sigma model
- HEFT —> Non-linear sigma model

The axial vector current in beta decay

M. Gell-Mann & M. Lévy

Il Nuovo Cimento (1955-1965) **16**, 705–726 (1960) | Cite this article

2132 Accesses | **2023** Citations | **3** Altmetric | Metrics

1960's!

HEFT - A new hope

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}[F(h)]^2 \partial_\mu \omega^i \partial^\mu \omega^j \left(\delta_{ij} + \frac{\omega^i \omega^j}{v^2}\right) + \frac{1}{2}\partial_\mu h \partial^\mu h \\
&+ \frac{4a_4}{v^4}\partial_\mu \omega^i \partial_\nu \omega^i \partial^\mu \omega^j \partial^\nu \omega^j + \frac{4a_5}{v^4}\partial_\mu \omega^i \partial^\mu \omega^i \partial_\nu \omega^j \partial^\nu \omega^j + \frac{g}{v^4}(\partial_\mu h \partial^\mu h)^2 \\
&+ \frac{2d}{v^4}\partial_\mu h \partial^\mu h \partial_\nu \omega^i \partial^\nu \omega^i + \frac{2e}{v^4}\partial_\mu h \partial^\nu h \partial^\mu \omega^i \partial_\nu \omega^i \ ,
\end{aligned}
$$

F(h) is the ww \to nh function:

$$F(h) = \sum_{n=0}^{\infty} c_n \left(\frac{h}{v}\right)^n$$

- Note that new, first work to connect the ChL with EWSB dates from 1993. Still the Chiral description of the EW sector has not yet been ruled out

- Big challenge: SMEFT and HEFT are related by field redefinition:

  - Classify them in terms of their SO(4) symmetry

What does SMEFT tell us about HEFT

$$\mathcal{L} = \frac{1}{2}\left[1 + 2\frac{h}{v} + \left(\frac{h}{v}\right)^2\right]\partial_\mu\omega^i\partial^\mu\omega^i + \left(\frac{1}{2} - \frac{c_{H\Box}(h+v)^2}{\Lambda^2}\right)\partial_\mu h\partial^\mu h$$

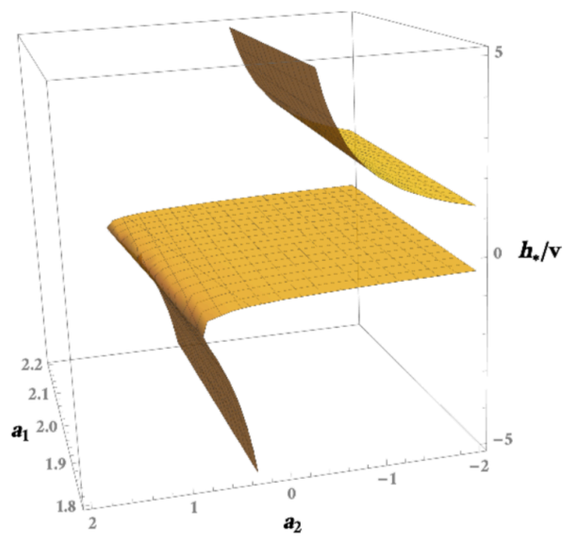
Add the SMEFT operators to the HEFT Lagrangian

$$F(h) = 1 + 2\frac{h}{v}\left(1 + \frac{c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h}{v}\right)^2\left(1 + \frac{4c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h}{v}\right)^3\left(\frac{8c_{H\Box}v^2}{3\Lambda^2}\right) + \left(\frac{h}{v}\right)^4\left(\frac{2c_{H\Box}v^2}{3\Lambda^2}\right)$$

a b c d

Compare the available constraints from both theories

$$a_1/2 = a \in [0.9, 1.1]\,, \quad a_2 = b \in [-2, 2]$$



Finding the O(4) symmetric point of F(h) could confirm or rule out HEFT

Work in progress with F. Llanes-Estrada, JJ Sanz-Cillero & A. Sala

Recap

- LHC fits as we know them are SMEFTcentric, and not efficient -> need alternatives

- Hundreds of papers address direct BSM searches, “exotics”, “invisibles”, as well as non-standard Higgs sectors

- Not so many works address the HEFT Vs SMEFT dilemma (though recently more and more do)

- POs might be the way out for both problems (scalability and universality)

A last trend: the environment

Workshop “Sustainable HEP”

Closing Statement (final list: 31th August 2021, 494 signatures)

On 28th–30th June 2021, the workshop “Sustainable High Energy Physics” took place by videoconferencing means with more than 350 registered participants from around 45 countries and five continents. The aim of this workshop was to initiate a community discussion on how to align the scientific operations within this particular subfield of physics with requirements of climate sustainability. Achieving the latter is a most pressing global issue for the present decade (as evidenced by the IPCC reports). The main focus of the workshop was on the scientific travel culture and the virtualisation of scientific exchange. The following topics were highlighted at this occasion:

- characteristics of the climate crisis
- best practice examples on the virtualisation of scientific meetings
- challenges for research institutions to improve their climate sustainability
- improvement of global inclusiveness in scientific exchange through virtualisation
- domains of action for large scale experiments to improve their climate sustainability

https://indico.cern.ch/event/1004432/page/22786-closing-statement

Conclusions:

Finding the (a) Higgs boson in 2012 was certainly satisfactory, and now we find ourselves in a complex period: several measurements remain to be done and the LHC is commissioned to run for another 20 years.

However, there are many different ways to perform and to report on these measurements and it seems that the process we are using might be hiding any hints of new physics.

The wisest thing might be to think out of the box and propose **creative solutions** to well known problems...

Grazie,
Gracias,
Thanks!