

New physics at the LHC

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IPPP Durham

LHC Run-3 just started
-> until 2025 (450 ifb)

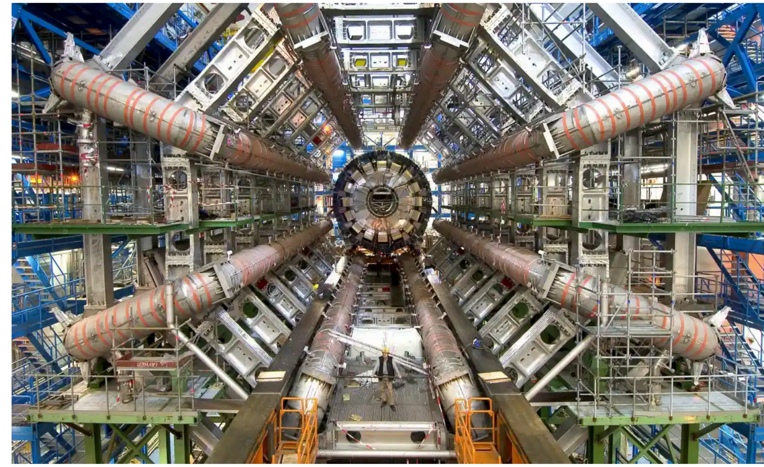
NEWS PARTICLE PHYSICS

The Large Hadron Collider has restarted with upgraded proton-smashing potential

After a three-year break, protons have begun circulating again in the particle accelerator

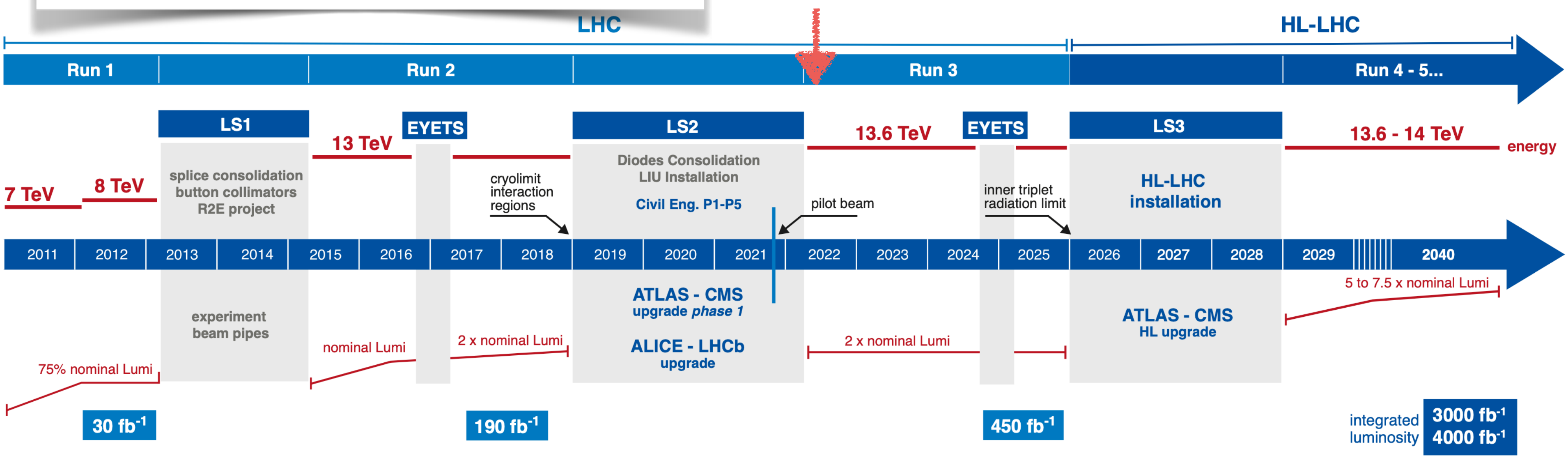
Large Hadron Collider to restart and hunt for a fifth force of nature

Latest run is expected to scrutinise findings from last year that may turn into another blockbuster discovery



The Large Hadron Collider has been given an upgrade ahead of its latest run, including the addition of powerful magnets designed to squeeze protons into finer, denser beams. Photograph: Cern/PA

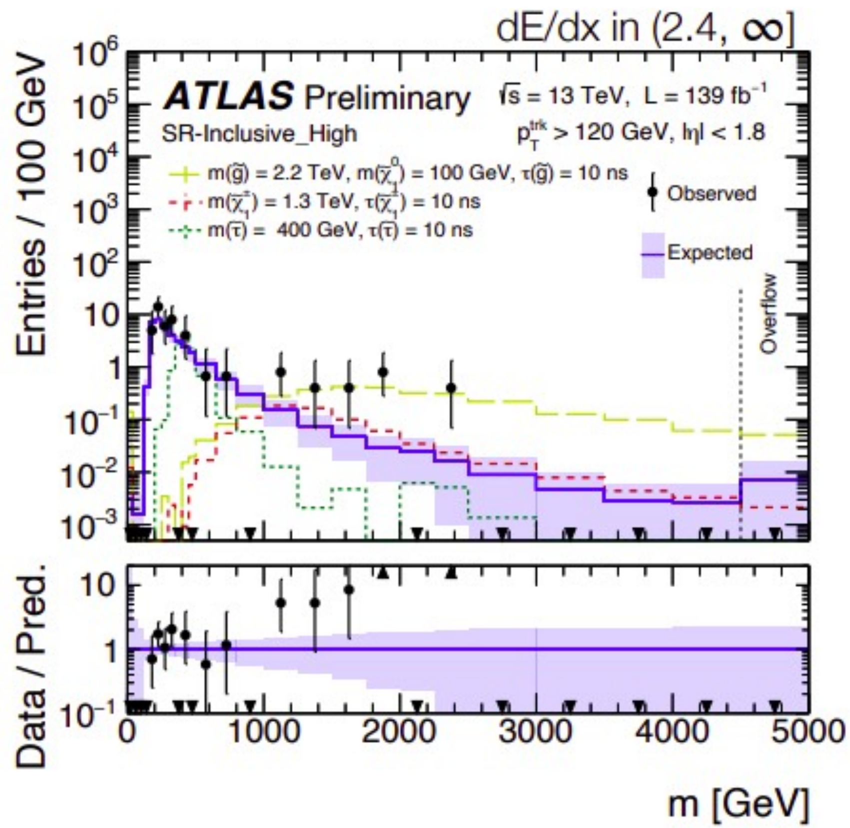
You are here



Some anomalies to keep an eye on

dE/dx - anomaly in ATLAS

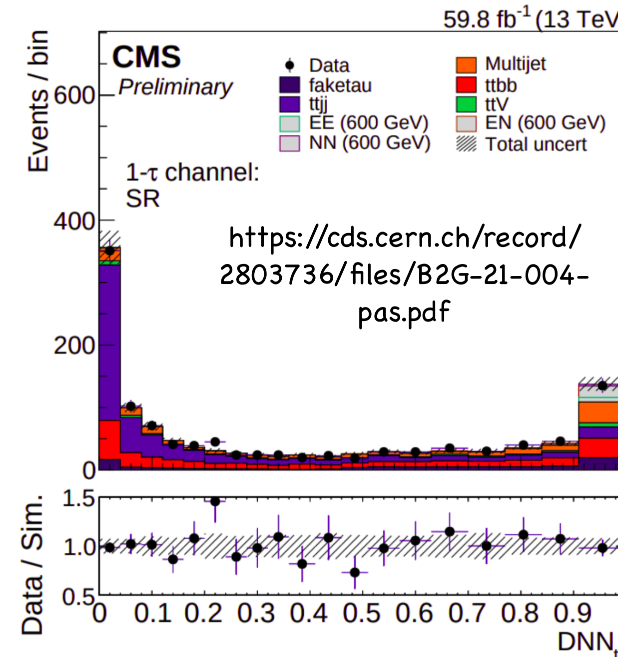
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2018-42/



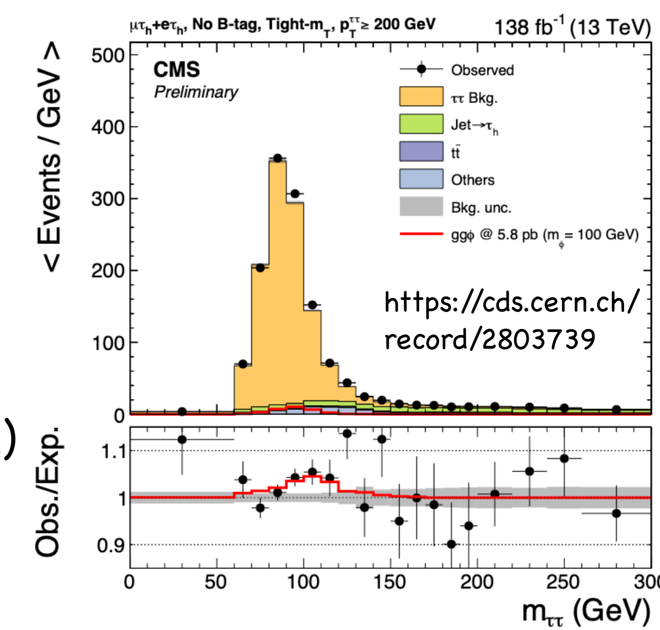
- Aim is to measure the masses of long-lived particles (decaying or not)
  - ➡ Idtify isolated tracks with large pT
  - ➡ reconstruct mass
  - ➡ use data-driven bkgs
- Energy-loss due to ionised radiation different from known particles
- Points towards heavy new particle
- Stat. signfic. 3.6 sigma local and 3.3 sigma global

Taus in CMS

- Search for vector-like leptons
  - ➡ final state 4b + 0/1/2 taus (hadr) + jets
  - ➡ rel. hard (b)-jets, HT > 400 GeV
  - ➡ DNN classifier (tt=signal vs tops)
  - ➡ Comb. 2017/18 -> 96.5 ifb -> 2.8 sigma

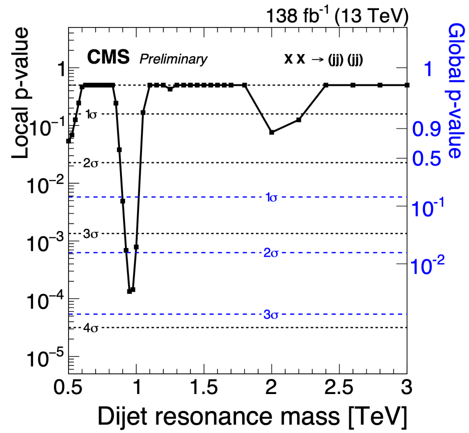


- Di-tau resonances at 0.1 and 1.2 TeV
  - ➡ Selection of leptonic, semileptonic and hadronic tau pairs
  - ➡ Isolation criteria for muons/electron
  - ➡ Transverse/Inv. masses point to two excesses:
    - ★ 100 GeV resonance 3.1 (2.7) local (global) (similar excess in 2 photon decay)
    - ★ 1.2 TeV resonance ~ 3 sigma



https://cds.cern.ch/record/2803669/files/EXO-21-010-pas.pdf

- di-jets in CMS



  - ➡ Search in events with 4 jets for large m_inv and di-jet combinations with m1~m2.
  - ➡ In resonant 4-jet production

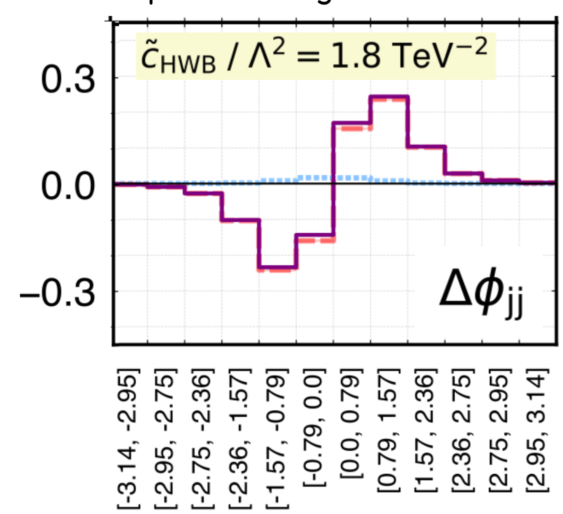
$$pp \to Y \to XX \to (jj)(jj)$$

find 3.6 (1.6) sigma local (global) at m4j=8TeV and m2j=2 TeV

  - ➡ In non-resonant 4-jet find 3.6 (2.5) sigma local (global) at m2j=0.95 TeV

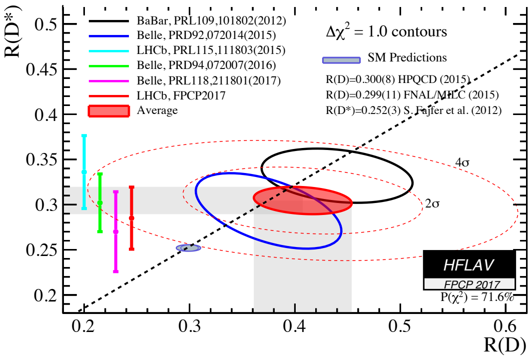
- CP-violation in ATLAS

https://arxiv.org/abs/2006.15458

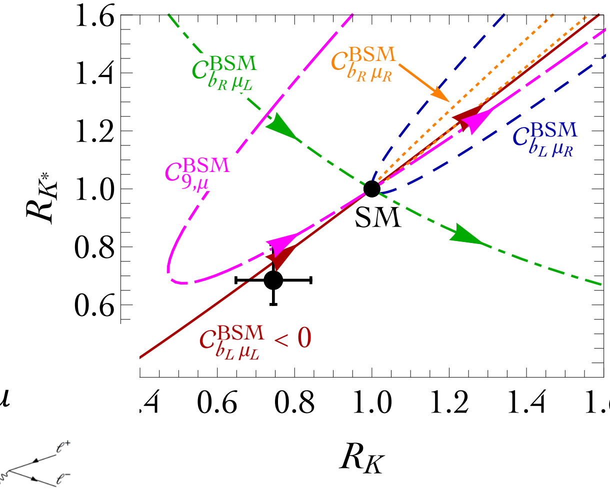


  - ➡ Search in ELW Zjj production
  - ➡ Leptonic decay of Z boson
  - ➡ VBF event selection cuts
  - ➡ $\Delta\phi_{jj}$ sensitive to CP-odd interactions
  - ➡ Disfavours SM ~ 3 sigma

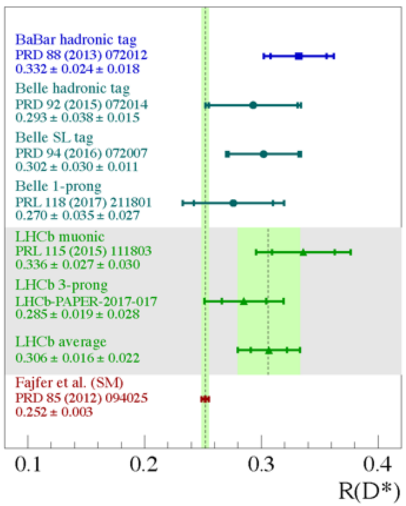
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}$$

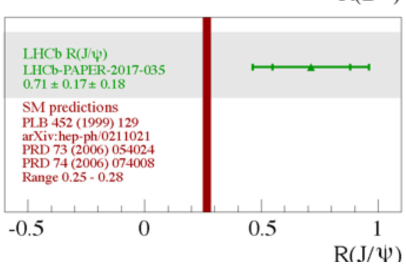


$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu\bar{\mu})}{\mathcal{B}(B \to K^{(*)}e\bar{e})}$$

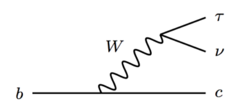
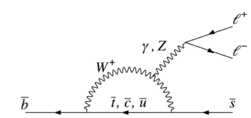


Flavour anomalies in Belle, BaBar and LHCb

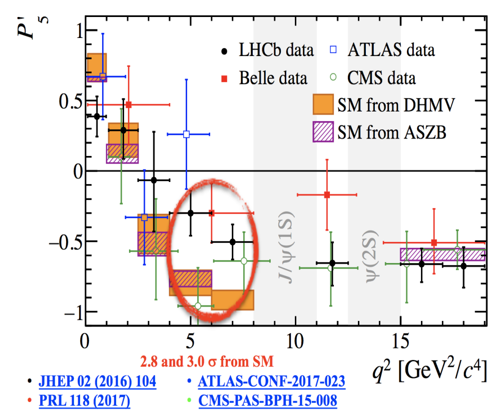




$$R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)}$$

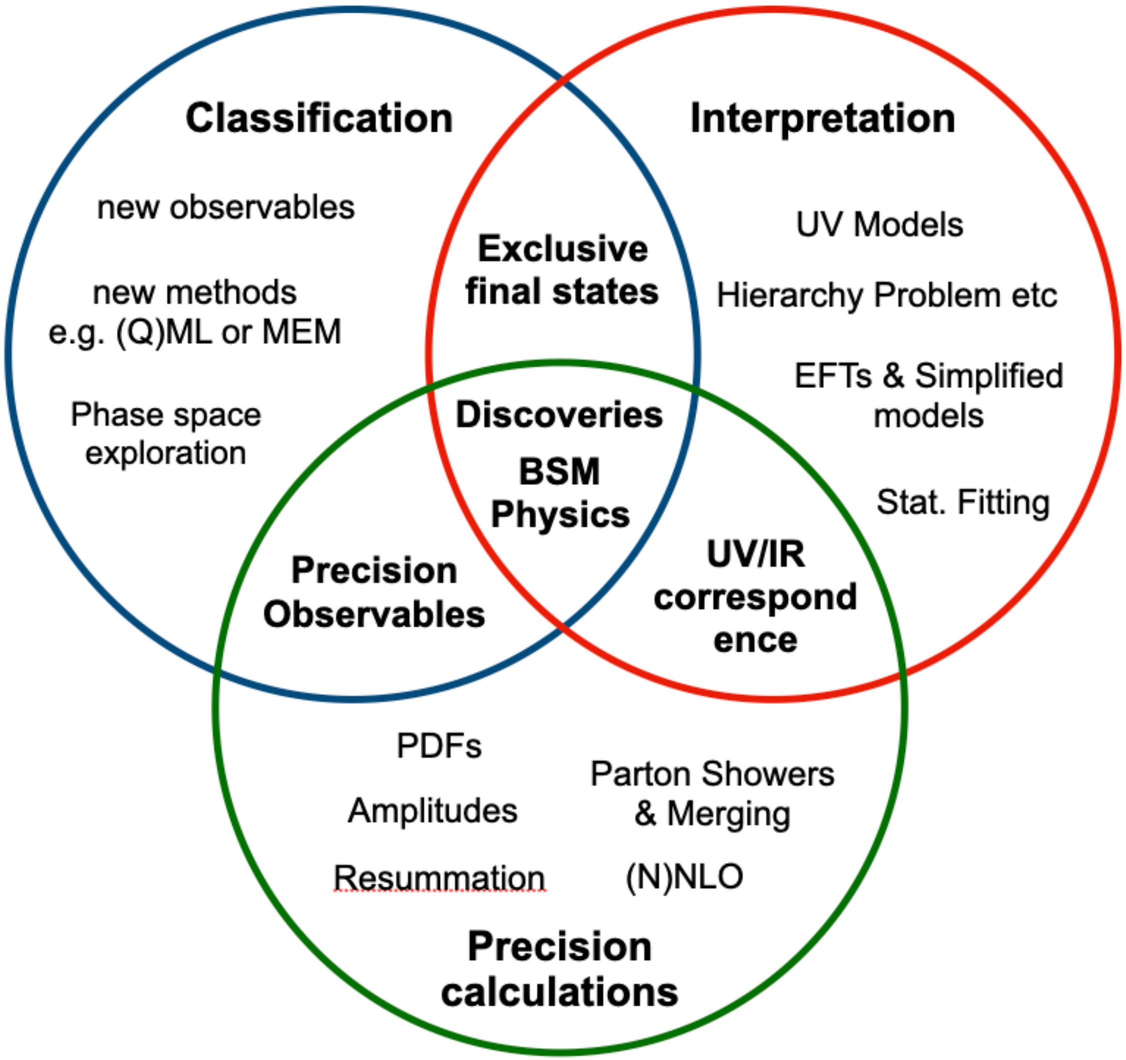
	$b \to c\tau\nu$	$b \to s\mu\mu$
		
Lepton Universality	$R(D), R(D^*), R(J/\psi)$	$R(K), R(K^*)$
Angular Distributions		$B \to K^*\mu\mu$ (P_5')
Differential BR $(d\Gamma/dq^2)$		$B \to K^{(*)}\mu\mu$ $B_s \to \phi\mu\mu$ $\Lambda_b \to \Lambda\mu\mu$

$$B \to (K^* \to K\pi)\mu\mu$$



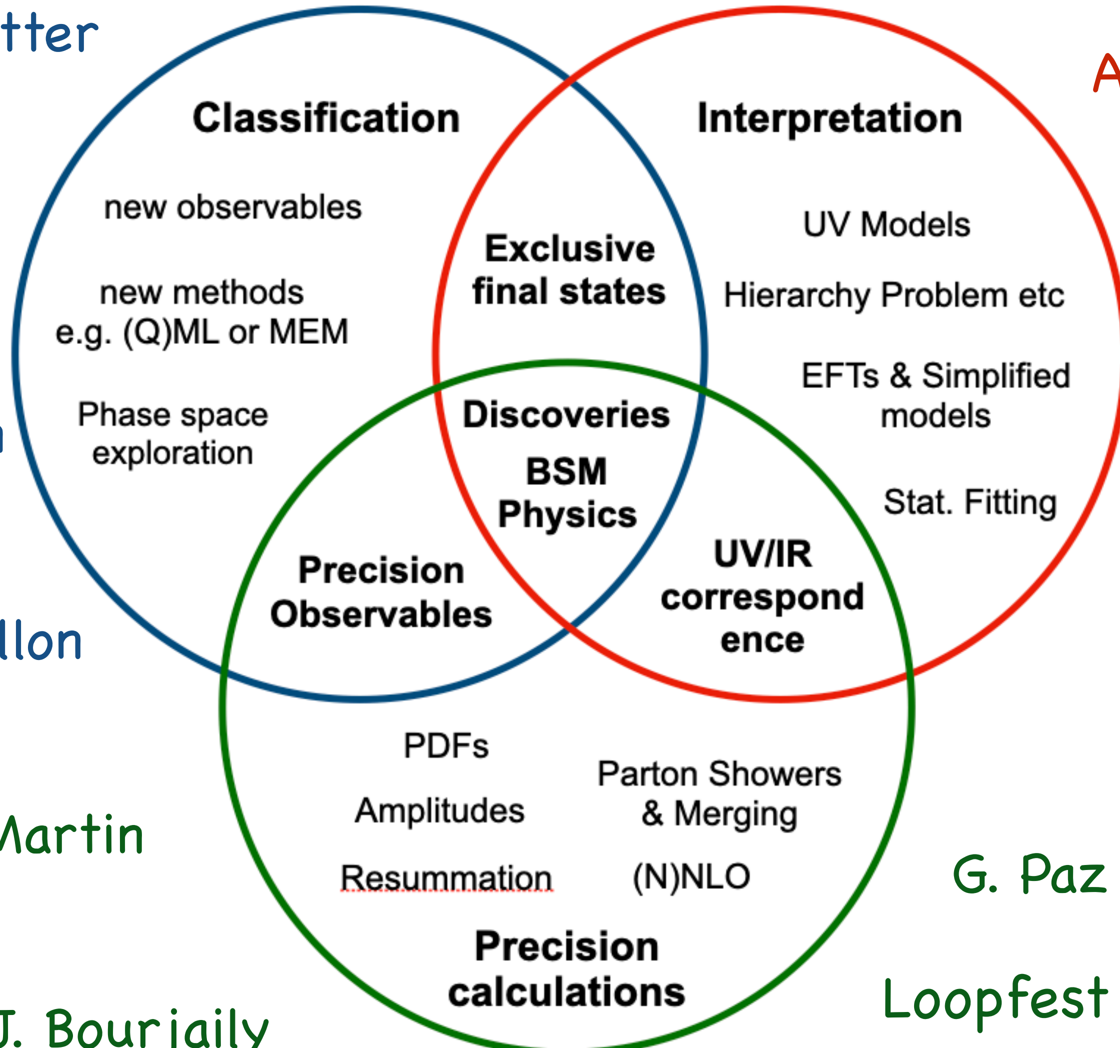
See also talk by M. Artuso

Interplay between Classification, Interpretation and Precision makes LHC (high-energy collider) unique discovery tool



Interplay between Classification, Interpretation and Precision makes LHC (high-energy collider) unique discovery tool

A. Butter
I. Moult
Z. Yu
Z. Dong
A. Hallin
R. Barman
B. Dillon

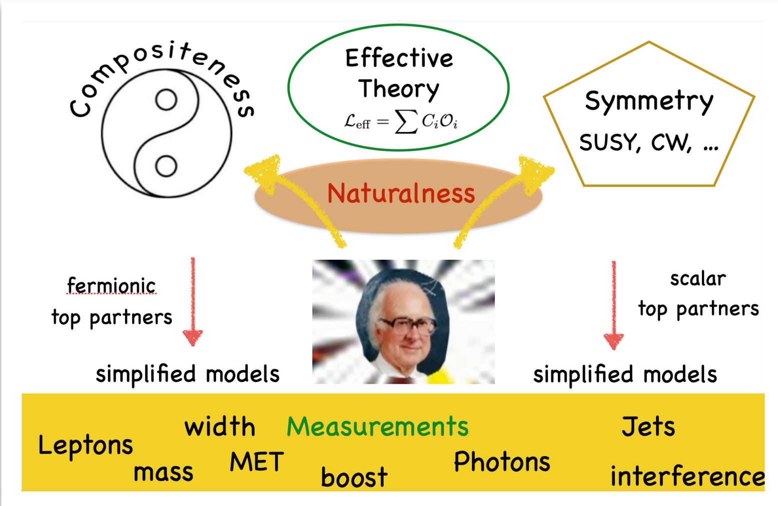


A. Dos Santos
J. Talbert
N. Okada
D. Goncalves
I. Lewis
M. Smylie

S. Willenbrock
S. Martin
G. Paz
R. Ruiz
J. Bourjaily

Loopfest 12.05-14.05

Interpretation



Ludwig Wittgenstein

The limits of my language mean the limits of my world

Connecting measurements with UV physics

Kappa Framework

- NP models simple rescaling of couplings
- No new Lorentz -structures or kinematics

EFT

- SM degrees of freedom and symmetries
- New kinematics/ Lorentz structures

Simplified Models

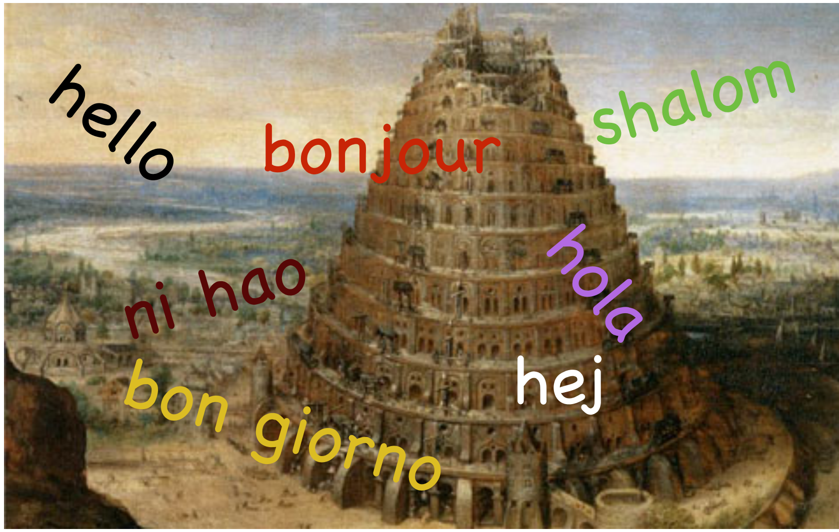
- New low-energy degrees of freedom
- Subset of states of full models, reflective at scale of measurement

Full (UV) Model

- Very complex and often high-dimensional parameter space
- Allows to correlate high-scale and low-scale physics

Complexity/Flexibility

EFTs currently lingua franca for elw-scale collider pheno



Basis

- Complete
- Inspired by UV physics?

Several available:

Warsaw Basis	[1008.4884]
SILH Basis	[hep-ph/070164]
Primary/Higgs Basis	[1405.0181]

Practicality / Assumptions

- Manageable number of operators for fit
- bottom up vs top down
- loop-induced operators vs tree-level operators

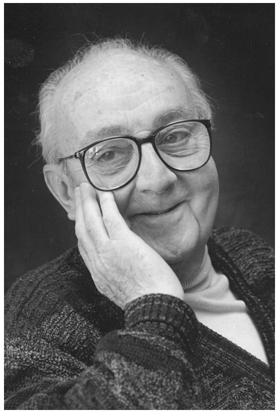
Validity

- Validity range of EFT set by kinematic of measurement

Precision

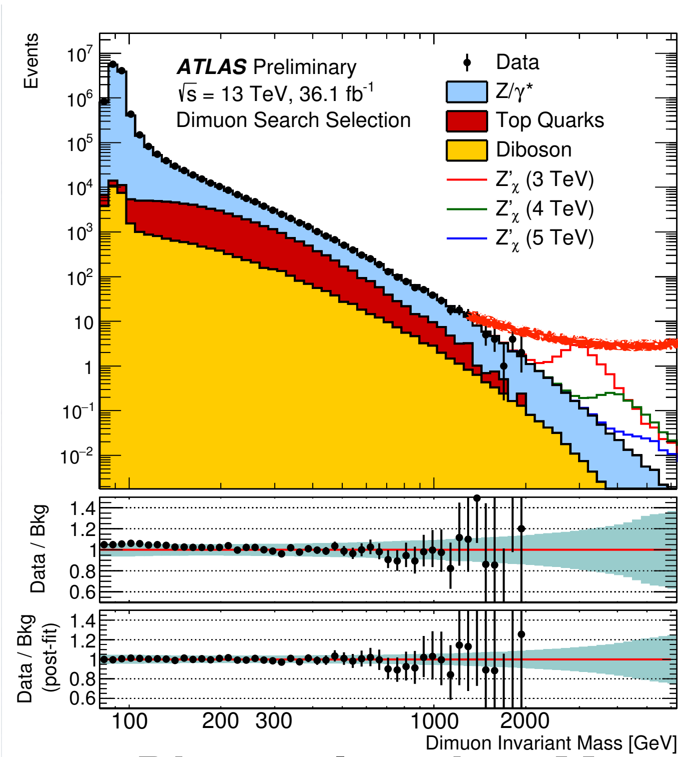
- RGE improved pert. theory / full NLO
- At what dimension to truncate

George Box

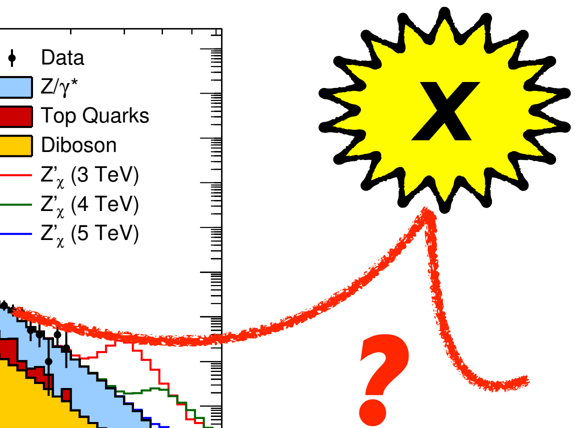


All models are wrong, some are useful

LHC (or future pp collider) can provide unique view on UV models



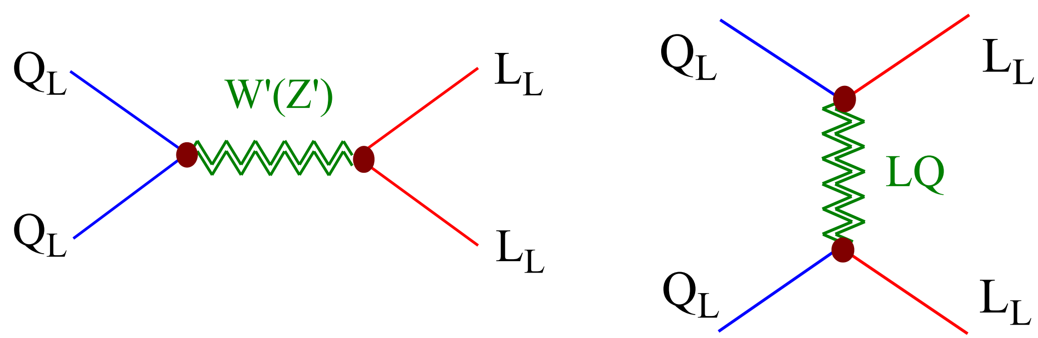
Dimuon Invariant Mass



$$\mathcal{L}^{\rm SMEFT} \supset \frac{C}{M^2}\overline{Q}\gamma^\mu Q \overline{L}\gamma_\mu L$$

$$\mathcal{A} \propto \frac{E^2}{M^2}$$ valid when E < M

Resonances that could induce LUV

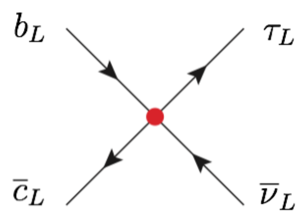


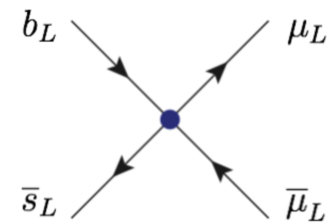
Inferring the scale of new physics with EFTs

[Bhattacharya et al '14]
[Alonso, Grinstein, Camalich '15]
...

$$\frac{1}{\Lambda^2}(\overline{Q}^i_L \sigma^a \gamma_\mu Q^j_L)(\overline{L}^k_L \sigma^a \gamma^\mu L^l_L) \quad \supset -\frac{1}{\Lambda^2_{R_D}} 2\, \overline{c}_L \gamma_\mu b_L \overline{\tau}_L \gamma^\mu \nu_L + \frac{1}{\Lambda^2_{R_K}} \overline{s}_L \gamma_\mu b_L \overline{\mu}_L \gamma^\mu \mu_L$$

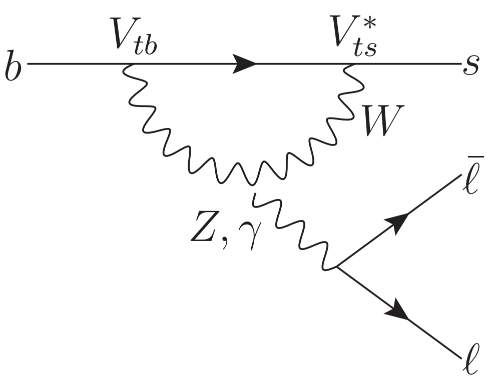
$SU(2)_L$ triplet operator





$\Lambda_{R_D} = 3.4$ TeV $\quad \ll \quad$ $\Lambda_{R_K} = 31$ TeV

What is the new physics scale?



$$\mathcal{L}_{\rm BSM} = \frac{c}{\Lambda^2} \left(\overline{s}_L \gamma_\alpha b_L\right) \left(\overline{\mu}_L \gamma^\alpha \mu_L\right)$$

No suppression:	$c = 1$	$\Lambda = 31$ TeV
MFV:	$c = V_{ts}$	$\Lambda = 6$ TeV
MFV + loop:	$c = V_{ts}/4\pi$	$\Lambda = 0.5$ TeV

[Di Luzio, Nardecchia '17]

Anomaly	$\mathcal{O}$	FS_Q	FS_L	Λ_A[TeV]	$\lvert\Lambda_{\mathcal{O}}\rvert$ [TeV]	Λ_U[TeV]	$M_\star$[TeV]
$b \to c\tau\bar{\nu}$	$Q_{23}L_{33}$	1	1	3.4	3.4	9.2	43
$b \to c\tau\bar{\nu}$	$Q_{33}L_{33}$	$\lvert V_{cb}\rvert$	1	3.4	0.7	1.9	8.7
$b \to s\mu\bar{\mu}$	$Q_{23}L_{22}$	1	1	31	31	84	390
$b \to s\mu\bar{\mu}$	$Q_{33}L_{22}$	$\lvert V_{ts}\rvert$	1	31	6.2	17	78

Λ_A: "Fermi constant" of the process [SU(3)$_C$ x U(1)$_{EM}$ invariant EFT]

$\lvert\Lambda_{\mathcal{O}}\rvert$: Scale of the SMEFT operator [SU(3)$_C$ x SU(2)$_L$ x U(1)$_{EM}$ invariant EFT]

$$\bar{Q}_3 Q_3 \longrightarrow V_{cb}\, \bar{c}_L b_L$$

$$\Lambda_{Q_{33}L_{33}} / \sqrt{|V_{cb}|} = \Lambda_{R_{D^{(*)}}}$$

Λ_U: Scale of unitarity violation ($\sqrt{s} = \Lambda_U$ saturates pert. unitarity criterium)

$$\Lambda_U = \sqrt{\frac{4\pi}{\sqrt{3}}}\, |\Lambda_{Q_{ij}L_{kl}}|$$

$M_\star$: NDA mass scale in the strongly-coupled regime $|g_\star| = 4\pi$

$$\frac{1}{|\Lambda_{\mathcal{O}}|} = \frac{4\pi}{M_\star}$$

→ $\sqrt{s}_{R_D} < 9.2$ TeV and $\sqrt{s}_{R_K} < 84$ TeV → No-loose for HE/HL LHC?

Inferring UV quantum numbers with precision observables

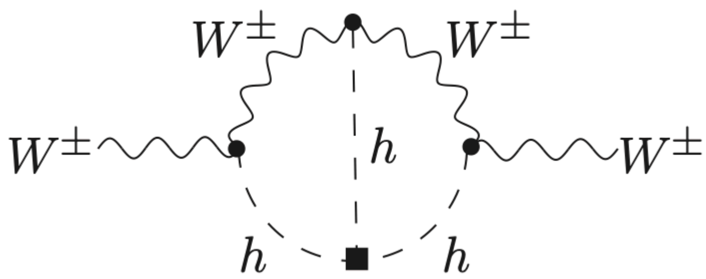
BSM field	Spin	SM quantum numbers			Mass	
		$SU(3)_C$	$SU(2)_L$	$U(1)_Y$		
$\mathcal{S}$	0	1	1	0	$m_{\mathcal{S}}$	real
Δ	0	1	3	0	m_{Δ}	real
$\mathcal{S}_1$	0	1	1	1	$m_{\mathcal{S}_1}$	complex
$\mathcal{S}_2$	0	1	1	2	$m_{\mathcal{S}_2}$	complex
Δ_1	0	1	3	1	m_{Δ_1}	complex
$\mathcal{H}_2$	0	1	2	$-\frac{1}{2}$	$m_{\mathcal{H}_2}$	complex
Σ	0	1	4	$\frac{1}{2}$	m_{Σ}	complex
φ_1	0	3	1	$-\frac{1}{3}$	m_{φ_1}	triplet
φ_2	0	3	1	$-\frac{4}{3}$	m_{φ_2}	triplet
Θ_1	0	3	2	$\frac{1}{6}$	m_{Θ_1}	triplet
Θ_2	0	3	2	$\frac{7}{6}$	m_{Θ_2}	triplet
Ω	0	3	3	$-\frac{1}{3}$	m_{Ω}	triplet
χ_1	0	6	3	$\frac{1}{3}$	m_{χ_1}	sextet
χ_2	0	6	1	$\frac{4}{3}$	m_{χ_2}	sextet
χ_3	0	6	1	$-\frac{2}{3}$	m_{χ_3}	sextet
χ_4	0	6	1	$\frac{1}{3}$	m_{χ_4}	sextet

Real/complex: Scalars elw. singlet/multiplet, color singlet

Triplet/sextet: Scalar Leptoquarks, color non-singlet

- Can we infer the quantum numbers of the UV model from EFT constraints from low-energy observables?
- Each UV resonance realisation will only induce a subset of effective operators
- Shows a completely agnostic bottom-up approach often not useful

Electroweak precision obs

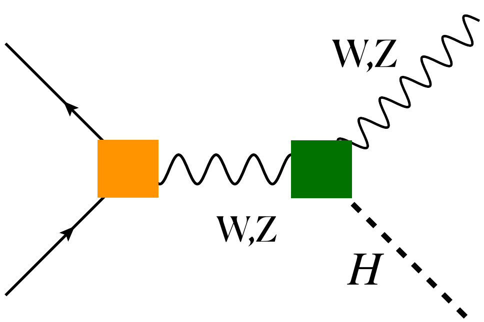


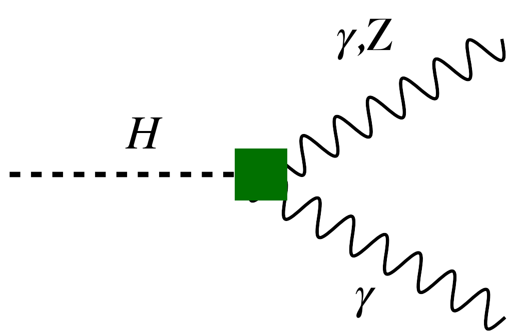
Flavour precision obs
Baryon/Lepton Nr violation

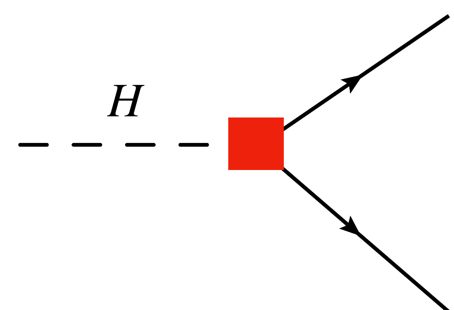
$Q_{\ell\ell}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{\ell}_k \gamma^\mu \ell_l)$
Q_{ee}	$(\bar{e}_i \gamma_\mu e_j)(\bar{e}_k \gamma^\mu e_l)$
$Q_{\ell e}$	$(\bar{\ell}_i \gamma_\mu \ell_j)(\bar{e}_k \gamma^\mu e_l)$

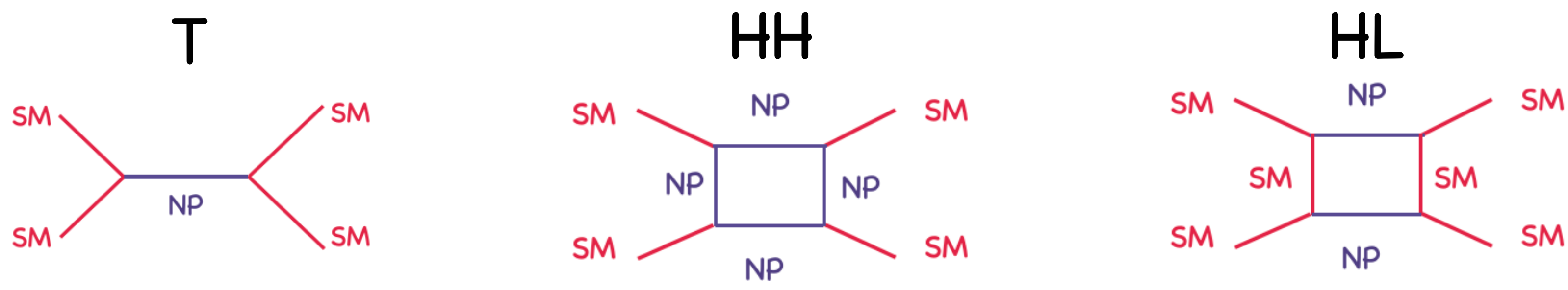
etc

Higgs measurements









Higgs signal strengths

EWPO-NLO-I

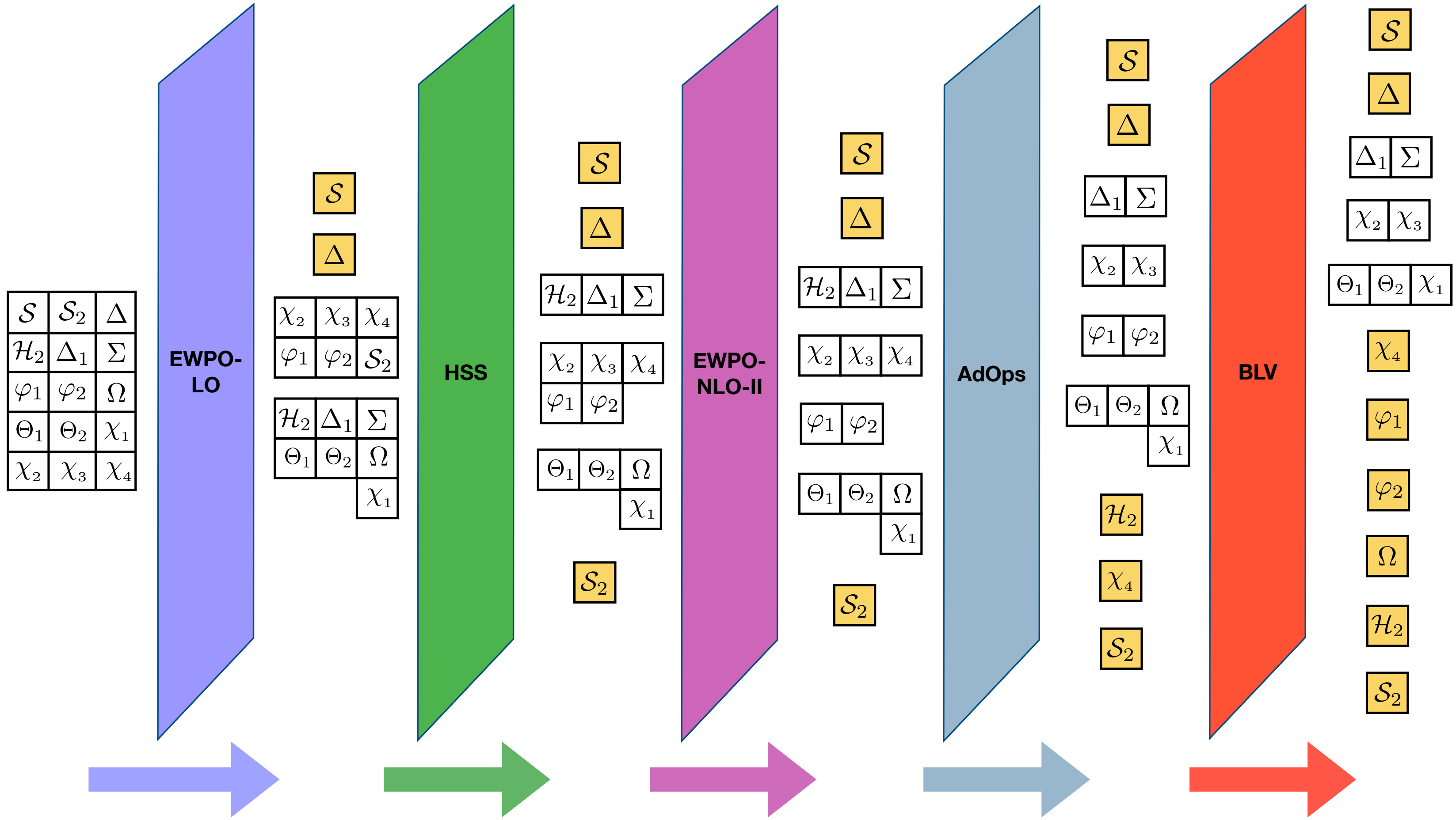
EWPO-LO

[Dawson, Giardino '19]

[Bagglio et al. '20]

Heavy BSM fields	$\mathcal{G}_{3,2,1}$	1 Q_{HD}	2 Q_{ll}	3 Q_{Hu}	4 Q_{Hd}	5 Q_{He}	6 $Q_{Hq}^{(1)}$	7 $Q_{Hl}^{(1)}$	8 $Q_{Hl}^{(3)}$	9 $Q_{Hq}^{(3)}$	10 Q_{HWB}	11 $Q_{H\Box}$	12 Q_{HB}	13 Q_{HW}	14 Q_H	15 Q_G	16 Q_{HG}	17 Q_{eH}	18 Q_{uH}	19 Q_{dH}
$\mathcal{S}$	(1,1,0)	HL	✗	✗	✗	✗	✗	✗	✗	✗	HL	T	HL	HL	T	✗	✗	HL	HL	HL
$\mathcal{S}_2$	(1,1,2)	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	✗	✗	✗	✗	✗
Δ	(1,3,0)	T	HH	✗	✗	✗	✗	✗	HH	HH	HL	T	HL	HH	T	✗	✗	T	T	T
$\mathcal{H}_2$	$(1,2,-\frac{1}{2})$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	T	✗	✗	T	T	T
Δ_1	(1,3,1)	T	T	HH	HH	HH	HH	HH	HH	HH	HH	T	HH	HH	T	✗	✗	T	T	T
Σ	$(1,4,\frac{1}{2})$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	✗	✗	HH	HH	HH
φ_1	$(3,1,-\frac{1}{3})$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
φ_2	$(3,1,-\frac{4}{3})$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
Θ_1	$(3,2,\frac{1}{6})$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
Θ_2	$(3,2,\frac{7}{6})$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
Ω	$(3,3,-\frac{1}{3})$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
χ_1	$(6,3,\frac{1}{3})$	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH	HH
χ_2	$(6,1,\frac{4}{3})$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
χ_3	$(6,1,-\frac{2}{3})$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗
χ_4	$(6,1,\frac{1}{3})$	HH	HH	HH	HH	HH	HH	HH	✗	✗	✗	HH	HH	✗	HH	HH	HH	✗	✗	✗

etc



[Das Bakshi, Chakrabortty, MS '20]

Existence and hierarchy of operators allows to infer the quantum numbers of the UV resonance

But more data needed to pin down UV scenario

[Dawson, Homiller, Lane '20]

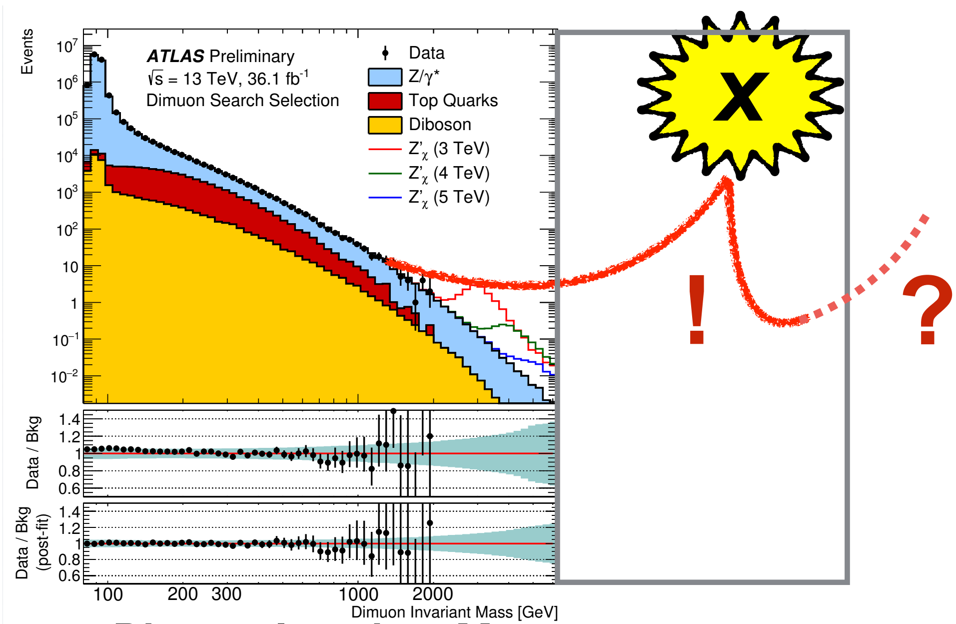
[Anisha et al '21]

Going beyond SMEFT

- Response to 750 GeV excess shows the way:

$$g_3^2 S\left(\frac{G_{\mu\nu}^2}{2\Lambda_g} + \frac{G_{\mu\nu}\tilde{G}^{\mu\nu}}{2\tilde{\Lambda}_g}\right) + e^2 S\left(\frac{F_{\mu\nu}^2}{2\Lambda_\gamma} + \frac{F_{\mu\nu}\tilde{F}^{\mu\nu}}{2\tilde{\Lambda}_\gamma}\right) + S\sum_\psi \bar{\psi}(y_{\psi S} + i\gamma_5\tilde{y}_{\psi S})\psi$$

→ New particle added to SM + effective operators



Dimuon Invariant Mass

- Expand the SM particle content by new degrees of freedom
- Expand Lagrangian consistently by effective interactions

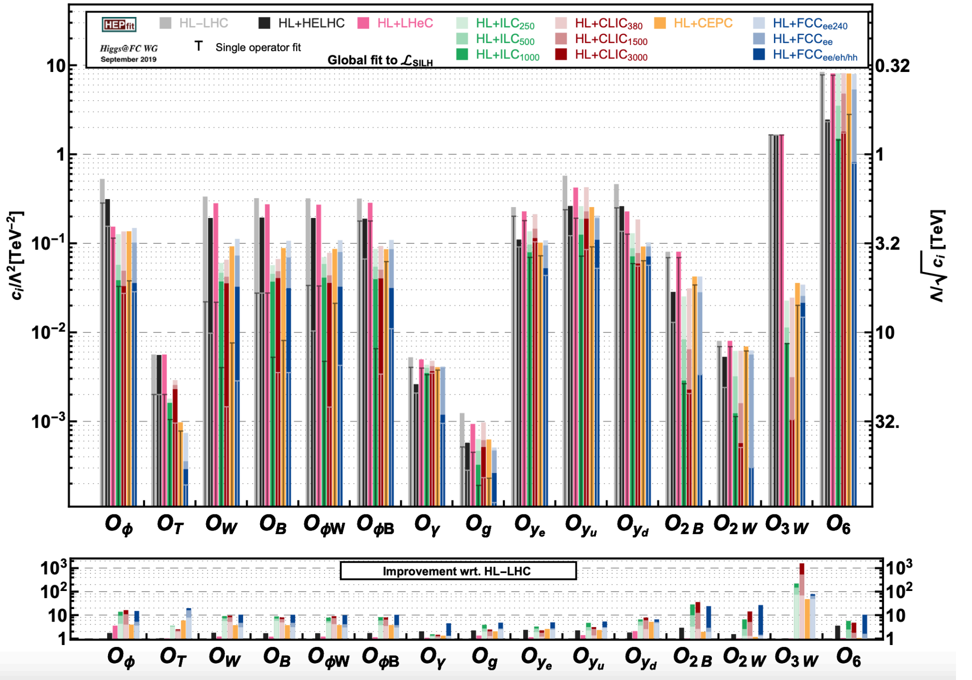
Automation progressed tremendously in recent years

- MatchingTools: Python package, Integrates out heavy degrees up to tree level, removes oper. redundancies [Criado '17]
- CoDEx: Calcs EFT operators, up to 1 loop, automatically integrating out BSM fields, RGE evolution [Das Bakshi, Chakrabortty, Patra '18]
- SuperTracer: Mathematica package to calculate functional supertraces to match UV model onto EFT up to 1 loop. [Fuentes-Martin et al. '20]
- STrEAM: Mathematica package to calculate functional supertraces to match UV model onto EFT. [Cohen, Lu, Zhang '20]
- Matchmakereft: fully automated tool to compute the tree-level and one-loop matching of arbitrary models onto arbitrary effective theories [Carmona, Lazopoulos, Olgoso, Santiago '21]

Classification

- Benefits of exclusive phase space and novel reconstruction methods often neglected in studies, see eg. 'Input to European Strategy'

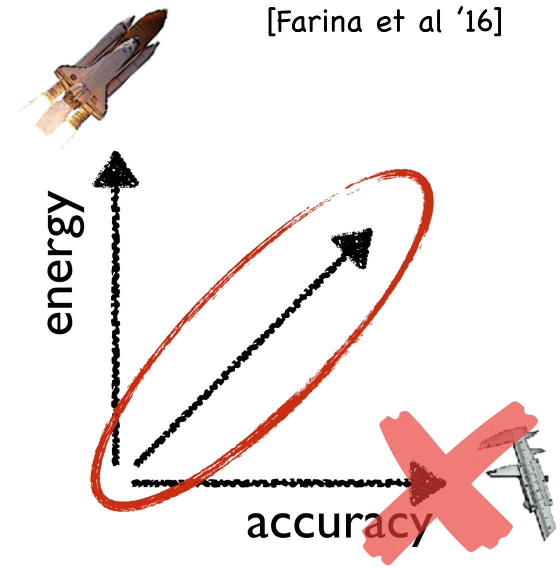
  [De Blas, Cepeda, D'Hondt, Ellis, Grojean, Heinemann, Maltoni, Nisati, Petit, Rattazzi, Verkerke '19]



- Many new methods to improve signal/background discrimination:
  - ➡ (Quantum) Machine Learning methods
  - ➡ Matrix Element Methods:
    HYTREES, Shower/Event Deconstruction etc

Energy <-> Precision

[Farina et al '16]



$$\frac{\mathcal{A}_{\mathrm{SM+BSM}}}{\mathcal{A}_{\mathrm{SM}}} \sim 1 + \# \frac{E^2}{\Lambda^2}$$

LHC can match LEP accuracy in high E regime

$$0.1\ \% \quad \text{at} \quad 100\ \text{GeV} \quad \longrightarrow \quad 10\ \% \quad \text{at} \quad 1\ \text{TeV}$$

LEP energy *LHC energy*

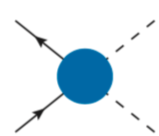
Higgs dynamics at high energies

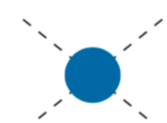
- at high goldstone equivalence allows to test Higgs dynamics

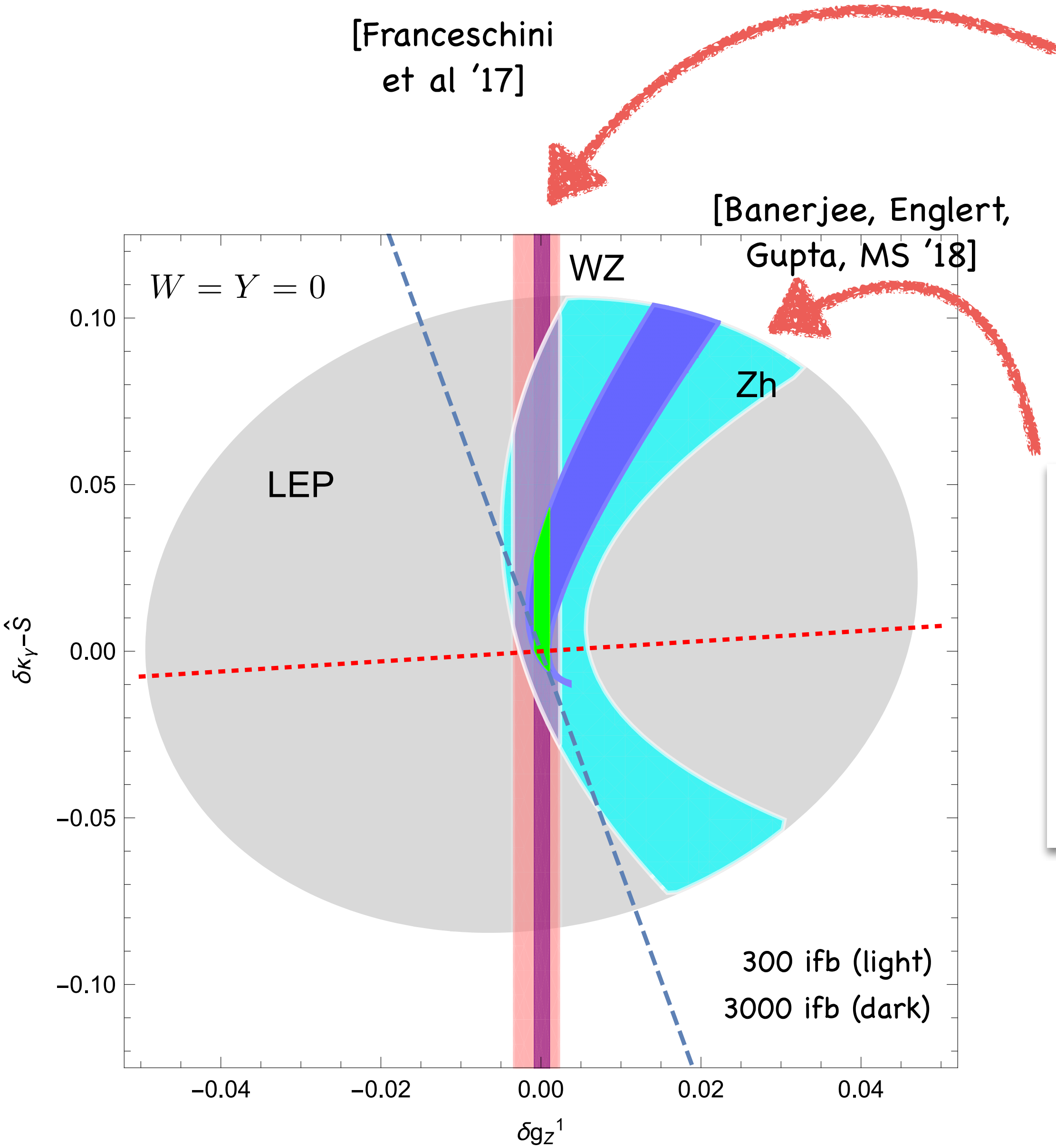
 $W^{\pm},\ Z$ $\longrightarrow$ $\phi^{\pm},\ \phi^{0}$

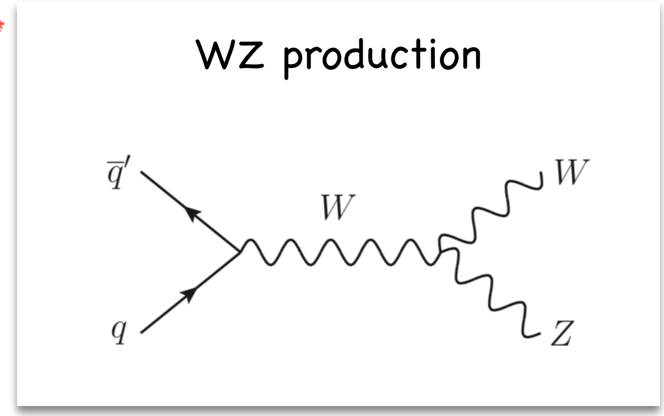
- Interference between the SM and new-physics (at dim-6 level) only at longitudinal

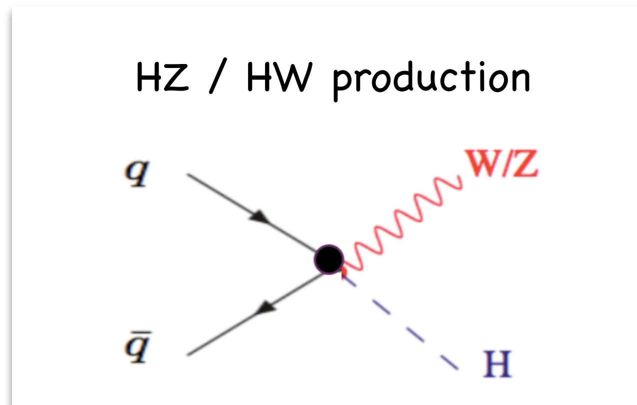
→ growth at high energy

$\psi\bar{\psi}V_L V_L$ 

$V_L V_L V_L V_L$ 







- Boosted Higgs (H->bb)Z analysis

Global fit including differential distributions

[Englert, Kogler, Schulz, MS `15]

Focus on linear contribution of EFT for theory prediction:

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \mathcal{M}_{d=6}$$

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 + 2\,\mathrm{Re}\{\mathcal{M}_{\rm SM}\mathcal{M}^*_{d=6}\} + \mathcal{O}(1/\Lambda^4)$$

Number of predicted events:

$$N_{\rm th} = \sigma(H+X) \times \mathrm{BR}(H \to YY) \times \mathcal{L} \times \mathrm{BR}(X, Y \to \text{final state})$$

We assume that production and decay factorise to good approximation

Each channel has own prod. and decay efficiencies:

$$N_{\rm ev} = \epsilon_p \epsilon_d N_{\rm th}$$

Wilson coefficients can be (over) constraint in many decay and production processes:

Decays:	$H \to f\bar{f}$	$H \to \gamma\gamma$	$H \to \gamma Z$
	$H \to ZZ^*$	$H \to WW^*$	
Production:	$pp \to H$	$pp \to Hj$	$pp \to Hjj$
	$pp \to HV$	$pp \to ttH$	

→

signal strength:

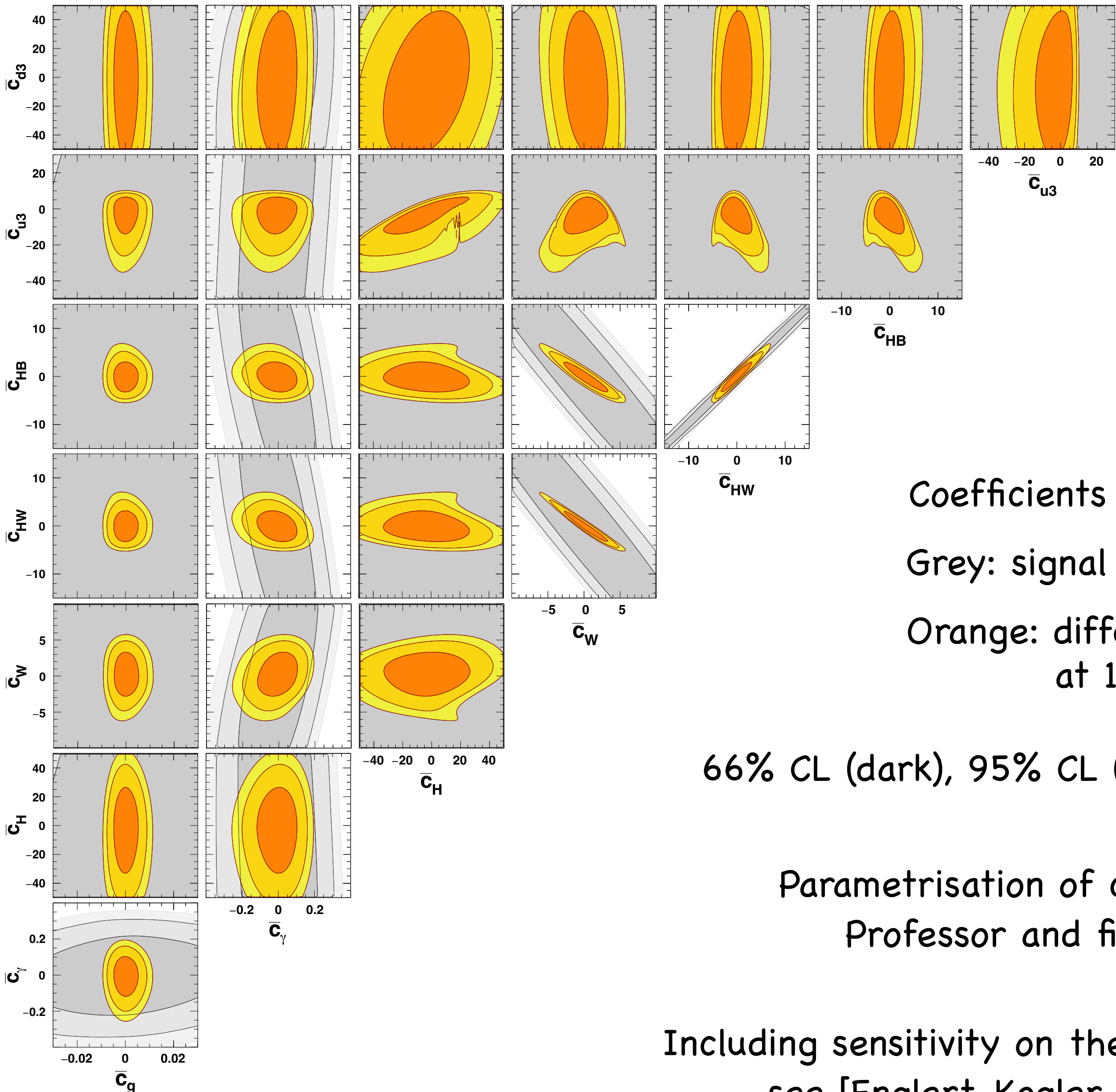
36 indep. meas. (300 ifb)

46 indep. meas. (3000 ifb)

differential:

88 indep. meas. (300 ifb)

123 indep. meas. (3000 ifb)



Coefficients multiplied by 10^3

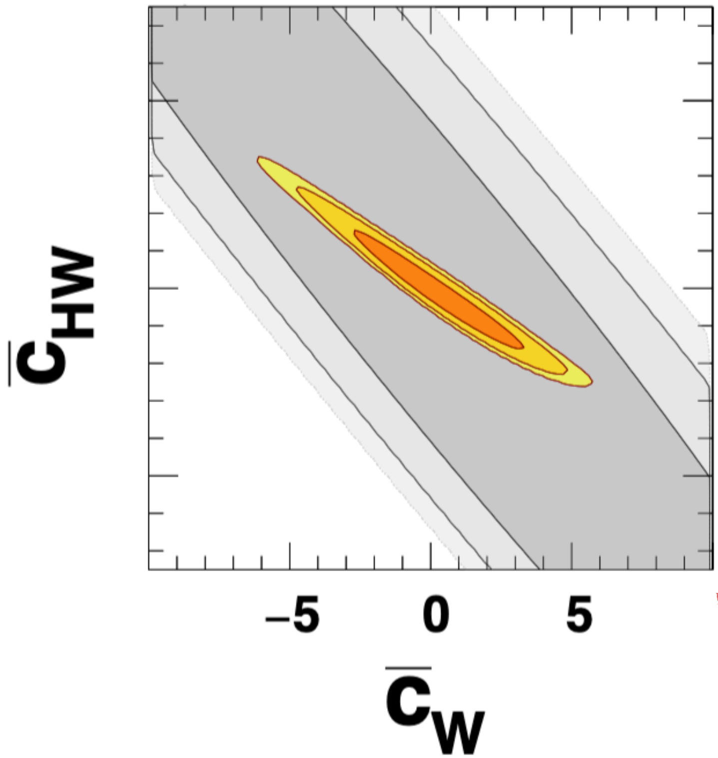
Grey: signal strength only

Orange: differential distributions at 14 TeV and 3000 ifb

66% CL (dark), 95% CL (middle), 99% CL (light)

Parametrisation of cross sections with Professor and fit using Gfitter

Including sensitivity on theoretical uncertainties see [Englert, Kogler, Schulz, MS '18]



$$\frac{i\bar{c}_{HW}\,g}{m_W^2}(D^\mu H)^\dagger\sigma^i(D^\nu H)W^i_{\mu\nu}$$

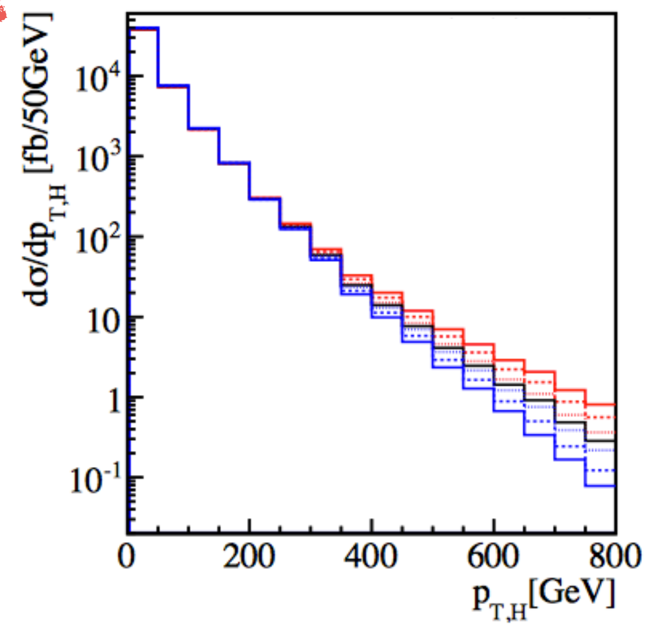
$$\frac{i\bar{c}_W\,g}{2m_W^2}\left(H^\dagger\sigma^i\overleftrightarrow{D^\mu}H\right)(D^\nu W_{\mu\nu})^i$$

Grey: signal strength only

Orange: differential distributions at 14 TeV and 3000 ifb

66% CL (dark), 95% CL (middle), 99% CL (light)

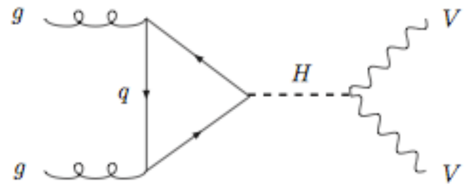
Operators affect tails of distribution differently



Due to access to exclusive phase space regions sensitivity scales much better than $\sqrt{\mathcal{L}}$ at HL-LHC

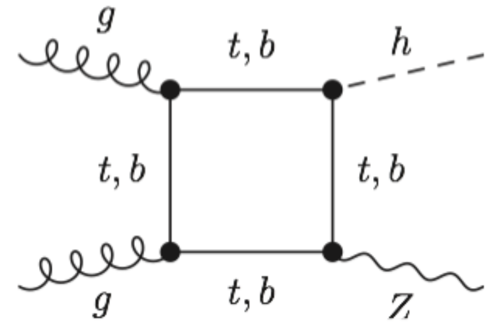
Energetic final states not only important for effective couplings

Off-shell Higgs (Width)



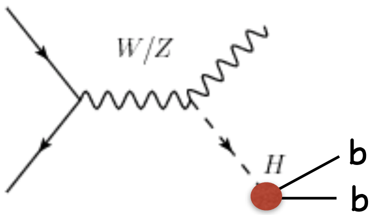
[Kauer, Passarino '12]
[Caola, Melnikov '14]

HZ final state



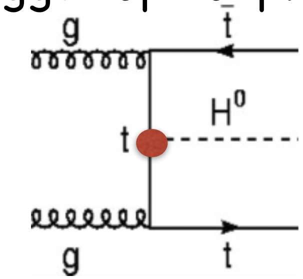
[Englert, McCullough, MS '13]

Higgs-bottom coupling



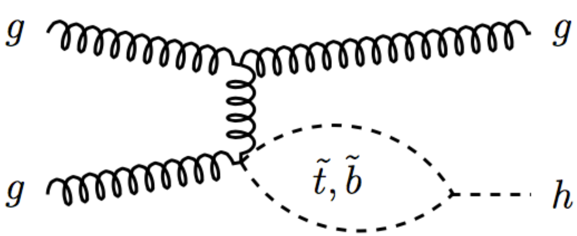
[Butterworth, Davison, Rubin, Salam '08]

Higgs-top coupling



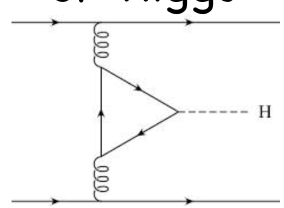
[Plehn, Salam, MS '09]
[Moretti, Petrov, Pozzorini, MS '15]

Boosted Higgs in H+jet



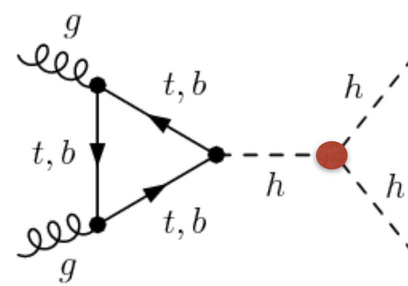
[Harlander, Neumann '13]
[Banfi, Martin, Sanz '13]
[Grojean, Salvioni, Schlaffer Weiler '14]

CP Higgs



[Plehn, Rainwater, Zeppenfeld '01]
[Klamke, Zeppenfeld '07]

Higgs selfcoupling



[Baur, Plehn, Rainwater '02 '03]
[Dolan, Englert, MS '12 '12]
[Baglio et al '13]

US Snowmass Process 2022

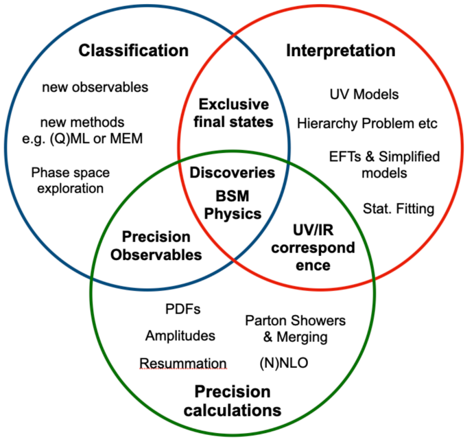
US Snowmass Process 2022

Many low-energy precision experiments	vs	High-energy collider flagship experiment

US Snowmass Process 2022

Many low-energy precision experiments **vs** High-energy collider flagship experiment

UP?



Summary

- Coming LHC runs will provide tremendous improvement for searches in exclusive phase space regions (beyond $\sqrt{\mathcal{L}}$)

  → will be more exciting than expected

- However, new analysis strategies need to be pushed to make most of LHC data

  → benefit currently still under appreciated

- Need strong support for high-energy collider flagship experiment