Higgs fits to new physics

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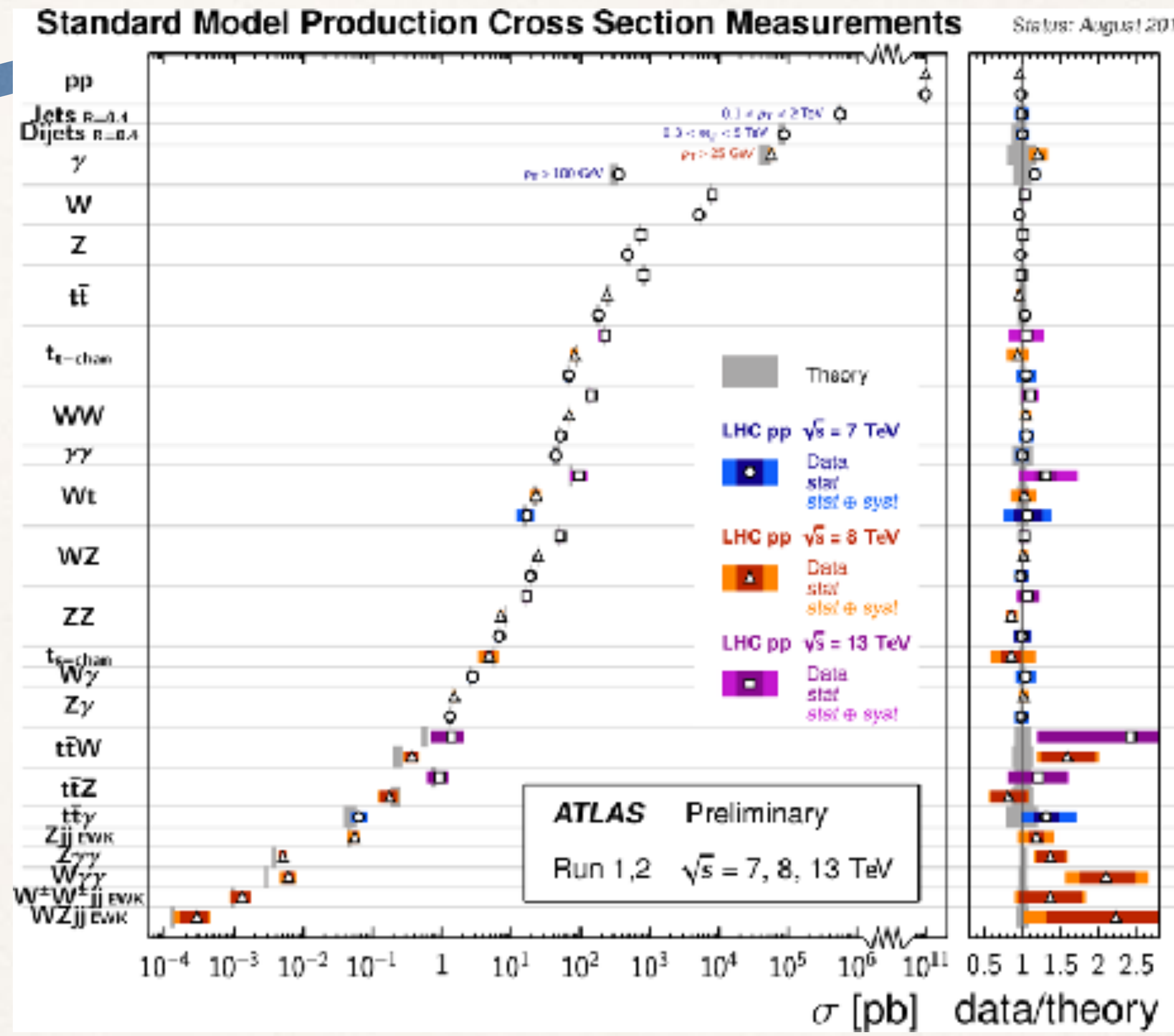
Higgs Hunting, Paris, 2017

Challenges ahead

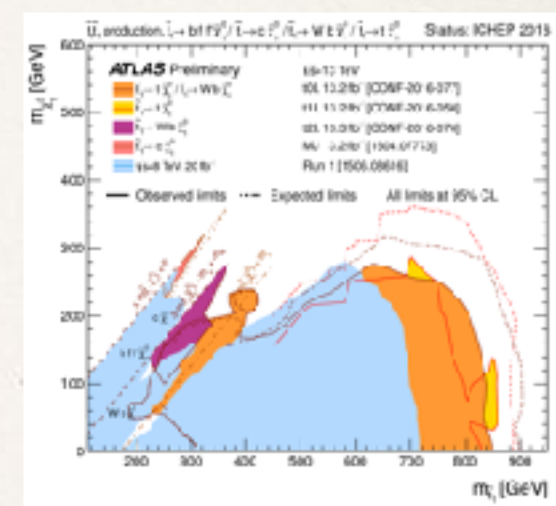
The LHC

The LHC is in a mature stage, already providing precision tests for the SM in most channels (excl the Higgs)

Precise tests of the full structure of the SM, based on QFT, symmetries (global/ gauge) and consistent ways to break them non-trivial tests of perturb.->non-perturb. QCD



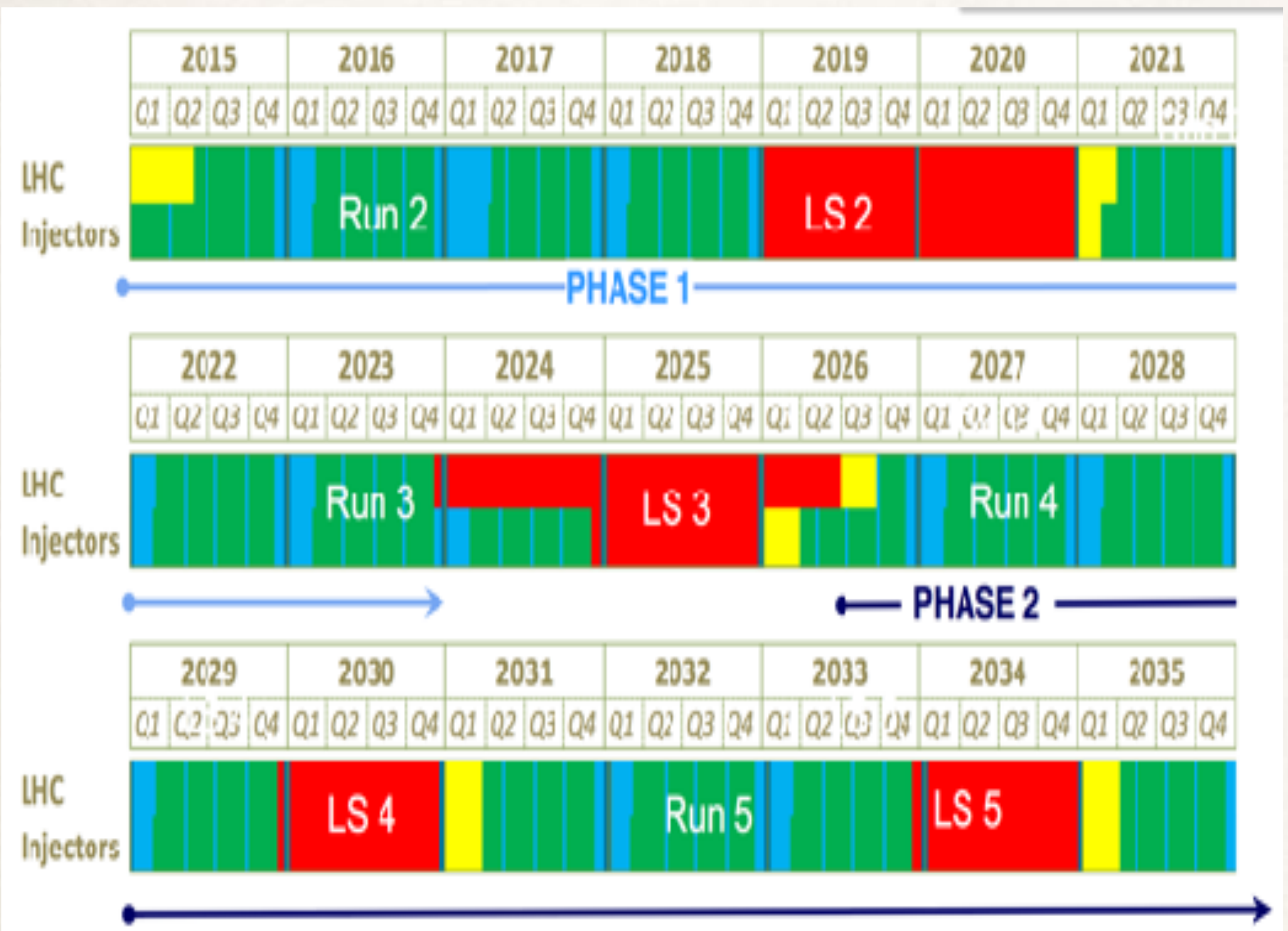
Absence of excesses: interpreted as new physics exclusions

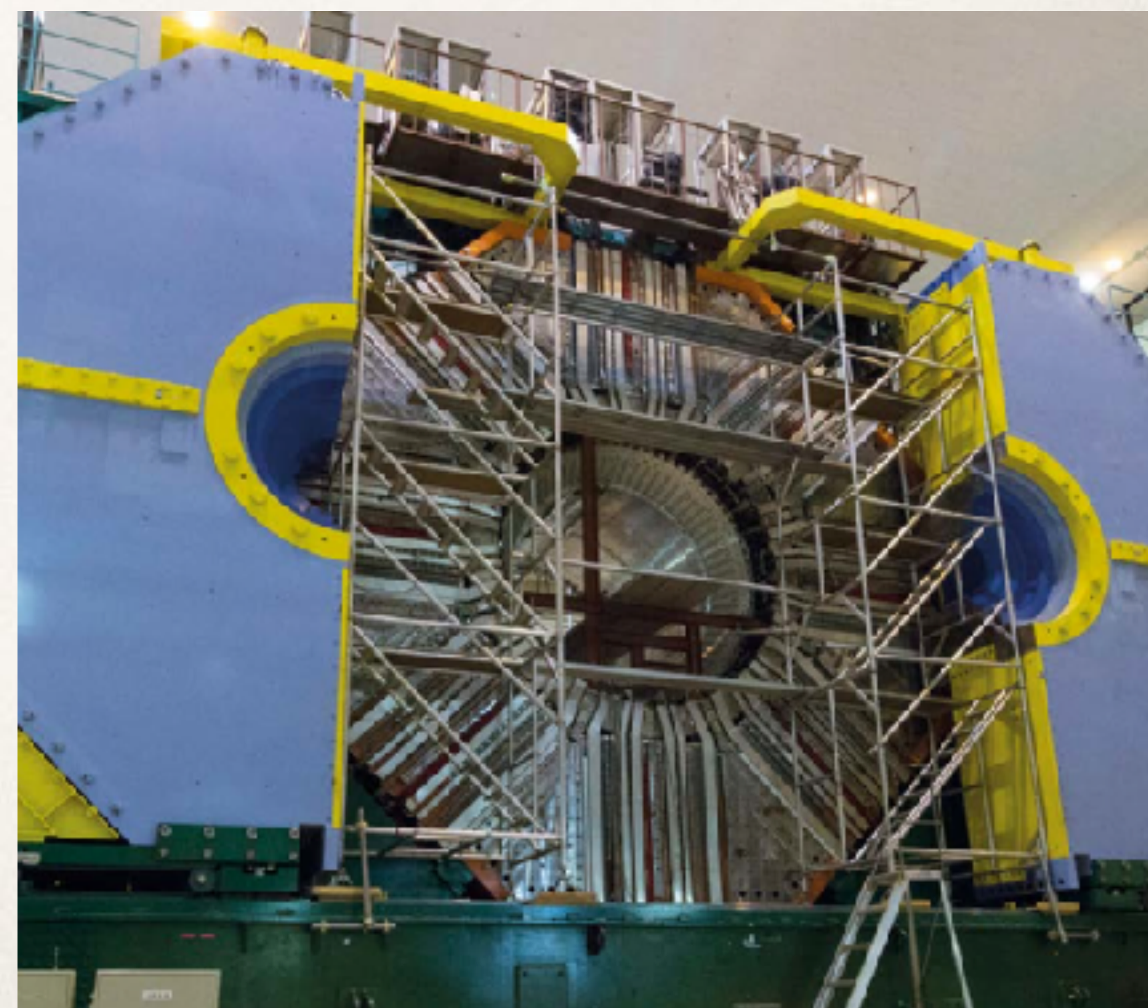


exclusions: rather impressive, many at the TeV
searches: outstanding coverage of possible topologies
any hints: (like in flavor) extremely tempting

This is just the beginning

HL-LHC (High-Luminosity) LHC approved, to deliver 3000 inverse fb of data.
Funding ensured until 2035.

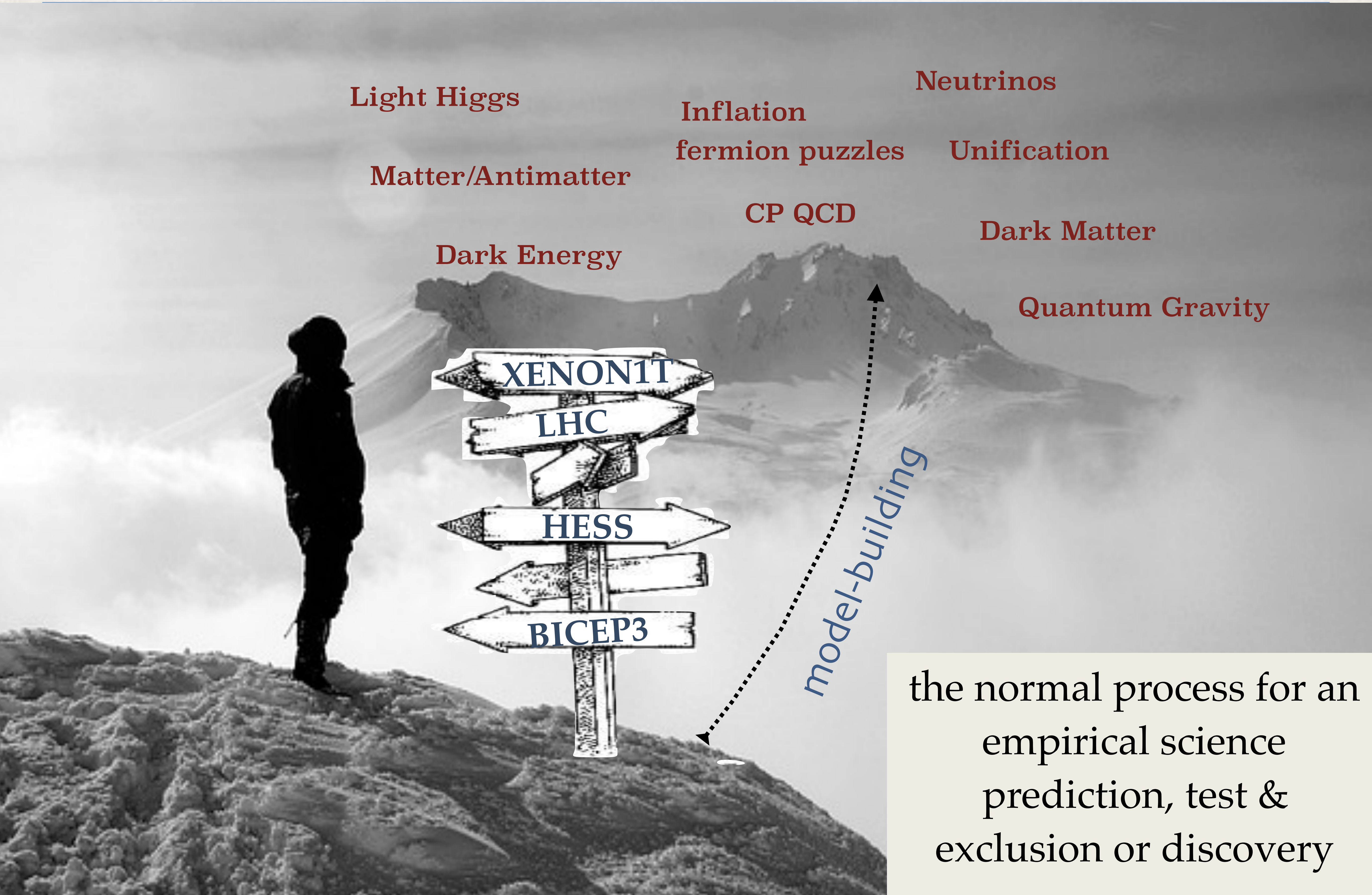




Plus other collider experiments testing SM at high precision e.g. super-B factory

So here we are

So here we are again, post-LHC Run1



the normal process for an empirical science prediction, test & exclusion or discovery

The Higgs as a key to new physics

A cosmological Higgs

HIGGS

Dark Matter
Higgs portal
Higgs DM mediator

UV sensitivity
Naturalness
heavy new physics
Relaxation

Inflation
Higgs inflation
Inflaton vs Higgs

Phase transitions
Baryogenesis
gravitational waves

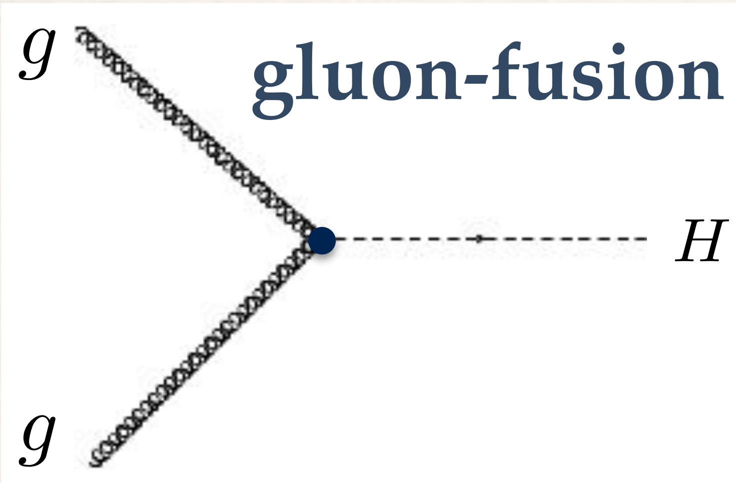
Fate of the Universe
Stability

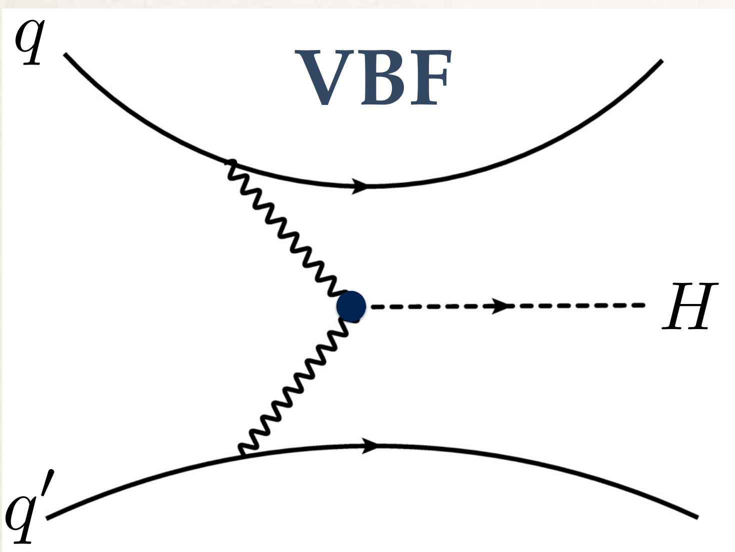
The LHC provides the most precise, controlled way of studying the Higgs and direct access to TeV scales
Exploiting complementarity with cosmo/astro probes

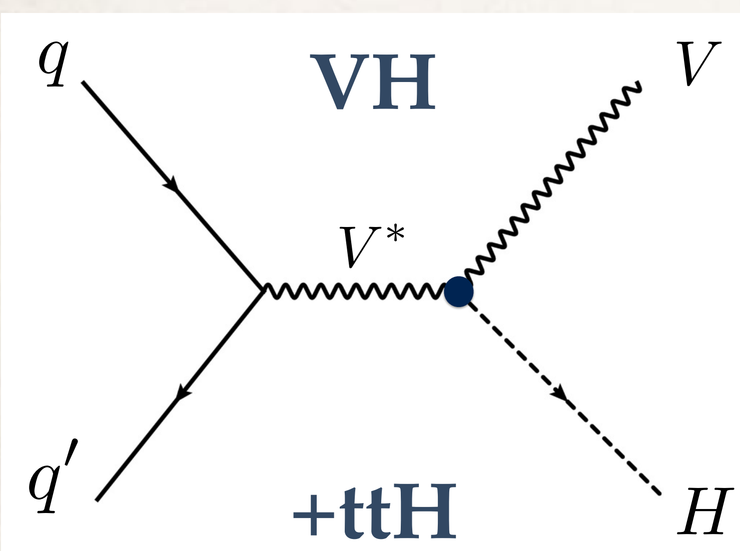
Similar story for Axions and ALPs, scalars are versatile

The Higgs at the LHC

LHC Higgs in a nutshell (I)

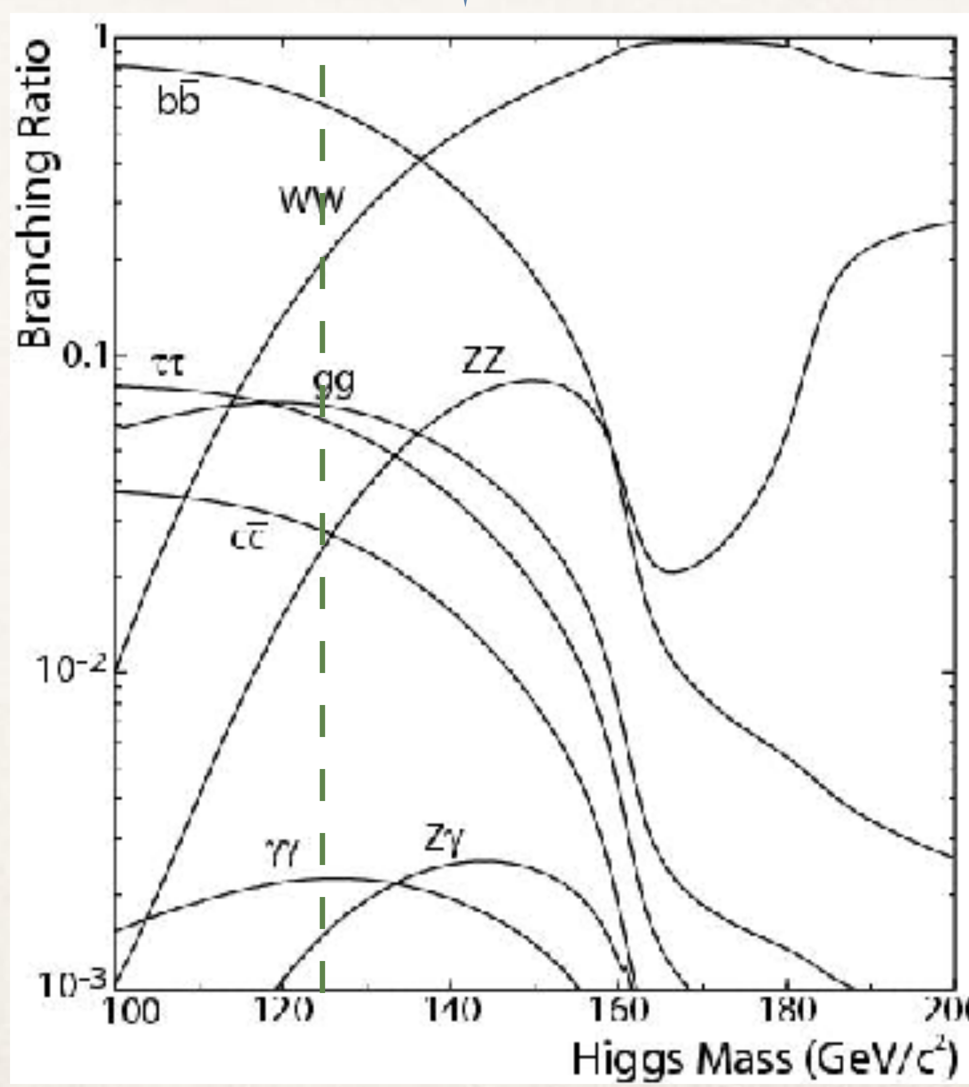






PRODUCTION
&
DECAY

The Higgs is **produced** in ggF, VBF, VH and ttH **decays** to channels with photons, leptons (e,mu), missing energy, tagged b's and taus



<u>easy to difficult</u>

diphotons

ZZ to 4L

WW to 2L

di-taus

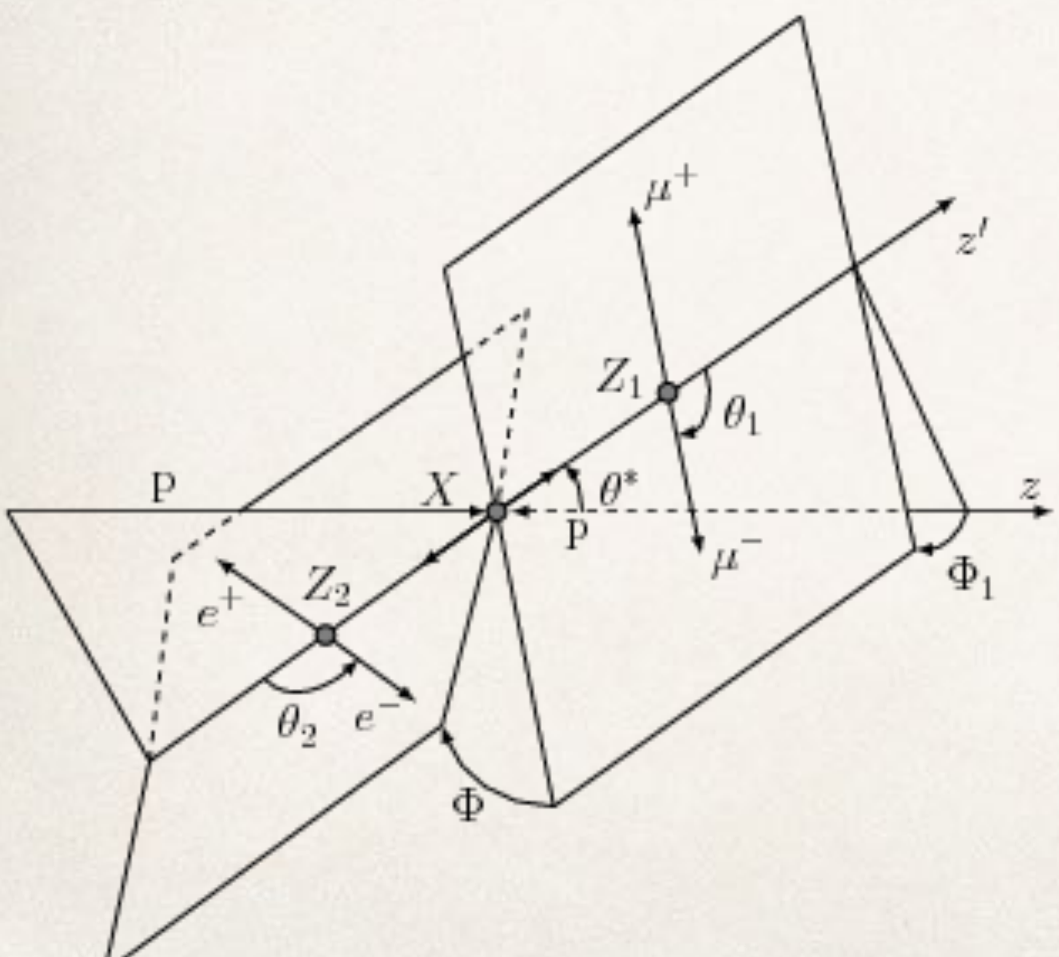
bb

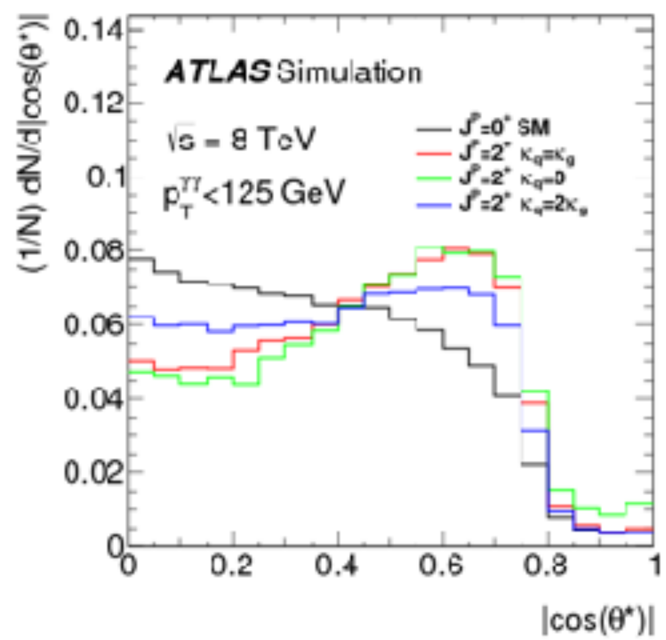
mass=125 GeV

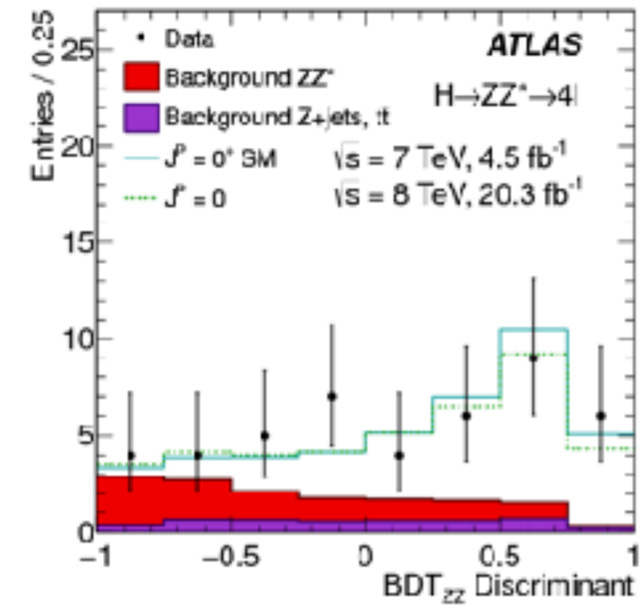
LHC Higgs in a nutshell (II)

QUANTUM NUMBERS

using kinematic distributions in ZZ, WW, …
determine the spin and parity as well as possible CP admixtures

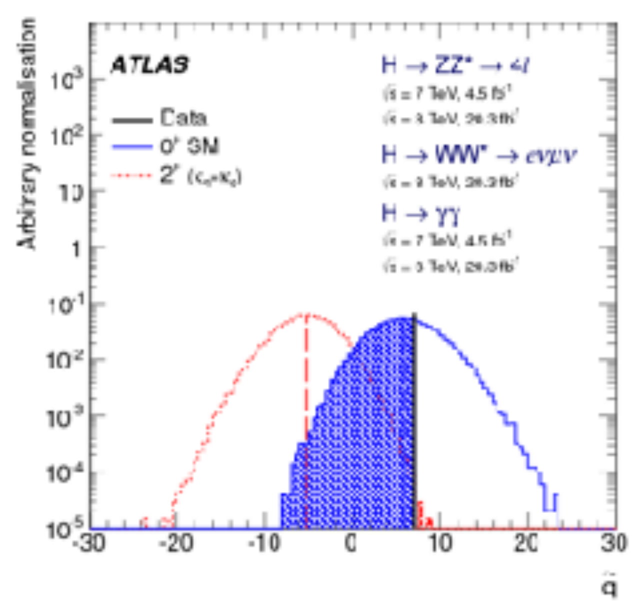


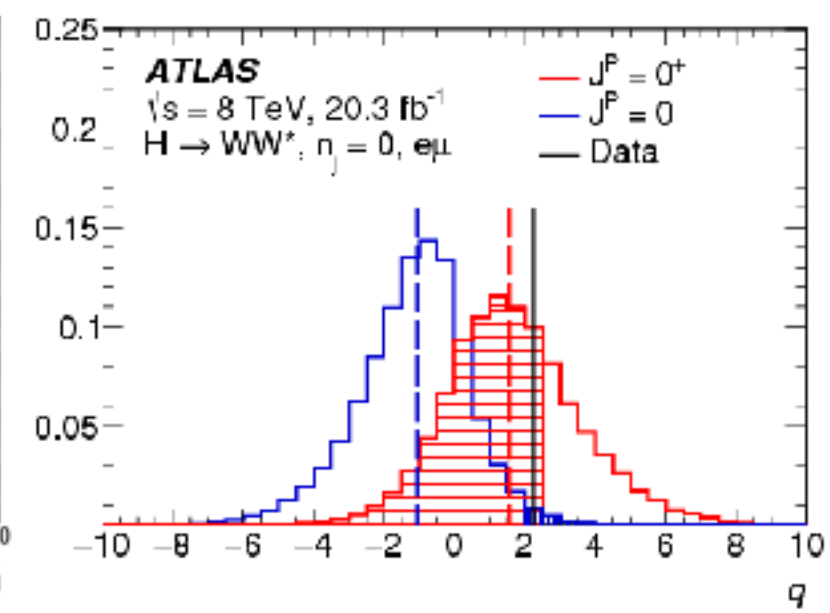




kinematics

hypothesis discrimination

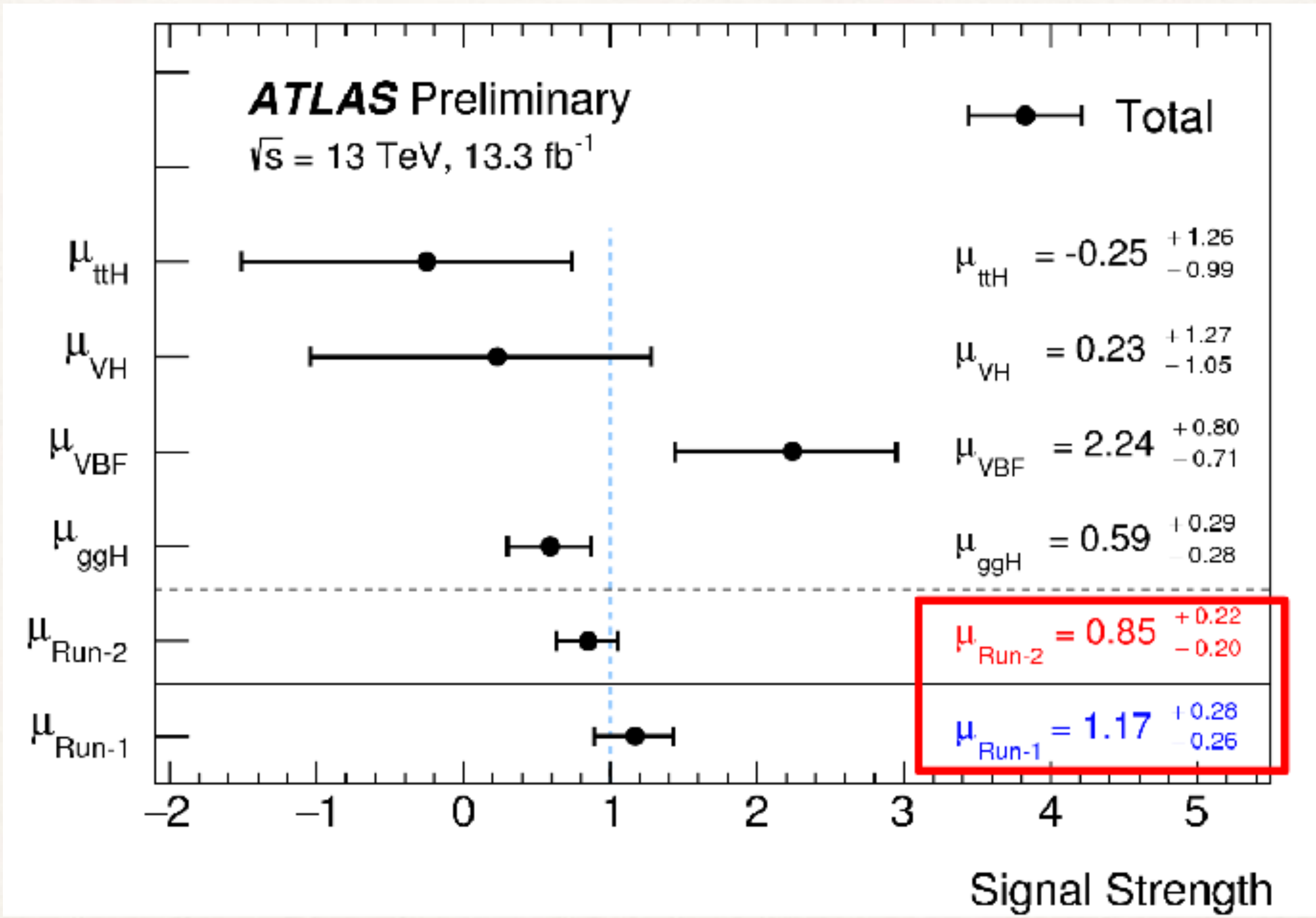




SM Higgs

Run1 (and now Run2) indicates a *SM-like* Higgs

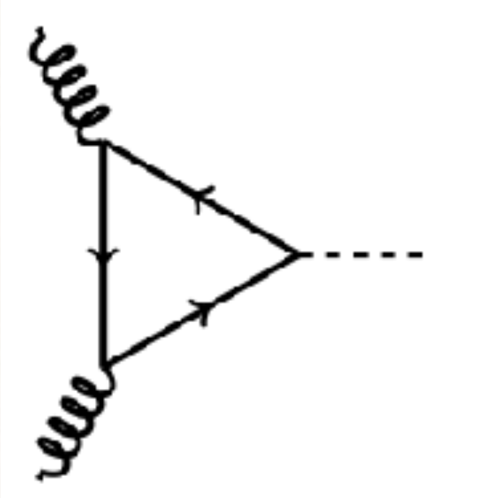
$$\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$$



but precision is **poor** (20-30%)

The low-hanging fruits:
SUSY and Composite Higgs

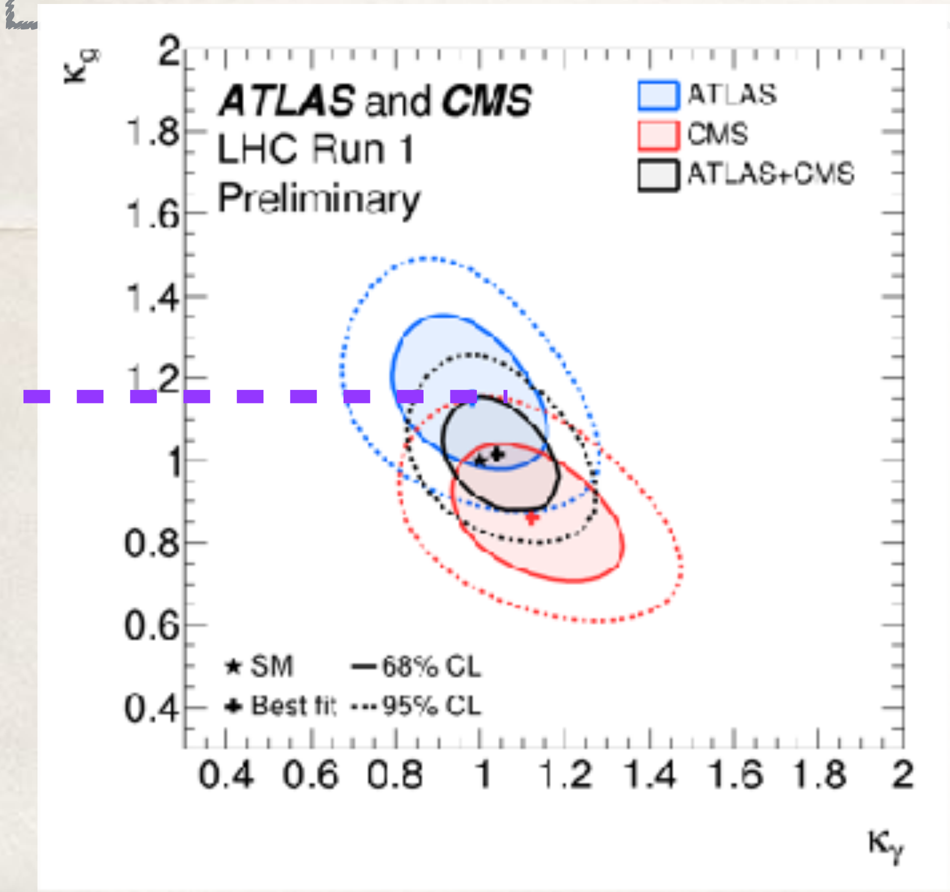
SUSY Higgs (I)



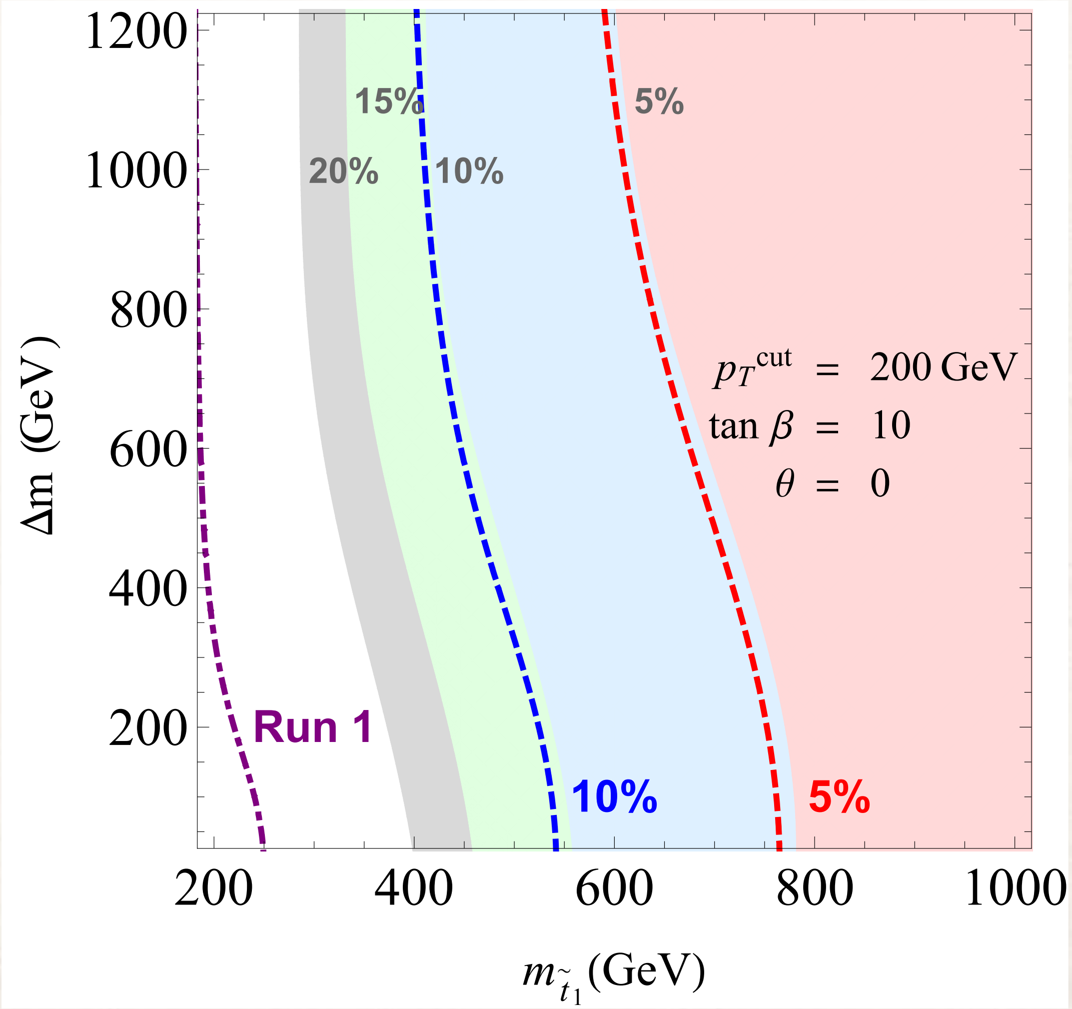
SUSY Higgs: loop corrections compete with gluon fusion and Higgs to diphotons
Main effect **stop contributions**

ESPINOSA, GROJEAN, **VS**, TROTT. 1207.7355

$$\kappa_g \simeq 1 + 0.3\,\frac{m_t^2}{m_{\tilde{t}}^2}$$



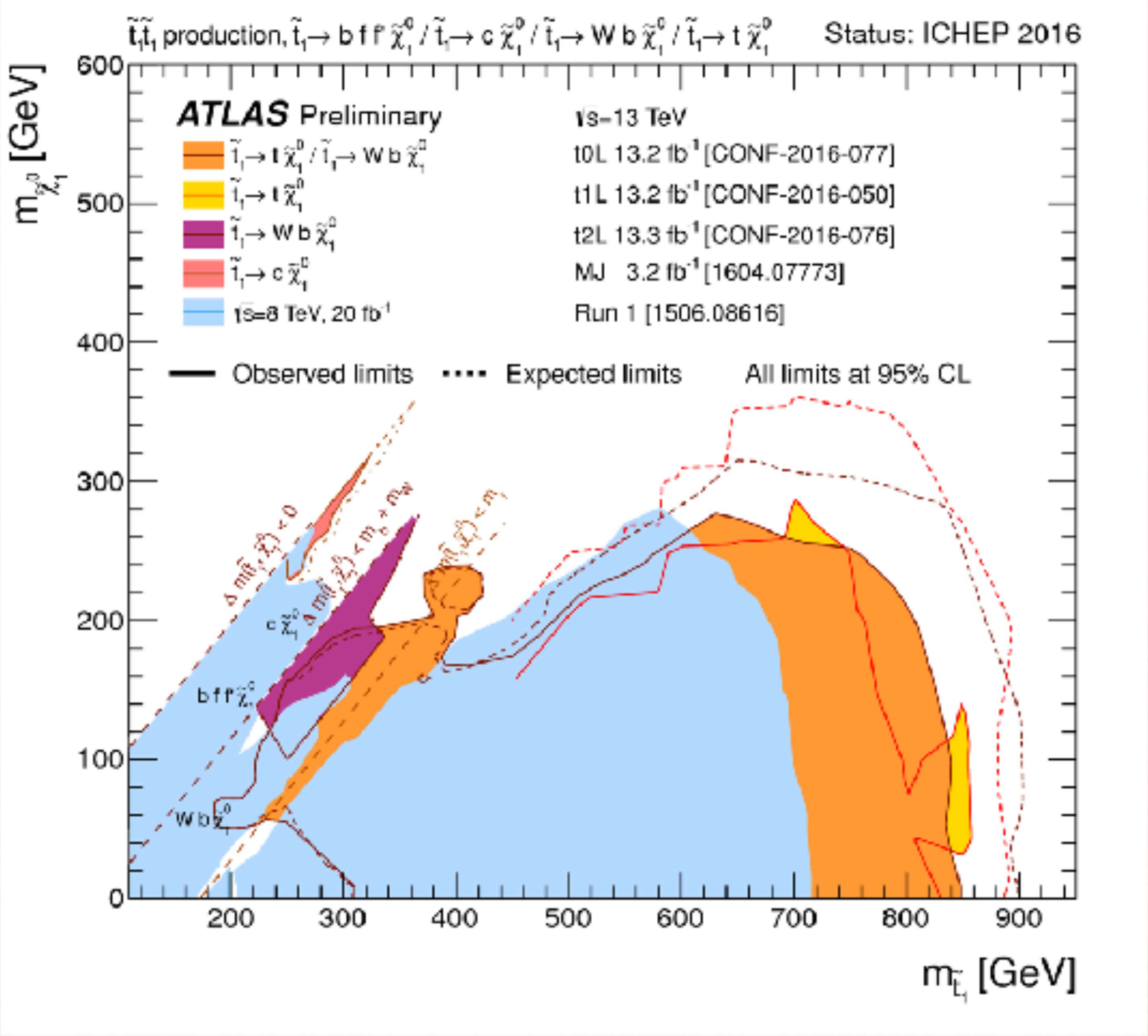
indirect searches for stops



BANFI, BOND, MARTIN, **VS.** 1708.XXXX

SUSY Higgs (II)

Higgs data vs direct searches for stops

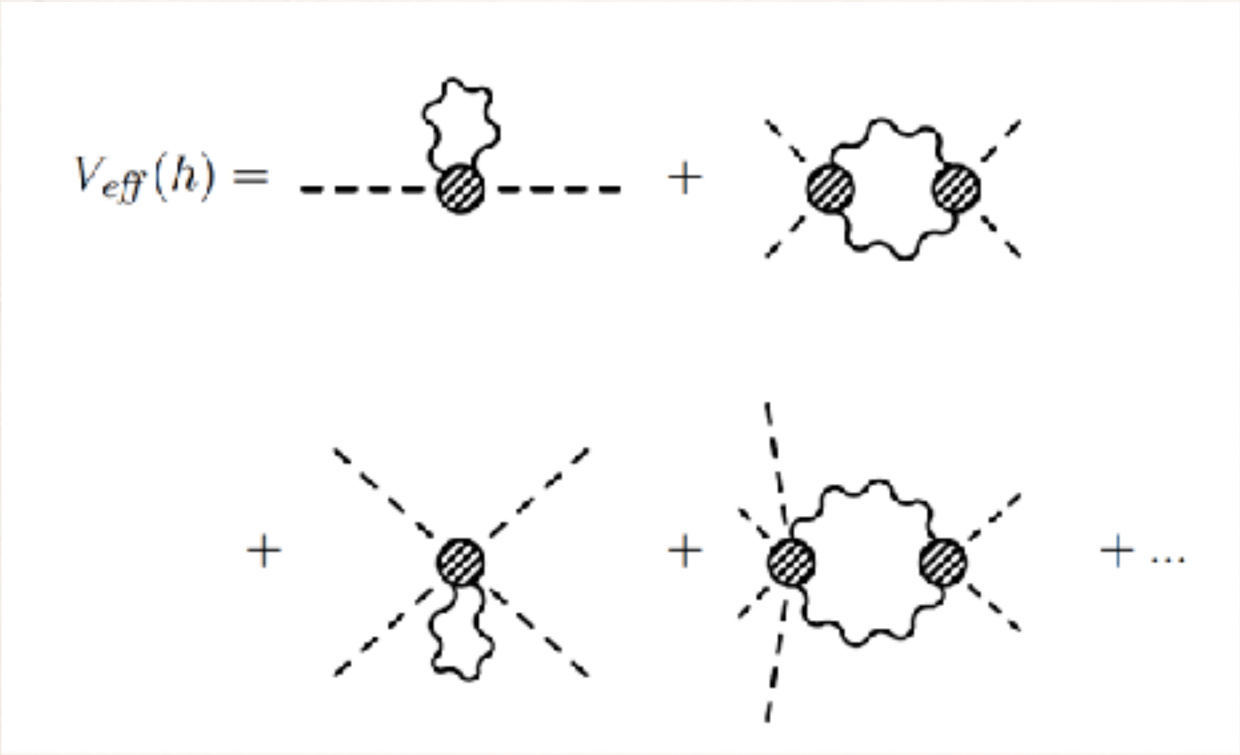


complementary

Composite Higgs (I)

Usual paradigm:
potential generated via **Coleman-Weinberg** contributions

e.g. GAUGE



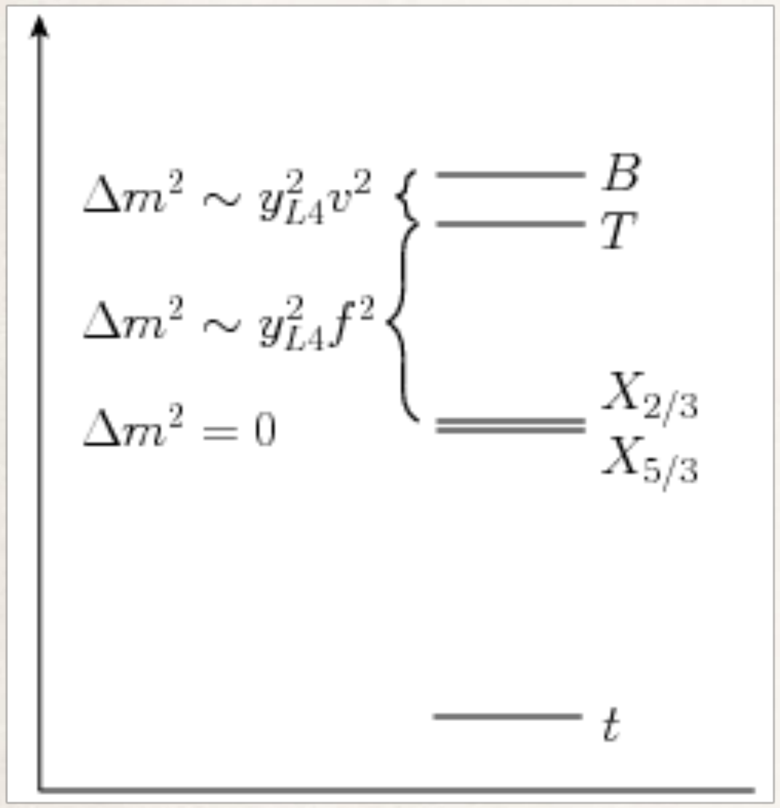
Georgi-Kaplan (80's)
gauge-top *does not* trigger EWSB
need new fermionic resonances
TOP-PARTNERS

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

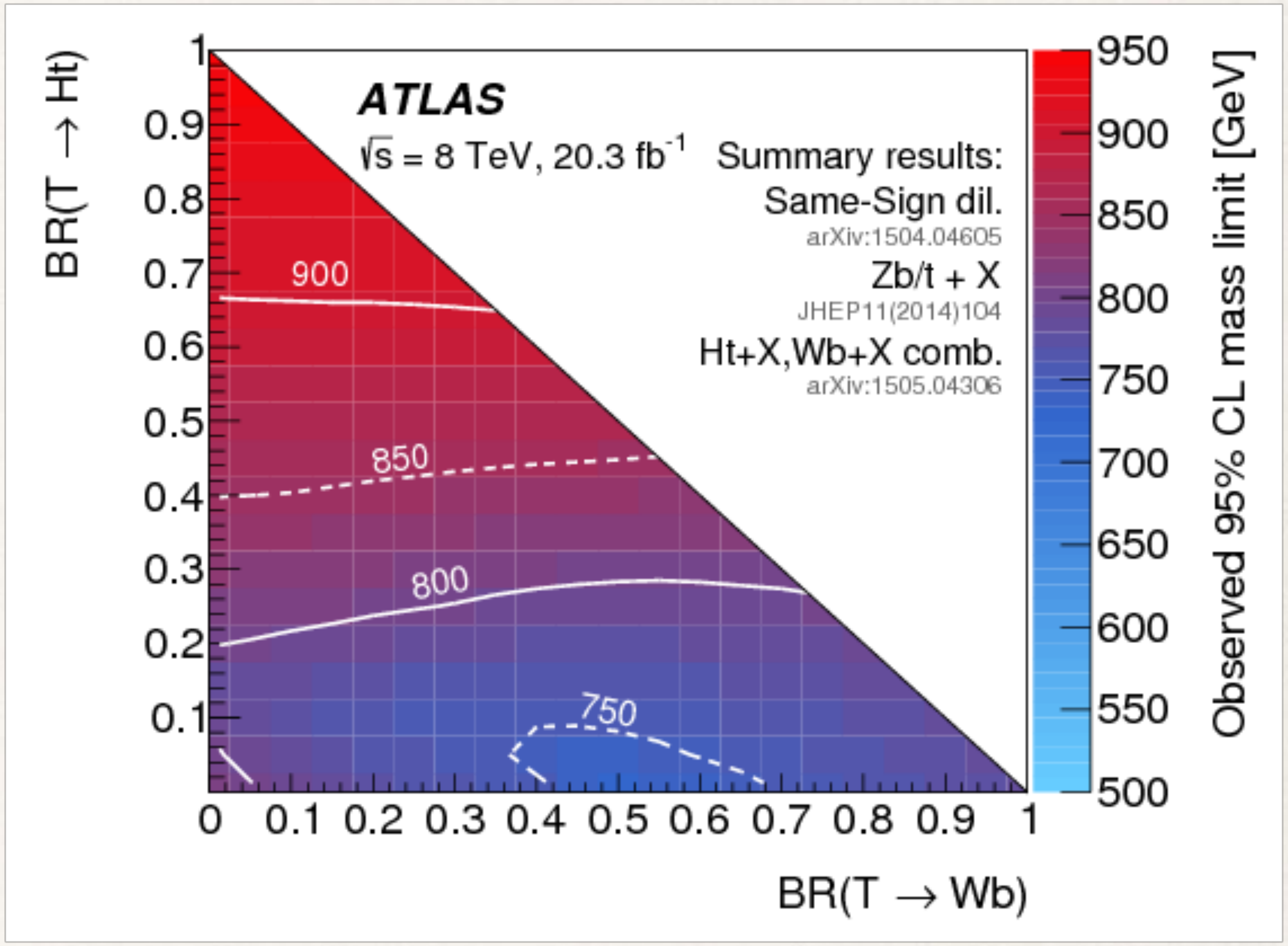
pheno: New, light (below TeV) techni-baryons
should couple to the Higgs, W, Z

Composite Higgs (II)

typical distribution of top-partners



Panico et al. 2016



resonances below ~ 800 GeV are excluded

$$m_h^2 \sim \frac{N_c y_t^2}{16\pi^2} \frac{v^2}{f^2} m_T^2$$

tuning in the Higgs potential severe

Composite Higgs after Run2

Composite Higgs models
Many realizations,
but some common features

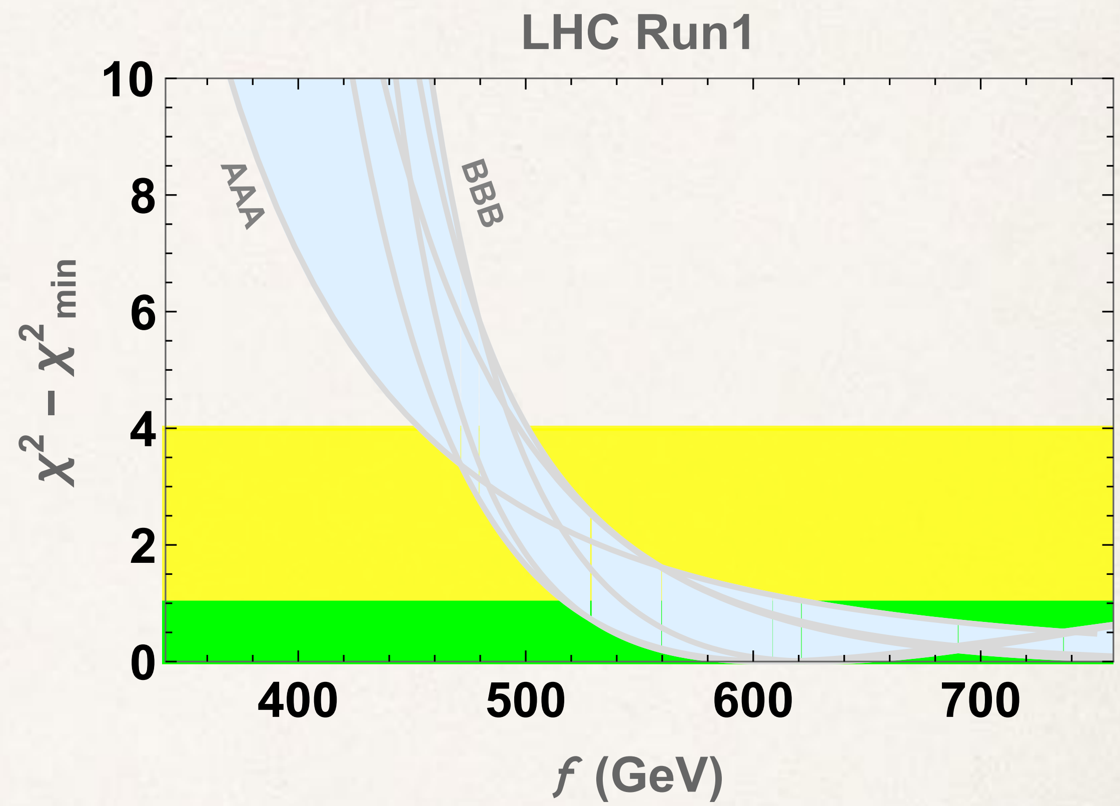
Boson couplings

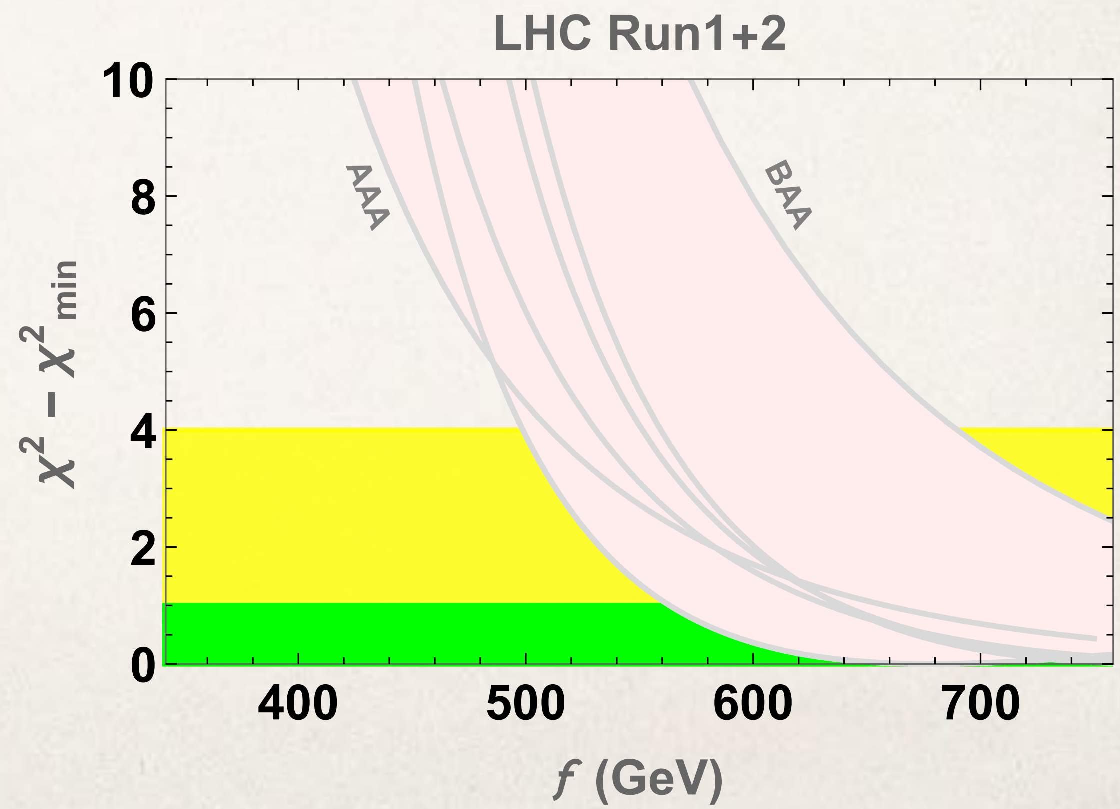
$$\kappa_V = \sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi$$

Fermion couplings

κ_F	Models
$\kappa_F^A = \sqrt{1-\xi}$	$SO(5)/SO(4)$ – [8, 9]
	$SO(6)/SO(4) \times SO(2)$ – [12, 13]
	$SU(5)/SU(4)$ [14]
	$SO(8)/SO(7)$ – [18, 19]
$\kappa_F^B = \frac{1-2\xi}{\sqrt{1-\xi}}$	$SO(5)/SO(4)$ [9, 11, 17]
	$SU(4)/Sp(4)$ – [3]
	$SU(5)/SO(5)$ – [4]
	$SO(6)/SO(4) \times SO(2)$ – [12, 13]

VS, SETFORD. 1703.10190





The EFT approach

Looking for small deviations from the SM

EFT approach

Well-defined theoretical approach

Assumes New Physics states are heavy

Write Effective Lagrangian with only light (SM) particles

BSM effects can be incorporated as a momentum expansion

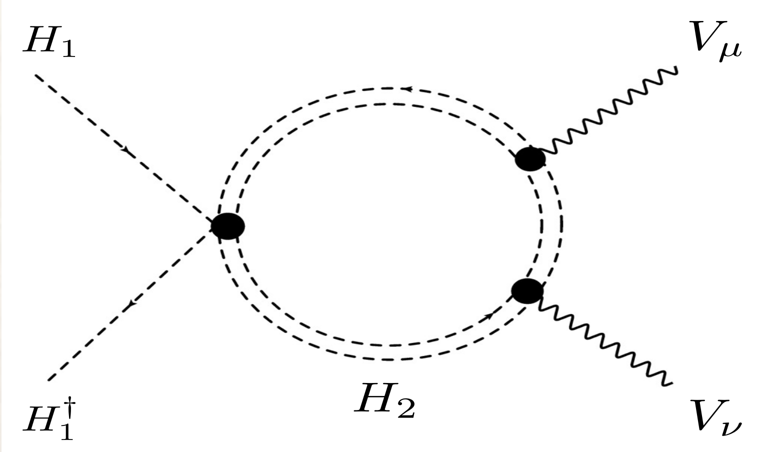
dimension-6 dimension-8

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i}{\Lambda^2}\,\mathcal{O}_i^{d=6} + \sum \frac{c_i}{\Lambda^4}\,\mathcal{O}_i^{d=8} + \dots$$

BSM effects SM particles

example:

2HDM



$$\frac{ig}{2m_W^2}\,\bar{c}_W \left[\Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi\right] D_\nu W^{k,\mu\nu}$$

where $\bar{c}_W = \dfrac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2}$

Beyond the kappa formalism

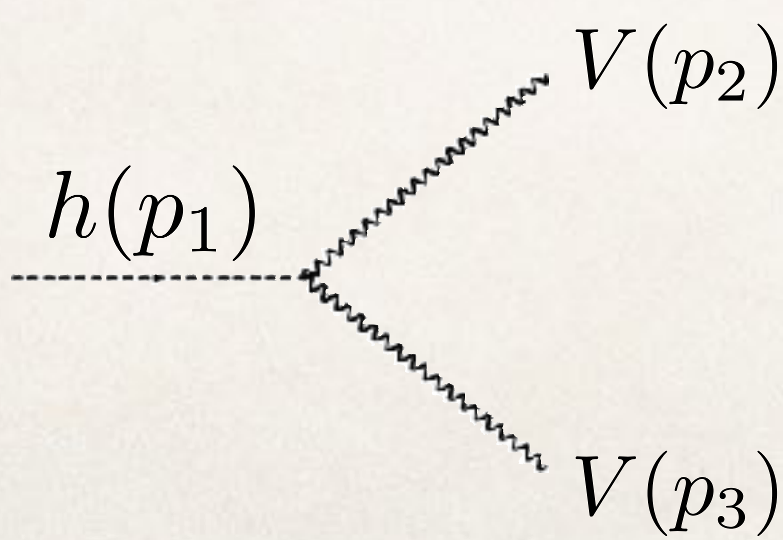
Kappa-formalism is useful when new physics effects are *very simple*

Just change the overall rates

squarks EWinos $(\kappa_\gamma,\ \kappa_g)$	non-linear, CHM singlet mixing $(\kappa_f,\ \kappa_V)$

Models offer richer kinematics, and EFT approach captures them

$$-\frac{1}{4} h\, g^{(1)}_{hVV} V_{\mu\nu} V^{\mu\nu} \quad -h\, g^{(2)}_{hVV} V_\nu \partial_\mu V^{\mu\nu} \quad -\frac{1}{4} h\, \tilde{g}_{hVV} V_{\mu\nu} \tilde{V}^{\mu\nu}$$



$$i\eta_{\mu\nu} \left(g^{(1)}_{hVV} \left(\frac{\hat{s}}{2} - m_V^2 \right) + 2 g^{(2)}_{hVV} m_V^2 \right)$$

$$-i g^{(1)}_{hVV} p_3^\mu p_2^\nu \quad -i \tilde{g}_{hVV} \epsilon^{\mu\nu\alpha\beta} p_{2,\alpha} p_{3,\beta}$$

$+$ *off-shell pieces*

EFT approach

THEORY

Model-independent parametrization deformations respect to the SM

Well-defined theory
can be improved order by order in momentum expansion
consistent addition of higher-order QCD and EW corrections

Connection to models is straightforward

EXPERIMENT

Beyond kappa-formalism: Allows for a richer and generic set of kinematic features

Higher-order precision in QCD/EW

The way to combine all Higgs channels and EW production

EFT: Matching with UV theories

Extended Higgs sectors

Gorbahn, No, **VS**. 1502.07352

To combine direct/indirect and evaluate the validity of the EFT approximation, matching of the EFT with a UV model is required

We did the matching to UV theories with extended Higgs sectors

	$\bar{c}_H$	$\bar{c}_6$	$\bar{c}_T$	$\bar{c}_W$	$\bar{c}_B$	$\bar{c}_{HW}$	$\bar{c}_{HB}$	$\bar{c}_{3W}$	$\bar{c}_\gamma$	$\bar{c}_g$
Higgs Portal (G)	L	L	X	X	X	X	X	X	X	X
Higgs Portal (Spontaneous $\not{G}$)	T	L	RG	RG	RG	X	X	X	X	X
Higgs Portal (Explicit $\not{G}$)	T	T	RG	RG	RG	X	X	X	X	X
2HDM Benchmark A ($c_{\beta-\alpha}=0$)	L	L	L	L	L	L	L	L	L	X
2HDM Benchmark B ($c_{\beta-\alpha}\neq 0$)	T	T	L	L	L	L	L	L	L	X
Radion/Dilaton	T	T	RG	T	T	T	T	L	T	T

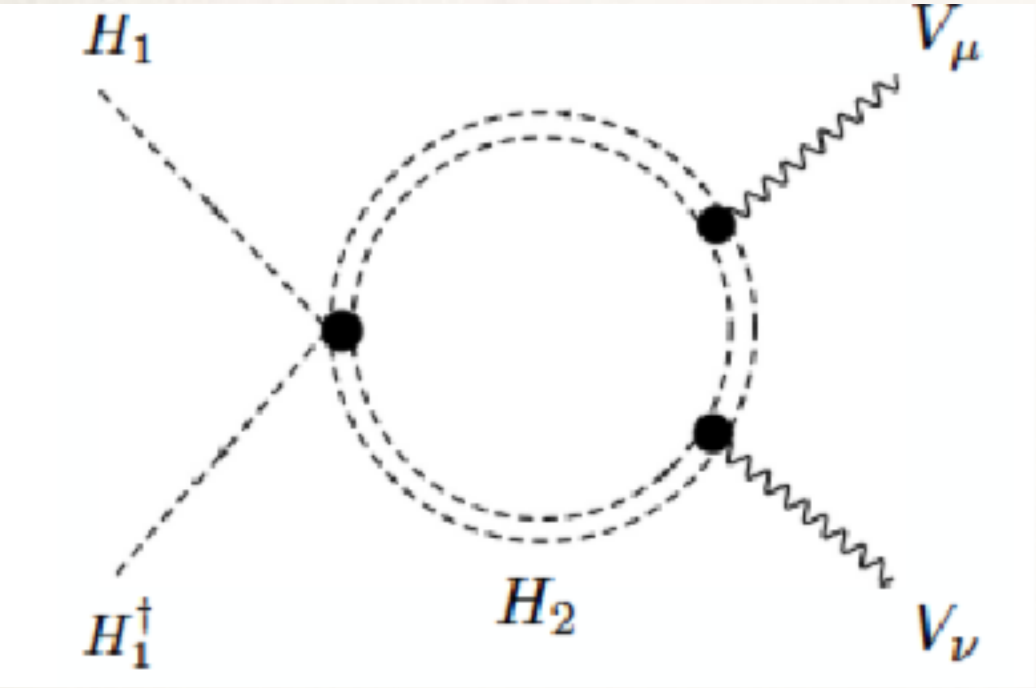
combined EWPTs, direct searches and Higgs limits from the EFT

50 pages of gory details…

Matching procedure

Gorbahn, No, **VS**. 1502.07352

Example: 2HDM



also matching with the broken phase

obtained EFT limits,
dimension-6 and dimension-8
and EWPTs

Matching EFT: unbroken phase

$$\bar{c}_H = -\left[-4\tilde{\lambda}_3\tilde{\lambda}_4 + \tilde{\lambda}_4^2 + \tilde{\lambda}_5^2 - 4\tilde{\lambda}_3^2\right]\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_6 = -\left(\tilde{\lambda}_4^2 + \tilde{\lambda}_5^2\right)\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T = (\tilde{\lambda}_4^2 - \tilde{\lambda}_5^2)\frac{v^2}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_W = -\bar{c}_{HW} = \frac{m_W^2\,(2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = \frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + \frac{m_W^2\,\tilde{\lambda}_4}{192\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_{3W} = \frac{\bar{c}_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde{\mu}_2^2}$$

$$\bar{c}_T(m_Z) \simeq \bar{c}_T(\tilde{\mu}_2) - \frac{3\,g'^2}{32\,\pi^2}\,\bar{c}_H(\tilde{\mu}_2)\log\left(\frac{\tilde{\mu}_2}{m_Z}\right)$$

$$\bar{c}_W(m_Z) + \bar{c}_B(m_Z) \simeq c_W(\tilde{\mu}_2) + \bar{c}_B(\tilde{\mu}_2) + \frac{1}{24\,\pi^2}\,\bar{c}_H(\tilde{\mu}_2)\log\left(\frac{\tilde{\mu}_2}{m_Z}\right).$$

Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

$$\bar c_H = -\left[-4\tilde\lambda_3\tilde\lambda_4 + \tilde\lambda_4^2 + \tilde\lambda_5^2 - 4\tilde\lambda_3^2\right]\frac{v^2}{192\,\pi^2\,\tilde\mu_2^2}$$

$$\bar c_6 = -\left(\tilde\lambda_4^2 + \tilde\lambda_5^2\right)\frac{v^2}{192\,\pi^2\,\tilde\mu_2^2}$$

$$\bar c_T = (\tilde\lambda_4^2 - \tilde\lambda_5^2)\frac{v^2}{192\,\pi^2\,\tilde\mu_2^2}$$

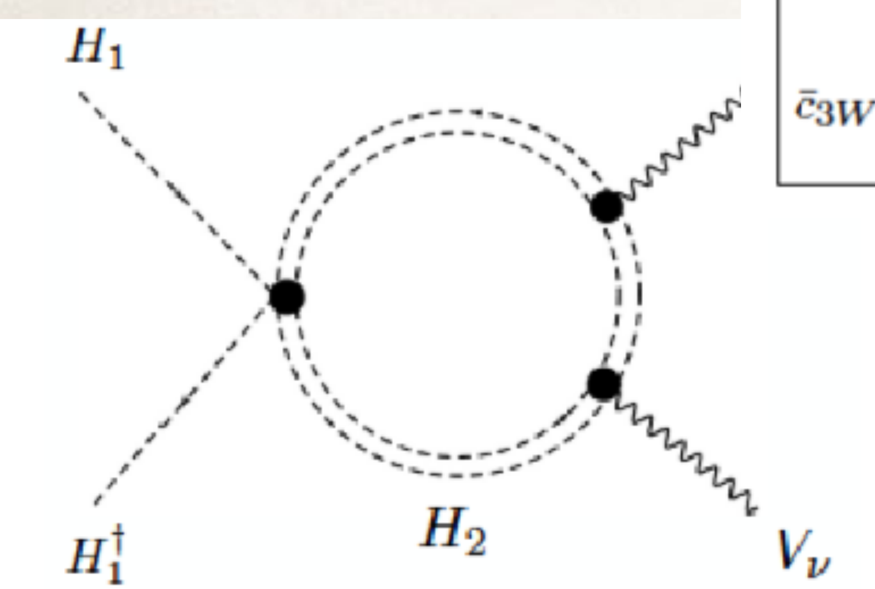
$$\bar c_\gamma = \frac{m_W^2\,\tilde\lambda_3}{256\,\pi^2\,\tilde\mu_2^2}$$

$$\bar c_W = -\bar c_{HW} = \frac{m_W^2\,(2\,\tilde\lambda_3 + \tilde\lambda_4)}{192\,\pi^2\,\tilde\mu_2^2} = \frac{8}{3}\,\bar c_\gamma + \frac{m_W^2\,\tilde\lambda_4}{192\,\pi^2\,\tilde\mu_2^2}$$

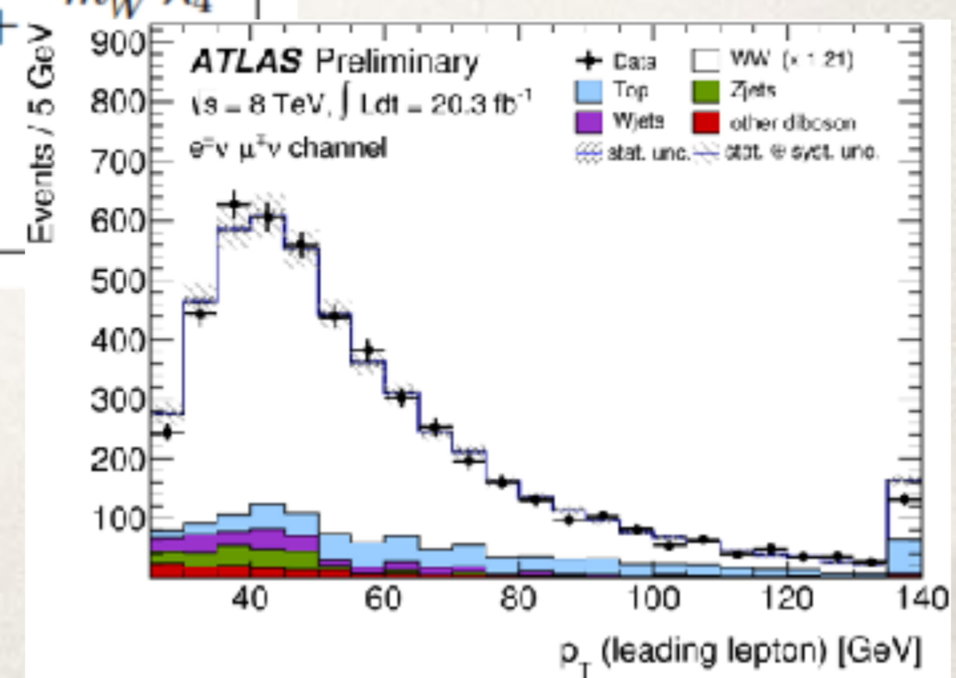
$$\bar c_B = -\bar c_{HB} = \frac{m_W^2\,(-2\,\tilde\lambda_3 + \tilde\lambda_4)}{192\,\pi^2\,\tilde\mu_2^2} = -\frac{8}{3}\,\bar c_\gamma + \frac{m_W^2\,\tilde\lambda_4}{\ldots}$$

$$\bar c_{3W} = \frac{\bar c_{2W}}{3} = \frac{m_W^2}{1440\,\pi^2\,\tilde\mu_2^2}$$

MODELS



DATA



EFT: Global analyses

Global analyses using EFTs

EFTs induce effects in many channels
ideal framework for combination

$\mathcal{L}_{3h}$ Couplings *vs* $SU(2)_L \times U(1)_Y$ ($D \leq 6$) **Wilson Coefficients**

$$g^{(1)}_{hhh} = 1 + \frac{5}{2}\,\bar{c}_6 \,, \quad g^{(2)}_{hhh} = \frac{g}{m_W}\,\bar{c}_H \,, \quad g_{hgg} = g^{\rm SM}_{hgg} - \frac{4\,g_s^2\,v\,\bar{c}_g}{m_W^2} \,, \quad g_{h\gamma\gamma} = g^{\rm SM}_{h\gamma\gamma} - \frac{8\,g\,s_W^2\,\bar{c}_\gamma}{m_W}$$

$$g^{(1)}_{hww} = \frac{2g}{m_W}\bar{c}_{HW} \,, \quad g^{(1)}_{hzz} = g^{(1)}_{hww} + \frac{2g}{c_W^2 m_W}\left[\bar{c}_{HB}s_W^2 - 4\bar{c}_\gamma s_W^4\right] \,, \quad g^{(2)}_{hww} = \frac{g}{2\,m_W}\left[\bar{c}_W + \bar{c}_{HW}\right]$$

$$g^{(2)}_{hzz} = 2\,g^{(2)}_{hww} + \frac{g\,s_W^2}{c_W^2 m_W}\left[(\bar{c}_B + \bar{c}_{HB})\right] \,, \quad g^{(3)}_{hww} = g\,m_W \,, \quad g^{(3)}_{hzz} = \frac{g^{(3)}_{hww}}{c_W^2}(1 - 2\,\bar{c}_T)$$

$$g^{(1)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} + 8\,\bar{c}_\gamma\,s_W^2\right] \,, \quad g^{(2)}_{haz} = \frac{g\,s_W}{c_W\,m_W}\left[\bar{c}_{HW} - \bar{c}_{HB} - \bar{c}_B + \bar{c}_W\right]$$

$\mathcal{L}_{4h}$ Couplings *vs* $SU(2)_L \times U(1)_Y$ ($D \leq 6$) **Wilson Coefficients**

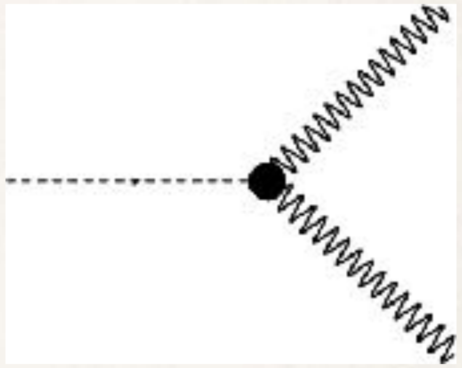
$$g^{(1)}_{hhhh} = 1 + \frac{15}{2}\,\bar{c}_6 \,, \quad g^{(2)}_{hhhh} = \frac{g^2}{4\,m_W^2}\,\bar{c}_H \,, \quad g_{hhgg} = -\frac{4\,g_s^2\,\bar{c}_g}{m_W^2} \,, \quad g_{hh\gamma\gamma} = -\frac{4\,g^2\,s_W^2\,\bar{c}_\gamma}{m_W^2}$$

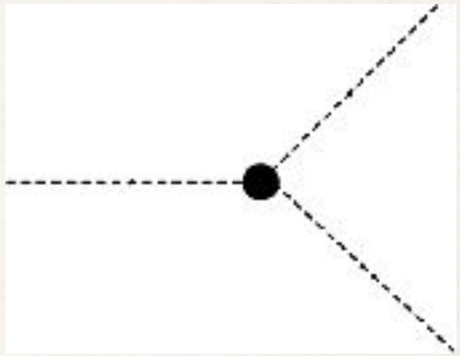
$$g^{(1,2)}_{hhxy} = \frac{g}{2\,m_W}\,g^{(1,2)}_{hxy} \quad (x, y = W, Z, \gamma) \,, \quad g^{(3)}_{hhww} = \frac{g^2}{2} \,, \quad g^{(3)}_{hhzz} = \frac{g^{(3)}_{hhww}}{c_W^2}(1 - 6\,\bar{c}_T)$$

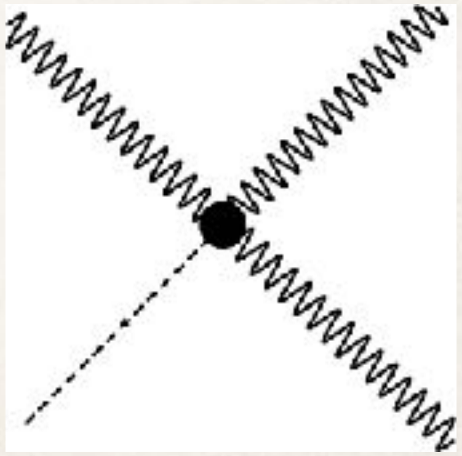
$$g^{(1)}_{haww} = \frac{g^2\,s_W}{m_W}\left[2\,\bar{c}_W + \bar{c}_{HW} + \bar{c}_{HB}\right] \,, \quad g^{(1)}_{hzww} = \frac{g^2}{c_W\,m_W}\left[c_W^2\,\bar{c}_{HW} - s_W^2\bar{c}_{HB} + (3 - 2s_W^2)\,\bar{c}_W\right]$$

$$g^{(2)}_{haww} = \frac{2\,g^2\,s_W}{m_W}\,\bar{c}_W \,, \quad g^{(2)}_{hzww} = \frac{g^2}{c_W\,m_W}\left[\bar{c}_{HW} + (3 - 2s_W^2)\,\bar{c}_W\right]$$

$$g^{(3)}_{haww} = \frac{g^2\,s_W}{m_W}\left[\bar{c}_W + \bar{c}_{HW}\right] \,, \quad g^{(3)}_{hzww} = \frac{s_W}{c_W}\,g^{(3)}_{haww}$$







Alloul, Fuks, VS. 1310.5150
Gorbahn, No, VS. 1502.07352

Global analyses using EFTs

EFTs induce effects in many channels
ideal framework for combination

TGCs, QGCs

$\mathcal{L}_{3V}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**

$$g_1^Z = 1 - \frac{1}{c_W^2}\Big[\bar{c}_{HW} - (2s_W^2 - 3)\bar{c}_W\Big] \ , \quad \kappa_Z = 1 - \frac{1}{c_W^2}\Big[c_W^2\,\bar{c}_{HW} - s_W^2\,\bar{c}_{HB} - (2s_W^2 - 3)\bar{c}_W\Big]$$

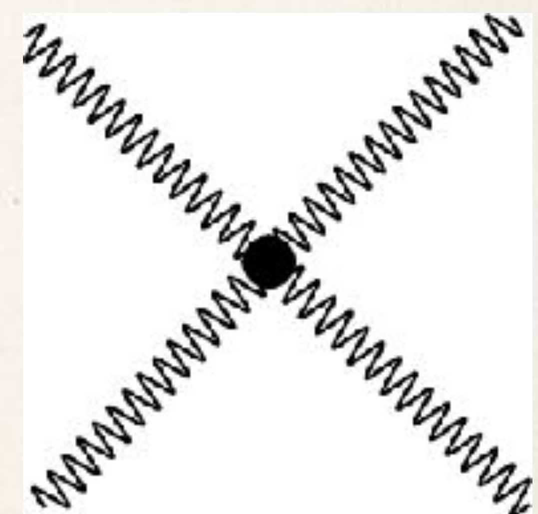
$$g_1^\gamma = 1 \ , \quad \kappa_\gamma = 1 - 2\,\bar{c}_W - \bar{c}_{HW} - \bar{c}_{HB} \ , \quad \lambda_\gamma = \lambda_Z = 3\,g^2\,\bar{c}_{3W}$$

$\mathcal{L}_{4V}$ **Couplings** *vs* $SU(2)_L \times U(1)_Y$ $(D \leq 6)$ **Wilson Coefficients**

$$g_2^W = 1 - 2\,\bar{c}_{HW} - 4\,\bar{c}_W \ , \quad g_2^Z = 1 - \frac{1}{c_W^2}\Big[2\,\bar{c}_{HW} + 2\,(2 - s_W^2)\,\bar{c}_W\Big]$$

$$g_2^\gamma = 1 \ , \quad g_2^{\gamma Z} = 1 - \frac{1}{c_W^2}\Big[\bar{c}_{HW} + (3 - 2s_W^2)\,\bar{c}_W\Big]$$

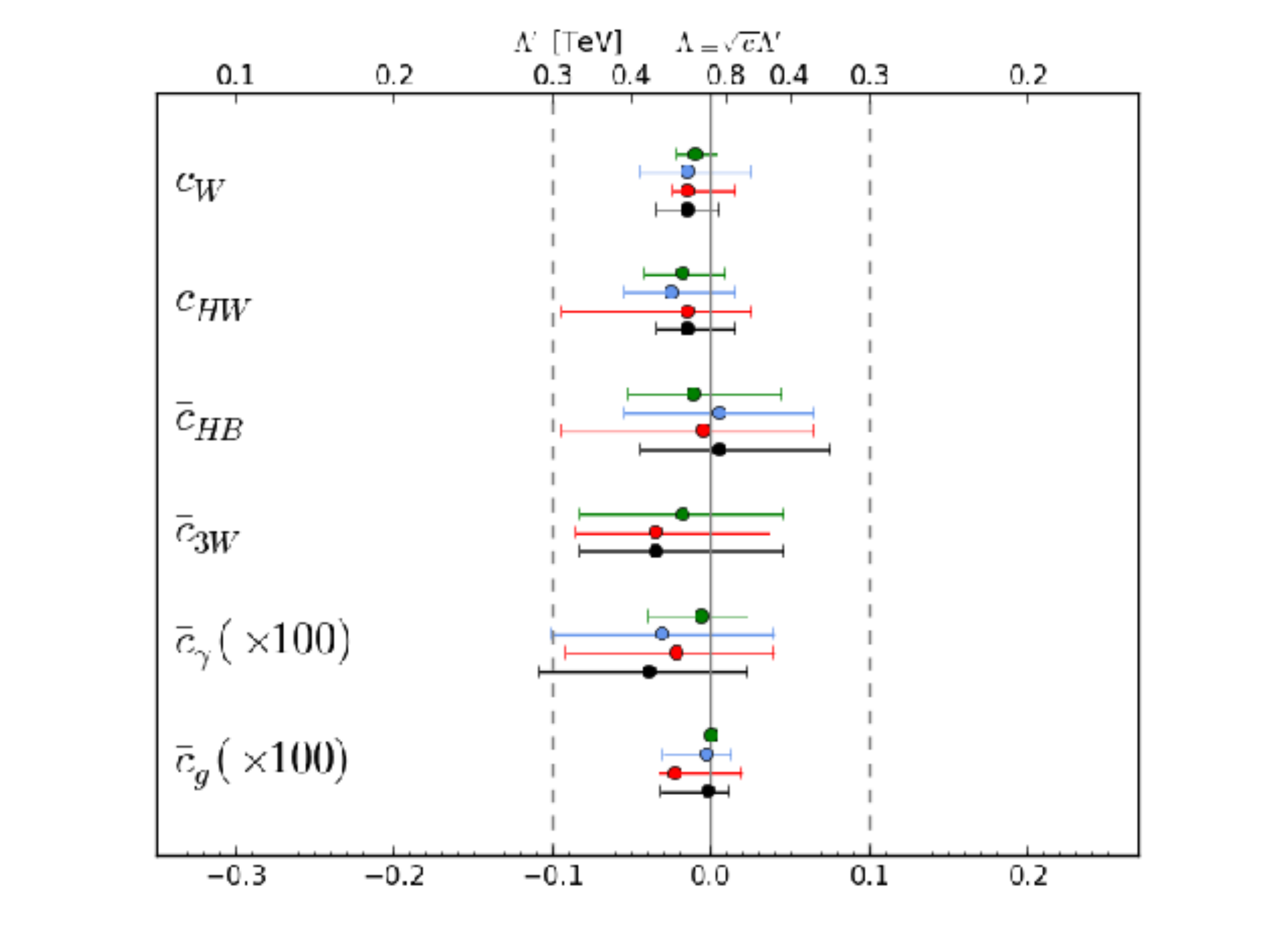
$$\lambda_W = \lambda_{\gamma W} = \lambda_{\gamma Z} = \lambda_{WZ} = 6\,g^2\,\bar{c}_{3W}$$



ALLOUL, FUKS, VS. 1310.5150
GORBAHN, NO, VS. 1502.07352

Global analyses using EFTs

Although the EFT has many parameters, the LHC is sensitive to a handful of them



State of the art: Global fit

ELLIS, **VS**, YOU. 1410.0773

LEP and LHC Run1 data

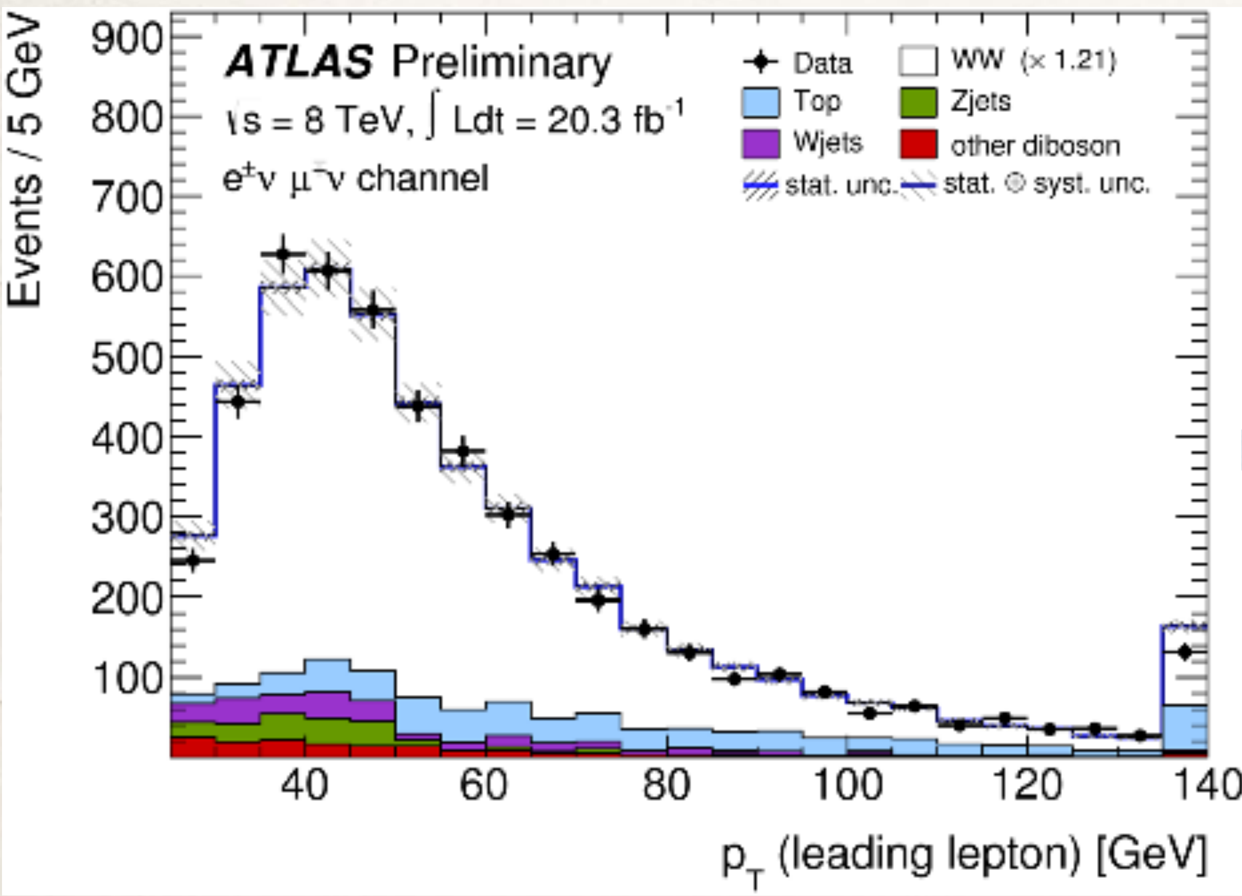
green: one-by-one

black: global fit

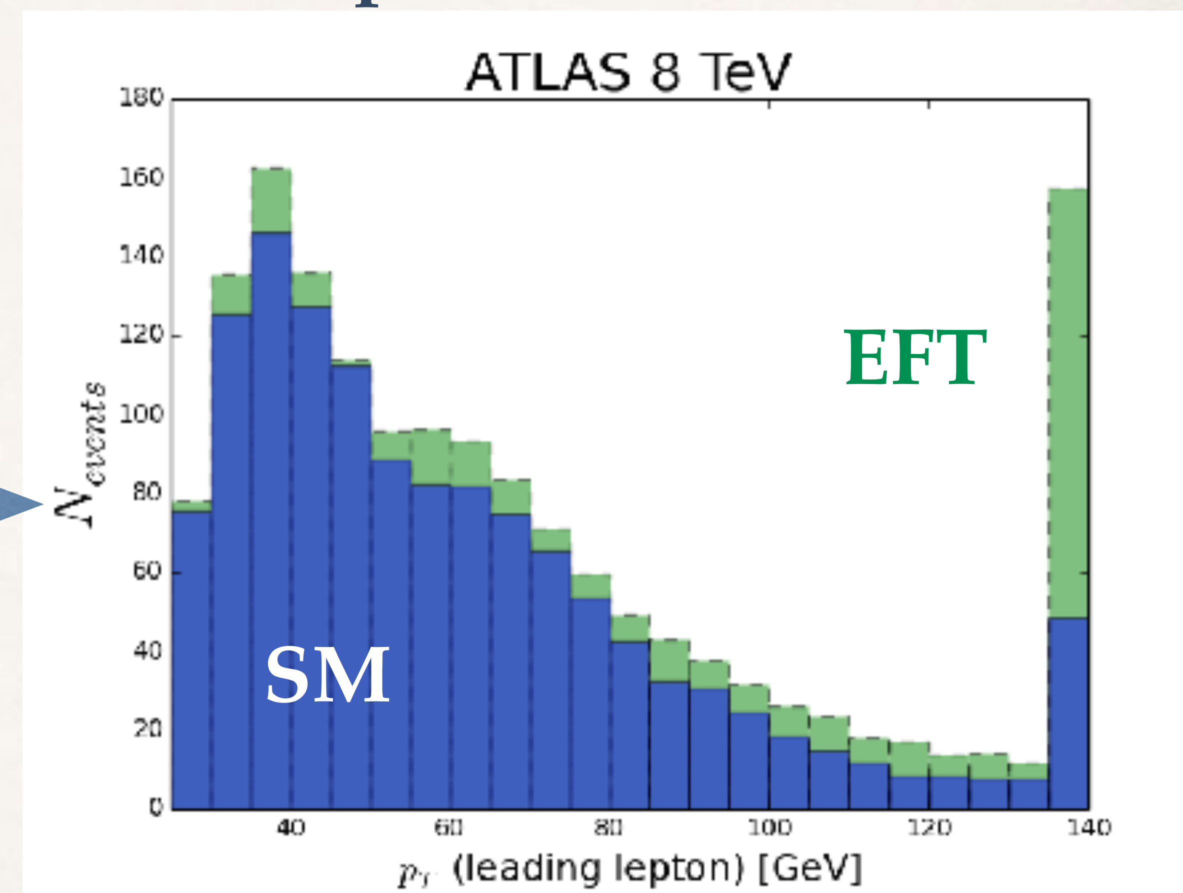
Global analyses using EFTs

sensitivity relies on combination of channels and on use of differential information

WW production



Dependence on EFT



Feynrules -> MG5-> pythia->Delphes3

verified for SM/BGs => expectation for EFT

theorists are working closely with the experiments to bring this to higher precision in the 13 TeV runs

EFT: Precision

Precision in the EFT

Within the EFT approach

- incorporate higher-order QCD and EW effects
- higher-order EFT effects (dimension-8)
- check validity of the approach

Need to exploit differential information
simulate cuts and detector effects in analysis
MC tools should match the level of SM BGs

we started incorporating the EFT at QCD NLO
NLO EW & dim-8 underway

Monte Carlo EFT@NLO QCD

At **LO** there are a handful of EFT implementations, incl SM NLO

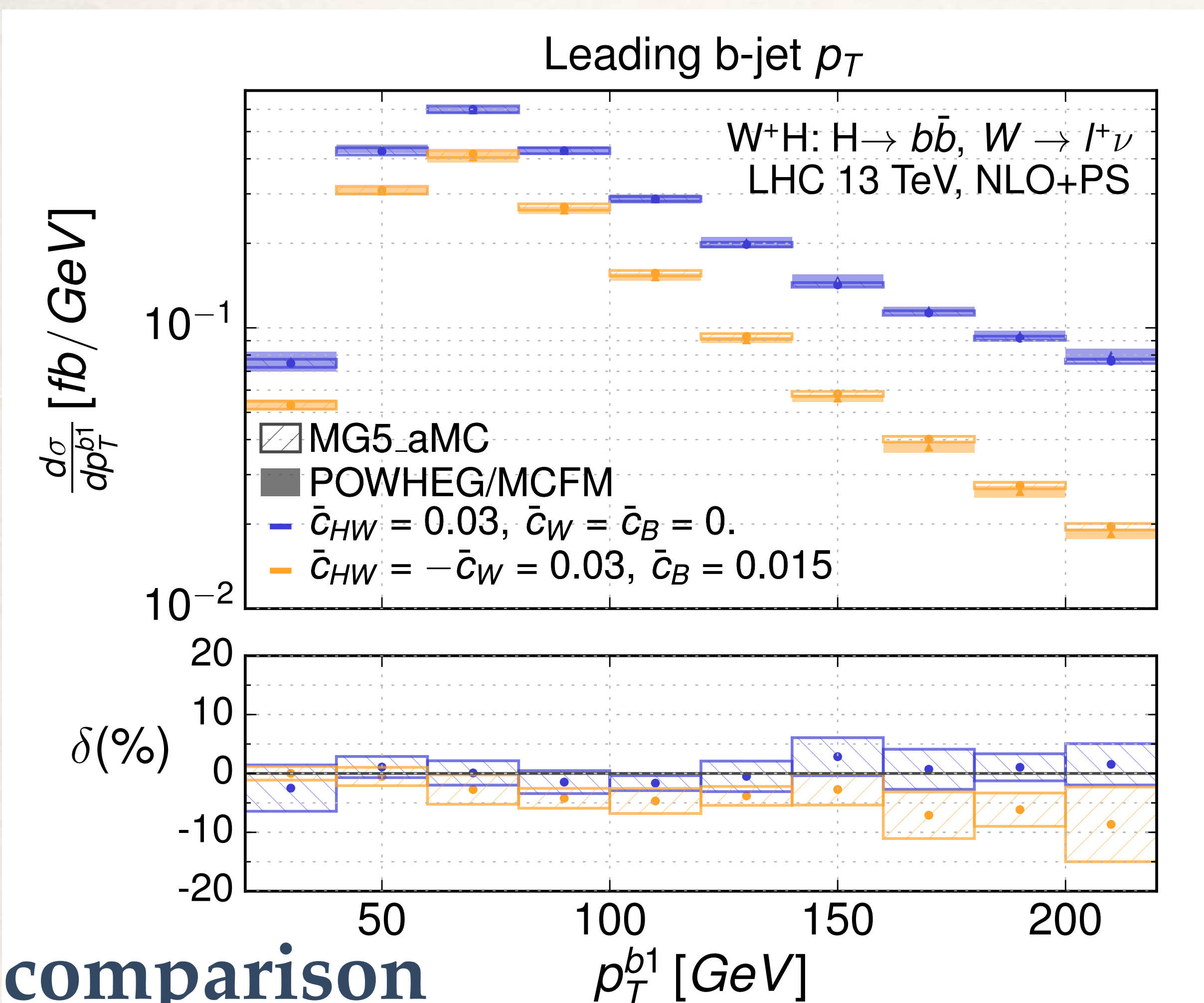
WHIZARD, JHU, VBFNLO, AMC@NLO, POWHEG

Largest collection of EFT operators in one MC (39 operators)

ALLOUL, FUKS, **VS**. 1310.5150

written in the SILH basis, we link to *Rosetta* for change of basis

MIMASU, **VS** ET AL. 1508.05895



comparison

we started incorporating QCD NLO EFT effects for a handful of operators

codes are now public

POWHEG-BOX

MIMASU, **VS**, WILLIAMS. 1512.02572. JHEP

aMC@NLO

DEGRANDE, FUKS, MAWATARI, MIMASU, **VS**. 1609.04833. EPJC

Conclusions

- The Higgs may be the key to discover new physics: lightness and association with the origin of mass

- The discovery of the Higgs in 2012 opened a new way to look for new physics via quantum effects (indirect). With Run2 at 13 TeV, the LHC is approaching a precision stage for Higgs measurements

- The EFT approach to interpret Higgs data is a theorist-friendly procedure and with a well-defined procedure for systematic improvement. It is motivated by the absence of excesses in direct searches

- To reach the precision needed for discovery, theorists are developing NLO MC tools to facilitate the communication with experimentalists. Expect to reach scales into the TeV