Looking for New Physics with the Higgs boson

Veronica Sanz (Sussex)

Planck, May 2017

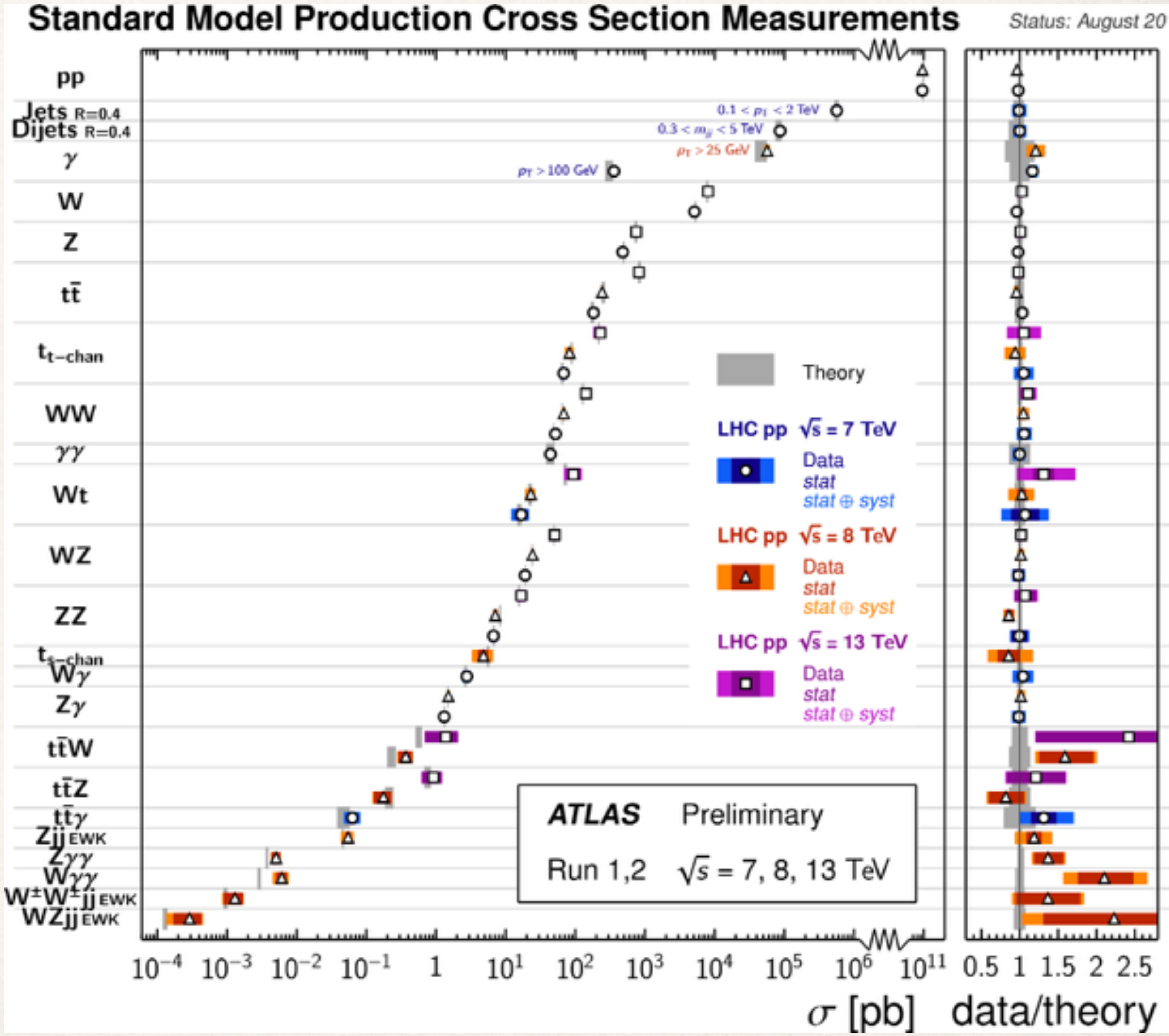
Challenges ahead

The SM in the precision era

Predictive, successful paradigm being tested to very high precision at the LHC

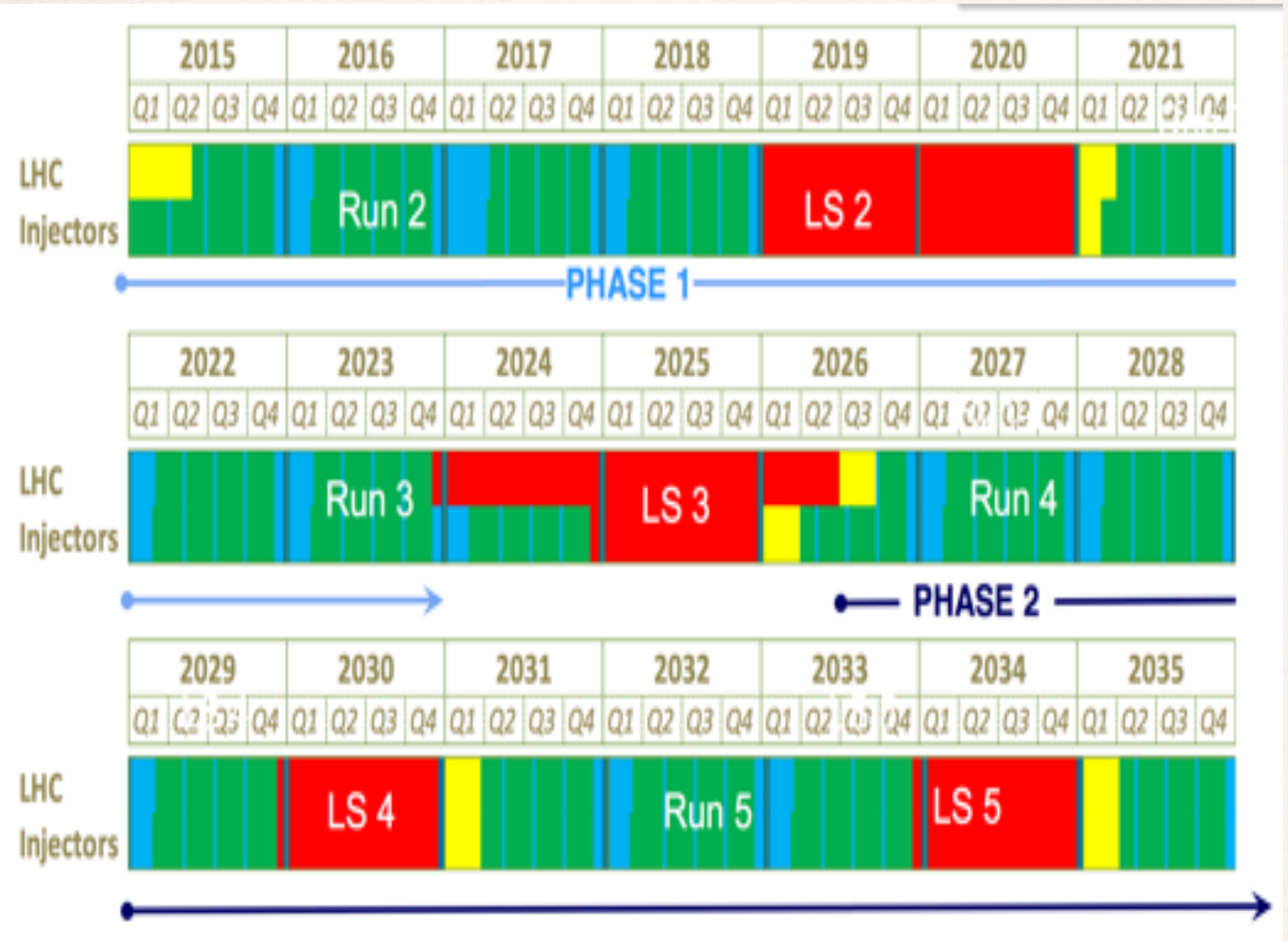
Based on QFT, symmetries (global/gauge) and consistent ways to break them

So far, the data and SM are in perfect agreement:
no excesses/inconsistencies

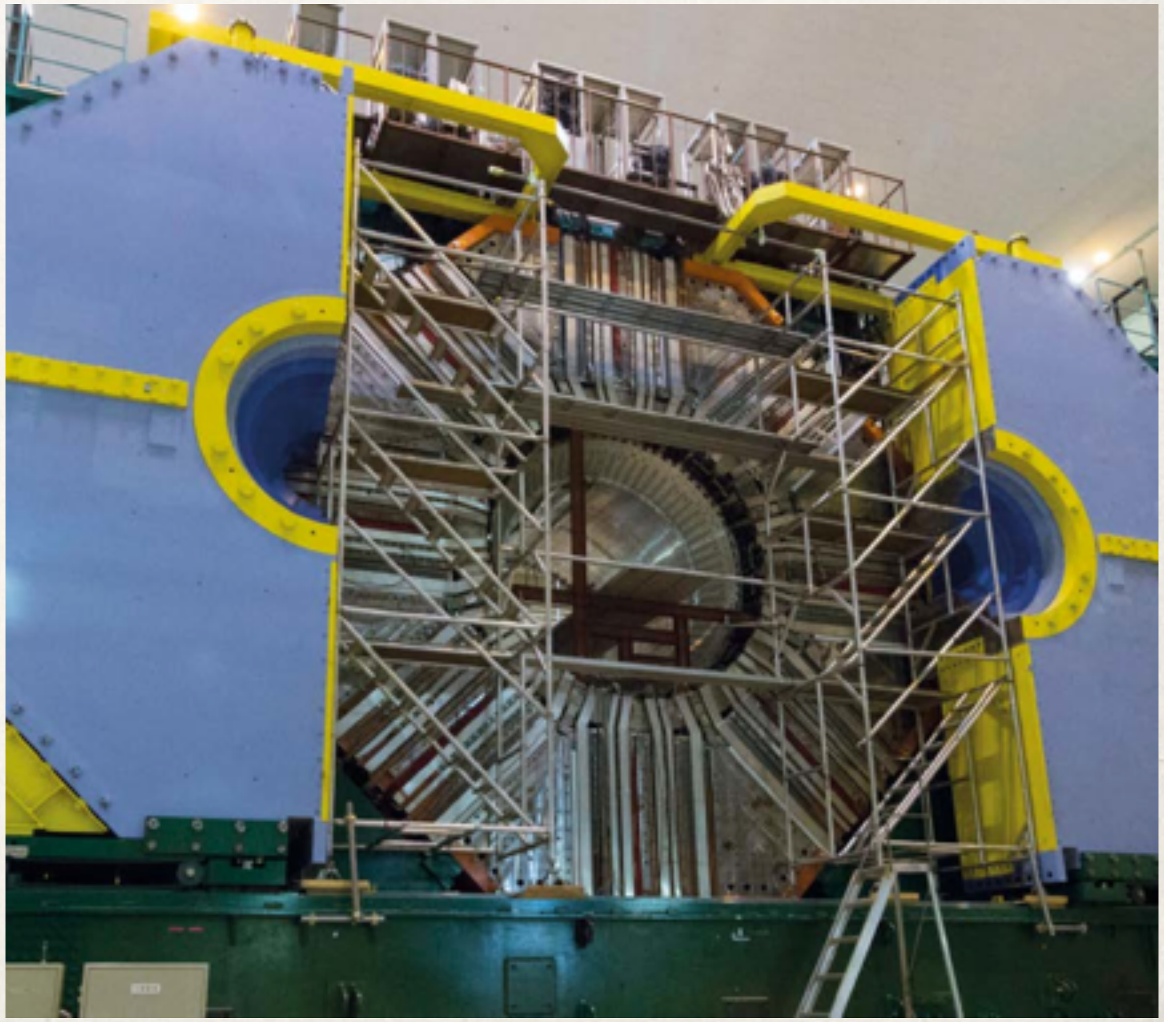


This is just the beginning

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



🟩 Physics
🟥 Shutdown
🟨 Beam commissioning
🟦 Technical stop



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

So here we are

Light Higgs

Inflation

Neutrinos

Unification

Matter/Antimatter

CP QCD

Dark Matter

Dark Energy

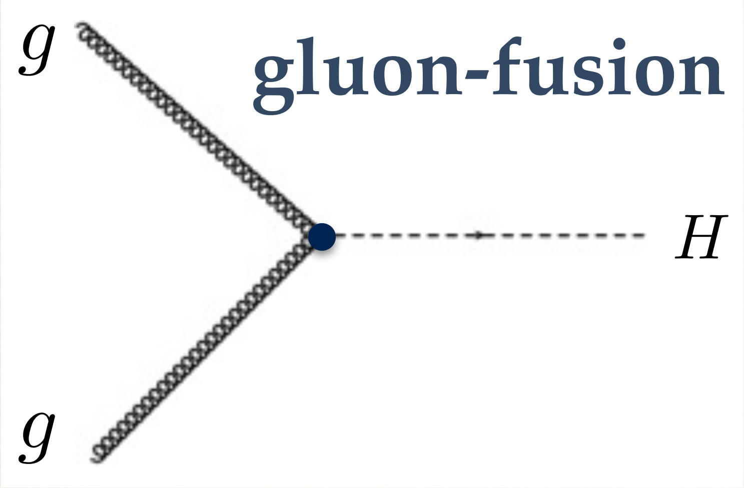
Quantum Gravity

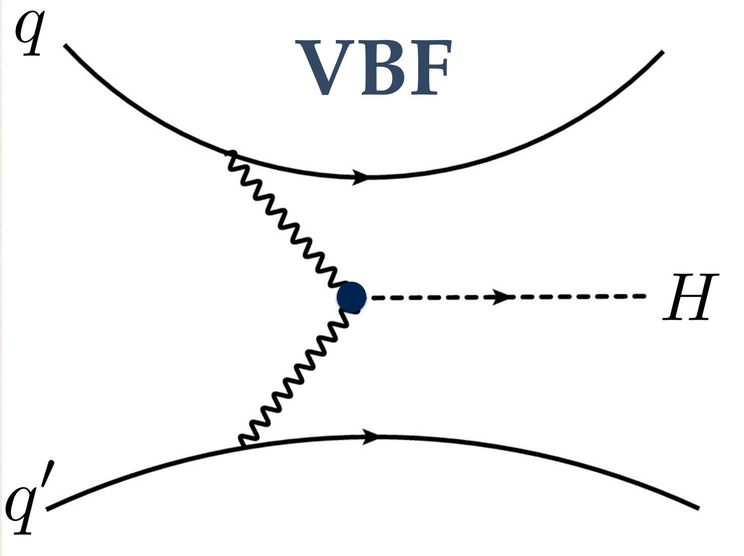
finding our path through **SYMMETRIES & DYNAMICS**

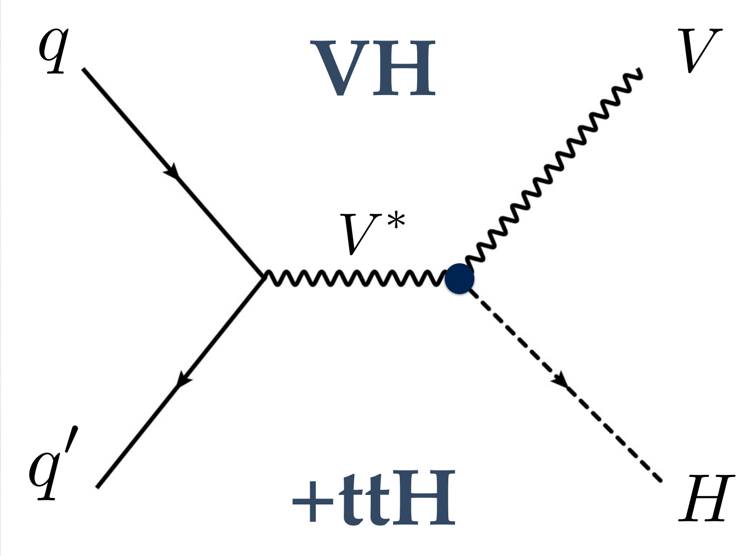
aiming for a **UNIFIED FRAMEWORK**

The Higgs at the LHC

LHC Higgs in a nutshell (I)

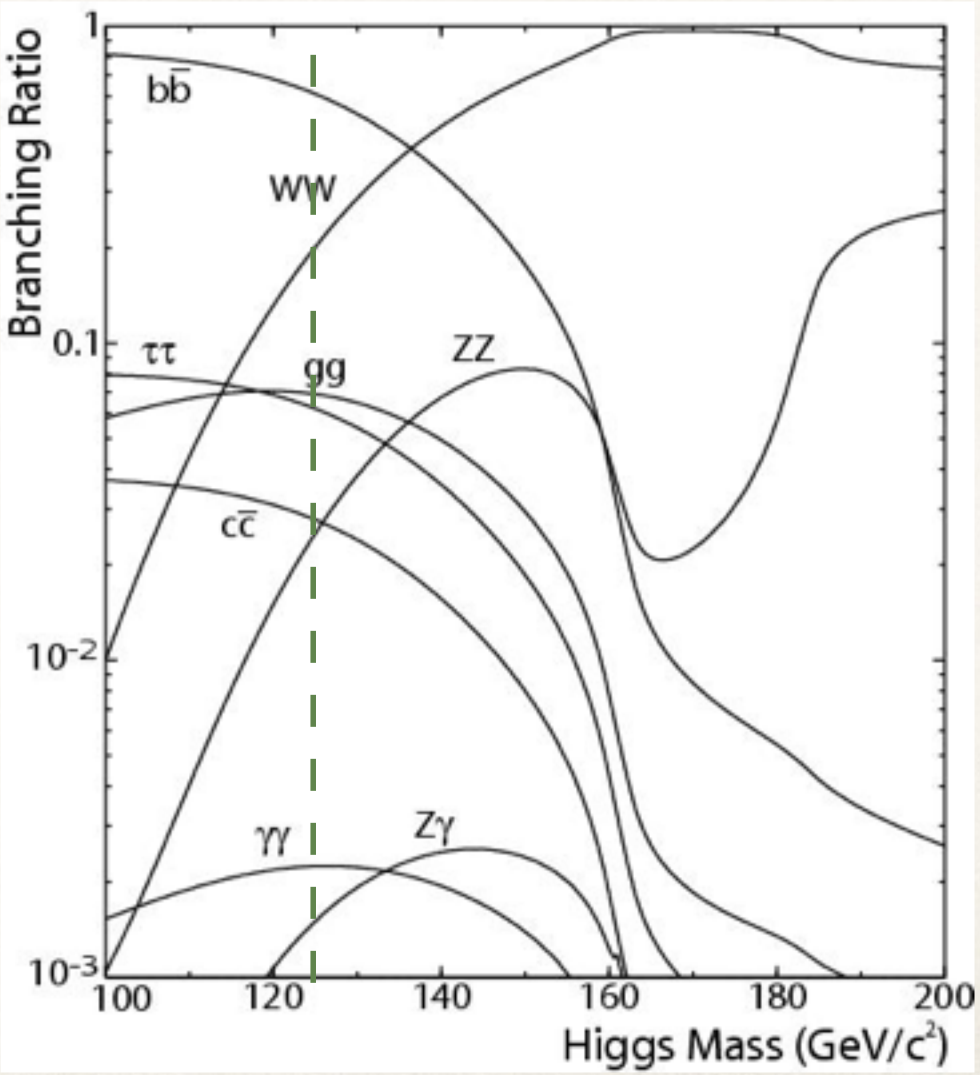






PRODUCTION
&
DECAY

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



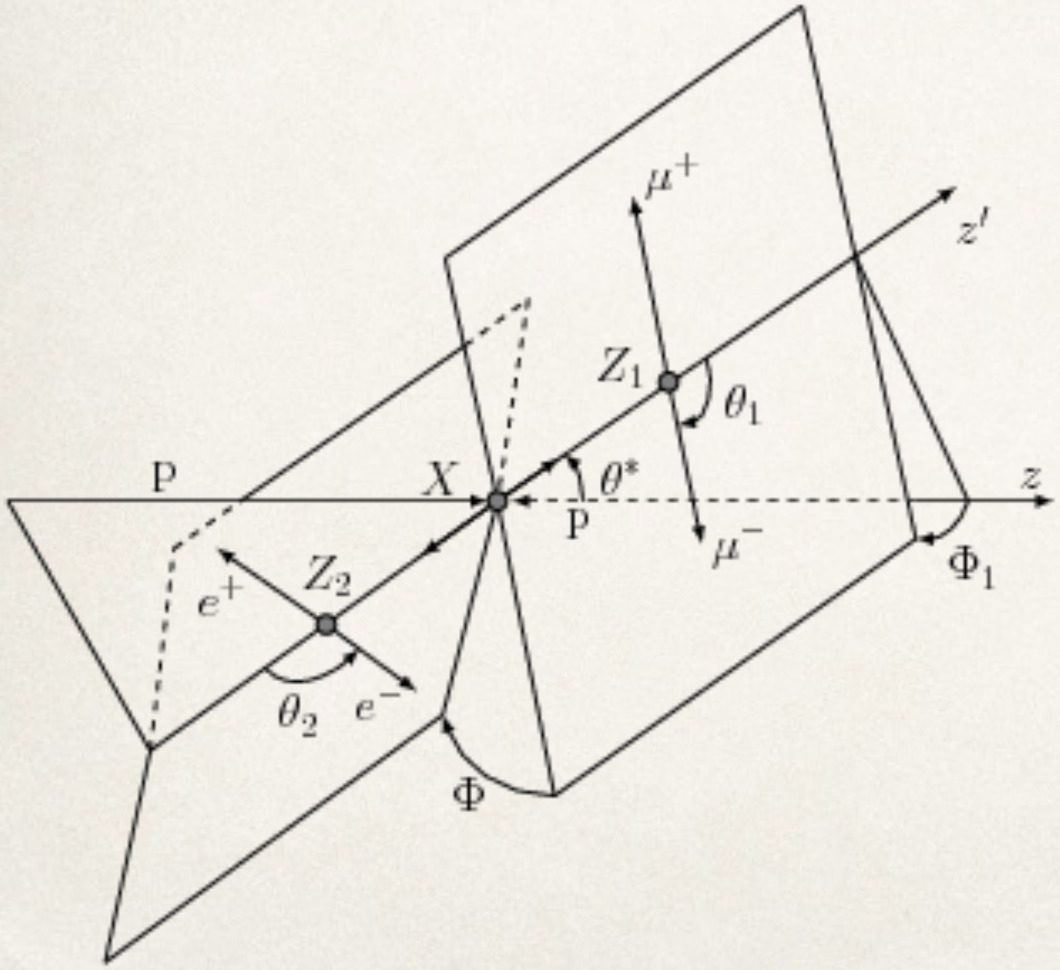
<u>easy to difficult</u>
diphotons
ZZ to 4L
WW to 2L
di-taus
bb

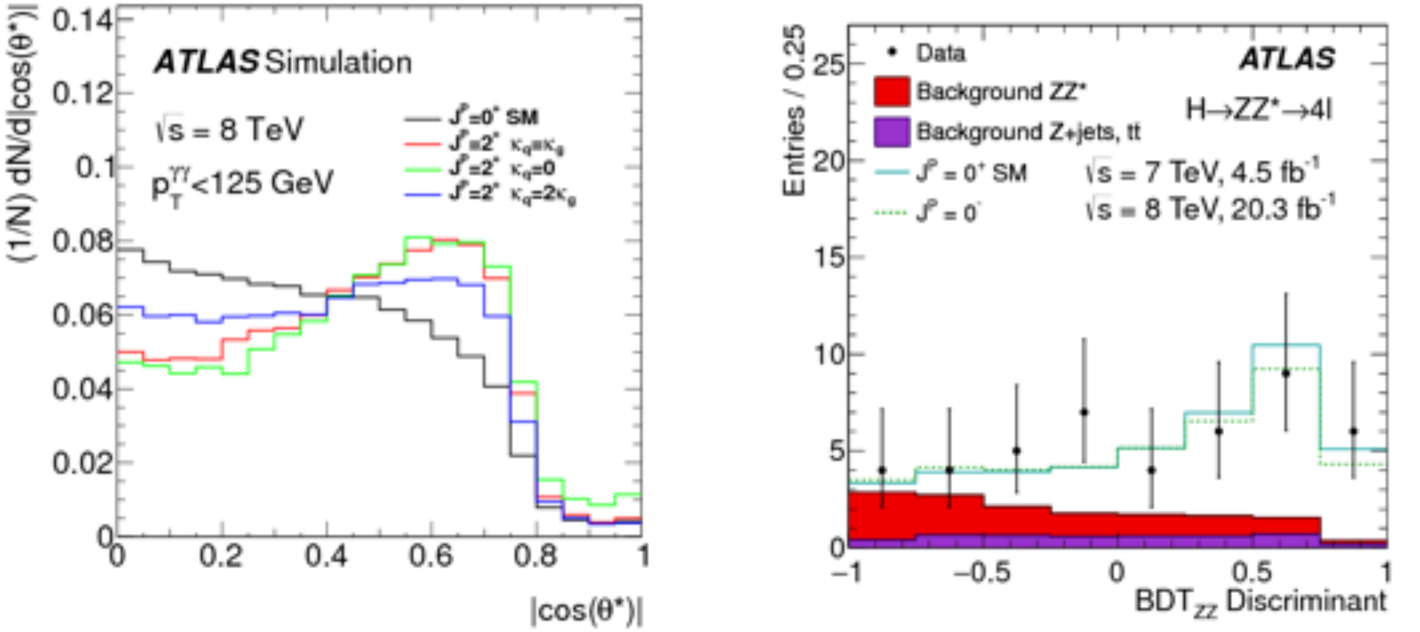
mass=125 GeV

LHC Higgs in a nutshell (II)

QUANTUM NUMBERS

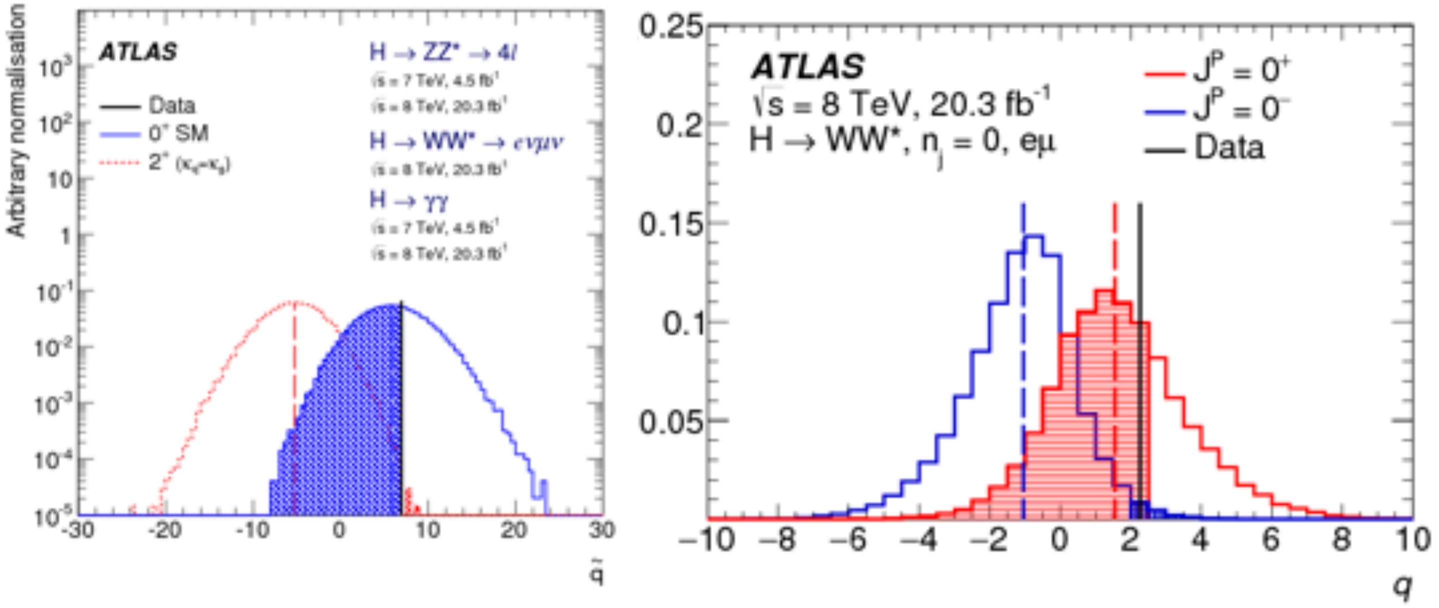
using kinematic distributions in ZZ, WW, …
determine the spin and parity as well as possible CP admixtures





kinematics

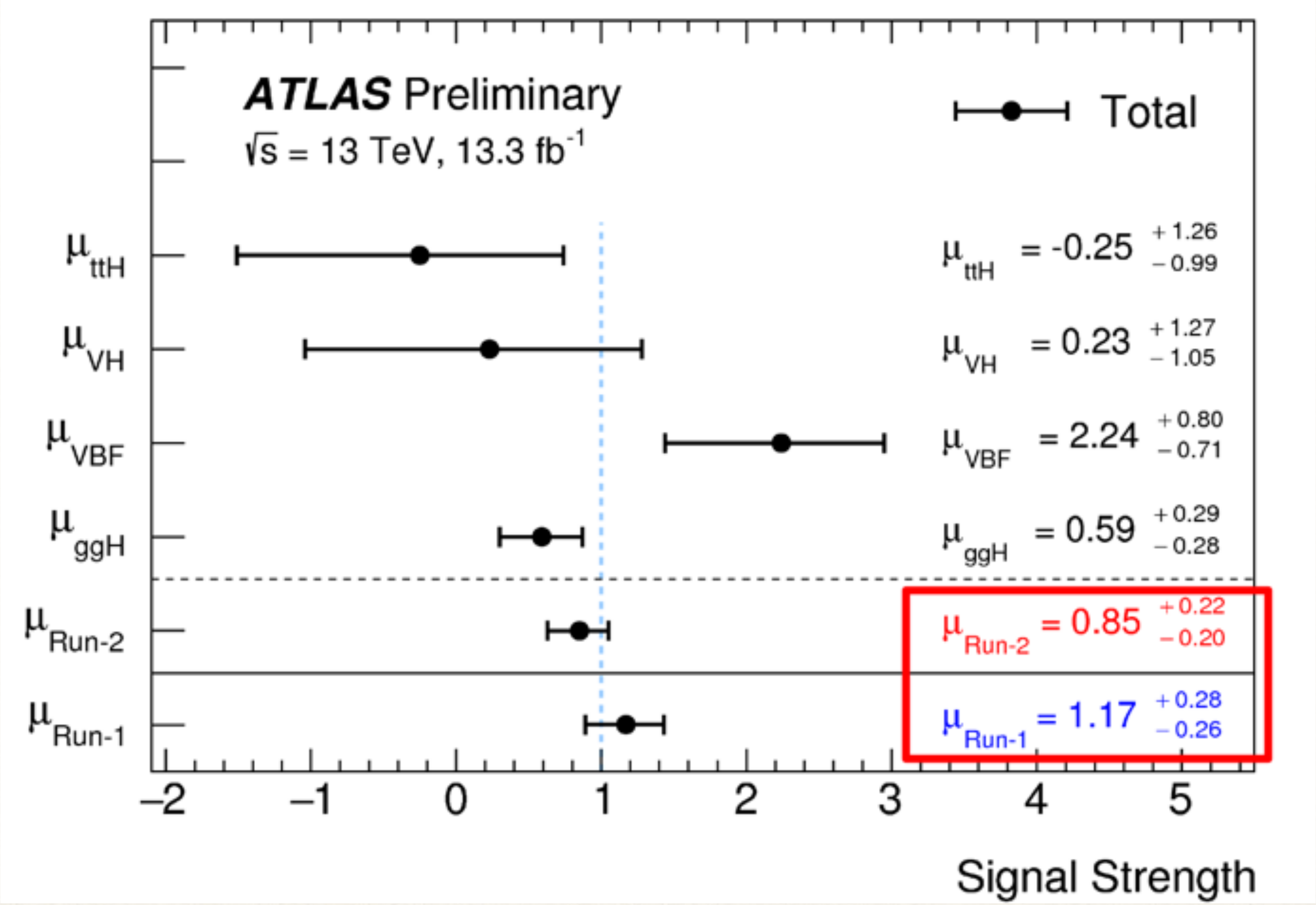
hypothesis discrimination



SM Higgs

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

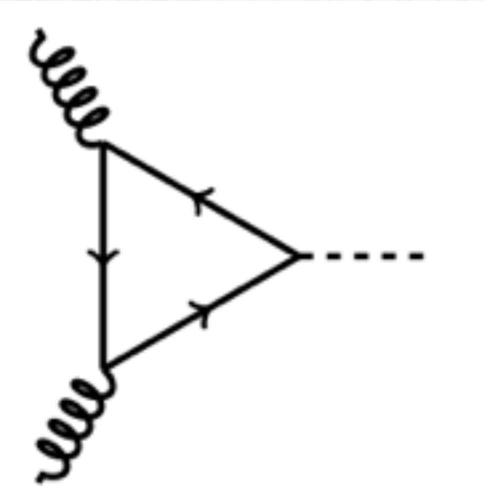
$$\mu = \frac{\sigma_{obs}}{\sigma_{SM}}$$



but precision is poor (20-30%)

SUSY and Composite Higgs

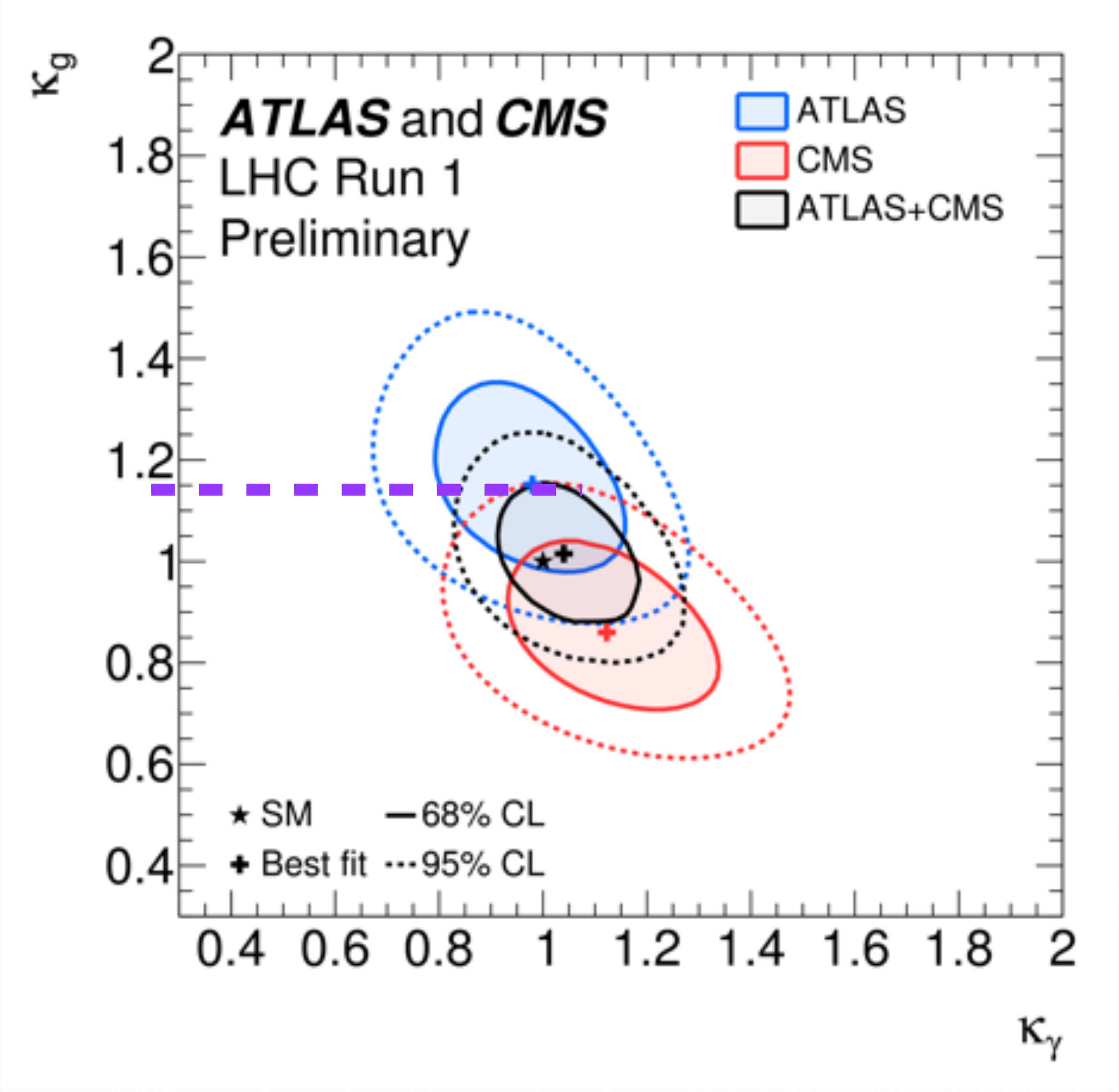
SUSY Higgs (I)



SUSY Higgs: loop corrections compete with gluon fusion and Higgs to diphotons

Main effect **stop contributions**

ESPINOSA, GROJEAN, VS, TROTT. 1207.7355



indirect searches for stops

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

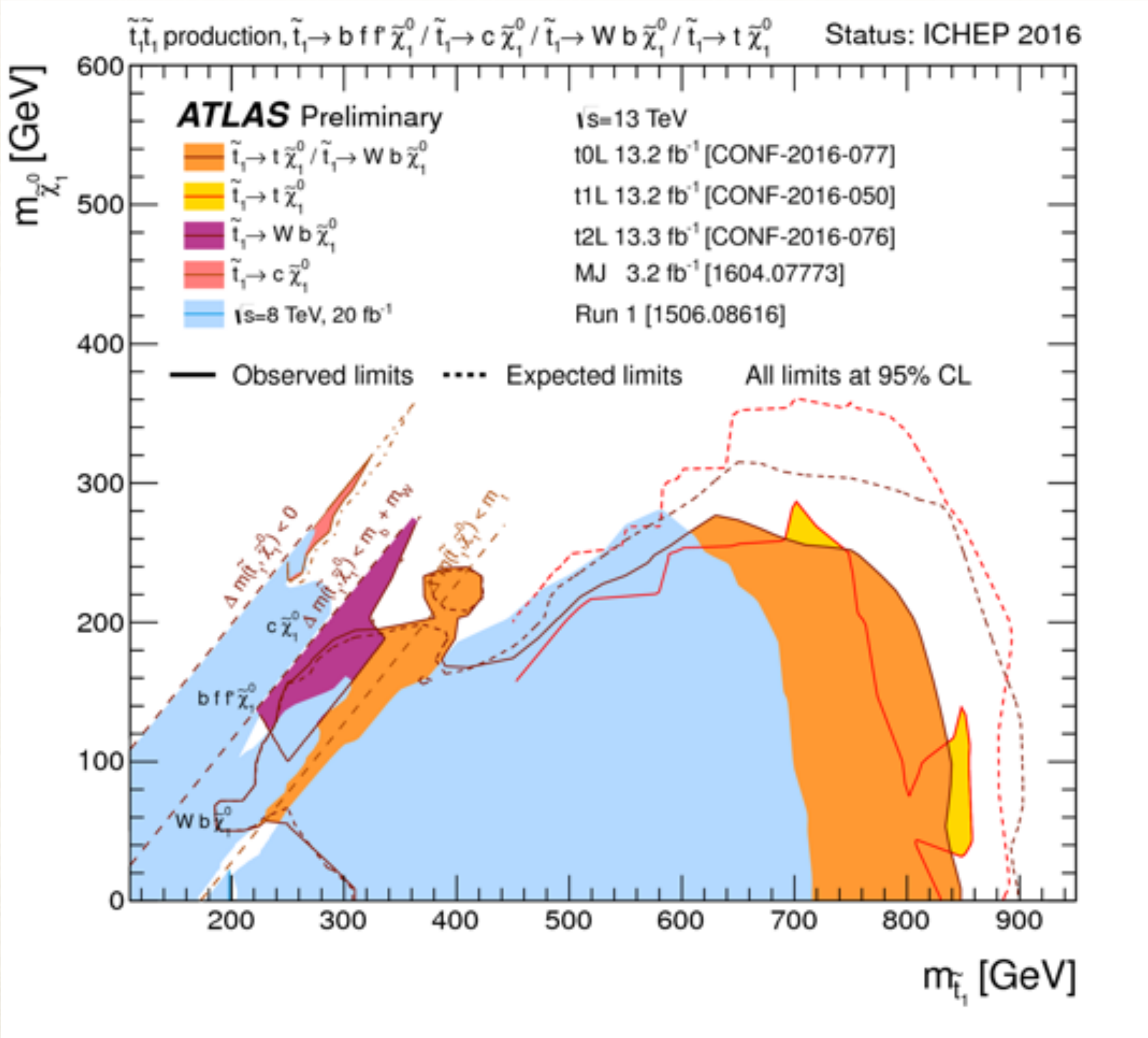
$$\Delta\kappa_g < 0.15$$

$$\boxed{m_{\tilde{t}} > 235\ \mathrm{GeV}}$$

SUSY Higgs (II)

$m_{\tilde t} > 235$ GeV

Higgs data vs direct searches for stops

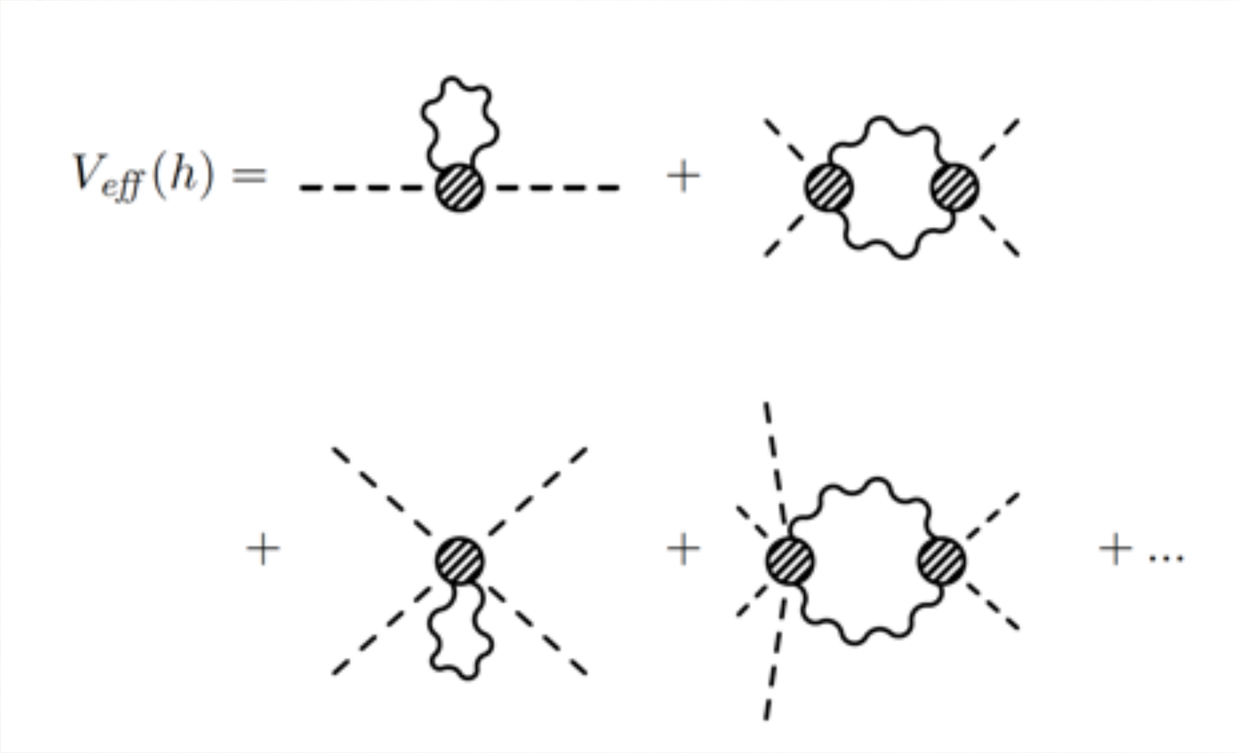


complementary

Composite Higgs (I)

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

e.g. GAUGE



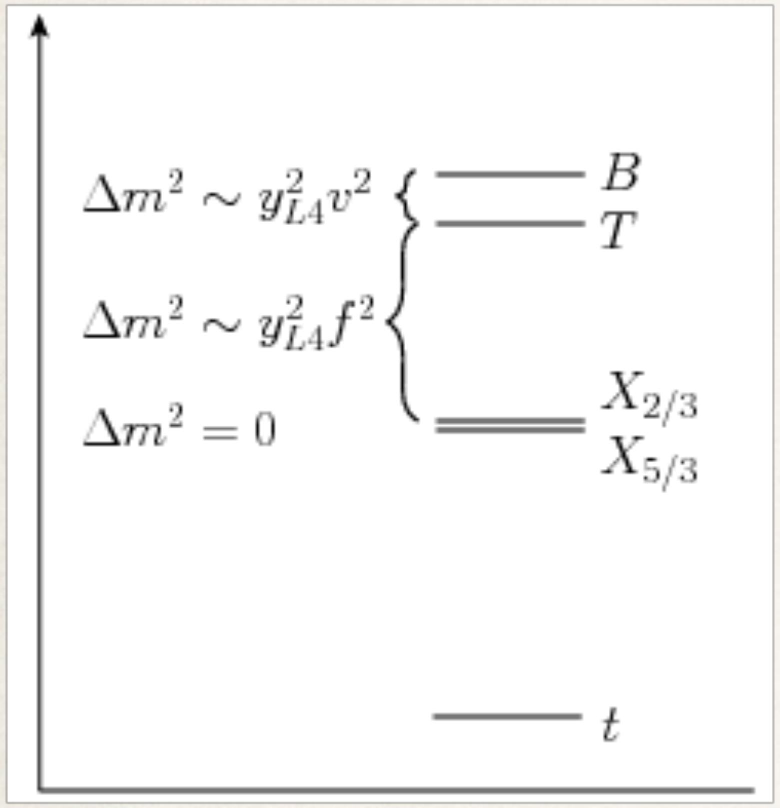
Georgi-Kaplan (80's)
gauge-top *does not* trigger EWSB
need new fermionic resonances
TOP-PARTNERS

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

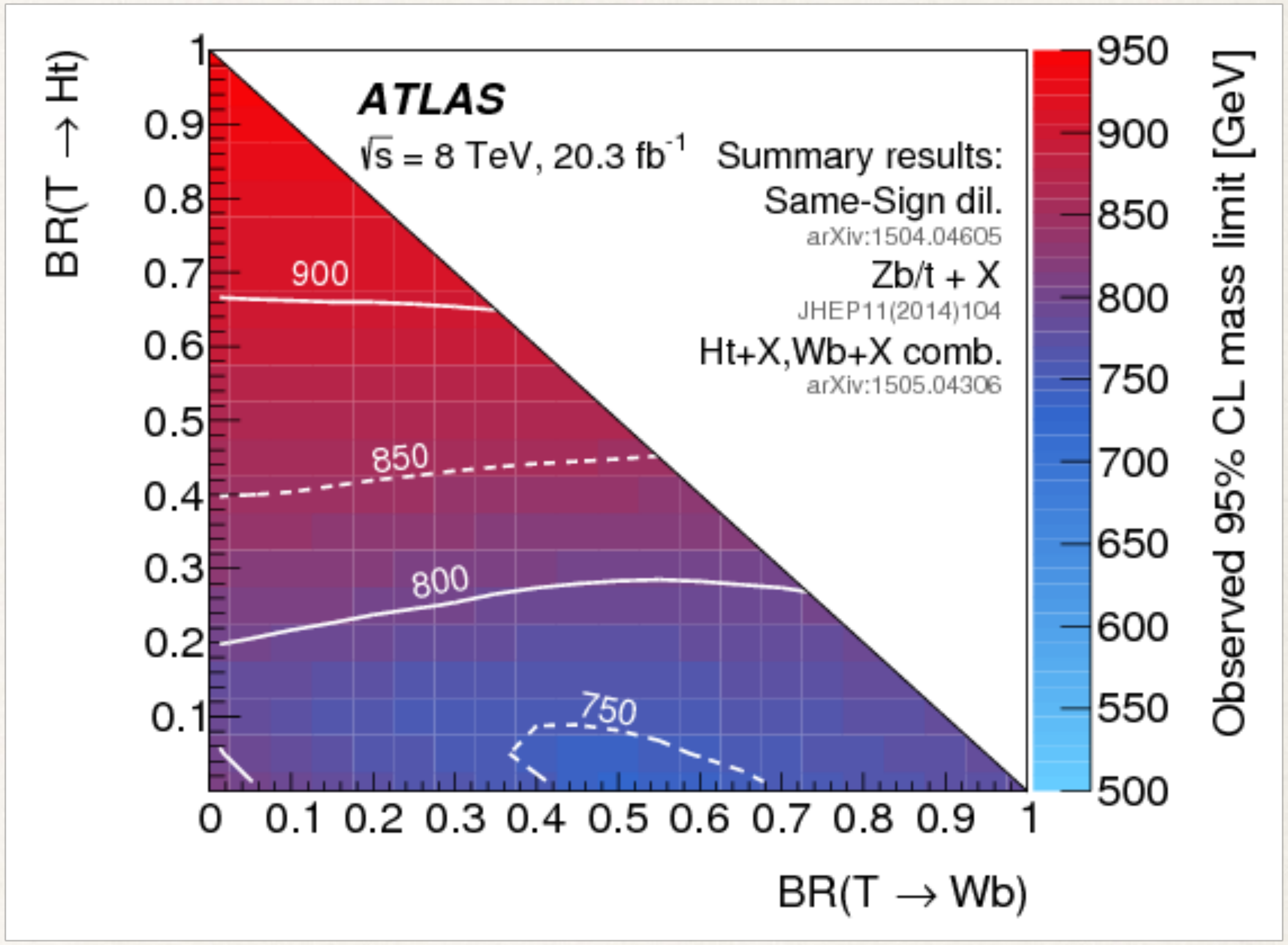
pheno: New, light (below TeV) techni-baryons
should couple to the Higgs, W, Z

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

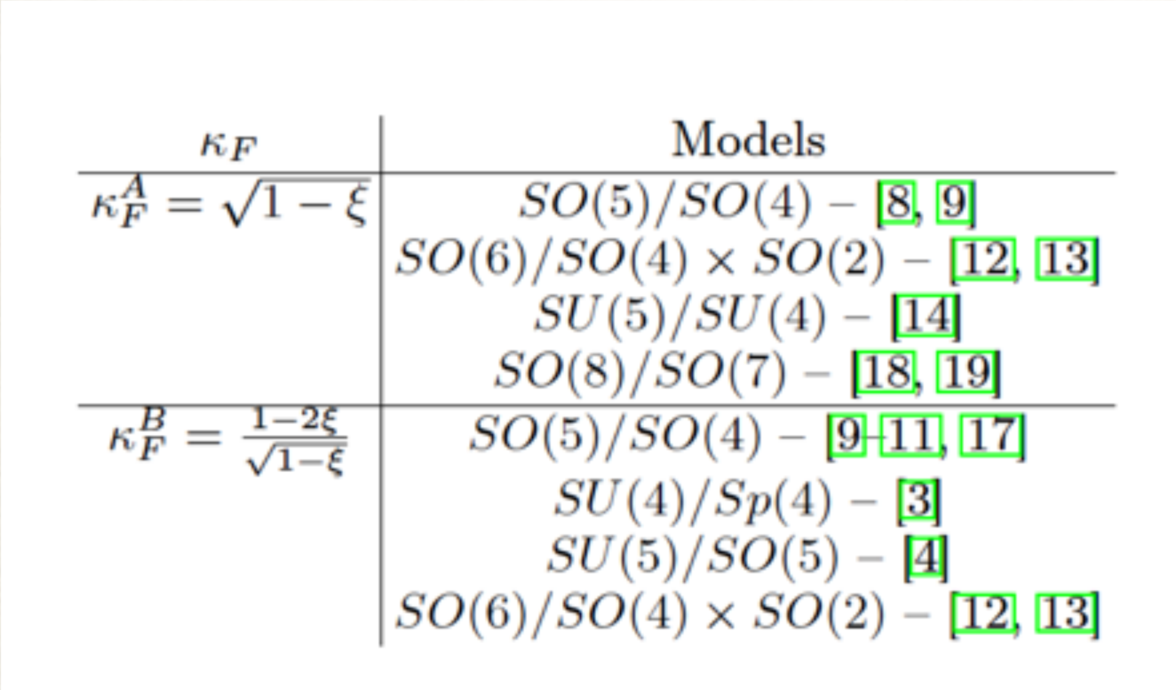
VS, SETFORD. 1703.10190

Composite Higgs models
Many realizations,
but some common features

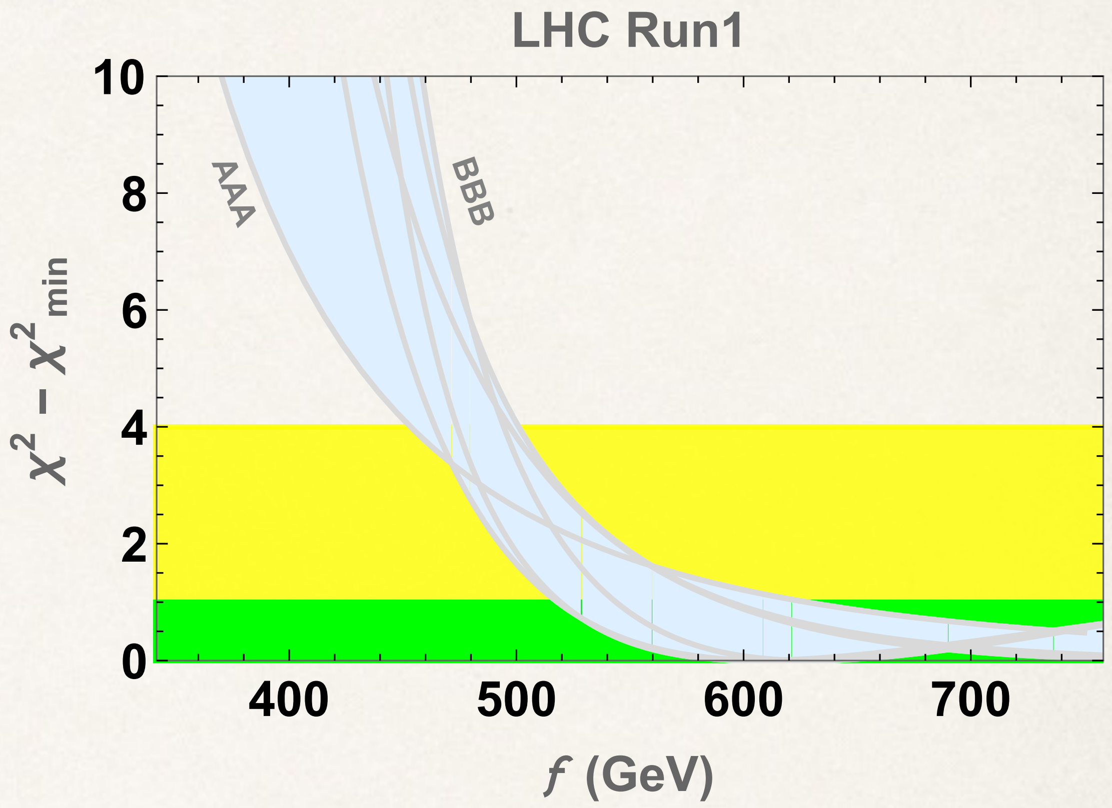
Boson couplings

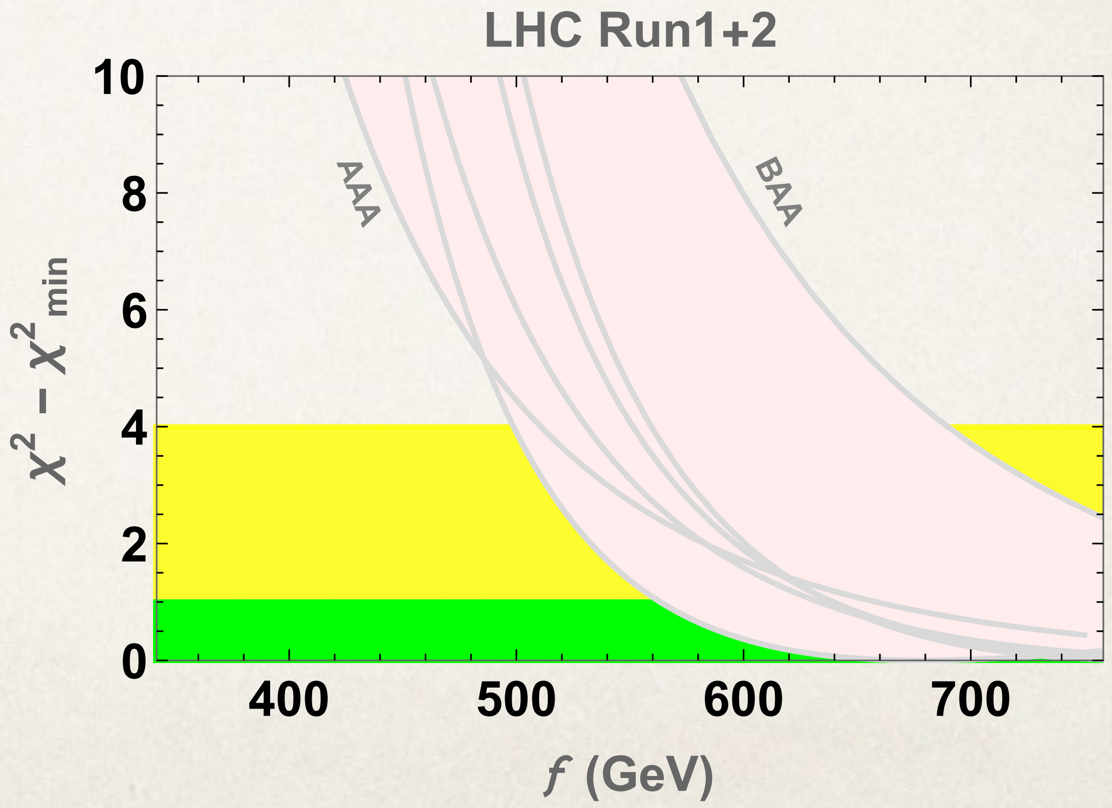
$$\kappa_V = \sqrt{1-\xi} \approx 1 - \frac{1}{2}\xi$$

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]





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

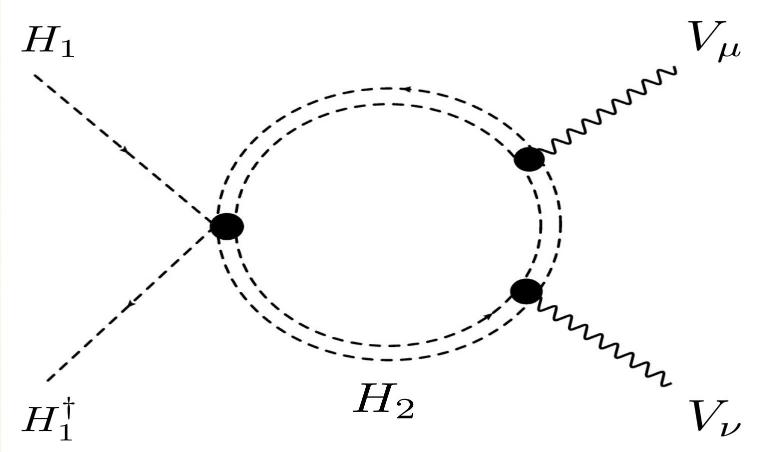
dimension-6 dimension-8

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

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

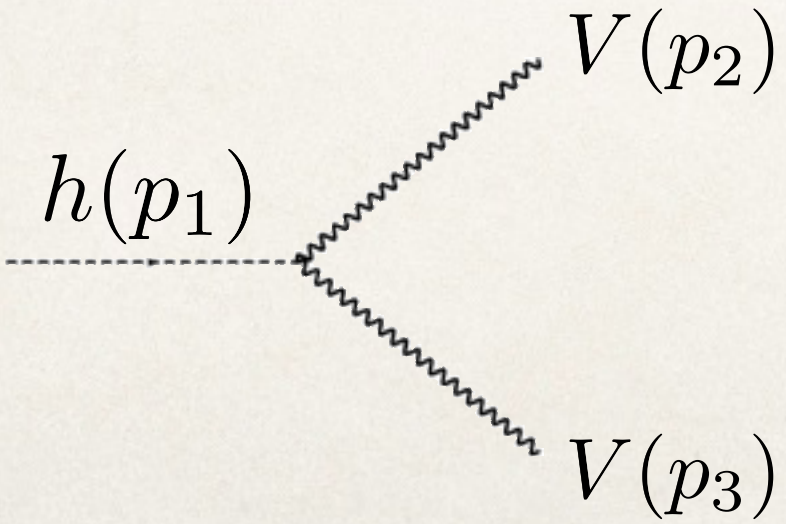
Kappa-formalism is useful when new physics effects are *very simple*
Just change the overall rates

squarks
EWinos
$(\kappa_\gamma,\ \kappa_g)$

non-linear, CHM
singlet mixing
$(\kappa_f,\ \kappa_V)$

Models offer richer kinematics, and EFT approach captures them

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



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

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

+ *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

Matching to UV theories

Within the EFT, connection to models is *straightforward*

EFT

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

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

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

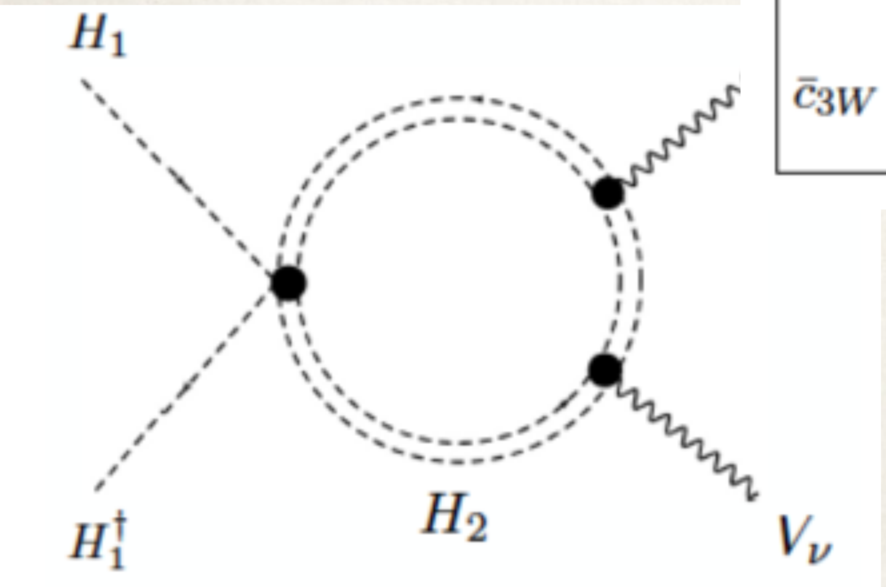
$$\bar{c}_\gamma = \frac{m_W^2\,\tilde{\lambda}_3}{256\,\pi^2\,\tilde{\mu}_2^2}$$

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

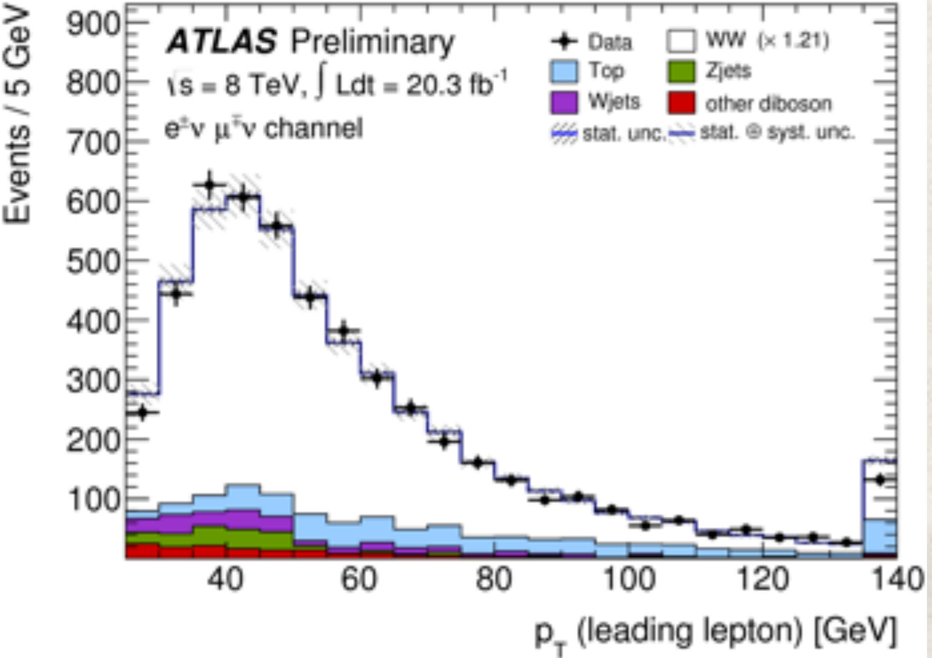
$$\bar{c}_B = -\bar{c}_{HB} = \frac{m_W^2\,(-2\,\tilde{\lambda}_3 + \tilde{\lambda}_4)}{192\,\pi^2\,\tilde{\mu}_2^2} = -\frac{8}{3}\,\bar{c}_\gamma + m_W^2\,\tilde{\lambda}_4$$

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

MODELS

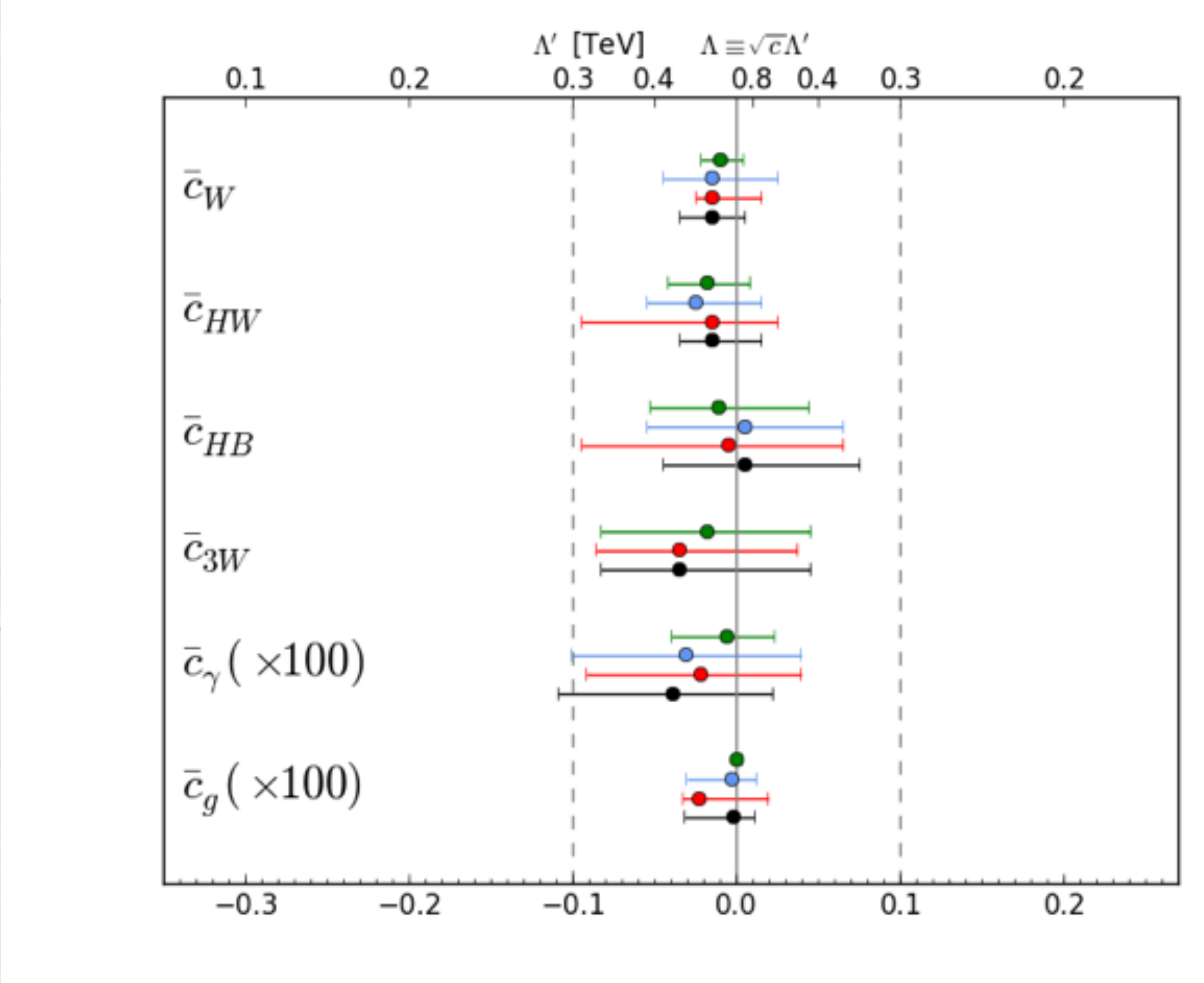


DATA



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

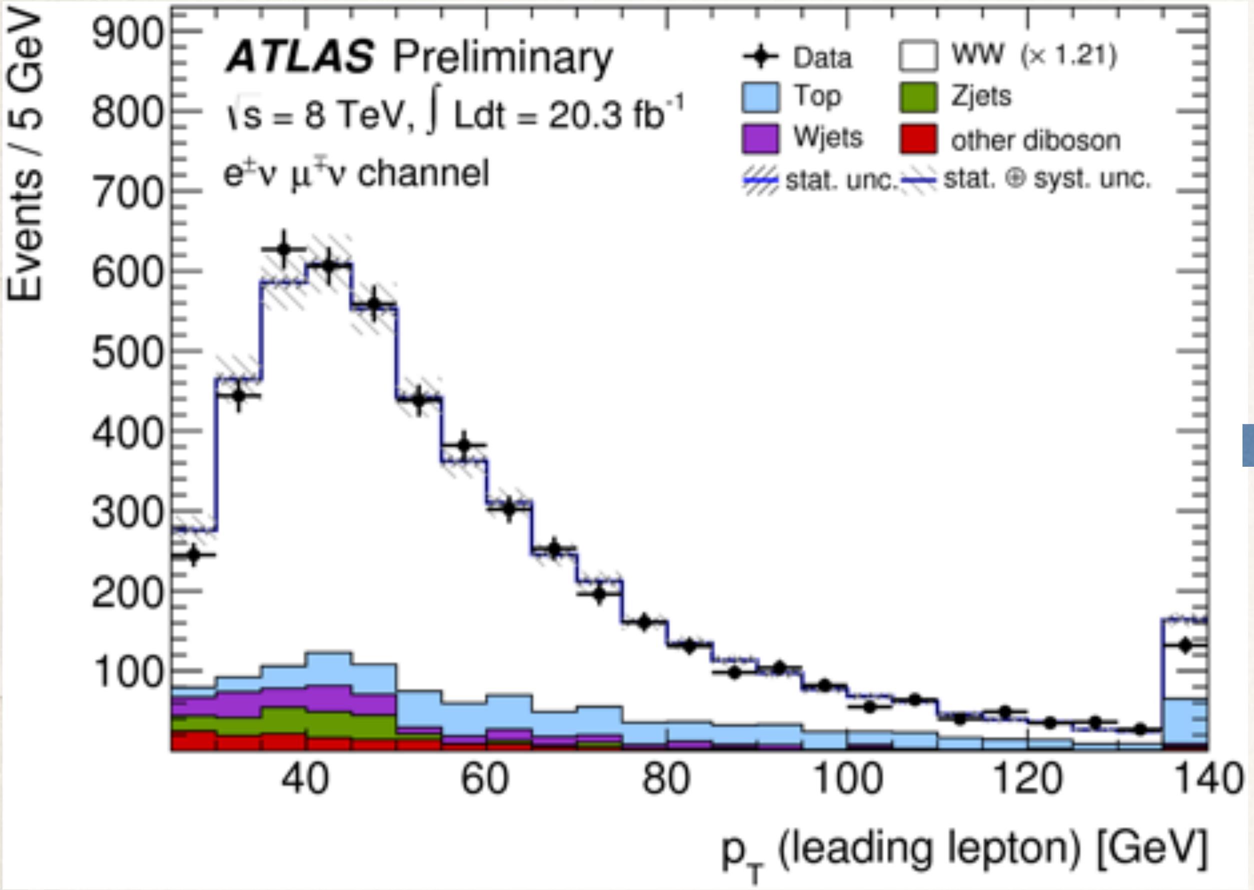
green: one-by-one

black: global fit

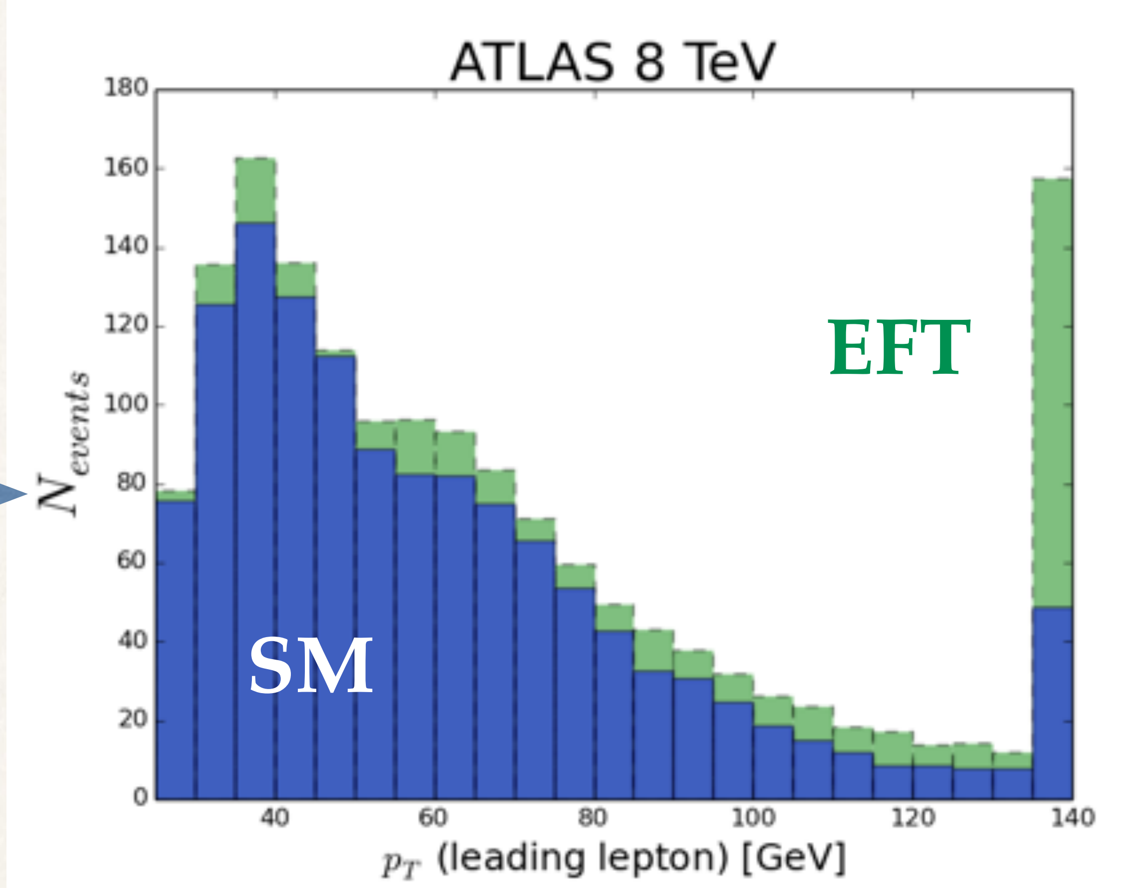
Global analyses using EFTs

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

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 are 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

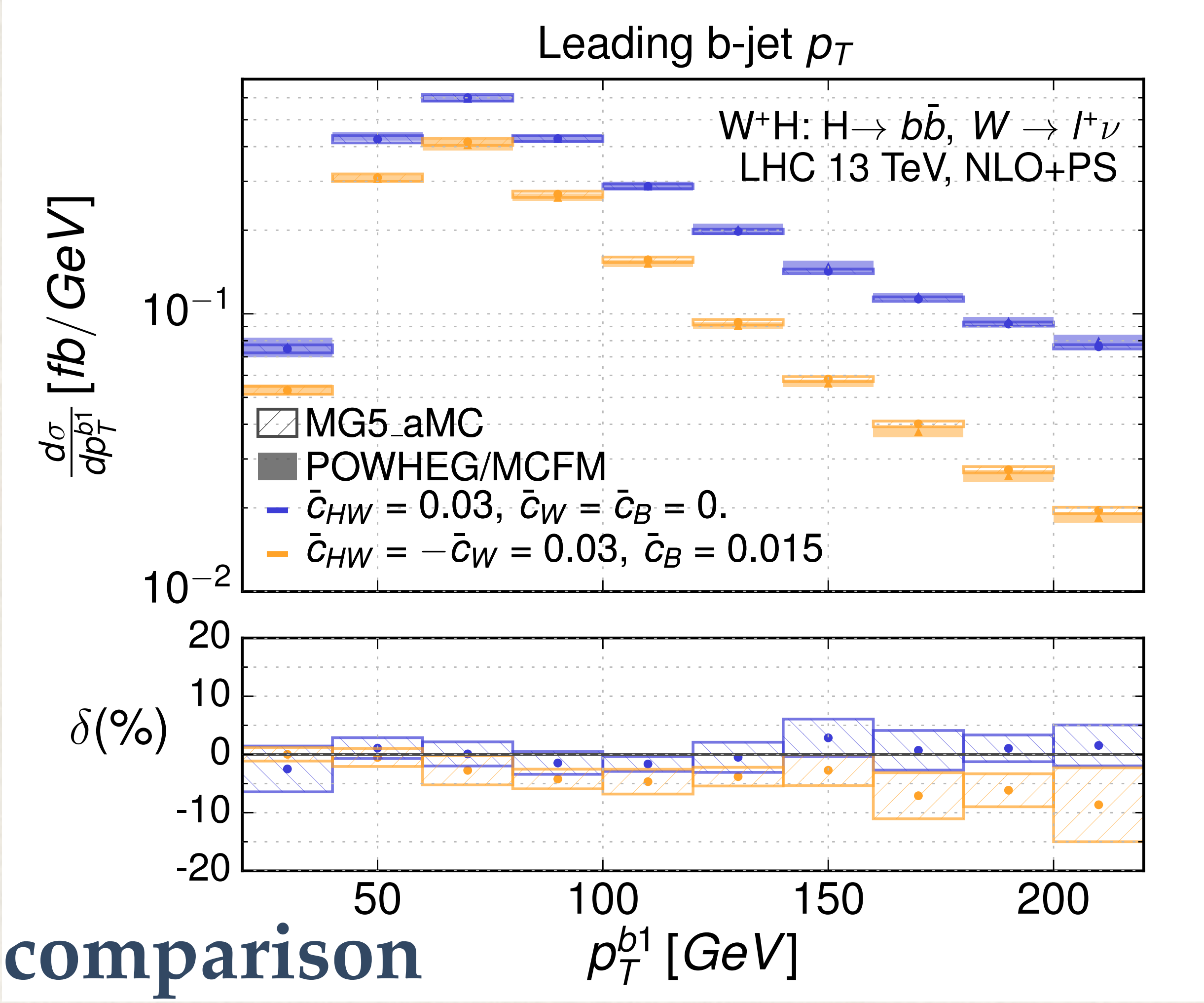
WHIZARD, JHU, VBFNLO, AMC@NLO, POWHEG

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

aMC@NLO

DEGRANDE, FUKS, MAWATARI, MIMASU, VS.
1609.04833

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

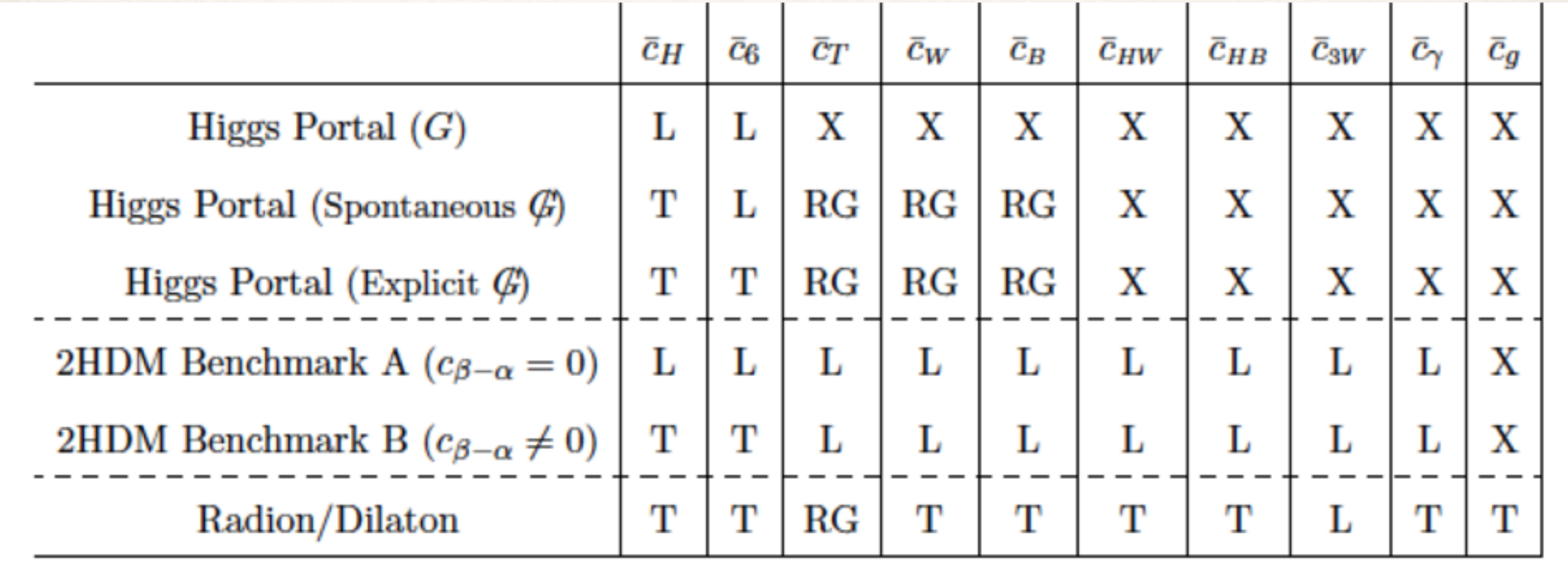
Matching with UV theories

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

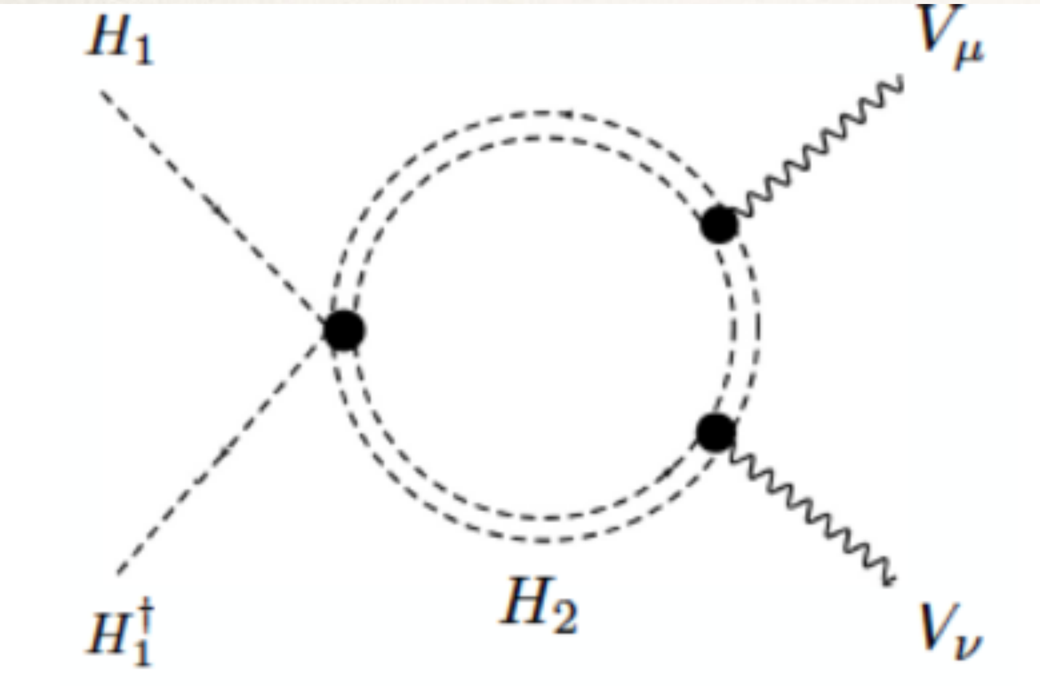
combined EWPTs, direct searches and Higgs limits from the EFT

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

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

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

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

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

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

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

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

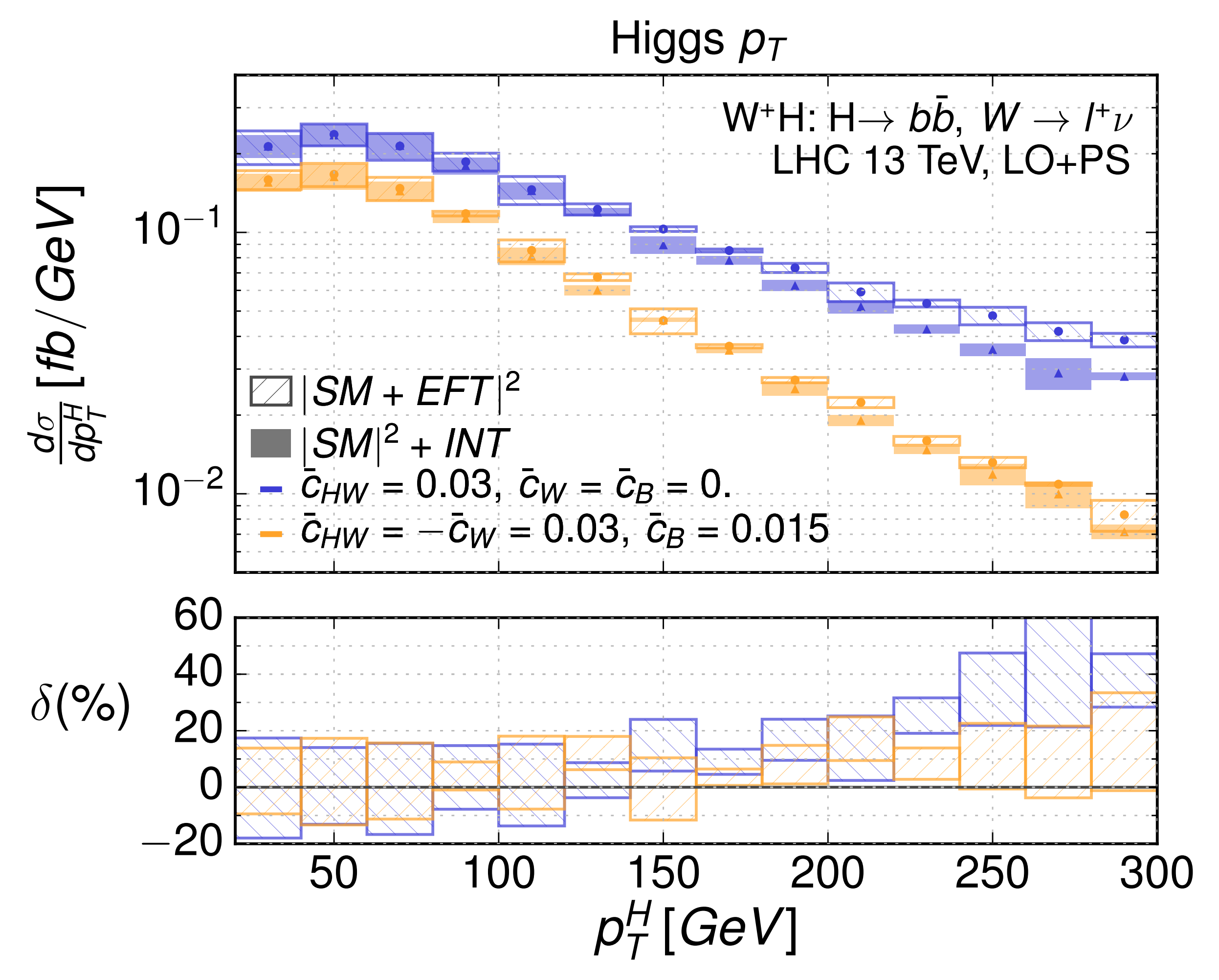
$$\bar{c}_T(m_Z) \simeq \bar{c}_T(\tilde{\mu}_2) - \frac{3\,g'^2}{32\,\pi^2}\,\bar{c}_H(\tilde{\mu}_2)\log\left(\frac{\tilde{\mu}_2}{m_Z}\right)$$

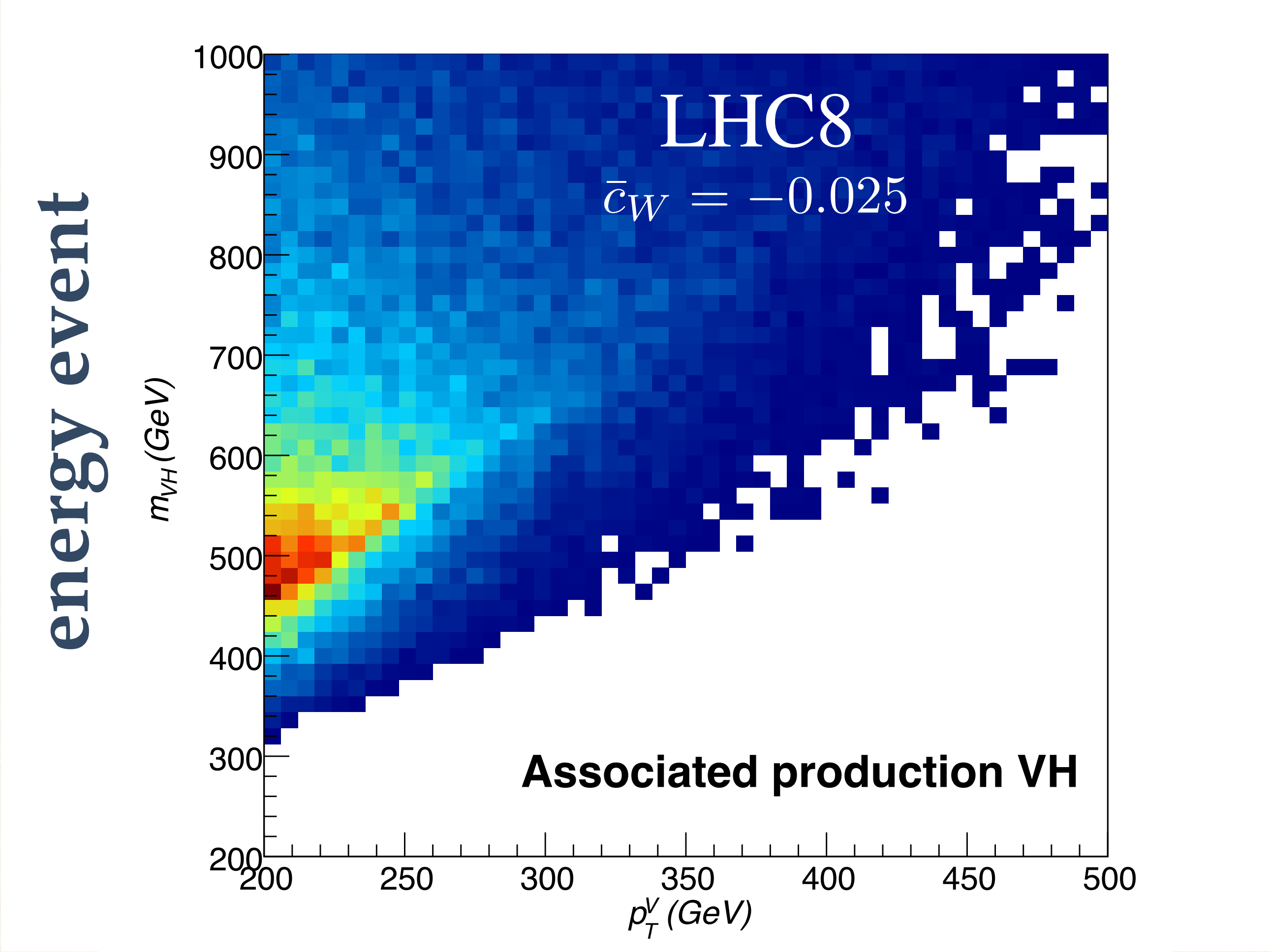
$$\bar{c}_W(m_Z) + \bar{c}_B(m_Z) \simeq c_W(\tilde{\mu}_2) + \bar{c}_B(\tilde{\mu}_2) + \frac{1}{24\,\pi^2}\,\bar{c}_H(\tilde{\mu}_2)\log\left(\frac{\tilde{\mu}_2}{m_Z}\right)\,.$$

Precision

Monte Carlo EFT and validity

The issue of validity of the EFT approach with the use of differential distributions is a hot topic of discussion





DEGRANDE ET AL. 1609.04833

ELLIS, VS, YOU. 1410.7703

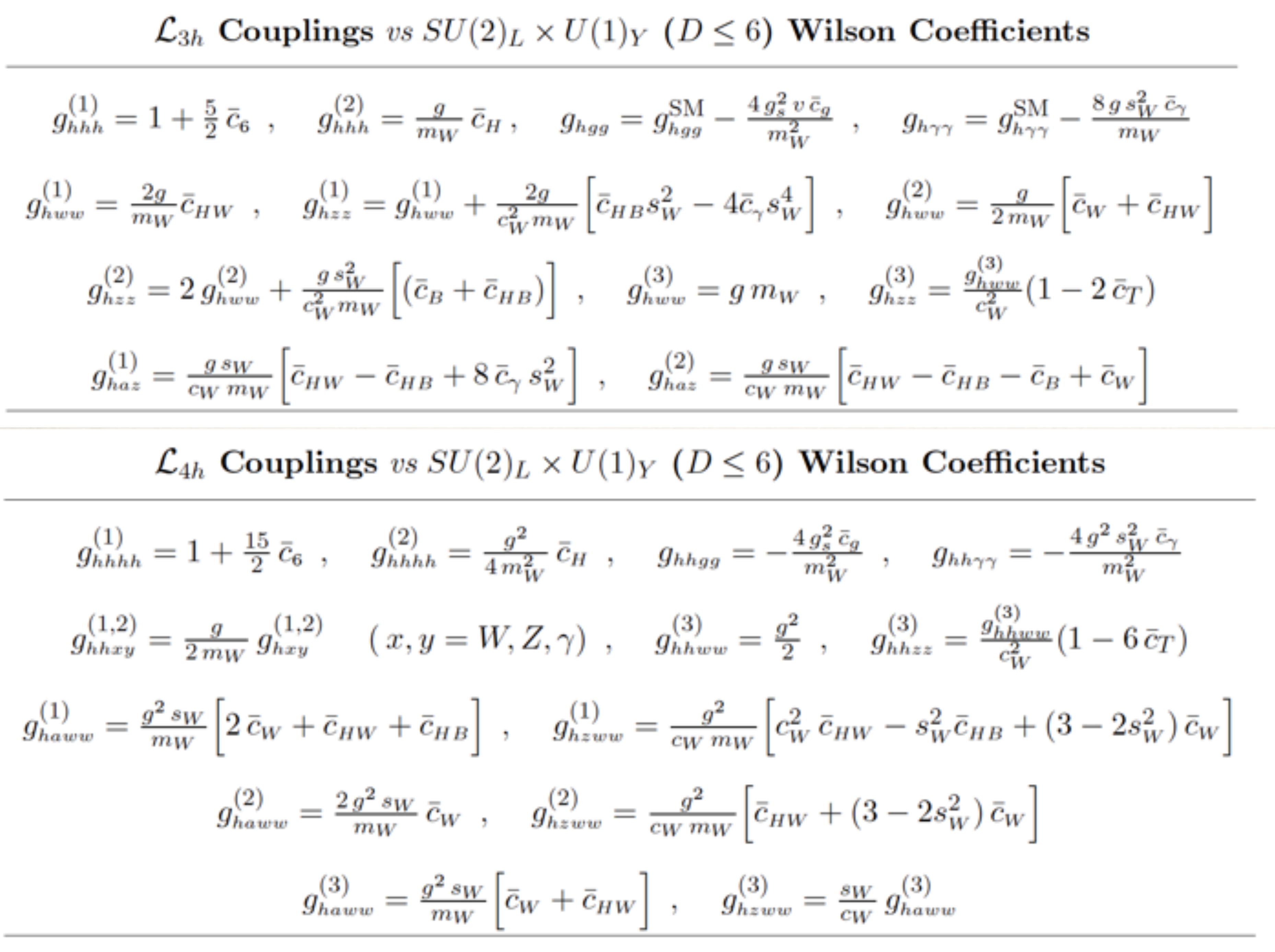
Proposals: cutoffs, matching to UV, templates, evaluation of dim-8…

Combination of data

Global analyses using EFTs

EFTs induce effects in many channels

ideal framework for combination



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

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

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

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

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

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

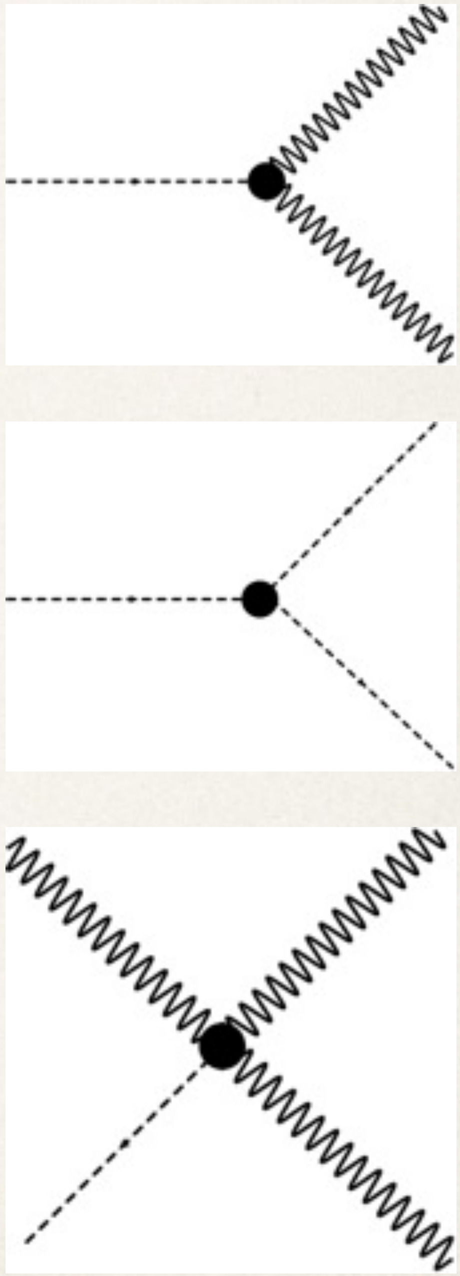
$$g^{(1)}_{hhhh} = 1 + \tfrac{15}{2}\,\bar{c}_6\ , \quad g^{(2)}_{hhhh} = \tfrac{g^2}{4\,m_W^2}\,\bar{c}_H\ , \quad g_{hhgg} = -\frac{4\,g_s^2\,\bar{c}_g}{m_W^2}\ , \quad g_{hh\gamma\gamma} = -\frac{4\,g^2\,s_W^2\,\bar{c}_\gamma}{m_W^2}$$

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

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

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

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

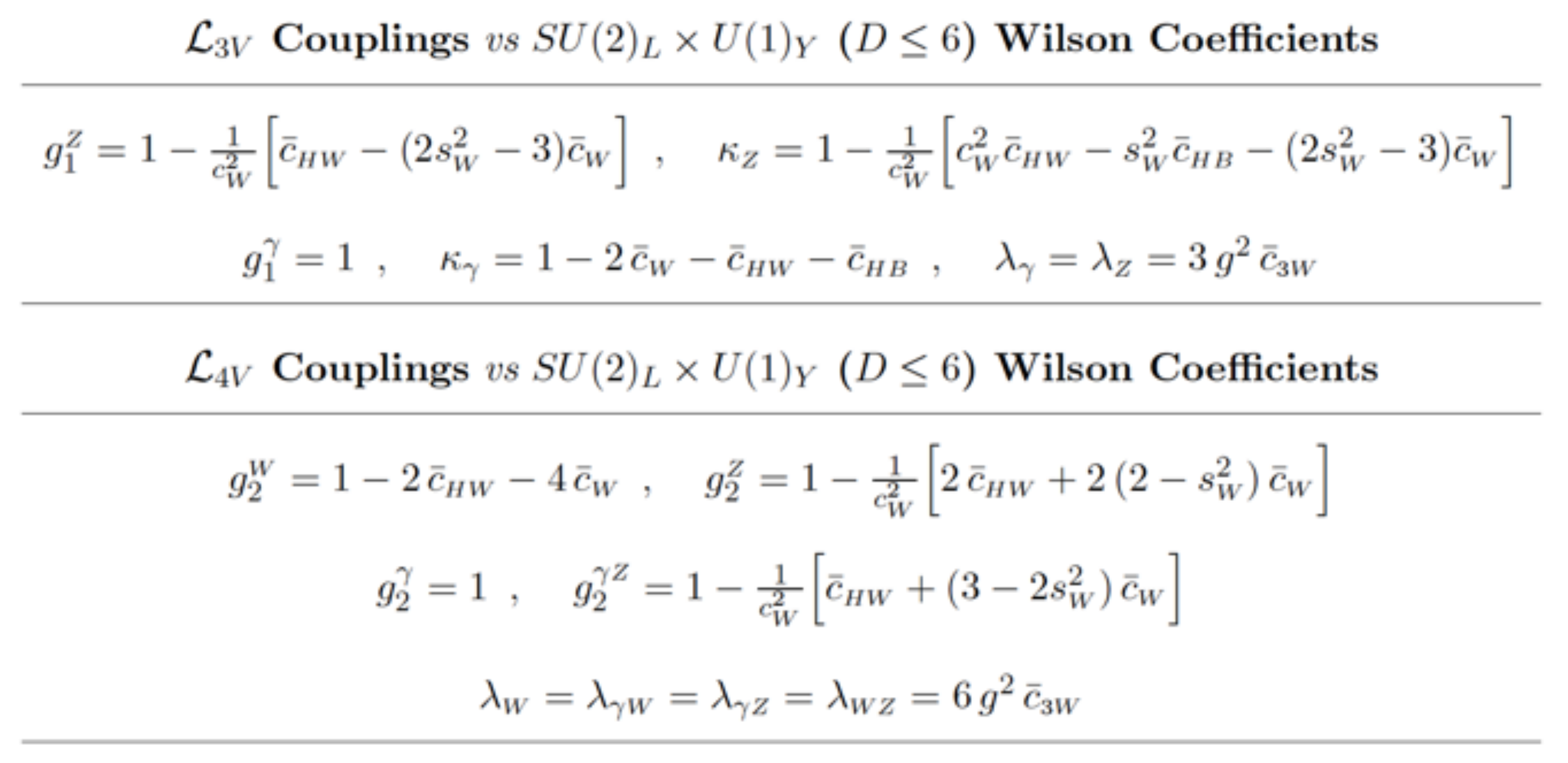


Alloul, Fuks, VS. 1310.5150
Gorbahn, No, VS. 1502.07352

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**

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

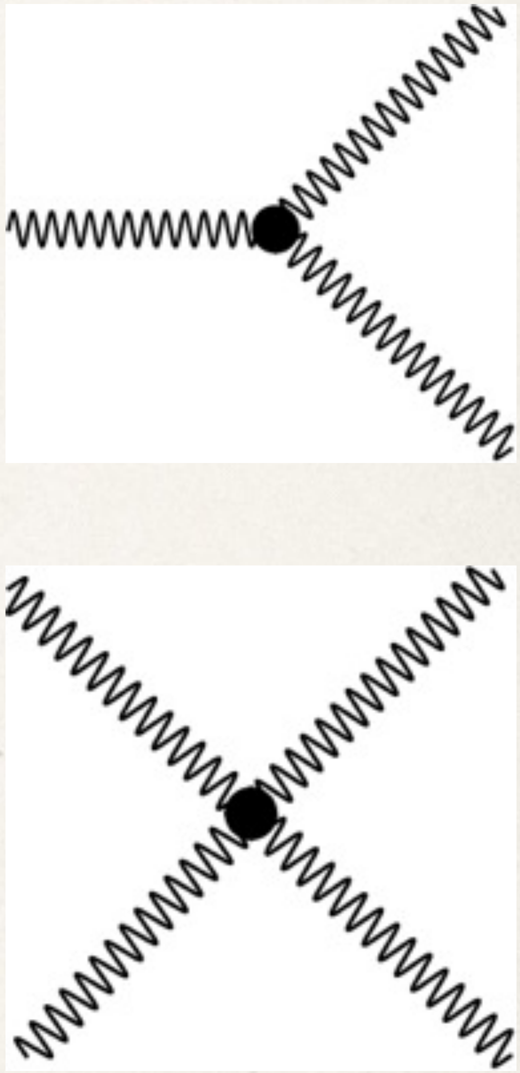
$$g_1^\gamma = 1 \ , \quad \kappa_\gamma = 1 - 2\,\bar{c}_W - \bar{c}_{HW} - \bar{c}_{HB} \ , \quad \lambda_\gamma = \lambda_Z = 3\,g^2\,\bar{c}_{3W}$$

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

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

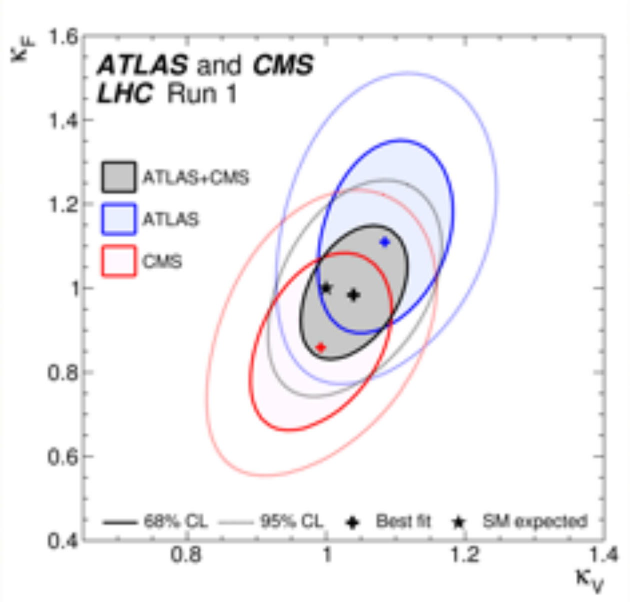
$$g_2^\gamma = 1 \ , \quad g_2^{\gamma Z} = 1 - \frac{1}{c_W^2}\Big[\bar{c}_{HW} + (3 - 2s_W^2)\,\bar{c}_W\Big]$$

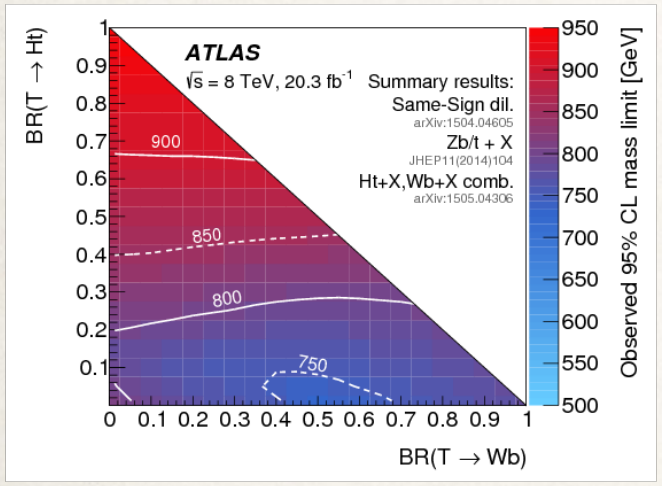
$$\lambda_W = \lambda_{\gamma W} = \lambda_{\gamma Z} = \lambda_{WZ} = 6\,g^2\,\bar{c}_{3W}$$



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

Composite Higgs: model-building





Given the experimental constraints,
lack of deviations in the Higgs behaviour and
absence for new composite fermions
interest in more natural (non-minimal) models

e.g. new ways to trigger EWSB and fermion mass generation, measure of tuning of the theory, un-coloured fermion resonances…

examples:

EWSB triggered by other scalars: see-saw CH

VS, SETFORD. 1508.06133

new symmetries in the global sector: Maximally symmetric CH

CSAKI, MA, SHU. 1702.00405

Beyond the kappa formalism

Besides EFT, there are other ways to improve upon the kappa-formalism

Higgs characterization

Higgs anomalous couplings
defined at Lagrangian level
Generic Lorentz structures
consistent with U(1)

Pseudo-observables

Generic Lorentz structures
defined at the amplitude level
momentum expansion around
poles

These approaches are related to each other
EFT : AC : PO
We have mappings among them
channel by channel

EFT vs others

Disclaimer: I don’t advocate for EFTs as the *only* way to interpret data each approach has pros and cons

Advantages of EFTs

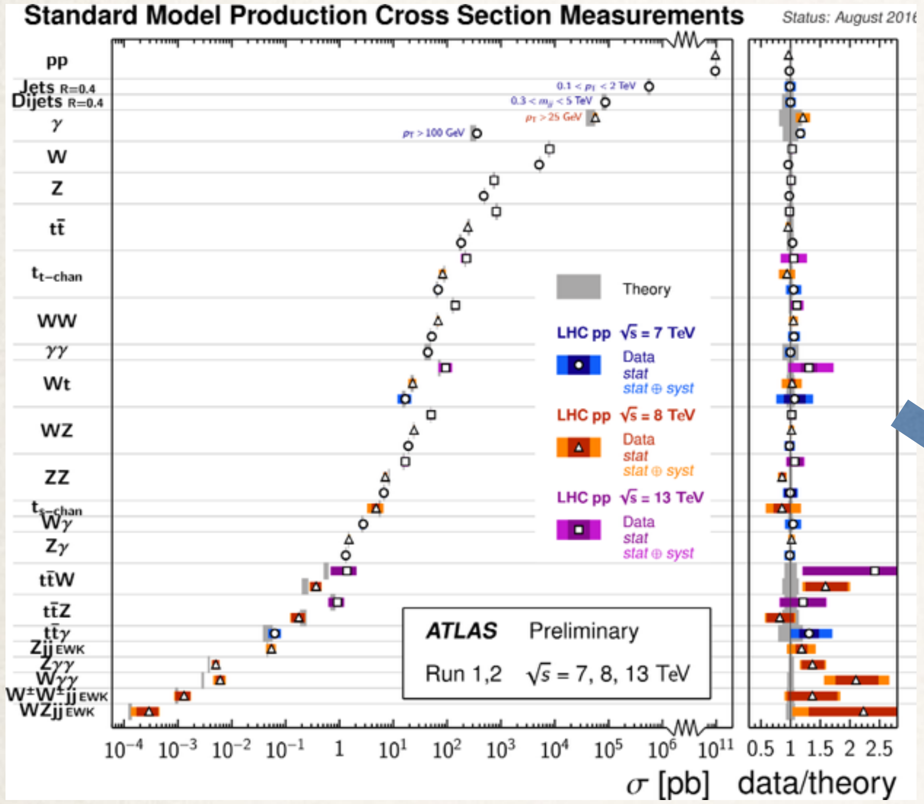
Clear pathway to achieve

- **Combination**: LHC Higgs and EW production, low energy, EWPTs
- **Precision:** higher-order EW and QCD, dimension-eight, validity EFT
- **Consistency:** Backgrounds and signal
- **Matching:** Direct connection to models

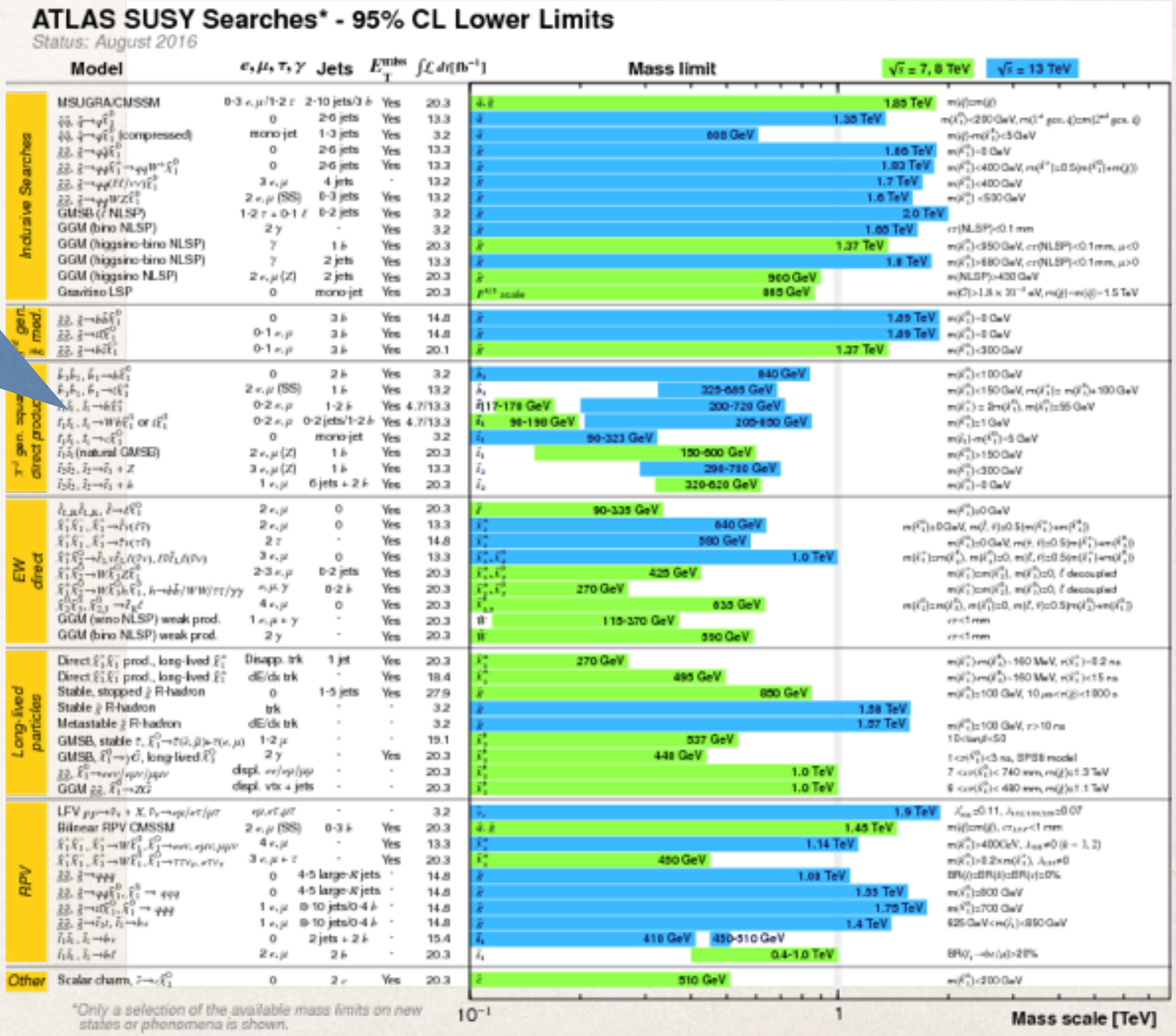
Direct versus indirect searches

Direct searches for new phenomena

consistency of data vs
SM predictions



Interpretation in models:
exclusion regions



Example: coloured SUSY

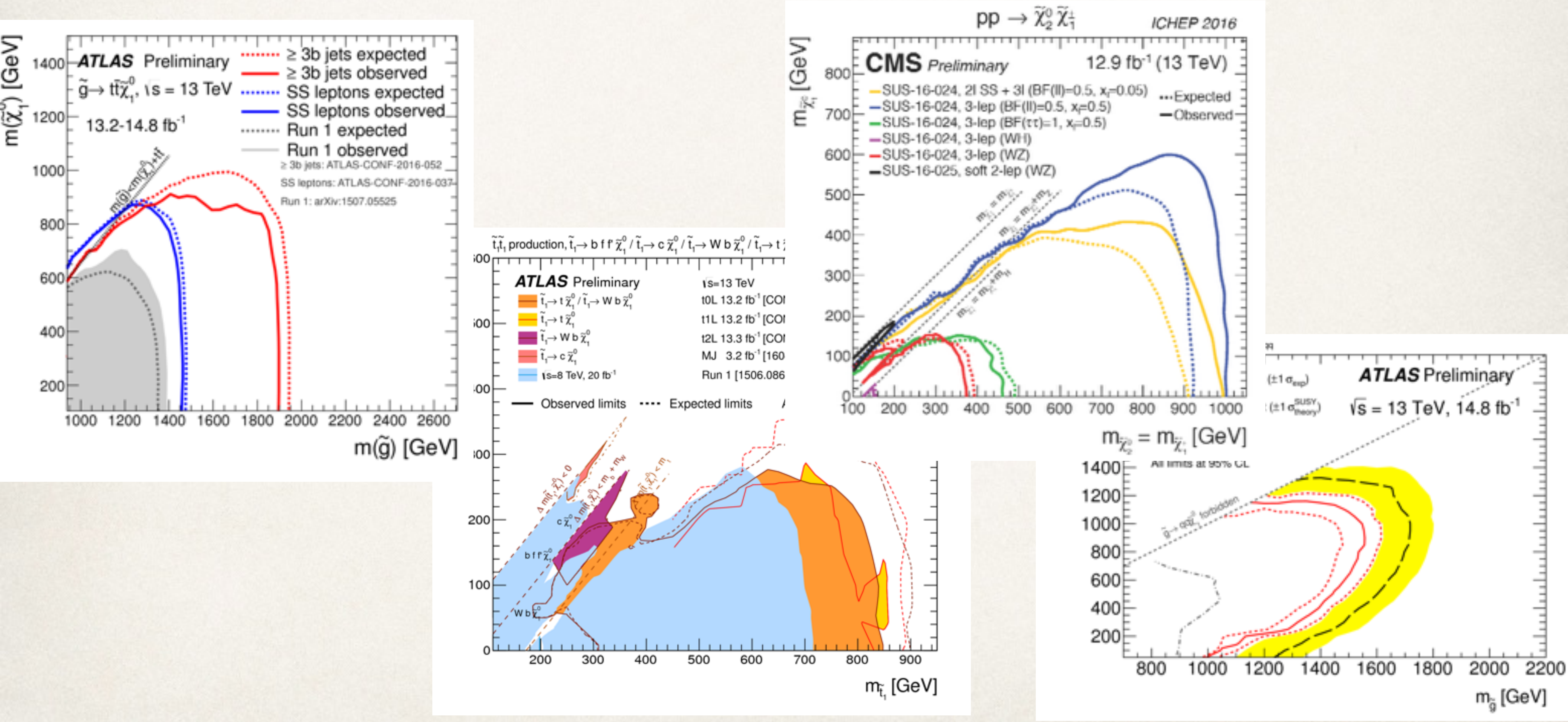
The 13 TeV data already undermining hopes energy increase could unveil new coloured states

Vanilla SUSY

Natural SUSY

EW SUSY

some-SUSY

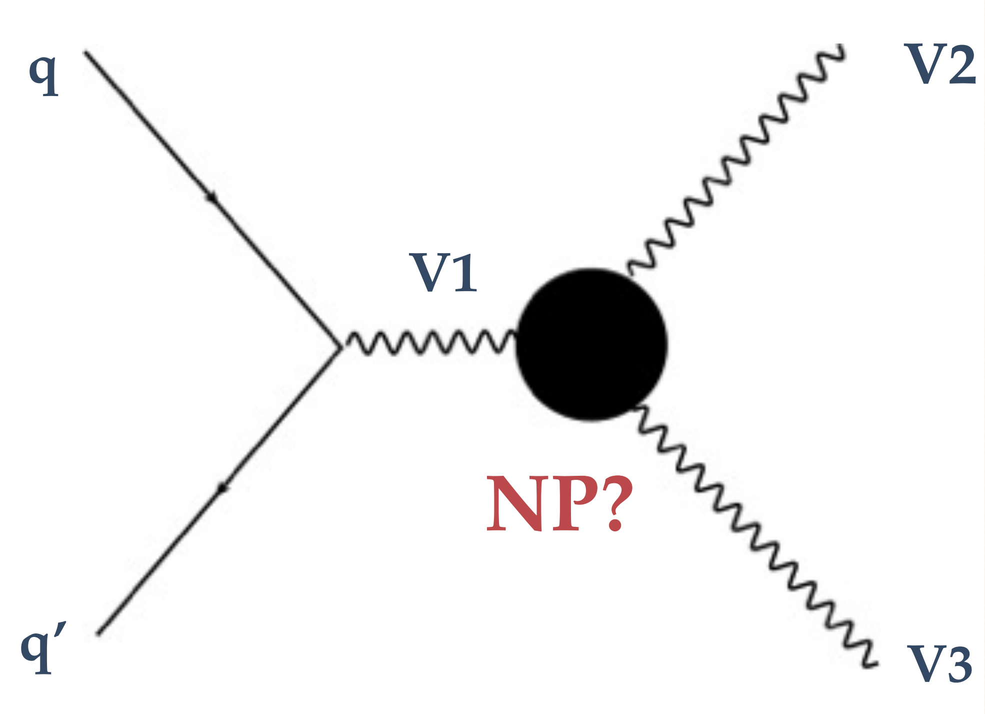


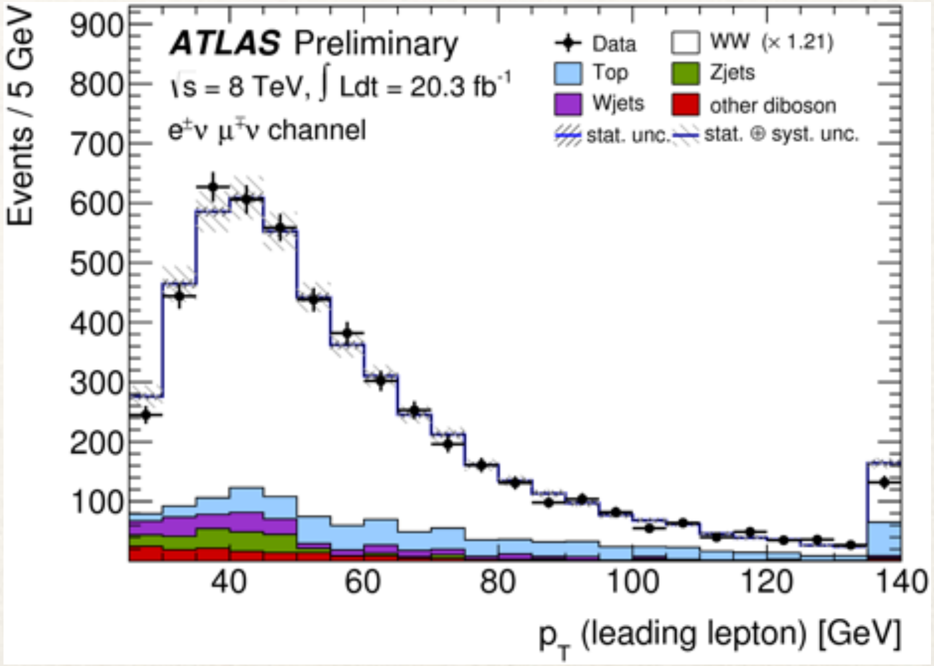
Indirect searches

Focus on SM particles' behaviour
precise determination of couplings and kinematics
comparison with SM,
search for deviations

Indirect searches using the Higgs
since 2012, relatively new
Higgs as a window to NP
expect deviations in its behaviour
Run2 data and beyond
precision in Higgs Physics

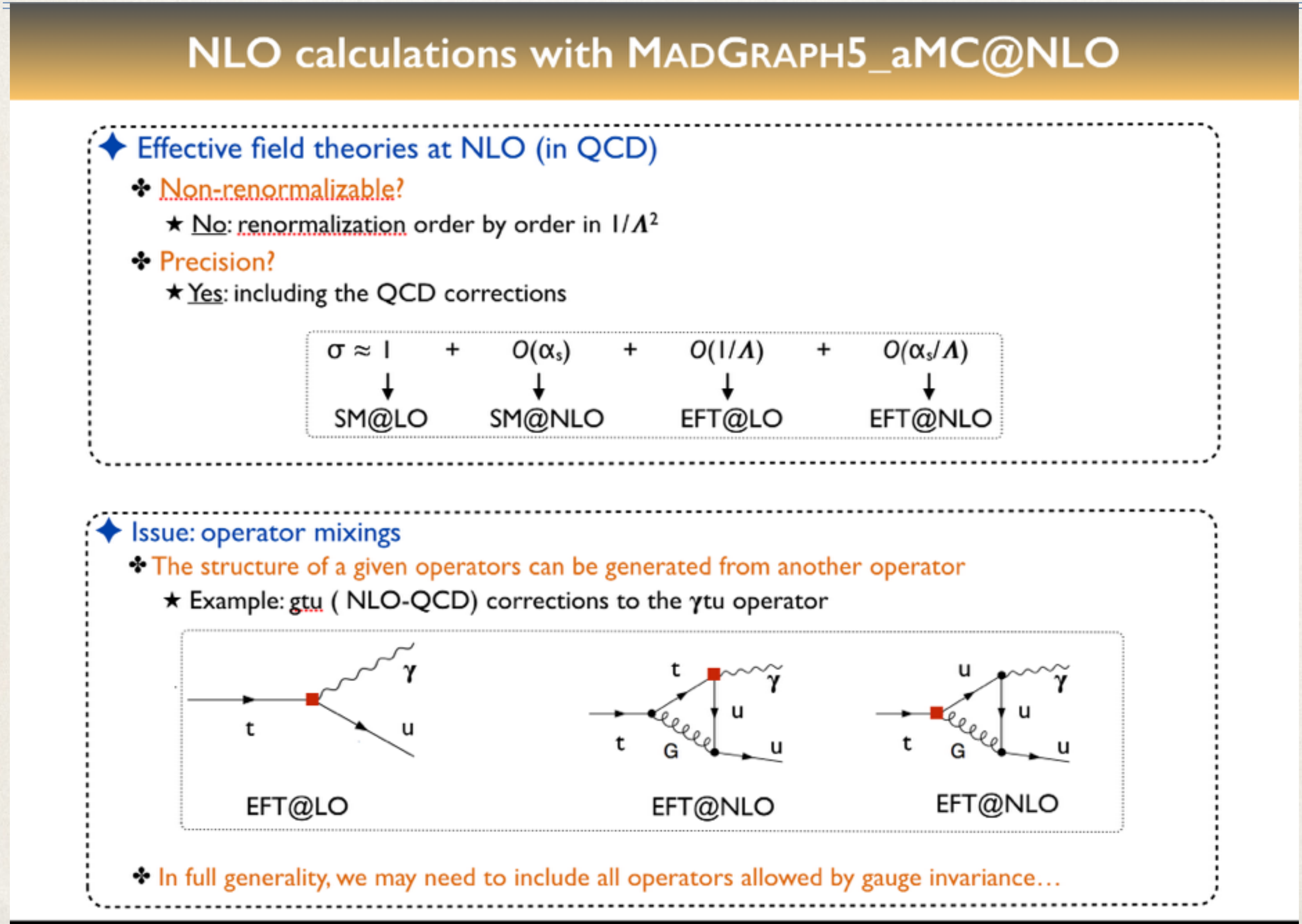
e.g. Anomalous trilinear gauge couplings, aka **TGCs**





LEP, Tevatron, LHC

Automated NLO MC



NLO calculations with MADGRAPH5_aMC@NLO

✦ Effective field theories at NLO (in QCD)

- Non-renormalizable?
  - ★ No: renormalization order by order in $1/\Lambda^2$
- Precision?
  - ★ Yes: including the QCD corrections

$\sigma \approx 1$	+	$O(\alpha_s)$	+	$O(1/\Lambda)$	+	$O(\alpha_s/\Lambda)$
↓		↓		↓		↓
SM@LO		SM@NLO		EFT@LO		EFT@NLO

✦ Issue: operator mixings

- The structure of a given operators can be generated from another operator
  - ★ Example: gtu (NLO-QCD) corrections to the γtu operator

EFT@LO

EFT@NLO

EFT@NLO

- In full generality, we may need to include all operators allowed by gauge invariance…