

Energizing Higgs Phenomenology at the LHC

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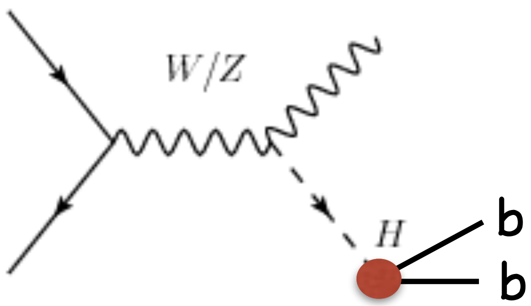
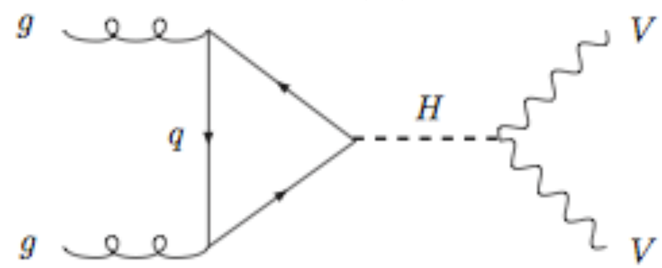
Incomplete list of final states that benefit from energy upgrade

Higgs-bottom coupling



[Butterworth, Davison, Rubin, Salam '08]

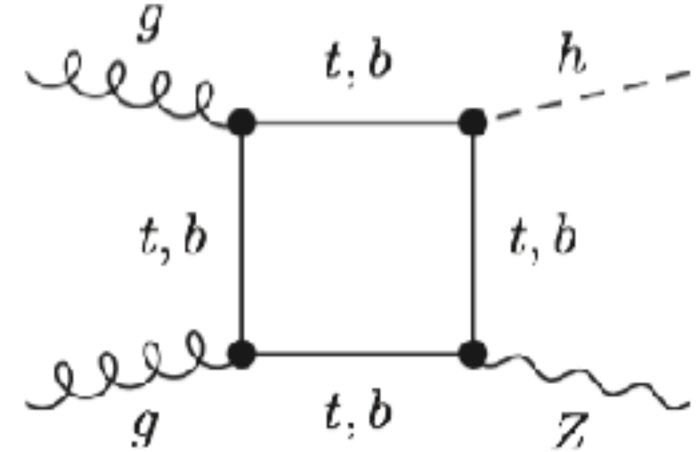
Off-shell Higgs (Width)



[Kauer, Passarino '12]

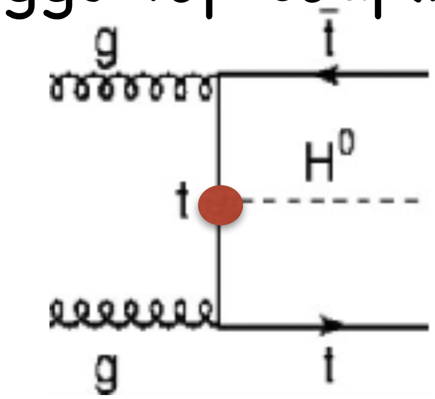
[Caola, Melnikov '14]

HZ final state



[Englert, McCullough, MS '13]

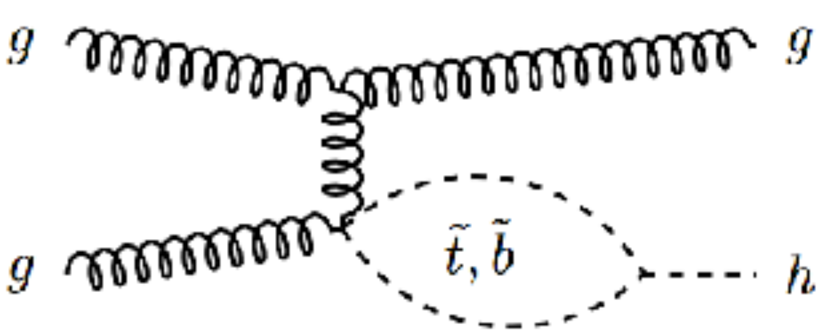
Higgs-top coupling



[Plehn, Salam, MS '09]

[Moretti, Petrov, Pozzorini, MS '15]

Boosted Higgs in H+jet

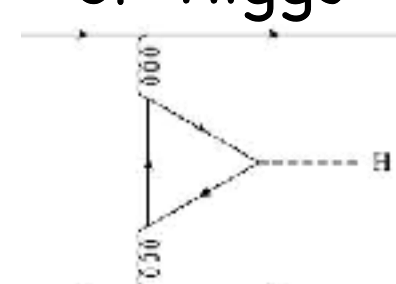


[Harlander, Neumann '13]

[Banfi, Martin, Sanz '13]

[Grojean, Salvioni, Schlaffer Weiler '14]

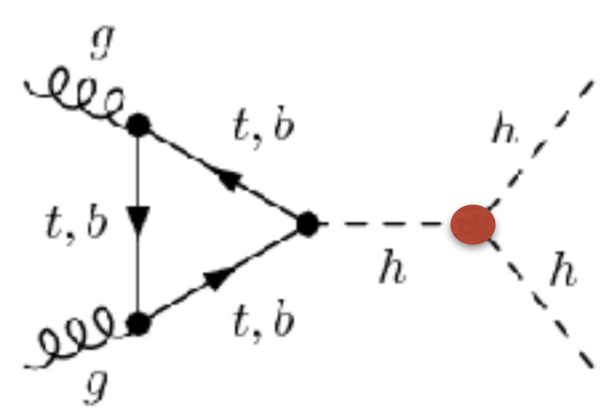
CP Higgs



[Plehn, Rainwater, Zeppenfeld '01]

[Klamke, Zeppenfeld '07]

Higgs selfcoupling

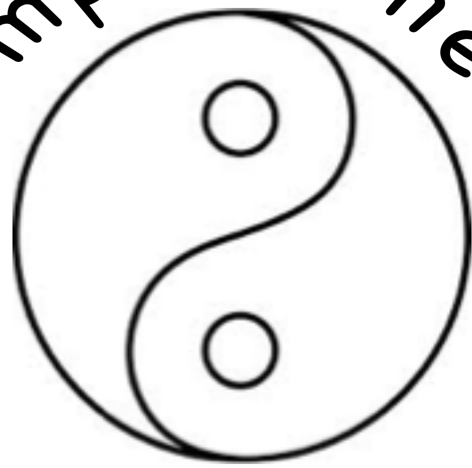


[Baur, Plehn, Rainwater '02 '03]

[Dolan, Englert, MS '12 '12]

[Baglio et al '13]

Compositeness



Effective Theory

$\mathcal{L}_{\text{eff}} = \sum C_i \mathcal{O}_i$

Symmetry

SUSY, CW, ...

Naturalness

fermionic top partners

simplified models

scalar top partners

simplified models

Measurements

Jets

Leptons

width

interference

mass

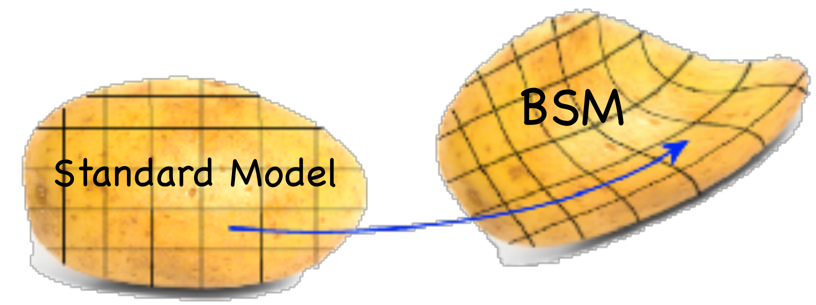
MET

boost

Photons

Improved/Unified way of interpretation of measurements

- interpretation of measurement is hypothesis test requires two competing hypotheses



- interpretation requires communication between different scales as well as theorists and experimentalists

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

Information extraction in different frameworks

Kappa framework

kappa is ratio of couplings:

$$\kappa_i = \frac{g_i}{g_{i,SM}}$$

so-called

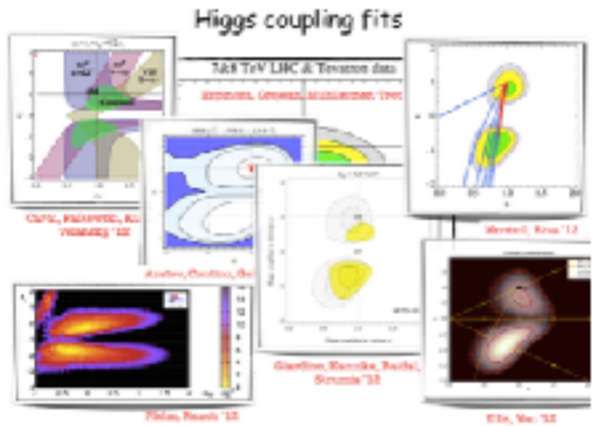
$\sigma(g_p) \times \mathrm{BR}(g_d)$ physics

Decay into spec. channel

Production

$$\sigma \cdot BR \propto g_p^2 \frac{g_d^2}{\Gamma_H}$$

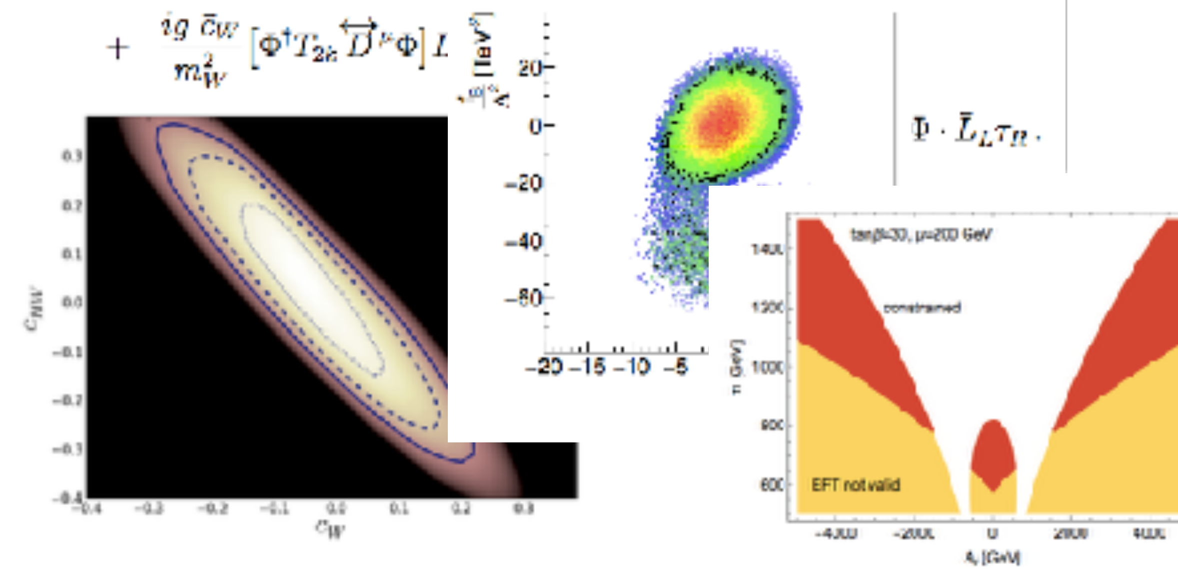
Sum of all possible decays



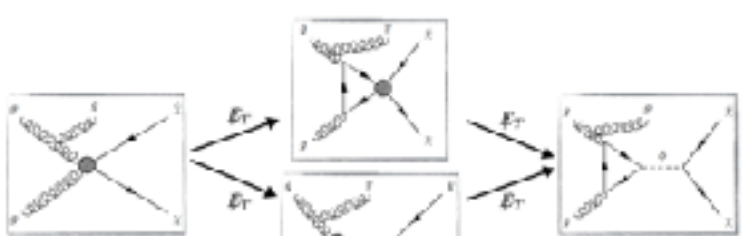
- try to over-constrain couplings basis
- Higgs width of particular importance

EFT framework

$$\mathcal{L} \supset \frac{\bar c_H}{2v^2}\partial^\mu[\Phi^\dagger\Phi]\partial_\mu[\Phi^\dagger\Phi] + \frac{g'^2\,\bar c_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar c_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}$$
$$+ \frac{2ig\,\bar c_{HW}}{m_W^2}[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi]W^k_{\mu\nu} + \frac{ig'\,\bar c_{HB}}{m_W^2}[D^\mu\Phi^\dagger D^\nu\Phi]B_{\mu\nu}$$
$$+ \frac{ig\,\bar c_W}{m_W^2}[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi]\,L \quad \ldots \quad \Phi\cdot\bar L_L\tau_R\,.$$



Simplified models



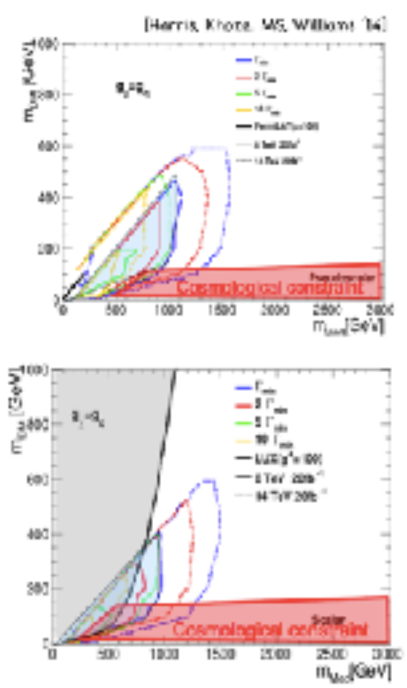
simplified model

[Buckley, Feld, Goncalves '14]

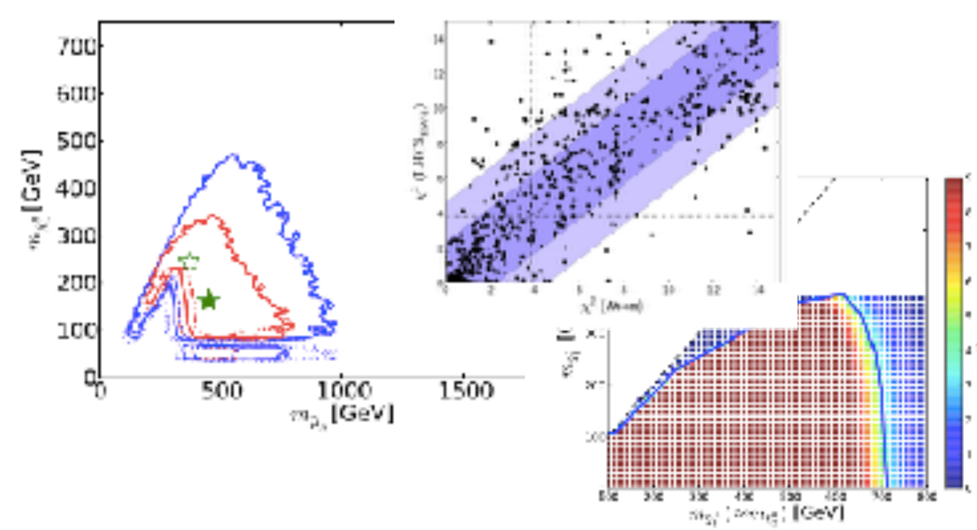
[Harris, Khoze, MS, Williams '14]

$$\mathcal{L}_{\text{pseudo-scalar}} \supset -\frac{1}{2}m^2_{\rm MED}P^2 - g_{\rm DM}P\bar\chi\gamma^5\chi - g^t_{SM}P\bar t\gamma^5 t - g^b_{SM}P\bar b\gamma^5 b$$

$$\mathcal{L}_{\text{scalar}} \supset -\frac{1}{2}m^2_{\rm MED}S^2 - g_{\rm DM}S\bar\chi\chi - g^t_{SM}S\bar t t - g^b_{SM}S\bar b b$$



UV models



MSSM, NMSSM, string pheno, ...

EFT fit for hadron collider needs to address:

Basis

- Complete
- Inspired by UV physics?

Several available:

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

Practicality

- Manageable number of operators for fit

Validity

- Validity range of EFT set by kinematic of measurement

Precision

- Resummation of large log (RGE improved pert. theory)
- Full NLO

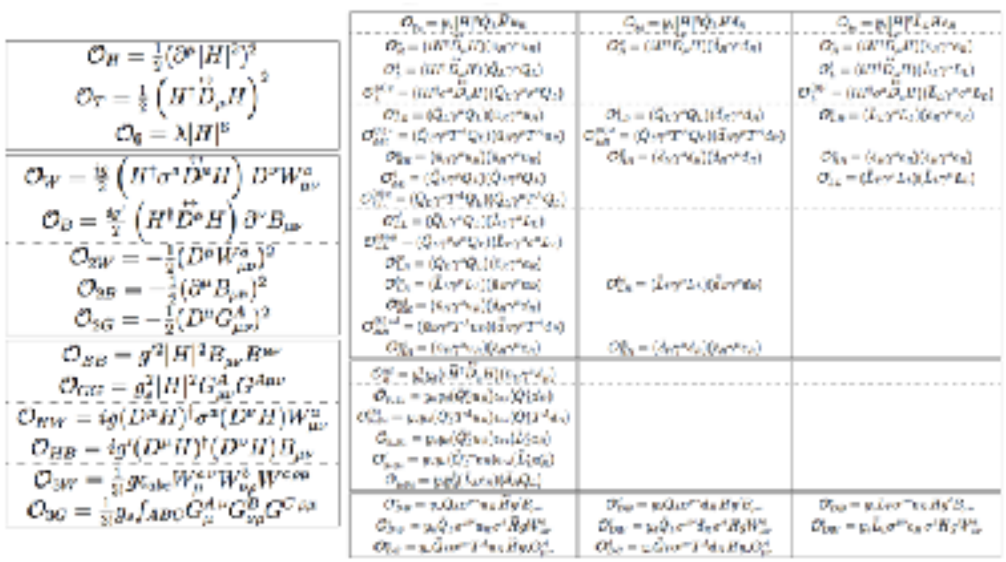
Basis and choice of operators to consider

Agnostic operator basis highly complex:

2499 non-redundant parameters at dim-6

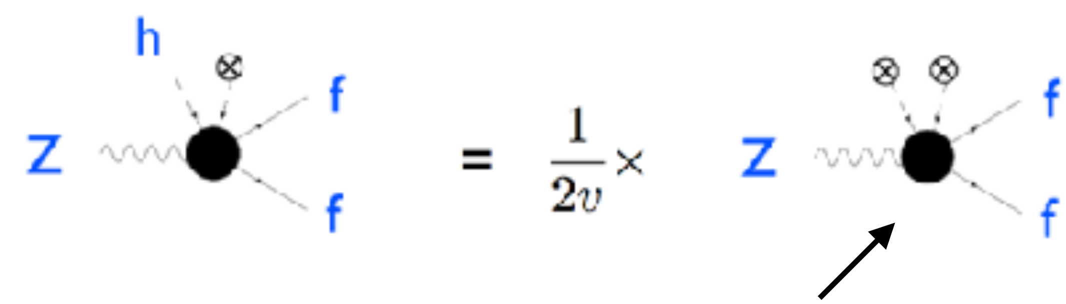
Flavor diagonal still complex:

59 operators



$$\mathcal{O}_H = \frac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$
$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\frac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\frac{1}{2}(D^\mu G^A_{\mu\nu})^2$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \frac{1}{3!} g \epsilon_{abc} W^{a\nu}_\mu W^b_{\nu\rho} W^{c\rho\mu}$$
$$\mathcal{O}_{3G} = \frac{1}{3!} g_s f_{ABC} G^{A\nu}_\mu G^B_{\nu\rho} G^{C\rho\mu}$$

- Focus on operators with Higgs involvement (new kid on the block)



constrained by LEP at permille level

- Focus on operators that are probed predominantly at LHC

Choose SILH basis:

$$\begin{aligned}
\mathcal{L}_{\rm SILH} = & \frac{\bar c_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar c_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar c_6 \lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar c_{u,i} y_{u,i}}{v^2} H^\dagger H \bar u_L^{(i)} H^c u_R^{(i)} + \text{h.c.}\right) + \left(\frac{\bar c_{d,i} y_{d,i}}{v^2} H^\dagger H \bar d_L^{(i)} H d_R^{(i)} + \text{h.c.}\right) \\
& + \frac{i\bar c_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar c_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar c_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar c_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar c_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar c_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
\end{aligned}$$

[Giudice, Grojean, Pomarol, Rattazzi '07]

here $c_T \sim T$ and

$c_B + c_W \sim S$

[Peskin, Takeuchi '91]

Validity and Relevance of EFT

EFT used to set limits on UV models from non-observation of new physics

Lagrangian dim-6: $\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_i \frac{g_i^2}{\Lambda_{\rm NP}^2} \mathcal{O}_i$

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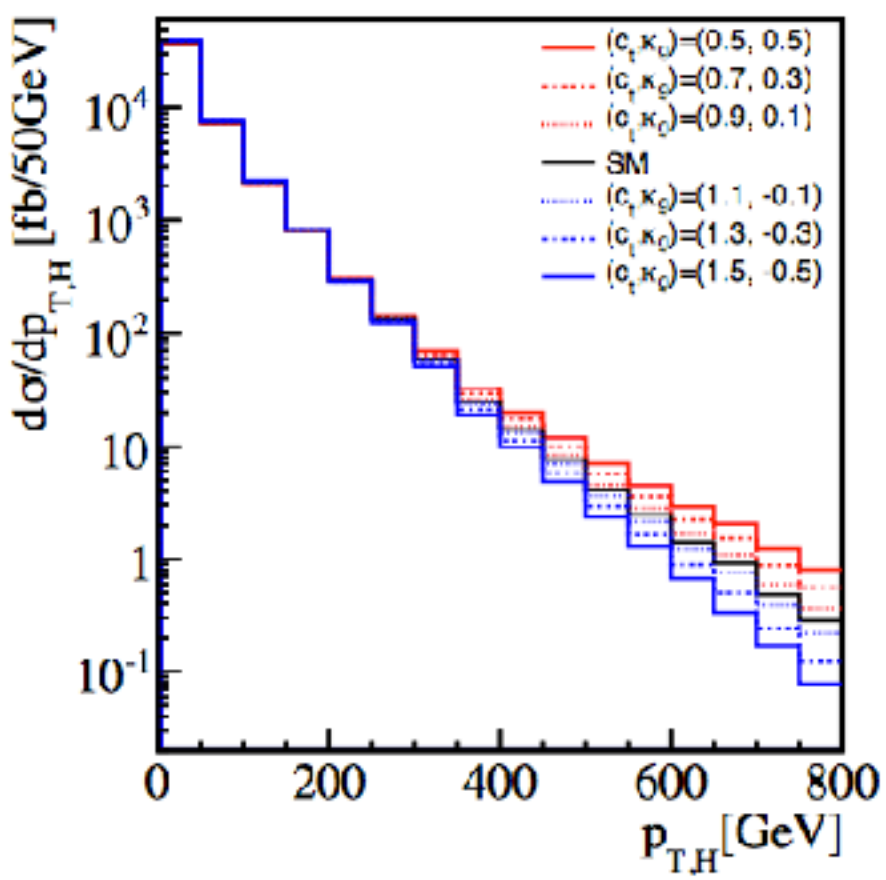
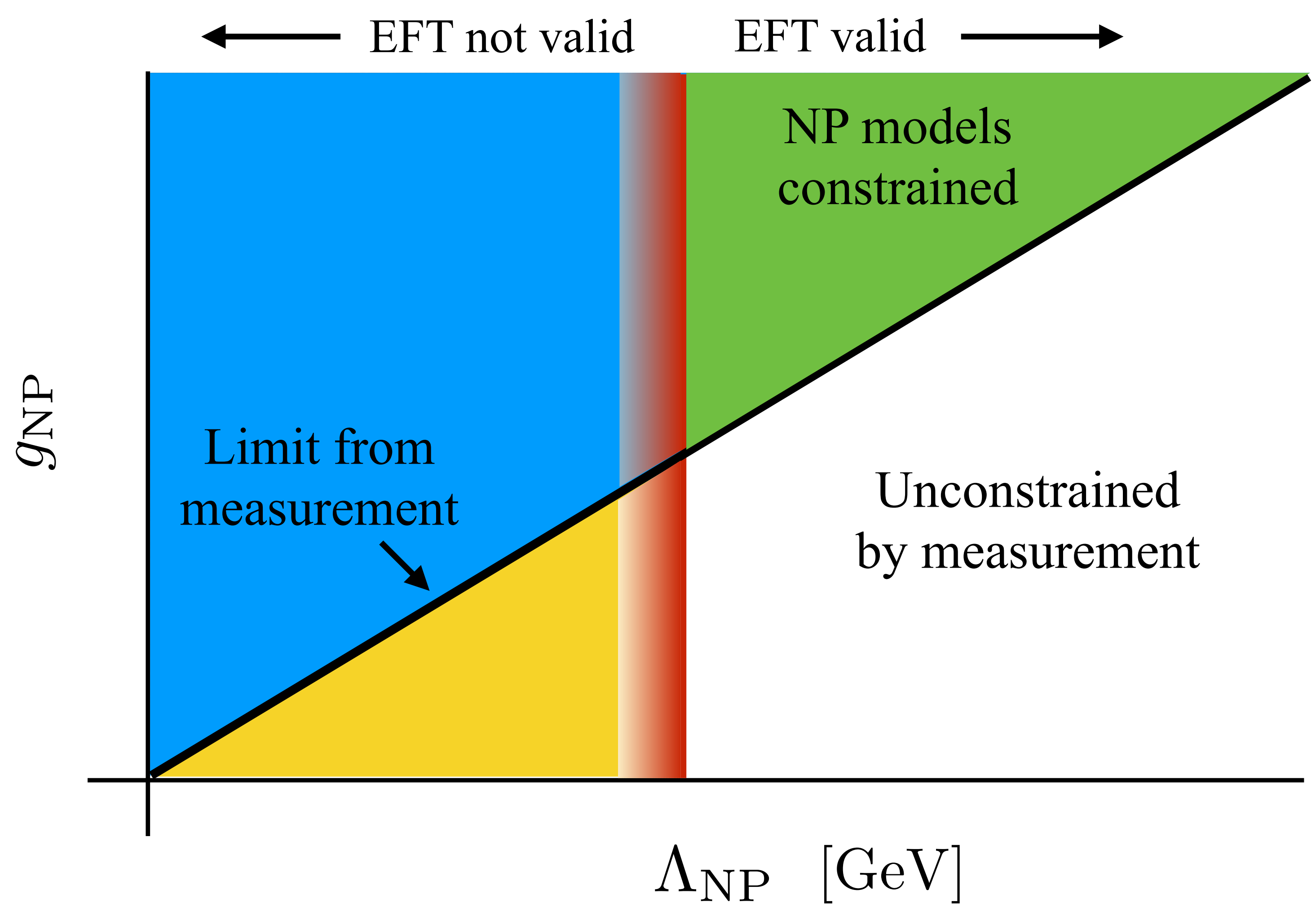
[Englert, MS 1408.5147]





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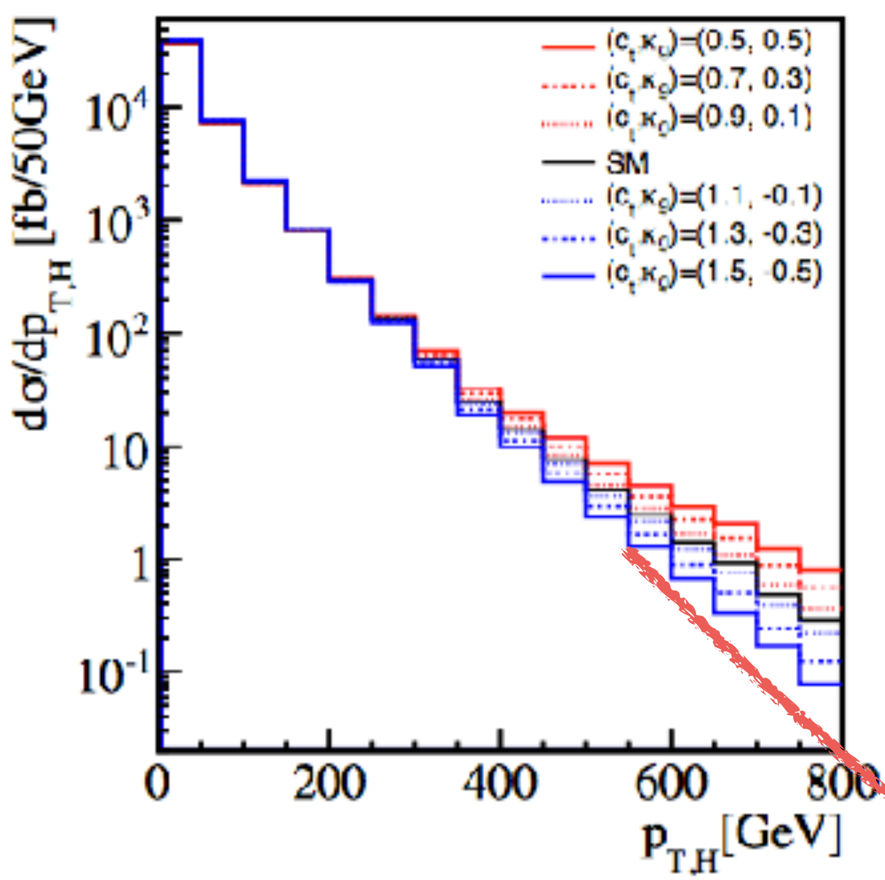

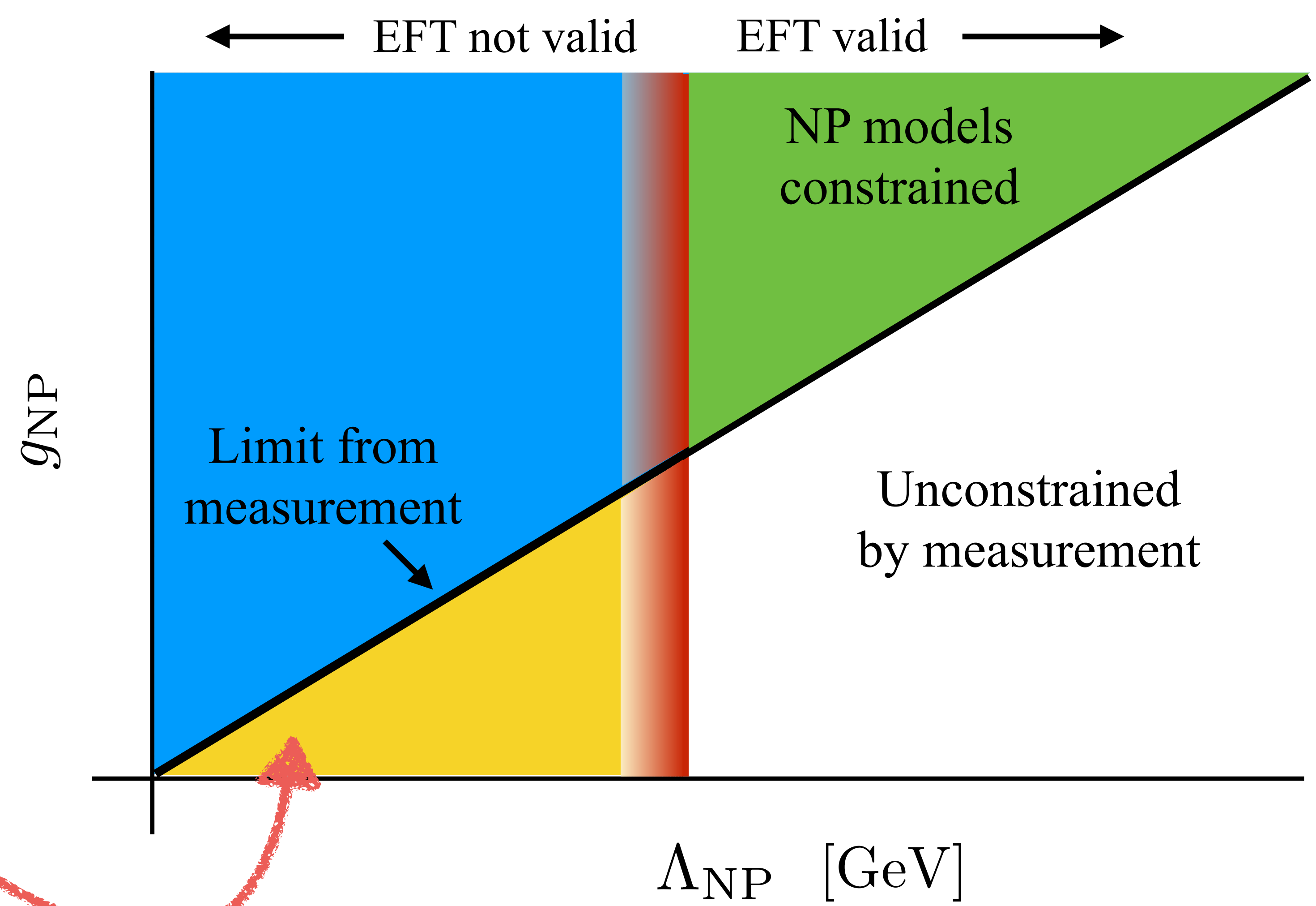

shape sets limit on Wilson coefficient (black line)

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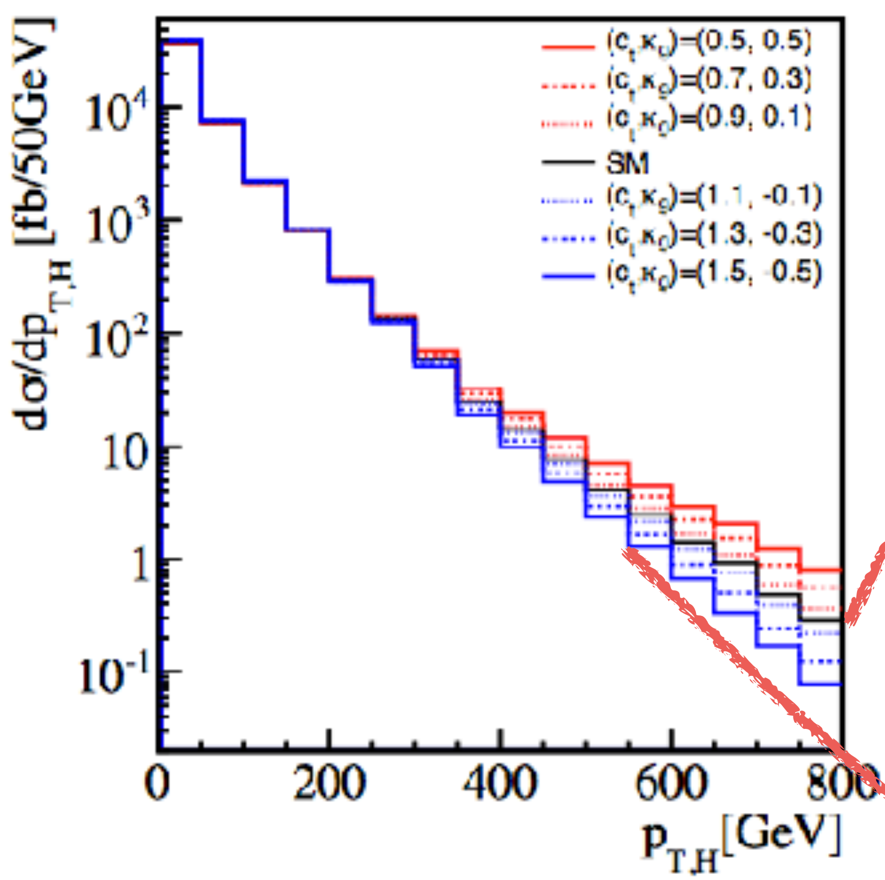
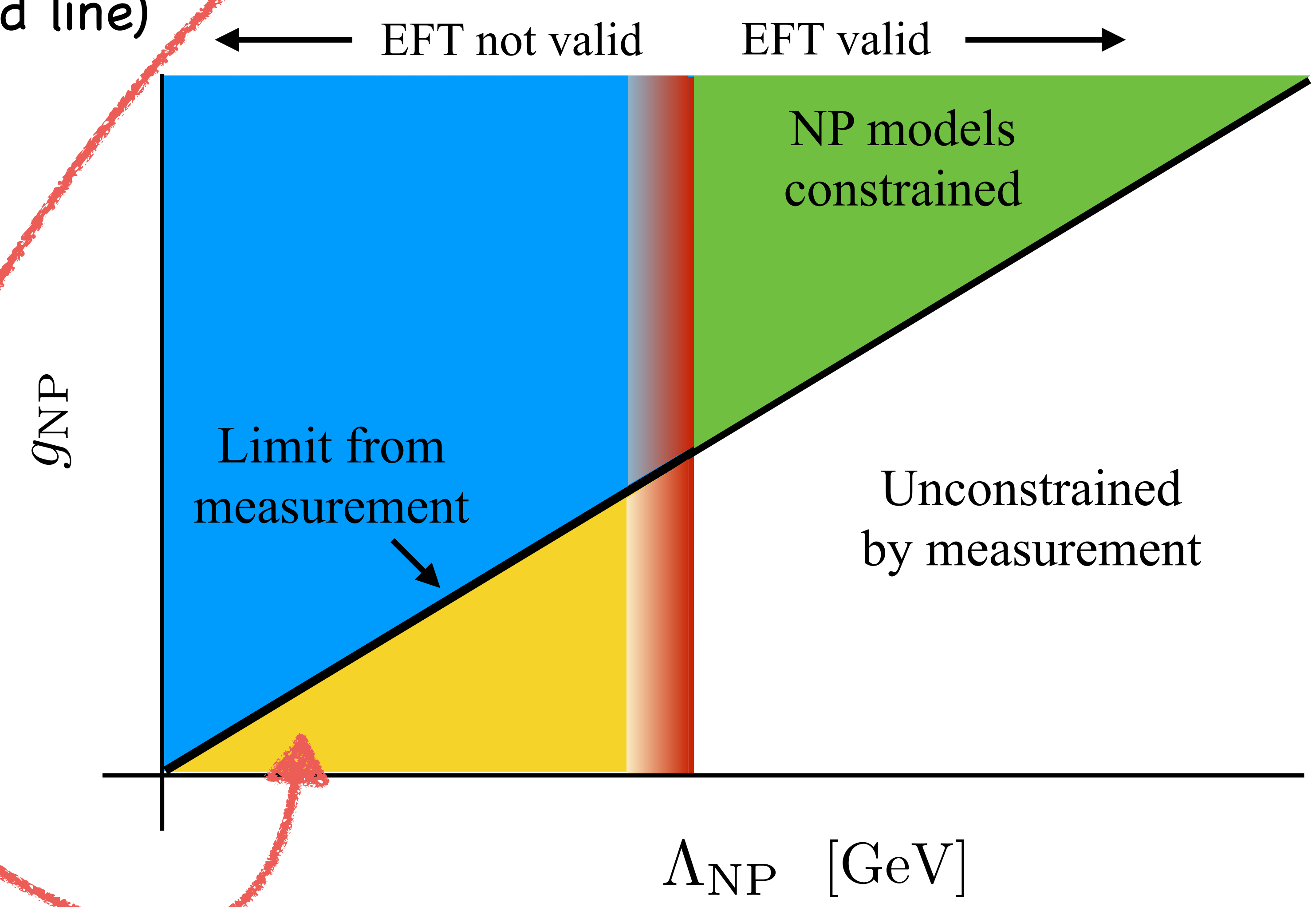
Endpoint of kinematic distribution sets lower cut-off for NP (red line)

[Englert, MS 1408.5147]





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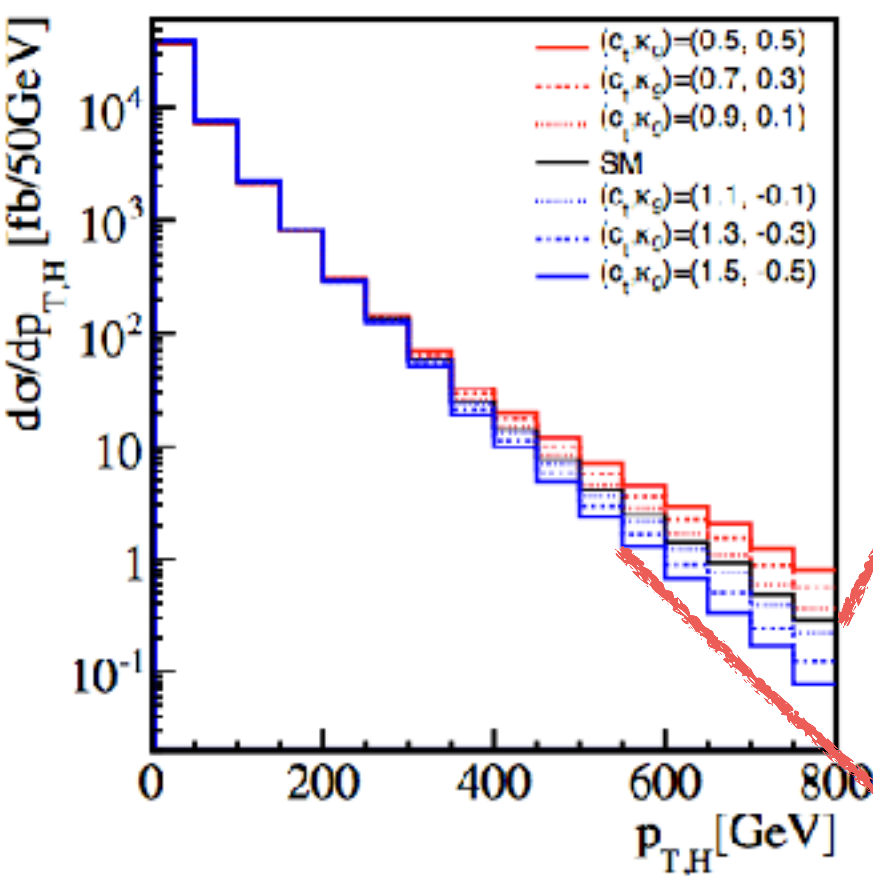
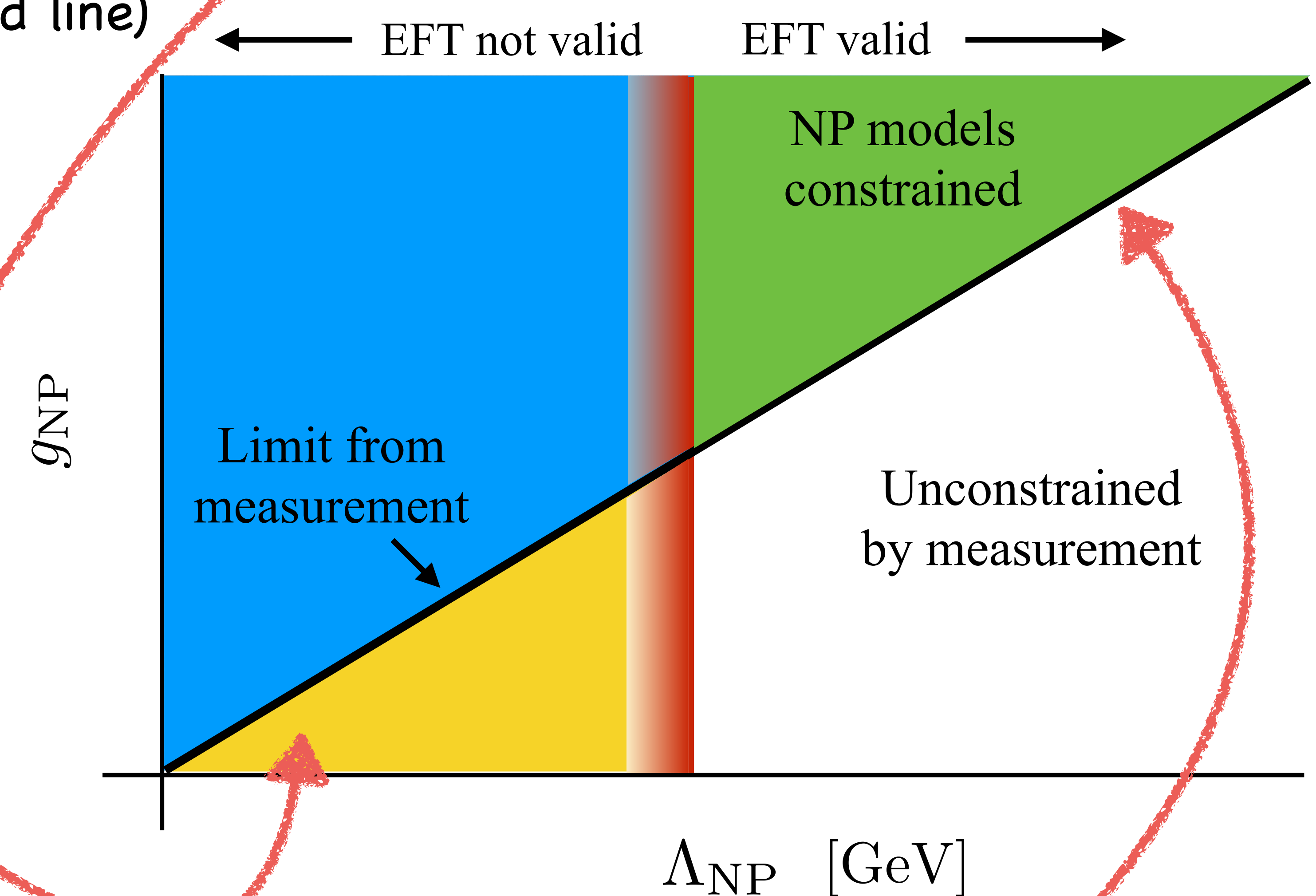
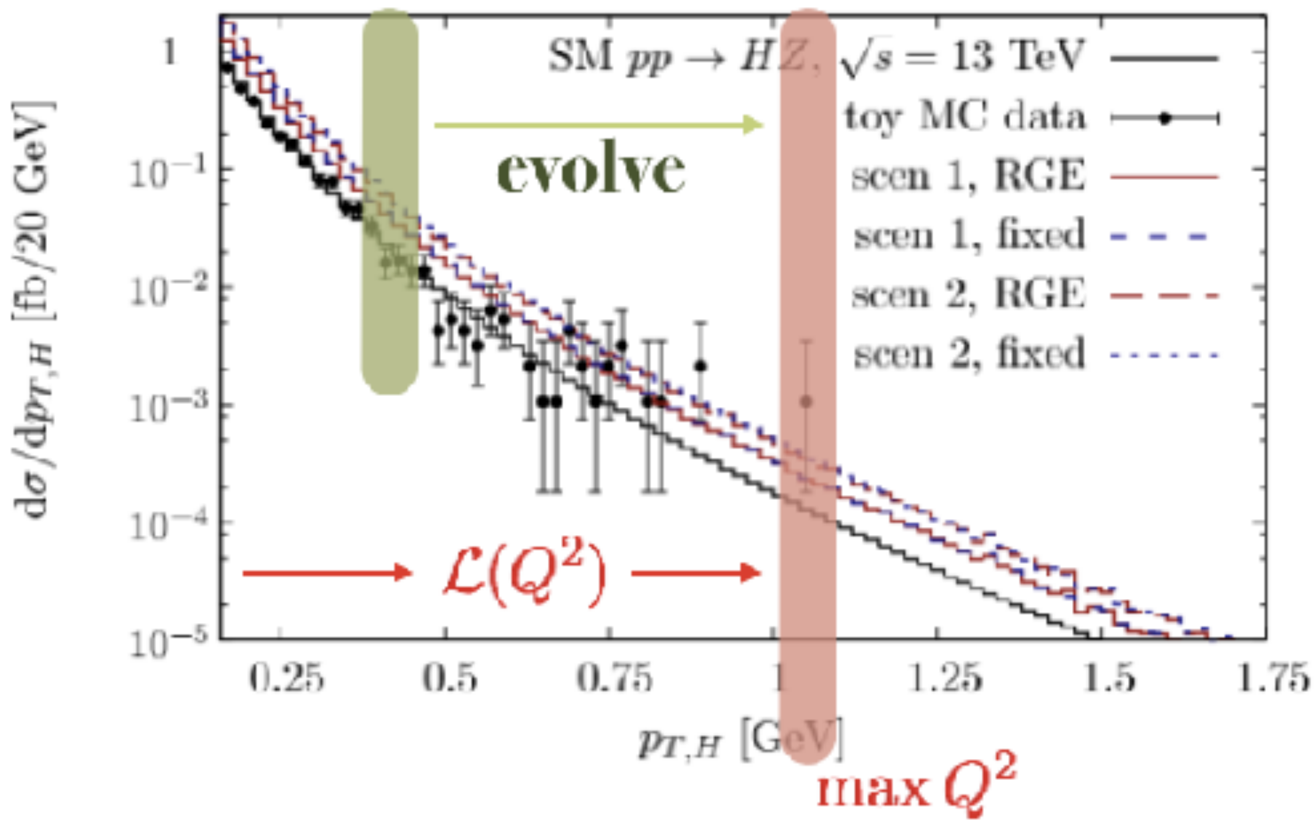




shape sets limit on Wilson coefficient (black line)

Any UV (weakly coupled) models left?



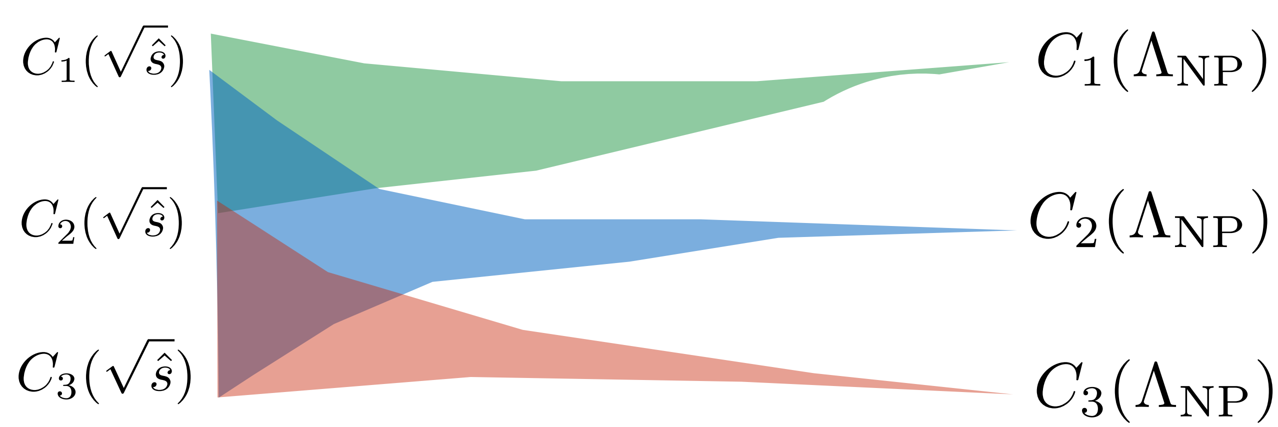
- scale hierarchies similar to flavor physics mW/mb~20
- evolution from renormalization group equations
  [Grojean, Jenkins, Manohar, Trott '13]
  [Jenkins, Manohar, Trott '13]
  [Elias-Miro et al '13]
- consistent interpretation requires **communication of resolved scales**

In general higher-order corrections induce scale dependence and mixing of operators

$$C_i(\sqrt{\hat{s}}) \simeq \left(\delta_{ij} + \gamma_{ij}(\sqrt{\hat{s}}) \log \frac{\sqrt{\hat{s}}}{\mu}\right) C_j(\mu)$$

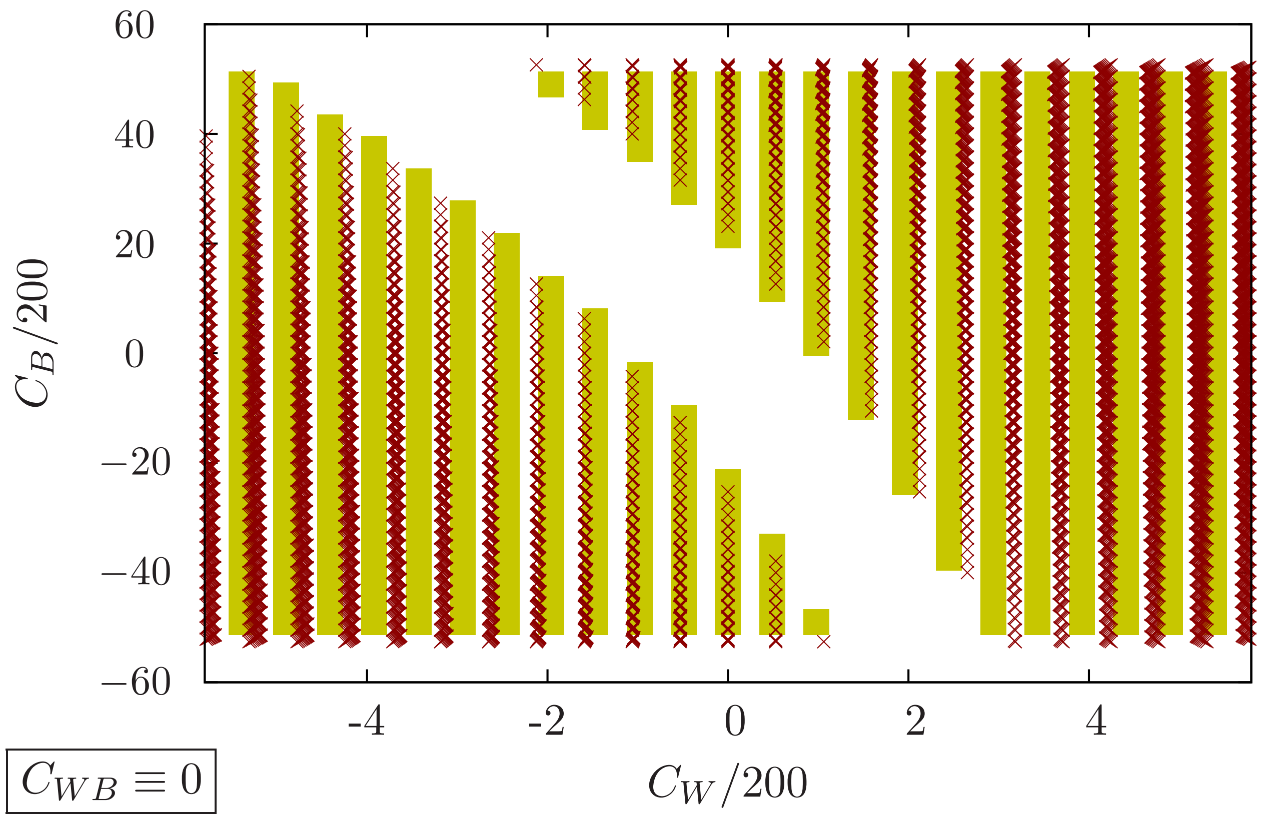
As a result, each measured **event** probes a different combination of operators

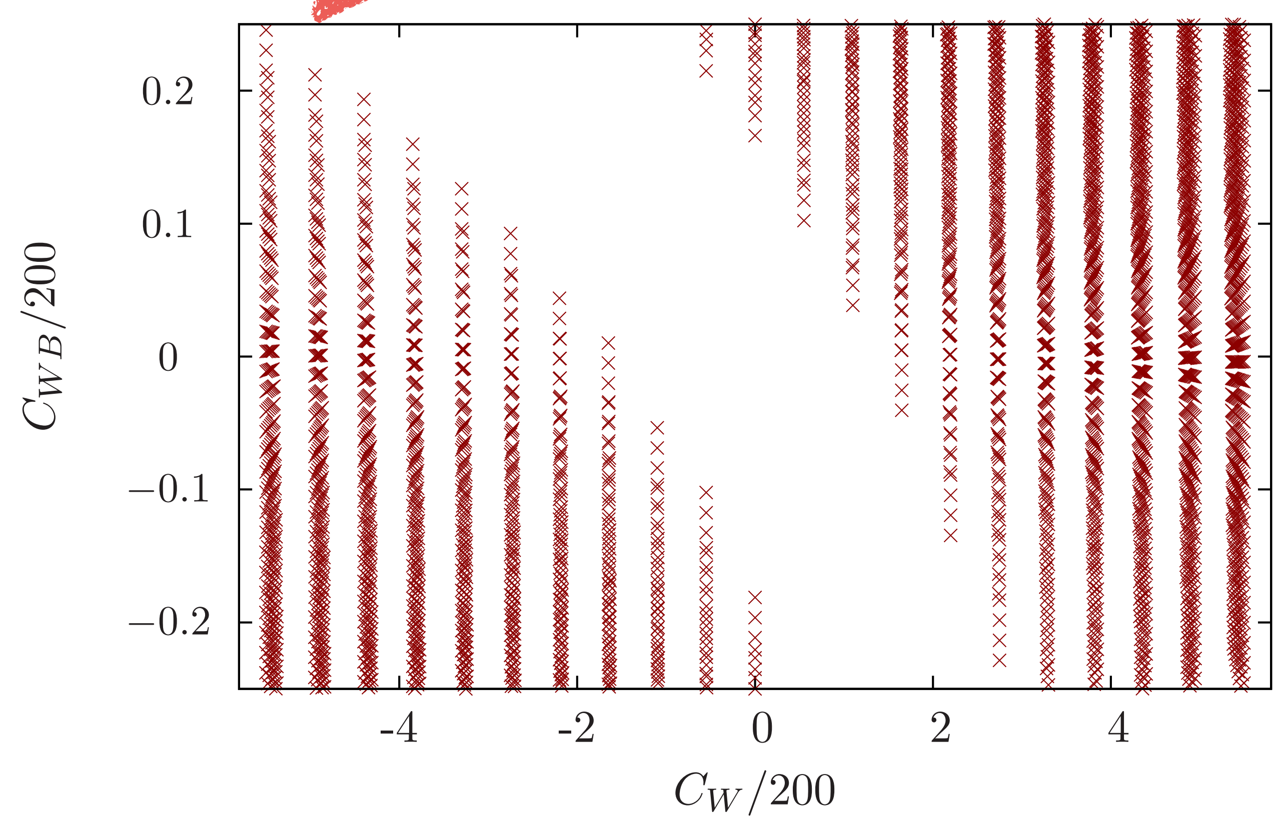
measurement at characteristic scale of event



Coefficients of operators at New Physics scale

T= C_{WB}= 0 at low scale but induced and allowed at high scale





$\max Q^2 = 2.4\ \text{TeV} \implies \mathcal{L}^{\text{BSM}}(2.4\ \text{TeV})$

Here maxQ=14 TeV

High-dim operators often momentum dependent

Sensitivity of measurement in tail of distribution

RG running potentially less important
as scale separation can be small (model dependent) [Hartmann, Trott '15]

Finite NLO pieces can be sizeable [Gauld, Pecjak, Scott '16]

Results for linearised LO EFT approach

[Englert, Kogler, Schulz, MS 1511.05170]

Focus on linear contribution of EFT for theory prediction:

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

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

Number of predicted events:

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

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)

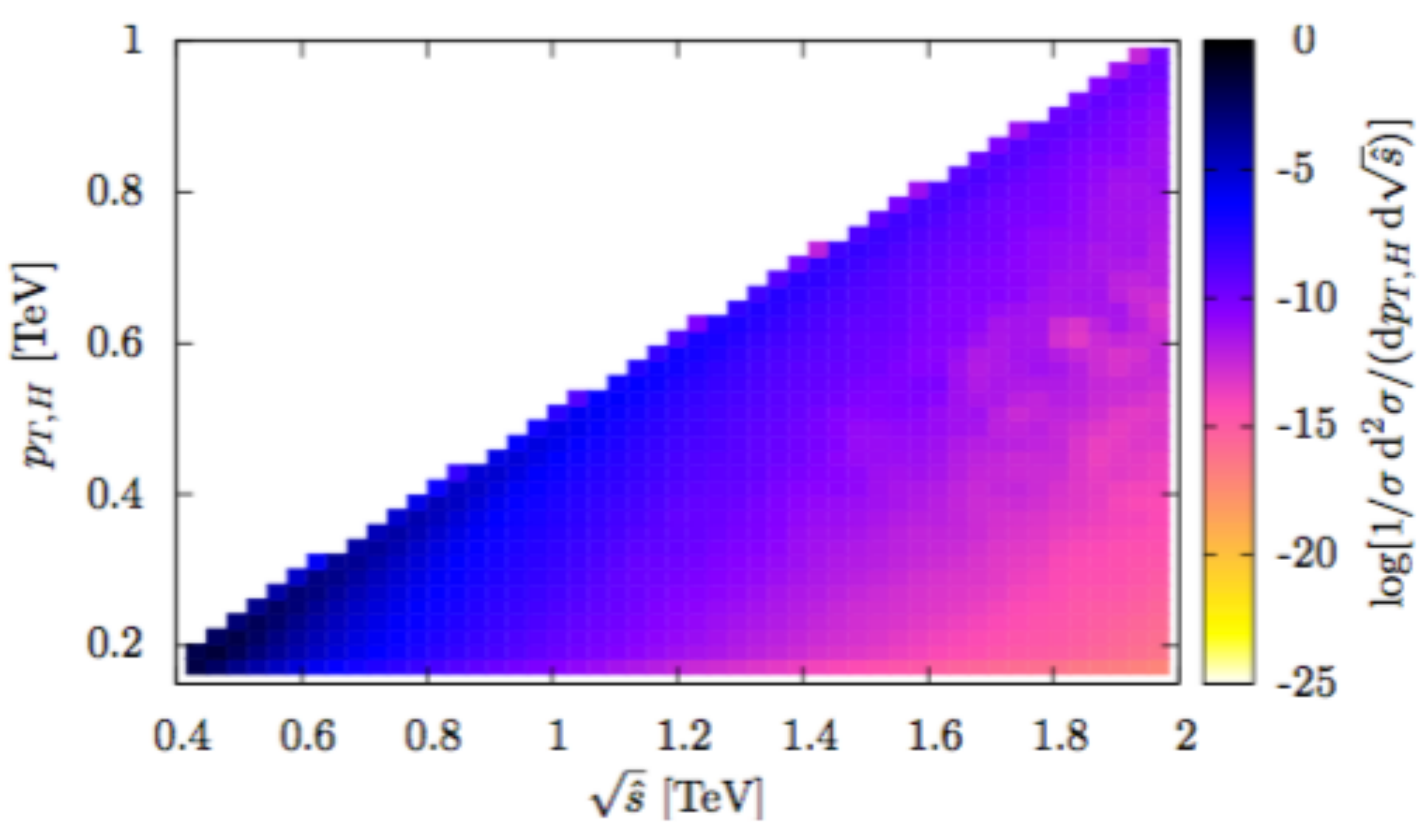
To show benefit of differential distribution need observable

- Different observables can give different results for fit
- 2->2 scattering leaves only 2 degrees of freedom, but 2->3 (tth, vbf) more complex
- However, exp. need to be able to provide unfolded distributions

→ most likely and practical **pT,H** unfolded

high correlation

$$\sqrt{\hat{s}} \sim m_H + p_{T,H}$$



Three sources of **uncertainties**

Theoretical uncertainties

(taken from exp. Run-1 papers)

Flat over pT,H range...

production process		decay process	
$pp \to H$	14.7	$H \to b\bar{b}$	6.1
$pp \to H + \mathrm{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H + 2\mathrm{j}$	15	$H \to \tau^+\tau^-$	2.8
$pp \to HZ$	5.1	$H \to 4l$	4.8
$pp \to HW$	3.7	$H \to 2l2\nu$	4.8
$pp \to t\bar{t}H$	12	$H \to \mu^+\mu^-$	2.8

→ Conservative for inclusive rate, aggressive for distributions

Systematic uncertainties

obtained for 7/8 TeV are scaled to 14 TeV with 300 and 3000 ifb respectively by $\sqrt{\mathcal{L}_8/\mathcal{L}_{14}}$

production process		decay process	
$pp \to H$	10	$H \to b\bar{b}$	25
$pp \to H + \mathrm{j}$	30	$H \to \gamma\gamma$	20
$pp \to H + 2\mathrm{j}$	100	$H \to \tau^+\tau^-$	15
$pp \to HZ$	10	$H \to 4l$	20
$pp \to HW$	50	$H \to 2l2\nu$	15
$pp \to t\bar{t}H$	30	$H \to Z\gamma$	150
		$H \to \mu^+\mu^-$	150

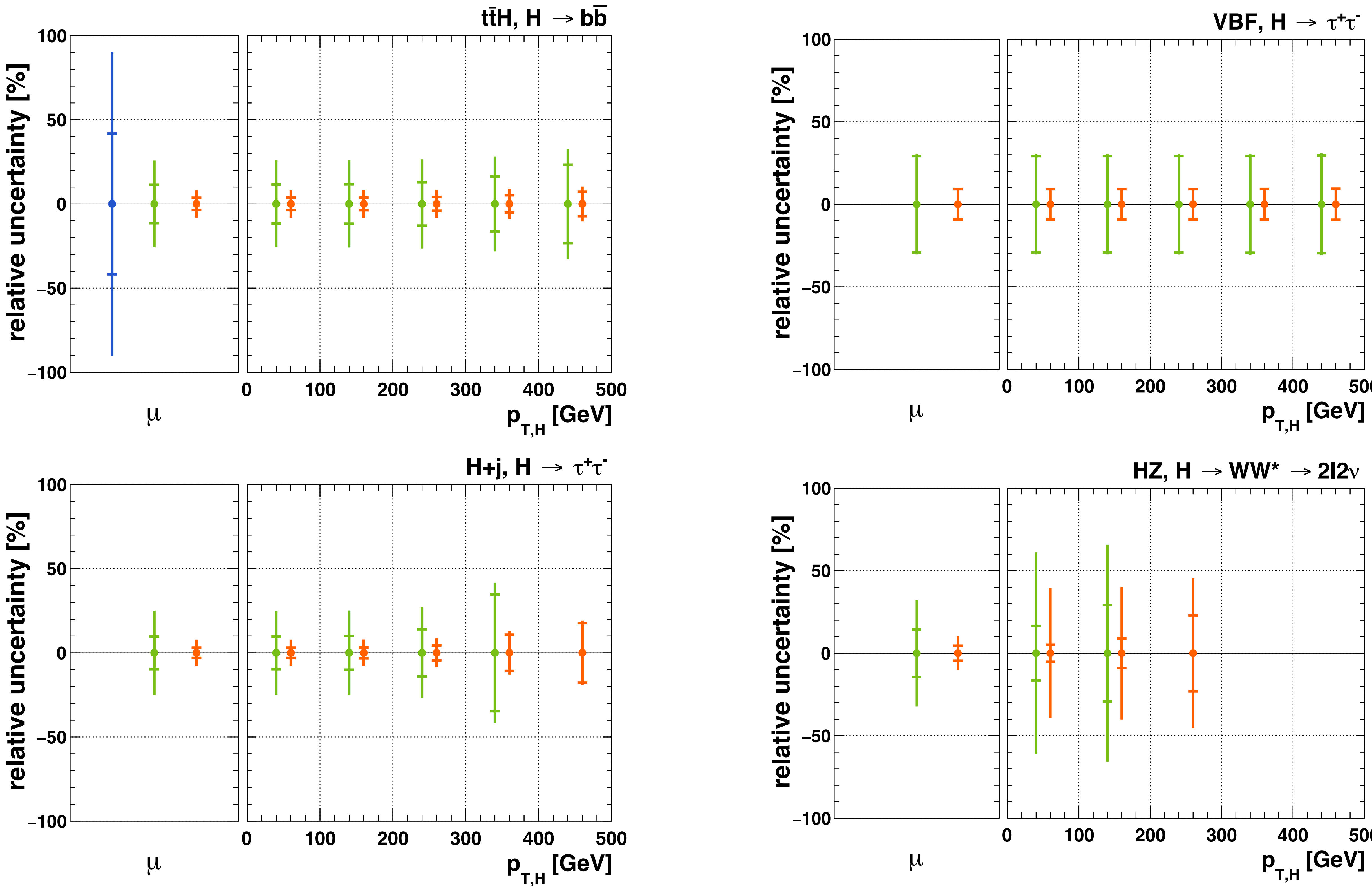
	$t\bar{t}H$	HZ	HW	H incl.	$H + \mathrm{j}$	$H + 2\mathrm{j}$
$H \to b\bar{b}$	80	25	40	100	100	150
$H \to \gamma\gamma$	60	70	30	10	10	20
$H \to \tau^+\tau^-$	100	75	75	80	80	30
$H \to 4l$	70	30	30	20	20	30
$H \to 2l2\nu$	70	100	100	20	20	30
$H \to Z\gamma$	100	100	100	100	100	100
$H \to \mu^+\mu^-$	100	100	100	100	100	100

rel. syst. uncertainty in %

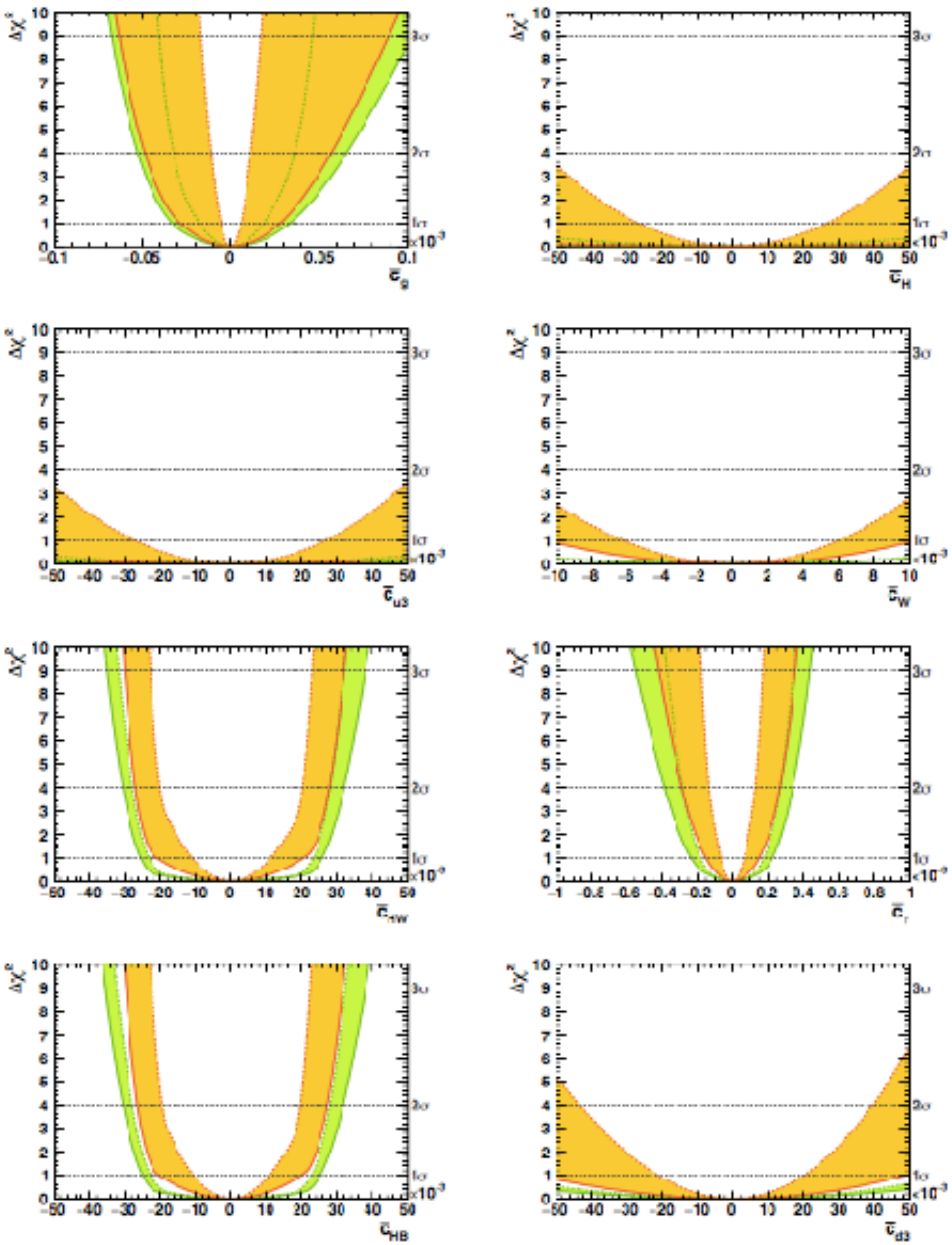
statistical uncertainties

part of fit and we require **5** events to consider a channel

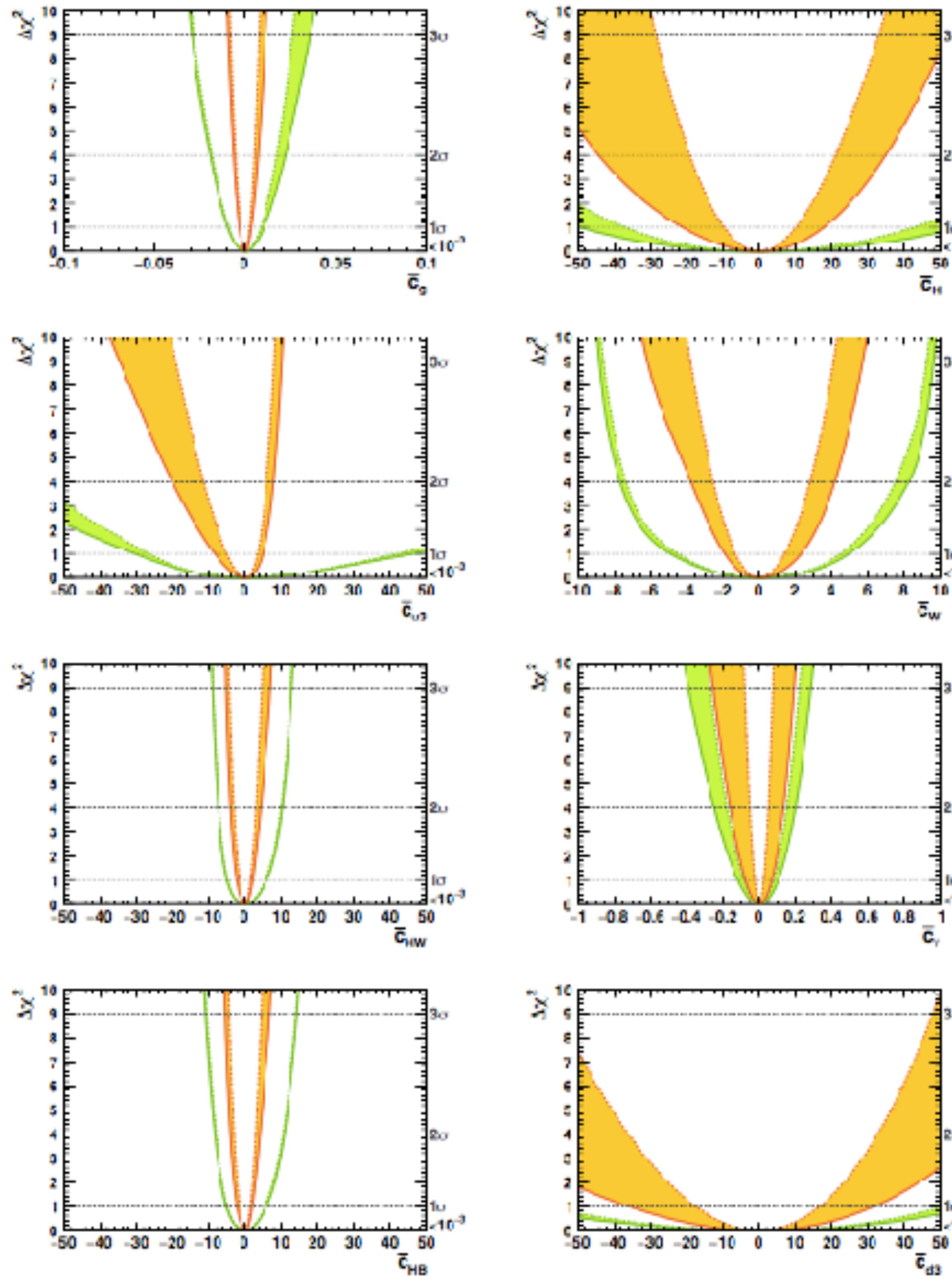
We generated pseudo-data for the extrapolation to 300 and 3000 ifb



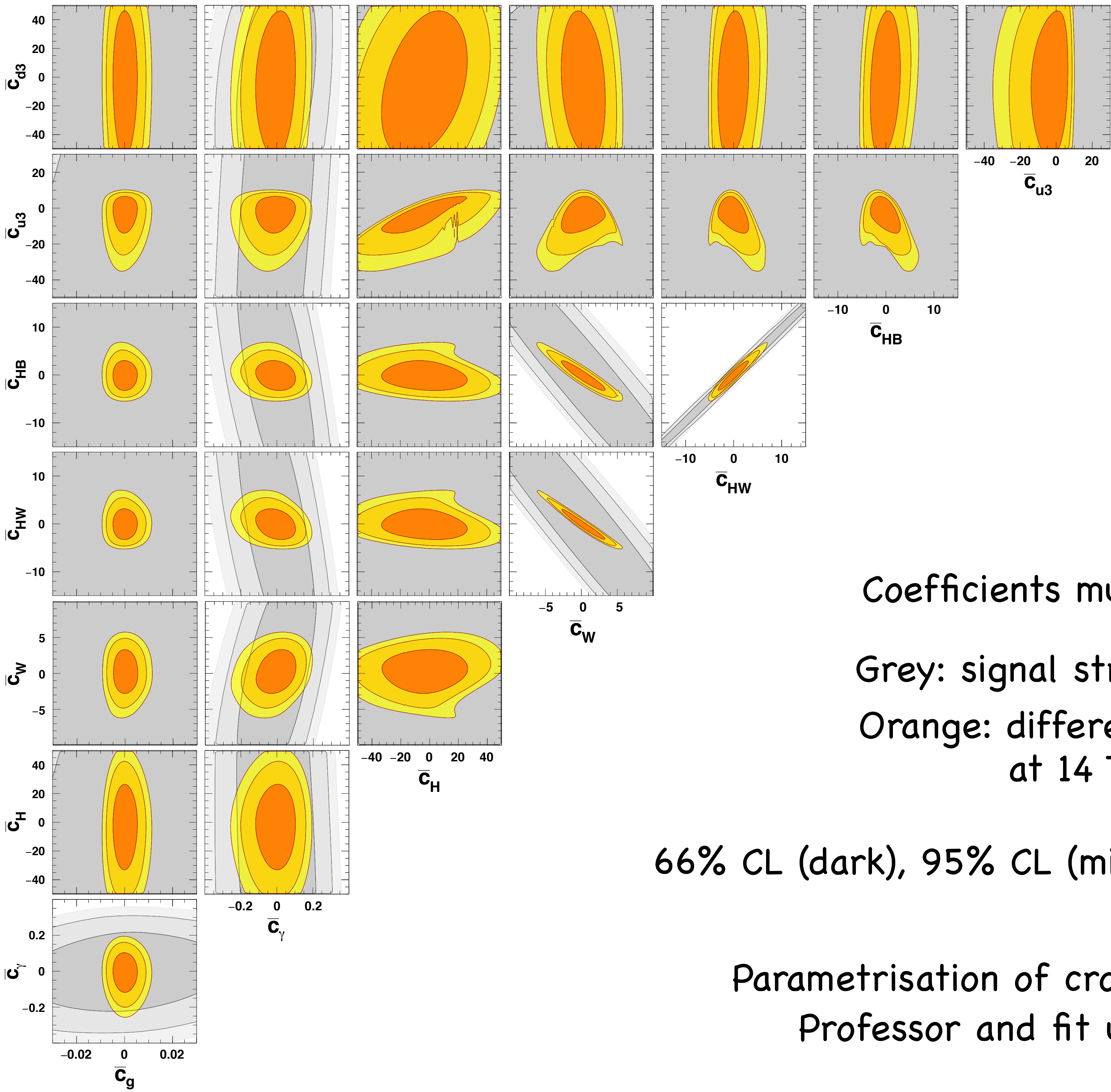
signal strength measurement



differential measurement



green = 300 ifb   orange = 3000 ifb



Coefficients multiplied by 10^3

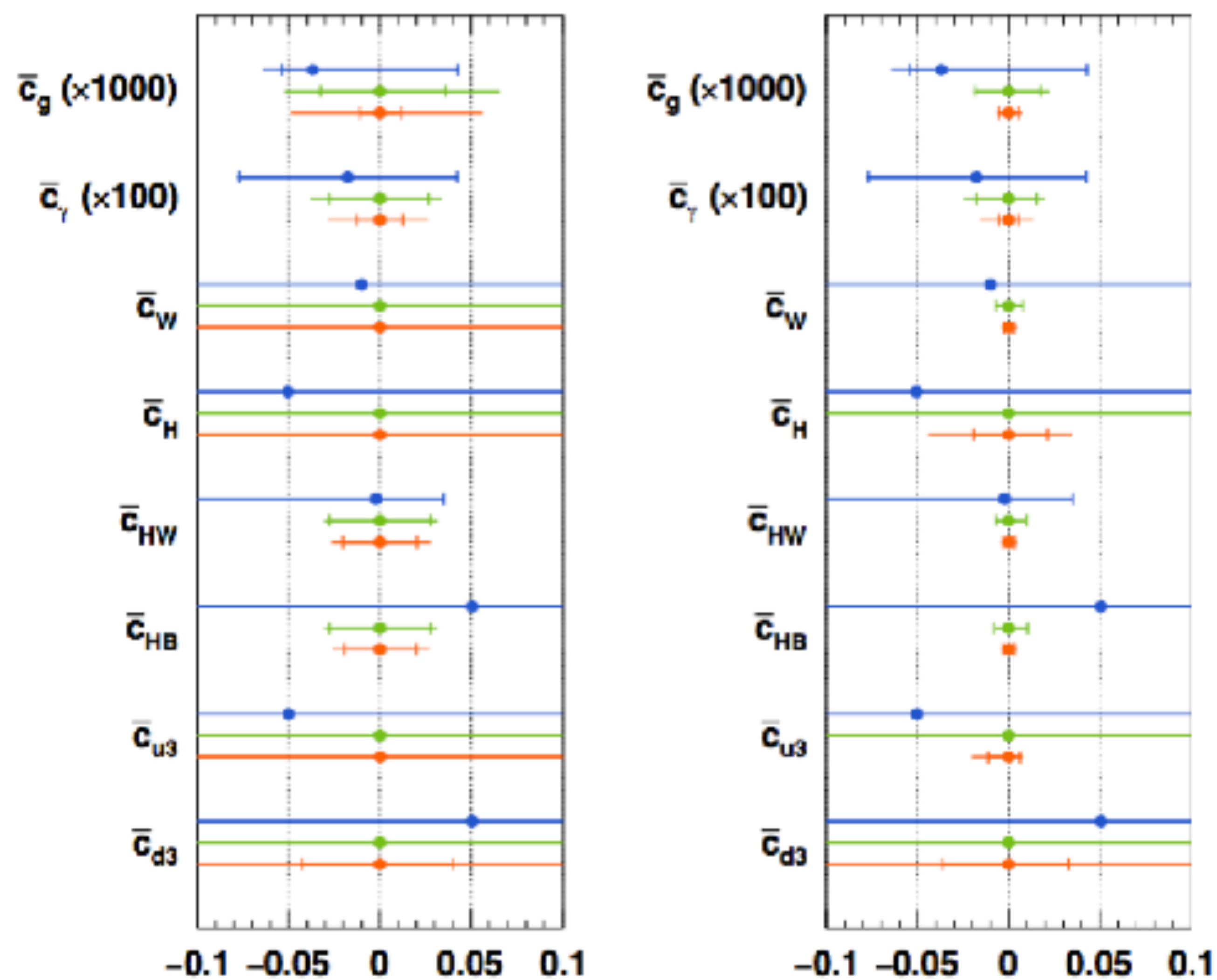
Grey: signal strength only

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

Signal strength only　　differential distributions



7/8 TeV (blue)

14 TeV, 300 ifb (green)

14 TeV, 3000 ifb (orange)

Setup allows to address most fundamental question for high-energy physics:

- Which theory calculations most important?
- Which systematic uncertainties most limiting?
- Where can we improve knowledge most?

Interpretation of results

Composite (SILH) Higgs:

One expects $\bar{c}_g \sim \frac{m_W^2}{16\pi^2}\frac{y_t^2}{\Lambda^2}$ with comp. scale $\Lambda \sim g_\rho f$

→ with $|\bar{c}_g| \lesssim 5 \times 10^{-6}$ we get $\Lambda \gtrsim 2.8$ TeV

→ new fundamental physics with higher scale cannot be probed using our Higgs observables (in this operator)

MSSM:

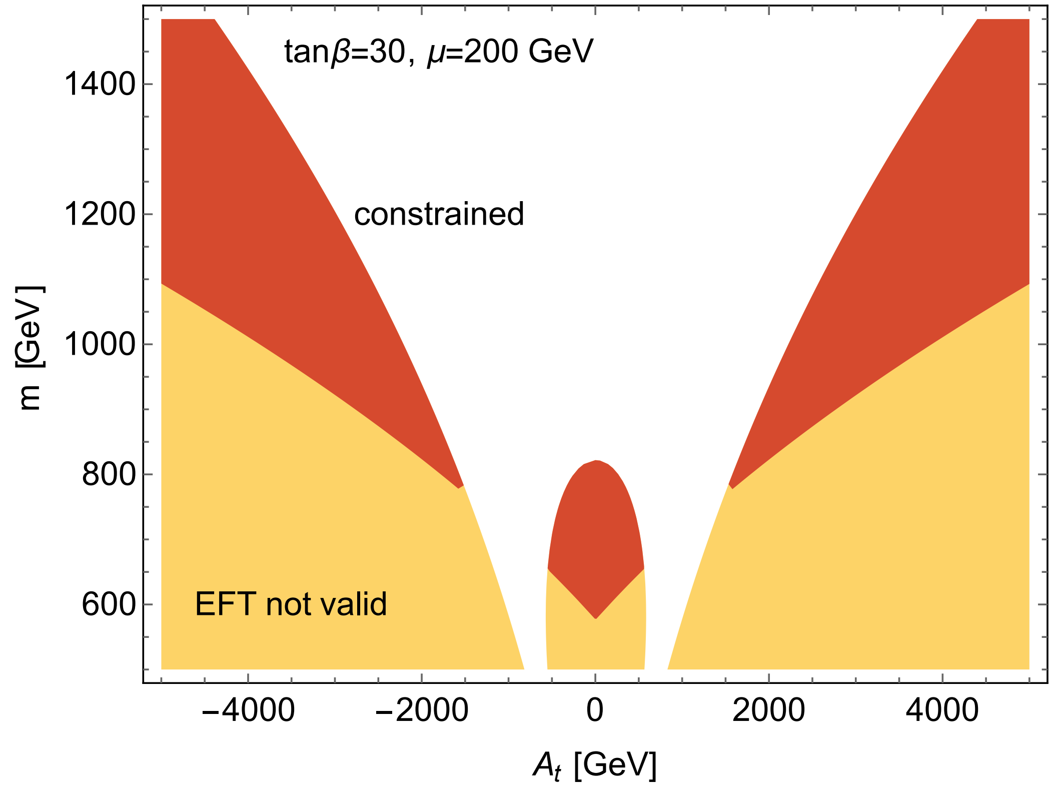
$$\bar{c}_g = \frac{m_W^2}{(4\pi)^2}\frac{1}{24}\left(\frac{h_t^2 - g_1^2 c_{2\beta}/6}{m_{\tilde{Q}}^2} + \frac{h_t^2 + g_1^2 c_{2\beta}/3}{m_{\tilde{t}_R}^2} - \frac{h_t^2 X_t^2}{m_{\tilde{Q}}^2 m_{\tilde{t}_R}^2}\right)$$

$$m_{\tilde{Q}} = m_{\tilde{t}} = m$$

$$\tan\beta = 30$$

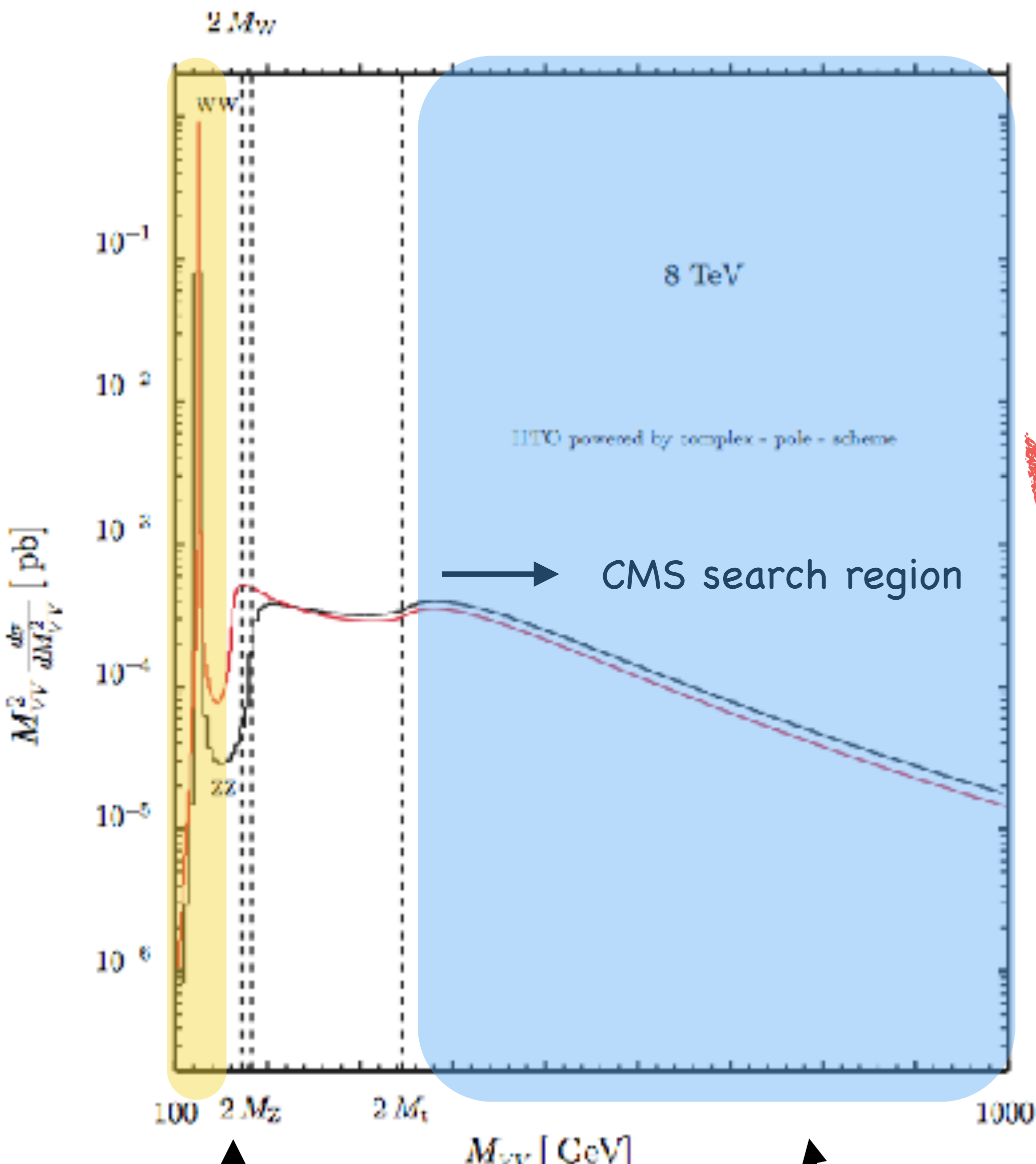
$$\mu = 200\ \mathrm{GeV}$$

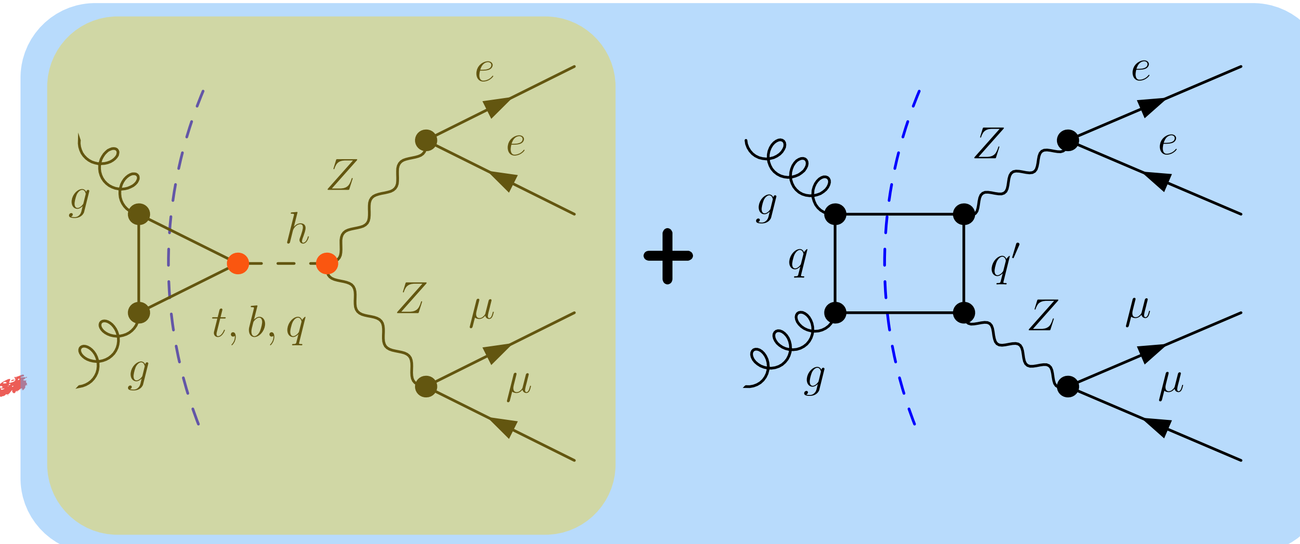
→ large At can be constrained



[Drozd, Ellis, Quevillon, You '15]

Chosen language affects answer: CMS 'width' Measurement





I. Count events in on-shell region

→ fix signal strength $\mu_{i,j} = \sigma_{H,i} \times BR_j \sim \frac{g_{ggH} g_{HZZ}}{\Gamma_H}$

II. measure $g_{ggH}^2 g_{HZZ}^2$ in off-shell region

using angular correlations of 4l decay products

III. insert off-shell coupling measurement in

on-shell signal strength to bound width

$$\sigma_{gg\to H\to ZZ}^{\mathrm{on-peak}} \sim \frac{g_{ggH}^2 g_{HZZ}^2}{\Gamma_H}$$

$$\sigma_{gg\to H\to ZZ}^{\mathrm{off-peak}} \sim g_{ggH}^2 g_{HZZ}^2$$

Obs.(exp.) @95% C.L:

Γ_H< 4.2(8.5) Γ_H^{SM}

Γ_H< 17.4 (35.3) MeV

[Kauer, Passarino 2011]

[Caola, Melnikov 2013]

Example 'width-measurement'

Measure coupling off-shell -> limit denominator on-shell

$$\sigma^{\text{on-peak}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{\Gamma_H} \quad \longleftrightarrow \quad \sigma^{\text{off-peak}}_{gg\to H\to ZZ} \sim g^2_{ggH}\, g^2_{HZZ}$$

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Kappa Framework	EFT	Simplified Models	Full (UV) Model

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EFT

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Simplified Models

Full (UV) Model

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Kappa Framework ✓

- Assuming global coupling rescaling

EFT ✓ ⚡

- Only if assuming no flat directions

Simplified Models ⚡

- Eg. **Higgs portal**, NP can contribute on-shell but not off-shell [Englert, MS ’14]
- Eg. **Higgs triplet**, new scalar below measurement range cancels on-shell enhancement [Logan ’15]

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Full (UV) Model

- Uninteresting width not a free parameter of the theory

  width derived and fully determined

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Kappa Framework

- Assuming global coupling rescaling

Coupling assumptions strong

LEP limits stronger than LHC

$$0.73\ \Gamma_{SM} \lesssim \Gamma_h \lesssim 1.87\ \Gamma_{SM}$$

[Englert, McCullough, MS '15]

EFT

- Only if assuming no flat directions

Simplified Models

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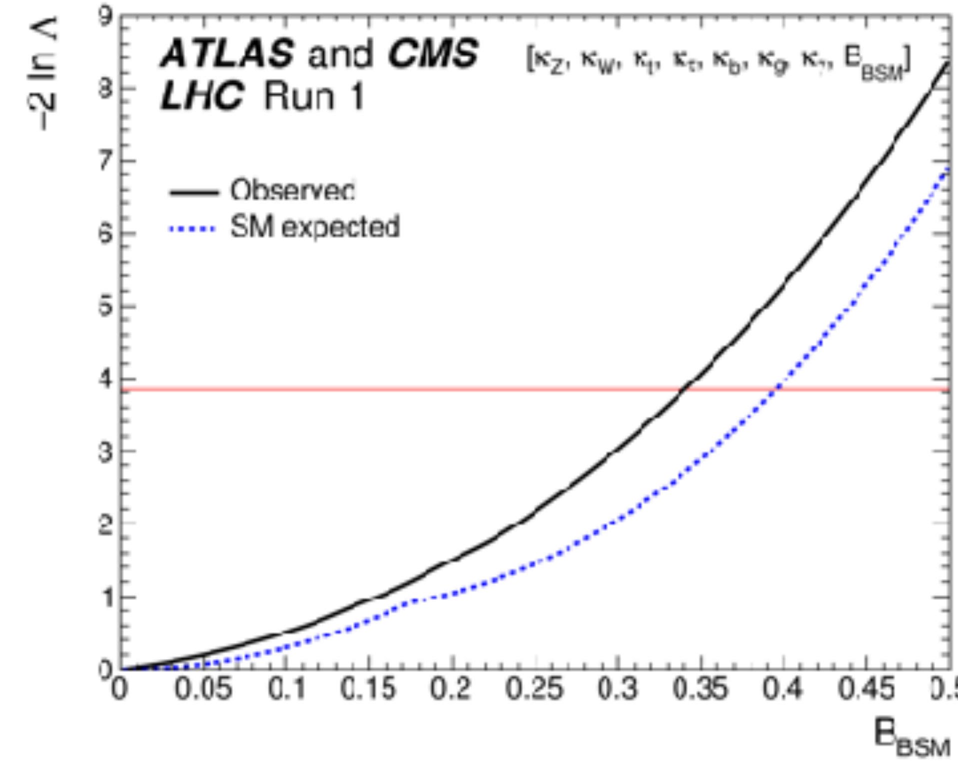
Limit on invisible branching ratio from global Higgs fit



- In Kappa framework for Run 1:
  BR < 0.34 at 95% CL
  (assumed kV < 1)

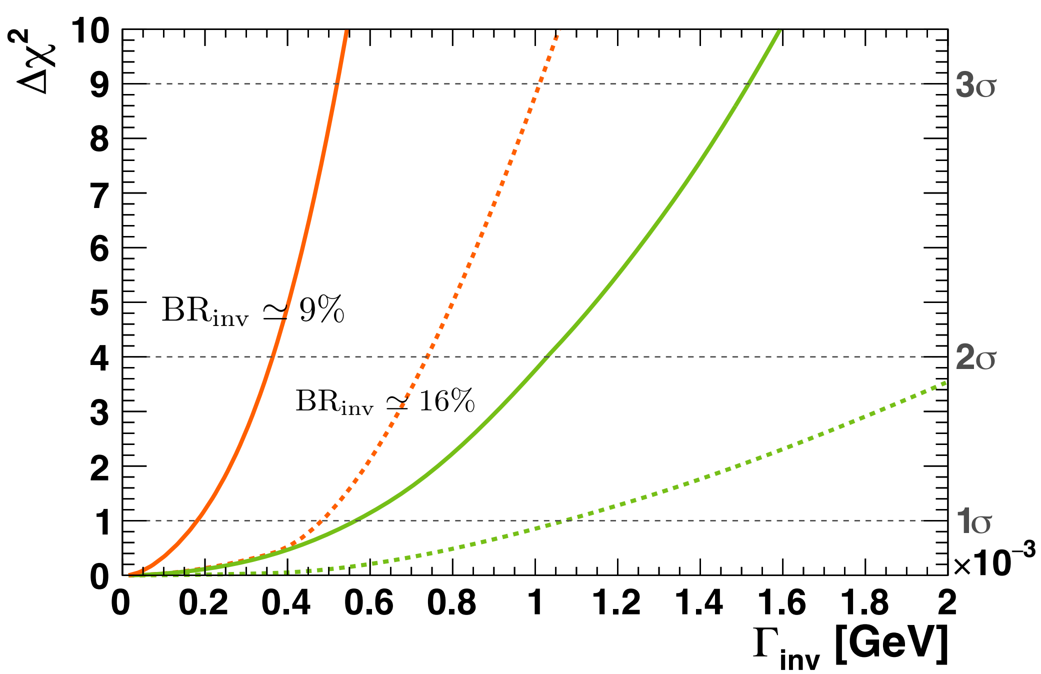
- Extend SM EFT by light degree of freedom, e.g. fermionic DM candidate

$$\mathrm{BR_{inv}} = \frac{\Gamma_{\rm inv}}{\Gamma_{\rm SM} + \Gamma_{\rm inv}}$$

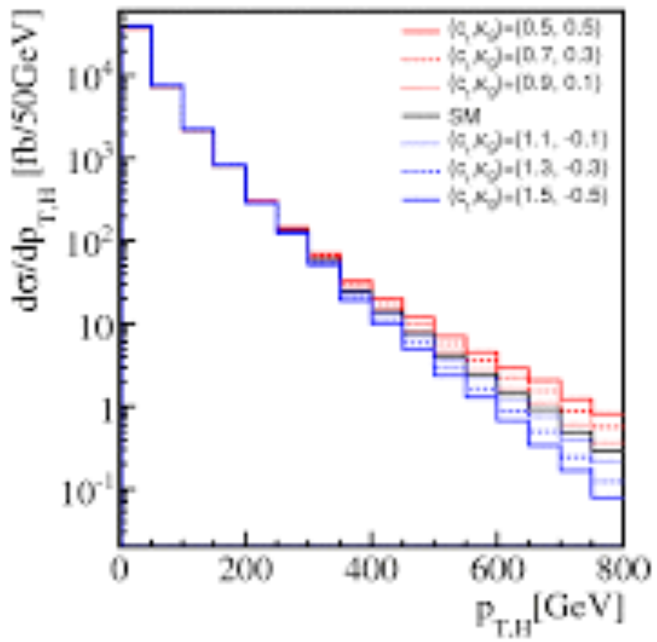
Flat reduction of event count in all channels

All/many operators need to conspire to compensate for loss in total rate

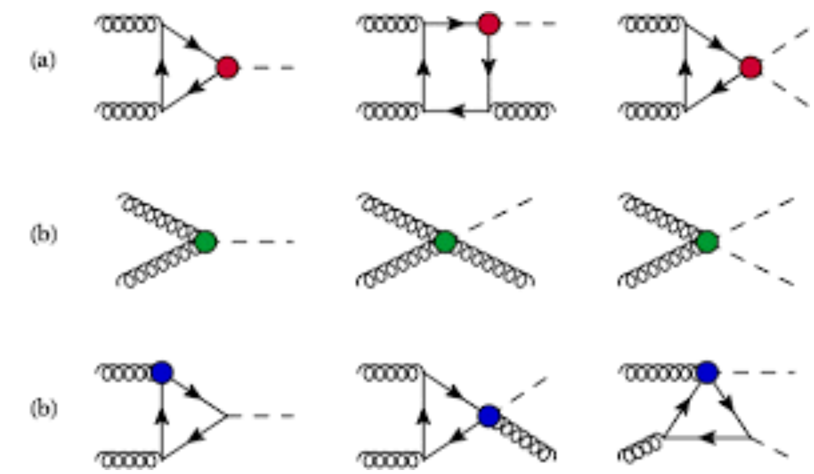
Most operators mom. dependent. Rate compensated by large increase in tail



orange/green = 3k/300 ifb sig. str. (dashed), pT (solid)



Summary



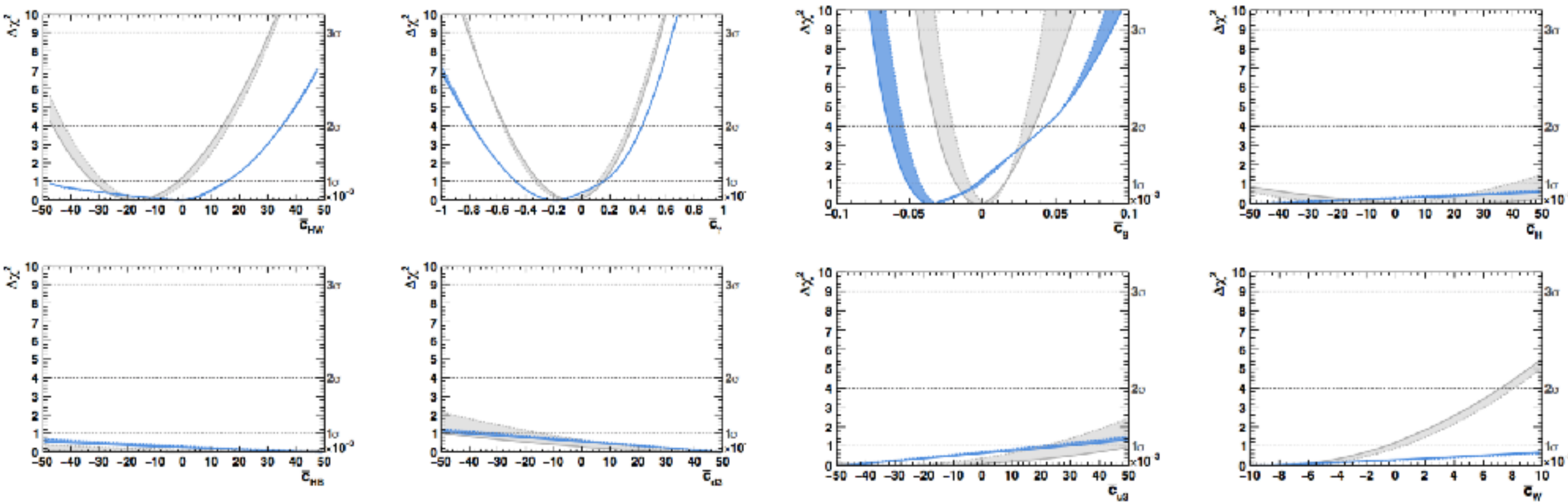
The LHC's high-energy regime will allow us to improve our understanding of nature using the well-defined framework of effective theories

Global fits allow to address most fundamental questions of HEP community, i.e. where can we improve effectively and efficiently

Most simplified models are EFTs
-> complexity of EFT affects our interpretation

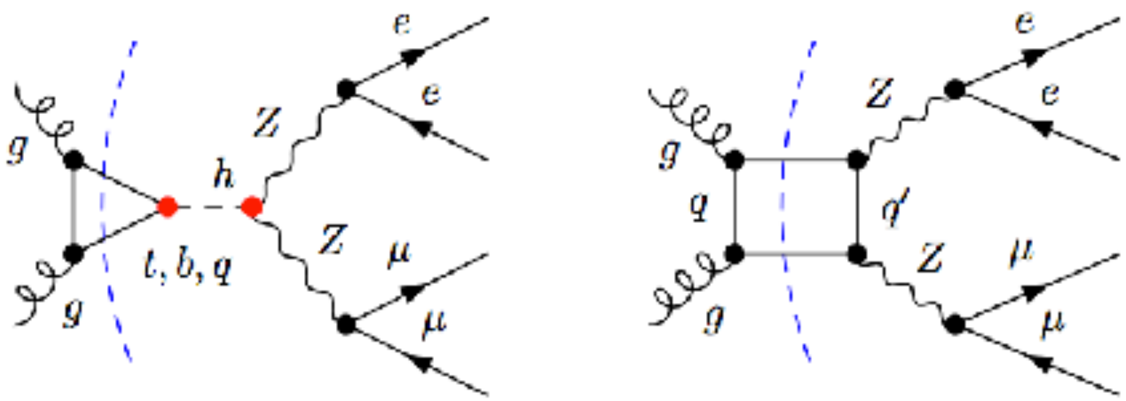
[McCullough, Englert, MS '16]

7/8 TeV signal strength fit result

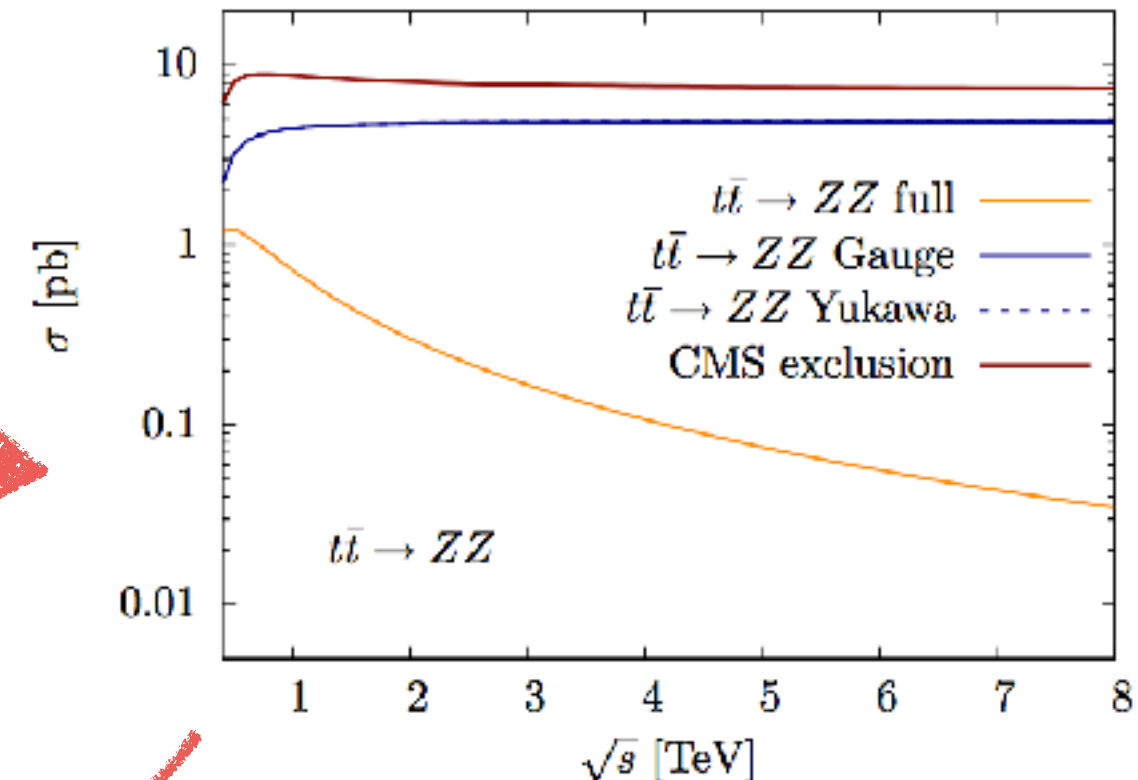


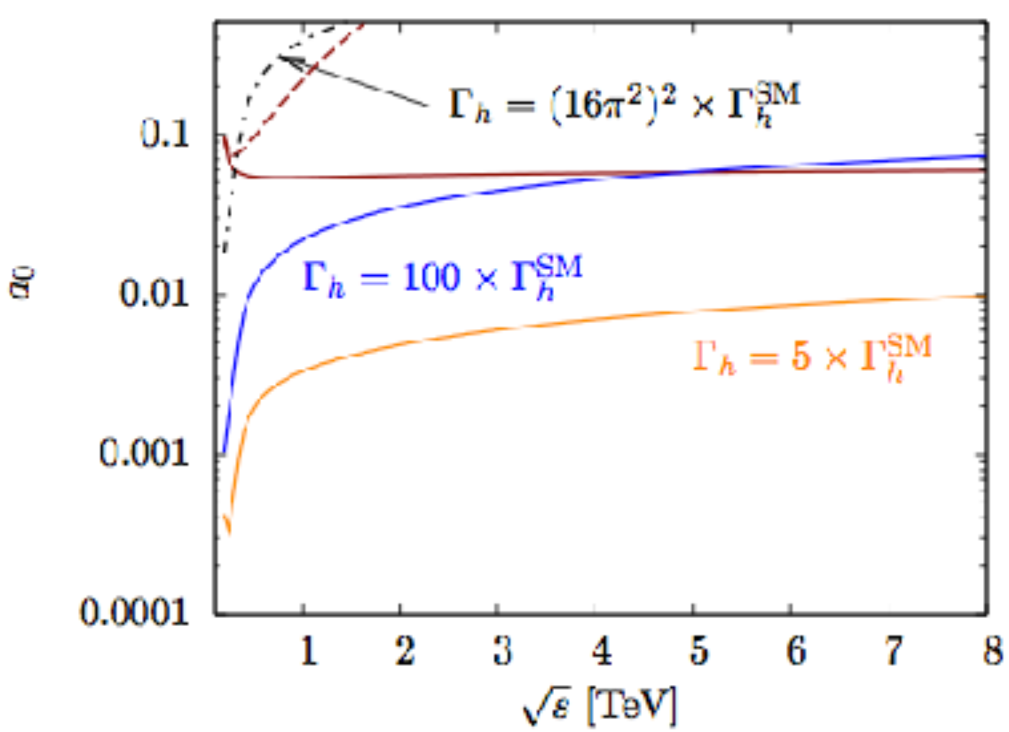
grey individual constraint   blue marginalised

1. Is measurement well defined?



modifying couplings violates unitarity
of fermion-gauge interactions





while CMS test-hypotheses
certainly ill-defined
not killer at accessible energies

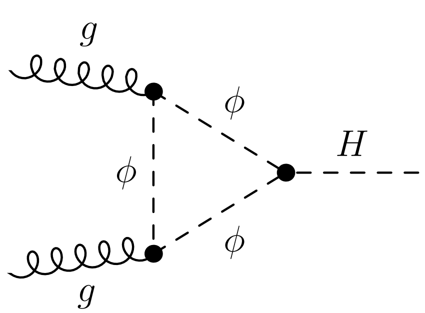
2. But how model independent is constraint?

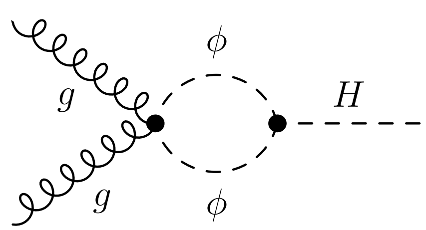
We have seen SM on-shell and off-shell region intimately related by unitarity requirements for fermion-gauge interactions

Direct correlation of on-shell $g_{ggh}^2\, g_{hZZ}^2$ and off-shell $g_{ggh}^2(\sqrt{s})\, g_{hZZ}^2(\sqrt{s})$

necessary ingredient for width measurement -> can be broken by BSM effects

Consider Higgs-portal (toy) model: $\mathcal{L}_\phi = |D_\mu \phi|^2 - \tilde{m}_\phi^2 |\phi|^2 - \lambda |\phi|^2 |H|^2 + \ldots .$





where ϕ scalar only charged under $\mathrm{SU}(3)_C$

$m_\phi^2 = \tilde{m}_\phi^2 + \lambda v^2$ free parameter

off-shell CS

m_ϕ	μ (h peak)	$\Gamma_h/\Gamma_h^{\mathrm{SM}}$	$\overline{\sigma}/\overline{\sigma}^{\mathrm{SM}}$ $[m(4\ell) \geq 330 \text{ GeV}]^a$
70 GeV	$\simeq 1.0$	$\simeq 5$	-2%
170 GeV	$\simeq 1.0$	$\simeq 4.7$	$+80\%$
170 GeV	$\simeq 1.0$	$\simeq 1.7$	$+6\%$

[a] We impose the cut set used by CMS [17] without the MELA cut [34].

$g_{ggh}(m_h) > g_{ggh,\mathrm{SM}} \longrightarrow \Gamma > \Gamma_{\mathrm{SM}}$ for $\mu \sim 1$

Despite increased on-shell coupling (and Higgs width) negligible contribution in off-shell region

Note, shown here only simplest toy model