  

Higgs EFT Fits at the LHC

in collaboration with
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[1511.05170]

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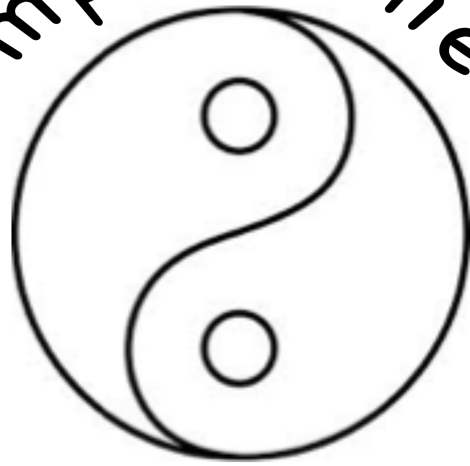
IPPP, Durham University

Compositeness



Effective Theory

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

Symmetry

SUSY, CW, ...

Naturalness

fermionic top partners

simplified models

scalar top partners

simplified models

Jets

Leptons

Measurements

width

MET

interference

mass

Photons

boost

Improved/Unified way of interpretation of measurements

- interpretation of any measurement model dependent
- 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

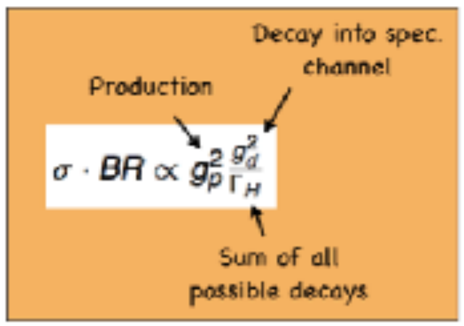
Kappa framework

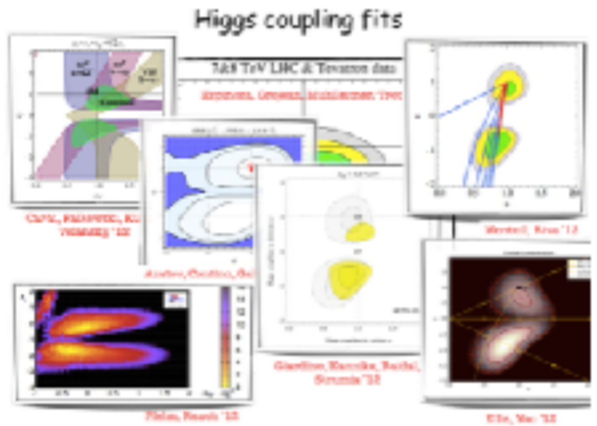
kappa is ratio of couplings:

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

so-called

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

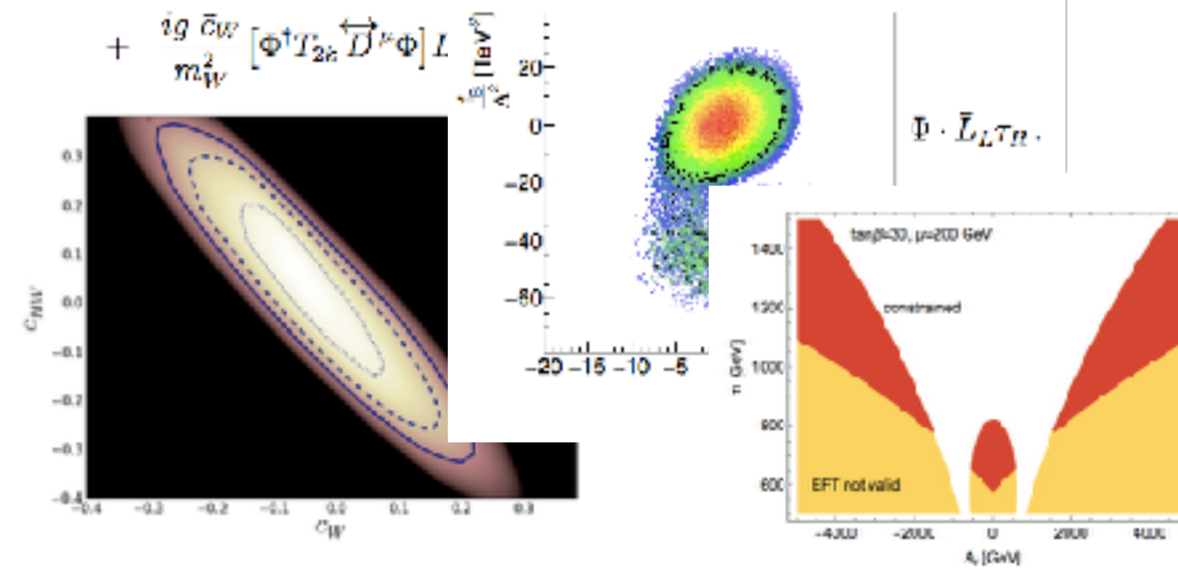




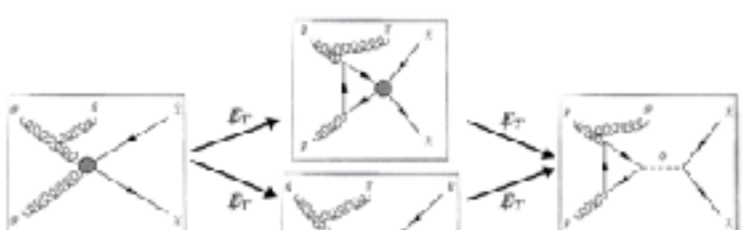
- try to over-constrain couplings basis
- Higgs width of particular importance

EFT framework

$$\mathcal{L} \supset \frac{\bar{c}_H}{2v^2}\partial^\mu[\Phi^\dagger\Phi]\partial_\mu[\Phi^\dagger\Phi] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu}$$
$$+ \frac{2ig\,\bar{c}_{HW}}{m_W^2}[D^\mu\Phi^\dagger T_{2k}D^\nu\Phi]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}[D^\mu\Phi^\dagger D^\nu\Phi]B_{\mu\nu}$$
$$+ \frac{ig\,\bar{c}_W}{m_W^2}[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi]\,L \quad \Phi\cdot\bar{L}_L\tau_R\,.$$



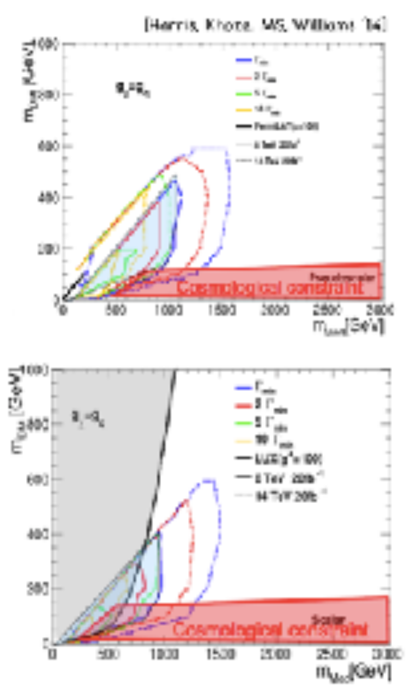
Simplified models



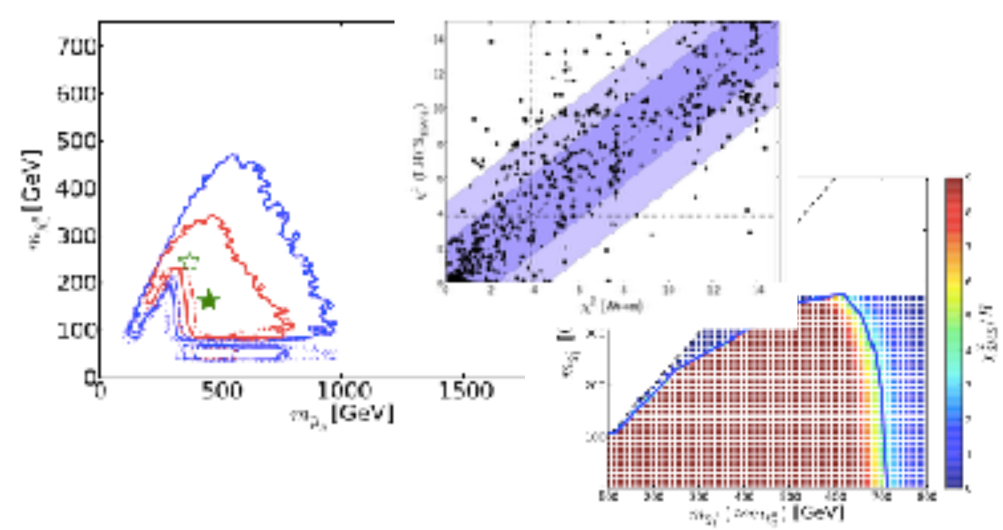
[Buckley, Feld, Goncalves '14]
[Harris, Khoze, MS, Williams '14]

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

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



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

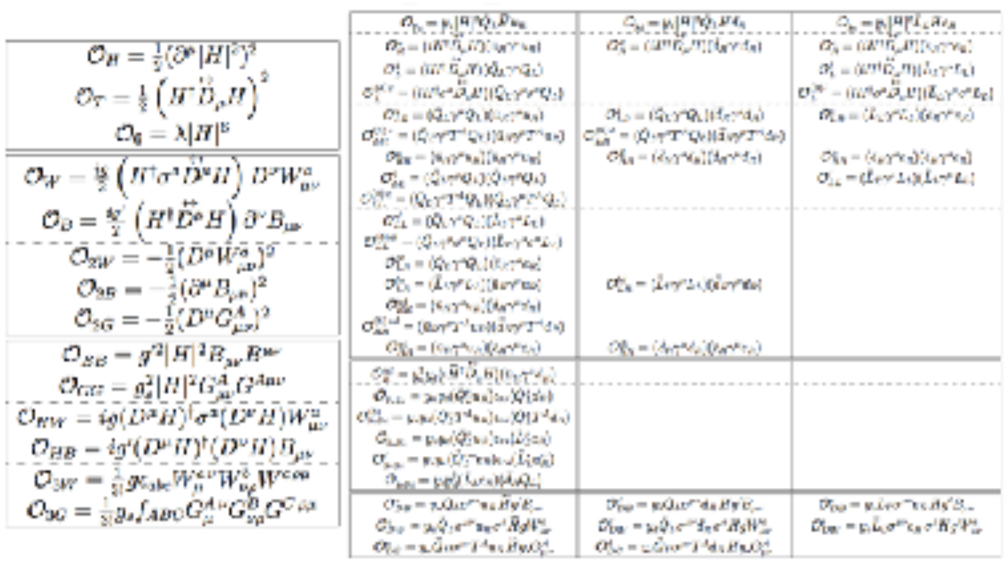
Basis and choice of operators to consider

Agnostic operator basis highly complex:

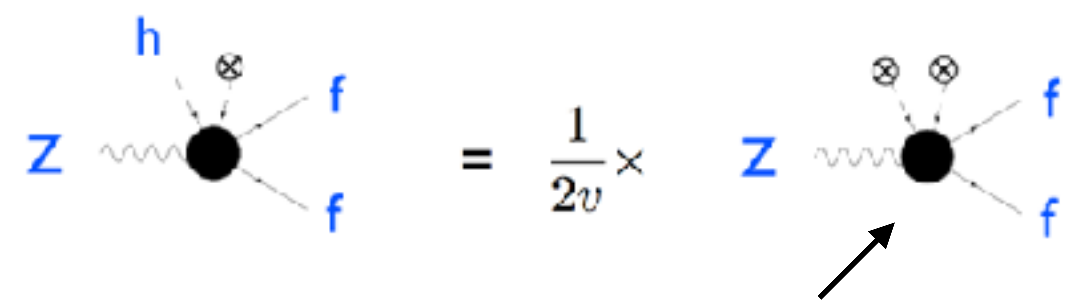
2499 non-redundant parameters at dim-6

Flavor diagonal still complex:

59 operators



- 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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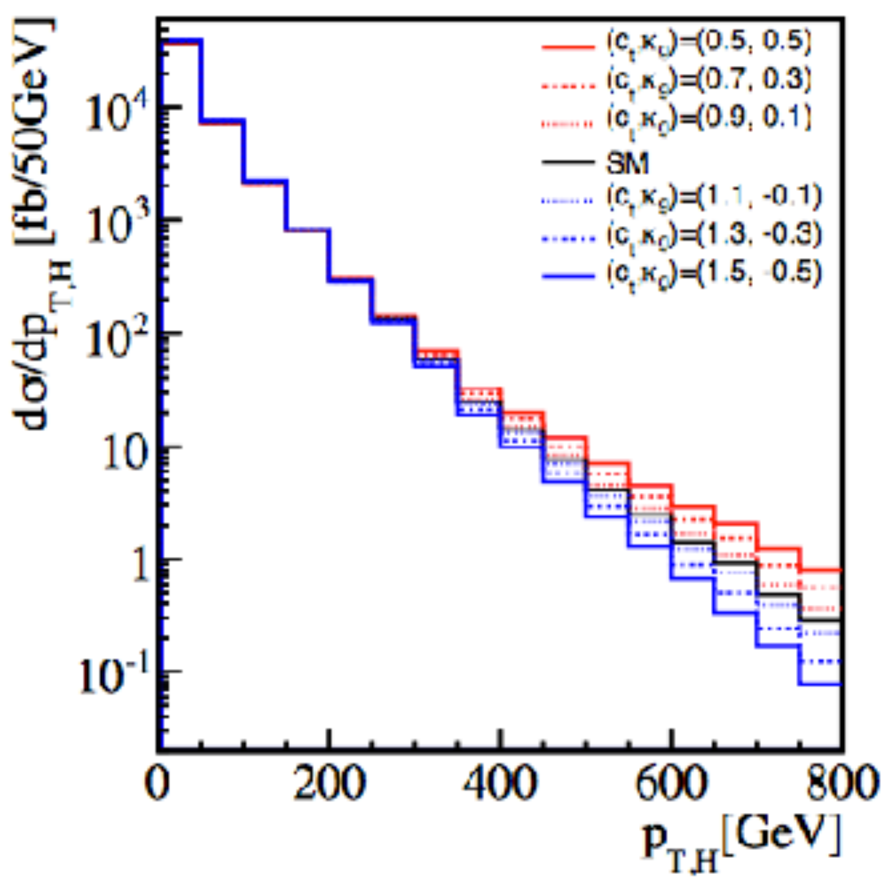
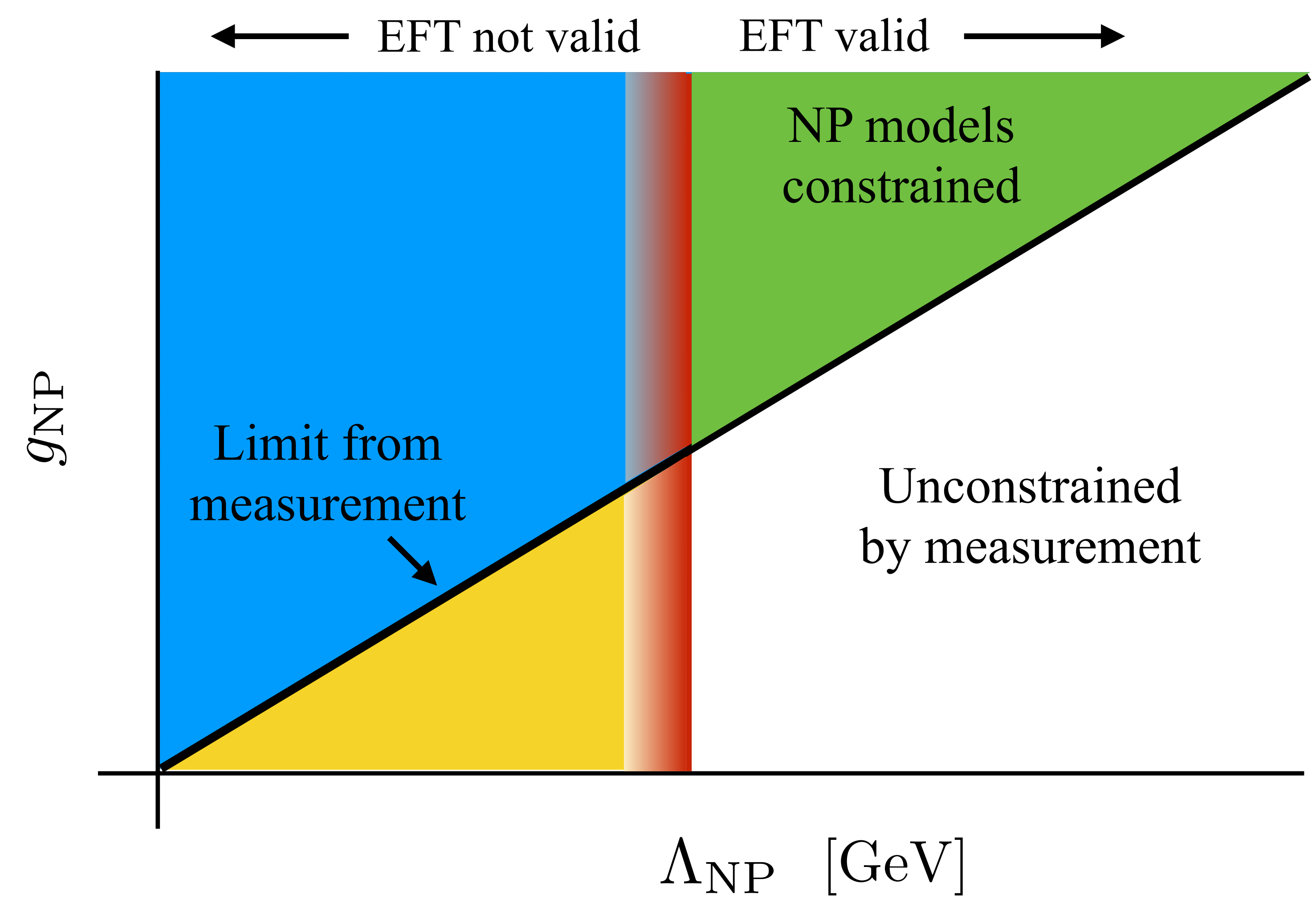
[Englert, MS 1408.5147]





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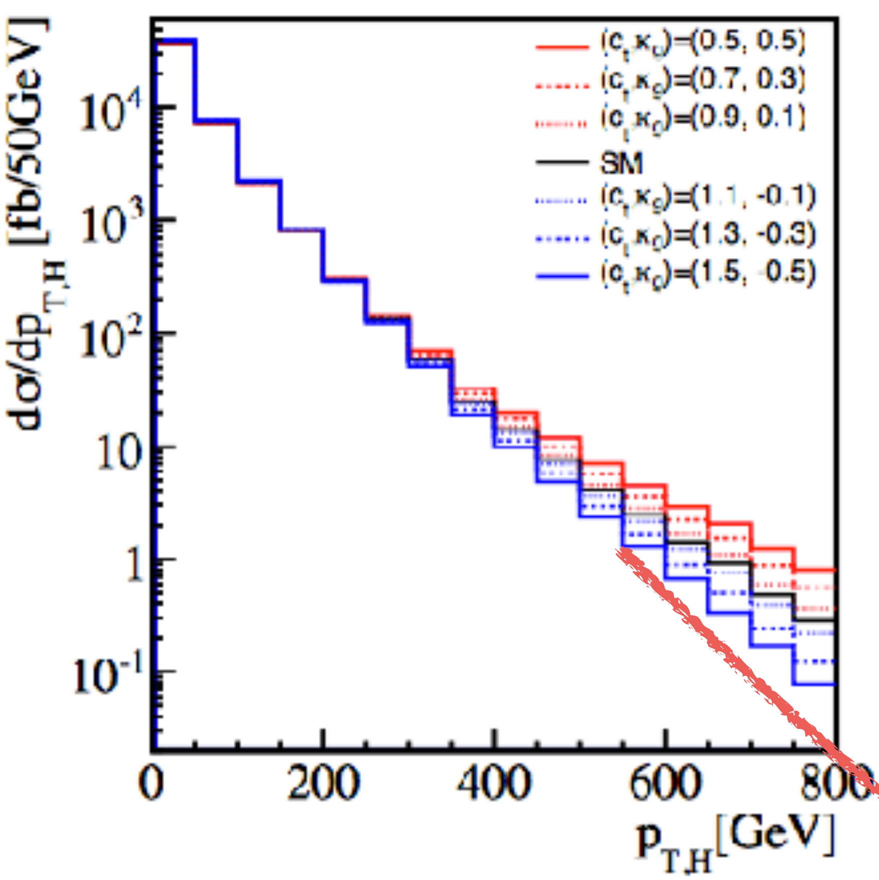

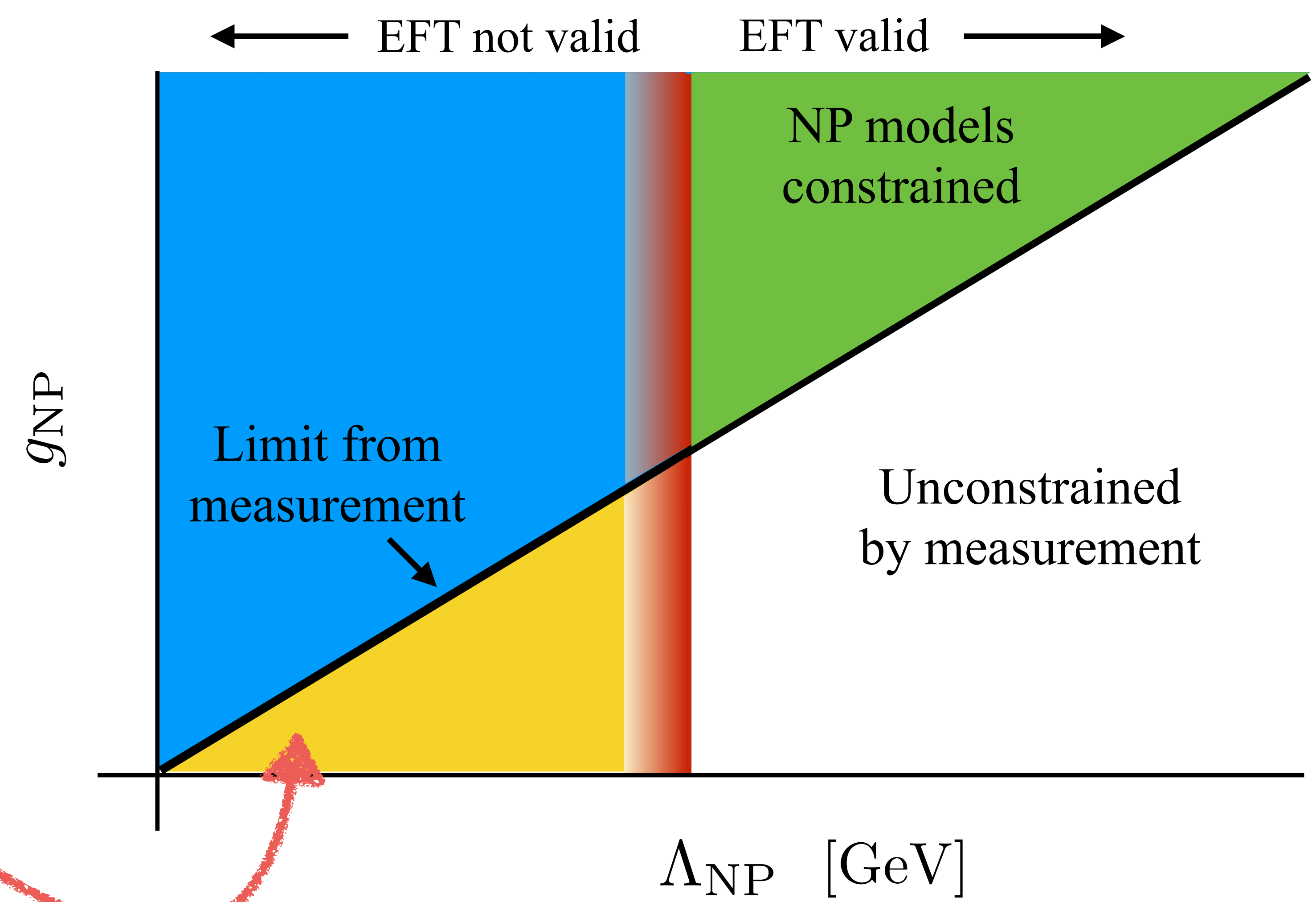

shape sets limit on Wilson coefficient (black line)

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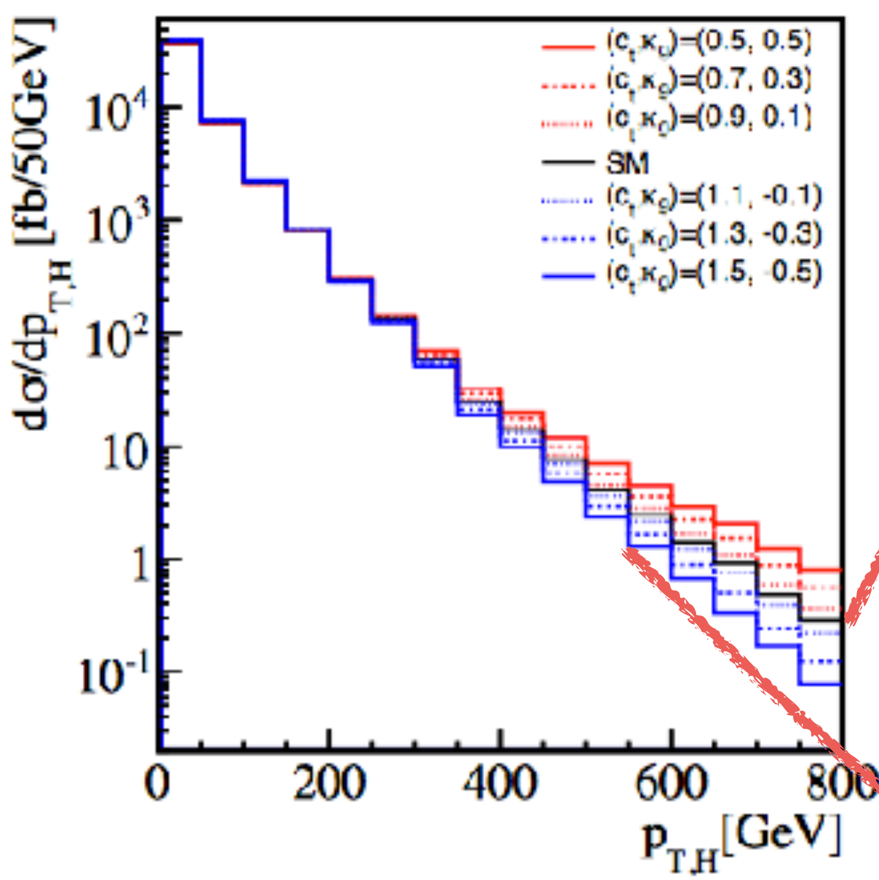
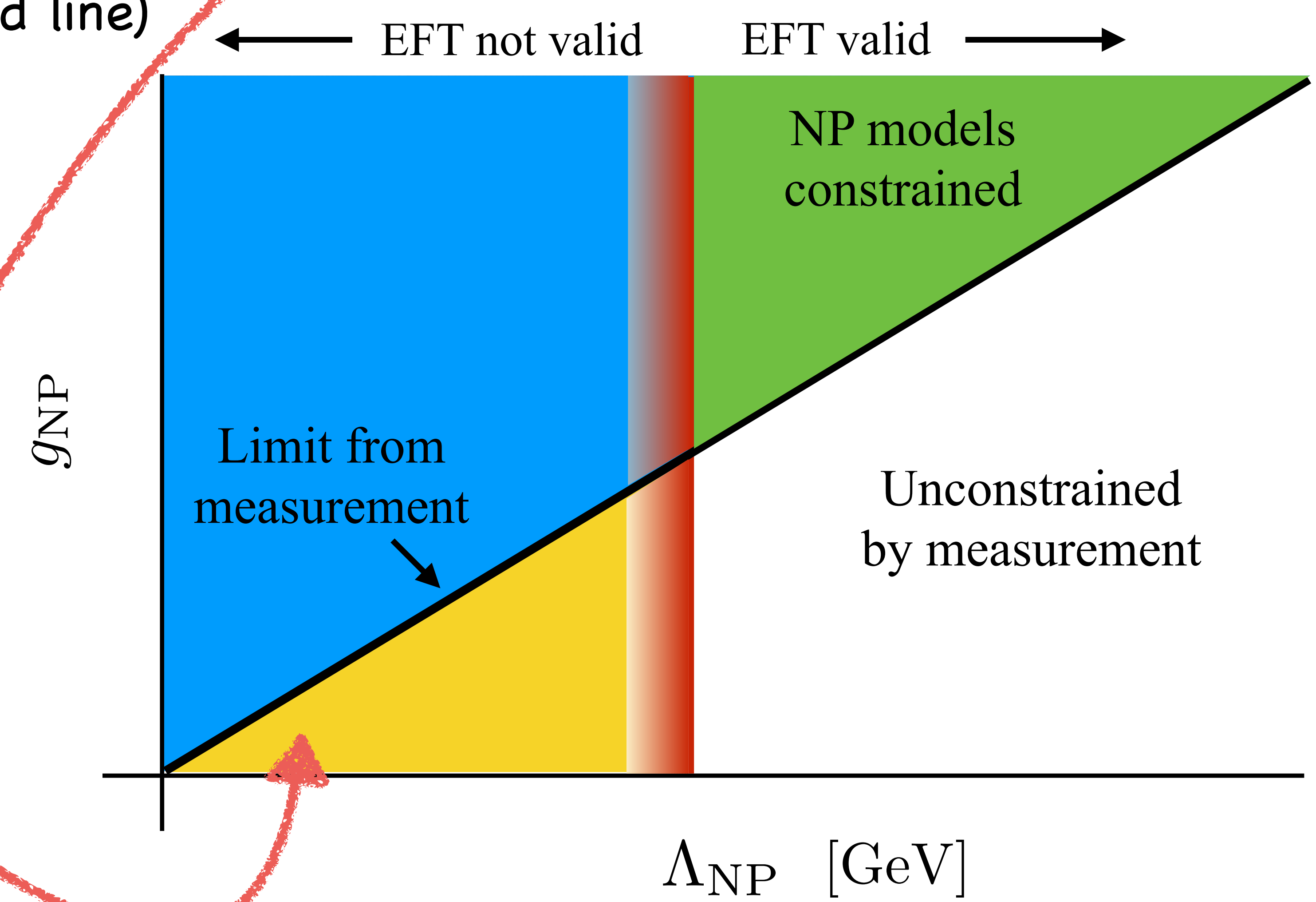
Endpoint of kinematic distribution sets lower cut-off for NP (red line)

[Englert, MS 1408.5147]





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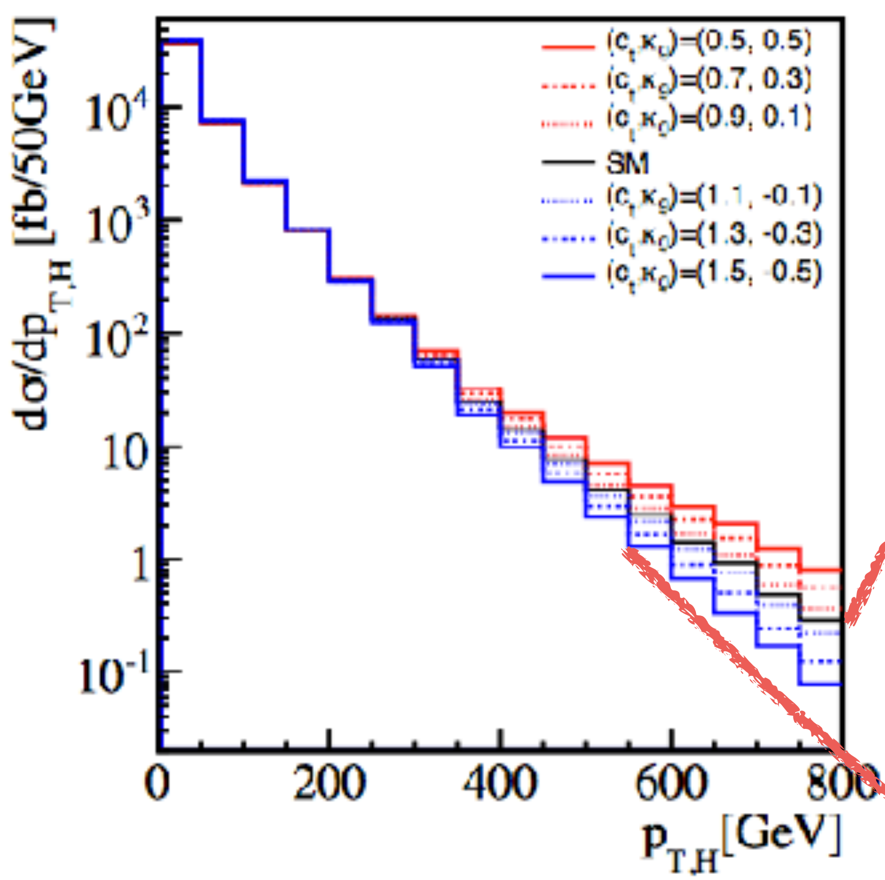
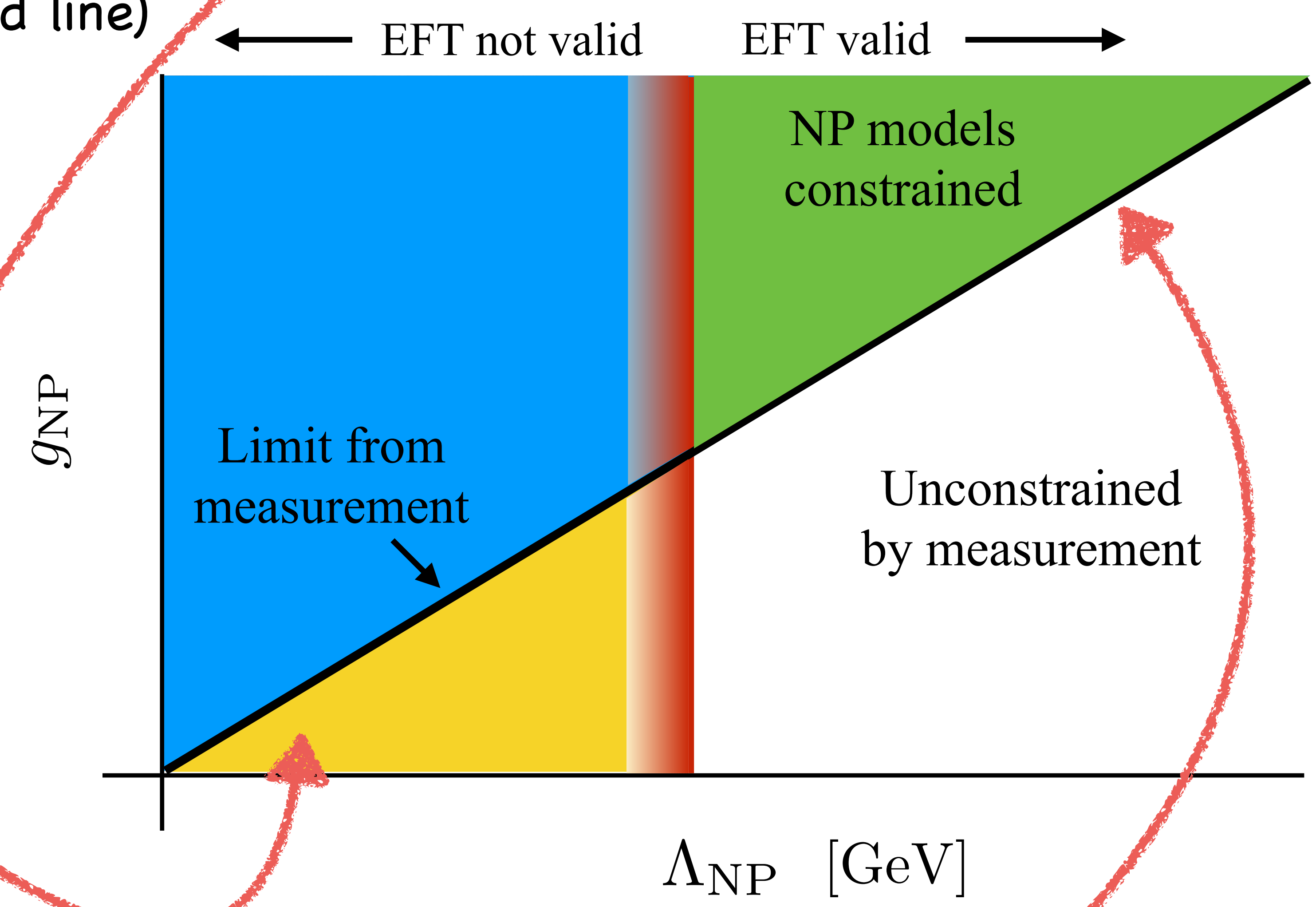
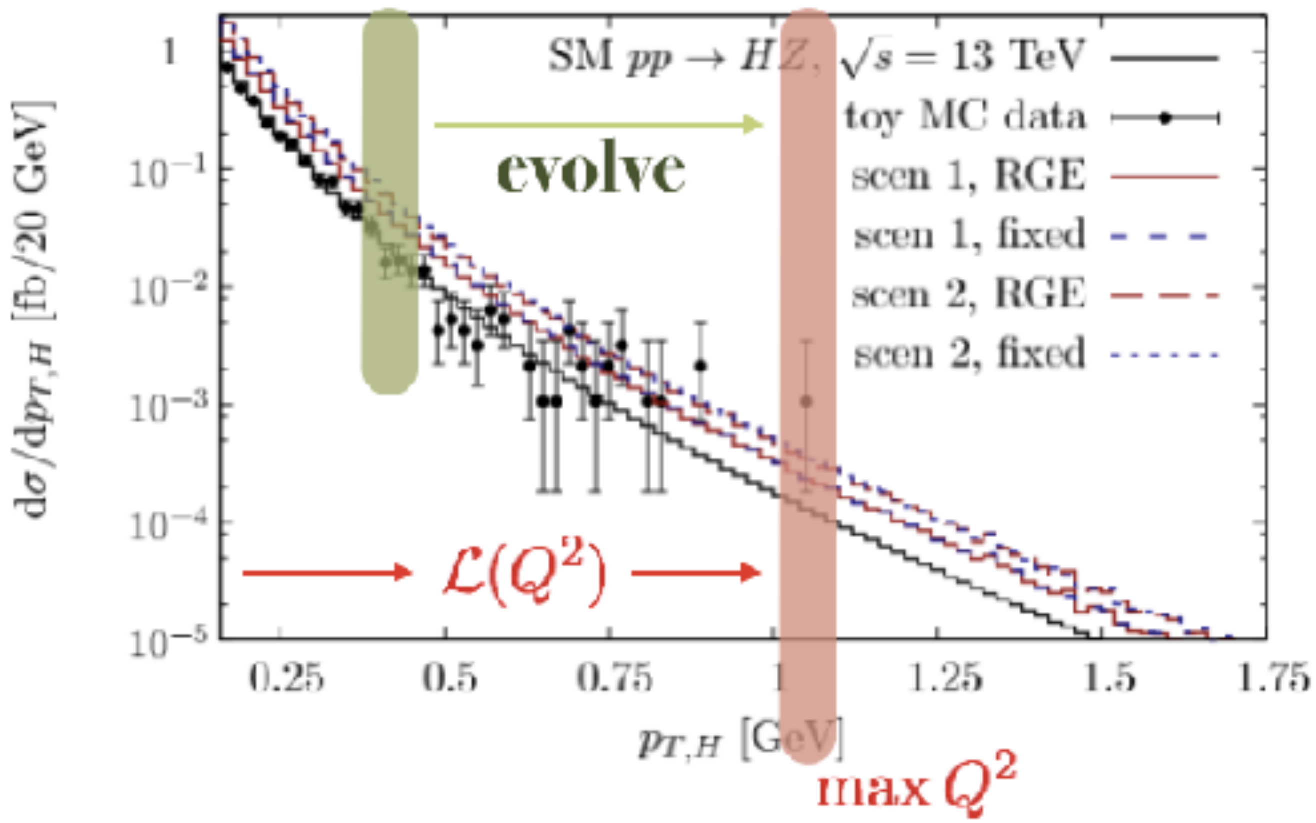




shape sets limit on Wilson coefficient (black line)

Any UV (weakly coupled) models left?



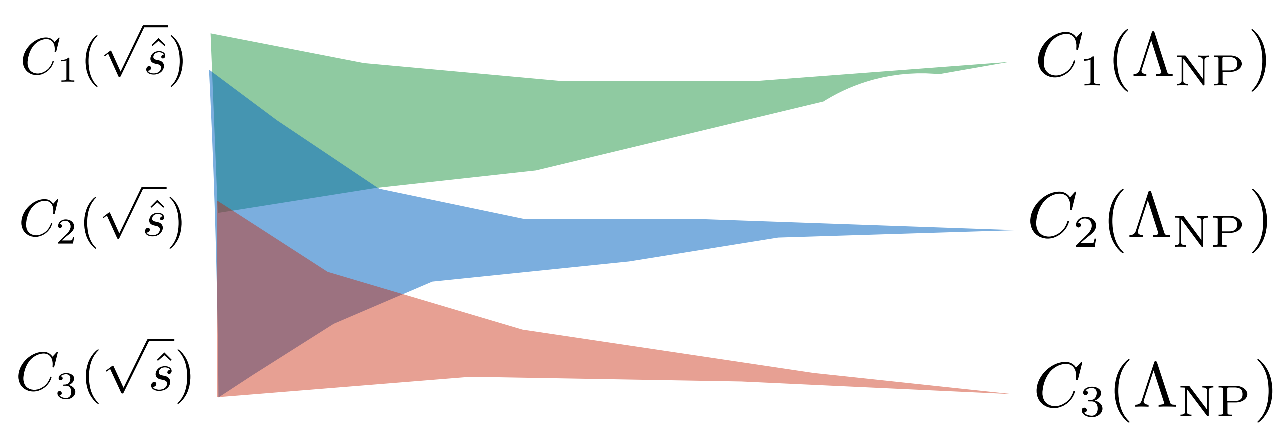
- scale hierarchies similar to flavor physics mW/mb~20
- evolution from renormalization group equations
  [Grojean, Jenkins, Manohar, Trott '13]
  [Jenkins, Manohar, Trott '13]
  [Elias-Miro et al '13]
- consistent interpretation requires **communication of resolved scales**

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

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

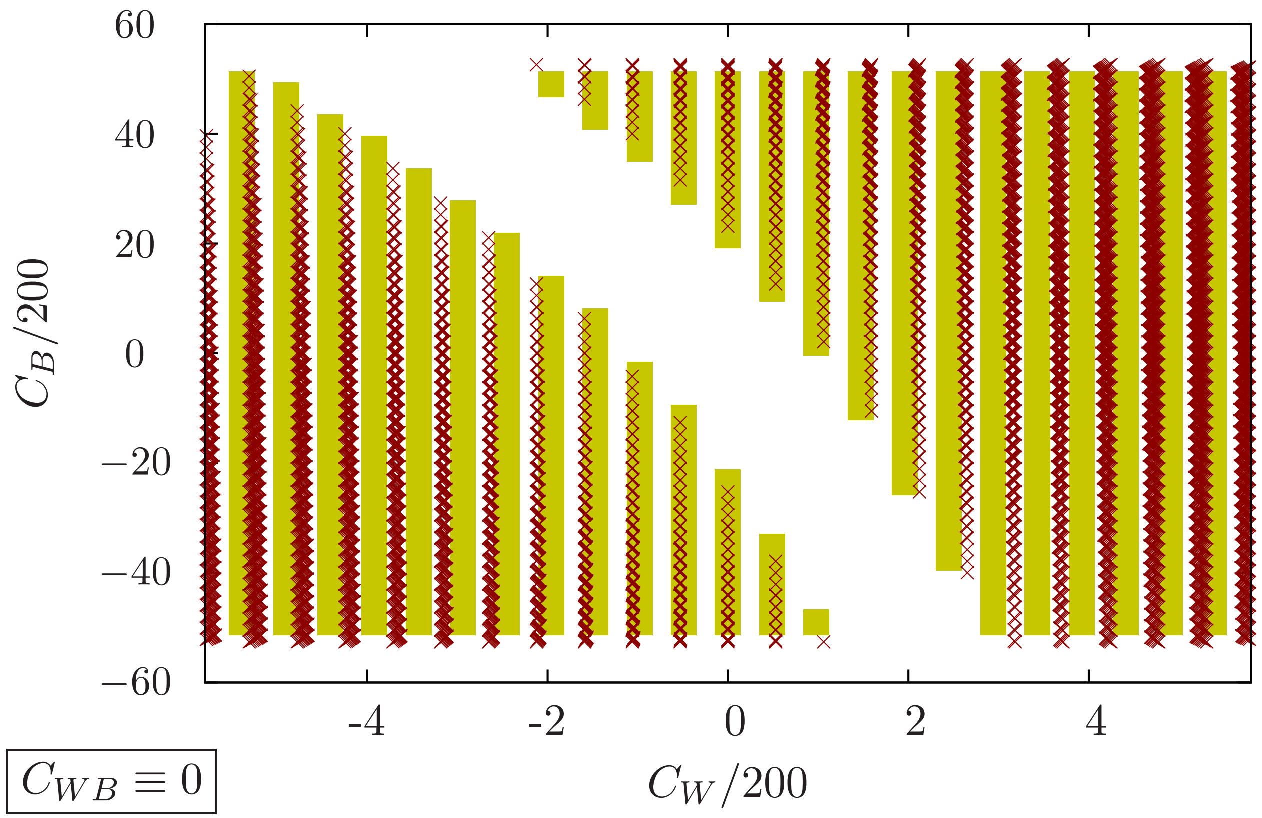
As a result, each measured **event** probes a different combination of operators

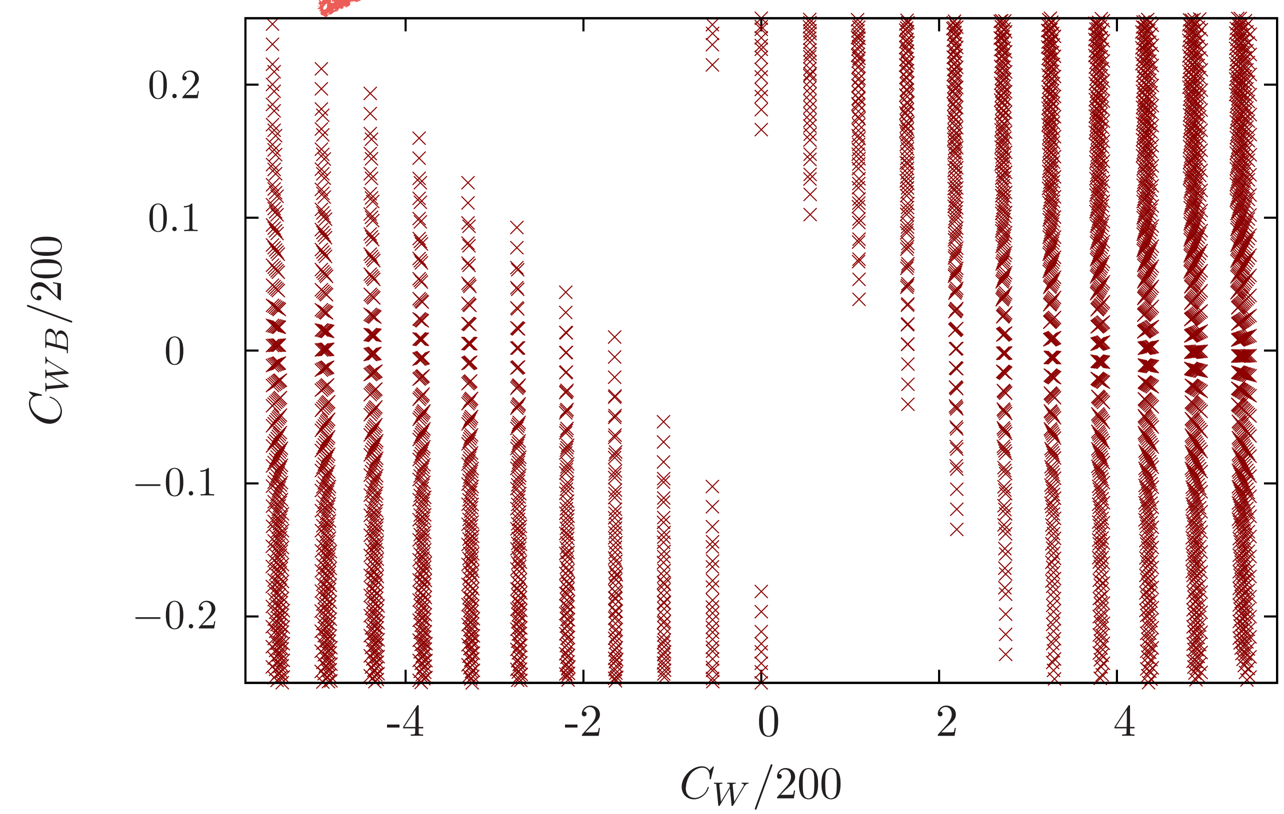
measurement at characteristic scale of event



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]

<u>Focus on linear contribution of EFT for theory prediction:</u>

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

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

<u>Number of predicted events:</u>

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

We assume that production and decay factorise to good approximation

<u>Each channel has own prod. and decay efficiencies:</u>

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

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

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

signal strength:

36 indep. meas. (300 ifb)

46 indep. meas. (3000 ifb)

differential:

88 indep. meas. (300 ifb)

123 indep. meas. (3000 ifb)

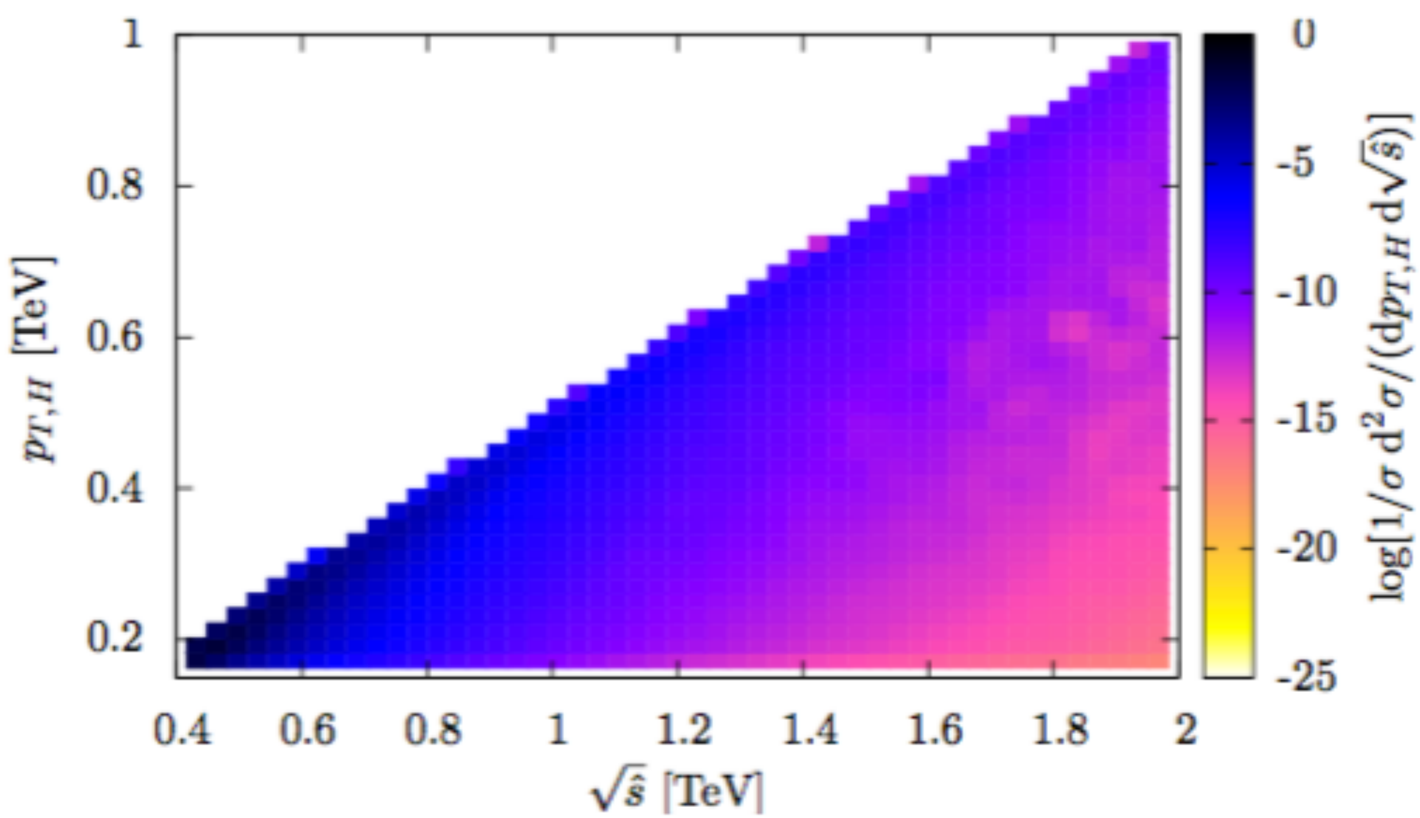
To show benefit of differential distribution need observable

- 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

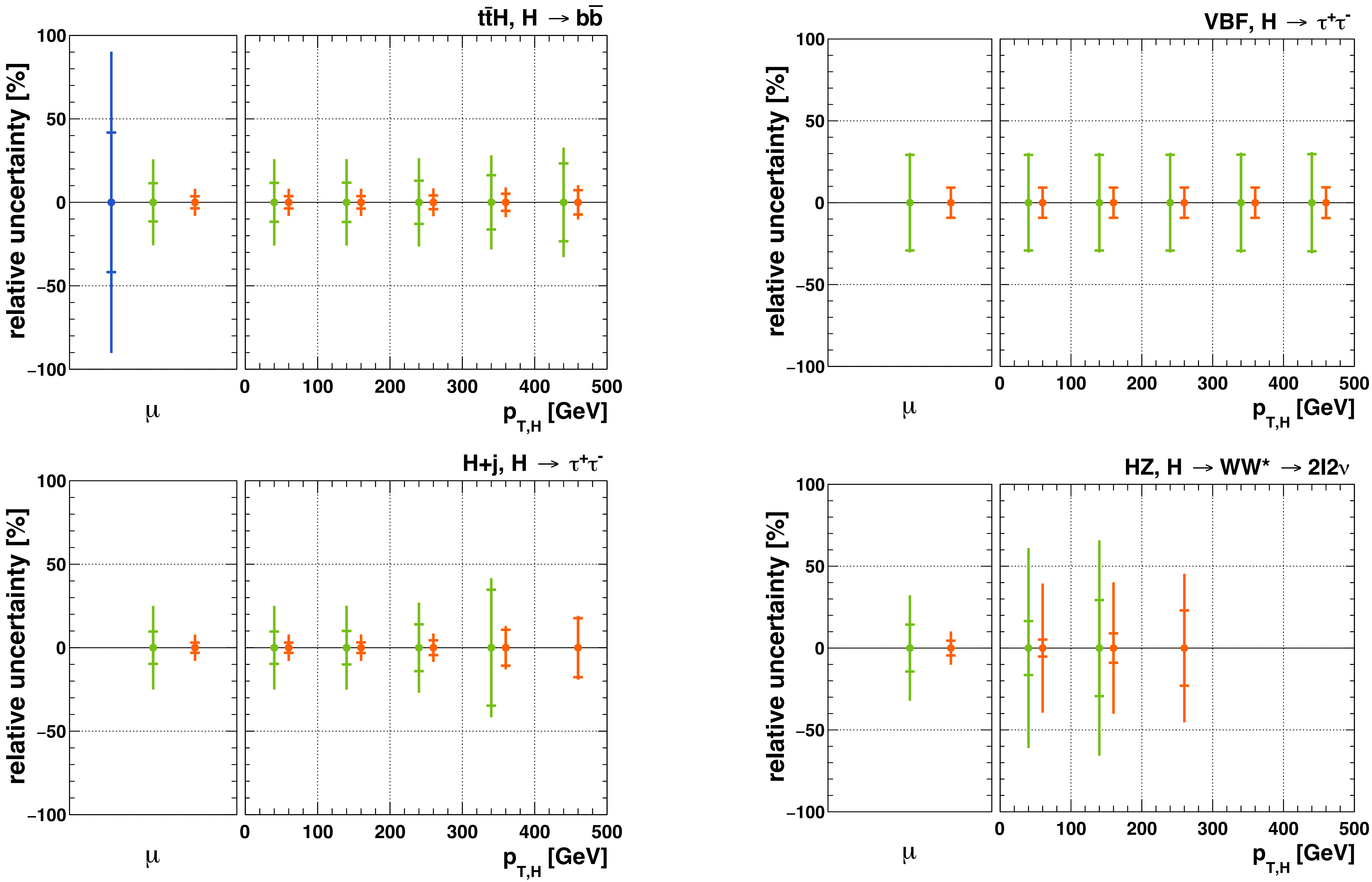
	$t\bar{t}H$	HZ	HW	H incl.	$H + \mathrm{j}$	$H + 2\mathrm{j}$
$H \to b\bar{b}$	80	25	40	100	100	150
$H \to \gamma\gamma$	60	70	30	10	10	20
$H \to \tau^+\tau^-$	100	75	75	80	80	30
$H \to 4l$	70	30	30	20	20	30
$H \to 2l2\nu$	70	100	100	20	20	30
$H \to Z\gamma$	100	100	100	100	100	100
$H \to \mu^+\mu^-$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

rel. syst. uncertainty in %

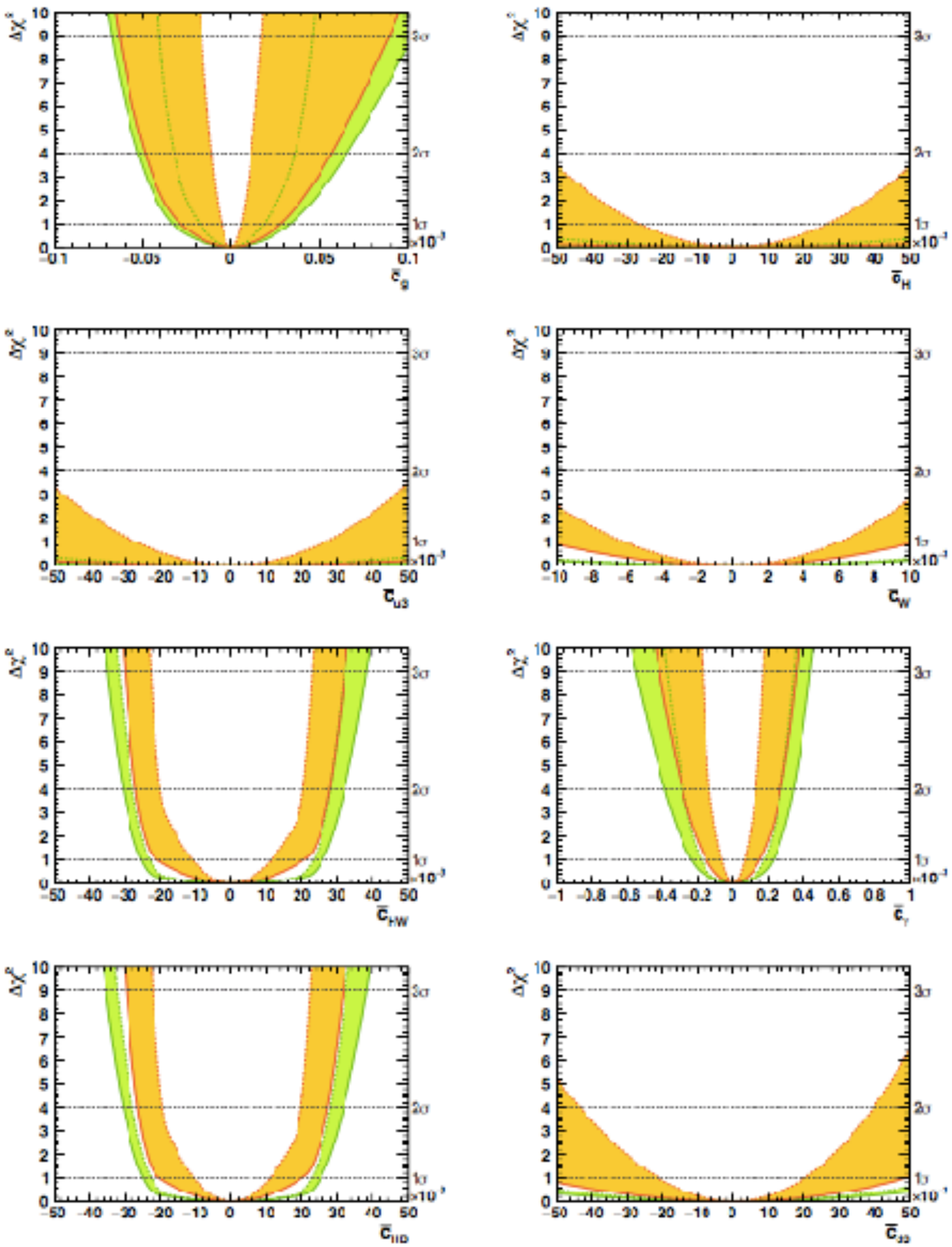
statistical uncertainties

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

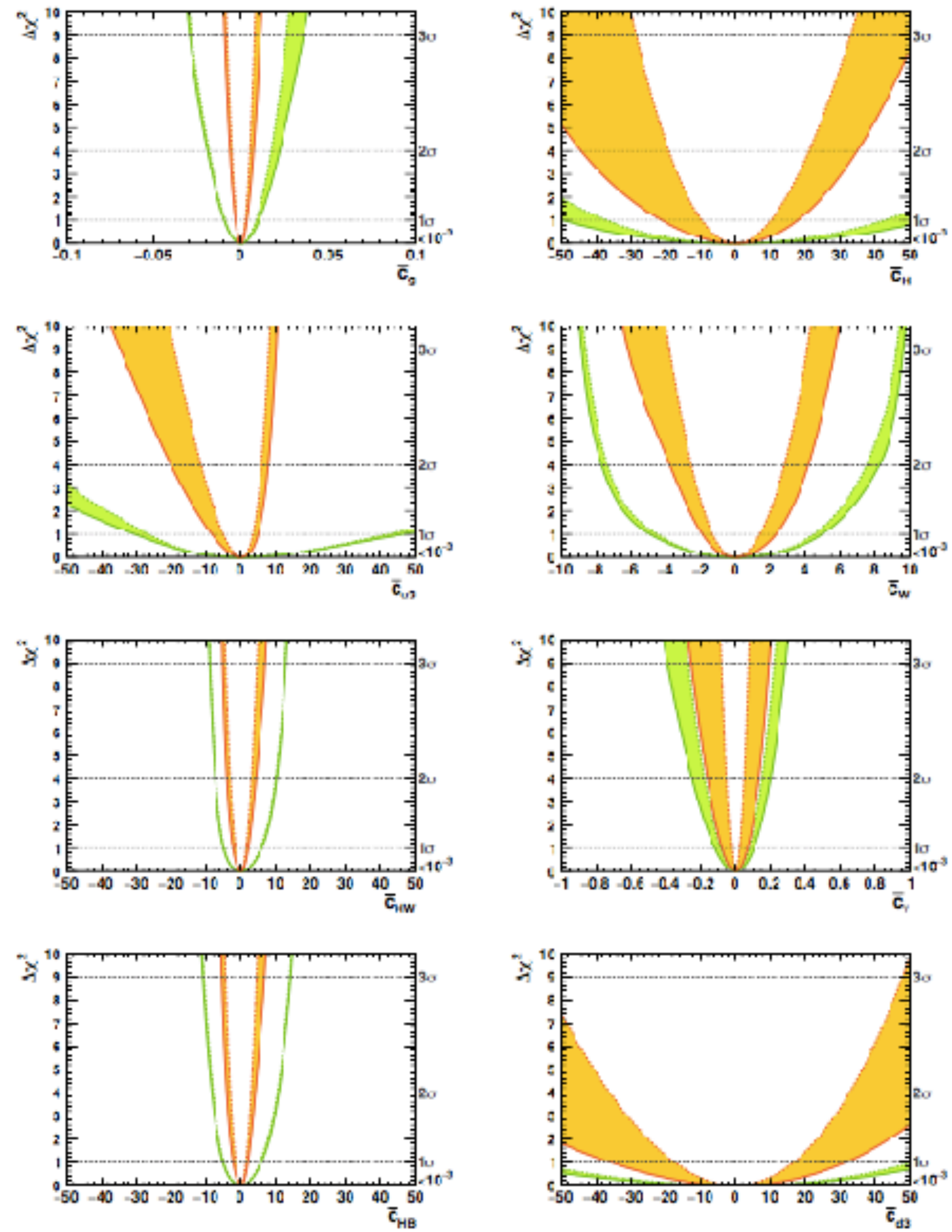
We generated pseudo-data for the extrapolation to 300 and 3000 ifb



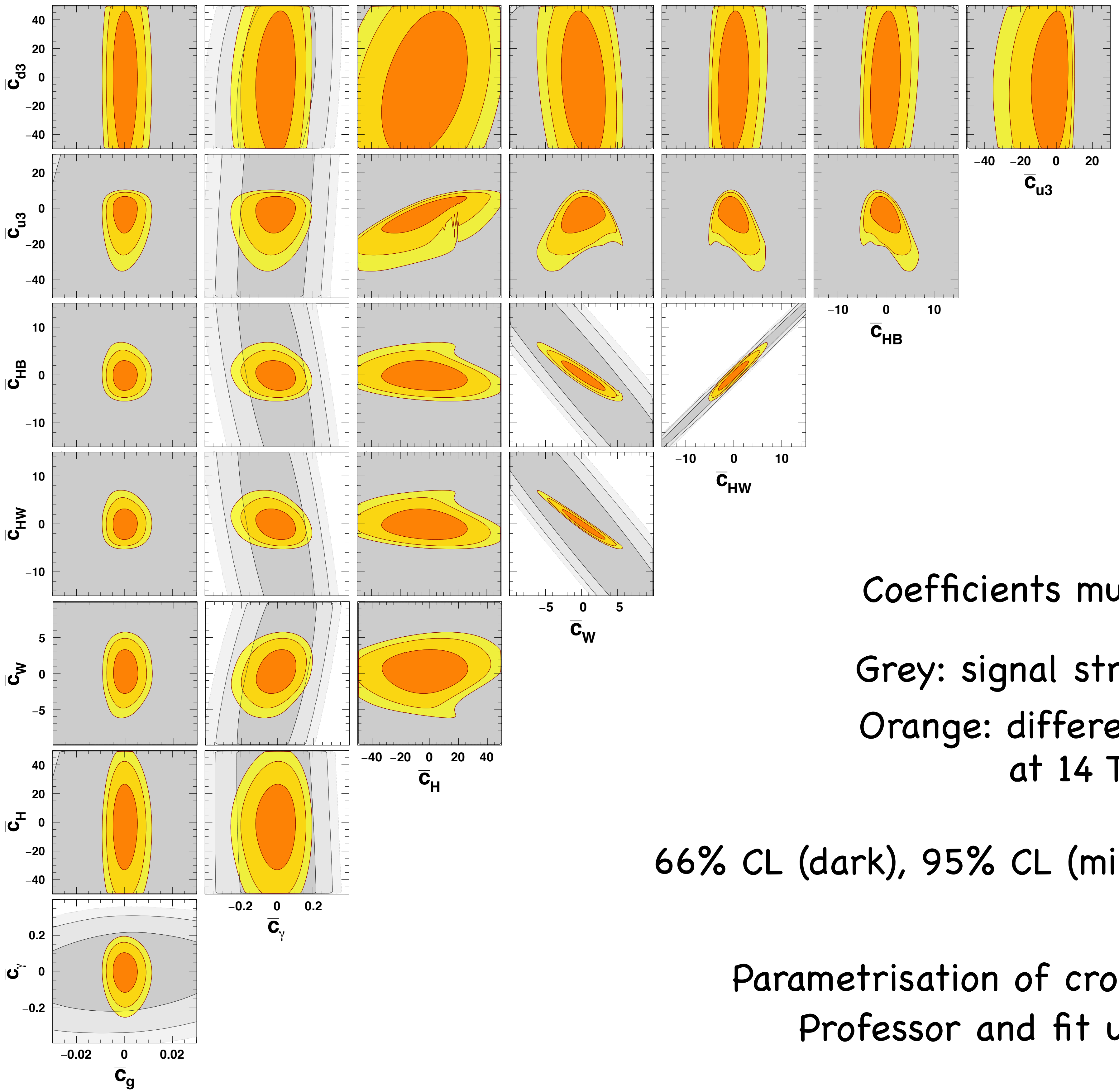
signal strength measurement



differential measurement



green = 300 ifb   orange = 3000 ifb



Coefficients multiplied by 10^3

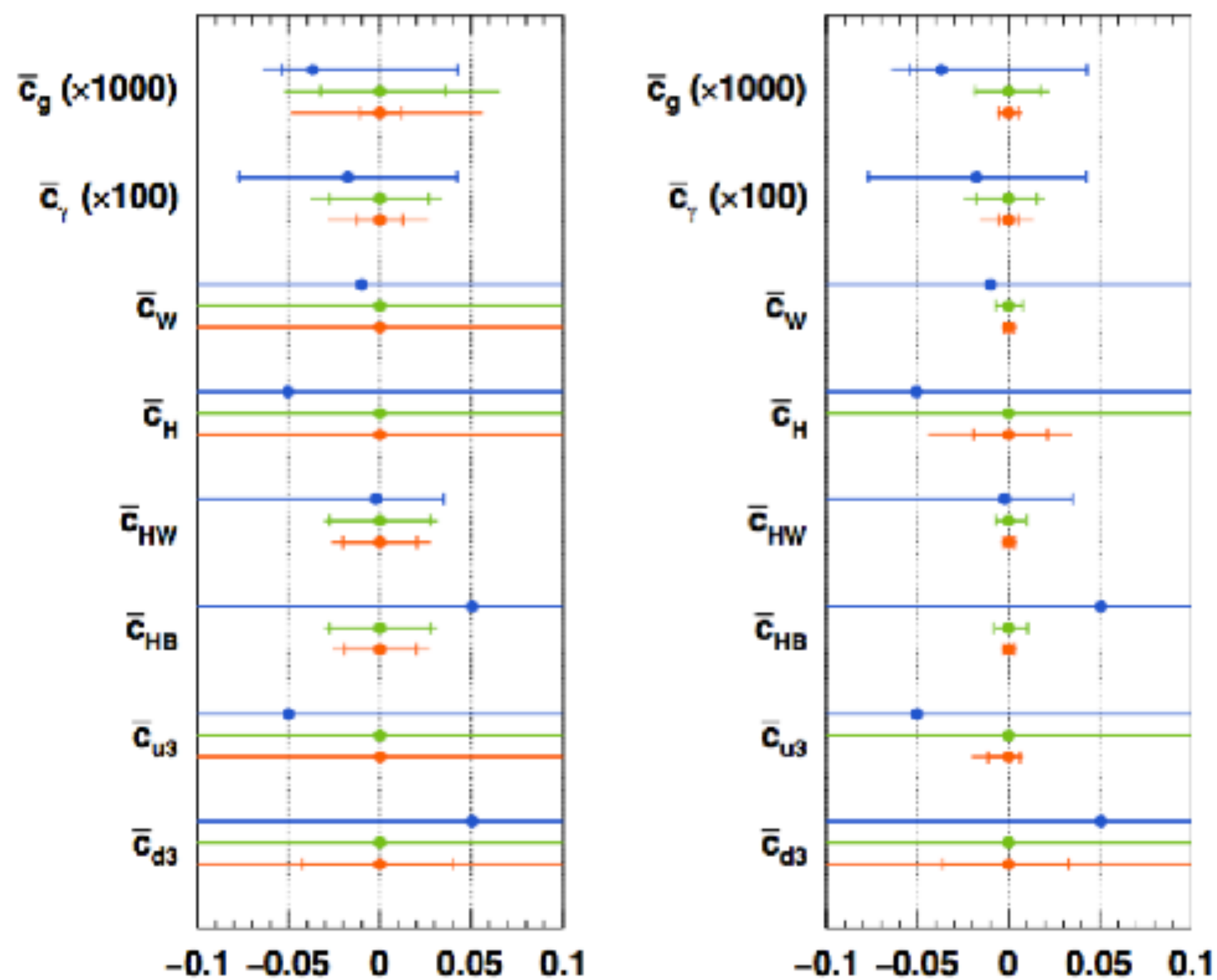
Grey: signal strength only

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:

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

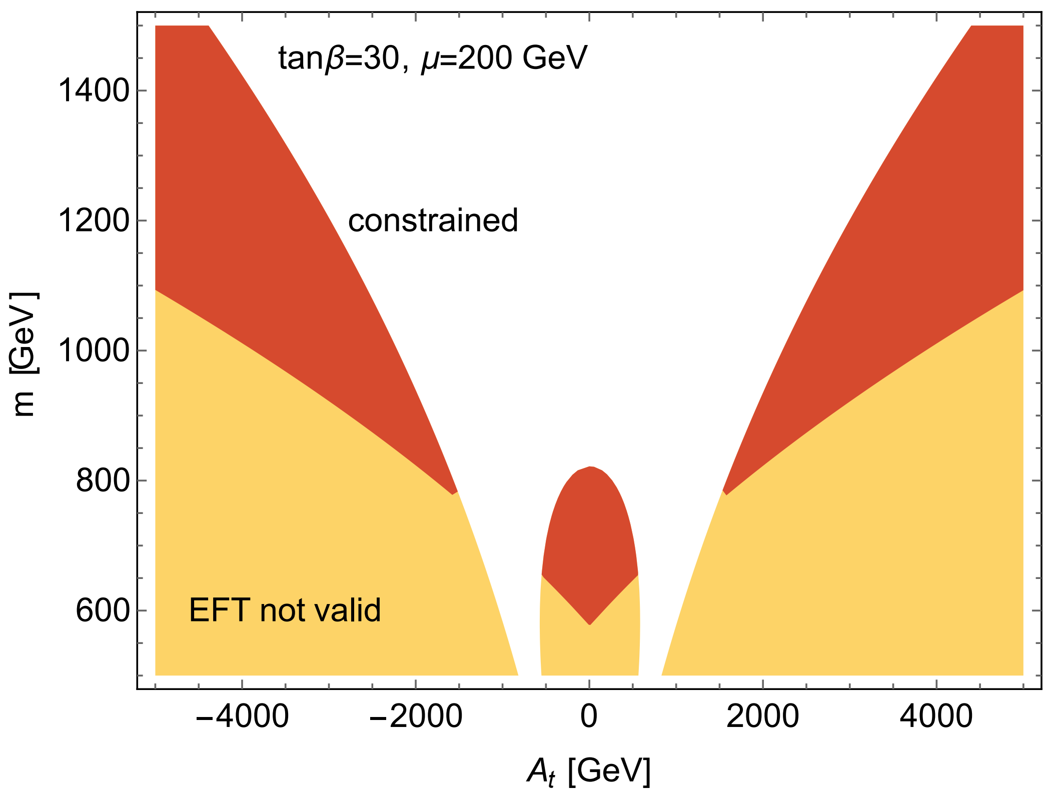
$$m_{\tilde{Q}} = m_{\tilde{t}} = m$$

$$\tan\beta = 30$$

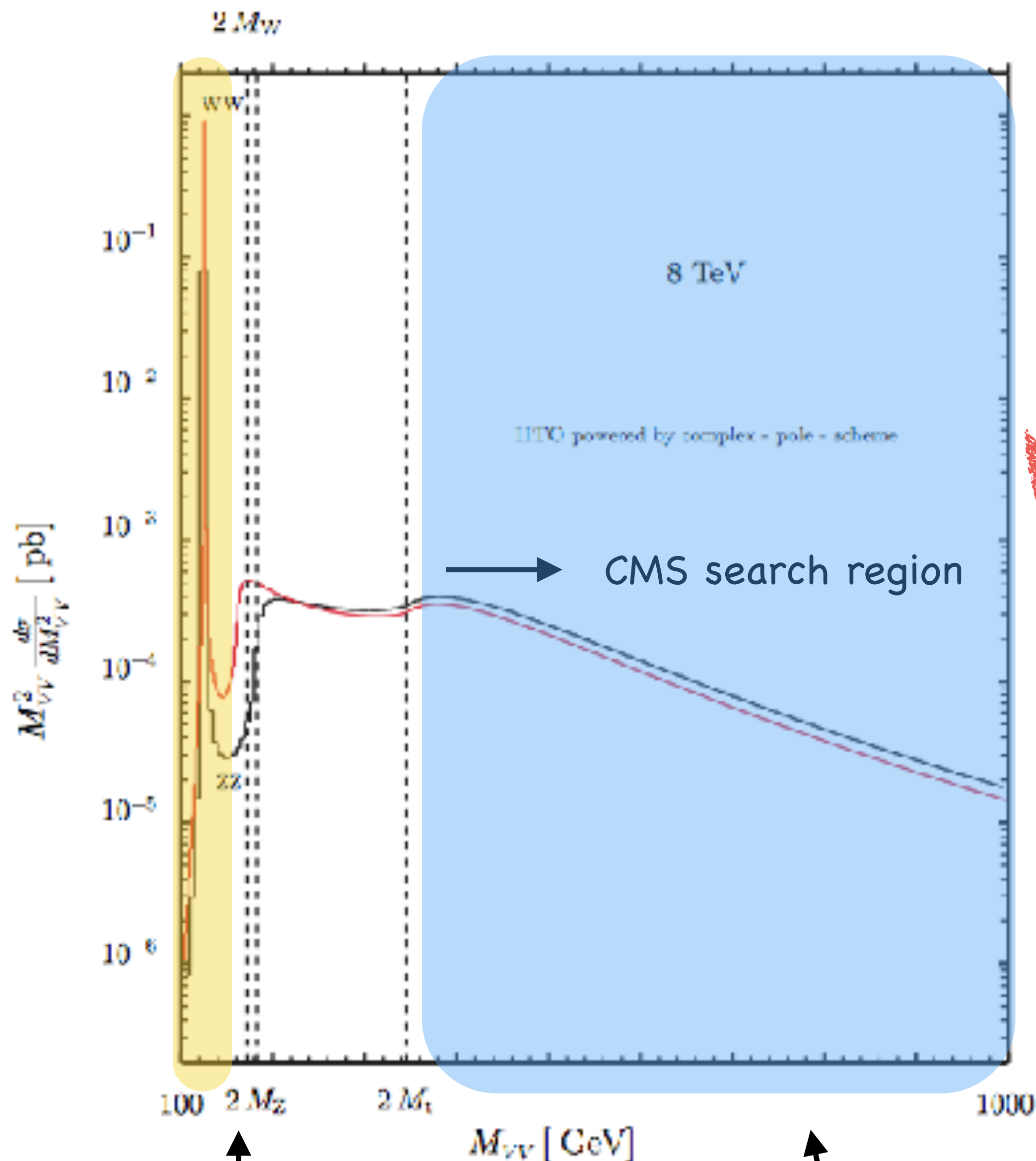
$$\mu = 200 \text{ GeV}$$

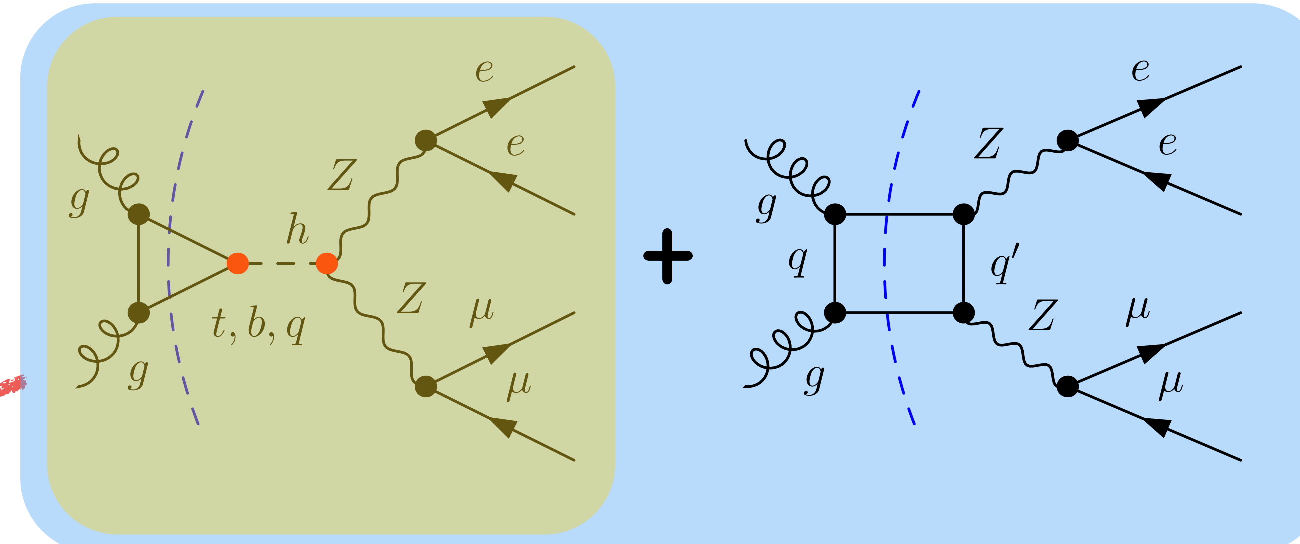
→ large At can be constrained

[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 $g^2_{ggH}g^2_{HZZ}$ 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

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

$$\sigma^{\text{off-peak}}_{gg\to H\to ZZ} \sim g^2_{ggH}g^2_{HZZ}$$

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

$\Gamma_H <$ 4.2(8.5) Γ_H^{SM}

$\Gamma_H <$ 17.4 (35.3) MeV

[Kauer, Passarino 2011]

[Caola, Melnikov 2013]

Example 'width-measurement'

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

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

Example ‘width-measurement’

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Kappa Framework | EFT | Simplified Models | Full (UV) Model

Example 'width-measurement'

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

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

Kappa Framework	EFT	Simplified Models	Full (UV) Model

- Assuming global coupling rescaling

Example 'width-measurement'

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

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Kappa Framework

- Assuming global coupling rescaling

EFT

- Only if assuming no flat directions

Simplified Models

Full (UV) Model

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EFT ✓ ⚡

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Kappa Framework

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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

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Simplified Models

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Full (UV) Model

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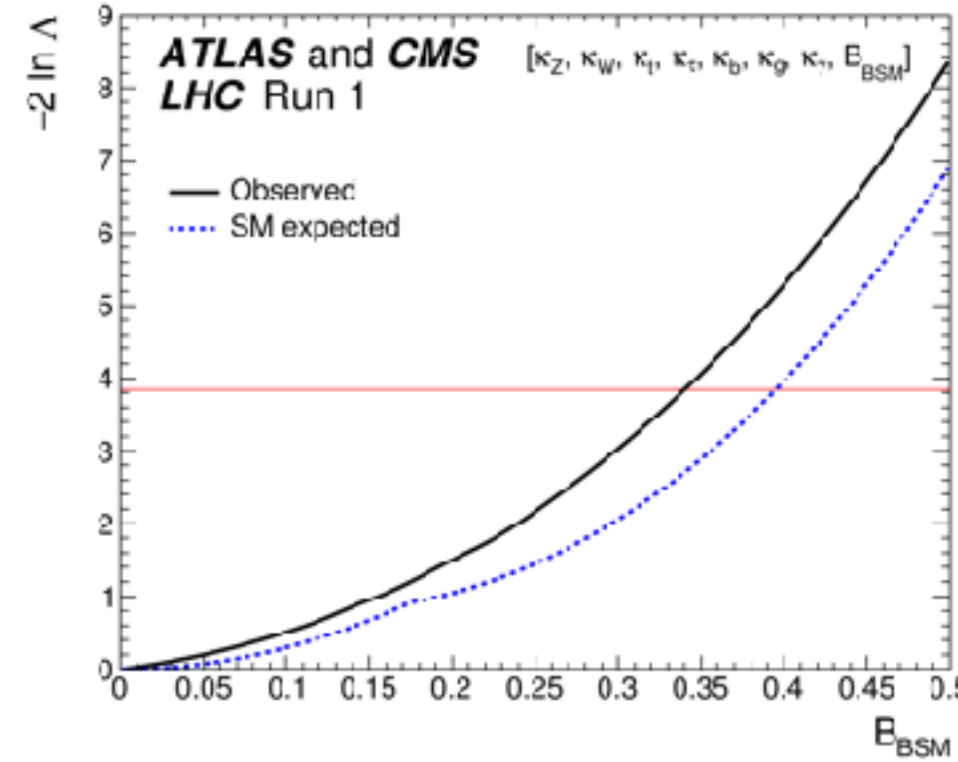
Limit on invisible branching ratio from global Higgs fit



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

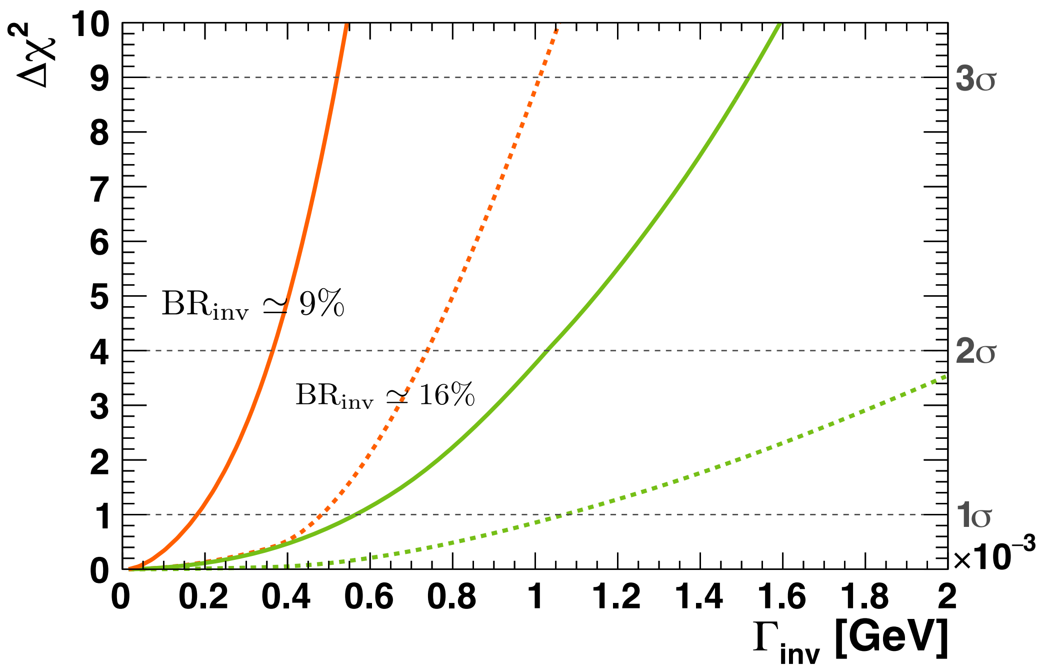
- Extend SM EFT by light degree of freedom, e.g. fermionic DM candidate

$$\mathrm{BR}_{\mathrm{inv}} = \frac{\Gamma_{\mathrm{inv}}}{\Gamma_{\mathrm{SM}} + \Gamma_{\mathrm{inv}}}$$

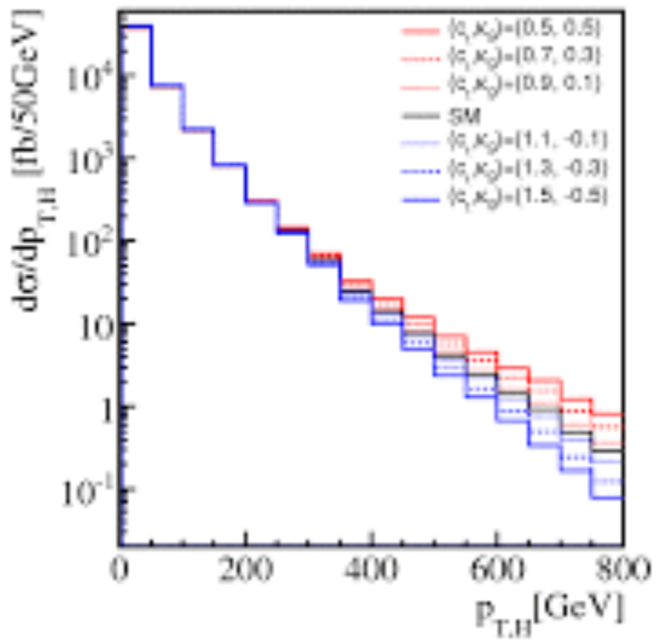
Flat reduction of event count in all channels

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

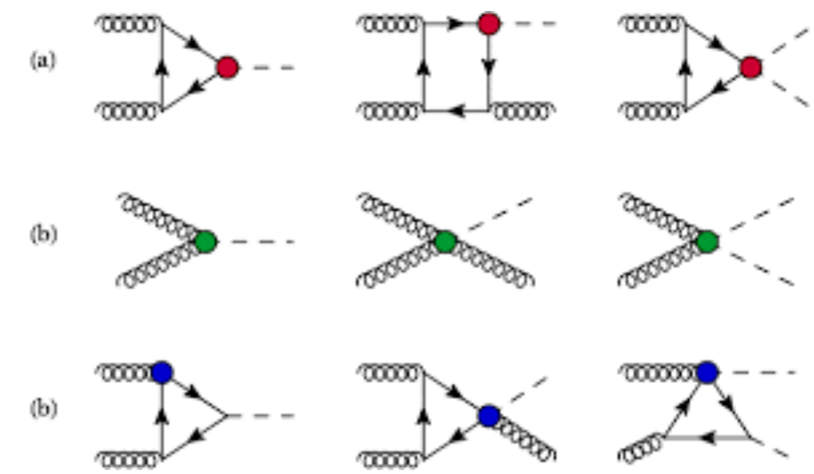
Most operators mom. dependent. Rate compensated by large increase in tail



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



Summary



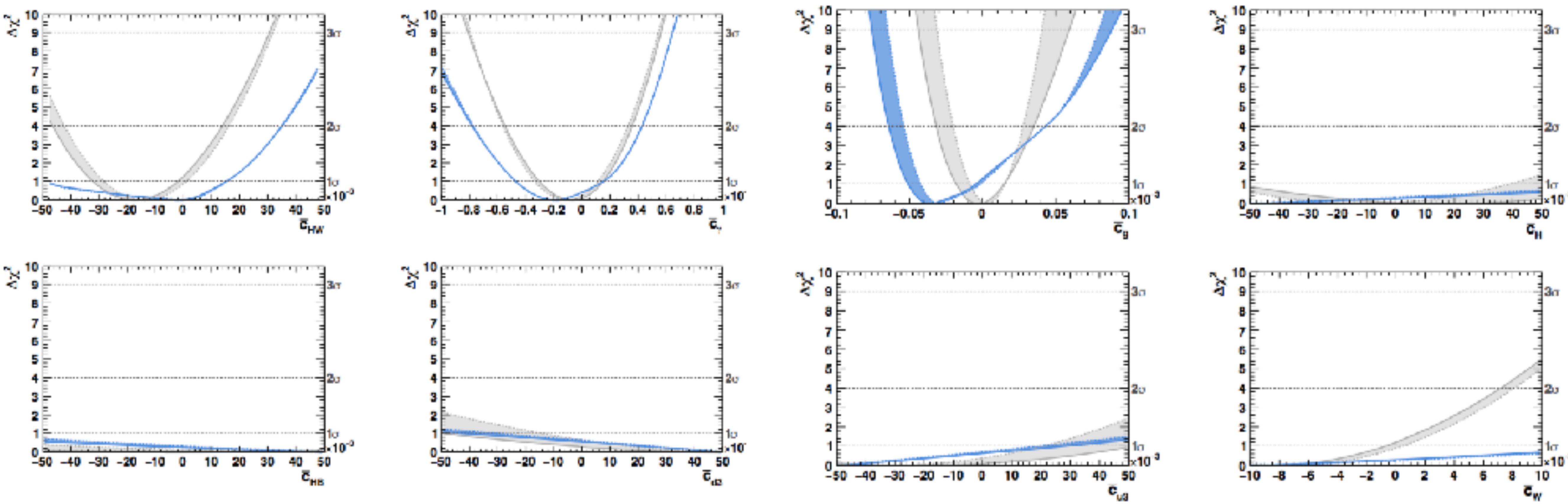
Effective field theories provide a well-defined language to give data an interpretation in terms of BSM physics

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