Higgs Hunting

July 23-25, 2018, Orsay-Paris, France

Results and prospects in the electroweak symmetry breaking sector

Higgs couplings: present and future

Eleni Vryonidou

CERN TH

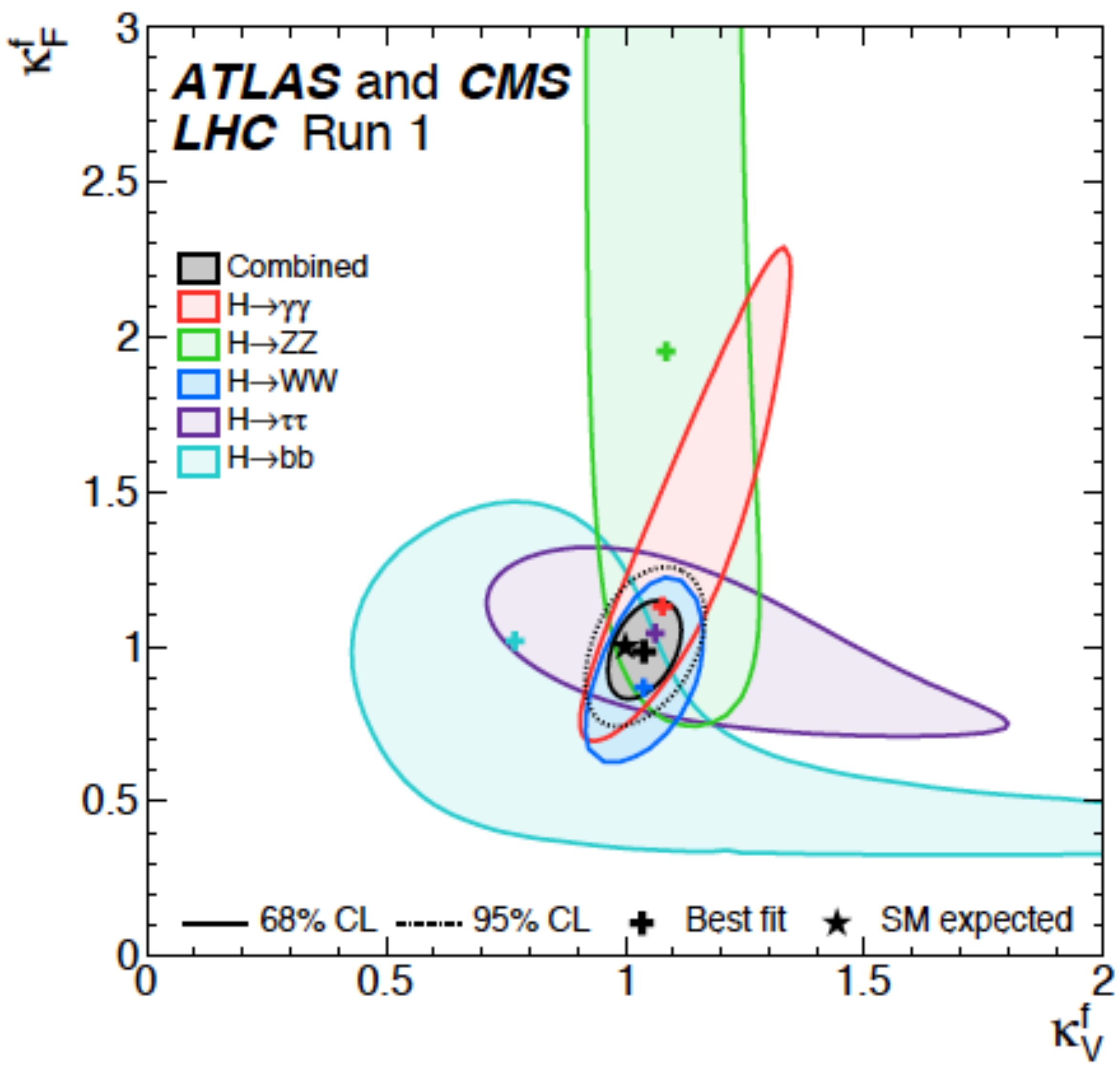
Higgs Hunting

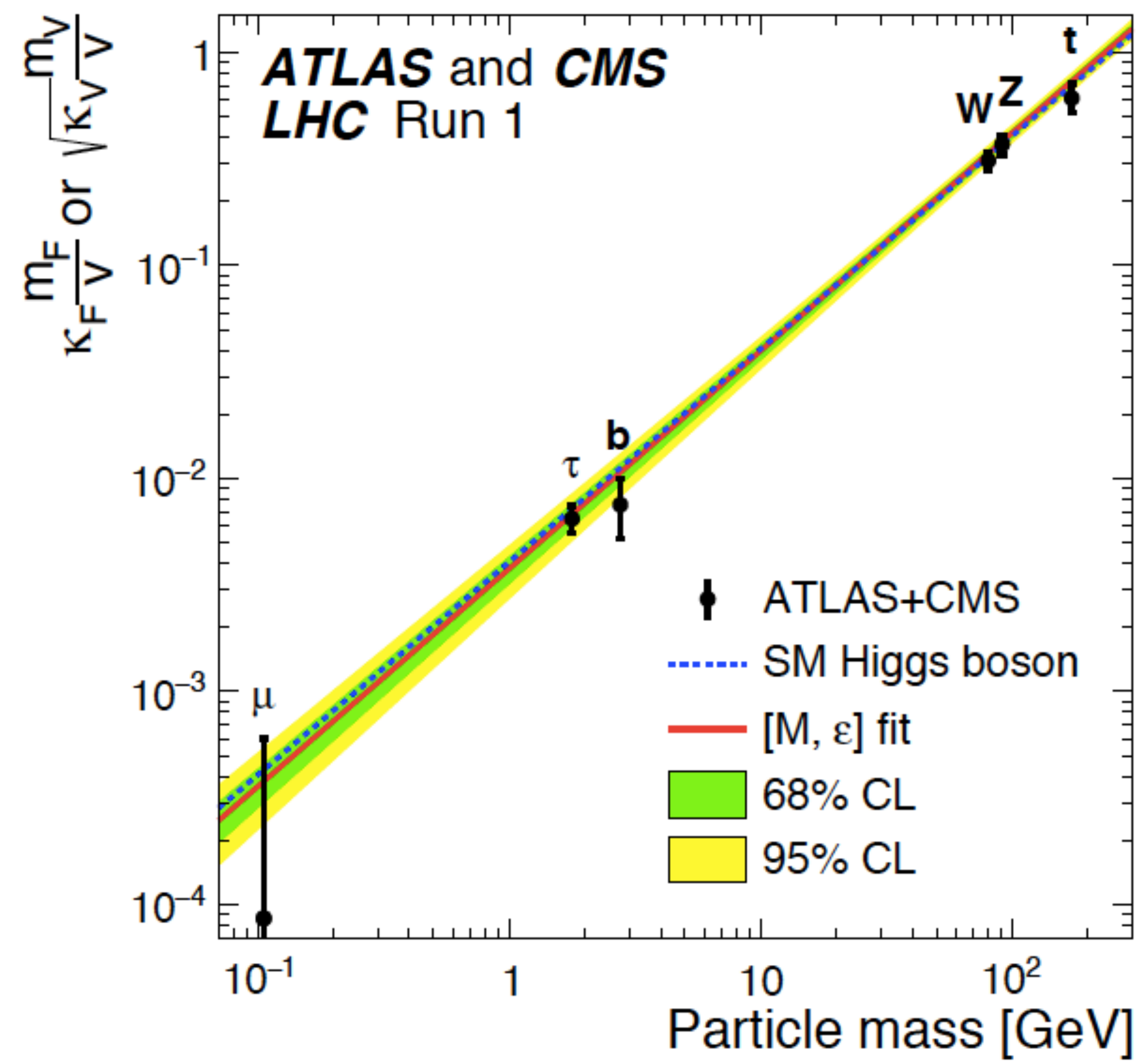
LPNHE, Jussieu

24/07/18

LHC: the story so far

Higgs couplings

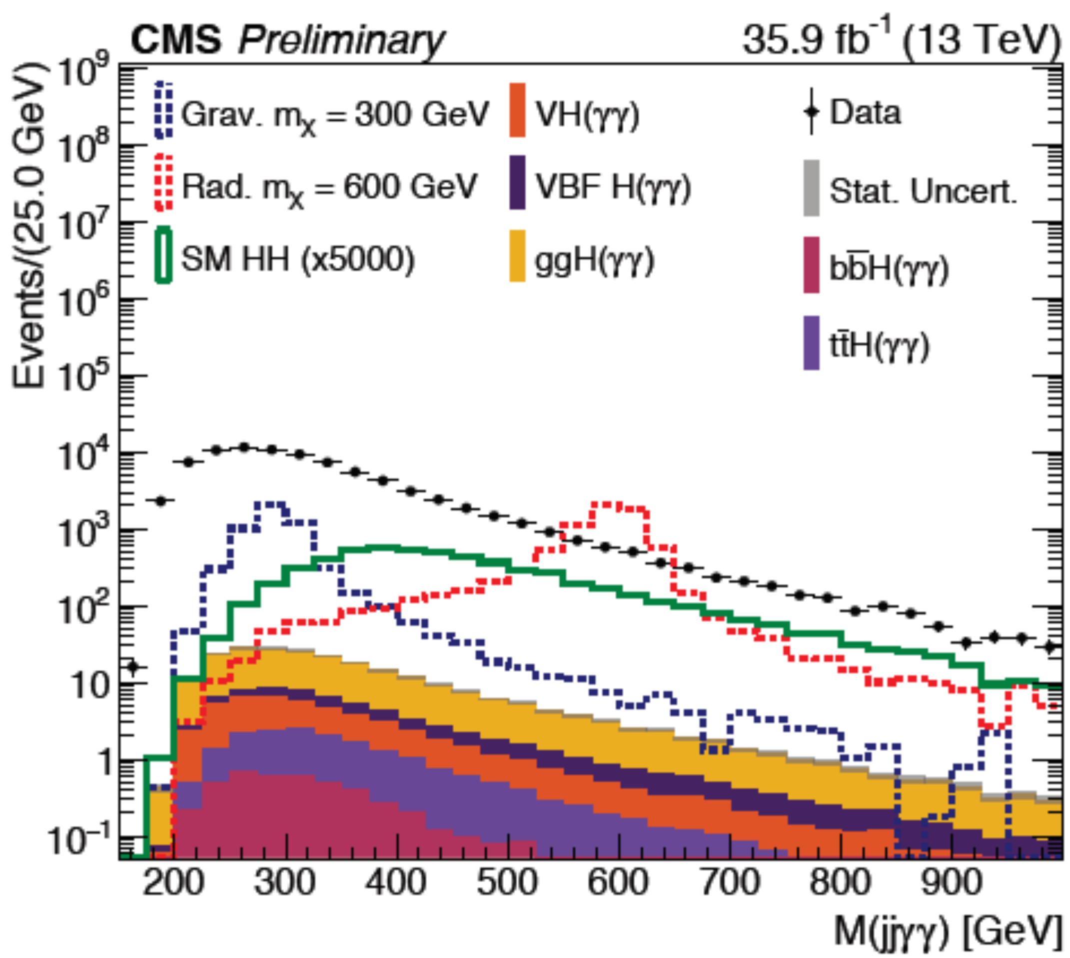




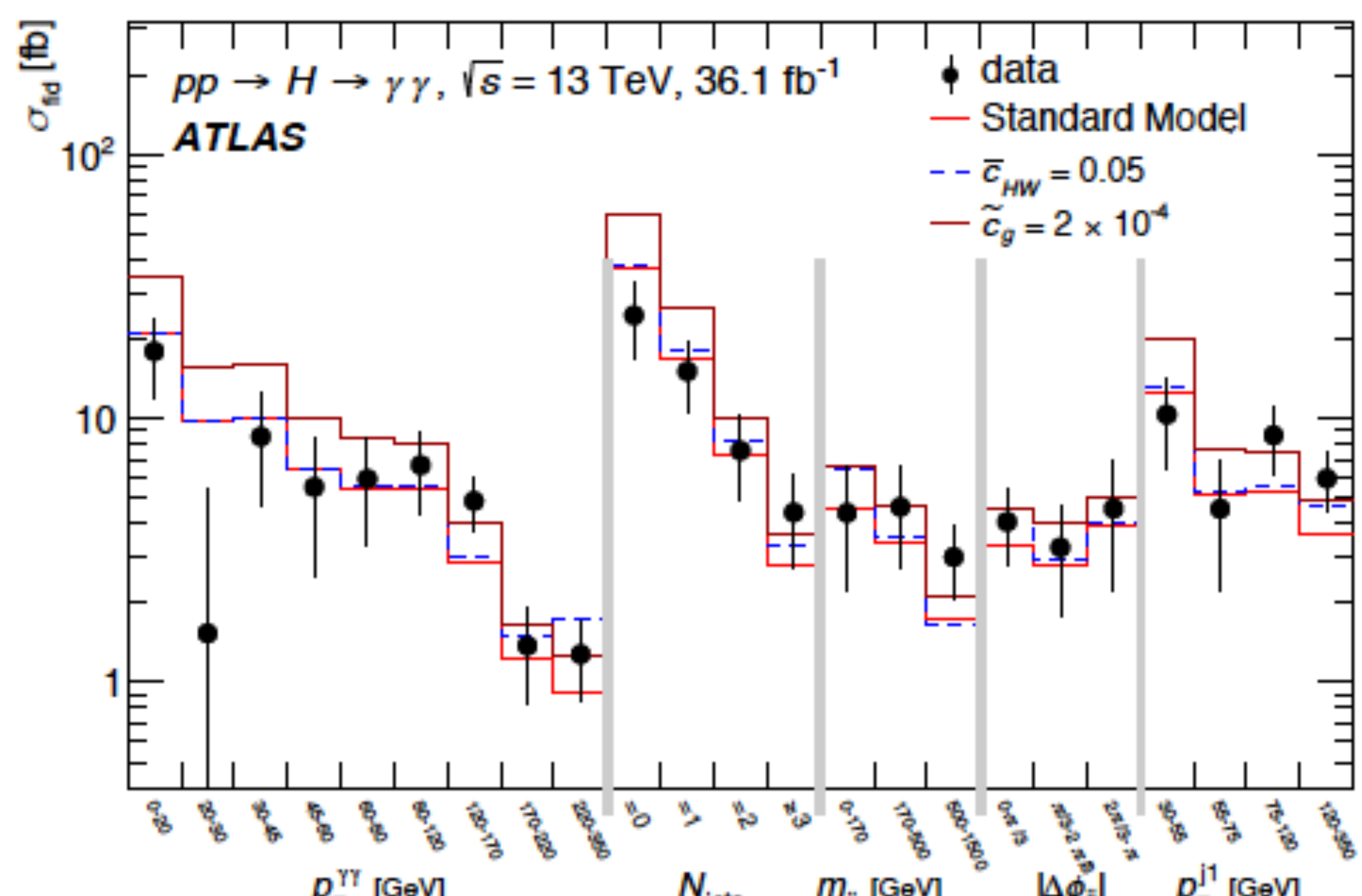
Good agreement with the SM predictions

How to look for new physics?

Model-dependent	Model-Independent
SUSY,1HSM,2HDM…	anomalous couplings, EFT
New particles	New Interactions



Resonance peaks



Deviations in tails

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Model-dependent

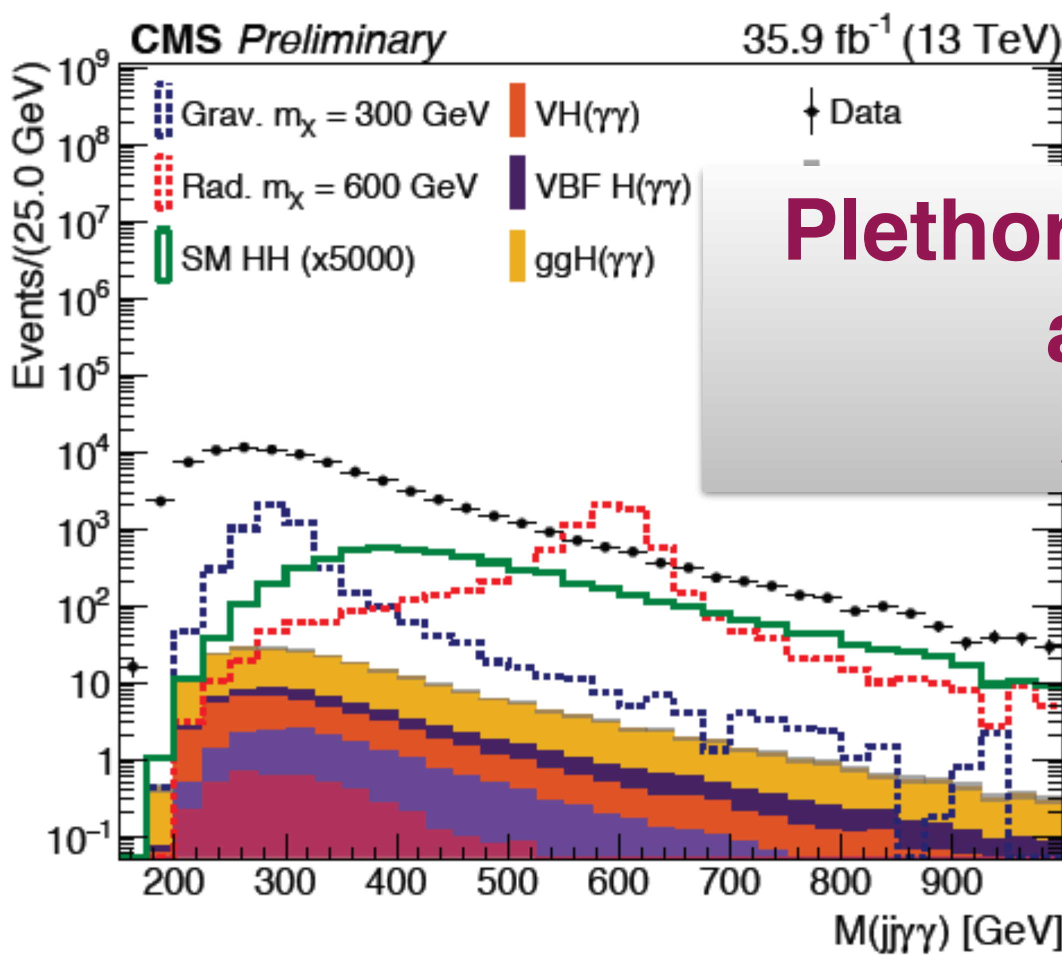
SUSY,1HSM,2HDM…

New particles

Model-Independent

anomalous couplings, EFT

New Interactions



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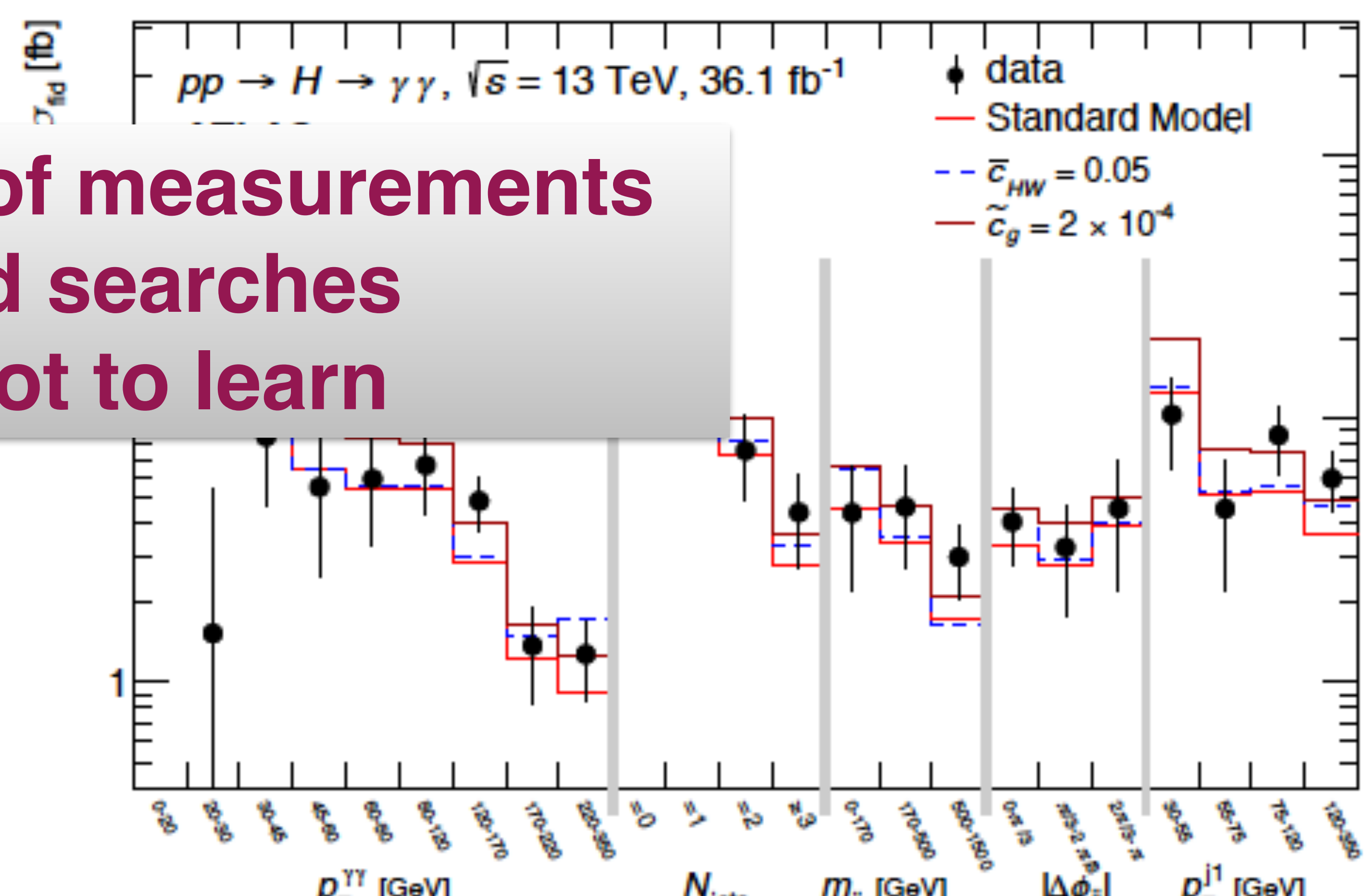
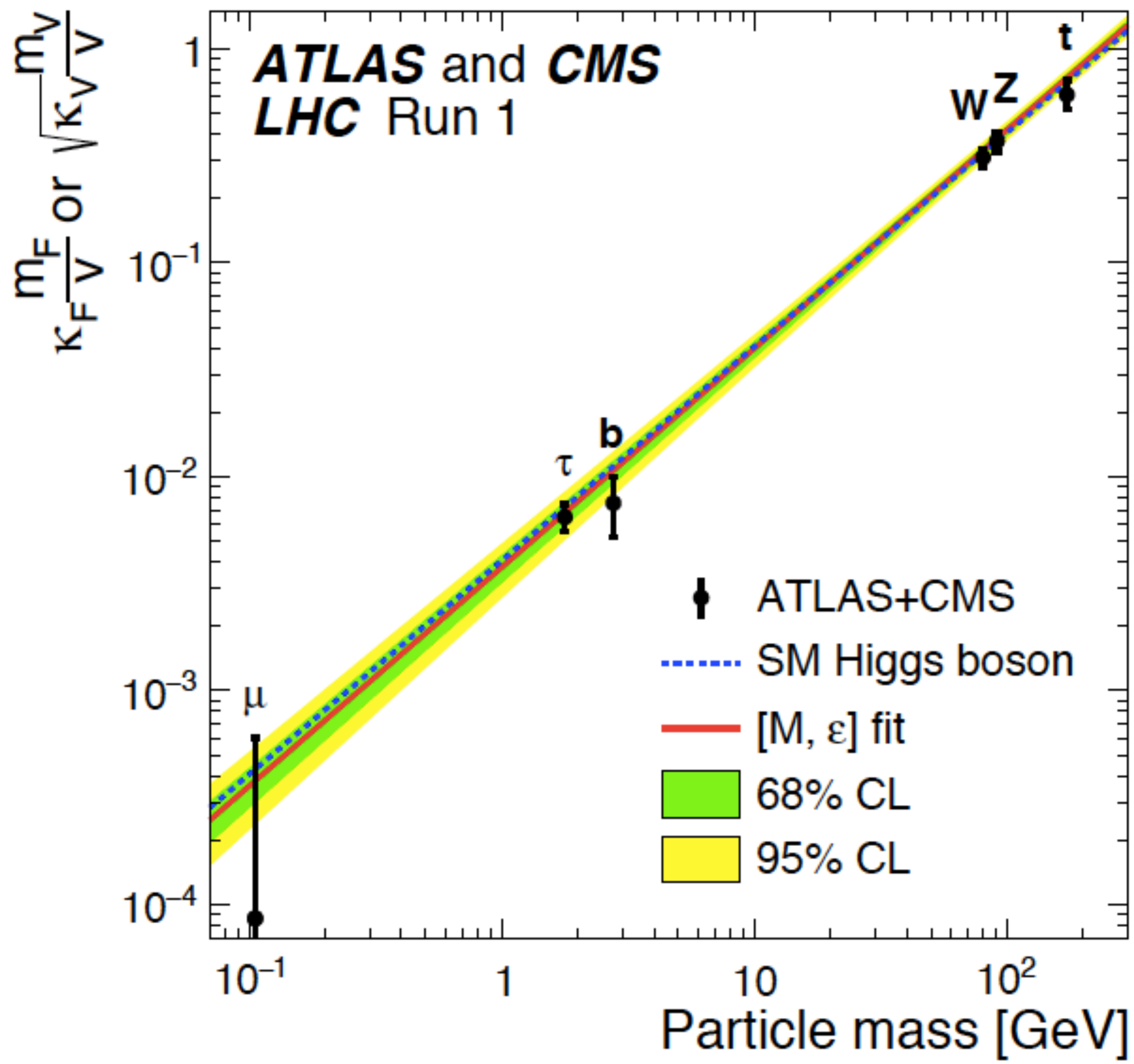


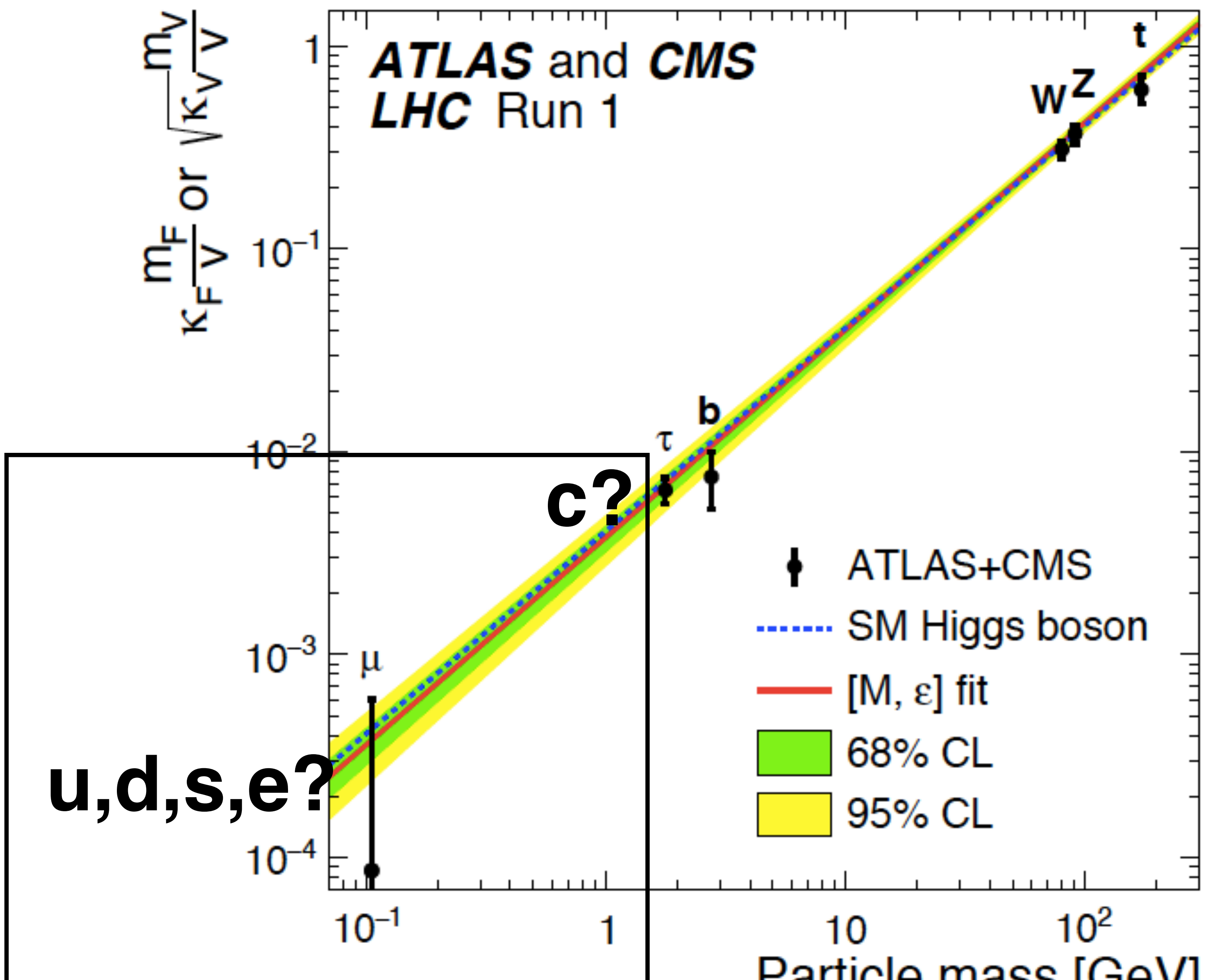
Deviations in tails

Plethora of measurements and searches
A lot to learn

Knowns and Unknowns



Knowns and Unknowns



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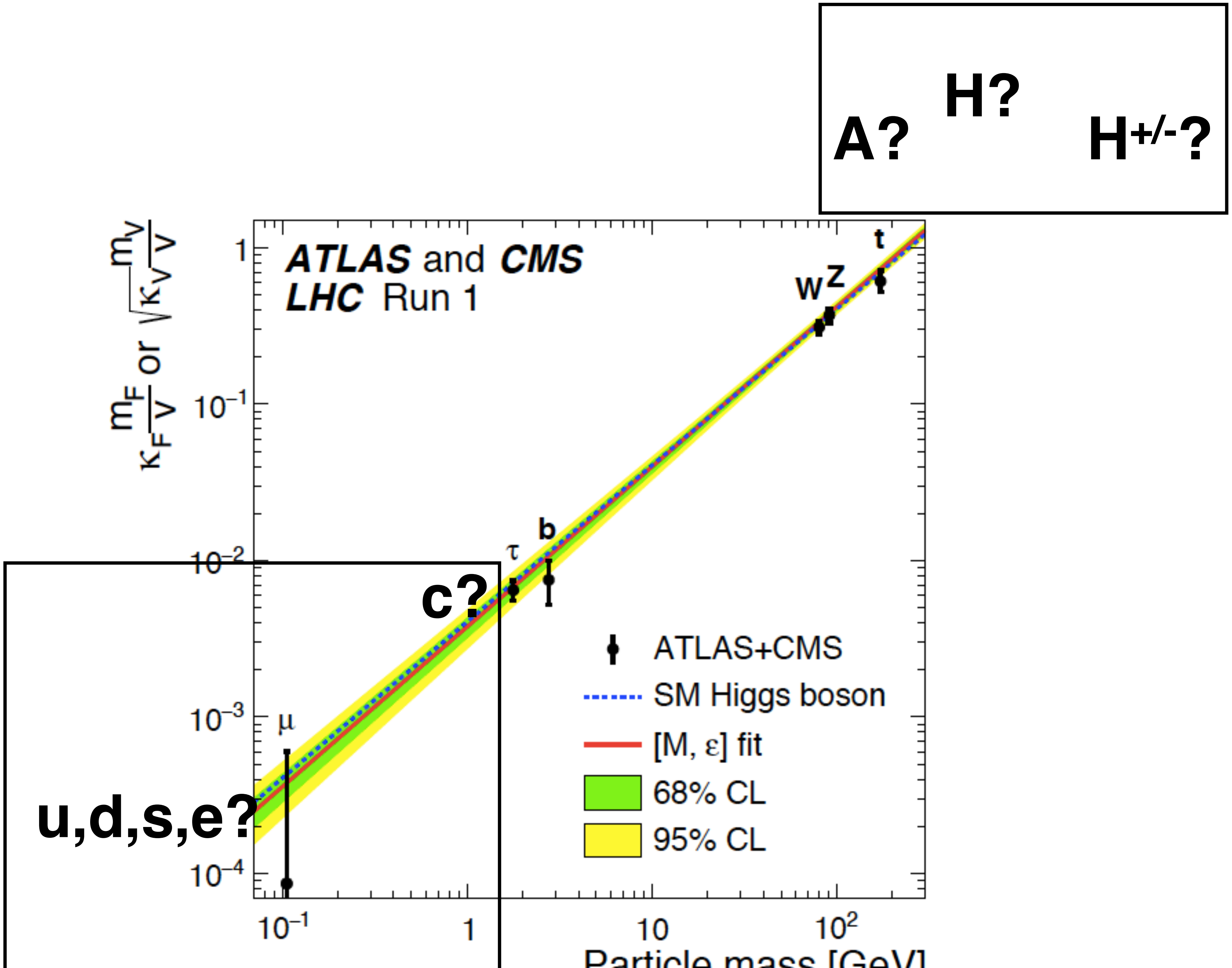

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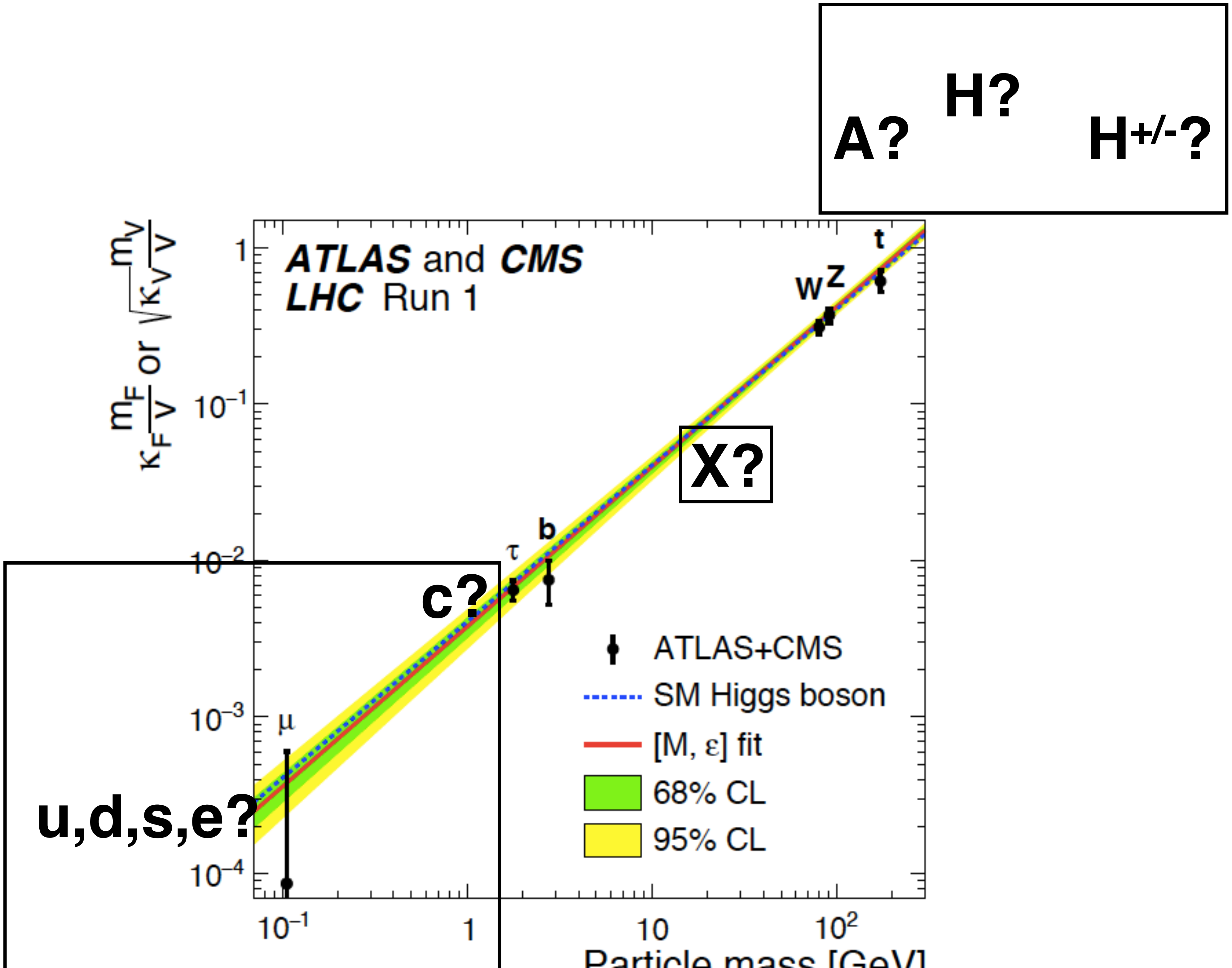

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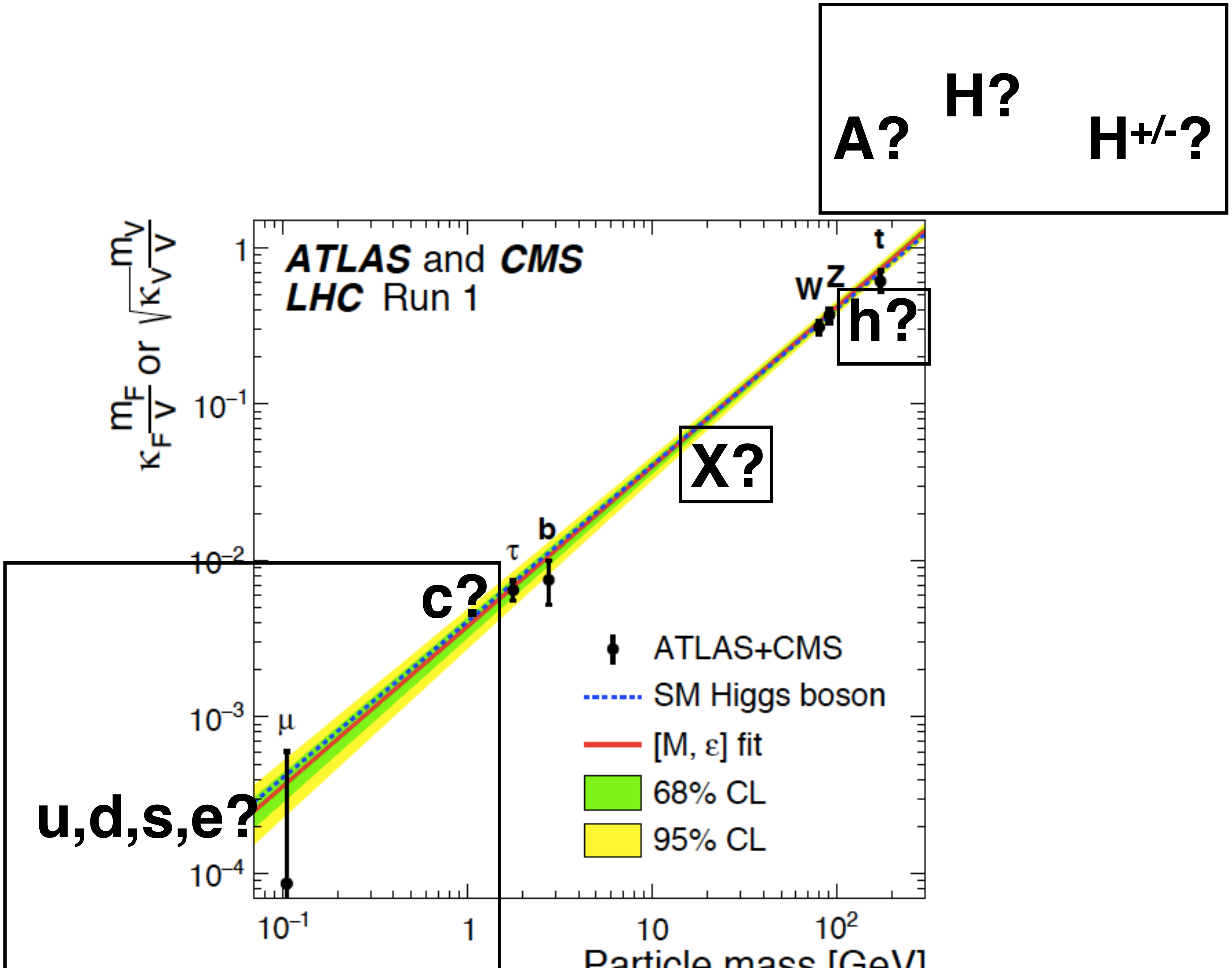
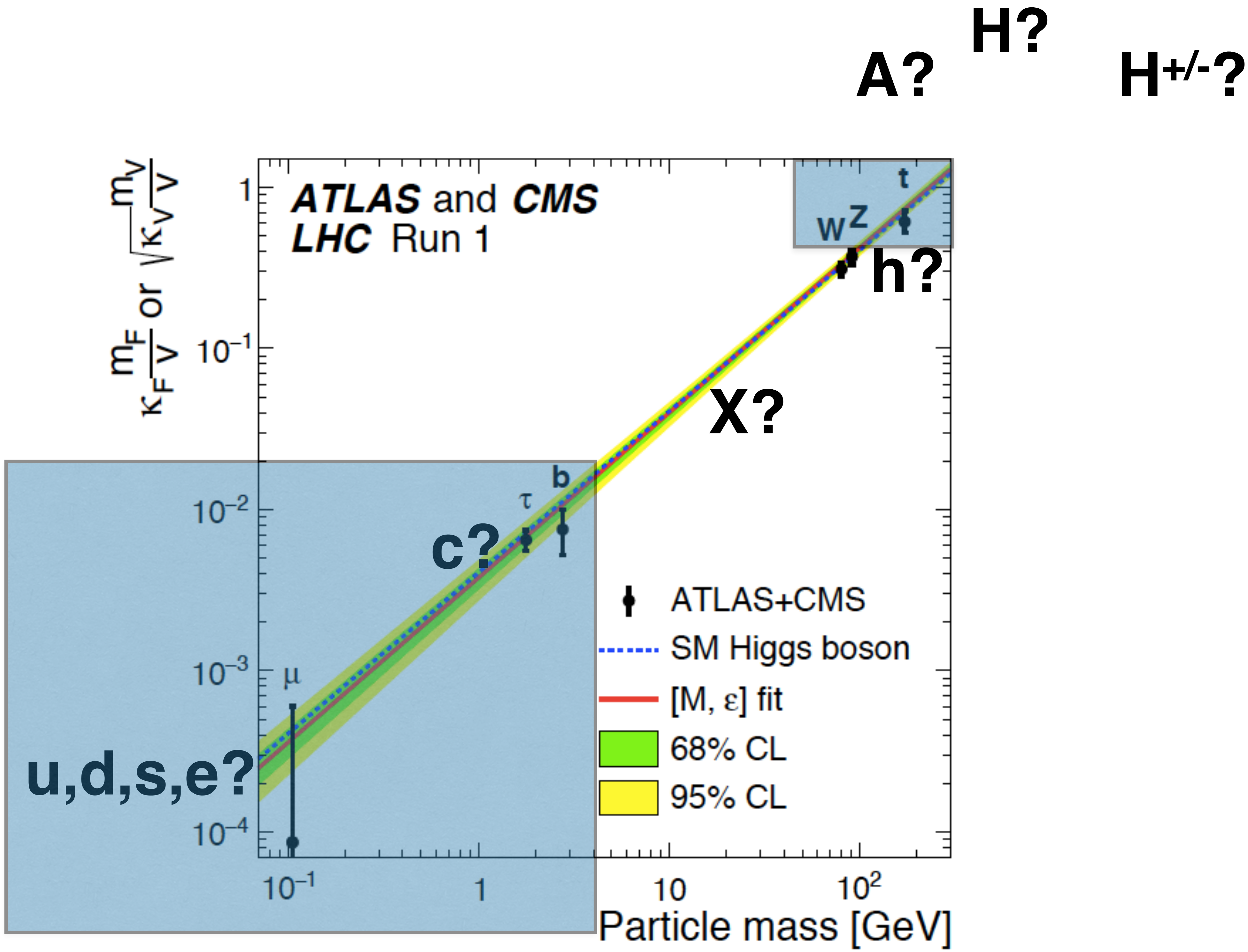


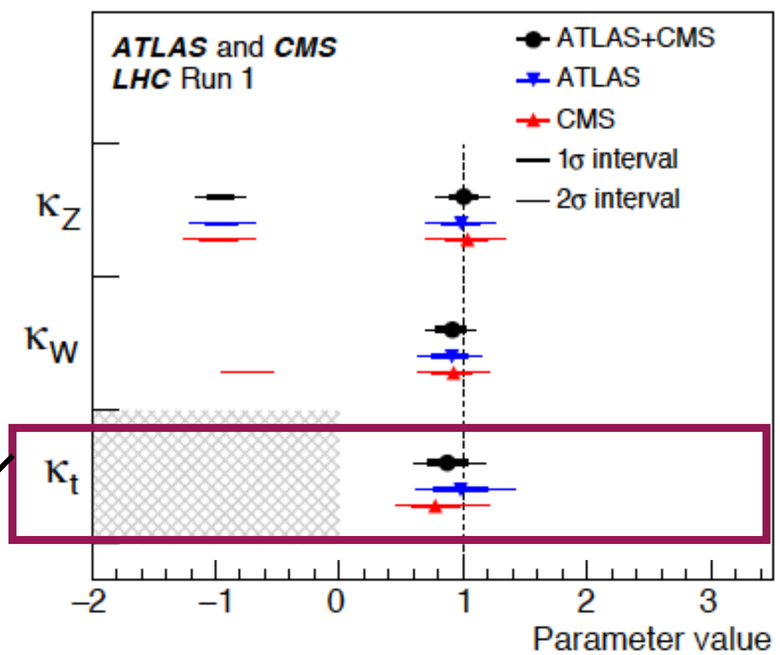
Outline

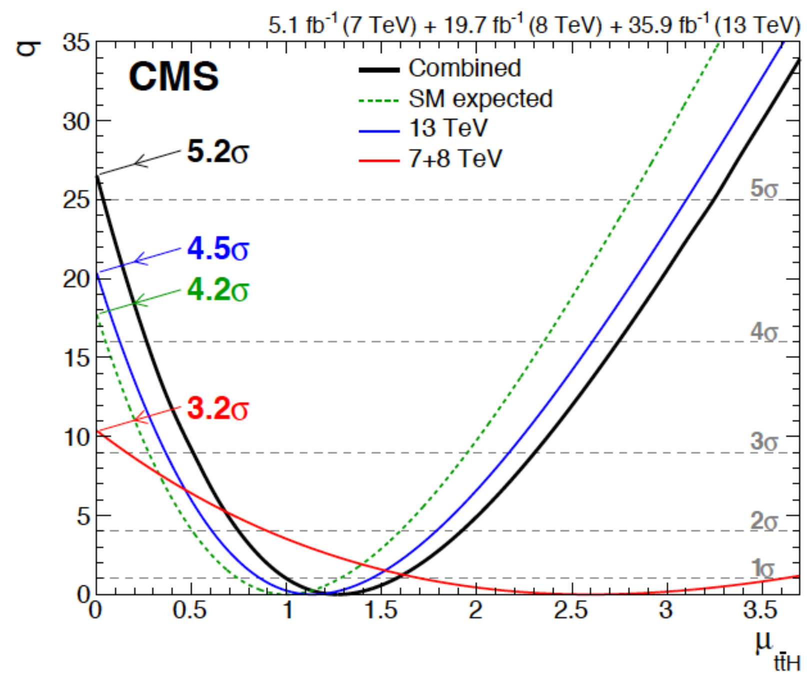
I. Higgs couplings
II. The Higgs potential

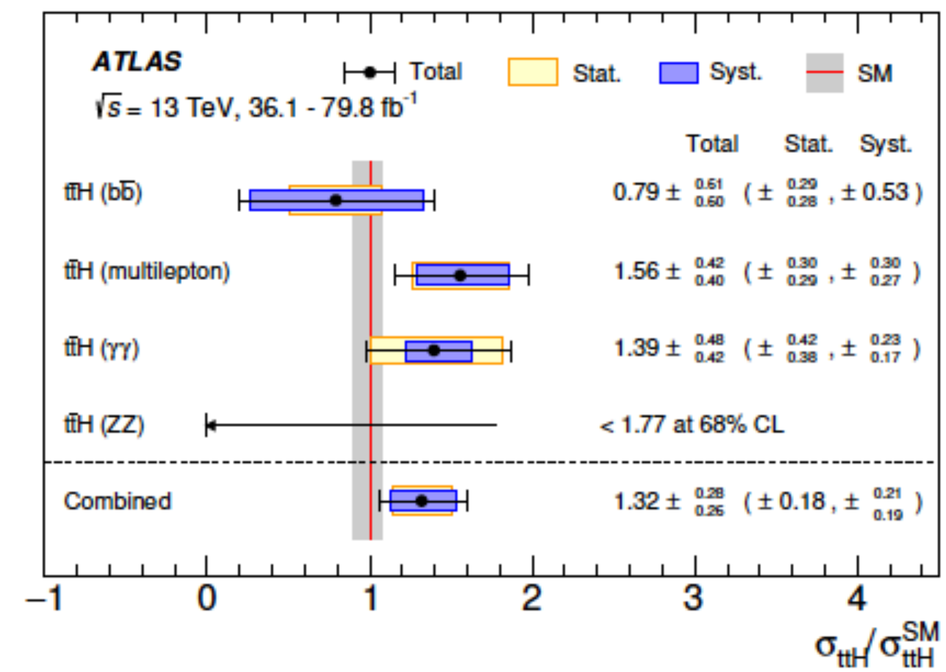


I. Higgs couplings

The good news:Top-Higgs interaction



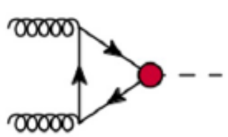




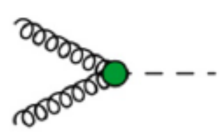
~20% accuracy

First observation of ttH

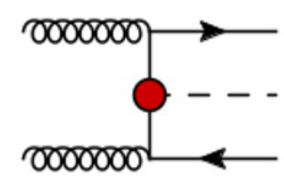
H

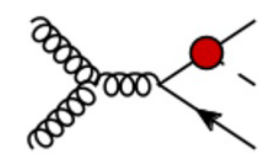


or



ttH





Heavy particles
in the loops?

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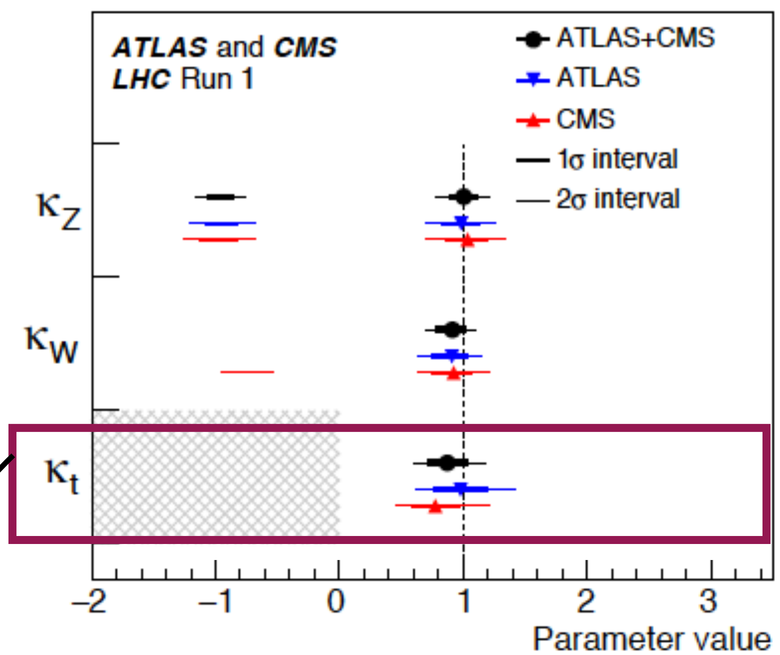

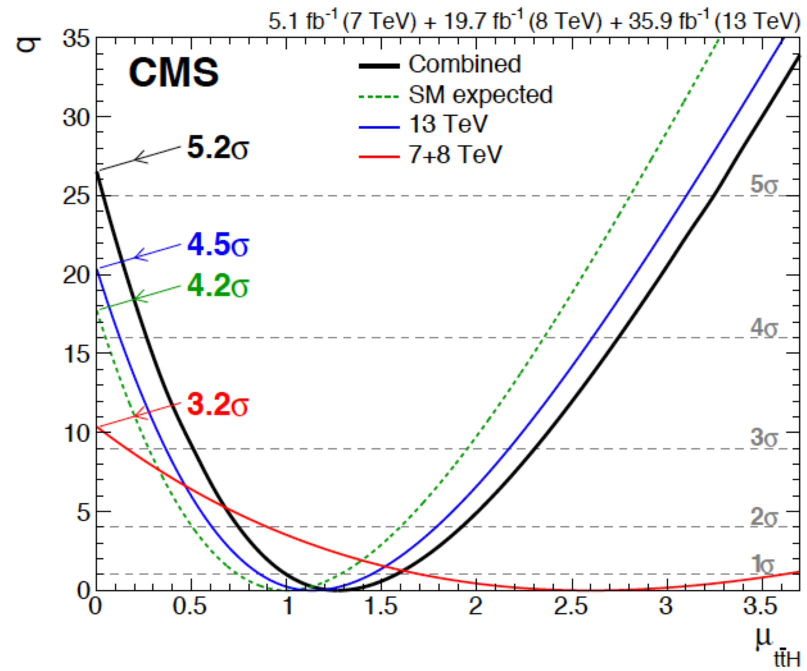

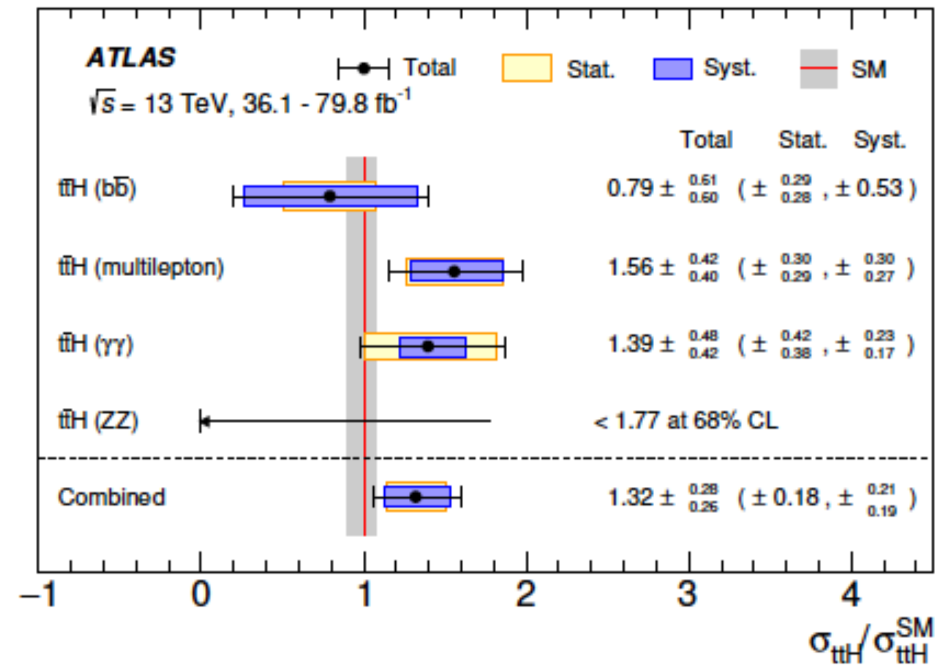

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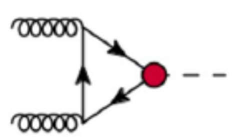
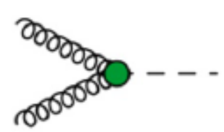
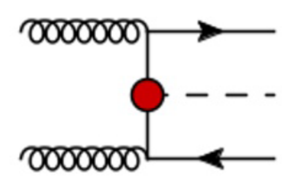
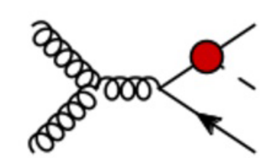


or



ttH

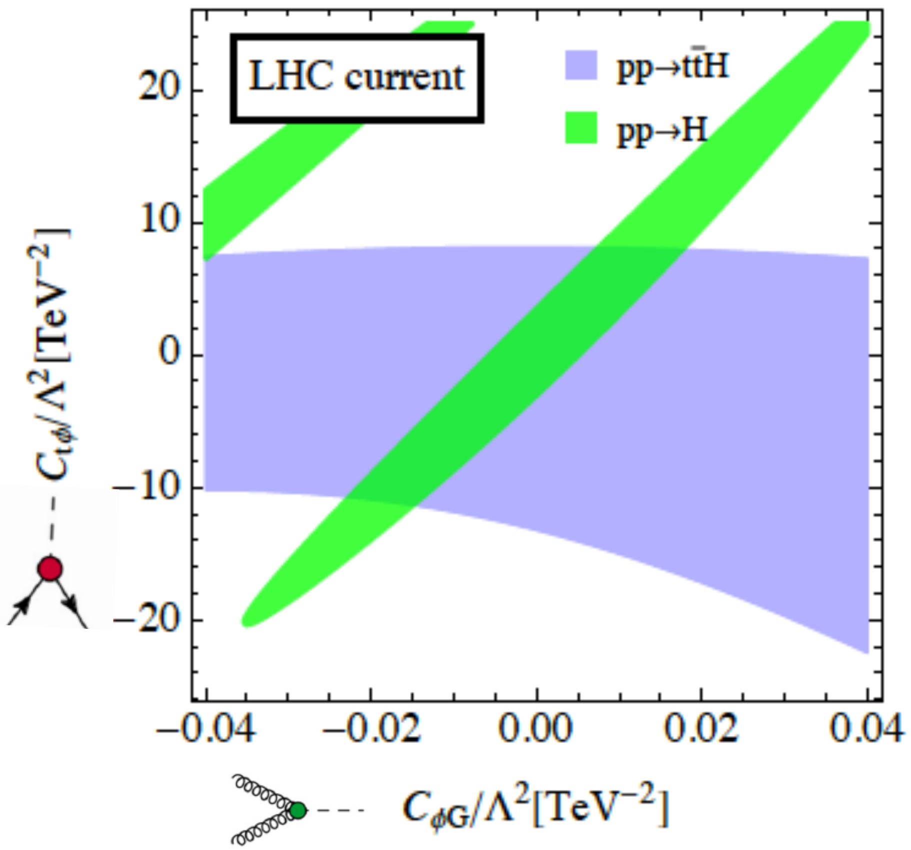


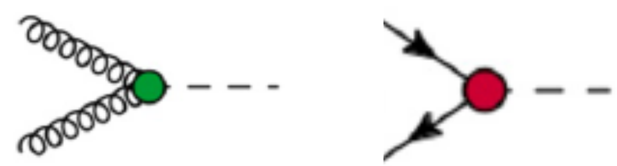


Heavy particles in the loops?

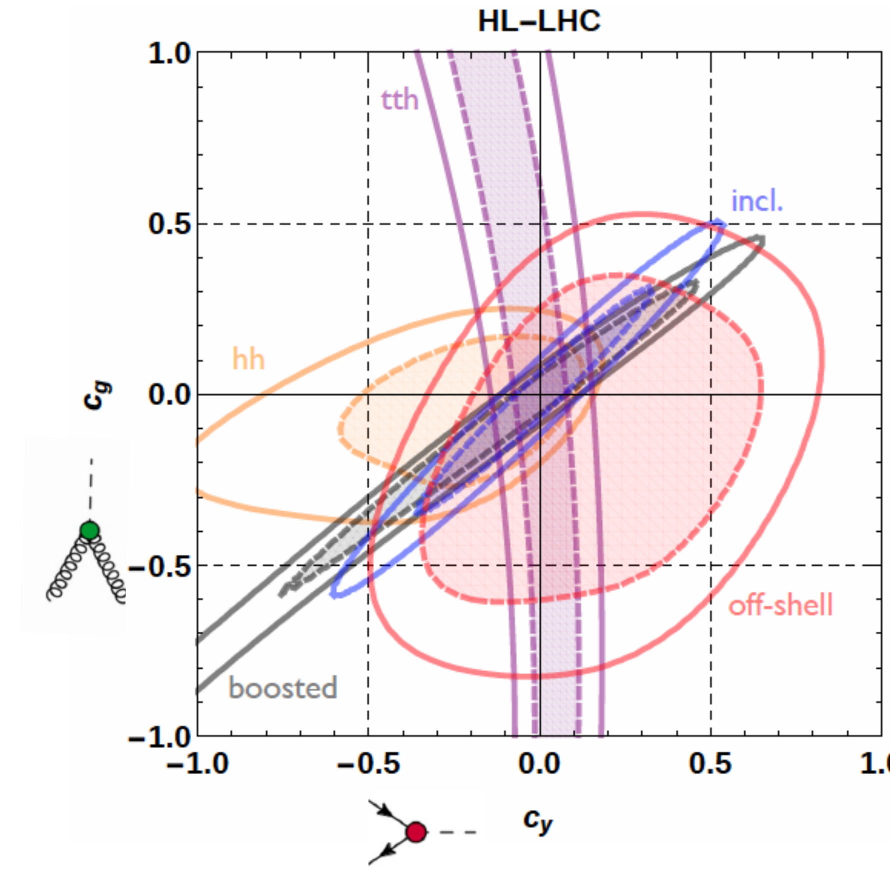
Direct evidence of the coupling of the top to the Higgs

Probing the top-Higgs interaction (1)

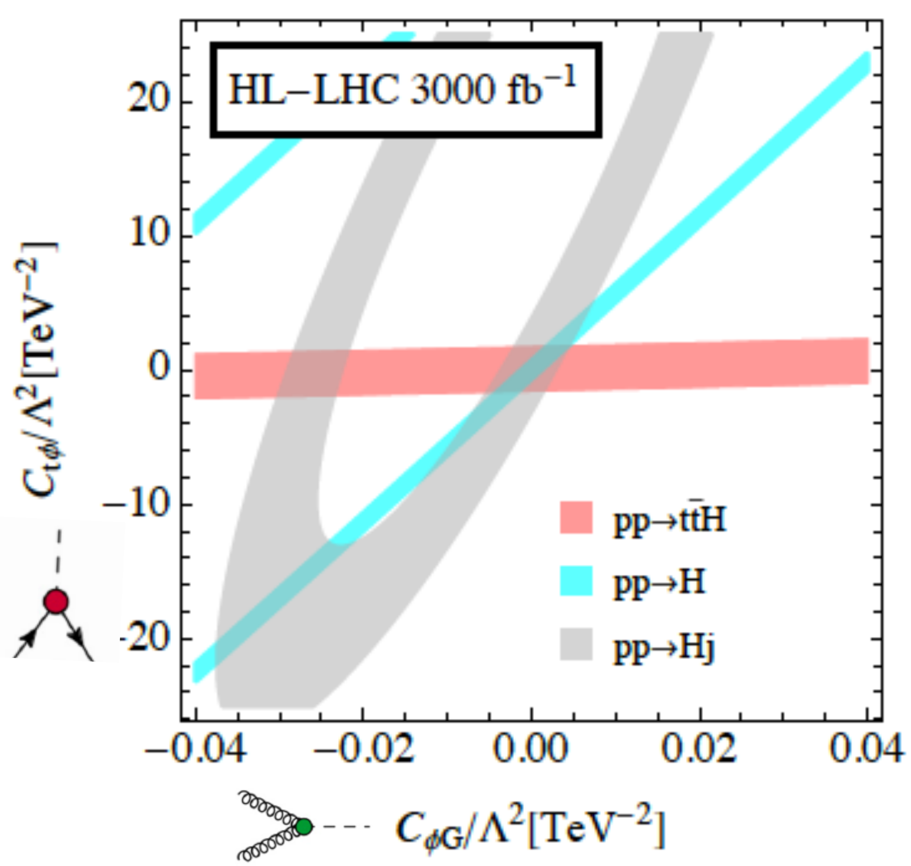




Current limits using LHC measurements



Azatov et al arXiv:1608.00977



14TeV projection 3000 fb^{-1}

Maltoni, EV, Zhang
arXiv:1607.05330

Combination:
- inclusive H
- boosted Higgs
- ttH
- HH
- off-shell Higgs

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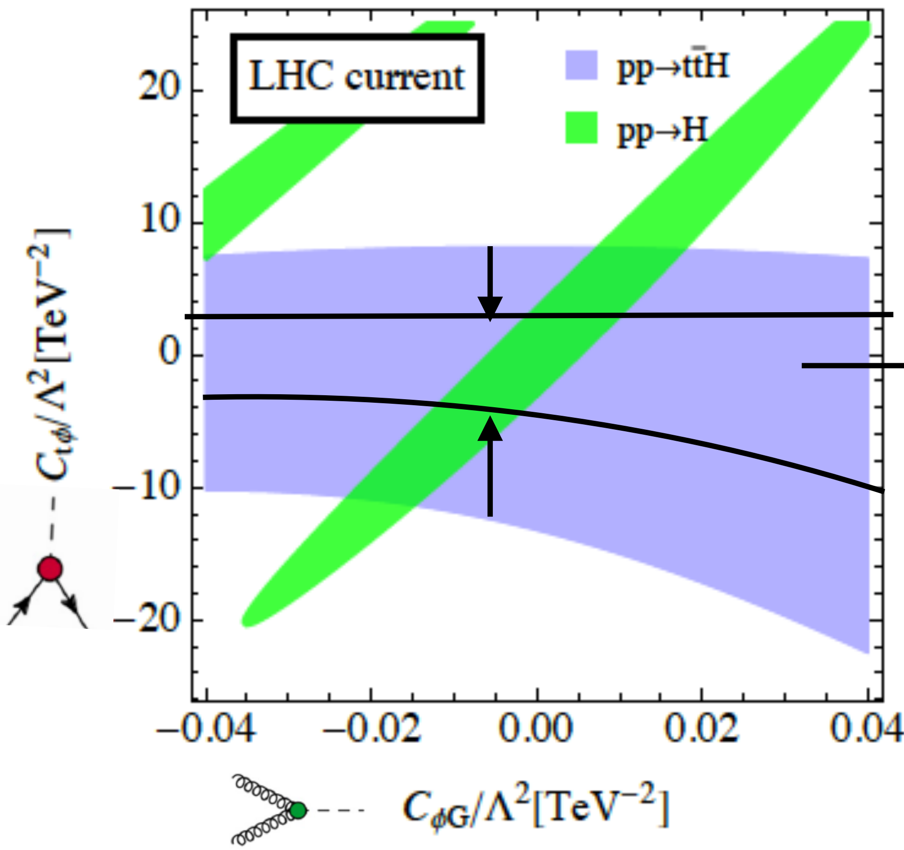
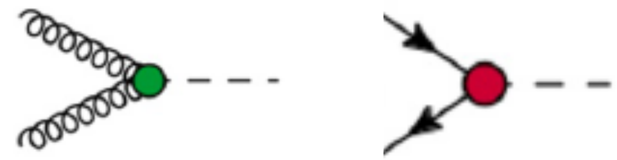
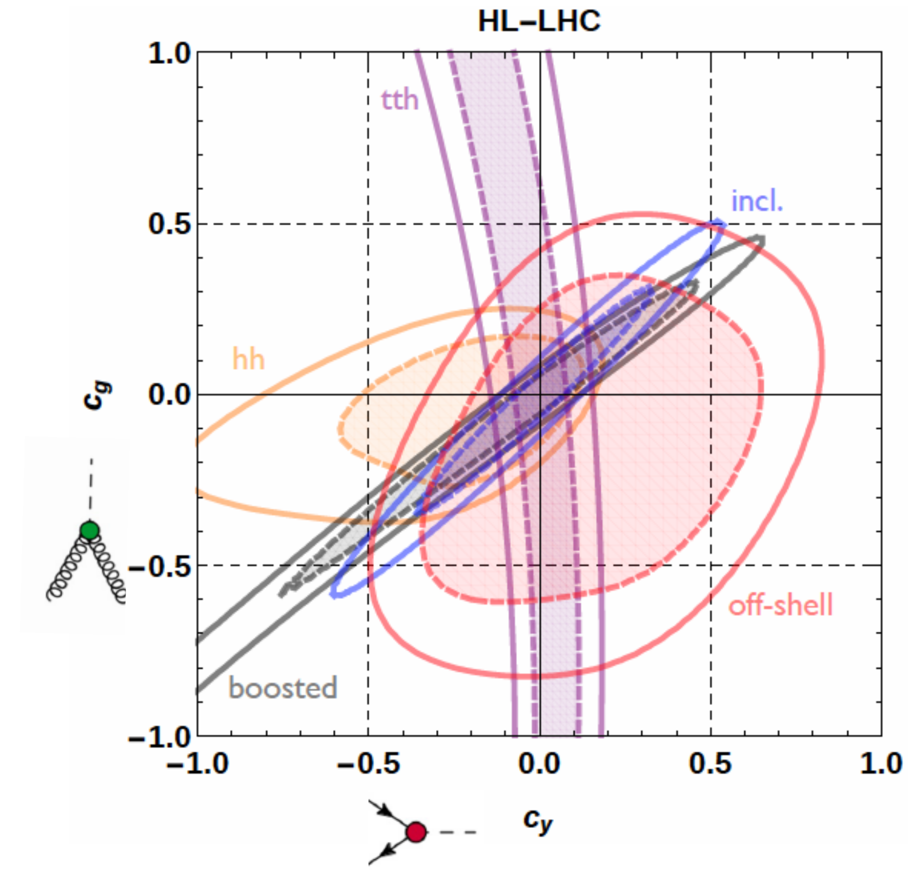




impact of recent ttH observation

Current limits using LHC measurements



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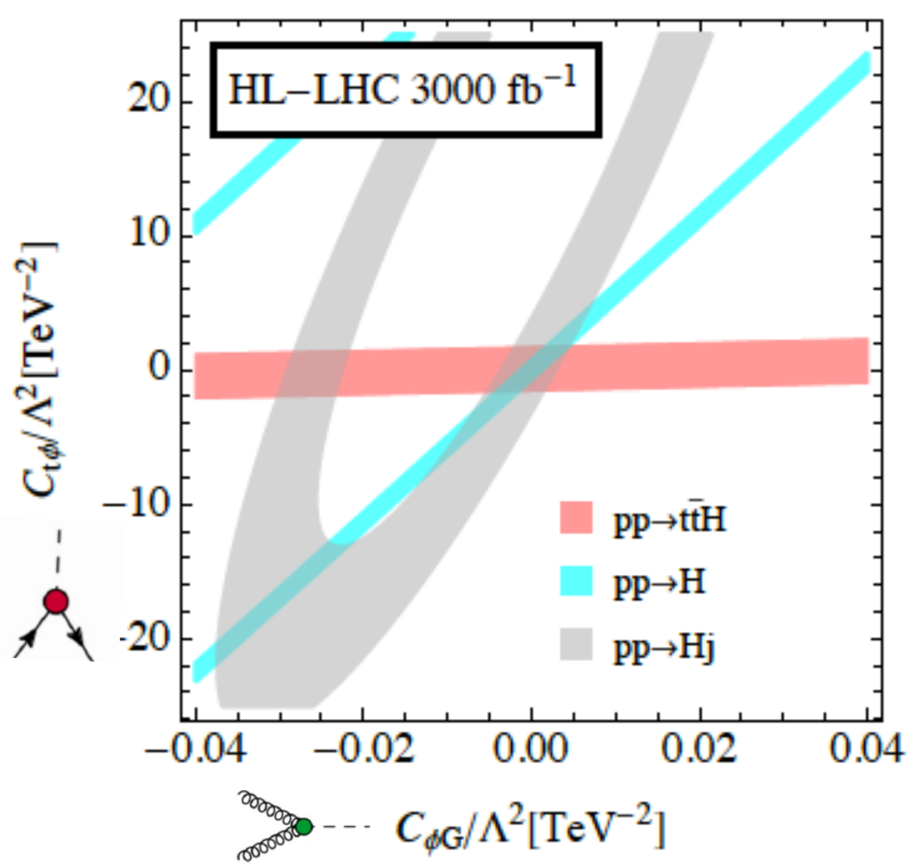

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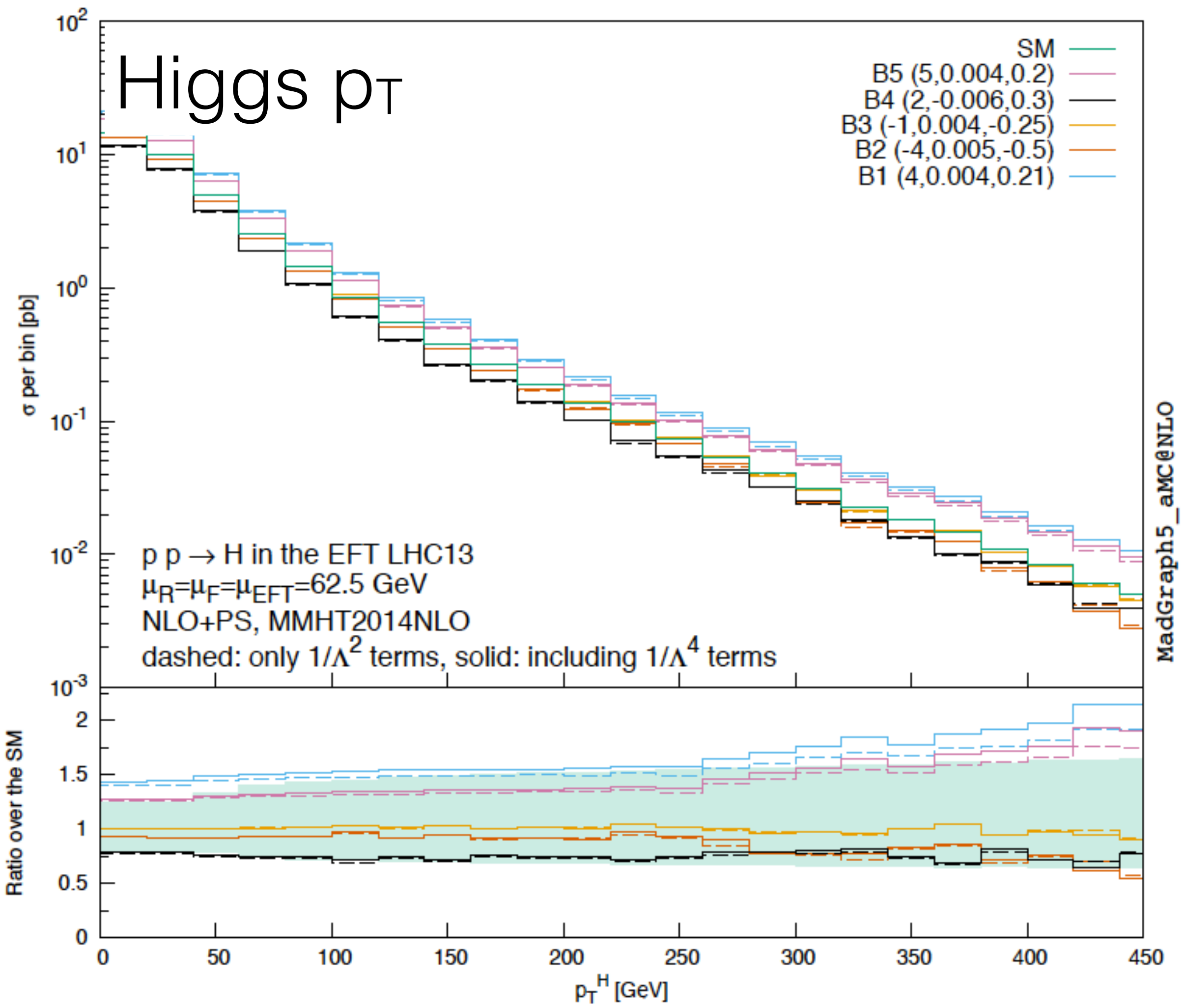
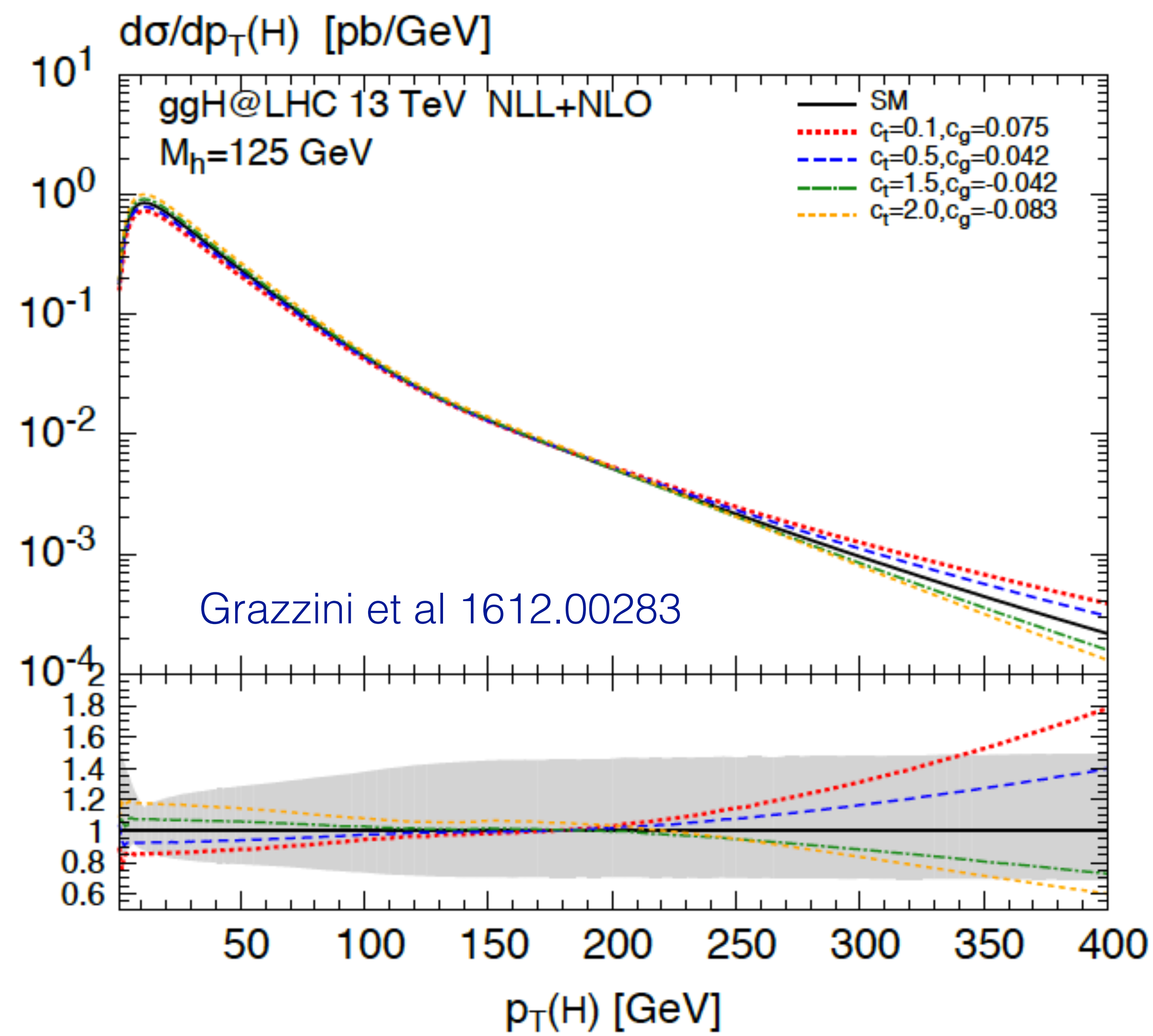
Probing the top-Higgs interaction (2)

Precise Higgs p_T distribution



Deutschmann, Duhr, Maltoni, EV arXiv:1708.00460



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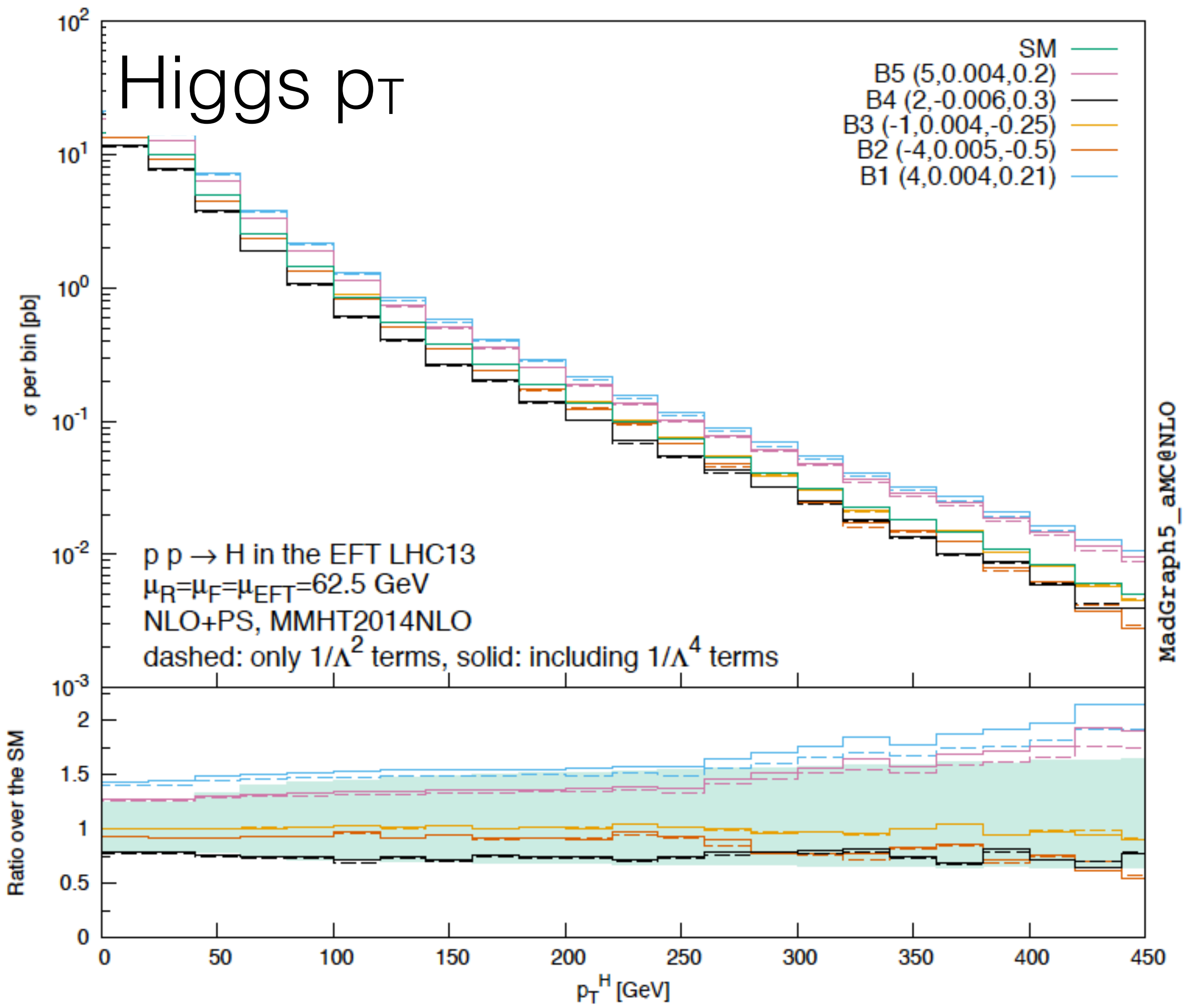

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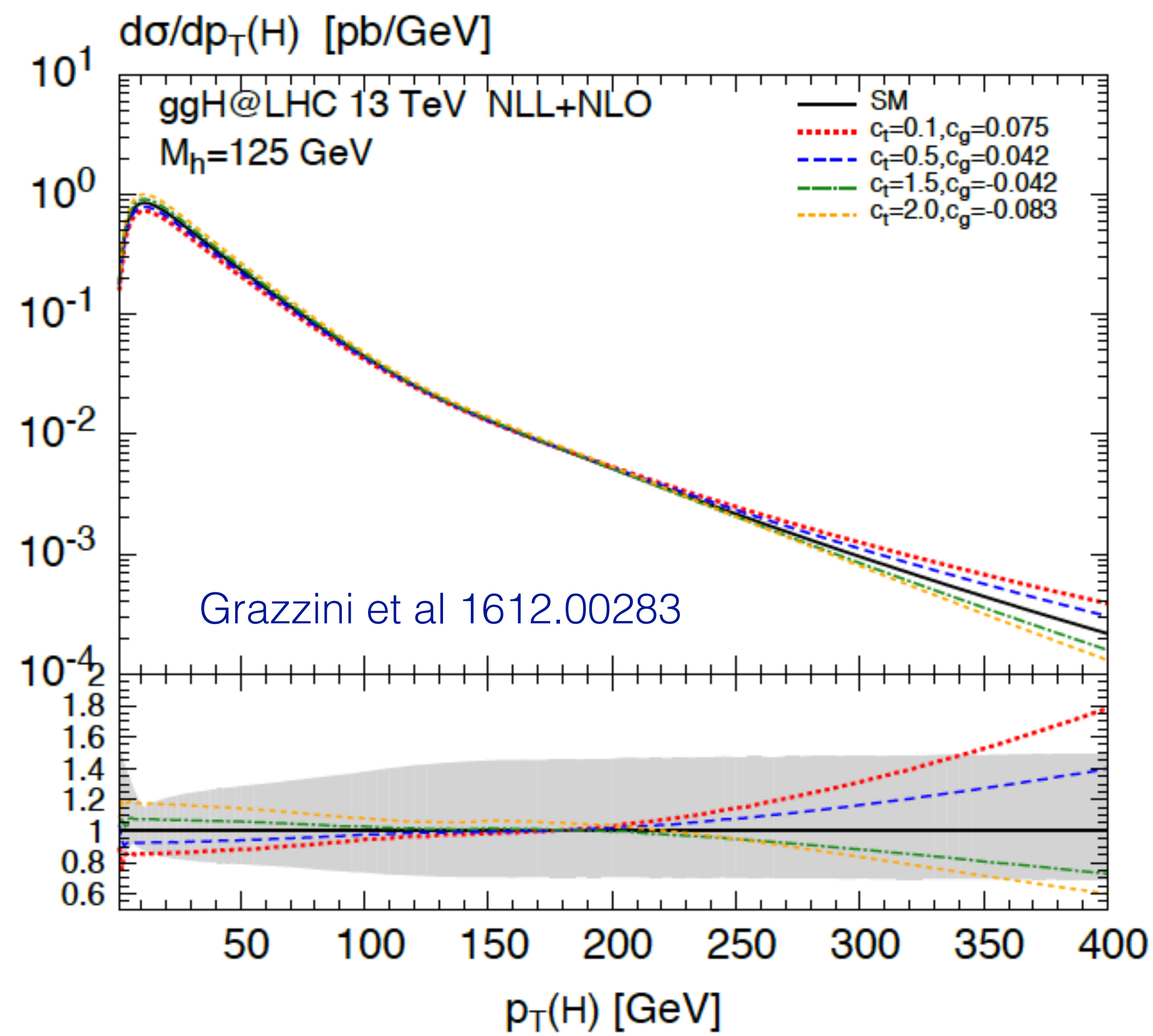
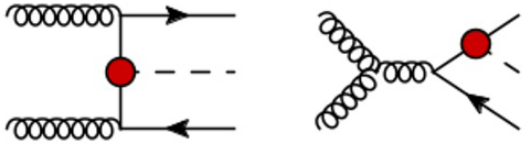
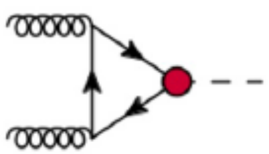


Non-trivial EFT parameter combinations not changing the inclusive cross-section but changing the distributions: **impact of differential measurements**

Going beyond…

ttH and ggH are more than just the top Yukawa:





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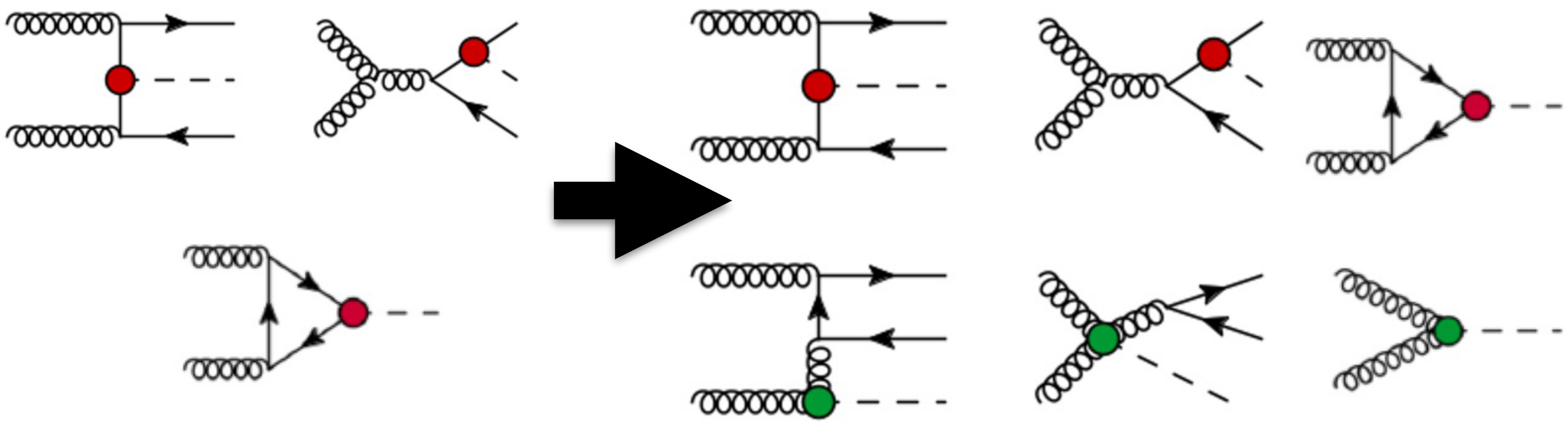

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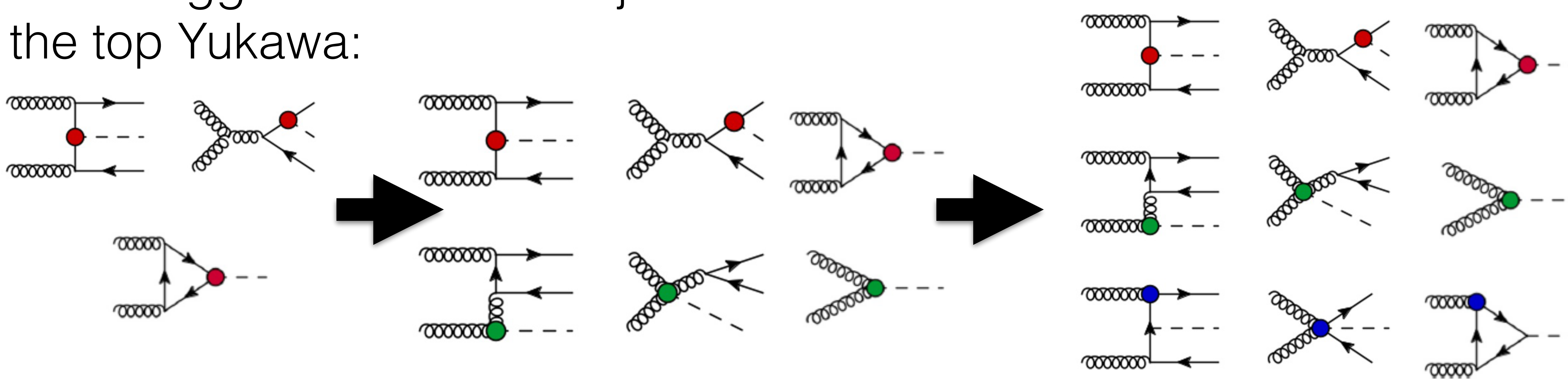

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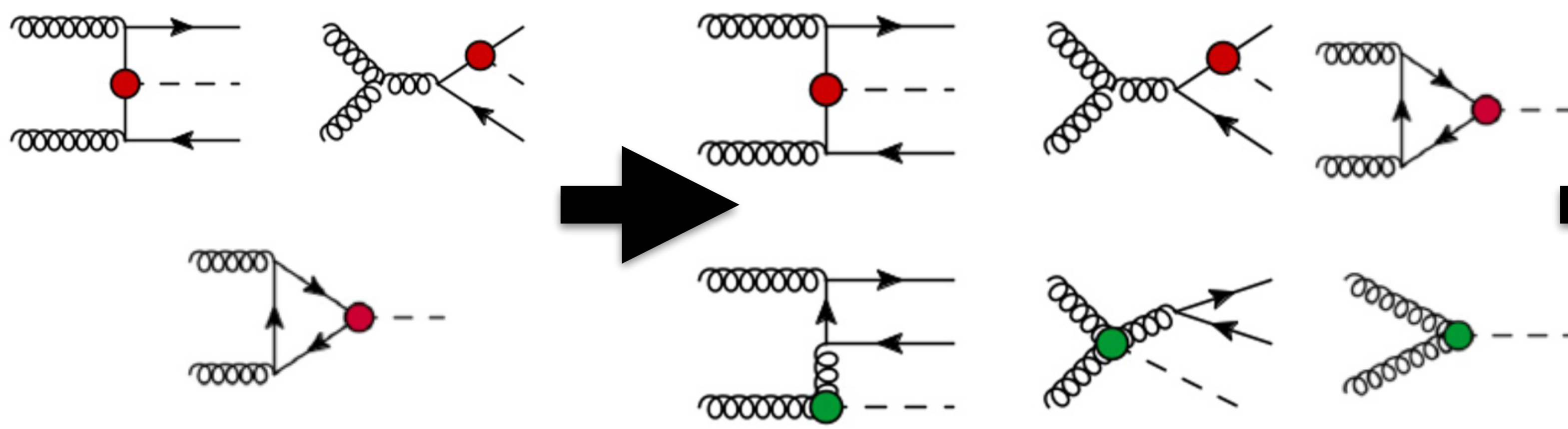

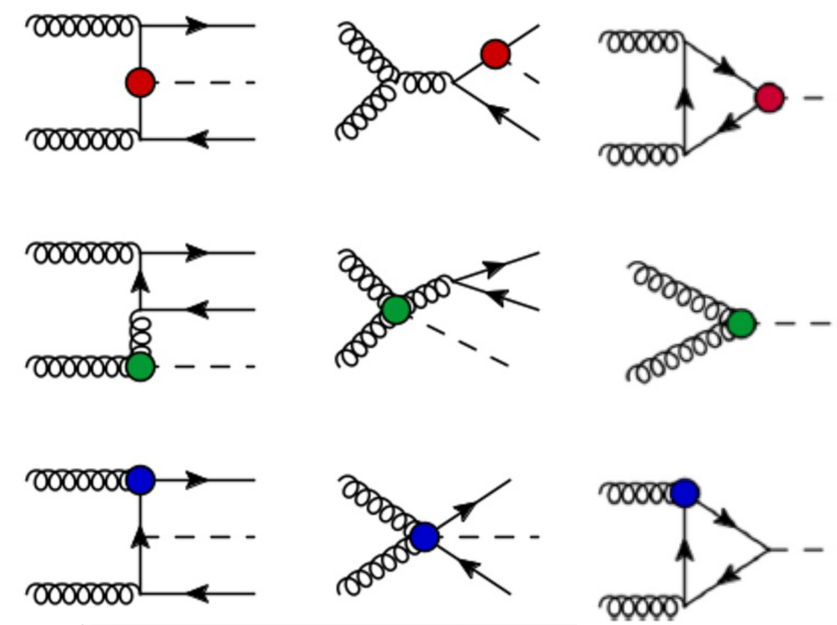

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$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

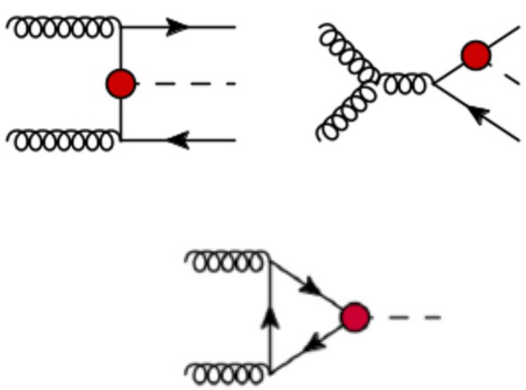
The SMEFT

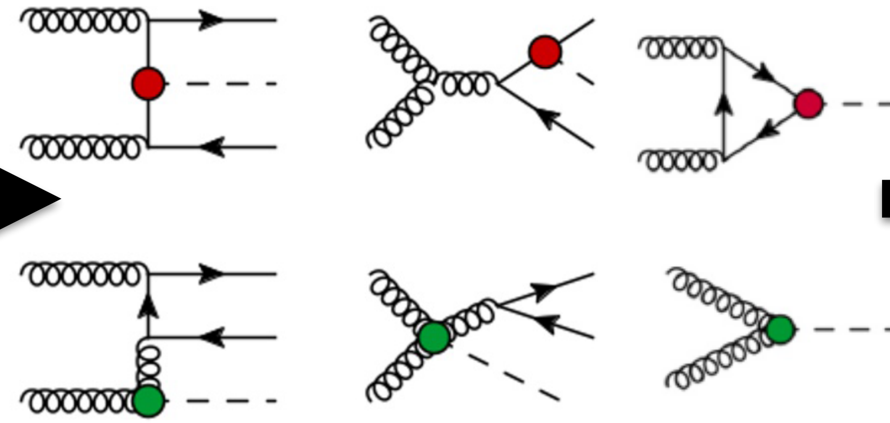
$$\mathcal{L}_{\rm Eff} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(6)} O_i^{(6)}}{\Lambda^2} + \mathcal{O}(\Lambda^{-4})$$

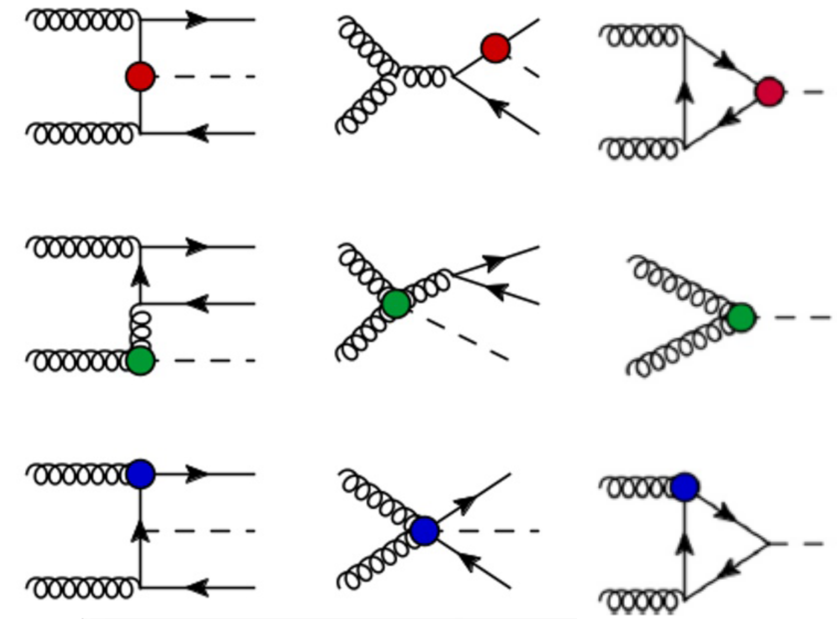
A model independent framework for parametrising deviations from the SM in the absence of light states

Going beyond…

ttH and ggH are more than just the top Yukawa:







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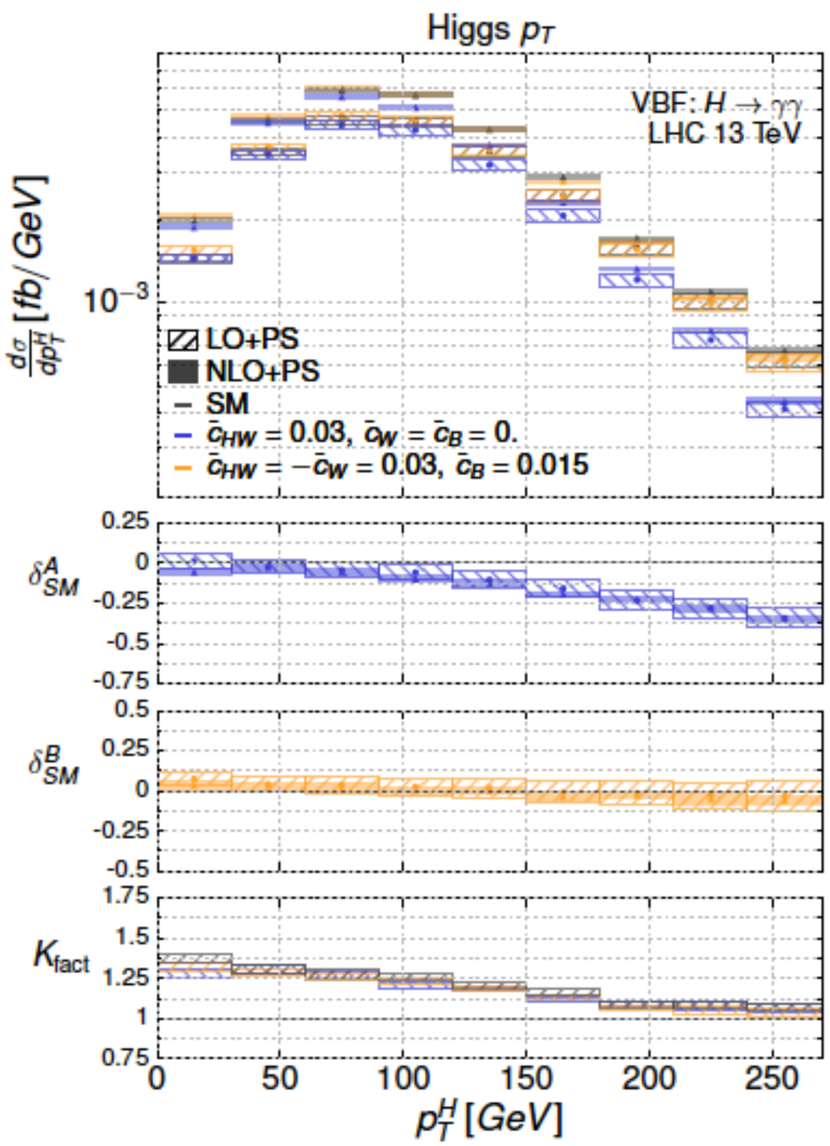
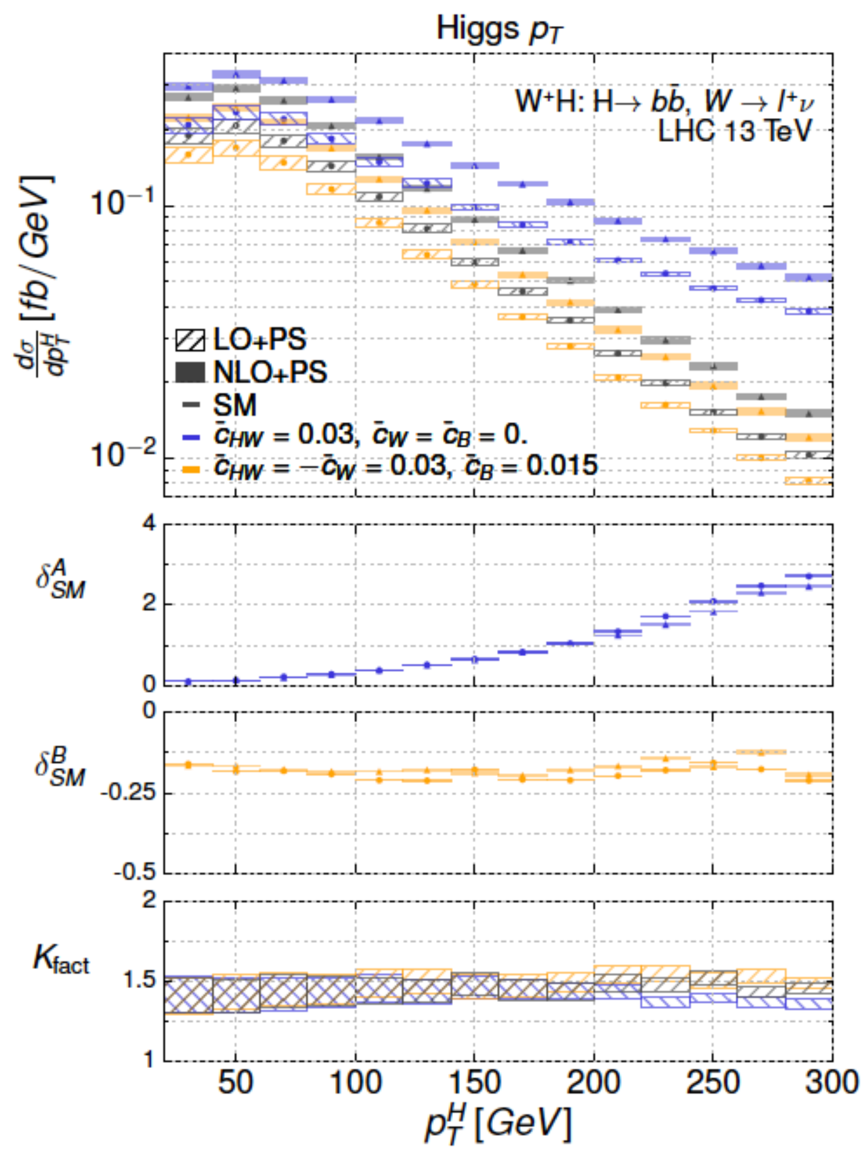
A model independent framework for parametrising deviations from the SM in the absence of light states

A gigantic effort lies ahead: determining the couplings of the dim-6 Lagrangian

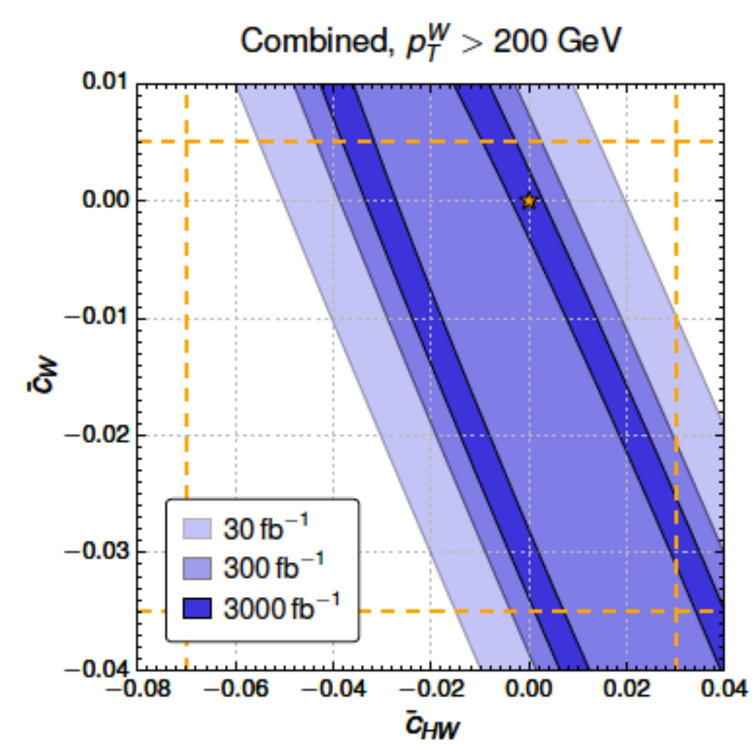
Optimising EFT interpretations(1)

Towards precision calculations in the EFT





$$
\begin{aligned}
\mathcal{L} = \mathcal{L}_{\rm SM} &+ \frac{g'^2}{4\Lambda^2}\bar{c}_{BB}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} \\
&+ \frac{ig}{2\Lambda^2}\bar{c}_W\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}_\mu\Phi\right]D_\nu W^{k,\mu\nu} \\
&+ \frac{ig'}{2\Lambda^2}\bar{c}_B\left[\Phi^\dagger\overleftrightarrow{D}_\mu\Phi\right]\partial_\nu B^{\mu\nu} \\
&+ \frac{ig}{\Lambda^2}\bar{c}_{HW}\left[D_\mu\Phi^\dagger T_{2k}D_\nu\Phi\right]W^{k,\mu\nu} \\
&+ \frac{ig'}{\Lambda^2}\bar{c}_{HB}\left[D_\mu\Phi^\dagger D_\nu\Phi\right]B^{\mu\nu}\ .
\end{aligned}
$$



Degrande et al: arXiv:1609.04833

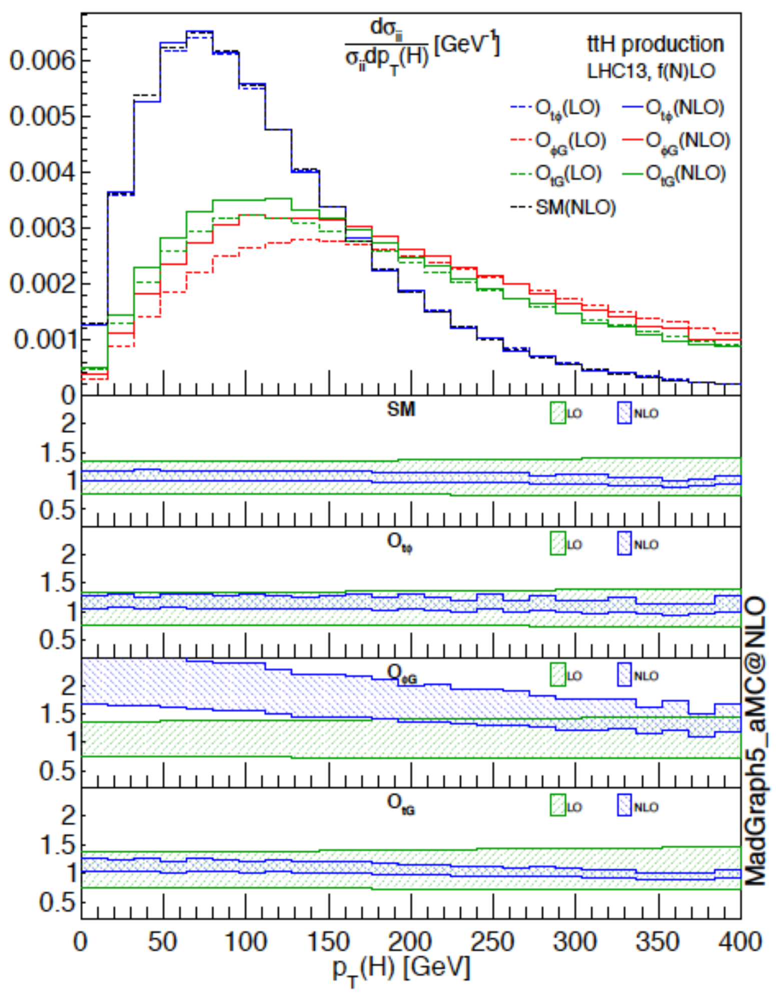
VBF **WH**

Use of differential information will be crucial

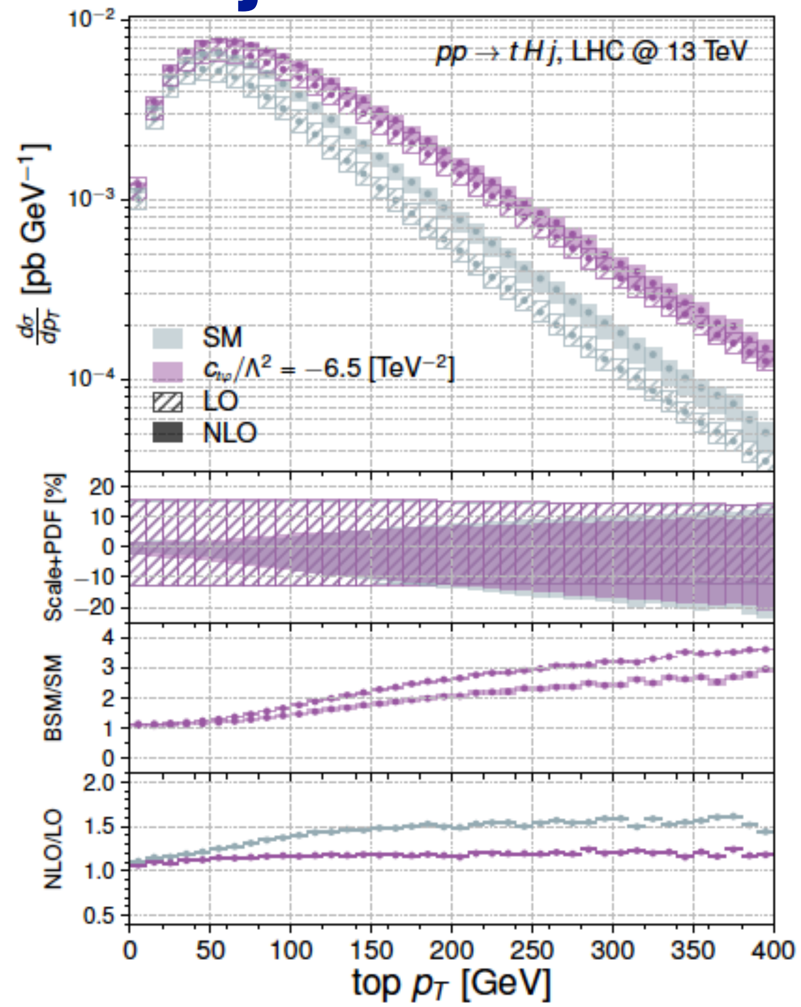
Optimising EFT interpretations(2)

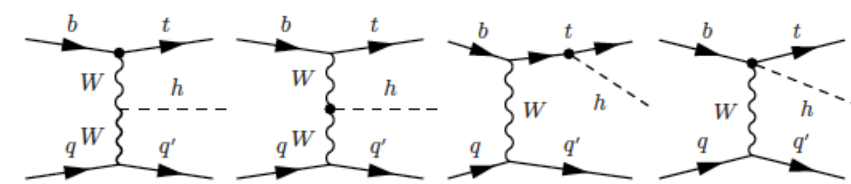
Towards precision calculations in the EFT

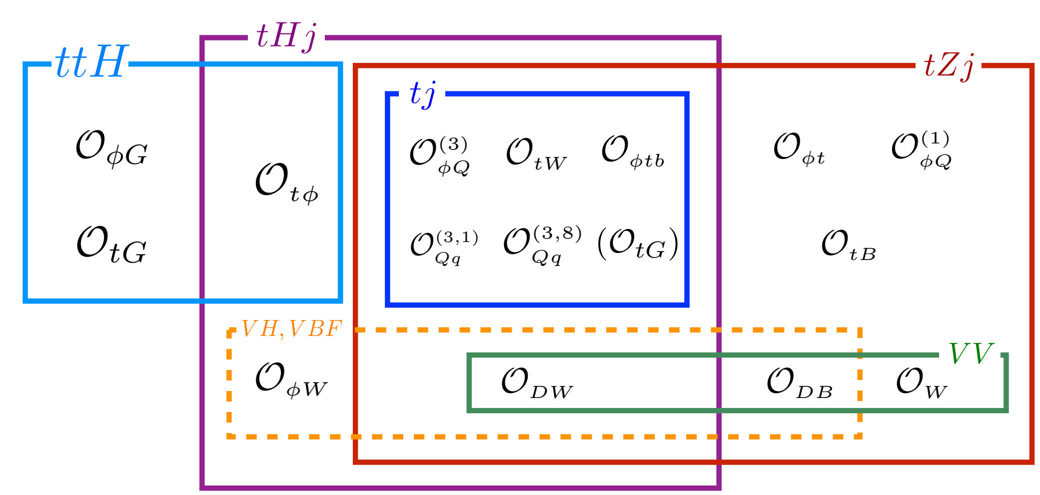
ttH



tHj







The global EFT picture

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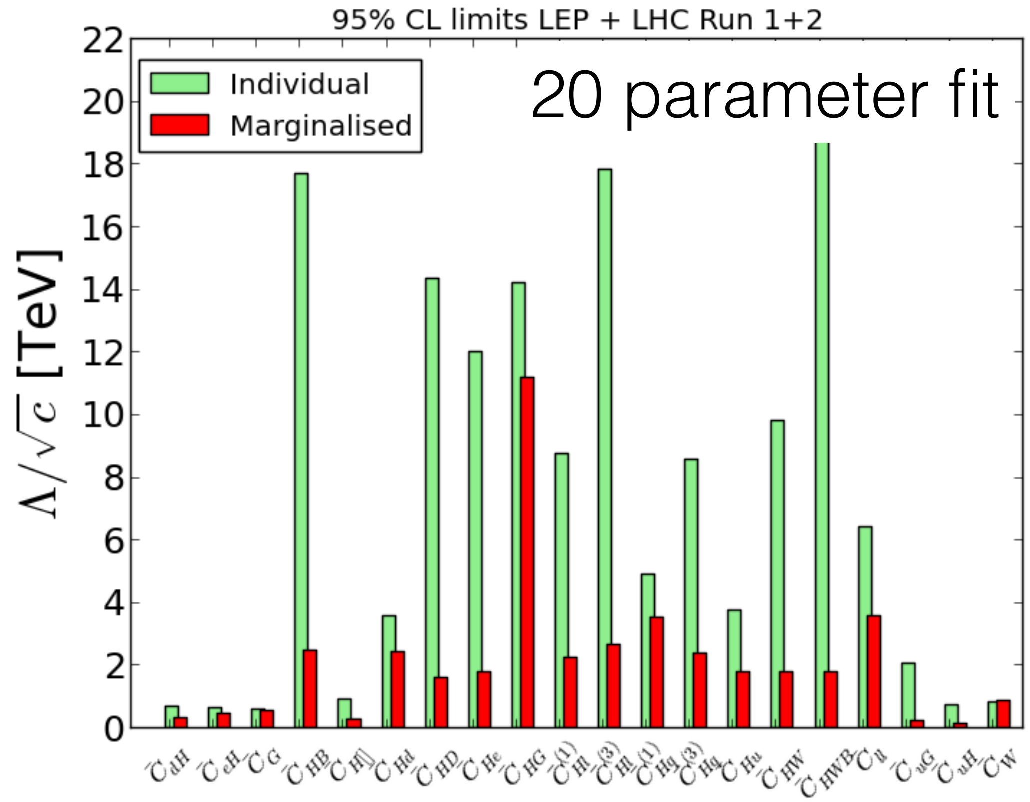
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

- Rare processes: important HL-LHC
- Use differential information
- Higher-order corrections for the EFT have become available for a range of processes

Towards EFT global fits



A Global fit: LEP and LHC Run I and II

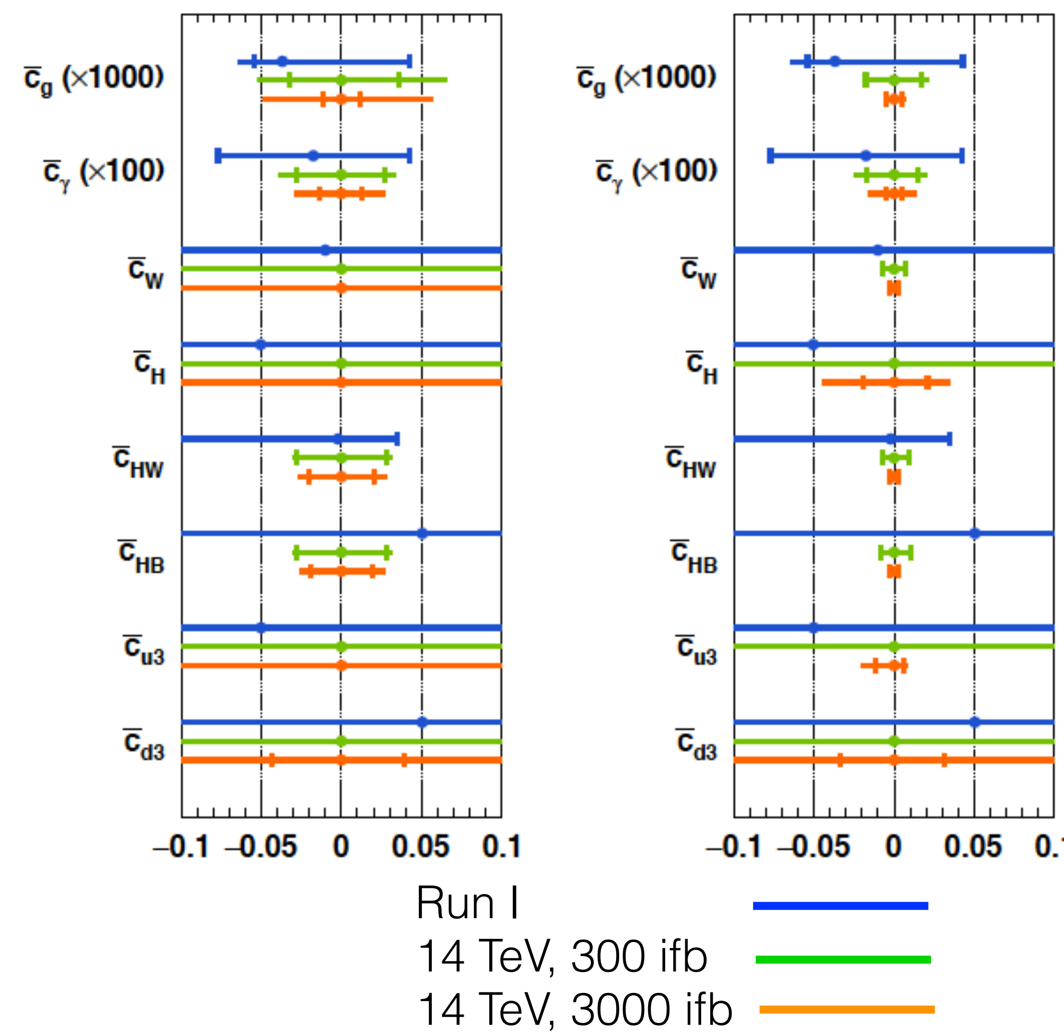
$$
\begin{aligned}
\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset\ & \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l) \\
& + \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2}H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu} \\
& + \frac{\bar{C}_{He}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d) \\
& + \frac{\bar{C}_{Hq}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}_{Hq}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset\ & \frac{\bar{C}_{eH}}{v^2}y_e(H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2}y_d(H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2}y_u(H^\dagger H)(\bar{q}u\widetilde{H}) \\
& + \frac{\bar{C}_G}{v^2}f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu} + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2}y_u(\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\,G_{\mu\nu}^A \\
& + \frac{\bar{C}_{HW}}{v^2}H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2}H^\dagger H\, B_{\mu\nu}B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2}H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}\,.
\end{aligned}
$$

Ellis et al arXiv:1803.03252

The future of global fits

Inclusive   Differential

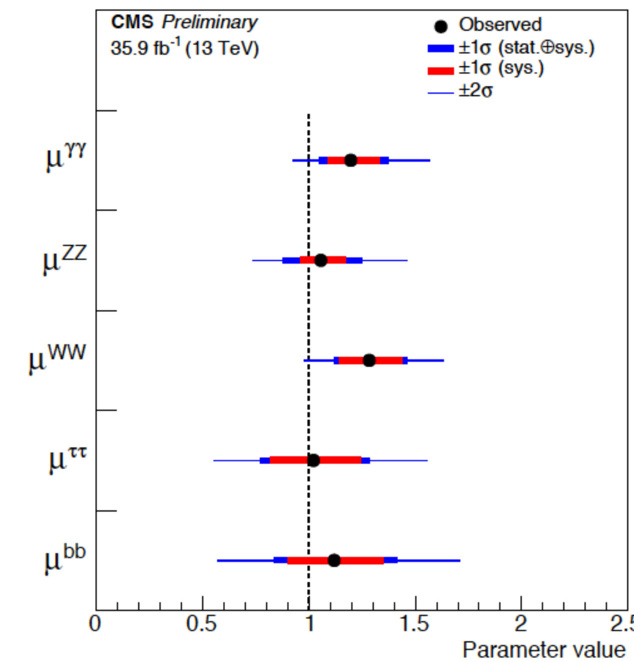


Using differential information will be crucial

Englert, Kogler, Spannowsky arXiv:1511.05170

Higgs couplings beyond the 3rd generation

Run I and II results indicate that vector bosons and third generation fermions get their masses from the Higgs



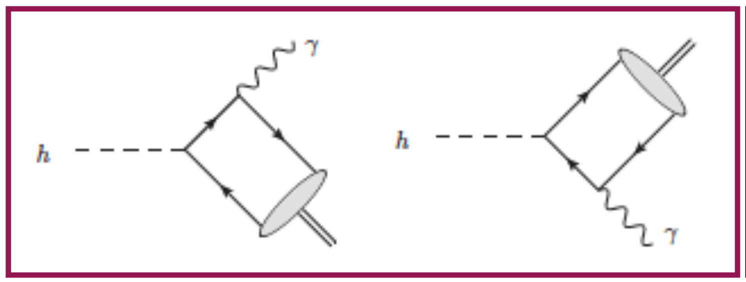
Is this the case for the 1st and 2nd generation? Do they get their masses from the same scalar doublet?

An opportunity to test flavour models which predict deviations from the SM

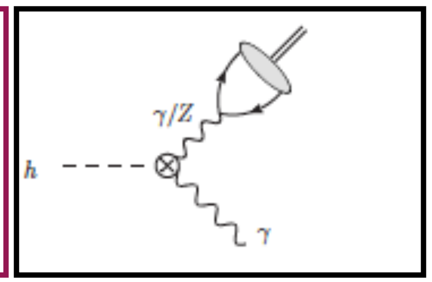
Light quark Yukawas (1)

A challenge and an opportunity:

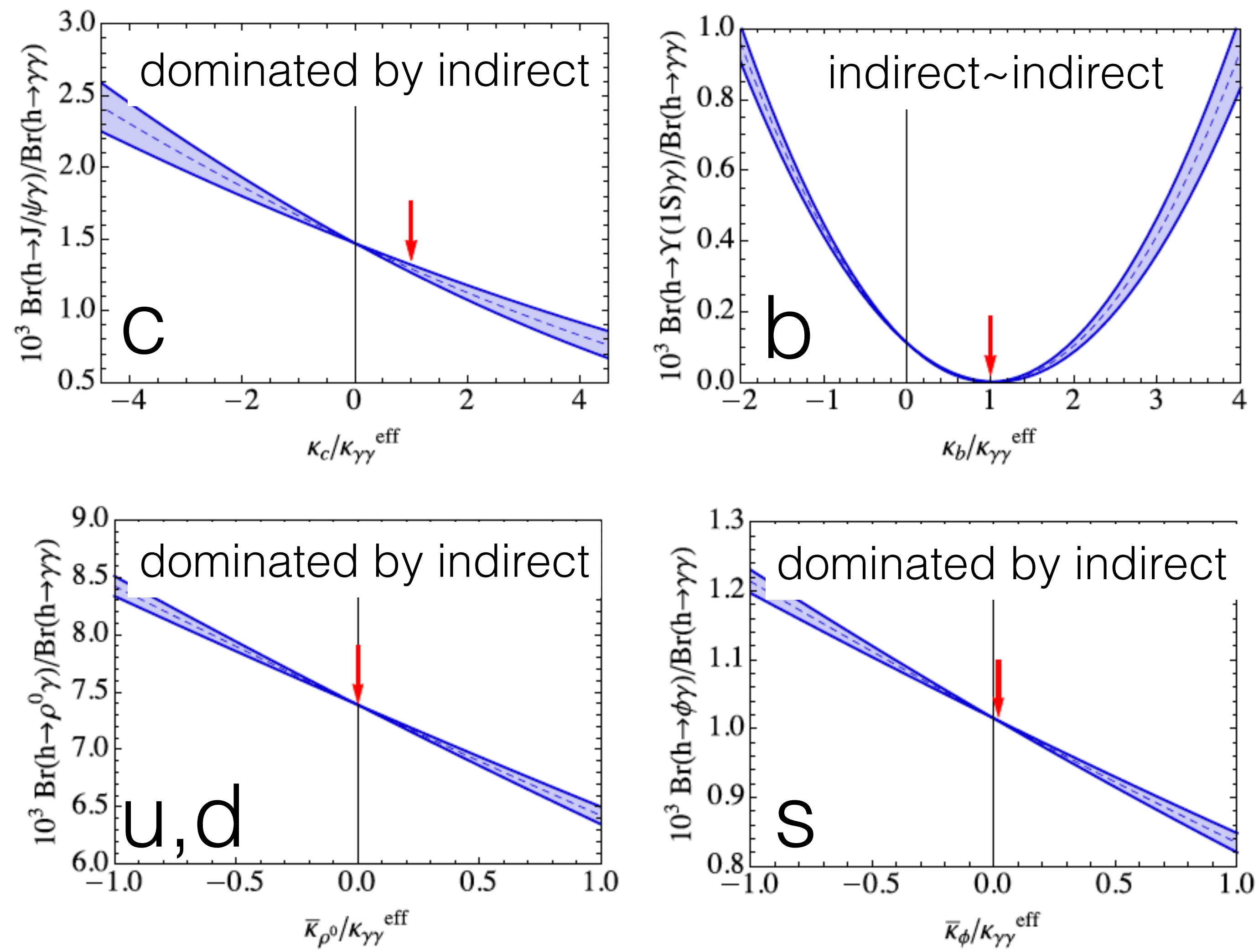
Rare radiative decays to vector mesons:



Direct: sensitive to the quark Yukawa



Indirect



Koenig, Neubert arXiv:1505.03870

SM predictions:

$\mathcal{B}(H \to J/\psi\gamma) \sim 3 \times 10^{-6}$ $\mathcal{B}(H \to Y(1S)\gamma) \sim 5 \times 10^{-9}$

$\mathcal{B}(H \to \rho\gamma) \sim 2 \times 10^{-5}$ $\mathcal{B}(H \to \phi\gamma) \sim 2 \times 10^{-6}$

First LHC results:

$\mathcal{B}(H \to J/\psi\gamma) < 1.5 \times 10^{-3} = 500\,\mathrm{x}\,\mathrm{SM}$

$\mathcal{B}(H \to \phi\gamma) < 4.8 \times 10^{-4} = 208\,\mathrm{x}\,\mathrm{SM}$

$\mathcal{B}(H \to \rho\gamma) < 8.8 \times 10^{-4} = 52\,\mathrm{x}\,\mathrm{SM}$

(arXiv:1501.03276 and ATLAS-CONF-2017-057)

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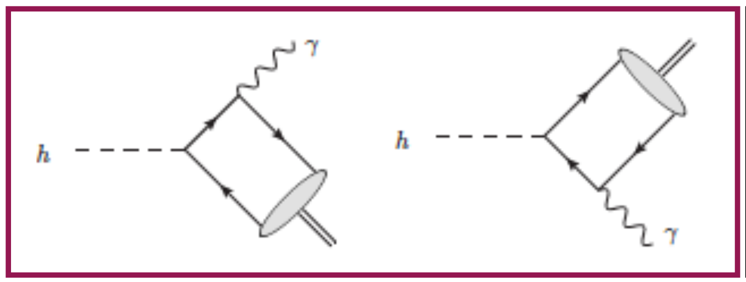

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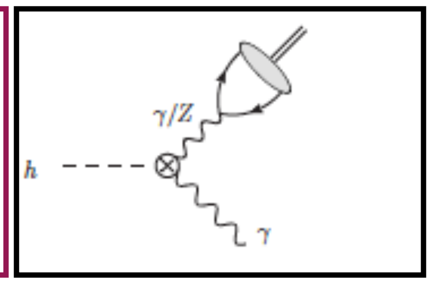
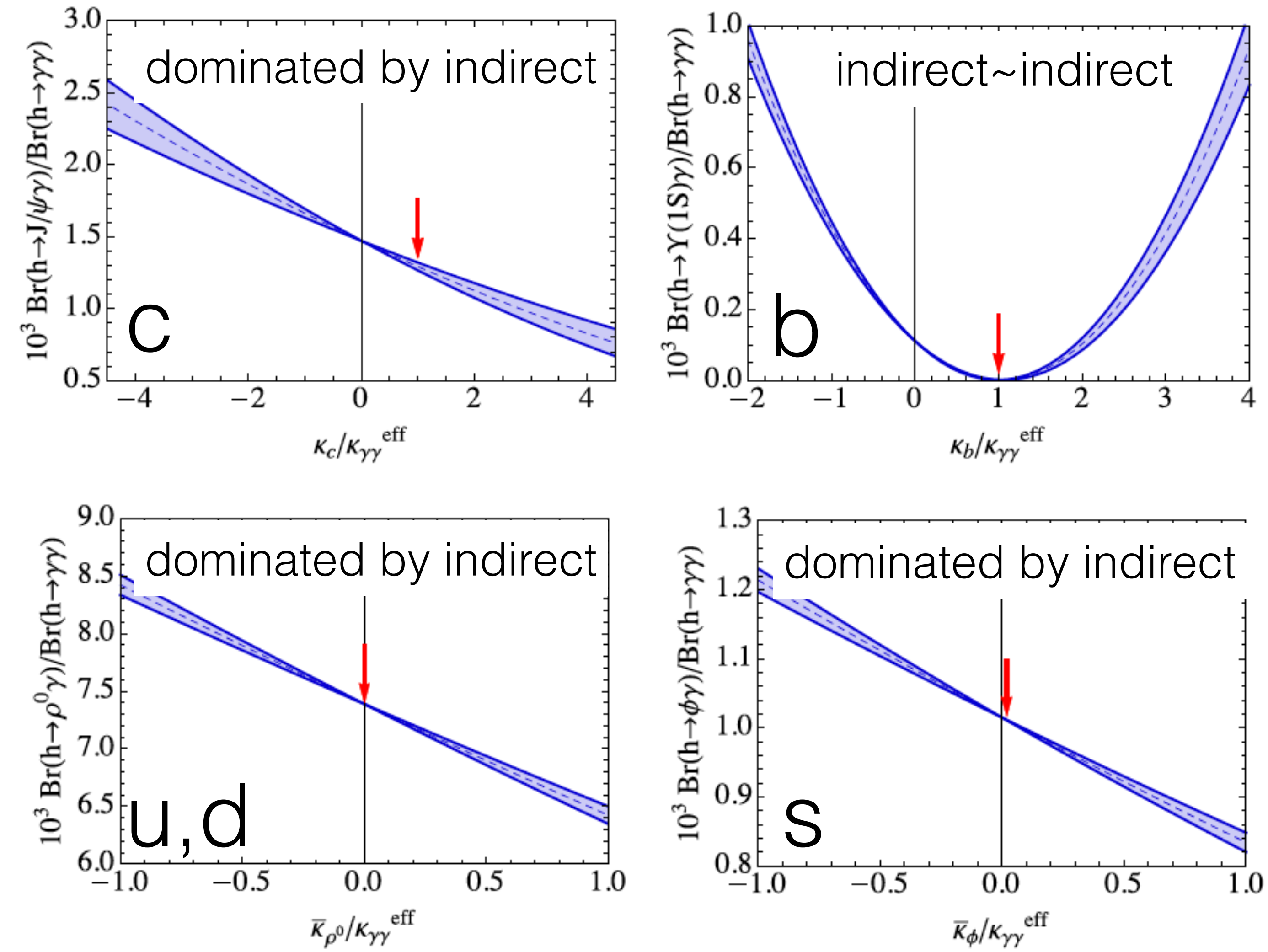


Indirect



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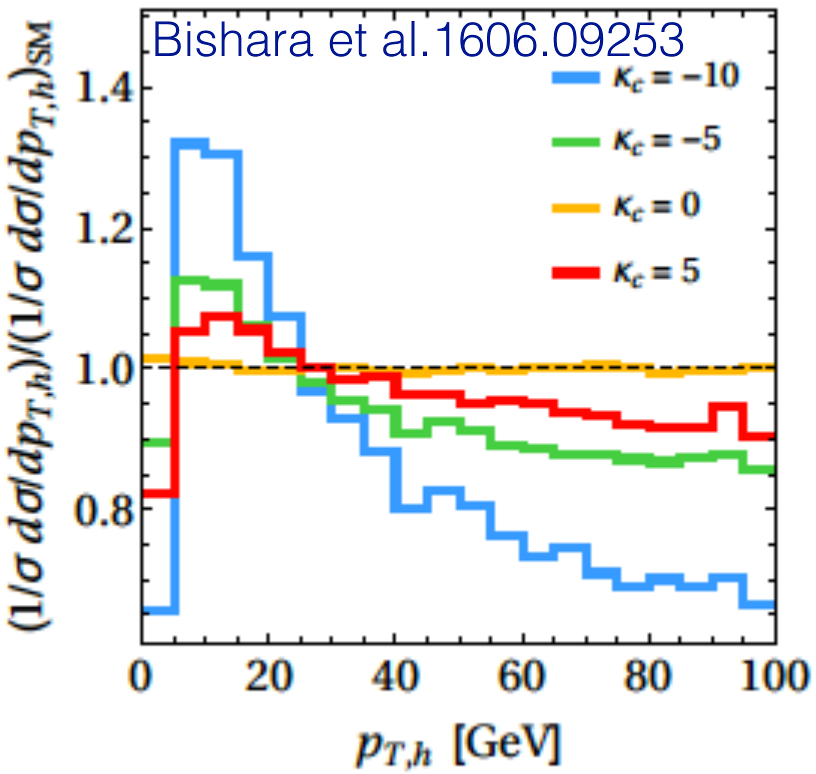
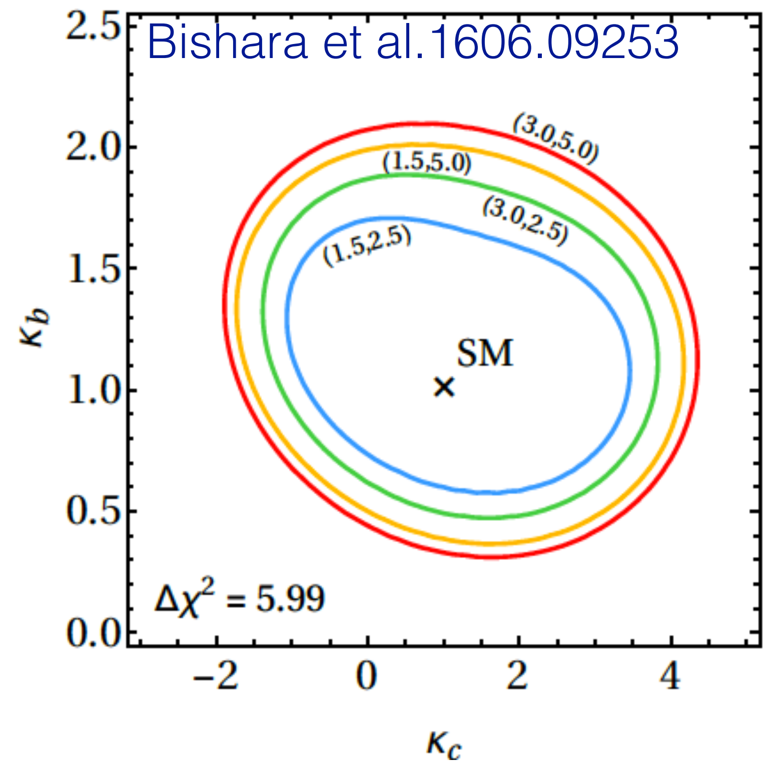
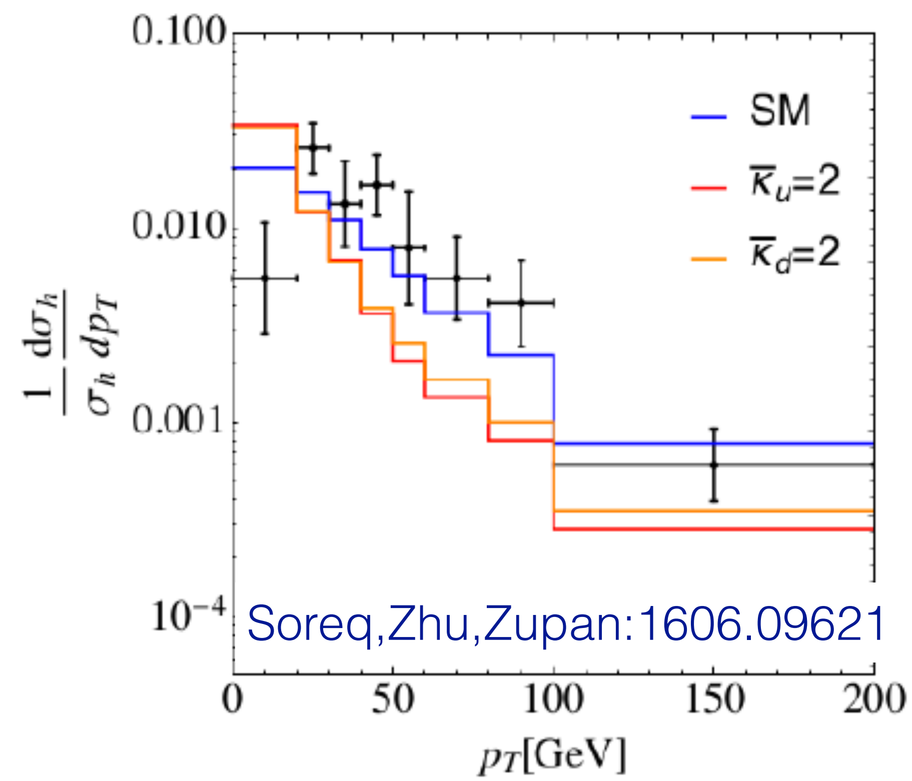
Lots of room for BSM deviations
Great opportunity for HL-LHC

Light quark Yukawas (2)

New idea: Using kinematic distributions i.e. the Higgs pT







κ_c

LHC Run I: $[-16, 18]$

LHC Run II: $[-1.4, 3.8]$

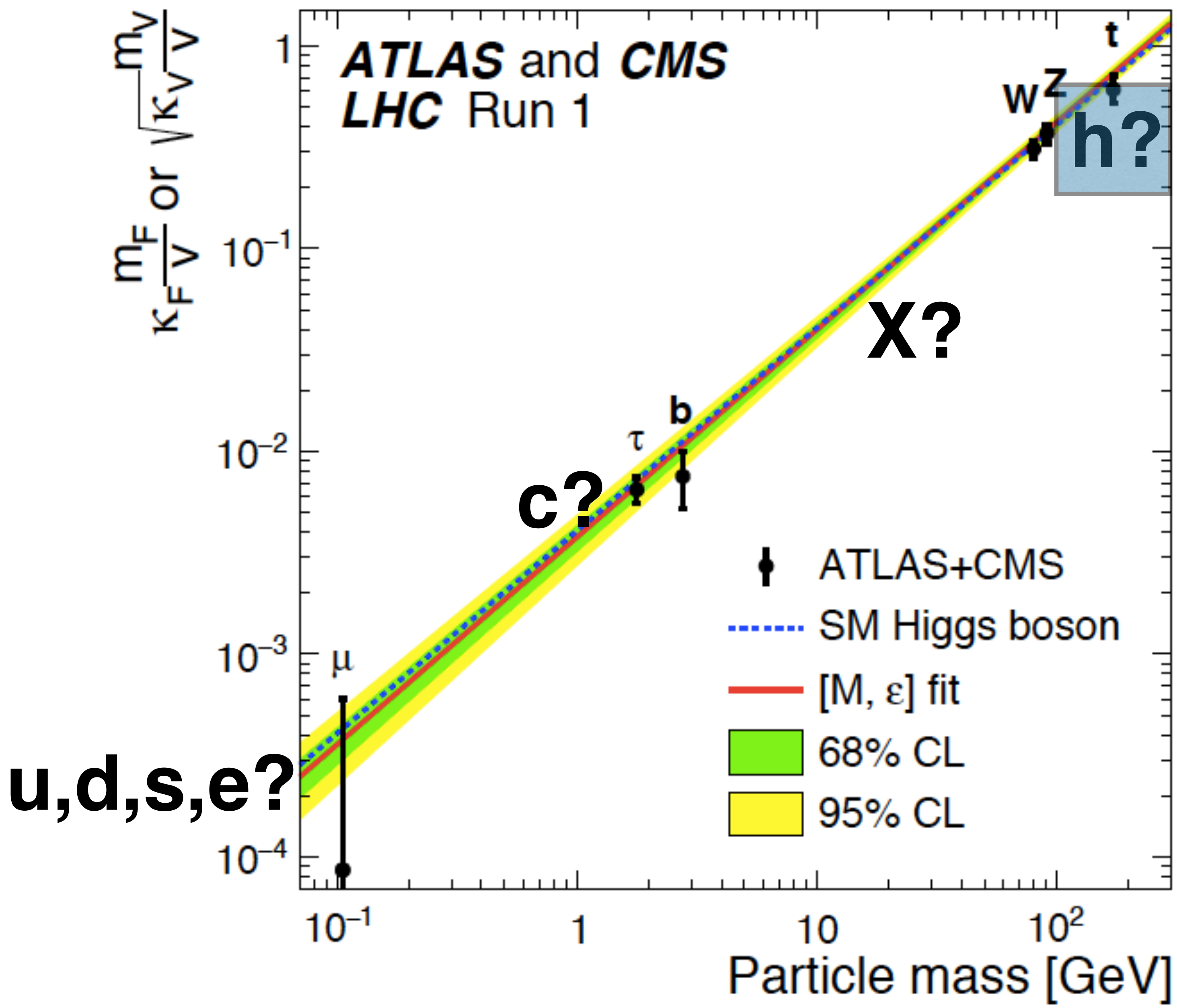
$\boxed{\text{HL-LHC: } [-0.6, 3.0]}$

1st generation

To be fully explored

Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging)
(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)
$ZH(H \to c\bar{c})$ gives a limit of 110 x SM expectation (ATLAS-CONF-2017-078)

A? H? $H^{+/-}$?



III. The Higgs potential

The Higgs potential

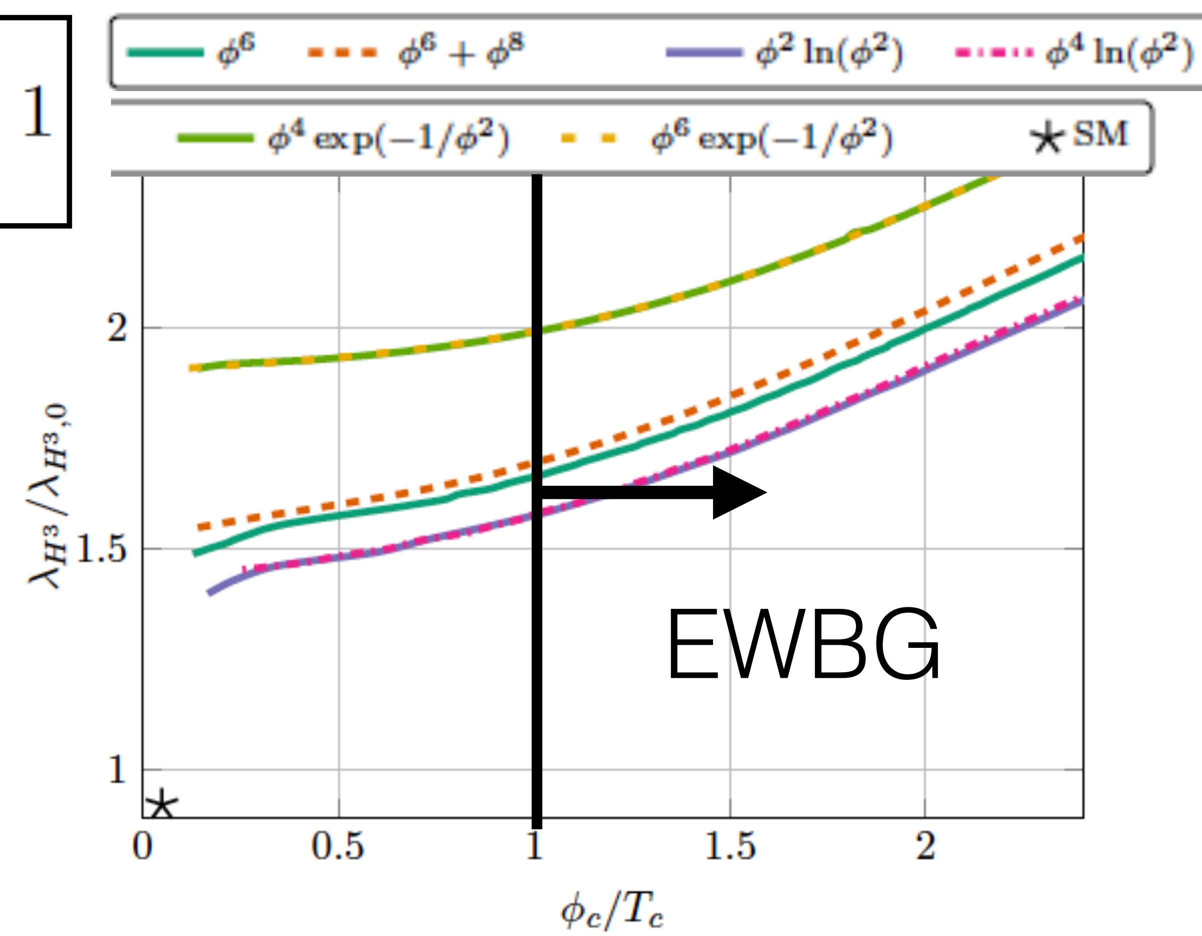
Higgs potential: $$\boxed{V(H)=\frac{1}{2}M_H^2H^2+\lambda_{HHH}vH^3+\frac{1}{4}\lambda_{HHHH}H^4}$$

Fixed values in the SM: $$\boxed{\lambda_{HHH}=\lambda_{HHHH}=\frac{M_H^2}{2v^2}}$$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

What can measuring λ_{HHH} tell us?

Electroweak baryogenesis requires a first order strong EWPT $\rightarrow$ $\boxed{\frac{\phi_c}{T_c}\gtrsim 1}$



Reichert et al: arXiv:1711.00019

The Higgs potential

Higgs potential: $$\boxed{V(H) = \frac{1}{2}M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4}$$

Fixed values in the SM: $$\boxed{\lambda_{HHH} = \lambda_{HHHH} = \frac{M_H^2}{2v^2}}$$

Measuring λ_{HHH} and λ_{HHHH} tests the SM

What can measuring λ_{HHH} tell us?

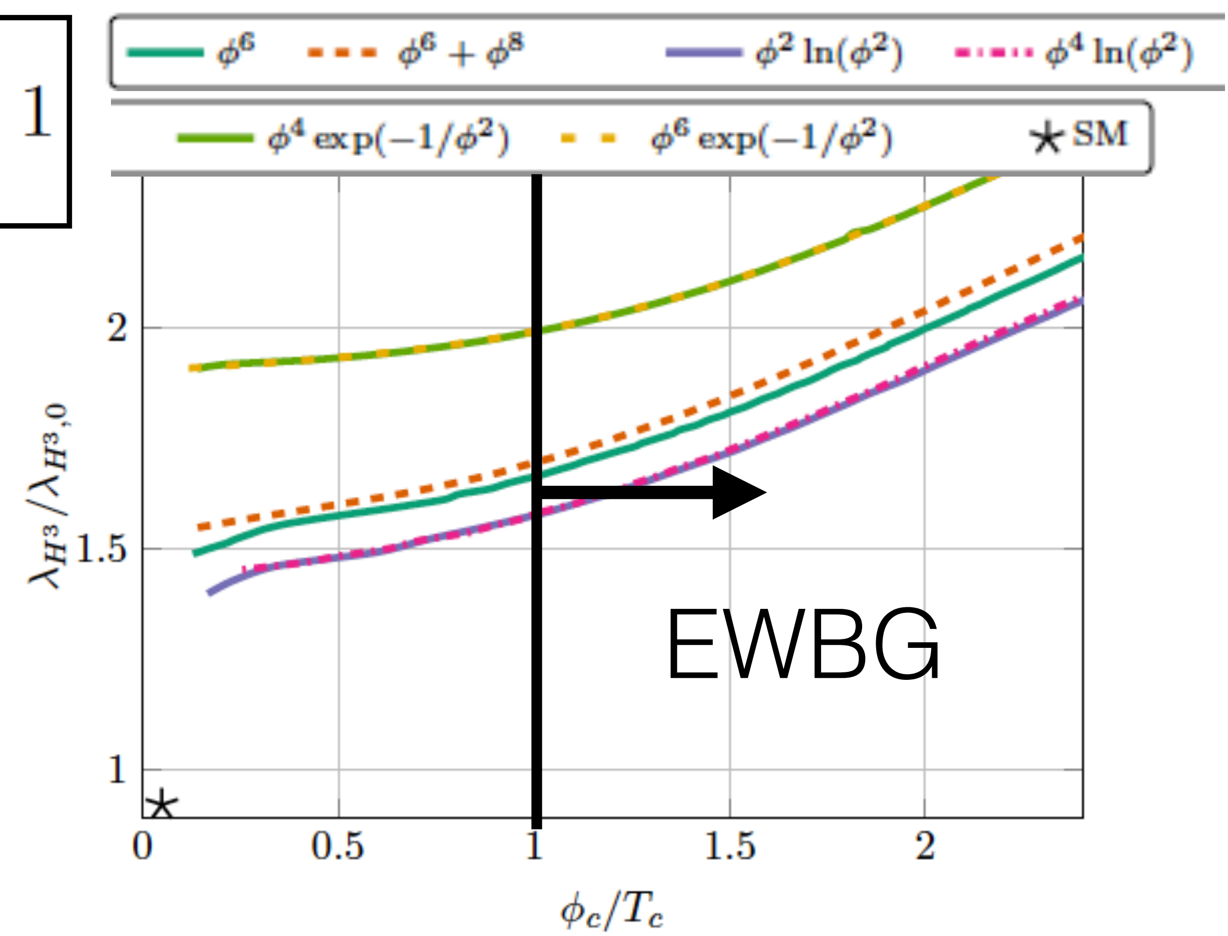
Electroweak baryogenesis requires a first order strong EWPT → $\boxed{\frac{\phi_c}{T_c} \gtrsim 1}$

$\lambda_{H^3}/\lambda_{H^3,SM} < 1.5 : \phi_c/T_c < 1$

EW baryogenesis is disfavoured

$\lambda_{H^3}/\lambda_{H^3,SM} > 2 : \phi_c/T_c > 1$

EW baryogenesis is favoured



Reichert et al: arXiv:1711.00019

Constraining the Higgs self-coupling

Theory constraints: How large can λ_{HHH} be (in particular given Higgs couplings measurements)?
Experimental prospects: Which measurements can be used to constrain λ_{HHH}?

Theoretical constraints on λ_{HHH}

Perturbativity:

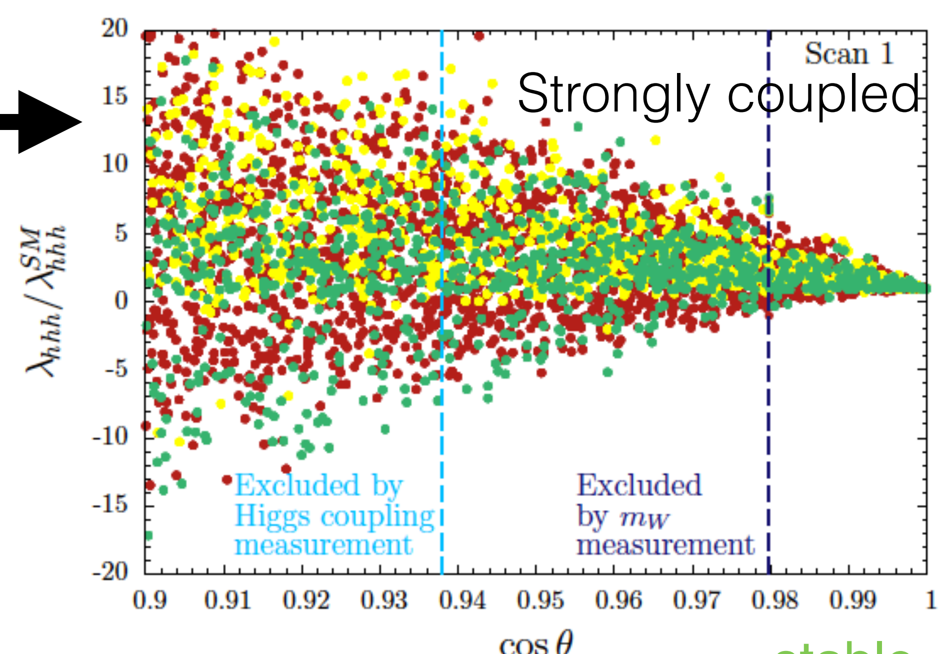
- Partial wave unitarity: $|\mathrm{Re}\, a^0_{hh\to hh}| < 1/2 \quad |\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}| \lesssim 6.5$
- Loop-corrections to λ smaller than λ $|\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}| \lesssim 6$

Di Luzio, Grober, Spannowsky arXiv:1704.02311

Specific UV complete models:

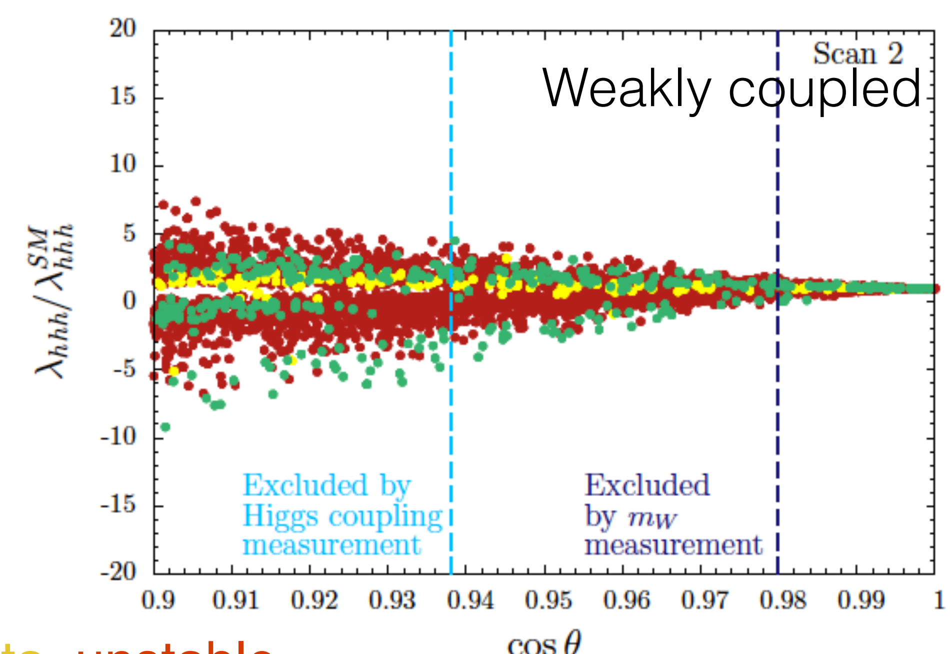
Scalar extensions:

Φ	$\mathcal{O}_\Phi$
$(1,1,0)$	$\Phi H H^\dagger$
$(1,2,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,3,0)$	$\Phi H H^\dagger$
$(1,3,1)$	$\Phi H^\dagger H^\dagger$
$(1,4,\frac{1}{2})$	$\Phi H H^\dagger H^\dagger$
$(1,4,\frac{3}{2})$	$\Phi H^\dagger H^\dagger H^\dagger$



$-1.5 < \lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh} < 8.7$

stable, meta, unstable

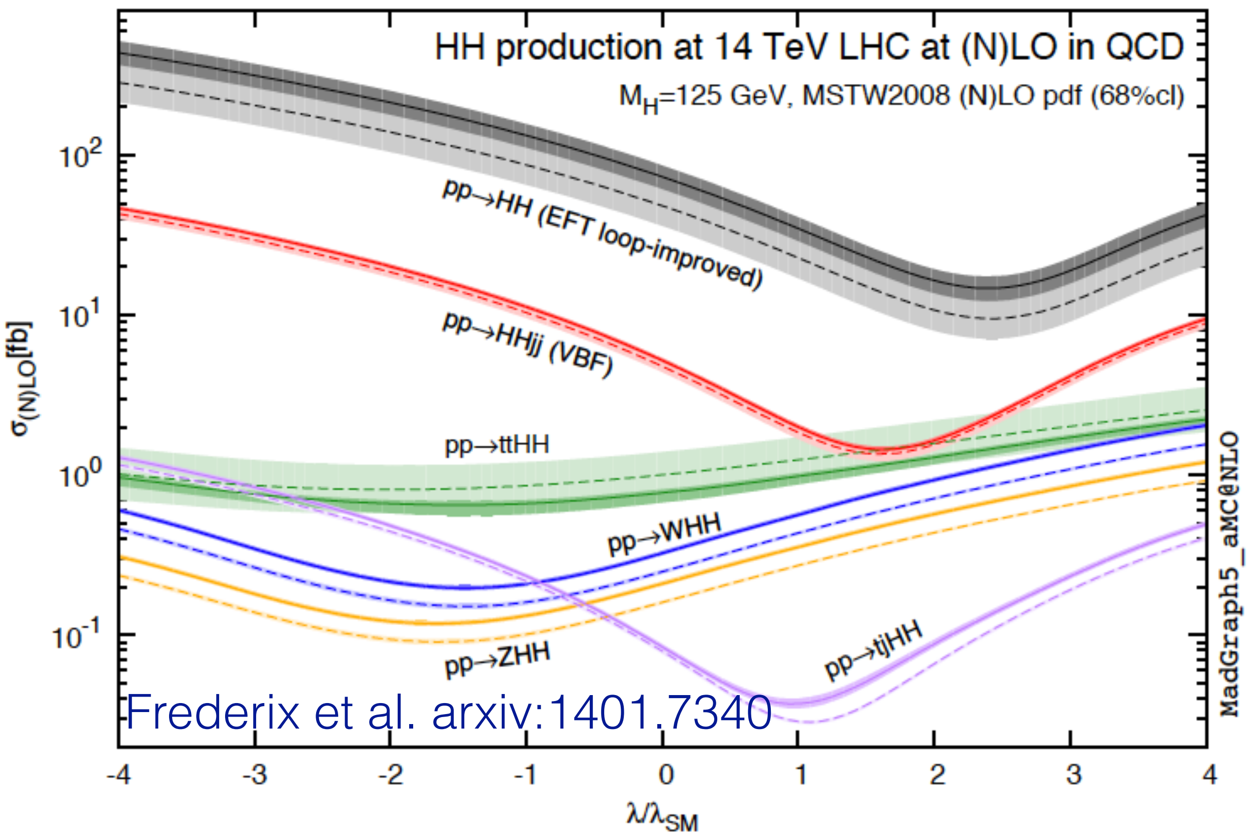


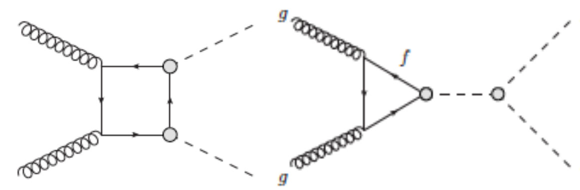
$-0.3 < \lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh} < 2.0$

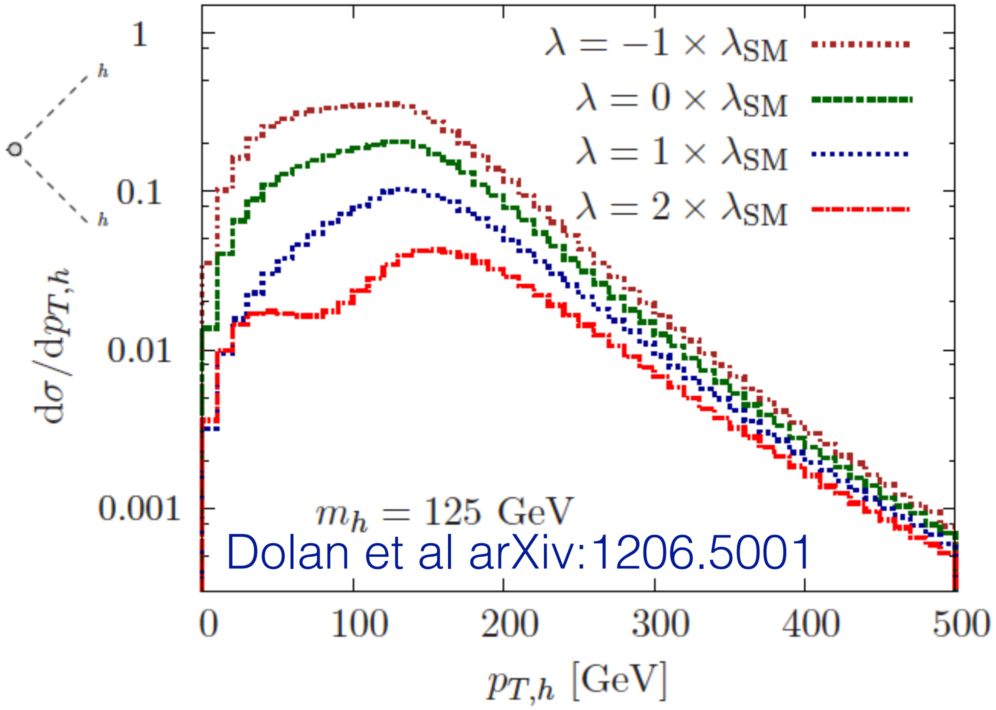
Di Luzio, Grober, Spannowsky arXiv:1704.02311

See also Di Vita et al. 1704.01953: Fine-tuned Higgs portal $|\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}| \lesssim 6$

How to extract λ_{HHH}: 1) HH







SM cross sections

$\sqrt{s}$	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma(HH)$[fb]	$31.05^{+2.2\%}_{-5.0\%}$	$36.69^{+2.1\%}_{-4.9\%}$	$139.9^{+1.3\%}_{-3.9\%}$	$1224^{+0.9\%}_{-3.2\%}$

Grazzini et al arXiv:1803.02463, see Gudrun's talk

Current limits:

CMS: $\sigma/\sigma_{\rm SM} < 19 (bb\gamma\gamma)$

ATLAS: $\sigma/\sigma_{\rm SM} < 30 (bbbb)$

CMS: $\sigma/\sigma_{\rm SM} < 28 (bb\tau\tau)$

Projections for HL-LHC:

$bbbb$ 0.2 < λ/λ_{SM} < 7.0 (stat)

ATL-PHYS-PUB -2016-024

$bb\gamma\gamma$ -0.8 < λ/λ_{SM} < 7.7 (stat)

ATL-PHYS-PUB -2015-046

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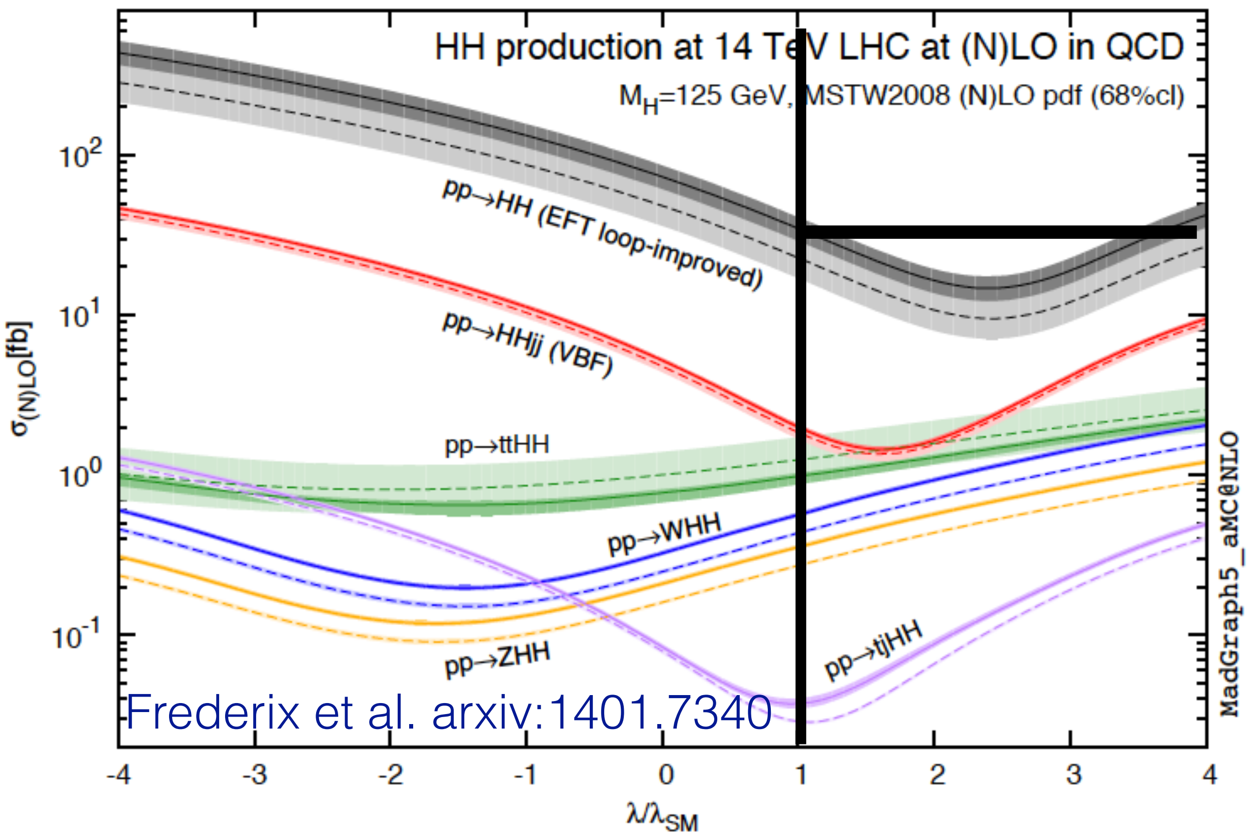

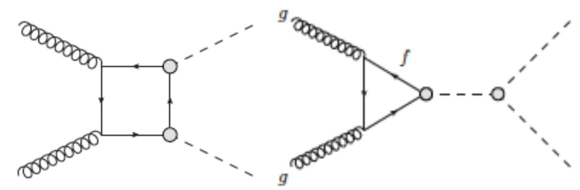

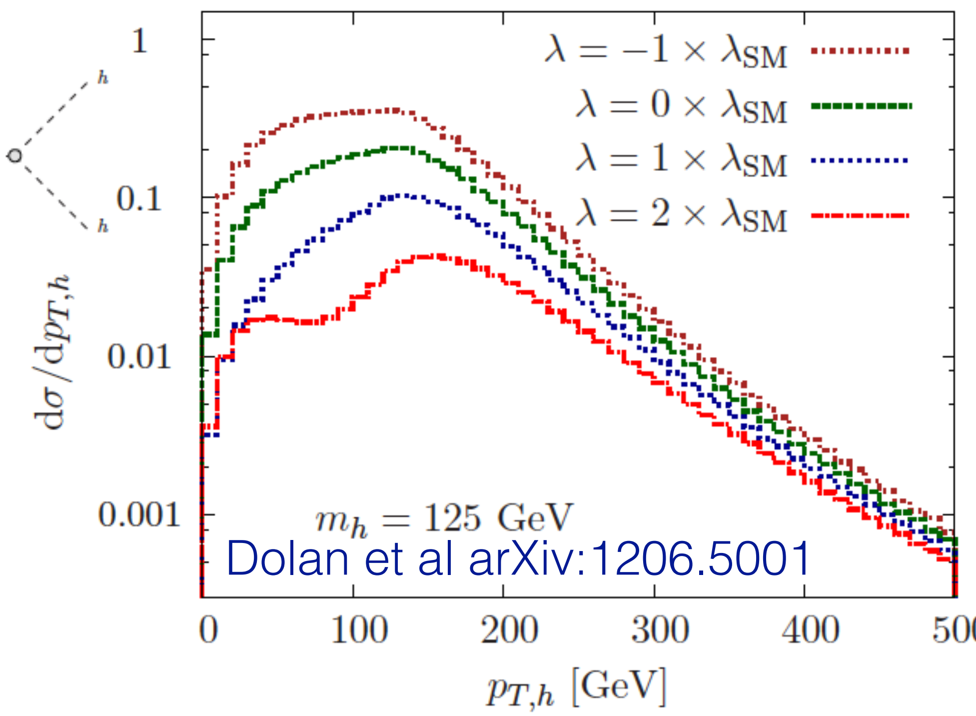

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ATL-PHYS-PUB -2016-024

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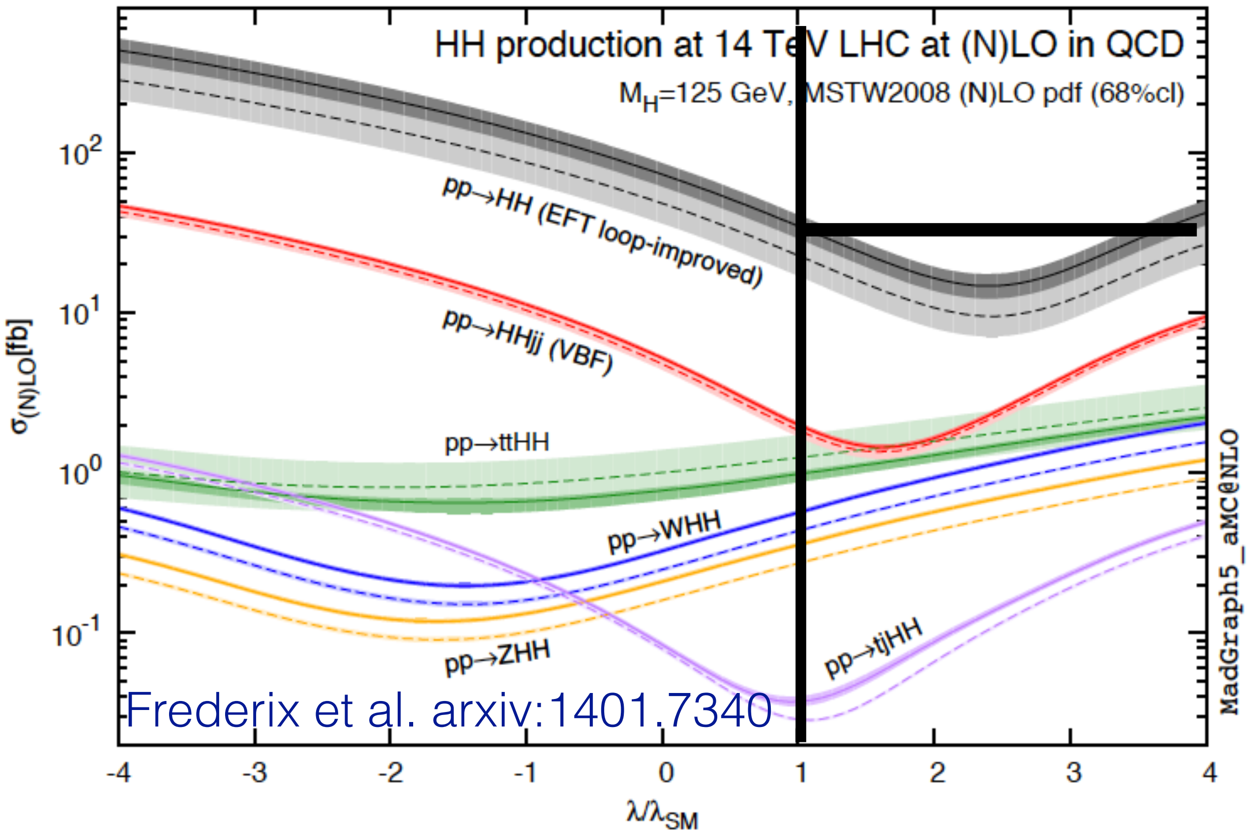

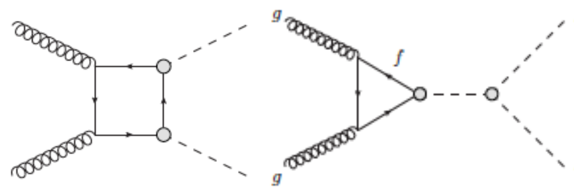

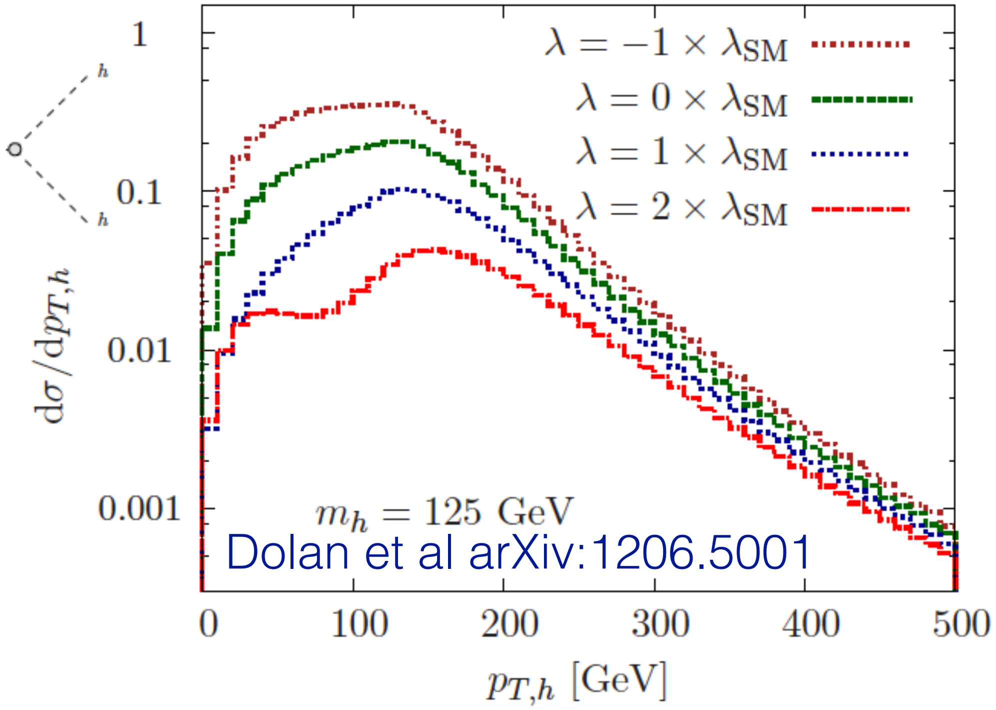

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ATL-PHYS-PUB -2016-024

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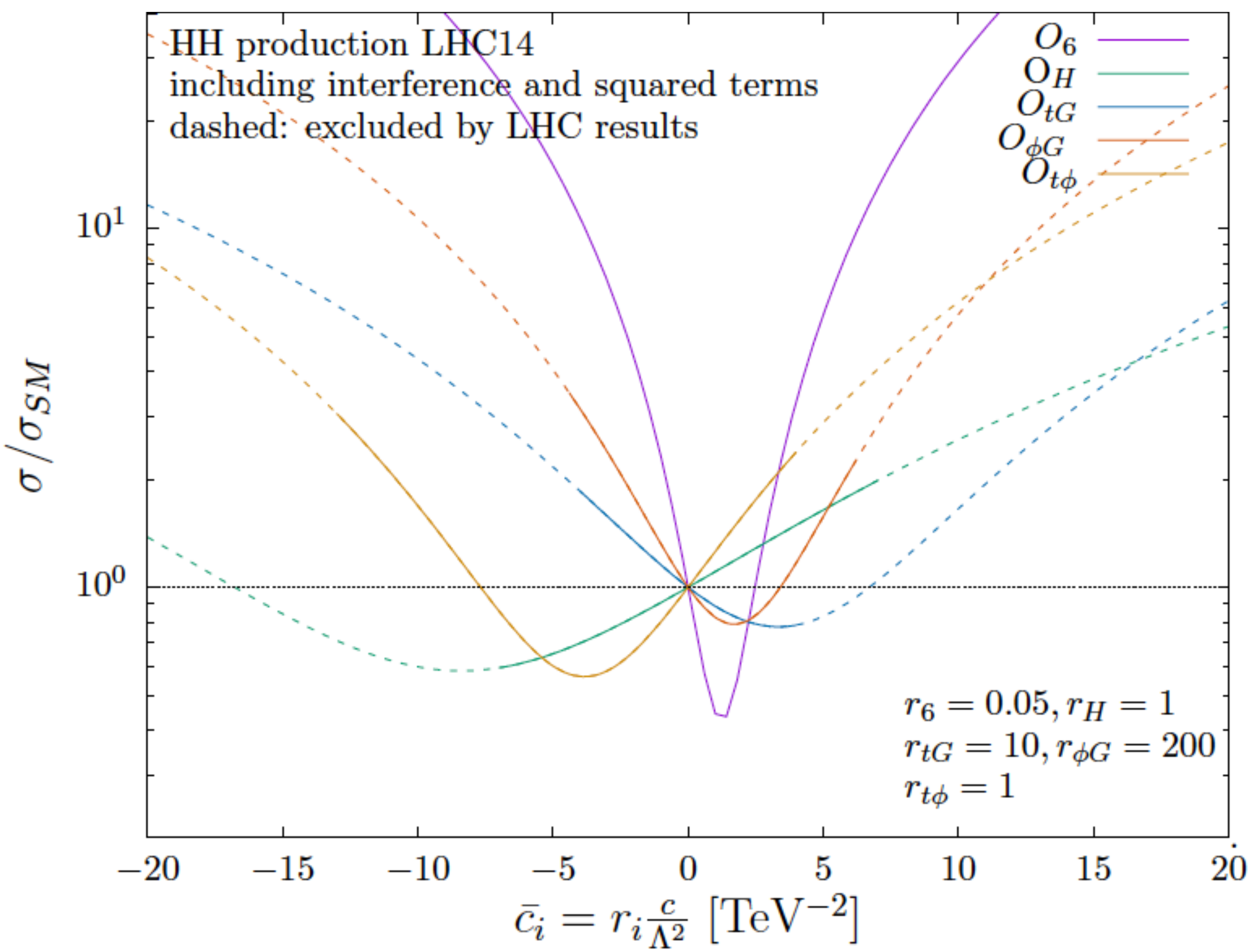
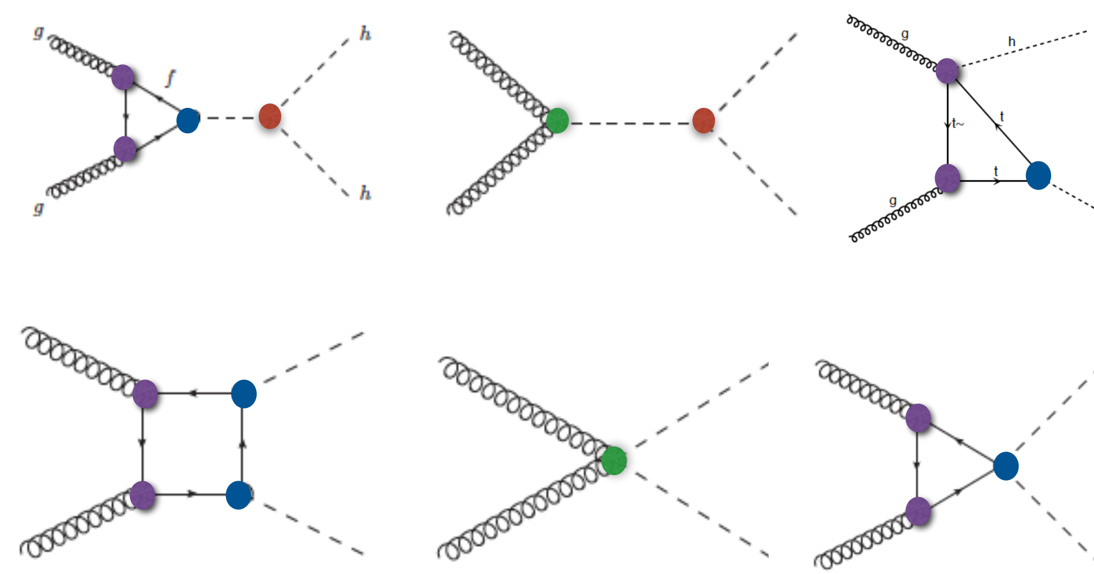
ATL-PHYS-PUB -2015-046

A challenge even for the HL-LHC

How to extract λ_{HHH} from HH?





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top Yukawa, ggh(h) coupling, top-gluon interaction

See also L.Scyboz talk

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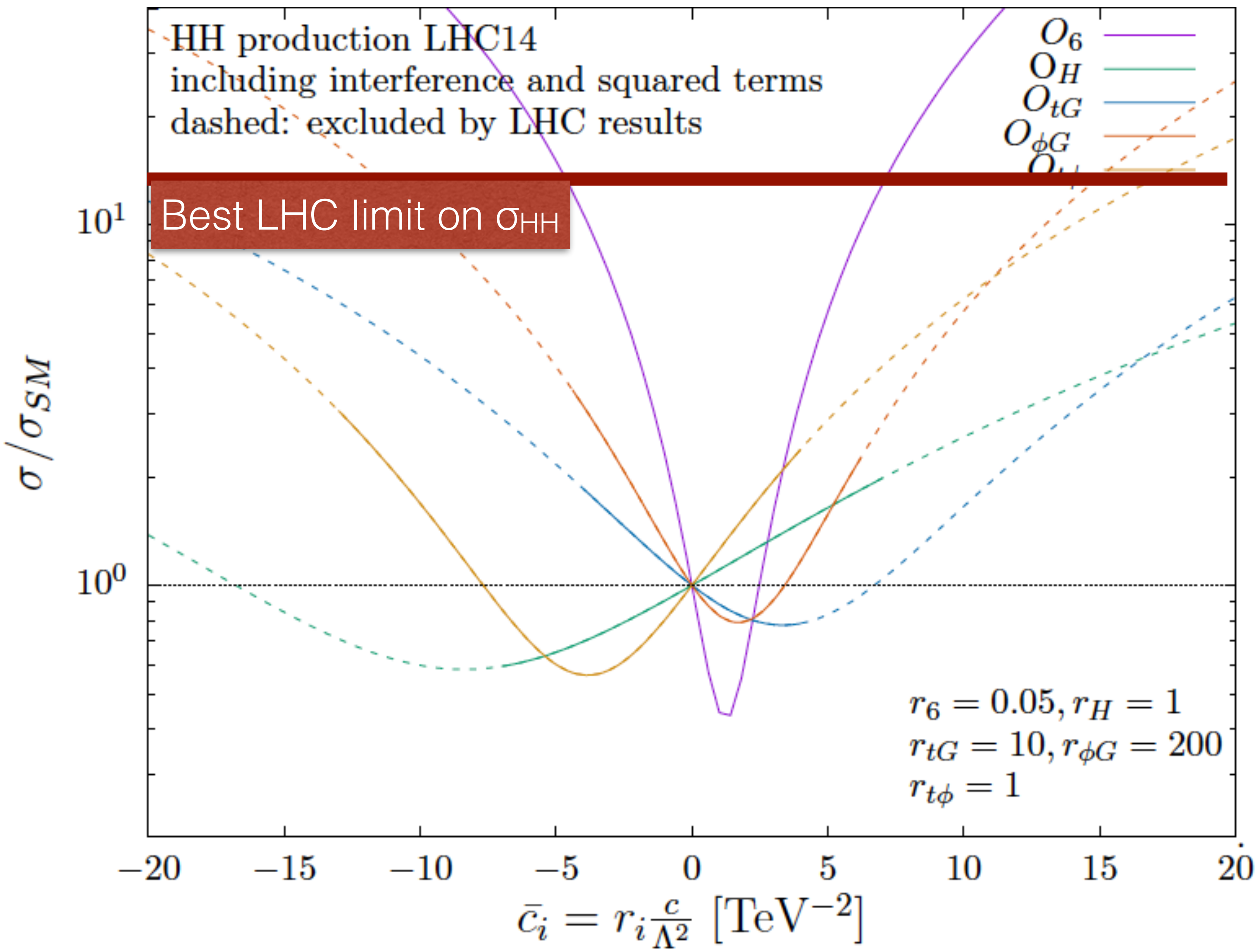

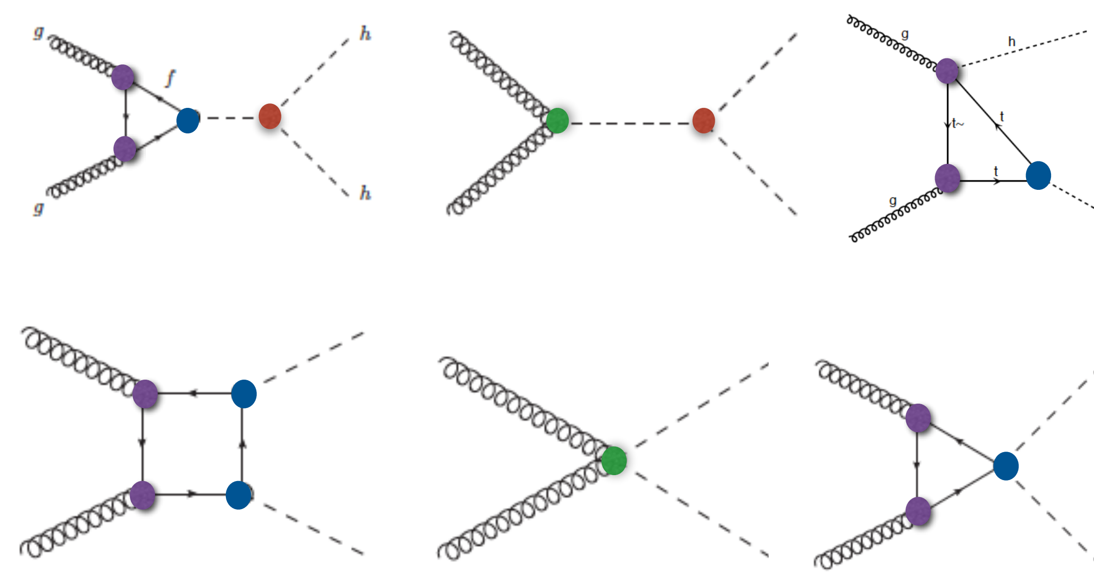

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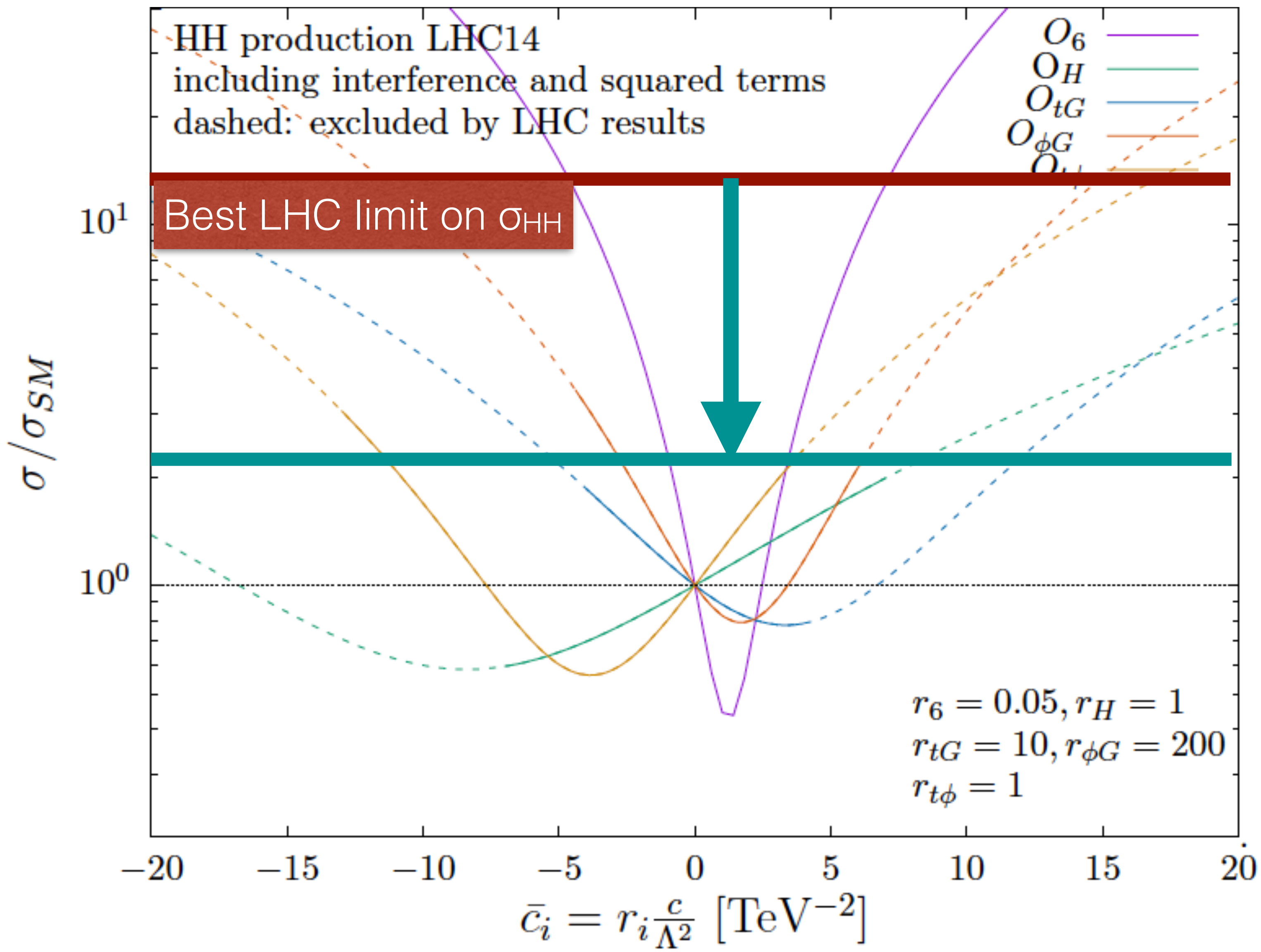
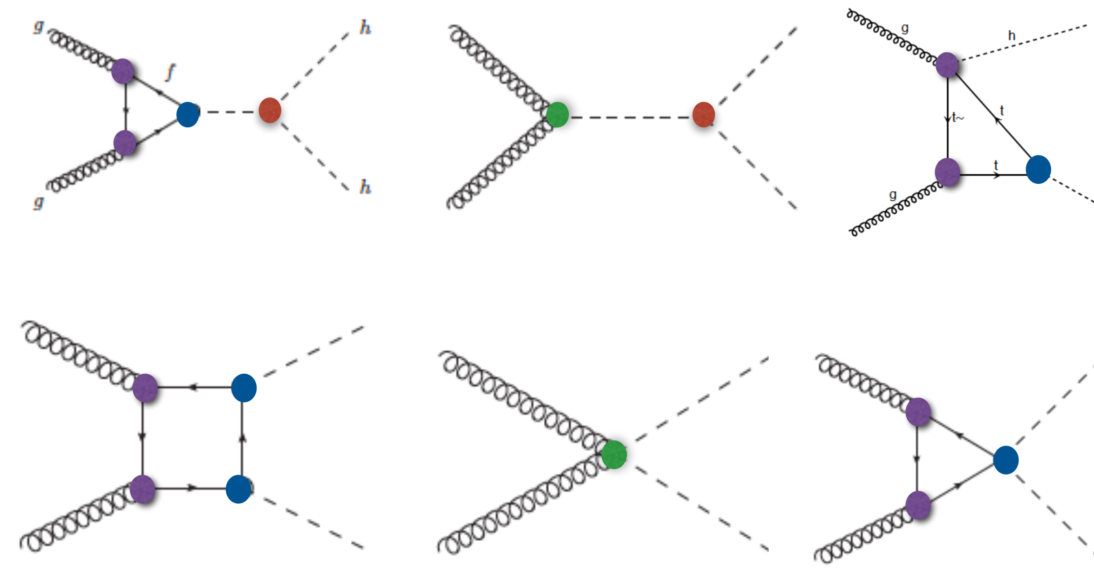
How to extract λ_{HHH} from HH?





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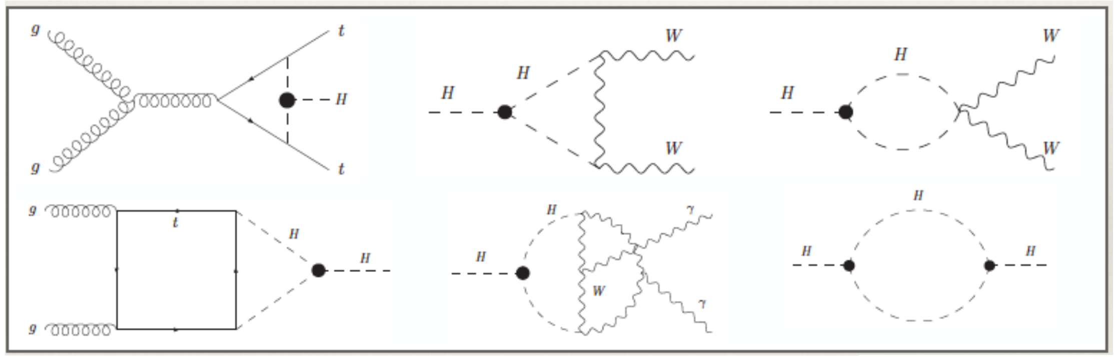
The future

Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM
Differential distributions will also be necessary

How to extract λ_{HHH}: 2) Indirectly



Higgs observables: production and decay at NLO (EW)

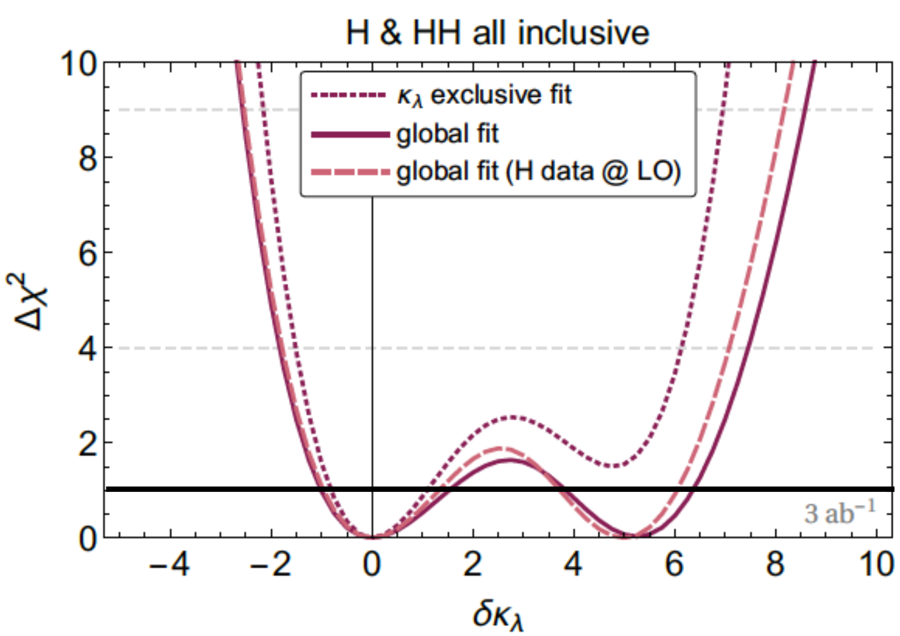
Run I single Higgs results: $\kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

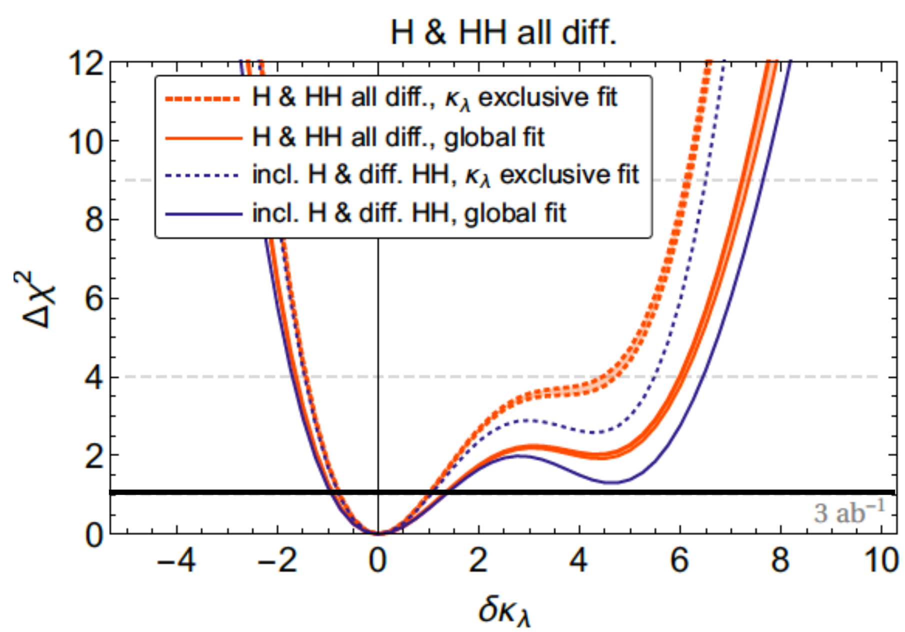
Degrassi et al. arXiv:1607.04251

c.f. HH: $\kappa_\lambda^{2\sigma} = [-8.82, 15.04]$

See also: Gorbahn, Haisch 1607.03773, Bizon et al 1610.05771, Maltoni et al 1709.08649

Future prospects:

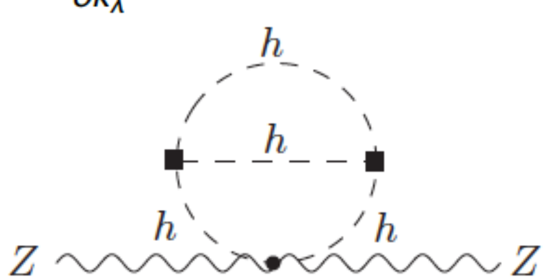


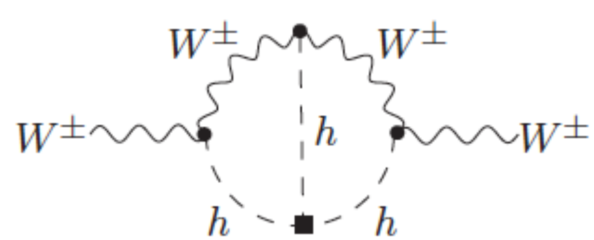


- Synergy between H and HH production
- Differential distributions crucial to break degeneracies at HL-LHC

Di Vita et al. arXiv:1704.01953

EWPO:





$\kappa_\lambda \in [-11.1, 14.6]$

Degrassi et al 1702.01737
Kribs et al 1702.07678

Summary

LHC Higgs measurements are exploring Higgs couplings to all SM particles and frantically searching for new physics in the scalar sector

No sign of deviation from the SM prediction, **yet**

But the exploration has just begun
Lots of questions will be answered over the coming years of the LHC

Thanks for your attention