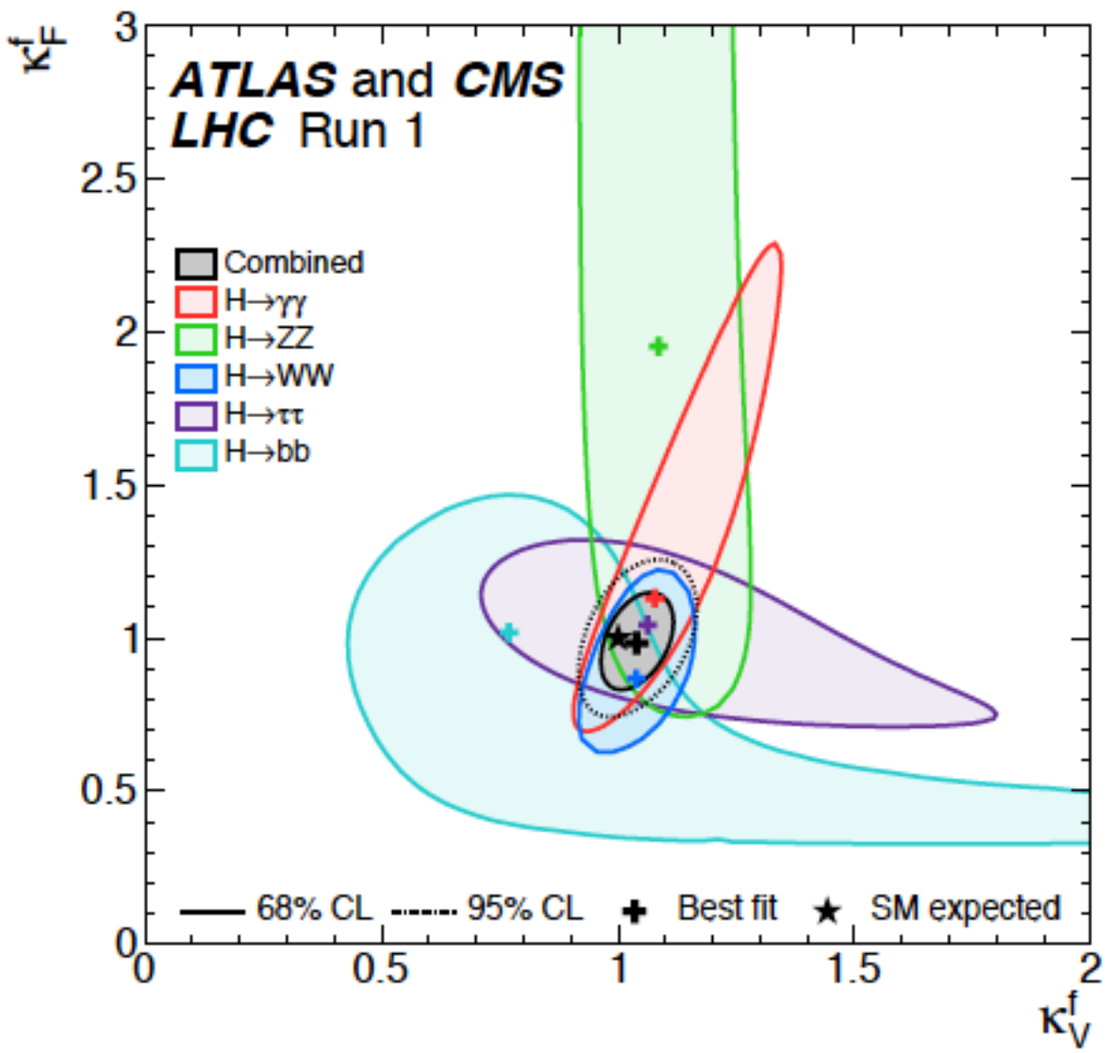
Theoretical implications of the LHC Higgs measurements

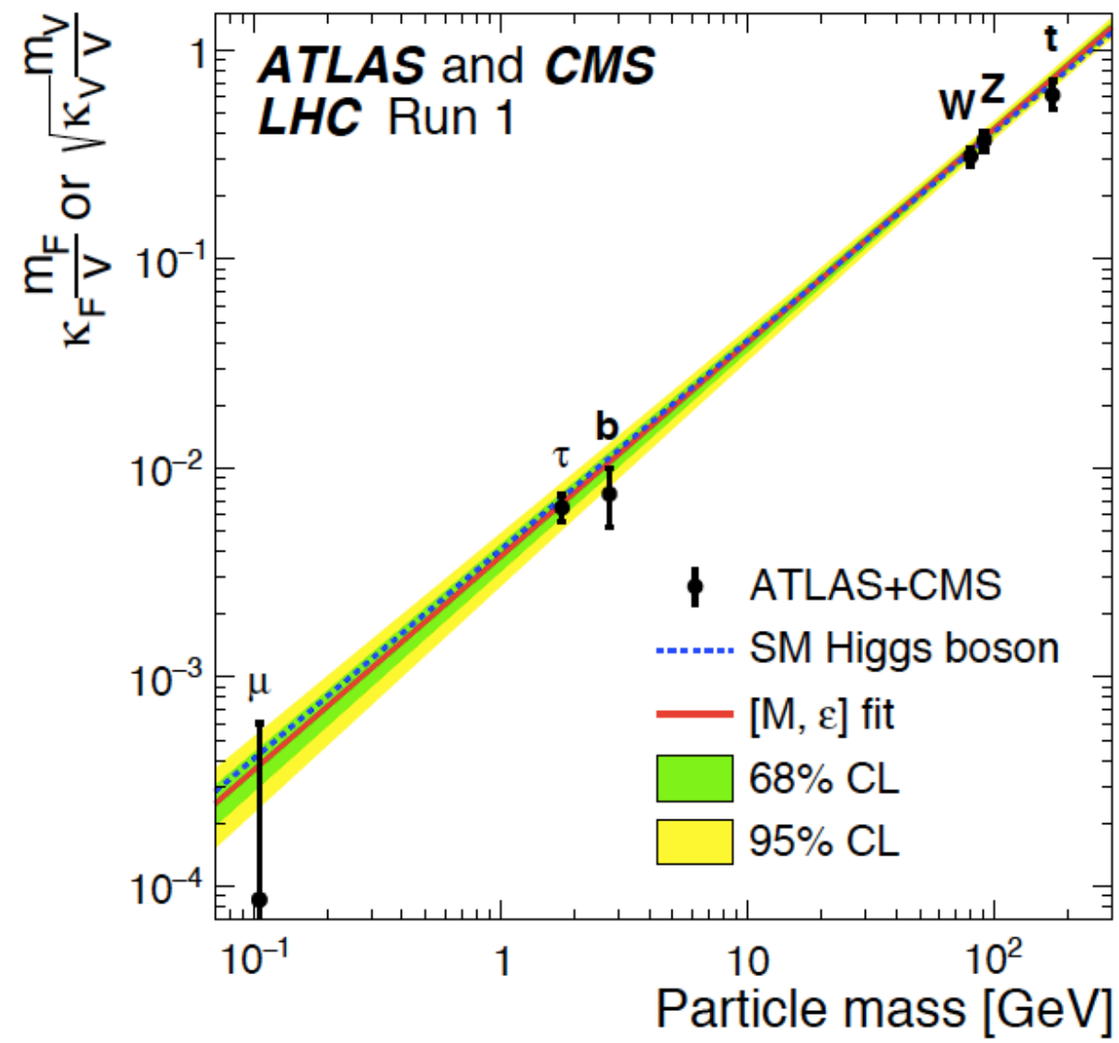
Eleni Vryonidou
CERN TH

LHCP2018
Bologna
4/6/18

LHC: the story so far

Higgs couplings





Good agreement with the SM predictions

How to look for new physics?

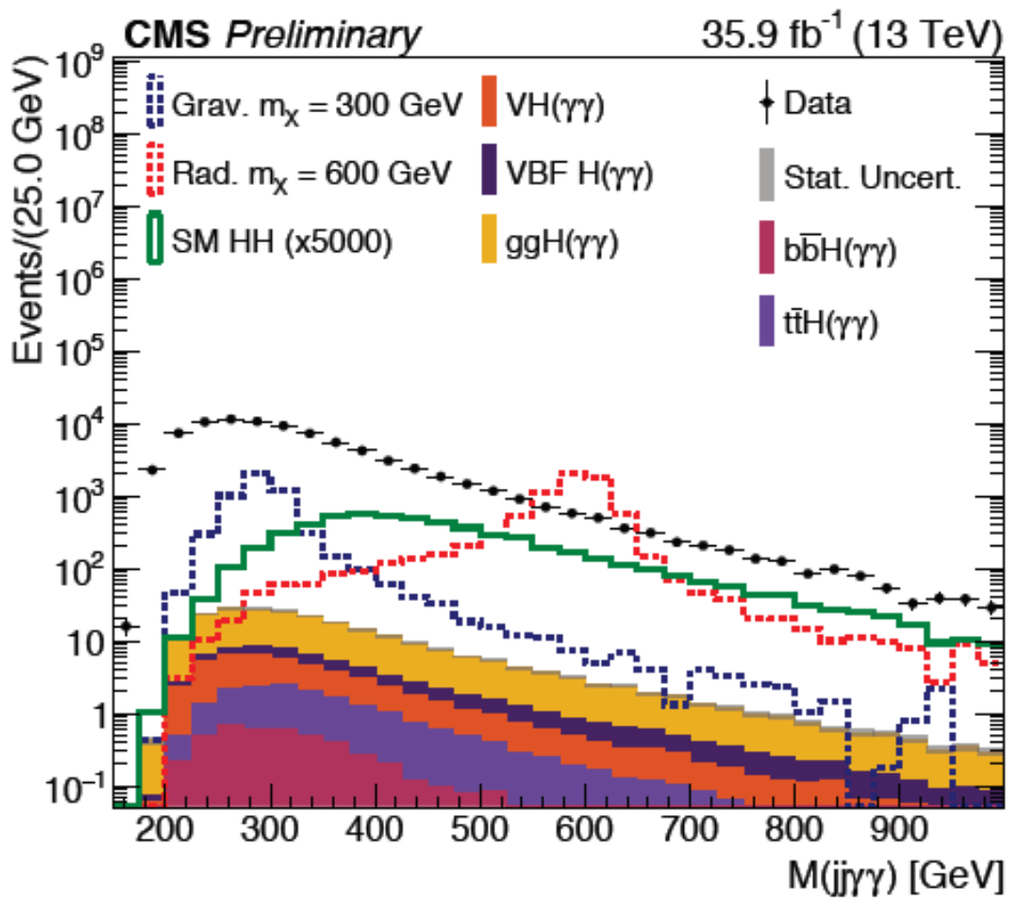
Model-dependent

SUSY,1HSM,2HDM…

Model-Independent

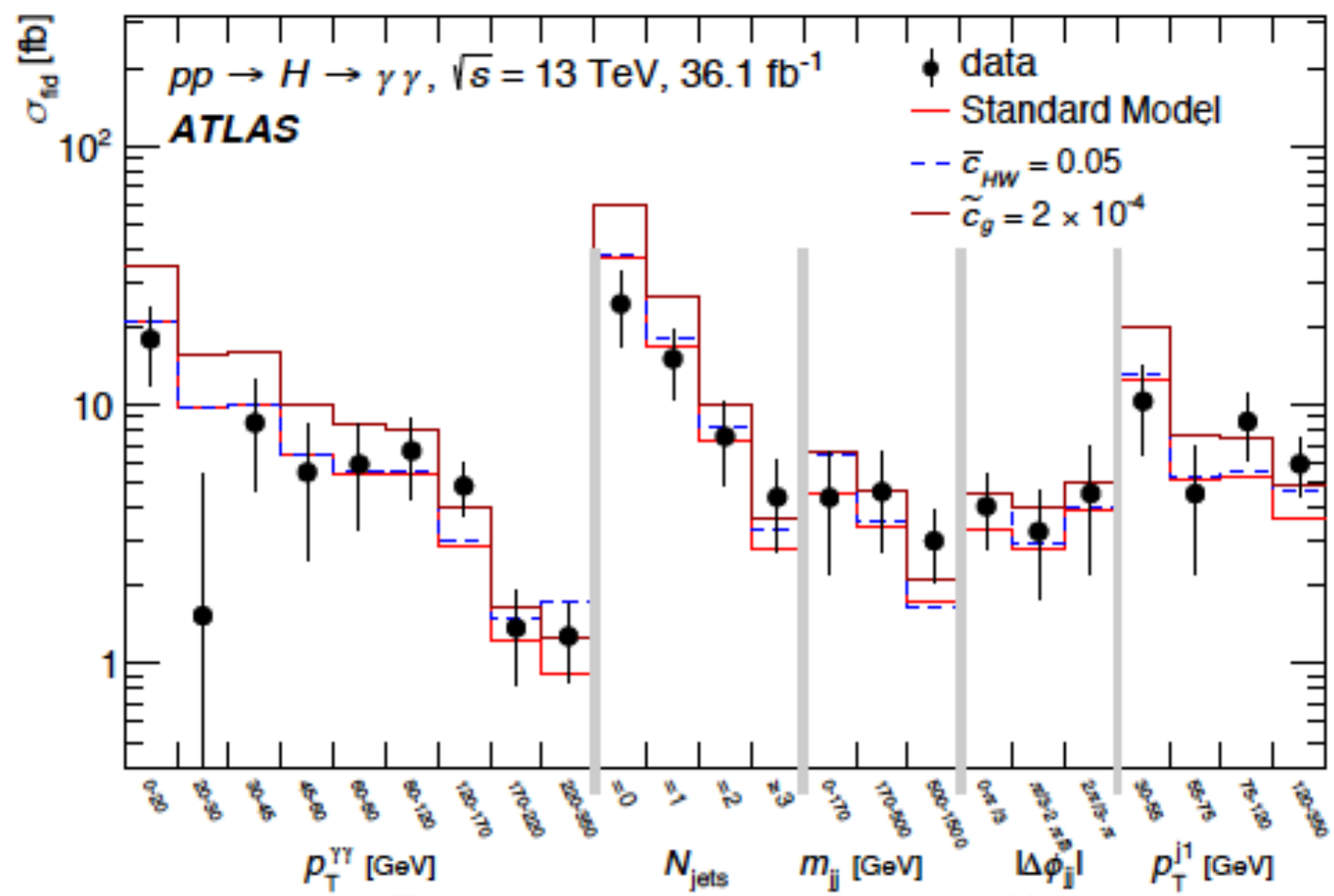
anomalous couplings, EFT

New particles



Resonance peaks

New Interactions



Deviations in tails

How to look for new physics?

Model-dependent

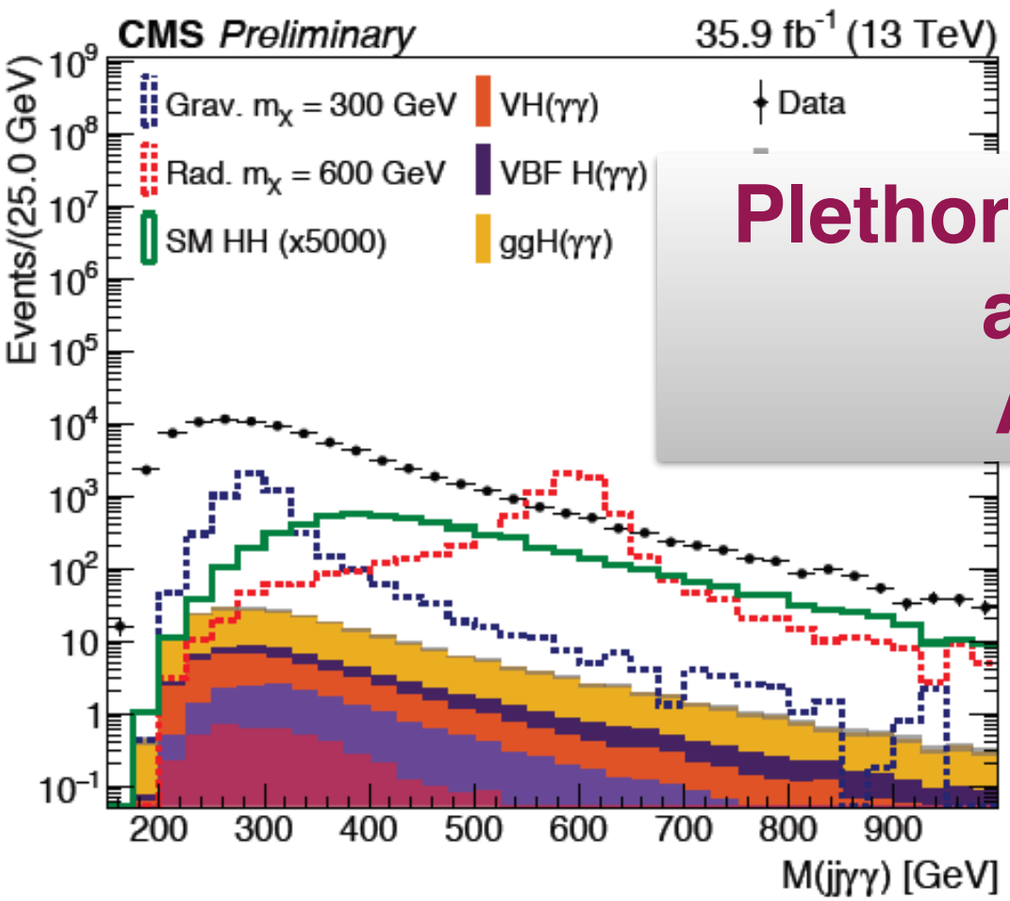
SUSY,1HSM,2HDM…

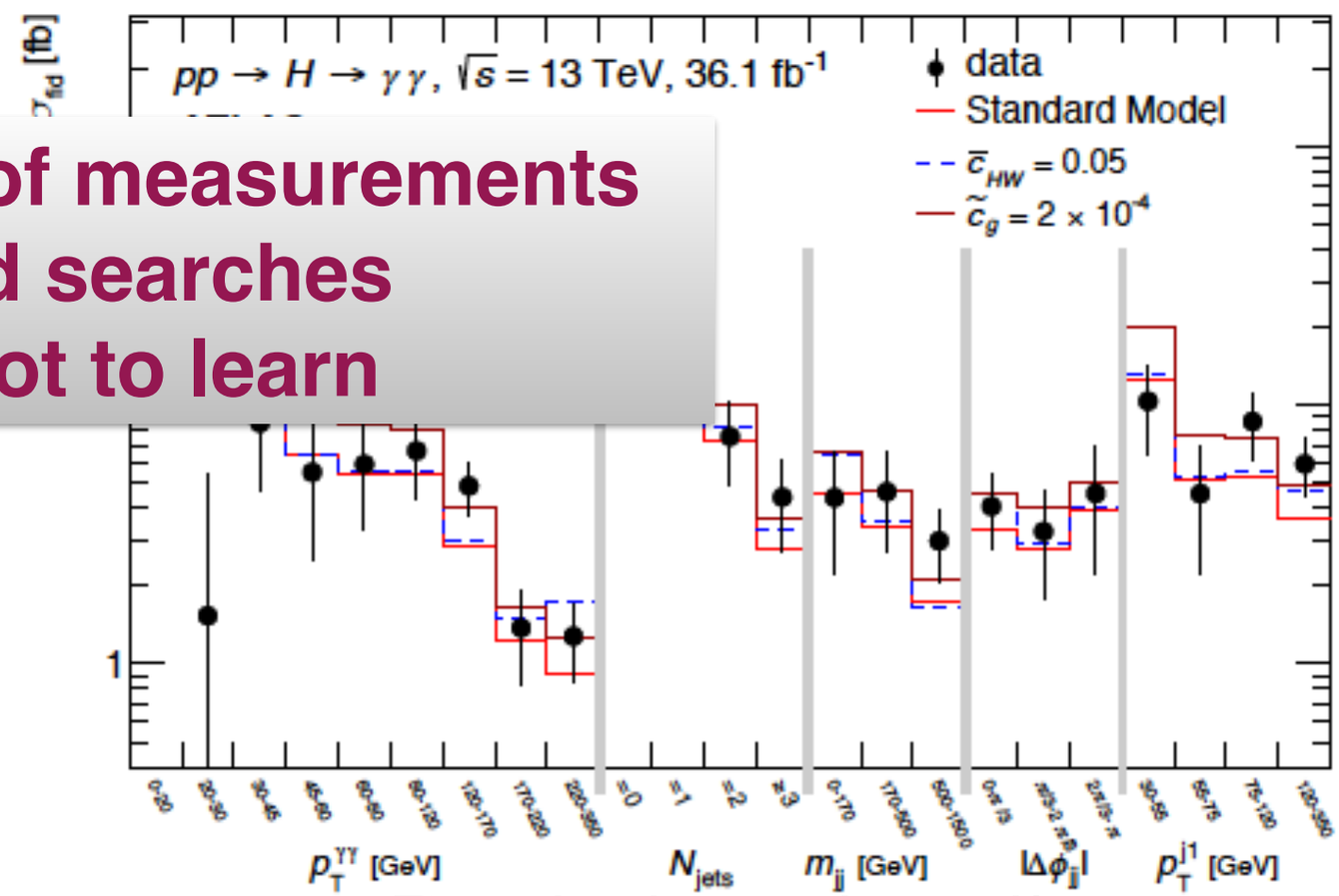
Model-Independent

anomalous couplings, EFT

New particles

New Interactions



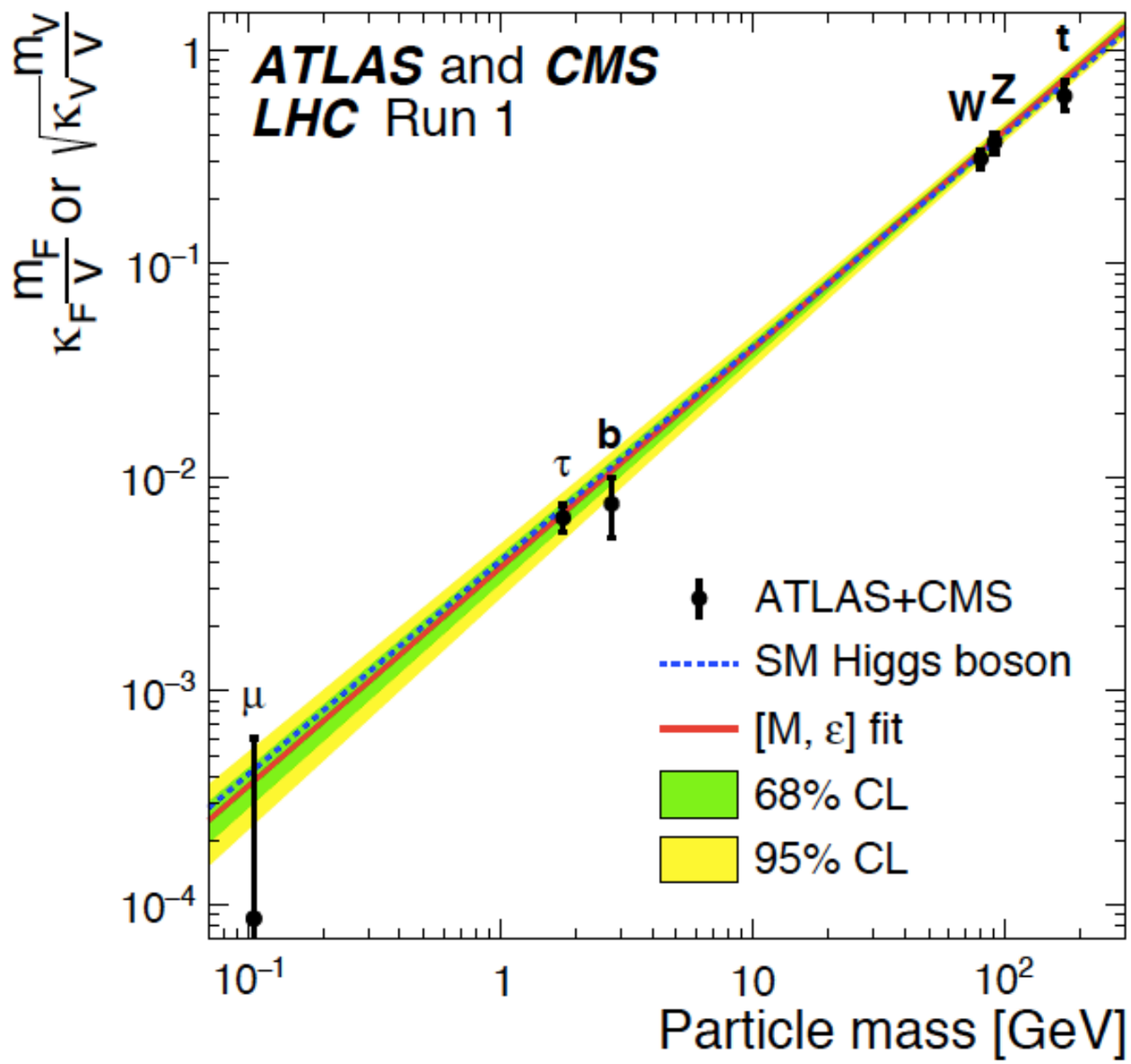


Plethora of measurements and searches
A lot to learn

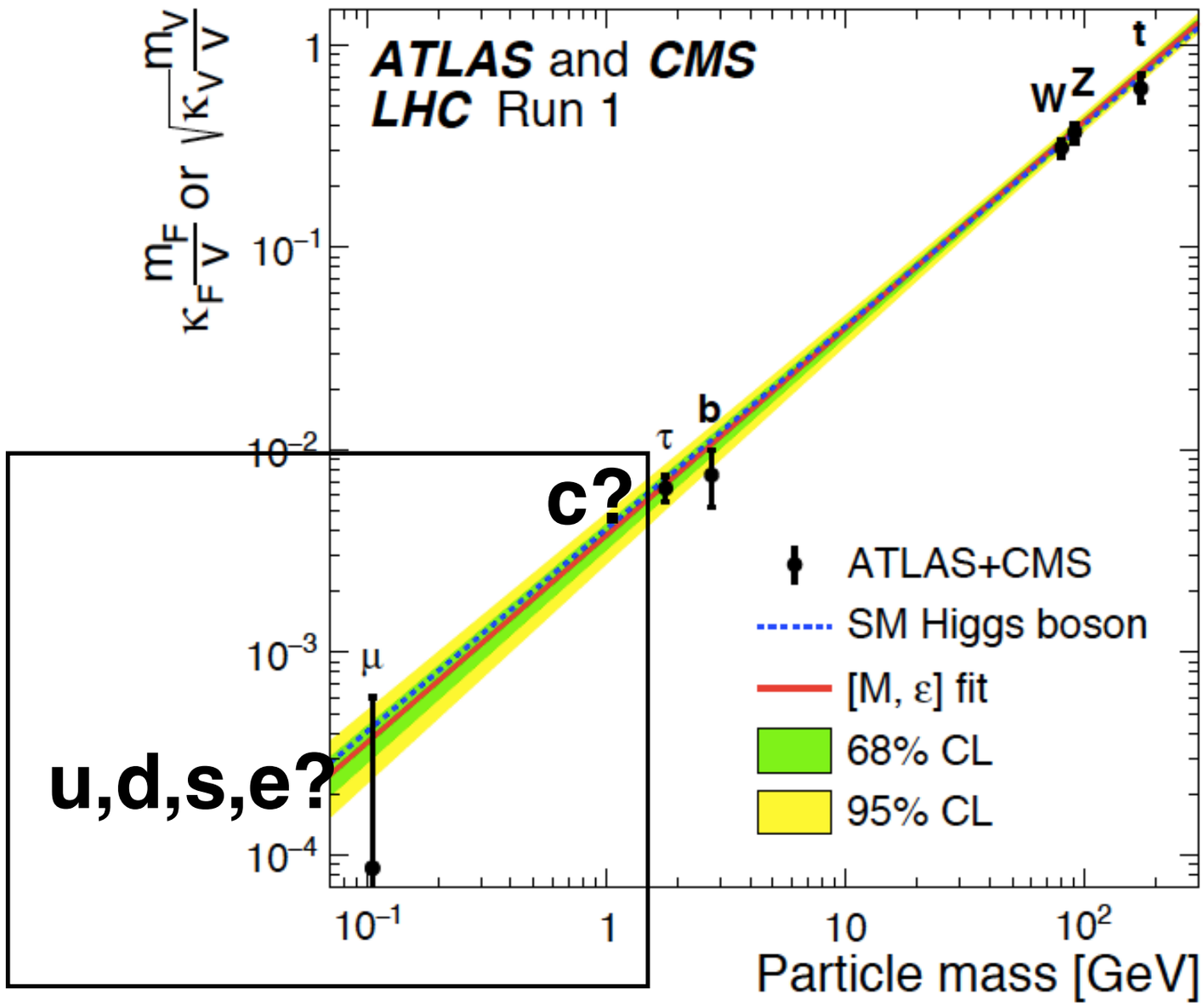
Resonance peaks

Deviations in tails

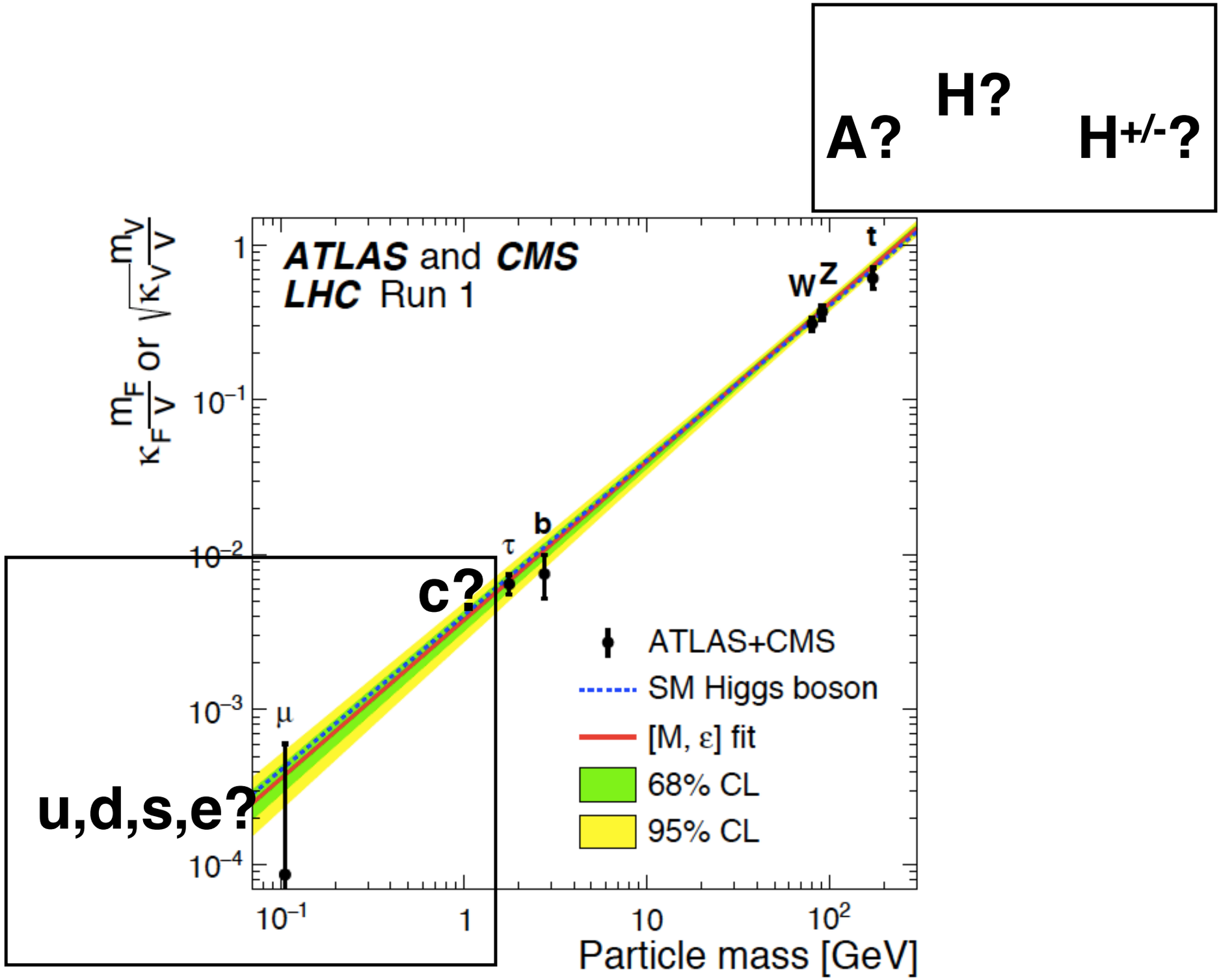
Knowns and Unknowns



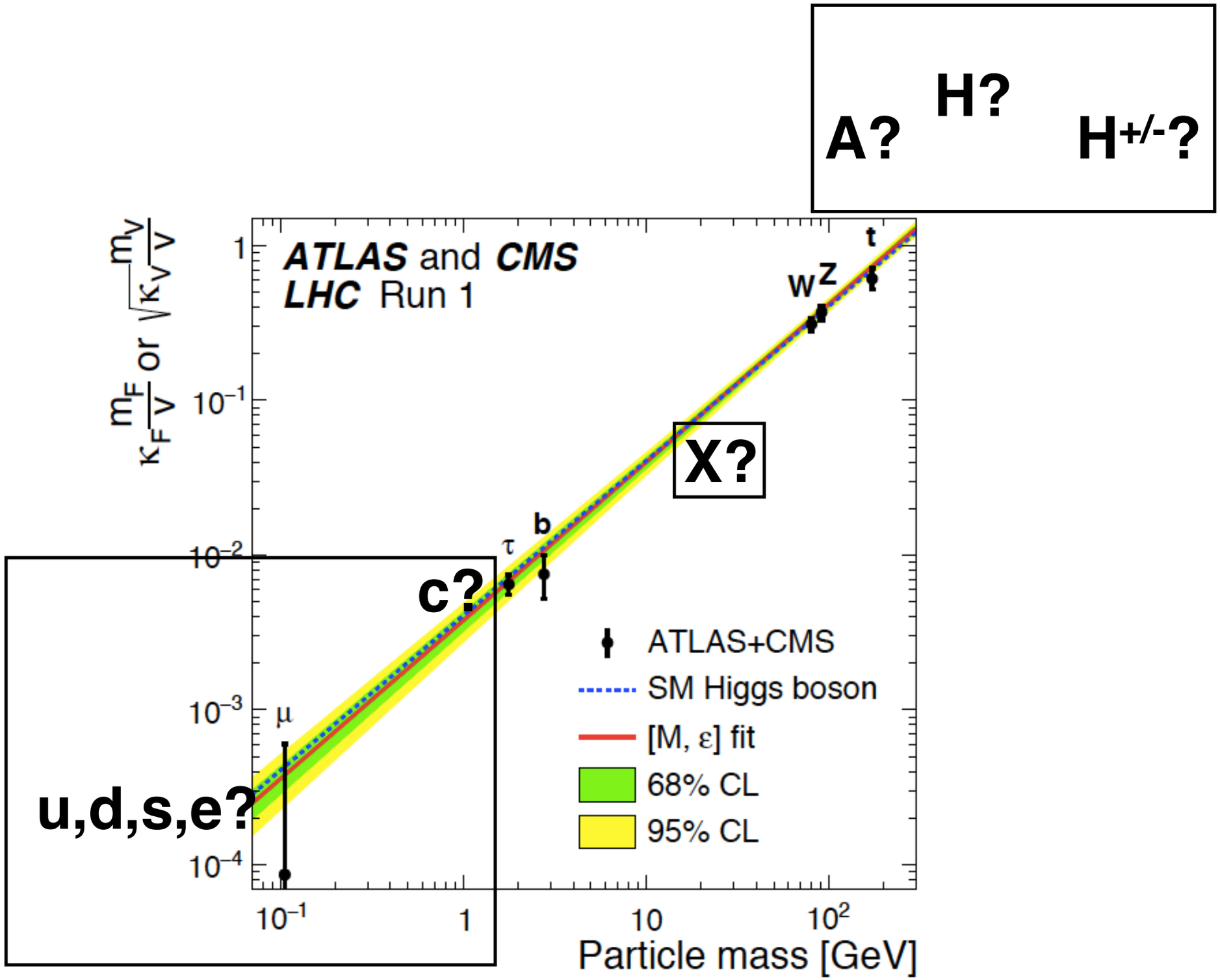
Knowns and Unknowns



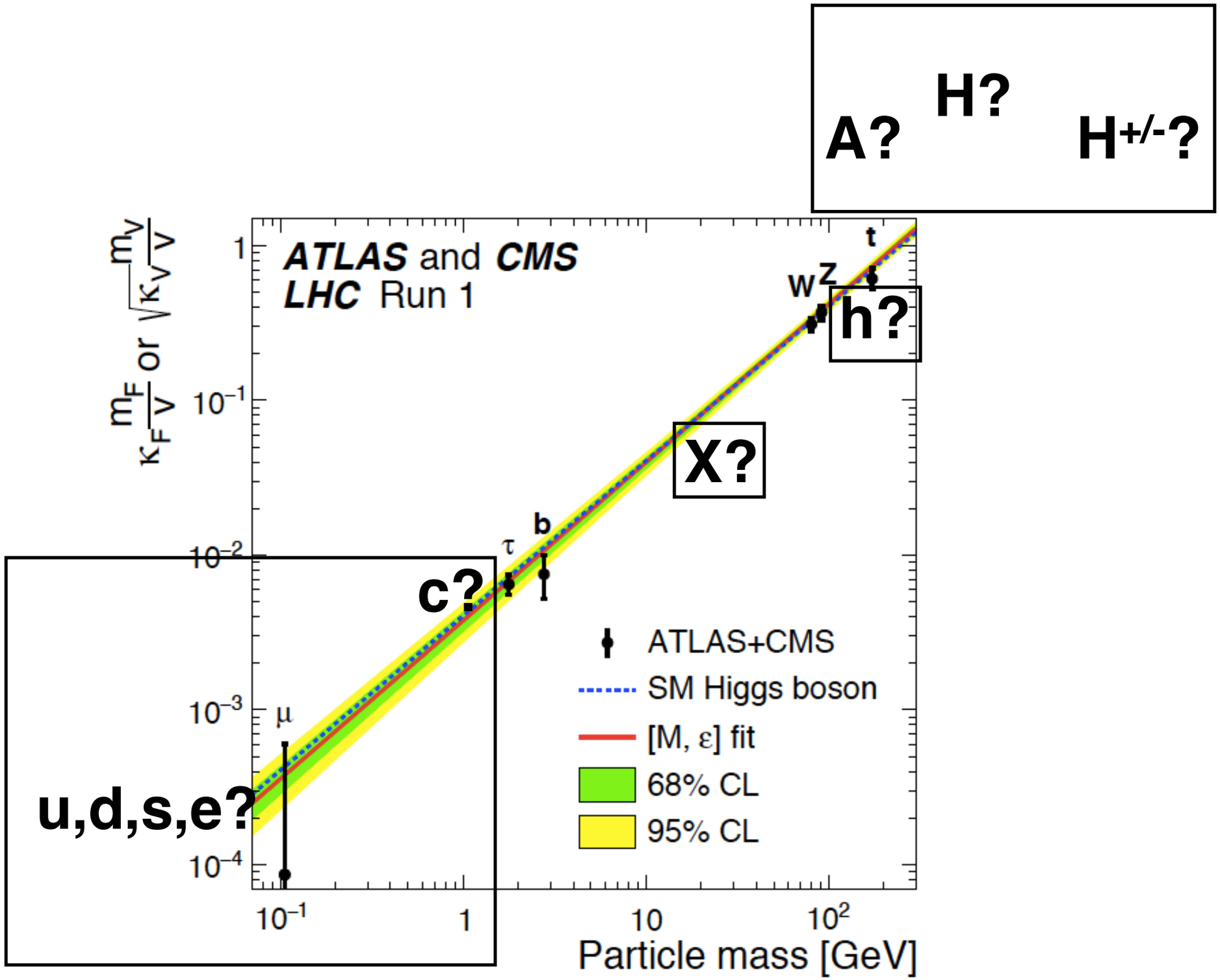
Knowns and Unknowns



Knowns and Unknowns

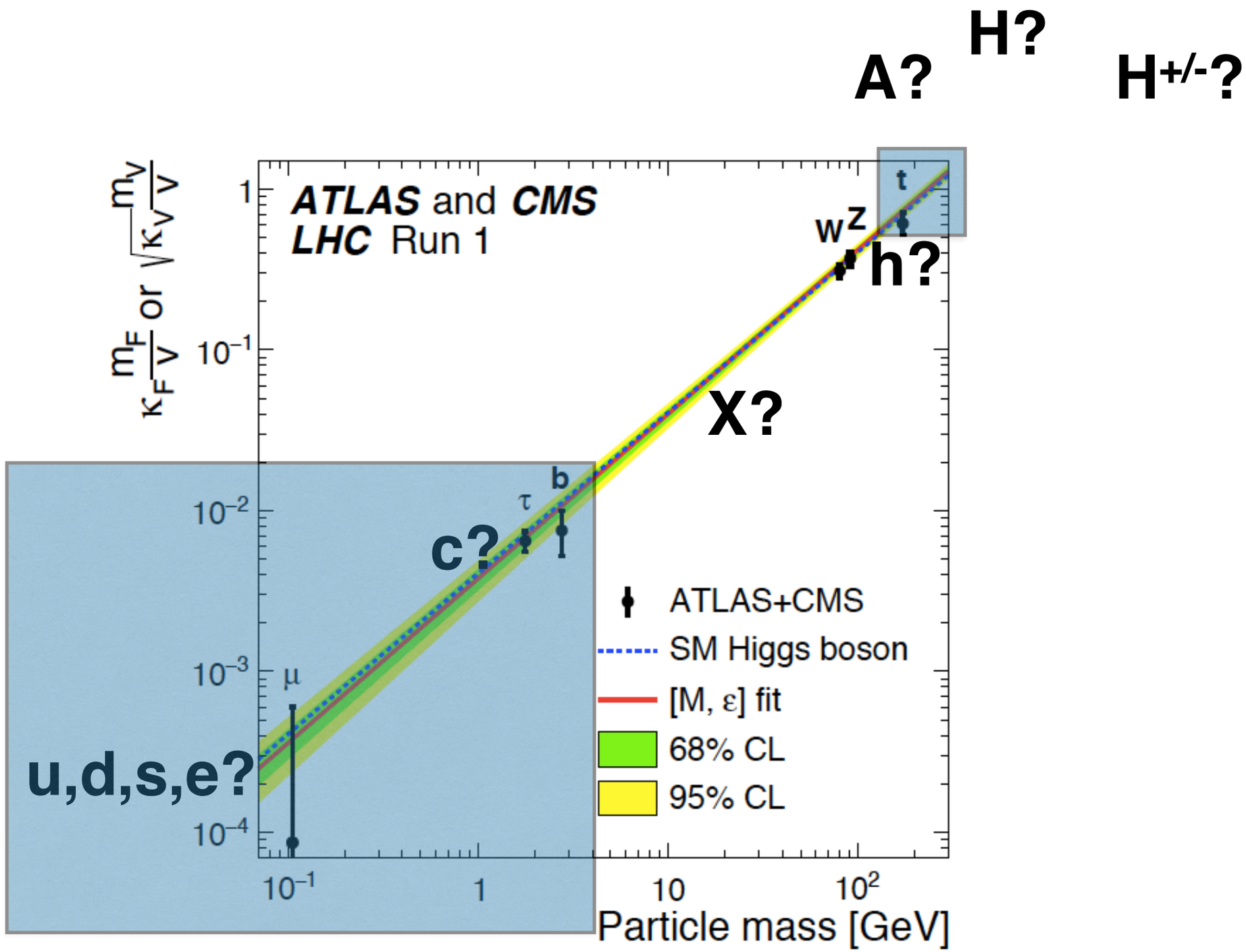


Knowns and Unknowns



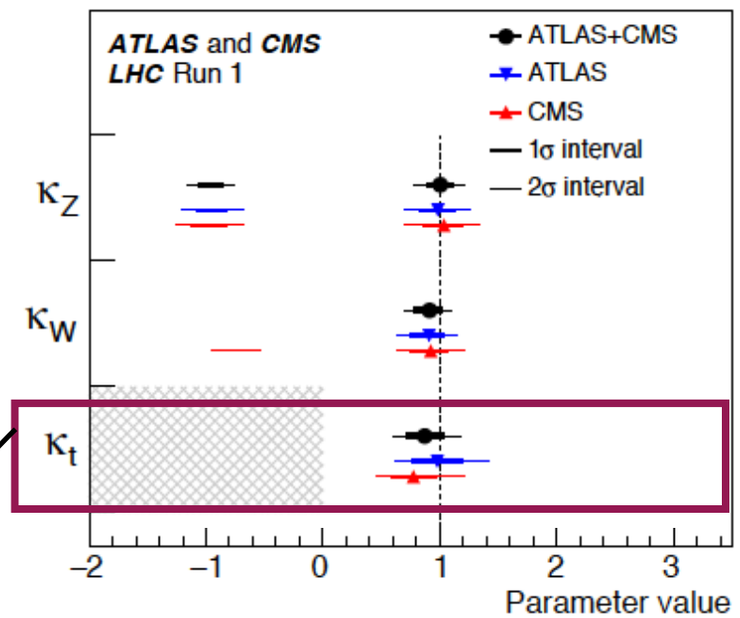
Outline

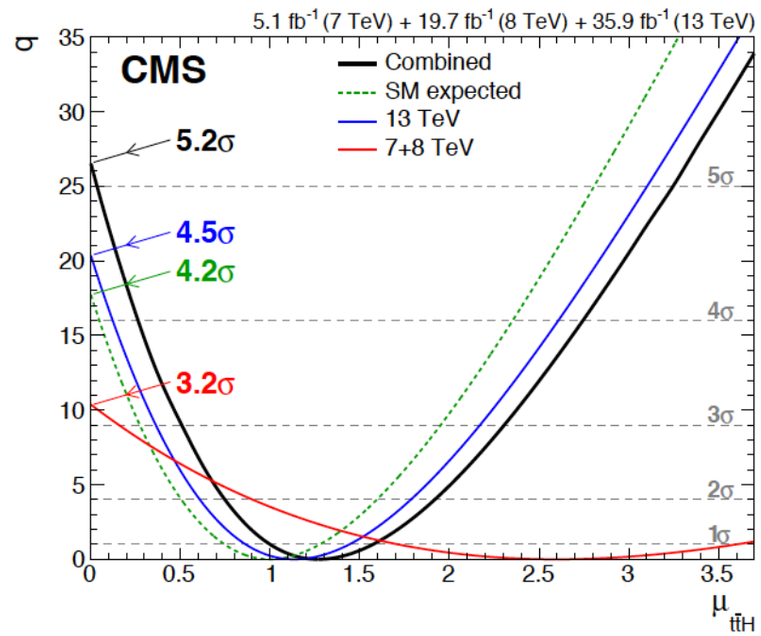
I. Higgs couplings
II. Searching for new states
III. The Higgs potential



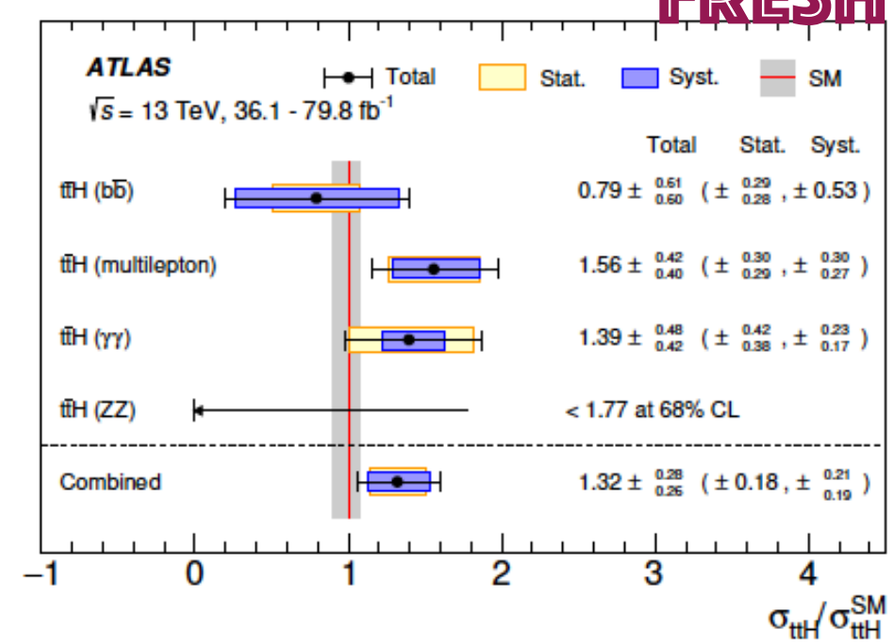
I. Higgs couplings

The big news: Top-Higgs interaction





FRESH

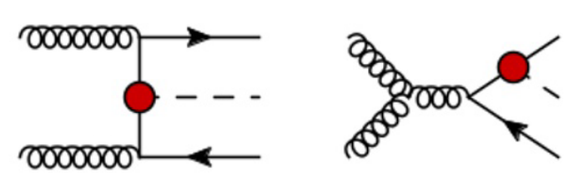


~20% accuracy

First observation of ttH

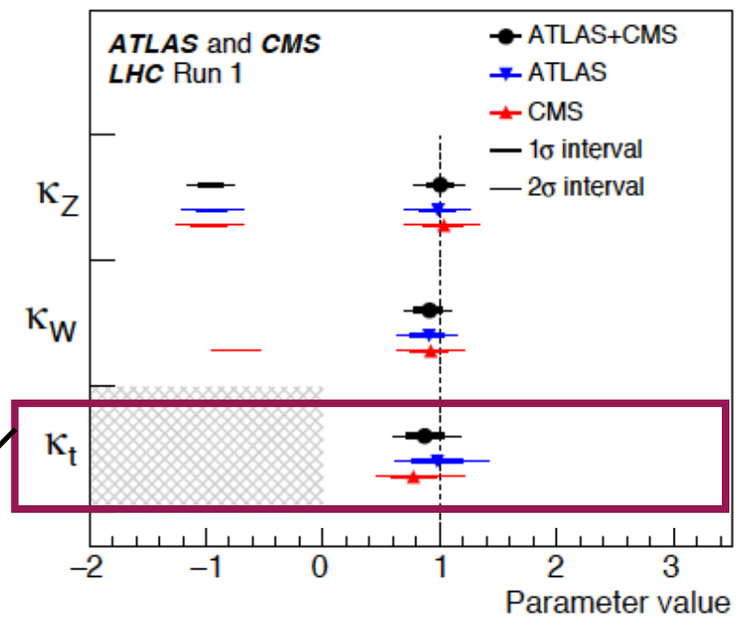
H

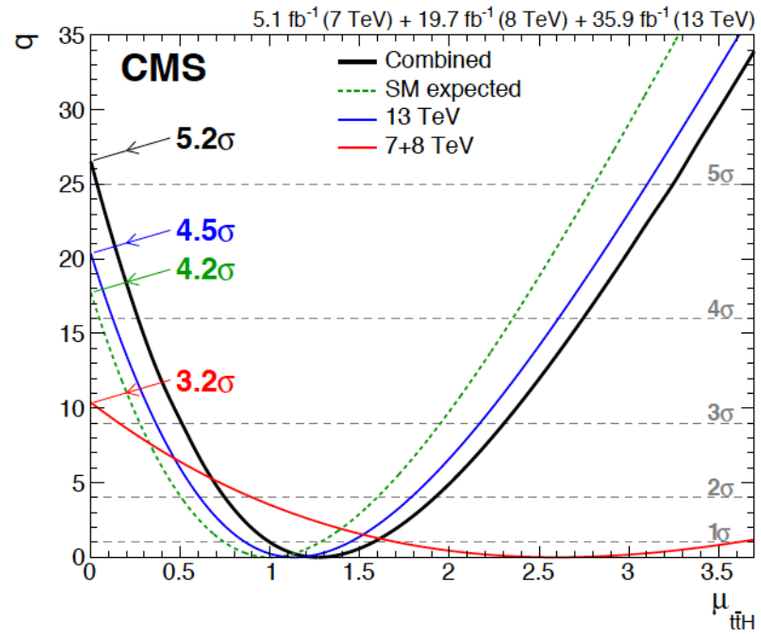
ttH



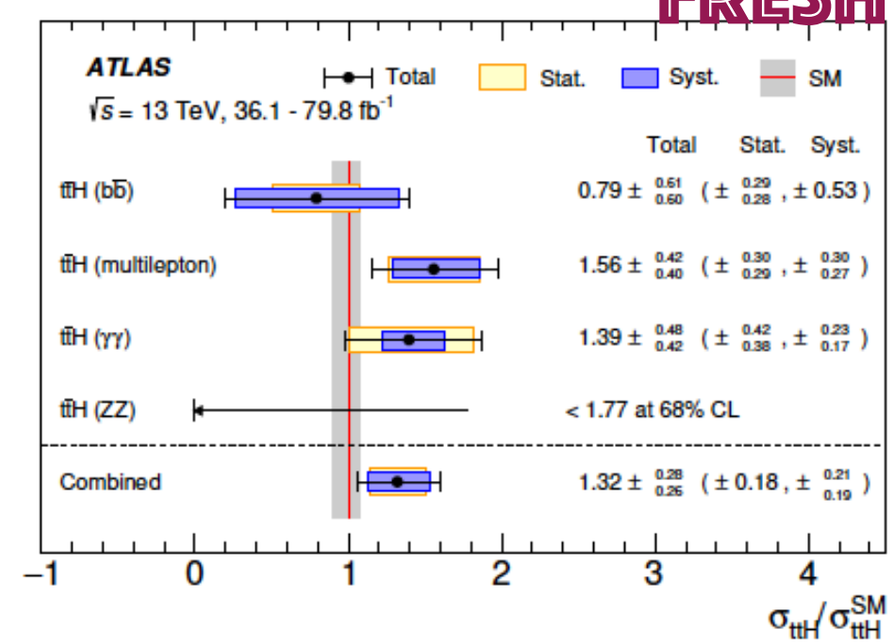
Heavy particles in the loops?

The big news: Top-Higgs interaction





FRESH

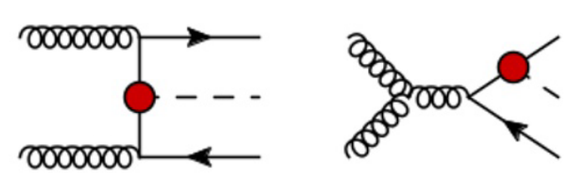


~20% accuracy

First observation of ttH

H

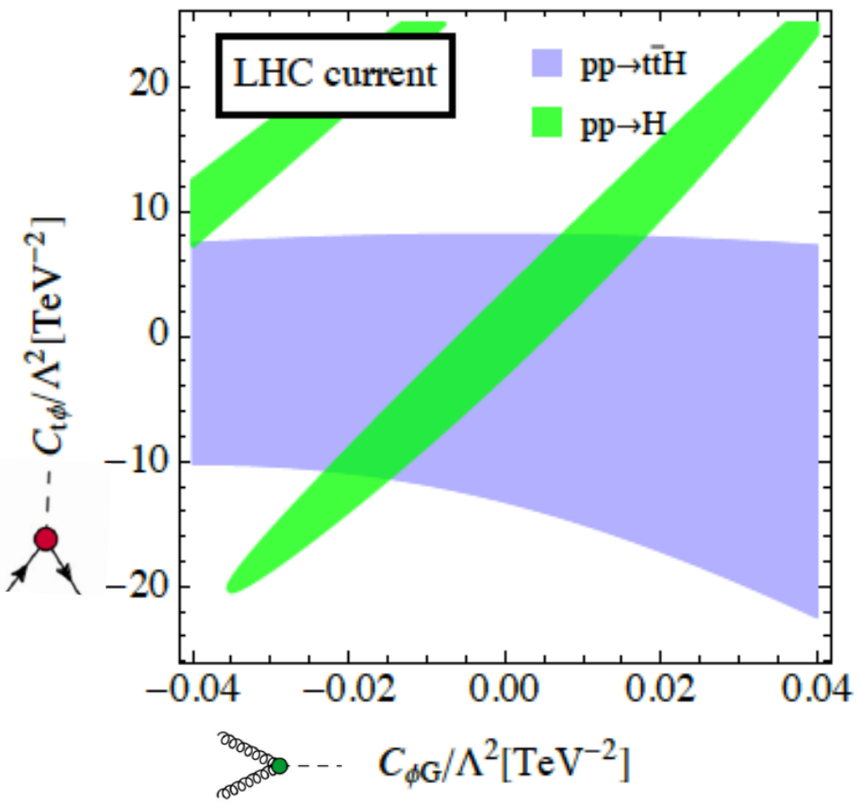
ttH

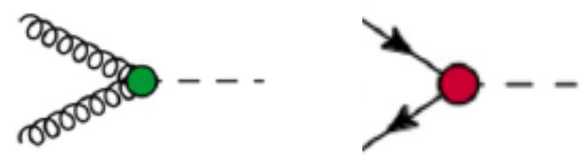


Heavy particles in the loops?

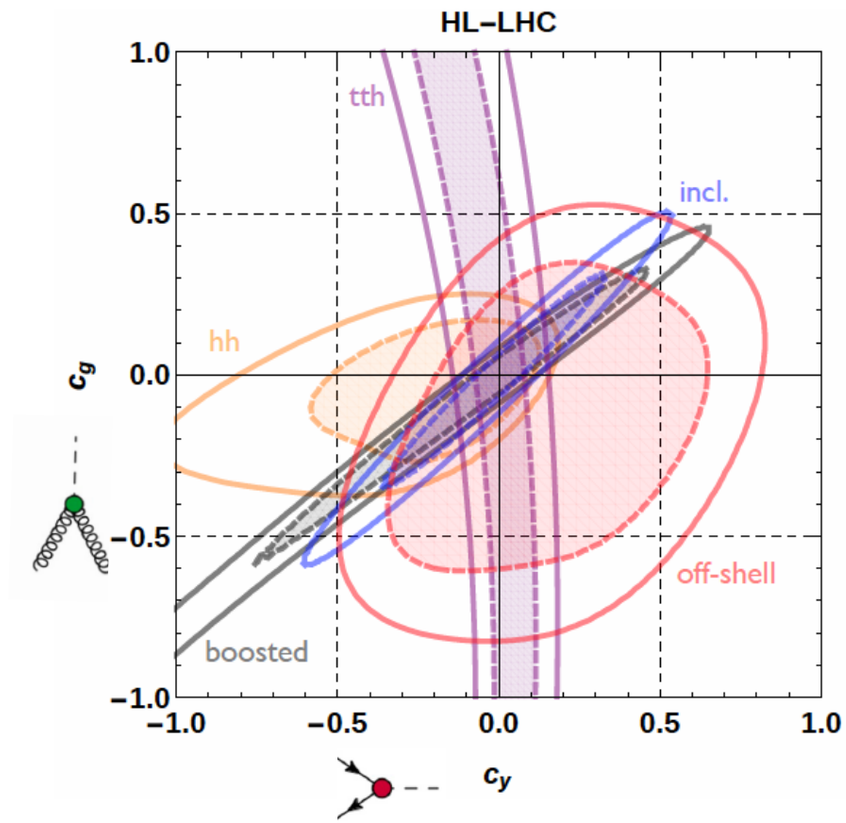
Direct evidence of the coupling of the top to the Higgs

Probing the top-Higgs interaction

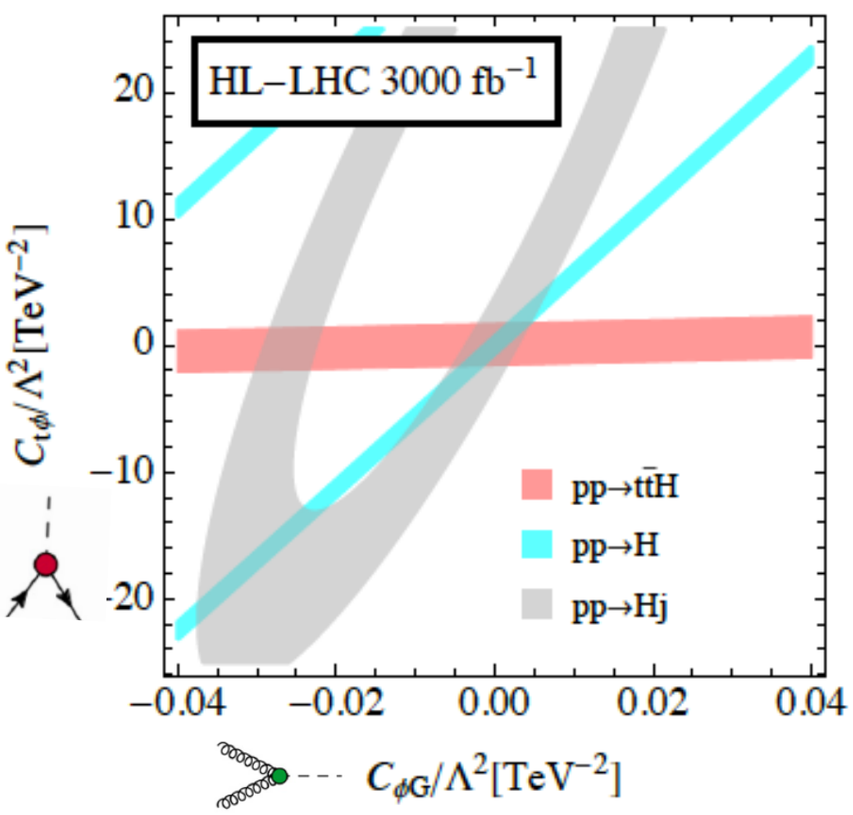




Current limits using LHC measurements



Azatov et al arXiv:1608.00977



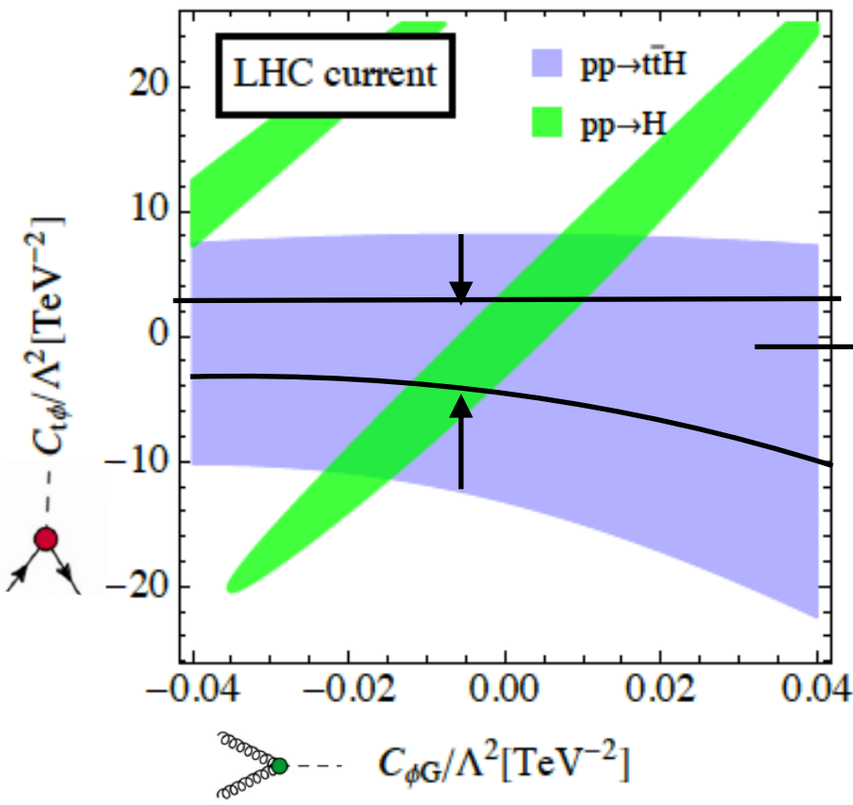
14TeV projection 3000 fb^{-1}

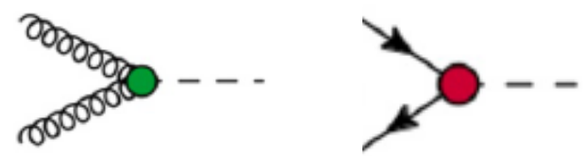
Maltoni, EV, Zhang arXiv:1607.05330

Combination:

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

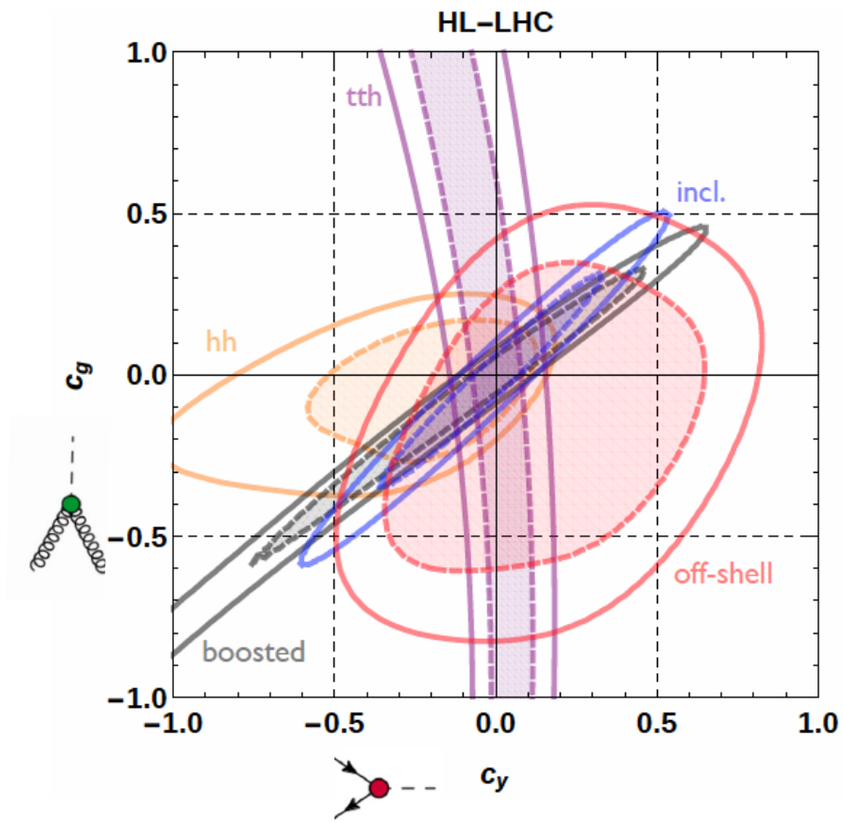
Probing the top-Higgs interaction



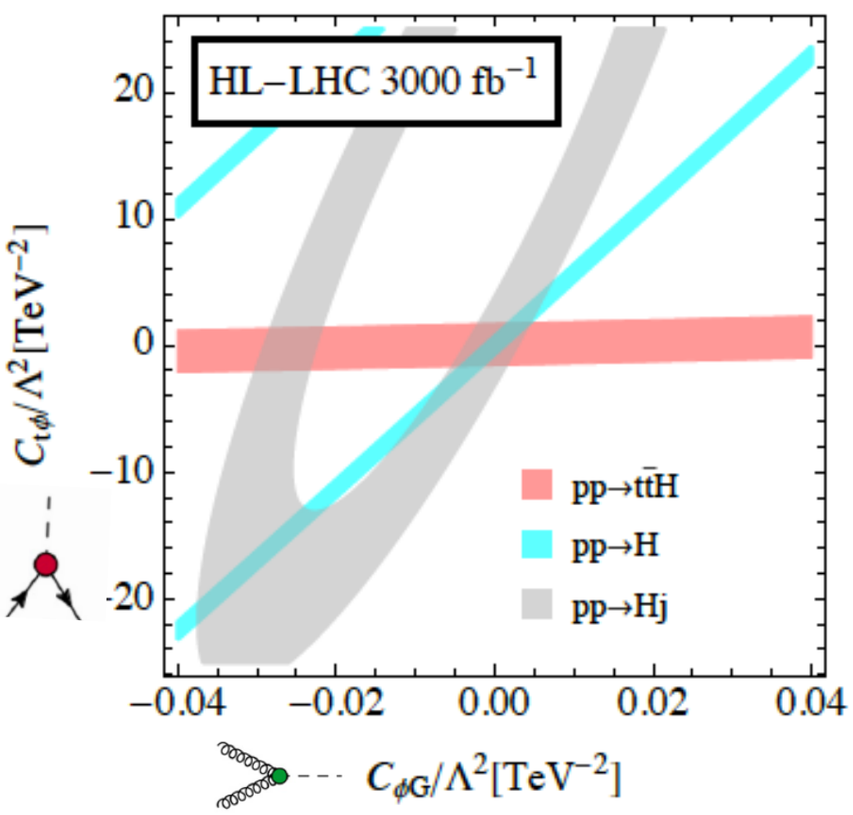


impact of recent ttH observation

Current limits using LHC measurements



Azatov et al arXiv:1608.00977



14TeV projection 3000 fb^{-1}

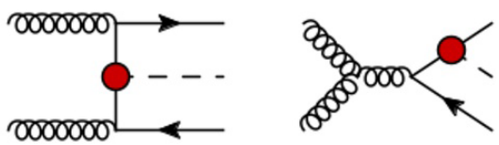
Maltoni, EV, Zhang arXiv:1607.05330

Combination:

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

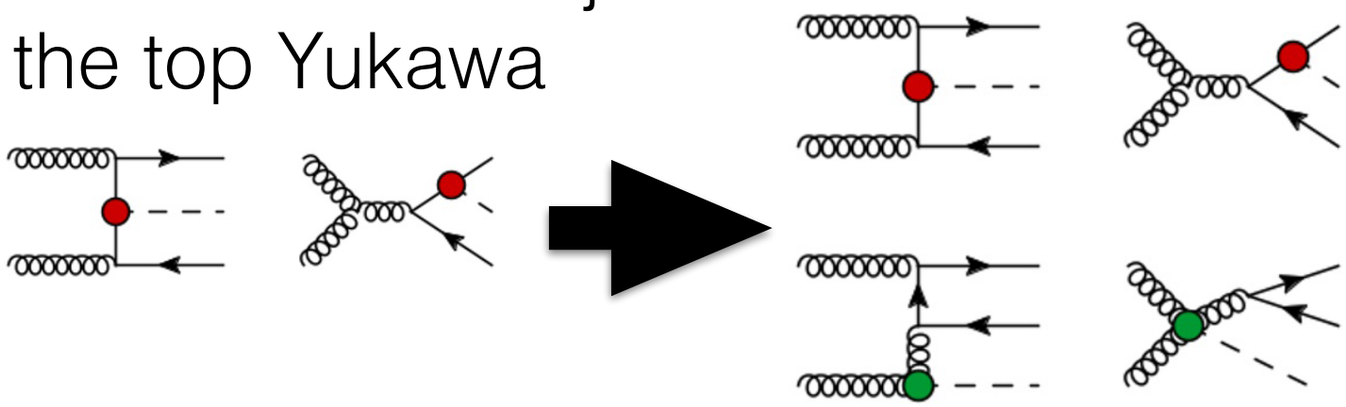
Going beyond…

ttH is more than just
the top Yukawa



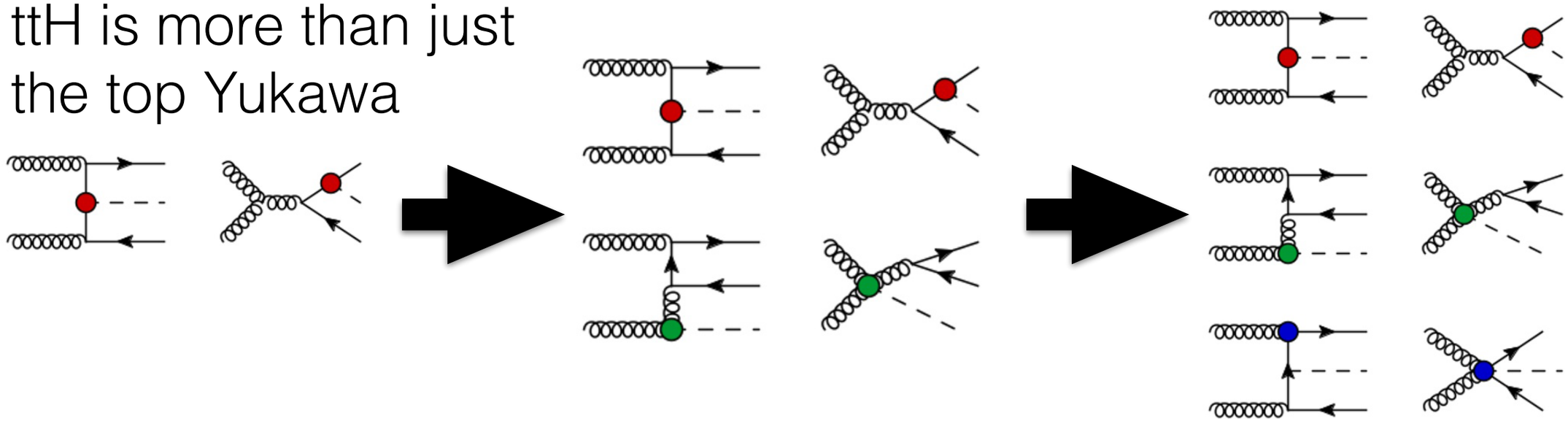
Going beyond…

ttH is more than just the top Yukawa



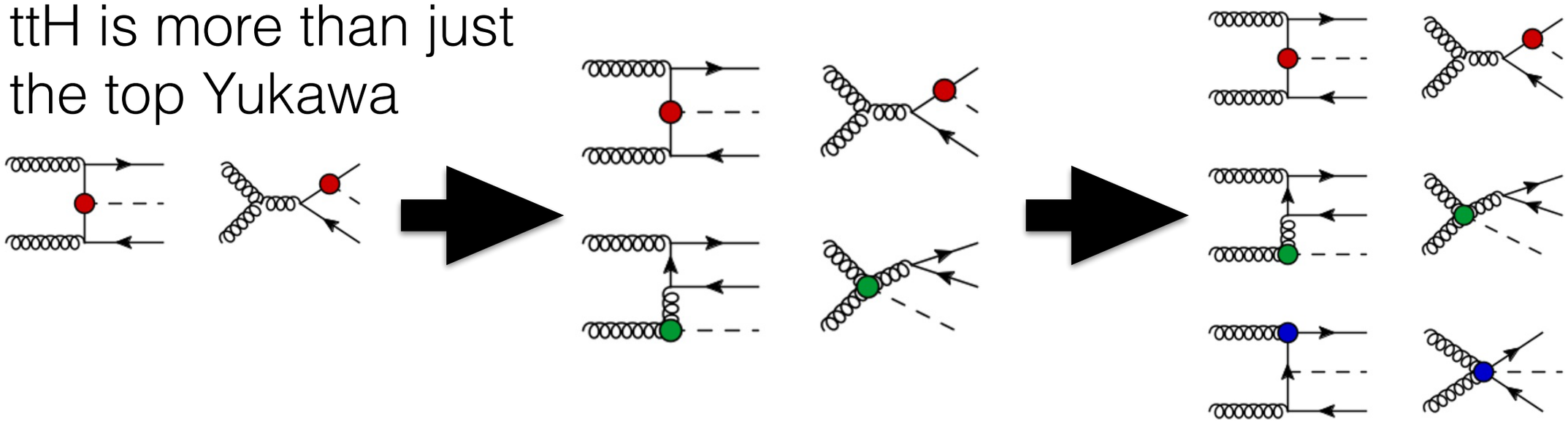
Going beyond…

ttH is more than just the top Yukawa



Going beyond…

ttH is more than just the top Yukawa



The SMEFT

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

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

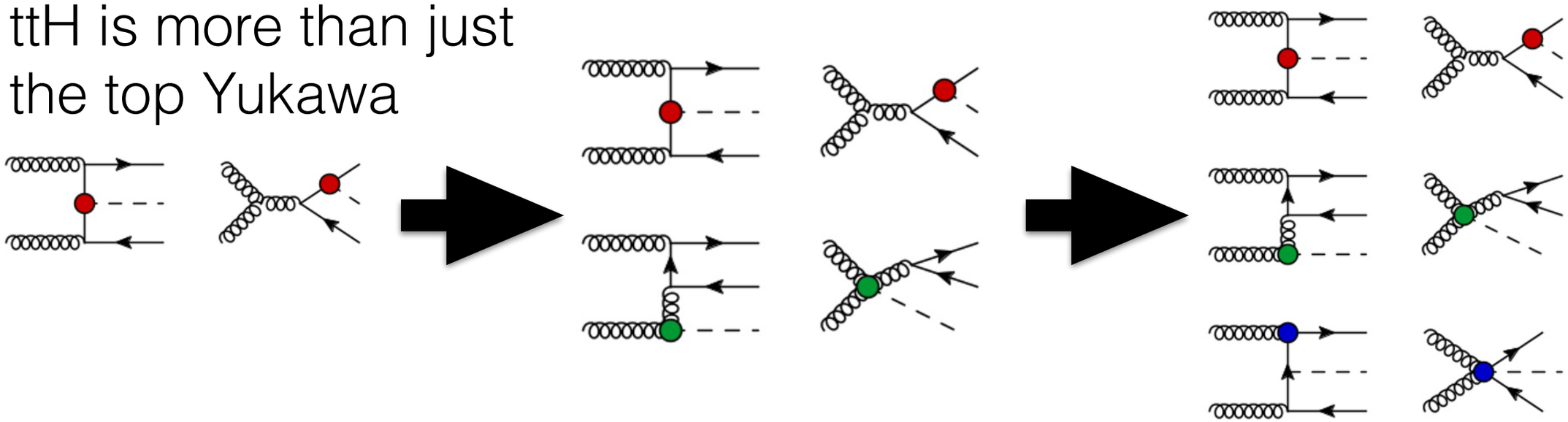
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

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

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

Going beyond…

ttH is more than just the top Yukawa



The SMEFT

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

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q} t)\, \tilde{\phi}$$

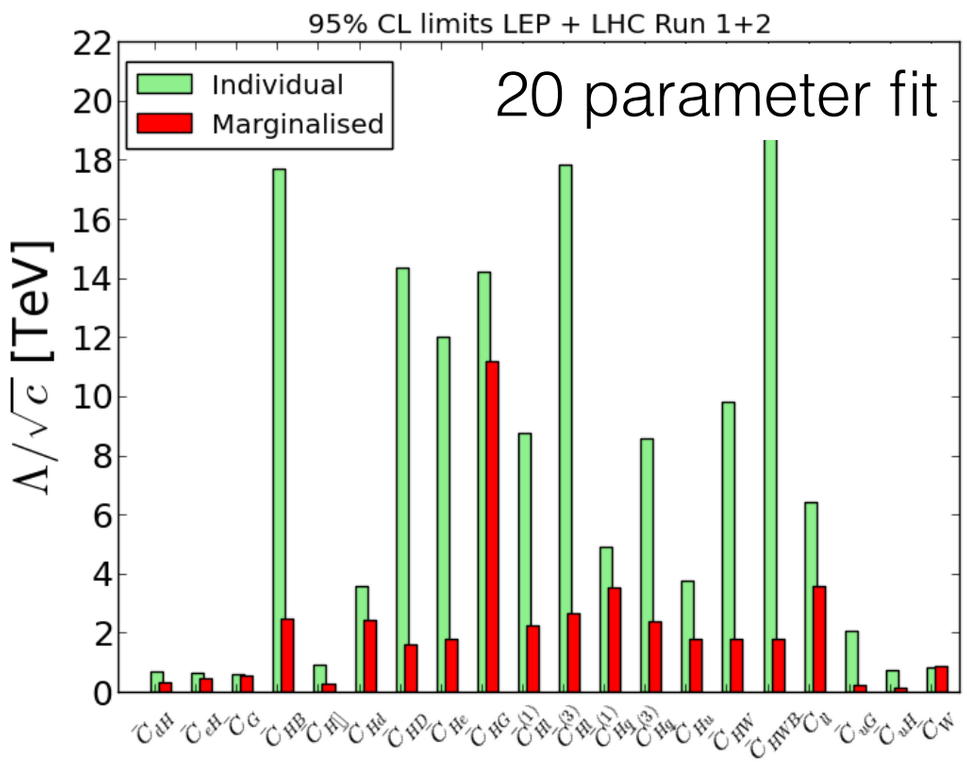
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

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

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

Towards EFT global fits



A Global fit: LEP and LHC Run I and II

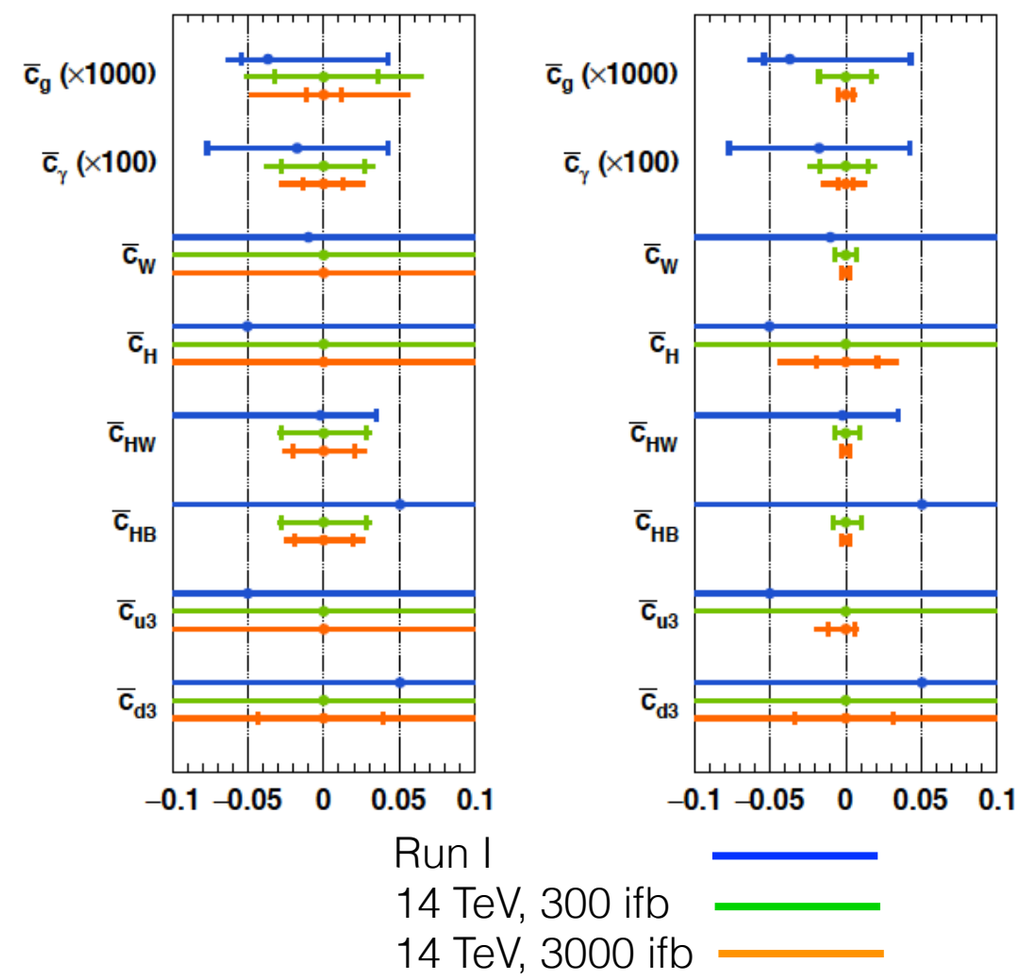
$$\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu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

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

Ellis et al arXiv:1803.03252

The future of global fits

Inclusive Differential



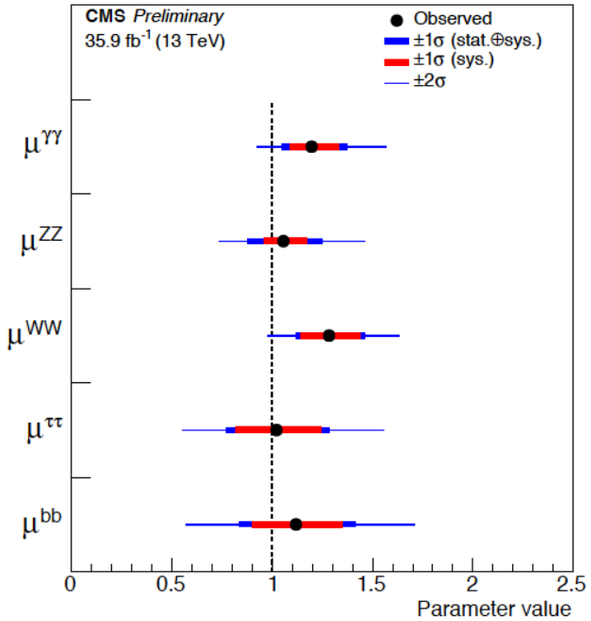
Using differential information will be crucial

Englert, Kogler, Spannowsky arXiv:1511.05170

See more in Veronica's talk

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



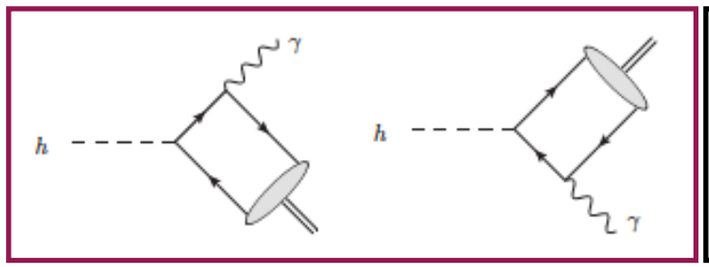
Is this the case for the 1st and 2nd generation? Do they get their masses from the same scalar doublet?

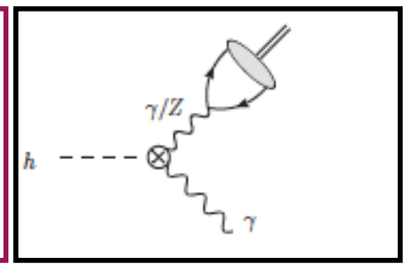
An opportunity to test flavour models which predict deviations from the SM

Light quark Yukawas (1)

A challenge and an opportunity:

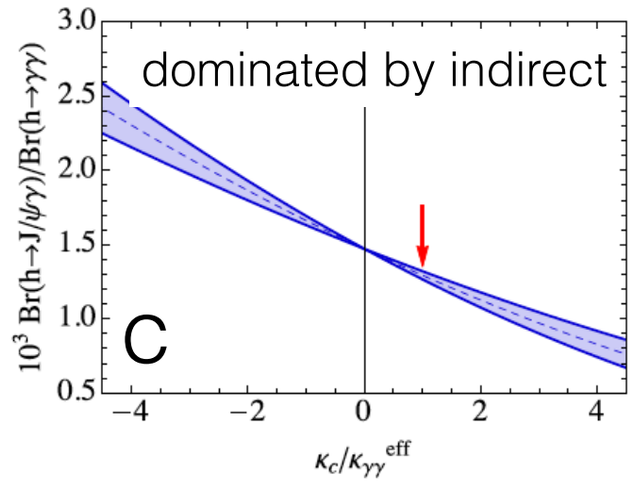
Rare radiative decays to vector mesons:

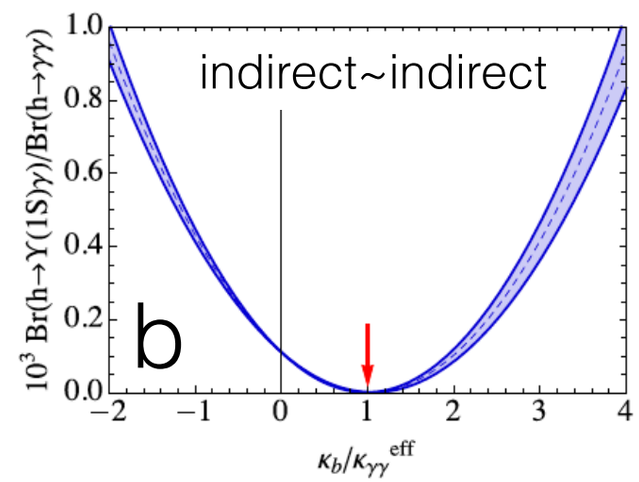


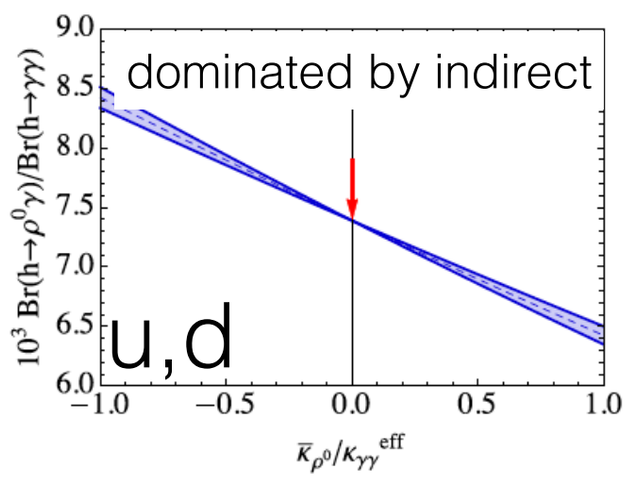


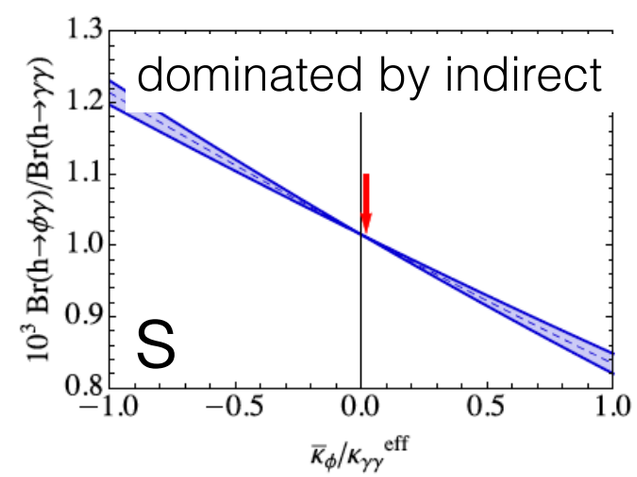
Direct: sensitive to the quark Yukawa

Indirect









Koenig, Neubert arXiv:1505.03870

SM predictions:

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

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

First LHC results:

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

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

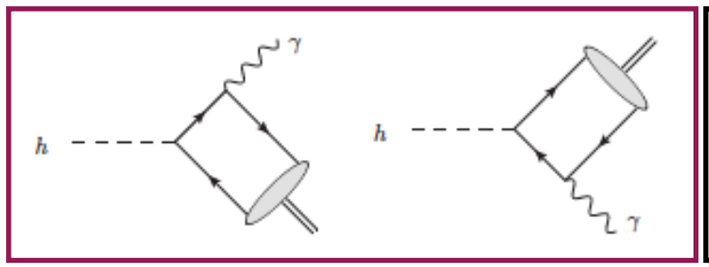
$\mathcal{B}(H \to \rho\gamma) < 8.8 \times 10^{-4} = 52\,\mathrm{x\,SM}$

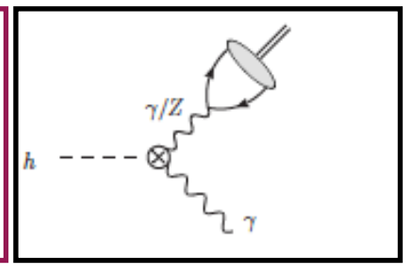
(arXiv:1501.03276 and ATLAS-CONF-2017-057)

Light quark Yukawas (1)

A challenge and an opportunity:

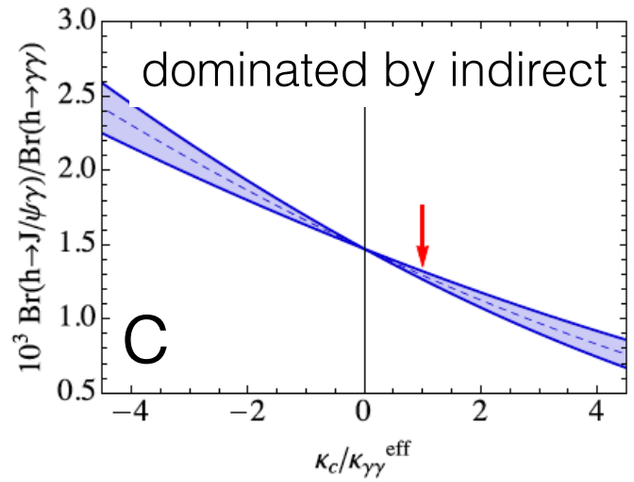
Rare radiative decays to vector mesons:

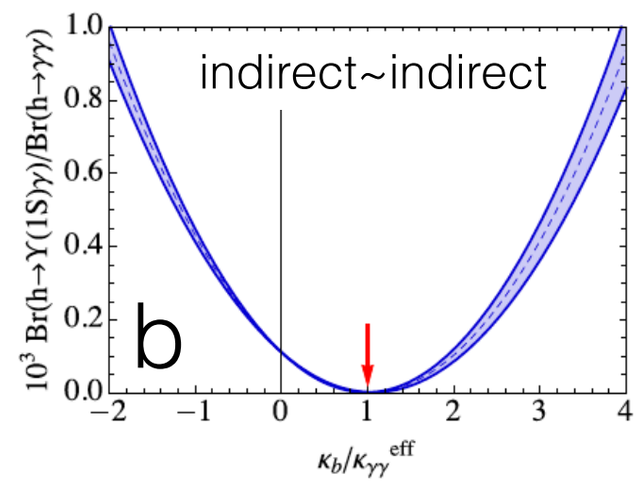


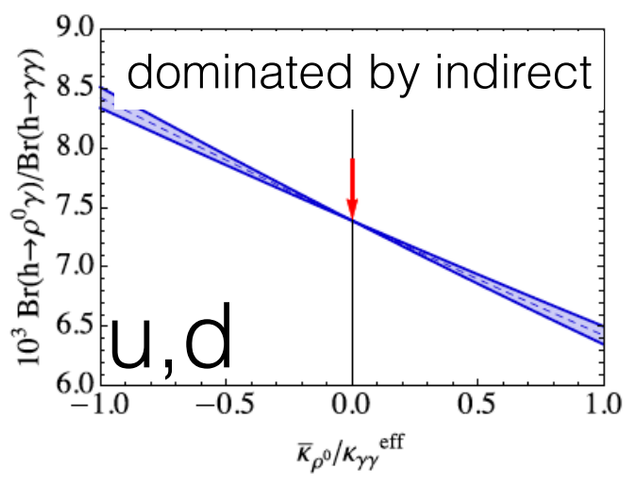


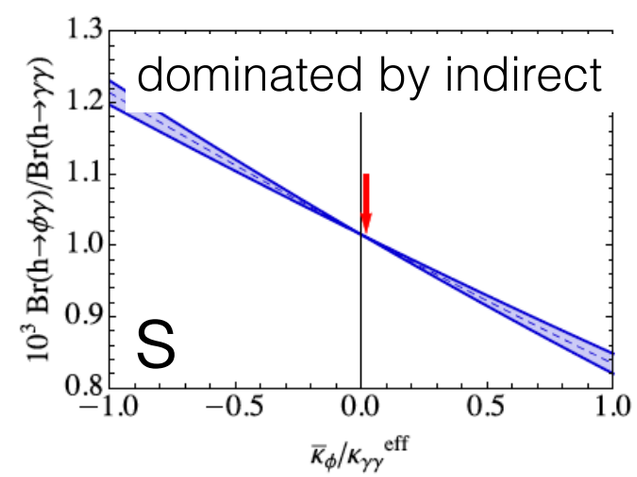
Direct: sensitive to the quark Yukawa

Indirect









Koenig, Neubert arXiv:1505.03870

SM predictions:

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

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

First LHC results:

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

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

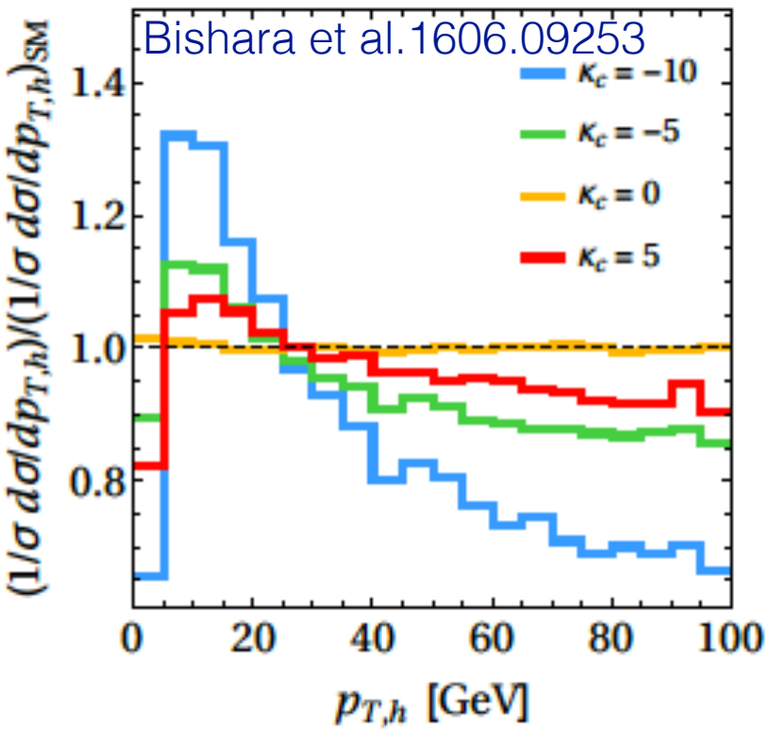
$\mathcal{B}(H \to \rho\gamma) < 8.8 \times 10^{-4} = 52\,\mathrm{x\,SM}$

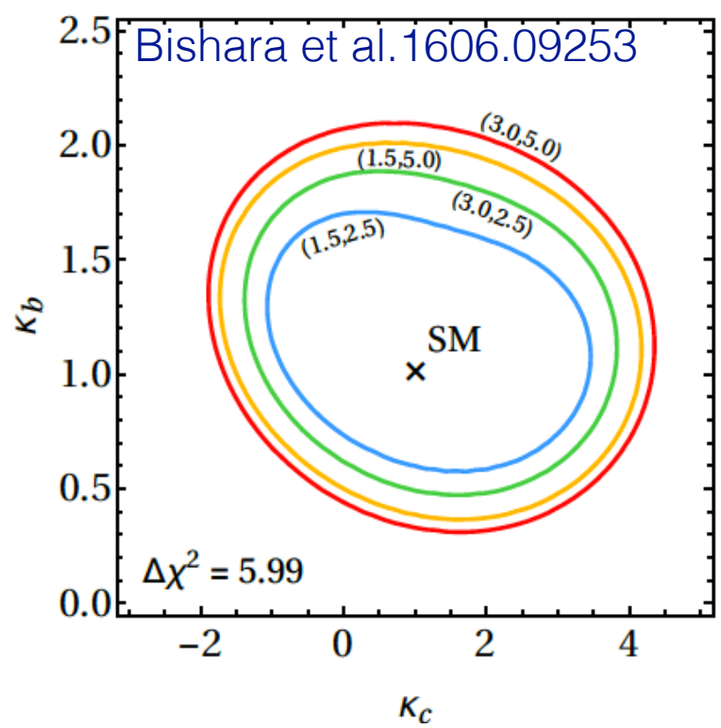
(arXiv:1501.03276 and ATLAS-CONF-2017-057)

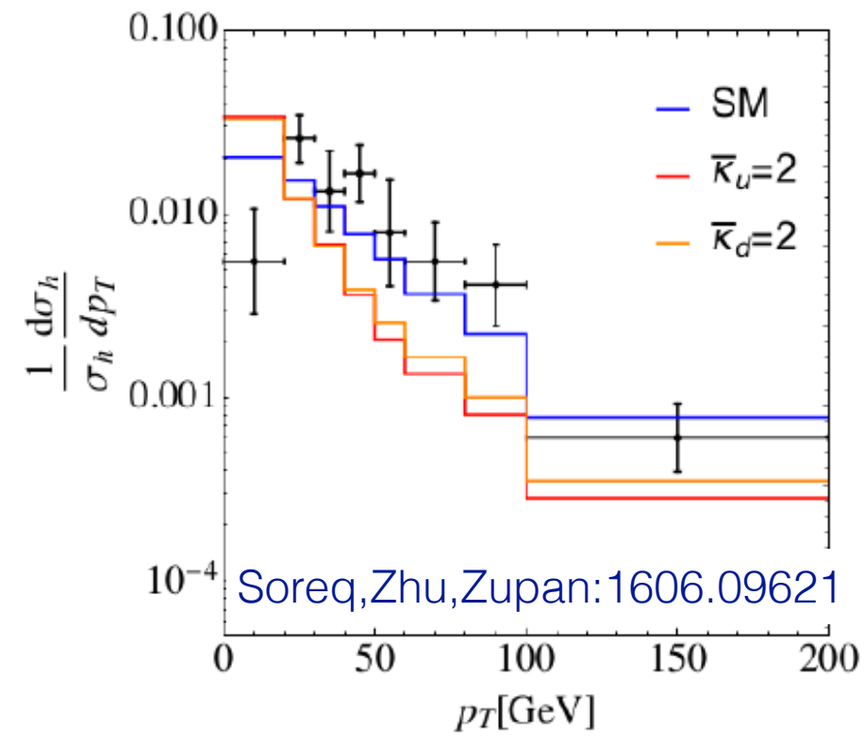
Lots of room for BSM deviations
Great opportunity for HL-LHC

Light quark Yukawas (2)

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







κ_c

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

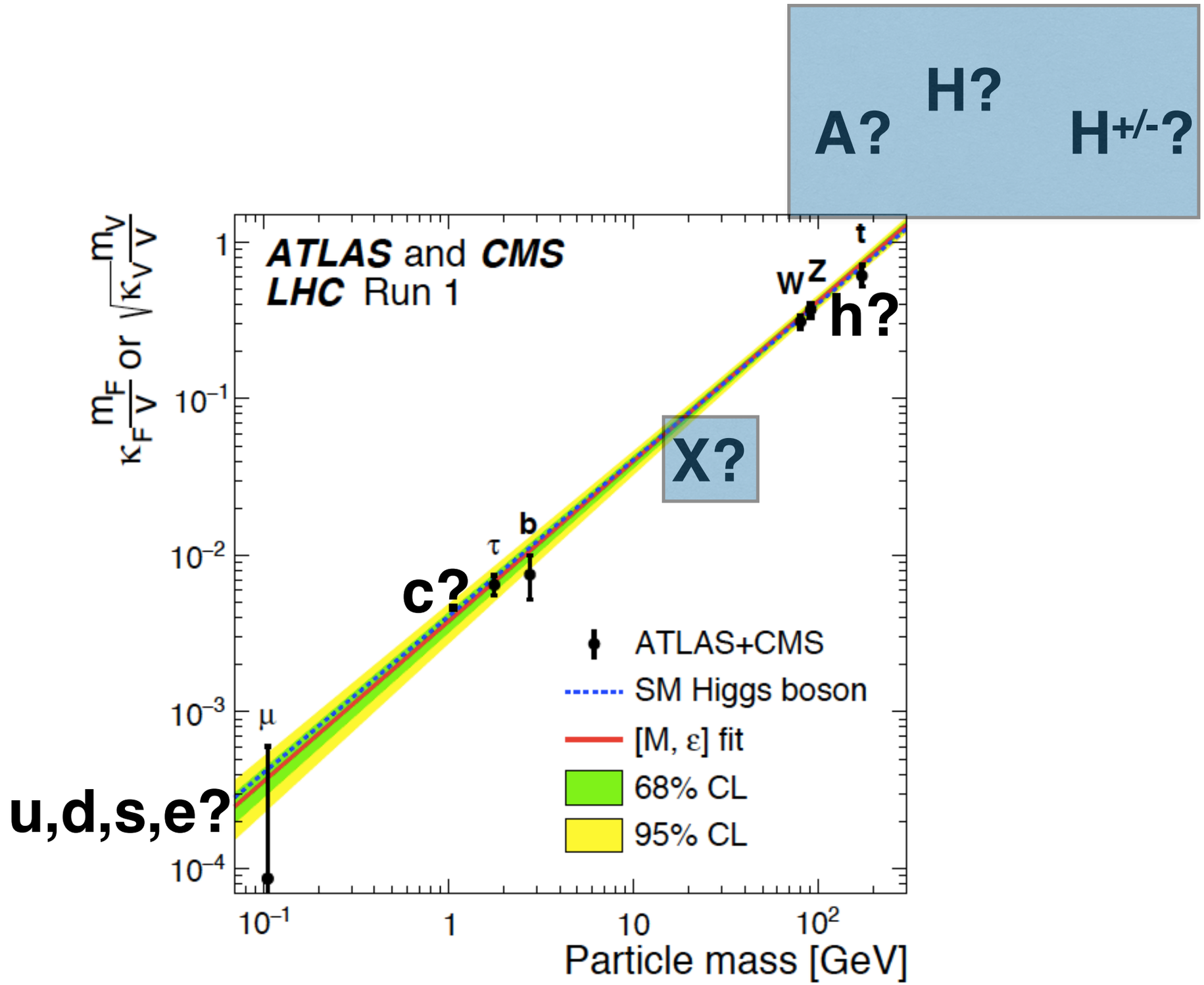
LHC Run II: $[-1.4, 3.8]$

HL-LHC: $[-0.6, 3.0]$

1st generation

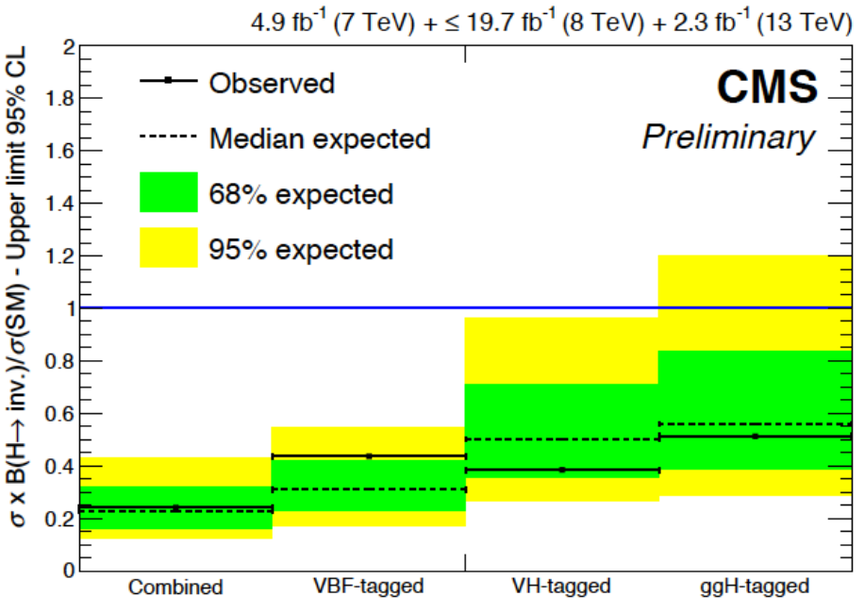
To be fully explored

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)



II. Searching for new states

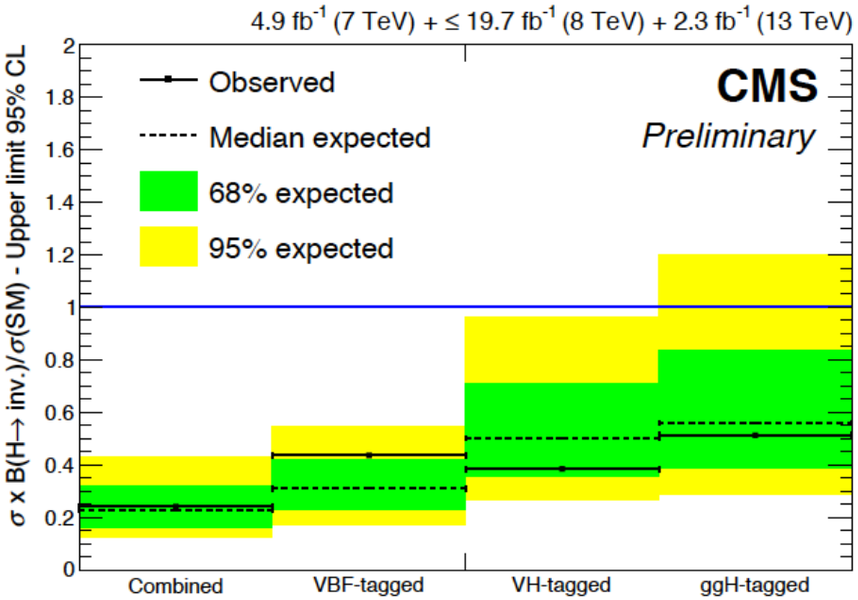
Searching for the invisible



CMS HIG-16-016 [JHEP 02 (2017) 135]

$B(H \to \text{inv.}) < 0.24\ (0.23)$ at a 95% CL

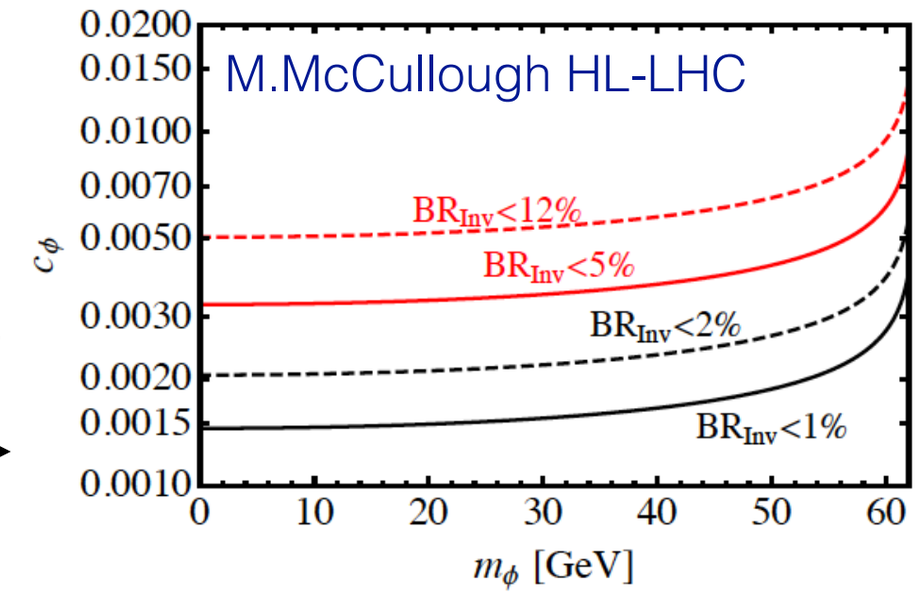
Searching for the invisible



CMS HIG-16-016 [JHEP 02 (2017) 135]

$B(H \to \text{inv.}) < 0.24\ (0.23)$ at a 95% CL

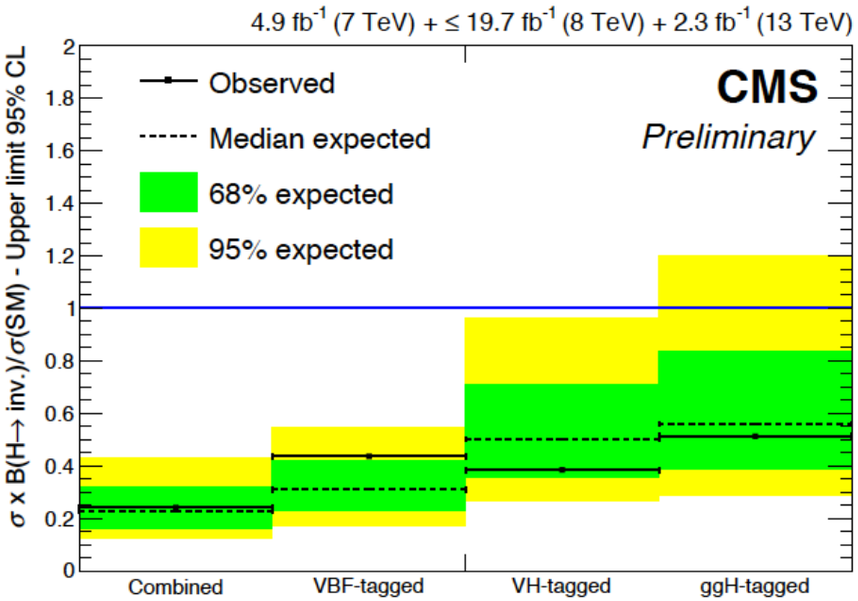
Immediate implications for any model with particles of mass $m<m_H/2$



$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

Simplest extension of the SM:
The Higgs portal
A window to the Dark Sector

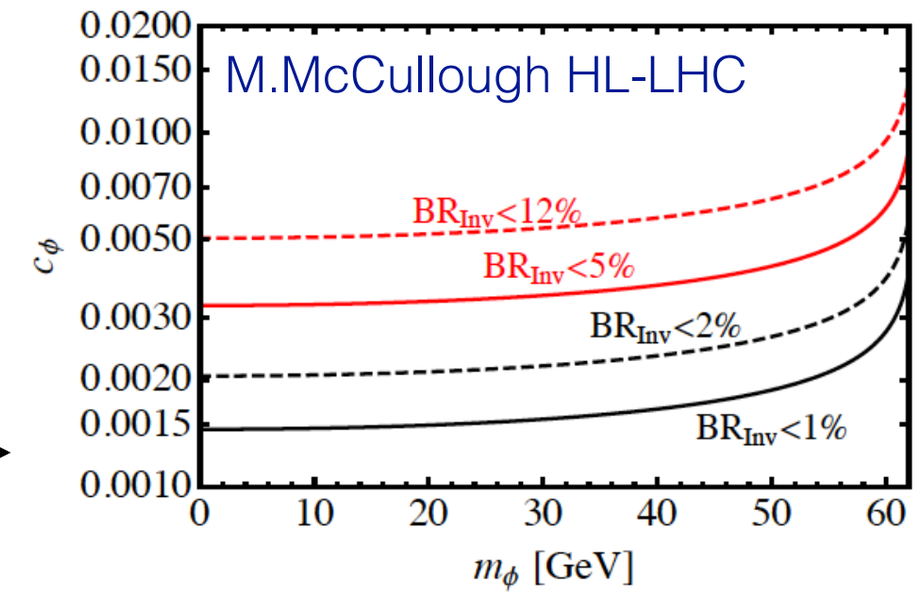
Searching for the invisible



CMS HIG-16-016 [JHEP 02 (2017) 135]

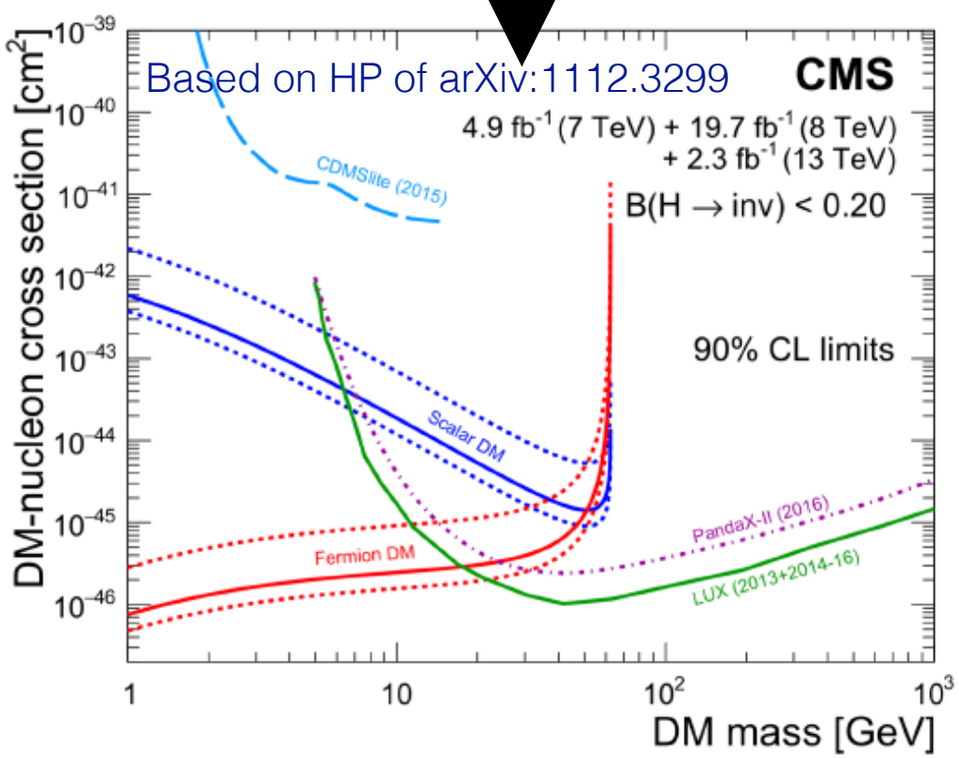
$B(H \to \text{inv.}) < 0.24\ (0.23)$ at a 95% CL

Immediate implications for any model with particles of mass $m<m_H/2$

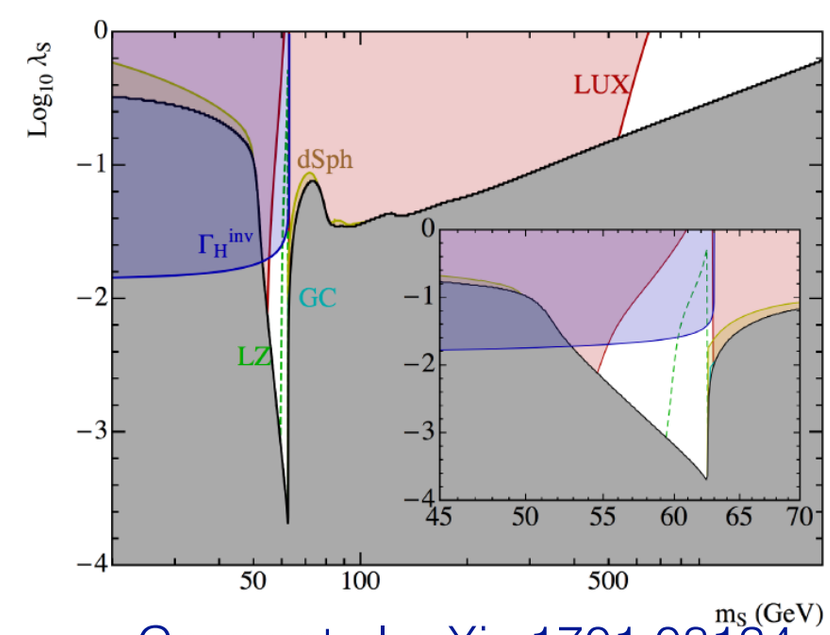


$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

Simplest extension of the SM:
The Higgs portal
A window to the Dark Sector



Important Dark Matter implications



Casas et al arXiv:1701.08134

Searching for the visible

LHC constrains extended scalar sectors using:

- Resonant searches VV, ZH, HH, tt, bb, ττ etc
- Single Higgs measurements:
  - Coupling strengths
  - Higgs exotic decays
  - Higgs width

The example of the 2HDM

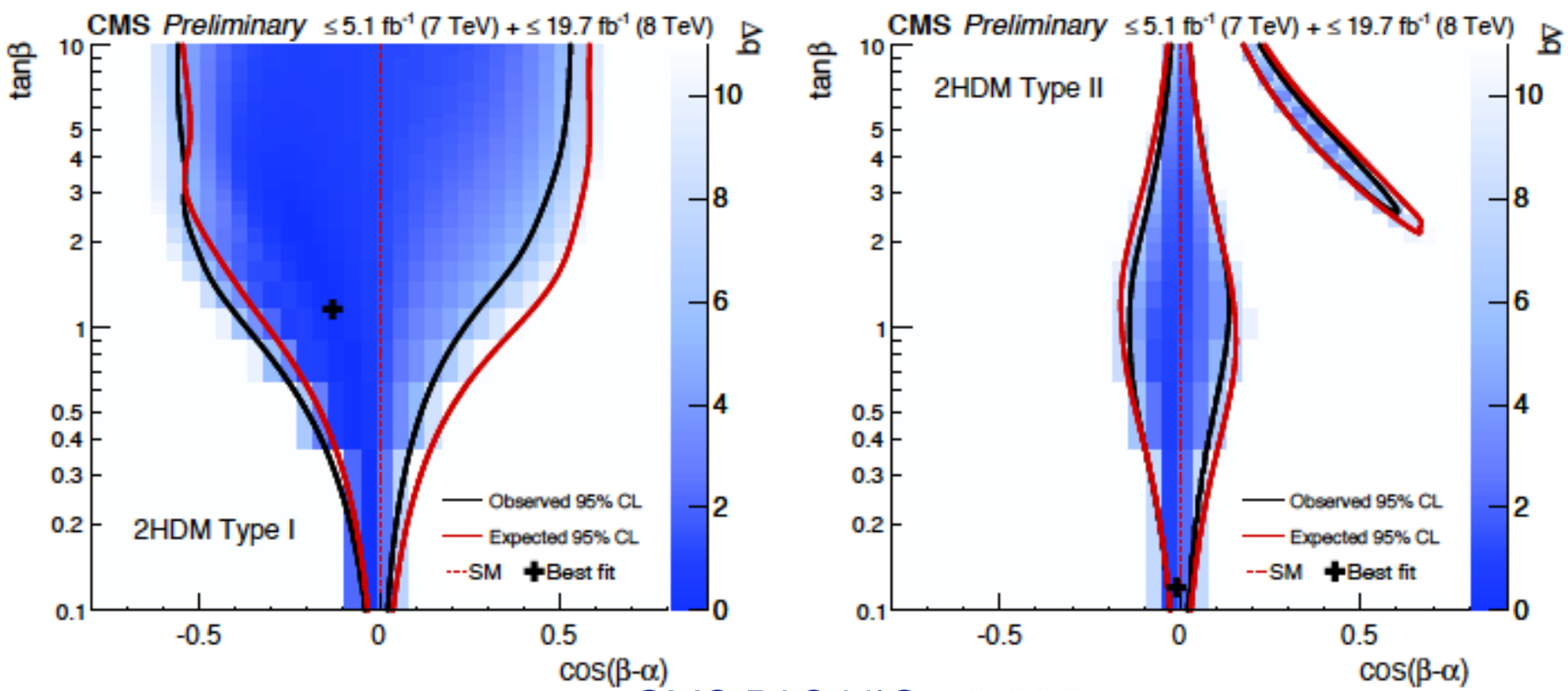
Second Higgs doublet ⟶ $h, H, A, H^{\pm}$ + modifications of the 125 GeV Higgs couplings

SM-like Higgs ⟶ approaching the alignment limit:

$$|\cos(\beta - \alpha)| \ll 1$$

Is decoupling avoidable? Or is $m_h \ll m_H,\ m_A,\ m_{H^{\pm}}$?

The LHC is doing its best to tell us



CMS PAS HIG-16-007

Constraints from:

$A/H/h \to \tau\tau$

$H \to WW/ZZ$

$H \to hh$

$A \to Zh$

+Light Higgs couplings

The example of the 2HDM

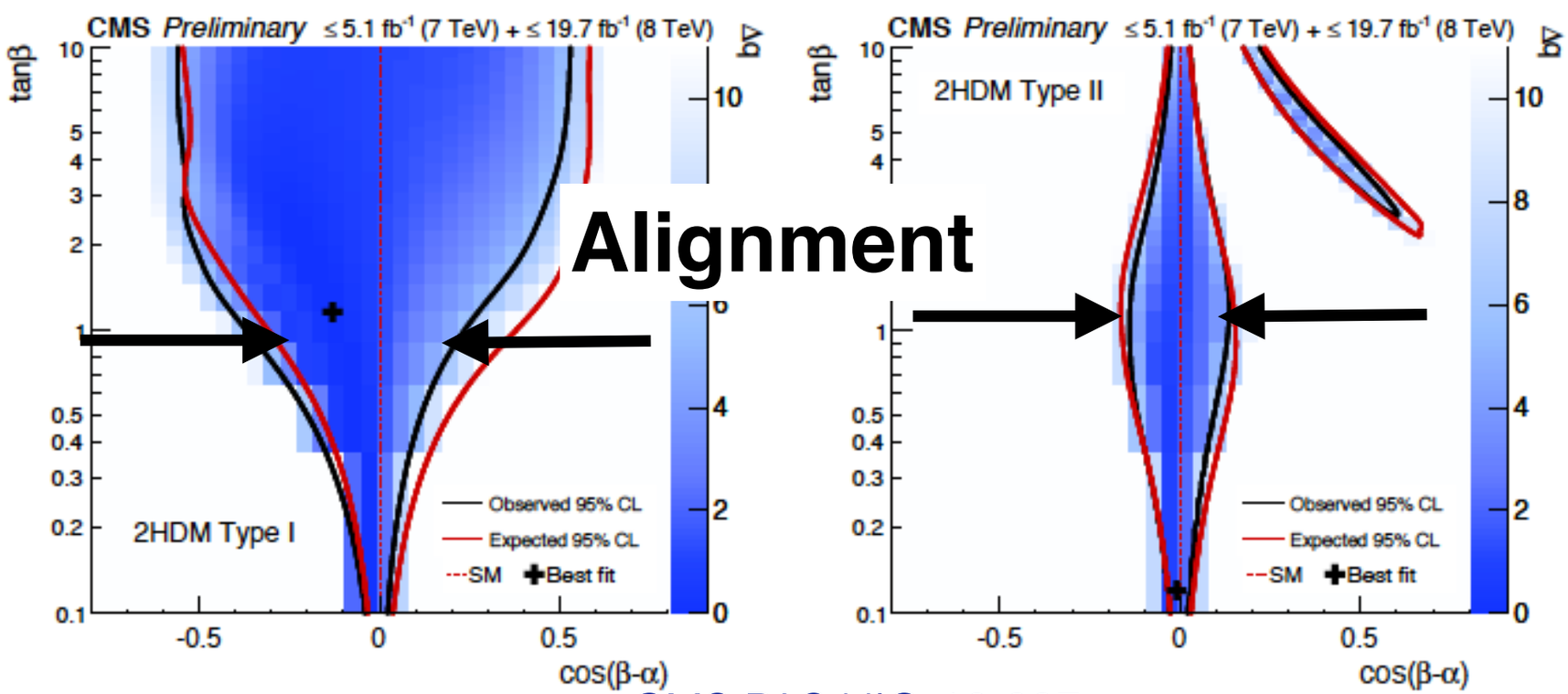
Second Higgs doublet ⟶ $h, H, A, H^{\pm}$ + modifications of the 125 GeV Higgs couplings

SM-like Higgs ⟶ approaching the alignment limit:

$$|\cos(\beta - \alpha)| \ll 1$$

Is decoupling avoidable? Or is $m_h \ll m_H,\ m_A,\ m_{H^{\pm}}$?

The LHC is doing its best to tell us



CMS PAS HIG-16-007

Constraints from:

$A/H/h \to \tau\tau$

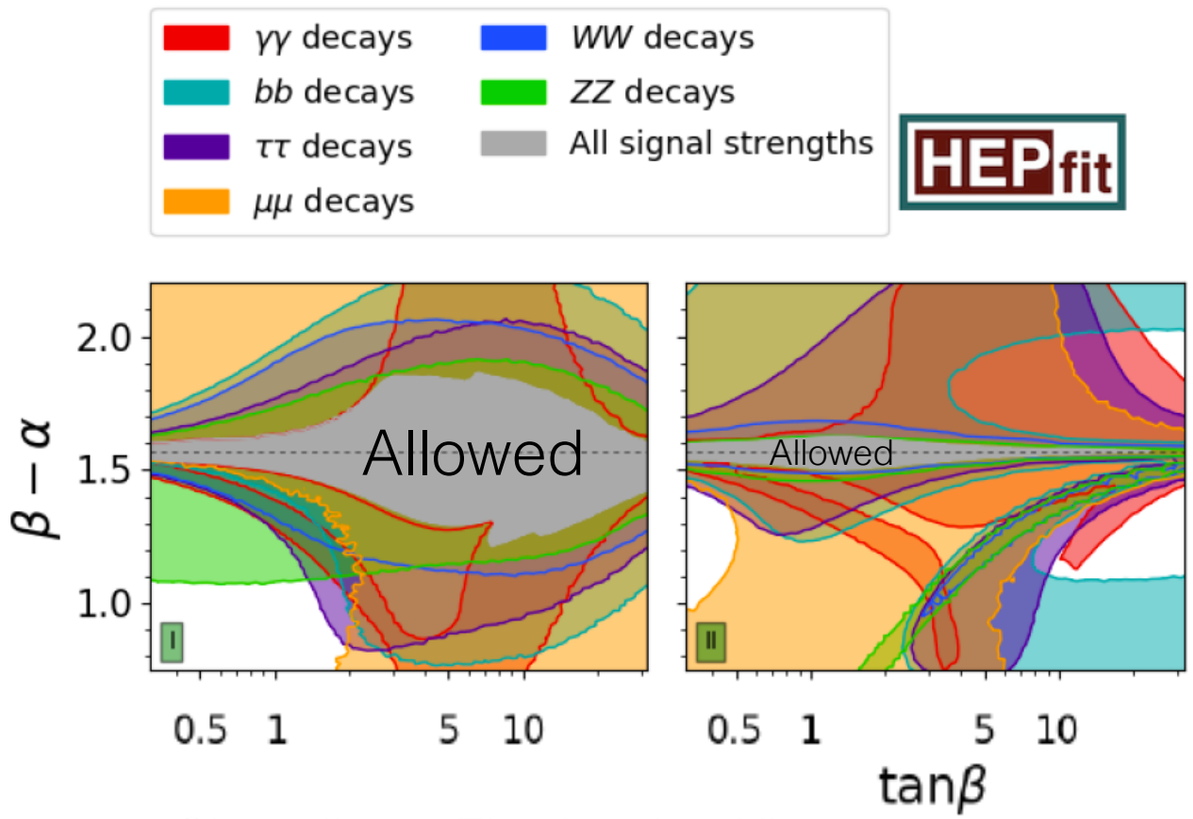
$H \to WW/ZZ$

$H \to hh$

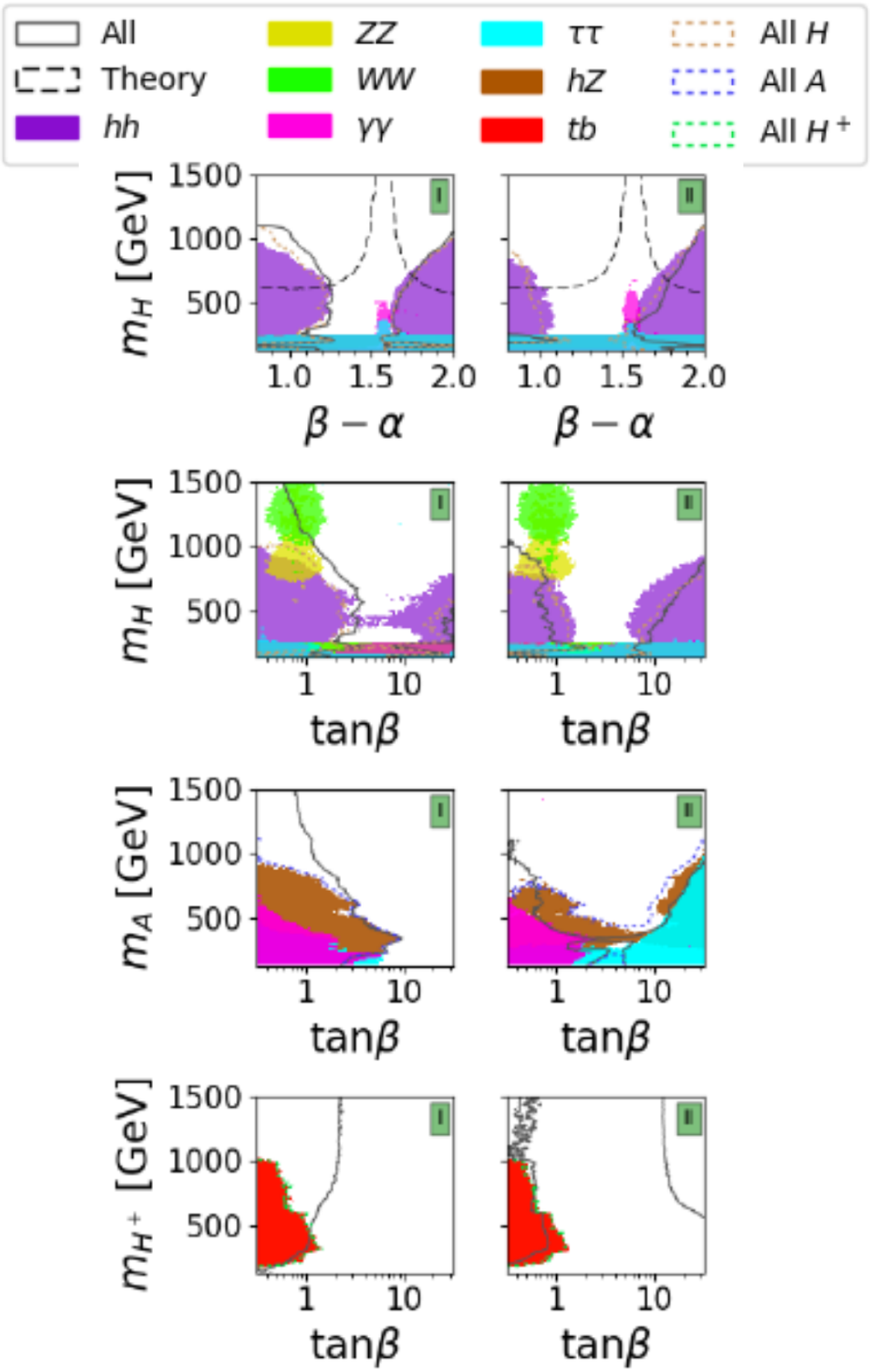
$A \to Zh$

+Light Higgs couplings

LHC impact on global 2HDM fits

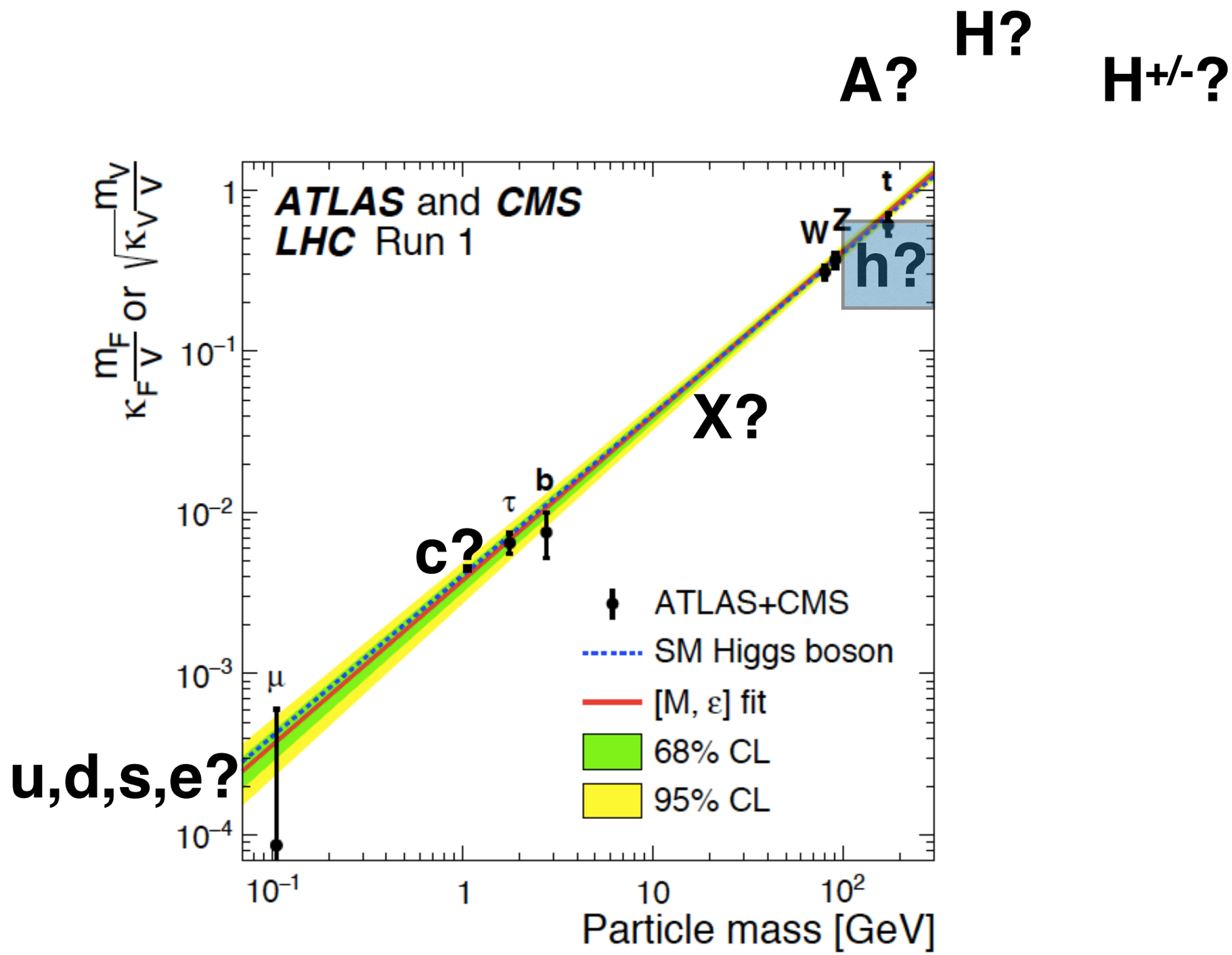


Chowdhury, Eberhardt arXiv:1711.02095



Signal strengths clearly pointing towards the alignment limit: more stringent for type II

A plethora of searches are being used to constrain the model
Allowed windows remain



III. The Higgs potential

The Higgs potential

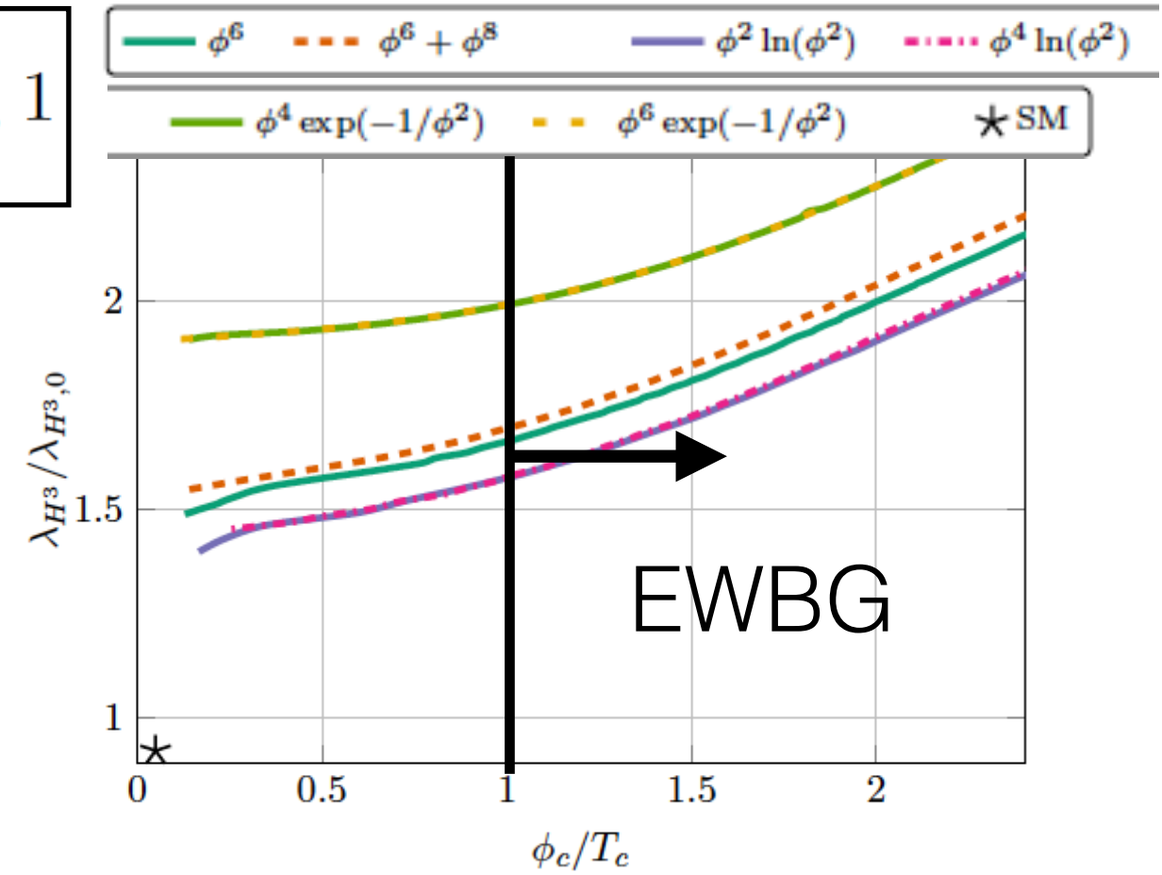
Higgs potential: $$V(H) = \frac{1}{2} M_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4} \lambda_{HHHH} H^4$$

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

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

What can measuring λ_{HHH} tell us?

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



Reichert et al: arXiv:1711.00019

The Higgs potential

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

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

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

What can measuring λ_{HHH} tell us?

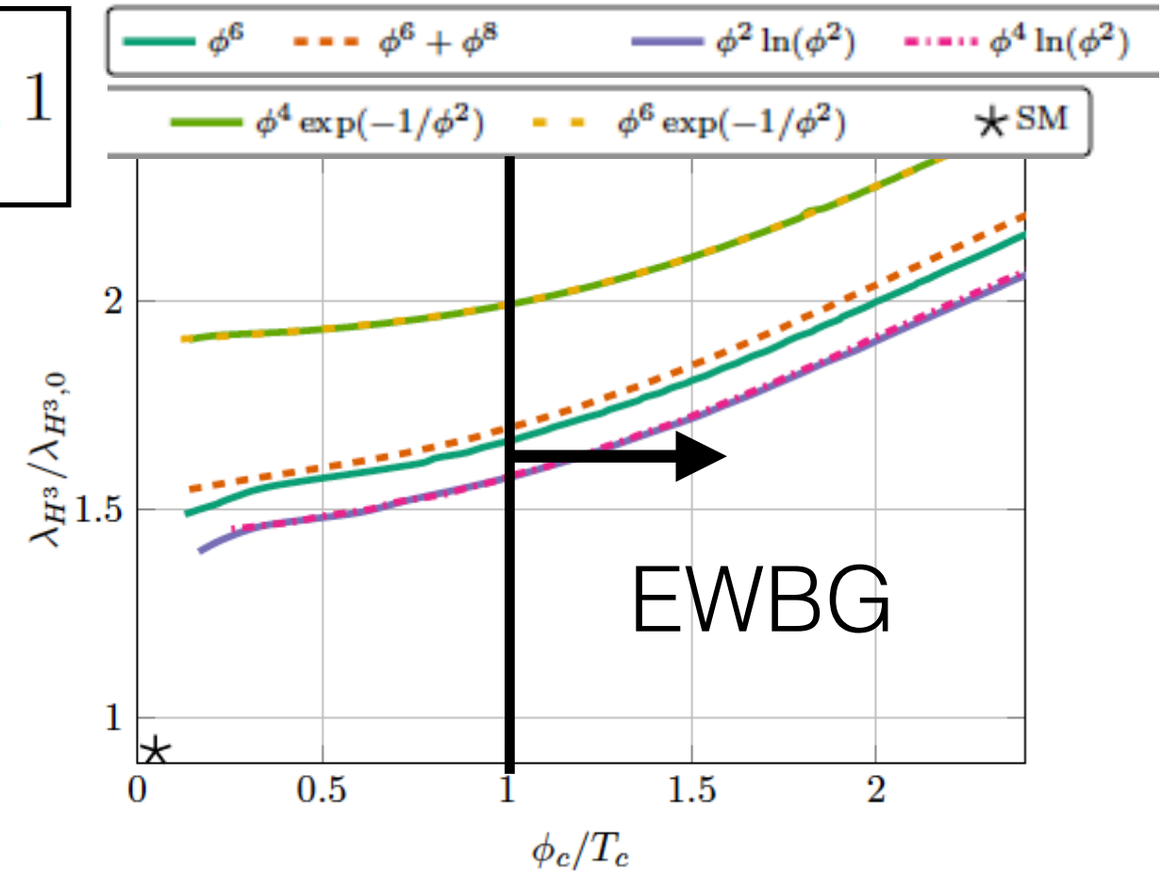
Electroweak baryogenesis requires a first order strong EWPT → $\frac{\phi_c}{T_c} \gtrsim 1$

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

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:

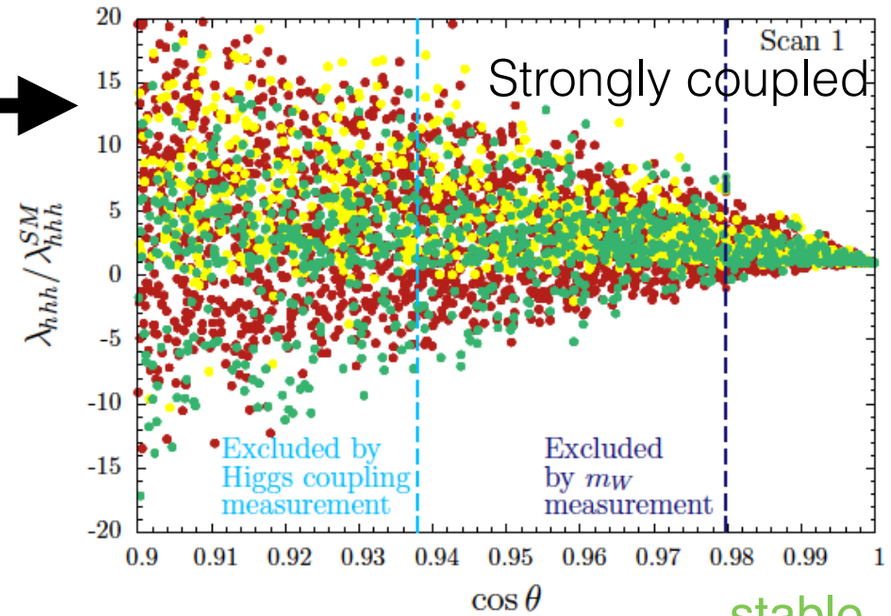
- Partial wave unitarity: $|\mathrm{Re}\, a^0_{hh\to hh}| < 1/2 \quad |\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}| \lesssim 6.5$
- Loop-corrections to λ smaller than λ $\left|\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}\right| \lesssim 6$

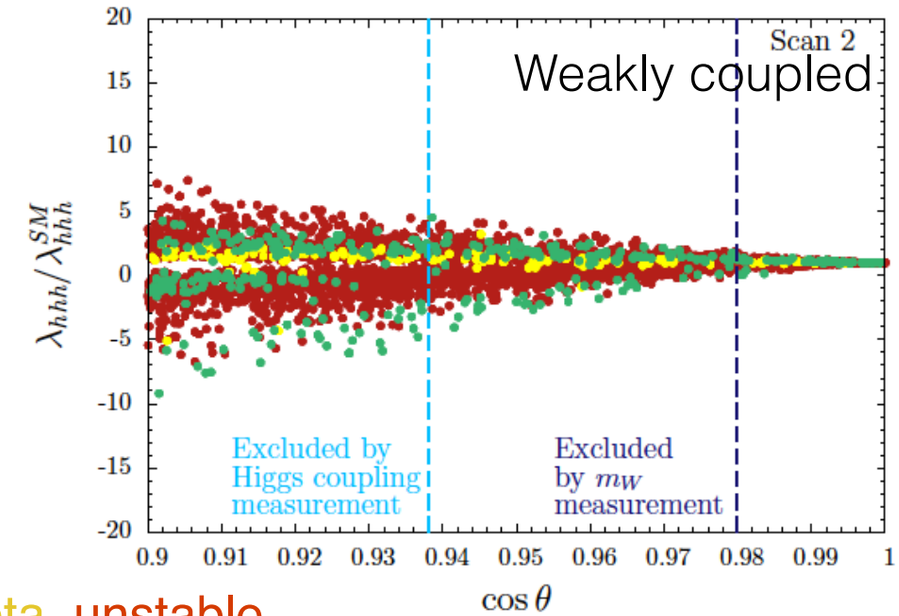
Di Luzio, Grober, Spannowsky arXiv:1704.02311

Specific UV complete models:

Scalar extensions:

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





stable, meta, unstable

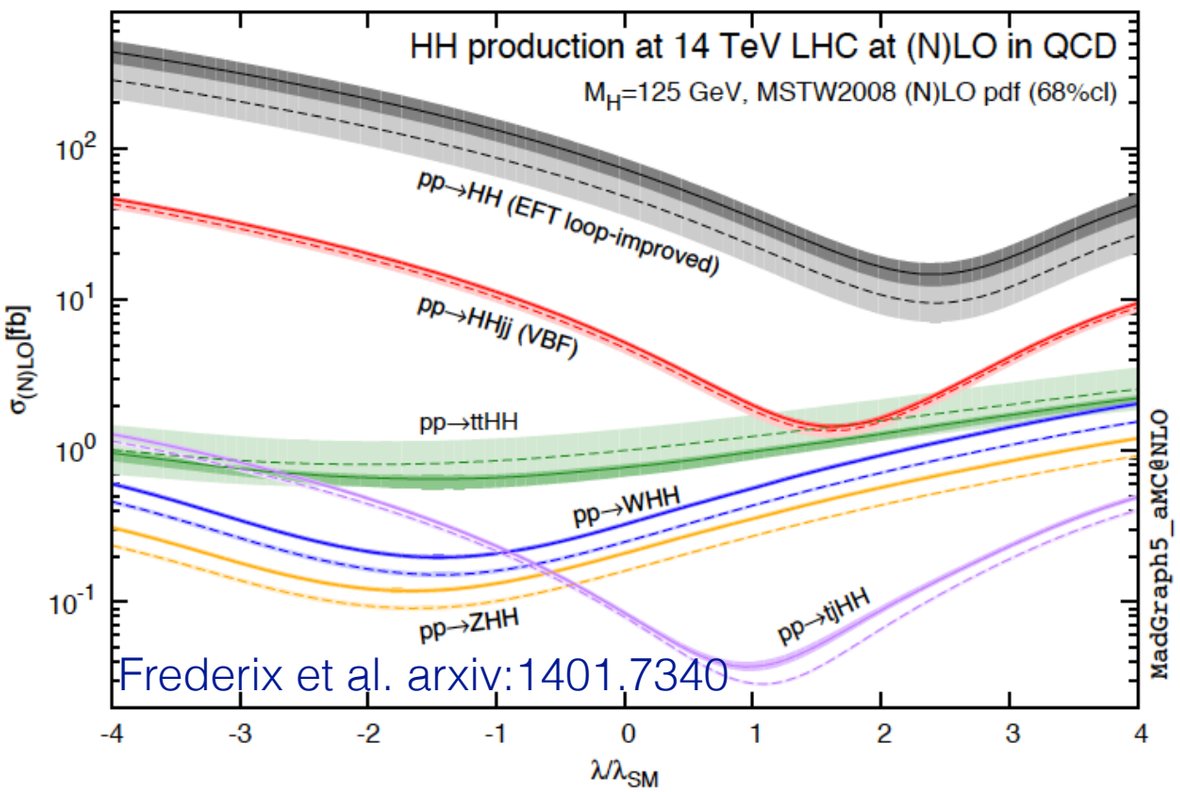
$-1.5 < \lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh} < 8.7$

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

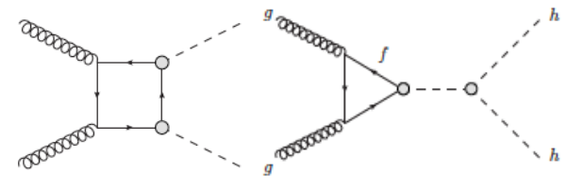
Di Luzio, Grober, Spannowsky arXiv:1704.02311

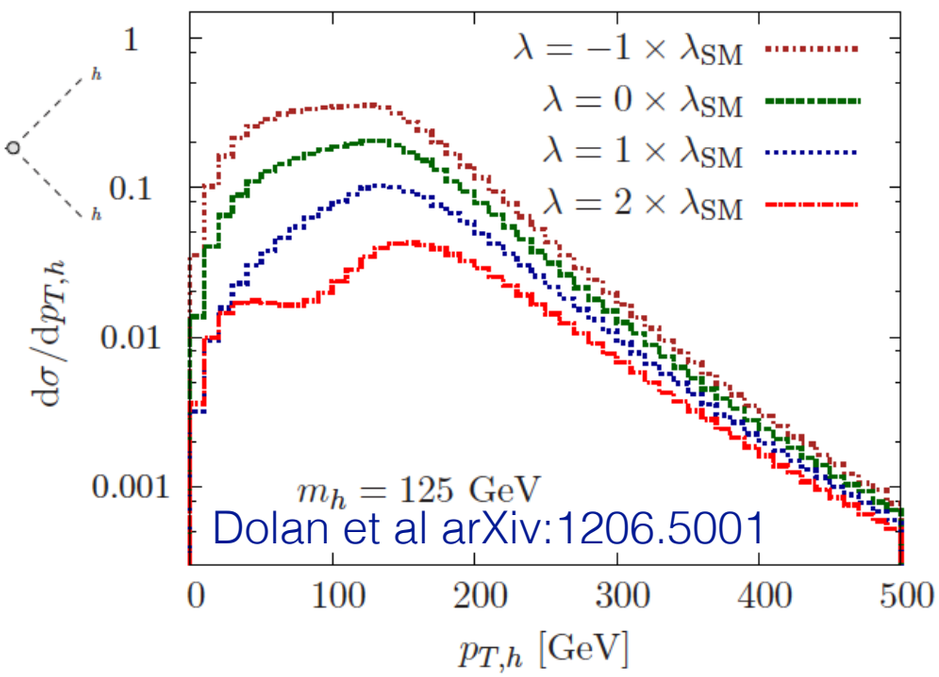
See also Di Vita et al. 1704.01953: Fine-tuned Higgs portal $\left|\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}\right| \lesssim 6$

How to extract λ_{HHH}: 1) HH



Frederix et al. arxiv:1401.7340





Dolan et al arXiv:1206.5001

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

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:

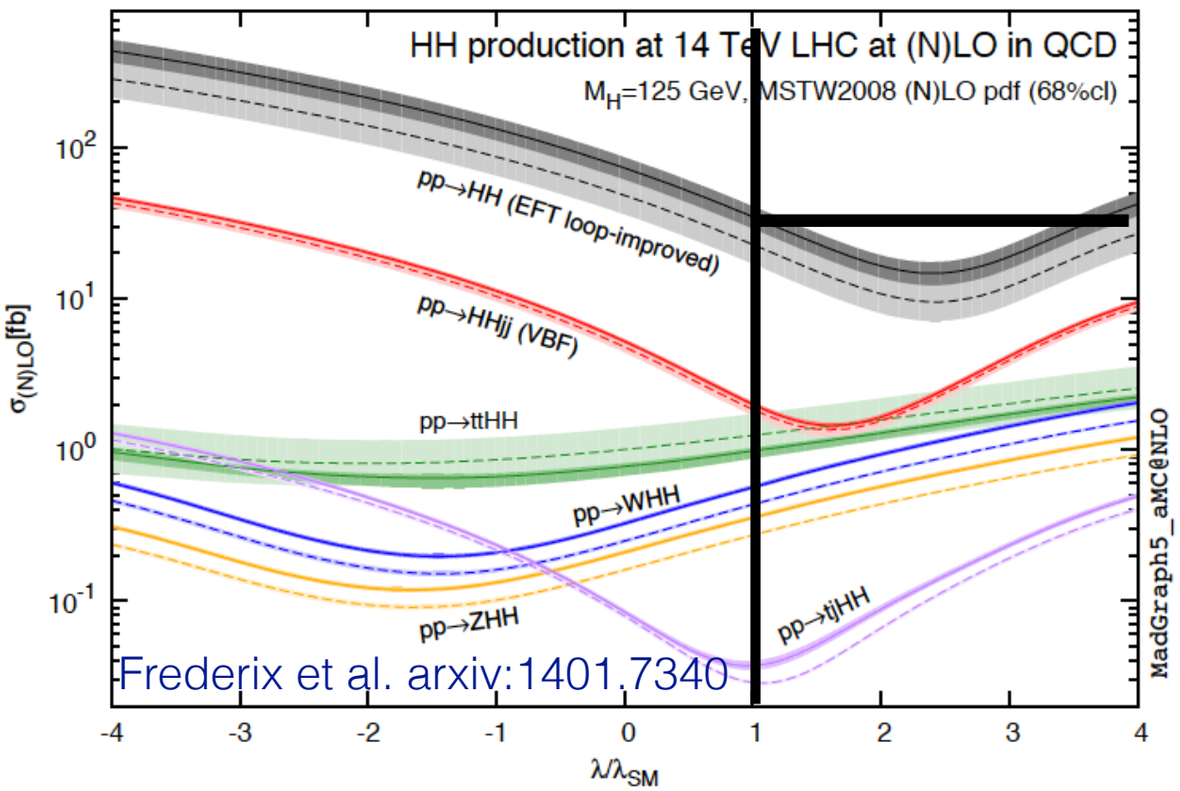
$bbbb$ $0.2 < \lambda/\lambda_{SM} < 7.0$ (stat)

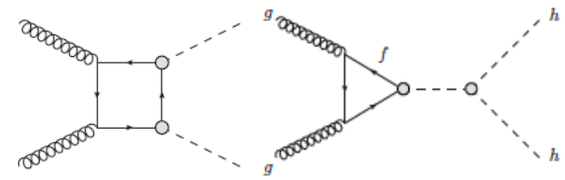
ATL-PHYS-PUB -2016-024

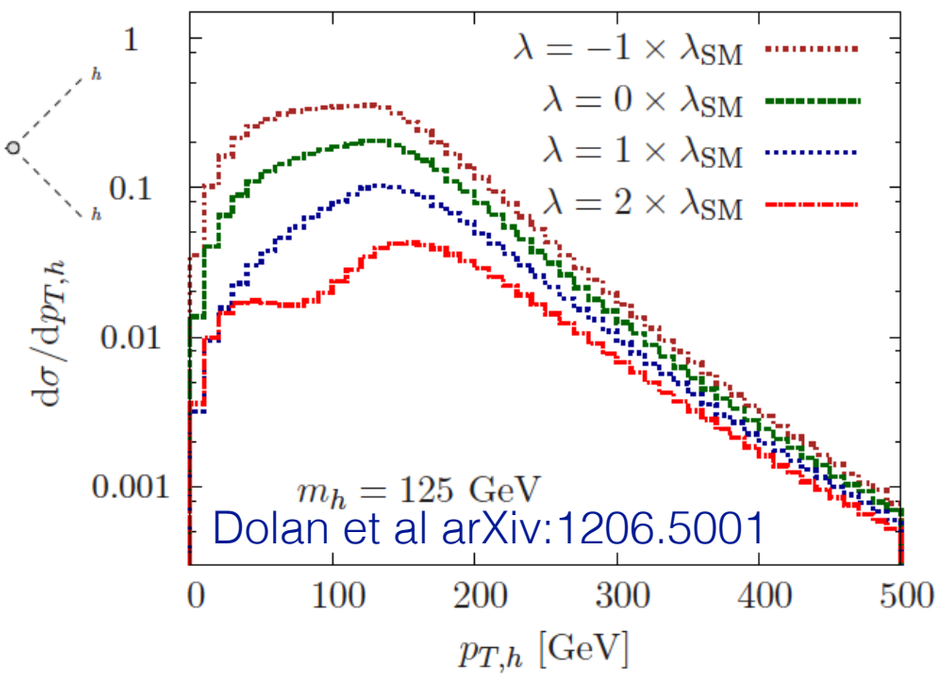
$bb\gamma\gamma$ $-0.8 < \lambda/\lambda_{SM} < 7.7$ (stat)

ATL-PHYS-PUB -2015-046

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

Current limits:

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

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

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

Projections for HL-LHC:

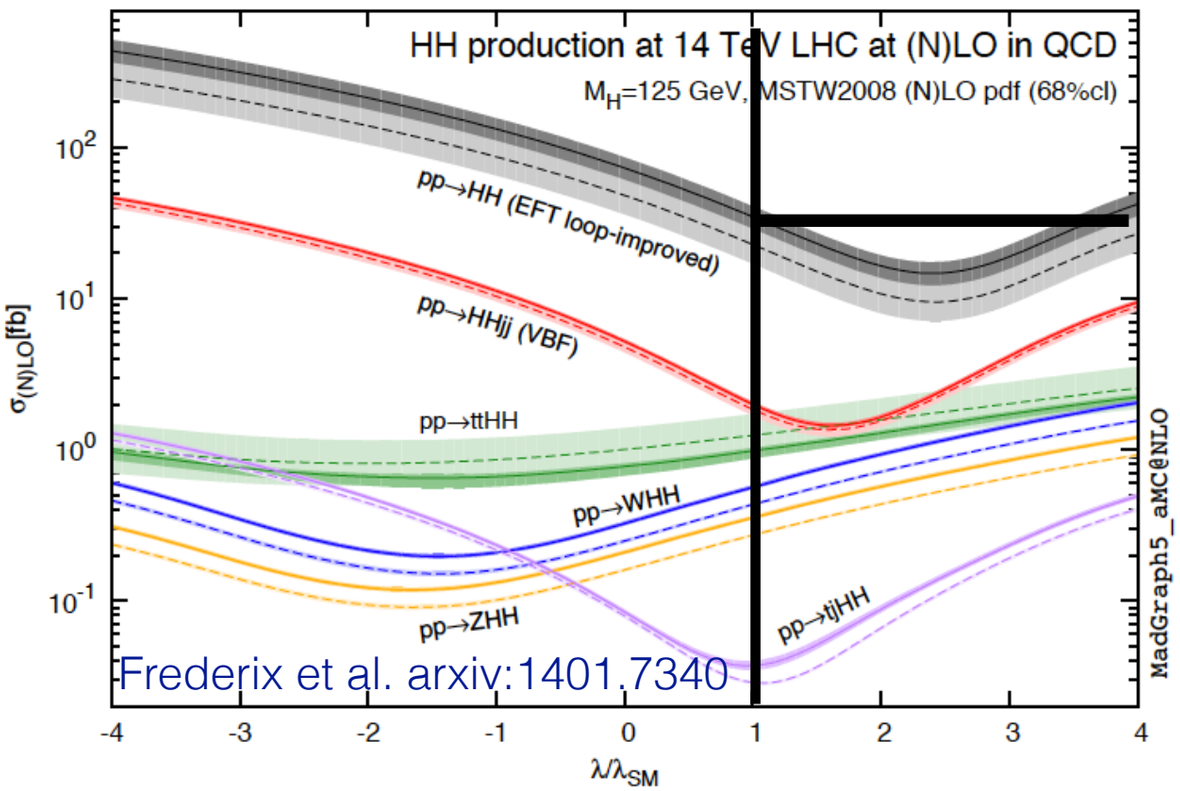
$bbbb$ $0.2 < \lambda/\lambda_{SM} < 7.0$ (stat)

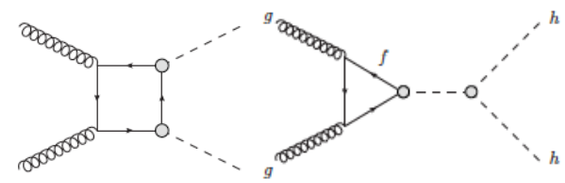
ATL-PHYS-PUB -2016-024

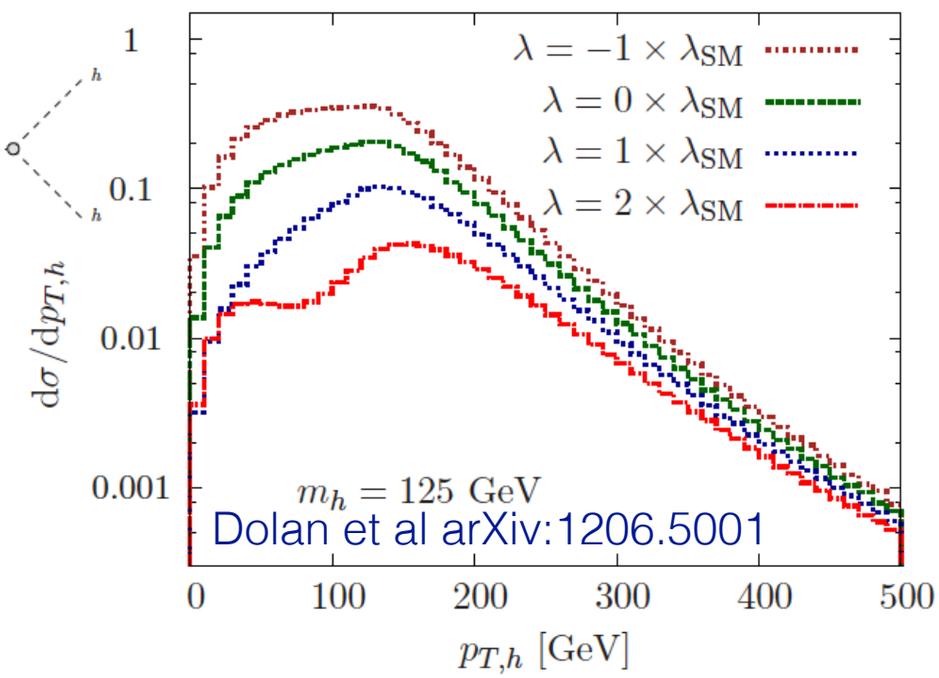
$bb\gamma\gamma$ $-0.8 < \lambda/\lambda_{SM} < 7.7$ (stat)

ATL-PHYS-PUB -2015-046

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

Projections for HL-LHC:

$bbbb$ $0.2 < \lambda/\lambda_{SM} < 7.0$ (stat)

ATL-PHYS-PUB -2016-024

$bb\gamma\gamma$ $-0.8 < \lambda/\lambda_{SM} < 7.7$ (stat)

ATL-PHYS-PUB -2015-046

Current limits:

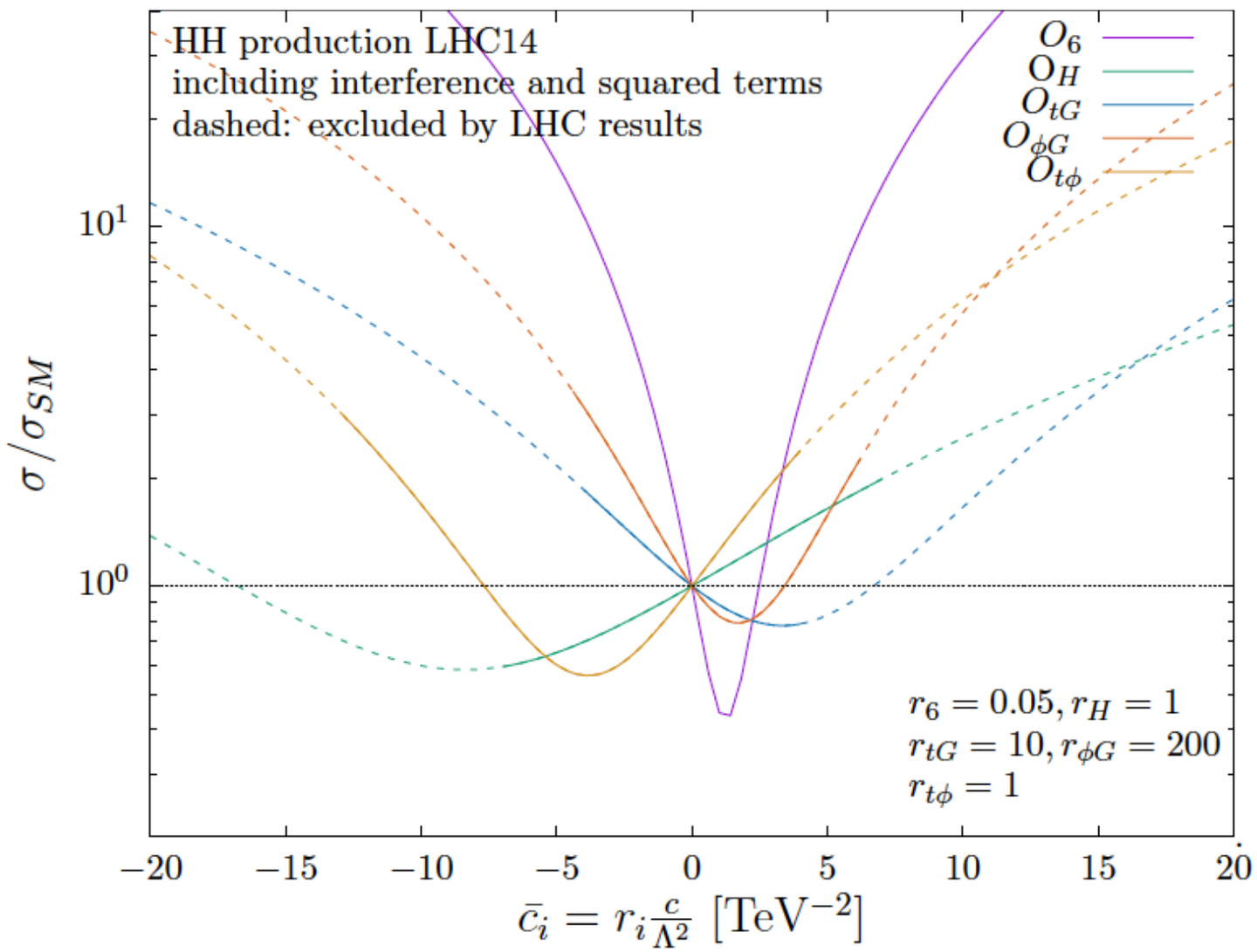
CMS: $\sigma/\sigma_{SM} < 19(bb\gamma\gamma)$

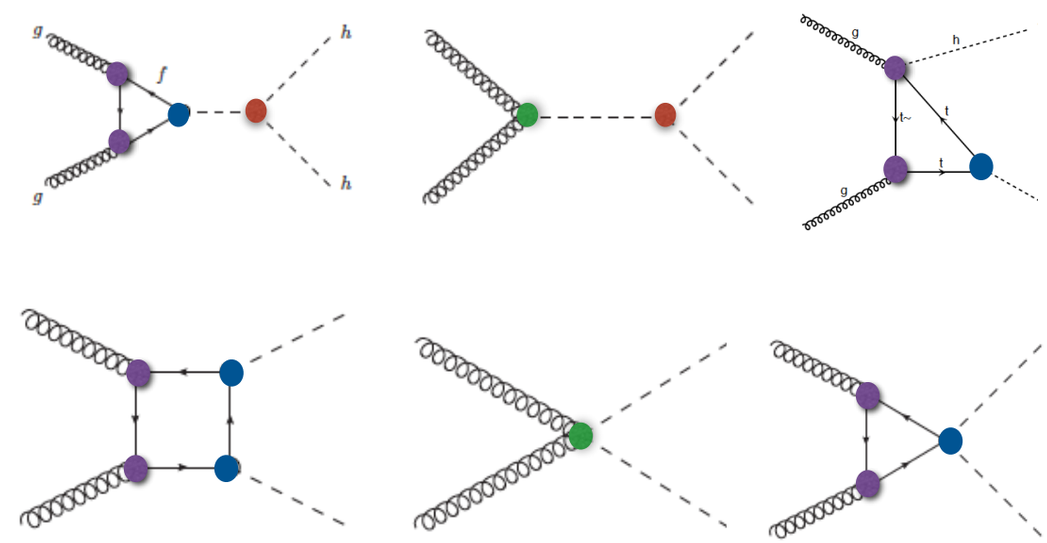
ATLAS: $\sigma/\sigma_{SM} < 30(bbbb)$

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

A challenge even for the HL-LHC

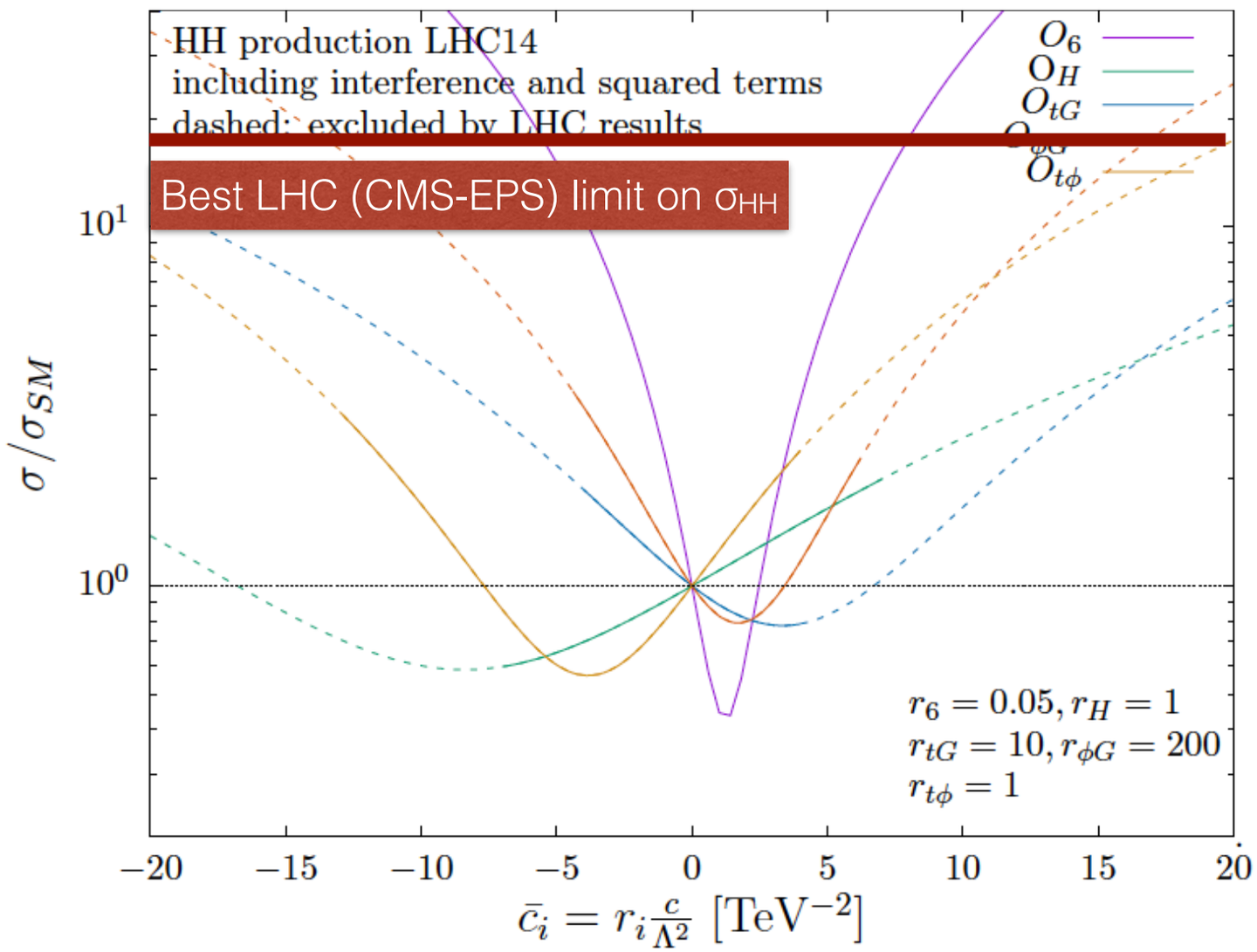
How to extract λ_{HHH} from HH?

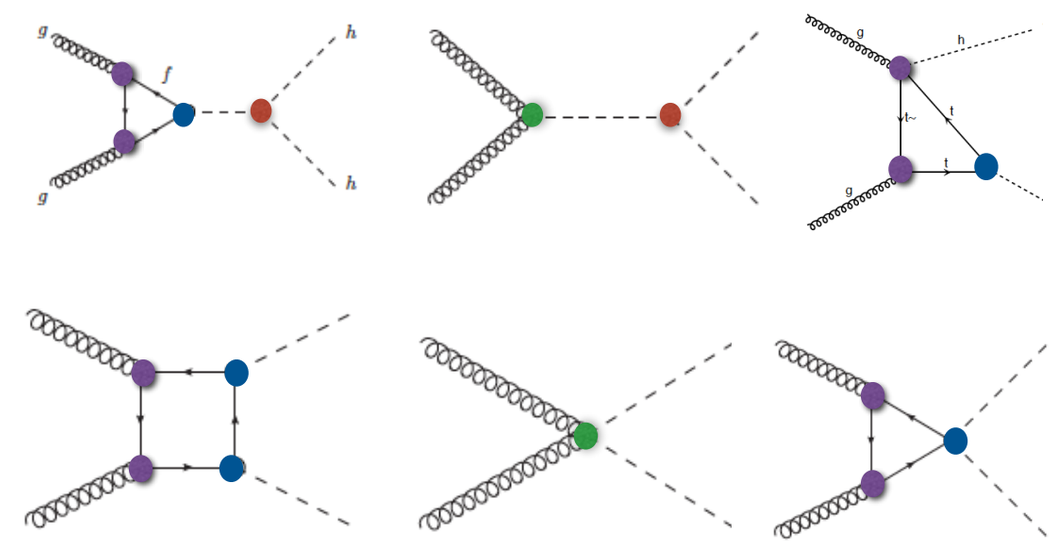




Other couplings enter in the same process:
top Yukawa, ggh(h) coupling, top-gluon interaction

How to extract λ_{HHH} from HH?



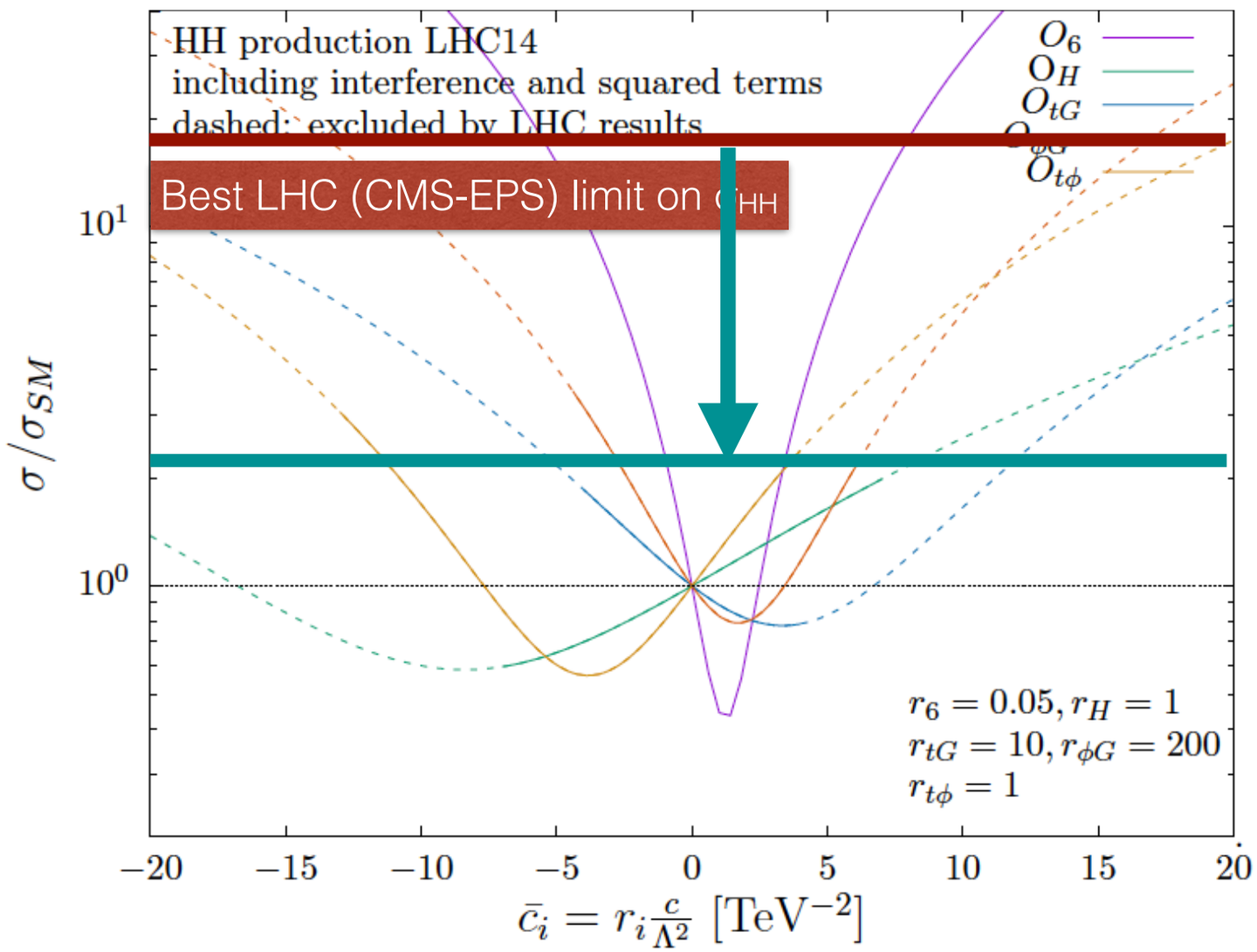


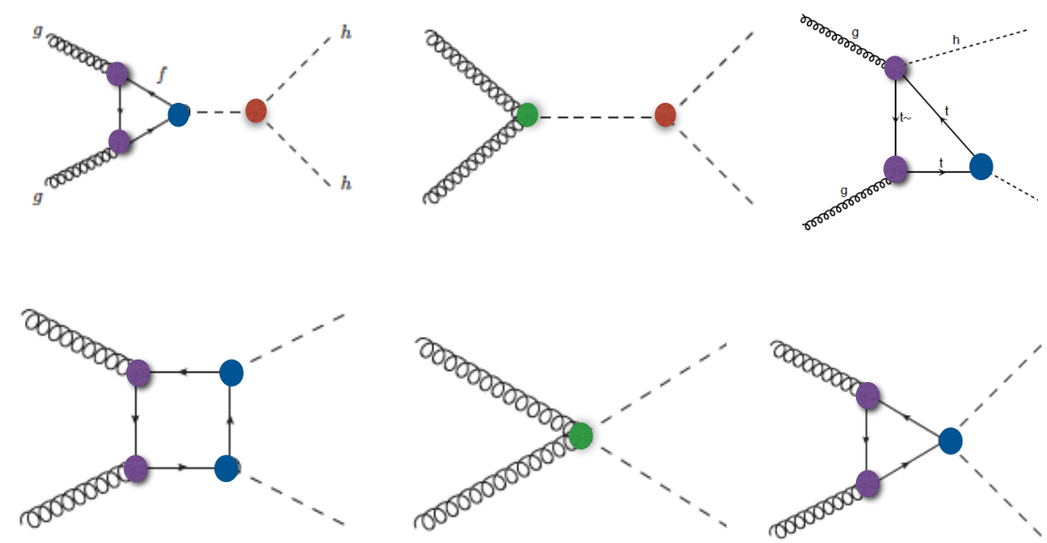
Other couplings enter in the same process:
top Yukawa, ggh(h) coupling, top-gluon interaction

The present

Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained "ignoring" other couplings

How to extract λ_{HHH} from HH?





Other couplings enter in the same process:
top Yukawa, ggh(h) coupling, top-gluon interaction

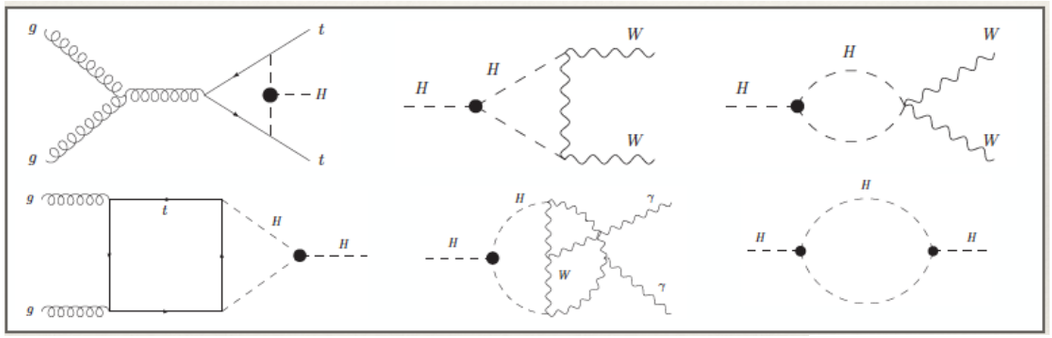
The present

Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained "ignoring" other couplings

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)

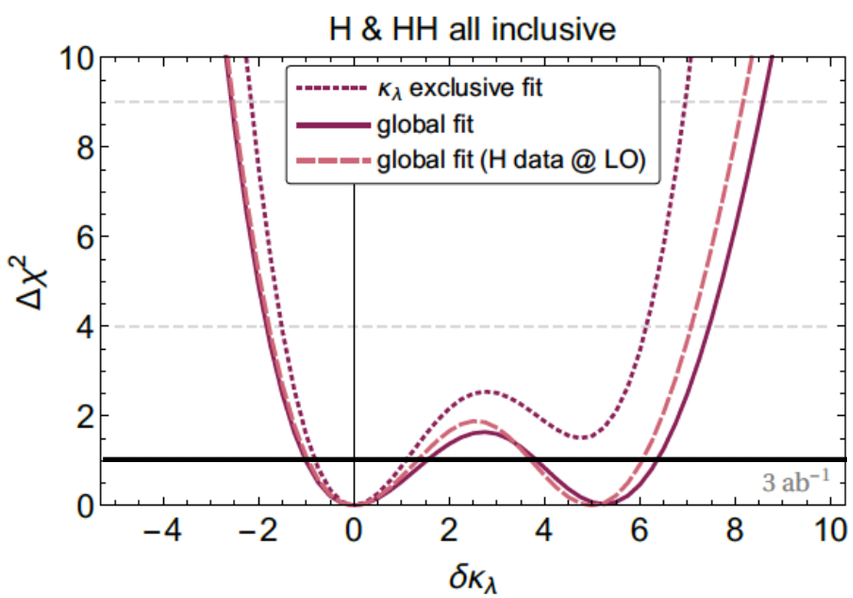
Run I single Higgs results: $\kappa_\lambda^{2\sigma} = [-9.4, 17.0]$

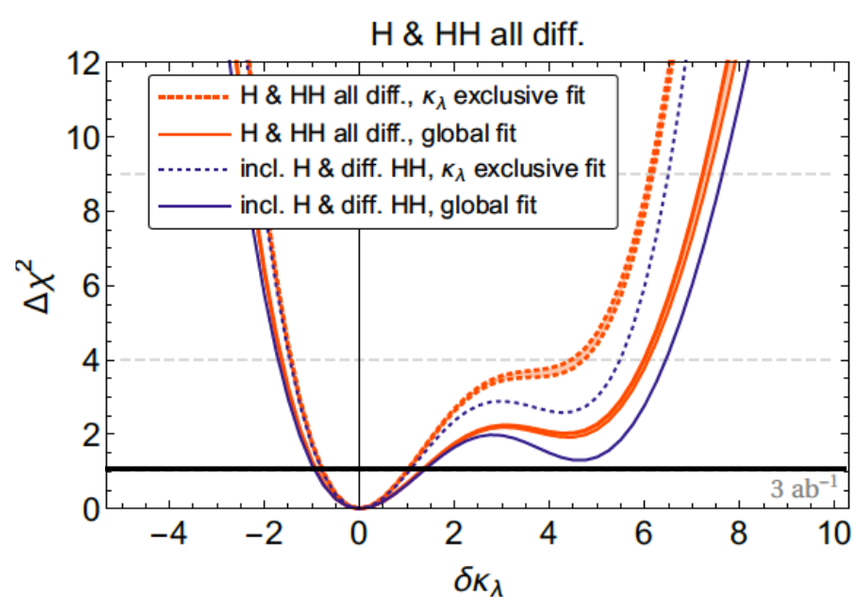
Degrassi et al. arXiv:1607.04251

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:

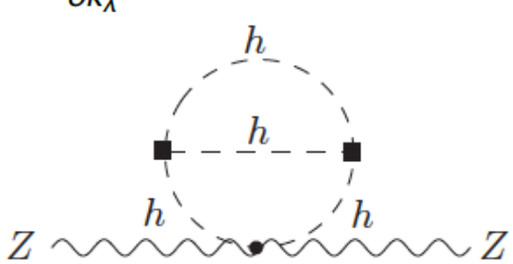


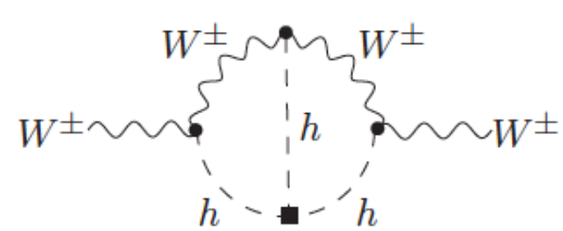


- Synergy between H and HH production
- Differential distributions crucial to break degeneracies at HL-LHC

Di Vita et al. arXiv:1704.01953

EWPO:





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

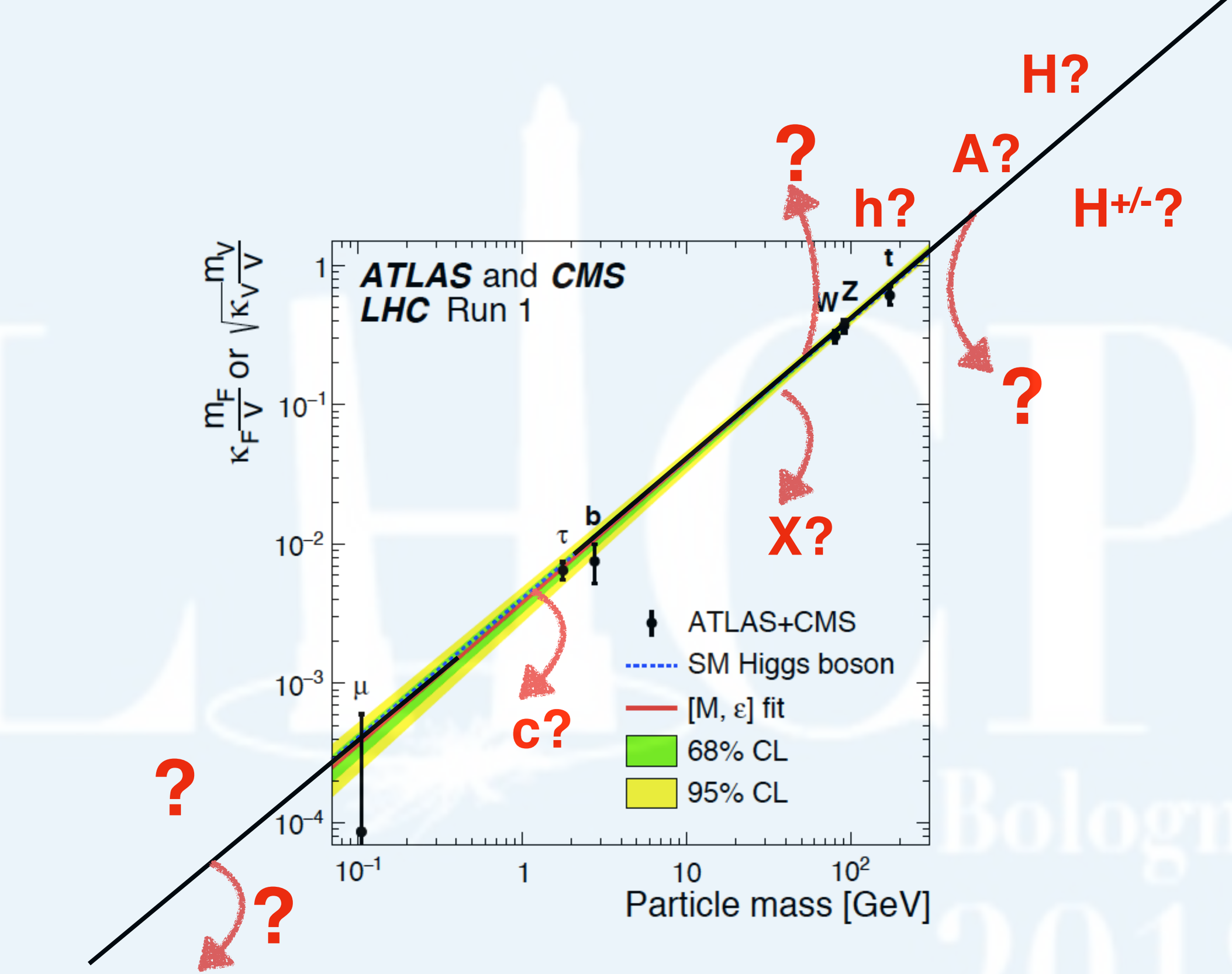
Degrassi et al 1702.01737
Kribs et al 1702.07678

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