# Anomalies and Expectations: An Express Overview

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**Hamburg. December 12th 2017.**

**On Charm:**

**I know she invented fire,**
**but what has she done recently?**

**Ikaros I. Bigi**

# what are we looking at?

$D^0$, $D^+$ and $D_s^+$ with $\pi$, $K$ in the final states

| SCS | | | CA & DCS | | |
|---|---|---|---|---|---|
| Channel | Fit ($\times 10^{-3}$) | Exp. ($\times 10^{-3}$) | Channel | Fit ($\times 10^{-3}$) | Exp. ($\times 10^{-3}$) |
| $D^0 \to \pi^+\pi^-$ | 1.42 ± 0.03 | 1.421 ± 0.025 | $D^+ \to \pi^+ K_S$ | 15.71 ± 0.41 | 15.3 ± 0.6 |
| $D_0^+ \to \pi^0\pi^0$ | 0.82 ± 0.04 | 0.826 ± 0.035 | $D^+ \to \pi^+ K_L$ | 14.25 ± 0.38 | 14.6 ± 0.5 |
| $D^+ \to \pi^+\pi^0$ | 1.25 ± 0.06 | 1.24 ± 0.06 | $D^0 \to \pi^+ K^-$ | 39.40 ± 0.40 | 39.3 ± 0.4 |
| $D^0 \to K^+K^-$ | 3.95 ± 0.06 | 4.01 ± 0.07 | $D^0 \to \pi^0 K_S$ | 12.14 ± 0.33 | 12.0 ± 0.4 |
| $D^0 \to K_S K_S$ | 0.17 ± 0.04 | 0.18 ± 0.04 | $D^0 \to \pi^0 K_L$ | 9.57 ± 0.27 | 10.0 ± 0.7 |
| $D^+ \to K^+ K_S$ | 3.06 ± 0.13 | 2.95 ± 0.15 | $D_s^+ \to K^+ K_S$ | 14.80 ± 0.49 | 15.0 ± 0.5 |
| $D_s^+ \to \pi^0 K^+$ | 1.05 ± 0.16 | 0.63 ± 0.21 | $D^+ \to \pi^0 K^+$ | 0.128 ± 0.012 | 0.189 ± 0.025 |
| $D_s^+ \to \pi^+ K_S$ | 1.22 ± 0.06 | 1.22 ± 0.06 | $D^0 \to \pi^- K^+$ | 0.141 ± 0.003 | 0.139 ± 0.0027 |

| $A_{CP}$ ($D^0$) | ($\mu \pm \sigma$) (%) | | $A_{CP}$ ($D^+_{(s)}$) | ($\mu \pm \sigma$) (%) | |
|---|---|---|---|---|---|
| | $\delta_i \to$ -ve | $\delta_i \to$ +ve | | $\delta_i \to$ -ve | $\delta_i \to$ +ve |
| $D^0 \to \pi^+\pi^-$ | 0.043 ± 0.054 | 0.045 ± 0.055 | $D^+ \to K^+ K_S$ | -0.012 ± 0.014 | -0.010 ± 0.014 |
| $D^0 \to \pi^0\pi^0$ | -0.019 ± 0.026 | 0.056 ± 0.030 | $D_s^+ \to \pi^+ K_S$ | 0.015 ± 0.018 | 0.013 ± 0.018 |
| $D^0 \to K^+K^-$ | -0.018 ± 0.022 | -0.016 ± 0.022 | $D_s^+ \to \pi^0 K^+$ | -0.045 ± 0.017 | 0.021 ± 0.018 |
| $D^0 \to K_S K_S$ | 0.019 ± 0.021 | 0.012 ± 0.024 | | | |

**FIT**

**PREDICTION**

# hence we need a parameterization…

the weak Hamiltonian:

$$\mathcal{H}_{\rm w} = \frac{G_F}{\sqrt{2}} V_{ud} V_{cd}^* \left[C_1 Q_1^d + C_2 Q_2^d\right] + \frac{G_F}{\sqrt{2}} V_{us} V_{cs}^* \left[C_1 Q_1^s + C_2 Q_2^s\right] - \frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \sum_{i=3}^{6} C_i Q_i + h.c.$$

the operator basis:

$$Q_1^d = \bar{u}^\alpha \gamma_\mu (1-\gamma_5) d_\beta \, \bar{d}^\beta \gamma^\mu (1-\gamma_5) c_\alpha \ ,$$
$$Q_2^d = \bar{u}^\alpha \gamma_\mu (1-\gamma_5) d_\alpha \, \bar{d}^\beta \gamma^\mu (1-\gamma_5) c_\beta \ ,$$
$$Q_3 = \bar{u}^\alpha \gamma_\mu (1-\gamma_5) c_\alpha \sum_q \bar{q}^\beta \gamma^\mu (1-\gamma_5) q_\beta ,$$
$$Q_4 = \bar{u}^\alpha \gamma_\mu (1-\gamma_5) c_\beta \sum_q \bar{q}^\beta \gamma^\mu (1-\gamma_5) q_\alpha ,$$
$$Q_5 = \bar{u}^\alpha \gamma_\mu (1-\gamma_5) c_\alpha \sum_q \bar{q}^\beta \gamma^\mu (1+\gamma_5) q_\beta .$$
$$Q_6 = \bar{u}^\alpha \gamma_\mu (1-\gamma_5) c_\beta \sum_q \bar{q}^\beta \gamma^\mu (1+\gamma_5) q_\alpha .$$

the *U*-spin components:

$$H_{\Delta U=1} = \frac{G_F}{2\sqrt{2}} (V_{us} V_{cs}^* - V_{ud} V_{cd}^*) [C_1 (Q_1^s - Q_1^d) + C_2 (Q_2^s - Q_2^d)]$$
$$\simeq \frac{G_F}{\sqrt{2}} \sin\theta_C \cos\theta_C [C_1 (Q_1^s - Q_1^d) + C_2 (Q_2^s - Q_2^d)].$$

***CP conserving***

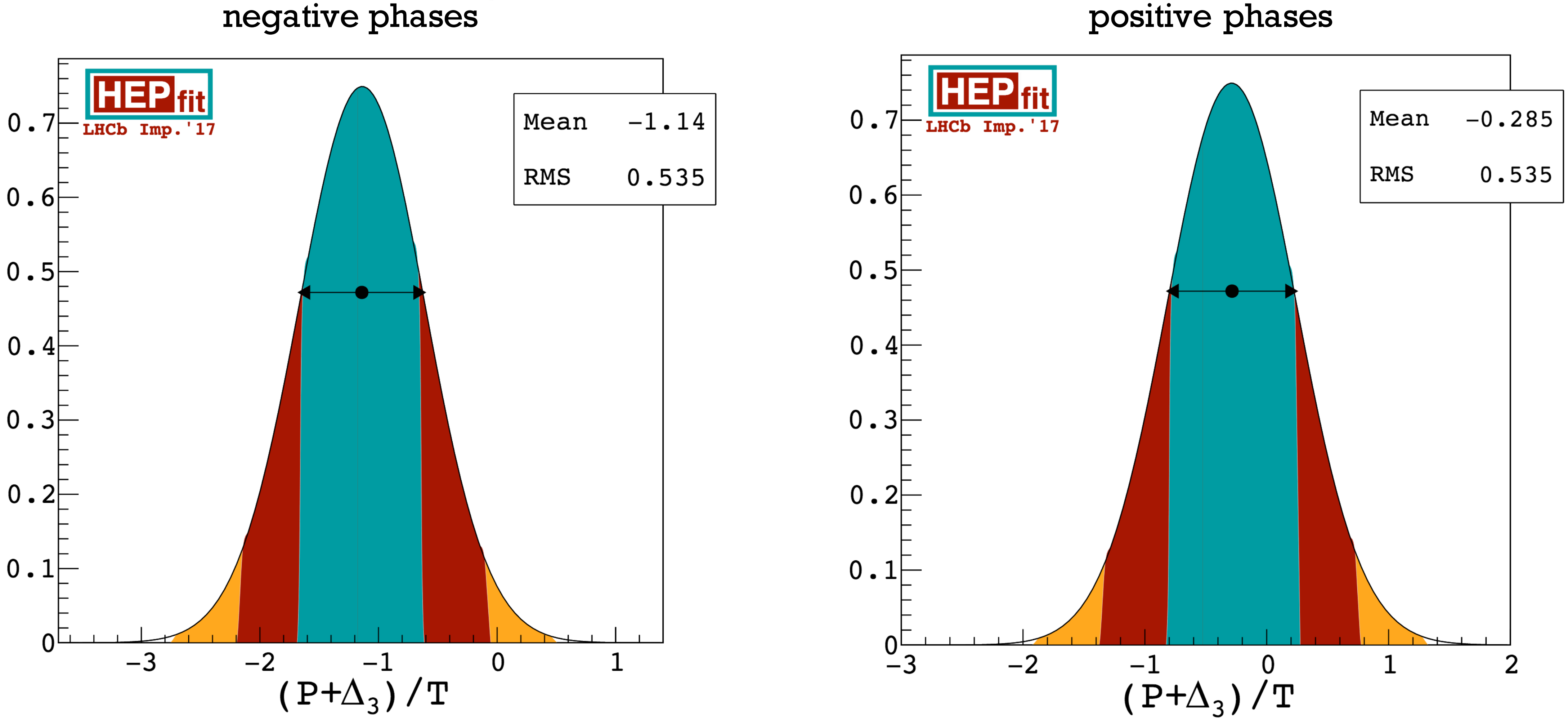
***CP violating***

$$H_{\Delta U=0} = -\frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \left\{ \sum_{i=3}^{6} C_i Q_i + \frac{1}{2} [C_1 (Q_1^s + Q_1^d) + C_2 (Q_2^s + Q_2^d)] \right\}$$

weak amplitude + rescattering + small $SU(3)_f$ breaking amplitudes

# fit to $\Delta A_{CP}$ (LHCb)

$$\Delta A_{CP}^{dir} = (-0.061 \pm 0.076)\%$$




LHCb: PRL 116 (2016) 191601 [arXiV:1602:03160]

# future prospects

| $A_{CP}$(channel) | mode (%) | RMS (%) | | | |
|---|---|---|---|---|---|
| | | Current Fit | Belle II | LHCb | |
| | | | 50 $ab^{-1}$ | 5 $fb^{-1}$ | 50 $fb^{-1}$ |
| $D^0 \to \pi^+\pi^-$ | 0.043 | 0.054 | 0.05 | – | – |
| $D^0 \to \pi^0\pi^0$ | -0.020 | 0.026 | 0.09 | – | – |
| $D^0 \to K^+K^-$ | -0.018 | 0.022 | 0.03 | – | – |
| $D^0 \to K_S K_S$ | 0.019 | 0.021 | 0.17 | – | – |
| $D^+ \to K^+ K_S$ | -0.011 | 0.014 | 0.05 | – | – |
| $D_s^+ \to \pi^+ K_S$ | 0.014 | 0.018 | 0.29 | – | – |
| $\Delta A_{CP}$ | -0.061 | – | – | 0.05 | 0.01 |

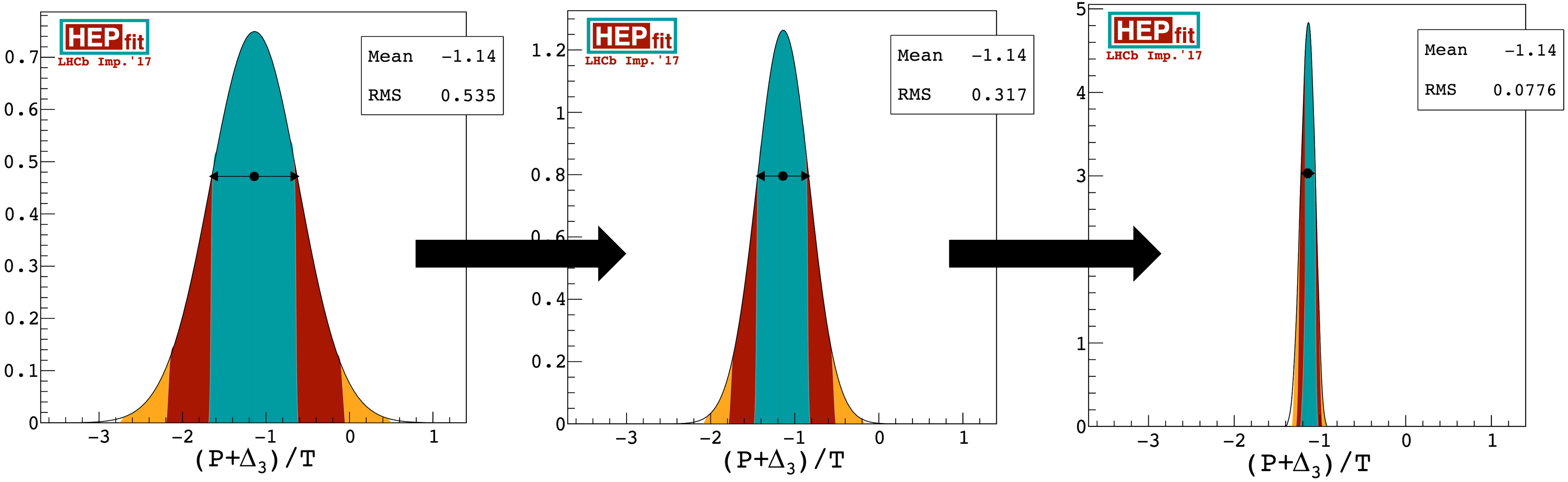
-- fit predictions from $\Delta A_{CP}$ have comparable or smaller errors than what Belle II will probe with 50 $ab^{-1}$

-- predicted errors do not depend on the sign of the phases

-- hence predicted errors do not depend on the size of $(P+\Delta_3)/T$ but only on the precision with which it can be determined.

# Measurement of $(P+\Delta_3)/T$

assuming the phases are negative




$\Delta A_{CP}^{\rm LHCb}$ (current) | Belle II 50 $\text{ab}^{-1}$ + $\Delta A_{CP}^{\rm LHCb}$ | Belle II 50 $\text{ab}^{-1}$ + LHCb 50 $\text{fb}^{-1}$

# On Beauty:

**Ever tried. Ever failed. No matter.**
**Try again. Fail again. Fail better.**

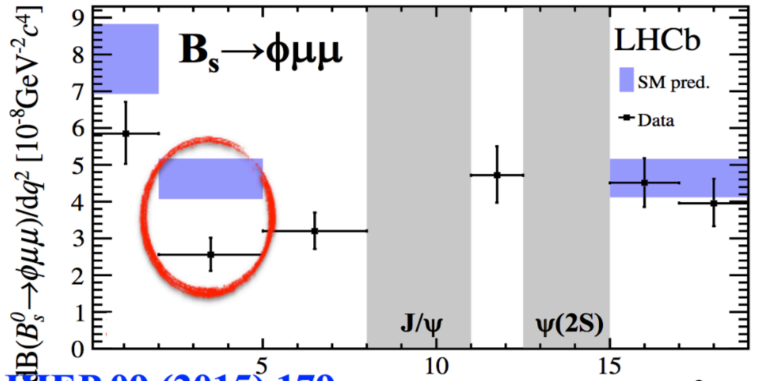
**Samuel Beckett**
***Worstward Ho!***

No tree-level flavour changing neutral currents (FCNC) in the Standard Model (SM).

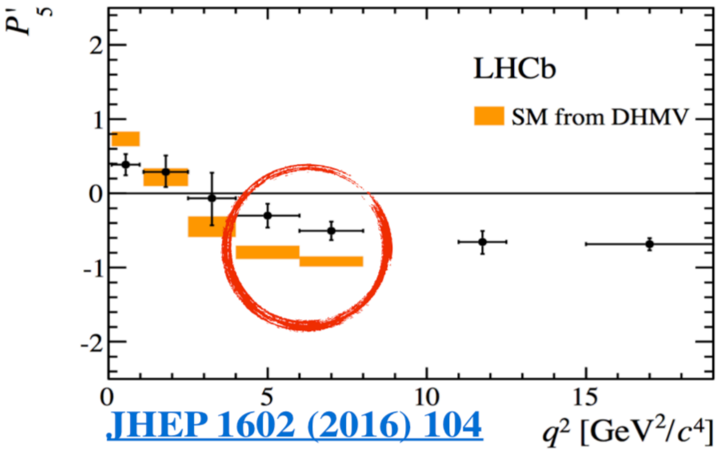
New Physics (NP) may sizably contribute in FCNC amplitudes

E.g.: b to s ll transitions

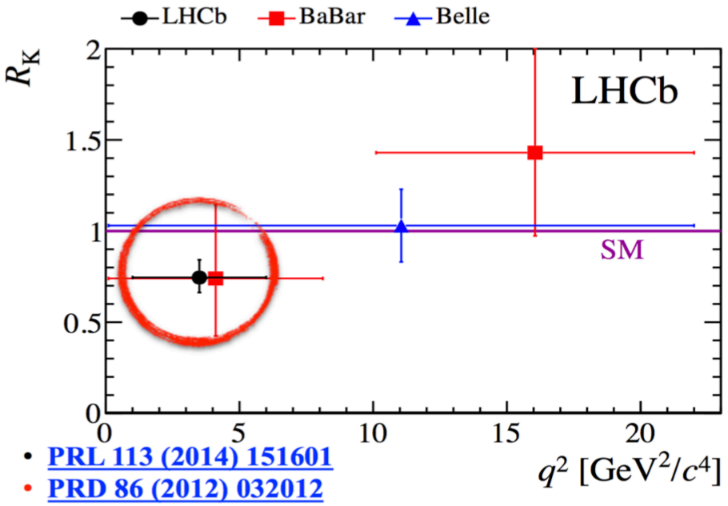
INTRIGUING SET OF "ANOMALIES" IN DATA OF EXCLUSIVE B RARE DECAYS




JHEP 09 (2015) 179




JHEP 1602 (2016) 104




- PRL 113 (2014) 151601
- PRD 86 (2012) 032012
- PRL 103 (2009) 171801

**~ 3.5 σ**

Angular analysis of $B \longrightarrow K^*\mu\mu$ for small dilepton mass, $4 < q^2 / \mathrm{GeV}^2 < 8$.

**~ 2.5 σ**

$R_{K^{(*)}} = Br(B \longrightarrow K^{(*)}ee) / Br(B \longrightarrow K^{(*)}\mu\mu)$ + $Br$ of other modes (e.g. $B_s \longrightarrow \phi\mu\mu$).

In the helicity basis, B —> V(P) $\ell^+\ell^-$ amplitude can be decomposed as:

$$H_\lambda^{(V)}(q^2) \propto C_9\,\tilde{V}_\lambda(q^2) + 2\frac{m_b m_B}{q^2} C_7\,\tilde{T}_\lambda(q^2) - 16\pi^2 \frac{m_B^2}{q^2}\tilde{h}_\lambda(q^2)\,,$$

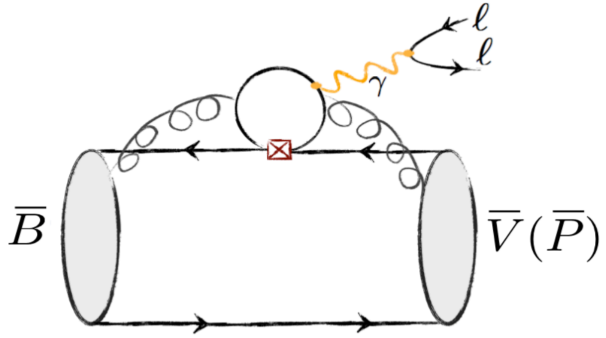
$$H_\lambda^{(A)}(q^2) \propto C_{10}\,\tilde{V}_\lambda(q^2)\,,$$

$$H^{(P)}(q^2) \propto 2\frac{m_\ell m_B}{q^2} C_{10}\left(1+\frac{m_s}{m_b}\right)\tilde{S}(q^2)\,.$$

Building blocks to compute Angular Obs & Br of interest!

$(\lambda = 0, \pm)$

At first order in $\alpha_{em}$ we can get a contribution from current-current quark operators & QCD penguins.




—> "hadronic" amplitude contributing to the process:

$$\tilde{h}_\lambda(q^2) \sim \epsilon_{\lambda,\mu}\int d^4x\, e^{iqx}\langle \overline{V}(\overline{P})|T\{J^{\mu,e.m.}_{had}(x)\mathcal{H}^{eff}_{had}(0)\}|\overline{B}\rangle$$

Loop suppressed amplitude can be enhanced by non-perturbative QCD effects!

In particular, charm current-current insertion not further parametrically suppressed.

$$\frac{d^{(4)}\Gamma}{dq^2\, d(\cos\theta_l) d(\cos\theta_k) d\phi} = \frac{9}{32\,\pi}\Big(I_1^s \sin^2\theta_k + I_1^c \cos^2\theta_k + (I_2^s \sin^2\theta_k + I_2^c \cos^2\theta_k)\cos 2\theta_l$$
$$+ I_3 \sin^2\theta_k \sin^2\theta_l \cos 2\phi + I_4 \sin 2\theta_k \sin 2\theta_l \cos\phi$$
$$+ I_5 \sin 2\theta_k \sin\theta_l \cos\phi + (I_6^s \sin^2\theta_k + I_6^c \cos^2\theta_K)\cos\theta_l$$
$$+ I_7 \sin 2\theta_k \sin\theta_l \sin\phi + I_8 \sin 2\theta_k \sin 2\theta_l \sin\phi$$
$$+ I_9 \sin^2\theta_k \sin^2\theta_l \sin 2\phi\Big)$$

Angular coefficients measured as function of dilepton invariant mass

$$S_i = \left(I_i^{(s,c)} + \bar{I}_i^{(s,c)}\right) / \Gamma'$$
$$(2\,\Gamma' \equiv d\Gamma/dq^2 + d\bar{\Gamma}/dq^2)$$

**8 CP-AVERAGED OBSERVABLES**

$$F_L, A_{FB}, S_{3,4,5,7,8,9}$$

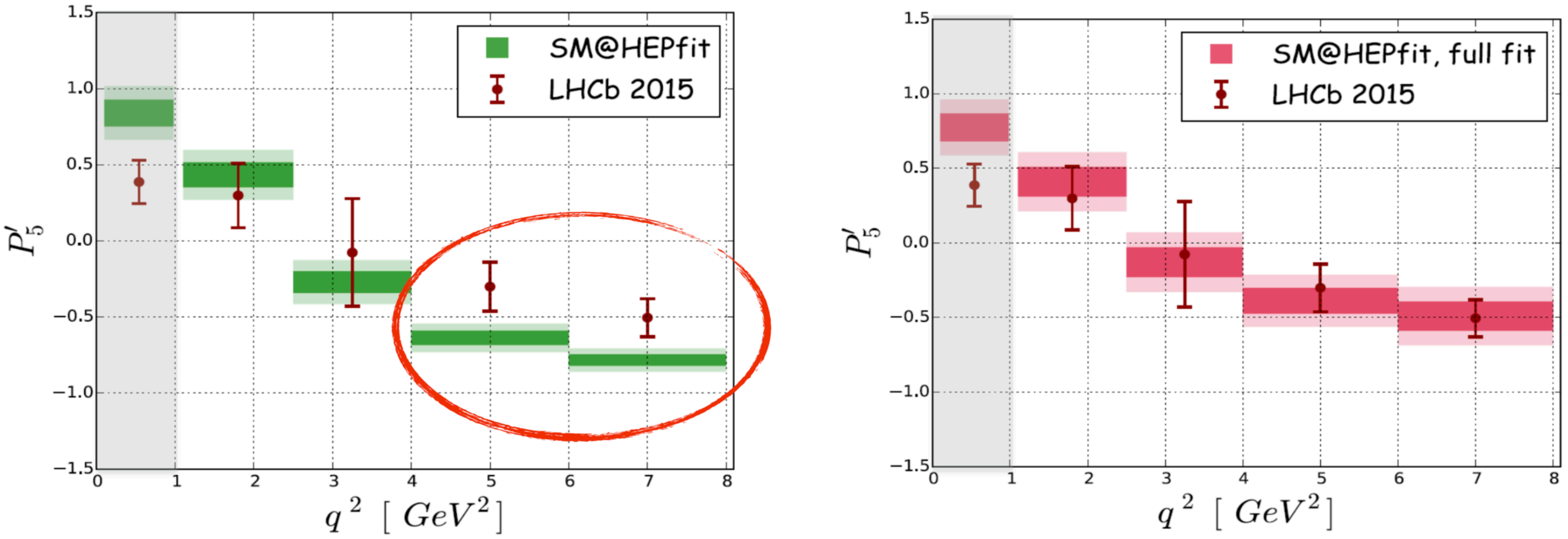
$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L)}}$$

<—> "Optimized" observables …"clean" only in HQ/LE limit!

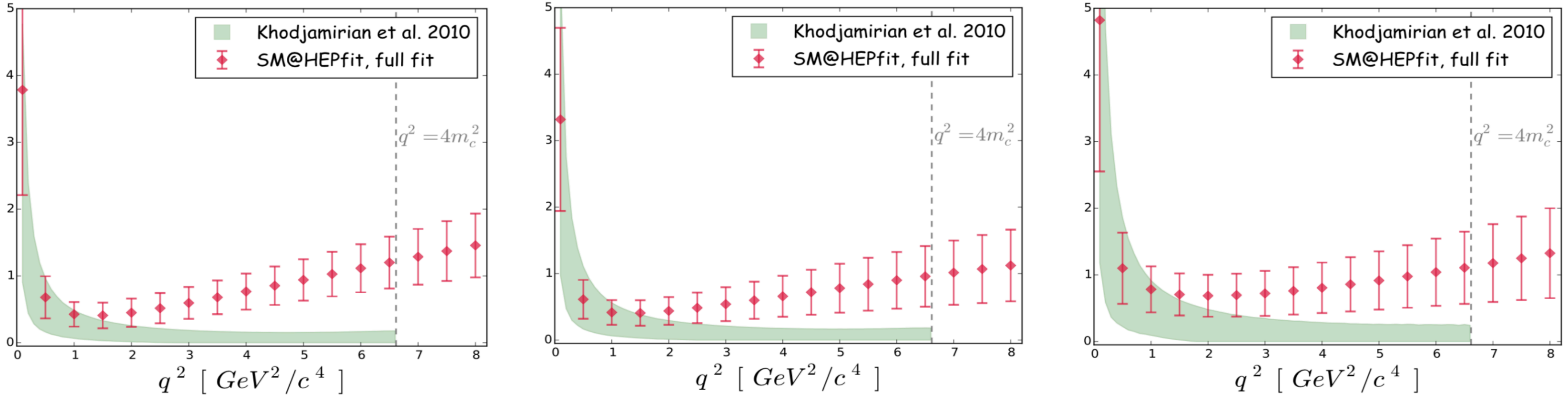
*Matias*, J. et al. '12 — Camalich & Jäger '13

FULL CC-LOOP ESTIMATE USED AS A PROXY FOR NON-FACTORIZABLE QCD CORRECTIONS

CONSERVATIVE EVALUATION RELYING ON LCSR RESULT ONLY FOR $q^2 \lesssim 1\,\mathrm{GeV}^2$



## Examining the size of the hadronic contributions in terms of $\Delta C_9$ shifts:




—> red points corresponds to the long distance effect extracted from our fit

—> green band is the charm-loop effect as given in JHEP 1009 (2010) 089

### REMARKS

1) **SIZABLE DEPARTURE FROM** THE THEORETICAL ESTIMATE BASED ON EXTRAPOLATED **LCSR CC-LOOP IN SINGLE SOFT GLUON APPROX.**

2) $q^2$ DEPENDENCE @ ODD WITH SHORT DISTANCE RE-INTERPRETATION. **OUR RESULT POINTS TO UNDERESTIMATED HADRONIC EFFECTS.**

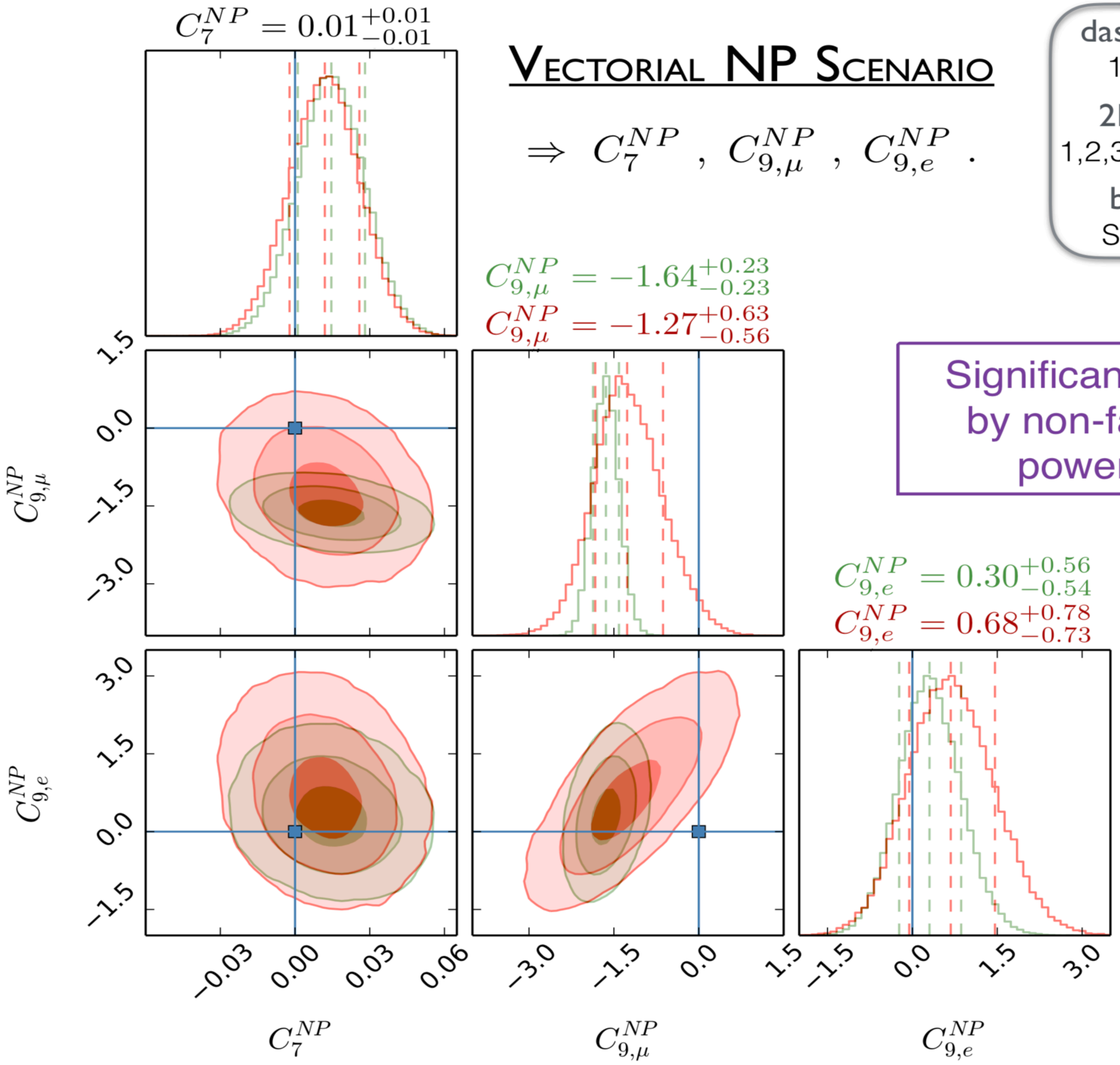
# Vectorial NP Scenario

$\Rightarrow\ C_7^{NP}\ ,\ C_{9,\mu}^{NP}\ ,\ C_{9,e}^{NP}\ .$

dashed lines in 1D histograms
16th, 50th, 84th percentiles

2D joint probability density
1,2,3 σ contours (darker to lighter)

blue lines and blue square
SM limit of NP Wilson coeffs




Significance of NP affected by non-factorizable QCD power corrections !

"optimistic" approach to QCD effects

conservative approach to QCD effects

# On the Higgs:

# two paths to the throne

-- find a new degree of freedom --

-- find a modified coupling --

JHEP

Published for SISSA by Springer

Received: *October 3, 2013*
Accepted: *December 14, 2013*
Published: *January 7, 2014*

# Probing Higgs couplings with high $p_T$ Higgs production

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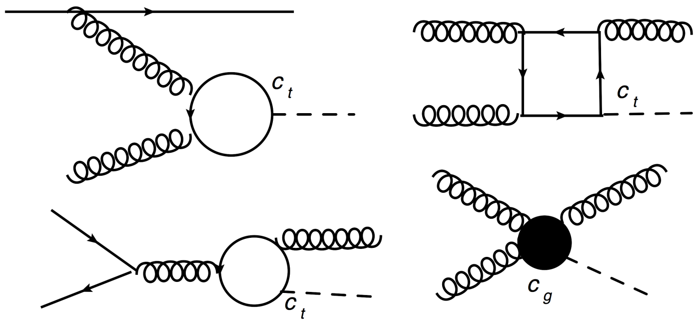
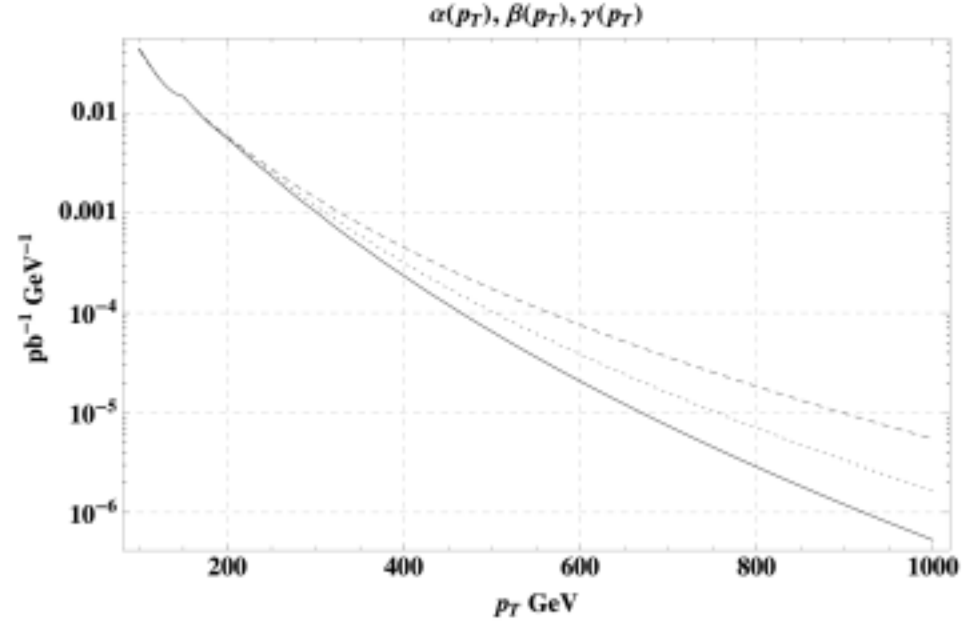
# the idea

$$\frac{d\sigma}{dp_T} = \sum_i \kappa_i |f^i(p_T)c_t + c_g|^2 \longrightarrow \left(\frac{d\sigma^{SM}(m_t)}{dp_T}\right) / \left(\frac{d\sigma^{SM}(m_t\to\infty)}{dp_T}\right) = \frac{\sum_i \kappa_i f^i(p_T)^2}{\sum_i \kappa_i}$$

Higgs production with an associated jet is driven by:




$$\left(\frac{d\sigma^{SM}(m_t)}{dp_T}\right) / \left(\frac{d\sigma^{SM}(m_t\to\infty)}{dp_T}\right)\Big|_{p_T=300\text{GeV}} \sim 0.7$$




$$M_i(c_t, c_g) = c_t M_i(m_t) + c_g M_i(m_t \to \infty)$$

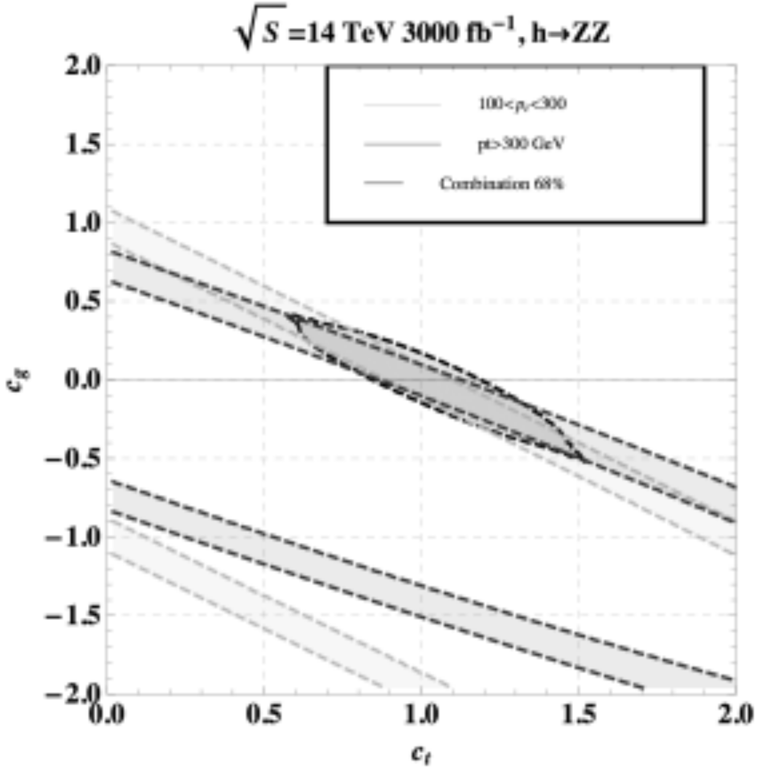
$$\frac{d\sigma}{dp_T} = \alpha(p_T)c_t^2 + \beta(p_T)c_g^2 + 2\gamma(p_T)c_t c_g.$$

$$\sigma^-(p_T < P_T) = \int_{p_T^{min}}^{P_T} \frac{d\sigma}{dp_T} dp_T, \quad N^- = \sigma^- \times \text{Luminosity}$$

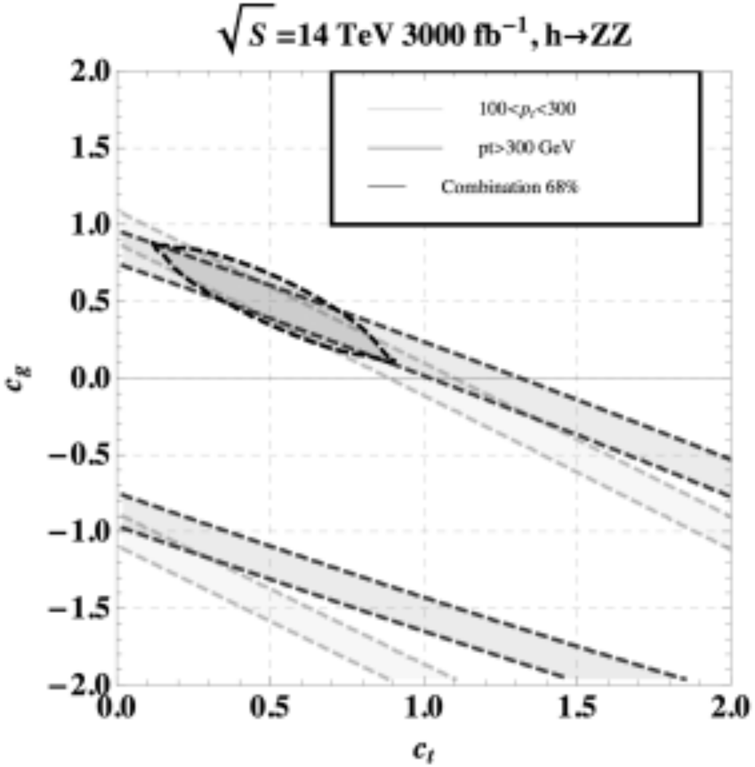
$$\sigma^+(p_T > P_T) = \int_{P_T}^{p_T^{max}} \frac{d\sigma}{dp_T} dp_T, \quad N^+ = \sigma^+ \times \text{Luminosity}$$

R. K. Ellis, I. Hinchliffe, M. Soldate and J. J. van der Bij, Nucl. Phys. B **297**, 221 (1988). U. Baur and E. W. N. Glover, Nucl. Phys. B **339**, 38 (1990).

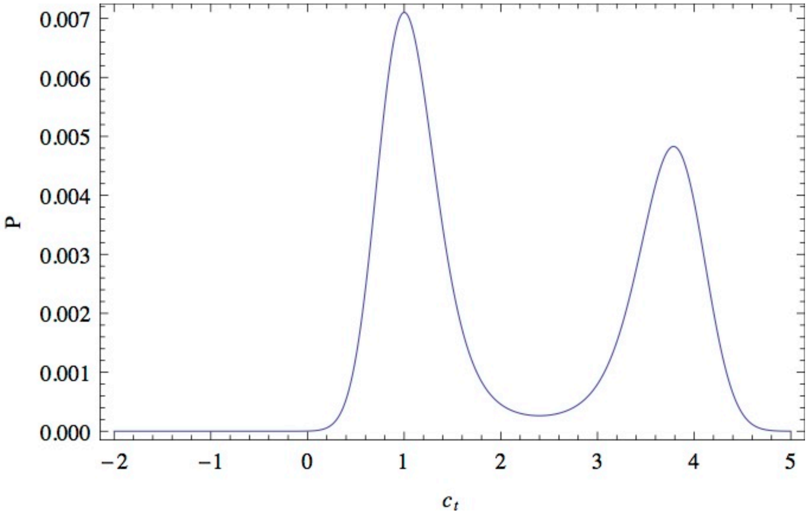
# the outcome




$(c_t = 1, c_g = 0)$




$(c_t = 0.5, c_g = 0.5)$




- ✓ We gauge LHC potential by looking into the $h \to ZZ^* \to l^- l^- l^+ l^+$ channel.
- ✓ We separate the events into a low and a high $p_T$ bins 300 GeV as the discriminating $p_T$ .
- ✓ We get a $c_t$ [0.66, 1.42] at 68% CL from our naïve estimate.

ISSN 1063-7761, Journal of Experimental and Theoretical Physics, 2015, Vol. 120, No. 3, pp. 354–368. © Pleiades Publishing, Inc., 2015.

# Taming the Off-Shell Higgs Boson[1]

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Received July 22, 2014

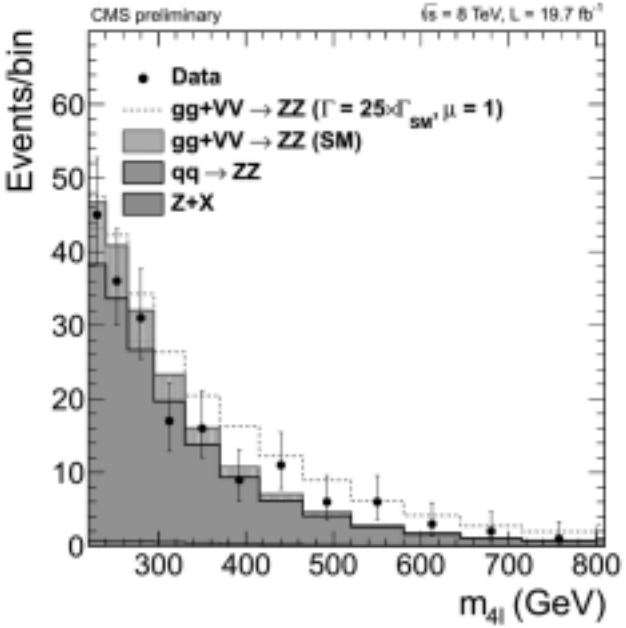
**Abstract**—We study the off-shell Higgs data in the process $pp \longrightarrow h^{(*)} \longrightarrow Z^{(*)}Z^{(*)} \longrightarrow 4l$, to constrain deviations of the Higgs couplings. We point out that this channel can be used to resolve the long- and short-distance contributions to Higgs production by gluon fusion and can thus be complementary to $pp \longrightarrow ht\bar{t}$ in measuring the top Yukawa coupling. Our analysis, performed in the context of effective field theory, shows that current data do not allow drawing any model-independent conclusions. We study the prospects at future hadron colliders, including the high-luminosity LHC and accelerators with higher energy, up to 100 TeV. The available QCD calculations and the theoretical uncertainties affecting our analysis are also briefly discussed.

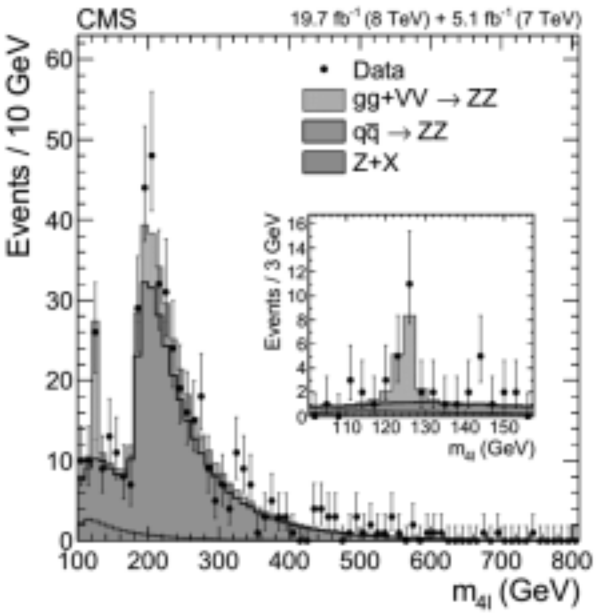


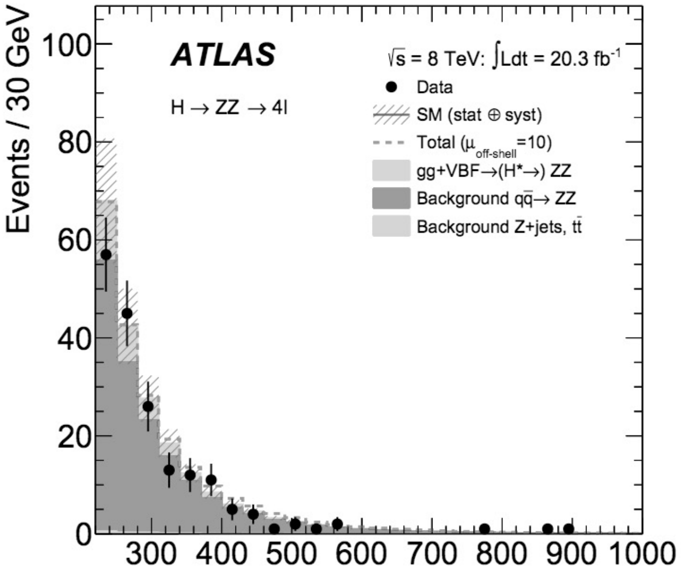
*Contribution for the JETP special issue in honor of V.A.Rubakov's 60th birthday*

# the context

$$pp \to Z^{(*)}Z^{(*)} \to 4\ell$$

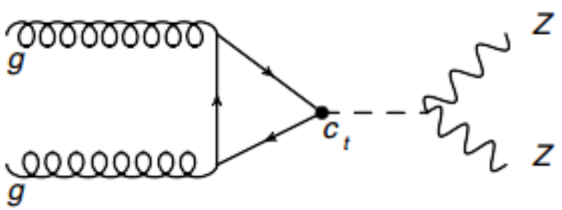


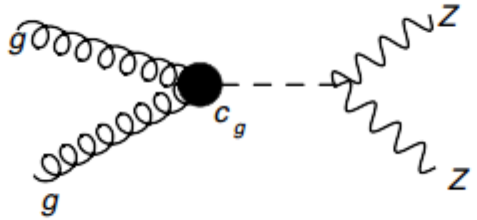




- ✓ there is an invisible Higgs decay width, so that the total width of the Higgs and its couplings can be varied independently
- ✓ variations of all the Higgs couplings are universal
- ✓ there are no higher dimensional operators affecting either Higgs decay or production

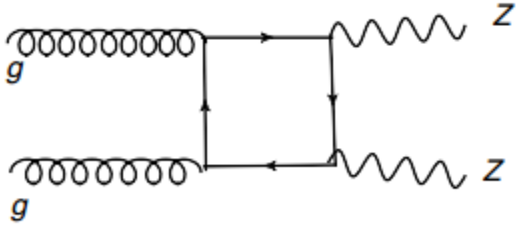
signal




signal




gg background



# the idea

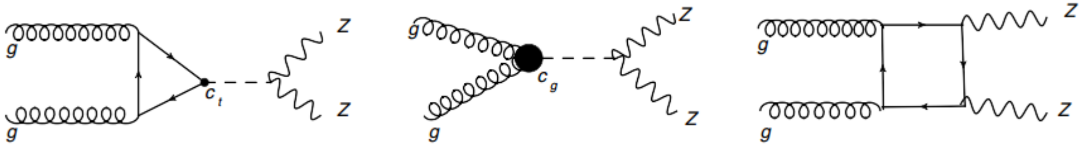
- ✓ There is no invisible Higgs decay width.
- ✓ There are dim. 6 operators affecting Higgs production.

$$\mathcal{L}^{\text{dim-6}} = c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} + \tilde{c}_g \frac{g_s^2}{32\pi^2 v^2} |H|^2 G_{\mu\nu} \tilde{G}^{\mu\nu}$$

$$\tilde{G}_{\mu\nu} = \frac{1}{2} \epsilon^{\mu\nu\lambda\rho} G_{\lambda\rho}$$

After EWSB: $$\mathcal{L} = -c_t \frac{m_t}{v} \bar{t} t h + \frac{g_s^2}{48\pi^2} c_g \frac{h}{v} G_{\mu\nu} G^{\mu\nu} \qquad c_t = 1 - \text{Re}(c_y)$$

While the signal is affected by the modified couplings, the background is not.

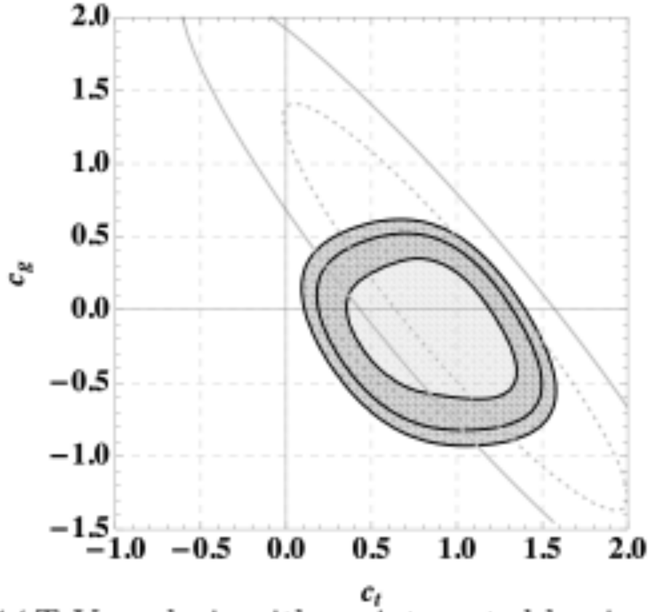



$$\mathcal{M}_{gg\to ZZ} = \mathcal{M}_h + \mathcal{M}_{bkg} = c_t \mathcal{M}_{c_t} + c_g \mathcal{M}_{c_g} + \mathcal{M}_{bkg}$$

The differential cross-section is given by: $$\frac{d\sigma}{dm_{4\ell}} = F_0(m_{4\ell}) + F_1(m_{4\ell}) c_R^2 + F_2(m_{4\ell}) c_I^2 + F_3(m_{4\ell}) c_R + F_4(m_{4\ell}) c_I$$

$$c_R = \frac{\text{Re}\,\mathcal{M}_\Delta^{\text{NP+SM}}}{\text{Re}\,\mathcal{M}_\Delta^{\text{SM}}}, \quad c_I = \frac{\text{Im}\,\mathcal{M}_\Delta^{\text{NP+SM}}}{\text{Im}\,\mathcal{M}_\Delta^{\text{SM}}}$$

# linearized vs. non-linearized analysis




Prospects for a 14 TeV analysis with an integrated luminosity of 3 $\mathrm{ab}^{-1}$ and for the injected SM signal: 68%, 95% and 99% expected probability regions in the $(c_t, c_g)$ plane.

The difference between the linear and non-linear analysis at 14 TeV is large.

This difference falls off at higher energy colliders.

| | 33 TeV | 50 TeV | 80 TeV | 100 TeV |
|---|---|---|---|---|
| non-linear < 2TeV | [0.92,1.14] | [0.95,1.11] | [0.96,1.08] | [0.97,1.07] |
| linear < 2 TeV | [0.83,1.18] | [0.9,1.11] | [0.94,1.07] | [0.95,1.05] |
| non-linear all | [0.94,1.11] | [0.96,1.08] | [0.98,1.05] | [0.98,1.04] |
| linear all | [0.84,1.16] | [0.91,1.09] | [0.95,1.05] | [0.96,1.04] |

The 68% probability intervals on the value of $c_t$, obtained assuming $c_t + c_g = 1$ and injecting the SM signal at various collider energies. In all cases an integrated luminosity of 3 $\mathrm{ab}^{-1}$ was assumed. The numbers in the second and the third row present the non-linear and linear analysis, respectively, for the low-energy bins only, $\sqrt{s} < 2$ TeV. The fourth and the fifth rows contain the corresponding numbers obtained including all the bins up to 5 TeV.

Open to improvement in both theoretical and experimental technologies.

Published for SISSA by Springer

Received: August 19, 2016
Accepted: September 13, 2016
Published: September 20, 2016

# Resolving gluon fusion loops at current and future hadron colliders

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# The Processes

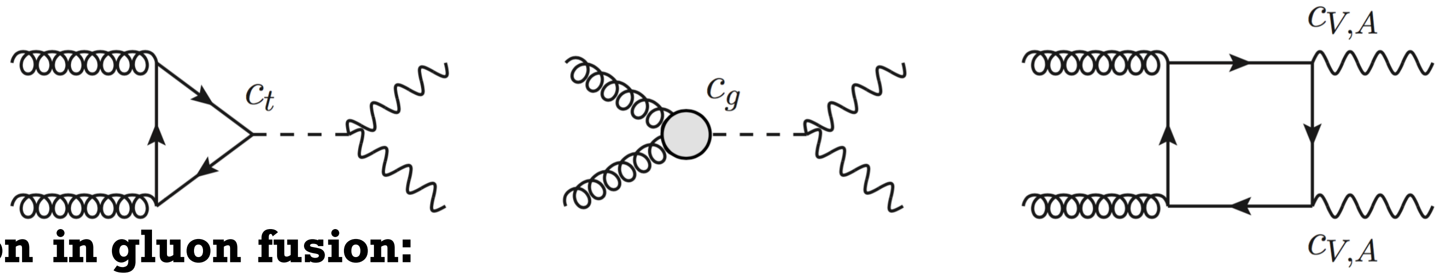
$$\mathcal{L}_6 \;=\; c_y \frac{y_t |H|^2}{v^2} \bar{Q}_L \widetilde{H} t_R + \text{h.c.} + \frac{c_g g_s^2}{48\pi^2 v^2} |H|^2 G_{\mu\nu} G^{\mu\nu} \qquad \mathcal{L}_{\text{nl}} \;=\; -\, c_t \frac{m_t}{v} \bar{t} t h + \frac{c_g g_s^2}{48\pi^2} \frac{h}{v} G_{\mu\nu} G^{\mu\nu} \,, \qquad c_t = 1 - c_y$$

$$c_g \frac{e^2}{18\pi^2} \frac{h}{v} F_{\mu\nu} F^{\mu\nu}$$

- **Higgs and top quark associated production:** almost a direct measurement of $c_t$ with very little pollution from $c_g$

- **boosted Higgs production:** sensitive to $c_t$ and $c_g$

- **off-shell Higgs production:** sensitive to $c_t$ and $c_g$ but also to effective *ttZ* couplings

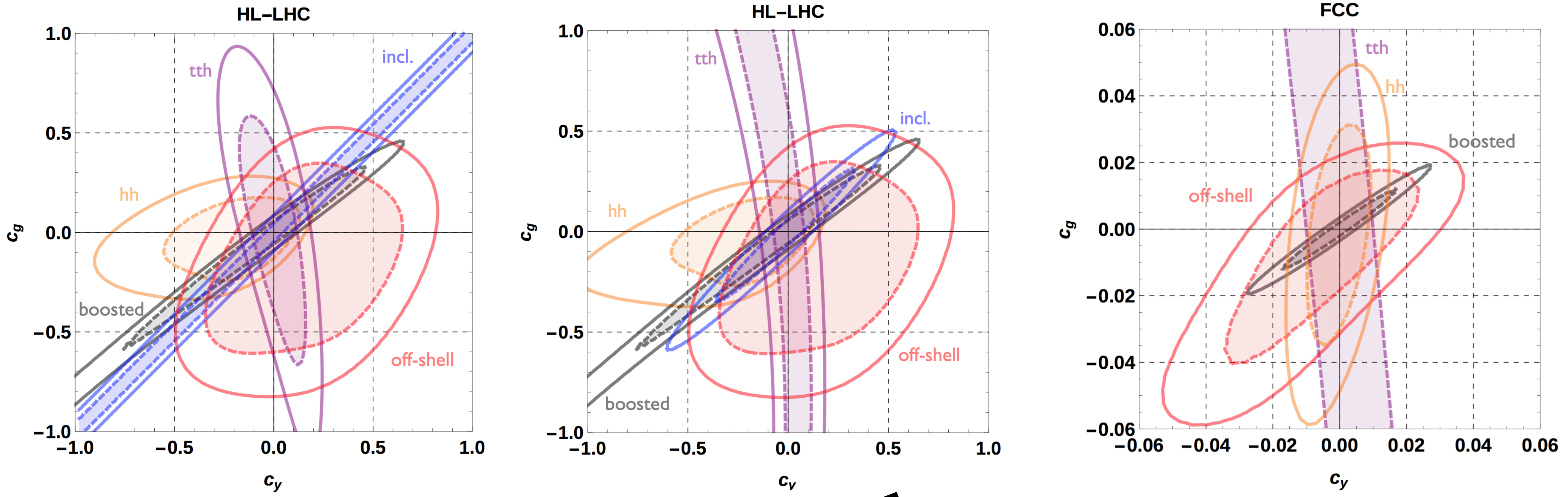



- **double Higgs production in gluon fusion:**
  - occurs at energies much above the top quark mass – top loops and contact interaction can be resolved
  - higher-point interactions make it really sensitive to the top-Yukawa sector

$$\mathcal{L}_{\text{nl}}^{hh} \;=\; -\frac{m_t}{v} \bar{t} t \left( c_t h + c_{2t} \frac{h^2}{v} \right) + \frac{c_g g_s^2}{48\pi^2} \left( \frac{h}{v} + \frac{h^2}{2v^2} \right) G_{\mu\nu} G^{\mu\nu} \,, \qquad c_{2t} = -\frac{3}{2} c_y$$

# The Combination

**SM signal injected**
**the Higgs is a part of a doublet**




$$c_g \frac{e^2}{18\pi^2} \frac{h}{v} F_{\mu\nu} F^{\mu\nu}$$

**inclusive production projection from:** ATLAS Collaboration, ATL-PHYS-PUB-2013-014, October 2013.

# an EFT is valid if…

- Small energy requirement:

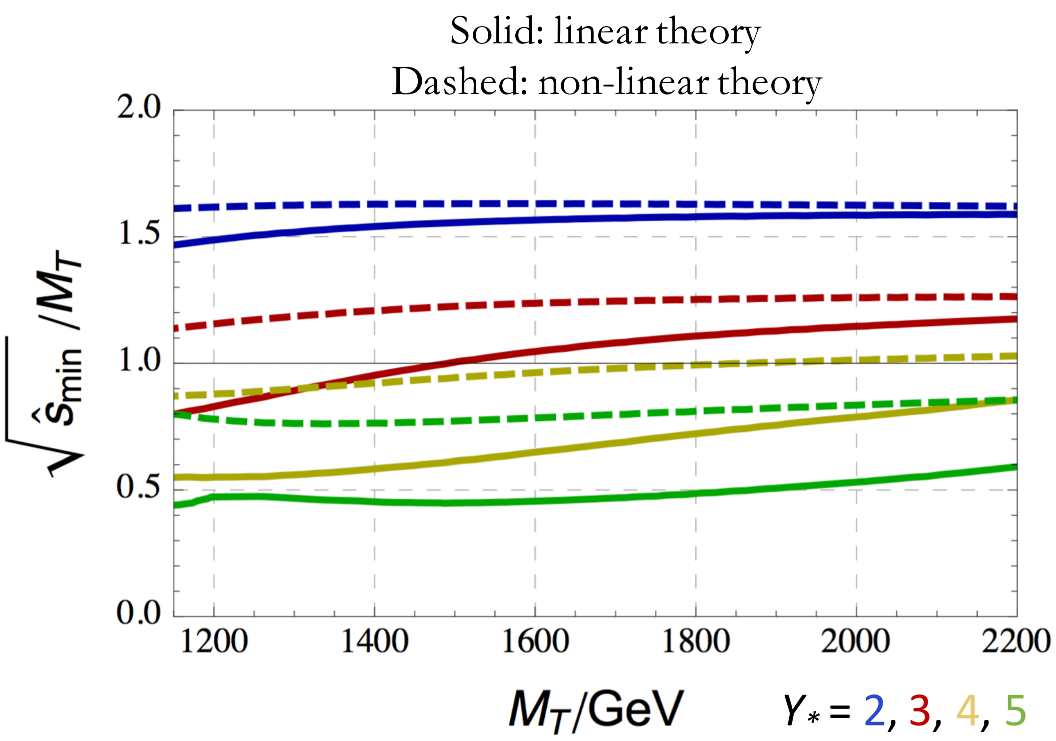
$$\frac{E}{M_*} \ll 1$$

- Small coupling requirement:

$$\frac{Y_* v}{M_*} \ll 1$$

- supression of dimension-8 operator:

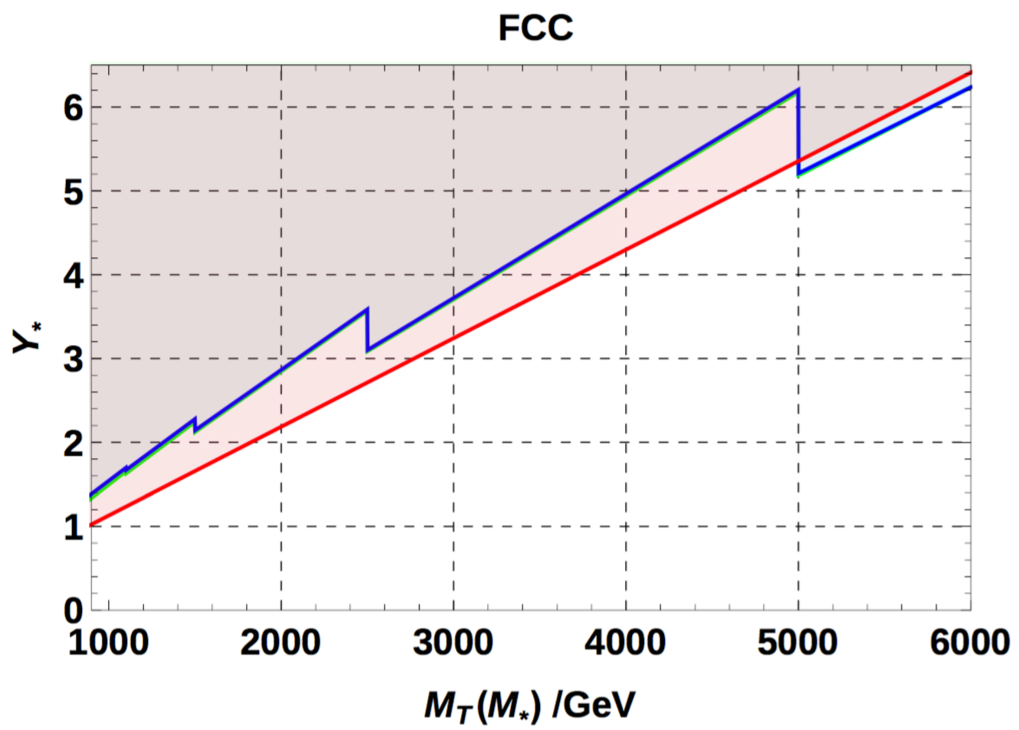
$$O_g^{(8)} \sim \frac{g_s^2}{16\pi^2}\frac{Y_*^2}{M_*^4}|D_\lambda H|^2 G_{\mu\nu}G^{\mu\nu}$$




$$\frac{\left|\left(\frac{d\hat{\sigma}}{d\hat{s}}\right)_{\text{full}} - \left(\frac{d\hat{\sigma}}{d\hat{s}}\right)_{\text{EFT}}\right|}{\left(\frac{d\hat{\sigma}}{d\hat{s}}\right)_{\text{full}}} < 0.05$$

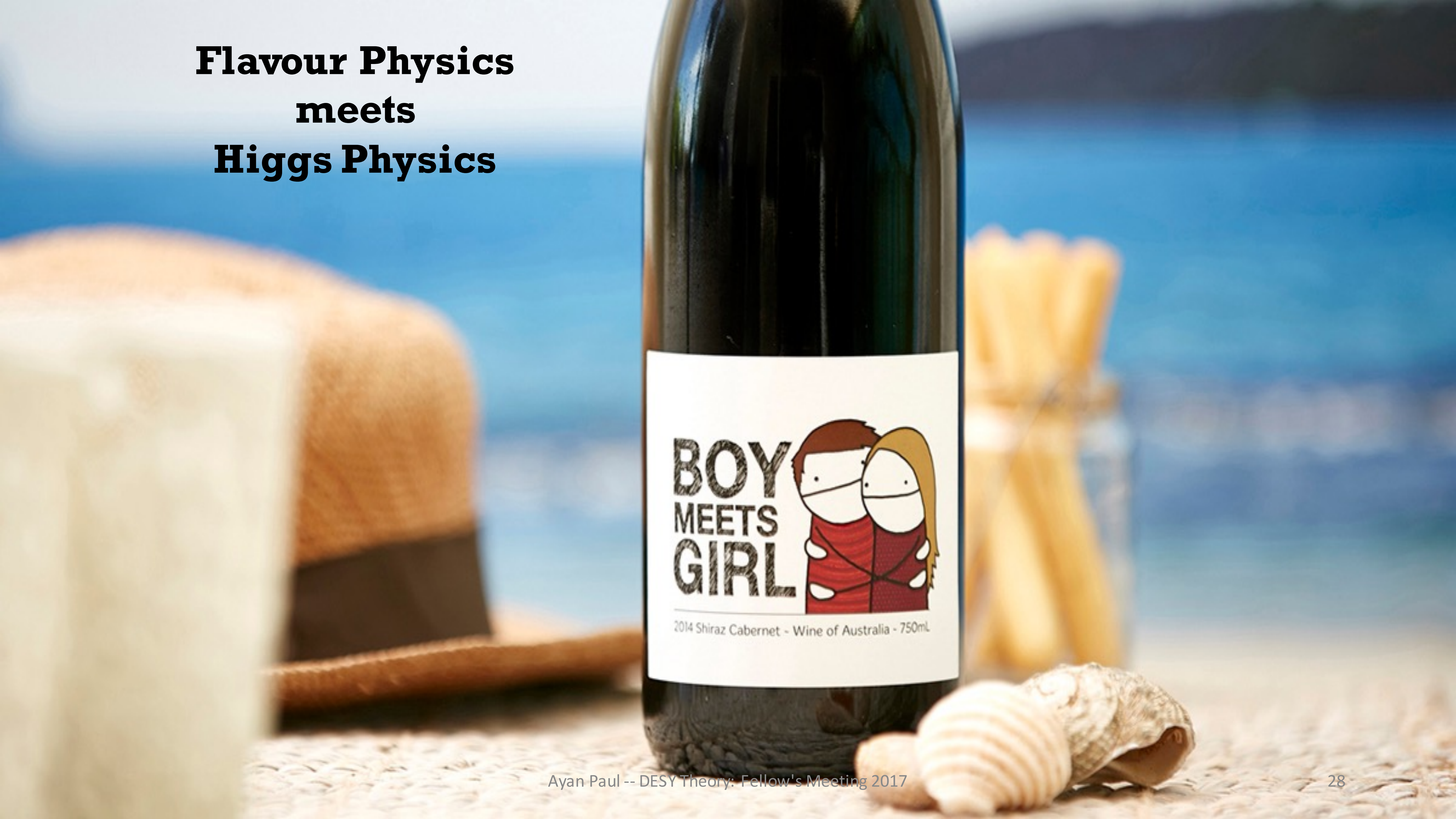
EFT simulation with MCFM
full theory computation with FeynArts/FormCalc/LoopTools

# full theory vs. EFT




- ✓ **SM signal injected**
- ✓ **the linear and the non-linear theory overlap**
- ✓ **bins are added with increasing mass and hence the jagged shape of the EFT/non-linear model**

# Flavour Physics meets Higgs Physics



# why…??

- ✓ The flavour paradigm of models with an extra Higgs doublet is often limited to escape flavour bounds. But there there are the recent results for $h \longrightarrow \tau\mu$ and $t \rightarrow ch$.

- ✓ Stringent bounds on the masses of the expanded Higgs sector can be avoided by proposing certain flavour textures for the Yukawa interactions.

- ✓ We show that we can go beyond the flavour diagonal regime for the couplings of the SM fermions to the neutral Higgs states, yet respect bounds from flavour phsyics.

- ✓ Once we allow for one or more of the expanded Higgs family to have lower masses, interesting and yet unexplored collider signatures can arise.

- ✓ We show this with a axion variant model with the right handed top quark charged -1, two Higgs doublets charged 0 and -1 under a Peccei-Quinn symmetry.

- ✓ We also introduce a top-charm mixing between right handed up-quark sector. We implement a similar structure in the lepton sector too.

$$U_R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\frac{\rho_u}{2} & \sin\frac{\rho_u}{2} \\ 0 & -\sin\frac{\rho_u}{2} & \cos\frac{\rho_u}{2} \end{pmatrix}, \quad L_R \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\frac{\rho_\ell}{2} & \sin\frac{\rho_\ell}{2} \\ 0 & -\sin\frac{\rho_\ell}{2} & \cos\frac{\rho_\ell}{2} \end{pmatrix}$$

$$\begin{aligned} \mathcal{L}_Y^u &= -\Phi_1 \overline{u}_{Ra}[Y_{u1}]_{ai} Q_i - \Phi_2 \overline{u}_{R3}[Y_{u2}]_i Q_i + \text{h.c.} \\ &= -\Phi^{\text{SM}} \overline{u}_{Ri}[Y_u^{SM}]_{ij} Q_j - \Phi' \overline{u}_{Ri}[Y'_u]_{ij} Q_j + \text{h.c.} \end{aligned}$$

# fits to the Higgs couplings

$$\kappa_{gZ} = \frac{\kappa_g \kappa_Z}{\kappa_h} \quad \text{and} \quad \lambda_{ij} = \frac{\kappa_i}{\kappa_j}, \quad (i,j) = (Z,g),(t,g),(W,Z),(\gamma,Z),(\tau,Z),(b,Z)$$

**Higgs width modifier:**

$$\kappa_h^2 \simeq 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 + 0.06\kappa_t^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2$$
$$+ 2.3\times10^{-3}\kappa_\gamma^2 + 1.6\times10^{-3}\kappa_{Z\gamma}^2 + 10^{-4}\kappa_s^2 + 2.2\times10^{-4}\kappa_\mu^2$$

**Higgs-gauge field coupling modifier:**

$$\kappa_W = \kappa_Z = \sin(\beta-\alpha),$$
$$\kappa_{Z\gamma}^2 = 0.00348\kappa_t^2 + 1.121\kappa_W^2 - 0.1249\,\kappa_t\kappa_W,$$
$$\kappa_g^2 = 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\,\kappa_b\kappa_t,$$
$$\kappa_\gamma^2 = 1.59\kappa_W^2 + 0.07\kappa_t^2 - 0.66\,\kappa_W\kappa_t,$$

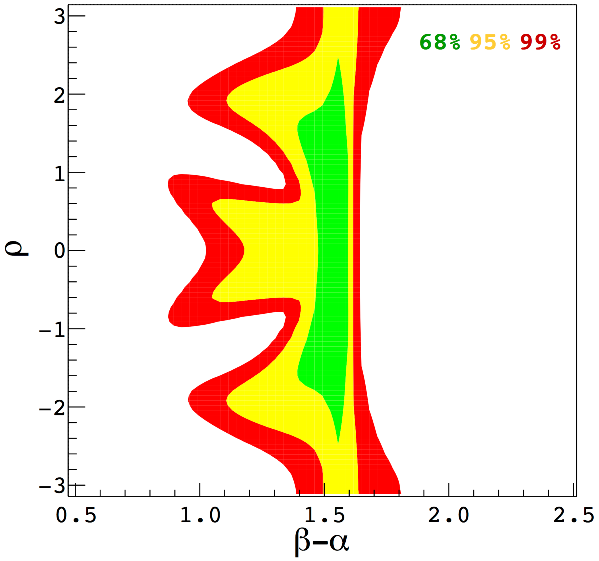
**Higgs-fermion coupling modifier:**

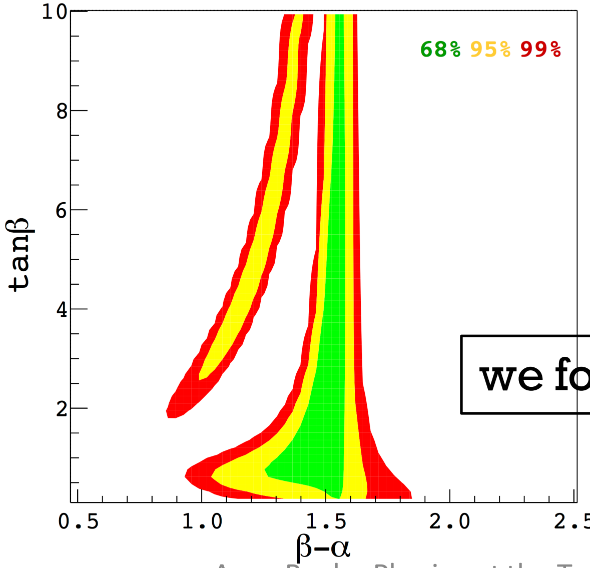
$$\kappa_f = \frac{\sqrt{2}v}{m_f} c_f^h$$

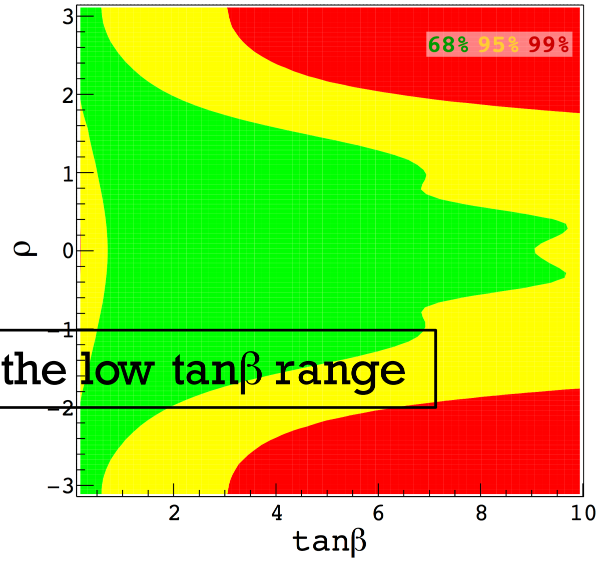
| | Mean | RMS |
|---|---|---|
| $\kappa_{gZ}$ | 1.090 | 0.110 |
| $\lambda_{Zg}$ | 1.285 | 0.215 |
| $\lambda_{tg}$ | 1.795 | 0.285 |
| $\lambda_{WZ}$ | 0.885 | 0.095 |
| $\lvert\lambda_{\gamma Z}\rvert$ | 0.895 | 0.105 |
| $\lvert\lambda_{\tau Z}\rvert$ | 0.855 | 0.125 |
| $\lvert\lambda_{bZ}\rvert$ | 0.565 | 0.175 |

| | $\kappa_{gZ}$ | $\lambda_{Zg}$ | $\lambda_{tg}$ | $\lambda_{WZ}$ | $\lvert\lambda_{\gamma Z}\rvert$ | $\lvert\lambda_{\tau Z}\rvert$ | $\lvert\lambda_{bZ}\rvert$ |
|---|---|---|---|---|---|---|---|
| $\kappa_{gZ}$ | 1.00 | -0.03 | -0.24 | -0.62 | -0.57 | -0.38 | -0.34 |
| $\lambda_{Zg}$ | -0.03 | 1.00 | 0.51 | -0.59 | -0.51 | -0.62 | -0.54 |
| $\lambda_{tg}$ | -0.24 | 0.51 | 1.00 | -0.21 | -0.23 | -0.28 | -0.35 |
| $\lambda_{WZ}$ | -0.62 | -0.59 | -0.21 | 1.00 | 0.66 | 0.55 | 0.55 |
| $\lvert\lambda_{\gamma Z}\rvert$ | -0.57 | -0.51 | -0.23 | 0.66 | 1.00 | 0.58 | 0.51 |
| $\lvert\lambda_{\tau Z}\rvert$ | -0.38 | -0.62 | -0.28 | 0.55 | 0.58 | 1.00 | 0.49 |
| $\lvert\lambda_{bZ}\rvert$ | -0.34 | -0.54 | -0.35 | 0.55 | 0.51 | 0.49 | 1.00 |

Run 1 ATLAS-CMS combination
arXiV:1606.02266



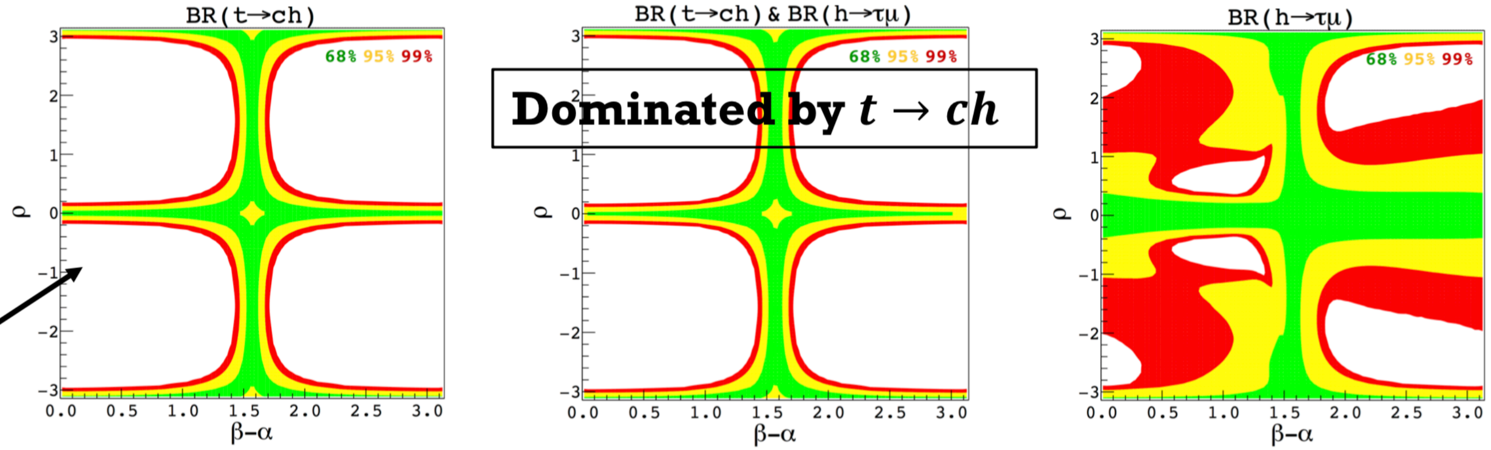

we focus on the low tanβ range

68.2 %
95.4 %
99.7 %

# fits to flavour violating Higgs and top decays

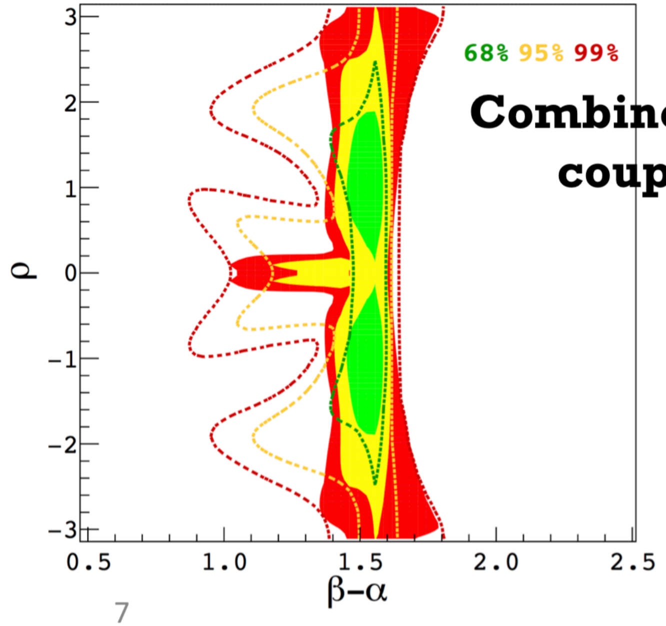
| Experiment | $BR(h \to \tau\mu)$ | $BR(t \to ch)$ |
|---|---|---|
| ATLAS 8 TeV 20.3 fb$^{-1}$ | $(0.53 \pm 0.51)\%$ | $(0.22 \pm 0.14)\%$ |
| CMS 8 TeV 19.7 fb$^{-1}$ | $(0.84^{+0.39}_{-0.37})\%$ | $< 0.40\%$ @ 95% CL$^\dagger$ |
| ATLAS 13 TeV 36.1 fb$^{-1}$ | – | $(0.069^{+0.075}_{-0.054})\%$ |
| CMS 13 TeV 35.9 fb$^{-1}$ | $(0.00 \pm 0.12)\%$ | – |
| Average | $(0.10 \pm 0.11)\%$ | $(0.109 \pm 0.061)\%$ |

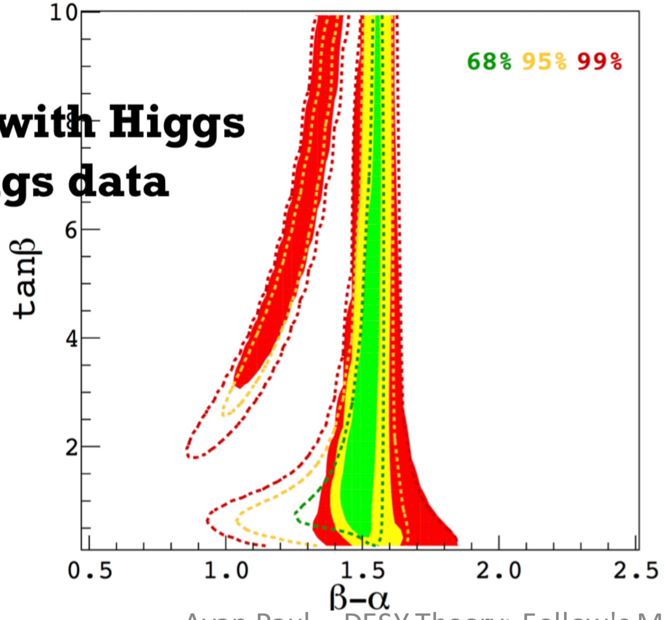
$$BR(t \to ch) \simeq 3.24 \times 10^{-2} a^2 \sin^2 \rho$$

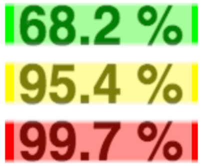


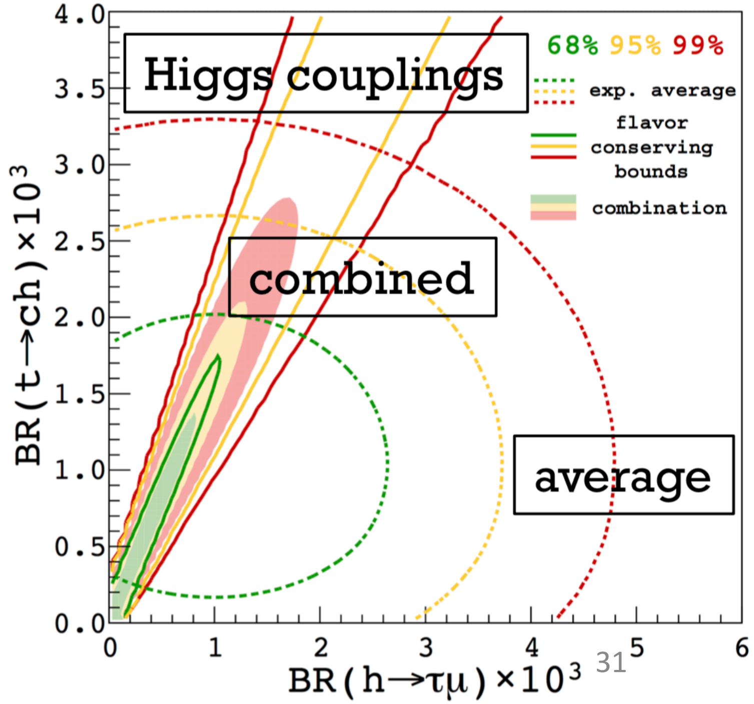

$$BR_{exp}(h \to \tau\mu) = \frac{\sigma^{pp\to h}}{\sigma^{pp\to h}_{SM}} BR_{th}(h \to \tau\mu) \simeq \frac{(\kappa_g)^2 a^2 \sin^2 \rho}{36.5(\kappa_b)^2 + 14.64 \sin^2(\beta-\alpha) + 5.44(\kappa_g)^2 + 4(\kappa_\tau)^2}$$

$$a = (\tan\beta + \cot\beta)\cos(\beta - \alpha)$$



# fits to low energy FCNC and charged current decays

| Process | Measurement | SM Prediction |
|---|---|---|
| $\mathrm{BR}(b \to s\gamma)$ | $(3.32 \pm 0.15) \times 10^{-4}$ | $(3.36 \pm 0.23) \times 10^{-4}$ |
| $\mathrm{BR}(B \to \tau\nu)$ | $(1.06 \pm 0.19) \times 10^{-4}$ | $(0.807 \pm 0.061) \times 10^{-4}$ |
| $R_D$ | $0.403 \pm 0.47$ | $0.299 \pm 0.003$ |
| $R_{D*}$ | $0.310 \pm 0.17$ | $0.257 \pm 0.003$ |

$$\mathrm{BR}(B \to \tau\nu) = \frac{G_F^2 |V_{ub}|^2}{8\pi} m_\tau^2 f_B^2 m_B \left(1 - \frac{m_\tau^2}{m_B^2}\right)^2 \tau_B \left|1 + \frac{m_B^2}{m_b m_\tau} \frac{C_R^{ub} - C_L^{ub}}{C_{\rm SM}^{ub}}\right|^2$$

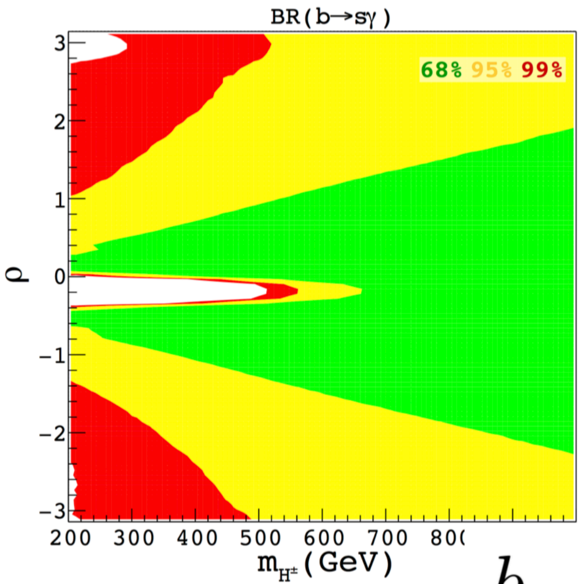
$$C_R^{ub} = -\frac{1}{m_{H^\pm}^2} \Gamma^{H^\pm}_{b_R u_L} \Gamma^{H^\pm}_{\nu_L \tau_R} \quad \text{and} \quad C_L^{ub} = -\frac{1}{m_{H^\pm}^2} \Gamma^{H^\pm}_{b_L u_R} \Gamma^{H^\pm}_{\nu_L \tau_R}$$

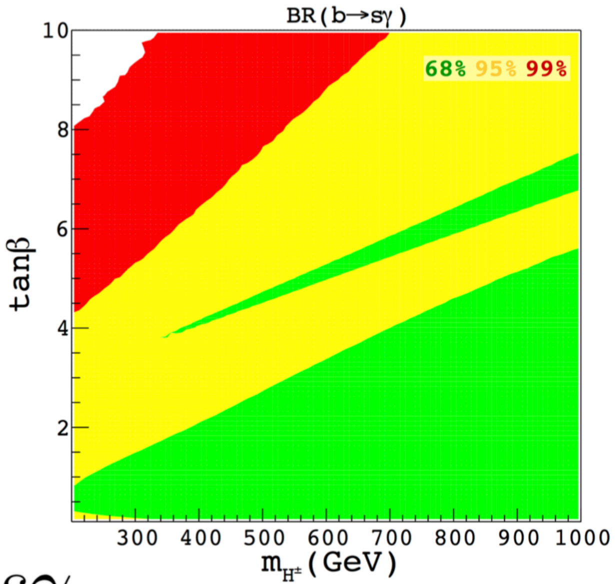
Large contributions to $B \to \tau\nu$ are not generated by this model

$$R_D = R_D^{\rm SM} \left(1 + 1.5\Re\left(\frac{C_R^{cb} + C_L^{cb}}{C_{\rm SM}^{cb}}\right) + 1.0 \left|\frac{C_R^{cb} + C_L^{cb}}{C_{\rm SM}^{cb}}\right|^2\right),$$

$$R_{D^*} = R_{D^*}^{\rm SM} \left(1 + 0.12\Re\left(\frac{C_R^{cb} - C_L^{cb}}{C_{\rm SM}^{cb}}\right) + 0.05 \left|\frac{C_R^{cb} - C_L^{cb}}{C_{\rm SM}^{cb}}\right|^2\right),$$

$R_D$ and $R_{D*}$ are not explained by this model but the fit to the parameter space is affected by these measurements




$b \to s\gamma$

$$\delta C_7^0 = \frac{v^2}{\lambda_t} \frac{1}{m_b} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_L^j b_R} \frac{C^0_{7,XY}(y_j)}{m_{u^j}} + \frac{v^2}{\lambda_t} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_R^j b_L} \frac{C^0_{7,YY}(y_j)}{m_{u^j}^2},$$

$$\delta C_8^0 = \frac{v^2}{\lambda_t} \frac{1}{m_b} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_L^j b_R} \frac{C^0_{8,XY}(y_j)}{m_{u^j}} + \frac{v^2}{\lambda_t} \sum_{j=1}^{3} \Gamma^{H^\pm *}_{u_R^j s_L} \Gamma^{H^\pm}_{u_R^j b_L} \frac{C^0_{8,YY}(y_j)}{m_{u^j}^2}$$

strong bound on charged Higgs mass (typical of THDM type II) is alleviated because of cancellations with the SM contributions at low $\tan\beta$

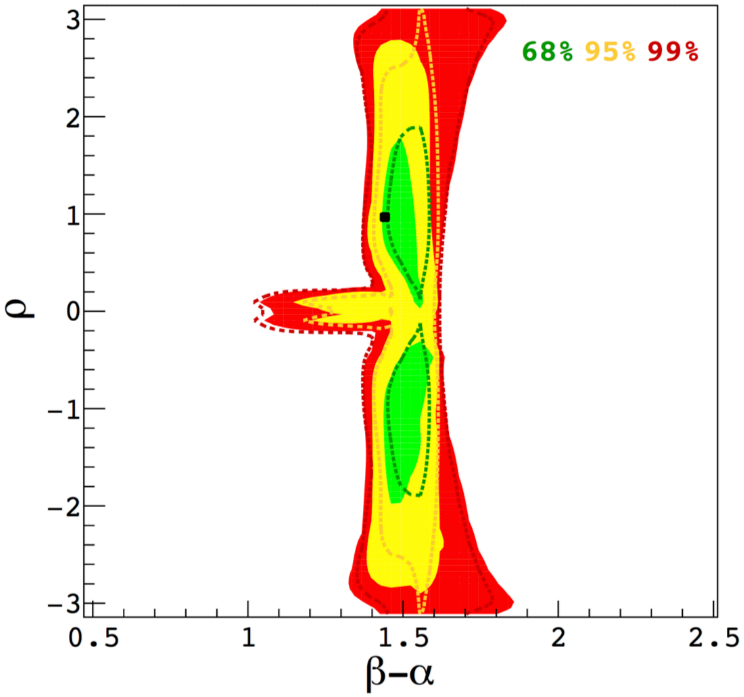
$m_{H^\pm} \gtrsim$ 580 GeV @ 95% CL in THDM type II

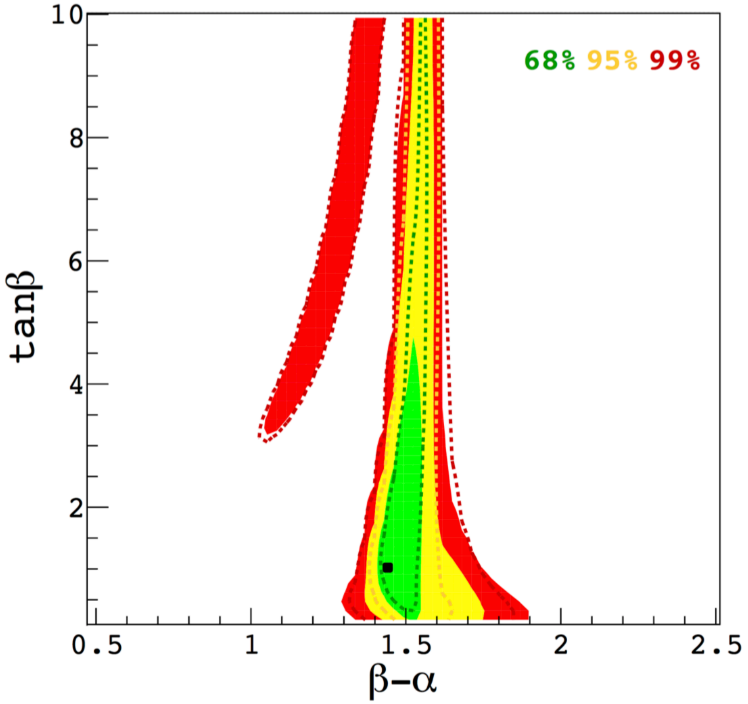
# combining all constraints

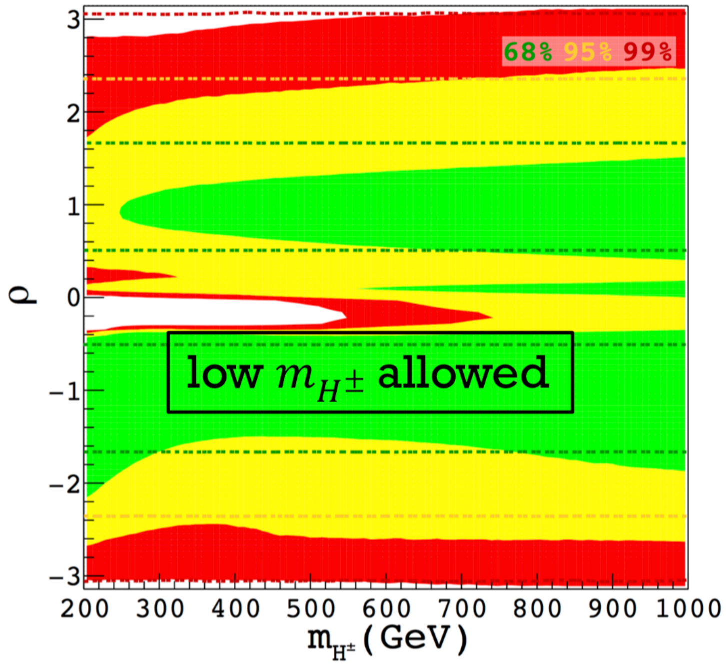
The picture is not only hopeful but quite promising!!

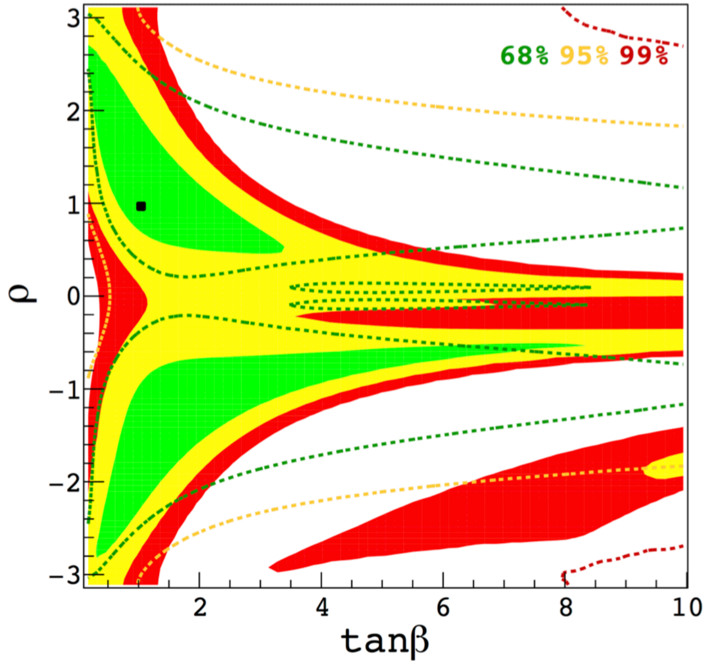
a preference for $\rho \neq 0$

a preference for low $\tan\beta$



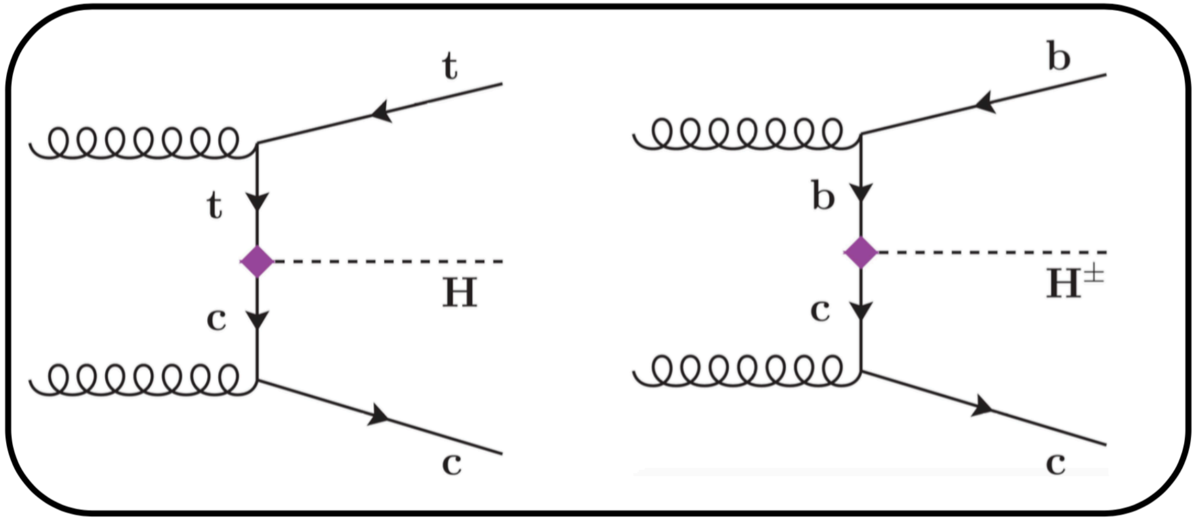



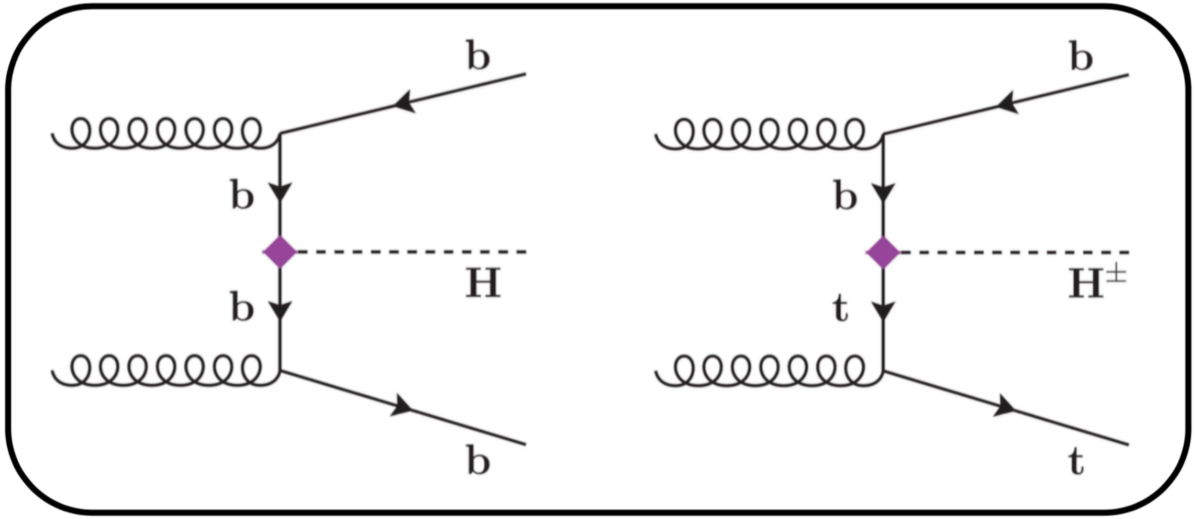




The black dots mark the benchmark point with discuss in our study of collider phenomenology

# collider phenomenology of the heavy Higgs



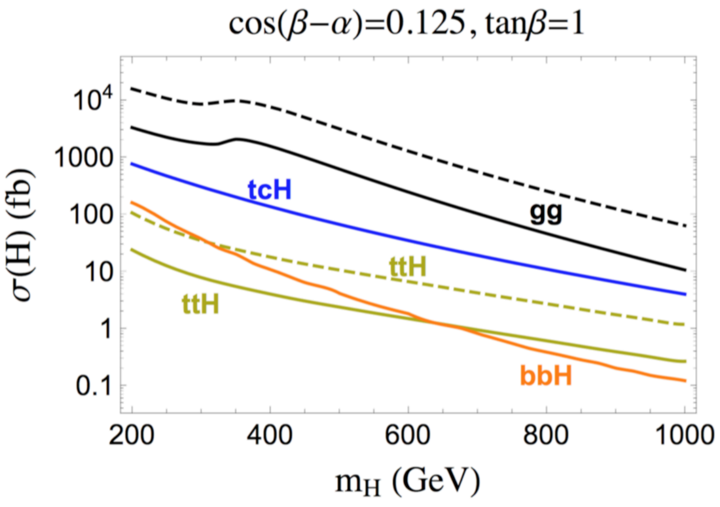

THDM type III
that we use

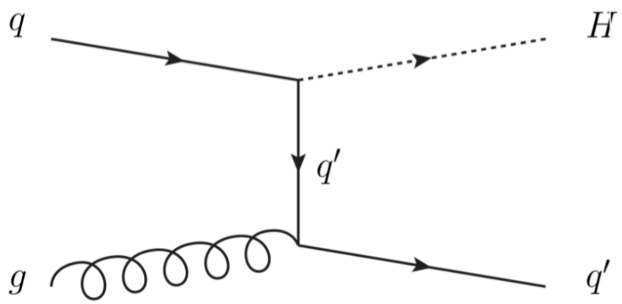
THDM type II

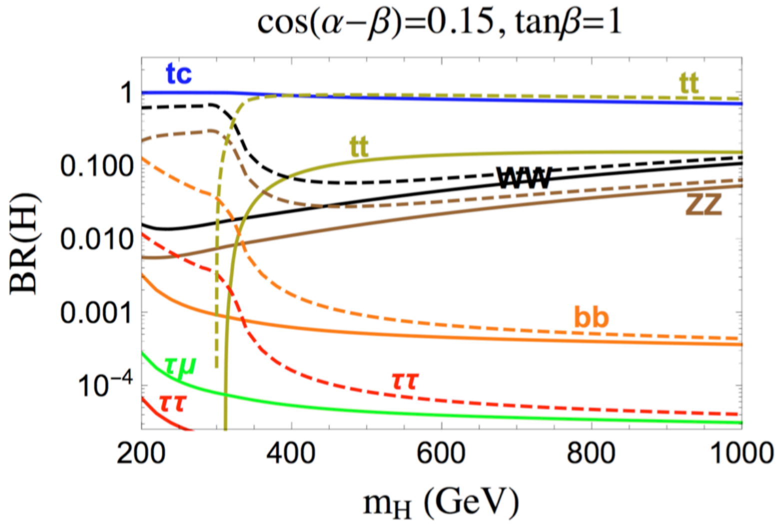
| $pp \to H \to tc$ | $pp \to tcH(\to tc)$ | $pp \to bcH^{\pm}(\to bc)$ | $pp \to bcH^{\pm}(\to Wh)$ |
|---|---|---|---|
| 1 charged lepton<br>$E_T^{miss}$<br>1 $b$-jet<br>1 $c$-jet | 2 same-sign leptons<br>2 $b$-jets<br>$\geq$1 $c$-jet | dijet resonance<br>$\geq$1 $b$-jet<br>$\geq$1 $c$-jet | $Wh$ resonance<br>$\geq$1 $b/c$-jet |

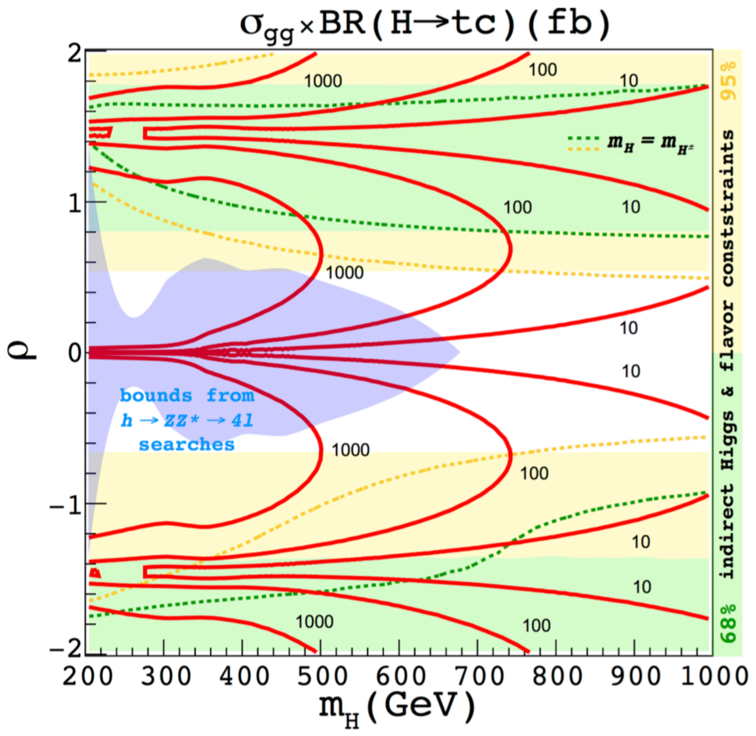
a list of interesting signatures

# collider phenomenology of the heavy neutral Higgs




excluded by 13 TeV

$gg \longrightarrow H \longrightarrow ZZ^* \longrightarrow 4l$

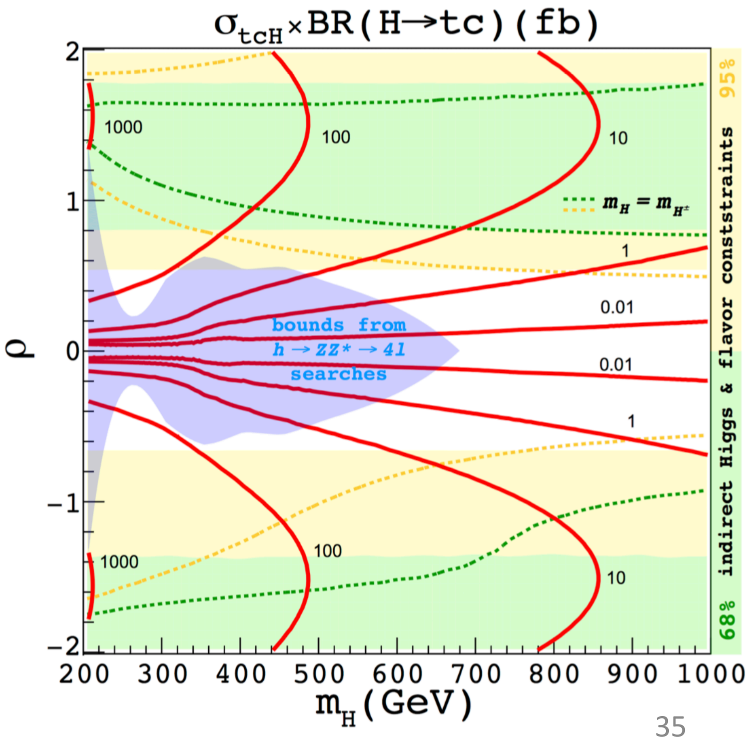
$\cos(\beta-\alpha) = 0.125$ and $\tan\beta = 1$

68.2 %

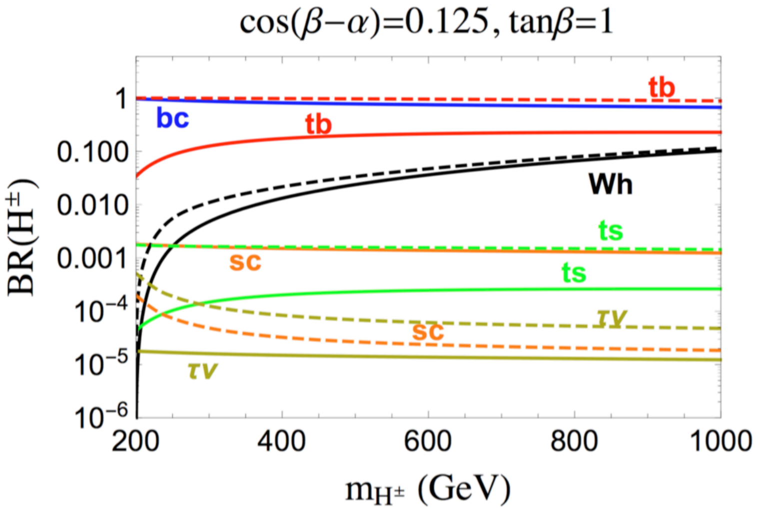
95.4 %

$m_{H^\pm} = m_{H^0}$

marginalized over $m_{H^\pm}$

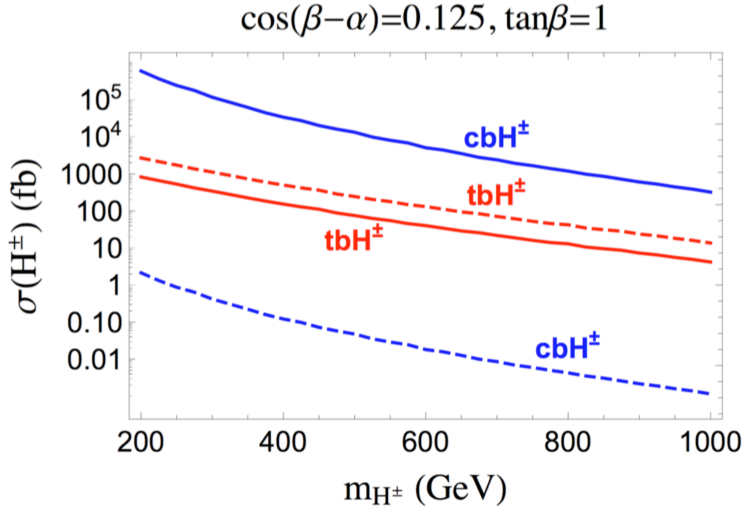


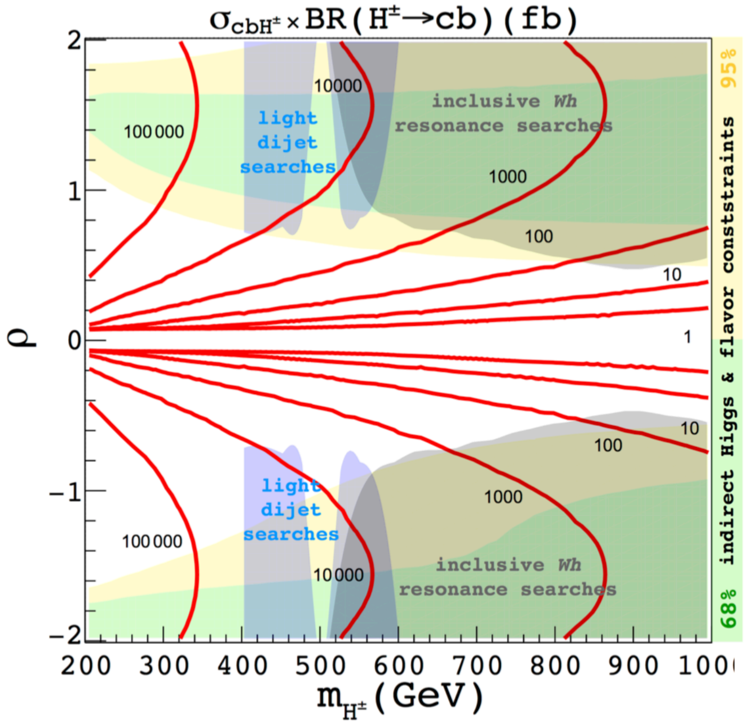
# collider phenomenology of the charged Higgs

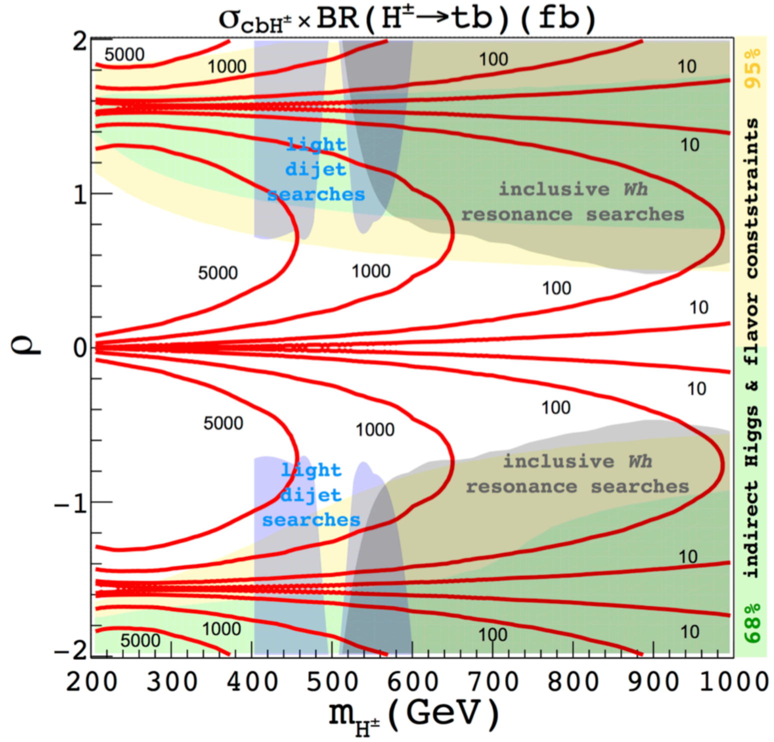


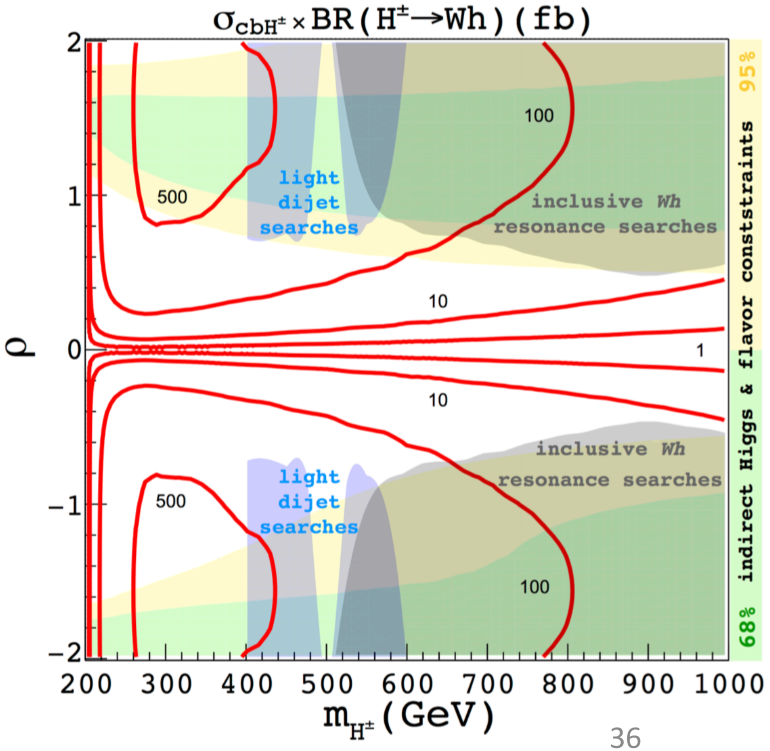

$\cos(\beta-\alpha)=0.125$ and $\tan\beta=1$

Already probed by light dijet searches



# On HEPfit:

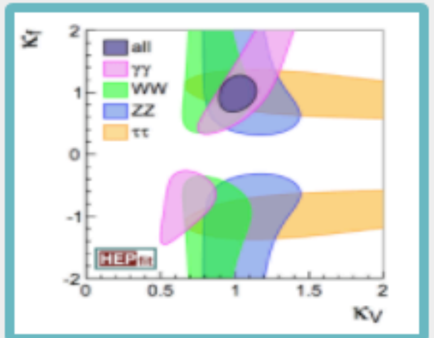
**When the going gets tough,**
**the tough get going.**

**J. P. Kennedy**
**or**
**Knute Rockne**

HEPfit

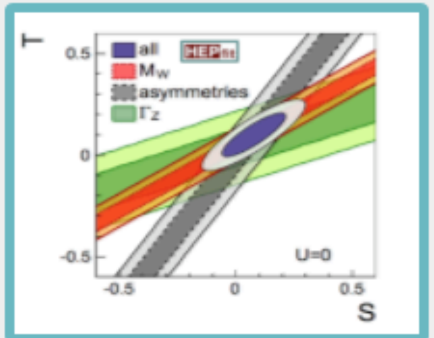
home developers samples documentation

# HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.



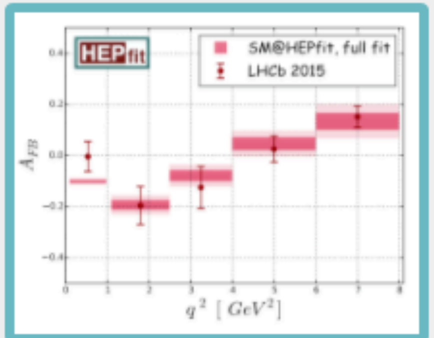

### Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.



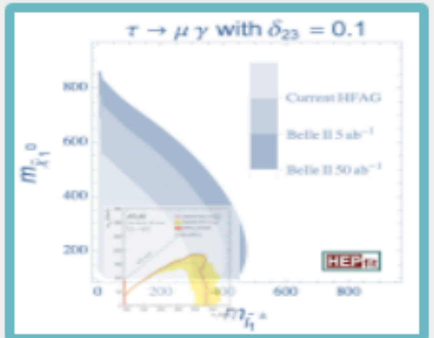

### Precision Electroweak

Electroweak precision observables are included in HEPfit




### Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.




### BSM Physics

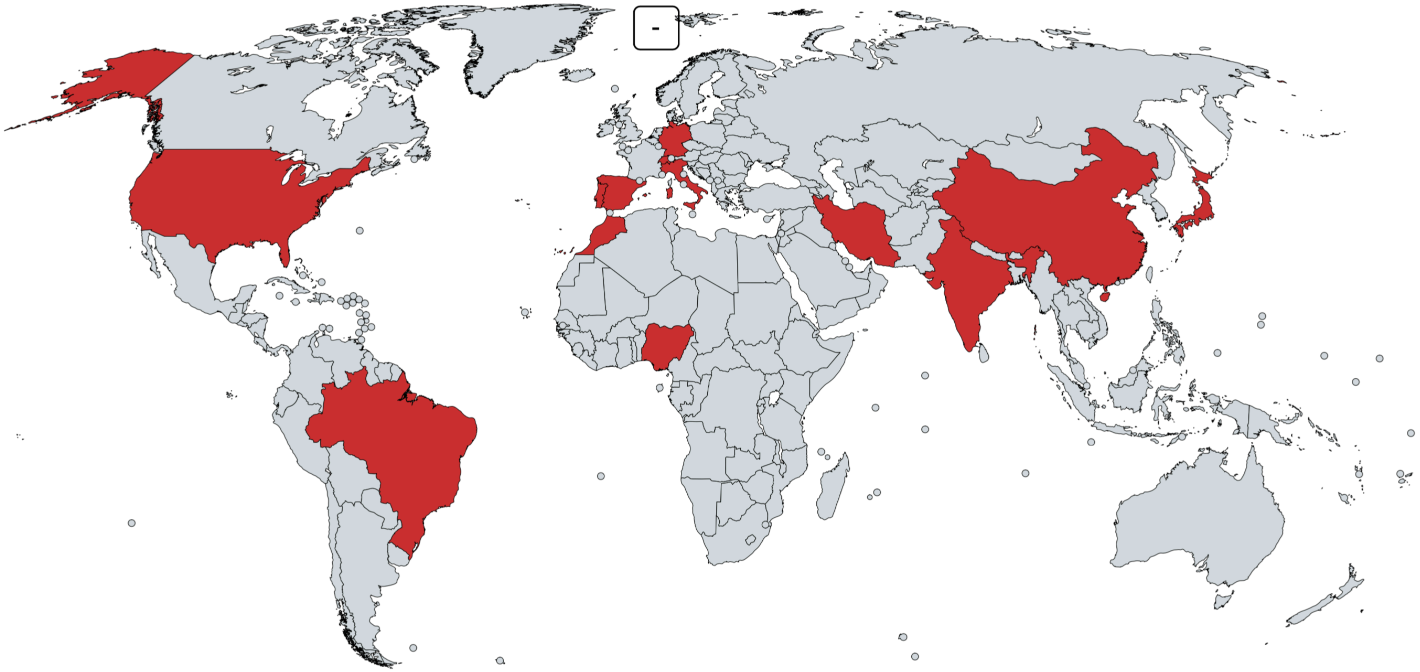
Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

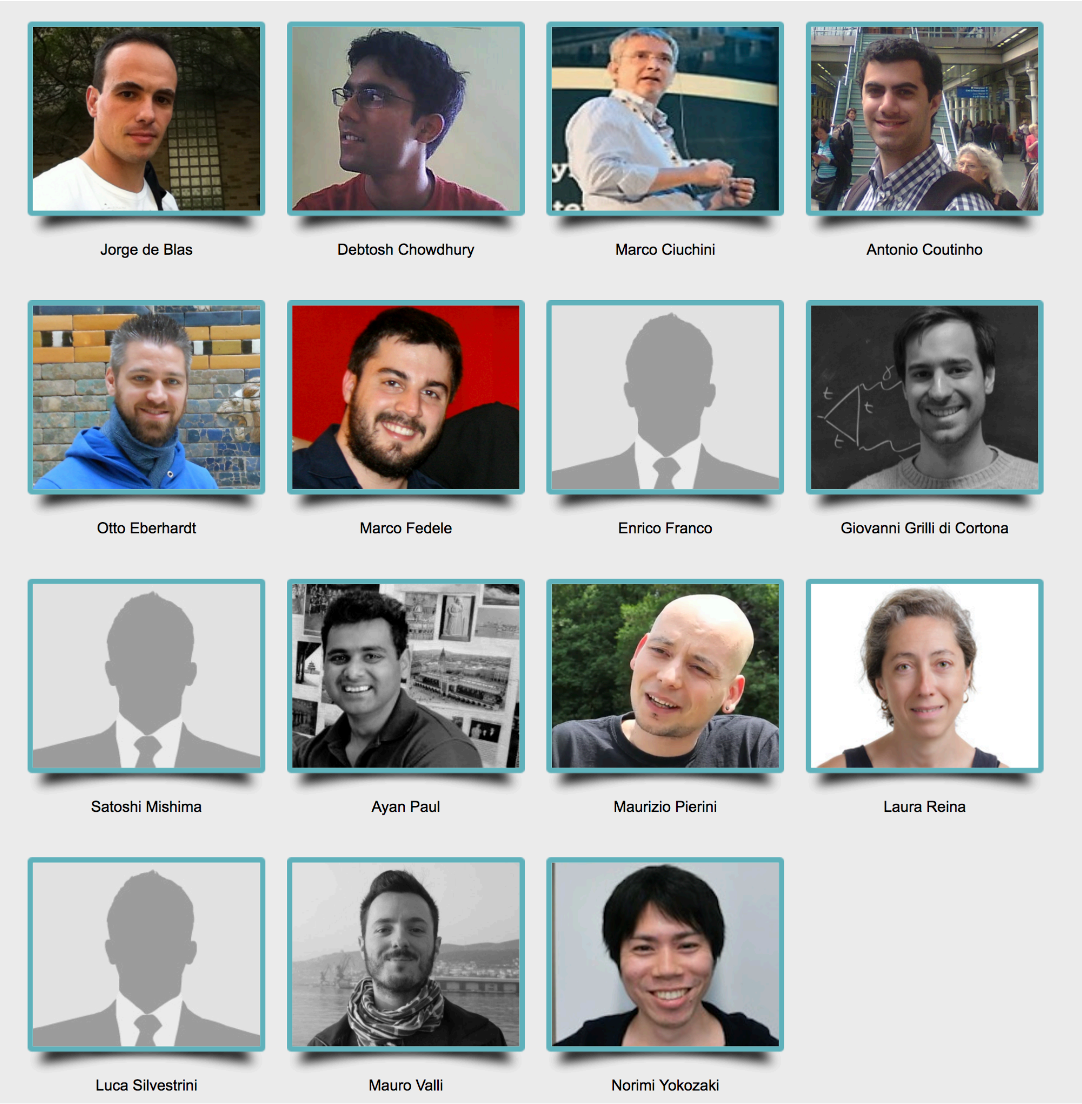
Exisiting fitters: CKMfitter (F), GAMBIT (B), GAPP (B), Gfitter (F), HiggsSignals (F), Mastercode (F), UTfit (B), ...

No fitters: CheckMate (yes/no), HiggsBounds (yes/no), Zfitter (no fitting algorithm)

Problems:
too slow, depend on external codes, mostly only one model defined


HEPfit

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# The release candidate 1.0 contains more than 600 observables:

| HEPfit name | Model(s) | Comments |
|---|---|---|
| MtMSbar | SM | |
| Mw | SM | |
| GammaW | SM | |
| GammaZ | SM | |
| sigmaHadron | SM | |
| sin2thetaEff | SM | |
| PtauPol | SM | |
| Alepton | SM | |
| Acharm | SM | |
| Abottom | SM | |
| AFBlepton | SM | |
| AFBcharm | SM | |
| AFBbottom | SM | |
| Rlepton | SM | |
| Rcharm | SM | |
| Rbottom | SM | |
| ggHx | SM | $x \in 7, 8, 13, 14, 100, 196$; without $x$ default is 8 |
| VBFx | SM | $x \in 7, 8, 13, 14, 100, 196$; without $x$ default is 8 |
| WHx | SM | $x \in 7, 8, 13, 14, 100$; without $x$ default is 8 |
| ZHx | SM | $x \in 7, 8, 13, 14, 100$; without $x$ default is 8 |
| VHx | SM | $x \in 7, 8, 13, 14, 100, 196$; without $x$ default is 8 |
| ggH+ttHx | SM | $x \in 8, 13, 14, 100$; without $x$ default is 8 |
| VBF+VHx | SM | $x \in 8, 13, 14, 100$; without $x$ default is 8 |
| ttHx | SM | $x \in 7, 8, 13, 14, 100, 196$; without $x$ default is 8 |
| eeZHx | SM | $x \in 240, 250, 500, 1000$ |
| eeWBFx | SM | $x \in 250, 350, 500, 1000$ |
| eettHx | SM | $x \in 500, 1000$ |
| BrHggRatio | SM | |
| BrHWWRatio | SM | |
| BrHZZRatio | SM | |
| BrHZgaRatio | SM | |
| BrHgagaRatio | SM | |
| BrHmumuRatio | SM | |
| BrHtautauRatio | SM | |
| BrHccRatio | SM | |
| BrHbbRatio | SM | |
| epsilonx | SM | $x = 1, 2, 3, b$ |
| DmBd | SM | |
| DmBs | SM, THDM | |
| SJPsiK | SM | |
| Betas_JPsiPhi | SM | |
| EpsilonK | SM | |
| DmK | SM | |
| Vij | SM | $i = u, c, t$; $j = d, s, b$ |
| alpha | SM | |
| alpha_2a | SM | |
| gamma | SM | |
| beta | SM | |
| betas | SM | |
| 2betapgamma | SM | |
| s2beta | SM | |
| c2beta | SM | |
| CKM_rho | SM | |
| CKM_eta | SM | |
| sintheta12 | SM | |
| sintheta13 | SM | |
| sintheta23 | SM | |
| ckmdelta | SM | |
| J_CP | SM | |
| Rt | SM | |
| Rts | SM | |
| Rb | SM | |
| VtdoVts | SM | |
| Abslam_x | SM | $x \in u, c, t, ud, cd, td, us, cs, ts$ |
| Relam_x | SM | $x \in u, c, t, ud, cd, td, us, cs, ts$ |
| Imlam_x | SM | $x \in u, c, t, ud, cd, td, us, cs, ts$ |
| BR_Bdmumu | SM | |
| BRbar_Bdmumu | SM | |
| Amumu_Bd | SM | |
| Smumu_Bd | SM | |
| BR_Bsmumu | SM | |
| BRbar_Bsmumu | SM | |
| Amumu_Bs | SM | |
| Smumu_Bs | SM | |
| BR_BdmumuOBR_Bsmumu | SM | |

| HEPfit name | Model(s) | Comments | Source |
|---|---|---|---|
| BR_bsgamma | SM | | |
| ACP_bsgamma | SM | | |
| BR_bdgamma | SM | | |
| ACP_bdgamma | SM | | |
| BR_bqgamma | SM | | |
| ACP_bqgamma | SM | | |
| P_i_BdKstmu | SM | $i \in 1, 2, 3, 4p, 5p, 6p, 8p$ | |
| P_i_BdKste | SM | $i \in 1, 2, 3$ | |
| Gammap_BdKstmu | SM | | |
| A_FB_BdKstmu | SM | | |
| BR_BdKstmu | SM | | |
| BR_BdKste | SM | | |
| RKst_BdKstll | SM | | |
| RKstL_BdKstll | SM | | |
| RKstT_BdKstll | SM | | |
| R6_BdKstll | SM | | |
| ACP_BdKstmu | SM | | |
| P3CP_BdKstmu | SM | | |
| F_L_BdKstmu | SM | | |
| F_L_BdKste | SM | | |
| M_i_BdKstmu | SM | $i \in 1p, 2p$ | |
| S_i_BdKstmu | SM | $i \in 3, 4, 5, 7, 8, 9$ | |
| A_i_BdKstmu | SM | $i \in 6, 9$ | |
| P_if_BdKstmu | SM | $i \in 1, 2, 3, 4p, 5p, 6p, 8p$ | |
| Gammapf_BdKstmu | SM | | |
| BRf_BdKstmu | SM | | |
| A_FBf_BdKstmu | SM | | |
| F_Lf_BdKstmu | SM | | |
| S_if_BdKstmu | SM | $i \in 3, 4, 5, 7, 8, 9$ | |
| P_relationf | SM | | |
| P_relation_exactf | SM | | |
| Vx_BdKstmu | SM | $x \in 0, p, m$ | |
| Tx_BdKstmu | SM | $x \in 0, p, m$ | |
| S_BdKstmu | SM | | |
| QCDfC9_if_BdKstmu | SM | $i \in 1, 2, 3$ | |
| QCDfC9p_if_BdKstmu | SM | $i \in 1, 2, 3$ | |
| Regtilde_i_BdKstmu | SM | $i \in 1, 2, 3$ | |
| Imgtilde_i_BdKstmu | SM | $i \in 1, 2, 3$ | |
| Absgtilde_i_BdKstmu | SM | $i \in 1, 2, 3$ | |
| Arggtilde_i_BdKstmu | SM | $i \in 1, 2, 3$ | |
| Reh_x_BdKstmu | SM | $x \in 0, p, m$ | |
| Imh_x_BdKstmu | SM | $x \in 0, p, m$ | |
| Absh_x_BdKstmu | SM | $x \in 0, p, m$ | |
| Argh_x_BdKstmu | SM | $x \in 0, p, m$ | |
| A_FB_BpKstmu | SM | | |
| F_L_BpKstmu | SM | | |
| BR_BpKstmu | SM | | |
| BR_BKstgamma | SM | | |
| C_BKstgamma | SM | | |
| S_BKstgamma | SM | | |
| ADG_BKstgamma | SM | | |
| DC7_i | SM | $i \in 1, 2$ | |
| AbsDC7_x | SM | $x \in L, R$ | |
| ReDC7_x | SM | $x \in L, R$ | |
| ImDC7_x | SM | $x \in L, R$ | |
| hp0_hm0 | SM | | |
| BR_BpKstgamma | SM | | |
| P_i_Bsphimu | SM | $i \in 1, 2, 3, 4p, 5p, 6p, 8p$ | |
| Gammap_Bsphimu | SM | | |
| A_FB_Bsphimu | SM | | |
| BR_Bsphimu | SM | | |
| Rphi_Bsphill | SM | | |
| RphiL_Bsphill | SM | | |
| RphiT_Bsphill | SM | | |
| R6_Bsphill | SM | | |
| ACP_Bsphimu | SM | | |
| P3CP_Bsphimu | SM | | |
| F_L_Bsphimu | SM | | |
| M_i_Bsphimu | SM | $i \in 1p, 2p$ | |
| S_i_Bsphimu | SM | $i \in 3, 4, 5, 7, 8, 9$ | |
| A_i_Bsphimu | SM | $i \in 6, 9$ | |
| BR_Bsphigamma | SM | | |
| C_Bsphigamma | SM | | |
| S_Bsphigamma | SM | | |
| ADG_Bsphigamma | SM | | |
| BR_BKmu | SM | | |
| BR_BKe | SM | | |
| RK_BKll | SM | | |
| btaunu | SM, THDM | | [?] |

| HEPfit name | Model(s) | Comments | Source |
|---|---|---|---|
| mu_e_gamma | SUSY | | |
| log_meg | SUSY | | |
| tau_mu_gamma | SUSY | | |
| log_tmg | SUSY | | |
| tau_e_gamma | SUSY | | |
| log_teg | SUSY | | |
| mu_3e | SUSY | | |
| tau_3mu | SUSY | | |
| tau_3e | SUSY | | |
| gminus2_mu | SUSY | | |
| Robs_mu_e_gamma | SUSY | | |
| Robs_tau_mu_gamma | SUSY | | |
| Robs_tau_mu_gamma_BelleII | SUSY | | |
| Robs_tau_e_gamma | SUSY | | |
| deltaLLi_f | SUSY | $i = 1, 2, 3$, $f = q, l$ | |
| deltaRL_ij_u | SUSY | $ij = 12, 13, 23$ | |
| deltaRL_ij_e | SUSY | $ij = 12, 13, 23, 21, 31, 32$ | |
| deltaRRi_f | SUSY | $i = 1, 2, 3$, $f = u, d, e$ | |
| CCBfij | SUSY | $f = u, d, e$, $ij = 11, 22, 33, 12, 13, 23$ | |
| MHl | SUSY | | |
| MHh | SUSY | | |
| MHa | SUSY | | |
| MHp | SUSY | | |
| Msfi | SUSY | $f = u, d, l$, $i = 1, 2, 3, 4, 5, 6$ | |
| Msnui | SUSY | $i = 1, 2, 3$ | |
| Mchi | SUSY | $i = 1, 2$ | |
| Msneui | SUSY | $i = 1, 2, 3, 4$ | |
| Mw_dRho | SUSY | | |
| mHl_THDM | THDM | | |
| mHh | THDM | | |
| mA | THDM | | |
| mHp | THDM | | |
| mHlmmA | THDM | | |
| mAmmHl | THDM | | |
| mHlmmHp | THDM | | |
| mHpmmHl | THDM | | |
| mHhmmA | THDM | | |
| mAmmHh | THDM | | |
| mHhmmHp | THDM | | |
| mHpmmHh | THDM | | |
| mAmmHp | THDM | | |
| mHpmmA | THDM | | |
| mii_2 | THDM | $ii = 11, 22$ | |
| lambdai | THDM | $i = 1, 2, 3, 4, 5$ | |
| lambda345 | THDM | | |
| g_hhh | THDM | | |
| g_hhHh | THDM | | |
| g_hHhHh | THDM | | |
| g_HhHhHh | THDM | | |
| g_hAA | THDM | | |
| g_HhAA | THDM | | |
| g_hHpHm | THDM | | |
| g_HhHpHm | THDM | | |
| Yi_THDM | THDM | $i = 1, 2, 3$ | |
| Zi_THDM | THDM | $i = 1, 2, 3, 4, 5, 6, 7$ | |
| xin_THDM | THDM | $n = 0, 1, 3$ | |
| etax_THDM | THDM | $x = 00, 3$ | |
| Eii_THDM | THDM | $ii = 11, 22, 33$ | |
| HHlambdai | THDM | $i = 1, 2, 3, 4, 5, 6$ | |
| Q_st | THDM | | |
| DeltaQ_THDM | THDM | | |
| giatQ | THDM | $i = 1, 2, 3$ | |
| YtopatQ | THDM | | |
| YbottomatQ | THDM | | |
| YtauatQ | THDM | | |
| mij_2atQ | THDM | $ij = 11, 22, 12$ | |
| lambdaiatQ | THDM | $i = 1, 2, 3, 4, 5$ | |
| positivityi | THDM | $i = 1, 2$ | [?] |
| globalminimum | THDM | | [?] |
| unitarityi | THDM | $i = \{1 \dots 12\}$ | [?, ?, ?, ?, ?] |
| unitarityal$\sigma$odd | THDM | $\sigma = 0, 1$ | [?, ?] |
| unitarityal$\sigma$oddRe | THDM | $\sigma = 0, 1$ | [?, ?] |
| unitarityal$\sigma$oddIm | THDM | $\sigma = 0, 1$ | [?, ?] |
| unitaritya$Y\sigma\mathbb{Z}_2s$ | THDM | $Y\sigma = 00, 01, 11$, $\mathbb{Z}_2 = odd, even$, $s = p, m$ | [?, ?] |
| unitaritya$Y\sigma\mathbb{Z}_2s$Re | THDM | $Y\sigma = 00, 01, 11$, $\mathbb{Z}_2 = odd, even$, $s = p, m$ | [?, ?] |
| unitaritya$Y\sigma\mathbb{Z}_2s$Im | THDM | $Y\sigma = 00, 01, 11$, $\mathbb{Z}_2 = odd, even$, $s = p, m$ | [?, ?] |
| unitarityRpi | THDM | $i = 1, 2, 3, 4, 5, 6, 9, 10, 13, 14, 19, 20$ | [?, ?] |
| unitarityRi | THDM | $i = 1, 2, 3, 4, 5, 6, 9, 10, 13, 14, 19, 20$ | [?, ?] |
| ggF_tth_htobb | THDM | | [?] |
| ggF_tth_htoWW | THDM | | [?] |
| ggF_tth_htotautau | THDM | | [?] |
| ggF_tth_htoZZ | THDM | | [?] |
| ggF_tth_htogaga | THDM | | [?] |
| VBF_Vh_htobb | THDM | | [?] |
| VBF_Vh_htoWW | THDM | | [?] |
| VBF_Vh_htotautau | THDM | | [?] |
| VBF_Vh_htoZZ | THDM | | [?] |
| VBF_Vh_htogaga | THDM | | [?] |
| Gamma_h_THDM | THDM | | |
| rh_gaga_THDM | THDM | | |
| rh_gg_THDM | THDM | | |

| HEPfit name | Model(s) | Comments | Source |
|---|---|---|---|
| Robs_B$\sigma$ | THDM | $B\sigma \in$ ggF_H_tautau_ATLAS, ggF_H_tautau_CMS, bbF_H_tautau_ATLAS, bbF_H_tautau_CMS, pp_H_gaga_ATLAS, ggF_H_gaga_CMS, mu_pp_H_VV_CMS, ggF_H_ZZ_ATLAS, VBF_H_ZZ_ATLAS, ggF_H_WW_ATLAS, VBF_H_WW_ATLAS, ggF_H_hh_ATLAS, pp_H_hh_CMS, ggF_H_hh_bbtautau_CMS, pp_H_hh_bbbb_CMS, pp_H_hh_gagabb_CMS, ggF_H_tt_ATLAS, bbF_H_bb_CMS | [?] |
| log10_B$\sigma$ | THDM | $B\sigma \in$ ggF_H_tautau_TH, bbF_H_tautau_TH, pp_H_gaga_TH, ggF_H_gaga_TH, mu_pp_H_VV_TH, ggF_H_ZZ_TH, VBF_H_ZZ_TH, ggF_H_WW_TH, VBF_H_WW_TH, ggF_H_hh_TH, pp_H_hh_TH, ggF_H_hh_bbtautau_TH, pp_H_hh_bbbb_TH, pp_H_hh_gagabb_TH, ggF_H_tt_TH, bbF_H_bb_TH | |
| Gamma_HH_THDM | THDM | | |
| rHH_gg_THDM | THDM | | |
| BR_HH_hh_THDM | THDM | | |
| BR_HH_AA_THDM | THDM | | |
| BR_HH_HpHm_THDM | THDM | | |
| BR_HH_AZ_THDM | THDM | | |
| BR_HH_HpW_THDM | THDM | | |
| Robs_B$\sigma$ | THDM | $B\sigma \in$ ggF_A_tautau_ATLAS, ggF_A_tautau_CMS, bbF_A_tautau_ATLAS, bbF_A_tautau_CMS, pp_A_gaga_ATLAS, ggF_A_gaga_CMS, pp_A_Zga_llga_CMS, ggF_A_hZ_bbll_CMS, ggF_A_hZ_bbZ_ATLAS, ggF_A_hZ_tautaull_CMS, ggF_A_hZ_tautauZ_ATLAS, ggF_A_tt_ATLAS, bbF_A_bb_CMS | [?] |
| log10_B$\sigma$ | THDM | $B\sigma \in$ ggF_A_tautau_TH, bbF_A_tautau_TH, pp_A_gaga_TH, ggF_A_gaga_TH, pp_A_Zga_llga_TH, ggF_A_hZ_bbll_TH, ggF_A_hZ_bbZ_TH, ggF_A_hZ_tautaull_TH, ggF_A_hZ_tautauZ_TH, ggF_A_tt_TH, bbF_A_bb_TH | |
| Gamma_A_THDM | THDM | | |
| rA_gg_THDM | THDM | | |
| BR_A_HZ_THDM | THDM | | |
| BR_A_hZ_THDM | THDM | | |
| BR_A_HpW_THDM | THDM | | |
| DeltaS | THDM | | [?] |
| DeltaT | THDM | | [?] |
| DeltaU | THDM | | [?] |
| B_BtoXsgammaTHDM | THDM | Interpolation of tabled values | [] |

**Thank you…!!**

To my Mother and Father, who showed me what I could do,

and to Ikaros, who showed me what I could not.

"To know what no one else does, what a pleasure it can be!"

– adopted from the words of

Eugene Wigner.