Probing the nature of the $hc\bar{c}$, $hb\bar{b}$ coupling and signals of new physics via $h \to \mathcal{Q}Z$ exclusive decays

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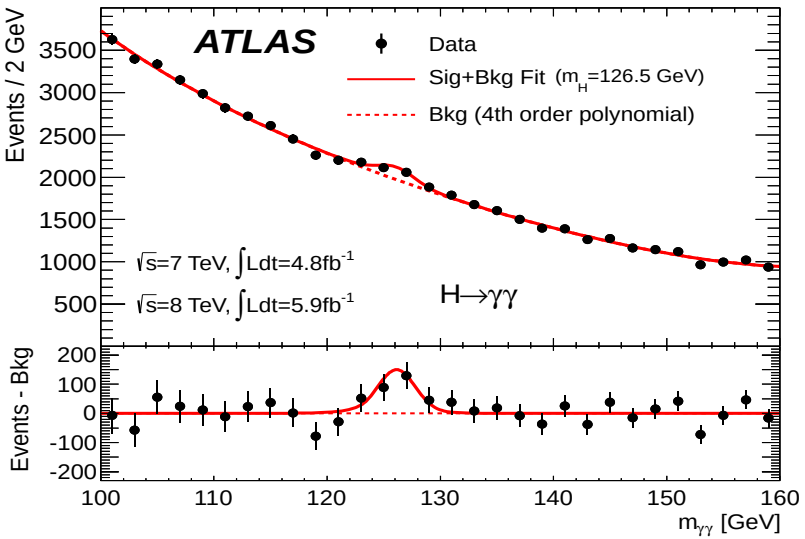
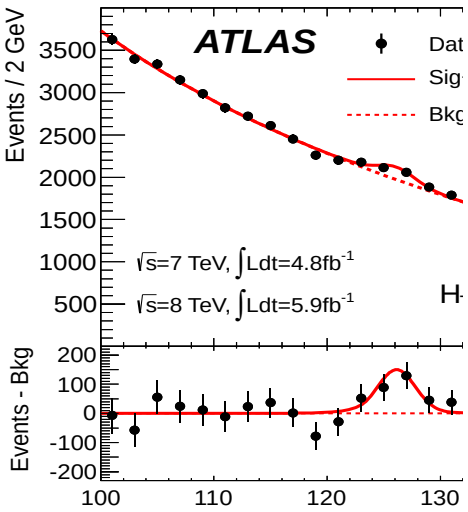
Institut Henri Poincare, Paris


ATLAS
Data
Sig+Bkg Fit (m_H=126.5 GeV)
Bkg (4th order polynomial)
√s=7 TeV, ∫Ldt=4.8fb^-1
√s=8 TeV, ∫Ldt=5.9fb^-1
H→γγ
Events / 2 GeV
Events - Bkg
m_γγ [GeV]


ATLAS
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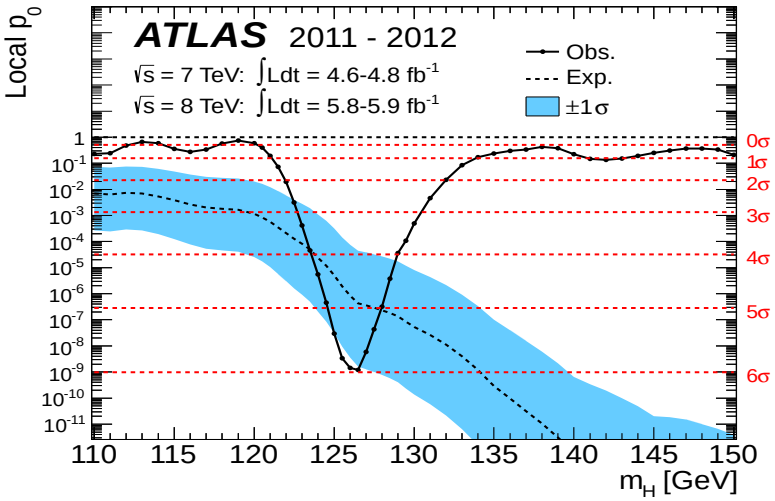
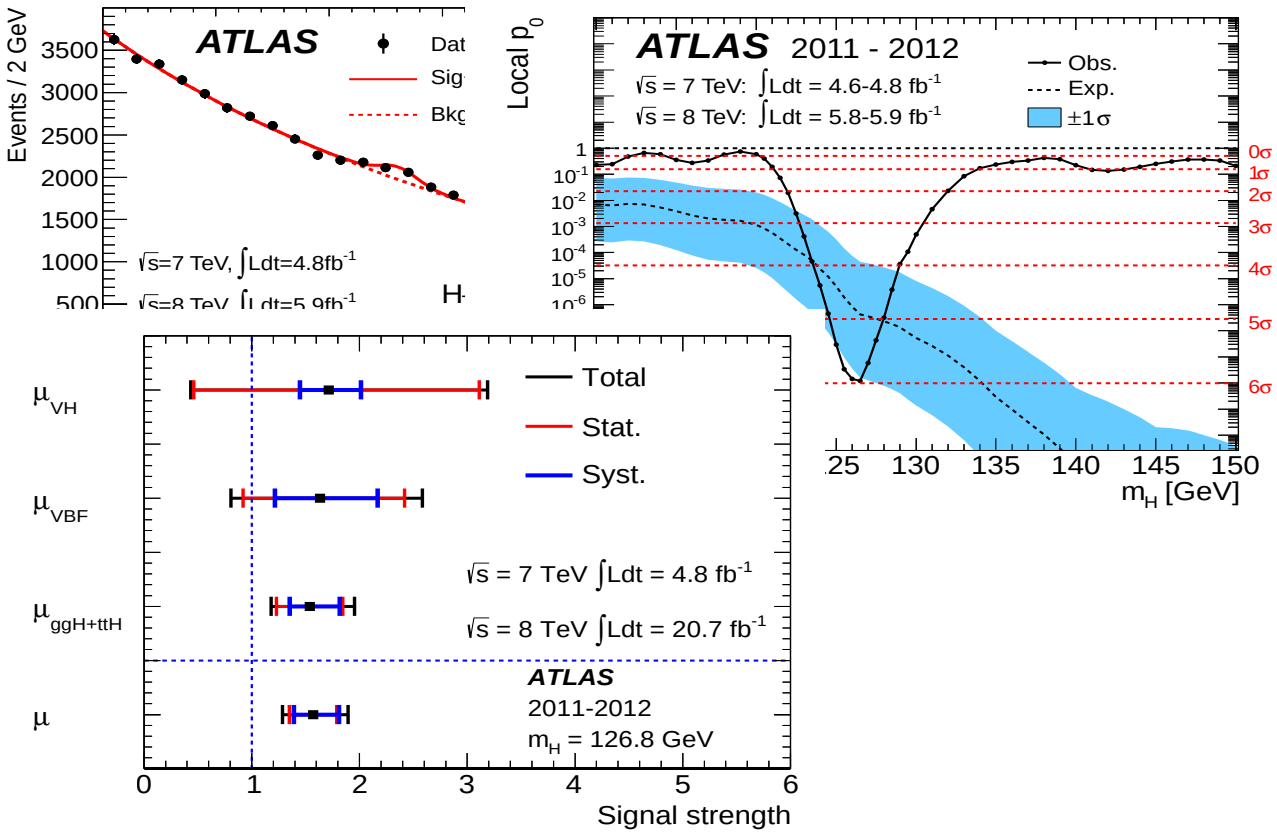
√s=7 TeV, ∫Ldt=4.8fb-1
√s=8 TeV, ∫Ldt=5.9fb-1
Events - Bkg


ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Obs.
Exp.
±1σ
Local p0
mH [GeV]


ATLAS
Events / 2 GeV
√s=7 TeV, ∫Ldt=4.8fb-1
ATLAS 2011 - 2012
Local p0
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
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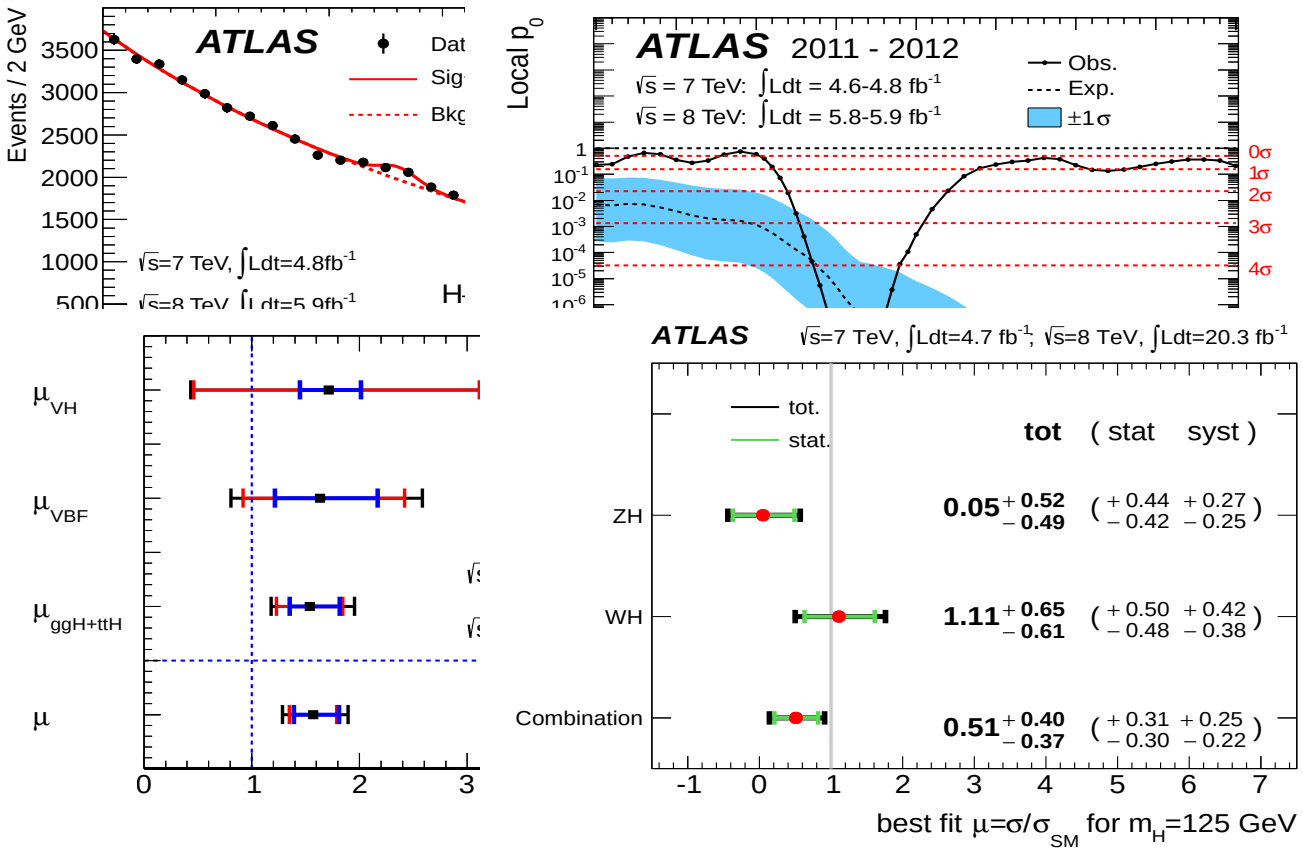
Obs.
Exp.
±1σ
mH [GeV]
Total
Stat.
Syst.
√s = 7 TeV ∫Ldt = 4.8 fb-1
√s = 8 TeV ∫Ldt = 20.7 fb-1
ATLAS
2011-2012
mH = 126.8 GeV
Signal strength


ATLAS
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√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
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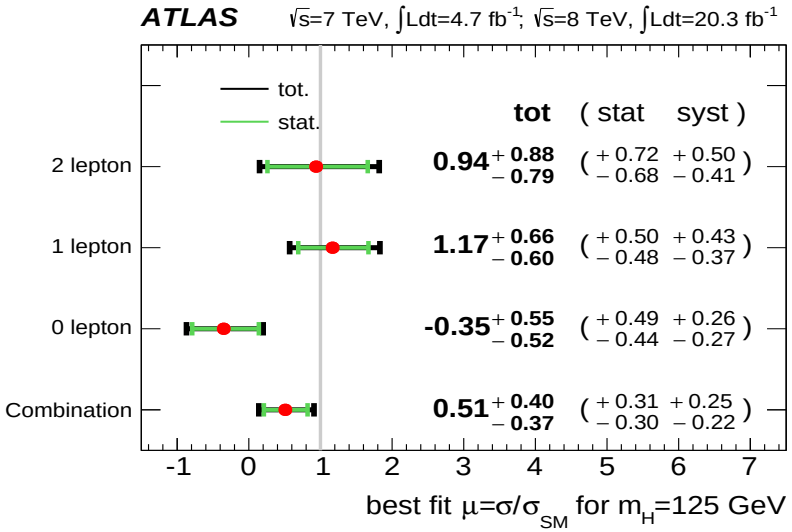
Obs.
Exp.
±1σ
0σ
1σ
2σ
3σ
4σ
ATLAS √s=7 TeV, ∫Ldt=4.7 fb-1; √s=8 TeV, ∫Ldt=20.3 fb-1
μVH
μVBF
μggH+ttH
μ
tot.
stat.
tot (stat syst)
ZH 0.05 +0.52 −0.49 (+0.44 −0.42 +0.27 −0.25)
WH 1.11 +0.65 −0.61 (+0.50 −0.48 +0.42 −0.38)
Combination 0.51 +0.40 −0.37 (+0.31 −0.30 +0.25 −0.22)
best fit μ=σ/σSM for mH=125 GeV


ATLAS
√s=7 TeV, ∫Ldt=4.7 fb⁻¹; √s=8 TeV, ∫Ldt=20.3 fb⁻¹
tot.
stat.
tot (stat syst)
2 lepton
0.94 +0.88 −0.79 (+0.72 −0.68 +0.50 −0.41)
1 lepton
1.17 +0.66 −0.60 (+0.50 −0.48 +0.43 −0.37)
0 lepton
-0.35 +0.55 −0.52 (+0.49 −0.44 +0.26 −0.27)
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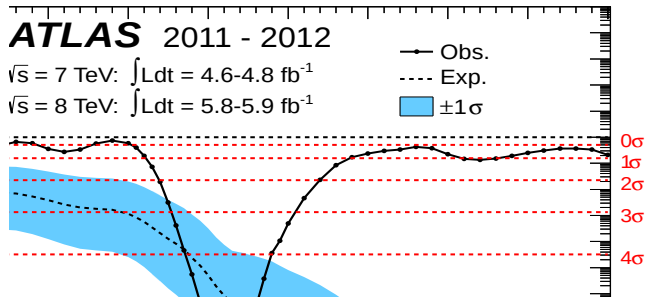
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Exp.
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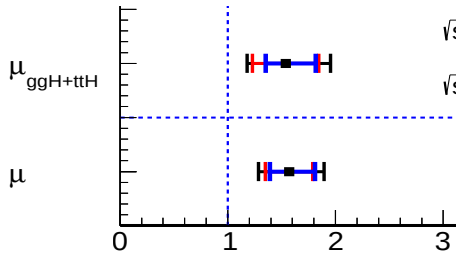
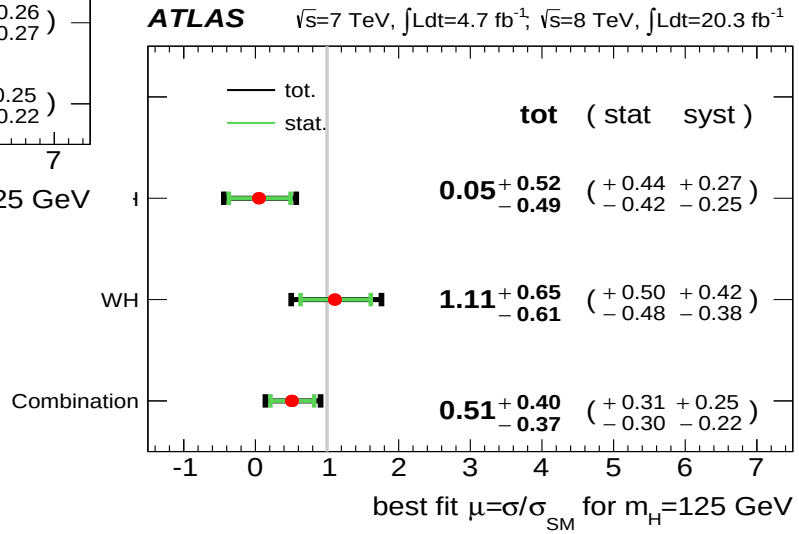
3σ
4σ


μggH+ttH
μ
0 1 2 3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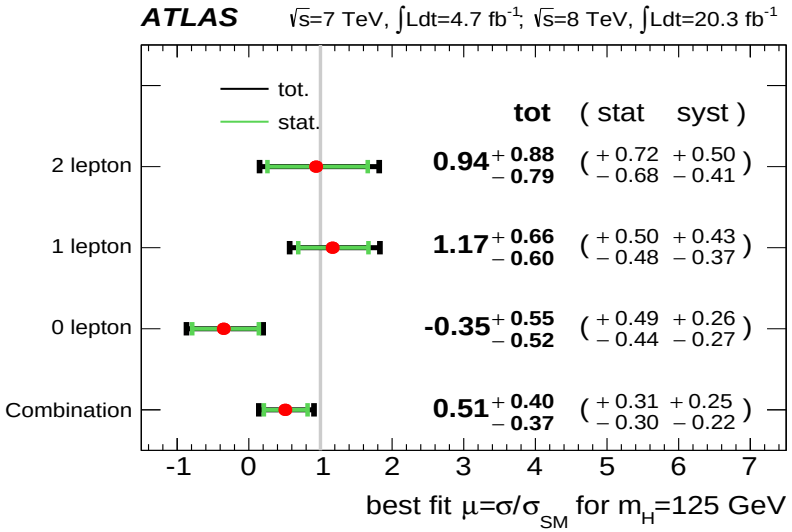
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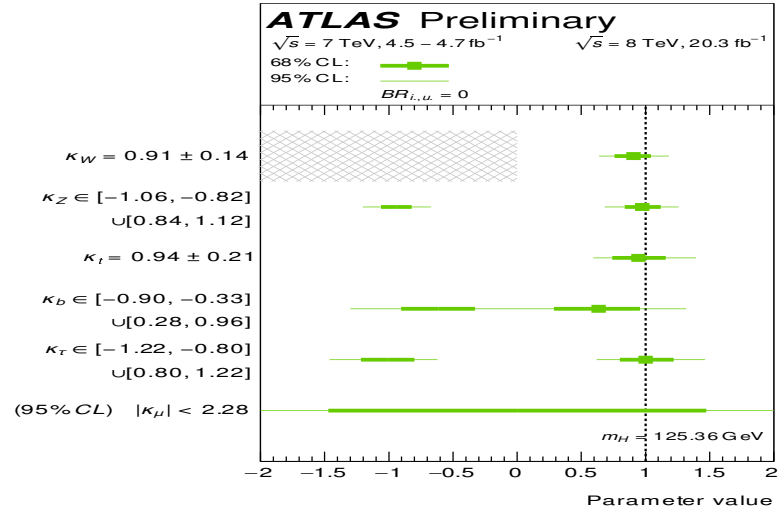
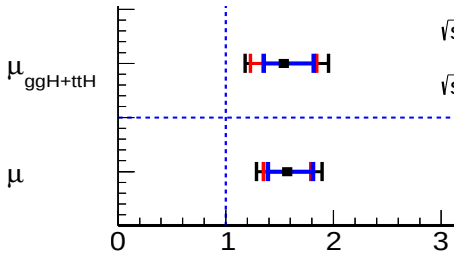
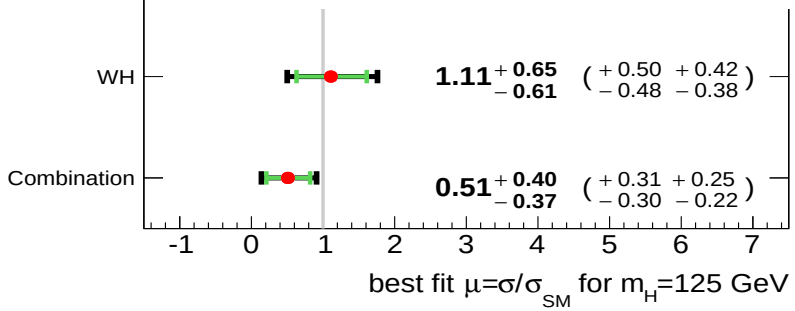

ATLAS Preliminary
√s = 7 TeV, 4.5 − 4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
68% CL:
95% CL:
BRi,u = 0
κW = 0.91 ± 0.14
κZ ∈ [−1.06, −0.82] ∪[0.84, 1.12]
κt = 0.94 ± 0.21
κb ∈ [−0.90, −0.33] ∪[0.28, 0.96]
κτ ∈ [−1.22, −0.80] ∪[0.80, 1.22]
(95% CL) |κμ| < 2.28
mH = 125.36 GeV
−2 −1.5 −1 −0.5 0 0.5 1 1.5 2
Parameter value


μggH+ttH
μ
0 1 2 3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Combination
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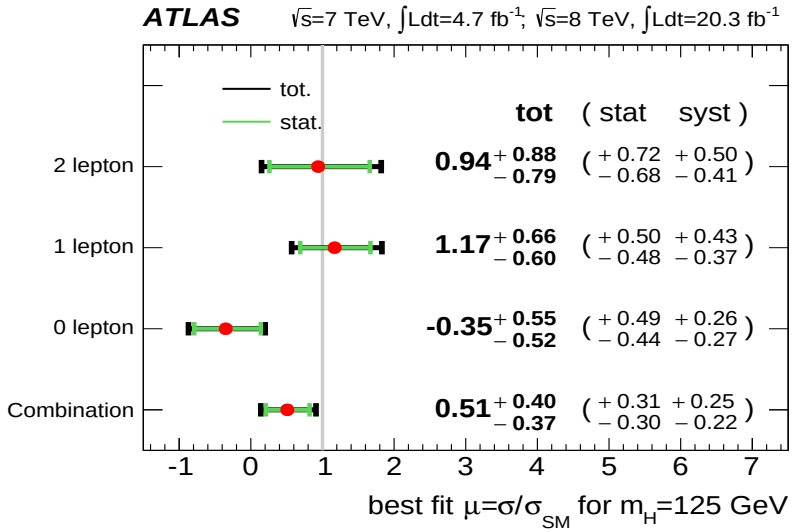
ATLAS
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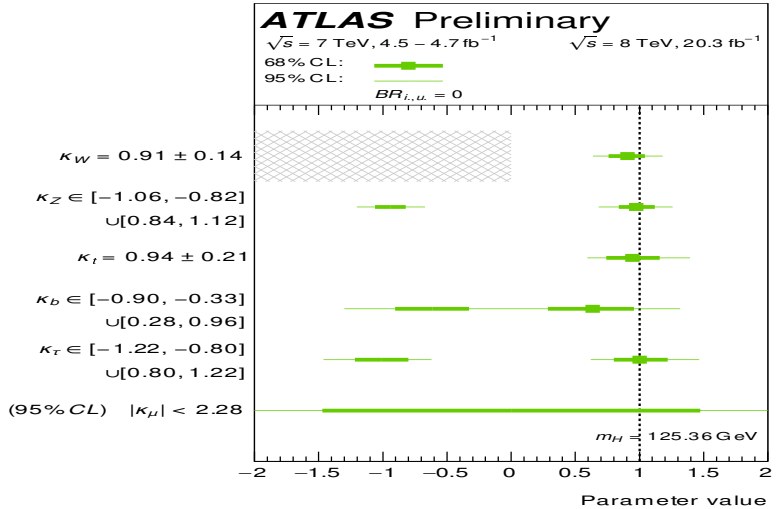
tot.
stat.
tot (stat syst)
2 lepton
1 lepton
0 lepton
Combination
best fit μ=σ/σ_SM for m_H=125 GeV


ATLAS Preliminary
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68% CL:
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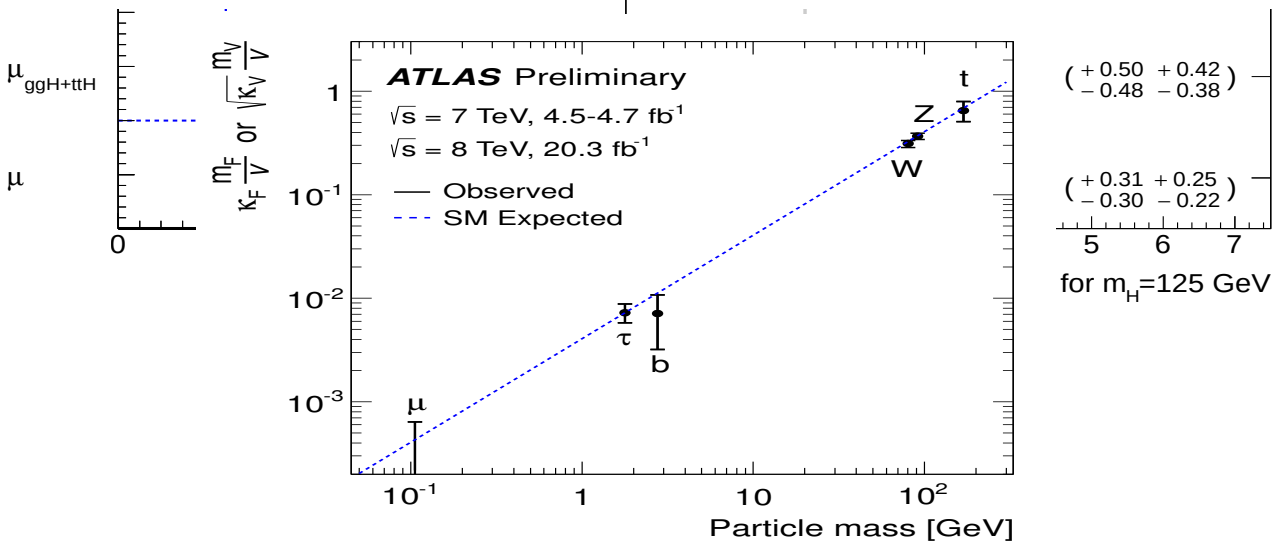
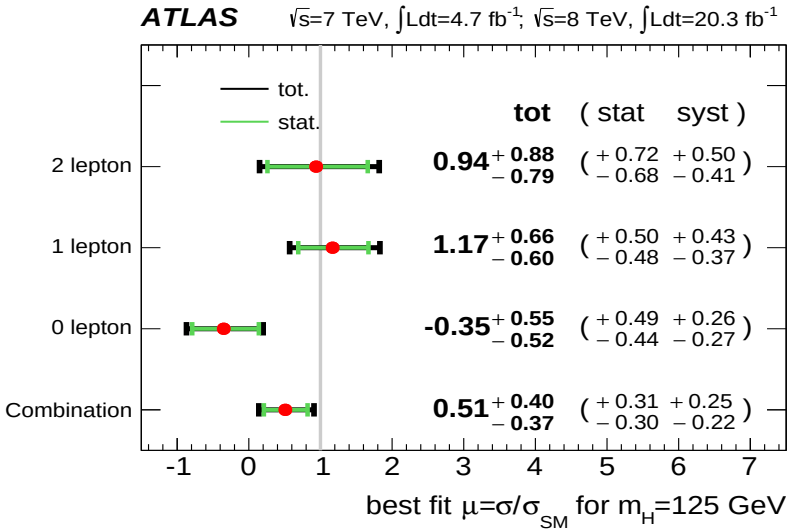
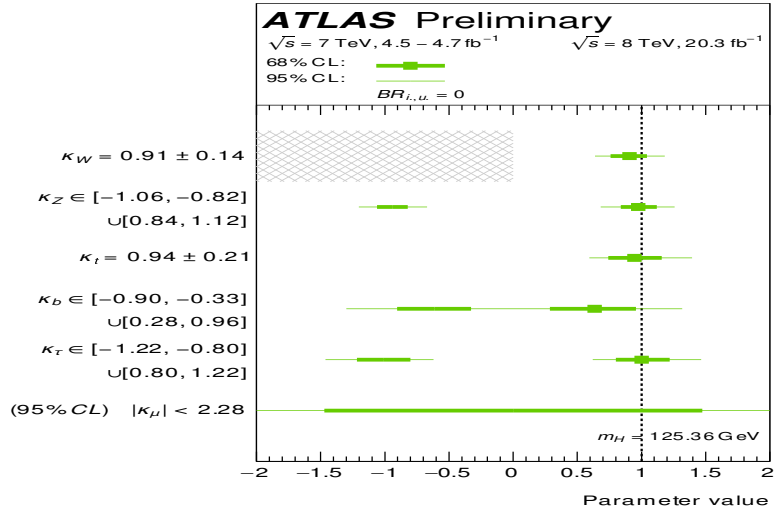
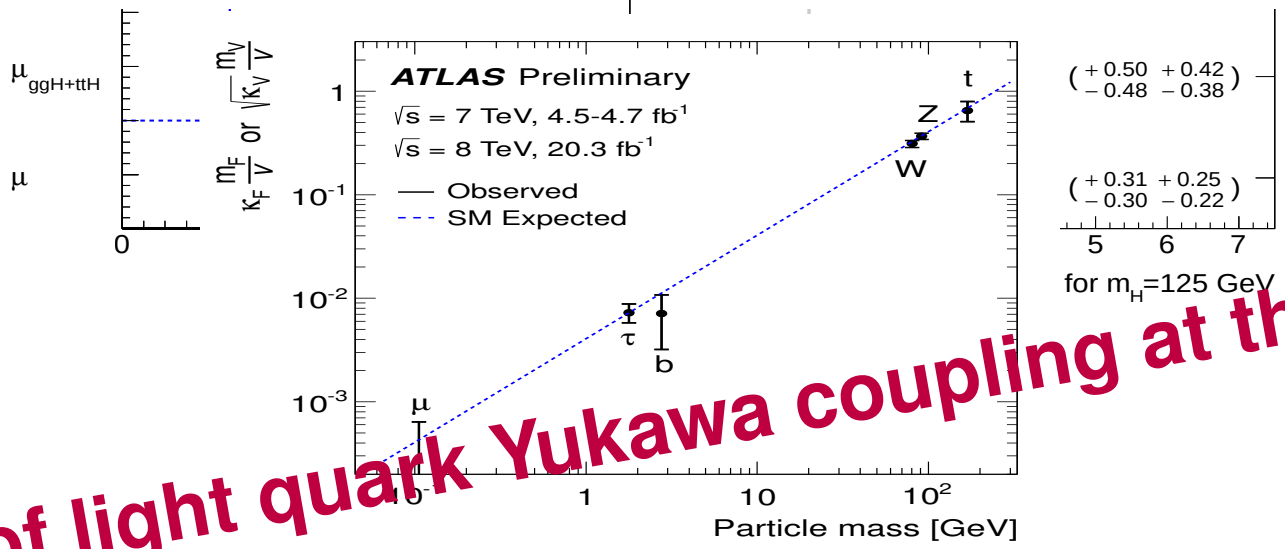

μ_ggH+ttH
μ
ATLAS Preliminary
√s = 7 TeV, 4.5-4.7 fb⁻¹
√s = 8 TeV, 20.3 fb⁻¹
Observed
SM Expected
t
Z
W
τ
b
μ
Particle mass [GeV]
for m_H=125 GeV

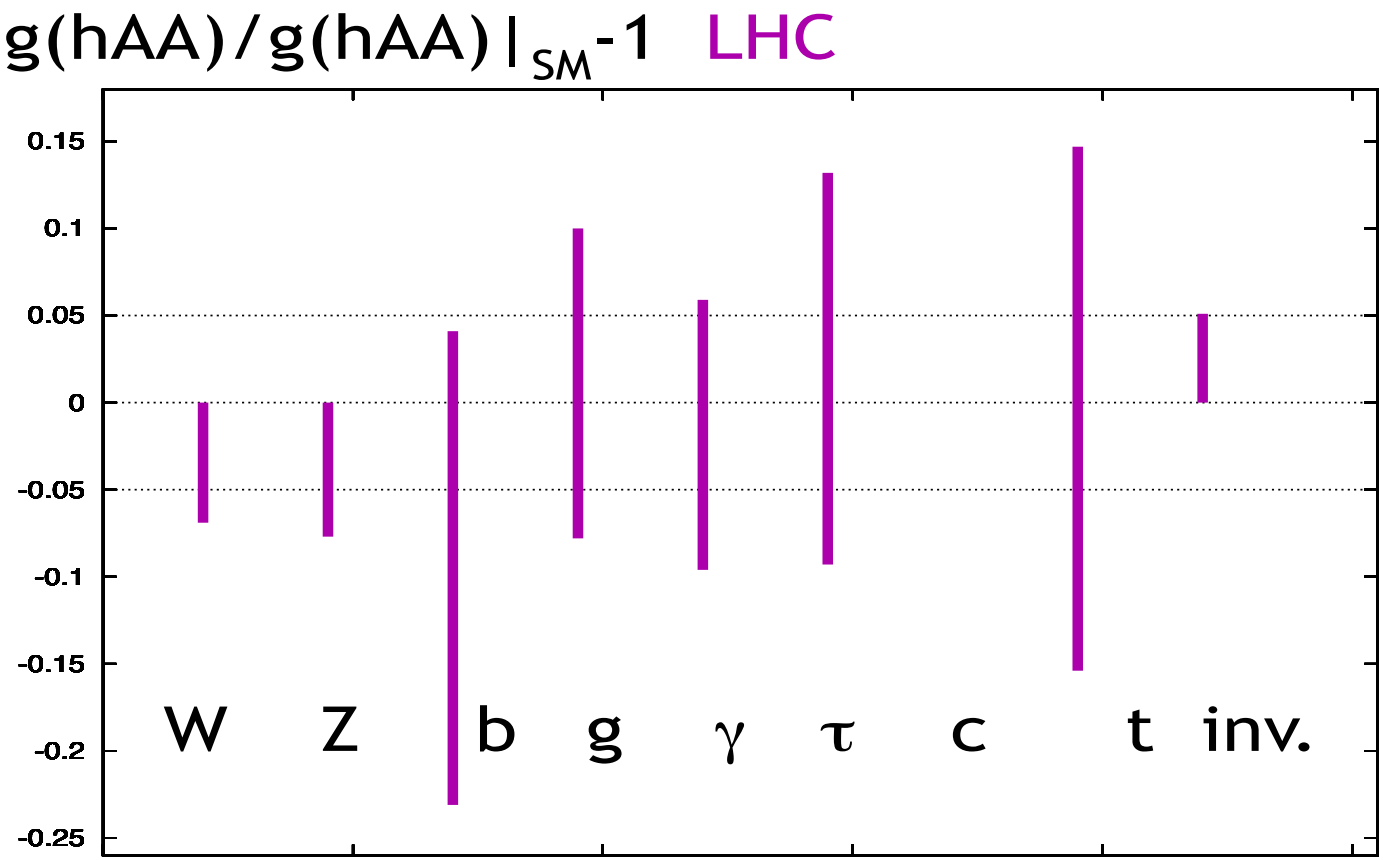






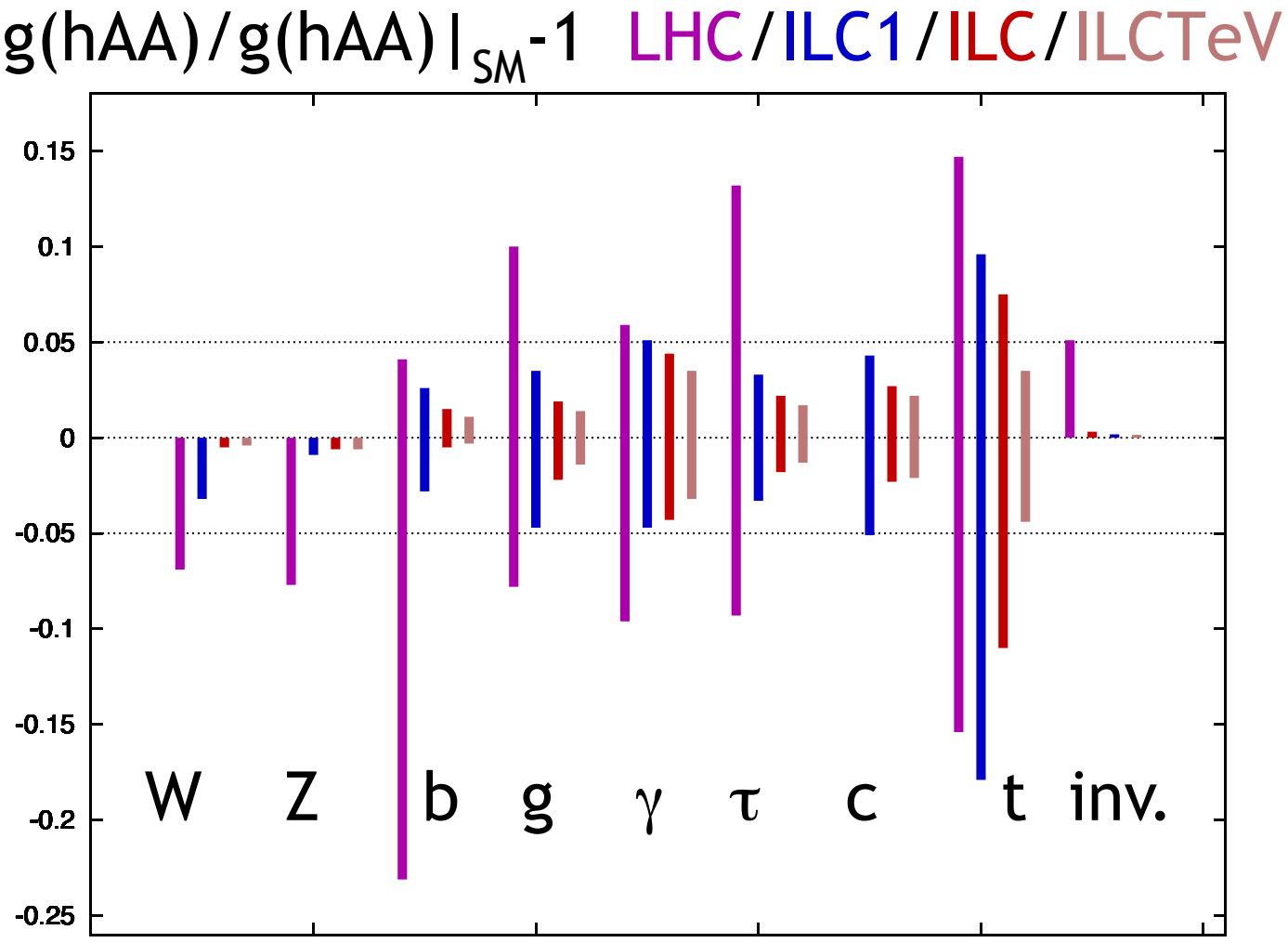
Future of light quark Yukawa coupling at the LHC ?

[Peskin, arXiv:1207.2516]



Capabilities of 14 TeV LHC with 300 fb^{-1} for model-independent measurements of Higgs boson couplings

Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs Boson couplings. 14 TeV, 300 fb^{-1}/250 GeV, 250 fb^{-1}/500 GeV, 500 fb^{-1}/1 TeV, 1000 fb^{-1} [Peskin, arXiv:1207.2516]



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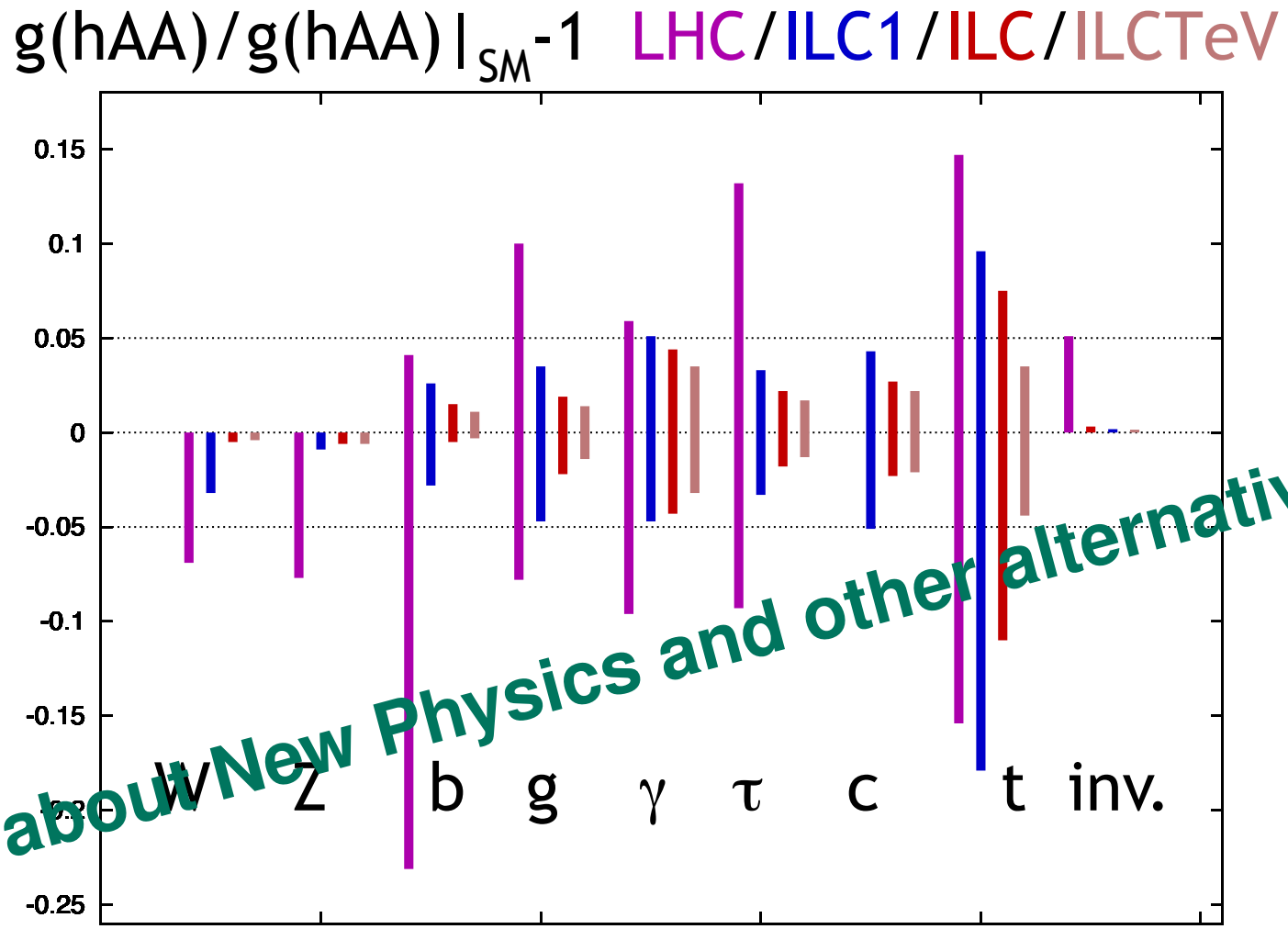

What about New Physics and other alternatives ?

Outline

- Current/Expected status of y_c, y_b at the LHC

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- Rare exclusive Higgs decay to a quarkonium and γ or Z final state

1. $h \to V\gamma$ $(V = J/\Psi, \Upsilon(nS))$ [Konig et.al. (1505.03870, 1609.06310), Bodwin et.al. 1306.5770]

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2. $h \to PZ$ $(P = \eta_c, \eta_b)$
3. $h \to Pl^+l^-$
   D.Becirevic, B.Melic, MP, O.Sumensari [1704.$\times\times\times\times\times$]

$h \to q\bar{q},\ q = c, b$

- Challenges faced by the LHC
  - Yukawa coupling $\propto m_q$, SM branching ratios very small
  - Huge QCD background
  - Requires tagging to identify the flavour of the final state quark

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c tag recently used at the LHC for exclusive SUSY searches,
$(\tilde{t}\tilde{t}^*),\ \tilde{t} \to c\chi_0,\ (\tilde{c}\tilde{c}^*)\ \tilde{c} \to c\tilde{\chi}$ [ATLAS arXiv:1501.01325, ATLAS-CONF-2013-063]

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- Different modes of measurement
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    1. Possible for b (Vh ($Vb\bar{b}$), hjj ($b\bar{b}jj$)) and c final state, limited by the $b,\ c$ tagging
    2. Large statistics at the LHC

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    1. $h \to V\gamma$ (V : vector meson), $h \to MZ$ (M : vector or pseudoscalar meson)
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Methods to constrain $\kappa_c = y_c/y_c^{\rm SM}$

- Recasting the vector-boson associated production, $Vh,\ h \to b\bar{b}$ [Perez, Soreq, Stamou, Tobioka arXiv:1503.00290]

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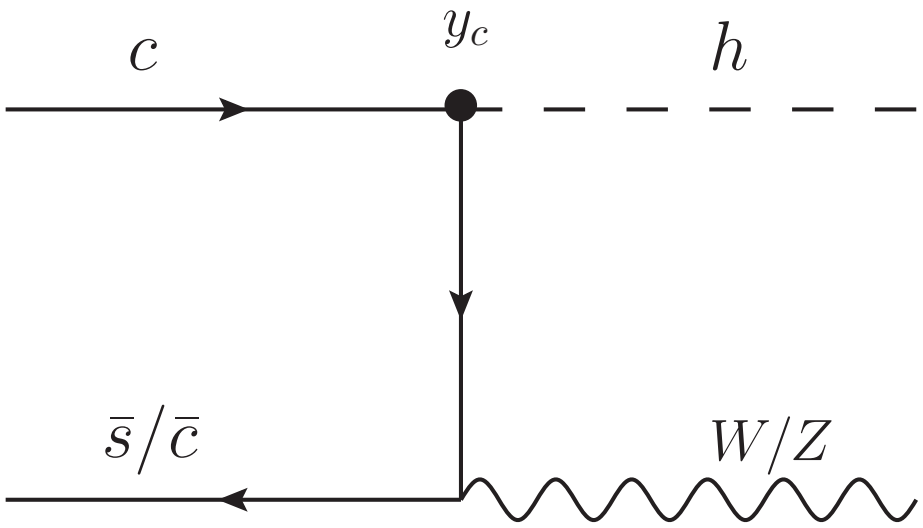
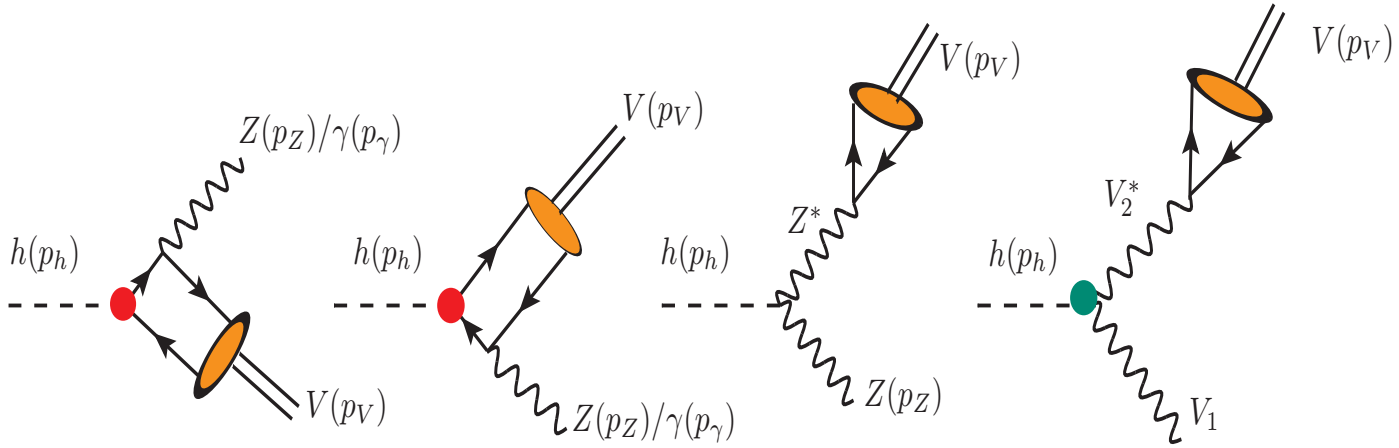


Diagram that modifies Vh production when the charm-quark Yukawa is enhanced, $\kappa_c \leq 234$ at 95% CL

- 95% CL allowed range for the charm Yukawa from a global analysis of the Higgs data, $\kappa_c \leq 6.2$

$h \to V\gamma$ ($V = J/\Psi, \Upsilon(nS)$)



Leading-order diagrams contributing to the decays $h \to VZ/\gamma$. Last graph contributes to one loop SM diagrams, $h \to Z\gamma, \gamma\gamma$

- "Direct" contribution calculated using the QCD factorization approach
- Expressed as a convolution of the calculated hard scattering amplitude with the Light Cone Distribution Amplitude of V
- "Indirect" contribution, meson is formed from an off-shell γ/Z through a local matrix element

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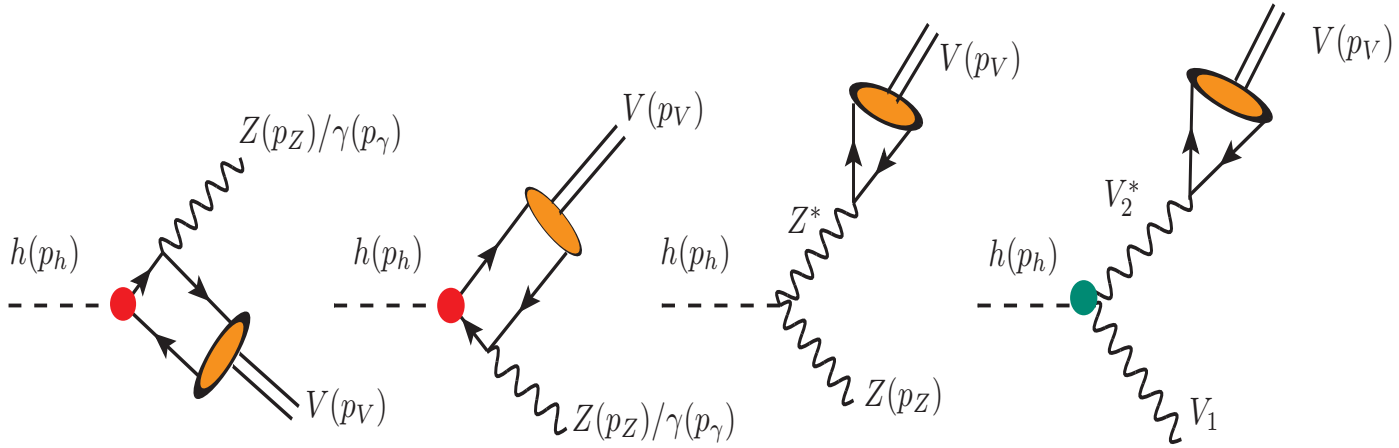

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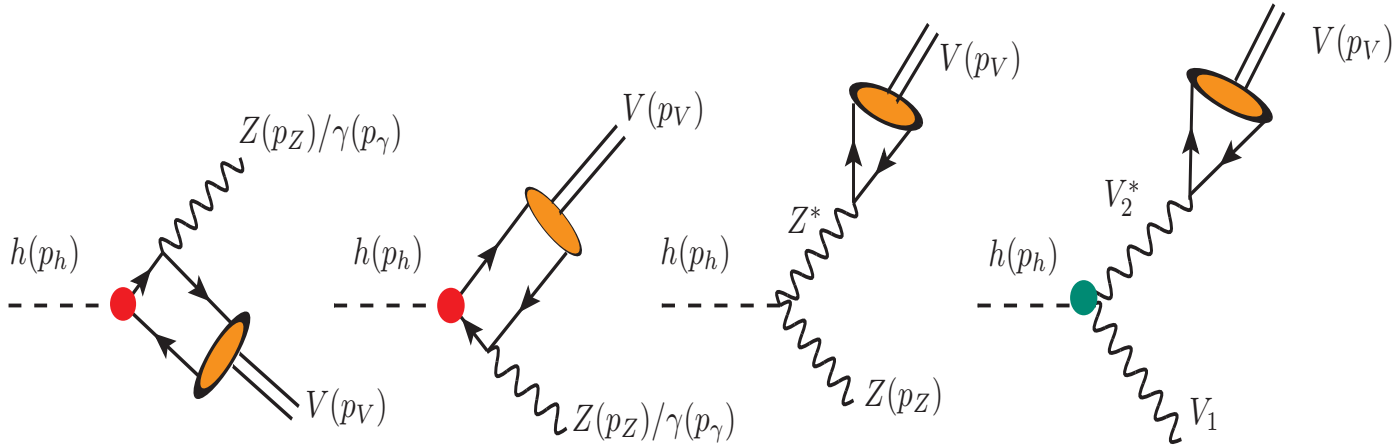
- Expressed as a convolution of the calculated hard scattering amplitude with the Light Cone Distribution Amplitude of V
- "Indirect" contribution, meson is formed from an off-shell γ/Z through a local matrix element
- Interplay between direct and indirect contributions, leads to a strong sensitivity on the quark Yukawa couplings

$h \to V\gamma$ ($V = J/\Psi, \Upsilon(nS)$)



Leading-order diagrams contributing to the decays $h \to VZ/\gamma$. Last graph contributes to one loop SM diagrams, $h \to Z\gamma, \gamma\gamma$

- The decay amplitude of the Higgs into V and γ is

$$\mathcal{M}(h \to V\gamma) = \frac{e}{v}\left(\epsilon_V^{\perp *} \cdot \epsilon_\gamma^{\perp *}\right) F_\perp^{V\gamma}, \qquad \boxed{F_\perp^{V\gamma} = F_{\perp(D)}^{V\gamma} + F_{\perp(ID)}^{V\gamma}}$$

$$= \frac{e}{v}\left(\epsilon_V \cdot \epsilon_\gamma - \frac{1}{p_V \cdot p_\gamma}(p_V \cdot \epsilon_\gamma)(p_\gamma \cdot \epsilon_V)\right) F_\perp^{V\gamma}$$

$h \to V\gamma$ ($V = J/\Psi, \Upsilon(nS)$)

$$\Gamma(h \to V\gamma) = \frac{\alpha}{4 m_h v^2}(1 - r_V)|F_\perp^{V\gamma}|^2$$

$$F_{\perp(D)}^{V\gamma} = Q_q \frac{\kappa_q m_q}{m_h^2}\left[f_V^\perp\,(3m_h^2 + 2m_V^2)\right]$$

$$F_{\perp(ID)}^{V\gamma} = \frac{\alpha}{\pi}\frac{m_h^2 - m_V^2}{2m_V} f_V^\perp \left[Q_q C_{\gamma\gamma}(p_{\gamma^*}^2) - \frac{g_V^q}{2 s_W c_W}\frac{m_V^2}{m_Z^2 - m_V^2} C_{\gamma Z}(p_{Z^*}^2)\right]$$

$h \to V\gamma$ ($V = J/\Psi, \Upsilon(nS)$)

- The direct and the indirect contributions to $h \to V\gamma$ decay amplitude interfere destructively in the SM [Konig, Neubert, arXiv:1505.03870]

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$$\mathcal{B}(h \to J/\Psi, \gamma) = 1.5 \times 10^{-3},$$
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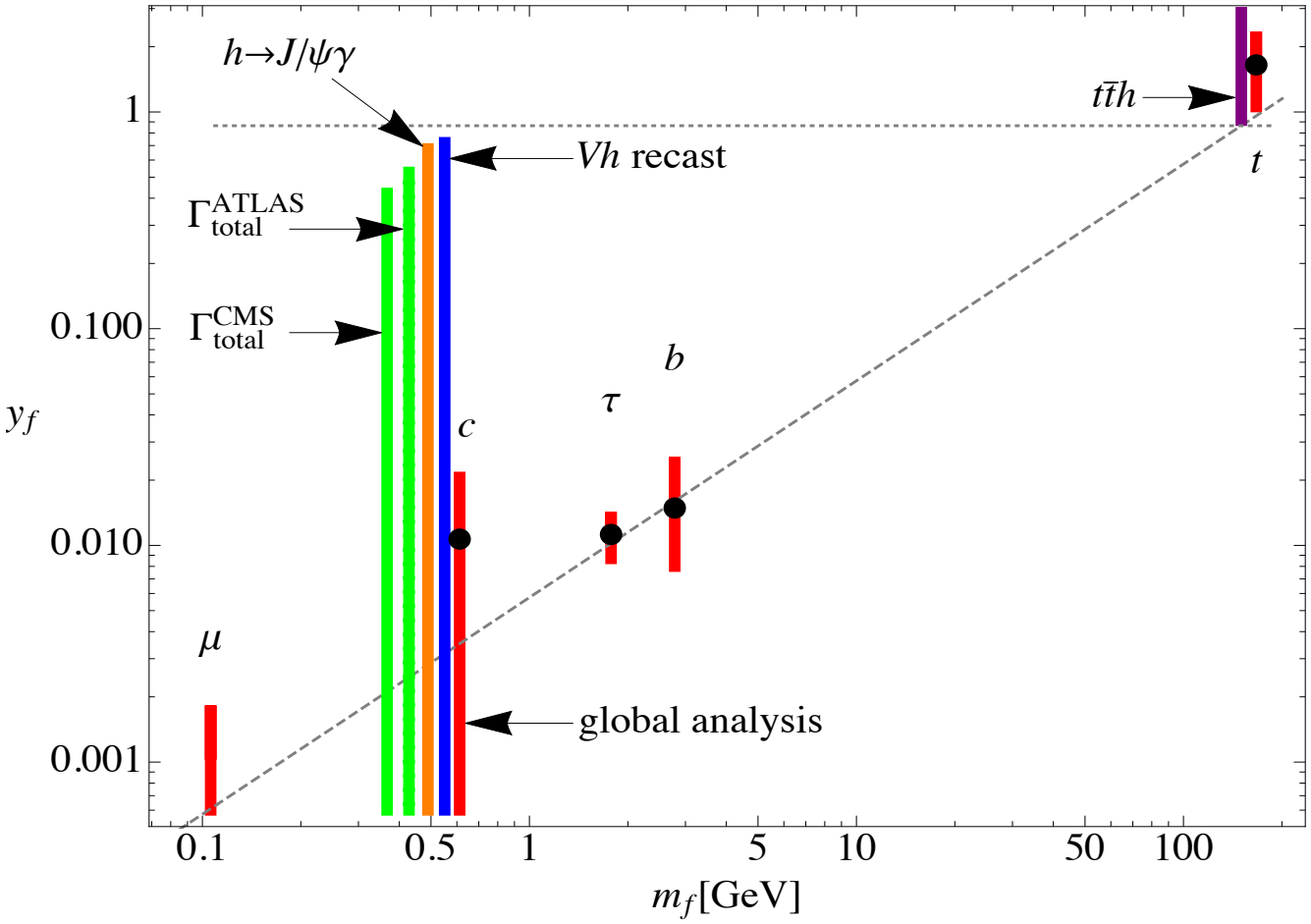
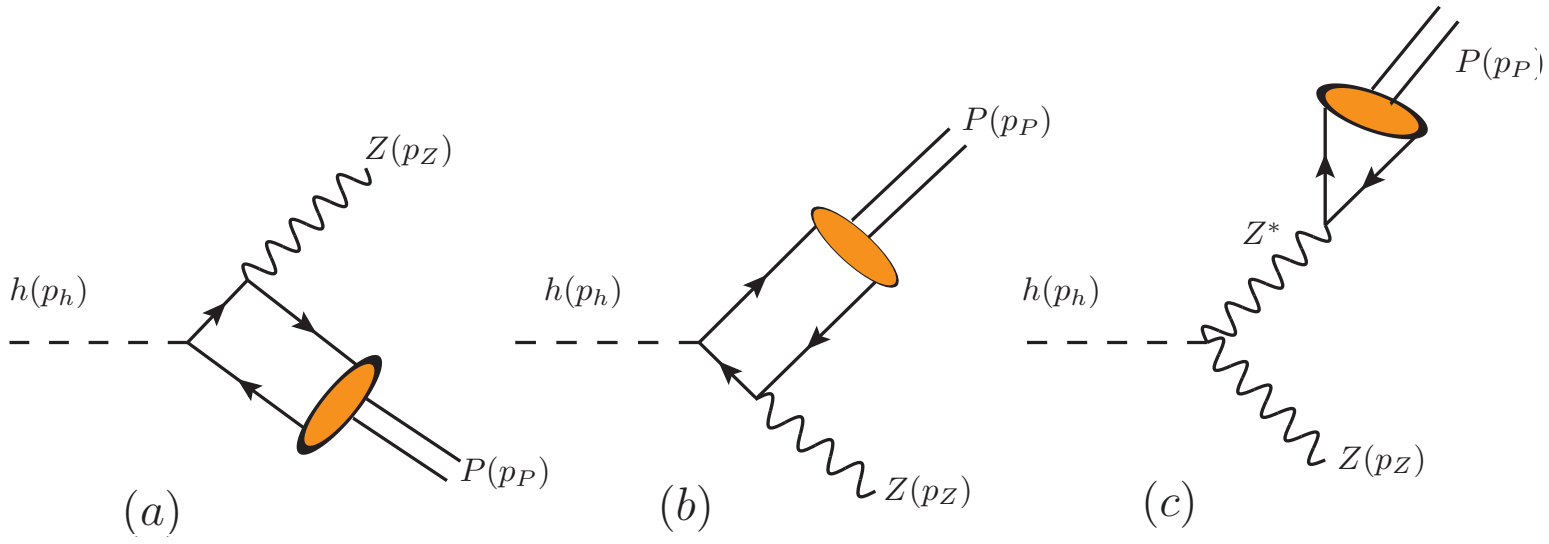
$\kappa_c < 429, \quad \kappa_b < 78$



[Perez, Soreq, Stamou, Tobioka arXiv:1503.00290]

$h \to PZ$ $(P = \eta_c, \eta_b)$



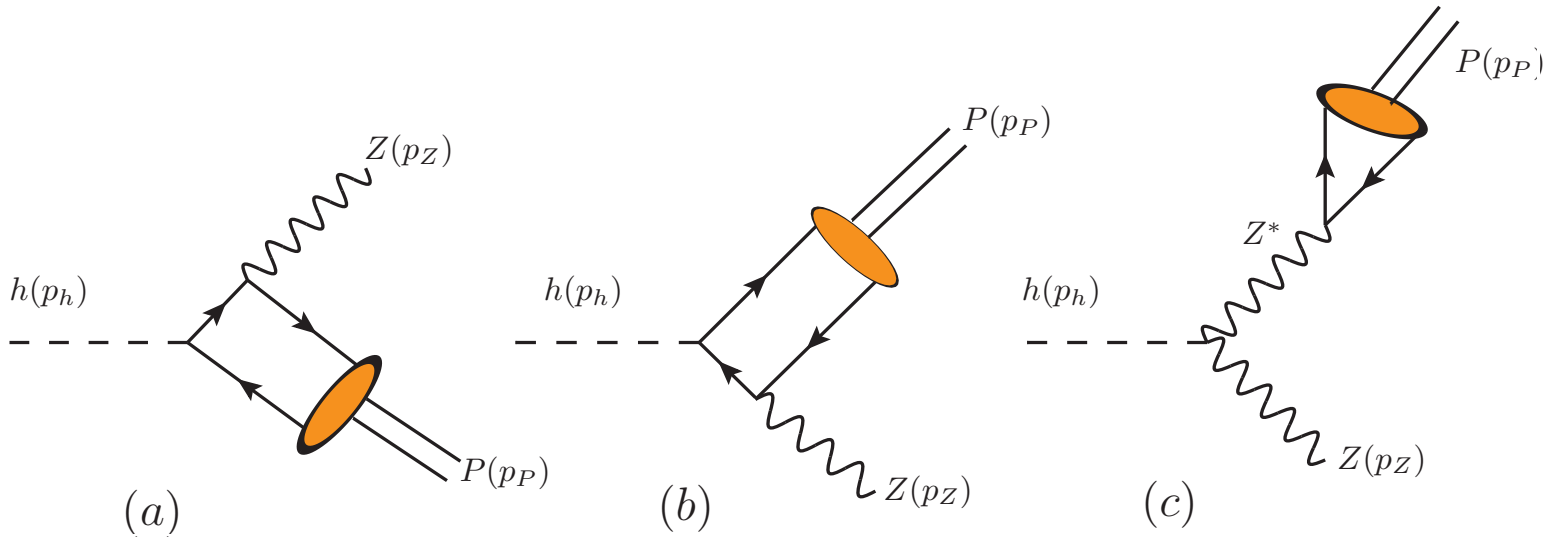
$$\Gamma(h \to PZ) = \frac{1}{16\pi v^4 m_h^3} \lambda^{3/2}(m_h^2, m_Z^2, m_P^2) |F^{PZ}|^2, \qquad \lambda(x,y,z) = (x-y-z)^2 - 4yz$$

$$F_D^{PZ} = -f_P\, g_A^q \left[m_P^2 - 3m_q^2\right] \frac{m_h^4 - m_Z^4 + 4m_Z^2 m_h^2 \ln \frac{m_Z}{m_h}}{(m_h^2 - m_Z^2)^3}$$

$$F_{ID}^{PZ} = -\frac{m_Z^2}{m_Z^2 - m_P^2} f_P\, g_A^q$$

$$\mathcal{B}(h \to \eta_c Z)|_{\rm SM} \approx (1.08 \pm 0.01) \times 10^{-5}, \quad \mathcal{B}(h \to \eta_b Z)|_{\rm SM} \approx (2.97 \pm 0.05) \times 10^{-5}$$

$h \to PZ$ $(P = \eta_c, \eta_b)$



- The strong suppression of the direct contributions sensitive to y_c, y_b, makes **h** $\to \eta_{\mathbf{b,c}}$**Z** unsuitable for searches for new-physics effects on light quark Yukawa couplings
- The theoretical calculation of these decay rates yields highly accurate predictions, subject to electroweak corrections only
- Could serve as a standard channel to look for effects from models giving additional contribution to **h** $\to \eta_{\mathbf{b,c}}$**Z**

Two Higgs Doublet Model Potential : Ideal Candidate?

Most general $SU(2) \times U(1)$ potential

$$V(\Phi_1, \Phi_2) = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 + m_{12}^2 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 \Phi_1^\dagger \Phi_1 \Phi_2^\dagger \Phi_2 + \lambda_4 \Phi_1^\dagger \Phi_2 \Phi_2^\dagger \Phi_1 + \frac{\lambda_5}{2} \left[(\Phi_1^\dagger \Phi_2)^2 + (\Phi_2^\dagger \Phi_1)^2 \right]$$

Most frequently studied model : softly broken with a $\mathbb{Z}_2$ symmetry $(\Phi_1 \to \Phi_1,\ \Phi_2 \to -\Phi_2)$

- Type I : All the fermions couple to only Φ_2
- Type II : The up-type quarks couple to Φ_2, whereas the down type quarks and the leptons couple to Φ_1
- Type X : All the quarks couple to Φ_2, whereas all the leptons couple to Φ_1 ('lepton specific')
- Type Z : The up-type quarks and the leptons couple to Φ_2, whereas the down-type quarks couple to Φ_1 ('flipped')

Scalar sector of the 2HDM is richer !

2 CP-even Higgs : $h,\ H$
1 CP-odd Higgs : A
A pair of charged Higgs : $H^{\pm}$

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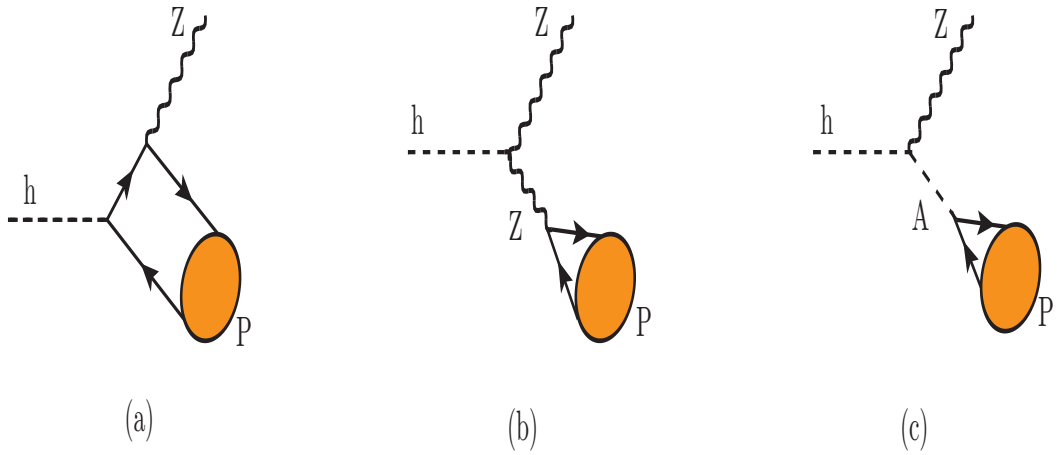

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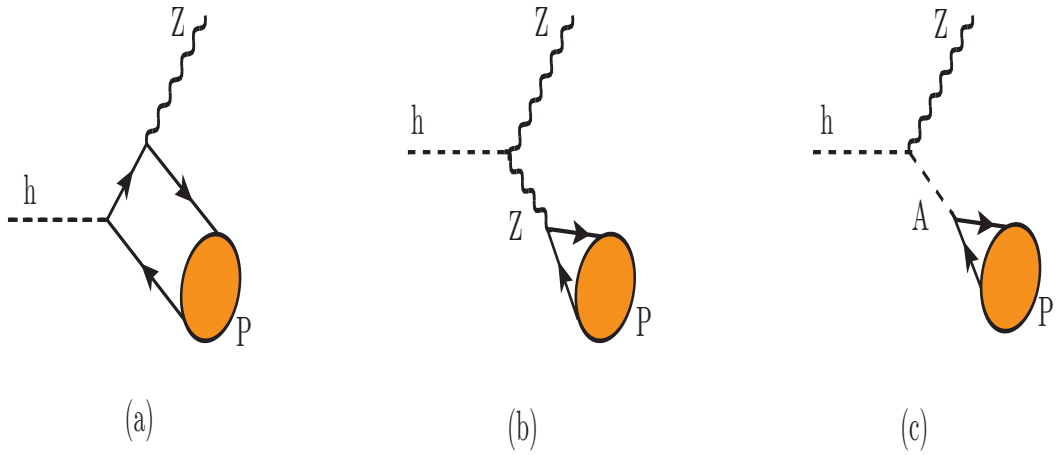

$$F_{NP}^{PZ} = \frac{f_P}{m_A^2 - m_P^2 + i m_A \Gamma_A} \frac{m_P^2}{2} \xi_A^q \cos(\beta - \alpha),$$

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Model	ξ_A^d	ξ_A^u	ξ_A^ℓ
Type I	$-\cot\beta$	$\cot\beta$	$-\cot\beta$
Type II	$\tan\beta$	$\cot\beta$	$\tan\beta$
Type X (lepton specific)	$-\cot\beta$	$\cot\beta$	$\tan\beta$
Type Z (flipped)	$\tan\beta$	$\cot\beta$	$-\cot\beta$

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Scanning the 2HDM parameter space

$$\tan\beta \in (0.2, 50), \qquad \alpha \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right), \qquad \left|M^2\right| \leq (1.2\ \mathrm{TeV})^2,$$

$$m_{H^\pm} \in (m_W, 1.2\ \mathrm{TeV}), \qquad m_H \in (m_h, 1.2\ \mathrm{TeV}), \qquad m_A \in (20\ \mathrm{GeV}, 1.2\ \mathrm{TeV})$$

- Concentrating on the alignment limit, $|\cos(\beta - \alpha)| \leq 0.3$

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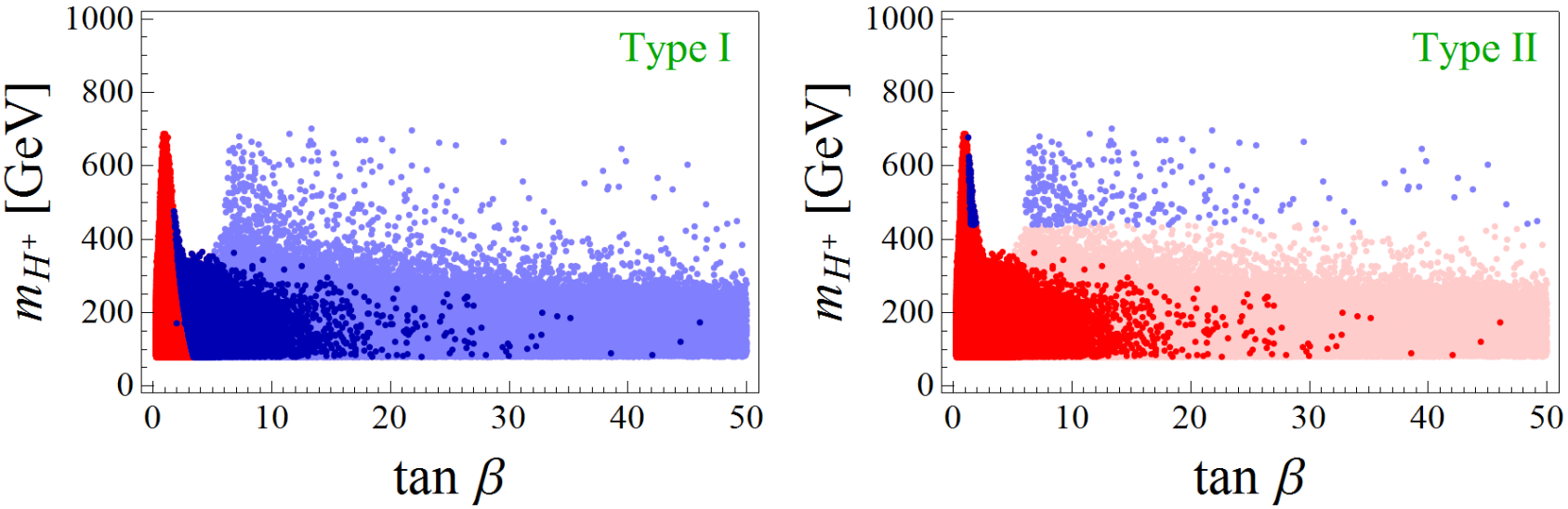
- Concentrating on the alignment limit, $|\cos(\beta - \alpha)| \leq 0.3$
- Constraint from $\Gamma_h/\Gamma_h^{\mathrm{SM}} \geq 4.2$ due to the additional decay channel provided $m_A \leq m_h/2$

$$\Gamma(h \to AA) = \frac{|\lambda_{hAA}|^2}{32\pi}\frac{v^2}{m_h}\sqrt{1 - \frac{4m_A^2}{m_h^2}}$$

$$\Gamma(h \to ZA) = \frac{1}{16\pi}\frac{\cos^2(\beta - \alpha)}{m_h^3 v^2}\lambda^{3/2}(m_h, m_Z, m_A)\,.$$

Results of the scan of parameters after imposing theoretical and experimental constraints. Darker/lighter points correspond to the *free*/*fine-tuned* scan. Red points are forbidden by the flavor bounds



- Moderate and small values of $\tan\beta \in (0.2, 15]$ favored
  Fine tuning scans designed to focus on "hard to reach" regions with $m_H \approx |M|$
- Strongly constrained by measurements of the inclusive radiative B-meson decay branching ratio ($B \to X_s\gamma,\ b \to s\mu\mu$) [Arnan et.al. arXiv:1703.03426]
- In Type I models, constraints are obtained only for $\tan\beta \leq 4$
- In Type II models, bounds are $\tan\beta$ independent and constrains $m_H^{\pm} \geq 439$ GeV

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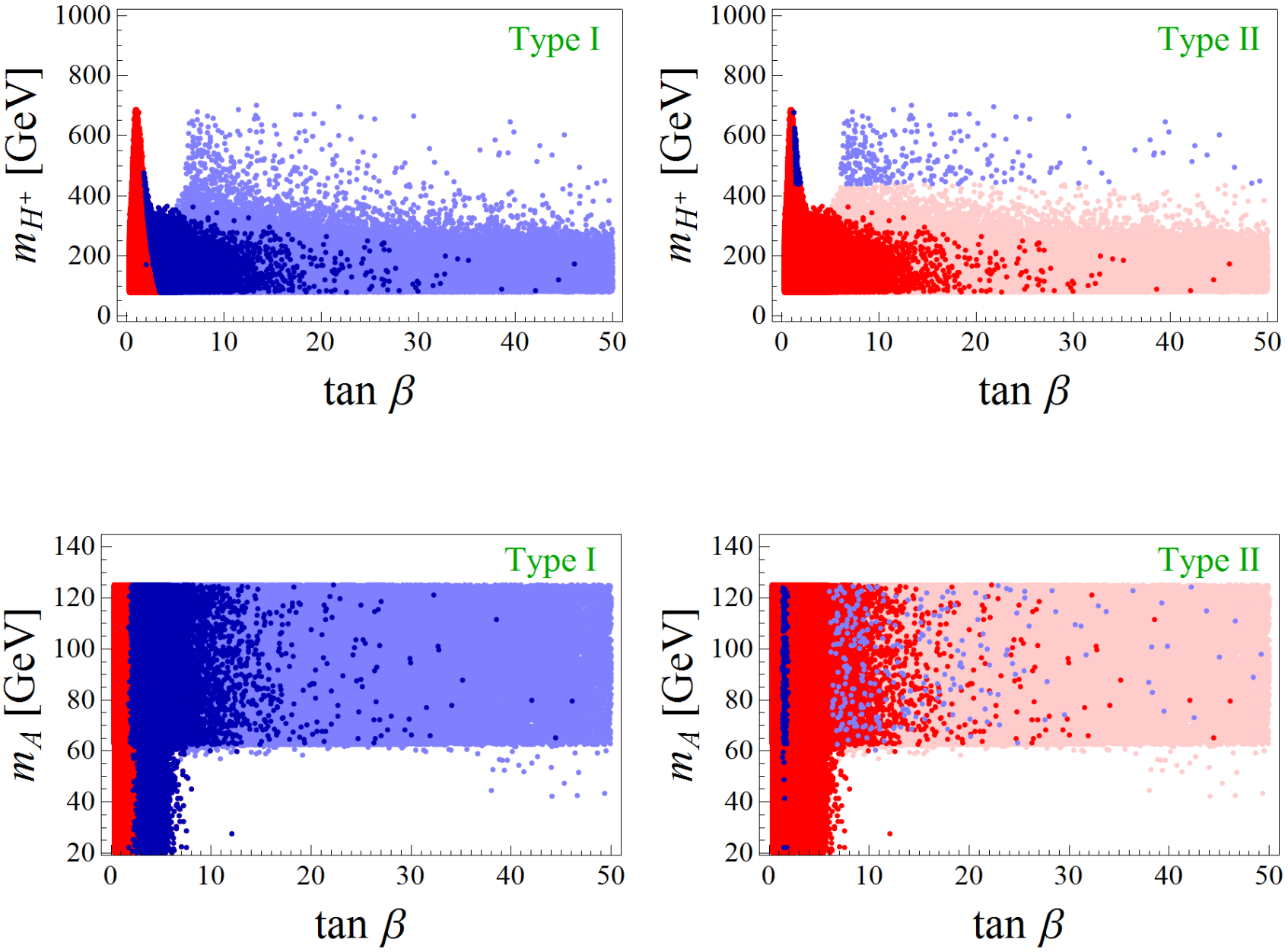

Exclusive $h \to PZ$ decay

$$F_{NP}^{PZ} = \frac{f_P}{m_A^2 - m_P^2 + i m_A \Gamma_A} \frac{m_P^2}{2} \xi_A^q \cos(\beta - \alpha),$$

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Ratio	$R_{\eta_c}^Z$	$R_{\eta_b}^Z$
Type I	$(0.7, 1.0)$	$(0.7, 1.0)$
Type II	$(0.7, 1.1)$	$(0.7, 1.0)$
Type X	$(0.7, 1.0)$	$(0.7, 1.0)$
Type Z	$(0.7, 1.0)$	$(0.7, 1.0)$

Resulting intervals for the ratios obtained from the scans in various types of 2HDM.

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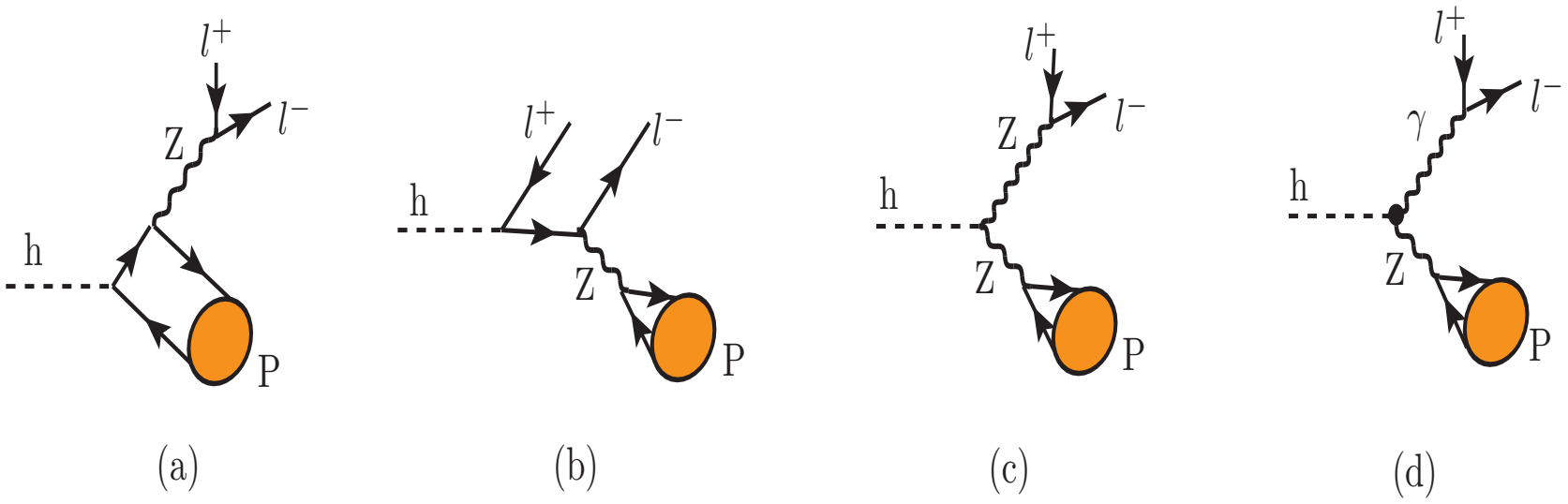
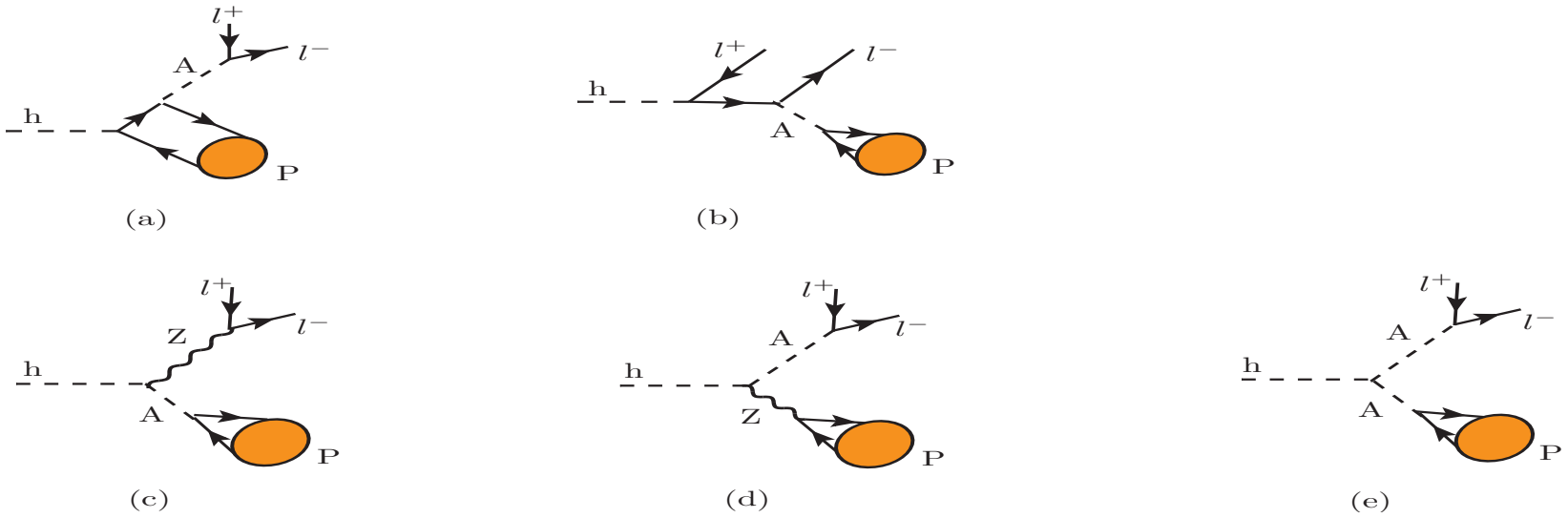
$h \to Pl^+l^-$ decay



$$\mathcal{B}(h \to \eta_c l^+ l^-)|_{\rm SM} = (3.26 \pm 0.07) \times 10^{-7}, \;\; \mathcal{B}(h \to \eta_b l^+ l^-)|_{\rm SM} = (8.67 \pm 0.06) \times 10^{-7}$$

Exclusive $h \to Pl^+l^-$ decay



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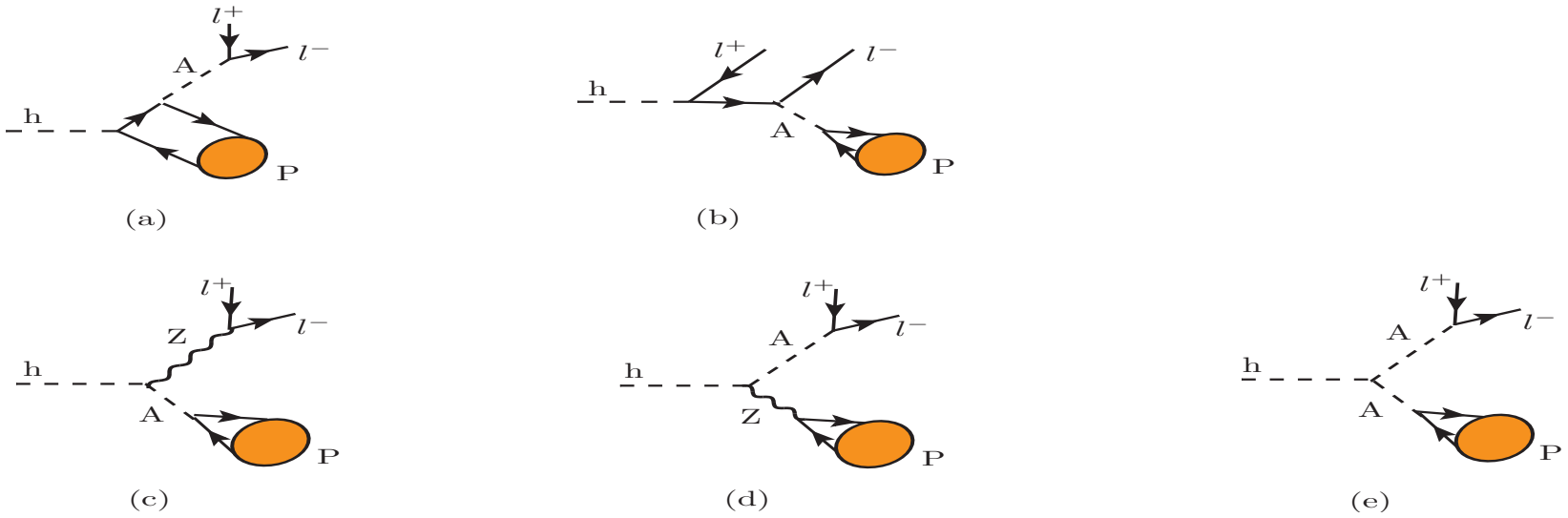

$$\Gamma(h \to PZ^* \to P\ell^+\ell^-) = \frac{f_P^2 m_Z^3}{384\pi^2 \Gamma_Z m_h^3 v^6}\left[\cos^2(2\theta_W) + 4\sin^4\theta_W\right]$$

$$\left(\underbrace{\boxed{g_A^q}}_{\text{SM}} - \frac{\xi_A^q m_P^2 \boxed{\cos(\beta-\alpha)}}{2(m_A^2 - m_P^2)}\right)^2 \lambda^{3/2}(m_h^2, m_P^2, m_Z^2),$$

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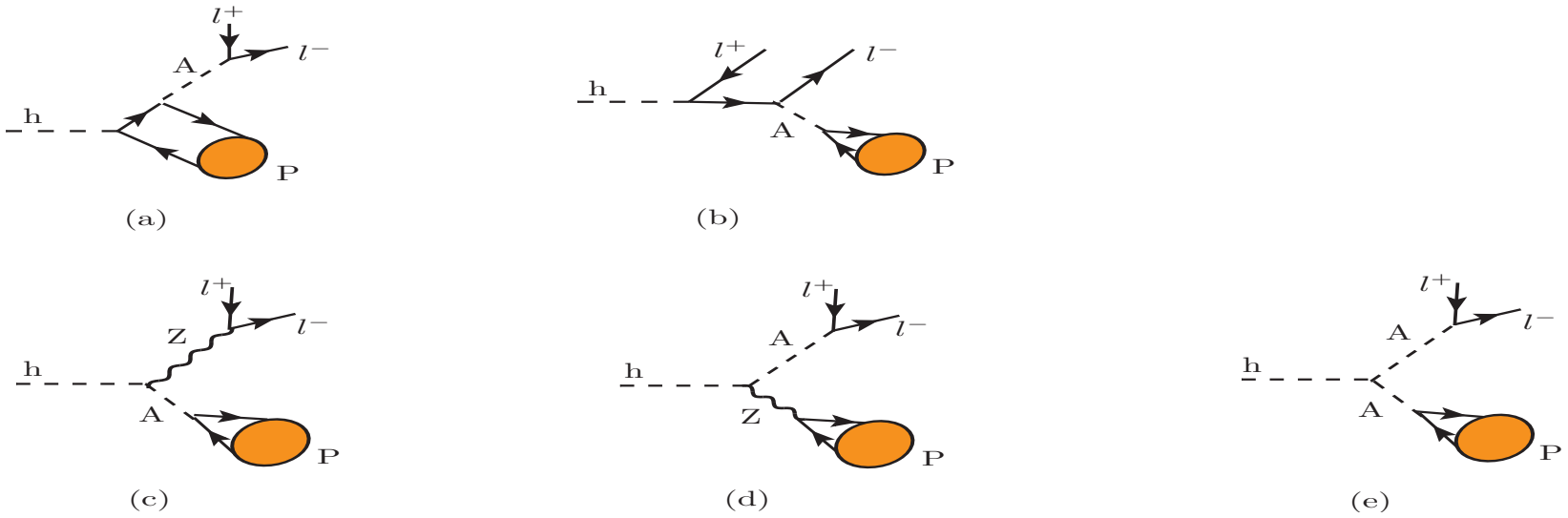

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$$\Gamma(h \to PA^* \to P\ell^+\ell^-) = \frac{f_P^2 m_A}{512\pi^2 \Gamma_A m_h^3 v^2}\left(\frac{m_\ell \xi_A^\ell}{v}\right)^2 \left[\boxed{\lambda_{hAA}} \frac{m_P^2}{m_A^2 - m_P^2}\frac{\xi_A^q}{v} v^2\right.$$

$$\left. + 2\boxed{\cos(\beta-\alpha)}\frac{g_A^q}{v}(m_h^2 - m_A^2)\right]^2 \lambda^{1/2}(m_h^2, m_P^2, m_A^2).$$

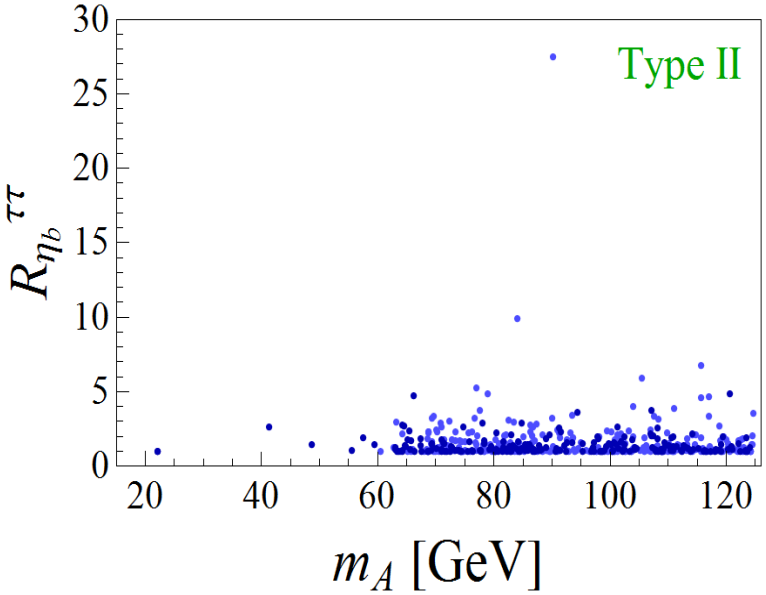
$$R^{\tau\tau}_{\eta_{cb}} = \frac{\mathcal{B}(h \to \eta_{cb}\tau^+\tau^-)^{\rm 2HDM}}{\mathcal{B}(h \to \eta_{cb}\tau^+\tau^-)^{\rm SM}} \ ,$$

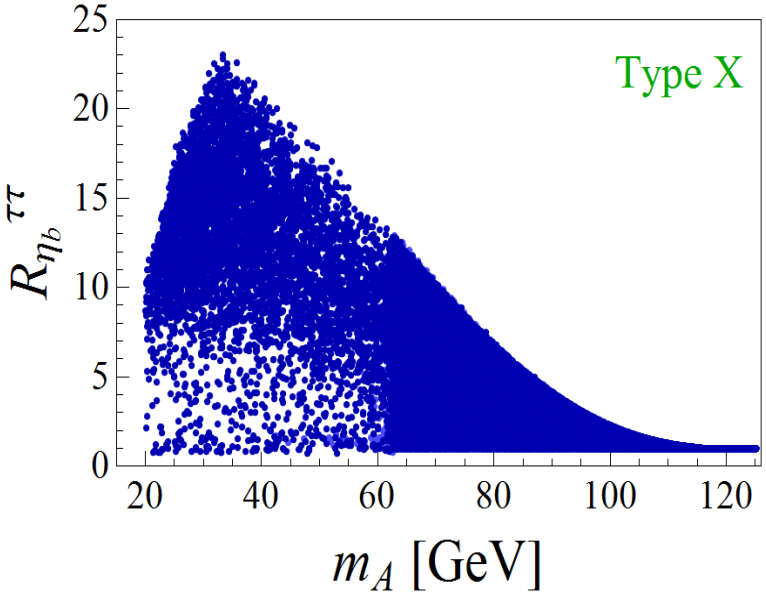
$$R^{\mu\mu}_{\eta_{cb}} = \frac{\mathcal{B}(h \to \eta_{cb}\mu^+\mu^-)^{\rm 2HDM}}{\mathcal{B}(h \to \eta_{cb}\mu^+\mu^-)^{\rm SM}} \ ,$$

Ratio	$R^{\mu\mu}_{\eta_c}$	$R^{\mu\mu}_{\eta_b}$	$R^{\tau\tau}_{\eta_c}$	$R^{\tau\tau}_{\eta_b}$
Type I	$(0.7, 1.0)$	$(0.7, 1.0)$	$(0.7, 3.3)$	$(0.7, 3.6)$
Type II	$(0.7, 1.0)$	$(0.7, 1.1)$	$(1.0, 3.2)$	$(0.9, 27)$
Type X	$(0.7, 1.1)$	$(0.7, 1.1)$	$(0.7, 20.8)$	$(0.7, 23.0)$
Type Z	$(0.7, 1.0)$	$(0.7, 1.1)$	$(0.7, 1.1)$	$(0.8, 1.2)$

Resulting intervals for the ratios obtained from the scans in various types of 2HDM

preliminary results





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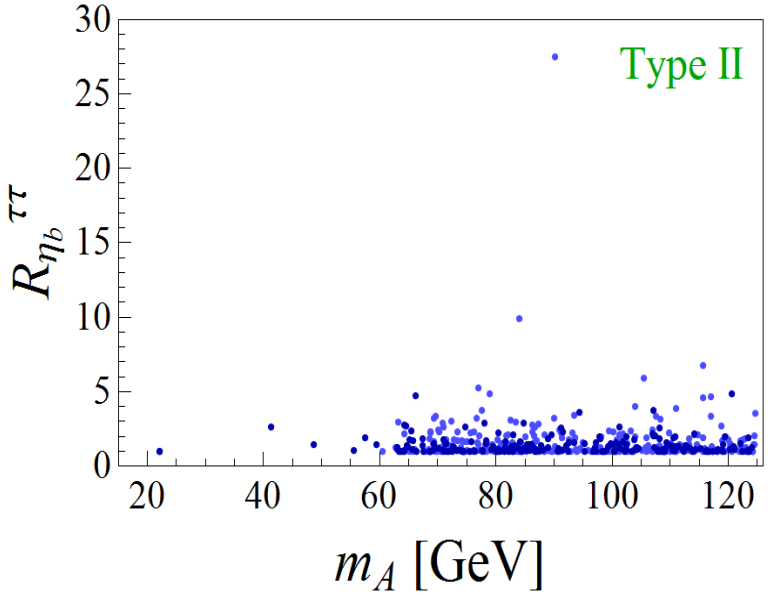

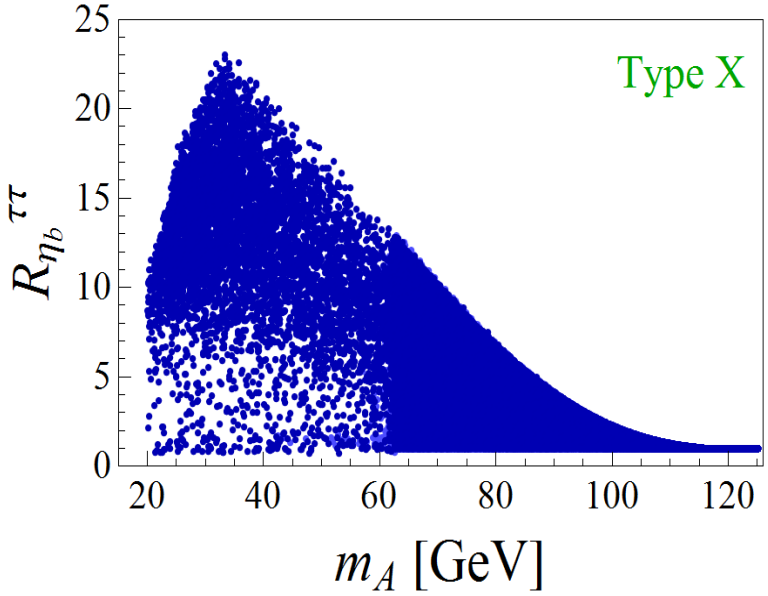

- Type II model is far more constrained than Type X because of $B \to X_s\gamma$ constraint
- Similar enhancement for $R_{\eta_b}^{\tau\tau}$, due to $\Gamma(h \to PA^* \to P\ell^+\ell^-) \propto m_\ell^2 \tan^2\beta$

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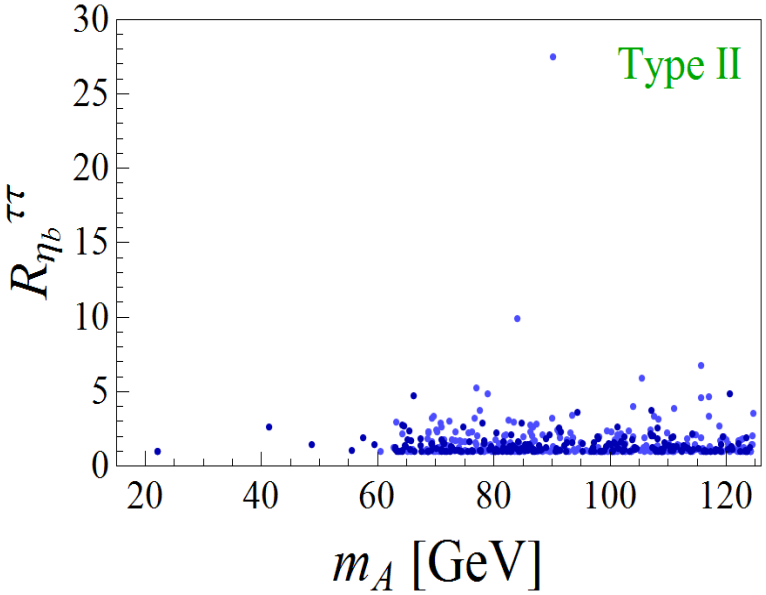
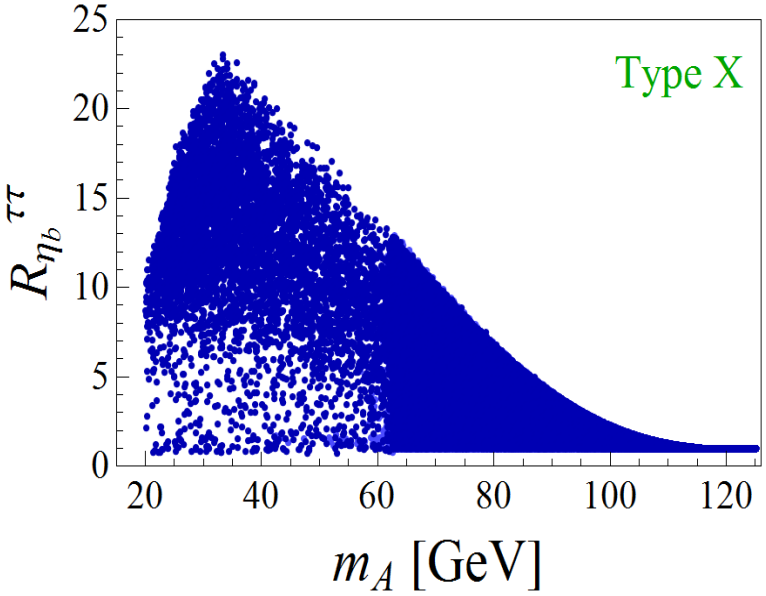
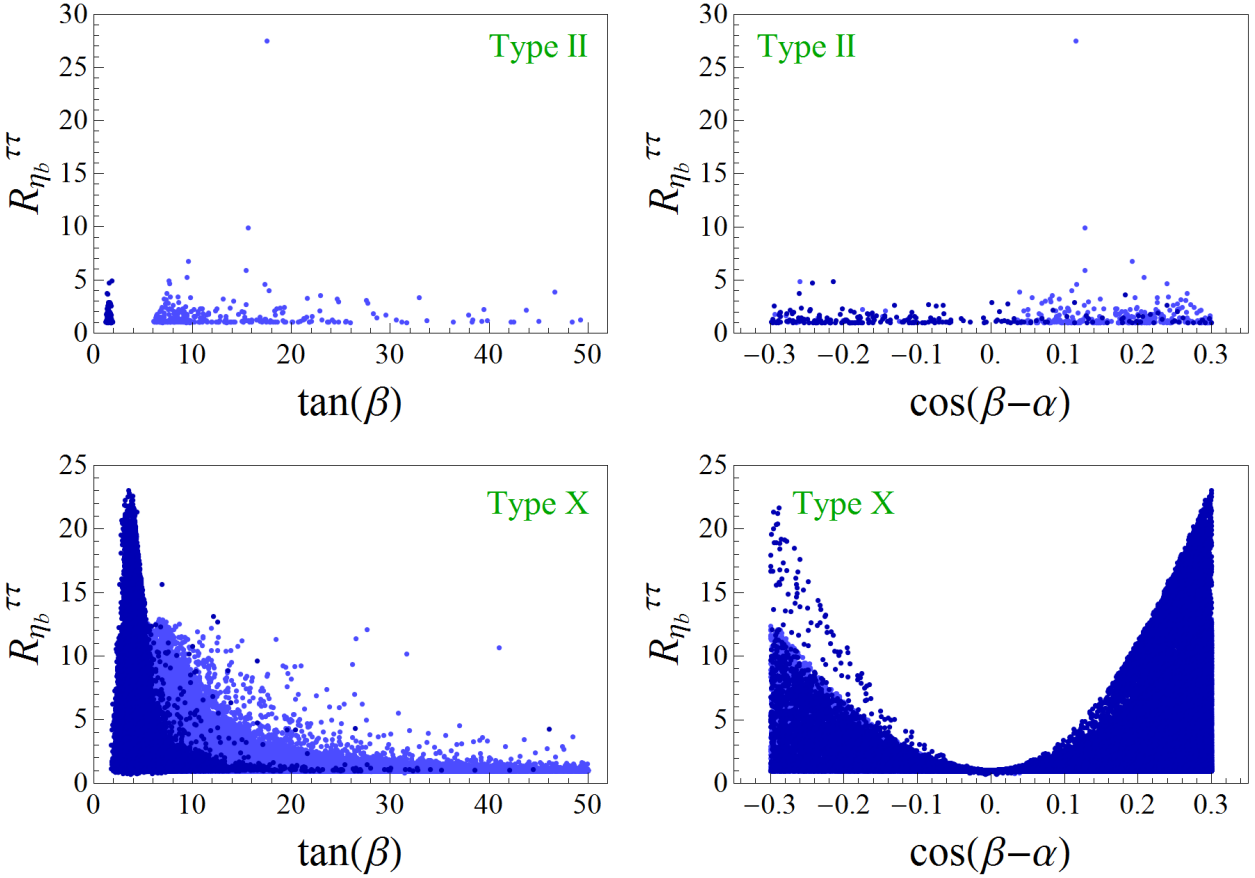


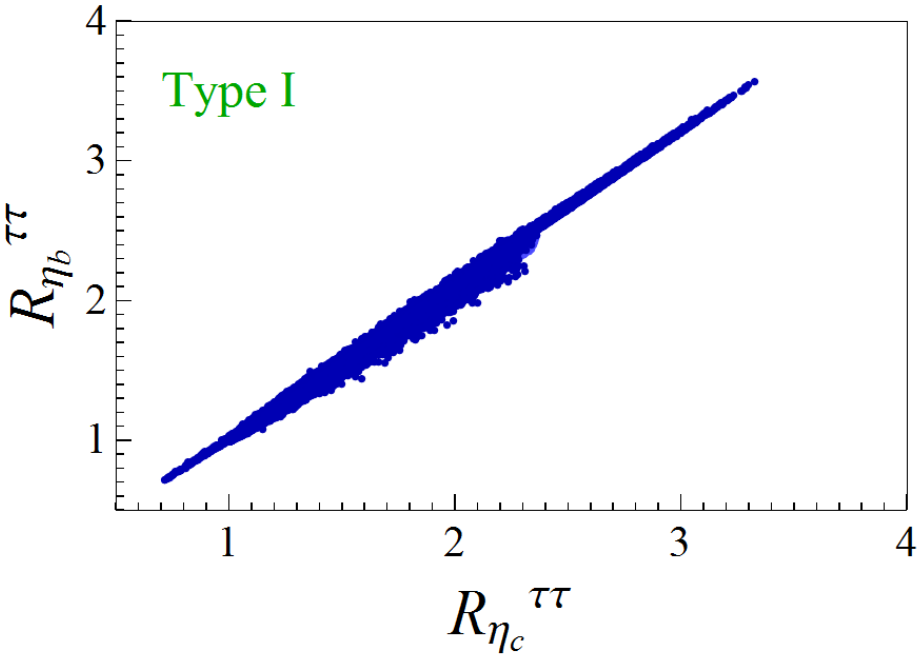


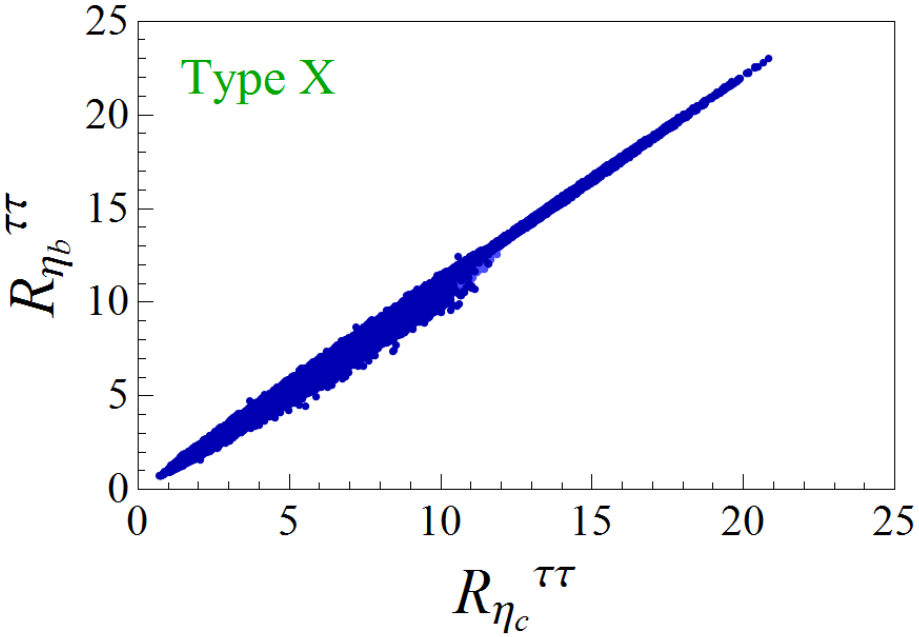
- Type II model is far more constrained than Type X because of $B \to X_s\gamma$ constraint
- Similar enhancement for $R_{\eta_b}^{\tau\tau}$, due to $\Gamma(h \to PA^* \to P\ell^+\ell^-) \propto m_\ell^2 \tan^2\beta$
- **These decay modes can serve as possible probes of the light CP-odd Higgs ($m_A \lesssim m_h$)**

preliminary results

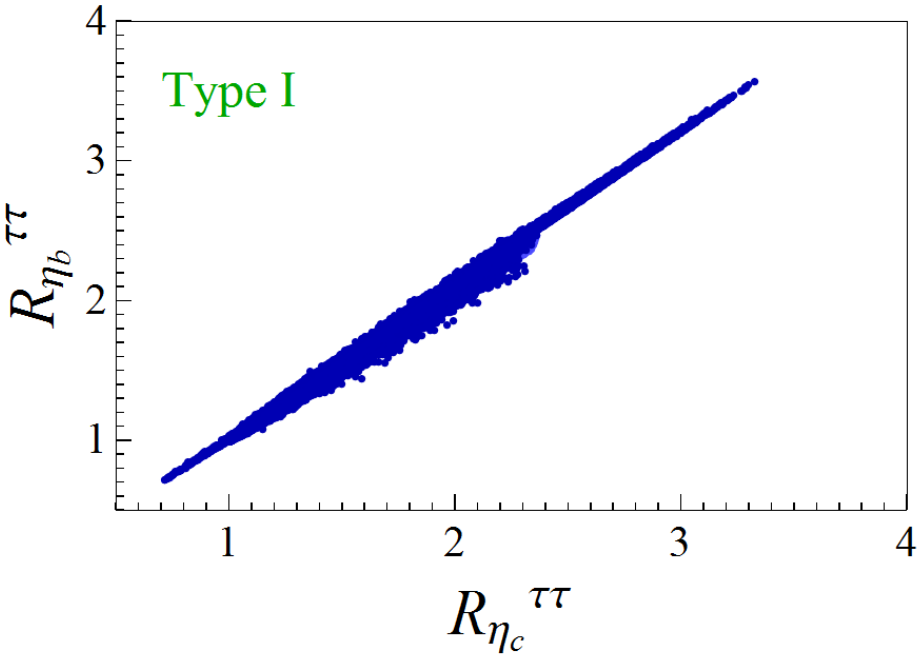


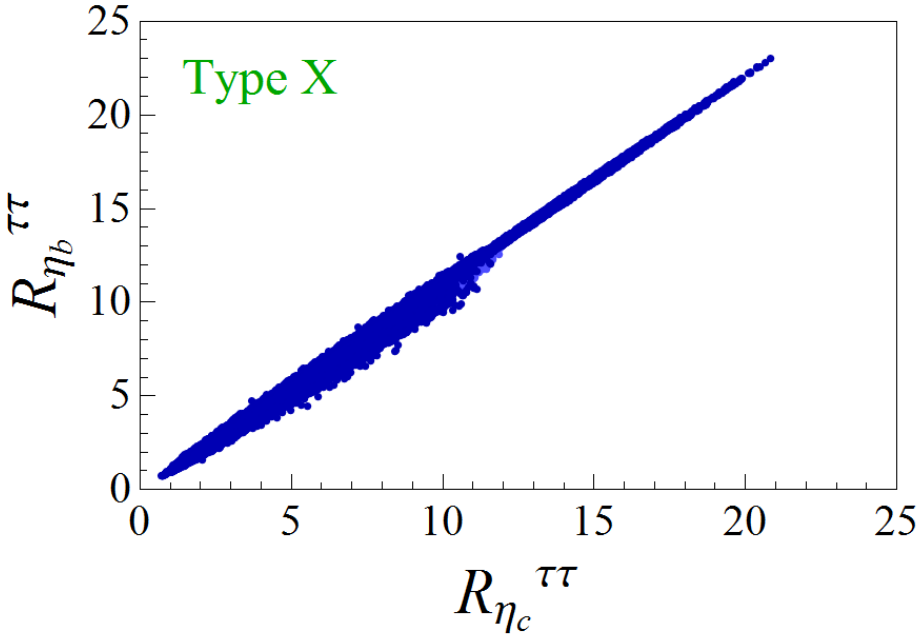
Large enhancements possible in allowed region of the parameter space, making $h \to P\ell^+\ell^-$ the ideal channel to look for CP-odd Higgs A





- Correlation of the ratios $R_{\eta_c}^{\tau\tau}$ and $R_{\eta_b}^{\tau\tau}$ in Type I and Type X models





- Correlation of the ratios $R_{\eta_c}^{\tau\tau}$ and $R_{\eta_b}^{\tau\tau}$ in Type I and Type X models
- $\Gamma(h \to PA^* \to P\ell^+\ell^-) \propto (m_\ell \xi_A^l)^2 \xi_A^q$, $\xi_A^c = \xi_A^b$

Model	ξ_A^d	ξ_A^u	ξ_A^ℓ
Type I	$-\cot\beta$	$\cot\beta$	$-\cot\beta$
Type X (lepton specific)	$-\cot\beta$	$\cot\beta$	$\tan\beta$

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- $h \to \eta_{c,b}\ell\bar{\ell}$ which has escaped attention this far, we find will be efficient channel to test 2HDMs