2HDM Fate after LHC8

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w/ J.F. Gunion, S. Kraml, B. Demount arXiv 1405.XXXX (appear soon)

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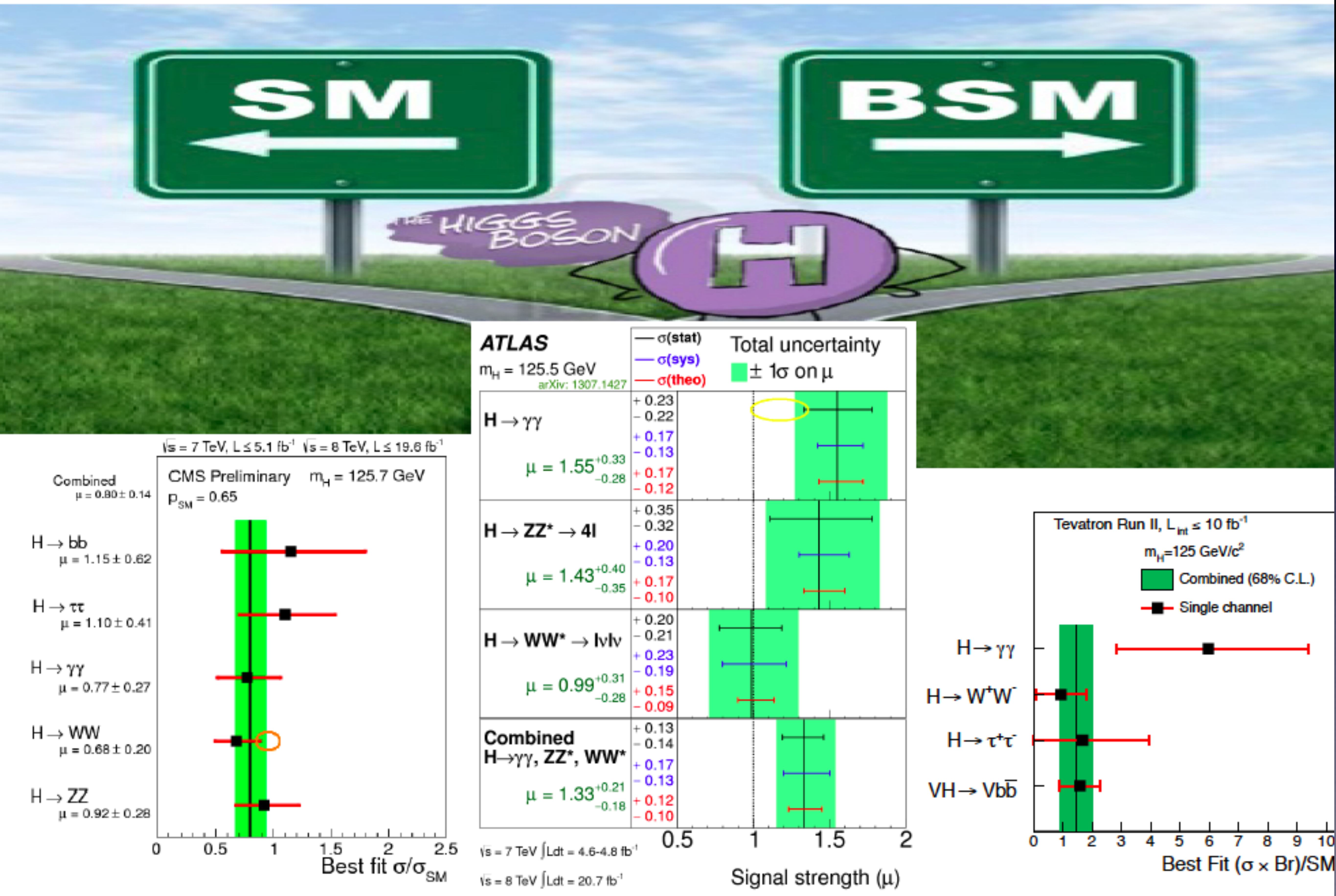
Outline

- 2HDM Snapshot
- Whether or not/How is the model parameter space constrained by
  A. Feed down effect
  B. Higher precision signal measurements
- Prospects at the LHC14/ILC
  - Triple Higgs coupling
  - Lightest Higgs h search and pseudoscalar A detection
- Conclusions

Whether or not it *is* the SM Higgs?



What's the naive extension?

Two Higgs Doublet Model

1. The simplest non-trivial extension on the Higgs sector beyond the SM.
   - Duplicate a complex $SU(2)_L$ Higgs doublet with the same hypercharge $Y = +1$.
   - More physical Higgs states.
2. Type II realized in the MSSM.
3. Existence of the charged Higgs boson $H^{\pm}$?

2HDM Higgs sector

$$\mathcal{V} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - \left[m_{12}^2 \Phi_1^\dagger \Phi_2 + \mathrm{h.c.} \right]$$
$$+ \frac{1}{2}\lambda_1 \left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{1}{2}\lambda_2 \left(\Phi_2^\dagger \Phi_2\right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right)$$
$$+ \left\{ \frac{1}{2}\lambda_5 \left(\Phi_1^\dagger \Phi_2\right)^2 + \mathrm{h.c.} \right\}$$

The models we studied

1. NO explicit $\mathcal{CP}$ violation: all λ_i and m_{12}^2 are assumed to be real.
2. NO spontaneous $\mathcal{CP}$ breaking: take $\xi = 0$.
3. **"soft"** Z_2 symmetry ($\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$) breaking: $m_{12}^2 \neq 0$; $\lambda_6 = \lambda_7 = 0$.

our inputs: $m_h, m_H, m_A, m_{H^+}, \tan\beta, \sin\alpha, m_{12}^2$

Electroweak symmetry breaking

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v\cos\beta + \rho_1 + i\eta_1)/\sqrt{2} \end{pmatrix}$$
$$\Phi_2 = \begin{pmatrix} \phi_2^+ \\ (e^{i\xi} v\sin\beta + \rho_2 + i\eta_2)/\sqrt{2} \end{pmatrix}$$

2 CP-even neutral scalars: $h = -\rho_1 \sin\alpha + \rho_2 \cos\alpha$, $H = \rho_1 \cos\alpha + \rho_2 \sin\alpha$

1 CP-odd neutral pseudoscalar: $A = -\eta_1 \sin\beta + \eta_2 \cos\beta$

2 charged scalars: $H^\pm$

2HDM Yukawa sector

$$\mathcal{L} = y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$$

We consider the Type I and Type II models, in which tree level FCNC are completely absent due to some symmetry. [1]

Model	u^i_R	d^i_R	e^i_R	Realization
Type I	Φ_2	Φ_2	Φ_2	$\Phi_1 \to -\Phi_1$
Type II	Φ_2	Φ_1	Φ_1	$\Phi_1 \to -\Phi_1, d^i_R \to -d^i_R$

$$\begin{aligned}\mathcal{L}^{\mathbf{2HDM}}_{\mathbf{Yukawa}} = & -\sum_{f=u,d,\ell} \frac{m_f}{v}\left(C^h_f \bar{f} f h + C^H_f \bar{f} f H - i C^A_f \bar{f}\gamma_5 f A\right) \\ & - \left\{ \frac{\sqrt{2}V_{ud}}{v}\,\overline{u}\left(m_u C^A_u \mathrm{P}_L + m_d C^A_d \mathrm{P}_R\right) d H^+ + \frac{\sqrt{2} m_\ell C^A_\ell}{v}\,\overline{\nu_L}\ell_R H^1 + \text{h.c.}\right\}\end{aligned}$$

	C^h_V	C^h_u	$C^h_{d,\ell}$	C^H_V	C^H_u	$C^H_{d,\ell}$	C^A_V	C^A_u	$C^A_{d,\ell}$
Type I	$\sin(\beta-\alpha)$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\cos(\beta-\alpha)$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$	0	$\cot\beta$	$-\cot\beta$
Type II	$\sin(\beta-\alpha)$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\cos(\beta-\alpha)$	$\frac{\sin\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\cos\beta}$	0	$\cot\beta$	$\tan\beta$

$$(C^h_V)^2 + (C^H_V)^2 + (C^A_V)^2 = 1$$

[1] *Paschos-Glashow-Weinberg theorem: if all fermions with the same quantum numbers couple to the same Higgs multiplet, then FCNC will be absent.*

Procedural details

Our focus

1. $h \sim 125$ scenario: $m_h \in [123, 128]$ GeV , $m_H \in [128$ GeV$, 2$ TeV$]$ (Gunion's talk)
2. $H \sim 125$ scenario: $m_H \in [123, 128]$ GeV , $m_h \in [12$ GeV$, 123$ GeV$]$

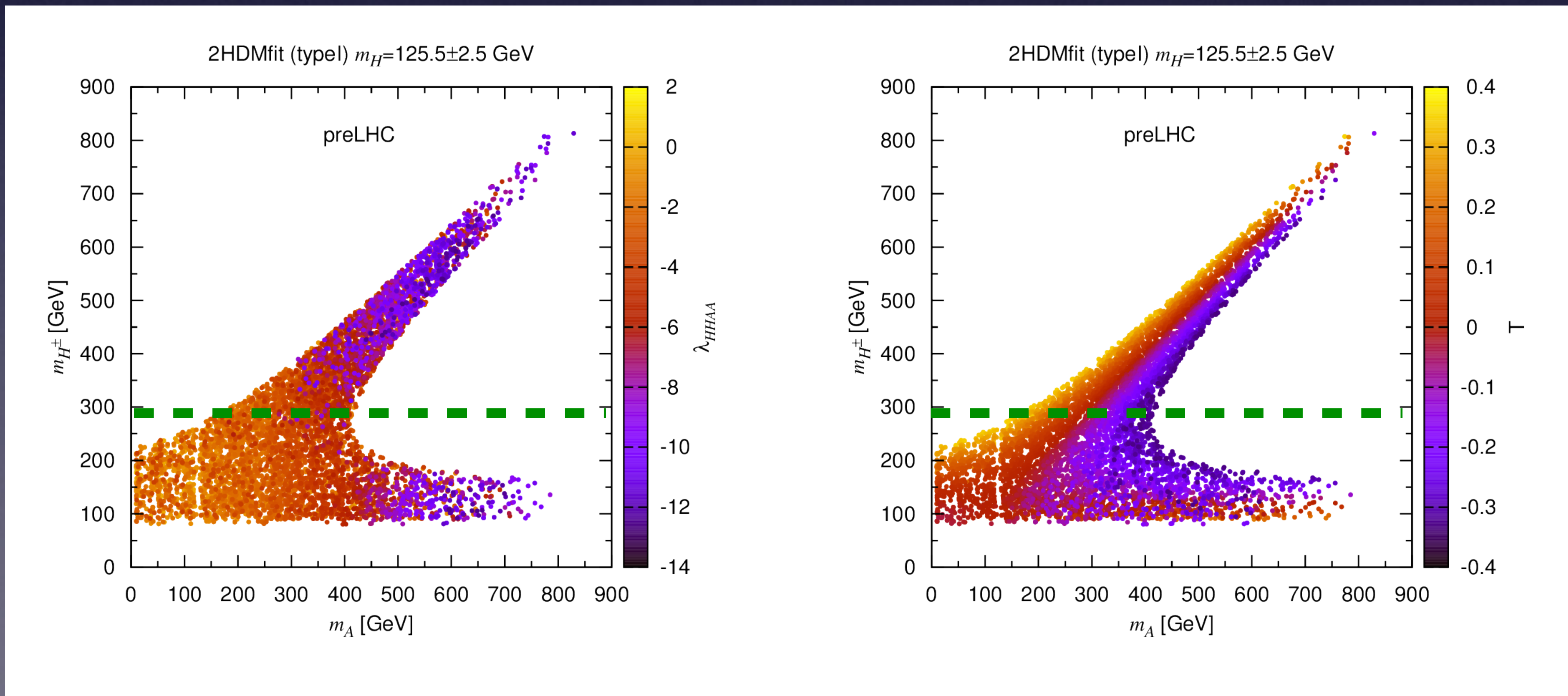
$$\alpha \in [-\pi/2, +\pi/2]\,, \quad \tan\beta \in [0.5, 60]$$

$$m_A \in [5 \text{ GeV}, 2 \text{ TeV}]\,, \quad m_{H^\pm} \in [m^*, 2 \text{ TeV}]$$

Points are retained only when "preLHC" constraints including are all satisfied.

preLHC:

- stability
- unitarity
- perturbativity
- EWK
- B-physics
- $(g\text{-}2)_\mu$
- LEP



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2. $H \sim 125$ scenario: $m_H \in [123, 128]$ GeV, $m_h \in [12 \text{ GeV}, 123 \text{ GeV}]$

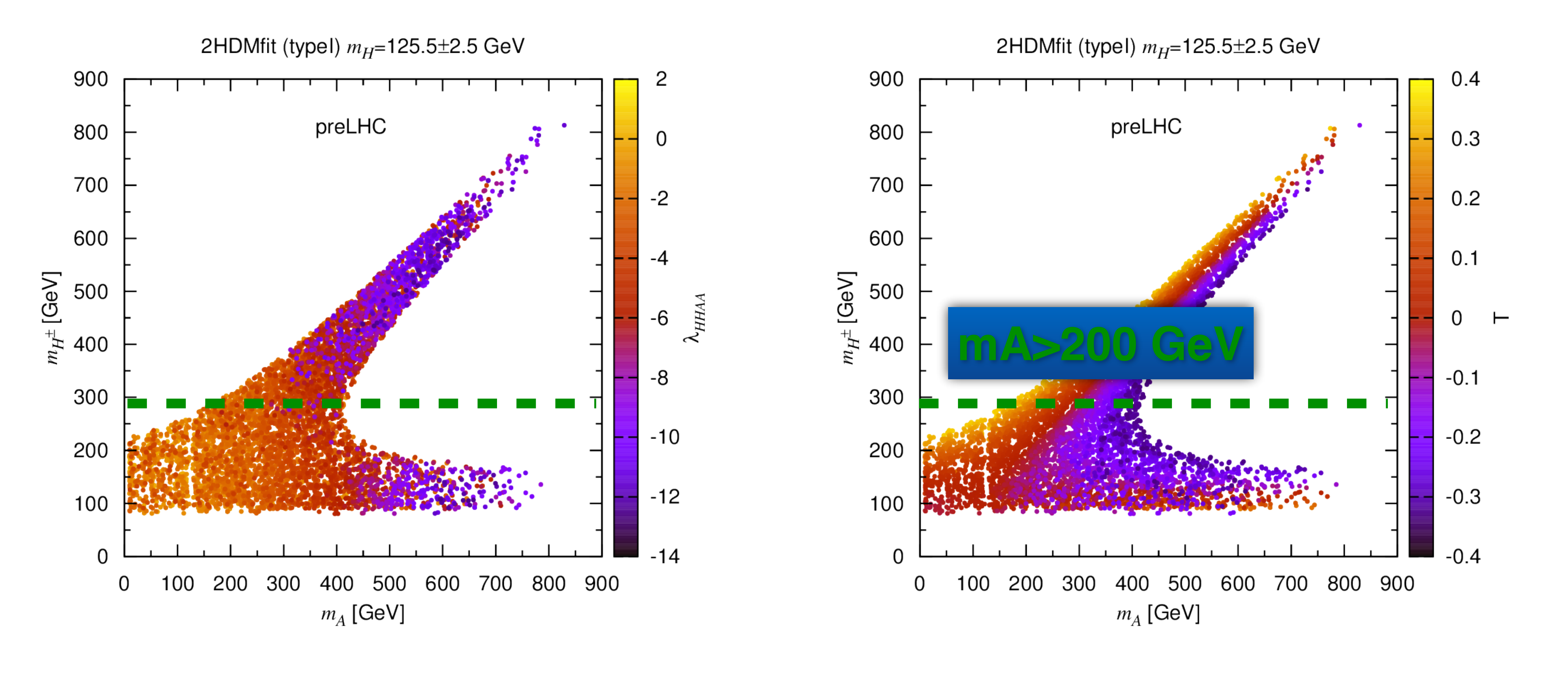
$$\alpha \in [-\pi/2, +\pi/2], \quad \tan\beta \in [0.5, 60]$$

$$m_A \in [5 \text{ GeV}, 900 \text{ GeV}], \quad m_{H^\pm} \in [m^*, 900 \text{ GeV}]$$

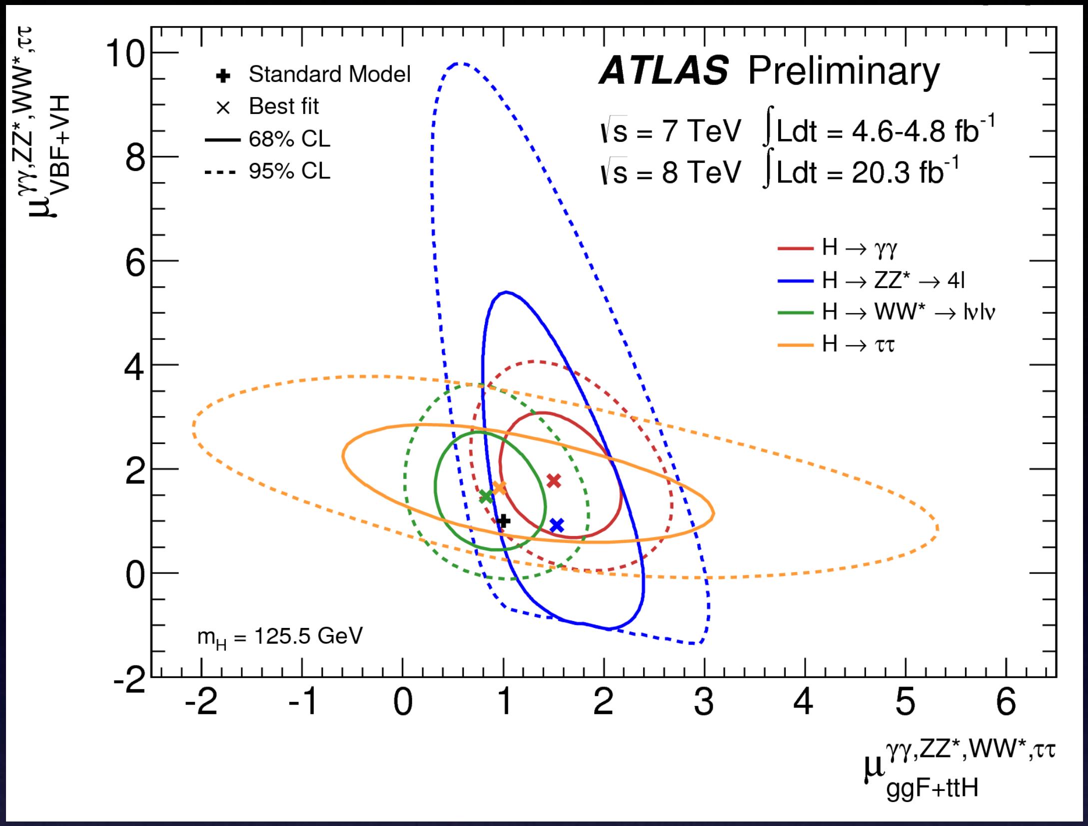
Points are retained only when "preLHC" constraints including are all satisfied.

preLHC:

- stability
- unitarity
- perturbativity
- EWK
- B-physics
- (g-2)μ
- LEP



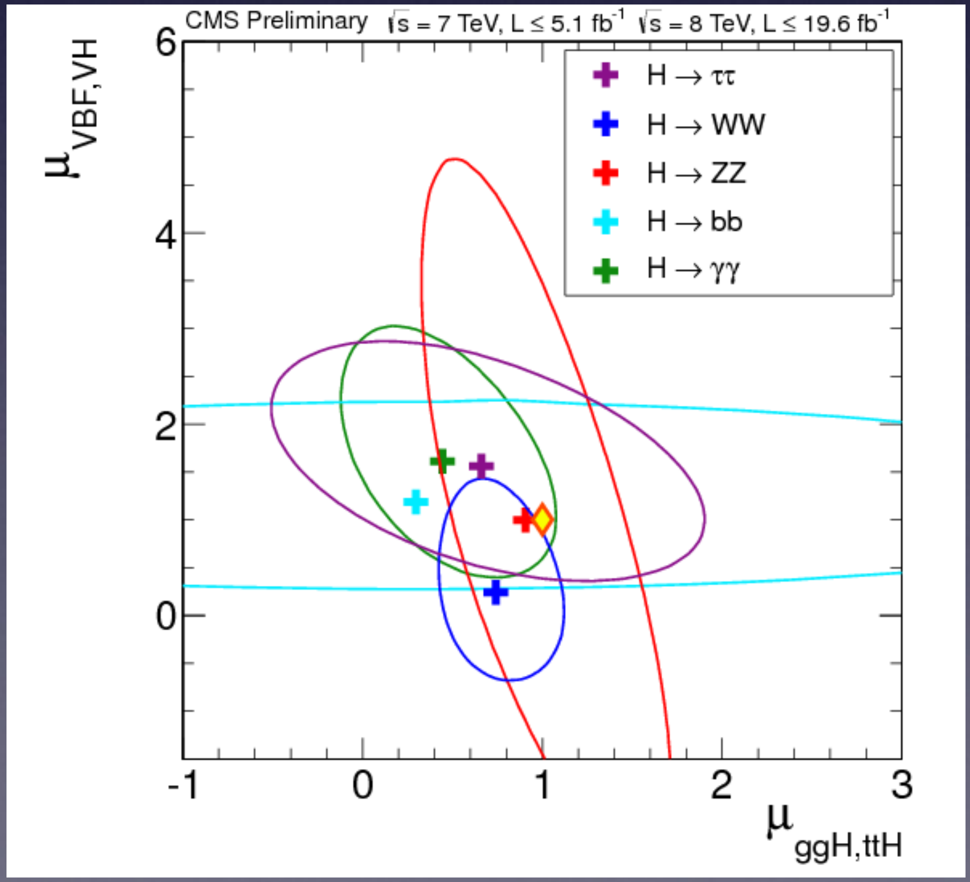
Current status



$$\chi^2_Y = \begin{pmatrix} \mu_{\mathrm{ggF},Y} - \hat{\mu}_{\mathrm{ggF},Y} \\ \mu_{\mathrm{VBF},Y} - \hat{\mu}_{\mathrm{VBF},Y} \end{pmatrix}^T \begin{pmatrix} a_Y & b_Y \\ b_Y & c_Y \end{pmatrix} \begin{pmatrix} \mu_{\mathrm{ggF},Y} - \hat{\mu}_{\mathrm{ggF},Y} \\ \mu_{\mathrm{VBF},Y} - \hat{\mu}_{\mathrm{VBF},Y} \end{pmatrix}$$

$$\chi = \sum_Y \chi^2_Y$$

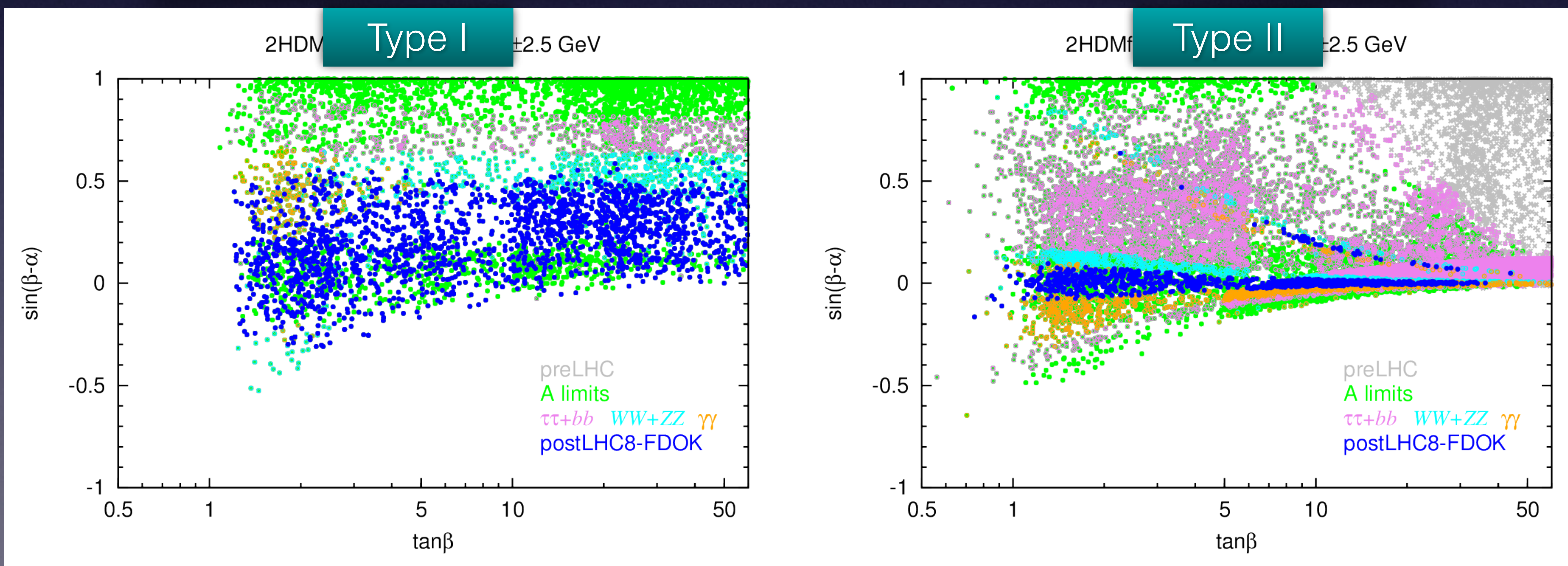
G.Belanger, B.Dumont, U. Ellwanger, J.F. Gunion & S. Kraml, arXiv:1306.2941



H~125-Parameter

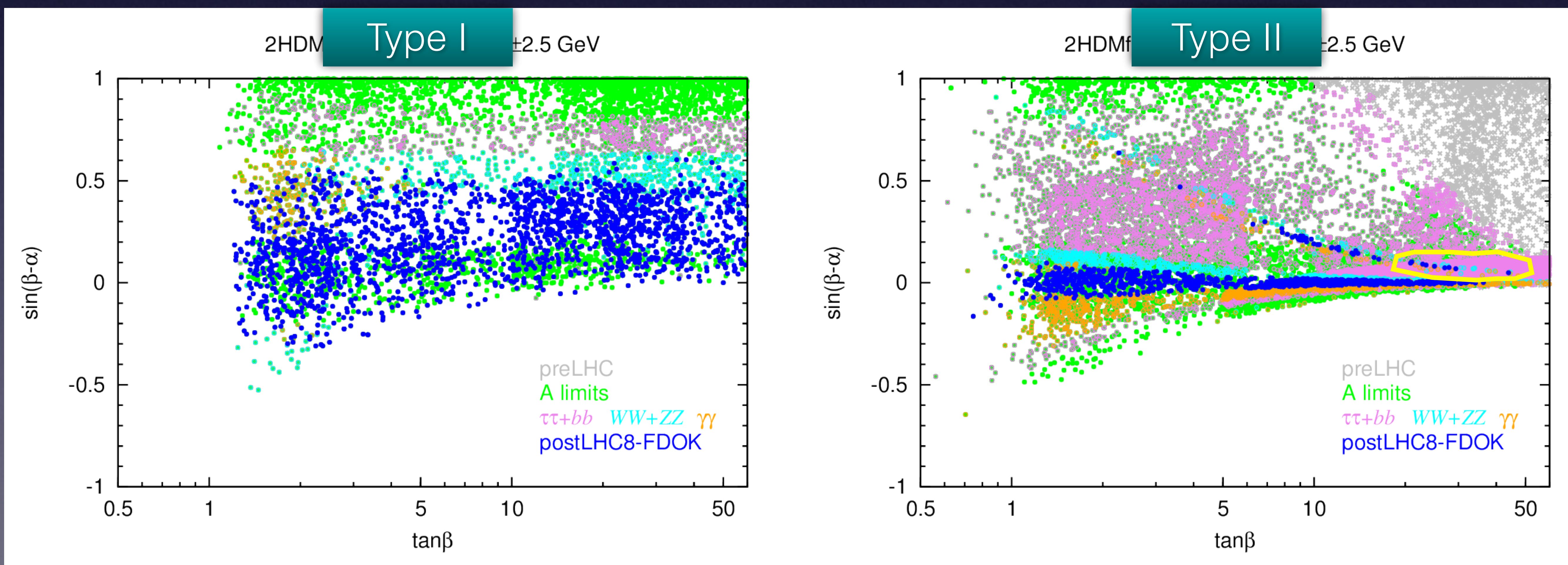
What we consider ...

- preLHC: Stability, Unitarity, Perturbativity, STU, B-physics, $(g-2)_\mu$, LEP
- A limits:
  - $A \to ZZ^{(*)} \to 4\ell$
  - $gg \to A \to \tau\tau$ and $gg \to bbA$ with $A \to \tau\tau$
- postLHC8: additionally, $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$ signals for 125 GeV Higgs



H~125-Parameter

- Generally, for the heavy Higgs boson H be SM like, $C_V^H = \cos(\beta - \alpha) \sim 1$.
- However, there are **two branches** present in Type II model. In addition to the trivial one, the upper strip has $C_D^H \sim -1$, called "wrong-sign Yukawa coupling" (arXiv:1403.4736), extending the C_V^H to ~ 0.7.
- $\tan\beta \lesssim 1$ is eliminated by the $m_{H^\pm}$ bound.

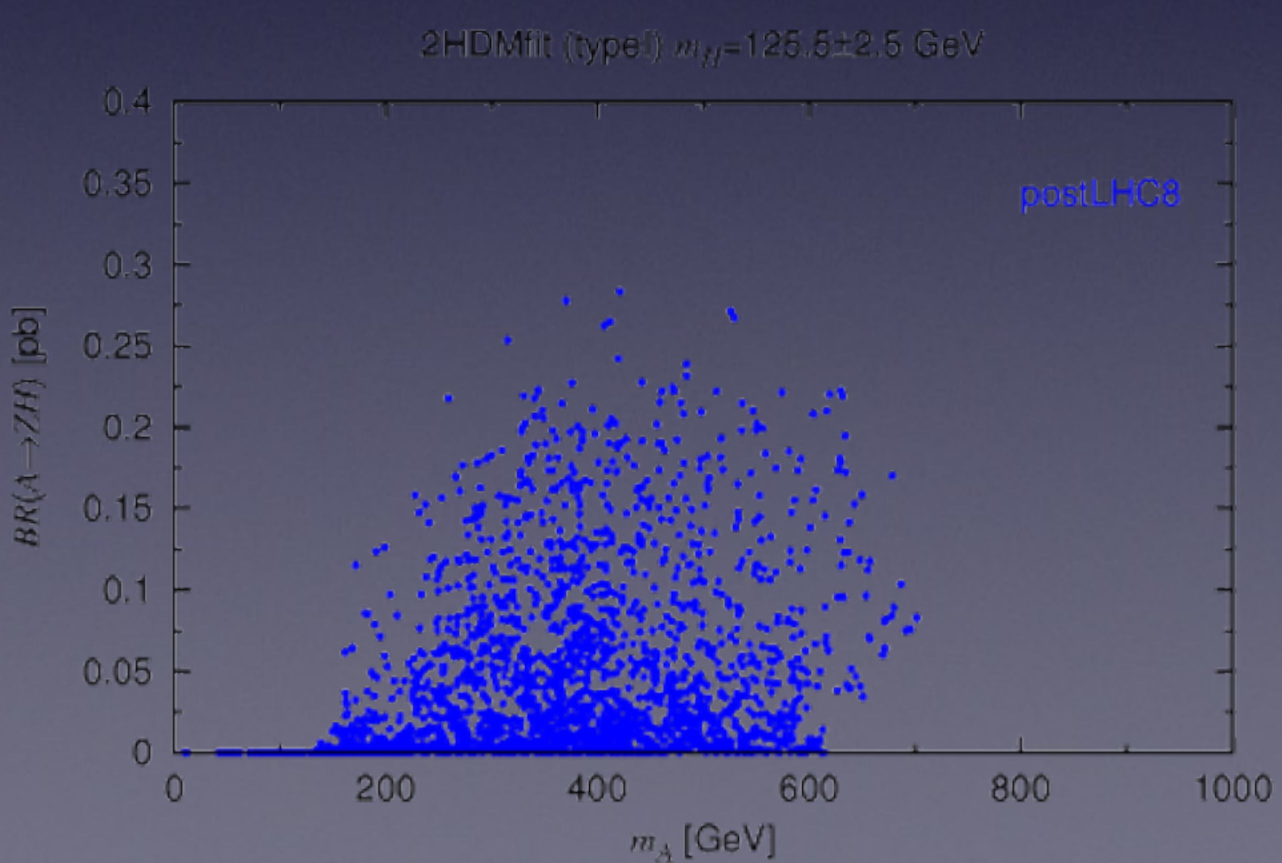


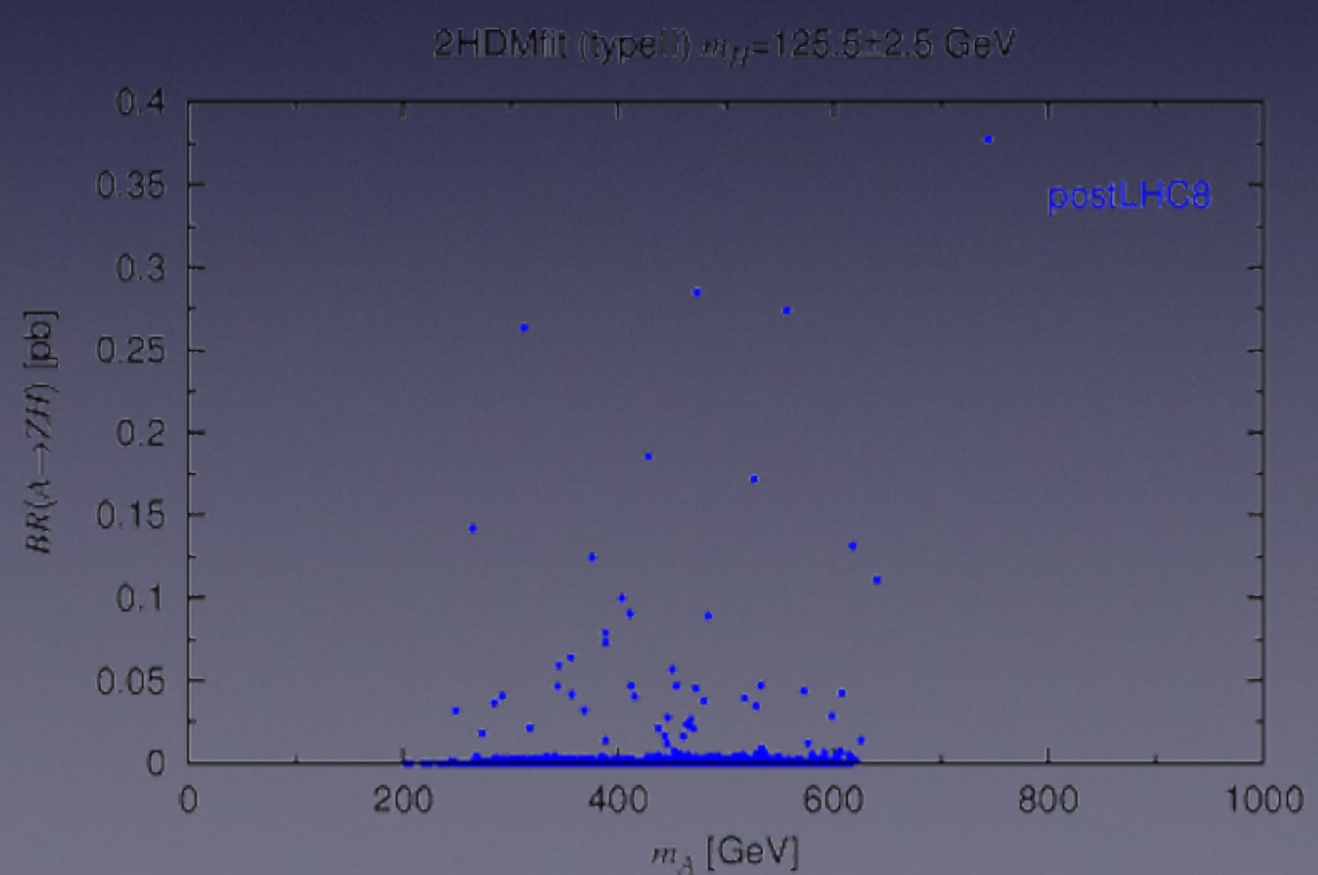
An intriguing possibility?

- heavier scalars like H/A may already be indirectly observed at the LHC, not through their decays into gauge bosons or fermions, but rather through their chain decays into **h**. **Arhrib, Ferreira and Santos (2013)**

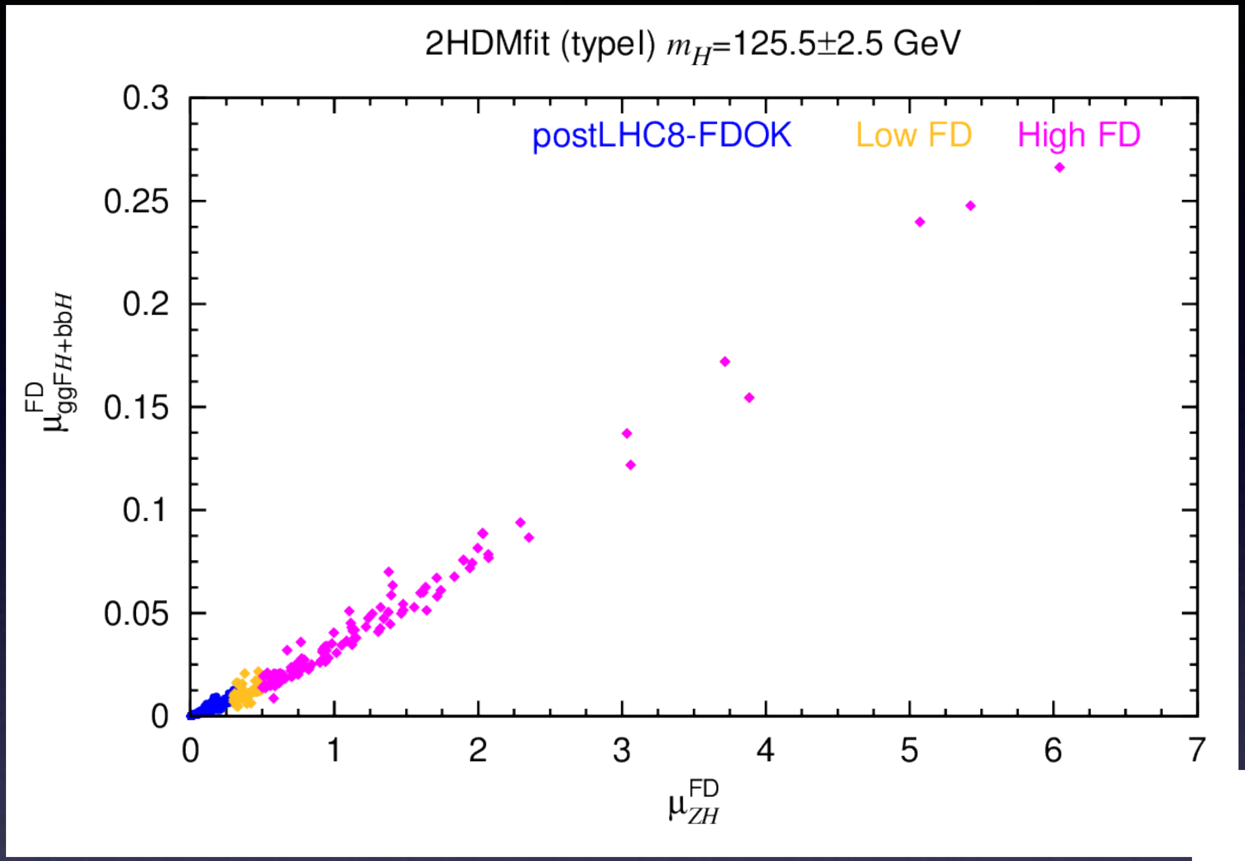
An intriguing possibility?

- heavier scalars like A may already be indirectly observed at the LHC, not through their decays into gauge bosons or fermions, but rather through their **chain decays** into H.





Feed down (FD)

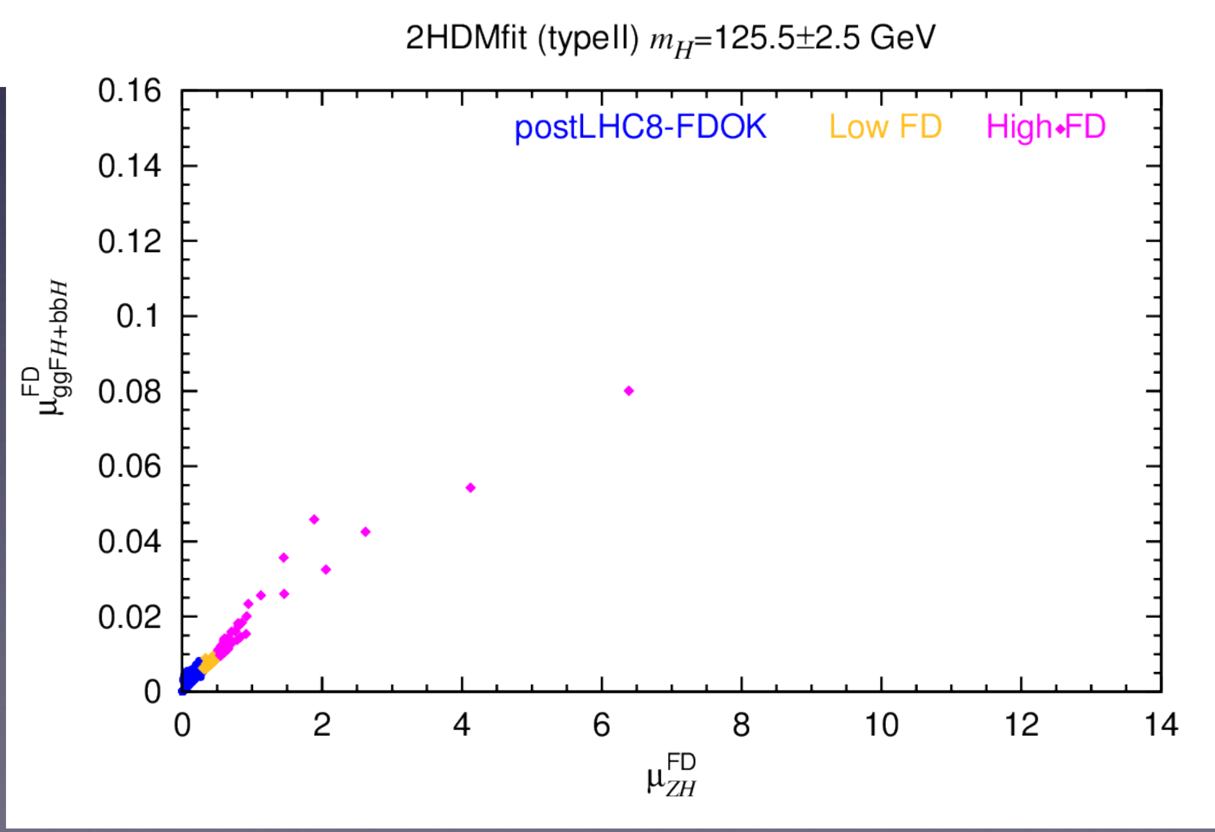


For all but VH

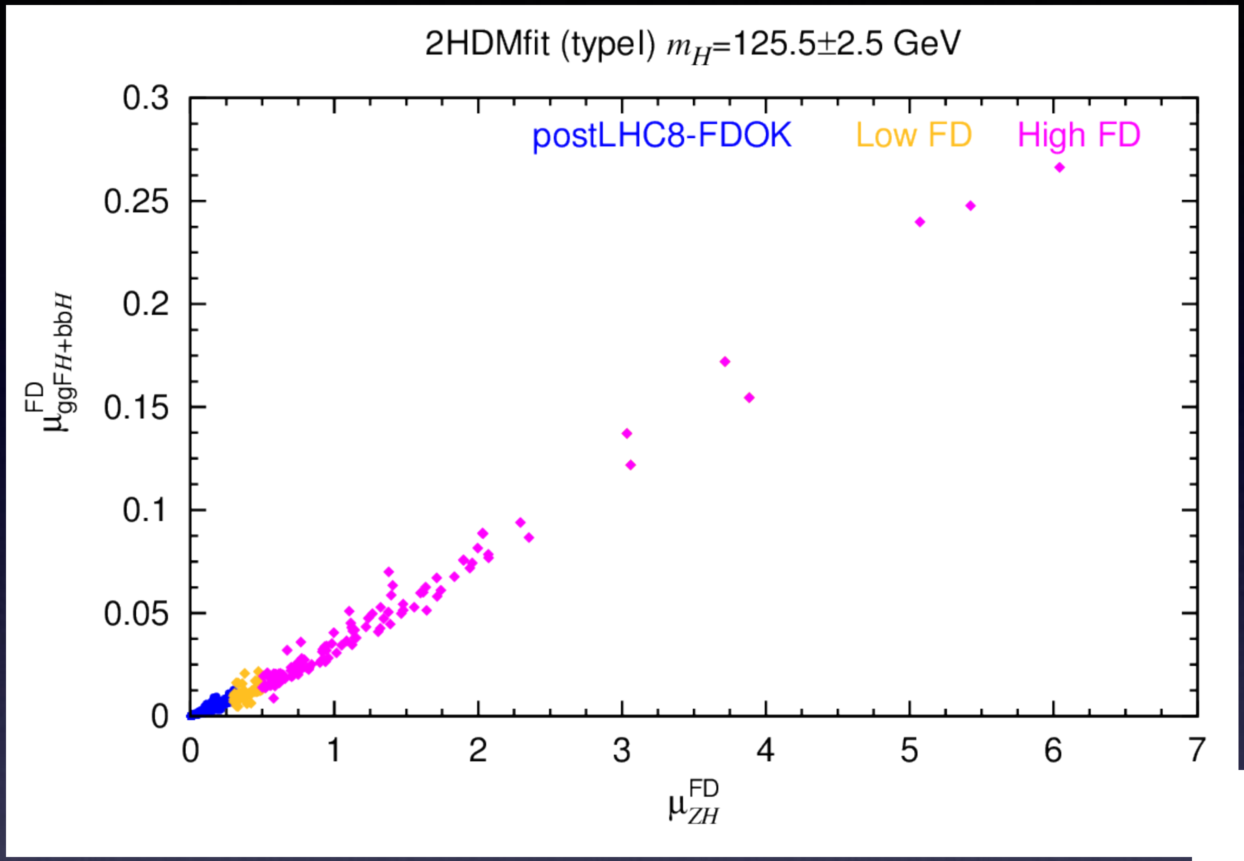
$$\mu^{\mathbf{FD}}_{\mathbf{XH}} \equiv \frac{\sum_{\mathcal{H}} \sigma_{X\mathcal{H}} P_{FD}(\mathcal{H} \to \mathbf{H} + \text{anything})}{\sigma_{\mathbf{XH}}}$$

$$P_{FD}(\mathcal{H} \to \mathbf{H} + \text{anything}) = 2P_{\mathcal{H},\mathbf{2H}} + P_{\mathcal{H},\mathbf{1H}}$$

$$\mu^{\mathbf{FD}}_{\mathbf{VH}} = \frac{\sigma_{\mathbf{ggF}A} \mathrm{BR}(A \to ZH)}{\sigma_{\mathbf{VH}}}$$



Feed down (FD)



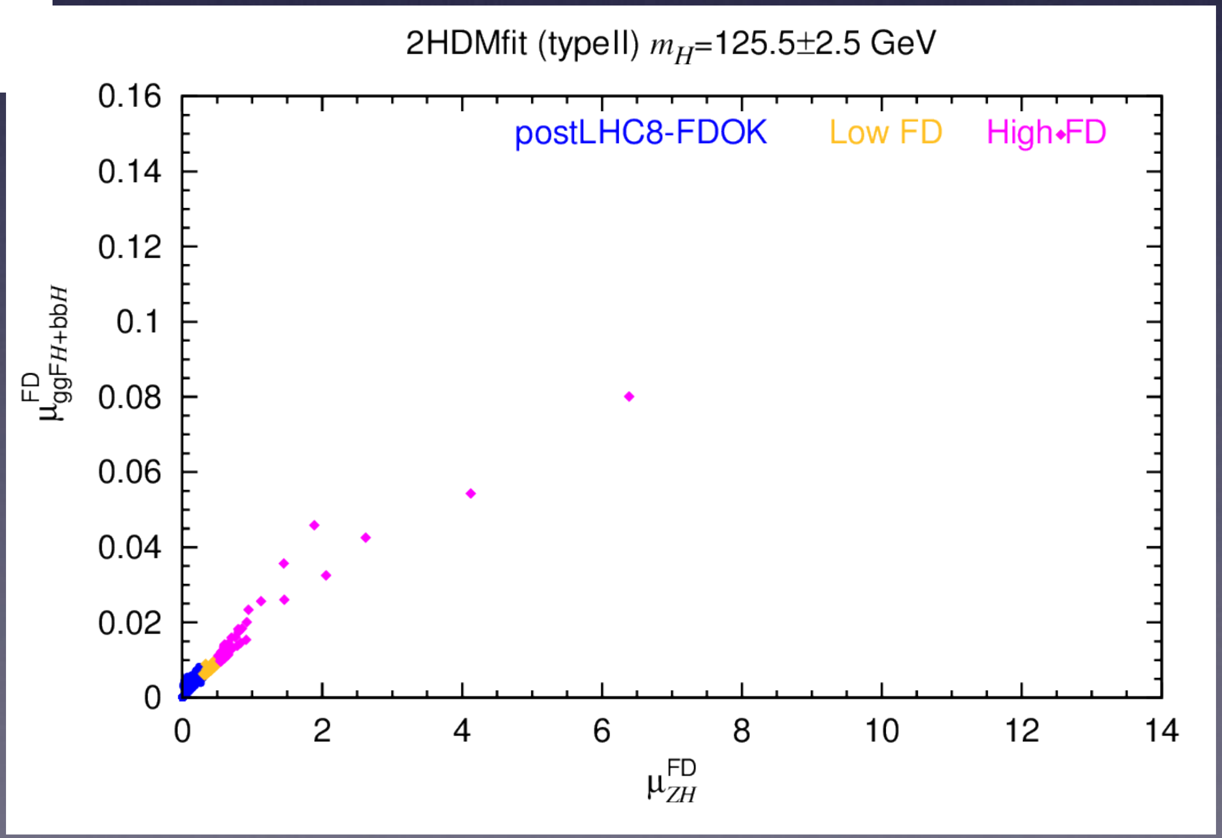
What amount of feed down is too large?

FDOK: $\mu^{\mathrm{FD}}_{\mathrm{ggF}H+\mathrm{bb}H} \leq 0.1 \quad \mu^{\mathrm{FD}}_{ZH} \leq 0.3$

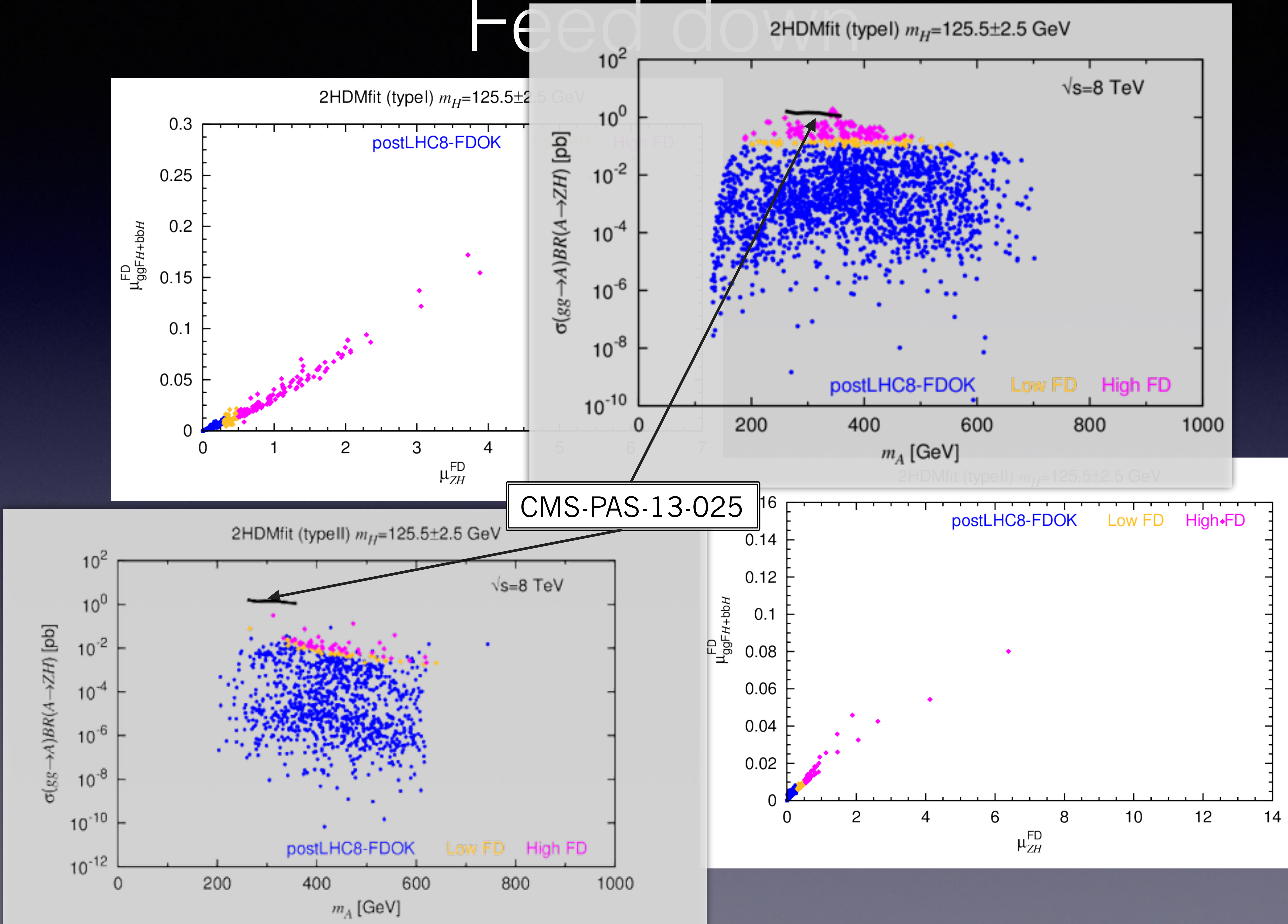
Low FD: $0.1 < \mu^{\mathrm{FD}}_{\mathrm{ggF}H+\mathrm{bb}H} \leq 0.2$

$0.3 < \mu^{\mathrm{FD}}_{ZH} \leq 0.5$

High FD: $\mu^{\mathrm{FD}}_{\mathrm{ggF}H+\mathrm{bb}H} > 0.2 \, \mu^{\mathrm{FD}}_{ZH} > 0.5$

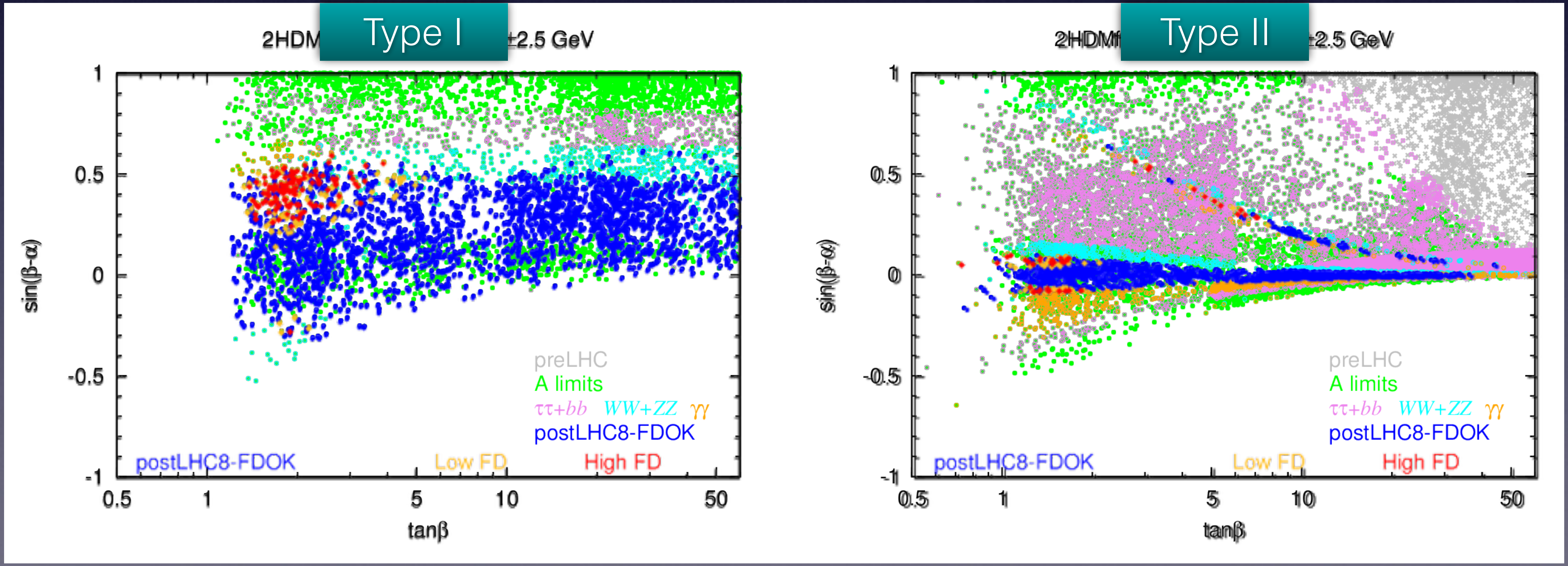


Feed down

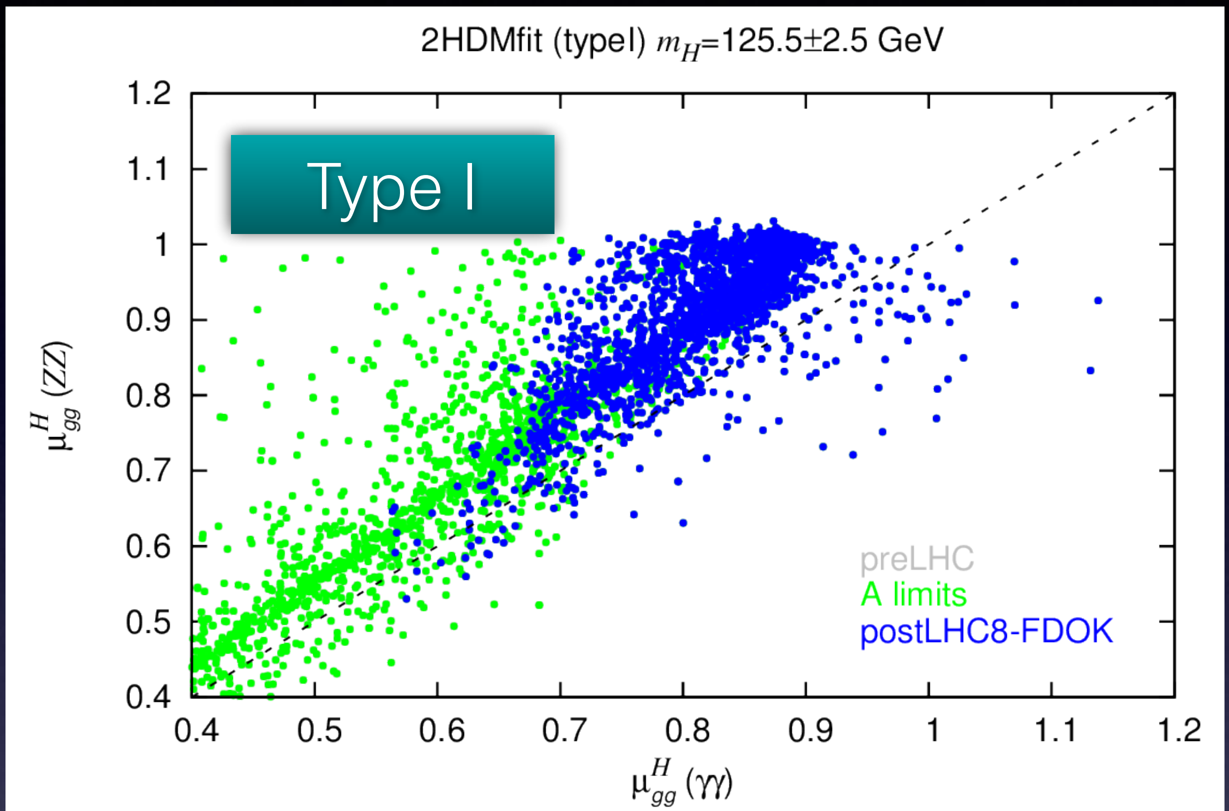

2HDMfit (typeI) m_H=125.5±2.5 GeV
postLHC8-FDOK
$\mu^{FD}_{ggFH+bbH}$
μ^{FD}_{ZH}
2HDMfit (typeI) m_H=125.5±2.5 GeV
√s=8 TeV
σ(gg→A)BR(A→ZH) [pb]
m_A [GeV]
postLHC8-FDOK
Low FD
High FD
CMS-PAS-13-025
2HDMfit (typeII) m_H=125.5±2.5 GeV
√s=8 TeV
σ(gg→A)BR(A→ZH) [pb]
m_A [GeV]
postLHC8-FDOK
Low FD
High FD
postLHC8-FDOK
Low FD
High FD
$\mu^{FD}_{ggFH+bbH}$
μ^{FD}_{ZH}

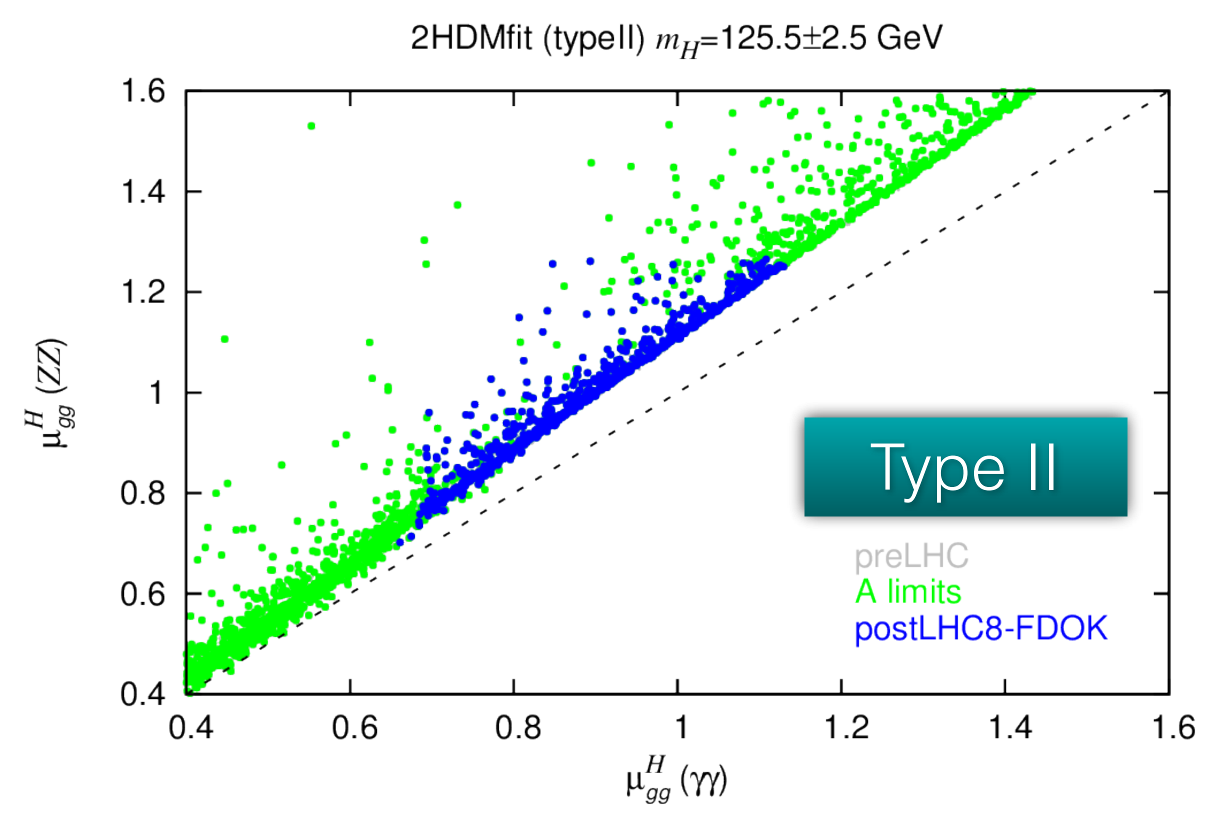
H~125-Parameter w/FD

- FD happens at the value of large sin$(\beta - \alpha)$, which is related to the *HAZ* coupling, and prefers small tan β.
- FD does NOT actually constrain the parameter space of the models.



H~125-Higgs Signals @125





eliminate low/high FD

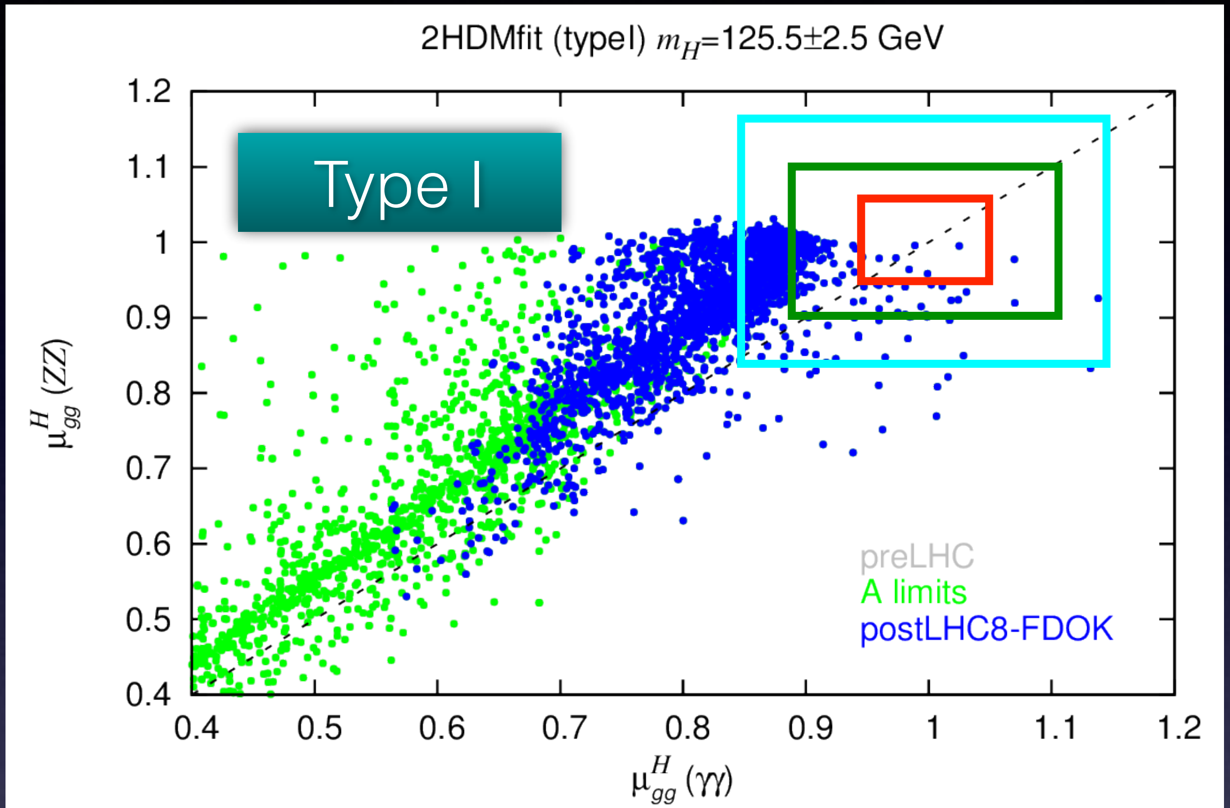
Type I

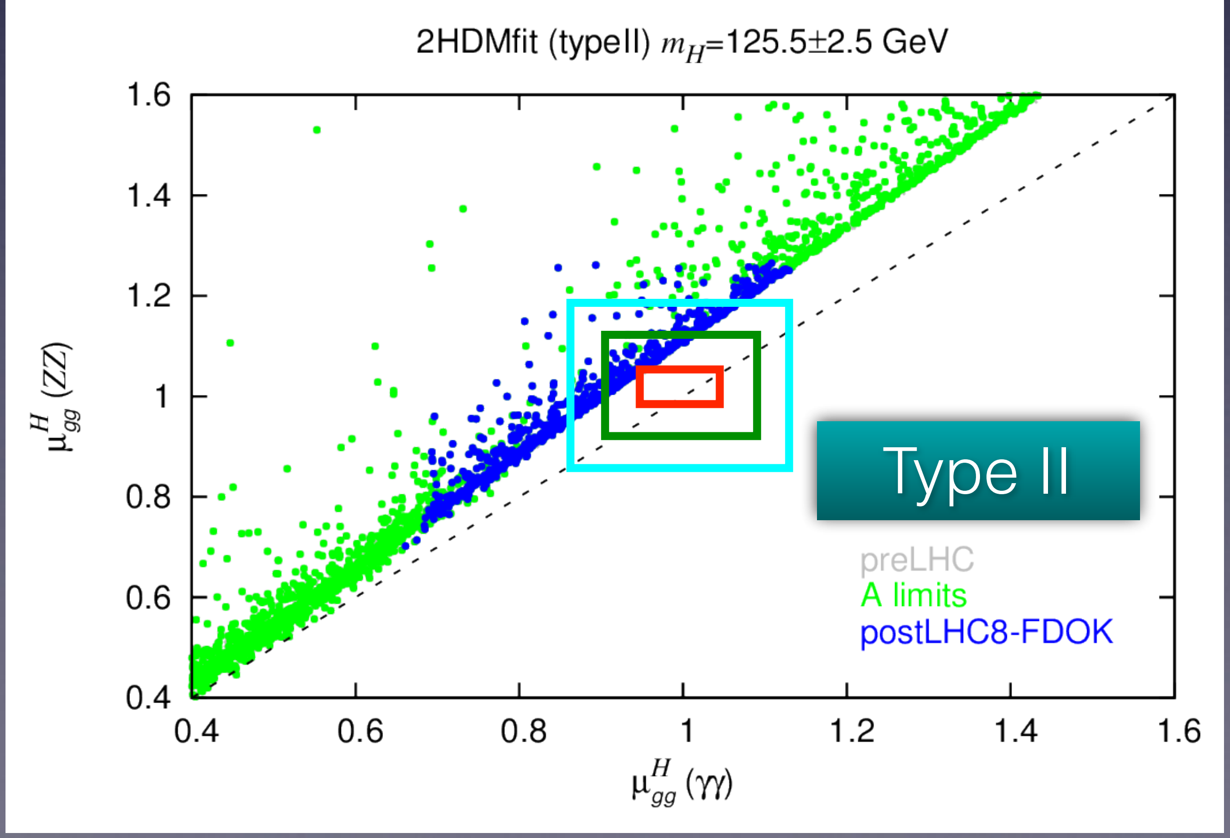
- **not too much above 1** because that gluon fusion production cannot be much enhanced (universal up and down type couplings).
- $\frac{\mu^{\boldsymbol{H}}_{\boldsymbol{gg}}(ZZ)}{\mu^{\boldsymbol{H}}_{\boldsymbol{gg}}(\gamma\gamma)} < 1$ for enhanced $\mu^{\boldsymbol{H}}_{\boldsymbol{gg}}(\gamma\gamma)$ rate.

Type II

- **easy realization of substantial enhancement**.
- $\mu^{\boldsymbol{H}}_{\boldsymbol{gg}}(ZZ)$ is strictly larger than $\mu^{\boldsymbol{H}}_{\boldsymbol{gg}}(\gamma\gamma)$ for enhanced $\mu^{\boldsymbol{H}}_{\boldsymbol{gg}}(\gamma\gamma)$ rate.

H~125-Higgs Signals @125





eliminate low/high FD

What happens if all measured signals converge to very SM?

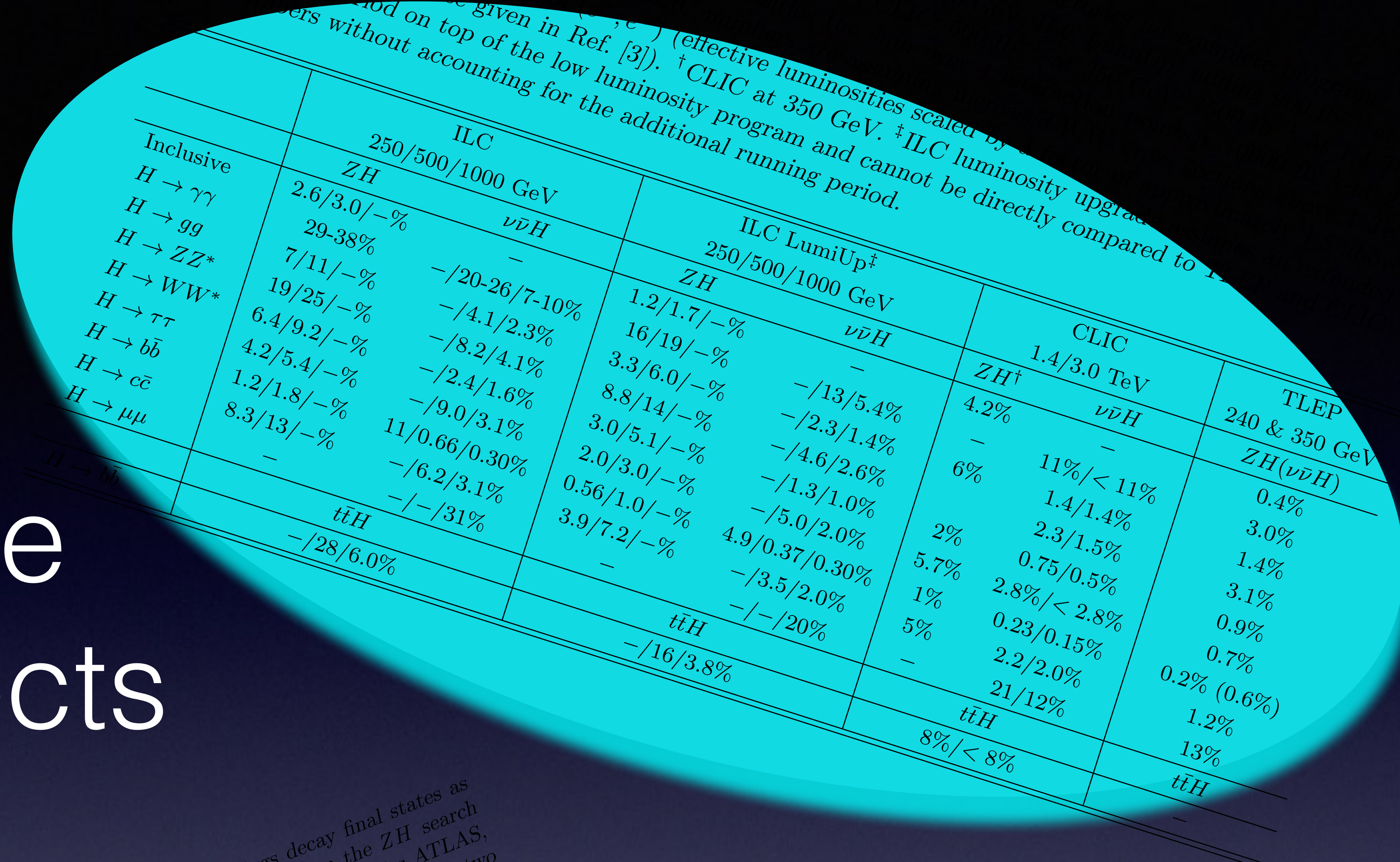
For example, if the observed values of $\mu^h_X(Y)$ *all* lie within $\pm15\%$, $\pm10\%$ and $\pm5\%$ of the SM prediction for the channels

$$(gg,\gamma\gamma),\ (gg,ZZ),\ (gg,\tau\tau),$$

$$(\mathrm{VBF},\gamma\gamma),\ (\mathrm{VBF},ZZ),$$

$$(\mathrm{VBF},\tau\tau)=(\mathrm{VH},bb),\ (\mathrm{ttH},bb)$$

Future prospects



...given in Ref. [3]) (effective luminosities scaled by ...
...od on top of the low luminosity program and cannot be directly compared to ...
...ers without accounting for the additional running period.
†CLIC at 350 GeV. ‡ILC luminosity upgra...

	ILC 250/500/1000 GeV		ILC LumiUp‡ 250/500/1000 GeV		CLIC 1.4/3.0 TeV		TLEP 240 & 350 GeV
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$	$ZH^\dagger$	$\nu\bar{\nu}H$	$ZH(\nu\bar{\nu}H)$
Inclusive	2.6/3.0/–%	–	1.2/1.7/–%	–	4.2%	–	0.4%
$H \to \gamma\gamma$	29-38%	–/20-26/7-10%	16/19/–%	–/13/5.4%	–	11%/< 11%	3.0%
$H \to gg$	7/11/–%	–/4.1/2.3%	3.3/6.0/–%	–/2.3/1.4%	6%	1.4/1.4%	1.4%
$H \to ZZ^*$	19/25/–%	–/8.2/4.1%	8.8/14/–%	–/4.6/2.6%		2.3/1.5%	3.1%
$H \to WW^*$	6.4/9.2/–%	–/2.4/1.6%	3.0/5.1/–%	–/1.3/1.0%	2%	0.75/0.5%	0.9%
$H \to \tau\tau$	4.2/5.4/–%	–/9.0/3.1%	2.0/3.0/–%	–/5.0/2.0%	5.7%	2.8%/< 2.8%	0.7%
$H \to b\bar{b}$	1.2/1.8/–%	11/0.66/0.30%	0.56/1.0/–%	4.9/0.37/0.30%	1%	0.23/0.15%	0.2% (0.6%)
$H \to c\bar{c}$	8.3/13/–%	–/6.2/3.1%	3.9/7.2/–%	–/3.5/2.0%	5%	2.2/2.0%	1.2%
$H \to \mu\mu$	–	–/–/31%	–	–/–/20%	–	21/12%	13%
	$t\bar{t}H$		$t\bar{t}H$		$t\bar{t}H$		$t\bar{t}H$
$H \to t\bar{t}$	–/28/6.0%		–/16/3.8%		8%/< 8%		–

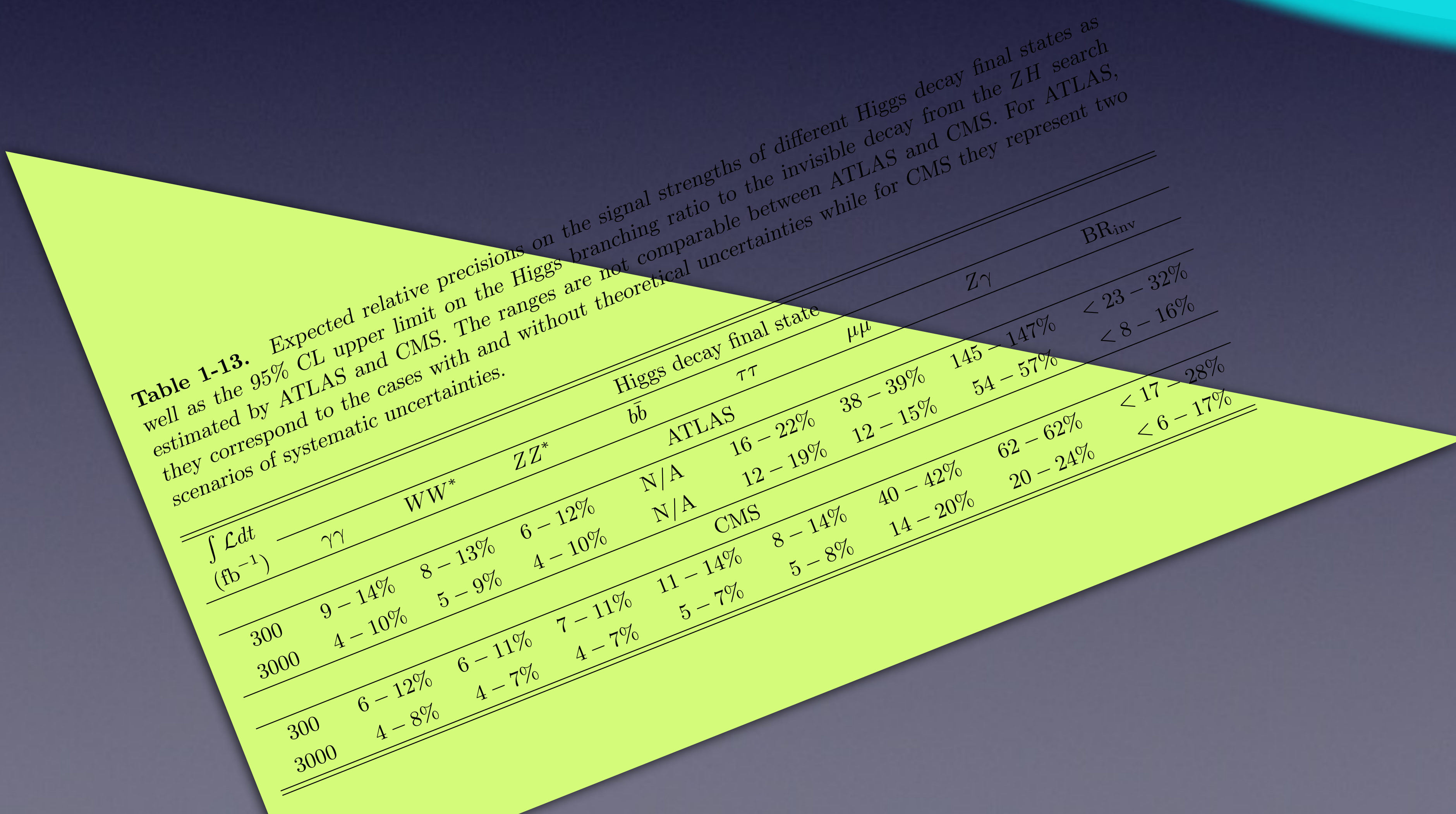
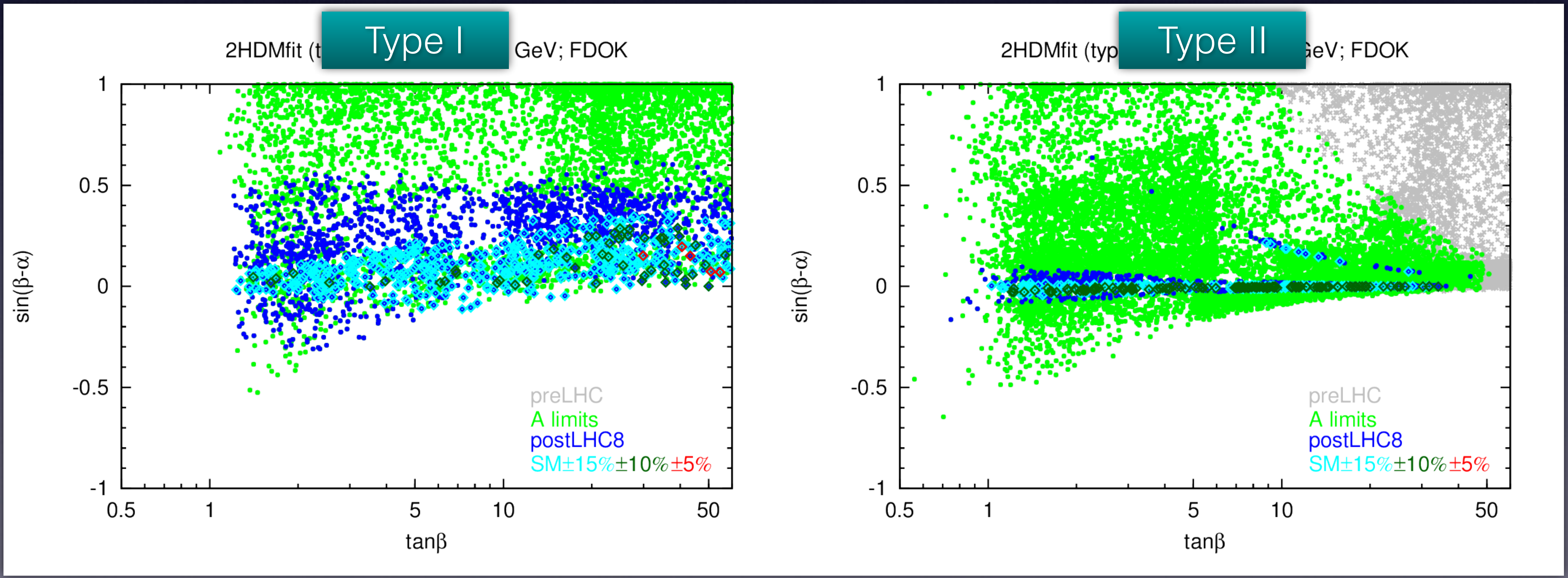


Table 1-13. Expected relative precisions on the signal strengths of different Higgs decay final states as well as the 95% CL upper limit on the Higgs branching ratio to the invisible decay from the ZH search estimated by ATLAS and CMS. The ranges are not comparable between ATLAS and CMS. For ATLAS, they correspond to the cases with and without theoretical uncertainties while for CMS they represent two scenarios of systematic uncertainties.

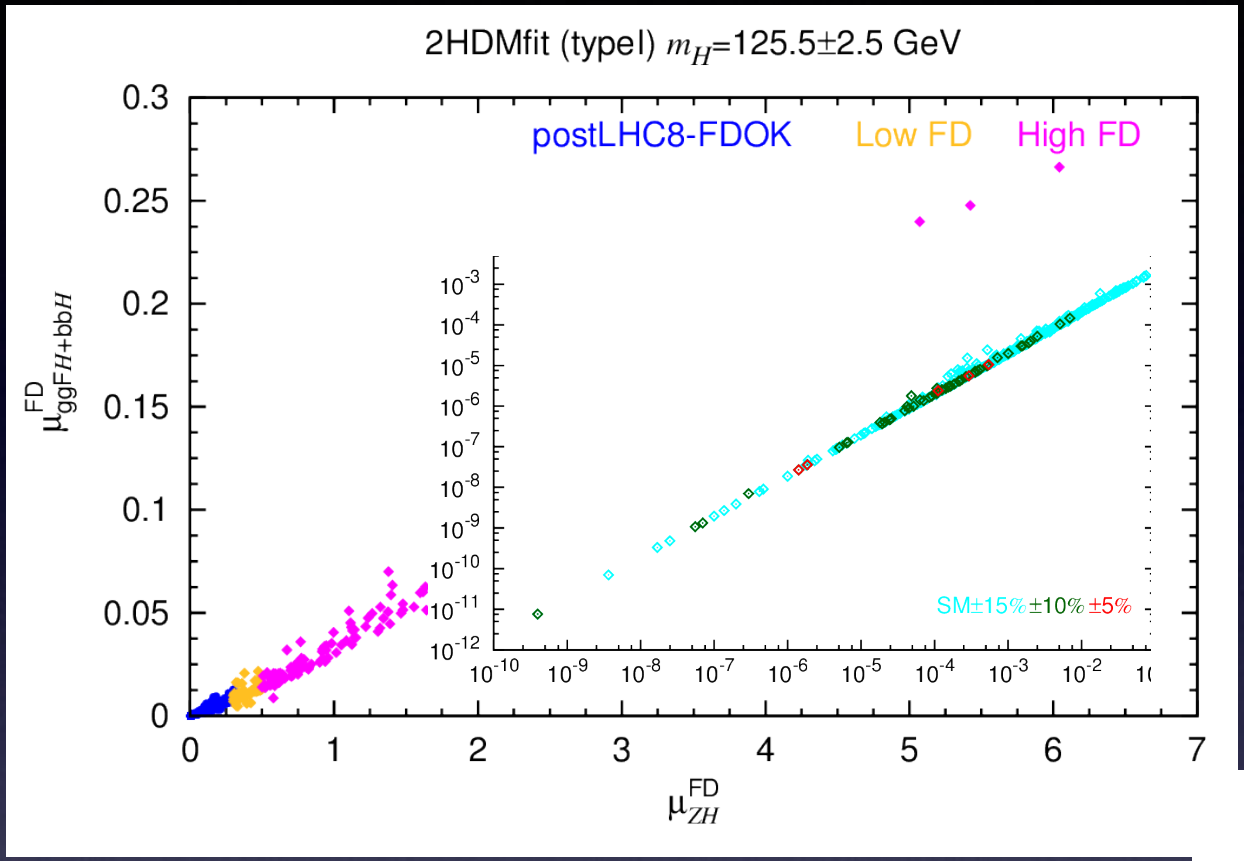
$\int \mathcal{L}dt$ (fb^{-1})	Higgs decay final state							
	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$	$Z\gamma$	BR_{inv}
	ATLAS							
300	9 – 14%	8 – 13%	6 – 12%	N/A	16 – 22%	38 – 39%	145 – 147%	< 23 – 32%
3000	4 – 10%	5 – 9%	4 – 10%	N/A	12 – 19%	12 – 15%	54 – 57%	< 8 – 16%
	CMS							
300	6 – 12%	6 – 11%	7 – 11%	11 – 14%	8 – 14%	40 – 42%	62 – 62%	< 17 – 28%
3000	4 – 8%	4 – 7%	4 – 7%	5 – 7%	5 – 8%	14 – 20%	20 – 24%	< 6 – 17%

H~125-Parameter @ higher precision

- Not unexpectedly, as increasingly precise agreement with the SM is imposed in the various final state channels one is quickly pushed to small $|\sin(\beta-\alpha)|$, but $\tan\beta$ remains unrestricted.
- SM±10% on each of the individual μ's will exclude the "wrong-sign" Yukawa region of the Type II model.
- If ±5% agreement with the SM can be verified in all the channels, then $m_H = 125.5$ GeV scenario will be eliminated in Type II and *all but* eliminated in Type I (due to the $H^\pm$ loop non-decoupling effect at large $m_{H^\pm}$).



Feed down vs. higher precision



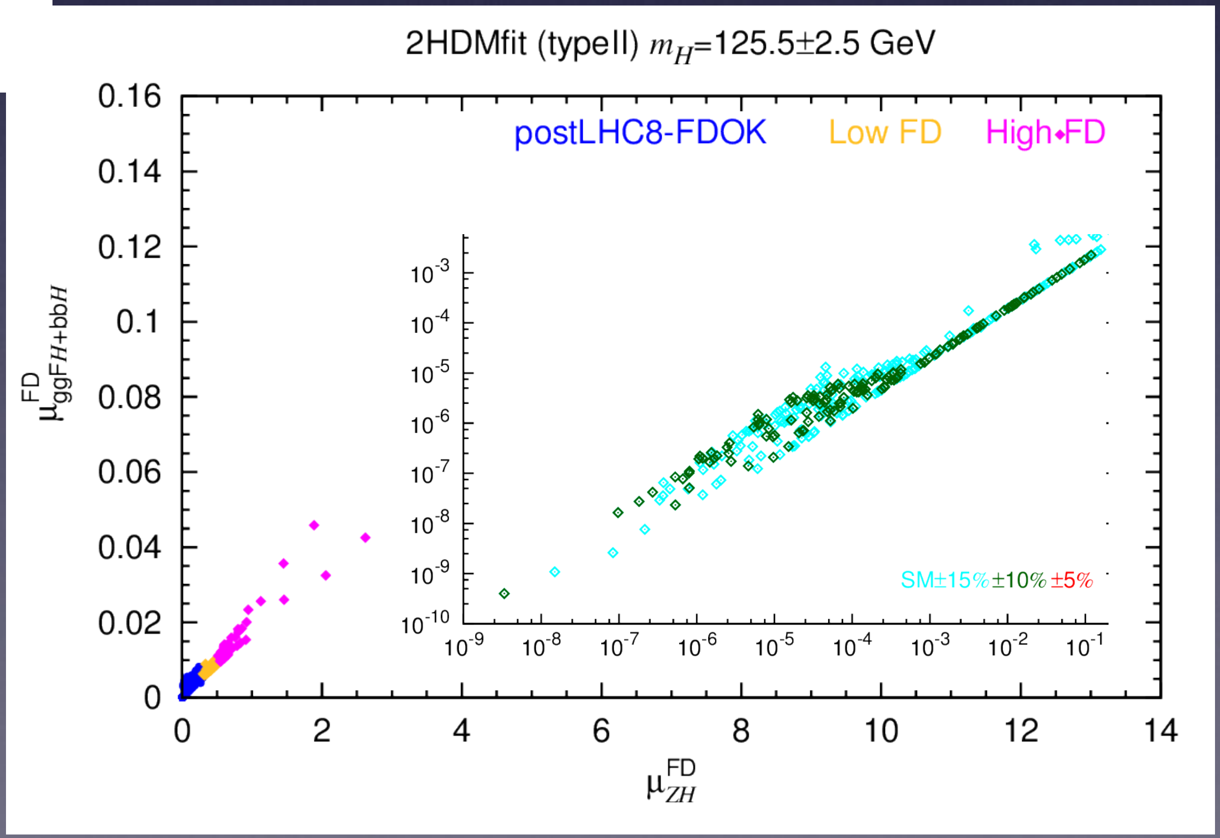
Increased precision in the signal strength measurements reduces the "danger" of FD contamination.

$\text{FDOK: } \mu^{FD}_{ggFH+bbH} \leq 0.1 \quad \mu^{FD}_{ZH} \leq 0.3$

$\text{Low FD: } 0.1 < \mu^{FD}_{ggFH+bbH} \leq 0.2$

$0.3 < \mu^{FD}_{ZH} \leq 0.5$

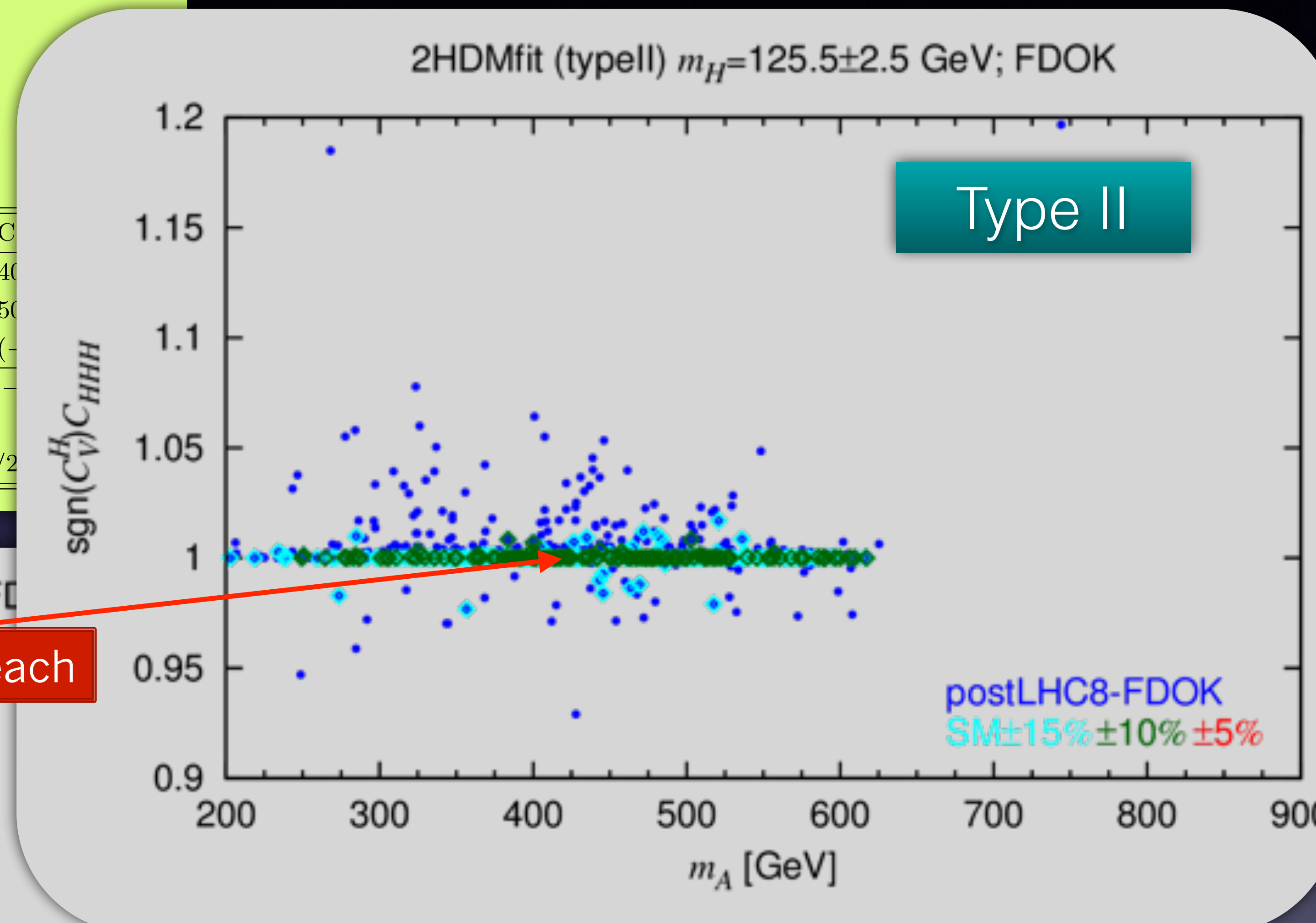
$\text{High FD: } \mu^{FD}_{ggFH+bbH} > 0.2 \; \mu^{FD}_{ZH} > 0.5$

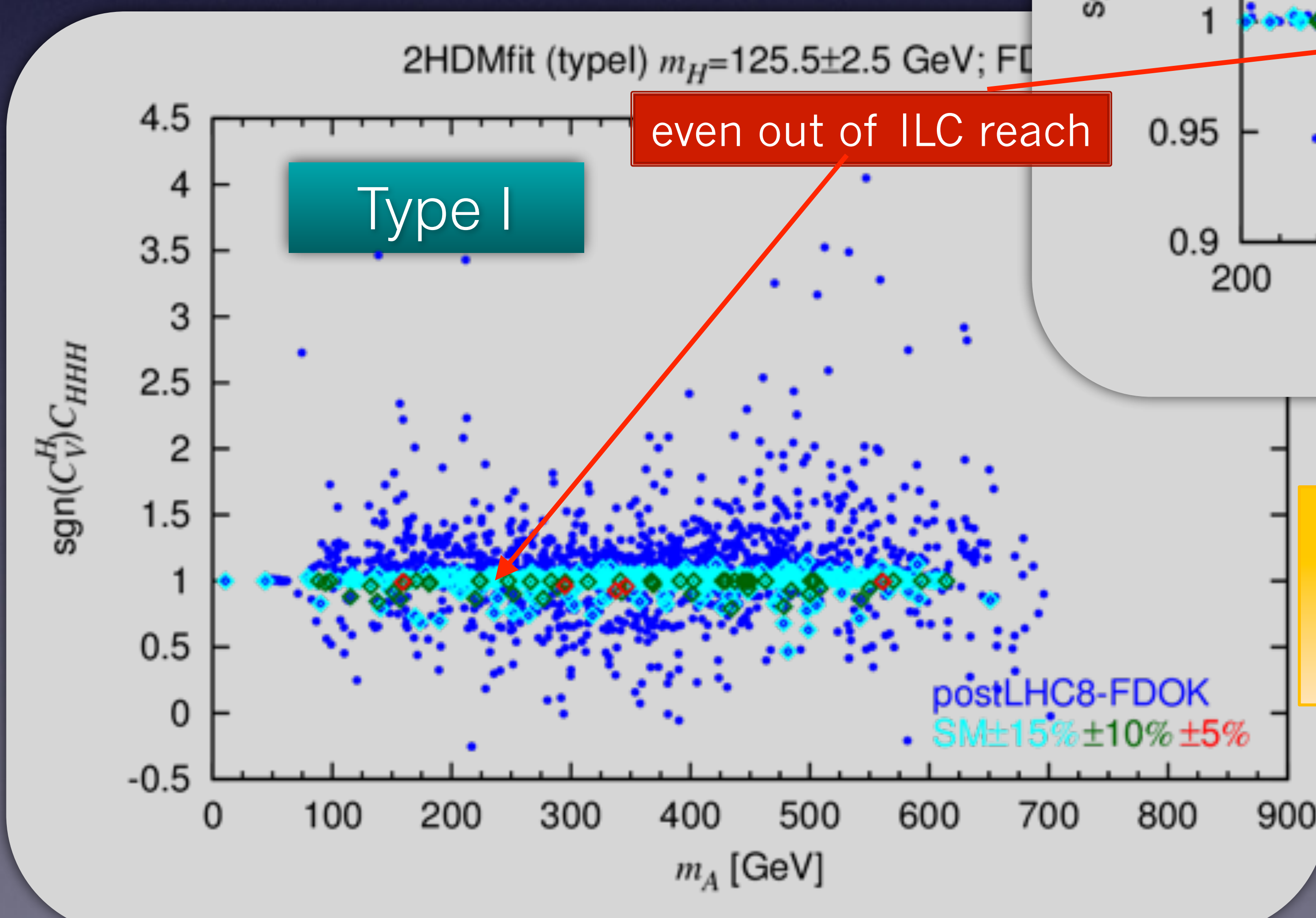


H~125-Triple H coupling

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	140
$\int \mathcal{L}dt$ (fb^{-1})	500	1600[‡]	500+1000	1600+2500[‡]	150
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0, 0)/(-$
$\sigma(ZHH)$	42.7%		42.7%	23.7%	–
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%	
λ	83%	46%	21%	13%	28/2



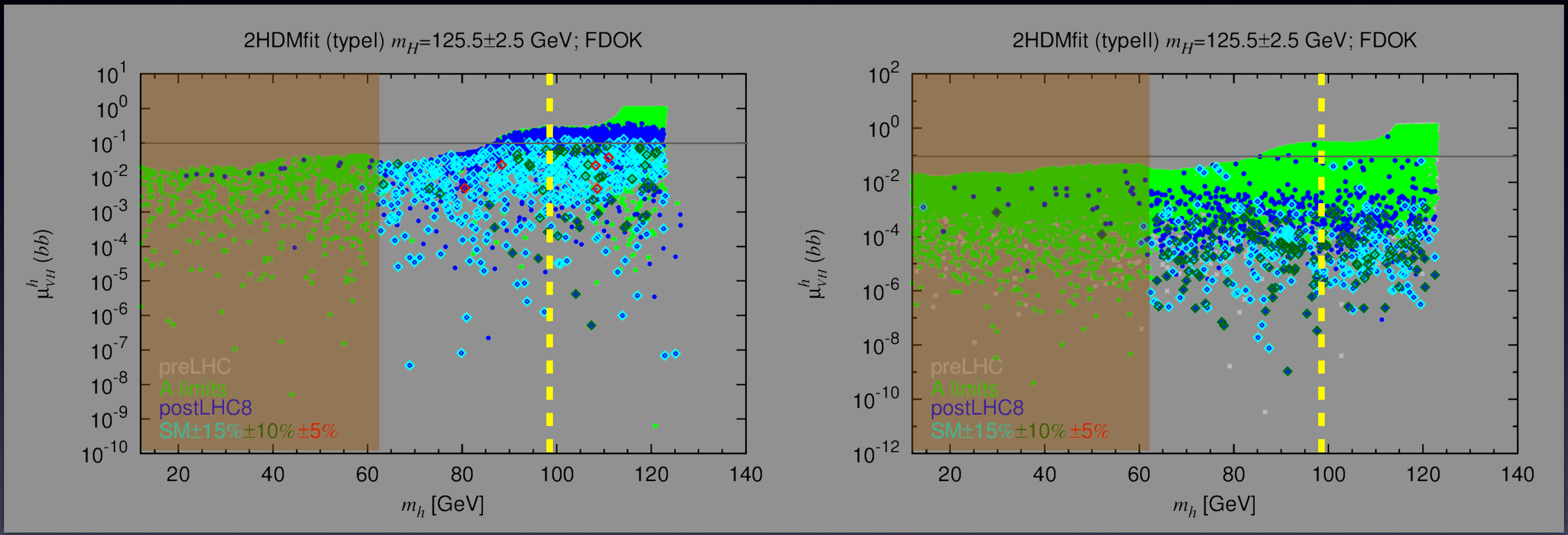


- Currently, a large deviation present.
- Tightly limited deviation if the signals become increasingly SM-like.

Other
Higgs bosons search
at the LHC/ILC

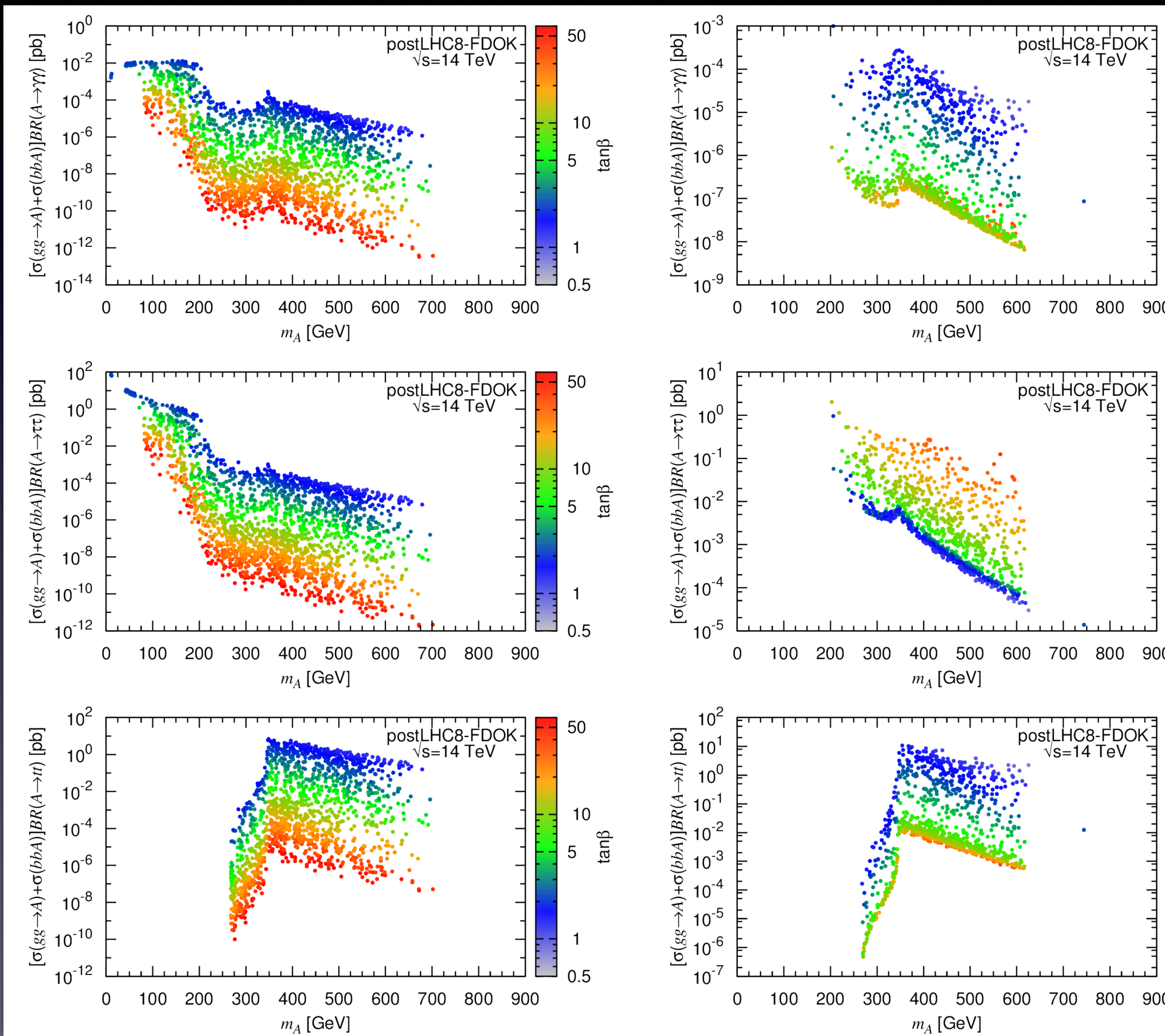
H~125-lightest h detection

LHC @ 8 TeV



- For $m_h \lesssim 60$ GeV, one can require $\mathrm{BR}(H \to hh)$ small enough to still allow the H rates in the various channels to fit the 125.5 GeV signal at the LHC8.
- Can explain the LEP $\sim 2.3\sigma$ excess at $m_h \sim 98$ GeV in both the Type I and Type II models given current postLHC8 constraints on the H properties. *However, the Type I $\pm 5\%$ level and the Type II $\pm 10\%$ level would have a signal level that is not consistent with this LEP excess observed.*

H~125-pseudoscalar A search



- In Type I **mA<60 GeV** is possible but must have small BR(H->AA). For **mA<100 GeV**, tautau cross section are quite large.
- LHC8 125 GeV Higgs data constrain **the A mass** <700 GeV in Type I and <625 GeV in Type II.
- A large range of possible cross section value. In average, Type II tends to be substantially larger than Type I. The lowest cross values are really very small and would not allow A detection.

Conclusions

- The latest Higgs data from LHC clearly favors a fairly SM-like Higgs boson with mass of 125.5 GeV.

- There is consistent descriptions with the LHC8 Higgs signal in the both Type I and Type II 2HDMs in which the H is identified as the 125.5 GeV state.

- Feed down effect does not eliminate much parameter space and will be dramatically reduced if the higher precision in the signal measurement is verified in the future.

- The ratio $\frac{\mu_{gg}(ZZ)}{\mu_{gg}(\gamma\gamma)}$ might be a possible signature to examine the Type I and II 2HDM if the diphoton rate is confirmed to be very SM-like or a bit enhanced in the future.

- The A can be detected in many modes (except ZZ). In addition, there is good probability for viable signals for the lighter h. The opportunity of such detection is still ample even if the 125.5 GeV signals converge to very SM-like. Of course, the direct search associated with other (heavier) Higgs bosons is awaiting for LHC 14 run.

Next focus

1. low mass Higgs?
2. low mass DM?


Thank You!