Two-Higgs-doublet model and singlet scalar dark matter

Yun Jiang

UC Davis
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LPSC Seminar
Grenoble, 12/3/2014

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2HDM globit fit, w/ Gunion, Kraml, Dumont, arXiv:1405.3584
light Higgs boson, w/ Gunion, Kraml, Bernon, arXiv:1412.XXXX
2HDM+Singlet DM, w/ Gunion, Grzadkowski, Drozd, arXiv:1408.2106
Isospin-violating DM, arXiv:1501.XXXX

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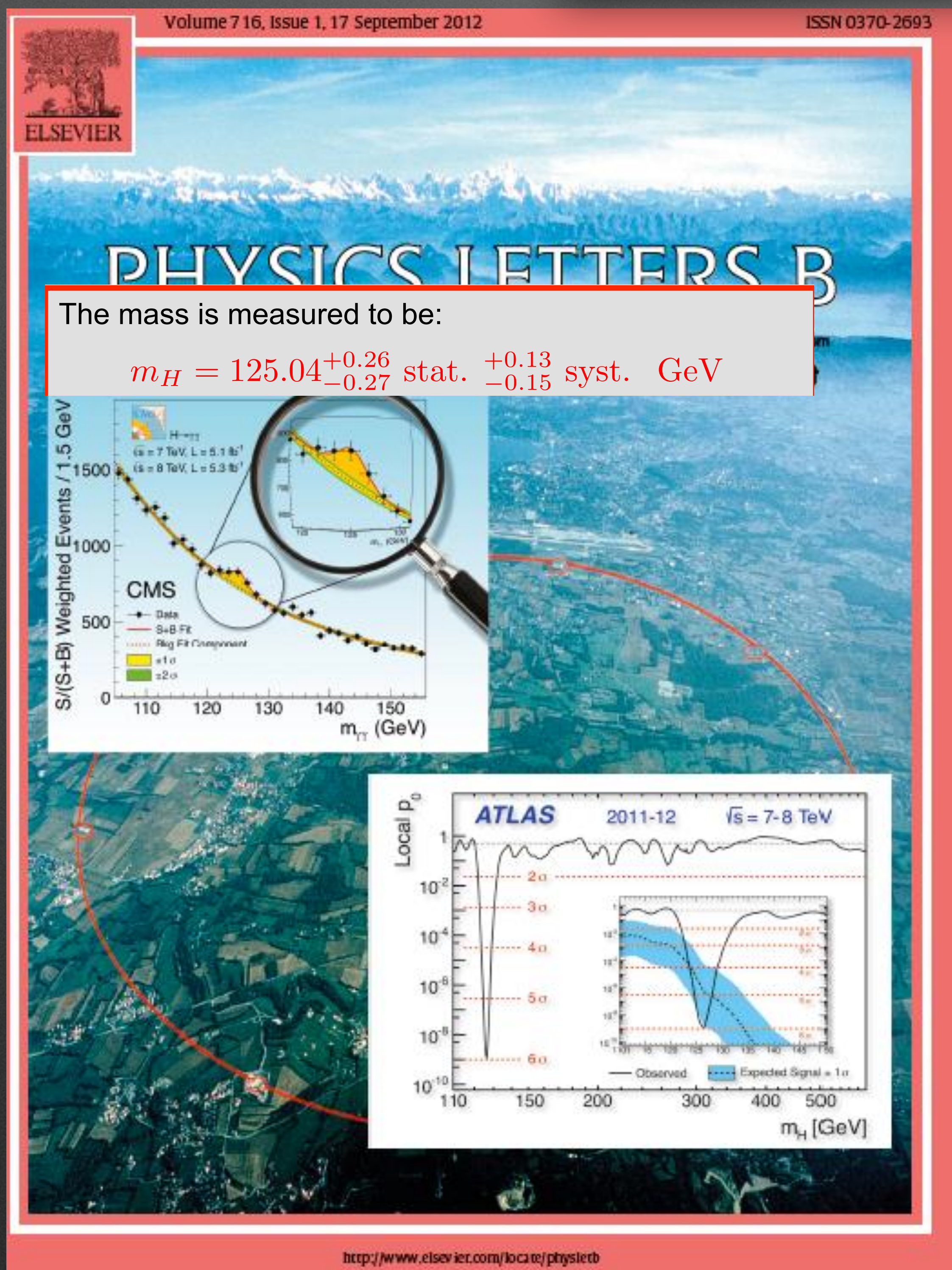
Outline

- Update of LHC Run-I analysis
- Current status and future prospects on the Two-Higgs-doublet model
  A. Higgs signal fit
  B. Higher precision signal measurements
  C. Search for other Higgs bosons
- Interplay between Higgs and dark matter sectors
- Conclusions and remarks

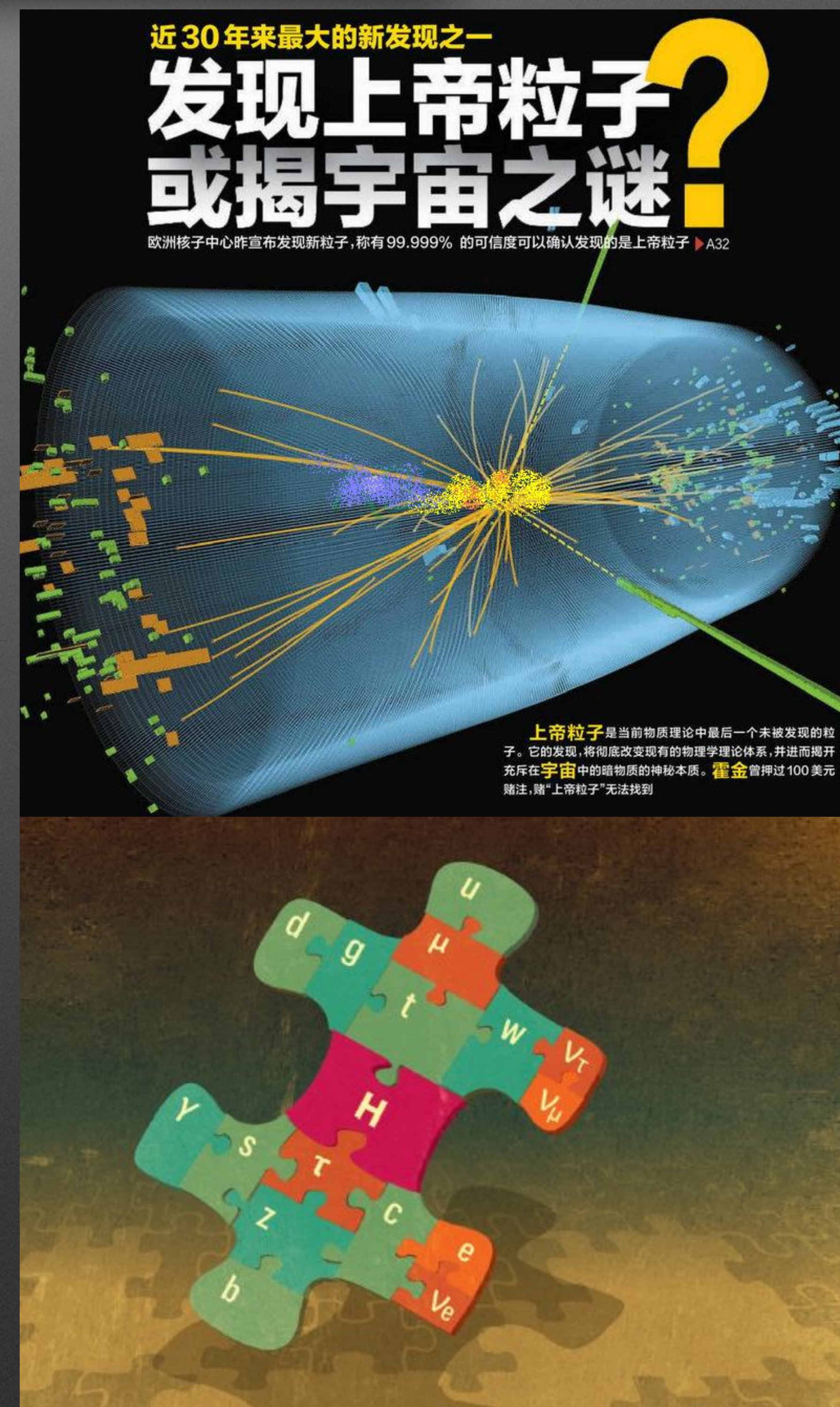
LHC discovered the Higgs boson

July 4th, 2012–A HISTORIC moment in science.



The mass is measured to be:

$$m_H = 125.04^{+0.26}_{-0.27}\ \text{stat.}\ ^{+0.13}_{-0.15}\ \text{syst.}\quad \text{GeV}$$



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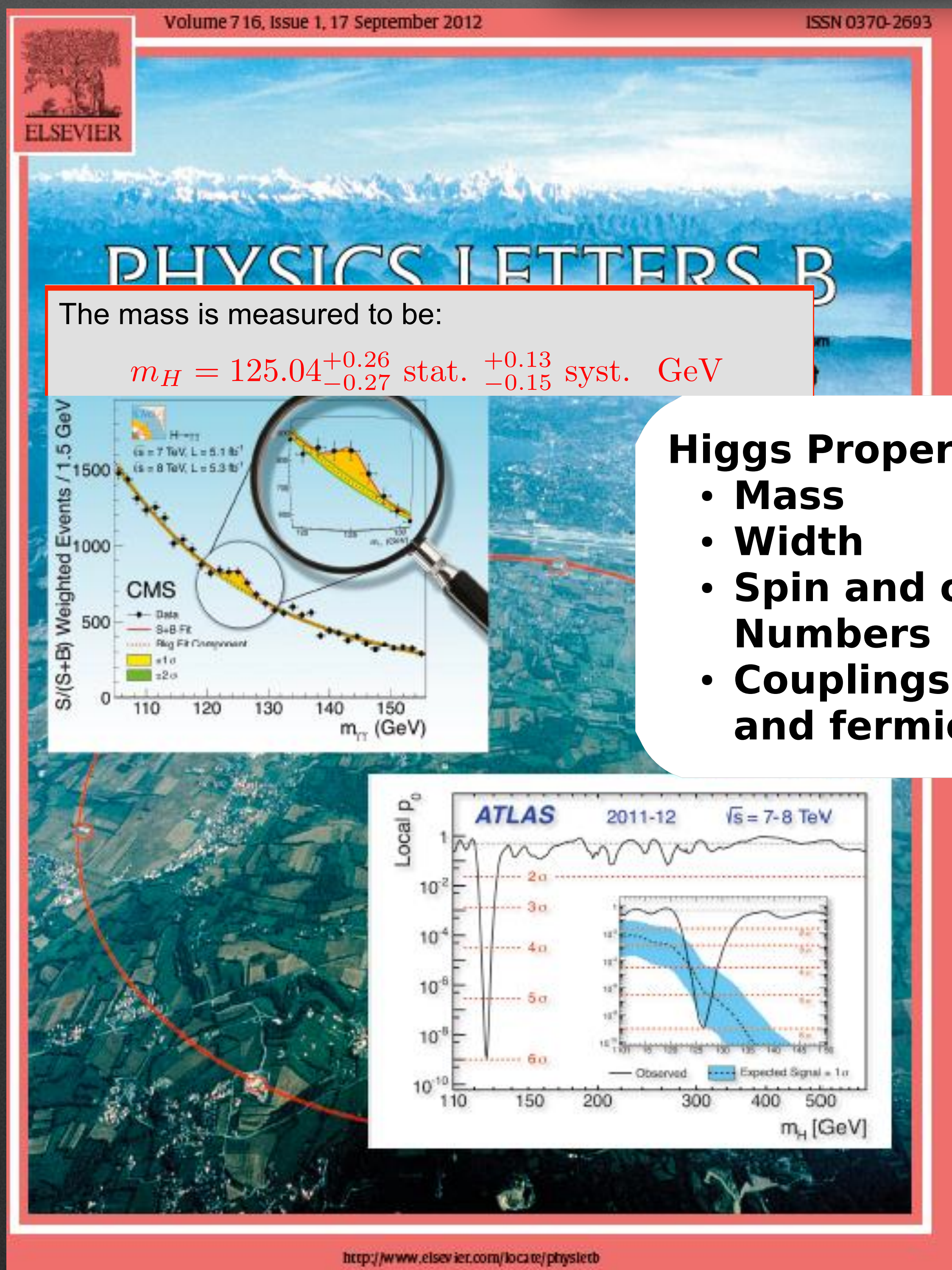

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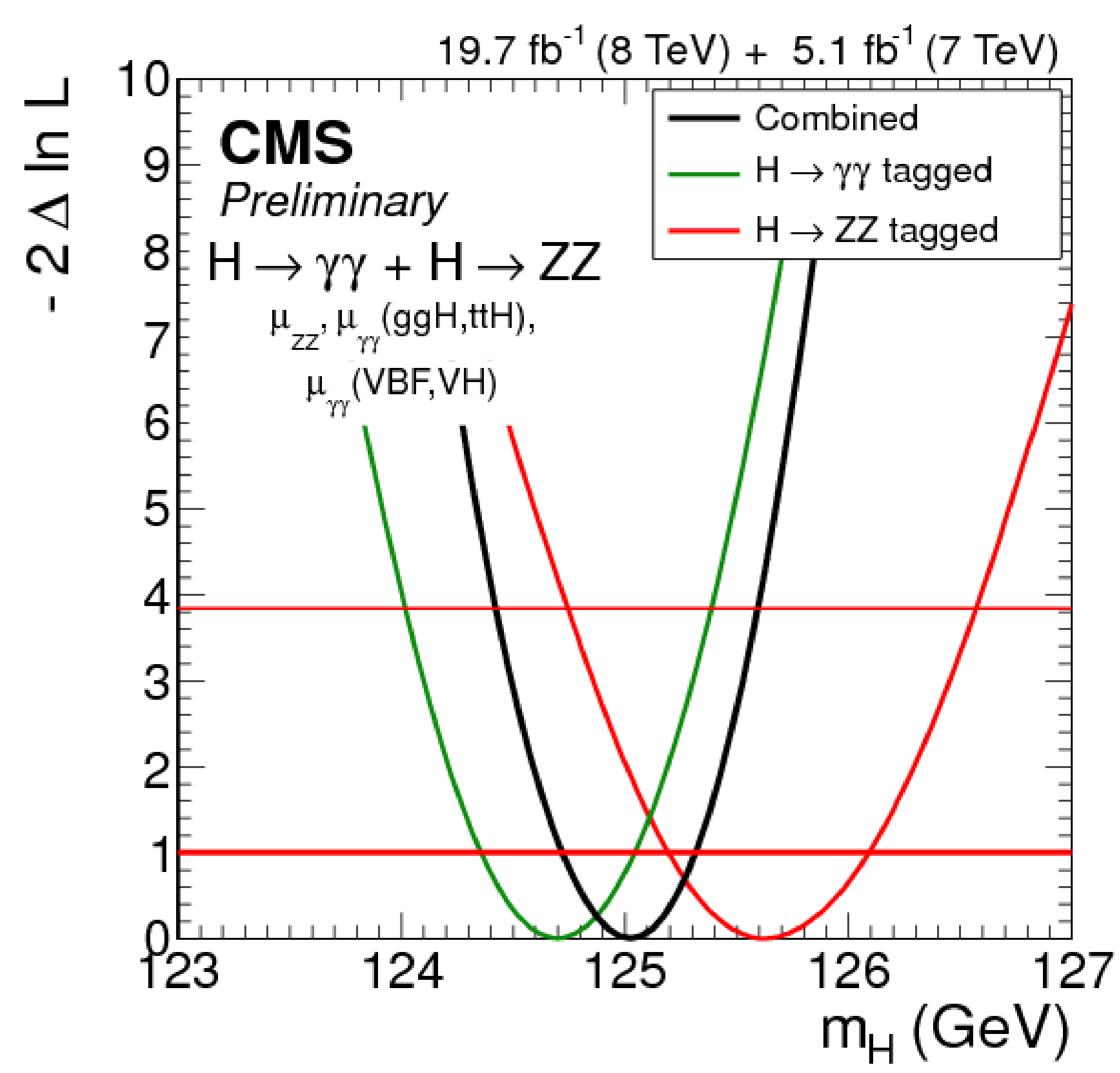
Higgs Properties:
- **Mass**
- **Width**
- **Spin and other Quantum Numbers**
- **Couplings (to vector bosons and fermions, and to itself)**

As of August 2014, CMS and ATLAS close chapter on Higgs measurements with the final harvest of results from the full Run I (7 & 8 TeV) dataset.



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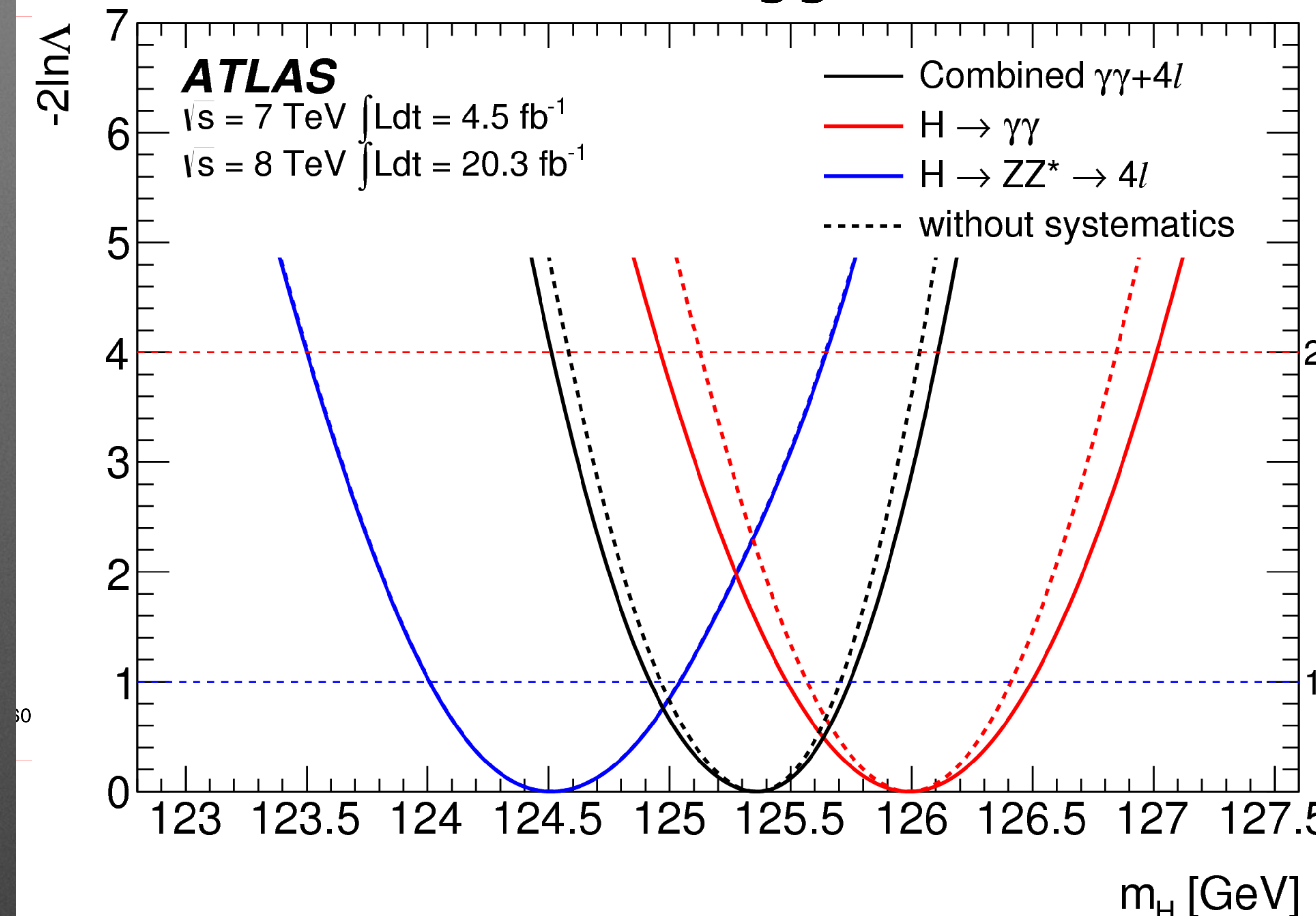
$$m_H = 125.04^{+0.26}_{-0.27} \text{ stat. } ^{+0.13}_{-0.15} \text{ syst. GeV}$$

And the two measurement (ZZ, γγ) agree at 1.6 sigma: $m_H^{\gamma\gamma} - m_H^{4l} = -0.87^{+0.54}_{-0.59}$ GeV

The Latest ATLAS Higgs Mass Results



$$m_H^{\gamma\gamma} = 125.98 \pm 0.42\,(\text{stat.}) \pm 0.28\,(\text{syst.})\text{ GeV}$$

$$m_H^{ZZ} = 124.51 \pm 0.52\,(\text{stat.}) \pm 0.06\,(\text{syst.})\text{ GeV}$$

$$m_H = 125.36 \pm 0.37\,(\text{stat.}) \pm 0.18\,(\text{syst.})\text{ GeV}$$

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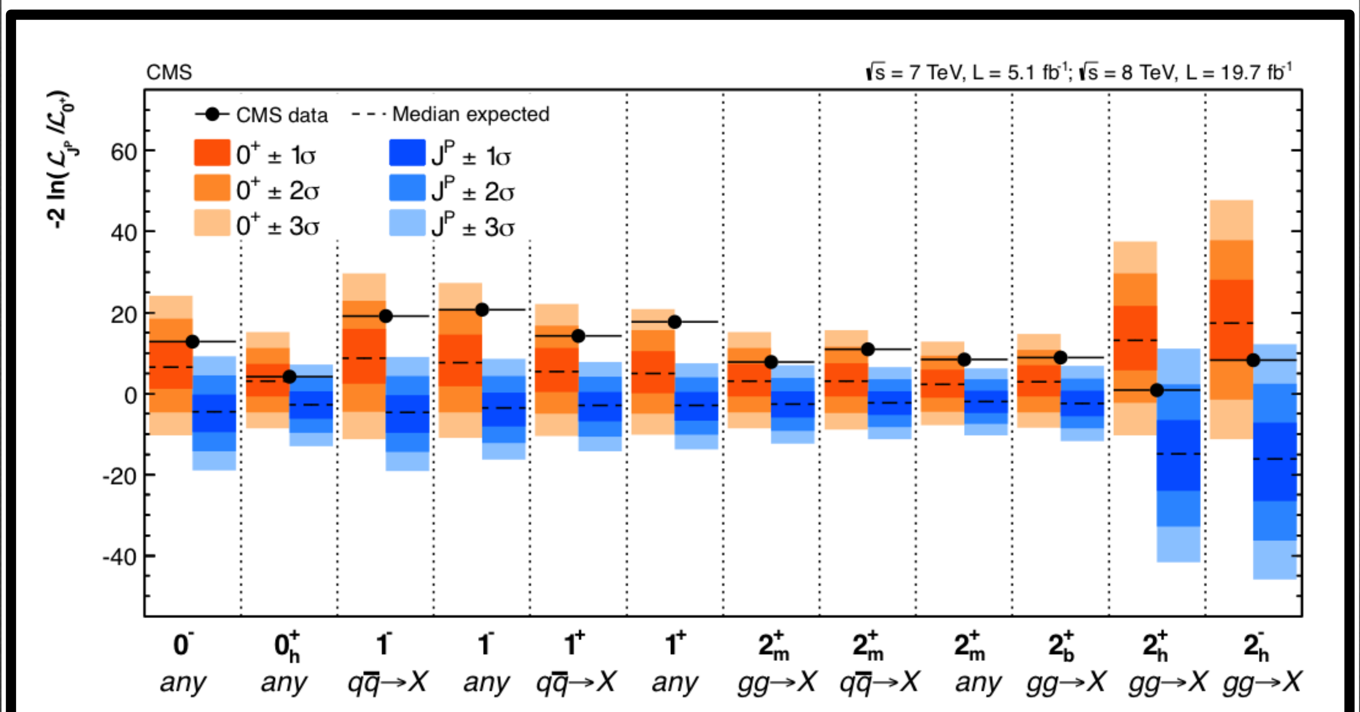
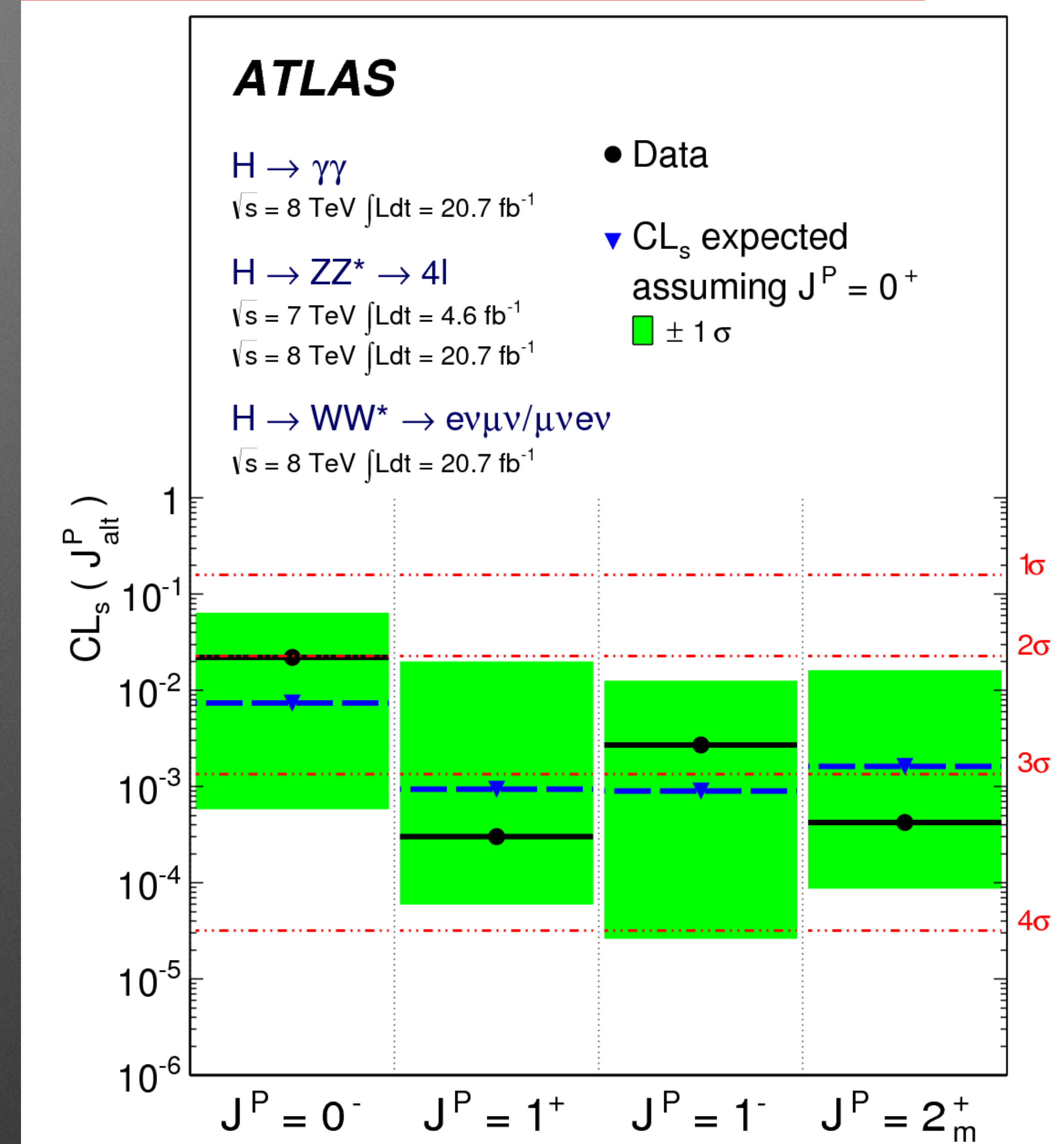


hypotheses excluded using the HZZ channel @99%C.L.

Phys. Lett. B 726 (2013), pp. 120-144

AT



$J^P = 0^+$ strongly favoured by measurements

Spin 1 and spin 2 and Pseudoscalar boson hypotheses: Excluded

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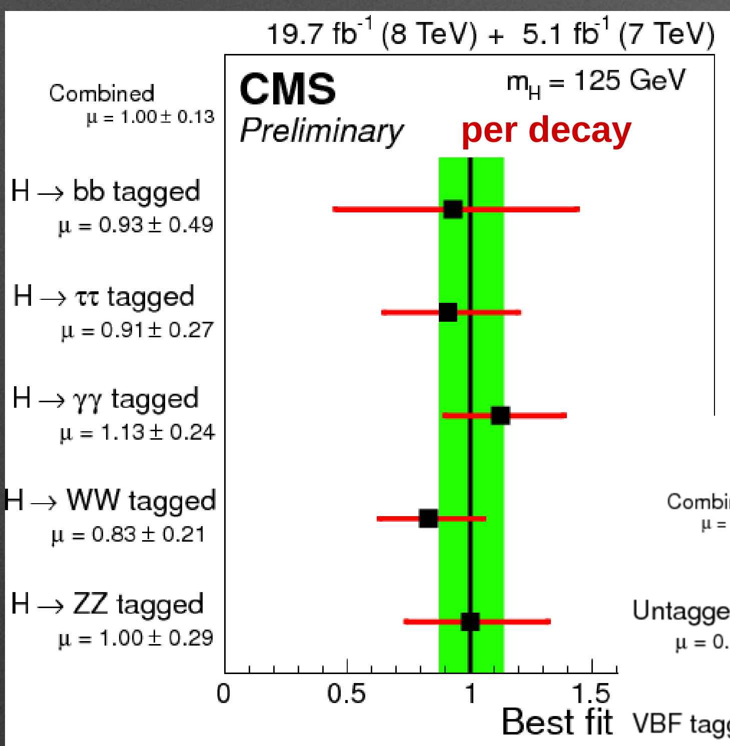
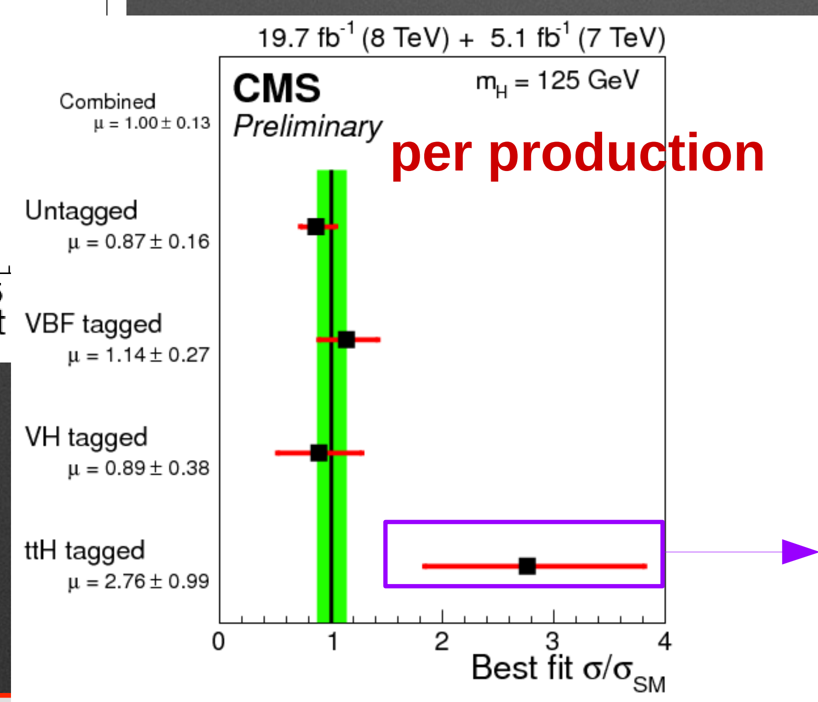
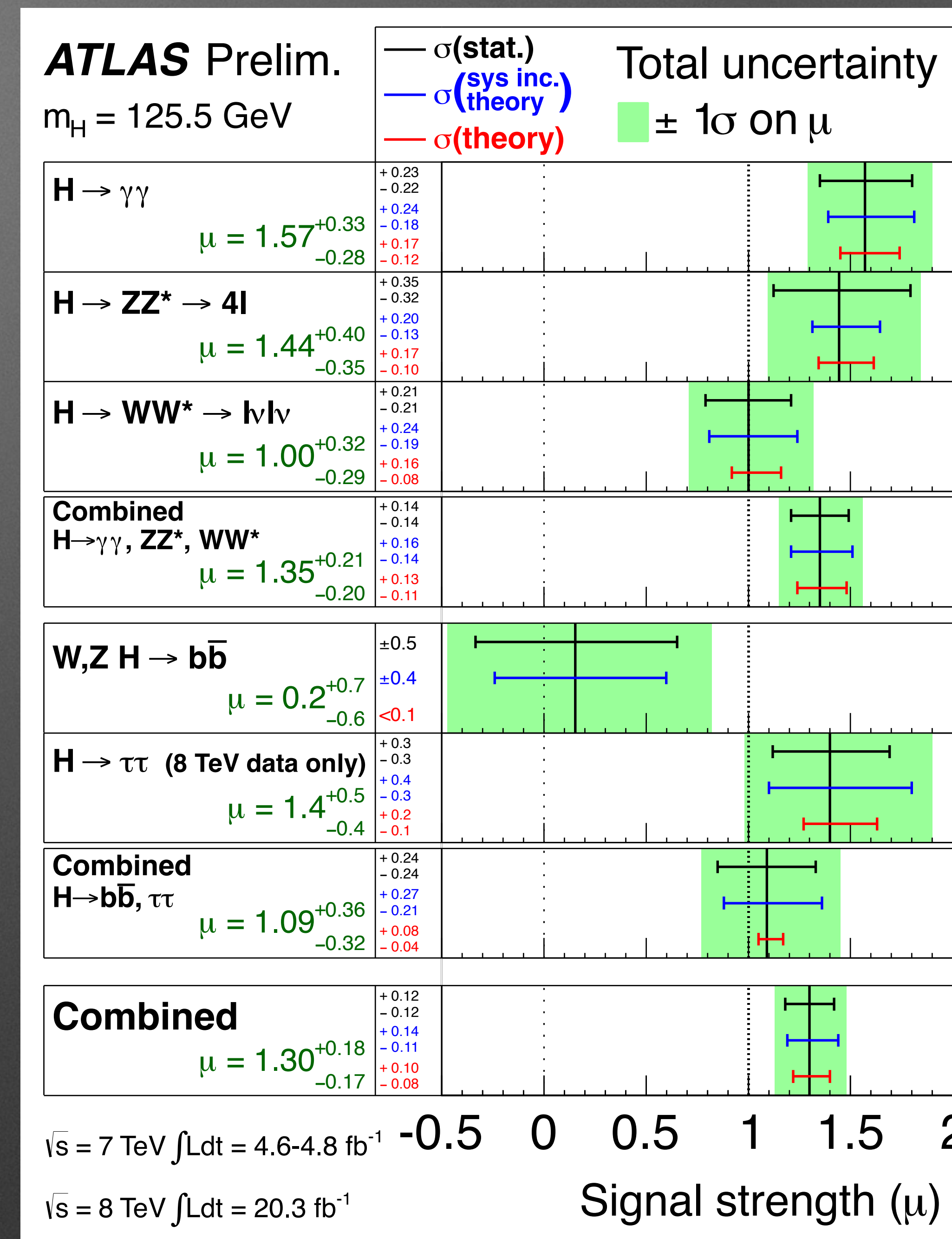
★ "seen" ☆ "tried"	$H\to b\bar{b}$	$H\to\tau\tau$	$H\to WW^*$	$H\to ZZ^*$	$H\to\gamma\gamma$	$H\to Z\gamma$	H→inv.	$H\to\mu\mu$
ggH		★	★	★	★	☆		☆
VBF	☆	★	★	☆	★	☆	☆	☆
VH	★	☆	☆	☆	☆		☆	
ttH	☆	☆	☆	☆	☆			







All measurements show that:
This particle is compatible with the SM Higgs boson!

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VBF	☆	★	★	☆	★	☆	☆	☆
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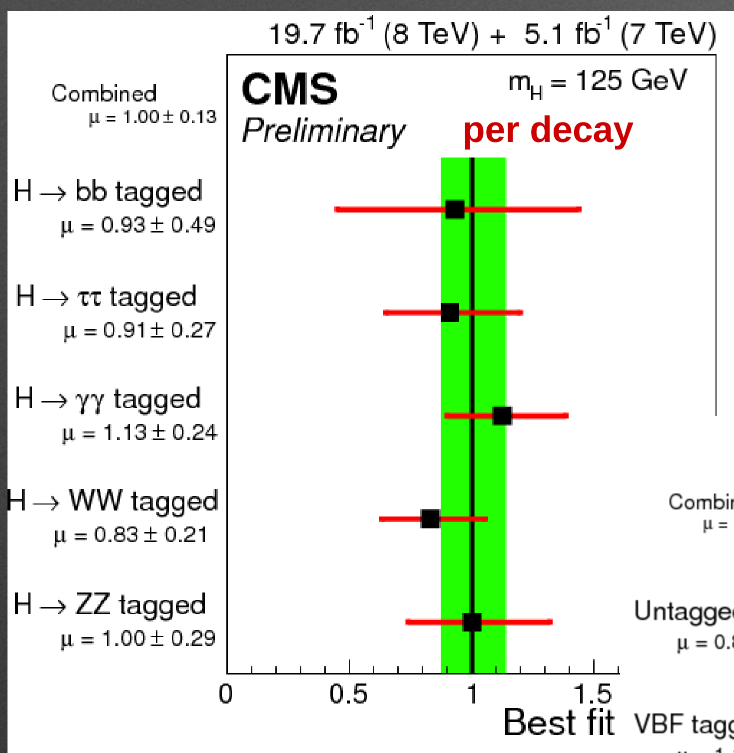
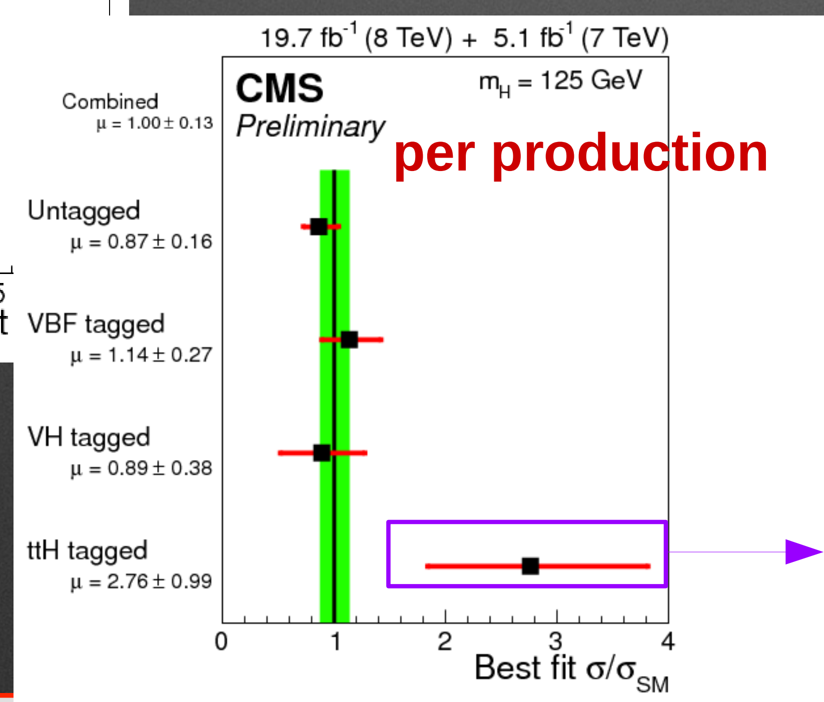
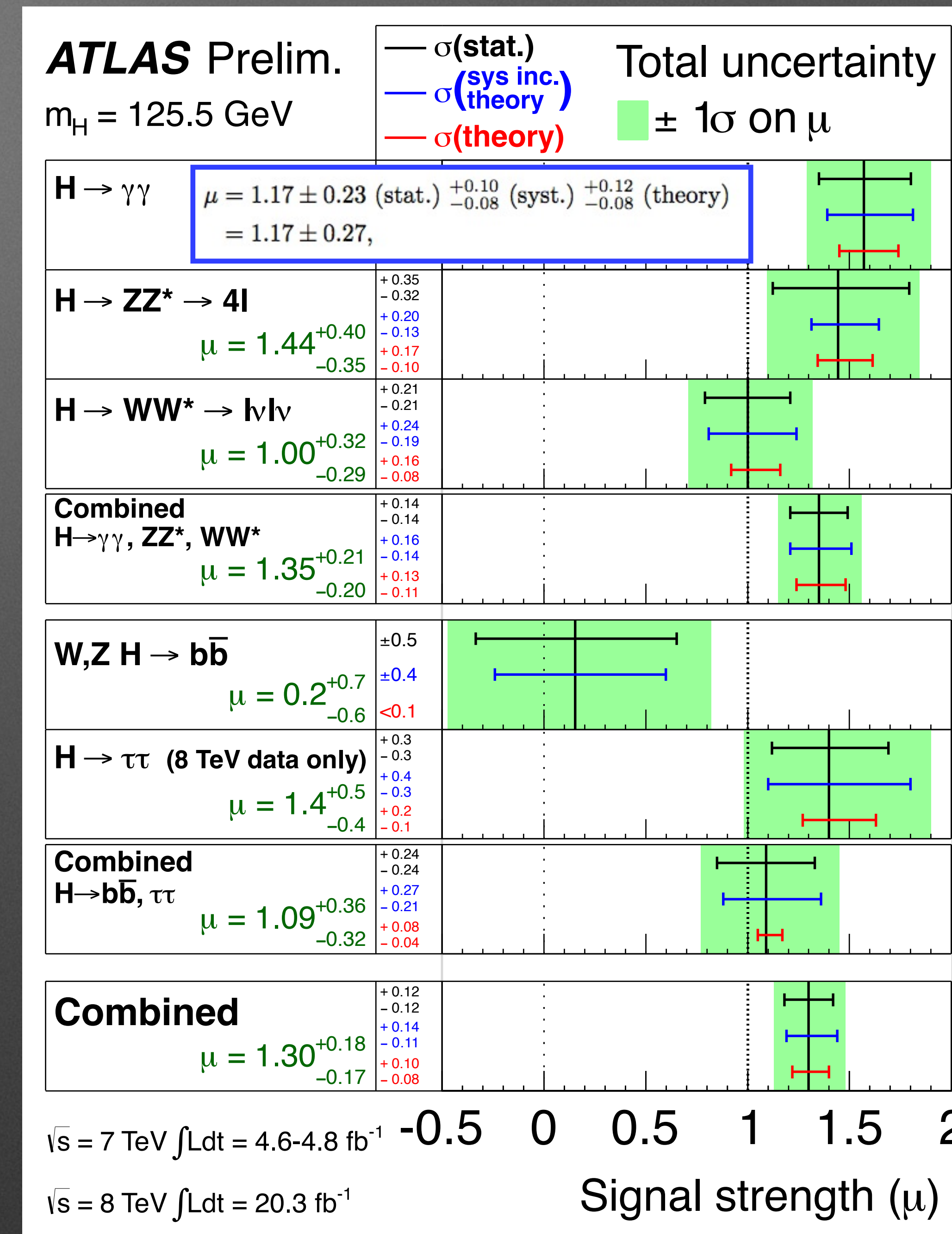
ttH	☆	☆	☆	☆	☆			







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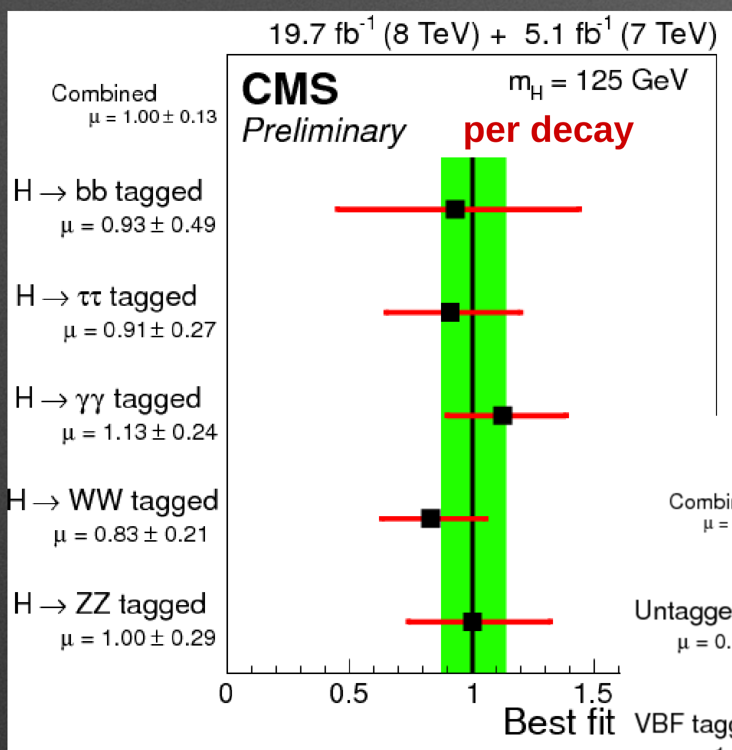
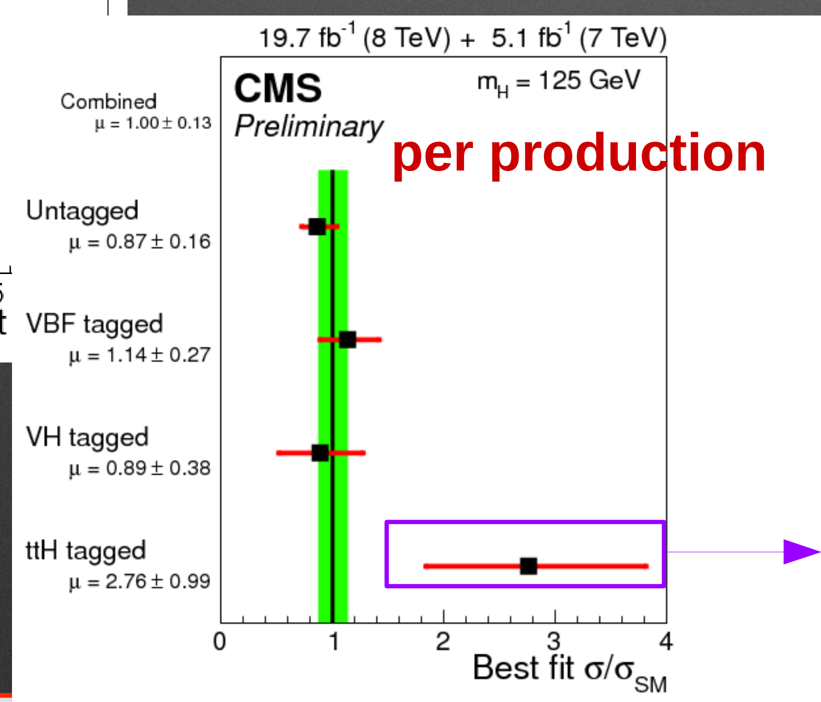
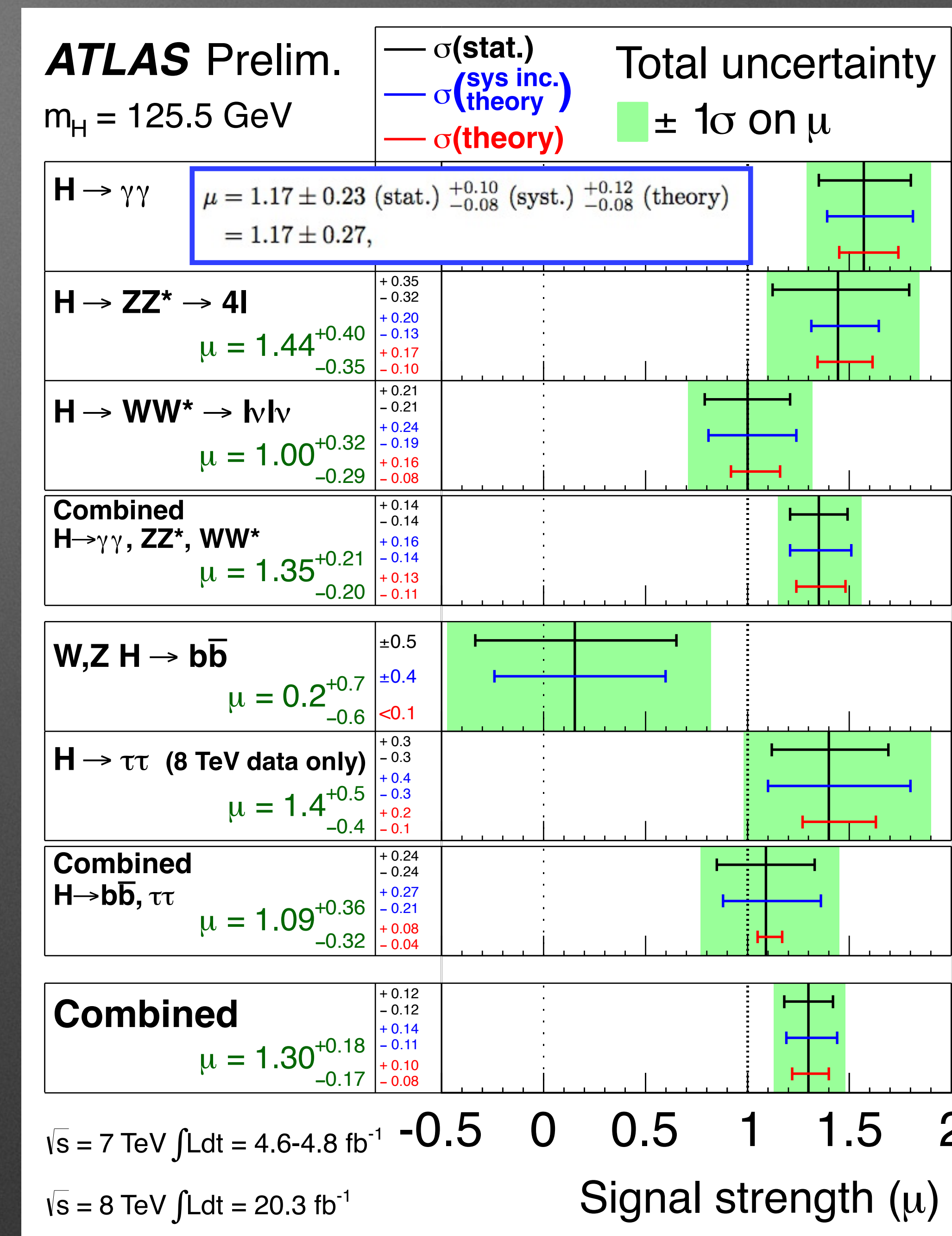
ttH	☆	☆	☆	☆	☆			







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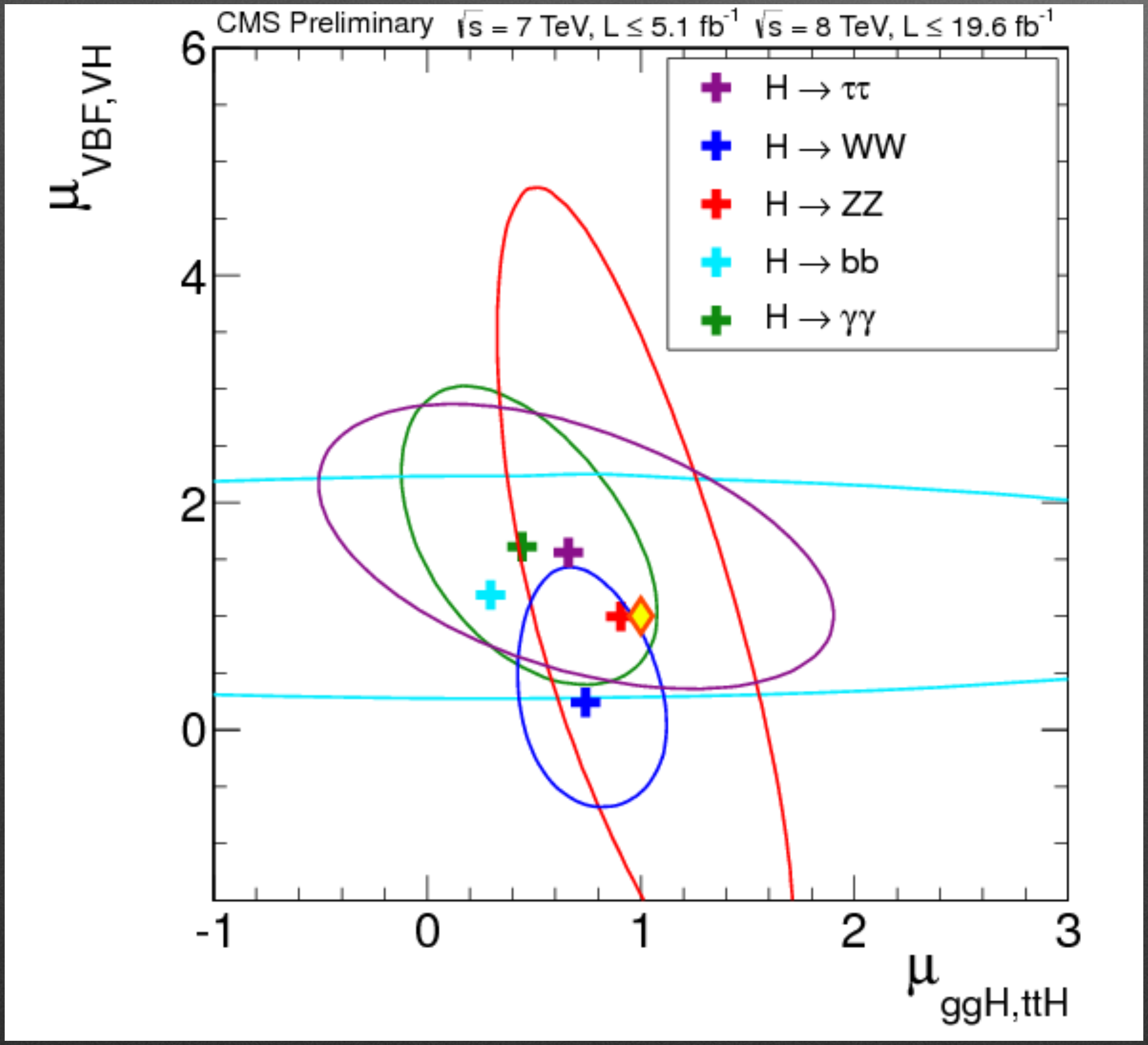
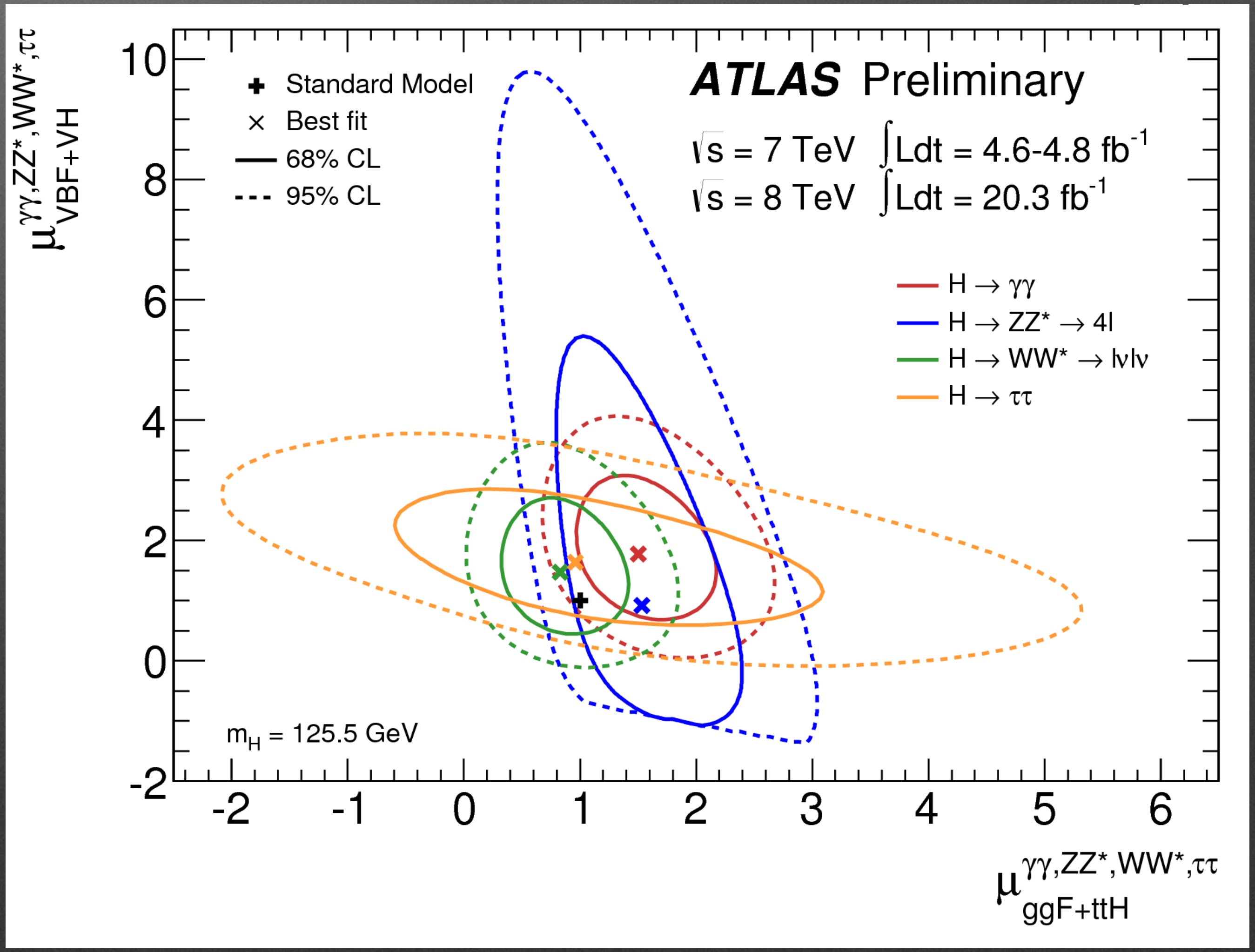
However, non-SM effect is still a possibility.

Deviation in Production Modes

125.5 GeV Higgs boson





SUMMER 2013

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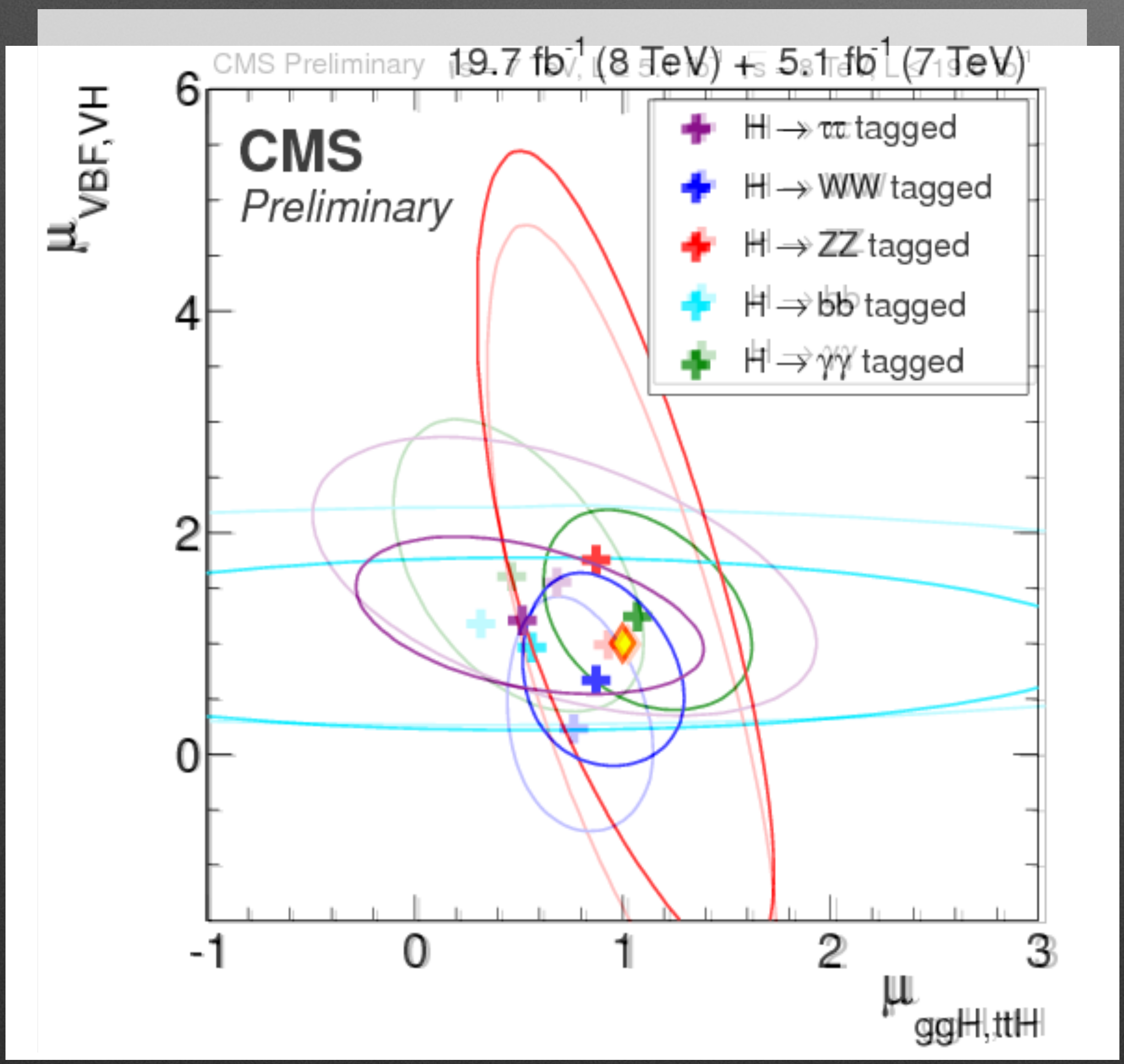

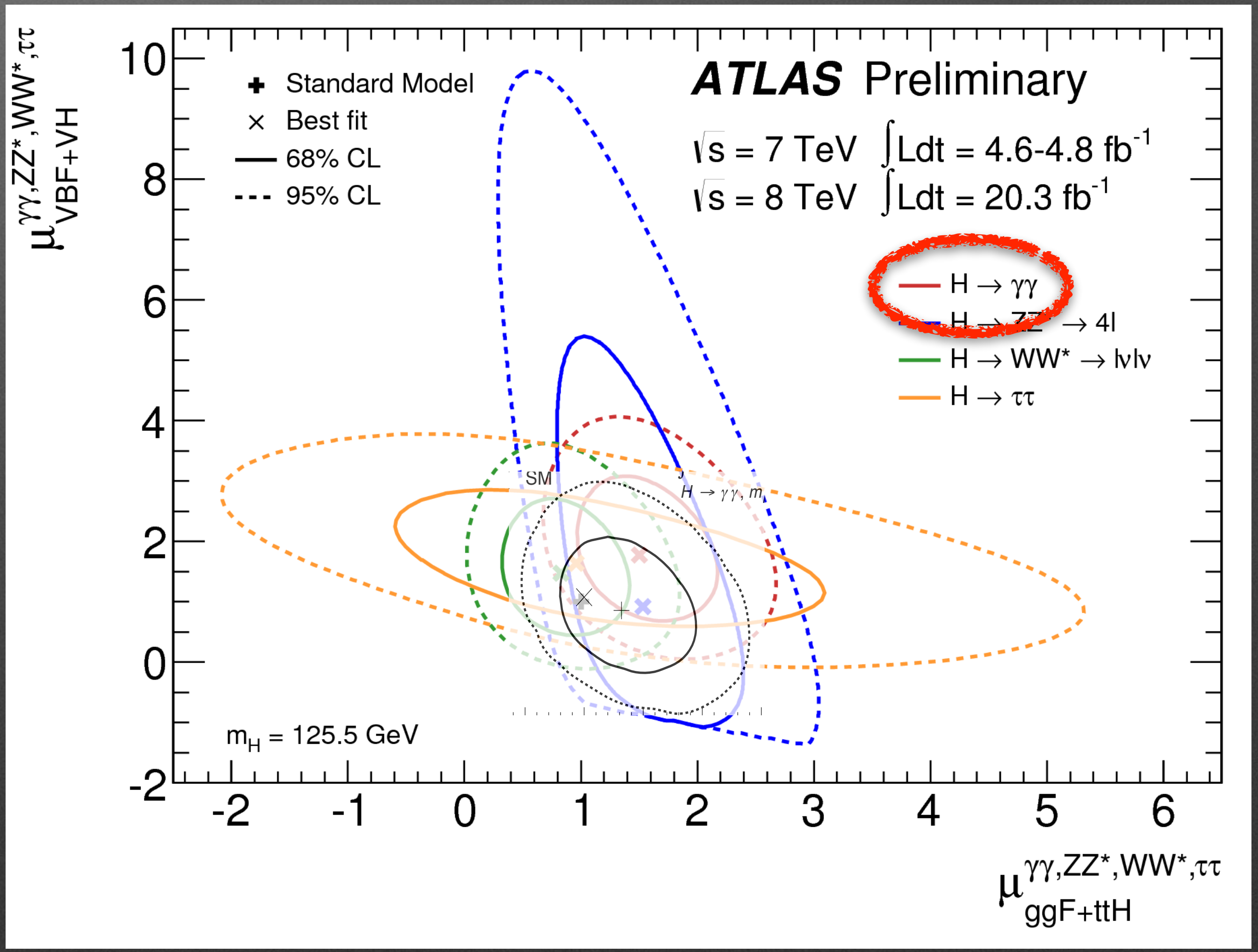

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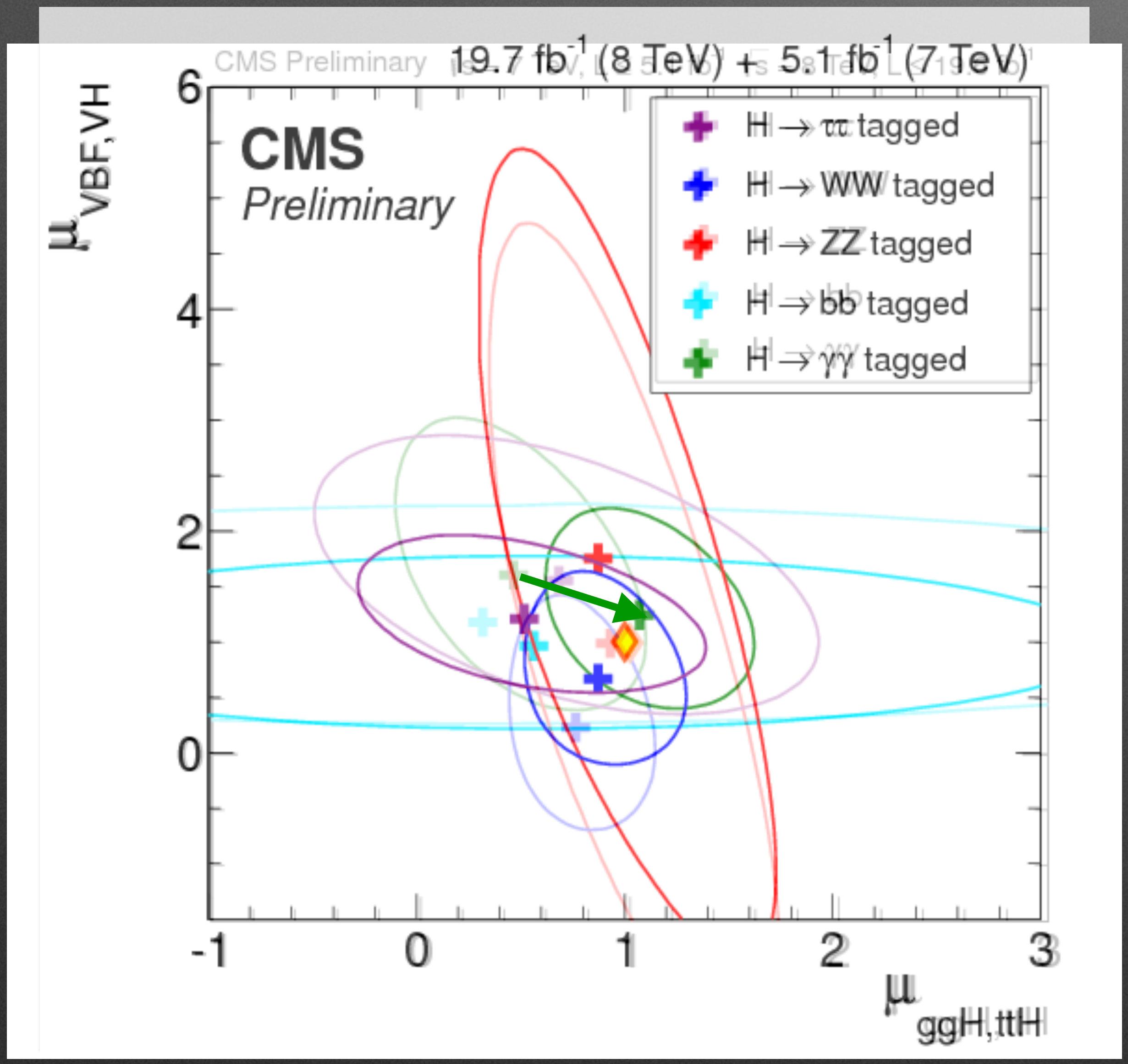

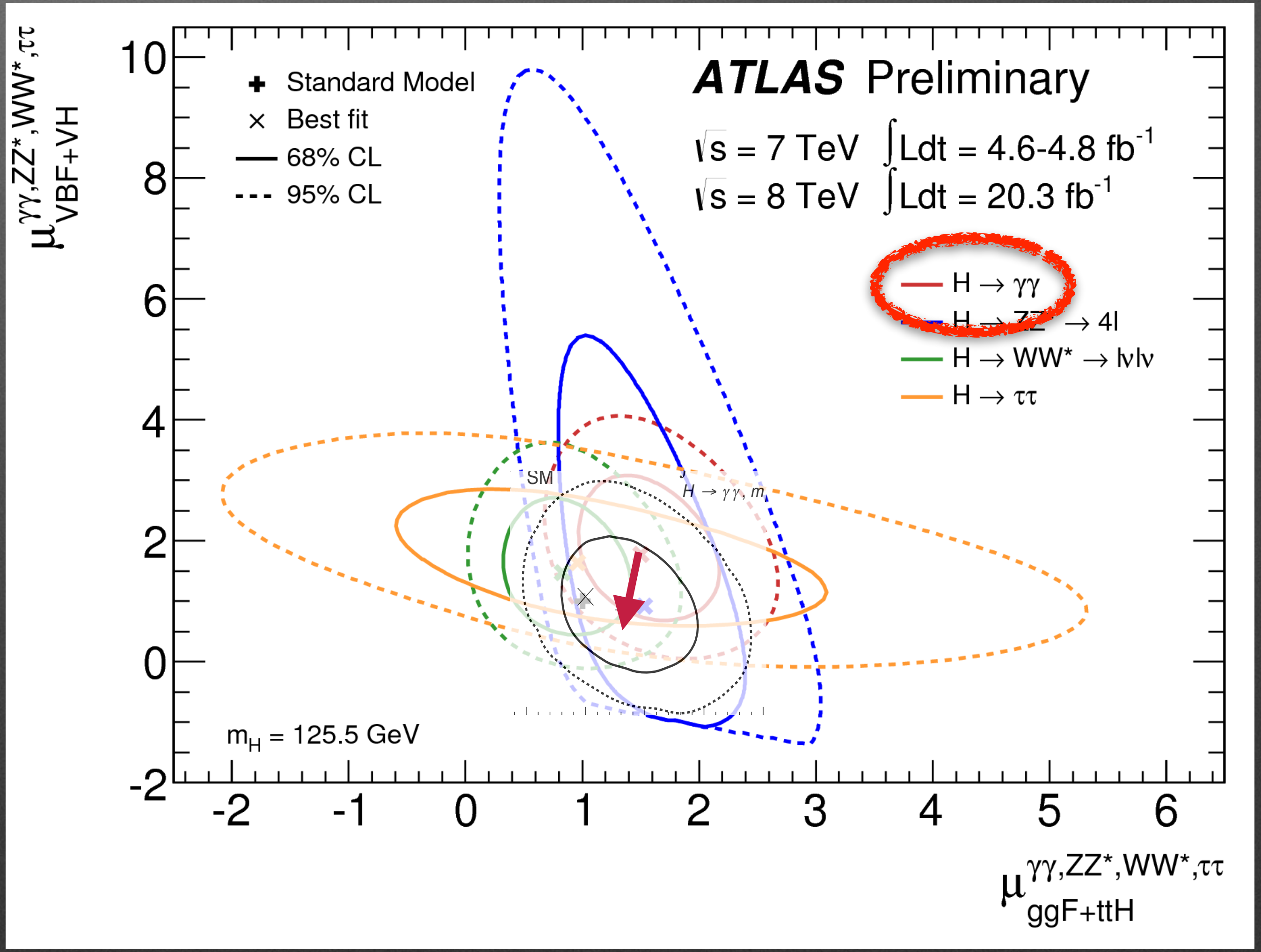

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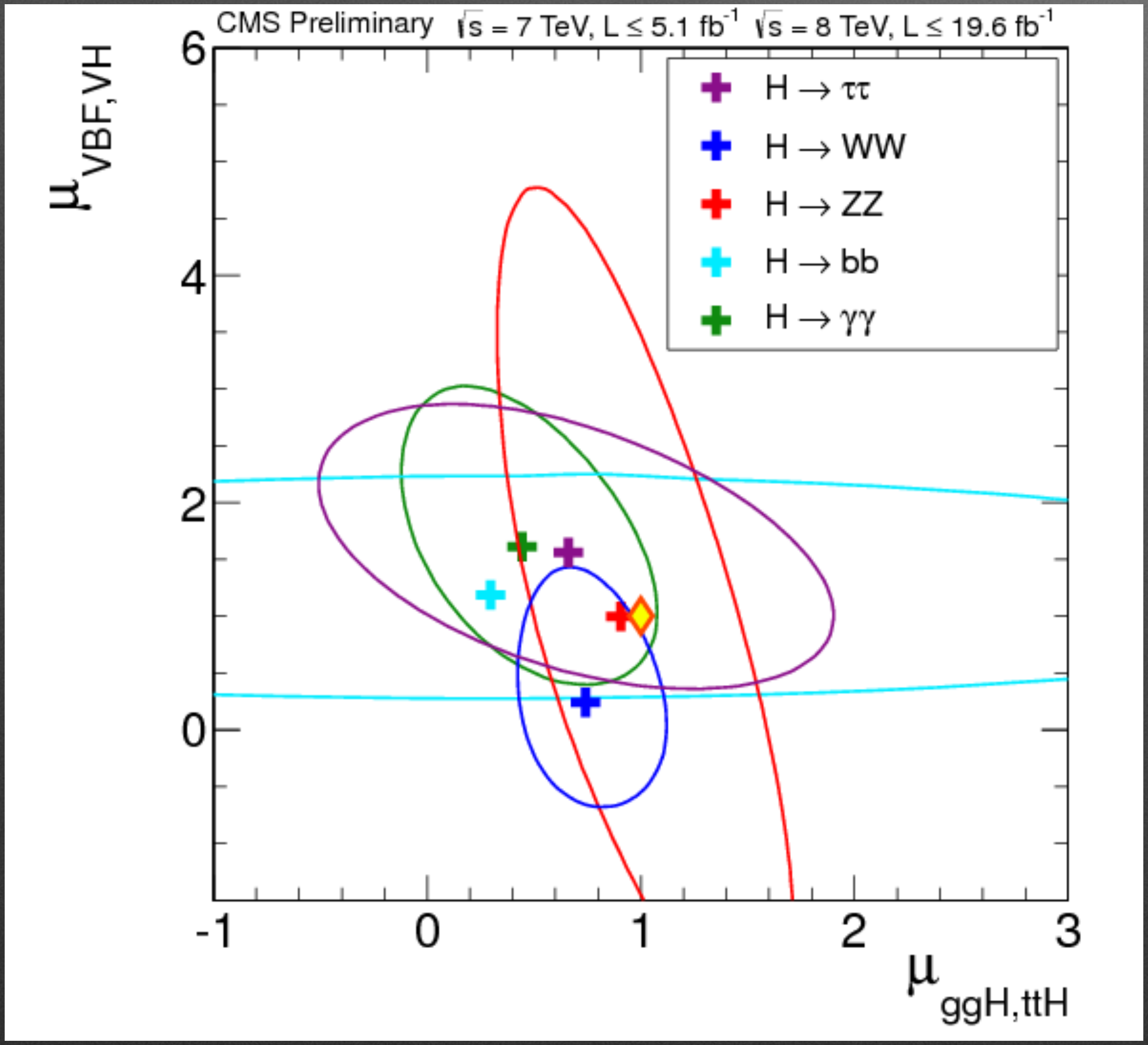

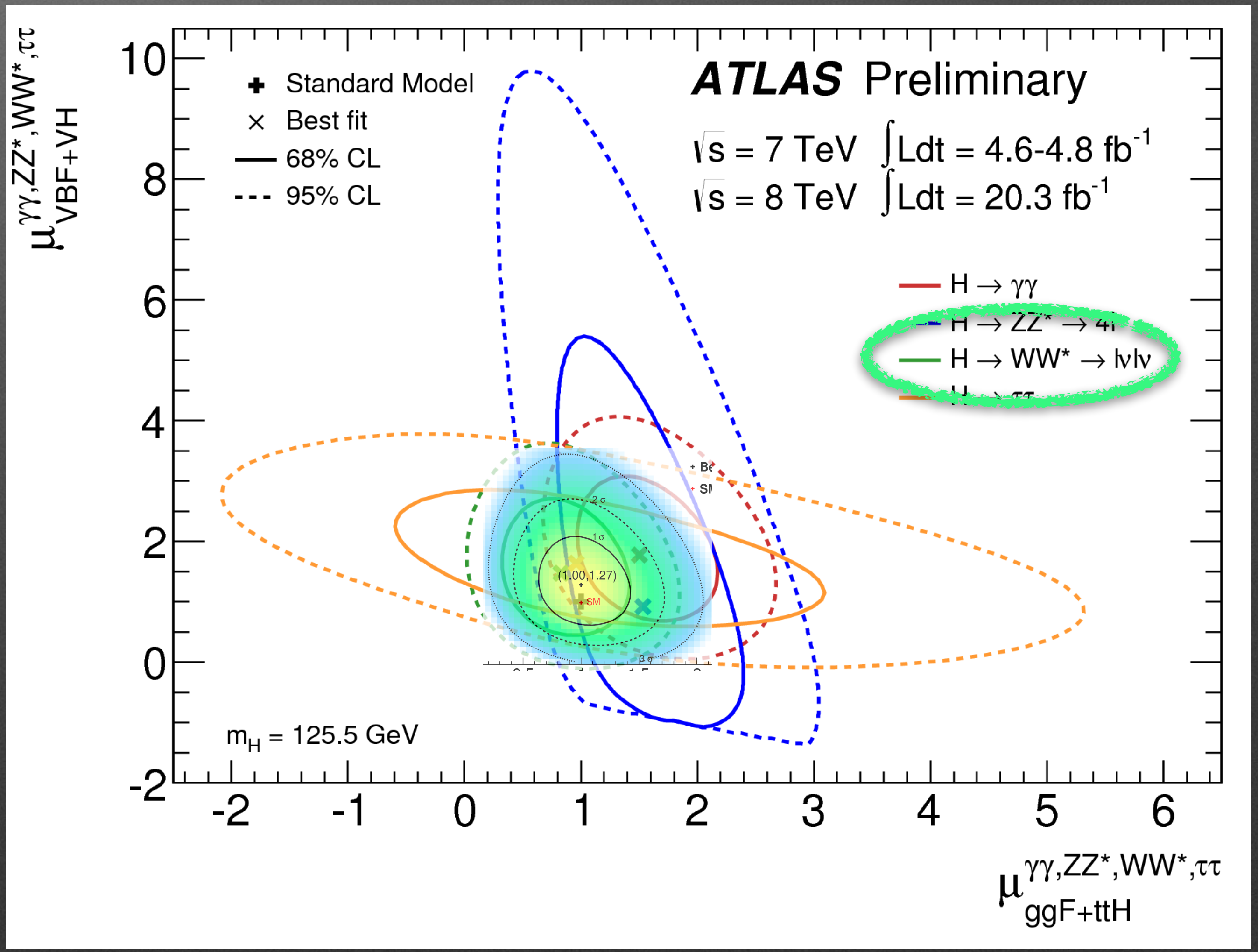

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Deviation in Production Modes

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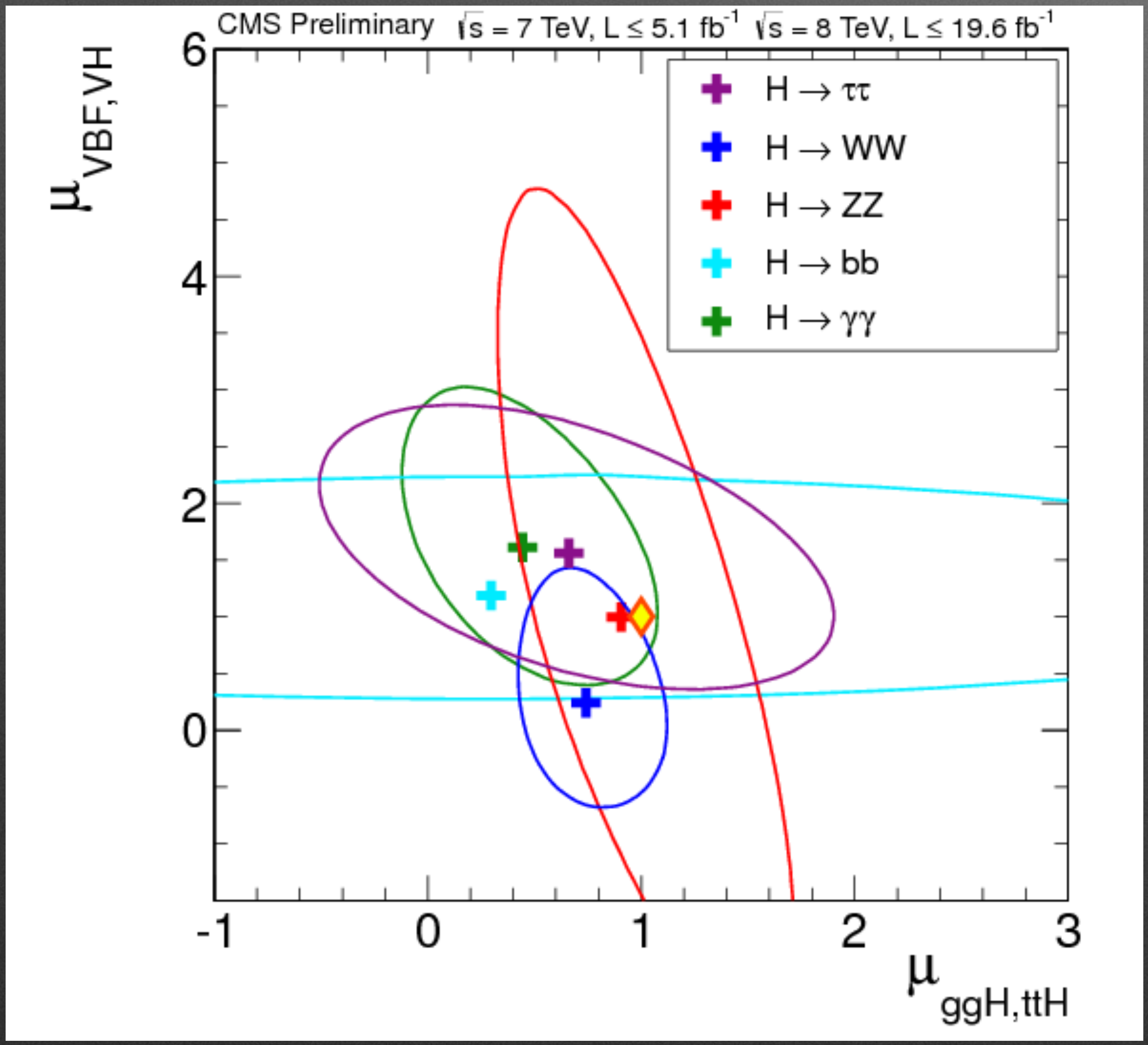

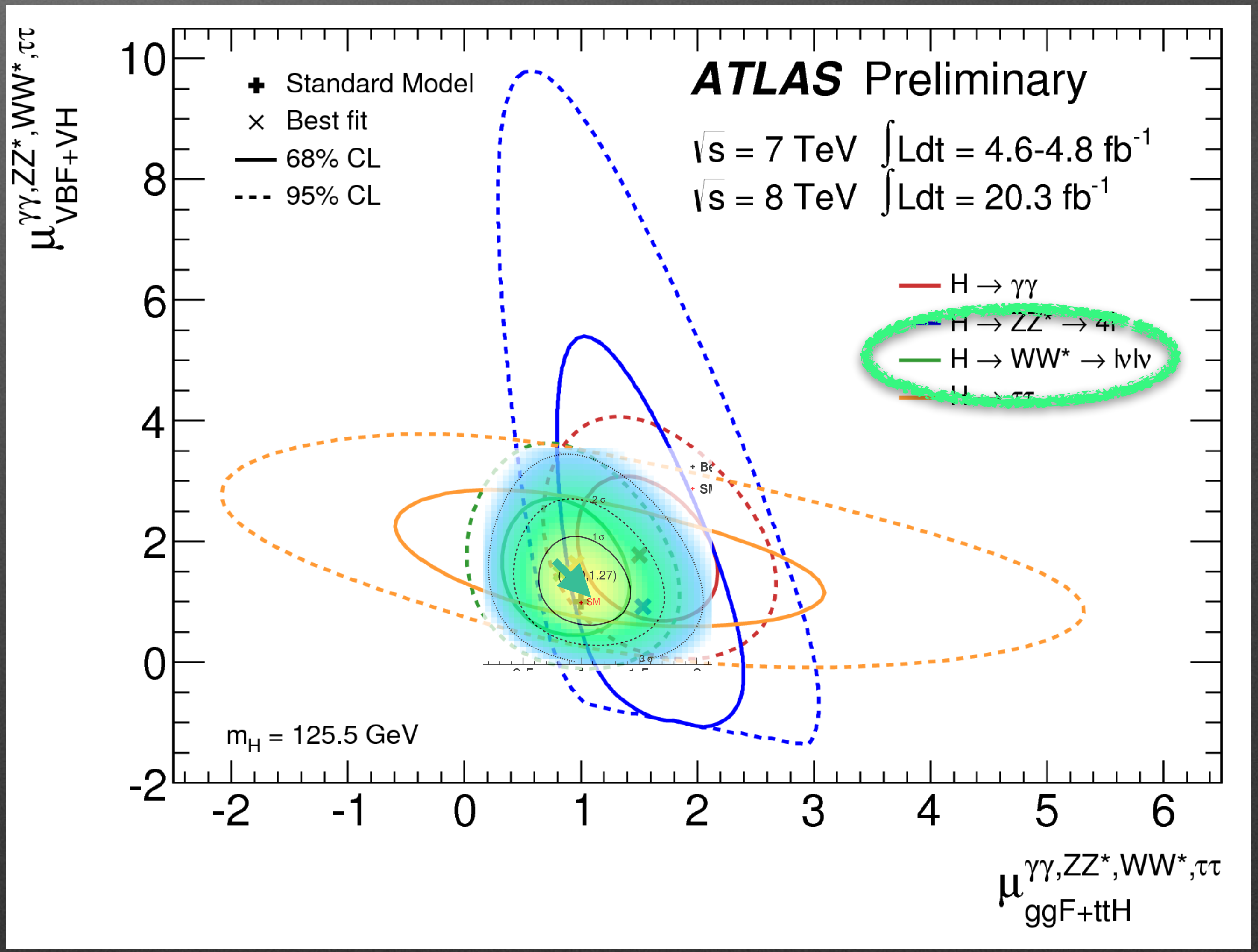

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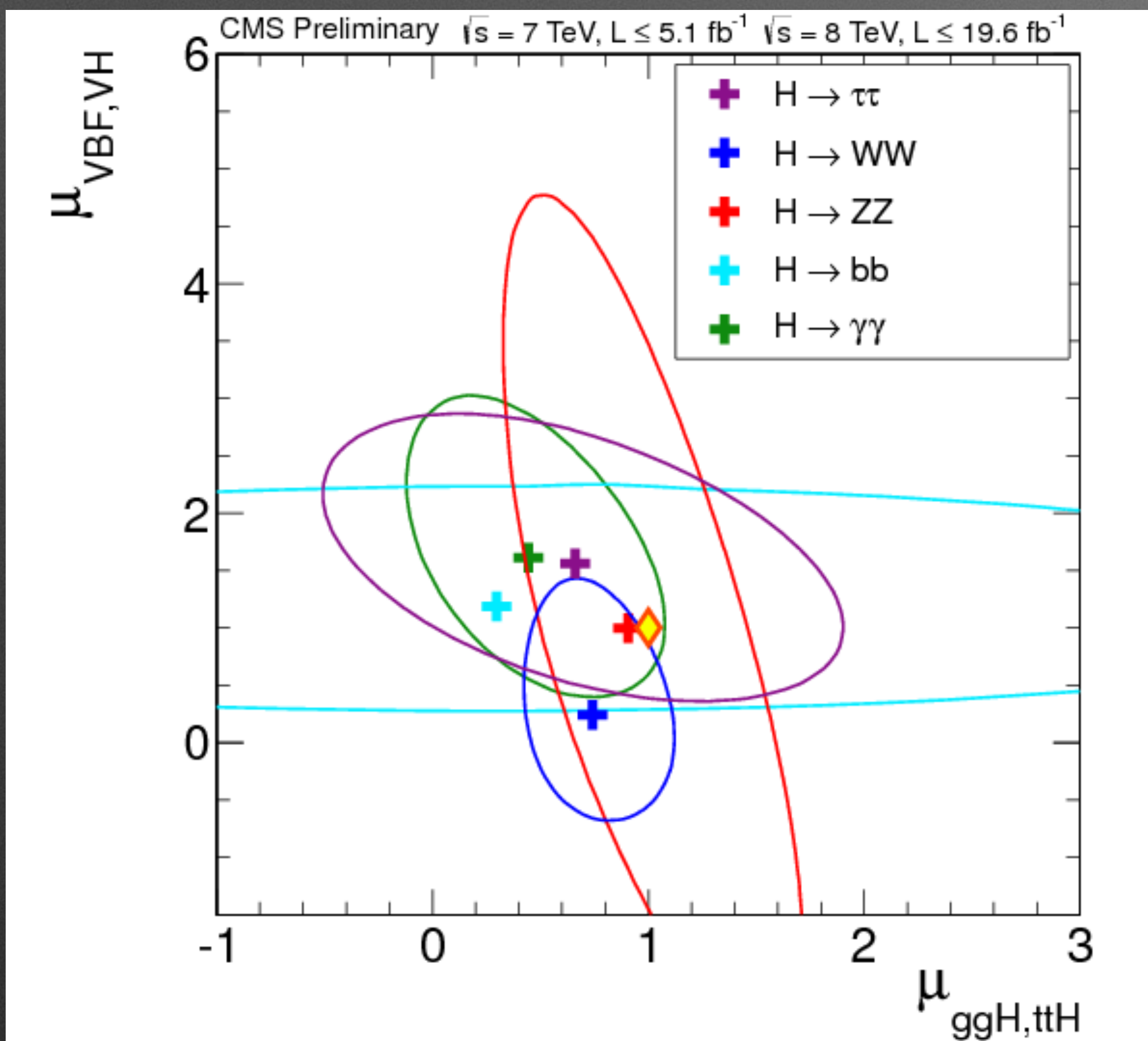

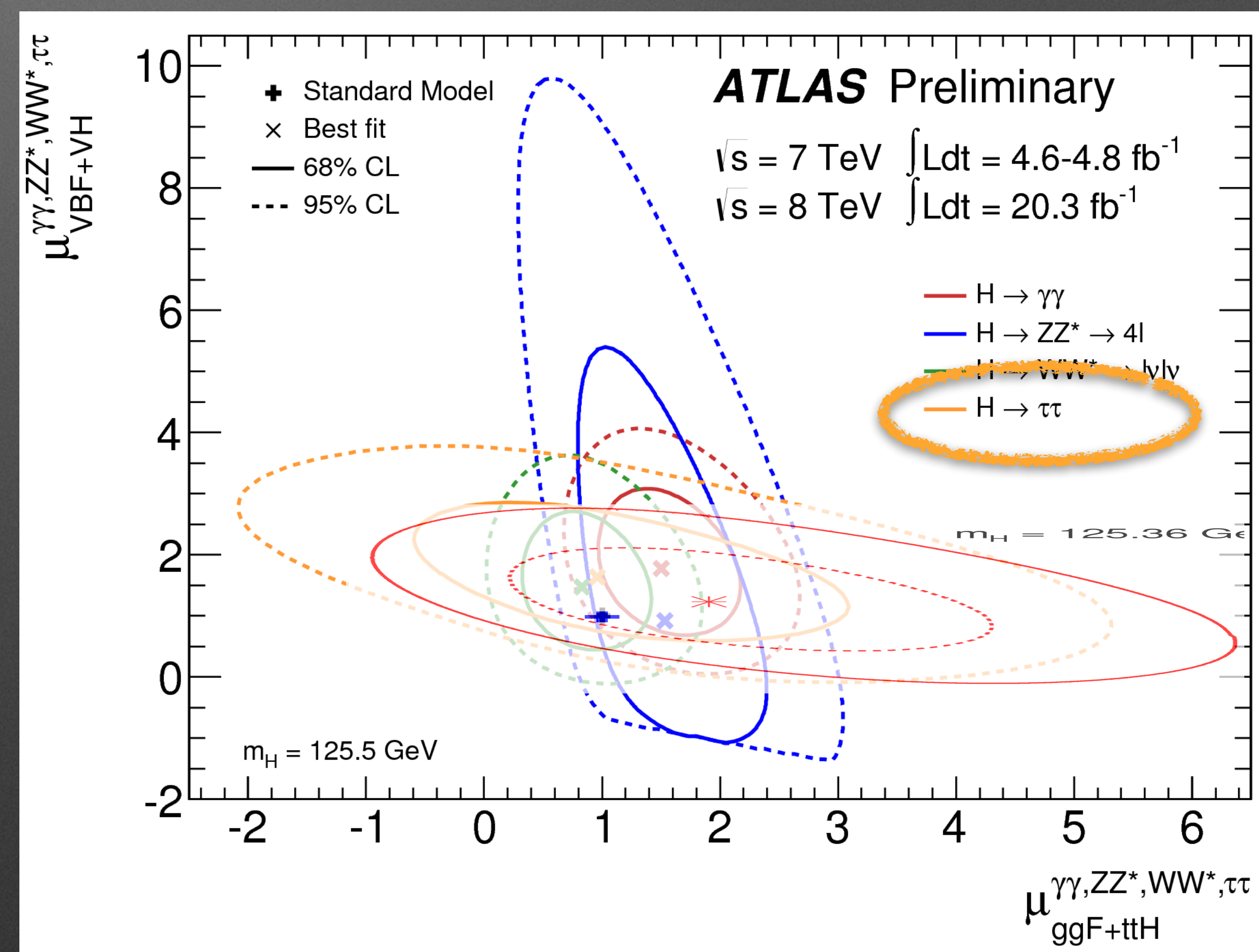

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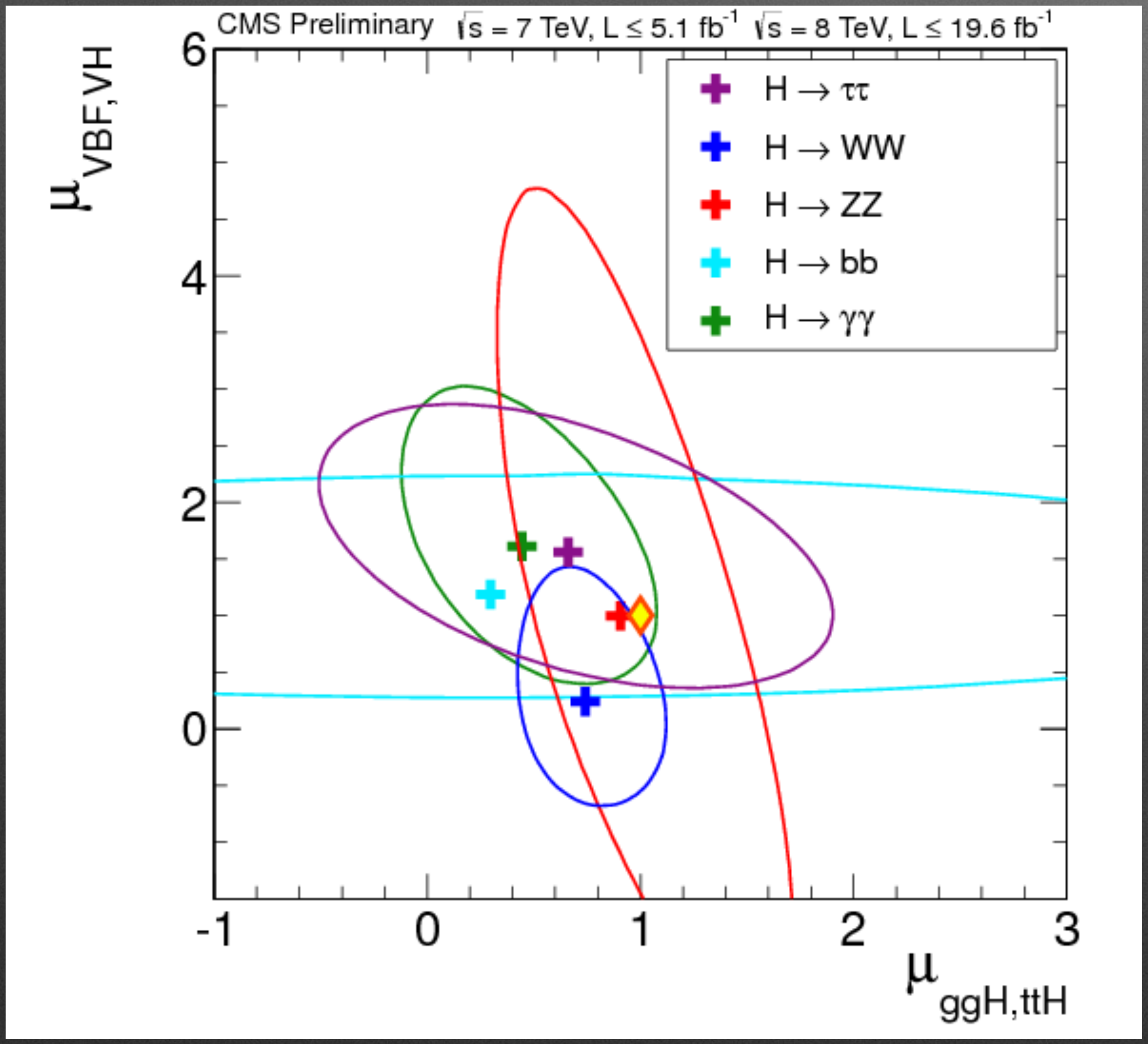

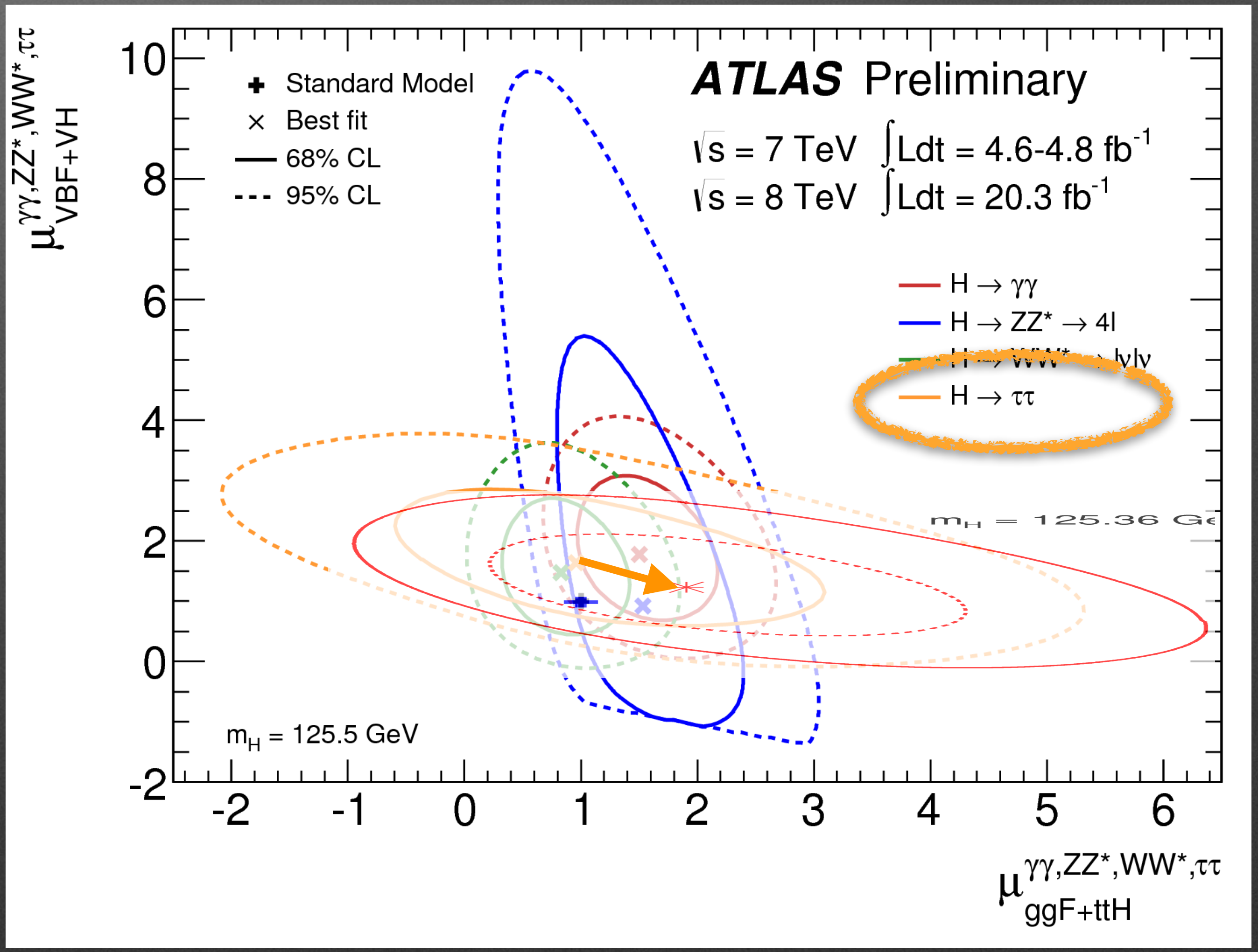

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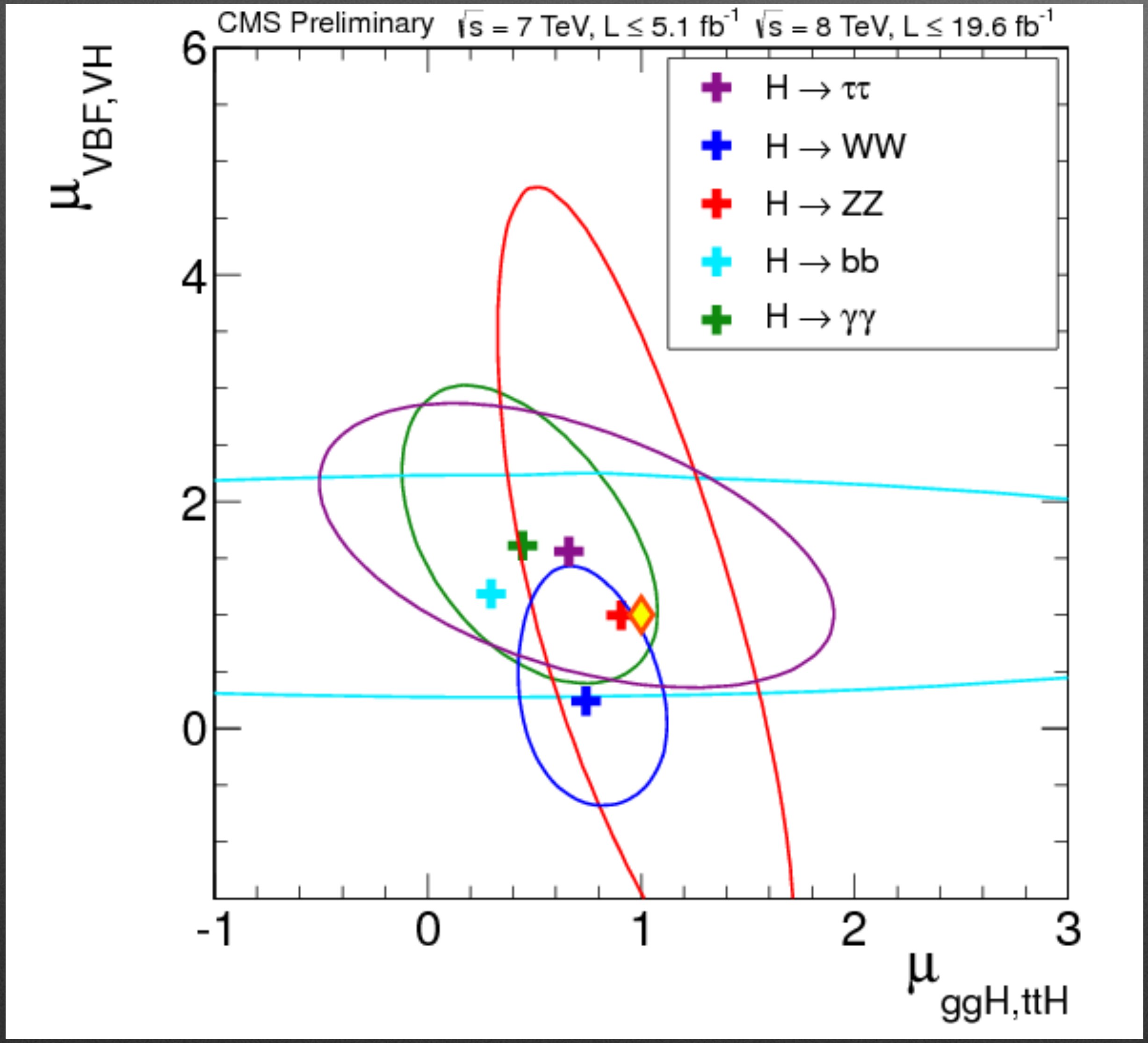

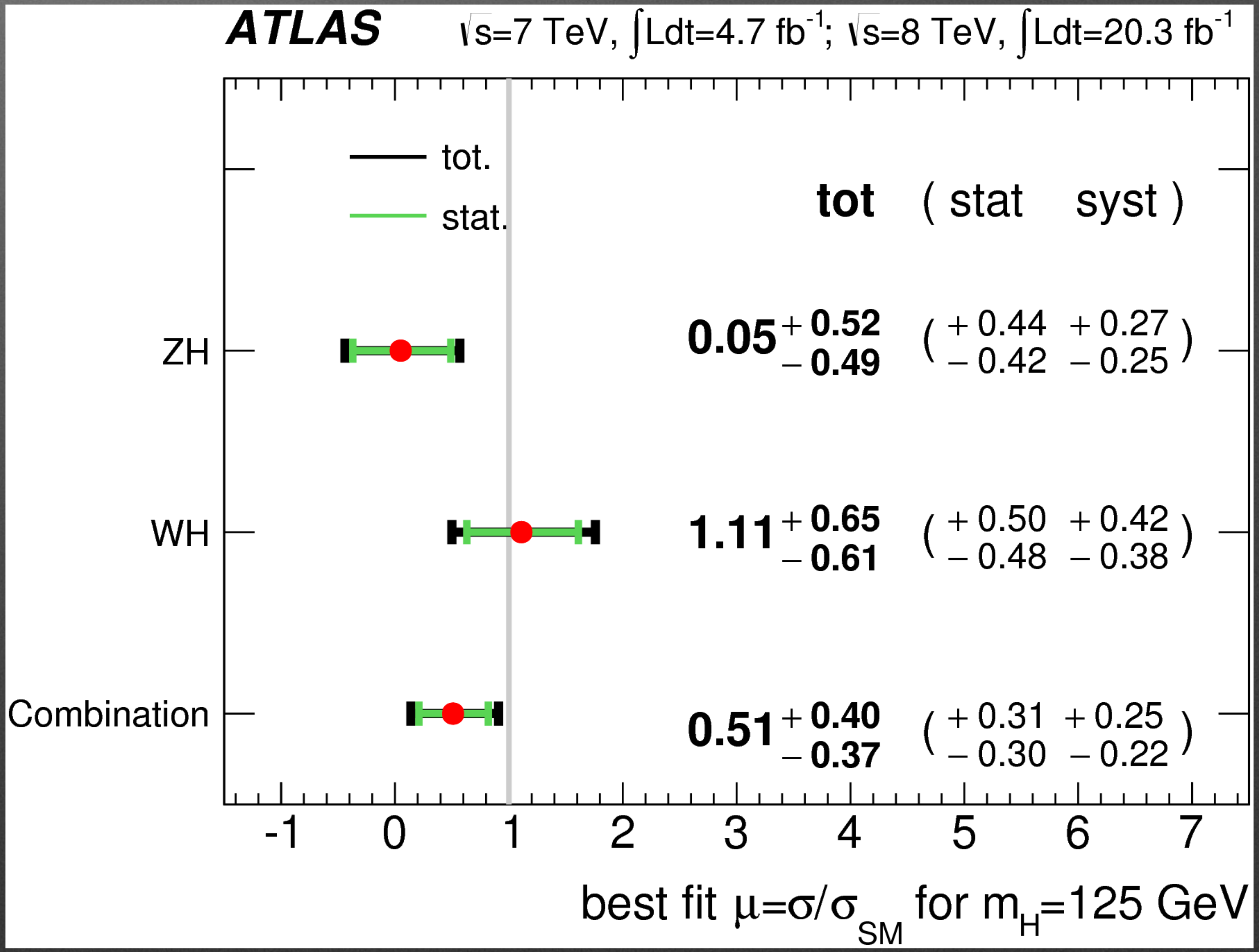

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$$\chi^2_Y = \begin{pmatrix} \mu_{\text{ggF},Y} - \hat{\mu}_{\text{ggF},Y} \\ \mu_{\text{VBF},Y} - \hat{\mu}_{\text{VBF},Y} \end{pmatrix}^T \begin{pmatrix} a_Y & b_Y \\ b_Y & c_Y \end{pmatrix} \begin{pmatrix} \mu_{\text{ggF},Y} - \hat{\mu}_{\text{ggF},Y}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

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

arXiv:1306.2941; 1409.1588

Lilith

Light **Li**kelihood **F**i**t** for the **H**iggs

http://lpsc.in2p3.fr/projects-th/lilith/index.html

Higgs fit update

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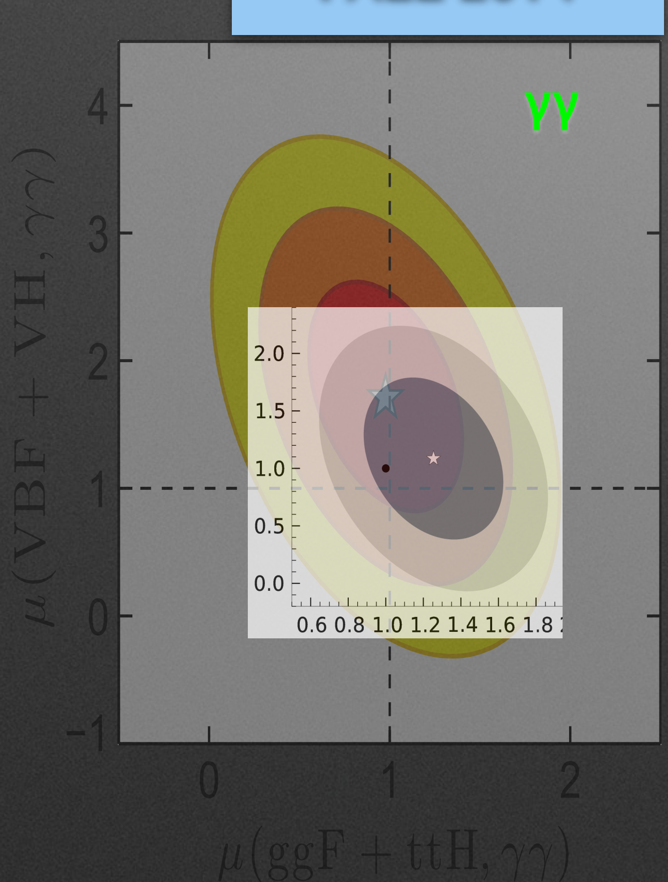

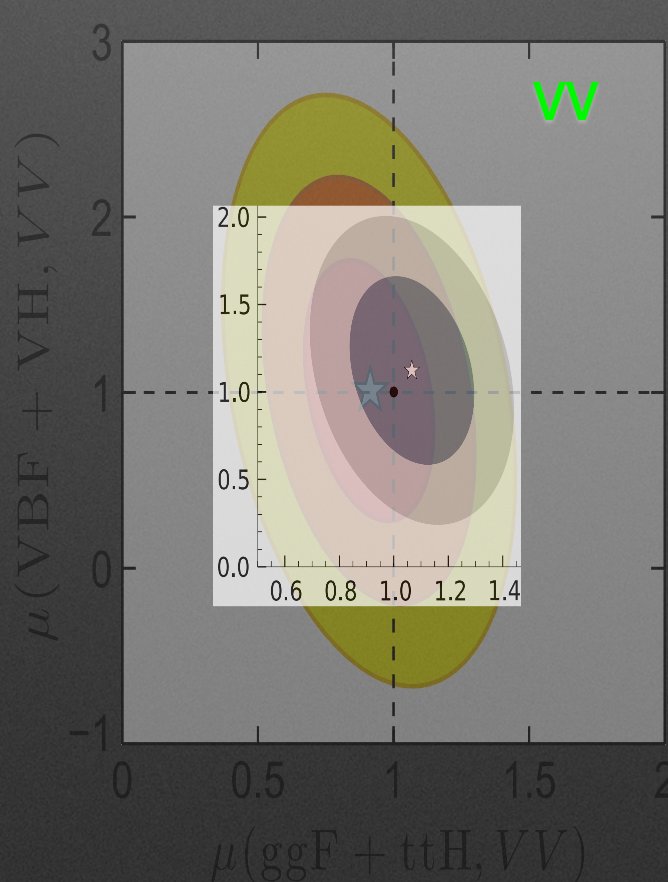

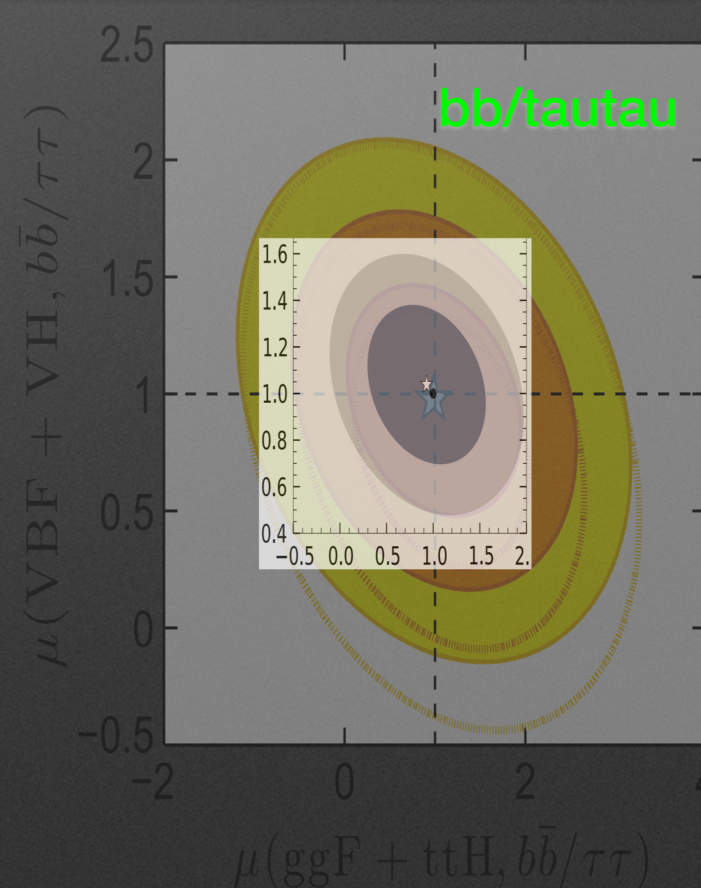

The most significant changes are slight downward/upward shifts of the central $\mu_{gg}(\gamma\gamma)$ and $\mu_{gg}(VV)$ value.

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	$\Phi_1 \to -\Phi_1, d^i_R \to -d^i_R$

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

	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.*

The J^P hypothesis 0^+ is highly favored

h-125.5 GeV

H-125.5 GeV

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preLHC

- stability
- unitarity
- perturbativity
- STU
- B-physics
- $(g-2)_\mu$
- LEP

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LHC8

- H/A limits:
  - $H \to ZZ^{(*)} \to 4\ell$
  - $gg \to H \to \tau\tau$ and $gg \to bbH$ with $H \to \tau\tau$

- postLHC: additionally, $\gamma\gamma$, ZZ, WW, bb, $\tau\tau$ signals

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Feed-down

Heavier scalars H/A may already be indirectly observed at the LHC, not through their decay into gauge bosons or fermions, but rather through **chain decays** into 125.5 GeV Higgs.

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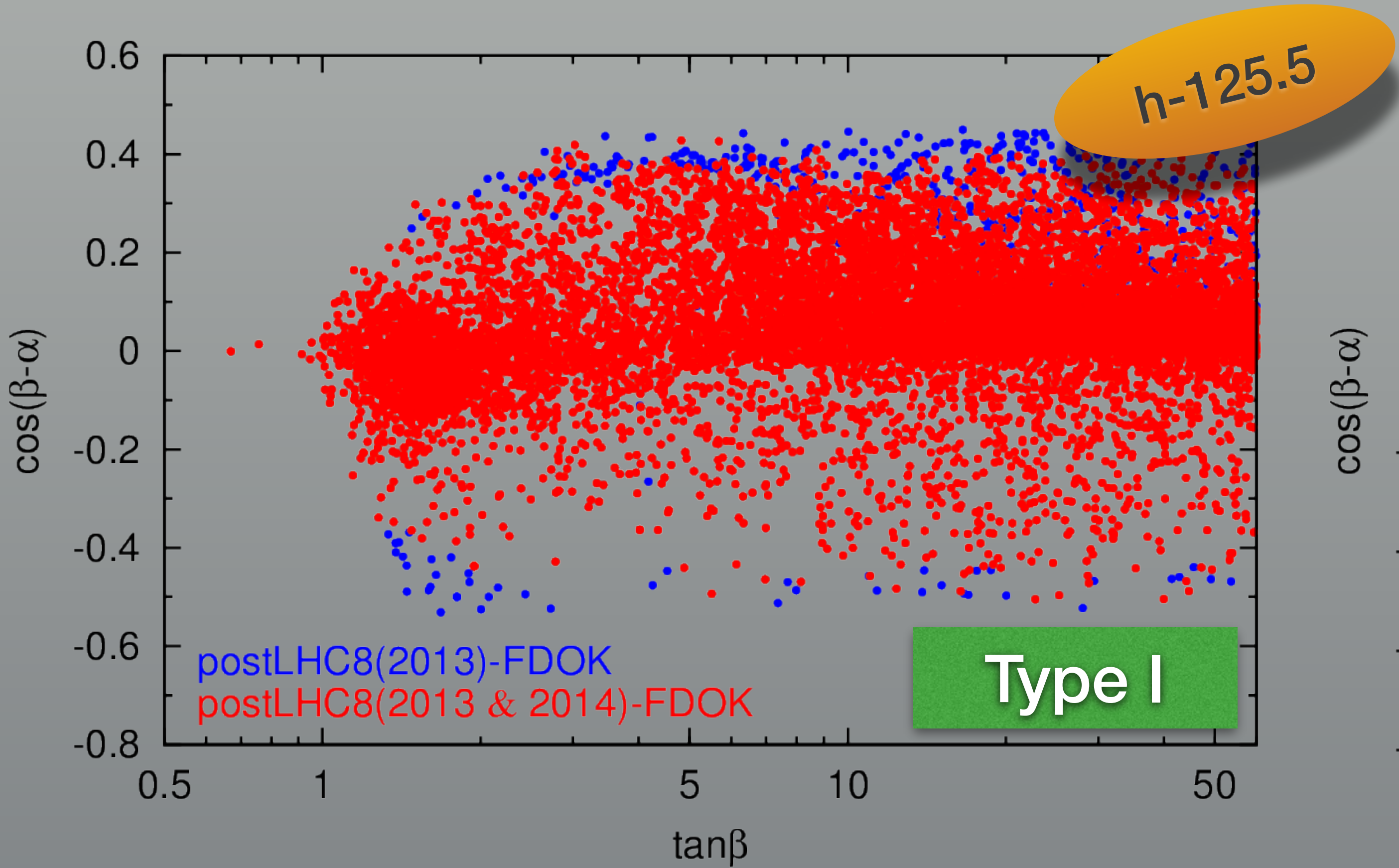
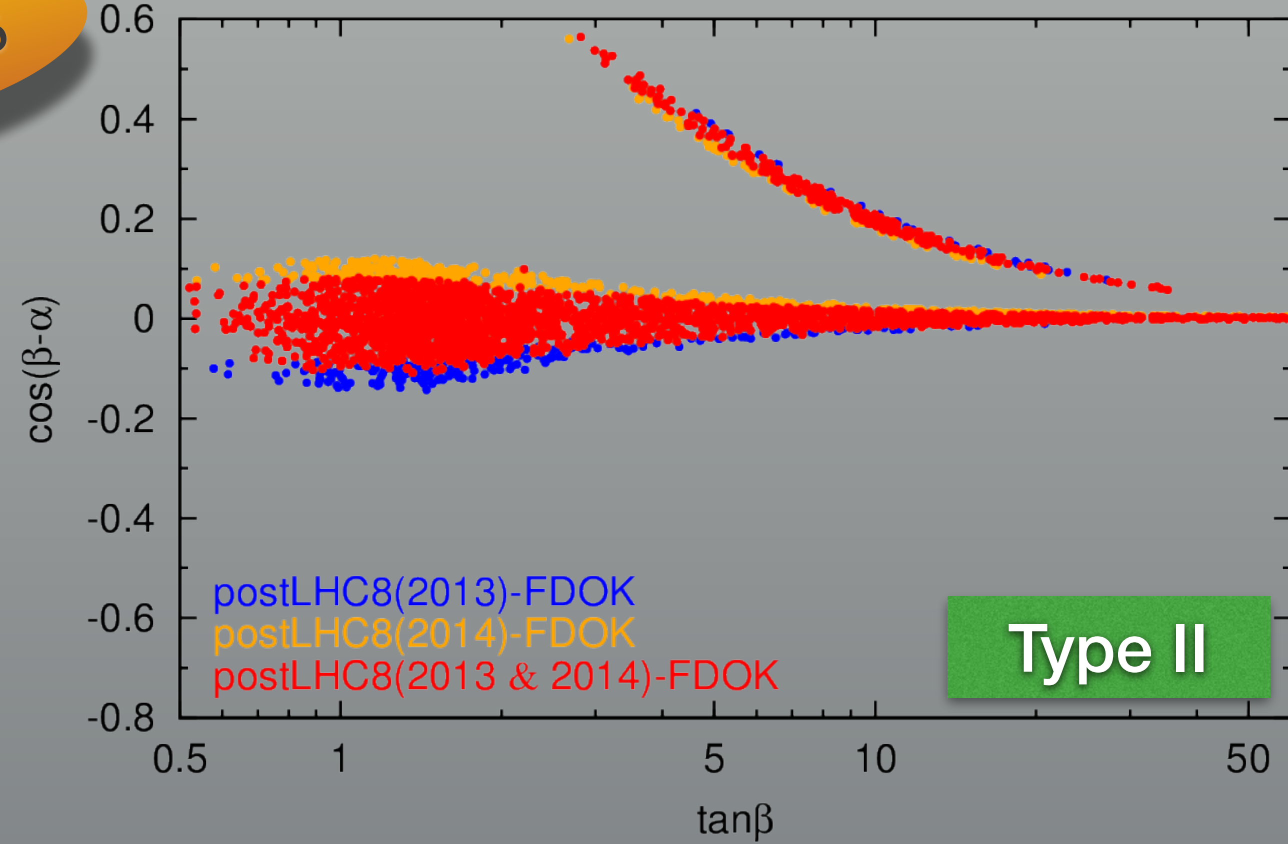
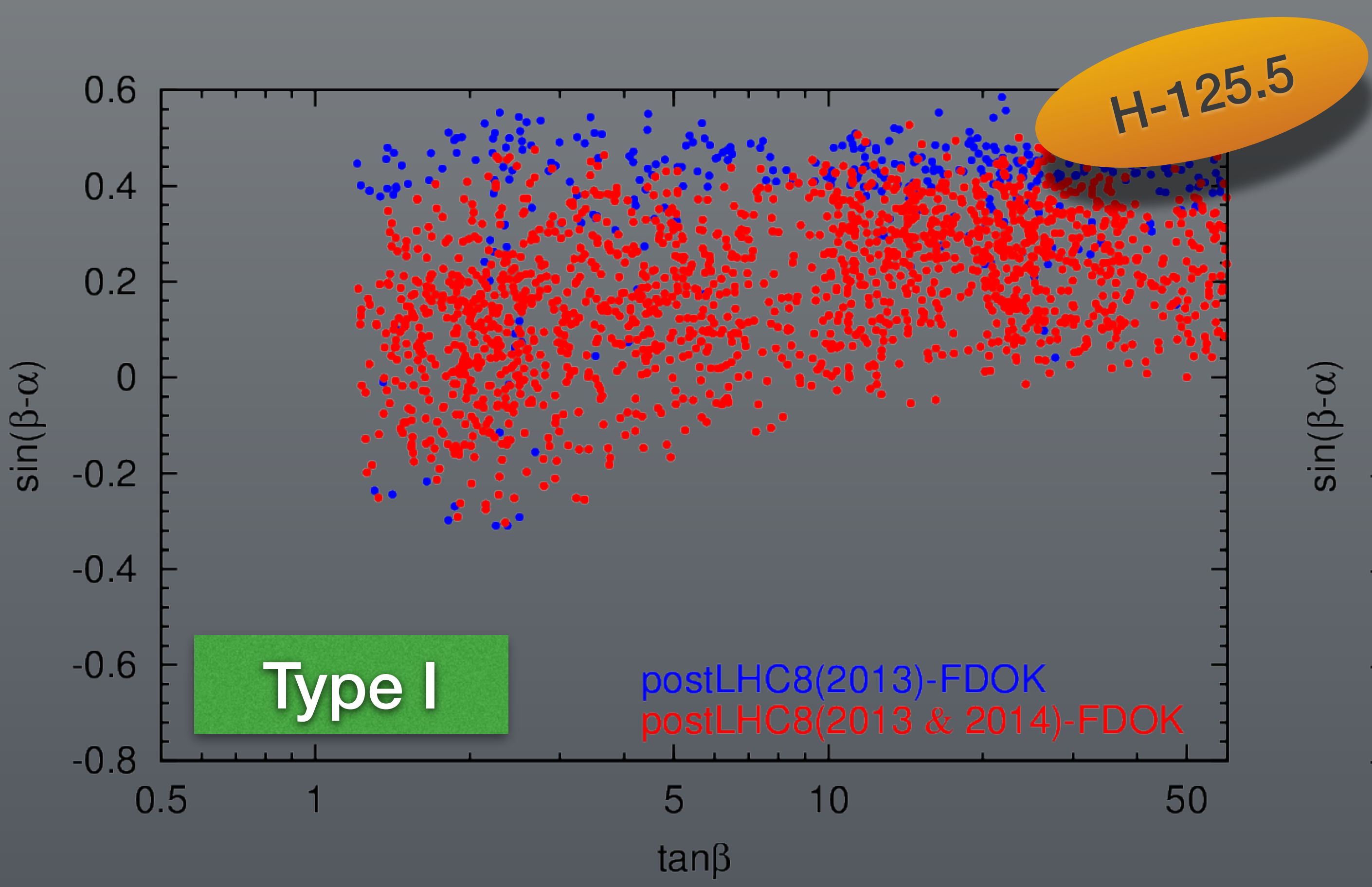
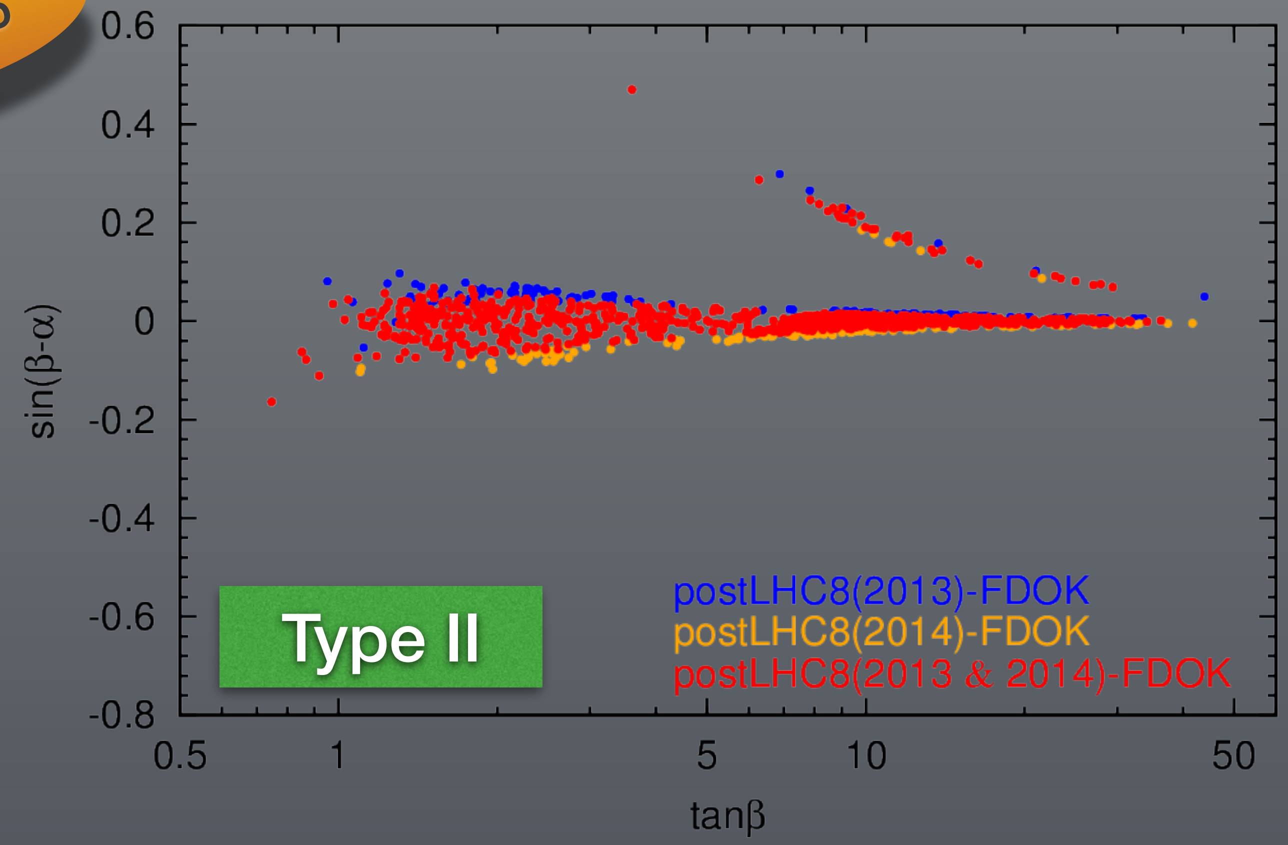
Points are retained only when “preLHC” constraints including are all satisfied.

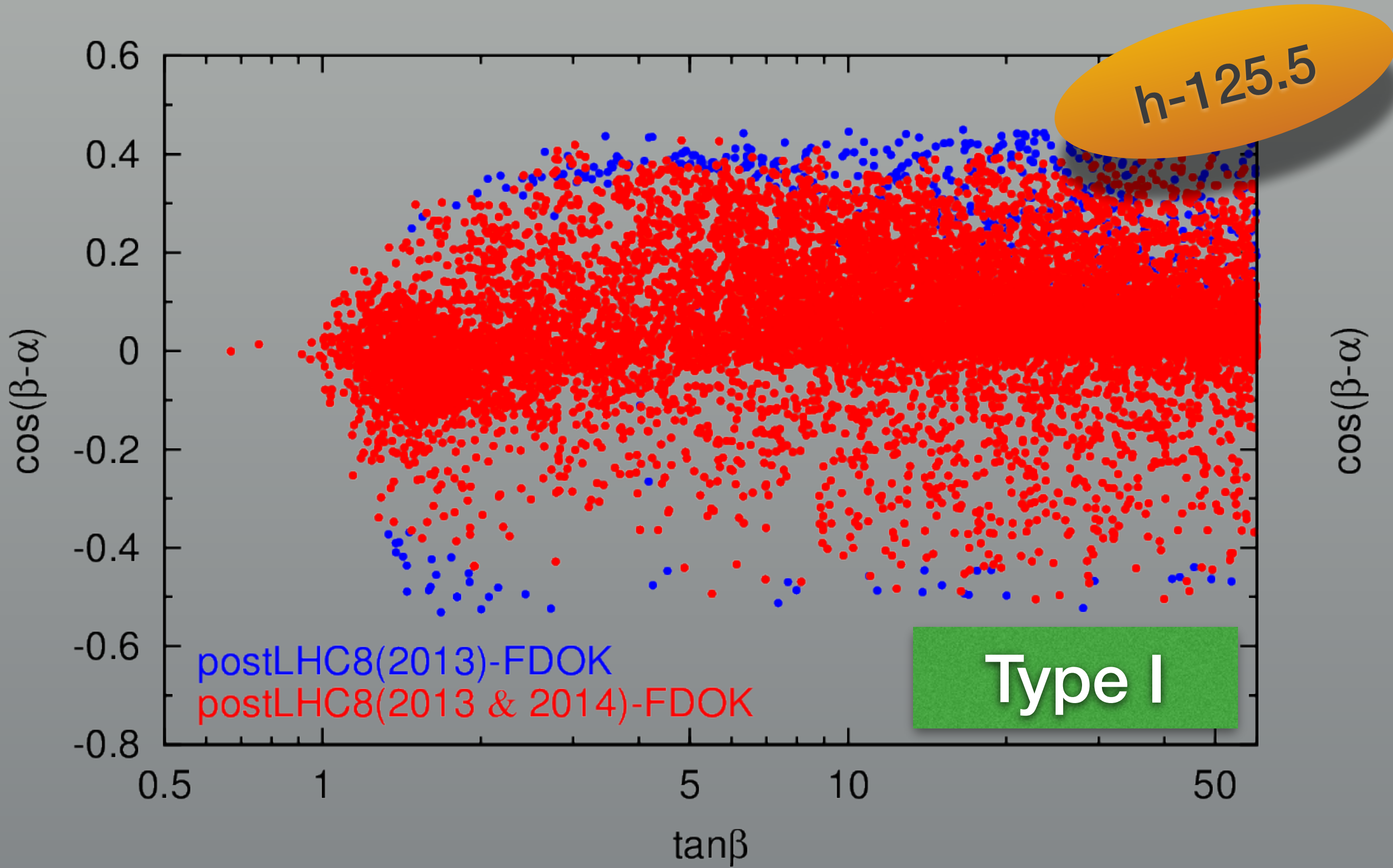


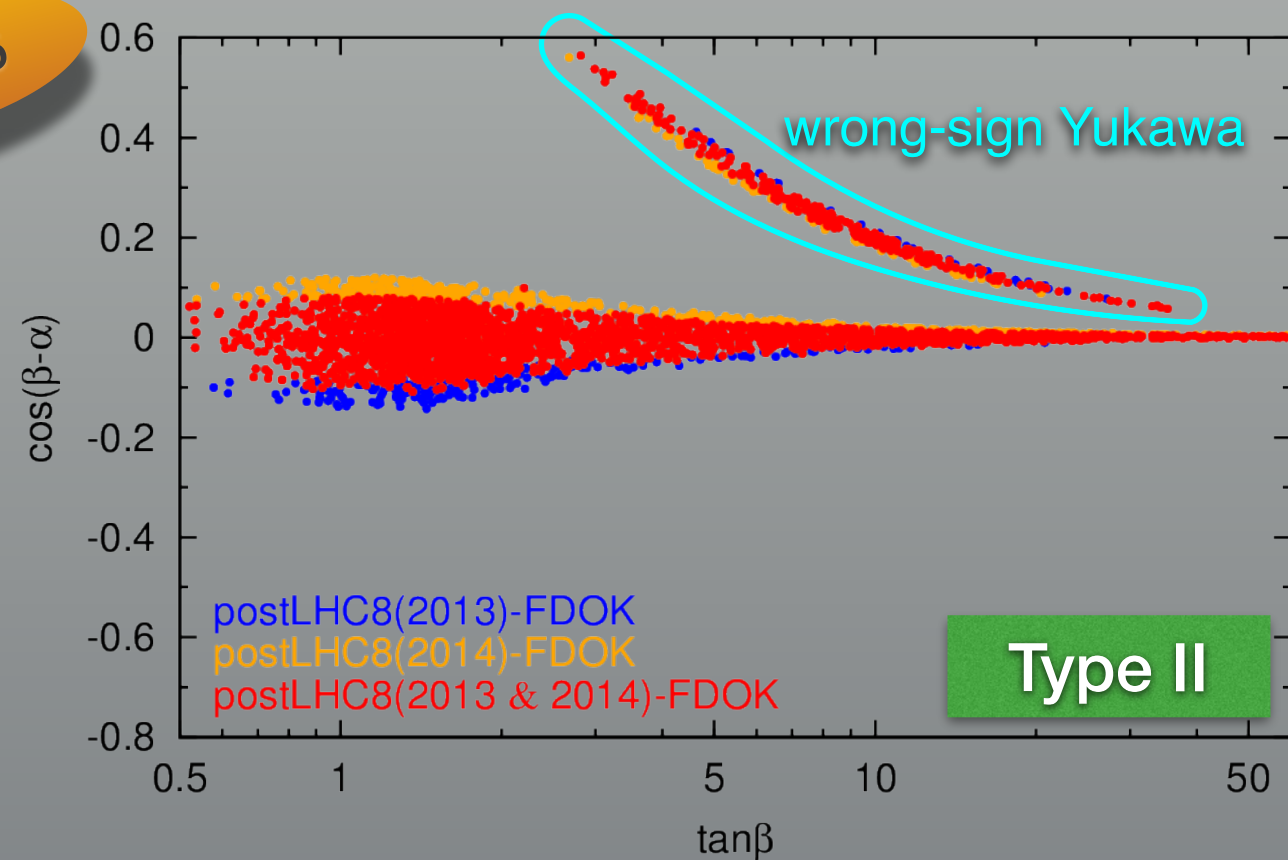


- In the Type II, sin(β – α) is pretty much forced into the decoupling/alignment regime
- A slight narrowing of the allowed sin(β – α) range, but no visible change in the tan β direction

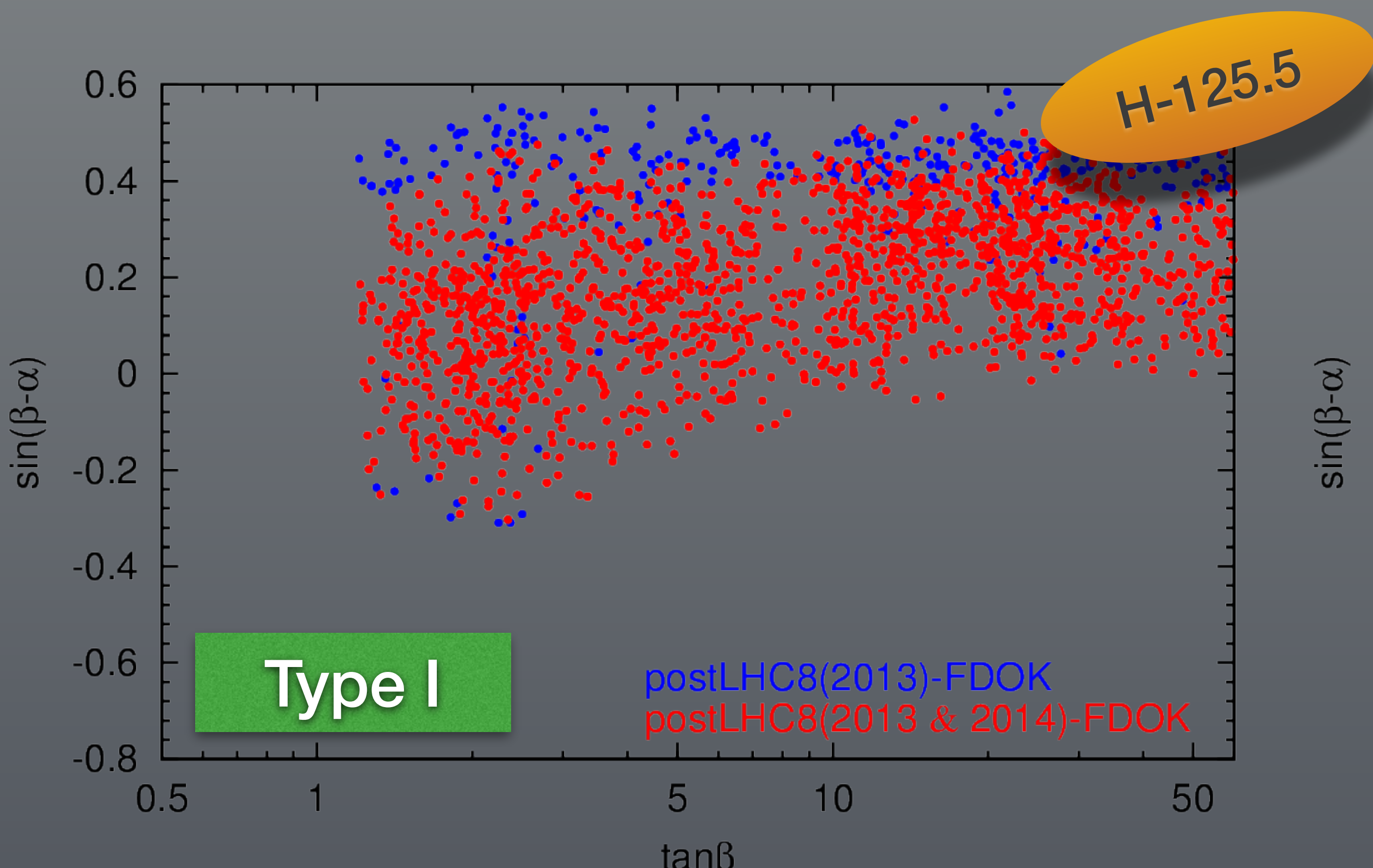


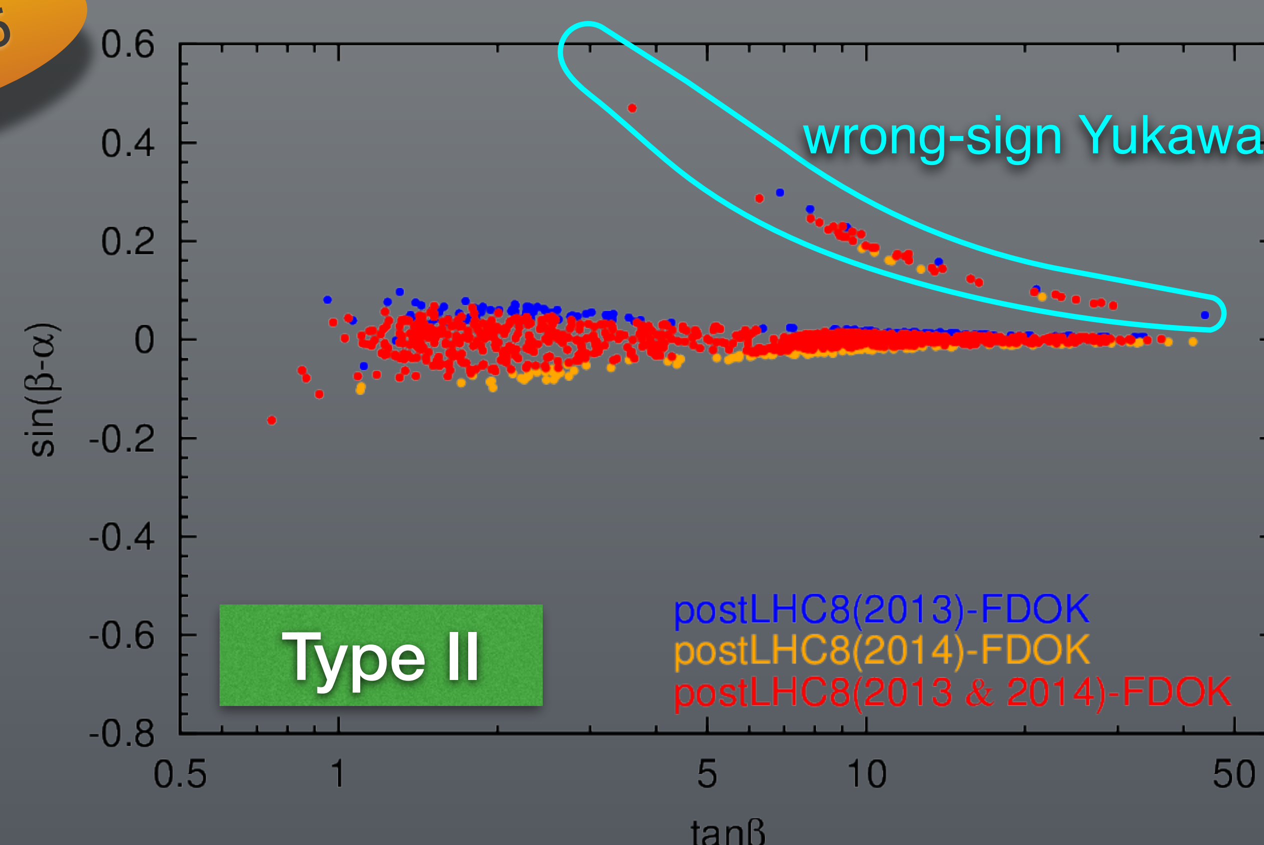




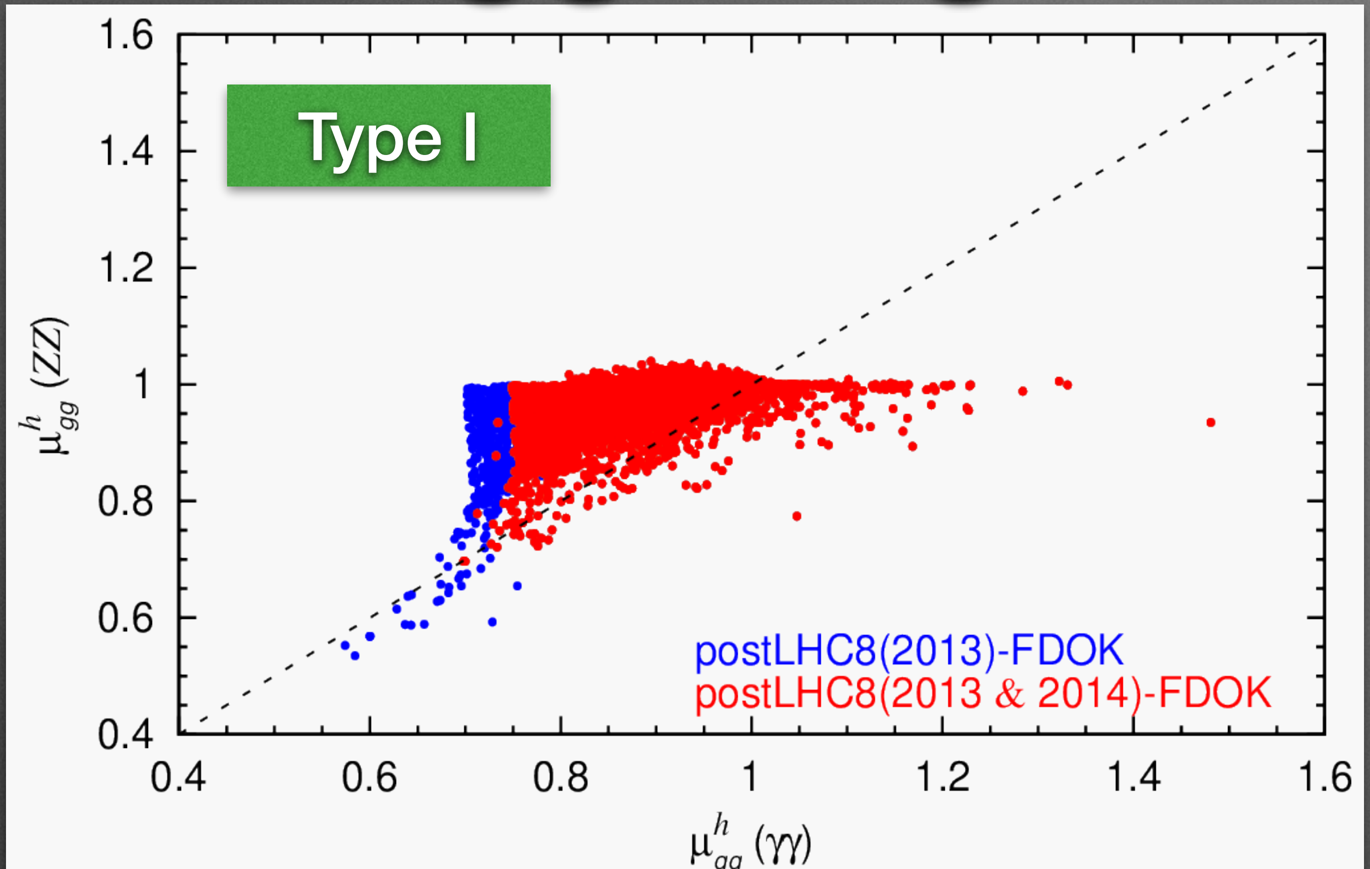


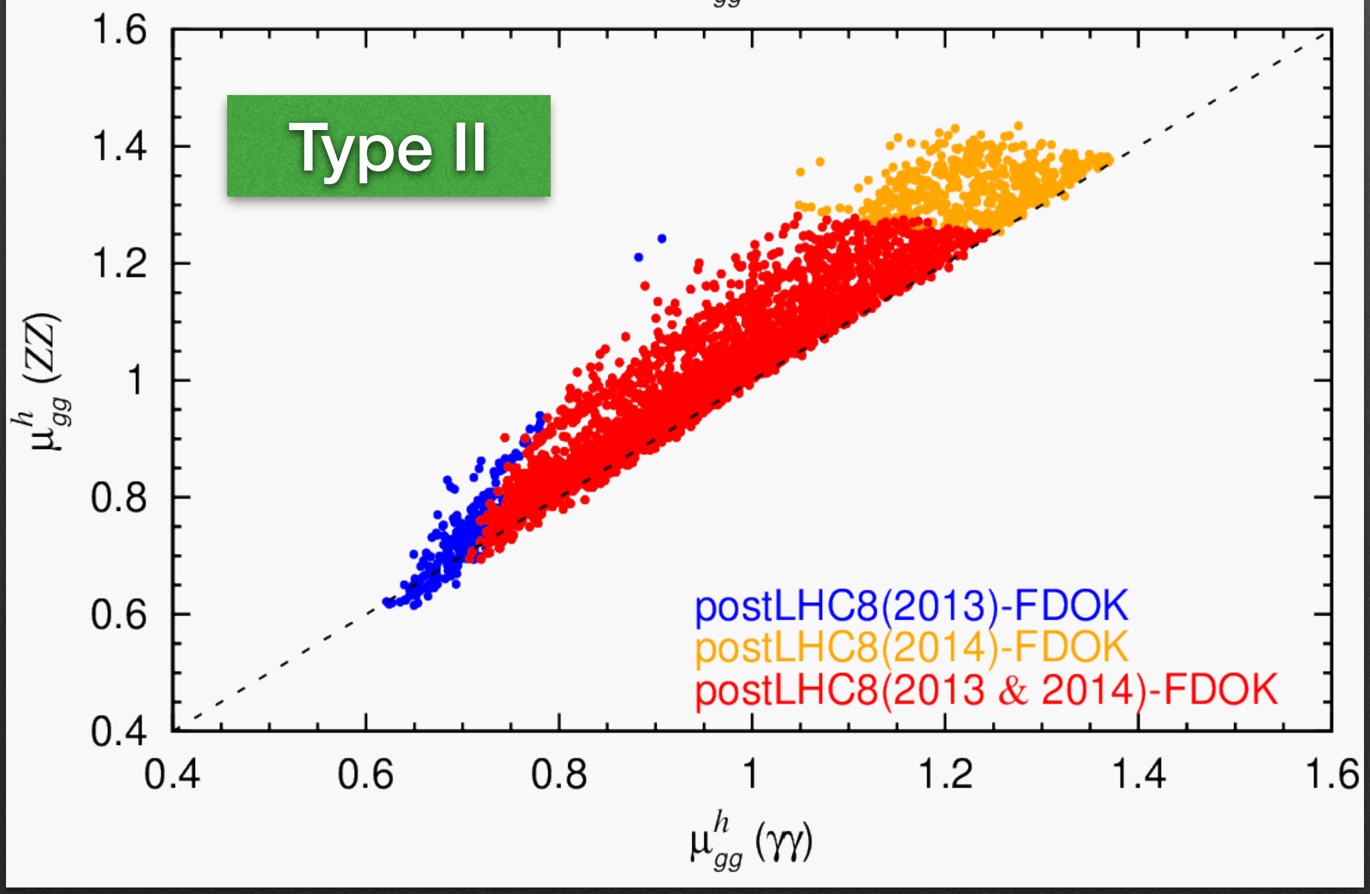
- In the Type II, sin(β – α) is pretty much forced into the decoupling/alignment regime
- A slight narrowing of the allowed sin(β – α) range, but no visible change in the tan β direction





Higgs Signals for h~125.5





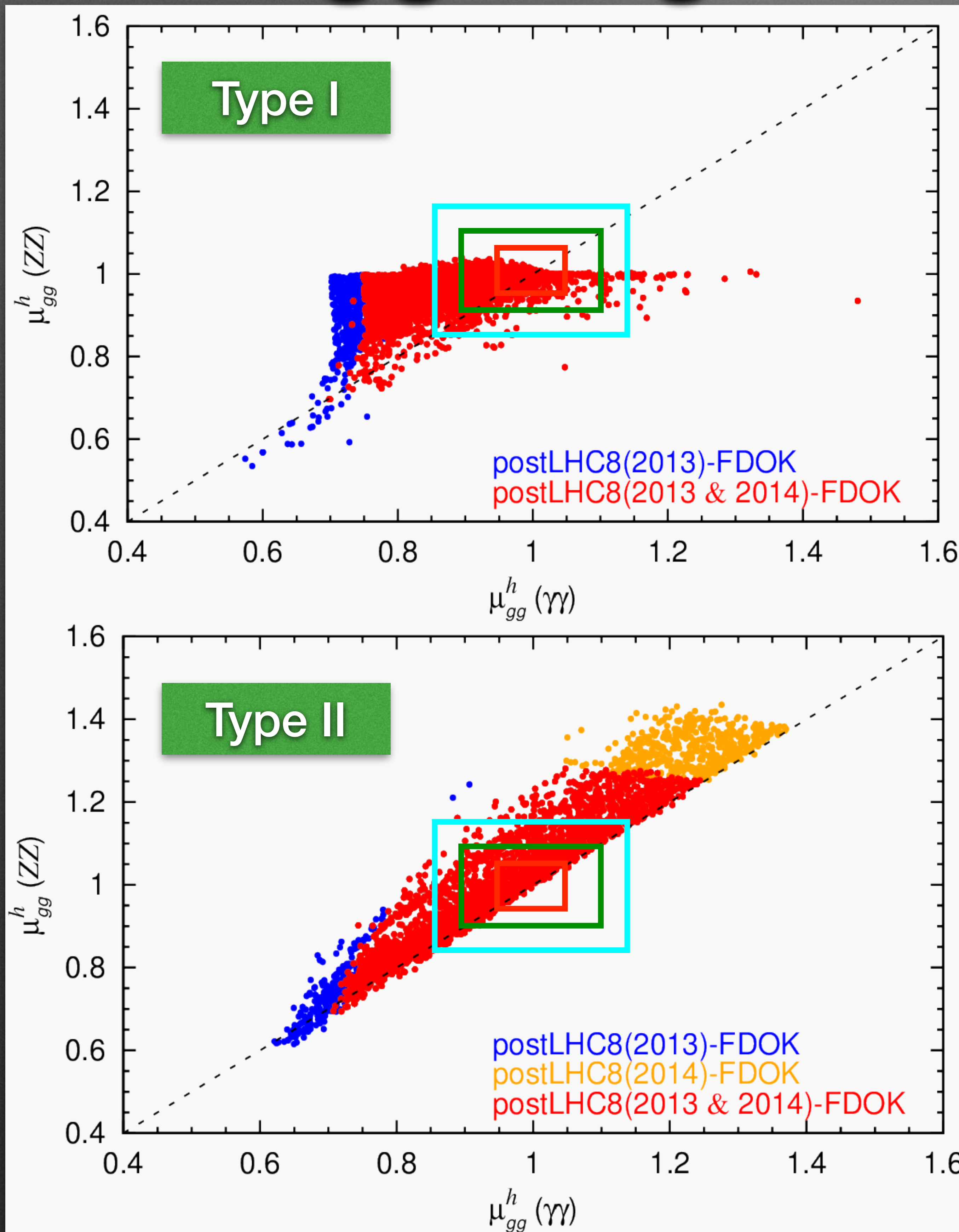
Type I

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

Type II

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

Higgs Signals for h~125.5



What happens if all measured signals converge to very SM?

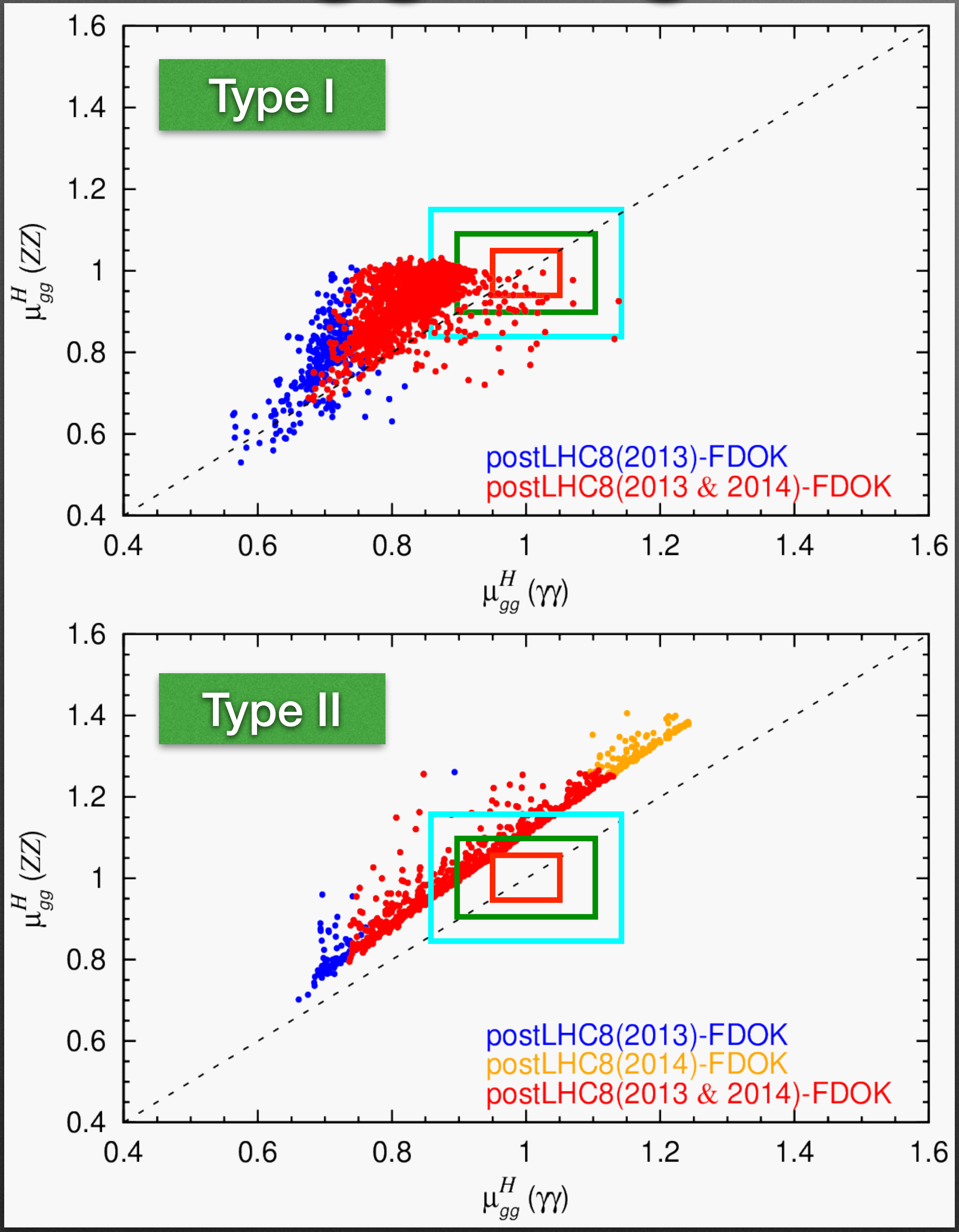
For example, if the observed values of $\mu^h_X(Y)$ *all* lie within $\pm 15\%$, $\pm 10\%$ and $\pm 5\%$ of the SM prediction for the channels

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

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

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

Higgs Signals for H~125.5



What happens if all measured signals converge to very SM?

For example, if the observed values of $\mu_X^h(Y)$ *all* lie within $\pm 15\%$, $\pm 10\%$ and $\pm 5\%$ 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

…ctories for complete programs: …
…GeV; ILC LumiUp: adding 900 fb^{-1} at …
…, CLIC: 500 fb^{-1} at 350 GeV, 1500 fb^{-1} at 1.4 Te…
…sities the sum over 4 interaction points): 10000 fb^{-1} at 2…
…LIC numbers are assuming increased WW cross sections above 1 Te…
…r (e^-, e^+) (effective luminosities scaled by a factor of approximately 1.8 above…
…given in Ref. [3]). †CLIC at 350 GeV. ‡ILC luminosity upgrade assumes an extended…
…iod on top of the low luminosity program and cannot be directly compared to TLEP and CLIC…
…mbers without accounting for the additional running period.

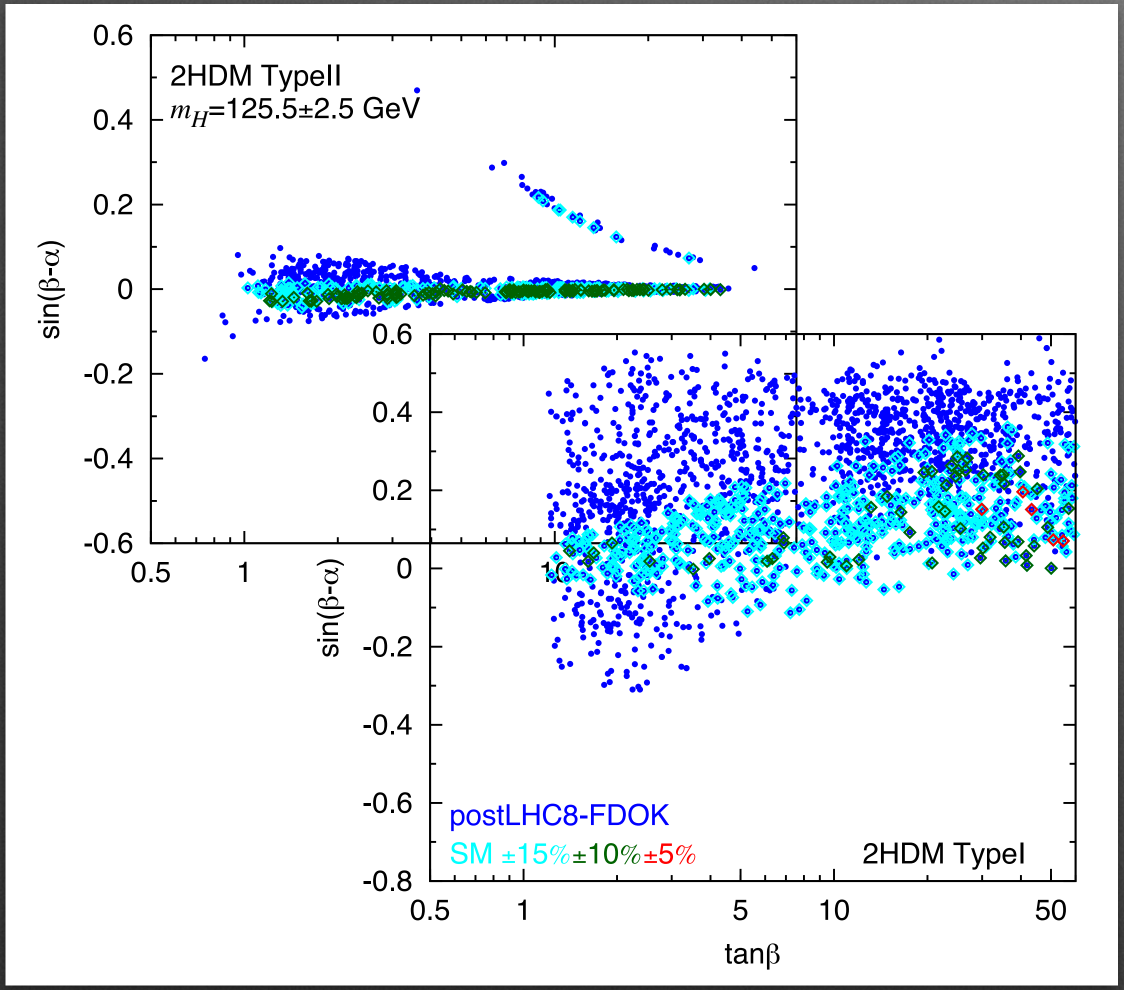
	ILC 250/500/1000 GeV		ILC LumiUp‡ 250/500/1000 GeV		CLIC 1.4/3.0 TeV		TLEP 240 & 350 GeV
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$	$ZH^\dagger$	$\nu\bar{\nu}H$	$ZH(\nu\bar{\nu}H)$
Inclusive	2.6/3.0/–%	–	1.2/1.7/–%	–	4.2%	–	0.4%
$H \to \gamma\gamma$	29-38%	–/20-26/7-10%	16/19/–%	–/13/5.4%	–	11%/< 11%	3.0%
$H \to gg$	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%
	$t\bar{t}H$		$t\bar{t}H$		$t\bar{t}H$		$t\bar{t}H$
$H \to b\bar{b}$	–/28/6.0%		–/16/3.8%		8%/< 8%		–

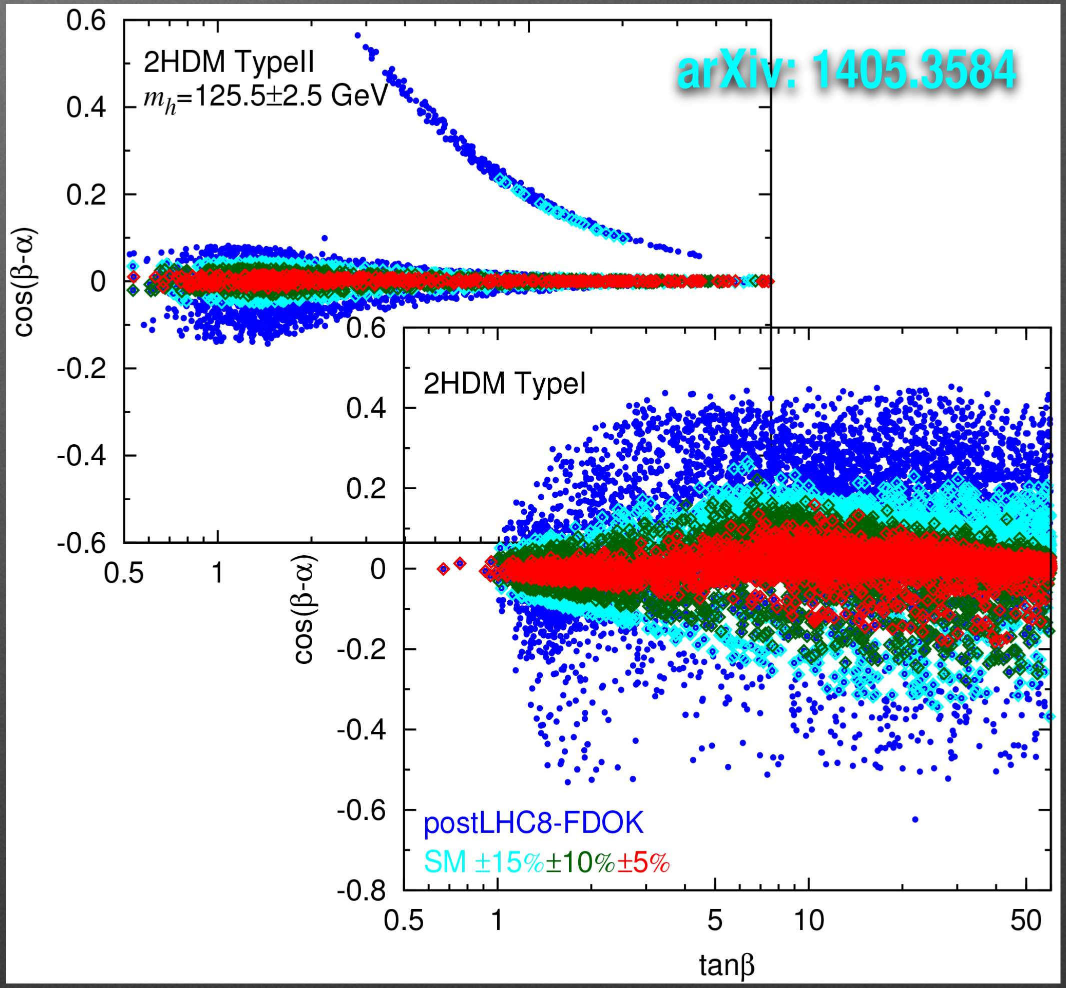
Table 1-13. Expected relative precisions on the signal strengths of different Higgs decay final states as well as the 95% CL upper limit on the Higgs branching ratio to the invisible decay from the ZH search estimated by ATLAS and CMS. The ranges are not comparable between ATLAS and CMS. For ATLAS, they 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$_{\rm inv}$
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%

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.

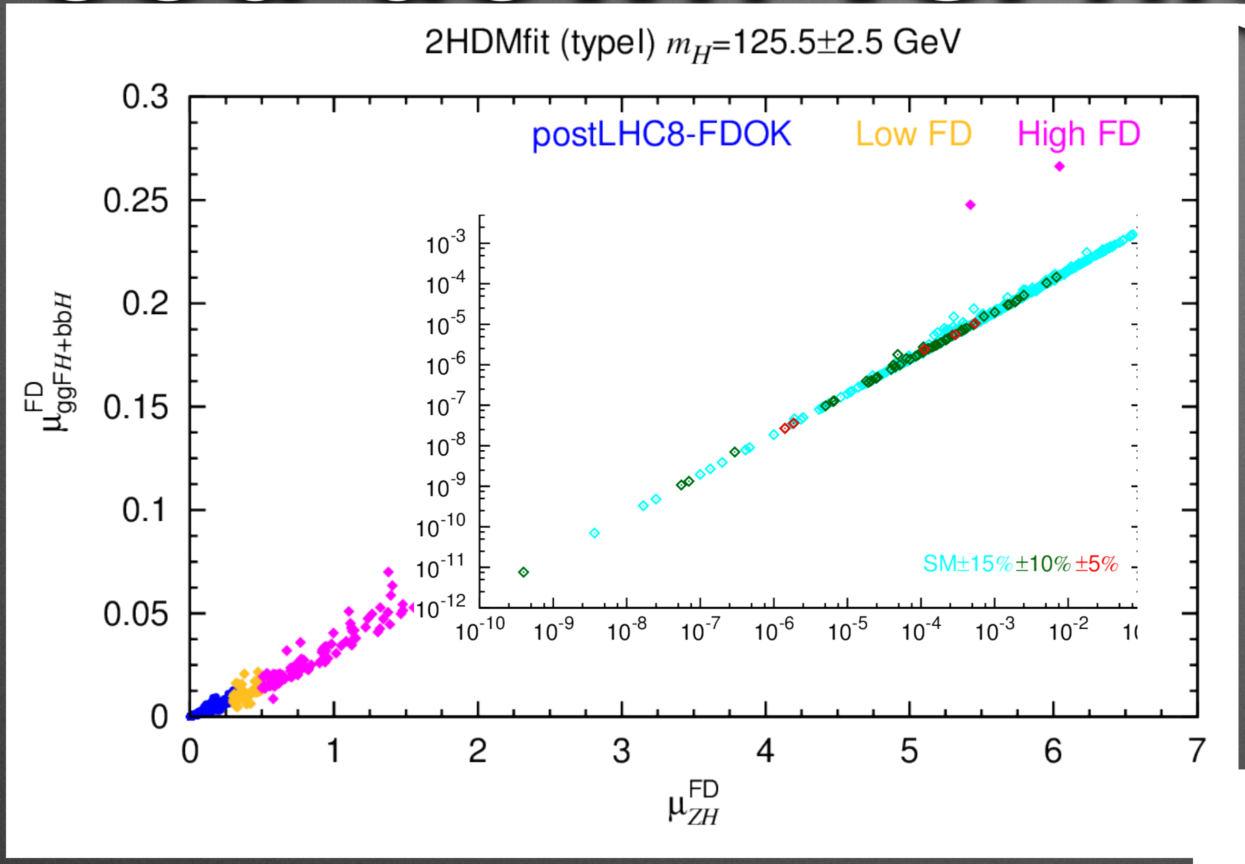


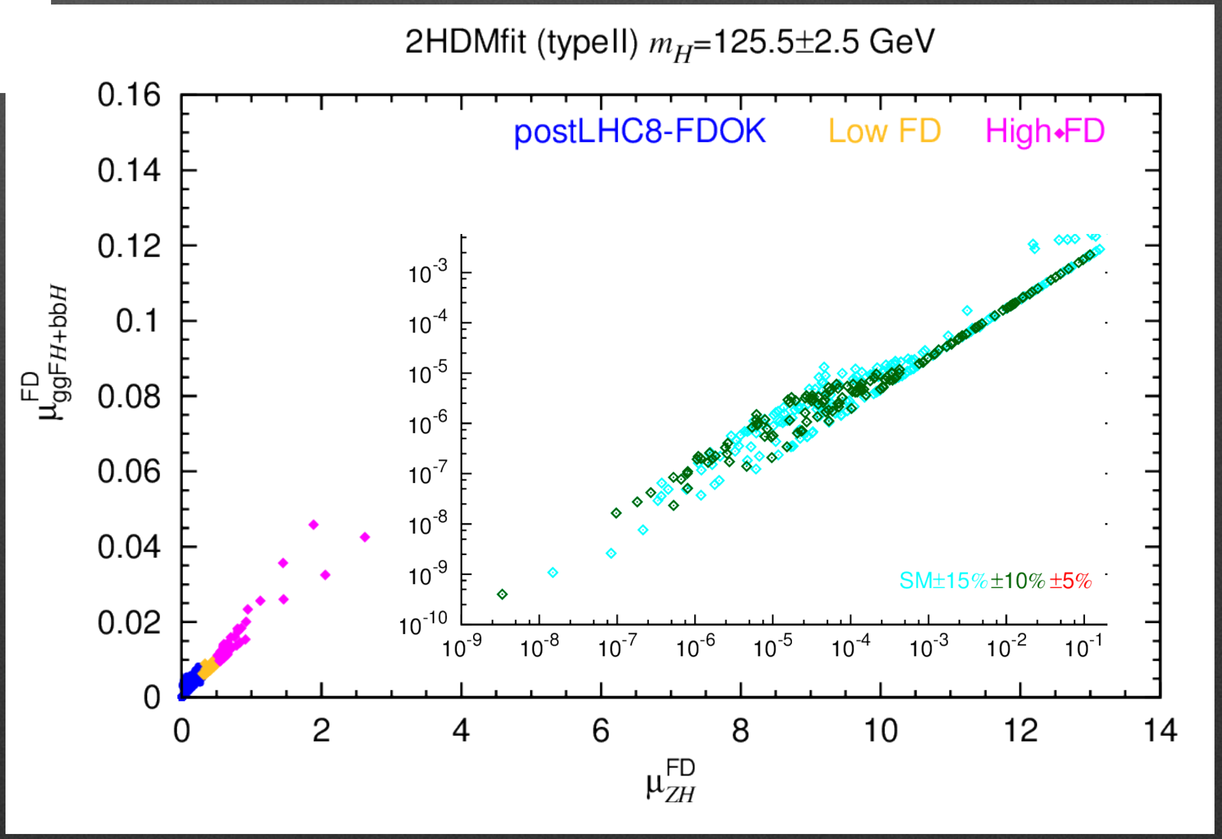


- SM±10% on each of the individual μ's will exclude the "wrong-sign" Yukawa region of the Type II model.

- If $\pm 5\%$ agreement with the SM can be verified in all the channels, then $m_H = 125.5\ \mathrm{GeV}$ 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





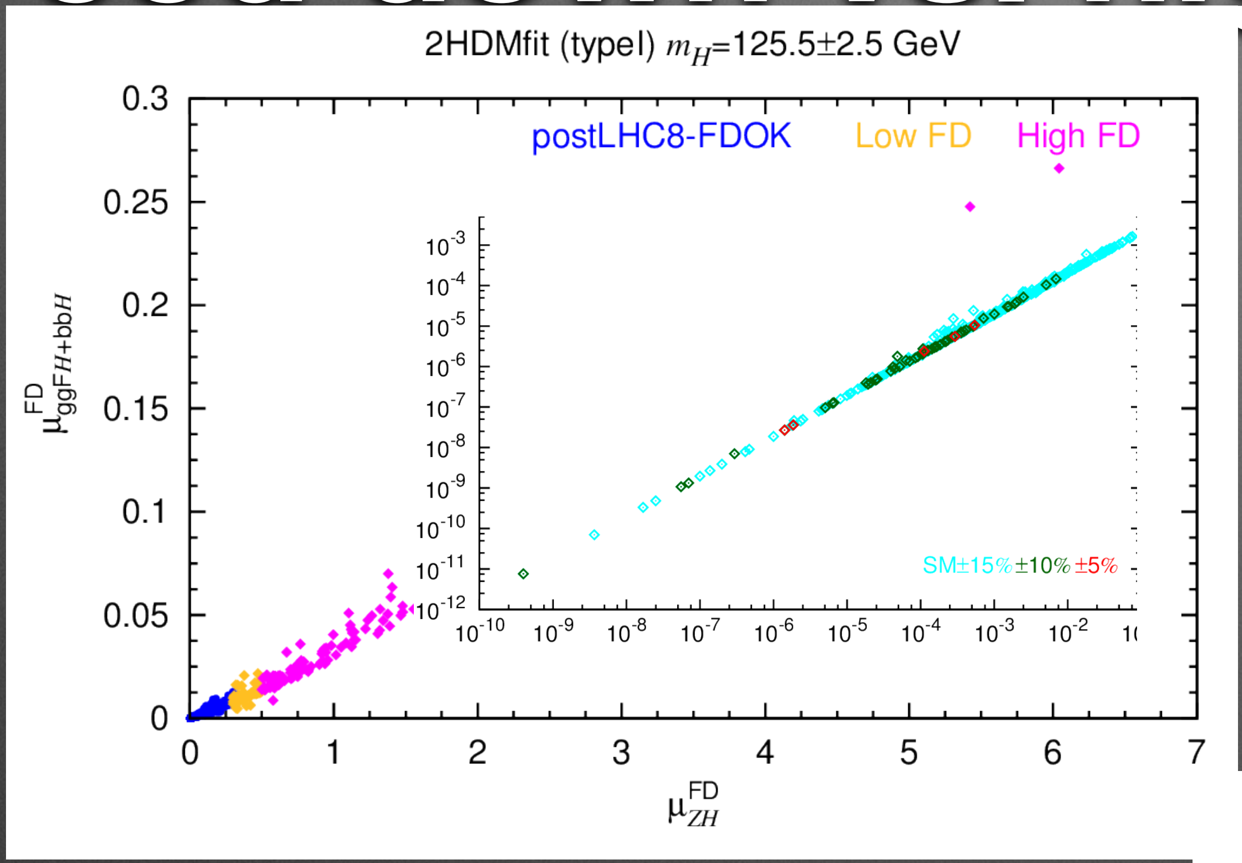
For all but VH

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

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

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

Feed down vs. higher precision



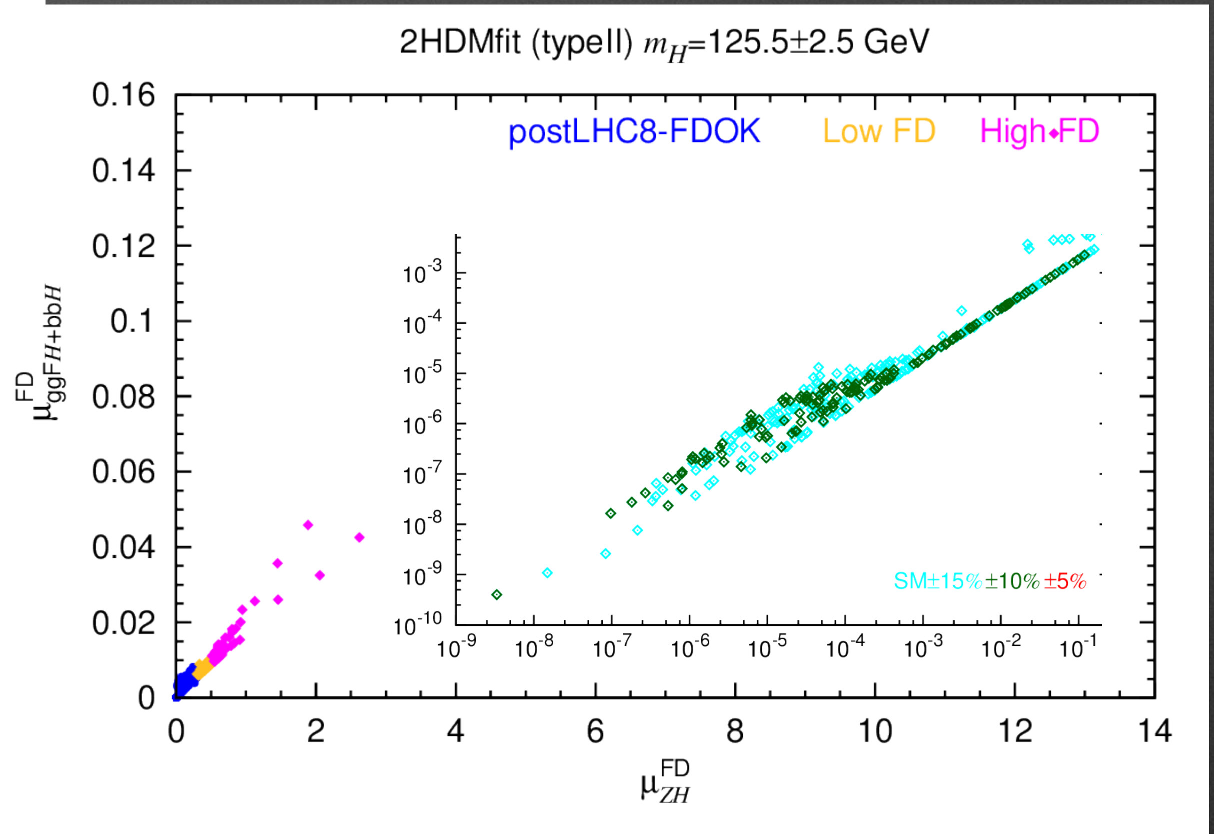
Increased precision in the signal strength measurements reduces the "danger" of FD contamination.

For all but VH

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

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

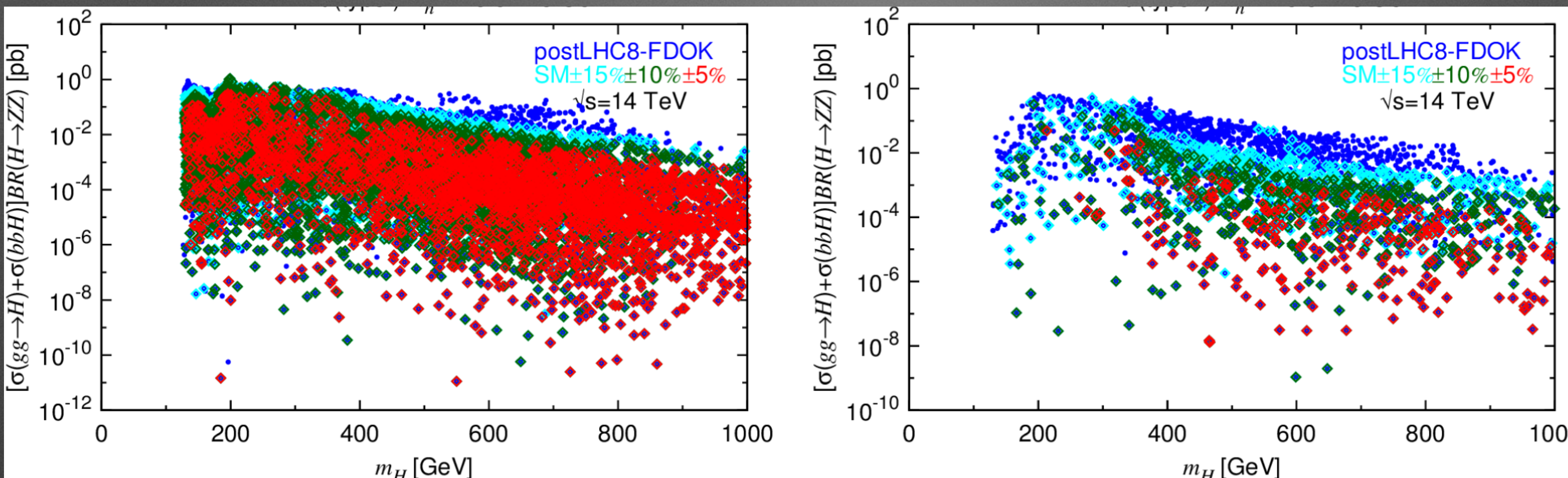
$$\mu^{\rm FD}_{\rm VH} = \frac{\sigma_{{\rm ggF}A} {\rm BR}(A \to ZH)}{\sigma_{\rm VH}}$$



Searches for additional Higgs bosons at the LHC Run-II

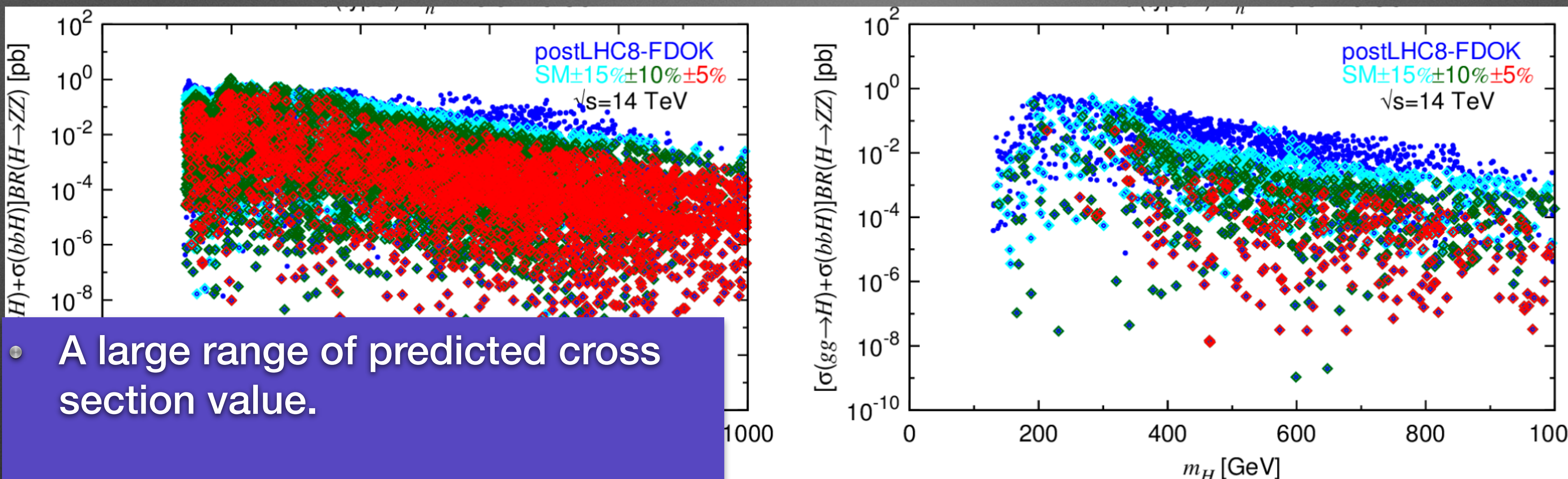
h-125.5 GeV

heavy H search



h-125.5 GeV

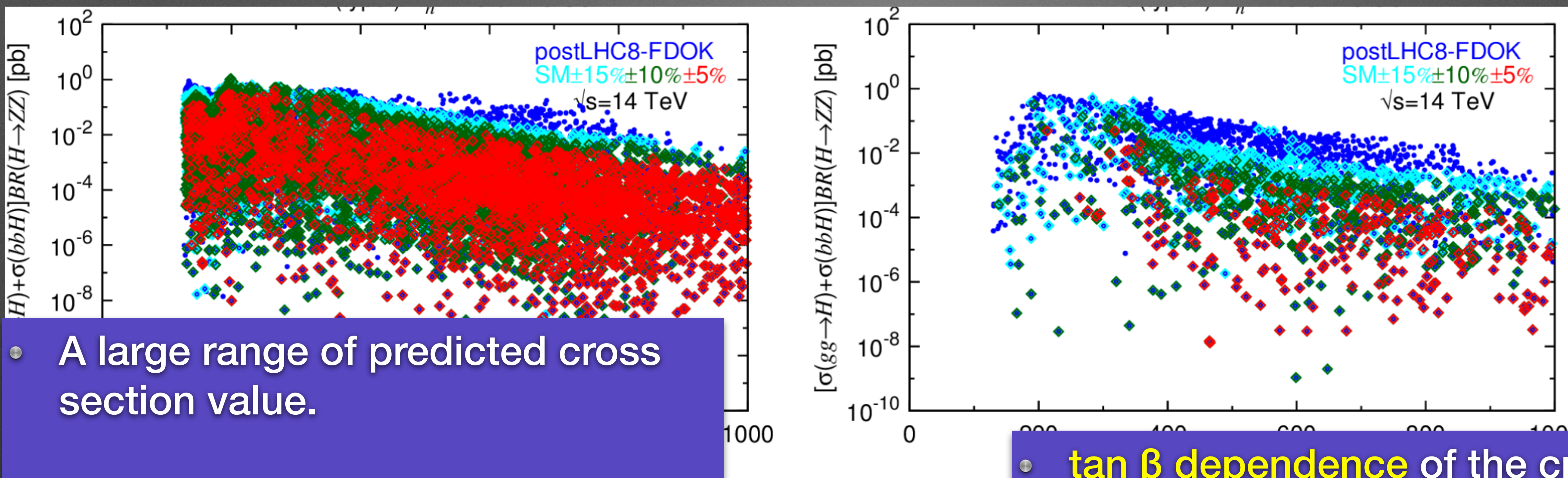
heavy H search



- A large range of predicted cross section value.
- Substantial maximum level are possible. However, in Type II, it will be greatly reduced and the minimum allowed m_H is of order 200 GeV if the h is determined to have SM-like rates within 5%.

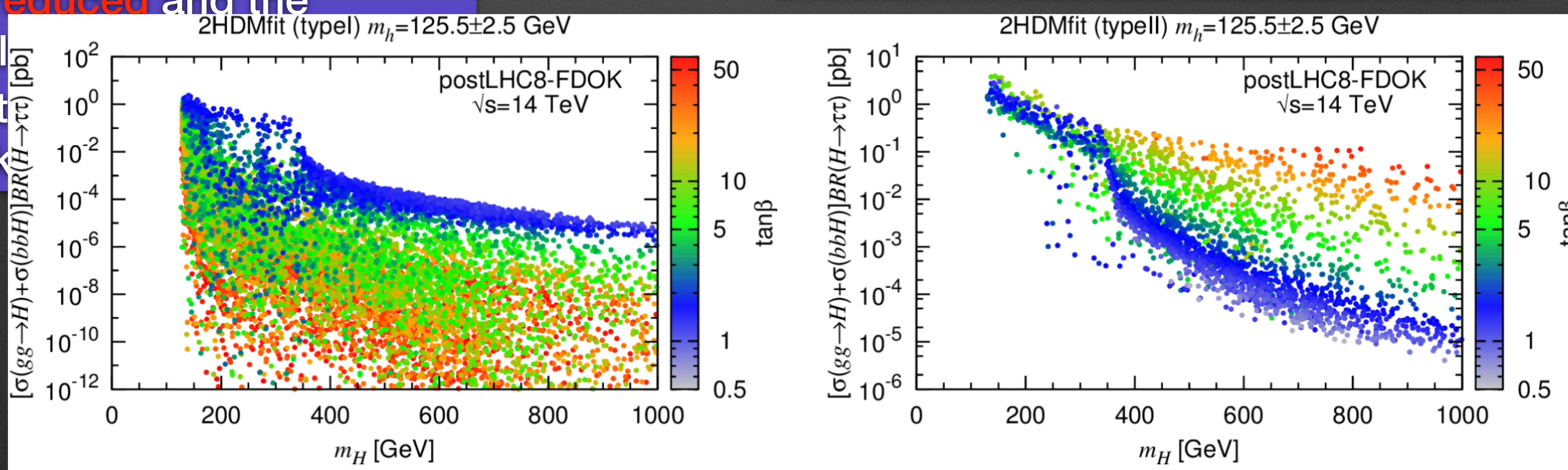
h-125.5 GeV

heavy H search



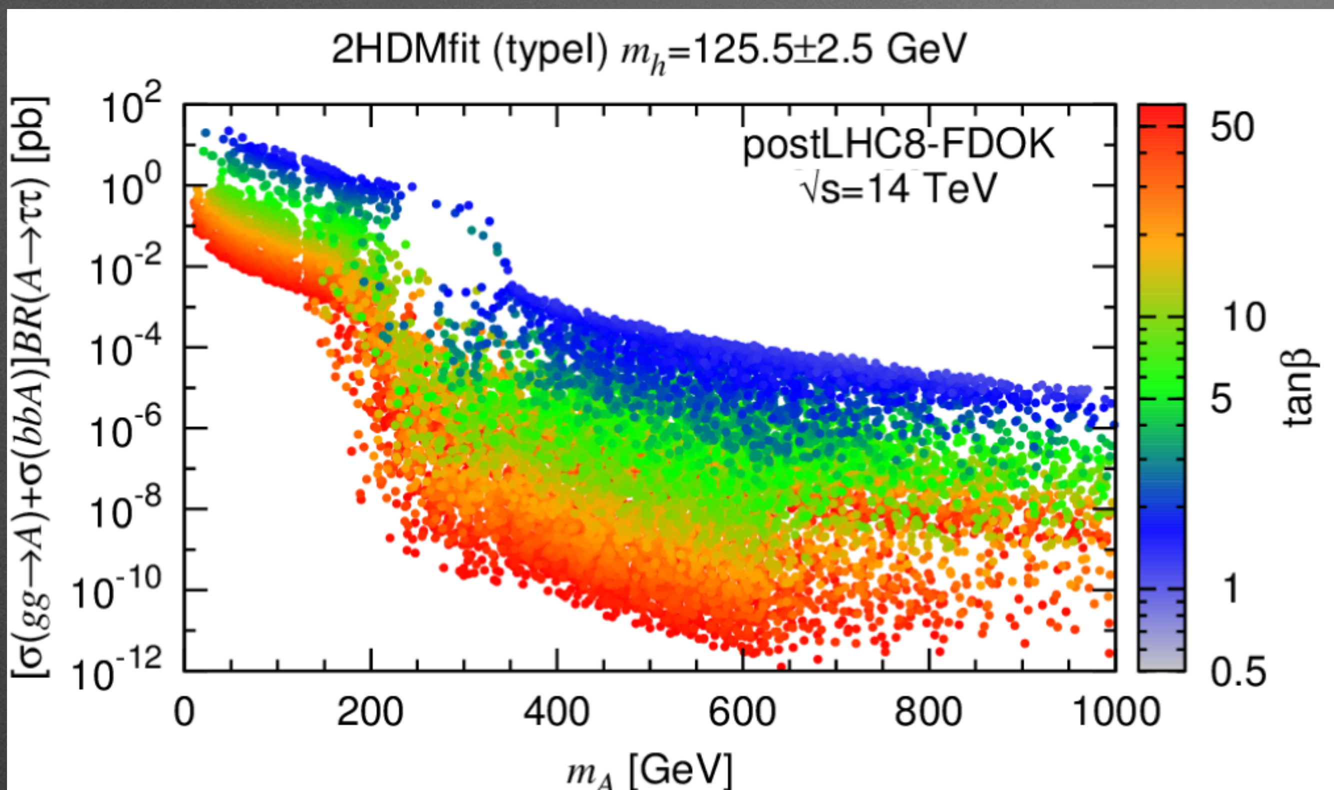
- A large range of predicted cross section value.
- Substantial maximum level are possible. However, in Type II, it will be greatly reduced and the minimum al 200 GeV if t have SM-lik

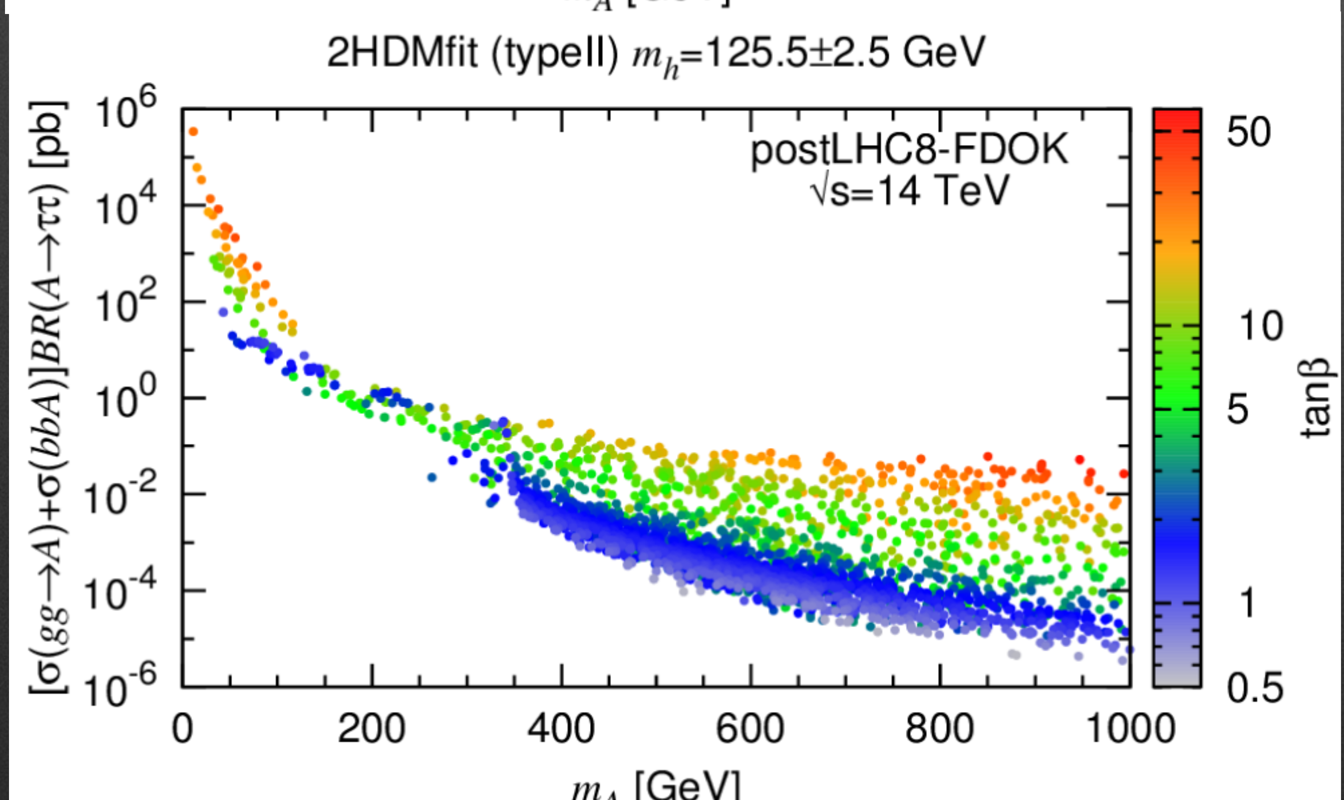
- **tan β dependence** of the cross sections is **opposite** in Type I and Type II.



h-125.5 GeV

pseudoscalar A search

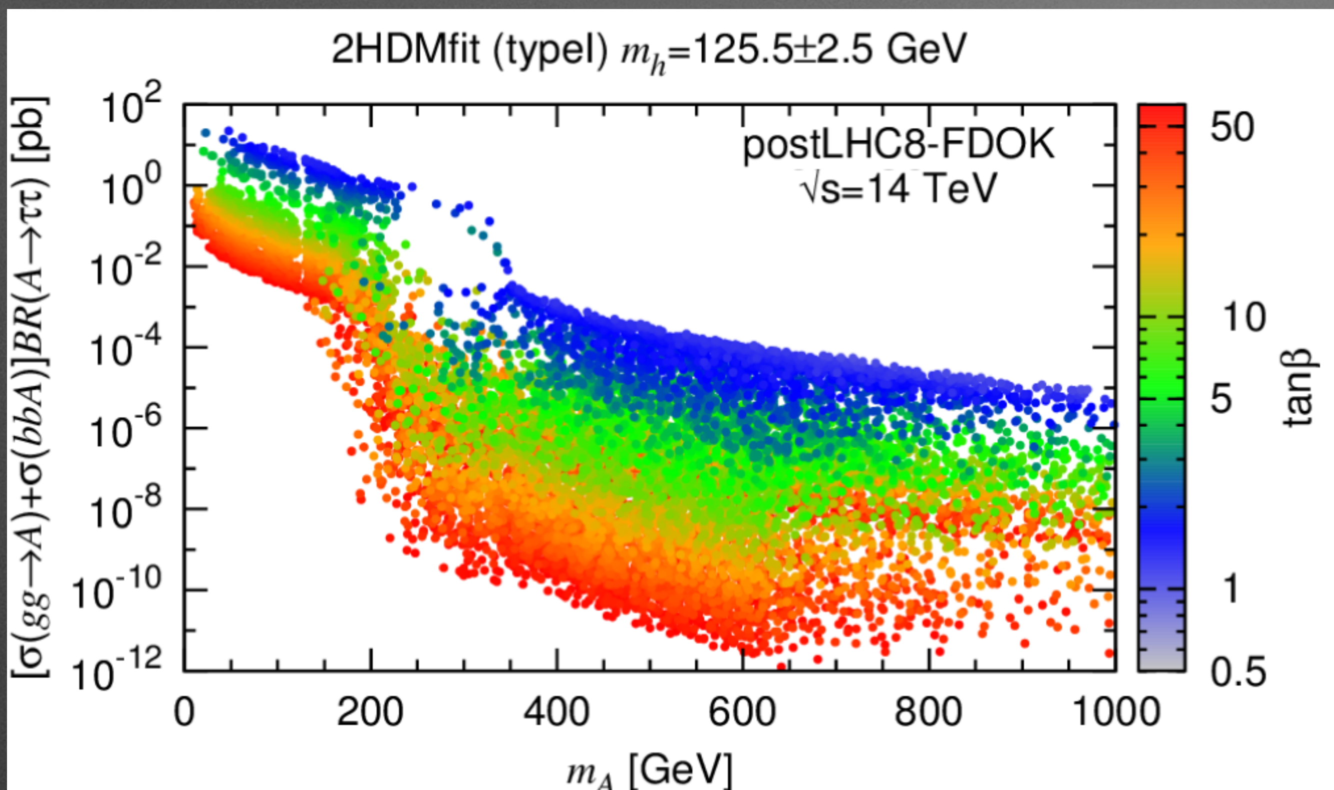


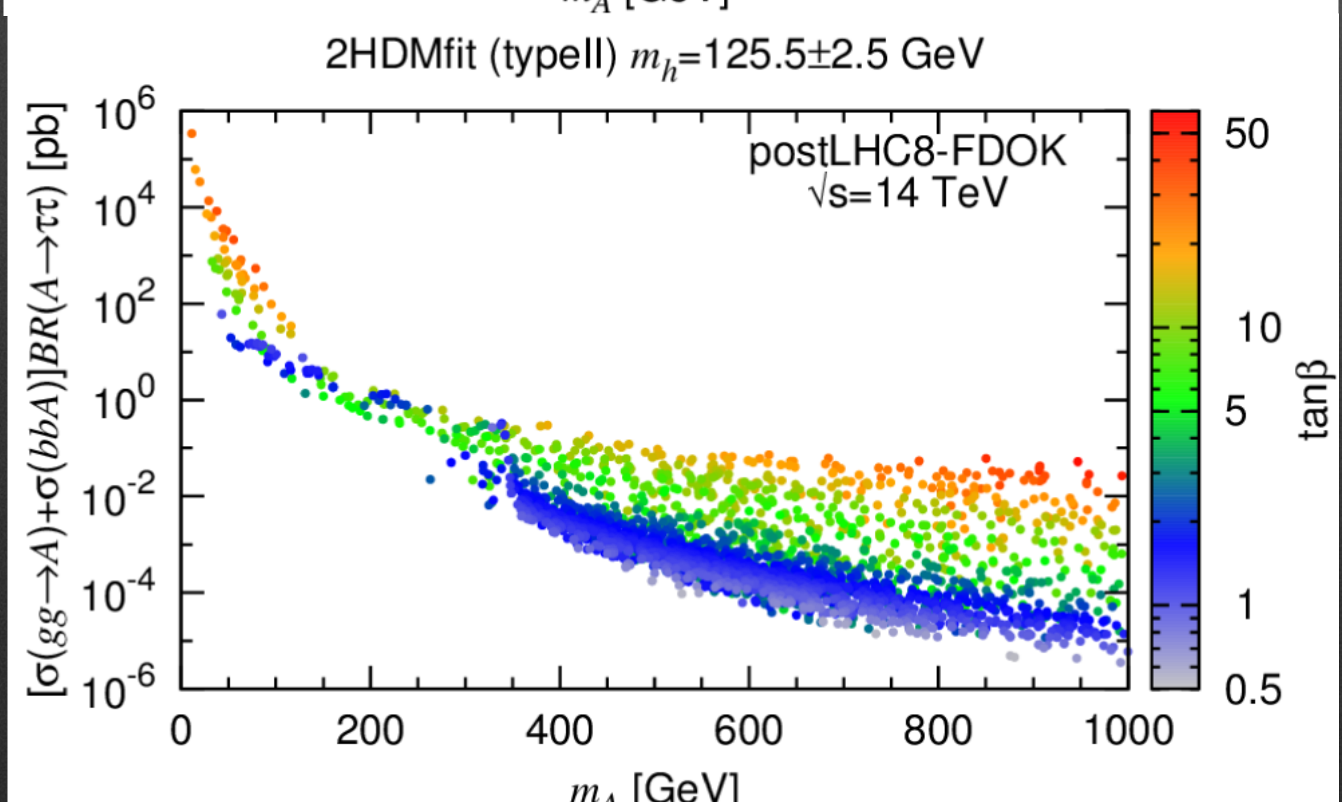


- A large range of possible cross section value. In average, Type II tends to be substantially larger than Type I. The lowest cross values are really very small and would not allow A detection.
- the tt threshold is not apparent for Type II due to the absence into ZZ decay.

h-125.5 GeV

pseudoscalar A search





- 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.
- the tt threshold is not apparent for Type II due to the absence into ZZ decay.

- low **mA<60 GeV** is possible but must have small BR(h->AA). For **mA<100 GeV**, tautau cross section are quite large.

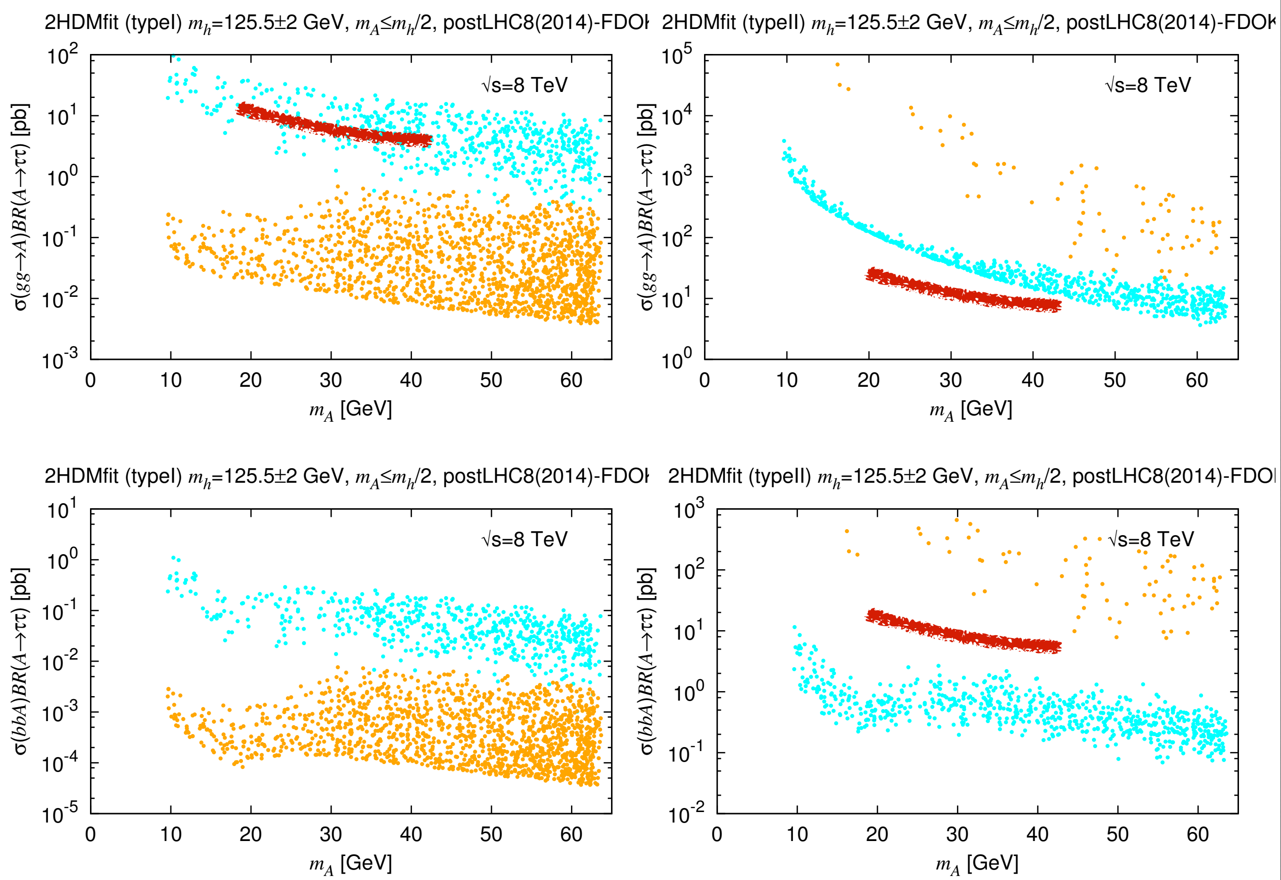
h-125.5 GeV

light A search highlight

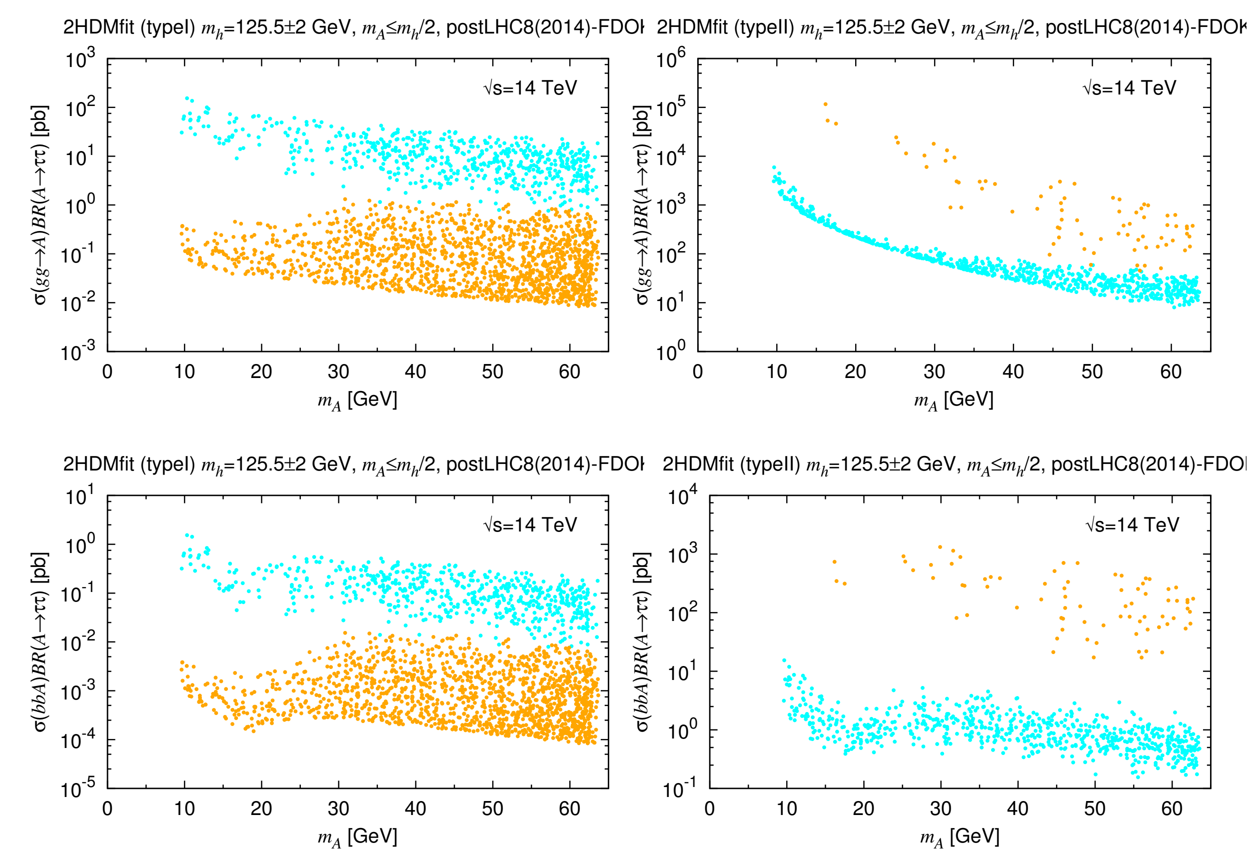
gg/bb->A->tautau

arXiv: 1412.XXXX

8 TeV



14 TeV



- The orange points have the smallest (largest) cross sections in the case of Type I (Type II).
- In the case of Type II, the levels are reached for essentially the entire $m_A \le m_h/2$ region in the case of gg fusion and for the orange points in the case of bb associated production. In particular, the orange point cross sections are really very large and should produce readily observable peaks.
- In the case of the Type I, many of the cyan points have gg fusion cross sections at the probably observable 10 pb (0.1 pb) level in the ττ (μμ) final states.

Stage I remarks

- There is consistent descriptions with the LHC8 Higgs signal in the both Type I and Type II 2HDMs in which either the h or the H is identified as the 125.5 GeV state. The updated ATLAS and CMS analyses in the Summer 2014 lead to relatively minor modifications of the preferred parameter ranges.

- Higher precision measurements could be accomplished at future colliders. Feed down effect will be dramatically reduced if the higher precision in the signal measurement is verified in the future.

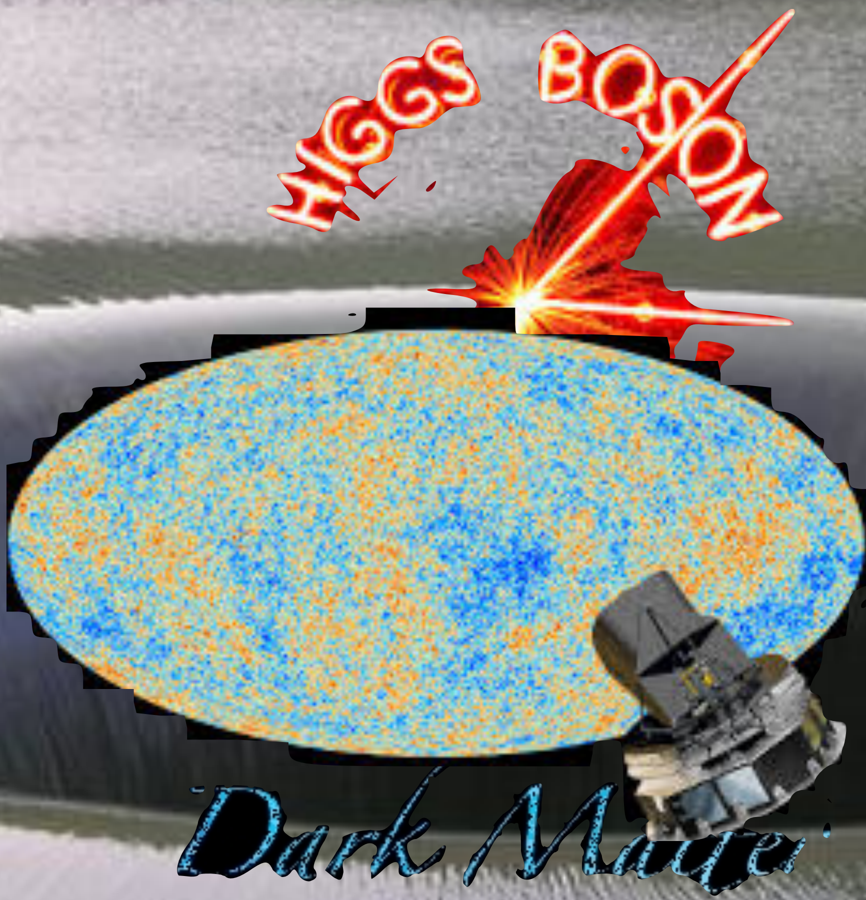
- The H/A can be detected in many modes at reachable cross section level. The opportunity of such detection is still ample even if the 125.5 GeV signals converge to very SM-like.

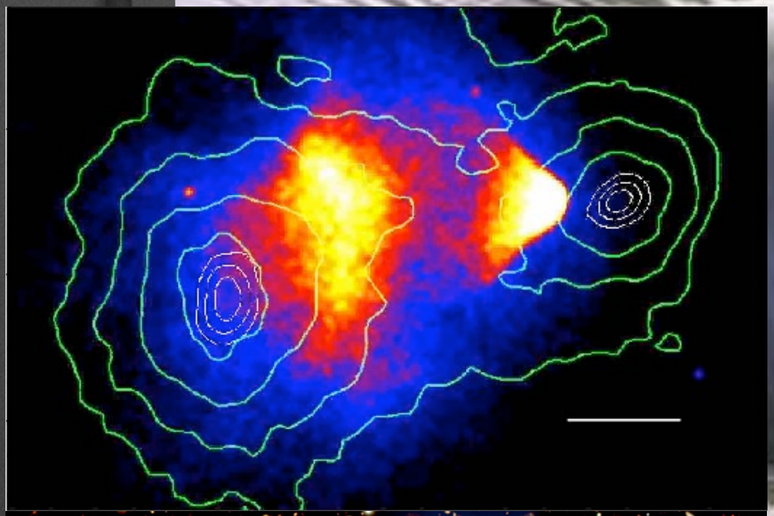
- In addition, there is good probability for viable signals in the $\tau\tau$ and $\mu\mu$ final states for the lighter h or A. If such a light Higgs is detected then models such as the MSSM will be eliminated and a strong preference in favor of a general 2HDM or similar model will arise.

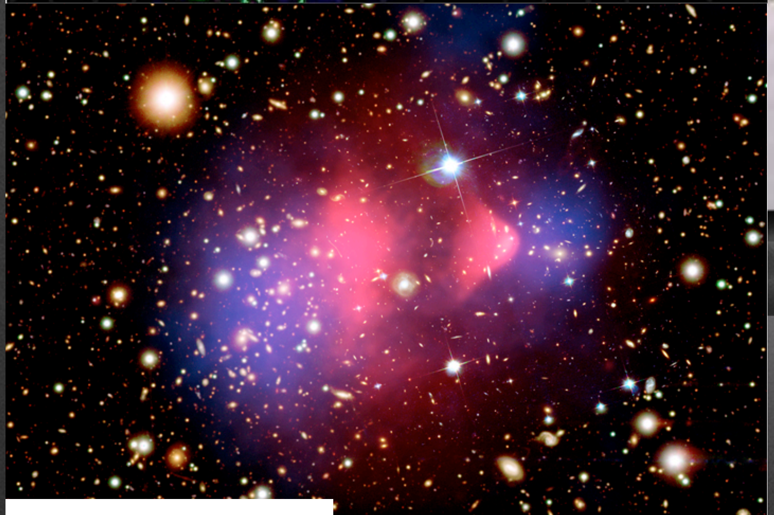
We are waiting for the exciting LHC 14 (Run II).


HIGGS BOSON


HIGGS BOSON
Dark Matte

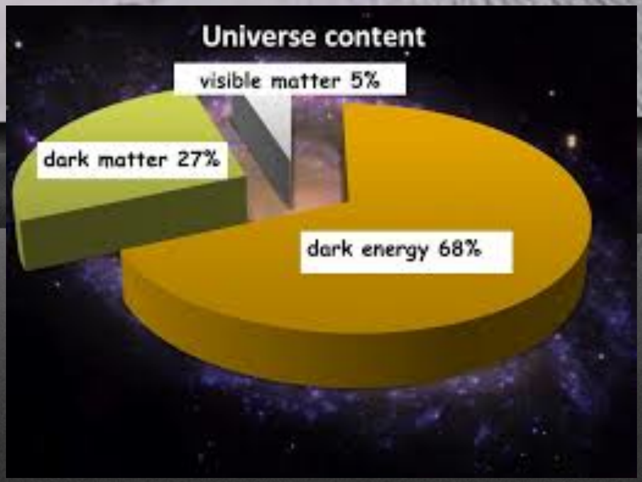


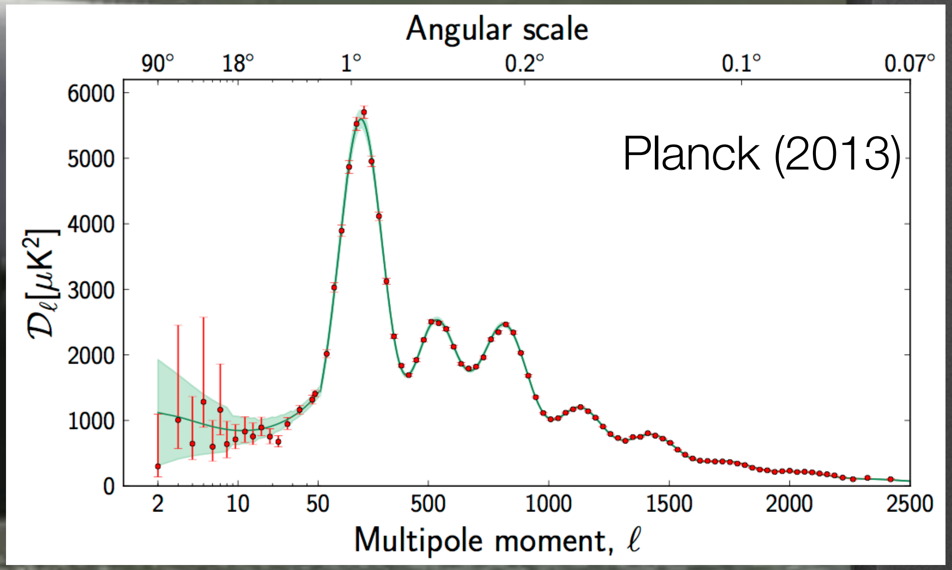


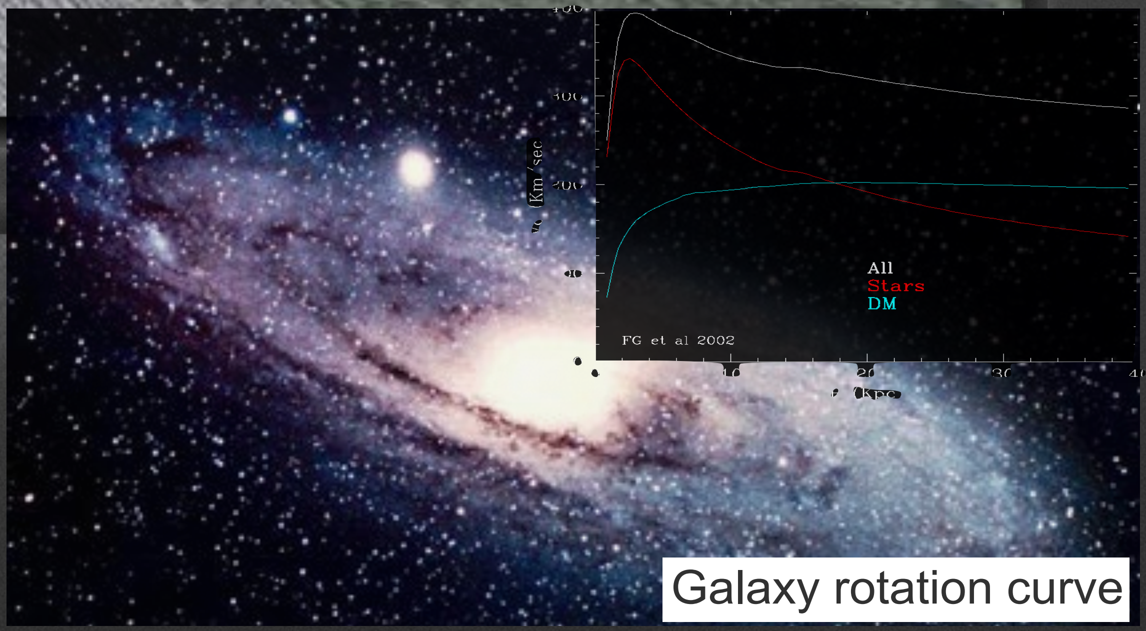


Bullet cluster

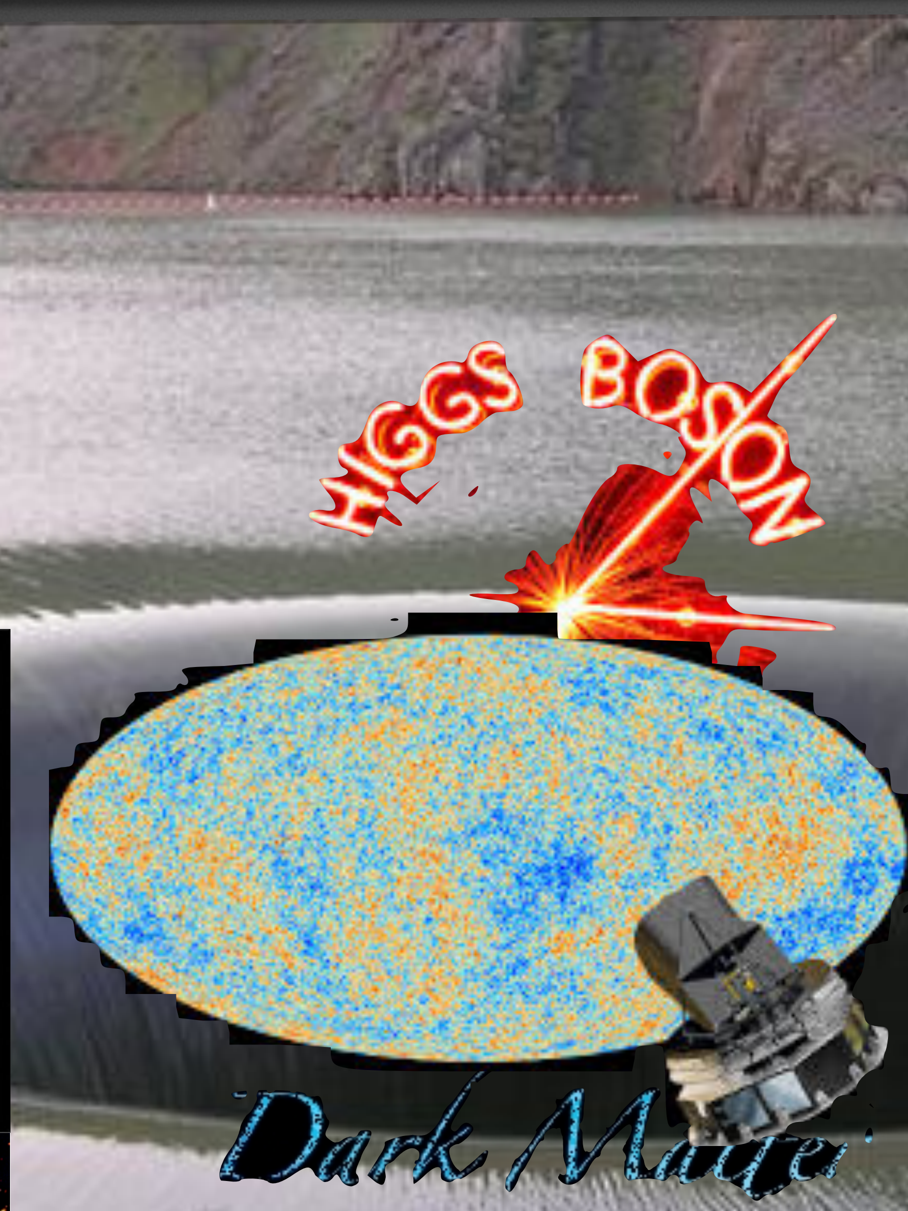
1E 0657-56, Bullet cluster

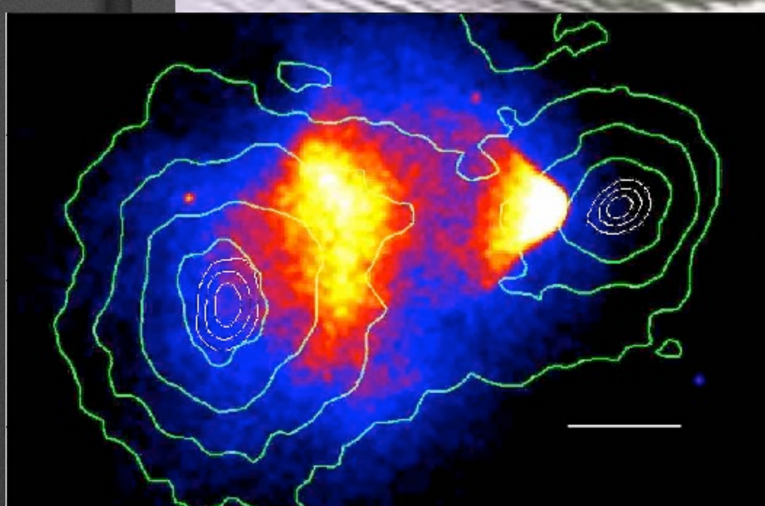


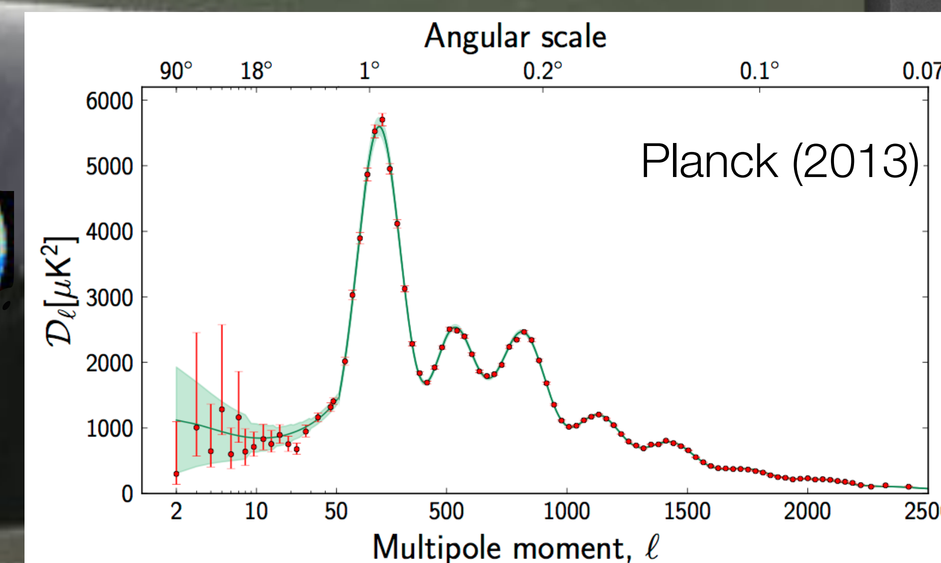


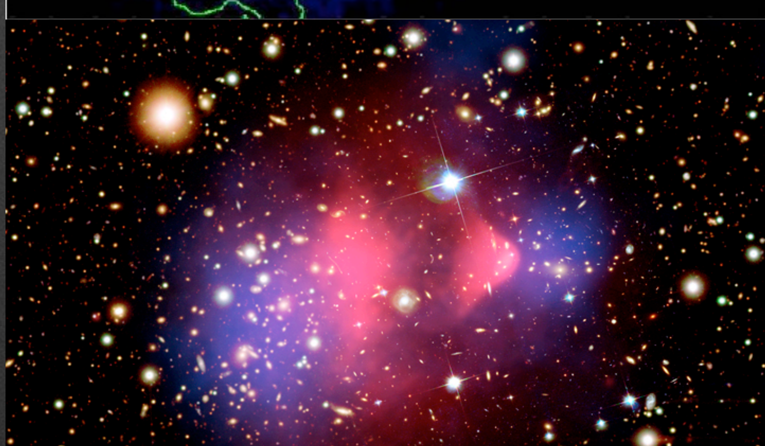


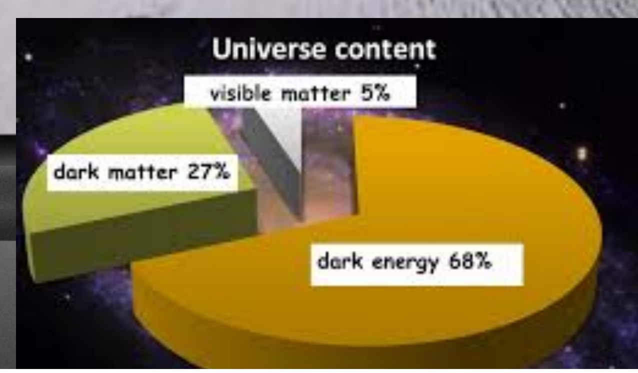
Galaxy rotation curve







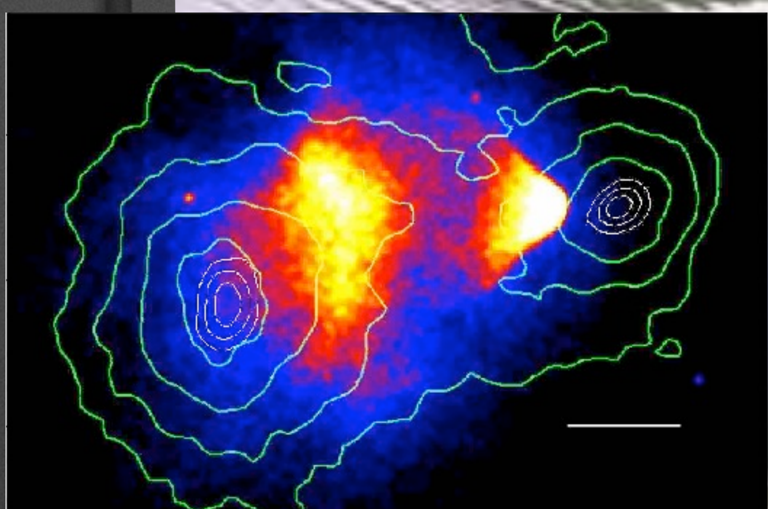


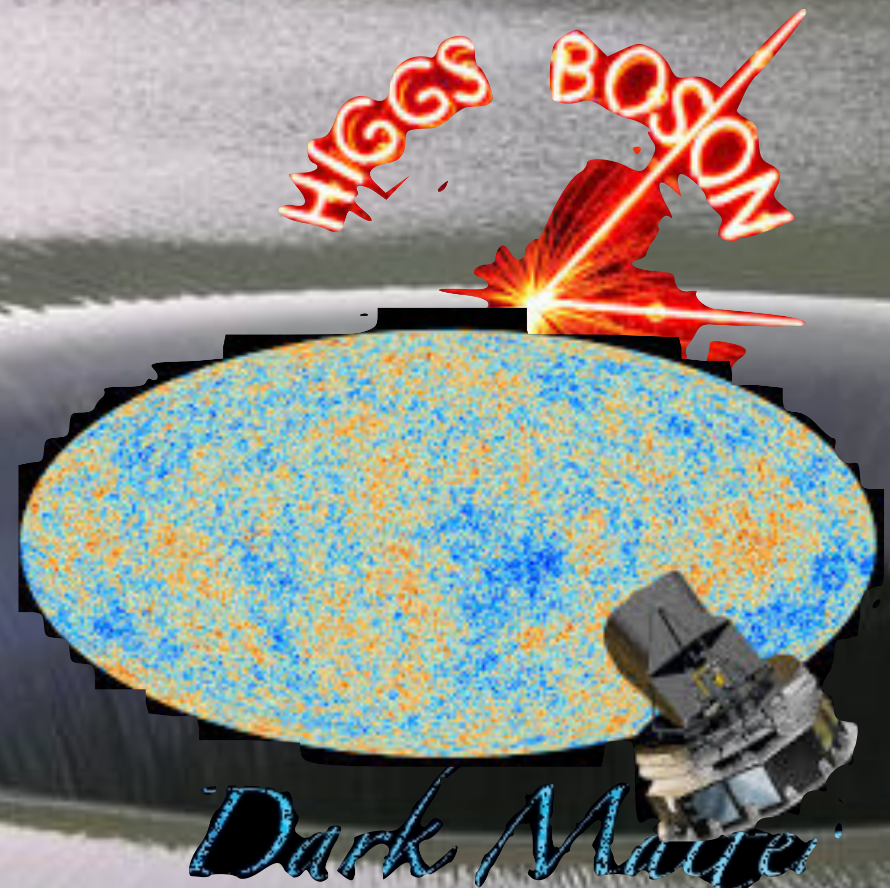


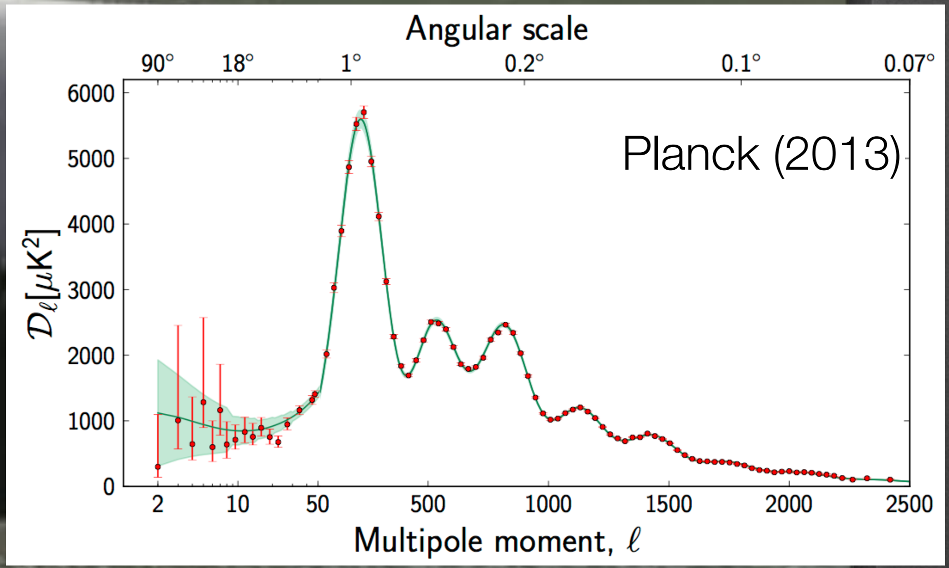
Bu

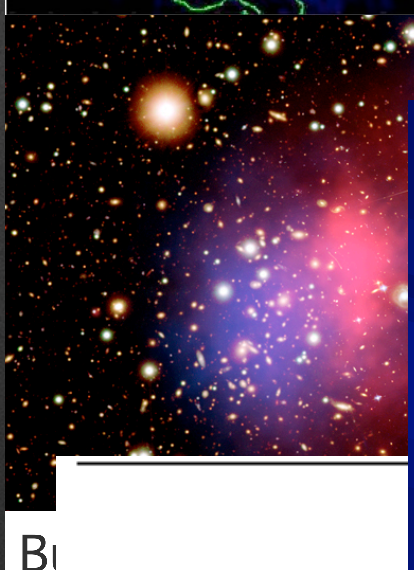
curve

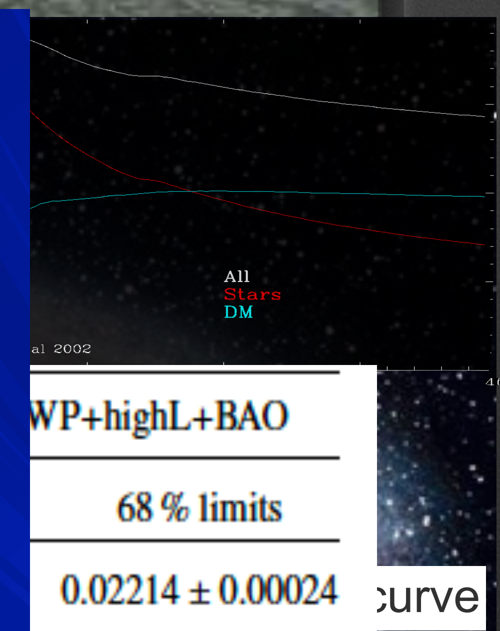
	Planck		*Planck*+lensing		*Planck*+WP		*Planck*+WP+highL+BAO	
Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68 % limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.0002	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027	0.11889	0.1187 ± 0.0017







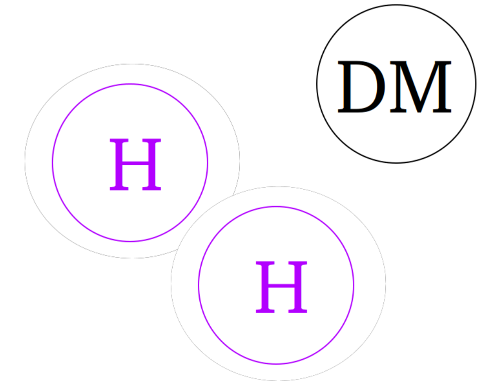




- Neutral (electric charge =0 and colorless)
- Very weakly interacting, no EM interaction
- Very long lived or absolutely stable
- Hot or warm or cold, prefer cold dark matter (CMD)
- Mass, spin not known

Parameter		WP+highL+BAO 68 % limits
$\Omega_b h^2$		0.02214 ± 0.00024
$\Omega_c h^2$		0.1187 ± 0.0017

2HDMS DM sector



- Add an extra gauge singlet S with <S>=0

	H_1	H_2	S
$\mathbb{Z}_2$	$+$	$-$	$+$
$\mathbb{Z}'_2$	$+$	$+$	$-$

S is stable, being a DM candidate

$$\mathcal{L}_S \supset -\frac{1}{2} m_0^2 S^2 - \kappa_1 S^2 (H_1^\dagger H_1) - \kappa_2 S^2 (H_2^\dagger H_2) - \frac{1}{4!} \lambda_S S^4$$

After EWSB:

$$\mathcal{L}_S \supset -\frac{1}{2} \underbrace{[m_0^2 + (\kappa_1 \cos^2\beta + \kappa_2 \sin^2\beta) v^2]}_{m_S^2} S^2$$

an additional physical state

$$- \underbrace{(\kappa_1 \cos\alpha \cos\beta + \kappa_2 \sin\alpha \sin\beta)}_{\lambda_h} v h S^2$$

$$- \underbrace{(-\kappa_1 \sin\alpha \cos\beta + \kappa_2 \cos\alpha \sin\beta)}_{\lambda_H} v H S^2$$

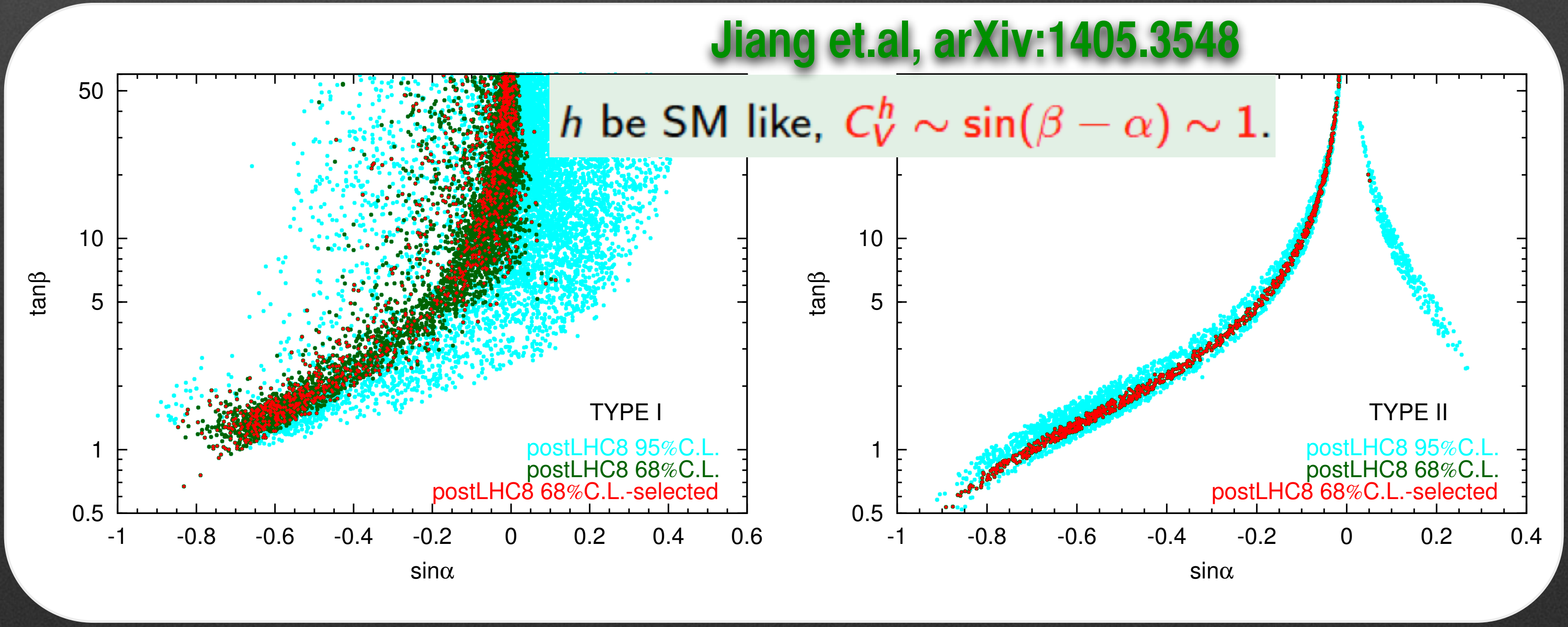
$$+ (HH, hH, hh, AA, H^+ H^-) S^2 \text{ terms}$$

NO AS^2 term !

Free inputs: $[\kappa_1, \kappa_2, m_S, \lambda_S]$ **or** $[\lambda_h, \lambda_H, m_S, \lambda_S]$

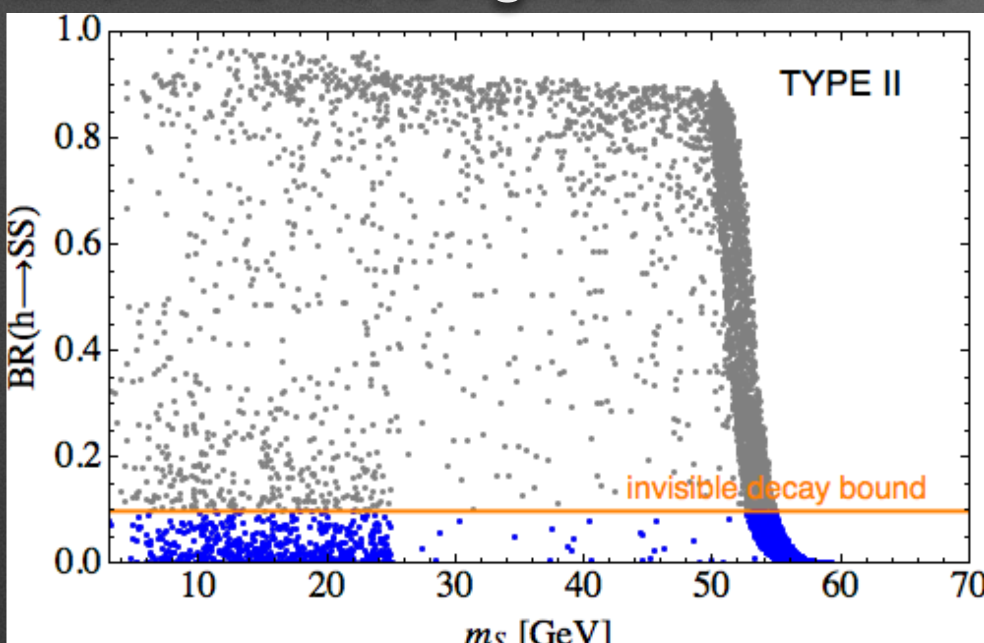
Interplay between Higgs & DM

Interplay between Higgs & DM



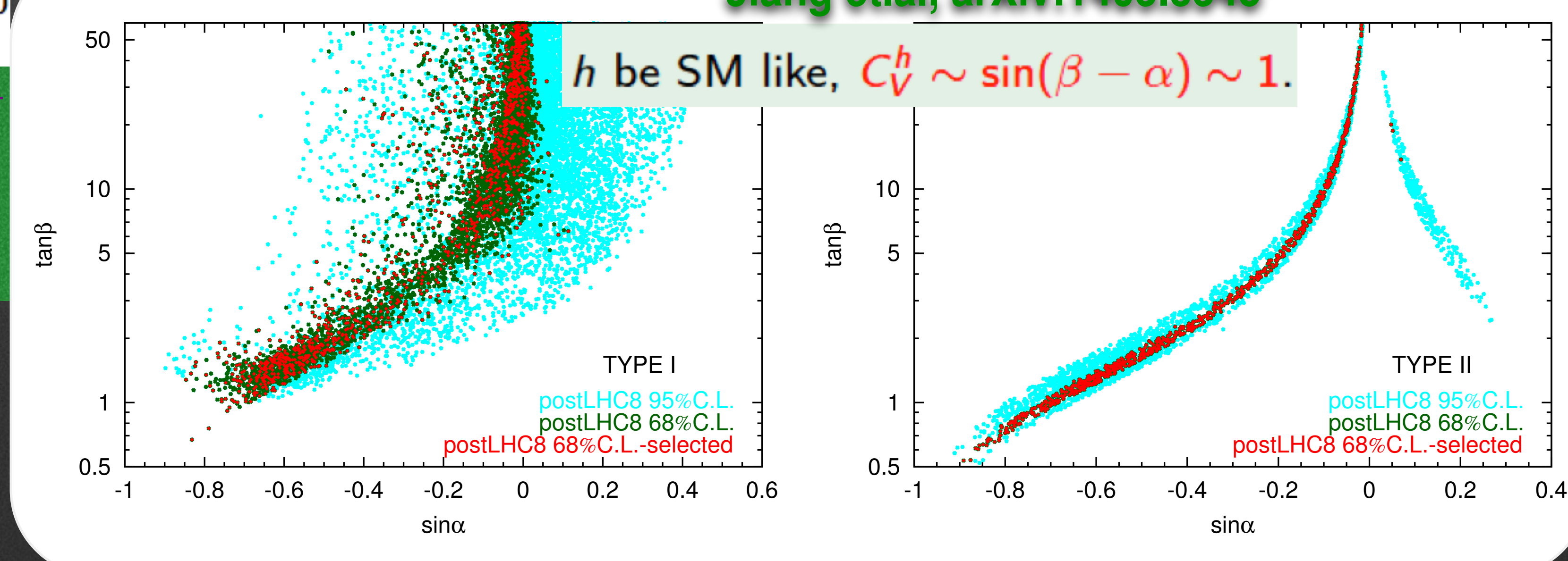
Interplay between Higgs & DM

when the m_S is lighter than $m_h/2$



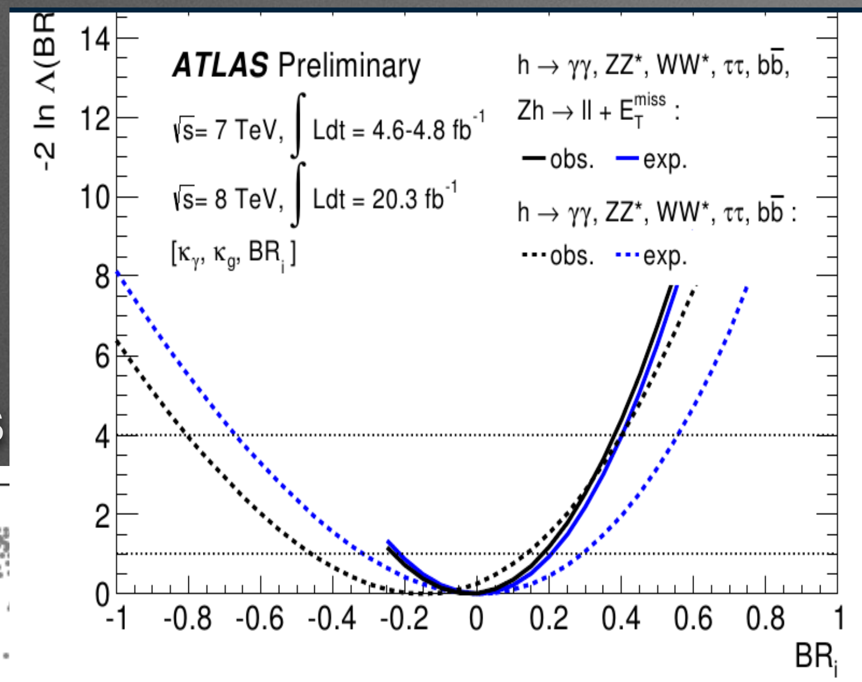
$$\Gamma(h \to SS) = \frac{1}{8\pi}\frac{\lambda_h^2 v^2}{m_h}\sqrt{1 - \frac{4m_S^2}{m_h^2}}$$

Jiang et.al, arXiv:1405.3548

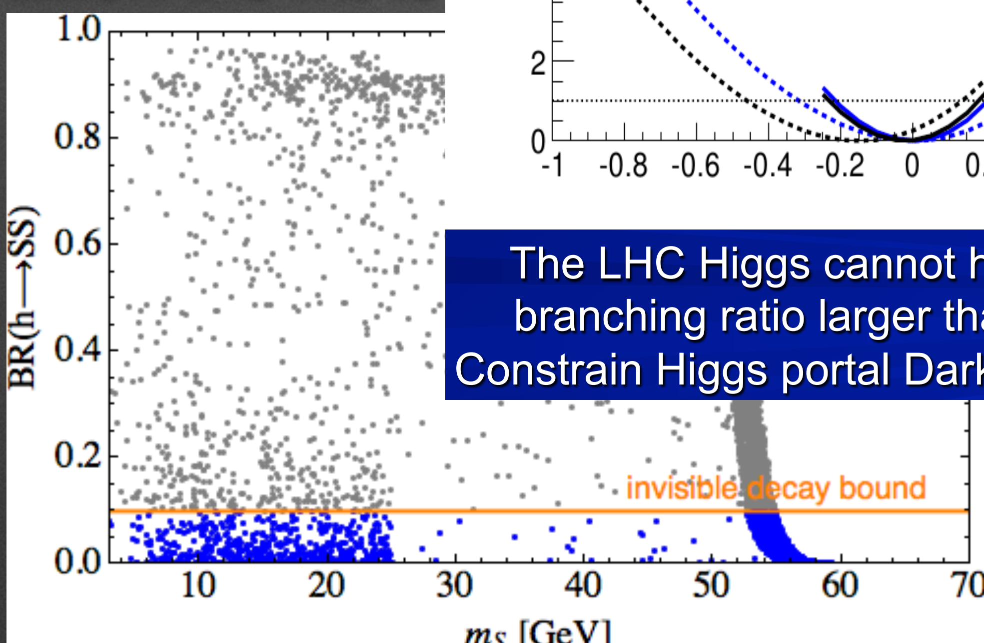


Interplay between Higgs & DM

when the ms is



The LHC Higgs cannot have invisible branching ratio larger than 20 ~ 30%! Constrain Higgs portal Dark Matter models.



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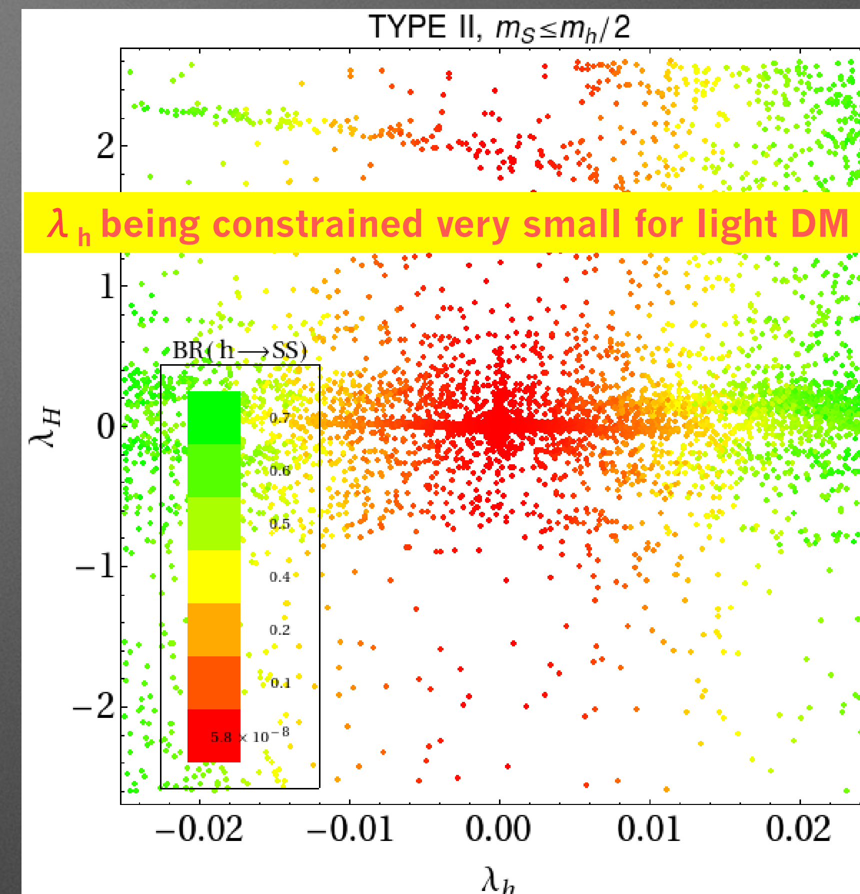

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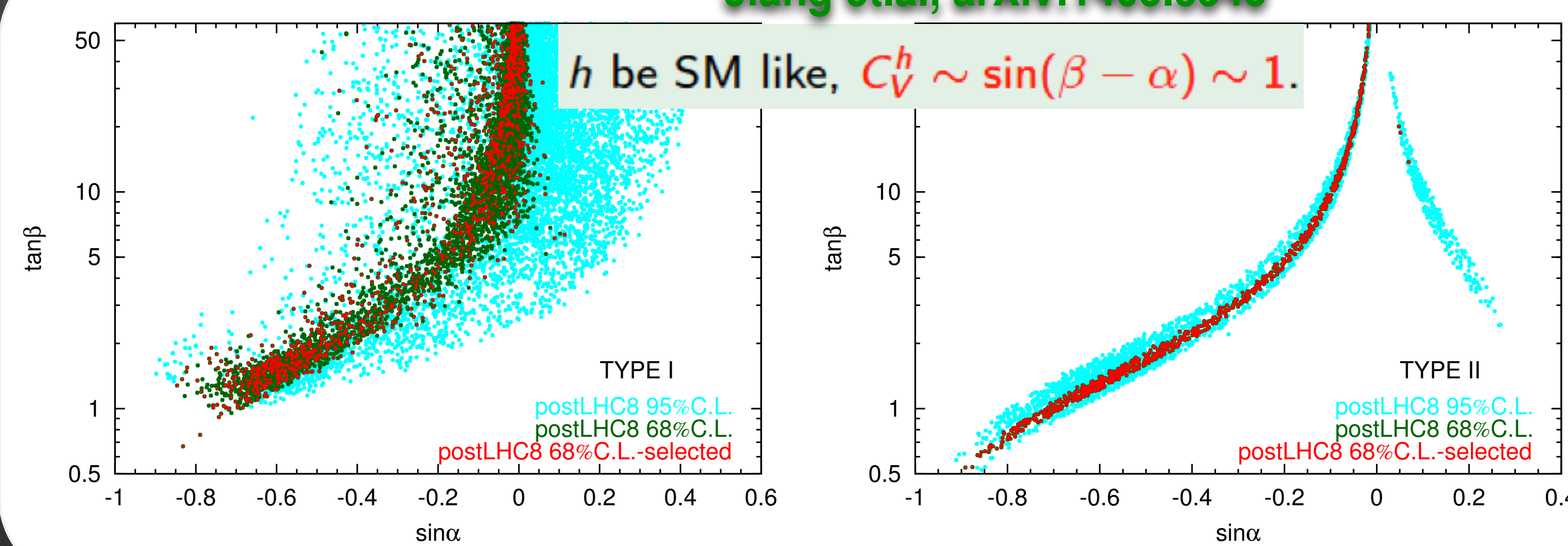
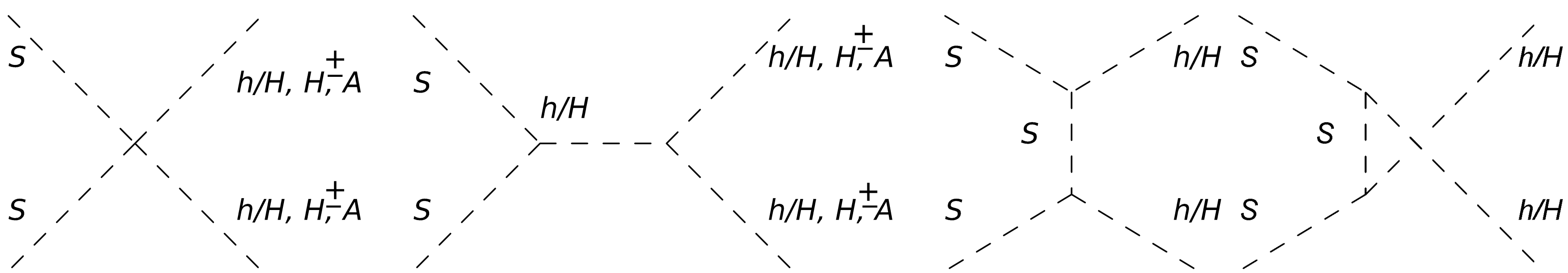


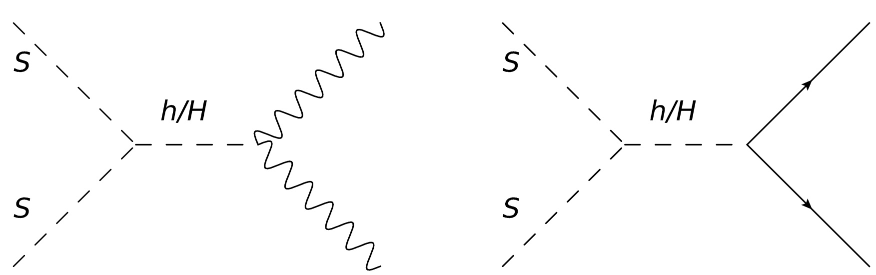
DM Physics

$$\Omega_S = \frac{\rho_S}{\rho_c} \simeq 1.07 \times 10^9 \frac{m_S}{\sqrt{g_*}\, T_f M_{\rm Pl} \langle \sigma_{\rm ann} v_{\rm rel} \rangle} \frac{1}{\rm GeV}$$

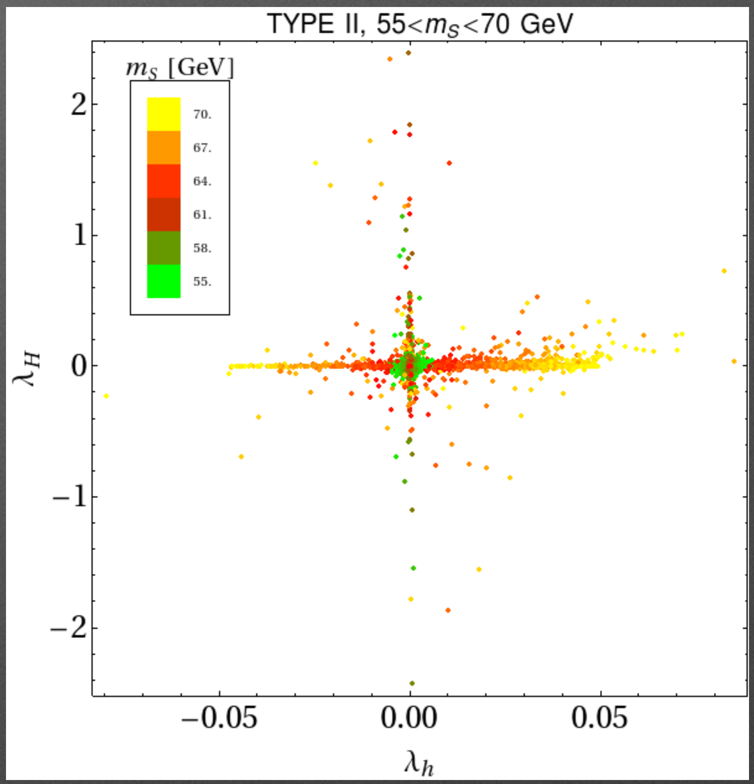
DM interaction

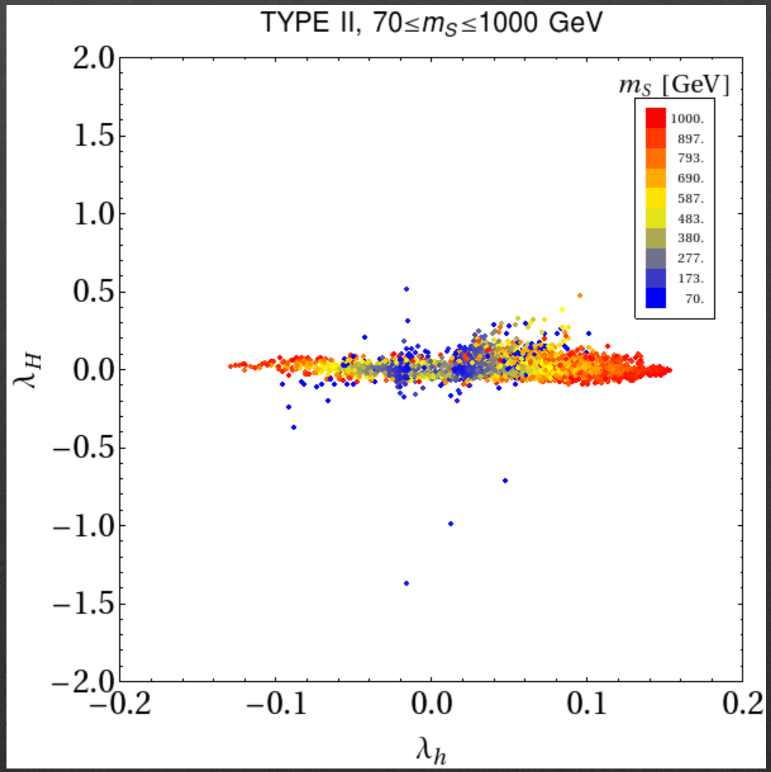


$$\langle \sigma_{SS\to H_i H_j} v_{\rm rel} \rangle = \frac{\beta(m_{H_i}, m_{H_j})}{32(1+\delta_{ij})\pi m_S^2} \left| g_{H_i H_j SS} + \sum_{\mathcal{H}=h,H} \frac{g_{\mathcal{H}SS}\, g_{\mathcal{H}H_i H_j}}{4m_S^2 - m_{\mathcal{H}}^2 + i\Gamma_{\mathcal{H}} m_{\mathcal{H}}} + 2\delta_{CP} \frac{g_{H_i SS}\, g_{H_j SS}}{\frac{1}{2}(m_{H_i}^2 + m_{H_j}^2) - 2m_S^2} \right|^2$$



$$\langle \sigma_{SS\to X\overline{X}} v_{\rm rel} \rangle = \sum_{\mathcal{H}=h,H} \left| \frac{g_{\mathcal{H}SS}\, C_X^{\mathcal{H}}}{4m_S^2 - m_{\mathcal{H}}^2 + i\Gamma_{\mathcal{H}} m_{\mathcal{H}}} \right|^2 \frac{\Gamma_{\rm SM}(\mathcal{H}^* \to X\overline{X})}{2m_S}$$





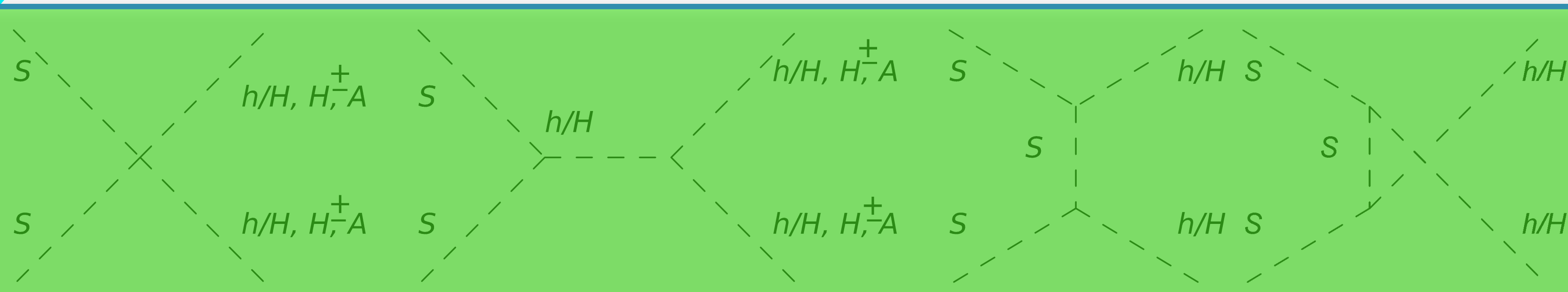
DM Physics

__light DM__ :

- small λ_h to avoid large Higgs invisible decay
- H-mediator responsible to DM relic density

$$\Omega_S = \frac{\rho_S}{\rho_c} \simeq 1.07 \times 10^9 \frac{m_S}{\sqrt{g_*}\, T_f M_{\rm Pl} \langle \sigma_{\rm ann} v_{\rm rel}\rangle} \frac{1}{\rm GeV}$$

DM interaction



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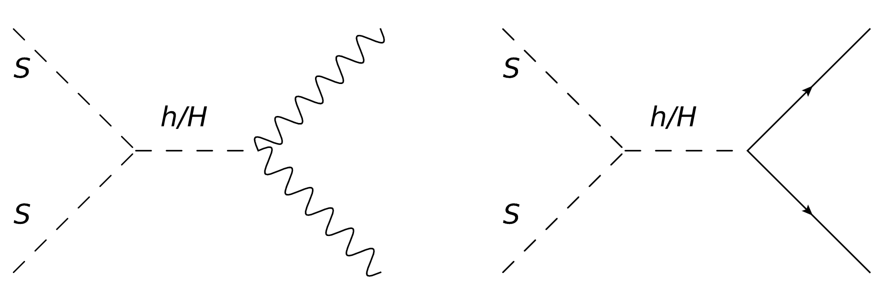

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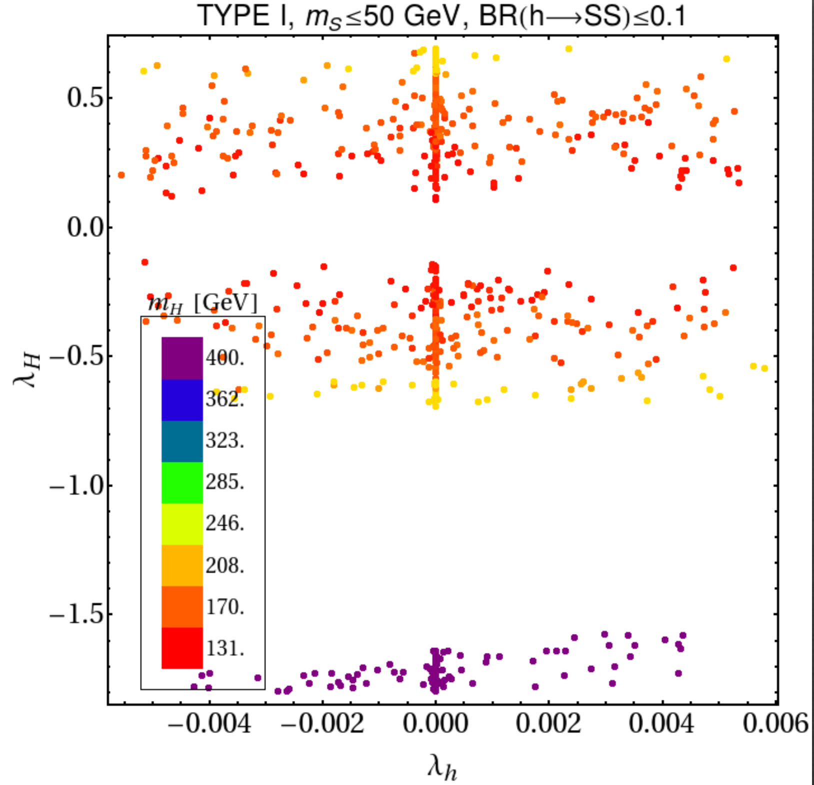
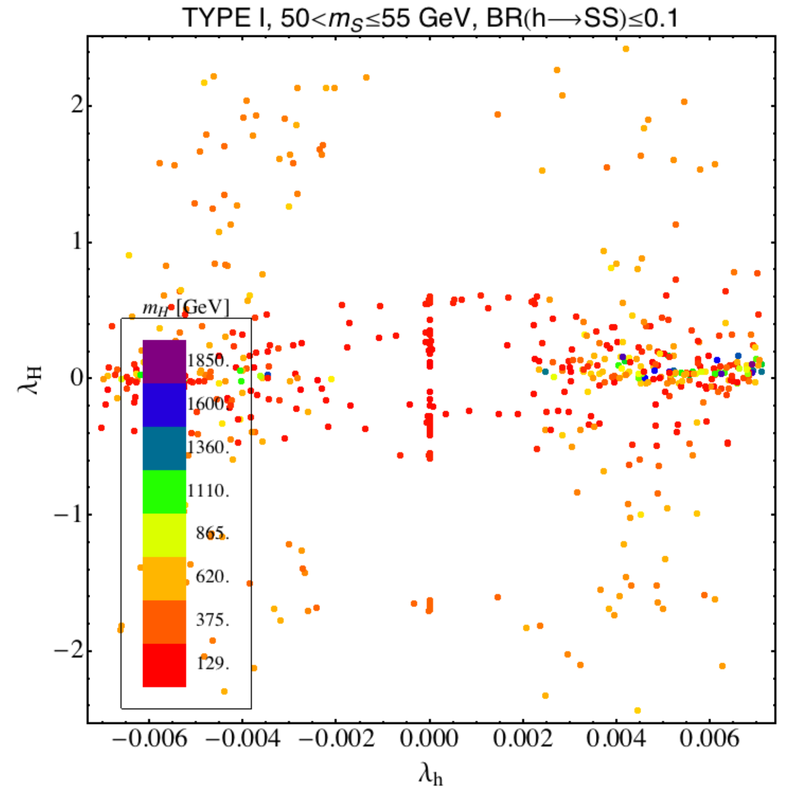
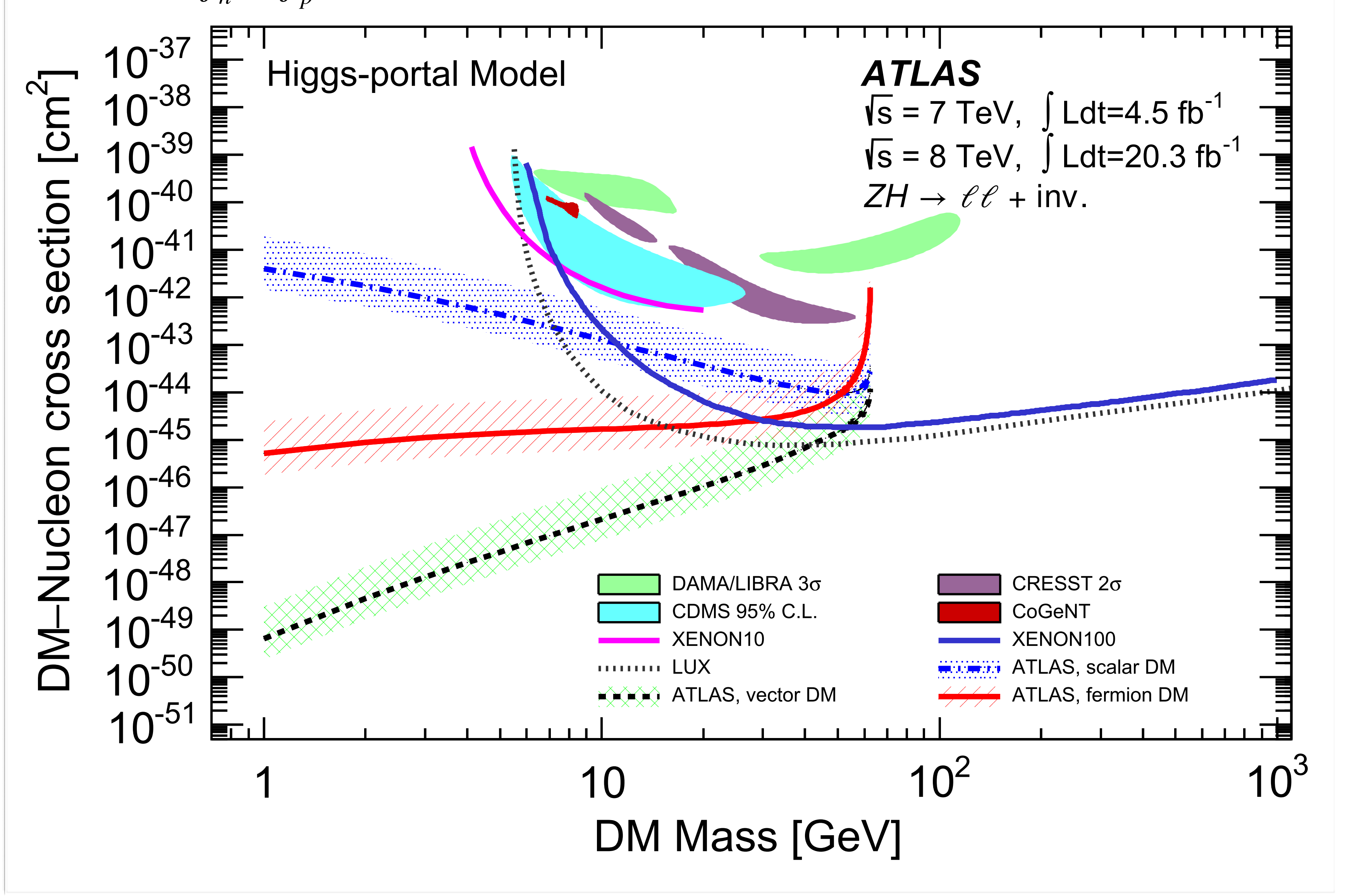
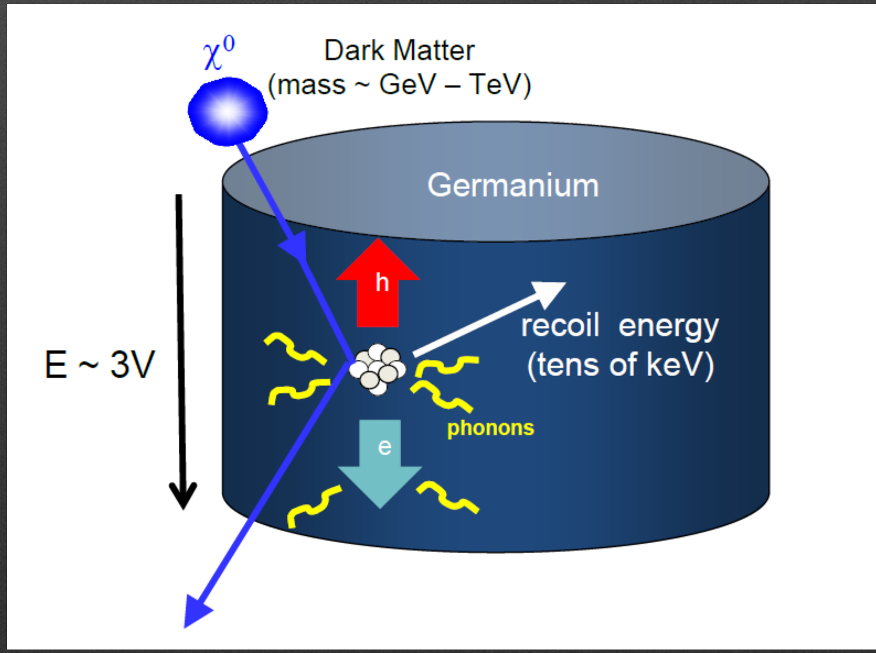




DM Direct detection

Assume $f_n = f_p$





$$\sigma_{\mathrm{DM}-N} = \int_0^{4\mu_r^2 v^2} \frac{d\sigma(q=0)}{d|\mathbf{q}|^2} d|\mathbf{q}|^2 = \frac{4\mu_r^2}{\pi} f_p^2 \left[Z + \frac{f_n}{f_p}(A-Z) \right]^2$$

DM Direct detection

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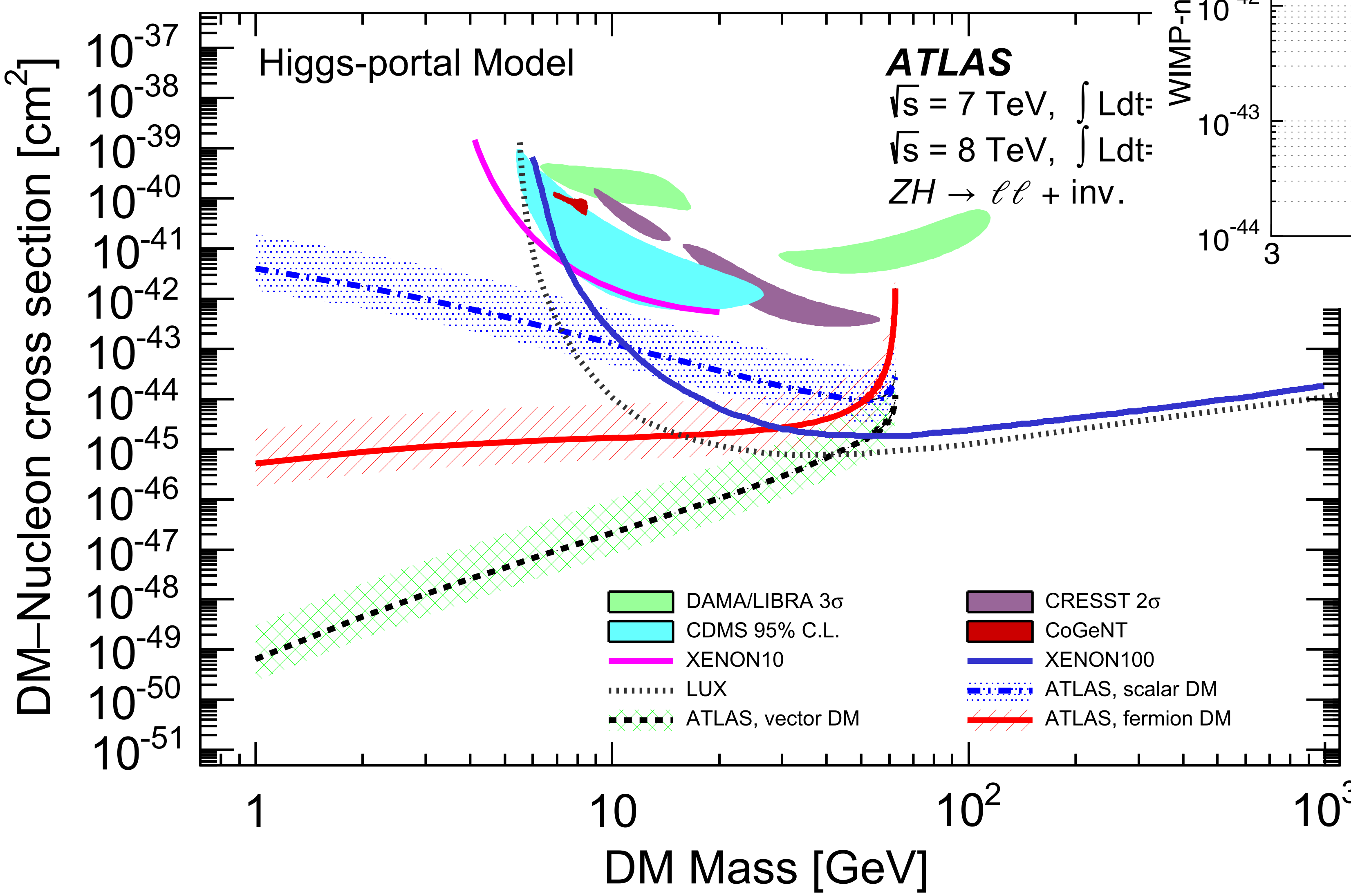

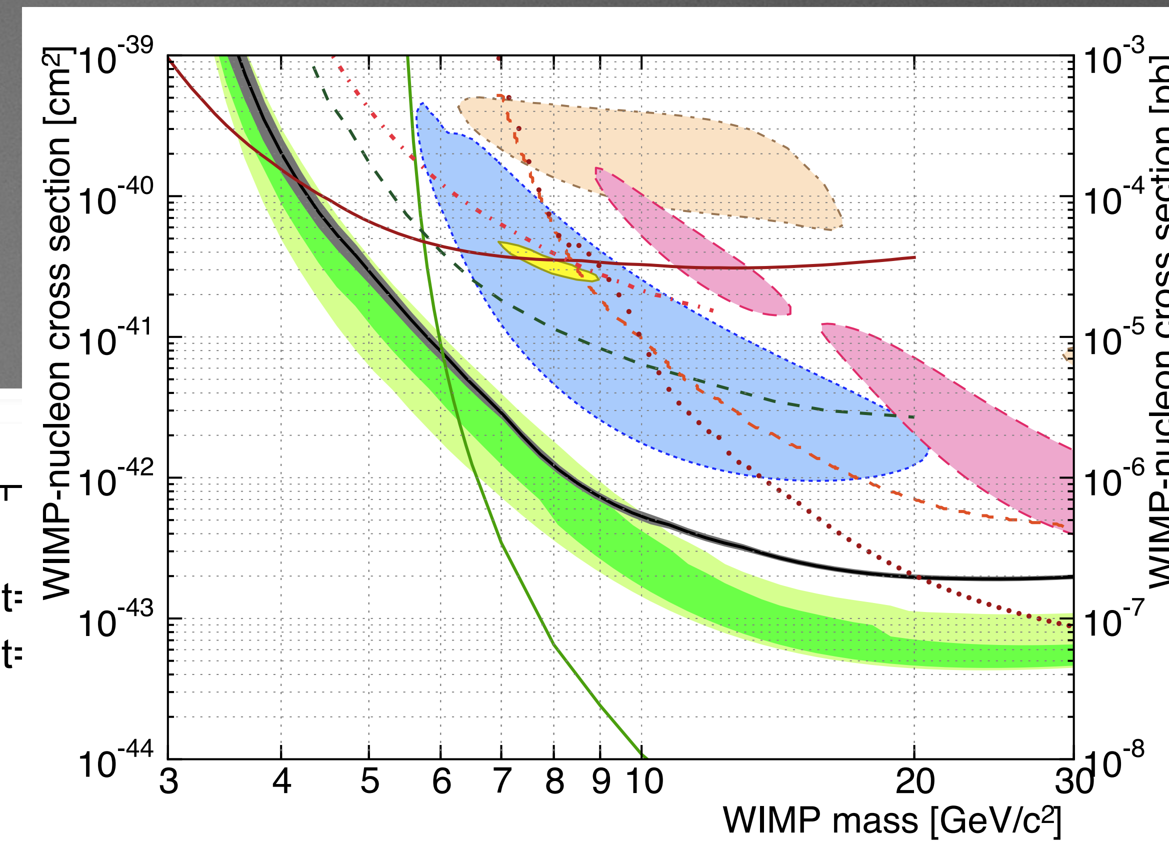

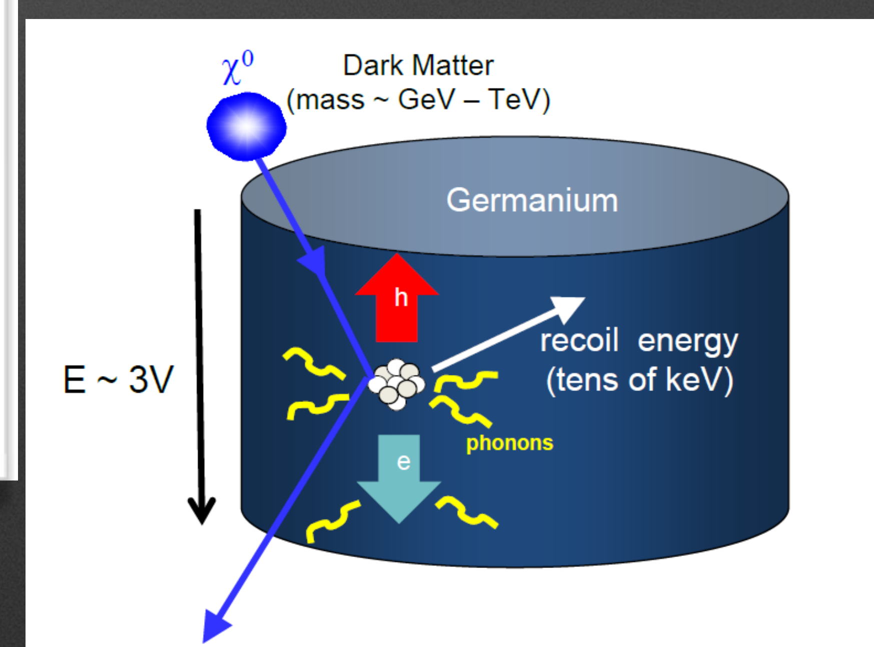

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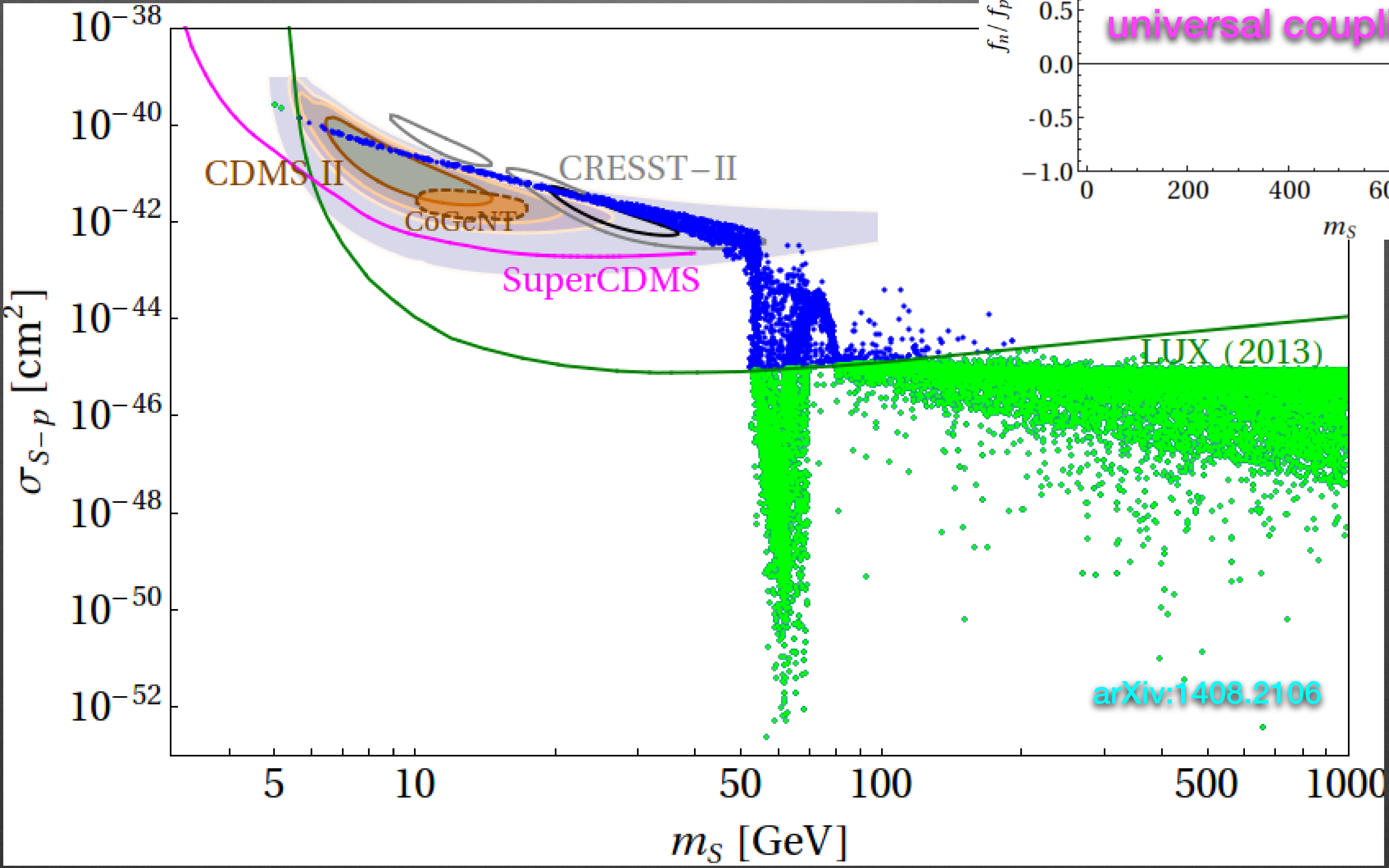
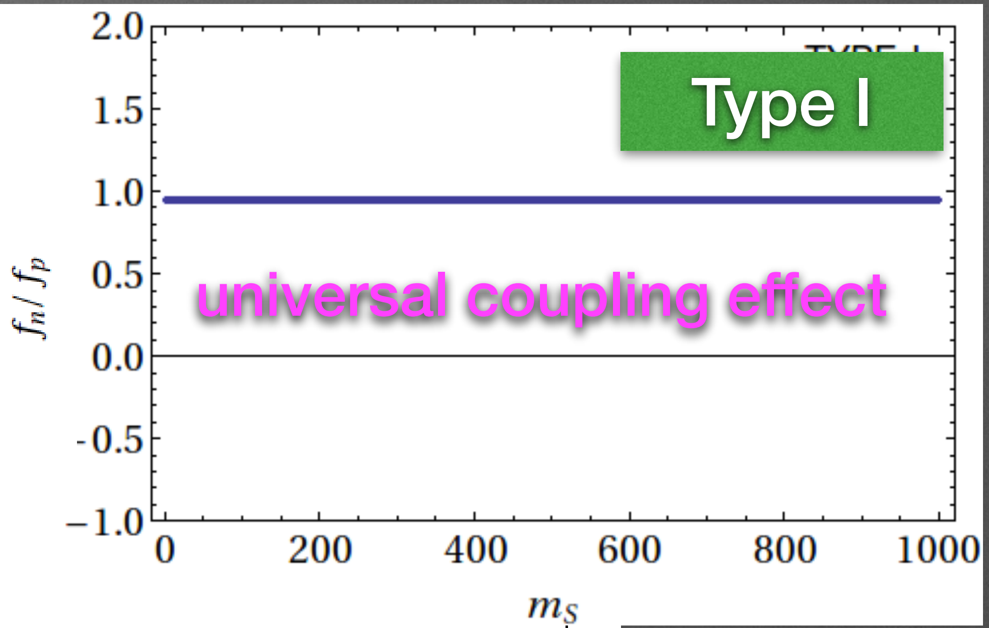
Type I analysis





- Very low mass region: few green points that pass the LUX limit are excluded by the SuperCDMS limit.
- low mass region: agree pretty well with CDMS II/CRESST-II data, of course, disobey the LUX limit.
- mS >~ 55 GeV region: the majority of points pass the LUX limit.

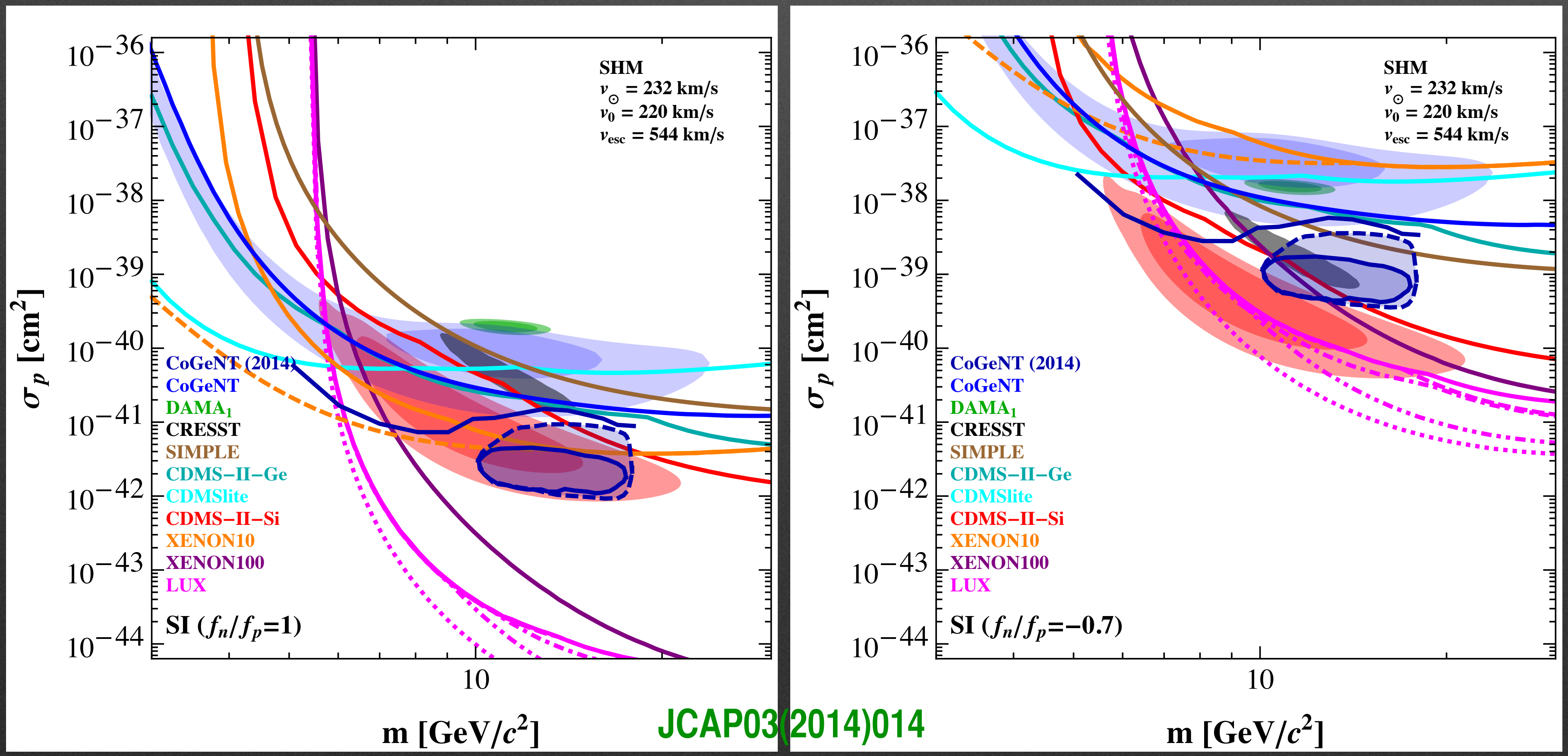
Isospin violating effect

However, this equality is not always true in the Type II model. In order to compare predicted the cross-sections for DM-nucleon scattering with the results presented by the experimental groups, we define the normalized-to-nucleon cross section, $\overline{\sigma}_{\mathrm{DM}-p}$, following [8]:

$$\overline{\sigma}_{\mathrm{DM}-p} = \sigma_{\mathrm{DM}-p}\, \Theta(f_n, f_p) \tag{21}$$

where $\sigma_{\mathrm{DM}-p}$ is the predicted DM-proton cross-section and the rescaling factor Θ is defined as

$$\Theta(f_n, f_p) \equiv \begin{cases} \left[\frac{Z}{A} + \frac{f_n}{f_p}\left(1 - \frac{Z}{A}\right)\right]^2, & \text{single isotope detector} \\ \frac{\sum_I \eta_I \mu_{A_I}^2 [Z + f_n/f_p (A_I - Z)]^2}{\sum_I \eta_I \mu_{A_I}^2 A_I^2}, & \text{multiple isotope detector} \end{cases} \tag{22}$$



JCAP03(2014)014

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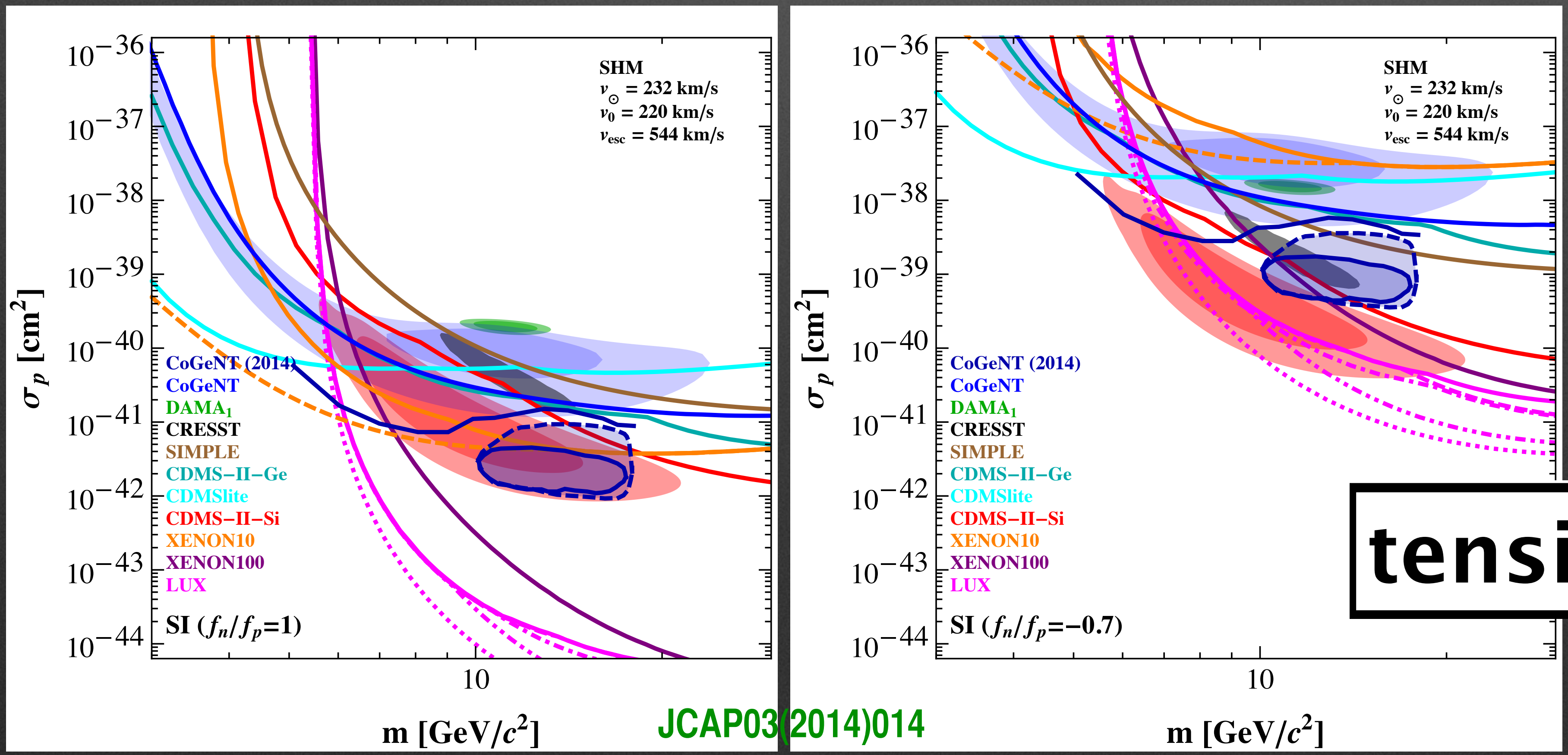

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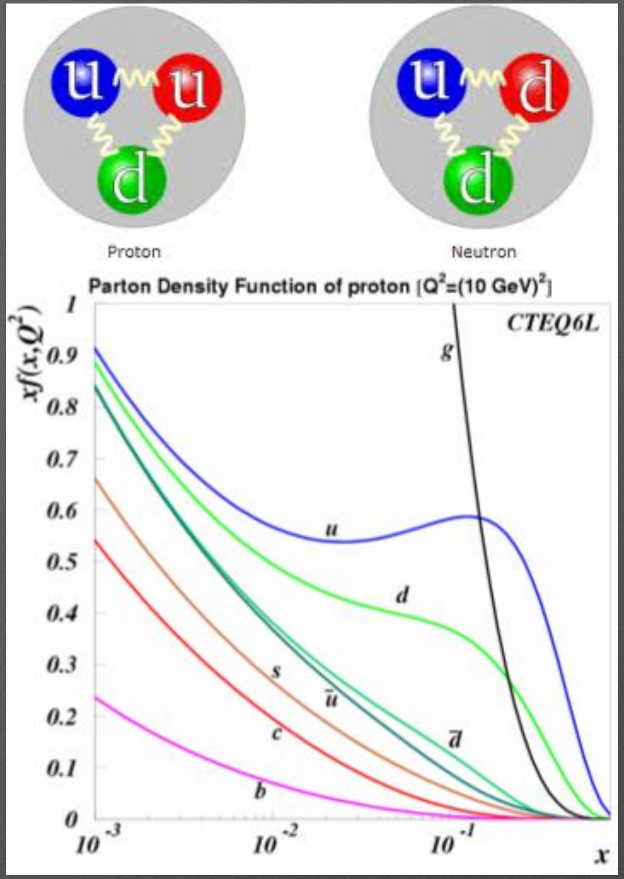
tension alleviated

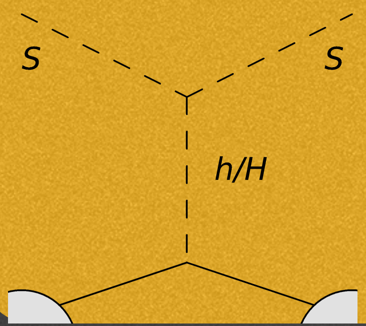
Isospin violating effect

- Isospin violation is found only in couplings to up and down

Quark-Level Realization

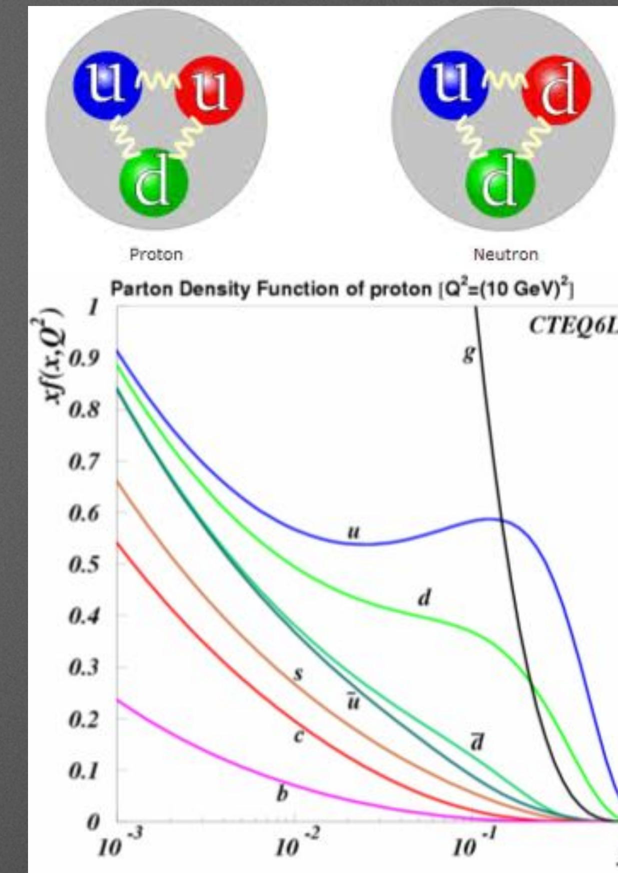


$$f_N = m_N \left(\sum_{q=u,d,s} f_{Tq}^N \frac{\lambda_{SSqq}}{m_q} + \frac{2}{27} f_{TG}^N \sum_{q=c,b,t} \frac{\lambda_{SSqq}}{m_q} \right), \quad f_{TG}^N = 1 - \sum_{q=u,d,s} f_{Tq}^N, \quad (N = p, n).$$



$$\lambda_{SSqq} = -\left(\frac{\lambda_h}{m_h^2} \xi_q^h + \frac{\lambda_H}{m_H^2} \xi_q^H \right) m_q$$

Isospin violating effect



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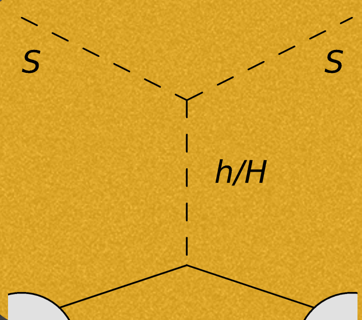

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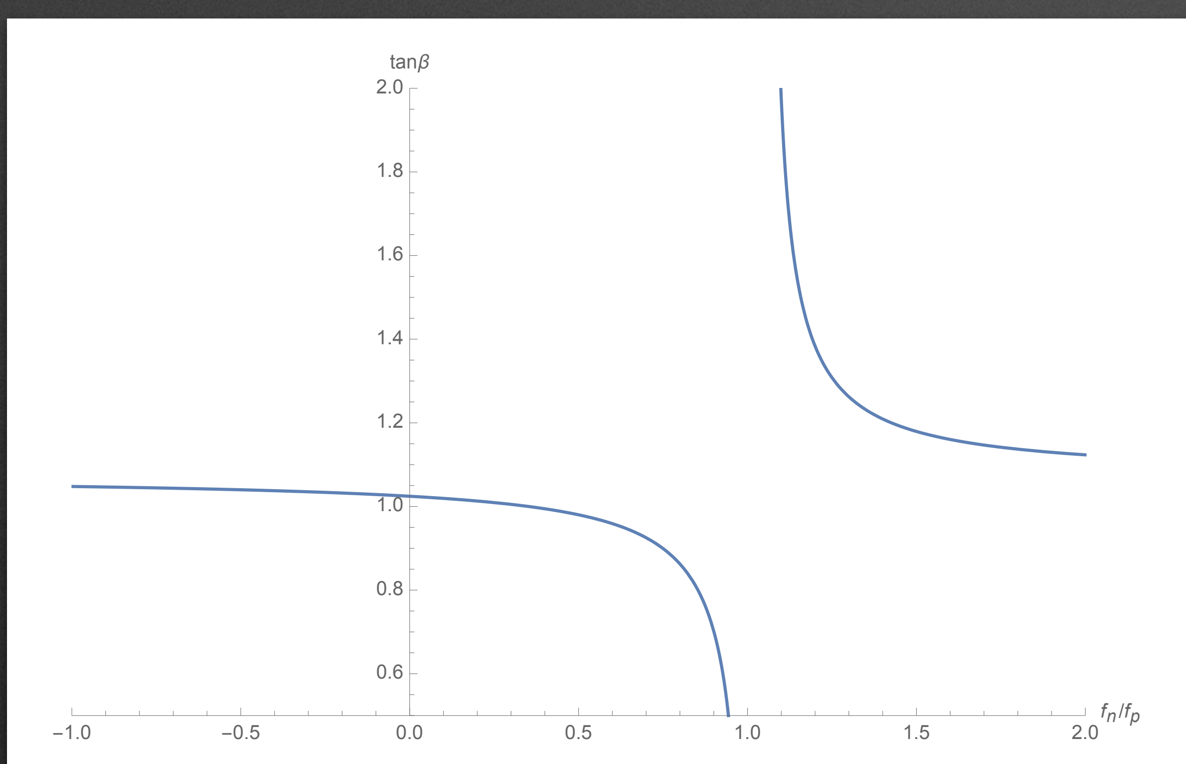

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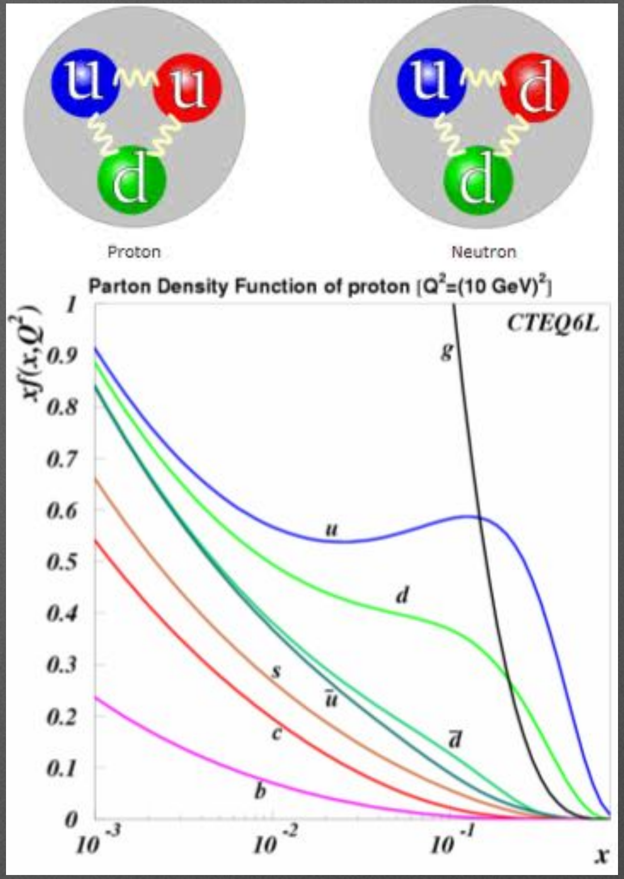

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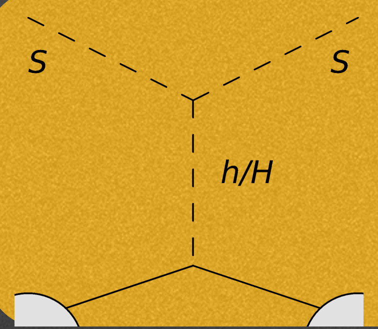

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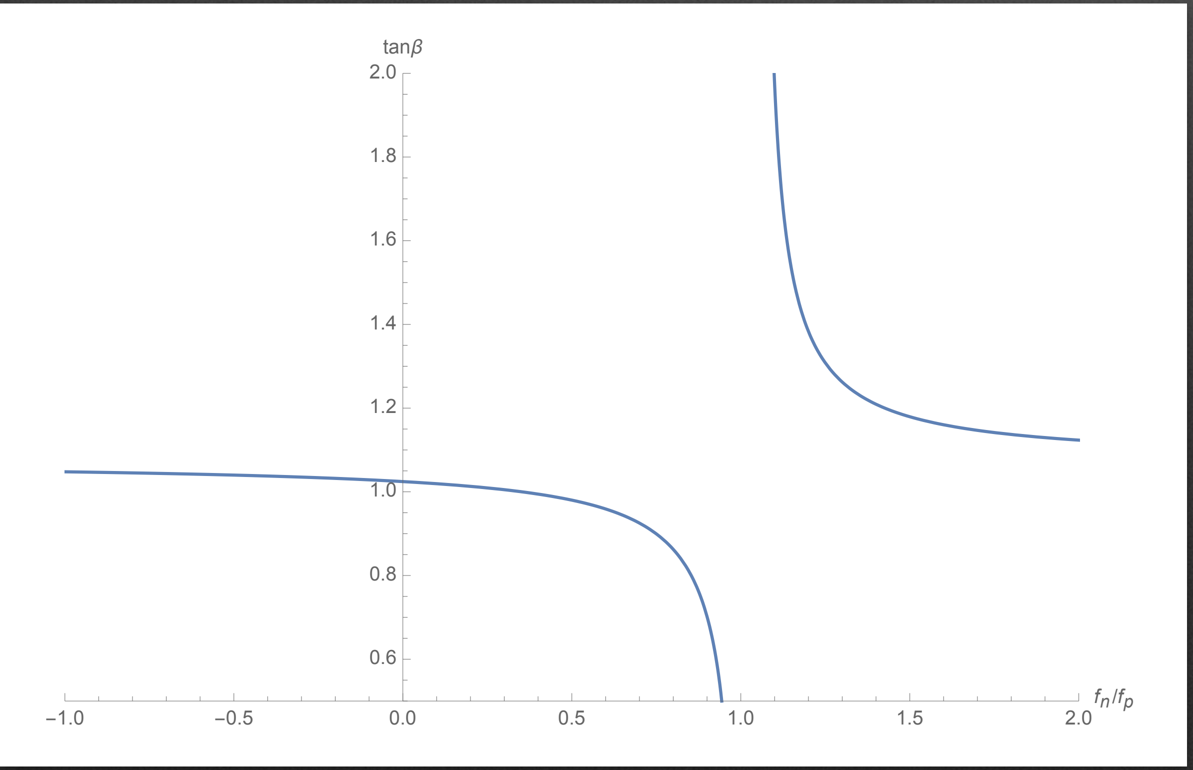
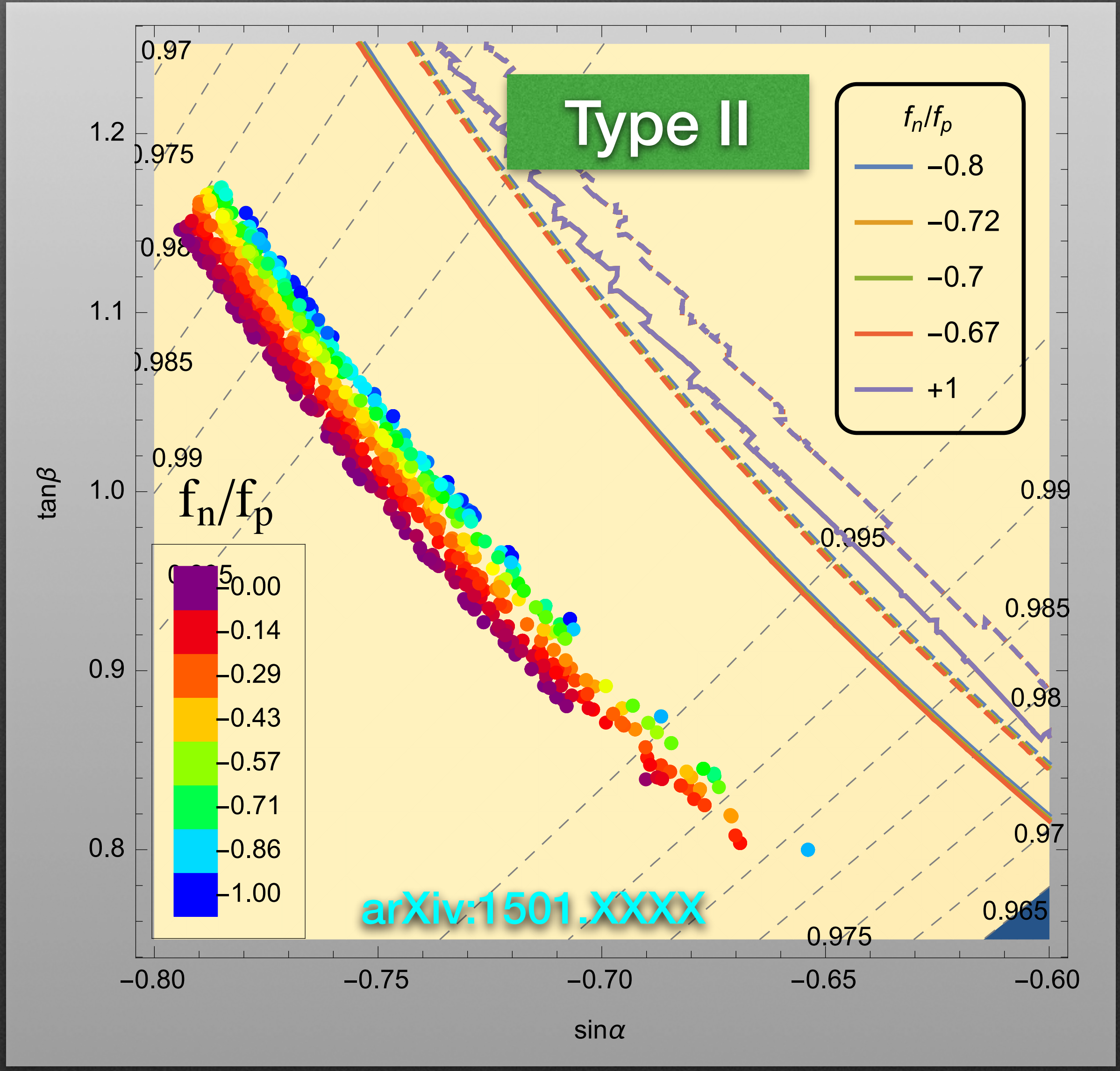
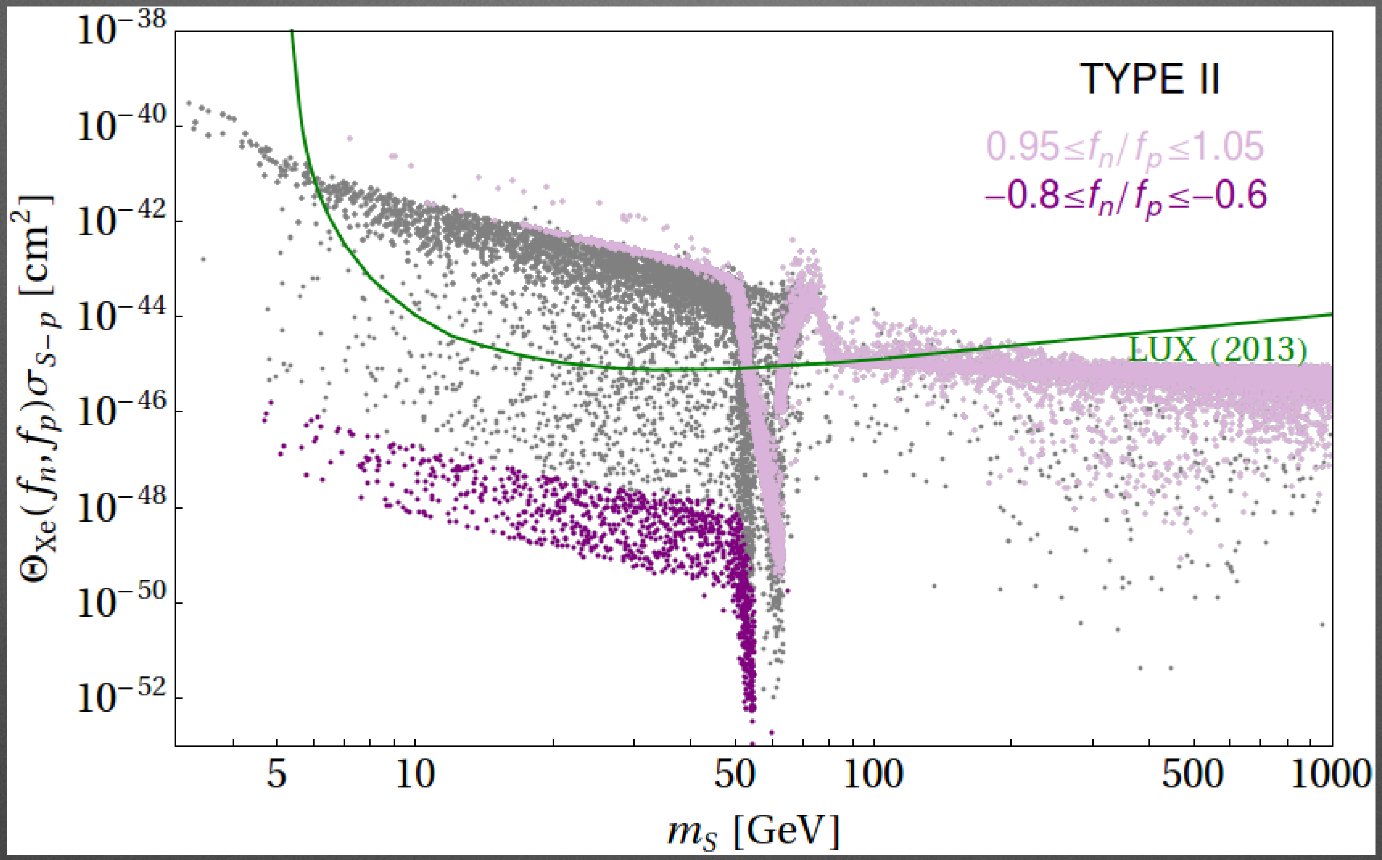
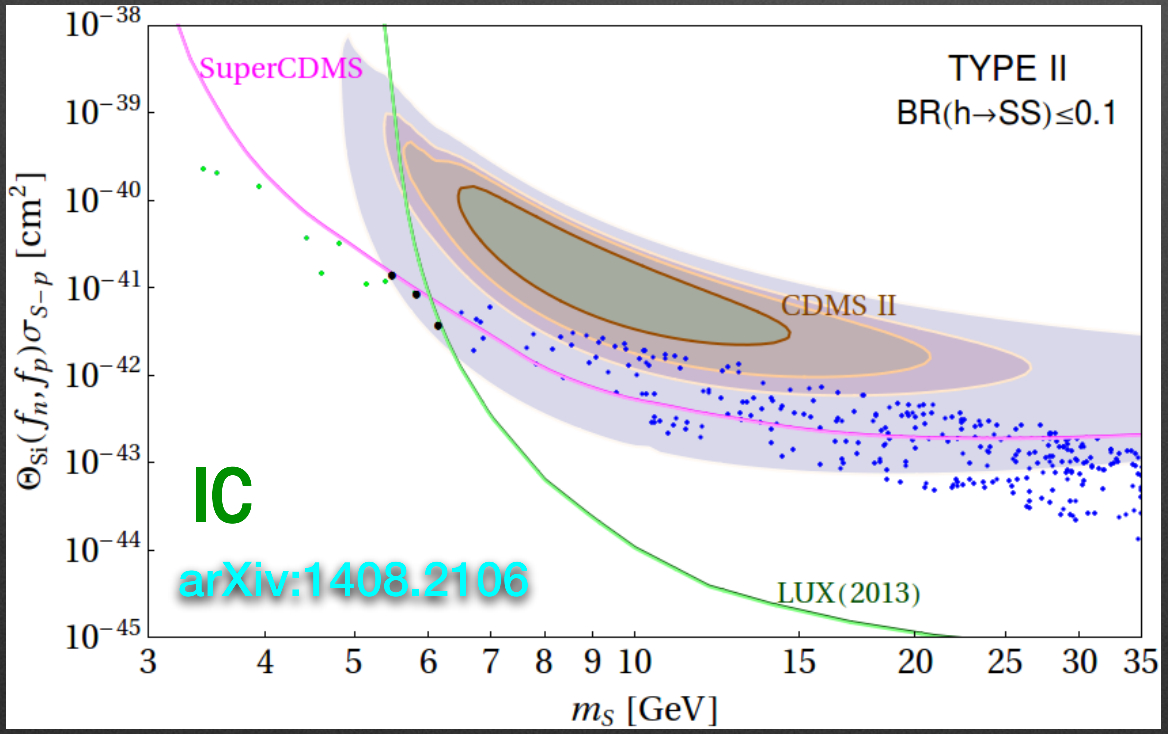




Type II is more attractive





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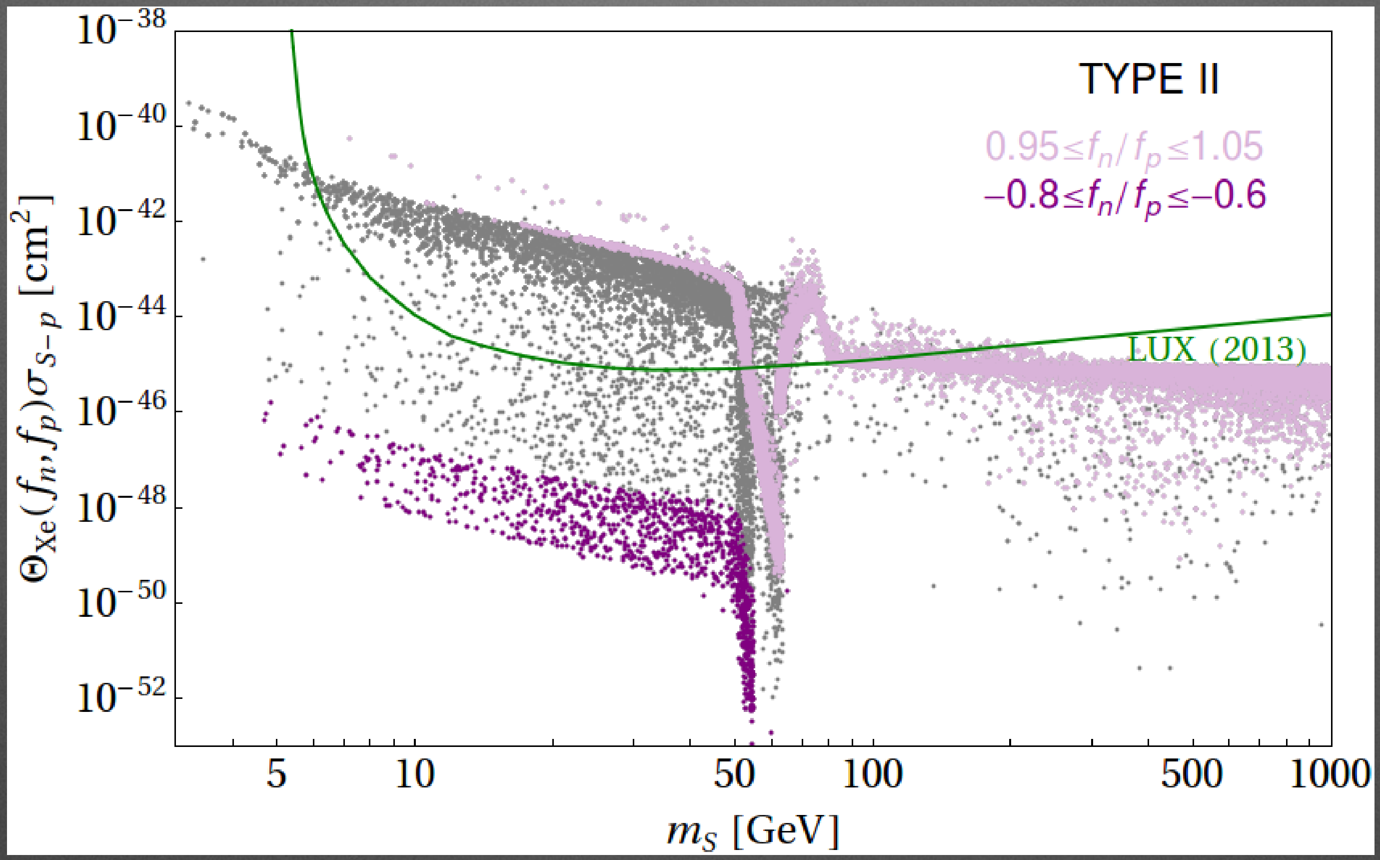

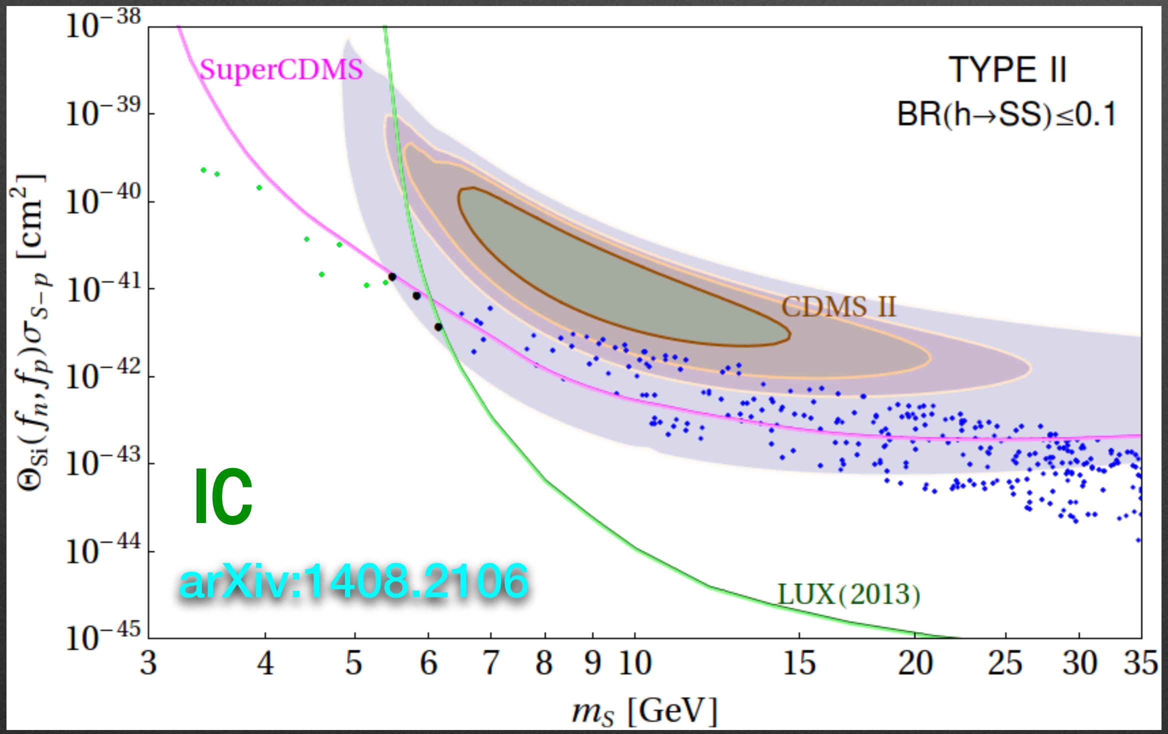

A light DM with mass 6-55 GeV strongly challenged by XENON/LUX null result, but could be consistent with CDMS-II data

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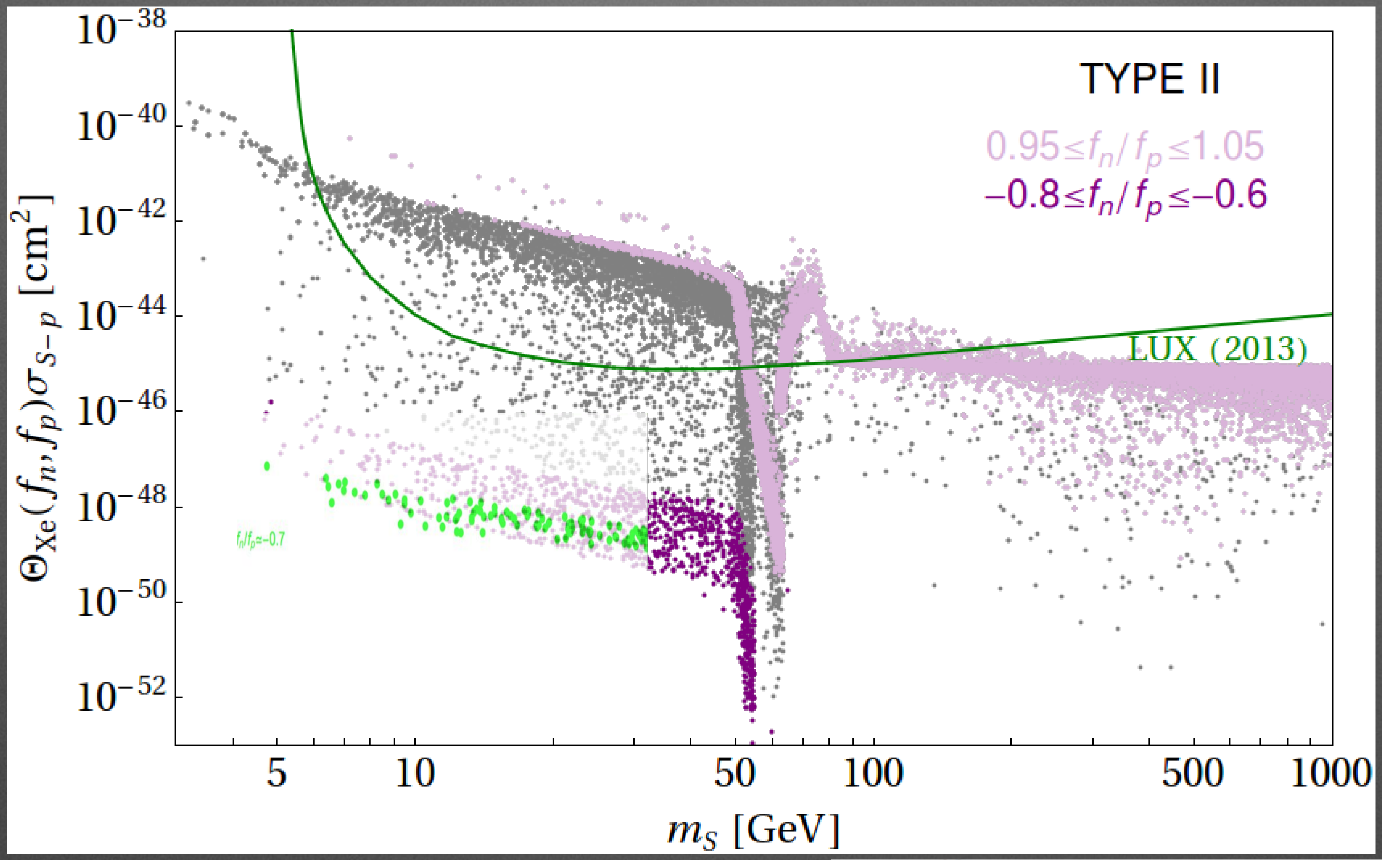
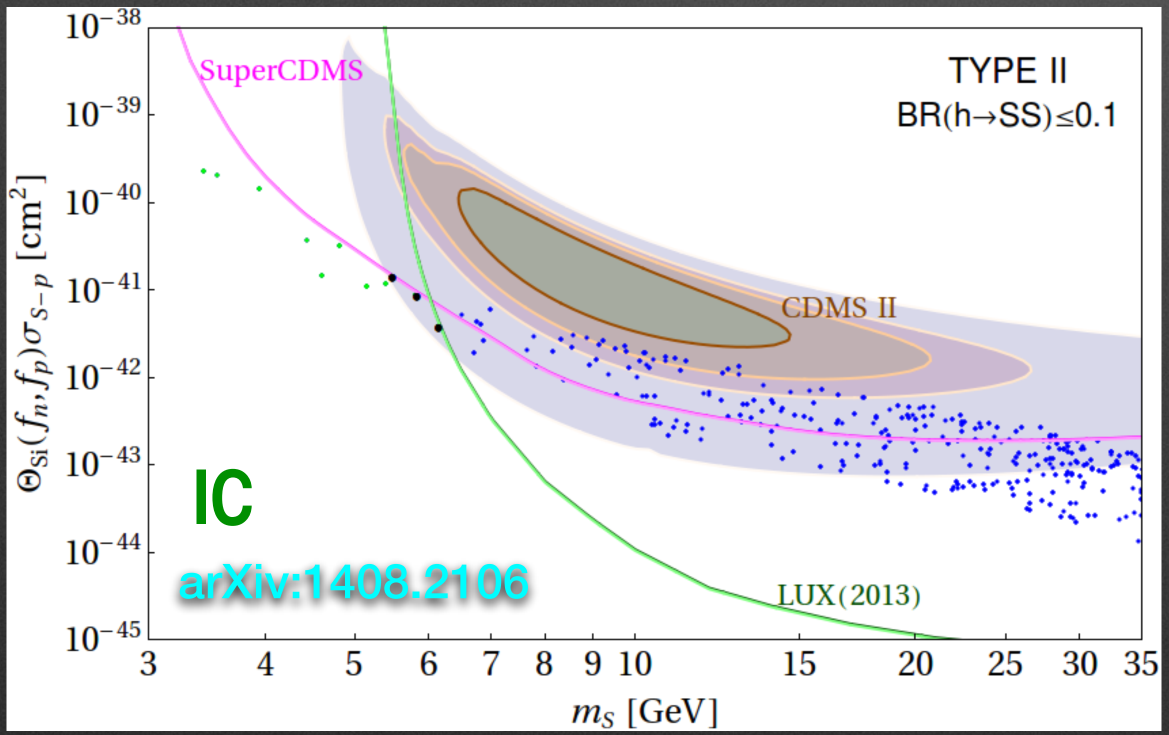
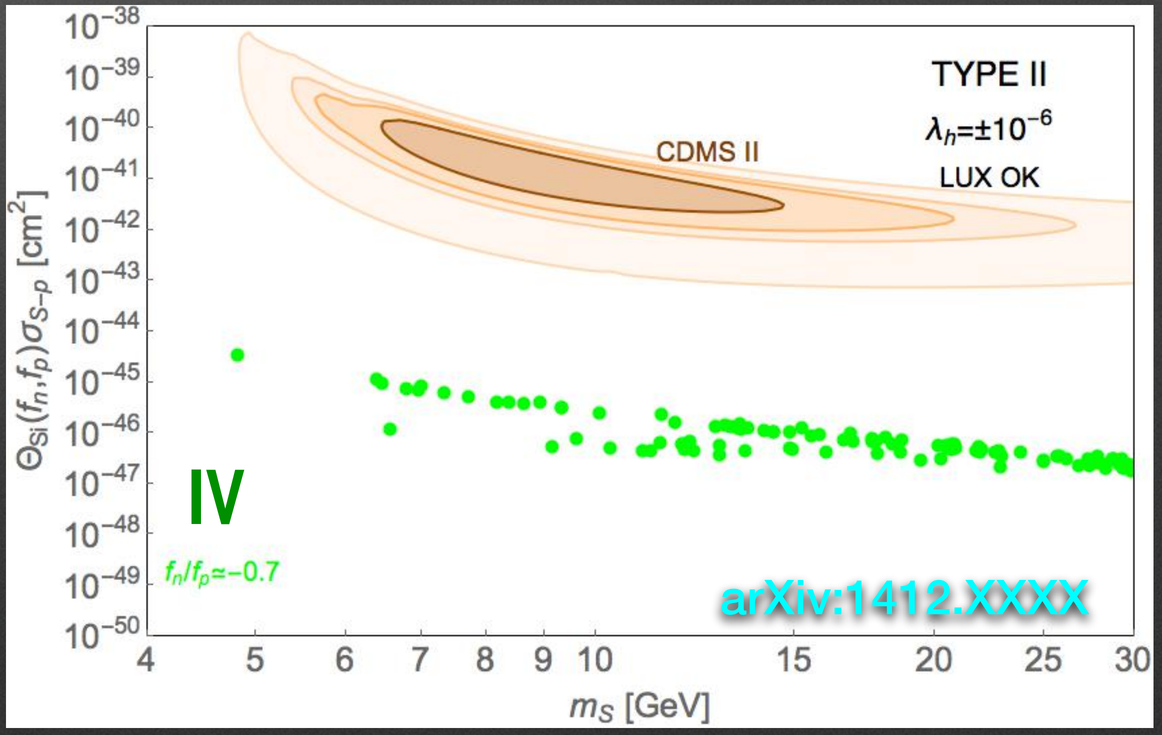






A light DM with mass 6-55 GeV strongly challenged by XENON/LUX null result, but could be consistent with CDMS-II data

Stage II remarks

- The Higgs and DM sectors may be intimately connected. If so, detecting the signs of one of sectors could shine light on still hidden elements of the other.

- It is of interest to explore some of the implications of recent developments in hunting for Higgs and detecting DM in the context of simple frameworks

- We are in the process of exploring the possibility of Isospin-Violating DM in the Type II.

"Dark matter study is becoming more and more complicated, however, maybe we are approaching the reality step by step …"

– Yun Jiang

Back up

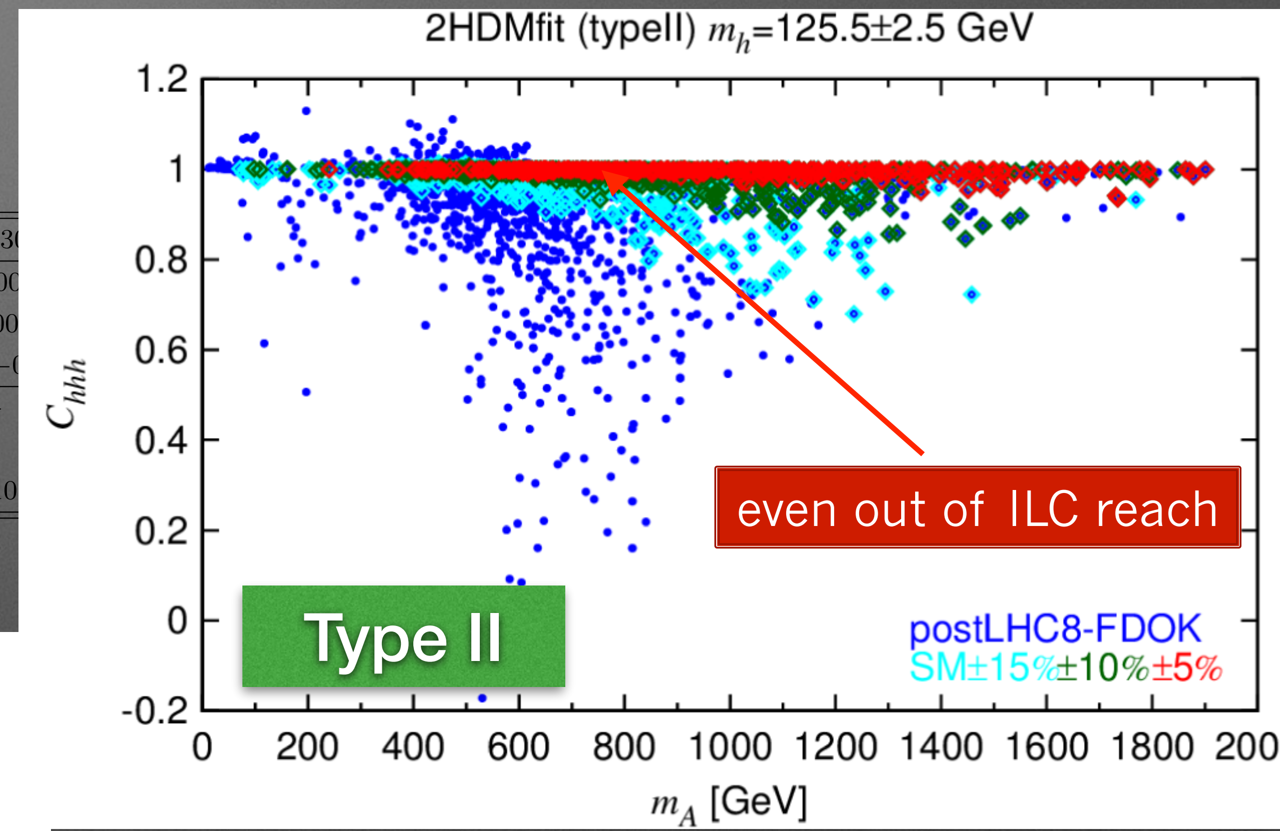
h~125-Triple h coupling

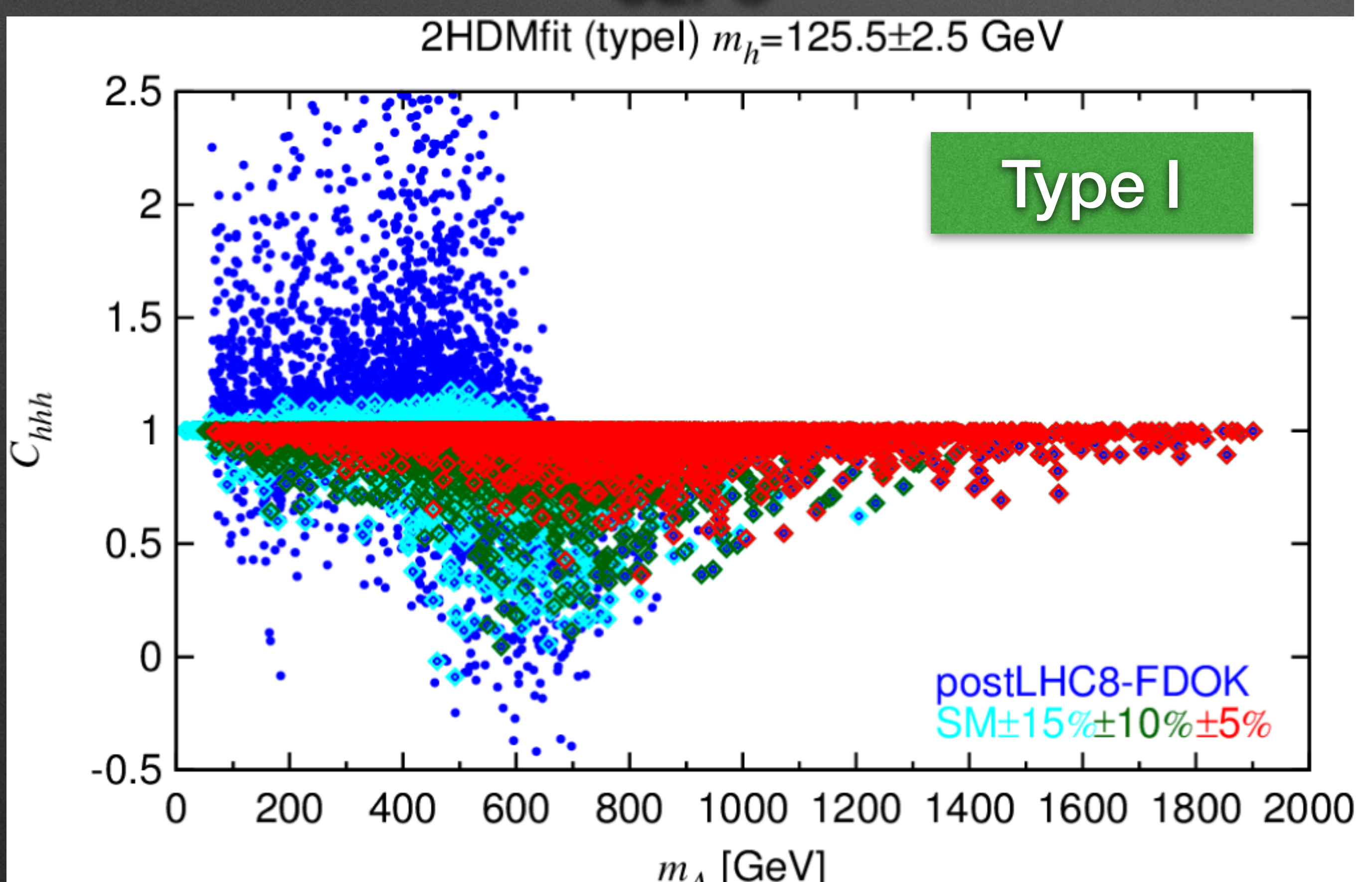
	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

SPPC

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡	1500	+200
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-$
$\sigma(ZHH)$	42.7%		42.7%	23.7%	–	–
$\sigma(\nu\bar{\nu}HH)$	–	–	26.3%	16.7%		
λ	83%	46%	21%	13%	28/21%	16/10

CEPC





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

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
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

SPPC

	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC30
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	500	1600‡	500+1000	1600+2500‡	1500	+200
$P(e^-, e^+)$	$(-0.8, 0.3)$	$(-0.8, 0.3)$	$(-0.8, 0.3/0.2)$	$(-0.8, 0.3/0.2)$	$(0,0)/(-0.8,0)$	$(0,0)/(-$
$\sigma(ZHH)$	42.7%		42.7%	23.7%	–	–
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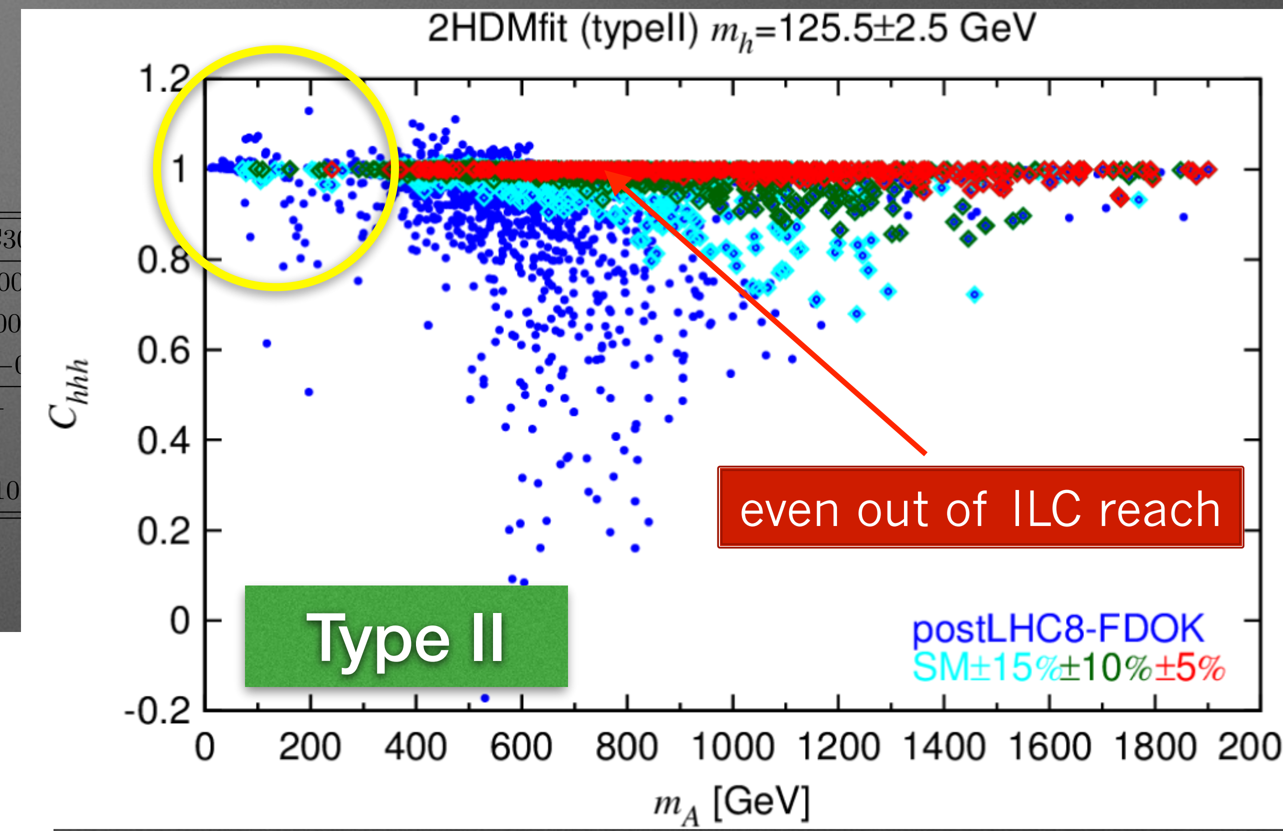
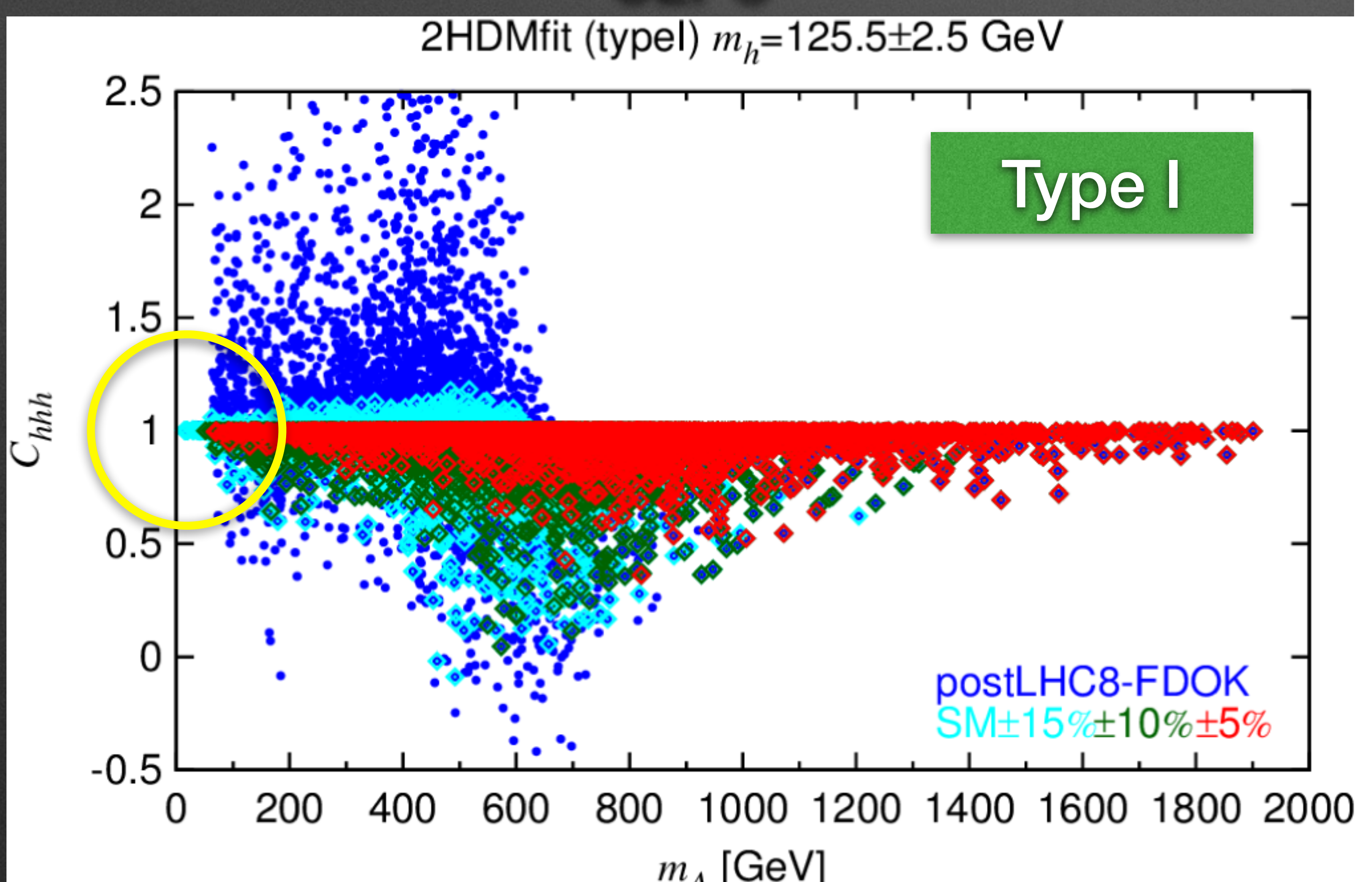
λ	83%	46%	21%	13%	28/21%	16/10

CEPC





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

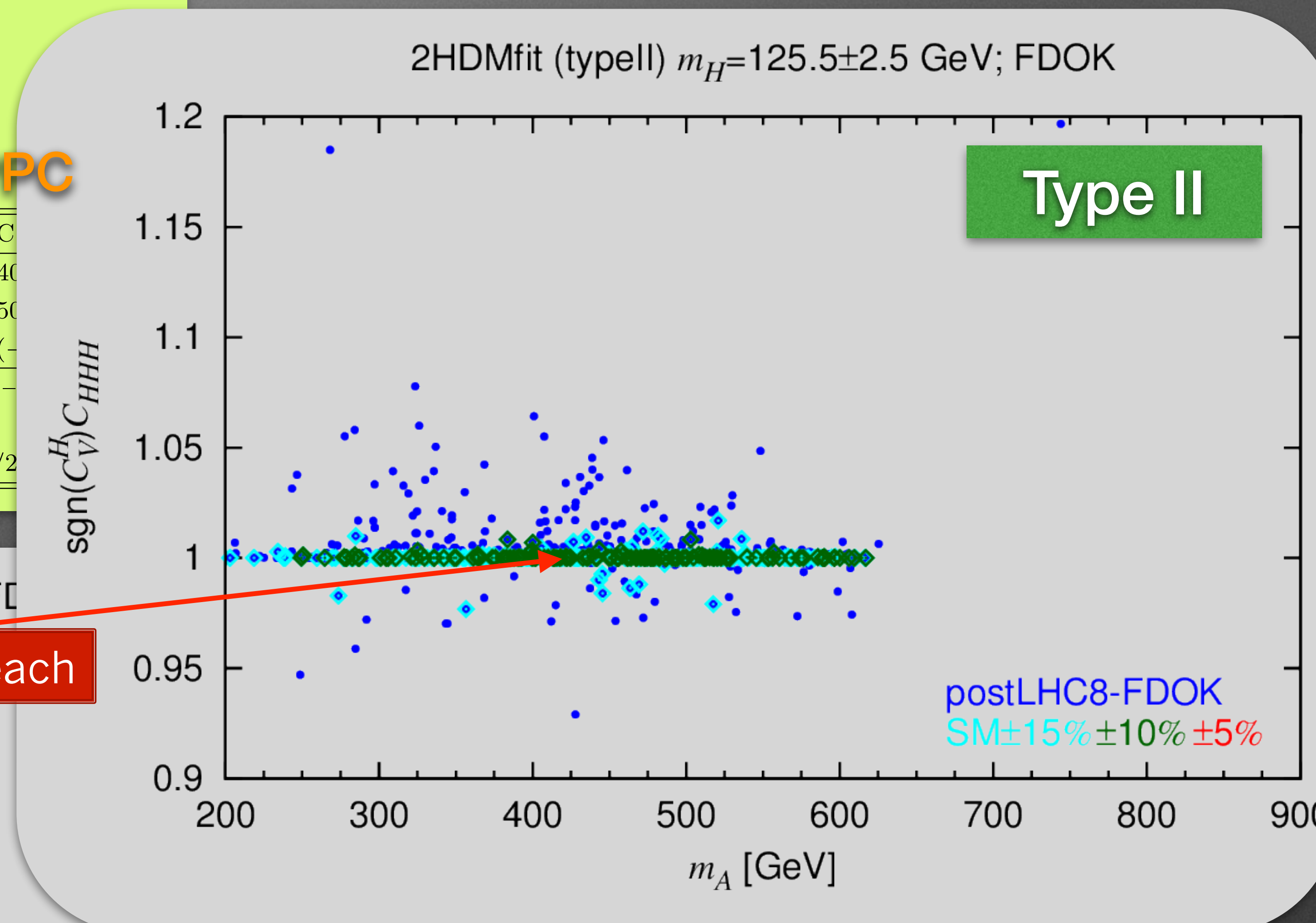
H~125-Triple H coupling

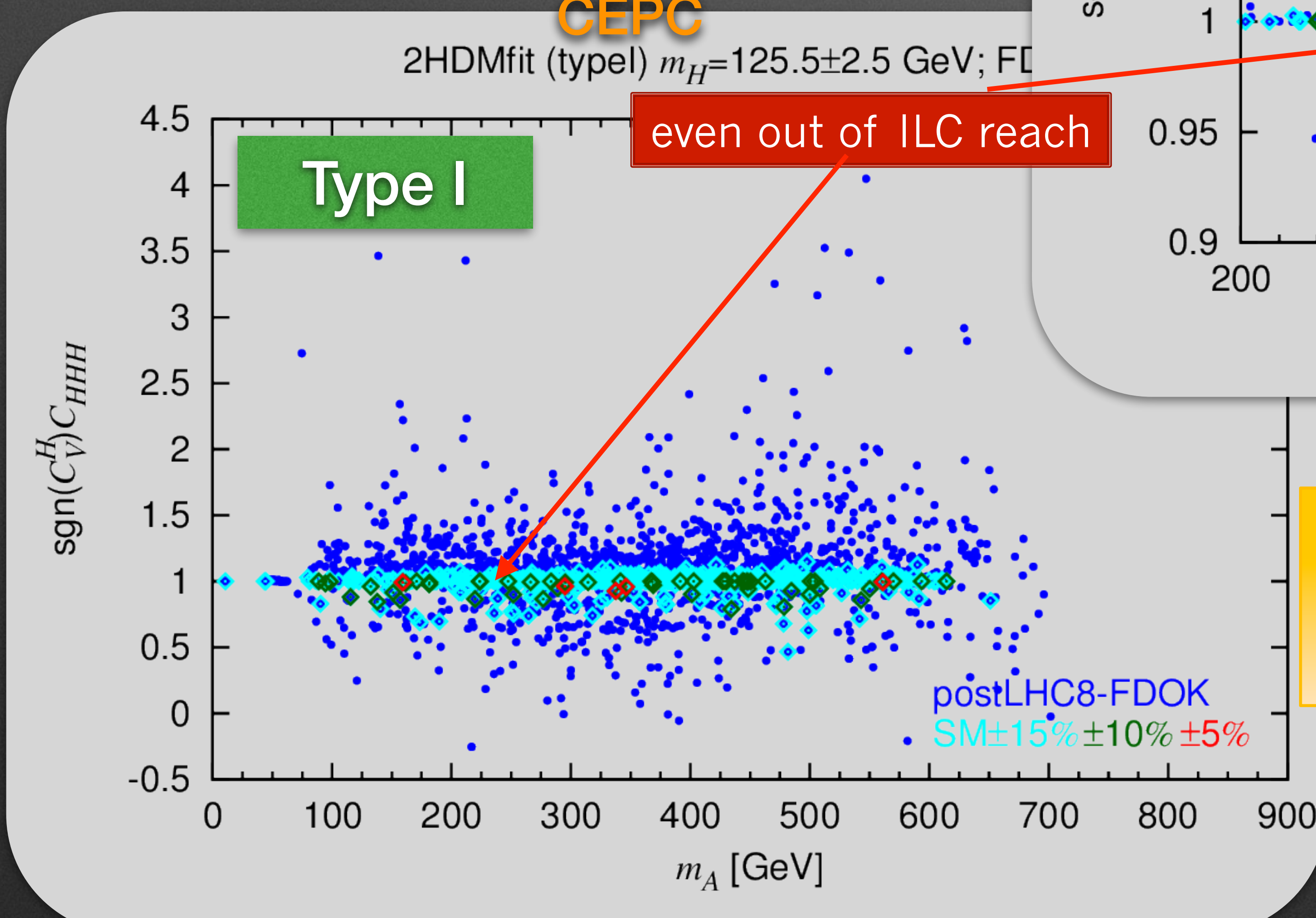
	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

SPPC

	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

CEPC



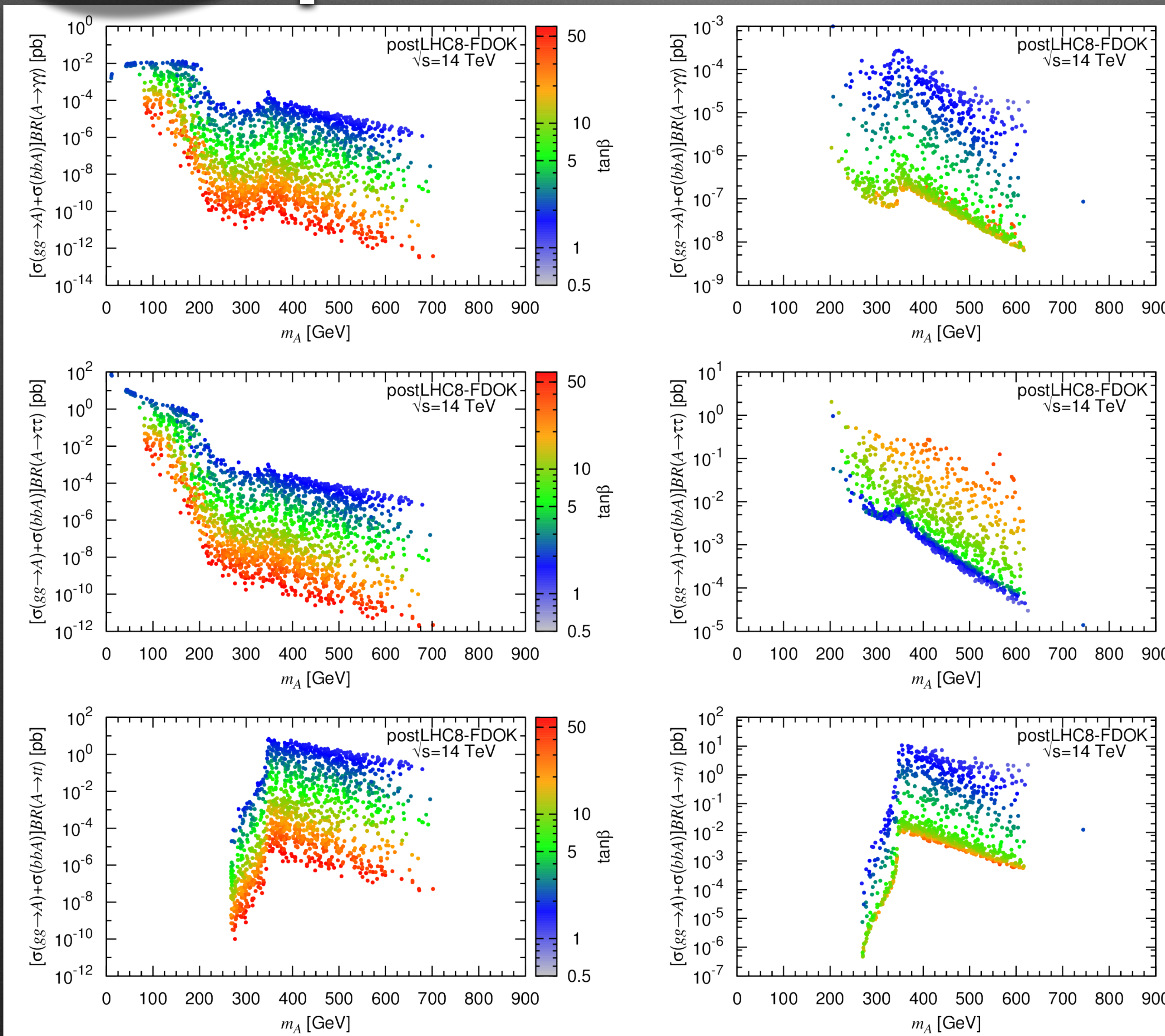


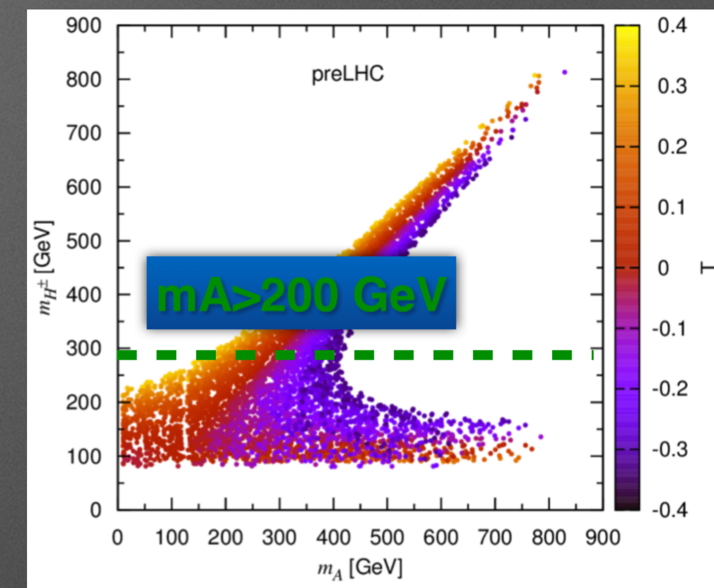
even out of ILC reach

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

H-125.5 GeV

pseudoscalar A search



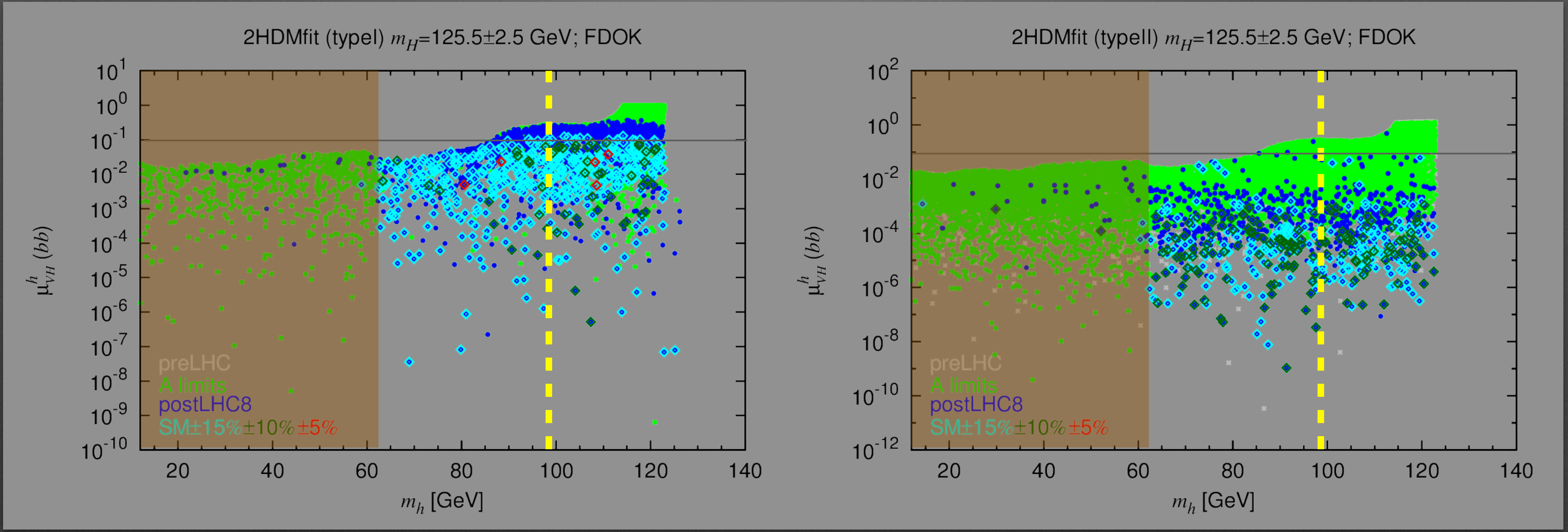


- **In Type I mA<60 GeV** is possible but must have small BR(H->AA). **In Type II, mA>200 GeV** due to the preLHC condition.
- LHC8 125 GeV Higgs data constrain **the A mass** <700 GeV in Type I and <625 GeV in Type II. **NON-DECOUPLING**

H-125.5 GeV

lighter 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 ±5% level and the Type II ±10% level would have a signal level that is not consistent with this LEP excess observed.*