



Two-Higgs-doublet model and singlet scalar dark matter

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UC Davis
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Seminar
Valencia, 11/27/2014



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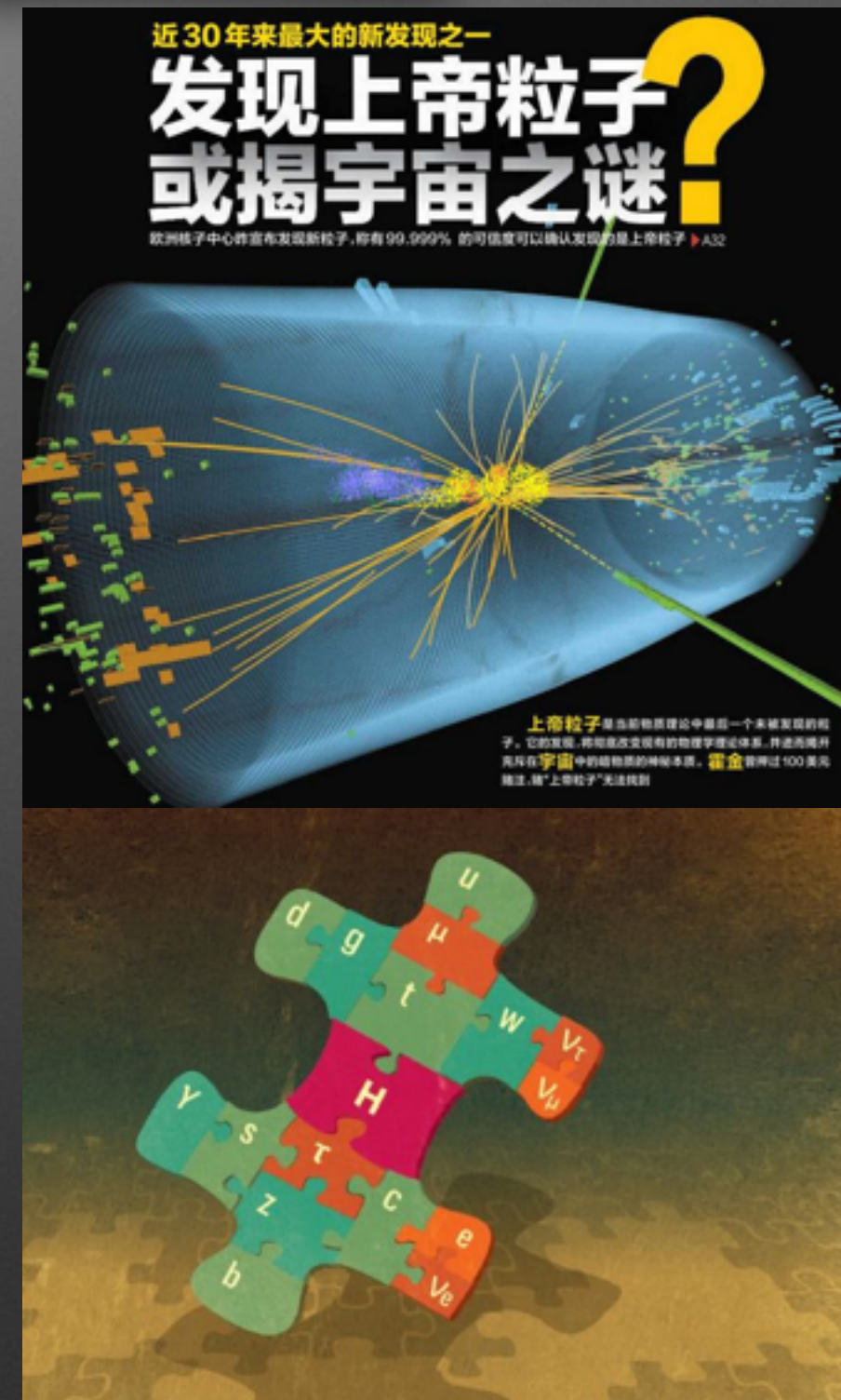
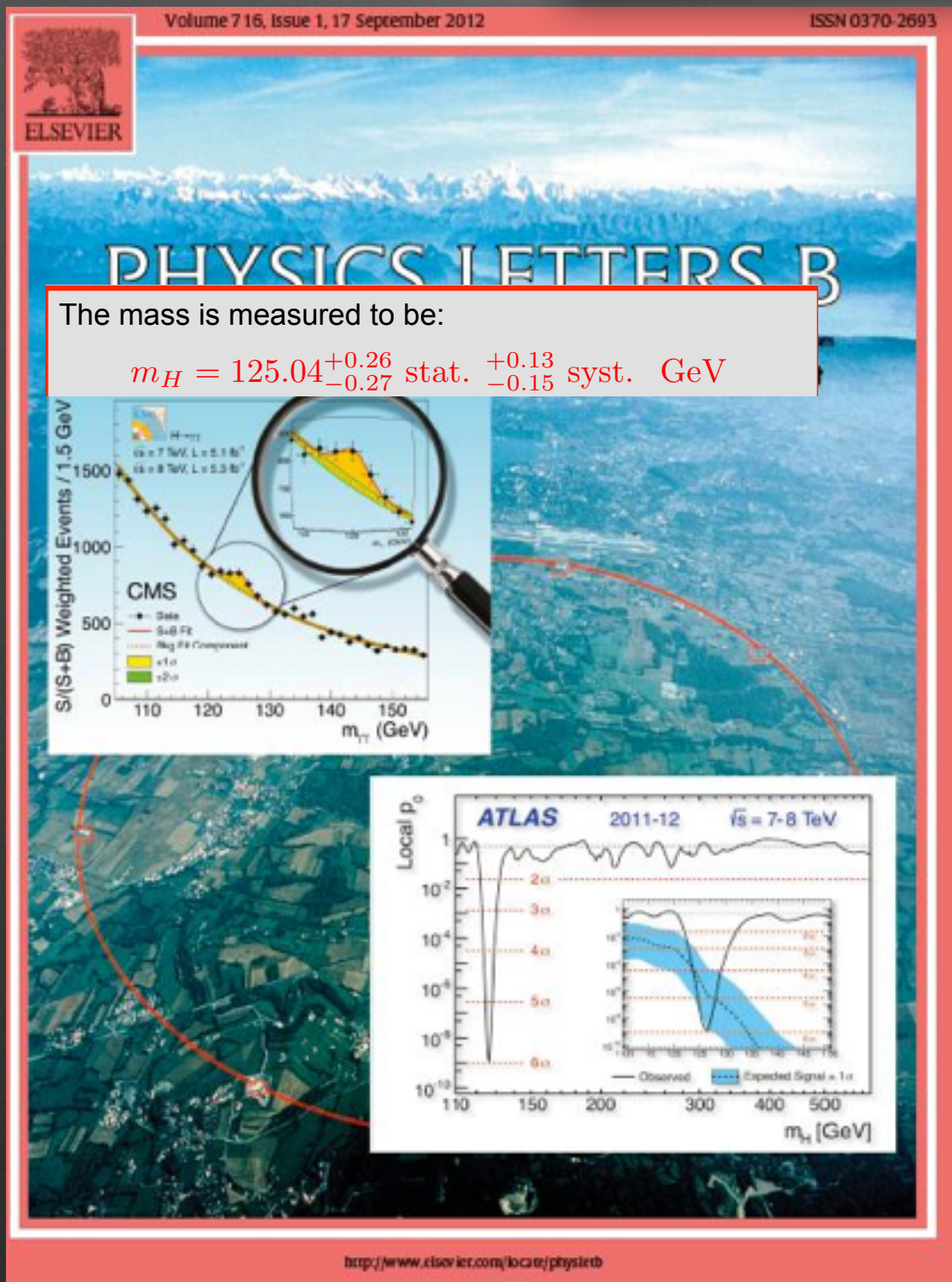
2HDM globit fit, w/ Gunion, Kraml, Dumont, arXiv:1405.3584
light Higgs boson, w/ Gunion, Kraml, arXiv:1412.XXXX
2HDM+Singlet DM, w/ Gunion, Grzadkowski, Drozd, arXiv:1408.2106
Isospin-violating DM, arXiv:1412.XXXX

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

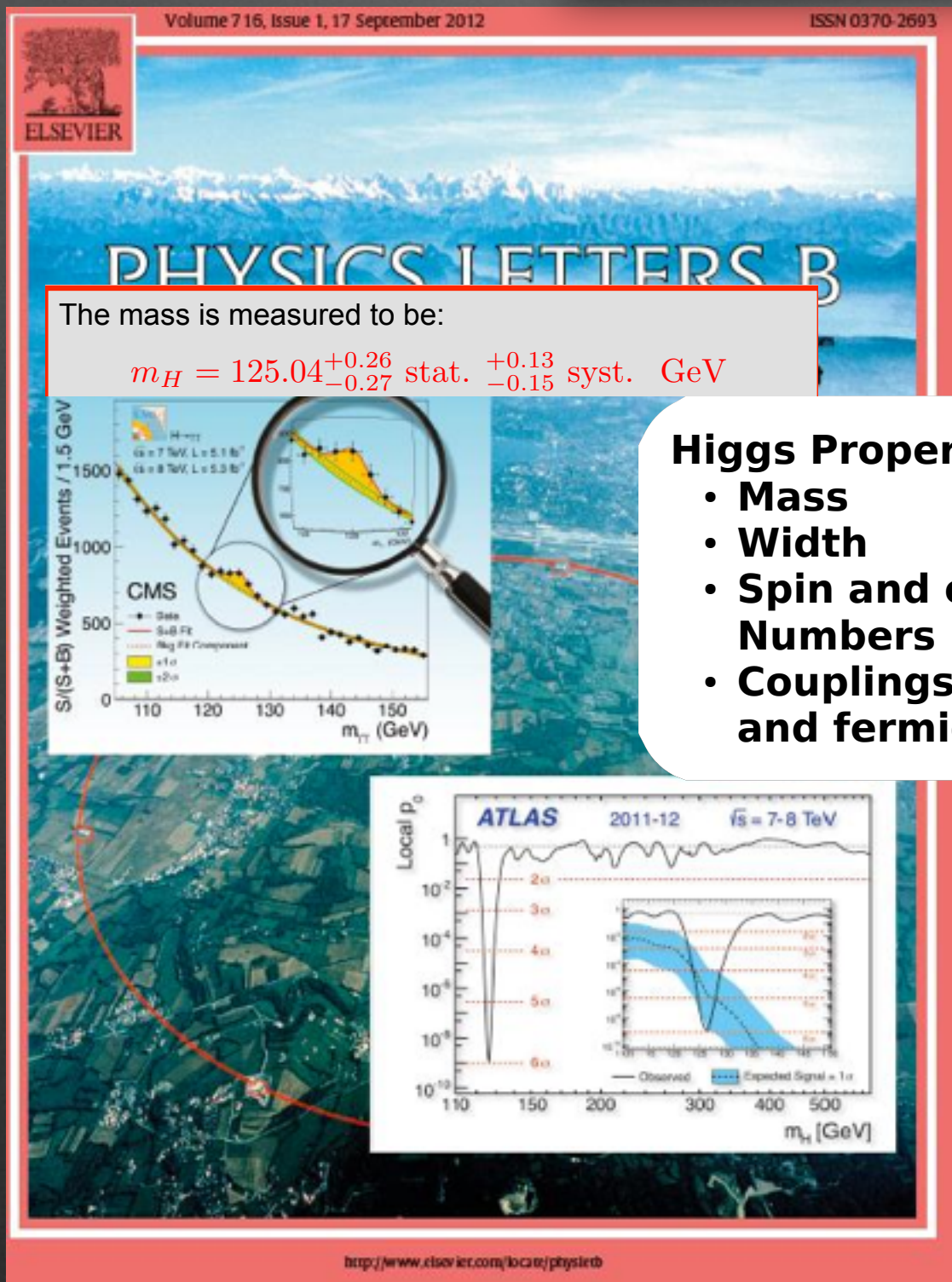
LHC discovered the Higgs boson

July 4th, 2012—A **HISTORIC** moment in science.



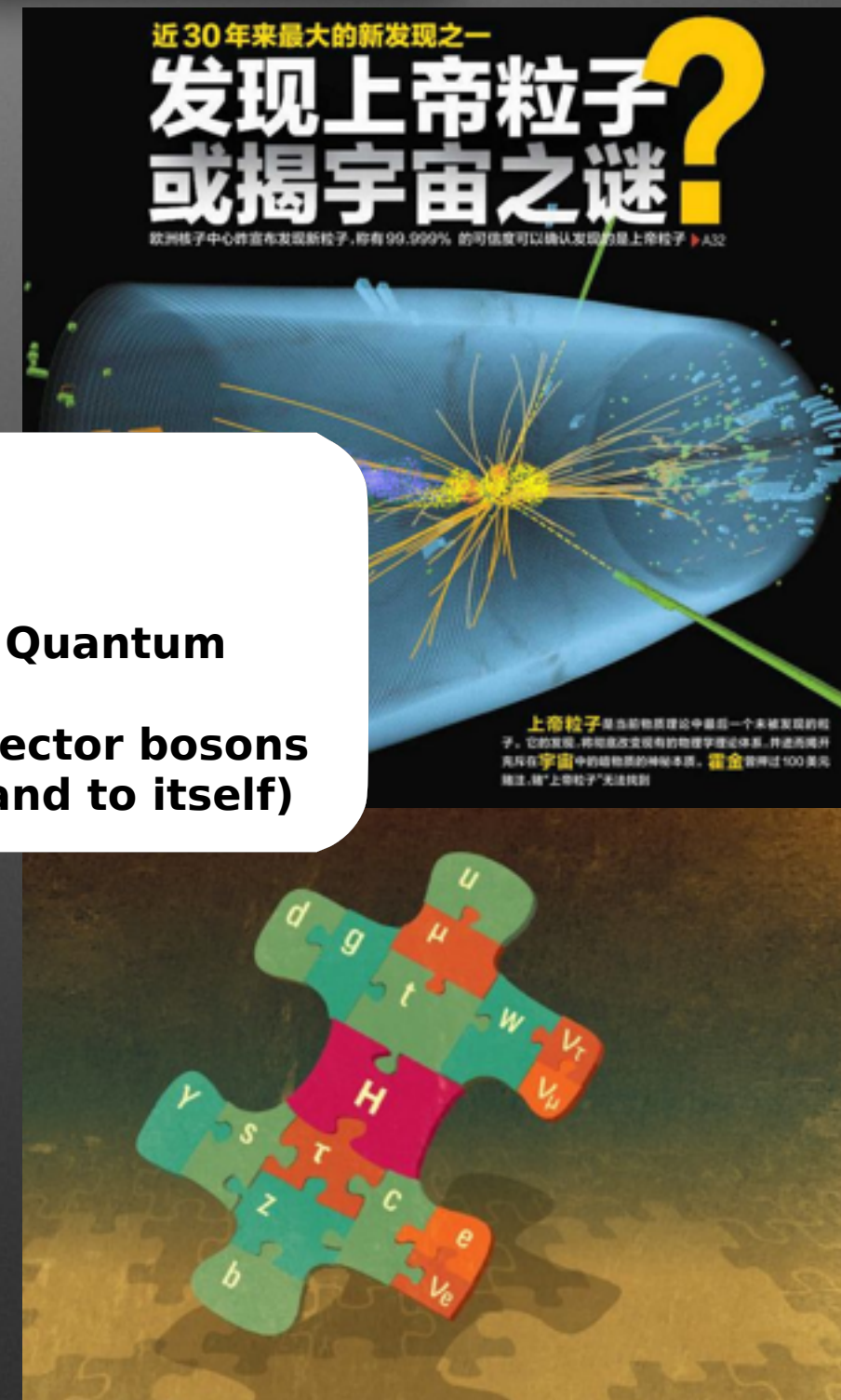
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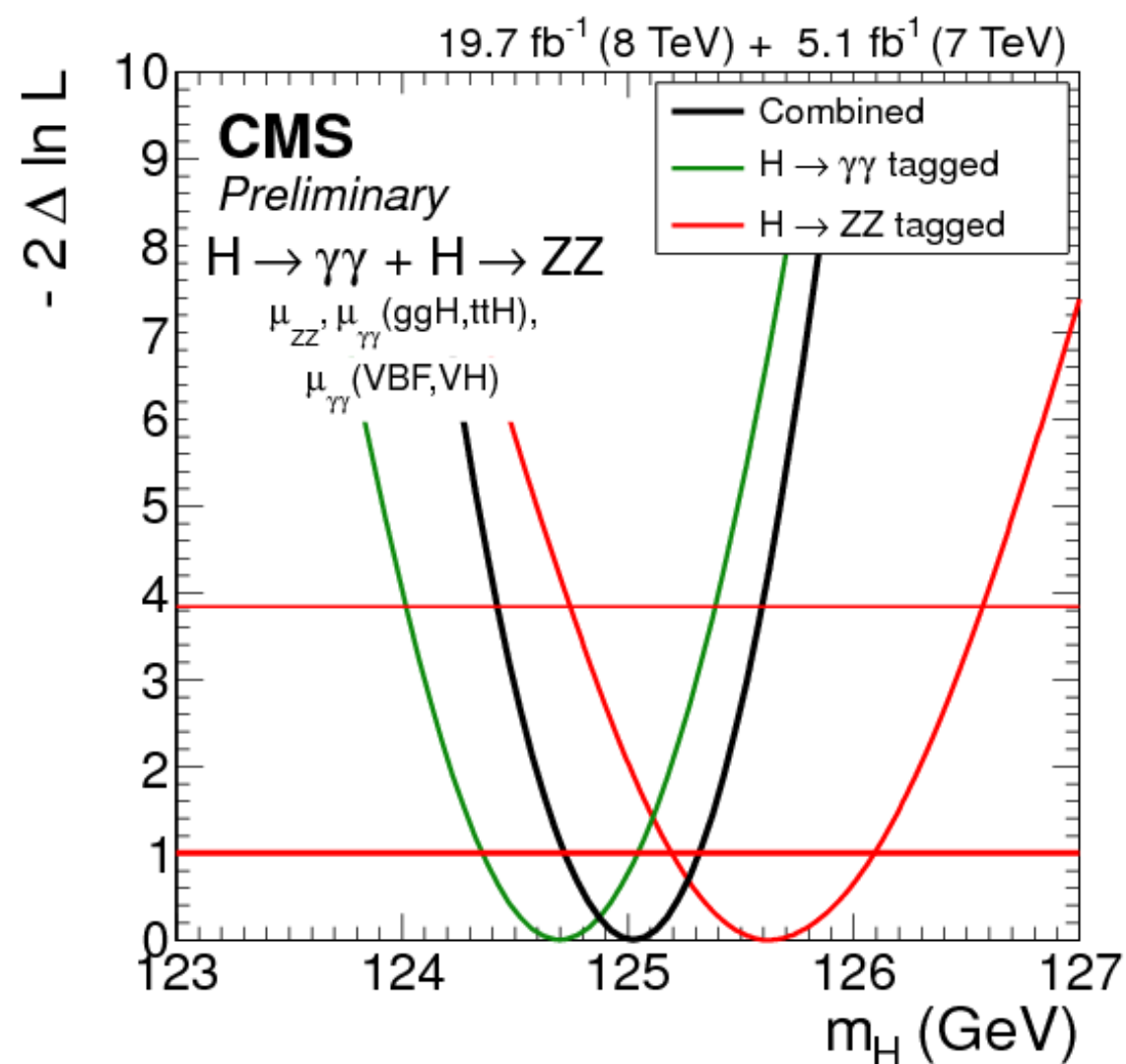


Higgs Properties:

- 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.

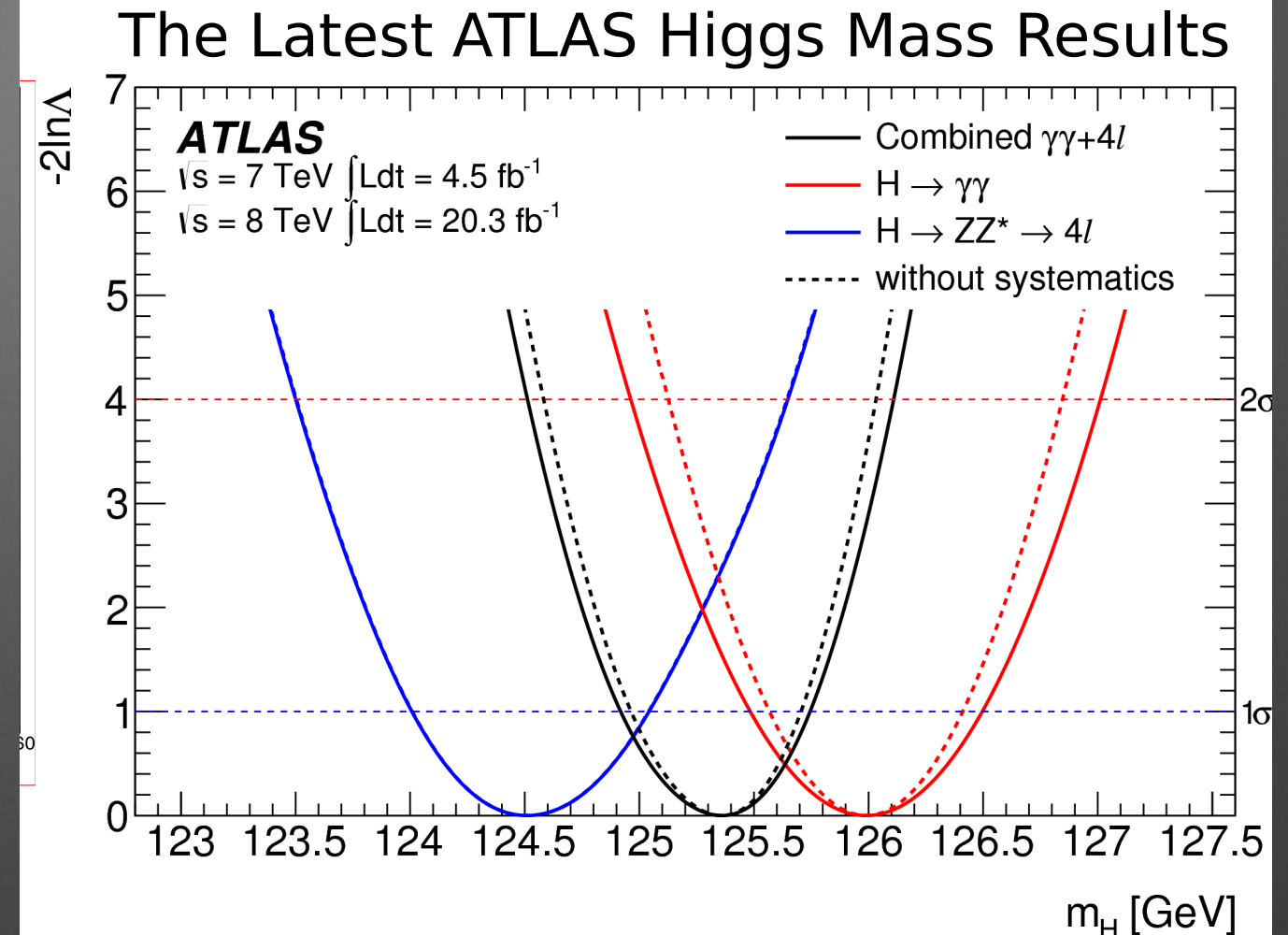


The mass is measured to be:

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

And the two measurement ($ZZ, \gamma\gamma$) agree at

1.6 sigma: $m_H^{\gamma\gamma} - m_H^{4l} = -0.87^{+0.54}_{-0.59} \text{ GeV}$

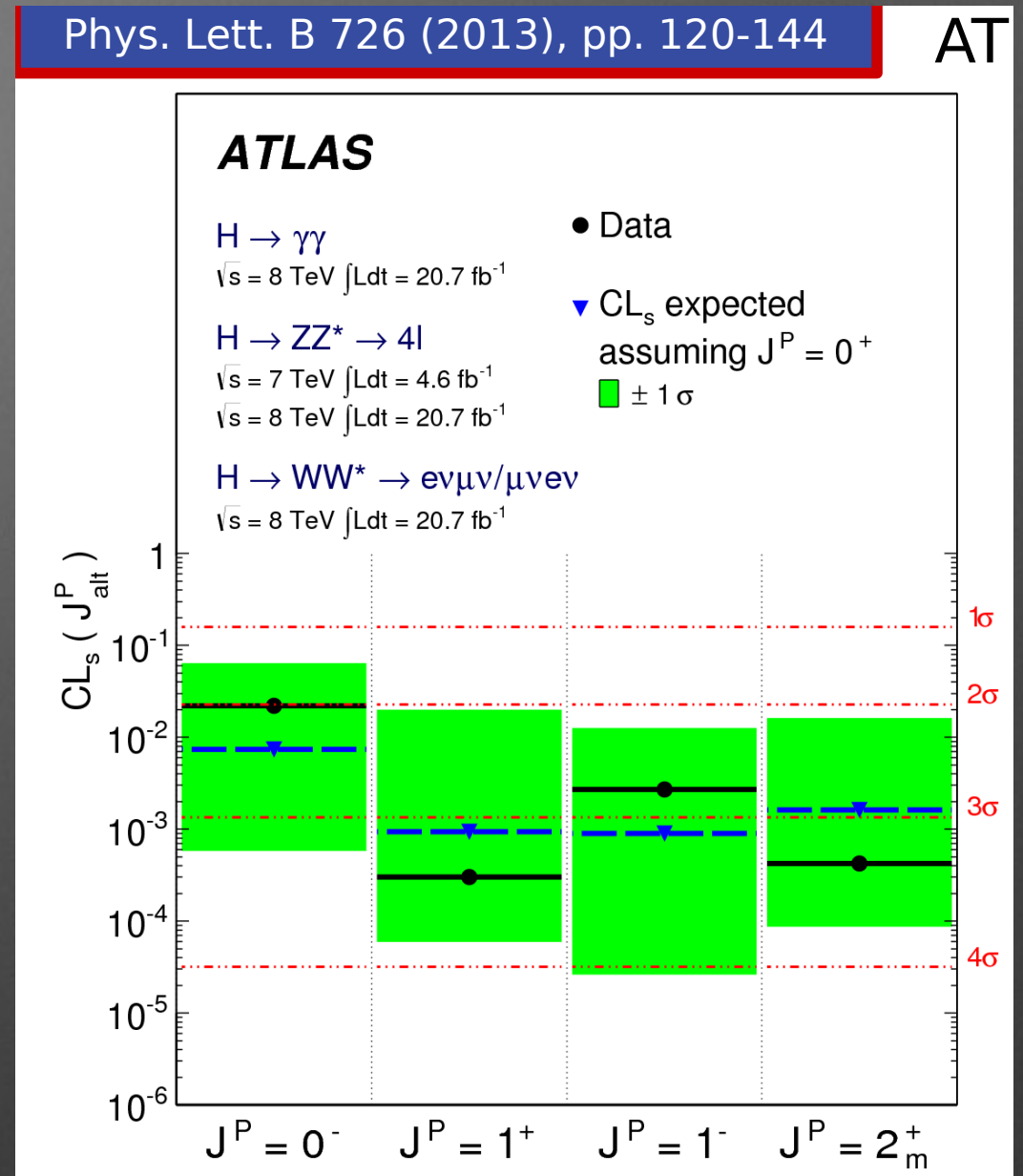
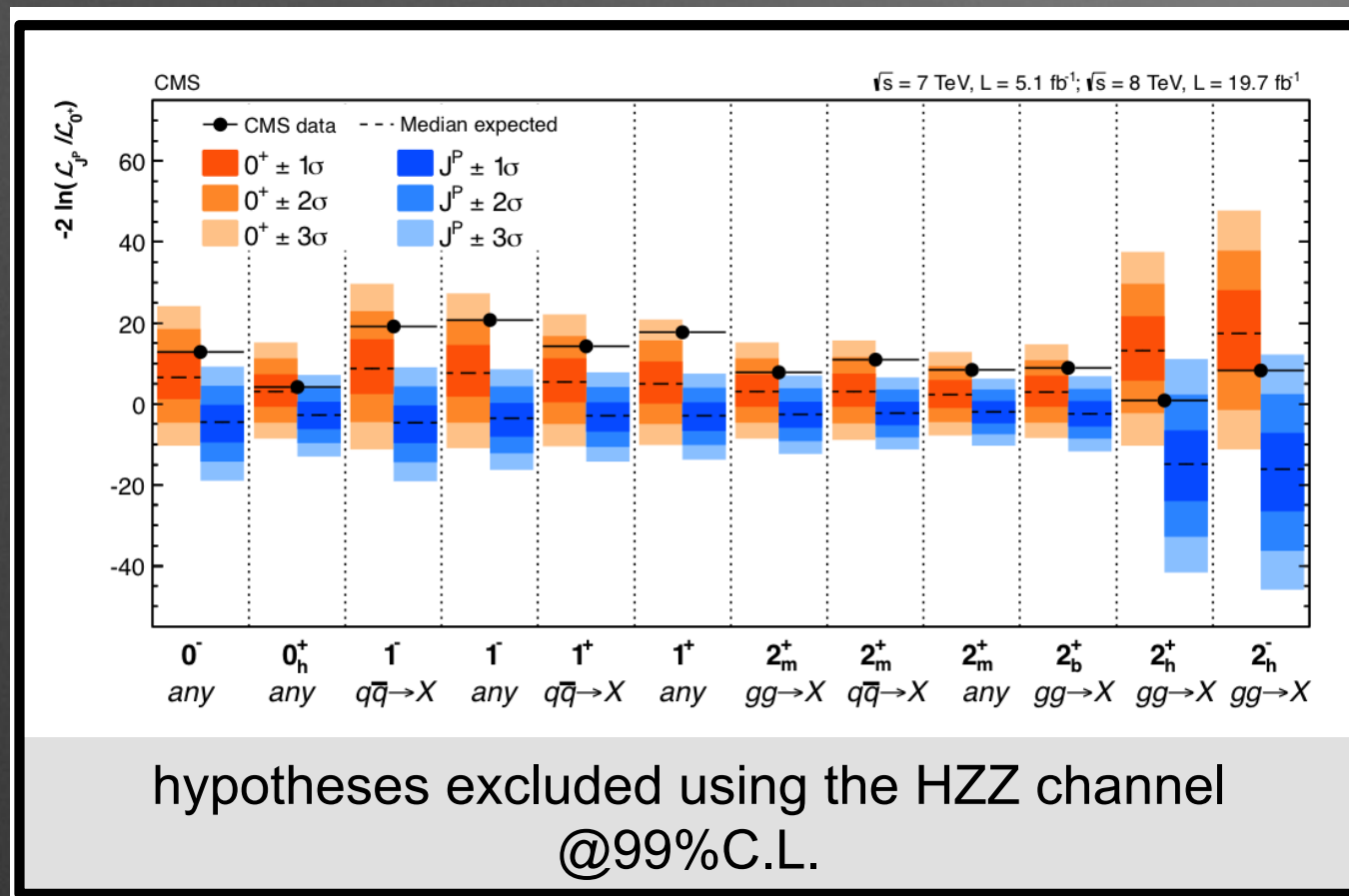


$$m_H^{\gamma\gamma} = 125.98 \pm 0.42 \text{ (stat.)} \pm 0.28 \text{ (syst.) GeV}$$

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

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

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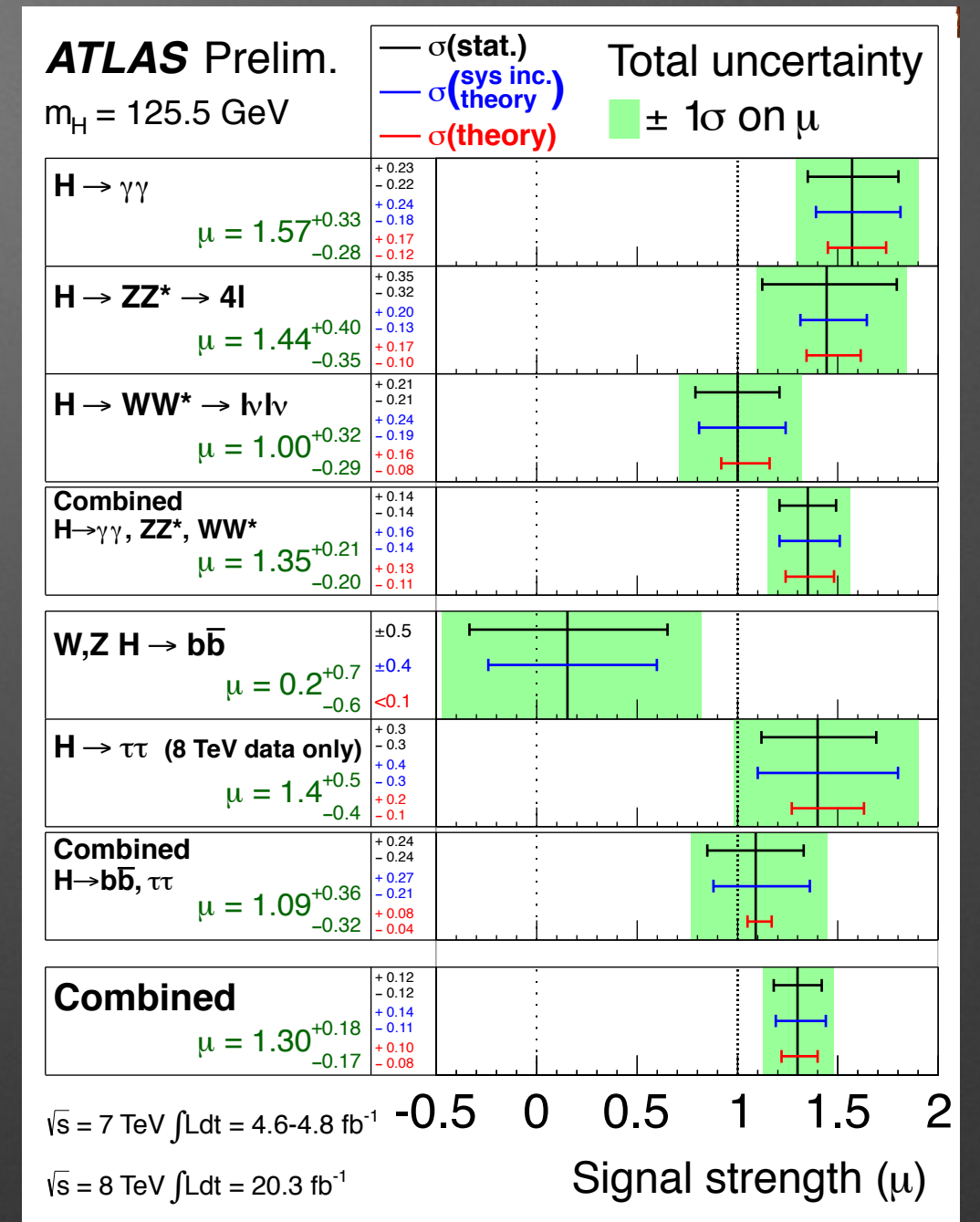
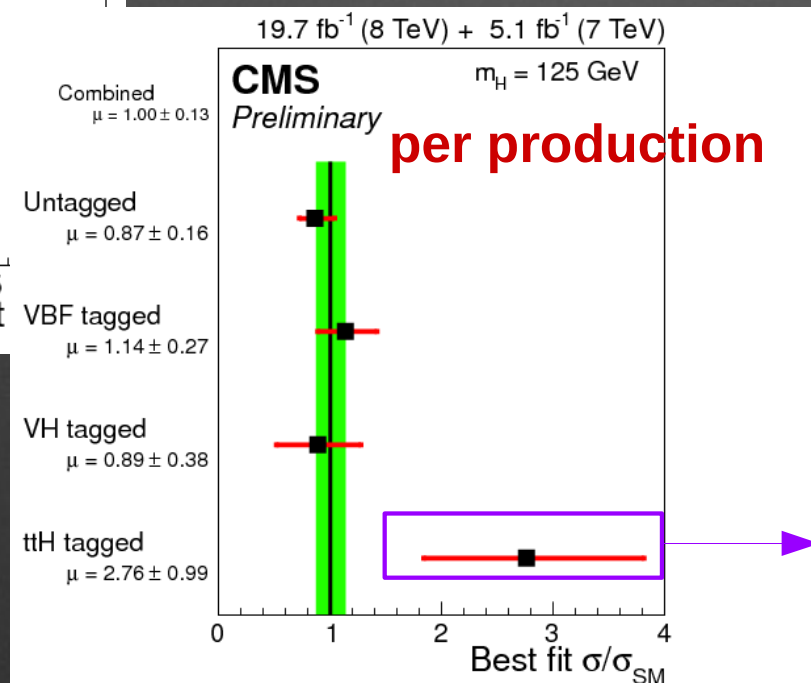
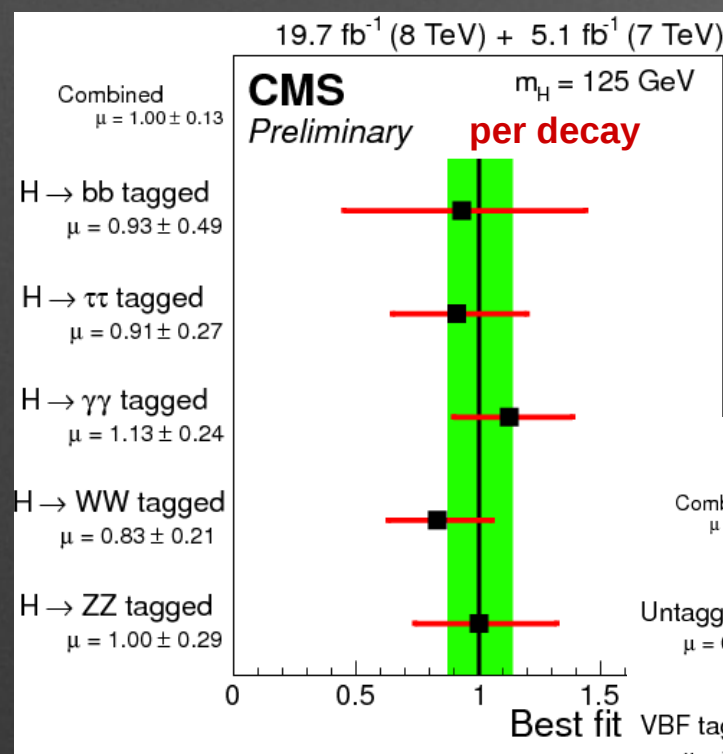


$J^P = 0^+$ strongly favoured by measurements

Spin 1 and spin 2 and Pseudoscalar boson hypotheses:
Excluded

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.

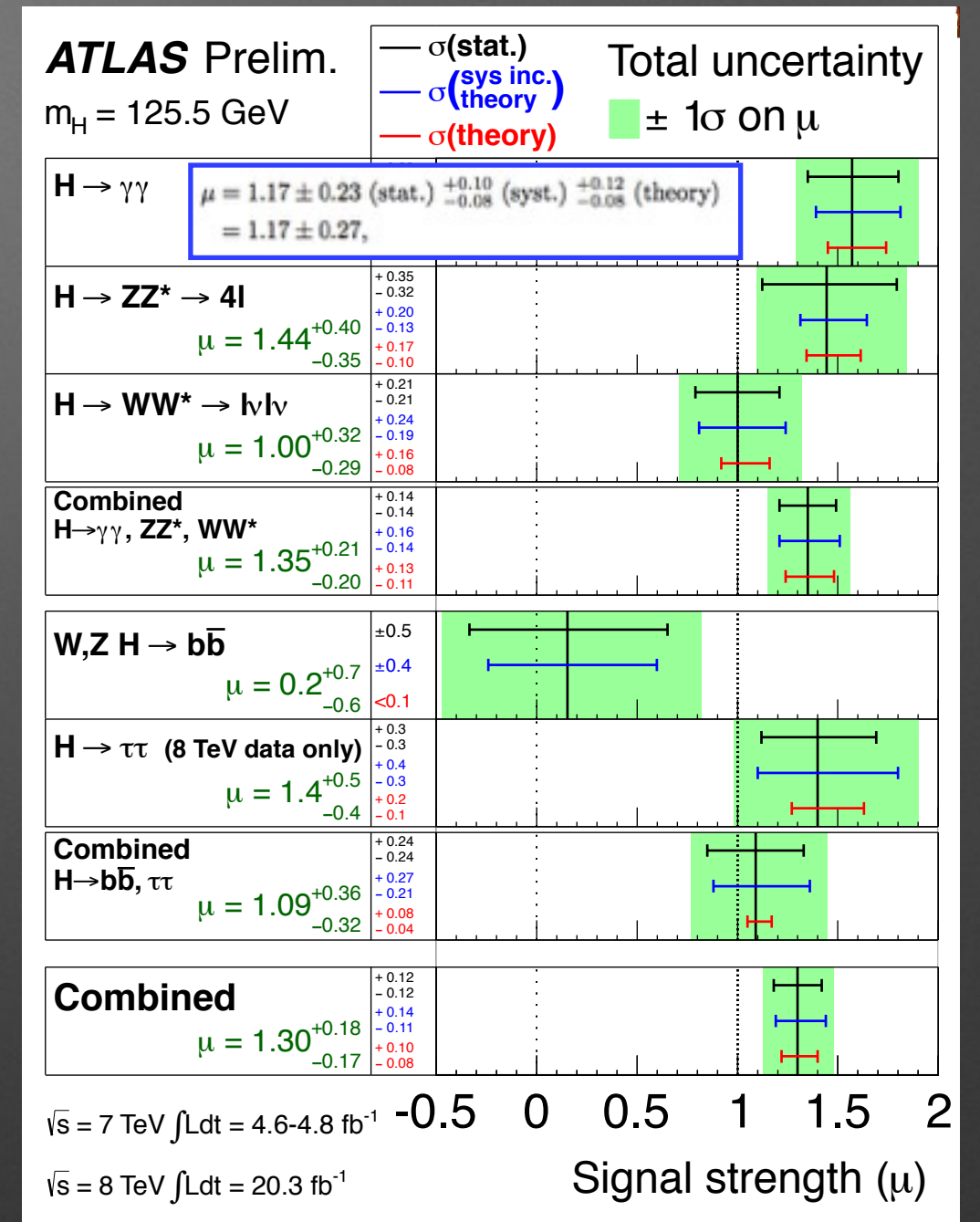
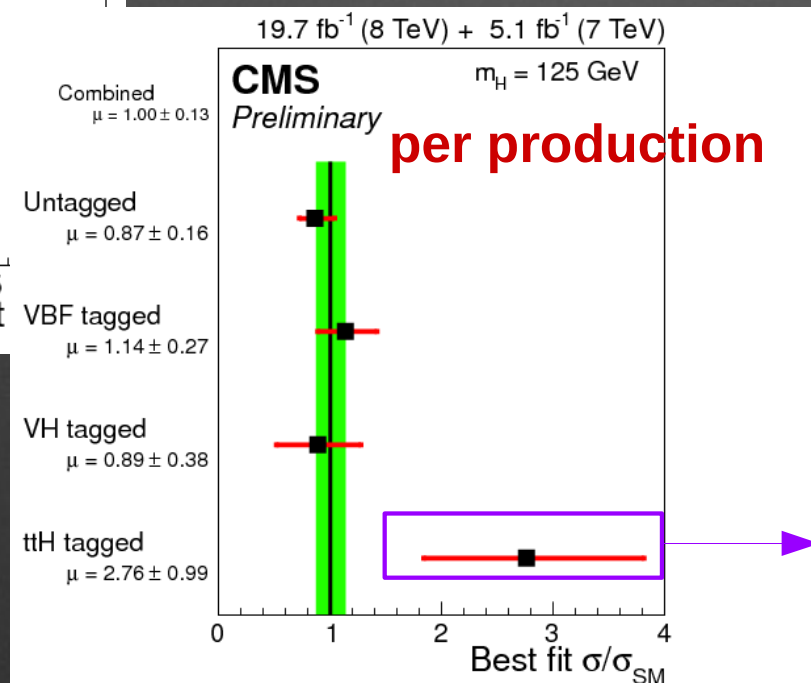
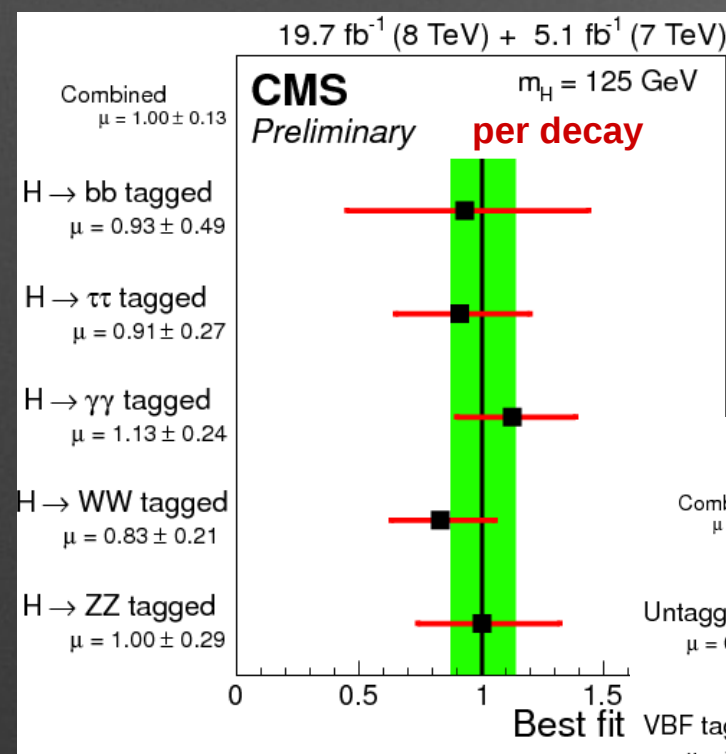
★ "seen" ☆ "tried"	H→b ̄ b	H→τ τ	H→WW*	H→ZZ*	H→γγ	H→Zγ	H→inv.	H→μμ
ggH		★	★	★	★	☆		☆
VBF	☆	★	★	☆	★	☆	☆	☆
VH	★	☆	☆	☆	☆		☆	
ttH	☆	☆	☆	☆	☆			



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

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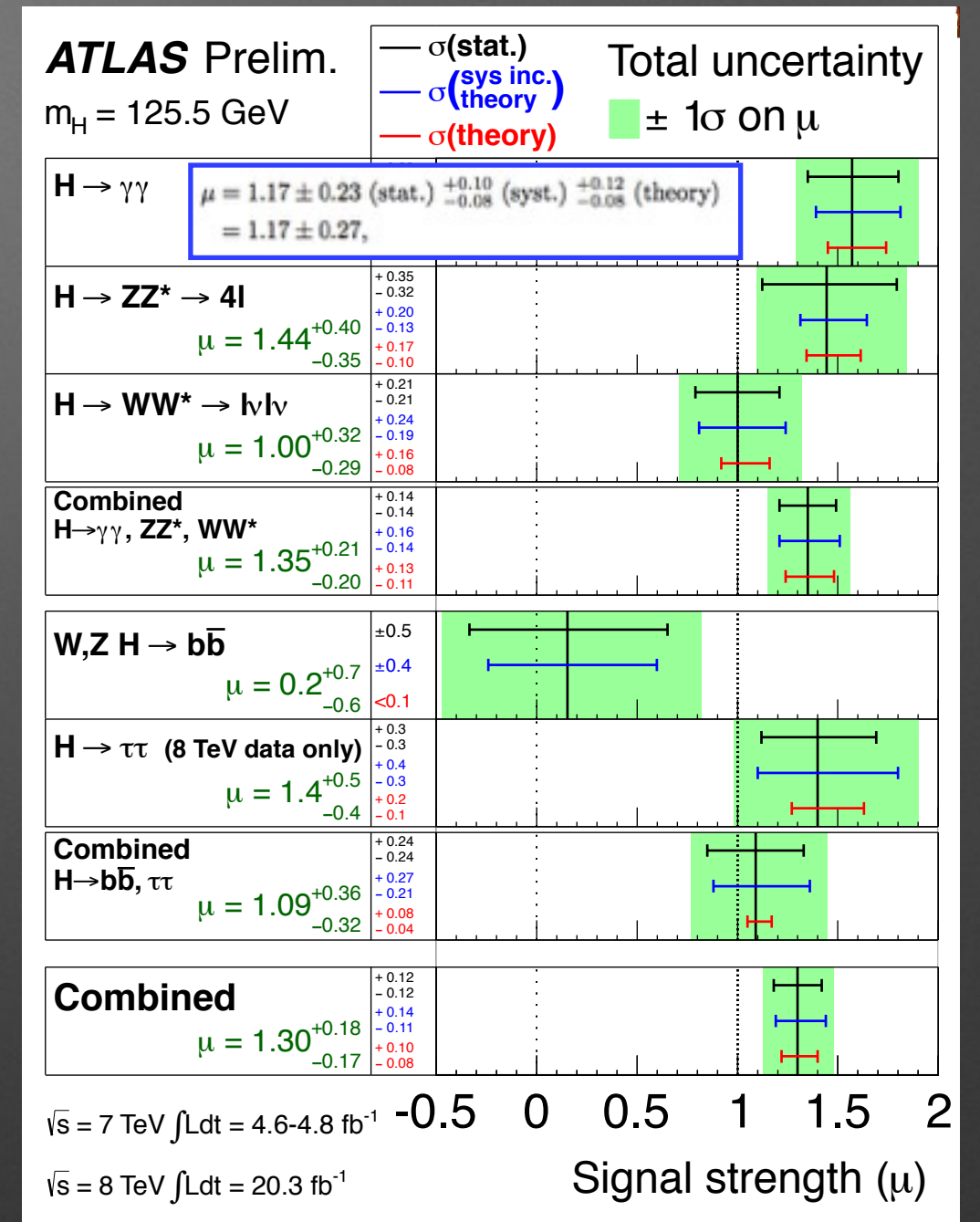
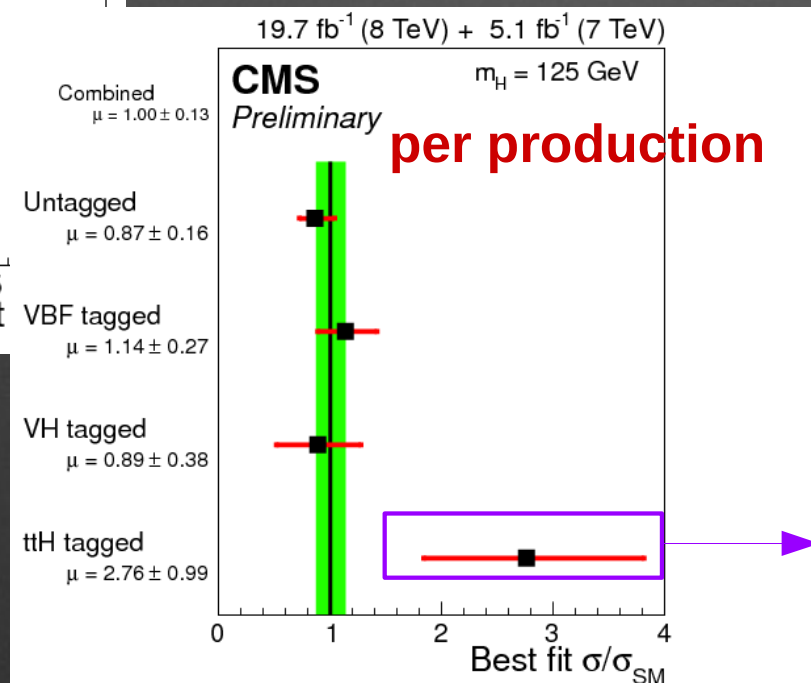
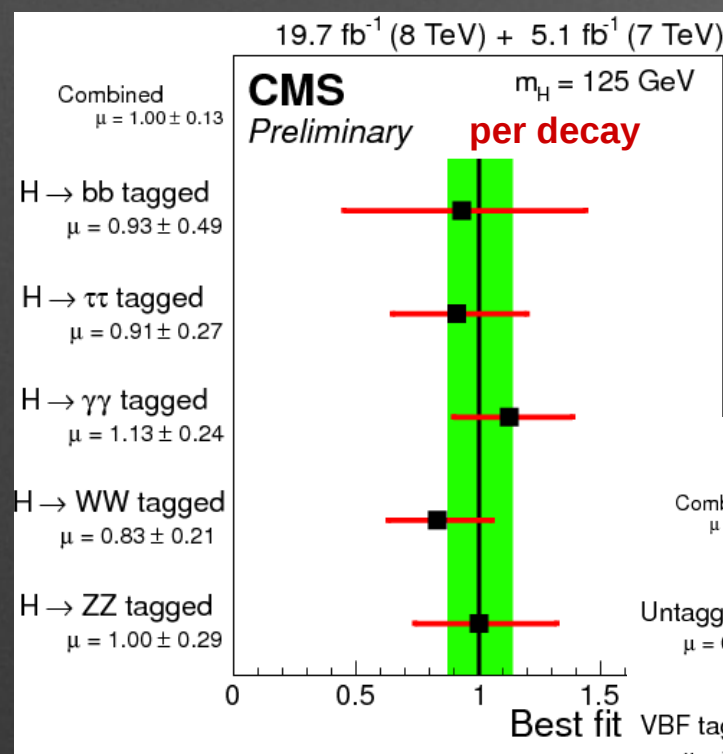
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VBF	☆	★	★	☆	★	☆	☆	☆
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ttH	☆	☆	☆	☆	☆			



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ggH		★	★	★	★	☆		☆
VBF	☆	★	★	☆	★	☆	☆	☆
VH	★	☆	☆	☆	☆		☆	
ttH	☆	☆	☆	☆	☆			



All measurements show that:

This particle is compatible with the SM Higgs boson!

However, non-SM effect is still a possibility.

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

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

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 ($\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2$) breaking: $m_{12}^2 \neq 0$; $\lambda_6 = \lambda_7 = 0$.

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

Electroweak symmetry breaking

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

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

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

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

Model	u_R^i	d_R^i	e_R^i	Realization
Type I	Φ_2	Φ_2	Φ_2	$\Phi_1 \rightarrow -\Phi_1$
Type II	Φ_2	Φ_1	Φ_1	$\Phi_1 \rightarrow -\Phi_1, d_R^i \rightarrow -d_R^i$

$$\mathcal{L}_{\text{Yukawa}}^{2\text{HDM}} = - \sum_{f=u,d,\ell} \frac{m_f}{v} \left(C_f^h \bar{f} f h + C_f^H \bar{f} f H - i C_f^A \bar{f} \gamma_5 f A \right) - \left\{ \frac{\sqrt{2} V_{ud}}{v} \bar{u} \left(m_u C_u^A P_L + m_d C_d^A P_R \right) d H^+ + \frac{\sqrt{2} m_\ell C_\ell^A}{v} \bar{\nu}_L \ell_R H^1 + \text{h.c.} \right\}$$

	C_V^h	C_u^h	$C_{d,\ell}^h$	C_V^H	C_u^H	$C_{d,\ell}^H$	C_V^A	C_u^A	$C_{d,\ell}^A$
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	$\cot \beta$	$\tan \beta$

$$(C_V^h)^2 + (C_V^H)^2 + (C_V^A)^2 = 1$$

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

The J^P hypothesis 0^+ is highly favored

preLHC

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

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LHC8

• H/A limits:

- $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$
- $gg \rightarrow H \rightarrow \tau\tau$ and $gg \rightarrow bbH$ with $H \rightarrow \tau\tau$

- **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.

The J^P hypothesis 0^+ is highly favored

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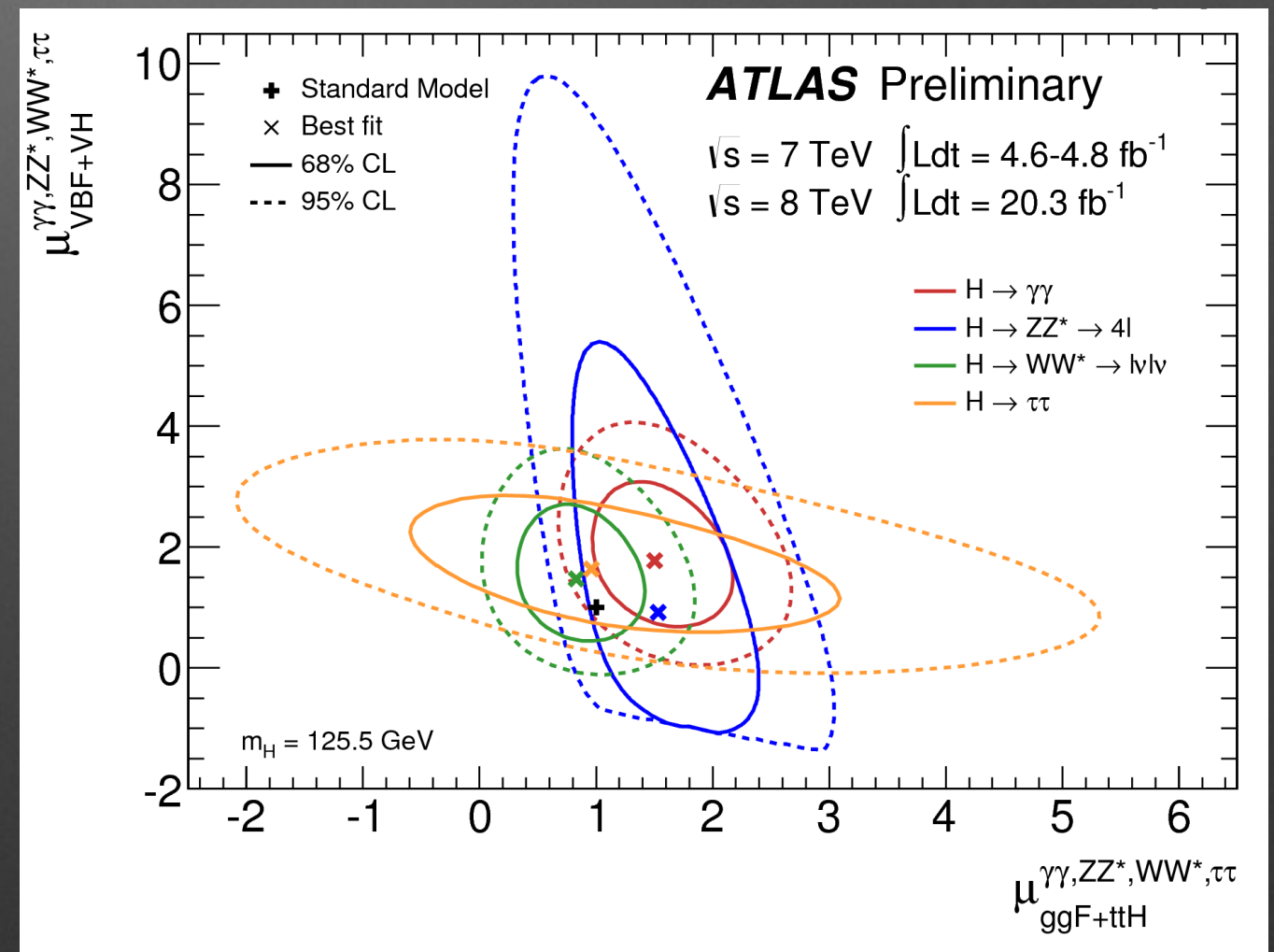
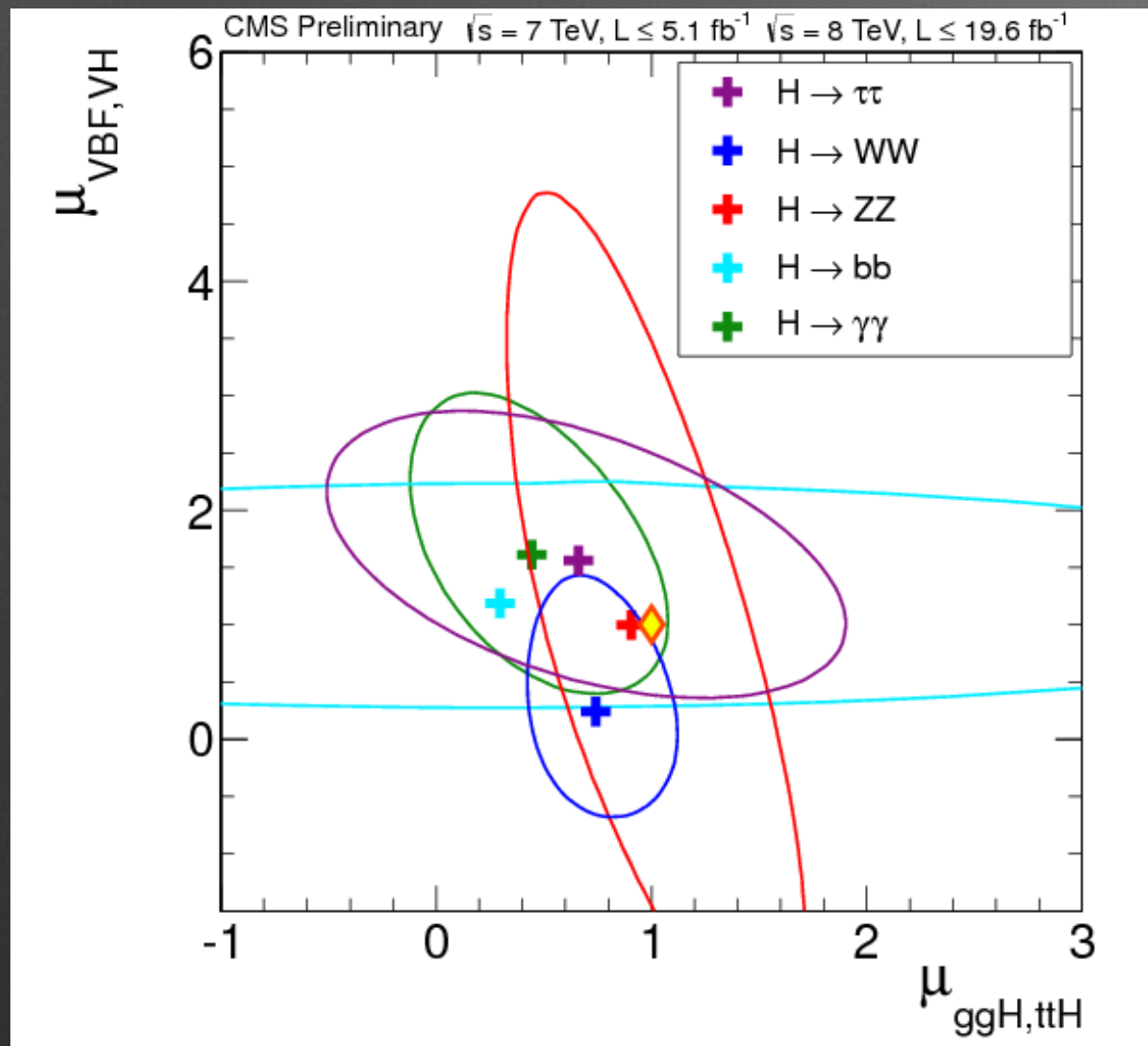
Feed-down

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

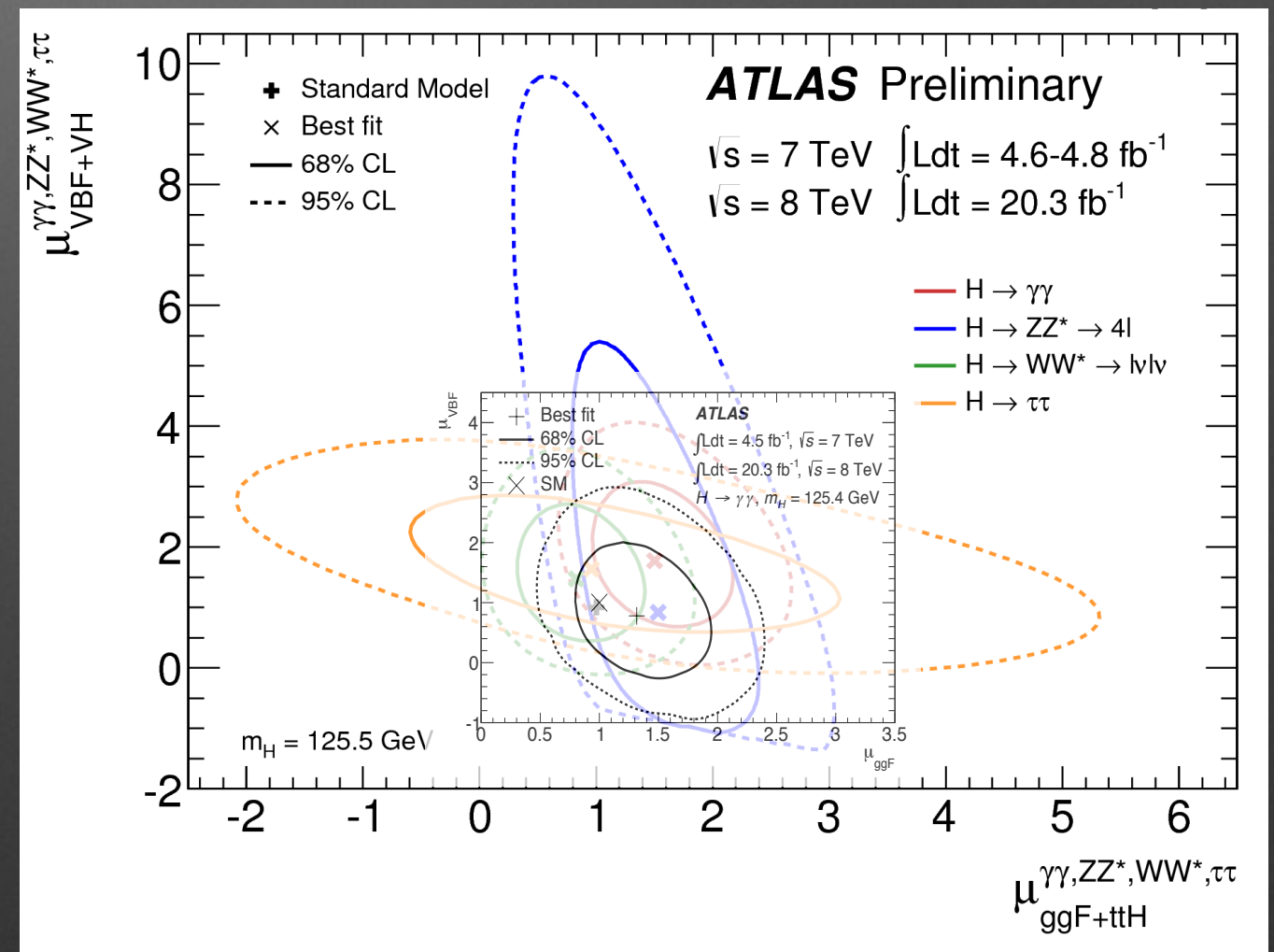
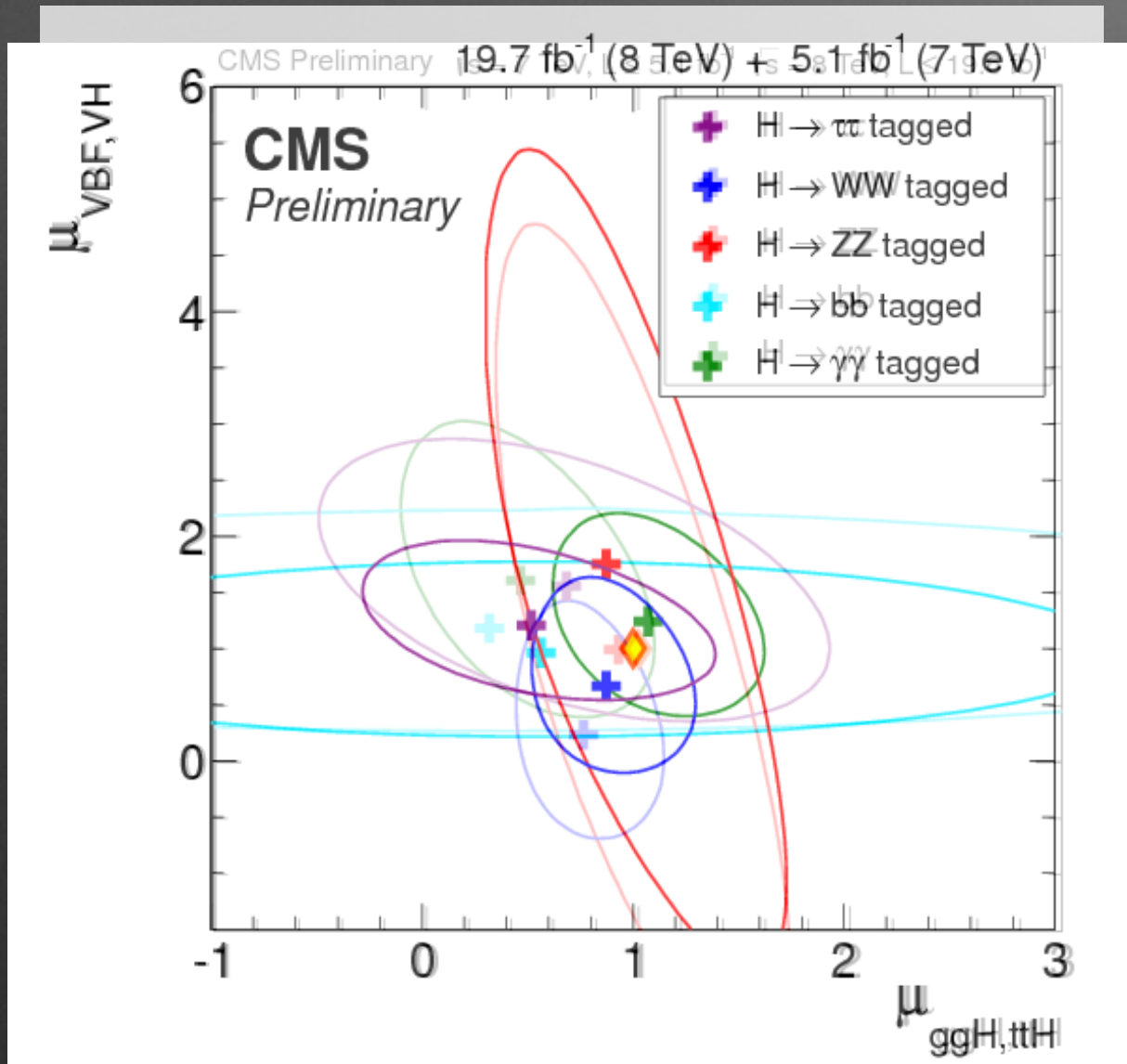
Deviation in Production Modes

125.5 GeV Higgs boson



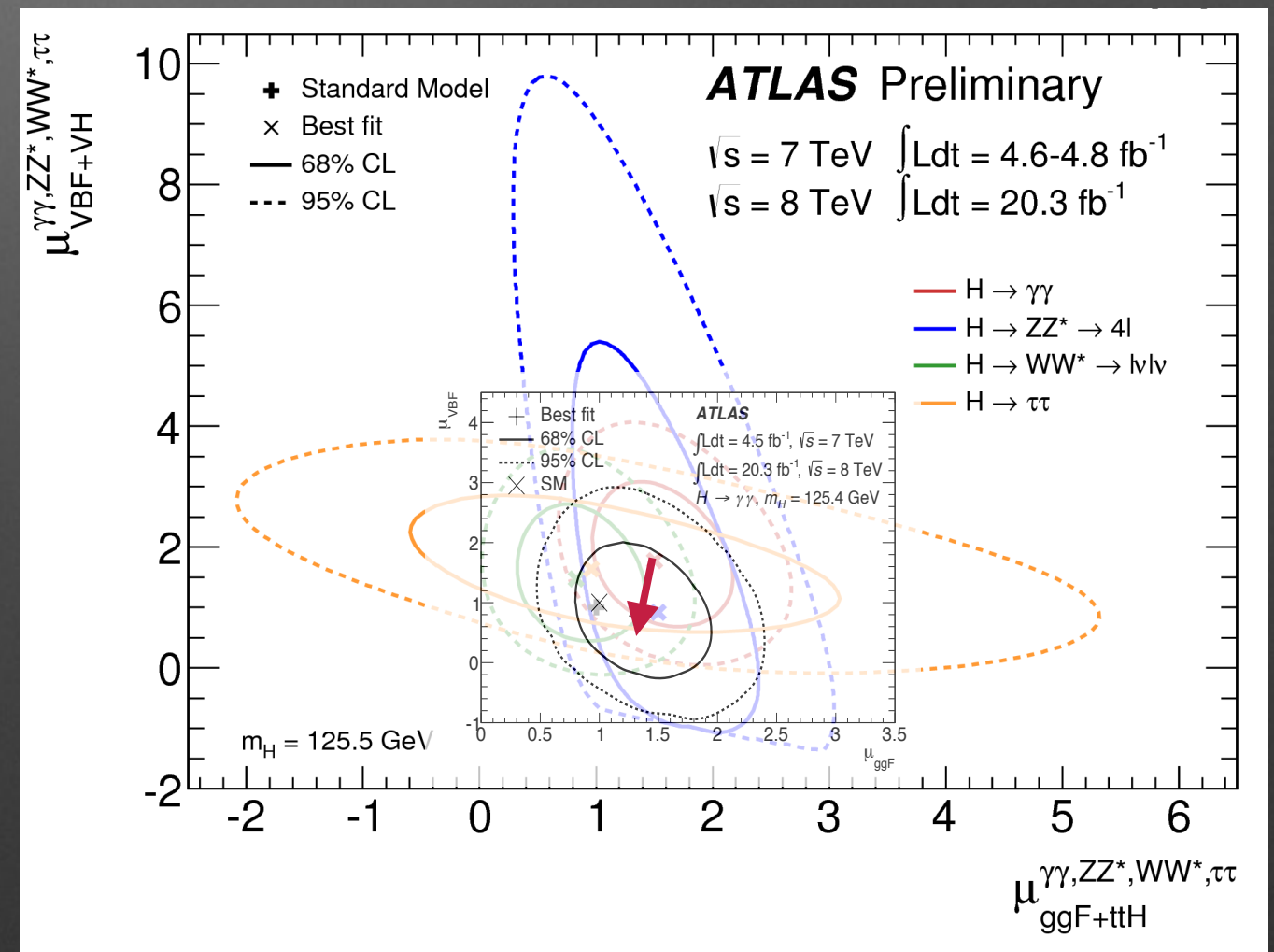
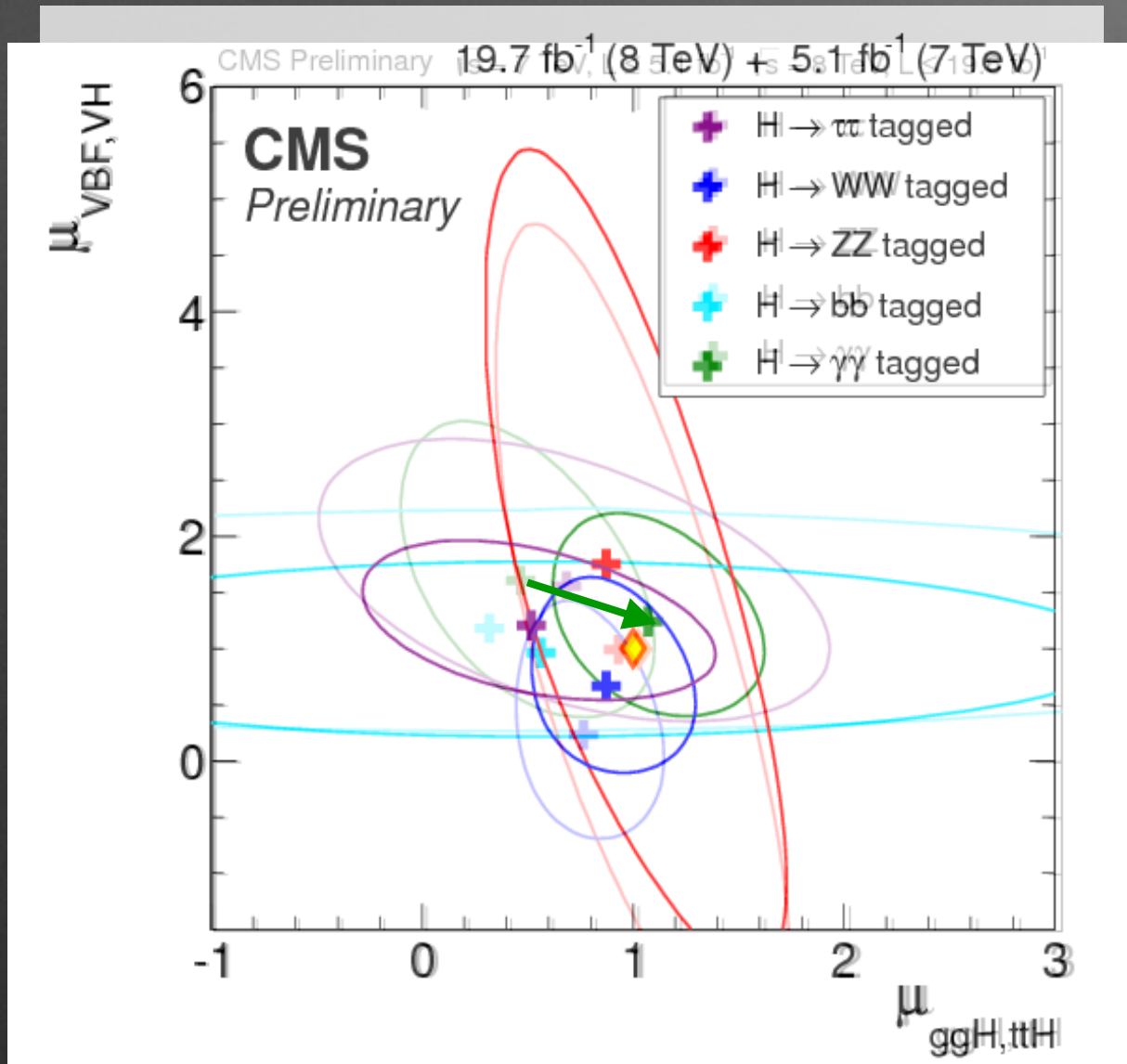
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Deviation in Production Modes

125.5 GeV Higgs boson



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

$$\chi = \sum_Y \chi_Y^2$$

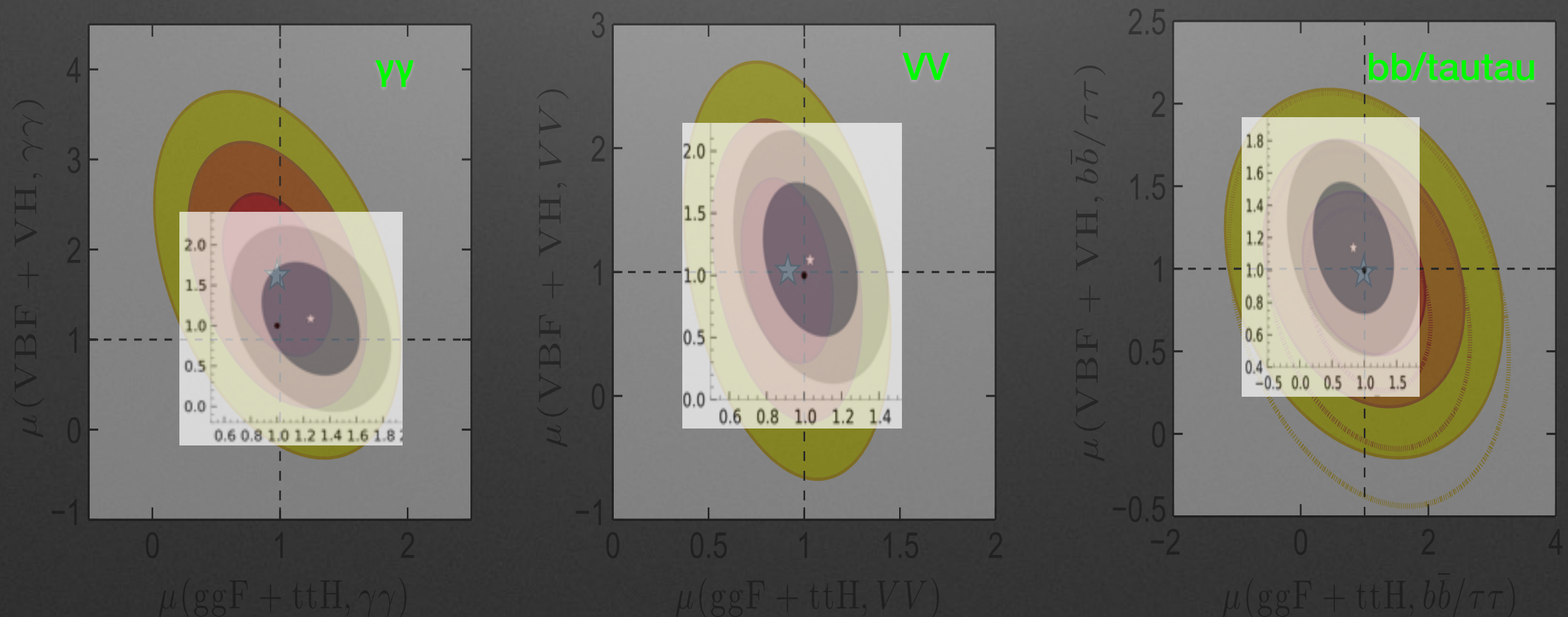
arXiv:1306.2941; 1409.1588

Lilith

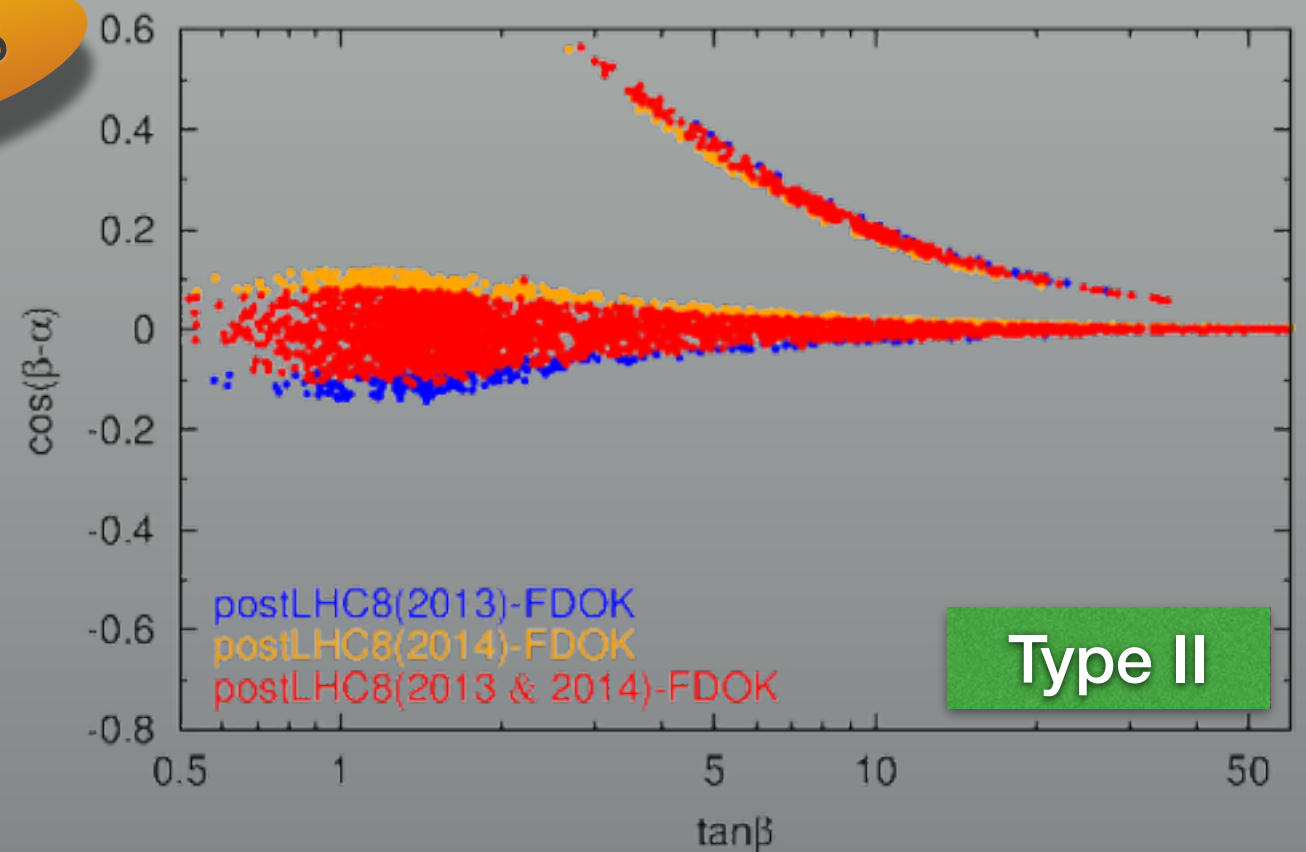
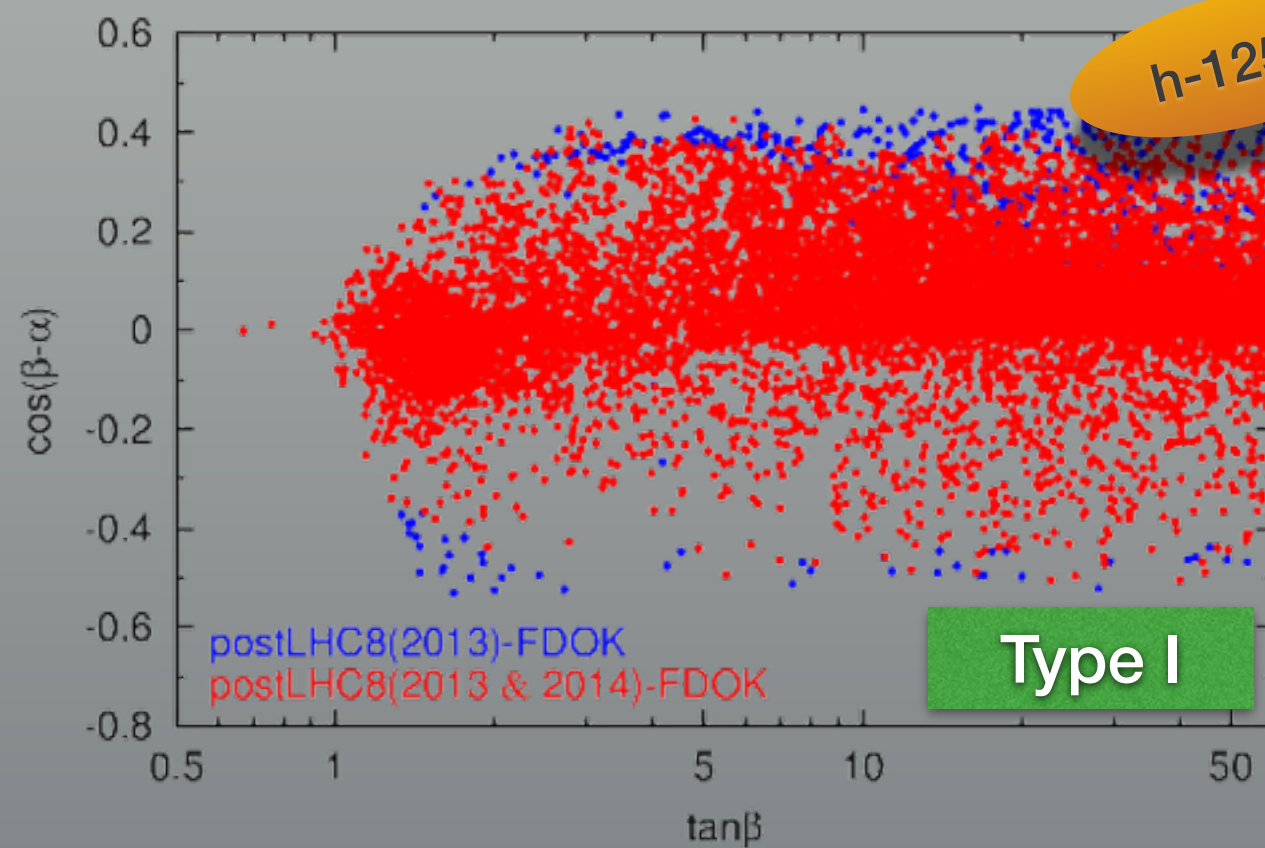
Light Likelihood Fit for the Higgs

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

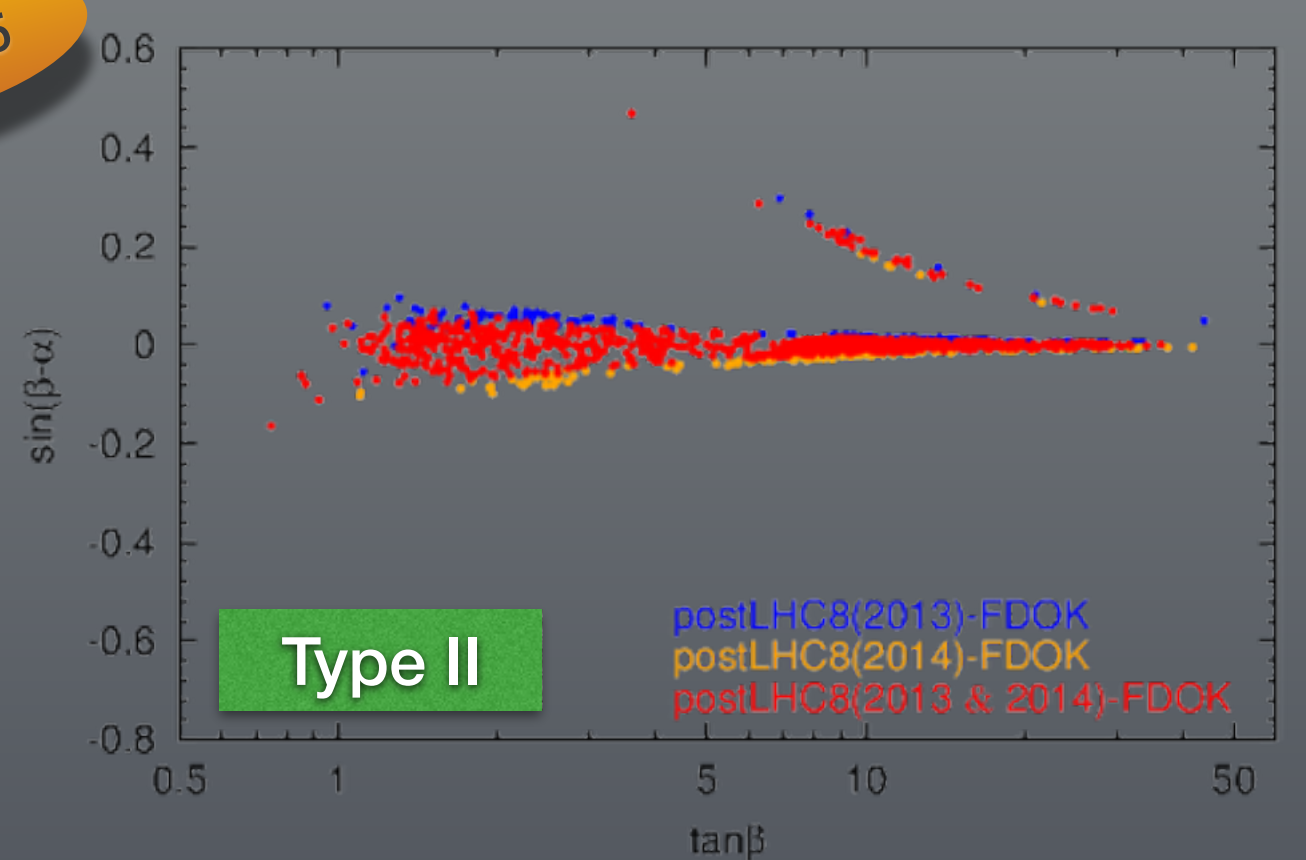
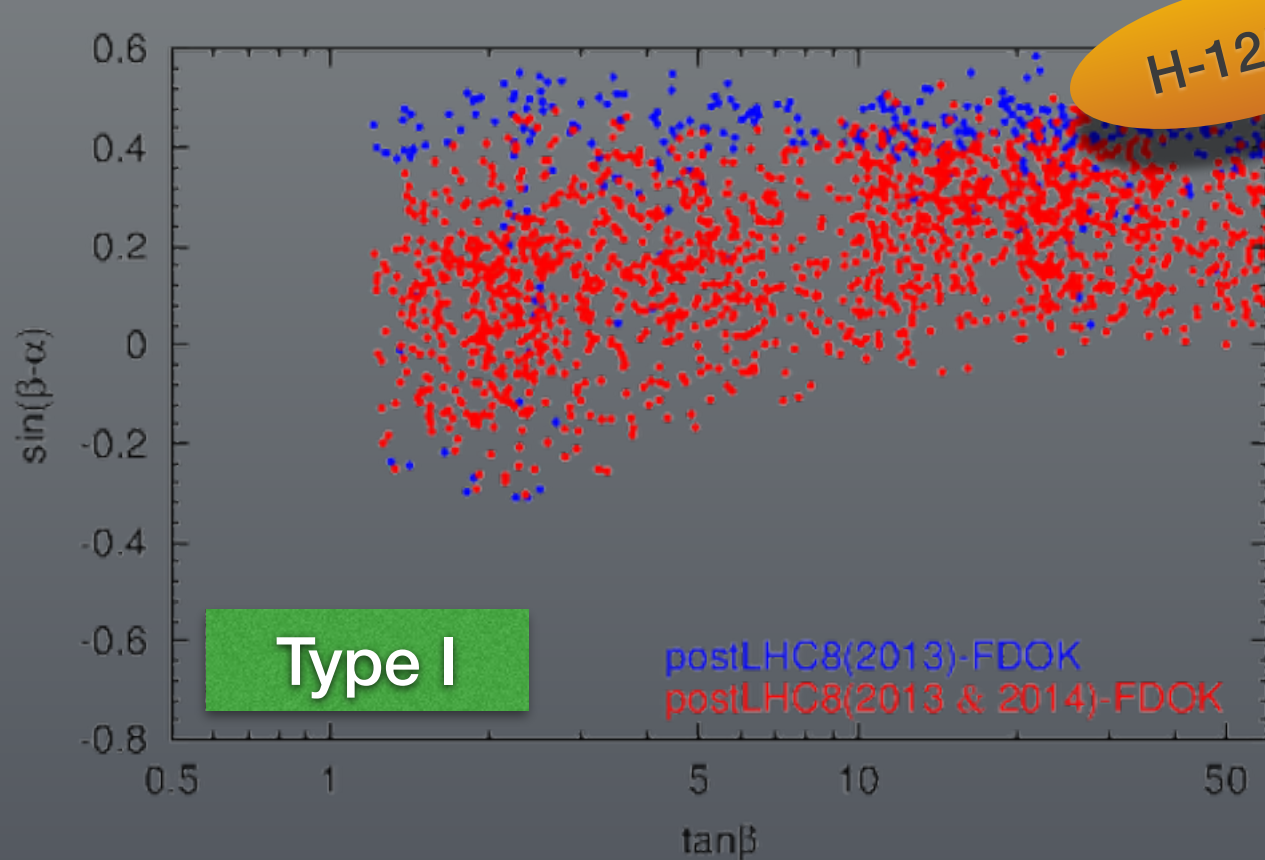
Higgs fit update

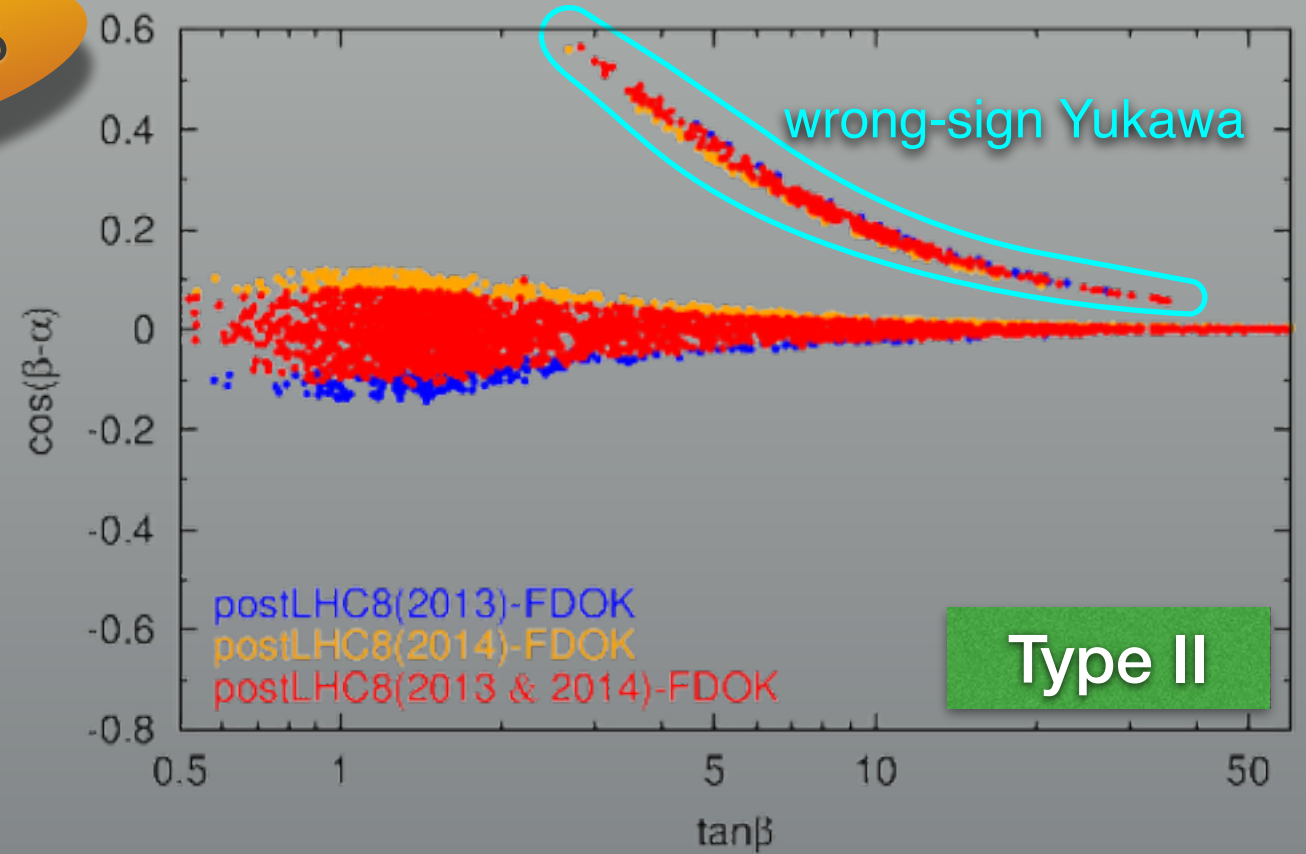
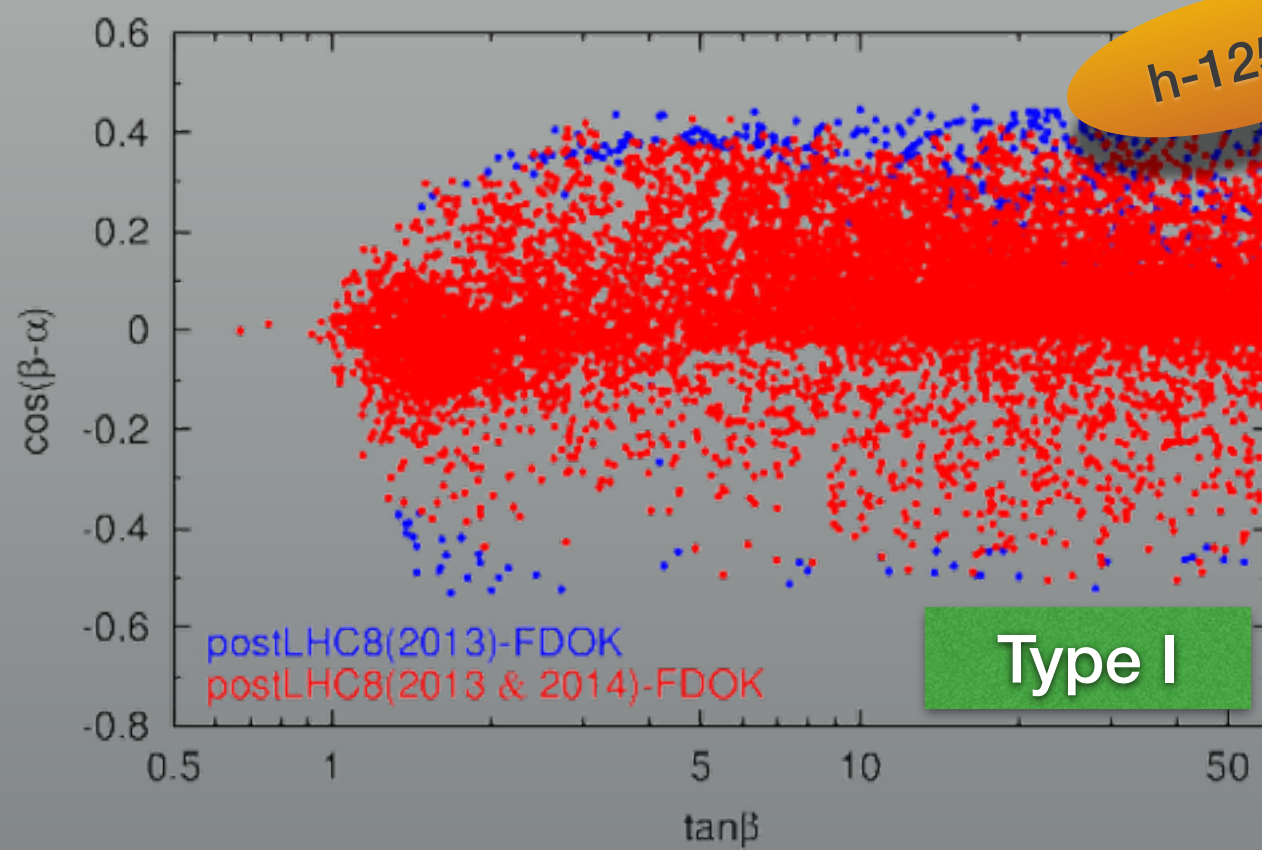


The most significant changes are slight downward/upward shifts of the central $\mu_{\text{gg}}(\gamma\gamma)$ and $\mu_{\text{gg}}(VV)$ value.

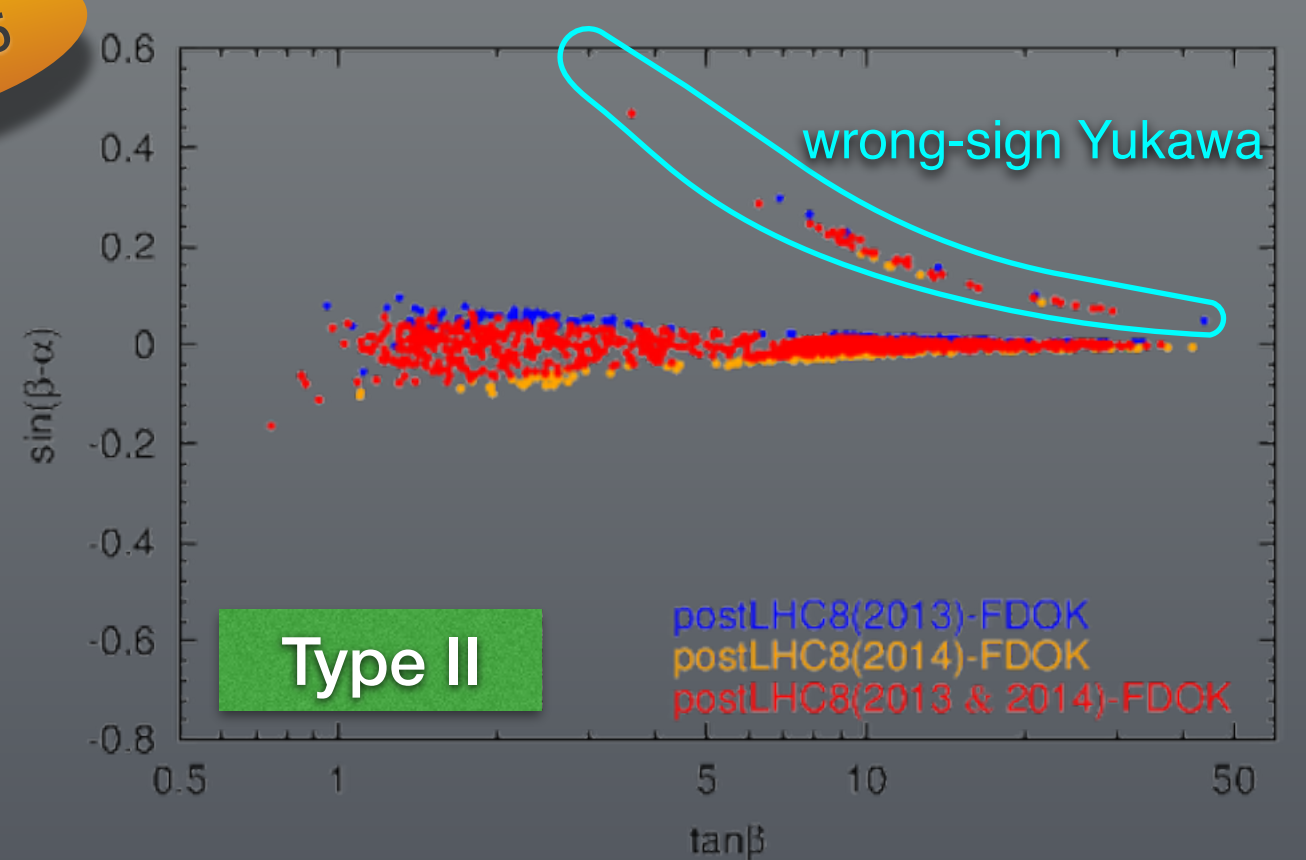
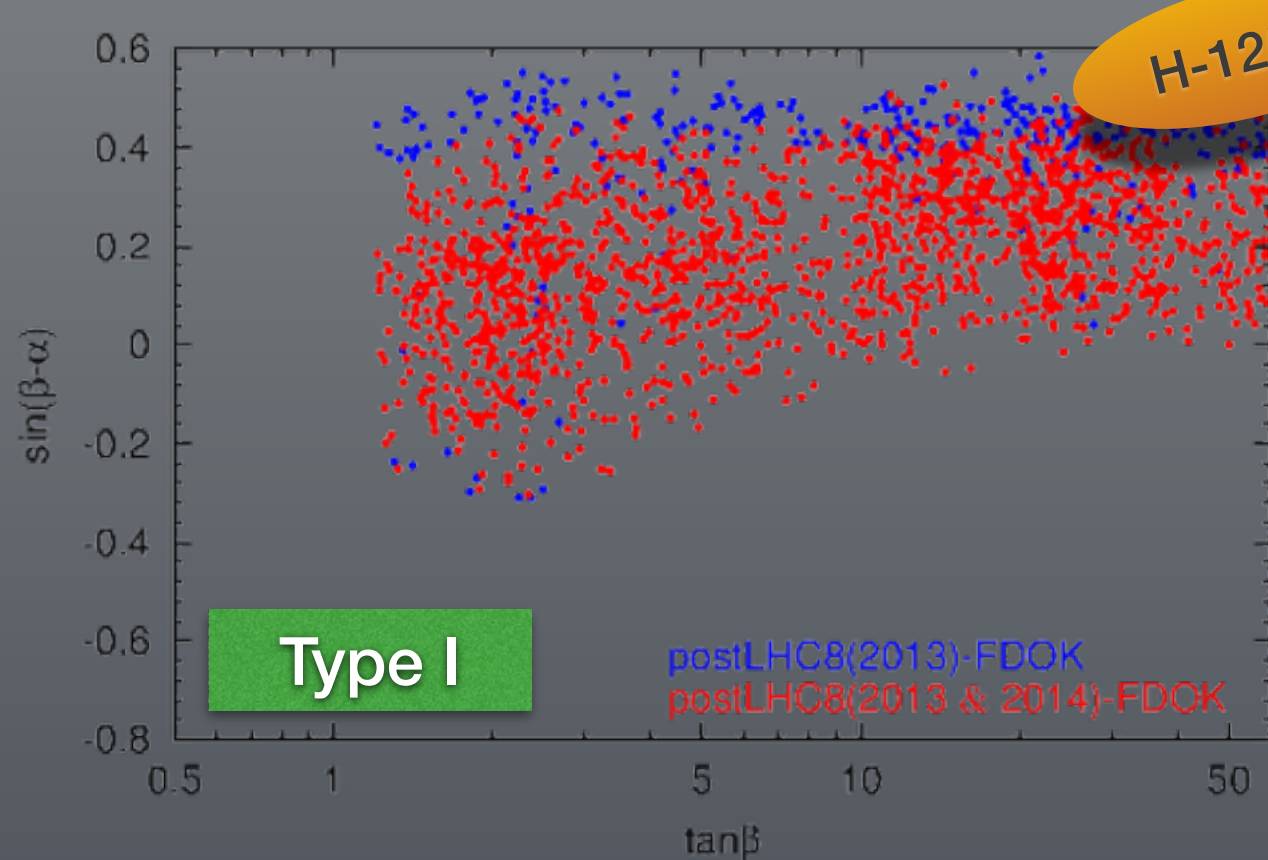


- In the Type II, $\sin(\beta - \alpha)$ is pretty much forced into the decoupling/alignment regime
- A slight narrowing of the allowed $\sin(\beta - \alpha)$ range, but no visible change in the $\tan \beta$ direction

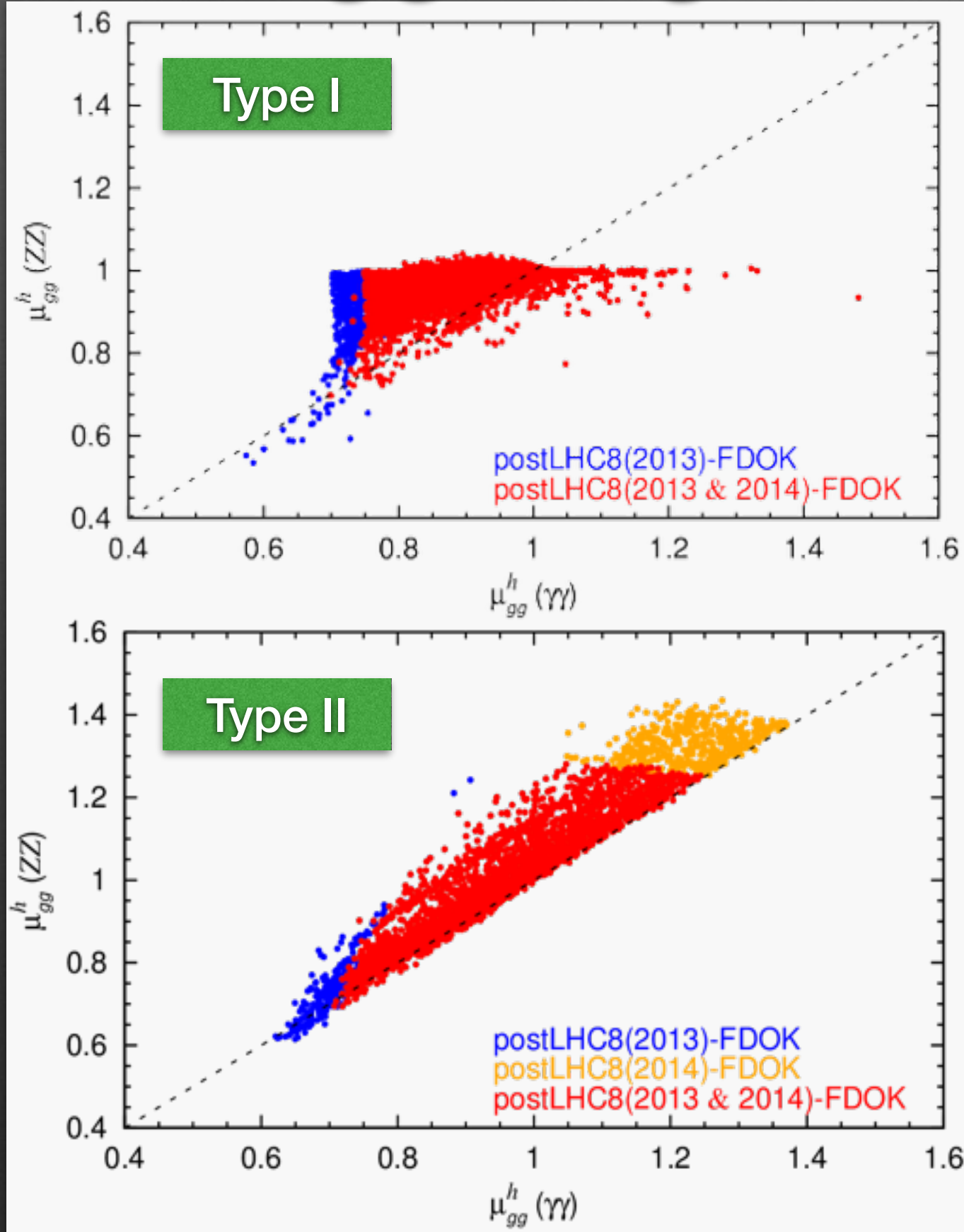




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Higgs Signals for $h \sim 125.5$



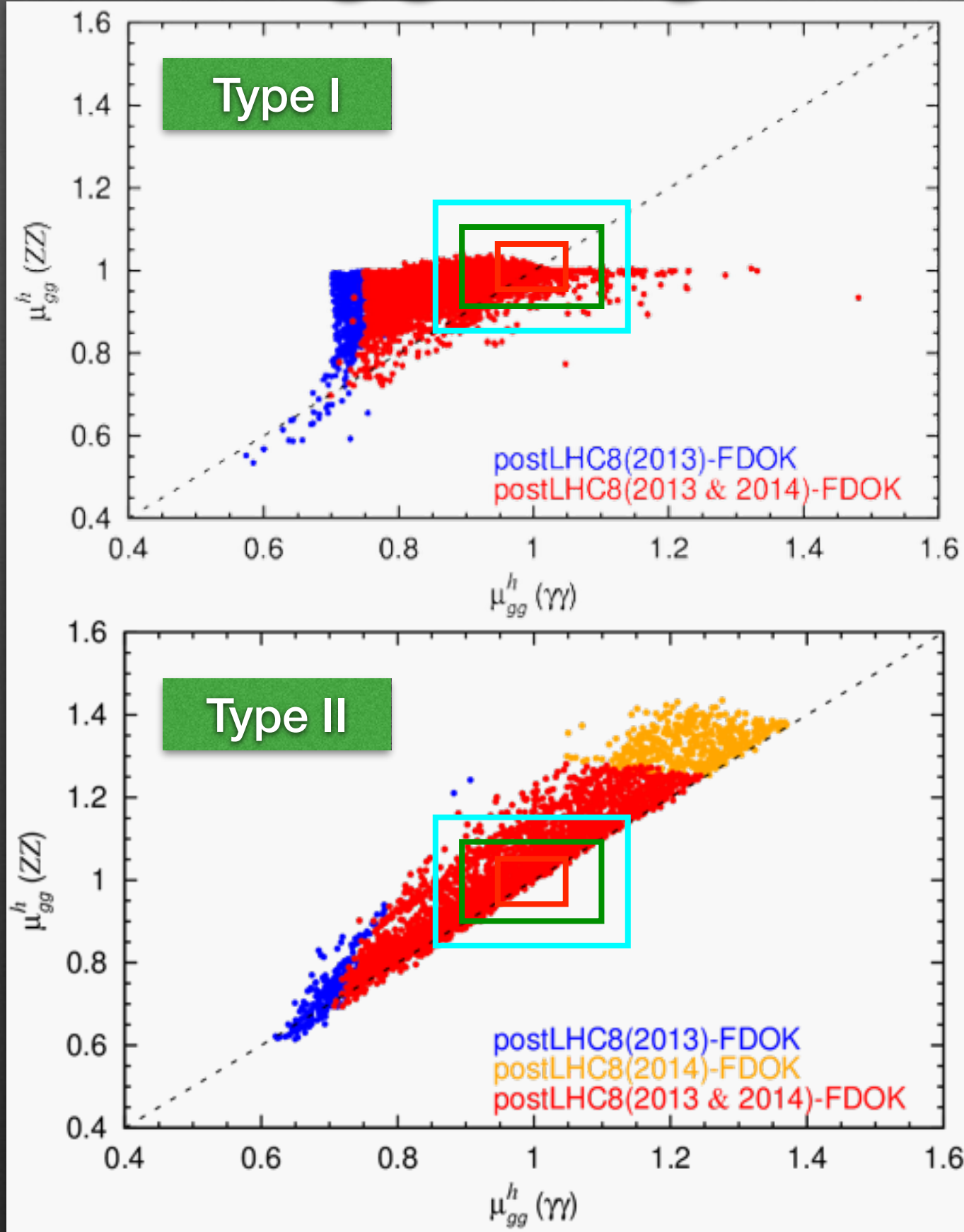
Type I

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

Type II

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

Higgs Signals for $h \sim 125.5$

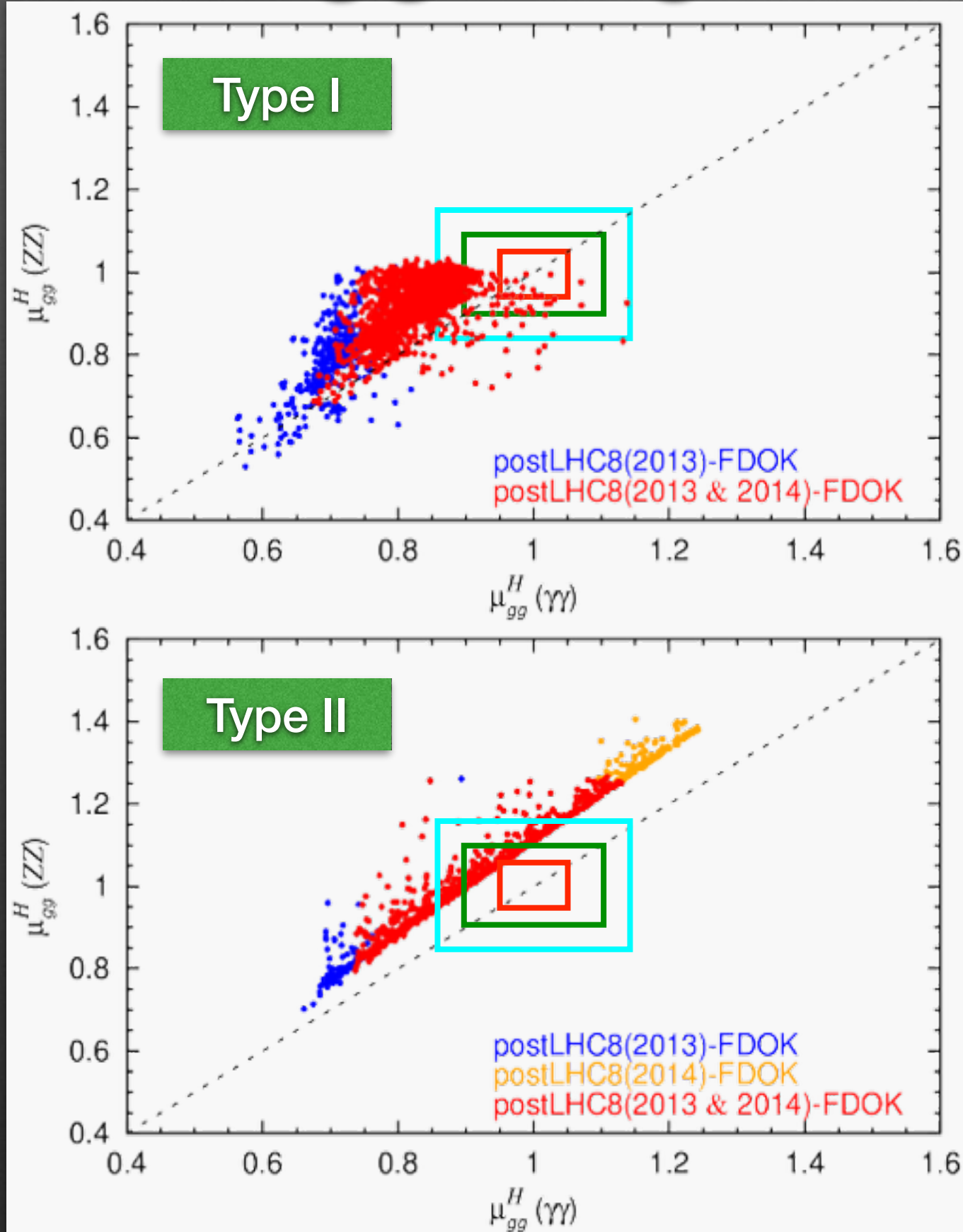


What happens if all measured signals converge to very SM?

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

$$\begin{aligned}
 &(gg, \gamma\gamma), (gg, ZZ), (gg, \tau\tau), \\
 &(VBF, \gamma\gamma), (VBF, ZZ), \\
 &(VBF, \tau\tau) = (VH, bb), (ttH, bb)
 \end{aligned}$$

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Future prospects

Inclusive	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 [†]	$\nu\bar{\nu}H$	ZH($\nu\bar{\nu}H$)
$H \rightarrow \gamma\gamma$	2.6/3.0/-%	-	1.2/1.7/-%	-	4.2%	-	0.4%
$H \rightarrow gg$	29-38%	-/20-26/7-10%	16/19/-%	-	6%	11%/ $< 11\%$	3.0%
$H \rightarrow ZZ^*$	7/11/-%	-/4.1/2.3%	3.3/6.0/-%	-/13/5.4%	-	1.4/1.4%	1.4%
$H \rightarrow WW^*$	19/25/-%	-/8.2/4.1%	8.8/14/-%	-/2.3/1.4%	2%	2.3/1.5%	3.1%
$H \rightarrow \tau\tau$	6.4/9.2/-%	-/2.4/1.6%	3.0/5.1/-%	-/4.6/2.6%	5.7%	0.75/0.5%	0.9%
$H \rightarrow b\bar{b}$	4.2/5.4/-%	-/9.0/3.1%	2.0/3.0/-%	-/1.3/1.0%	1%	2.8%/ $< 2.8\%$	0.7%
$H \rightarrow c\bar{c}$	1.2/1.8/-%	11/0.66/0.30%	0.56/1.0/-%	-/5.0/2.0%	5%	0.23/0.15%	0.2% (0.6%)
$H \rightarrow \mu\mu$	8.3/13/-%	-/6.2/3.1%	3.9/7.2/-%	4.9/0.37/0.30%	-	2.2/2.0%	1.2%
$H \rightarrow b\bar{b}$	-	-/-/31%	-	-/3.5/2.0%	-	21/12%	13%
	$t\bar{t}H$		$t\bar{t}H$		$t\bar{t}H$		$t\bar{t}H$
	-/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.

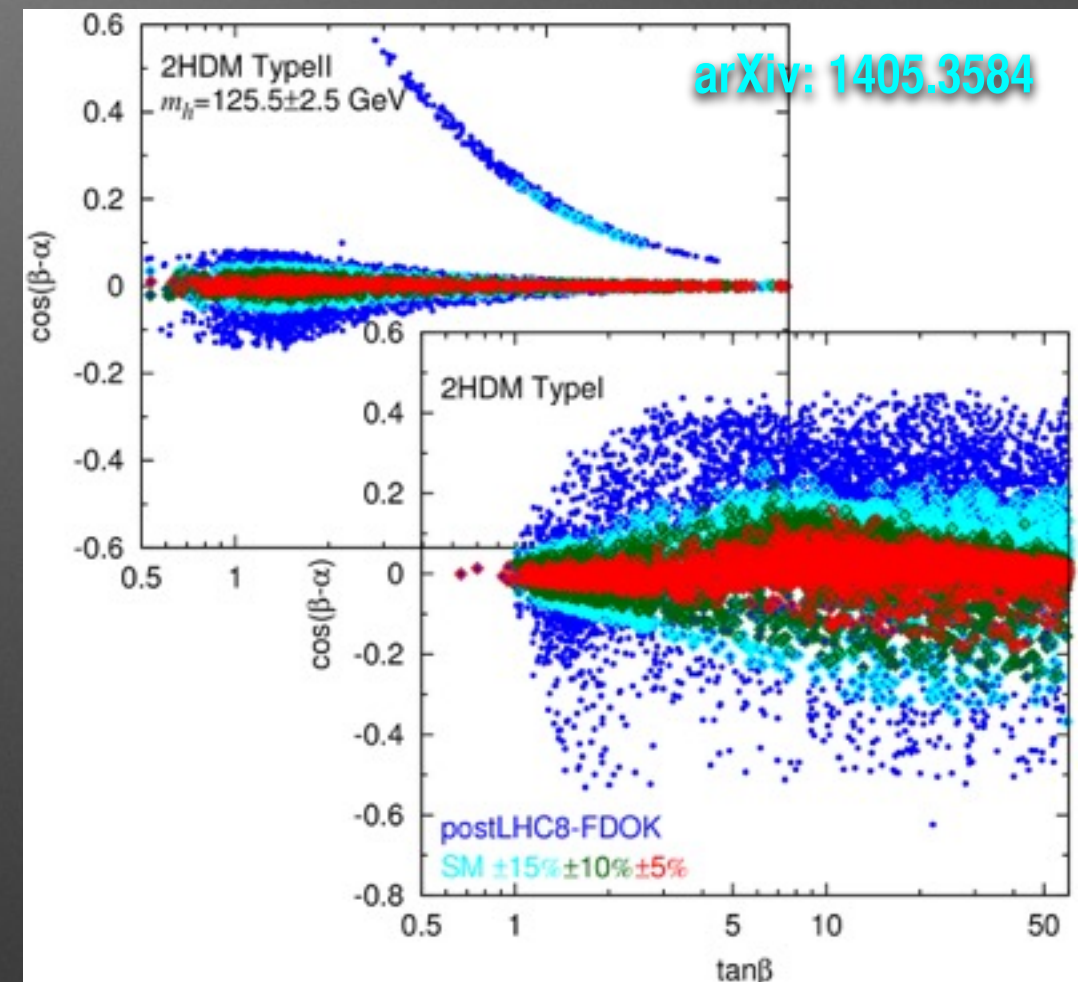
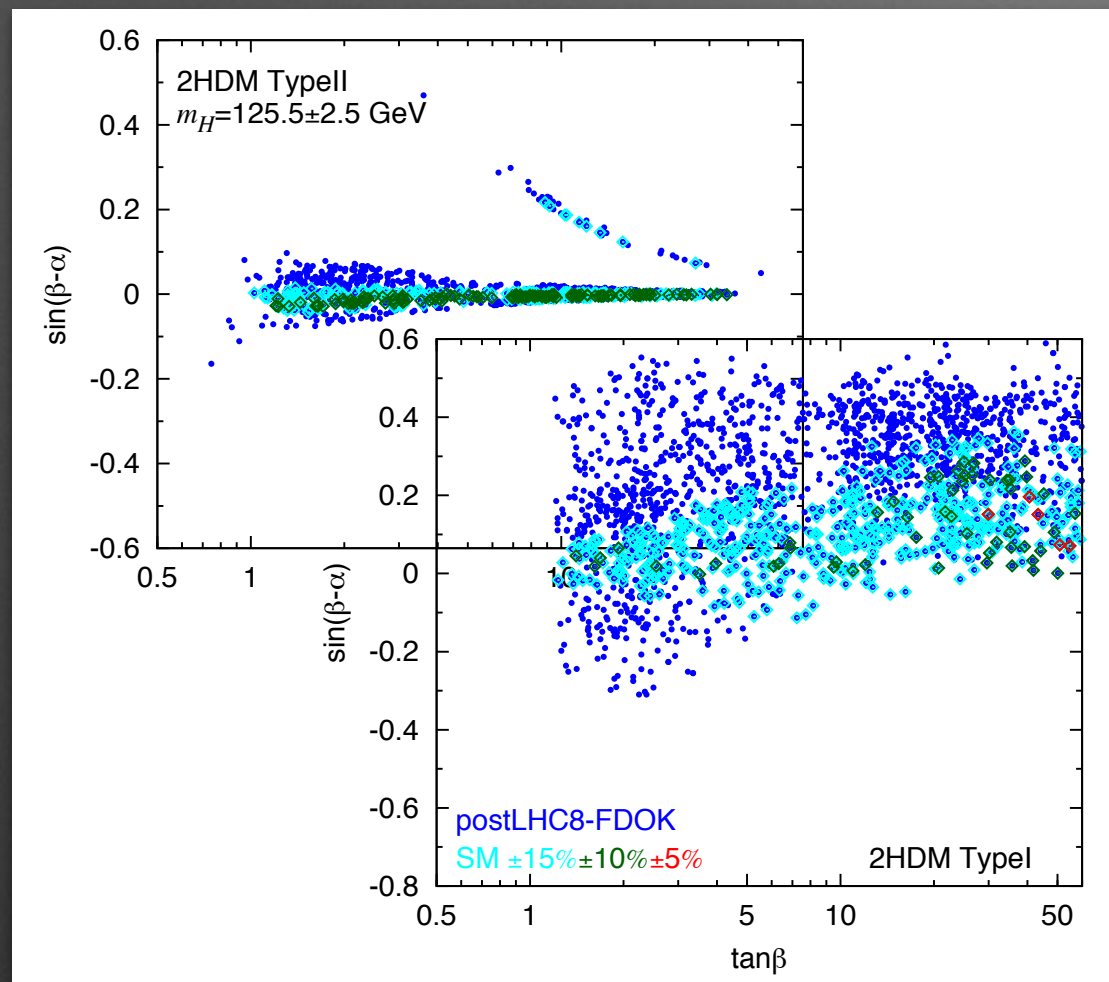
	WW*	ZZ*	bb	ττ	μμ	Zγ	BR _{inv}
ATLAS	12%	N/A	16 – 22%	38 – 39%	145 – 147%	< 23	
CMS	N/A	12 – 19%	12 – 15%	54 – 57%	< 8		
				40 – 42%	62 – 62%		
				20%	20 – 24%		

Table 1-13. Expected relative precisions on the signal strengths of dimensionless couplings as the 95% CL upper limit on the Higgs branching ratio to the invisible channel is estimated by ATLAS and CMS. The ranges are not comparable between ATLAS and CMS, they correspond to the cases with and without theoretical uncertainties while for CMS they correspond to scenarios of systematic uncertainties.

$\int \mathcal{L} dt$ (fb ⁻¹)	Higgs decay final state						$Z\gamma$	BR_{inv}
	$\gamma\gamma$	WW^*	ZZ^*	$b\bar{b}$	$\tau\tau$	$\mu\mu$		
				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%

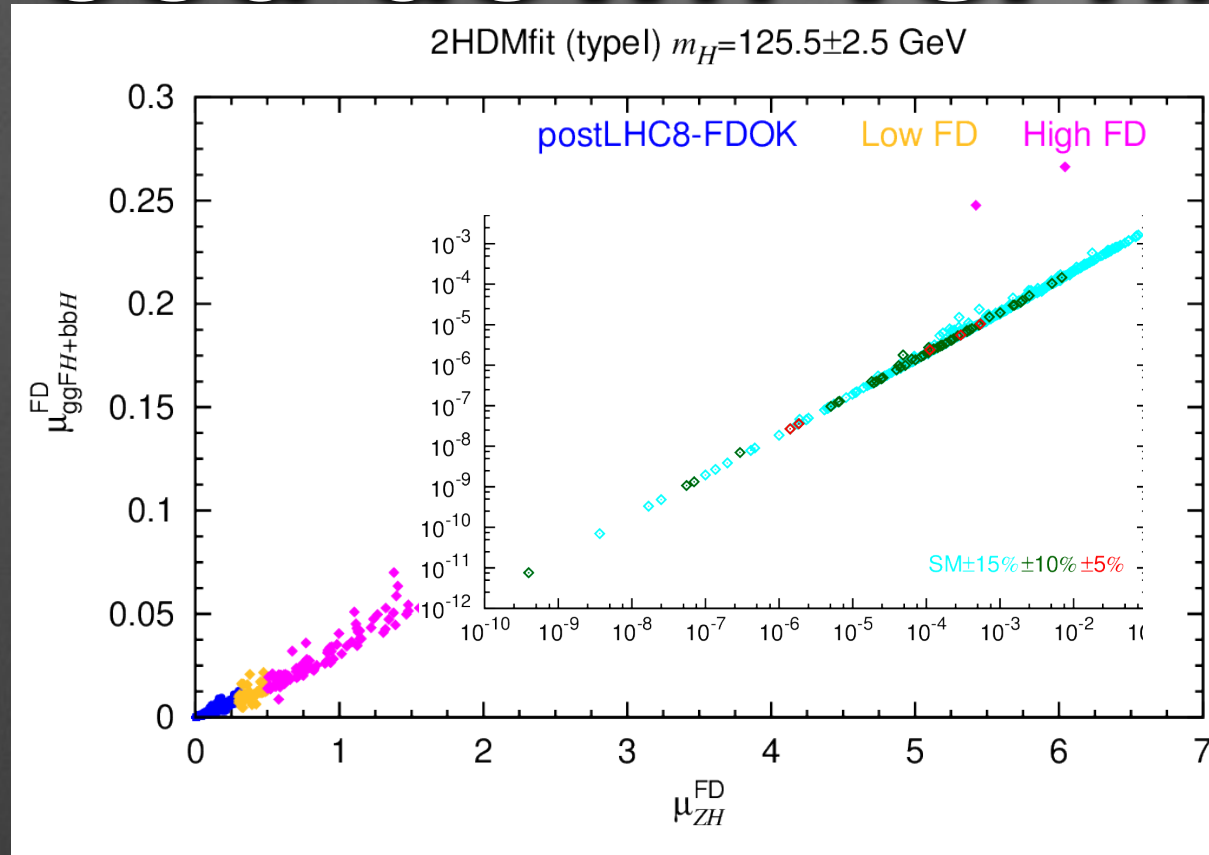
Parameter @ higher precision

- 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 $\pm 10\%$** 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 $m_H = 125.5$ 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

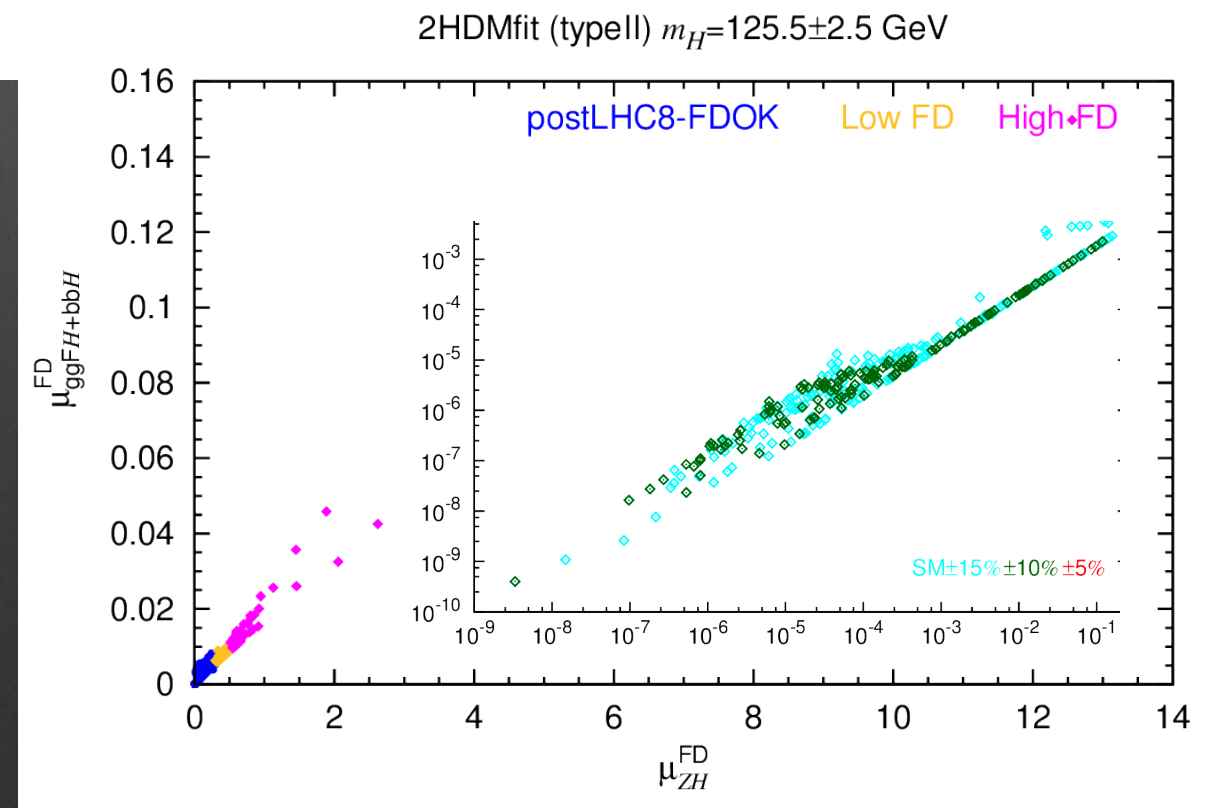


For all but VH

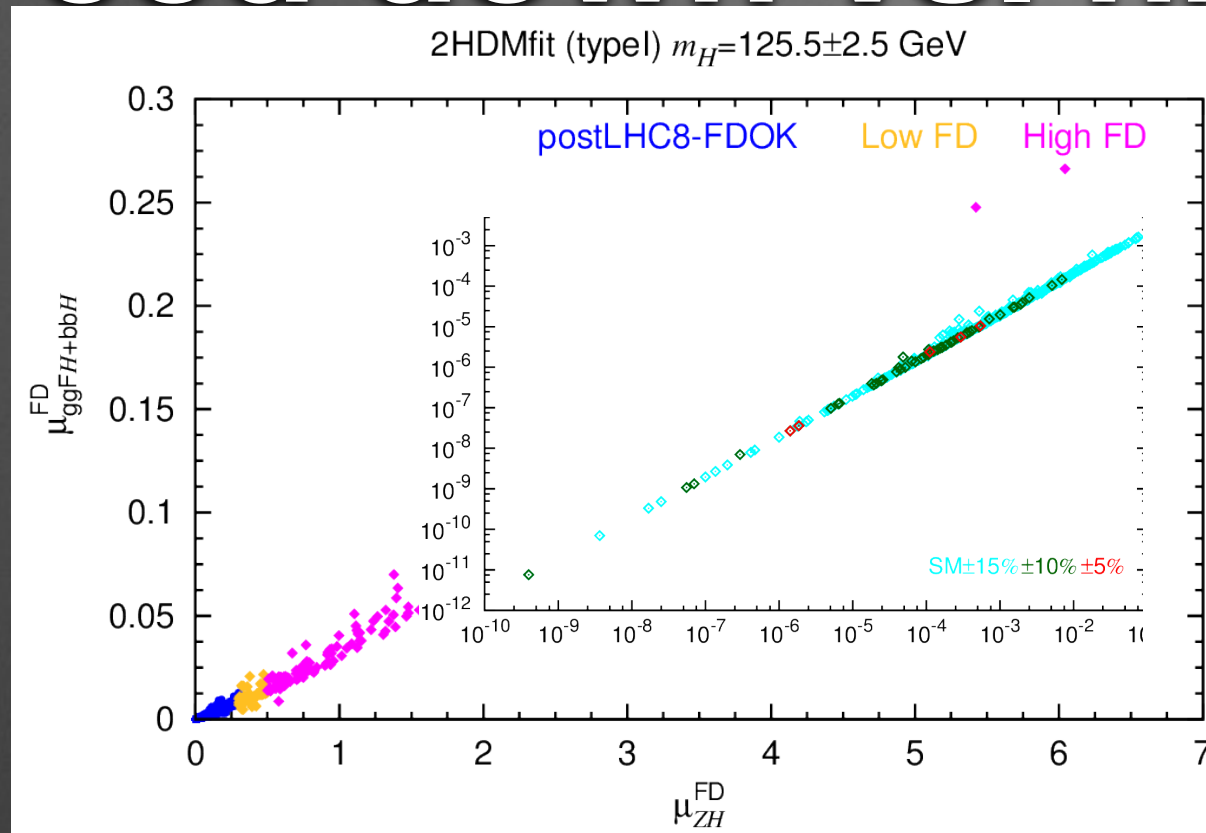
$$\mu_{\text{XH}}^{\text{FD}} \equiv \frac{\sum_{\mathcal{H}} \sigma_{\text{XH}} P_{\text{FD}}(\mathcal{H} \rightarrow \text{H} + \text{anything})}{\sigma_{\text{XH}}}$$

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

$$\mu_{\text{VH}}^{\text{FD}} = \frac{\sigma_{\text{ggFA}} \text{BR}(A \rightarrow \text{ZH})}{\sigma_{\text{VH}}}$$



Feed down vs. higher precision



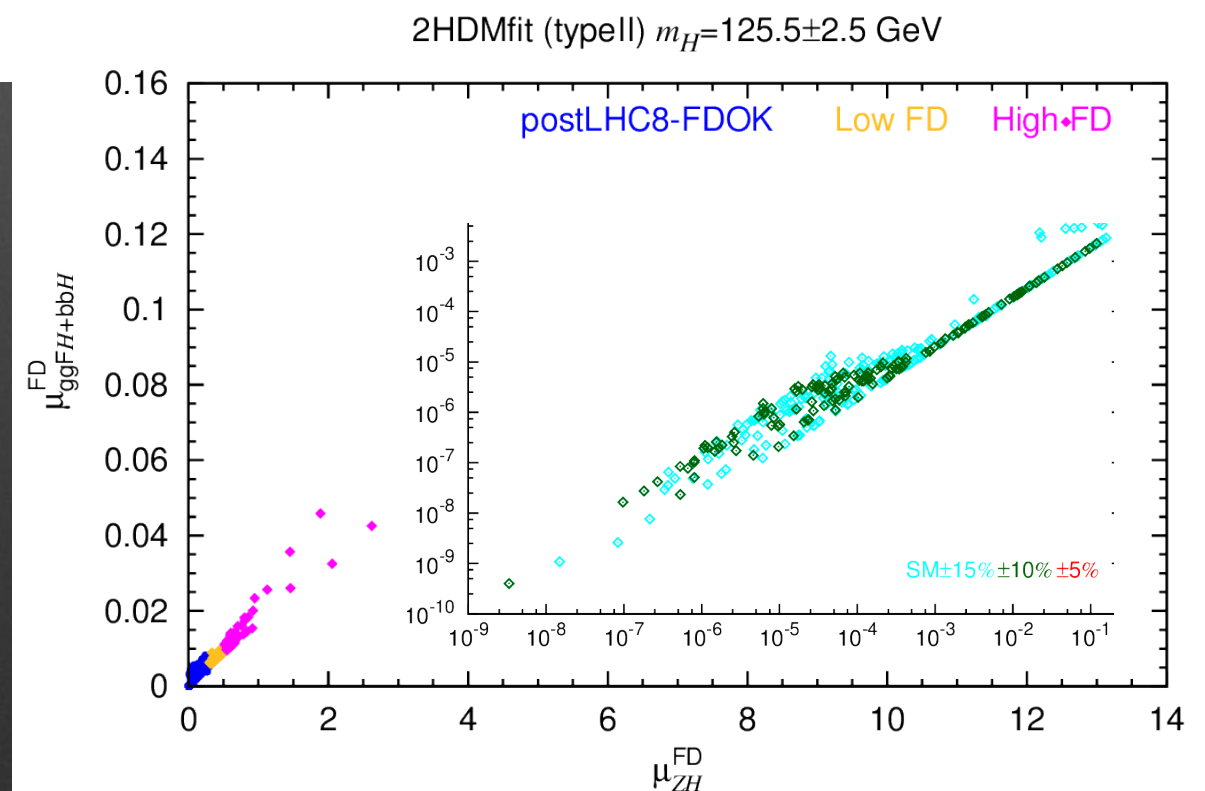
Increased precision in the signal strength measurements reduces the “danger” of FD contamination.

For all but VH

$$\mu_{\text{XH}}^{\text{FD}} \equiv \frac{\sum_{\mathcal{H}} \sigma_{\text{XH}} P_{\text{FD}}(\mathcal{H} \rightarrow \text{H} + \text{anything})}{\sigma_{\text{XH}}}$$

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

$$\mu_{\text{VH}}^{\text{FD}} = \frac{\sigma_{\text{ggFA}} \text{BR}(A \rightarrow \text{ZH})}{\sigma_{\text{VH}}}$$

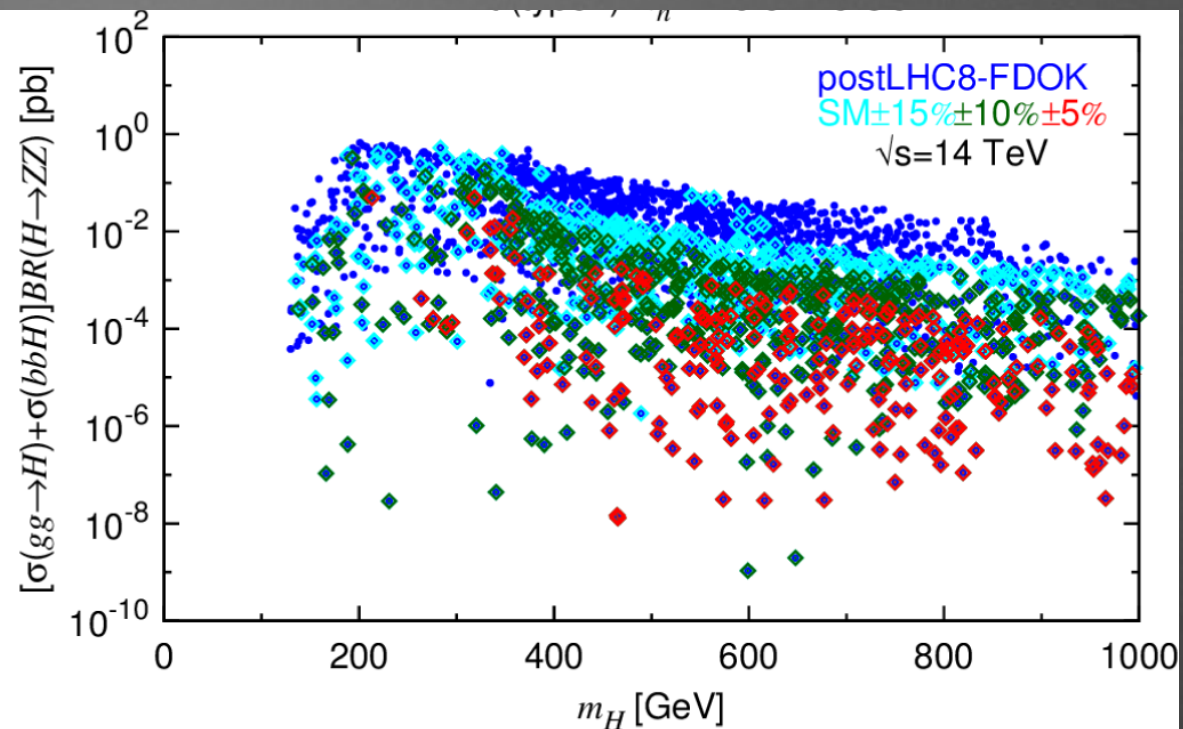
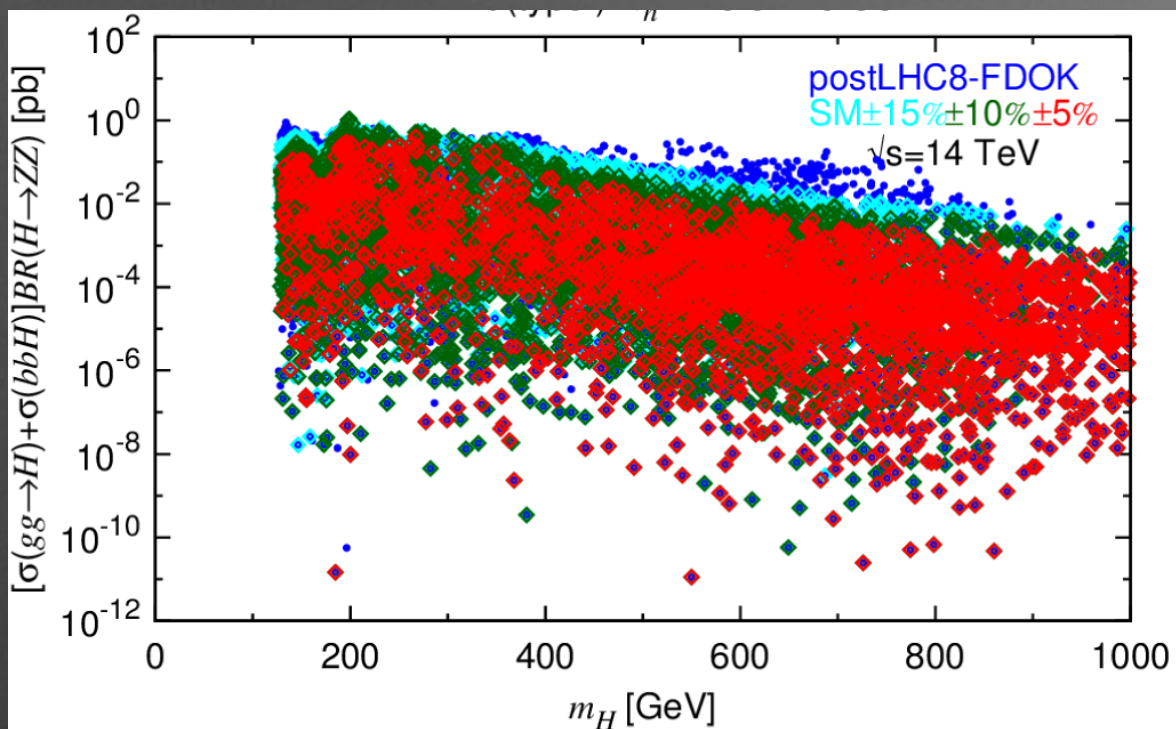


**Searches for
additional Higgs
bosons
at the LHC Run-II**



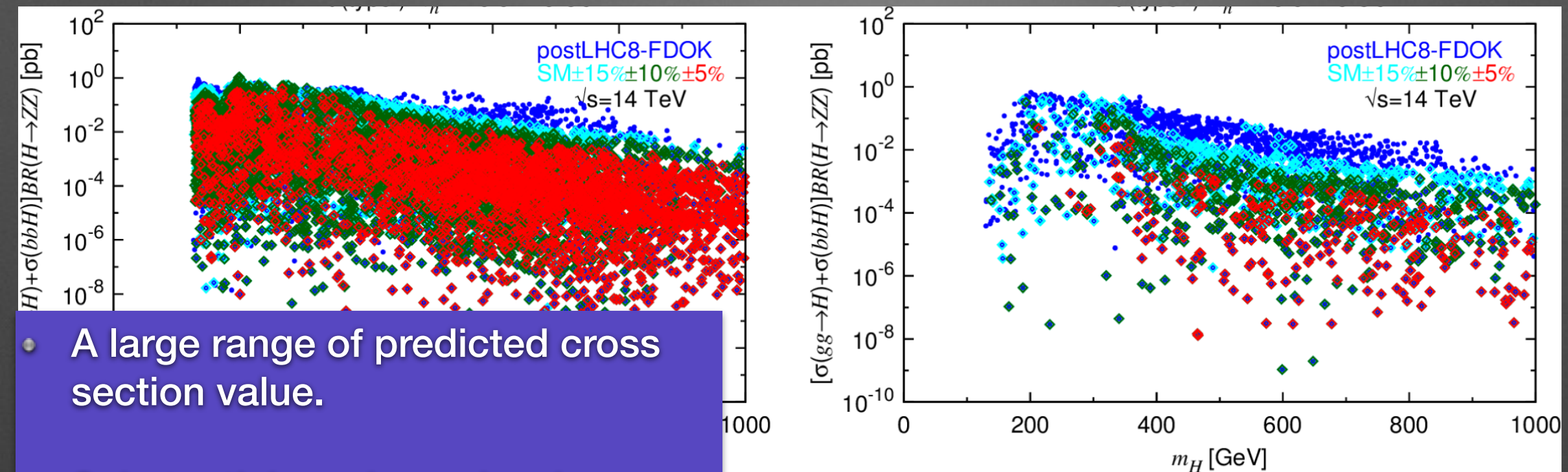
h-125.5
GeV

heavy H search



h-125.5
GeV

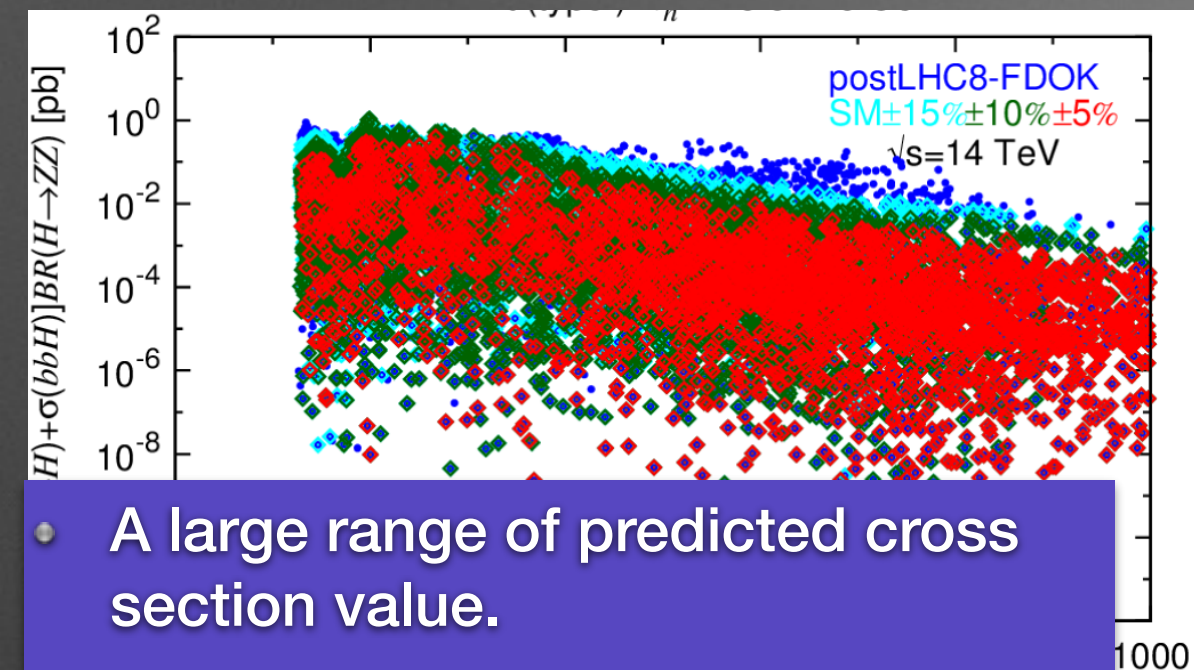
heavy H search



- 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%.

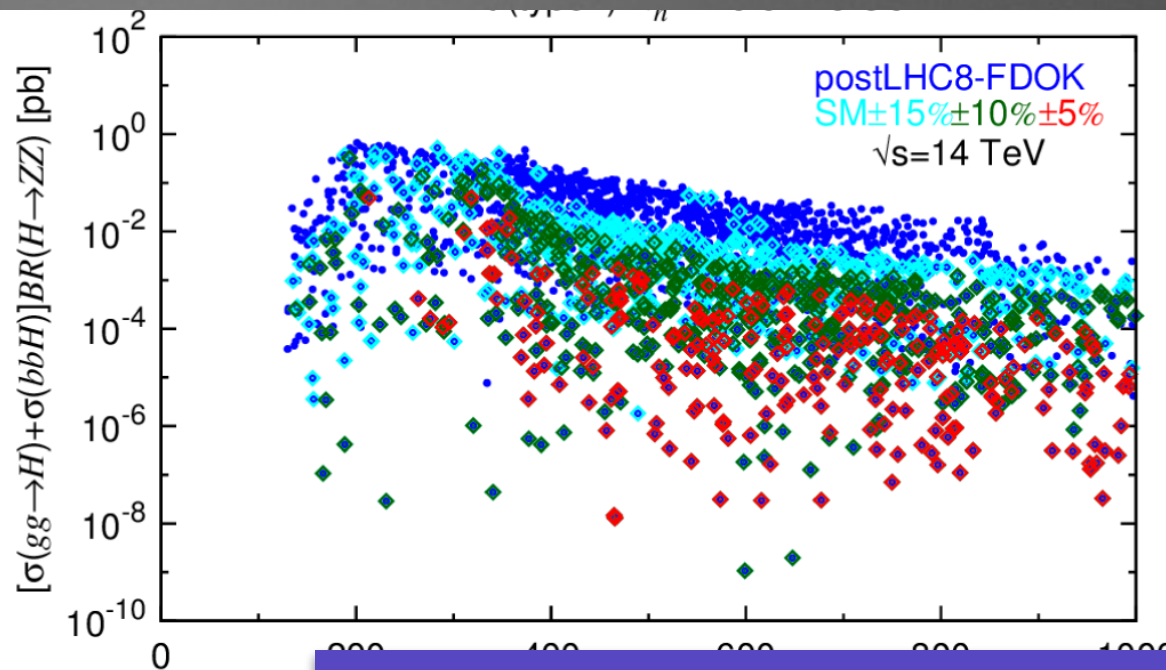
h-125.5
GeV

heavy H search

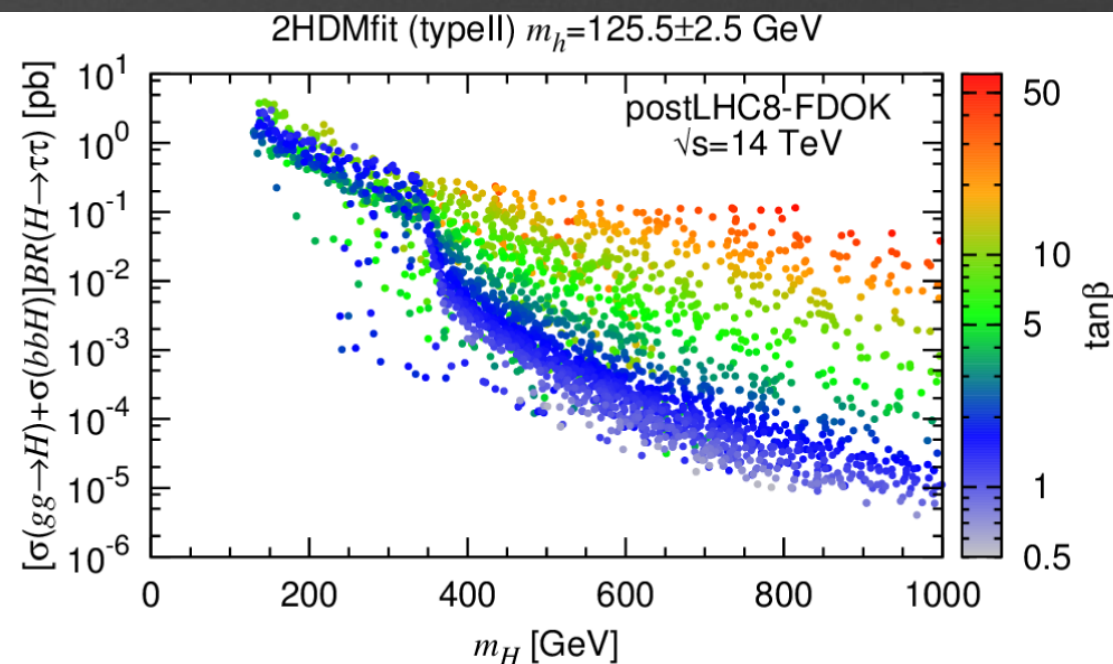
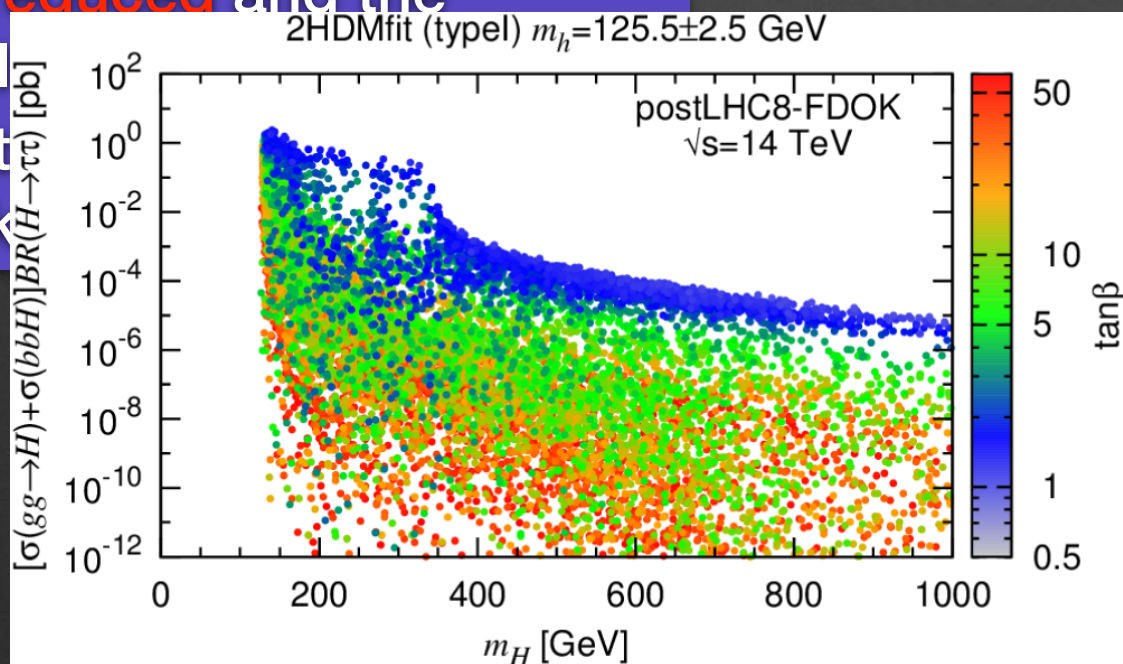


A large range of predicted cross section value.

Substantial maximum level are possible. However, in Type II, it will be **greatly reduced** and the minimum at 200 GeV if the have SM-like

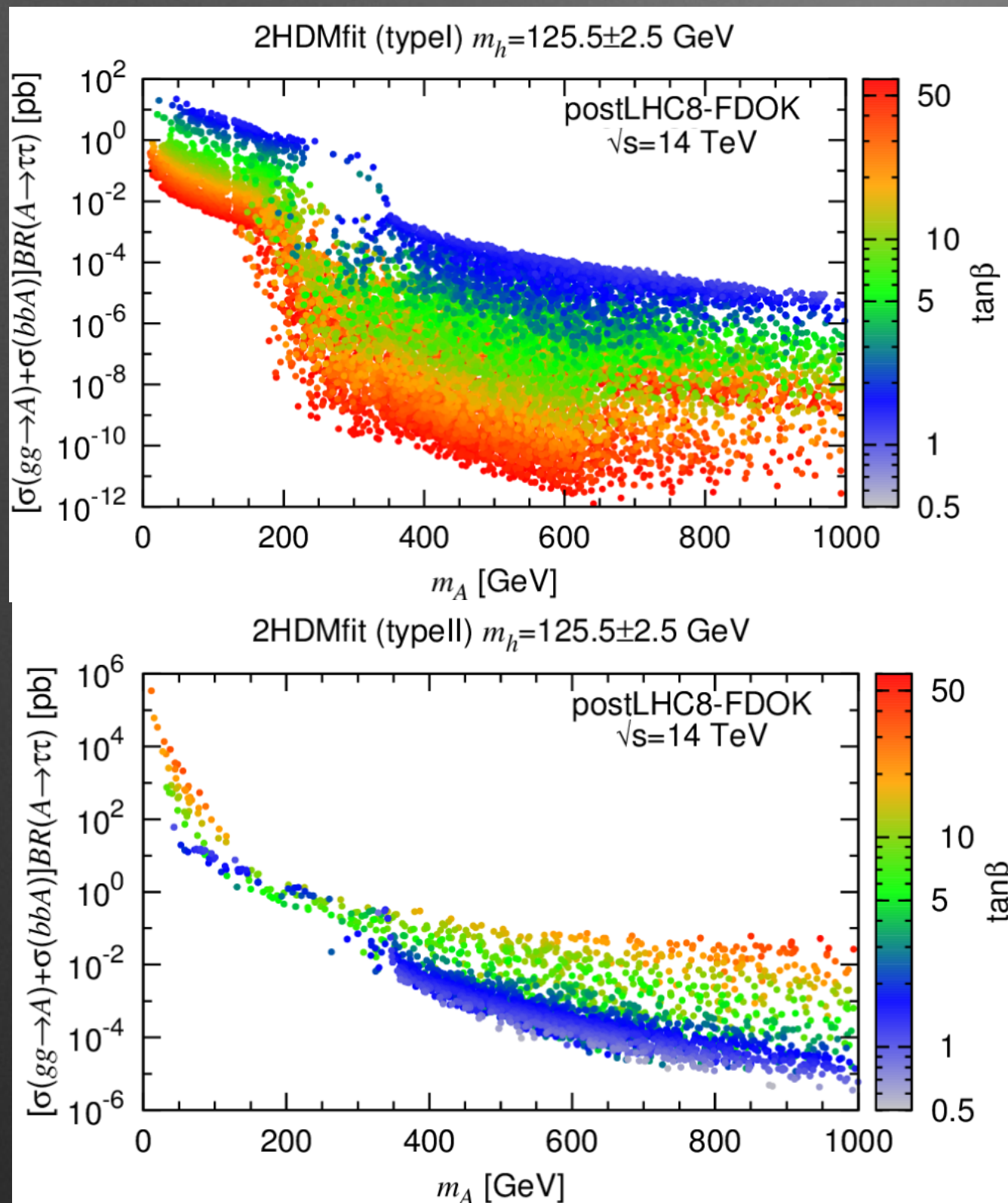


tan β dependence of the cross sections is **opposite** in Type I and Type II.



$h=125.5$
GeV

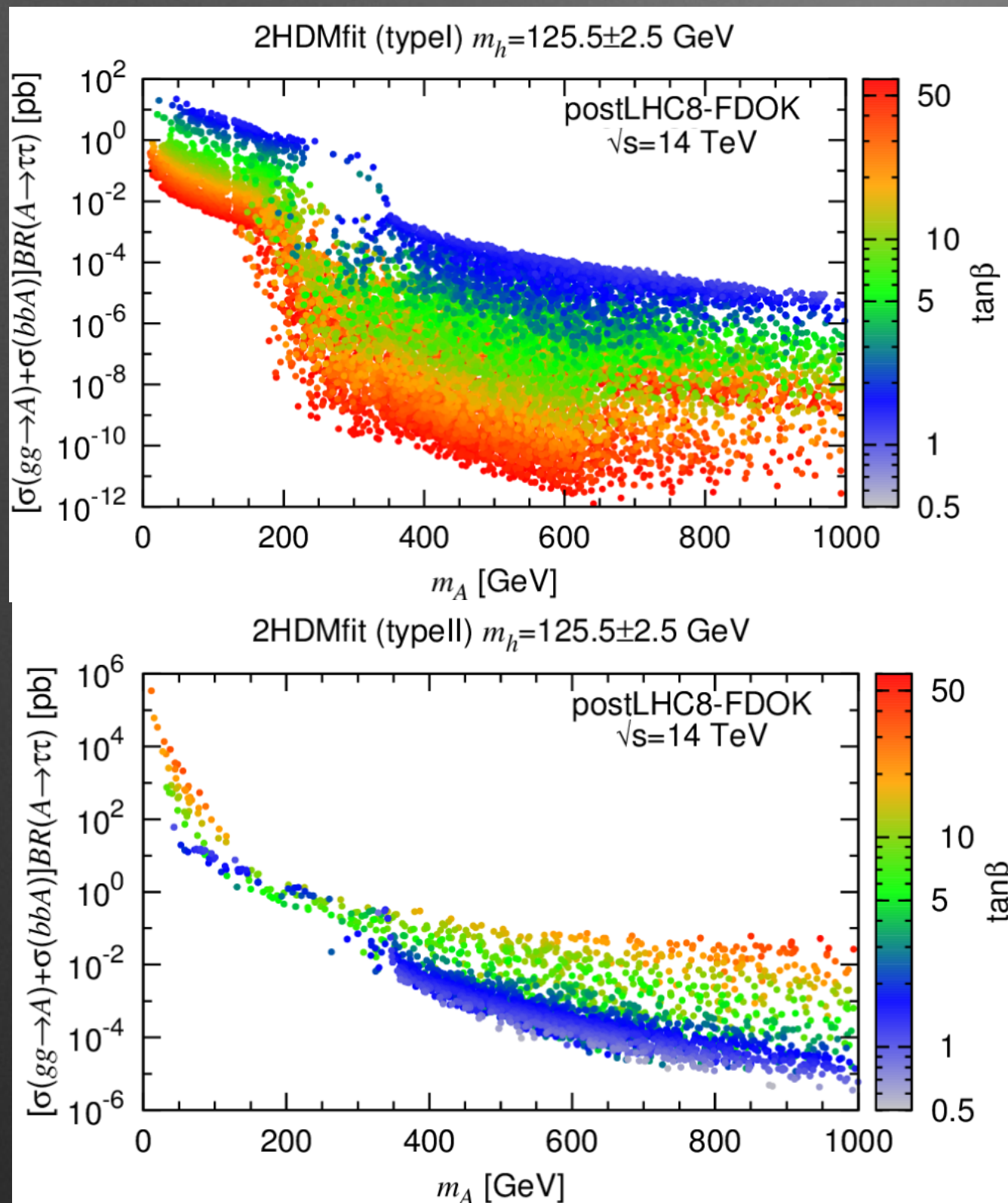
pseudoscalar A search



- 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 $t\bar{t}$ 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 $t\bar{t}$ threshold is not apparent for Type II due to the absence into ZZ decay.
- low $m_A < 60$ GeV is possible but must have small $BR(h \rightarrow AA)$. For $m_A < 100$ GeV, tautau cross section are quite large.

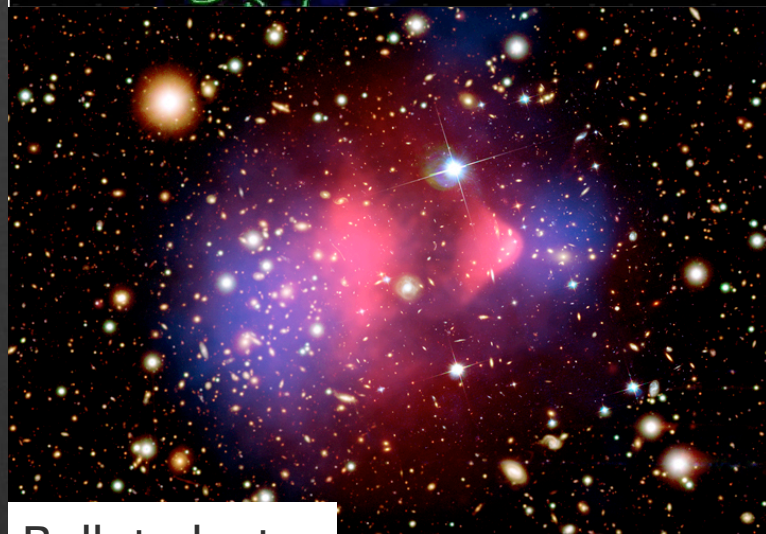
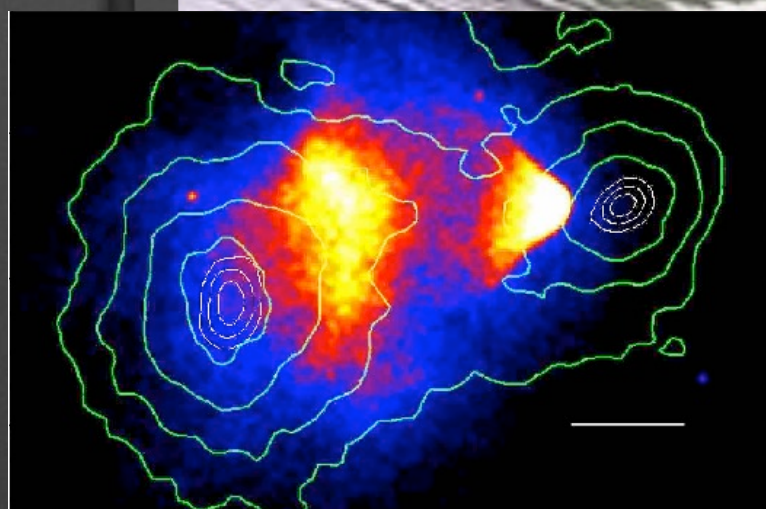
Stage I remarks

- 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).

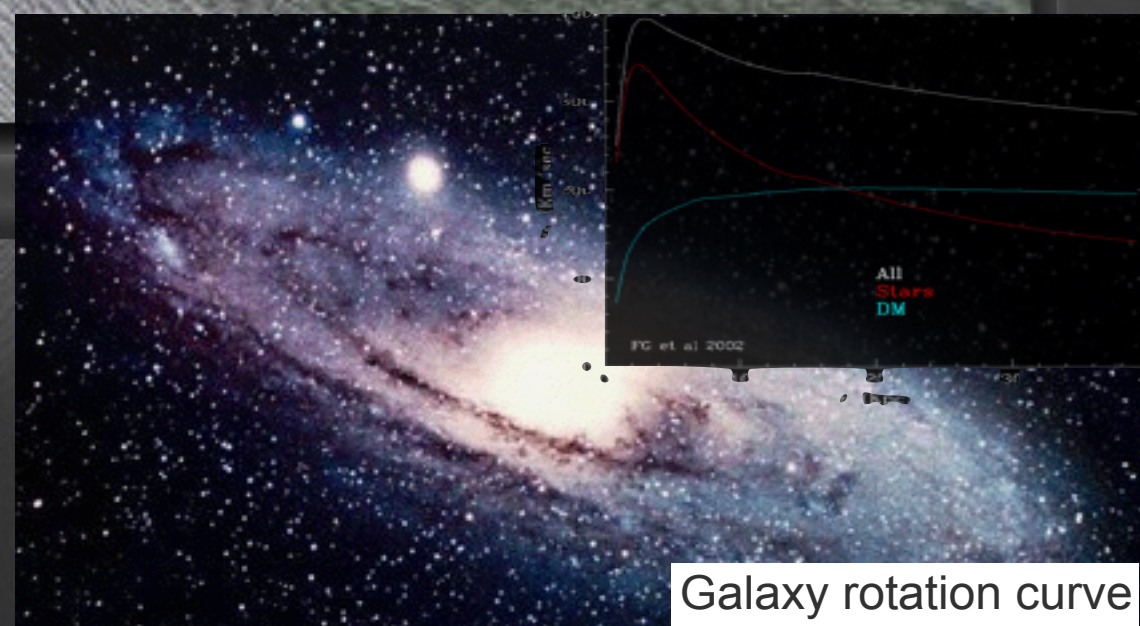
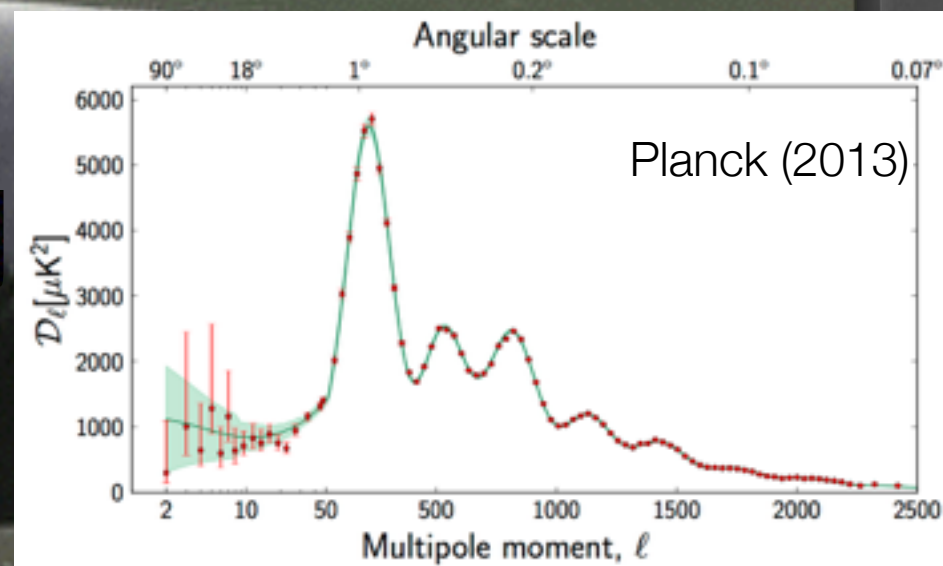
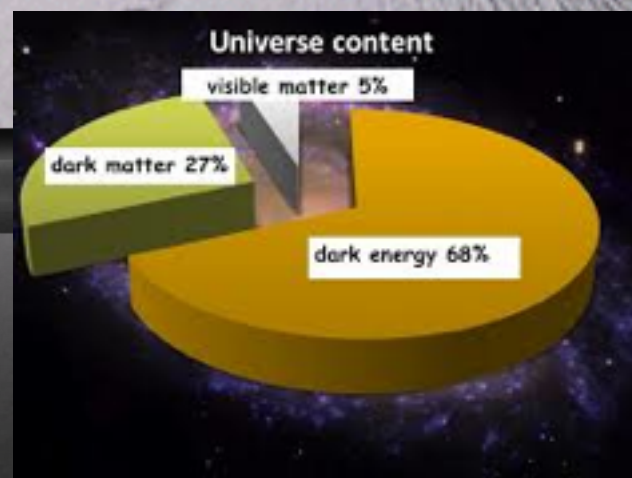
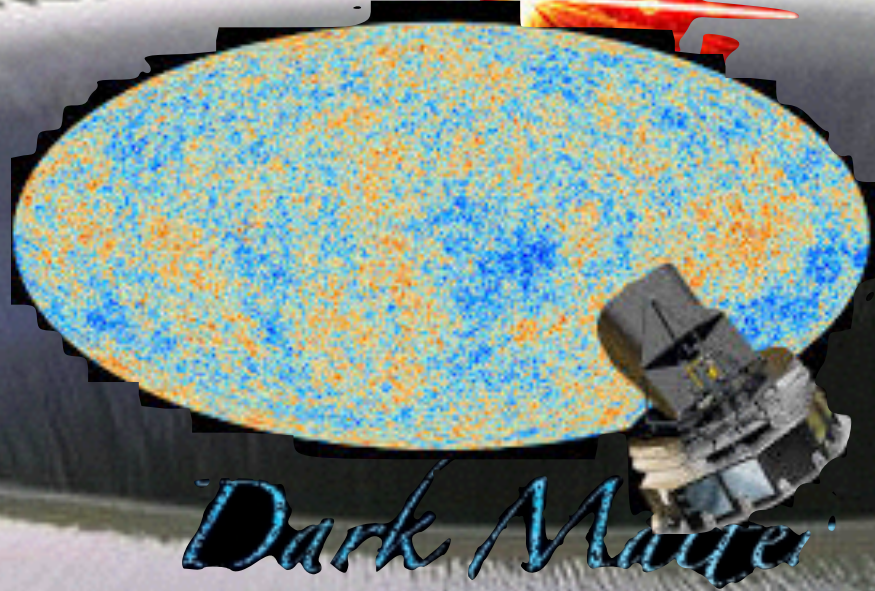


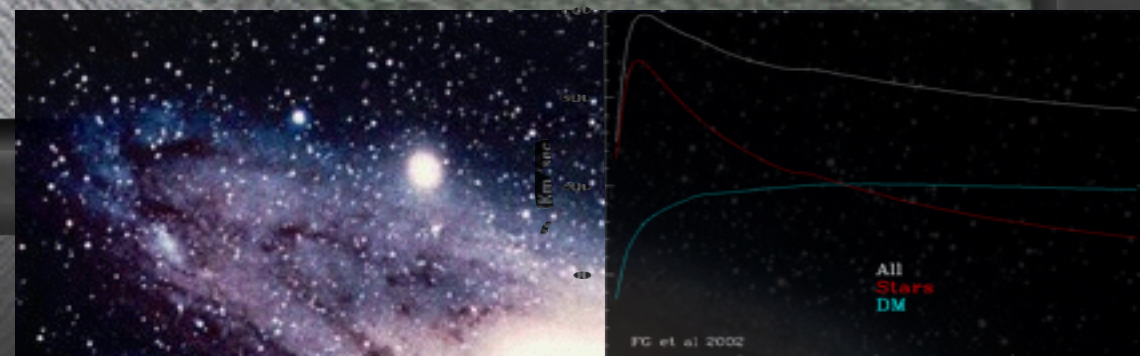
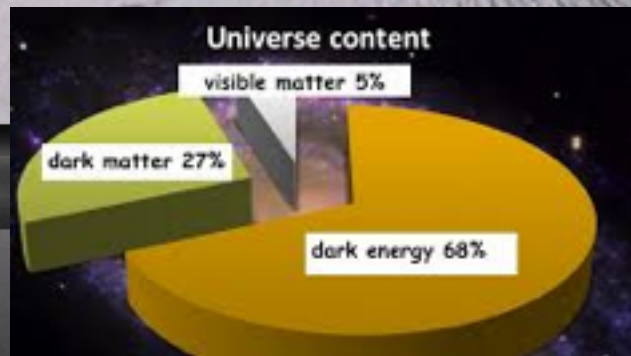
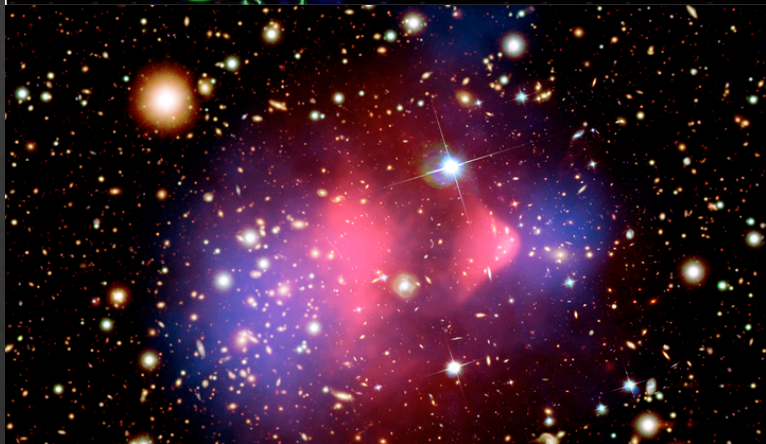
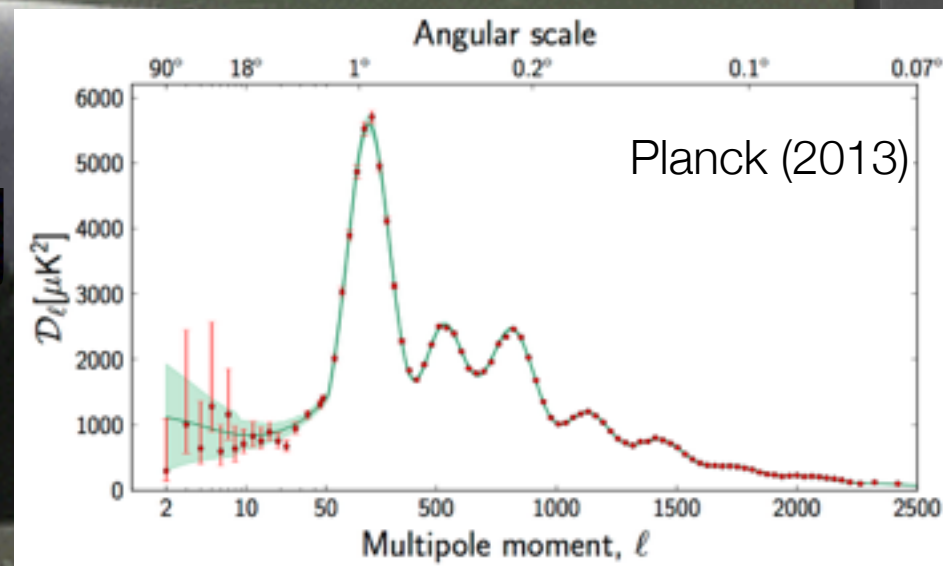
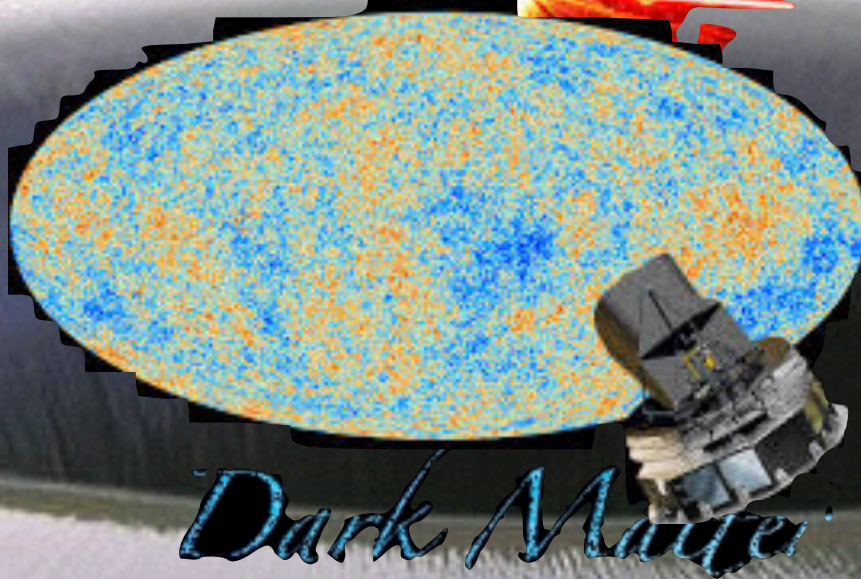
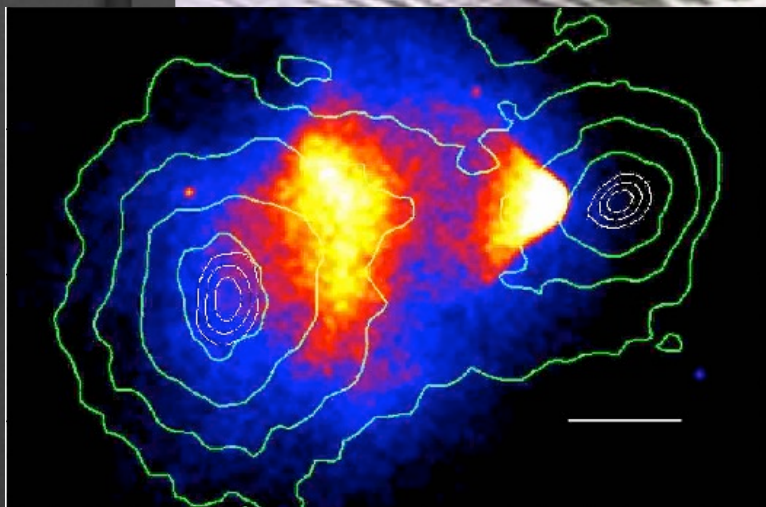




Bullet cluster

1E 0657-56, Bullet cluster

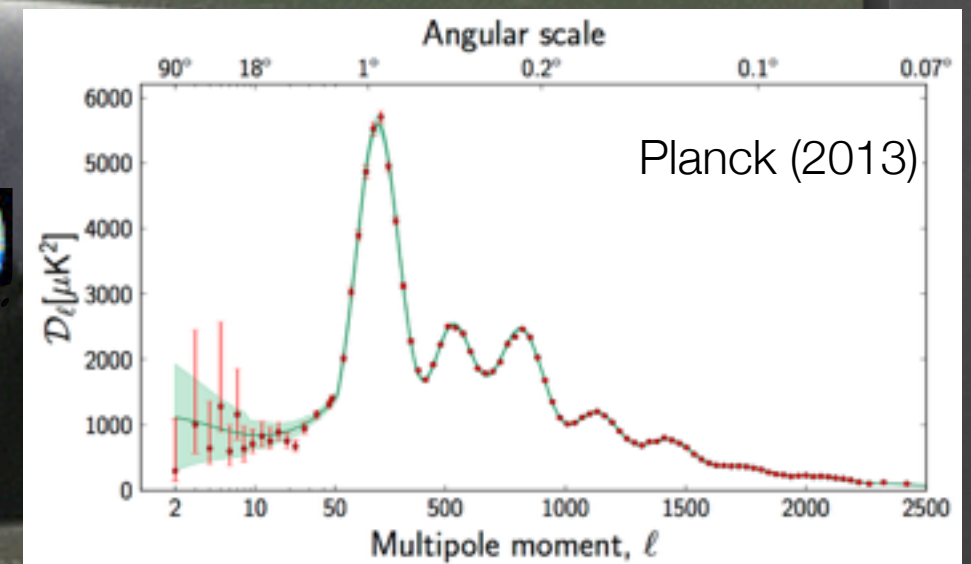
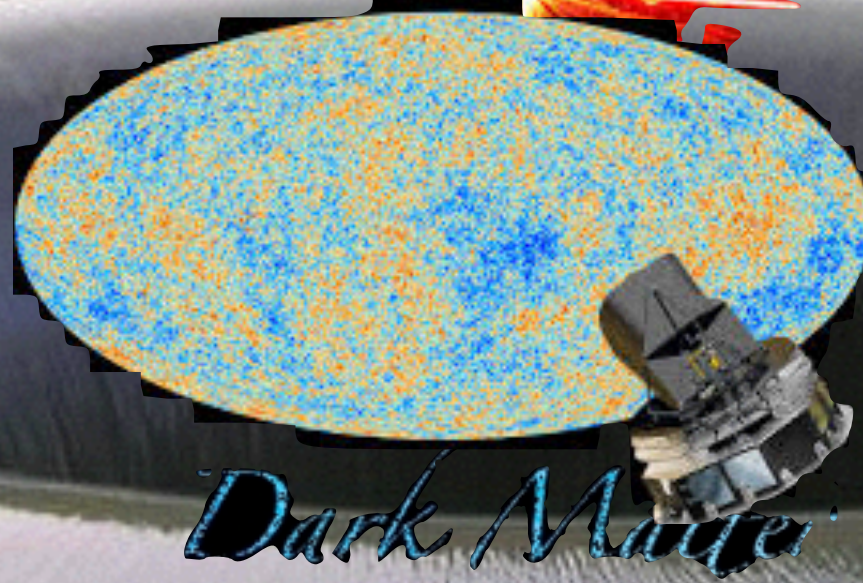
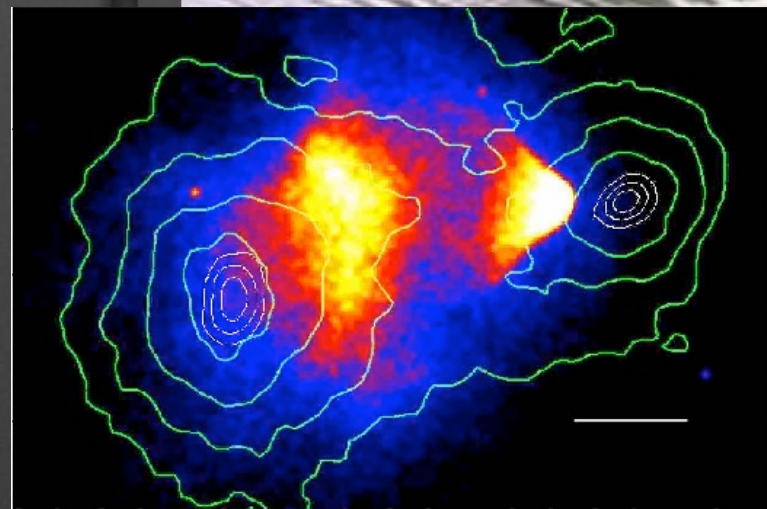




Parameter	<i>Planck</i>		<i>Planck+lensing</i>		<i>Planck+WP</i>		<i>Planck+WP+highL+BAO</i>	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68 % limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.0002	0.022161	0.02214 ± 0.00024
$\Omega_c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

Bl

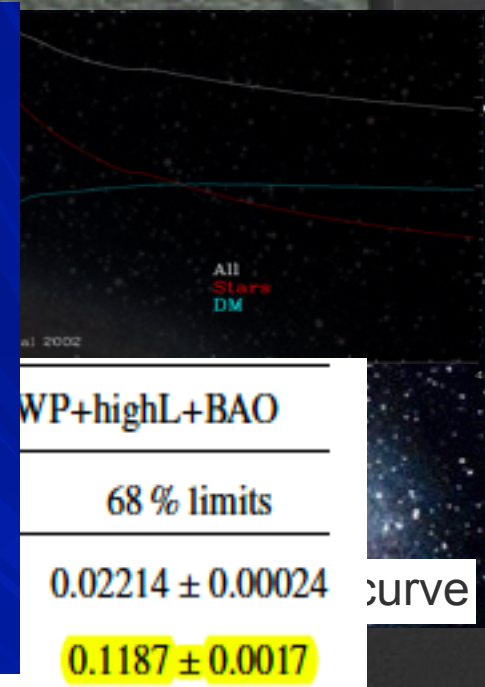
curve



- 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

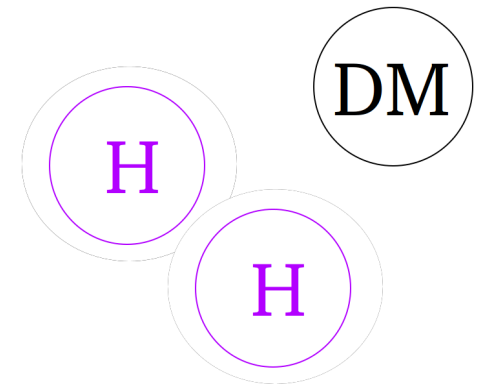


Parameter
$\Omega_b h^2$
$\Omega_c h^2$



WP+highL+BAO
68 % limits
0.02214 ± 0.00024
0.1187 ± 0.0017

2HDMS DM sector



- Add an extra gauge singlet S with $\langle S \rangle = 0$

	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:

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

an additional physical state

$$- (\kappa_1 \cos \alpha \cos \beta + \kappa_2 \sin \alpha \sin \beta) v h S^2$$

λ_h

$$- (-\kappa_1 \sin \alpha \cos \beta + \kappa_2 \cos \alpha \sin \beta) v H S^2$$

λ_H

NO AS^2 term !

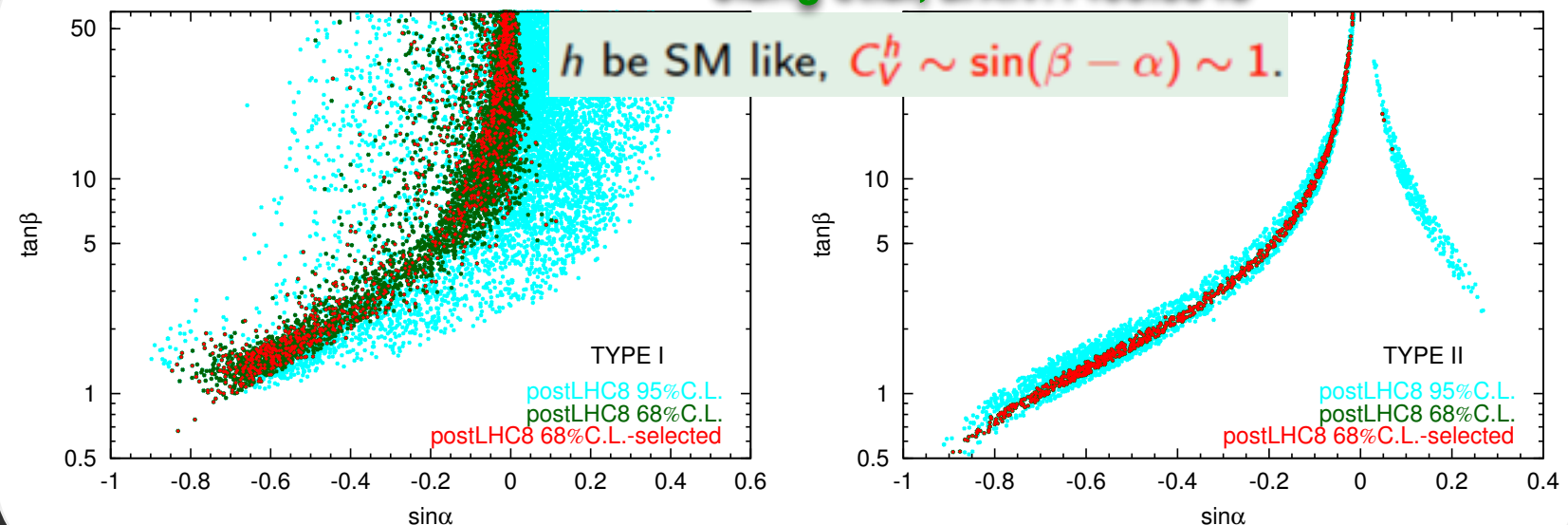
+ $(HH, hH, hh, AA, H^+ H^-) S^2$ terms

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

Interplay between Higgs & DM

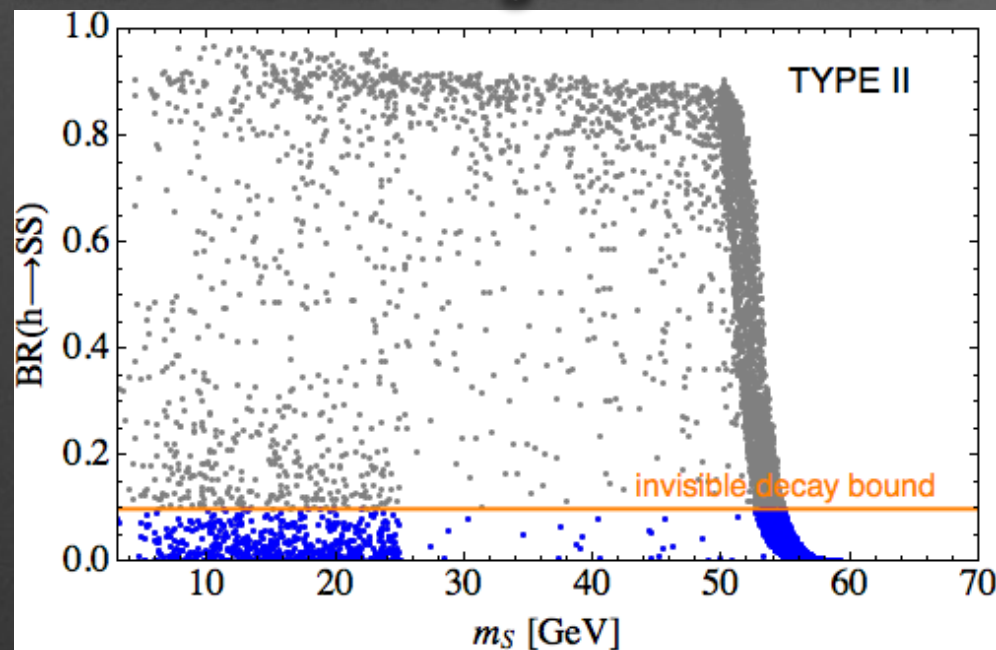
Interplay between Higgs & DM

Jiang et.al, arXiv:1405.3548



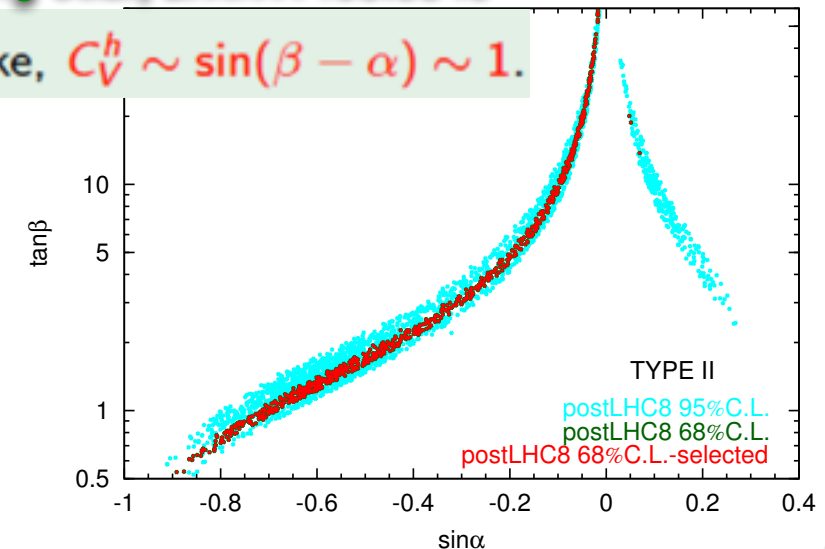
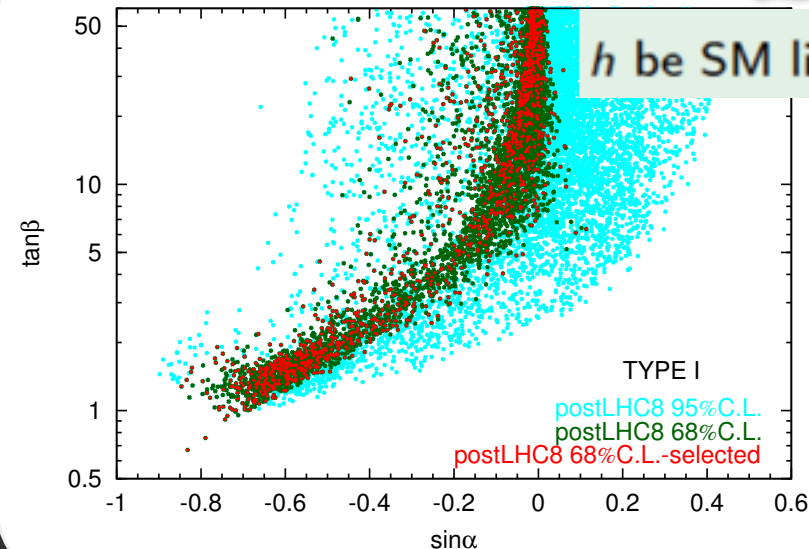
Interplay between Higgs & DM

when the m_S is lighter than $m_h/2$



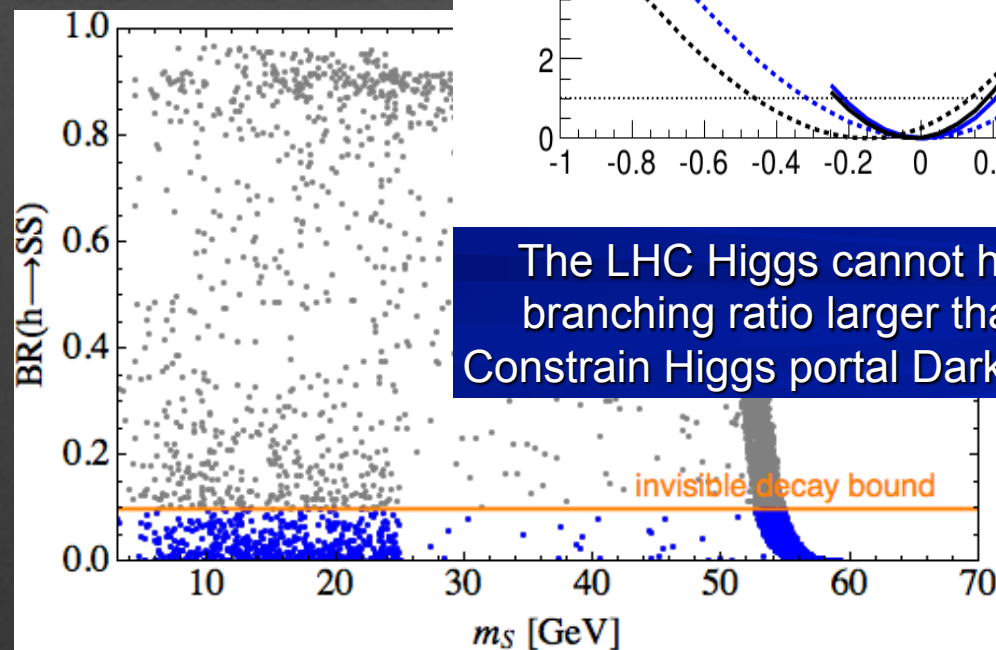
$$\Gamma(h \rightarrow SS) = \frac{1}{8\pi} \frac{\lambda_h^2 v^2}{m_h} \sqrt{1 - \frac{4m_S^2}{m_h^2}}$$

Jiang et.al, arXiv:1405.3548



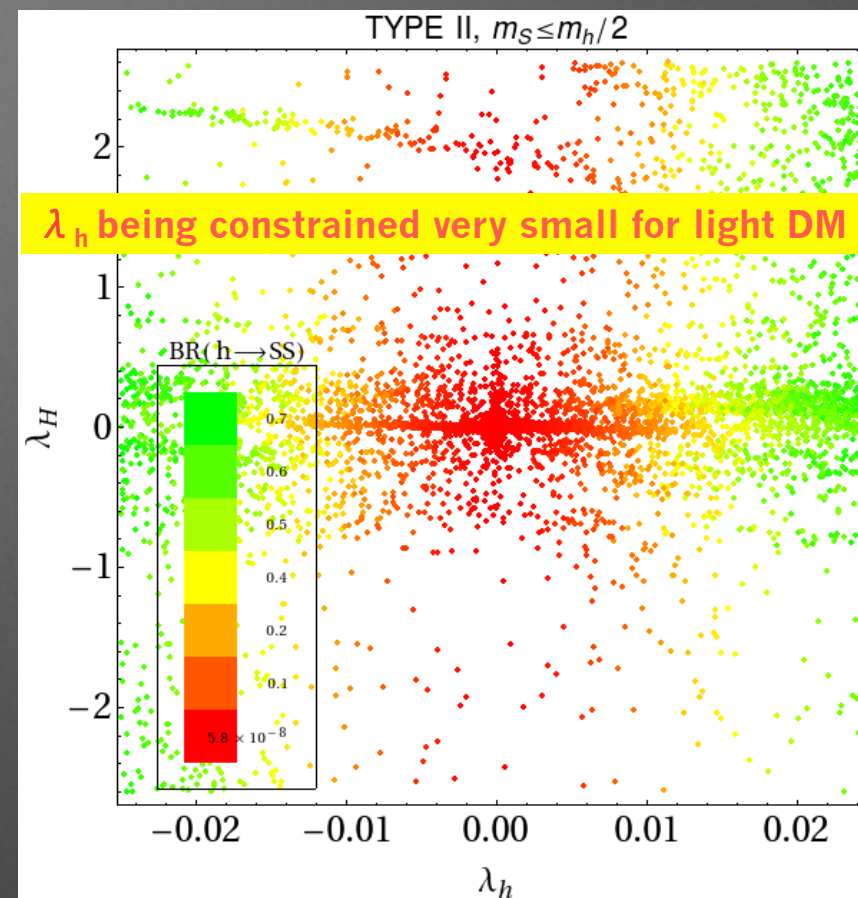
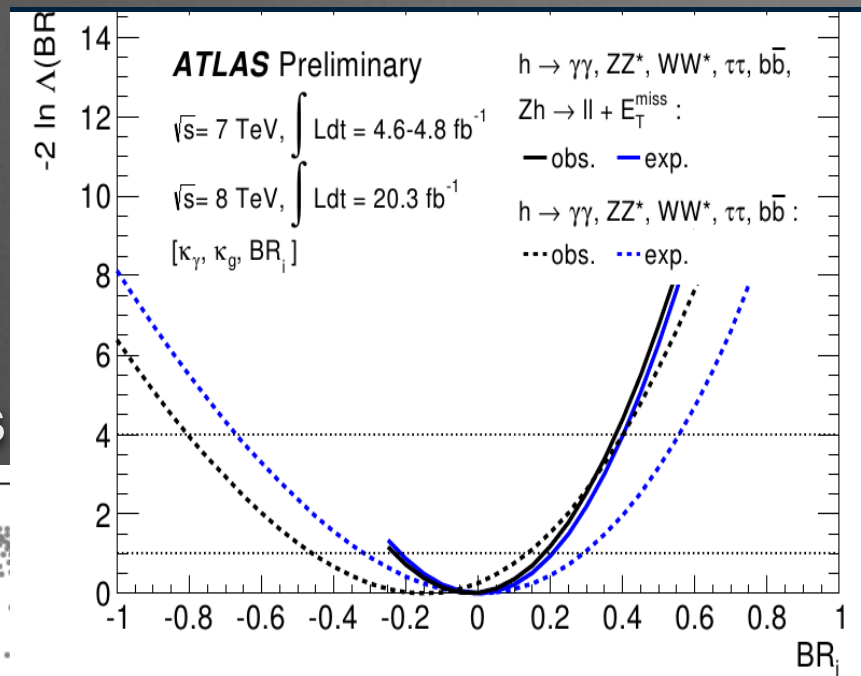
Interplay between Higgs & DM

when the m_S is

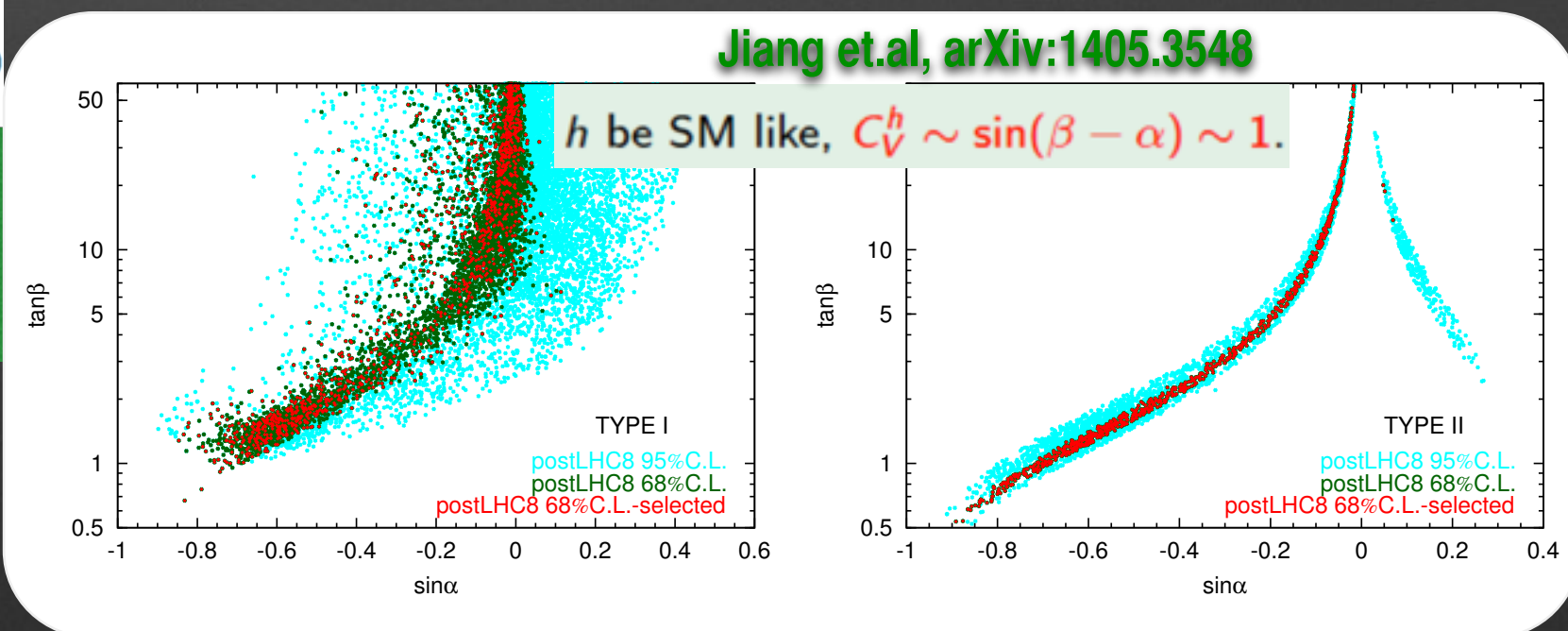


The LHC Higgs cannot have invisible branching ratio larger than 20 ~ 30%!
Constrain Higgs portal Dark Matter models.

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



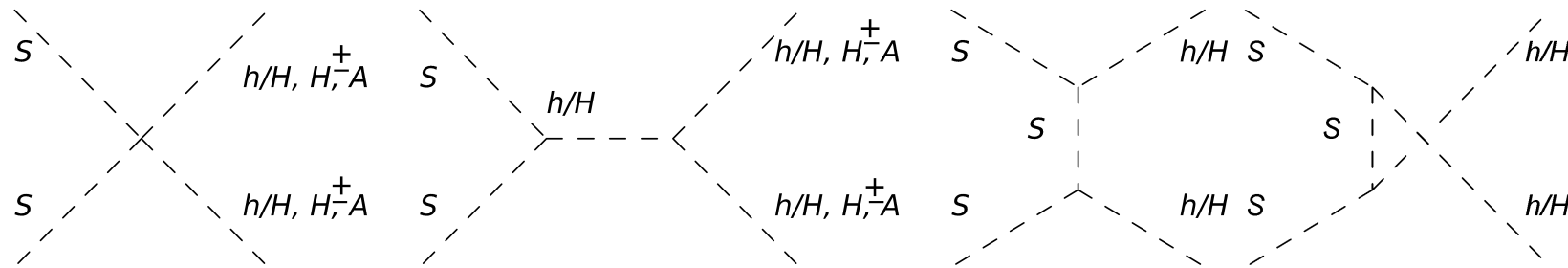
Jiang et.al, arXiv:1405.3548



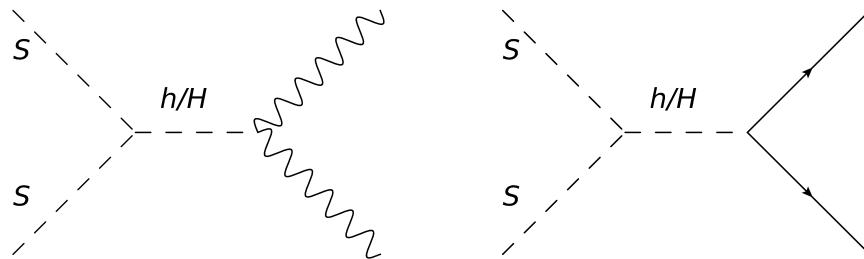
DM Physics

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

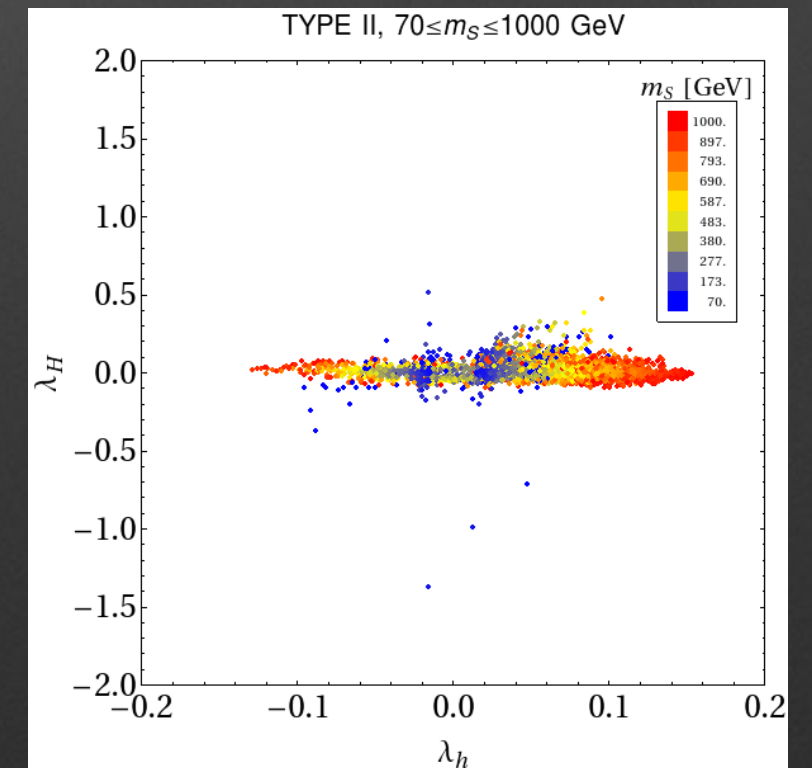
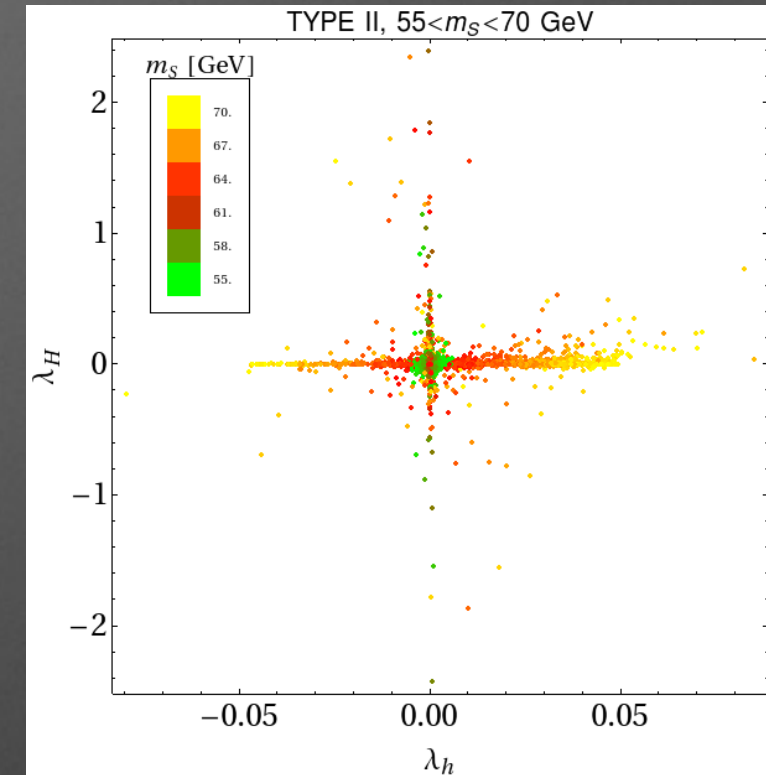
DM interaction



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



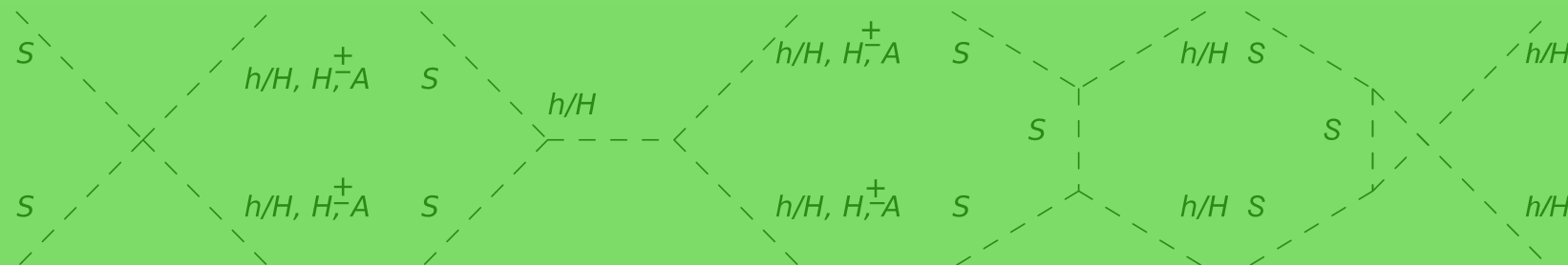
$$\langle \sigma_{SS \rightarrow X \bar{X}} v_{\text{rel}} \rangle = \sum_{\mathcal{H}=h,H} \left| \frac{g_{\mathcal{H}SS} C_X^{\mathcal{H}}}{4m_S^2 - m_{\mathcal{H}}^2 + i\Gamma_{\mathcal{H}} m_{\mathcal{H}}} \right|^2 \frac{\Gamma_{\text{SM}}(\mathcal{H}^* \rightarrow X \bar{X})}{2m_S}$$



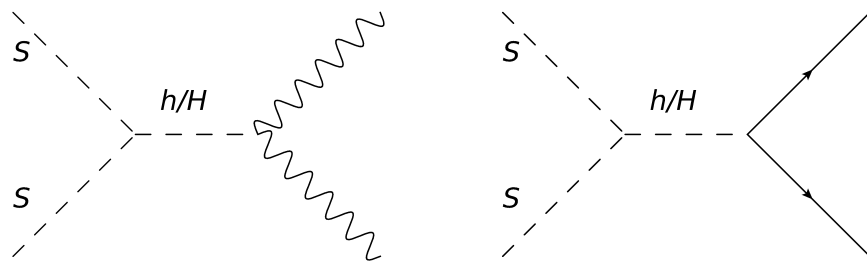
DM Physics

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

DM interaction



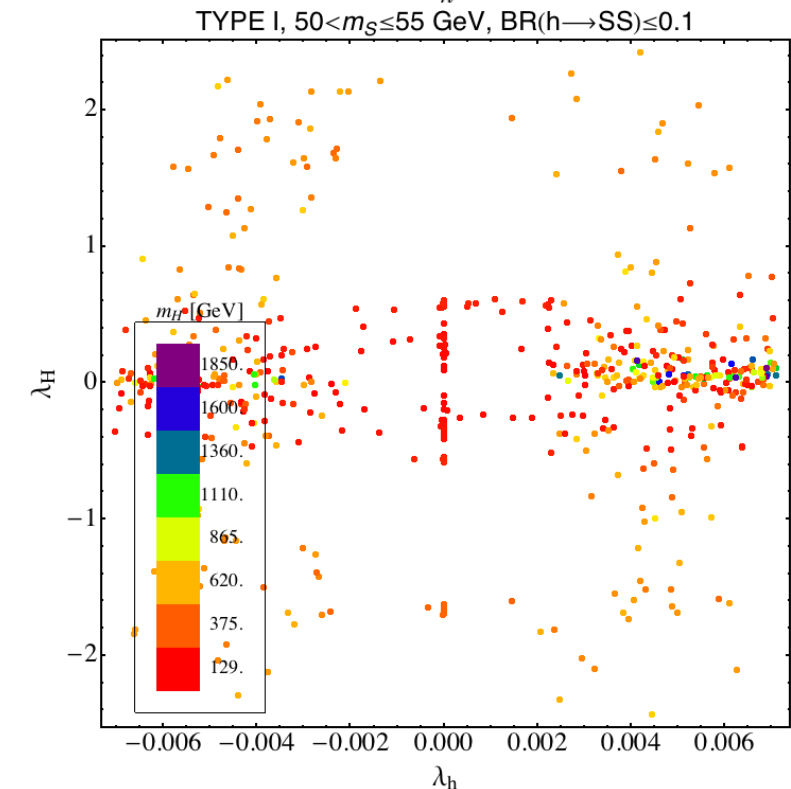
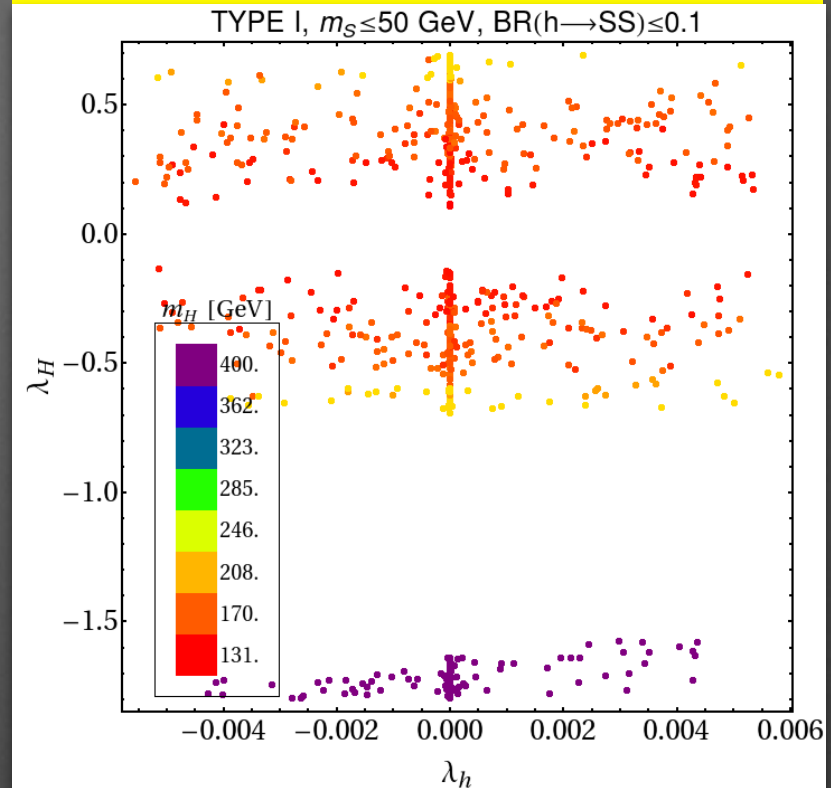
$$\langle \sigma_{SS \rightarrow H_i H_j} v_{\text{rel}} \rangle = \frac{\beta(m_{H_i}, m_{H_j})}{32(1 + \delta_{ij})\pi m_S^2} \left| g_{H_i H_j SS} + \sum_{\mathcal{H}=h,H} \frac{g_{\mathcal{H}SS} g_{\mathcal{H}H_i H_j}}{4m_S^2 - m_{\mathcal{H}}^2 + i\Gamma_{\mathcal{H}} m_{\mathcal{H}}} + 2\delta_{CP}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



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

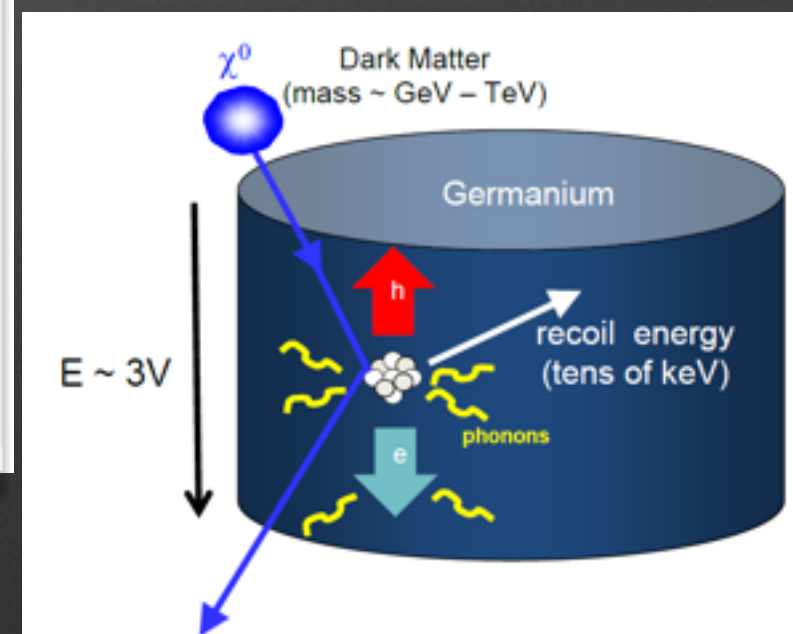
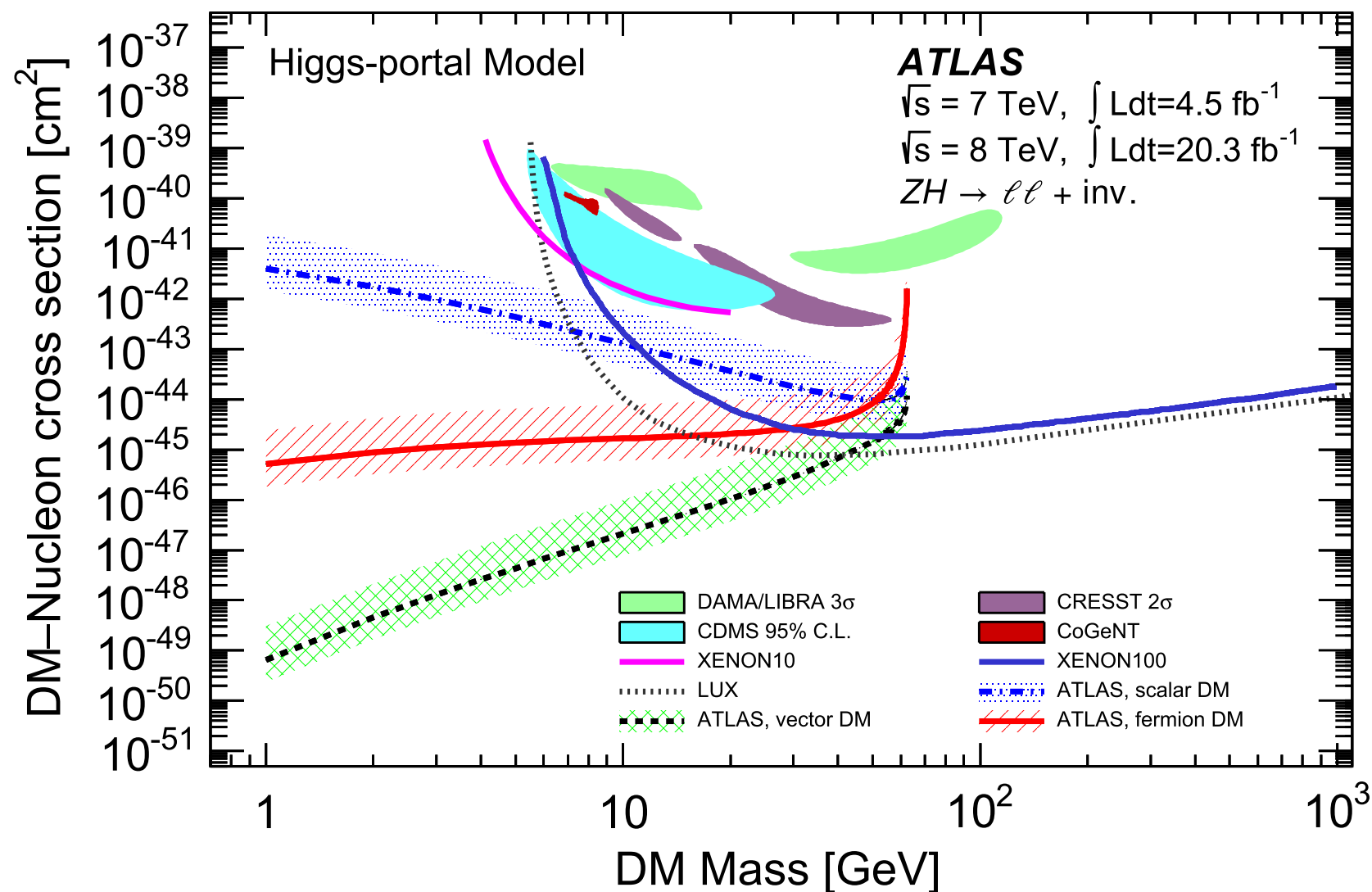
light DM :

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



DM Direct detection

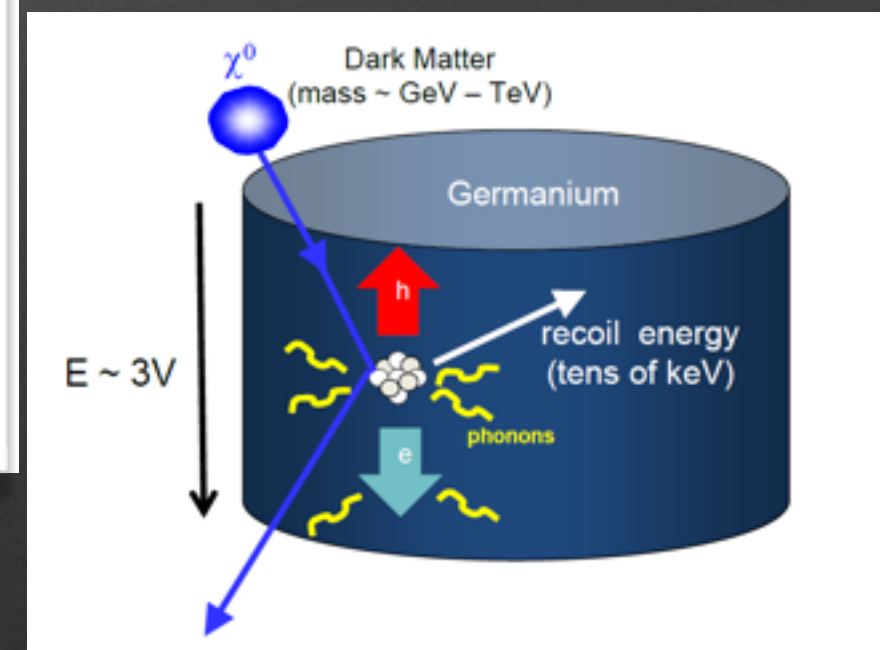
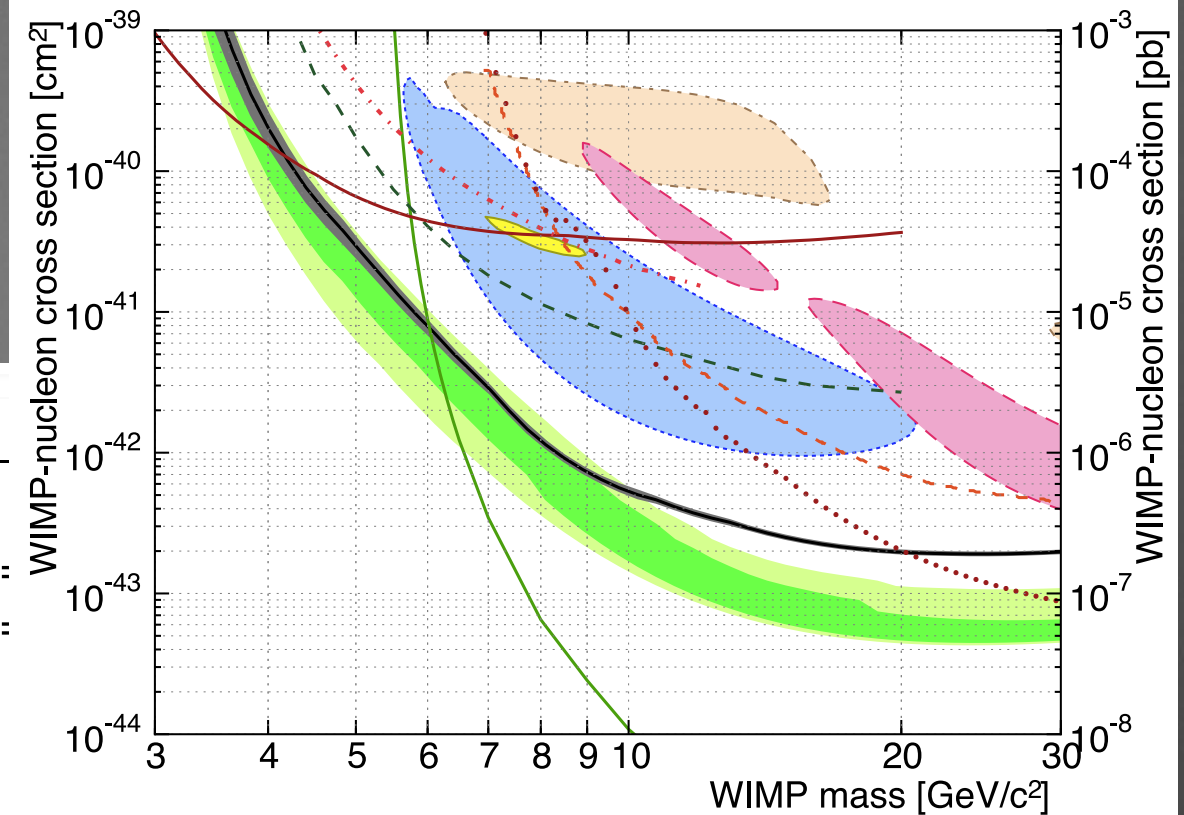
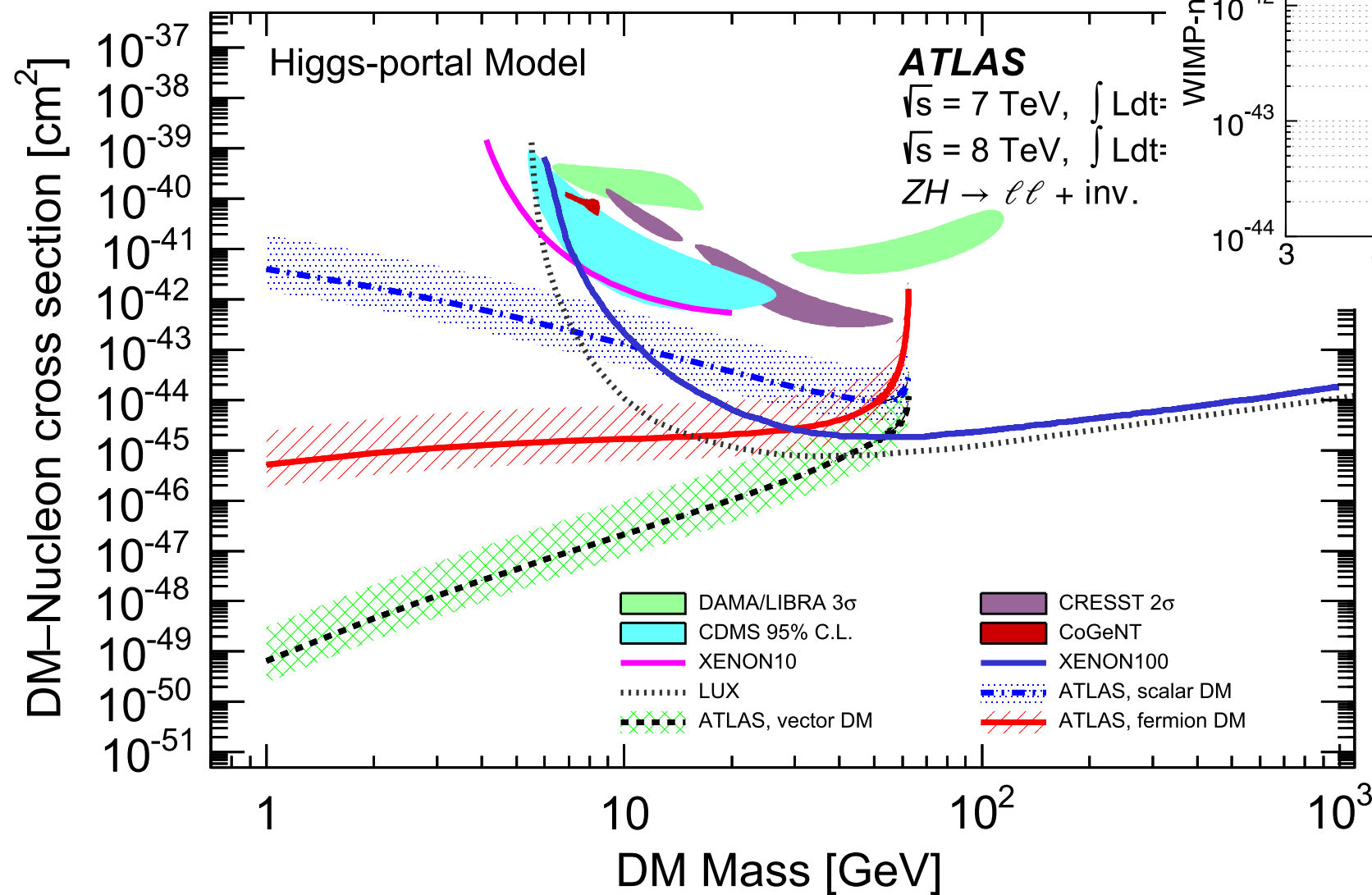
Assume $f_n = f_p$



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

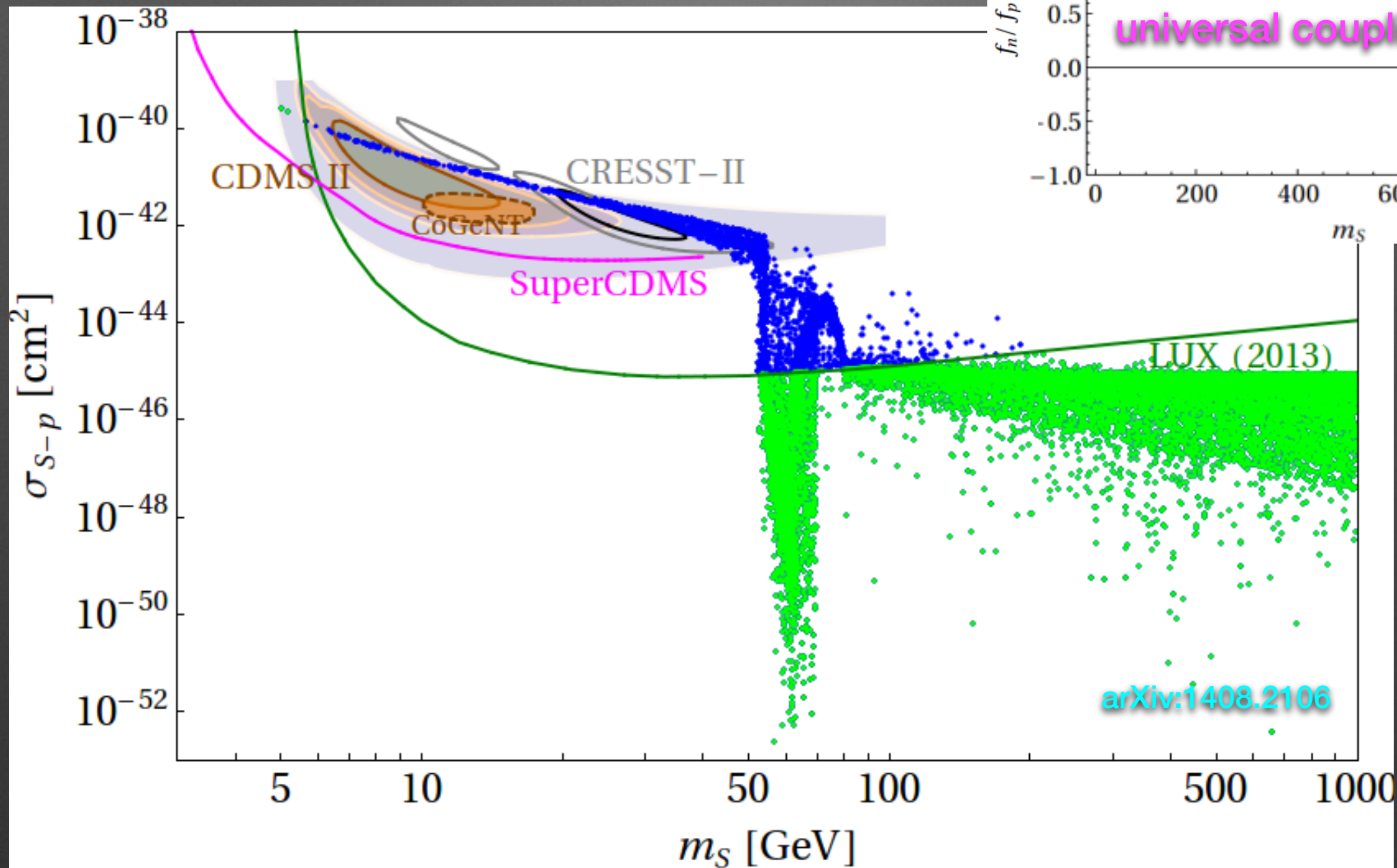
DM Direct detection

Assume $f_n = f_p$



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

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.
- $m_S \gtrsim 55$ GeV region: the majority of points pass the LUX limit.

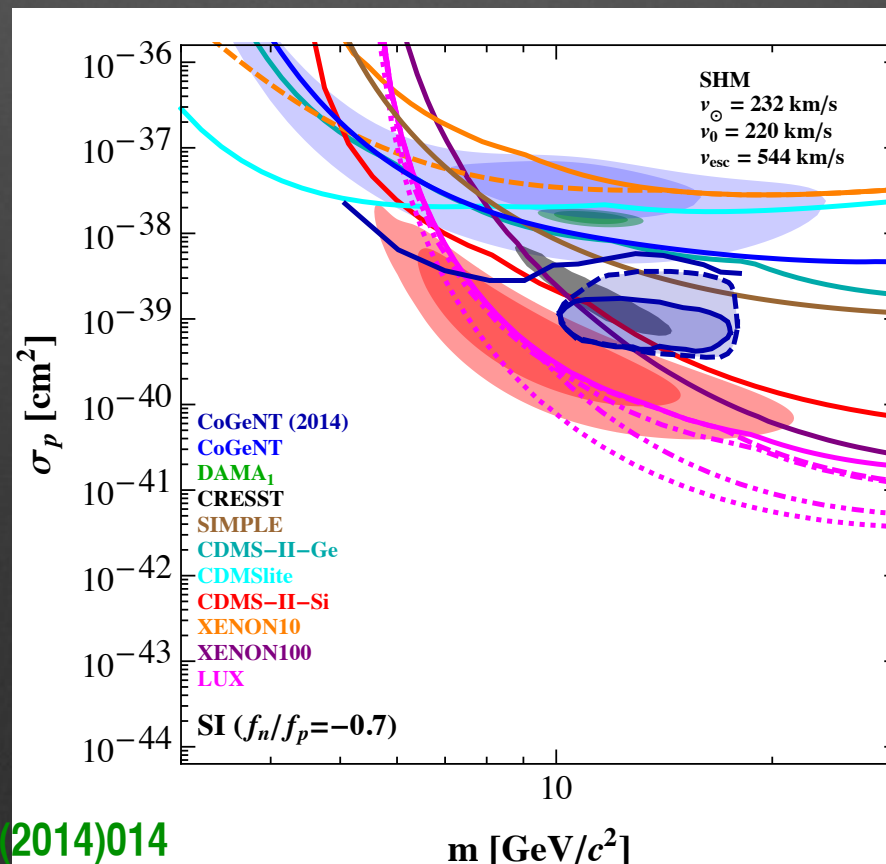
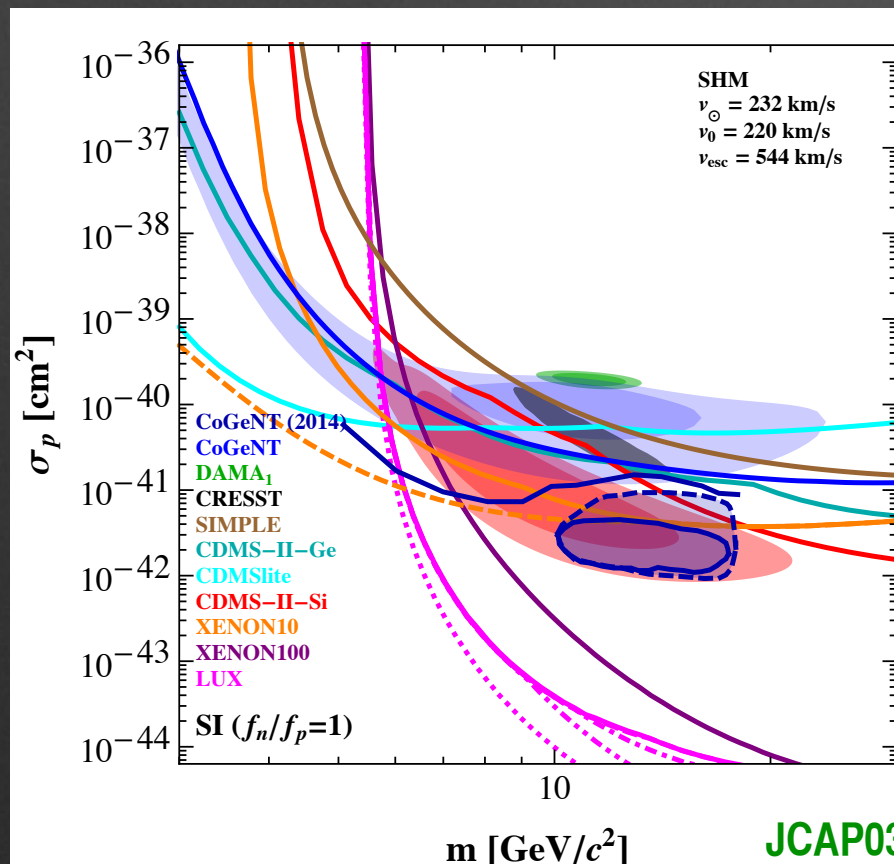
Isospin violating effect

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, $\bar{\sigma}_{\text{DM}-p}$, following [8]:

$$\bar{\sigma}_{\text{DM}-p} = \sigma_{\text{DM}-p} \Theta(f_n, f_p) \quad (21)$$

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

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



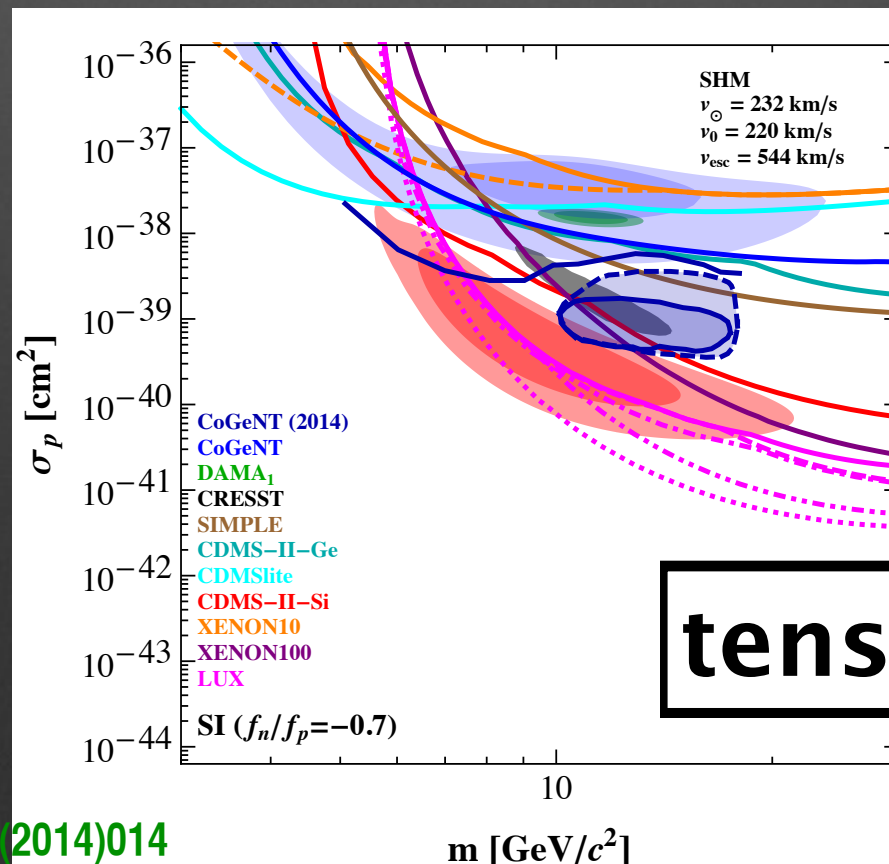
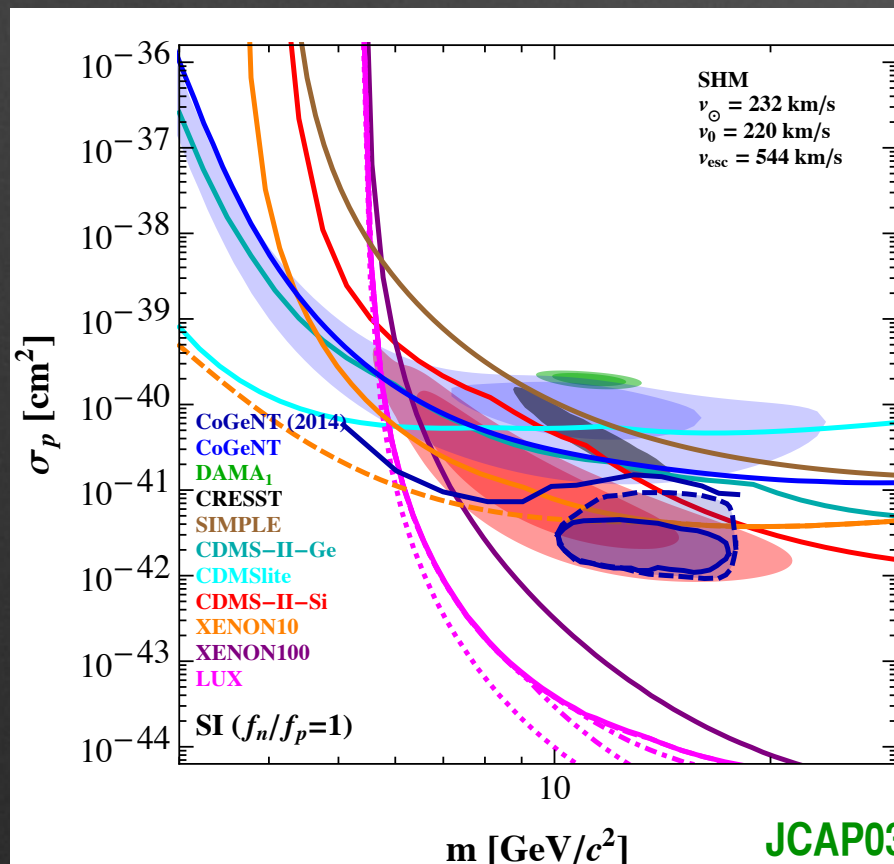
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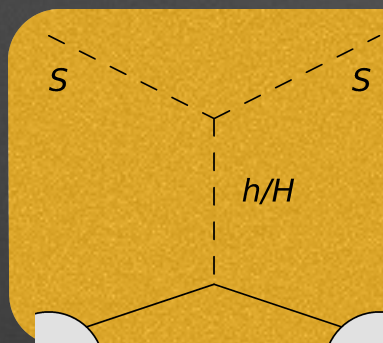


tension alleviated

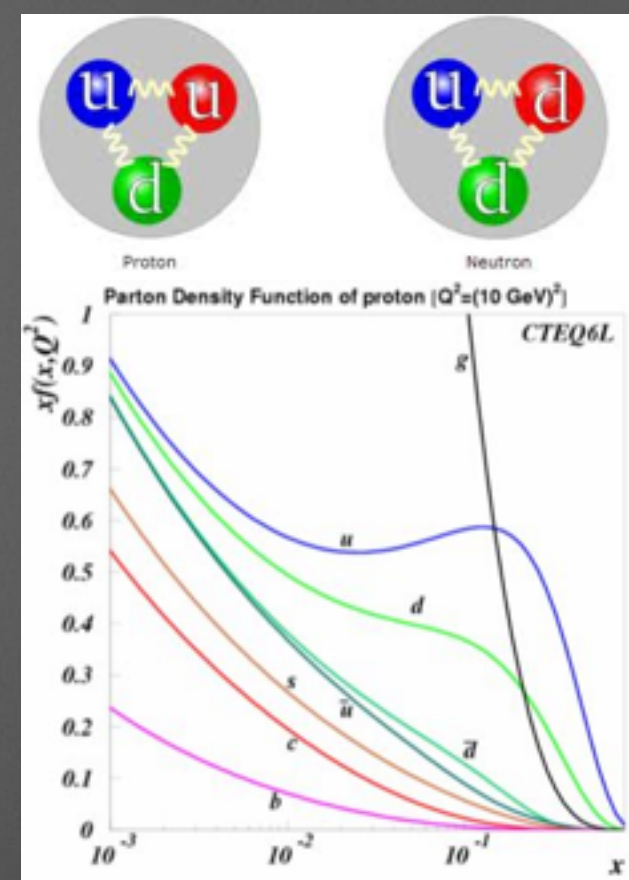
Isospin violating effect

► Isospin violation is found only in couplings to up and down **Quark-Level Realization**

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



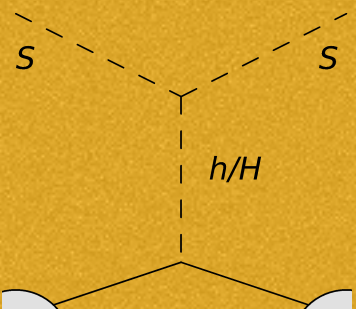
$$\lambda_{SSqq} = - \left(\frac{\lambda_h}{m_h^2} \xi_q^h + \frac{\lambda_H}{m_H^2} \xi_q^H \right) m_q$$



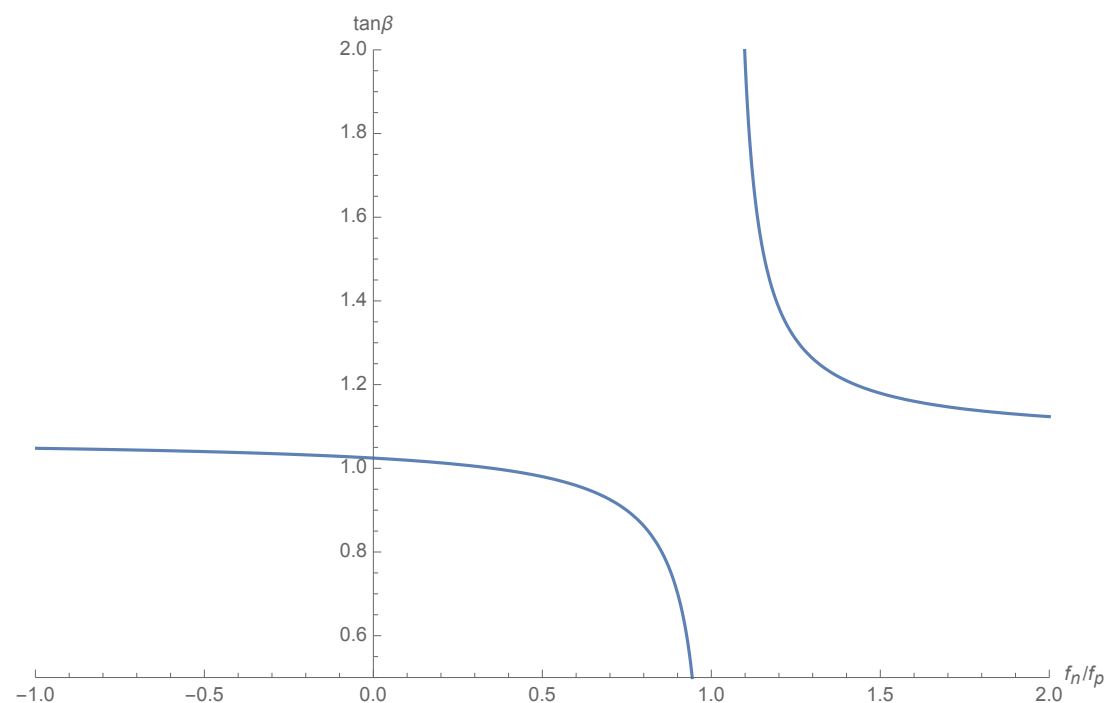
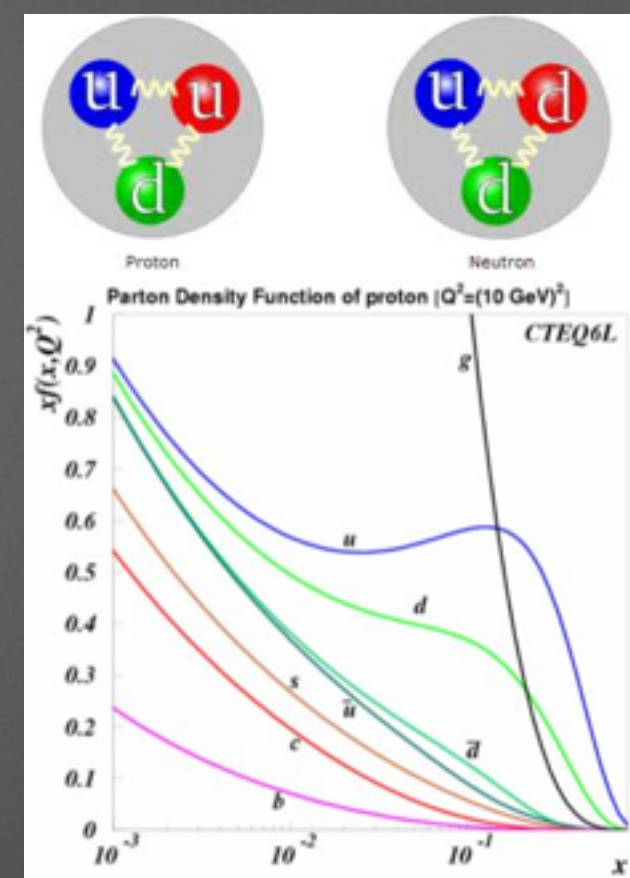
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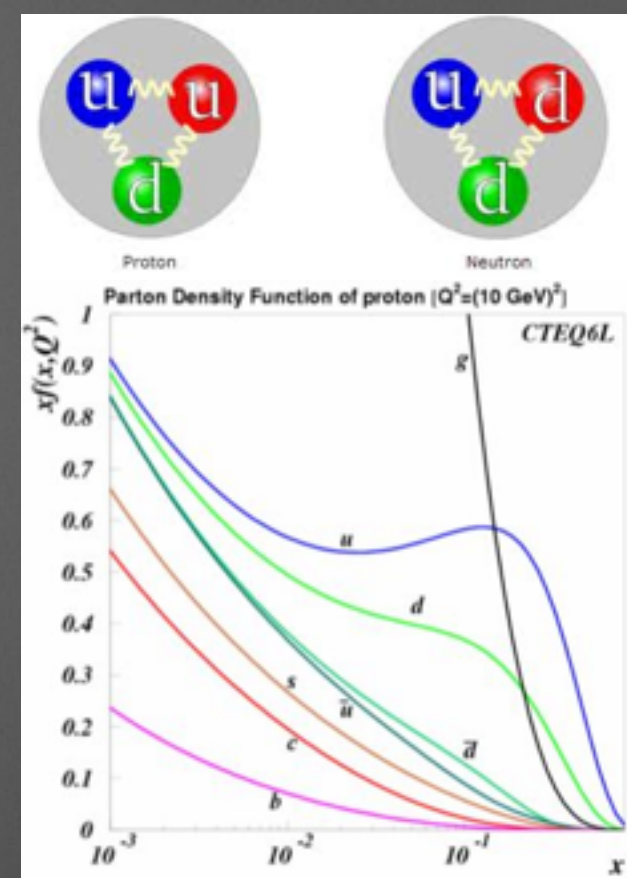
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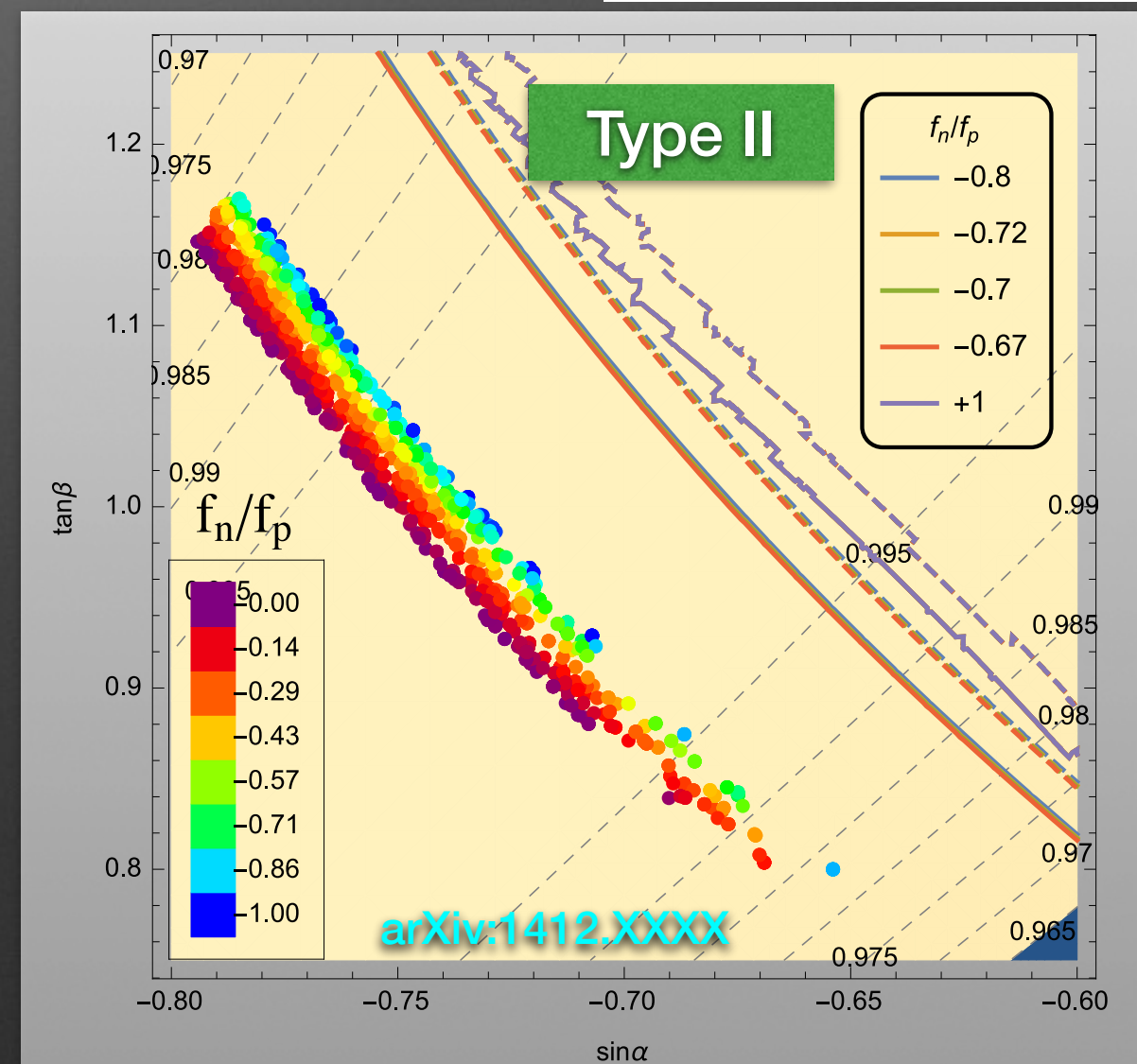
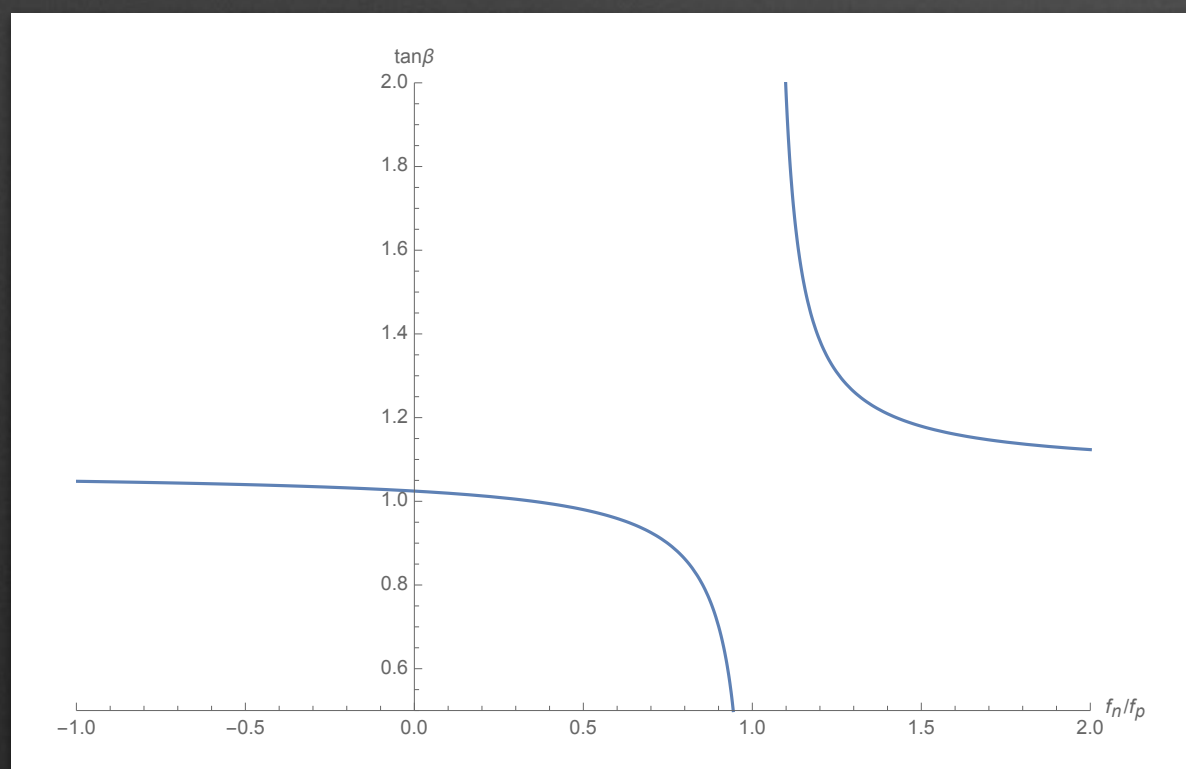
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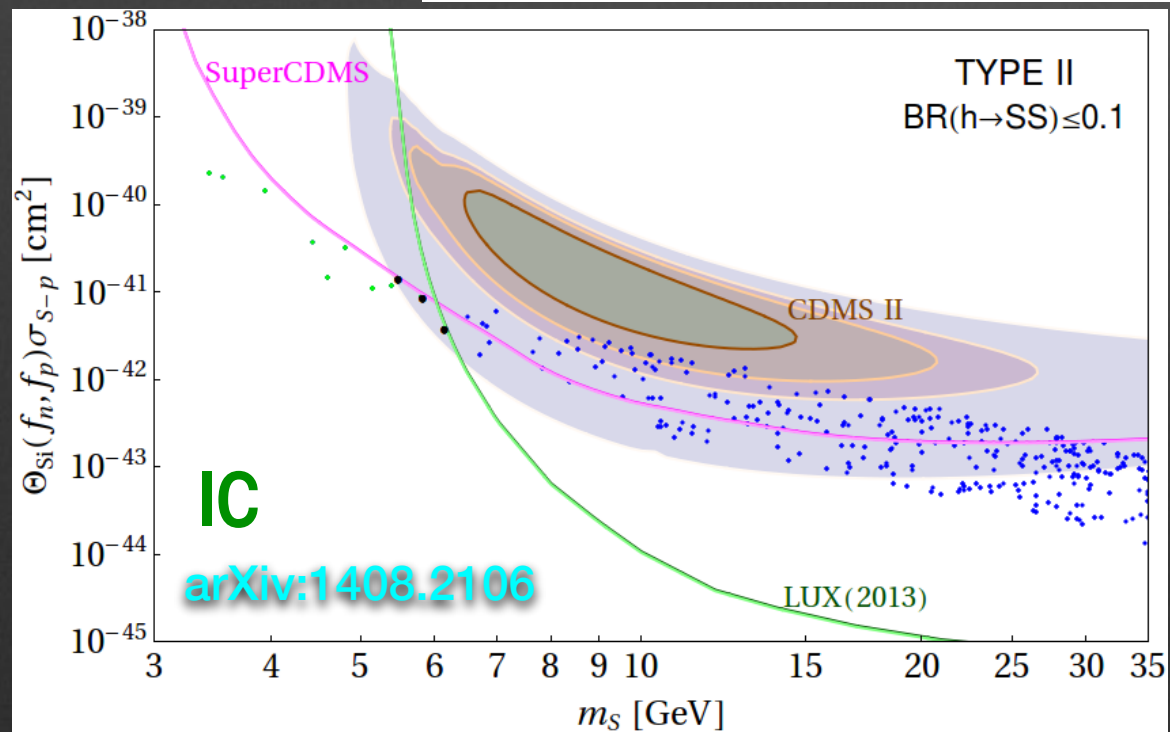
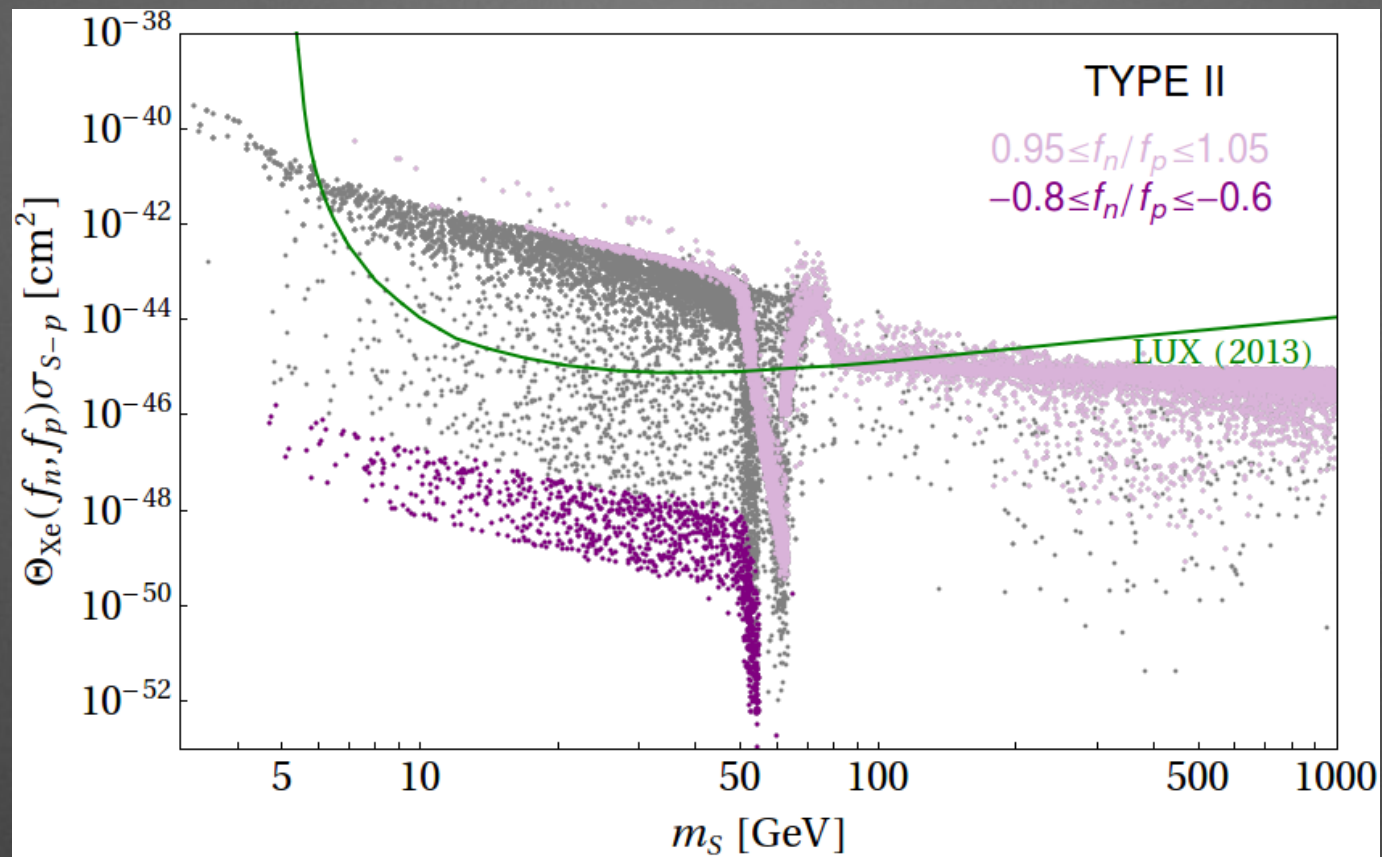


The diagram shows a scalar particle h/H coupling to two scalars S . The coupling is represented by a vertex with two external lines labeled S and one internal line labeled h/H .

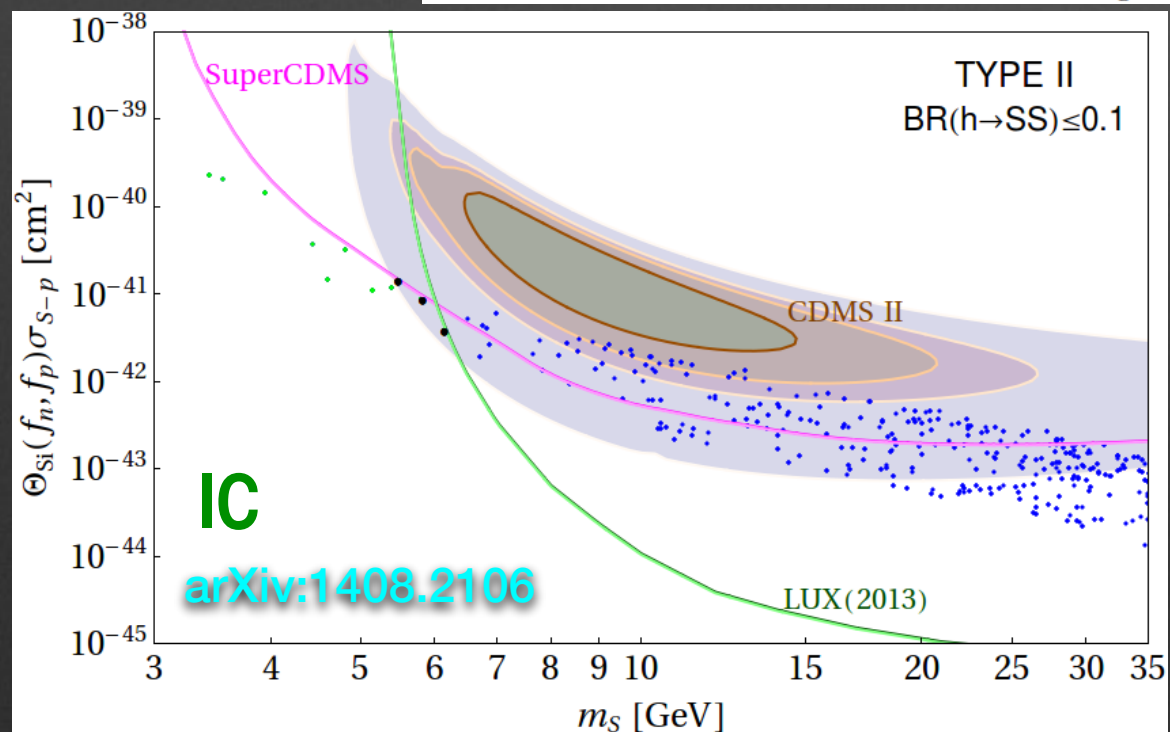
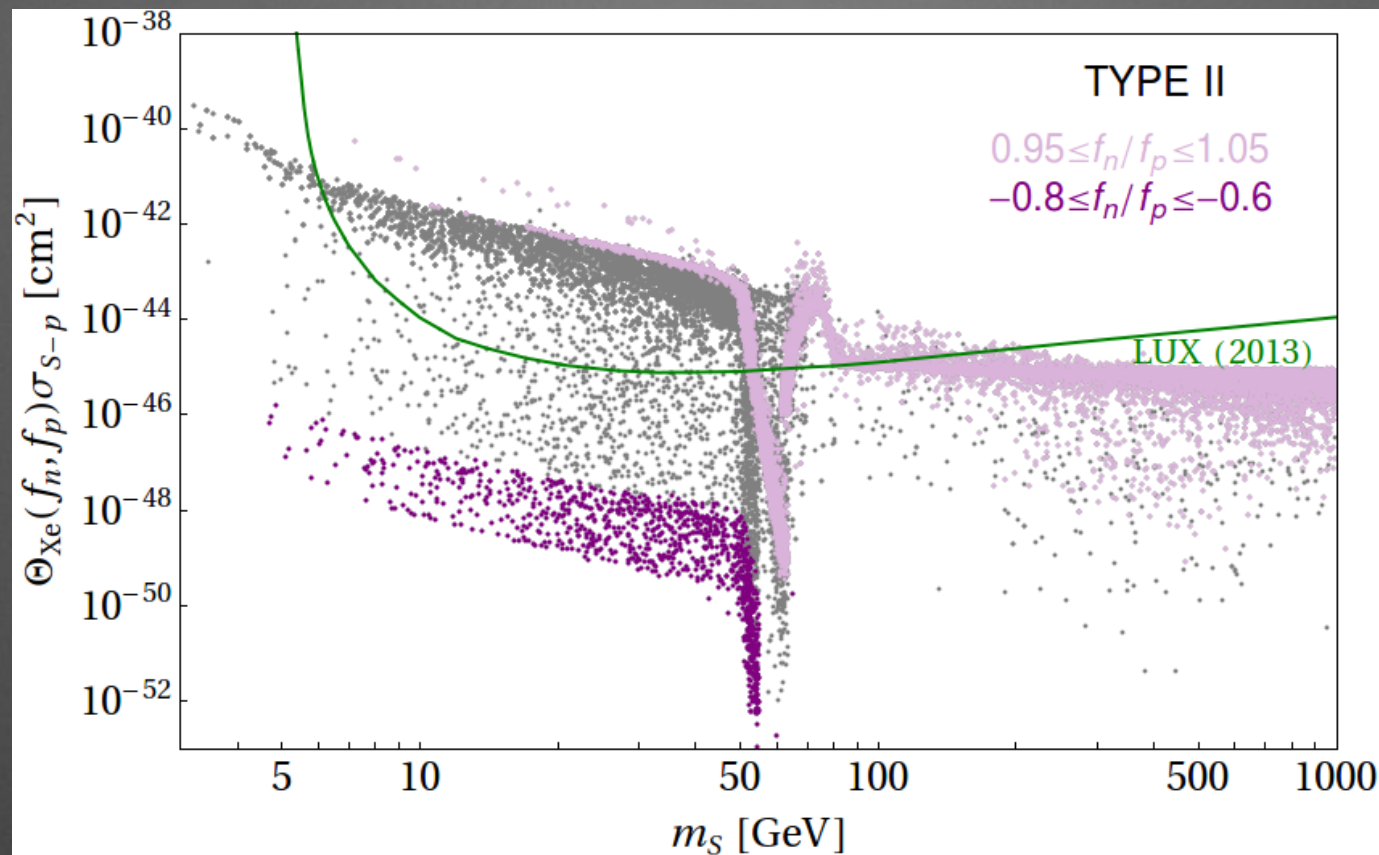
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Type II is more attractive

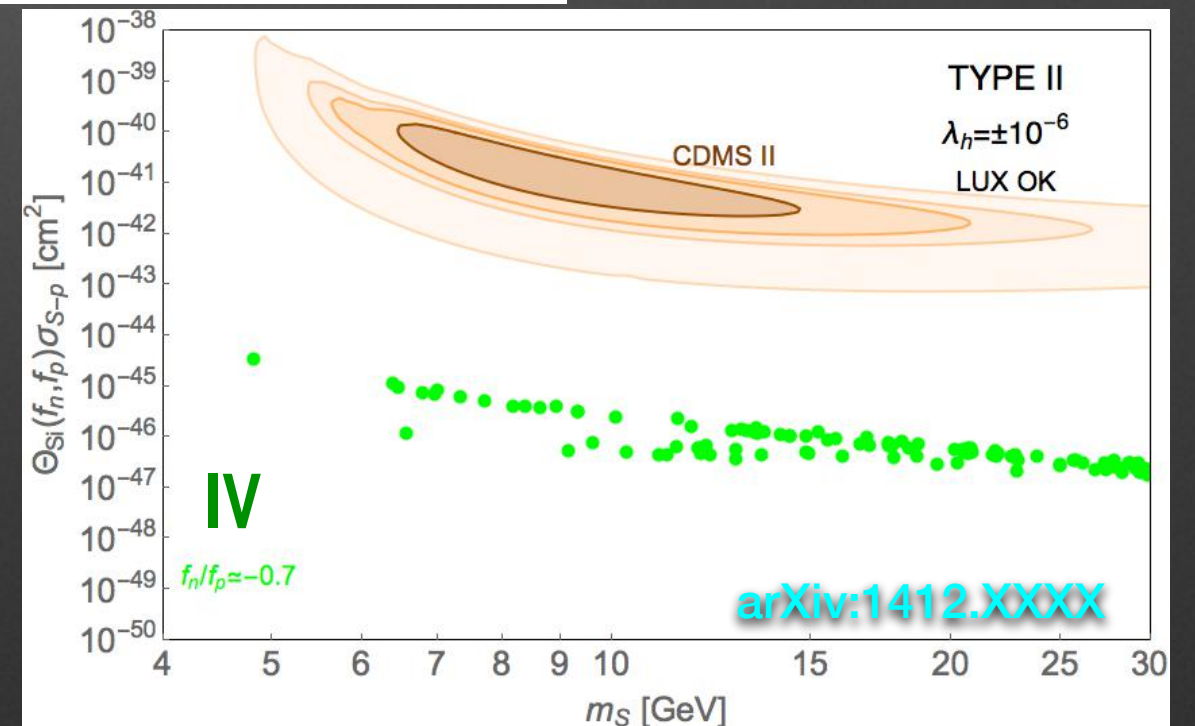
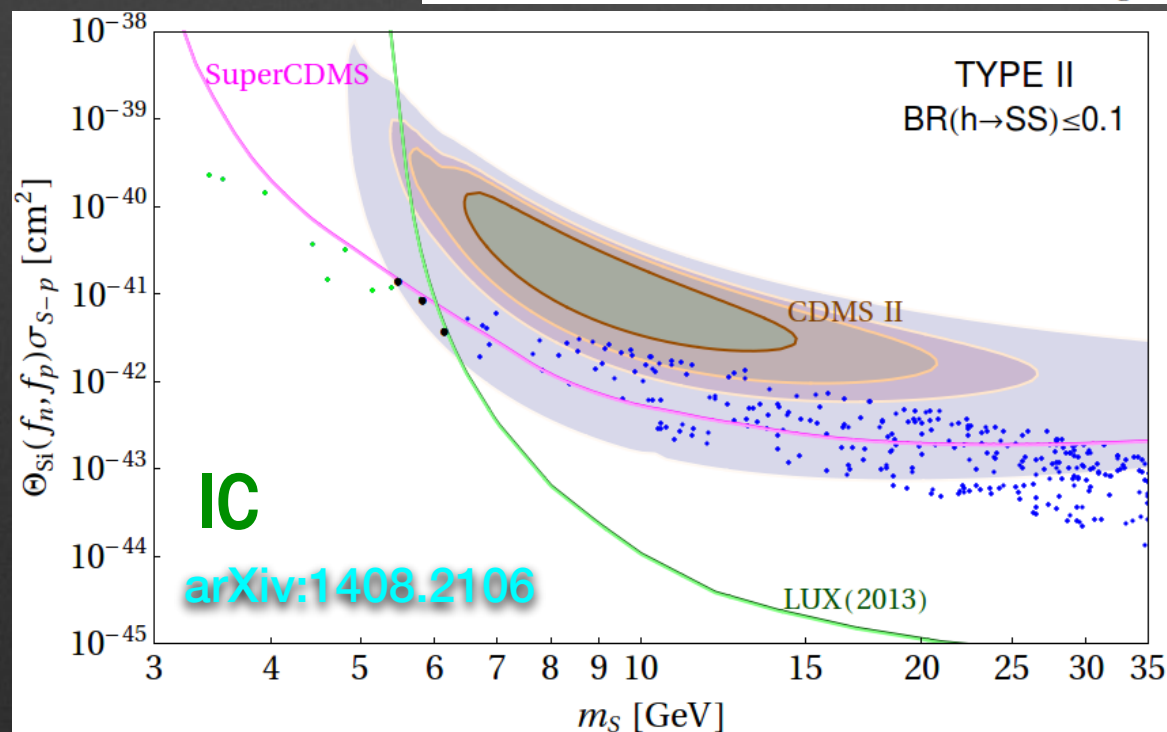
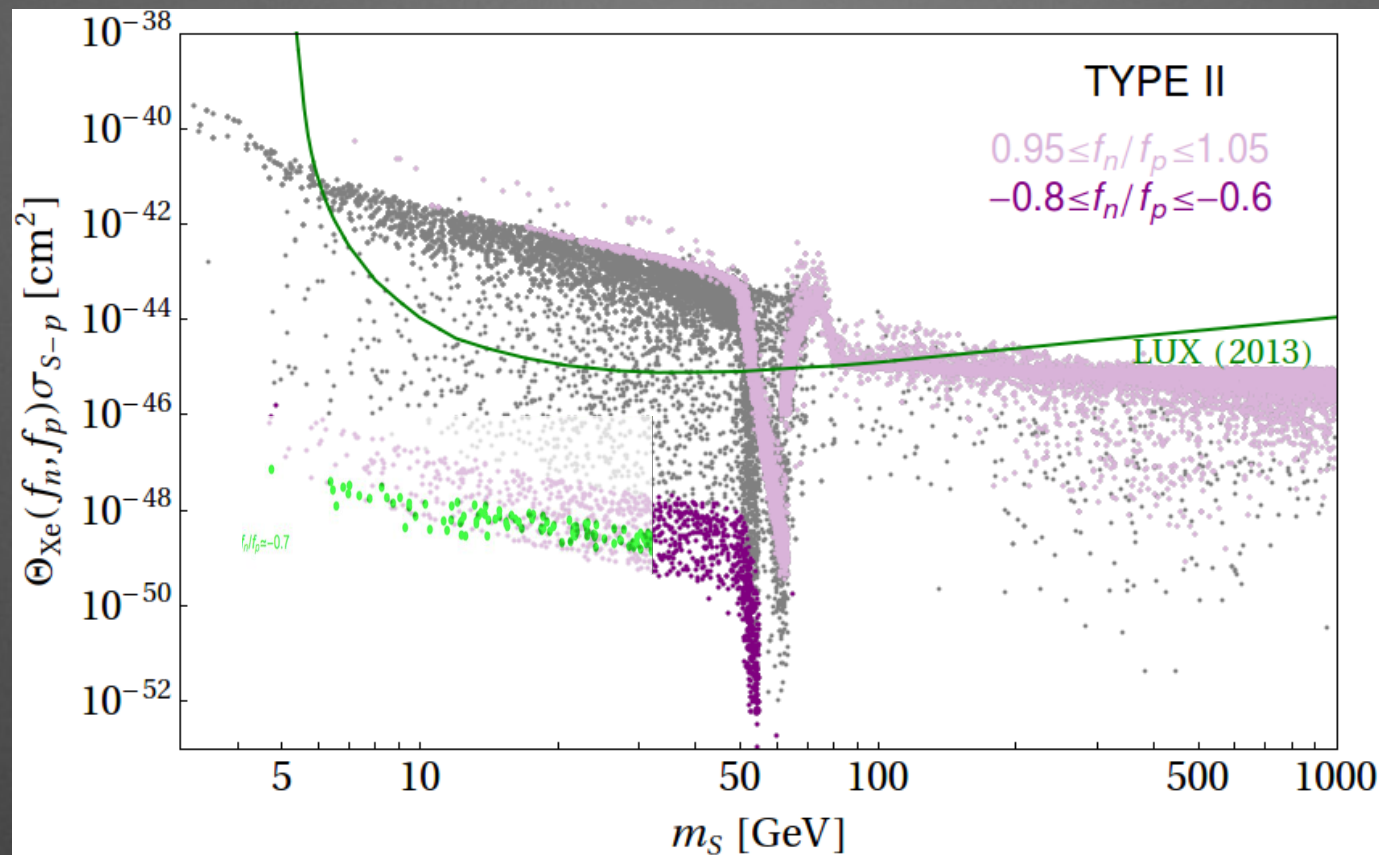


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A light DM with mass 6-55 GeV strongly challenged by XENON/
LUX null result, but could be consistent with CDMS-II data

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A light DM with mass 6-55 GeV strongly challenged by XENON/
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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

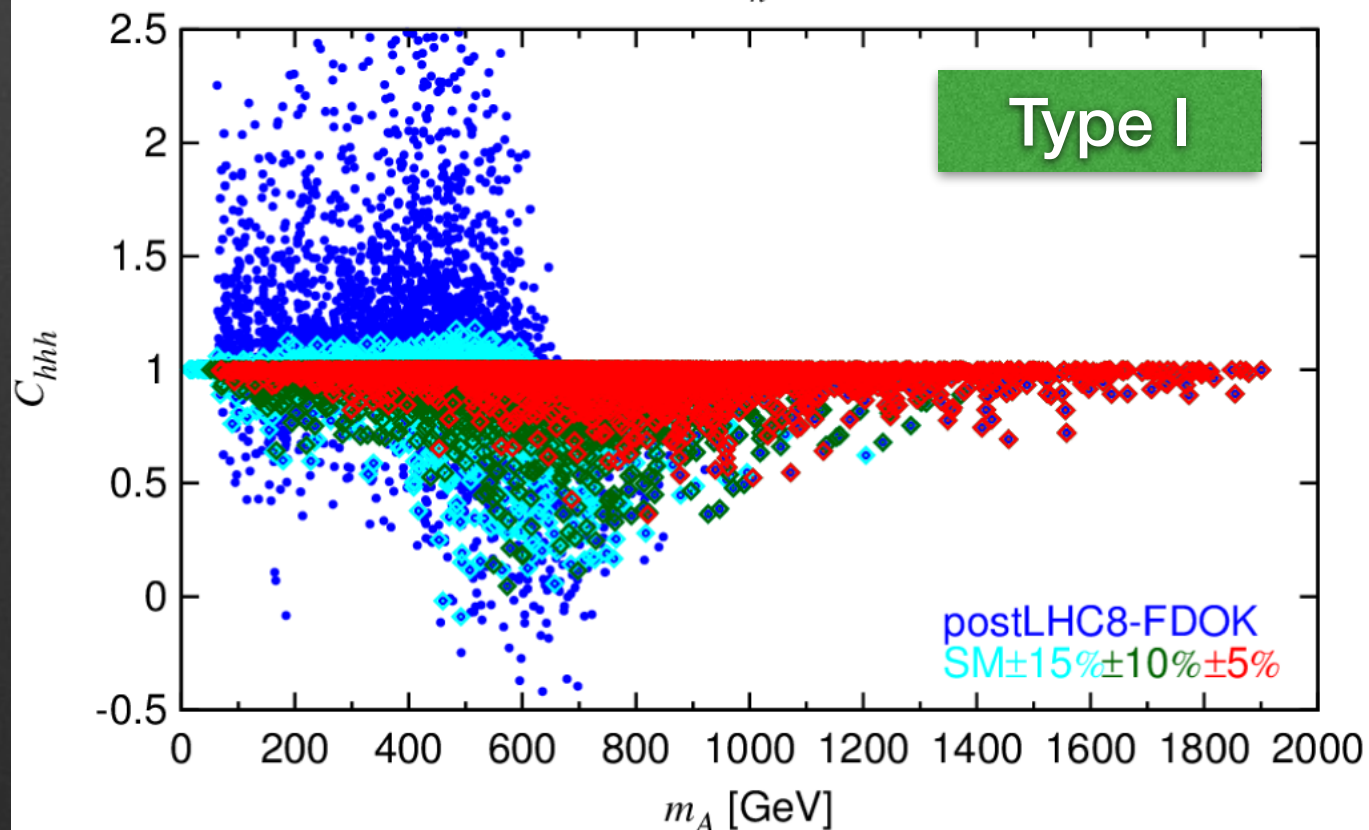
	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L} dt$ (fb $^{-1}$)	3000	3000	3000
$\sigma \cdot \text{BR}(pp \rightarrow HH \rightarrow bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

SPPC

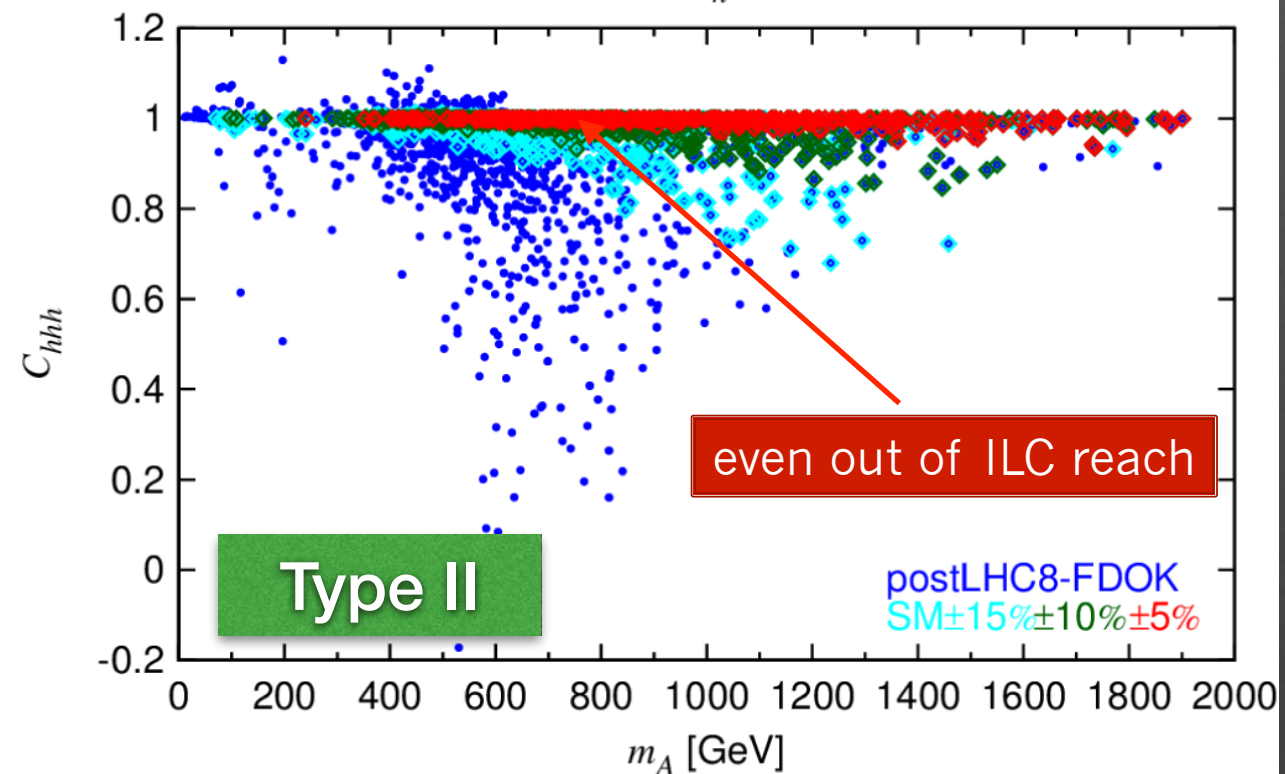
	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC1400	CLIC3000
$\sqrt{s}$ (GeV)	500	500	500/1000	500/1000	1400	3000
$\int \mathcal{L} dt$ (fb $^{-1}$)	500	1600 †	500+1000	1600+2500 †	1500	+2000
$P(e^-, e^+)$	(-0.8, 0.3)	(-0.8, 0.3)	(-0.8, 0.3/0.2)	(-0.8, 0.3/0.2)	(0, 0)/(-0.8, 0)	(0, 0)/(-0.8, 0)
$\sigma(ZHH)$	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

2HDMfit (typel) $m_h=125.5\pm 2.5$ GeV



2HDMfit (typell) $m_h=125.5\pm 2.5$ GeV



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

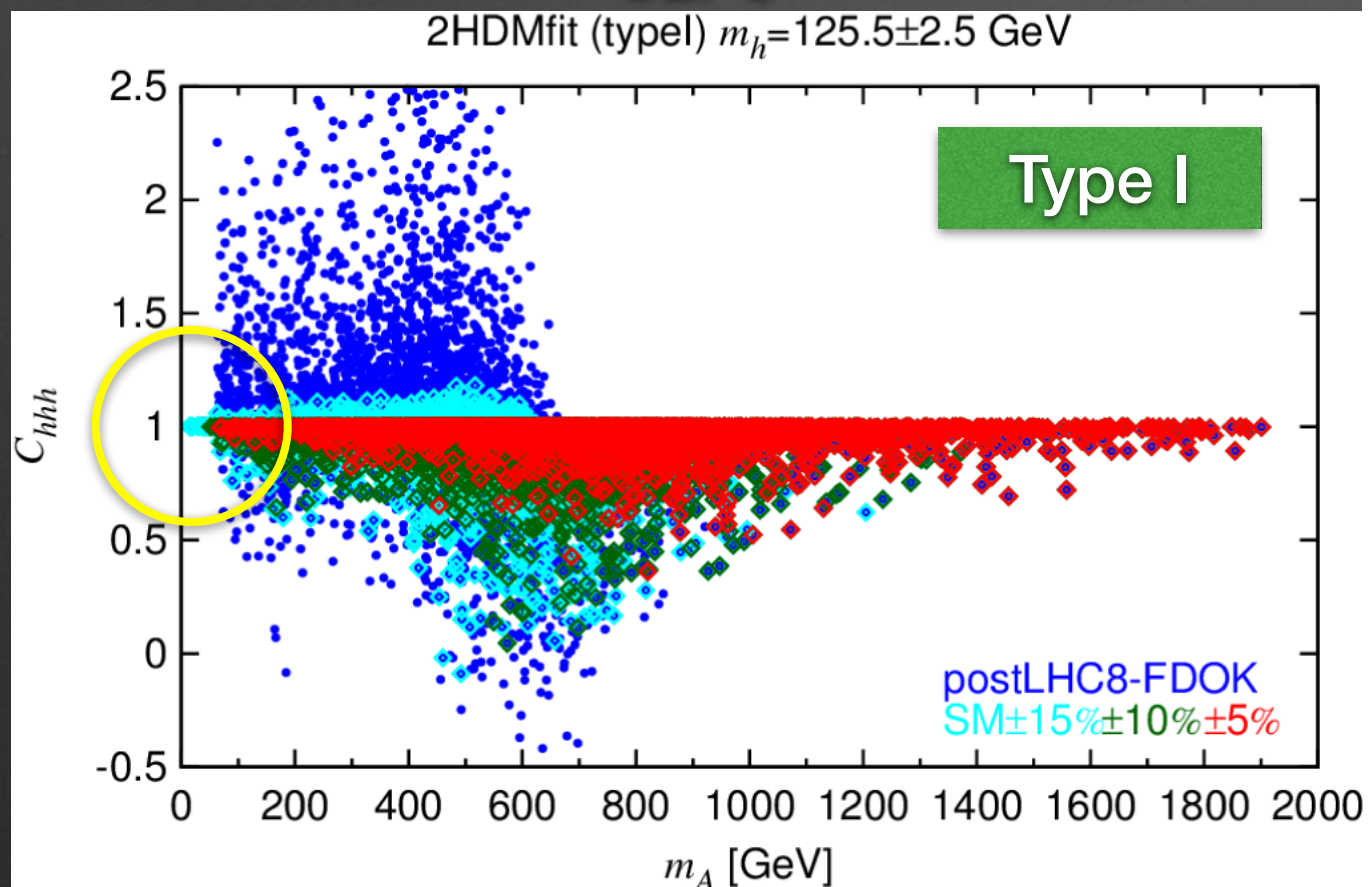
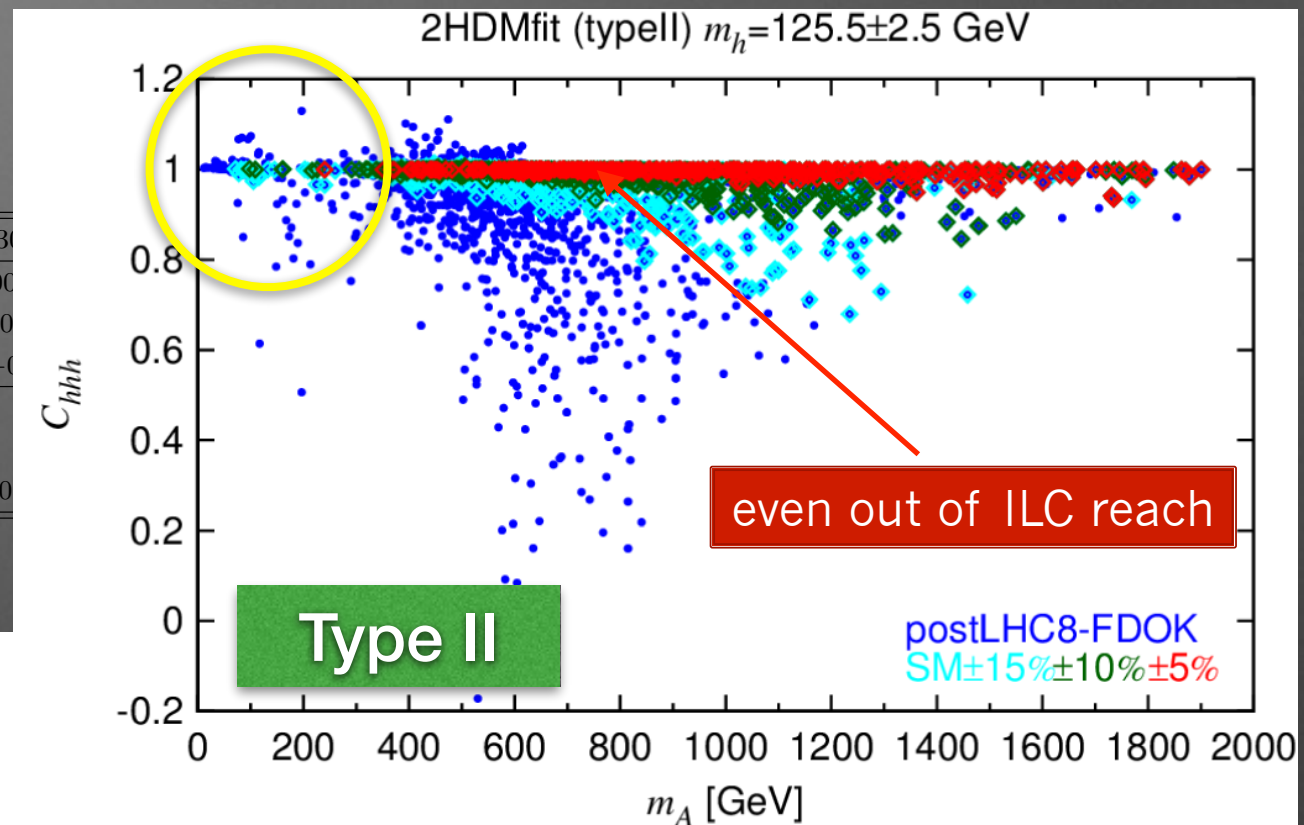
h~125-Triple h coupling

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CEPC



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H~125-Triple H coupling

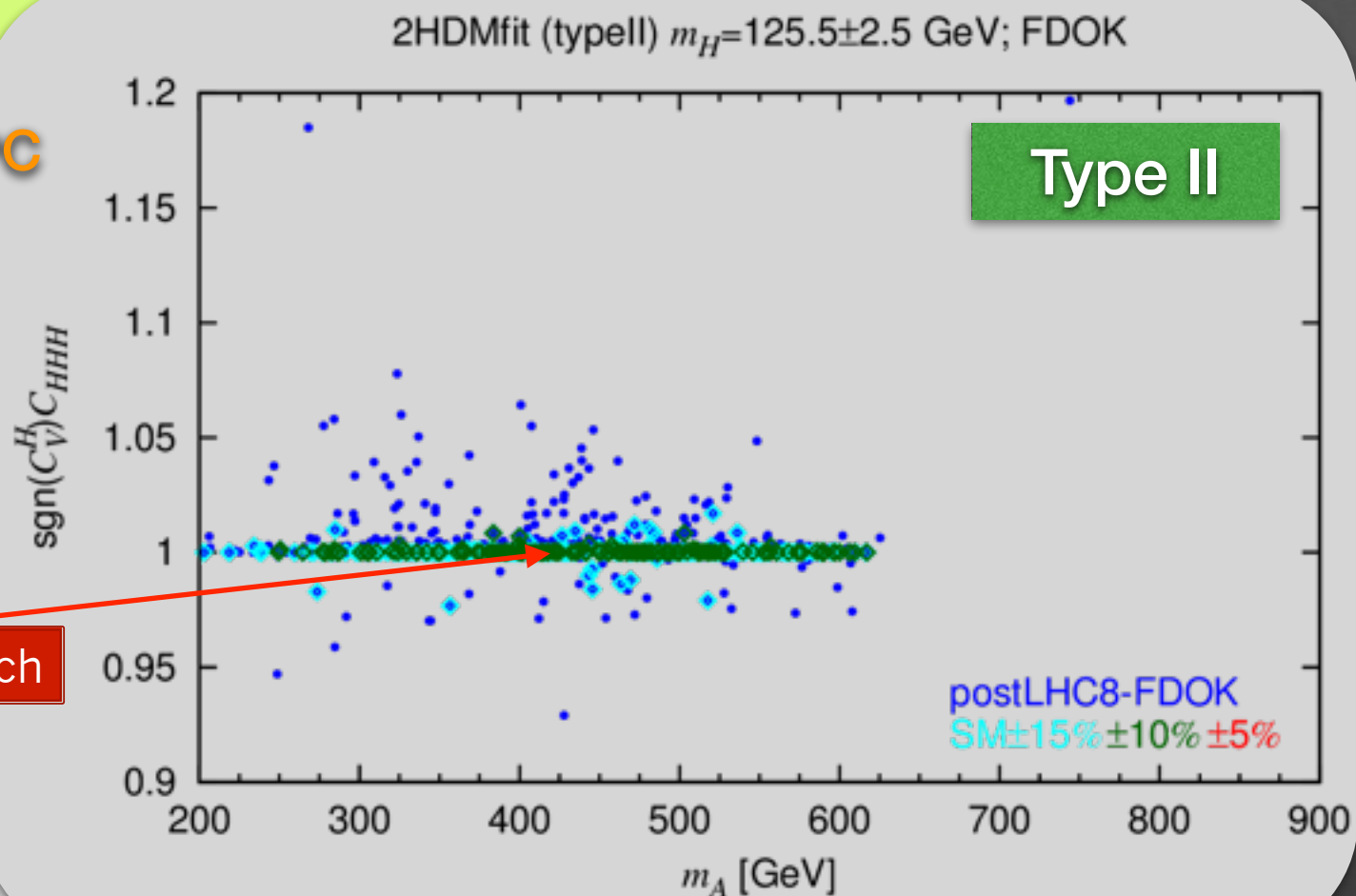
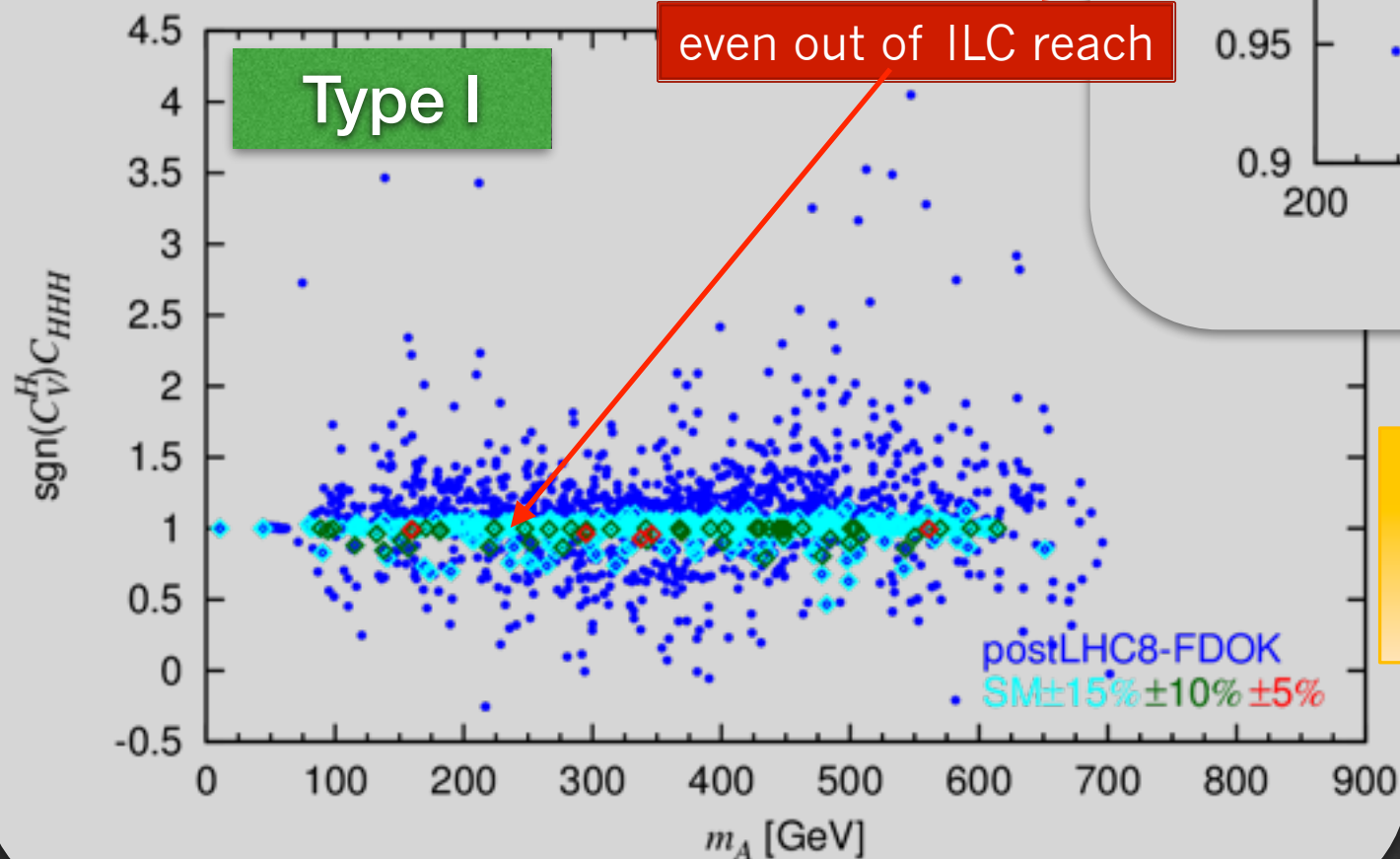
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SPPC

	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

2HDMfit (typell) $m_H=125.5\pm 2.5$ GeV; FDOK



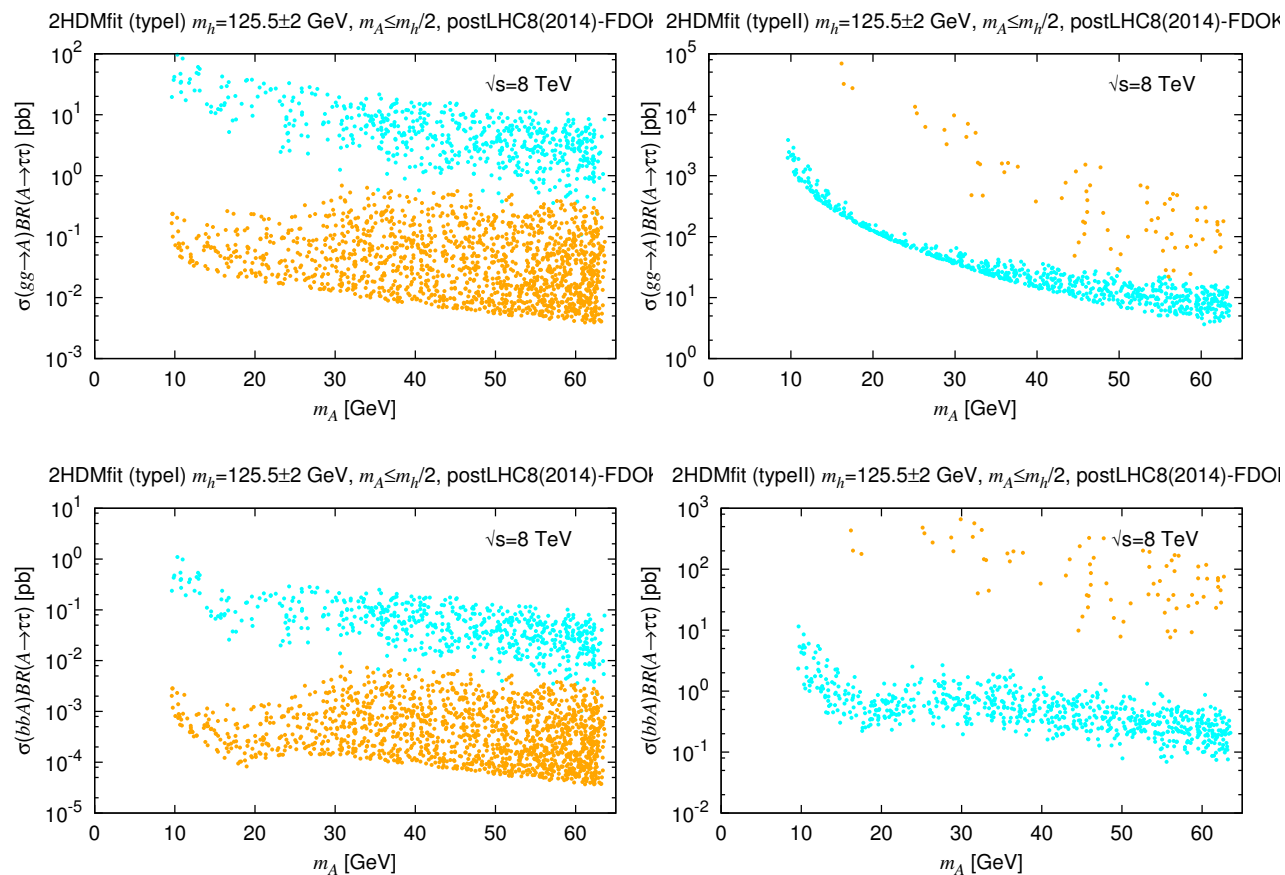
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h-125.5
GeV

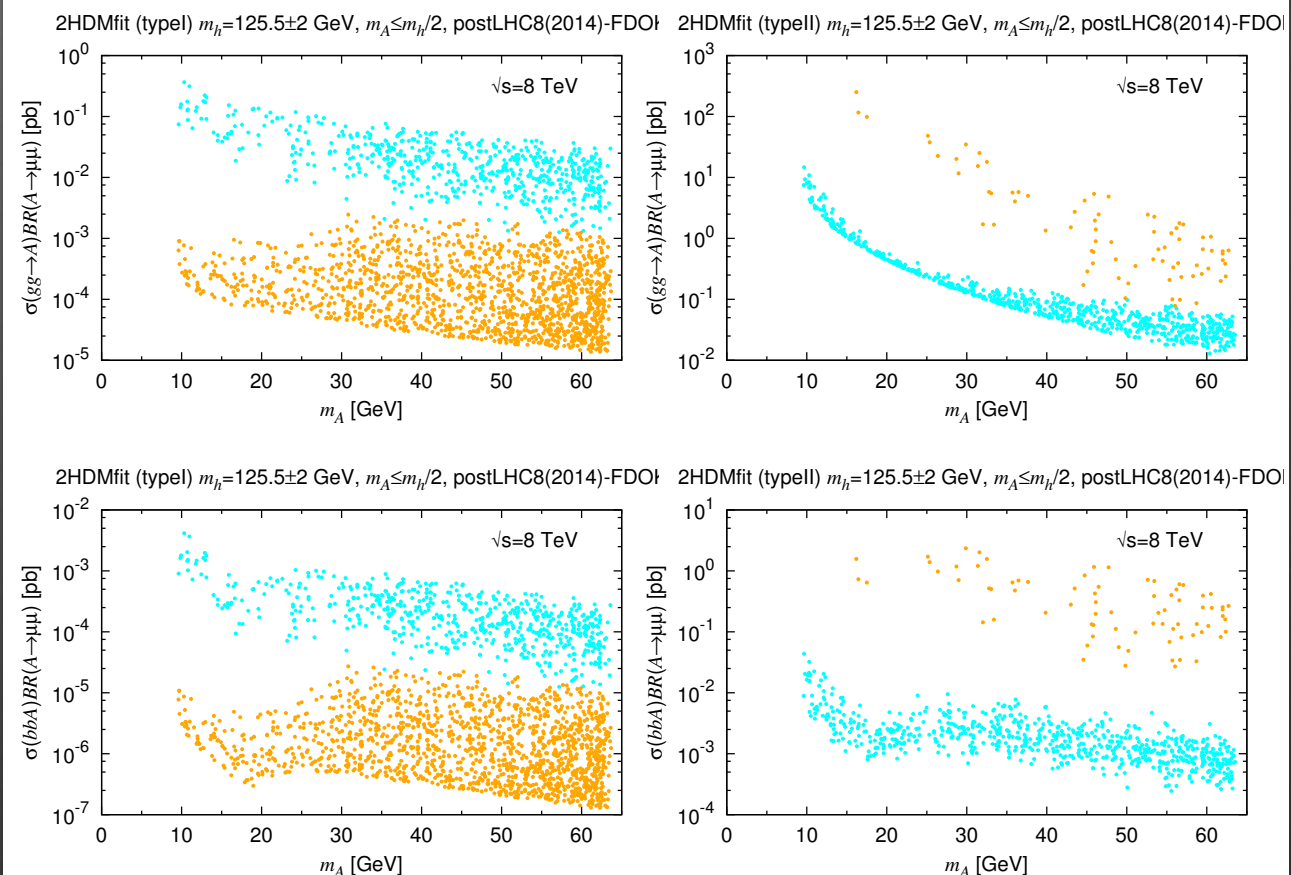
light A search highlight

arXiv: 1412.XXXX

bb



mu mu

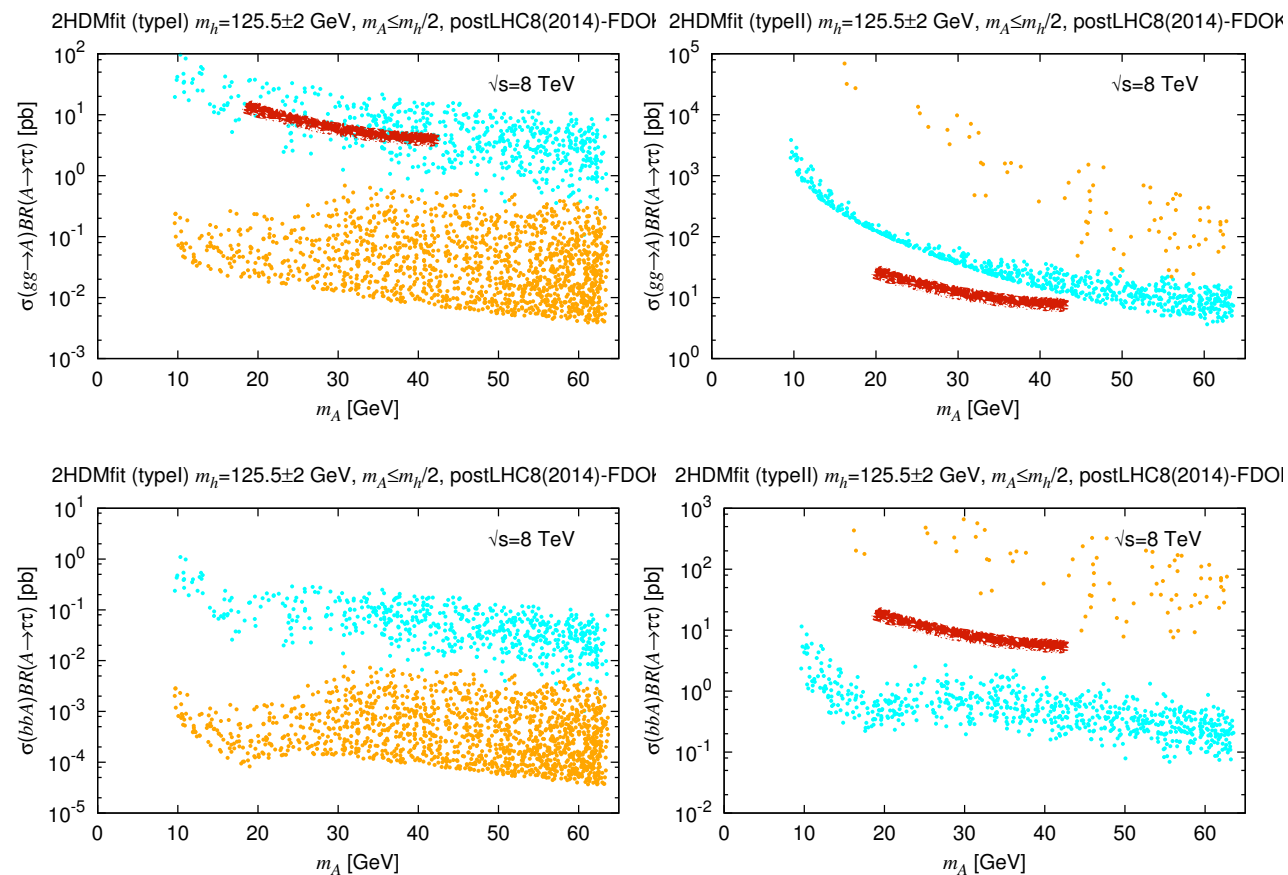


**h-125.5
GeV**

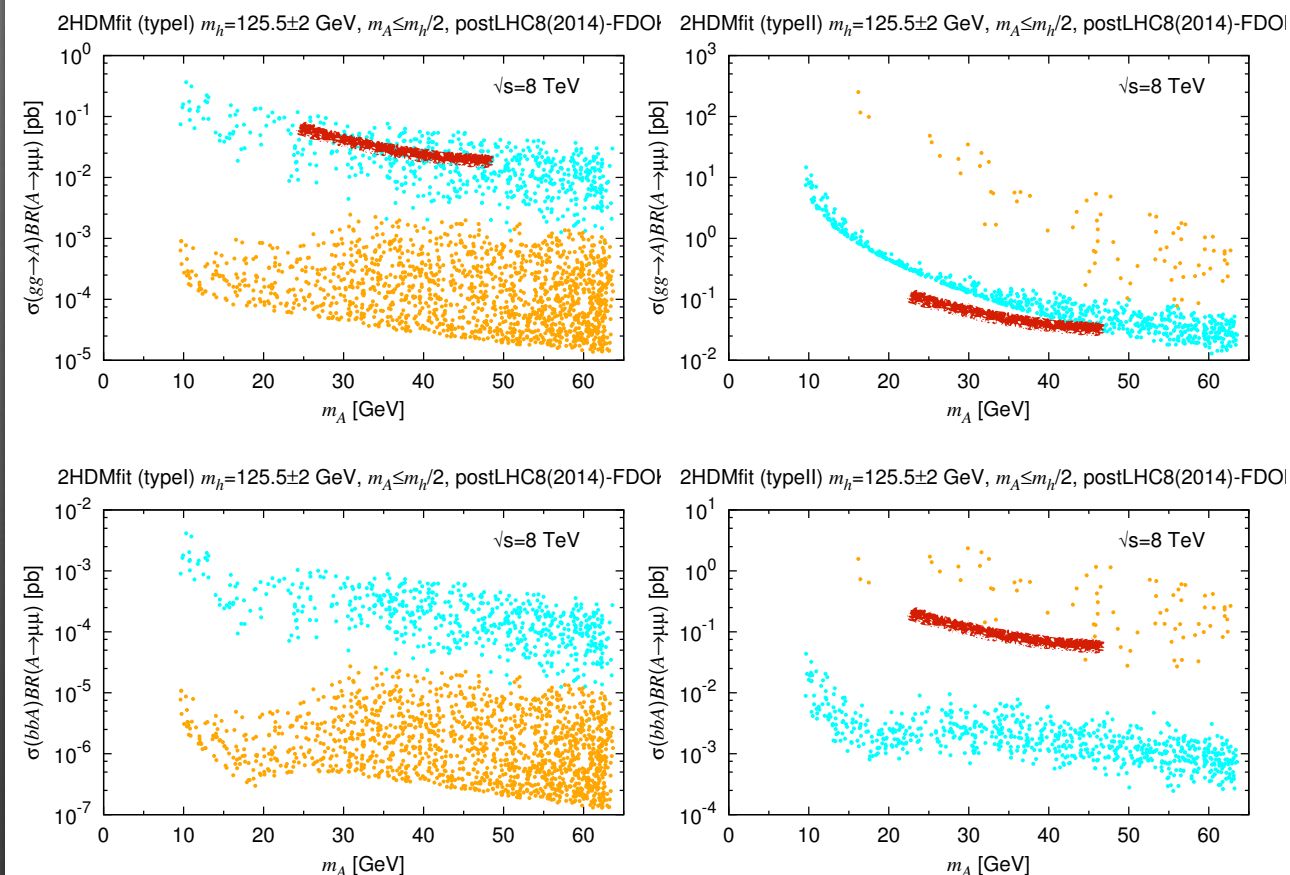
light A search highlight

arXiv: 1412.XXXX

bb



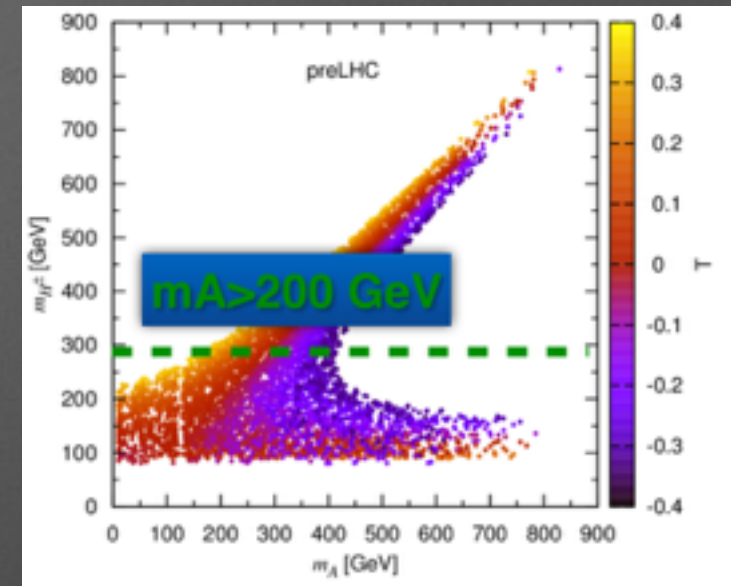
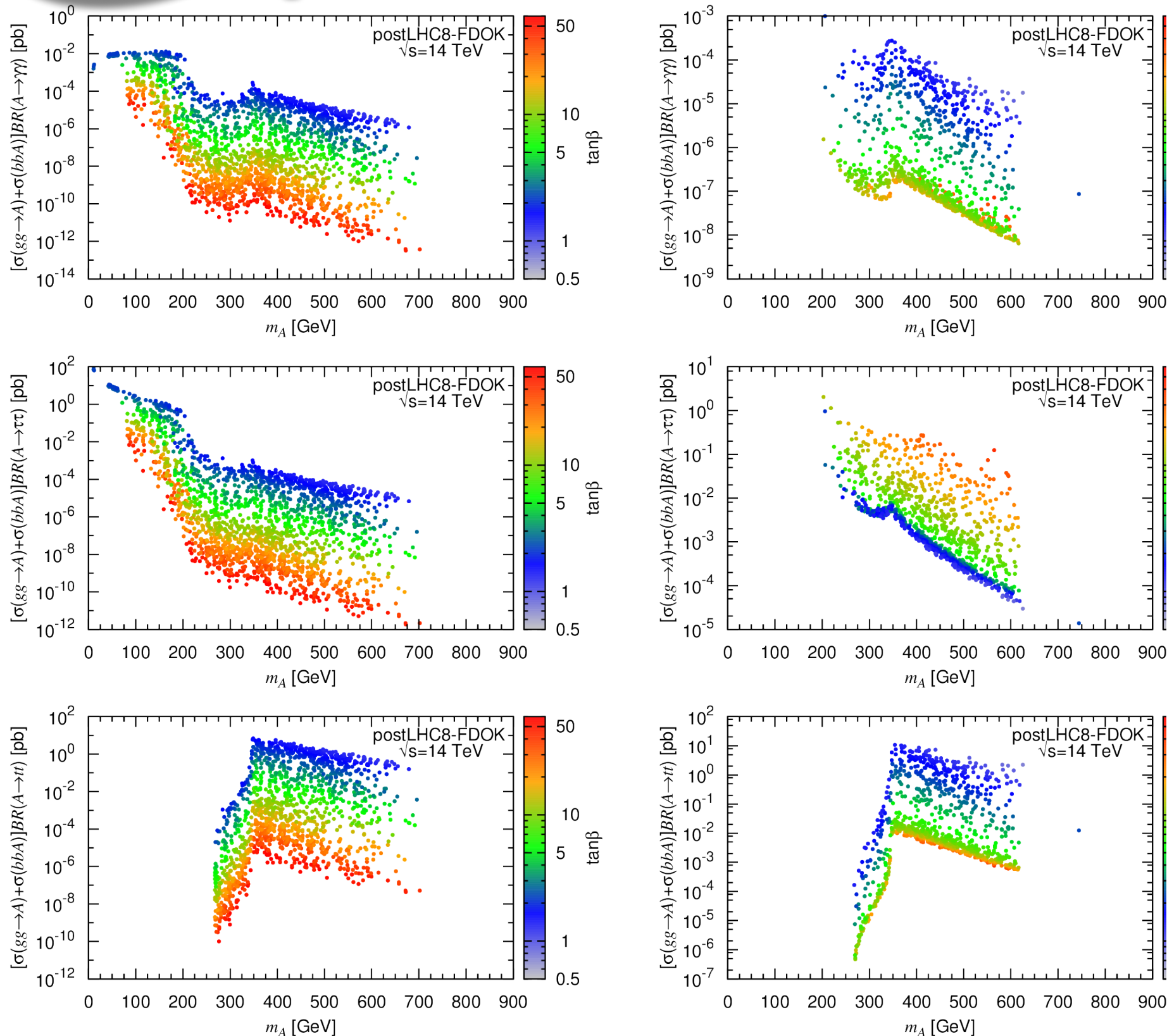
mu mu



- 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 $m_A \leq m_h/2$ 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 $\tau\tau$ ($\mu\mu$) final states.

H-125.5
GeV

pseudoscalar A search

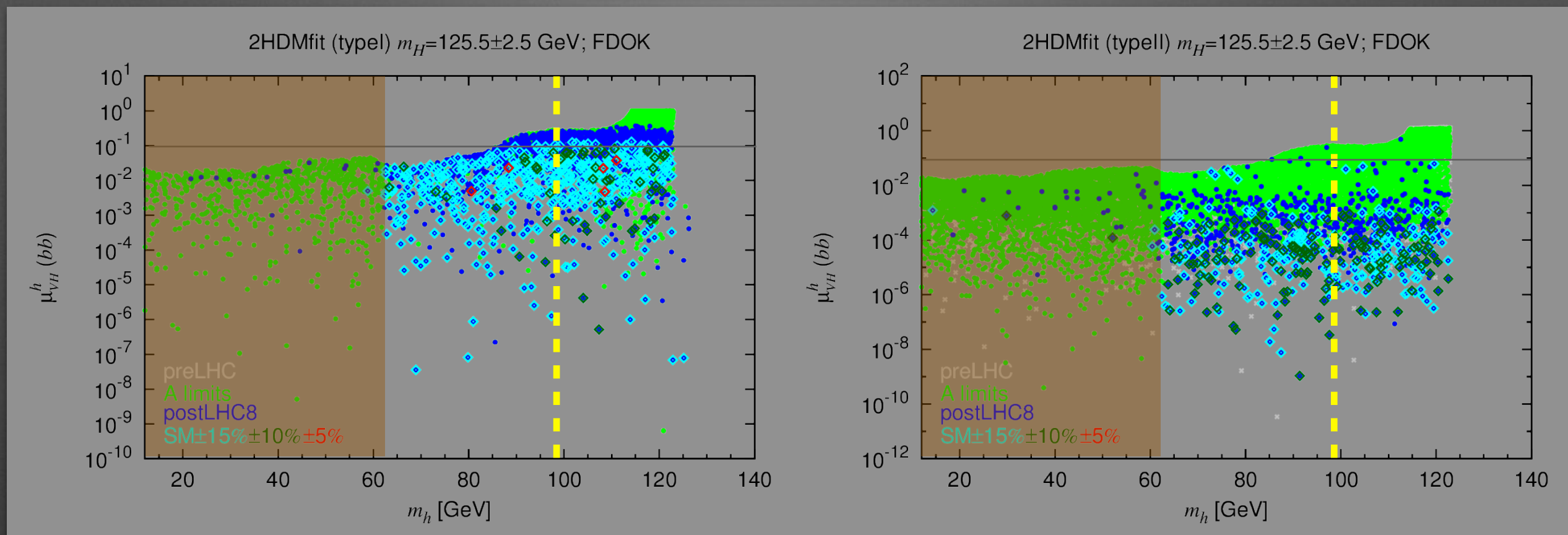


- In Type I $m_A < 60$ GeV is possible but must have small $BR(H \rightarrow AA)$. In Type II, $m_A > 200$ GeV due to the preLHC condition.
 - LHC8 125 GeV Higgs data constrain the A mass < 700 GeV in Type I and < 625 GeV in Type II.
- NON-DECOUPLING**

H-125.5
GeV

lighter h detection

LHC @ 8 TeV



- For $m_h \lesssim 60$ GeV, one can require $\text{BR}(H \rightarrow hh)$ 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.