Associated production of Higgses in 2HDMs

S. Banik, GC, A. Crivellin, H. Haber - IN PREPARATION

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6.11.2024

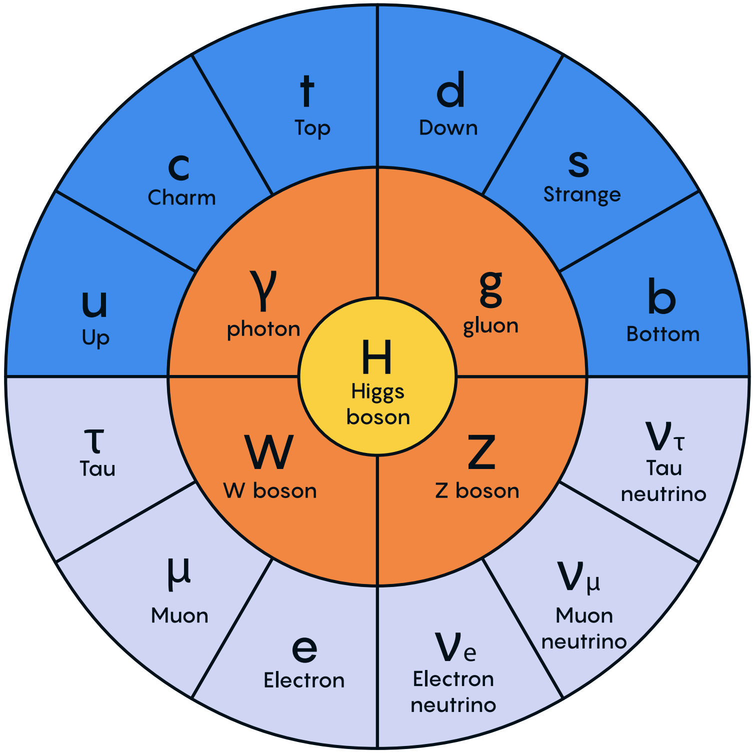
Outline

1. (Asymmetric-) associated production of Higgses at the LHC
2. Drell-Yan production of Higgses in 2HDMs
3. The flavored aligned 2HDM (A-2HDM)
4. Correlating Br$[A \to \gamma\gamma]$ with EDMs
5. The 152 GeV and 95 GeV di-photon excesses

Scalar sector

$$\mathcal{L} = +\mu^2|\Phi|^2 - \lambda|\Phi|^4$$

- **Minimality of the scalar sector of the SM not guaranteed theoretically**
- Scalar extensions common to multiple NP models
- Run-3 data (on their way) and HL-LHC stage will provide a unique opportunity to inspect non-trivial signatures



(Asymmetric-) associated production

[ATLAS and CMS review]

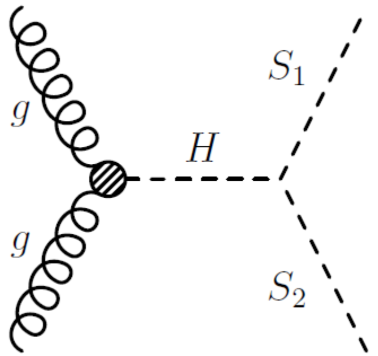
[Talk by Maggie]
[Talk by Davide]

- Provides a yet unexplored window on new physics

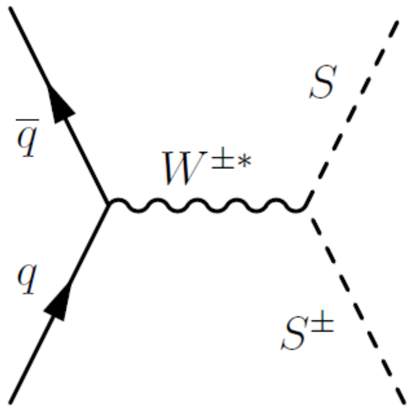
- Additional particles required in the signal regions (on top of the decays of the NP candidate)

- **Reduced SM background and enhanced NP sensitivity**

Future lepton colliders!



Gluon-fusion initiated via a heavy scalar



Drell-Yan production

Drell-Yan production

New Higgses mostly produced via Drell-Yan at the LHC must have specific properties

Transform non-trivially under $SU(2)_L$	}	Gauge interaction with SM fields
No direct (or tiny) Yukawa couplings	}	Suppressed gluon-fusion production
Have small vacuum expectation value	}	Suppressed VBF and VH production
Small mixing with the SM Higgs boson	}	Alignment limit

2HDMs and Drell-Yan

2HDMs strongly motivated:
MSSM, GUT, PQ (strong CP), custodial symmetry

$Y_{\Phi_{\mathrm{NP}}} \ll 1$

$\langle \Phi_{\mathrm{SM}} \rangle \approx v, \langle \Phi_{\mathrm{NP}} \rangle \ll 1$

Small mixing

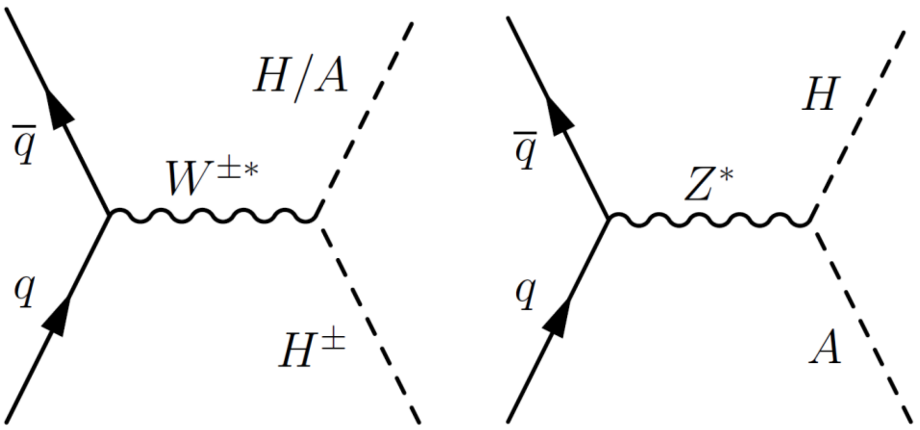
⇒

Suppressed GF

Suppressed VBF/VH

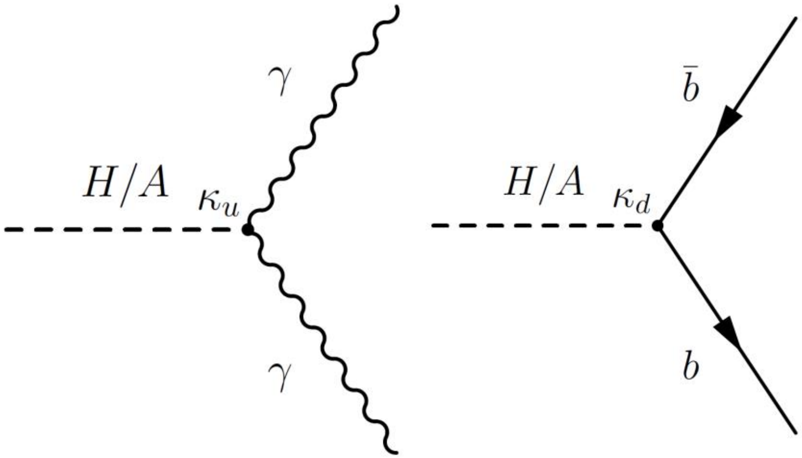
Higgs/Flavor bounds

Drell-Yan is the main production mechanism



2HDMs and Drell-Yan

- Difficult to obtain sizable Br$[H/A \to \gamma\gamma]$ with Z_2 symmetries for masses around the EW scale



Alignment limit $(\beta - \alpha) \approx 0$

	Type-I	Type-II
κ_u	$-1/\tan(\beta)$	$-1/\tan(\beta)$
κ_d	$1/\tan(\beta)$	$\tan(\beta)$

$\kappa_u \gg 1 \Rightarrow \kappa_d \gg 1$

$\kappa_u \gg 1, \kappa_d \ll 1$
Flavor bounds: $m_{H^\pm} > 600$ GeV

[J. Haller, A. Hoecker et al.]

- Composite Higgs? **Relaxing Z_2 symmetries?**

A-2HDM

[S. Banik, GC, A. Crivellin, H. Haber - IN PREPARATION]

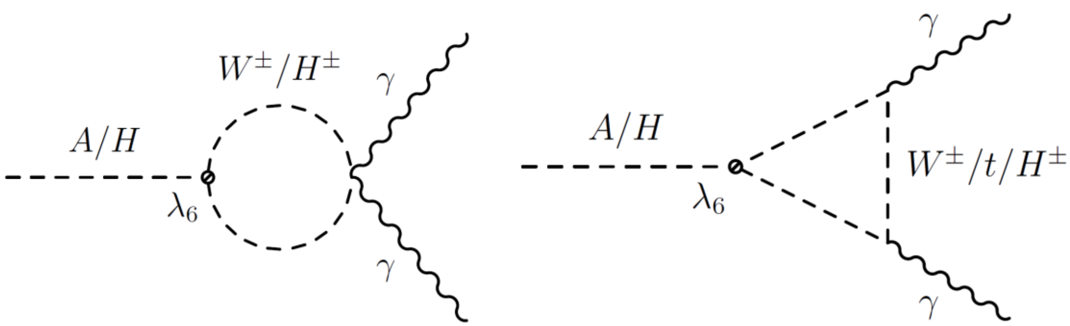
- Yukawa's of ϕ_1 $\propto$ Yukawa's of ϕ_2 $\Longrightarrow$ **NO FCNC (tree)**

$$\mathcal{L}_Y = -\overline{Q}_L Y_d(\phi_1 + \zeta_d \phi_2) d_R - \overline{Q}_L Y_u(\tilde{\phi}_1 + \zeta_u^* \tilde{\phi}_2) u_R - \overline{L}_L Y_\ell(\phi_1 + \zeta_\ell \phi_2)\ell_R + \text{h.c.}$$

$\zeta_u \ll 1$ → suppressed GF (small mixing)

- No Z_2 symmetry imposed $\Longrightarrow$ **λ_6 and λ_7 terms allowed**

$$\mathcal{V} = \mathcal{V}_{Z_2} + [\lambda_6(\phi_1^\dagger \phi_1) + \lambda_7(\phi_2^\dagger \phi_2)]\phi_1^\dagger \phi_2 + \text{h.c.}$$



Sizable Br$[H/A \to \gamma\gamma]$ through $H^\pm$ loop

A-2HDM: CP-violation

[S. Banik, GC, A. Crivellin, H. Haber - IN PREPARATION]

- CP-violation of the model (Baryogenesis?)
  [K. Enomoto, S. Kanemura, Y. Mura]

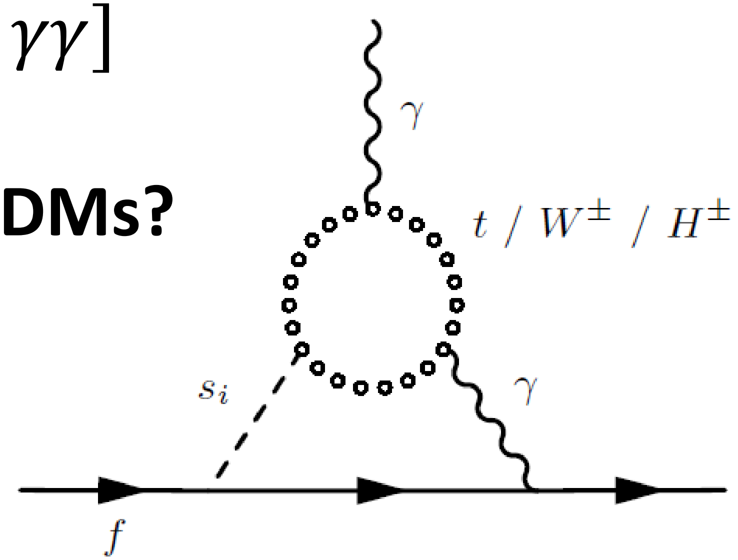
Yukawa sector: $\zeta_u, \zeta_d, \zeta_\ell$

Scalar potential: $\lambda_5, \lambda_6, \lambda_7$

- $\Re[\lambda_6]/\Im[\lambda_6]$ drives Br$[H/A \to \gamma\gamma]$

- **Correlating Br$[A \to \gamma\gamma]$ with EDMs?**

$$i\, d_f\, \bar{f} \sigma^{\mu\nu} q_\mu \gamma_5 f \subset$$



Higgs basis

[S. Davidson, H. Haber]

- Higgs-flavor symmetry: $U(2)^{ab}_{HF}\Phi_a = \Phi_b$
- $\langle\Phi_1\rangle = v,\ \langle\Phi_2\rangle = 0$; $\lambda_{1,2,3,4,5} \Longleftrightarrow Z_{1,2,3,4,5}$, $\lambda_{6,7} \Longleftrightarrow Z_{7,6}$

  Suppressed VBF / VH (small mixing)
- **Explicit treatment of CP-violation**

$$\Im(Z_5^* Z_6^2) = \Im(Z_5^* Z_7^2) = \Im(Z_6^* Z_7) = 0$$

SM-Higgs mass | Alignment | H/A mixing

$$\mathcal{M}^2_{hHA} = v^2 \begin{pmatrix} Z_1 & \Re(Z_6) & -\Im(Z_6) \\ \Re(Z_6) & \frac{1}{2}[Z_{34} + \Re(Z_5)] & -\frac{1}{2}\Im(Z_5) \\ -\Im(Z_6) & -\frac{1}{2}\Im(Z_5) & \frac{1}{2}[Z_{34} - \Re(Z_5)] \end{pmatrix}$$

Br[$H/A \to \gamma\gamma$] sizable!

Z_7 independent of mixing angles

EDMs

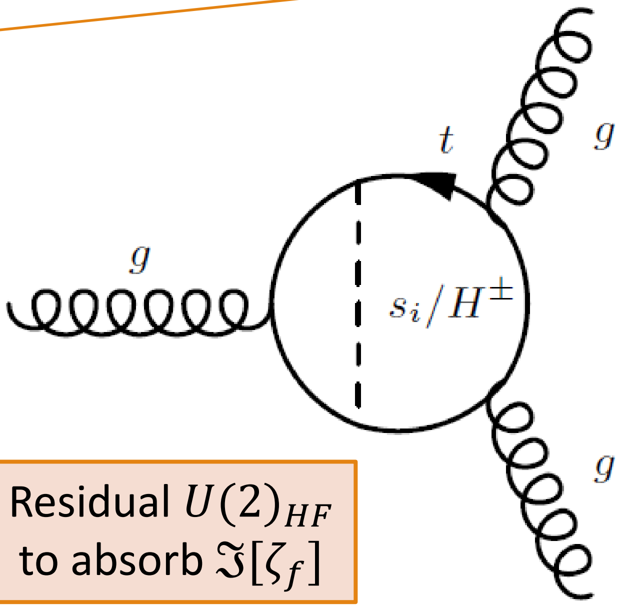
Constraints on Br$[H/A \to \gamma\gamma]$

[M. Jung, A. Pich]

- Electron gives stringent bounds (10^{-30} e cm^{-1})
- Projections for neutron/proton ($10^{-28}/10^{-29}$ e cm^{-1})

$$d_n = +(0.78 \pm 0.03) d_d - (0.20 \pm 0.01) d_u \\ - e(1.1 \pm 0.55)\tilde{d}_d - e(0.55 \pm 0.28)\tilde{d}_u) + e(50 \pm 40)\ \mathrm{MeV}\ d_G$$

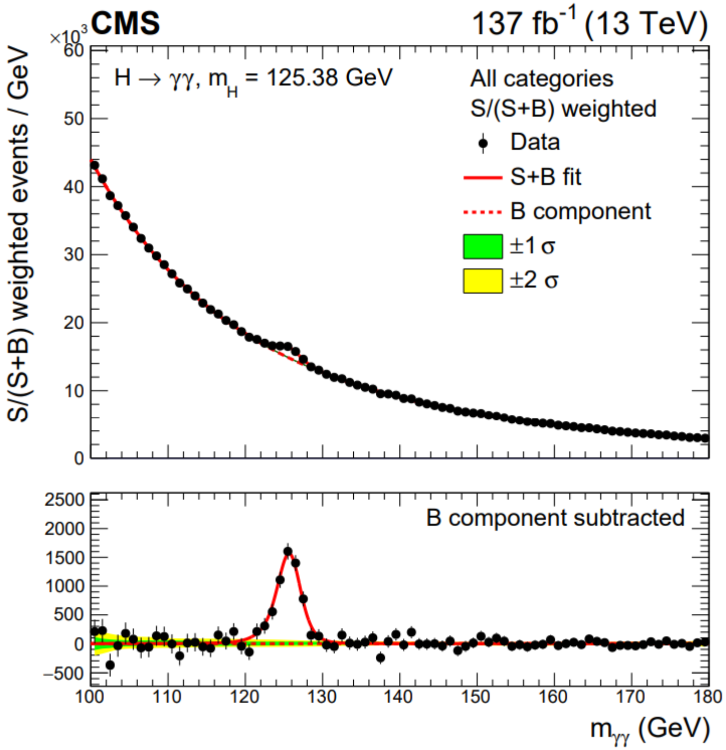
- RGE improved chromo-magnetic contributions
- Analytic results [W. Altmannshofer, S. Gori, N. Hamer, H. Patel]
- $H^\pm$ contribution $\propto \Im[\zeta_u^* \zeta_d]$



Residual $U(2)_{HF}$ to absorb $\Im[\zeta_f]$

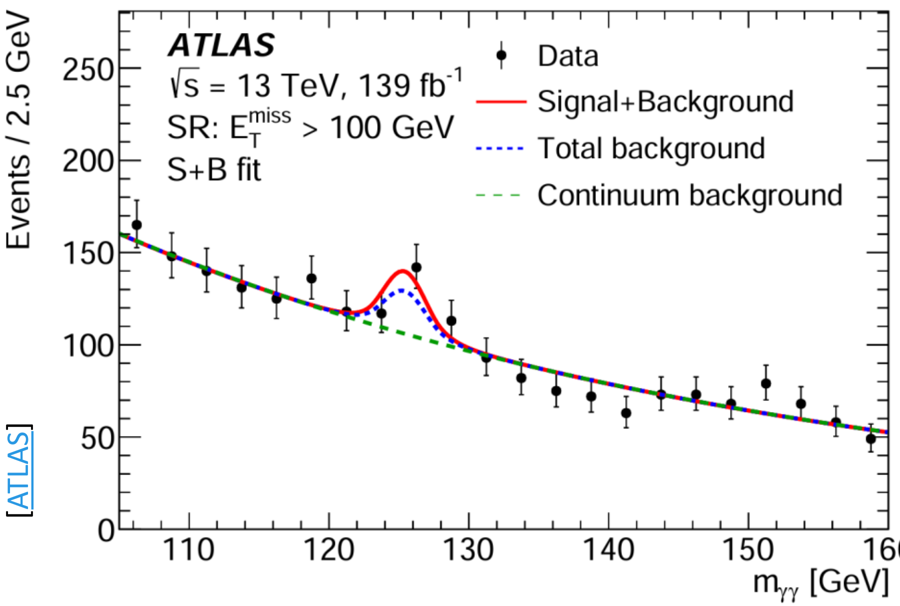
Hints for New Physics at 152 GeV

No significant excess in **inclusive $\gamma\gamma$** searches



[CMS]

Interesting excesses in $\gamma\gamma + X$ (X represents additional particles in the signal regions)

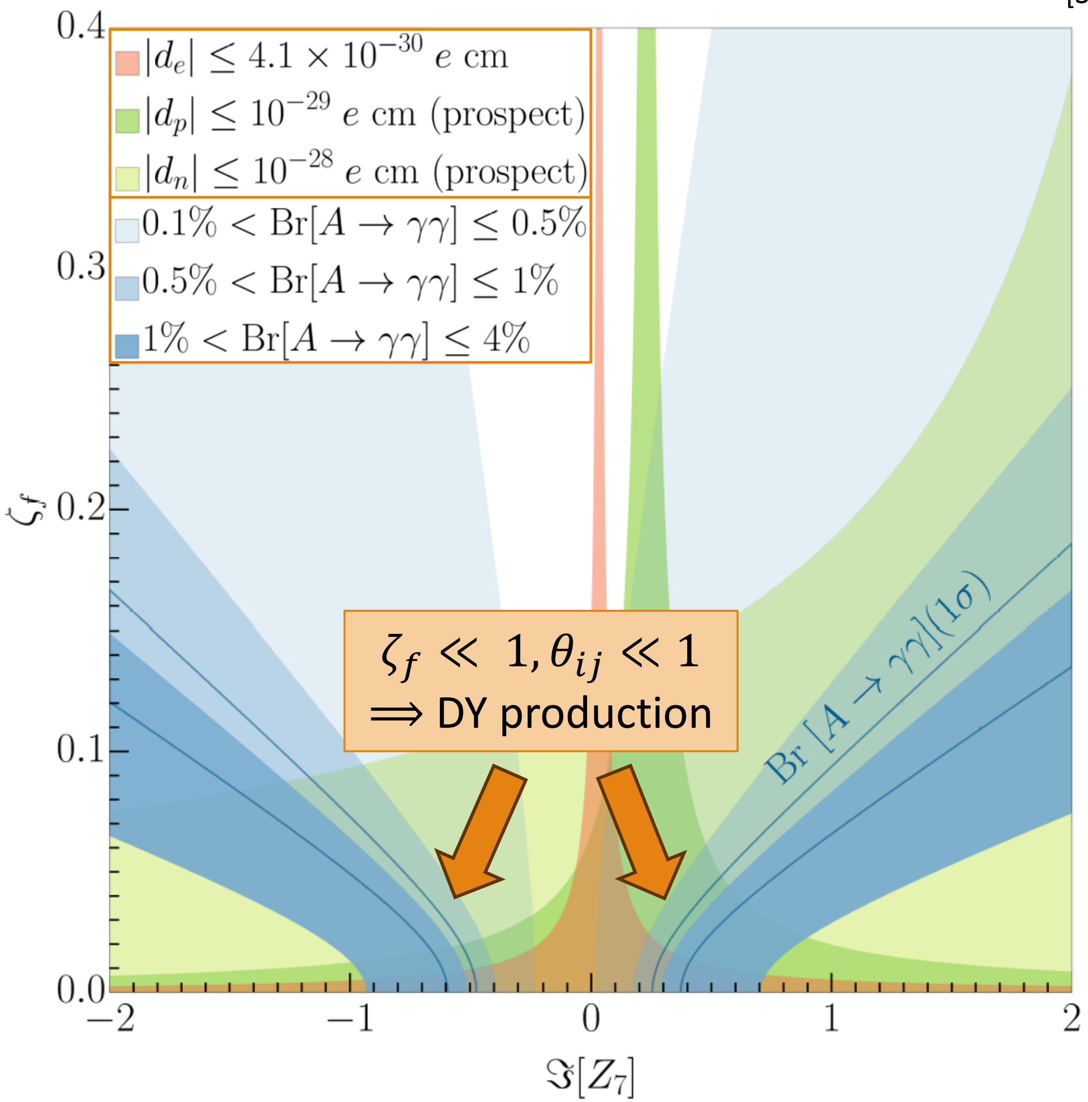


[ATLAS]

Associated production mechanism

A-2HDM: $A_{152} \to \gamma\gamma$

[S. Banik, GC, A. Crivellin, H. Haber - IN PREPARATION]



m	h	H	A	$H^\pm$
[GeV]	125	200	152	130

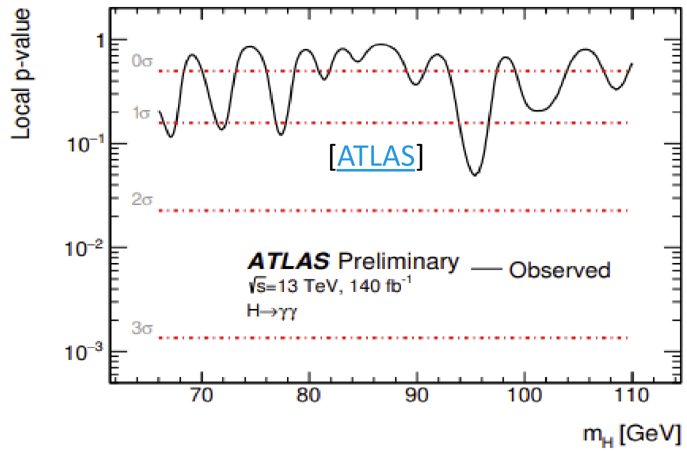
[ATLAS]

- $\zeta_u = \zeta_d = \zeta_\ell = \zeta_f \in \mathbb{R}$
- $\theta_{12} = 10^{-3}$
  $\theta_{13} = \theta_{23} = 10^{-2}$
- $Z_2 = -Z_3 = 0.2$
- $\Re[Z_7] = 0.1$
- HiggsTools, perturbativity, vacuum stability

Hints at 95/98 GeV

Inclusive searches

- LEP: $Z + b\bar{b}$ (2.3 σ)
- ATLAS: $\gamma\gamma$ (1.7 σ)
- CMS: $\gamma\gamma$ (2.9 σ)
- CMS: $\bar{\tau}\tau$ (2.4 σ)
  (but not seen by ATLAS)



[U. Haisch, A. Malinauskas]
[T. Biekotter, S. Heinemeyer, C. Munoz]
[T. Biekotter, S. Heinemyer, G. Weiglein et al.]
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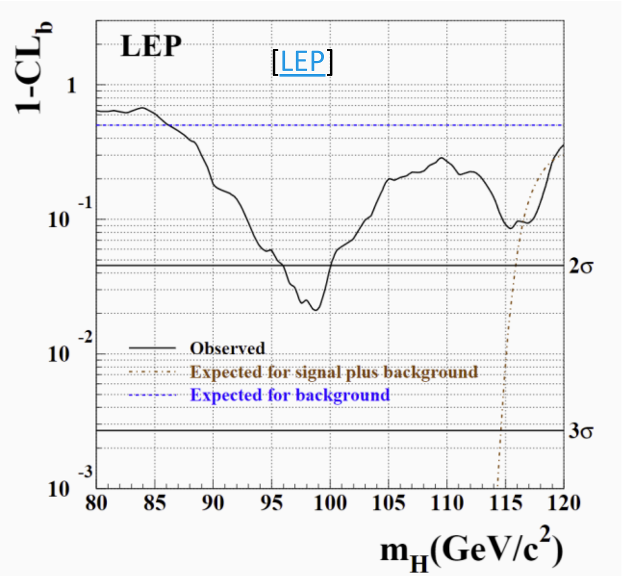
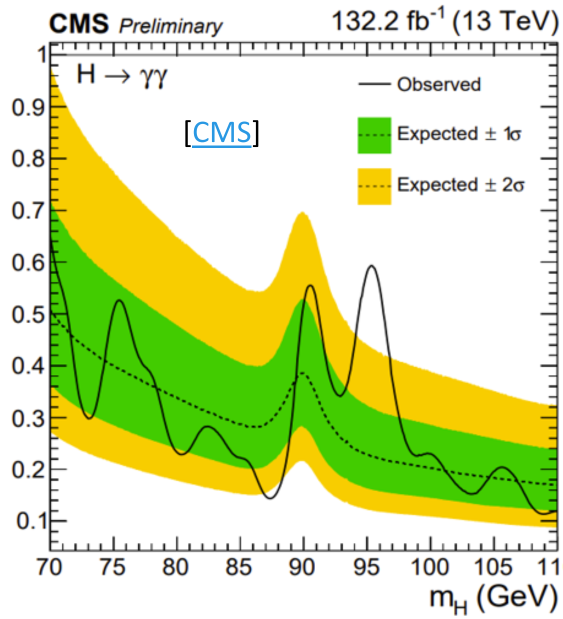
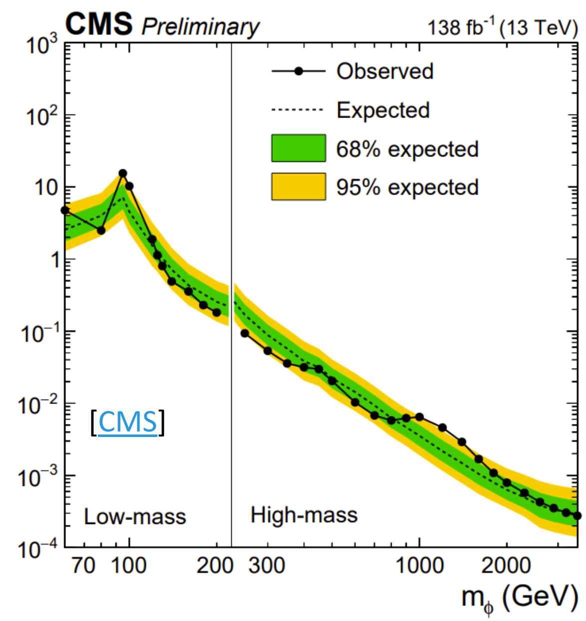
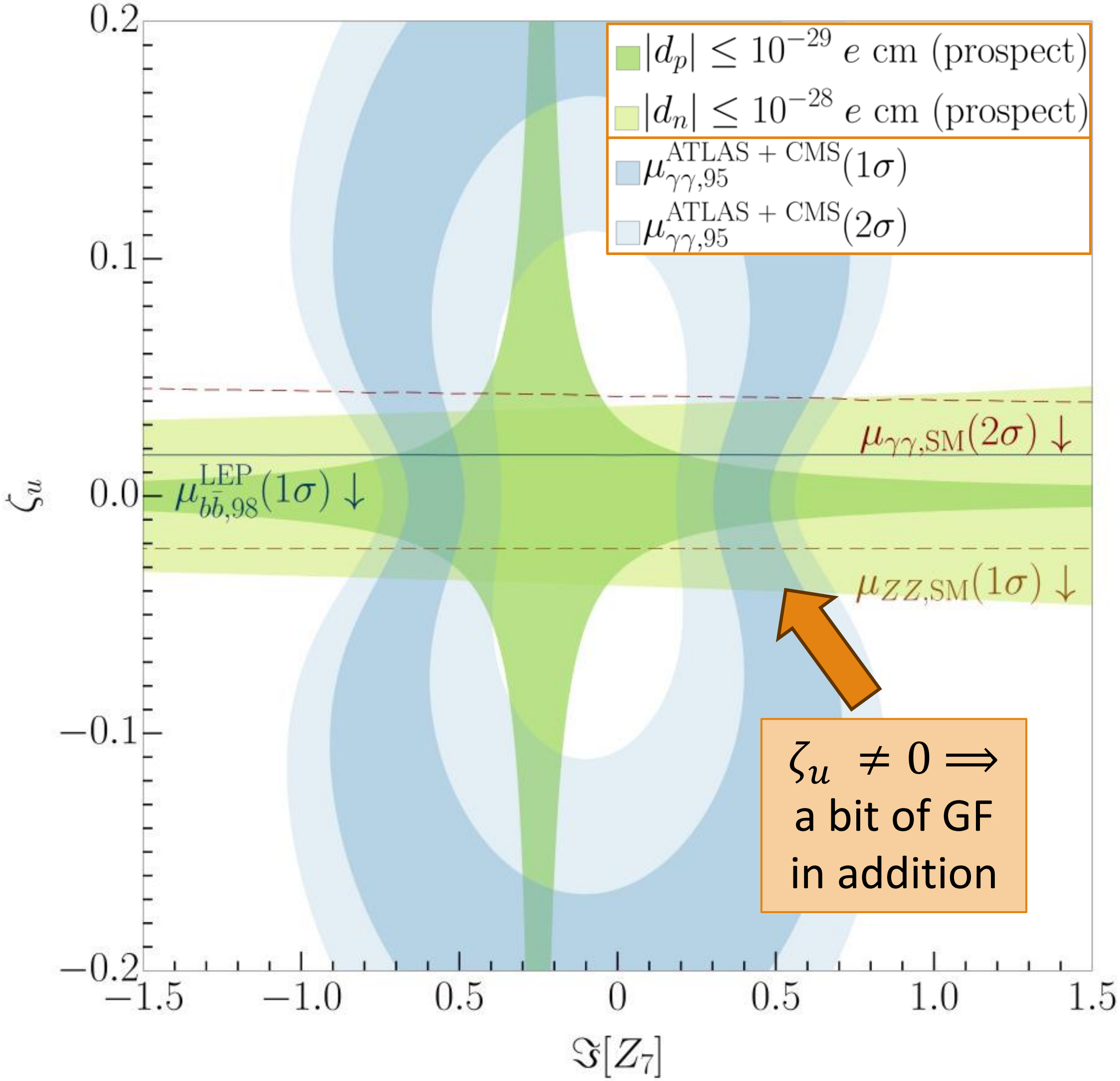






A-2HDM: $A_{95} \to \gamma\gamma,\, H_{98} \to b\bar{b}$

[S. Banik, GC, A. Crivellin, H. Haber - IN PREPARATION]



m	h	H	A	$H^{\pm}$
[GeV]	125	98	95	130

[ATLAS]

- Gluon fusion contribution: $\zeta_d = \zeta_\ell = 0,\ \zeta_u \in \mathbb{R}$
- $\theta_{12} = 0.25\ (\mu_{b\bar{b},98}^{\text{LEP}})$
  $\theta_{13} = 10^{-2}, \theta_{23} = 3 \times 10^{-2}$
- $Z_2 = -Z_3 = 0.2$
- $\Re[Z_7] = 0.1$
- HiggsTools, perturbativity, vacuum stability

Conclusions and Outlook

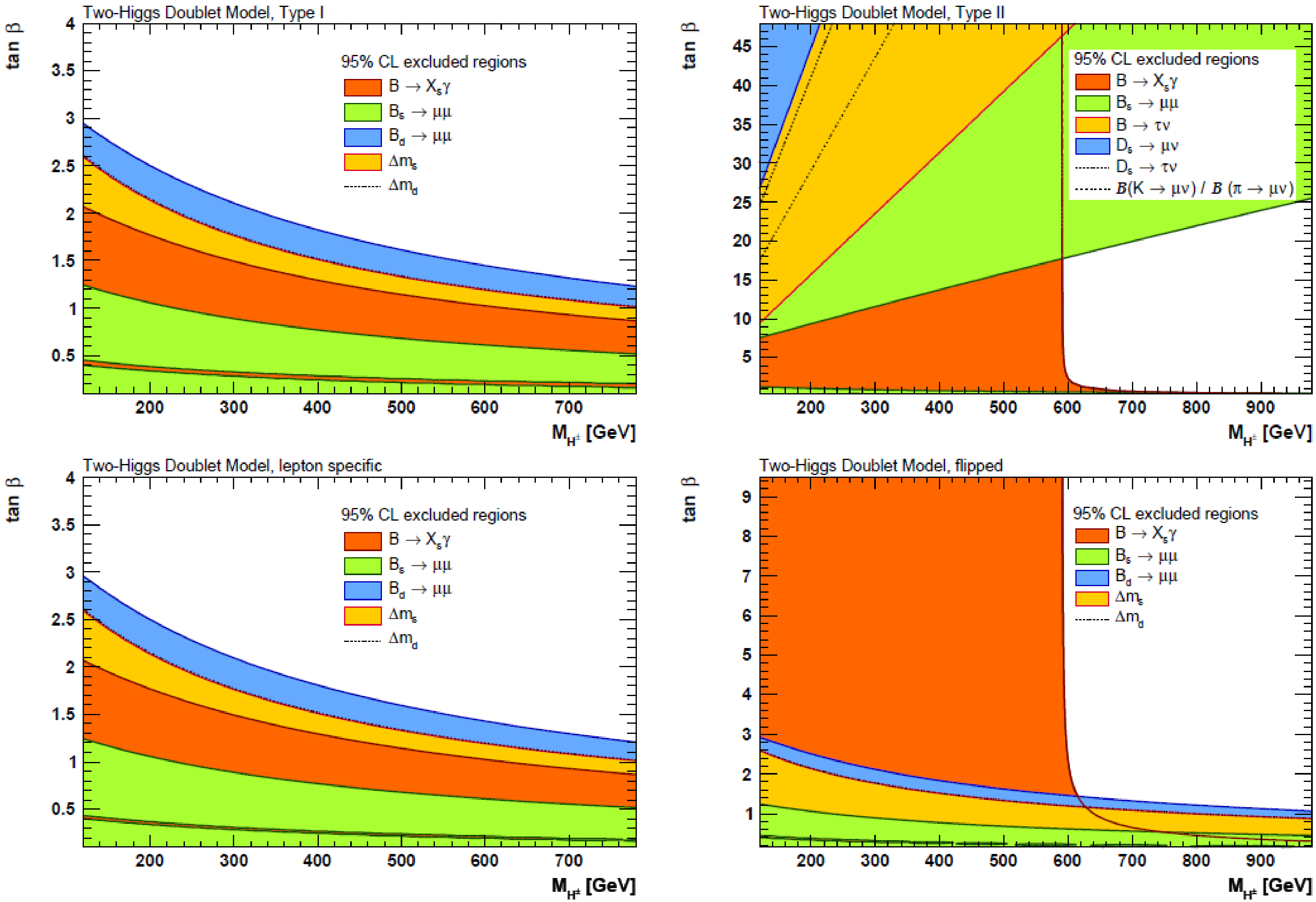
- Asymmetric associated production of scalars is a prominent signature to look for NP at the LHC
- A-2HDM offers sizable Br$[H/A \to \gamma\gamma]$ which can be correlated to CP-violating effects such as EDMs
- A-2HDM provides an independent explanation of the diphoton excesses at 95 GeV and at 152 GeV
- Outlook: correlate Br$[H/A \to \gamma\gamma]$ to Baryogenesis, SFOPT and the effects in the trilinear SM-Higgs coupling

THANK YOU FOR THE ATTENTION!

BACK UP SLIDES

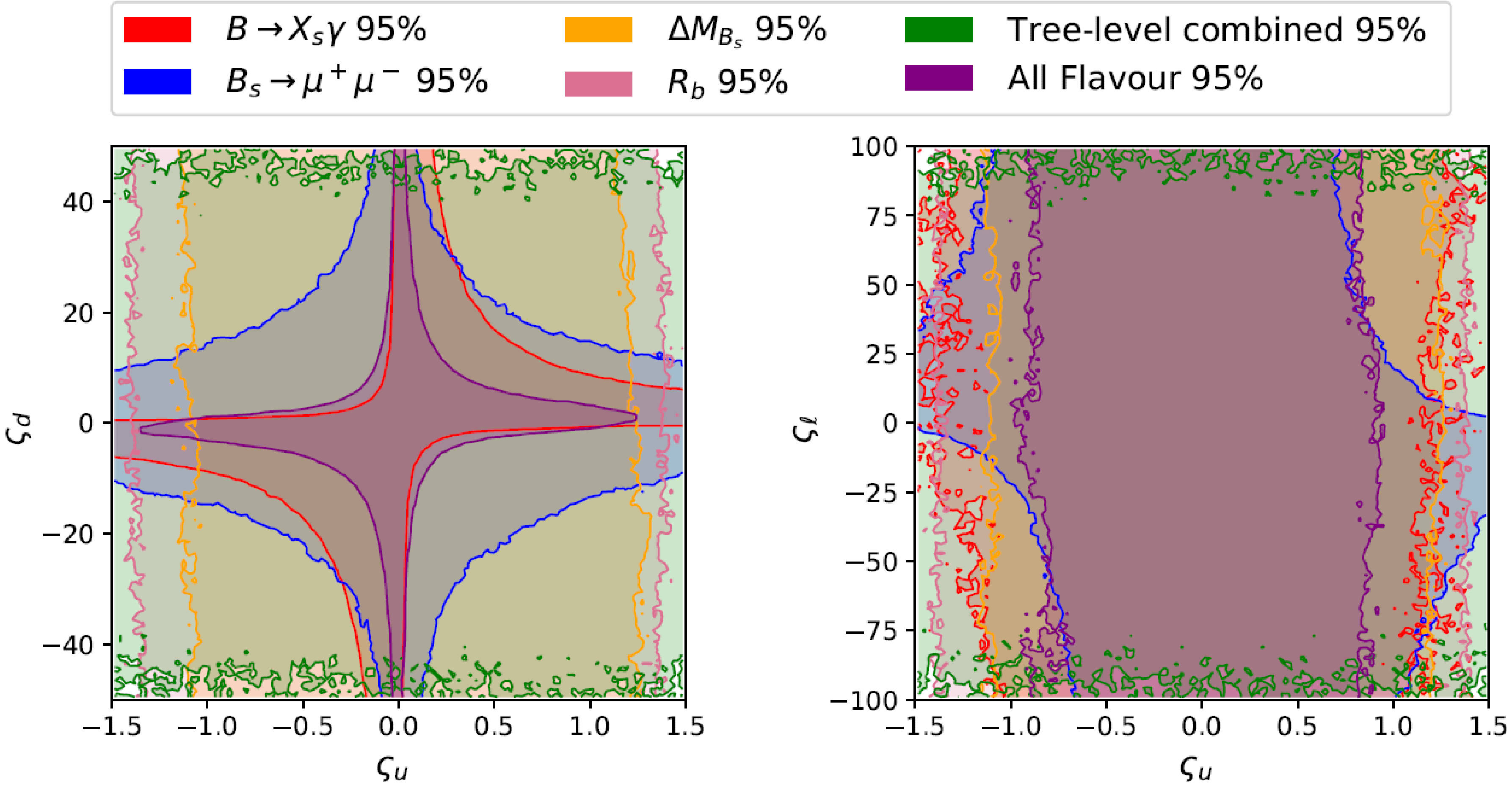
2HDMs: flavor bounds

[J. Haller, A. Hoecker et al.]



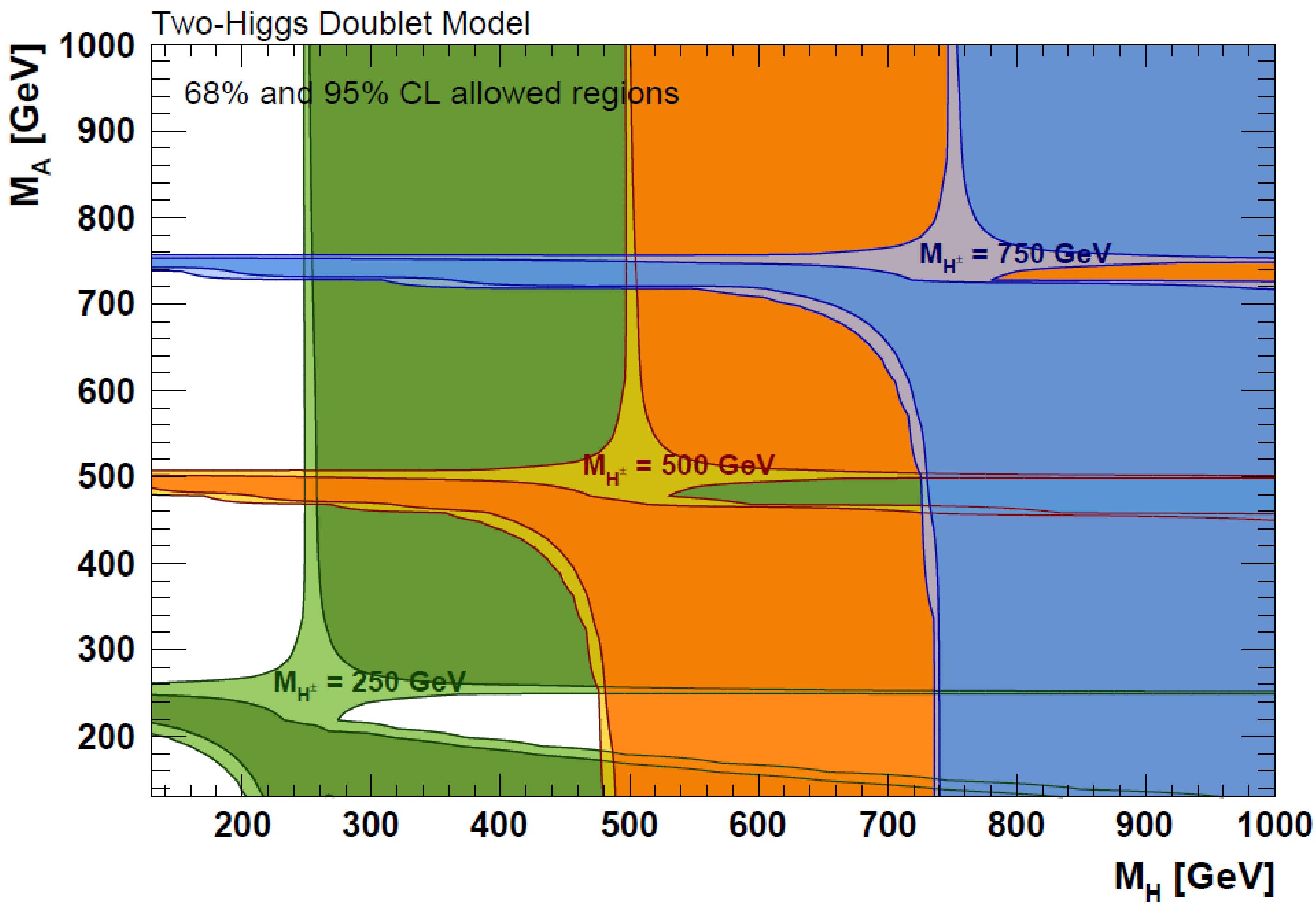
A-2HDM: flavor bounds

[A. Karan, V. Miralles, A. Pich]



2HDMs: EW precision

[J. Haller, A. Hoecker et al.]



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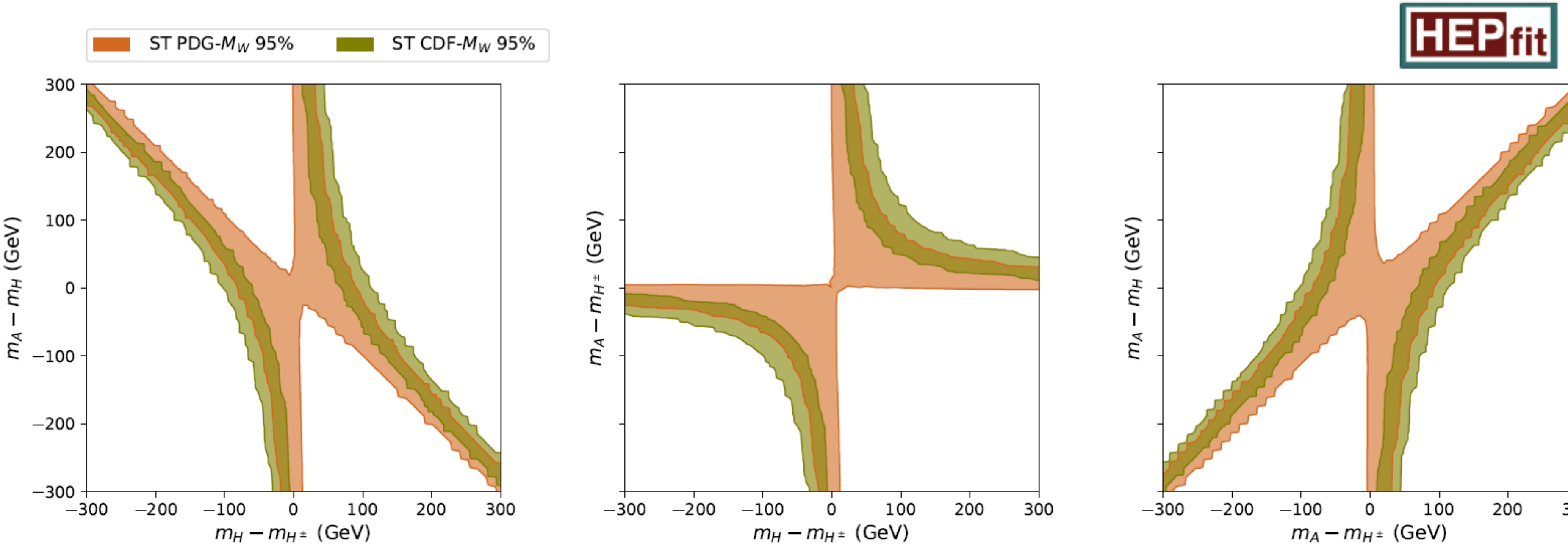


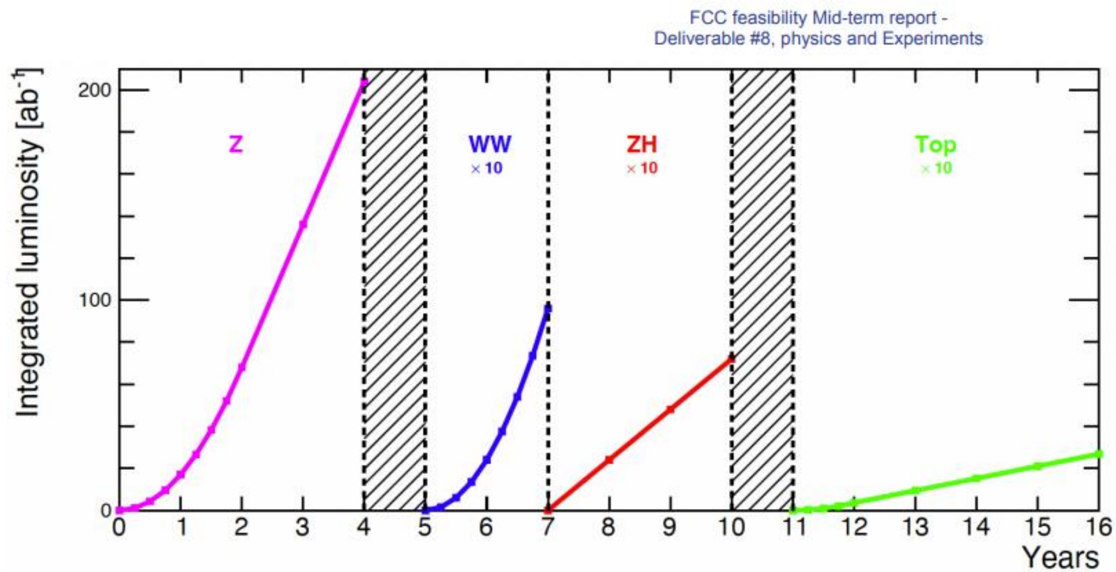
FCC-ee prospects

Courtesy of Rebeca Gonzalez Suarez

- Scalars produced in associated production via DY are a prominent candidate for FCC-ee

FCC-ee

- 16 years, 4 IPs
- Flexibility in the run scenario: in order and operation periods.
  - Additional runs, e.g. 125GeV possible
- Stringent experimental requirements



integrated luminosity per year summed over 4 IPs corresponding to 185 days of physics per year and 75% efficiency

Working point	Z, years 1-2	Z, later	WW, years 1-2	WW, later	ZH	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163		240	340–350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	70	140	10	20	5.0	0.75	1.20
Lumi/year (ab^{-1})	34	68	4.8	9.6	2.4	0.36	0.58
Run time (year)	2	2	2	–	3	1	4
Number of events	6×10^{12} Z		2.4×10^{8} WW		1.45×10^{6} ZH + 45k WW → H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW → H	

all the data of LEP1 in minutes

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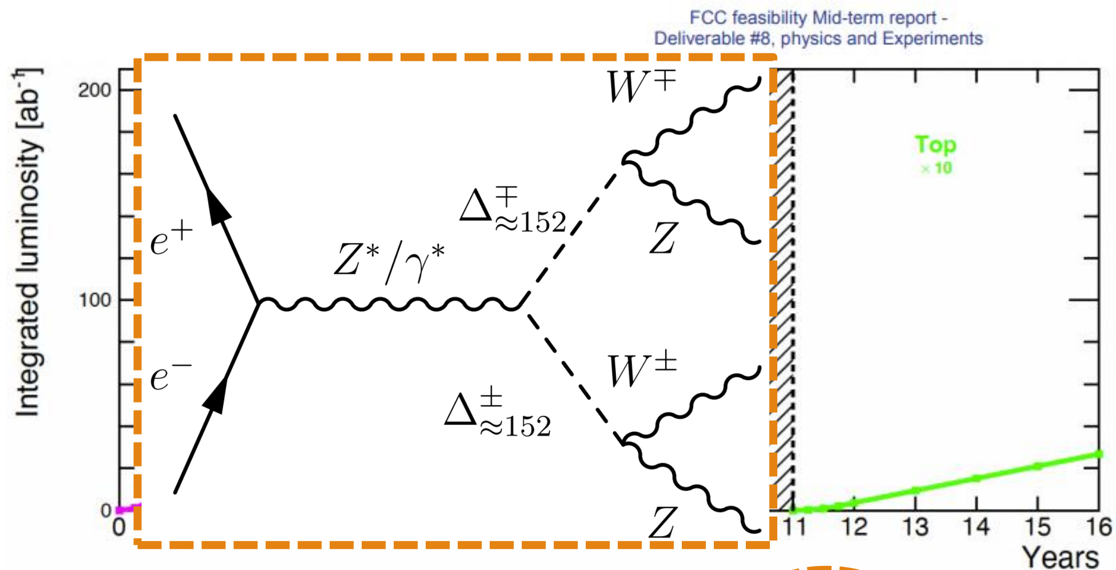

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all the data of LEP1 in minutes

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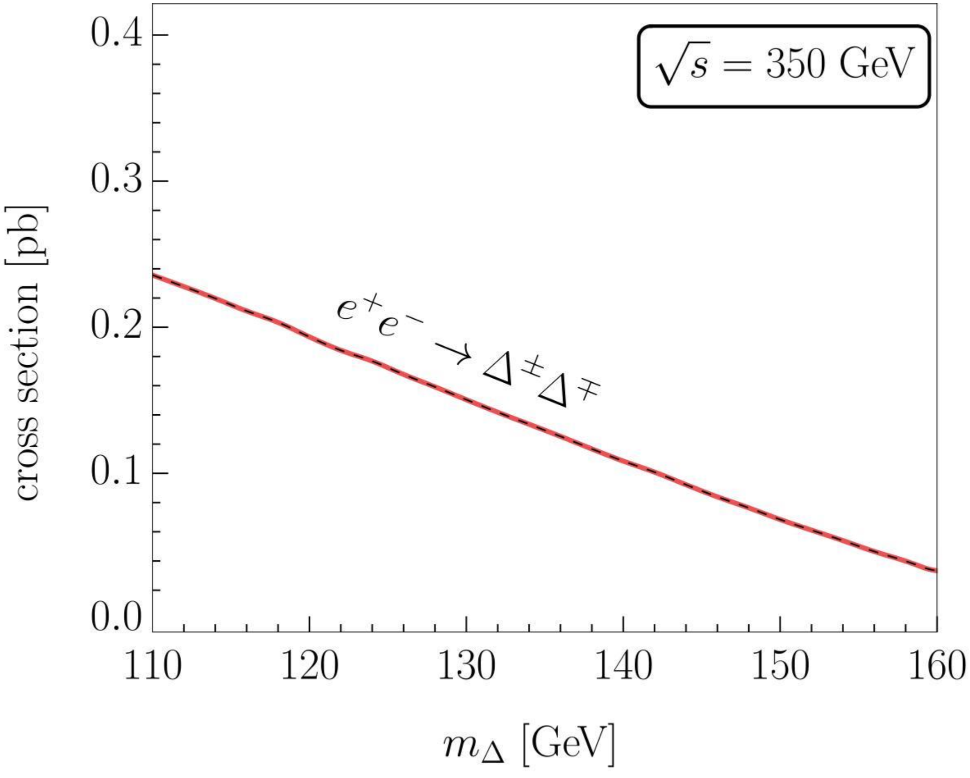
Real triplet at the FCC-ee

- Only Z^*/γ^* s-channel (suppressed $\Delta^0\Delta^0$ production)
- Pair production of the charged components



	$SU(2)_L$	$U(1)_Y$
Δ	3	0

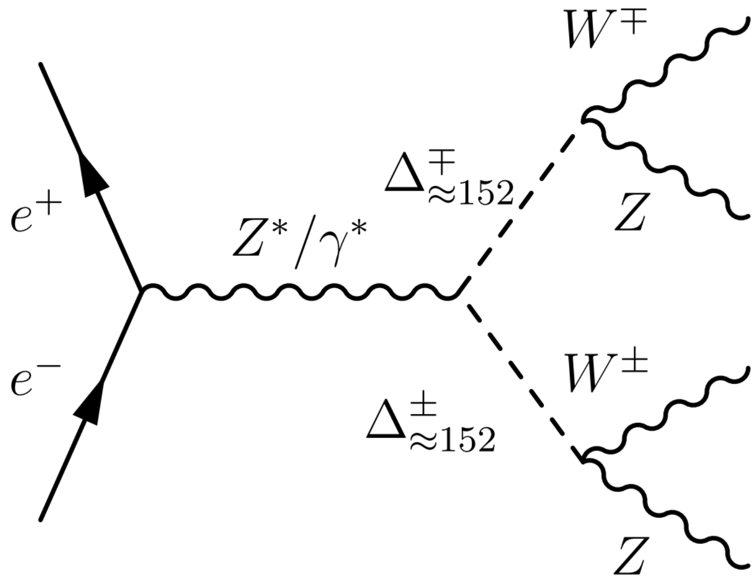
Parameters → $\langle\Delta\rangle = v_\Delta,\ \alpha_\Delta$
Fields → neutral Δ^0, charged $\Delta^\pm$

$6\ell + 2\nu$ at the FCC-ee

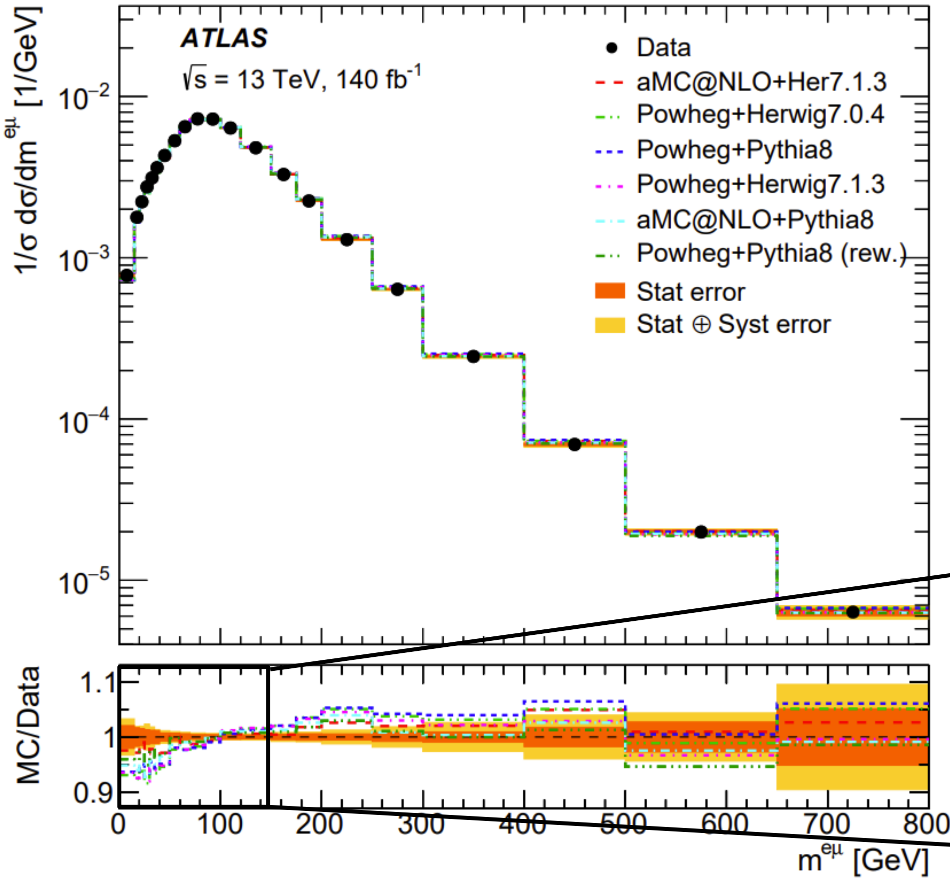
- The decay $\Delta^{\pm} \to W^{\pm}Z$ leads to a 6ℓ(+ MET) signature

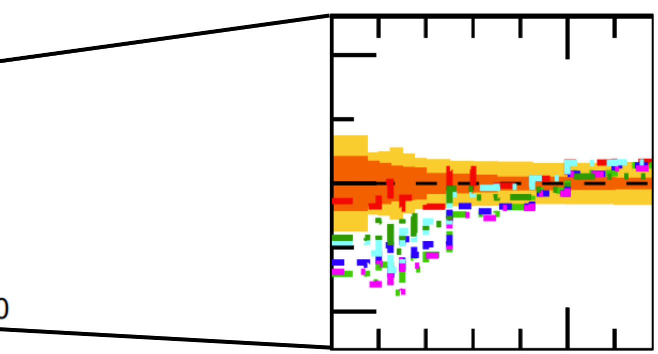
Events expected in the SM model	Events expected in the ΔSM model
$e^+e^- \to 6\ell(+\text{MET}) \approx 1$	$e^+e^- \to \Delta^{\pm}\Delta^{\mp} \to 6\ell + \text{MET} \approx 46$

- Assuming the integrated luminosity at the $t\bar{t}$ working point (4 years run)
- Log-Likely-hood ratio yields $\chi^2 \approx 80$
- $\sigma(e^+e^- \to \Delta^{\pm}\Delta^{\mp})$ could be measured at $\approx 9\sigma$



$t\bar{t}$ distributions as a probe for NP





e^+e^- future colliders have a dedicated $t\bar{t}$ run: is there any new physics testable scenario?

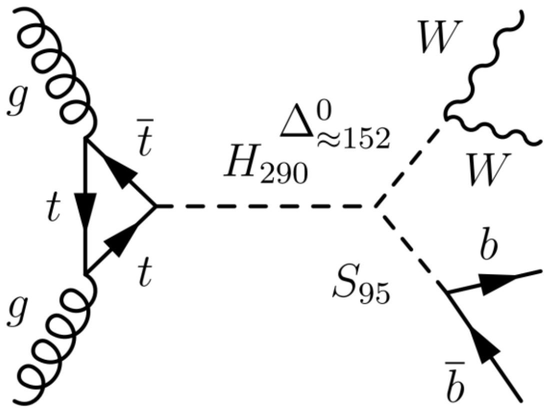
“No model can describe all measured distributions within their uncertainties.” [ATLAS]

- Higher order corrections? Toponium?
- New Physics pollution of this SM measurement?

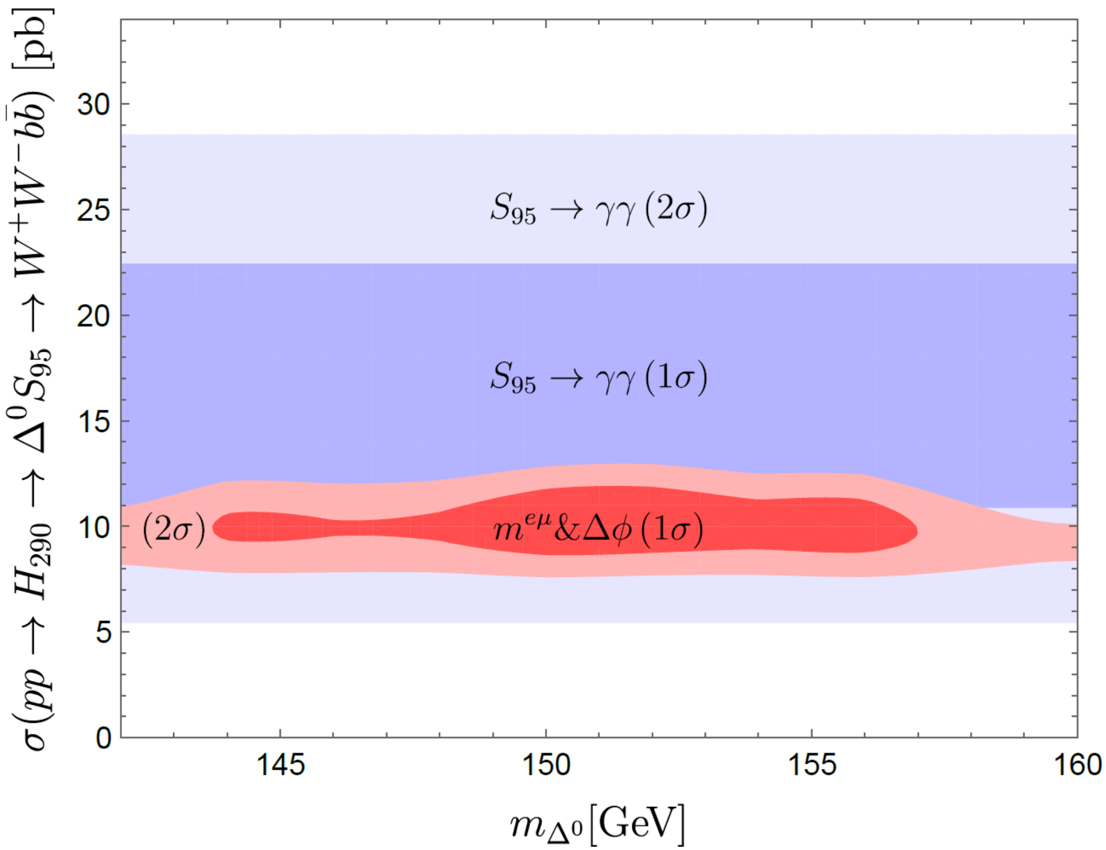
[F. Maltoni, D. Pagani et al.] [F. Maltoni, C. Severi et al.] [Bagnschi, Corcella et al.]

95 GeV and 152 GeV excesses?

[S. Banik, GC, A. Crivellin, B. Mellado]



- S_{95}: SM singlet mostly decaying to $b\bar{b}$
- Δ^0: real Higgs triplet mostly decaying to WW



Consistent with the 95 GeV $\gamma\gamma$ signal strength and a mass for Δ^0 of 152 GeV