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Swiss National Science Foundation

Drell-Yan Production of Higgses in 2HDMs

S. Banik, **G. Coloretti**, A. Crivellin, H. Haber

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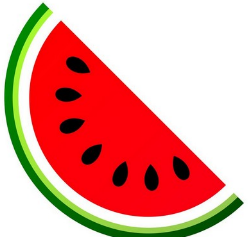


Guglielmo Coloretti
University of Zurich

Scalars 2025
Warsaw, 24.09.2025

Outline

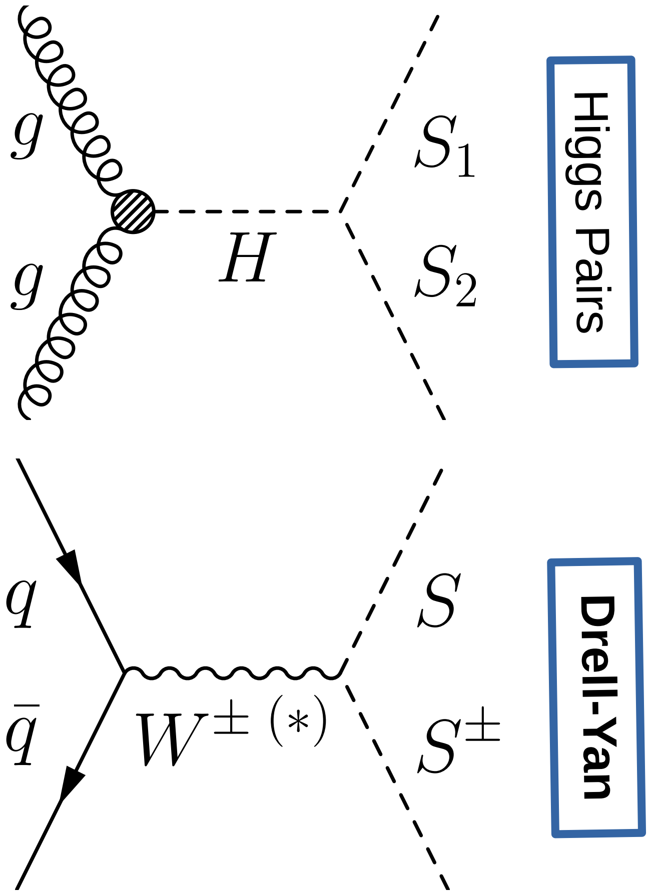
- (Asymmetric-) associated production of Higgses at the LHC
- Drell-Yan production of Higgses in 2HDMs
- The flavored-Aligned 2HDM (A-2HDM)
- Correlating di-photon branching ratios with EDMs
- The 95 GeV and 152 GeV di-photon excesses

(Asymmetric-) Associated Production

- Provides a yet unexplored window on new physics
  [ATLAS and CMS reviews]

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

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



Drell-Yan Production

Higgses produced via Drell-Yan at the LHC satisfy specific properties

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Higgses produced via Drell-Yan at the LHC satisfy specific properties

No direct or tiny Yukawa couplings	⇒	Suppressed gluon-fusion produciton
Have small vacuum expectation value	⇒	Suppressed VBF and VH production
Small mixing with the SM Higgs boson	⇒	Alignment limit

Higgs Doublet

- Higgs basis: $\langle \mathcal{H}_2 \rangle = 0$ and (for small mixing) VBF/VH naturally suppressed
- Cross section fixed by $SU(2)_L$ representation ($\approx 100\ \mathrm{fb}$) **and** difficult to have large di-photon branching ratios for EW scalars with usual Z_2 symmetries

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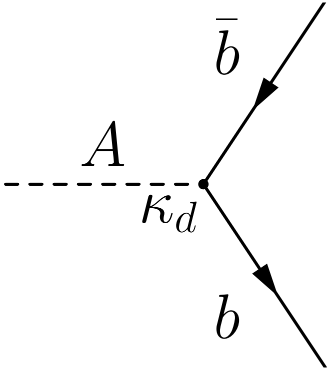

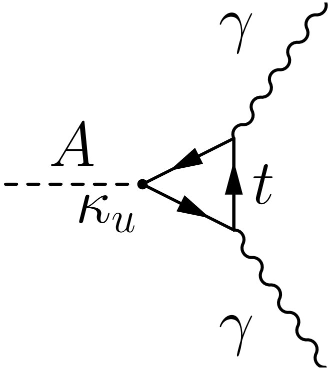

	Type-I	Type-II
κ_u	$\cot(\beta)$	$\cot(\beta)$
κ_d	$\cot(\beta)$	$-\tan(\beta)$

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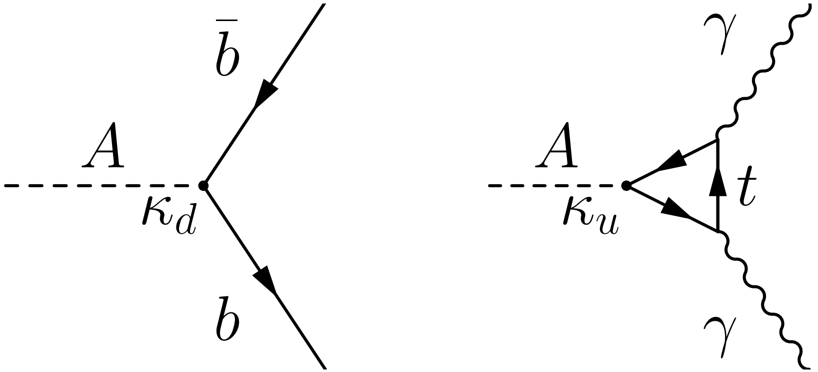

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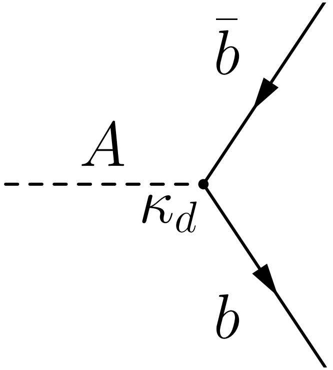

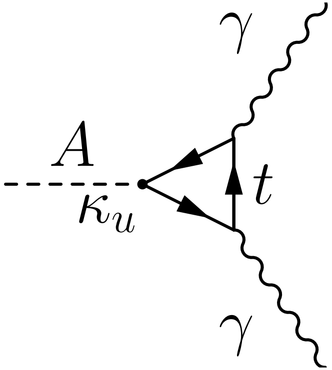

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$$m_{H^\pm} \geq 800\mathrm{GeV}$$

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

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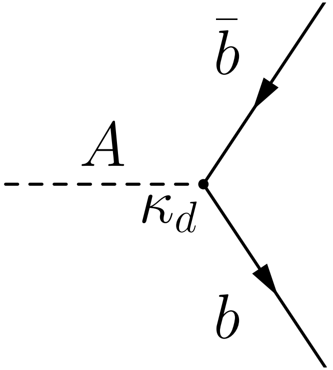

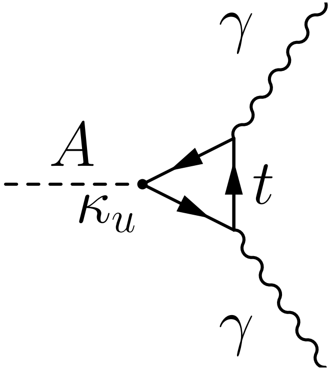

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Composite Higgs? **Relaxing the Z_2 symmetries?**

Flavor-Aligned 2HDM [P. Tuzon and A. Pich]

$$\begin{aligned} -\mathcal{L}_Y = & Y_d \overline{Q}_L (\mathcal{H}_1 + a_d \mathcal{H}_2) d_R + \\ & Y_l \overline{L}_L (\mathcal{H}_1 + a_l \mathcal{H}_2) l_R \\ & Y_u \overline{Q}_L (\tilde{\mathcal{H}}_1 + a_u^* \tilde{\mathcal{H}}_2) u_R + \mathrm{H.c.} \end{aligned}$$

$\longrightarrow$

- Yukawa terms are aligned in flavor space
- No FCNC !

Flavor-Aligned 2HDM
[P. Tuzon and A. Pich]

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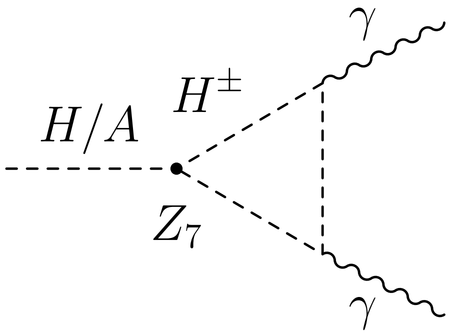
$$
\mathcal{V}_{\mathrm{A2HDM}} \supset
\left[Z_6 \mathcal{H}_1 \mathcal{H}_1^\dagger + Z_7 \mathcal{H}_2 \mathcal{H}_2^\dagger \right] \mathcal{H}_1 \mathcal{H}_2^\dagger + \mathrm{H.c.}
$$



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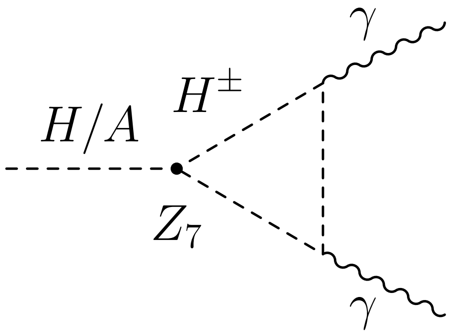

$$
\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \Re Z_6 & -\Im Z_6 \\ \Re Z_6 & \frac{1}{2}\left[Z_{4c} + \Re Z_5\right] & -\frac{1}{2}\Im Z_5 \\ -\Im Z_6 & -\frac{1}{2}\Im Z_5 & \left[Z_{4c} - \Re Z_5\right] \end{pmatrix}
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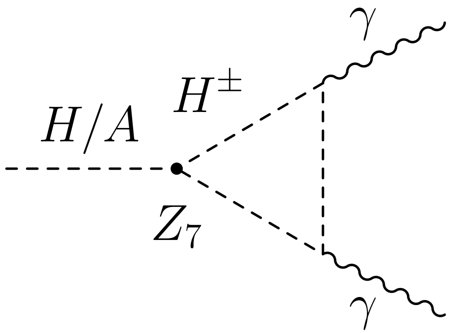


- Z_7 **independent** of neutral mixing angles!
- CP-violation can mediate large EDMs

CP-violation

- CP-violation of the model **(Baryogenesis?)**

  [K. Enomoto, S. Kanemura and Y. Mura]

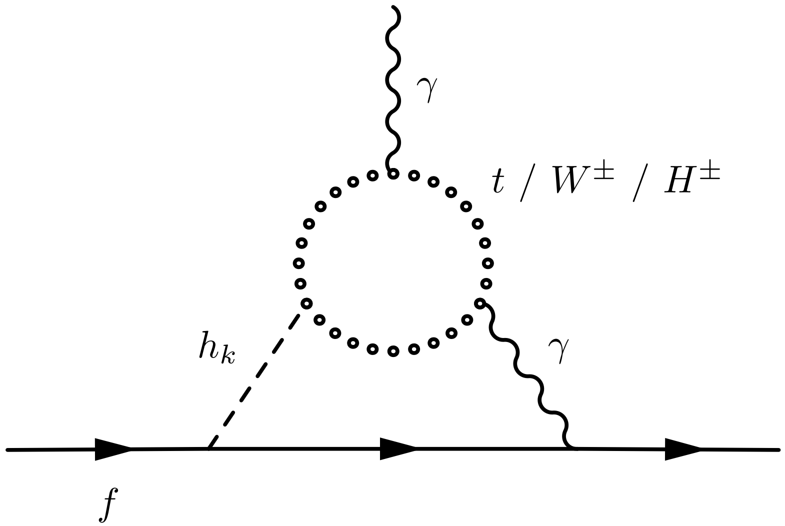
Yukawa sector: a_U, a_D, a_L

Scalar potential: Z_5, Z_6, Z_7

- $\Re[Z_7]\,/\,\Im[Z_7]$ drives the di-photon branching ratios of $H\,/\,A$

- Correlating $\mathrm{Br}[A \to \gamma\gamma]$ to EDMs?

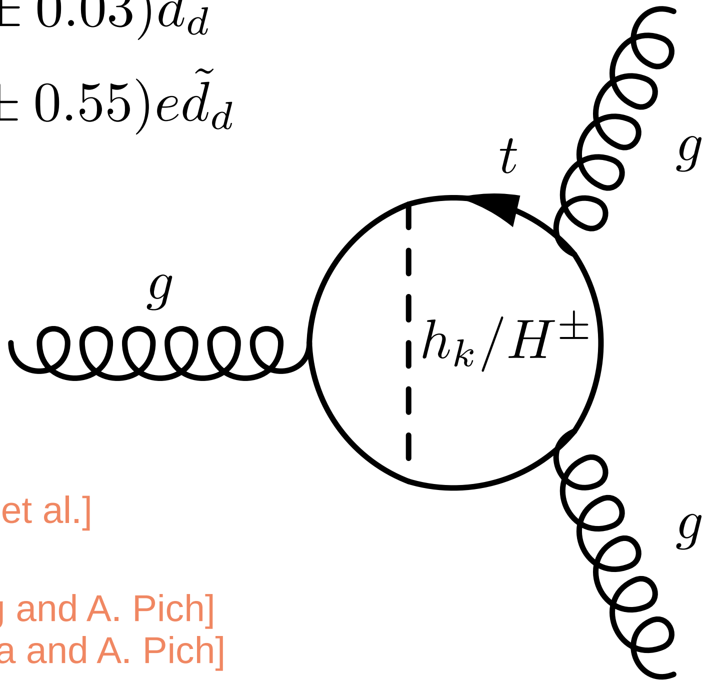
$$i d_f \bar{f} \sigma^{\mu\nu} F_{\mu\nu} f \subset$$



EDMs

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

$$
\begin{aligned}
d_n = &-(0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d \\
&-(0.55 \pm 0.28) e\tilde{d}_u - (1.1 \pm 0.55) e\tilde{d}_d \\
&+(50 \pm 40)\ \text{MeV}\ e\tilde{d}_G
\end{aligned}
$$

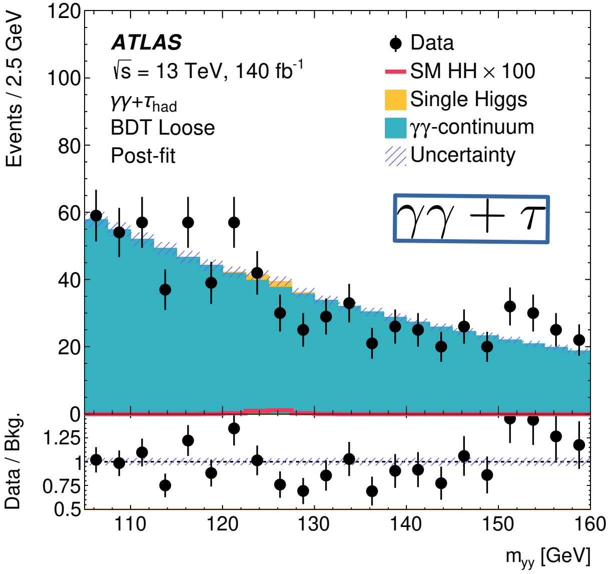


- RGE improved chromo-magnetic contributions
- Analytic results [W. Altmannshofer, S. Gori et al.]
- $H^{\pm}$ contributions $\propto \Im[a_U^*\, a_D]$ [M. Jung and A. Pich] [J. Davila and A. Pich]

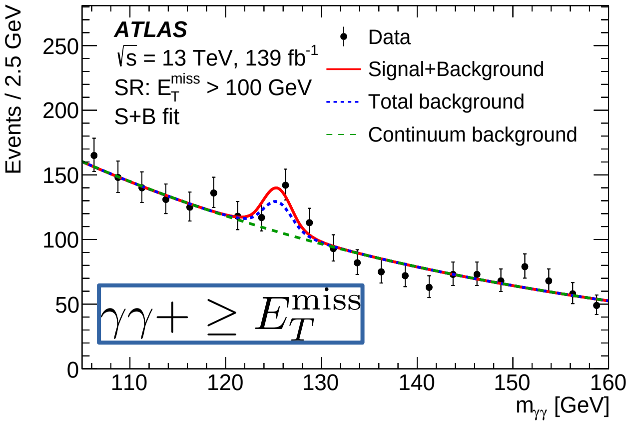
Excesses at 152 GeV

- Several signal regions (2 ATLAS analyses)
- Associated **SM Higgs** boson production

[ATLAS-1]



[ATLAS-2]



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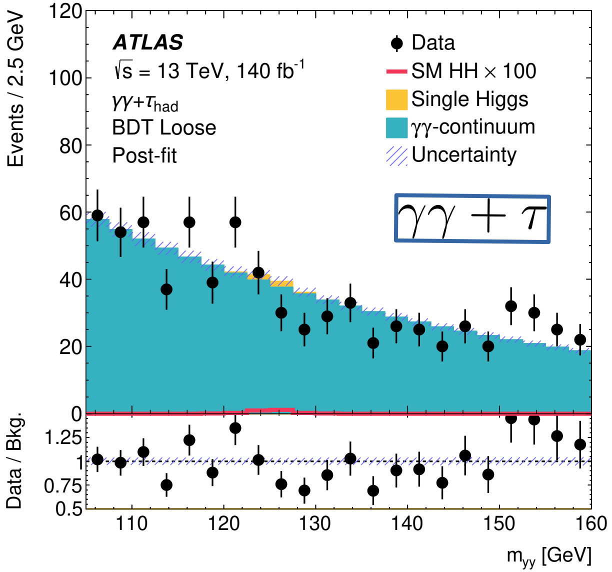

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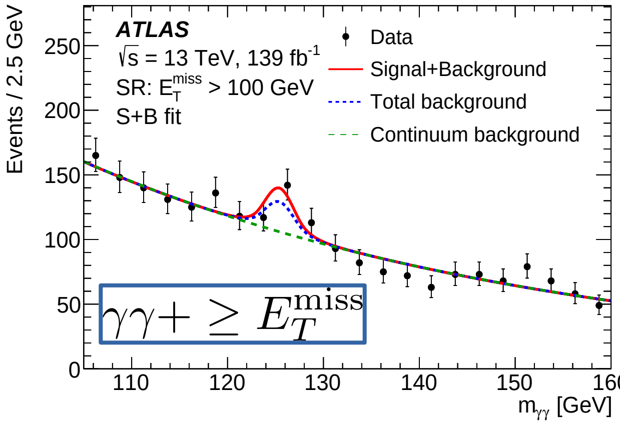

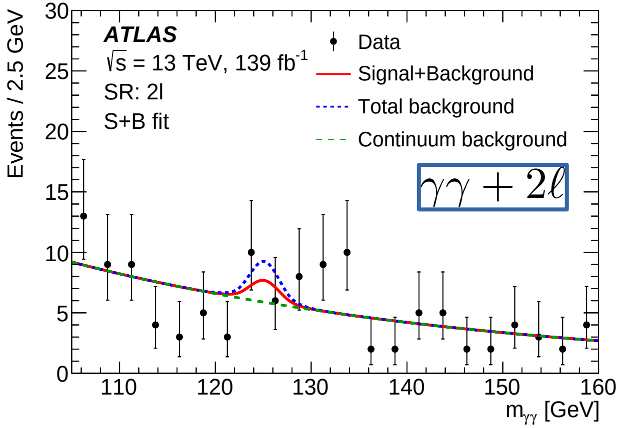

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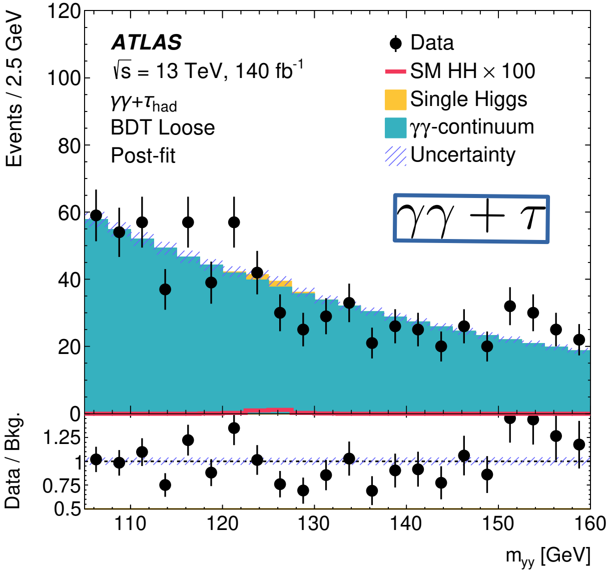
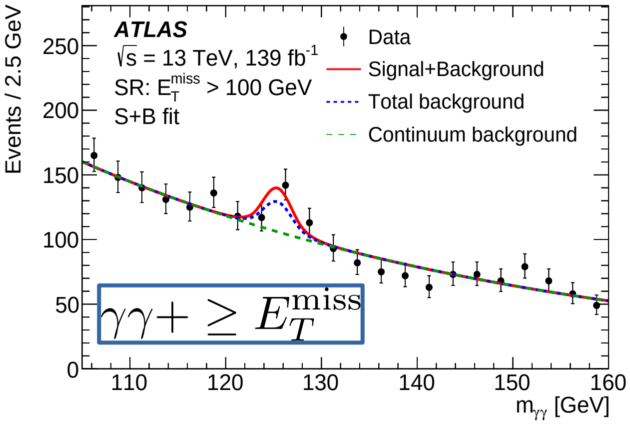
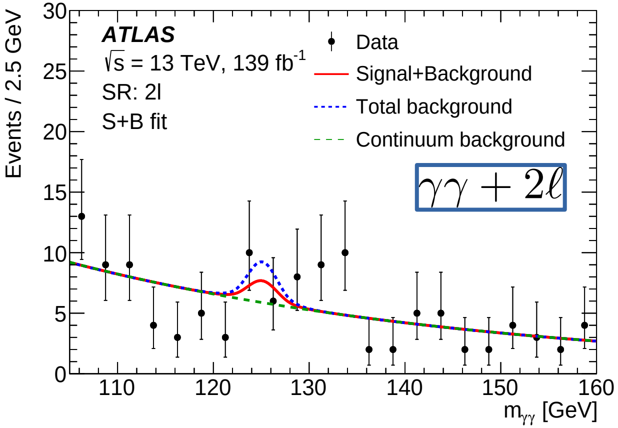


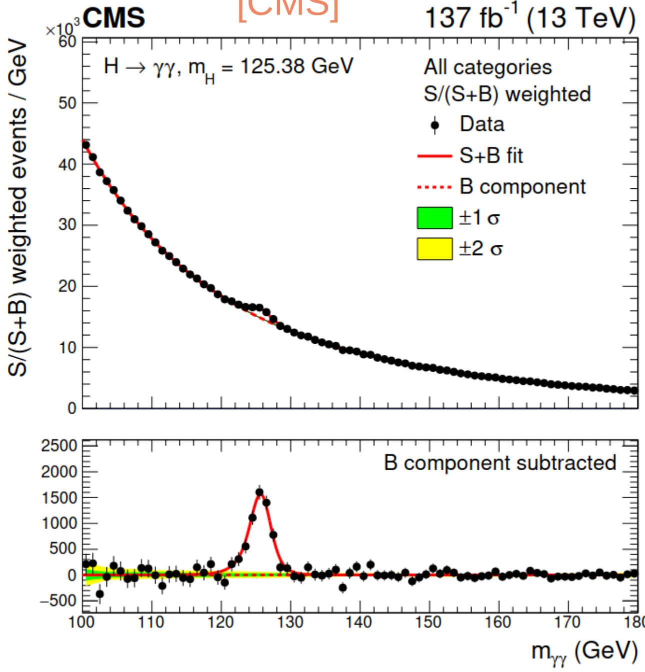
[ATLAS-2]





Only mild excess in inclusive analyses

[CMS]



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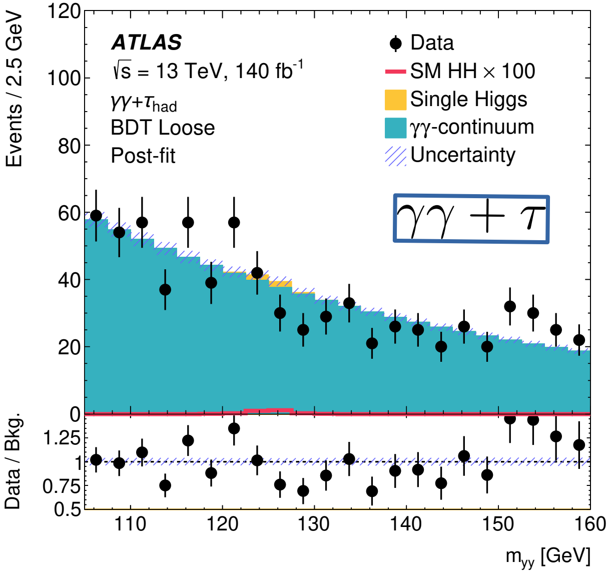
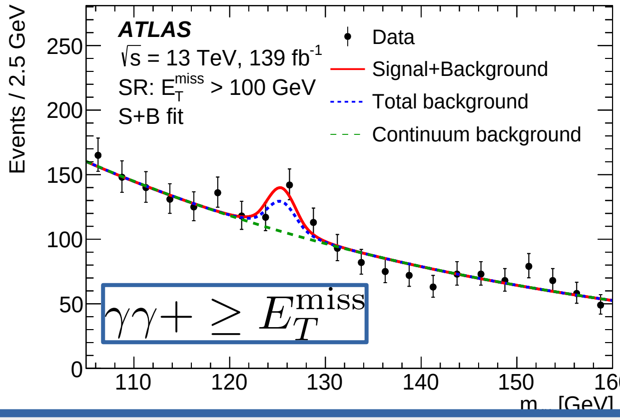
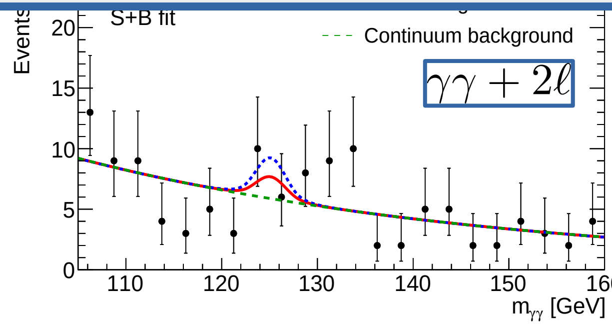


[ATLAS-2]



Associated production of a neutral Higgs!



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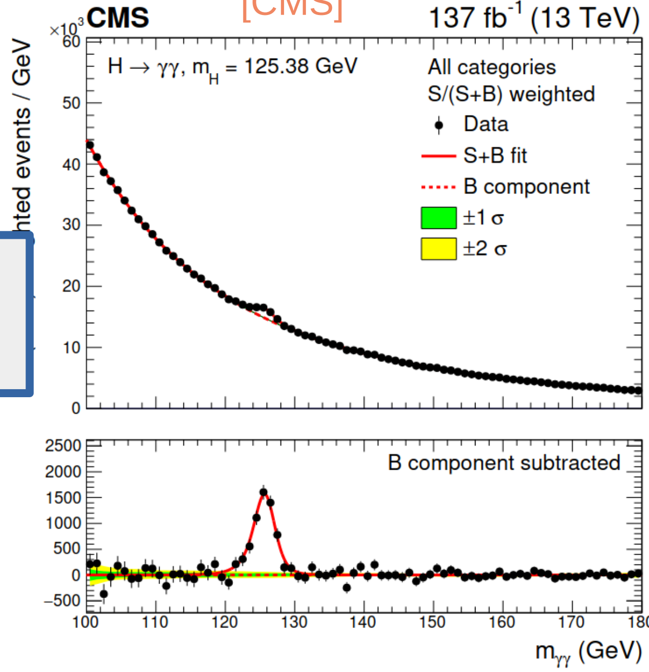
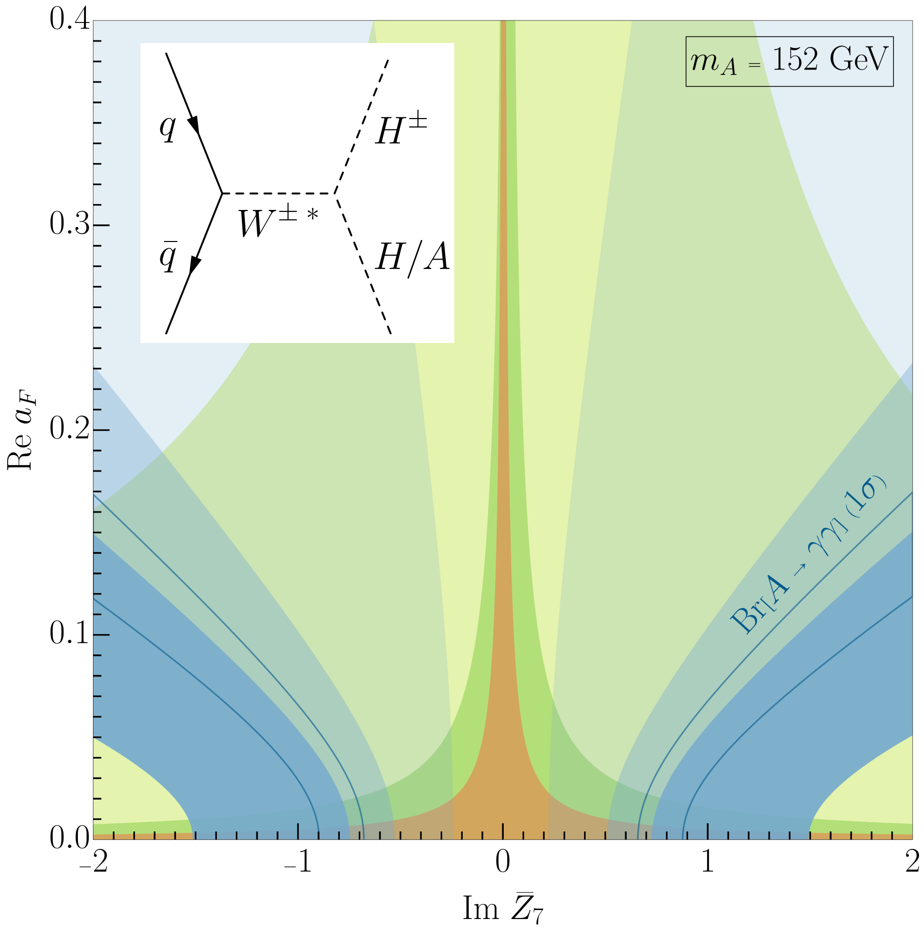


Results (152 GeV)



$|d_e| \leqslant 4.1 \times 10^{-30}$ e cm

$|d_p| \leqslant 10^{-29}$ e cm (prospect)

$|d_n| \leqslant 10^{-28}$ e cm (prospect)

$0.1\% < \mathrm{Br}[A \to \gamma\gamma] \leqslant 0.5\%$

$0.5\% < \mathrm{Br}[A \to \gamma\gamma] \leqslant 1\%$

$1\% < \mathrm{Br}[A \to \gamma\gamma] \leqslant 4\%$

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

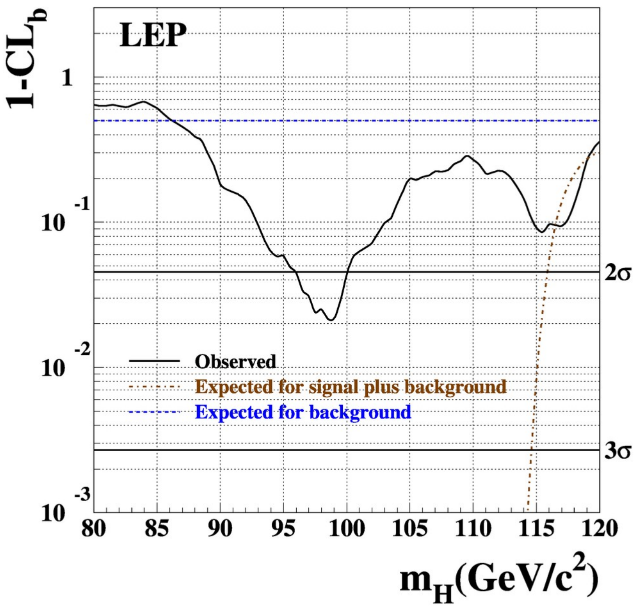
- a_F controls the Yukawa couplings (gluon fusion)
- Z_7 governs the $\gamma\gamma$ rate
- Suppressed mixing among neutral scalars

Excesses at 95/98 GeV

[T. Biekotter, S. Heinemeyer, G. Weiglein]

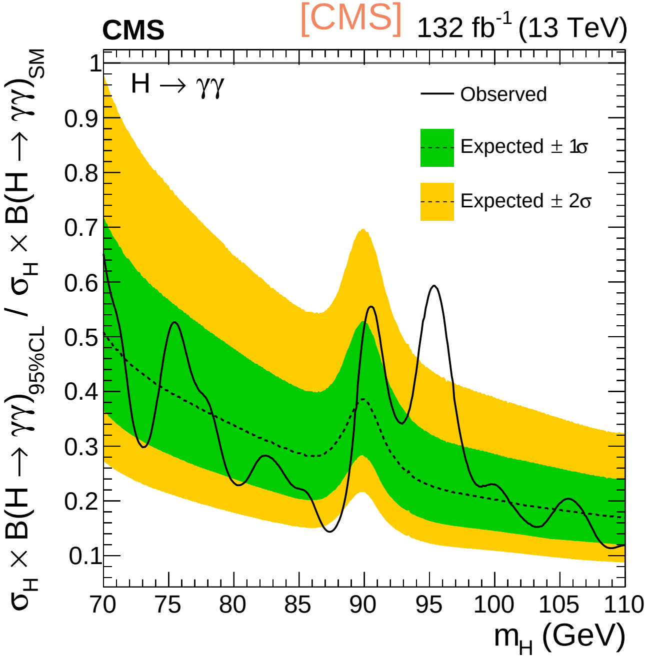
LEP: $Z+bb$ $(2.3\,\sigma)$

[LEP]



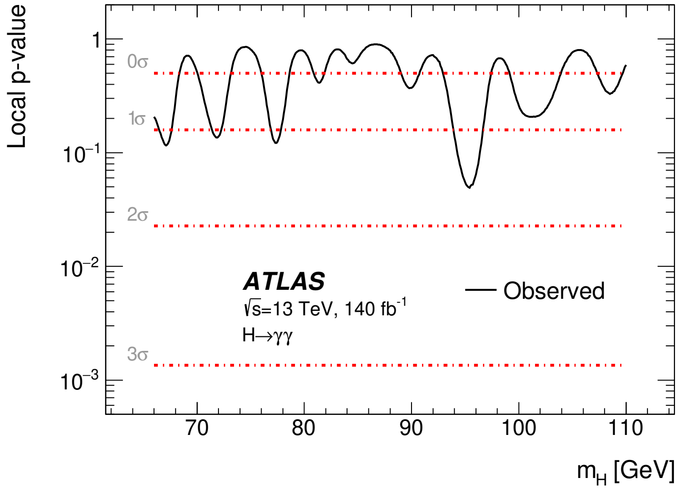
CMS: $\gamma\gamma$ $(2.9\,\sigma)$

[CMS]



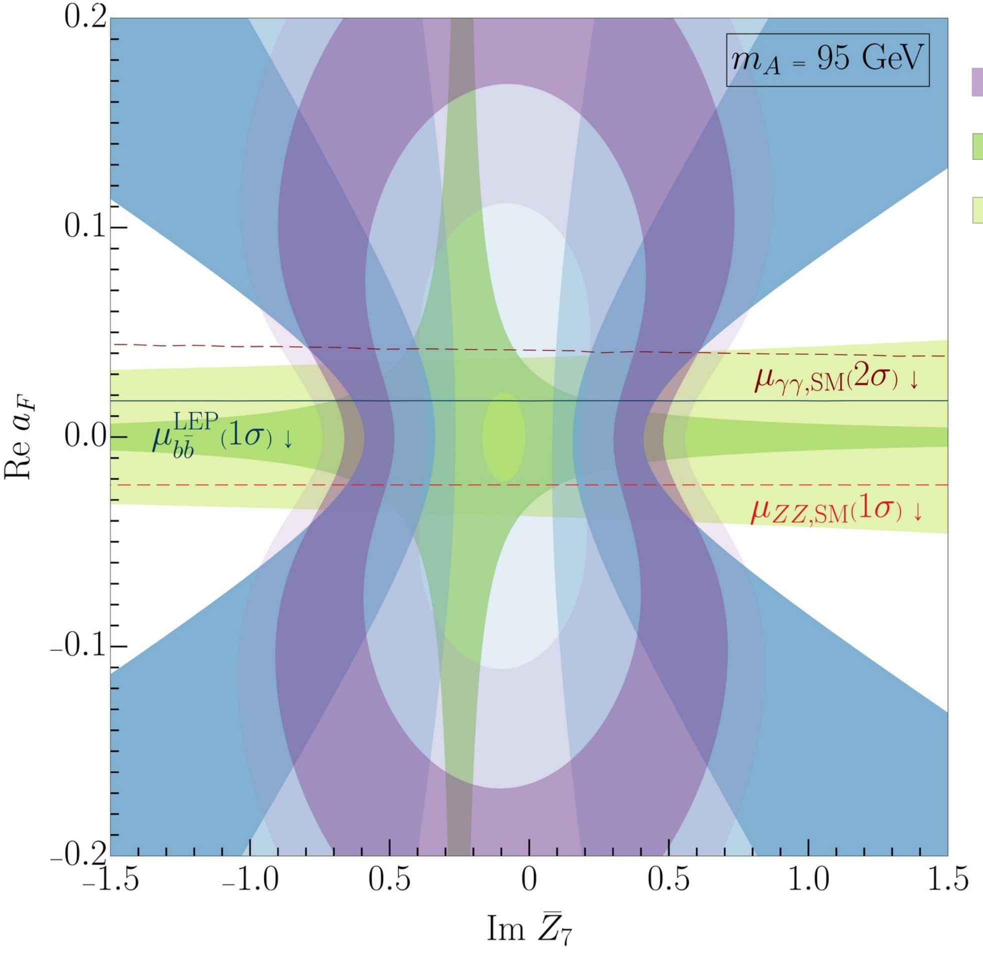
ATLAS: $\gamma\gamma$ $(1.7\,\sigma)$

[ATLAS]



Inclusive dedicated searches for light EW scalars

Results (95 GeV)



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[GeV]	125	98	95	130

- Little gluon fusion production needed
- Sizable mixing of H with SM Higgs boson (bb excess in Higgs strahlung at LEP at $98\,\text{GeV}$)

Conclusions and Outlook

- Asymmetric associated production of scalars is a prominent signature to look for NP at the LHC
- Flavor-Aligned 2HDM offers sizable $\mathrm{Br}[A \to \gamma\gamma]$ for EW scale masses which can be correlated to CP-violating effects such as EDMs
- Achieved independent explanation of the diphoton excesses at $95\,\mathrm{GeV}$ and at $152\,\mathrm{GeV}$

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THANK YOU FOR THE ATTENTION!