



University of
Zurich^{UZH}



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Drell-Yan Production of Higgses in 2HDMs

S. Banik, **G. Coloretti**, A. Crivellin, H. Haber
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Guglielmo Coloretti
University of Zurich

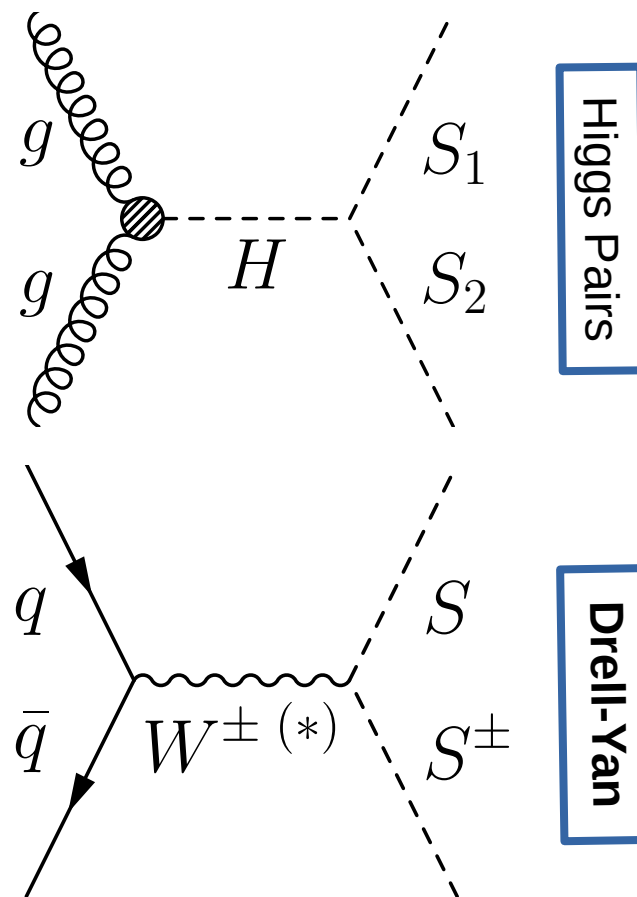
Scalars 2025
Warsaw, 24.09.2025

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**



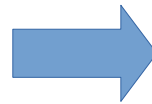
Drell-Yan Production

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

Drell-Yan Production

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

No direct or tiny Yukawa couplings



Suppressed gluon-fusion production

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Suppressed gluon-fusion production

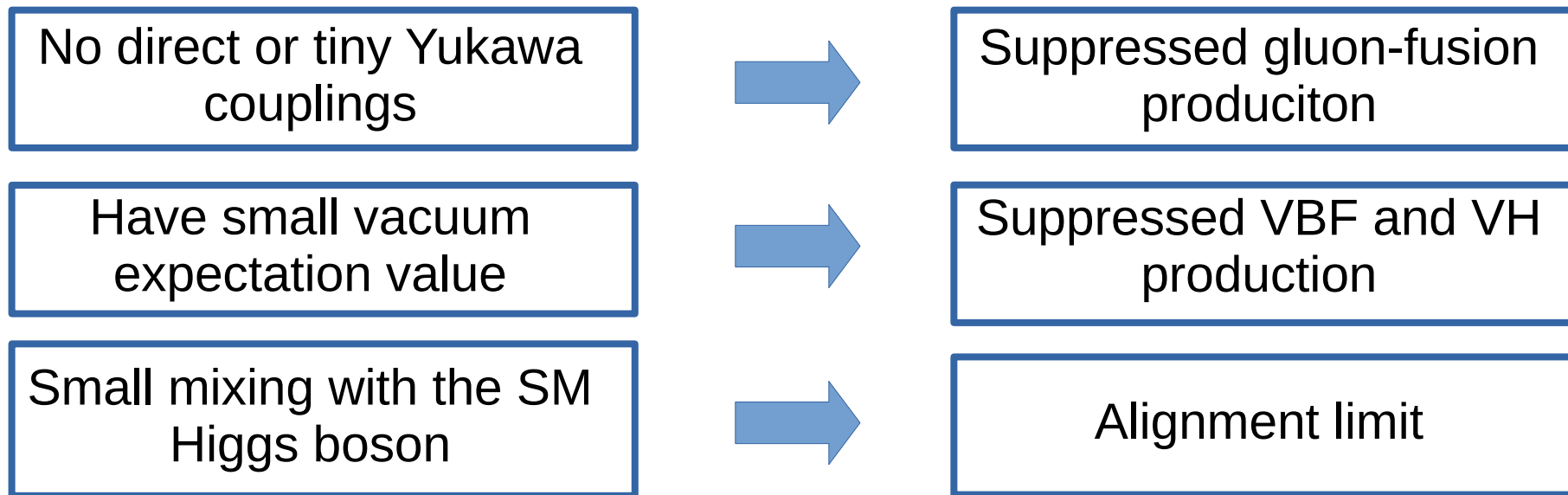
Have small vacuum expectation value



Suppressed VBF and VH production

Drell-Yan Production

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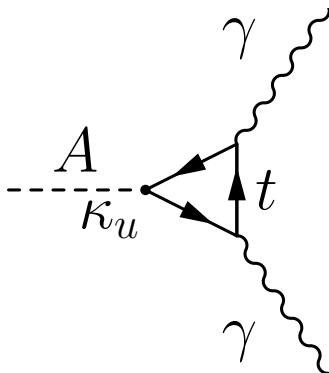
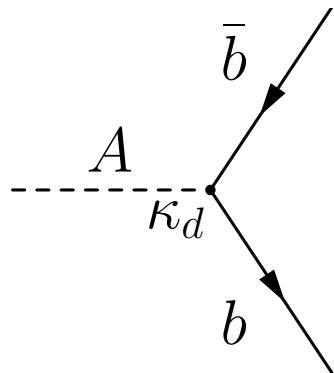


Higgs Doublet

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

Higgs Doublet

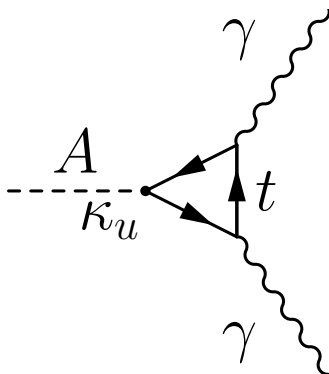
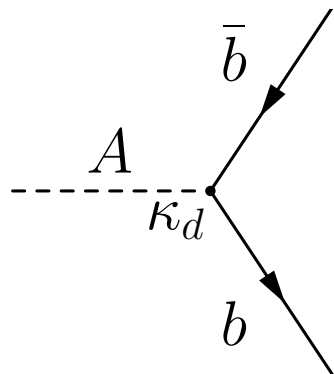
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	Type-I	Type-II
κ_u	$\cot(\beta)$	$\cot(\beta)$
κ_d	$\cot(\beta)$	$-\tan(\beta)$

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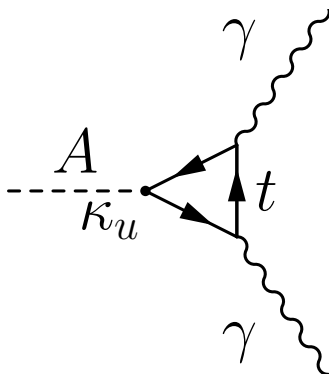
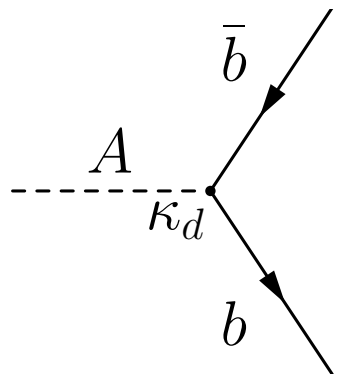


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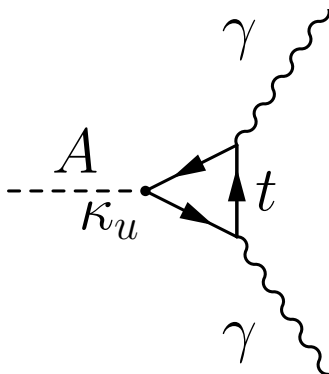
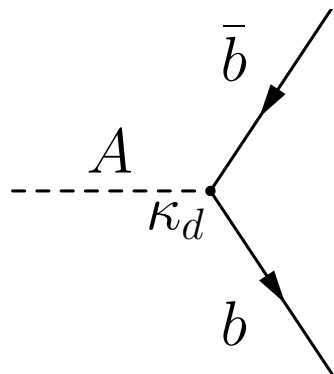
$$m_{H^\pm} \geq 800 \text{ GeV}$$

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

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

Flavor-Aligned 2HDM

[P. Tuzon and A. Pich]

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



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

Flavor-Aligned 2HDM

[P. Tuzon and A. Pich]

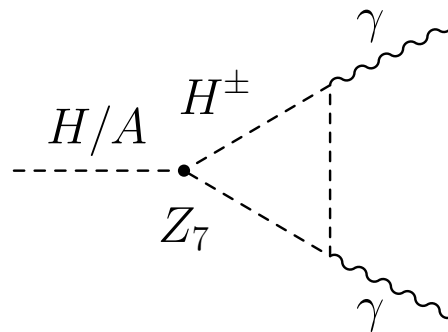
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$$\mathcal{V}_{\text{A2HDM}} \supset$$

$$\left[Z_6 \mathcal{H}_1 \mathcal{H}_1^\dagger + Z_7 \mathcal{H}_2 \mathcal{H}_2^\dagger \right] \mathcal{H}_1 \mathcal{H}_2^\dagger + \text{H.c.}$$



Flavor-Aligned 2HDM

[P. Tuzon and A. Pich]

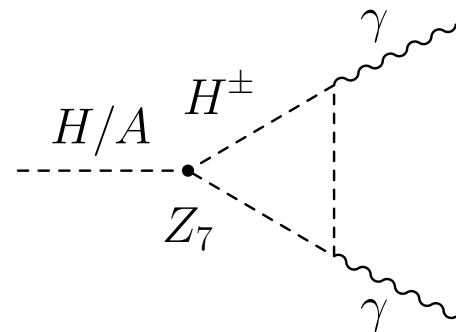
$$\begin{aligned}
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$$\mathcal{M}^2 = v^2 \begin{pmatrix} Z_1 & \Re Z_6 & -\Im Z_6 \\ \Re Z_6 & \frac{1}{2} [Z_{4c} + \Re Z_5] & -\frac{1}{2} \Im Z_5 \\ -\Im Z_6 & -\frac{1}{2} \Im Z_5 & [Z_{4c} - \Re Z_5] \end{pmatrix}$$

Flavor-Aligned 2HDM

[P. Tuzon and A. Pich]

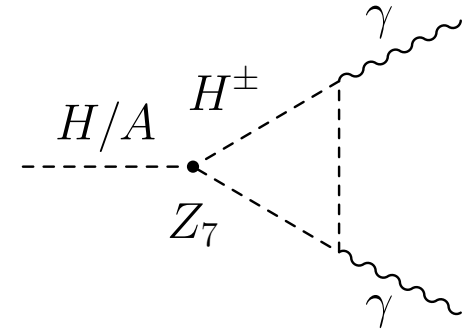
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- Z_7 **independent** of neutral mixing angles!
- CP-violation can mediate large EDMs

CP-violation

- CP-violation of the model
(Baryogenesis?)

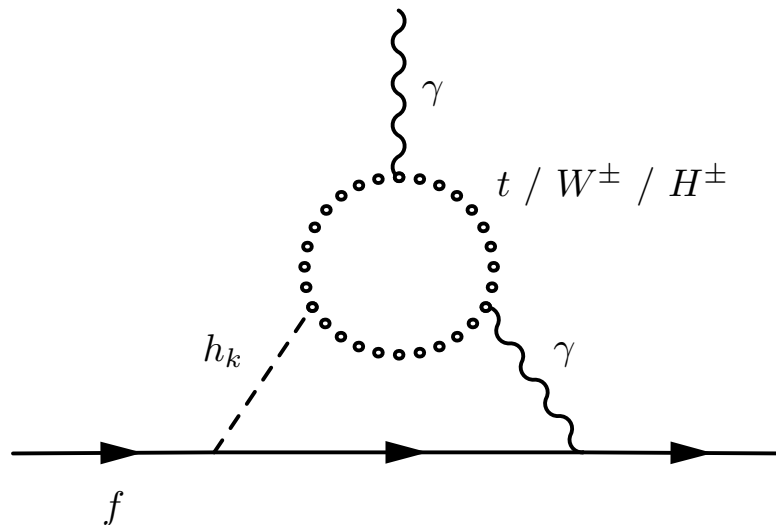
[K. Enomoto, S. Kanemura and Y. Mura]

- $\Re[Z_7] / \Im[Z_7]$ drives the di-photon branching ratios of H / A
- Correlating $\text{Br}[A \rightarrow \gamma\gamma]$ to EDMs?

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

Yukawa sector: a_U, a_D, a_L

Scalar potential: Z_5, Z_6, Z_7

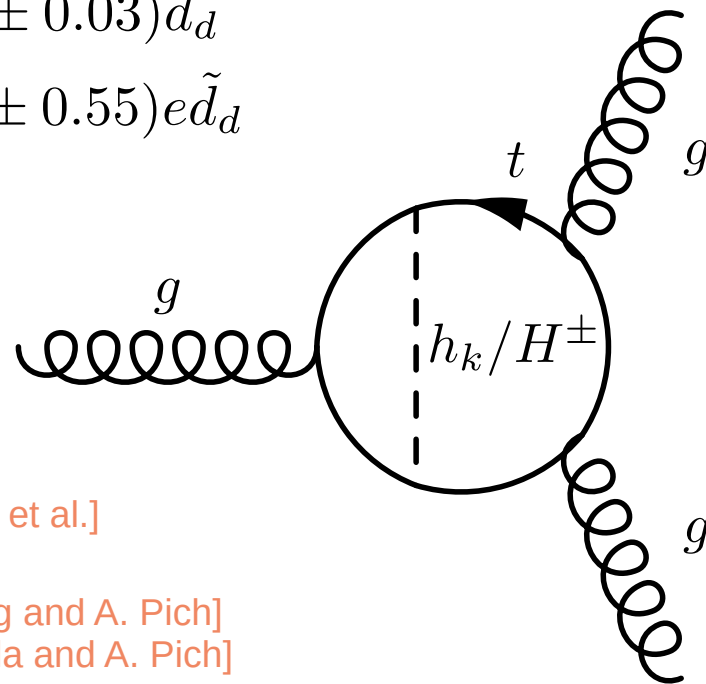


EDMs

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

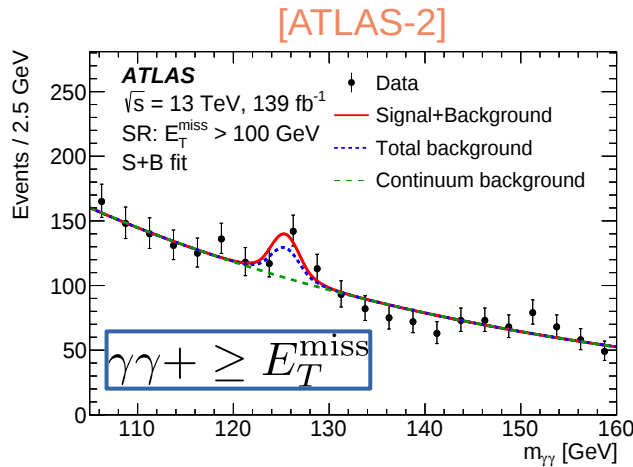
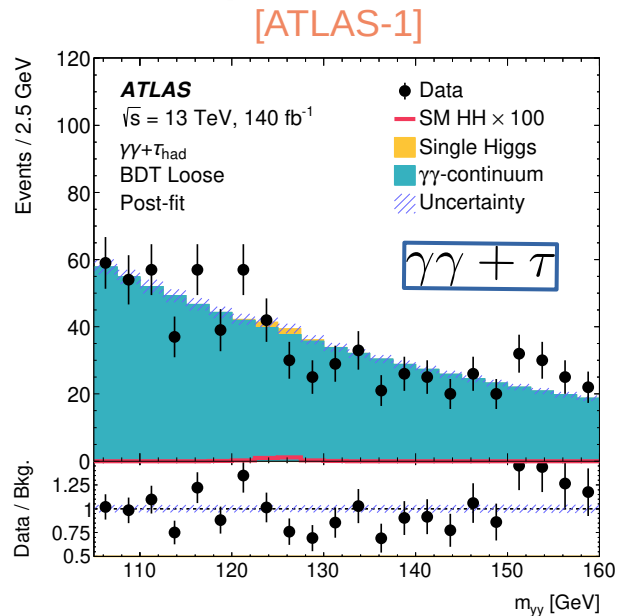
$$\begin{aligned} d_n = & - (0.20 \pm 0.01) d_u + (0.78 \pm 0.03) d_d \\ & - (0.55 \pm 0.28) e \tilde{d}_u - (1.1 \pm 0.55) e \tilde{d}_d \\ & + (50 \pm 40) \text{ MeV } e \tilde{d}_G \end{aligned}$$

- 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]



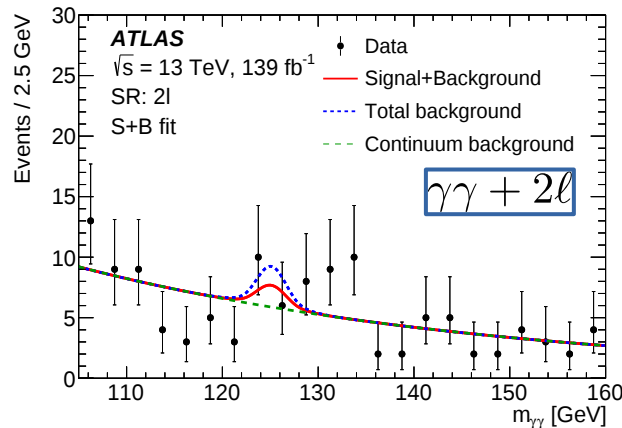
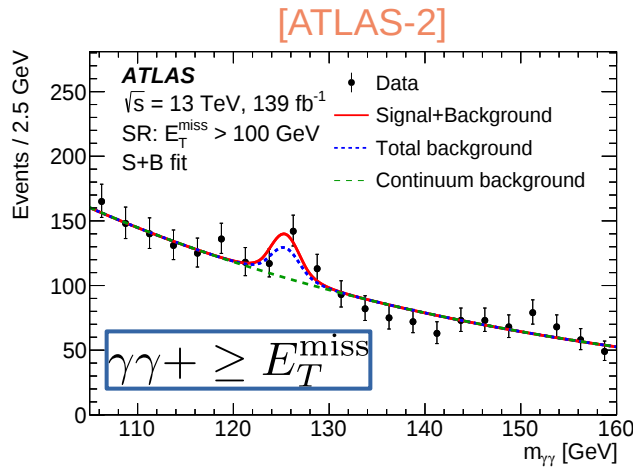
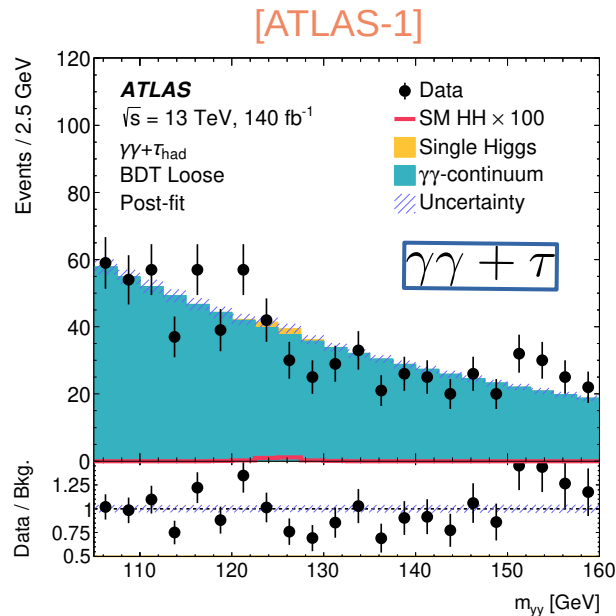
Excesses at 152 GeV

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



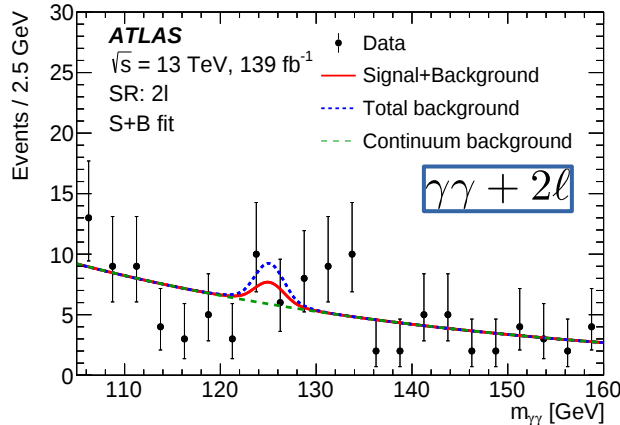
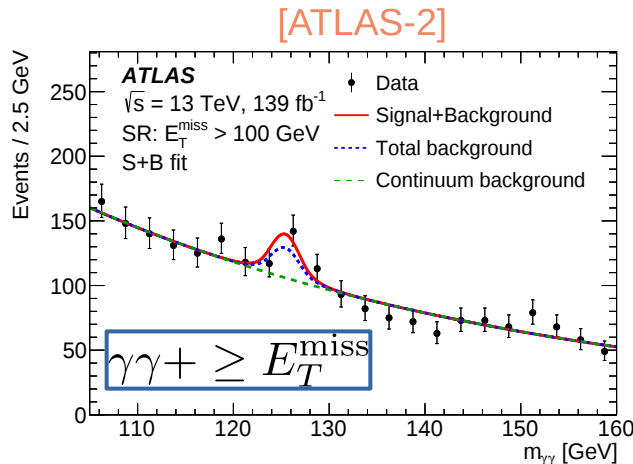
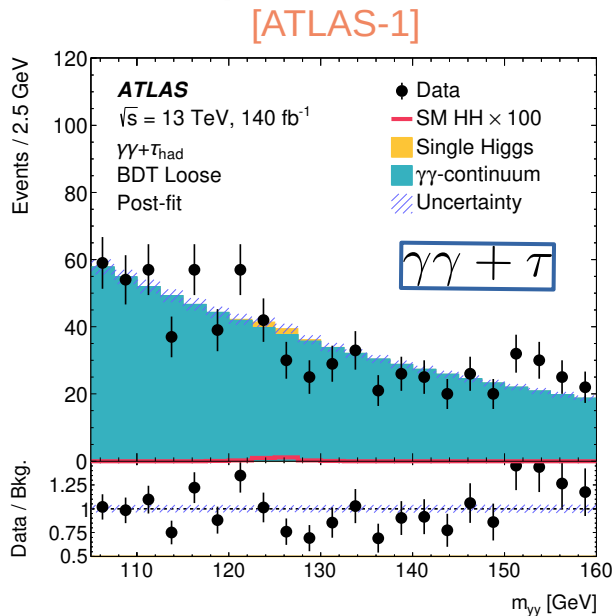
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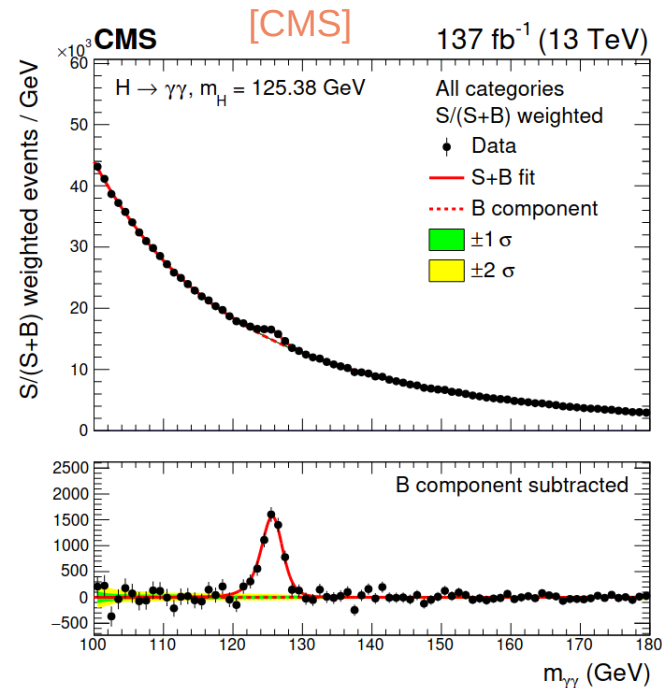


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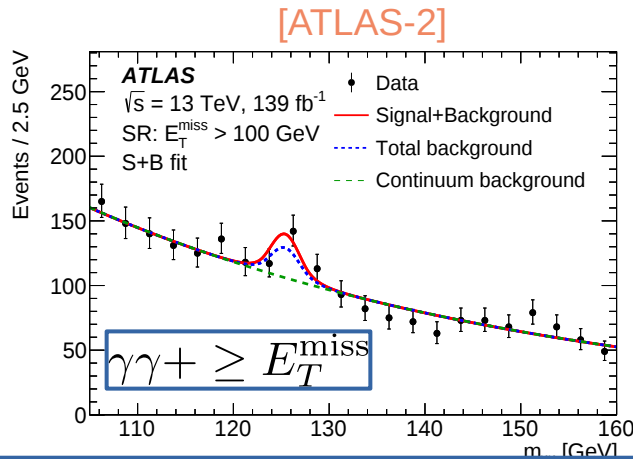
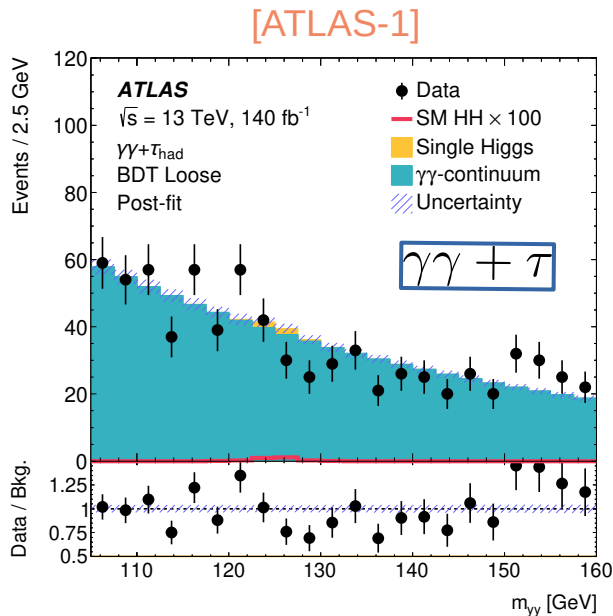


Only mild excess in inclusive analyses

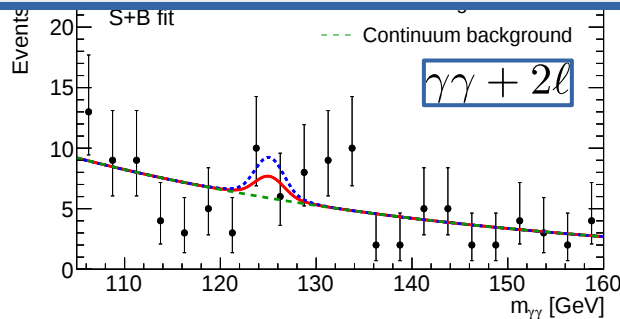


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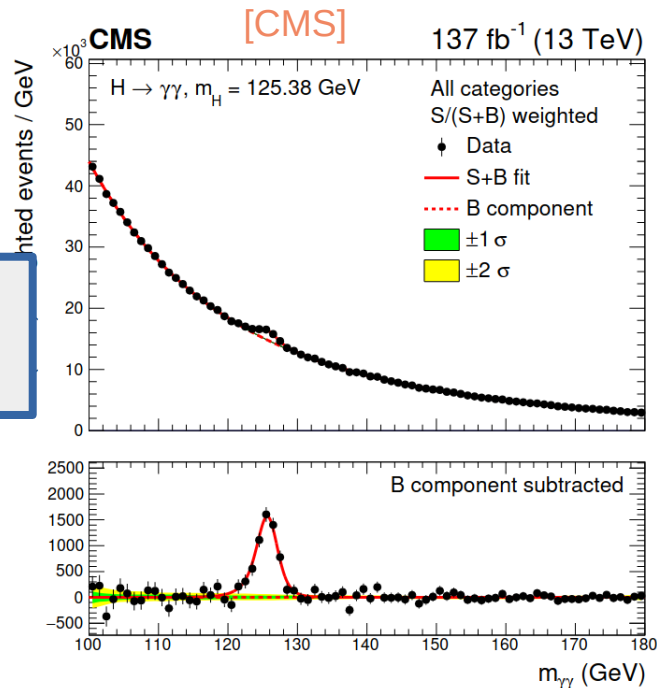
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- Associated **SM Higgs** boson production



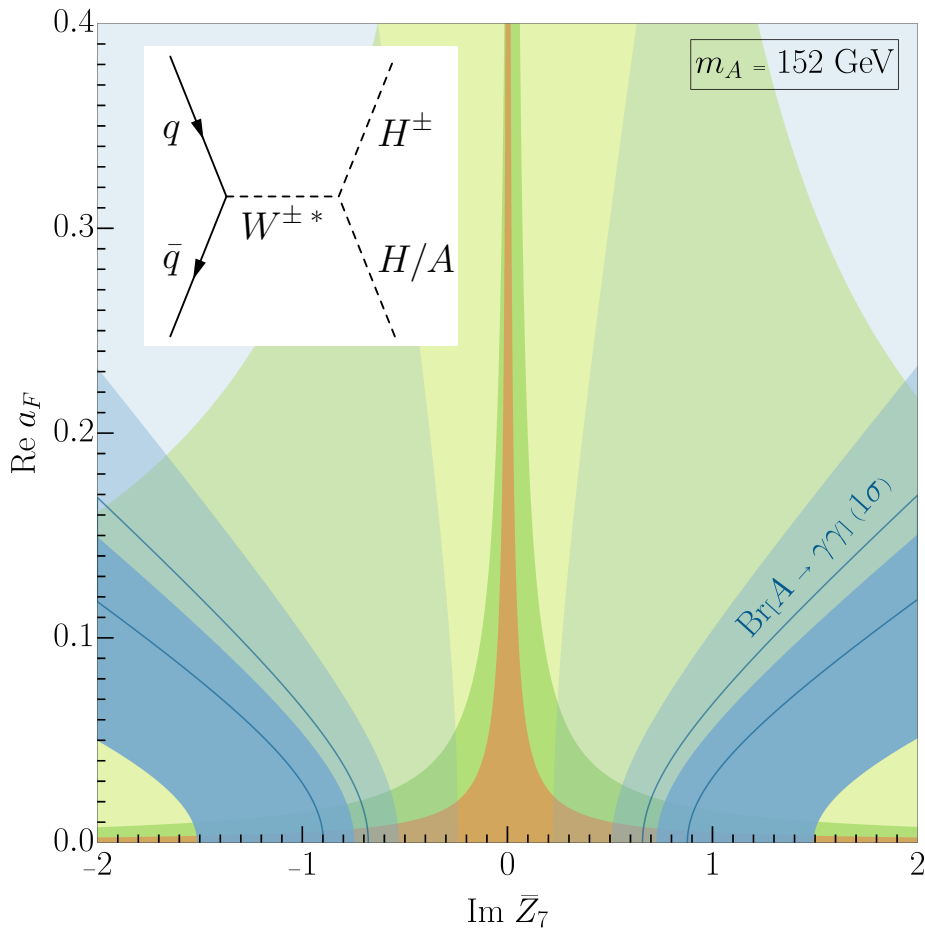
Associated production of a neutral Higgs!



Only mild excess in inclusive analyses



Results (152 GeV)



- $|d_e| \leq 4.1 \times 10^{-30} \text{ e cm}$
- $|d_p| \leq 10^{-29} \text{ e cm}$ (prospect)
- $|d_n| \leq 10^{-28} \text{ e cm}$ (prospect)
- $0.1\% < \text{Br}[A \rightarrow \gamma\gamma] \leq 0.5\%$
- $0.5\% < \text{Br}[A \rightarrow \gamma\gamma] \leq 1\%$
- $1\% < \text{Br}[A \rightarrow \gamma\gamma] \leq 4\%$

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

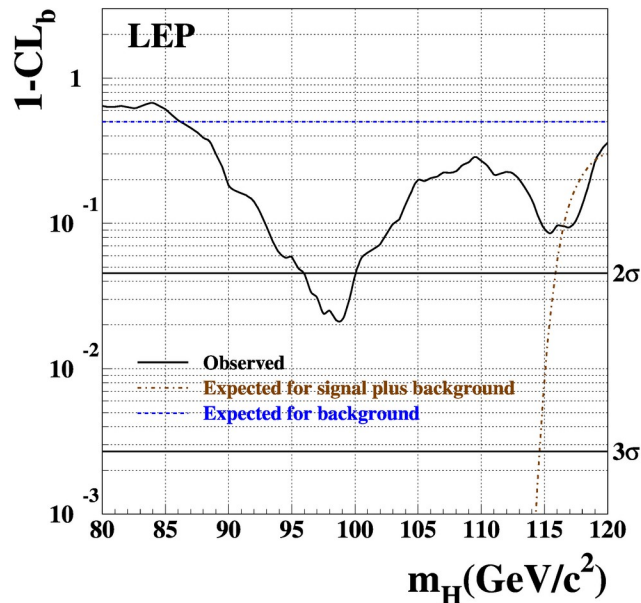
- a_F controls the Yukawa couplings (gluon fusion)
- Z_7 governs the $\gamma\gamma$ rate
- Suppressed mixing among neutral scalars

Excesses at 95/98 GeV

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

LEP: $Z + bb$ (2.3σ)

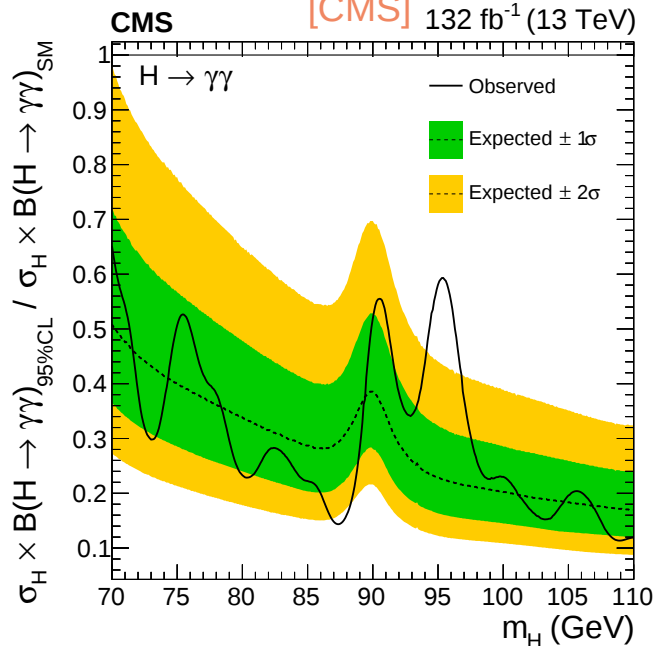
[LEP]



CMS: $\gamma\gamma$ (2.9σ)

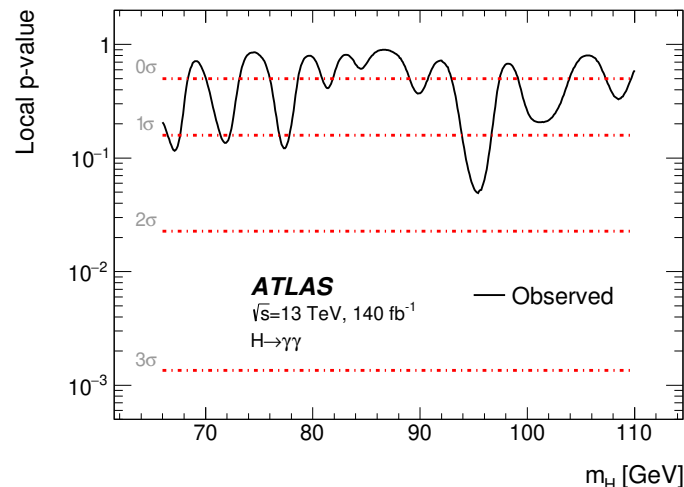
[CMS]

132 fb⁻¹ (13 TeV)



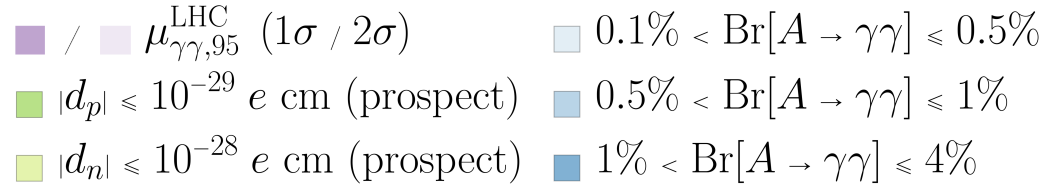
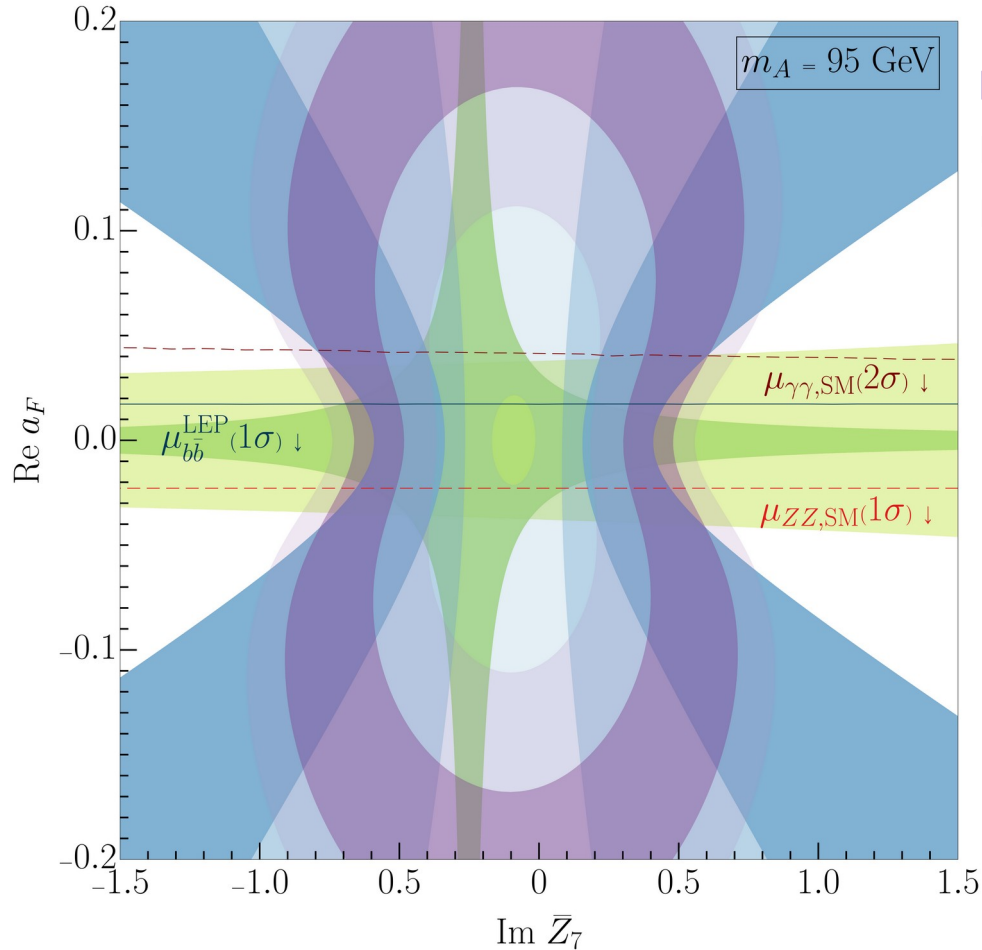
ATLAS: $\gamma\gamma$ (1.7σ)

[ATLAS]



Inclusive dedicated searches for light EW scalars

Results (95 GeV)



m	h	H	A	$H^\pm$
[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 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 $\text{Br}[A \rightarrow \gamma\gamma]$ for EW scale masses which can be correlated to CP-violating effects such as EDMs
- Achieved independent explanation of the diphoton excesses at 95 GeV and at 152 GeV

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THANK YOU FOR THE ATTENTION!