Associated production of Higgses in 2HDMs

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

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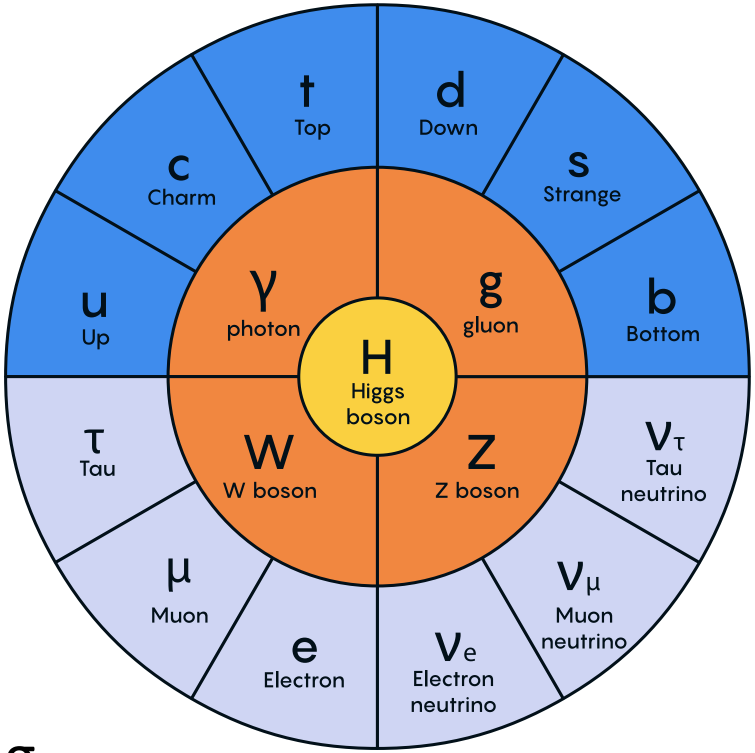
Outline

1. LHC di-photon excesses
2. Associated production at the LHC
3. Flavored aligned 2HDM (A2HDM)
4. CP violation and EDMs

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
- Electroweak (EW) scalars must play a sub-leading role in EW spontaneous symmetry breaking

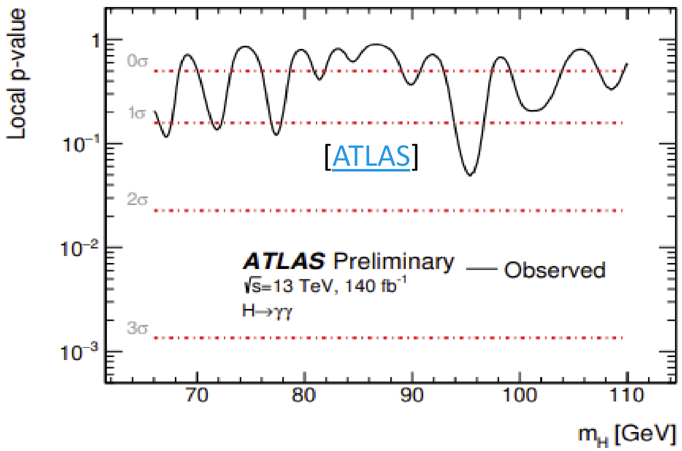


Di-photon excesses

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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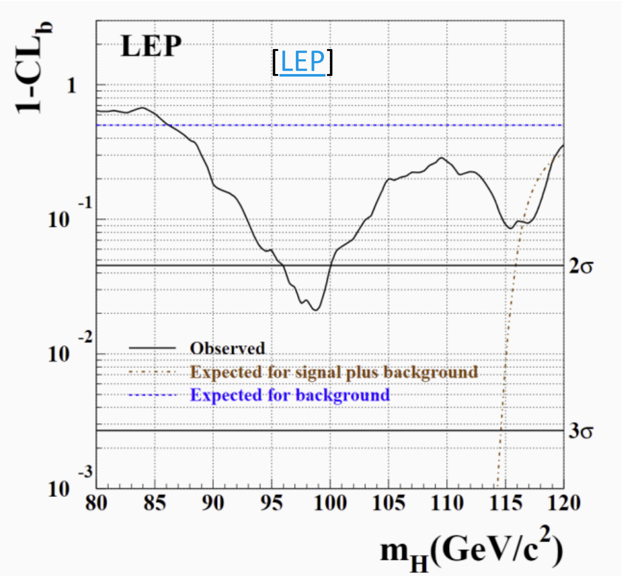
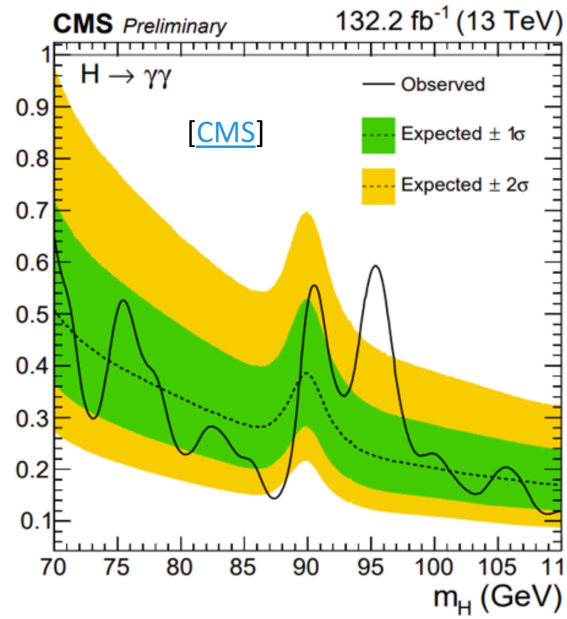
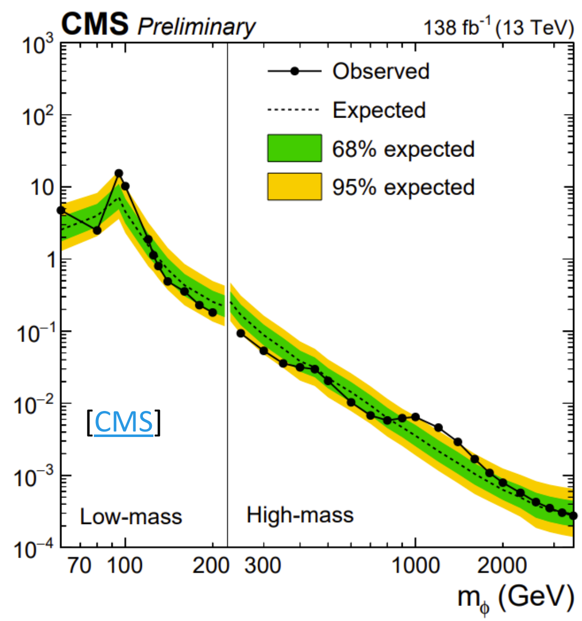
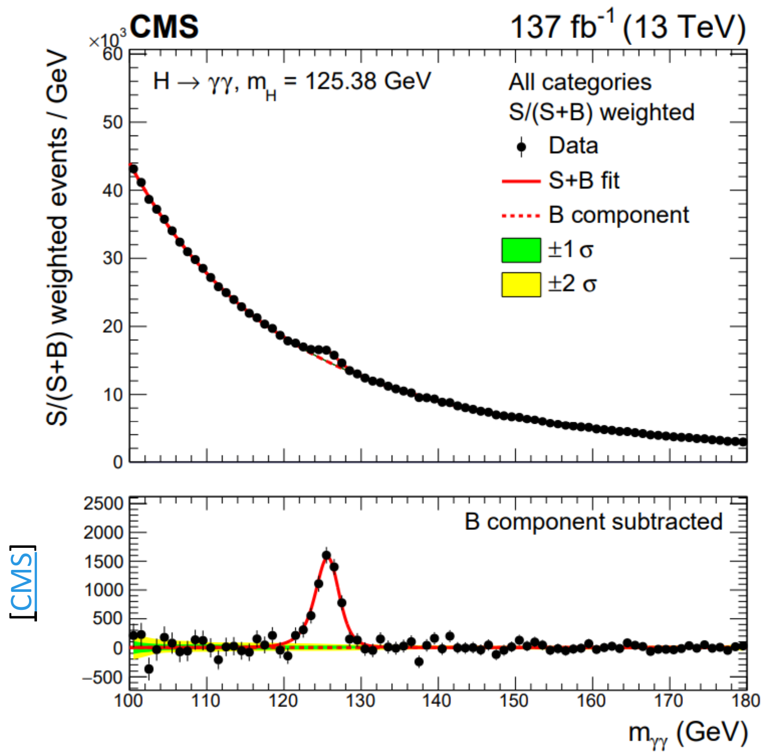




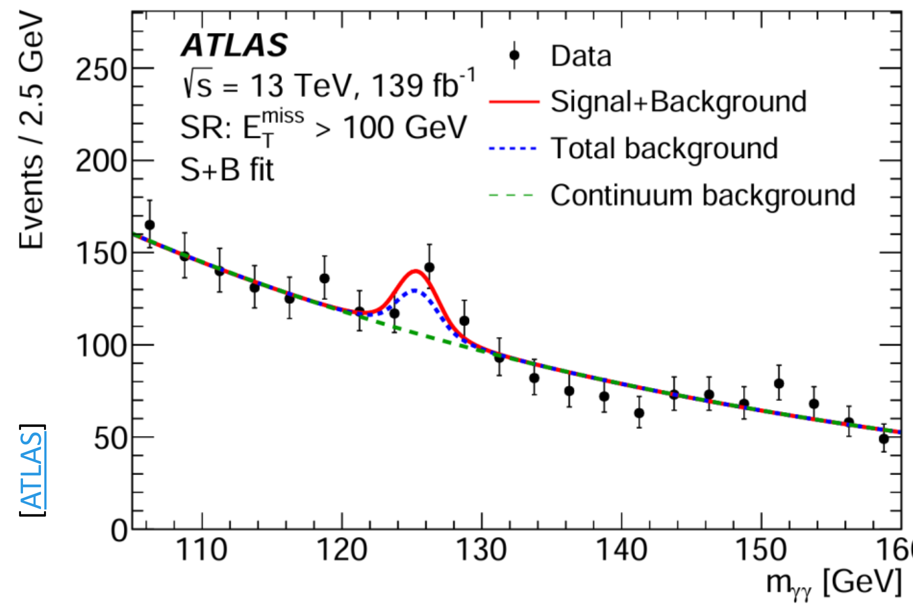


Hints for New Physics at 152 GeV

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



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



Associated production mechanism

ATLAS: $H \to \gamma\gamma + X$

[ATLAS]

- ATLAS search for associated production with **full Run2 data**
- **SM search for $H \to \gamma\gamma + X$ ($m_{\gamma\gamma}$ = 105-160 GeV)**
- 22 categories ($X = l, j, j_b, E_T^{miss}$ ...)

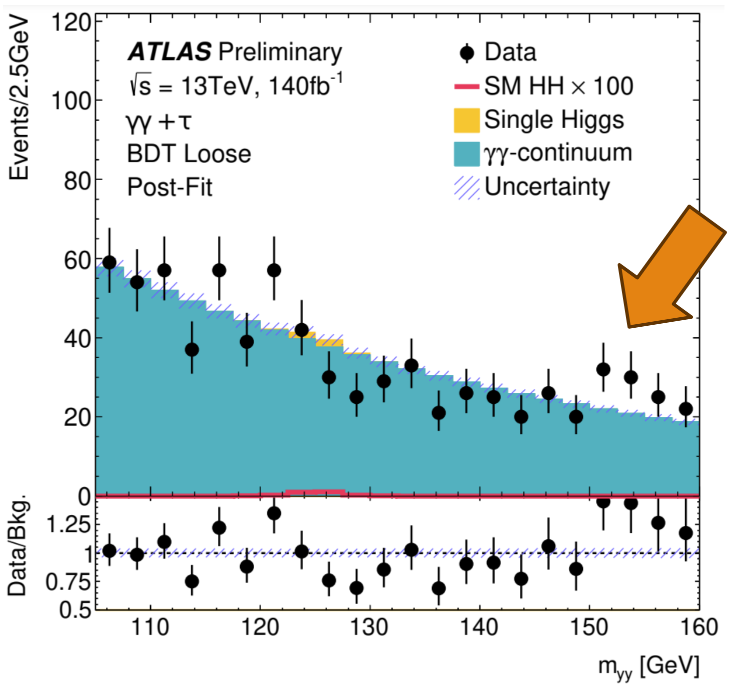
Target	Signal region	Detector level	Correlations
High jet activity	$4j$	$n_j \geq 4$	-
Top	ℓb t_{lep}	$n_\ell \geq 1, n_{b-\text{jet}} \geq 1$ $n_{\ell=e,\mu} = 1, n_{\text{jet}} = n_{b-\text{jet}} = 1$	-
Lepton	2ℓ 1ℓ	$ee, \mu\mu$ or $e\mu$ $n_\ell = 1, n_{t_{\text{had}}} = 0, n_{b-\text{jet}} = 0$	$< 26\%$
Tau	$1\tau_{\text{had}}$	$n_\ell = 0, n_{\tau_{\text{had}}} = 1, n_{b-\text{jet}} = 0$	$-$
$E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 100$ GeV $E_{\text{T}}^{\text{miss}} > 200$ GeV	$E_{\text{T}}^{\text{miss}} > 100$ GeV $E_{\text{T}}^{\text{miss}} > 200$ GeV	29%

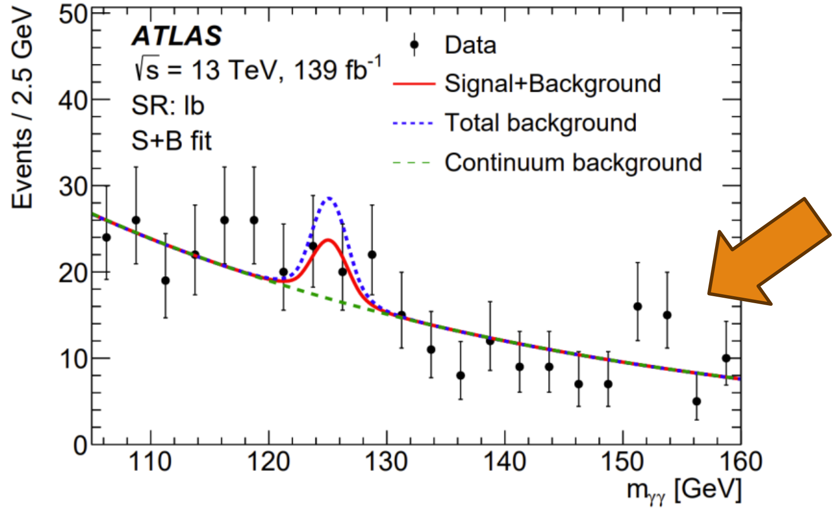
Excesses at $m_{\gamma\gamma} = 152$ GeV

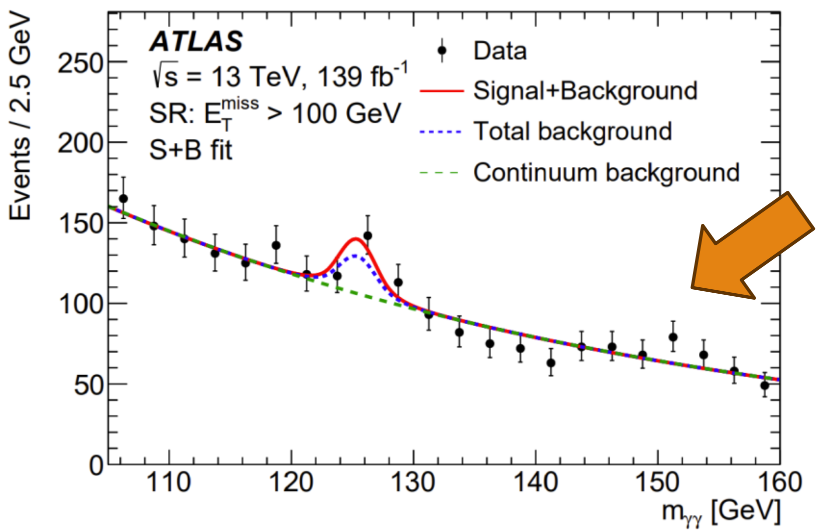
[ATLAS]

- $\gamma\gamma + lb$ ($\geq 1l$, $\geq 1b$–jet)
- $\gamma\gamma + E_T^{miss} > 100$ GeV
- $\gamma\gamma + 1\tau$

[Moriond 2024]







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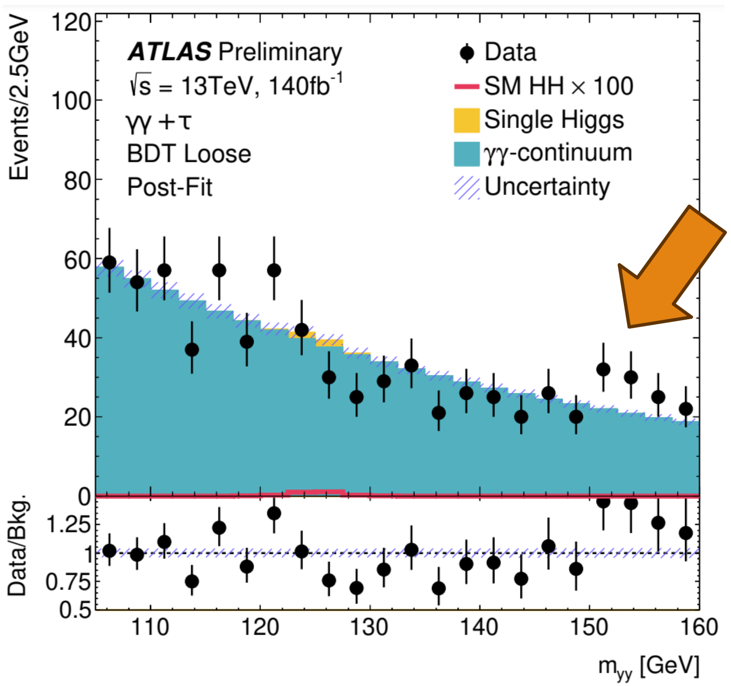

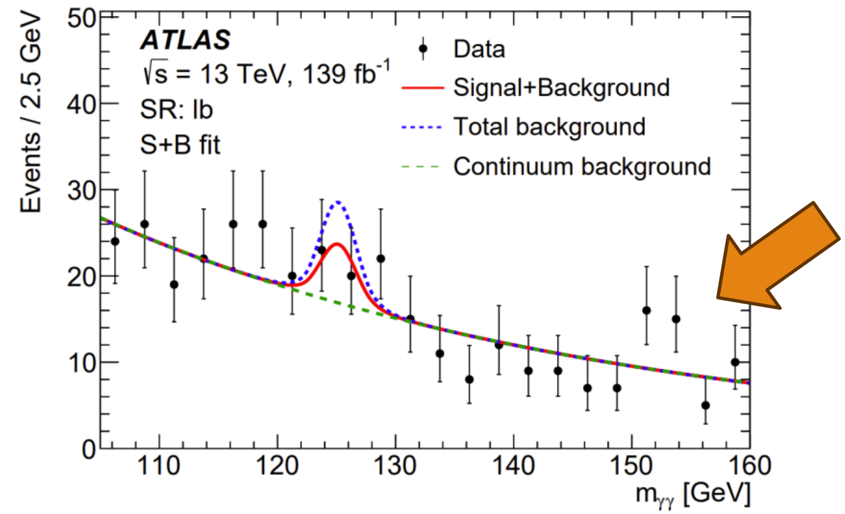

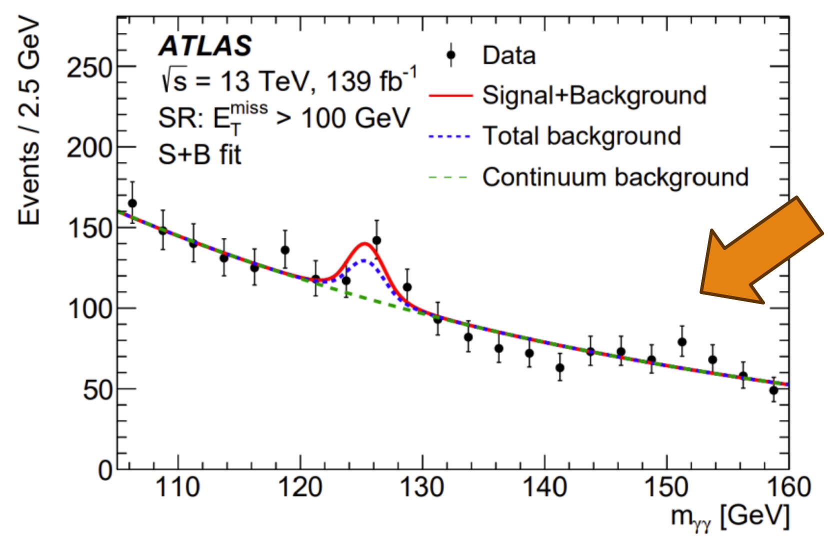

Hints for pp $\rightarrow S_{152}S^{\pm}$

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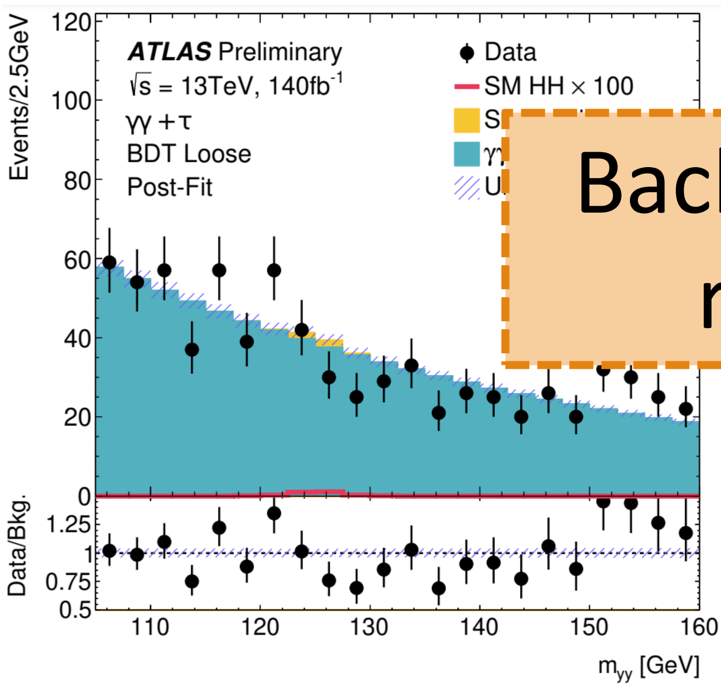
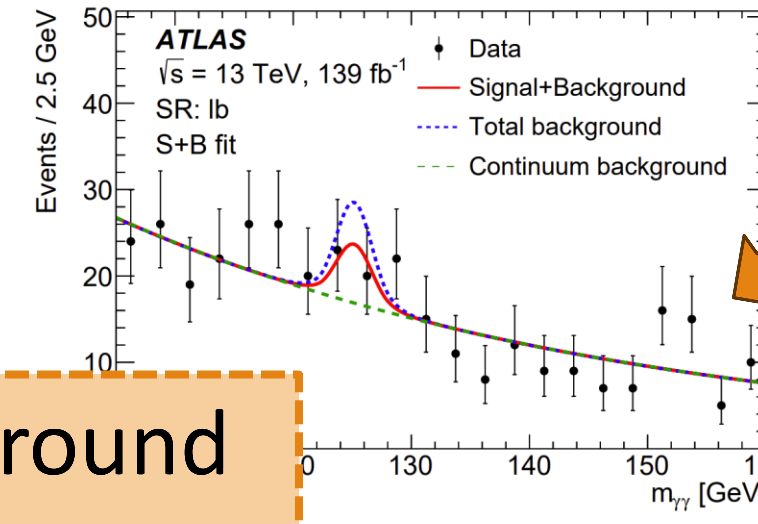
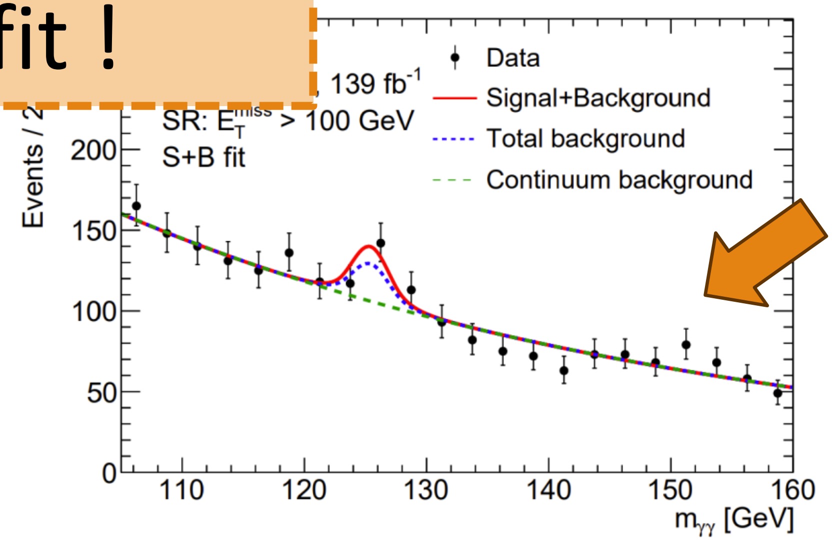






Background refit !

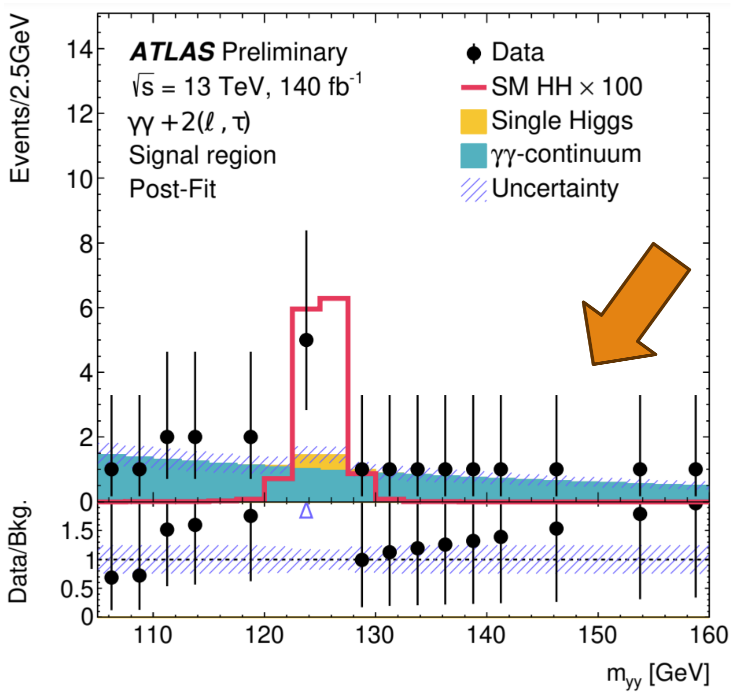
Hints for pp → $S_{152}S^{\pm}$

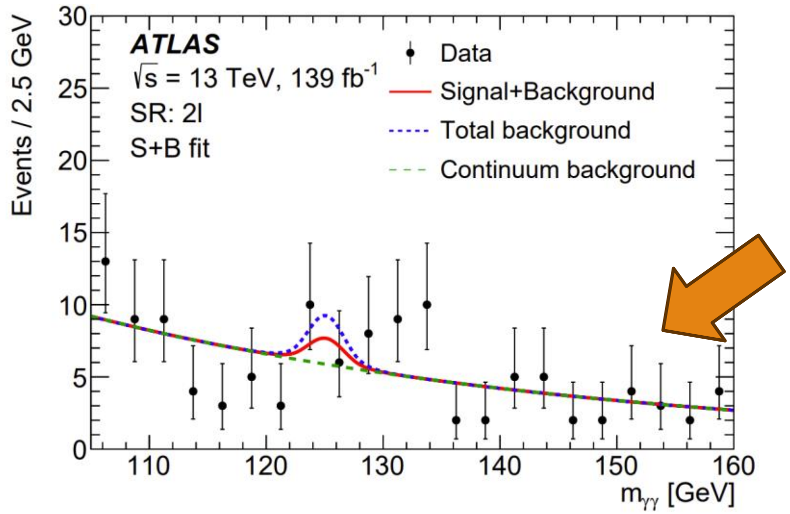
NO excesses at $m_{\gamma\gamma} = 152$ GeV

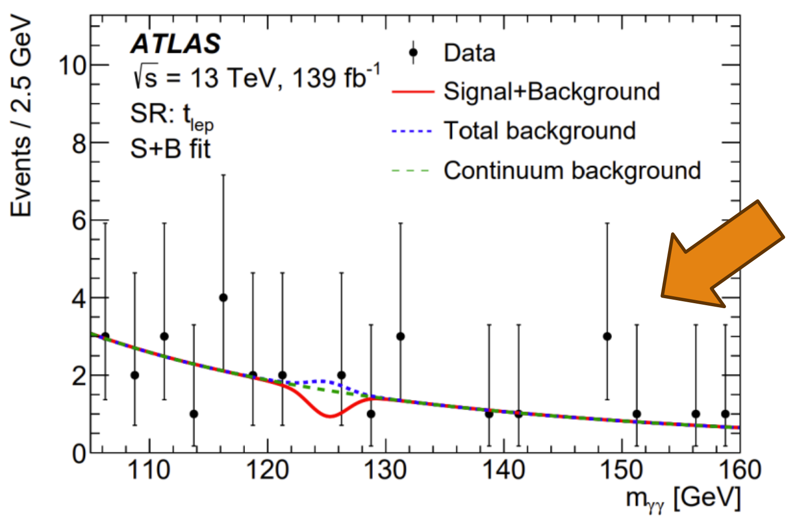
[ATLAS]

- $\gamma\gamma + 2l$
- $\gamma\gamma + t_{\text{lep}}$ $(= 1l\,, = 1b\text{–jet})$
- $\gamma\gamma + 2\tau$

[Moriond 2024]







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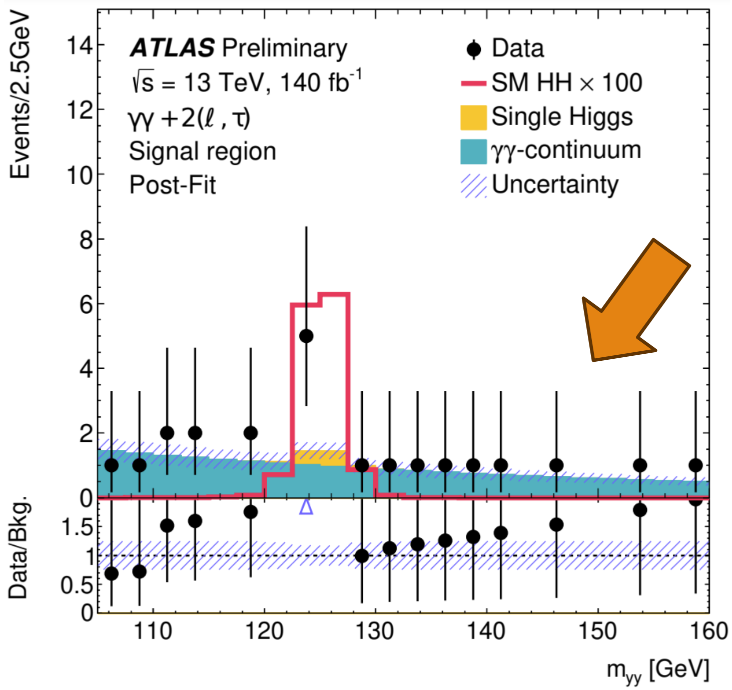

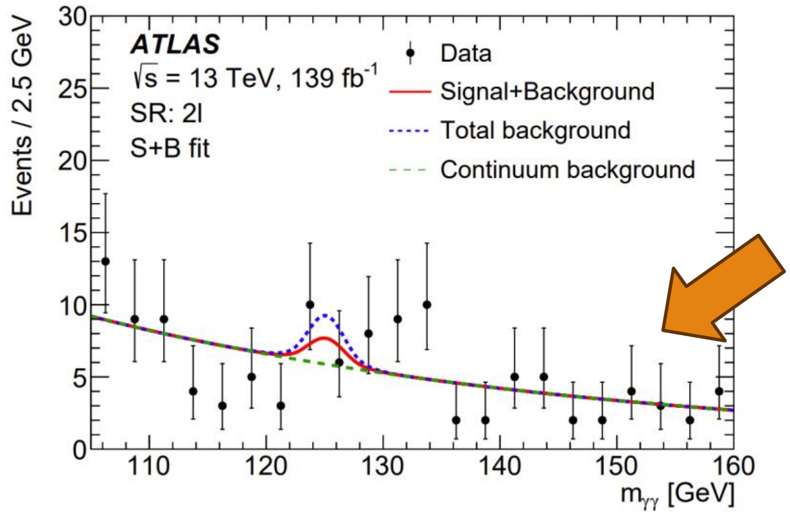

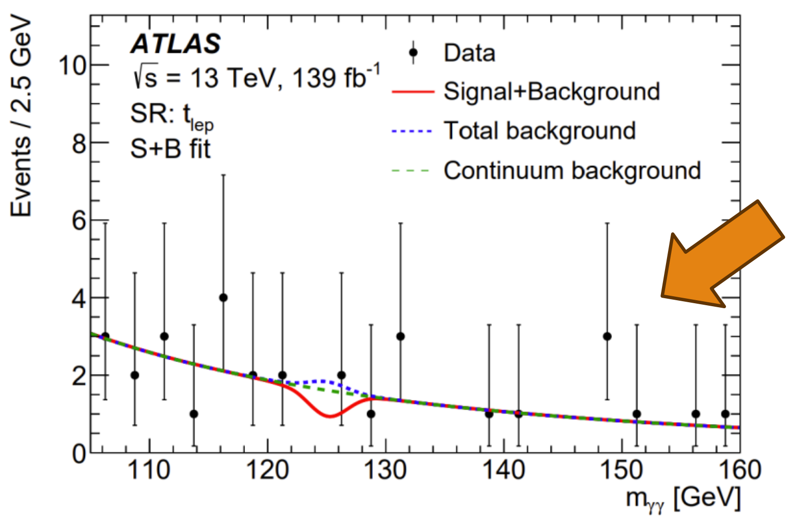

Disfavored pp → $S_{152}S'$

Associated production

(Asymmetric-) associated production

[ATLAS and CMS review]

- Provides a yet unexplored window on new physics
- Additional particles required in the signal regions (on top of the decays of the NP candidate)

Searches at high energy

Suffers from

Small cross sections

Searches at low energy

Swamped by

Large background

(Asymmetric-) associated production

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

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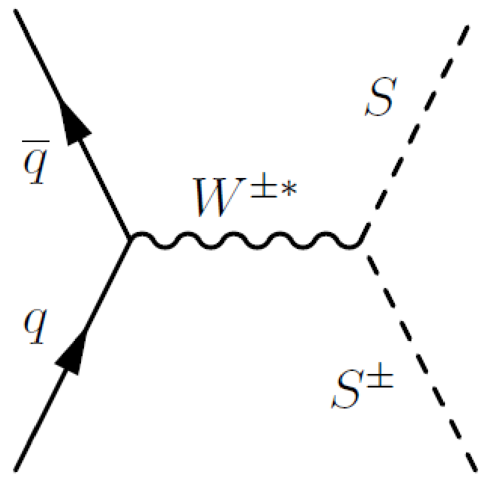
Future lepton colliders!



Drell-Yan production

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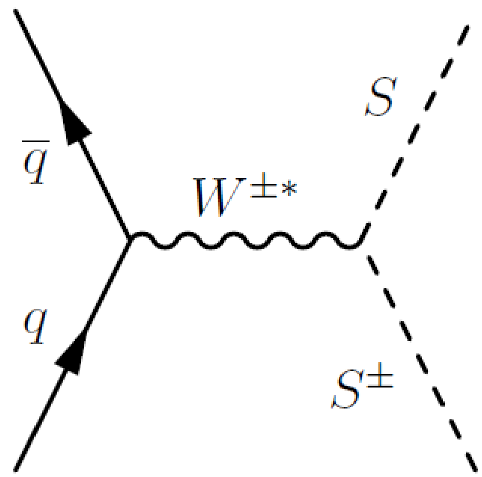
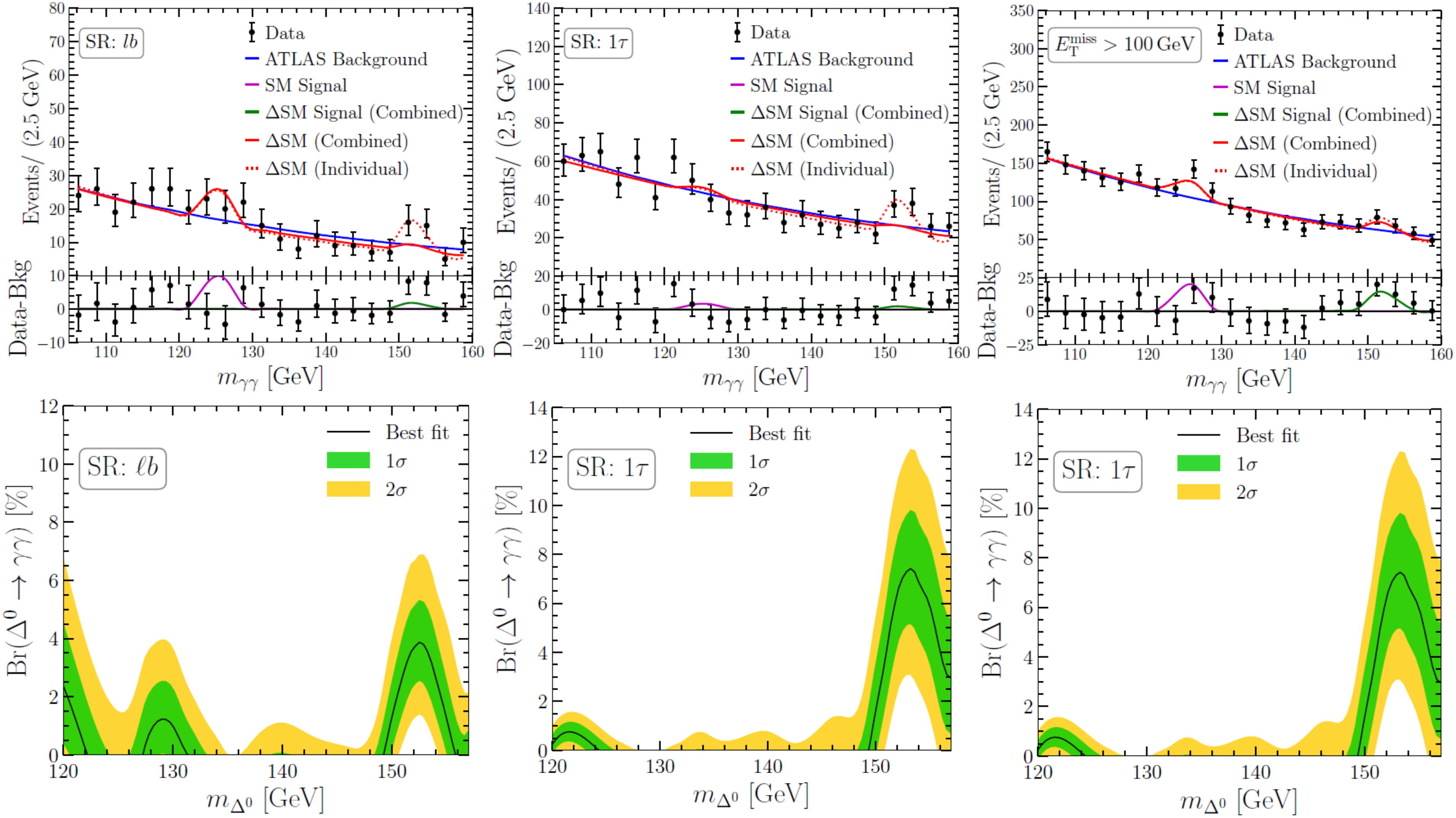


Drell-Yan production

Possible explanation of the 152 GeV excesses:
real Higgs triplet
(preferred over SM by $\approx 4\sigma$)

[S. Banik, GC, A. Crivellin et al.]

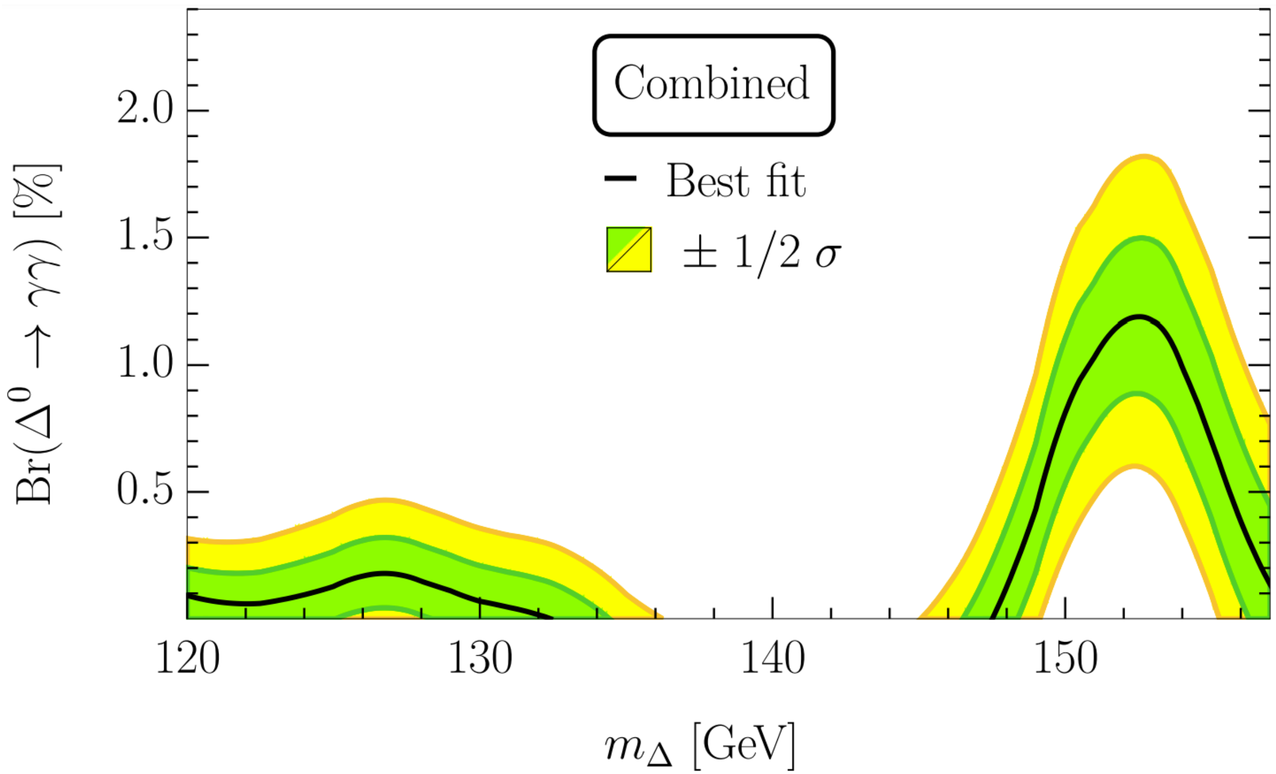
Real Higgs Triplet



Real Higgs Triplet

[S. Banik, GC, A. Crivellin et al.]

- **$Br(\Delta^0 \to \gamma\gamma) \approx 1\%$ preferred over SM by $\approx 4\sigma$**
- SFOPT induced within our benchmark points [Bandyopadhyay et al.]



Can we do even better?

A2HDM & CP-violation

Associated production of Higgses

Tiny couplings to fermions

Tiny VEV

Alignment

→

Suppressed GF

Suppressed VBF/VH

Higgs/Flavor bounds

2HDMs and Drell-Yan

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

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

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

Small mixing

⇒

Suppressed GF

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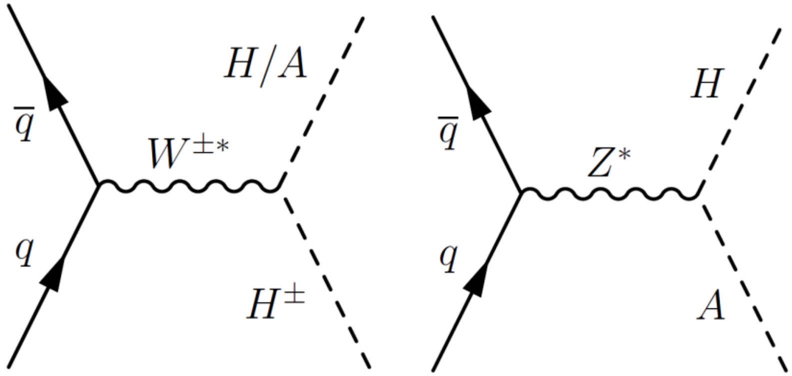
Drell-Yann is the main production mechanism



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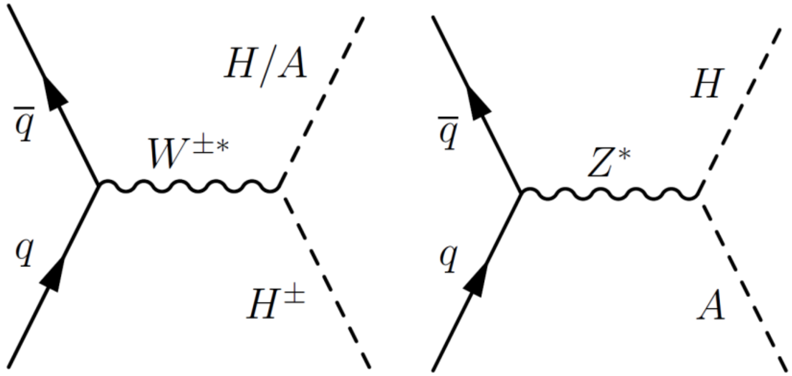

- Difficult to obtain sizable di-photon branching ratios with Z_2 symmetries (type I, type II, etc.)
- Composite Higgs? **Relaxing Z_2 symmetries?**

A2HDM

[P. Tuzon, A. Pich]

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

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

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

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

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

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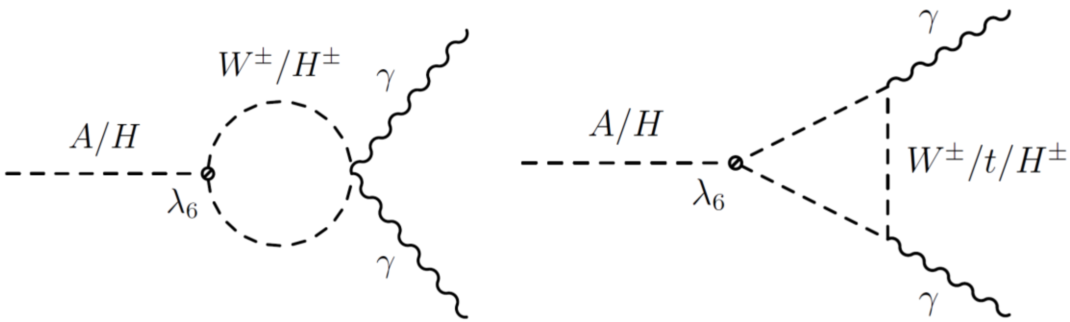

Sizable Br$[H/A \to \gamma\gamma]$ through $H^\pm$ loop

A2HDM: CP-violation

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

- CP-violation of the model (Baryogenesis?)

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

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

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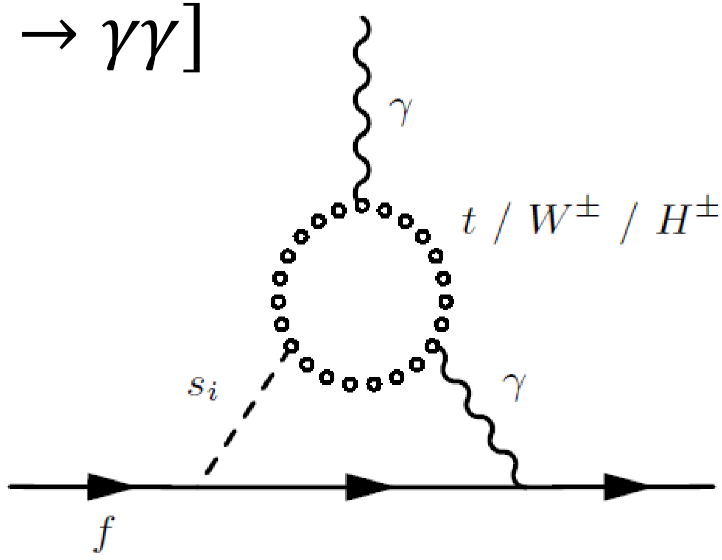
- $\Re[\lambda_6]$ / $\Im[\lambda_6]$ drives Br$[H / A \to \gamma\gamma]$
- **Correlating Br$[A \to \gamma\gamma]$ with EDMs?**

$$i\, d_f\, \bar{q} \sigma^{\mu\nu} p_\mu \gamma_5 q \subset$$



Higgs basis

[S. Davidson, H. Haber]

- Higgs-flavor symmetry: $U(2)_{ab}\Phi_a = \Phi_b$
- $\langle\Phi_1\rangle = v, \langle\Phi_2\rangle = 0 \quad ; \quad \lambda_i \Longleftrightarrow Z_i$

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

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

Z_7 (λ_6) independent of mixing angles

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

EDMs

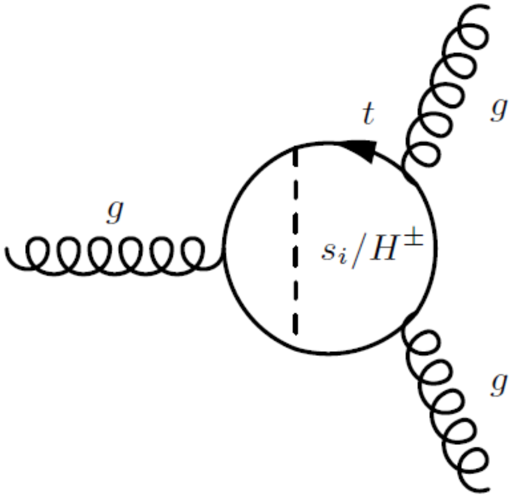
[M. Jung, A. Pich]

- Electron gives stringent bounds (10^{-30} e cm^{-1})
- Projection for neutron and proton are also considered (10^{-28}/10^{-29} e cm^{-1})

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

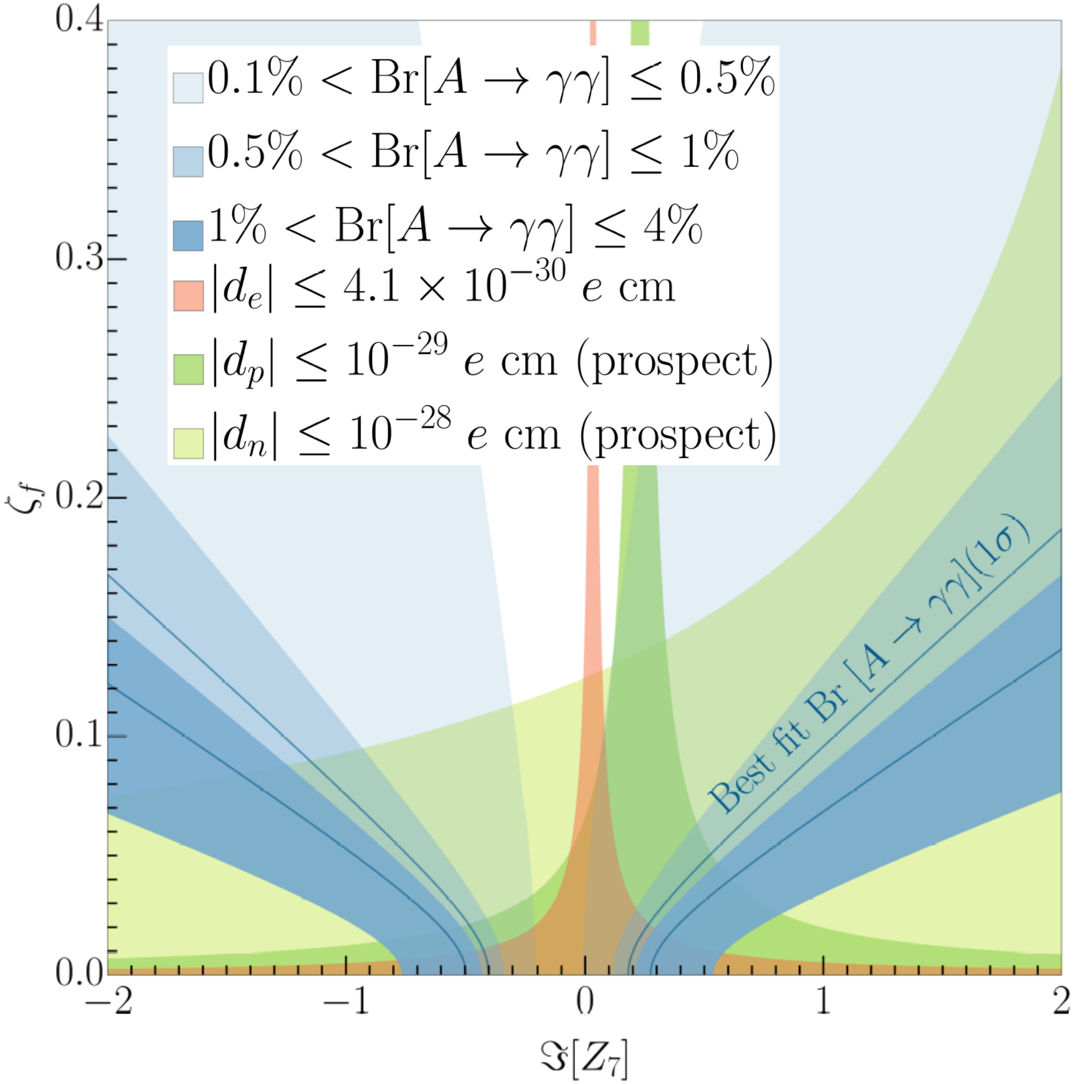
- RGE improved chromo-magnetic contributions
- Analytic results

[W. Altmannshofer, S. Gori, N. Hamer, H. Patel]



A2HDM: $A_{152} \to \gamma\gamma$

[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

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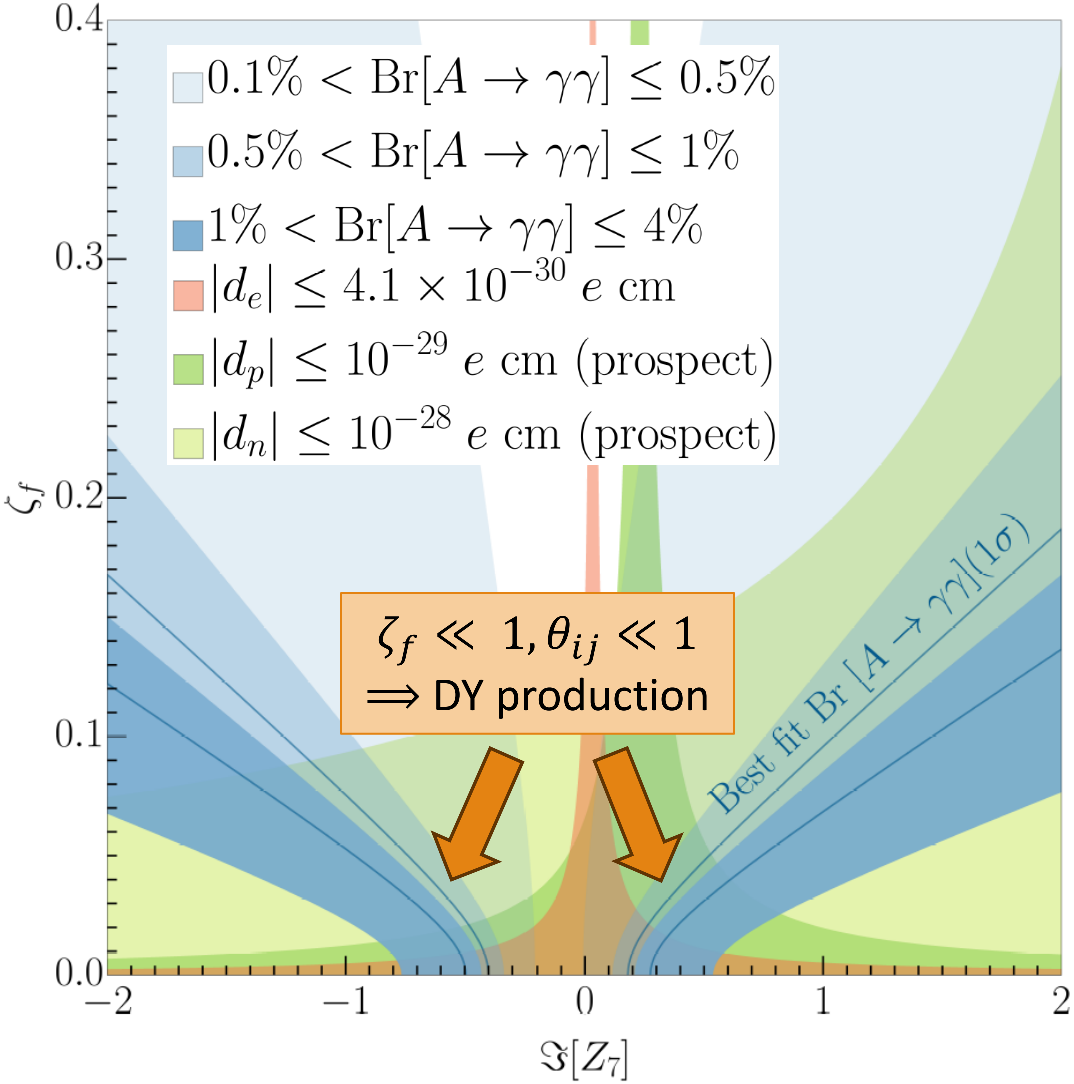

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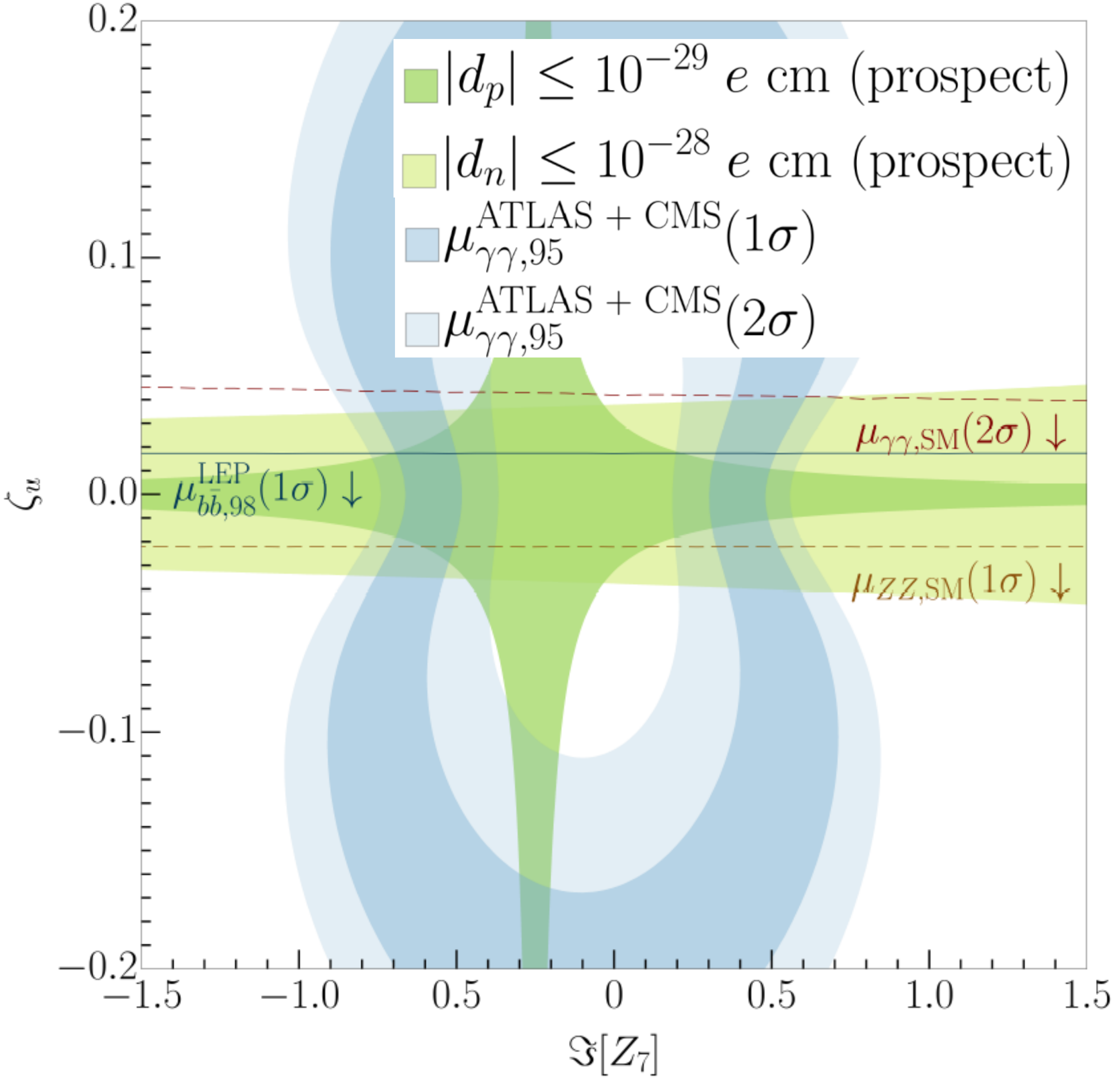
A2HDM: $A_{95} \to \gamma\gamma, H_{98} \to b\bar{b}$

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



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[ATLAS]

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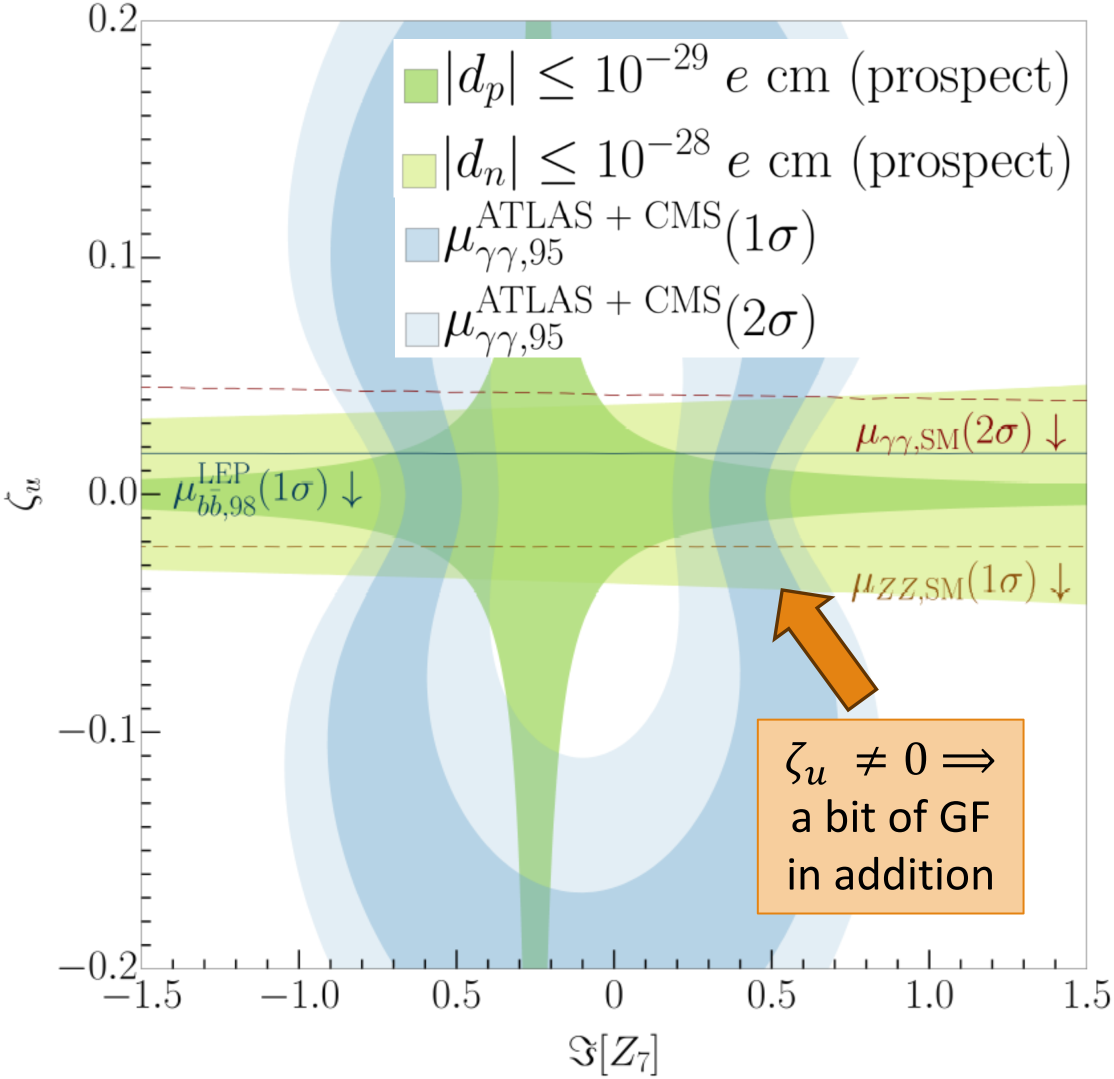

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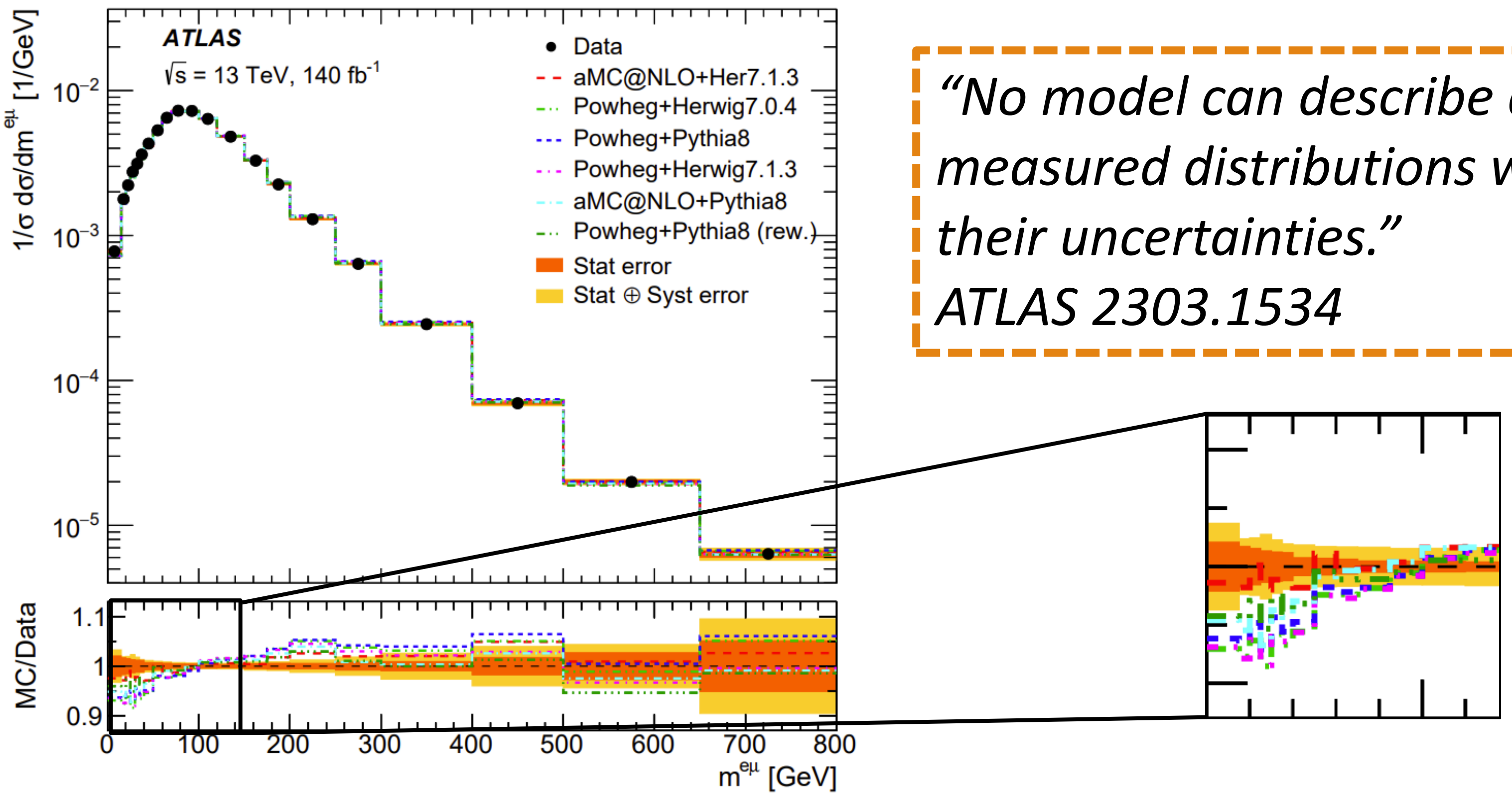
[GeV]	125	98	95	130

[ATLAS]

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

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

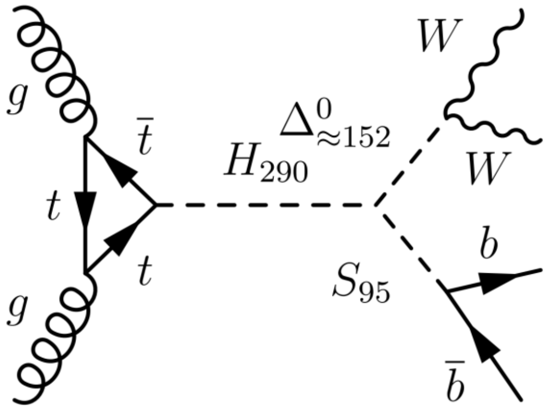
[ATLAS]



“No model can describe all measured distributions within their uncertainties.”
ATLAS 2303.1534

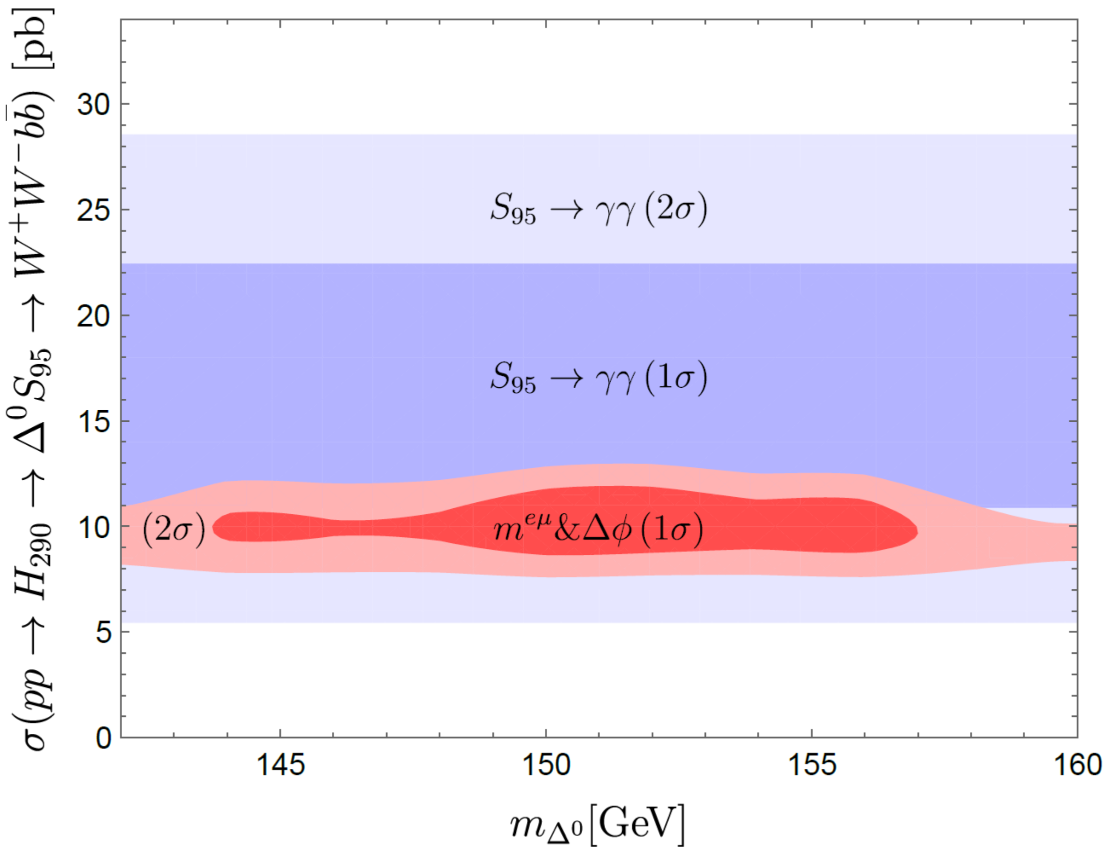
- Higher order corrections? Toponium?
- New Physics pollution of this SM measurement?

95 GeV and 152 GeV excesses?



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

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



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

Conclusions and Outlook

- Asymmetric associated production of scalars is a prominent signature to look for NP at the LHC
- A2HDM achieves sizable Br$[H/A \to \gamma\gamma]$ and can be correlated to EDMs (Baryogenesis?)
- A2HDM provides explanation of the diphoton excesses at 95 GeV and 152 GeV

Conclusions and Outlook

- Asymmetric associated production of scalars is a prominent signature to look for NP at the LHC

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- A2HDM provides explanation of the diphoton excesses at 95 GeV and 152 GeV

THANK YOU FOR THE ATTENTION!

BACK UP SLIDES

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		Bounds from Higgs data

Minimal model

Is there a minimal model to explain the 152 excesses?

Real Higgs triplet

[S. Banik, GC, A. Crivellin et al.]

Is there a minimal model to explain the 152 excesses?

	$SU(2)_L$	$U(1)_Y$
Δ	3	0

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

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Vacuum expectation value of the triplet Δ

Mixing angle between SM Higgs h – neutral component of the triplet Δ^0

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Δ	3	0

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

No direct coupling to SM fermions:

- Gluon fusion $\propto \alpha_\Delta \ll 1$
- Flavour effects $\propto \frac{v_\Delta}{v_{SM}} \ll 1$

Vacuum expectation value of the triplet Δ

Mixing angle between SM Higgs h – neutral component of the triplet Δ^0

Real Higgs triplet

[S. Banik, GC, A. Crivellin et al.]

≈152 GeV mostly produced in association (AP)

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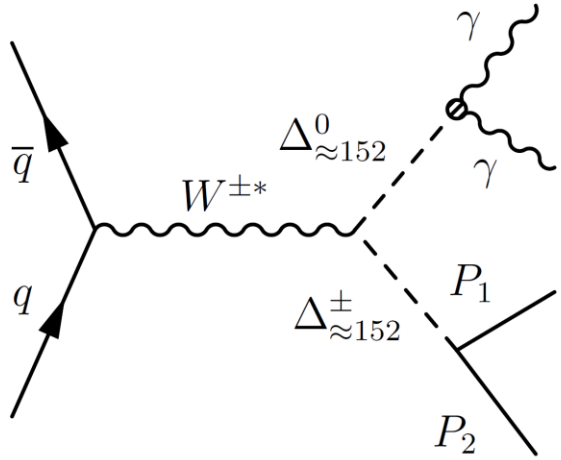

Produced in AP via Drell-Yan (DY)

Real Higgs triplet

[GC, A. Crivellin et al.] → Multi- lepton anomalies

[S. Banik, GC, A. Crivellin et al.]

≈152 GeV mostly produced in association (AP)	No room for NP at ≈152 GeV in ZZ but in WW	

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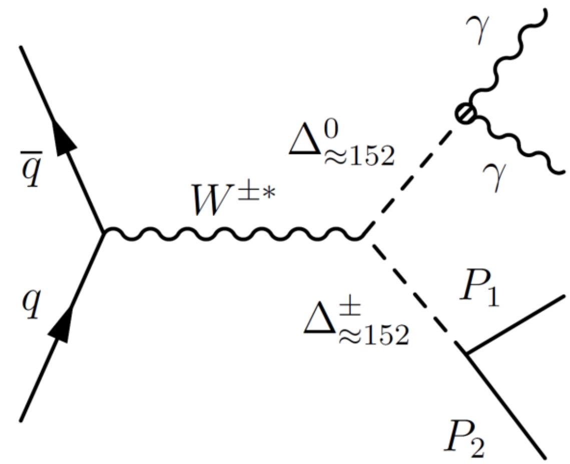

Produced in AP via Drell-Yan (DY)	$\Delta^0 WW$ but no $\Delta^0 ZZ$ (tree level, $\alpha_\Delta = 0$)	

Real Higgs triplet

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[S. Banik, GC, A. Crivellin et al.]

≈152 GeV mostly produced in association (AP)	No room for NP at ≈152 GeV in ZZ but in WW	W mass ($1.4/3.5\sigma$ over SM w/o CDFII)

	$SU(2)_L$	$U(1)_Y$
Δ	3	0

- Fields → neutral Δ^0, charged $\Delta^{\pm}$
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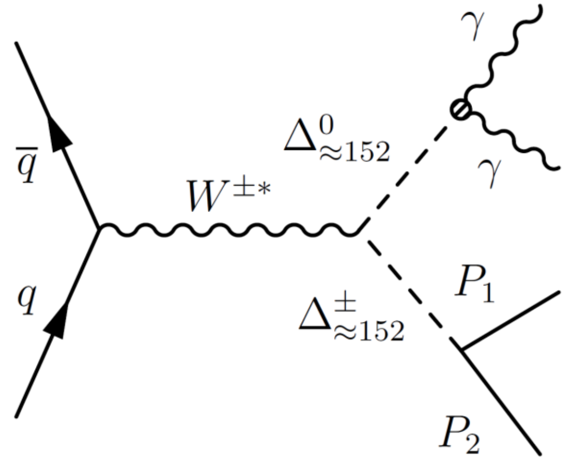


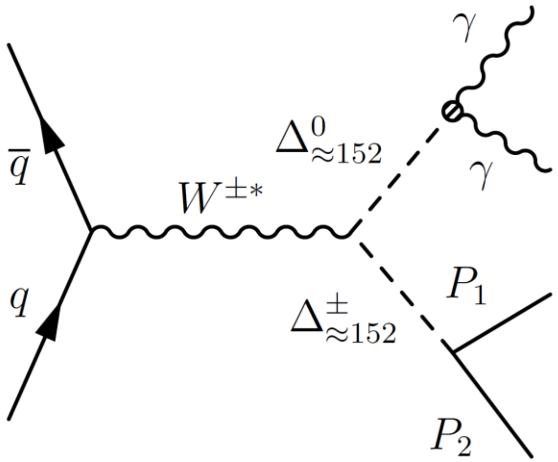
Produced in AP via Drell-Yan (DY)	$\Delta^0 WW$ but no $\Delta^0 ZZ$ (tree level, $\alpha_\Delta = 0$)	$v_\Delta \approx 2.3/3.4$ GeV ($m_{\Delta^0} \approx m_{\Delta^\pm}$)

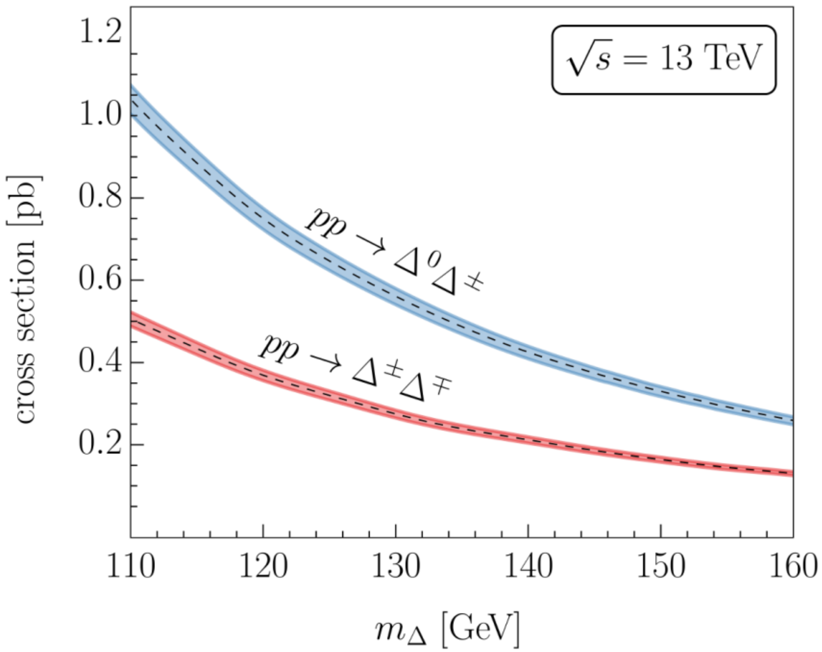
[T. Blank, W. Hollik]

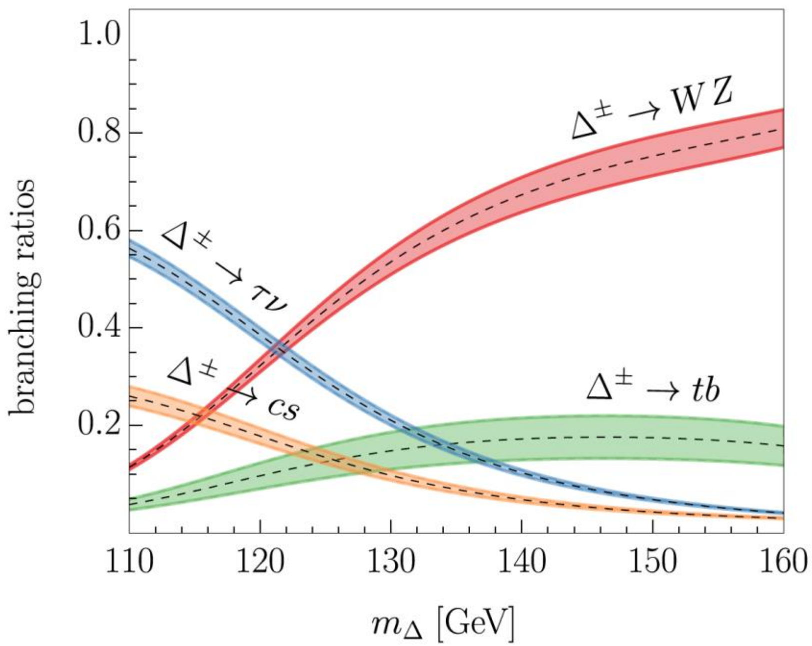
The ΔSM model

[S. Banik, GC, A. Crivellin et al.]

- Production cross section and Br($\Delta^{\pm}$) fixed
- Free parameters: $\boldsymbol{m_{\Delta^0,\Delta^{\pm}}}$ **, Br**$(\boldsymbol{\Delta^0 \to \gamma\gamma})$

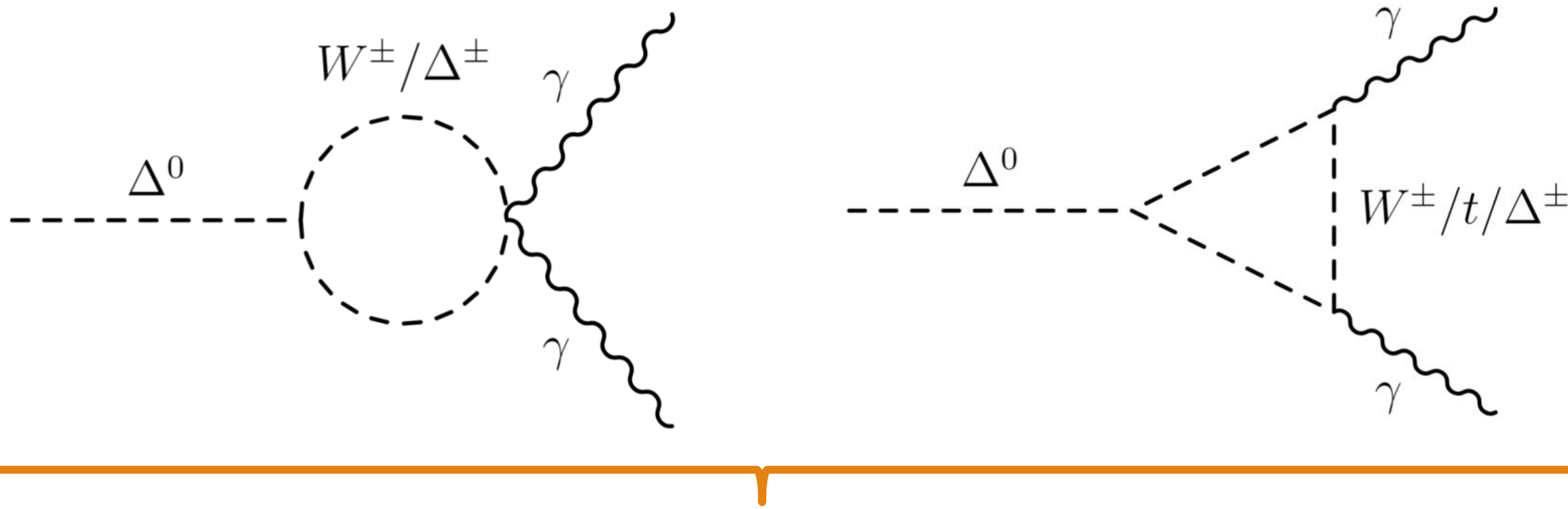






Fit: $\Delta^0 \to \gamma\gamma$

[S. Banik, GC, A. Crivellin et al.]



$$f(m_{\Delta^0}\,,\ \alpha\,, m_{\Delta^\pm} - m_{\Delta^0}\,, v_\Delta\,; \dots)$$

For the fit, all parameters subsumed into single relevant phenomenological one

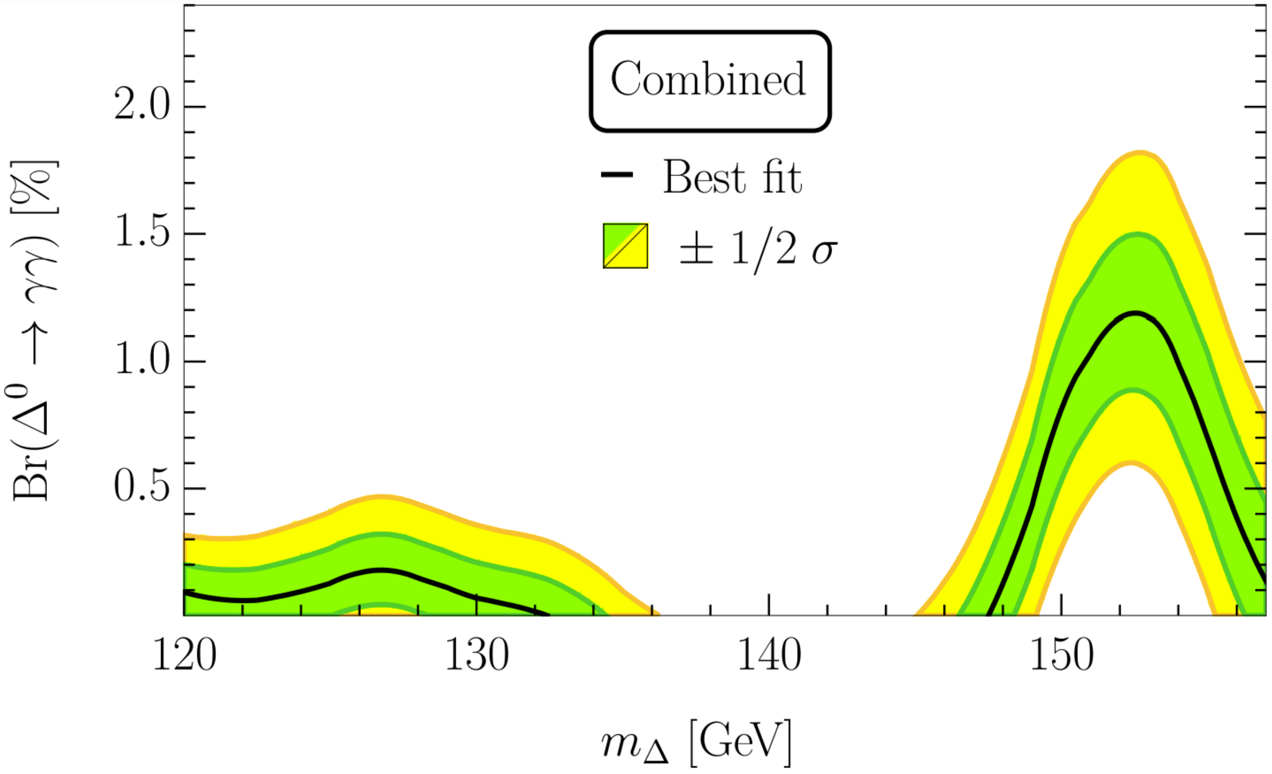
$\mathrm{Br}[\Delta^0 \to \gamma\gamma]$

(although explicit formulae used to compute, for instance, bounds on SM $h \to \gamma\gamma$)

Results: $\Delta^0 \to \gamma\gamma + X$

[S. Banik, GC, A. Crivellin et al.]

- **$\mathrm{Br}(\Delta^0 \to \gamma\gamma) \approx 1\%$ preferred over SM by $\approx 4\sigma$**
- SFOPT induced within our benchmark points [Bandyopadhyay et al.]



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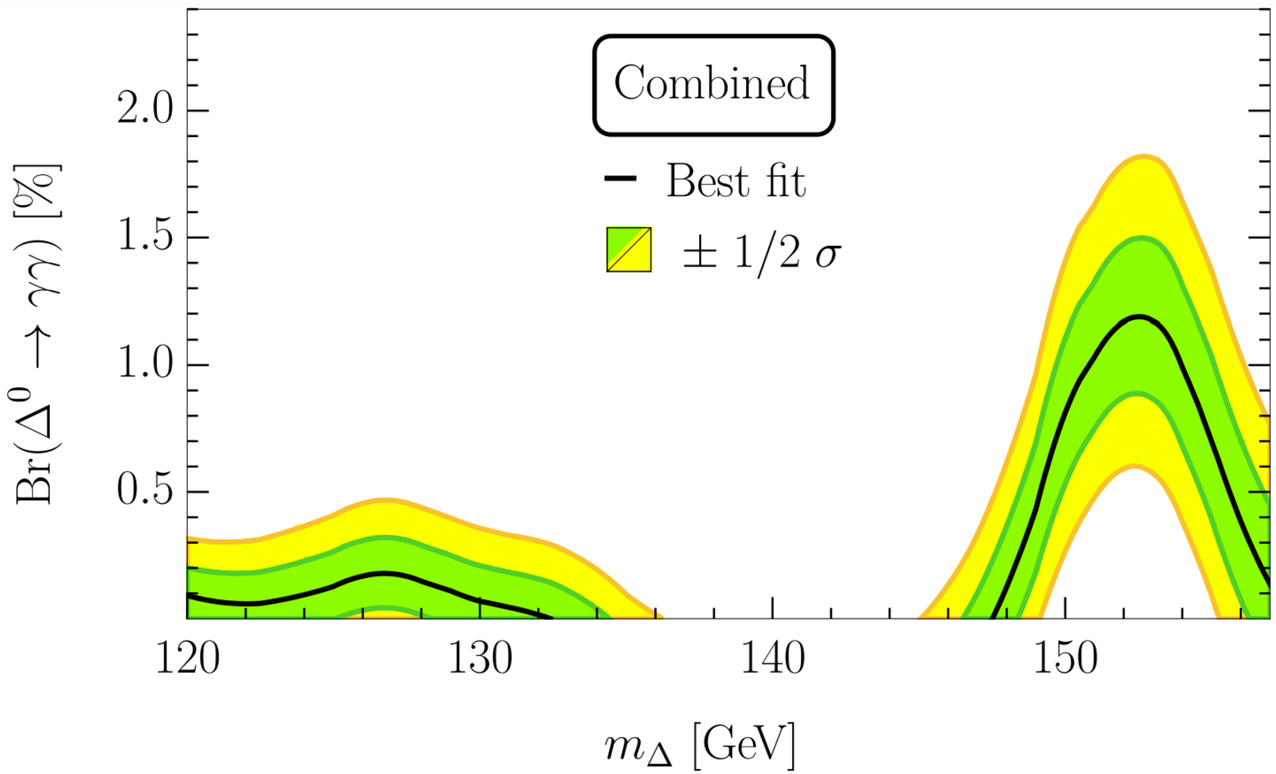
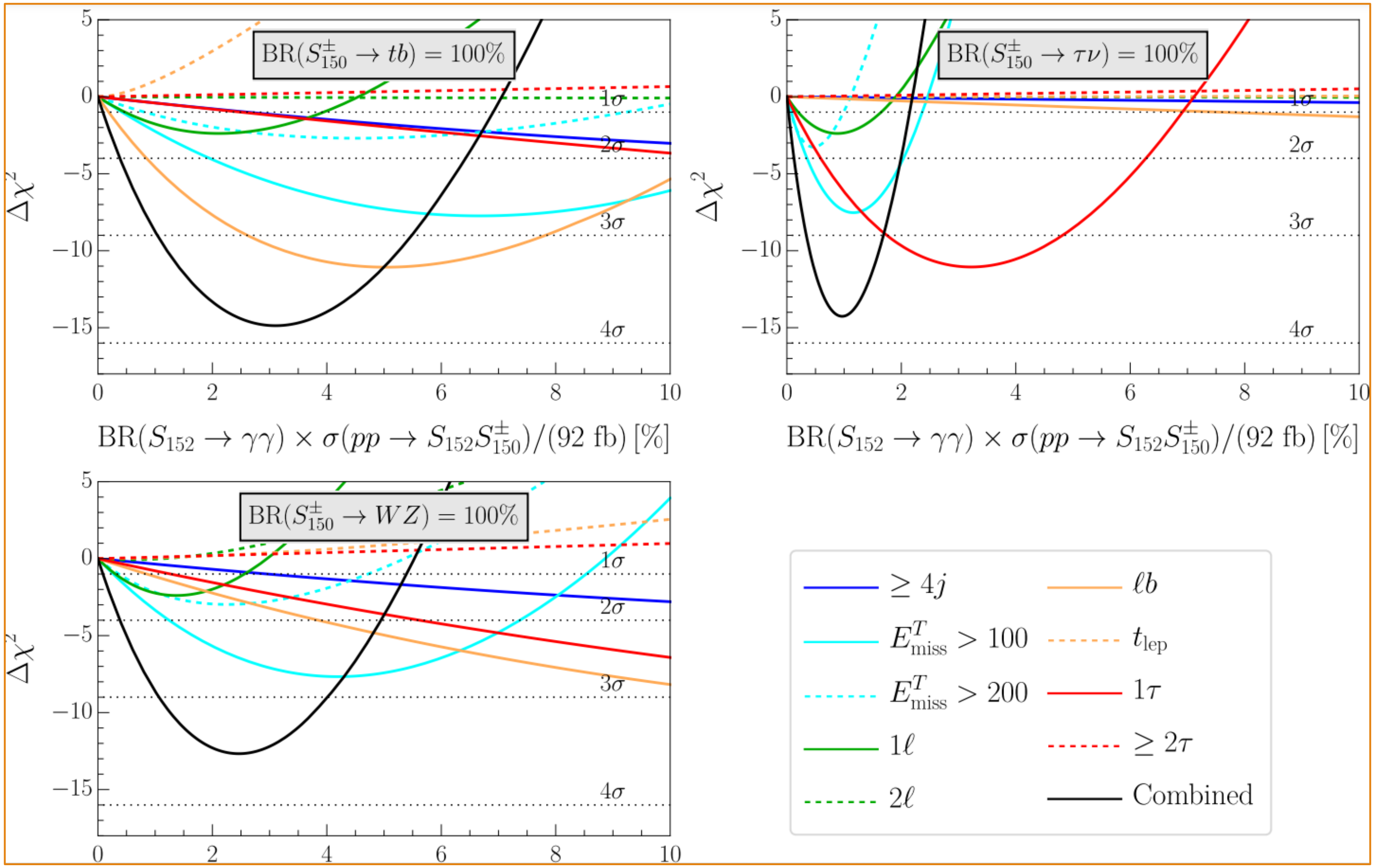


Can we do even better?

Simplified model analysis

[S. Banik and A. Crivellin]



Simplified model analysis

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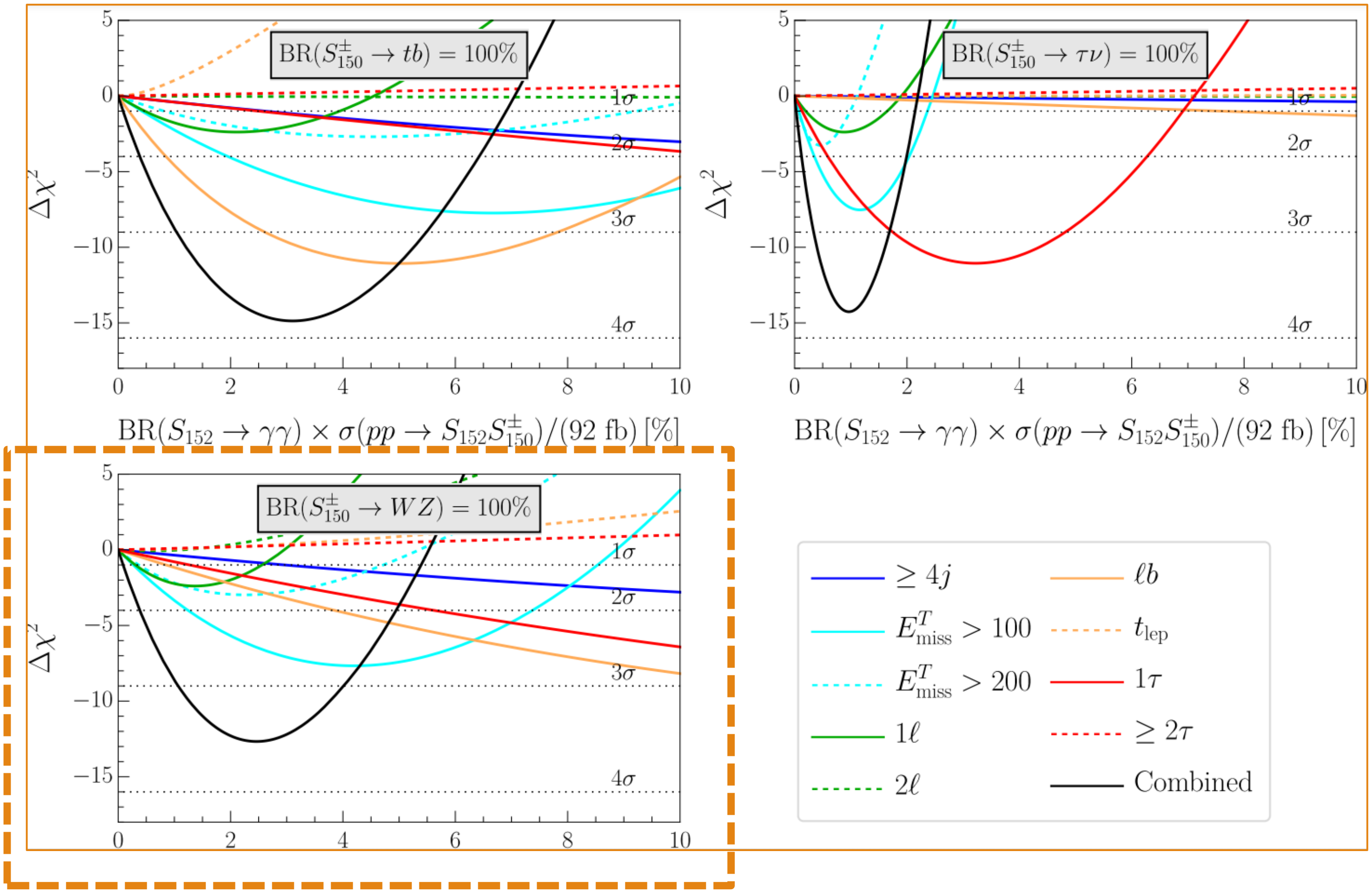

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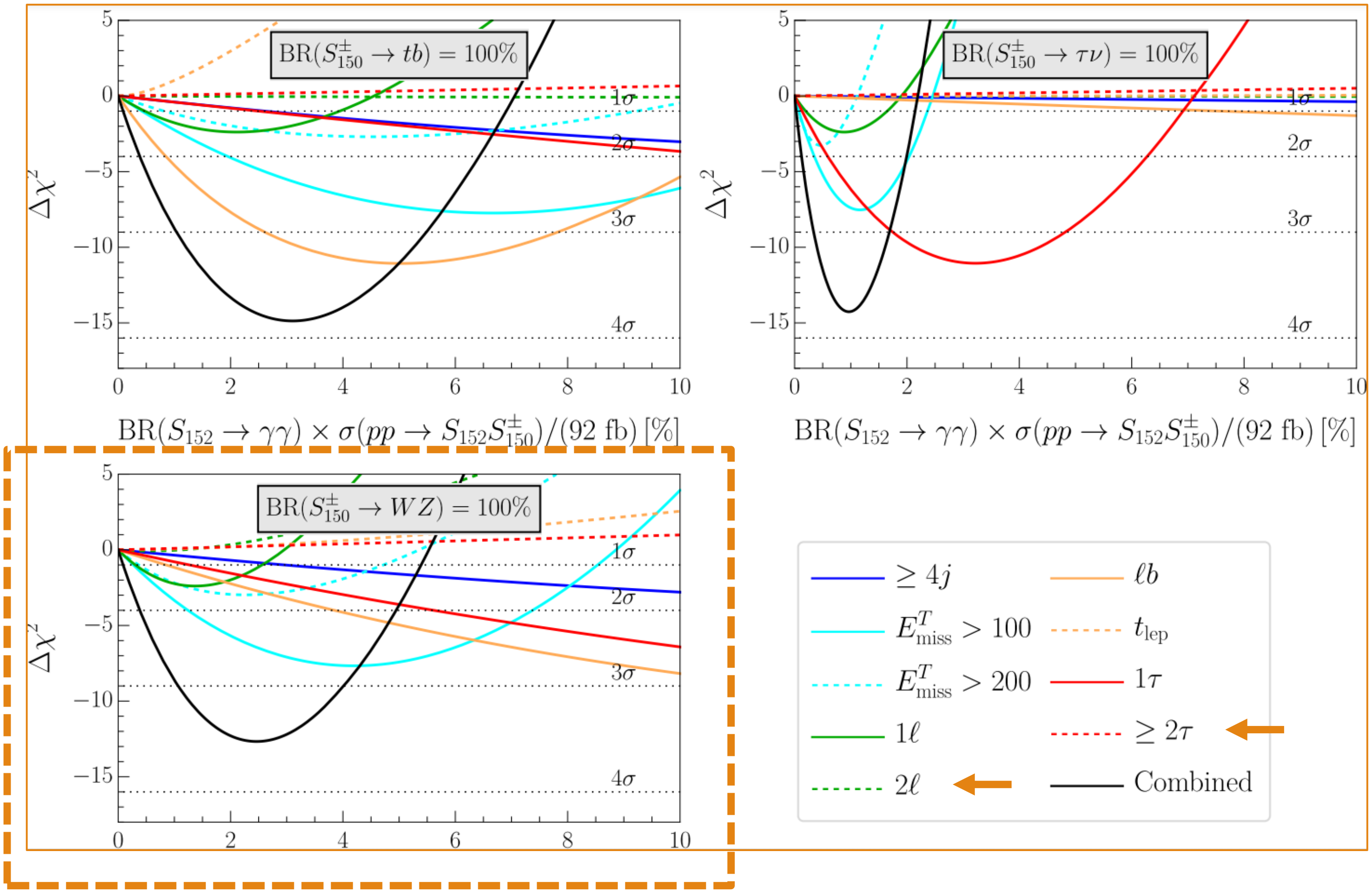

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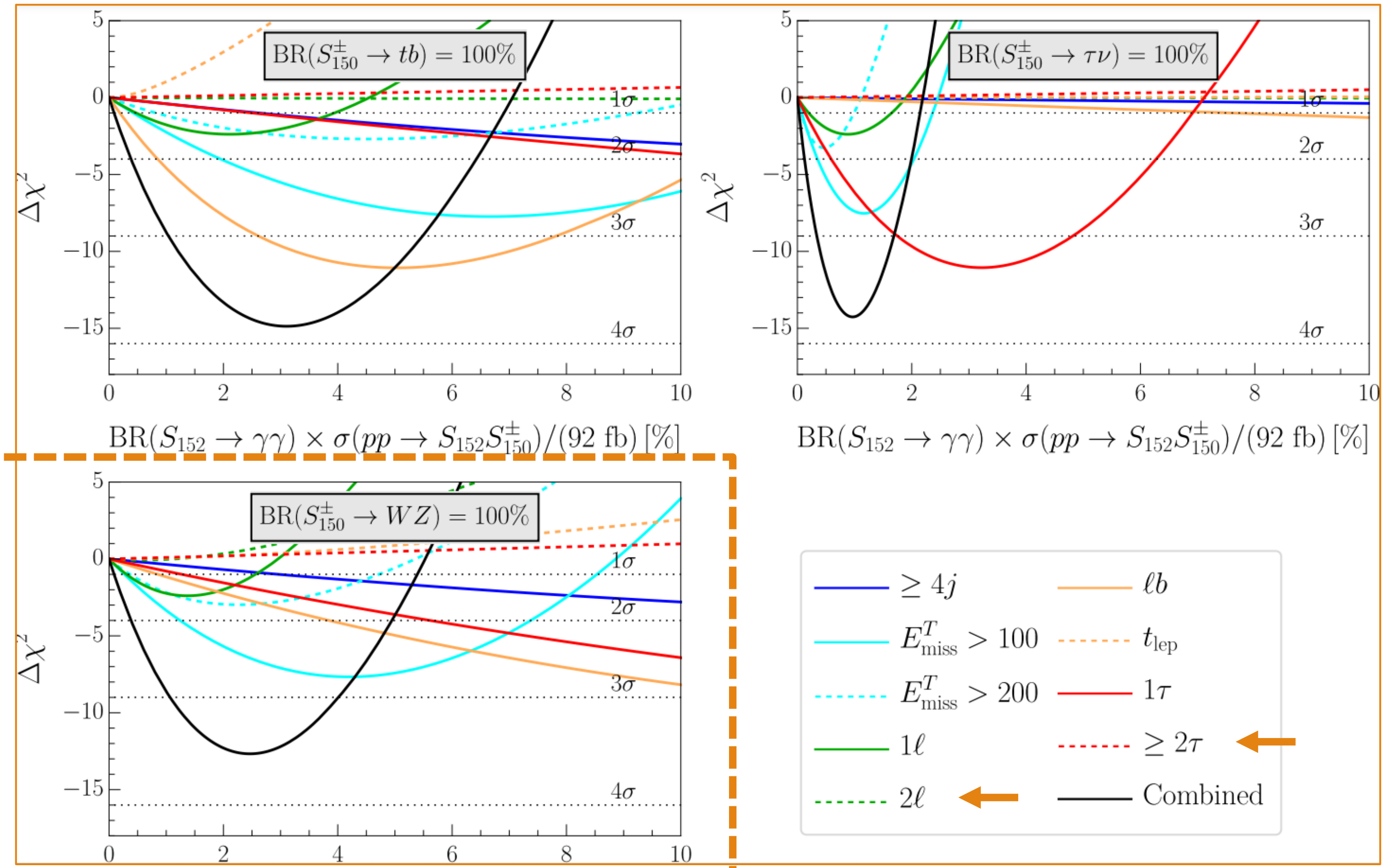
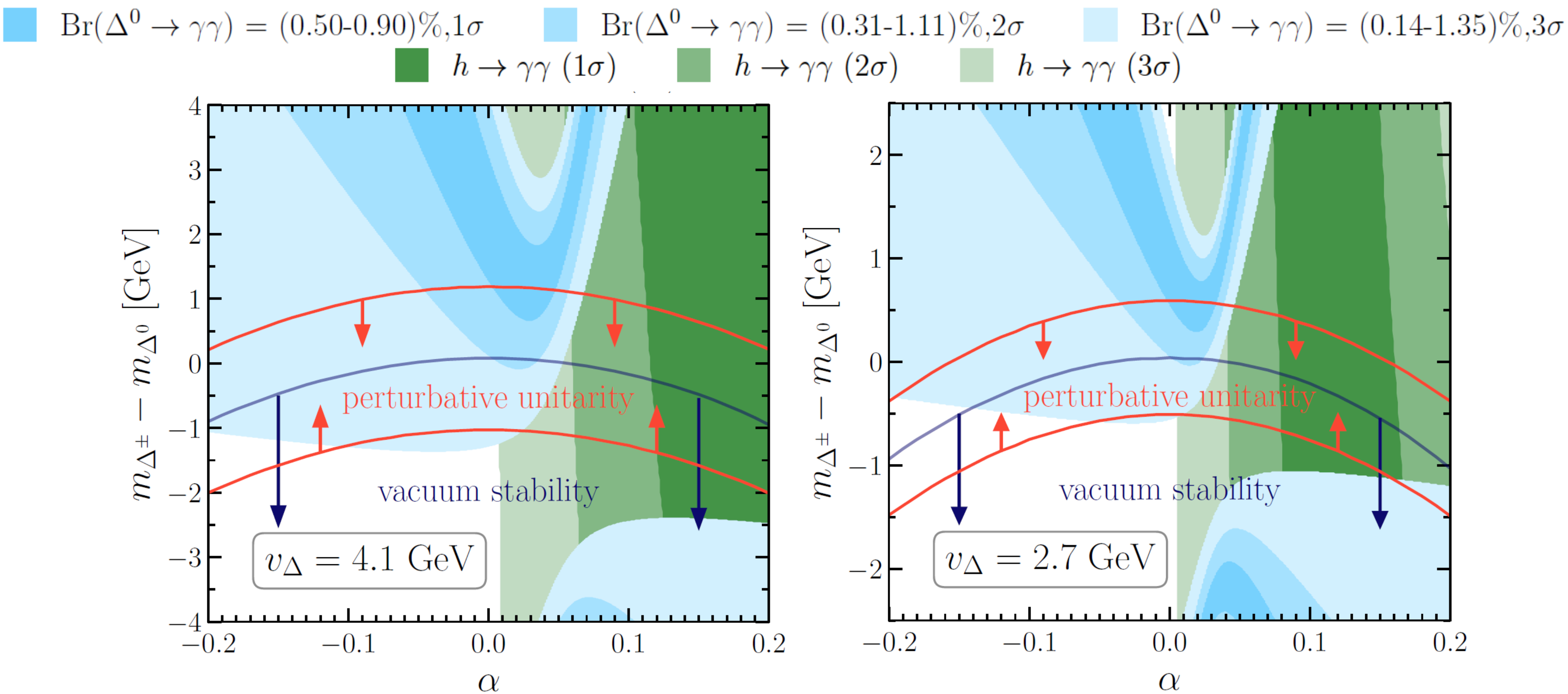


$W^\pm Z$ leads to too many leptons

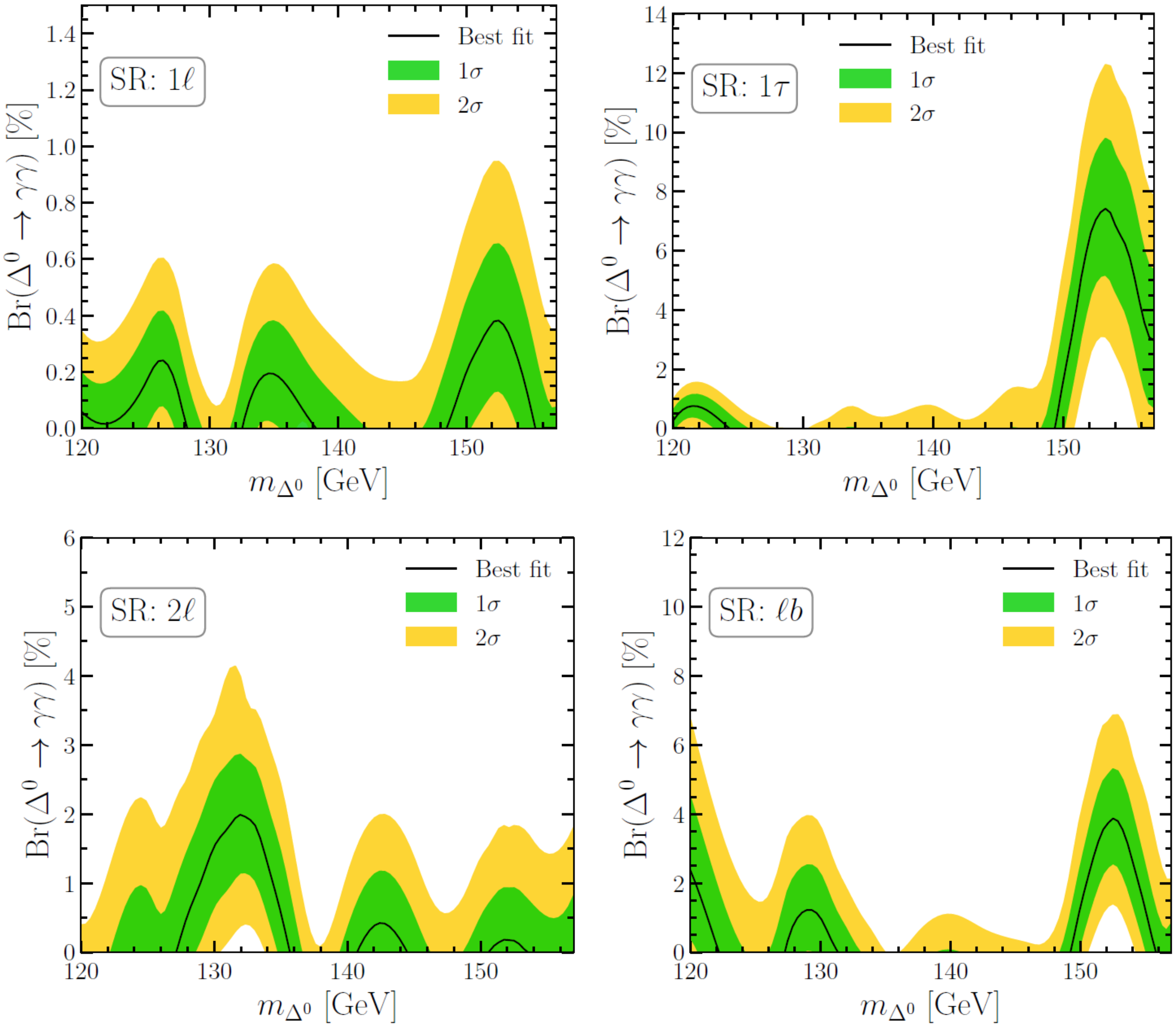
Scalar potential

[S. Banik, GC, A. Crivellin et al.]

- Vacuum stability and perturbative unitarity in slight tension with other phenomenological observables
- Pointing to additional fields at or above the EW scale



Real Triplet: individual SRs



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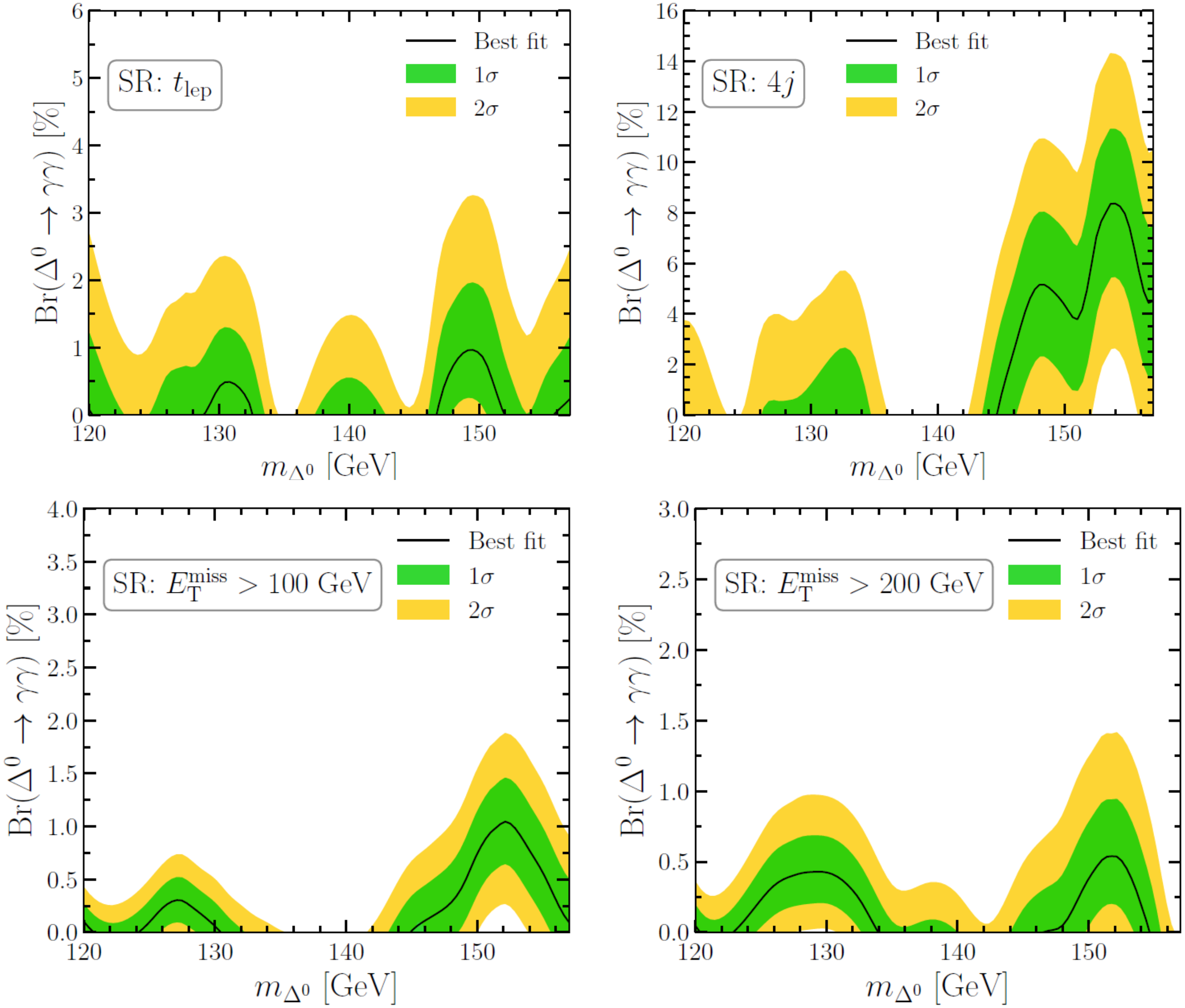
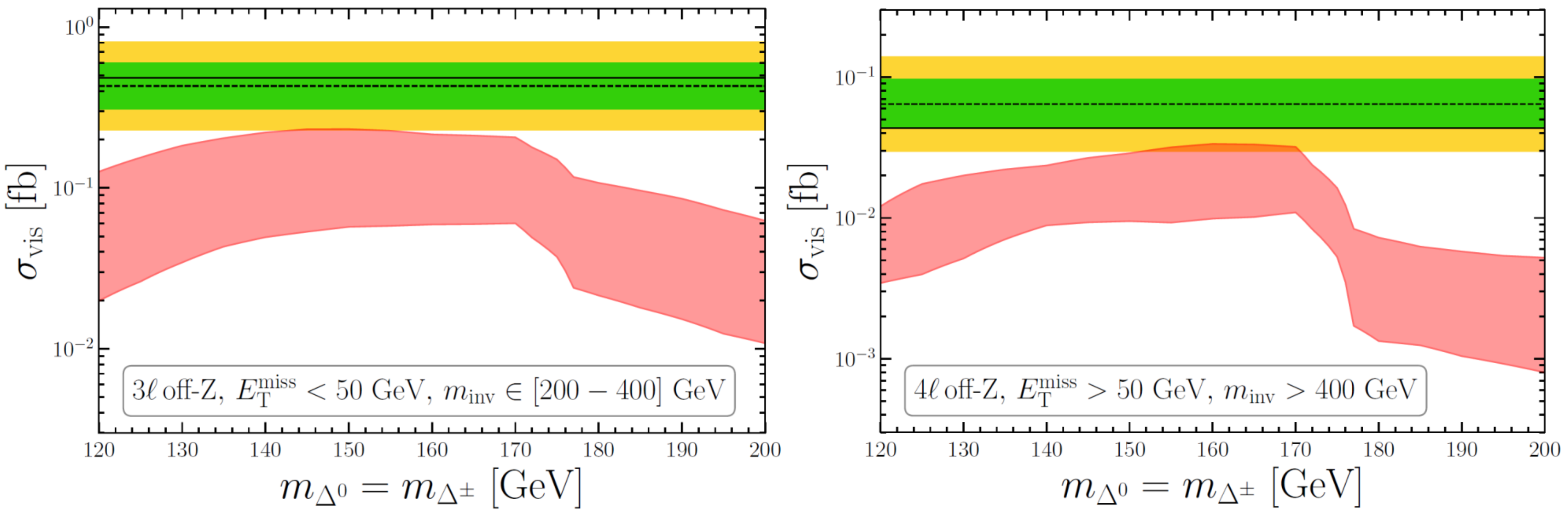


3 and 4 – leptons bounds

[In prepation…]

- Multi-lepton searches with 3 and 4 leptons as final states are not excluding a real Higgs triplet at low masses

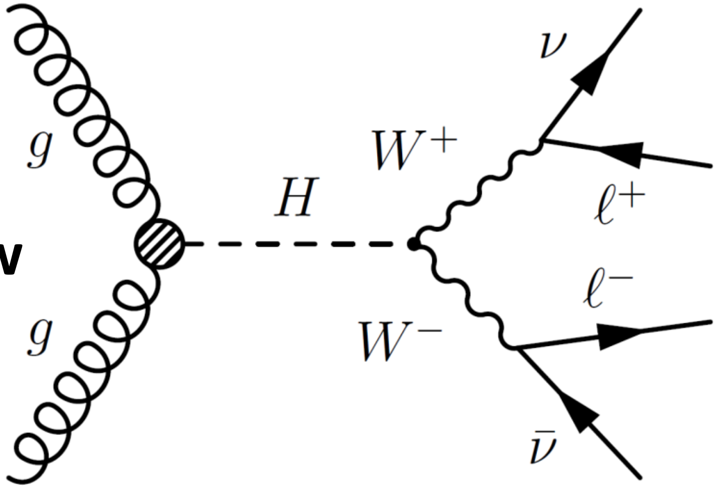


[ATLAS]

WW analysis

[GC, A. Crivellin et al.]

- **No dedicated BSM search for $gg \to H \to WW$** with full luminosity and including 90 GeV for the range of m_H
- CMS and ATLAS analyses available for **SM Higgs (135 $\mathbf{fb^{-1}}$)**



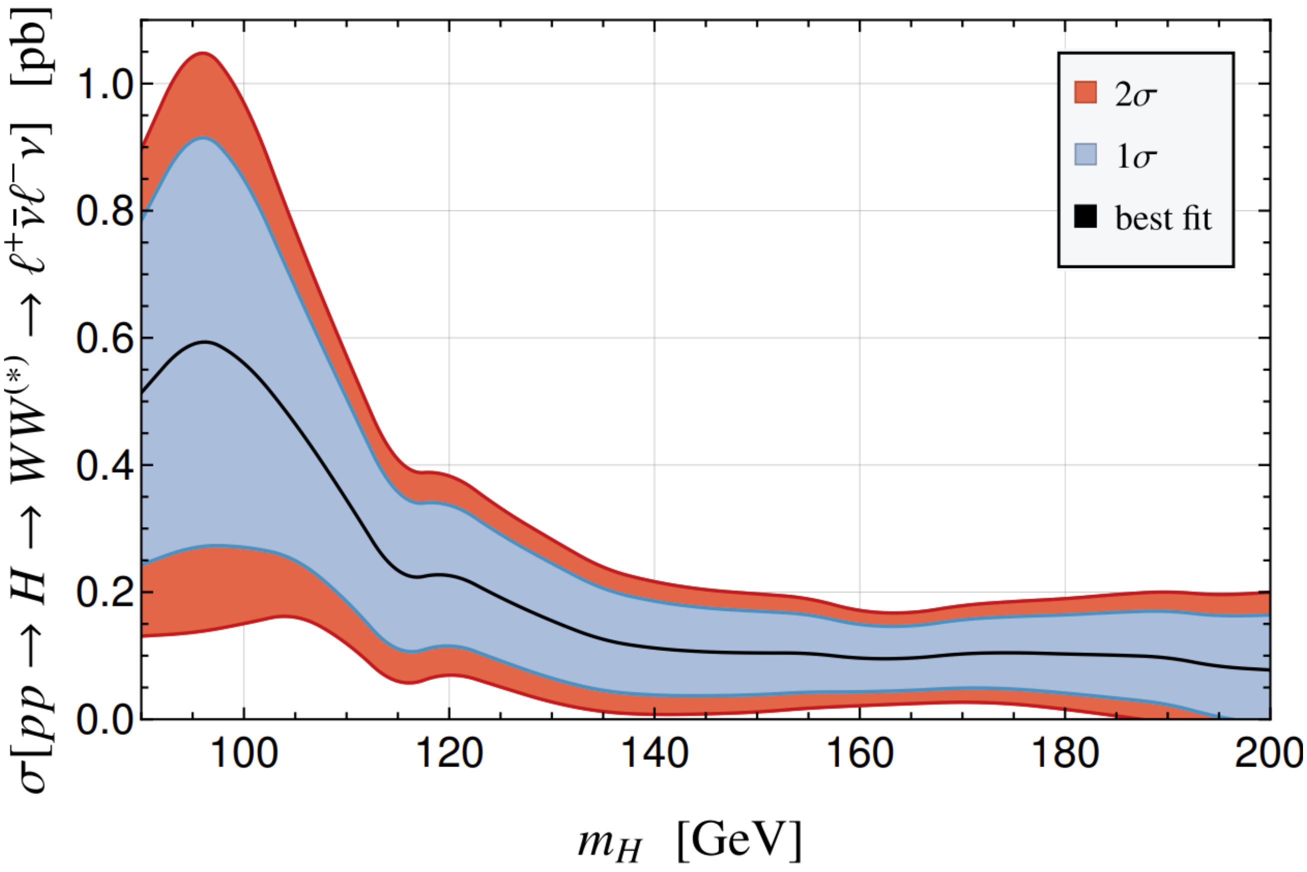
- Re-casting analyses to search **for new scalars**
- **Simulation with MadGraph5_aMC@NLO (Pythia8, Delphes)**

Leptonic decays → jet veto

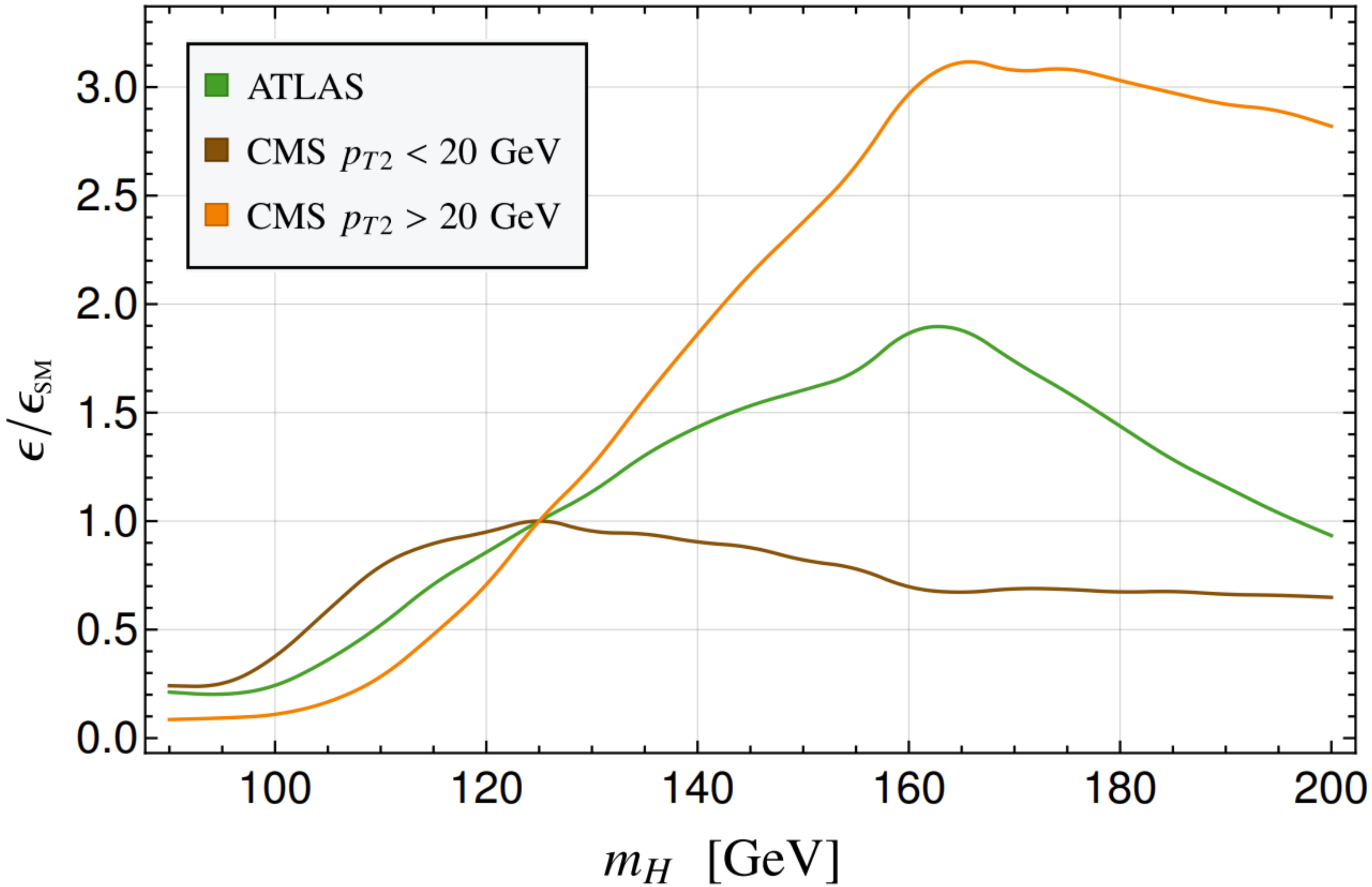
WW results

[GC, A. Crivellin et al.]

- Observed limit is weaker than expected over the whole mass range (**room for BSM** $\geq 2\sigma$)

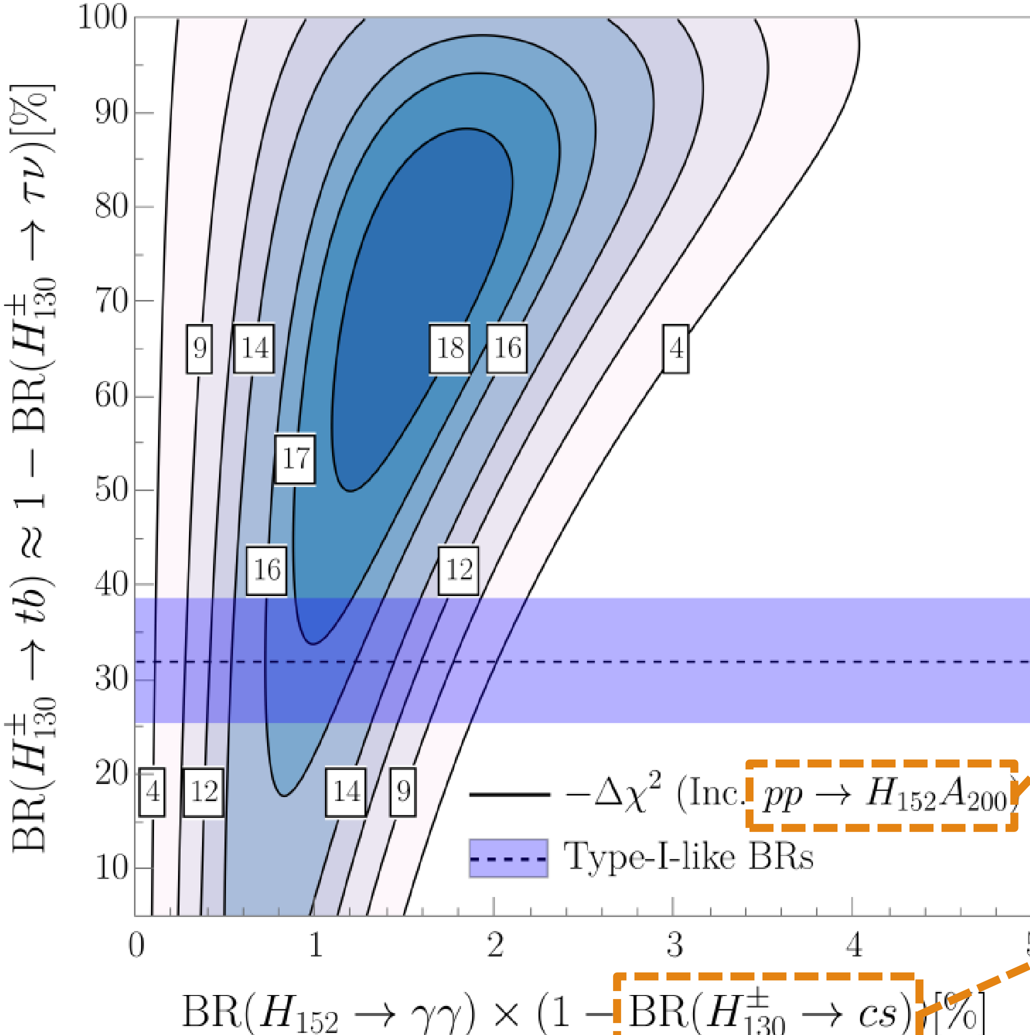


WW simulation efficiency [GC, A. Crivellin et al.]



2HDM Type-I: Results

[S. Banik and A. Crivellin]



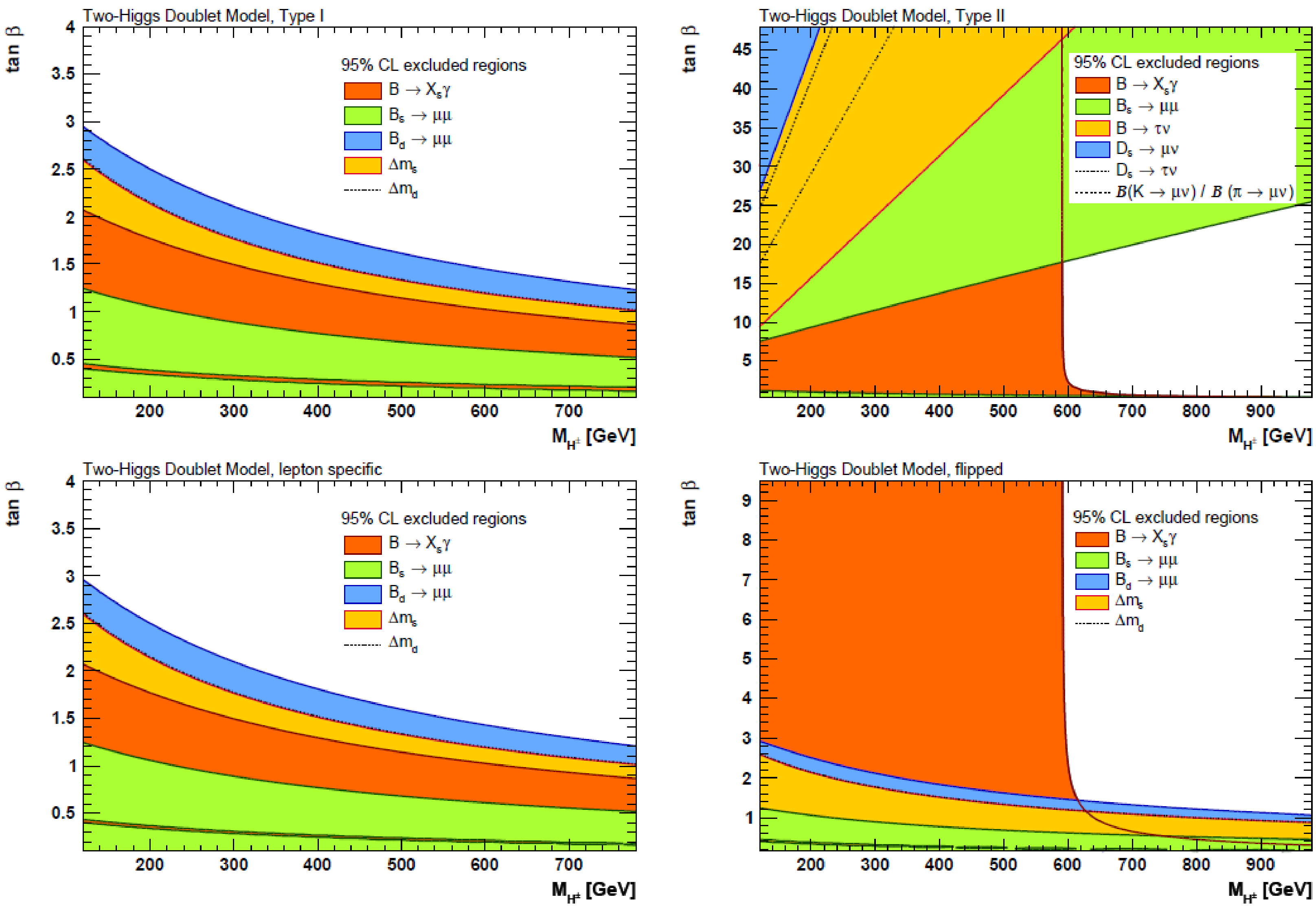
m	h	H	A	$H^\pm$
[GeV]	125	152	200	130

- $\alpha - \beta \approx \pi/2$
- $\tan(\beta) = 20$
- $m_{12} = 1100$ GeV

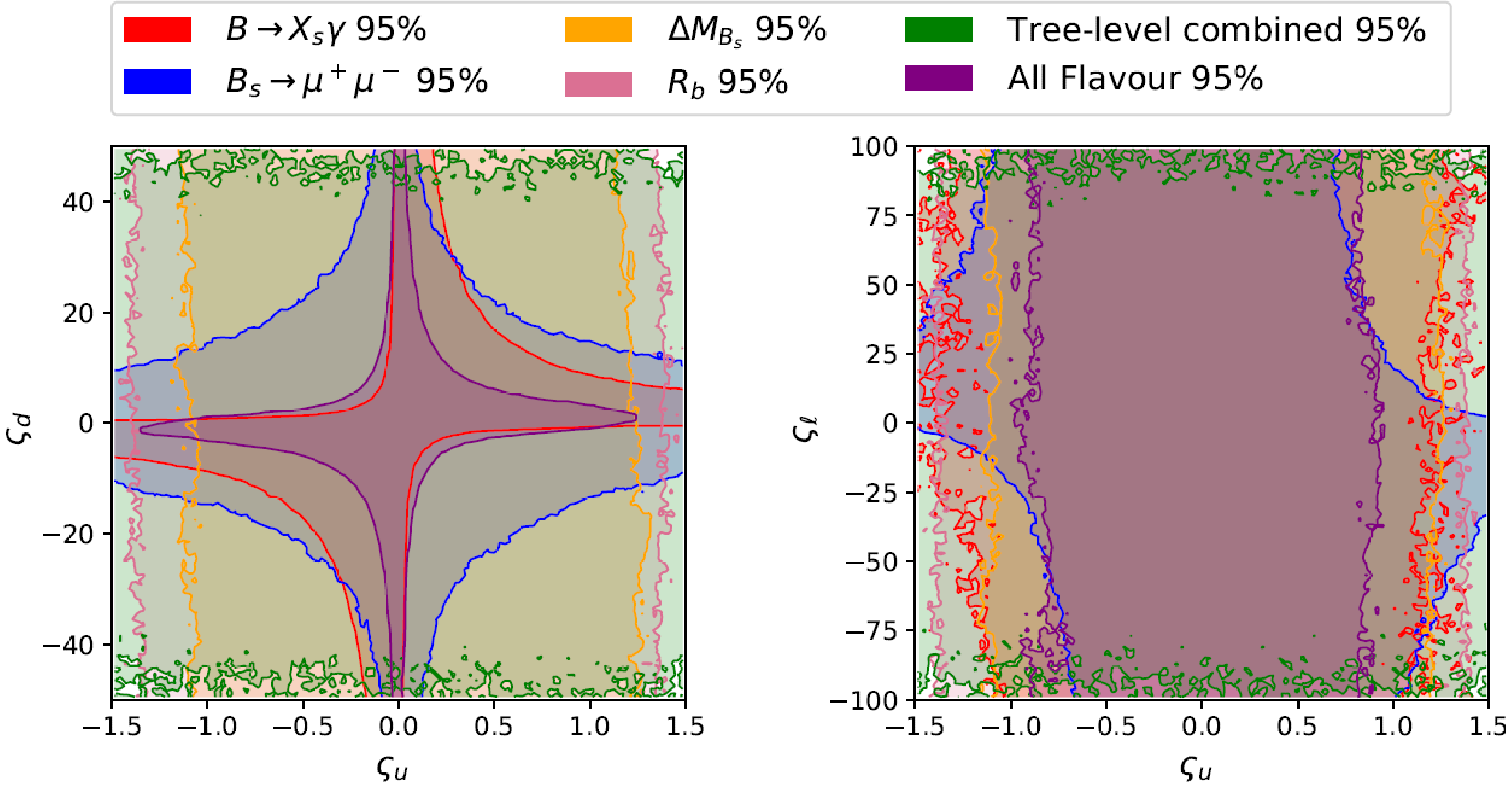
- Br$[A \to W^\pm H^\mp] \approx 100\%$
- Increased significance w.r.t. simplified model

$H^\pm \to cs$ can be numerically sizable but small impact in all signal regions

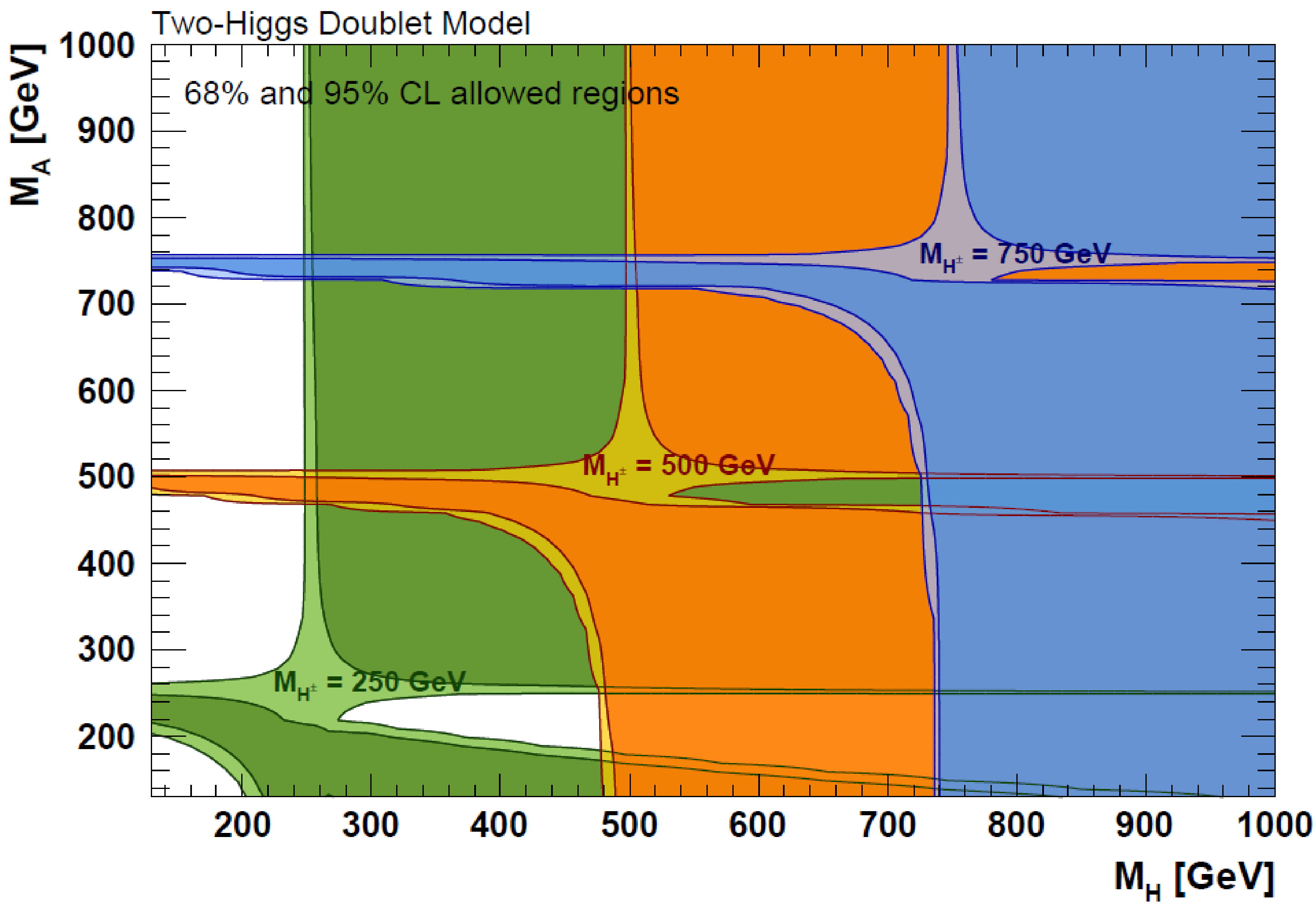
2HDMs: flavor bounds



A2HDM: flavor bounds



2HDMs: EW precision



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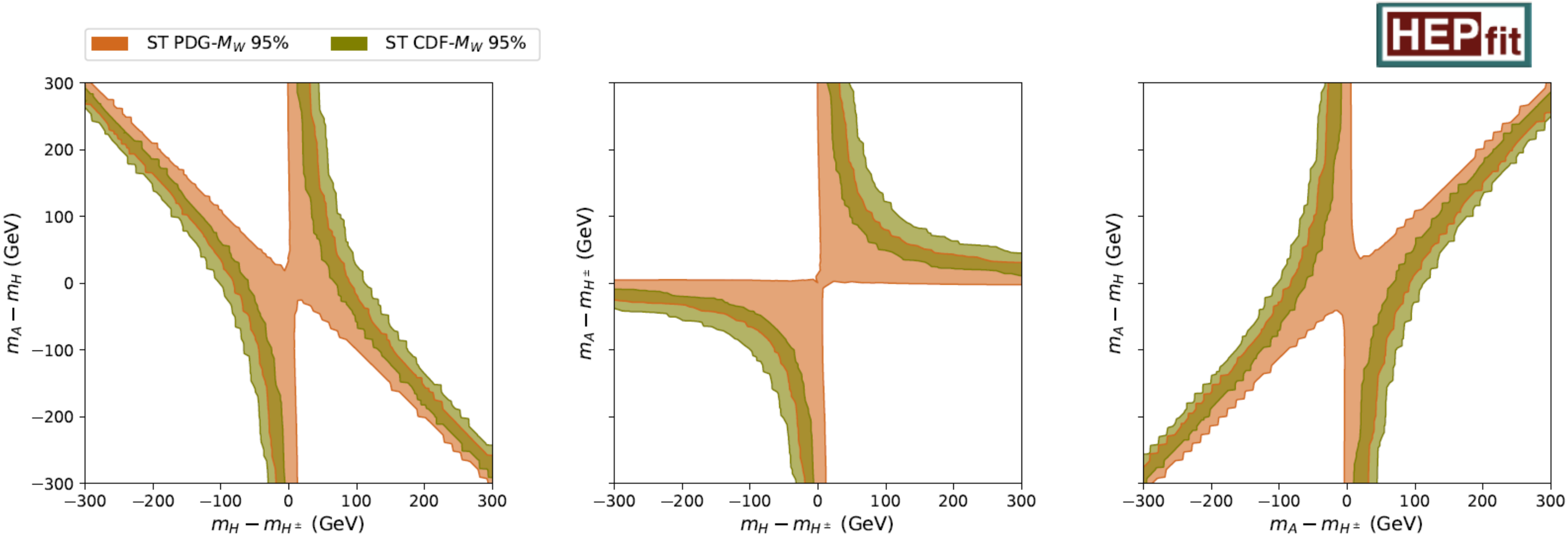


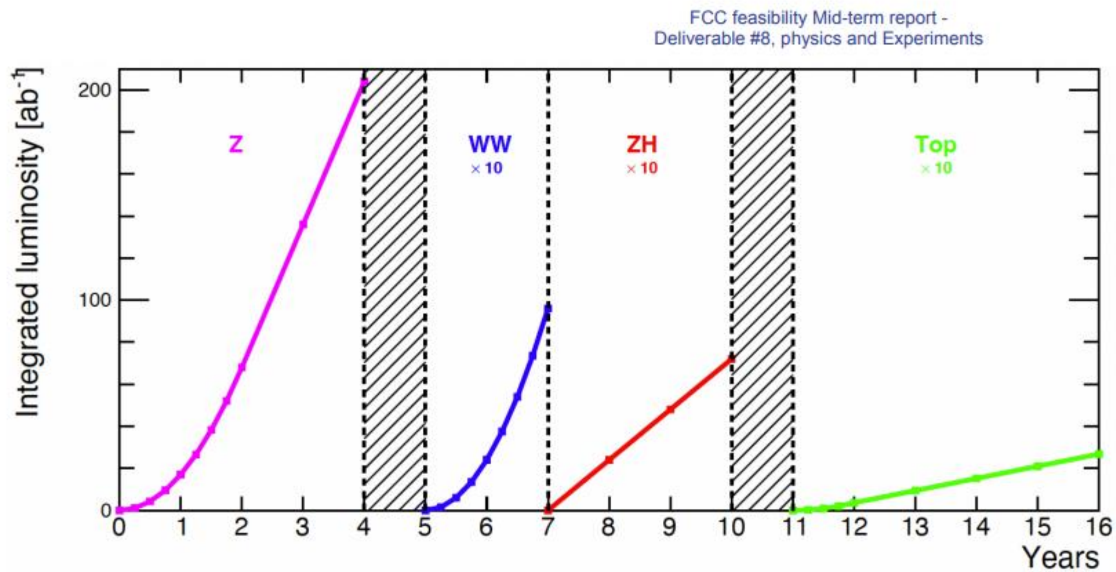
FCC-ee prospects

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



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 $\to$ H	1.9×10^{6} $t\bar{t}$ +330k ZH +80k WW $\to$ H	

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

all the data of LEP1 in minutes

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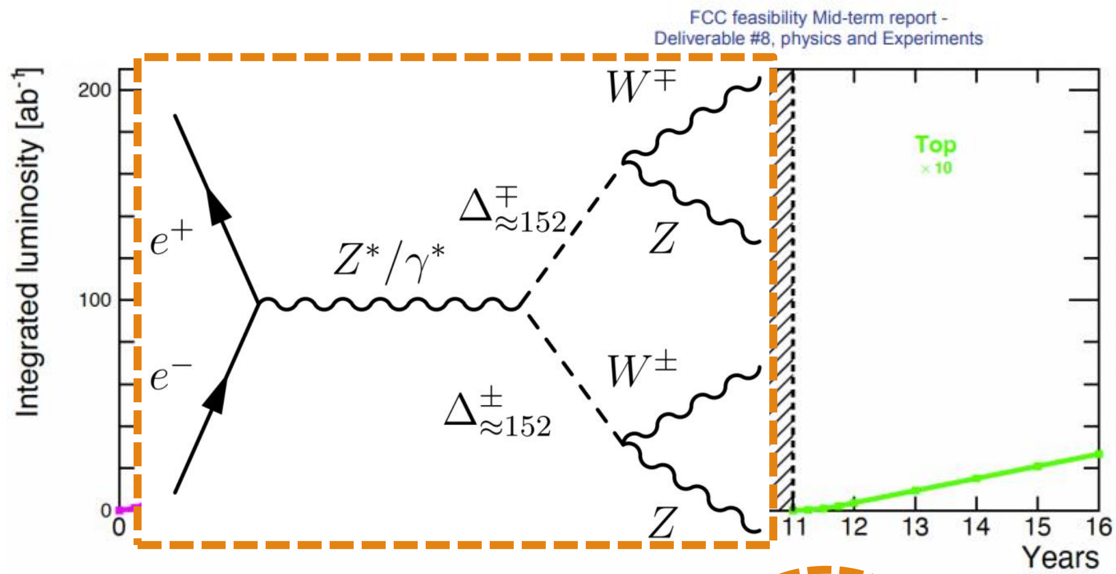

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all the data of LEP1 in minutes

Rebeca Gonzalez Suarez (UU) - PSI Particle Physics Summer School 2024

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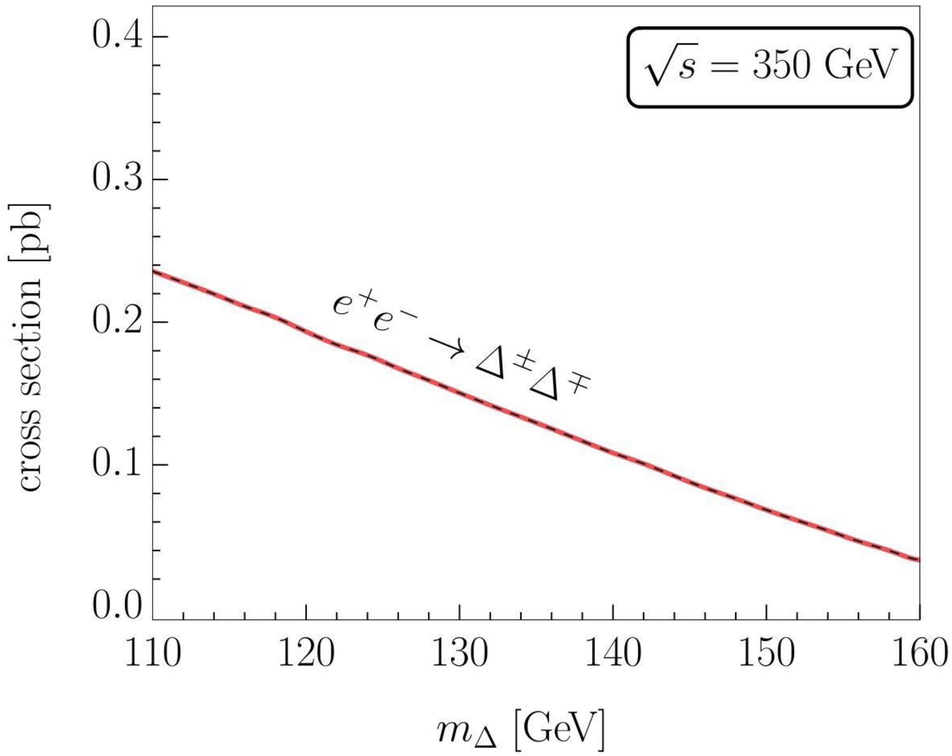
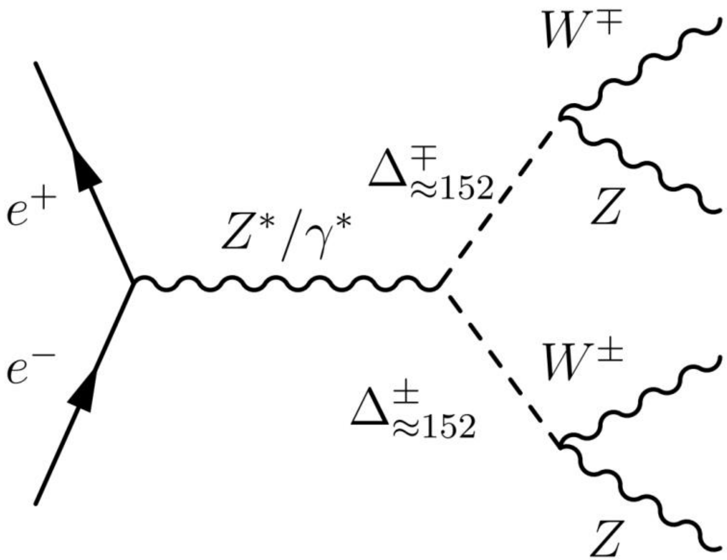
Real triplet at the FCC-ee

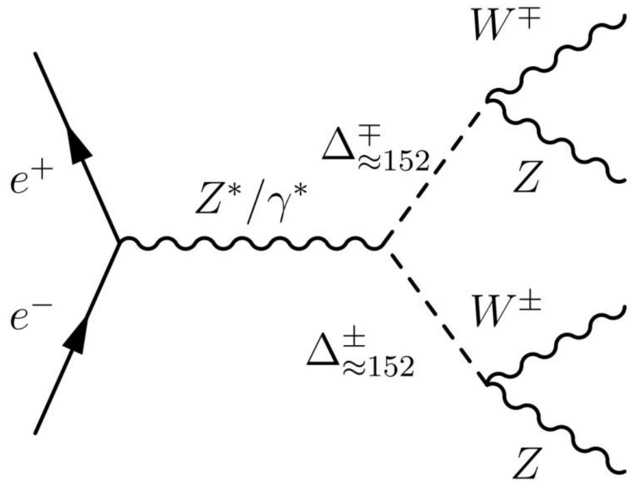
- Only Z^*/γ^* s-channel
- Suppressed $\Delta^0\Delta^0$ production for a real triplet
- Pair production of the charged components





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

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



Events expected in the ΔSM model

$$e^+e^- \to \Delta^{\pm}\,\Delta^{\mp} \to 6\ell + \text{MET} \approx 46$$

Events expected in the SM model

$$e^+e^- \to 6\ell(+\text{MET}) \approx 1$$

- Log-Likely-hood ratio yields $\chi^2 \approx 80$
- $\sigma(e^+e^- \to \Delta^{\pm}\,\Delta^{\mp})$ could be measured at $\approx 9\sigma$