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PSI

Indications of New Higgses at the LHC and Implications for FLC

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University of Zurich and Paul Scherrer Institut
18.09.2024

Outline

1. $\gamma\gamma$ hints for new Higgses at the LHC

2. Interpretation of the $\gamma\gamma$ excesses at 152 GeV
   Real Higgs triplet? Doublet?

3. $t\bar{t}$ run at LFC as a probe for new physics

4. FCC-ee projections

Hints at 95 GeV

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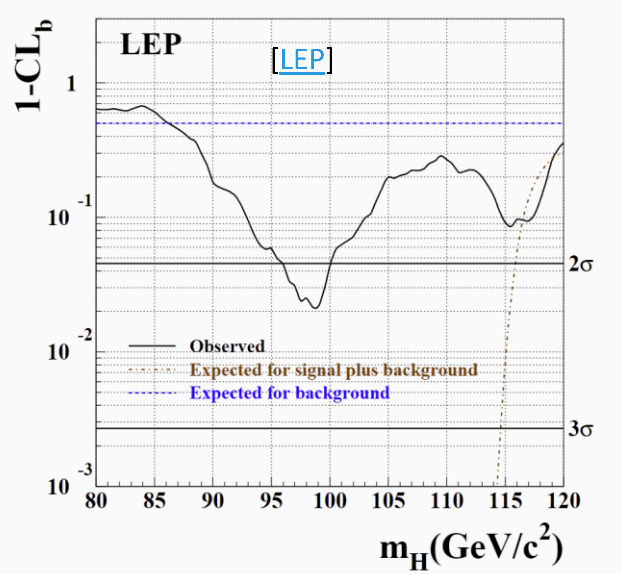
- LEP: $Z + b\bar{b}$ (2.3 σ)



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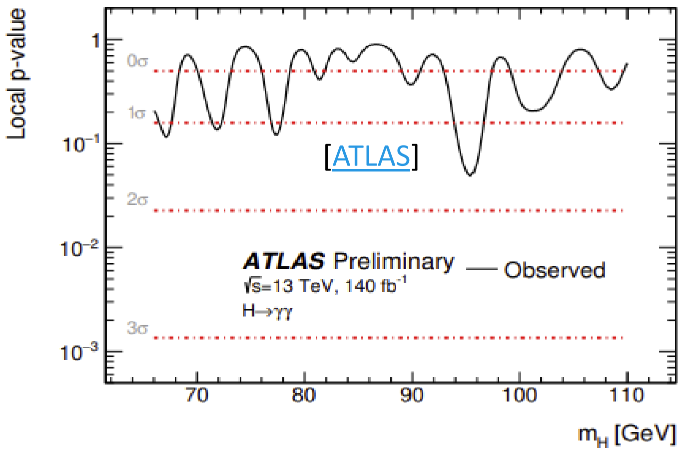

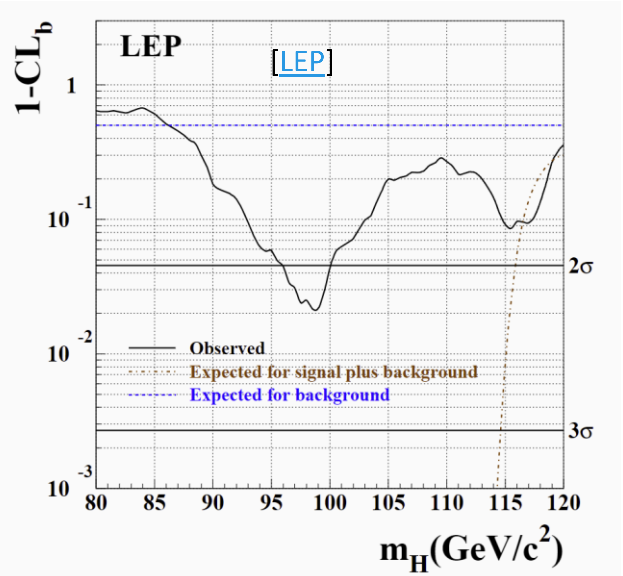

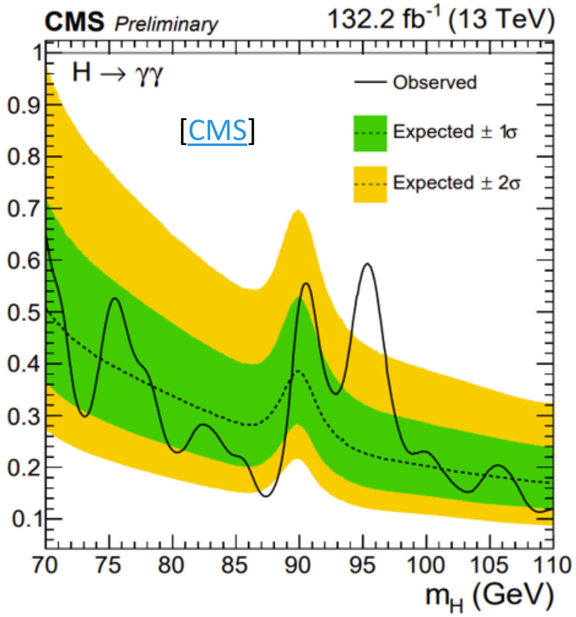

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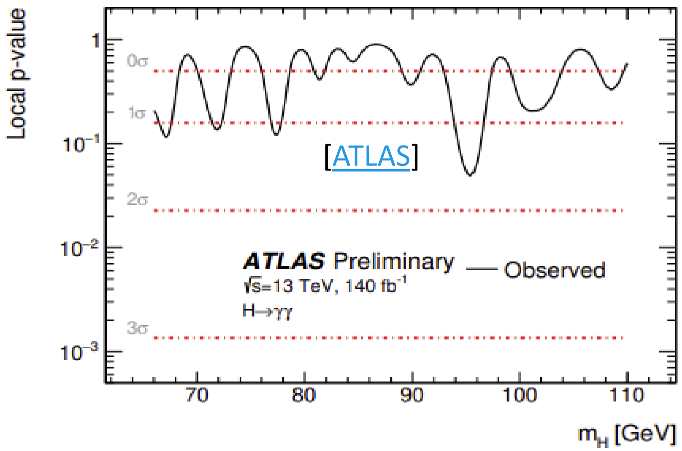

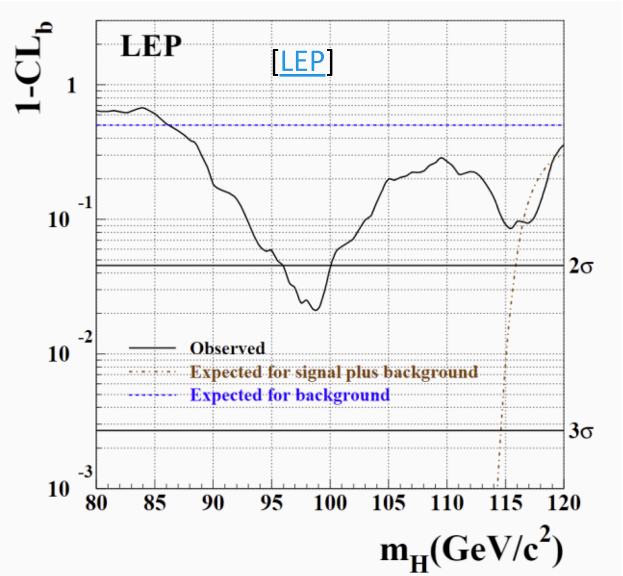

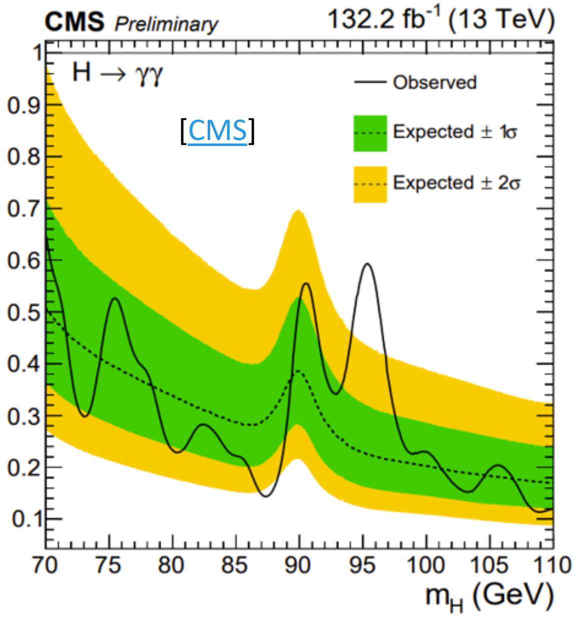

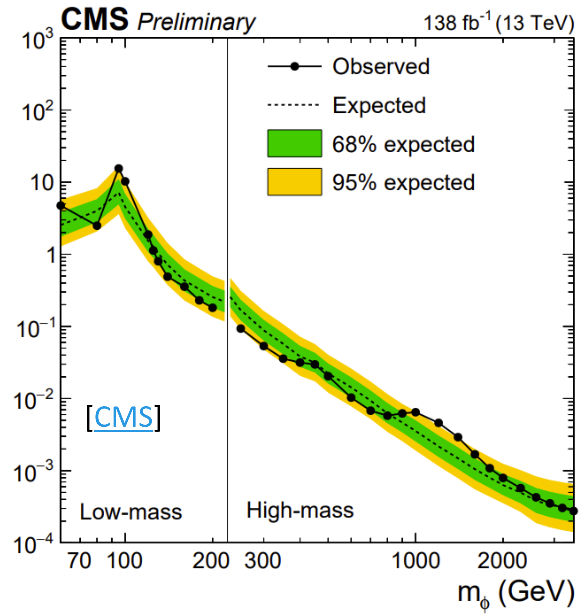

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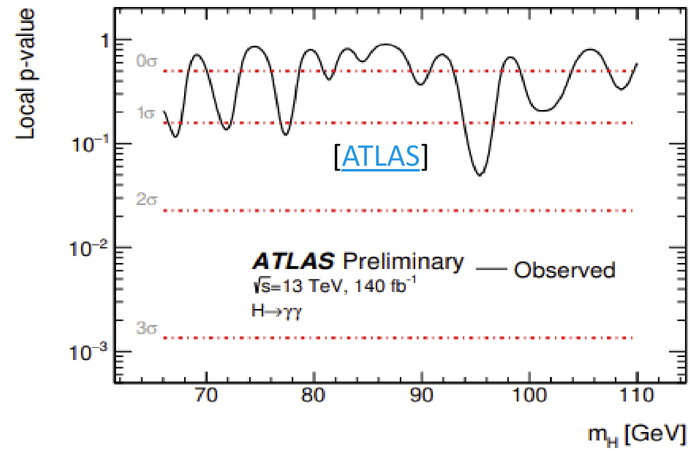

[U. Haisch, A. Malinauskas]
[T. Biekotter, S. Heinemeyer, C. Munoz]
[T. Biekotter, S. Heinemyer, G. Weiglein et al.]
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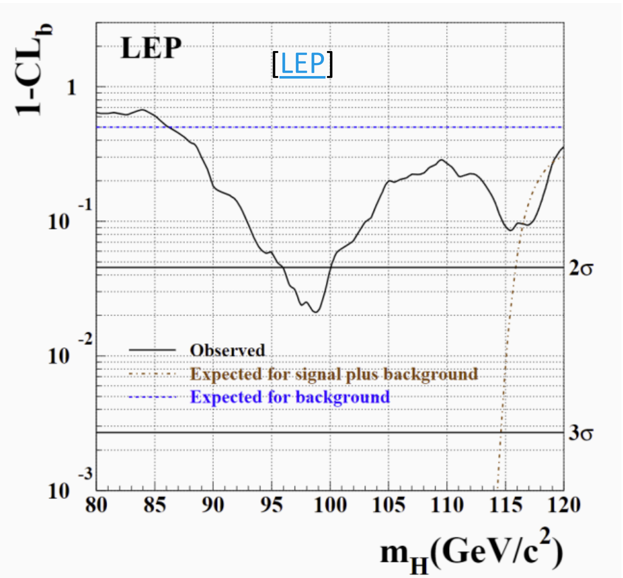

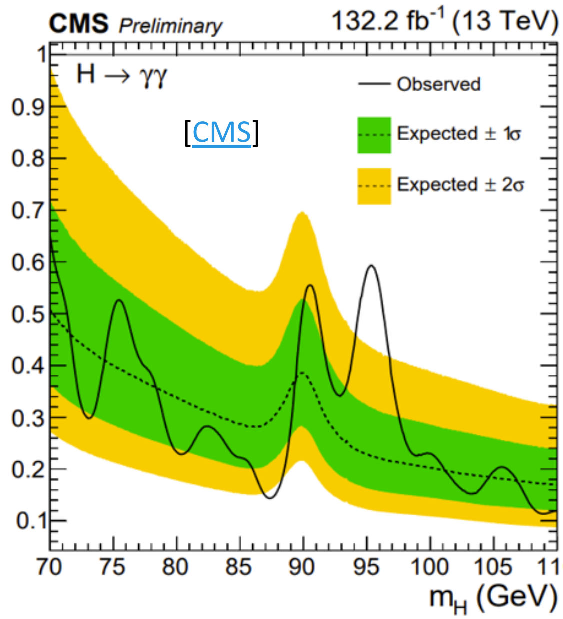

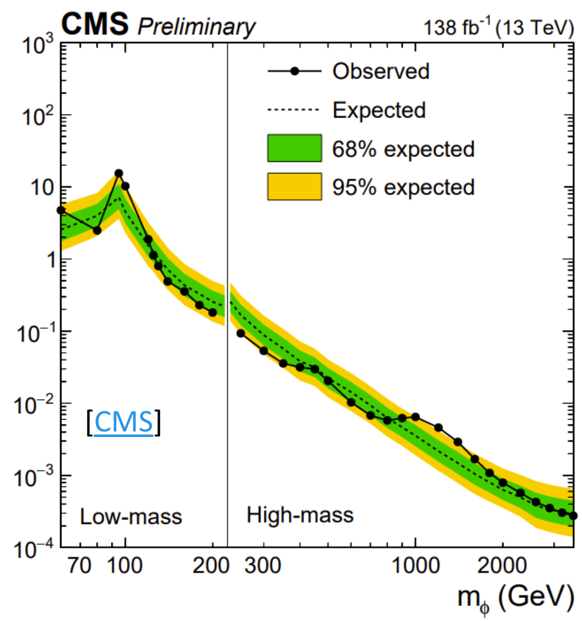

Hints at 152 GeV

[ATLAS] [Moriond 2024]

- **SM search for $H \to \gamma\gamma + X$ ($m_{\gamma\gamma} =$ 105-160 GeV)**
- Hints for a resonance decaying to photons **in associated production with l, MET, jets, etc.**
- **Reduced SM background and enhanced NP sensitivity**

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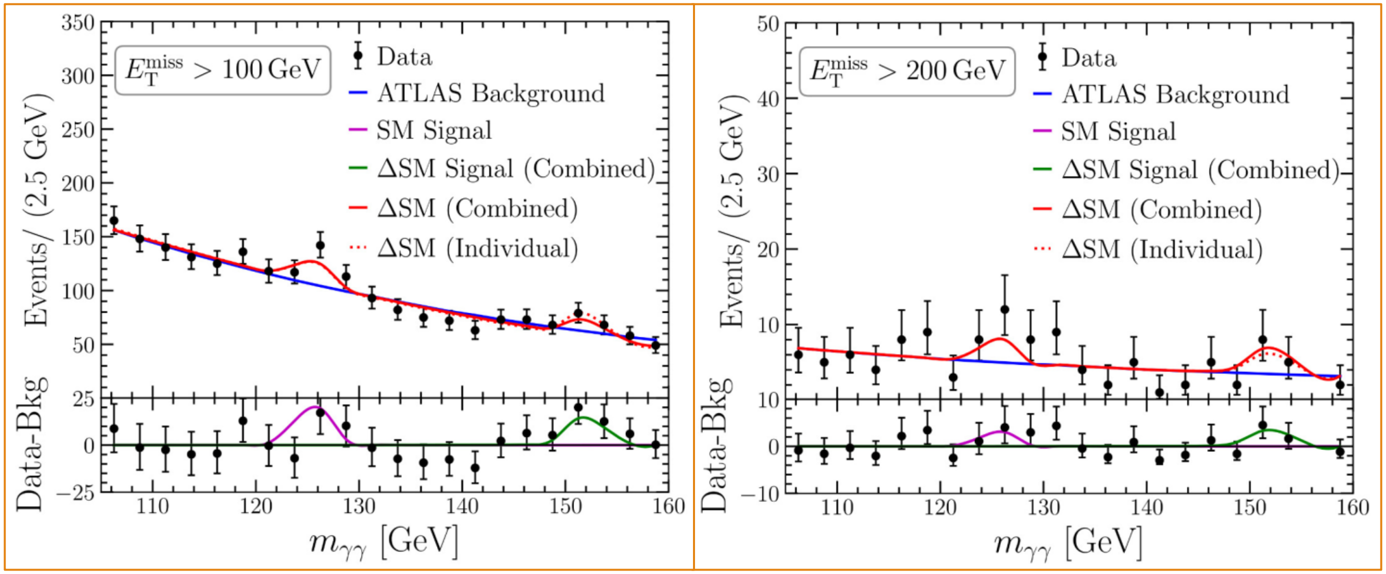

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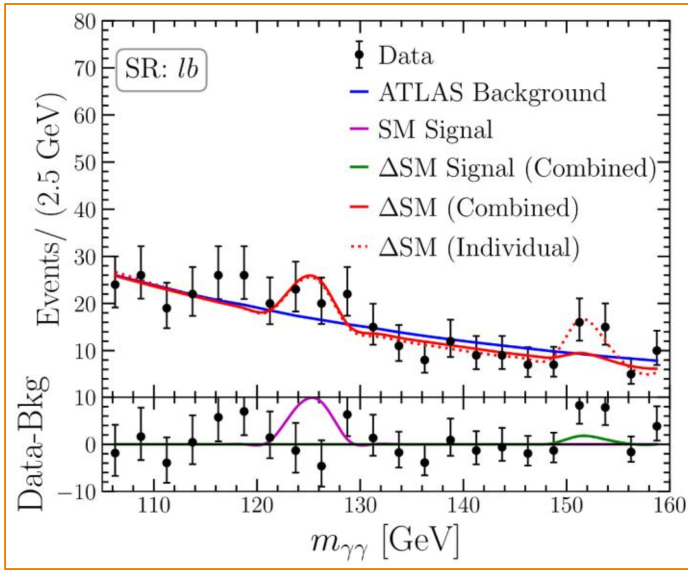

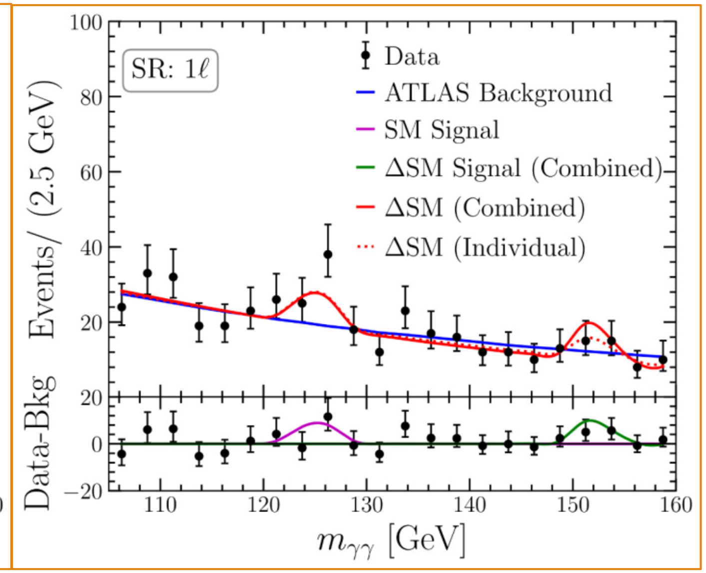

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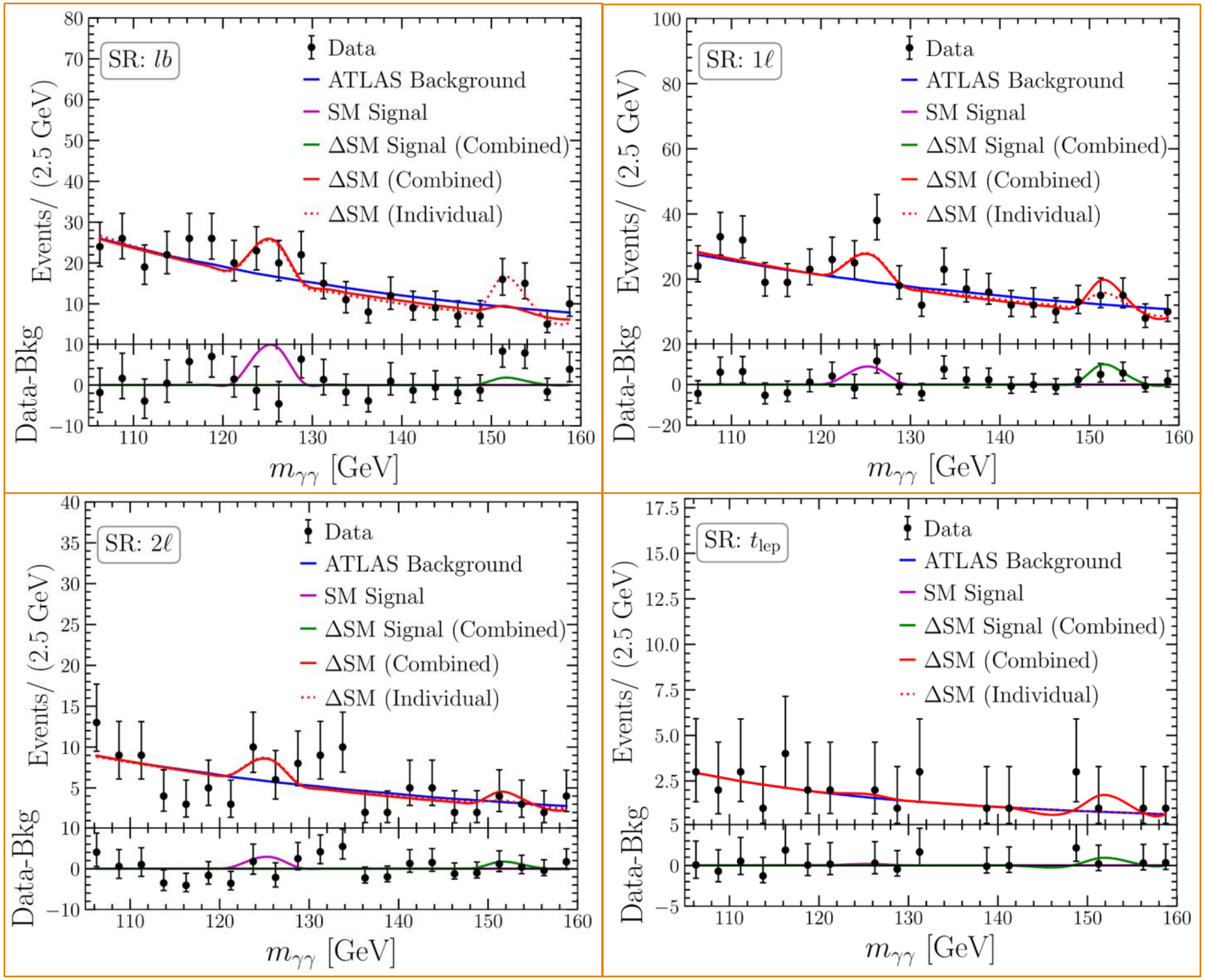

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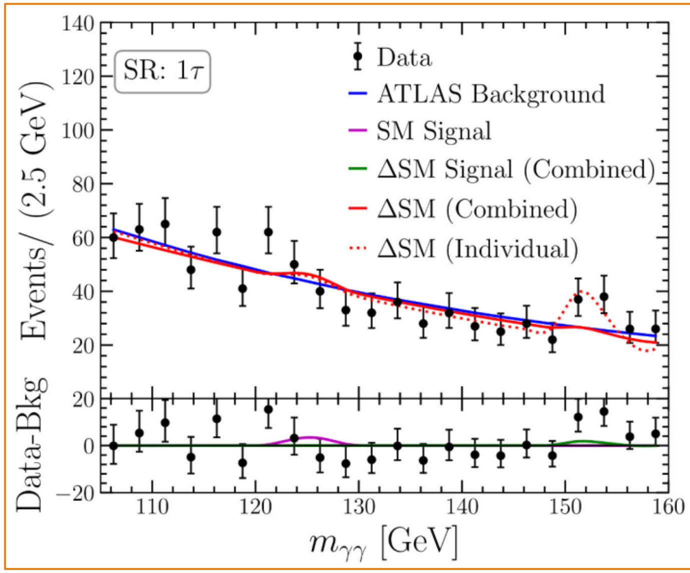

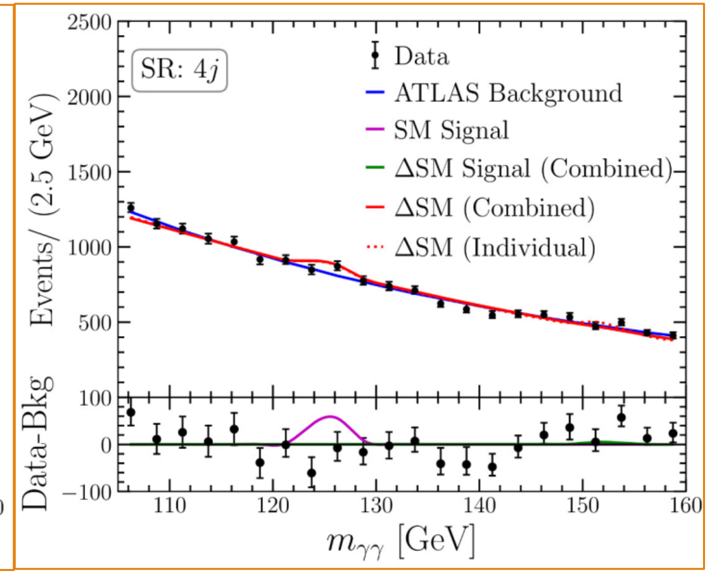

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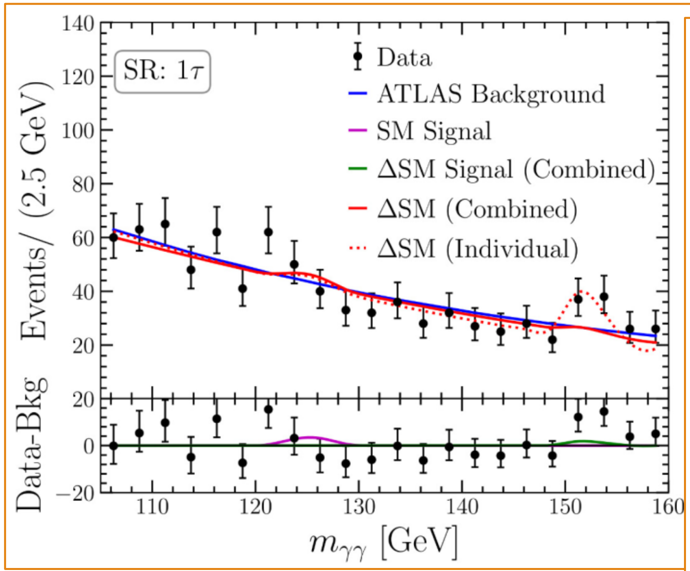

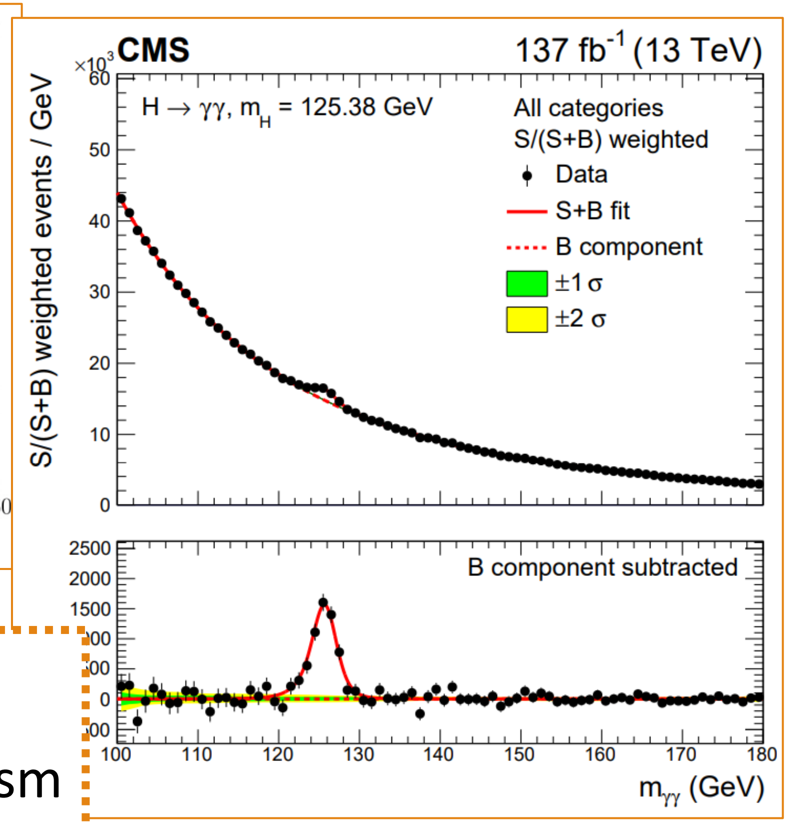

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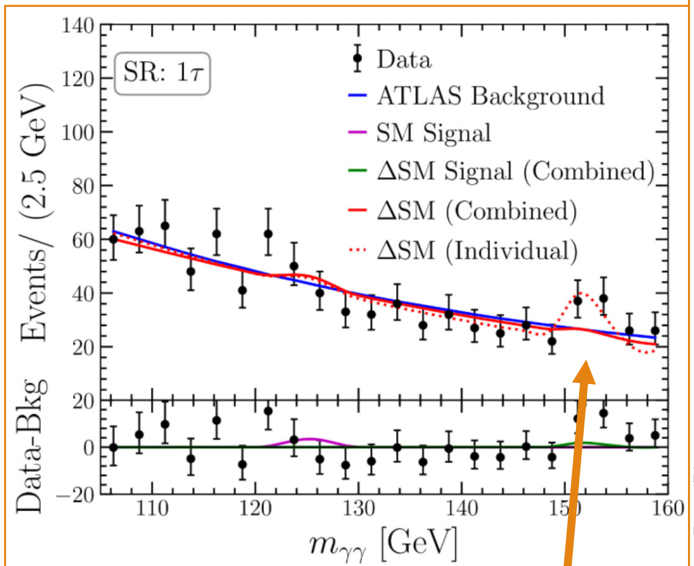
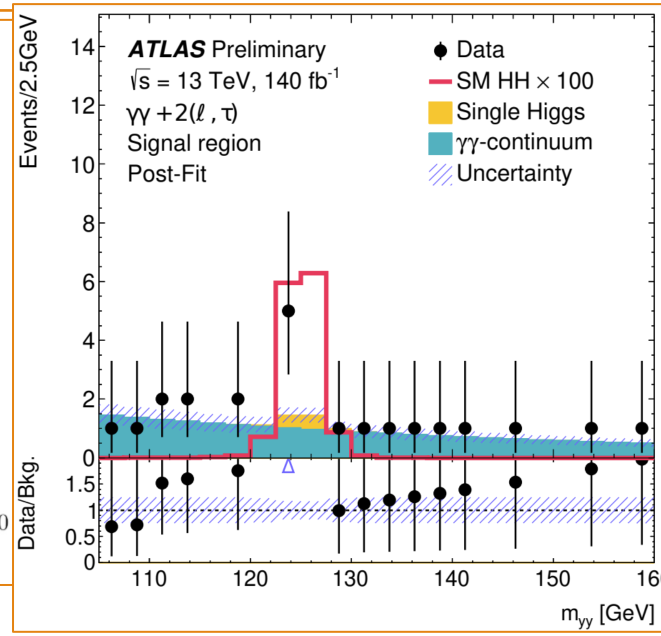
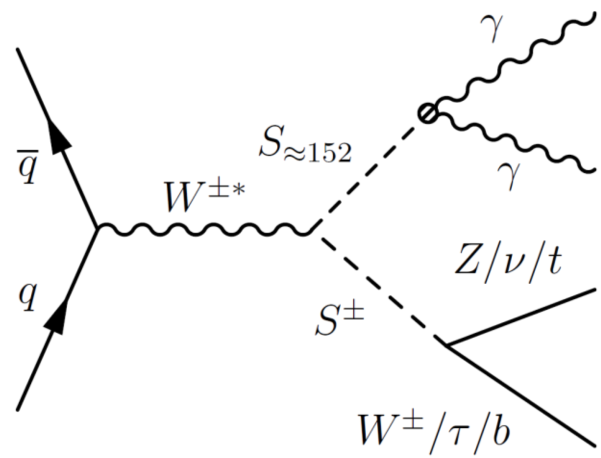




- **Drell Yan** is suggested as associated production mechanism
- 152 GeV neutral Higgs boson produced **in combination with a charged scalar** (1τ signal region)



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Have small vacuum expectation value	Suppressed VBF and VH production
Small mixing with the SM Higgs boson	Bounds from Higgs data

Interpretation of the excesses

Is there a minimal model to explain the 152 excesses?

Interpretation of the excesses

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

≈152 GeV mostly produced in association (AP)		

152 GeV scalar?

Interpretation …

[GC, A. Crivellin et al.]

Multi- lepton anomalies

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

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Real Higgs triplet

[GC, A. Crivellin et al.]

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Δ	3	0

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

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No direct coupling to SM fermions:
- Gluon fusion $\propto \alpha \ll 1$
- Flavour effects $\propto \frac{v_\Delta}{v_{SM}} \ll 1$

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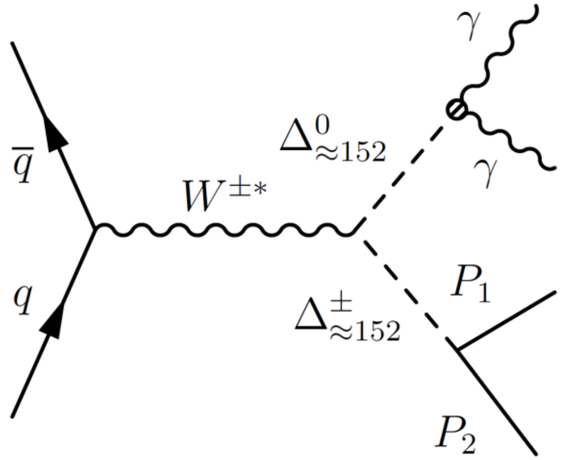

Produced in AP via Drell-Yan (DY)		

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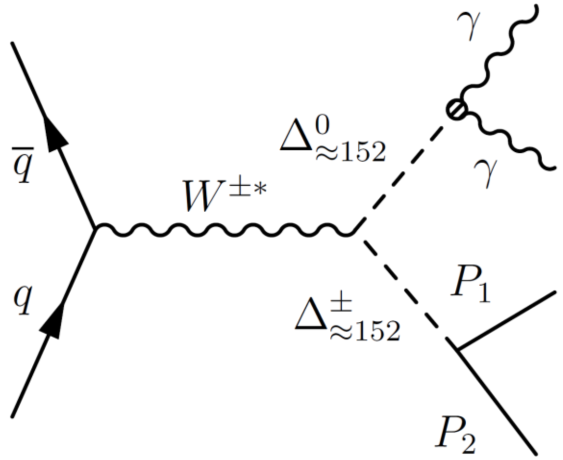

Produced in AP via Drell-Yan (DY)	$\Delta^0 WW$ but no $\Delta^0 ZZ$ (tree level, $\alpha_\Delta = 0$)	

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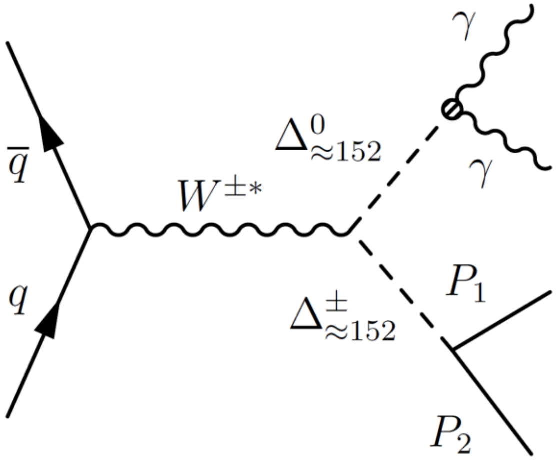


Produced in AP via Drell-Yan (DY)	$\Delta^0 WW$ but no $\Delta^0 ZZ$ (tree level, $\alpha_\Delta = 0$)	$v_\Delta \approx 2.3/3.4$ GeV ($m_{\Delta^0} \approx m_{\Delta^\pm}$)

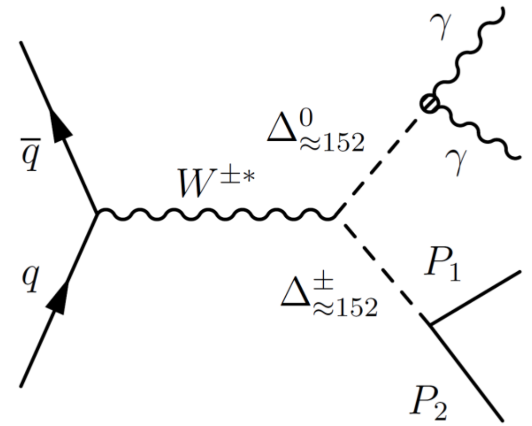
[T. Blank, W. Hollik]

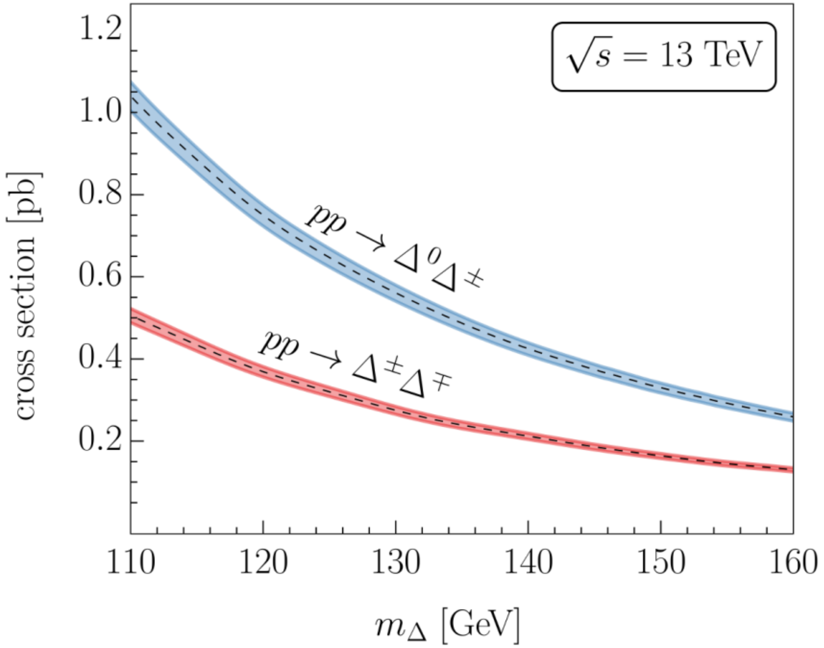
The ΔSM model

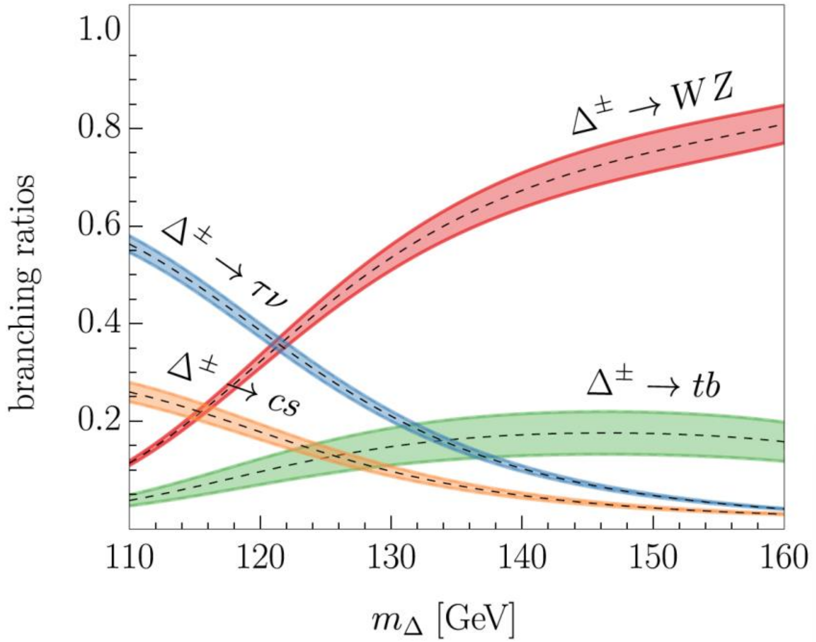
[S. Banik, GC, A. Crivellin et al.]

Production cross section and Br($\Delta^{\pm}$) fixed

- $\boldsymbol{m_{\Delta^0,\,\Delta^{\pm}}}$
- $\mathbf{Br}(\boldsymbol{\Delta^0 \to \gamma\gamma})$



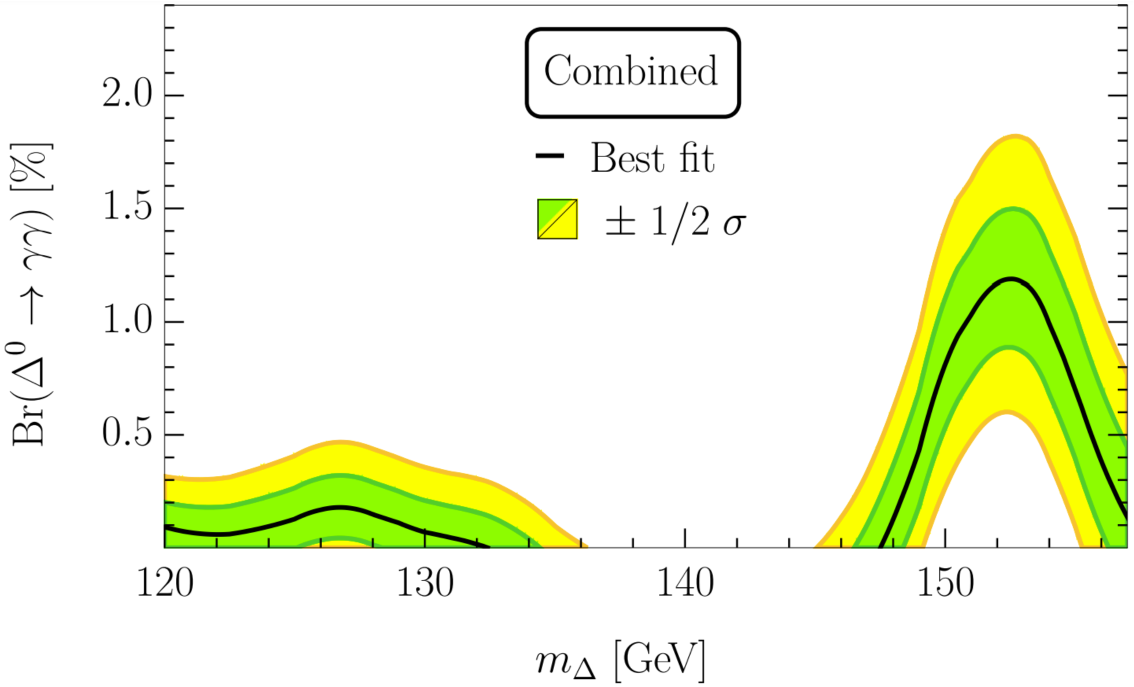




Results: $\Delta^0 \to \gamma\gamma + X$

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

- Combination of all relevant signal regions
- Bonus: SFOPT induced within our benchmark points [Bandyopadhyay et al.]
- Connection with dark matter? [B. Fuks, M. D. Goodsell, T. Murphy]

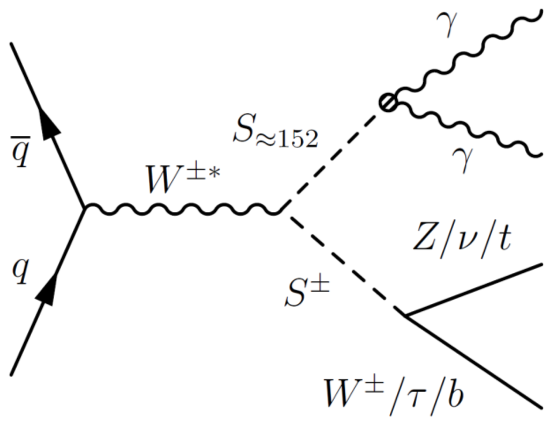


$\mathrm{Br}\left(\Delta^0_{152} \to \gamma\gamma\right) \approx 1\%$ preferred over SM by $\approx 4\sigma$

Can we do even better?

[S. Banik and A. Crivellin]

- **Two new scalars: S_{152} and $S^{\pm}$**
- **S_{152} produced only via DY**
- **Dominant decays of $S^{\pm}$:** $\begin{cases} tb \\ \tau\nu \\ W^{\pm}Z \end{cases}$



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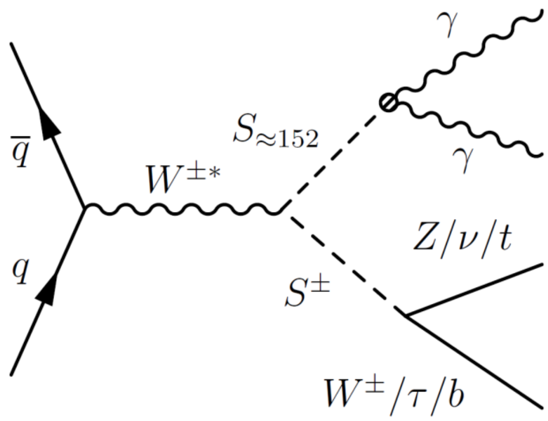
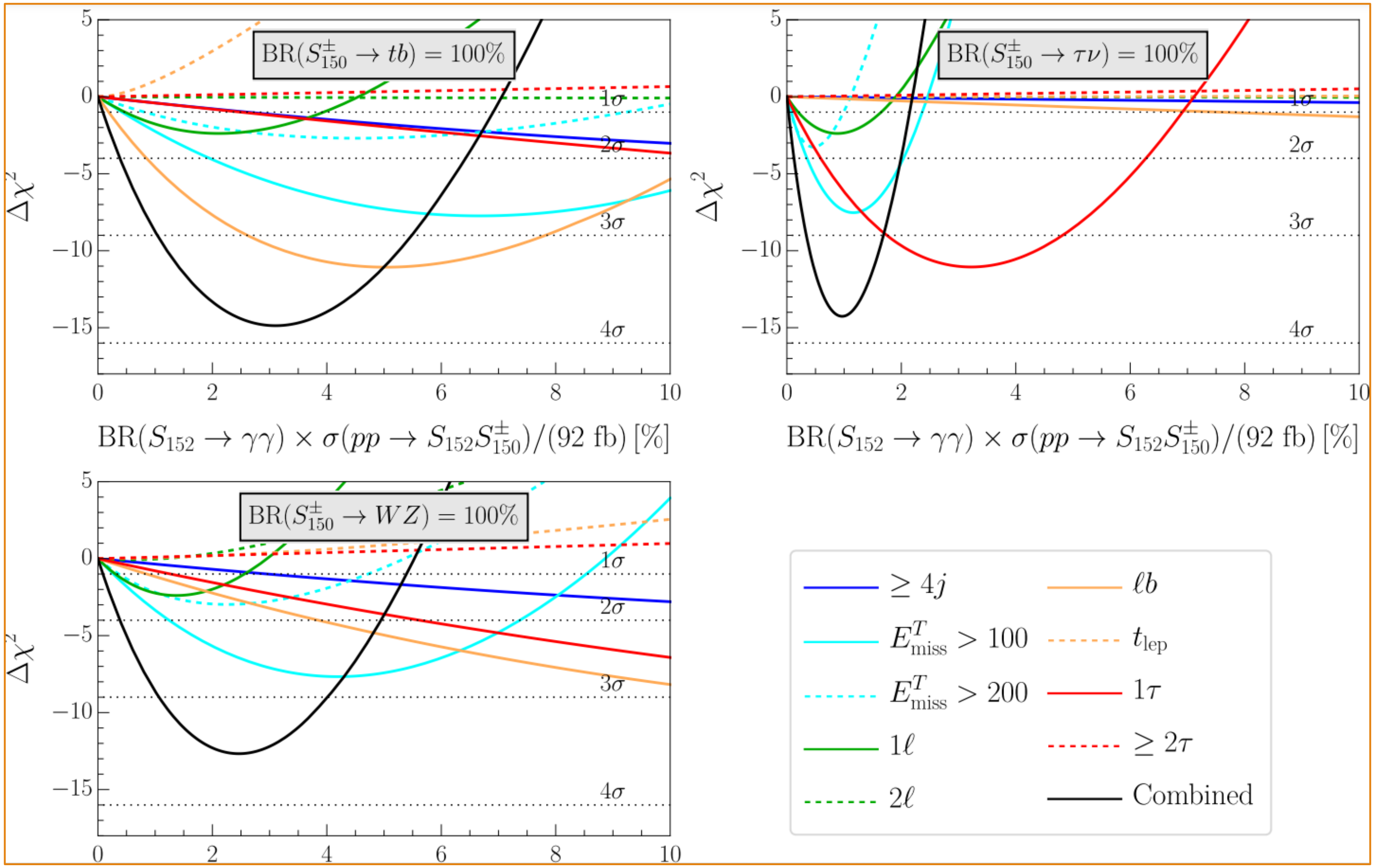


- Separate study of each decay mode of $S^{\pm}$
- UFO model (at NLO) generated using FeynRules
- Simulation set-up: MG5@NLO + Pythia8 + Delphes3

Simplified model analysis



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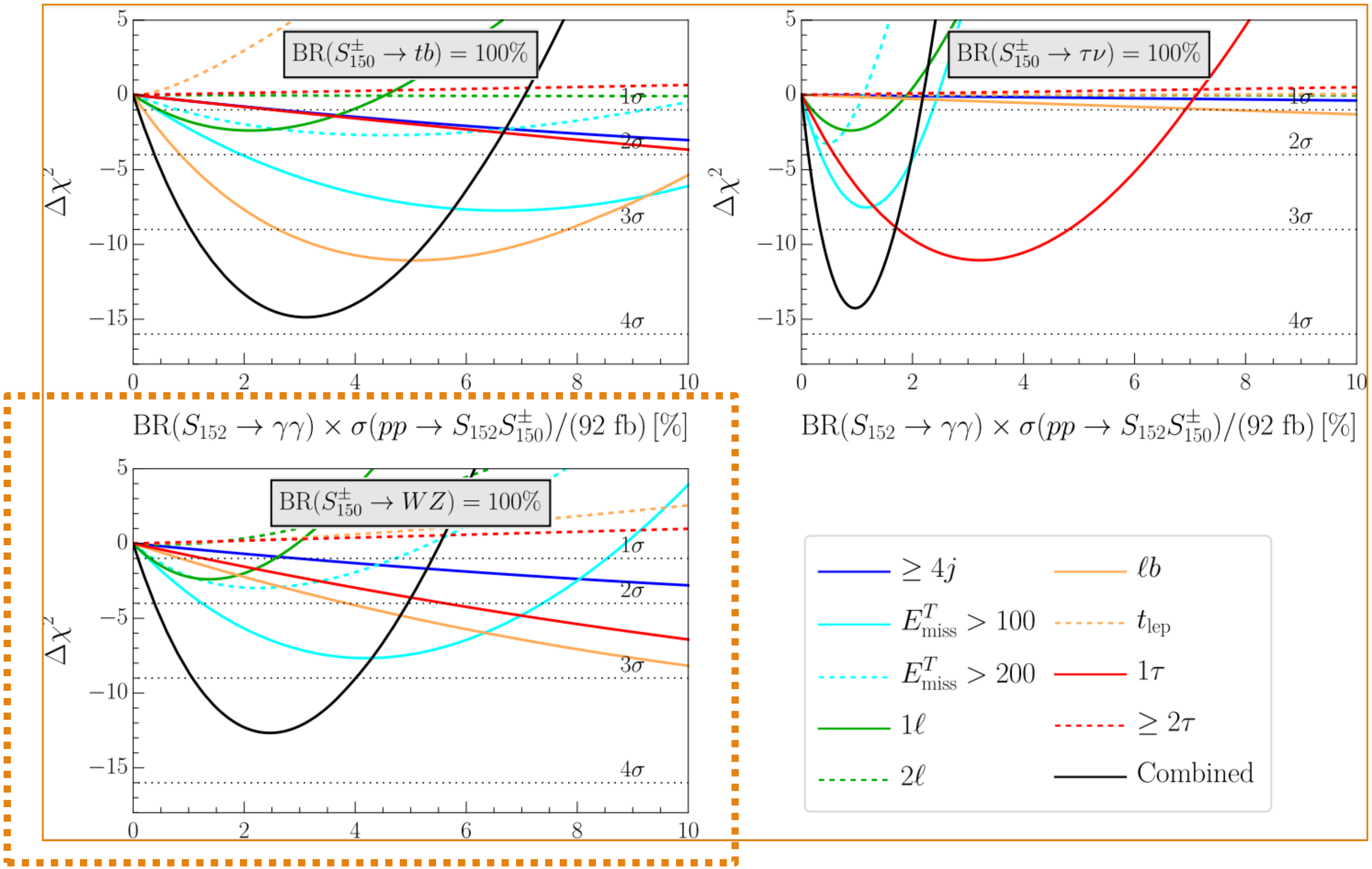

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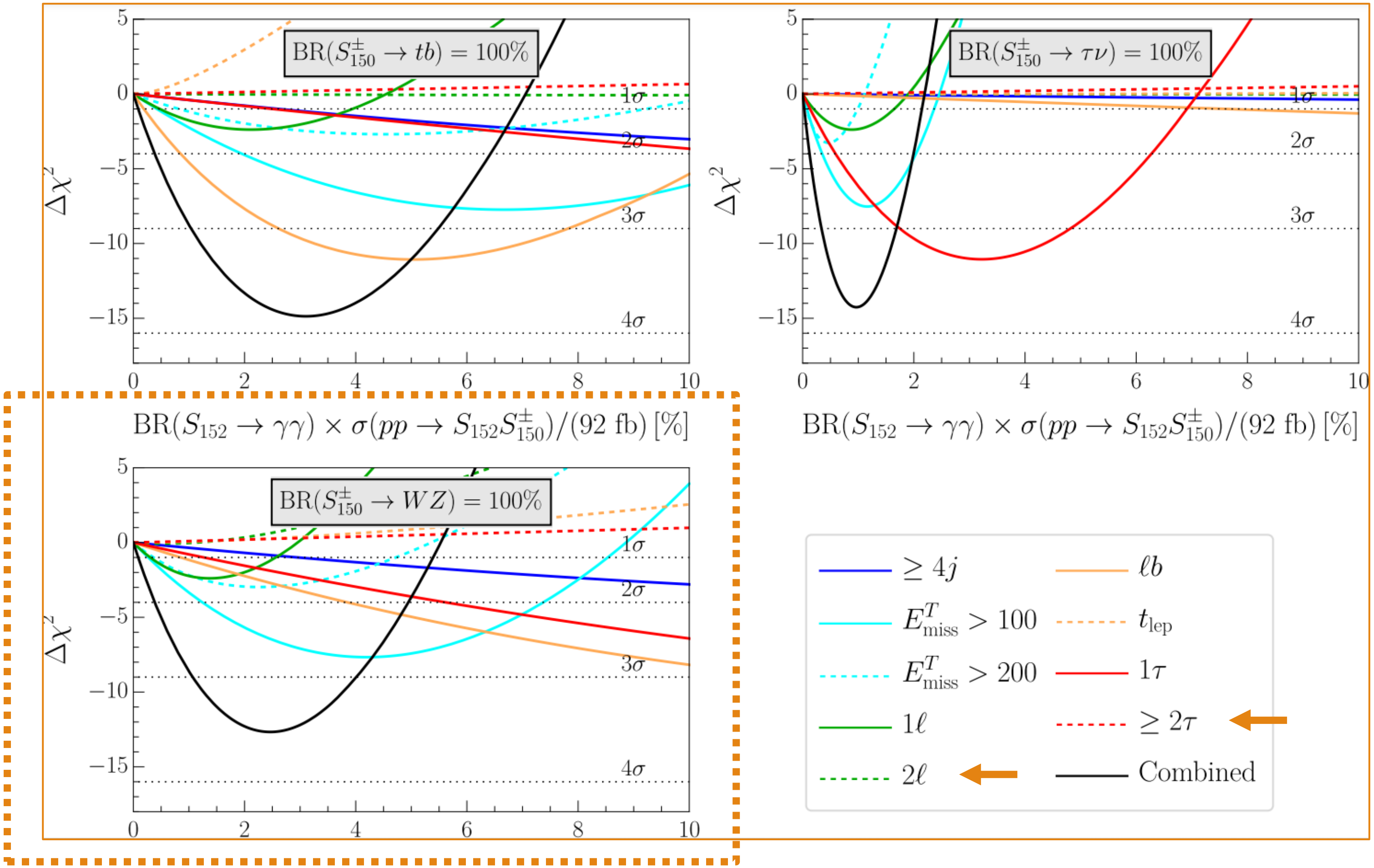

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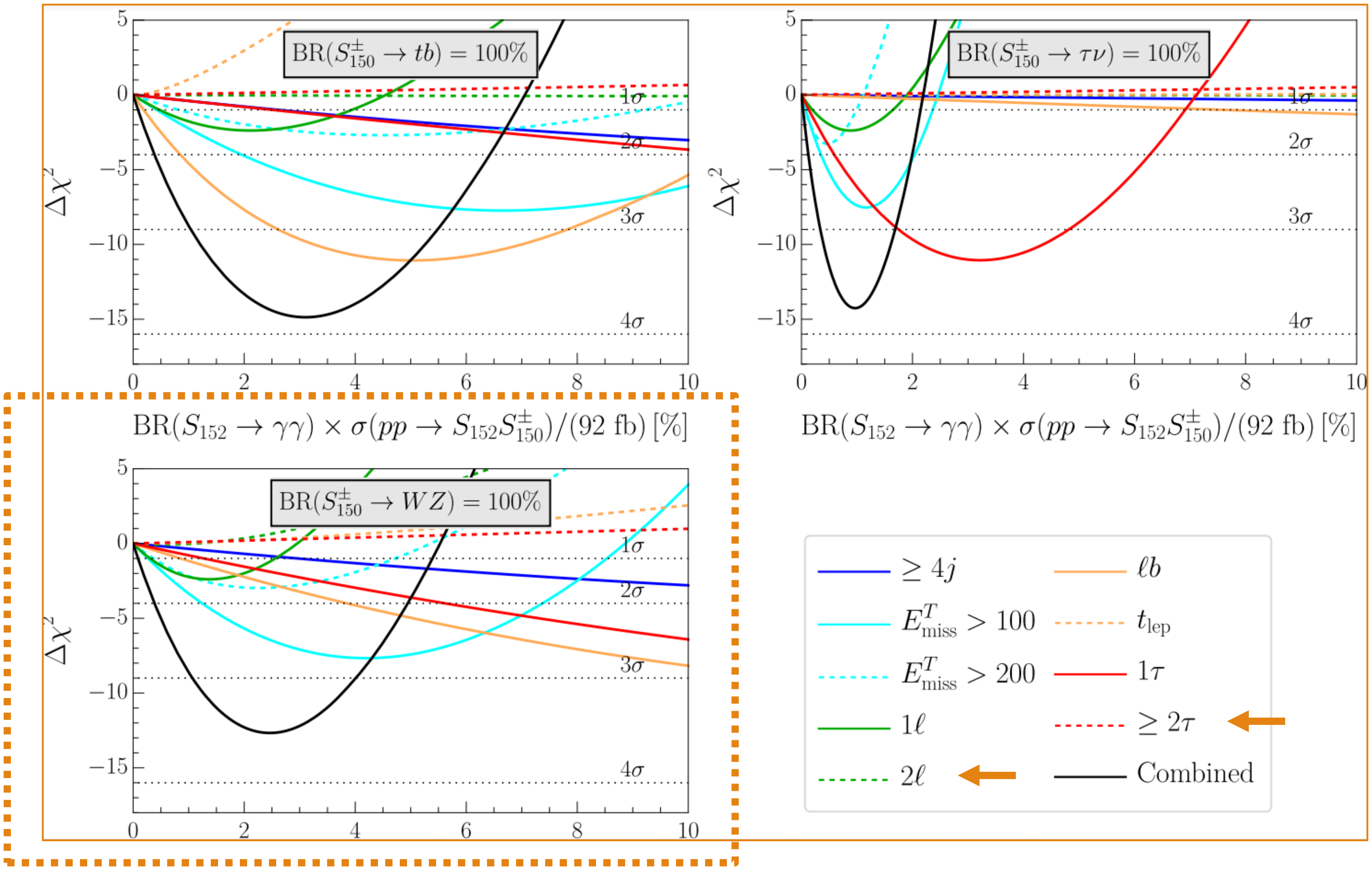

$W^{\pm}Z$ **leads to too many leptons**

2HDM Type-I

- Scalar sector: two $SU(2)_L$ doublets ϕ_1 and ϕ_2
- Z_2 symmetry to avoid FCNC leads to the scalar potential:

$$V(\phi_1, \phi_2) = m_{11}\phi_1^\dagger \phi_1 + m_{22}\phi_2^\dagger \phi_2 - m_{12}(\phi_1^\dagger \phi_2 + h.c.) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \lambda_5[(\phi_1^\dagger \phi_2)^2 + h.c.]$$

- Scalar particles: $h, H, A, H^\pm$
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$H^\pm \to W^\pm Z$ not allowed at tree level

2HDM Type-I: Drell-Yan

$\tan(\beta) \gg 1$
and
$\alpha \ll 1$

- **Suppressed gluon fusion ($\cot(\beta)$), VBF and VH ($\sin(\beta - \alpha)$)**

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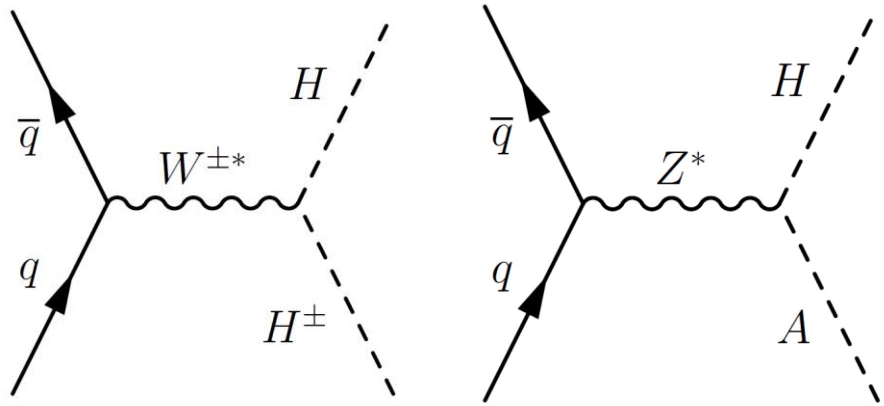

Dominant Drell-Yan production

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$\tan(\beta) \gg 1$
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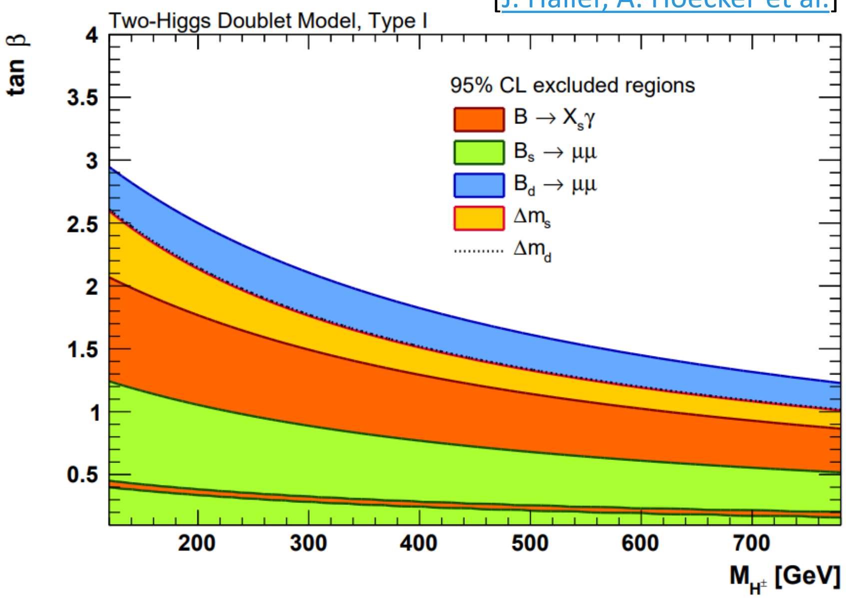
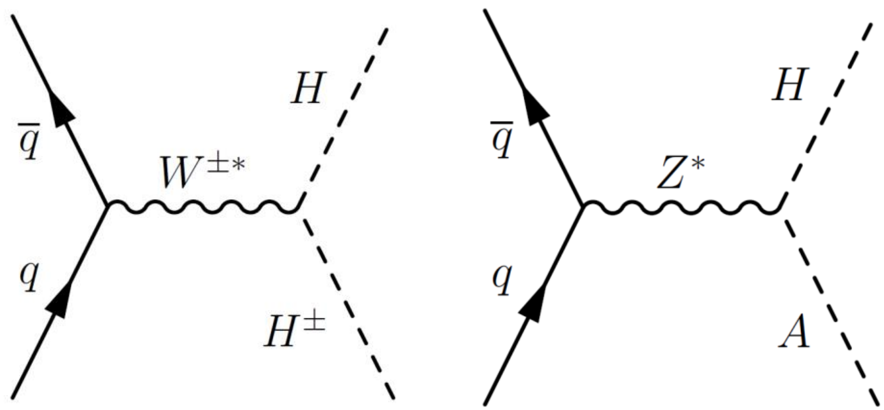
- Allowed by flavor bounds

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

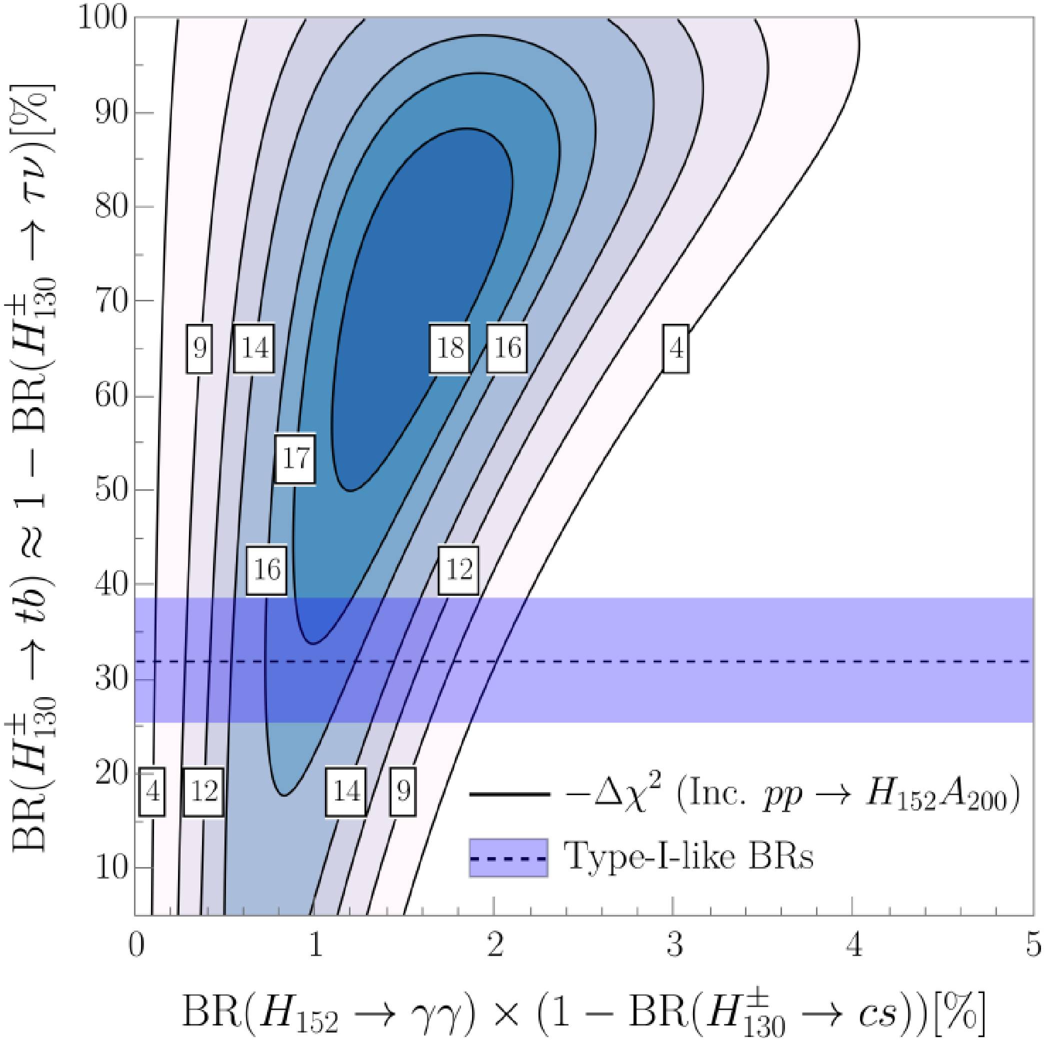




Dominant Drell-Yan production

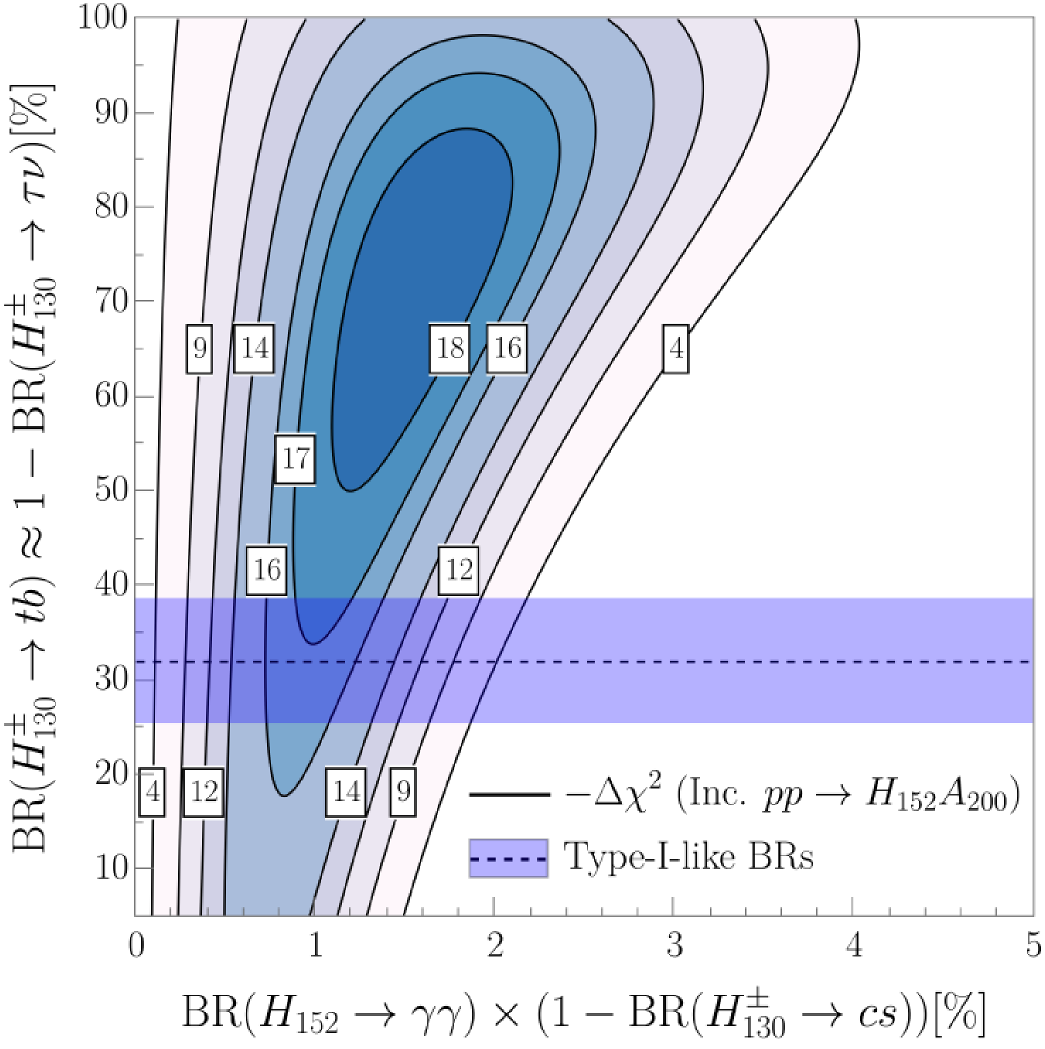
2HDM Type-I: Results

[S. Banik and A. Crivellin]



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

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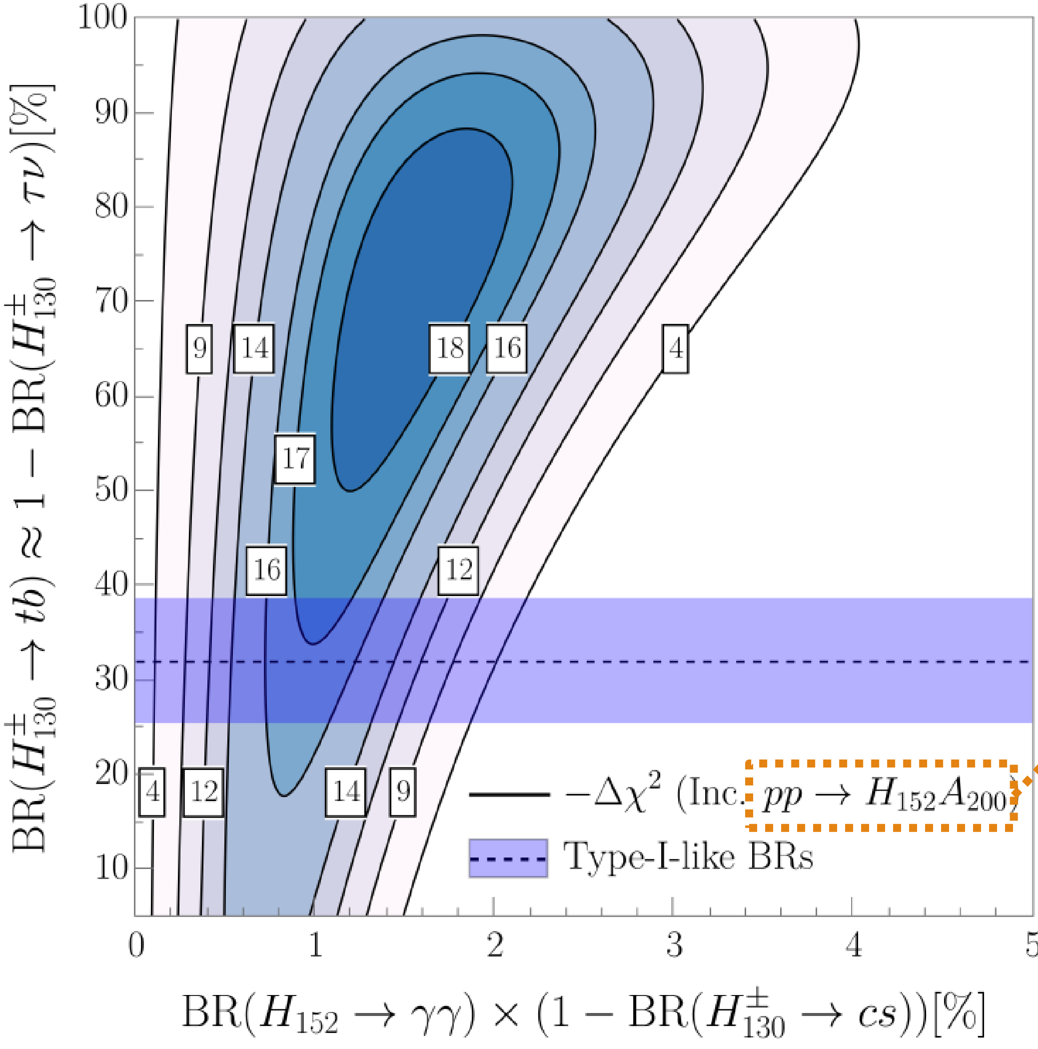

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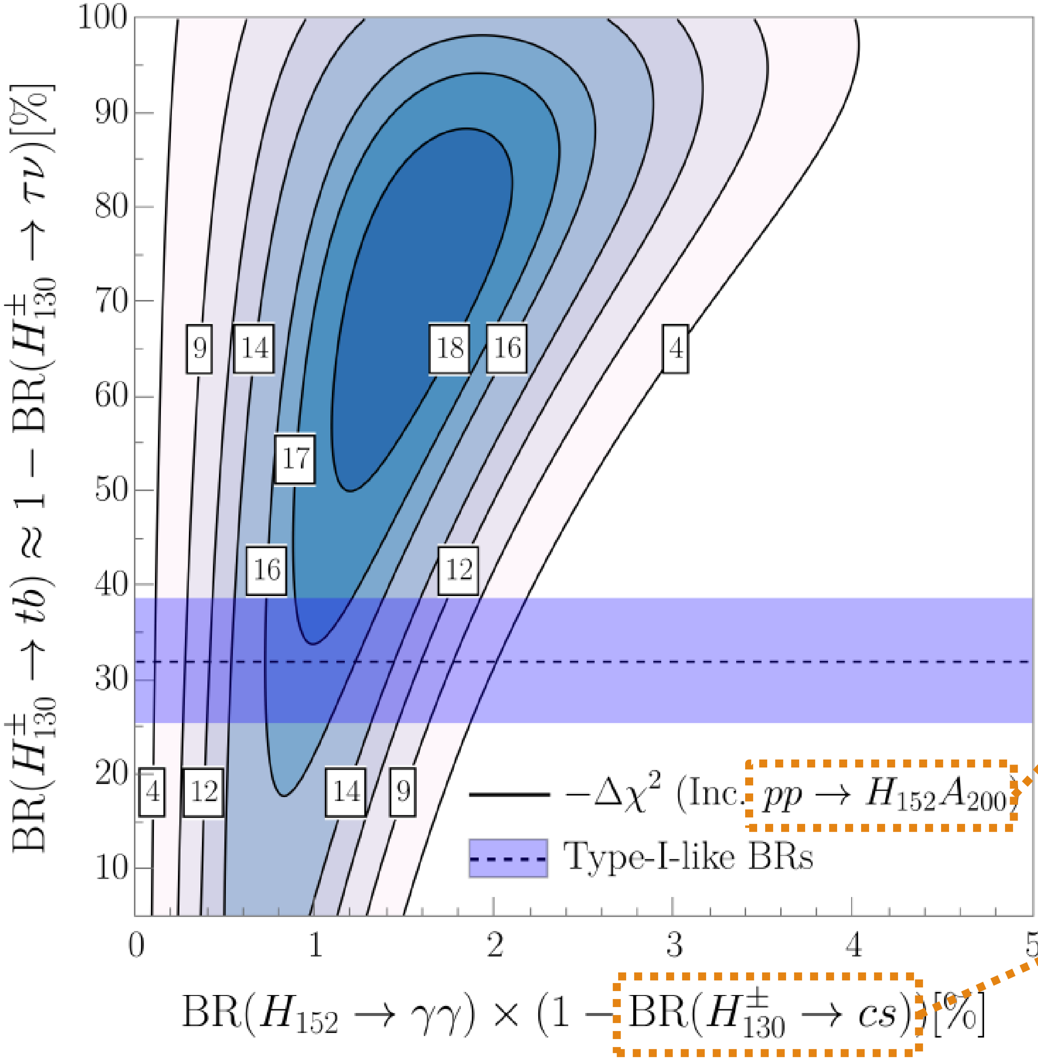

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- Increased significance w.r.t. simplified model

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

2HDM Type-I: Br$(\boldsymbol{H_{152}} \rightarrow \boldsymbol{\gamma\gamma})$

Br$(H_{152} \rightarrow \gamma\gamma)$ required at the % level

- Type-I: $\tan(\beta) \gg 1 \implies$ reduced Br$(H_{152} \rightarrow \gamma\gamma)$

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Flavor aligned 2HDM

[A. Pich, P. Tuzon]

- Yukawa's of $\phi_1 \quad \propto$ Yukawa's of $\phi_2 \implies$ **NO FCNC**

$$L_Y = -\overline{Q_L} Y_d (\phi_2 + \boldsymbol{\zeta_d} \phi_1) d_R - \overline{Q_L} Y_u (\phi_2 + \boldsymbol{\zeta_u} \phi_1) d_R - \overline{L_L} Y_\ell (\phi_2 + \boldsymbol{\zeta_\ell} \phi_1) \ell_R$$

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

$$V(\phi_1, \phi_2)_{\text{Type-I}} + \left(\lambda_6 \phi_1^\dagger \phi_1 \phi_1^\dagger \phi_2 + h.c.\right) + \left(\lambda_7 \phi_2^\dagger \phi_2 \phi_1^\dagger \phi_2 + h.c.\right)$$

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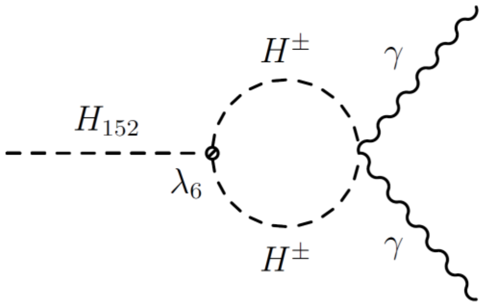

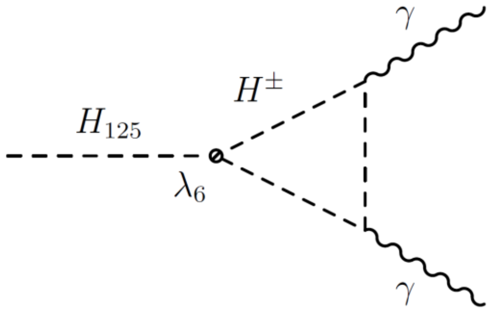

Sizable Br($H_{152} \to \gamma\gamma$) through $H^\pm$ loop

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

[F. Maltoni, D. Pagani et al.]
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- After Run3, LHC will provide approximately 10^9 top-quark pairs
- Top-quark data in quite good agreement with SM higher order computations (NNLO in QCD, NLO in EW)
- **However: tension in $t\bar{t}$ differential distributions at low invariant masses**

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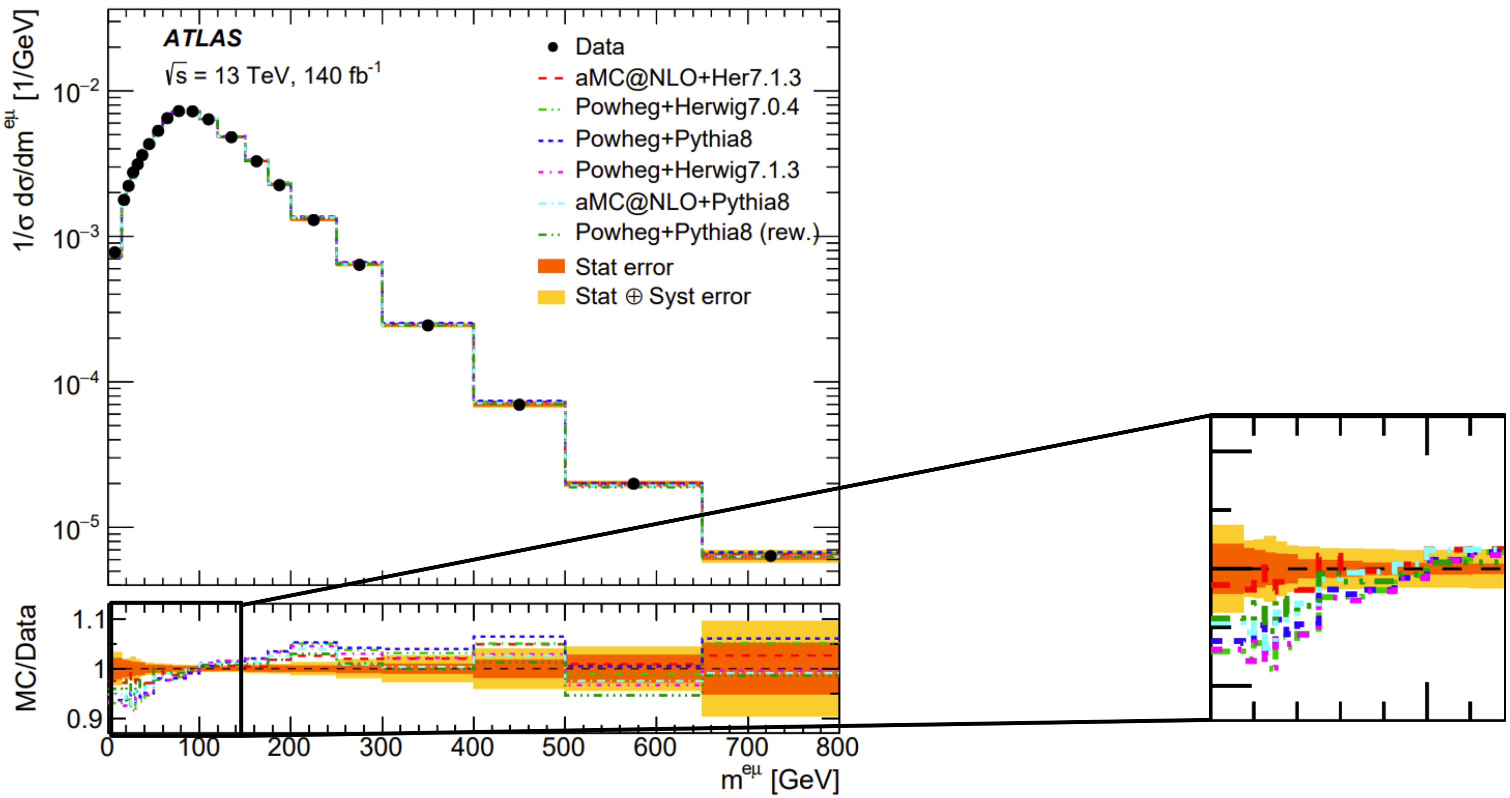
- **However: tension in $t\bar{t}$ differential distributions at low invariant masses**
- **LFC have a dedicated $t\bar{t}$ run**
- Clean initial states and precise measurements of $t\bar{t}$ distributions

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

[ATLAS]



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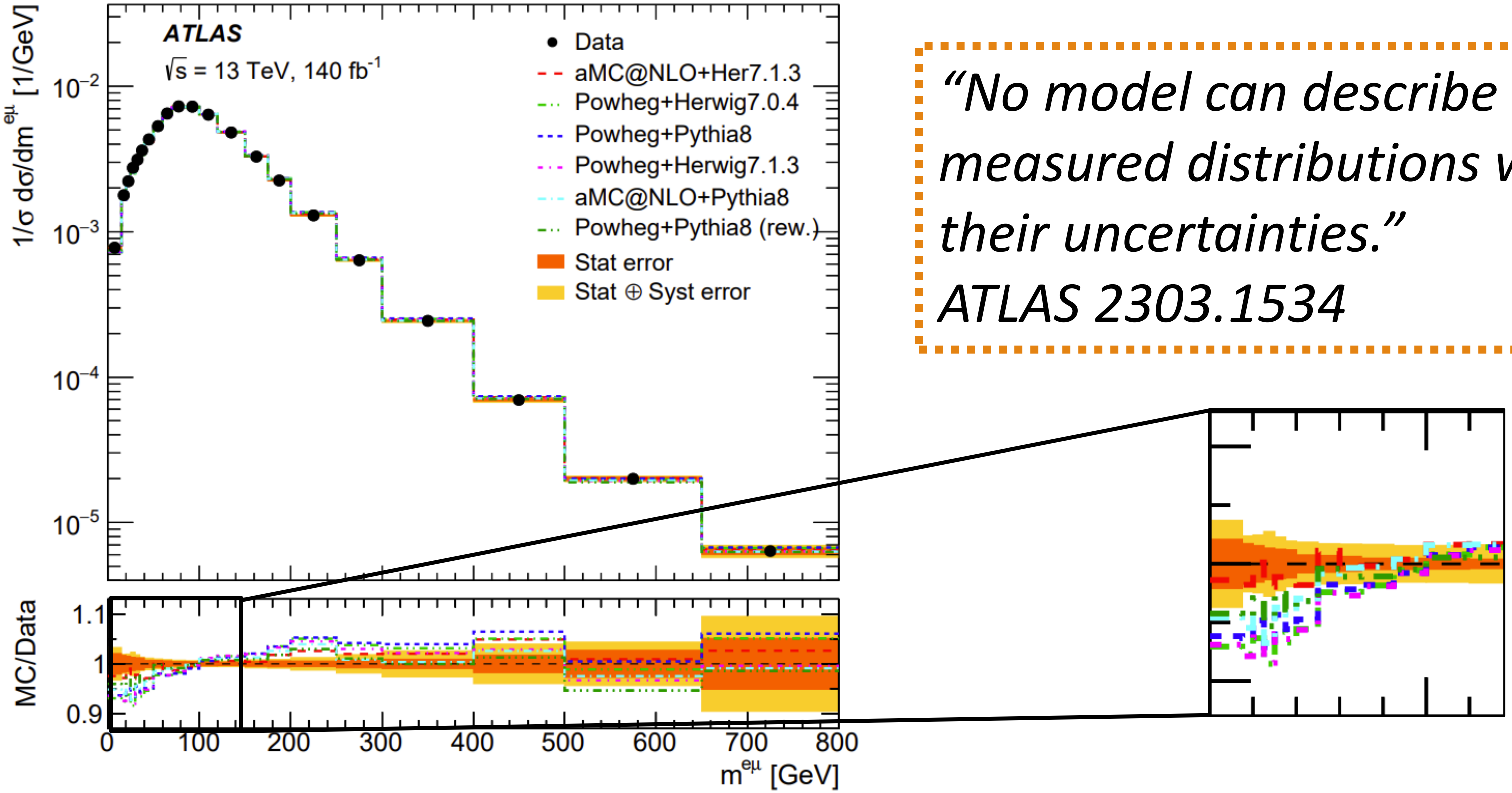

“No model can describe all measured distributions within their uncertainties.”
ATLAS 2303.1534

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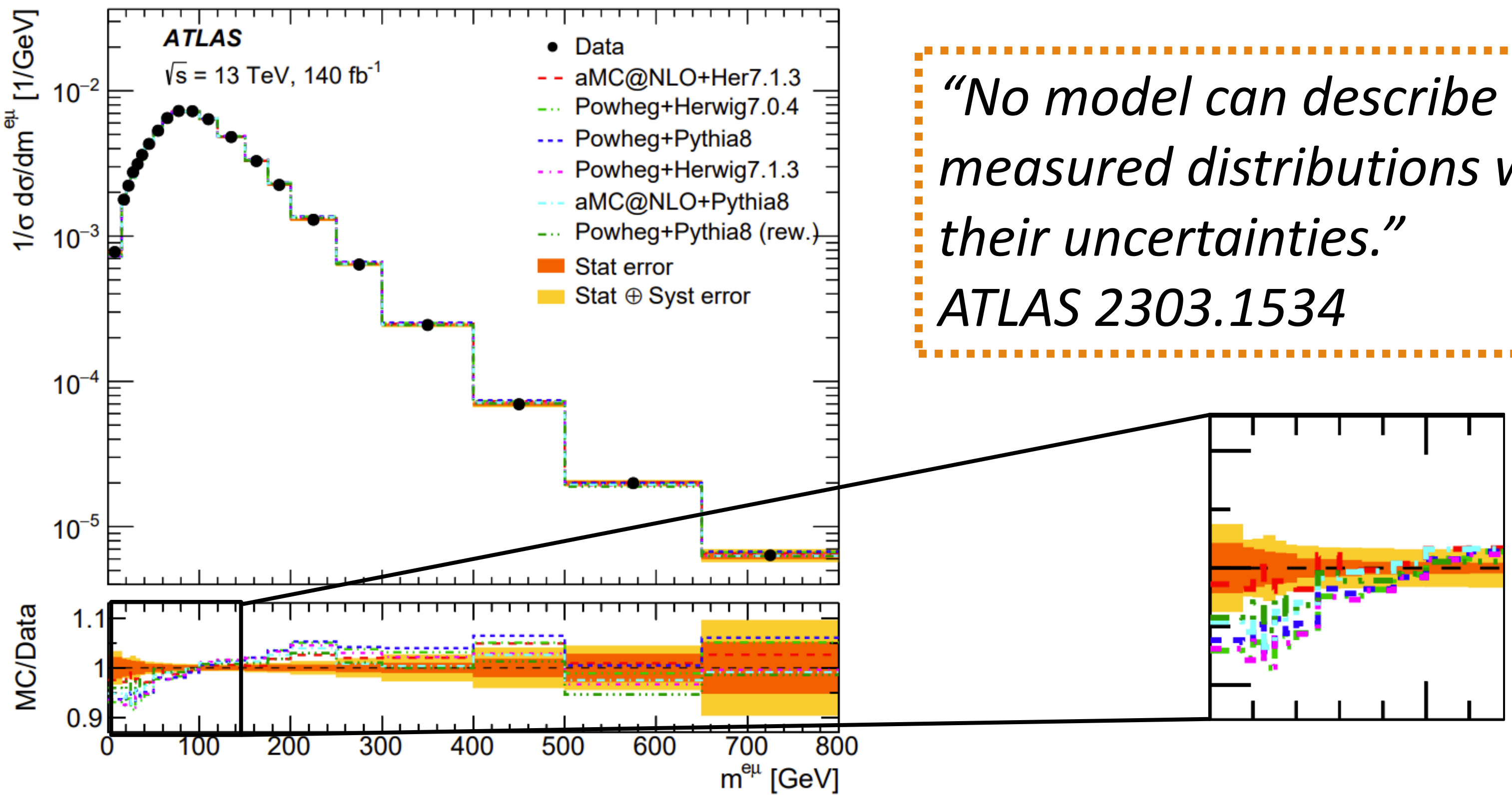

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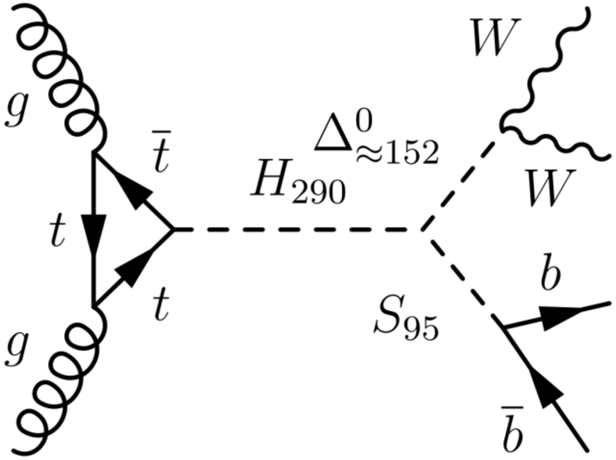
- Higher order corrections? Toponium?
- New Physics pollution of this SM measurement?

A simple NP model

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



- Associated production of new scalars decaying to WW and $b\bar{b}$ has a top-like signature
- Fix $m_{\Delta^0} = 152$ GeV and $m_S = 95$ GeV by the hints for narrow resonances
- Weak $m_H = 290$ GeV dependence

A simple NP model

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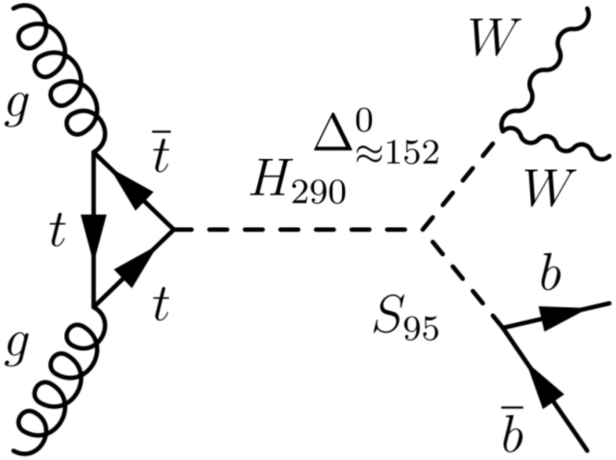
- ATLAS analysis **normalized to the total cross section**
- **Only sensitive to the shape of NP**



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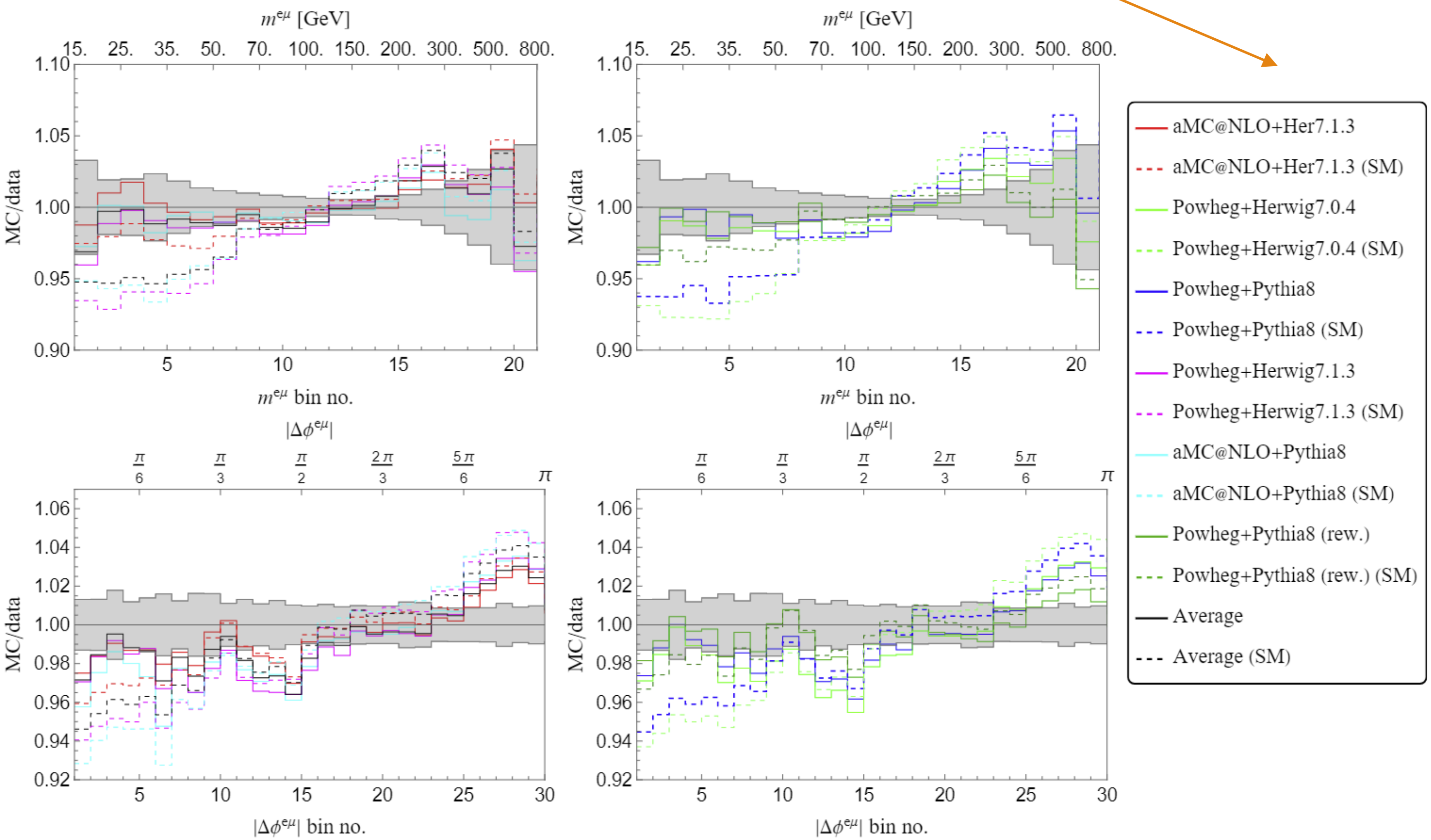
$H_{290} \to \Delta^0_{152} S_{95} \to WWb\bar{b}$

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

ATLAS generated $t\bar{t}$ samples with **several different** matrix element generators, parton shower, and fragmentation simulation



FCC-ee improvement

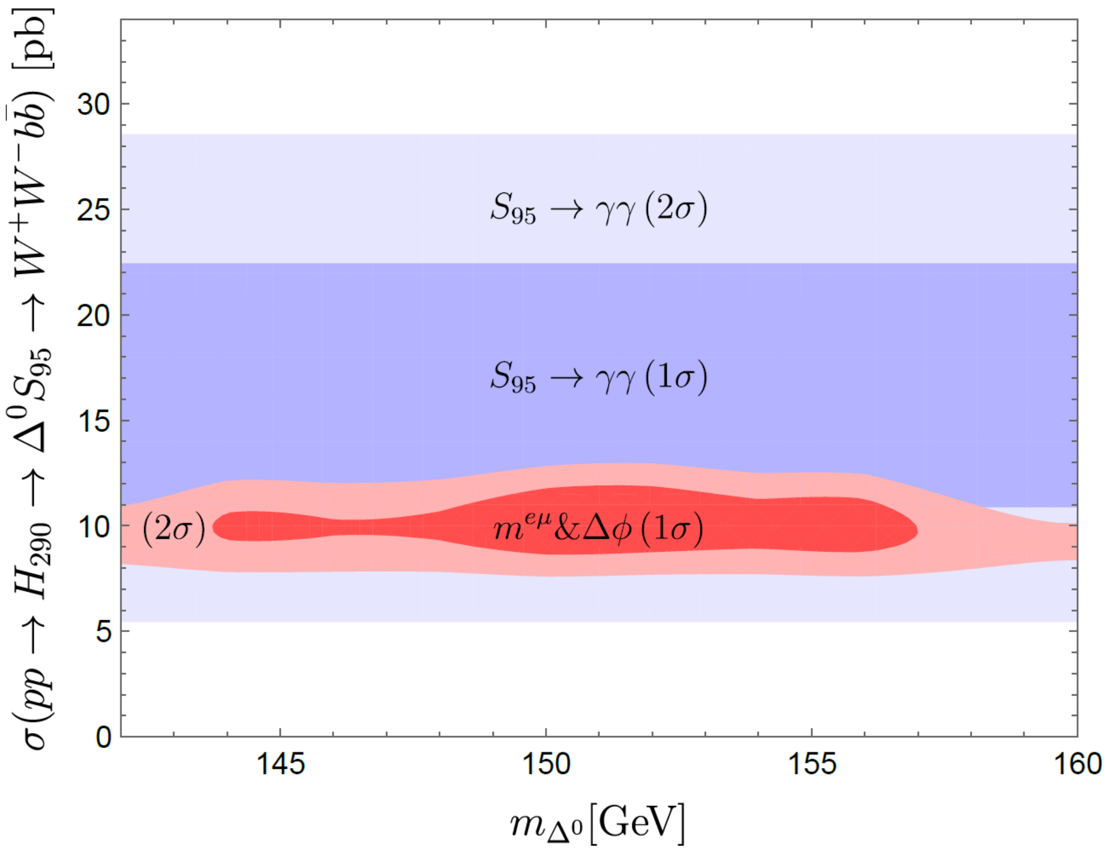
Monte Carlo	χ^2_{SM}	χ^2_{NP}	σ_{NP}	m_S[GeV]
Powheg+Pyhtia8	213	102	9pb	143 – 156
aMC@NLO+Herwig7.1.3	102	68	5pb	– –
aMC@NLO+Pythia8	291	163	10pb	148-157
Powheg+Herwig7.1.3	261	126	10pb	149-156
Powheg+Pythia8 (rew)	69	35	5pb	– –
Powheg+Herwig7.0.4	294	126	12pb	149-156
Average	182	88	9pb	143-157

- **Improvement of SM prediction imperative!**
- **FCC-ee $t\bar{t}$ run** will provide top-quark differential distributions in a clean environment
- Test of NP faking $t\bar{t}$ production and decay

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



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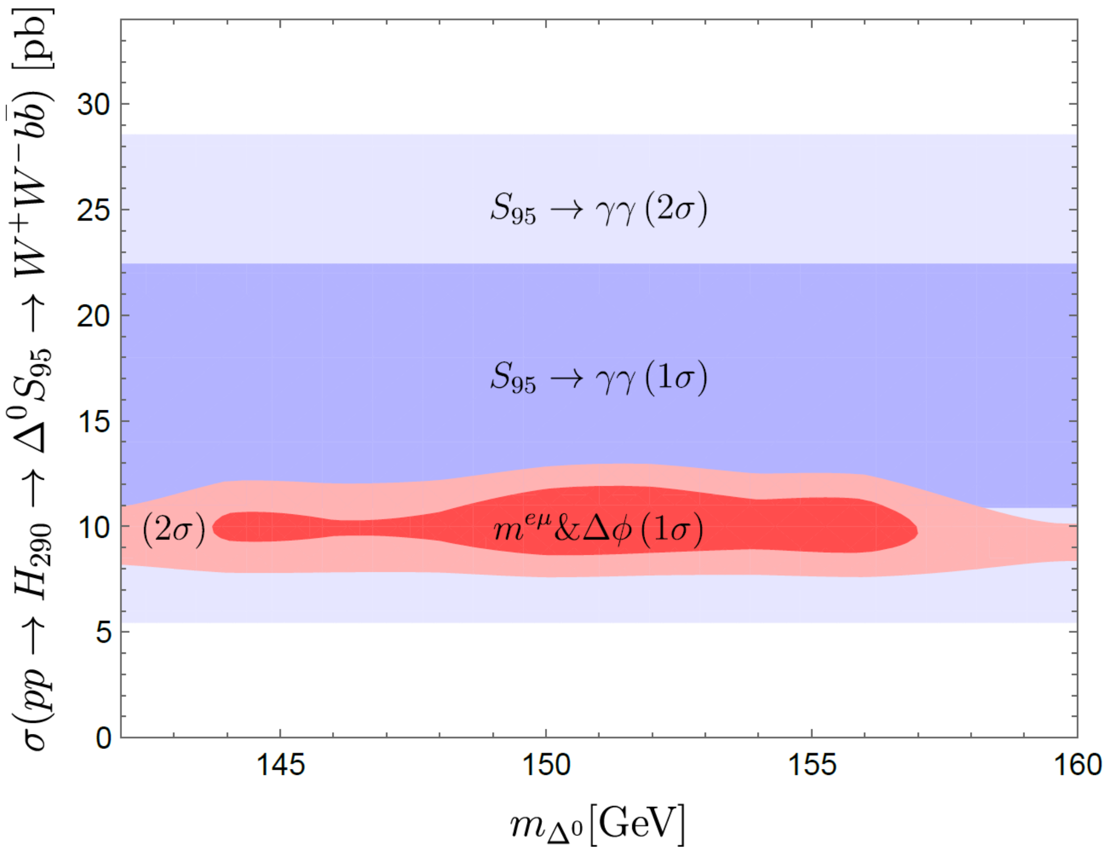
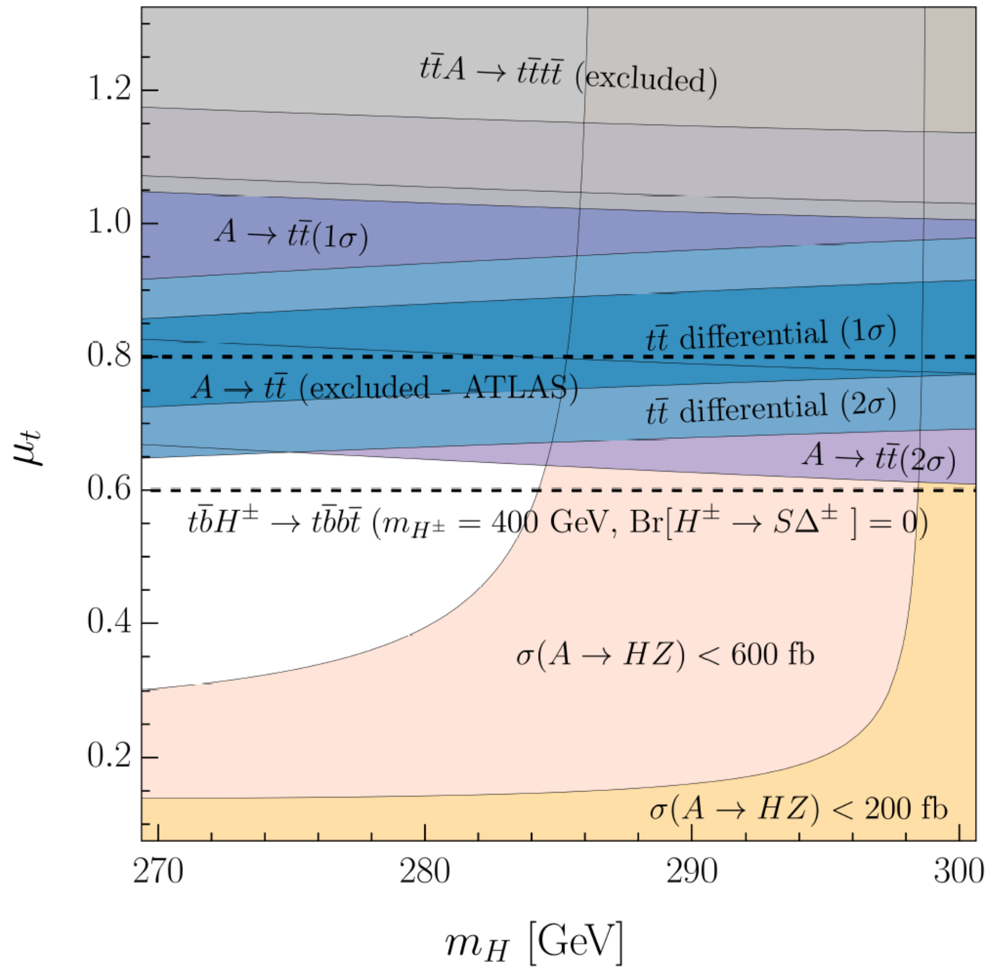


Consistent with the 95 GeV $\gamma\gamma$ signal strength and a mass for Δ^0 of 152 GeV

The Δ2HDMS



Field	$SU(2)_L$	$U(1)_Y$
ϕ_s	1	0
ϕ_2	2	1/2
ϕ_1	2	1/2
Δ	3	0

- $t\bar{t}$ differential distributions
- $\gamma\gamma$ excesses
- Resonant elevated $\sigma(pp \to \bar{t}t(A \to t\bar{t}))$
- EW baryogenesis

[M. Ramesey-Musolf et al.]

Combined explanation possible

LFC projections

- **Indications for new Higgses at the LHC**
- 95 GeV Higgs produced via Z-strahlung
- 152 GeV Higgs produced via Drell-Yan
- $t\bar{t}$ differential distributions as a probe for NP

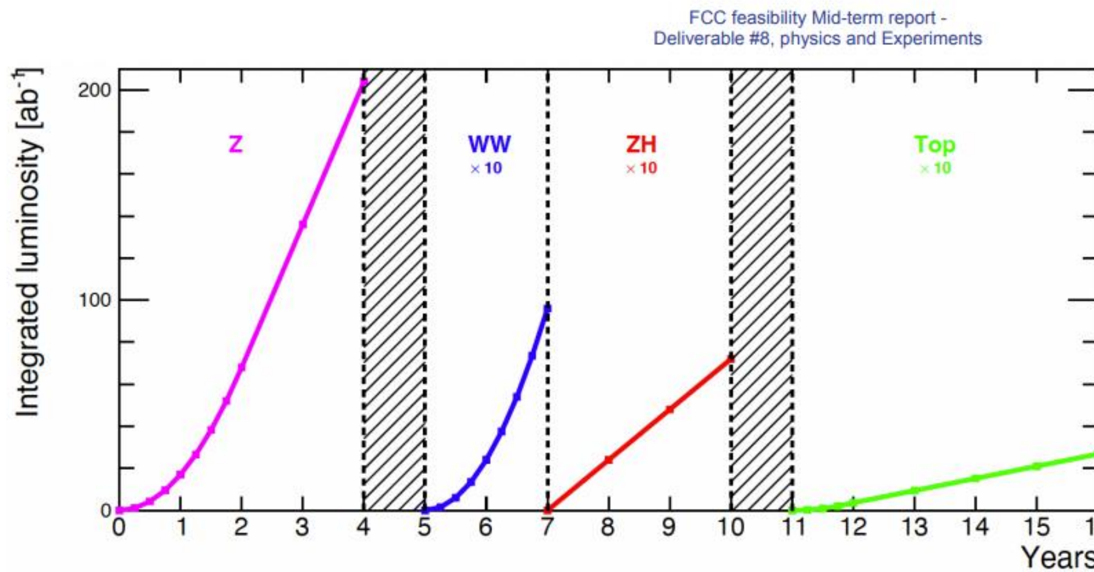
FCC-ee: $t\bar{t}$ run

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

Rebeca Gonzalez Suarez (UU) - PSI Particle Physics Summer School 2024 76

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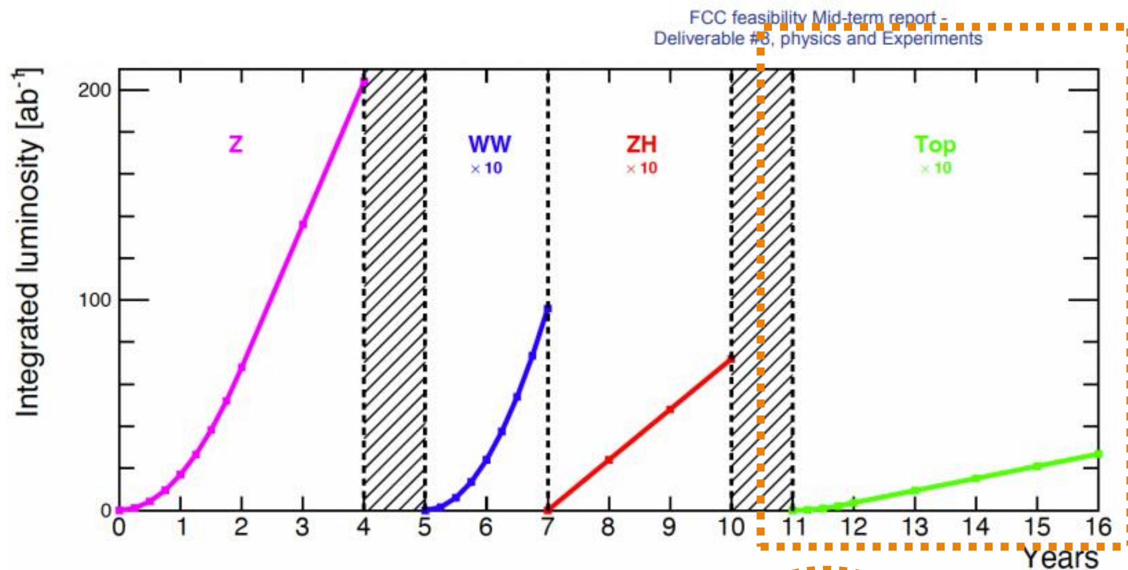

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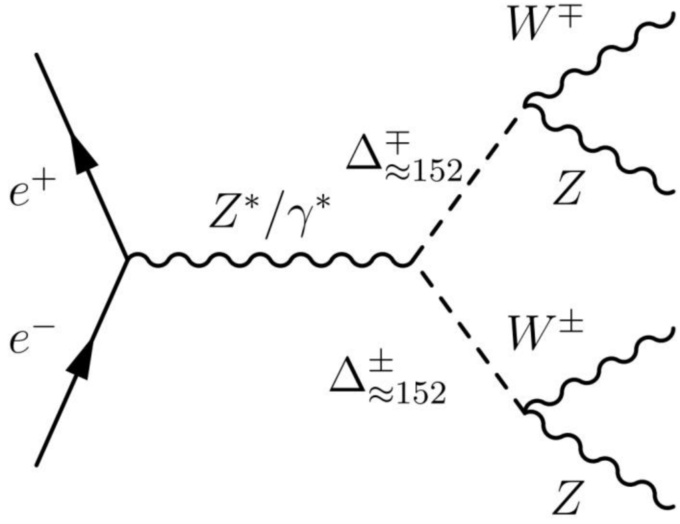
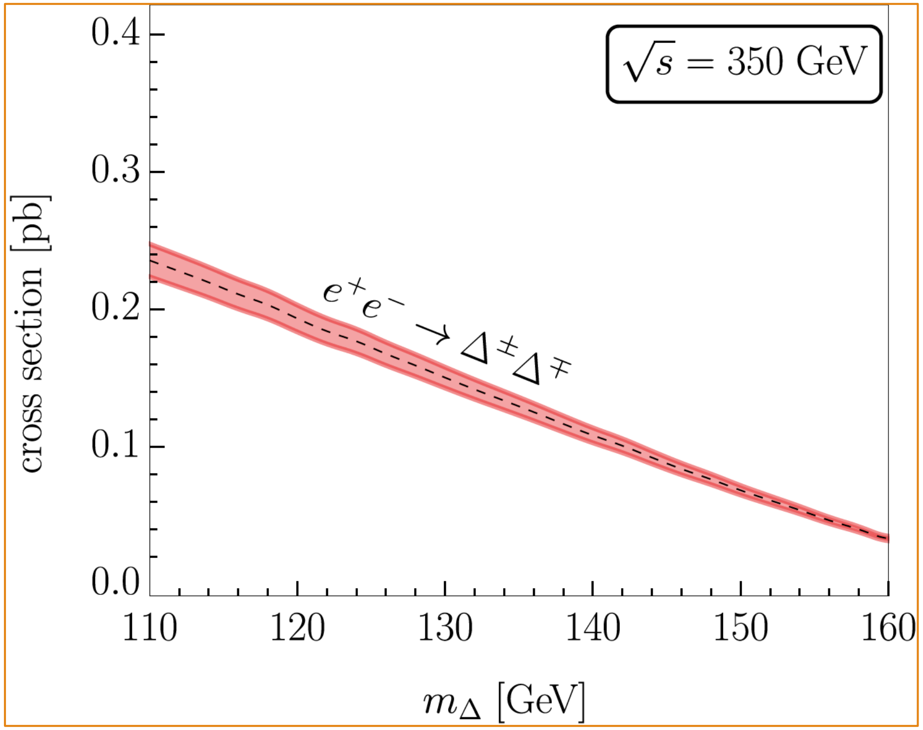
Real triplet at the FCC-ee

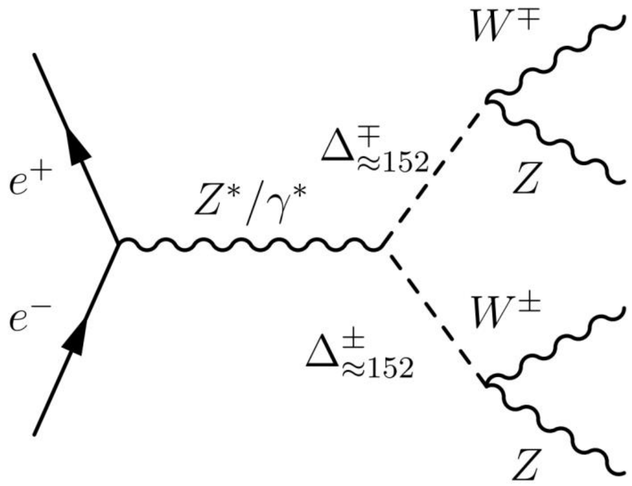
- Only Z^*/γ^* s-channel
- Suppressed $\Delta^0\Delta^0$ production for a real triplet
- Pair production of the charged components





6ℓ + MET at the FCC-ee

- Br($\Delta^{\pm} \rightarrow\ W^{\pm}Z$) ≈ 80%
- The decay $\Delta^{\pm} \rightarrow W^{\pm}Z$ leads to a 6ℓ(+ MET) signature



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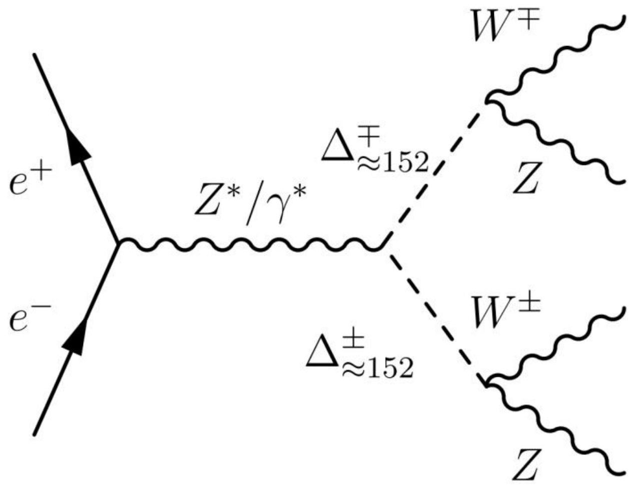

Events expected in the ΔSM model

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

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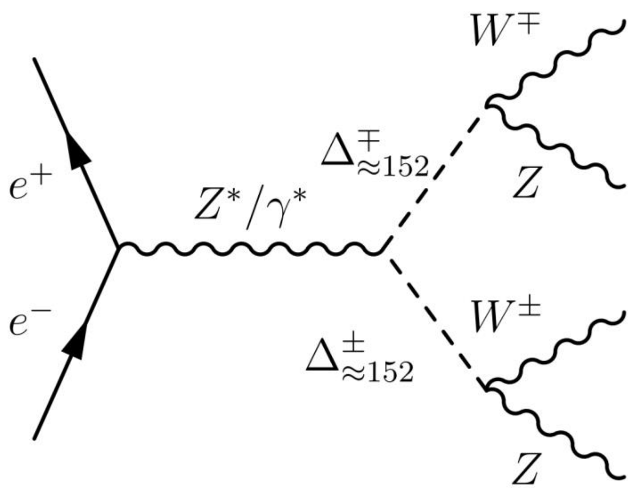

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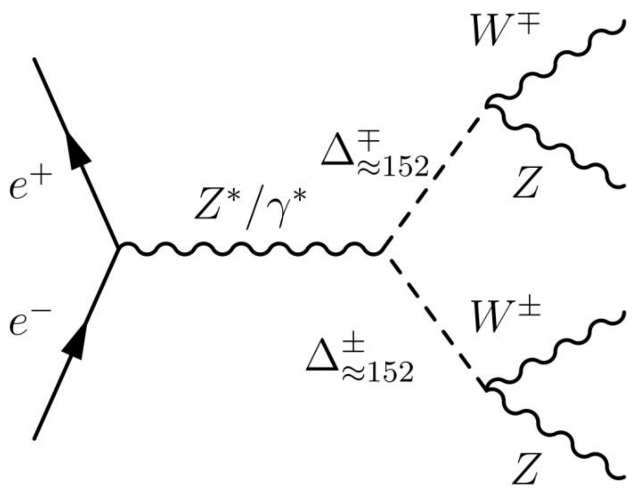

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Events expected in the SM model

$$e^{+}e^{-} \rightarrow 6\ell(+\mathrm{MET}) \approx 1$$

- $\sigma(e^{+}e^{-} \rightarrow \Delta^{\pm}\,\Delta^{\mp})$ determined at 13% confidence level
- FCC-ee nicely suited for this NP scenario

Conclusions and Outlook

- **Interesting indications for new Higgses at the LHC**
- 95 GeV would be produced via Z-strahlung at LFC
- Drell-Yan production is suggested at 152 GeV
- **New Higgses produced via Drell-Yan are prominent scalar extensions to test at LFC**
- $t\bar{t}$ run at LFC will provide a clean environment for the study of $t\bar{t}$ differential distributions

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THANK YOU FOR THE ATTENTION!

BACK UP SLIDES

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

[ATLAS]

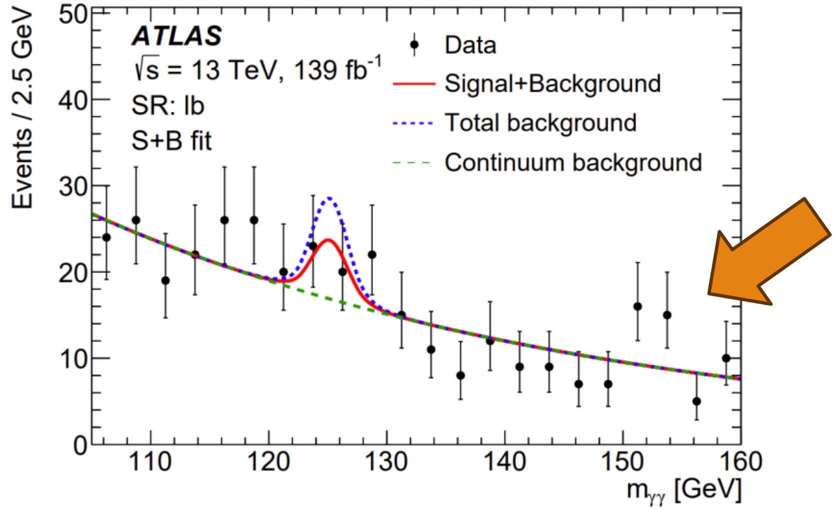
- ATLAS search for associated production with **full Run2 data**
- **SM search for $H \rightarrow \gamma\gamma + X$ ($m_{\gamma\gamma}$ = 105-160 GeV)**
- 22 categories ($X = l, j, j_b, E_T^{miss}$ ...)

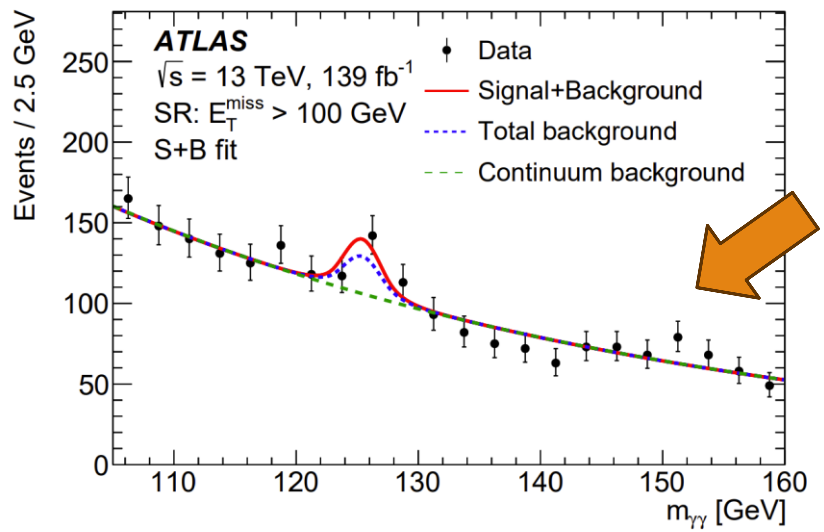
Target	Signal region	Detector level	Correlations
High jet activity	$4j$	$n_j \geq 4$	-
Top	ℓb t_{lep}	$n_\ell \geq 1, n_{b-\text{jet}} \geq 1$ $n_{\ell=e,\mu} = 1, n_{\text{jet}} = n_{b-\text{jet}} = 1$	-
Lepton	2ℓ 1ℓ	$ee, \mu\mu$ or $e\mu$ $n_\ell = 1, n_{t_{\text{had}}} = 0, n_{b-\text{jet}} = 0$	$< 26\%$
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 @ $m_{\gamma\gamma} = 152$ GeV

[ATLAS]

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





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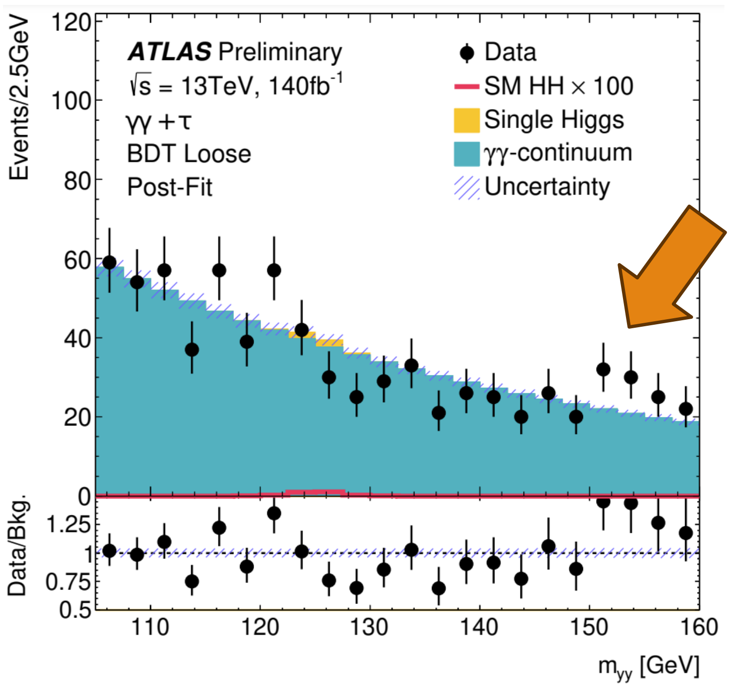
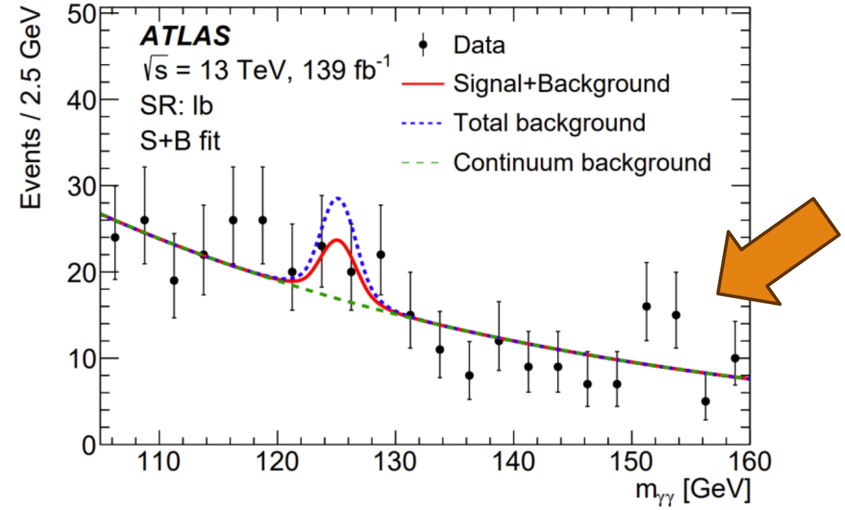
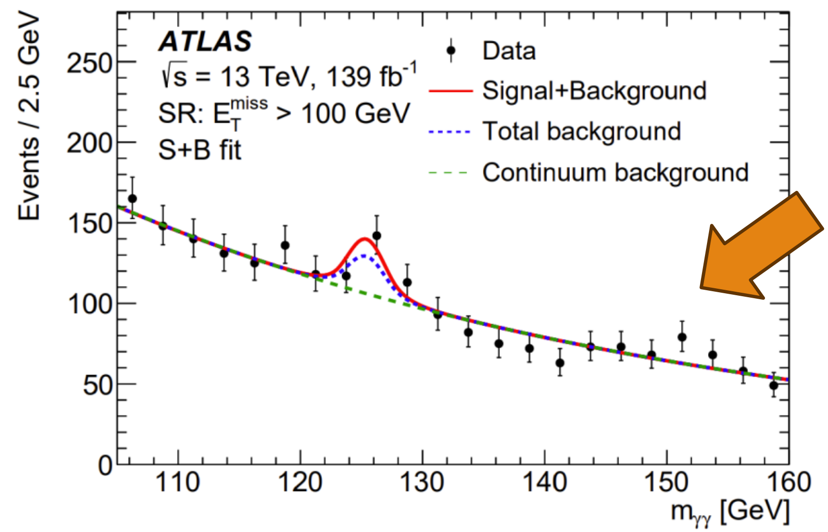
- $\gamma\gamma + 1\tau$

[Moriond 2024]



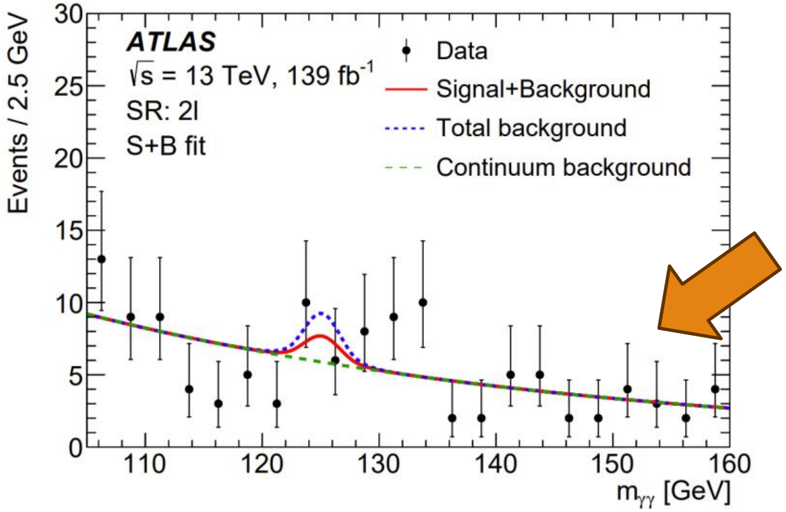


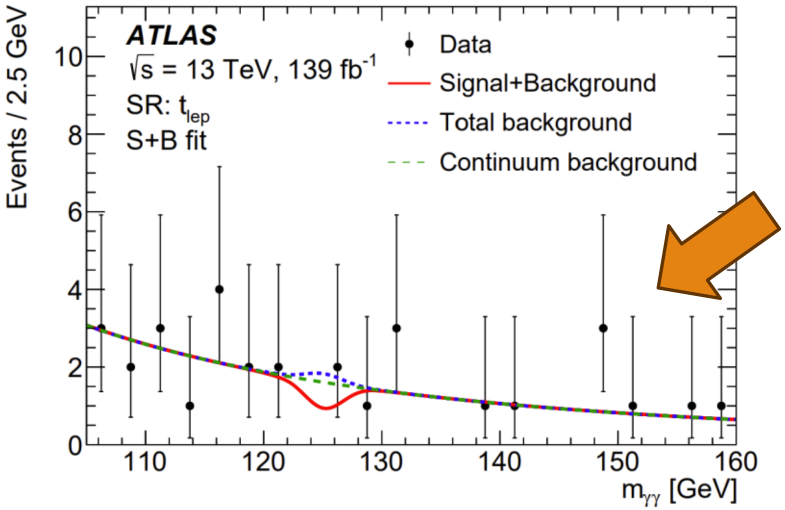


Hints for pp → $S_{152}S^{\pm}$

NO excesses @ $m_{\gamma\gamma} = 152$ GeV [ATLAS]

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





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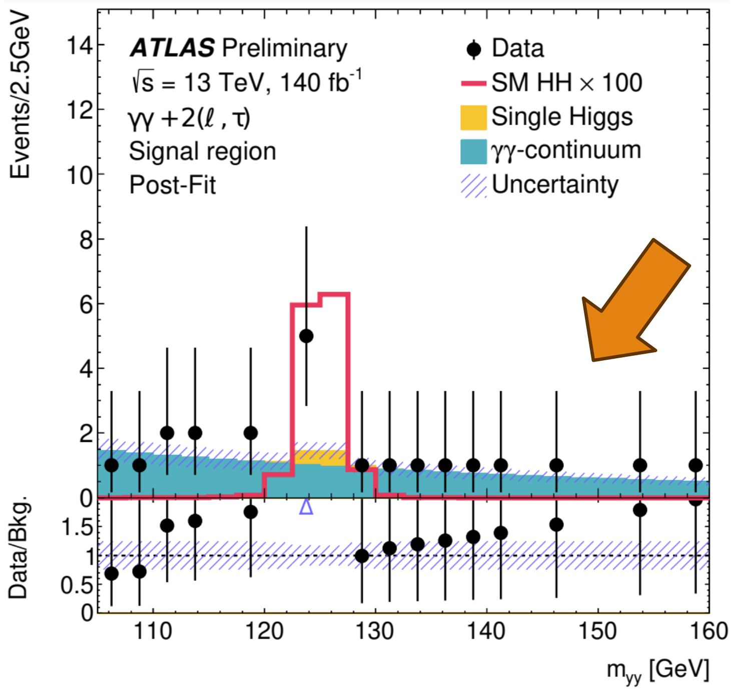
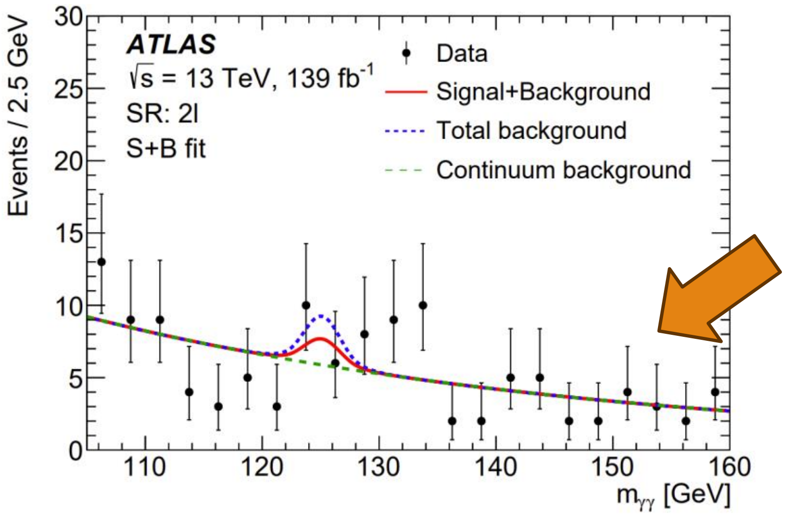
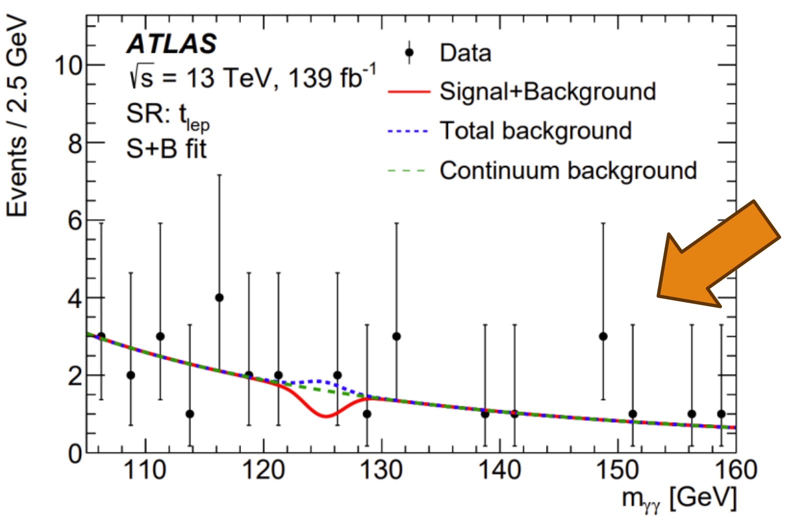
- $\gamma\gamma + 2\tau$

[Moriond 2024]



Disfavored pp → $S_{152}S'$

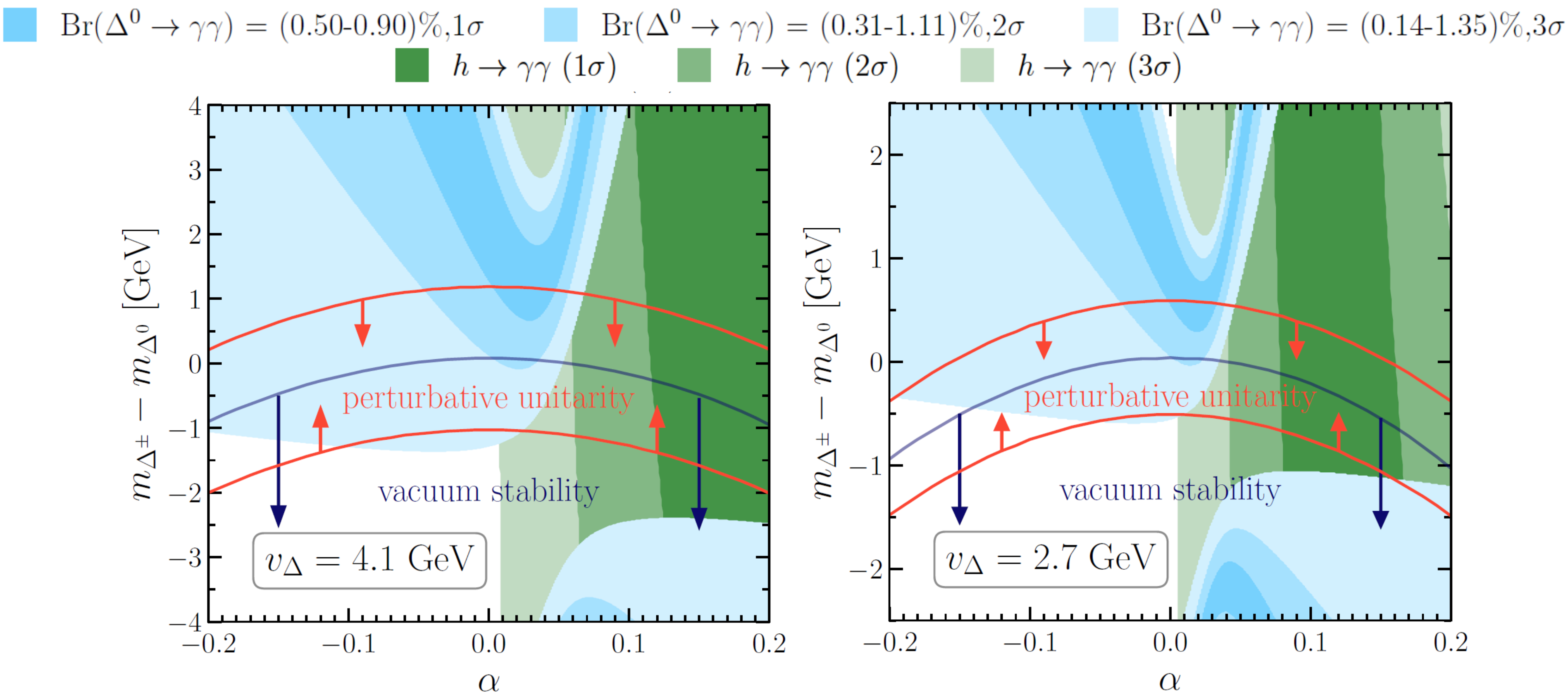




Scalar potential

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

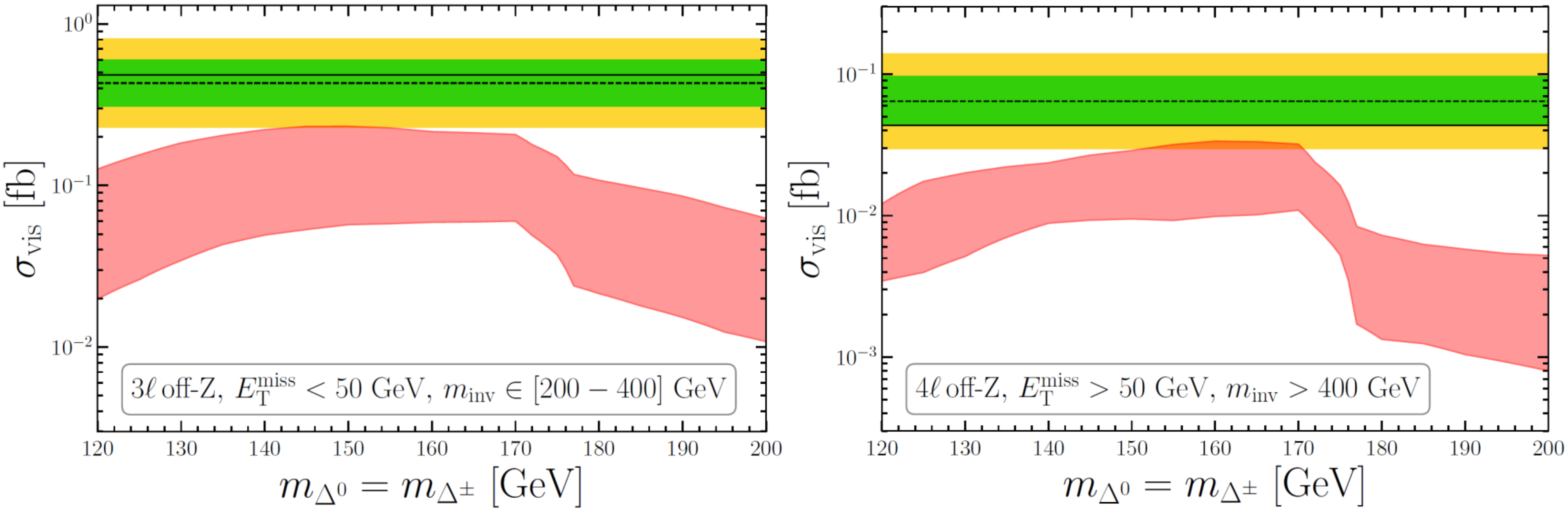
- Vacuum stability and perturbative unitarity in slight tension with other phenomenological observables
- Pointing to additional fields at or above the EW scale



3 and 4 – leptons bounds

[In prepation…]

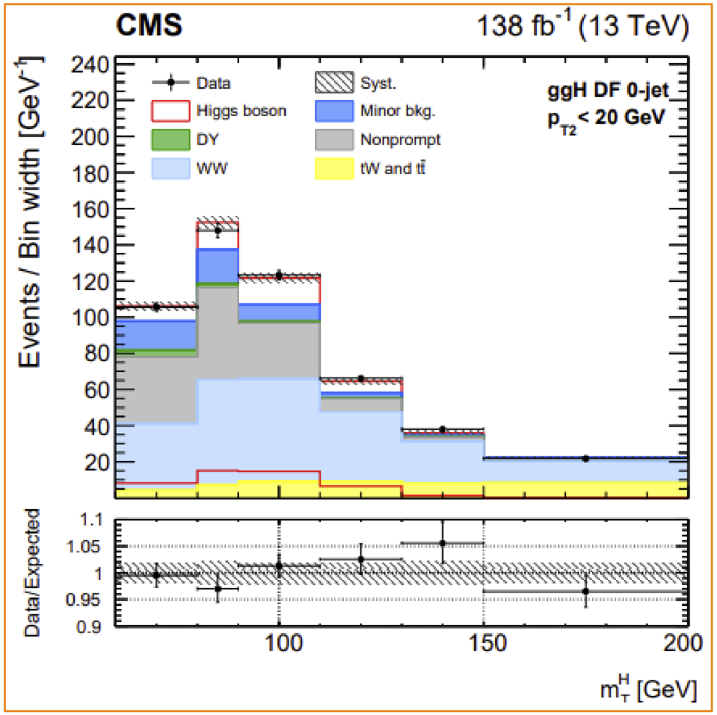
- Multi-lepton searches with 3 and 4 leptons as final states are not excluding a real Higgs triplet at low masses



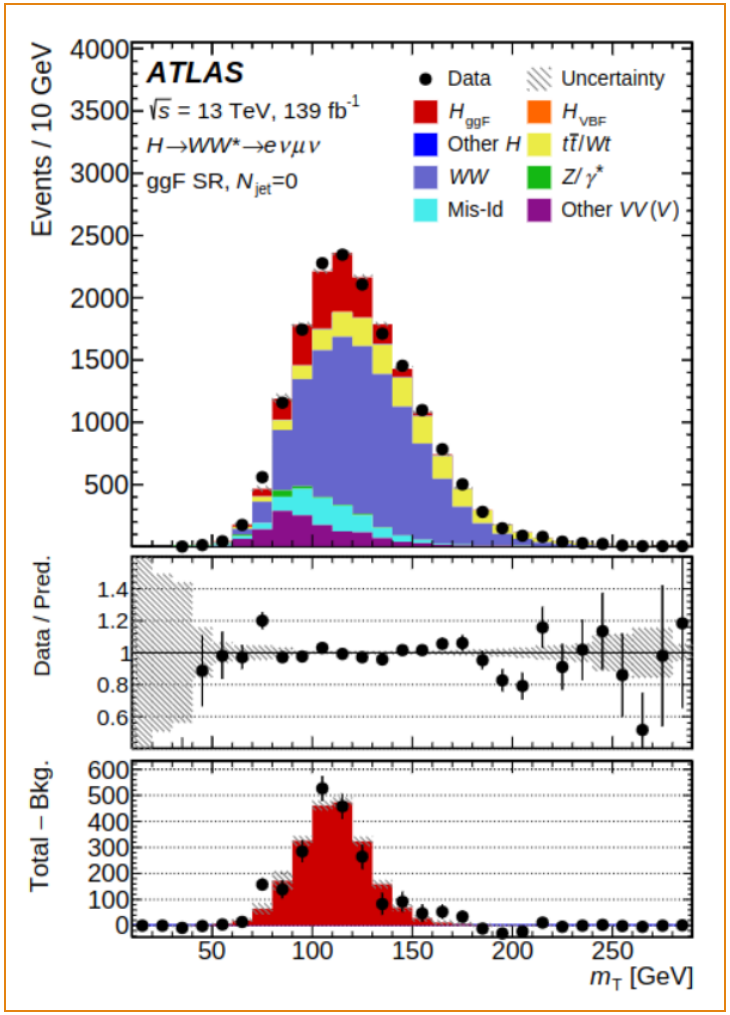
[ATLAS]

Low mass WW searches (139 fb^{-1})

- **ATLAS: SM Higgs rescaled by 1.21**
- **CMS: bkg refitted**



[CMS]



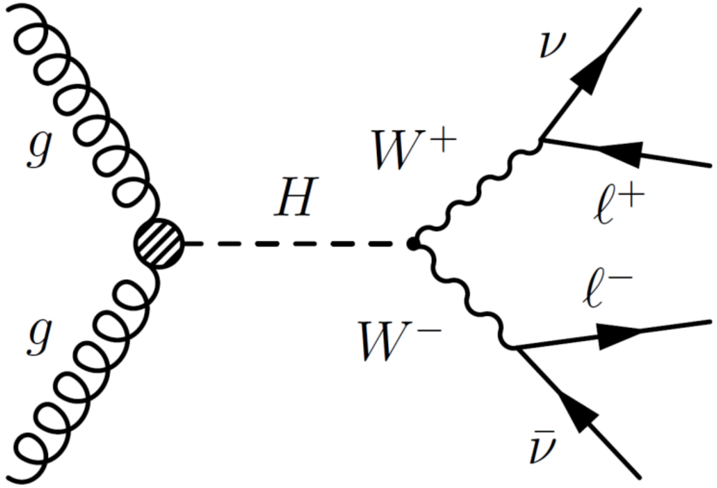
[ATLAS]

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

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

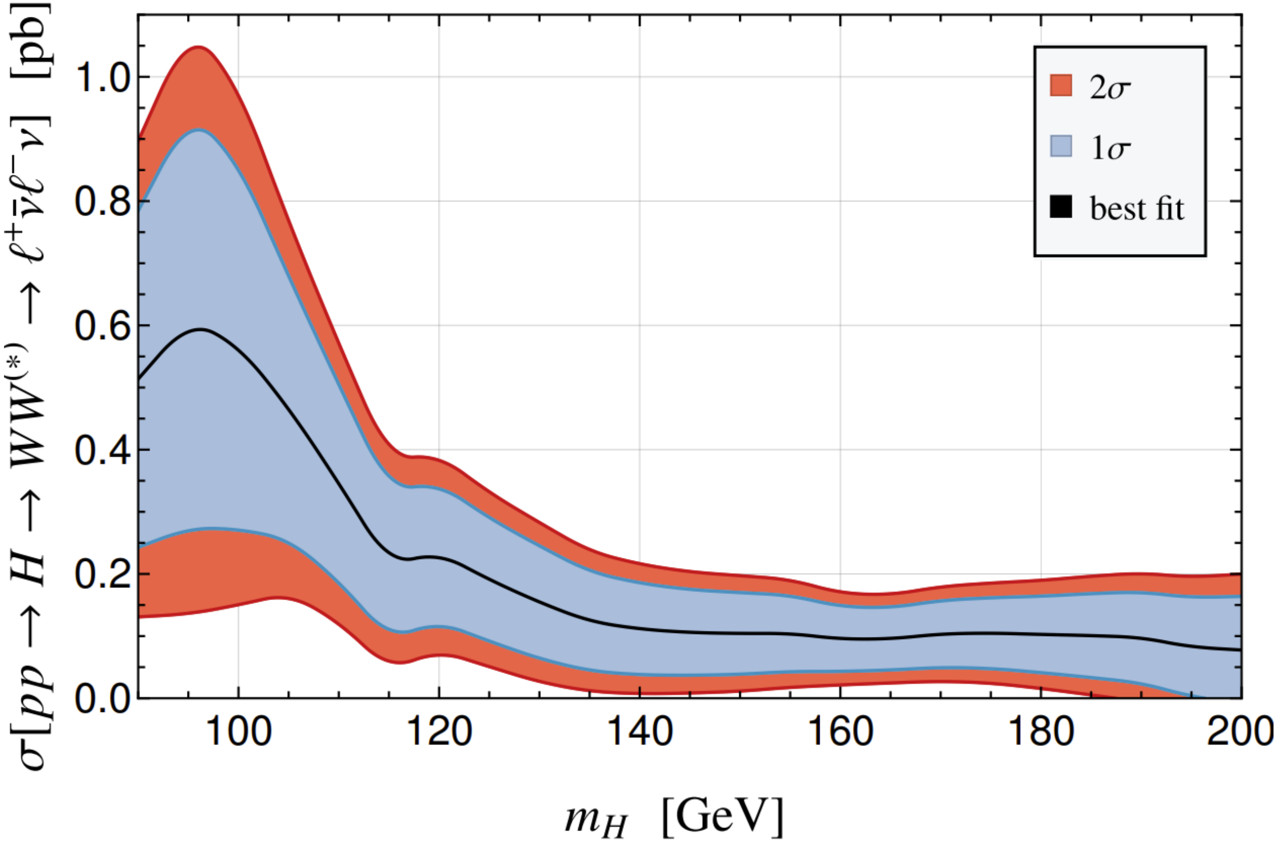


Leptonic decays + jet veto

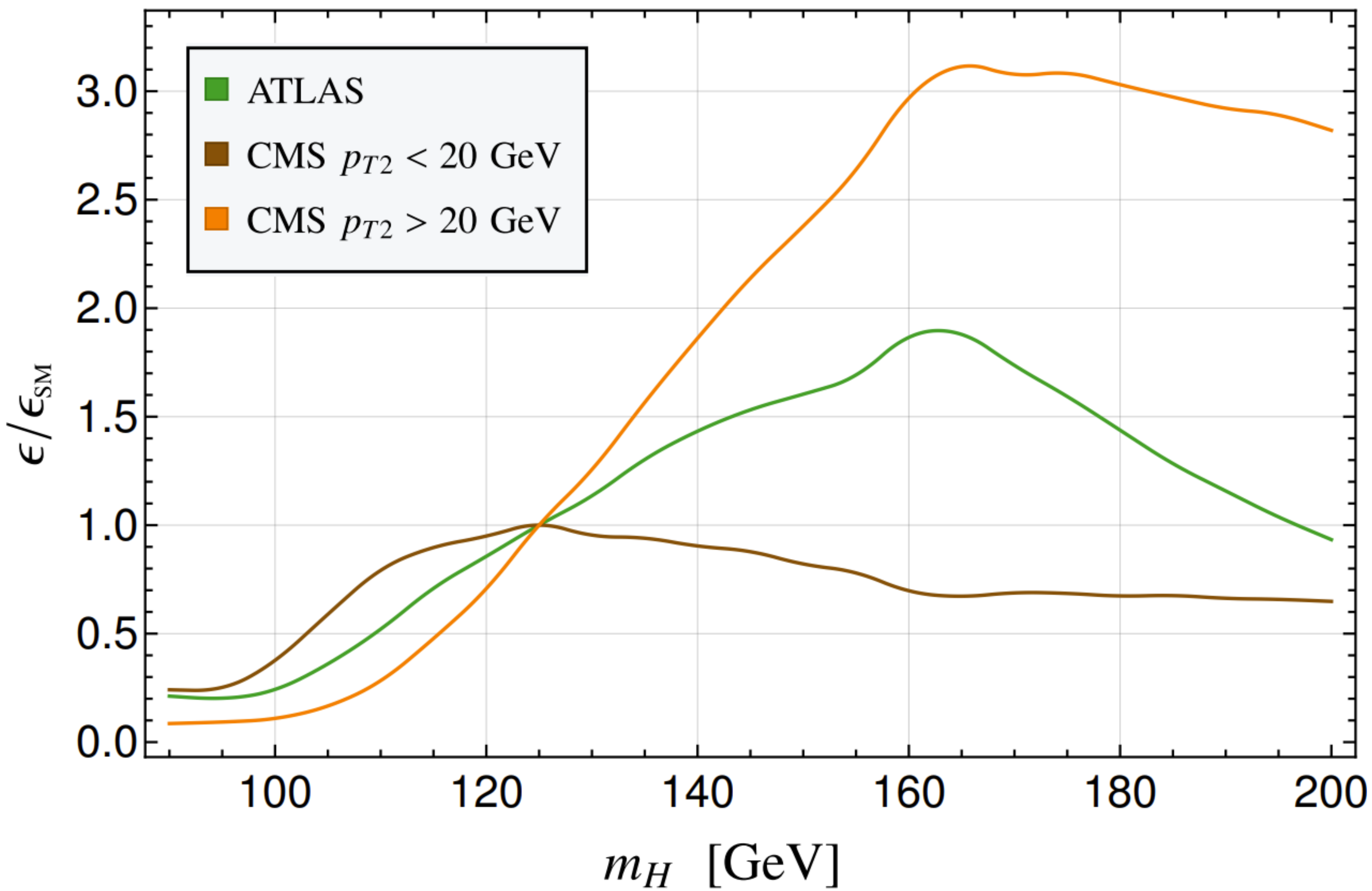
WW results

[GC, A. Crivellin et al.]

- CMS and ATLAS combined
- Observed limit is weaker than expected over the whole mass range (**room for NP $\geq 2\sigma$**)

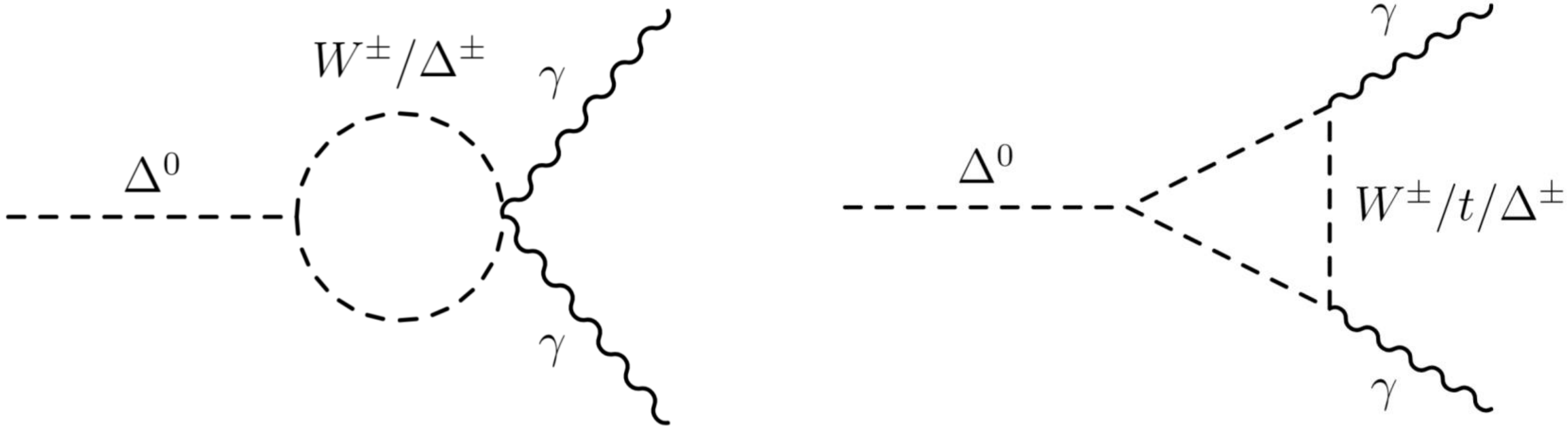


WW simulation efficiency [GC, A. Crivellin et al.]



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

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



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

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

$\Rightarrow$

$\mathrm{Br}[\Delta^0_{152} \to \gamma\gamma]$

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

Different MCs in $pp \to t\bar{t}$

[ATLAS]

The uncertainty associated with the matrix element generation is estimated using MadGraph5_aMC@NLO [36] interfaced with Pythia 8.230 as an alternative generator, with the A14 tune and the NNPDF2.3 set of PDFs for the underlying event, parton shower and fragmentation. Since the 'matrix element correction' (MEC) in Pythia 8.230 is switched off in this simulation [37], a sample of Powheg+Pythia 8.230 events with MEC switched off, with the same PDF sets as the nominal Powheg+Pythia 8.230 generator, was also produced for comparison with MadGraph5_aMC@NLO. In order to estimate the uncertainty associated with the modelling of fragmentation and parton showering, a sample was generated with Powheg interfaced with Herwig 7.0.4 [38, 39] with the H7UE tune [40] and the NNPDF3.0 PDF set.

Additional samples using alternative generators were produced for comparison with data. These include Powheg interfaced with Herwig 7.1.3 [41], MadGraph5_aMC@NLO interfaced with Herwig 7.1.3, and Powheg+Pythia 8.230 with the PDF4LHC15_nnlo_mc set [33, 42]. Finally, a reweighted Powheg+Pythia 8.230 sample was generated. The reweighting is performed on the top-quark p_T variable, using the kinematics of the top quarks in the MC sample after initial- and final-state radiation. The prediction for the top-quark p_T spectrum is calculated to next-to-next-to-leading order (NNLO) in QCD with NLO EW corrections [43, 44] with the NNPDF3.0 QED PDF set using dynamic renormalisation and factorisation scales $m_{T,t}/2$, i.e. half the top-quark transverse mass,[3] for the top-quark p_T as proposed in Ref. [43], with $m_t = 173.3$ GeV. The reweighting was applied such that at the end of the procedure the reweighted MC sample is in good agreement with the higher-order prediction for the reweighted variable [45]. This sample is referred to as being reweighted to the NNLO prediction in the remainder of the document.

The Δ2HDMS: prediction

[GC, A. Crivellin, B. Mellado]

- Deviations from SM prediction in $m_{b\bar{b}e\mu}$

$m_H = 290$ GeV, $m_S = 95$ GeV, $m_{\Delta^0} = 151.5$ GeV