Probing rare Higgs decays at ATLAS and CMS

Higgs Couplings

November 7th 2017

Heidelberg

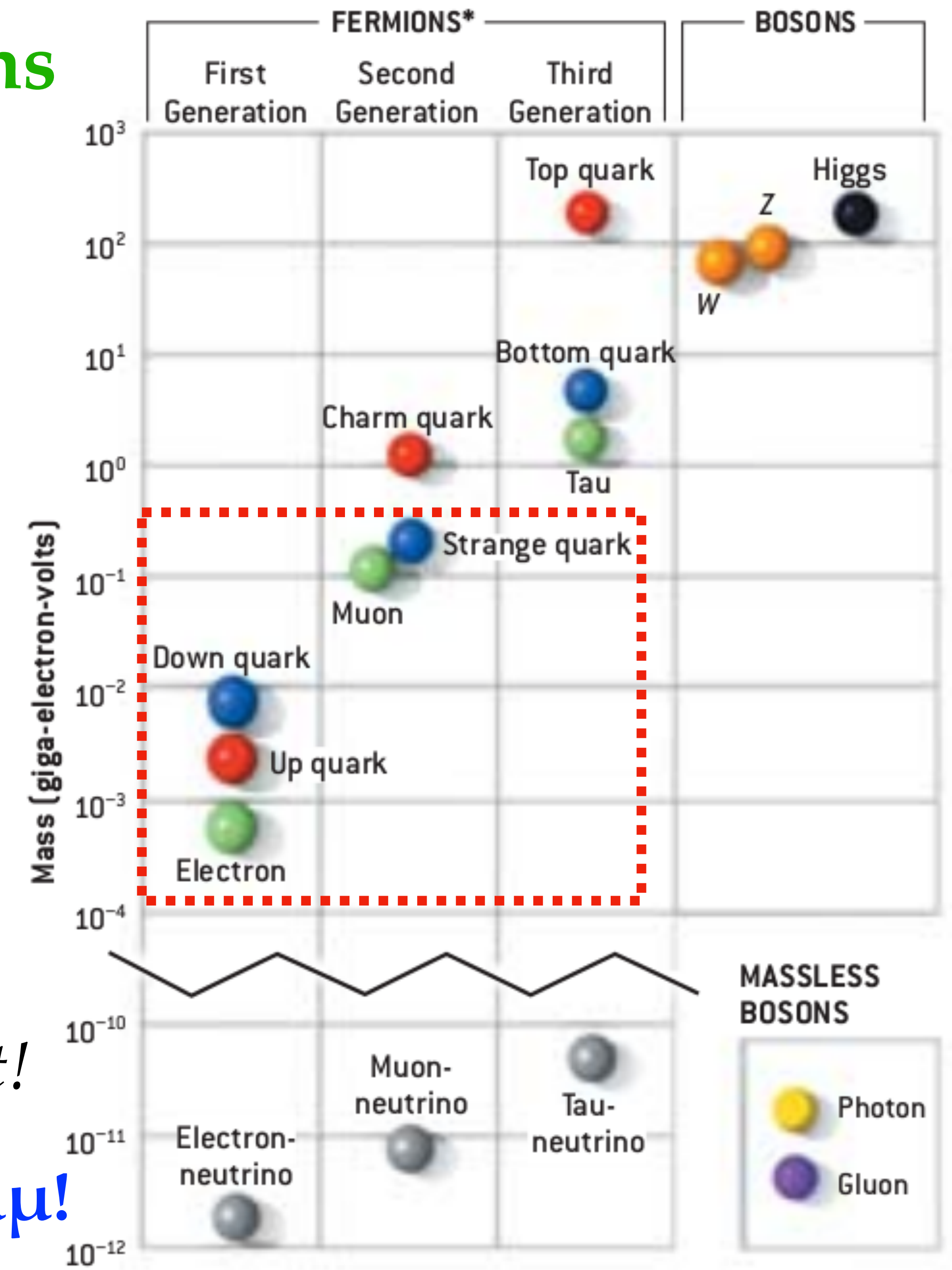
Andrew Brinkerhoff

abrinke1@cern.ch

UF UNIVERSITY of FLORIDA

Standard Model couplings

- Rare SM Higgs decays to **light fermions**
  - e, μ, or bound quarks; directly or via Z/γ
  - Between electrons and strange quarks, a factor of **200** range in particle mass (and **40k** in Higgs branching fraction)
  - Branching fractions: 0.0000005% - 0.02%
  - Huge backgrounds for u, d, and s quark jets at the LHC - have to get clever (also applies to charm)
  - H→ee decays out of reach - *if SM is correct!*
  - **Edging closer to SM sensitivity for H→μμ!**



[1] Image: http://scienceblogs.com/startswithabang/files/2013/08/particle_masses.png
Credit: Gordon Kane, Scientific American, May 2003.

Non-SM couplings

- Many BSM scenarios enhance the light-fermion couplings
- Potential for lepton flavor-violating H→μτ, H→eτ, or H→eμ decays
- **Up to 34% of H(125) decays could be non-SM (CMS+ATLAS limits)**
- One summary of BSM implications for Higgs→μ/τ decays below: a few ruled out experimentally **("X")**, most not yet confirmed or excluded **("?")**

	Model	$\left(\frac{\sigma(pp\to h)^{\rm SM}}{\sigma(pp\to h)}\frac{\Gamma_{\rm tot}}{\Gamma_{\rm tot}^{\rm SM}}\right) R_{\tau^+\tau^-}$		$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$		$X_{\mu\tau}$	
Standard Model	SM	1	?	1	?	0	?
Nat. Flav. Conservation	NFC	$(V_{h\ell}^* v/v_\ell)^2$	?	1	?	0	?
Minimal SUSY	MSSM	$(\sin\alpha/\cos\beta)^2$	?	1	?	0	?
Min. Flav. Violation	MFV	$1+2av^2/\Lambda^2$	?	$1-4bm_\tau^2/\Lambda^2$	?	0	?
Froggatt-Nielsen	FN	$1+\mathcal{O}(v^2/\Lambda^2)$	?	$1+\mathcal{O}(v^2/\Lambda^2)$	?	$\mathcal{O}(\lvert U_{23}\rvert^2 v^4/\Lambda^4)$	?
Higgs-depend. Yukawa	GL	9	X	$25/9$	X	$\mathcal{O}(X_{\mu^+\mu^-})$	?

[1] https://arxiv.org/abs/1302.3229

$H \to$ SM particle analyses

<table>
<tr><th rowspan="2">Decay mode</th><th colspan="3">ATLAS</th><th colspan="3">CMS</th></tr>
<tr><th>Dataset</th><th>ID</th><th>Link</th><th>Dataset</th><th>ID</th><th>Link</th></tr>
<tr><td>$H \to ee$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td><td>25 fb^{-1}, 7/8 TeV</td><td>PLB 744</td><td>1410.6679</td></tr>
<tr><td>$H \to \mu\mu$</td><td>36 fb^{-1}, 13 TeV</td><td>PRL 119</td><td>1705.04582</td><td>36 fb^{-1}, 13 TeV</td><td>HIG-17-019</td><td>cds:2292159</td></tr>
<tr><td>$H \to e\mu$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td><td>20 fb^{-1}, 8 TeV</td><td>PLB 763C</td><td>1607.03561</td></tr>
<tr><td>$H \to e\tau$</td><td rowspan="2">20 fb^{-1}, 8 TeV</td><td rowspan="2">EPJC 77</td><td rowspan="2">1604.07730</td><td rowspan="2">36 fb^{-1}, 13 TeV</td><td rowspan="2">HIG-17-001</td><td rowspan="2">cds:2264540</td></tr>
<tr><td>$H \to \mu\tau$</td></tr>
<tr><td>$H \to Z\gamma \to \ell\ell\gamma$</td><td>36 fb^{-1}, 13 TeV</td><td>JHEP 10</td><td>1708.00212</td><td>25 fb^{-1}, 7/8 TeV</td><td>PLB 726</td><td>1307.5515</td></tr>
<tr><td>$H \to \gamma^{*}\gamma \to \ell\ell\gamma$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td><td rowspan="2">20 fb^{-1}, 8 TeV</td><td rowspan="2">PLB 753</td><td rowspan="2">1507.03031</td></tr>
<tr><td>$H \to J/\psi\, \gamma$</td><td rowspan="2">20 fb^{-1}, 8 TeV</td><td rowspan="2">PRL 114</td><td rowspan="2">1501.03276</td></tr>
<tr><td>$H \to \Upsilon\gamma$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \to \phi\gamma$</td><td rowspan="2">36 fb^{-1}, 13 TeV</td><td rowspan="2">CONF-17-057</td><td rowspan="2">cds:2273873</td><td rowspan="2">- - - - -</td><td rowspan="2">- - - - -</td><td rowspan="2">- - - - -</td></tr>
<tr><td>$H \to \rho\gamma$</td></tr>
</table>

- Many channels, not all ATLAS+CMS, ~half with full 13 TeV dataset so far

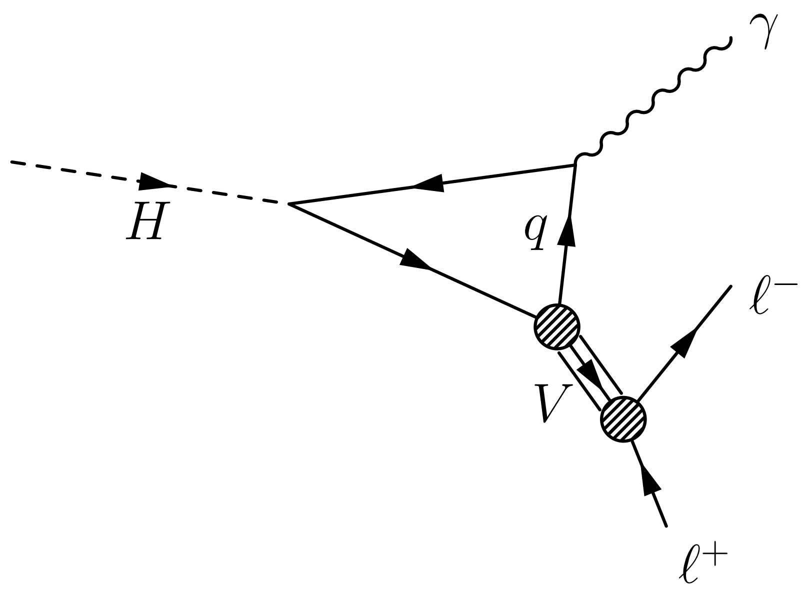
H→SM particle results

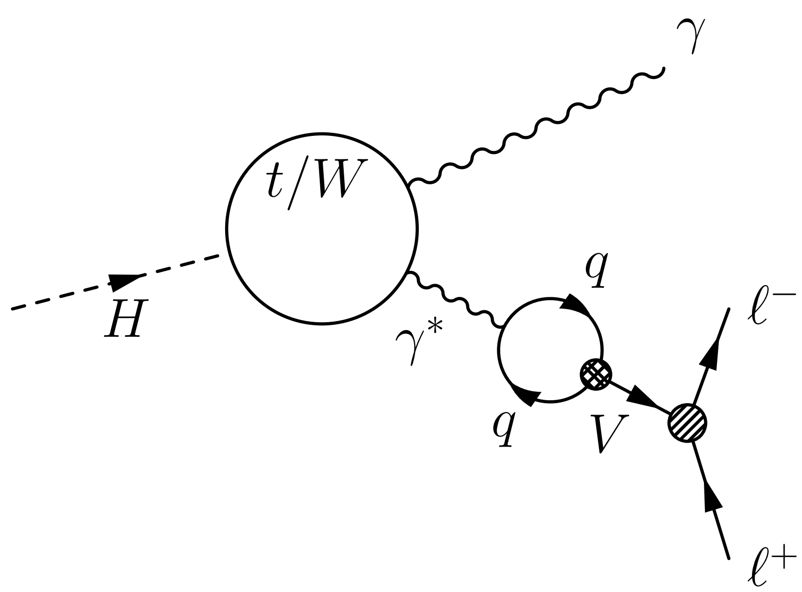
Decay mode	SM BR	ATLAS			CMS		
		Dataset	Exp. lim.	Obs. lim.	Dataset	Exp. lim.	Obs. lim.
H→ee	~5 × 10^{-9}	- - - - -	- - - - -	- - - - -	20 fb^{-1}, 8 TeV	2.4 × 10^{-3}	1.9 × 10^{-3}
H→μμ	**2.2 × 10^{-4}**	**36 fb^{-1}, 13 TeV**	**6.4 × 10^{-4}**	**6.2 × 10^{-4}**	**36 fb^{-1}, 13 TeV**	**4.1 × 10^{-4}**	**5.7 × 10^{-4}**
H→eμ	0	- - - - -	- - - - -	- - - - -	20 fb^{-1}, 8 TeV	4.8 × 10^{-4}	3.5 × 10^{-4}
H→eτ	0	20 fb^{-1}, 8 TeV	1.2 × 10^{-2}	1.0 × 10^{-2}	**36 fb^{-1}, 13 TeV**	**3.7 × 10^{-3}**	**6.1 × 10^{-3}**
H→μτ	0		1.0 × 10^{-2}	1.4 × 10^{-2}		**2.5 × 10^{-3}**	**2.5 × 10^{-3}**
H→Zγ→ℓℓγ	**1.0 × 10^{-4}**	**36 fb^{-1}, 13 TeV**	**4.6 × 10^{-4}**	**6.8 × 10^{-4}**	25 fb^{-1}, 7/8	~1 × 10^{-3}	~1 × 10^{-3}
H→γ*γ→ℓℓγ	**1.2 × 10^{-4}**	- - - - -	- - - - -	- - - - -	20 fb^{-1}, 8 TeV	**7.0 × 10^{-4}**	**7.9 × 10^{-4}**
H→J/ψ γ	3.0 × 10^{-6}	20 fb^{-1}, 8 TeV	1.2 × 10^{-3}	1.5 × 10^{-3}		1.6 × 10^{-3}	1.5 × 10^{-3}
H→ ϒγ	5.1 × 10^{-9}		2.5 × 10^{-3}	2.0 × 10^{-3}	- - - - -	- - - - -	- - - - -
H→φγ	2.3 × 10^{-6}	**36 fb^{-1}, 13 TeV**	4.2 × 10^{-4}	4.8 × 10^{-4}	- - - - -	- - - - -	- - - - -
H→ργ	1.7 × 10^{-5}		8.4 × 10^{-4}	8.8 × 10^{-4}	- - - - -	- - - - -	- - - - -

- H→μμ and H→Zγ/γ*γ branching limits **< 7 × SM**, H→eτ/μτ **< 0.6%**

H→vector meson+γ

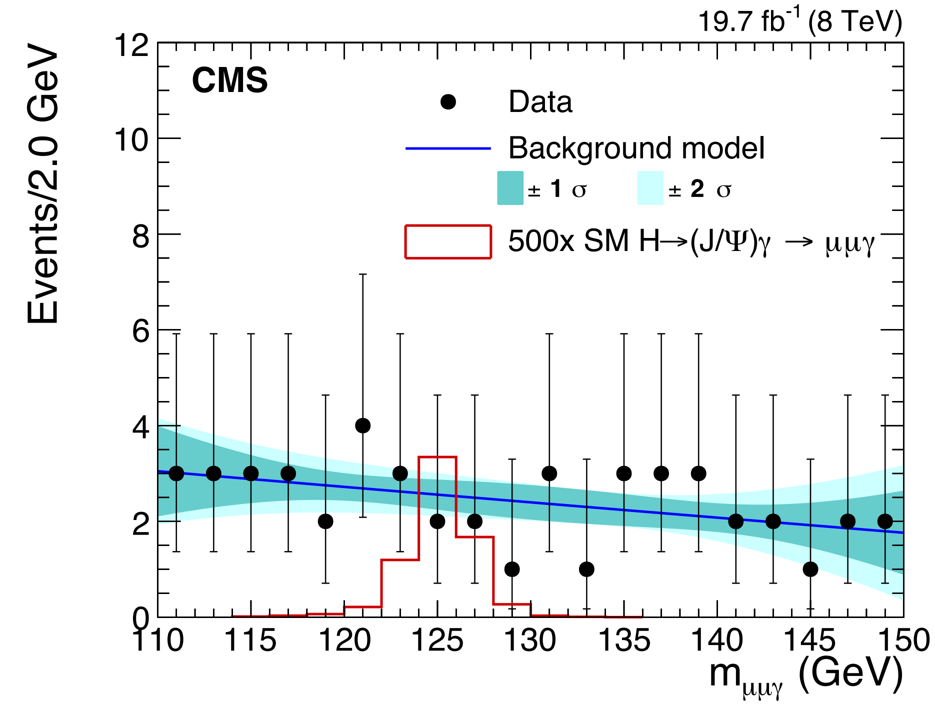
- H→uu/dd/ss/cc decays difficult to find
  - Smaller BR than H→bb, higher backgrounds
  - qq bound states provide a cleaner signature (lower backgrounds, better mass resolution) but with a much reduced production rate: **10 - 5000 × smaller than H→μμ!**
  - Diagram interference, sometimes destructive
- Search for resonances with a high-p_T γ + J/ψ→μμ or ϒ→μμ, or ϕ or ρ meson decays to charged hadrons

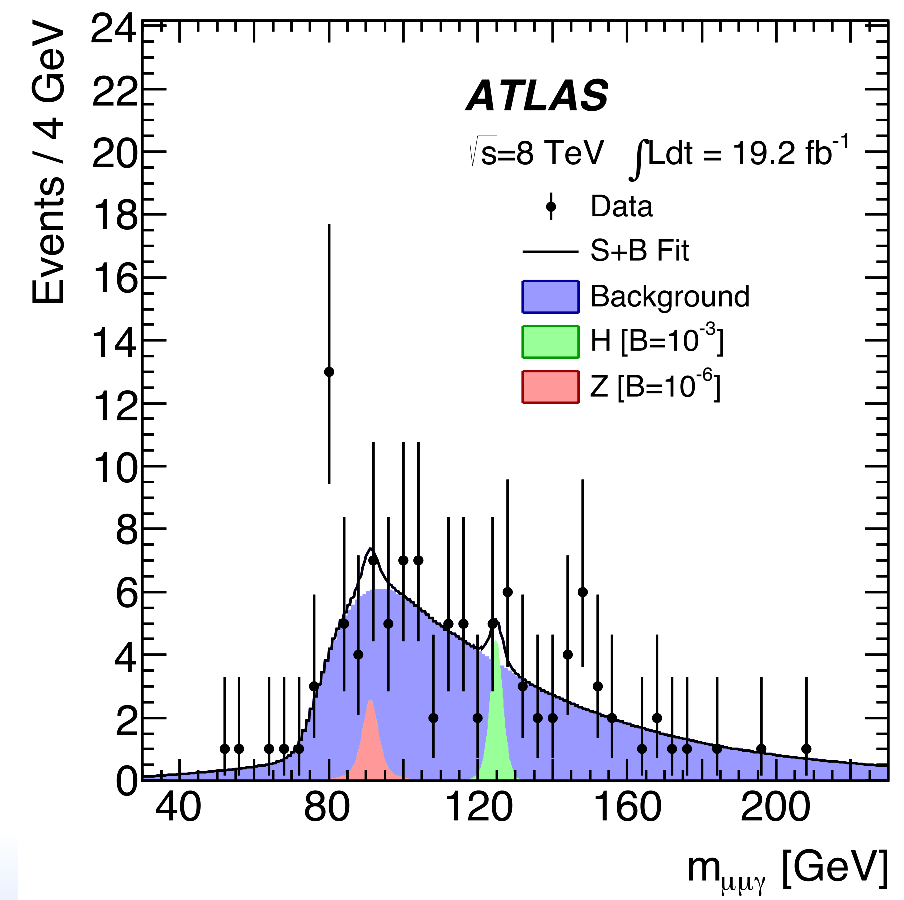




$H \rightarrow J/\psi\,\gamma \rightarrow \mu\mu\gamma$

- Latest results use 8 TeV dataset
- Even in $2.9 < m(\mu\mu) < 3.3$ GeV window, **5 × more $H \rightarrow \gamma^{*}\gamma \rightarrow \mu\mu\gamma$ signal** than $H \rightarrow J/\psi\,\gamma$
- **CMS:** Fit $m(\mu\mu\gamma)$ in data, with 4^{th} order polynomial modeling the background
- **ATLAS:** Single bkg. estimate for Z and Higgs
  - Create pdf models of QCD background kinematics from data with looser selection on p_T of $\mu\mu$ and γ, generate pseudo-data events with 4-vector and isolation values for μ and γ
  - Simultaneous S+B fit to $m(\mu\mu\gamma)$ and $p_T(\mu\mu\gamma)$
- **ATLAS BR limit: 1.5 obs. (1.2 exp.) × 10^{-3}**
- **CMS BR limit: 1.5 obs. (1.6 exp.) × 10^{-3}**

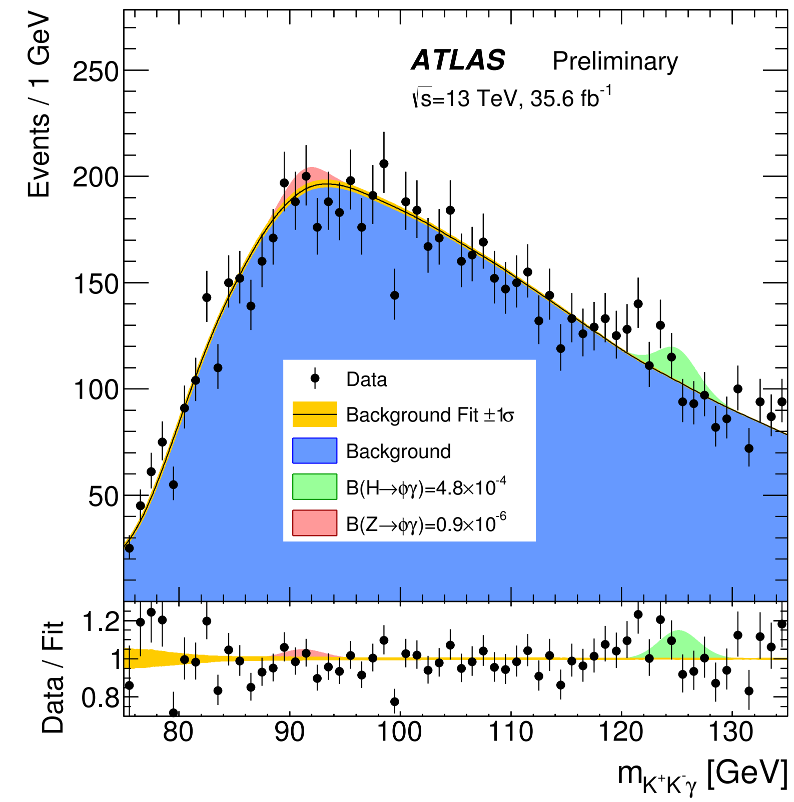


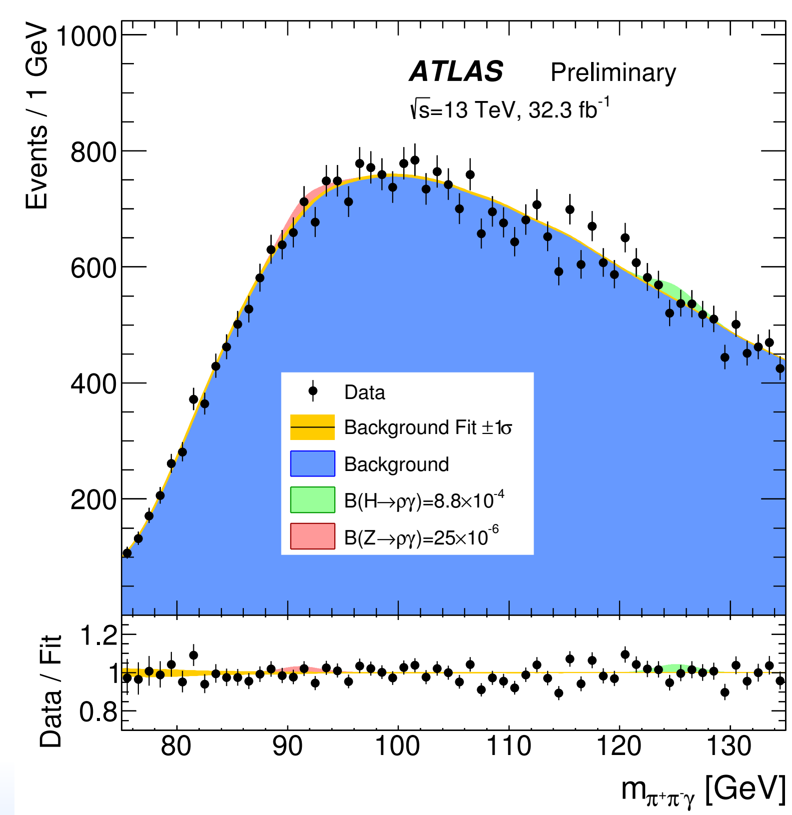


H→φγ and H→ργ

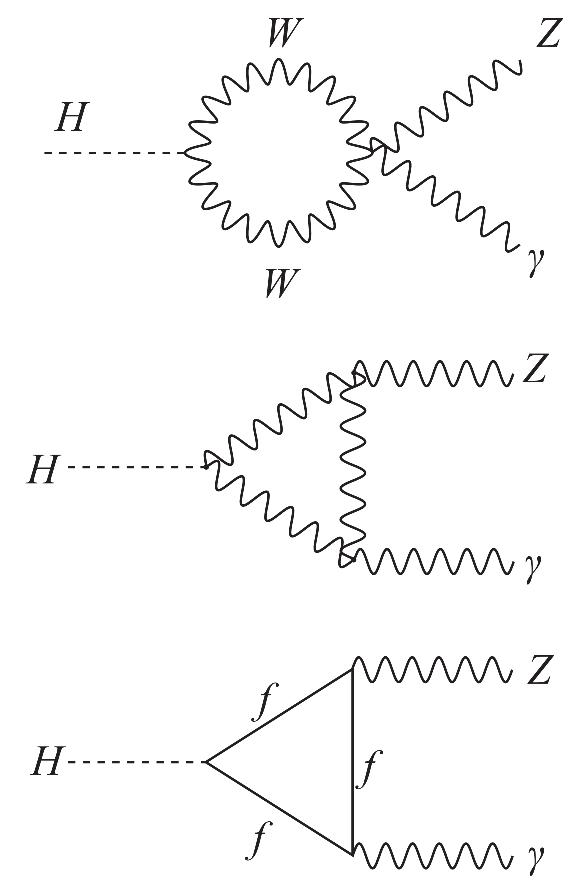
- **ATLAS-only** on 36 fb^{-1} 13 TeV dataset
- Target φ→KK and ρ→ππ decays, visible only as **pairs of oppositely-charged tracks**
- Requires dedicated triggers: high p_T γ plus high p_T tracks with invariant mass cuts
- Much more data to reach SM sensitivity to H→φγ (2.3×10^{-6}) or H→ργ (1.7×10^{-5})

Branching Fraction Limit (95% CL)	Expected	Observed
$\mathcal{B}(H \to \phi\gamma)$ [10^{-4}]	$4.2^{+1.8}_{-1.2}$	4.8
$\mathcal{B}(Z \to \phi\gamma)$ [10^{-6}]	$1.3^{+0.6}_{-0.4}$	0.9
$\mathcal{B}(H \to \rho\gamma)$ [10^{-4}]	$8.4^{+4.1}_{-2.4}$	8.8
$\mathcal{B}(Z \to \rho\gamma)$ [10^{-6}]	33^{+13}_{-9}	25

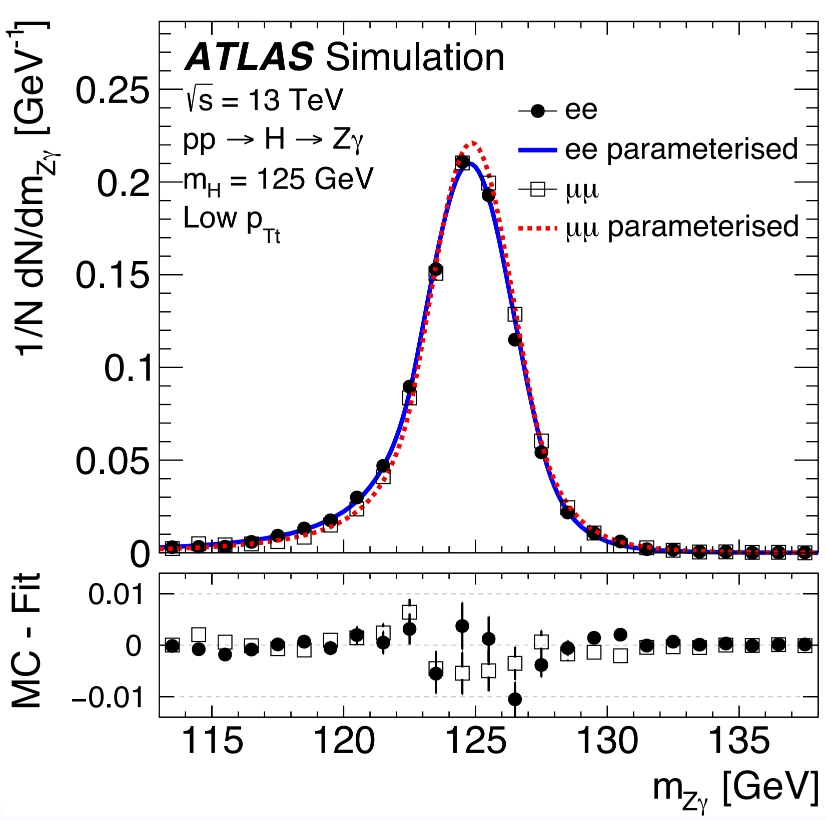




$H \to Z\gamma \to \ell\ell\gamma$

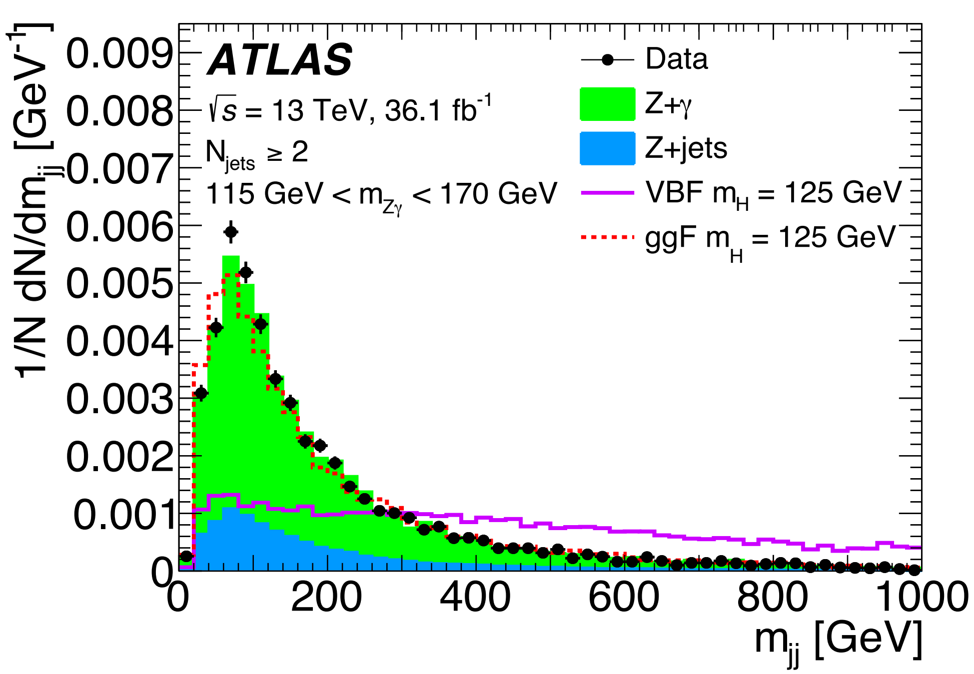


- **$H \to Z\gamma$ decays very similar to $H \to \gamma\gamma$**
  - $Z\gamma$ branching fraction = 0.154%, $\gamma\gamma$ = 0.227%
  - But huge backgrounds in $Z \to qq$ and $Z \to \nu\nu$, only **6.7% in "golden" $Z \to ee$ /$\mu\mu$** channels
  - Even here, higher backgrounds from SM $Z+\gamma$
- **Basic analysis strategy (ATLAS & CMS)**
  - Select $ee\gamma$ / $\mu\mu\gamma$ events with $m(\ell\ell) \sim 91$ GeV
  - Categorize to suppress $Z+\gamma$ background and enhance VBF Higgs signal
  - Measure $m(\ell\ell\gamma)$ signal peak over analytic fit to data in wide mass window as background



H→Zγ→ℓℓγ categories

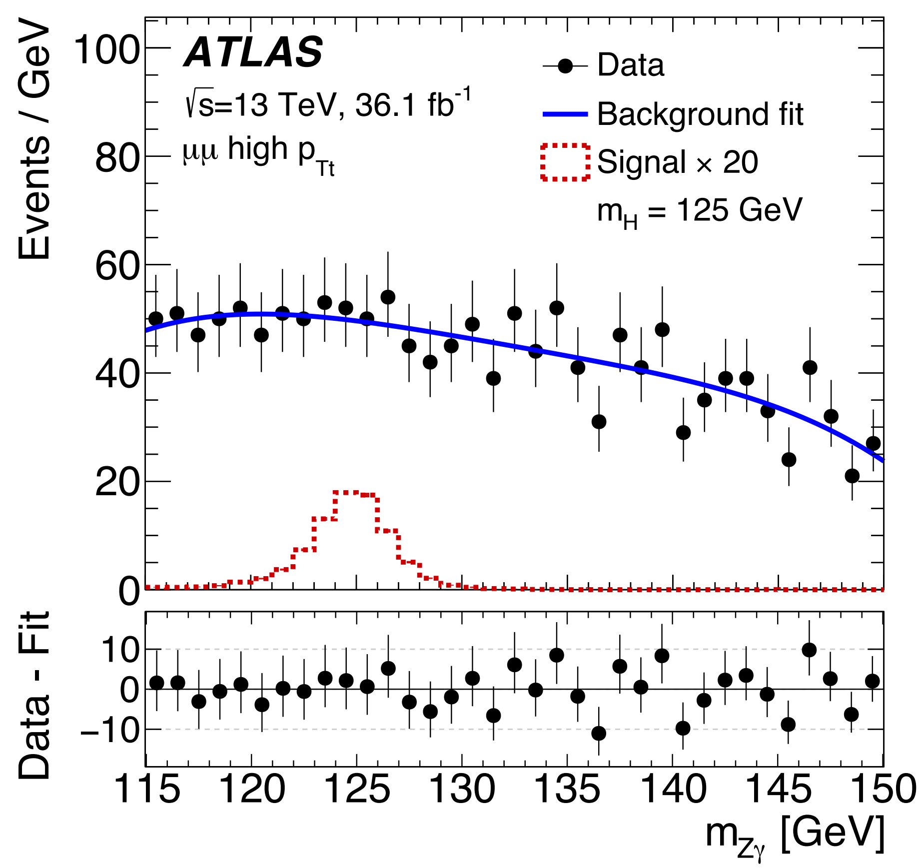
- **5 cut-based** categories in **CMS**: high m(jj) forward dijets (VBF), forward γ, plus 3 categories defined by ℓ rapidity and γ quality
- **ATLAS** uses a **BDT** to identify VBF Higgs events, one category for $p_T(\gamma) > 0.4 \times m(\ell\ell\gamma)$, others divided by p_T of ℓℓγ system
  - Higher stats, more kinematic separation using **36 fb^{-1} 13 TeV dataset**

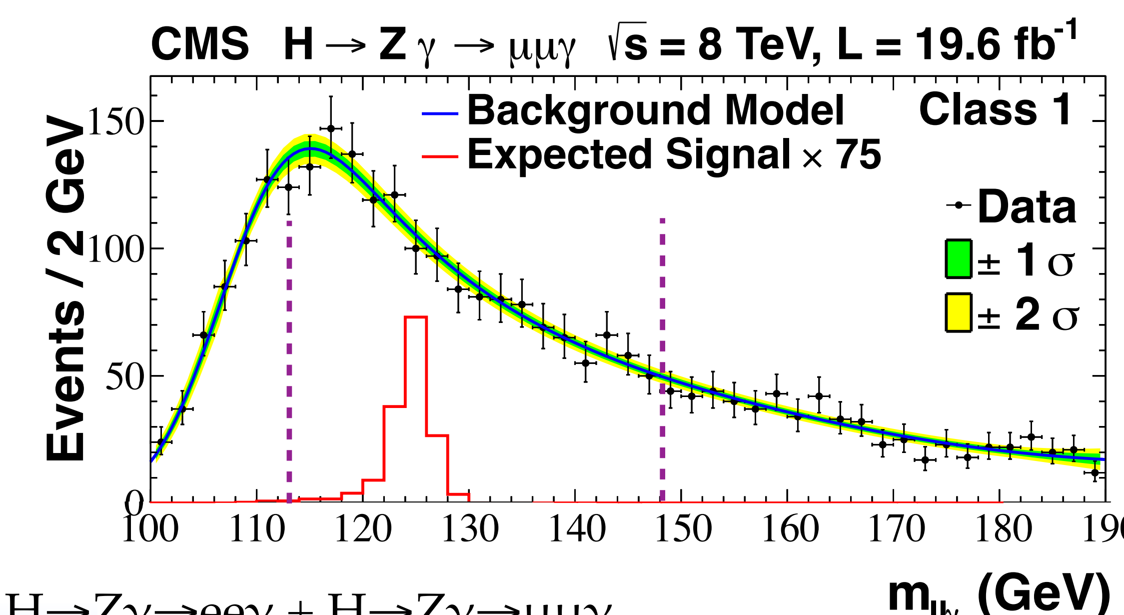


Category	ggF $\epsilon[\%]$	ggF $f[\%]$	VBF $\epsilon[\%]$	VBF $f[\%]$	WH $\epsilon[\%]$	WH $f[\%]$	ZH $\epsilon[\%]$	ZH $f[\%]$
VBF-enriched	0.25	30.5	6.5	67.5	0.34	1.3	0.24	0.6
High relative p_T	1.1	71.5	2.6	14.3	4.0	8.3	4.1	5.3
ee high p_{Tt}	1.7	80.8	2.8	11.0	3.2	4.7	3.6	3.3
ee low p_{Tt}	7.1	93.2	3.6	4.1	3.7	1.5	4.2	1.1
$\mu\mu$ high p_{Tt}	2.2	80.4	3.6	11.3	4.1	4.8	4.2	3.1
$\mu\mu$ low p_{Tt}	9.2	93.4	4.7	4.1	4.6	1.5	4.8	1.0
Total efficiency (%)	21.5		23.8		20.2		21.0	
Expected events	35		3.3		1.0		0.7	

H→Zγ→ℓℓγ signal extraction

- **Non-trivial background shapes**
  - ATLAS uses Bernstein polynomials (2nd to 4th order) to fit data, CMS uses Gaussian × step × polynomial
- **Be careful not to introduce bias!**
  - Background function predictions near 125 GeV can differ by several × signal
  - ATLAS cross-checks vs. Z+γ/jets MC, CMS vs. pseudo-data from fits
- **H→Zγ→ℓℓγ BR limits [SM = 10^{-4}]**
  - **ATLAS: 6.8 obs. (4.6 exp.) × 10^{-4} ****
  - **CMS: ~10 obs. (10 exp.) × 10^{-4} ****

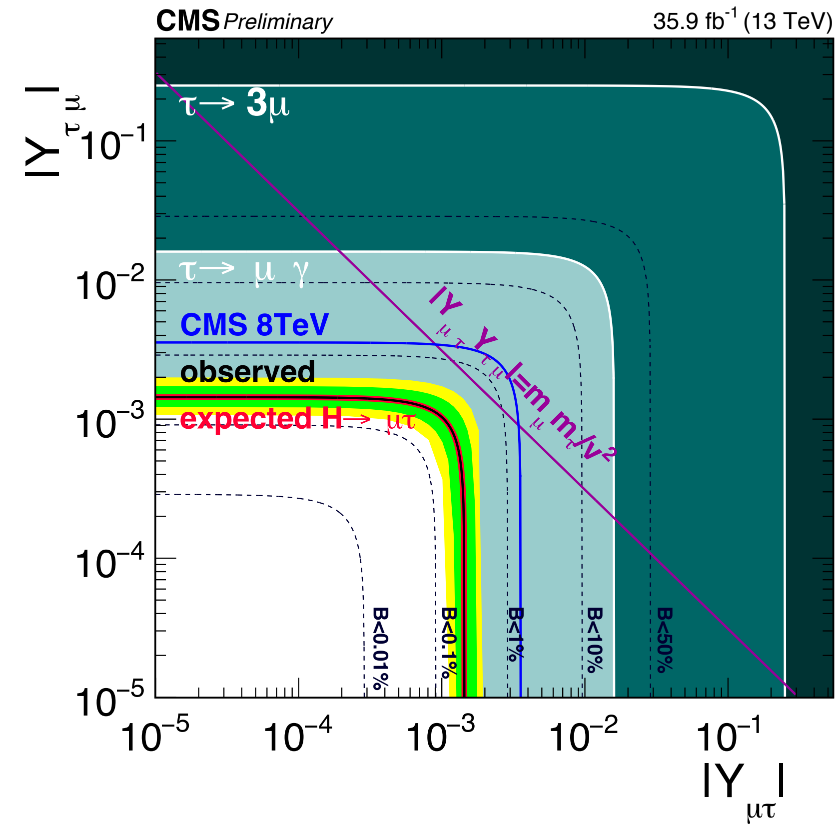


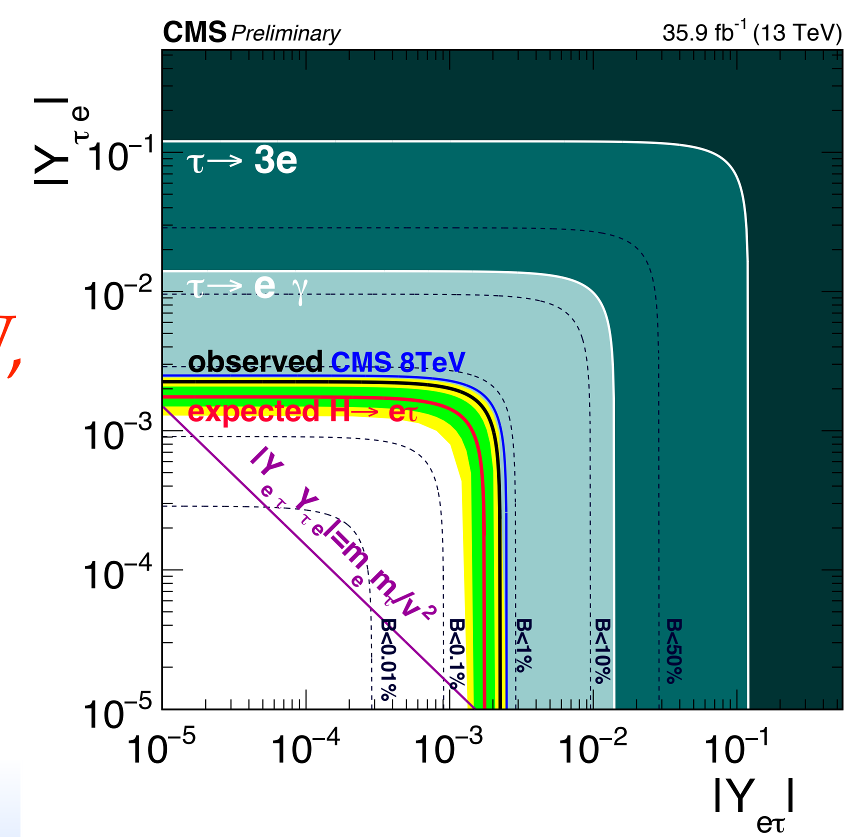


** Papers quote limits on H→Zγ. Here I scale by 6.73% to get limits on H→Zγ→eeγ + H→Zγ→μμγ.

Lepton flavor-violating decays

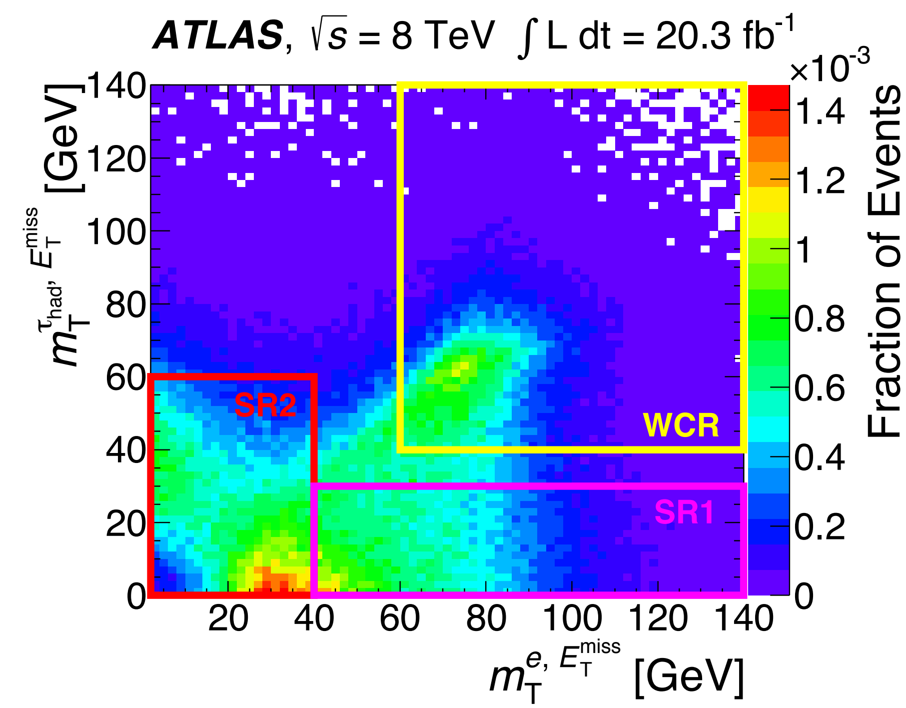
- H→μτ and H→eτ decays provide unique probe of off-diagonal Yukawa couplings
  - **LHC can provide stronger constraints than any current precision measurements**
  - H→eμ decays also interesting, but existing μ→eγ searches highly constrain coupling
- CMS results sparked interest with H→μτ excess in 8 TeV analysis
  - Not seen in subsequent ATLAS result at 8 TeV, motivated even more sophisticated analysis and cross-checks from **CMS in 13 TeV** data

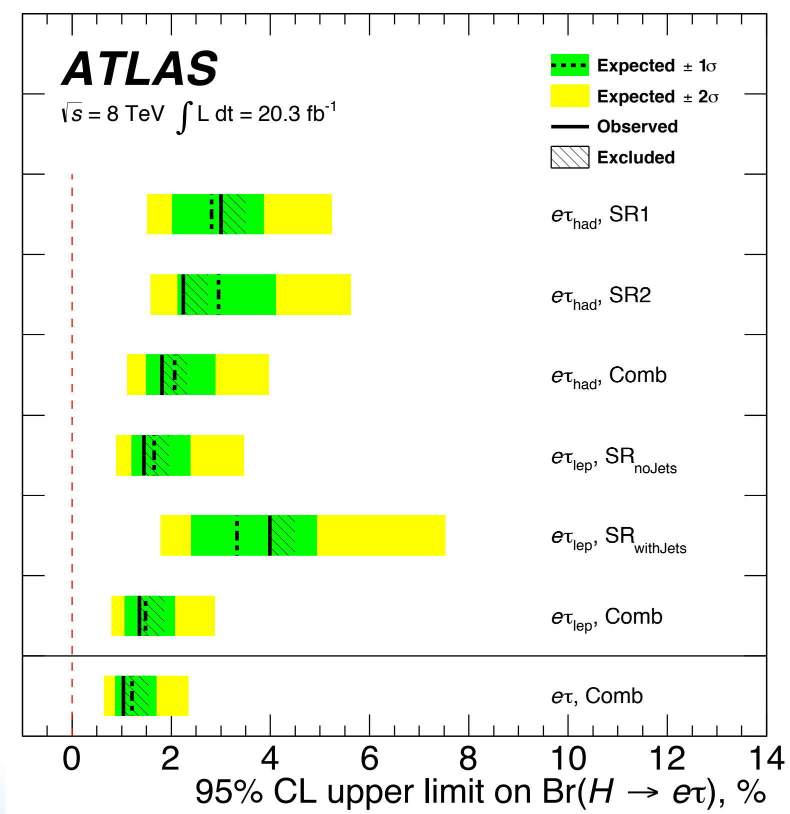


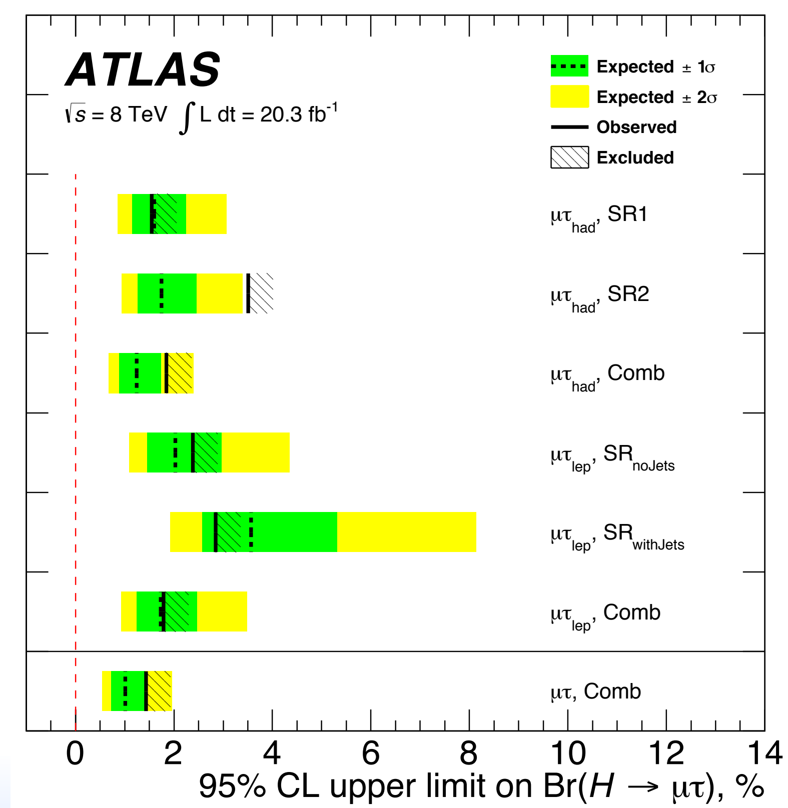


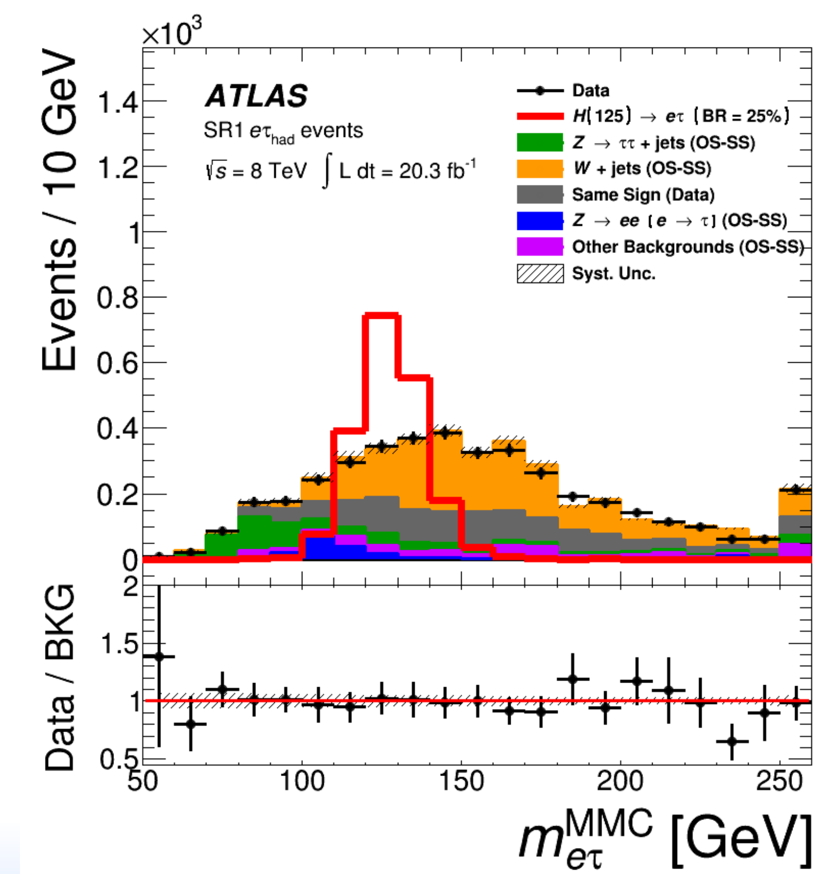
H→μτ and H→eτ in ATLAS

- τ_{had} channels: MC bkg, Missing Mass Calculator for signal (accounts for ν direction in τ decay)
- τ_{lep} channels: Measure *difference* between (ℓ, τ_{lep}) collinear mass spectrum in $\mu\tau_{lep}$ and $e\tau_{lep}$ data
- Categories: $m_T(\tau_{had}, MET)$ vs. $m_T(e/\mu, MET)$
- **H→μτ BR limit: 1.4 × 10^{-2} obs. (1.0 × 10^{-2} exp.)**
- **H→eτ BR limit: 1.0 × 10^{-2} obs. (1.2 × 10^{-2} exp.)**



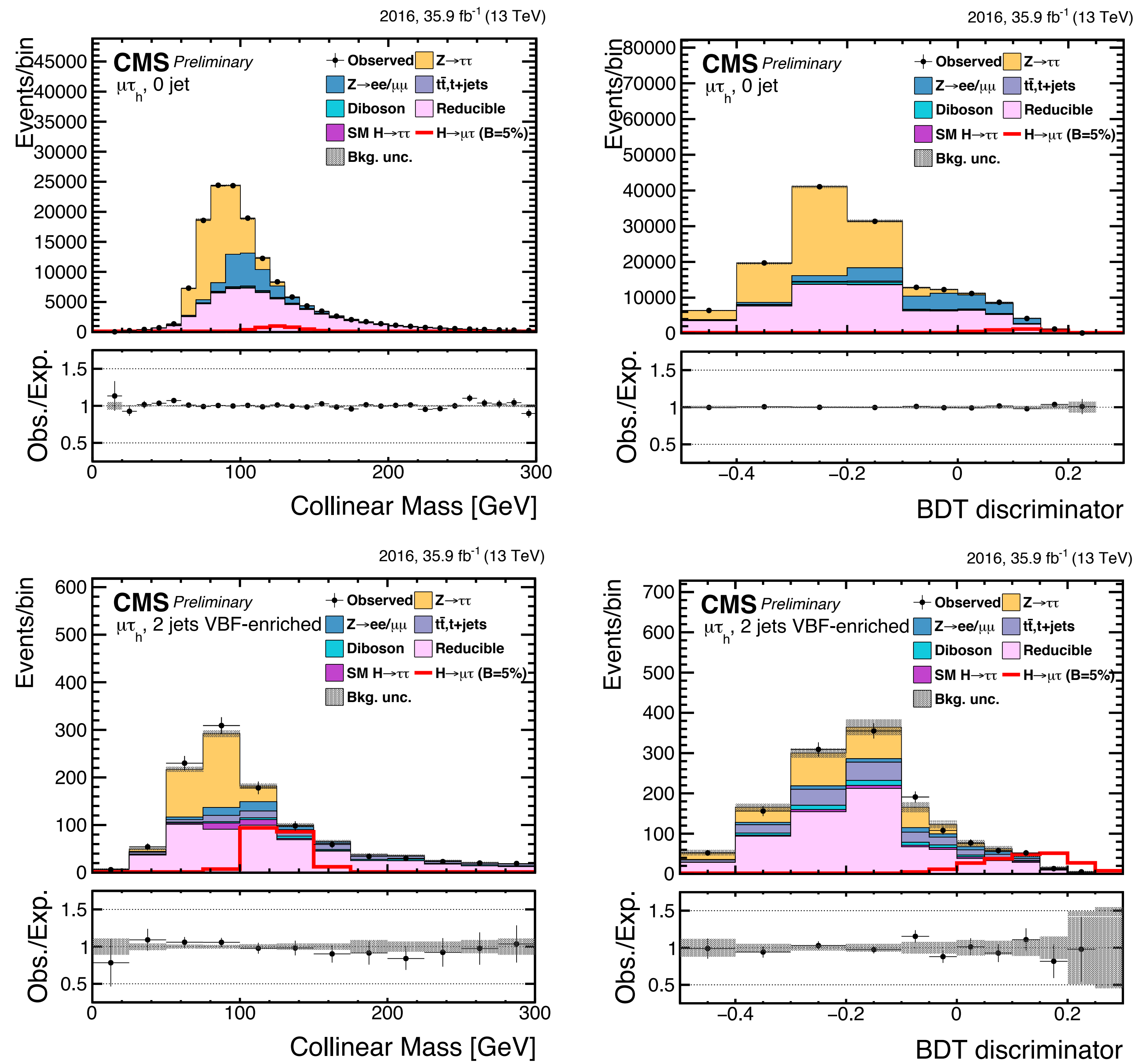






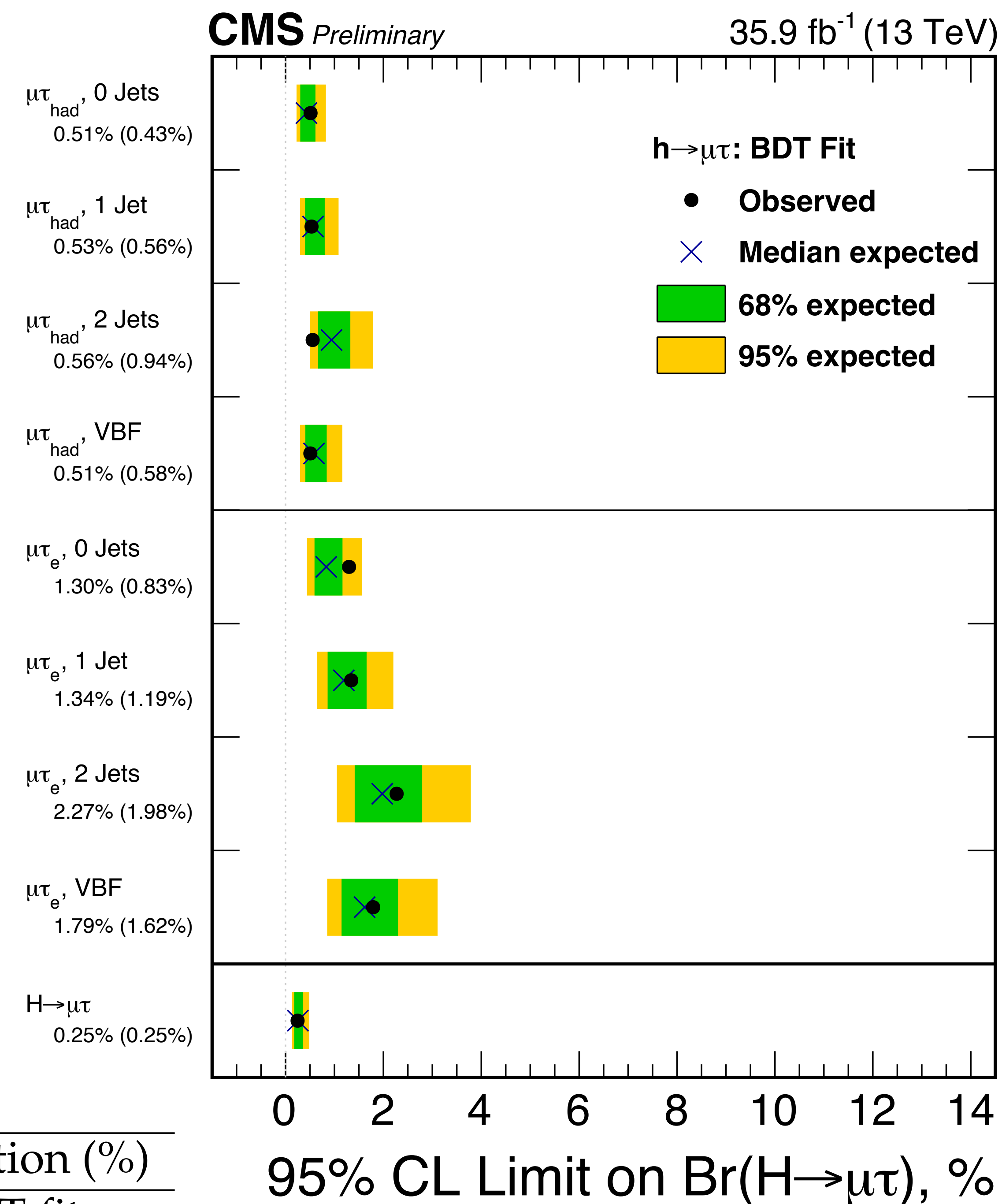
H→μτ and H→eτ in CMS

- Both τ_{lep} and τ_{had} channels, backgrounds modeled with MC and data sidebands
- Categories with 0, 1, and 2 jets, plus exclusive 2-jet VBF
- Train a signal vs. background BDT in each category with many kinematic discriminants (p_T, m_T, mass, $\Delta\phi/\eta$ of $e/\mu/\tau$), used for signal extraction
- Parallel measurement only uses collinear mass (with ν)



H→μτ and H→eτ in CMS

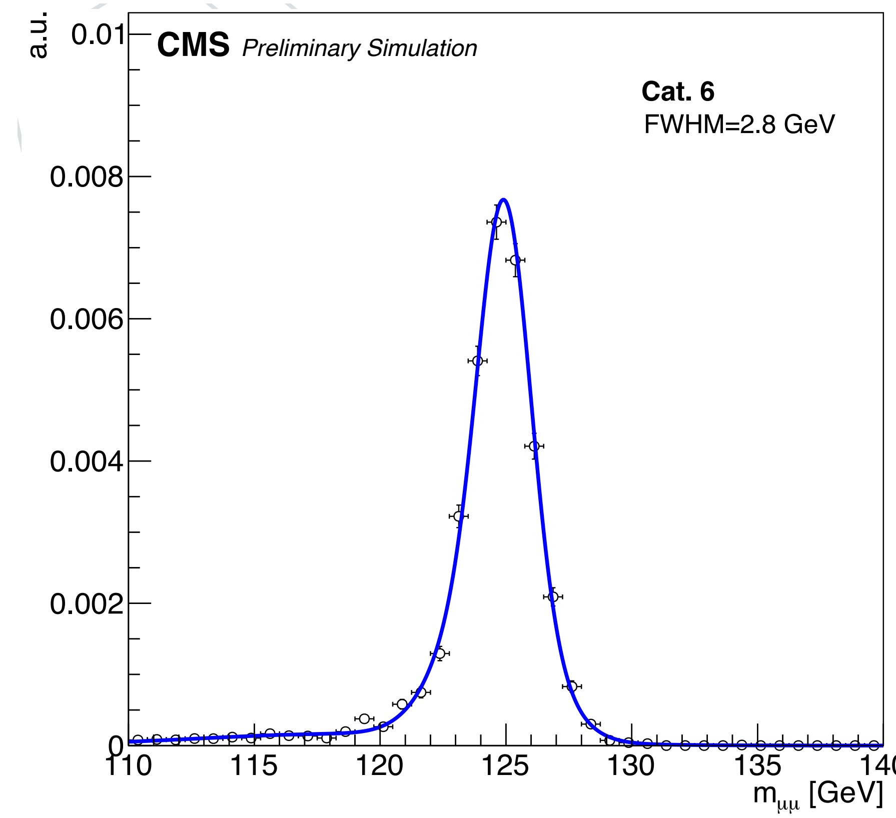
- 4 × 2 × 2 × 2 = 32 measured channels
- **No significant excess** in individual channels or combination, for BDT or collinear mass analysis
- BDT expected limits a factor of 1.5 - 2 lower than collinear mass alone
- Expected limits improved over 8 TeV
  - **H→μτ : 7.5 × 10^{-3} → 2.5 × 10^{-3} [2.5 obs.]**
  - **H→eτ : 7.5 × 10^{-3} → 3.7 × 10^{-3} [6.2 obs.]**

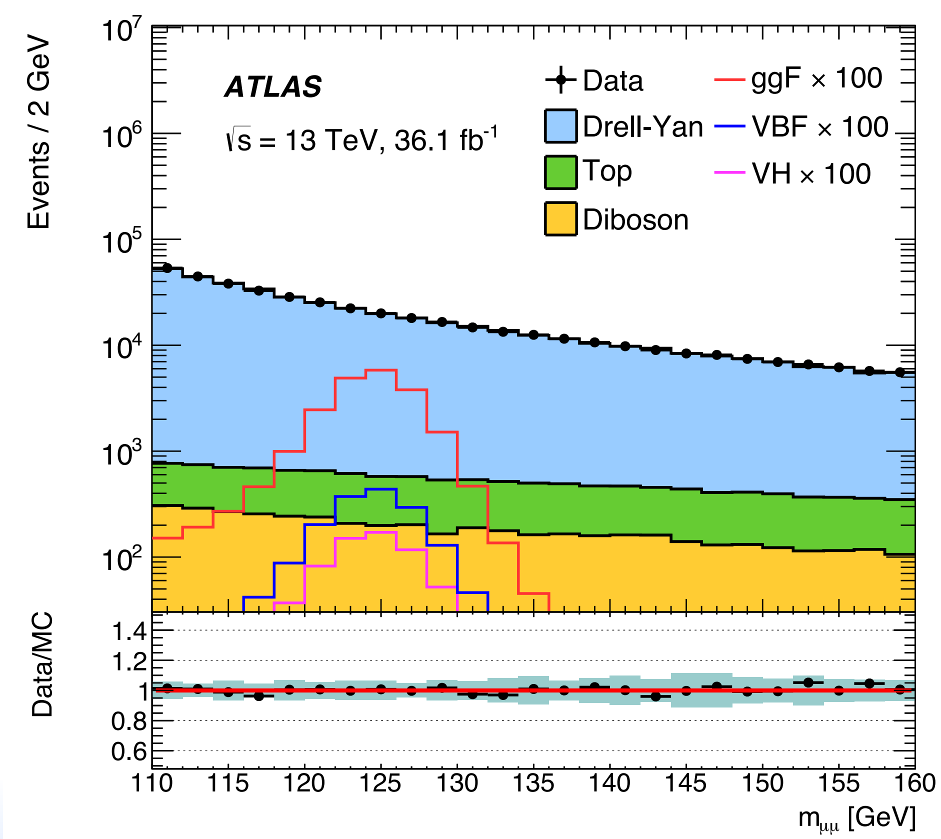


	Observed(Expected) limits (%)		Best fit branching fraction (%)	
	M_{col}-fit	BDT-fit	M_{col}-fit	BDT-fit
$H \to \mu\tau$	<0.51 (0.49) %	<0.25 (0.25)%	0.02 ± 0.20%	0.00 ± 0.12 %
$H \to e\tau$	<0.72 (0.56) %	<0.61 (0.37) %	0.23 ± 0.24 %	0.30 ± 0.18 %

H→μμ

- "Rare" decay with closest-to-SM sensitivity
  - If found, will provide first direct evidence of Higgs coupling to non-3rd generation fermions
  - **ATLAS** and **(new!) CMS** results on 13 TeV data
- Clean signature, good mass resolution
  - Backgrounds mostly from Z+jets and ttbar
- Similar strategies in ATLAS and CMS
  - Muons in barrel have the best p_T resolution
  - Categorize using kinematics of μμ system (p_T, Δϕ, and/or Δη) to separate ggH from Z+jets
  - Distinct VBF signal region(s) with forward jets
  - S+B fit to m(μμ) distribution in each category

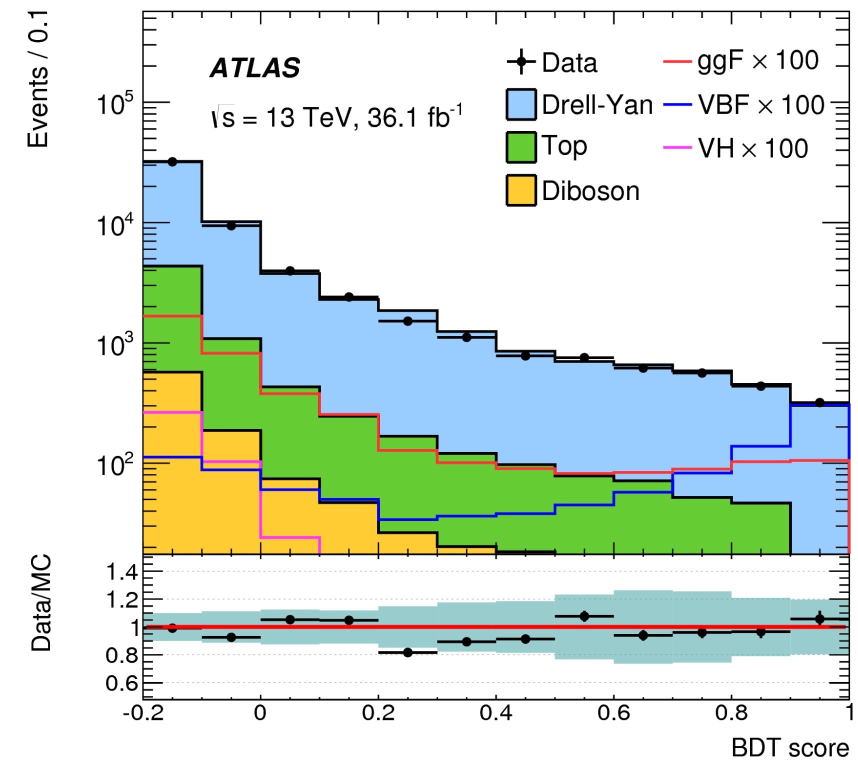


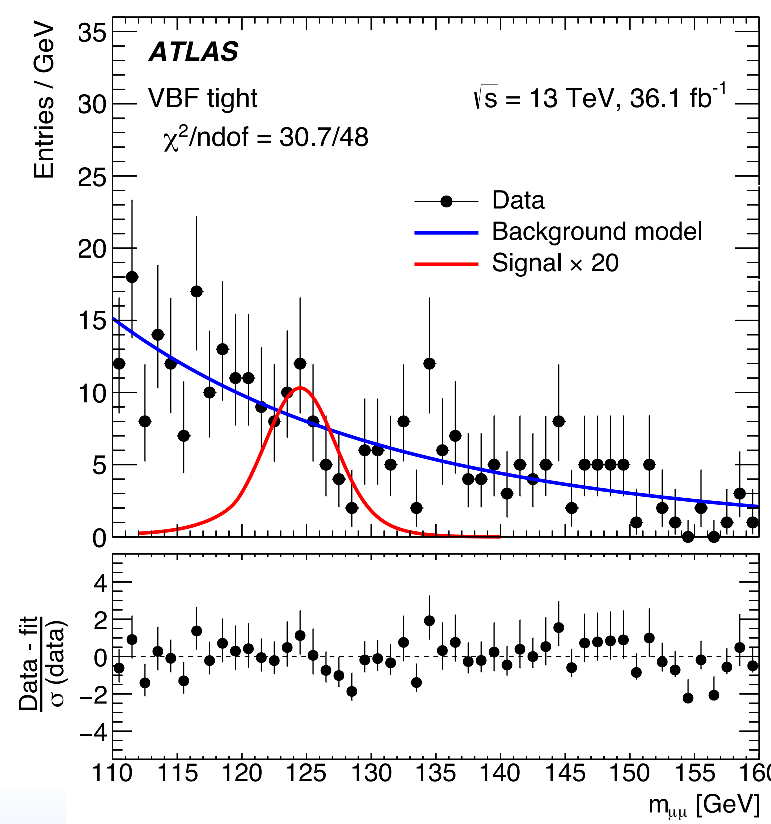


H→μμ in ATLAS

- 2 categories from **BDT** targeting **VBF Higgs**, 6 **cut-based** categories targeting **ggH**, reject **ttbar** background with **b-jet veto**
- Background m(μμ) fit analytically in data
  - Breit-Wigner × Gaussian × exponential / cubic
  - Bias evaluated against Z+jets MC
- **7+8+13 TeV BR limit: 6.2 obs. (6.4 exp.) × 10^{-4}**

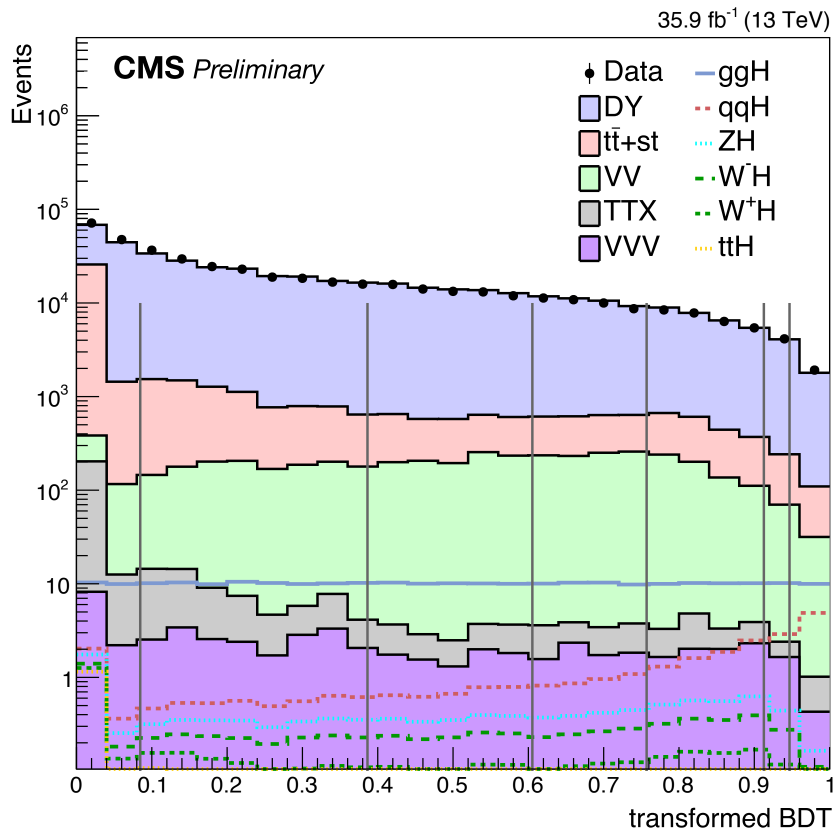
	S	B	$S/\sqrt{B}$	FWHM (GeV)	Data
Central low $p_T^{\mu\mu}$	11	8000	0.12	5.6	7885
Noncentral low $p_T^{\mu\mu}$	32	38000	0.16	7.0	38777
Central medium $p_T^{\mu\mu}$	23	6400	0.29	5.7	6585
Noncentral medium $p_T^{\mu\mu}$	66	31000	0.37	7.1	31291
Central high $p_T^{\mu\mu}$	16	3300	0.28	6.3	3160
Noncentral high $p_T^{\mu\mu}$	40	13000	0.35	7.7	12829
VBF loose	3.4	260	0.21	7.6	274
VBF tight	3.4	78	0.38	7.5	79

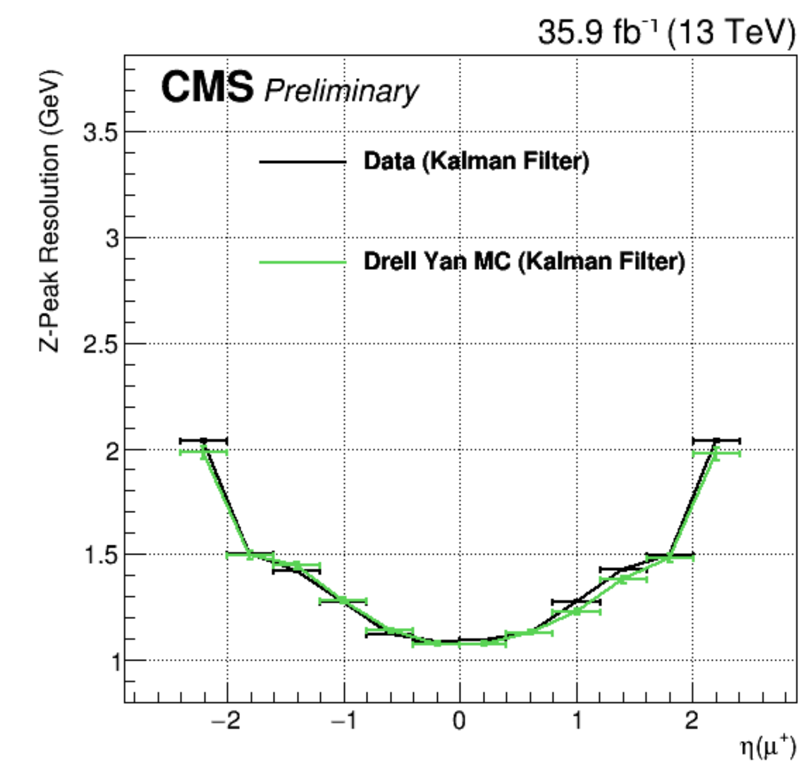




H→μμ in CMS

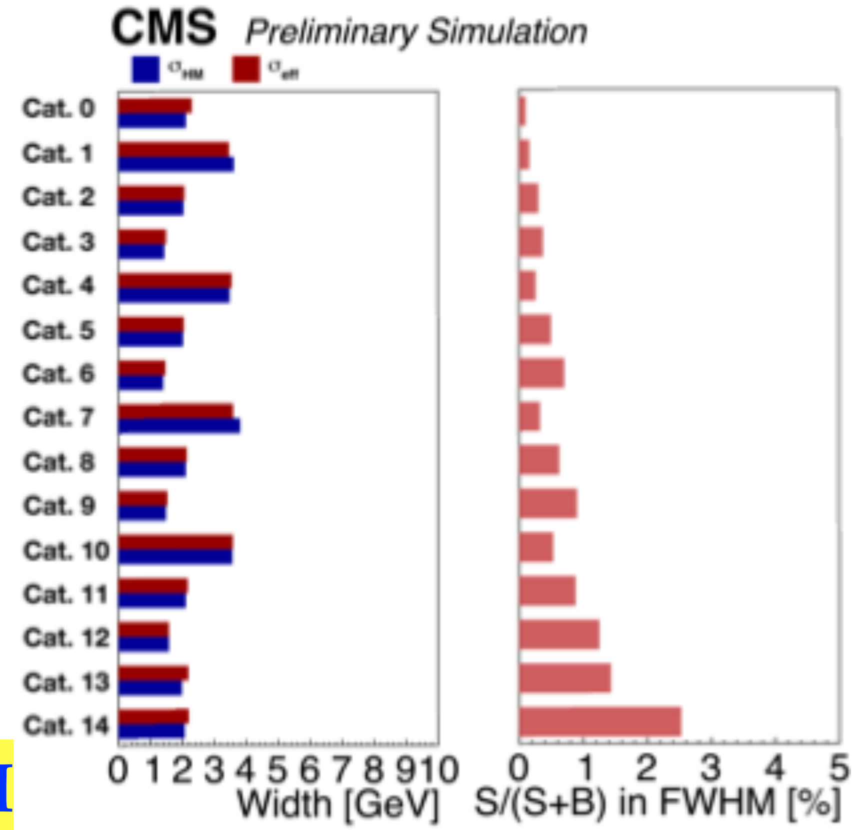
- Two-stage categorization: **BDT** + **muon η**
- Inclusive BDT for all signal vs. all bkg.
  - Only variables un-correlated to m(μμ)
  - ggH somewhat separated from Z+jets
  - ttbar rejected with jet b-tagging
  - **VBF signal events have highest BDT score**
- Mass resolution by maximum muon |η|
  - **Custom signal vs. background decision tree** combines BDT and η info to generate categories with optimal expected signal sensitivity
  - **15 categories** based on 7 BDT and 3 η regions



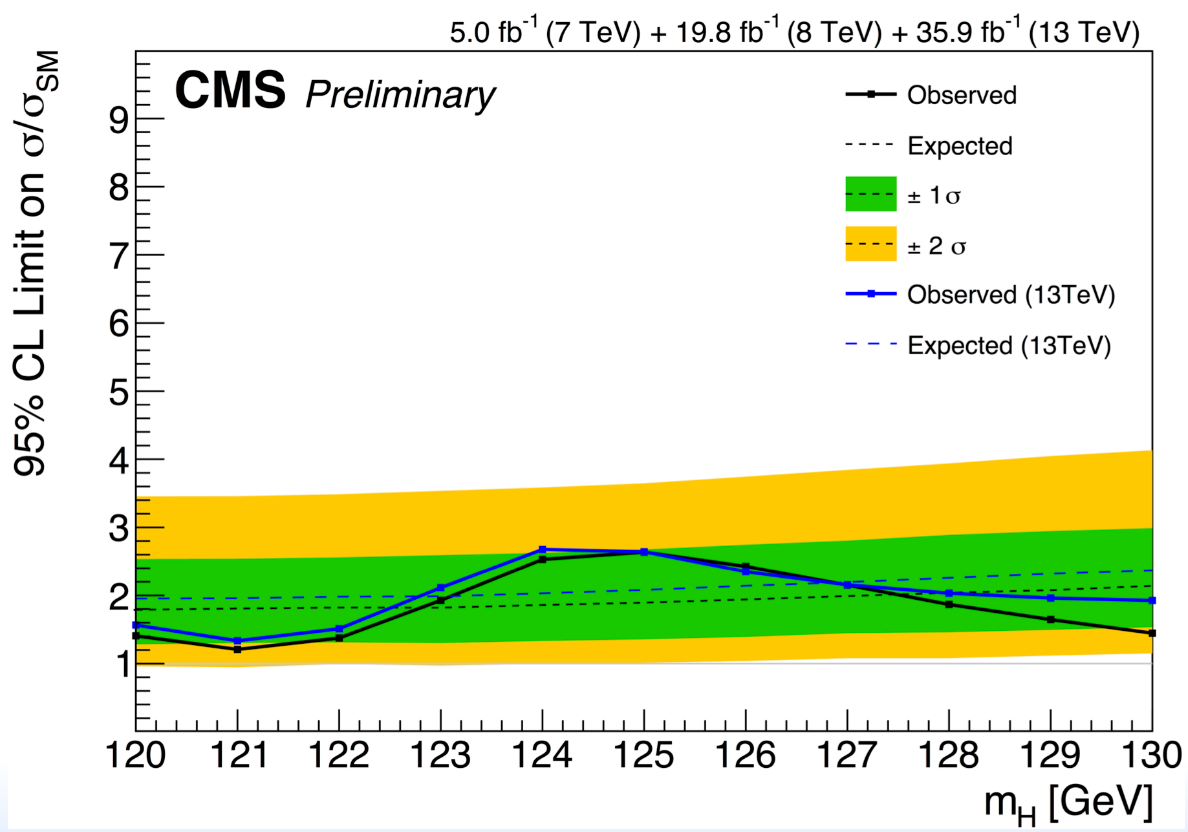


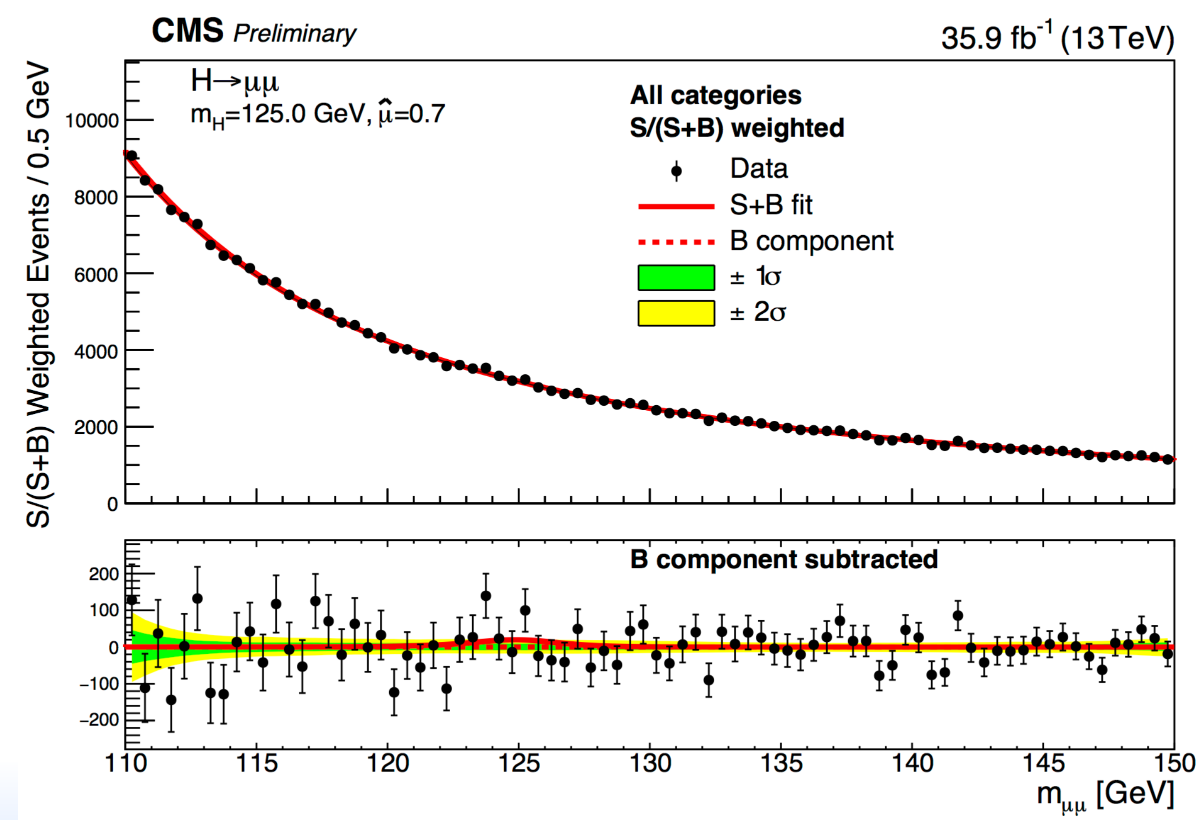
H→μμ in CMS

- Background fit functions vary by category
  - Modified Breit-Wigner × polynomial (order 0 - 4), sum of 2 exponentials
  - Chosen to minimize bias relative to pseudo-data generated by 10 other functions: Breit-Wigners, exponentials, NNLO FEWZ template, polynomials

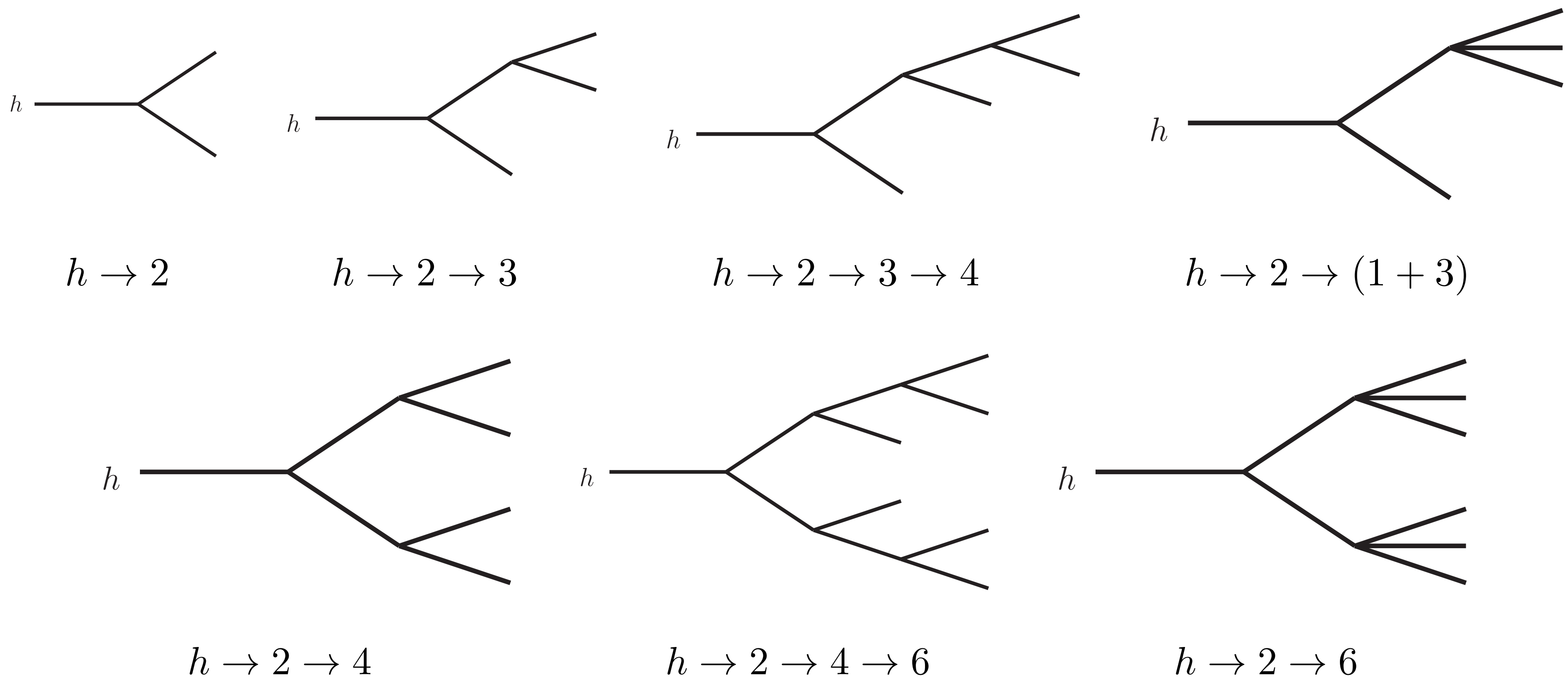


- **7+8+13 TeV limt: 5.7 obs. (5.1 exp.) × 10^{-4}, 2.6 (2.1) × SM**





Higgs decays to BSM particles



https://arxiv.org/abs/1312.4992/

- Many possible **$H \to X_1X_2$** decays, where Xs are neutral BSM particles
- **X→SM or BSM** particles: multiple **μ**, **τ**, or **(b)-jet** objects (plus **MET**)
- Mostly lower p_T, sometimes highly collimated (for low X masses) - usually need unique triggering and offline reconstruction
- Huge phase space, highly specialized analyses: **What to prioritize?**

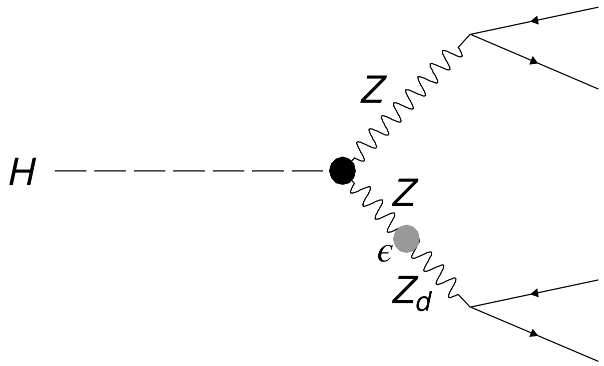
$H \to$BSM particle analyses

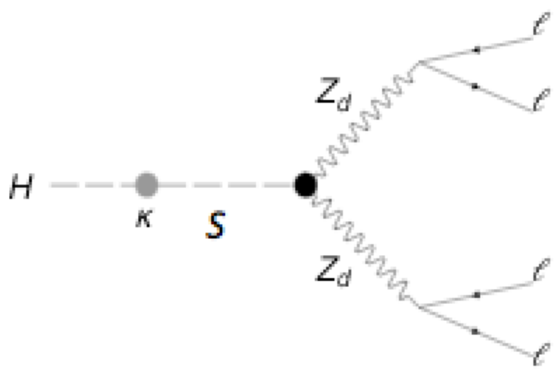
<table>
<tr><th rowspan="2">Decay mode</th><th colspan="3">ATLAS</th><th colspan="3">CMS</th></tr>
<tr><th>Dataset</th><th>ID</th><th>Link</th><th>Dataset</th><th>ID</th><th>Link</th></tr>
<tr><td>$H \to aa \to 4b$</td><td>3.2 fb^{-1}, 13 TeV</td><td>EPJC 76</td><td>1606.08391</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \to aa \to \mu\mu bb$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td><td rowspan="3">20 fb^{-1}, 8 TeV</td><td rowspan="3">JHEP 10</td><td rowspan="3">1701.02032</td></tr>
<tr><td>$H \to aa \to \mu\mu\tau\tau$</td><td>20 fb^{-1}, 8 TeV</td><td>PRD 92</td><td>1505.01609</td></tr>
<tr><td>$H \to aa \to 4\tau$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \to aa \to 4\mu$</td><td rowspan="2">36 fb^{-1}, 13 TeV</td><td rowspan="2">CONF-17-042</td><td rowspan="2">cds:2273848</td><td>20 fb^{-1}, 8 TeV</td><td>PLB 744</td><td>1506.00424</td></tr>
<tr><td>$H \to Z_{(d)}Z_d \to 4\ell$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \to G\chi \to GG\gamma$</td><td rowspan="2">20 fb^{-1}, 8 TeV</td><td rowspan="2">CONF-15-001</td><td rowspan="2">cds:1988425</td><td>20 fb^{-1}, 8 TeV</td><td>PLB 753</td><td>1507.00359</td></tr>
<tr><td>$H \to \chi\chi \to G\gamma G\gamma$</td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \to f_d f_d \to 4\ell + \chi$</td><td rowspan="2">3.2 fb^{-1}, 13 TeV</td><td rowspan="2">CONF-16-042</td><td rowspan="2">cds:2206083</td><td rowspan="2">- - - - -</td><td rowspan="2">- - - - -</td><td rowspan="2">- - - - -</td></tr>
<tr><td>$H \to f_d f_d \to 8\ell + \chi$</td></tr>
</table>

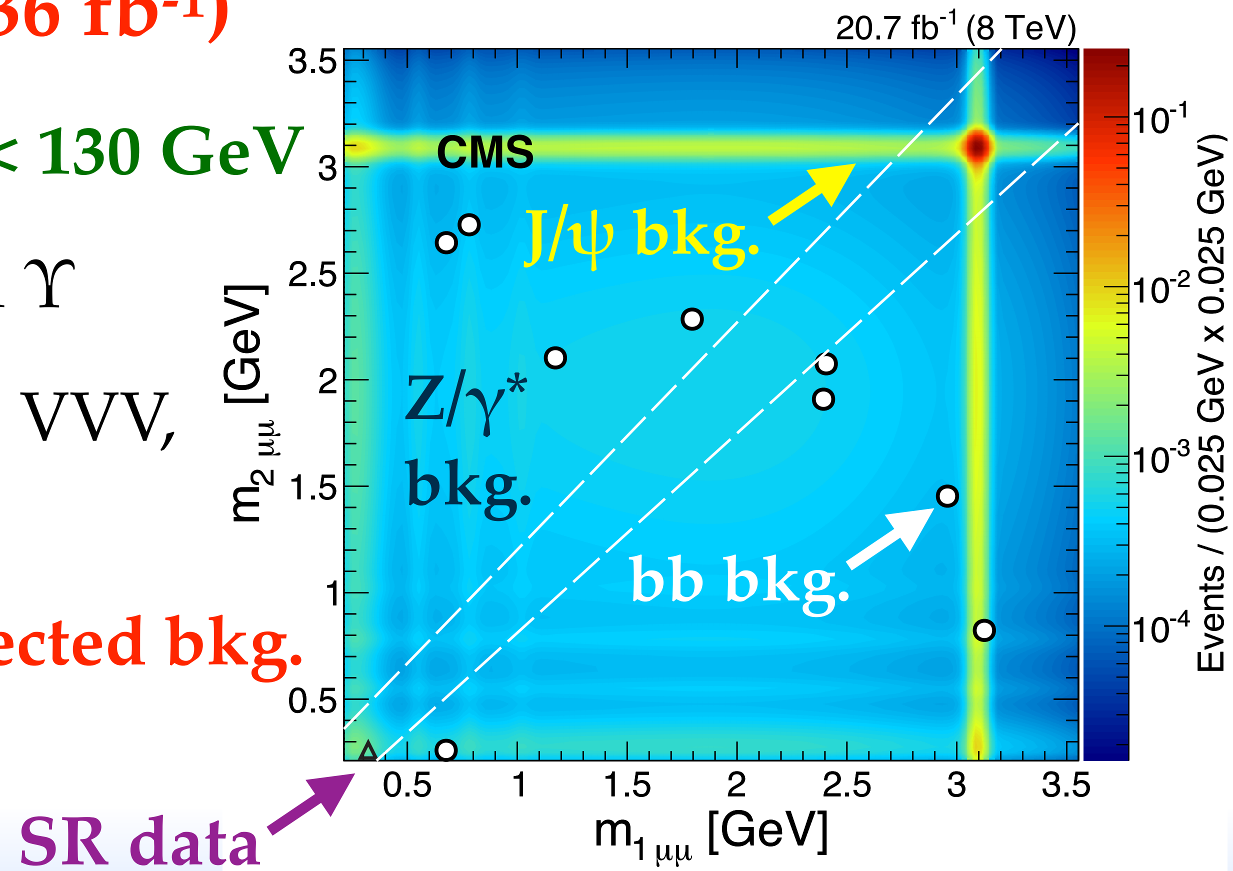
- Eclectic set of final states, not much overlap between ATLAS andCMS, **just one analysis so far with full 13 TeV dataset**

H→aa / $Z_d Z_d$→4μ (low mass)

- **H→aa→4μ** (CMS 8 TeV)
  - 2 m(μ) < m(a) < 2 m(τ) : highest BR(a→μμ)
  - $|m_1(\mu\mu) - m_2(\mu\mu)| < 0.13$ GeV + 0.033 × (m_1+m_2)
  - Count events over bb, J/ψ, and Z/γ* background
  - **1 event observed over 2.2 ± 0.7 expected bkg.**
- **H→aa/$Z_d Z_d$→4μ** **(ATLAS 13 TeV, 36 fb^{-1})**
  - 0.88 < m(μμ) < 15 GeV, **120 < m(4μ) < 130 GeV**
  - $m_2(\mu\mu)$ / $m_1(\mu\mu)$ > 0.85, veto J/ψ and ϒ
  - Bkg. ~30% ZZ*, ~29% H→ZZ*, ~19% VVV, remainder from multi-b events
  - **0 events observed over 0.4 ± 0.1 expected bkg.**

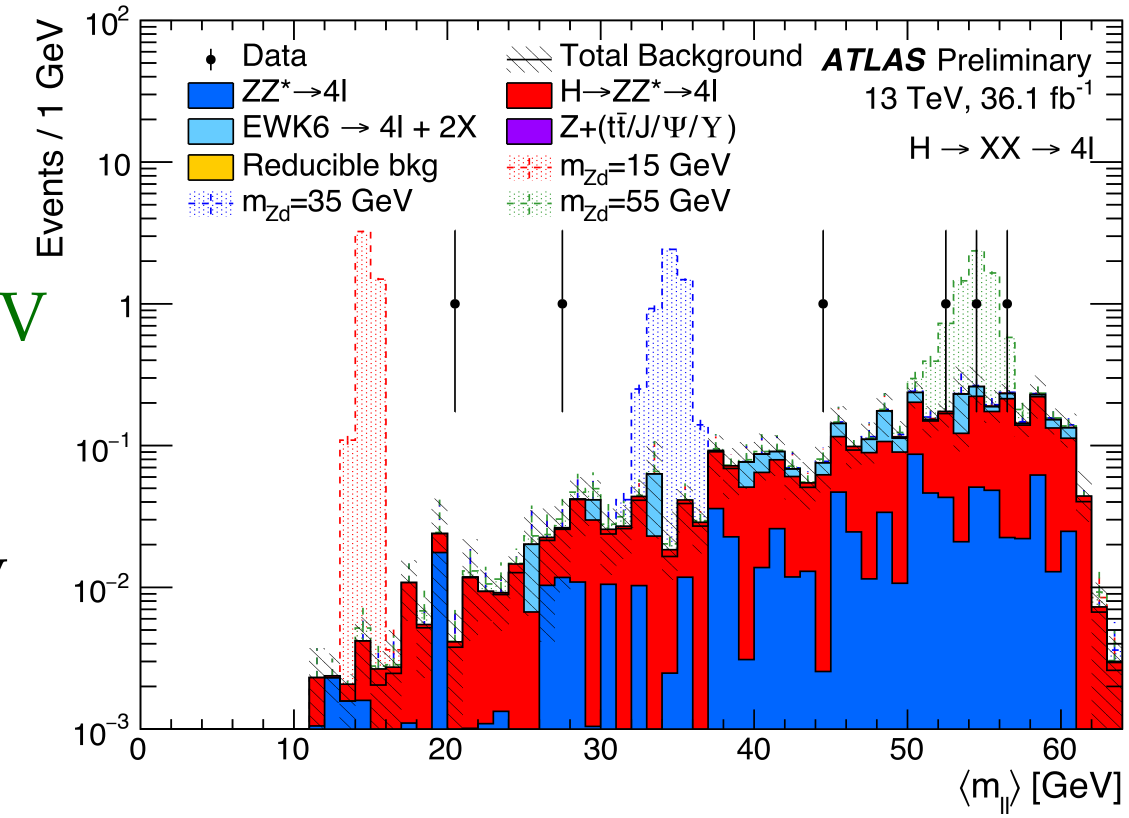


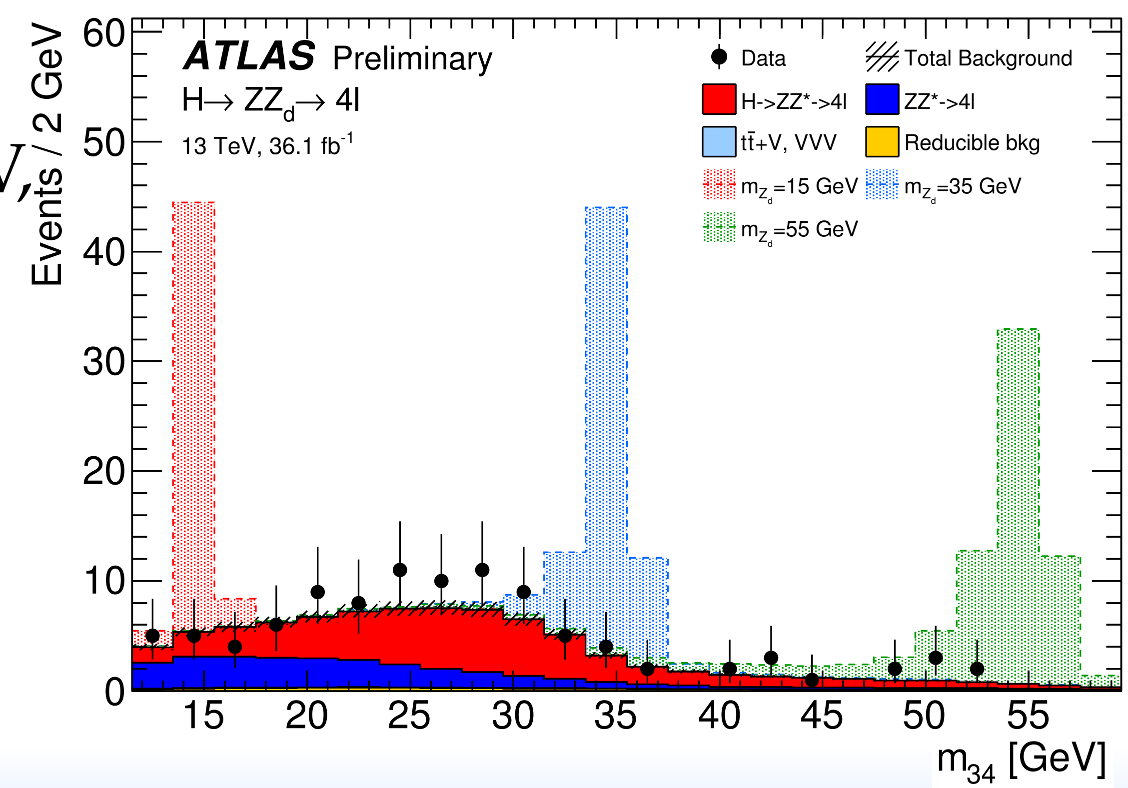




$H \to Z_{(d)} Z_d \to 4\ell$ (high mass)

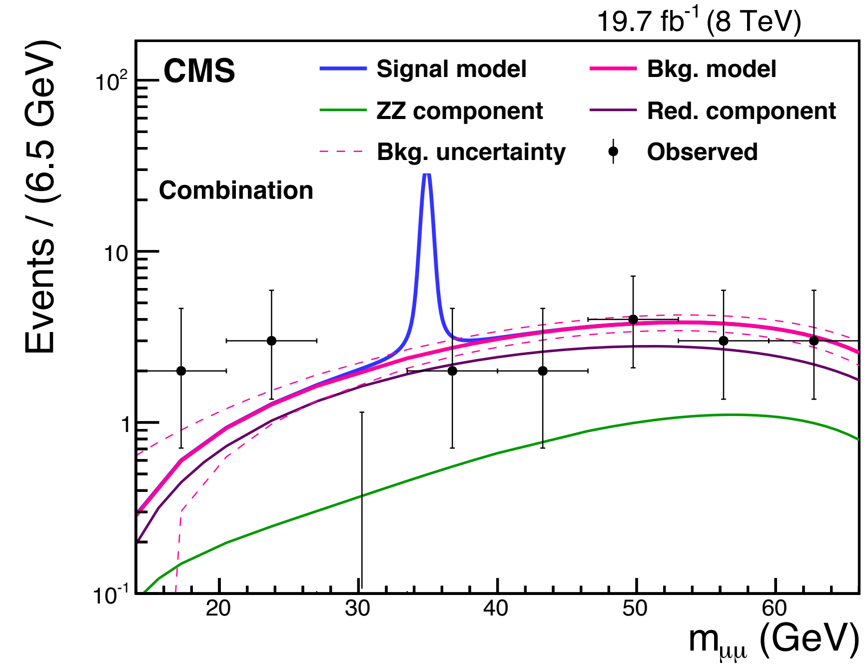
- **$H \to Z_d Z_d \to 4\ell$** (ATLAS 13 TeV, 36 fb^{-1})
  - $15 < m(Z_d) < 60$ GeV, $120 < m(4\ell) < 130$ GeV
  - $m_2(\ell\ell) / m_1(\ell\ell) > 0.85$, veto J/ψ, Υ, and Z
  - Bkg. ~29% ZZ*, ~63% H→ZZ*, ~17% VVV
  - **6 observed over 3.9 ± 0.3 expected bkg.**
- **$H \to Z Z_d \to 4\ell$** (ATLAS 13 TeV, 36 fb^{-1})
  - $50 < m(Z) < 106$ GeV, $12 < m(Z_d) < 115$ GeV, $115 < m(4\ell) < 130$ GeV, veto J/ψ
  - Bkg. ~30% ZZ*, ~64% H→ZZ*, ~6% non-prompt leptons from Z+jets/ttbar/WZ
  - **102 observed over 87 ± 7 expected bkg.**

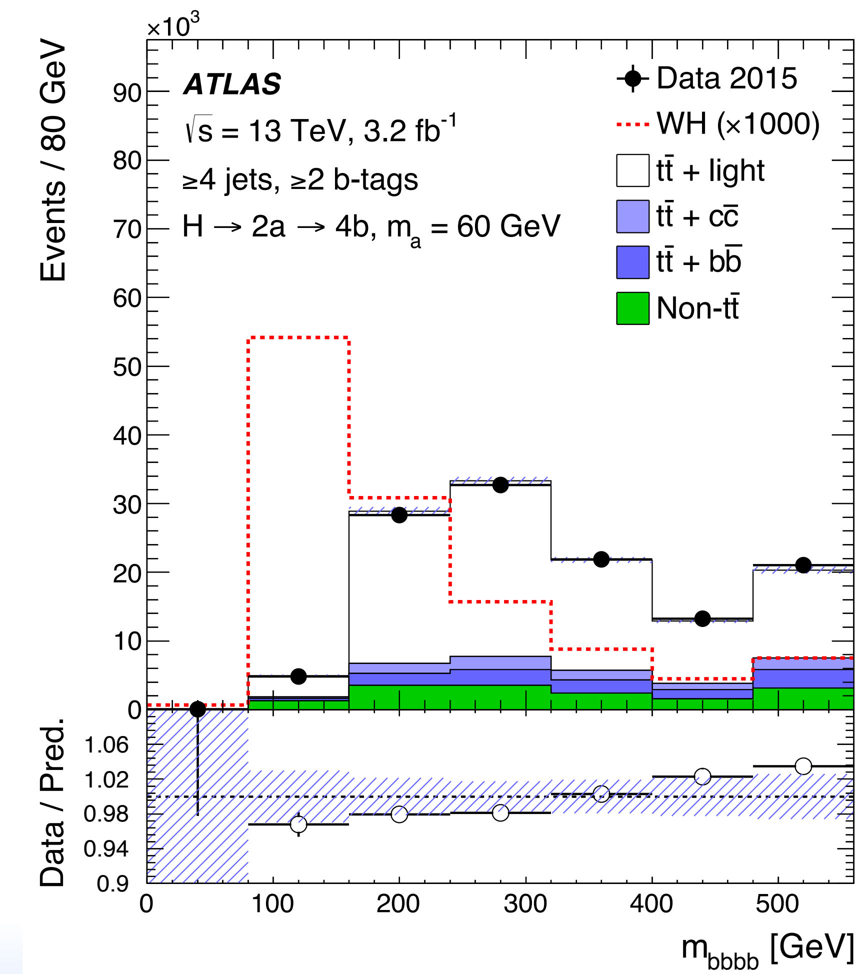




H→aa, a→μμ/ττ/bb

- **H→aa→bbbb** (ATLAS 13 TeV, 3.2 fb^{-1})
  - WH, W→ℓν to trigger, 20 < m(a) < 60 GeV
  - Sig. vs bkg. BDT including m(3b) and m(4b)
- **H→aa→μμbb/μμττ** (CMS 8 TeV, 20 fb^{-1})
  - 15 < m(a) < 65 GeV, 100 < m(μμττ) < 150 GeV
  - Find m(a) with m(μμ) peak over poly. bkg.
  - **ATLAS μμττ** scans down to m(a) = 3.7 GeV, includes J/ψ and ϒ resonances in bkg. model
- **H→aa→ττττ** (CMS 8 TeV, 20 fb^{-1})
  - 5 < m(a) < 15 GeV, at least one a→$\tau_\mu\tau_X$ decay
  - Trigger on μ from high-p_T τ_μ, or VH, V→μν/μμ
  - Special reconstruction for $\tau_\mu\tau_X$ merged object





Conclusions and questions

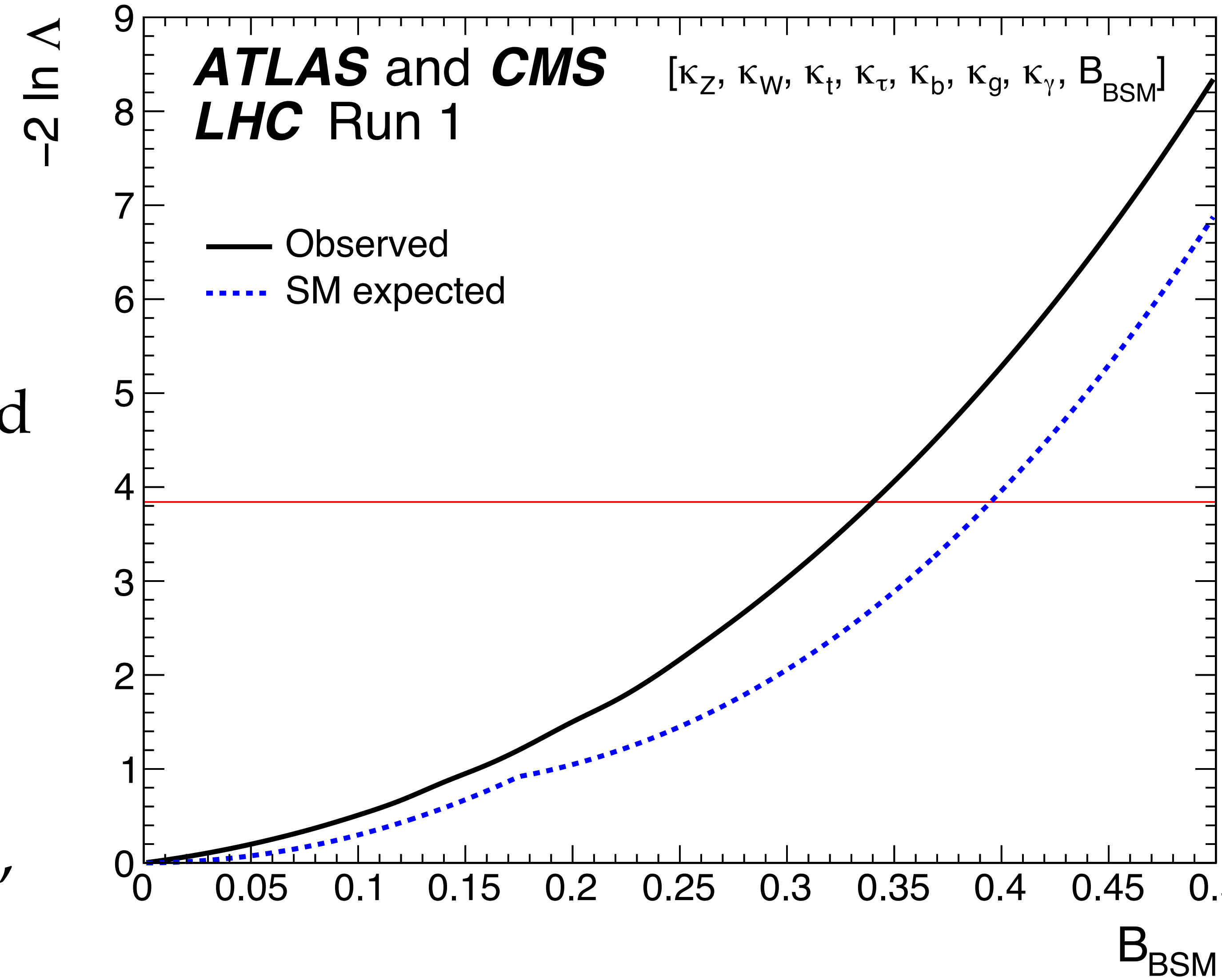
- Searches for **H→ℓℓ** well-advanced at both CMS and ATLAS
  - **H→μμ sensitivity now close to 2 × SM!**
  - **How low** do we need to push limits on processes we don't expect to see (in the SM) at the LHC, e.g. **ee, flavor-violating**?
- **H→γ*γ** and **Zγ** limits already < 7 × SM, searches will likely continue until we find them
- **H→vector meson+γ** long time to reach SM sensitivity, some never
  - **How interesting** are these searches right now?
- **H→BSM** coverage hit-or-miss, analyses technically challenging
  - **Which** are the most interesting channels, providing unique insight?
  - **How much** will indirect constrains limit this phase space anyway?

BACKUPS

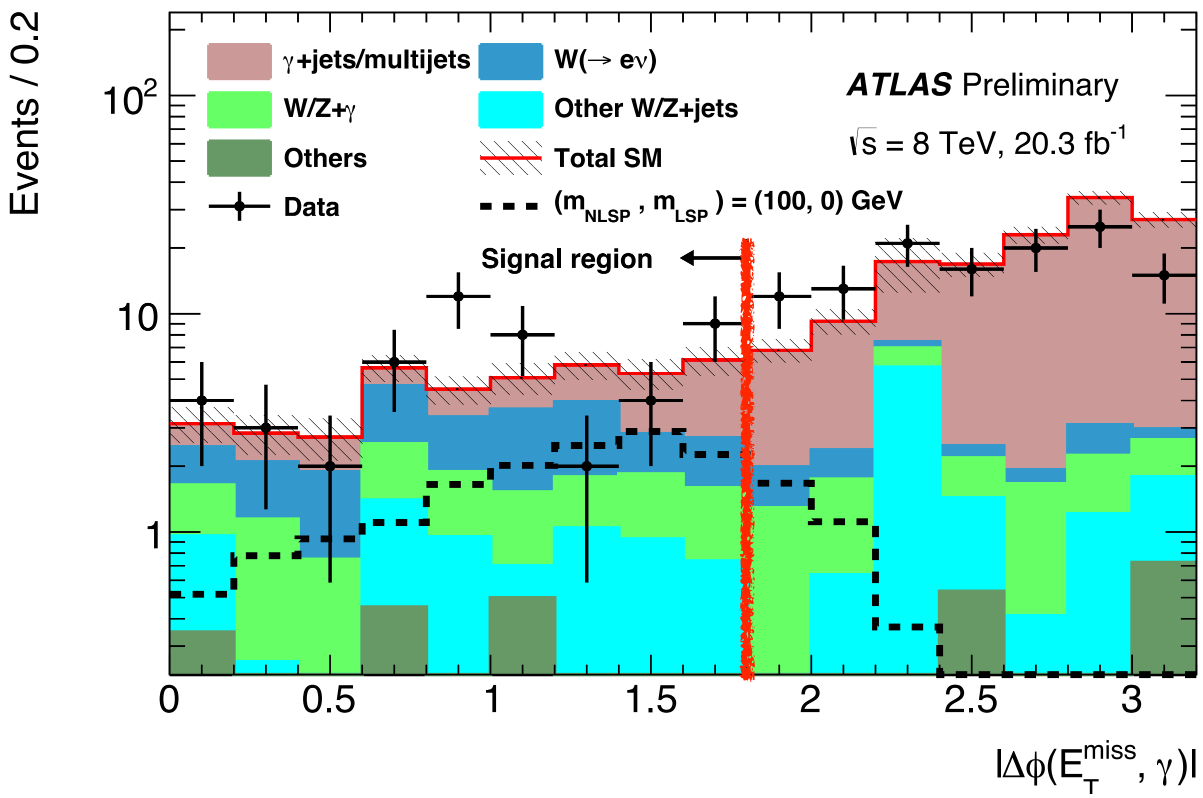
Non-SM branching

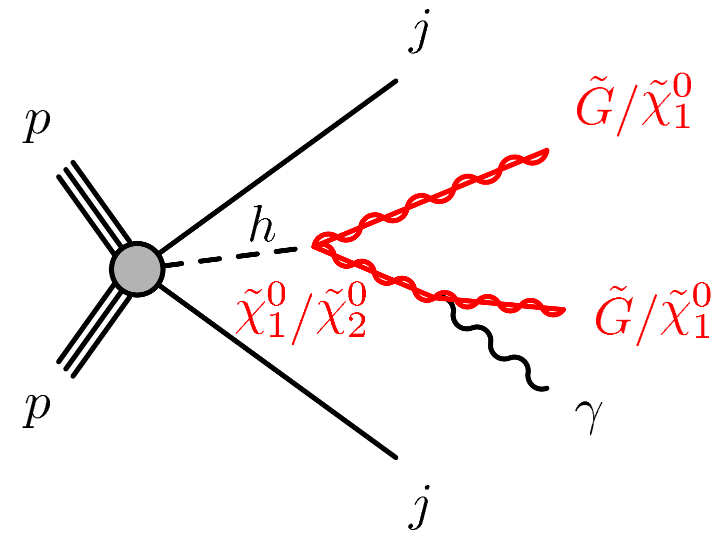
https://arxiv.org/abs/1606.02266

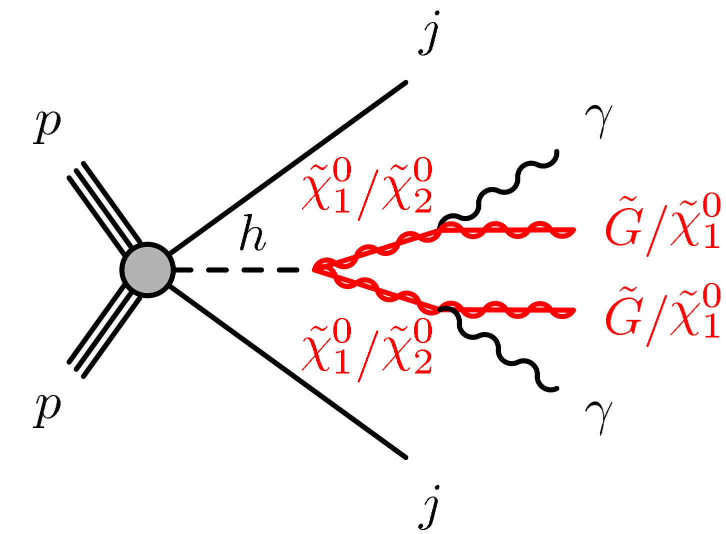
- ATLAS+CMS combination from 7 and 8 TeV data restrict non-SM Higgs decay fraction to **< 34%** with 95% confidence
  - Simultaneous fit to Z, W, t, b, and τ couplings, plus effective γ and gluon "couplings", using measured production cross sections × branching fractions
  - Assumes $|\kappa_W| \leq 1$ and $|\kappa_Z| \leq 1$, κ_W and κ_Z have the same sign

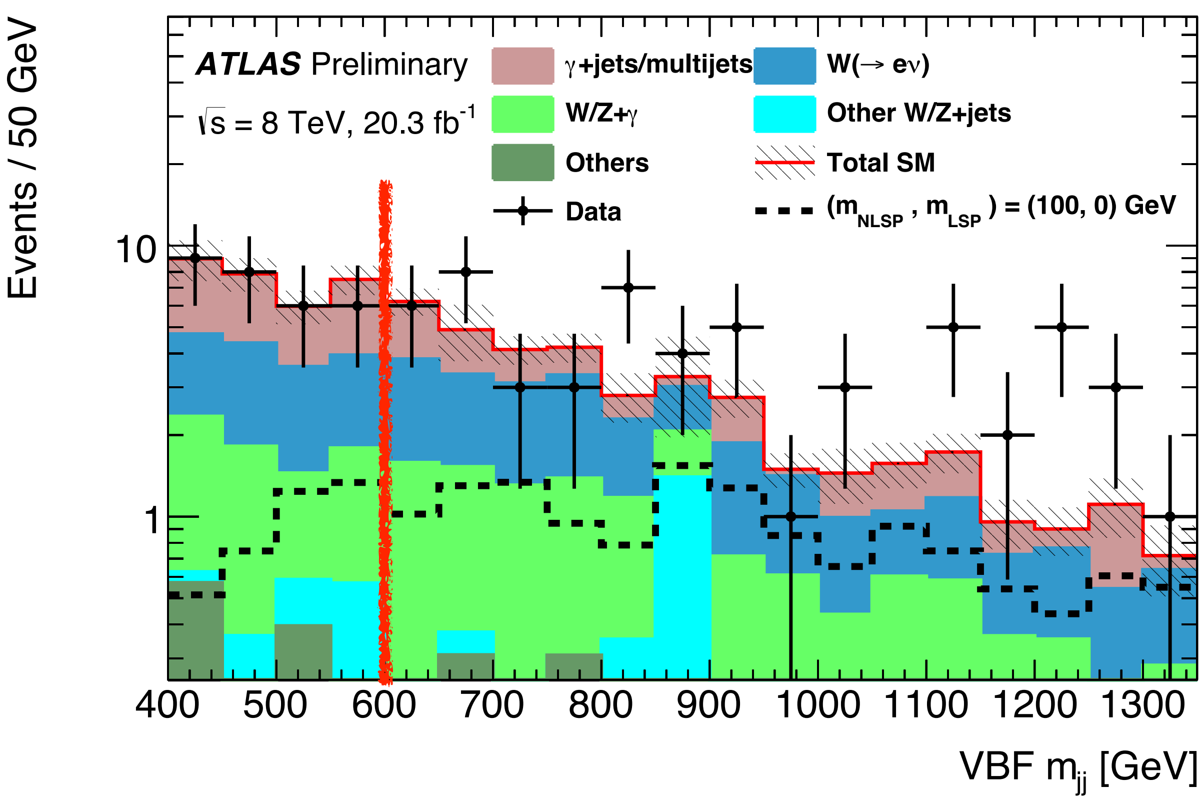


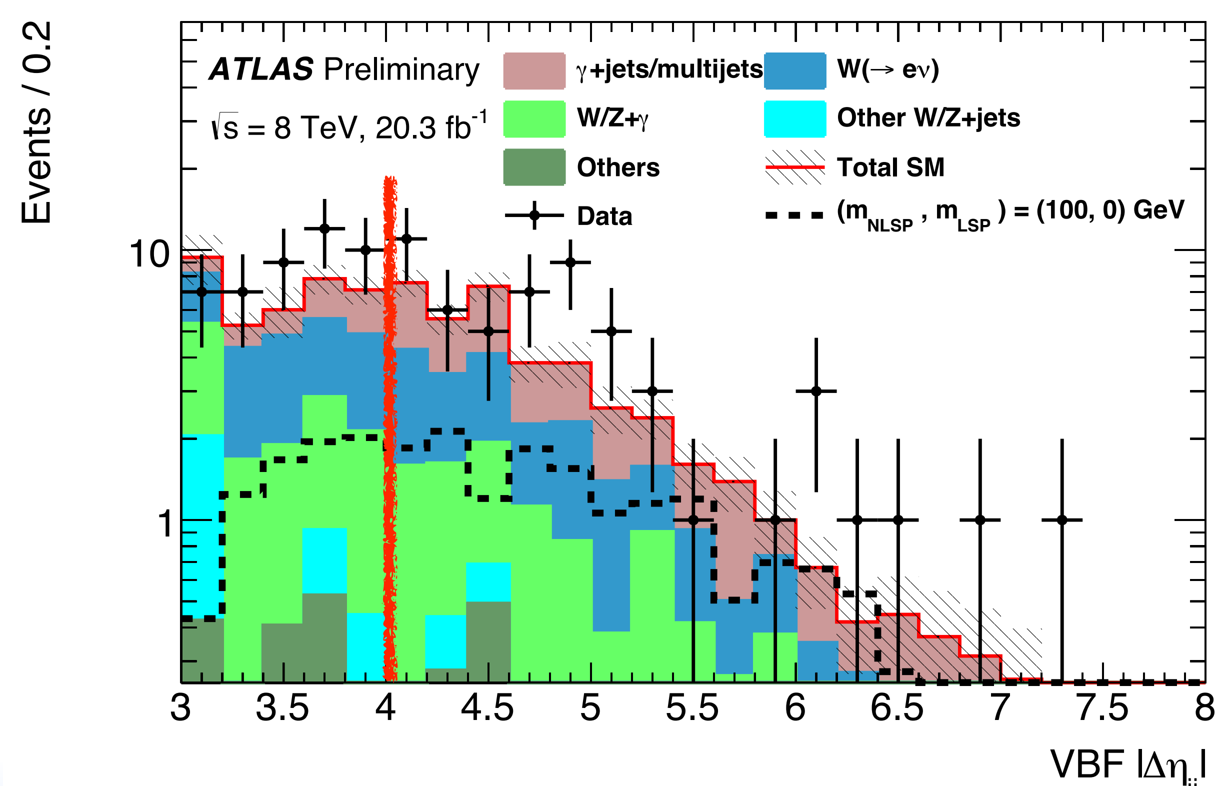
H→Gχ / χχ→GGγ(γ) in ATLAS



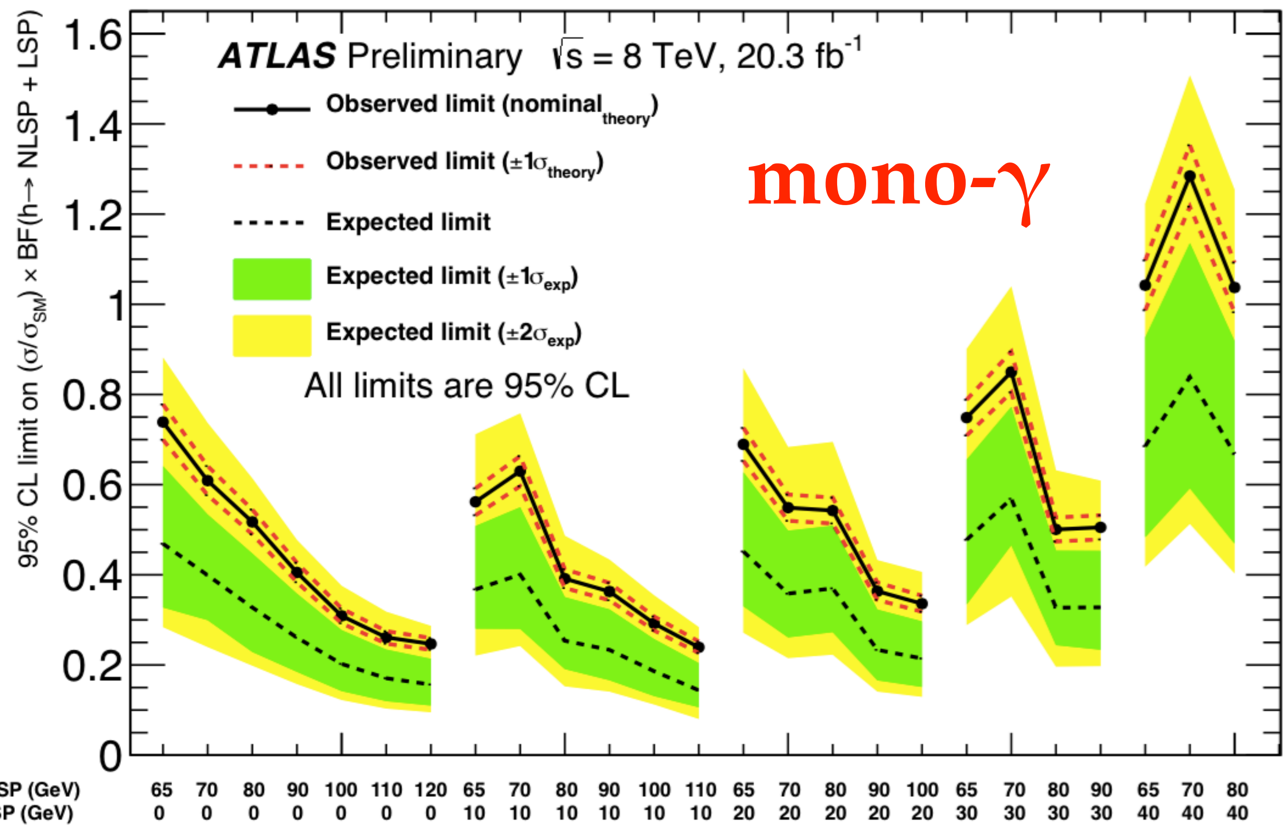


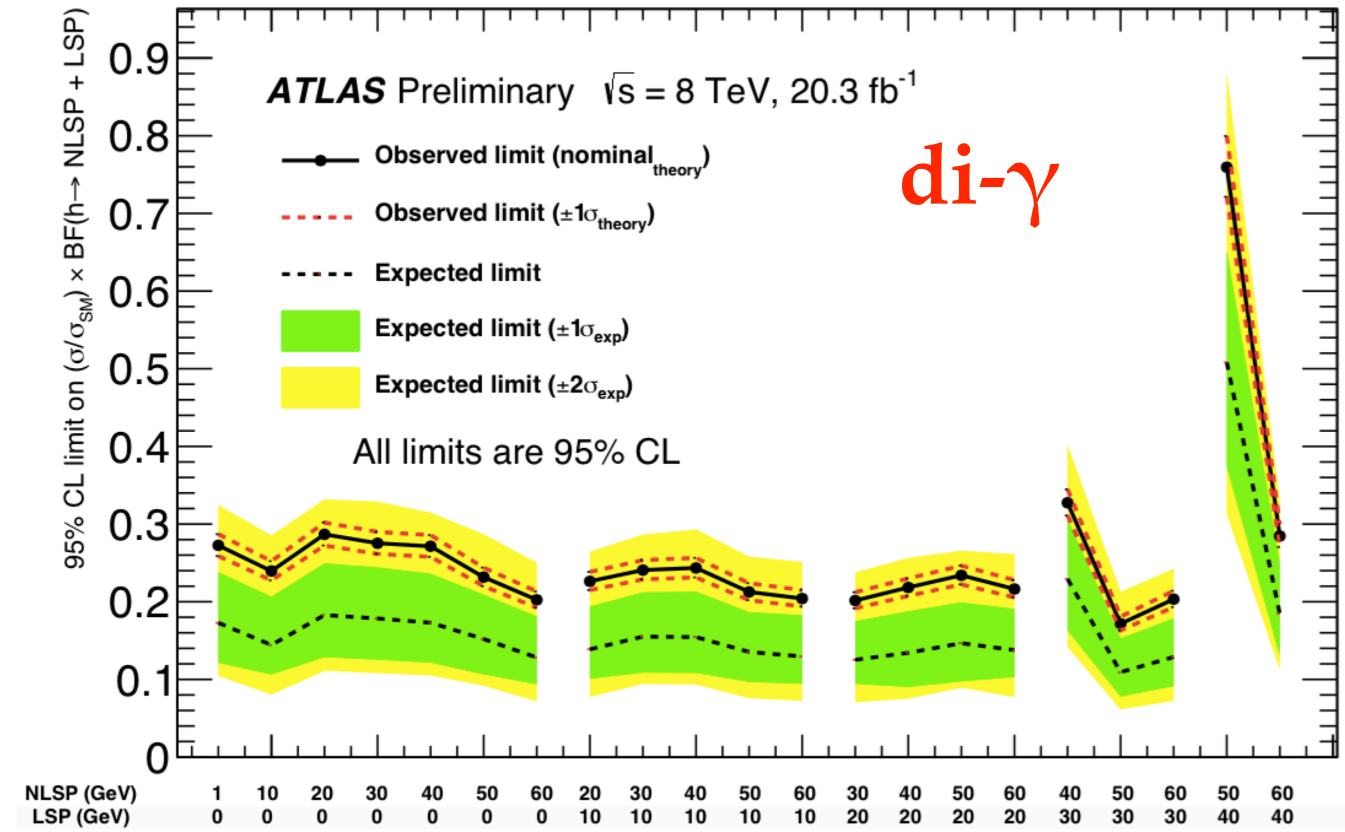






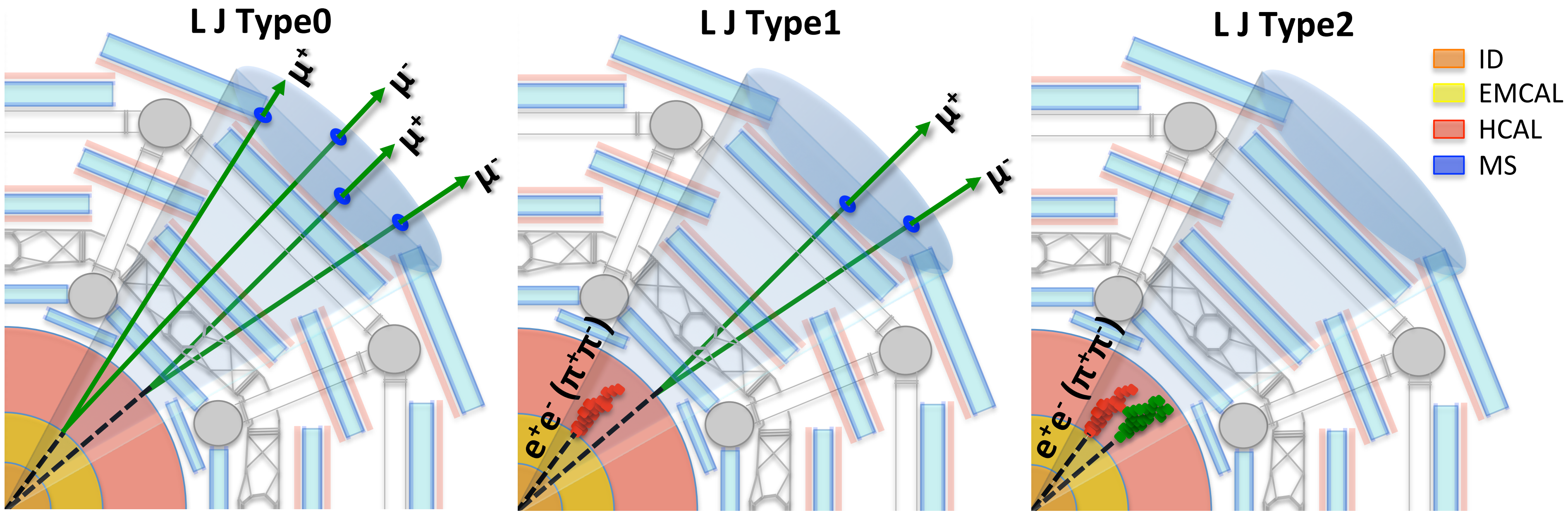
H→Gχ / χχ→GGγ(γ) in ATLAS

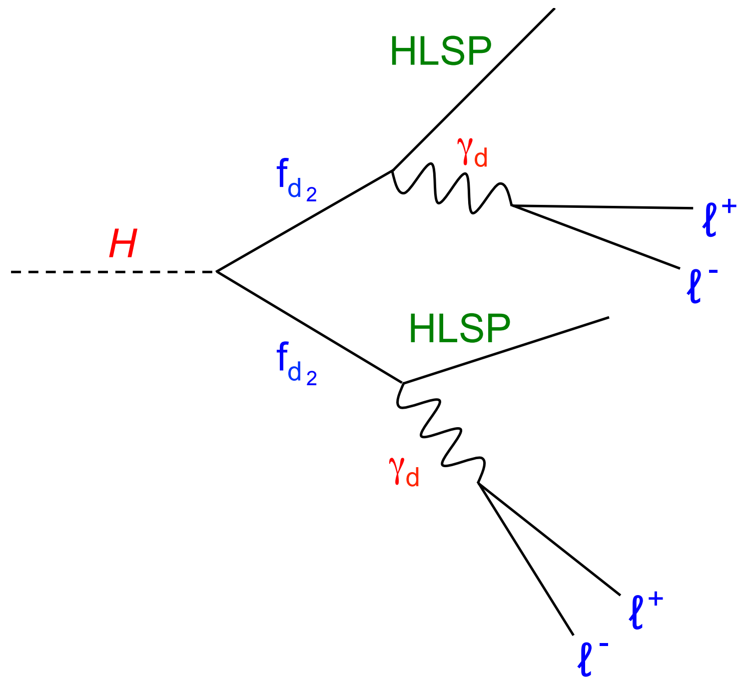




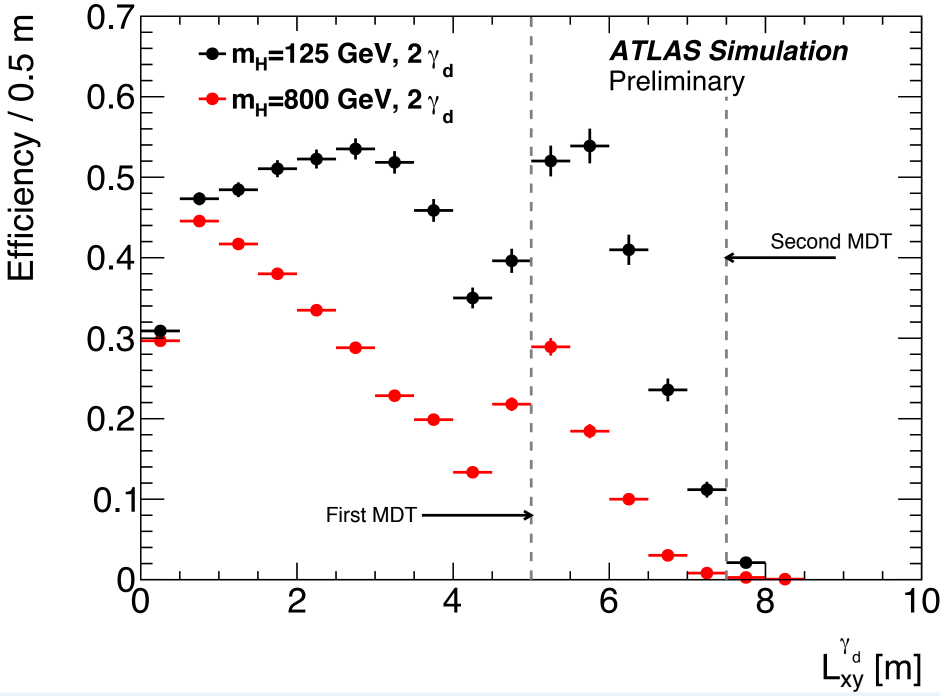
- Primarily target VBF production with γ+MET trigger (40+60 GeV)

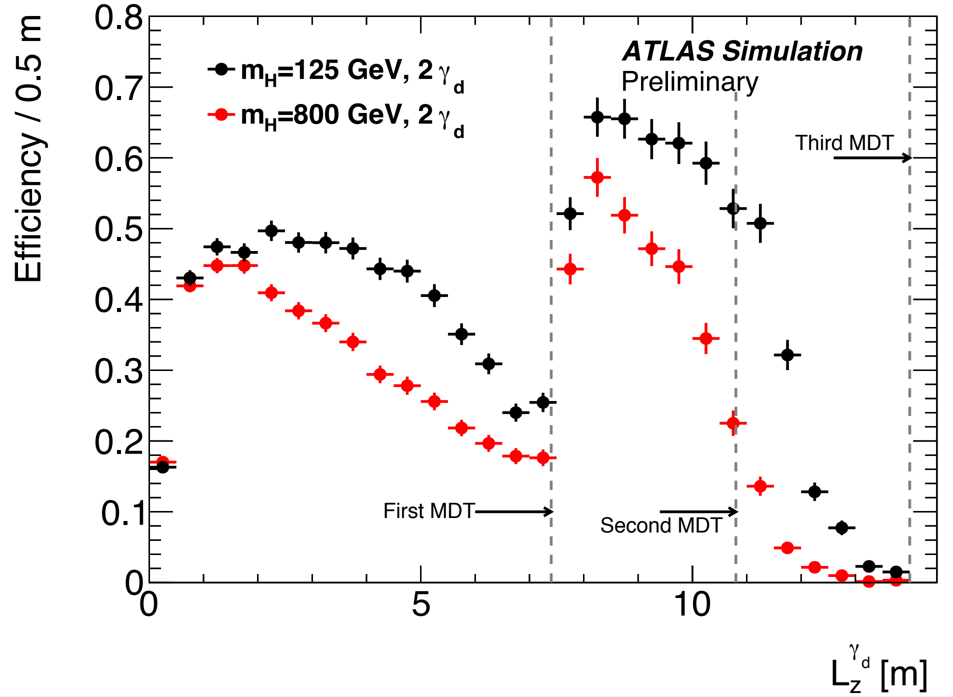
H→$f_d f_d$→4(8)ℓ+2(4) *LSP* in ATLAS

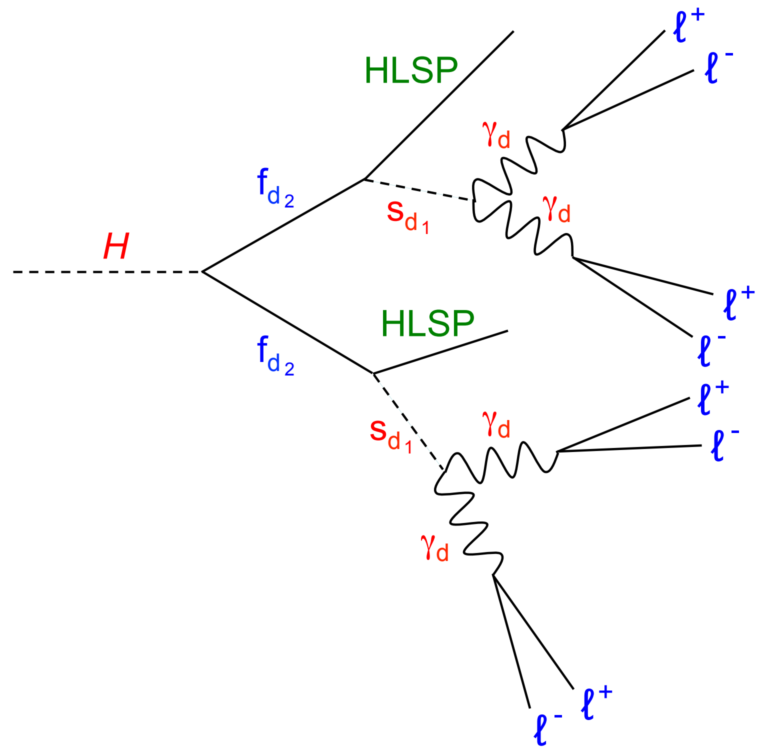




- Search for collimated lepton-jets, ΔR < 0.5
  - **Displaced from vertex** by up to 163 mm







$H \to f_d f_d \to 4(8)\ell + 2(4)$ *LSP* in ATLAS

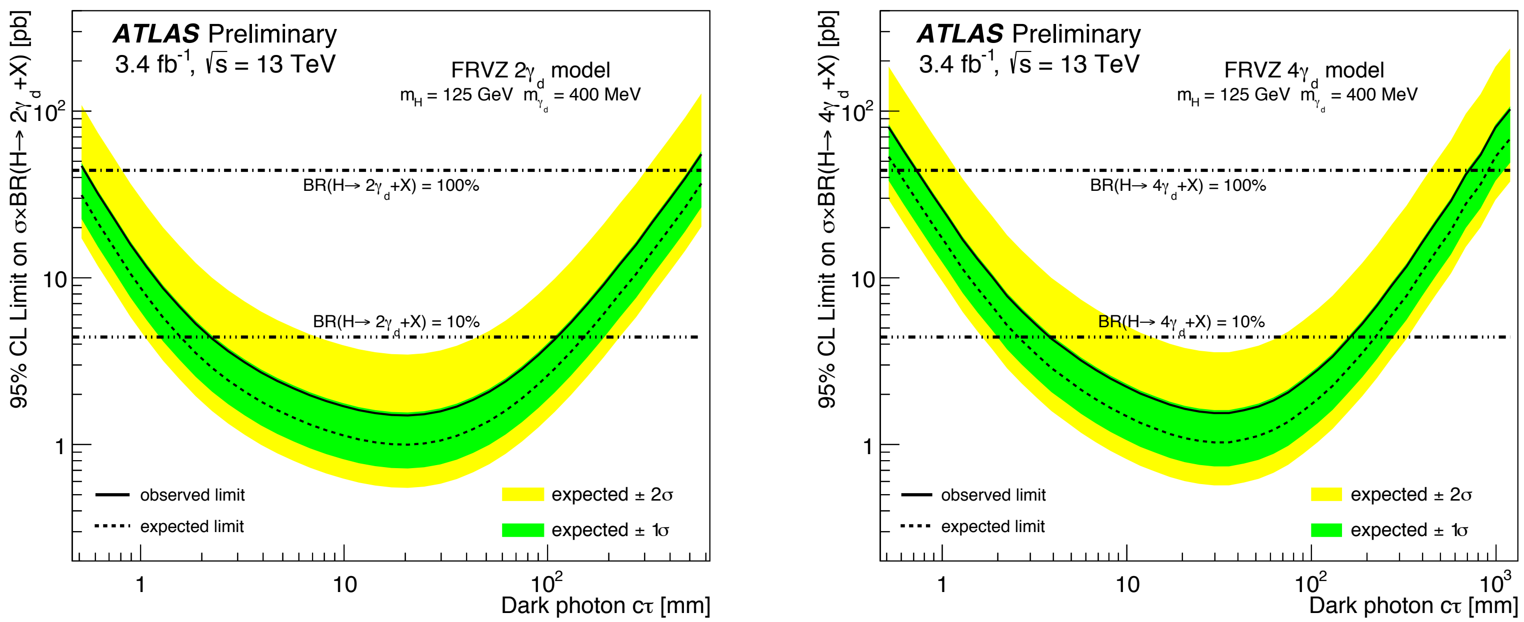
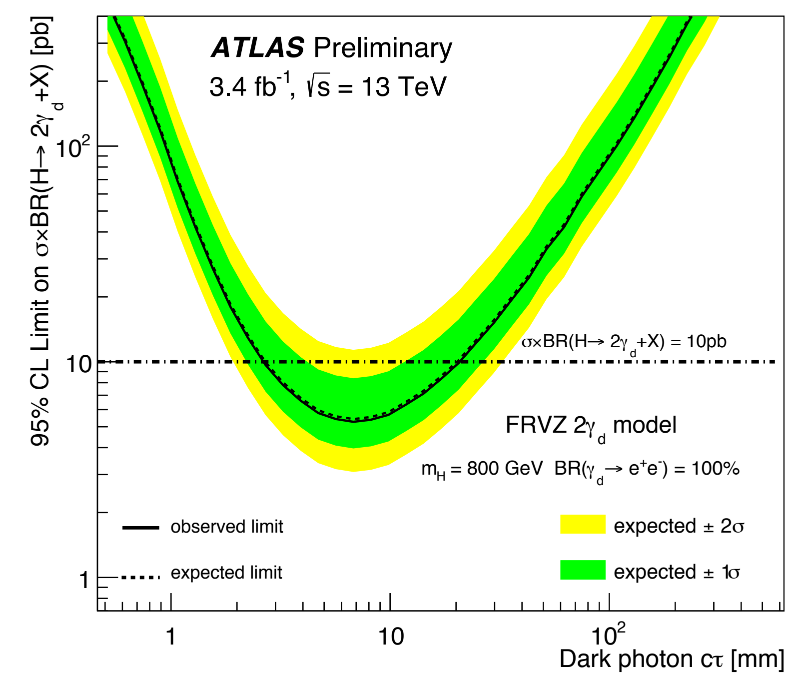


Figure 10: The 95% upper limits on the $\sigma\times$BR for the FRVZ 125 GeV Higgs $\to 2\gamma_d + X$ (left) and Higgs $\to 4\gamma_d + X$ (right) benchmark models as a function of the γ_d lifetime ($c\tau$). The horizontal lines correspond to $\sigma\times$BR for two values of the BR of the Higgs boson decay to dark photons.



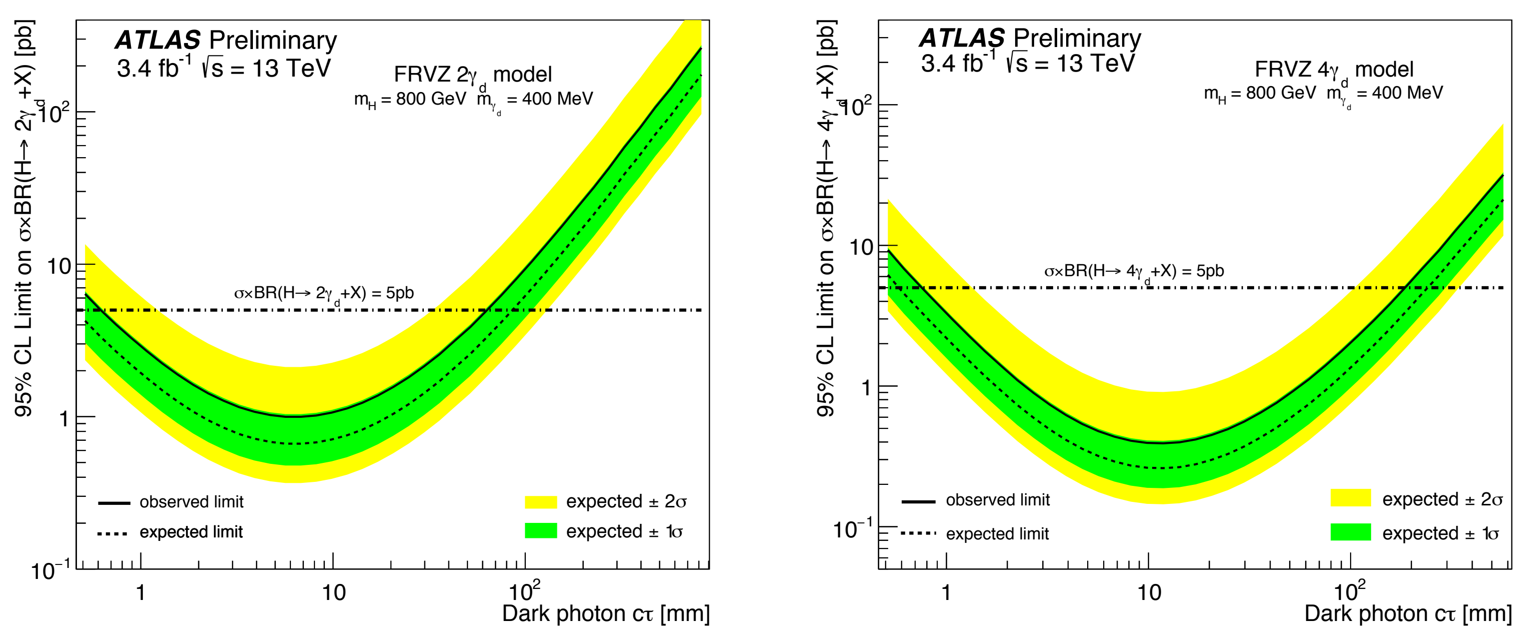
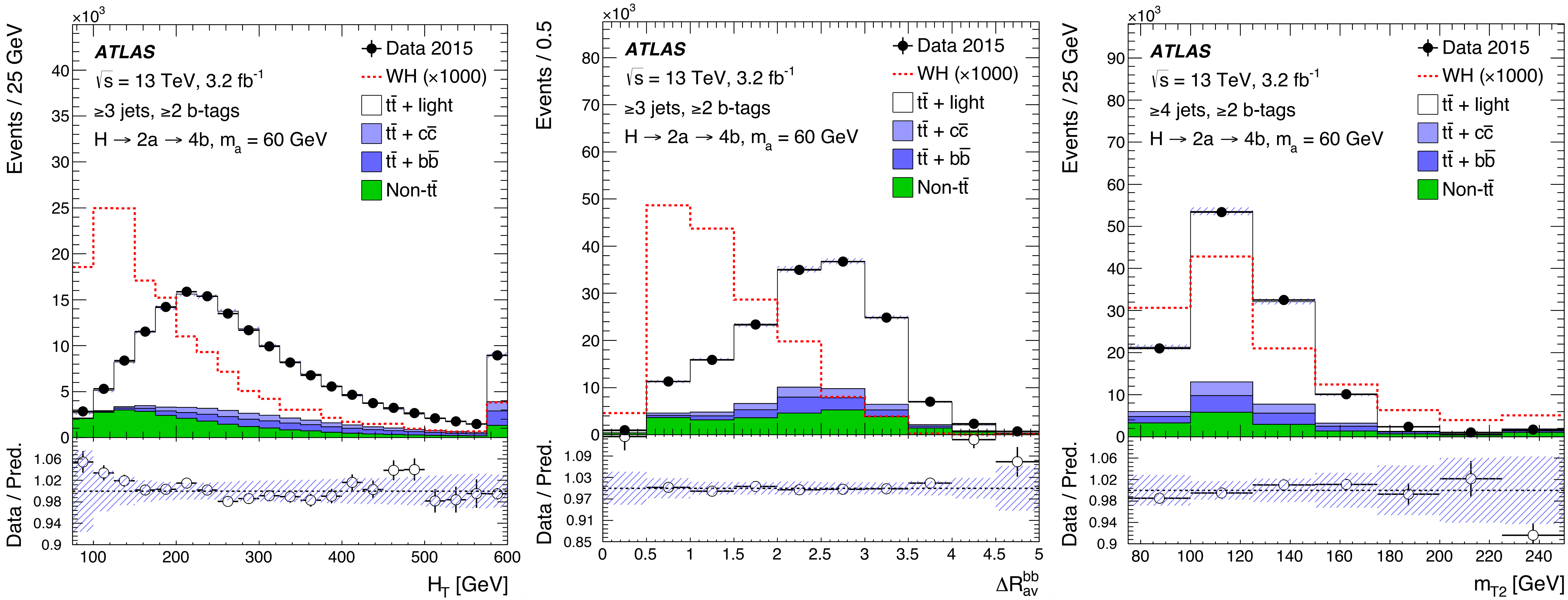


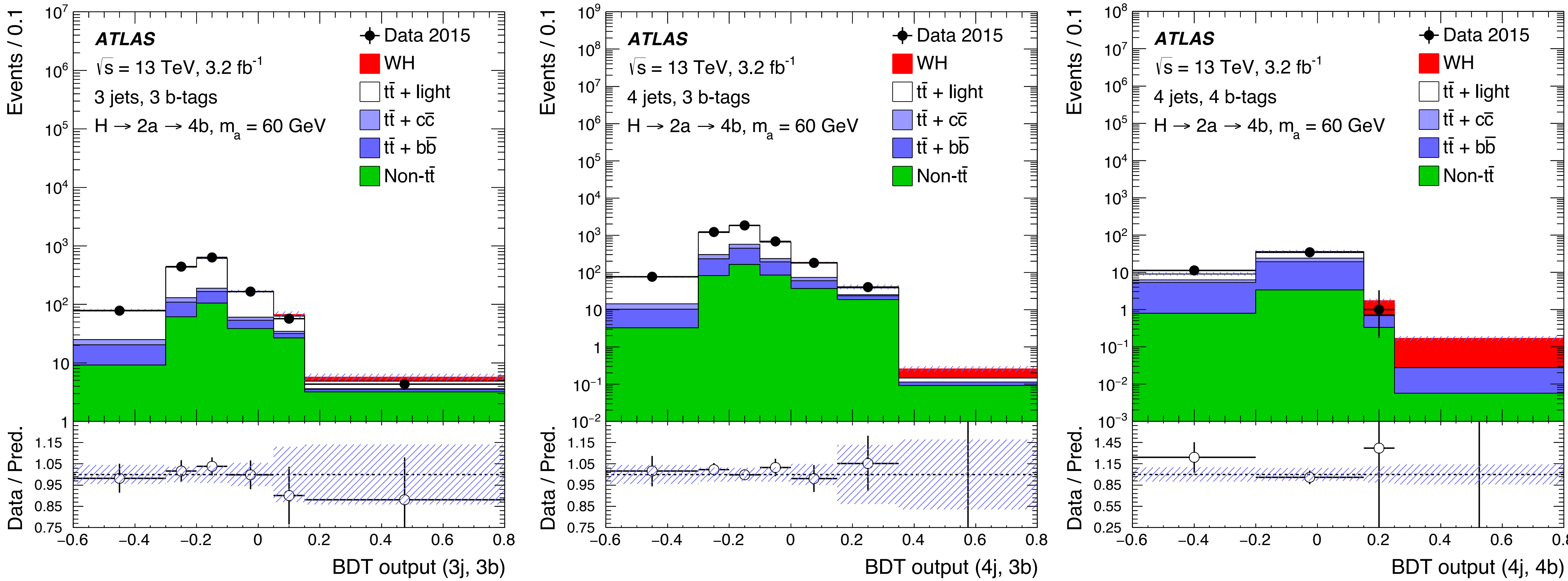
Figure 11: The 95% upper limits on the $\sigma\times$BR for the FRVZ 800 GeV Higgs $\to 2\gamma_d + X$ benchmark model as a function of the γ_d lifetime ($c\tau$). The horizontal lines correspond to a $\sigma\times$BR of 5 pb.

H→aa→4b in ATLAS

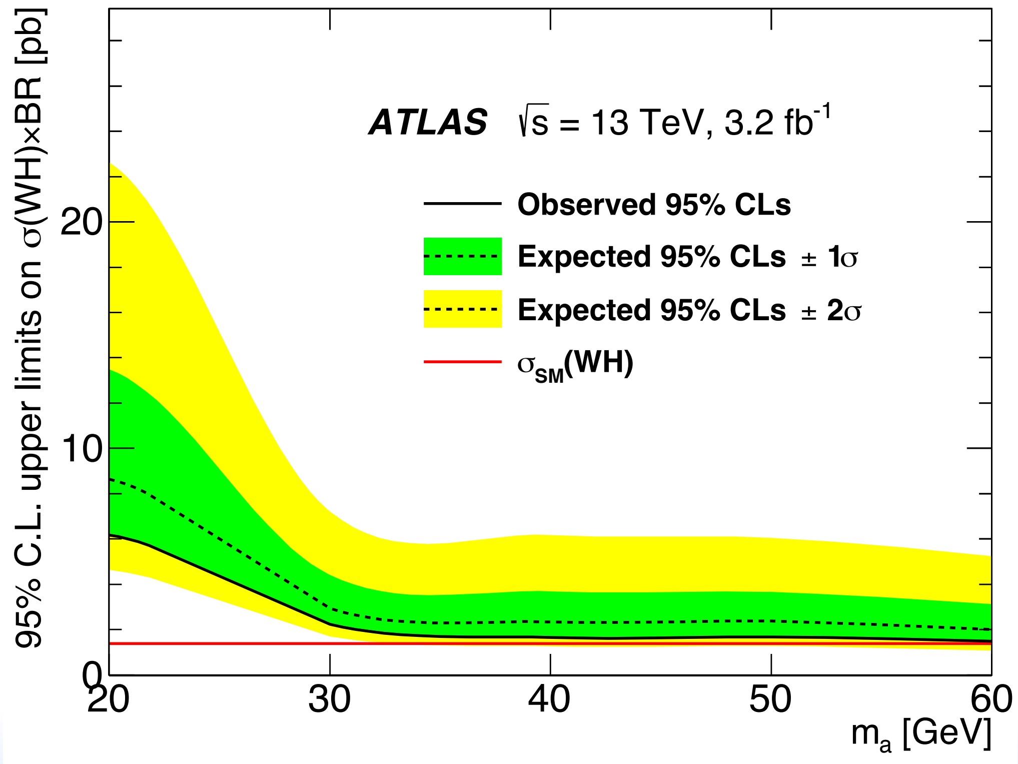
Region		m_{bbb}	m_{bbbb}	$\Delta m^{bb}_{\mathrm{min}}$	H_{T}	p^{W}_{T}	$\Delta R^{bb}_{\mathrm{av}}$	$\Delta R^{\ell b}_{\mathrm{min}}$	m_{bbj}	m_{T2}
Signal	(3j, 3b)	✓			✓	✓	✓	✓		
	(4j, 3b)	✓			✓	✓	✓		✓	
	(4j, 4b)		✓	✓	✓		✓			✓
Control					✓					



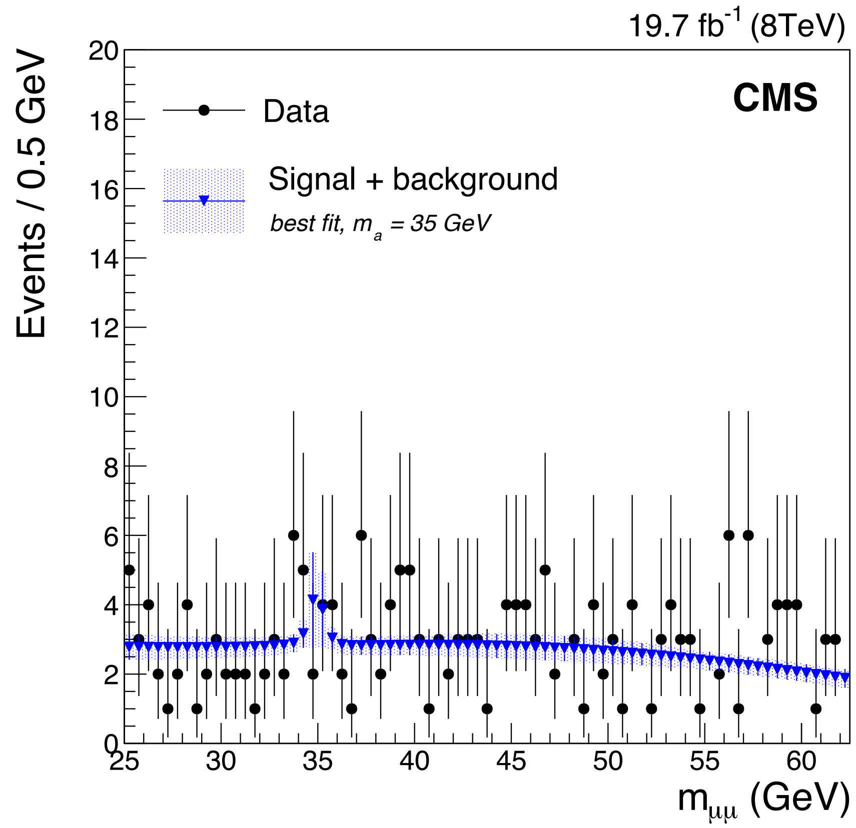
H→aa→4b in ATLAS

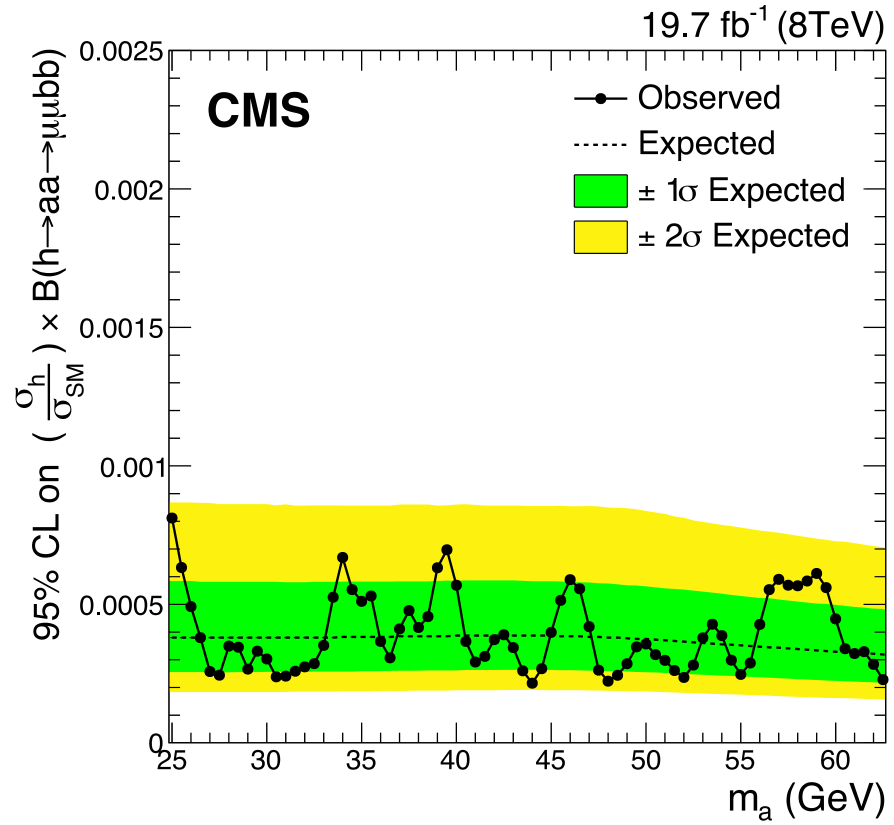


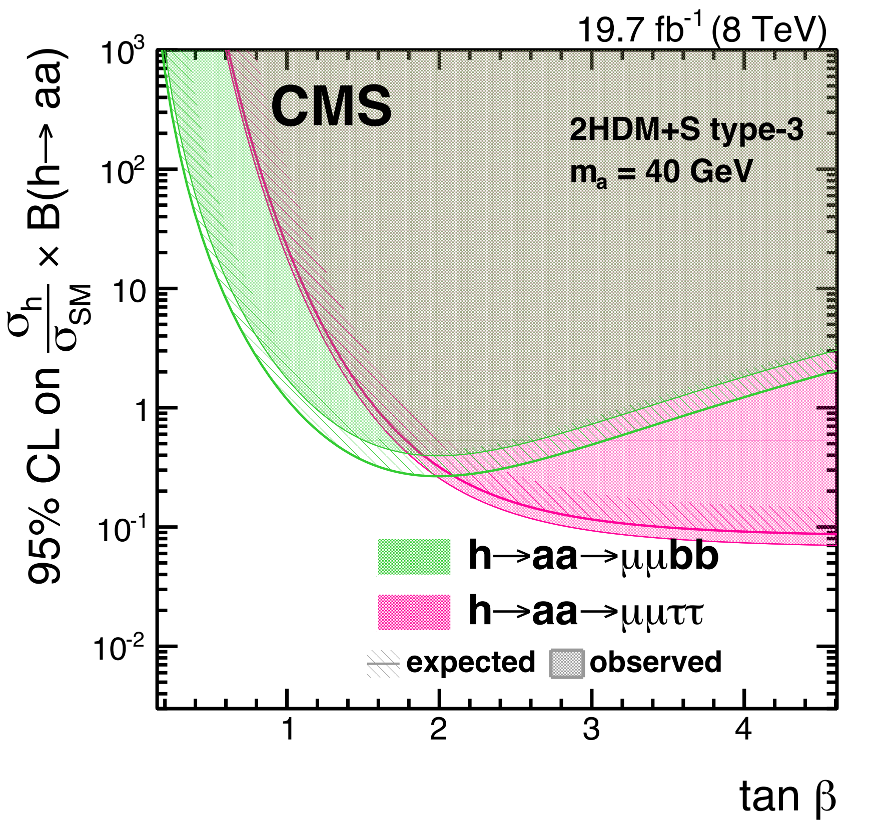
Process	(3j, 3b)	(4j, 3b)	(4j, 4b)
$t\bar{t}$ + light	1089 ± 76	2940 ± 180	53 ± 16
$t\bar{t} + c\bar{c}$	70 ± 28	280 ± 110	21 ± 11
$t\bar{t} + b\bar{b}$	172 ± 55	610 ± 160	74 ± 15
Total	1640 ± 58	4270 ± 130	165 ± 15
Data	1646	4302	166
$WH, H \to 2a \to 4b$			
m_a = 60 GeV	10 ± 2	9 ± 1	3 ± 1
m_a = 40 GeV	11 ± 2	10 ± 2	2 ± 1
m_a = 20 GeV	6 ± 1	5 ± 1	0.7 ± 0.2

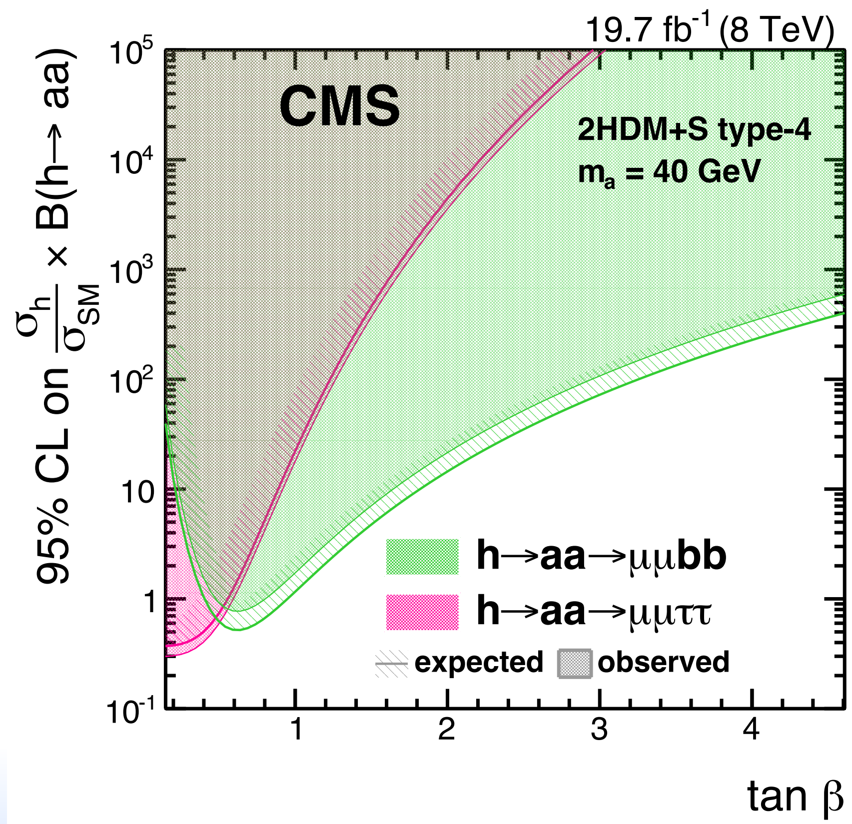


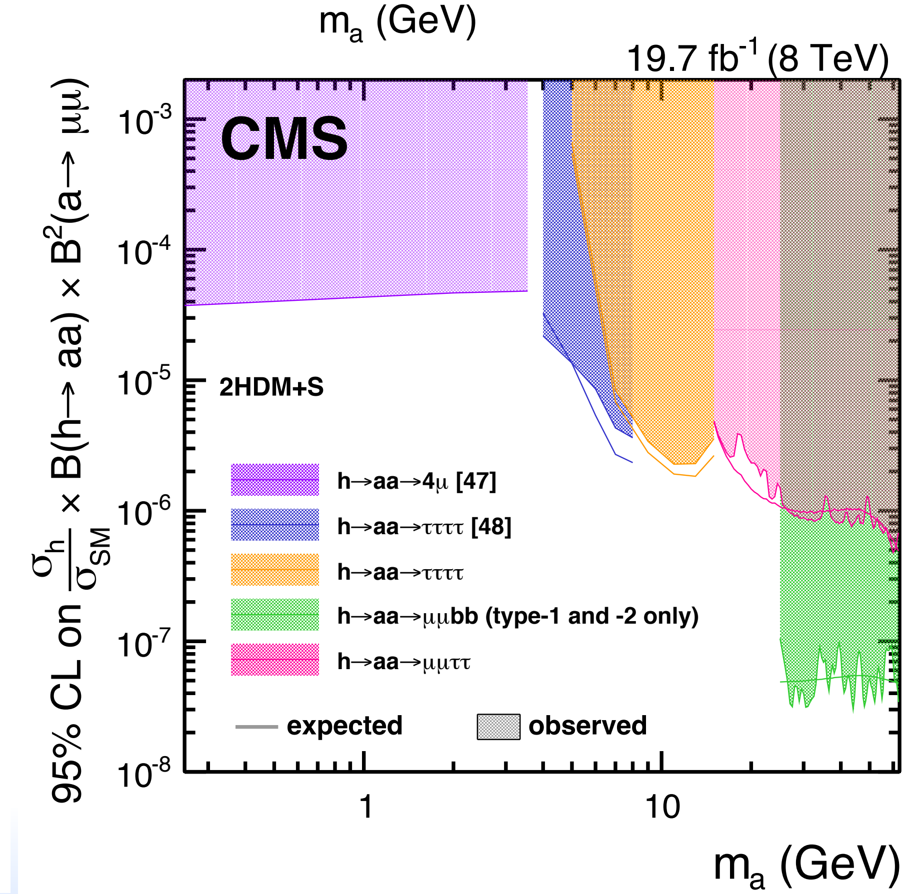
H→aa→μμbb in CMS



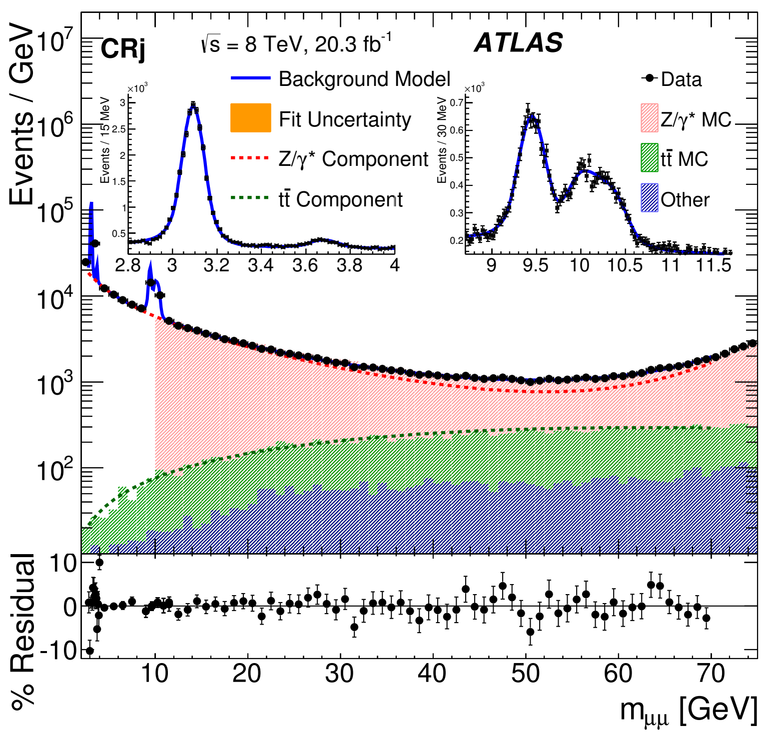


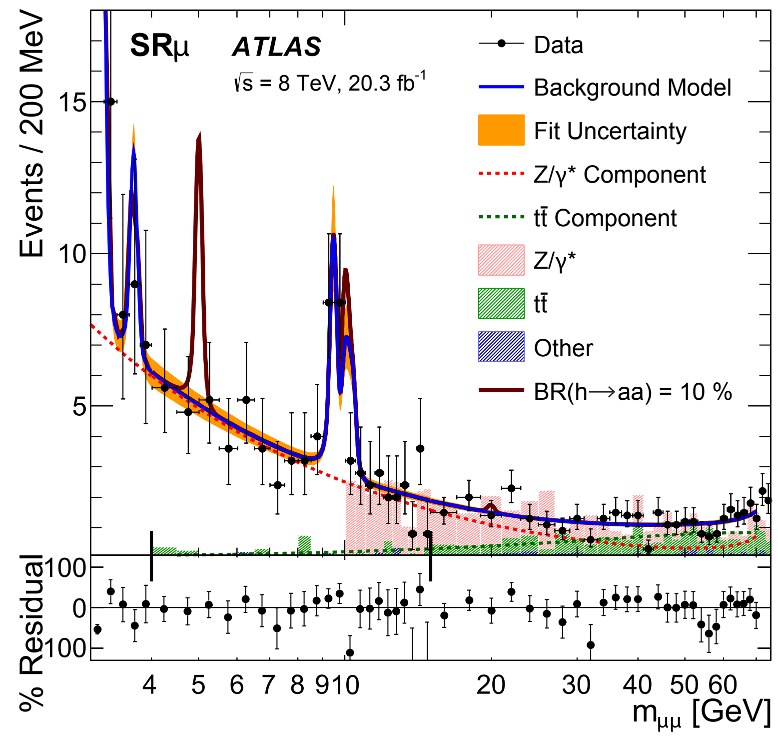


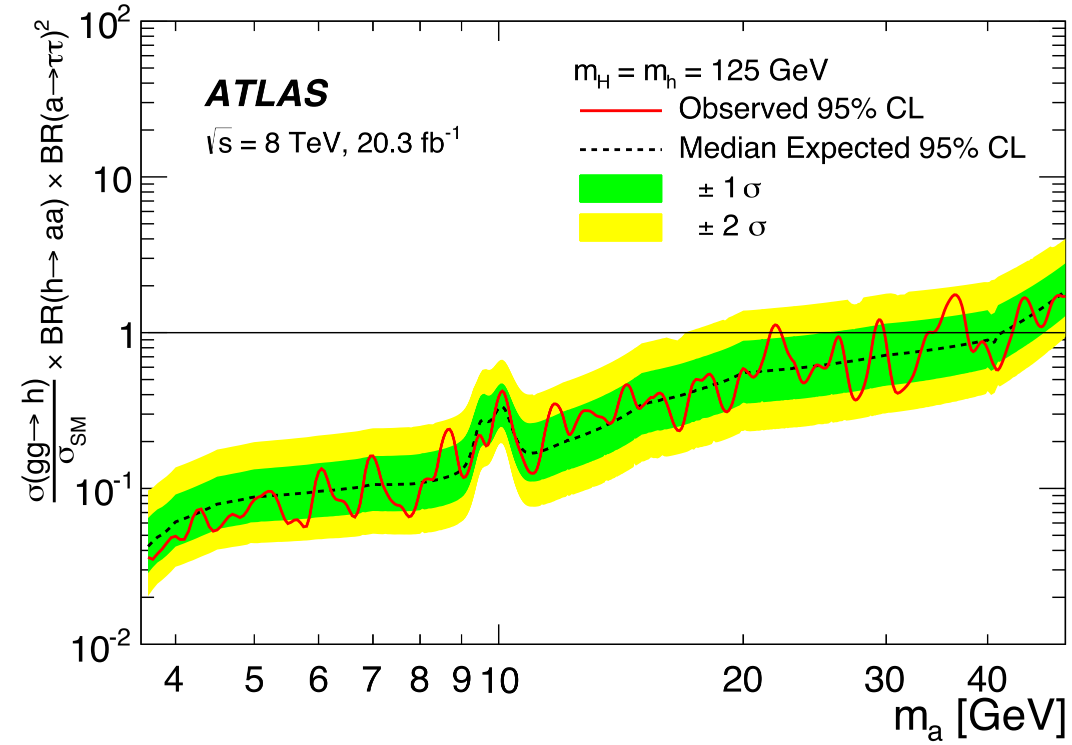


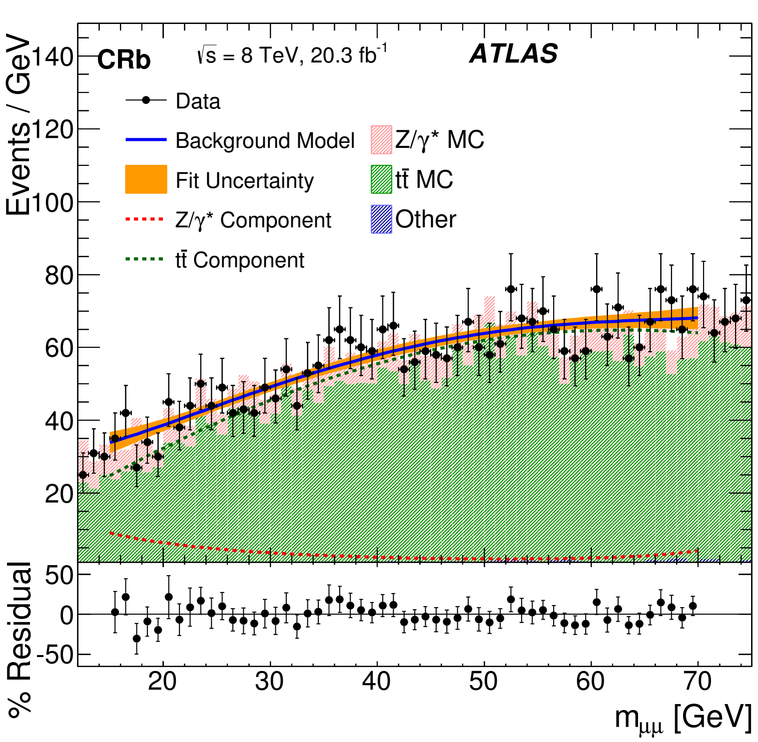


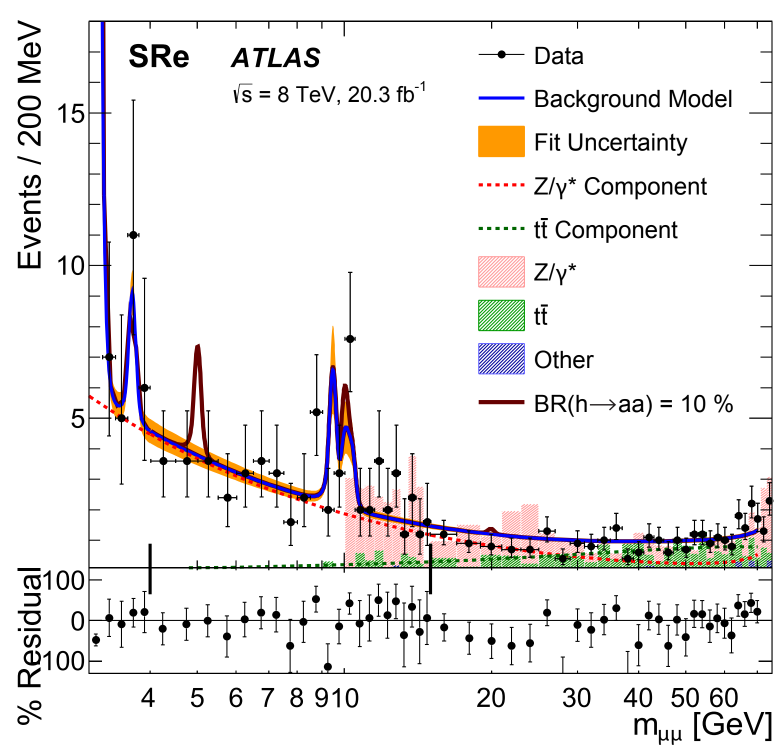
H→aa→μμττ in ATLAS

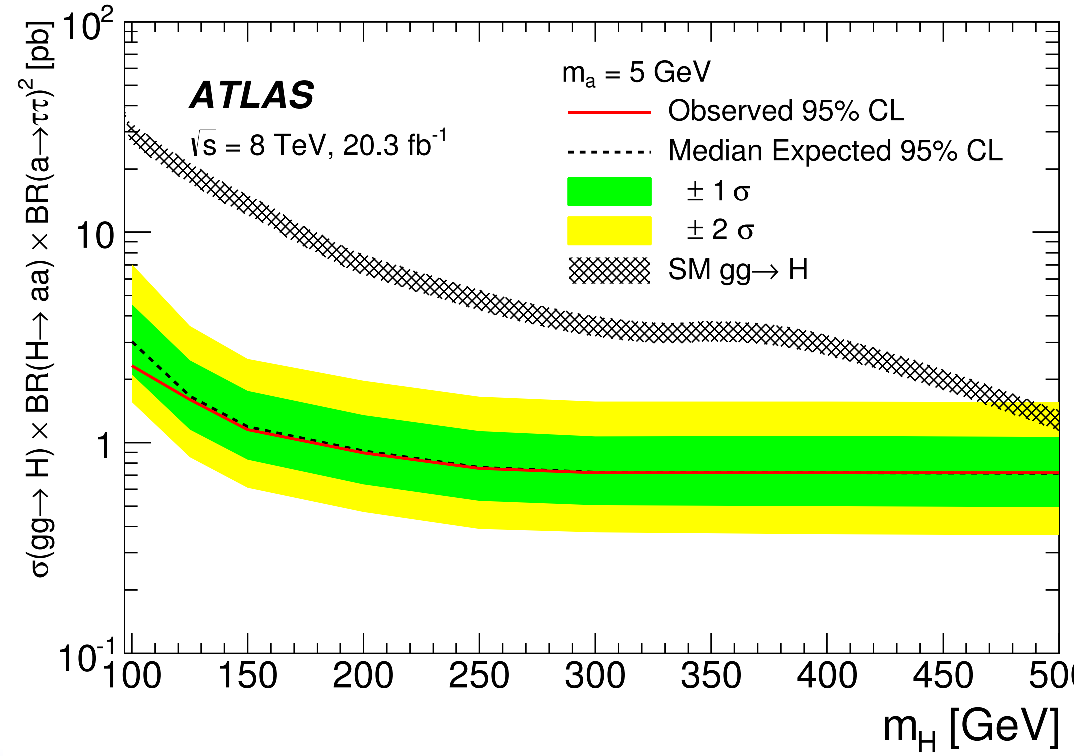






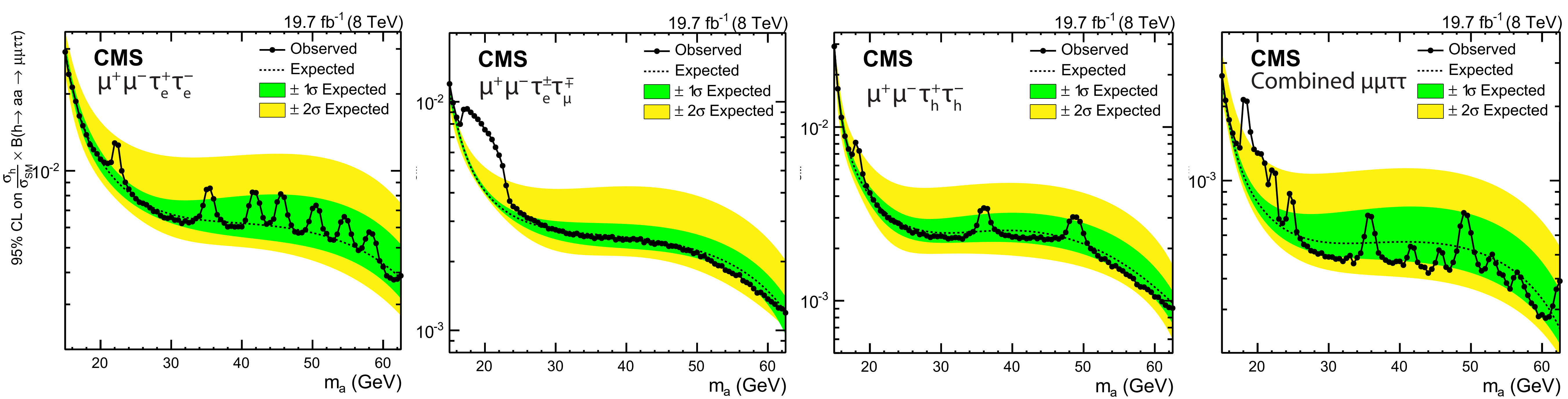




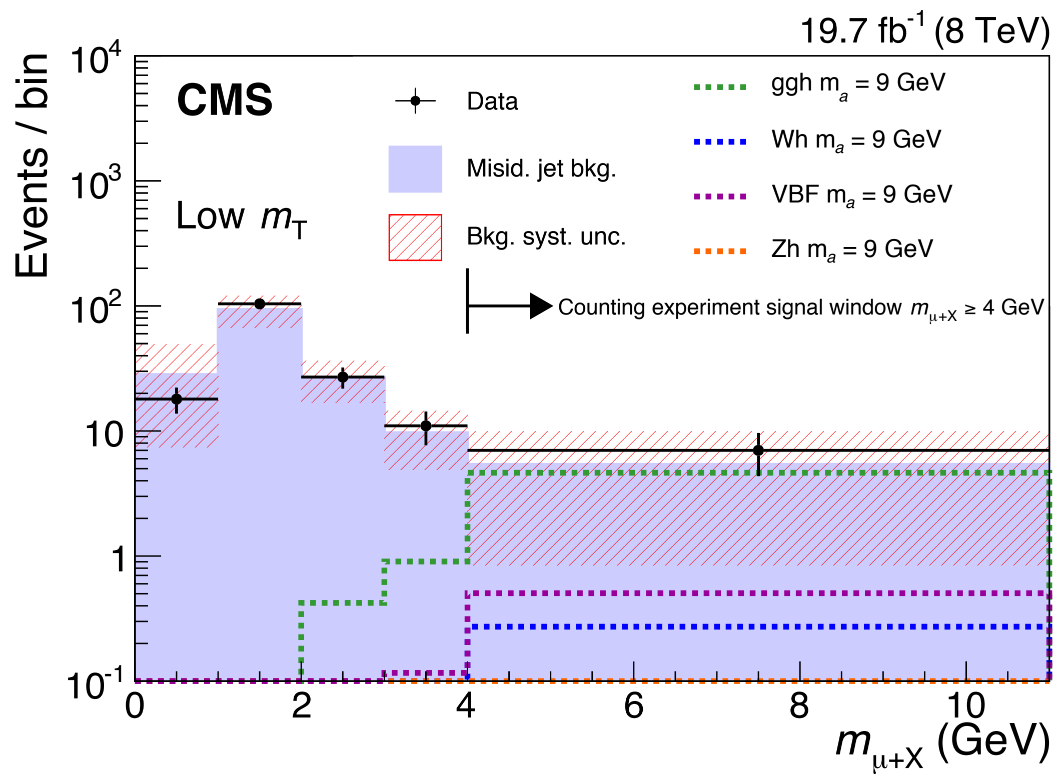


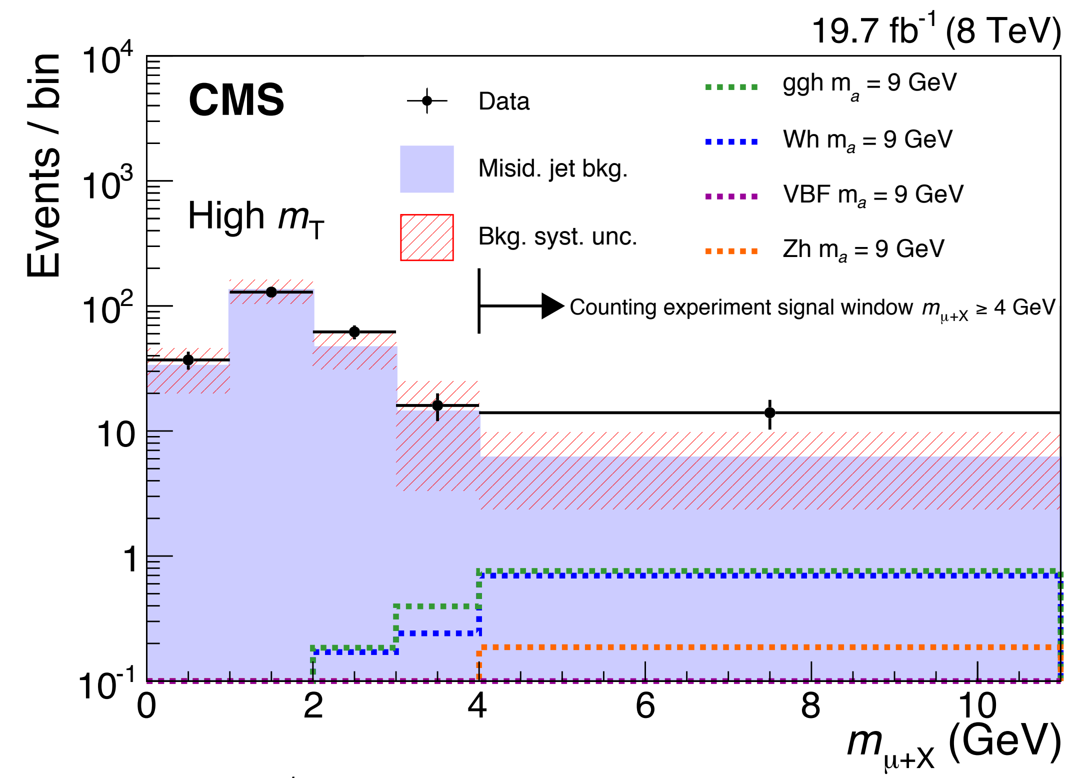
H→aa→μμττ in CMS

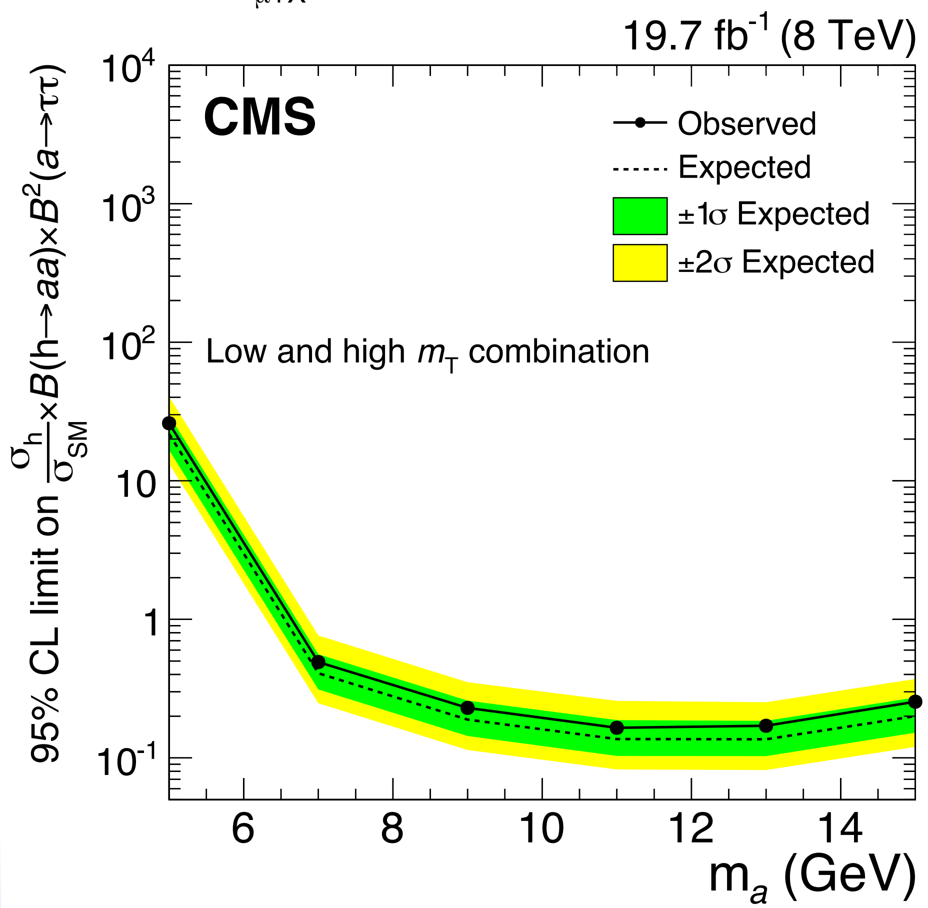
	Signal		Backgrounds			Obs.
	$m_a = 20\,GeV$	$m_a = 60\,GeV$	ZZ	Reducible	Total	
$\mu^+\mu^-\tau_e^+\tau_e^-$	0.20±0.02	0.58±0.06	4.71±0.47	2.56±1.06	7.27±1.16	8
$\mu^+\mu^-\tau_e^\pm\tau_\mu^\mp$	0.58±0.08	1.42±0.16	0.10±0.01	1.68±0.70	1.78±0.70	2
$\mu^+\mu^-\tau_e^\pm\tau_h{}^\mp$	0.74±0.08	2.02±0.20	0.16±0.02	5.66±1.48	5.82±1.48	5
$\mu^+\mu^-\tau_\mu^\pm\tau_h{}^\mp$	0.96±0.10	2.30±0.22	0.13±0.02	0.91±0.28	1.14±0.29	1
$\mu^+\mu^-\tau_h{}^+\tau_h{}^-$	0.60±0.06	1.90±0.18	0.06±0.02	4.64±0.94	4.70±0.94	3
Combined	3.08±0.31	8.22±0.82	5.09±0.39	15.47±2.41	20.71±2.23	19



H→aa→ττττ in CMS

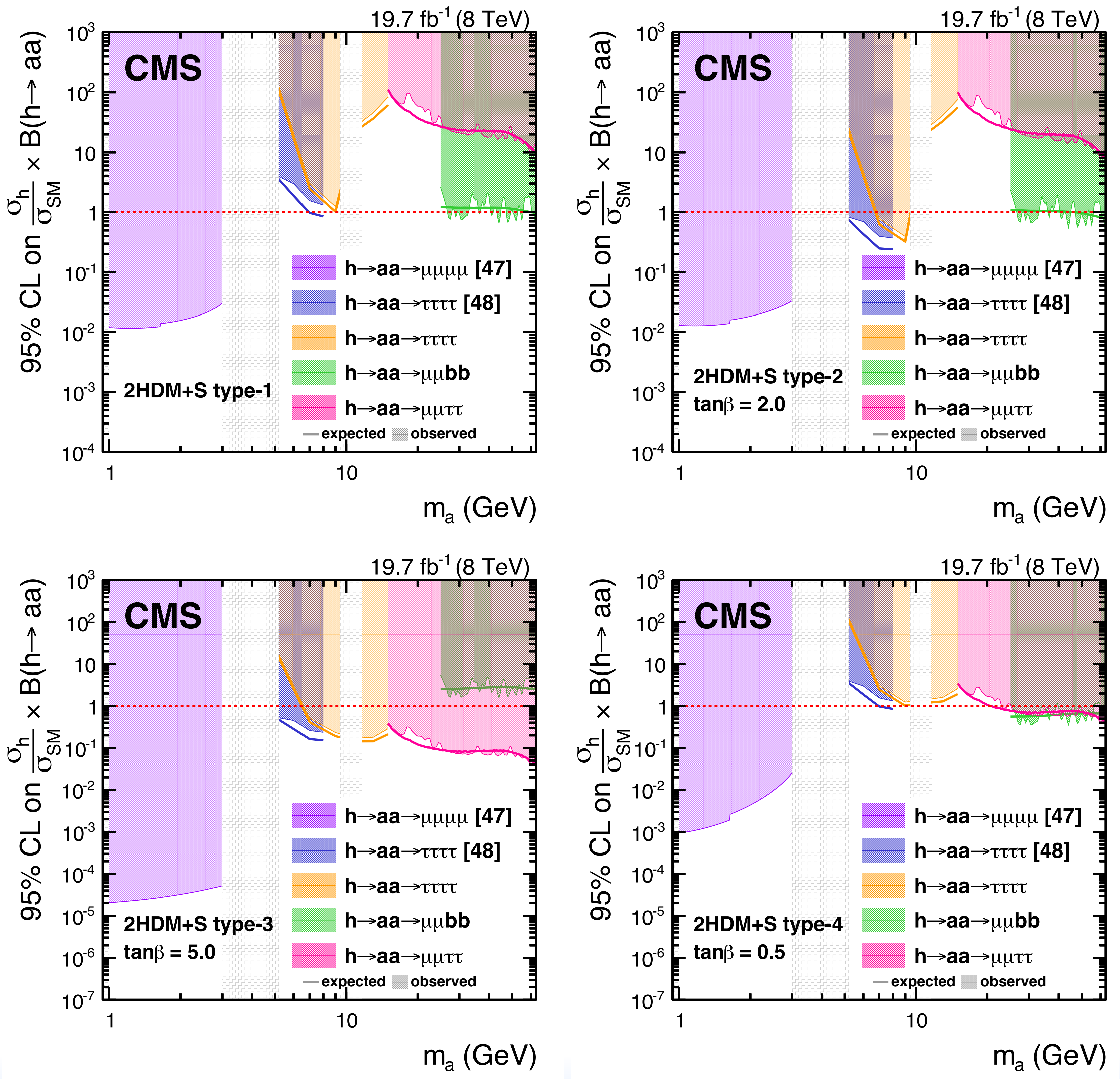






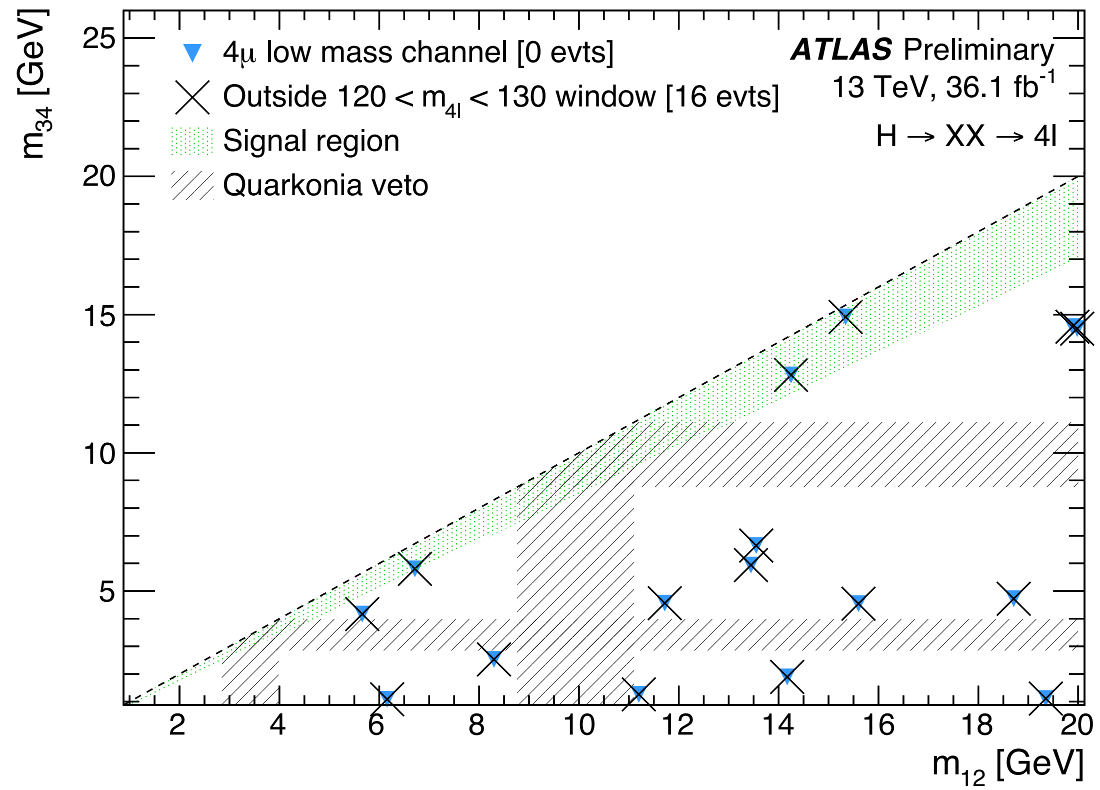
Andrew Brinkerhoff

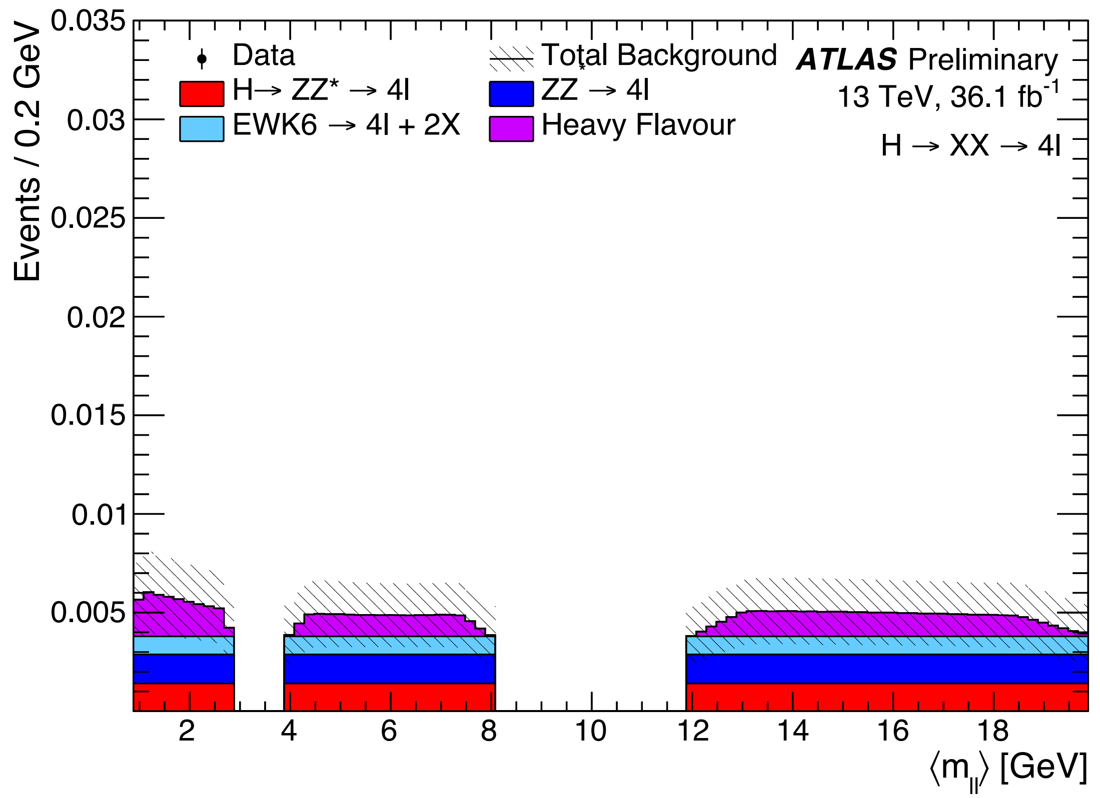
H→aa, a→μμ/ττ/bb in CMS

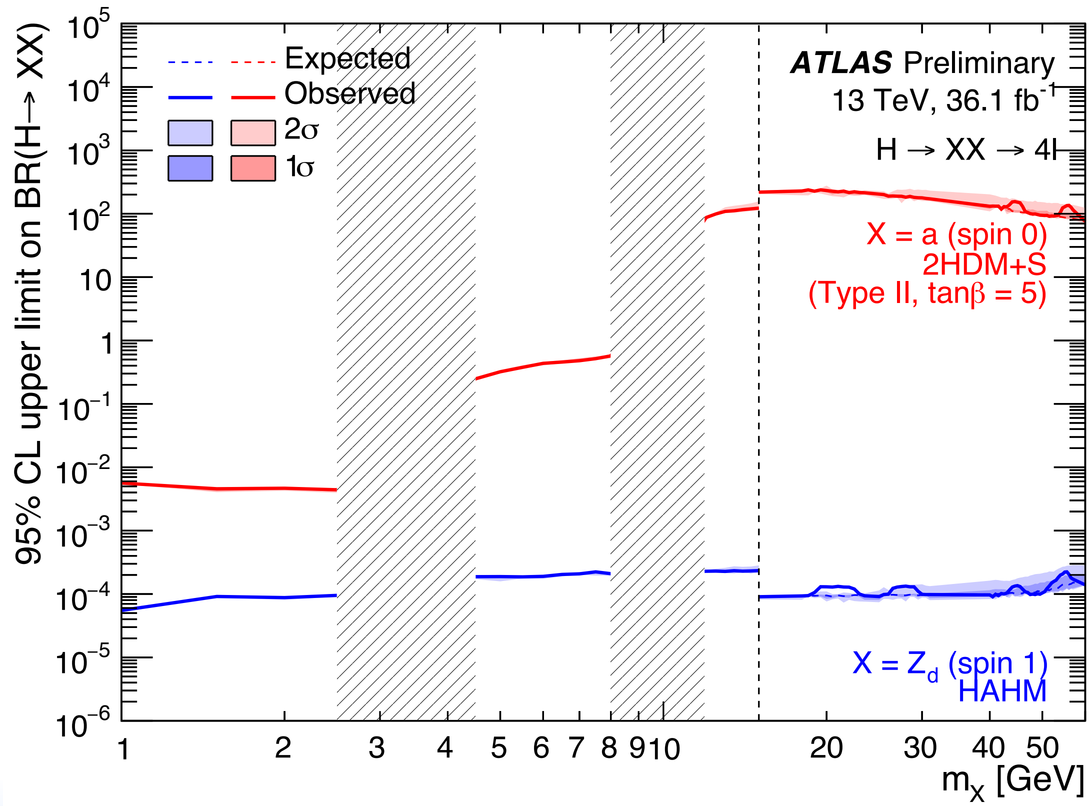


H→aa / Z_dZ_d→4μ (low mass, ATLAS)

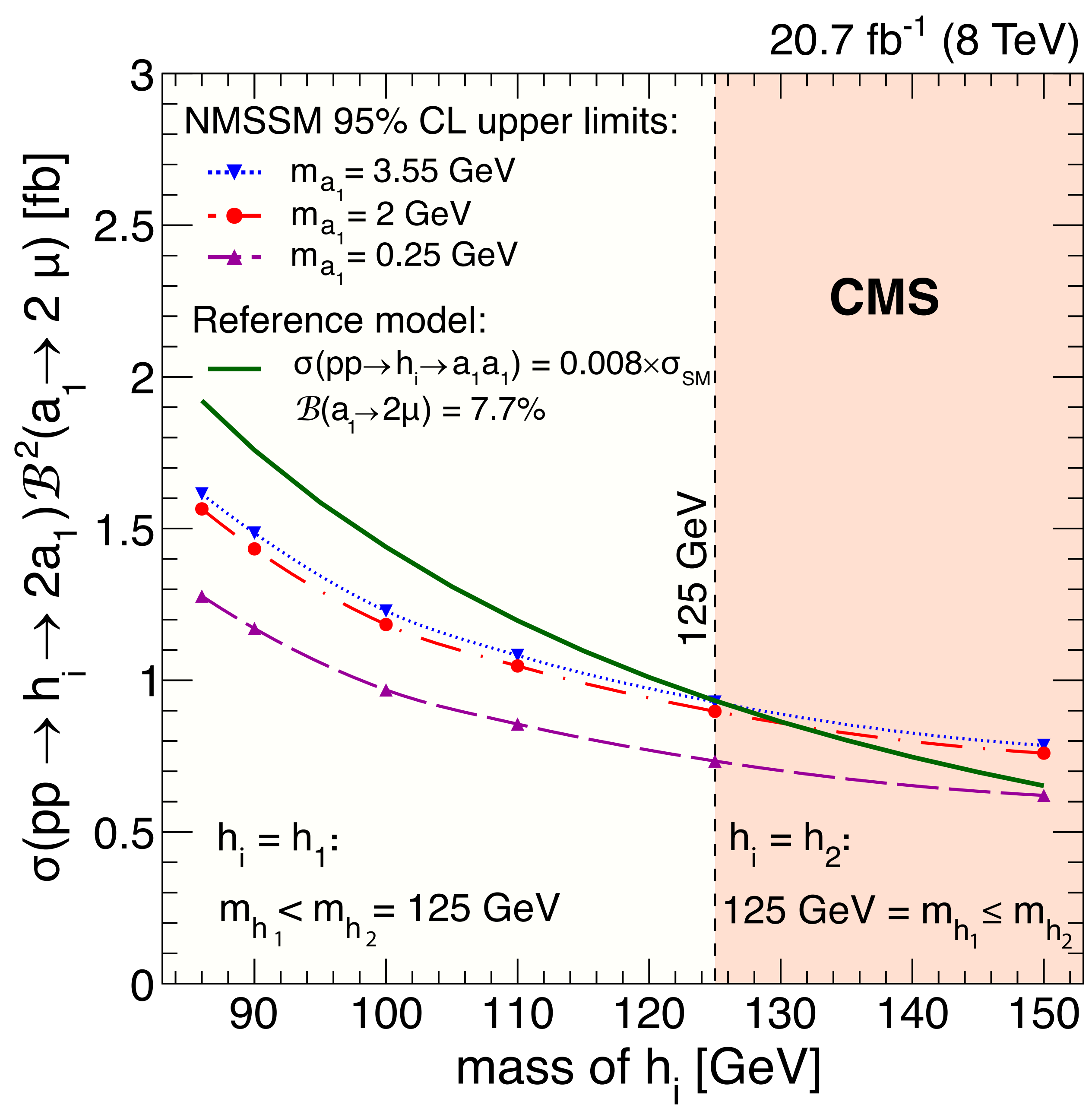
Process	Low Mass selection (for 1 GeV < m_X < 15 GeV)
$ZZ^* \to 4\ell$	0.10 ± 0.01
$H \to ZZ^* \to 4\ell$	0.1 ± 0.1
EWK6	0.06 ± 0.03
$Z + (t\bar{t}/J/\psi/\Upsilon) \to 4\ell$	–
Heavy Flavour	0.07 ± 0.04
Reducible background	–
Total	0.4 ± 0.1
Data	0

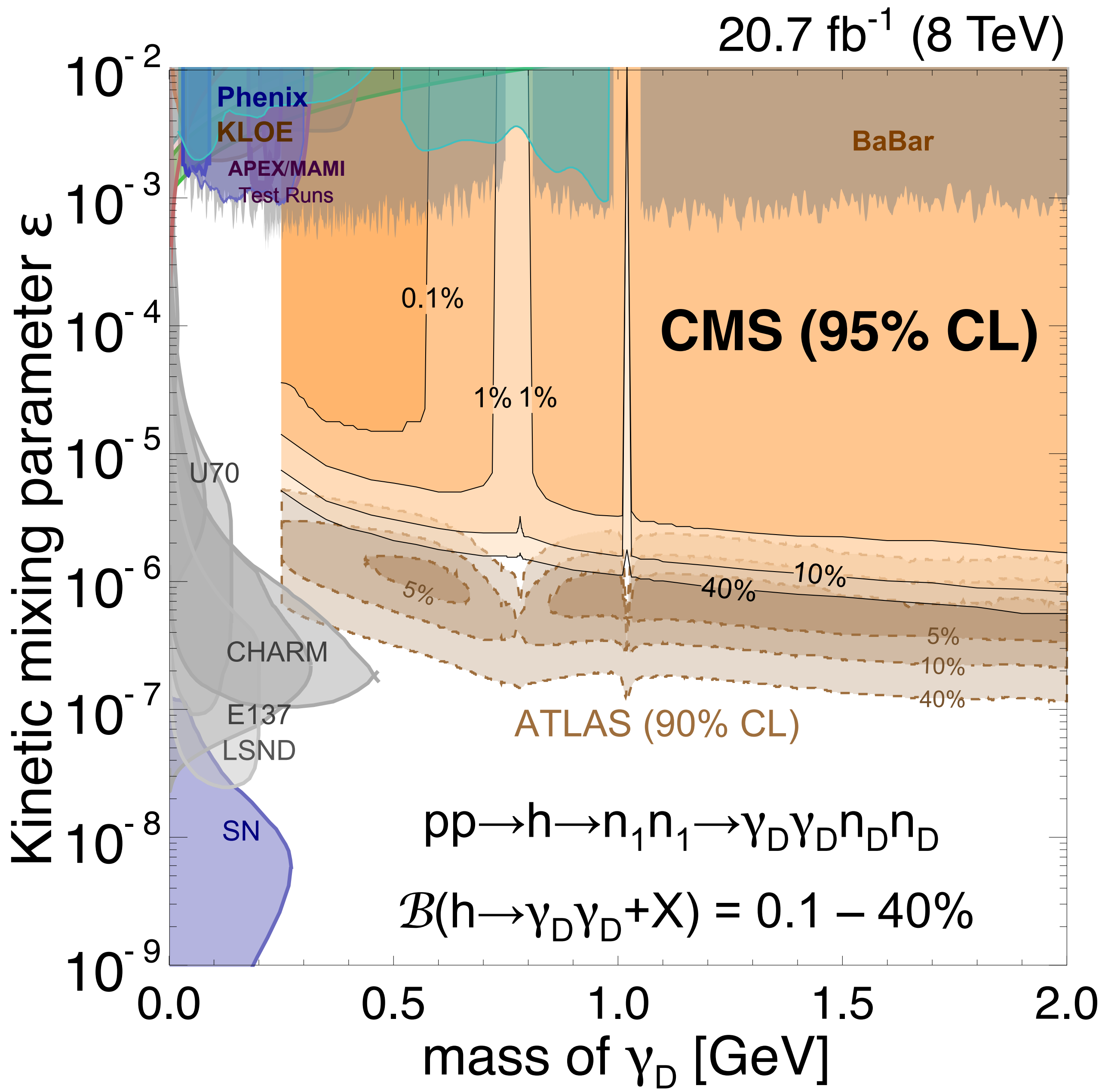






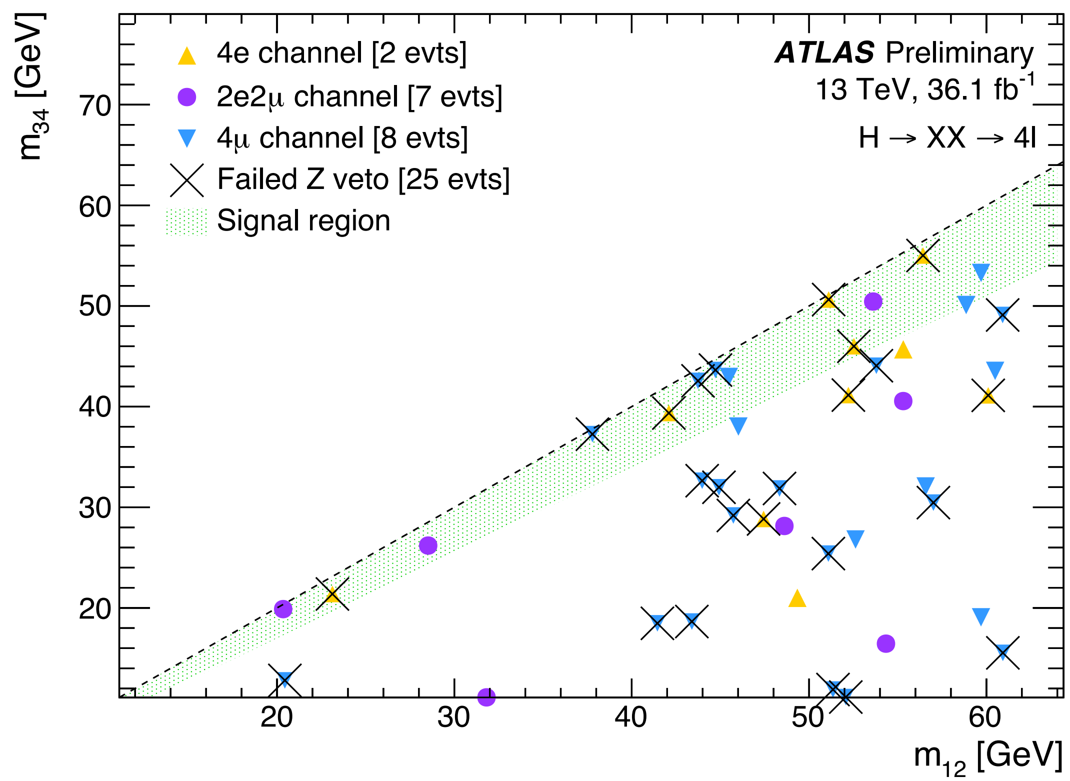
H→aa →4μ (low mass, CMS)

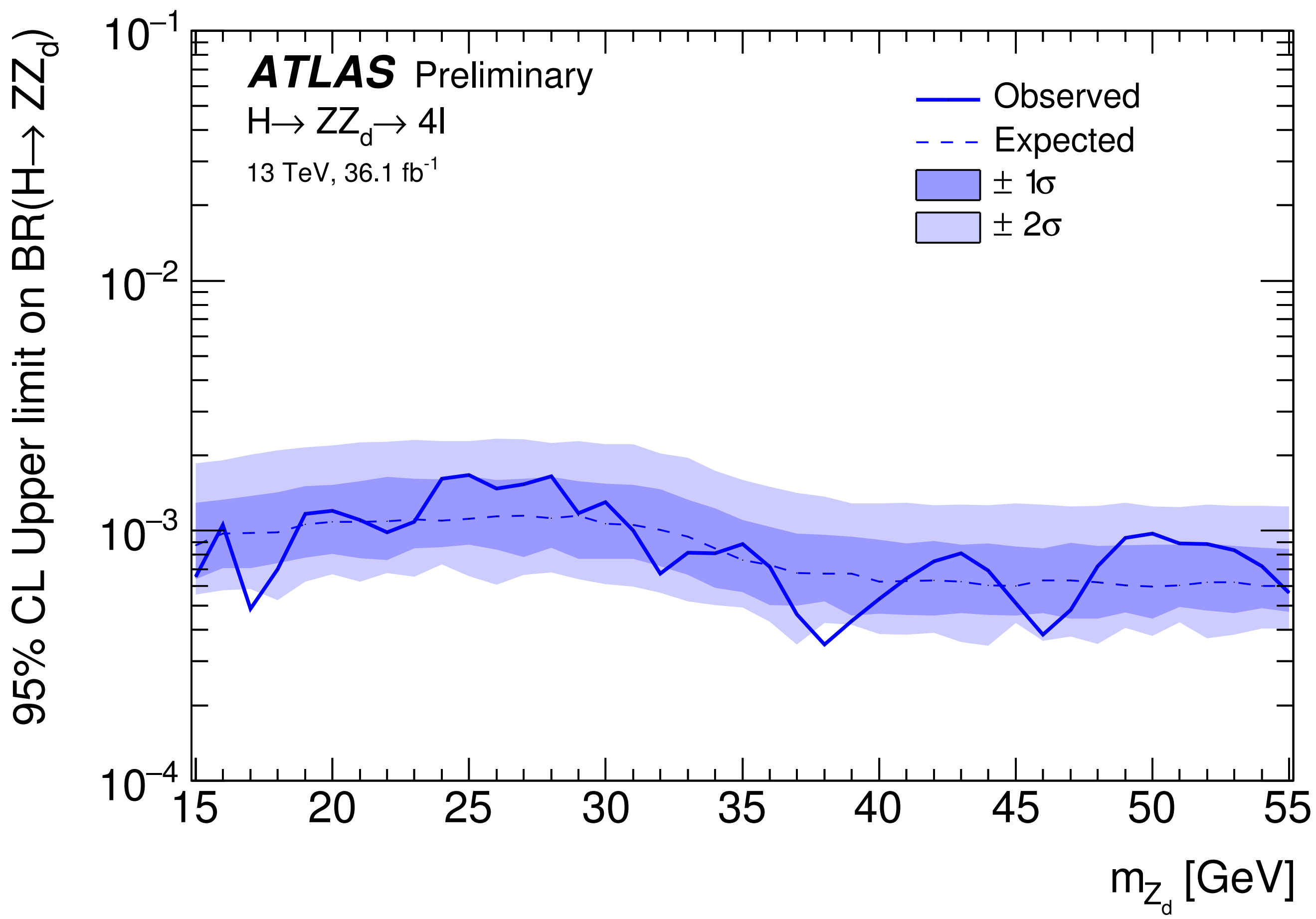


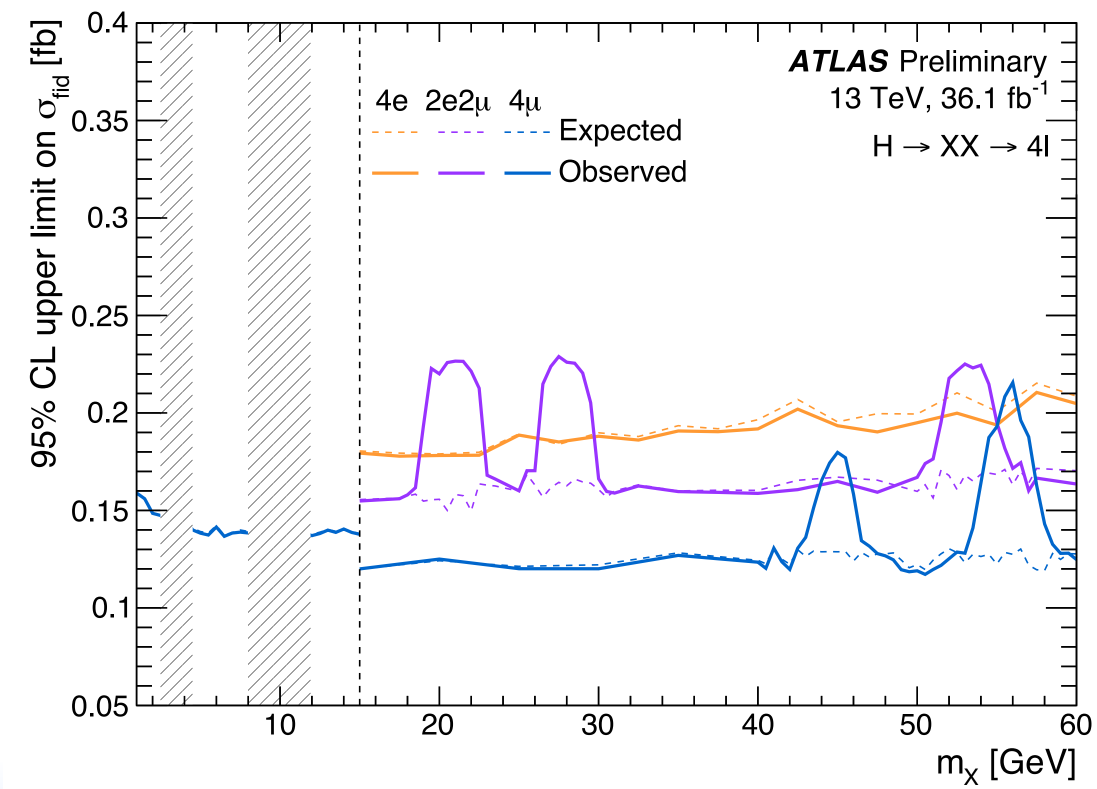


$H \to Z_{(d)} Z_d \to 4\ell$ (high mass, ATLAS)

Process	High Mass selection (for 15 GeV < m_X < 60 GeV)
$ZZ^* \to 4\ell$	0.8 ± 0.1
$H \to ZZ^* \to 4\ell$	2.6 ± 0.3
EWK6	0.51 ± 0.18
$Z + (t\bar{t}/J/\psi/\Upsilon) \to 4\ell$	0.004 ± 0.004
Heavy Flavour	–
Reducible background	0 ± 0
Total	3.9 ± 0.3
Data	6







Decays to BSM particles

<table>
<tr><th rowspan="2">Decay mode</th><th colspan="3">ATLAS</th><th colspan="3">CMS</th></tr>
<tr><th>Dataset</th><th>Exp. lim.</th><th>Obs. lim.</th><th>Dataset</th><th>Exp. lim.</th><th>Obs. lim.</th></tr>
<tr><td>$H \rightarrow aa \rightarrow 4b$</td><td>3.2 fb^{-1}, 13 TeV</td><td></td><td></td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \rightarrow aa \rightarrow \mu\mu bb$</td><td></td><td>- - - - -</td><td>- - - - -</td><td rowspan="3">20 fb^{-1}, 8 TeV</td><td></td><td></td></tr>
<tr><td>$H \rightarrow aa \rightarrow \mu\mu\tau\tau$</td><td>20 fb^{-1}, 8 TeV</td><td></td><td></td><td></td><td></td></tr>
<tr><td>$H \rightarrow aa \rightarrow 4\tau$</td><td></td><td>- - - - -</td><td>- - - - -</td><td></td><td></td></tr>
<tr><td>$H \rightarrow aa \rightarrow 4\mu$</td><td></td><td>- - - - -</td><td>- - - - -</td><td>20 fb^{-1}, 8 TeV</td><td></td><td></td></tr>
<tr><td>$H \rightarrow Z_d Z_d \rightarrow 4\ell$</td><td>20 fb^{-1}, 8 TeV</td><td></td><td></td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \rightarrow G\chi \rightarrow GG\gamma$</td><td rowspan="2">20 fb^{-1}, 8 TeV</td><td></td><td></td><td>20 fb^{-1}, 8 TeV</td><td></td><td></td></tr>
<tr><td>$H \rightarrow \chi\chi \rightarrow G\gamma G\gamma$</td><td></td><td></td><td>- - - - -</td><td>- - - - -</td><td>- - - - -</td></tr>
<tr><td>$H \rightarrow f_d f_d \rightarrow 4\ell\ 2LSP$</td><td rowspan="2">3.2 fb^{-1}, 13 TeV</td><td></td><td></td><td rowspan="2">- - - - -</td><td rowspan="2">- - - - -</td><td rowspan="2">- - - - -</td></tr>
<tr><td>$H \rightarrow f_d f_d \rightarrow 8\ell\ 2LSP$</td><td></td><td></td></tr>
</table>

$H \to Z\gamma \to \ell\ell\gamma$

Kinematic selection		
	ATLAS	CMS
ℓ_1/ℓ_2 p_T	> ~25/10 GeV	> 20/10 GeV
γ p_T	> 15 GeV	> 15 GeV
$\Delta R(\gamma, \ell)$	> 0.3	> 0.4
$m(\ell\ell)$	76 - 106 GeV	> 50 GeV
$m(\ell\ell\gamma)$	115 - 170 GeV	100 - 190 GeV
Other		$m(\ell\ell) + m(\ell\ell\gamma)$ > 185 GeV