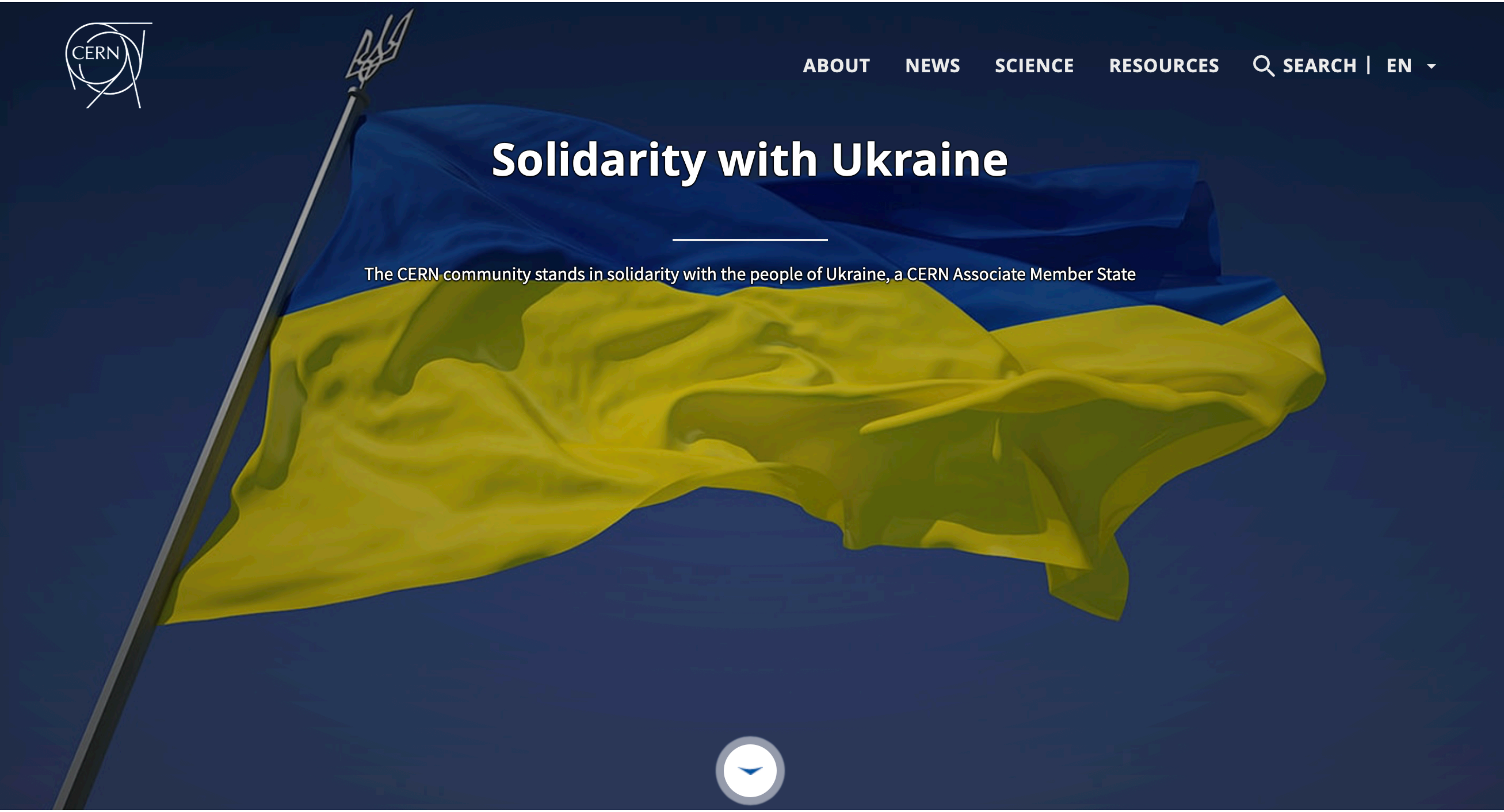
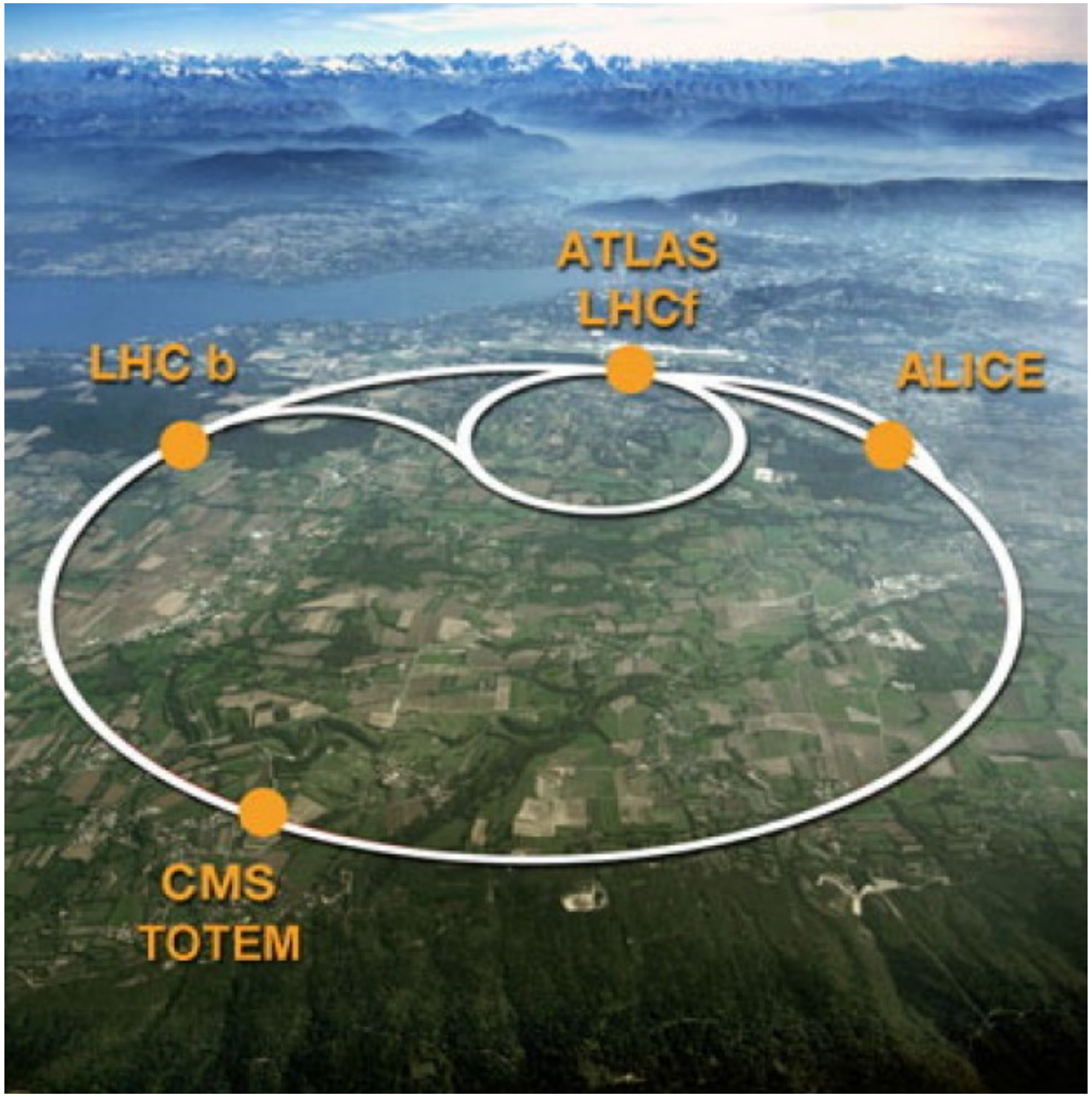
HH production, rare Higgs decays and Higgs BSM in ATLAS and CMS

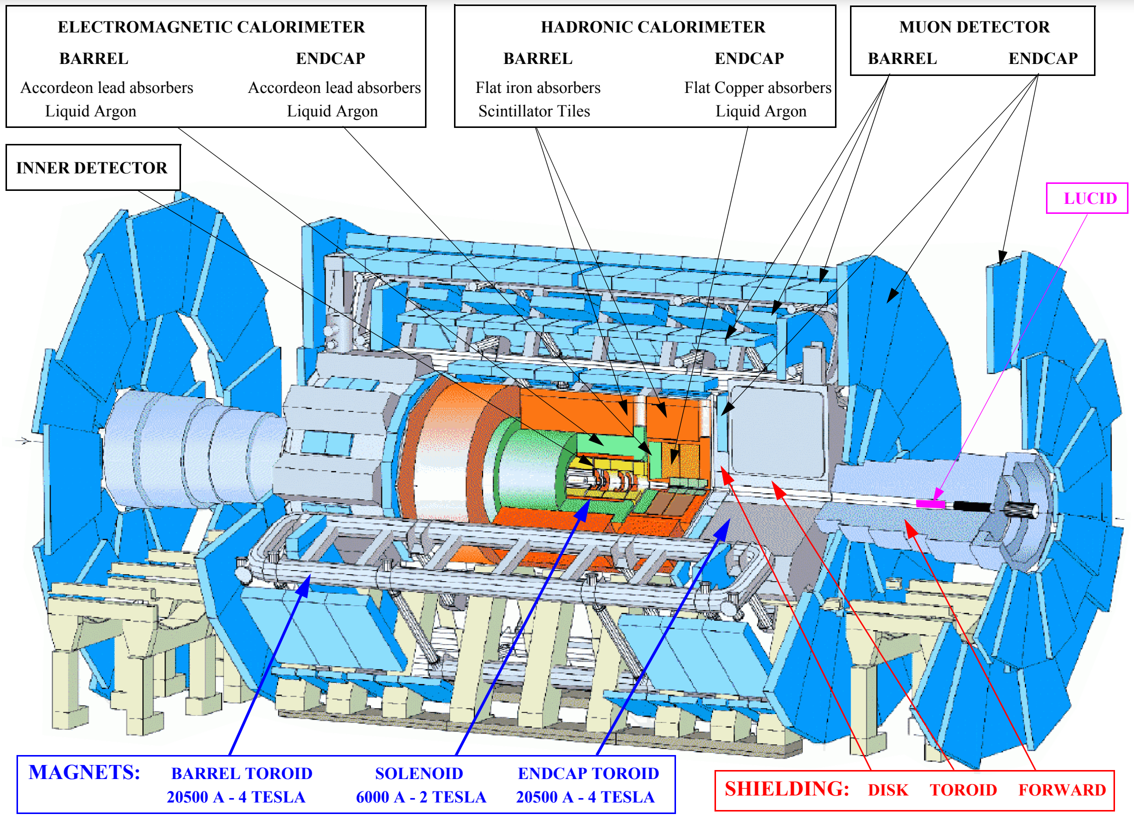
Simone Gennai on behalf of ATLAS and CMS Collaborations

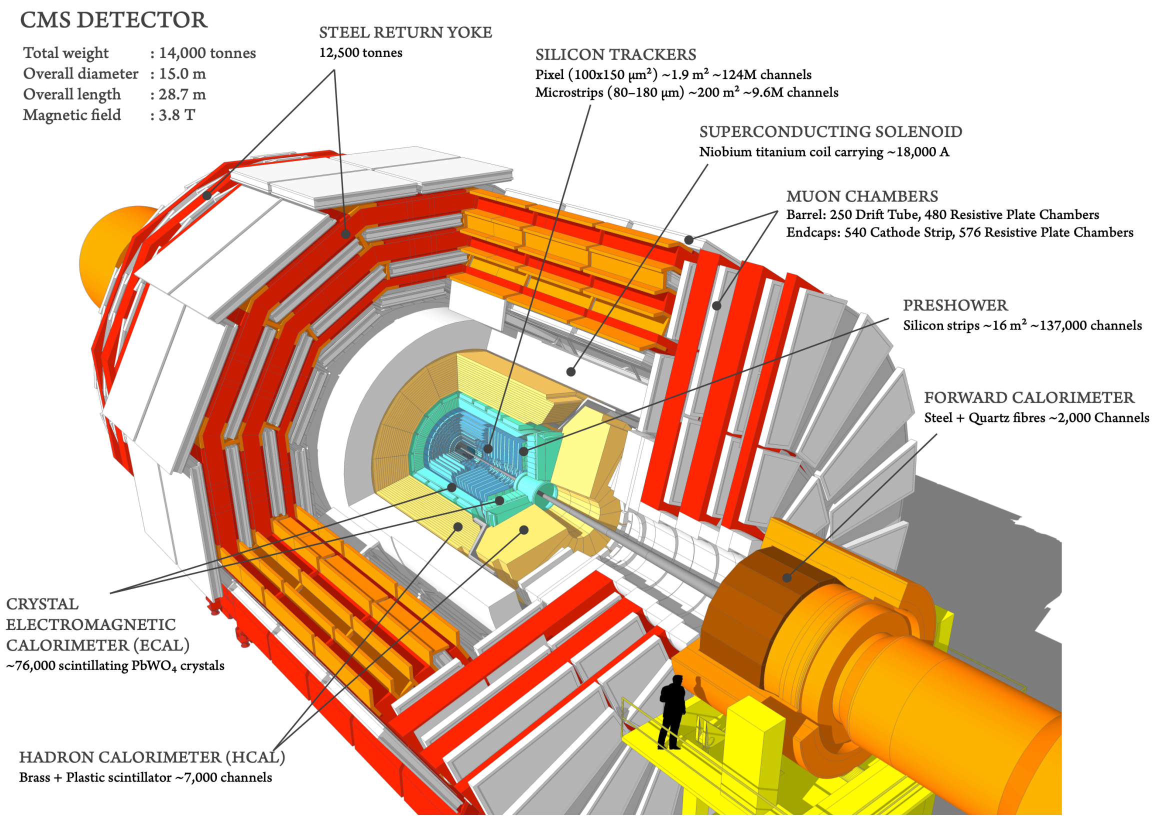
https://home.cern/solidarity-ukraine



ATLAS and CMS detectors

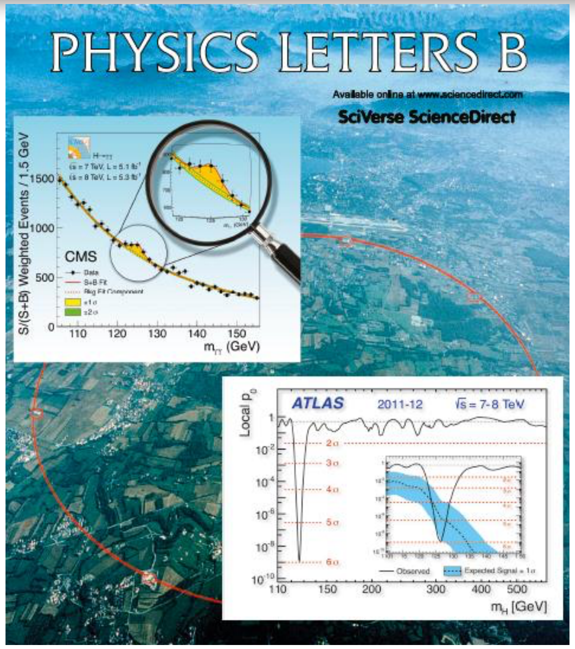




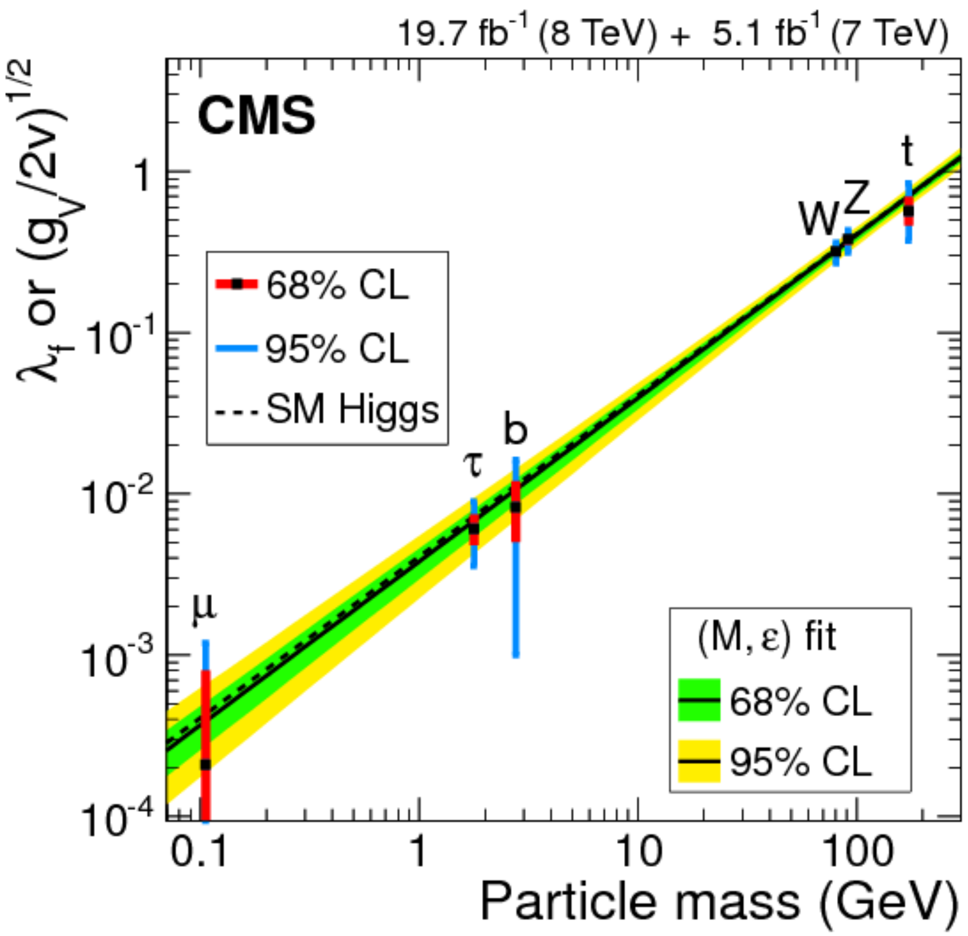


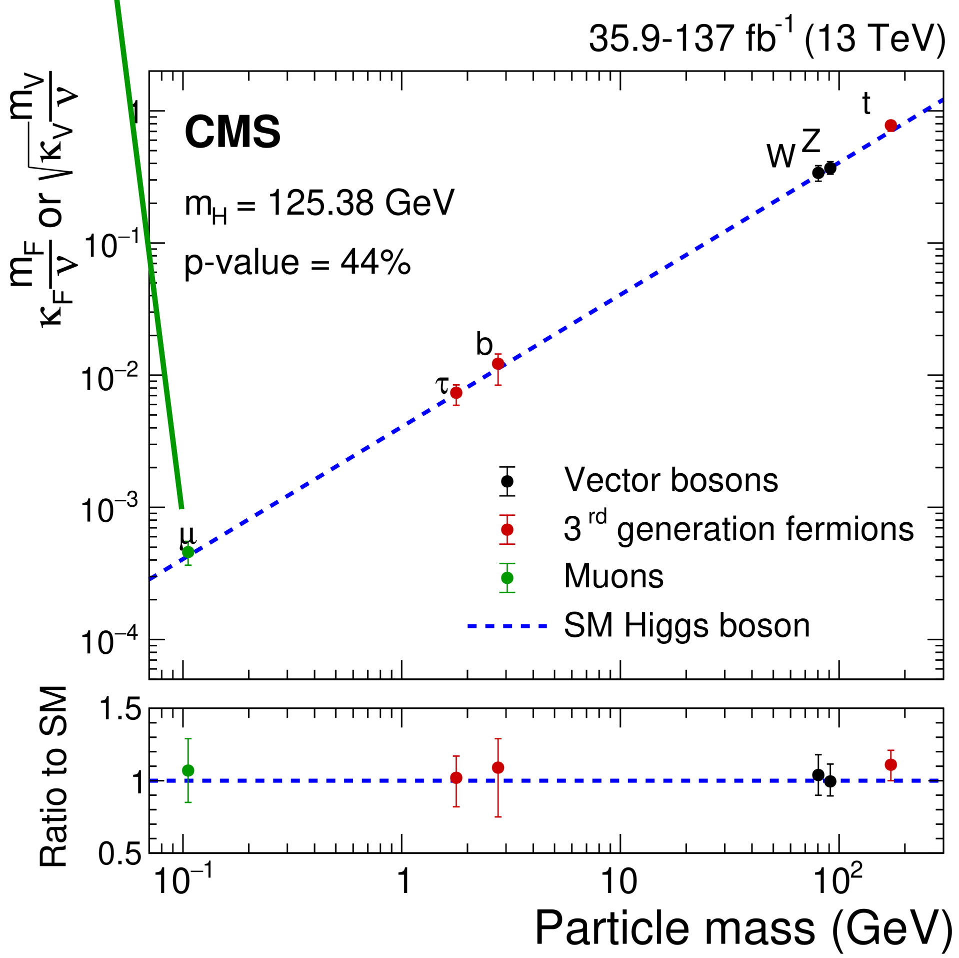
10 years from the discovery

- It is incredible how far we are wrt 10 years ago



Best μ value: 1.19 ± 0.43 JHEP 01 (2021)





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Double Higgs boson production

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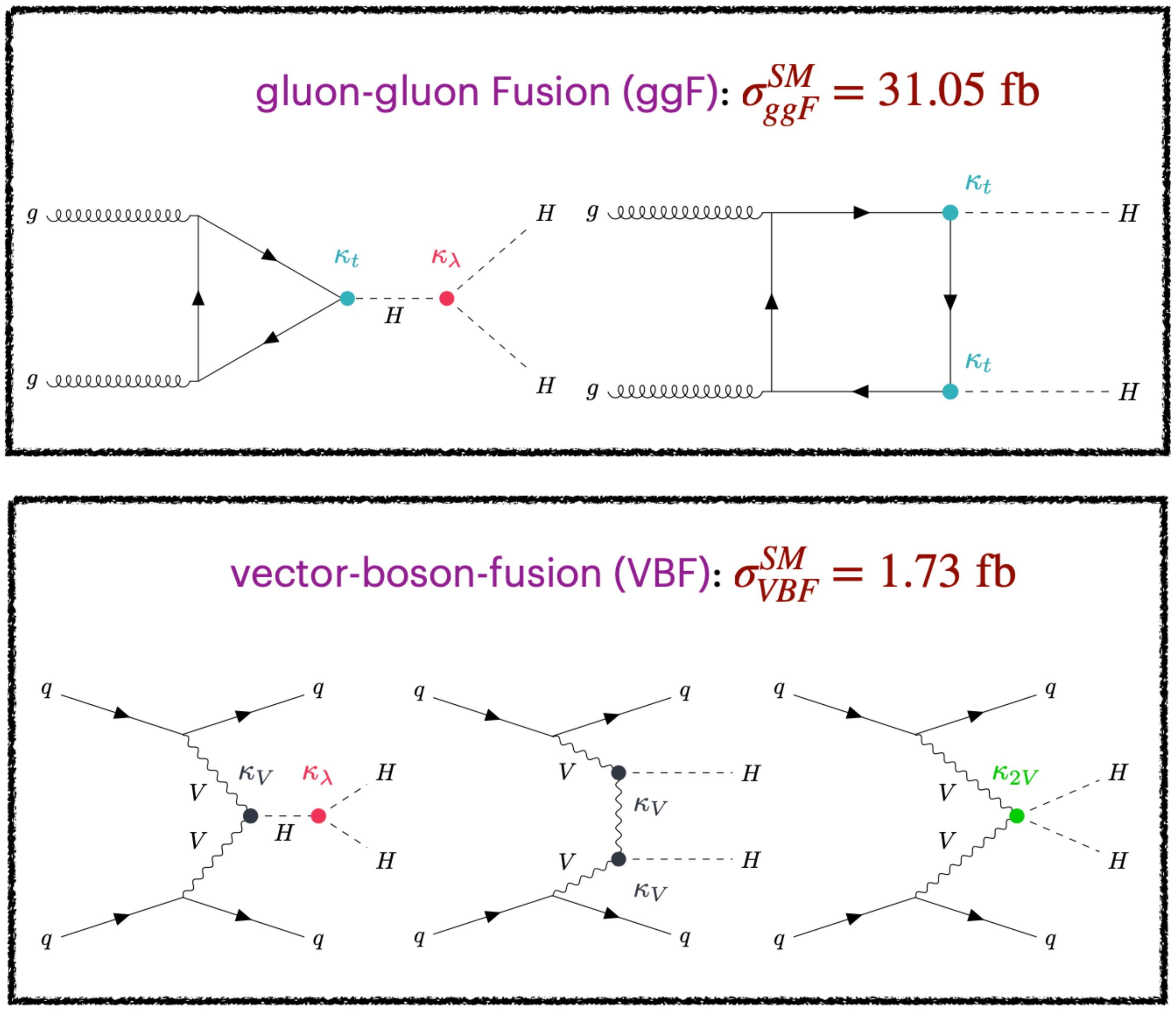
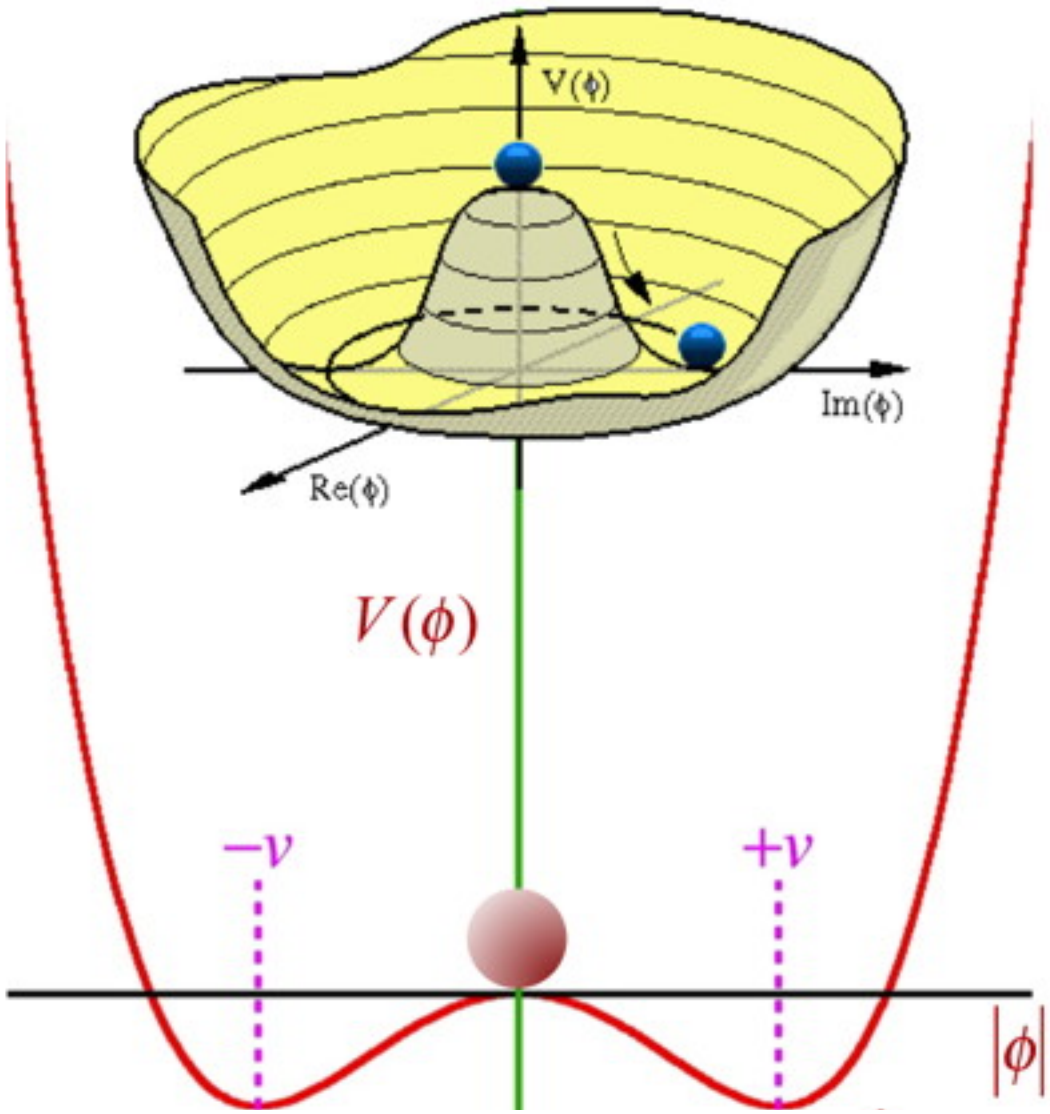
Double Higgs boson production

- Direct access to the Higgs self coupling
  - Hence important information on the shape of the Higgs potential





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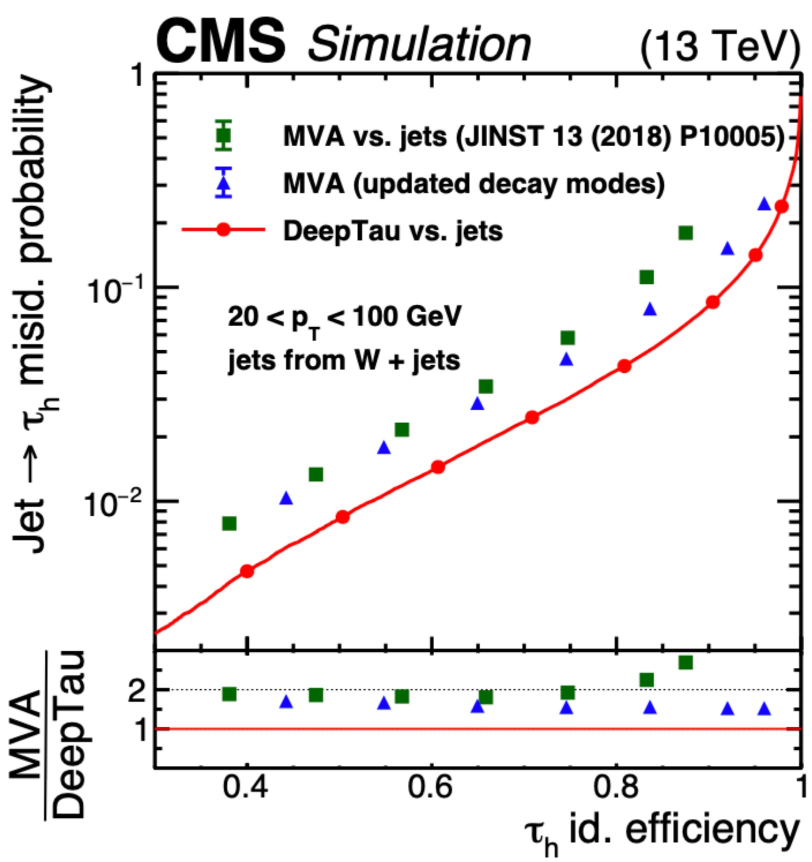
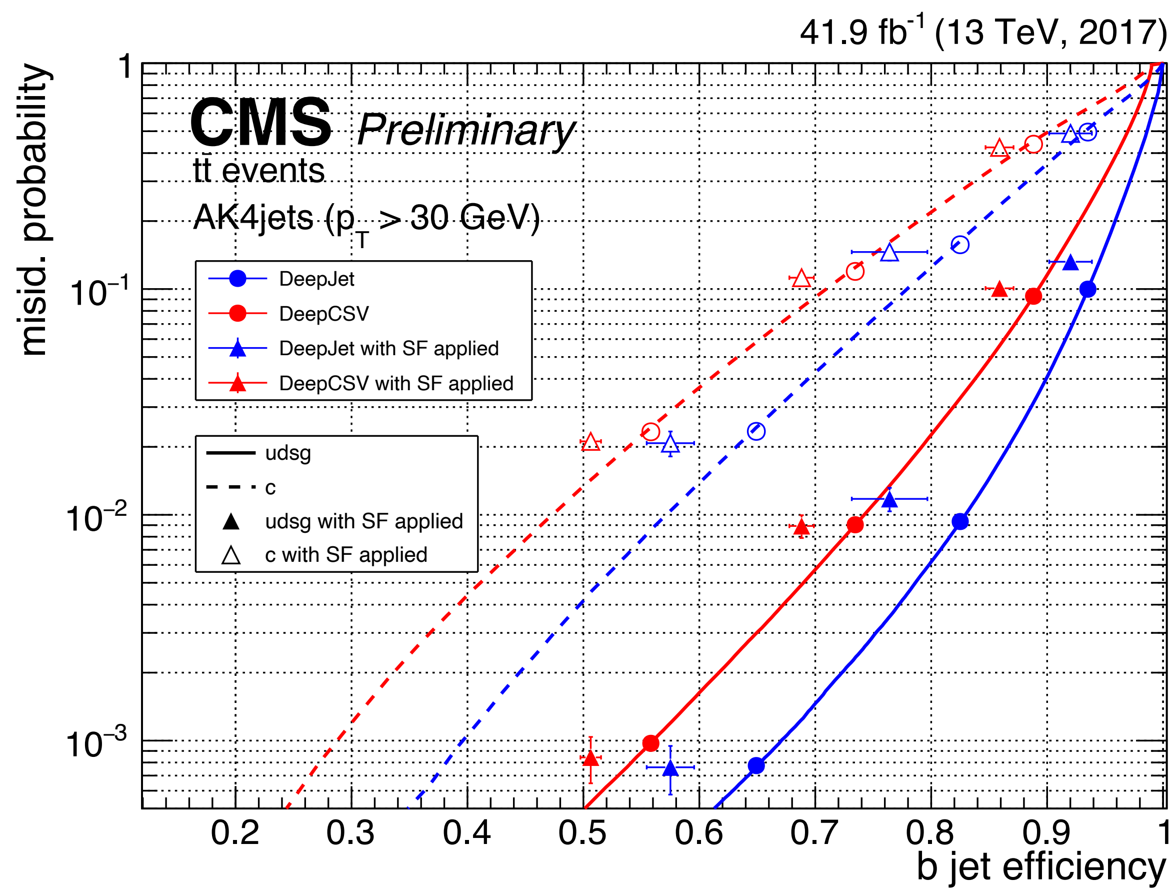
Double Higgs boson production

- Several channels have been updated recently with full Run2 data sample for the non resonant analysis
  - ATLAS:
    - $2b2\gamma$,$2b2\tau$ and their combination: ATLAS-CONF-2021-052
  - CMS:
    - 4b, $2b2\tau$, $2b2\gamma$, 4leptons
- Analysis sensitivity has improved substantially wrt previous combination also thanks to extensive use of state-of-the-art machine learning techniques for object identification





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  - ATLAS:
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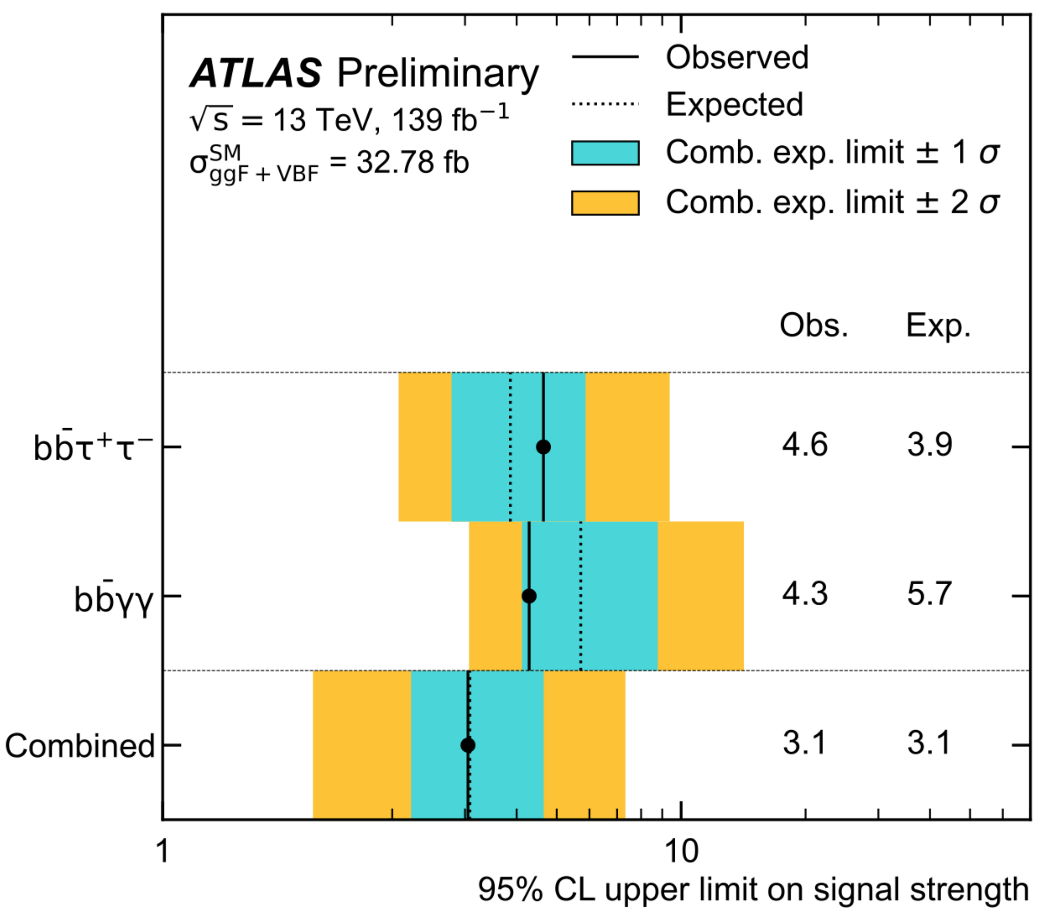

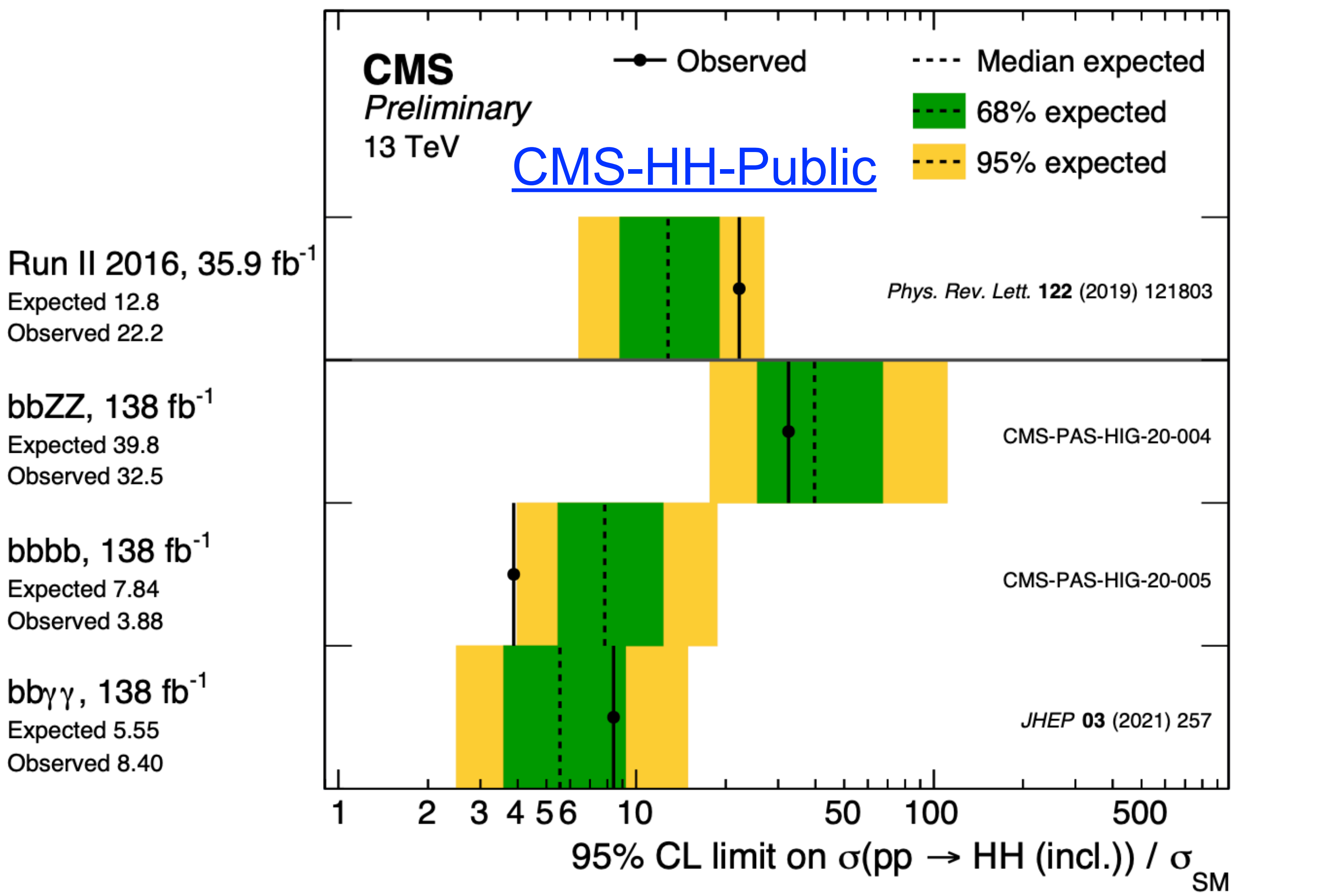

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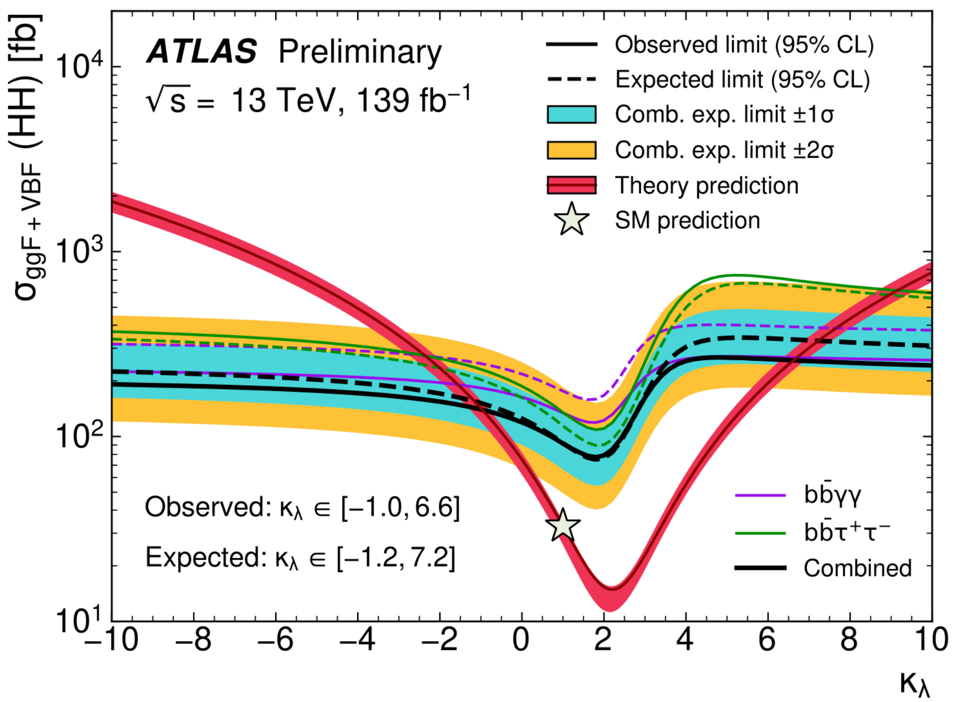
ATLAS projection to HL-LHC

- Results from latest combination yield better projection for HL-LHC than previous one



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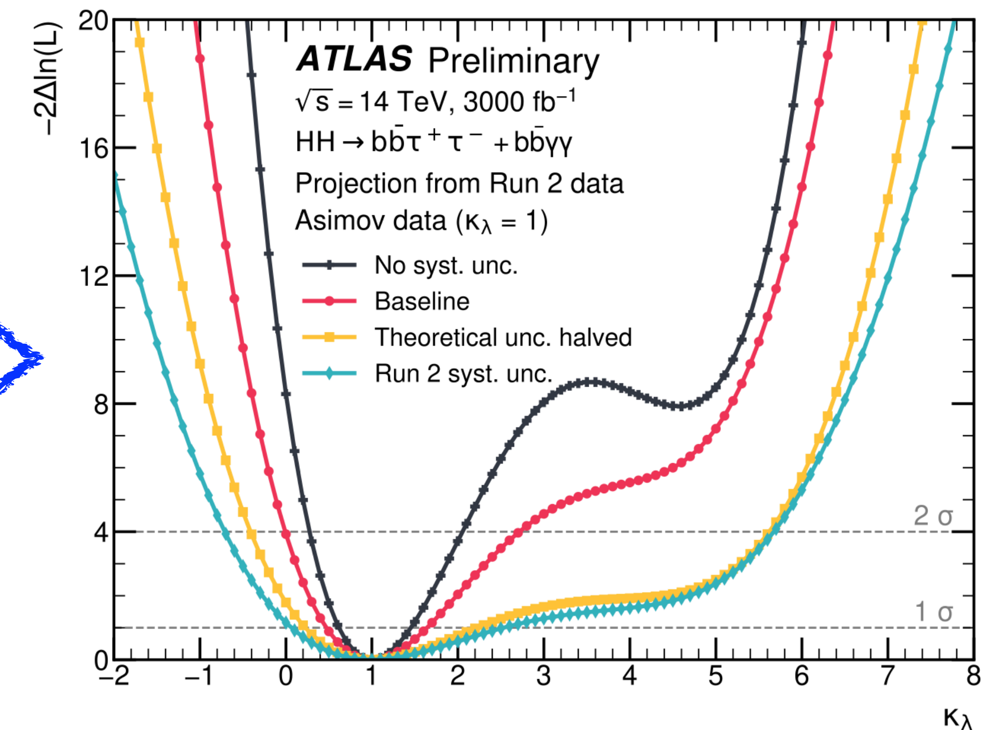
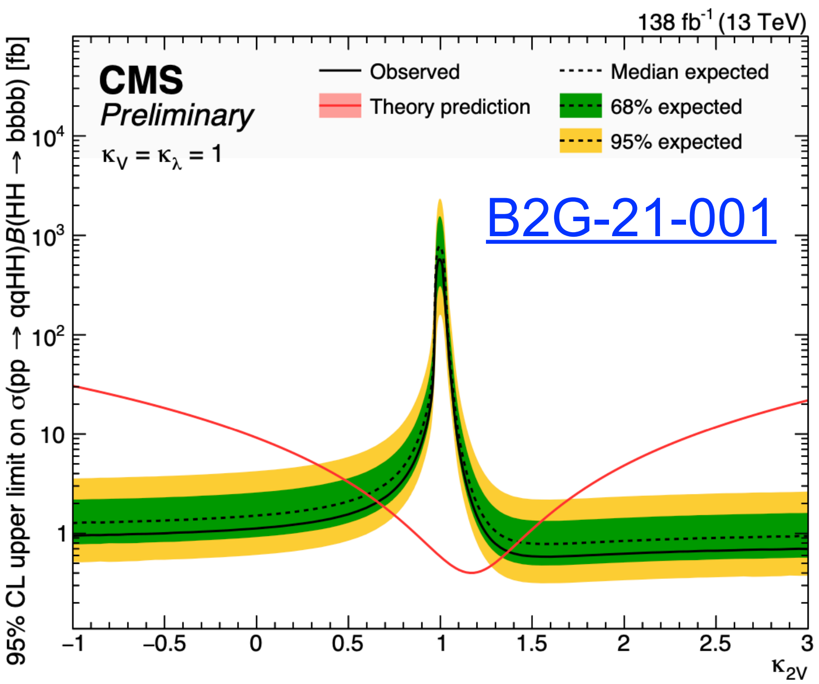
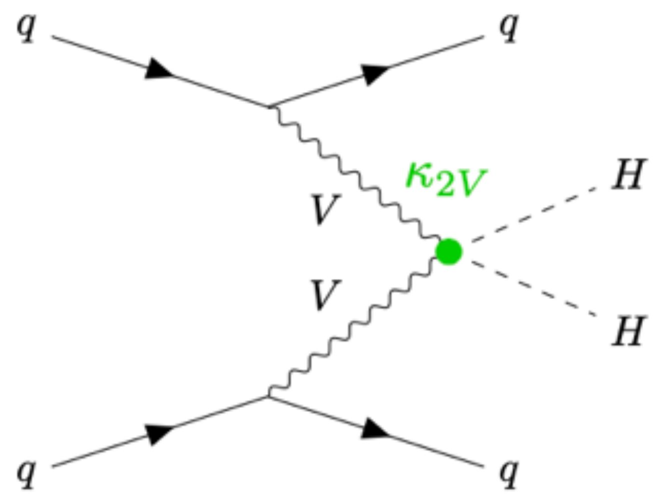


Uncertainty scenario	Likelihood scan 1 σ CI	Likelihood scan 2 σ CI
No syst. unc.	[0.6, 1.5]	[0.3, 2.1]
Baseline	[0.5, 1.6]	[0.0, 2.7]
Theoretical unc. halved	[0.2, 2.2]	[−0.4, 5.6]
Run 2 syst. unc.	[0.1, 2.5]	[−0.7, 5.7]

CMS latest results for: $4b$, multileptons, $2b2\tau$

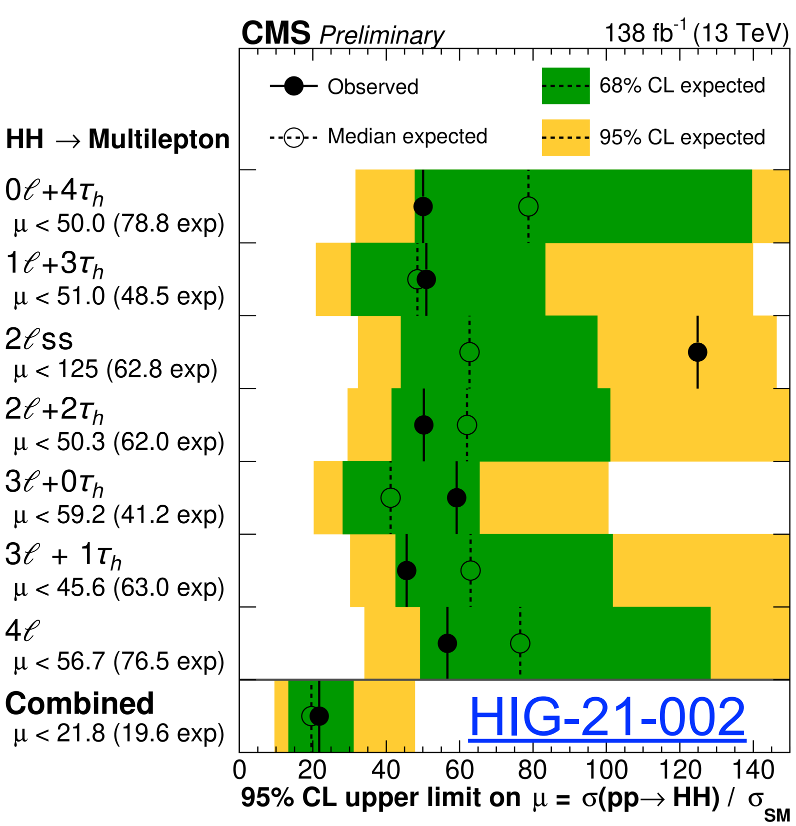


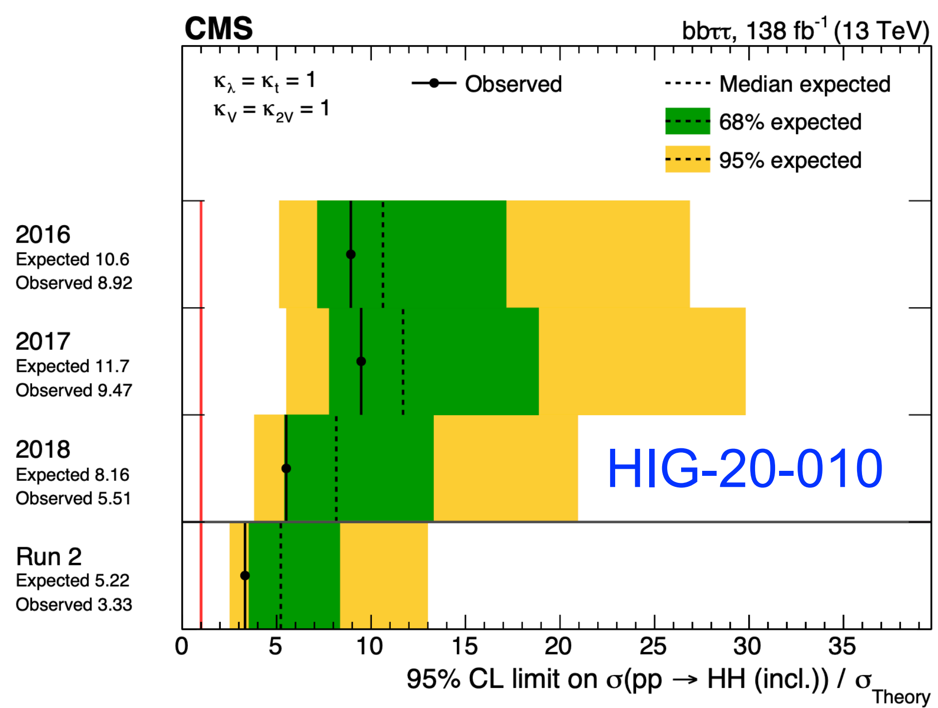


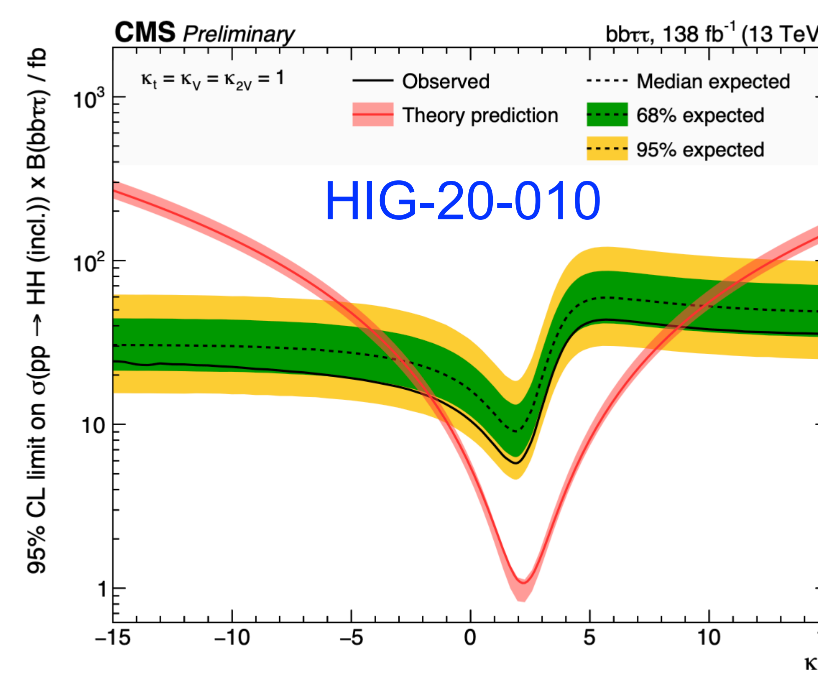
4b boosted topology: 2 large radius jets.

Very sensitive to k_{2V}

$0.6 < k_{2V} < 1.4$ at 95% C.L.

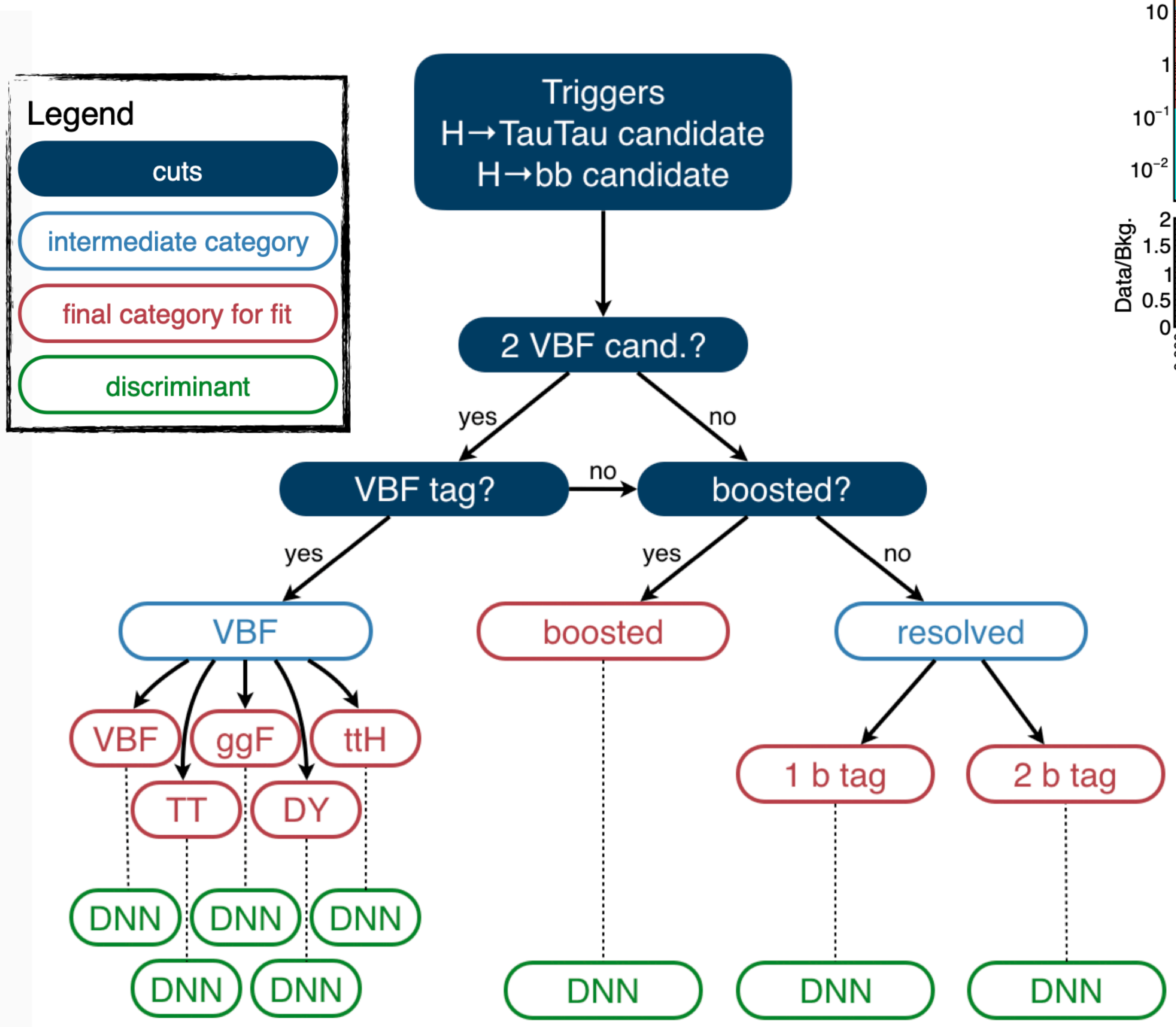


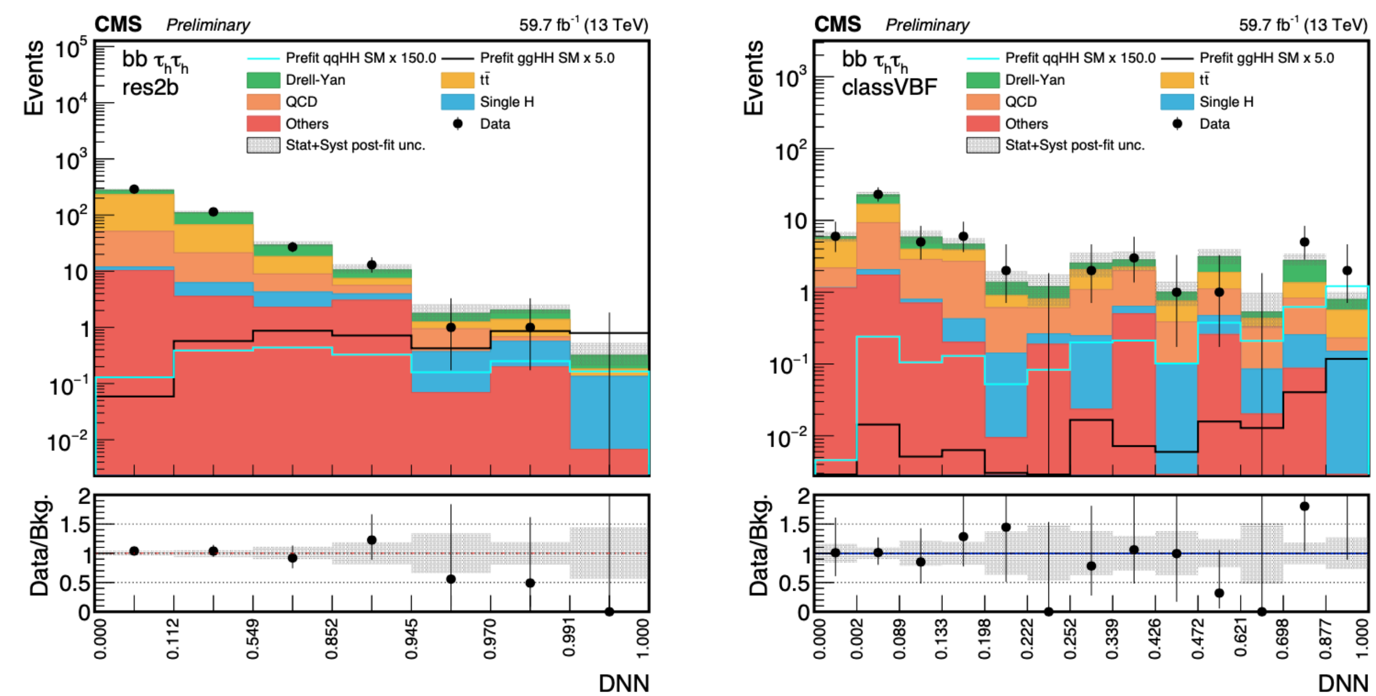


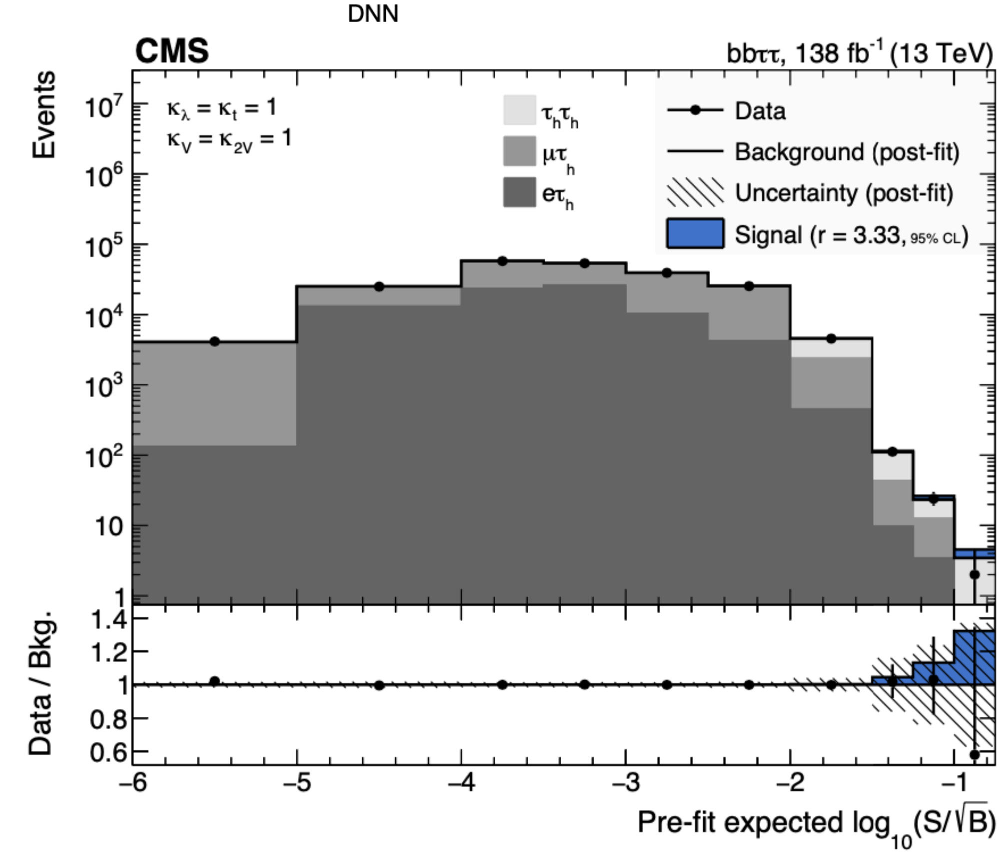


Few details on $HH \to bb\tau\tau$

- Three different final states considered: $\tau_\mu\tau_h$, $\tau_e\tau_h$, $\tau_h\tau_h$
  - Plus a number of categories designed to extract the signal as well as constraint bkg uncertainties

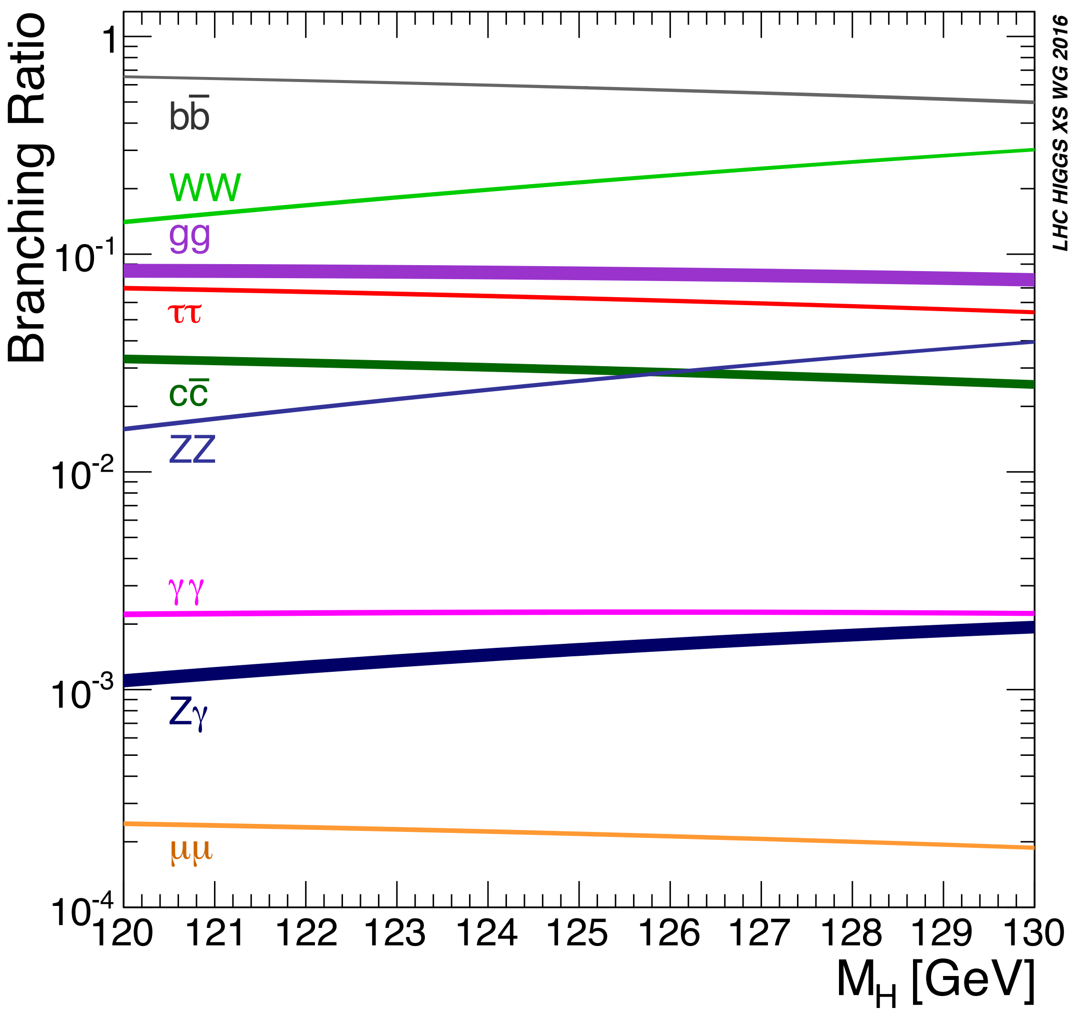






Higgs boson rare decays

Higgs boson rare decays



ATLAS CMS

Analysis	Final states	13 TeV $\mathcal{L}$ [fb^{-1}]	BR (SM)	$\sigma_H \times$ BR(H decays)
$c\bar{c}$		139, 35.9	2.9%	26 × SM, 70 × SM
invisible		139, 35.9	~10^{-3}	
Zγ	ee/μμ+γ	139, 35.9	~10^{-3}	**evd. μ = 1.5**, 3.9 × SM
$\mu^+\mu^-$		139, 137	~10^{-4}	2.2 × SM, **evd. μ = 1.19**
				BR(H decays)
ργ	$\pi^+\pi^-\gamma$	35.6	~10^{-5}	8.8 × 10^{-4}
$\phi\gamma$	$K^+K^-\gamma$		~10^{-6}	4.8 × 10^{-4}
Zρ	ee/μμ + $\pi^+\pi^-$	137	~10^{-5}	(1.04–1.31) × 10^{-2}
Zϕ	ee/μμ + K^+K^-	137	~10^{-6}	(3–4) × 10^{-3}
Zη_c	ee/μμ + had	139	~10^{-5}	(σ × BR =110 pb)
ZJ/ψ			~10^{-6}	(σ × BR =100 pb)
J/ψ γ	$\mu^+\mu^-\gamma$	36.1, 35.9	~10^{-6}	3.5 × 10^{-4}, 7.6 × 10^{-4}
ψ(2S)γ		36.1	~10^{-6}	2.0 × 10^{-3}
ϒ(nS)γ (n=1,2,3)		36.1	~10^{-9}	(4.9, 5.9, 5.7) × 10^{-4}
ϒϒ	4μ	37.5	~10^{-9}	1.4 × 10^{-3}
J/ψ J/ψ			~10^{-10}	1.8 × 10^{-3}
e^+e^-		139	~10^{-9}–10^{-10}	3.6 × 10^{-4}

Updated results in the next slides

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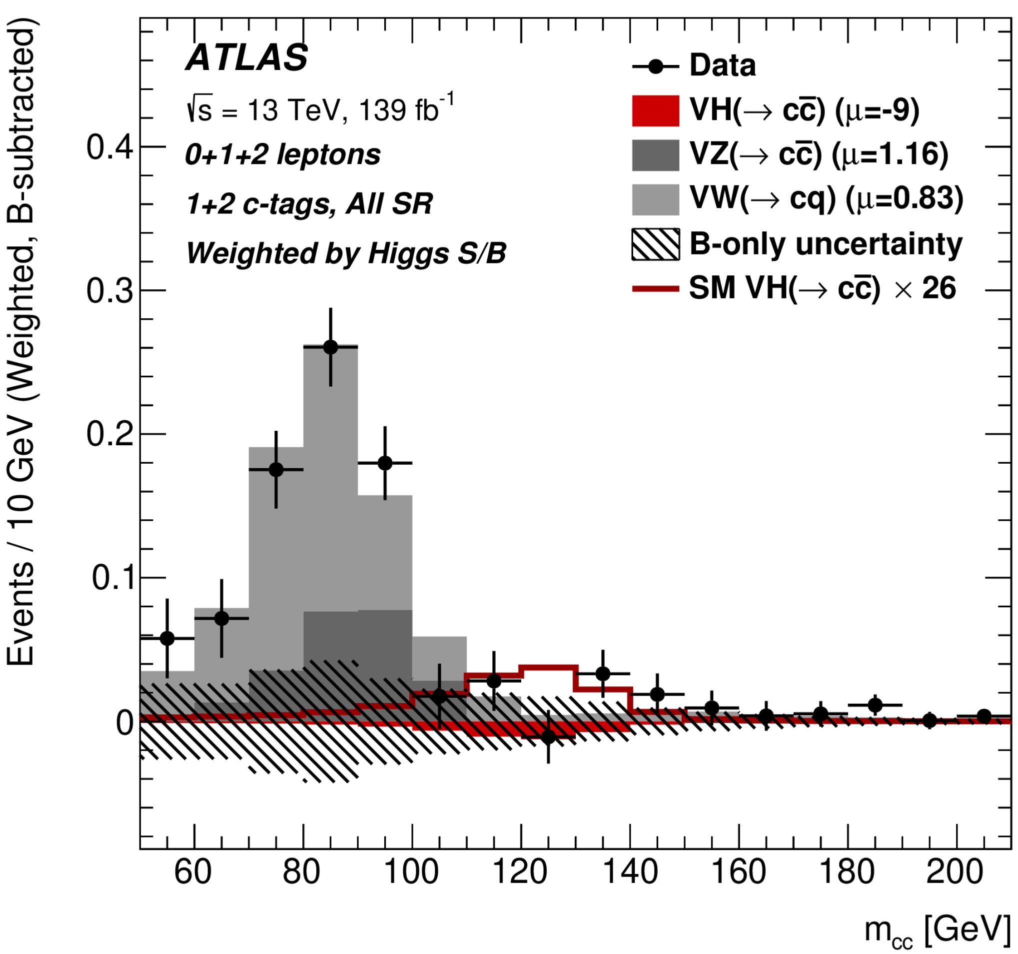
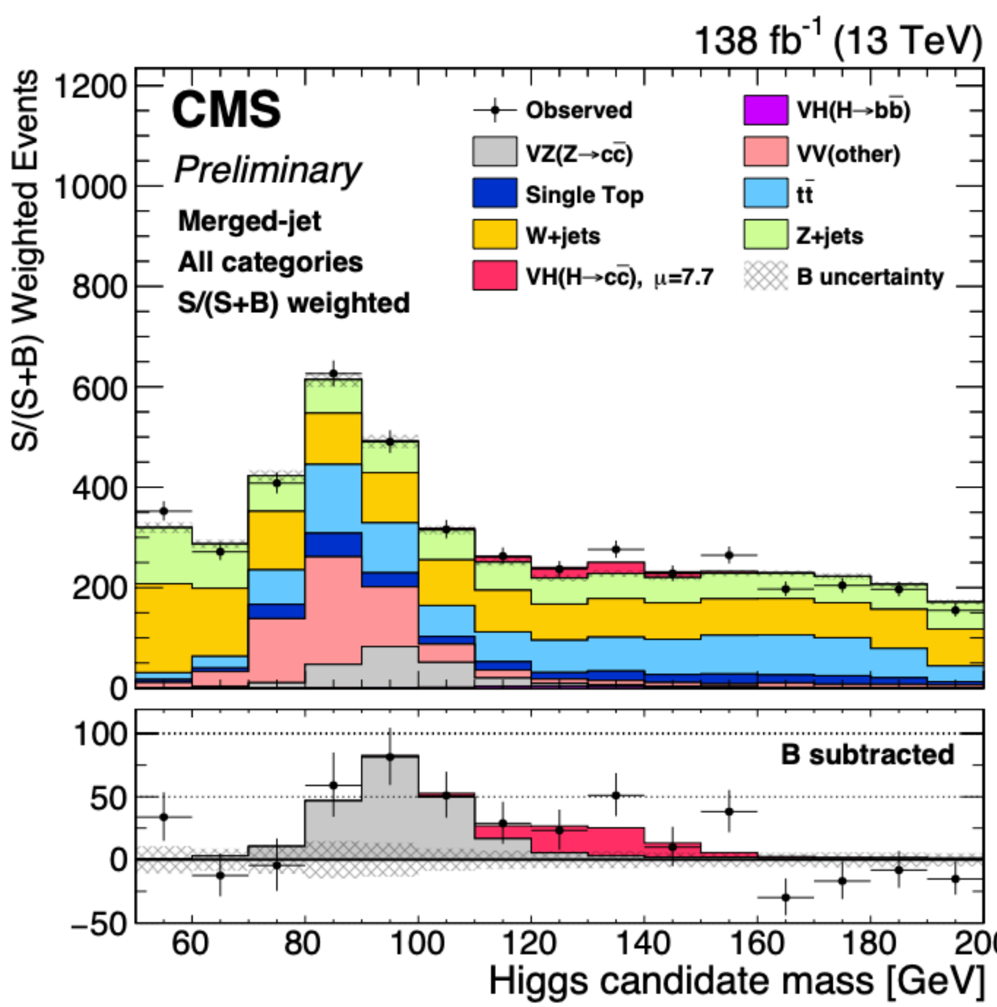
VH→cc (BR: 2.88×10^{-2})

- ATLAS best limit is 26 x SM
  - But combining VH→cc with VH→bb measured $|k_c/k_b|$ to be < 4.5: HIGG-2021-12
    - Evidence for VW->cq decay, for more details see Antonio Jacques Costa talk
- CMS best limit is 7.7 x SM
  - **Best stringent limit on 1.1 <$|k_c|$ < 5.5 and first observation of VZ→cc** at a hadronic collider : HIG-21-008





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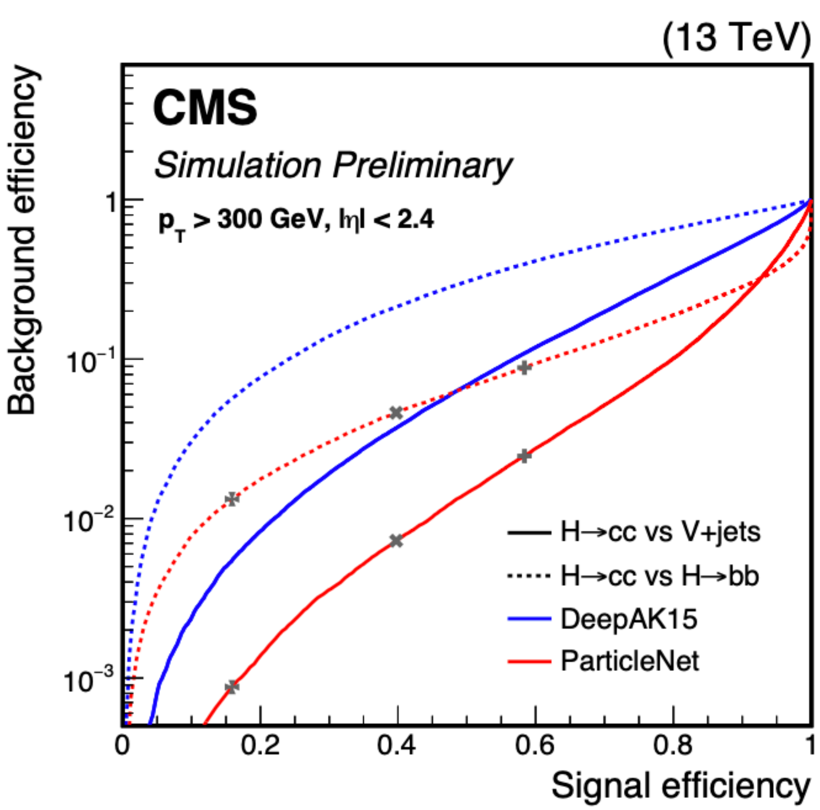
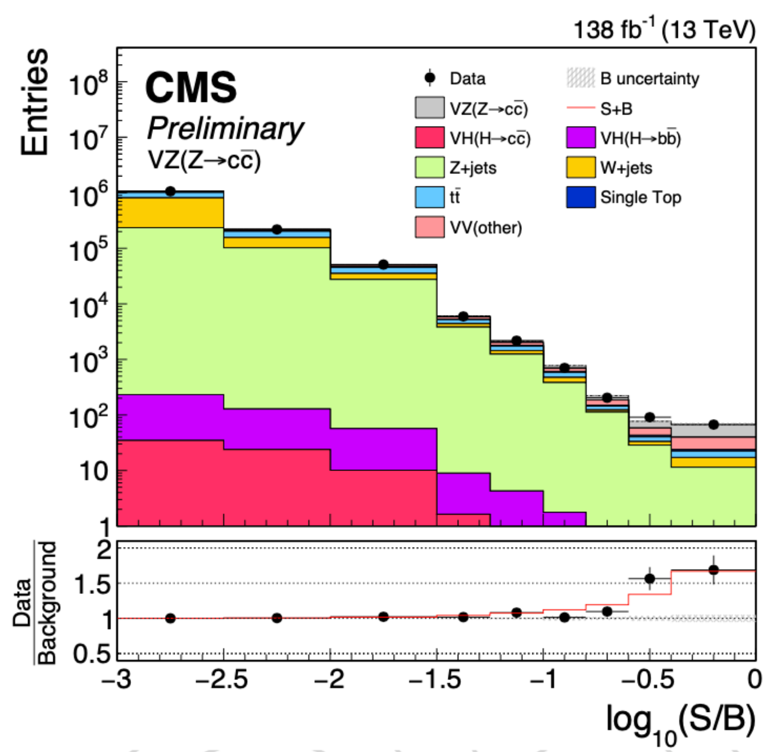
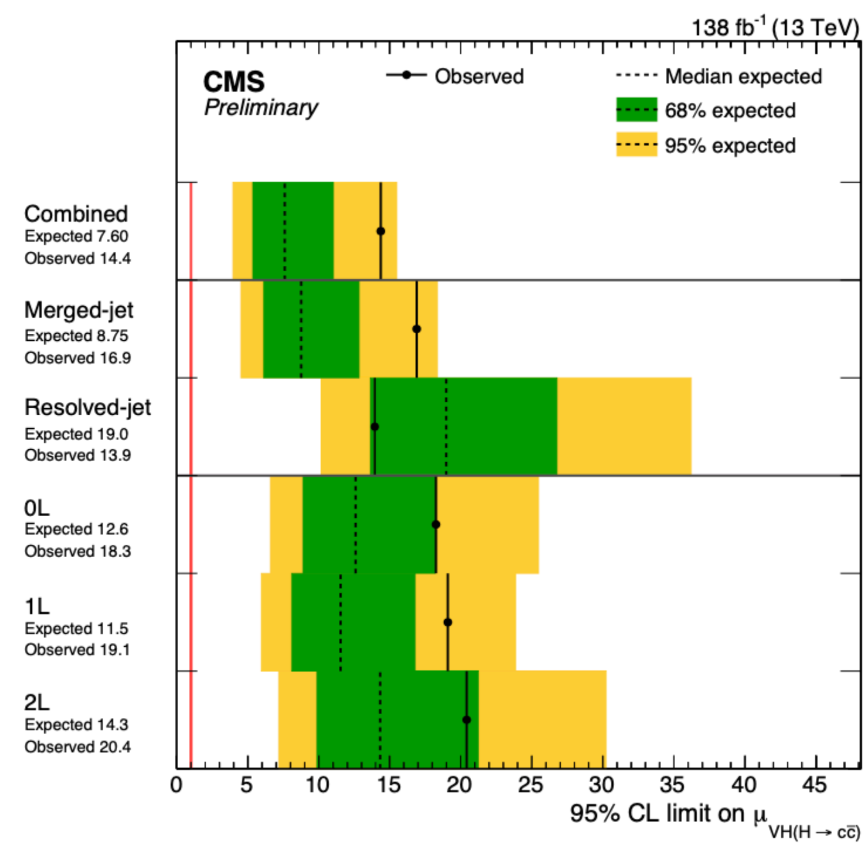
VH→cc: few more details

- CMS adopted the choice of looking for boosted events and even if they yield only 5% of signal events they allow a better discrimination
- A special c-jet tagger specialised in boosted jets has been developed
  - Dense environment, large multiplicity. Deep neural network based on the ParticleNet algorithm
  - It achieves a factor ~3 better background rejection wrt previous tagger
- Signal is extracted with the help of a DNN classification and a fit to the invarinat mass of the two c-jets
  - For the resolved case the DNN distribution is used a the place of the cc invariant mass

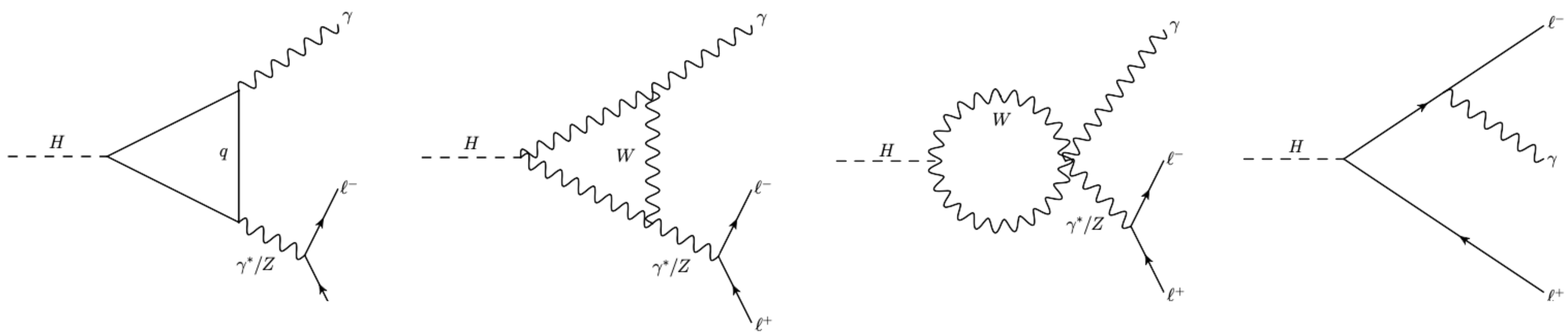


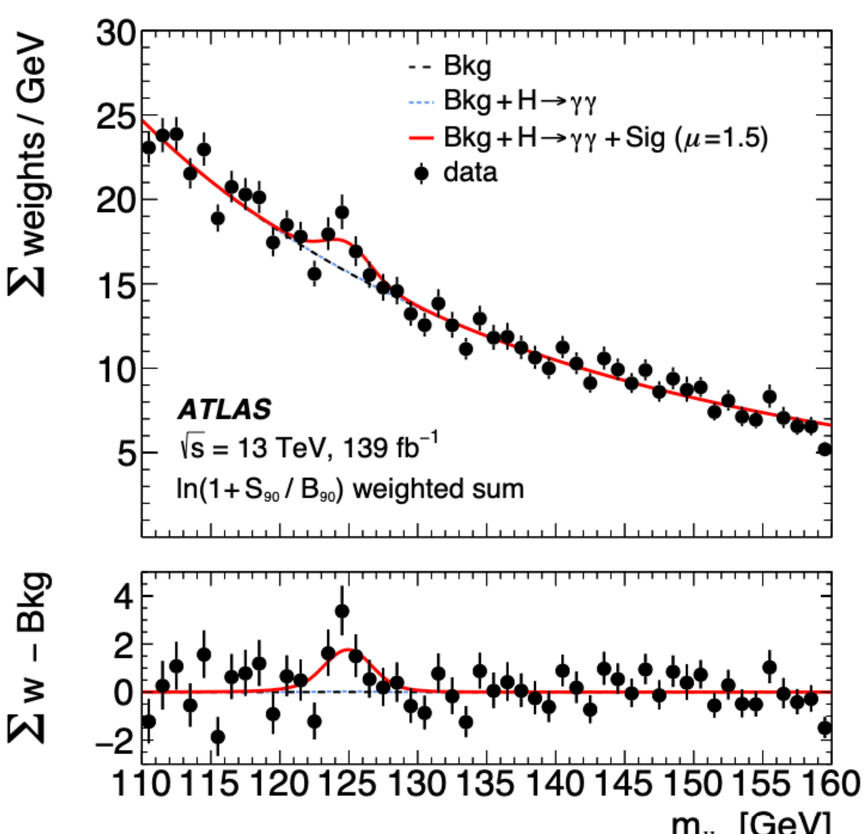


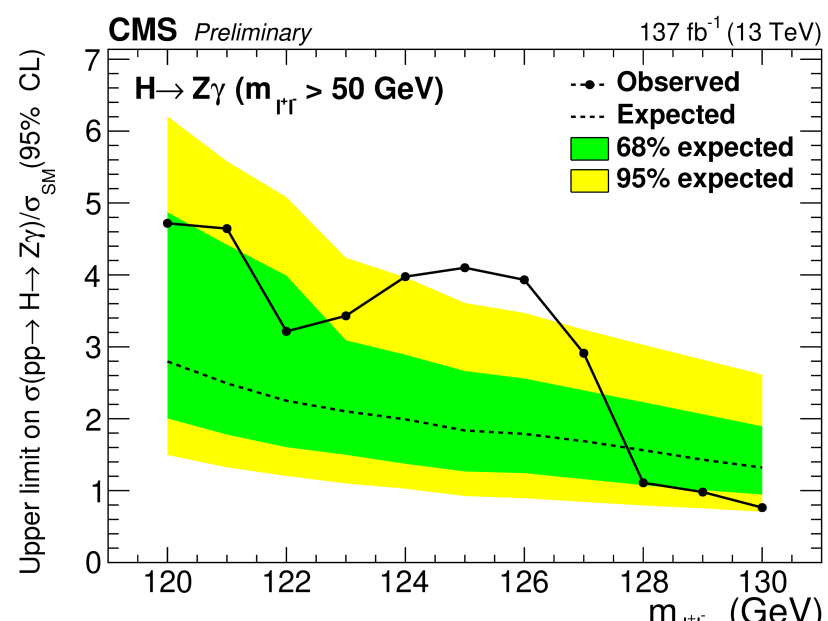


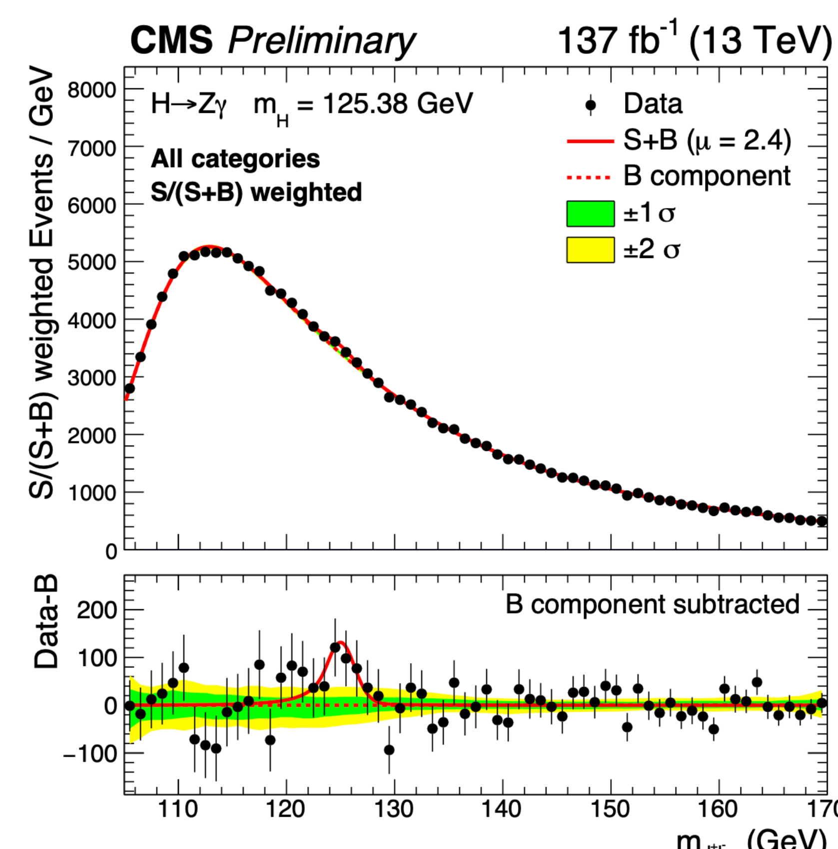
H → $\ell\ell\gamma$

- ATLAS claimed the first evidence for this final state : [Phys. Lett. B 819 (2021)]
  - $m_{\ell\ell} < 30\,\mathrm{GeV}$: 3.2$\sigma$ with a best fit $\mu = 1.5 \pm 0.5$
  - 9 different categories, signal is extracted fitting the $m_{\ell\ell\gamma}$ distribution
- Due to the boost of the di-electron system a special trigger and identification has been developed
- CMS has a similar analysis but focused on the $Z\gamma$ channel (2.7 sigma excess): [HIG-19-014]









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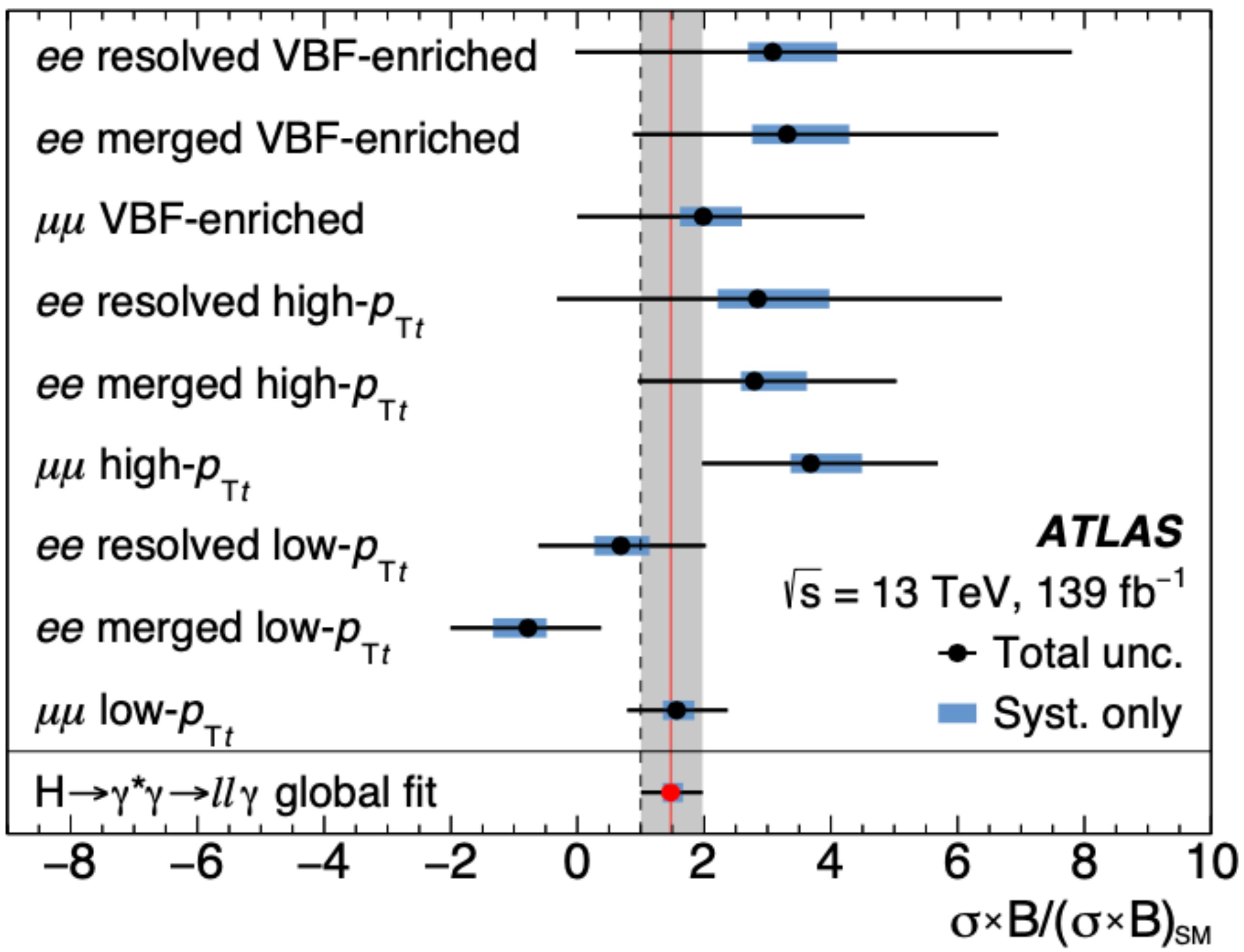
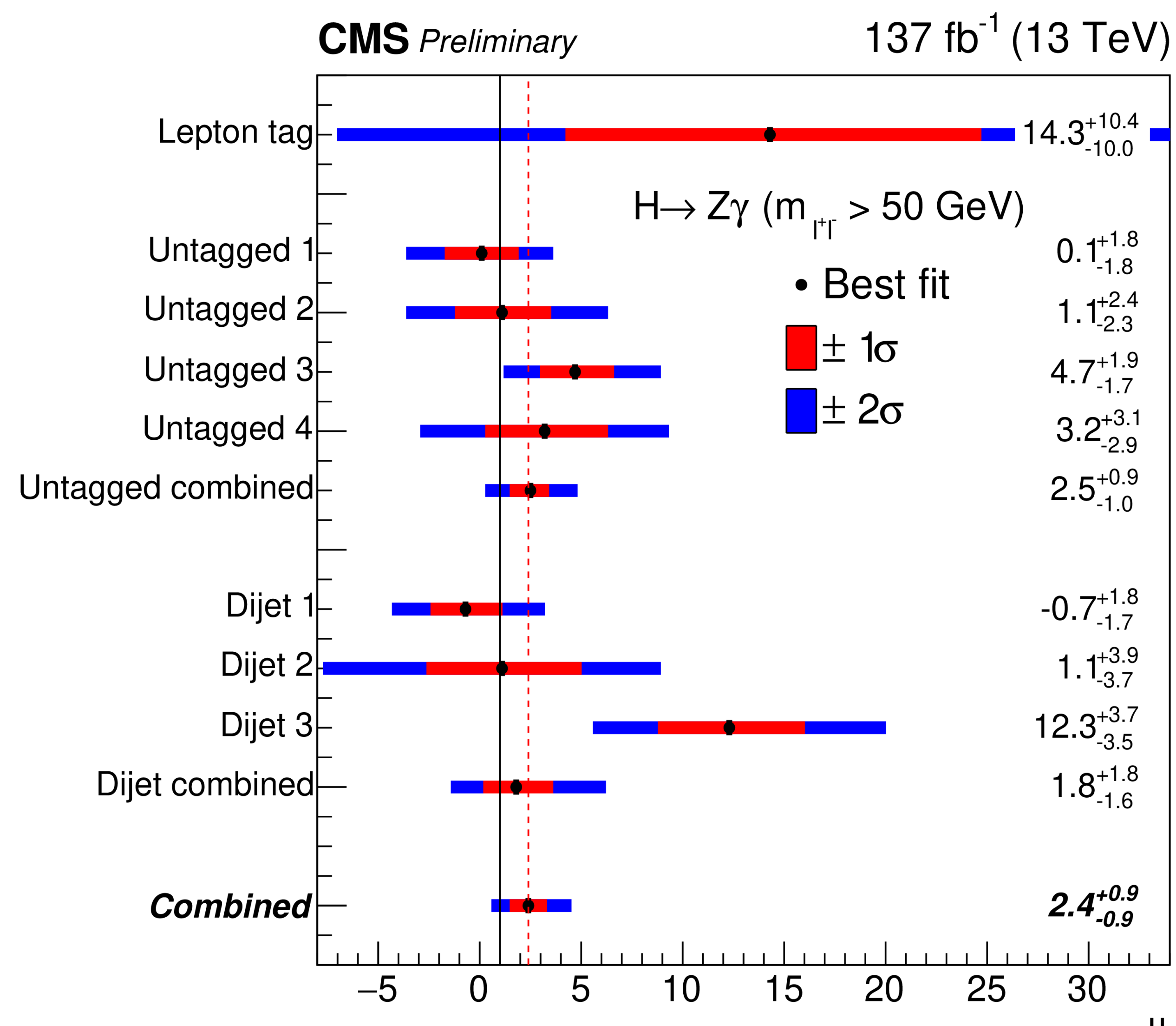
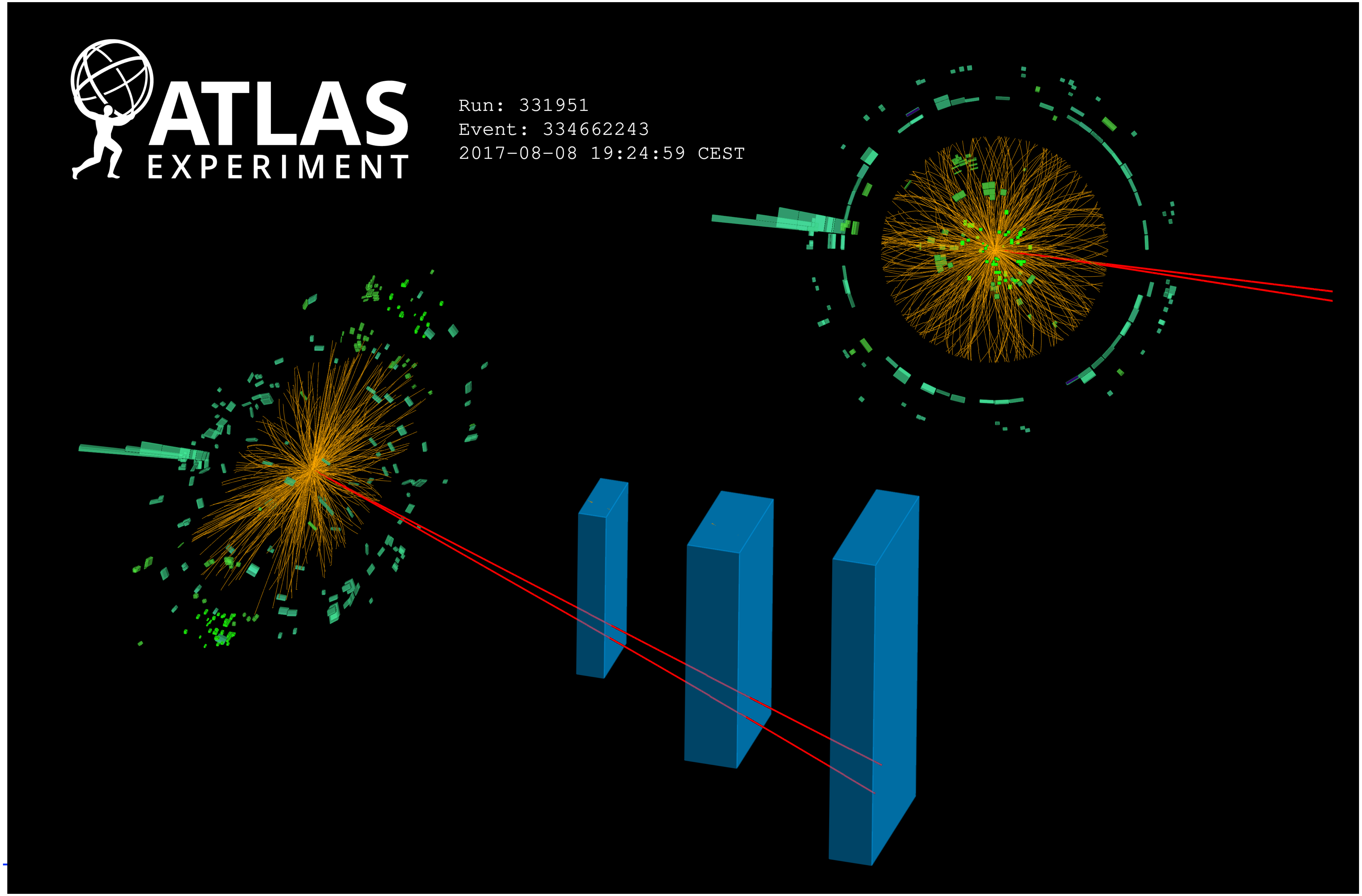




Events display for H $\rightarrow \ell\ell\gamma$



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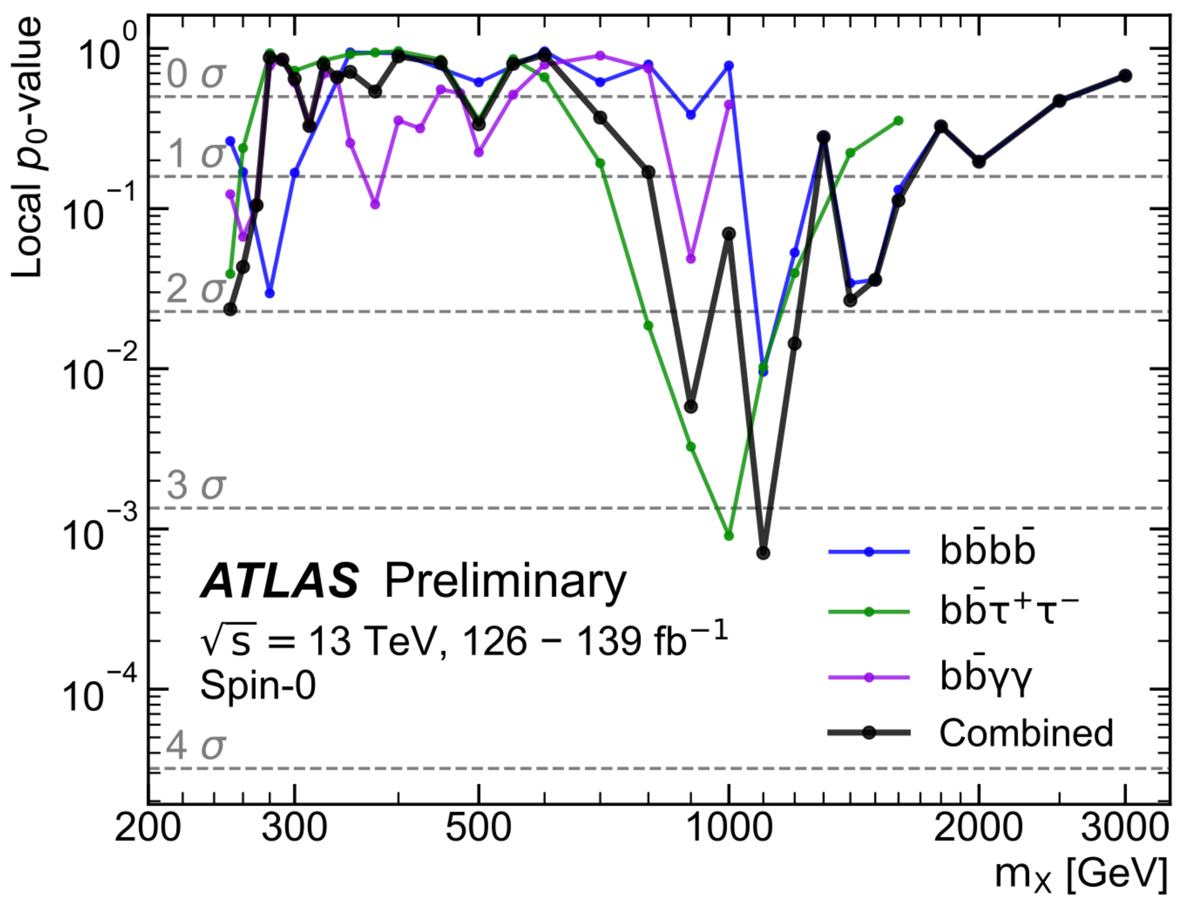
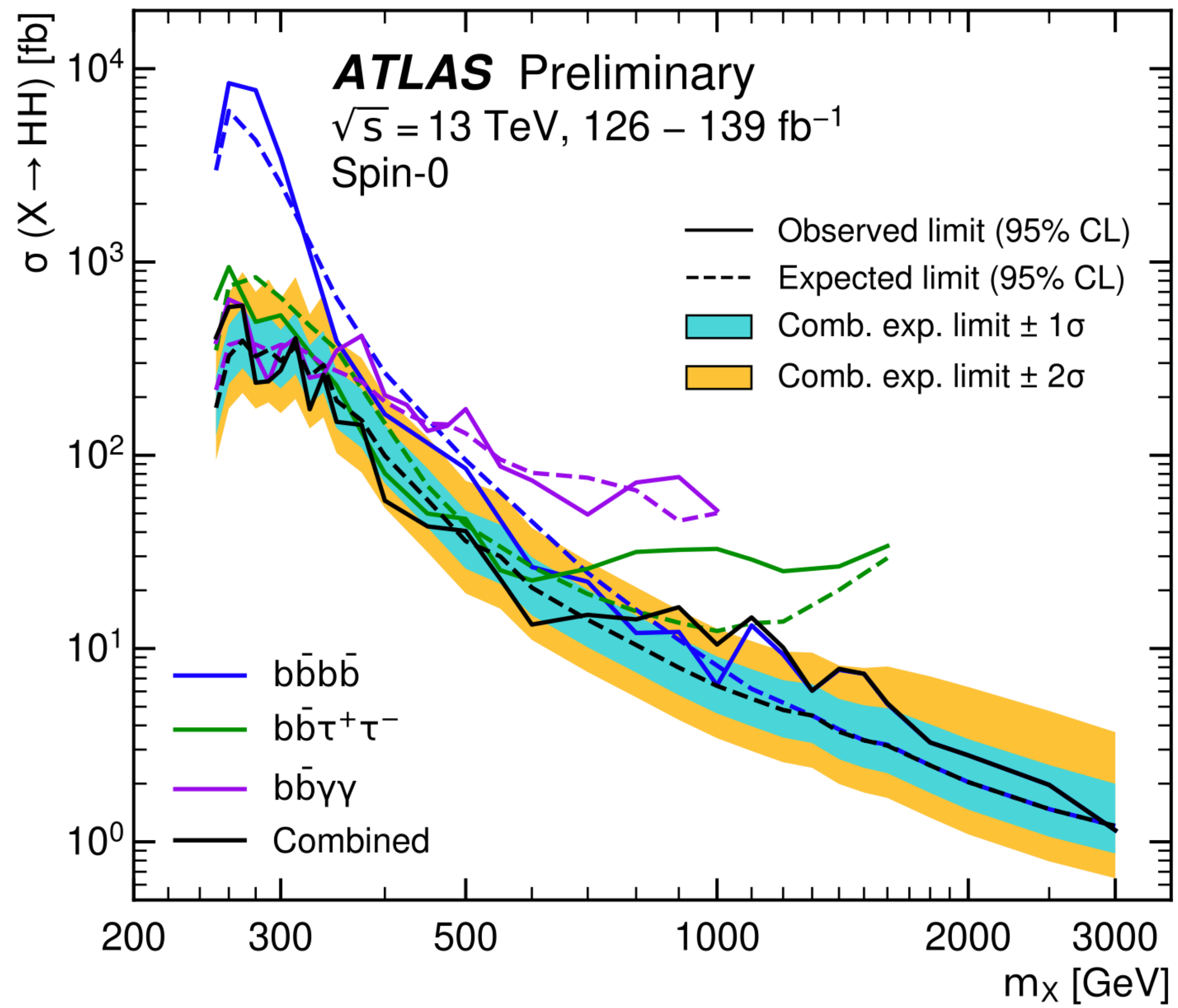
Beyond Standard Model

HH from heavy scalar decay





[ATLAS-CONF-2021-052]

More on BSM Higgs bosons

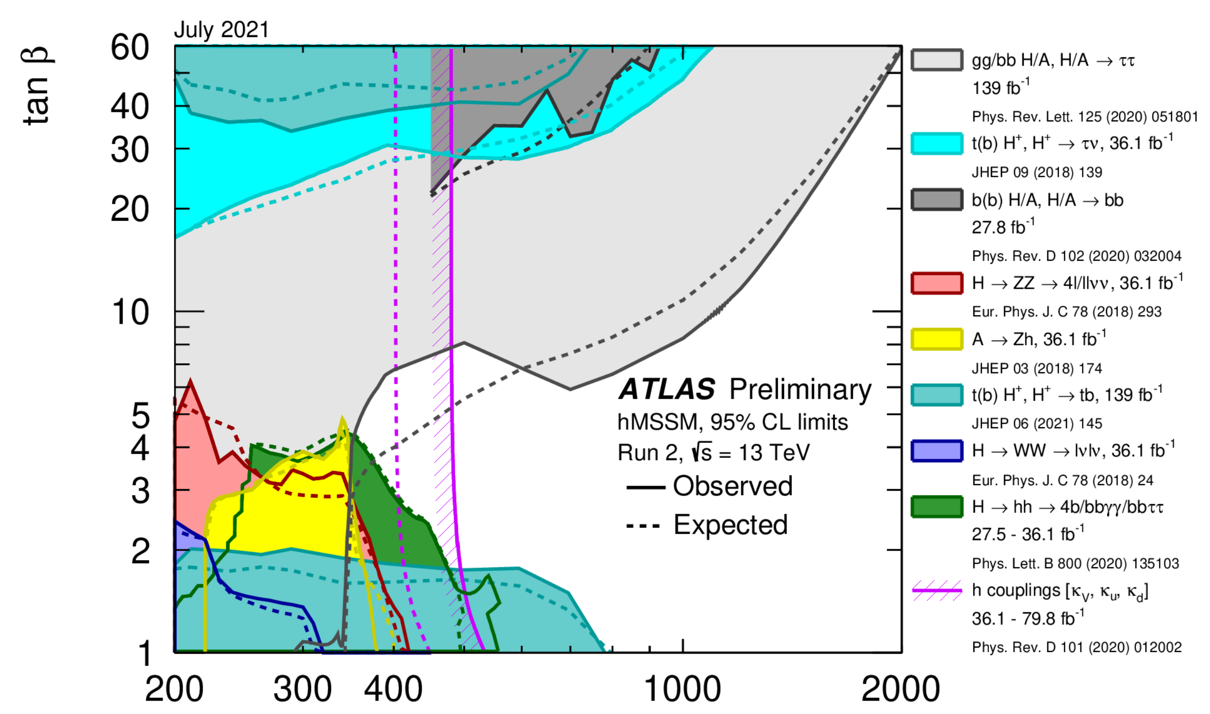
- LFV : Phys. Rev. D. (2021) 104 032013
  - BR(H $\rightarrow \mu\tau$) < 0.15% @ 95% CL
  - BR(H $\rightarrow e\tau$) < 0.22% @ 95% CL

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \rightarrow H_{SM}$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} + \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} \rightarrow h, H, A, H^\pm$$

$$\begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} + \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} + s \rightarrow h_{(1,2,3)}, a_{(1,2)}, h^\pm$$

- Search for extra scalar particles in a wide range of masses
  - Motivated by several extension of the SM which predict a larger number of bosons
  - Limits on cross sections and BR usually interpreted in 2HDM
    - Most famous ones being the MSSM, a number of benchmarks model has been prepare by the LHC WG: LHCHWG-2021-001
    - The precise measurement of the SM Higgs Boson couplings and mass, poses stringent limits to parameter space that has to include a SM-like Higgs Boson with a mass of 125 GeV



ATL-PHYS-PUB-2021-030

- Mixing of the SM Higgs bosons with a dark sector mediator is also a prolific field of research

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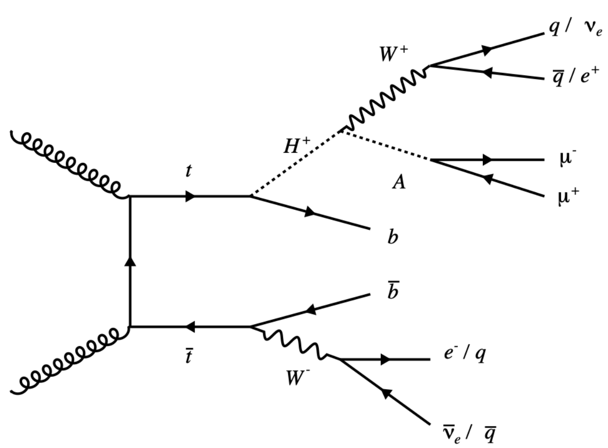
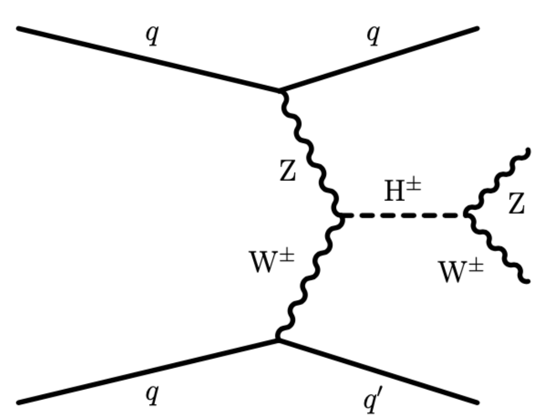
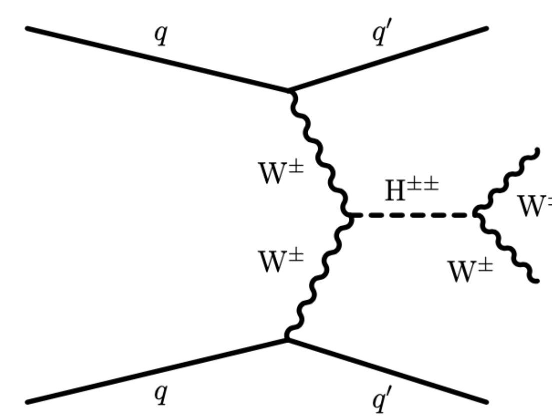
Charged Higgs

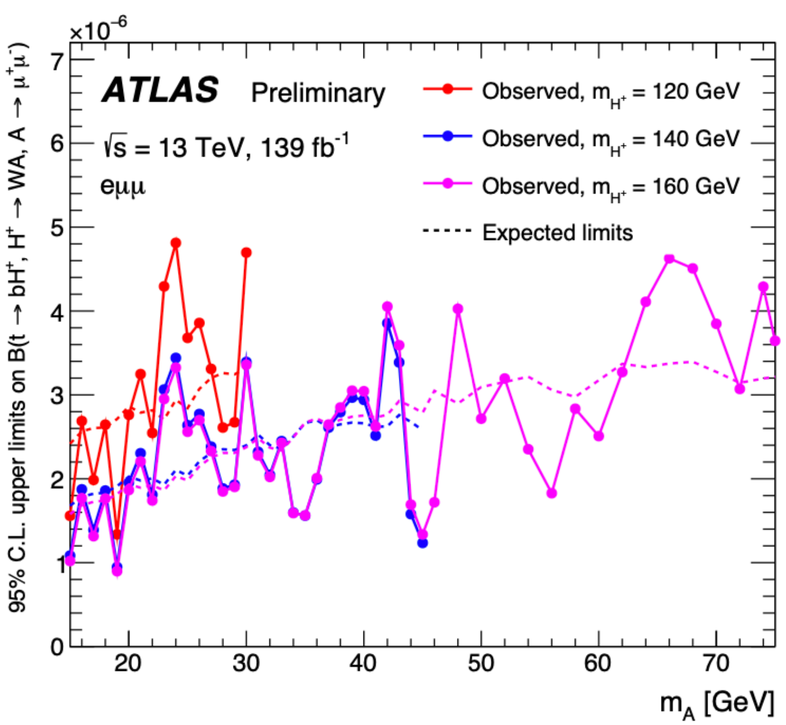
- Several models foresees $H^{\pm}$ bosons: 2HDM are the most common, but others are interesting as well
  - Some foresee also $H^{\pm\pm}$, like exotic model (Georgi-Machacek), where extra (charged) Higgs bosons couple to vector bosons only

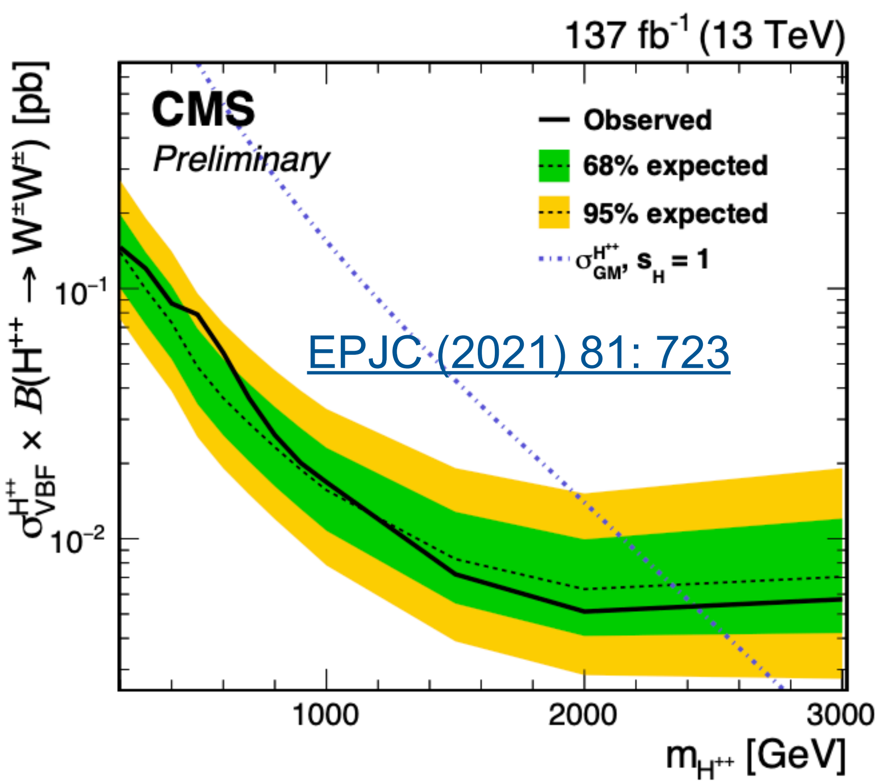




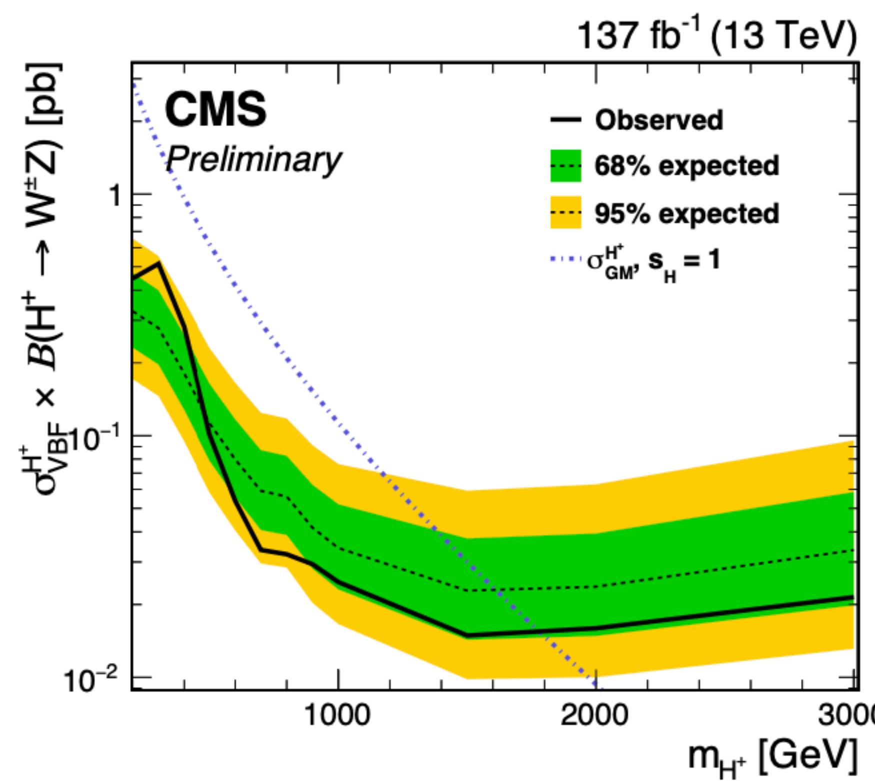


ATLAS-CONF-2021-047
ATLAS-CONF-2021-037

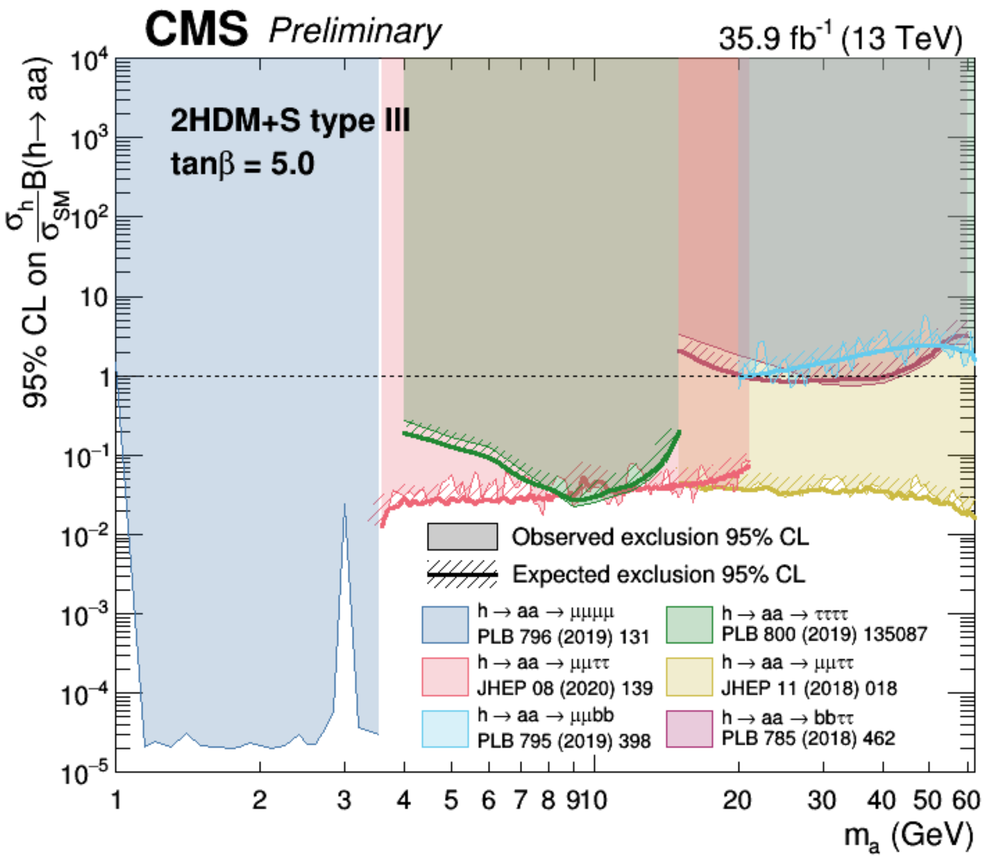


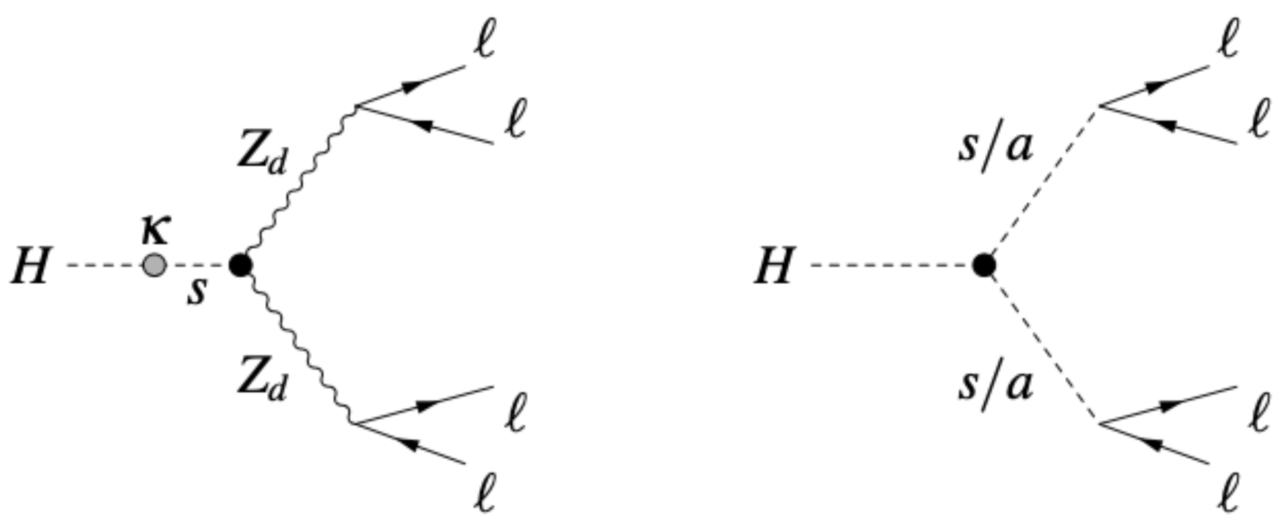


EPJC (2021) 81: 723

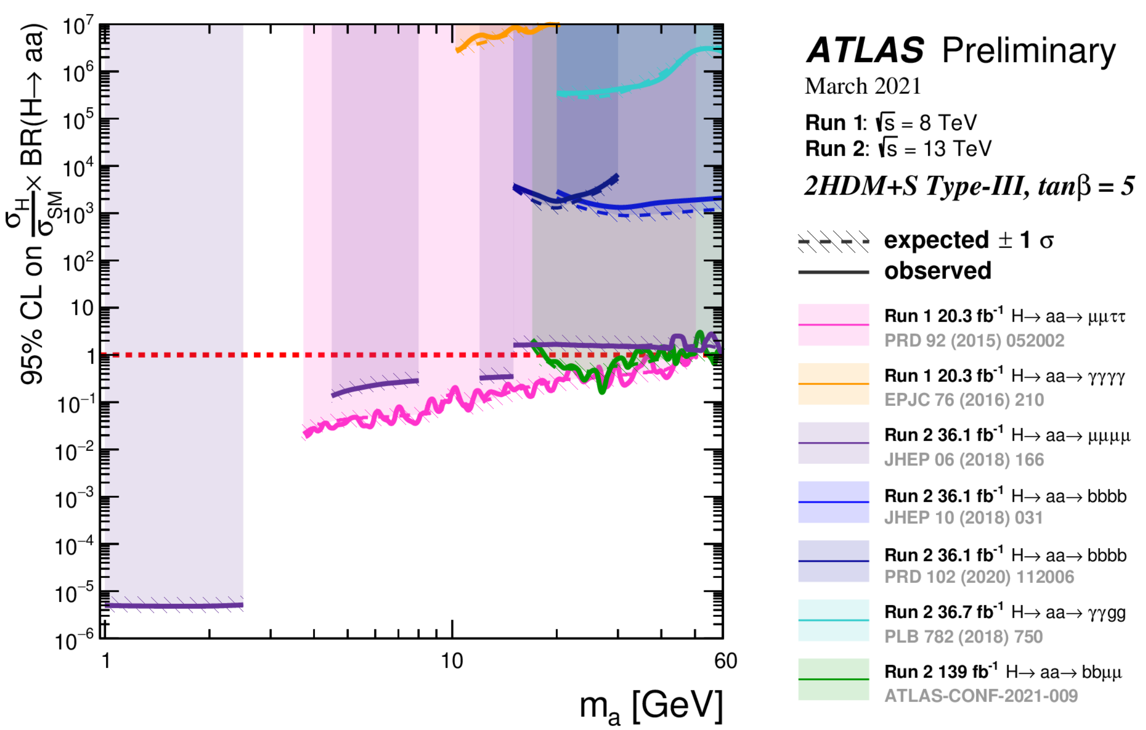


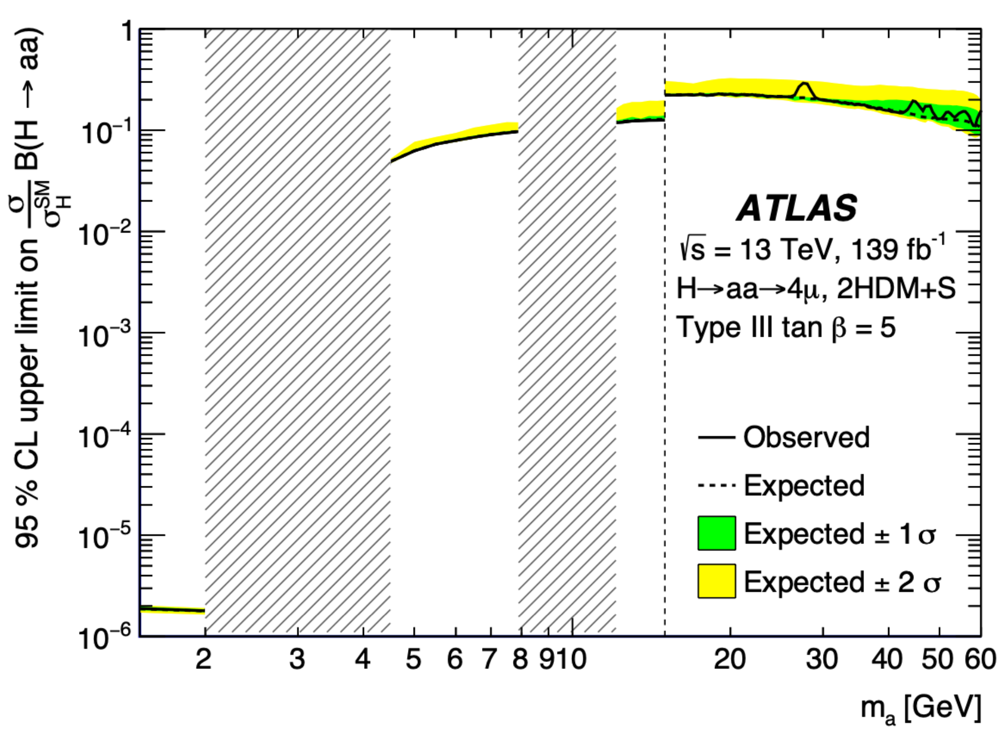
NMSSM summary plots





arXiv:2110.13673





Summary

- In the past 10 years we passed from a discovery phase to the measurement of the Higgs boson proprerties
  - Also with the hope to reveal something beyond the SM …
  - Analysis complexity has improved also thanks to to extensive use of state-of-the-art machine learning techniques for object identification
- We managed to measure final states not conciveable at the beginning of 2016
- Next challenge is the measurement of the Higgs boson self coupling
  - Out of reach for LHC, but it may not be so far away at HL-LHC

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Back up

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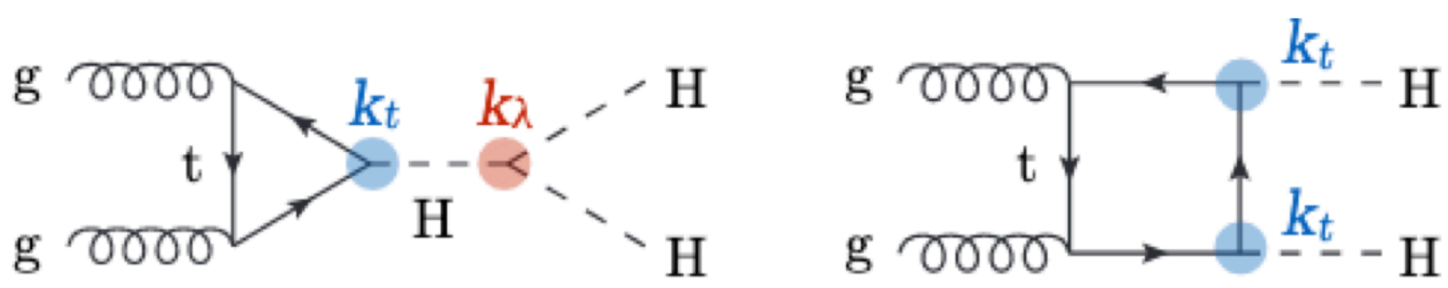
evd. = evidence

Analysis	Final states	13 TeV $\mathcal{L}$ [fb^{-1}]	BR (SM)	$\sigma_H \times$ BR(H decays)	ATLAS/CMS references
$c\bar{c}$		139, 35.9	2.9%	26 × SM, 70 × SM	**ATLAS-CONF-2021-021**, JHEP 03 (2020) 131
invisible		139, 35.9	$\sim 10^{-3}$		ATLAS-CONF-2020-052, PLB 793 (2019) 520
$Z\gamma$	ee/μμ+γ	139, 35.9	$\sim 10^{-3}$	**evd. μ = 1.5**, 3.9 × SM	**arXiv:2103.10322 (PLB 2021)**, JHEP 11 (2018) 152
$\mu^+\mu^-$		139, 137	$\sim 10^{-4}$	2.2 × SM, **evd. μ = 1.19**	**PLB 812 (2021) 135980**, **JHEP 01 (2021) 148**
				BR(H decays)	
$\rho\gamma$	$\pi^+\pi^-\gamma$	35.6	$\sim 10^{-5}$	8.8×10^{-4}	JHEP 07 (2018) 127
$\phi\gamma$	$K^+K^-\gamma$		$\sim 10^{-6}$	4.8×10^{-4}	
$Z\rho$	ee/μμ + $\pi^+\pi^-$	137	$\sim 10^{-5}$	$(1.04–1.31) \times 10^{-2}$	JHEP 11 (2020) 039
$Z\phi$	ee/μμ + K^+K^-	137	$\sim 10^{-6}$	$(3–4) \times 10^{-3}$	
$Z\eta_c$	ee/μμ + had	139	$\sim 10^{-5}$	(σ × BR =110 pb)	PRL 125 (2020) 221802
ZJ/ψ			$\sim 10^{-6}$	(σ × BR =100 pb)	
$J/\psi\ \gamma$	$\mu^+\mu^-\gamma$	36.1, 35.9	$\sim 10^{-6}$	3.5×10^{-4}, 7.6×10^{-4}	PLB 786 (2018) 134, EPJ C 79 (2019) 94
$\psi(2S)\gamma$		36.1	$\sim 10^{-6}$	2.0×10^{-3}	PLB 786 (2018) 134
$\Upsilon(nS)\gamma$ (n=1,2,3)		36.1	$\sim 10^{-9}$	$(4.9, 5.9, 5.7) \times 10^{-4}$	
$\Upsilon\Upsilon$	4μ	37.5	$\sim 10^{-9}$	1.4×10^{-3}	PLB 797 (2019) 134811
$J/\psi\ J/\psi$			$\sim 10^{-10}$	1.8×10^{-3}	
e^+e^-		139	$\sim 10^{-9}–10^{-10}$	3.6×10^{-4}	PLB 801 (2020) 135148



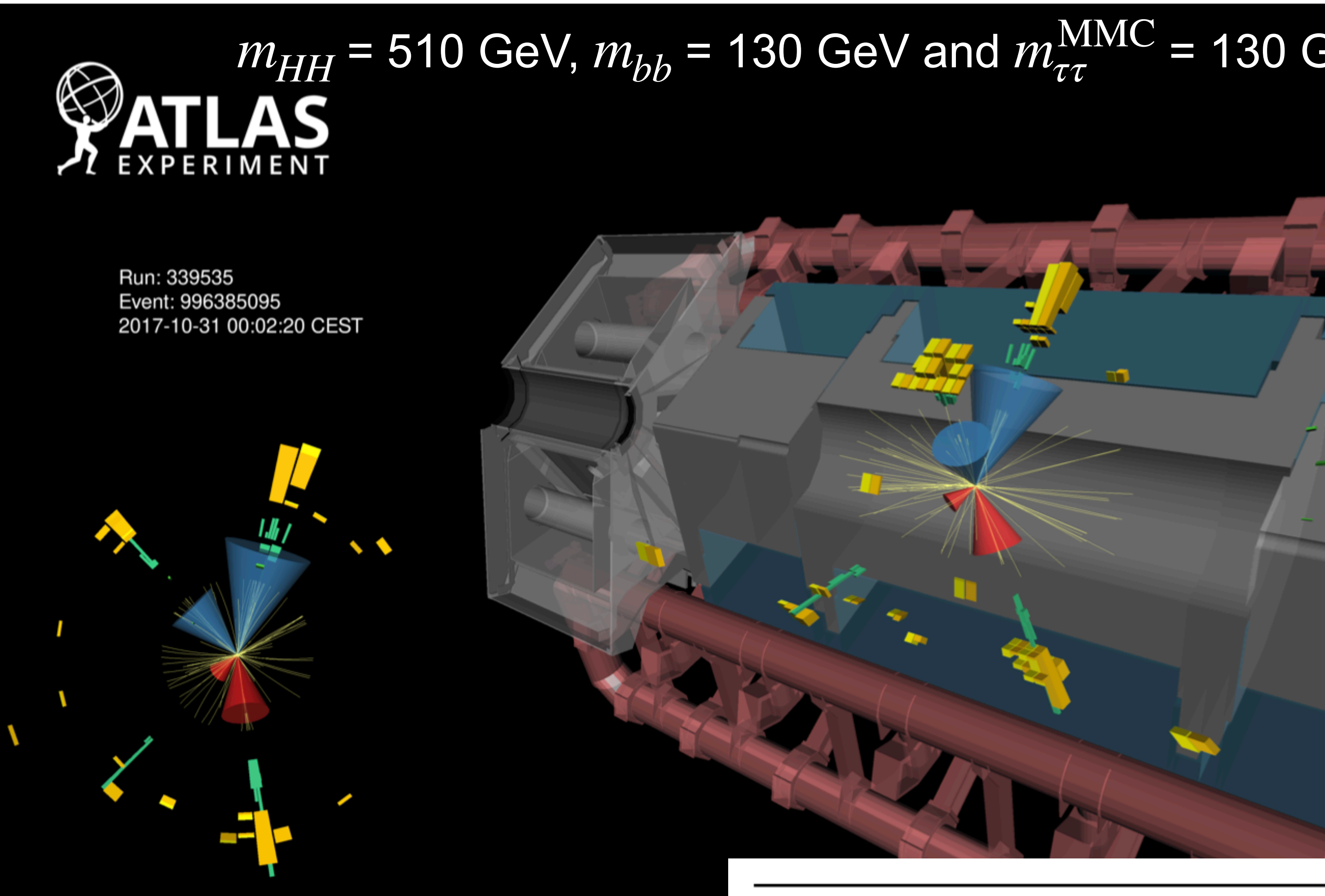
$$A = k_t\, k_\lambda\, T + k_t^2\, B$$

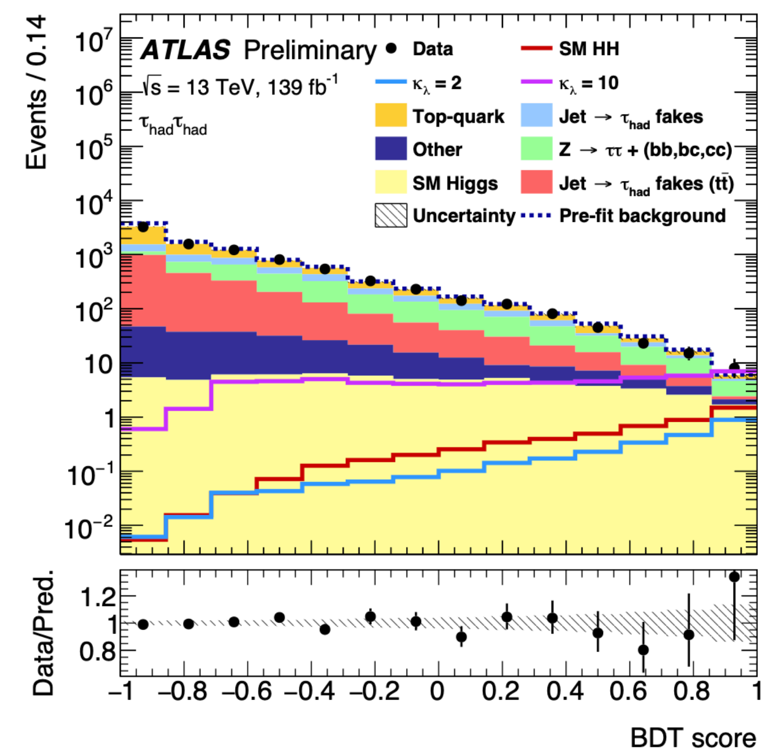
$$\sigma(k_t, k_\lambda) \sim |A|^2 = k_t^2\, k_\lambda^2\, |T|^2 + k_t^4\, |B|^2 + k_t^3\, k_\lambda\, |T^*B + B^*T|$$

$$= k_t^2\, k_\lambda^2\, t + k_t^4\, b + k_t^3\, k_\lambda\, i$$

triangle *box* *interference*

ATLAS HH->bb$\tau\tau$





		Observed	$-2\,\sigma$	$-1\,\sigma$	Expected	$+1\,\sigma$	$+2\,\sigma$
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	145	70.5	94.6	131	183	245
	$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{SM}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF}$ [fb]	265	124	167	231	322	432
	$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{SM}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{ggF+VBF}$ [fb]	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{SM}$	4.65	2.08	2.79	3.87	5.39	7.22

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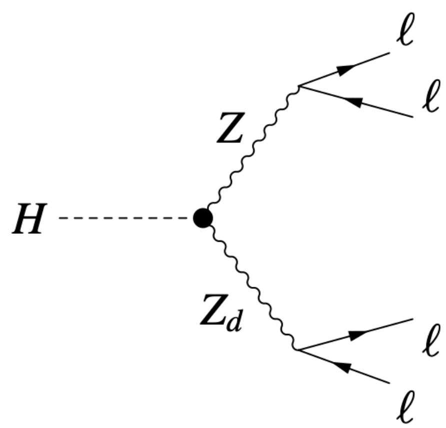
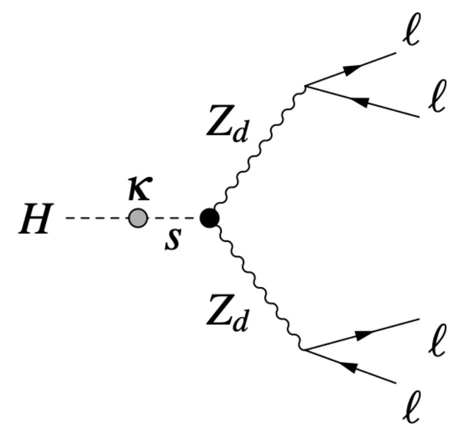
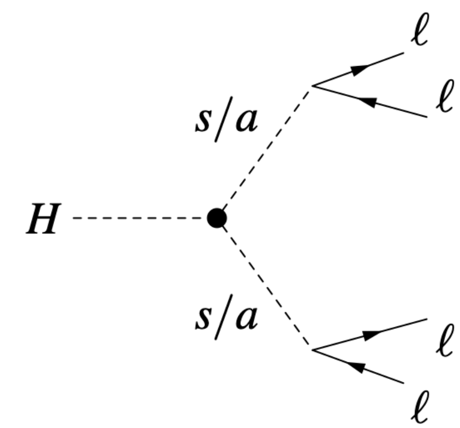
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

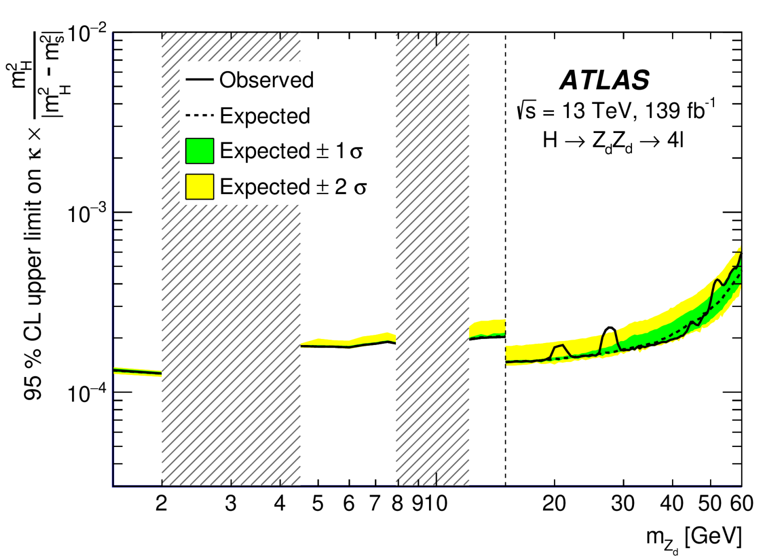
H → XX searches

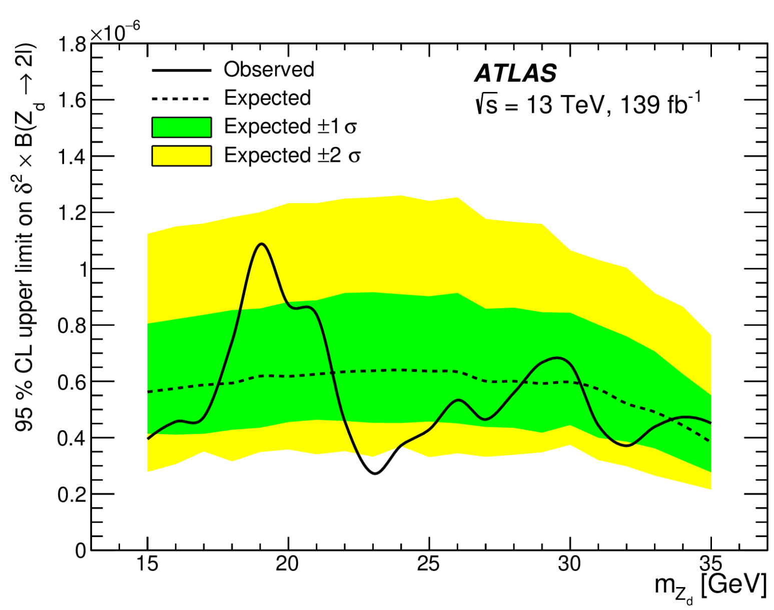
- ATLAS: [arXiv:2110.13673](https://arxiv.org/abs/2110.13673)
  - **Limits on the BR H->xx can also be extracted**

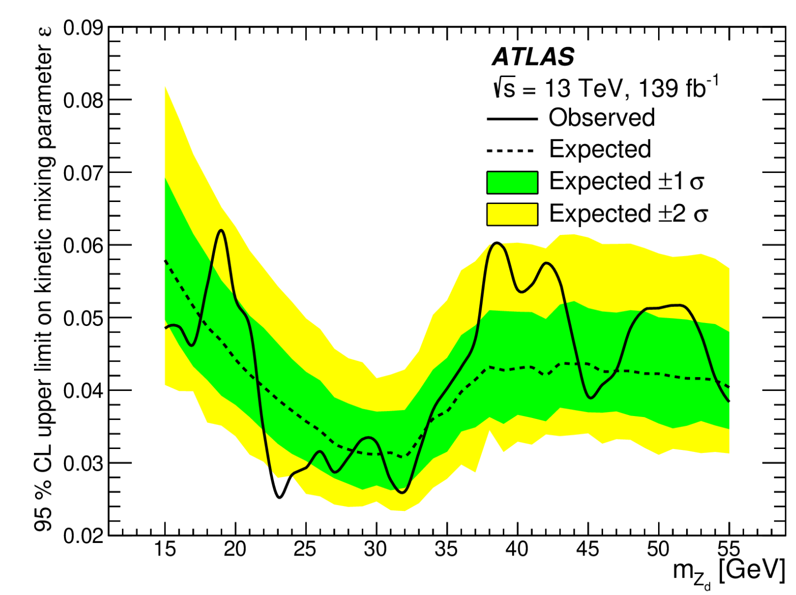






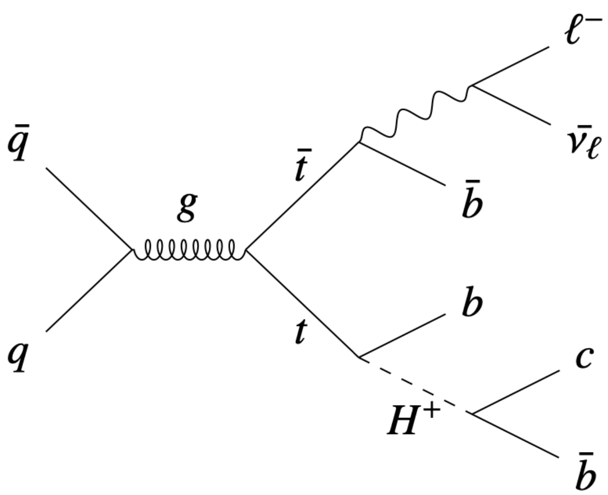
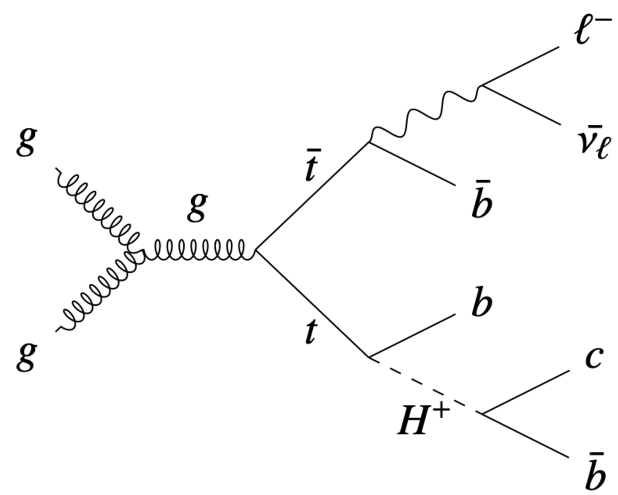


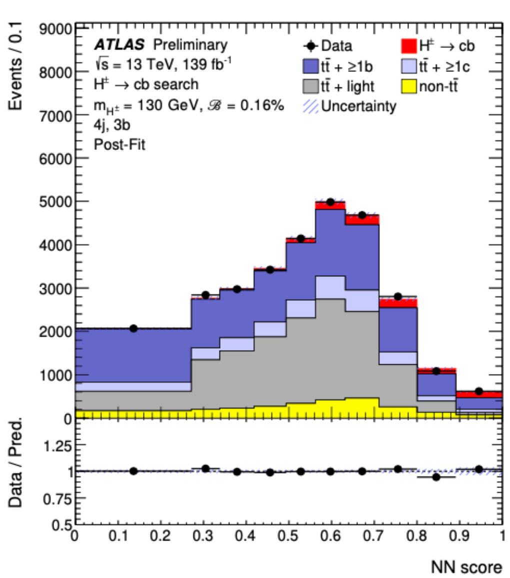


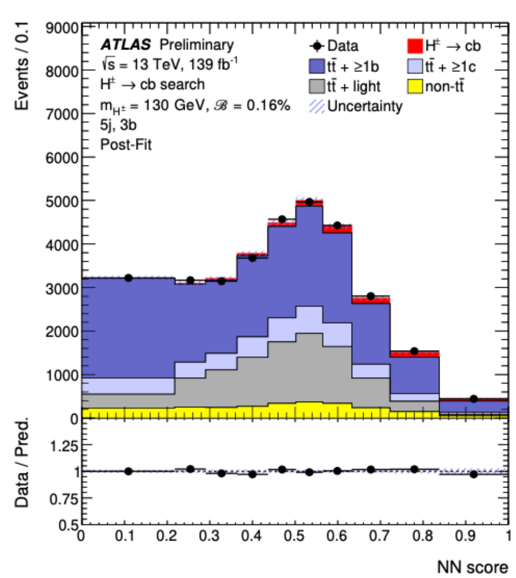


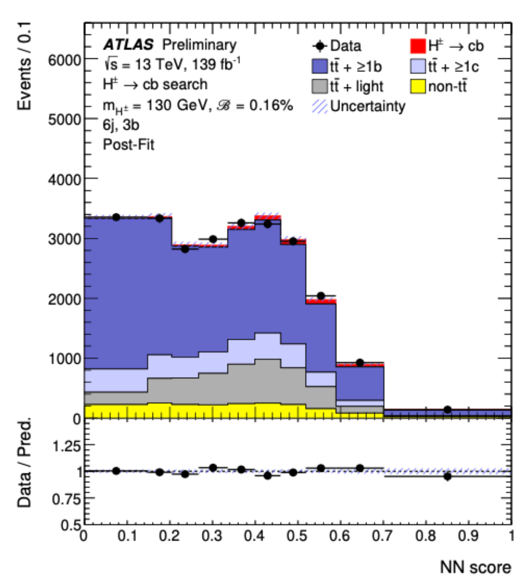
Latest one from ATLAS

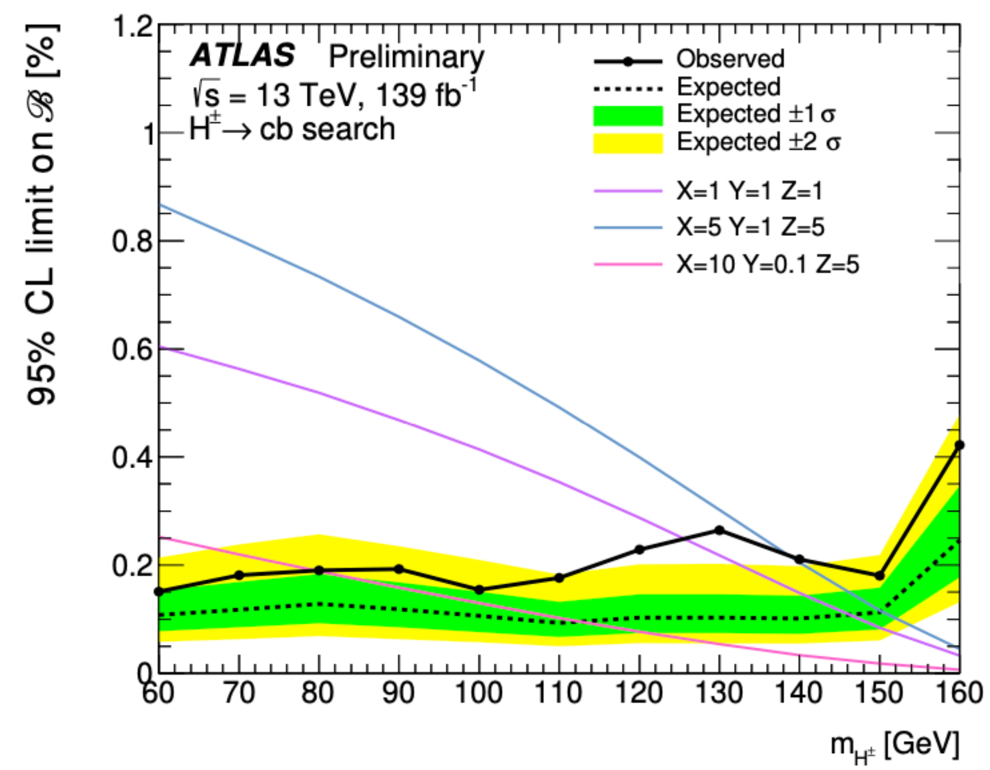
- http://cdsweb.cern.ch/record/2779169/files/ATLAS-CONF-2021-037.pdf



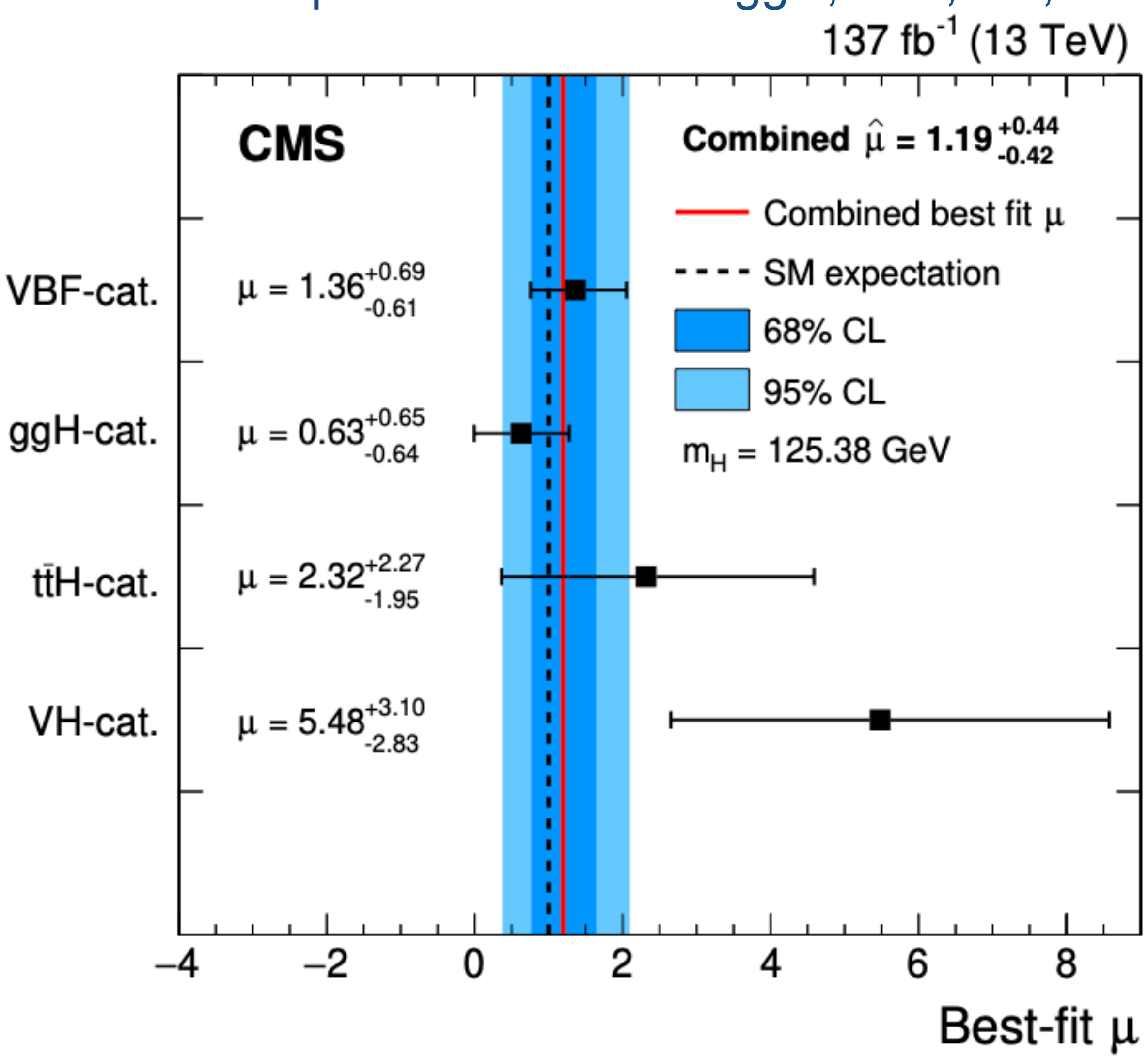


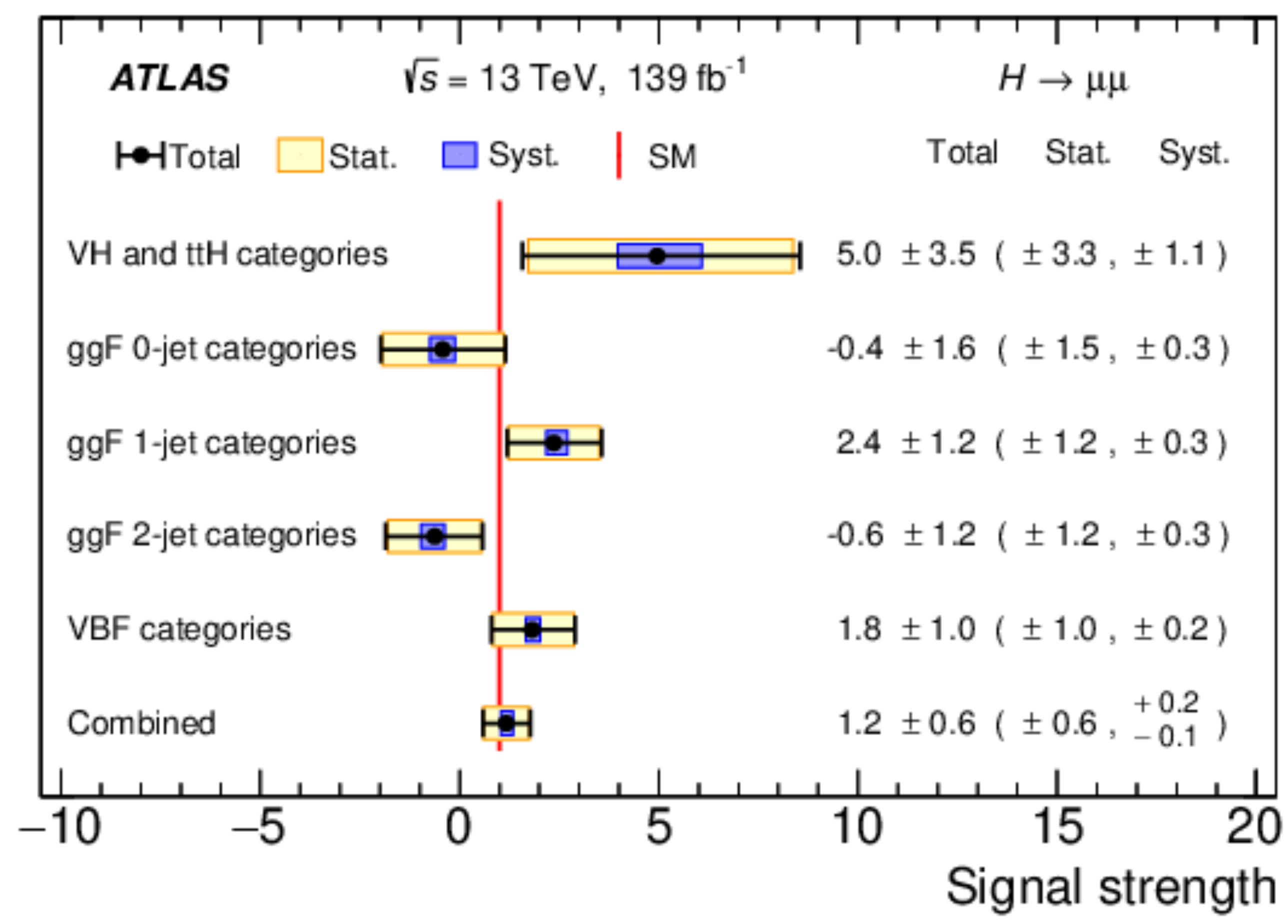




$\mathbf{H \rightarrow \mu\mu}$ (BR: 2.17x10-4)

- ATLAS: 2 σ signal for a best μ value of 1.2 ± 0.6
  - Phys. Lett. B 812 (2021)
- CMS : **first evidence** of this decay mode
  - Best μ value: $1.19 \pm 0.40 \pm 0.17$ JHEP 01 (2021)
    - 4 production modes: ggH, VBF, VH, ttH





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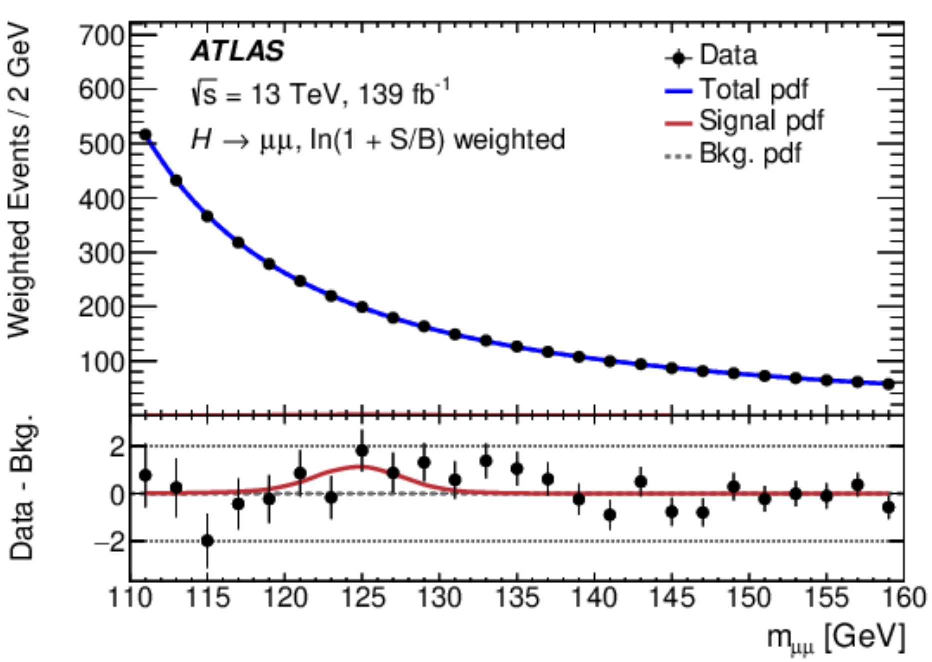
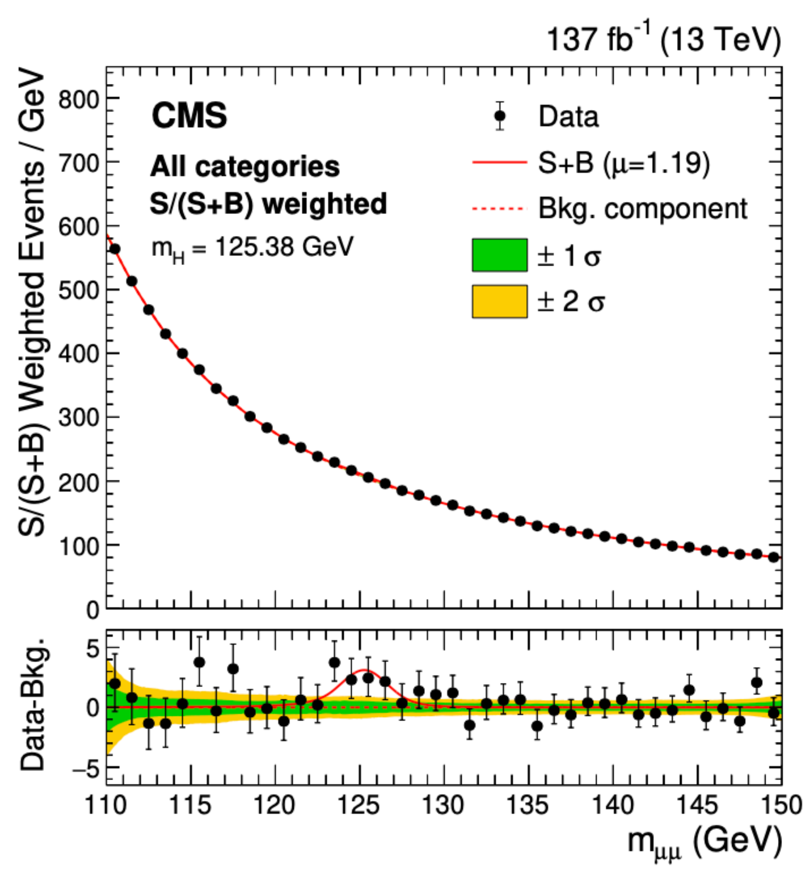
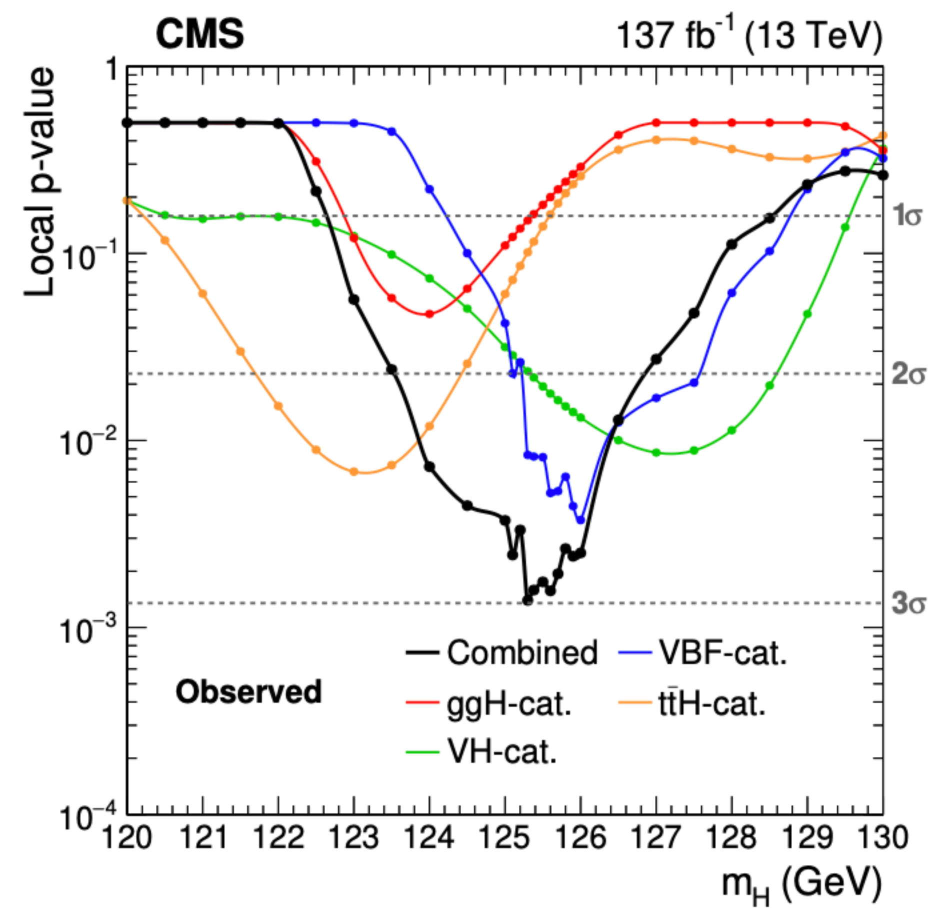
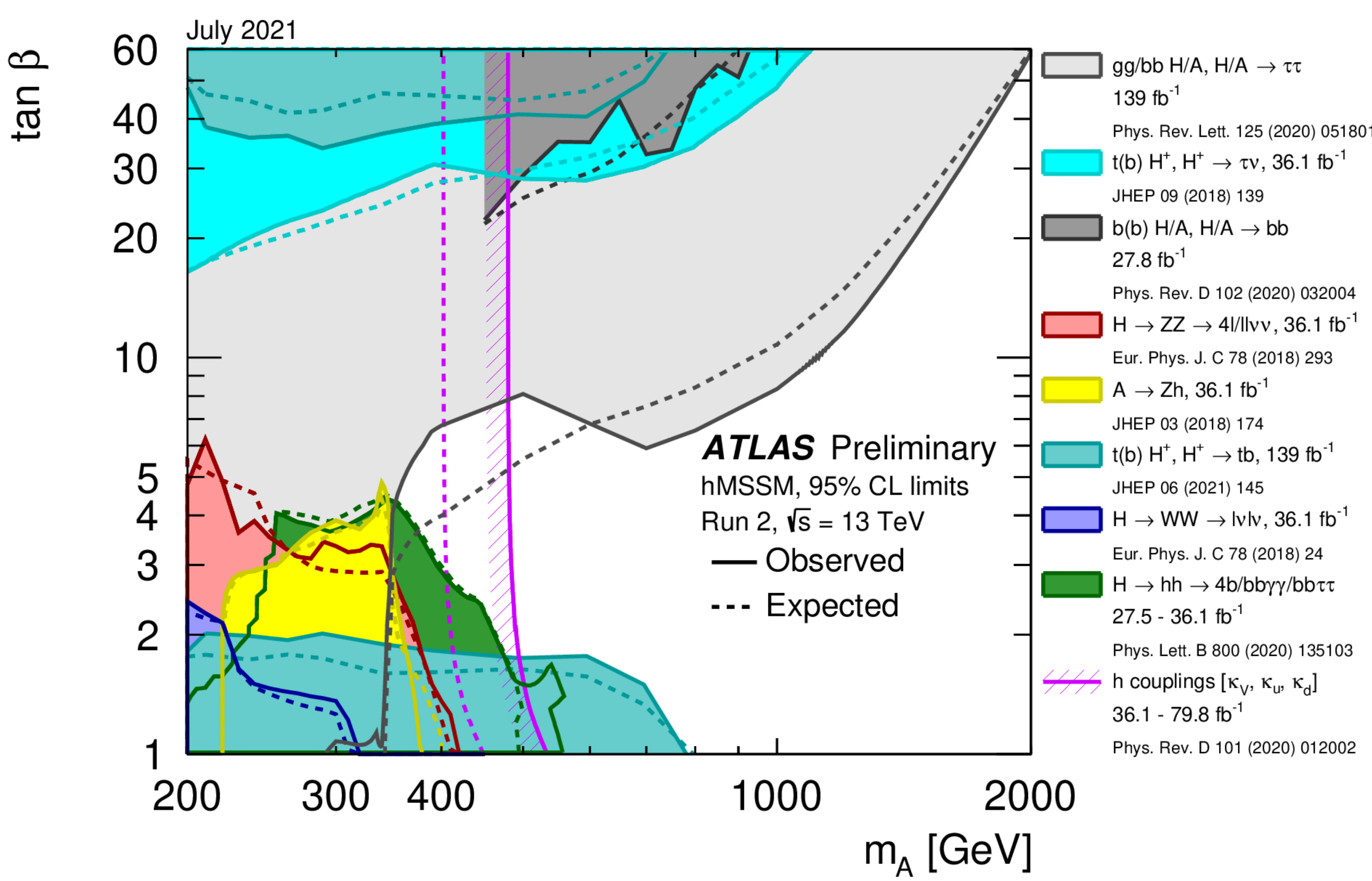


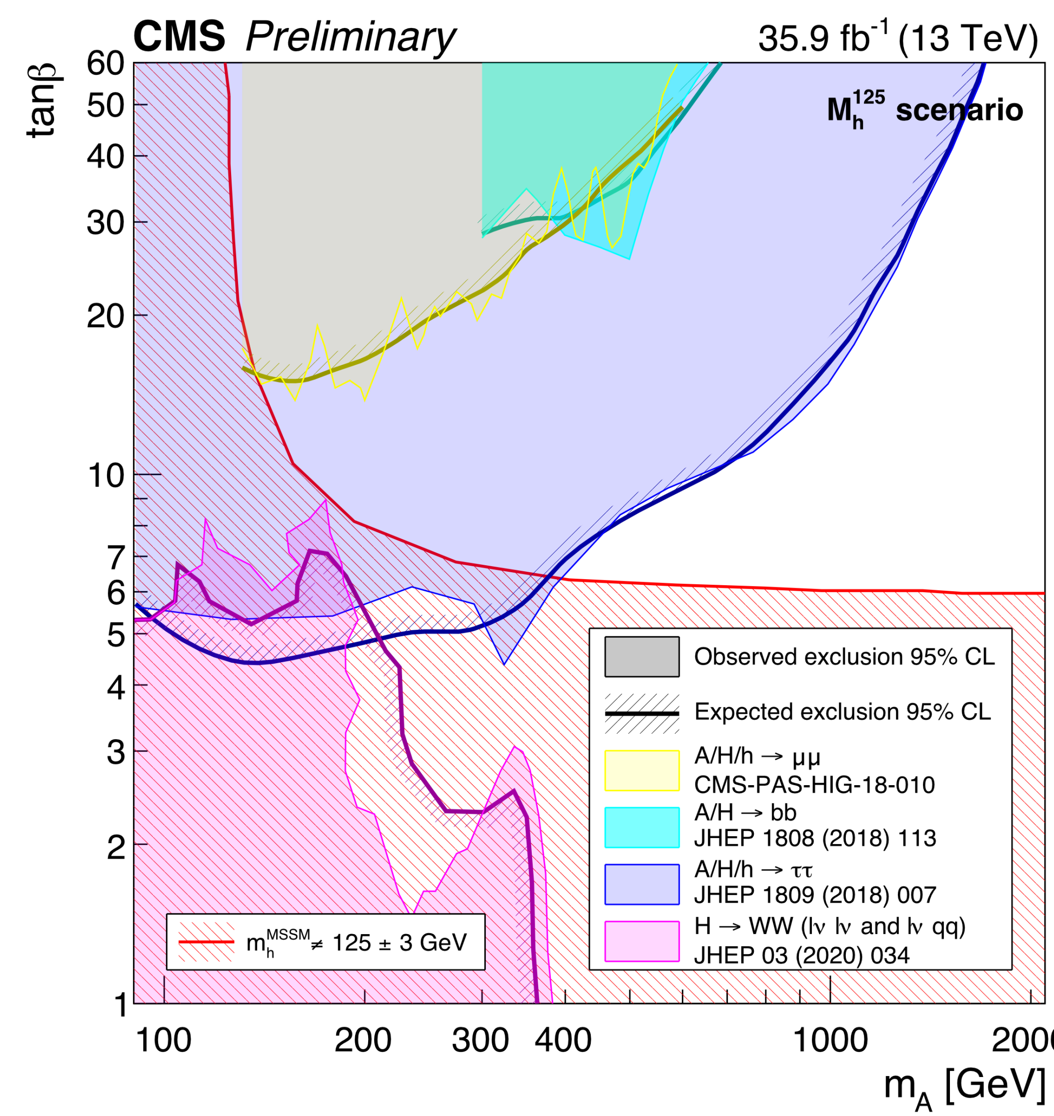




Latest (approved) MSSM Summary

ATL-PHYS-PUB-2021-030





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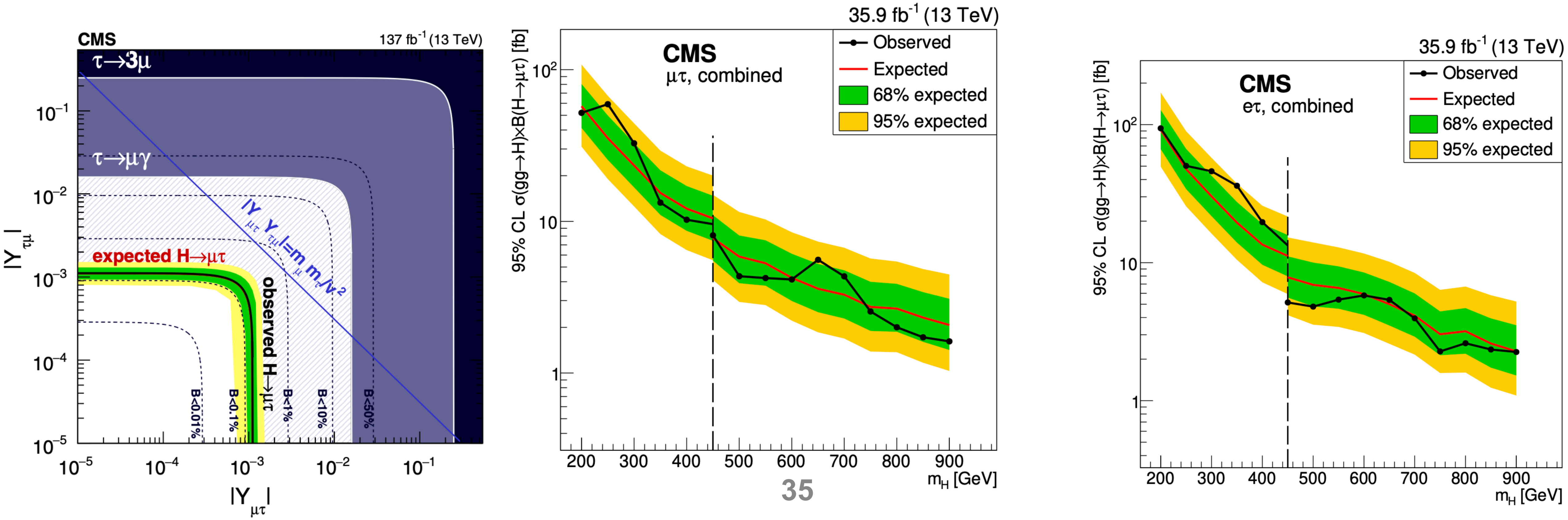
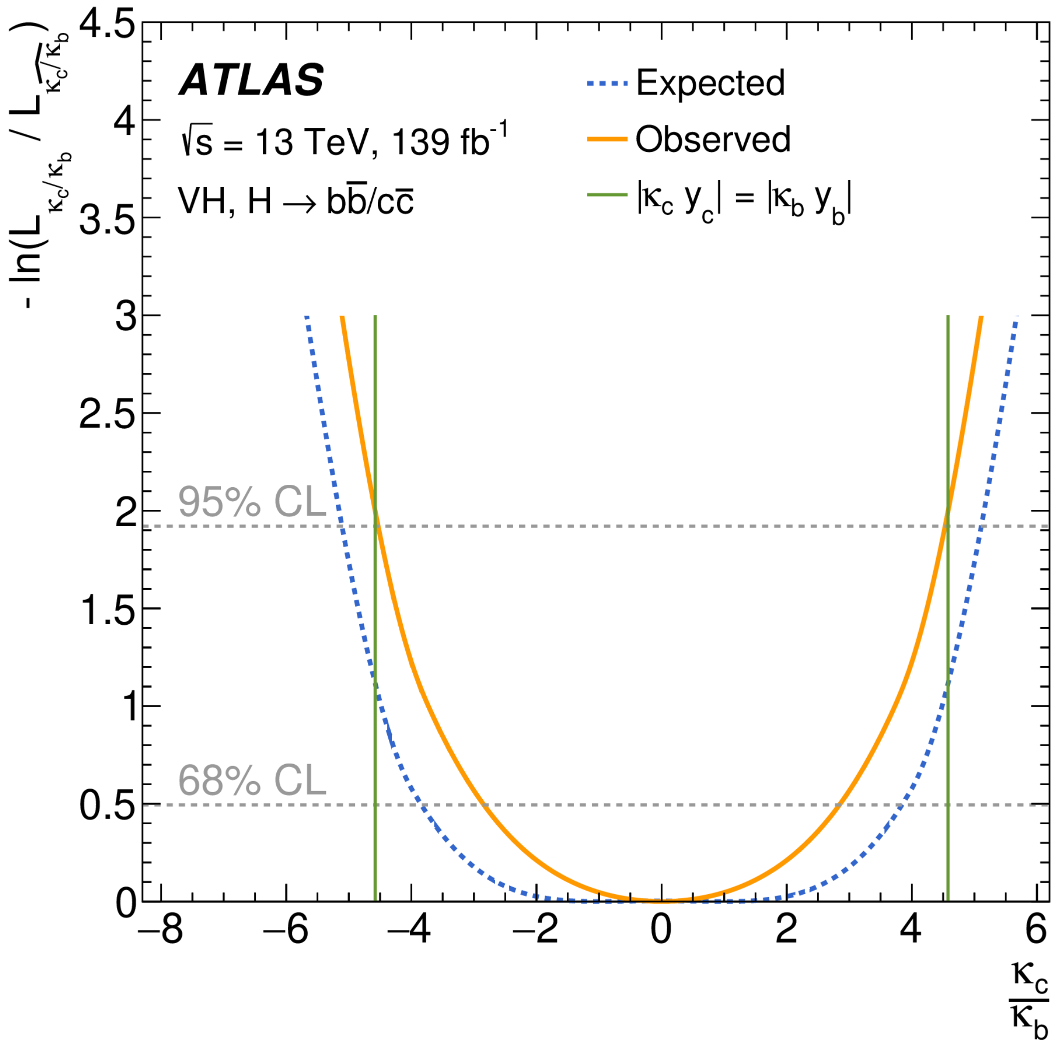
LFV Higgs decays

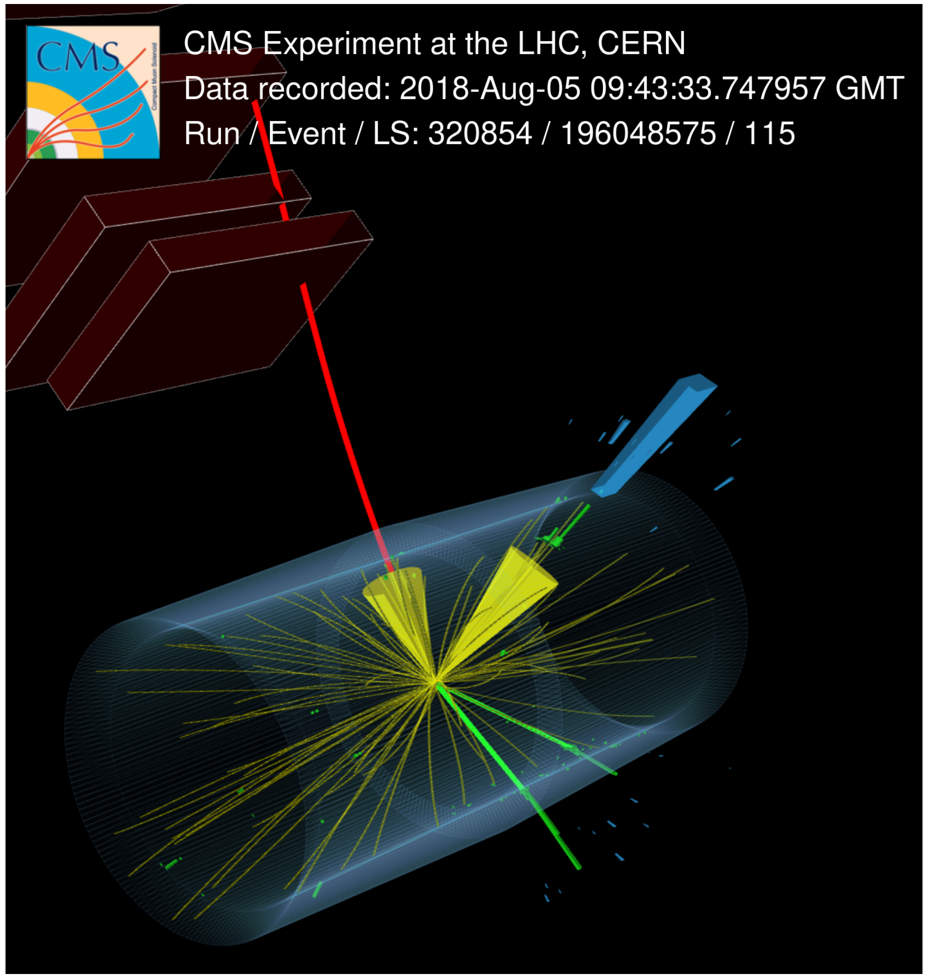
- Clearly interesting also in view of the BPH “anomalies"
  - ATLAS and CMS has similar analyses, only CMS has one covering the full Run2 data
    - e-mu channel has tighter constraints from $\mu \to e\gamma$ process
- SM Higgs : [Phys. Rev. D. (2021) 104 032013]
  - BR(H $\to \mu\tau$) < 0.15% @ 95% CL
  - BR(H $\to e\tau$) < 0.22% @ 95% CL
- BSM Higgs : [JHEP (2020) 03 103]
  - Limits on the sigmaxBR as a function of the mass is set



VH→cc (BR: 2.88x10^{-2})

- ATLAS best limit is 26 x SM
  - But combining VH→cc with VH→bb measured $|k_c/k_b|$ to be < 4.5: HIGG-2021-12
    - Evidence for VW->cq decay, for more details see Antonio Jacques Costa talk
- CMS best limit is 7.7 x SM
  - **Best stringent limit on 1.1 <$|k_c|$ < 5.5 and first observation of VZ→cc** at a hadronic collider : HIG-21-008





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VH → cc systematics

Table 1: The relative contributions to the total uncertainty on the signal strength modifier μ for the VH(H $\rightarrow$ c$\bar{c}$) process.

Uncertainty source	$\Delta\mu / (\Delta\mu)_{\text{tot}}$
Statistical	**85%**
Background normalizations	37%
Experimental	**48%**
Sizes of the simulated samples	37%
Charm identification efficiencies	23%
Jet energy scale and resolution	15%
Simulation modeling	11%
Luminosity	6%
Lepton identification efficiencies	4%
Theory	**22%**
Backgrounds	17%
Signal	15%