BSM HIGGS AT LHC

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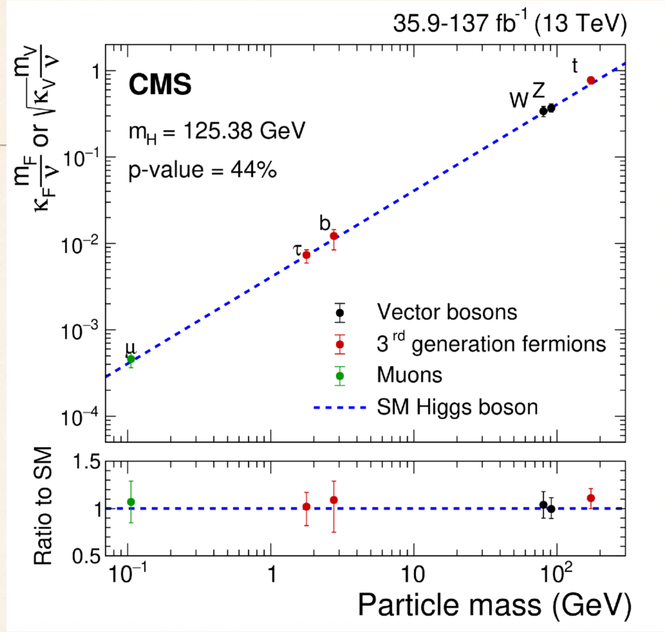
MOTIVATION

- Signs of the new physics can come from the departure from the SM or through observation of the new particles
- Many new models explaining various phenomena, Naturalness, Higgs portal to dark matter, neutrino masses, etc., predict extended Higgs sector

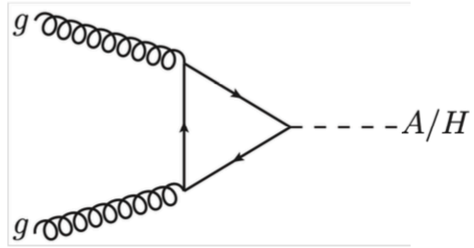


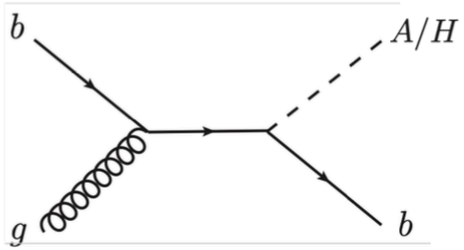
- To the SM doublet add singlet or doublet or doublet and singlet or make it triplet...
- 2HDM: 5 physical states - h, H, A, $H^{\pm}$; parameters - masses and mixing angles ($\tan\beta = v_2/v_1$, $\cos(\beta-\alpha)$)
- 2HDM+S: introduces light pseudoscalar a
- Triplet models predict $H^{\pm\pm}$

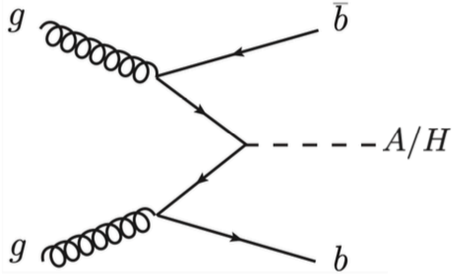
- Production of additional Higgs-like scalars
  - Neutral or charged decaying to SM particles
- Exotic Higgs decays
  - Light resonances, LLP, invisible, flavour violating, etc

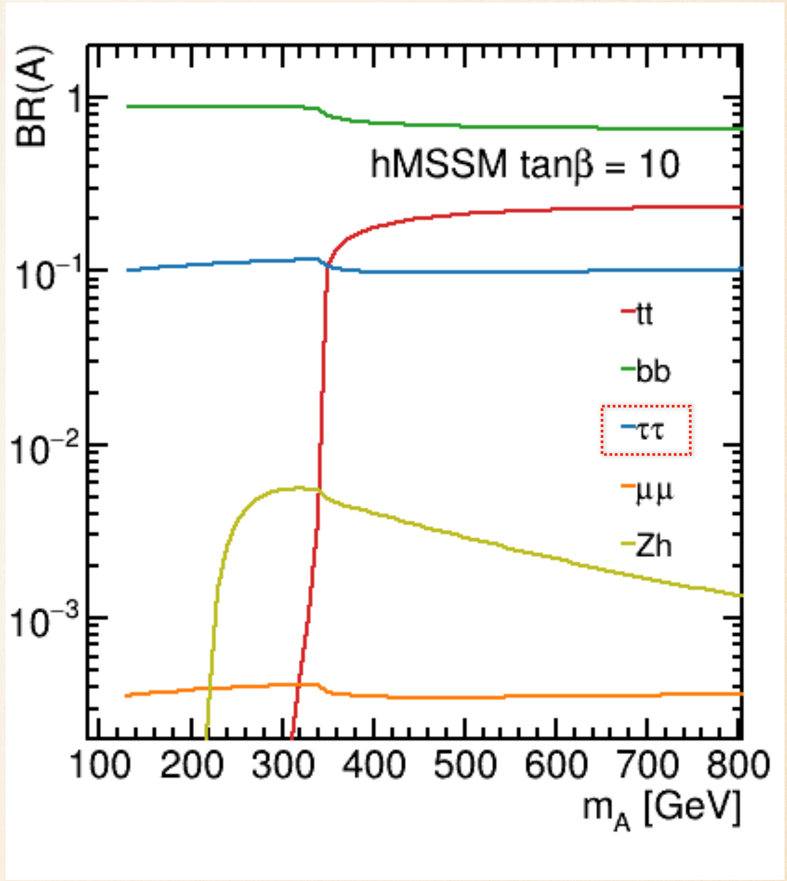
HEAVY NEUTRAL HIGGS BOSON

- $A/H \rightarrow \tau\tau$
- $A \rightarrow ZH$









Decays of heavy scalar to SM Higgs boson pairs,
or to SM Higgs boson and another scalar covered by F. Monti

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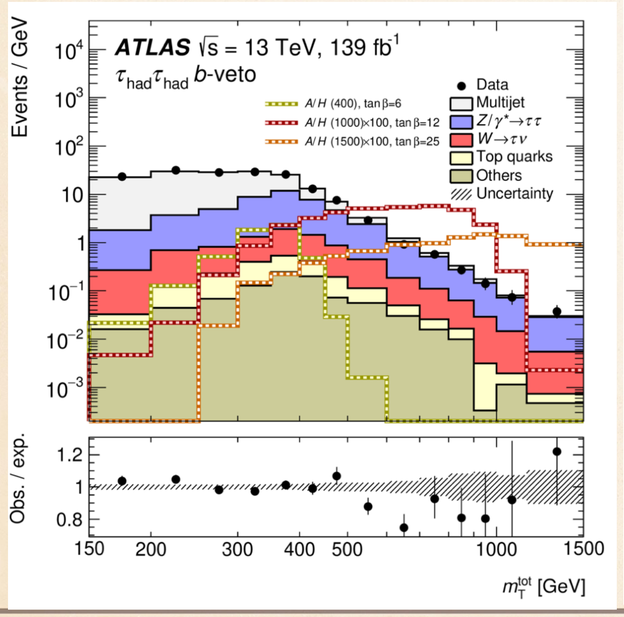
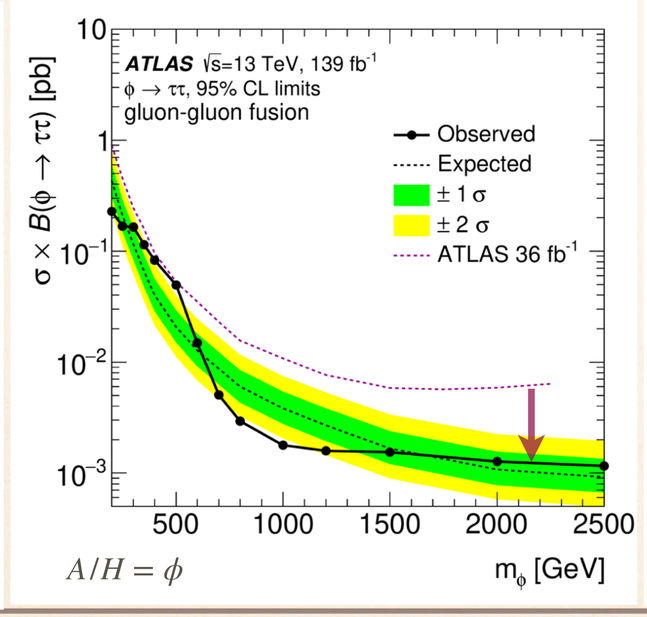
$A/H \to \tau\tau$

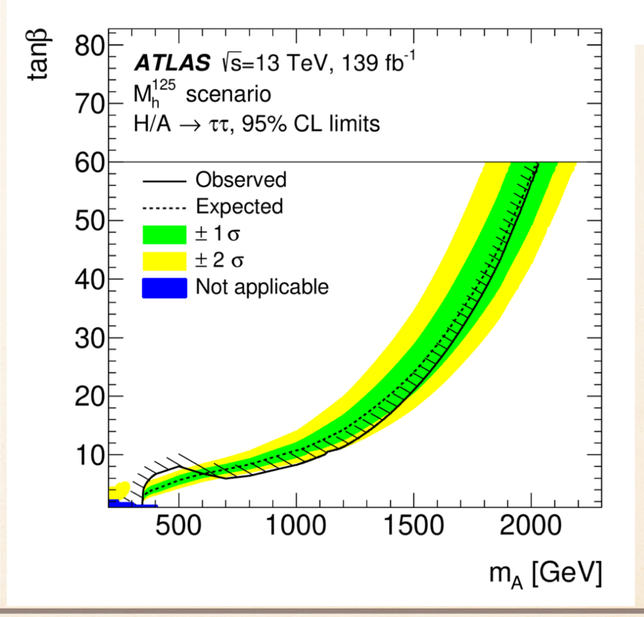
PRL 125 (2020) 051801

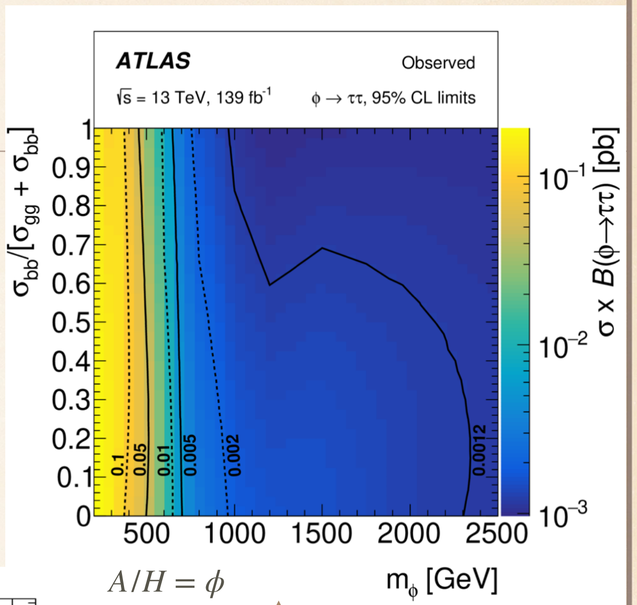
- The most sensitive channel in many scenarios
- Events in $\tau_h\tau_h$ and $\tau_h\tau_l$ final state are separated in b-veto and b-tag category
- Besides improvements due to increased luminosity, improved tau ID and optimization of analysis significantly contributed

$$m_T^{tot} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\overrightarrow{p_T^{\tau_1}} + \overrightarrow{p_T^{\tau_2}} + \overrightarrow{E_T^{miss}})^2}$$



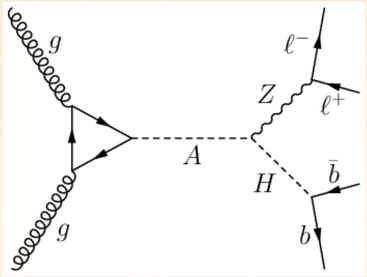






Limits as a function of the fraction of bbφ production

$A \to ZH \to \ell\ell\, bb$



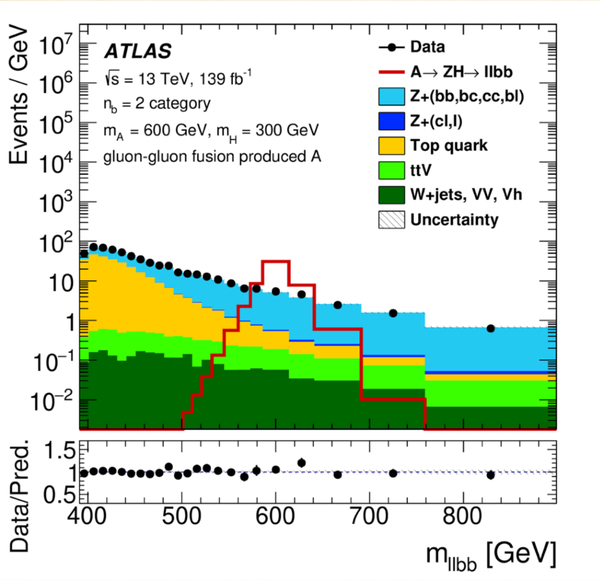
Trigger

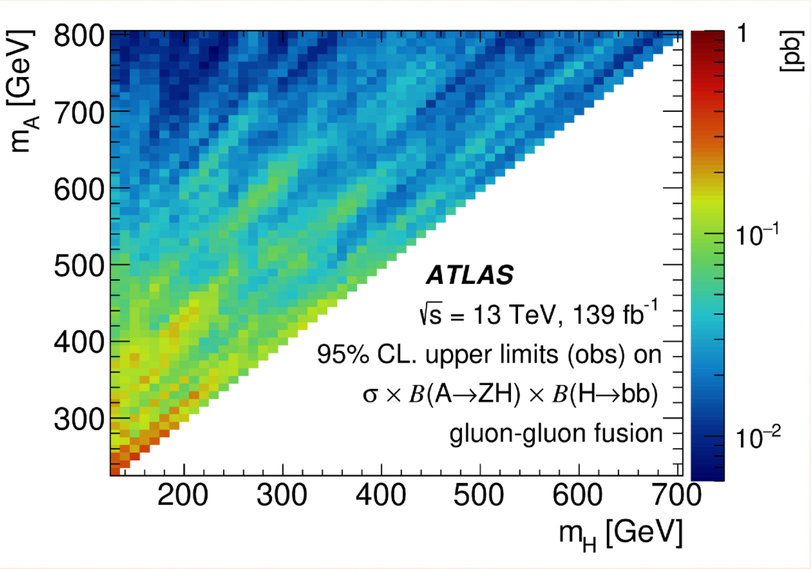
Mass reconstruction

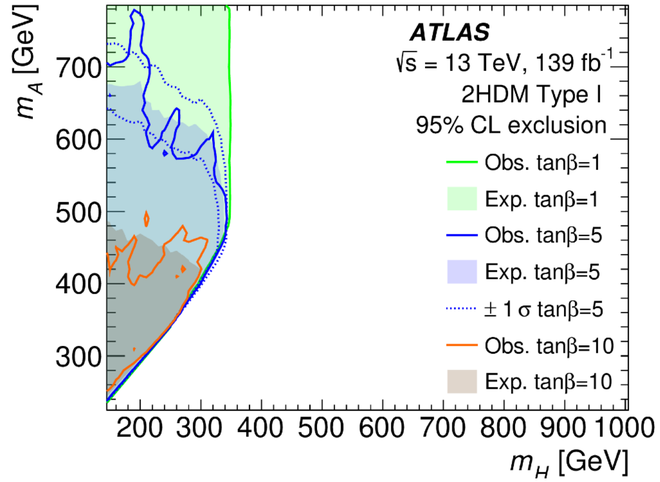
arXiv:2011.05639 Accepted by EPJC

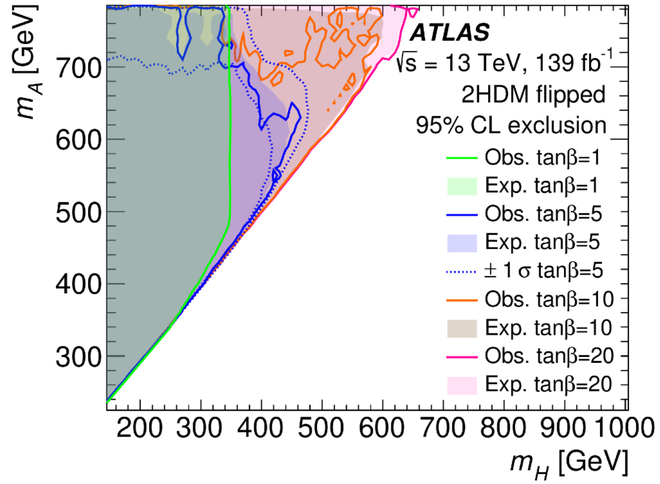
- The $m_A \neq m_H$ case is allowed in 2HDM, in particular, large mass splitting is favoured by the electroweak baryogenesis model in 2HDM
- Gluon fusion and associated with b-quark production motivate separation into 2b and >3b categories
- To improve $m_{llbb}(=m_A)$ mass resolution, m_{bb} is constrained to agree with the assumed m_H

$cos(\beta-\alpha)=0$

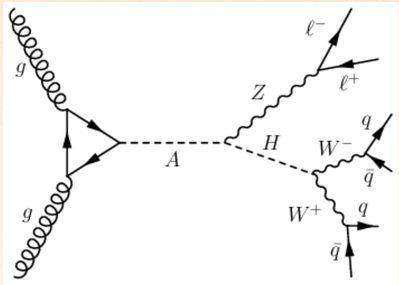








$A \to ZH \to \ell\ell\, WW(qqqq)$

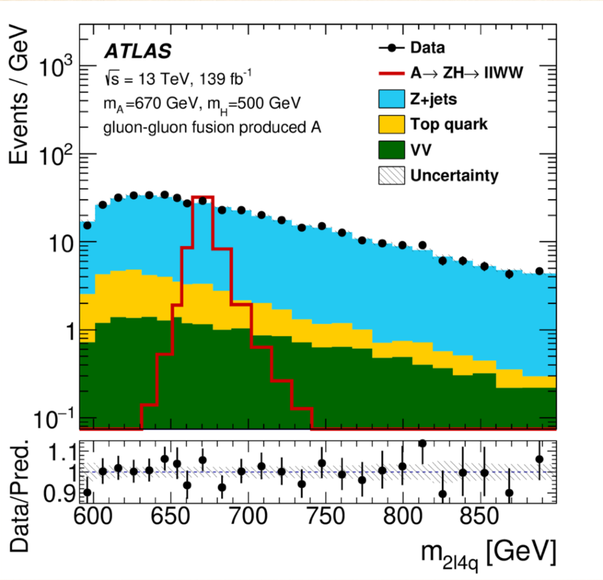


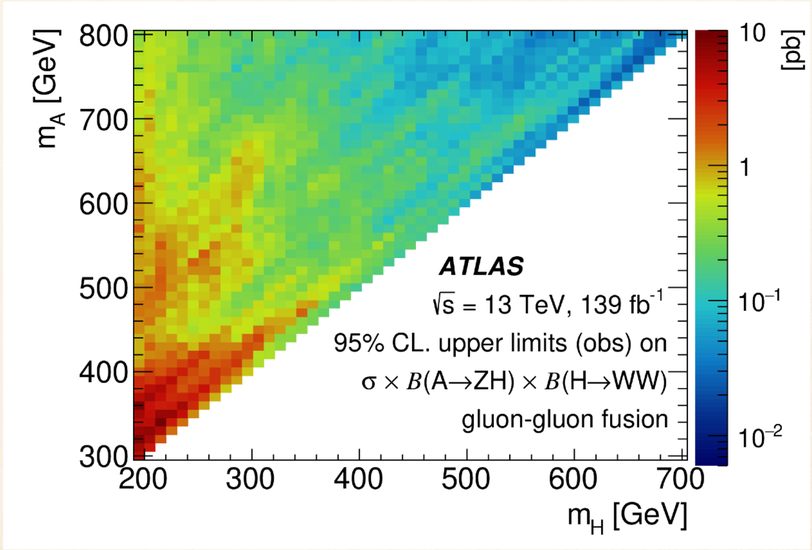
Trigger

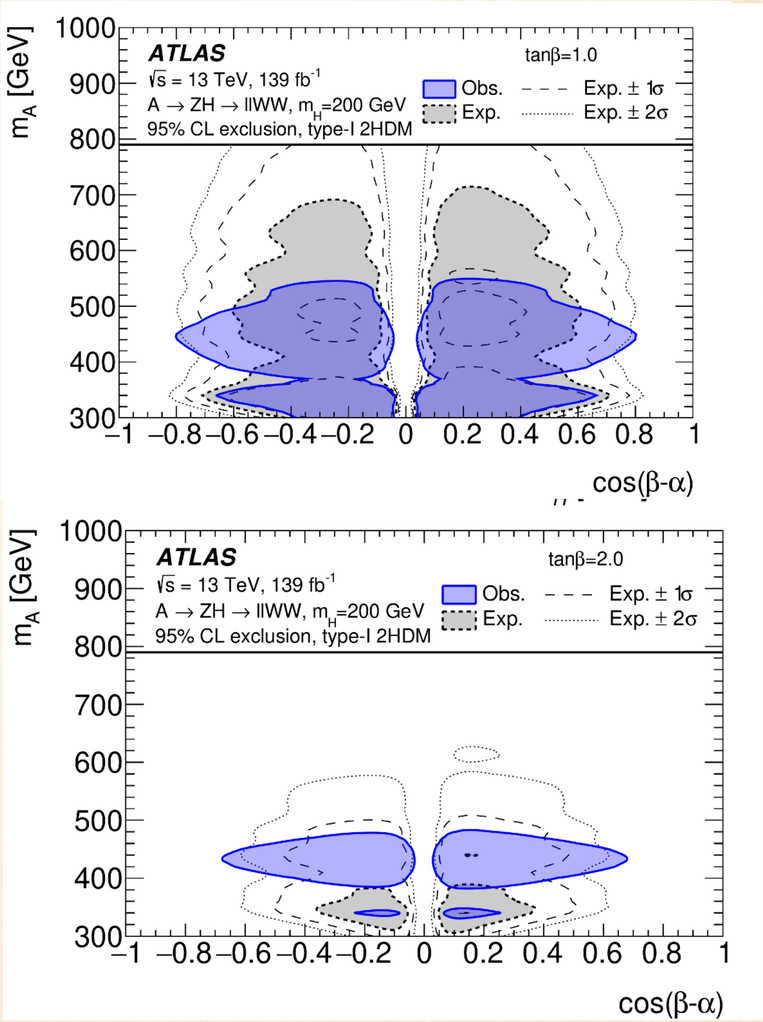
Mass reconstruction

arXiv:2011.05639 Accepted by EPJC

- The $m_A \neq m_H$ case is allowed in 2HDM, in particular, large mass splitting is favoured by the electroweak baryogenesis model in 2HDM
- Similar as before, to improve $m_{2l4j}(=m_A)$ mass resolution, m_{4j} is constrained to agree with the assumed m_H
- Sensitivity to the parameter space near weak decoupling limit



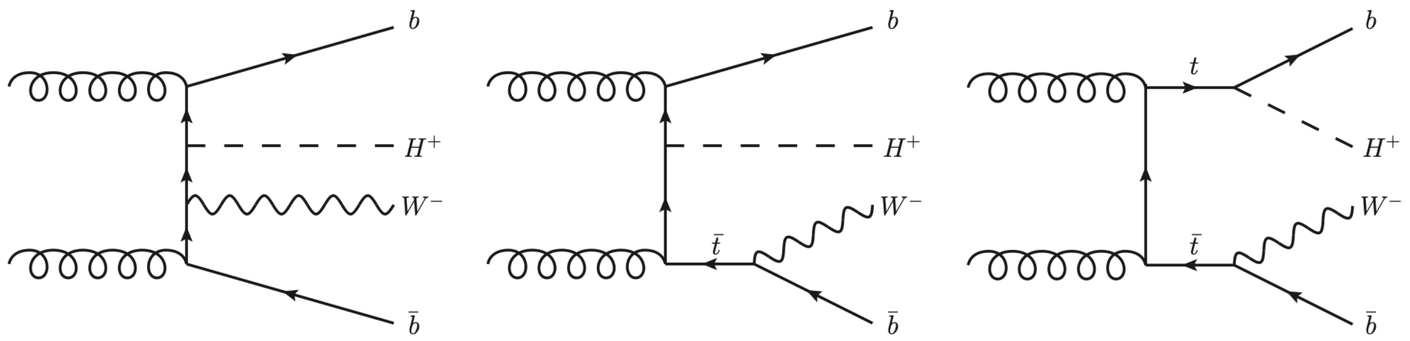


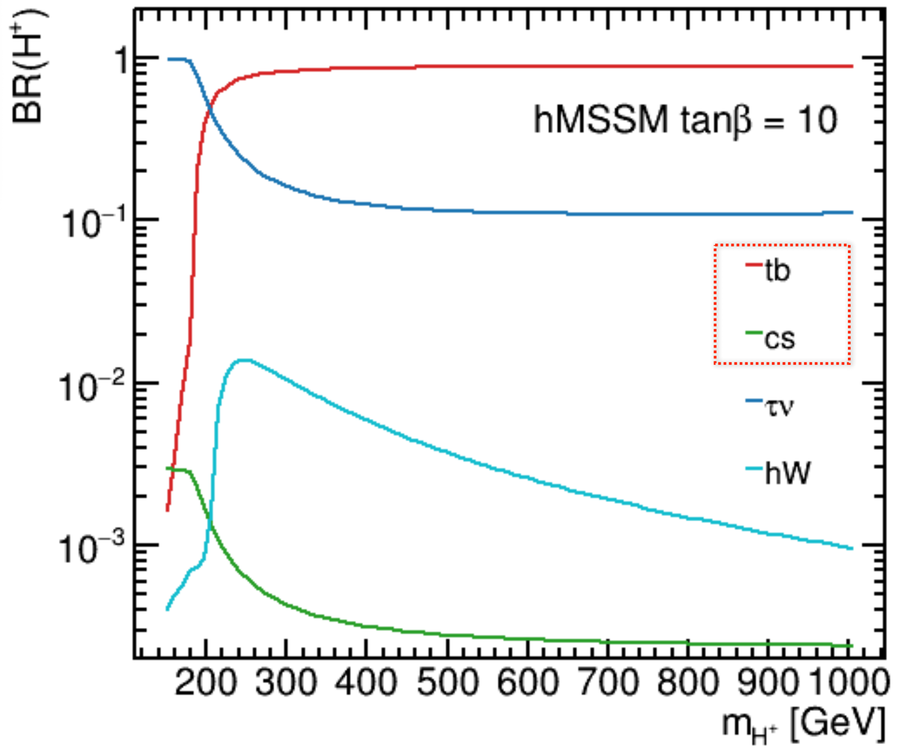


CHARGED HIGGS

- $H^{\pm} \rightarrow tb$
- $H^{\pm} \rightarrow cs$
- Charged and doubly charged Higgs

High masses $m_{H^{\pm}} > m_{top}$ Low masses, $m_{H^{\pm}} < m_{top}$





ATLAS EXPERIMENT

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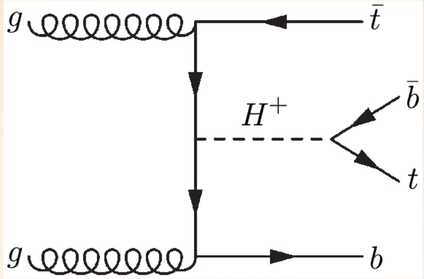
$H^{\pm} \rightarrow tb$

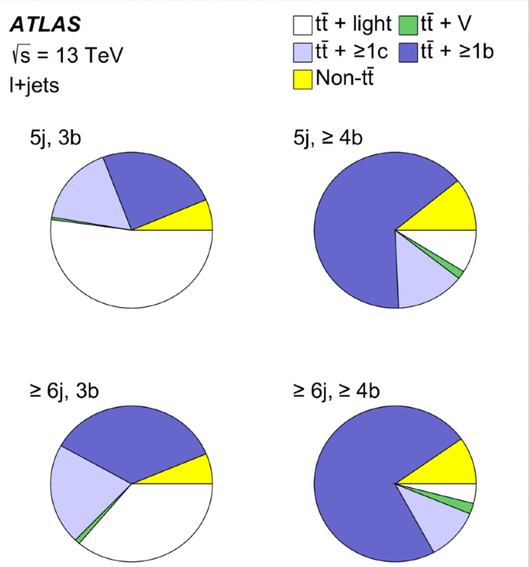


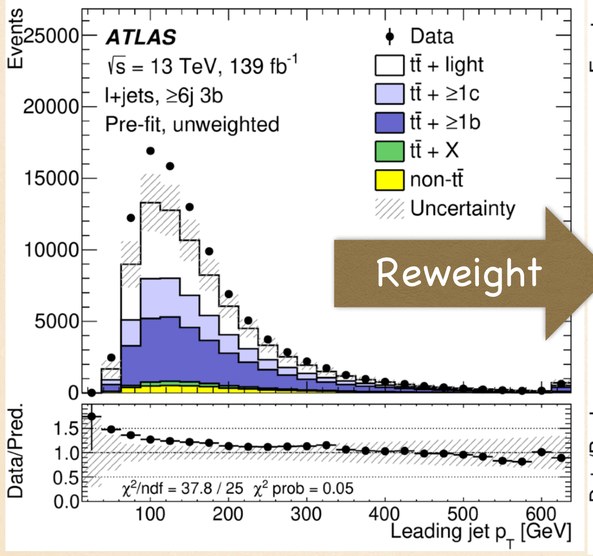
ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД

arXiv:2102.10076

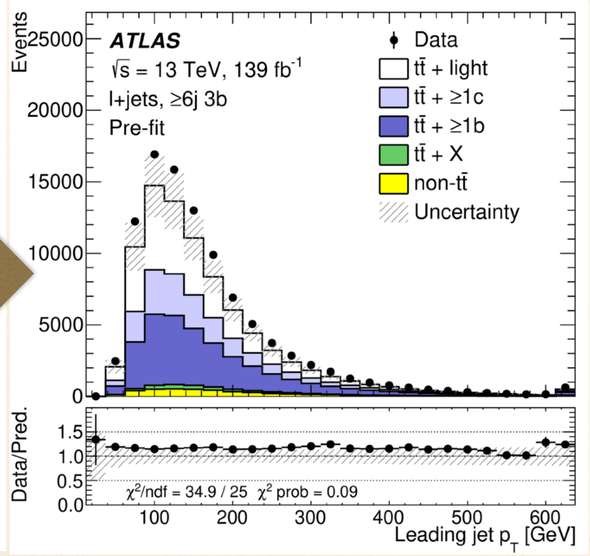
Submitted to JHEP

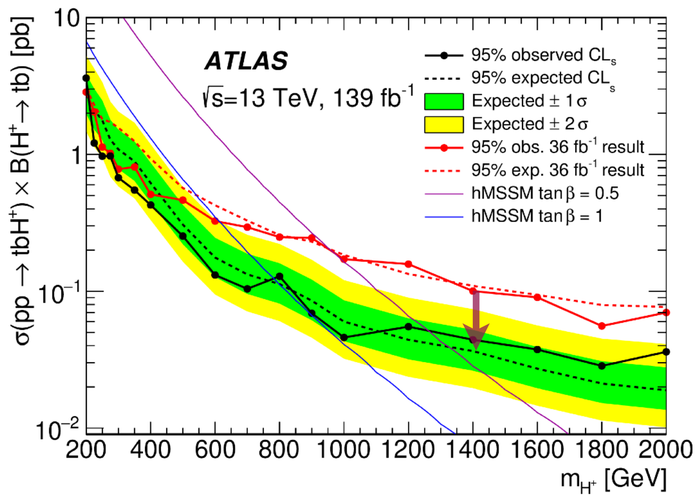
- Dominant process for $m_{H^{\pm}} > m_{top}$
- Events with 1 lepton (trigger), ≥ 5 jets with at least 2 b-tagged considered
  - Categorised into four separate signal regions
- Dominant background tt+jets is modelled with Powheg-Box and corrected using ≥5j(exactly 2b) control region
- NN used as final discriminant

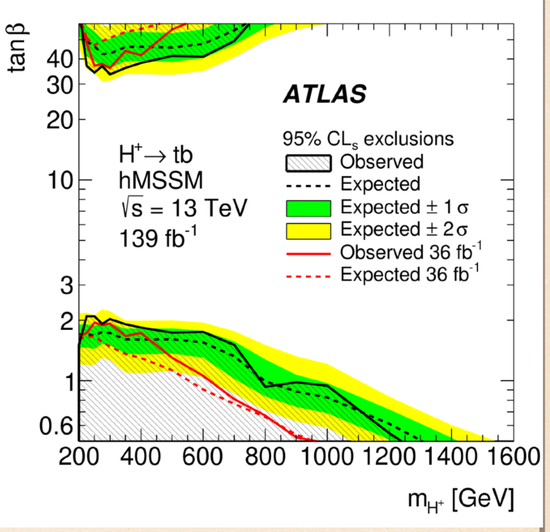




Reweight

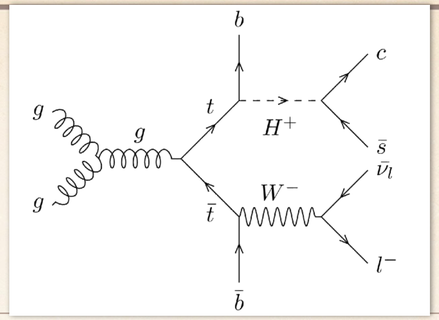






$H^{\pm} \to cs$

Phys. Rev. D 102, 072001



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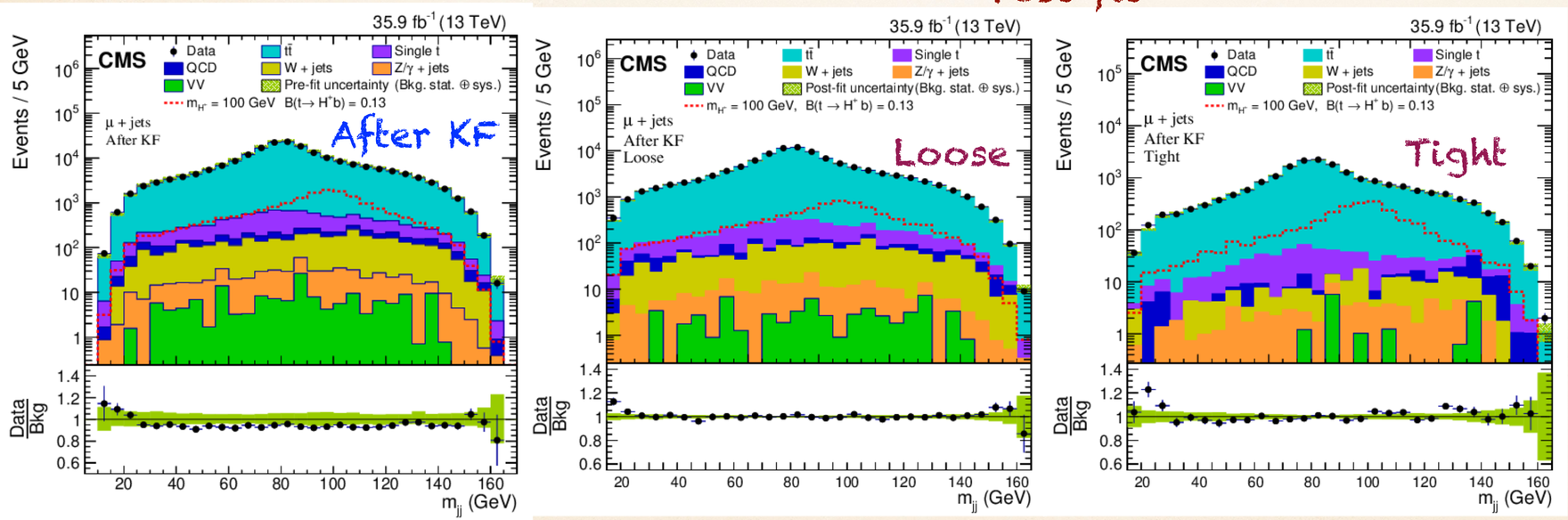
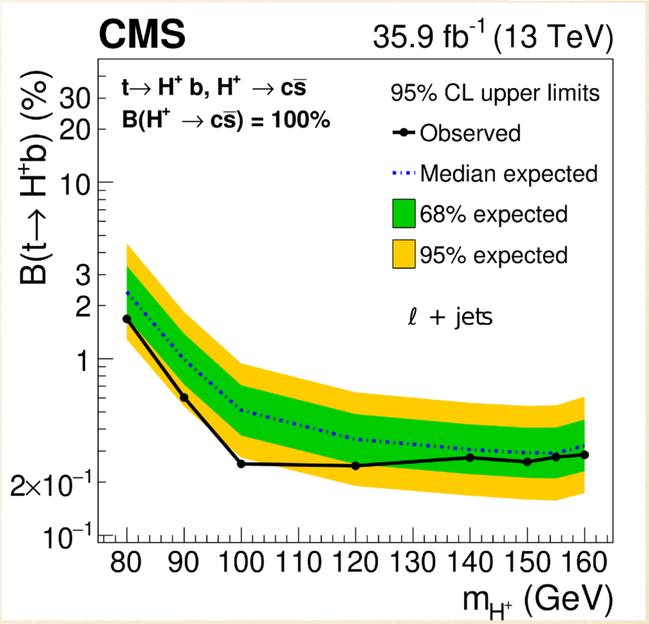
- Significant in several 2HDM models, especially with light H+, $m_{H^{\pm}} < m_{top}$
  - Developing a charm-jet tagger opens exciting possibility of other final states with a c-quark
- Kinematic fit assuming $m(b\ell\nu) = m(bjj) = m_{top}$ used to constrain tt system
- Events are categorised based on c-jet ID, and $m(jj)$ is used as a final discriminant

Post fit





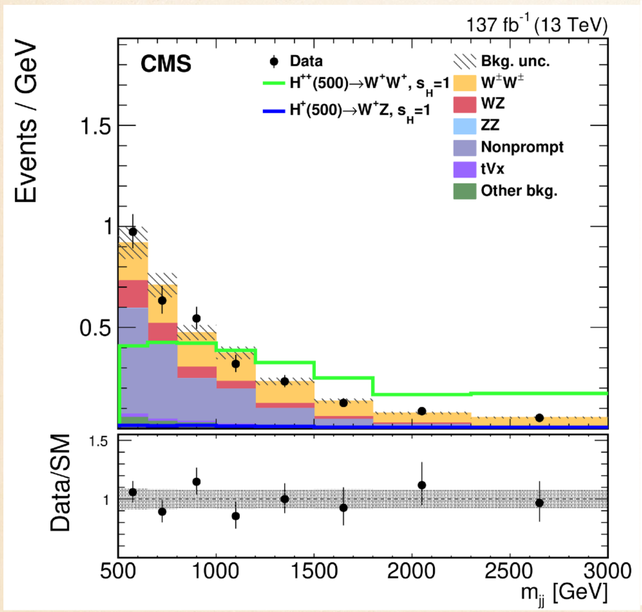
CHARGED AND DOUBLY CHARGED HIGGS

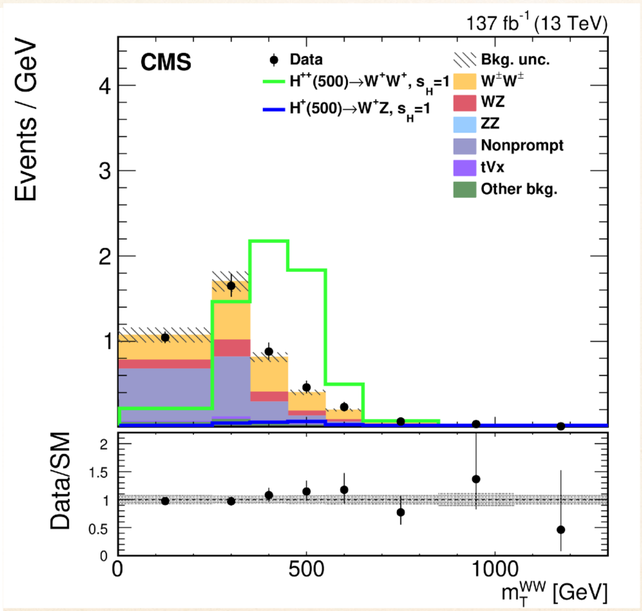
CMS-HIG-20-017 Submitted to EPJC

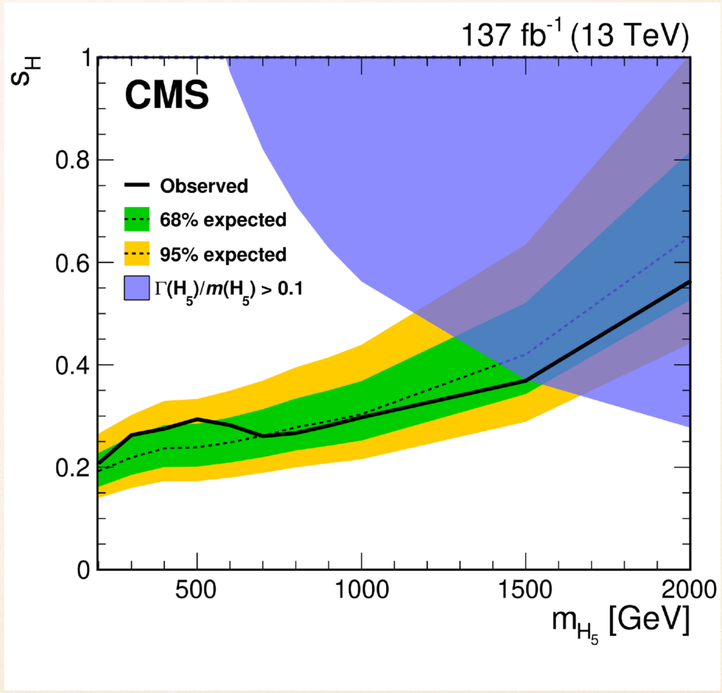
137 fb-1

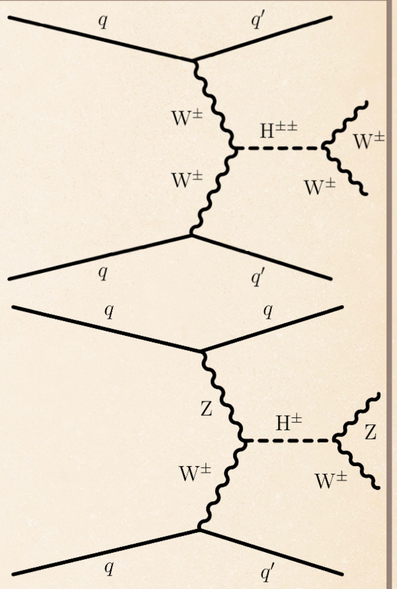
New

- An excess of events in measurements of vector boson scattering processes can indicate new resonance
- Singly or doubly charged Higgs bosons investigated in a context of Georgi-Machacek model
- Searched for in fully leptonic decays
- A 2D distribution $(m_{\mathrm{T}}^{\mathrm{VV}}, m_{\mathrm{jj}})$ is used as final discriminant









GM:
$H^{\pm}, H^{\pm\pm} = H_5$
s_H^2 = fraction of m_W^2 and m_Z^2 generated by the triplet vev's

CHARGED AND DOUBLY CHARGED HIGGS

arXiv:2101.11961 Submitted to JHEP

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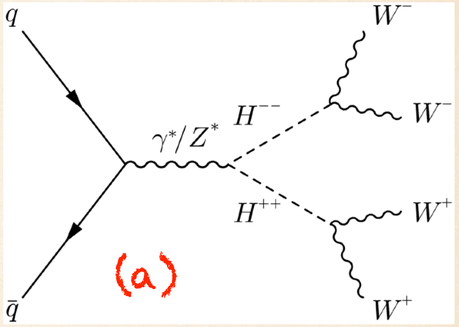
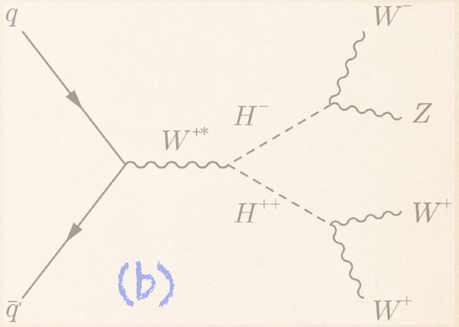
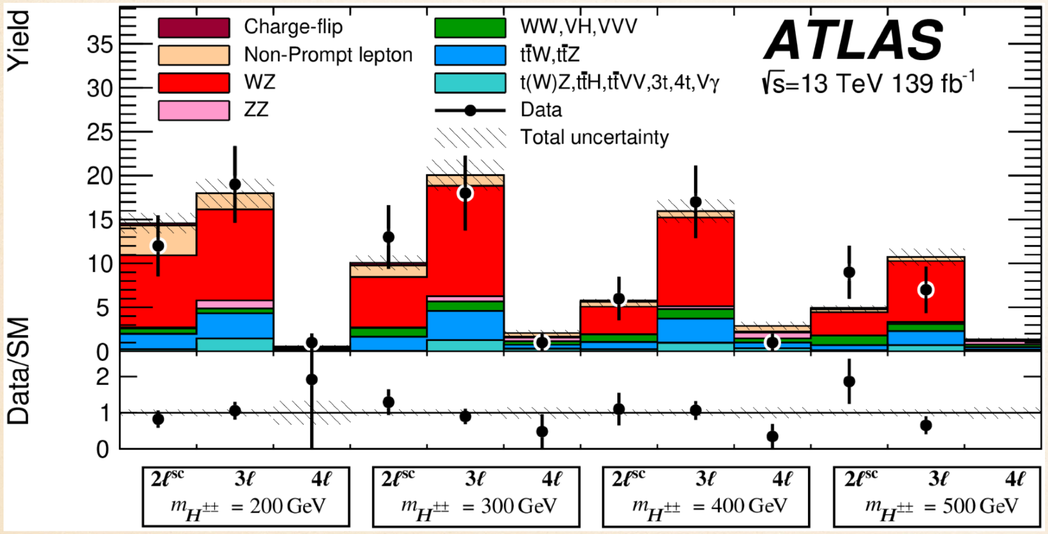
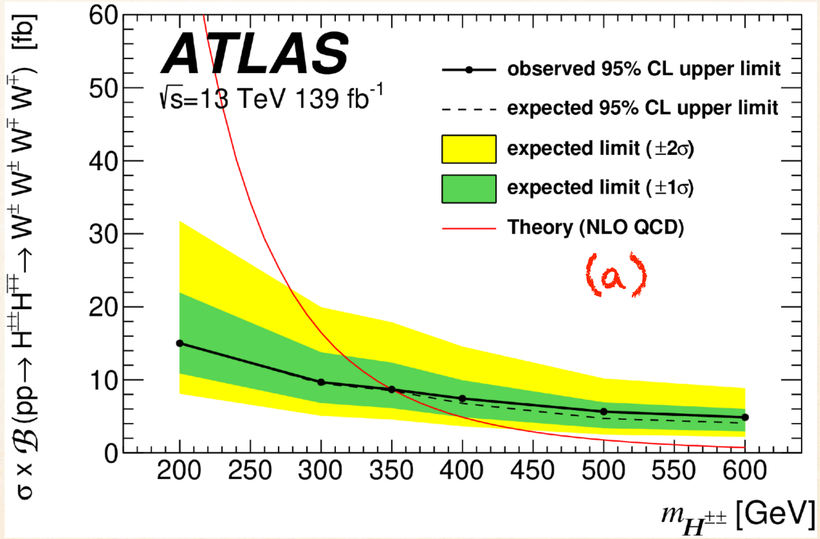
New

- Doubly charged and charged Higgs bosons are predicted in type II seesaw model
- Decay products will contain charged leptons, missing transverse momentum and jets
- Three final states: two same-charge leptons, three leptons, and four leptons
- Prompt (non-prompt) backgrounds from MC (data)
- Two scenarios considered: (a) $(m_{H^{\pm}} - m_{H^{\pm\pm}}) > 100$ GeV; (b) $|m_{H^{\pm}} - m_{H^{\pm\pm}}| > 5$ GeV









ATLAS EXPERIMENT

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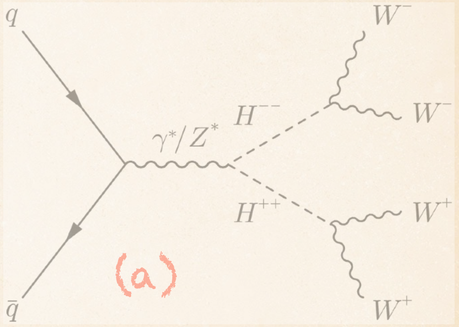
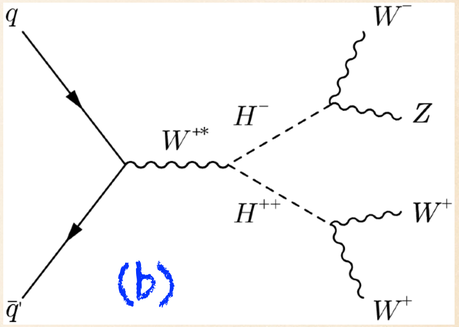
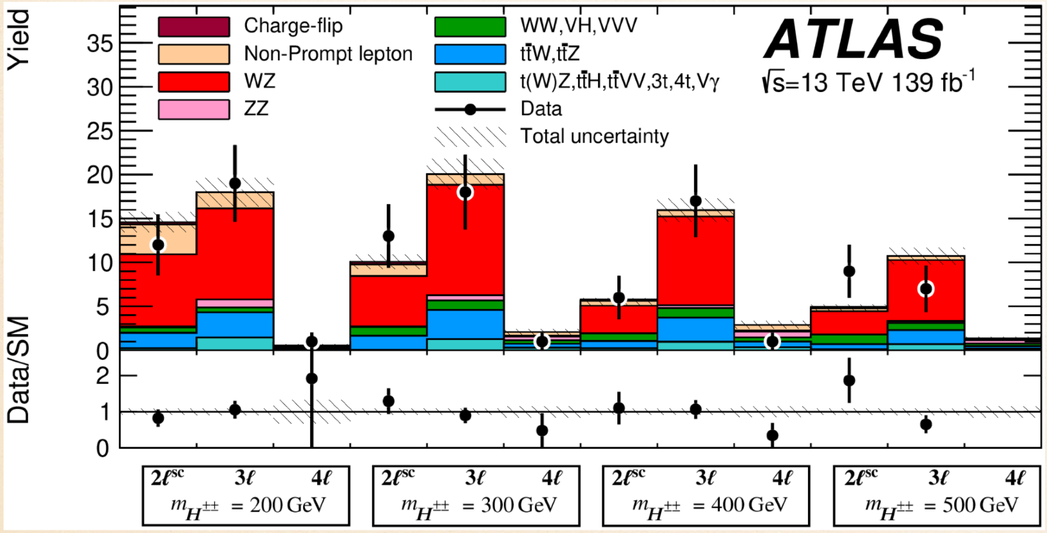
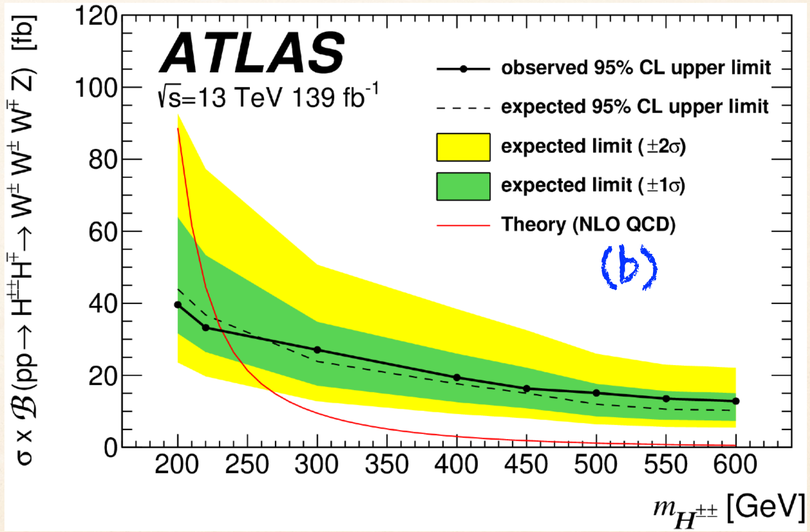








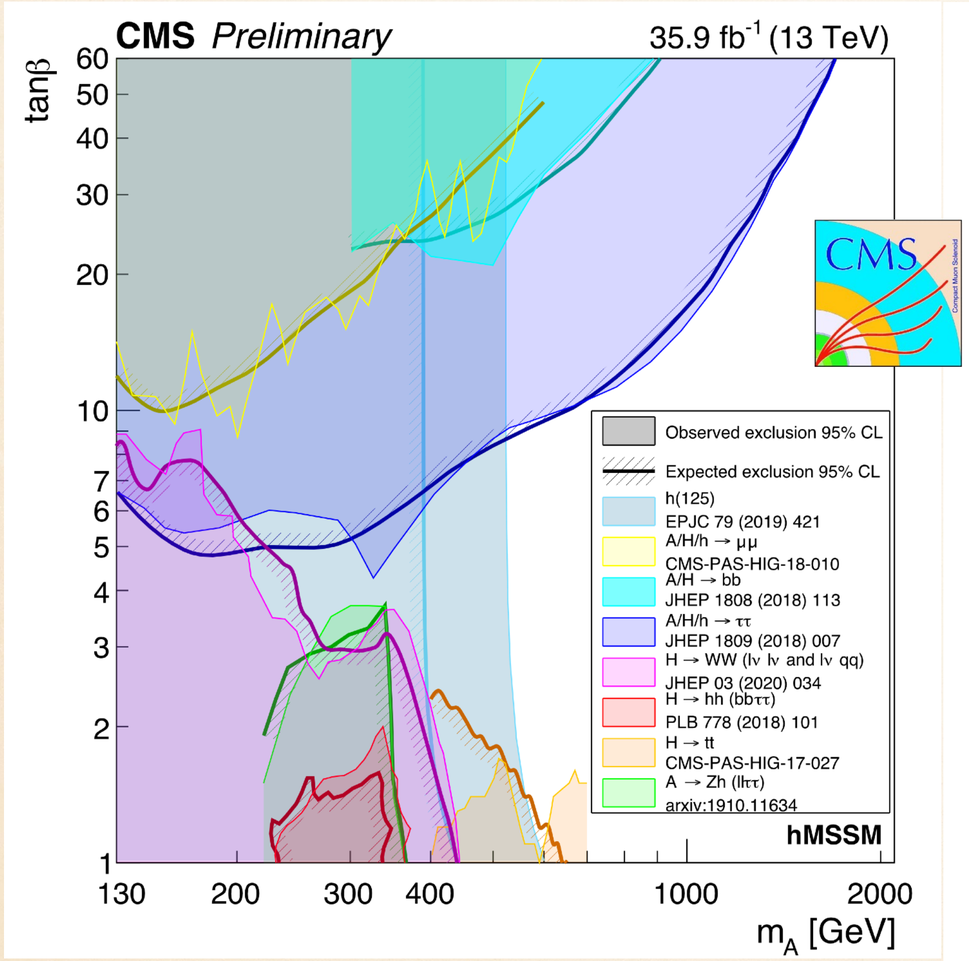
LET'S PUT THEM ALL TOGETHER

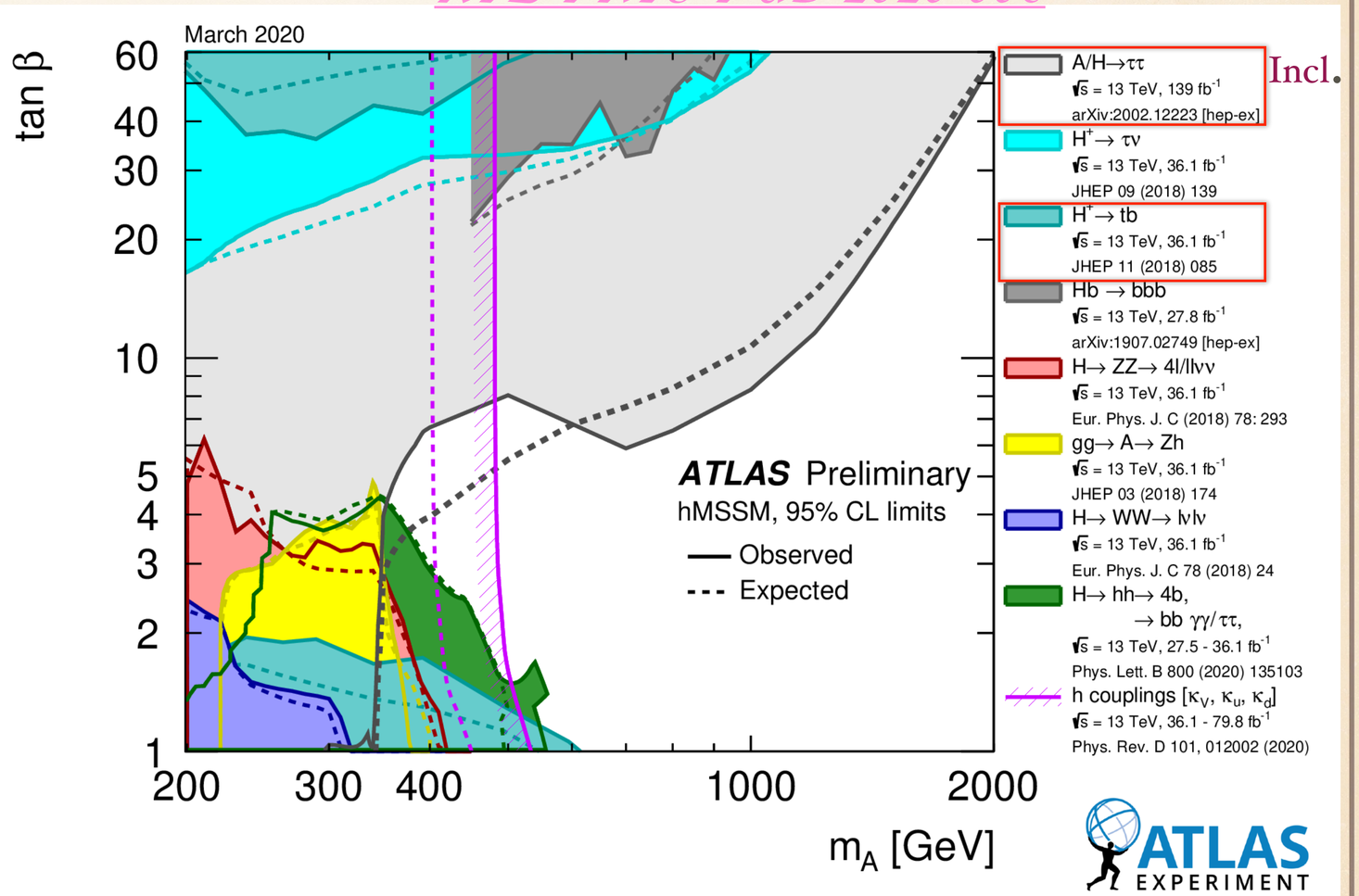
УНИВЕРЗИТЕТ У БЕОГРАДУ | ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

Combination from SM Higgs properties in backup

hMSSM

ATL-PHYS-PUB-2020-006





EXOTIC HIGGS DECAYS

- *Lepton flavour violation*
- *Higgs decays to light resonances*
- *Higgs decays to long lived light resonances*
- *Higgs decays to semivisible or invisible*
- …

Rare Higgs boson decays covered by S. Donato

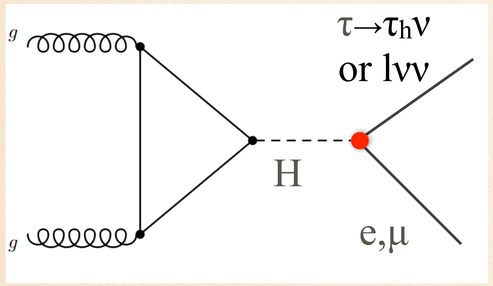
LEPTON FLAVOUR VIOLATION IN HIGGS DECAYS

CMS-PAS-HIG-20-009

New

- Forbidden in Standard Mode; LFV in Higgs decay will arise in the models with extensions of the Higgs sector or warped extra dimension
  - To enhance sensitivity, BDT is used for final analysis
    - Inputs include p_T, masses, angular distances
- Observed (exp.) upper limits on $\mathcal{B}(H \to \mu\tau)$ is 0.15% (0.15%) and on $\mathcal{B}(H \to e\tau)$ is 0.22% (0.16%) @95% C.L.

VBF production also included



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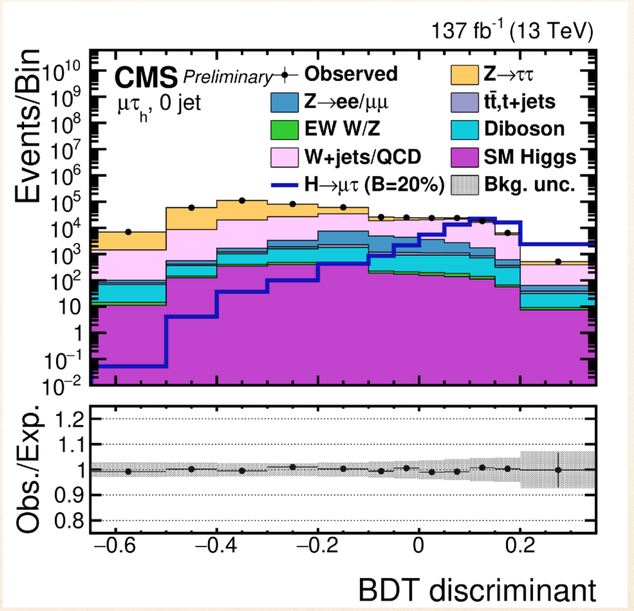
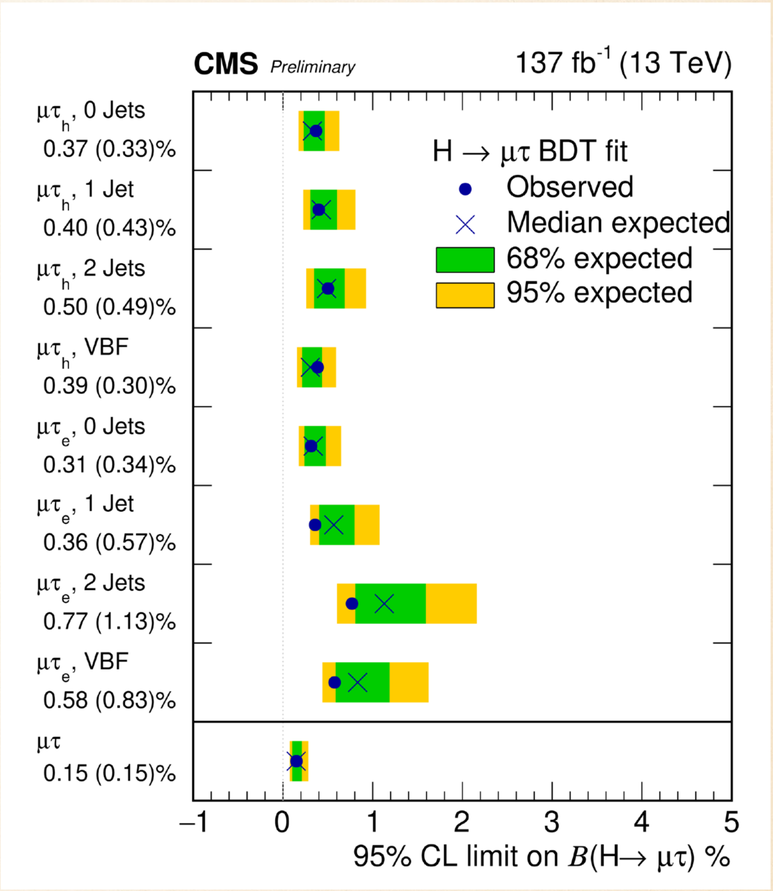




LEPTON FLAVOUR VIOLATION IN HIGGS DECAYS

CMS-PAS-HIG-20-009

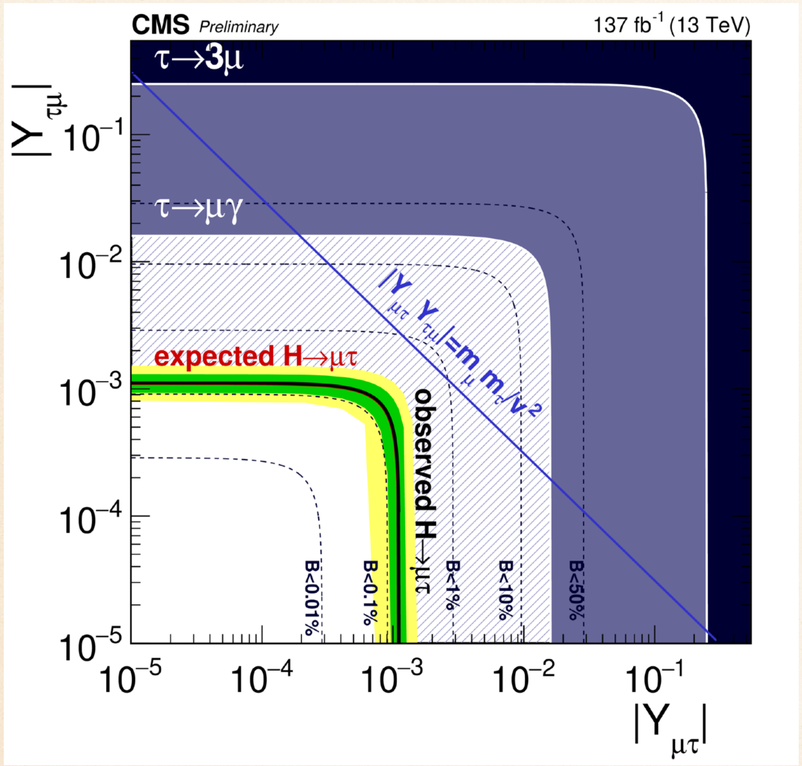
New

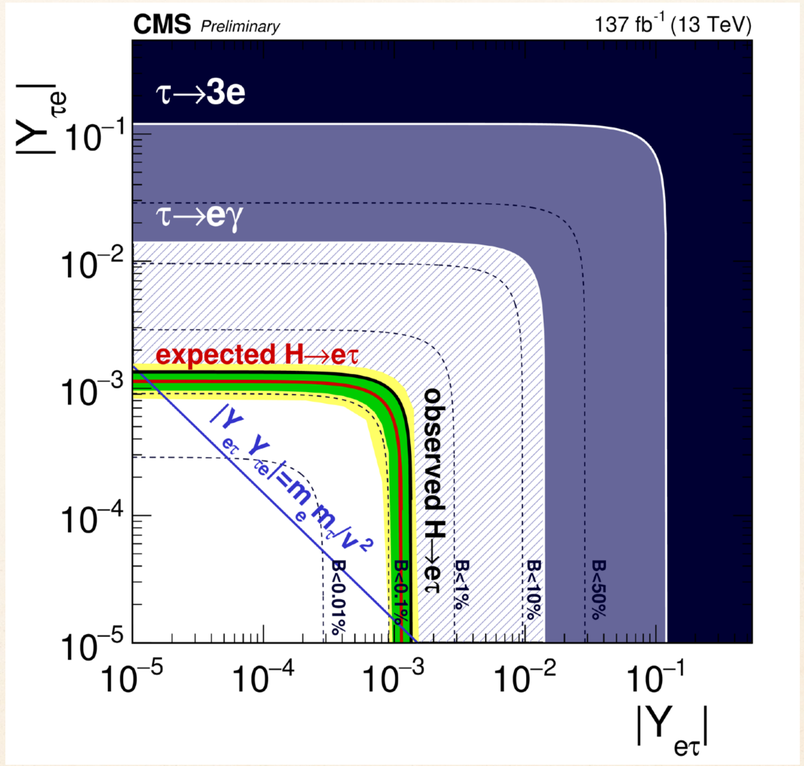
Off-diagonal Yukawa

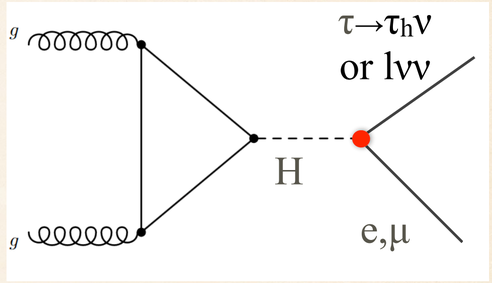
$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3} \qquad \sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$$

137 fb^{-1}

VBF production also included







Naturalness is satisfied for $|Y_{\ell_1\ell_2} Y_{\ell_2\ell_1}| < \frac{m_{\ell_1} m_{\ell_2}}{v^2}$

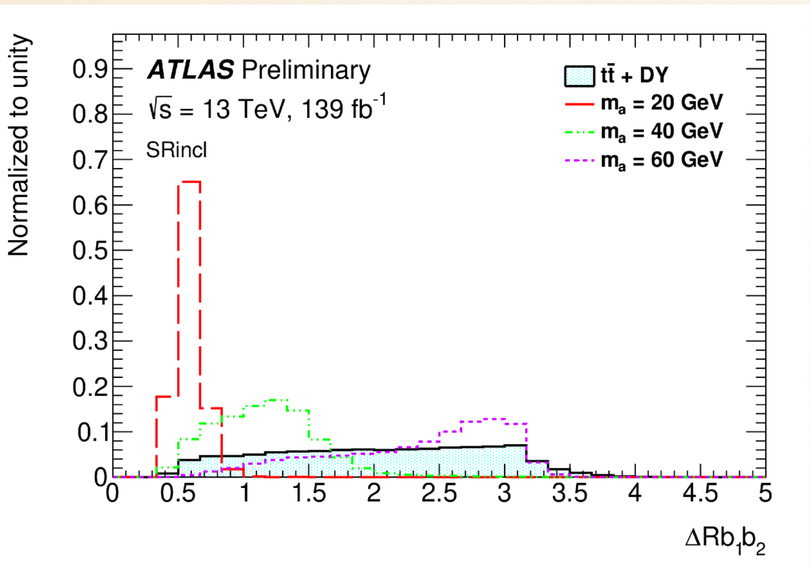
$H \to aa \to bb\mu\mu$

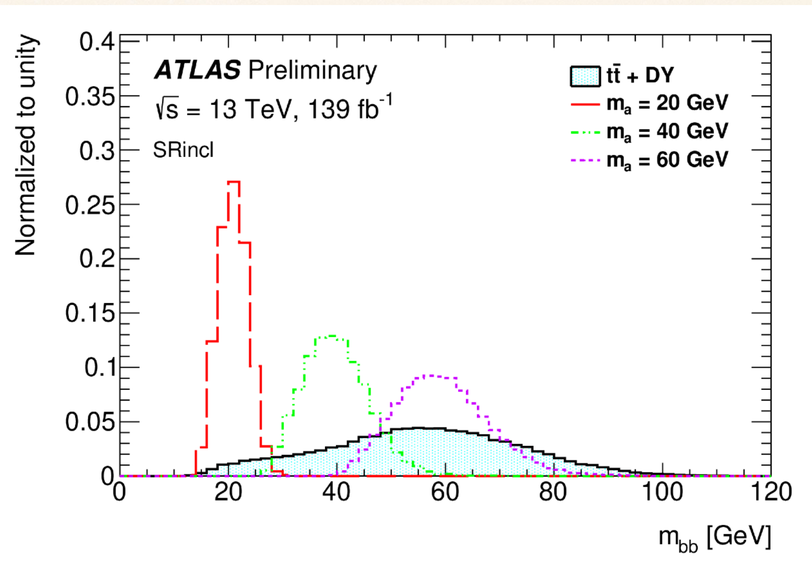
ATLAS-CONF-2021-009

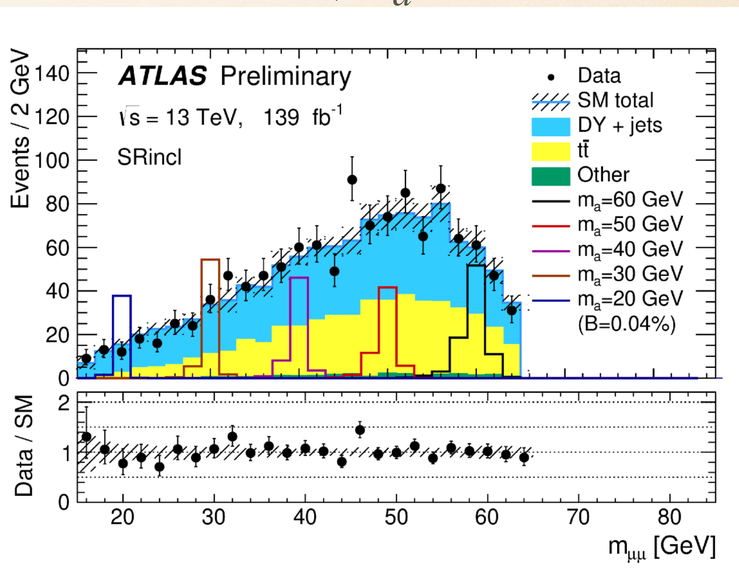
139 fb-1

New

- Final state benefits from large $\mathcal{B}(a \to bb)$ and a clean $a \to \mu\mu$
- Kinematic fit exploiting $m_{bb} = m_{\mu\mu}$ used to improve mass resolution
- BDT employed to reduce backgrounds
- Excess is searched for in $m_a - X < m_{\mu\mu} < m_a + X$ bins $\begin{cases} X{=}1\ GeV, m_a{<}45\ GeV \\ X{=}1.5\ GeV, m_a{>}45\ GeV \end{cases}$







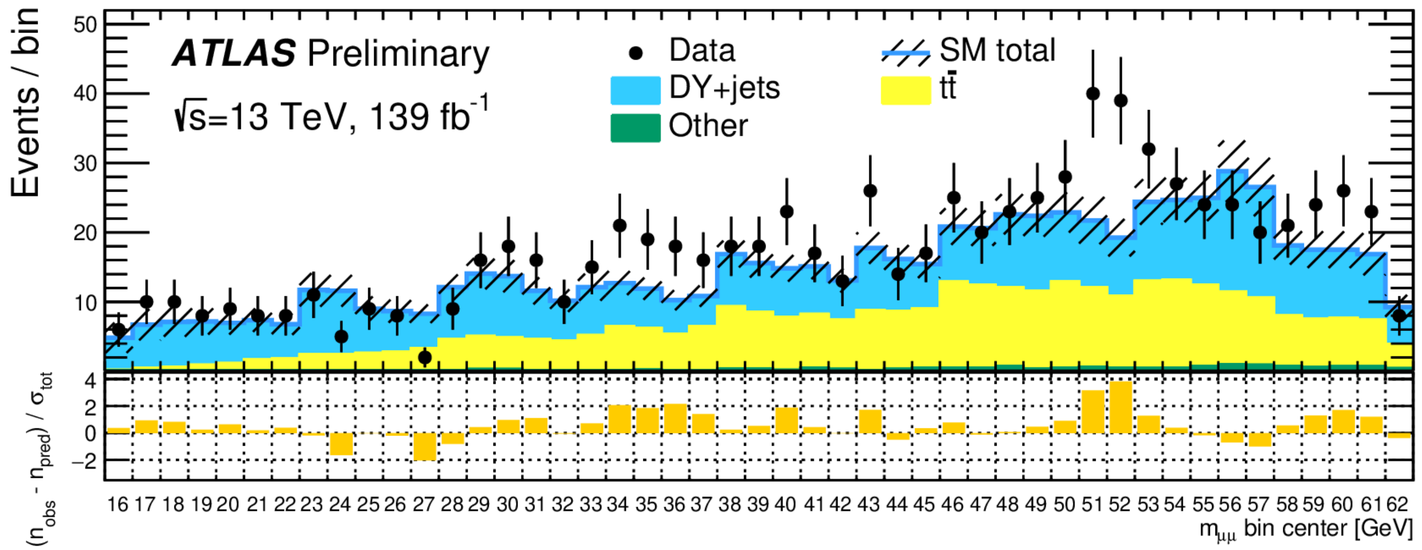
ATLAS-CONF-2021-009

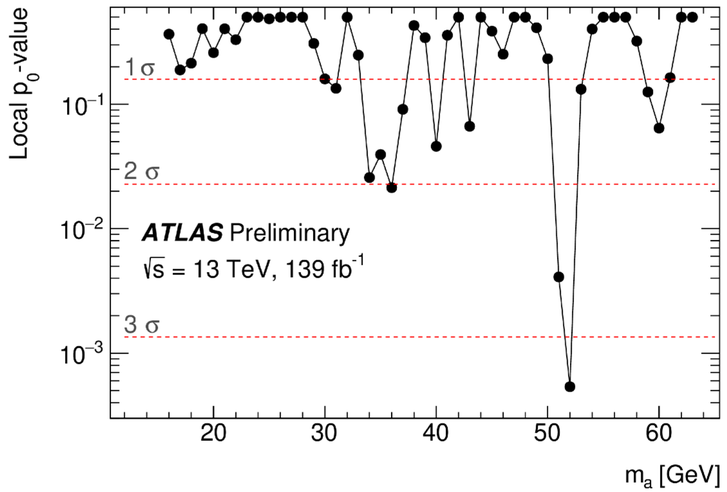
New

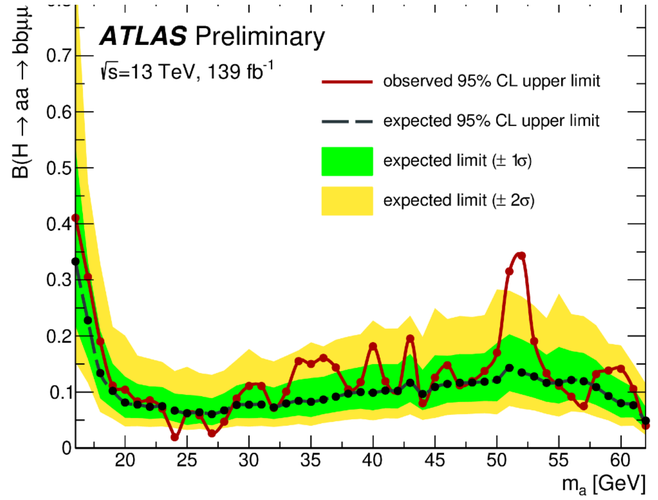
$H \to aa \to bb\mu\mu$

139 fb^{-1}

- Excess is searched $m_a - X < m_{\mu\mu} < m_a + X$ bins $\begin{cases} X=1\ GeV, m_a<45\ GeV \\ X=1.5\ GeV, m_a>45\ GeV \end{cases}$
- The largest excess is observed at $m_{\mu\mu} = 52$ GeV with local (global) significance of 3.3σ (1.7σ).







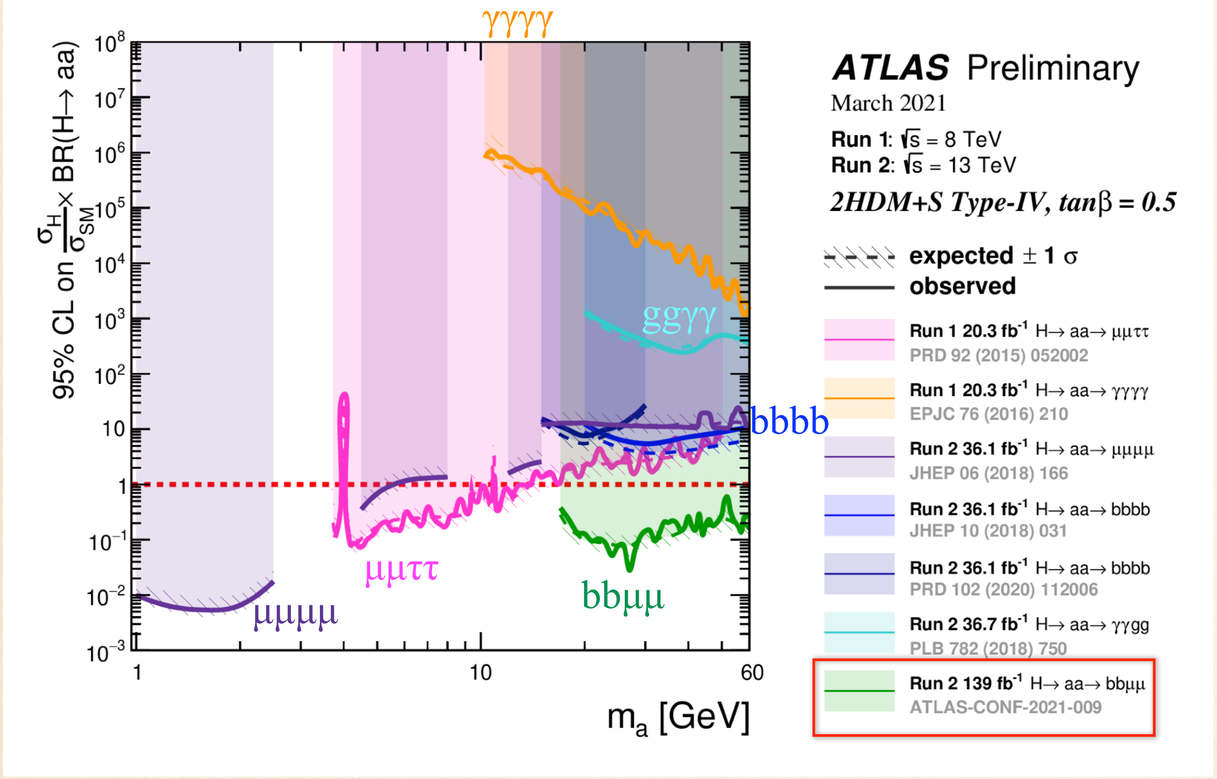
$H \to aa$ - SUMMARY

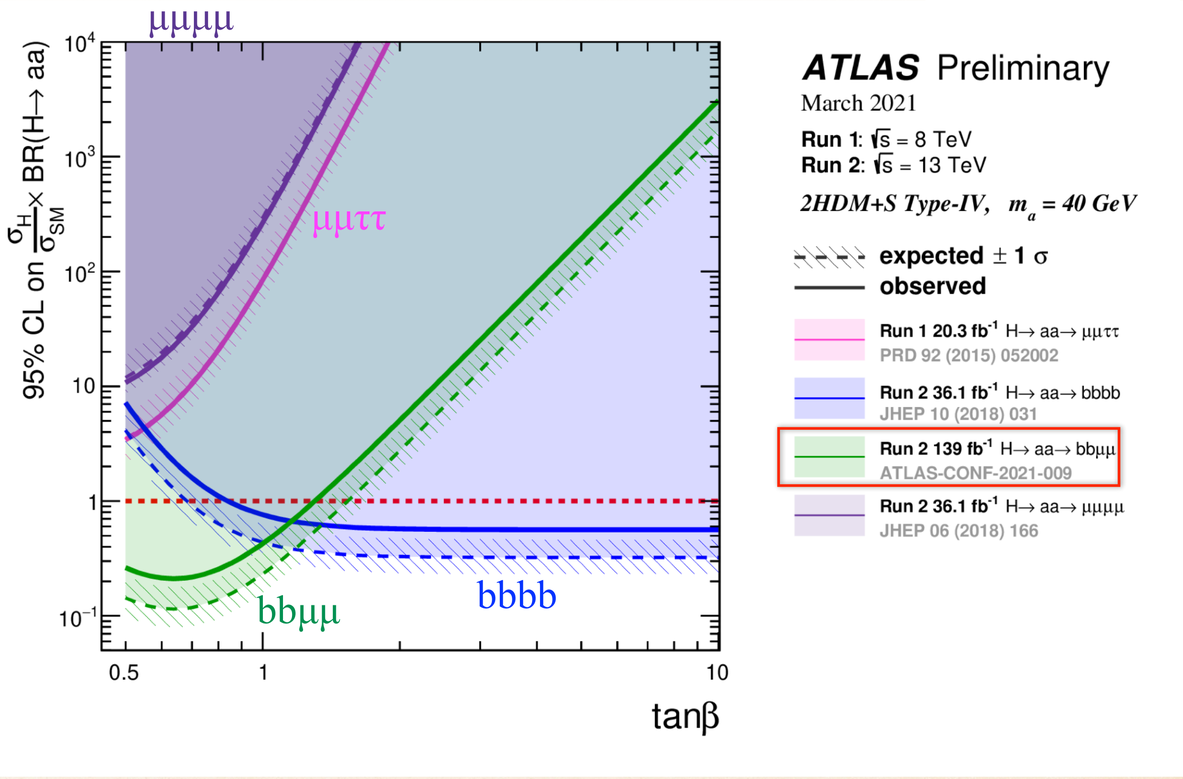
New

ATL-PHYS-PUB-2021-008

More in backup

2HDM+S Limits





$ZH \to \ell\ell aa \to \ell\ell bbbb$ - LONG LIVED

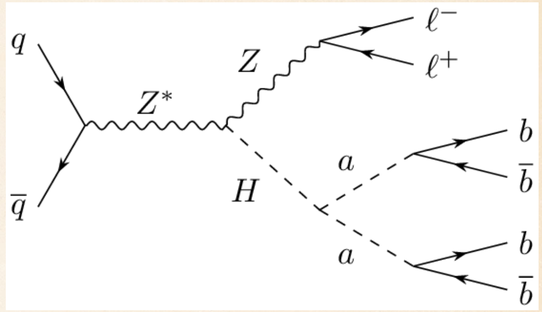
ATLAS EXPERIMENT

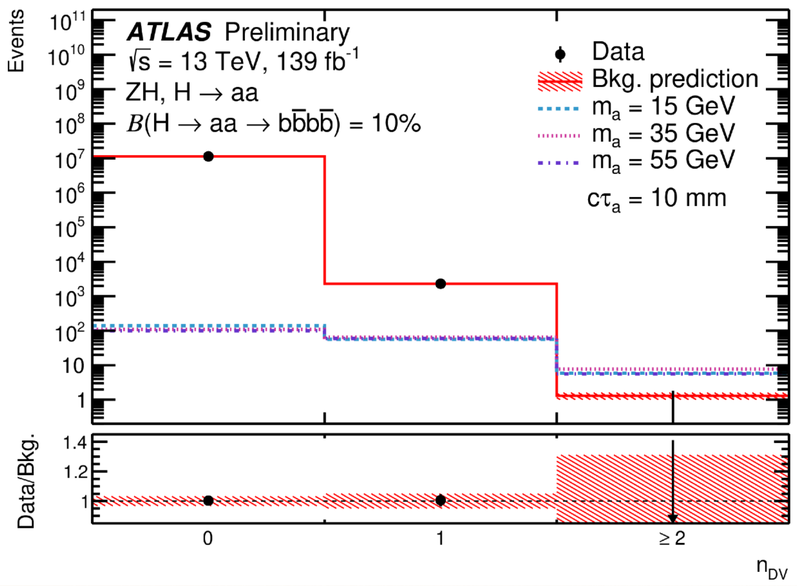
ATLAS-CONF-2021-005

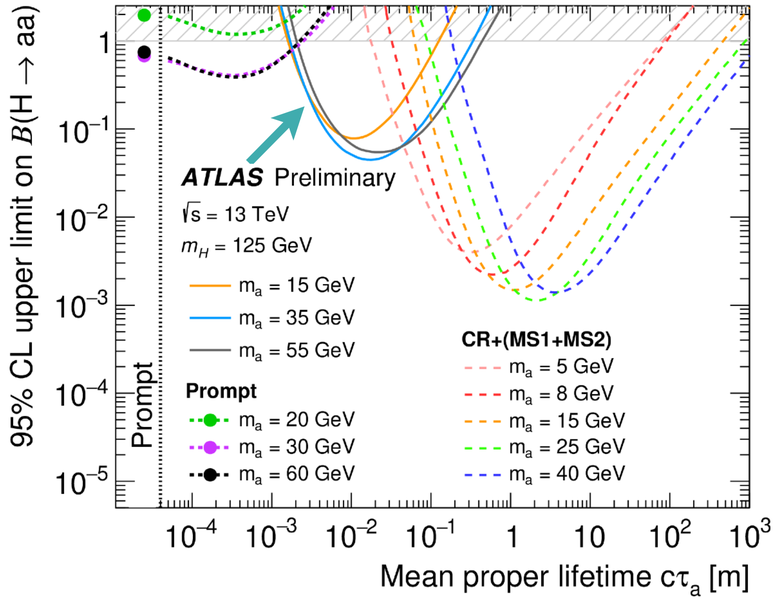
139 fb^{-1}

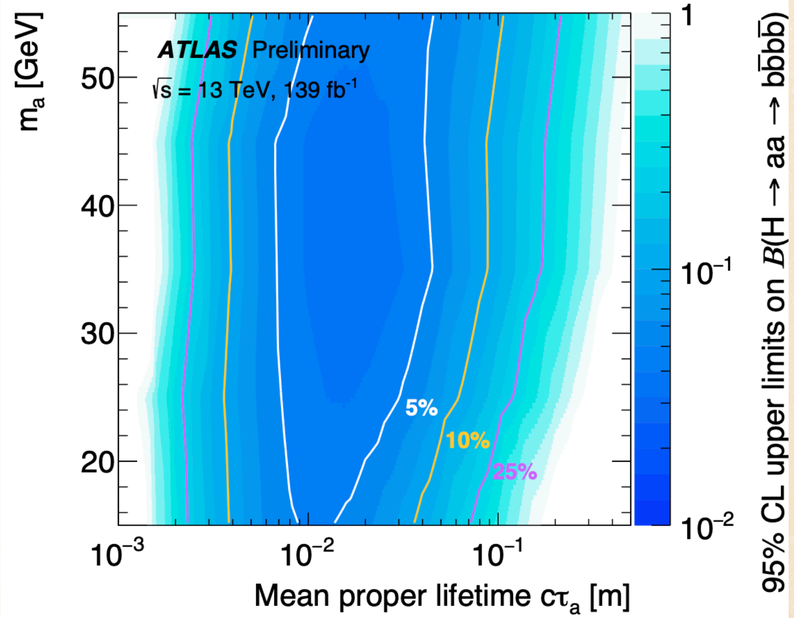
New

- LLP decays in ID, resulting in at least two displaced vertices
- Events preselected to pass basic selection, 2 leptons and 4 b-jets
- Then large radius tracking (with looser ID criteria) is used to identify events with DVs









130 fb-1

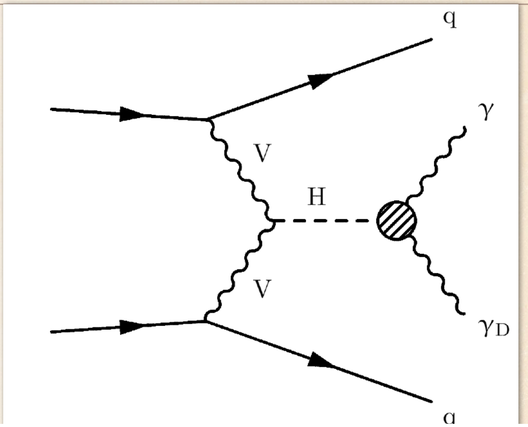
139 fb-1

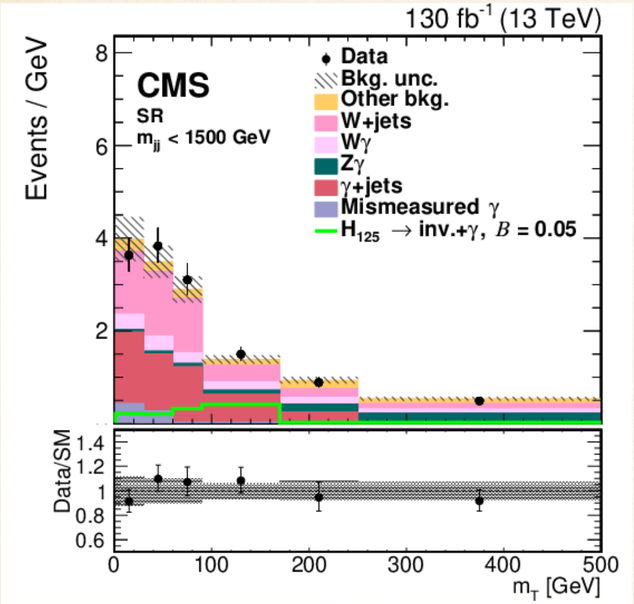
$VBF\ H \rightarrow \gamma\gamma_D$ - SEMIVISIBLE

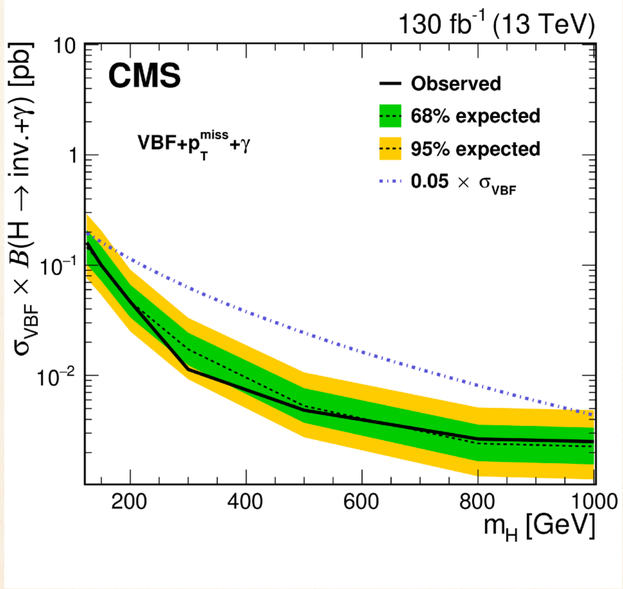
JHEP 03 (2021) 011

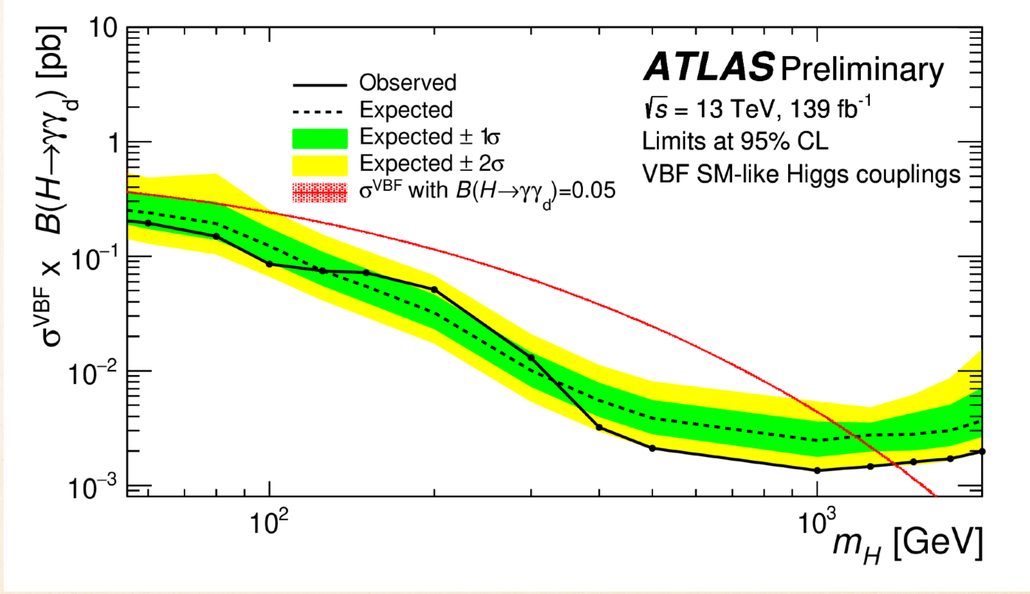
ATLAS-CONF-2021-004

- Dark photon model predicts a massless dark photon coupled with the Higgs boson through a U(1) unbroken dark sector
- Select events with 2 forward jets from VBF, one photon and large E_T^{miss}
- The $m_T = \sqrt{2p_T^{miss} p_T^{\gamma}[1 - cos(\Delta\phi_{\overrightarrow{p}_T^{miss}, \overrightarrow{p}_T^{\gamma}})]}$ used as discriminant
- For $m_H = 125$ GeV limits on $\mathcal{B}(H \rightarrow \gamma\gamma_D)$: CMS - 3.5%(comb. 2.9%) an and ATLAS 1.4%









HIGGS TO INVISIBLE

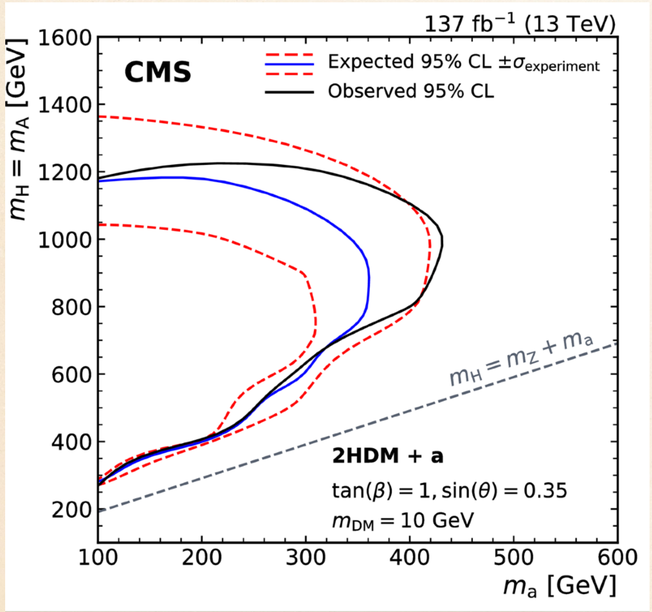
EPJC 81 (2021) 13

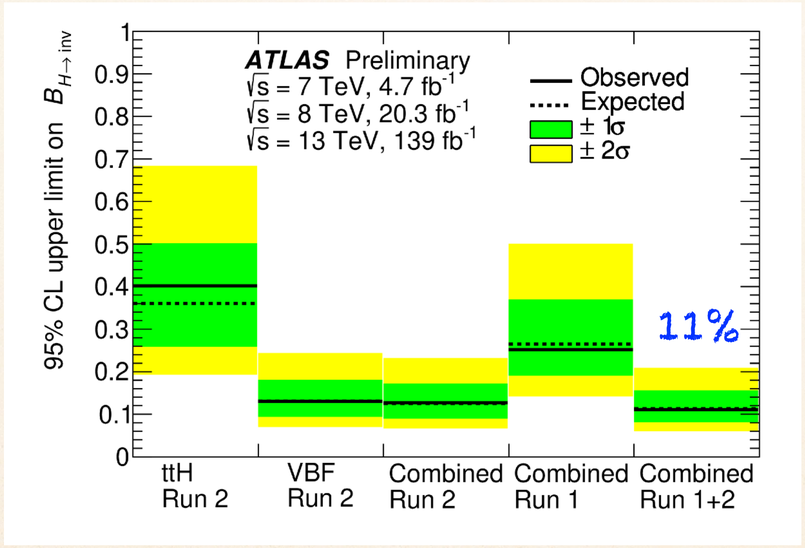
ATLAS-CONF-2020-052

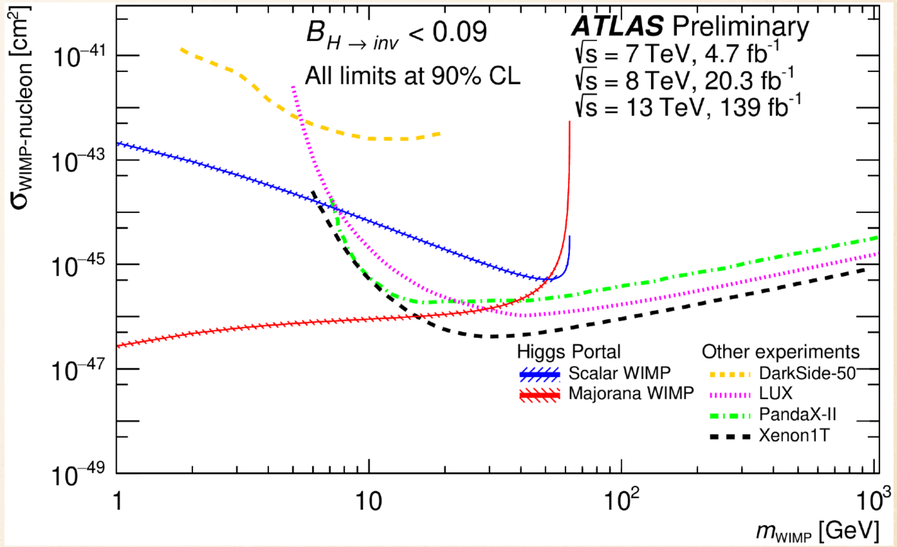
- Either Higgs or another (pseudo)scalar can be a mediator coupling to DM

- CMS: $(Z^* \rightarrow Zh, h \rightarrow Za) \rightarrow Z + E_T^{miss}$
- Limit $\mathcal{B}(h \rightarrow inv.)$: obs. 29% (exp. 25%)
- To be compared with 19% from combination

- ATLAS: Combination of searches for $h \rightarrow inv.$ produced in VBF (dominant) and ttH mode



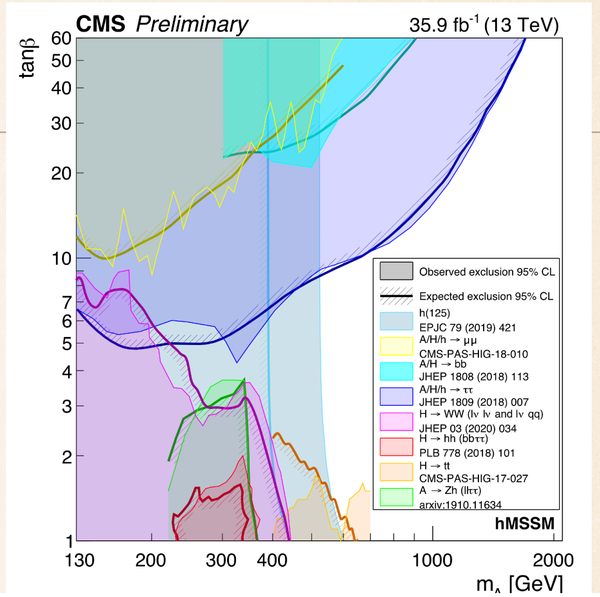


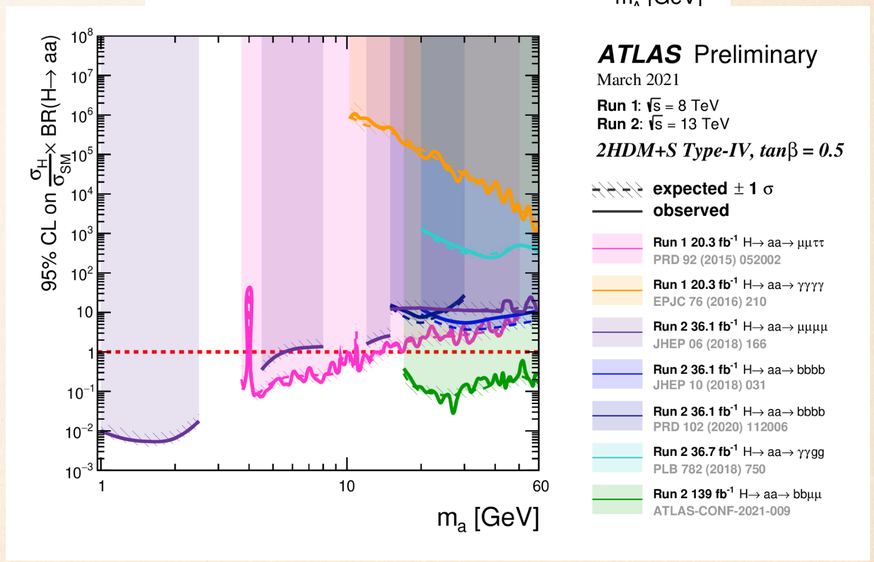


SUMMARY

- Rich Beyond SM Higgs physics program at the ATLAS and CMS experiments
  - Additional Higgs particles
  - Exotic and forbidden decays
- Many new results with the full data set
  - Better object identification, optimisation of analyses, including better background modelling, and new techniques led to improvement beyond the gain from luminosity

Public results from ATLAS and CMS





BACKUP

arXiv:2102.13405

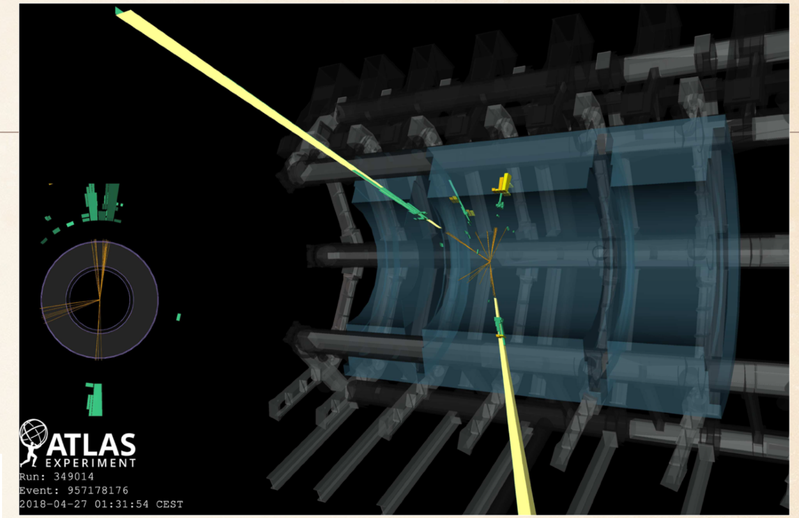
Submitted to PLB

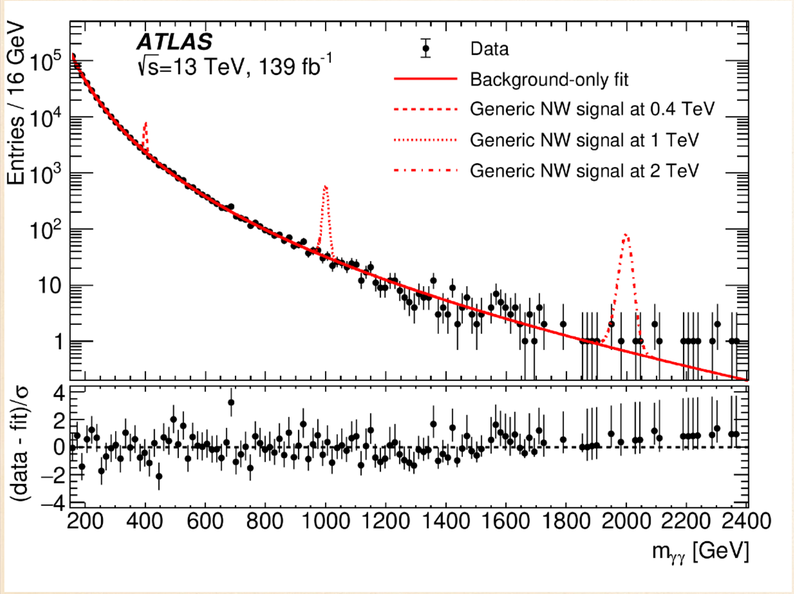
$H \to \gamma\gamma$

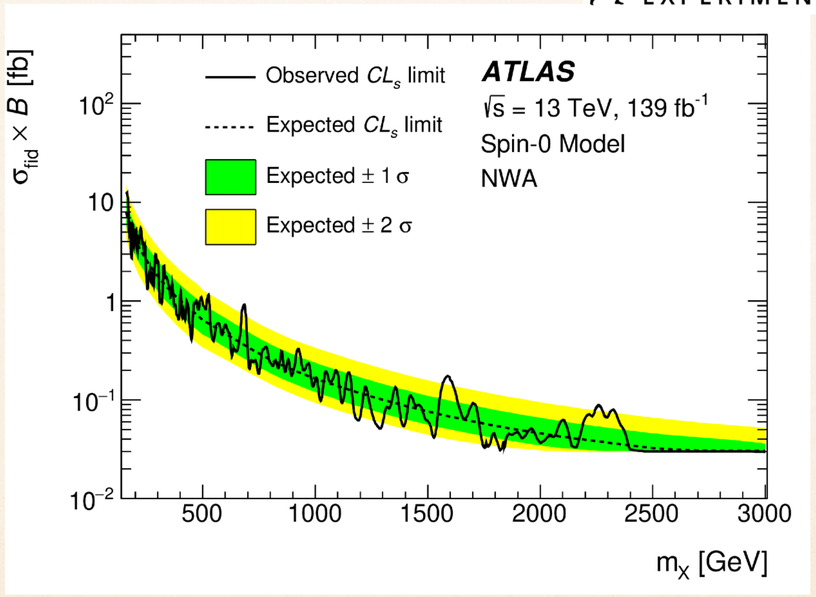
New

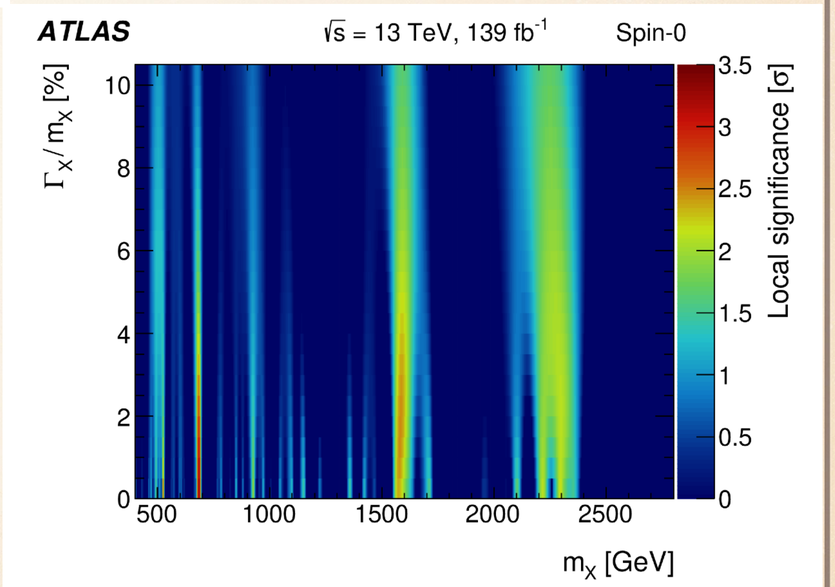
139 fb-1

- Generic spin-0 resonance with $\Gamma_X/m_X = [0,10]\,\%$
- Signal modelled with a double-sided Crystal Ball function
- Background dominated with $\gamma\gamma$ events modelled with a functional fit





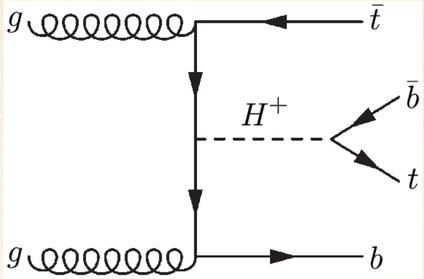




ATLAS EXPERIMENT

139 fb-1

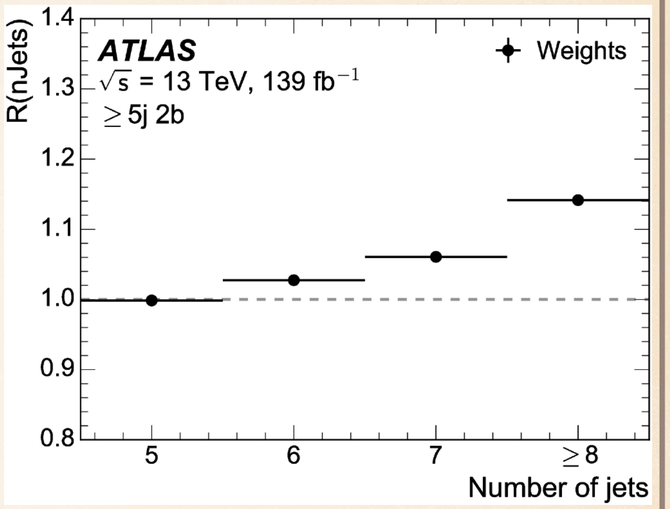
$H^{\pm} \rightarrow tb$

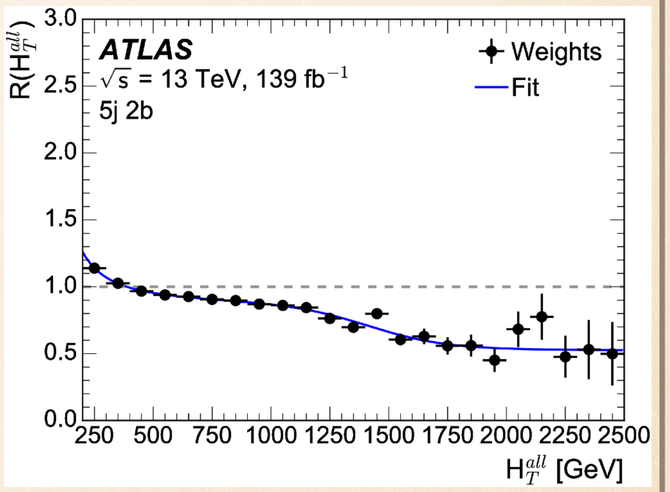


arXiv:2102.10076

Submitted to JHEP

- Dominant background tt+jets is modelled with Powheg-Box and corrected using ≥5j(exactly 2b) control region
  - N_{Jets} and p_T of additional jets mismodeled, so weights derived as $R(N_{jets}) \times R(H_T^{all})$
  - Mismodeling independent of the flavour of additional jets
- The final $tt + \geq 1b$ and $tt + \geq 1b$ normalisation factors and their uncertainties, which account for the remaining mismodelling observed after applying the reweighting, are not applied.
- These normalisations are extracted from the fit to data

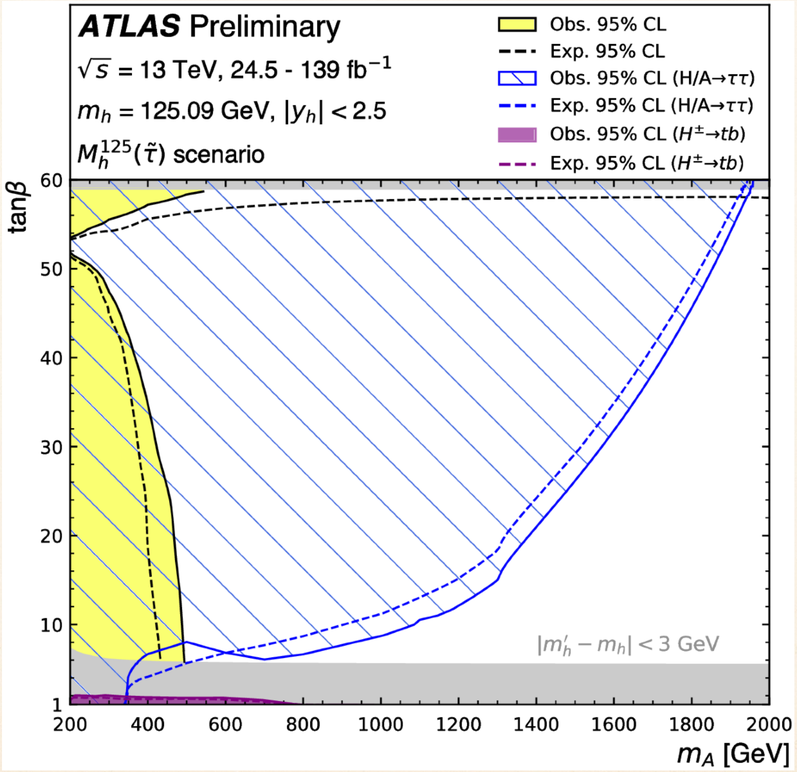


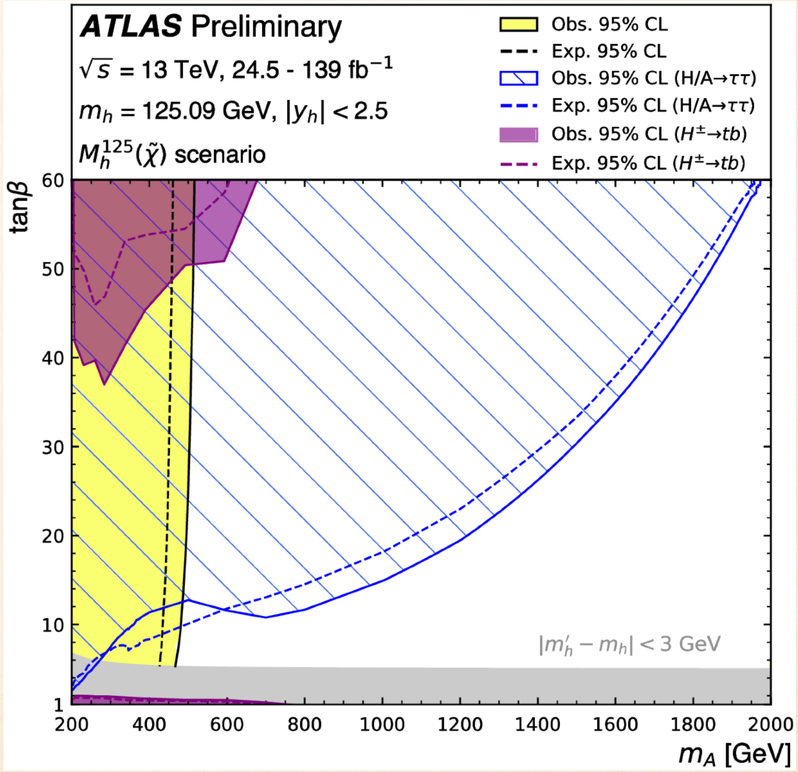


COMBINATION

ATLAS-CONF-2020-053

- Combined measurement of the SM-like Higgs boson interpreted in MSSM
  - Assumption is that observed Higgs boson is the light CP-even Higgs boson from MSSM



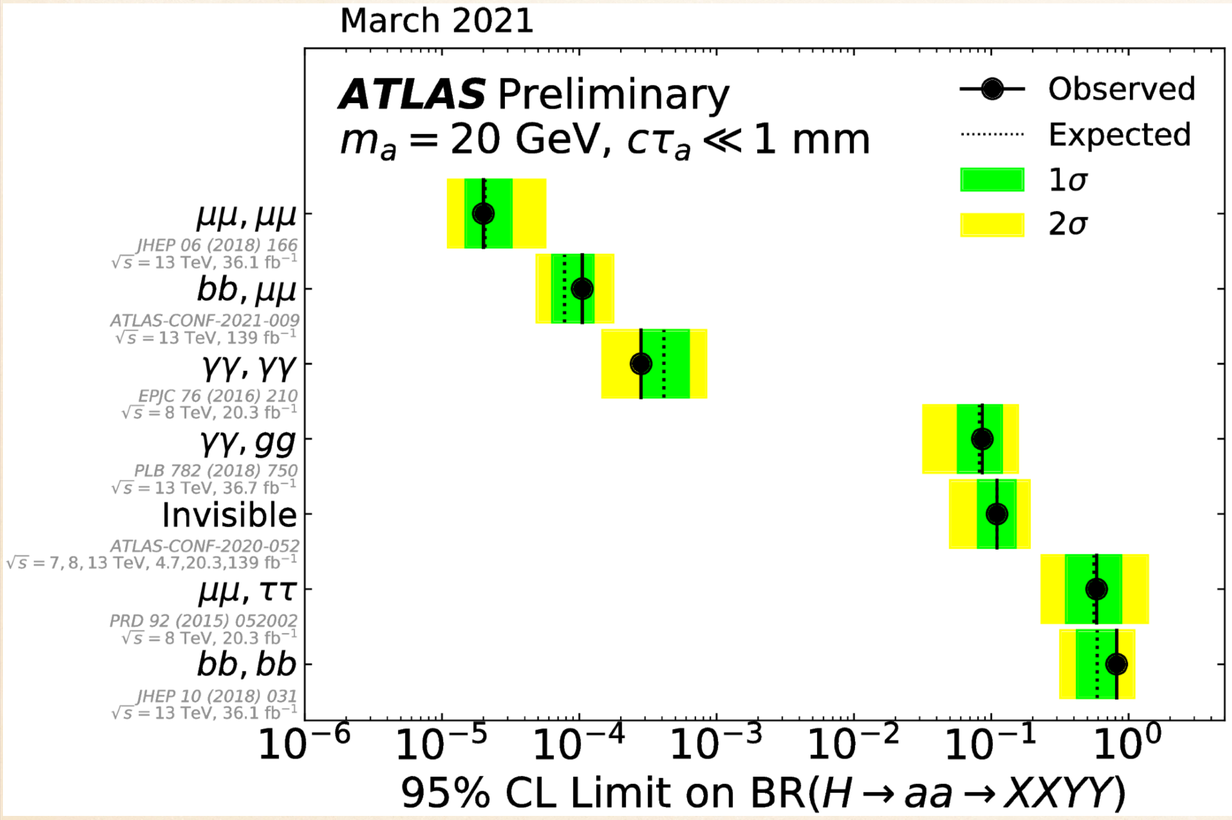


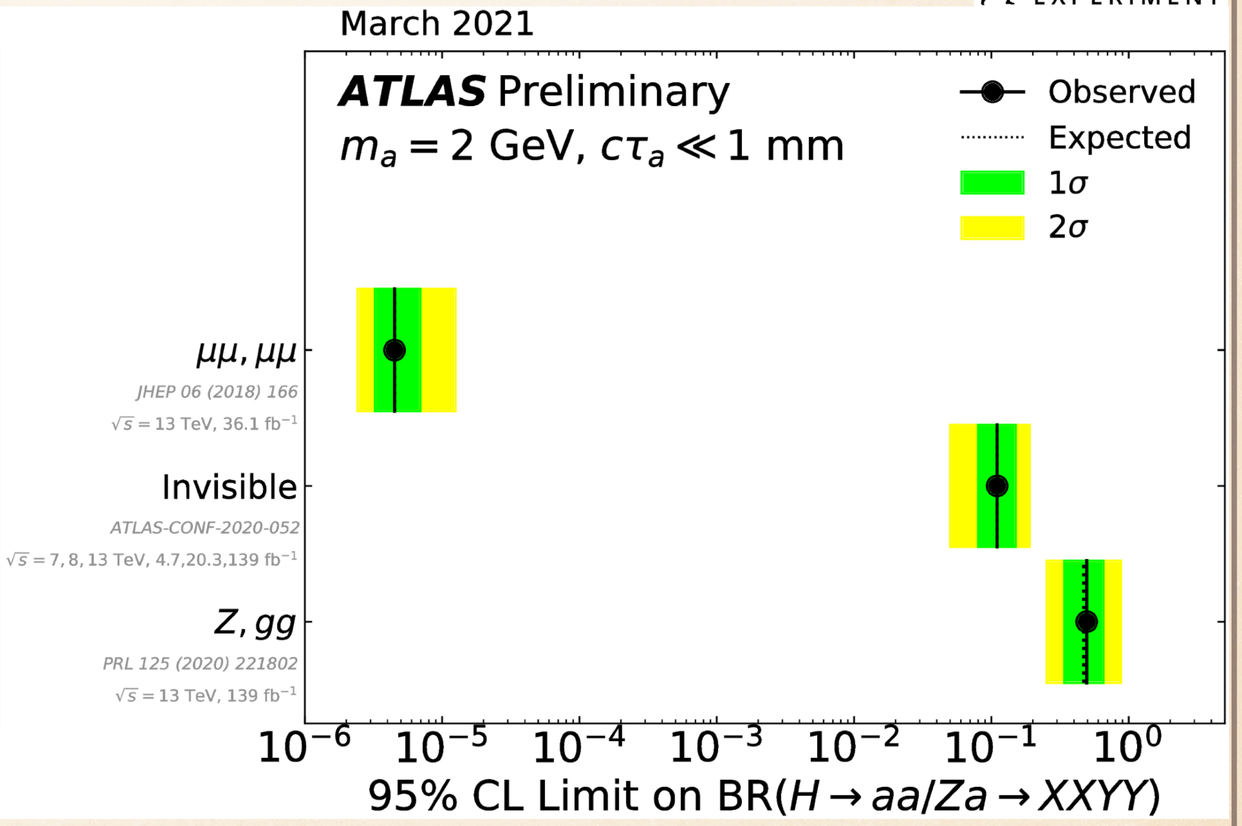
$H \to aa$ - SUMMARY

New

ATL-PHYS-PUB-2021-008

Model independent limits





LEPTON FLAVOUR VIOLATION IN HIGGS DECAYS

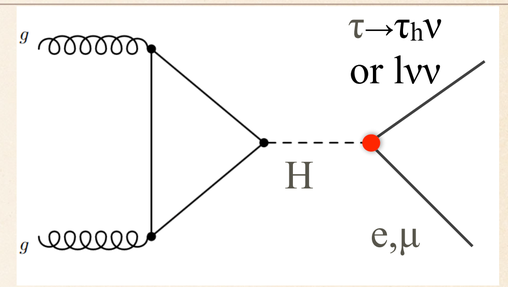
CMS-PAS-HIG-20-009

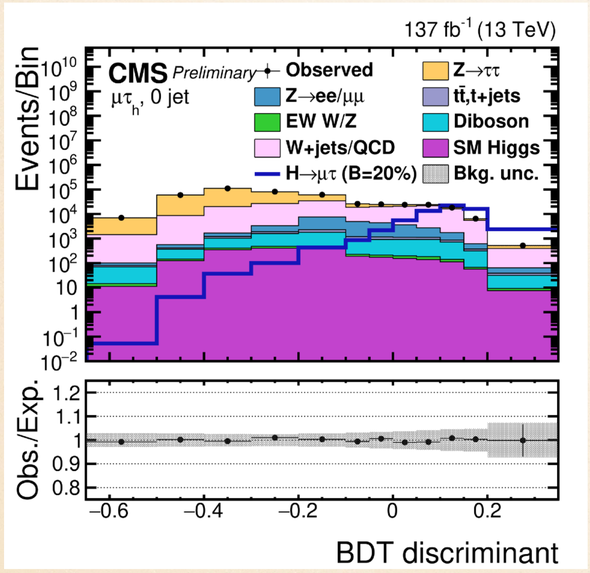
New

VBF production also included

- Forbidden in Standard Mode; LFV in Higgs decay will arise in the models with extensions of the Higgs sector or warped extra dimension
  - To enhance sensitivity, BDT is used for final analysis
    - Inputs include p_T, masses, angular distances
- Observed (exp.) upper limits on $\mathcal{B}(H \to \mu\tau)$ is 0.15% (0.15%) and on $\mathcal{B}(H \to e\tau)$ is 0.22% (0.16%) @95% C.L.

137 fb^{-1}

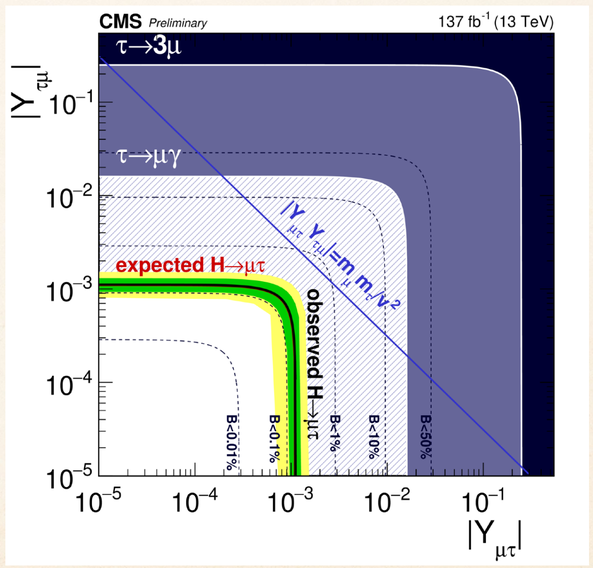


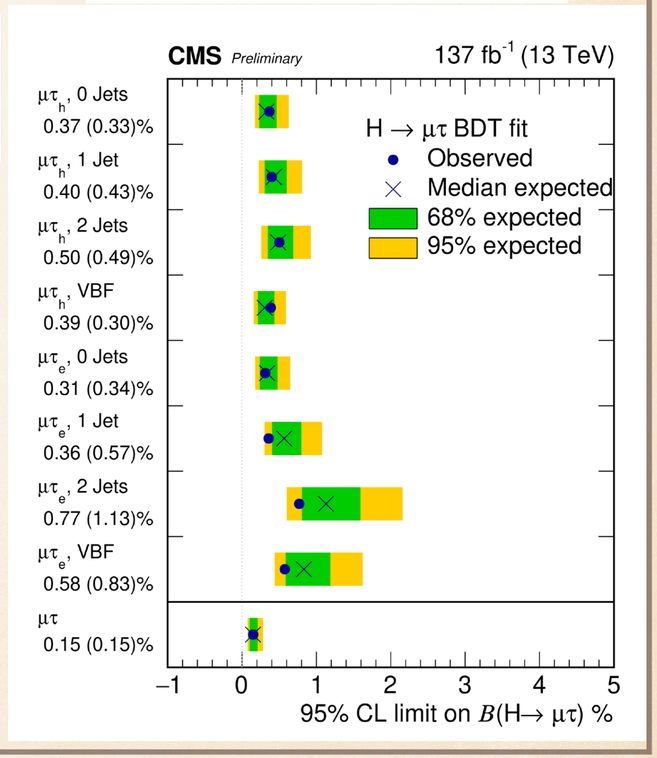


$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.11 \times 10^{-3}$$

$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 1.35 \times 10^{-3}$$

Naturalness is satisfied for $|Y_{\ell_1\ell_2} Y_{\ell_2\ell_1}| < \dfrac{m_{\ell_1} m_{\ell_2}}{v^2}$





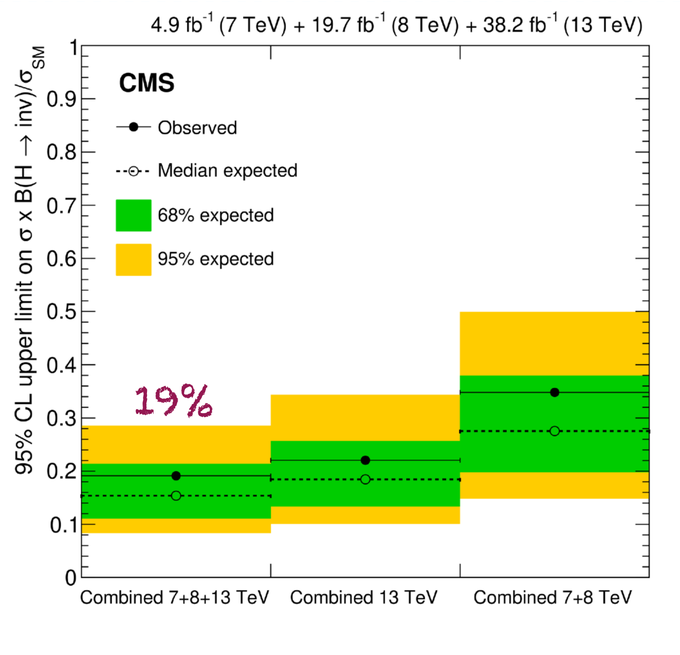
HIGGS TO INVISIBLE

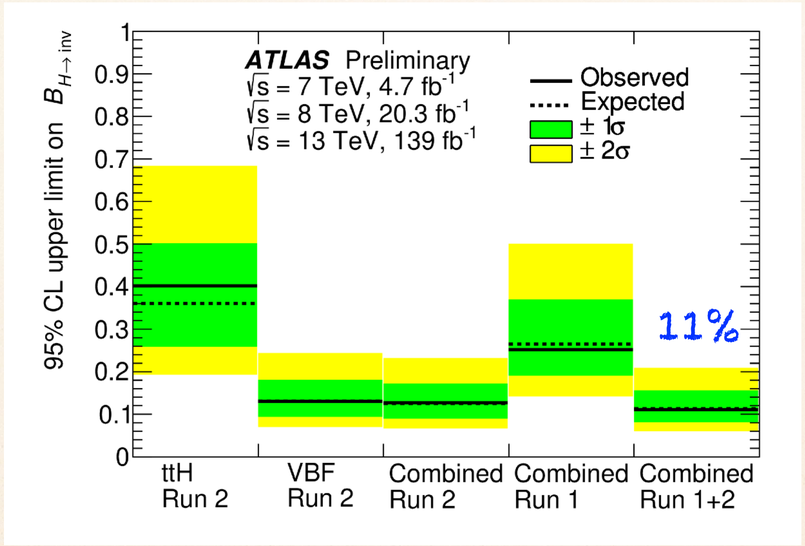
PLB 793 (2019) 520

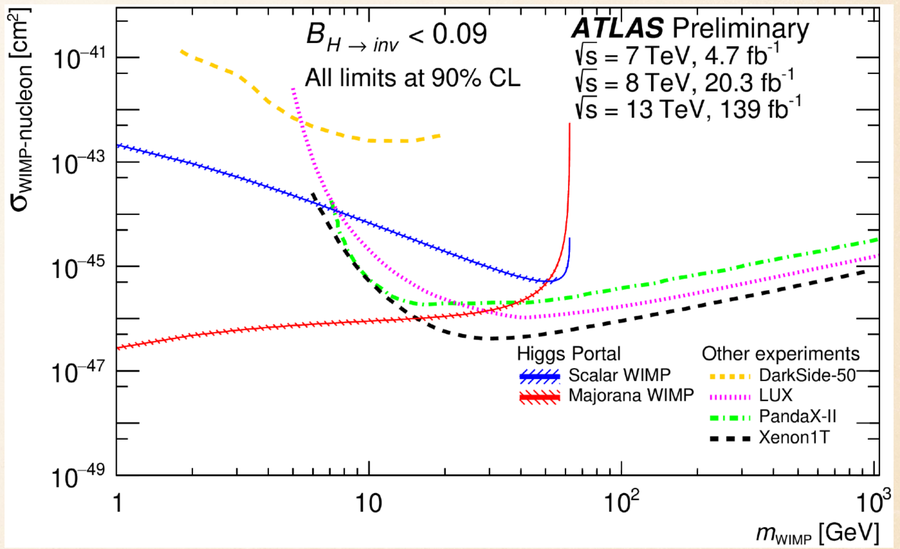
ATLAS-CONF-2020-052

- Either Higgs or another (pseudo)scalar can be a mediator coupling to DM
- Combination of the searches for $H \to inv$.

- CMS: ggF, VH and VBF (dominant)
- ATLAS: VBF (dominant) and ttH mode







ATLAS EXPERIMENT

New

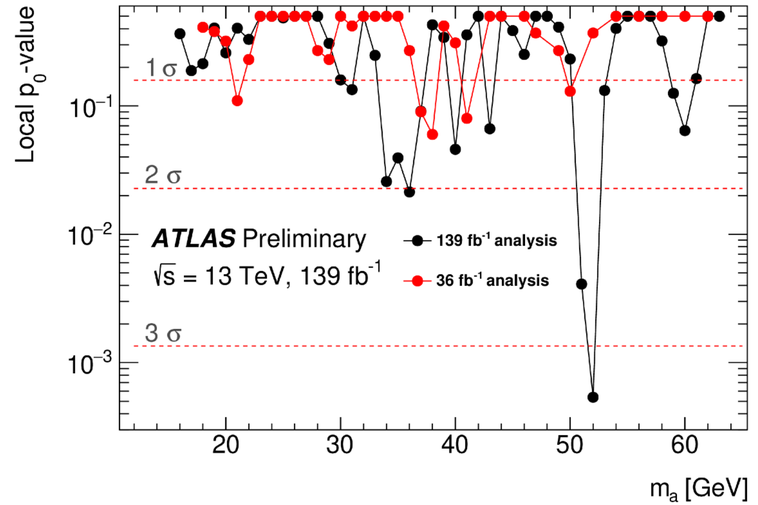
$H \to aa \to bb\mu\mu$

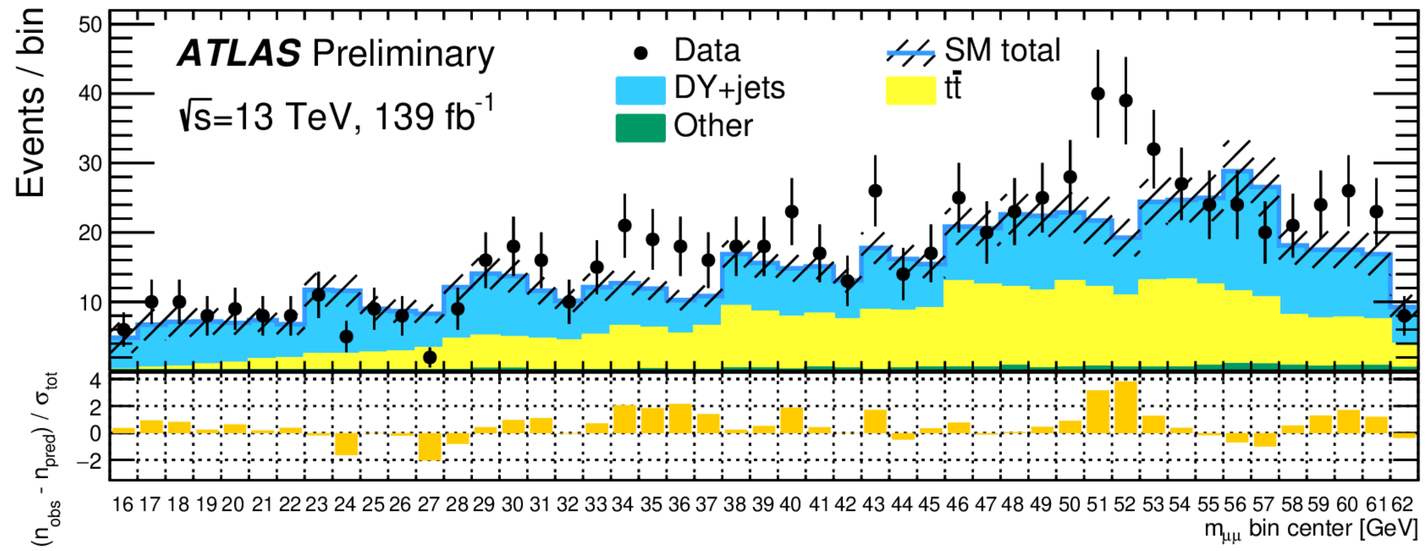
139 fb^{-1}

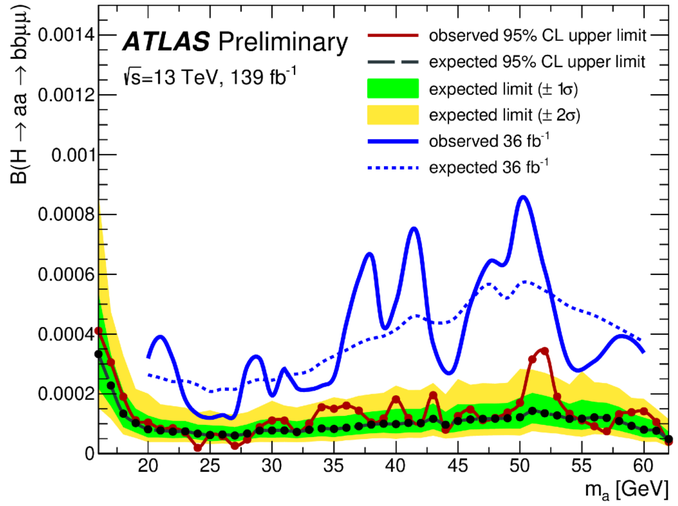
УНИВЕРЗИТЕТ У БЕОГРАДУ | ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

ATLAS-CONF-2021-009

- Excess is searched $m_a - X < m_{\mu\mu} < m_a + X$ bins
- The largest excess is observed at $m_{\mu\mu} = 52$ GeV with local (global) significance of 3.3σ (1.7σ).







$ZH \to \ell\ell aa \to \ell\ell bbbb$ - LONG LIVED

ATLAS EXPERIMENT

ATLAS-CONF-2021-005

139 fb^{-1}

New

- LLP decays in ID, resulting in at least two displaced vertices
- Events preselected to pass basic selection, 2 leptons and 4 b-jets
- Then large radius tracking (with looser ID criteria) ran to identify events with DVs