Exotic Higgs decays (in ATLAS)

Forbidden decays to SM particles & Decays to BSM particles

Shikma Bressler I Higgs24 I November 4-8, 2024

- $H \rightarrow aa \rightarrow 2b2\tau$ [link]
- $H \rightarrow aa \rightarrow 4\gamma$ [link]
- $H \rightarrow Za \rightarrow 2\ell 2\gamma$ [link]
- $H \rightarrow \tau\ell$ [link]

Physics motivation

- The Higgs could be a window to BSM physics in several avenues
  - Precision measurements of coupling constants

    → search for deviation from the SM predictions
  - Discovery of forbidden decays to SM particles
  - Discovery of decays to BSM particles

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} today's talk

Decays to BSM particles

Decays to BSM particles

- The Higgs is the only known elementary scalar
- Provides a unique window to a variety of light BSM particles
- In particular light scalars and pseudo-scalars that are singles of the SM
- Couplings and hence BRs could be large (up to 12%)
  - Scalar models
  - Axion models

arXiv:2111.12751

$$Br(h \to ss) \simeq \frac{v^2 \kappa^2}{32\pi m_h \Gamma_h} \sqrt{1 - \frac{4m_s^2}{m_h^2}},$$

$$\Gamma(h \to aa) = \frac{v^2 m_h^3}{32\pi\Lambda^4} |C_h|^2 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}},$$

$$\Gamma(h \to Za) = \frac{m_h^3 v^4}{64\pi\Lambda^6} |C_Z|^2 \lambda^{3/2}\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2}\right),$$

The experimental challenge

- Analysis dictated by the properties of the BSM particle
  - Decay products
    - Scalars mix with the SM Higgs →
      Decay preferably to the heaviest SM particles that are kinematically accessible
    - ALPs → Some models prefer decays to photons and gluons
    - Vectors → Mostly fermion pairs
  - Lifetime
    - Short → Prompt decay
    - Medium → Displaced vertex
    - Long → Invisible decay
  - Mass
    - Massive particles → resolved decay products
    - Light particles → merged decay products

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Each combination requires different analysis
→ collaboration effort

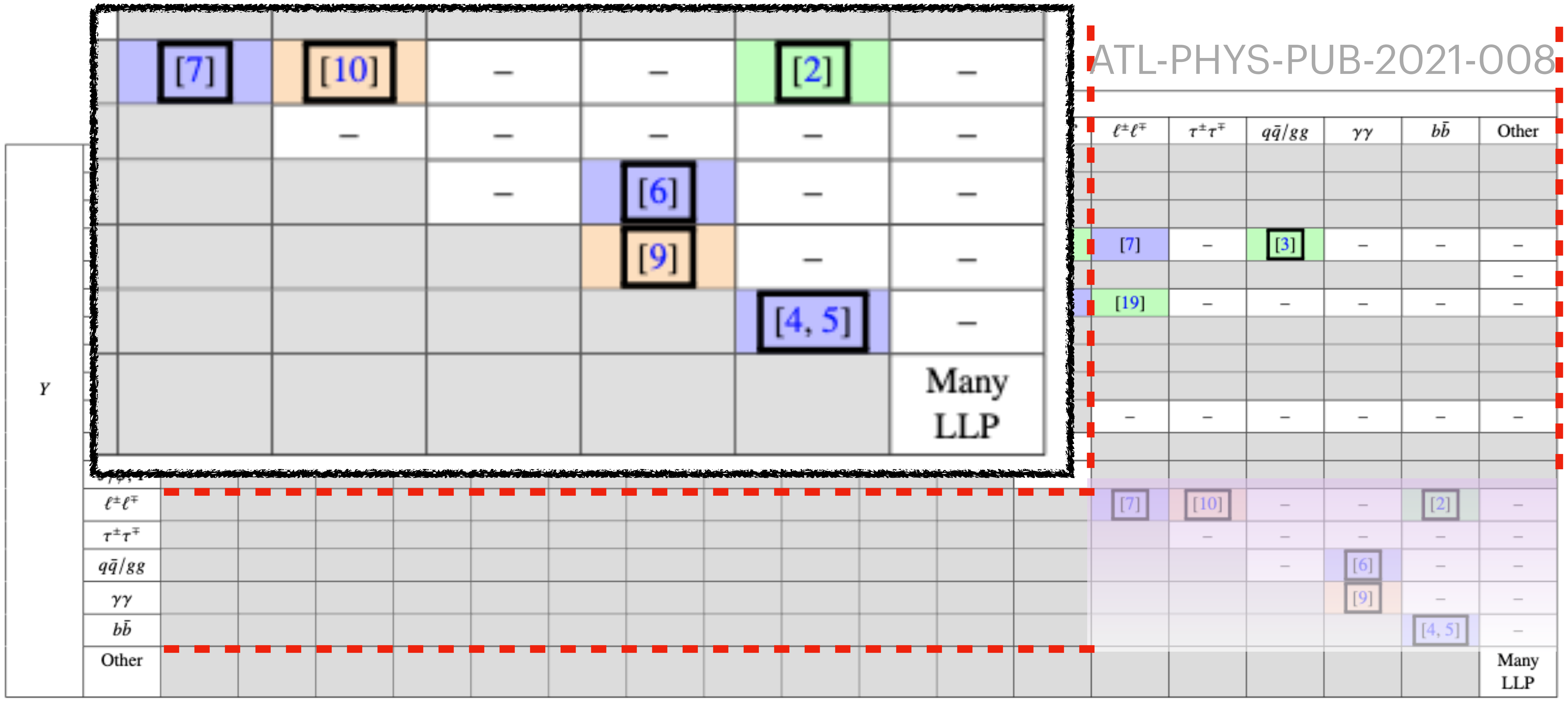
The experimental challenge

ATL-PHYS-PUB-2021-008

		X																	
		$e^\pm$	$\mu^\pm$	$\tau^\pm$	Z	W	γ	q/g	c	b	Inv.	ϕ,ρ	$J/\psi,\Upsilon$	$\ell^\pm\ell^\mp$	$\tau^\pm\tau^\mp$	$q\bar{q}/gg$	$\gamma\gamma$	$b\bar{b}$	Other
Y	$e^\mp$	[12]	[12]	[13]															
	$\mu^\mp$		[14]	[13]															
	$\tau^\mp$			SM															
	Z/Z^*				SM		[15]				–	–	[3]	[7]	–	[3]	–	–	–
	W/W^*					SM													–
	γ						SM				[16]	[17]	[18]	[19]	–	–	–	–	–
	q/g							–	–	–									
	c								[20]										
	b									SM									
	Inv.										[21]			–	–	–	–	–	–
	ϕ,ρ											–	–						
	$J/\psi,\Upsilon$												–						
	$\ell^\pm\ell^\mp$													[7]	[10]	–	–	[2]	–
	$\tau^\pm\tau^\mp$														–	–	–	–	–
	$q\bar{q}/gg$															–	[6]	–	–
	$\gamma\gamma$																[9]	–	–
	$b\bar{b}$																	[4, 5]	–
	Other																		Many LLP

Table 1: A summary of the most recent ATLAS results targeting exotic decays of the Standard Model Higgs boson $H \to XY$, where X is specified by the column in the table and Y is specified by the row. SM indicates that the channel is one of the main Higgs boson characterization channels, Inv. stands for invisible (neutrinos or other weakly interacting BSM), ℓ represents an electron or muon, and q represents a u,d, or s quark. LLP stands for 'long lived particles'. White cells with marked with an "–" indicate channels which are not covered by an ATLAS search. Blue cells are for partial Run 2 results, green cells represent full Run 2 results, black cells represent forbidden (violate electric/color charge or baryon number conservation) or duplicate entries, and orange cells represent Run 1 results. The results that contribute to the summary plots in this note are indicated with squares around the references. Note that the $b\bar{b} + \ell^+\ell^-$ result is only $b\bar{b} + \mu^+\mu^-$ and the $\tau^+\tau^- + \ell^+\ell^-$ result is only $\tau^+\tau^- + \mu^+\mu^-$.

The experimental challenge



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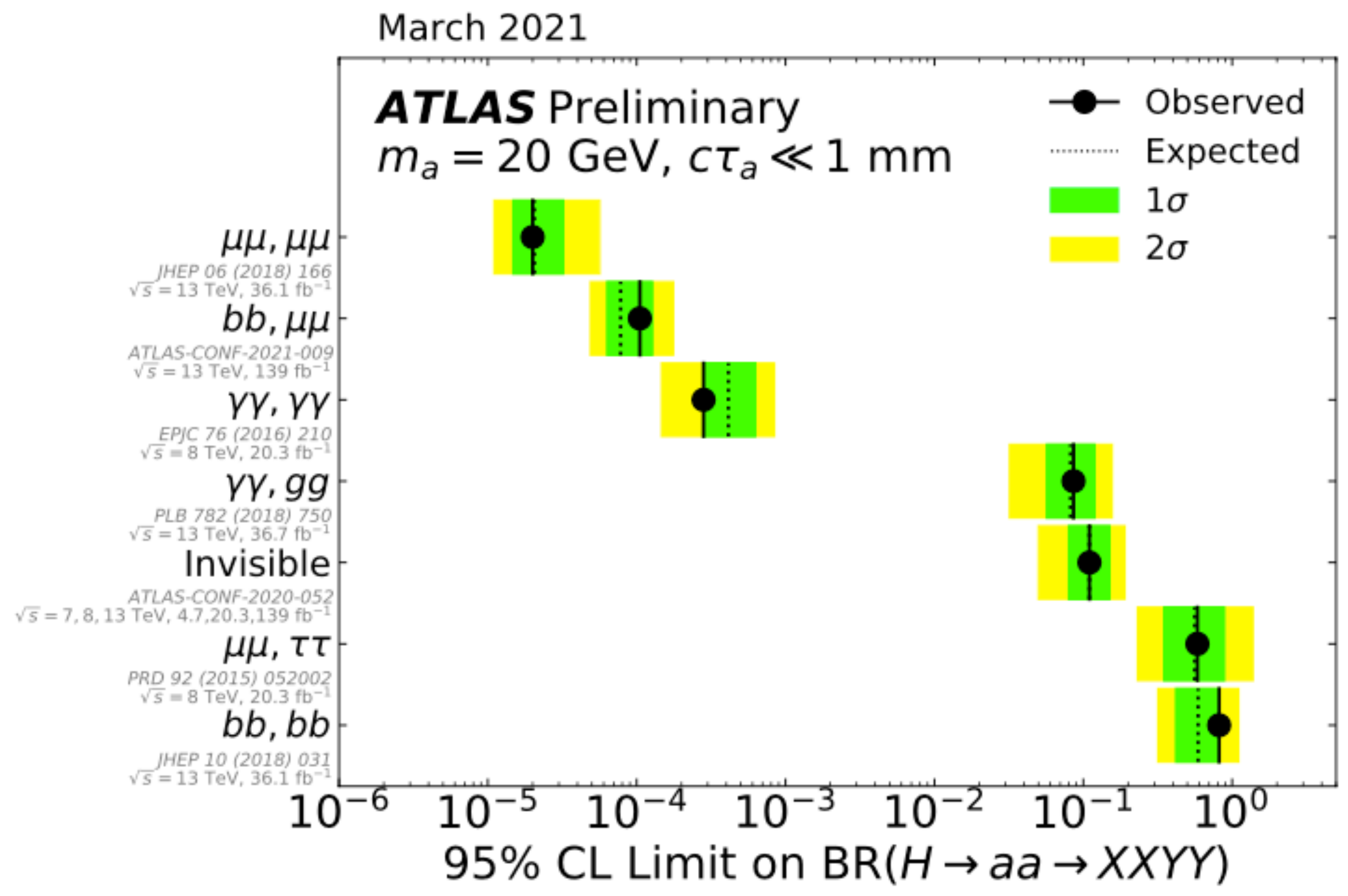


Figure 1: Observed and expected 95% CL upper limits on BR($h \to aa \to XXYY$) assuming no other BSM decays, $m_a = 20$ GeV, the a decays are prompt (proper lifetime is short, $c\tau \ll 1$ mm), and the predicted Standard Model Higgs boson production cross section is correct within uncertainty. gg indicates an a decay to two gluons.

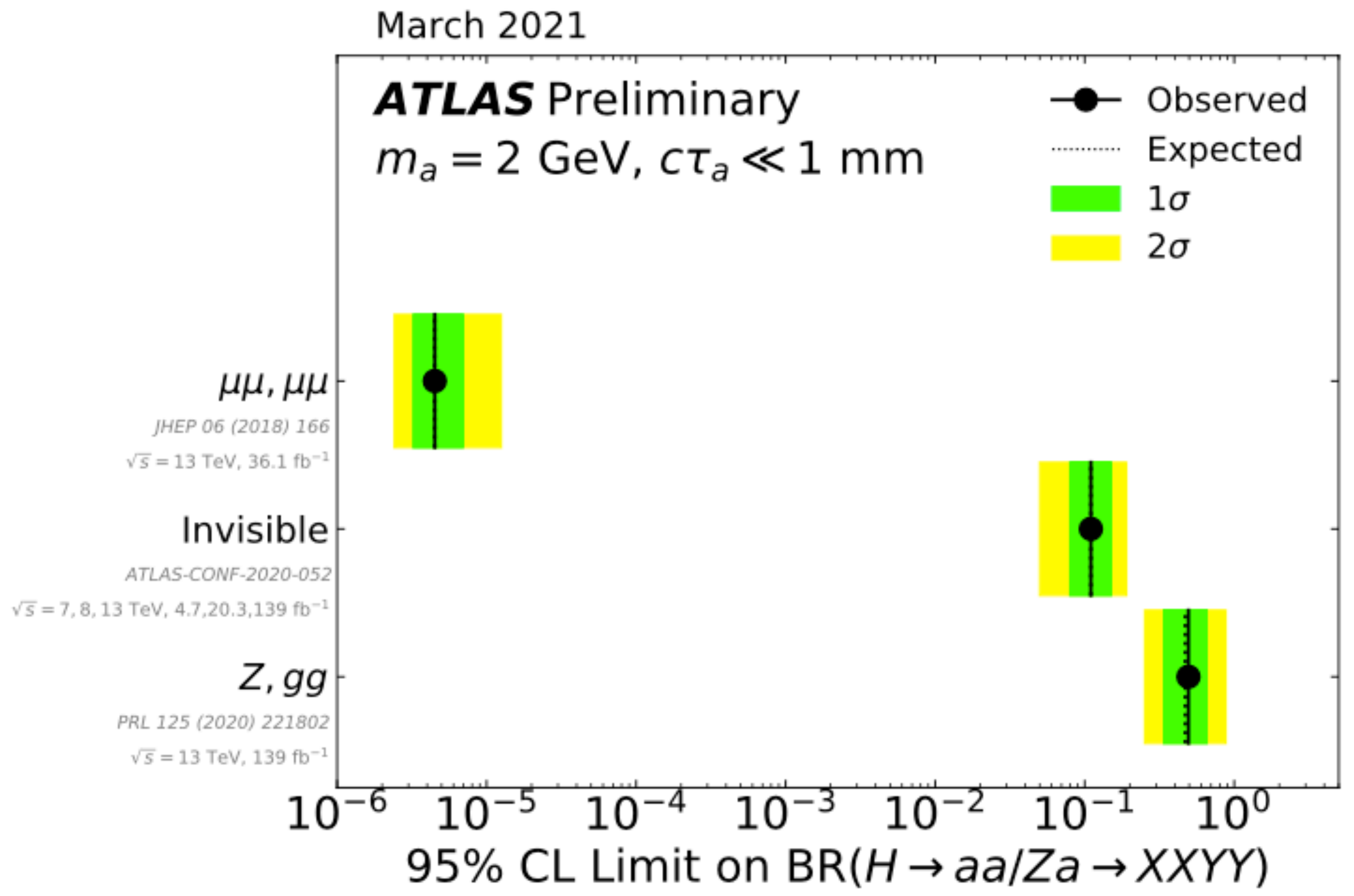
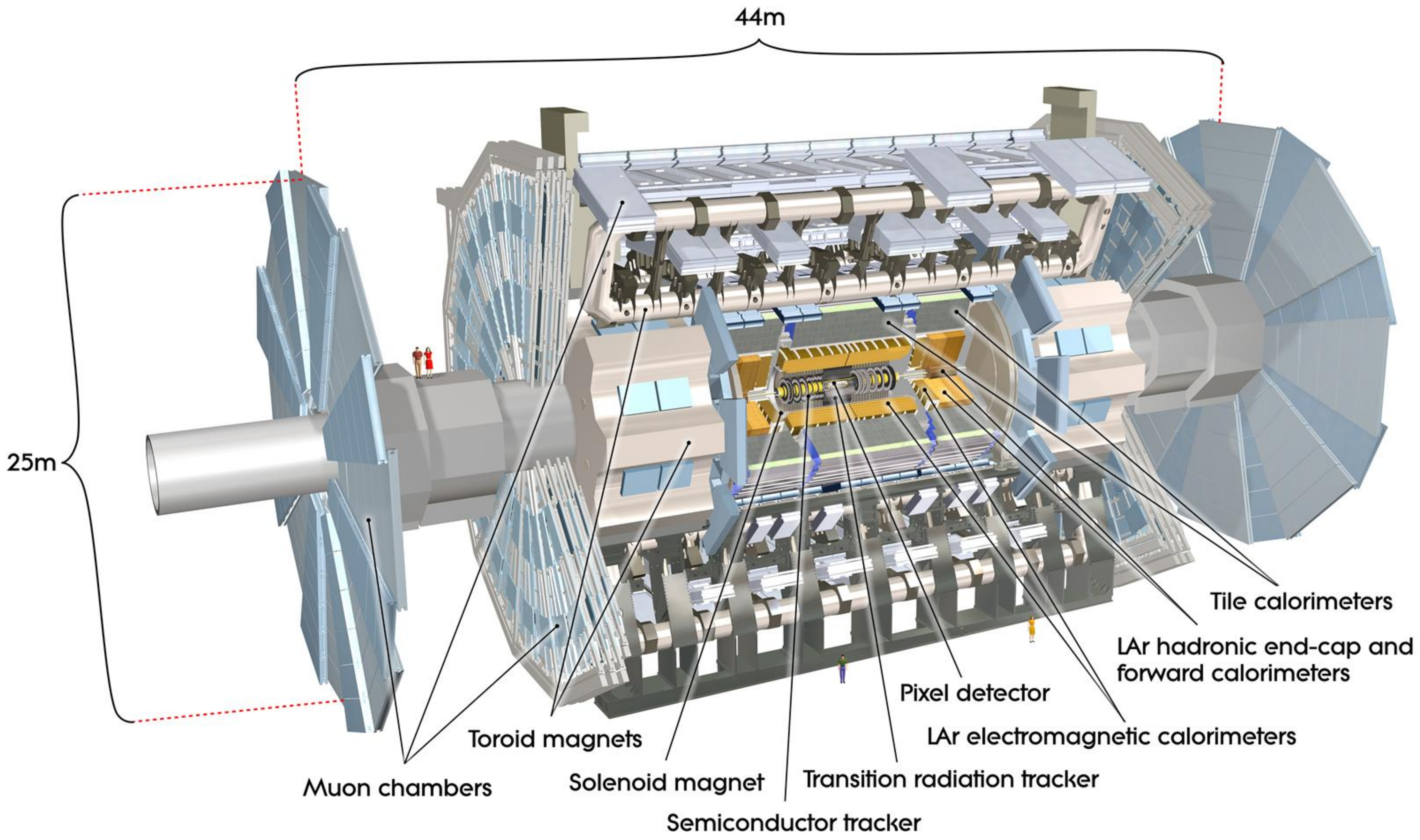
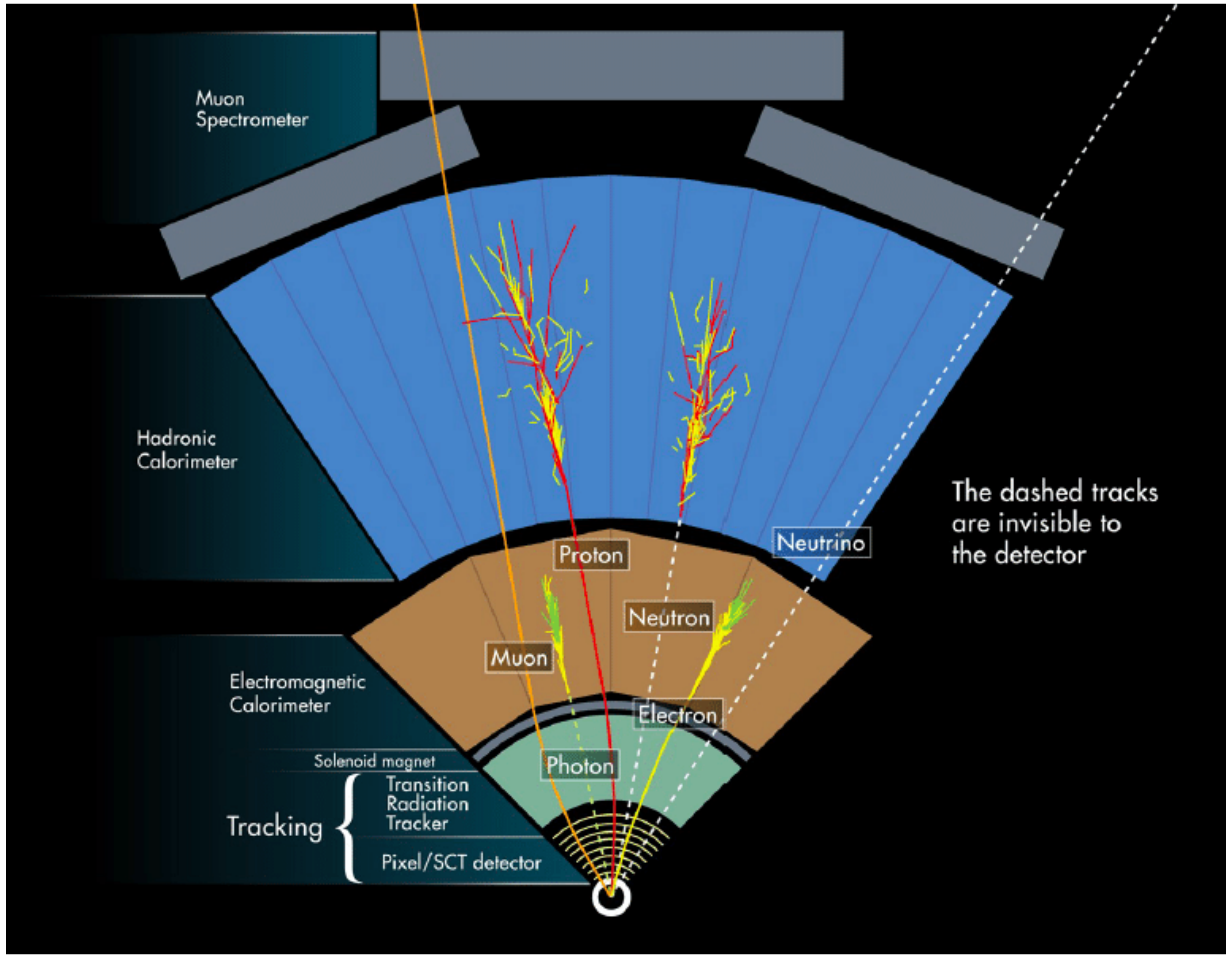


Figure 2: Observed and expected 95% CL upper limits on BR($h \to aa/Za \to XXYY$) assuming no other BSM decays, $m_a = 2$ GeV, the a decays are prompt (proper lifetime is short, $c\tau \ll 1$ mm), and the predicted Standard Model Higgs boson production cross section is correct within uncertainty. gg indicates an a decay to two gluons.

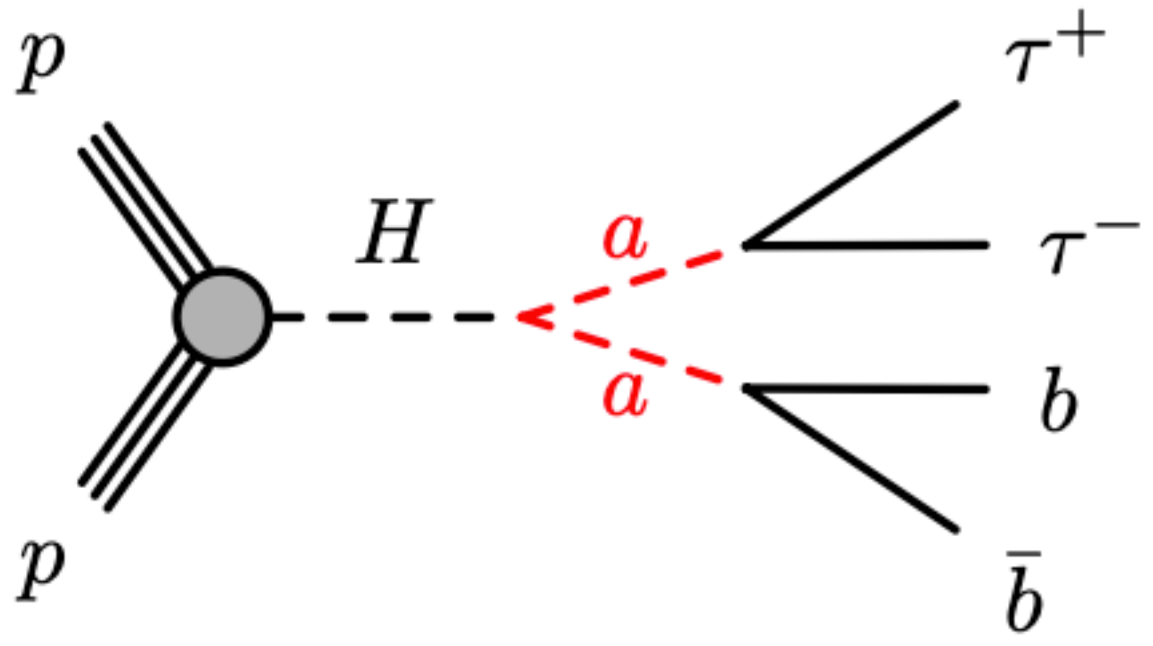
The ATLAS experiment





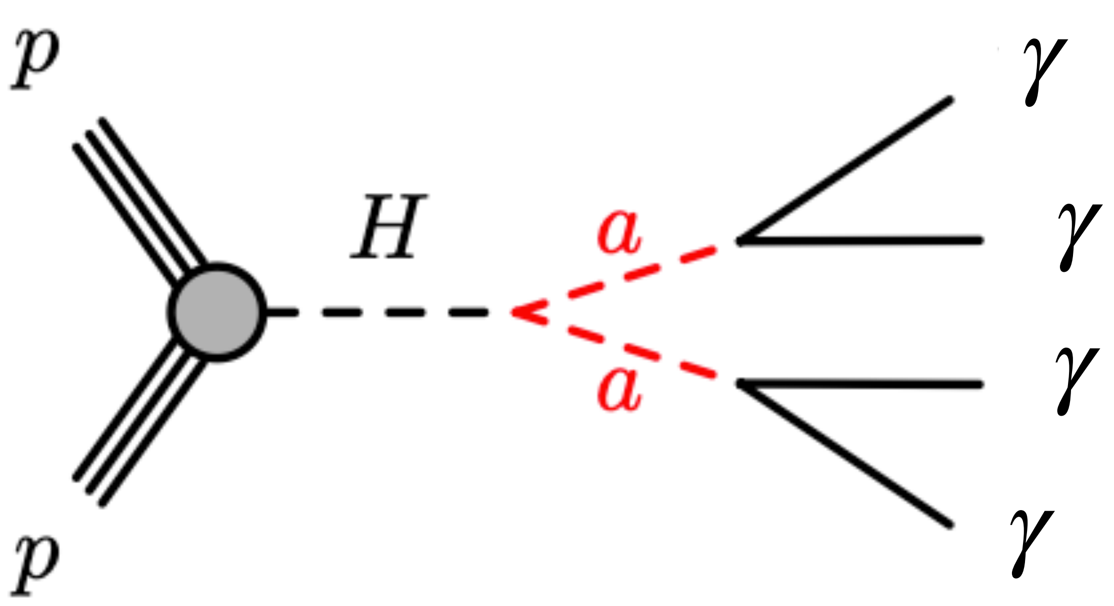
$H \to aa \to 2b2\tau$ $H \to aa \to 4\gamma$ $H \to Za \to 2\ell 2\gamma$

arXiv:2407.01335



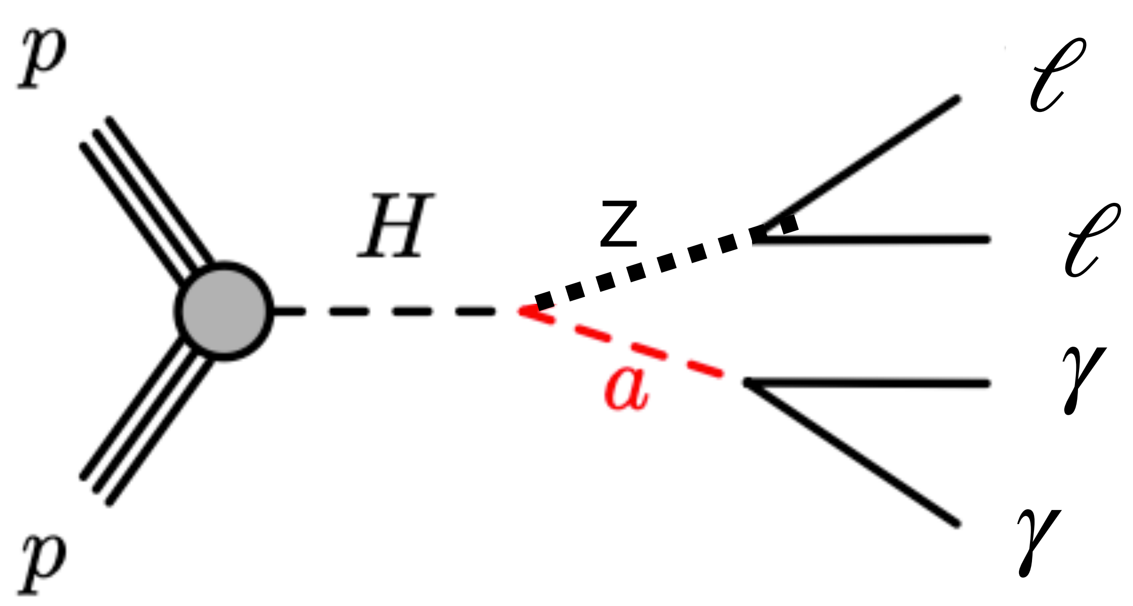
- Targeting models in which the new particle mixes with the SM Higgs and inherits its coupling to fermions

arXiv:2312.03306



- Targeting models with Higgs decay to Axion Like Particles (ALPs)
- Sensitive to models proposed to explain the $(g-2)_\mu$ discrepancy

arXiv:2312.01942



- Targeting models with Higgs decay to Axion Like Particles (ALPs) and extended scalar sector
- Takes advantage of intermediate Z to enhance signal over background

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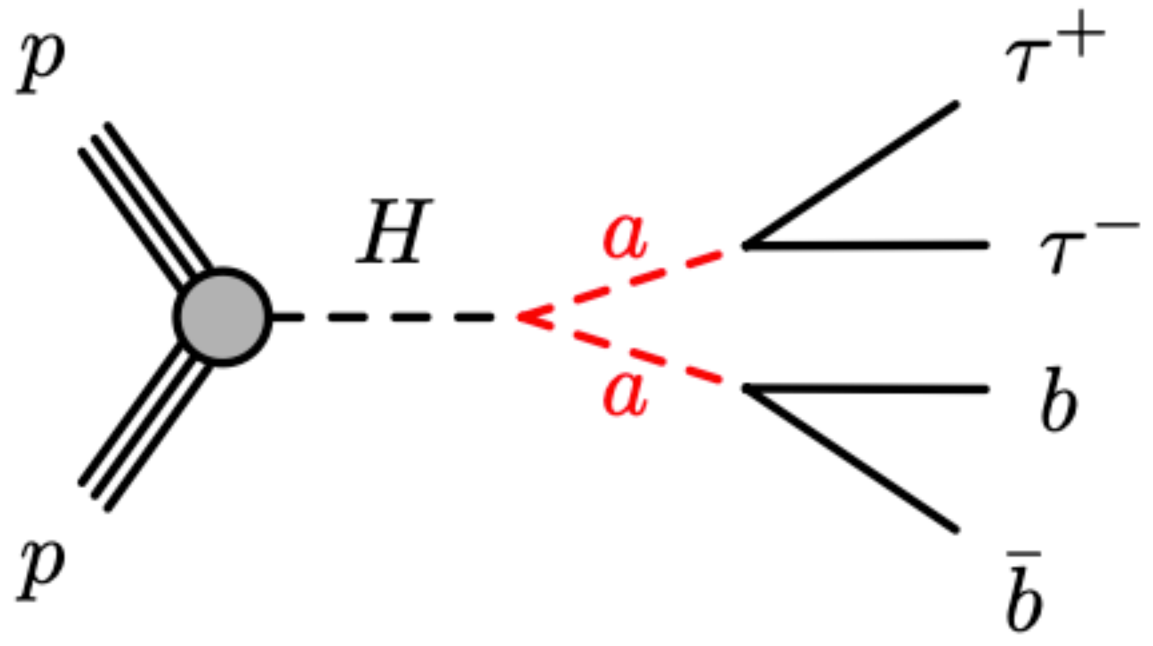

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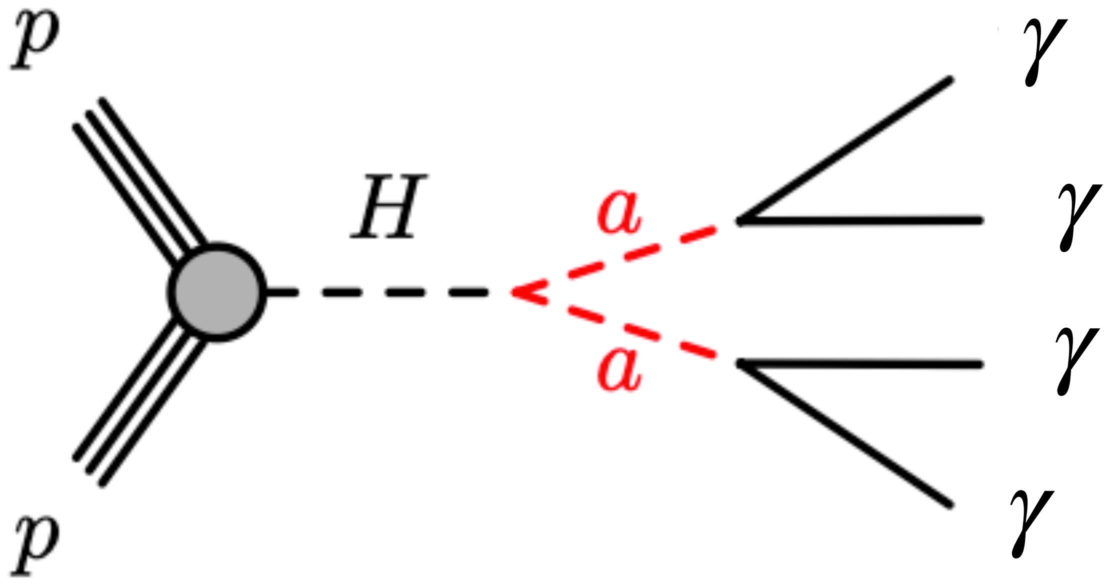

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See Nadav's talk

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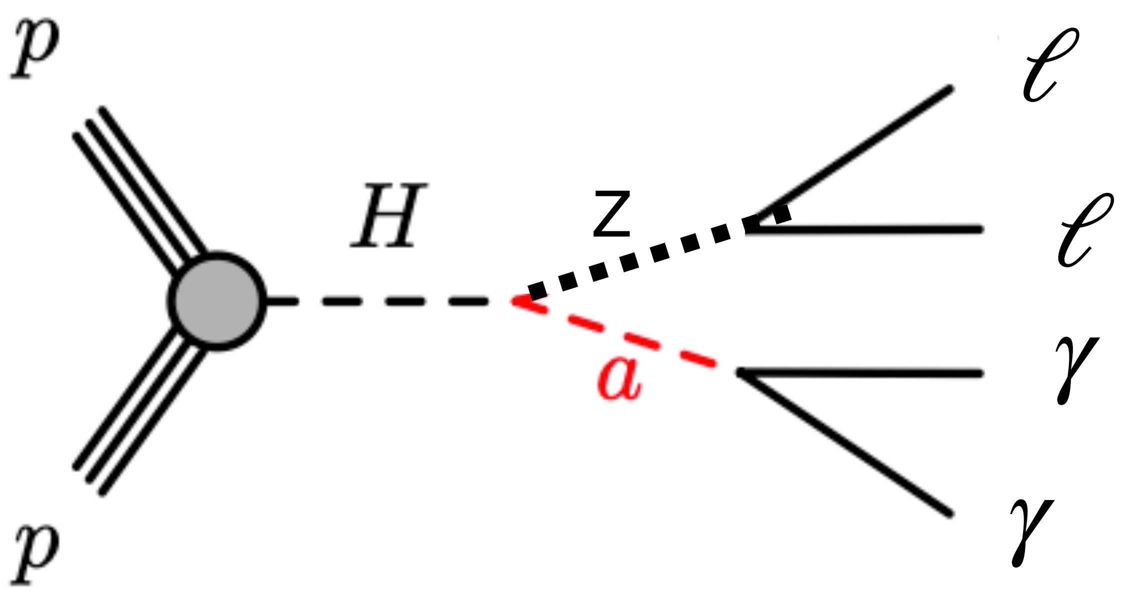

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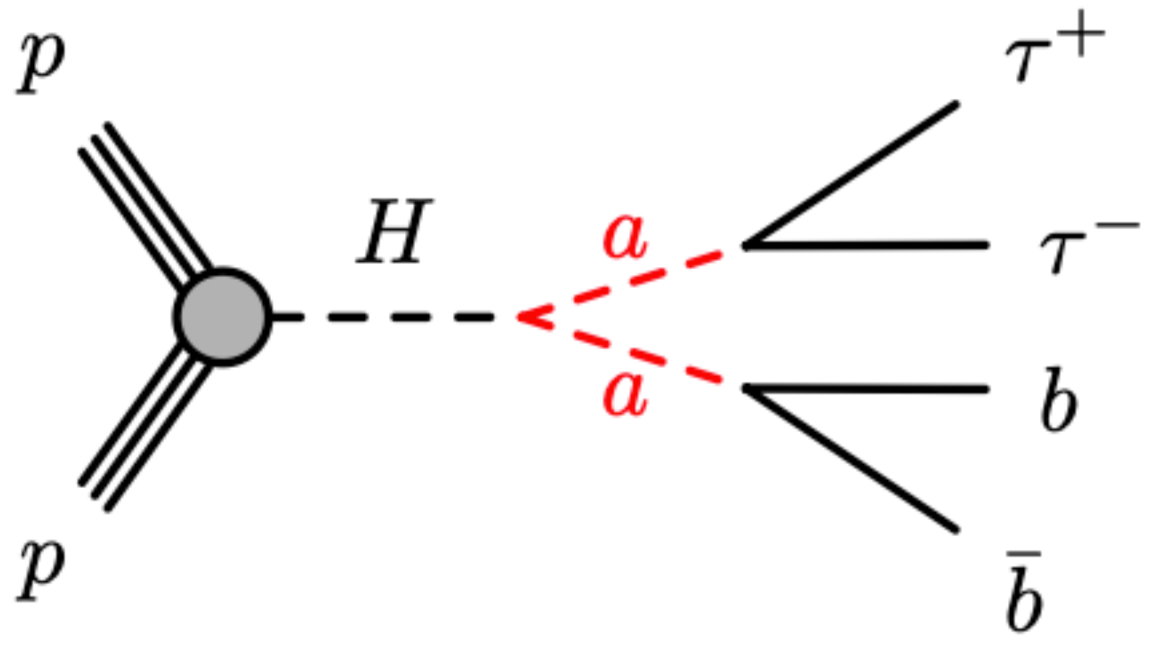

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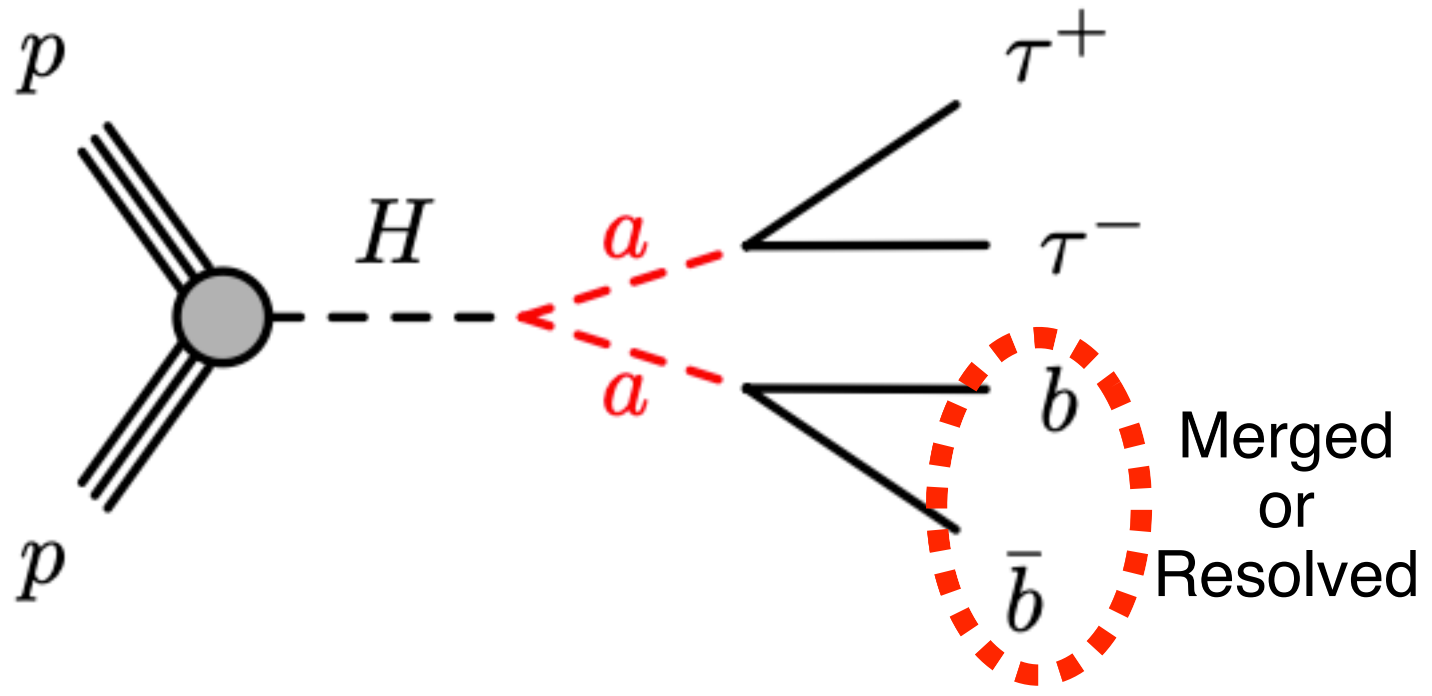
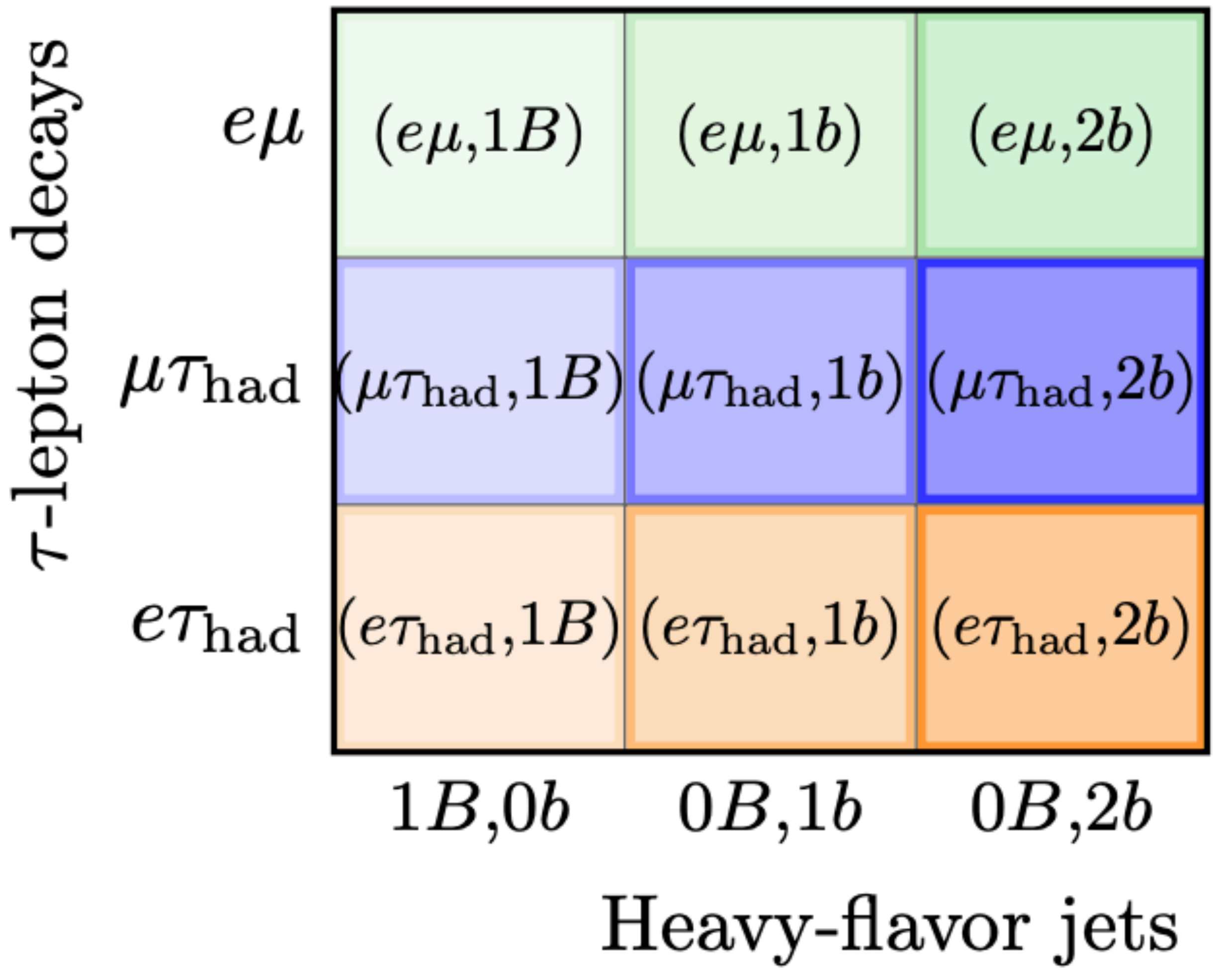


- Single ℓ triggers

- 9 signal categories
  - τ decay mode
  - 1 b-jet, 2 b-jets, 1 unresolved 2b ("B") jet
- Jet categories classified with a new algorithm



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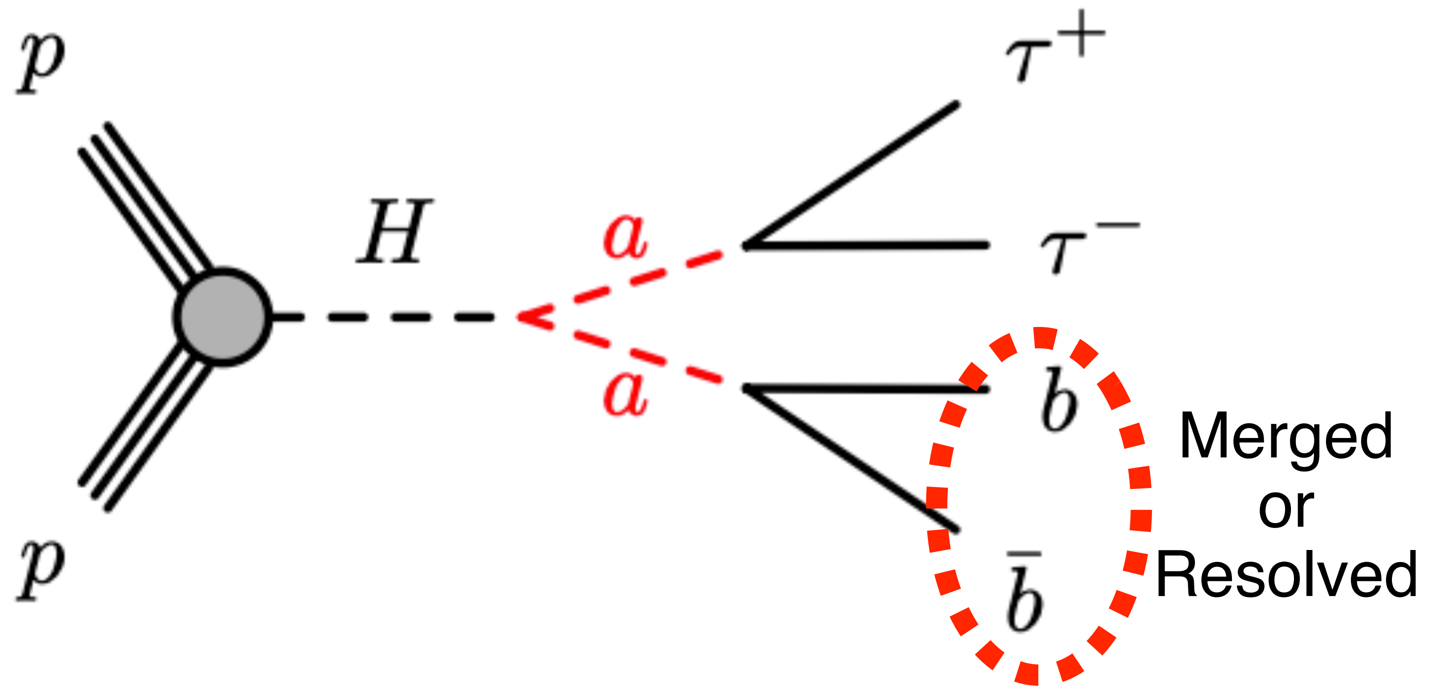

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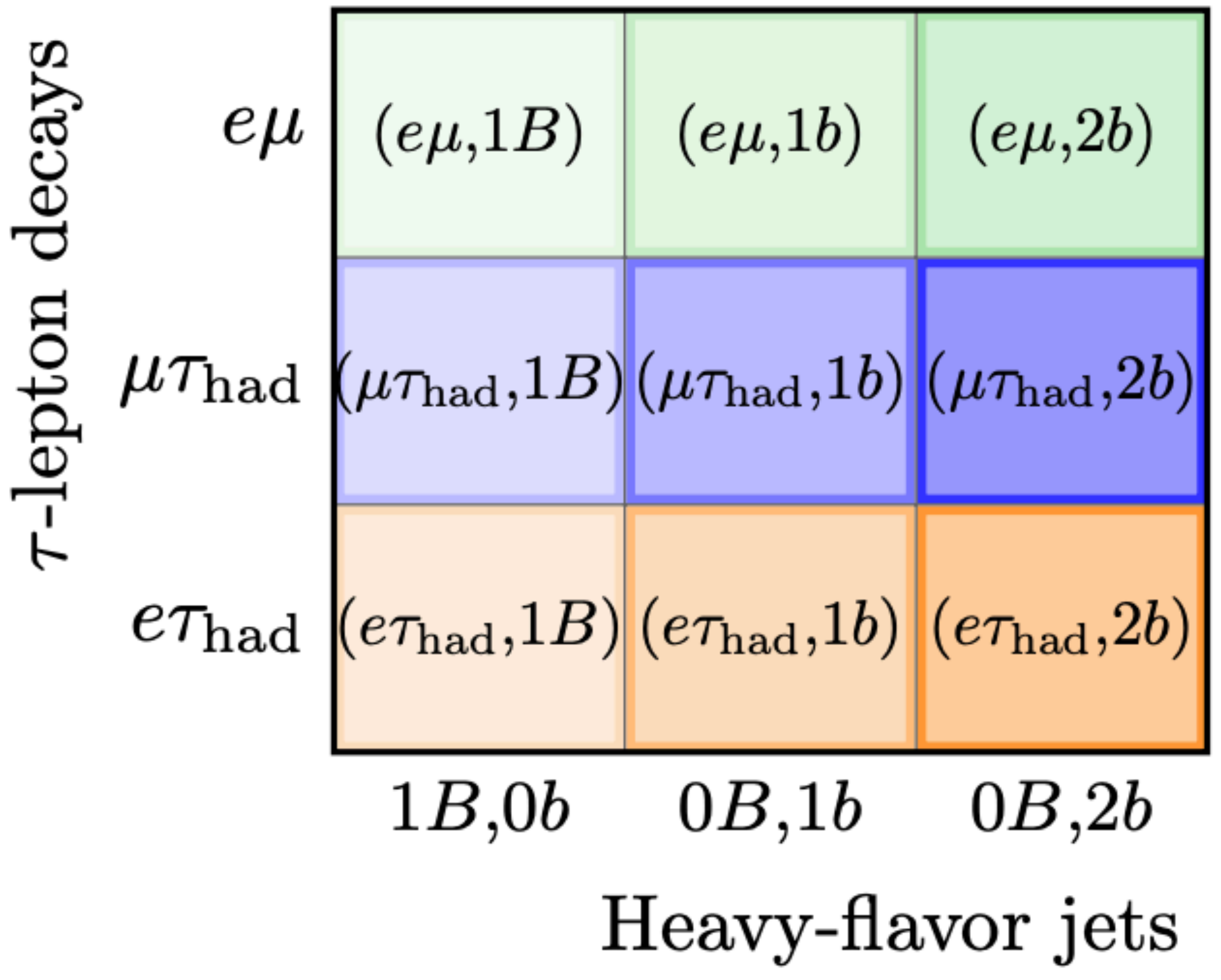

- Main background
  - Drell-Yan of $\tau's$ +jets
  - $t\bar{t}$ and single t
  - non-prompt $\ell + \tau_{had}$

Region	$e\mu$	$e\tau_{\text{had}}$ or $\mu\tau_{\text{had}}$
Signal region	1 OS signal $e\mu$ pair 0 signal τ_{had} $\Delta R(e,\mu) > 0.1$ $4 < m^{\text{vis}}(\tau\tau) < 45$ GeV	1 OS signal $e\tau_{\text{had}}$ or $\mu\tau_{\text{had}}$ pair 1 signal τ_{had} $\Delta R(\ell,\tau) > 0.2$ $4 < m^{\text{vis}}(\tau\tau) < 60$ GeV
	$\Sigma m_T < 120$ GeV 1 B-jet or 1 or 2 b-jets	
Z region	$m^{\text{vis}}(\tau\tau) > 45$ GeV	$m^{\text{vis}}(\tau\tau) > 60$ GeV
$t\bar{t}$ region	$\Sigma m_T > 120$ GeV, no $m^{\text{vis}}(\tau\tau)$ requirement	
SS region	1 SS signal $e\mu$ pair	1 SS signal $e\tau_{\text{had}}$ or $\mu\tau_{\text{had}}$ pair

$H \to aa \to 2b2\tau$

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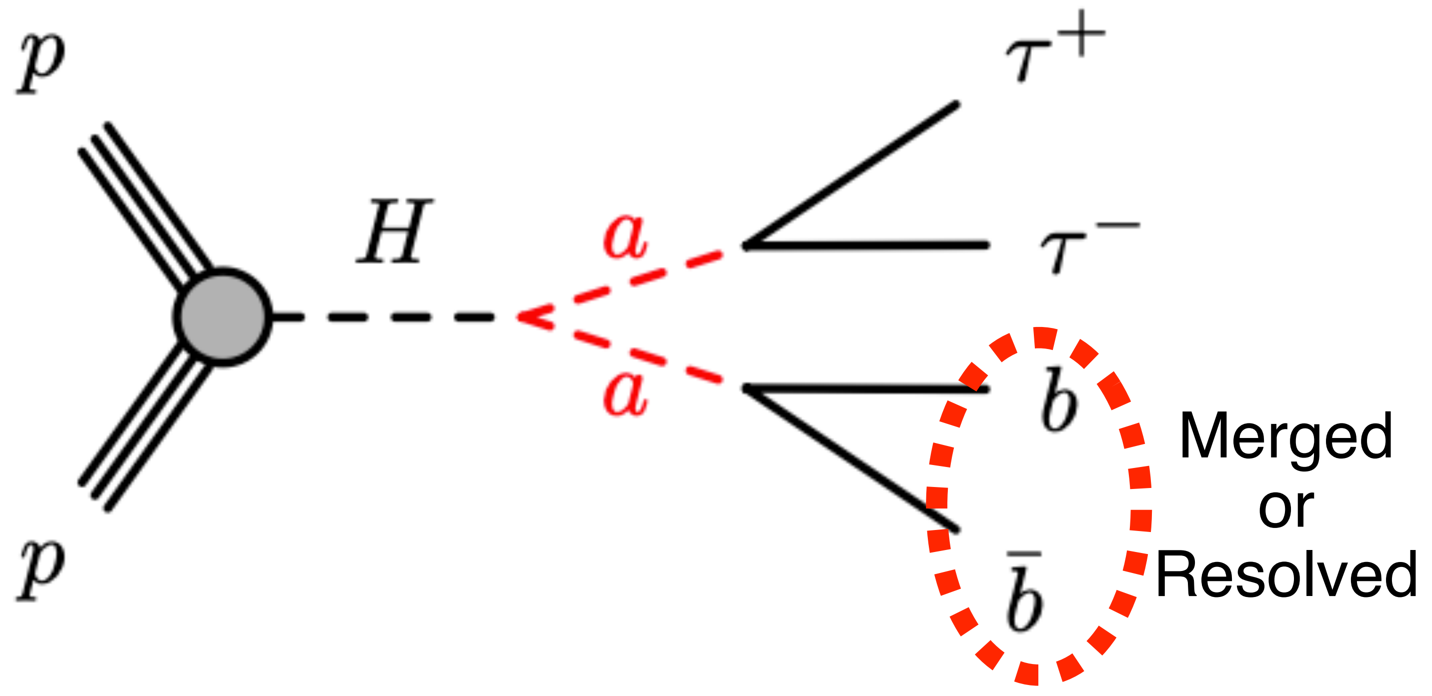

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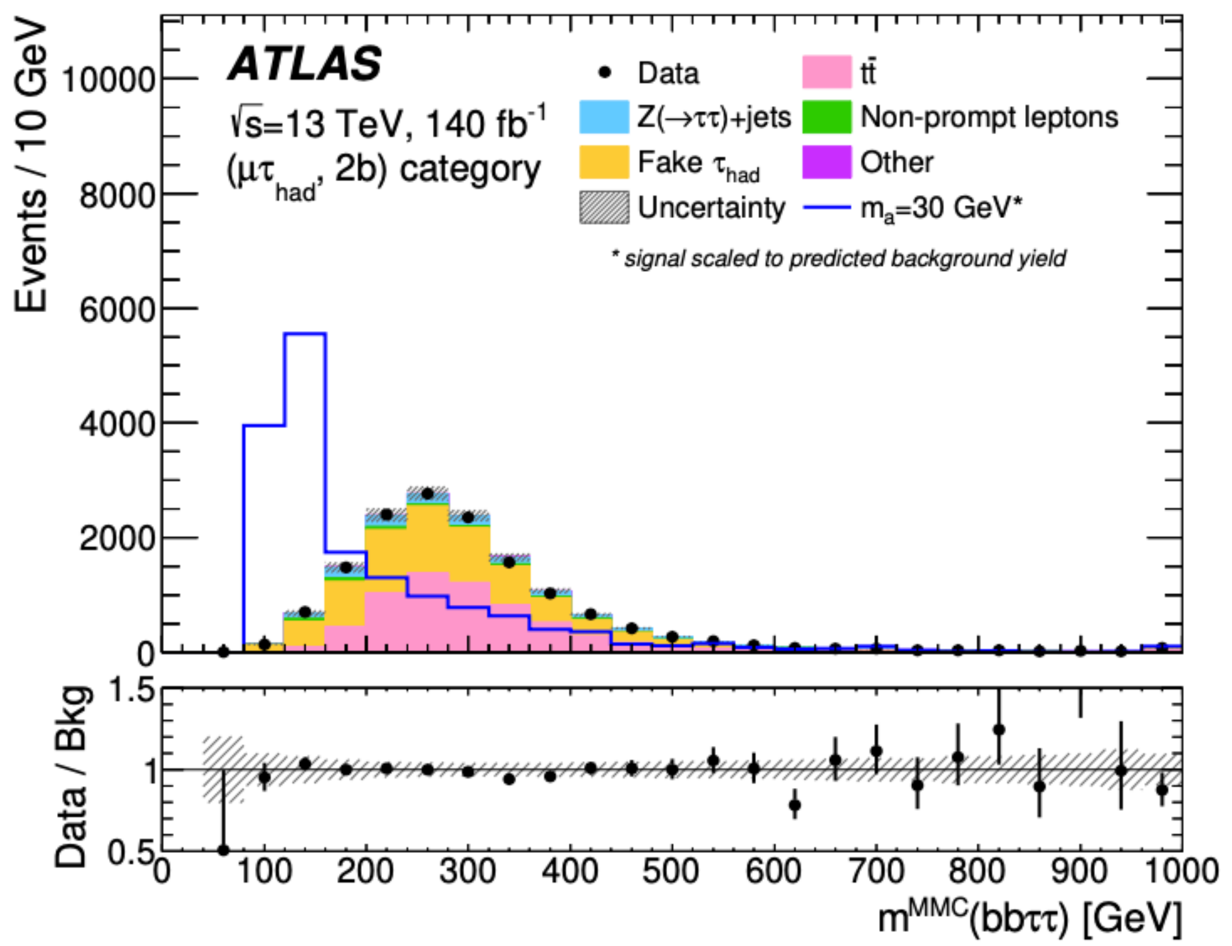

- Discriminators
  - Variables used as input variables for NN-base classifier
  - b-jet variables important for 2b and B categories

Feature	Description
$m^{\text{true}}(\tau\tau)$	During training: generated a-boson mass for signal MC. Background events are assigned a random value of the eight signal masses. During testing: the mass hypothesis under consideration.
$m^{\text{vis}}(\tau\tau)$	Visible mass of the $\tau\tau$ system.
$p_{\text{T}}(\tau\tau)$	p_{T} of the $\tau\tau$ system.
$m^{\text{MMC}}(\nu\nu)$	MMC-based mass of the two neutrinos in $\tau \to e\nu_\tau\bar{\nu}_e$ or $\tau \to e\nu_\tau\bar{\nu}_\mu$ decays.
$E_{\text{T}}^{\text{miss}}$	Missing transverse energy.
$m_{\text{T}}(\tau)$	Transverse mass calculated with the visible p_{T} of the final-state τ-leptons.
$p_{\text{T}}(b^{\text{lead}})$	Transverse momentum of the leading final-state b-jet.
$p_{\text{T}}^{\text{vis}}(\tau\tau b^{\text{lead}})$	Visible p_{T} of the $\tau\tau b^{\text{lead}}$ system.
D_ζ	Misalignment between the $\vec{E}_T^{\text{miss}}$ vector and the $\tau\tau$ system.
Categories with a B-jet or 2 b-jets	
$p_{\text{T}}(b^{\text{sublead}})$	Transverse momentum of the subleading final-state b-jet.
$p_{\text{T}}(bb)$	Transverse momentum of the bb system.
$m(bb)$	Mass of the bb system.
$m^{\text{vis}}(bb\tau\tau)$	Visible mass of the Higgs boson system.
$m^{\text{MMC}}(bb\tau\tau)$	MMC-based mass of the Higgs boson system.

$H \to aa \to 2b2\tau$

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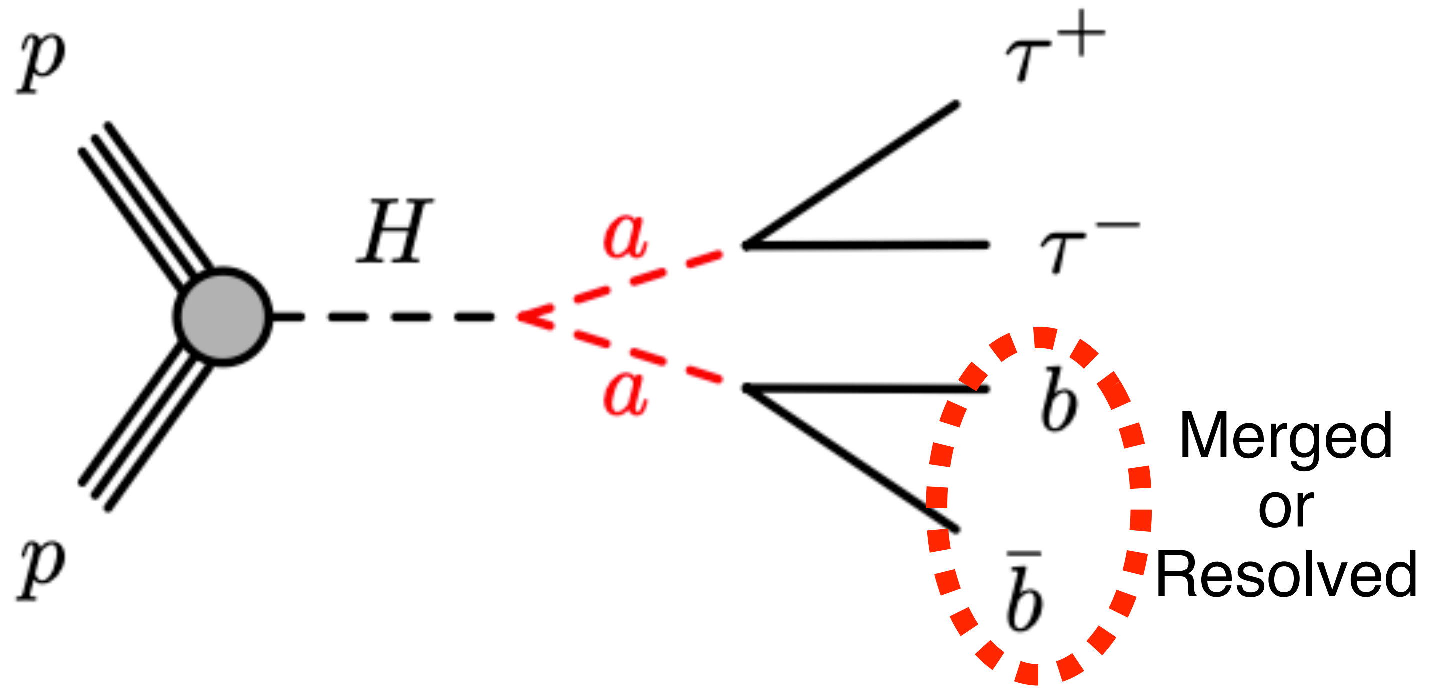
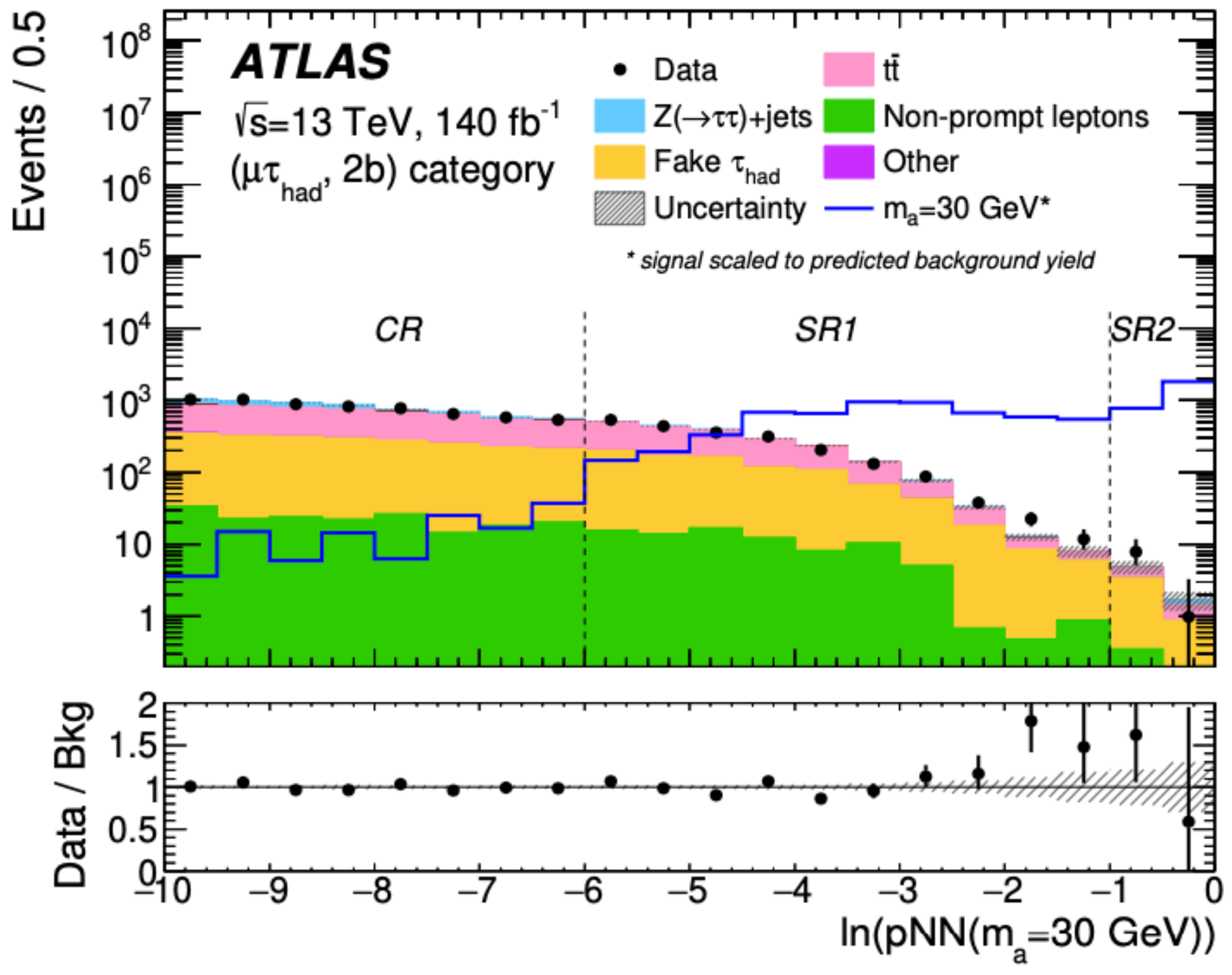
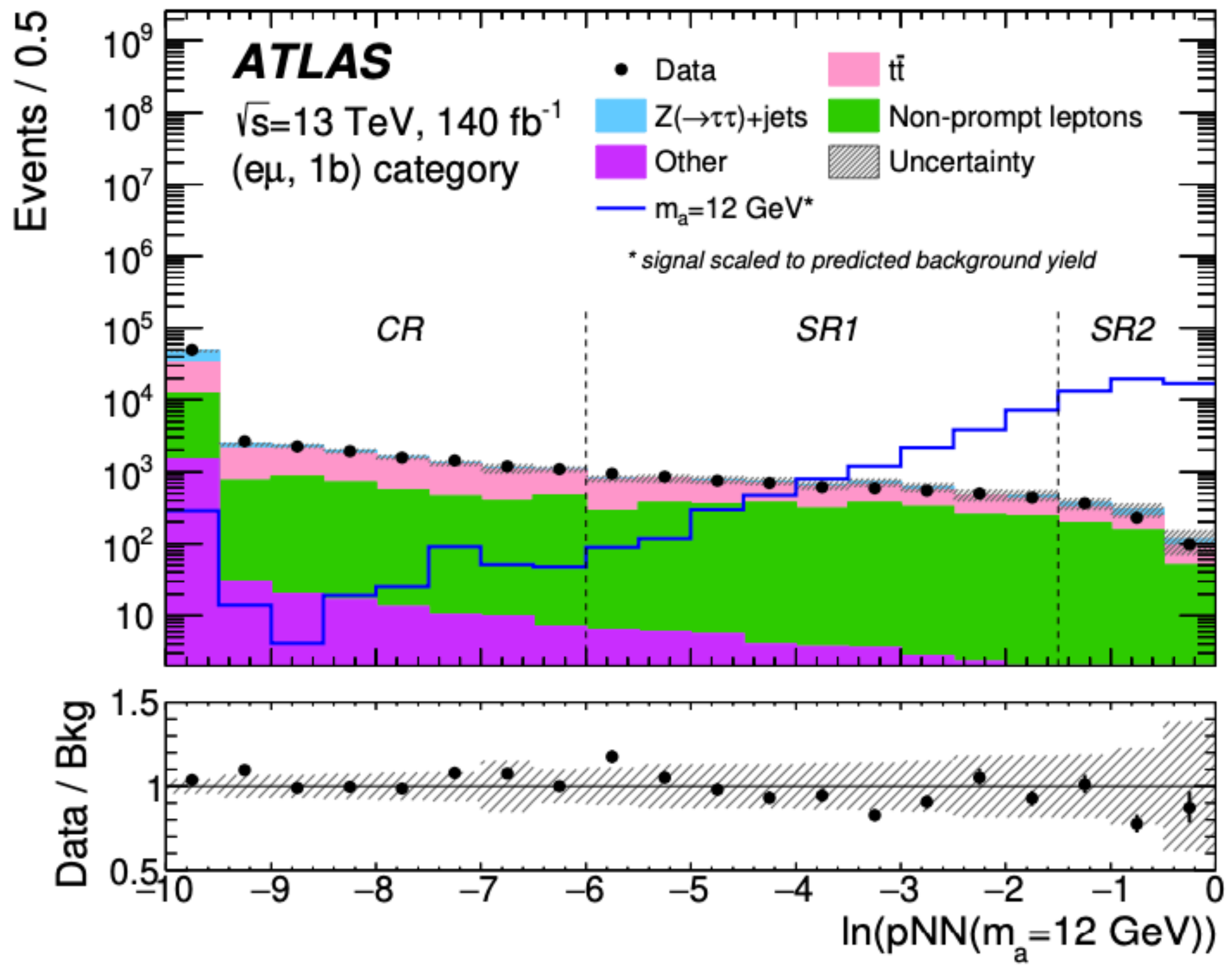


- Background modeled from MC corrected in CR (Drell-Yan, $t\bar{t}$) and data (non-prompt leptons)
- Statistical analysis - for each m_a with a simultaneous fit to the NN output (in CR, SR1 and SR2 bins) in all 9 categories





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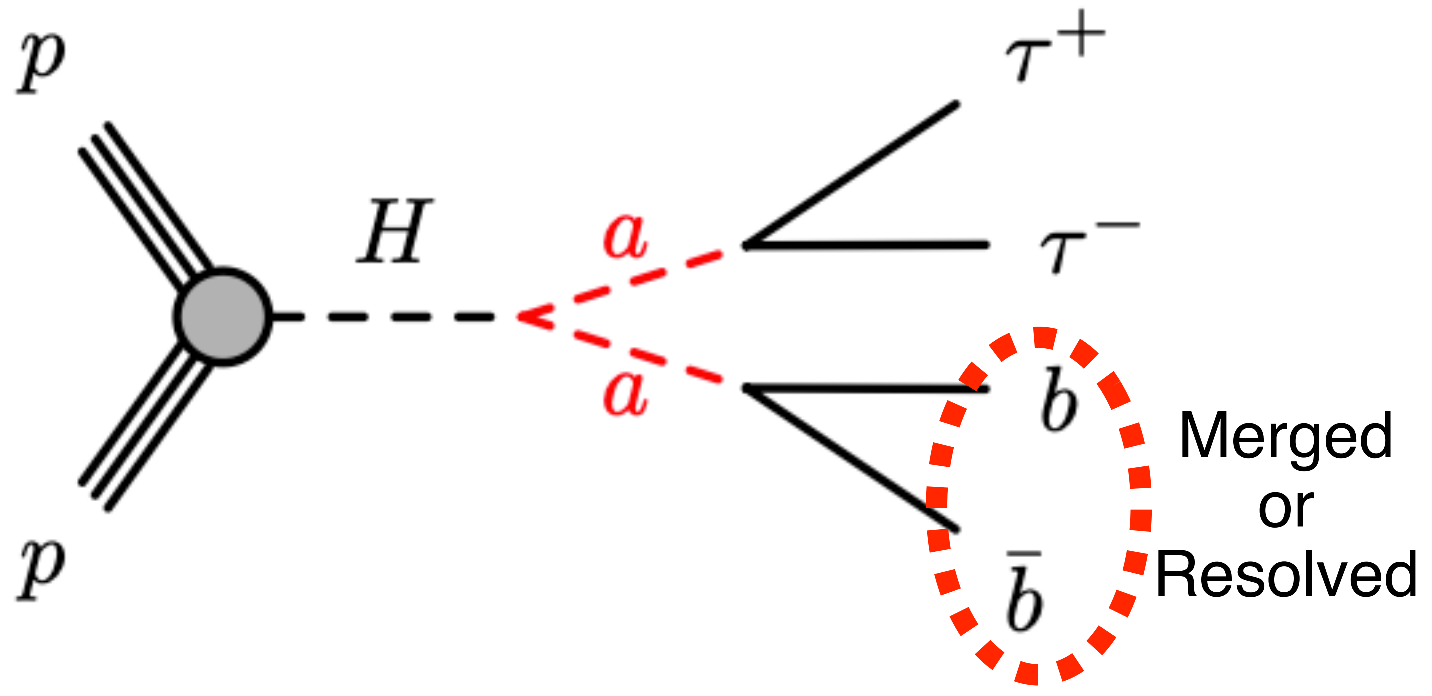

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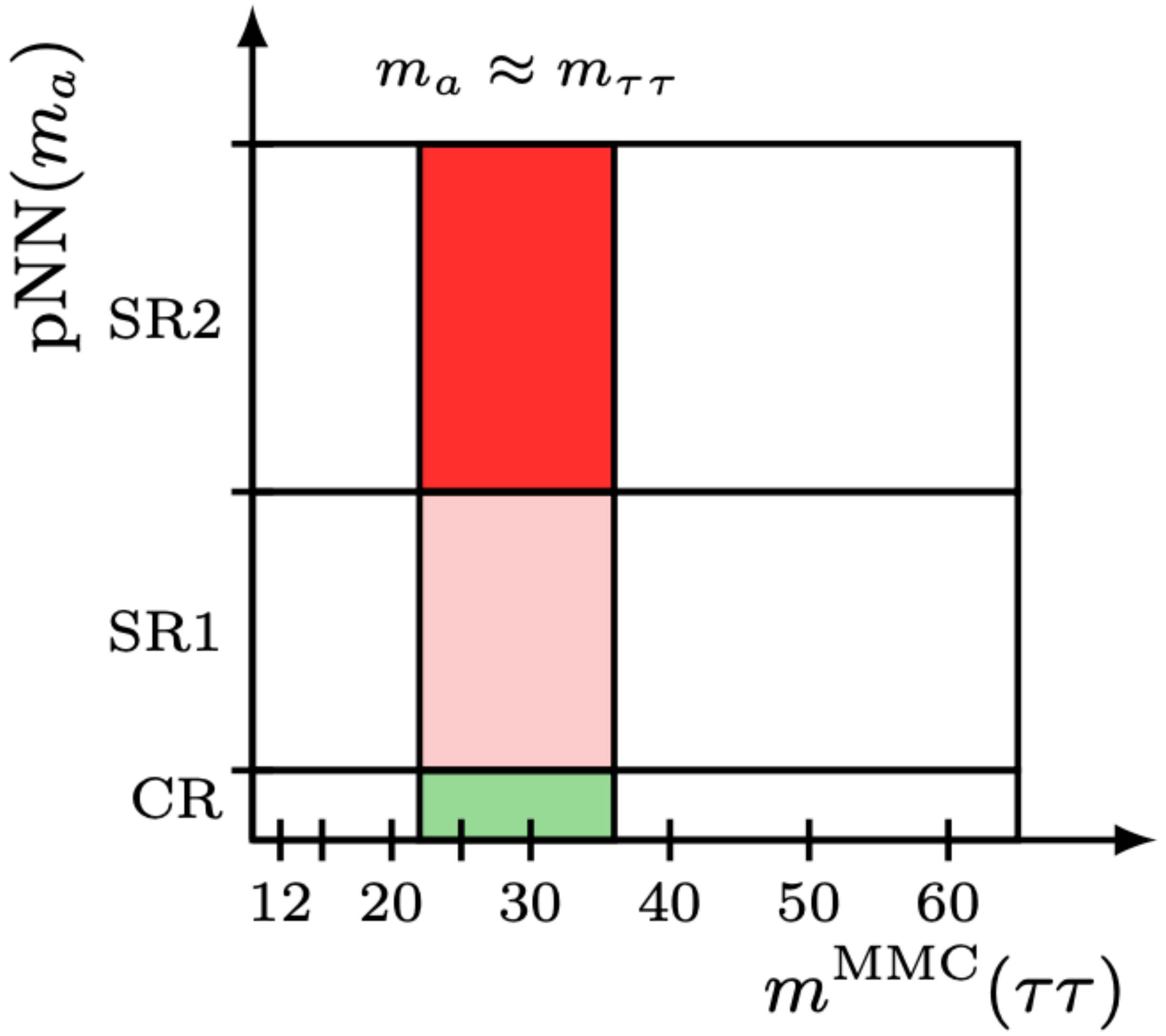
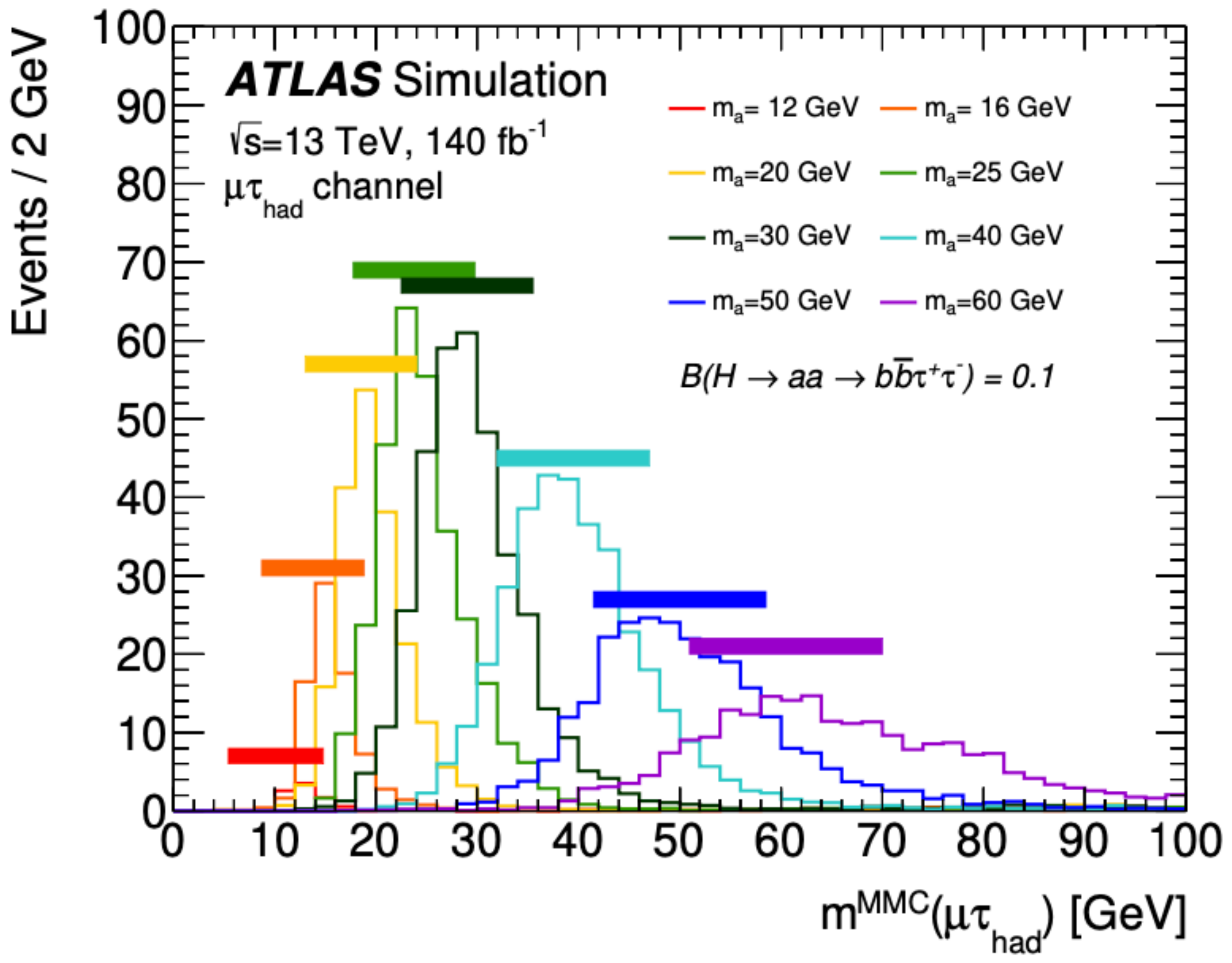
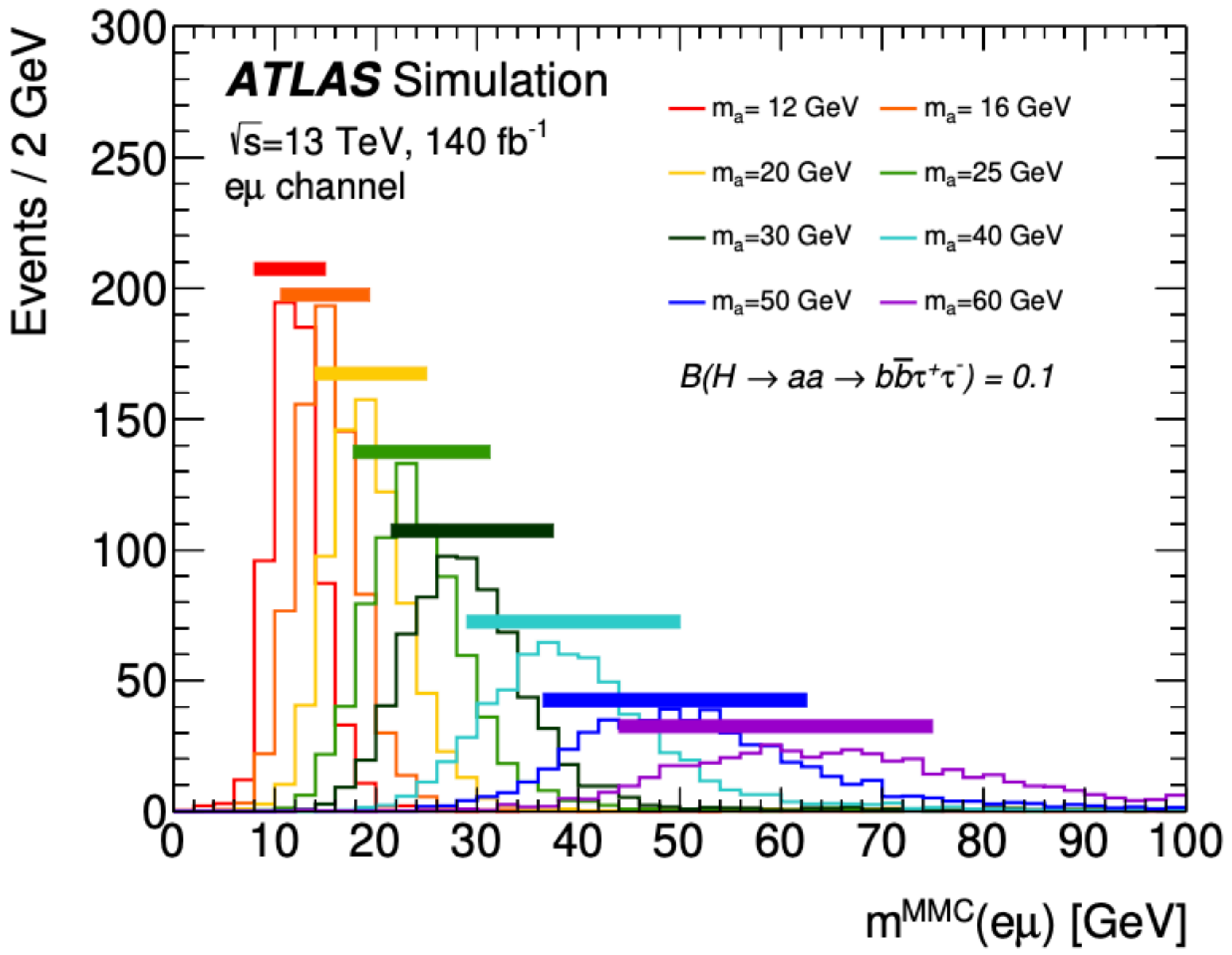
- Statistical analysis - for each m_a with a simultaneous fit to the NN output (in CR, SR1 and SR2 bins) in all 9 categories
- Mass range varies with m_a







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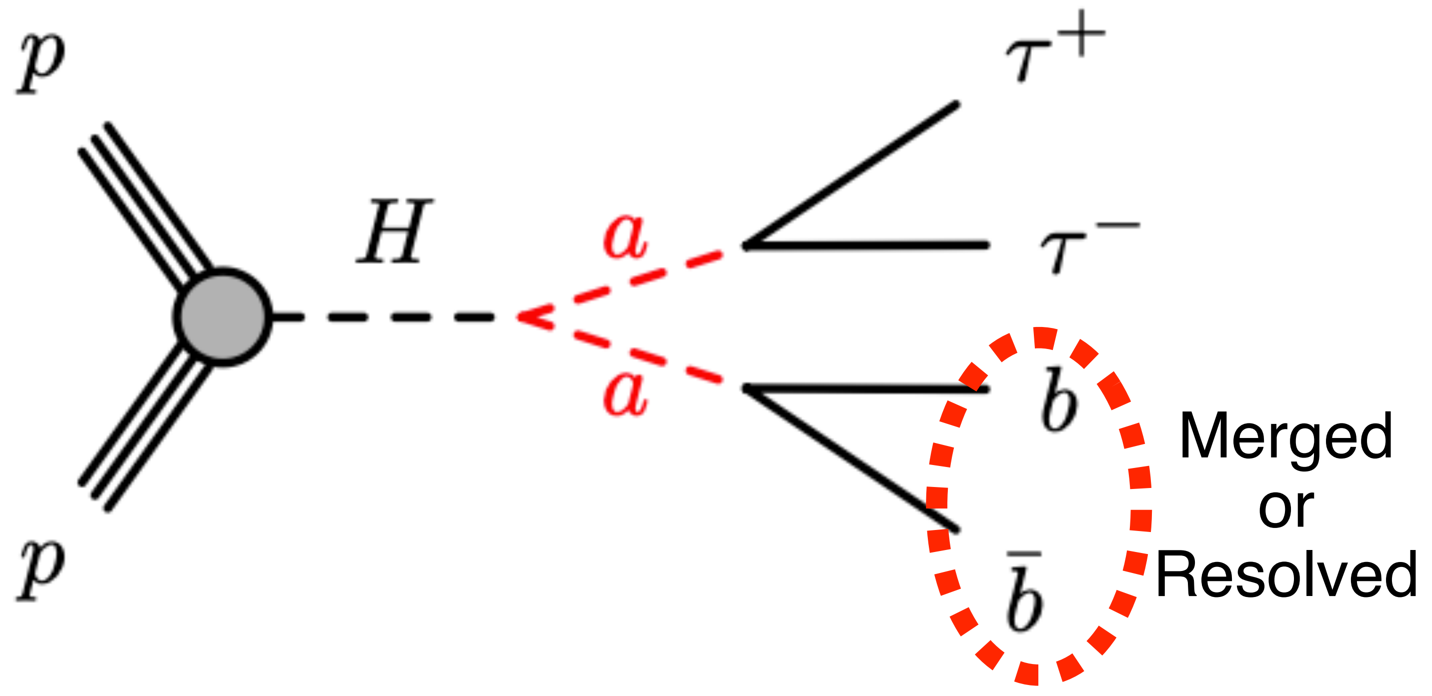
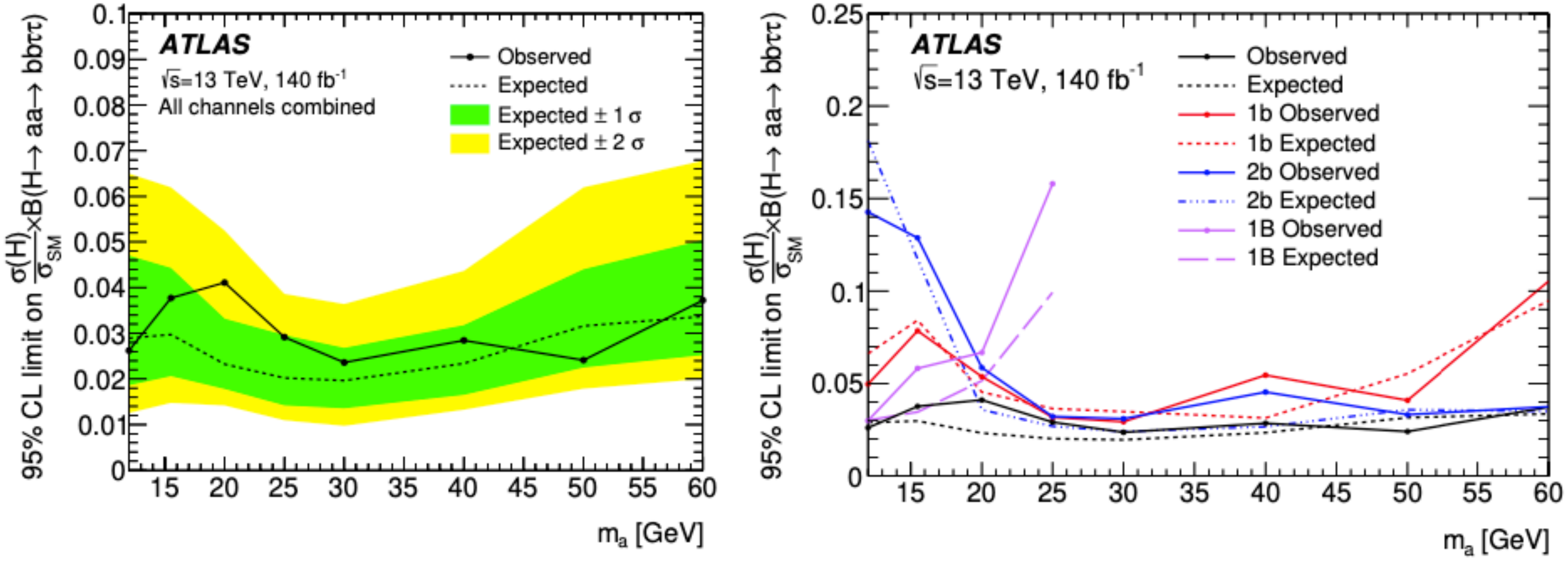


$$BR(H \to aa \to b\bar{b}\tau^+\tau^-) < 2.2\% - 3.9\,\%$$

$$12\text{ GeV} \le m_a \le 60\text{ GeV}$$



(a) (b)

Figure 10: The observed (solid) 95% C.L. upper limits on $(\sigma(H)/\sigma_{SM}(H))\mathcal{B}(H \to aa \to b\bar{b}\tau^+\tau^-)$ as a function of m_a and the expected (dashed) limits under the background-only hypothesis when (a) combining all categories and (b) considering different categories based on the heavy-flavor objects separately. In the combined plot (a) the inner green and outer yellow shaded bands show the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties of the expected limits. The mass hypothesis m_a is probed between 12 and 60 GeV for the values shown with markers. A linear interpolation validated with MC simulation between adjacent mass points is used.

Forbidden decays to SM particles

Forbidden decays to SM particles

- At tree level, the SM predicts four special features of the Yukawa couplings
  - Proportionality: $\frac{y_i}{y_j} = \frac{m_i}{m_j}$
  - Factor of proportionality: $\frac{y_i}{m_i} = \frac{\sqrt{2}}{v}$
  - Diagonality: $y_{ij} = 0$ for $i \neq j$
  - CP conservation: $Im(\frac{y_i}{m_i}) = 0$

Y. Grossman and Y. Nir,
“The Standard Model: From Fundamental Symmetries to Experimental Tests"
Princeton University Press, 2023

- All four relations are violated by many extensions of the SM
  - SMEFT, 2HDM, vector-like fermions, …

Forbidden decays to SM particles

- At tree level, the SM predicts four special features of the Yukawa couplings
  - Proportionality: $\frac{y_i}{y_j} = \frac{m_i}{m_j}$ — Precision Higgs measurements
  - Factor of proportionality: $\frac{y_i}{m_i} = \frac{\sqrt{2}}{v}$ — Precision Higgs measurements
  - Diagonality: $y_{ij} = 0$ for $i \neq j$ — today's talk
  - CP conservation: $Im(\frac{y_i}{m_i}) = 0$
- All four relations are violated by many extensions of the SM
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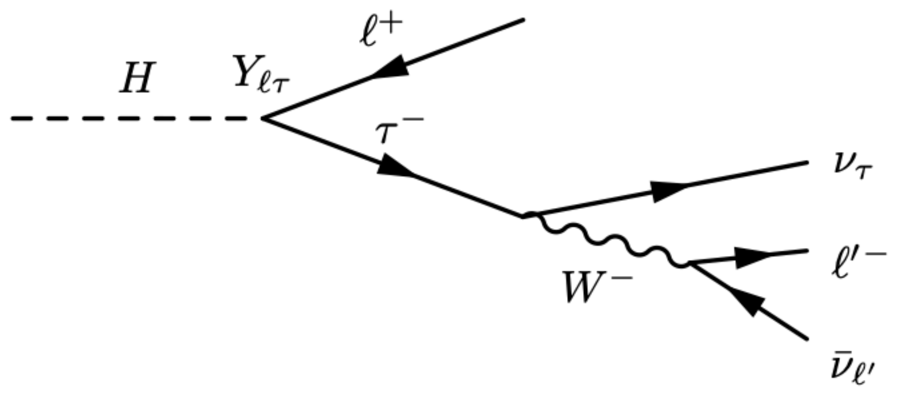
Forbidden decays to SM particles

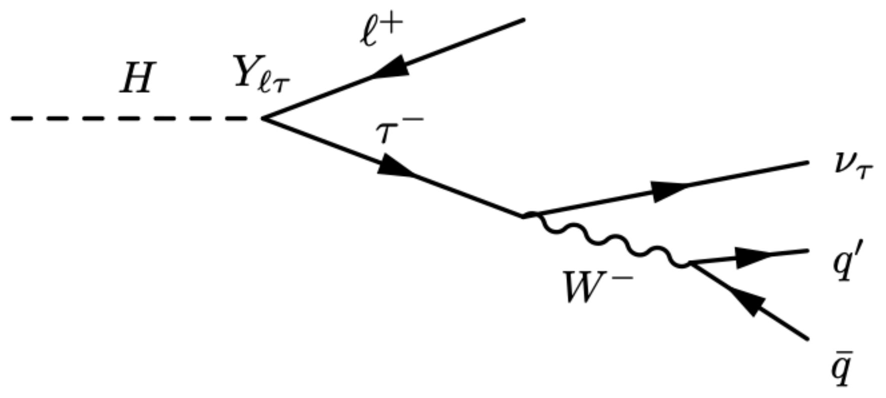
- ATLAS search for $H \to \ell_1^+ \ell_2^-$ in all $\ell_1^+ \ell_2^-$ combinations
  - $e\mu \to$
    - Stringent (model dependent) bound from $\mu \to e\gamma$ experiment — arXiv:1303.0754
    - Model independent bound from LHC experiment — arXiv:1909.10235
  - $e\tau$ and $\mu\tau \to$ most stringent bounds from LHC experiments — today's talk

$H \to e\tau/\mu\tau$

arXiv:2302.05225

- Two analysis channels based on τ decay mode
  - leplep $H \to e\tau/\mu\tau \to e\mu 2\nu/\mu e 2\nu$
  - lephad $H \to e\tau_{had}/\mu\tau_{had}$





$H \rightarrow e\tau/\mu\tau$

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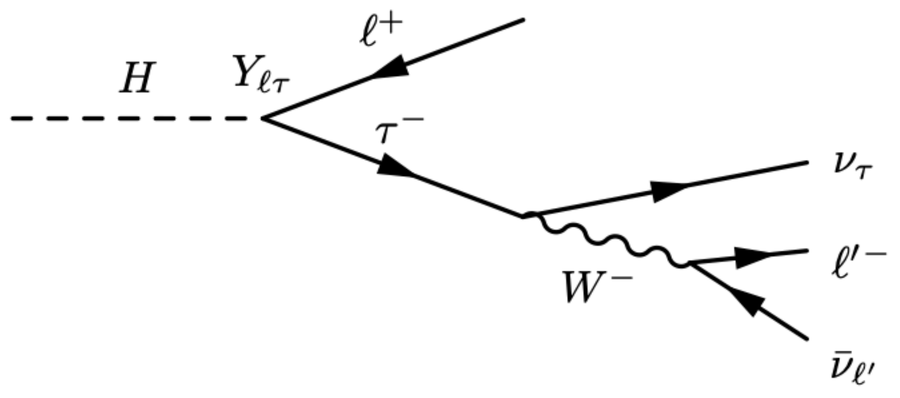
- Two analysis channels based on τ decay mode
  - leplep $H \rightarrow e\tau/\mu\tau \rightarrow e\mu 2\nu/\mu e 2\nu$
  - lephad $H \rightarrow e\tau_{had}/\mu\tau_{had}$
- Two analysis categories based on Higgs production
  - non-VBF (mostly ggH)
  - VBF
- Two background estimation method
  - MC template
  - e/μ symmetry based

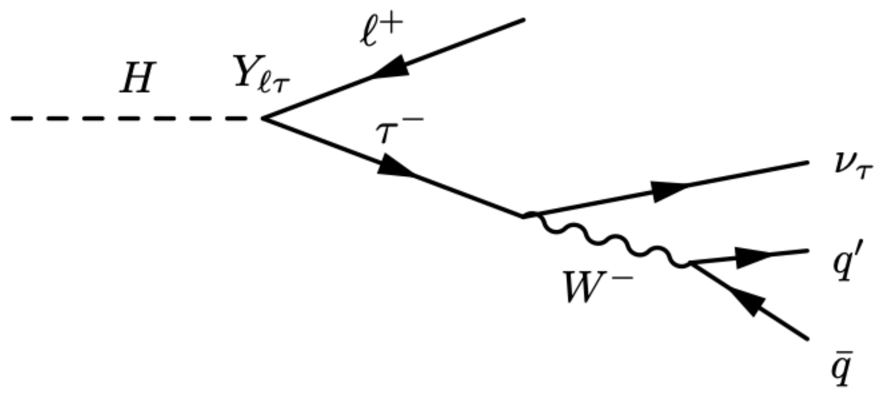
Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\mathrm{had}}$
Baseline	exactly $1e$ and 1μ, OS τ_{had}-veto – b-veto $p_{\mathrm{T}}^{\ell_1} > 45\ (35)$ GeV MC-template (Symmetry method) $p_{\mathrm{T}}^{\ell_2} > 15$ GeV $30\ \mathrm{GeV} < m_{\ell_1\ell_2} < 150\ \mathrm{GeV}$ $0.2 < p_{\mathrm{T}}^{\mathrm{track}}(\ell_2 = e)/p_{\mathrm{T}}^{\mathrm{cluster}}(\ell_2 = e) < 1.25$ (MC-template) track d_0 significance requirement (see text) $\lvert z_0 \sin\theta\rvert < 0.5$ mm	exactly 1ℓ and $1\tau_{\mathrm{had\text{-}vis}}$, OS τ_{had} Tight ID Medium eBDT ($e\tau_{\mathrm{had}}$) b-veto $p_{\mathrm{T}}^{\ell} > 27.3$ GeV $p_{\mathrm{T}}^{\tau_{\mathrm{had\text{-}vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\mathrm{had\text{-}vis}}}\rvert < 2.4$ $\sum_{i=\ell,\tau_{\mathrm{had\text{-}vis}}} \cos\Delta\phi(i, E_{\mathrm{T}}^{\mathrm{miss}}) > -0.35$ $\lvert\Delta\eta(\ell, \tau_{\mathrm{had\text{-}vis}})\rvert < 2$
VBF	*Baseline* ≥ 2 jets, $p_{\mathrm{T}}^{\mathrm{j}_1} > 40$ GeV, $p_{\mathrm{T}}^{\mathrm{j}_2} > 30$ GeV $\lvert\Delta\eta_{\mathrm{jj}}\rvert > 3$, $m_{\mathrm{jj}} > 400$ GeV	
non-VBF	*Baseline* plus fail *VBF* categorisation –	veto events if $90 < m_{\mathrm{vis}}(e, \tau_{\mathrm{had\text{-}vis}}) < 100$ GeV

$H \to e\tau/\mu\tau$

arXiv:2302.05225

- Two analysis channels based on τ decay mode
  - leplep $H \to e\tau/\mu\tau \to e\mu2\nu/\mu e2\nu$
  - lephad $H \to e\tau_{had}/\mu\tau_{had}$
- Main background sources
  - leplep: $Z \to \tau\tau$, $t\bar{t}$, diboson, non prompt ℓ
  - lephad: $Z \to \tau\tau$, diboson, mis-identified τ

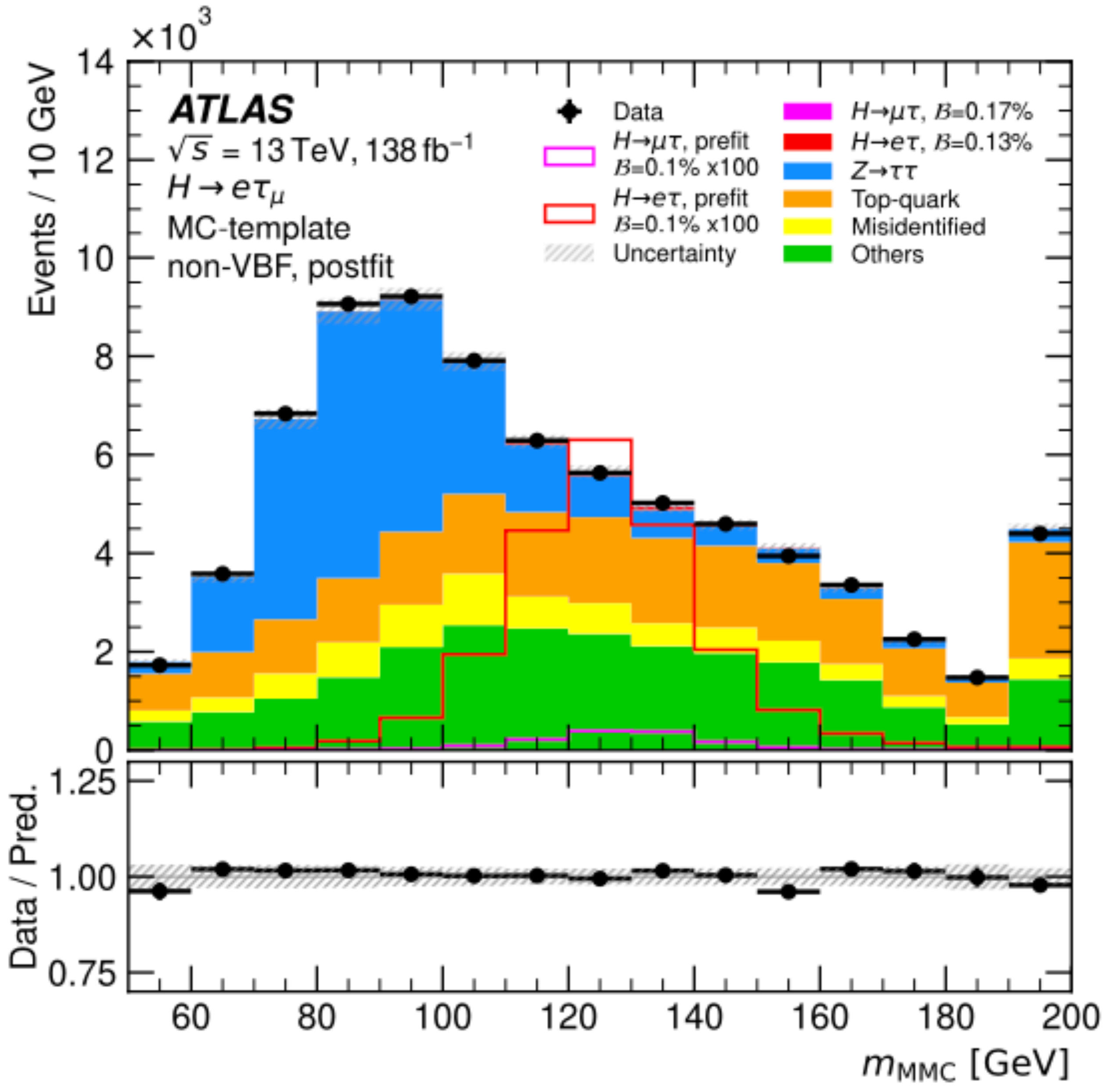


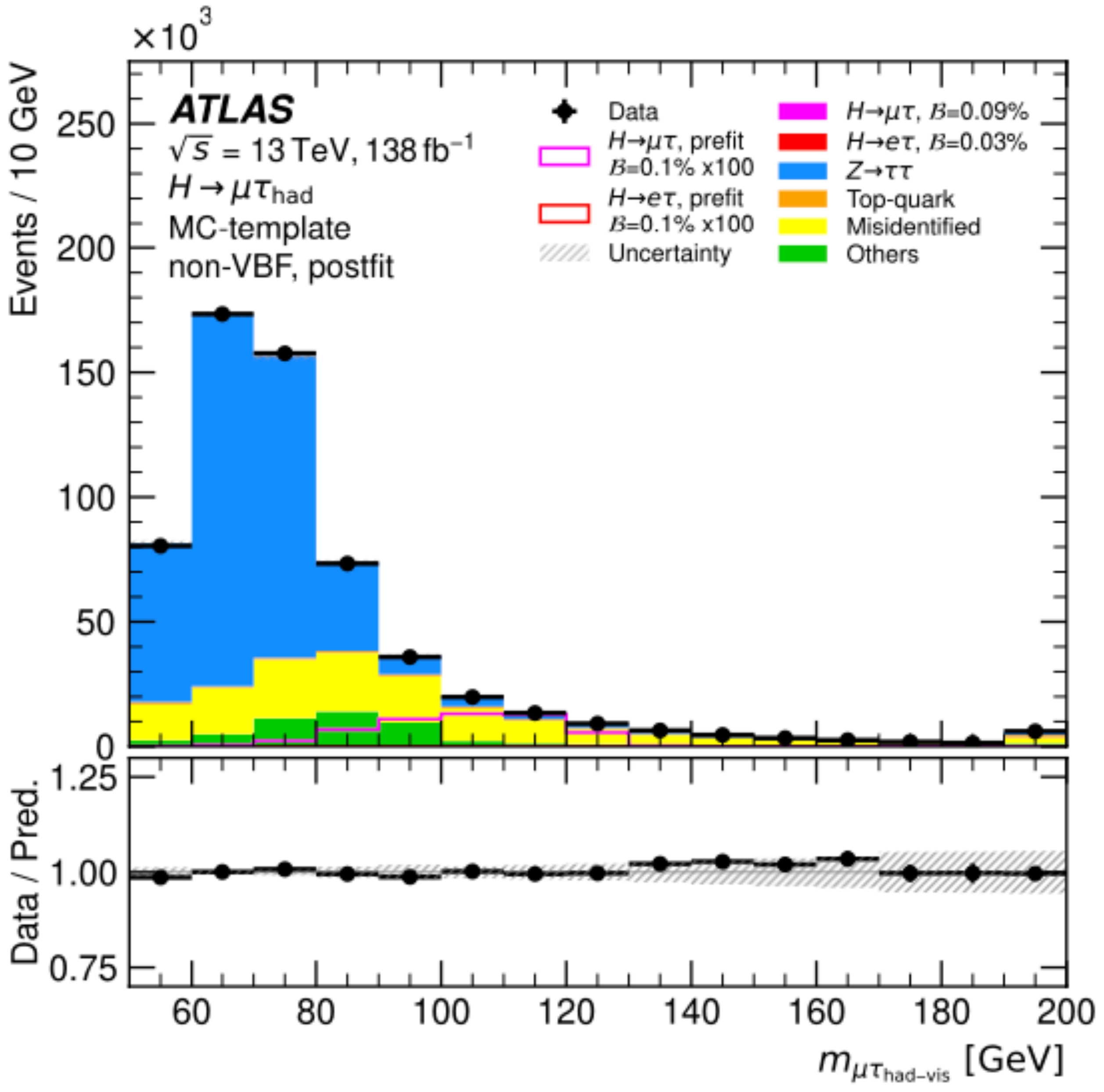


$H \to e\tau/\mu\tau$ MC template method

arXiv:2302.05225

- leplep & lephad
  - Background from prompt leptons estimated from MC normalized to data in dedicated CRs
  - Background from non prompt leptons or mis-identified ones modeled with data driven methods





$H \rightarrow e\tau/\mu\tau$ symmetry method

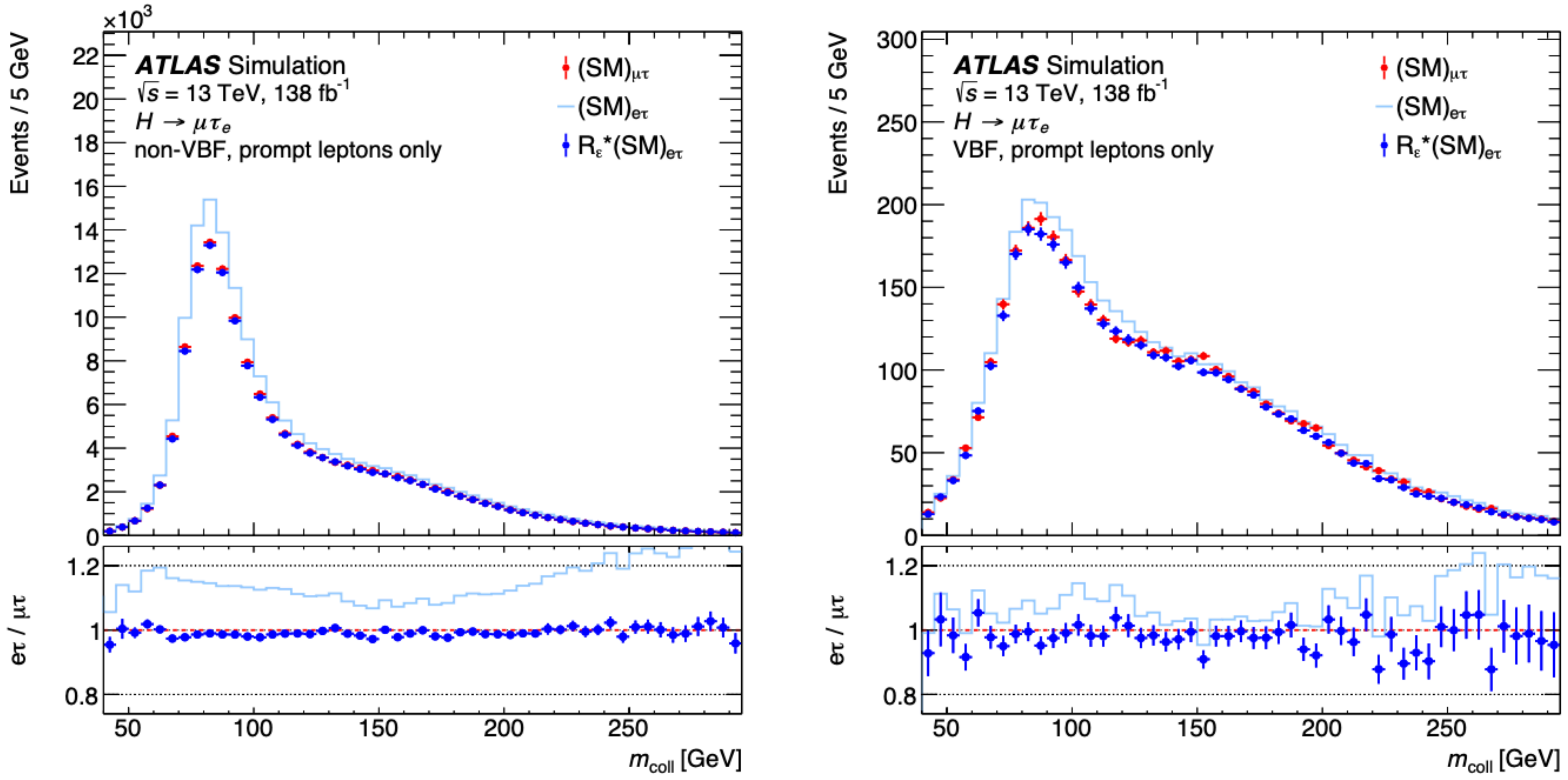
arXiv:2302.05225

- Two underlying assumptions
  - High energy SM processes are symmetric under the exchange of prompt electrons with prompt muons to a good approximation. As a consequence, the kinematic distributions of prompt electrons and prompt muons are approximately the same
  - Flavour-violating decays of the Higgs boson break this symmetry
- leplep channel - $H \rightarrow \mu\tau \rightarrow \mu e 2\nu$ results in events with $p_T^{\mu} > p_T^{e}$
  - Use events with $p_T^{e} > p_T^{\mu}$ to model background of events with $p_T^{\mu} > p_T^{e}$
  - Correct for detector effects that break the symmetry
    - Trigger, reconstruction, identification and isolation efficiency
    - Events with non prompt leptons

$H \rightarrow e\tau/\mu\tau$ symmetry method

arXiv:2302.05225

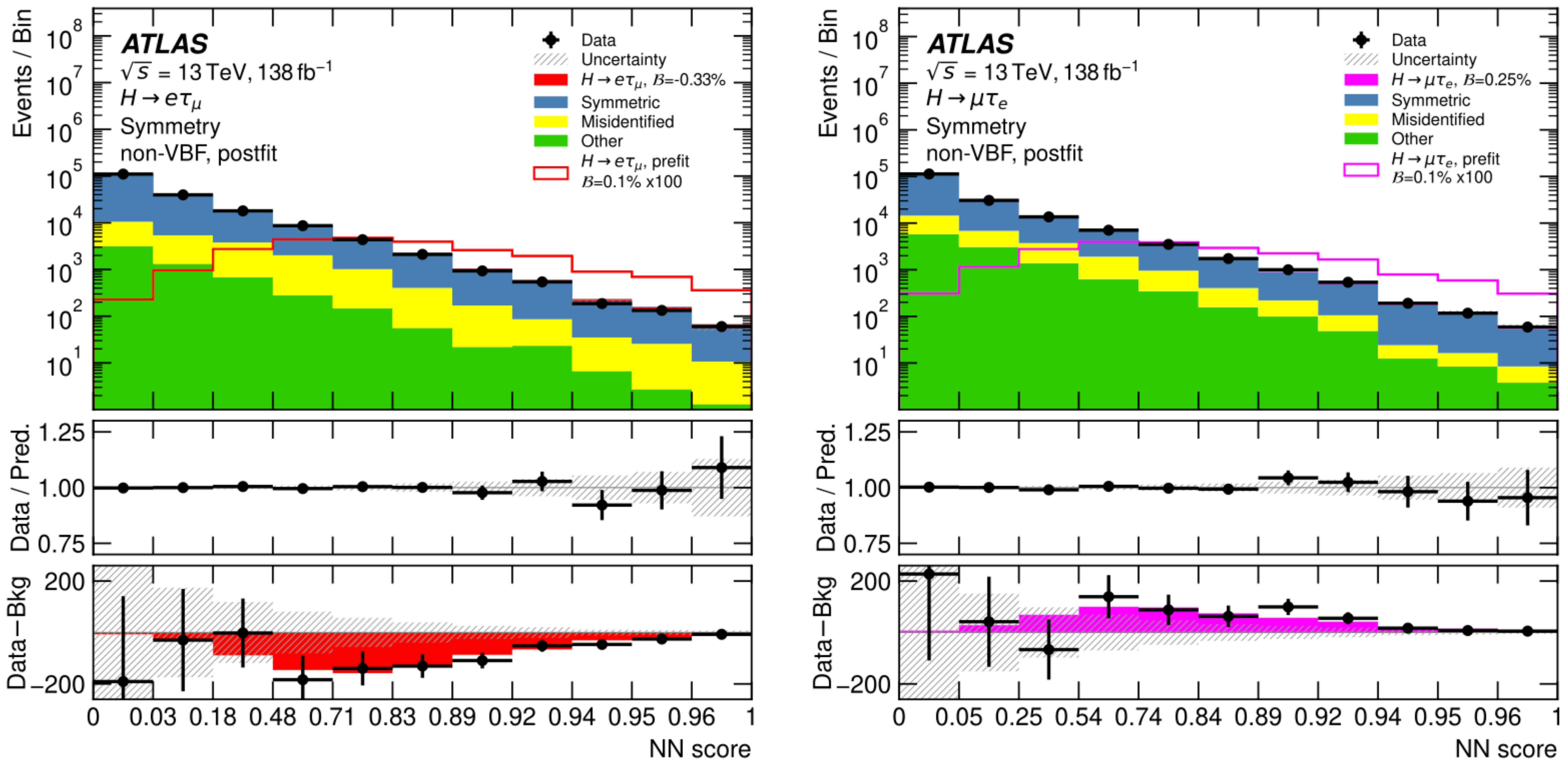
- Correction works well
  - In MC when only efficiency correction applied



$H \to e\tau/\mu\tau$ symmetry method

arXiv:2302.05225

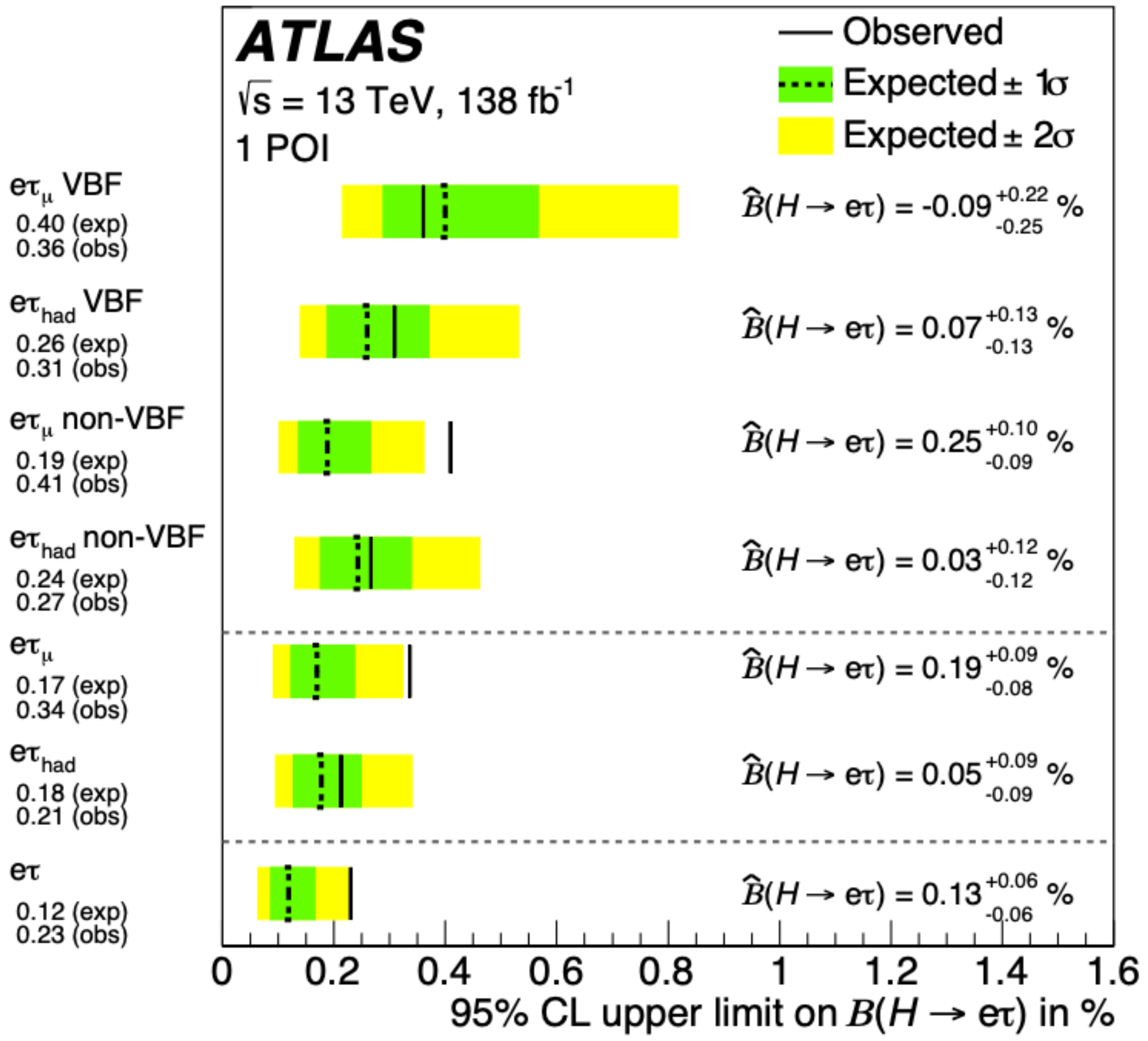
- Correction works well
  - In MC when only efficiency correction applied
  - In data when also non-prompt leptons estimated
    - An excess in one final state translates into a deficit in the other channel

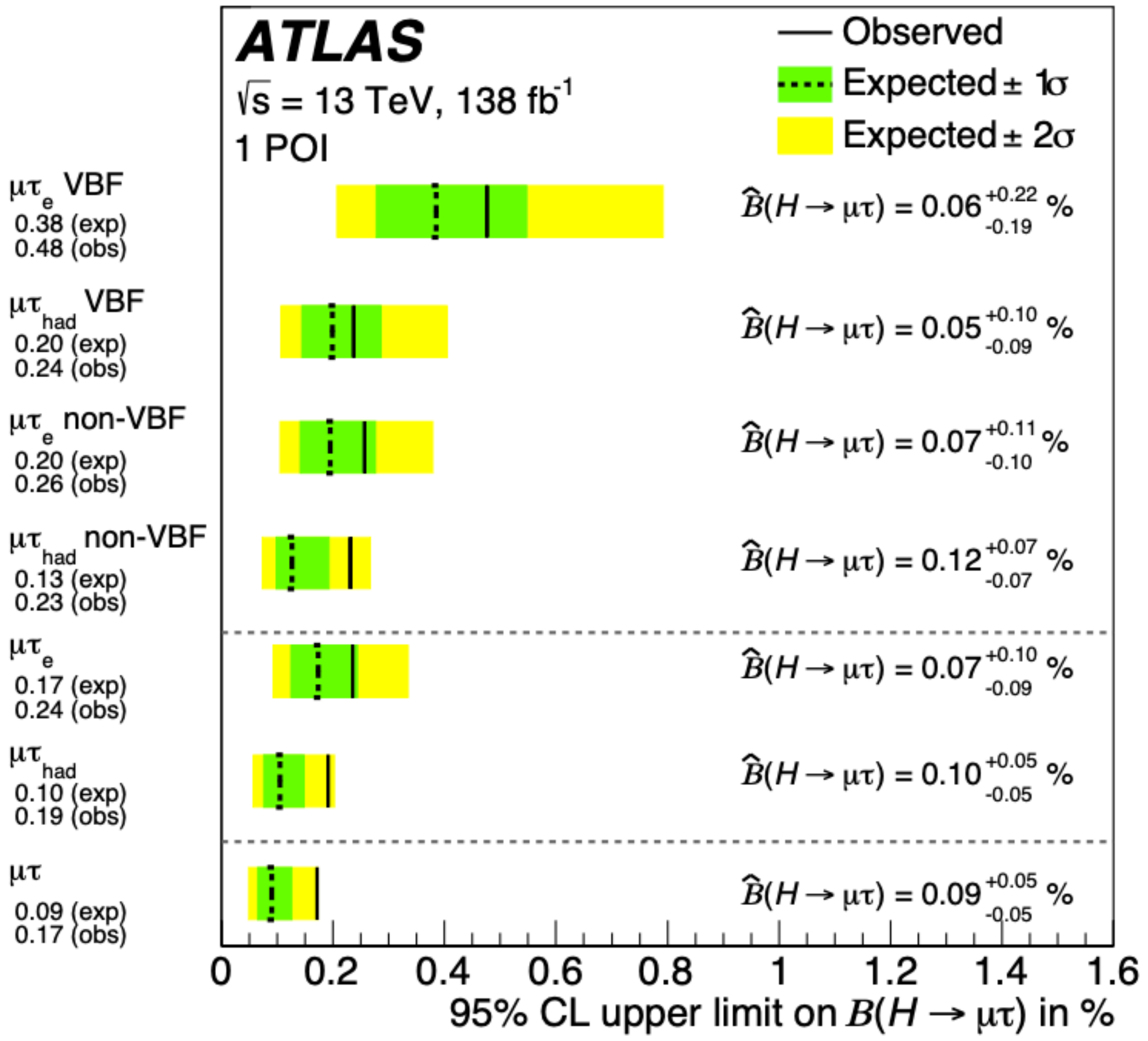


$H \to e\tau/\mu\tau$ bottom line

arXiv:2302.05225

- Final results obtained by combining the most sensitive approach in each region and category

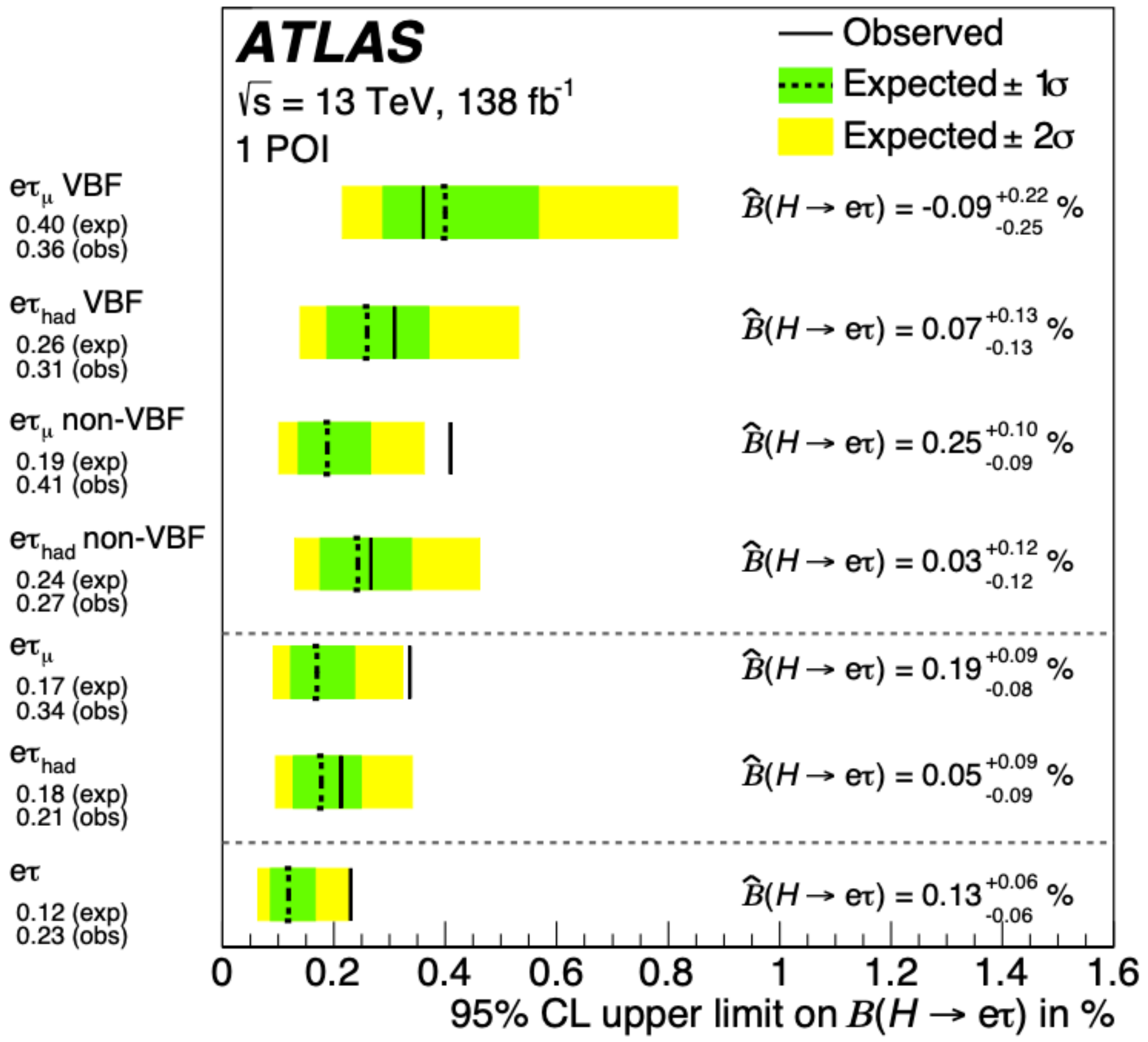


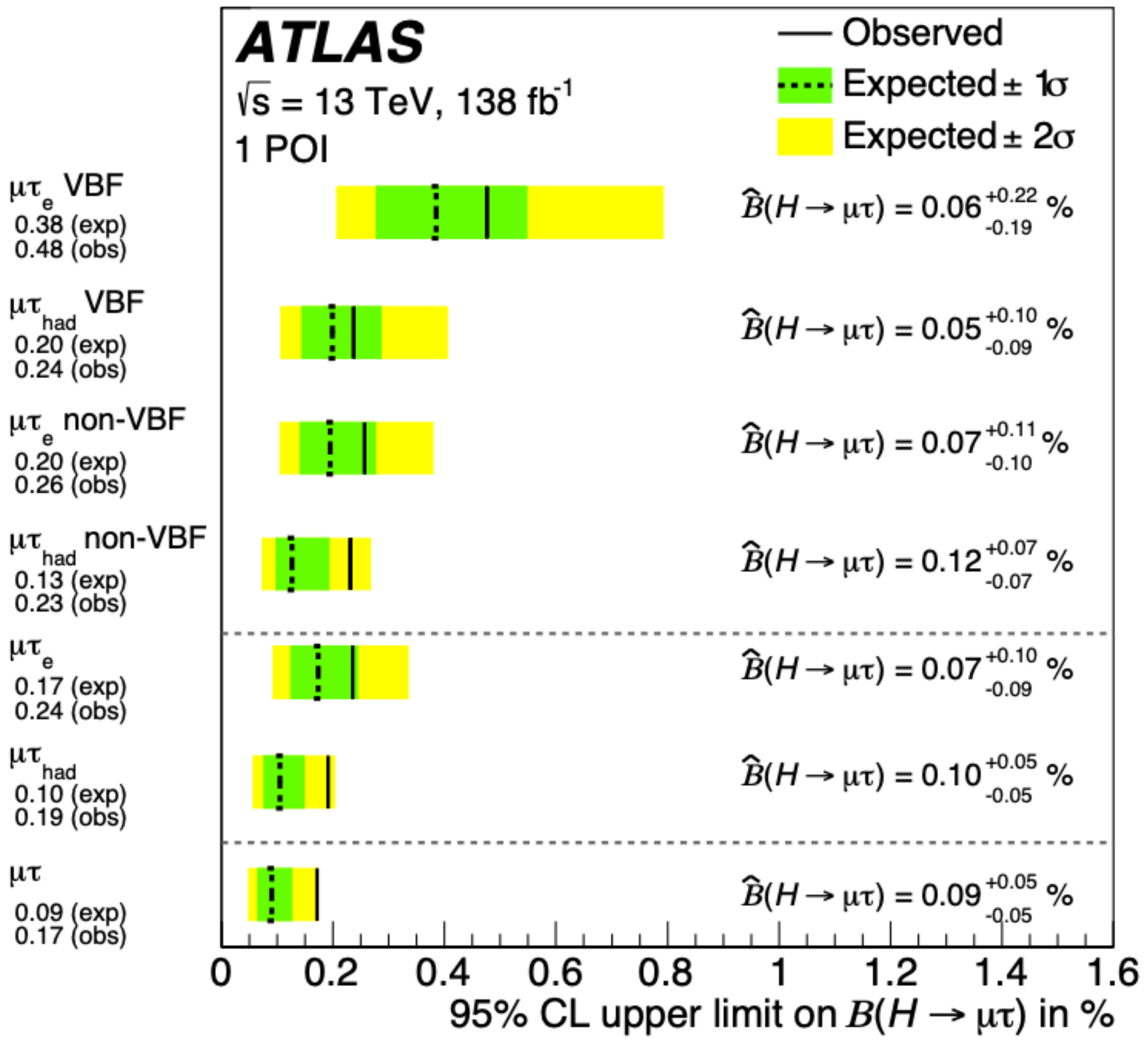


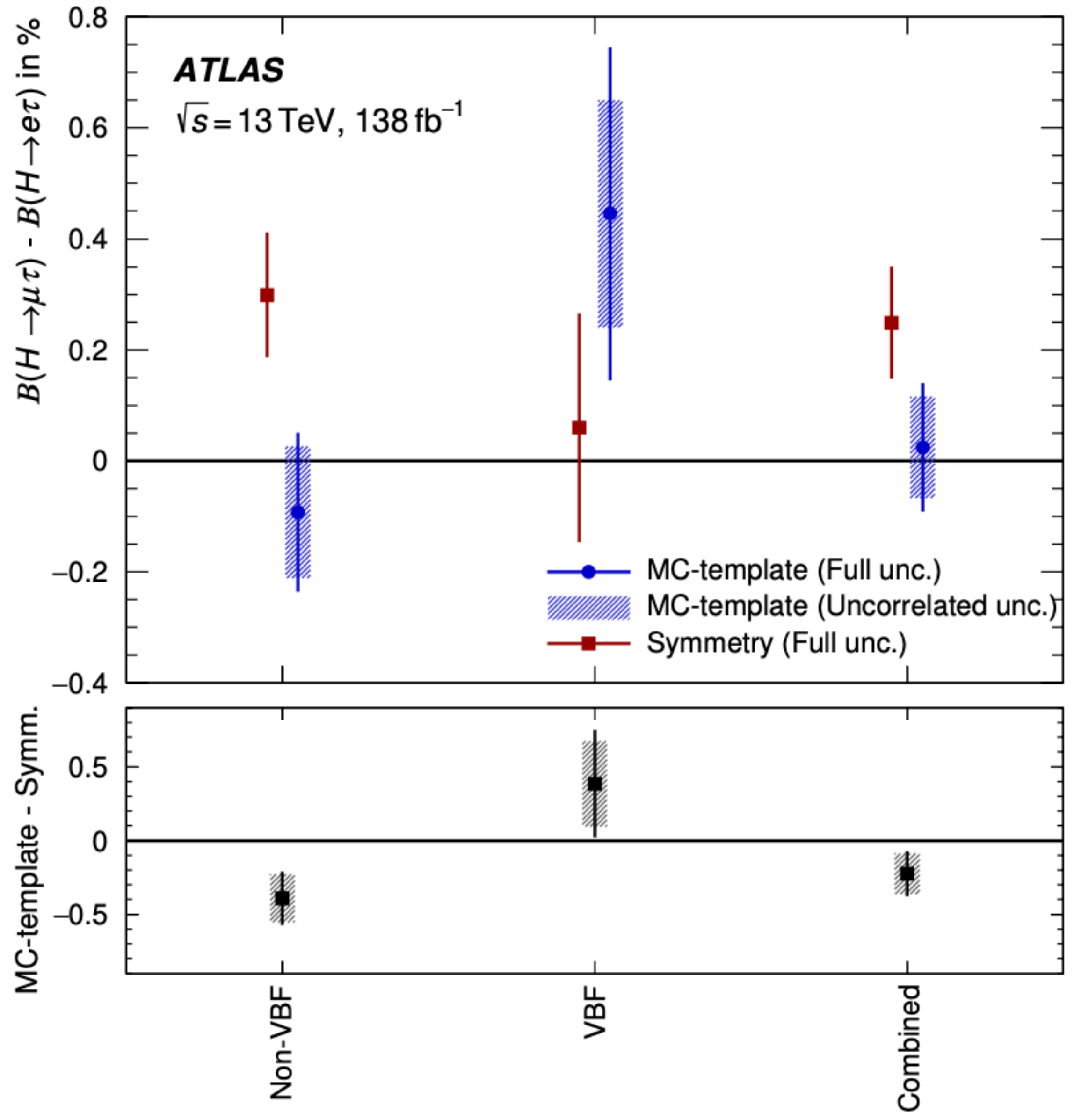
$H \to e\tau/\mu\tau$ bottom line

arXiv:2302.05225

- Final results obtained by combining the most sensitive approach in each region and category
- Symmetry based analysis sensitive to difference in decay rates



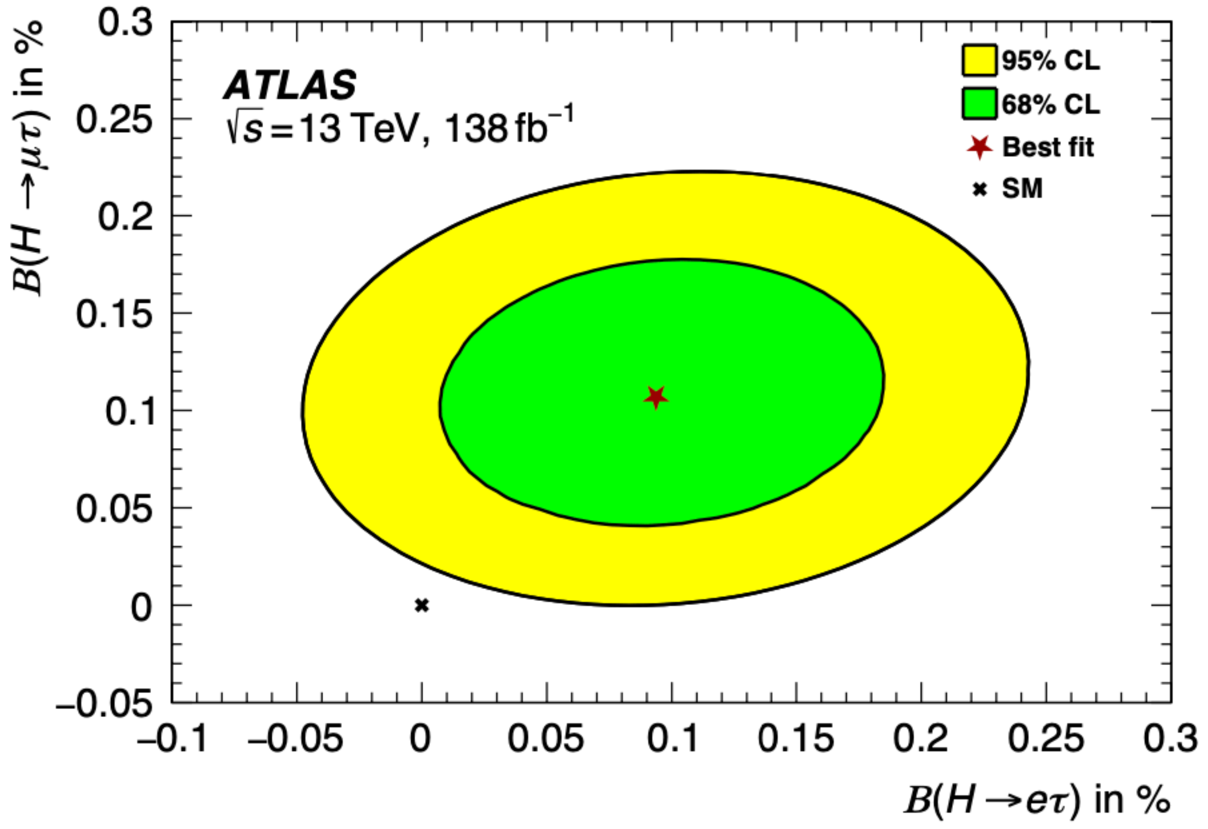


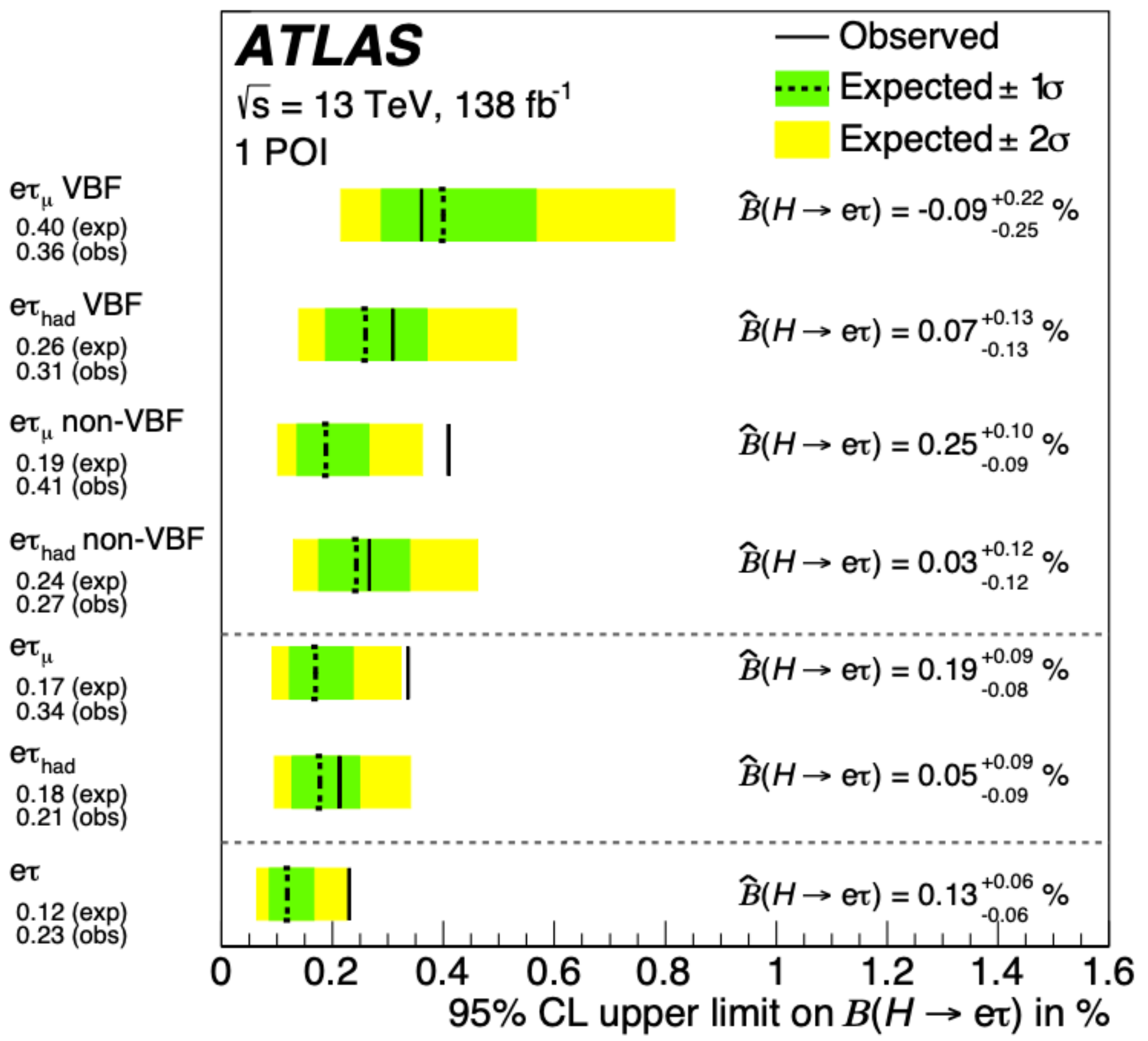


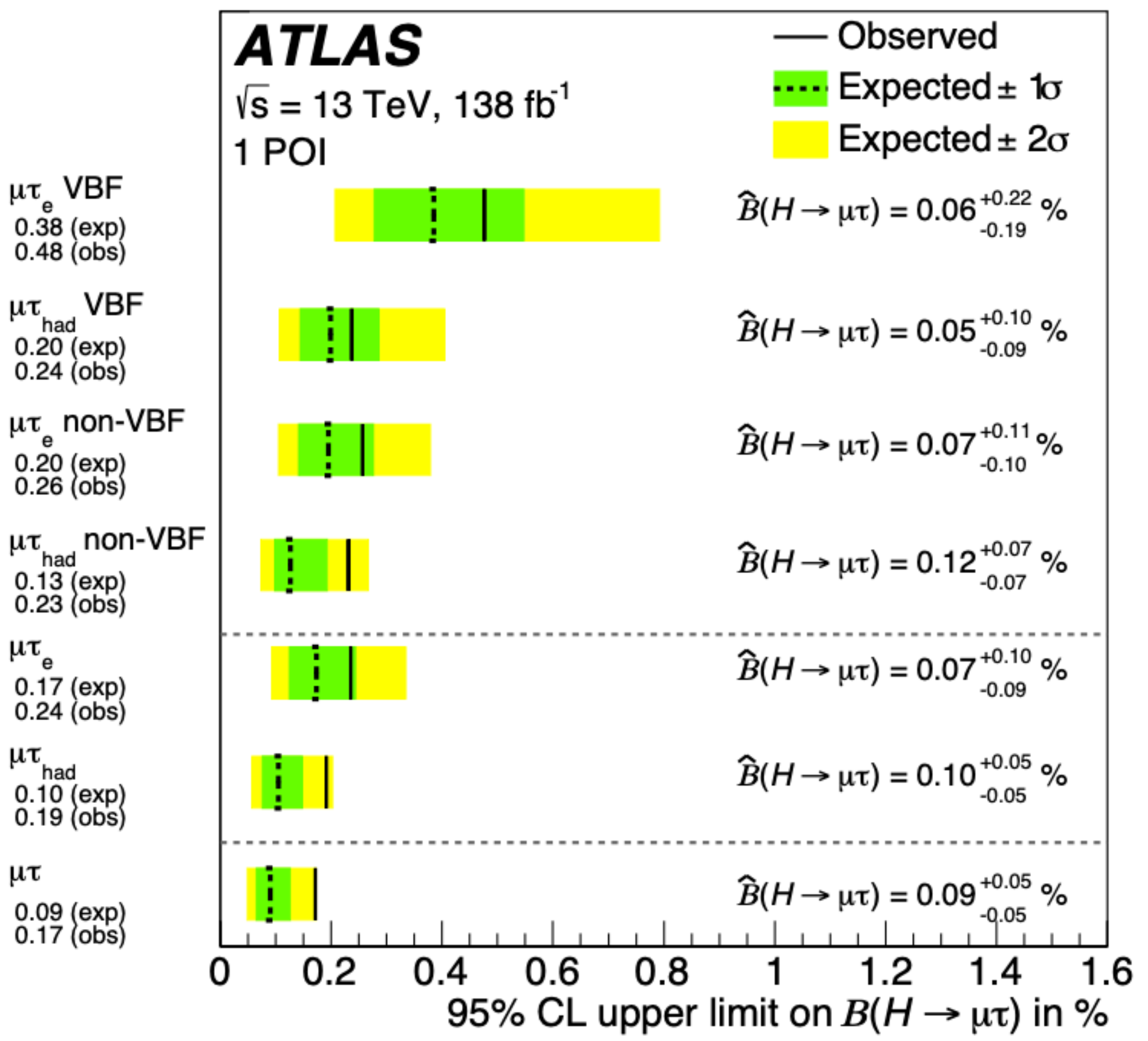
$H \to e\tau/\mu\tau$ bottom line

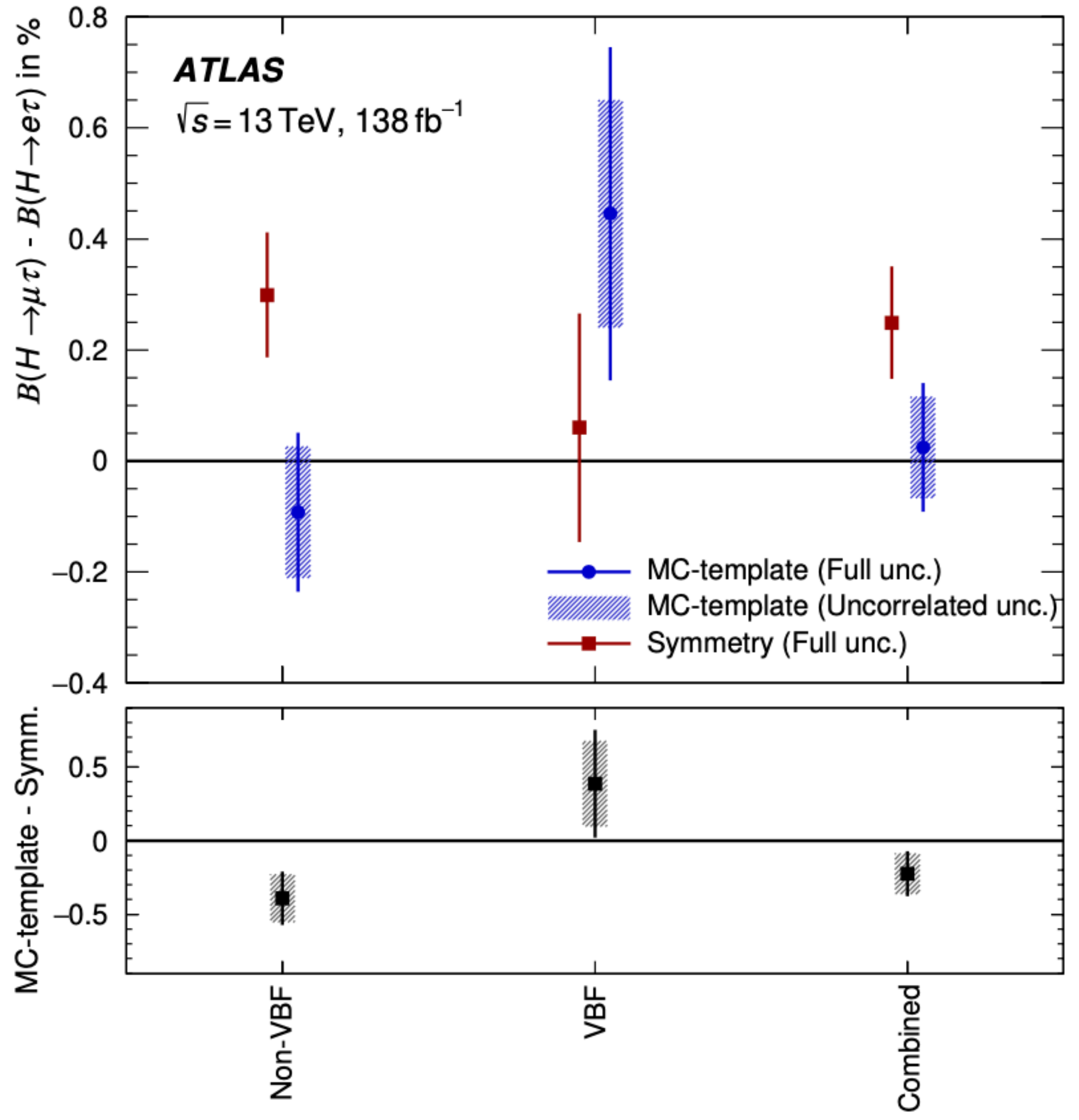
arXiv:2302.05225

- Final results obtained by combining the most sensitive approach in each region and category
- Symmetry based analysis sensitive to difference in decay rates
- MC template method allow fitting with 2 POIs









Conclusions

- We have done a lot
  - Set unique bounds on features of light, SM-singlet (pseudo)scalars
  - We set strong(est) model-independent bounds on off-diagonal Yukawa couplings leading to significant constraints on SMEFT, 2HDM, vector-like fermions

- Yet, we have done too little
  - BSM physics could easily still be just behind the corner

- Room for improvement of existing searches
- Room for new searches
- Room for new methods
- Room for new approaches