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Rheinische
Friedrich-Wilhelms-
Universität Bonn

Search for HH → $bb\tau\tau$ in ATLAS

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on behalf of the ATLAS collaboration

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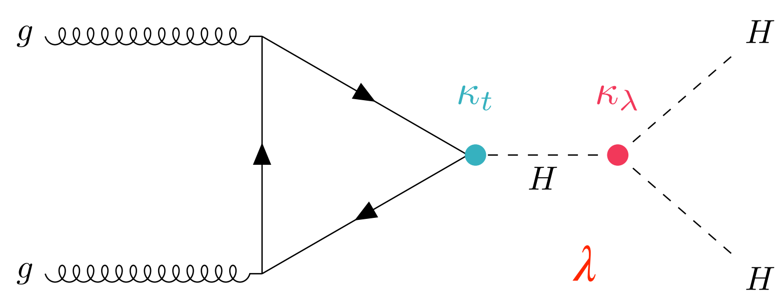
Why to search for HH?

- **Higgs potential**

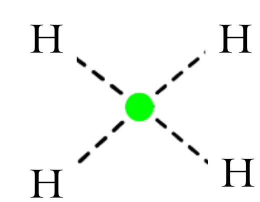
$$V(H) = \frac{m_H^2}{2}H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4 \qquad \text{SM:} \quad \lambda = \frac{m_H^2}{2v^2} = 0.13$$

mass term | triple Higgs coupling | quartic Higgs coupling

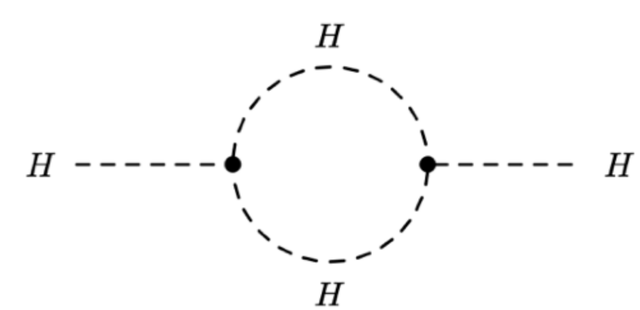
$m_{\mathrm{H}} = 125.10 \pm 0.14\,\mathrm{GeV}$
(PDG 2020)



$$\kappa_\lambda = \frac{\lambda}{\lambda_{\mathrm{SM}}}$$

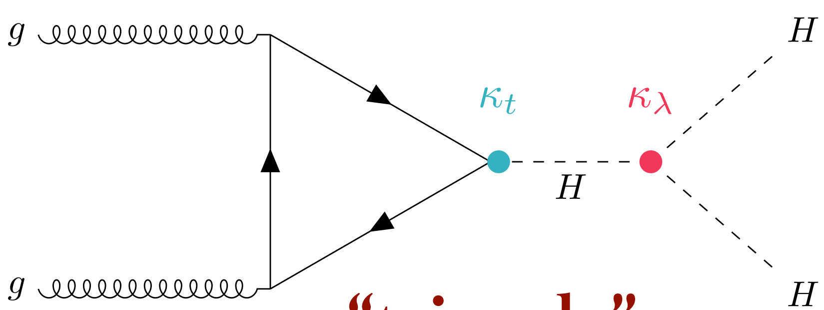


- **Higgs self-interactions**
  - **indirect** via **single Higgs** production at higher order
  - **direct** via **di-Higgs** production



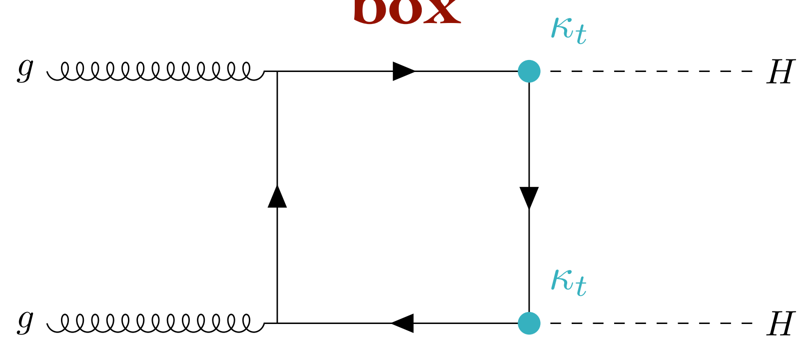
HH Production SM

- **HH production** → 2 diagrams in the SM



"triangle"

"box"



SM

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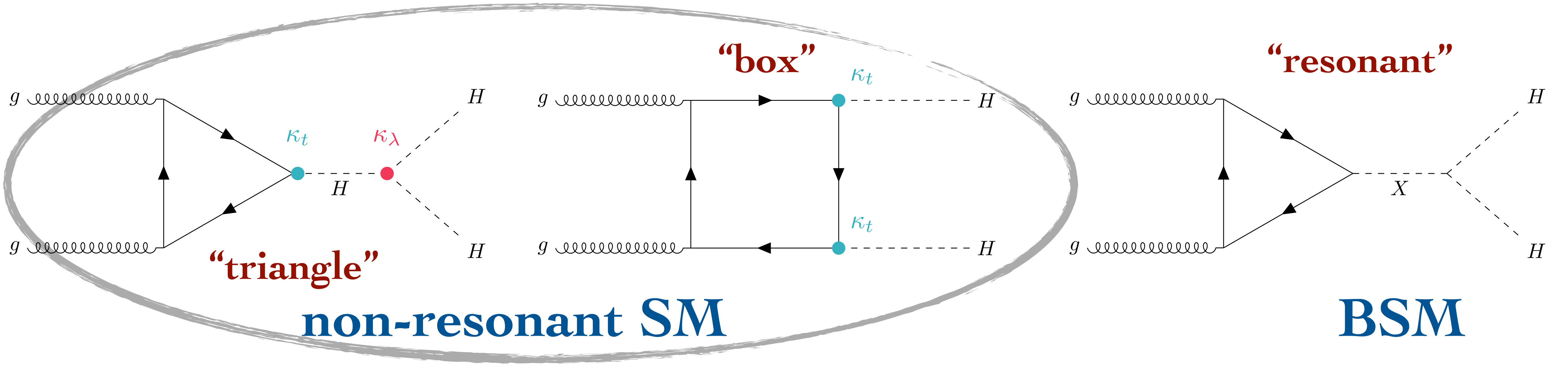
HH Production SM & BSM

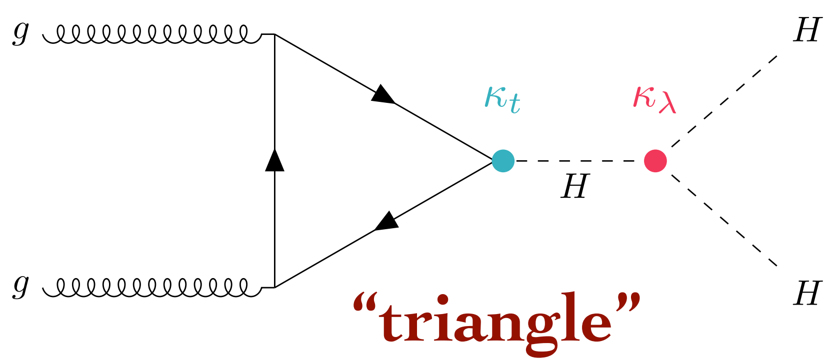
- **HH production** → non-resonant and resonant



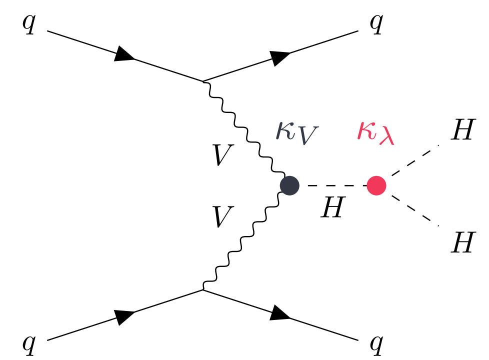
- **SM HH production** cross section 1000 times smaller than $pp \to H$
  - two diagrams with **destructive interference** = **31 fb @ 13 TeV**
- **BSM** can lead to enhancement in the HH production
  - **non-resonant** production due to modified λ, new vertices or new particles in the loop
  - **resonant** production modes: KK gravitons, H in 2HDM, new scalar singlets, cross sections up to O(pb)

HH Production ggF & VBF

- **HH production** → non-resonant via ggF and VBF



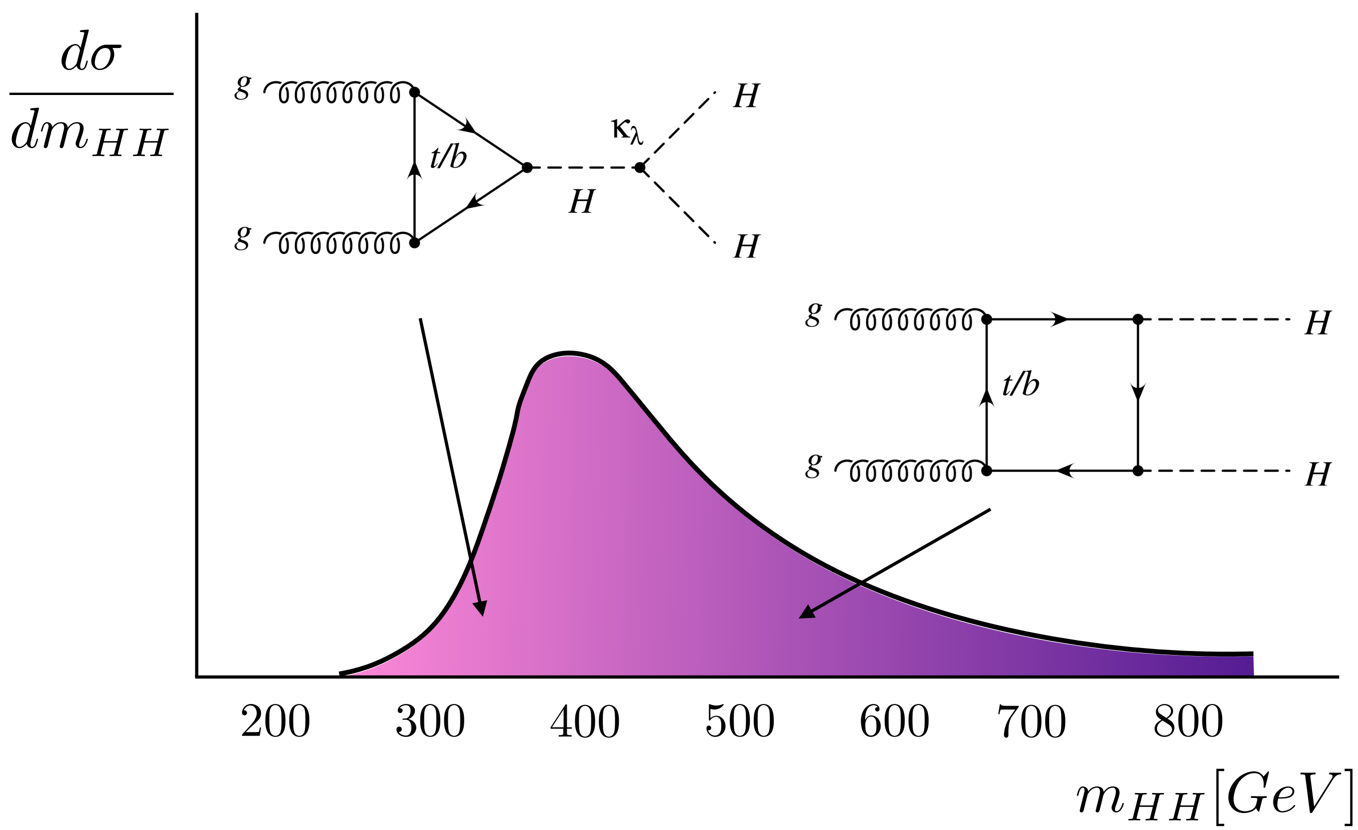
non-resonant ggF



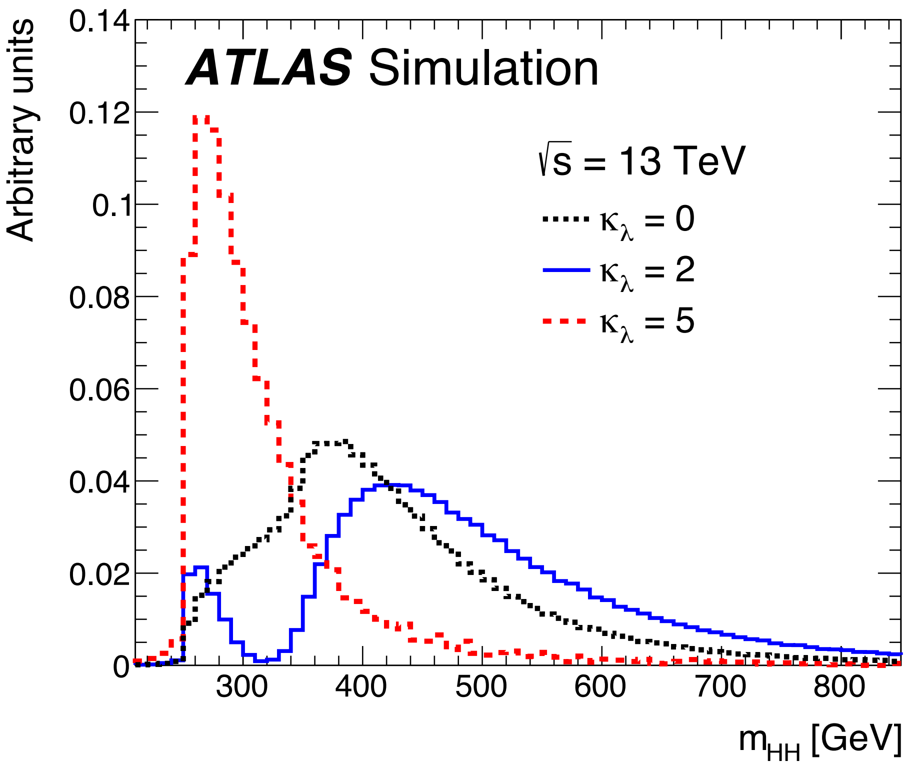
non-resonant VBF

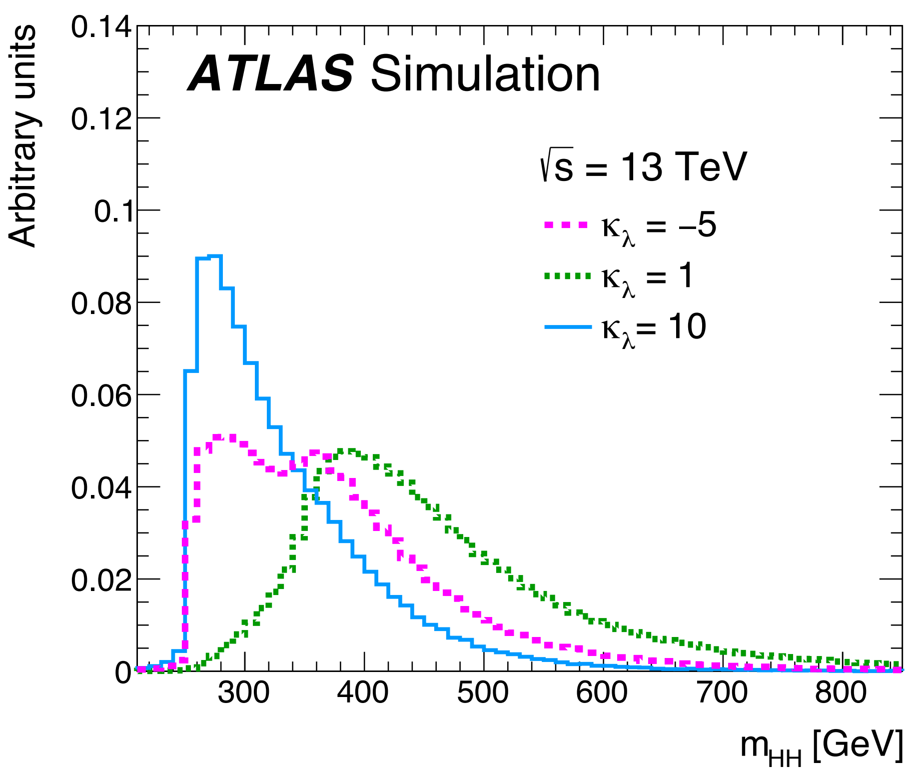
- VBF production is sub-dominant = **1.7 fb @ 13 TeV**

How to search for HH?



$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$





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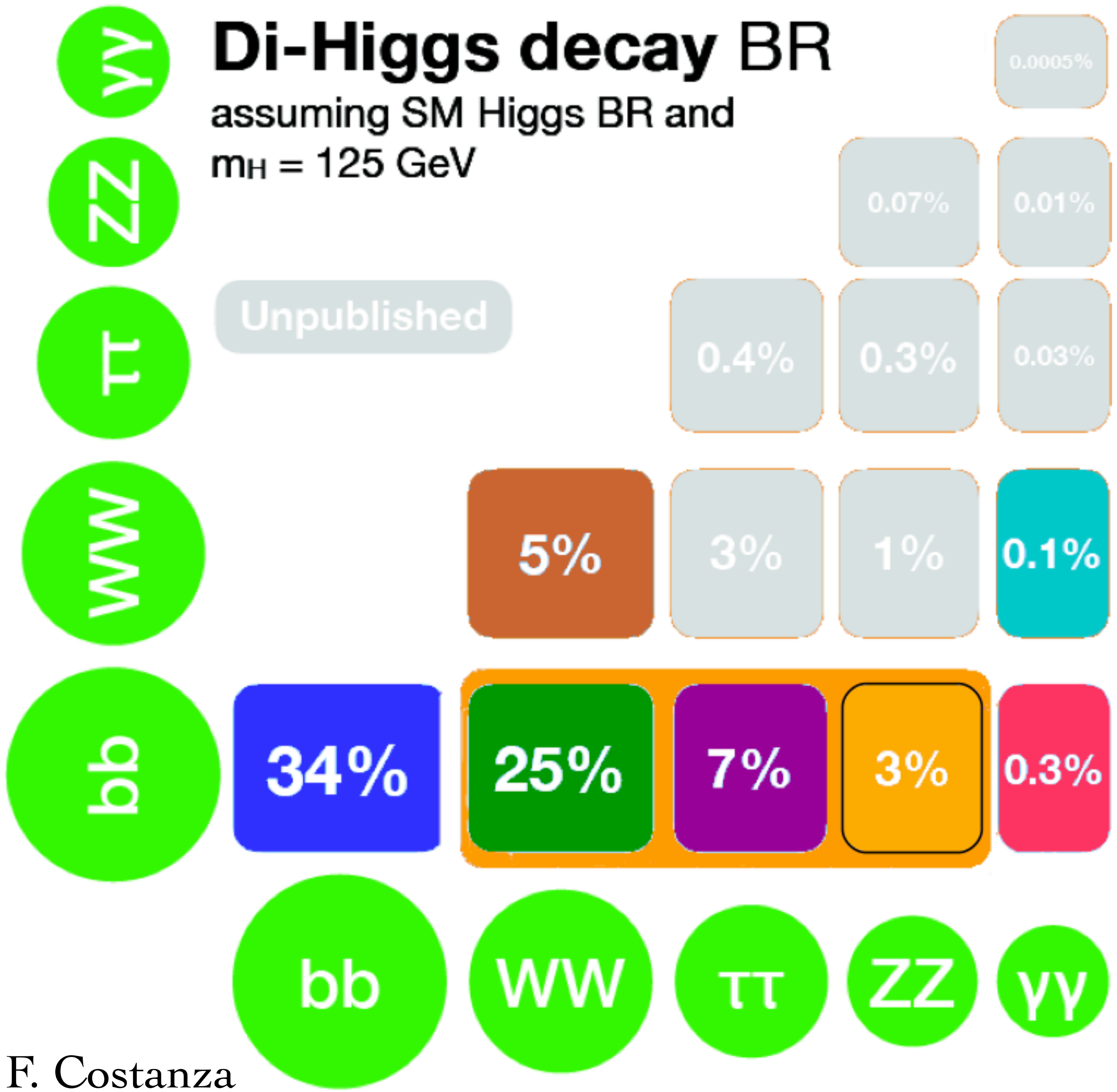
HH Decays

Channel	Lumi, fb^{-1}	Reference
4b	28-36 126-139	JHEP 01 (2019) 030 ATLAS-CONF-2021-035
2b2W	36	JHEP 04 (2019) 029
2b2τ	139	ATLAS-CONF-2021-030
4W	36	JHEP 05 (2019) 124
2b2γ	139	ATLAS-CONF-2021-016
2W2γ	36	EPJC 78 (2018) 1007
comb	36	1906.02025
2blvlv	139	1908.0676
VBF 4b	126	JHEP 07 (2020) 108



F. Costanza

most promising channels at LHC: 4b, bbττ and bbγγ

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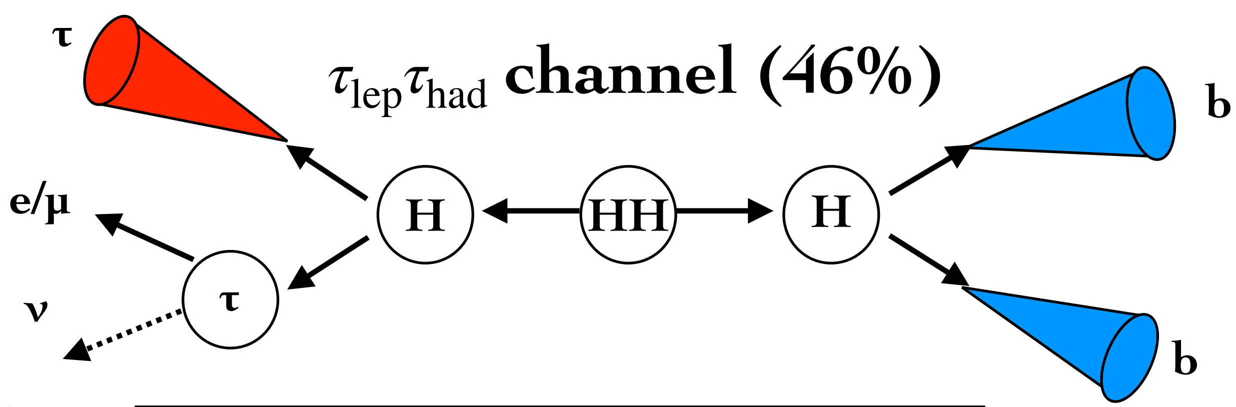
HH → bbττ

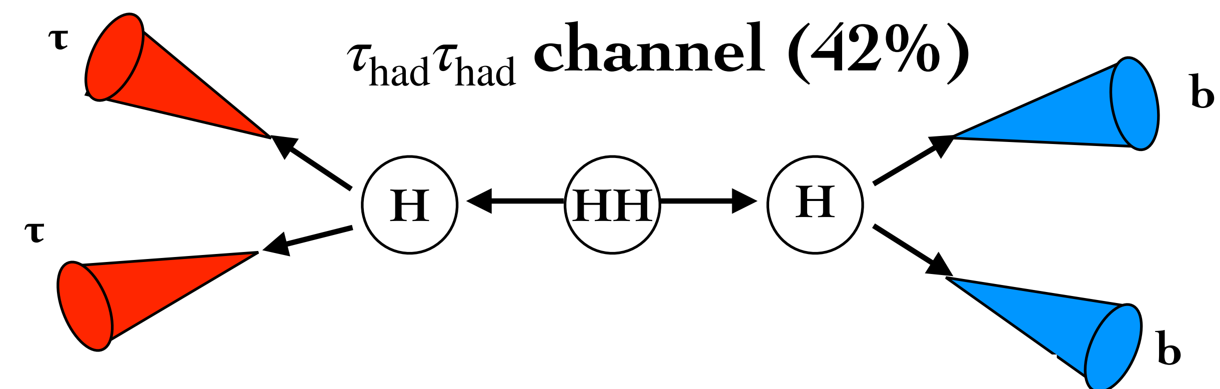
Pros:

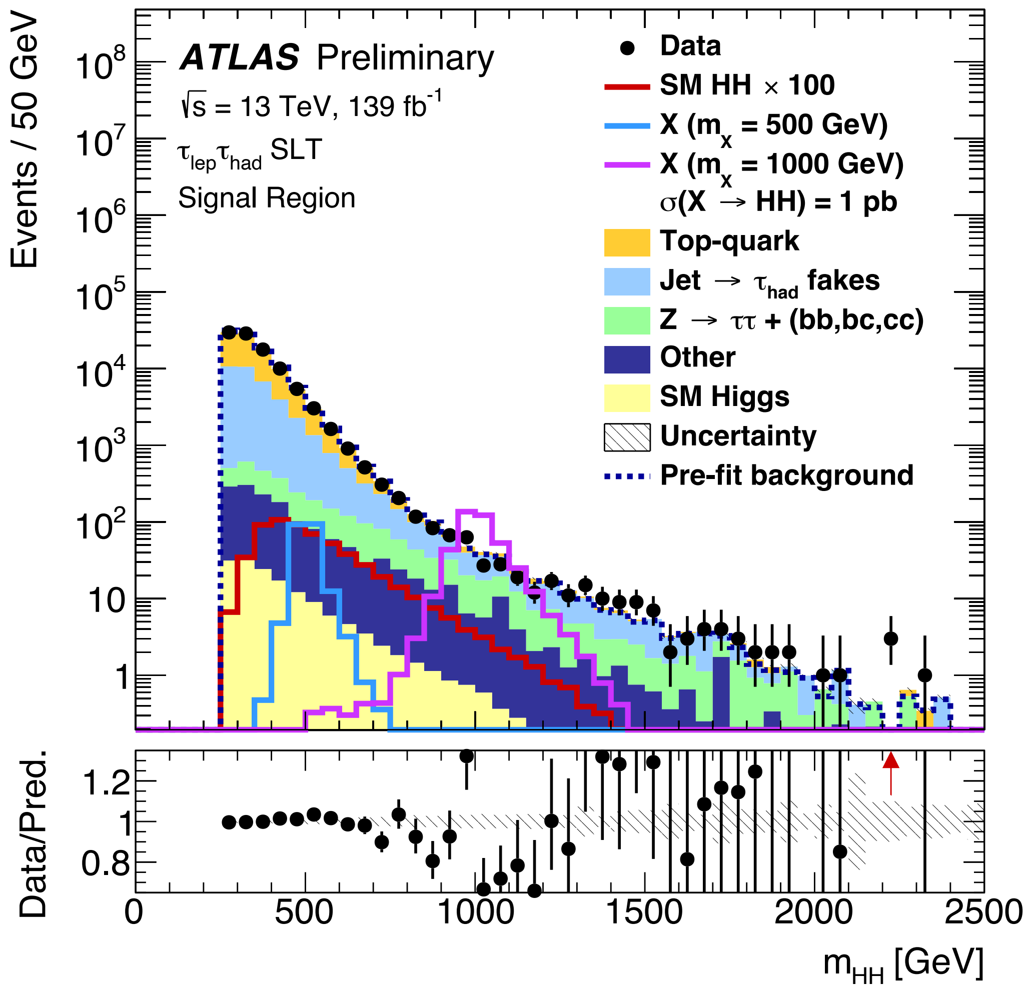
- sizeable branching ratio (7%)
- moderate bkg contamination

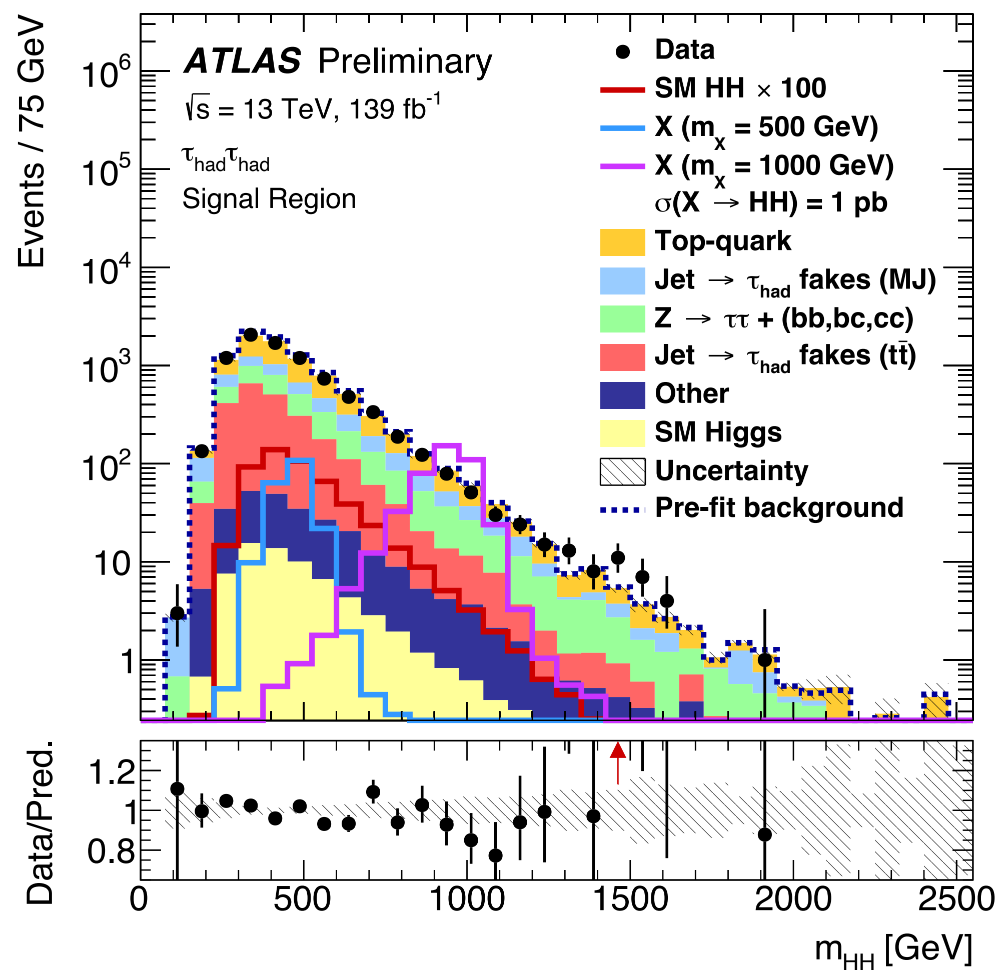
Cons:

- neutrinos in τ decays
- challenging had. τ reco and triggering









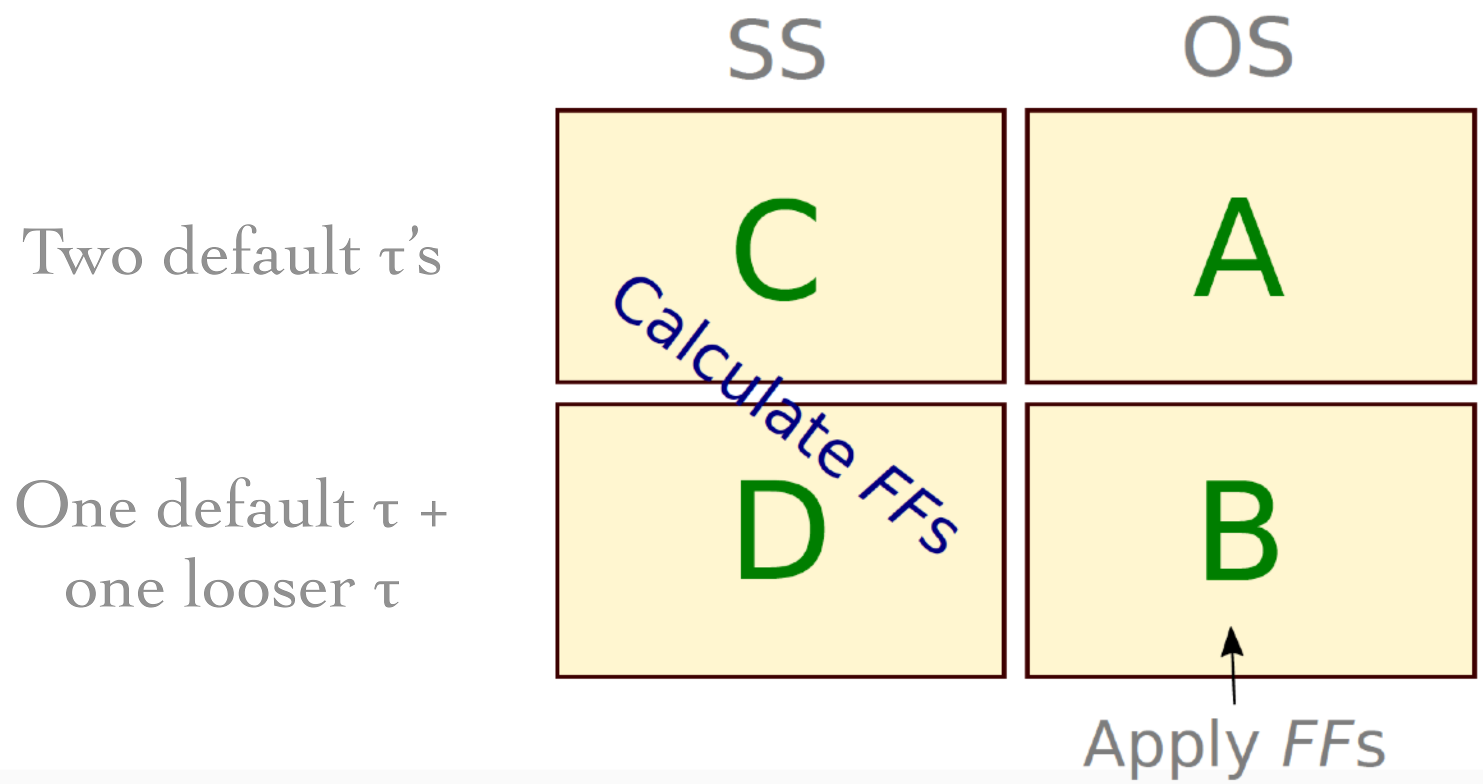
HH bbττ: Event Selection

$\tau_{\text{had}}\tau_{\text{had}}$ category		$\tau_{\text{lep}}\tau_{\text{had}}$ categories	
single-τ trigger STT	di-τ trigger DTT	single-lepton trigger SLT	lepton-τ trigger LTT
e/μ selection			
No loose e/μ with $p_{\text{T}} > 7$ GeV		Exactly one tight e or medium μ	
		$p_{\text{T}}^{e} > 25, 27$ GeV	18 GeV $< p_{\text{T}}^{e} <$ SLT cut
		$p_{\text{T}}^{\mu} > 21, 27$ GeV	15 GeV $< p_{\text{T}}^{\mu} <$ SLT cut
		$\lvert\eta^{e}\rvert < 2.47$, not $1.37 < \lvert\eta^{e}\rvert < 1.52$	
		$\lvert\eta^{\mu}\rvert < 2.7$	
$\tau_{\text{had-vis}}$ selection			
Two loose $\tau_{\text{had-vis}}$		One loose $\tau_{\text{had-vis}}$	
$\lvert\eta\rvert < 2.5$		$\lvert\eta\rvert < 2.3$	
$p_{\text{T}} > 100, 140, 180\ (25)$ GeV	$p_{\text{T}} > 40\ (30)$ GeV	$p_{\text{T}} > 20$ GeV	$p_{\text{T}} > 30$ GeV
Jet selection			
≥ 2 jets with $\lvert\eta\rvert < 2.5$			
$p_{\text{T}} > 45\ (20)$ GeV	Trigger dependent	$p_{\text{T}} > 45\ (20)$ GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{\text{MMC}} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{\text{had-vis}}$ and $\tau_{\text{had-vis}}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

HH bbττ: Fake τ_{had} Bkg

- **Jets** can **fake** hadronic **τ's**
  - source: multijet, W+jets, $t\bar{t}$
  - fake-probability depends on jet-type: gluon- or quark-jet
- **Data-driven approach**
- Fake-enriched sample: τ fails default τ-identification but satisfies a looser τ-identification
- Contribution from non-fake bkgs evaluated using MC

multijet fakes in $\tau_{\text{had}}\tau_{\text{had}}$ channel



$$N_A = \frac{N_C}{N_D} \cdot N_B = FF \cdot N_B$$

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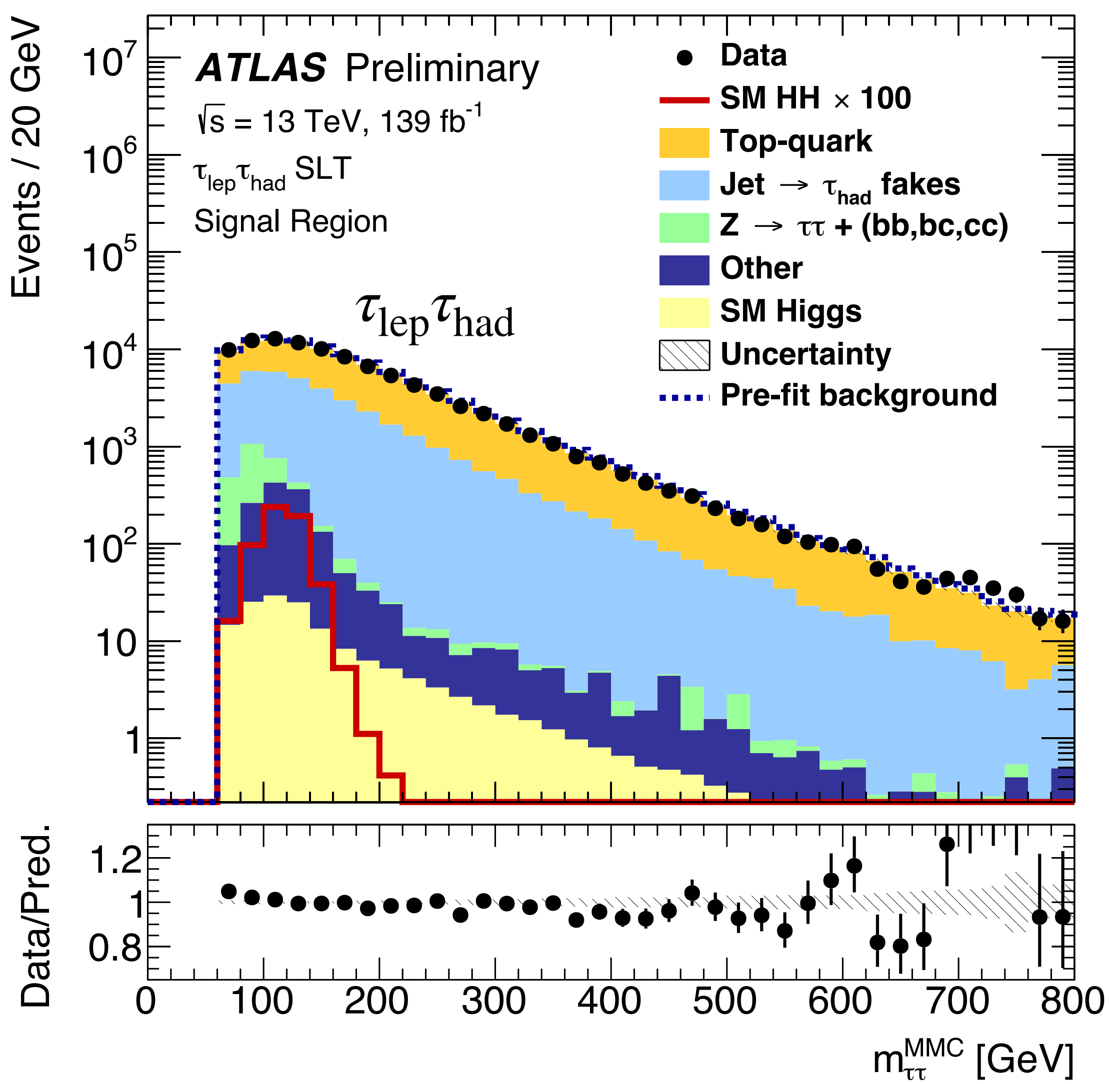
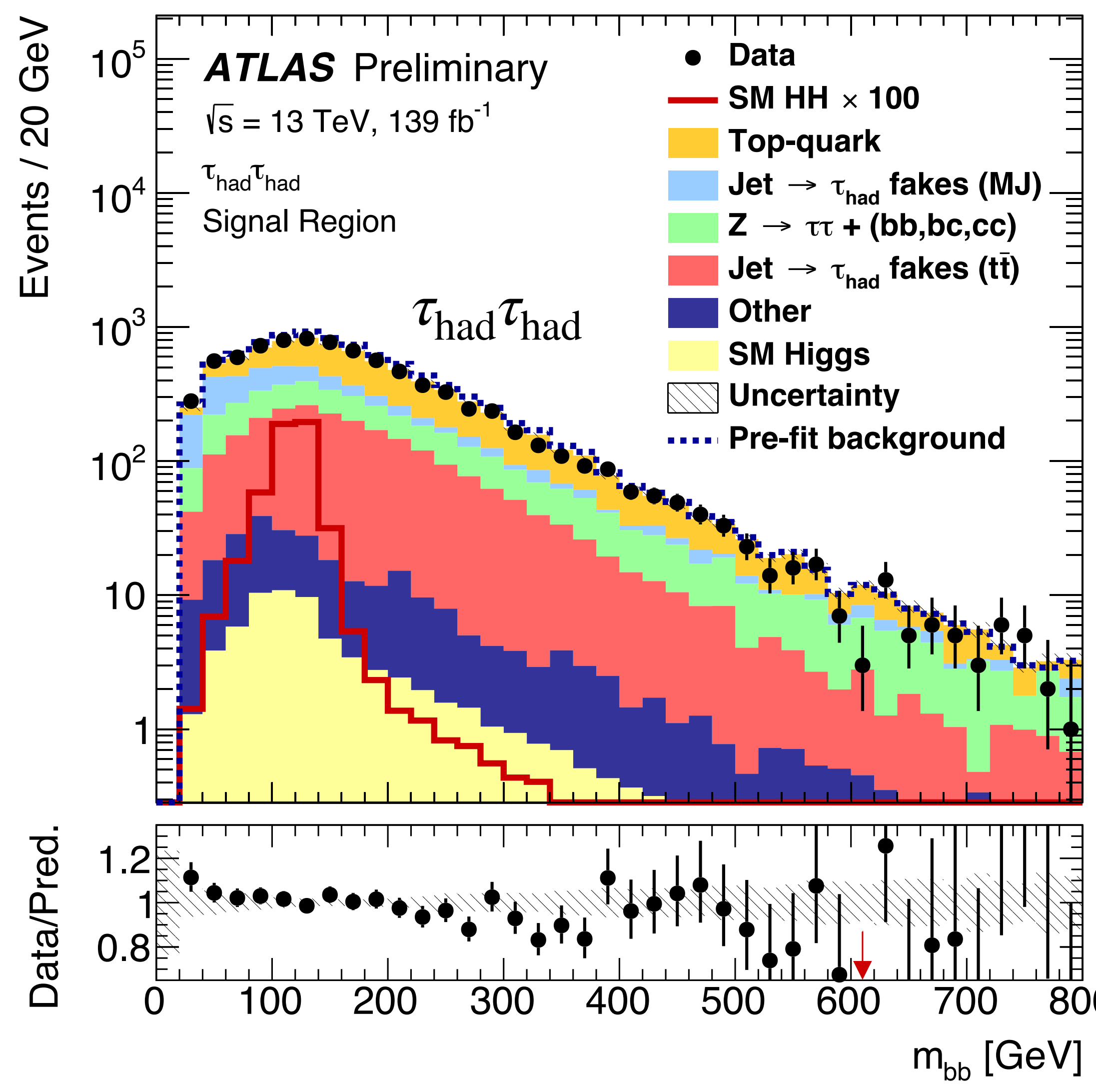
HH bbττ: MVA Analysis

- Multivariate techniques to separate signal and bkgs
  - **P**arametric **N**eural **N**etworks (PNN) for resonant search
  - **N**eural **N**etwork (NN) / **B**oosted **D**ecision **T**rees (BDT) for non-resonant search
- 6 - 11 input variables depending on the channel
  - strongest separation: inv. mass of HH-, bb- and ττ-systems and angular distance between b-jets and τ's
- Use **MVA score** as final **discriminant** in the fit





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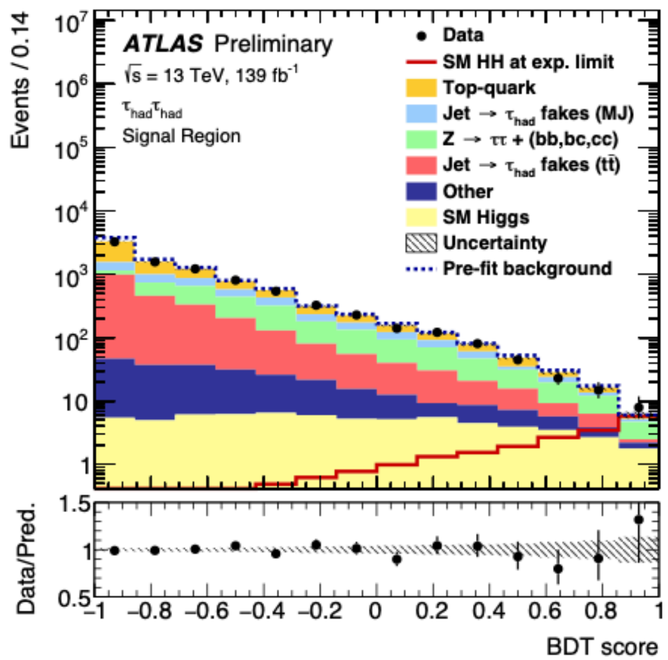
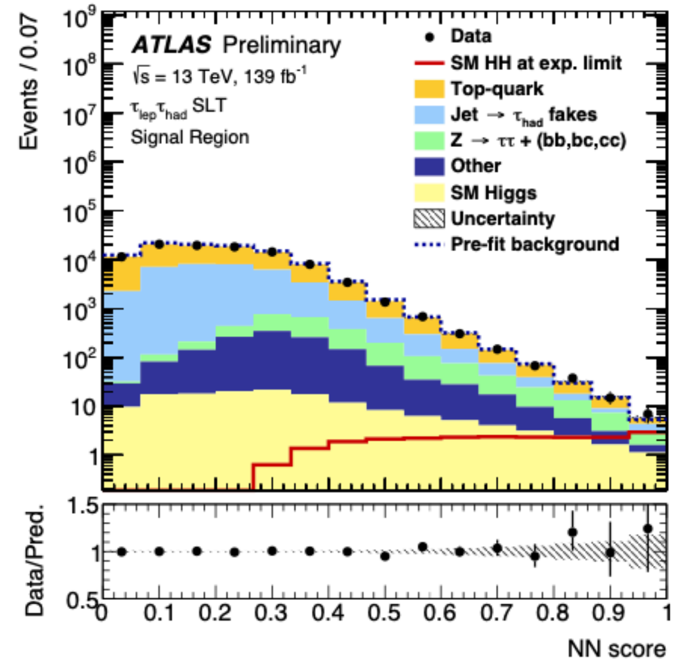
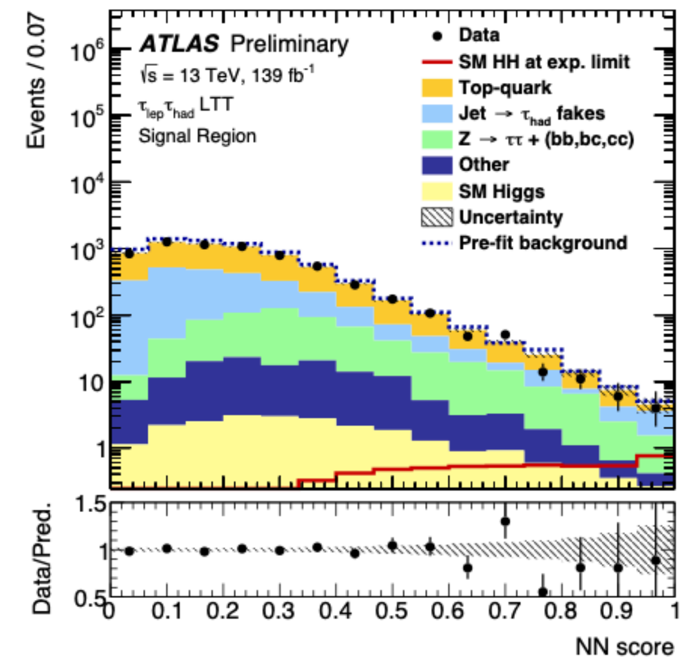
MVA Score Distributions



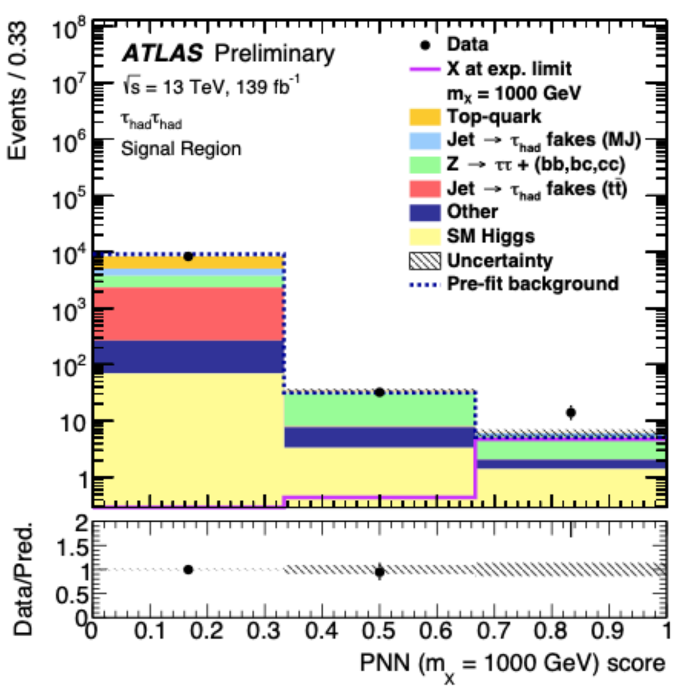
$\tau_{had}\tau_{had}$

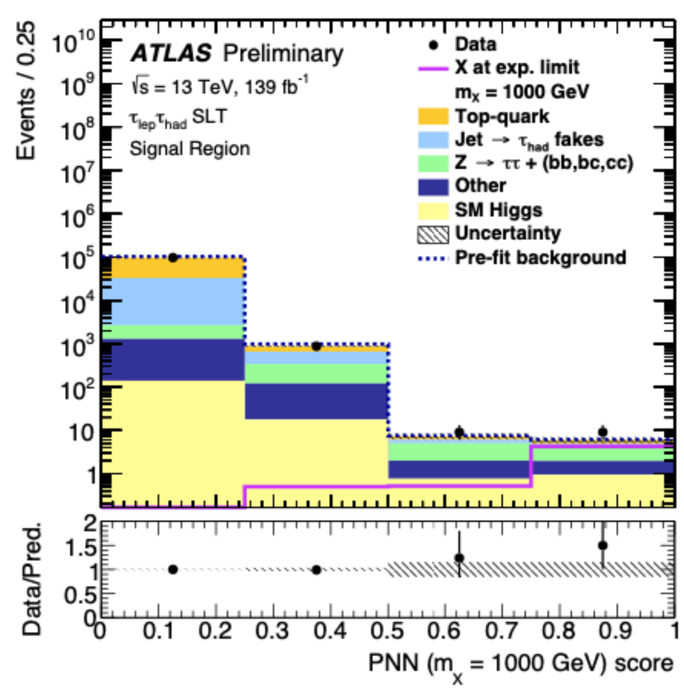


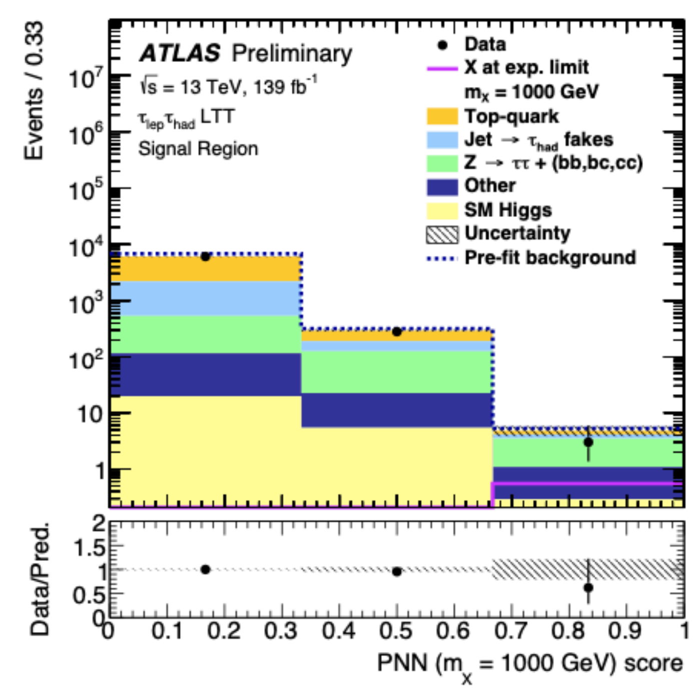
$\tau_{lep}\tau_{had}$ SLT



$\tau_{lep}\tau_{had}$ LTT







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HH bbττ: Systematics

- Relative contribution to the uncertainty in the extracted signal cross-sections (sum in quadrature)

Uncertainty source	Non-resonant HH	Resonant $X \to HH$ 300 GeV	500 GeV	1000 GeV
Data statistical	81%	75%	89%	88%
Systematic	59%	66%	46%	48%
$t\bar{t}$ and $Z+$HF normalisations	4%	15%	3%	3%
MC statistical	28%	44%	33%	18%
Experimental				
Jet and $E_{\mathrm{T}}^{\mathrm{miss}}$	7%	28%	5%	3%
b-jet tagging	3%	6%	3%	3%
$\tau_{\text{had-vis}}$	5%	13%	3%	7%
Electrons and muons	2%	3%	2%	1%
Luminosity and pileup	3%	2%	2%	5%
Theoretical and modelling				
Fake-$\tau_{\text{had-vis}}$	9%	22%	8%	7%
Top-quark	24%	17%	15%	8%
$Z(\to \tau\tau)+$HF	9%	17%	9%	15%
Single Higgs boson	29%	2%	15%	14%
Other backgrounds	3%	2%	5%	3%
Signal	5%	15%	13%	34%

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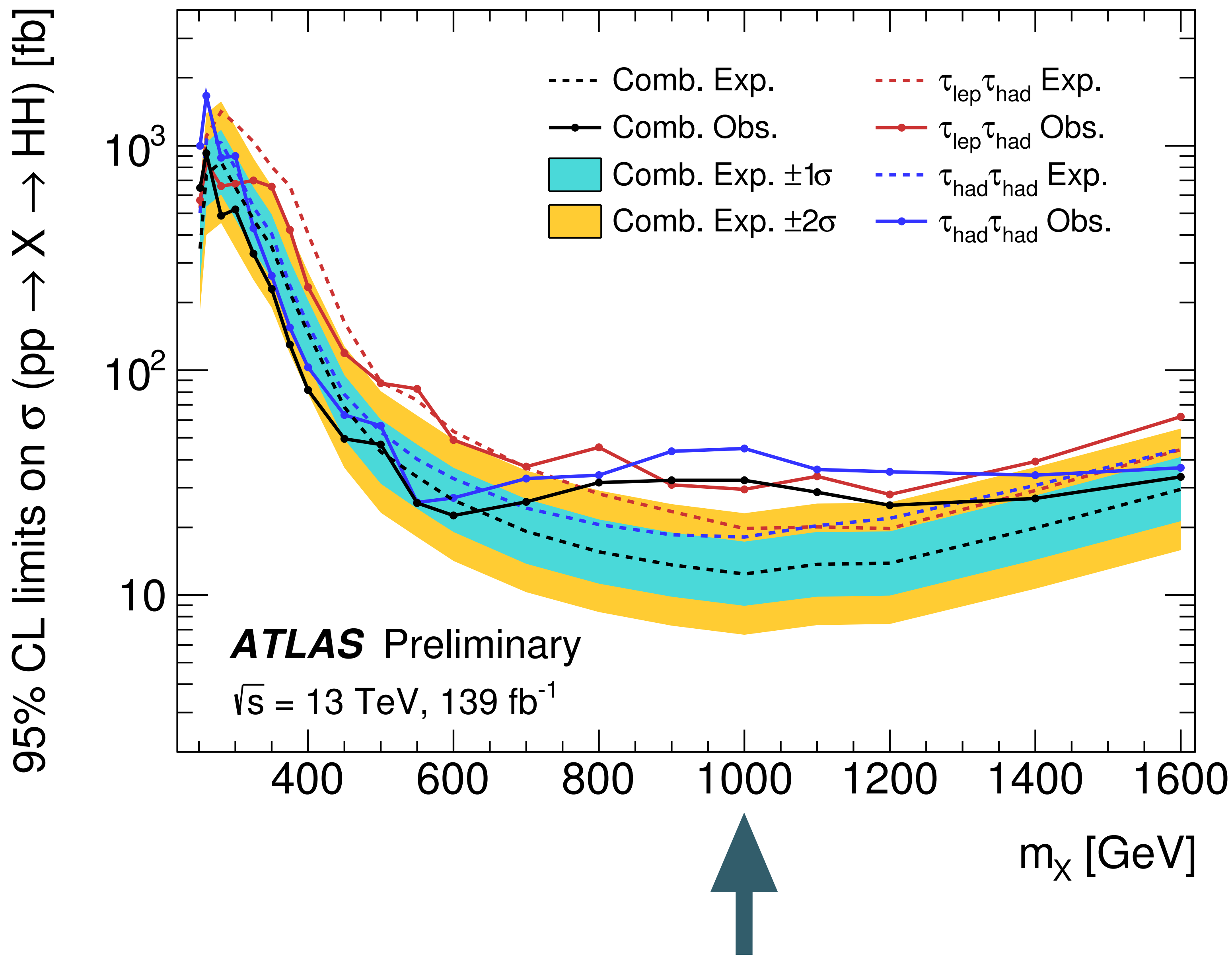
HH bbττ Resonant Production



most significant local excess

at 1.0 (1.1) TeV in the $\tau_{had}\tau_{had}(\tau_{lep}\tau_{had})$ channel of 2.8σ (1.5σ)

→ combined at 1 TeV: local (global) excess of 3.0σ (2.0σ)

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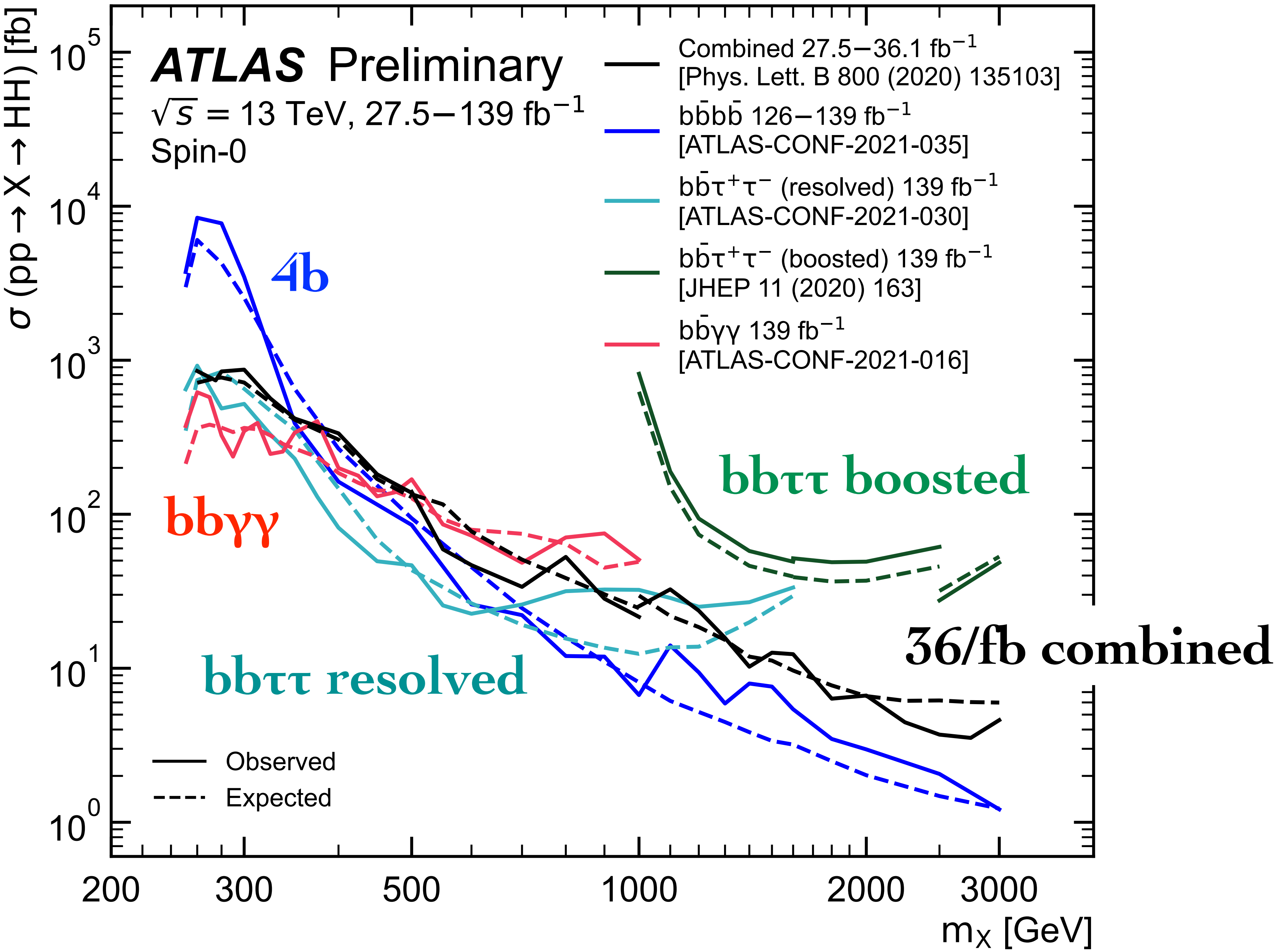
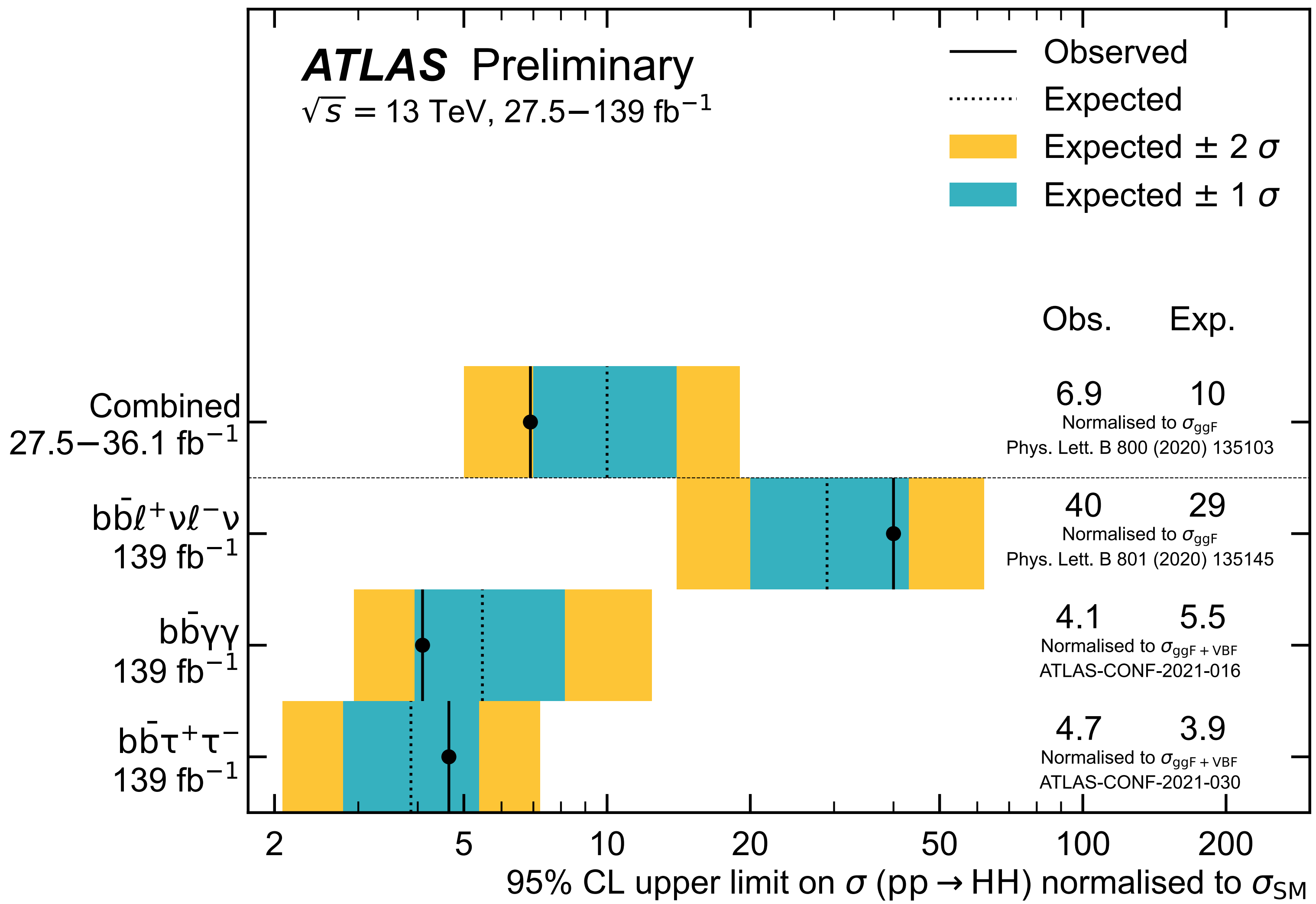
HH Resonant Production



results can be used for re-interpretations
if resonance width below experimental resolution

HH Non-Resonant Production



CMS: obs(exp) 22.2 (12.8) x SM
Phys. Rev. Lett. 122 (2019) 121803

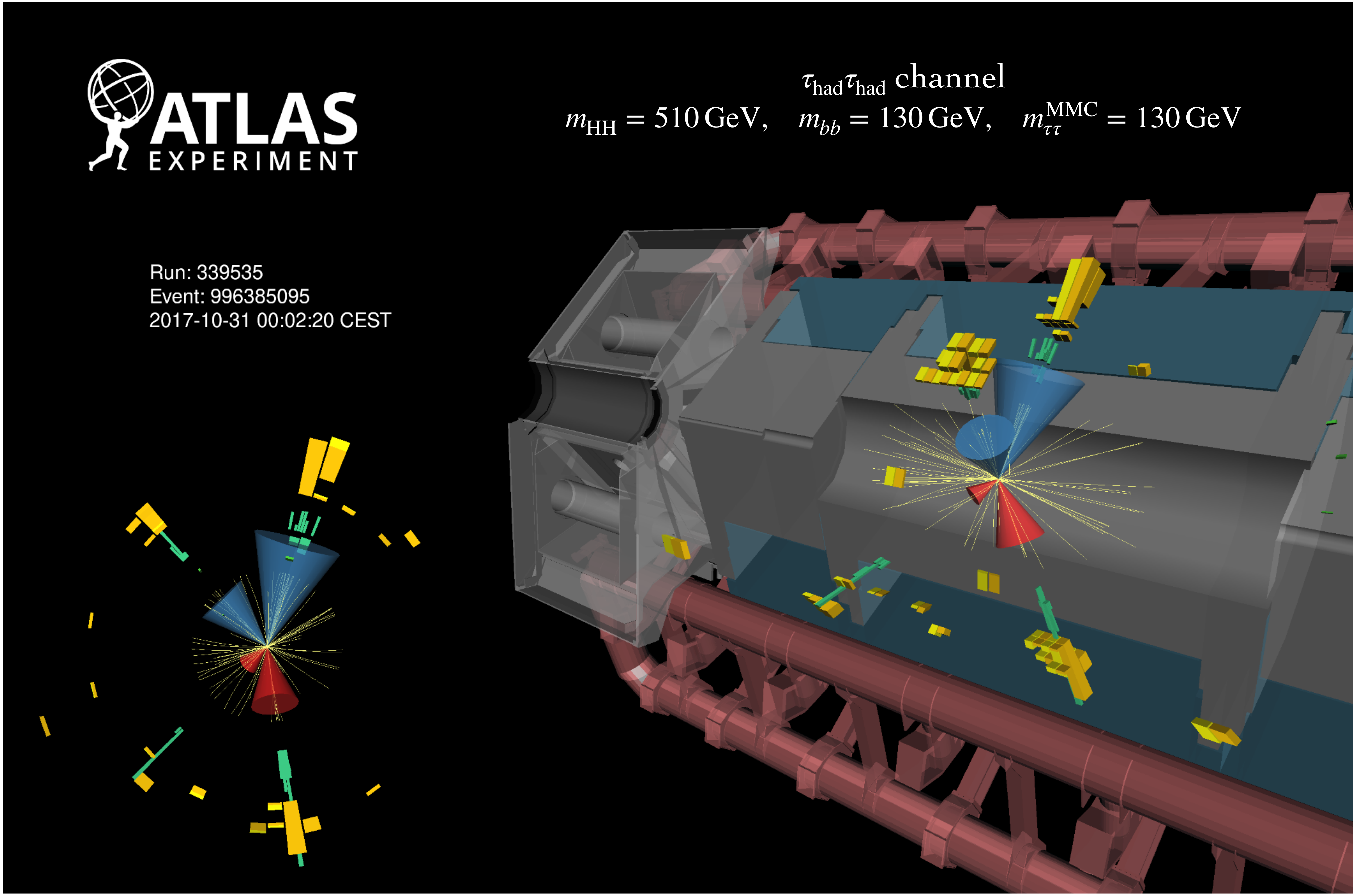
CMS: obs(exp) *7.7* (5.2) x SM
JHEP03(2021)257

		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
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	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
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	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
	$\sigma_{ggF+VBF}/\sigma^{SM}_{ggF+VBF}$	4.65	2.08	2.79	3.87	5.39	7.22

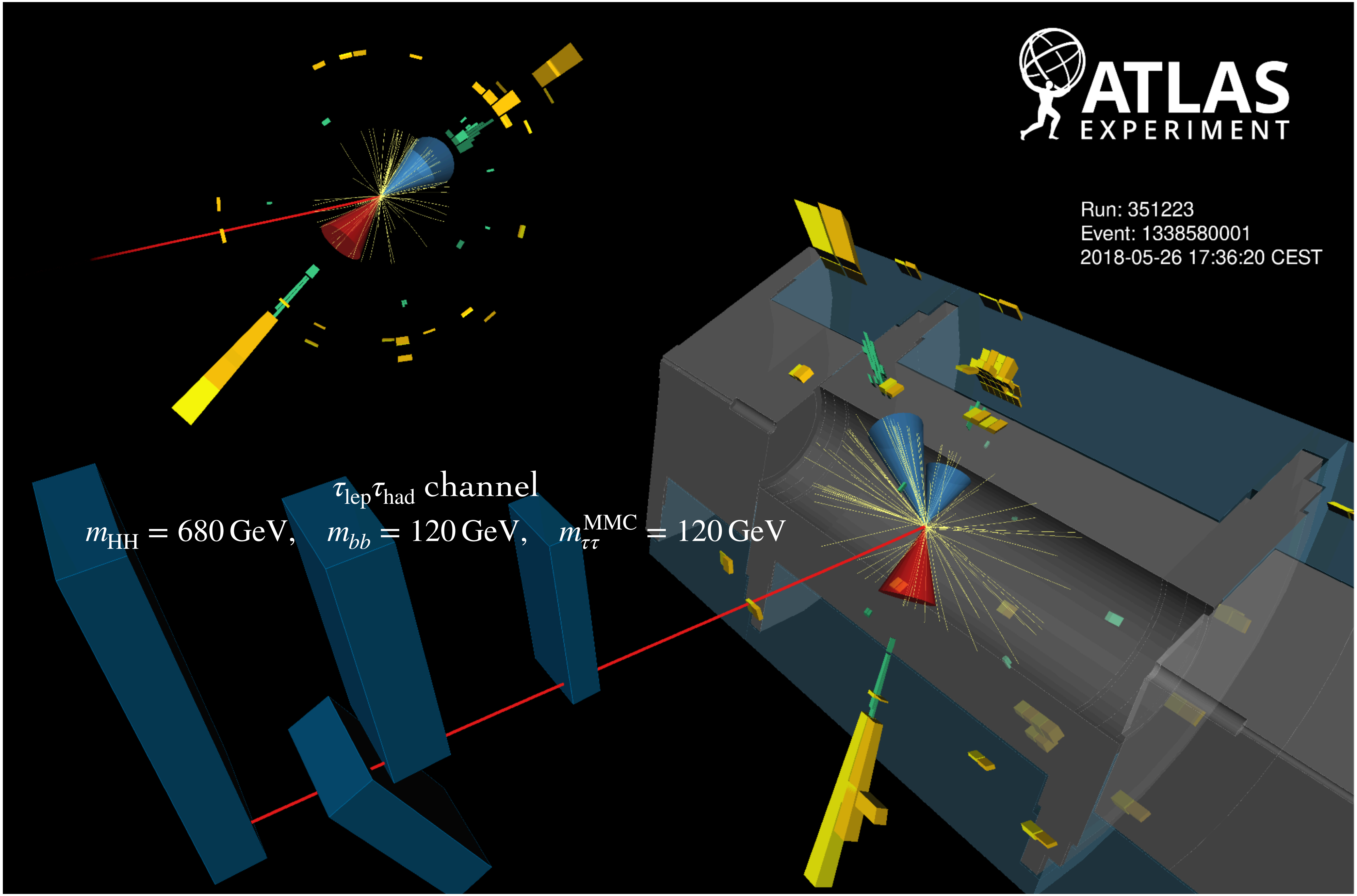
Conclusions

- Strong $HH \to bb\tau\tau$ result with 139 fb^{-1} ATLAS data
  non-resonant: obs (exp) 4.7 (3.9) x SM
  resonant: obs (exp) 23 - 920 fb (12 - 840 fb)
  - **factor 4 improvement** compared to 36 fb^{-1}
    - 50% due to luminosity increase
    - 50% due to improved τ_{had} and b-jet reconstruction and identification and analysis-level improvements
  - **highest expected sensitivity** to non-resonant SM HH
  - excess at 1 TeV with global significance of 2σ

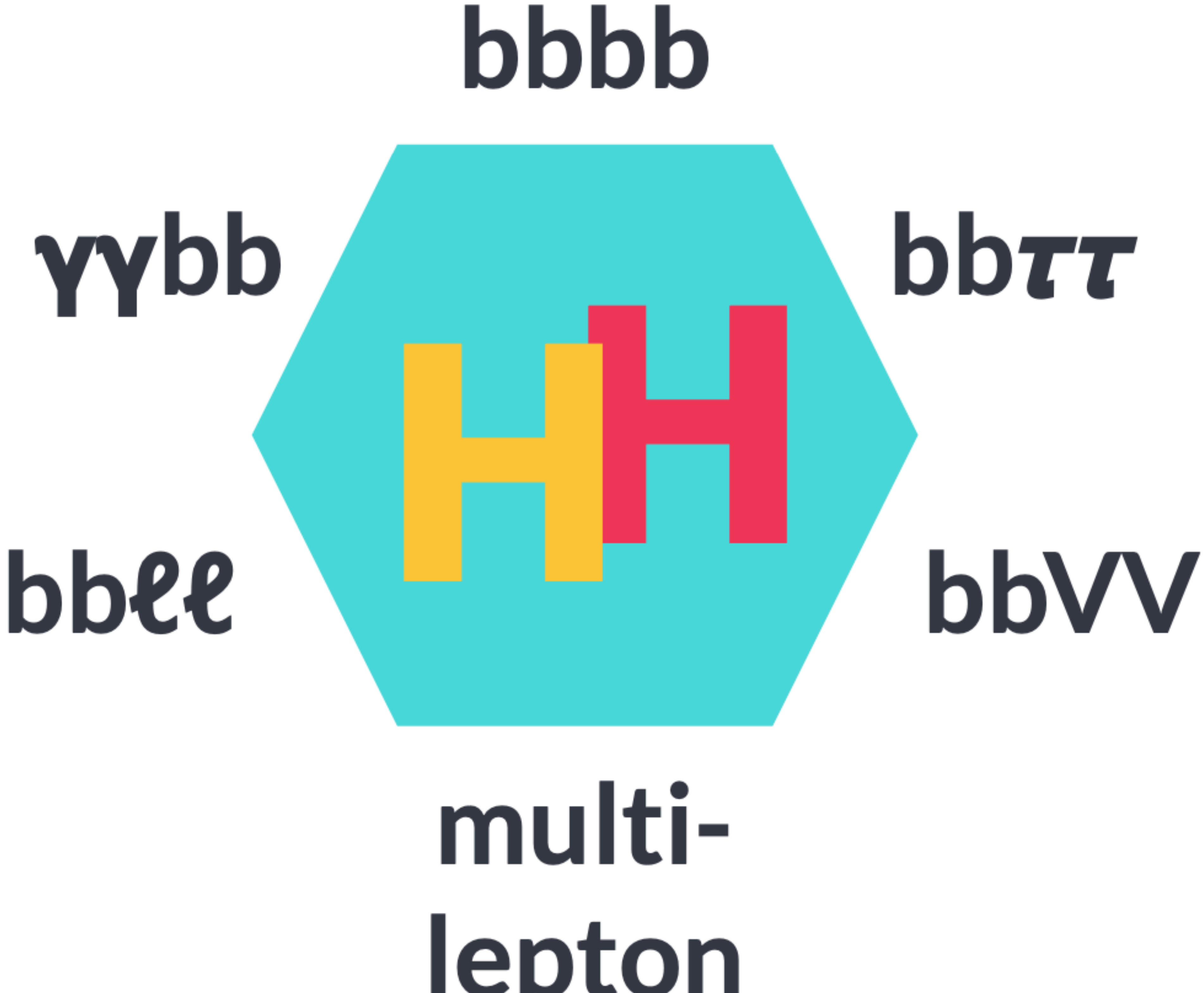
- Looking forward to the combination of the HH channels!!!



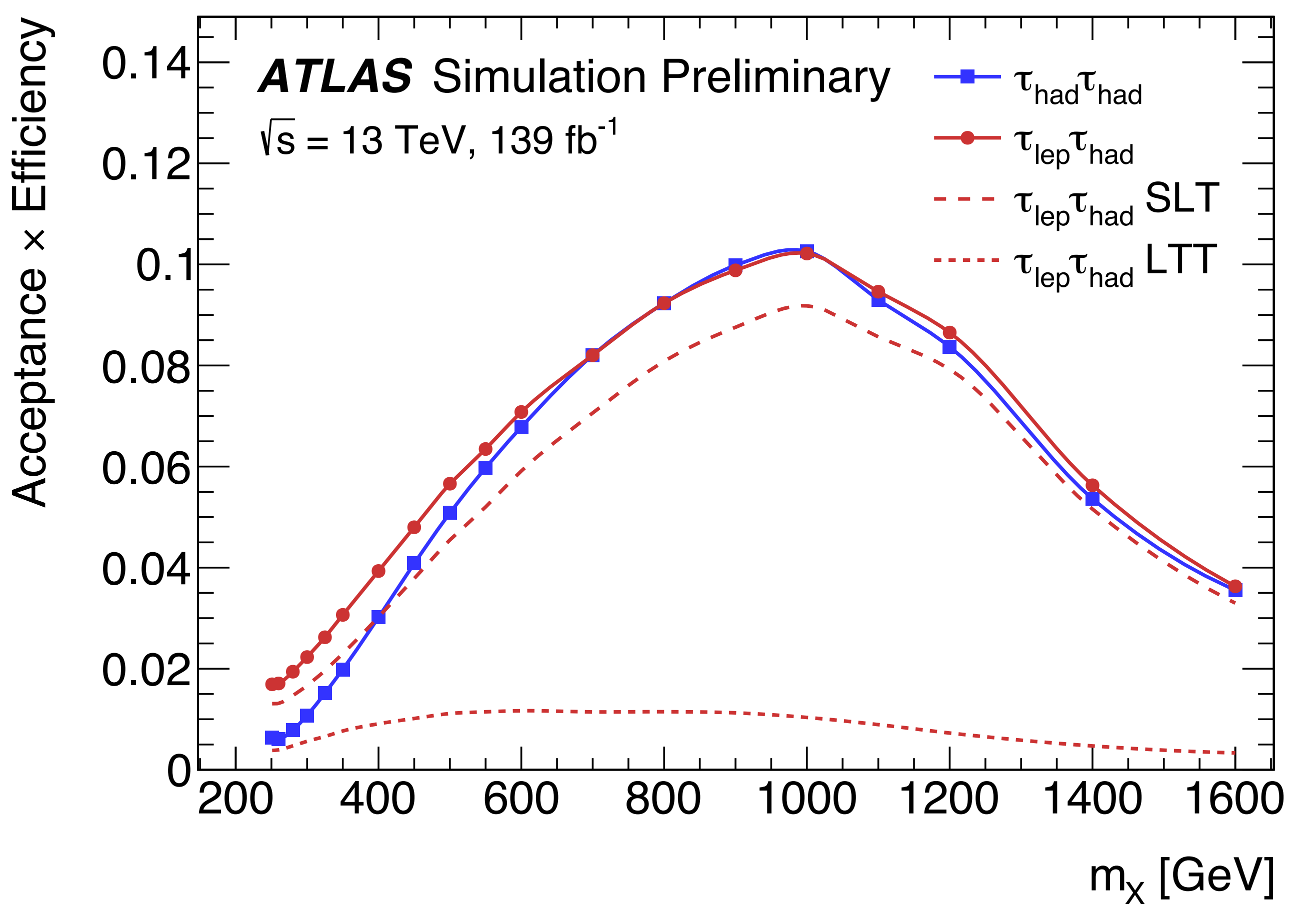
ATLAS
EXPERIMENT
$\tau_{\text{had}}\tau_{\text{had}}$ channel
$m_{\text{HH}} = 510\,\text{GeV}, \quad m_{bb} = 130\,\text{GeV}, \quad m_{\tau\tau}^{\text{MMC}} = 130\,\text{GeV}$
Run: 339535
Event: 996385095
2017-10-31 00:02:20 CEST



ATLAS
EXPERIMENT
Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel
$m_{\mathrm{HH}} = 680\,\mathrm{GeV}$, $m_{bb} = 120\,\mathrm{GeV}$, $m_{\tau\tau}^{\mathrm{MMC}} = 120\,\mathrm{GeV}$


bbbb
γγbb
bbττ
bbℓℓ
bbVV
HH
multi-
lepton

Acceptance x Efficiency



SM non-resonant HH signal

$\tau_{had}\tau_{had}$ channel: 4%

$\tau_{lep}\tau_{had}$ SLT channel: 4%

$\tau_{lep}\tau_{had}$ LTT channel: 1%

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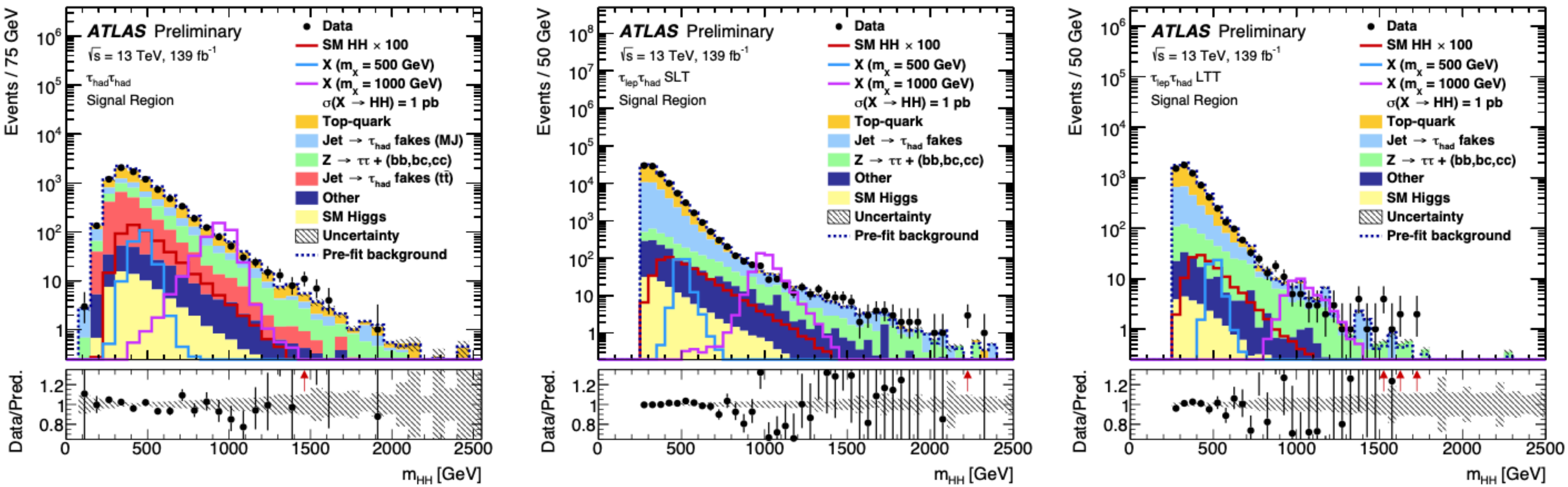
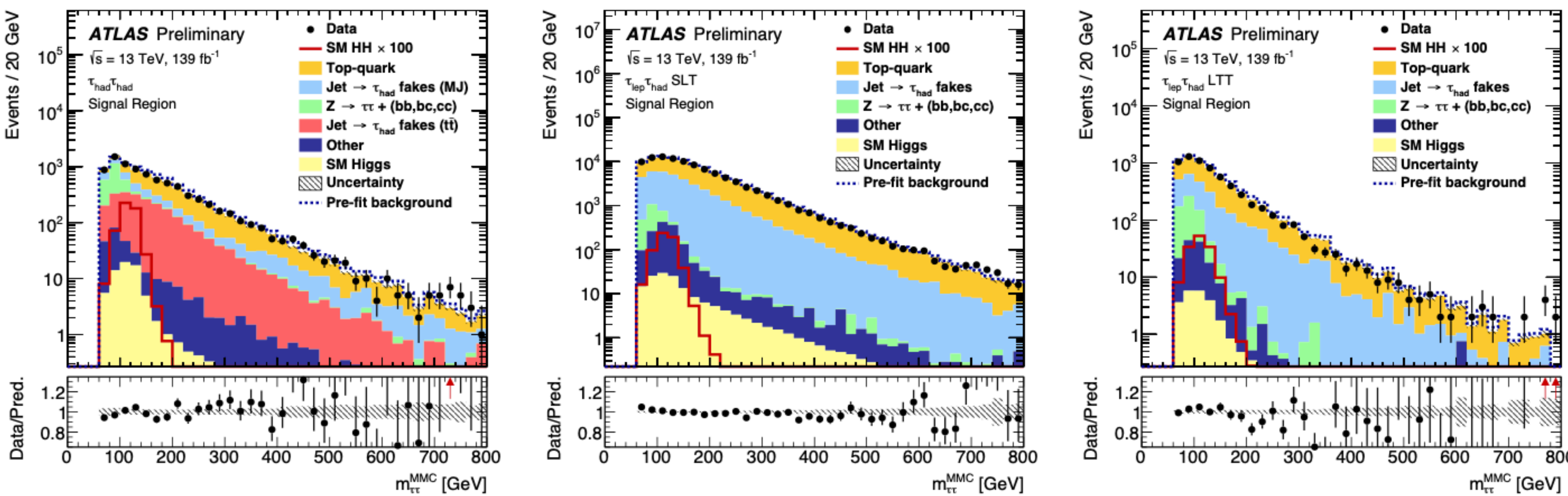
MVA Input Variables

Variable	$\tau_{\rm had}\tau_{\rm had}$	$\tau_{\rm lep}\tau_{\rm had}$ SLT	$\tau_{\rm lep}\tau_{\rm had}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\rm MMC}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{\rm T}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet $p_{\rm T}$		✓	
$m_{\rm T}^{W}$		✓	
$E_{\rm T}^{\rm miss}$		✓	
$\mathbf{p}_{\rm T}^{\rm miss}$ ϕ centrality		✓	
$\Delta\phi(\tau\tau, bb)$		✓	
$\Delta\phi(\ell, \mathbf{p}_{\rm T}^{\rm miss})$			✓
$\Delta\phi(\ell\tau, \mathbf{p}_{\rm T}^{\rm miss})$			✓
$S_{\rm T}$			✓

MVA Input Variables



MVA Input Variables



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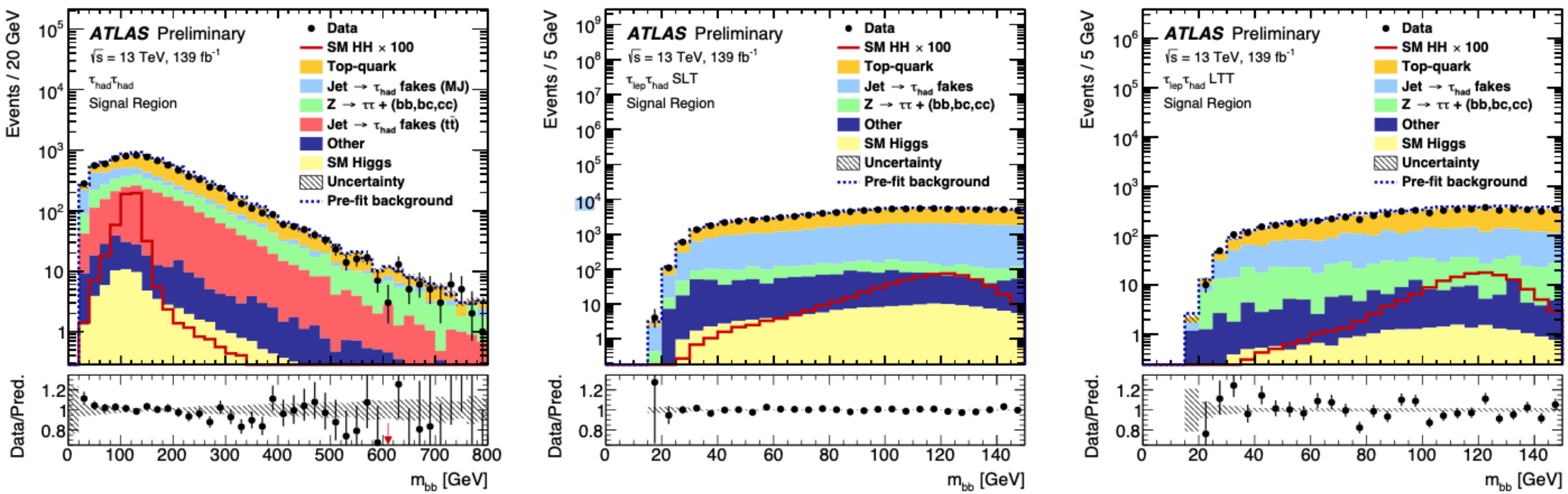
MVA Input Variables



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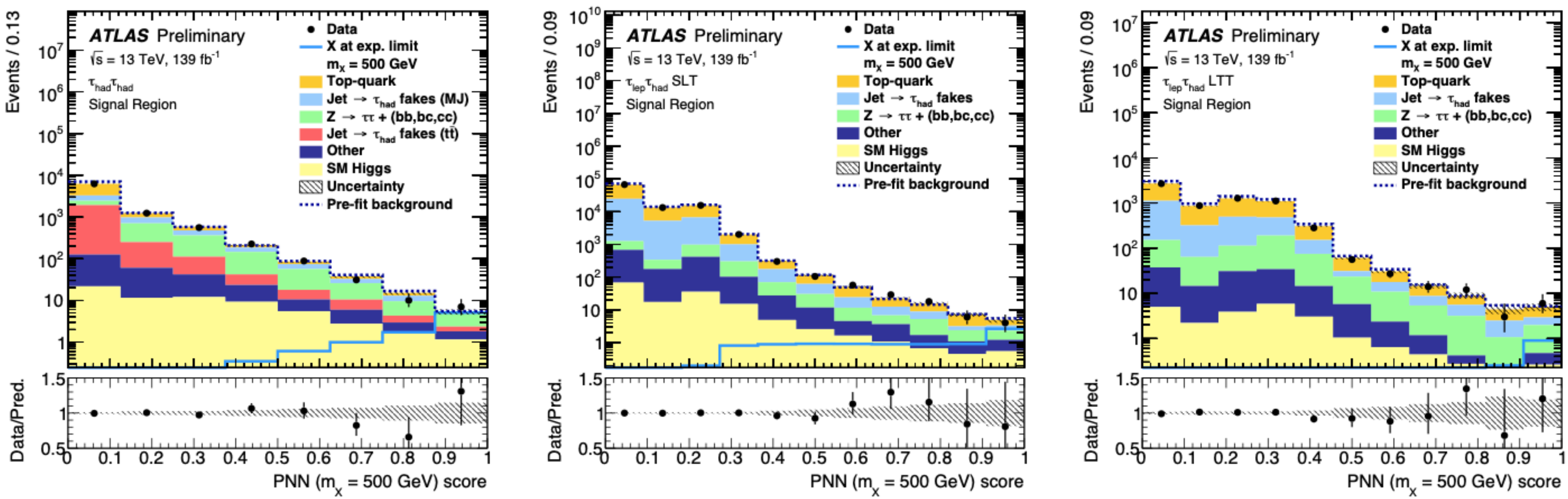
PNN Score @ 500 GeV



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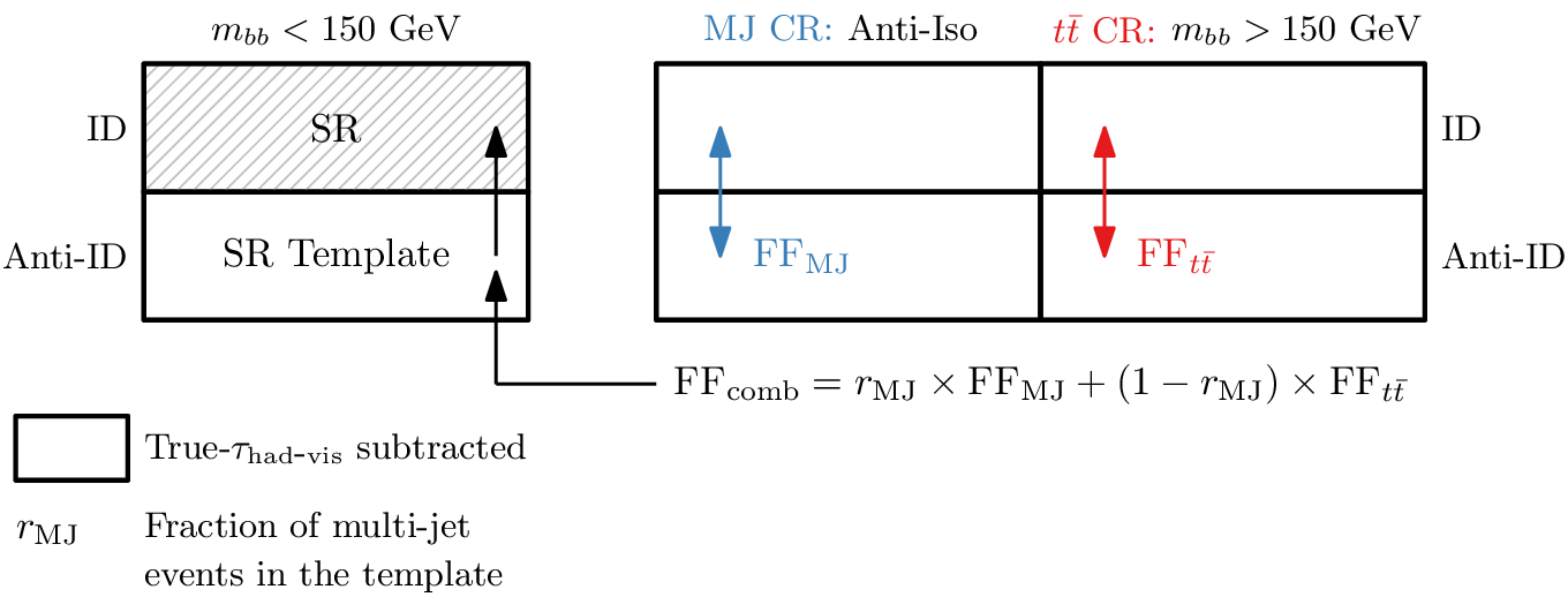
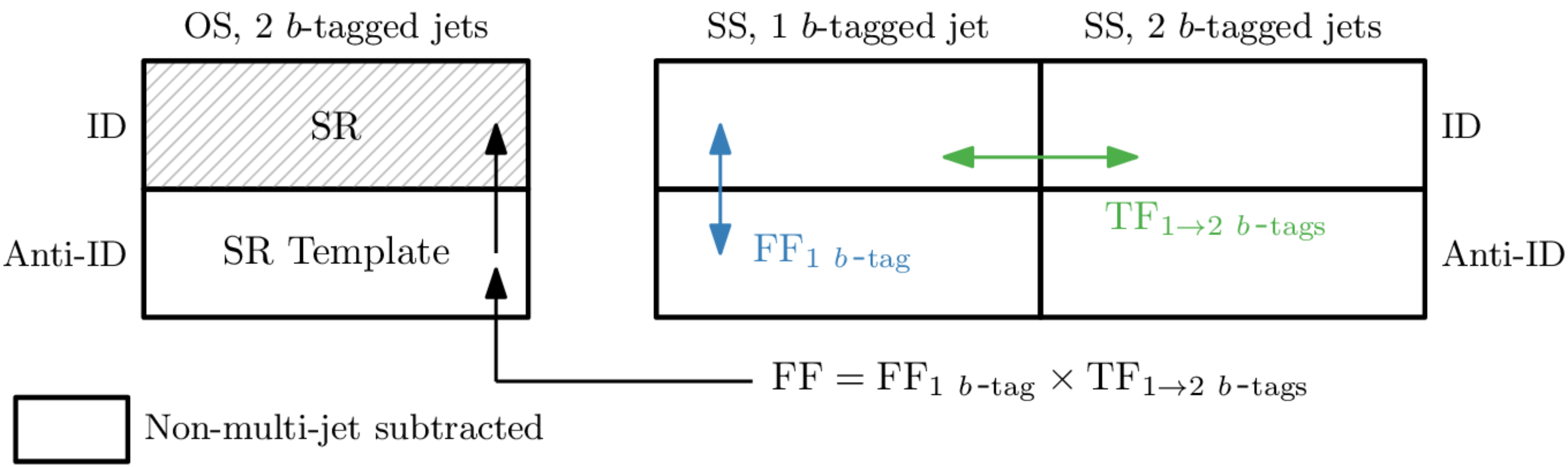
Fake Factor Method in $\tau_{lep}\tau_{had}$



Fake Factor Method in $\tau_{had}\tau_{had}$



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Fake Scale Factor Method in $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$