

Improved analysis of non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state

ATLAS Run 2 + partial Run 3, 196 fb^{-1} at $\sqrt{s} = 13$ and 13.6 TeV

Salah-Eddine Dahbi (Academia Sinica)
On behalf of the ATLAS collaboration



Higgs Hunting 2026

Results and prospects in the electroweak symmetry breaking sector

16-18 September
Orsay/Paris

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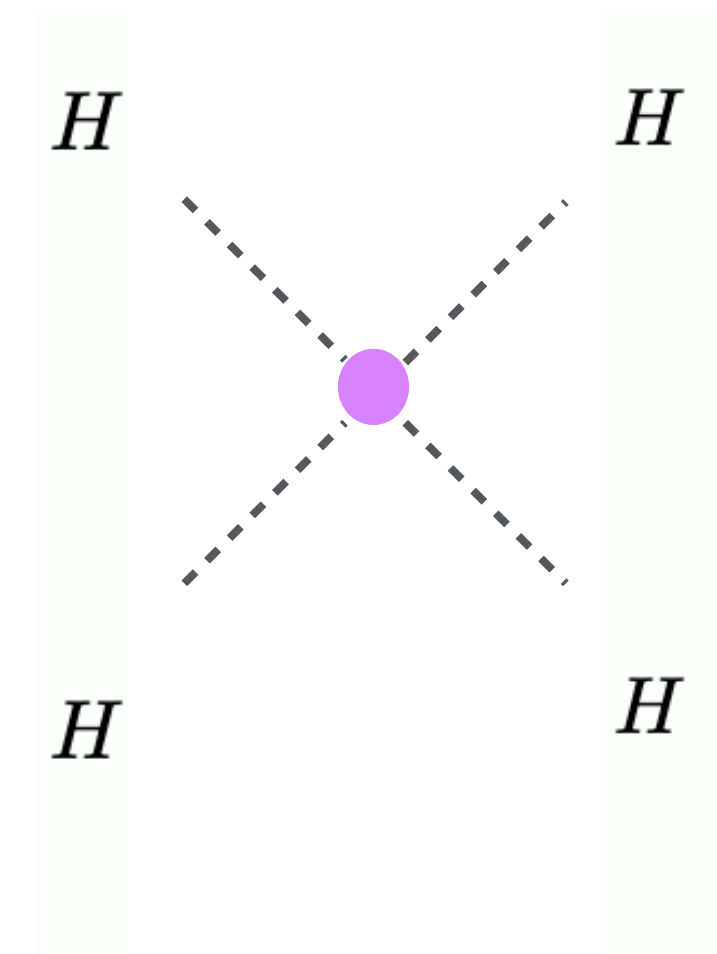
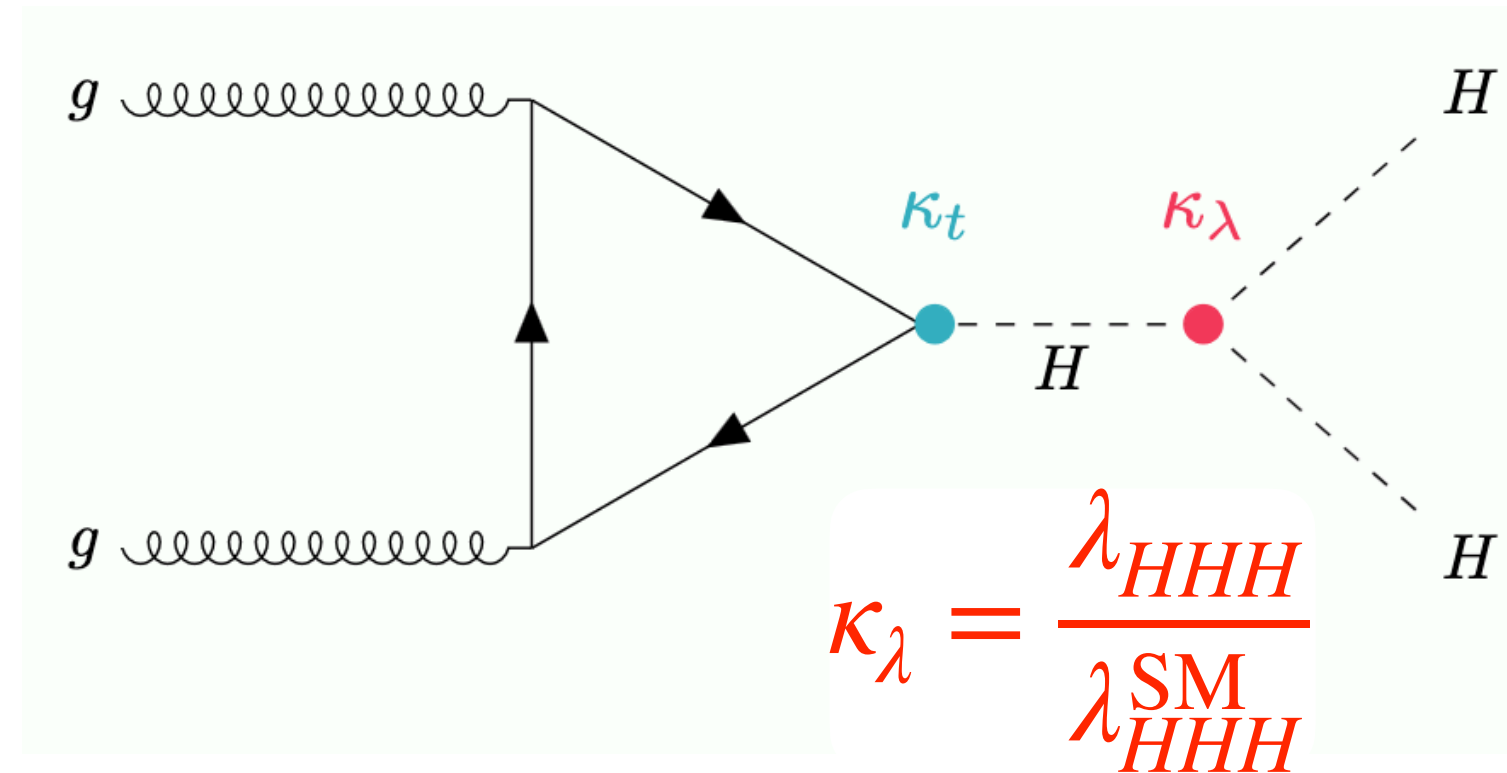
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- Higgs potential:**

$$V(H) = \underbrace{\frac{1}{2}m_H^2 H^2}_{\text{Higgs mass term}} + \underbrace{\lambda_\nu H^3}_{\text{Trilinear self-coupling}} + \underbrace{\frac{\lambda}{4} H^4}_{\text{Quartic self-coupling}}$$

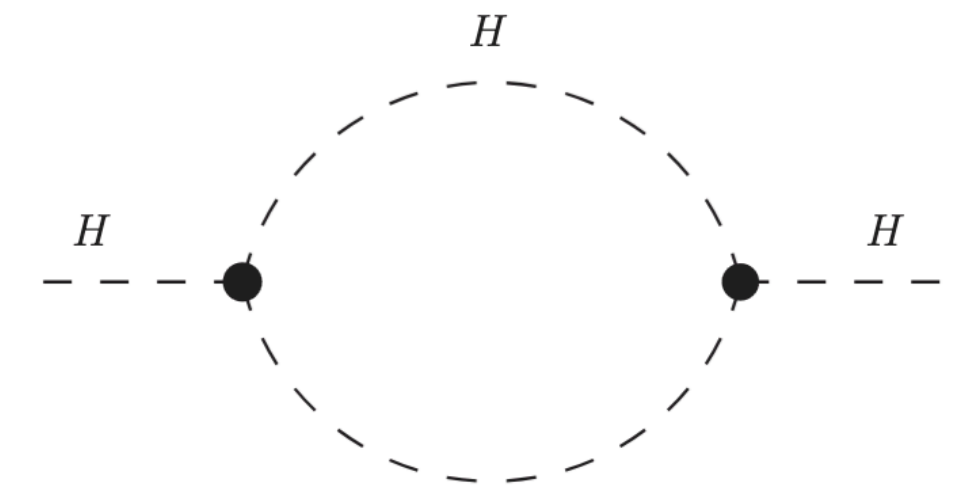
$$m_H = 125.13 \pm 0.11 \text{ GeV}$$

PDG 2026

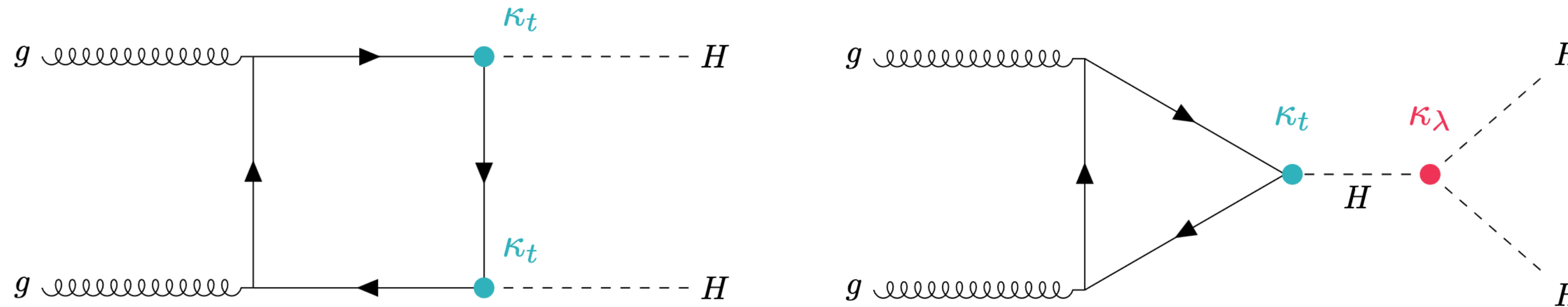


- Higgs self-interaction:**

- Indirect constraints:** higher-order effects in single-Higgs production.
- Direct constraints:** Higgs boson pair (HH) production.

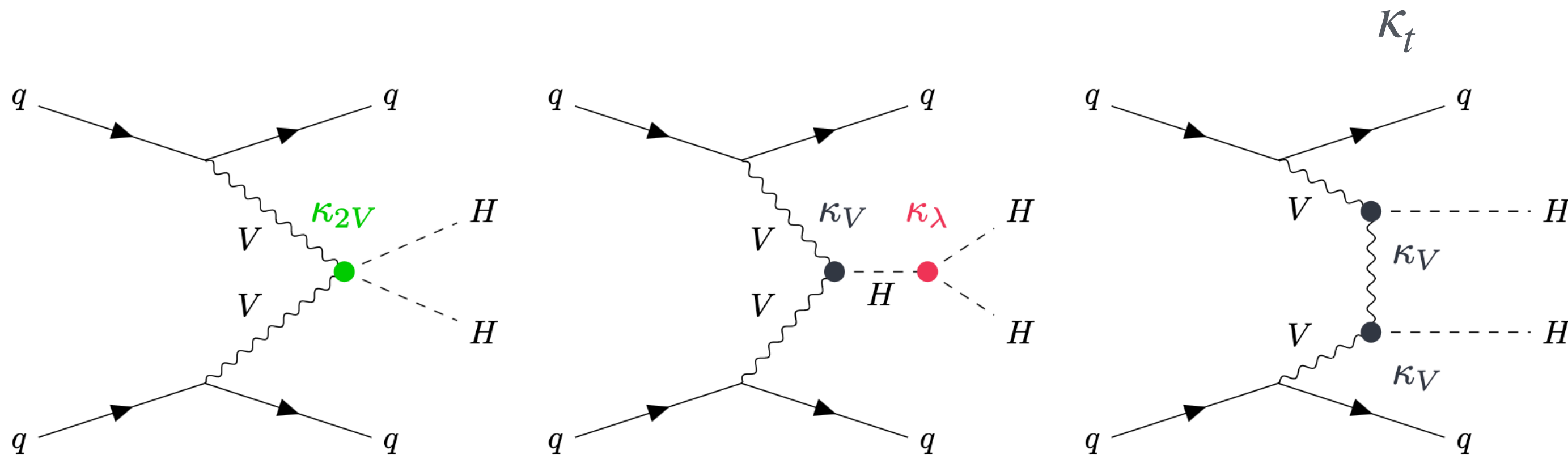


- ggF HH— dominant production mode:** $\sigma_{HH}^{\text{ggF}}(13 \text{ TeV}) \approx 31 \text{ fb}$, $\sigma_{HH}^{\text{ggF}}(13.6 \text{ TeV}) \approx 34 \text{ fb}$



- Sensitive to the Higgs self-coupling κ_λ .
- Sensitive to top-Yukawa coupling κ_t .

- VBF HH— subleading production mode:** $\sigma_{HH}^{\text{VBF}}(13 \text{ TeV}) \approx 1.7 \text{ fb}$, $\sigma_{HH}^{\text{VBF}}(13.6 \text{ TeV}) \approx 1.9 \text{ fb}$



- Characterised by two energetic forward jets.
- Sensitive to κ_{2V} , κ_λ and κ_V

- BSM:** Modified couplings can significantly enhance the non-resonant HH production rate.

$$\kappa_\lambda \neq 1, \quad \kappa_t \neq 1, \quad \kappa_{2V} \neq 1$$

Why $b\bar{b}\tau^+\tau^-$?

Complementary HH final states

- Large branching fraction $\leftrightarrow$ clean experimental signature
- Different channels provide complementary sensitivity

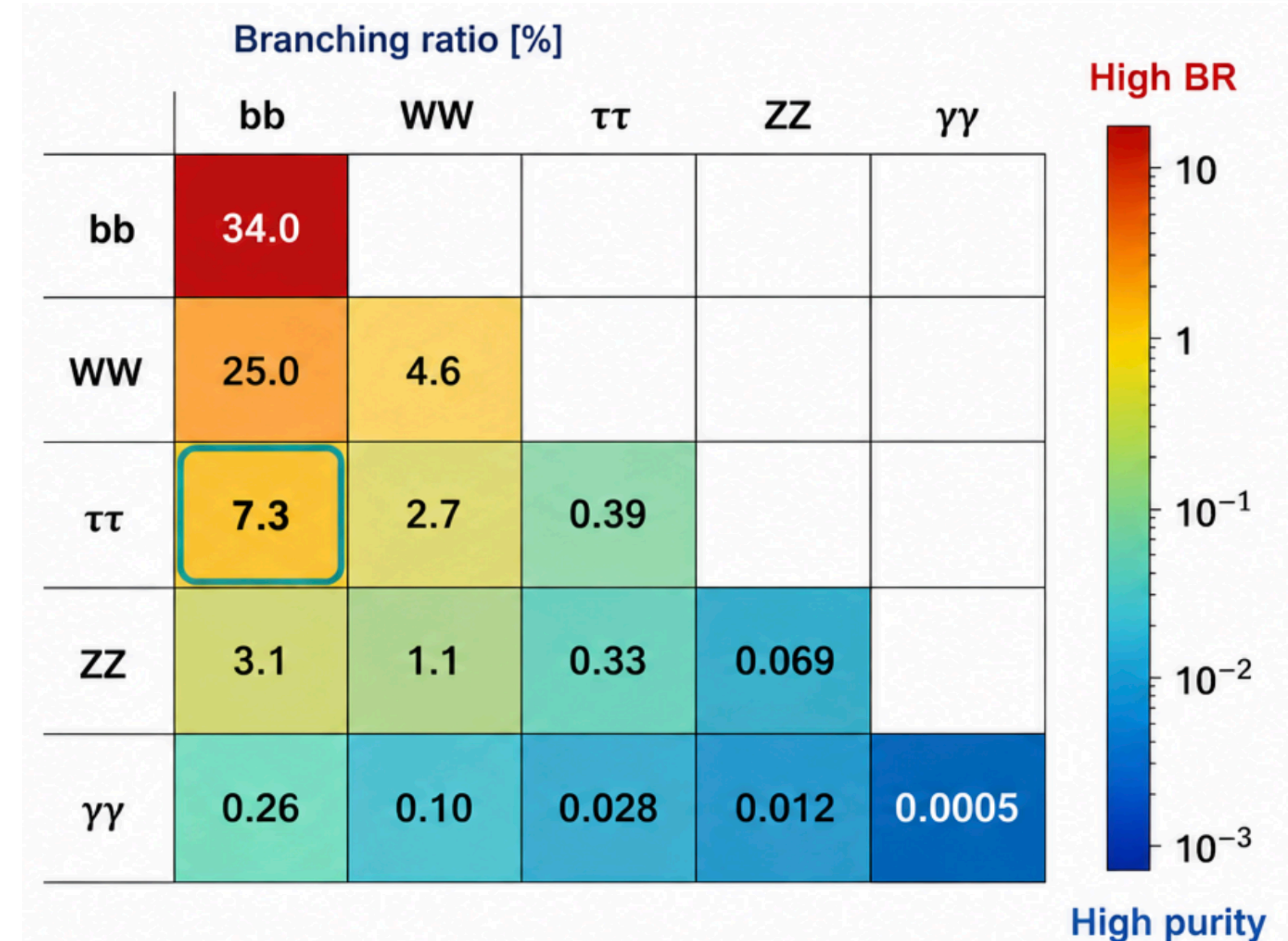
$HH \rightarrow b\bar{b}\tau^+\tau^-$

- **Sizeable branching fraction: $\sim 7.3\%$**
- Good balance between signal yield and background rejection
- Combines $H \rightarrow b\bar{b}$ high BR with $H \rightarrow \tau^+\tau^-$ clean signature

$b\bar{b}b\bar{b}$ — Highest branching fraction, analyses provide strong sensitivity to κ_{2V} .

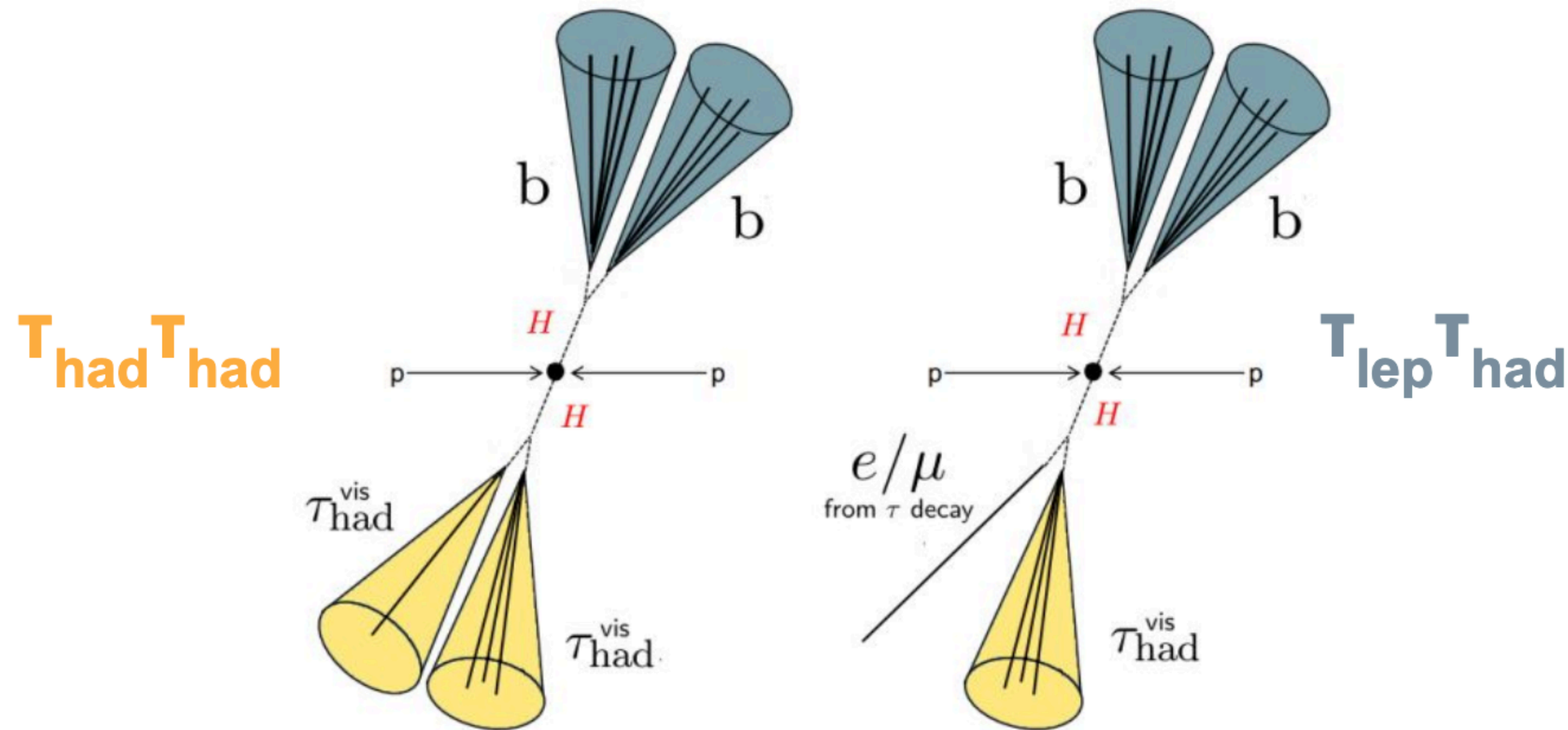
$b\bar{b}\gamma\gamma$ — Excellent mass resolution and purity, analyses provide strong sensitivity to κ_λ .

$b\bar{b}\tau^+\tau^-$ — Balance of branching fraction and sensitivity, best for μ_{HH}



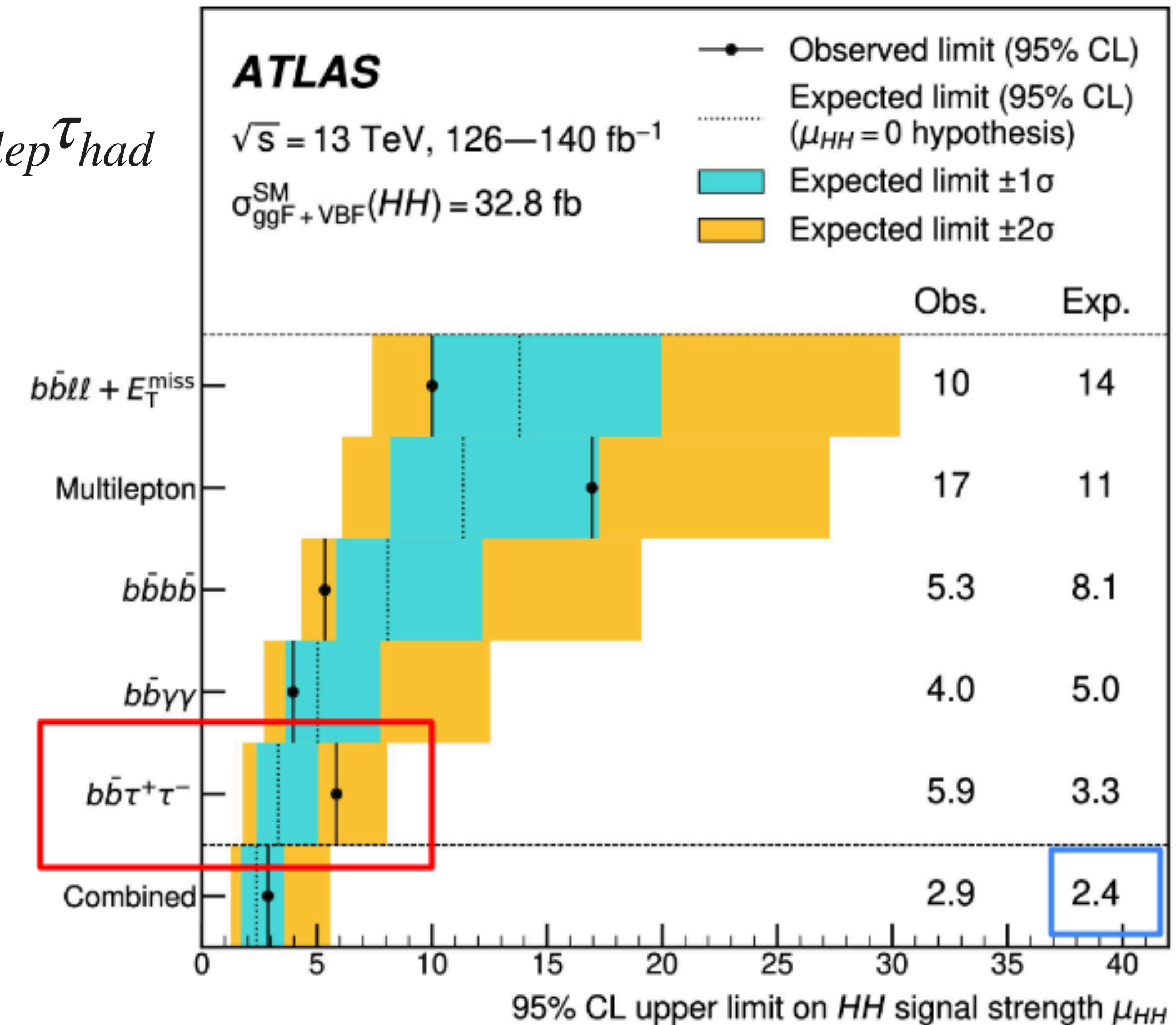
$HH \rightarrow b\bar{b} \tau^+ \tau^-$ Run-2 Legacy [[PhysRevLett.133.101801](#)]:

- One of the leading channels for non-resonant HH searches.
- Expected Run2 limit: $\mu_{HH} < 3.3$ at 95% CL.
- Targeted two complementary final states: $\tau_{had}\tau_{had}$ and $\tau_{lep}\tau_{had}$



Latest ATLAS combination of HH searches

[PhysRevLett.133.101801](#)



$HH \rightarrow b\bar{b} \tau^+ \tau^-$ Most sensitive individual Run-2 analysis to μ_{HH} .

$HH \rightarrow b\bar{b}\tau^+\tau^-$: What Is New?

CERN-EP-2026-227

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)



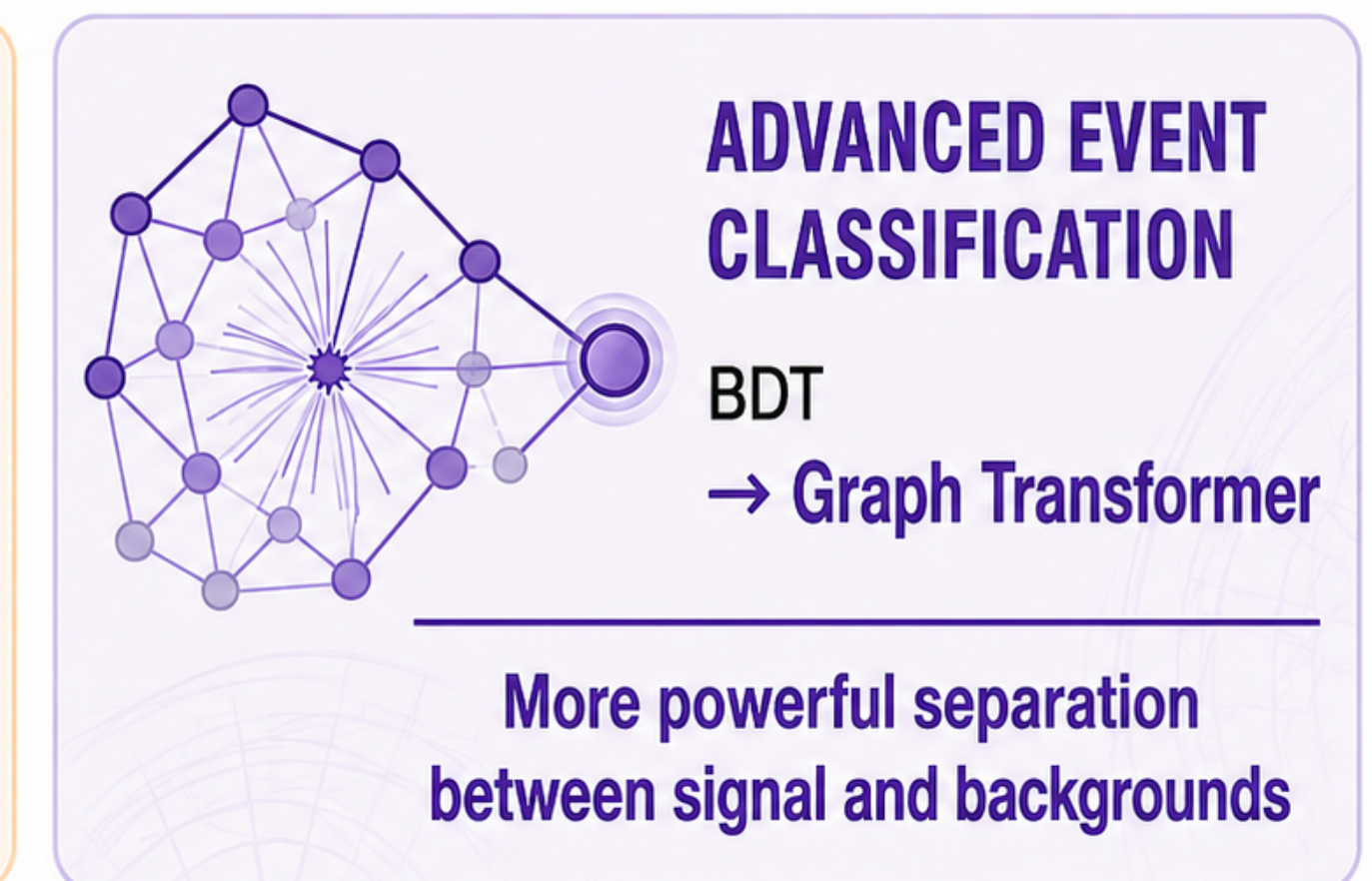
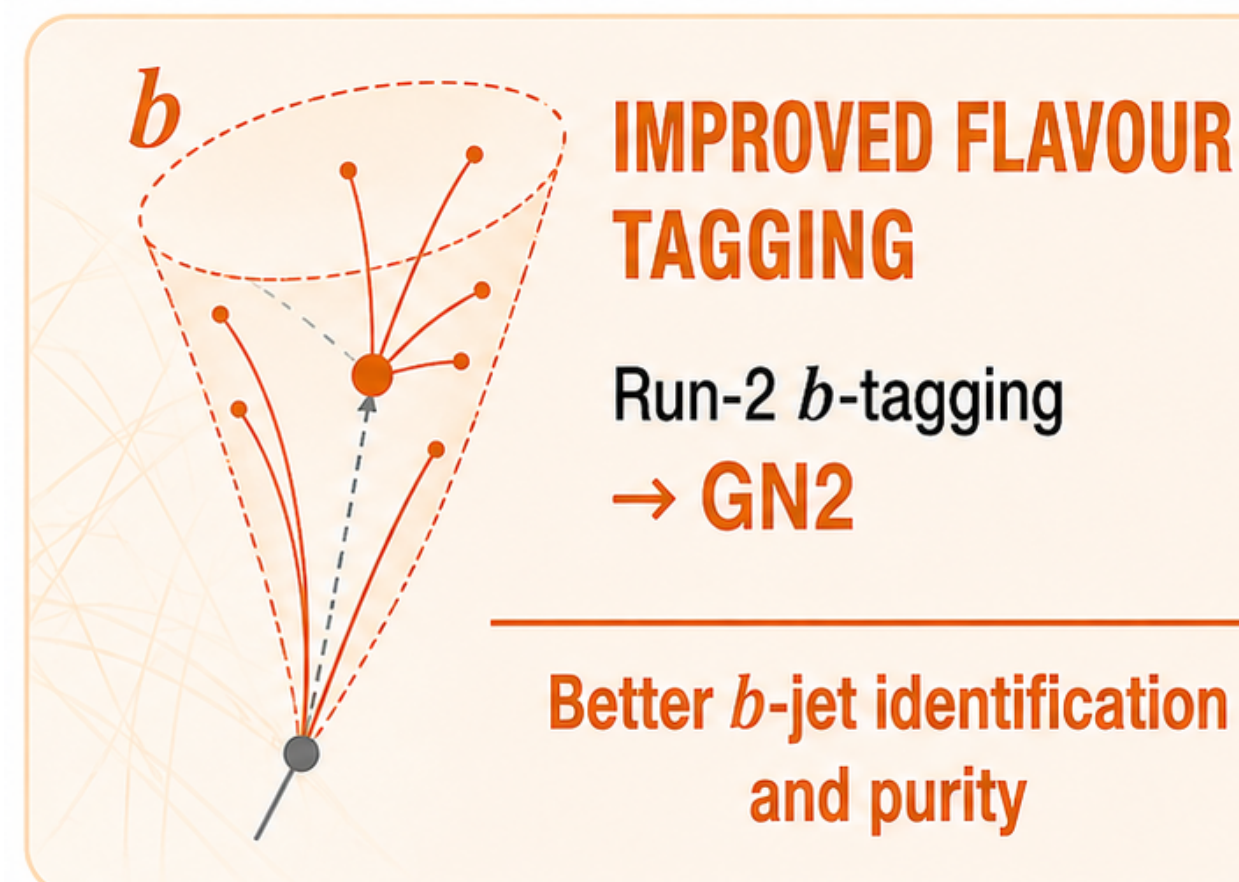
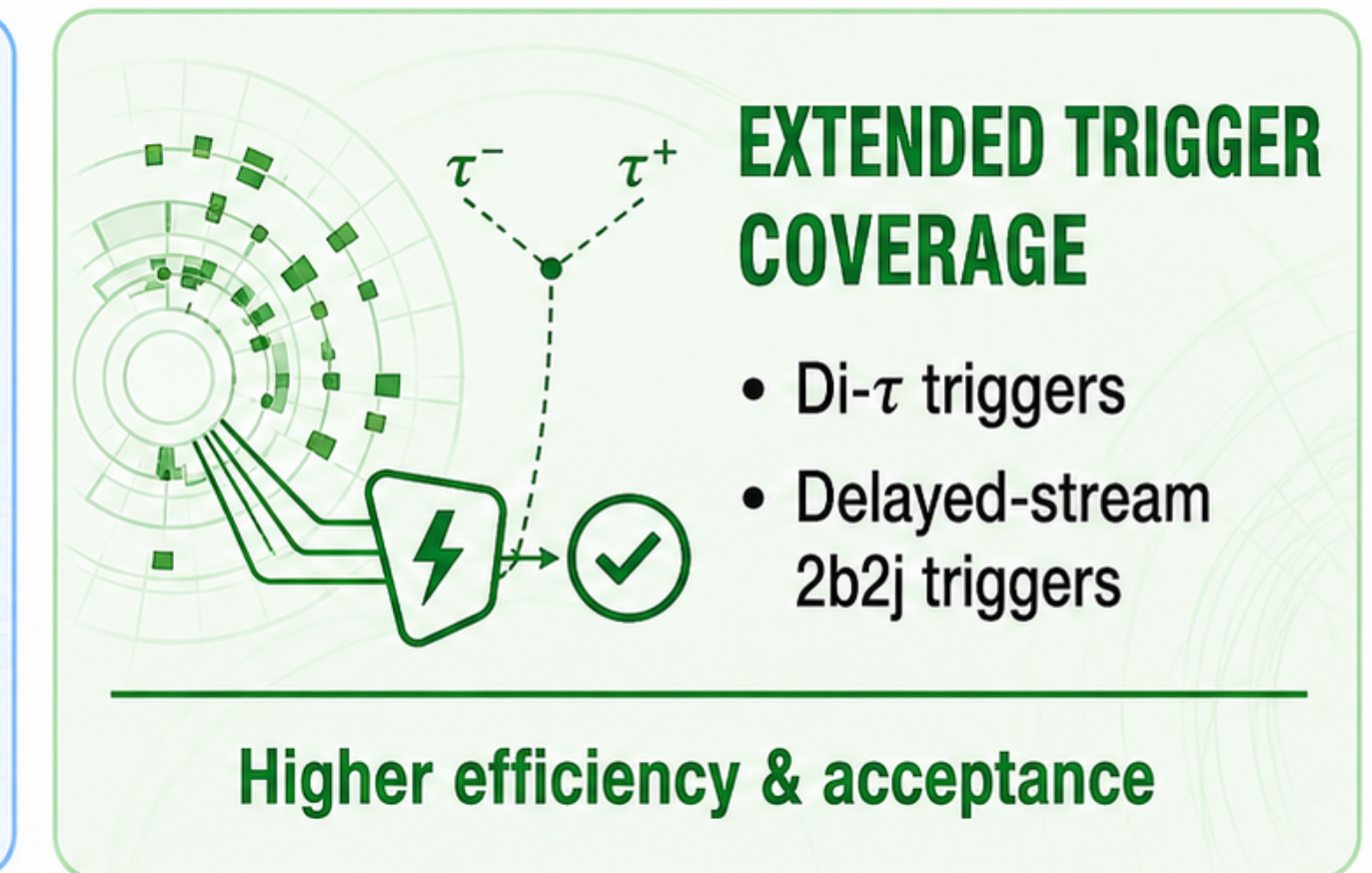
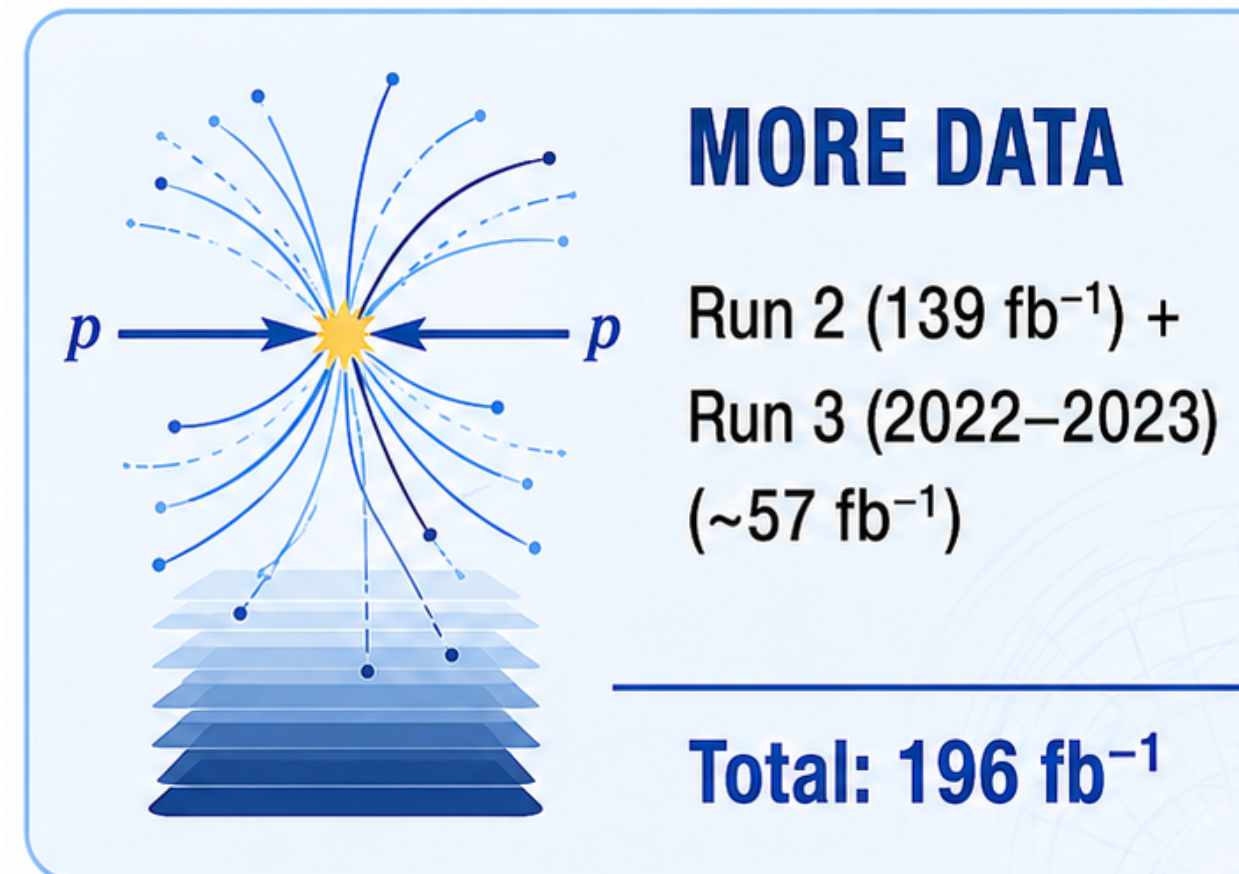
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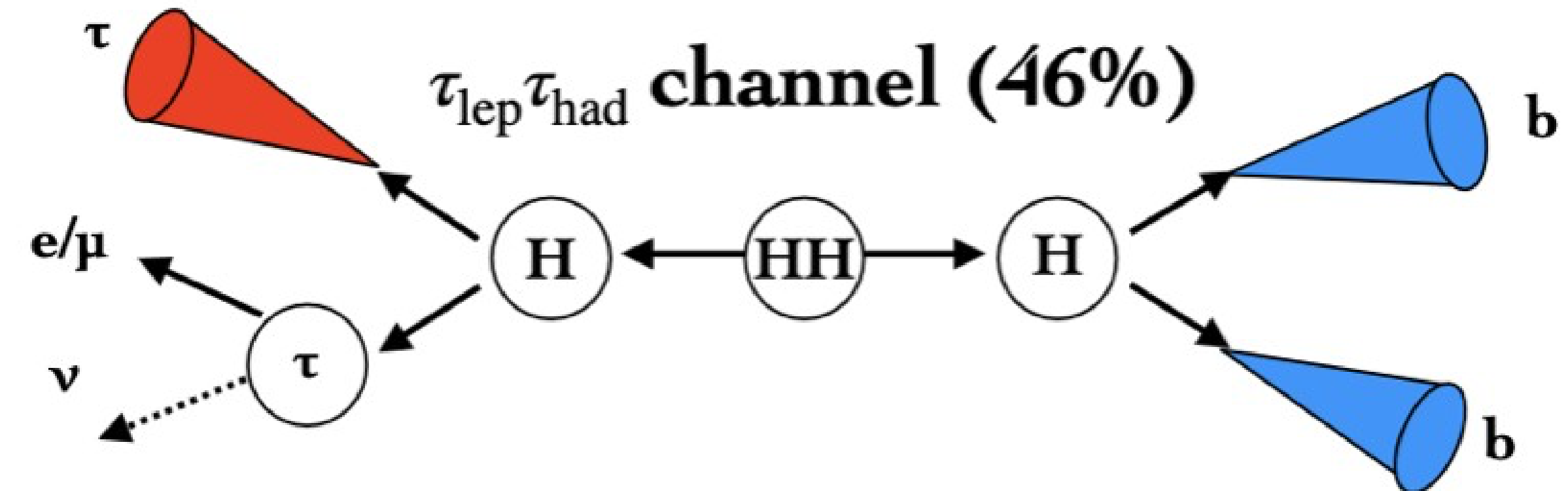
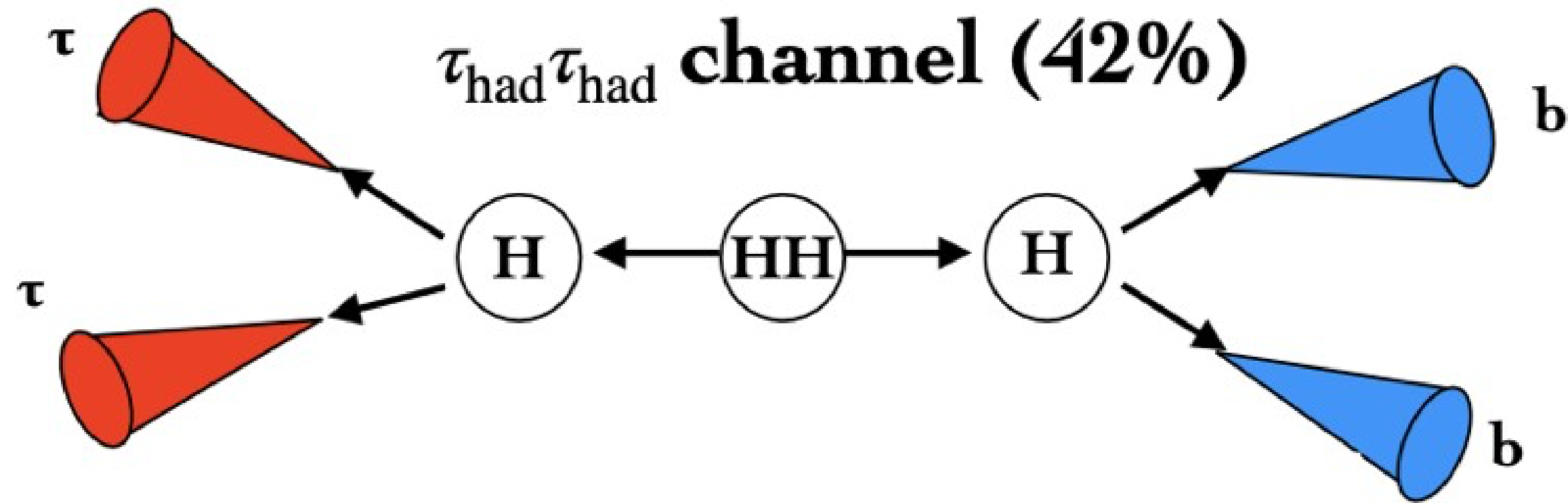
CERN-EP-2026-227
30th July 2026

Improved analysis of non-resonant Higgs boson pair production in the $b\bar{b}\tau^+\tau^-$ final state with 196 fb^{-1} of data collected at $\sqrt{s} = 13\text{ TeV}$ and 13.6 TeV with the ATLAS detector

The ATLAS Collaboration



Improve sensitivity to non-resonant HH production and Higgs-coupling interpretations



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

- Exactly 2 hadronic τ ; no identified e/μ
- Exactly 2 b-tagged jets (GN2, 85% WP)
- Dedicated mbb and $m_{\tau\tau}$ cuts for each SR / CR

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

- Exactly 1 e/μ and 1 τ_{had}
- Exactly 2 b-tagged jets (GN2, 85% WP)
- Dedicated mbb and $m_{\tau\tau}$ cuts for each SR / CR

Common object requirements

Jets: ≥ 2 central jets; leading jet $p_T > 45$ GeV

b-tagging: exactly 2 b-tagged jets (GN2, 85% WP)

Lepton / τ identification and isolation requirements

Ingredients

GN2 b-tagging
85% WP

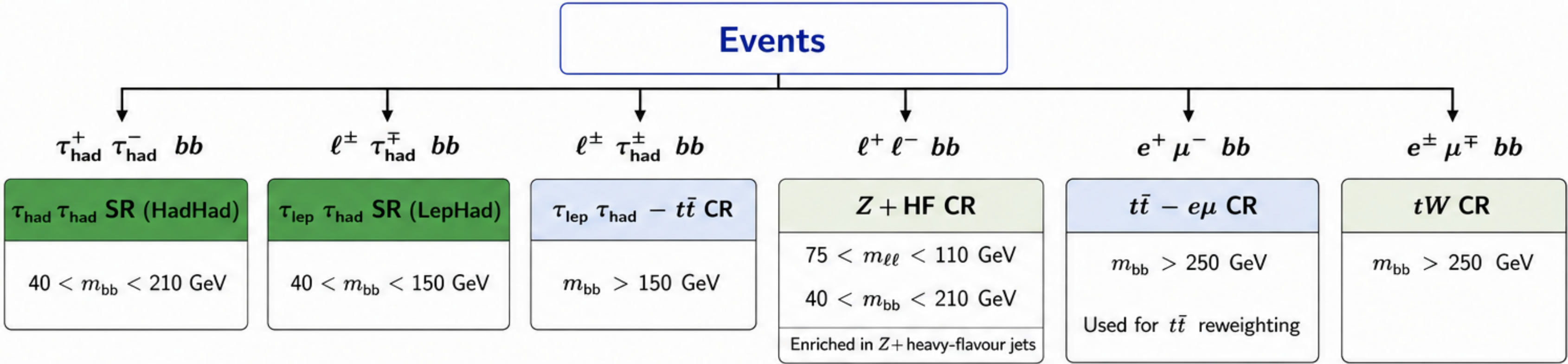
MMC reconstruction
of $m_{\tau\tau}$

Channel-specific*
trigger selection

Preselected events

Before the Signal and Control Region definitions

* Detailed trigger selections are provided in the backup slides



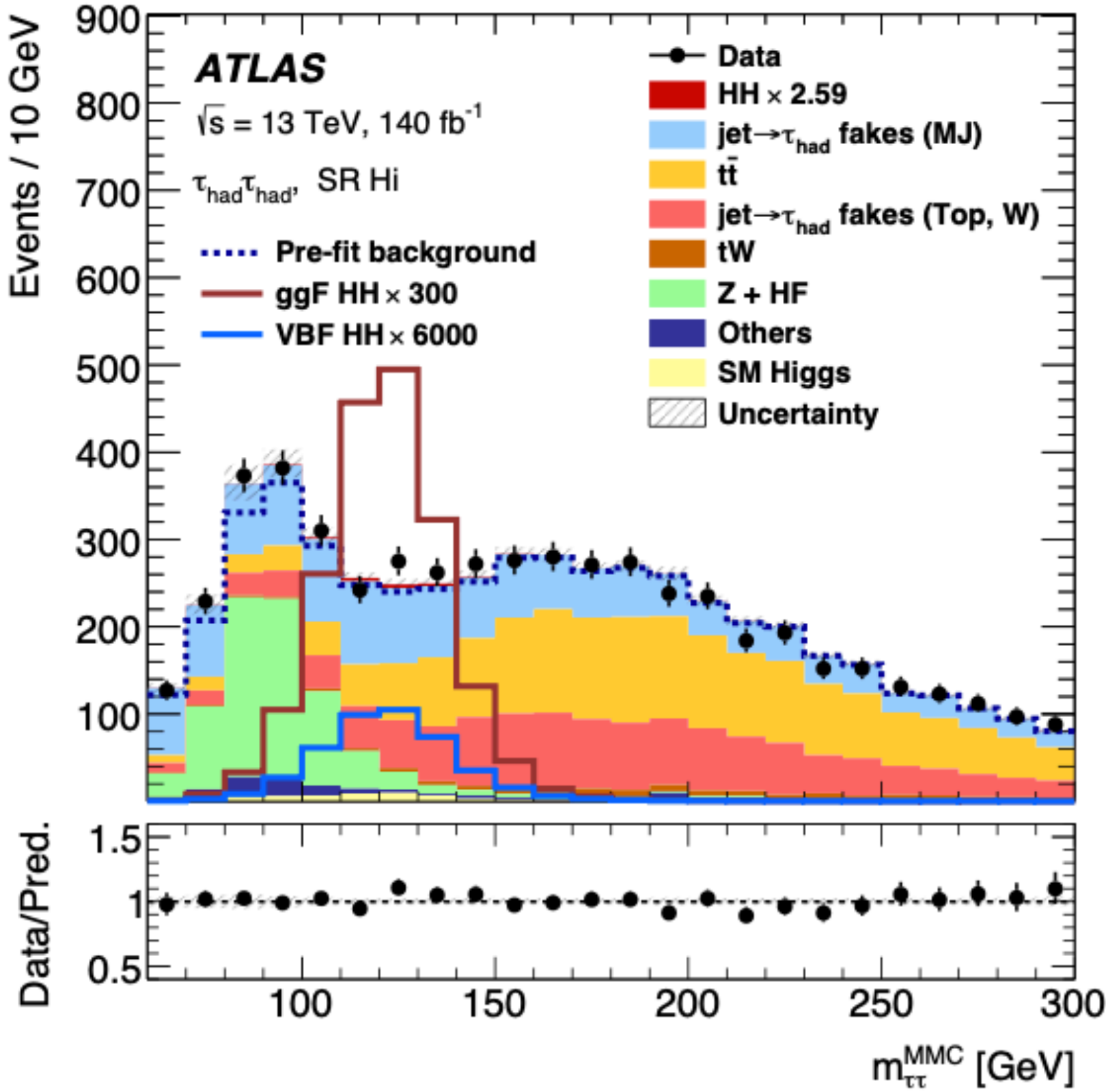
Main backgrounds:

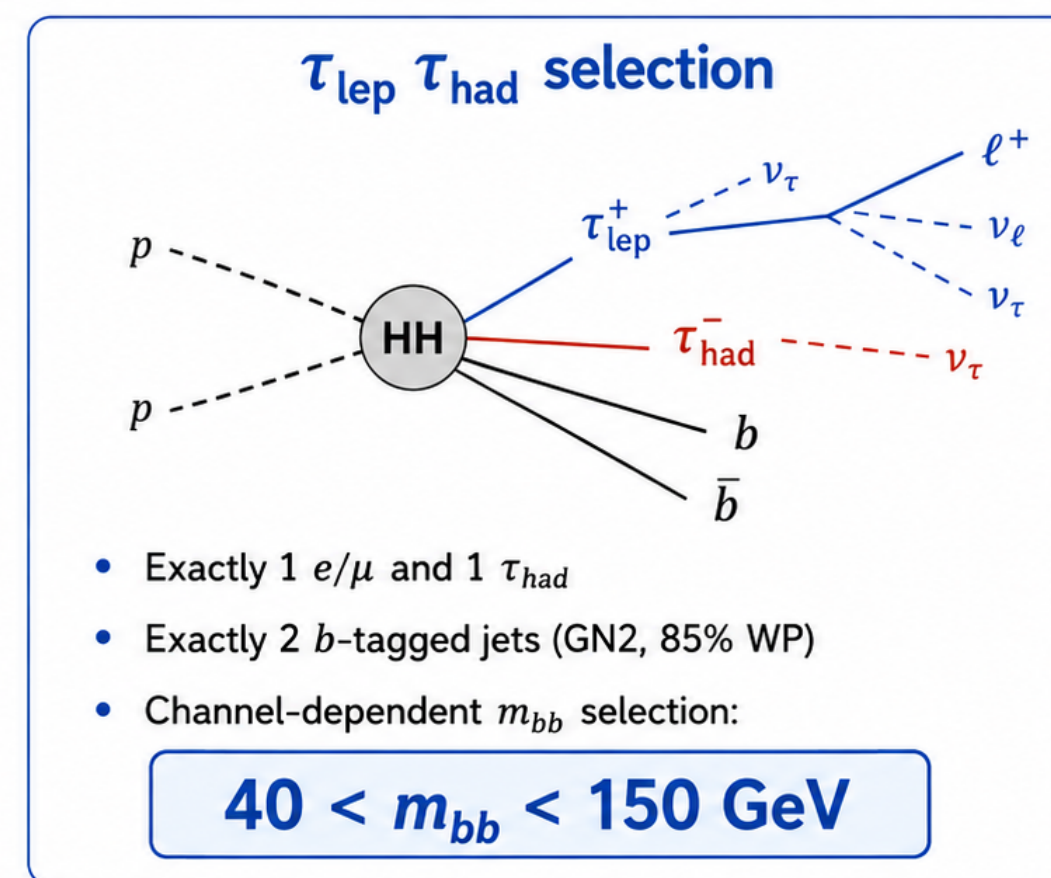
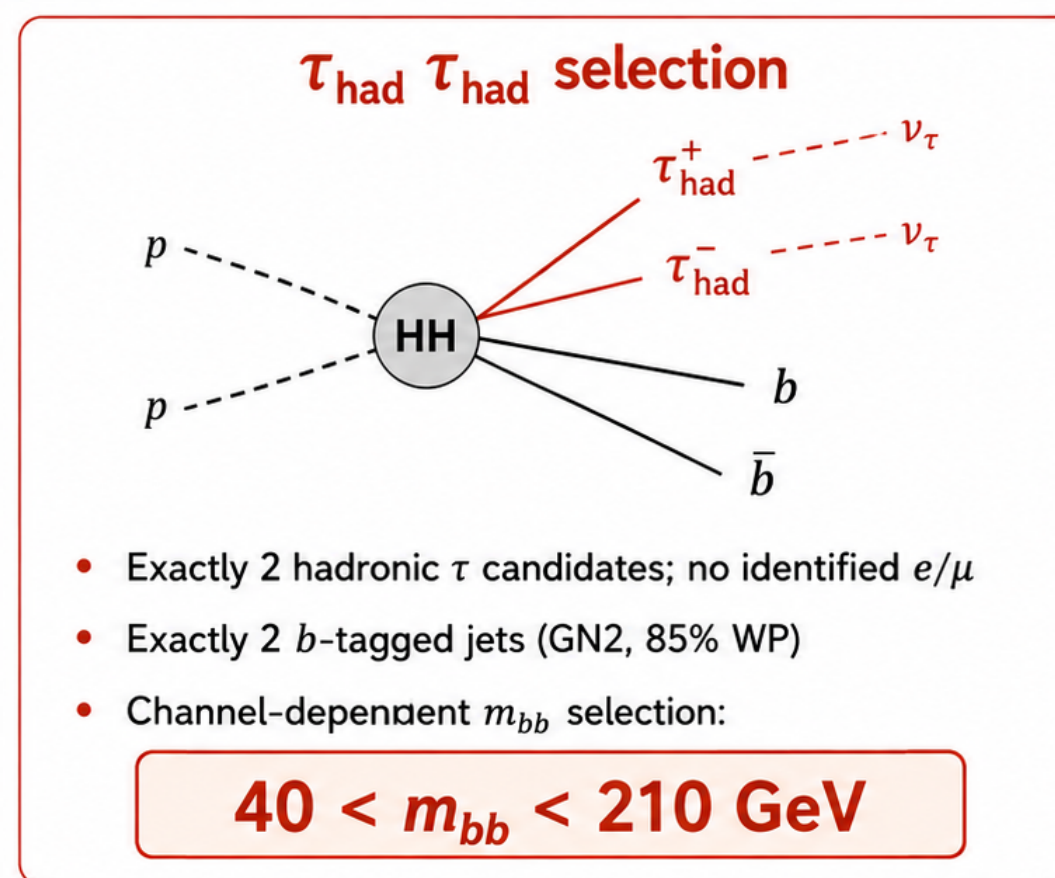
1. $t\bar{t}$, Z+HF.
2. Hadronic jets faking τ_{had}
 - From MJ
 - From $t\bar{t}$ +tW or W
 - (Data driven methods)

SS CR	Same-sign electric charge: $\tau_{\text{had}}^\pm \tau_{\text{lep/had}}^\pm$
1-tag CR	Only 1 b-tagged jet required
Anti- τ_{had} CR	$\tau_{\text{lep/had}}$ + anti- τ_{had}
Multijet CR	e/μ in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel required to fail isolation requirements

These auxiliary CRs are used to estimate/validate jet $\rightarrow$ fake- τ_{had} background

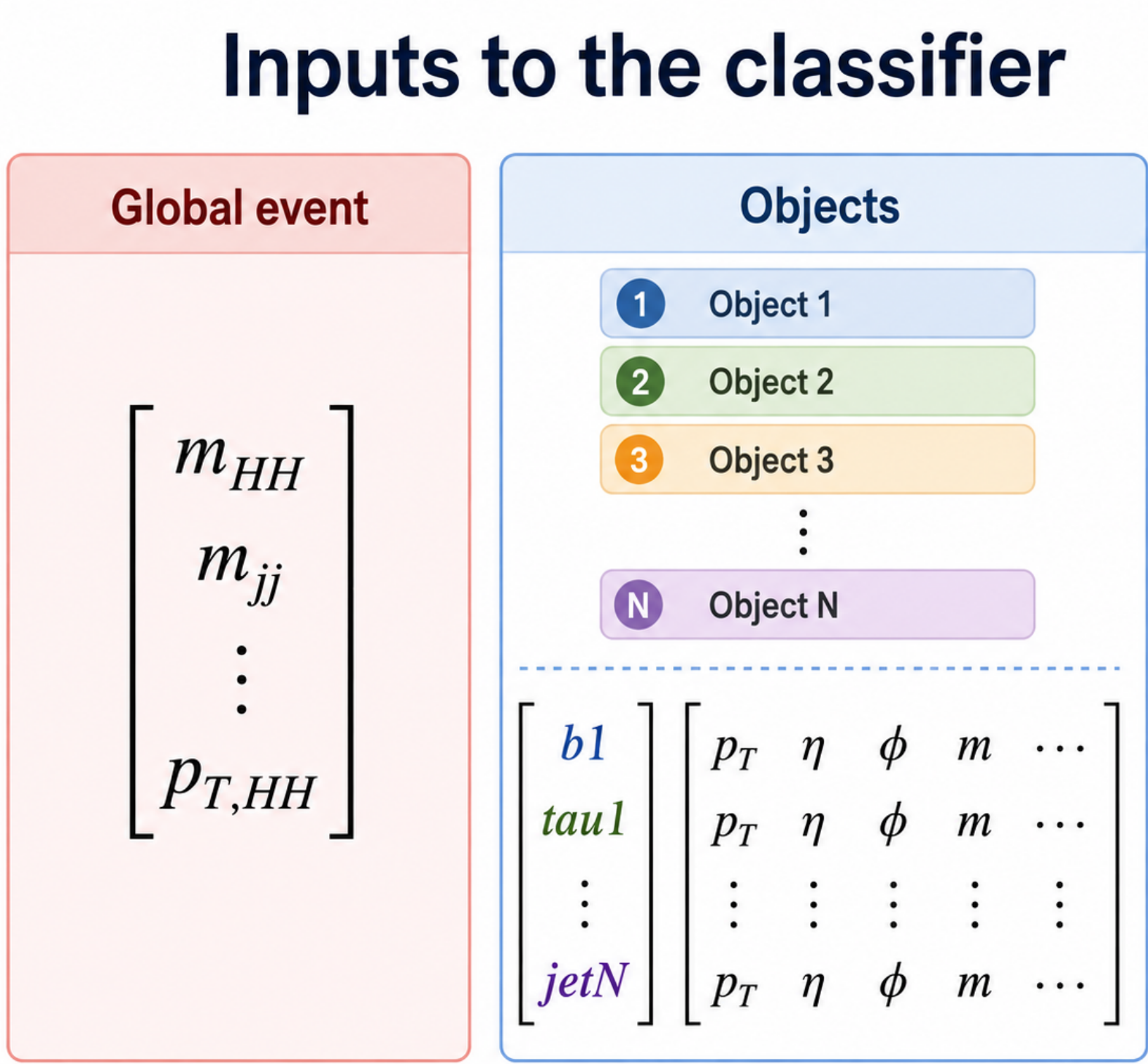
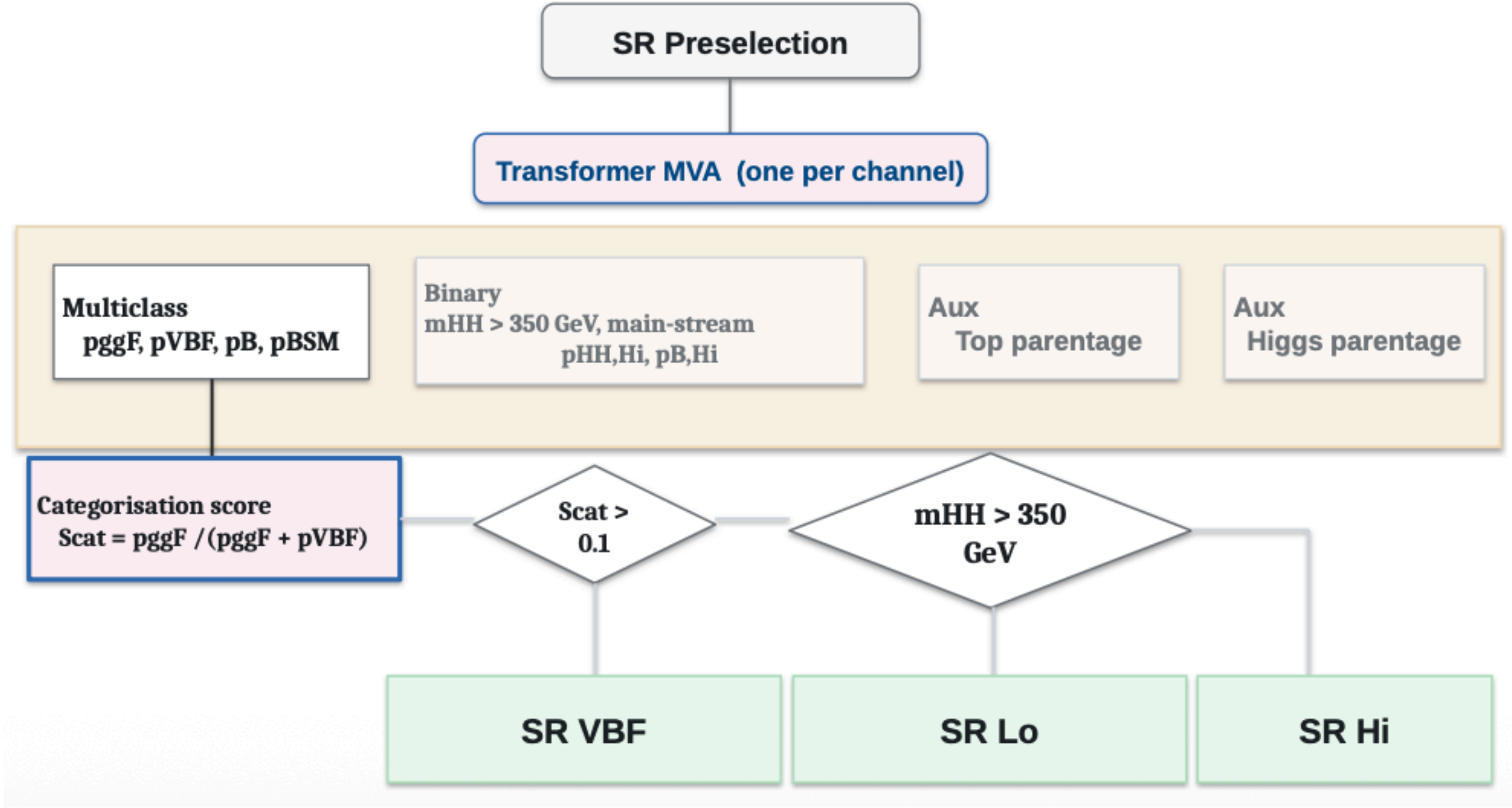
- SRs (signal regions)
- CRs used in the fit
- CRs not used in the fit (auxiliary CRs for fake- τ_{had} estimation/validation or used for $t\bar{t}$ reweighting)





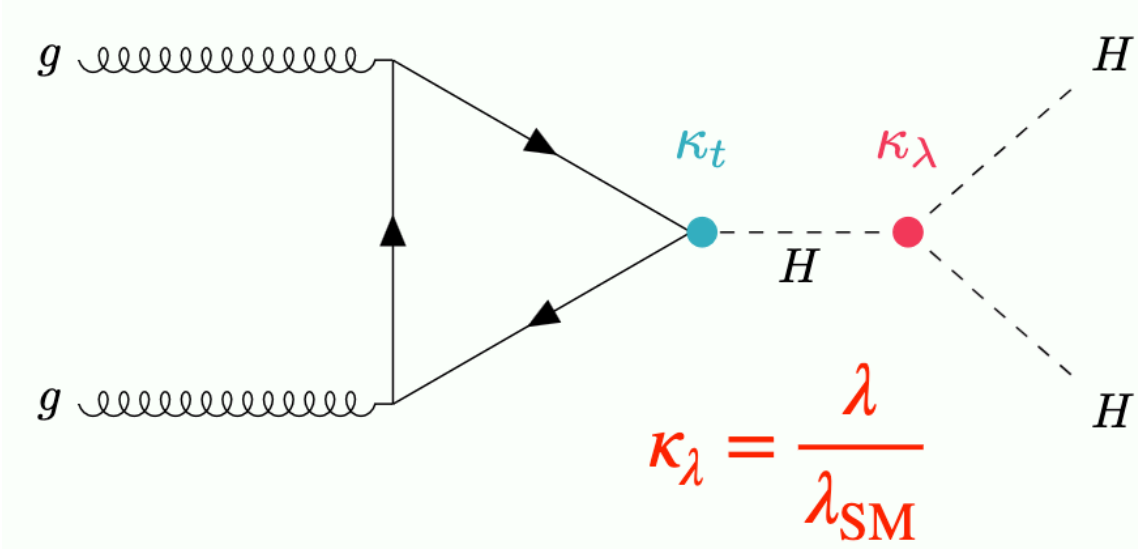
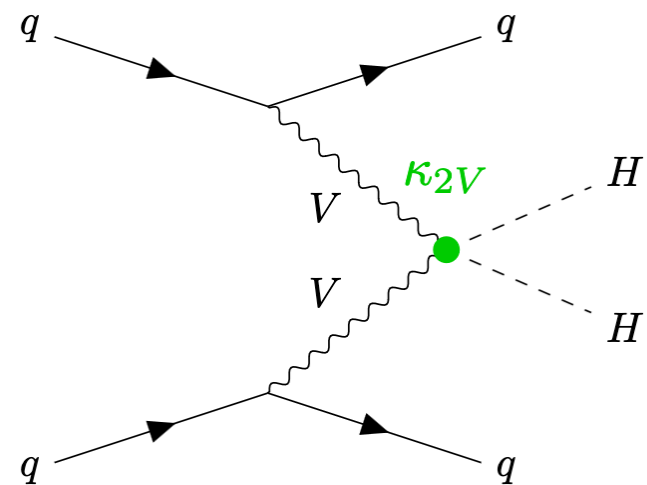
**How we discriminate
 $HH \rightarrow b\bar{b} \tau^+ \tau^-$ signal from
background in the SR?**

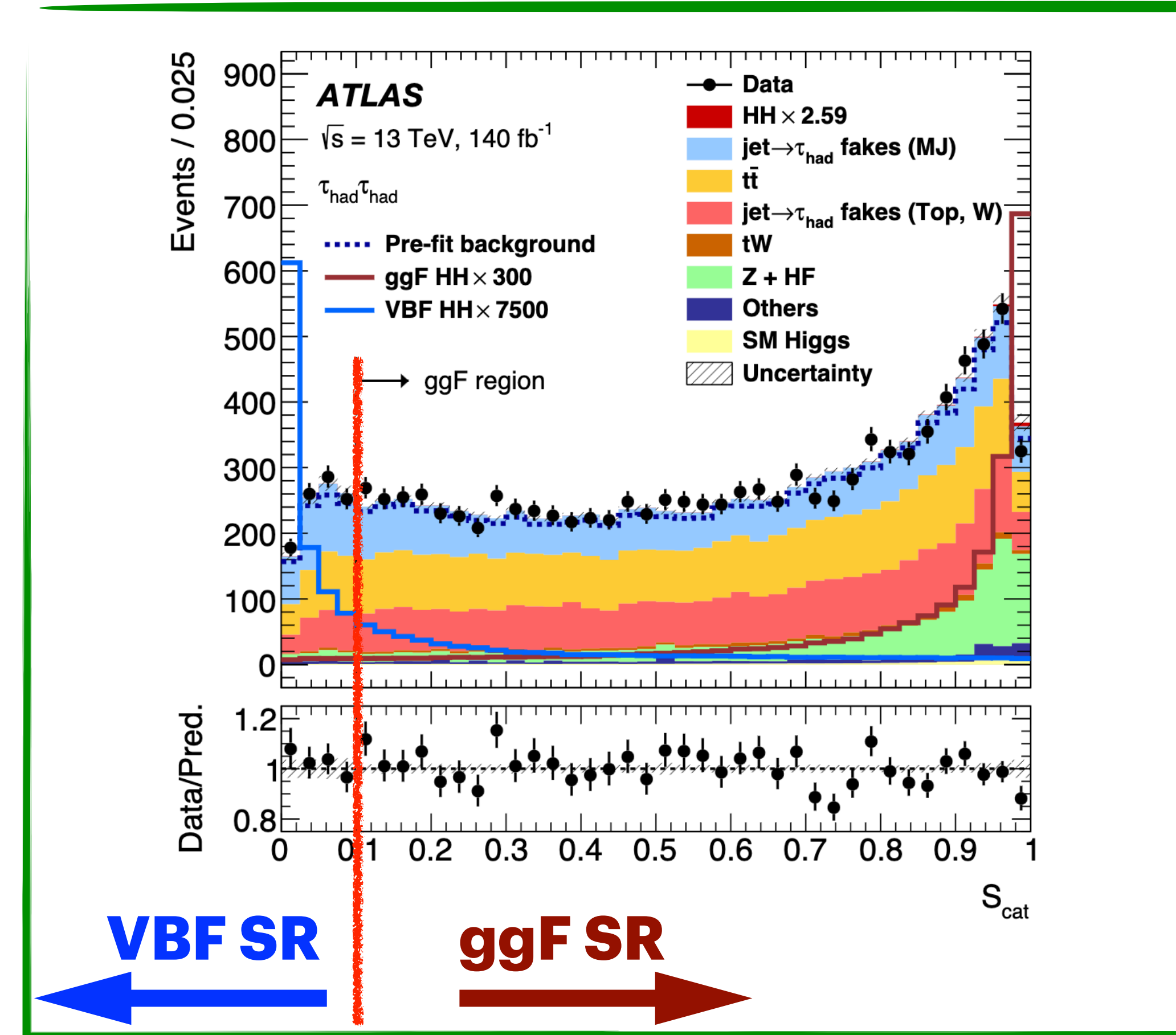
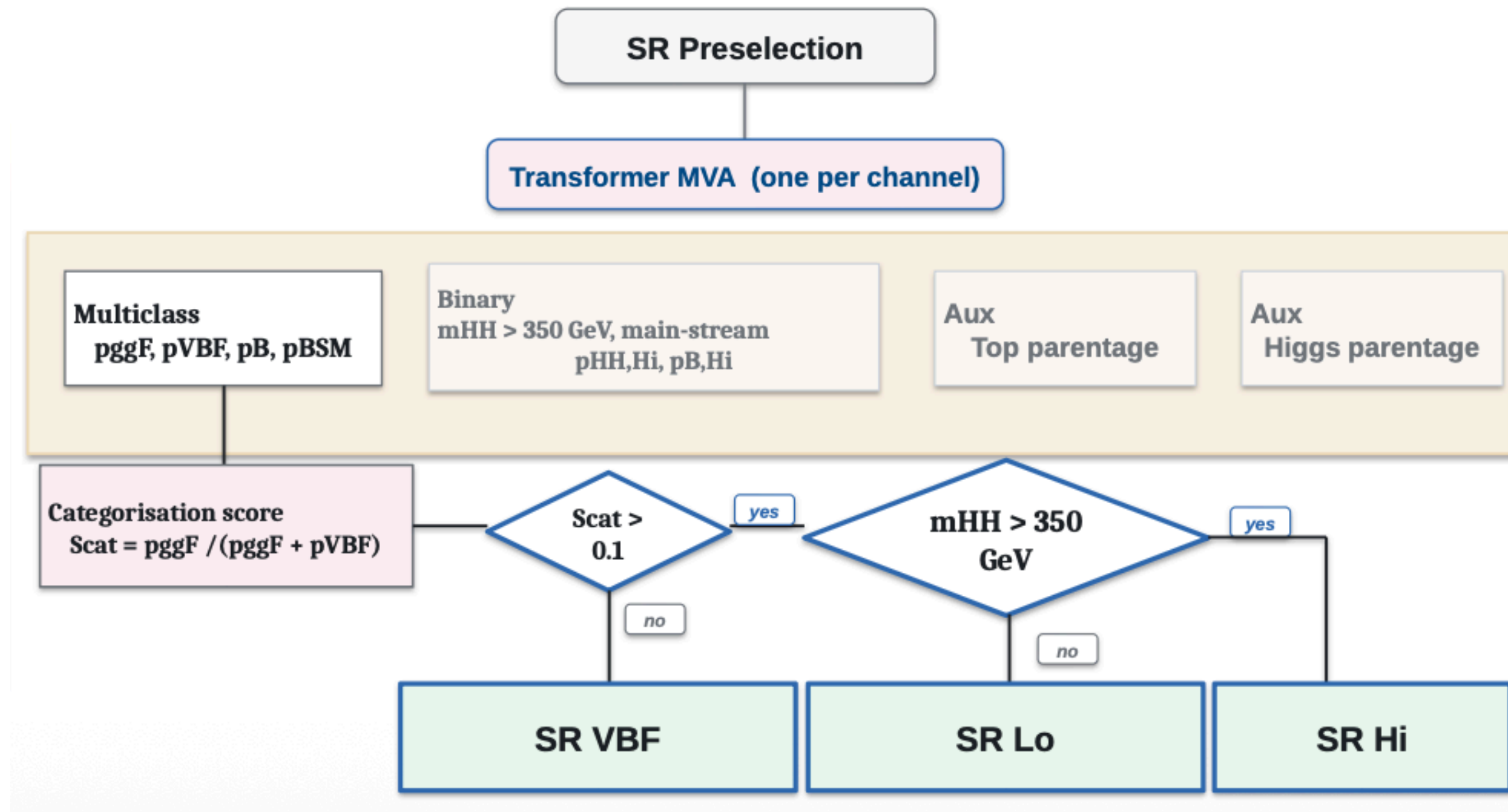




1. Multiclass output used to identify the HH production topology:

- The multiclass outputs are $p_B, p_{ggF}, p_{VBF}, p_{BSM}$.



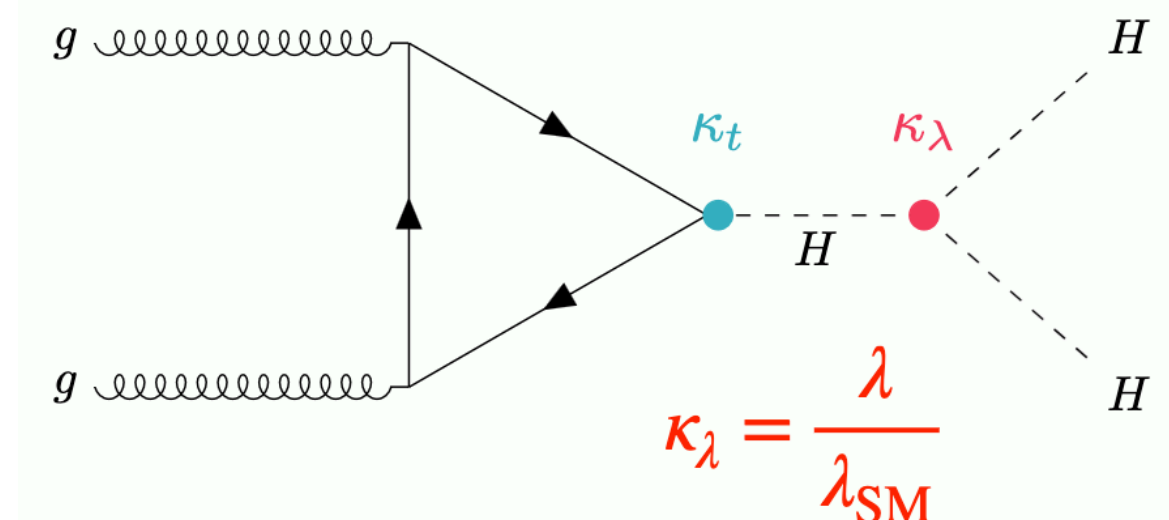
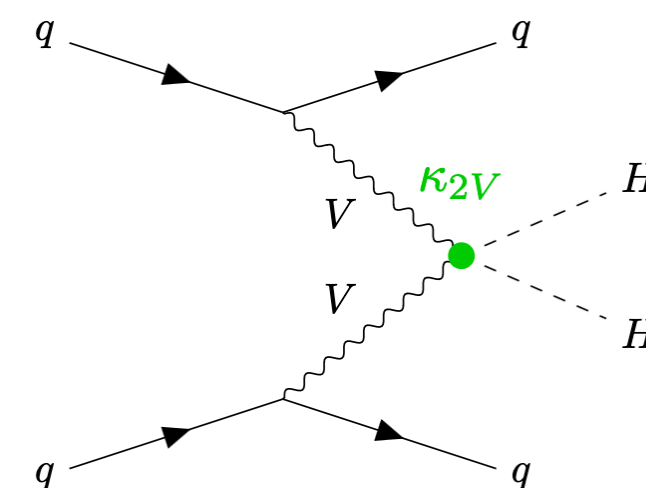


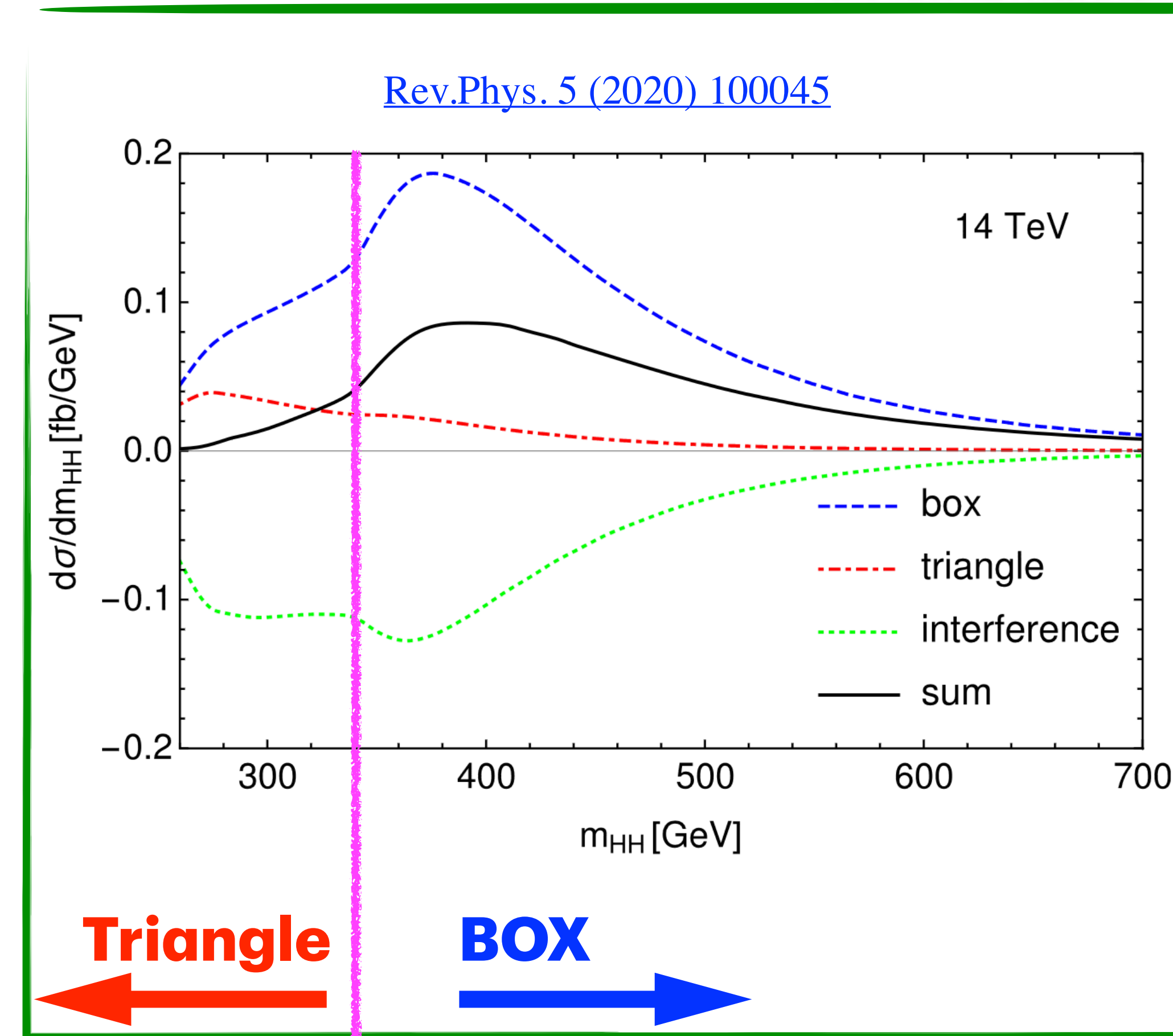
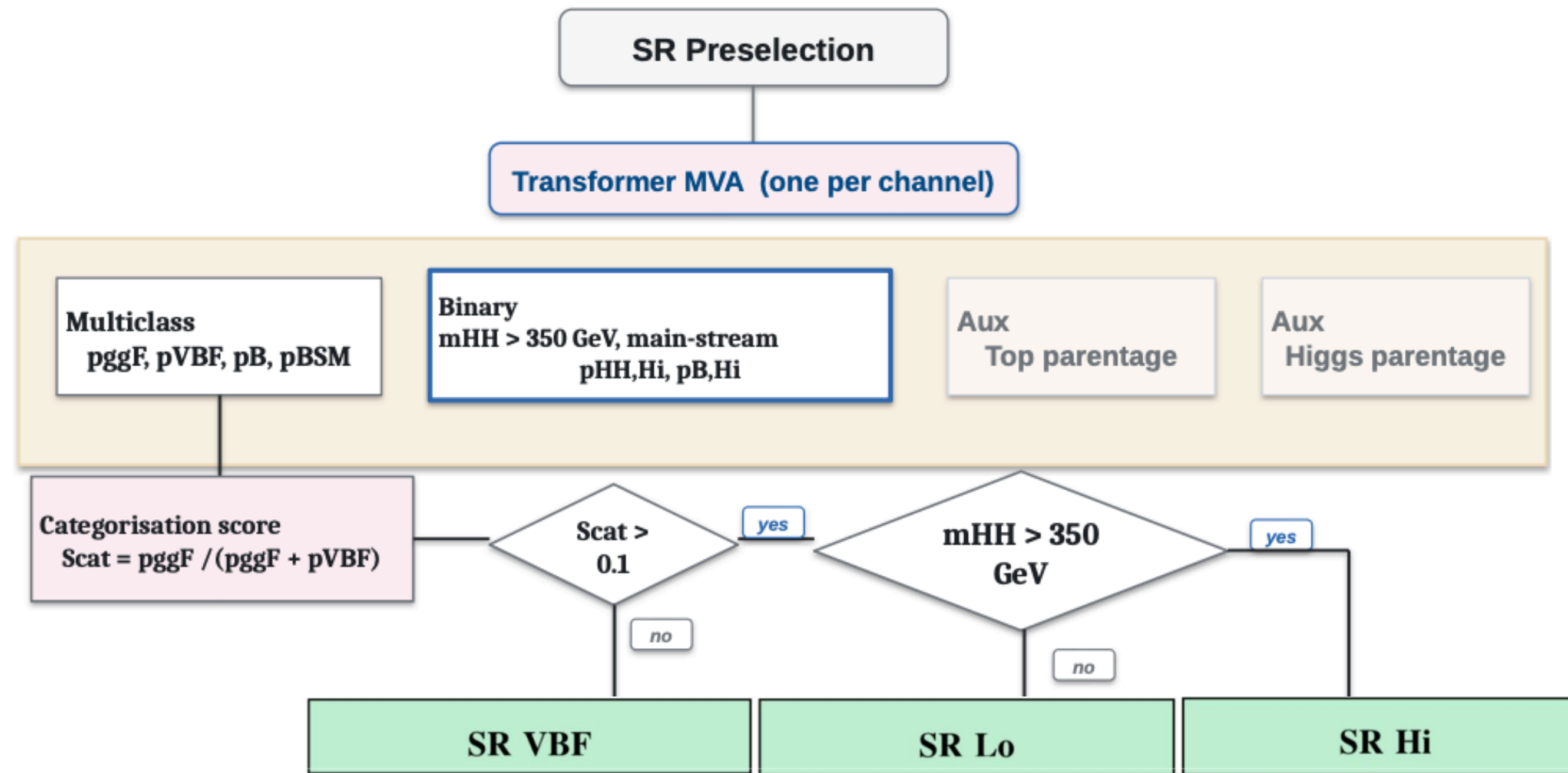
1. Multiclass output used to identify the HH production topolog:

- The multiclass outputs are p_B , p_{ggF} , p_{VBF} , p_{BSM} .
- From the ggF and VBF probabilities we construct the categorisation score S_{cat} :

$$S_{cat} = \frac{p_{ggF}}{p_{ggF} + p_{VBF}}$$

Improve κ_{2V} , and reduce $\kappa_{2V} - \kappa_\lambda$ correlation.

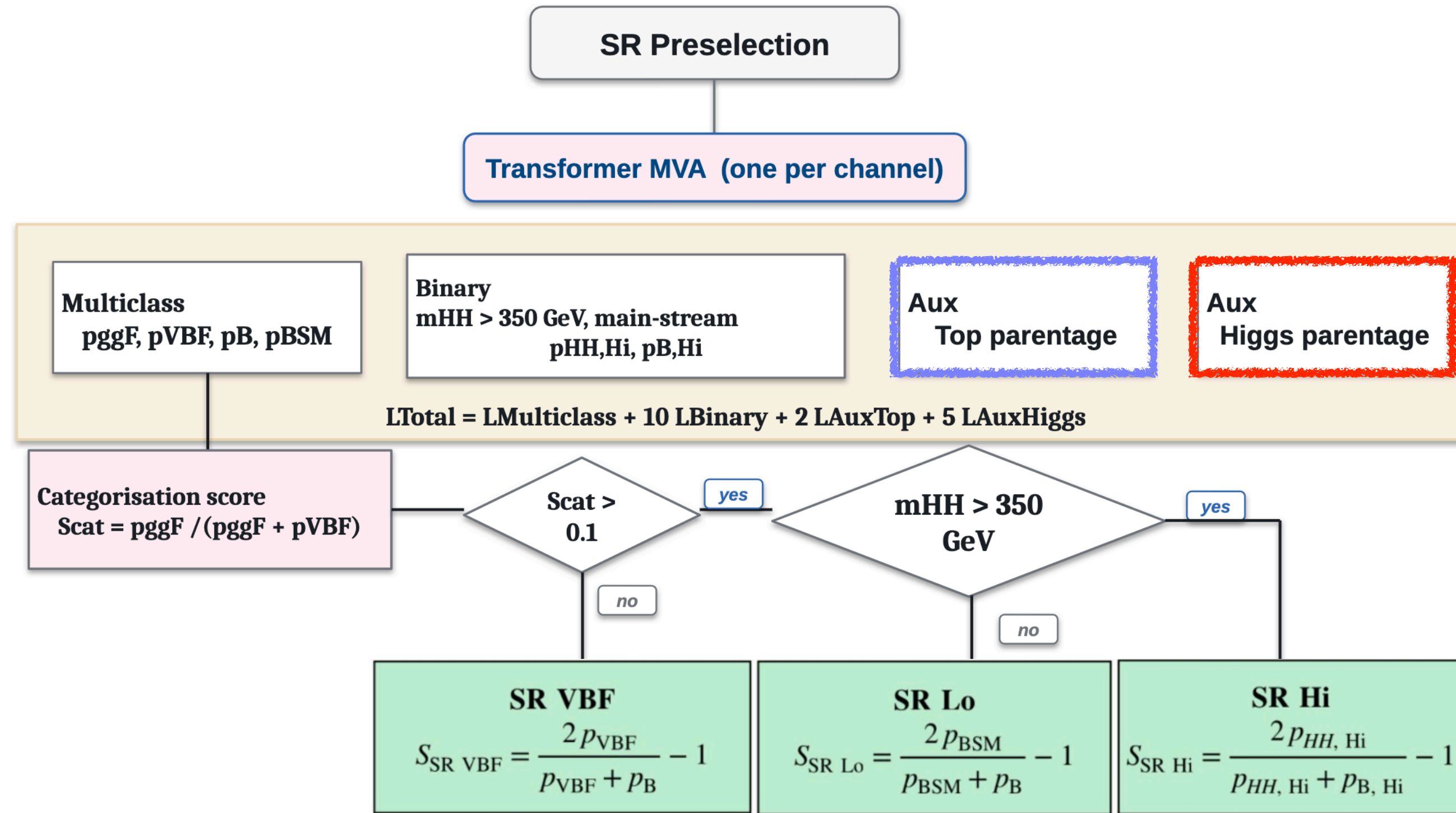




2. Dedicated binary classifier in the most SM-sensitive region:

- It is trained for $m_{HH} > 350$ GeV, Background vs Signal,
- with main-stream-trigger events and output $P_{HH,Hi}$, $P_{B,Hi}$

This additional binary task improves the expected sensitivity by about **10%** in both channels.



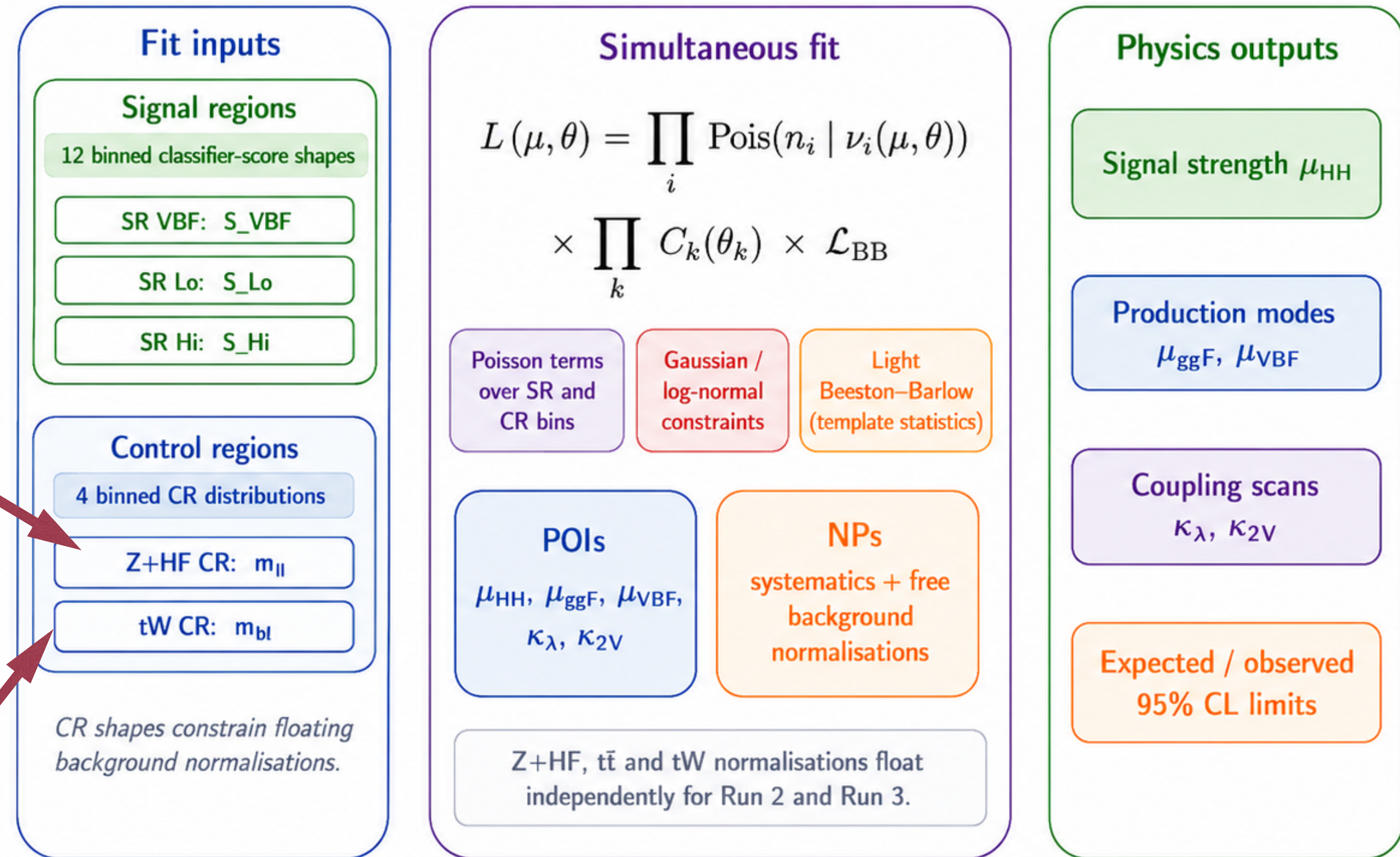
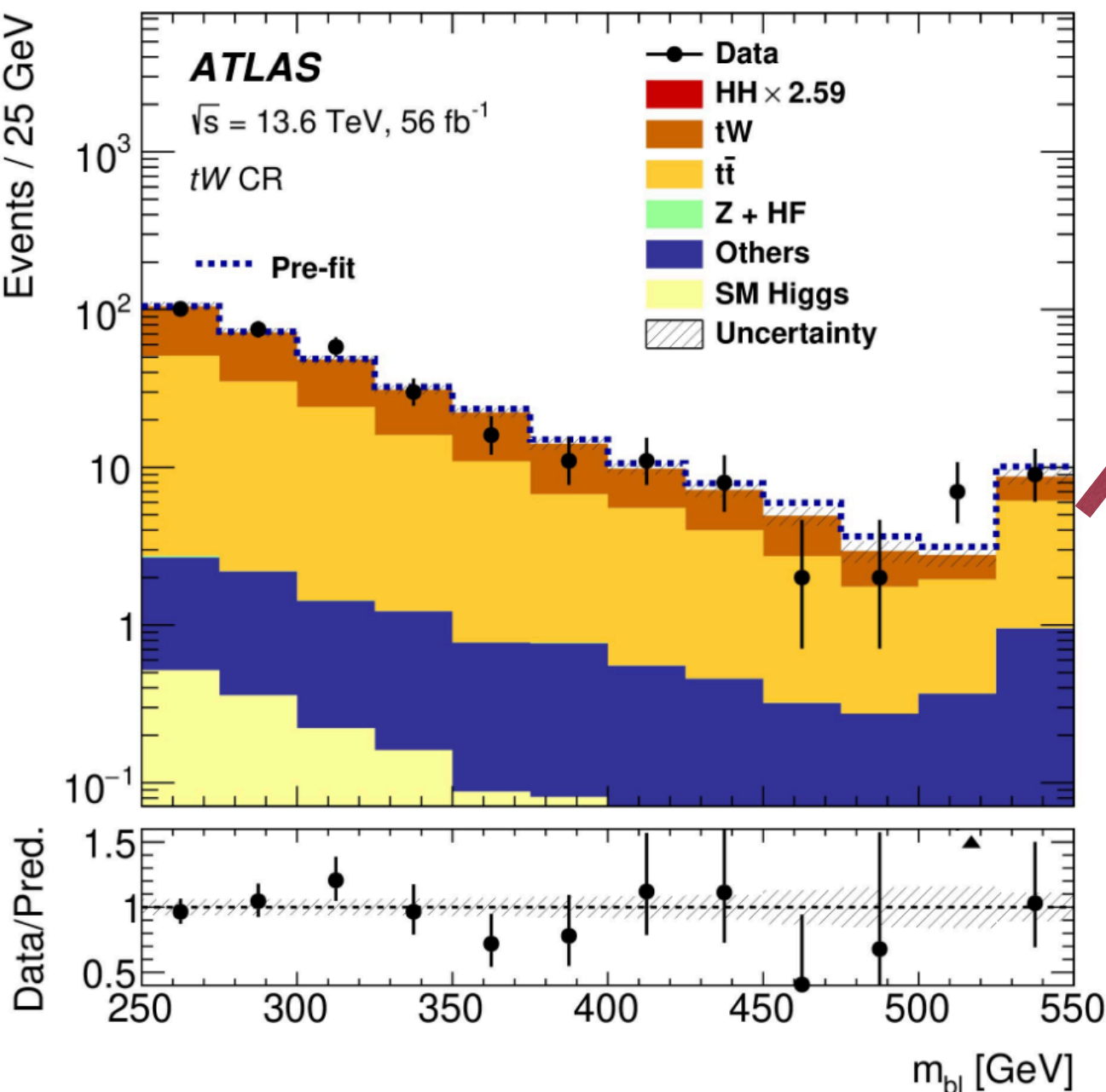
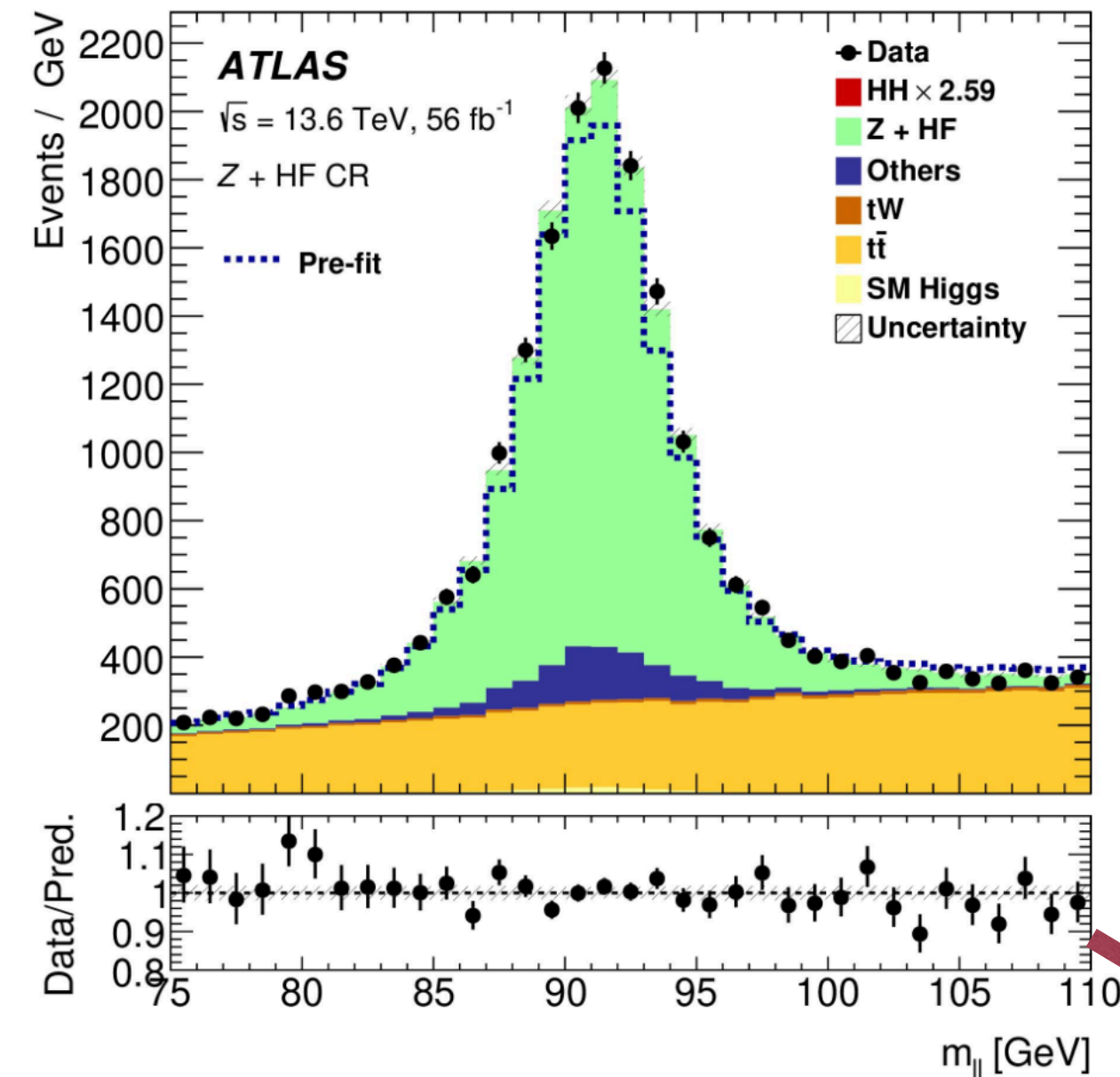
- The Higgs-parentage task teaches the network which objects look compatible with a Higgs decay. Improves sensitivity by roughly **2–10%**
- The top-parentage task helps reject **2-8 %** of $t\bar{t}$ and single-top backgrounds.

3. Multi-task Transformer:

- All four tasks are trained jointly, [Multiclass, Binary, Aux Top, Aux Higgs].

- Three final SR observable are defined: $S_{VBF} = \frac{2p_{VBF}}{p_{VBF} + p_B} - 1$, $S_{Lo} = \frac{2p_{BSM}}{p_{BSM} + p_B} - 1$, $S_{Hi} = \frac{2p_{HH,Hi}}{p_{HH,Hi} + p_{B,Hi}} - 1$

These three scores are the final fit observables: their binned distributions are fitted simultaneously across all signal regions to extract the HH signal strength and coupling constraints



SR shapes provide the signal sensitivity, while CR shapes constrain the dominant backgrounds in one simultaneous fit.



RESULTS

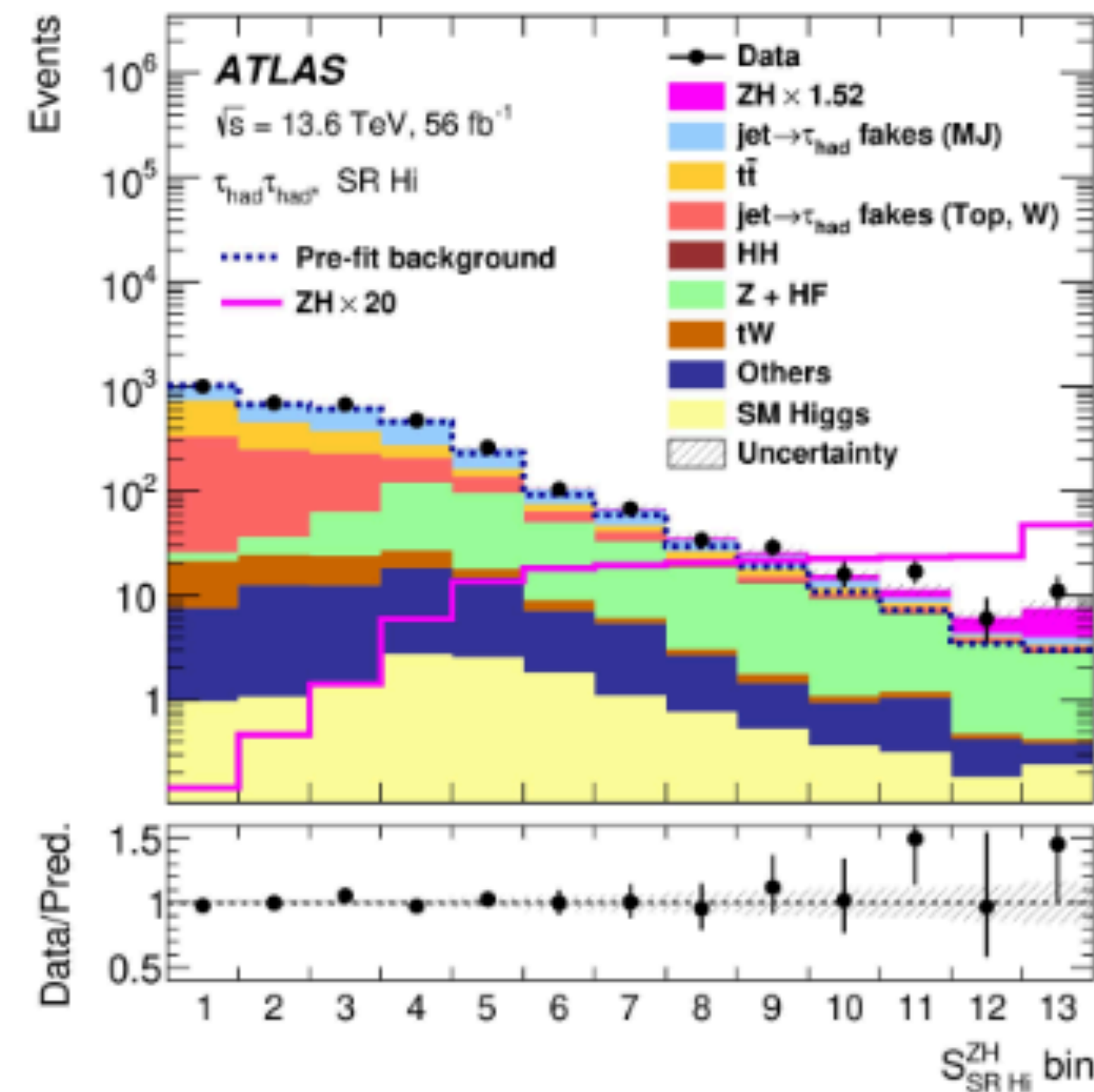
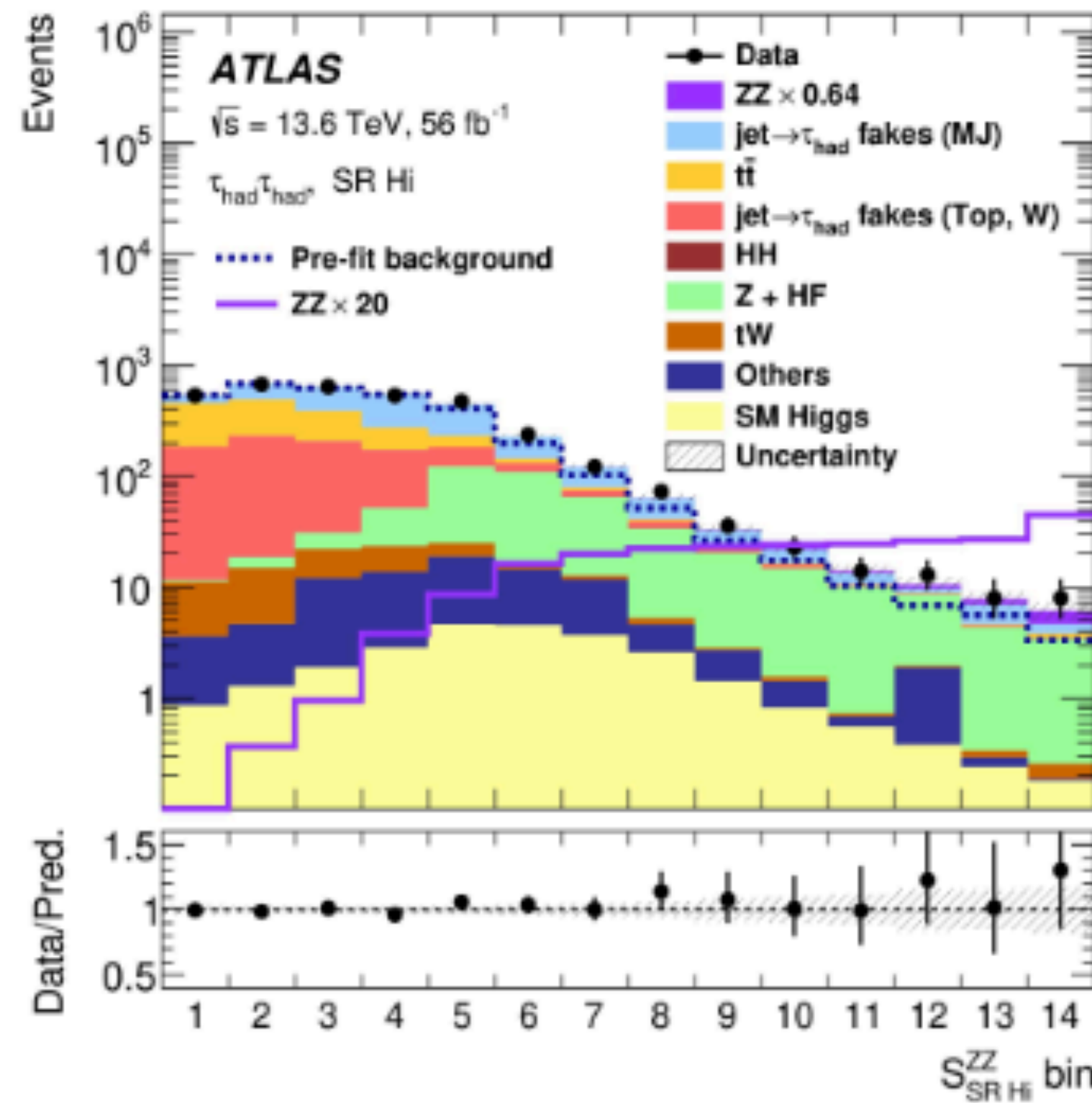
NEW

Limits · coupling interpretation · sensitivity



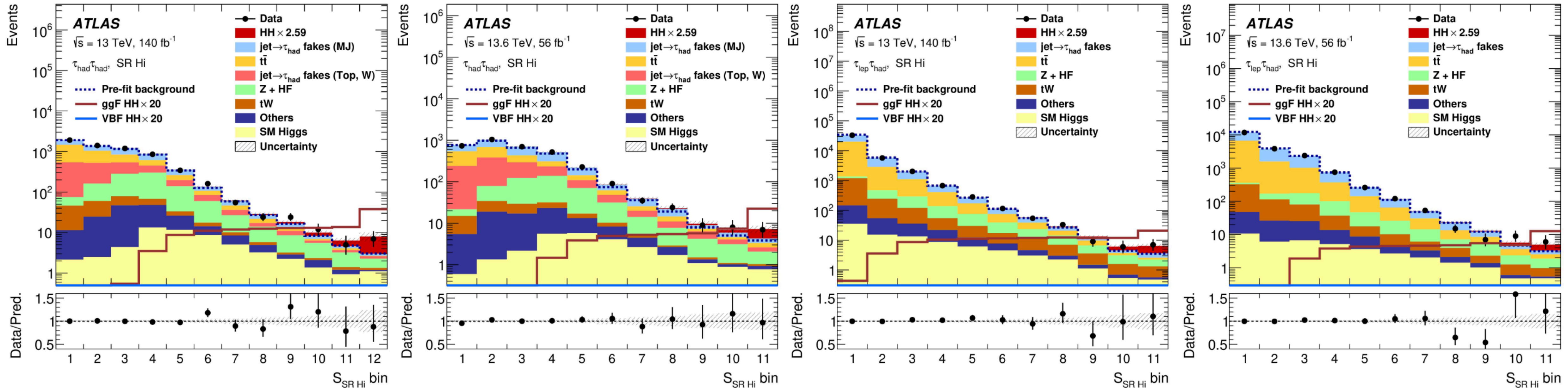
- $ZH/ZZ \rightarrow b\bar{b}\tau^+\tau^-$, measurements are used to validate the HH analysis chain.
- Keeping the same analysis strategy and MVA setup.
- Both measurements are compatible with SM prediction:

More details in Leonardo's talk
– Friday, 18 September



First evidence for $ZH \rightarrow b\bar{b}\tau^+\tau^-$ at 3.5σ .

HH signal strength

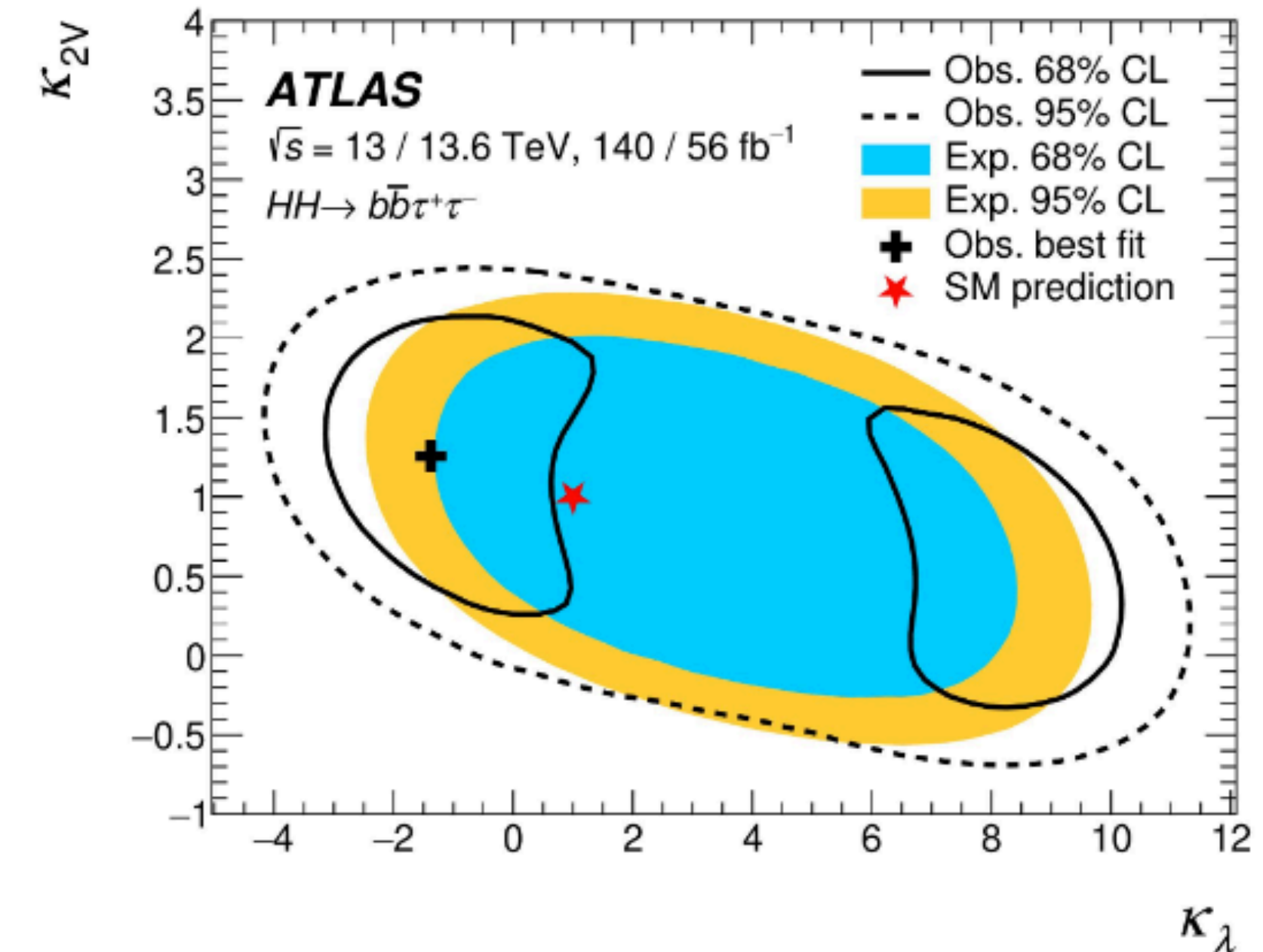
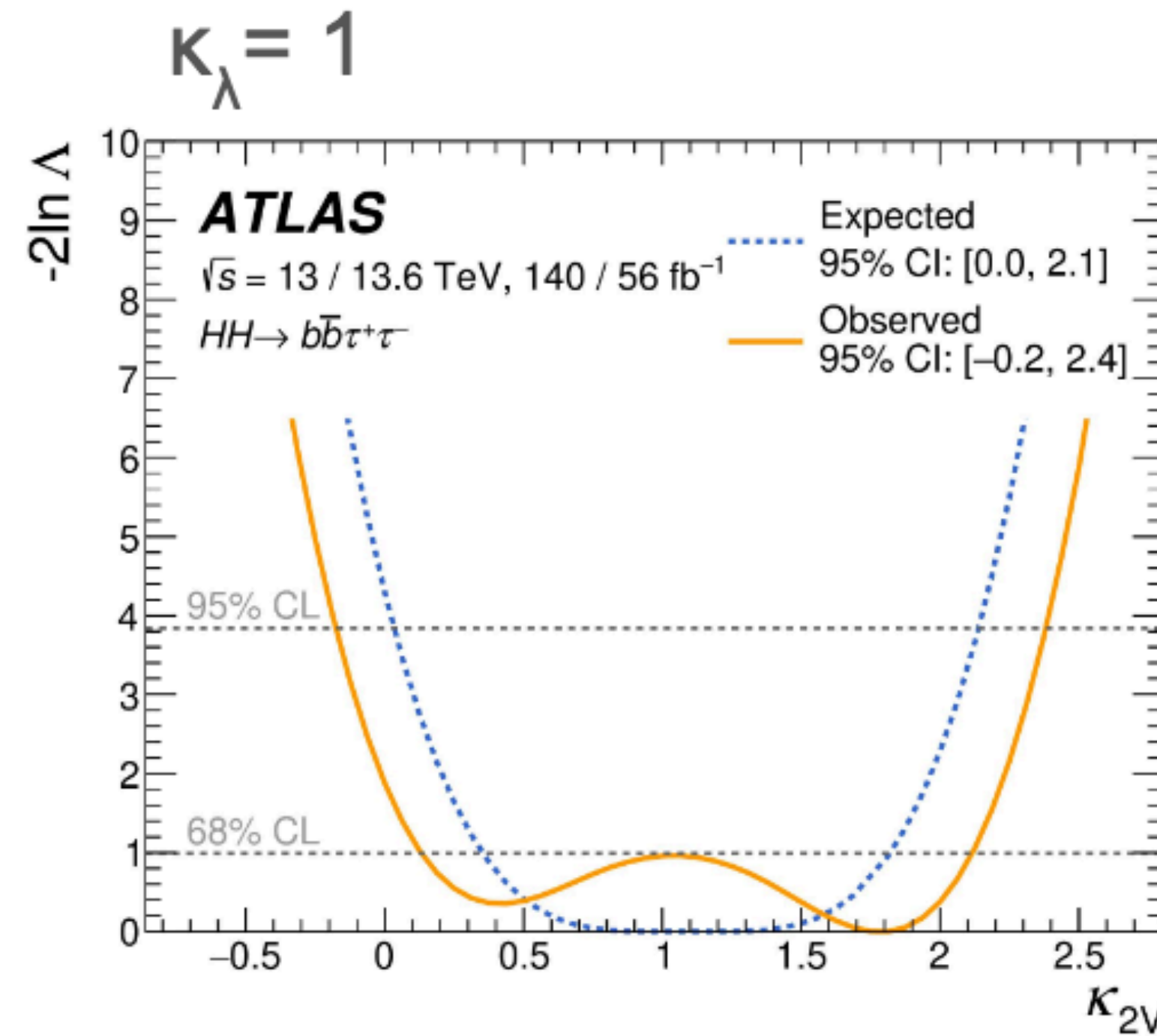
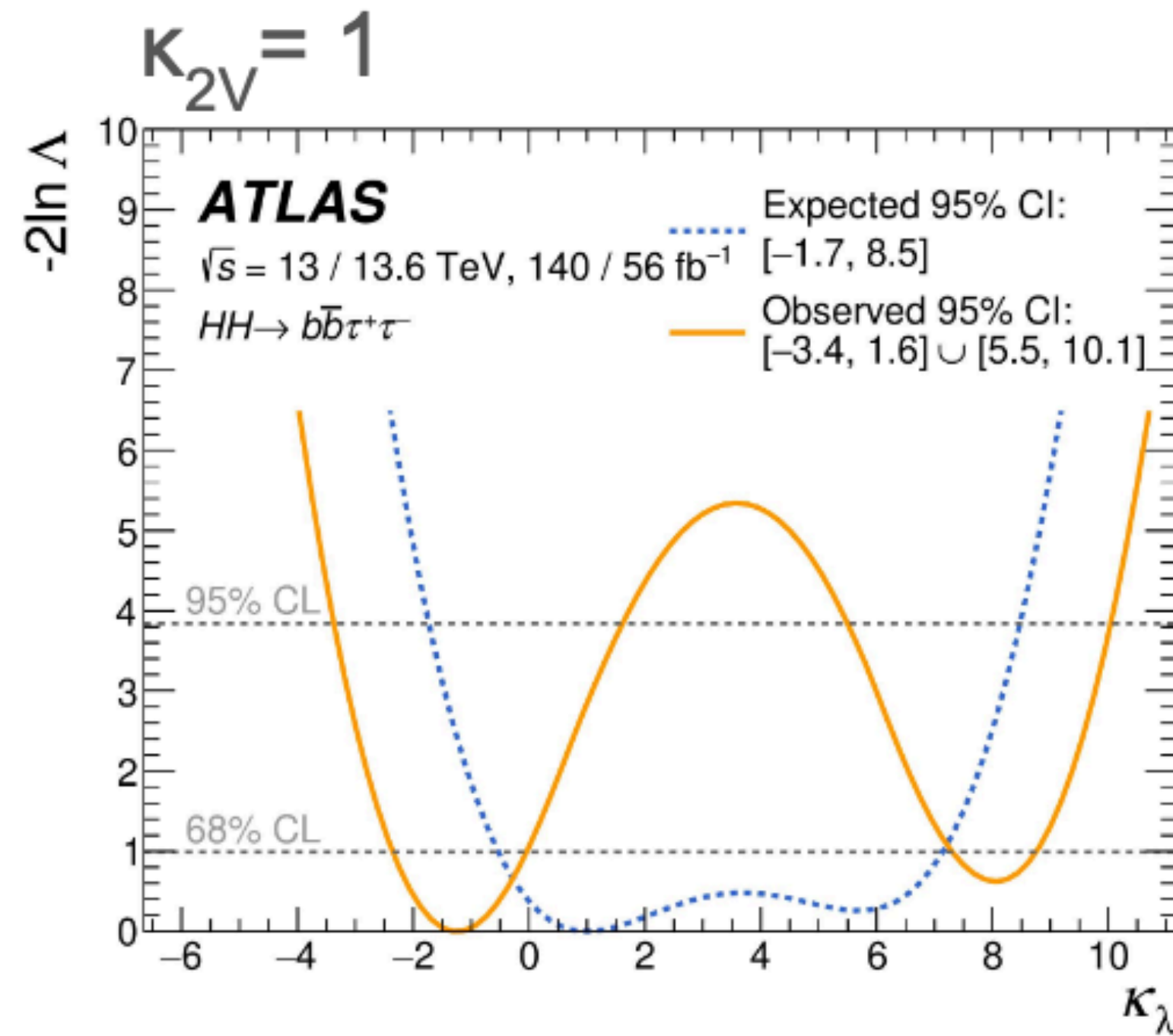


- The combined fit yields the inclusive HH signal strength:

$$\mu_{HH} = 2.6^{+1.4}_{-1.0} = 2.6^{+1.0}_{-0.9} (\text{stat.})^{+1.0}_{-0.5} (\text{syst.}).$$

- Compatible with the SM HH prediction at **1.65 σ** ($p_{\text{SM}} \approx 10\%$).
- Observed** (**Expected**) significance against the background-only hypothesis is **2.6 σ** (**1.2 σ**), with the expected value assuming SM HH.
- Production-mode limits: $\mu_{\text{ggF}} < 5.5$ (2.5), $\mu_{\text{VBF}} < 41$ (39) at 95% CL.

- Measurement is statistically dominated
- Leading systematic uncertainties:
 - ggF HH theory modelling.
 - ggH+HF modelling.
 - $t\bar{t} - tW$ interference modelling.
 - Limited statistics in background templates.



- Observed 95% CL constraints:

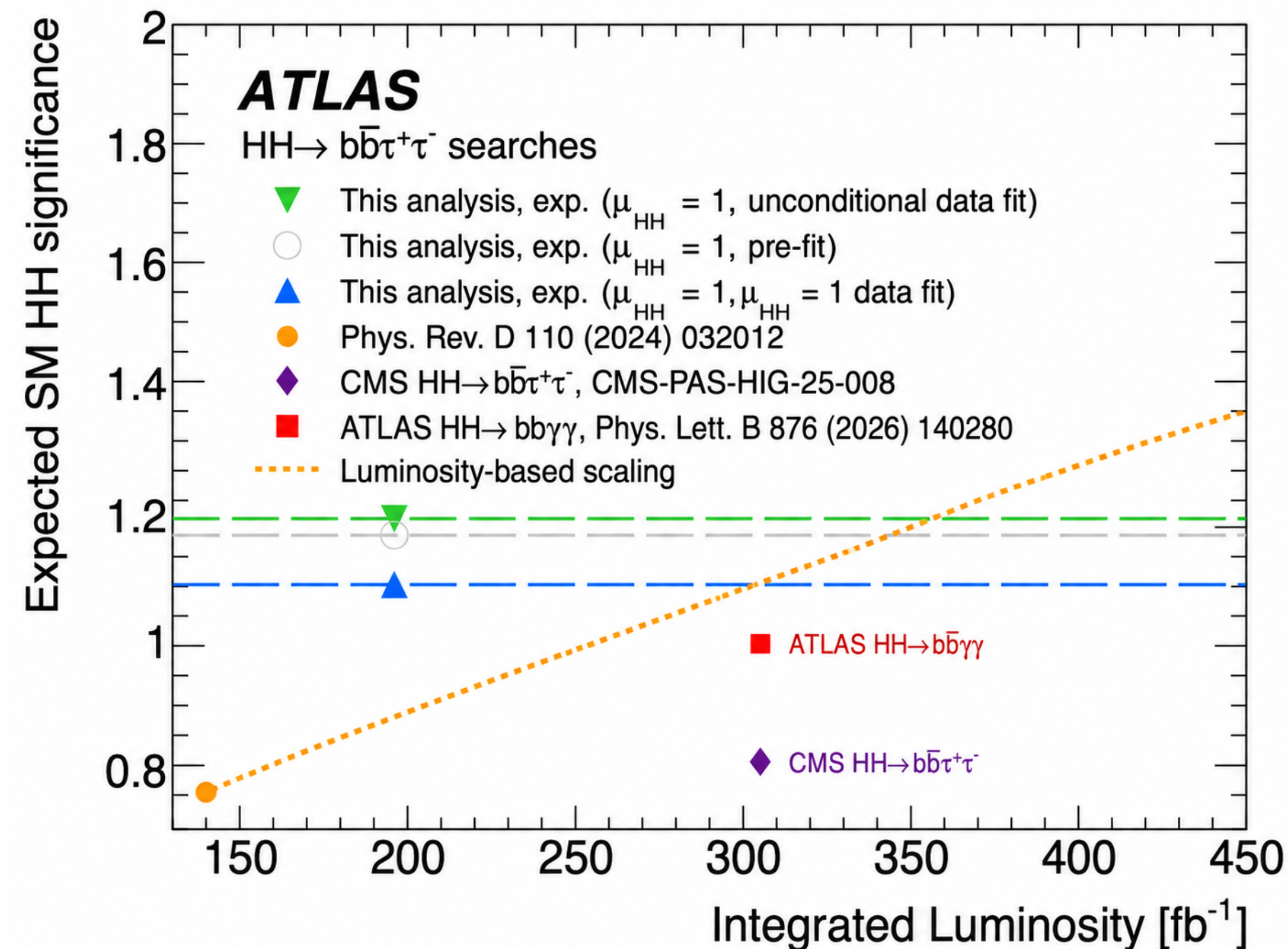
$$\kappa_\lambda \in [-3.4, 1.6] \cup [5.5, 10.1], \quad \kappa_{2V} \in [-0.2, 2.4].$$

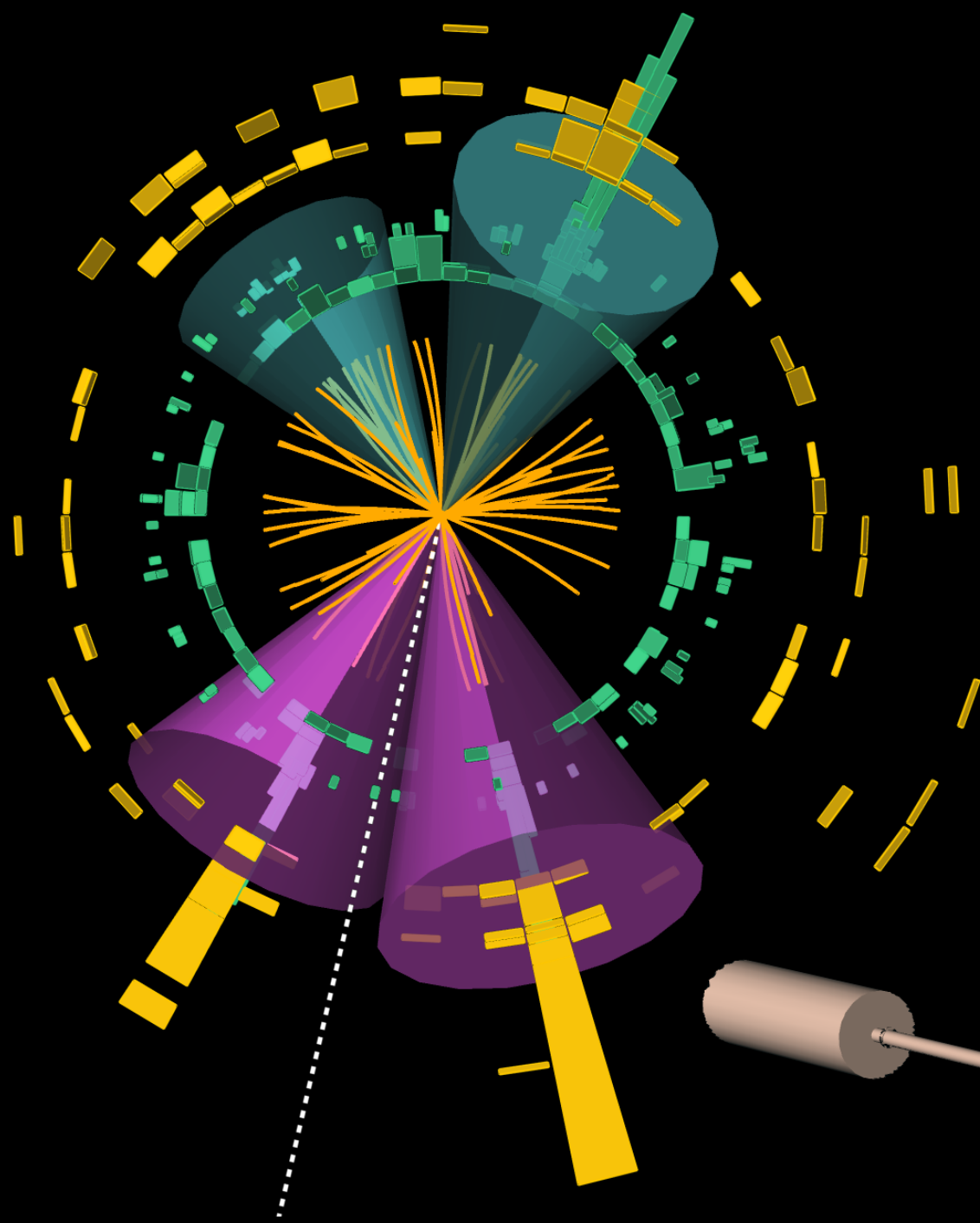
- The shifted likelihood minima are mainly driven by the observed HH excess ($\mu_{HH} = 2.6$).
- The likelihood shape reflects the coupling dependence of the HH cross section, acceptance and kinematics.
- Results remain compatible with the SM.

- Most sensitive ATLAS non-resonant $HH \rightarrow b\bar{b}\tau^+\tau^-$ search to date using full Run 2 + 2022–2023 Run 3 data.
- Combined inclusive signal strength: $\mu_{HH} = 2.6^{+1.4}_{-1.0}$ with an observed (expected) significance of 2.6σ (1.2σ).
- The result is compatible with the SM HH prediction at 1.65σ .
- The expected significance improves by 65% compared with the previous $HH \rightarrow b\bar{b}\tau^+\tau^-$ analysis.



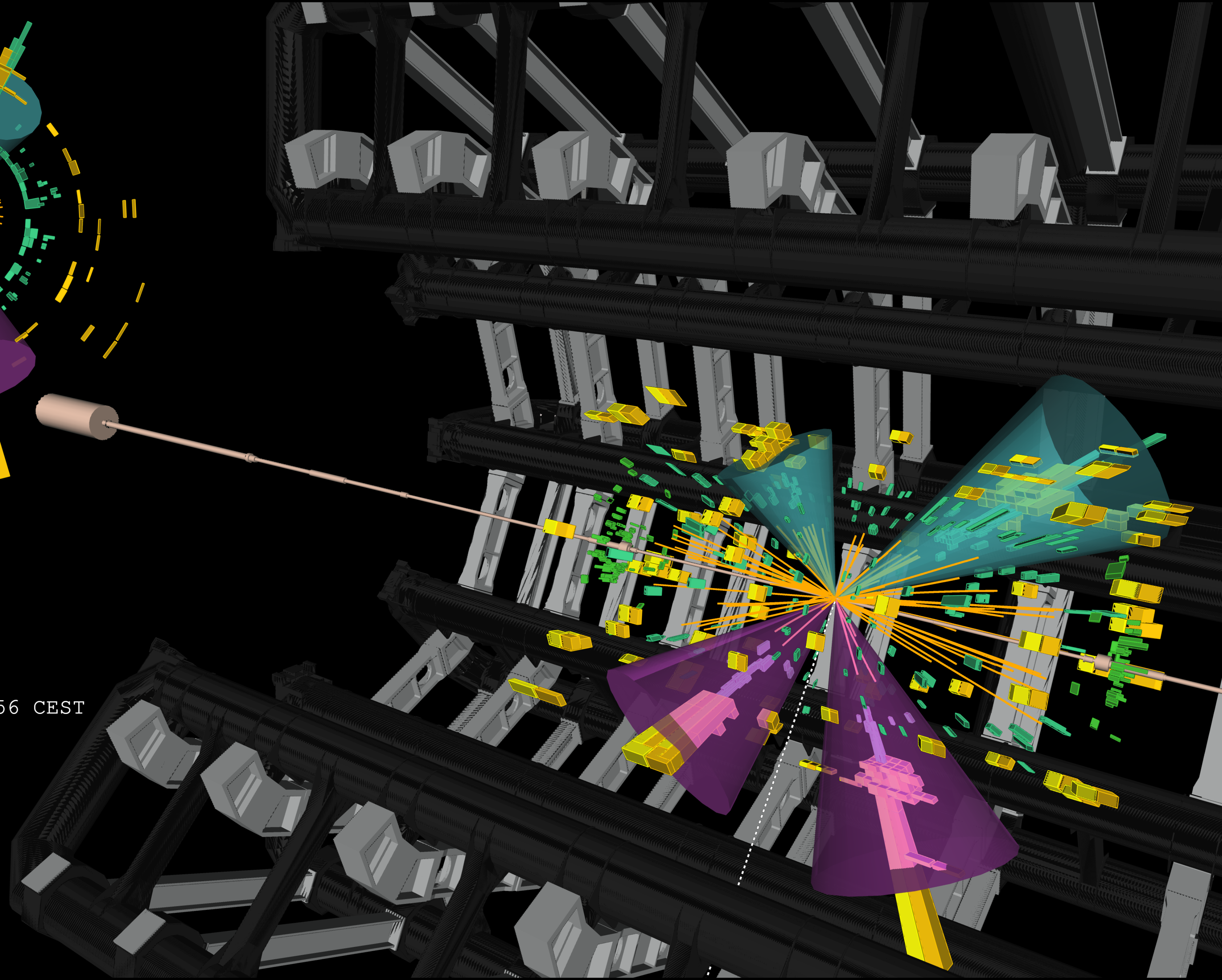
- The largest sensitivity gain comes from:
 1. New Transformer-based MVA, about 15–20% improvement.
 2. Inclusion of Run 3 data (~15%).
 3. Improved flavour tagging (~10%),
 4. New $\tau_{had}\tau_{had}$ trigger strategy raises the $\tau_{had}\tau_{had}$, $A \times \epsilon$ to ~6.3%.
 5. Removal of the eVeto in the $\tau_{had}\tau_{had}$ channel (~5%).
- Dedicated ZZ and ZH validation measurements are compatible with the SM.
 - First evidence for $ZH \rightarrow b\bar{b}\tau^+\tau^-$ at 3.5σ .





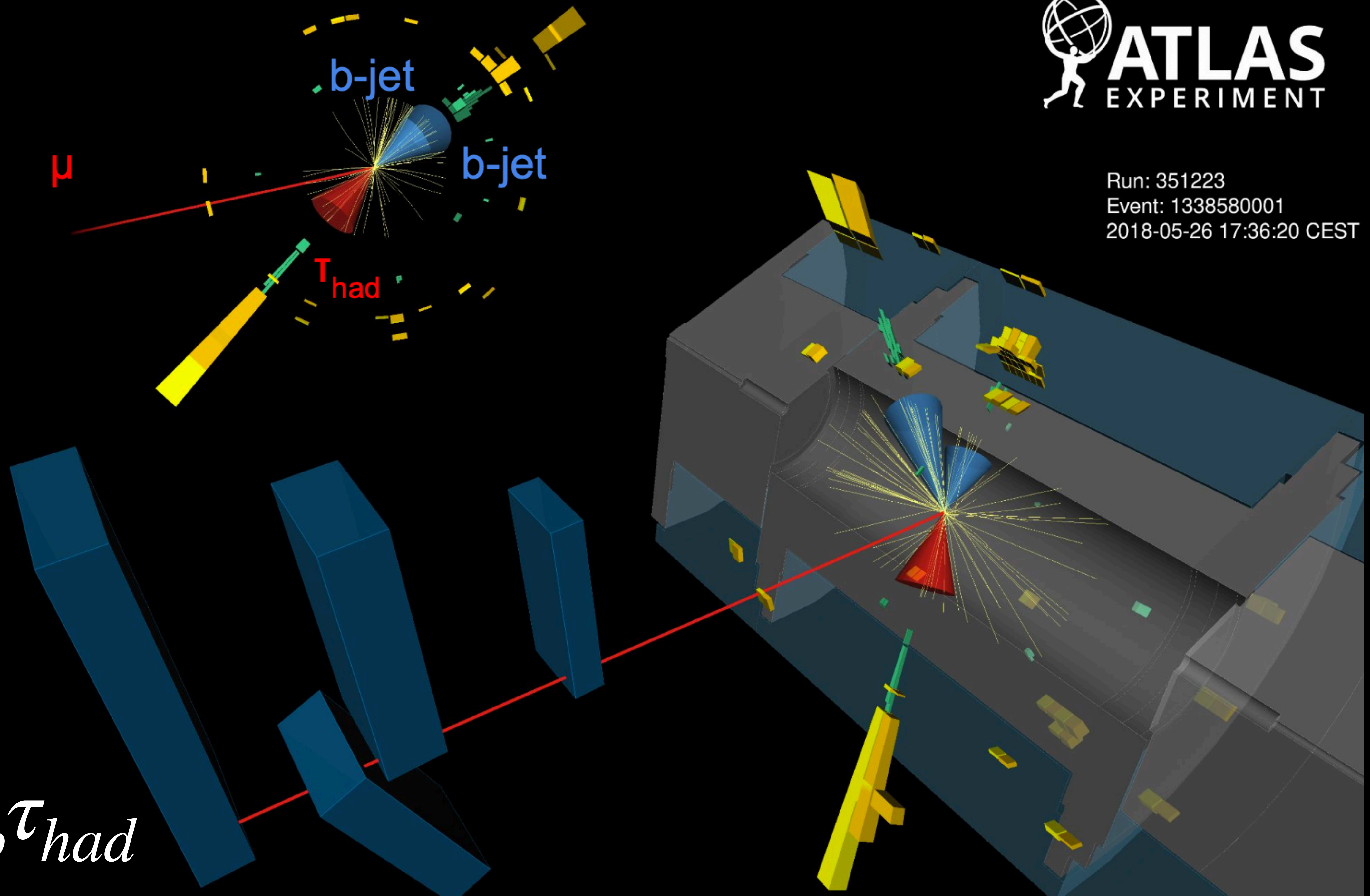
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Event: 229974012
2022-10-02 05:46:56 CEST

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



Run: 351223
Event: 1338580001
2018-05-26 17:36:20 CEST

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



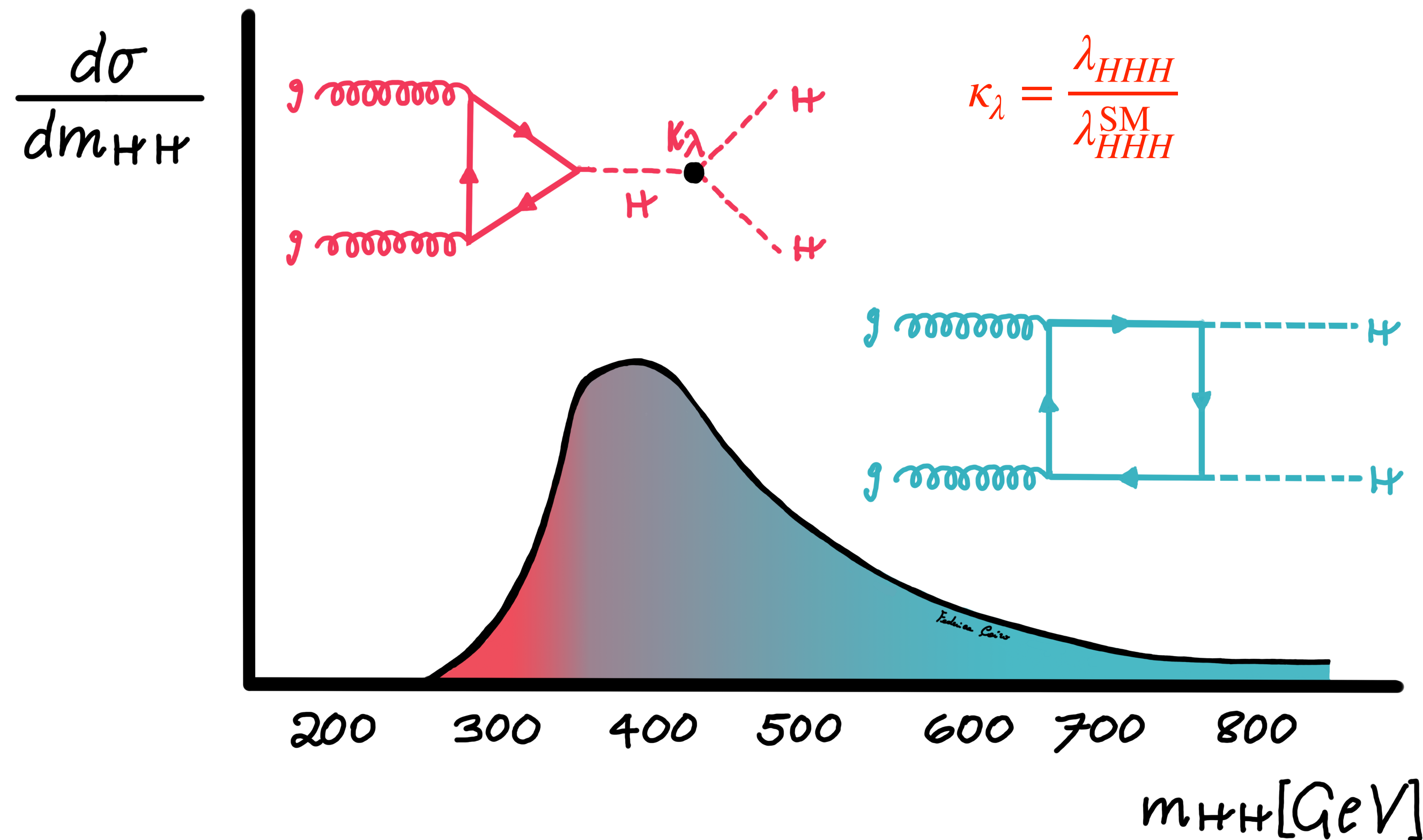
BACKUP SLIDES

Additional material & supporting details

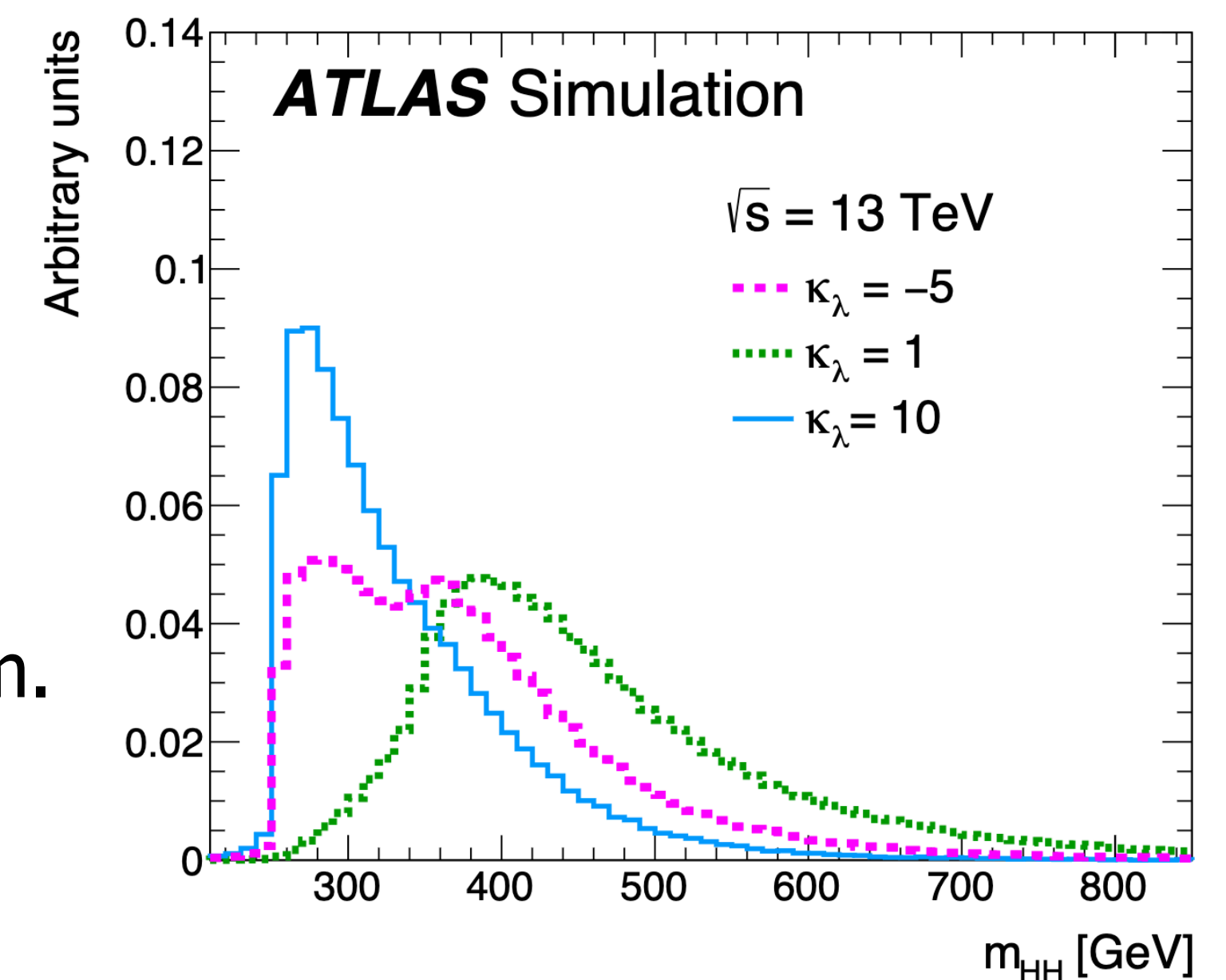
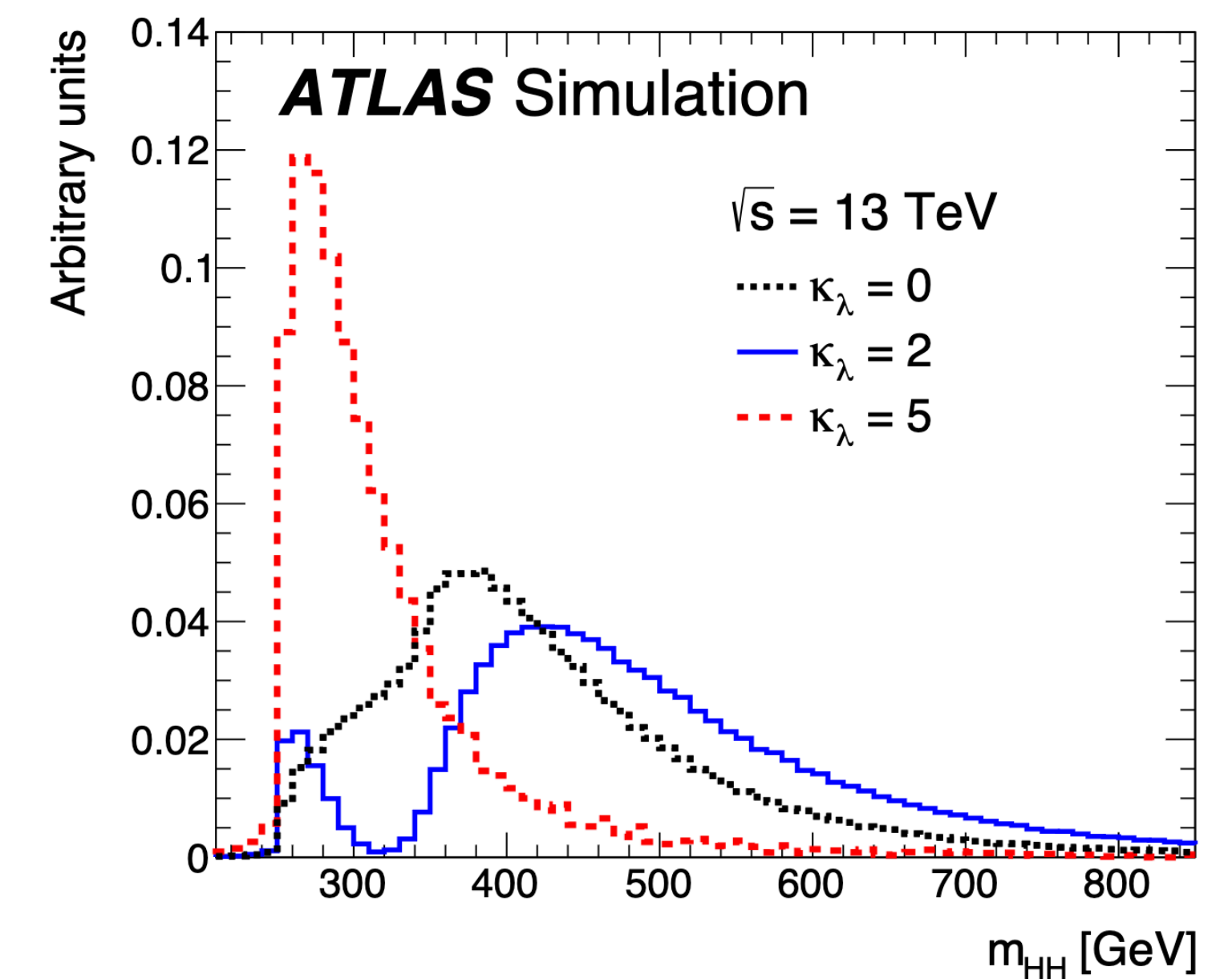
Trigger strategy · Selection details · Supporting results



- m_{HH} is a key observable for probing κ_λ



- Coupling variations modify the interference between HH amplitudes.
- This affects both the production rate and the shape of the m_{HH} spectrum.
- Different couplings therefore lead to distinct kinematic signatures.



Process	ME Generator	PDF set	Showering	Tune
Signal				
$gg \rightarrow HH$ (ggF)	POWHEG Box v2	PDF4LHC21	PYTHIA 8	A14 NNPDF2.3LO
$qq \rightarrow qqHH$ (VBF)	MADGRAPH5_AMC@NLO 3.3.1	NNPDF3.0NLO	PYTHIA 8	A14 NNPDF2.3LO
Top-quark				
$t\bar{t}$	POWHEG Box v2	NNPDF3.0NLO	PYTHIA 8	A14 NNPDF2.3LO
t -channel	POWHEG Box v2	NNPDF3.0NLO	PYTHIA 8	A14 NNPDF2.3LO
s -channel	POWHEG Box v2	NNPDF3.0NLO	PYTHIA 8	A14 NNPDF2.3LO
Wt	POWHEG Box v2	NNPDF3.0NLO	PYTHIA 8	A14 NNPDF2.3LO
$t\bar{t}W$	SHERPA 2.2.14	NNPDF3.0NNLO	SHERPA 2.2.14	-
$t\bar{t}Z$	MADGRAPH5_AMC@NLO 3.5.1	NNPDF3.0NLO	PYTHIA 8	A14 NNPDF2.3LO
Vector boson + jets				
W/Z +jets	SHERPA 2.2.14	NNPDF3.0NNLO	SHERPA 2.2.14	-
Diboson				
WW, WZ, ZZ	SHERPA 2.2.14, SHERPA 2.2.16	NNPDF3.0NNLO	SHERPA 2.2.14, SHERPA 2.2.16	-
Single Higgs boson				
ggF	POWHEG Box v2	PDF4LHC15NLO	PYTHIA 8	A14 NNPDF2.3LO
VBF	POWHEG Box v2	PDF4LHC15NLO	PYTHIA 8	A14 NNPDF2.3LO
$qq \rightarrow WH$	POWHEG Box v2	PDF4LHC15NLO	PYTHIA 8	A14 NNPDF2.3LO
$qq \rightarrow ZH$	POWHEG Box v2	PDF4LHC15NLO	PYTHIA 8	A14 NNPDF2.3LO
$gg \rightarrow ZH$	POWHEG Box v2	PDF4LHC15NLO	PYTHIA 8	A14 NNPDF2.3LO
$t\bar{t}H$	POWHEG Box v2	PDF4LHC21, NNPDF3.0	PYTHIA 8	A14 NNPDF2.3LO

Event selection is mainly driven by triggers

$\tau_{\text{lep}} \tau_{\text{had}}$ channel		$\tau_{\text{had}} \tau_{\text{had}}$ channel	
Single- ℓ trigger SLT	Single- τ_{had} trigger STT	Di- τ_{had} trigger DTT	Di- b trigger DBT
e/μ selection			
One trigger-matched tight e or medium μ $p_{\text{T}}^e > 25, 27 \text{ GeV}$ $p_{\text{T}}^\mu > 21, 27, 25 \text{ GeV}$	$ \eta^e < 2.47$ and $!(1.37 < \eta^e < 1.52)$; $ \eta^\mu < 2.7$ No (additional) loose e/μ with $p_{\text{T}} > 7 \text{ GeV}$		
τ_{had} selection			
One loose τ_{had} $p_{\text{T}} > 20 \text{ GeV}$	One trigger-matched $p_{\text{T}} > 100, 140, 180 \text{ (20) GeV}$	Two loose τ_{had} Two trigger-matched $p_{\text{T}} > 40 \text{ (30) GeV}$ 2023 (2400b): $p_{\text{T}} > 35 \text{ (25) GeV}$	See below
$ \eta^{\tau_{\text{had}}} < 2.5$ and $!(1.37 < \eta^{\tau_{\text{had}}} < 1.52)$; eVeto applied in $\tau_{\text{lep}} \tau_{\text{had}}$			
Jet selection			
≥ 2 central jets: $p_{\text{T}} > 45 \text{ (20) GeV}$			
		$p_{\text{T}}(\eta < 3.2) > 70 \text{ GeV}$ 2017 (B4)–2023, L1Topo $p_{\text{T}}(\eta < 3.2) > 70 \text{ GeV}$ and $\Delta R_{\tau_{\text{had}} \tau_{\text{had}}} < 2.5$ 2017 (B4)–2023, L1 4J12 $p_{\text{T}}(\eta < 2.5) > 50 \text{ (50) GeV}$ 2018: $p_{\text{T}}(\eta < 2.3) > 50 \text{ (50) GeV}$	For p_{T} -ordered array of objects matched to HLT jets: $\{\tau_{\text{had},i}, j_i\}$ $p_{\text{T}} > \{85, 60, 50, 25\} \text{ GeV}$ $ \eta < \{2.1, 2.5, 2.5, 2.5\}$
Additional selection			
$m_{\tau\tau}^{\text{vis}} > 30 \text{ GeV}$	$!\text{STT bucket}$ $m_{\tau\tau}^{\text{vis}} > 40 \text{ GeV}$ $m_{\tau\tau}^{\text{MMC}} > 60 \text{ GeV}$		$!\text{STT and } !\text{DTT buckets}$
Opposite-sign electric charges of $e/\mu/\tau_{\text{had}}$ and τ_{had} Exactly two b -tagged jets (85% efficiency, trigger-matched for the DBT bucket)			
$40 < m_{bb} < 150 \text{ GeV}$	$40 < m_{bb} < 210 \text{ GeV}$		

ggF High- m_{HH} SR

Targets the high- m_{HH} regime where sensitivity to SM-like HH production is highest.

Signal-region categorisation

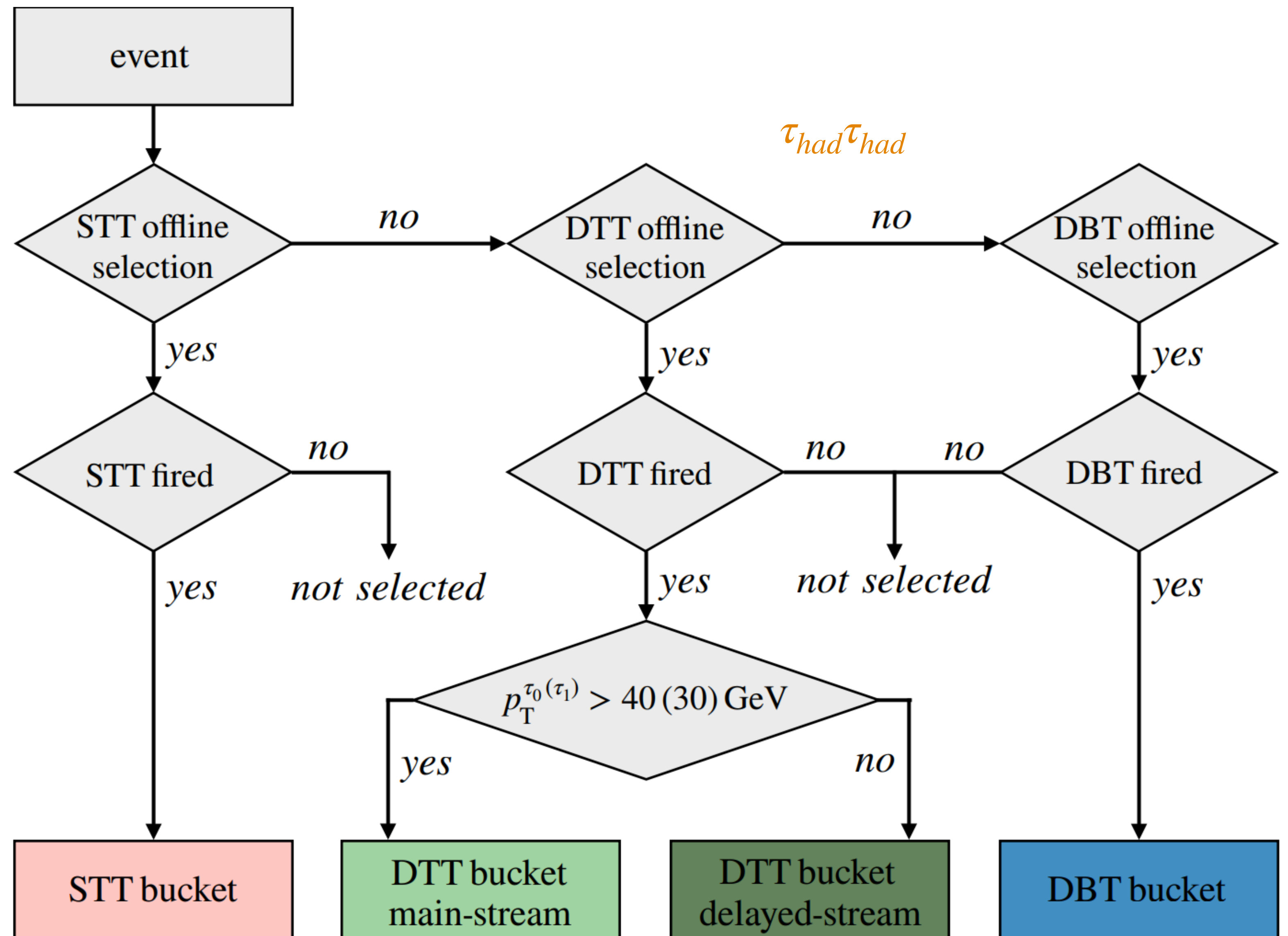
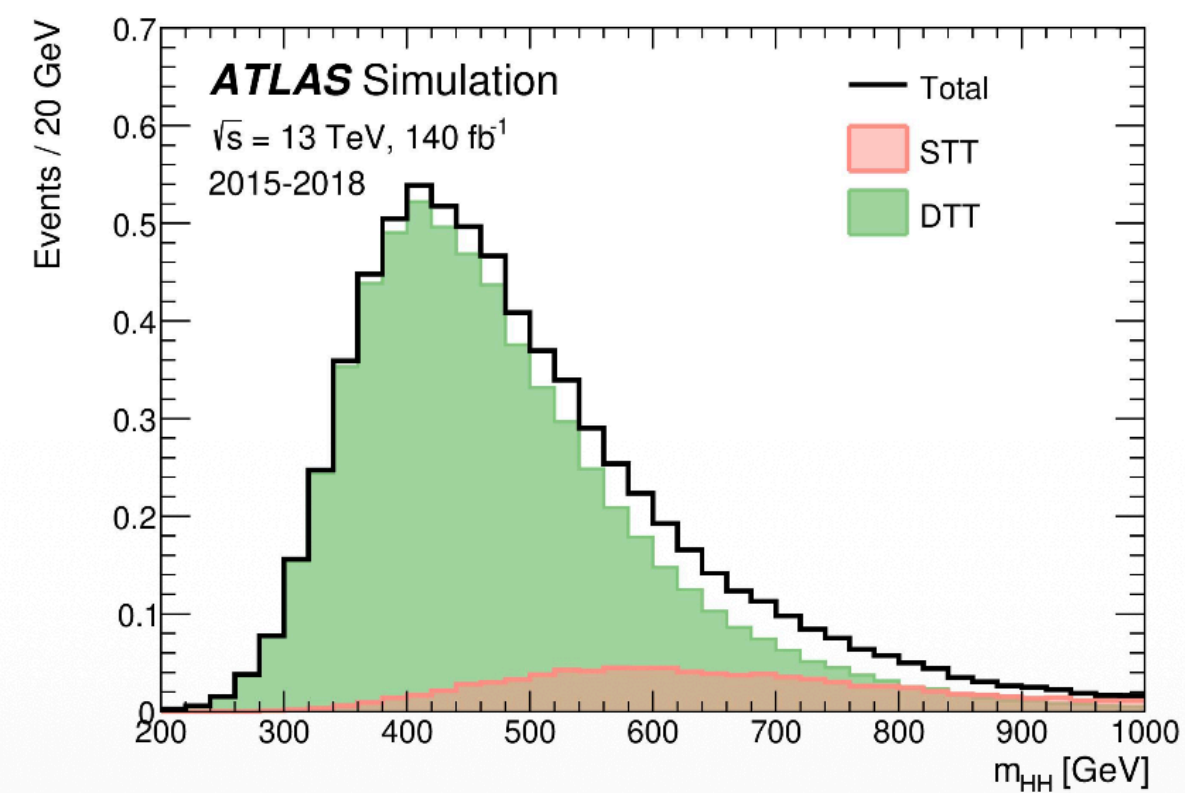
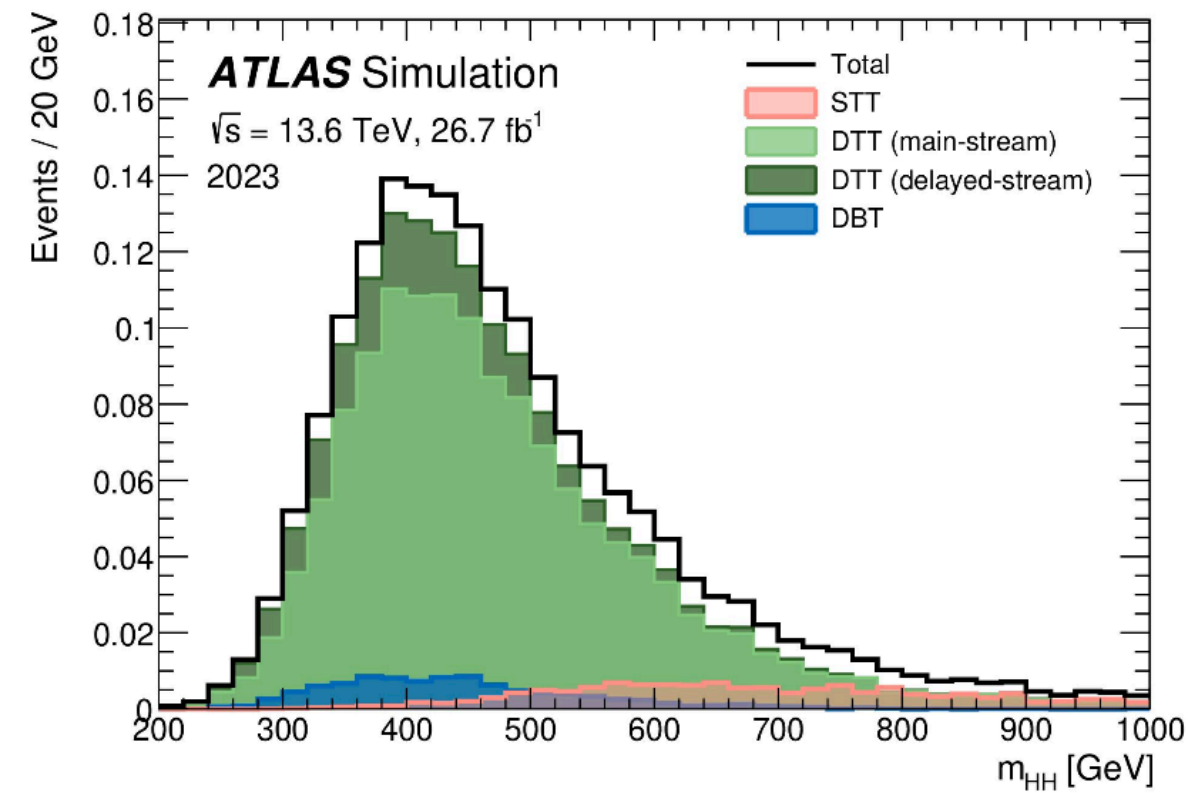
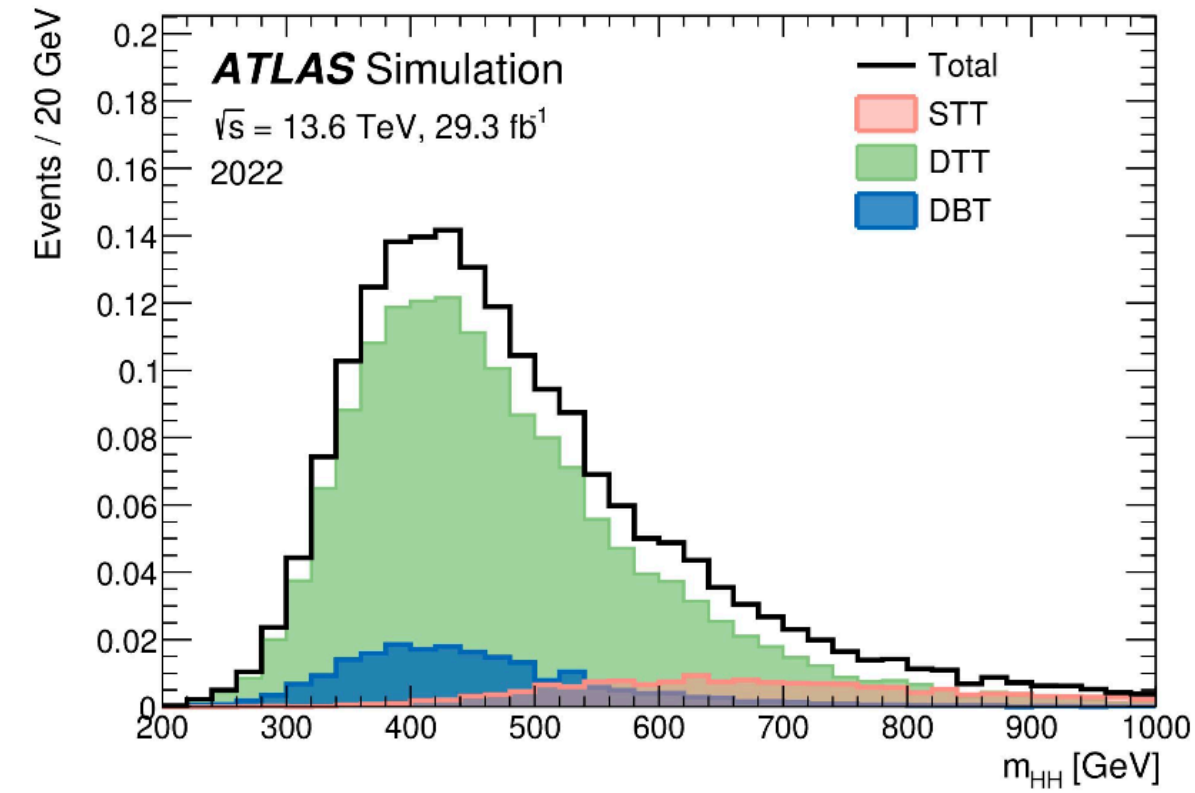
ggF Low- m_{HH} SR

Enhances sensitivity to κ_λ and helps resolve coupling degeneracies.

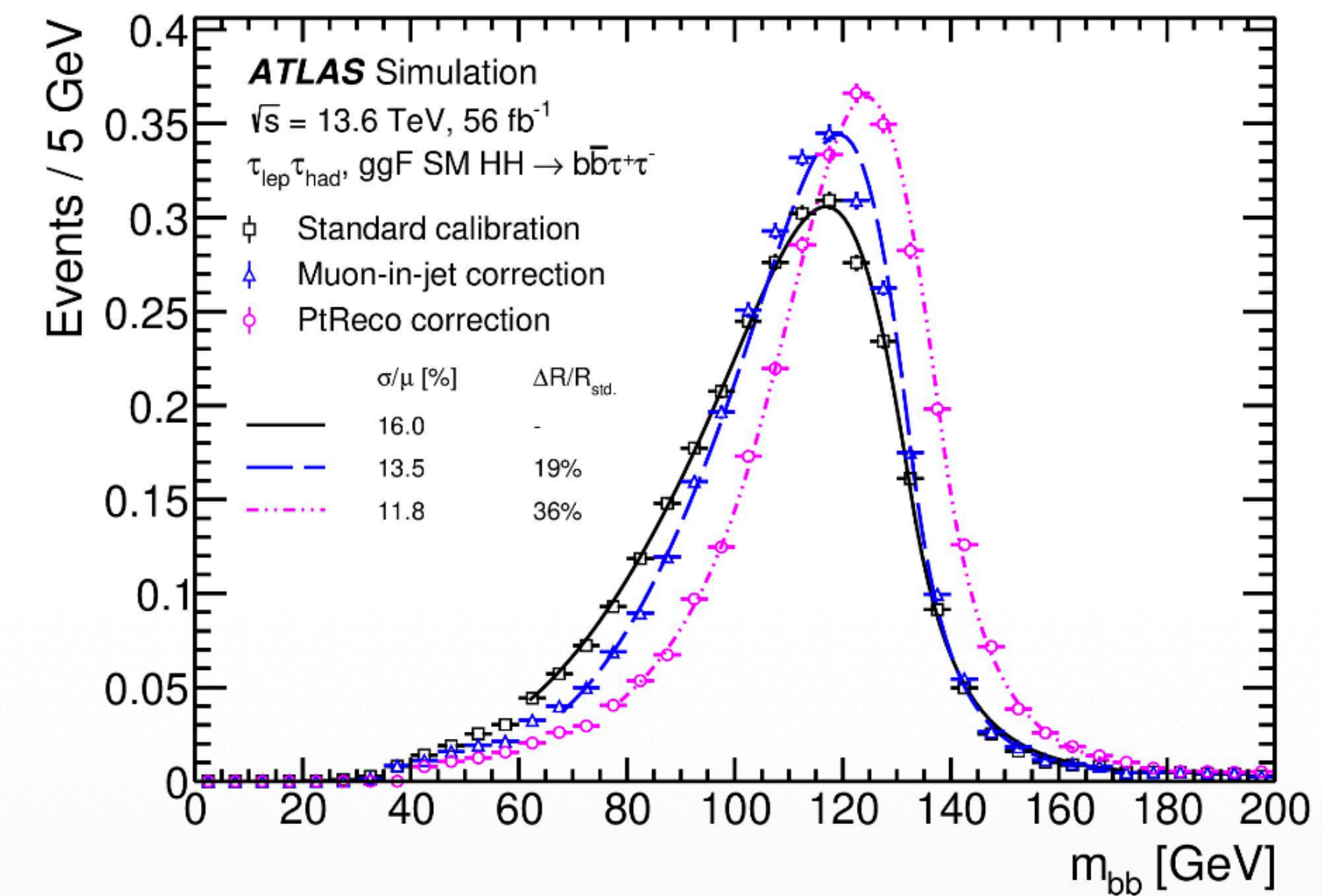
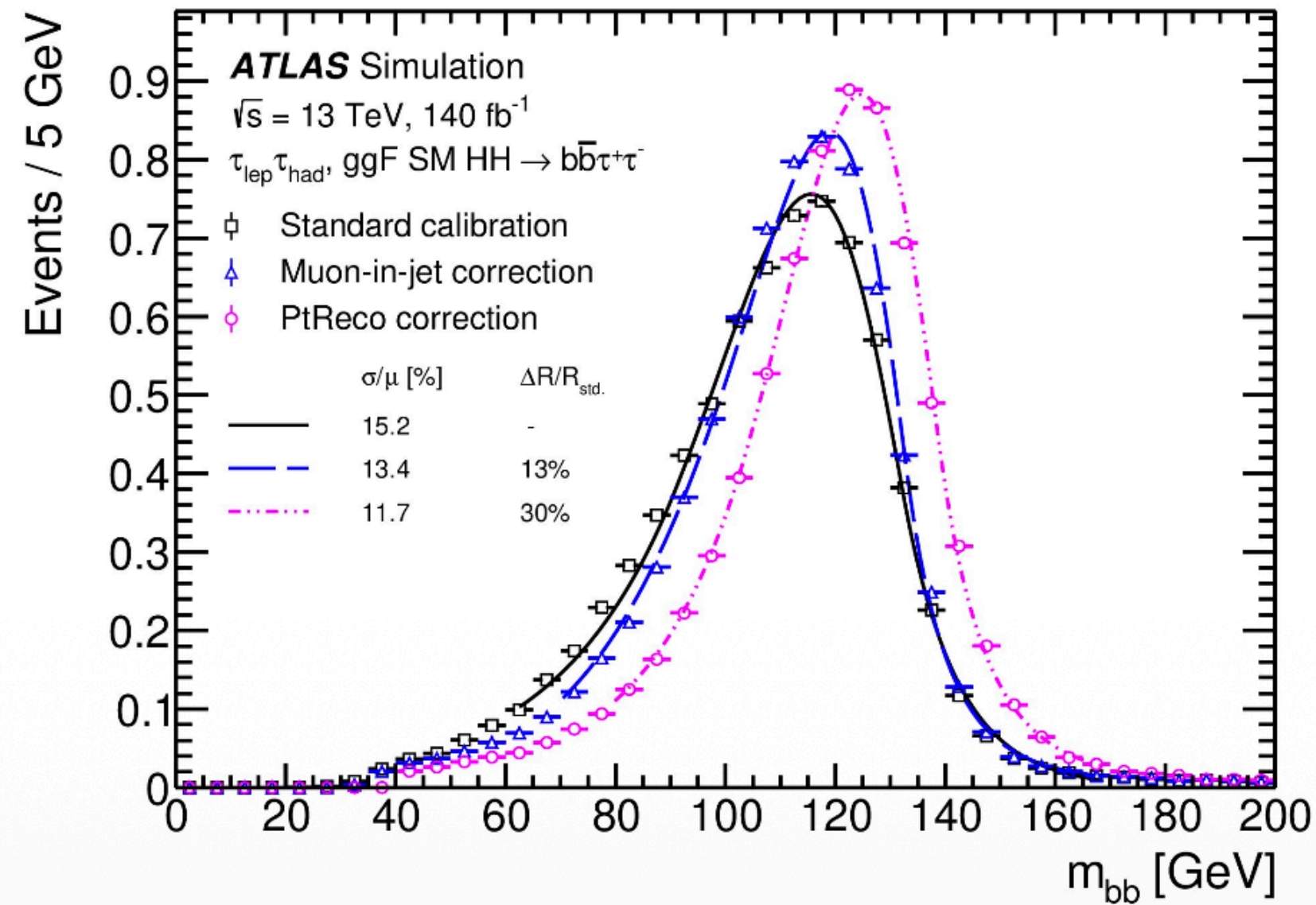
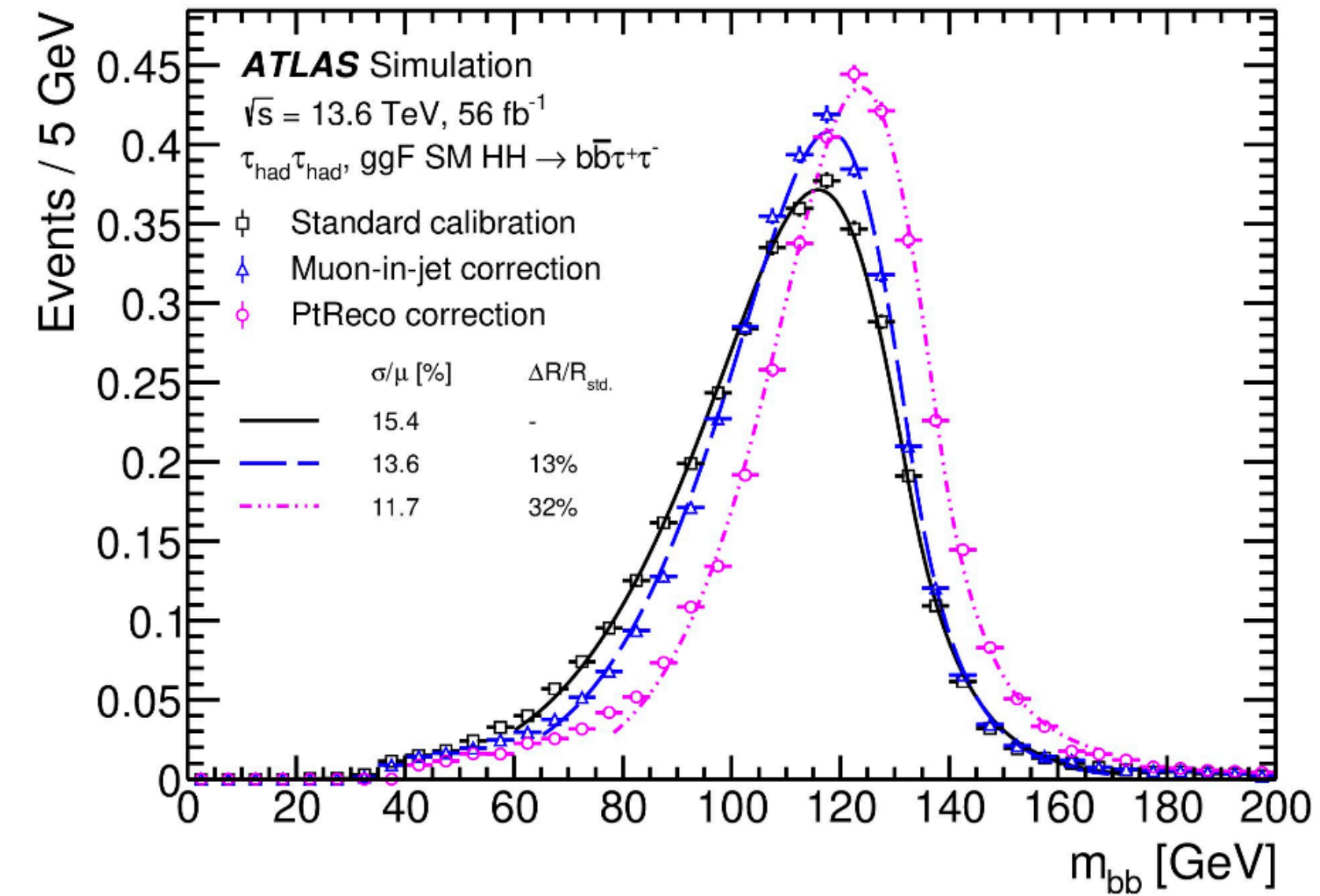
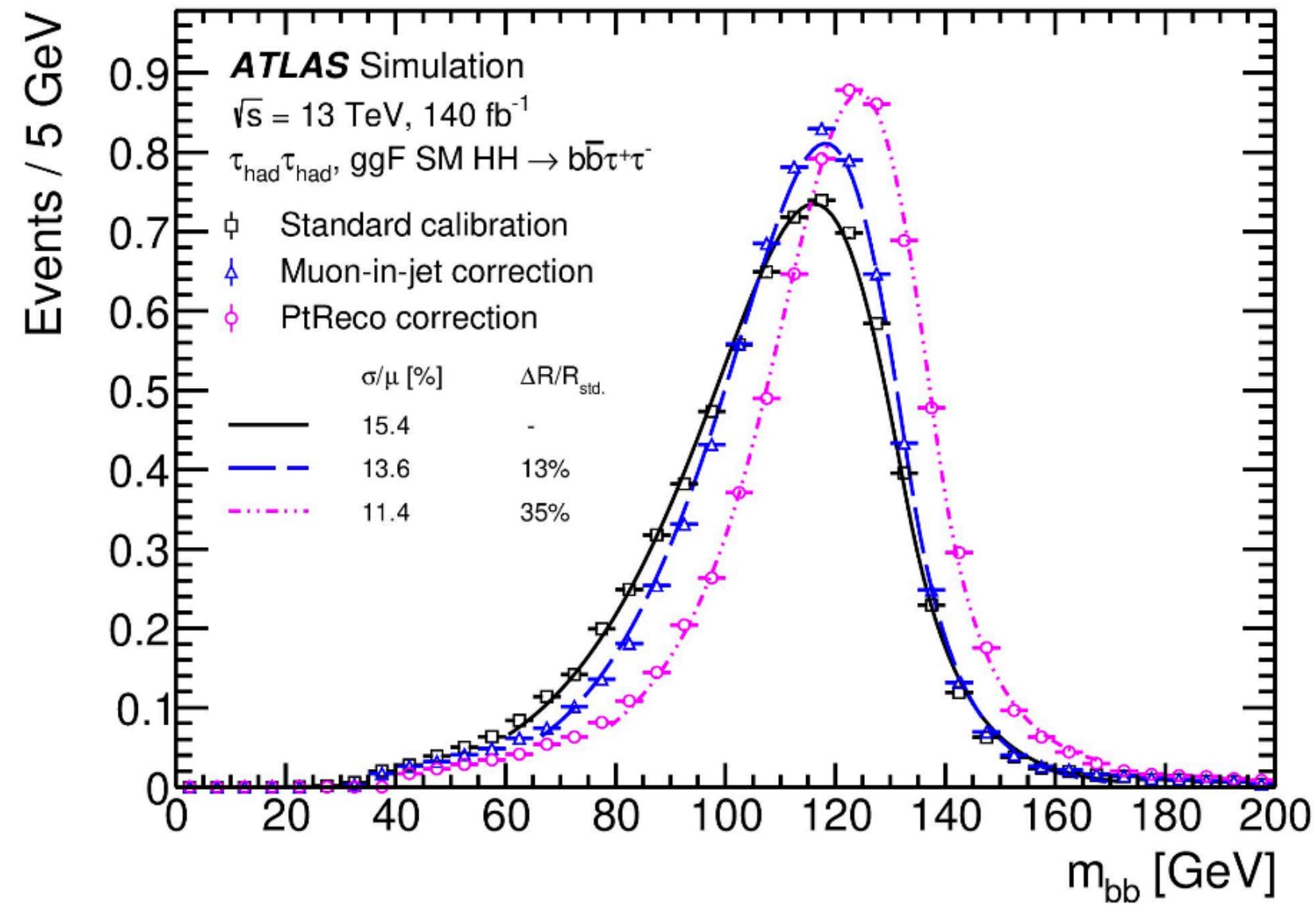
VBF SR

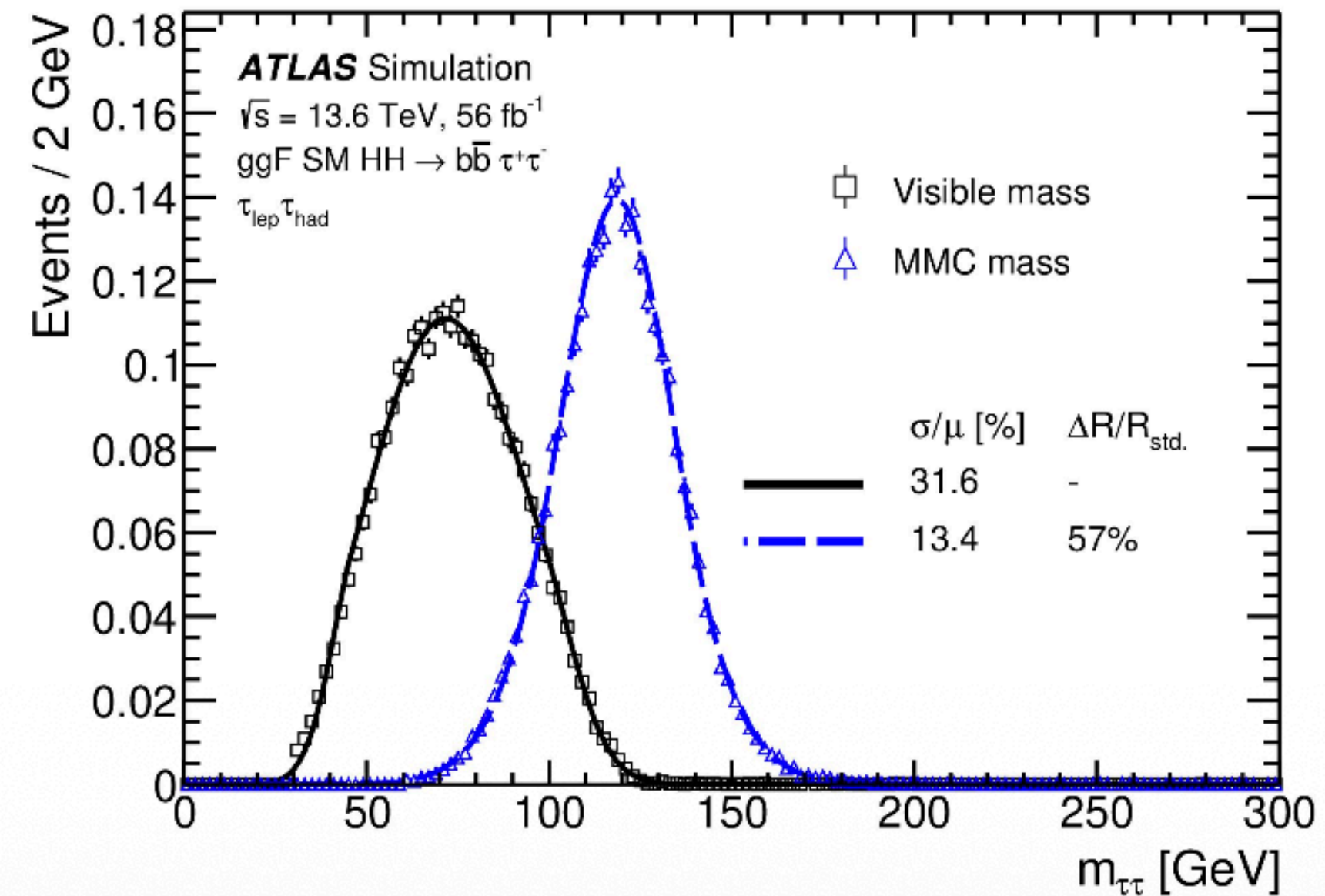
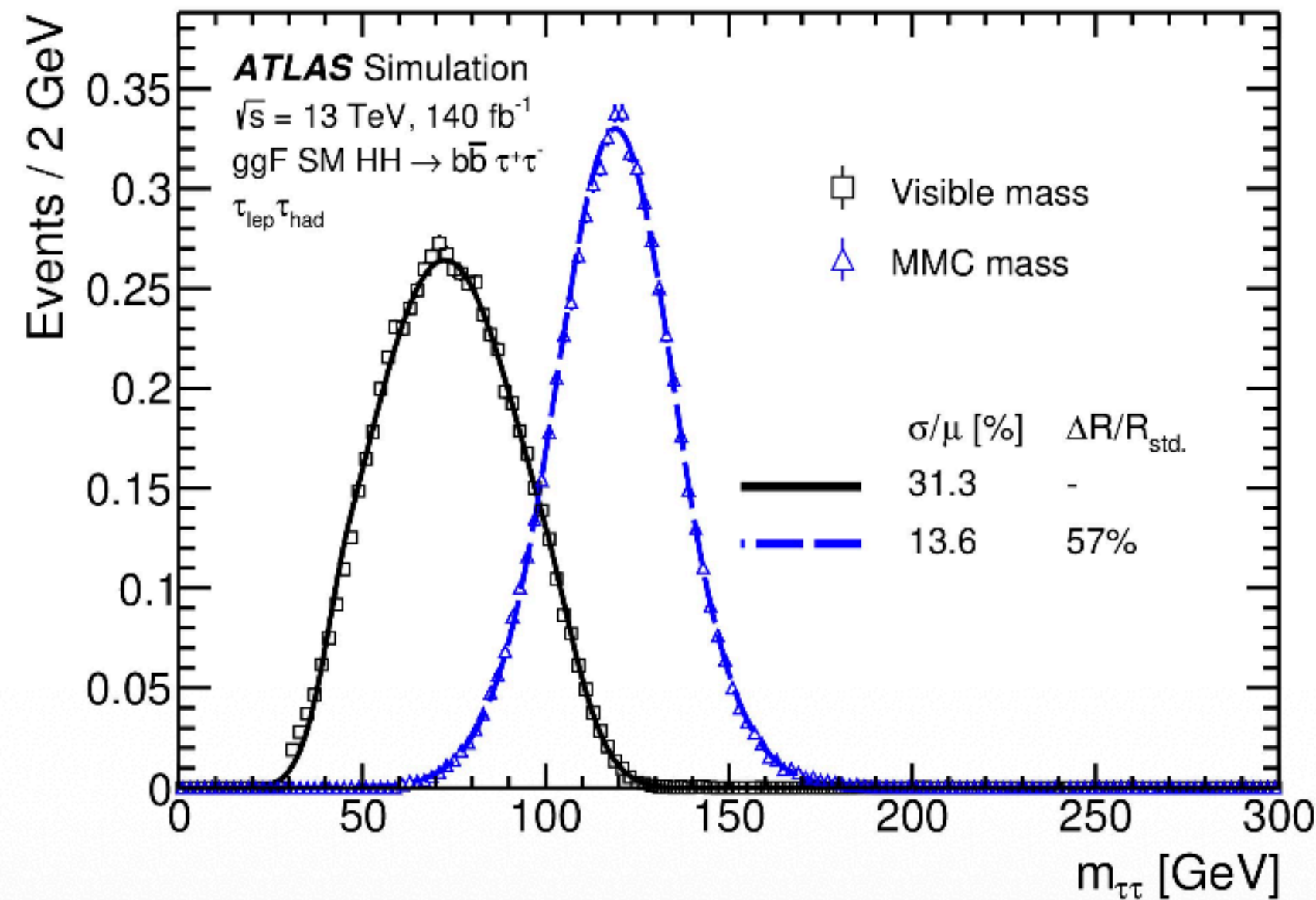
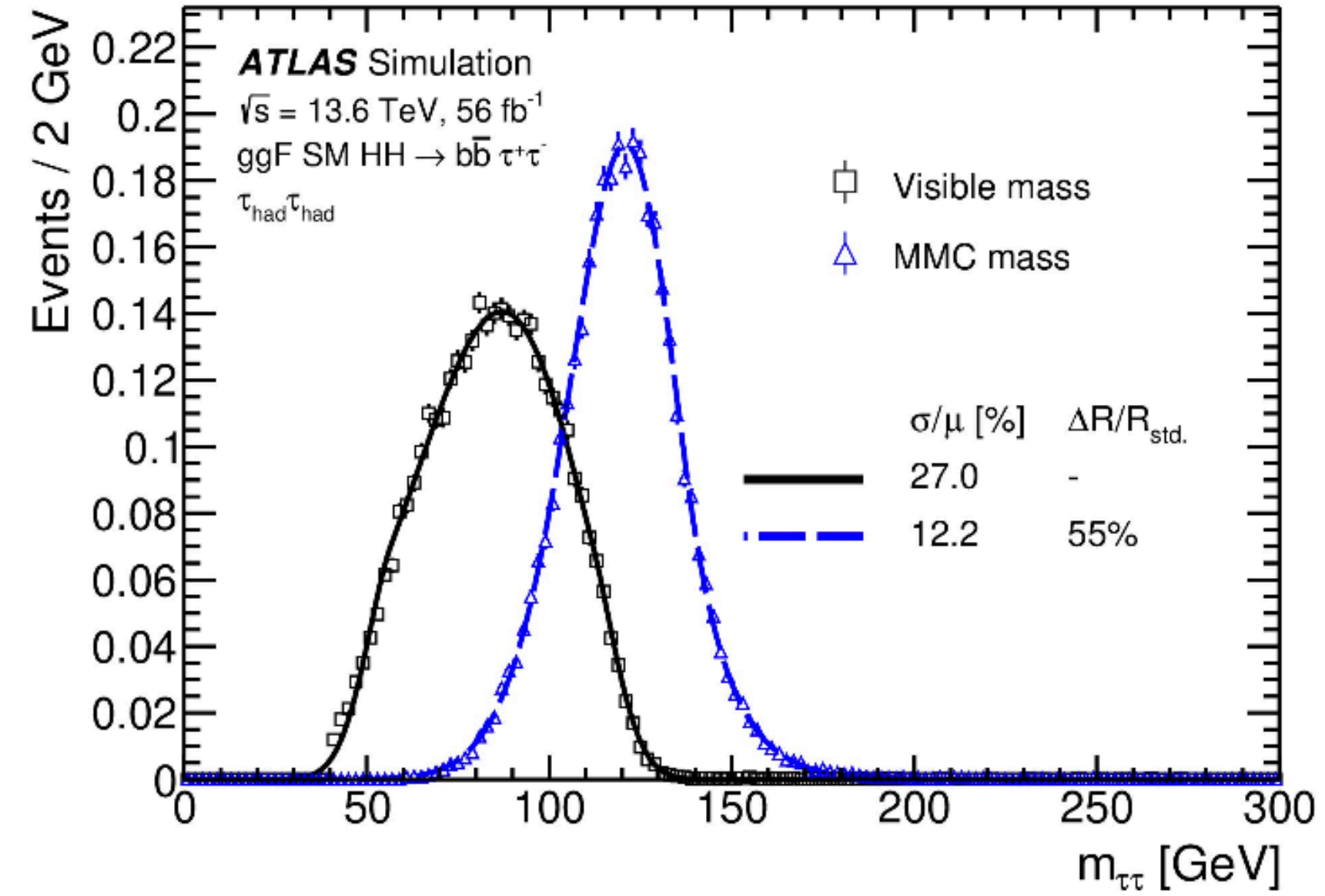
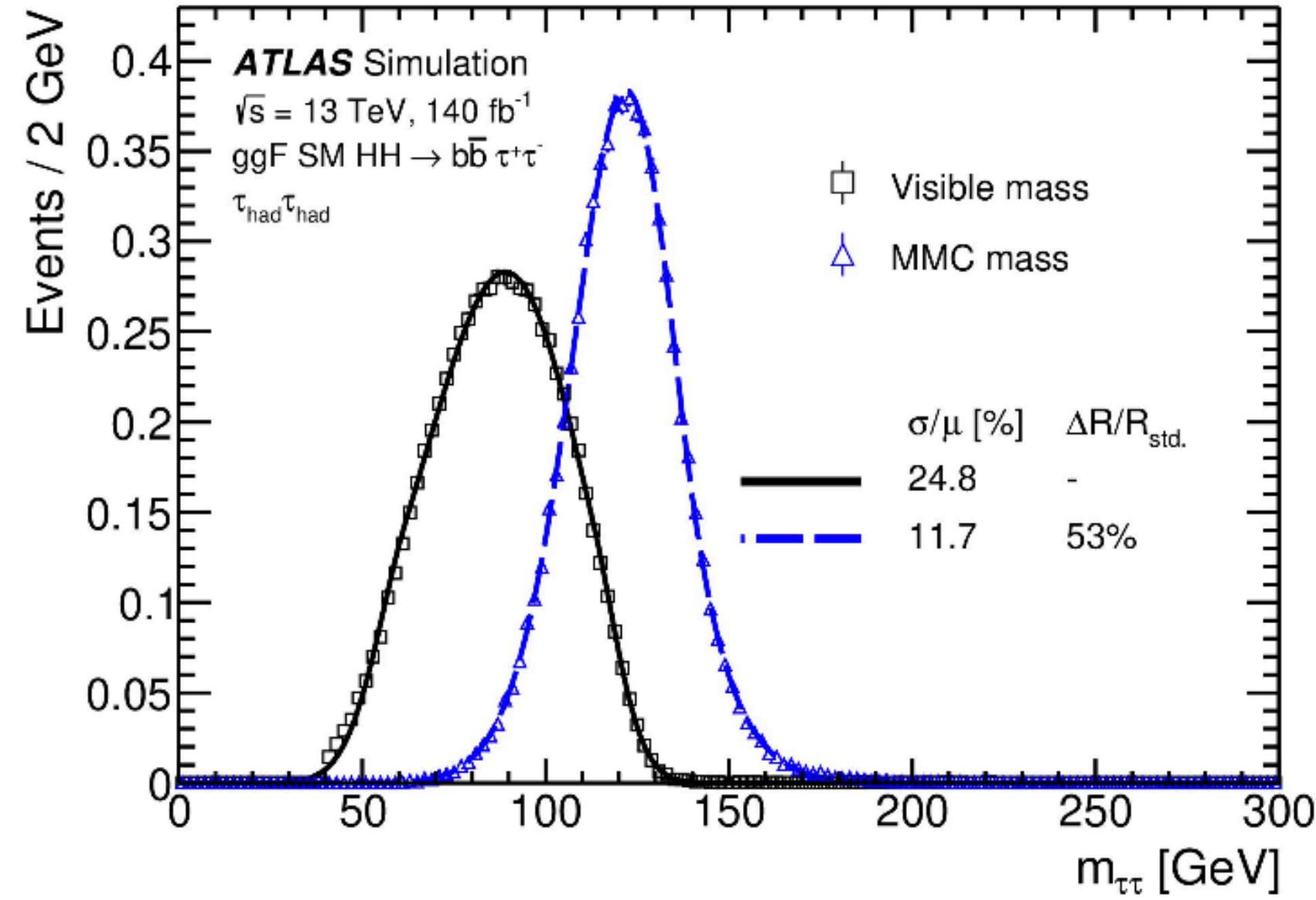
Targets VBF HH production and provides sensitivity to κ_{2V} .

$\tau_{had}\tau_{had}$ trigger strategy



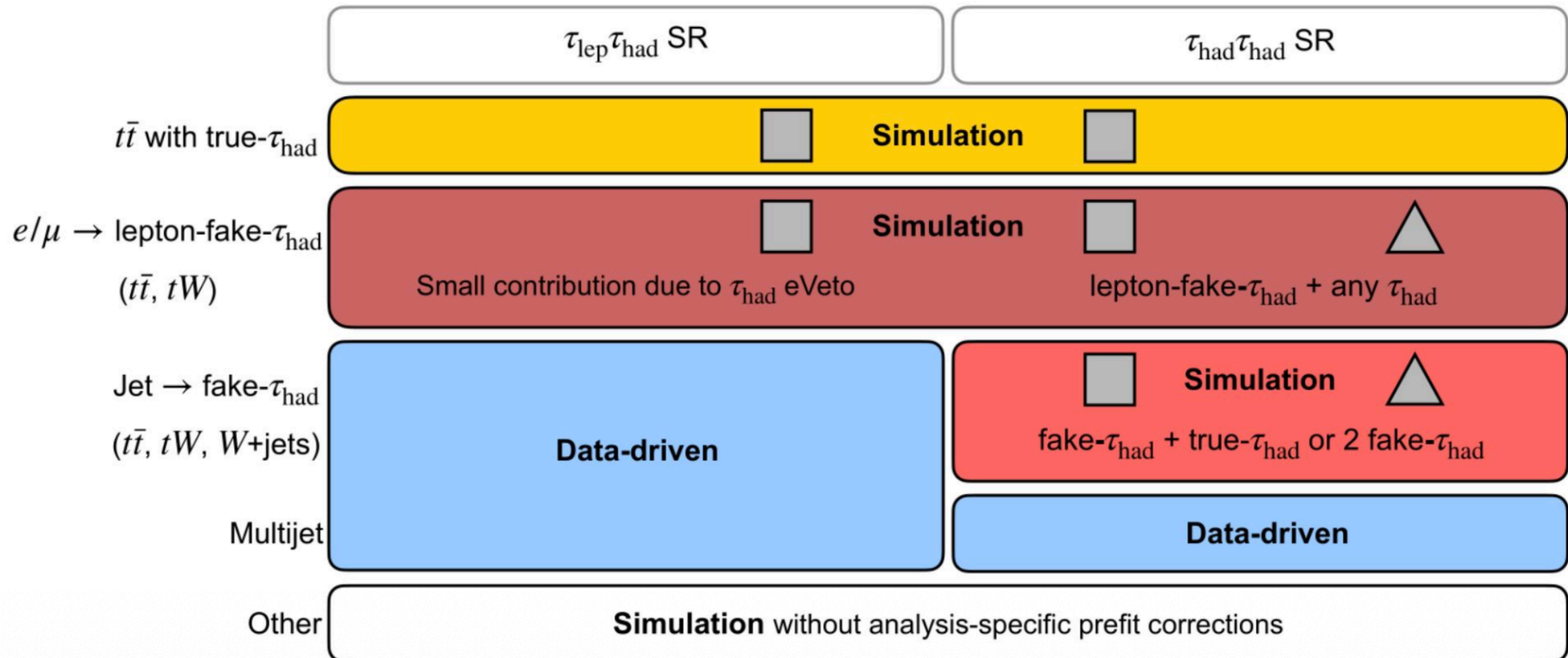
m_{bb} resolution improvement





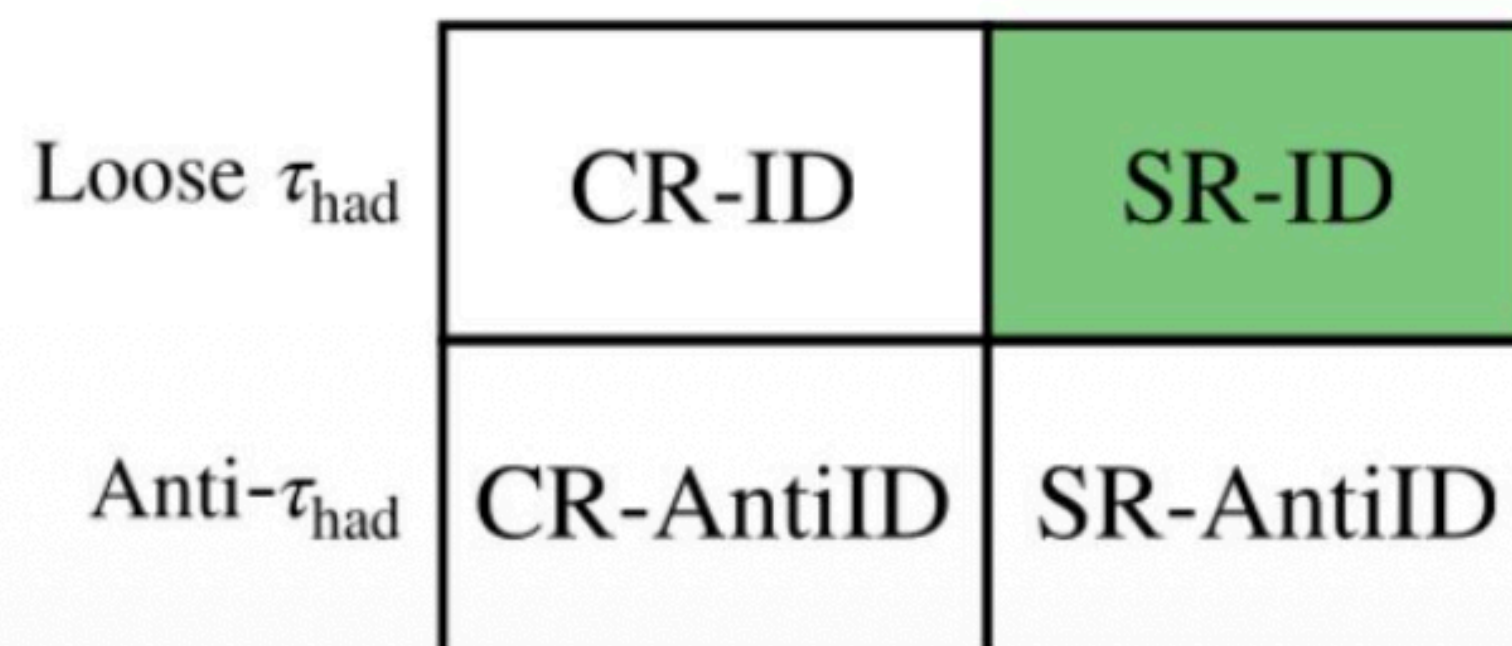
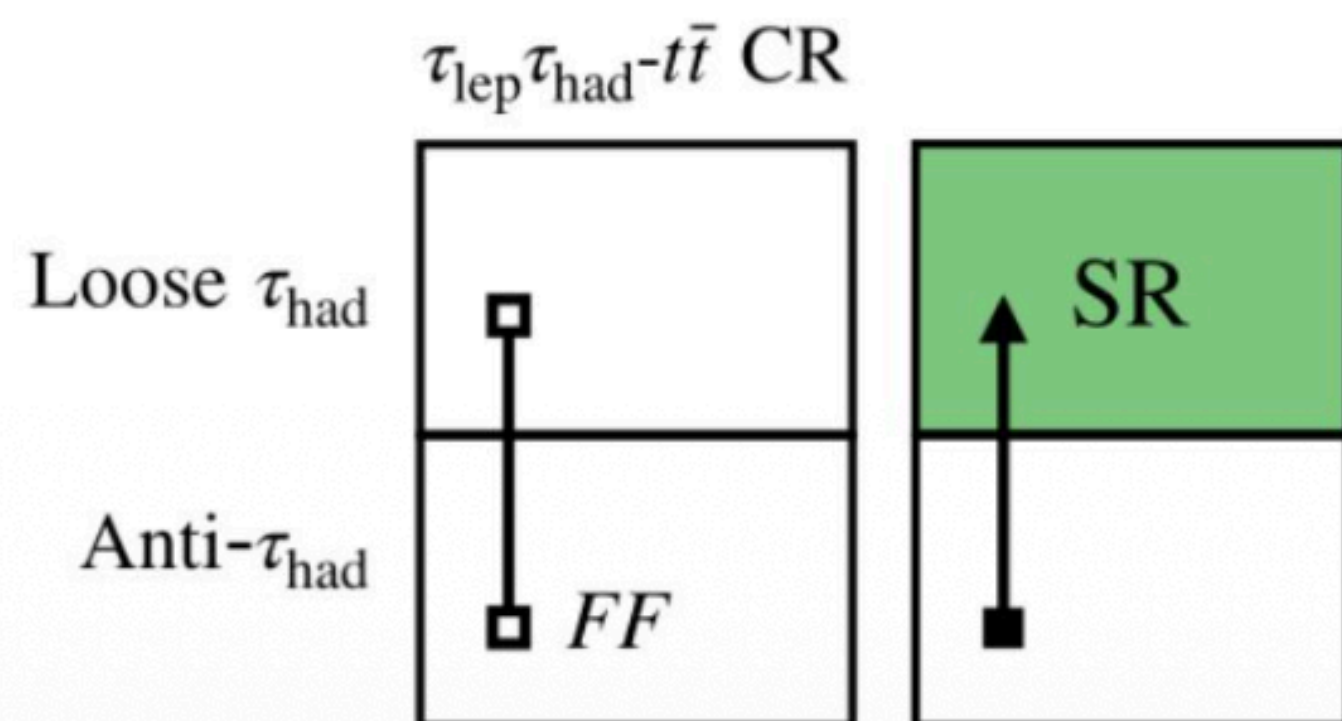
■ $t\bar{t}$ reweighting (derived in the $t\bar{t} - e\mu$ CR)

▲ Scale factors per jet $\rightarrow$ fake- τ_{had} (derived in the $\tau_{\text{lep}}\tau_{\text{had}} - t\bar{t}$ CR)

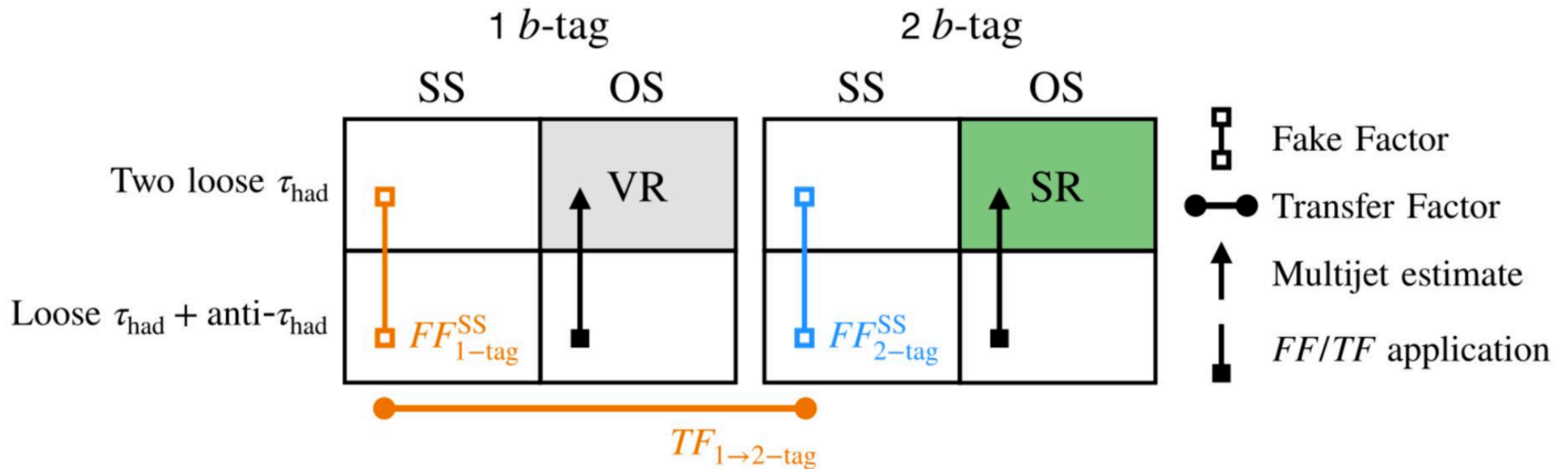


The FF method provides a data-driven estimate of the background contribution involving fake- τ_{had} . Four regions are defined:

- **SR-ID**: The region where the fake- τ_{had} background estimate is made. Exactly one τ_{had} passing the loose τ_{had} identification criteria is required in the event.
- **SR-AntiID**: Identical to the SR but requiring one anti- τ_{had} instead of one loose τ_{had} .
- **CR-ID**: A region orthogonal to the signal region. Exactly one τ_{had} passing the loose τ_{had} identification criteria is required in the event.
- **CR-AntiID**: Identical to the CR-ID but requiring one anti- τ_{had} instead of one loose τ_{had} .



$$FF = \frac{N_{CR-ID}^{Data} - N_{CR-ID}^{MC}(\text{true-}\tau_{had})}{N_{CR-AntiID}^{Data} - N_{CR-AntiID}^{MC}(\text{true-}\tau_{had})}.$$



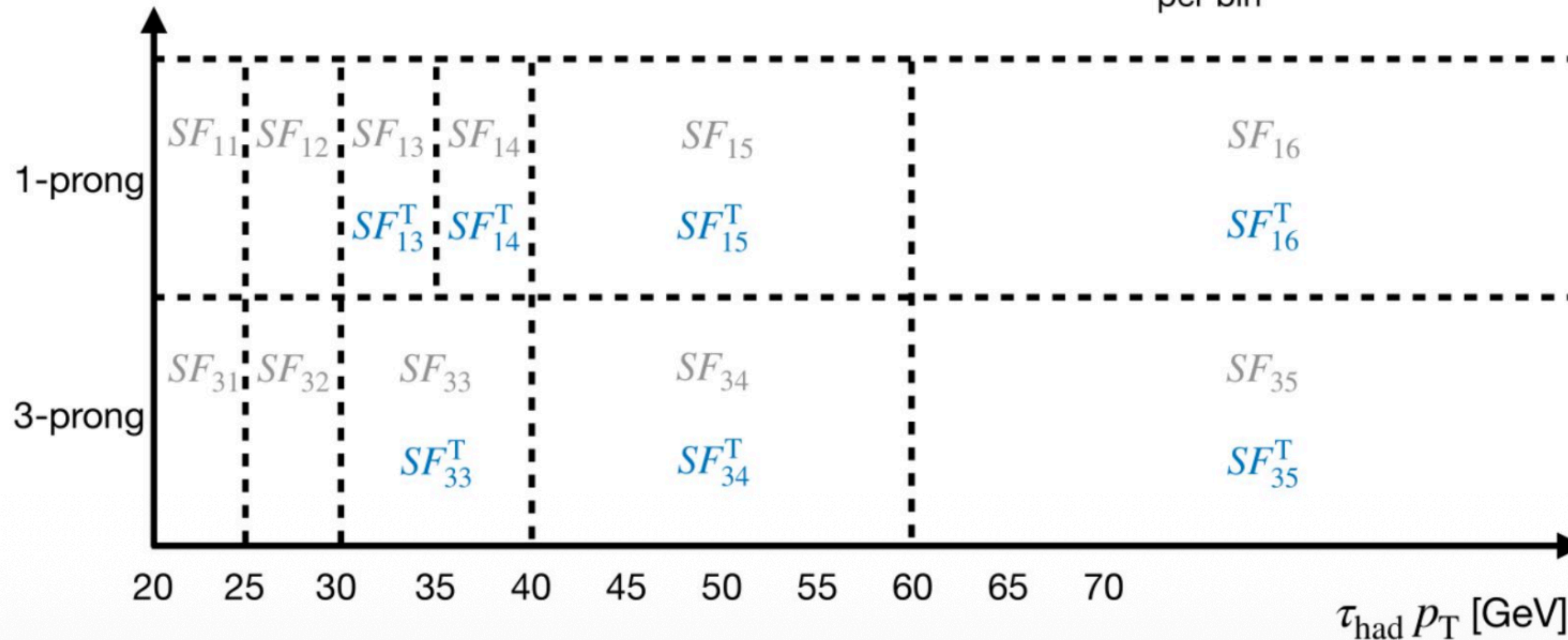
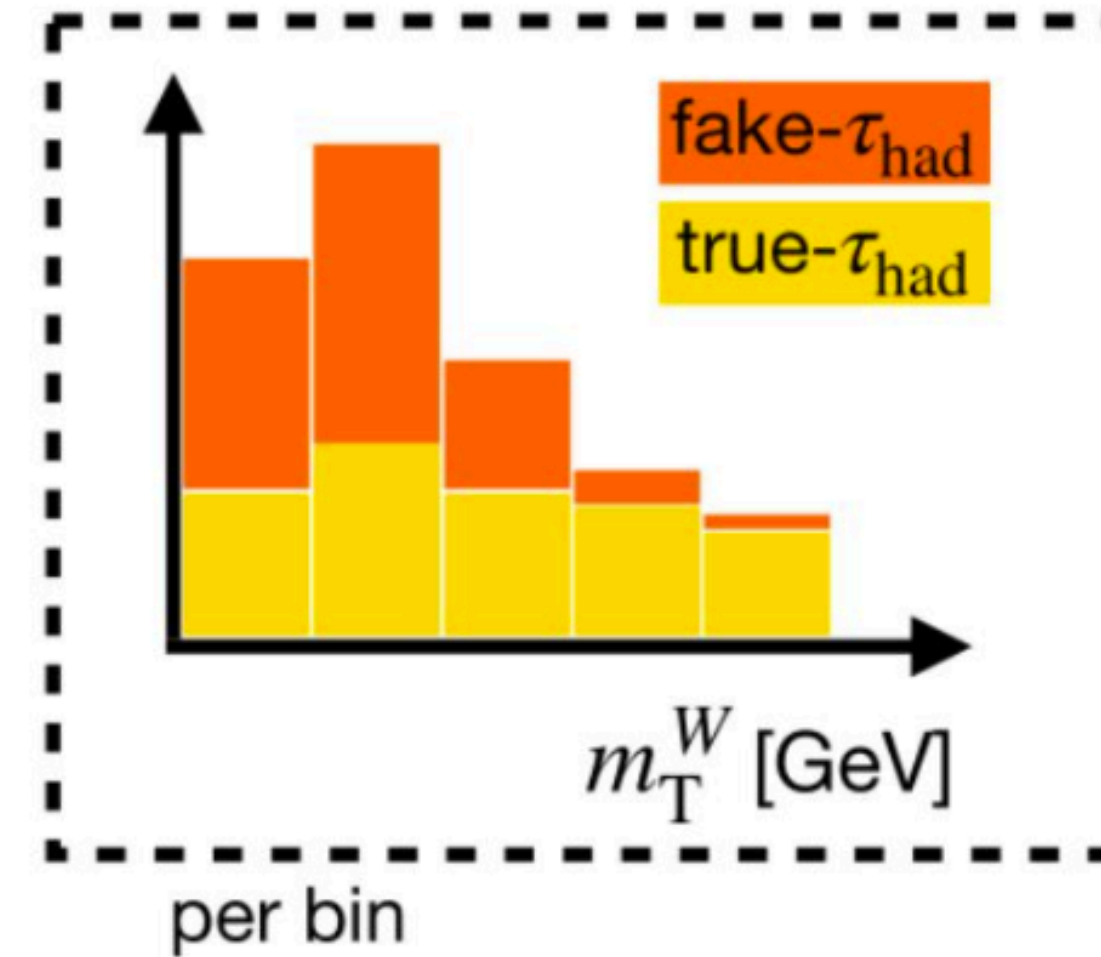
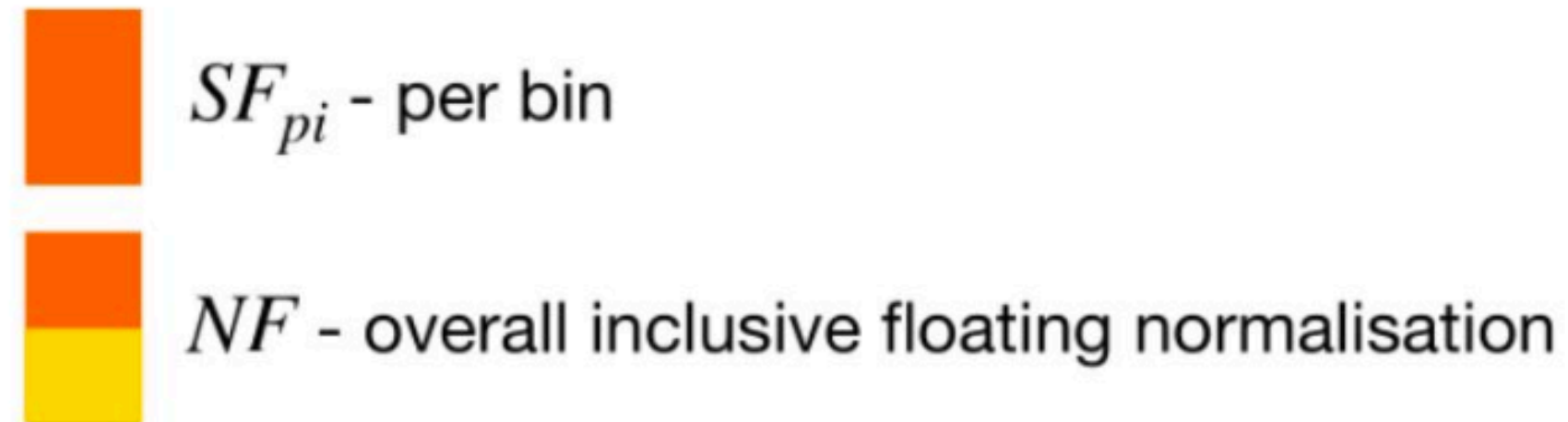
$$\text{STT/DTT} : FF_{1-tag}^{SS, \text{STT/DTT}} \cdot TF_{1 \rightarrow 2-tag} \cdot \{e_{2-tag, OS-AntiID, \text{STT/DTT}, i}^{\text{Data-MC}}\}$$

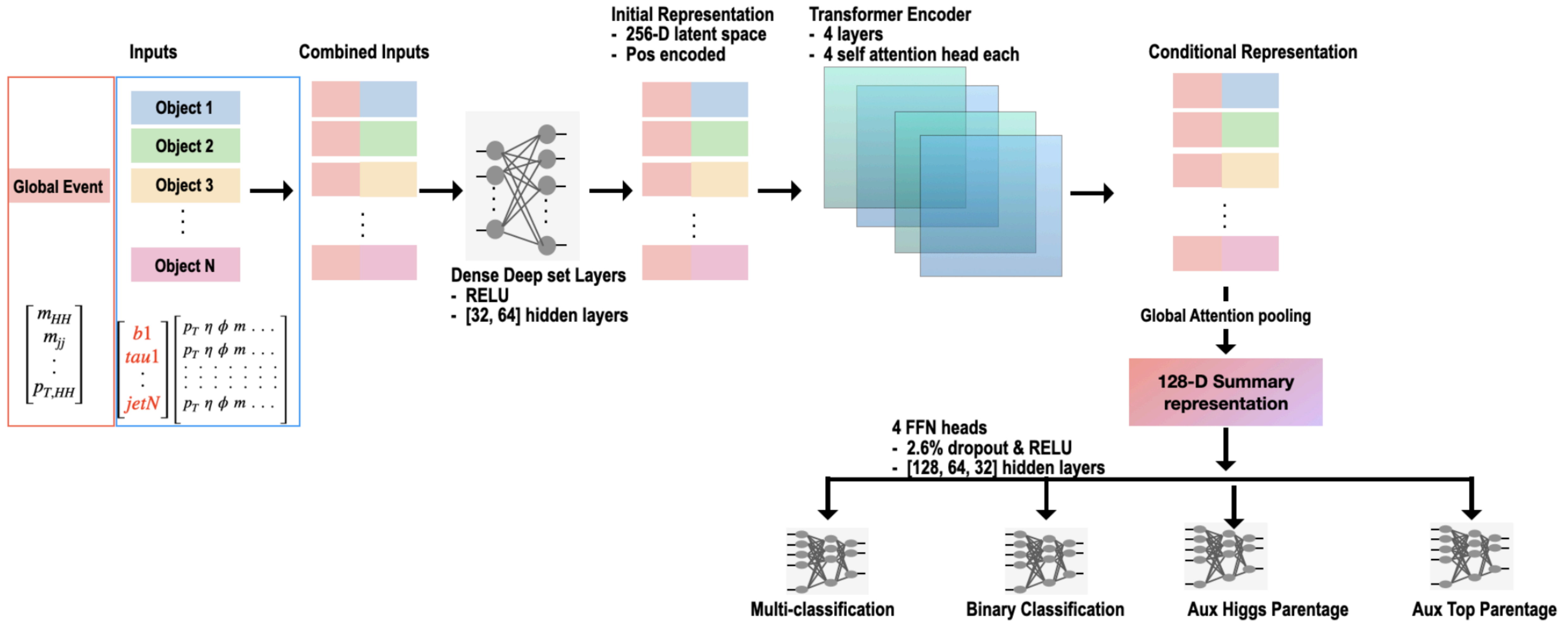
$$\text{DBT} : FF_{2-tag}^{SS, \text{DBT}} \cdot \{e_{2-tag, OS-AntiID, \text{DBT}, i}^{\text{Data-MC}}\}$$

Fakes from Top + W in $\tau_{had}\tau_{had}$ SF method

Fit 1: SF_{pi} - Offline ID fake- τ_{had} SFs

Fit 2: SF_{pi}^T - Offline + online ID fake- τ_{had} SFs

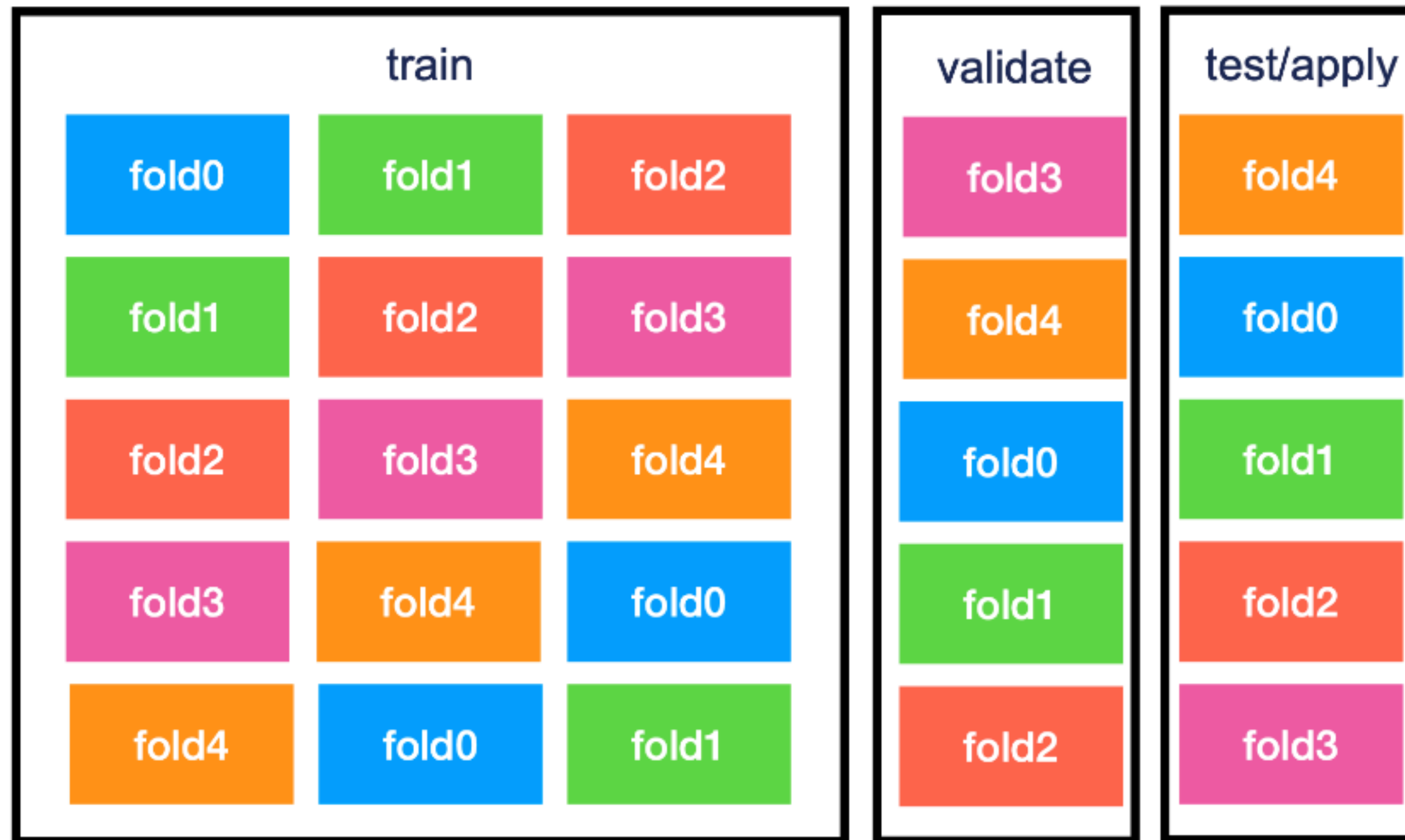




Event Variable	Description
Event-level features used in both the $\tau_{\text{had}}\tau_{\text{had}}$ and $\tau_{\text{lep}}\tau_{\text{had}}$ channels MVA	
m_{HH}	Mass of the reconstructed HH system (di- τ based on MMC)
m_{bb}	Invariant mass of the di- b -jet system
$\Delta R(b, b)$	ΔR between two b-jets
m_{jj}	Invariant mass of the system of two p_{T} -leading VBF jets
ΔR_{jj}	ΔR between the two p_{T} -leading VBF jets
$\eta_{\text{VBF } j_0} \cdot \eta_{\text{VBF } j_1}$	Product of pseudorapidities of the two p_{T} -leading VBF jets
Event-level features used only in the $\tau_{\text{had}}\tau_{\text{had}}$ channel MVA	
$\Delta R(\tau, \tau)$	ΔR between the two τ_{had}
Event-level features used only in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel MVA	
$\Delta R(\tau_{\text{had}}, \ell)$	ΔR between the τ_{had} and electron or muon
$p_{\text{T}, HH}$	Transverse momentum of the reconstructed HH system (di- τ based on MMC)
η_{HH}	Pseudorapidity of the reconstructed HH system (di- τ based on MMC)
$E_{\text{T}}^{\text{miss}}$	Missing transverse energy
$\Delta R(b_0, \tau_{\text{had}})$	ΔR between the p_{T} -leading b -jet and the τ_{had}
$\Delta R(b_1, \tau_{\text{had}})$	ΔR between the p_{T} -subleading b -jet and the τ_{had}
$m_{b\ell}$	$\min(x, y)$, where $x = \max(m_{b_1, \ell_1}, m_{b_2, \ell_2})$ and $y = \max(m_{b_1, \ell_2}, m_{b_2, \ell_1})$
$m_{\tau\tau}^{\text{vis}}$	Mass of the visible decay products in the di- τ system
$p_{\text{T}, \tau\tau}^{\text{vis}}$	Transverse momentum of the visible decay products in the di- τ system
T_1	Topness, as defined in Ref. [37] assuming $\sigma_t = 5 \text{ GeV}$ and $\sigma_W = 5 \text{ GeV}$
H_{T}	Total hadronic transverse energy in the event, perpendicular to the beamline
$\Delta\eta(bb, \tau\tau)$	$\Delta\eta$ between the di- b -jet and di- τ (from MMC) systems
$\Delta\phi(\tau\tau, E_{\text{T}}^{\text{miss}})$	$\Delta\phi$ between the missing transverse energy and the di- τ system (from MMC)
$\Delta R(b_1, l)$	The ΔR between the sub-leading b -tagged jet and lepton
$m_{\text{T}}(\tau_{\text{had}}, 0)$	Transverse mass of the leading $\tau_{\text{had-vis}}$

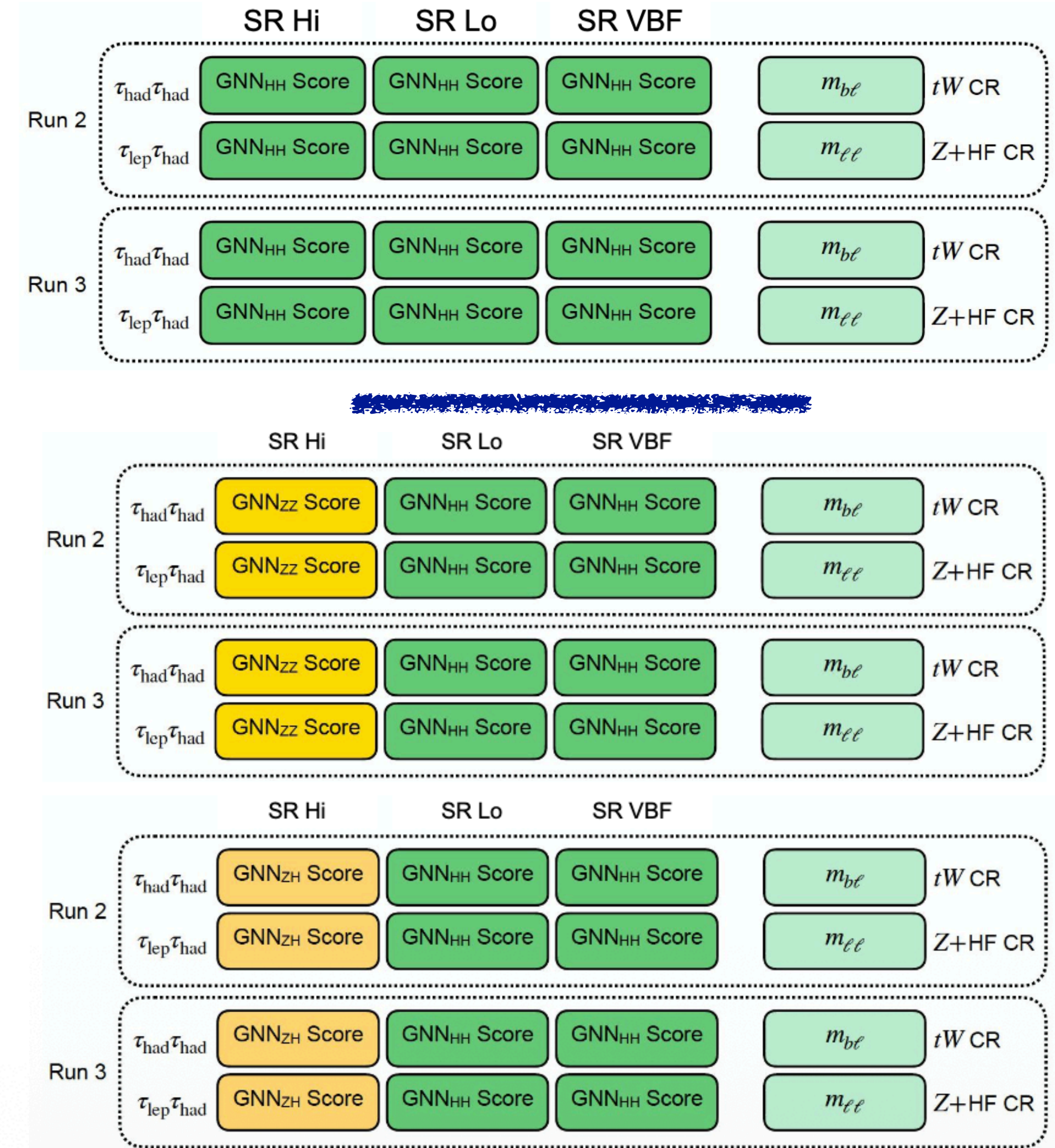
Object Variable	Description
η	Pseudorapidity
ϕ	Azimuthal angle
m	Mass
p_{T}	Transverse momentum
isTau	Flag indicating whether the object is a τ_{had}
isJet	Flag indicating whether the object corresponds to a jet that is not identified as b-tagged.
isBjet	Flag indicating whether the object is a b -jet
PCBT	GN2 pseudocontinuous b -tagging score ranging from 3 to 6 (85-77-70-65-0 efficiency bins). The default value is set to -2.0 for objects that are not b-jets.
isMET	Flag indicating whether the object is missing transverse energy
isMMC	Flag indicating whether the object is the MMC di- τ system

5-fold cross validation

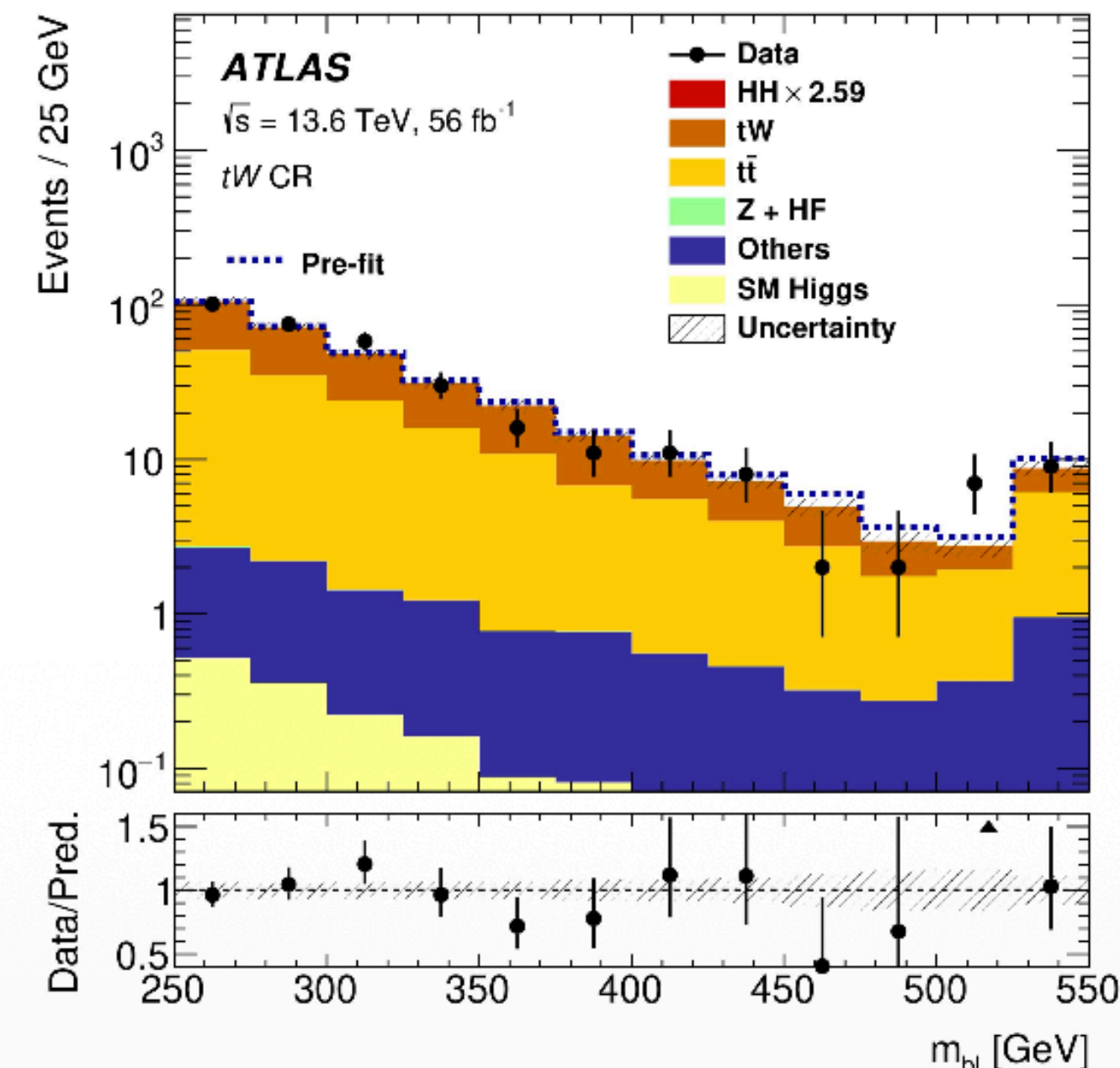
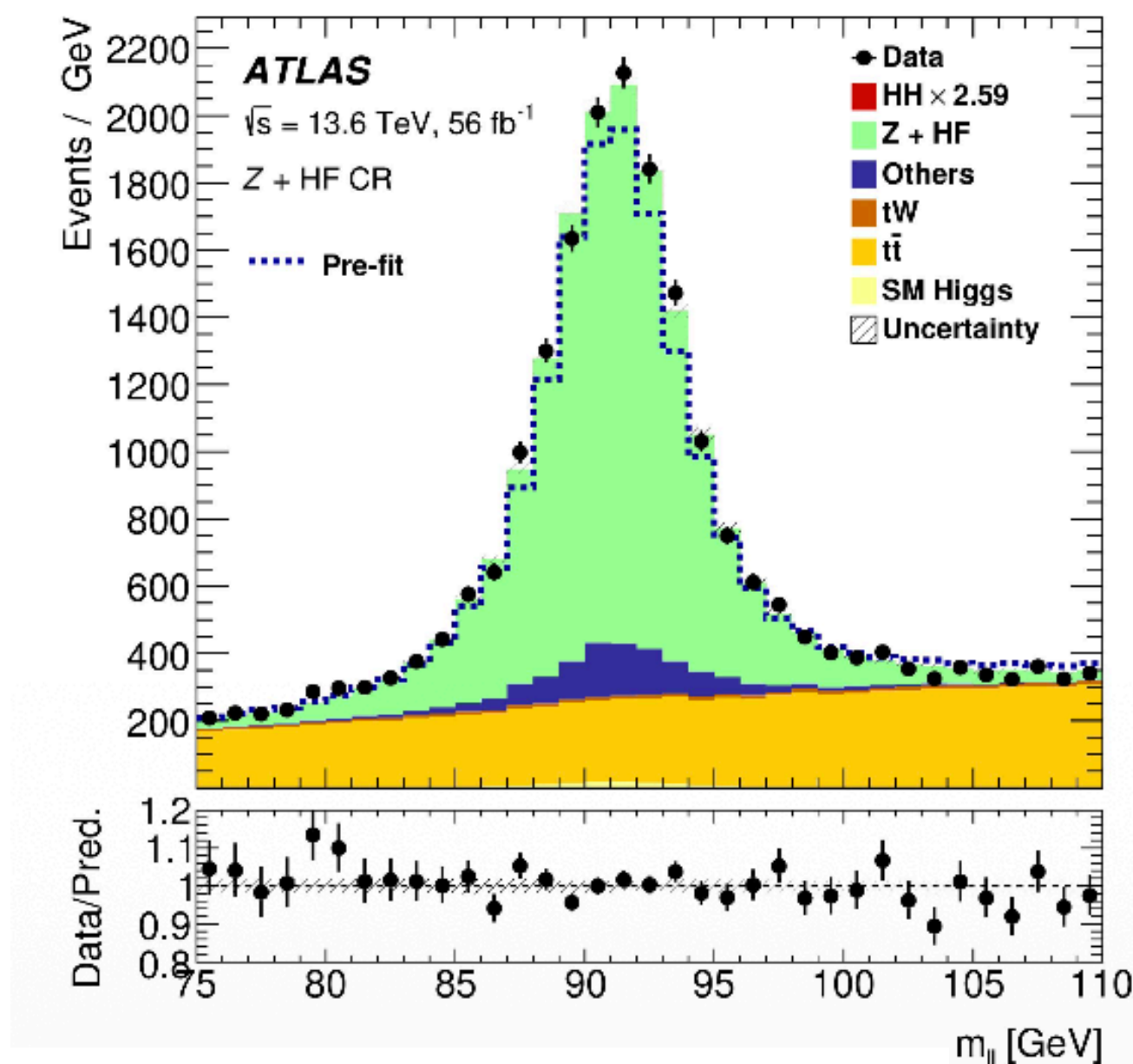
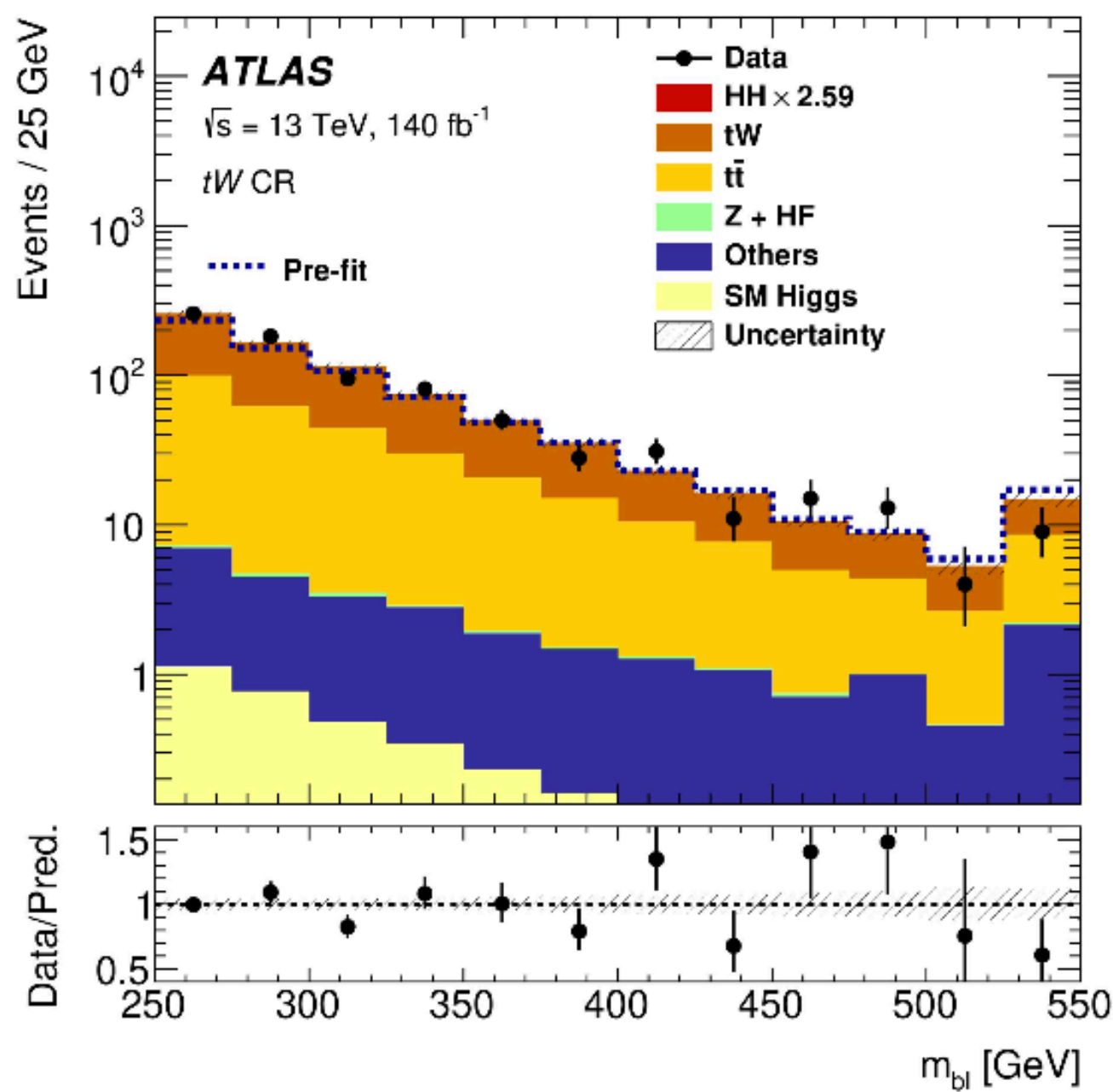
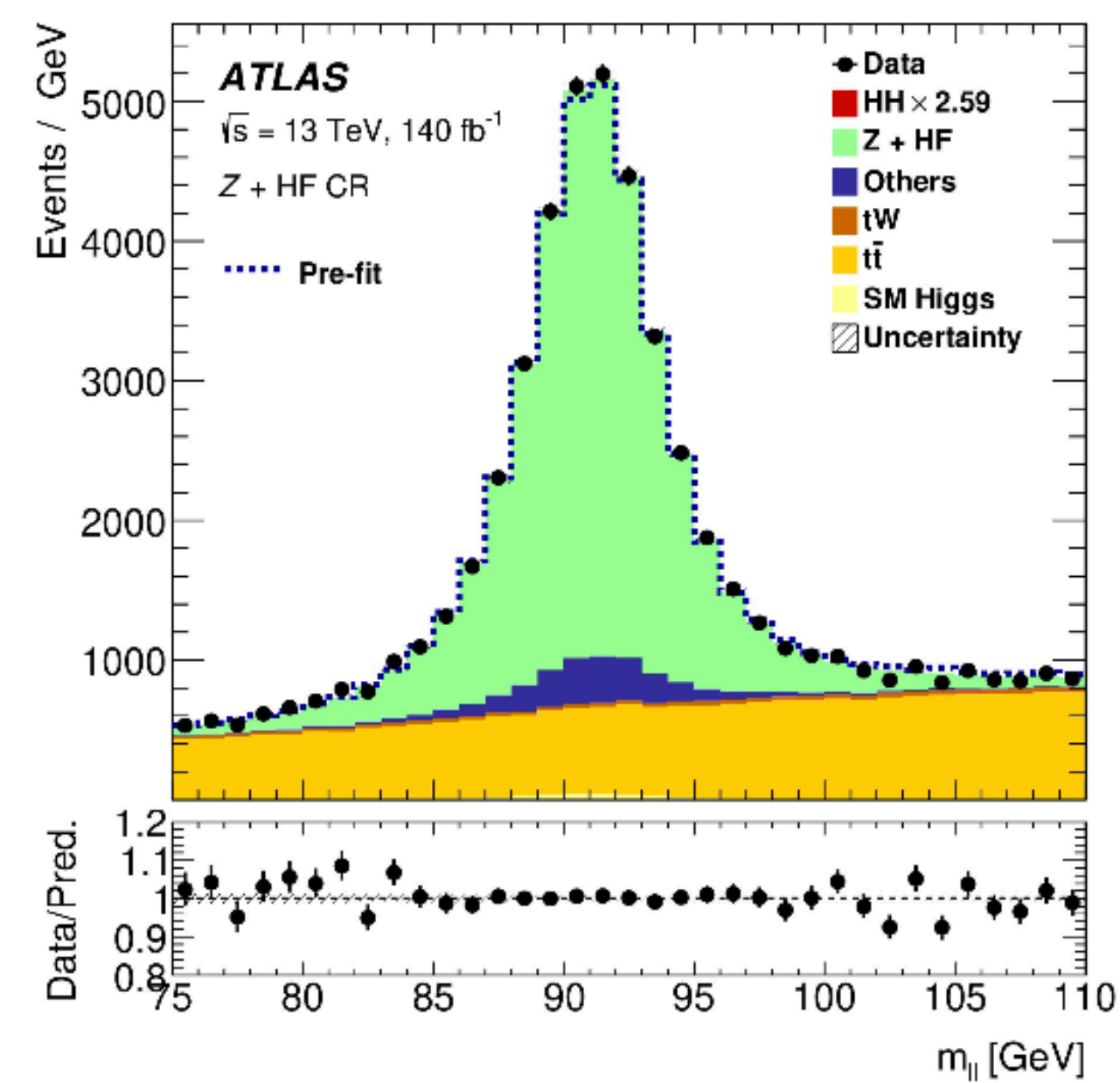


train ensemble of networks with different seeds, take the one closest to mean performance

- Standard profile-likelihood fit using 16 regions:
 - SR Hi, Lo, VBF and Z+HF, tW CRs (per channel, Run)
 - Floating normalisations factors for: ttbar, Z+HF, and tW
 - POIs: HH signal strength
- SRs use rebinned MVA scores to maximize expected HH significance
- To study individual contributions: can run the fit with multiple POIs per HH component/region
 - E.g. μ_{HH}^{Run2} , μ_{HH}^{Run3}
- Auxiliary ZZ/ZH measurements use same setup
 - only changing the MVA model and POIs in SR Hi to target ZZ/ZH
- Experimental uncertainties uncorrelated between Run 2 and Run 3
 - Except: the jet energy scale and resolution are treated as correlated between Run 2 and Run 3 → Run 2 data is used to provide Run 2 and Run 3 recommendations

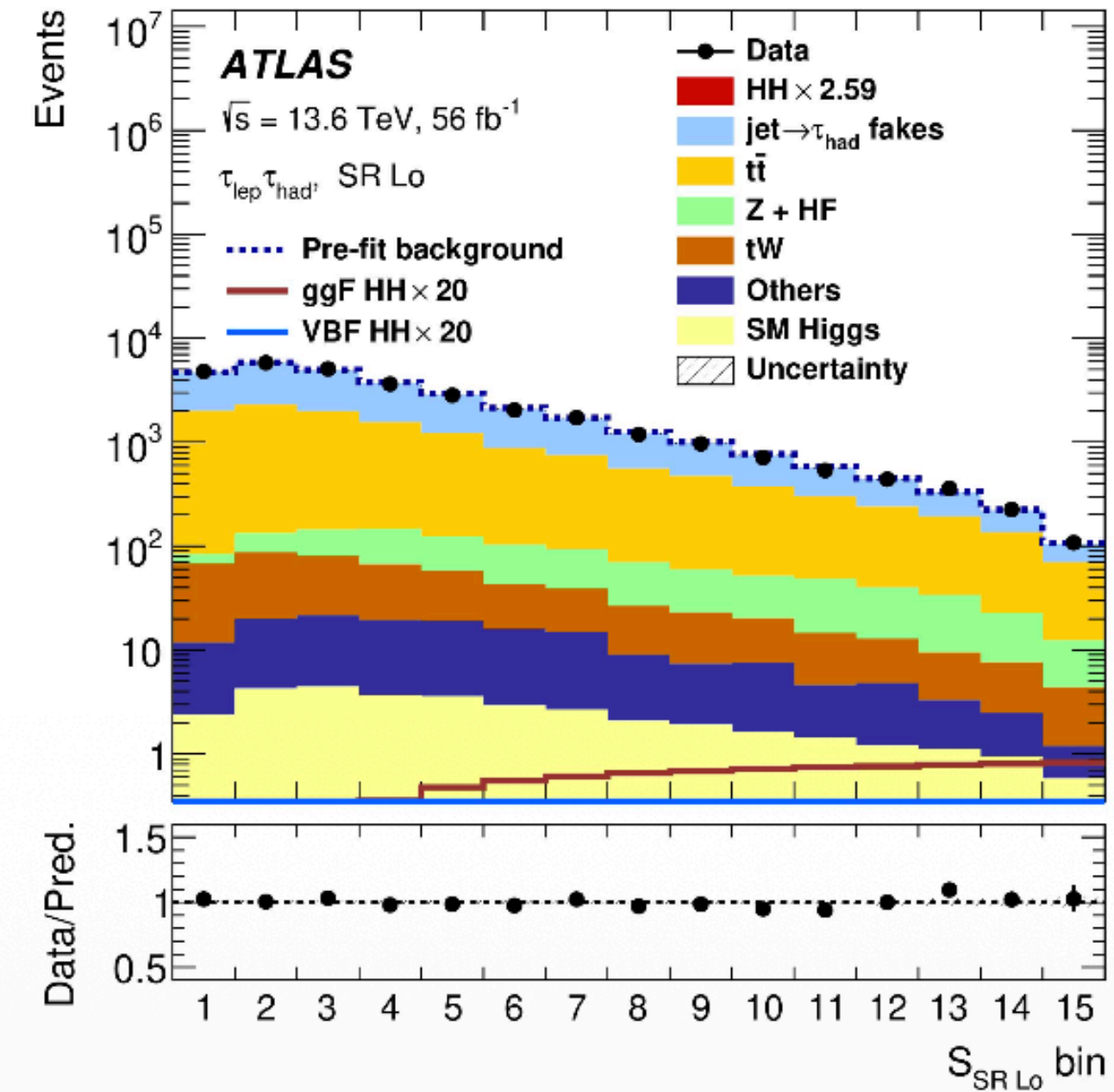
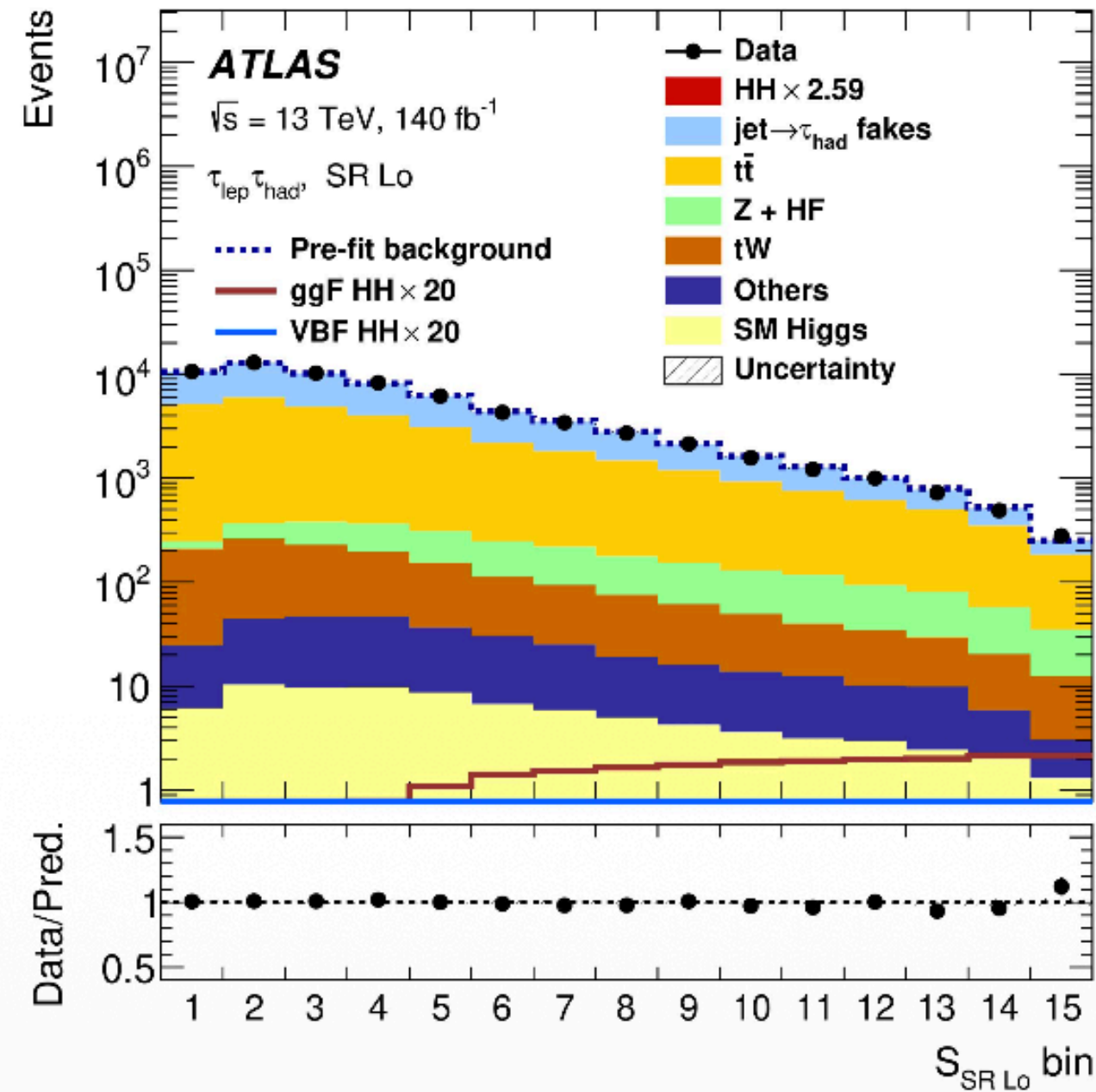
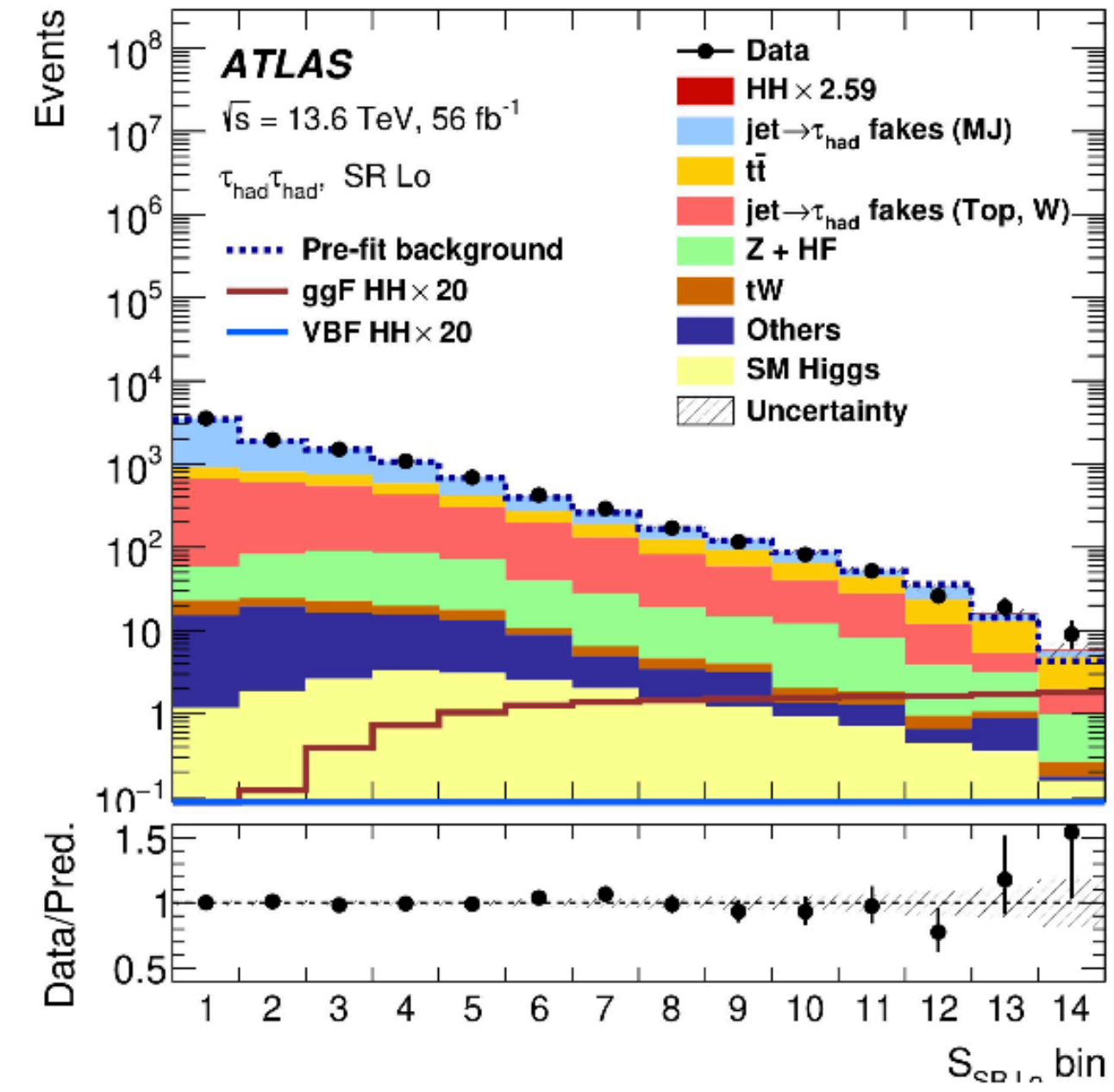
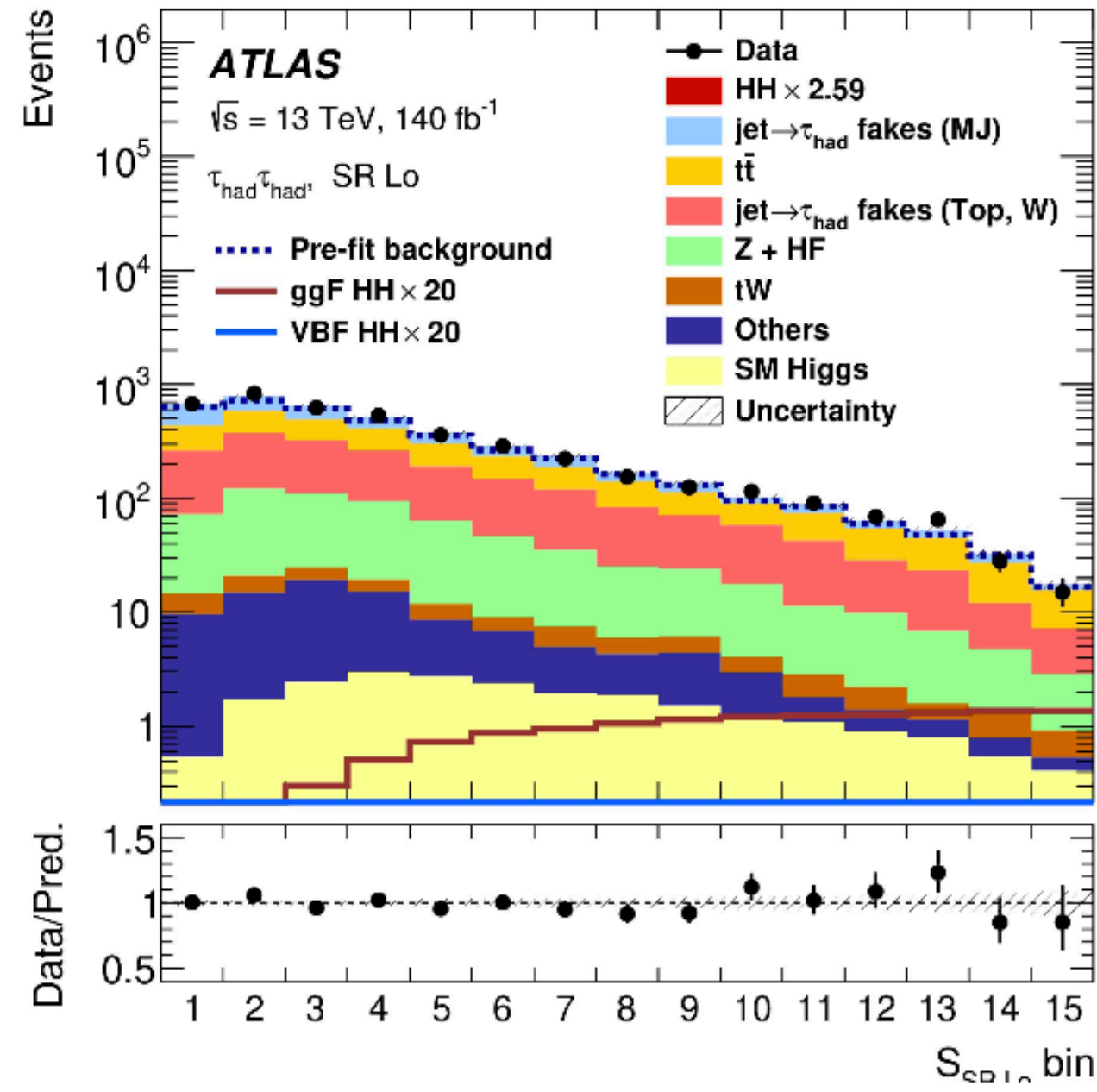


Control regions post-fit plots and NF values

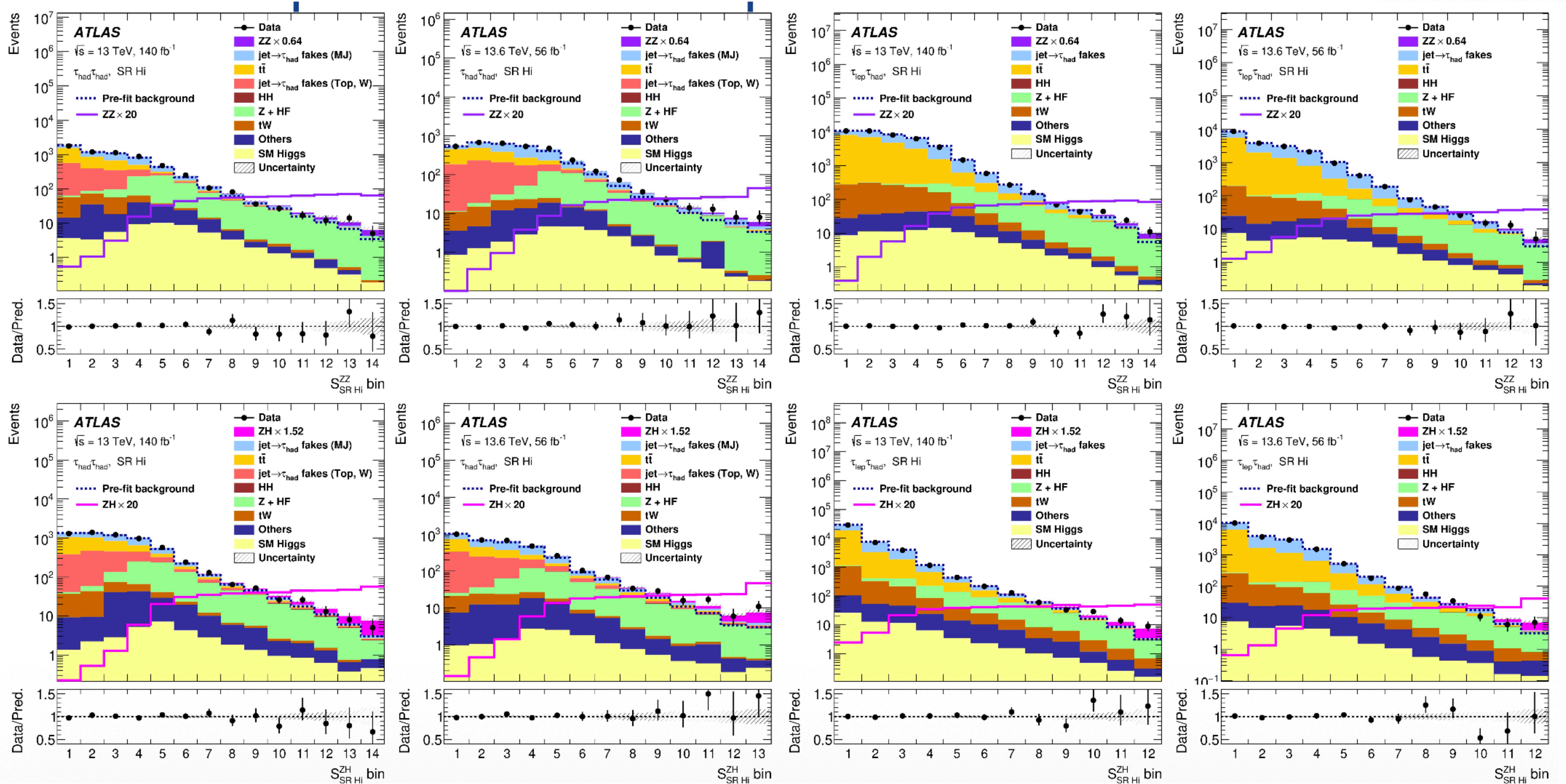


	NF_{Z+HF}	$NF_{t\bar{t}}$	NF_{tW}
Run 2	1.11 ± 0.08	0.97 ± 0.04	1.34 ± 0.16
Run 3	1.21 ± 0.11	0.96 ± 0.05	1.05 ± 0.19

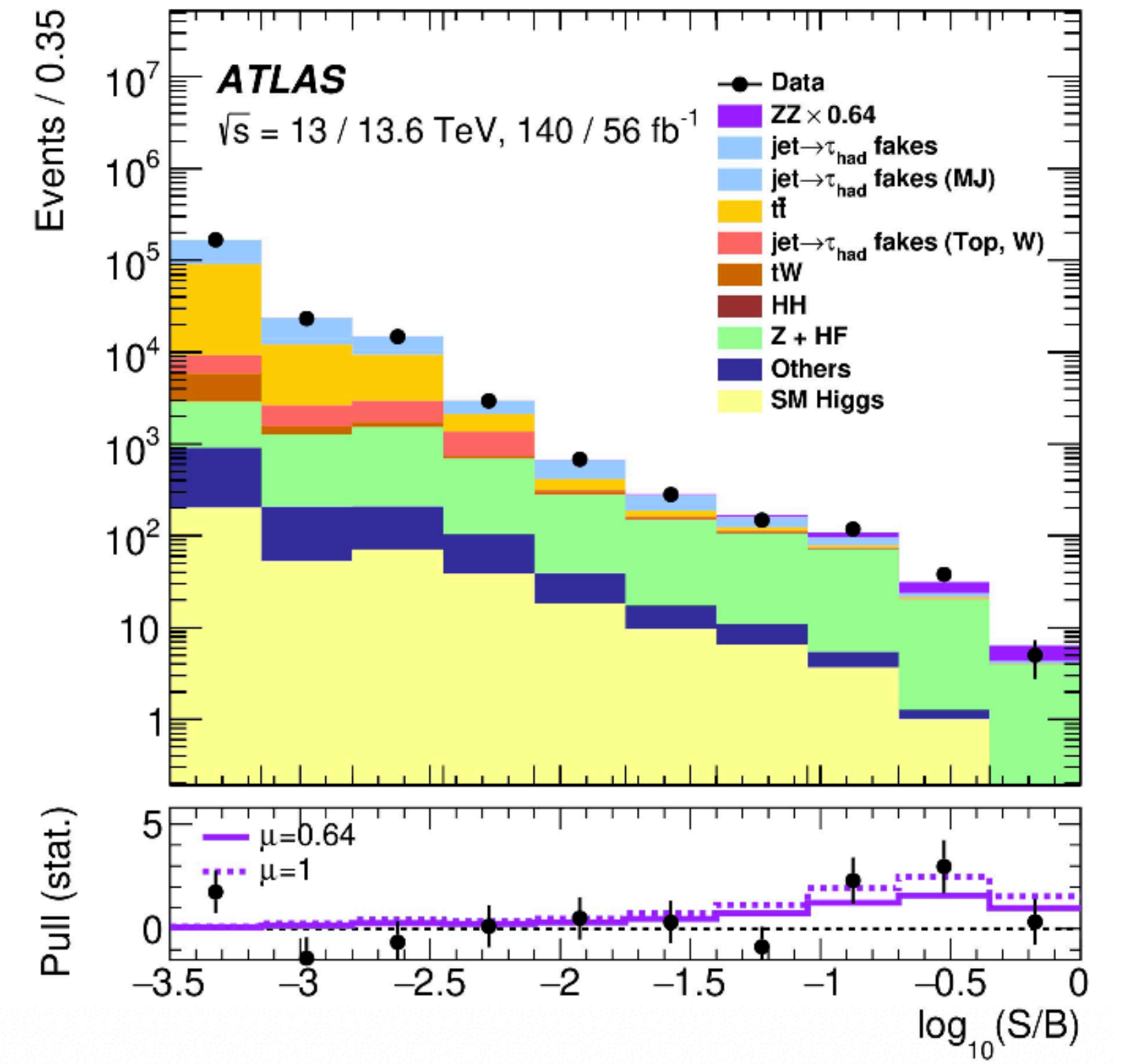
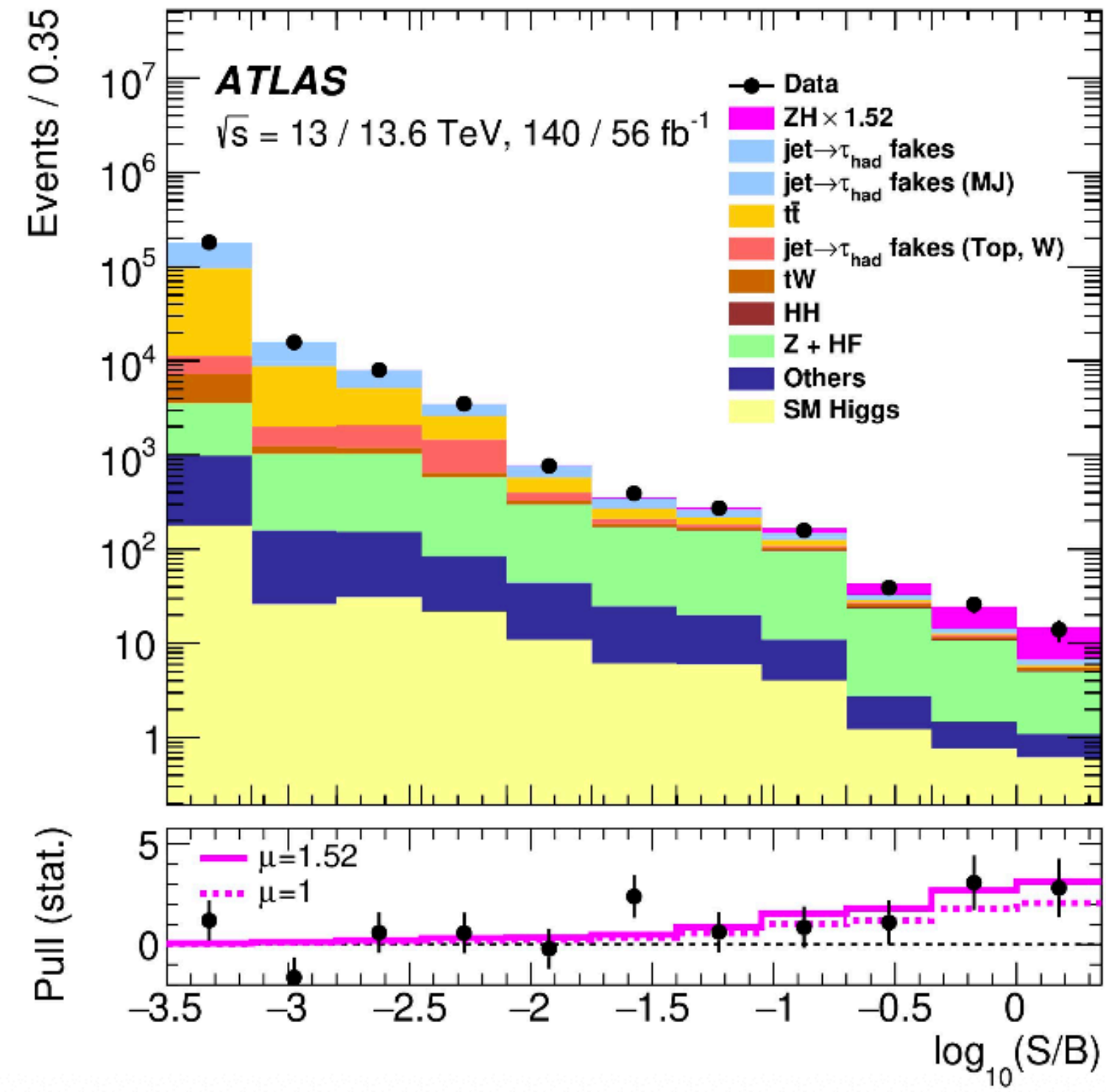
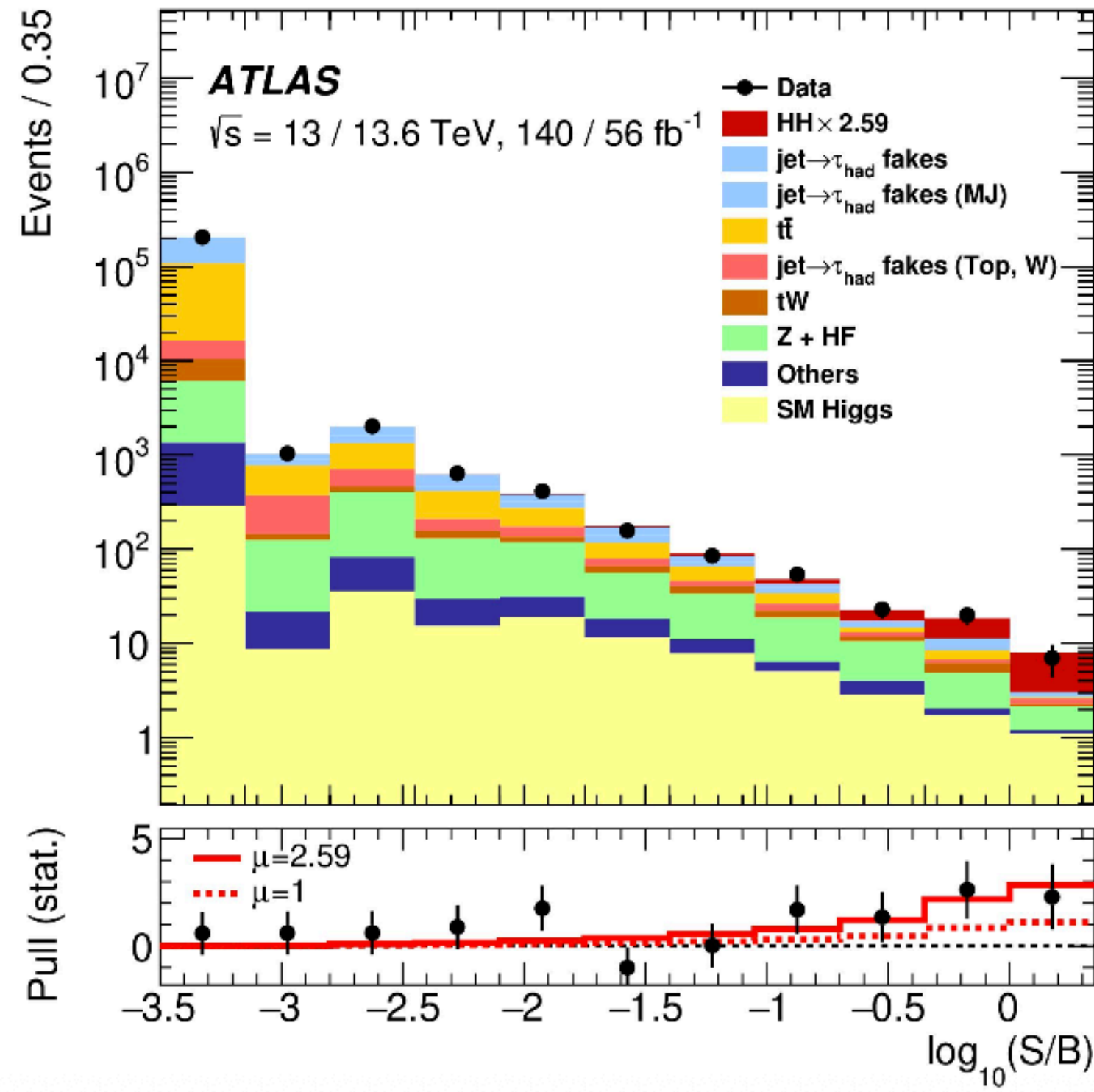
SR Lo post-fit plots

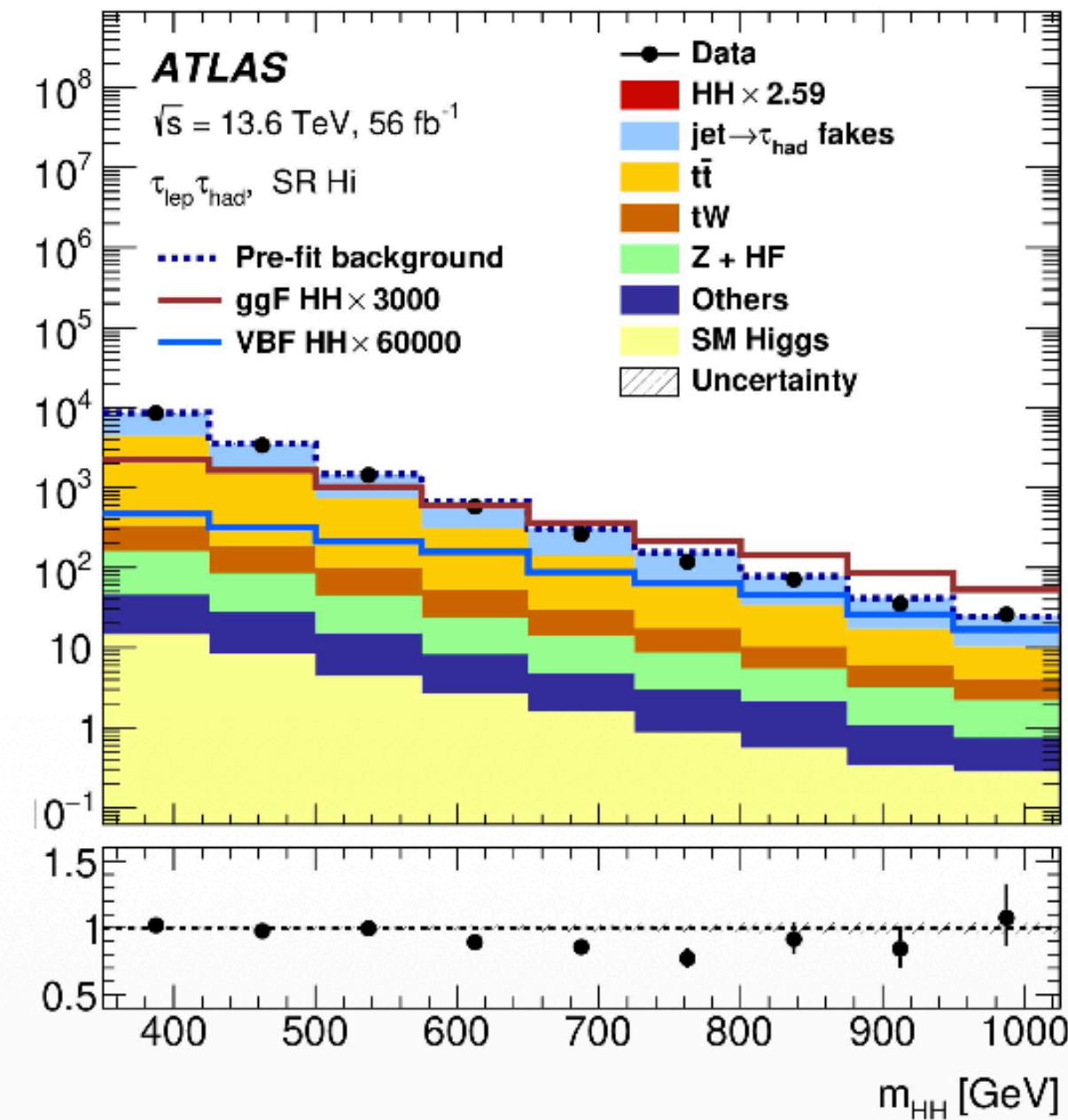
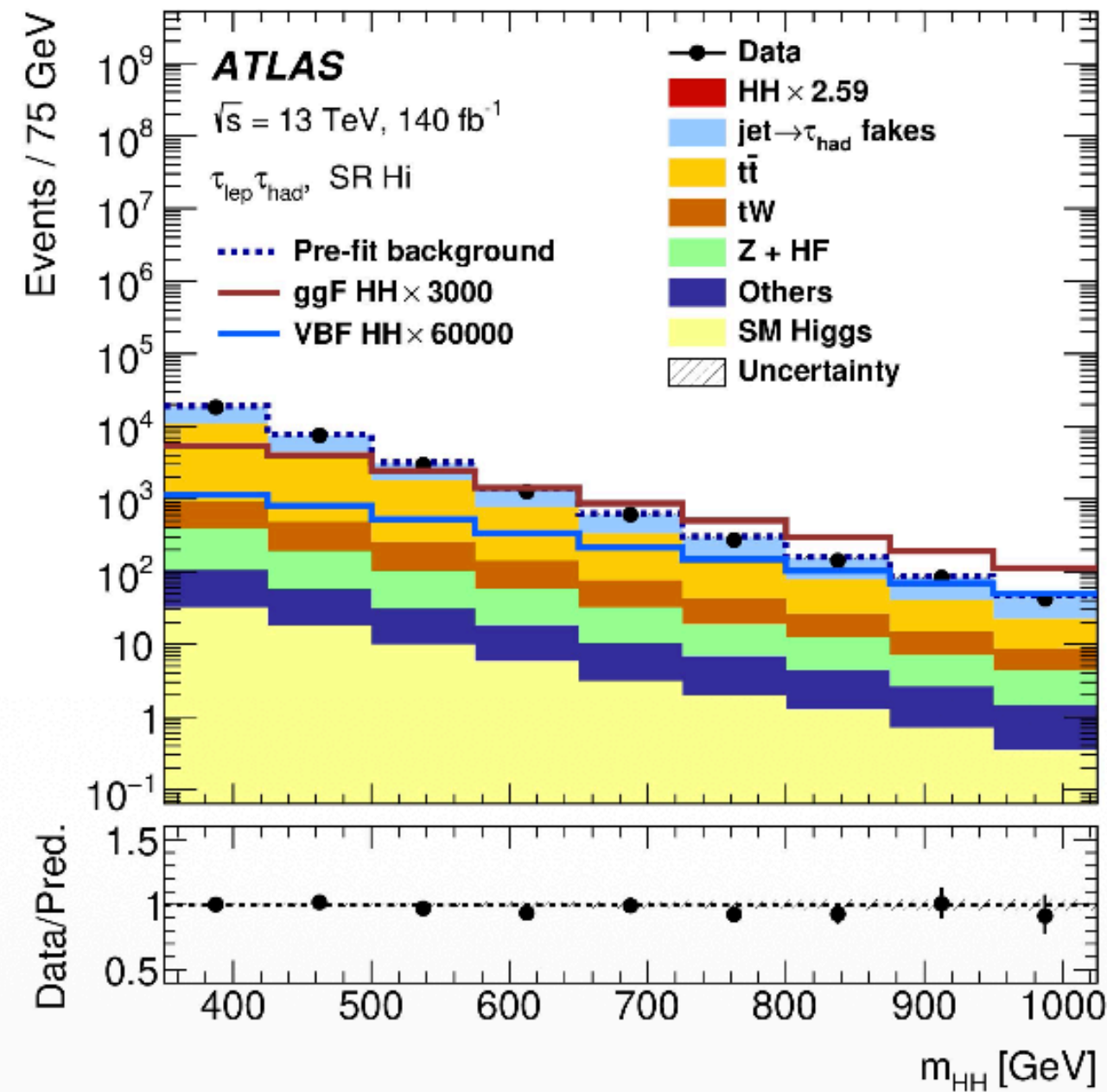
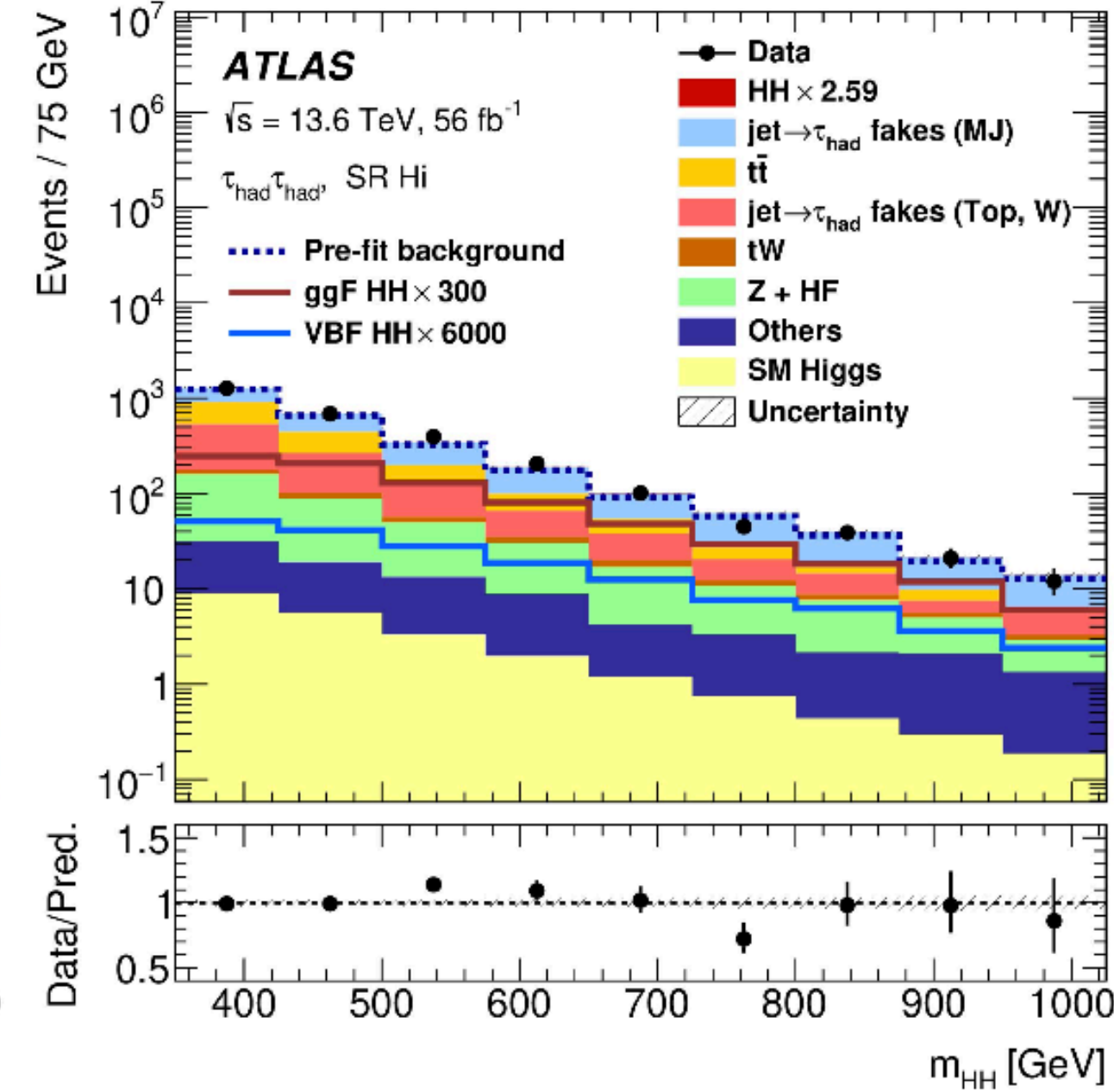
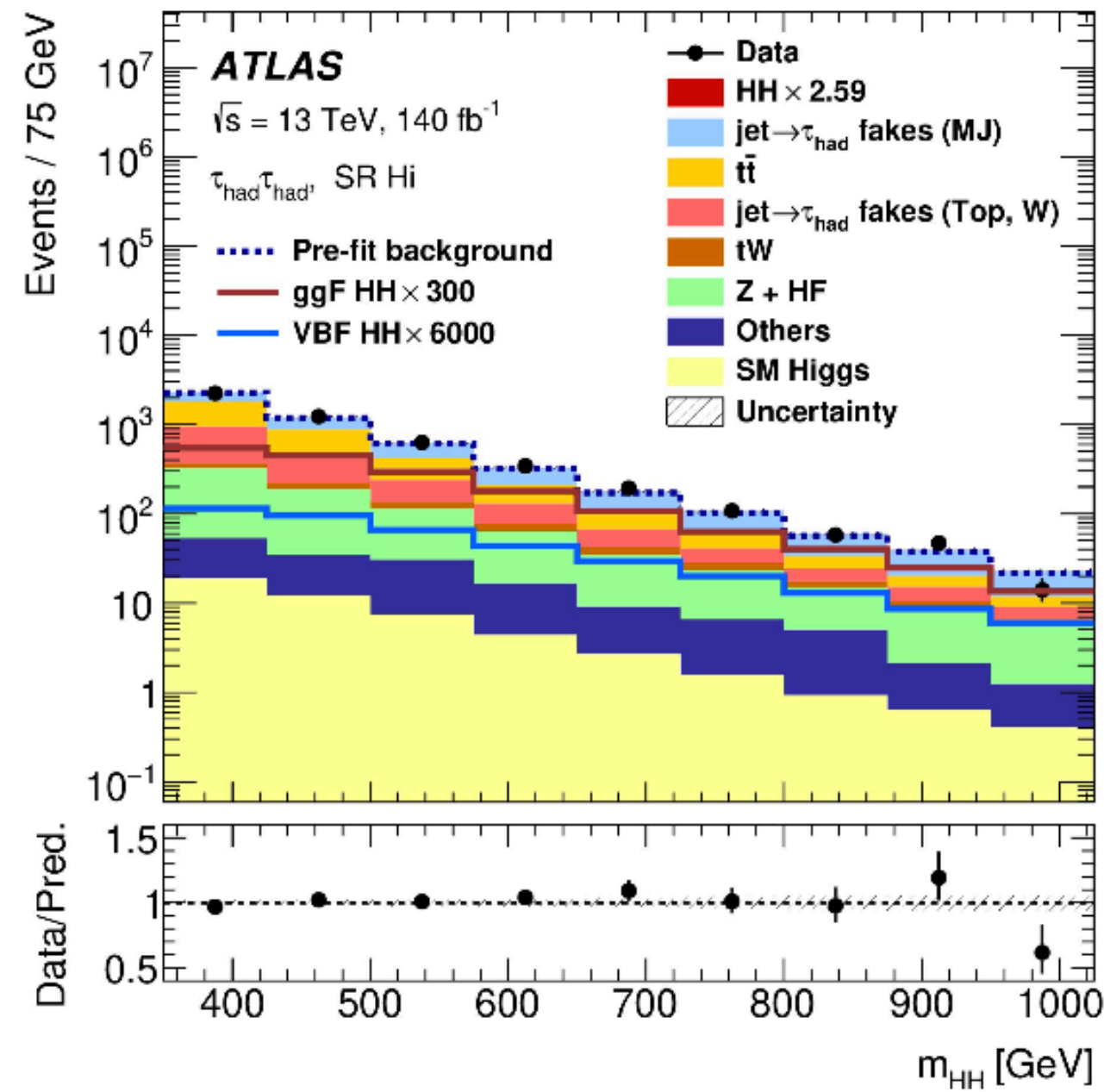


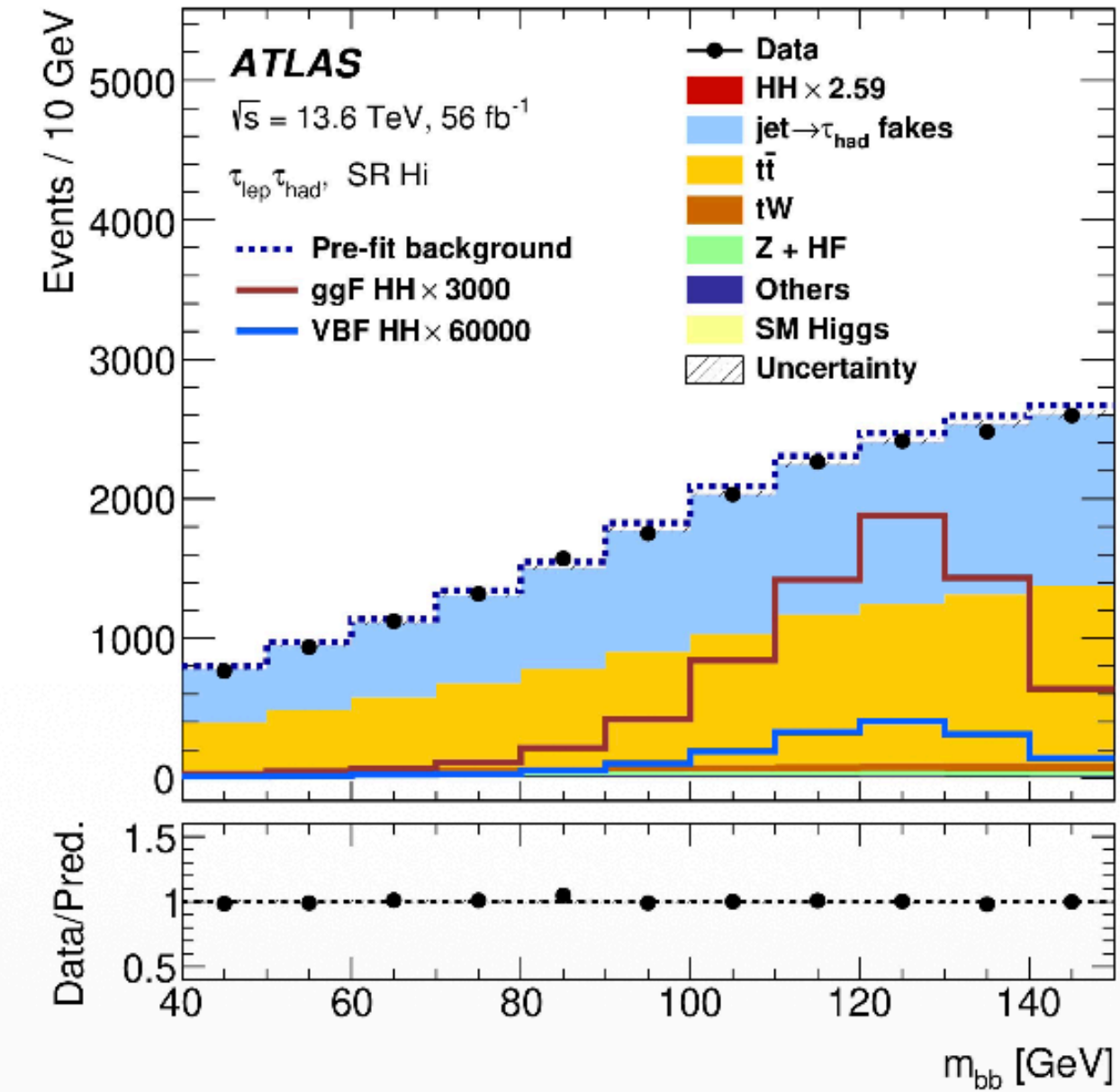
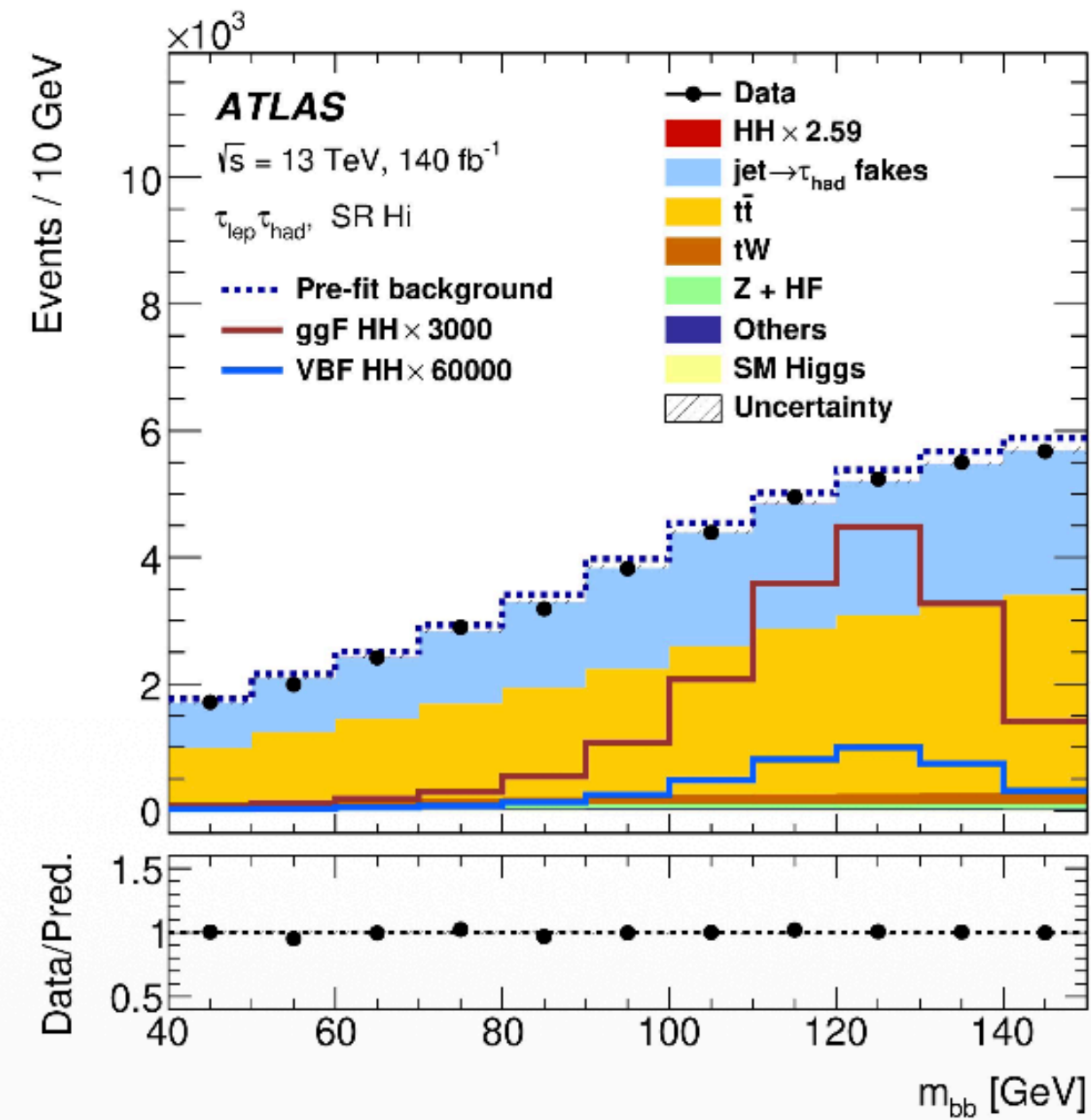
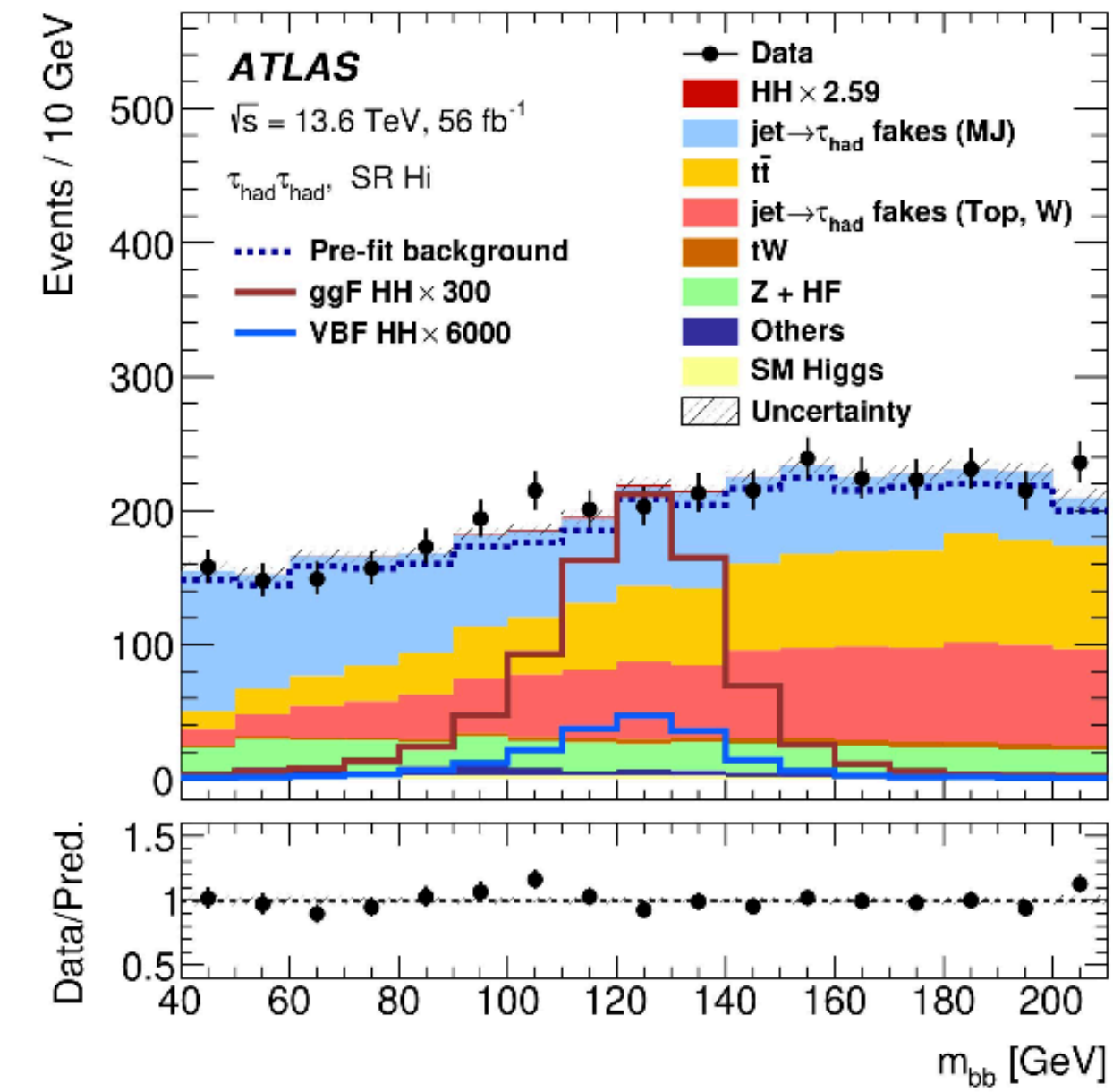
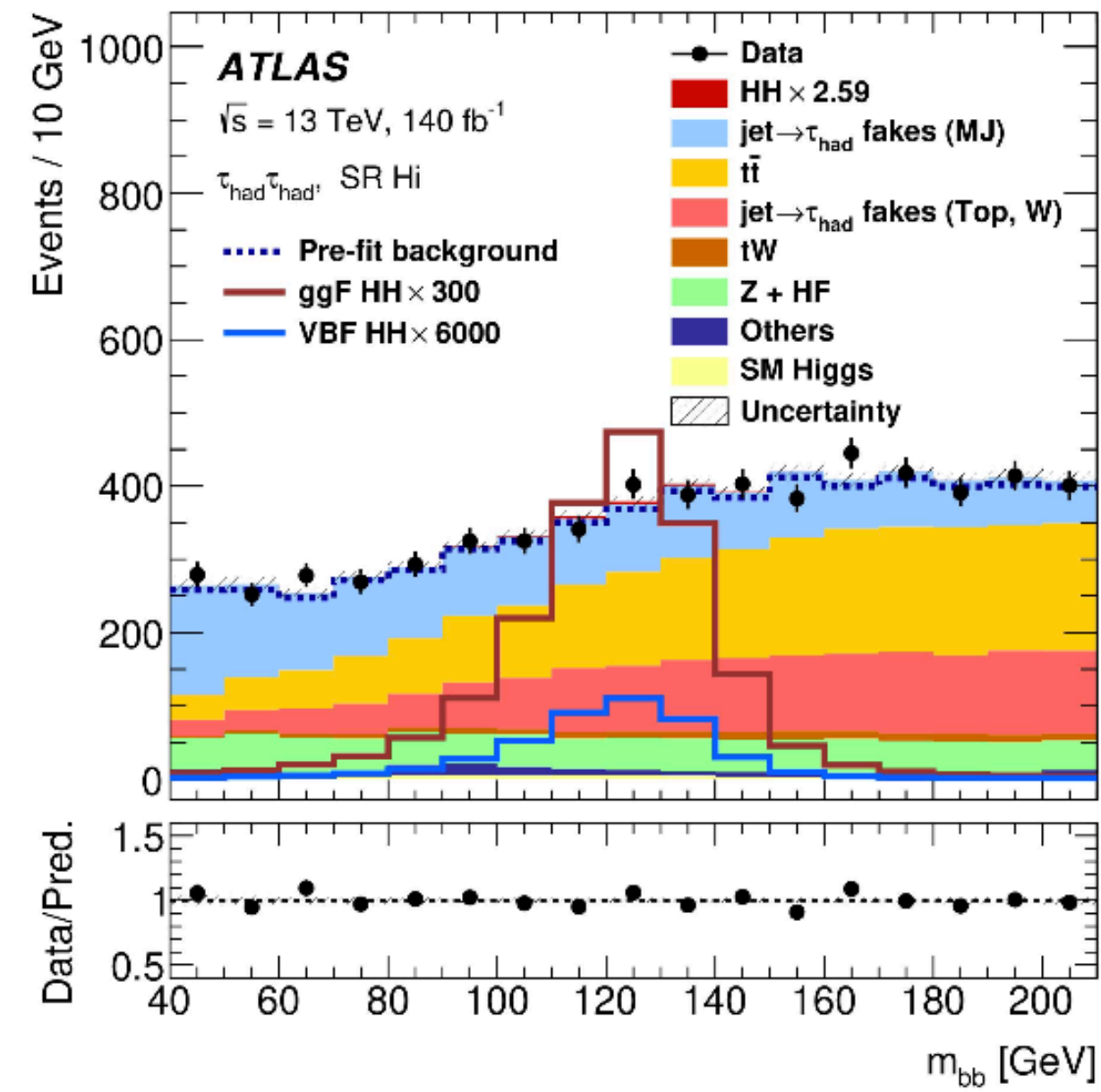
ZZ and ZH postfit GNN score plots

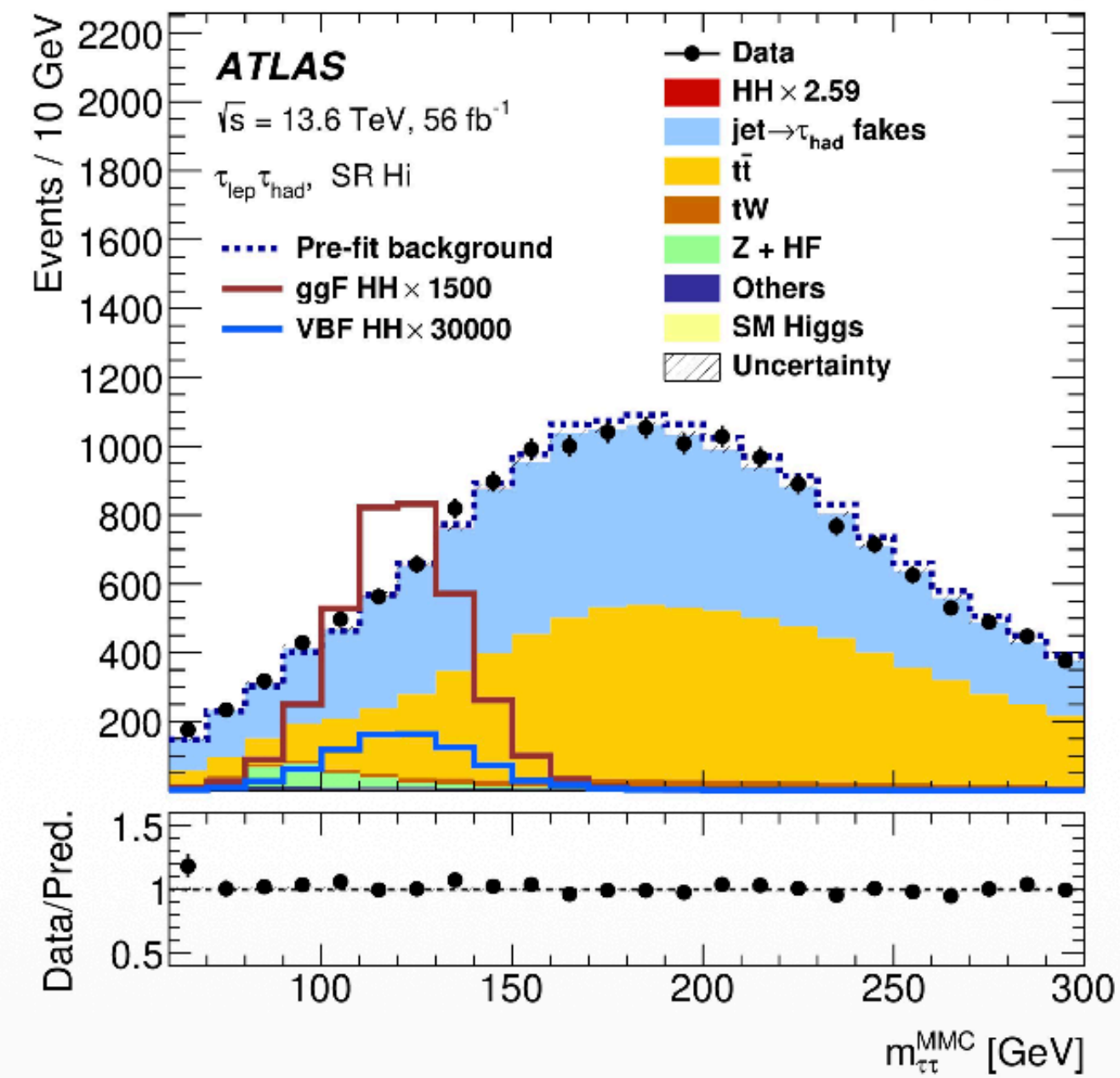
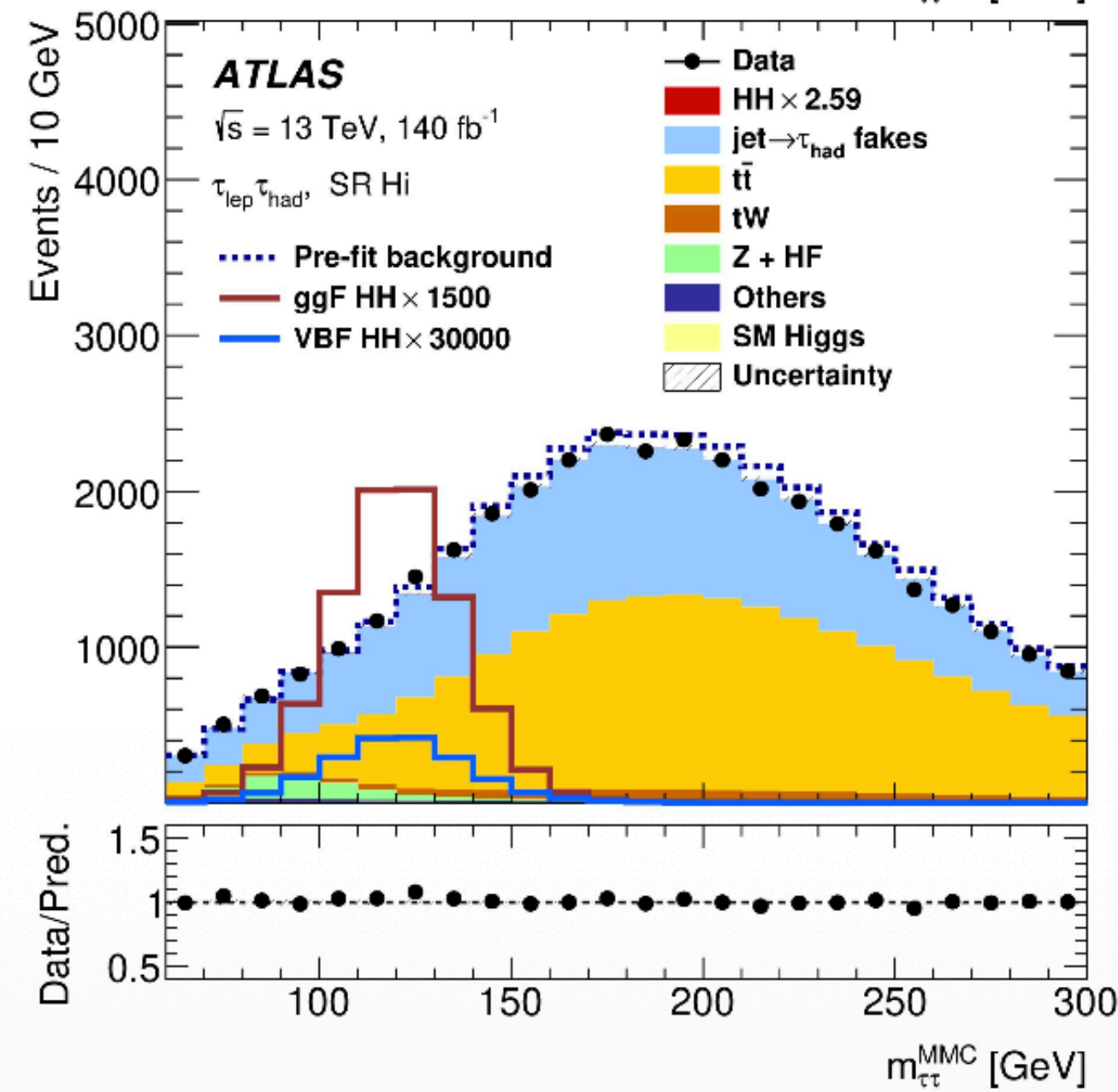
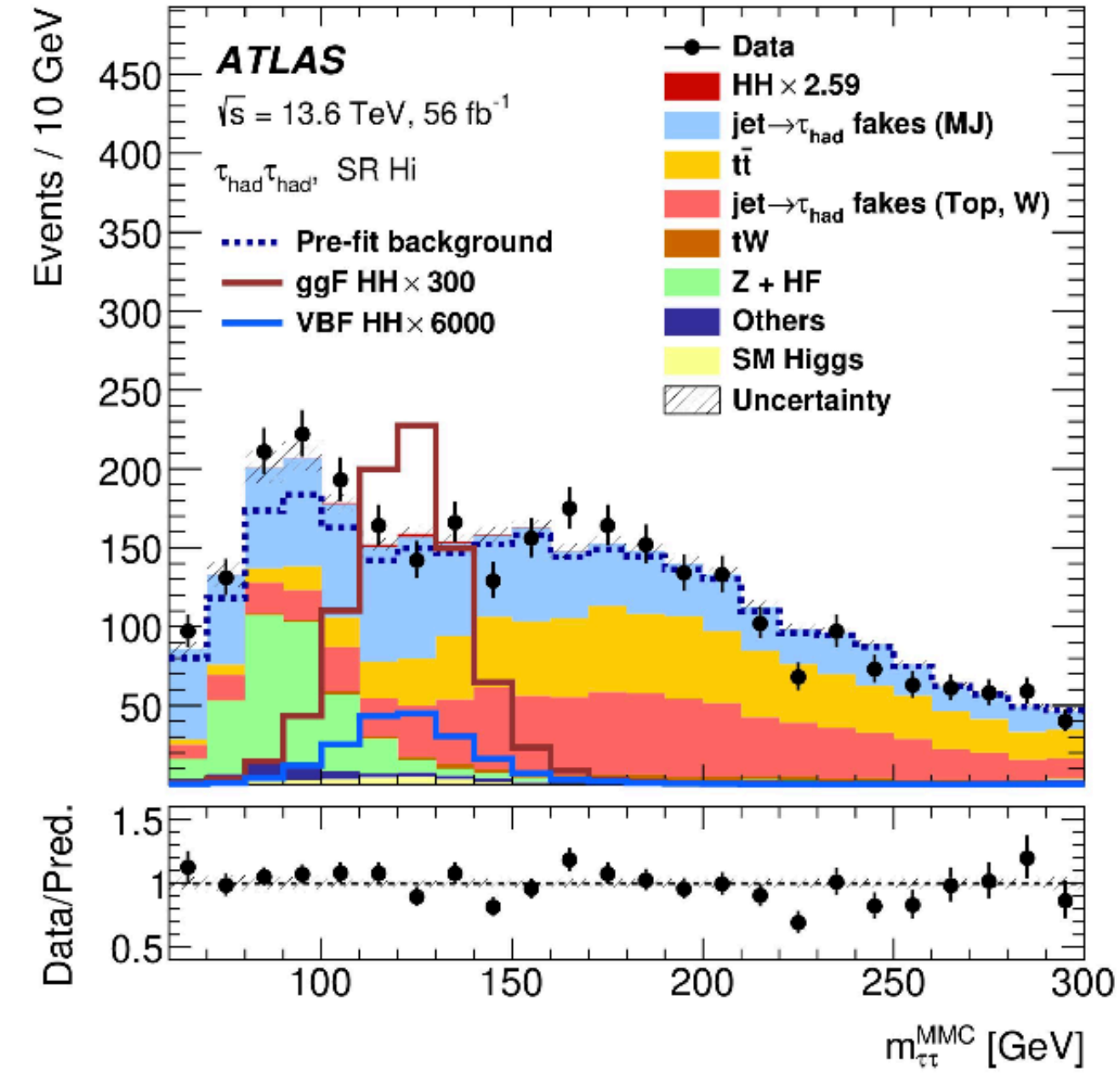
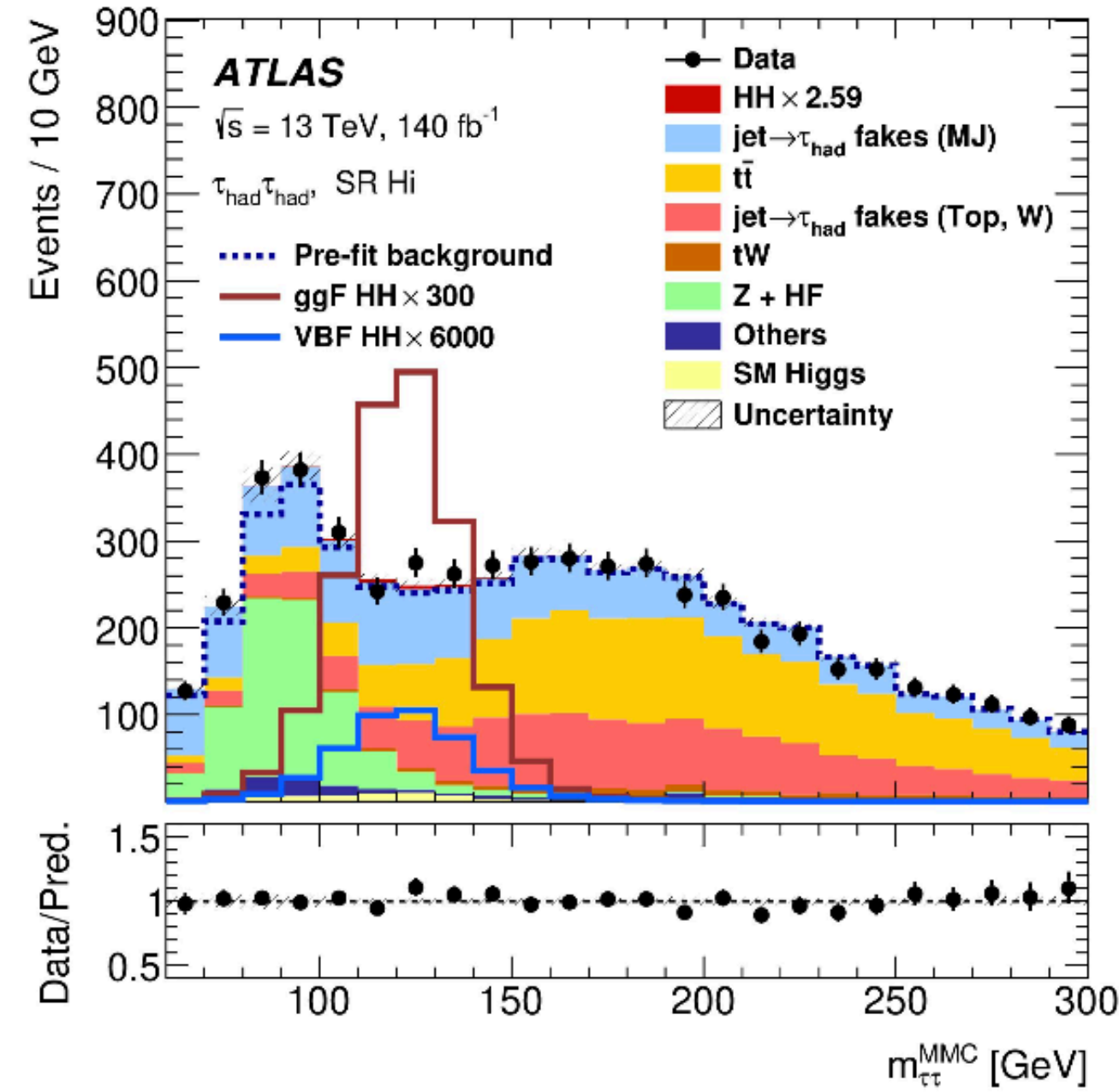


log(S/B) plots



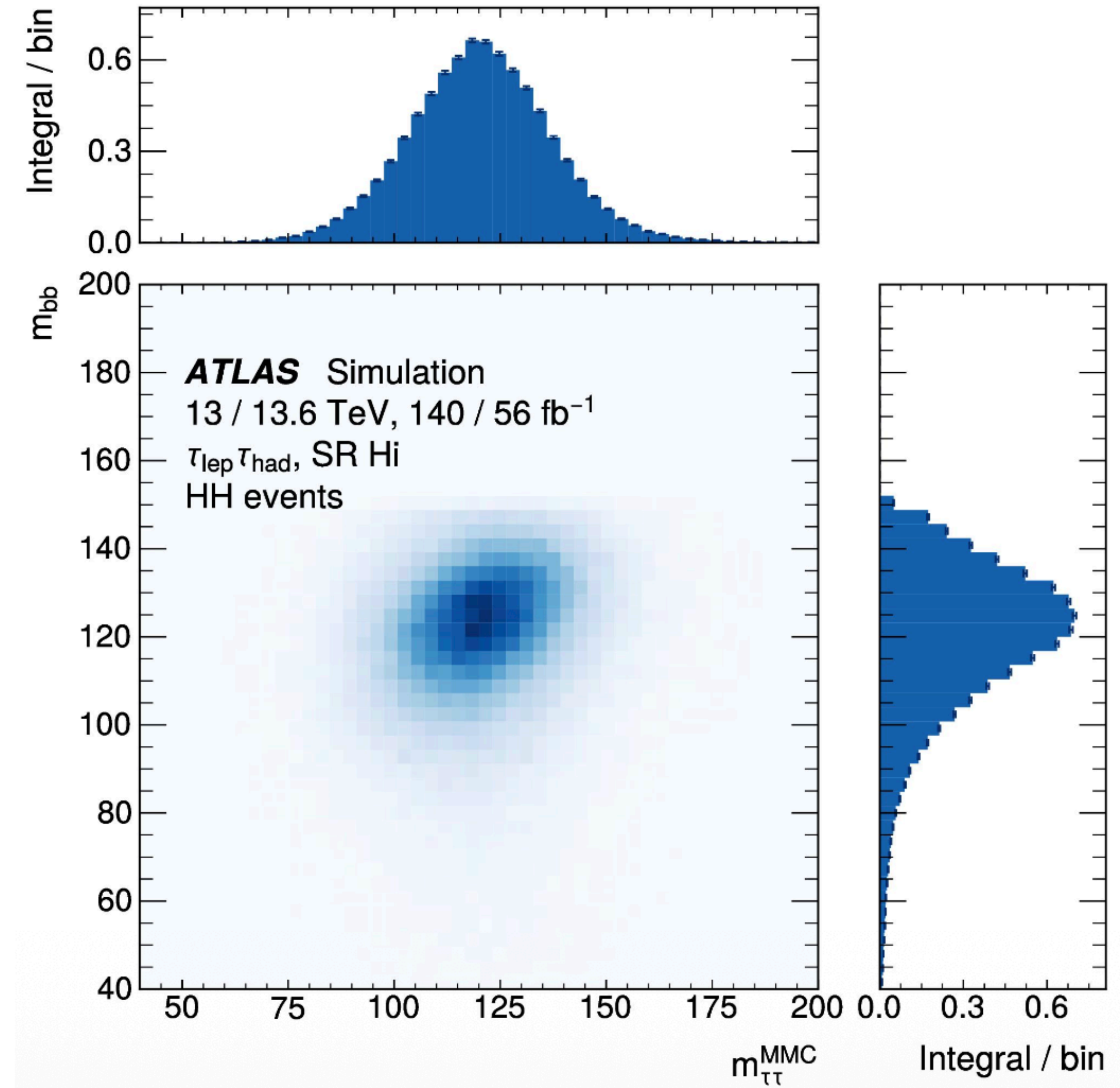
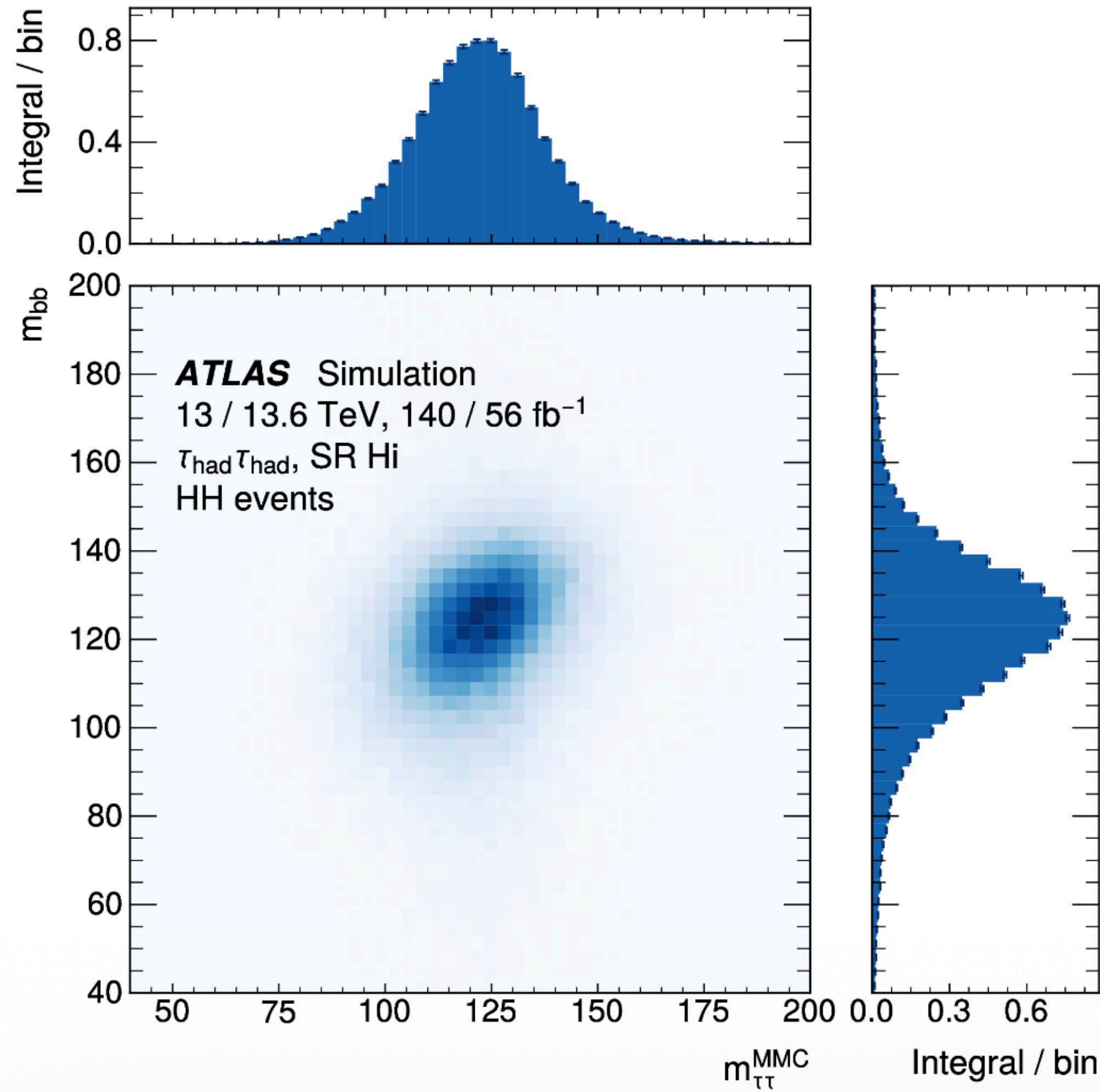




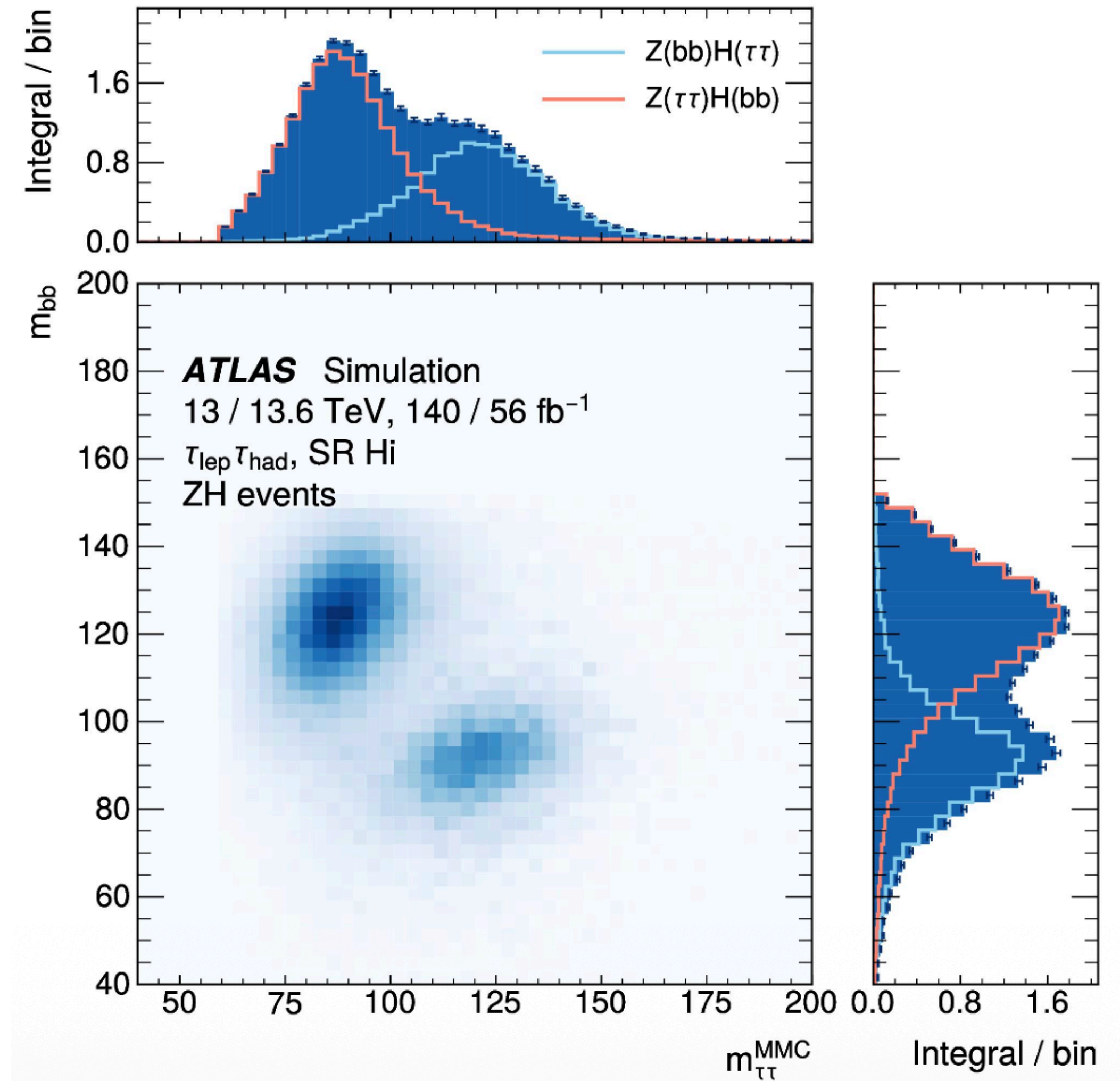
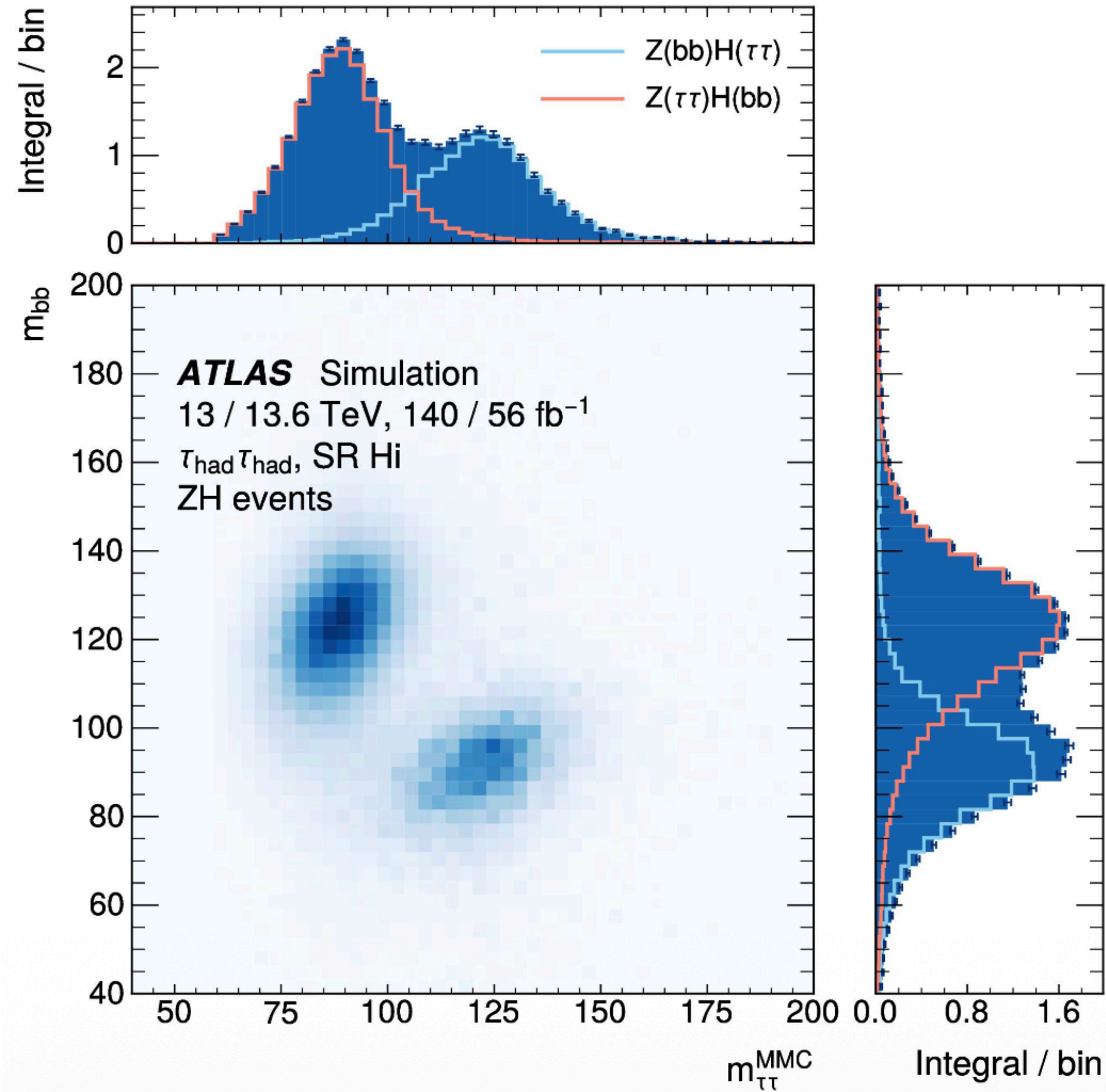


Process	SR Hi Run 2	SR Hi Run 3	SR Lo Run 2	SR Lo Run 3	SR VBF Run 2	SR VBF Run 3
Fake- τ_{had}	16990 ± 780	9270 ± 310	32900 ± 1000	17310 ± 370	6770 ± 270	3940 ± 120
$t\bar{t}$	21859 ± 760	8847 ± 330	29485 ± 910	11640 ± 400	9804 ± 400	4066 ± 150
tW	1360 ± 600	460 ± 220	1210 ± 730	390 ± 240	460 ± 280	160 ± 97
Lepton-fake- τ_{had} ($t\bar{t}$)	507 ± 26	204.4 ± 8.5	649 ± 34	261 ± 14	218 ± 14	85.7 ± 6.5
Z+HF	739 ± 69	310 ± 23	1400 ± 110	606 ± 49	193 ± 47	82 ± 22
Single Higgs boson	91 ± 11	40.5 ± 4.8	81.8 ± 8.1	34.9 ± 3.8	10.9 ± 1.6	5.14 ± 0.70
Other	267 ± 21	125 ± 12	329 ± 31	160 ± 21	81.7 ± 9.4	37.1 ± 4.6
Total background	41810 ± 210	19250 ± 140	66010 ± 260	30400 ± 170	17540 ± 130	8378 ± 86
Observed	41778	19259	66066	30457	17538	8353
ggF HH	14.8 ± 5.9	6.1 ± 2.4	2.7 ± 1.1	1.07 ± 0.44	0.29 ± 0.12	0.121 ± 0.050
VBF HH	0.168 ± 0.072	0.069 ± 0.030	0.052 ± 0.023	0.0207 ± 0.0091	0.38 ± 0.16	0.155 ± 0.066
Signal	14.9 ± 5.9	6.2 ± 2.5	2.8 ± 1.1	1.09 ± 0.45	0.67 ± 0.27	0.28 ± 0.11

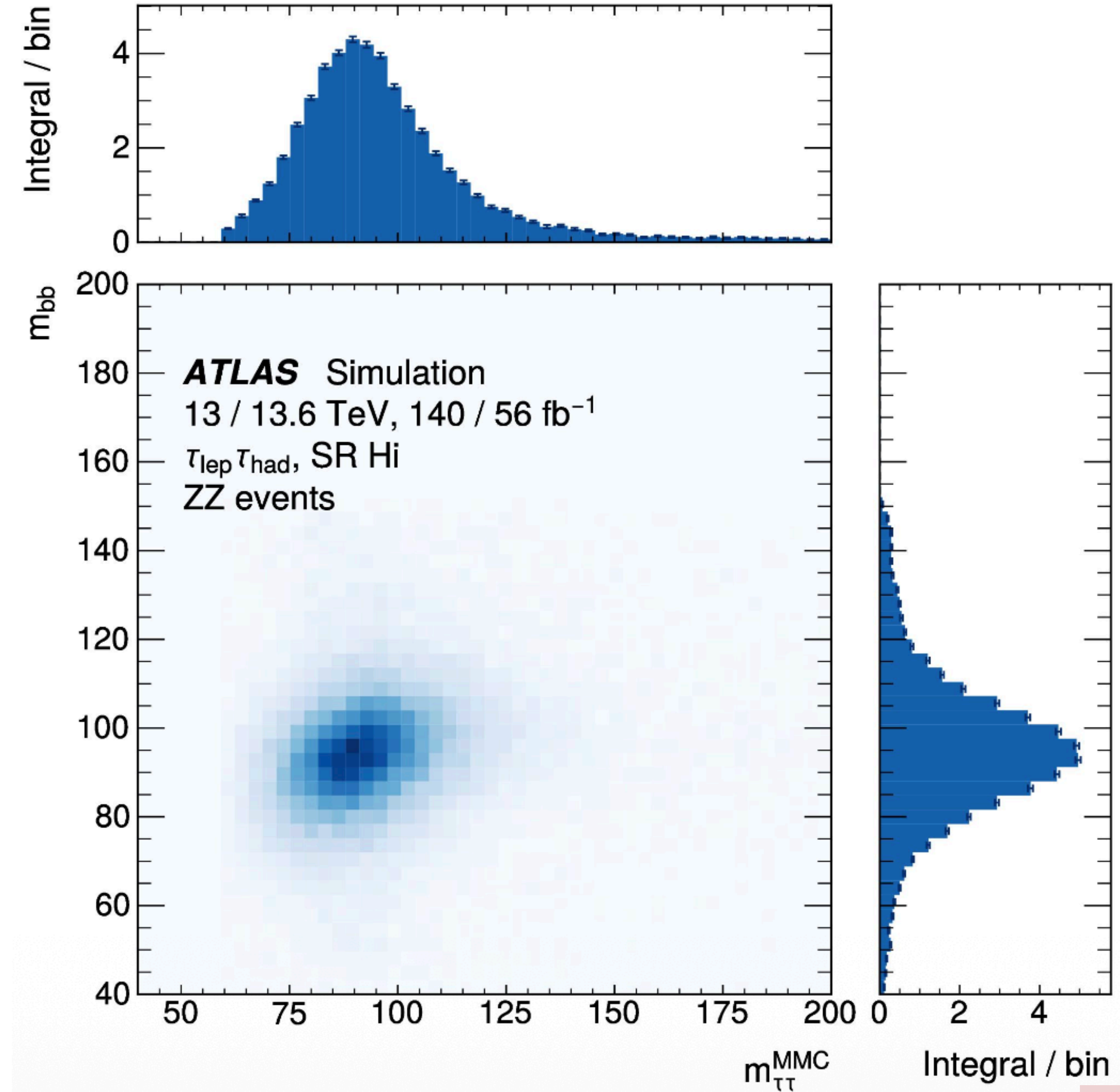
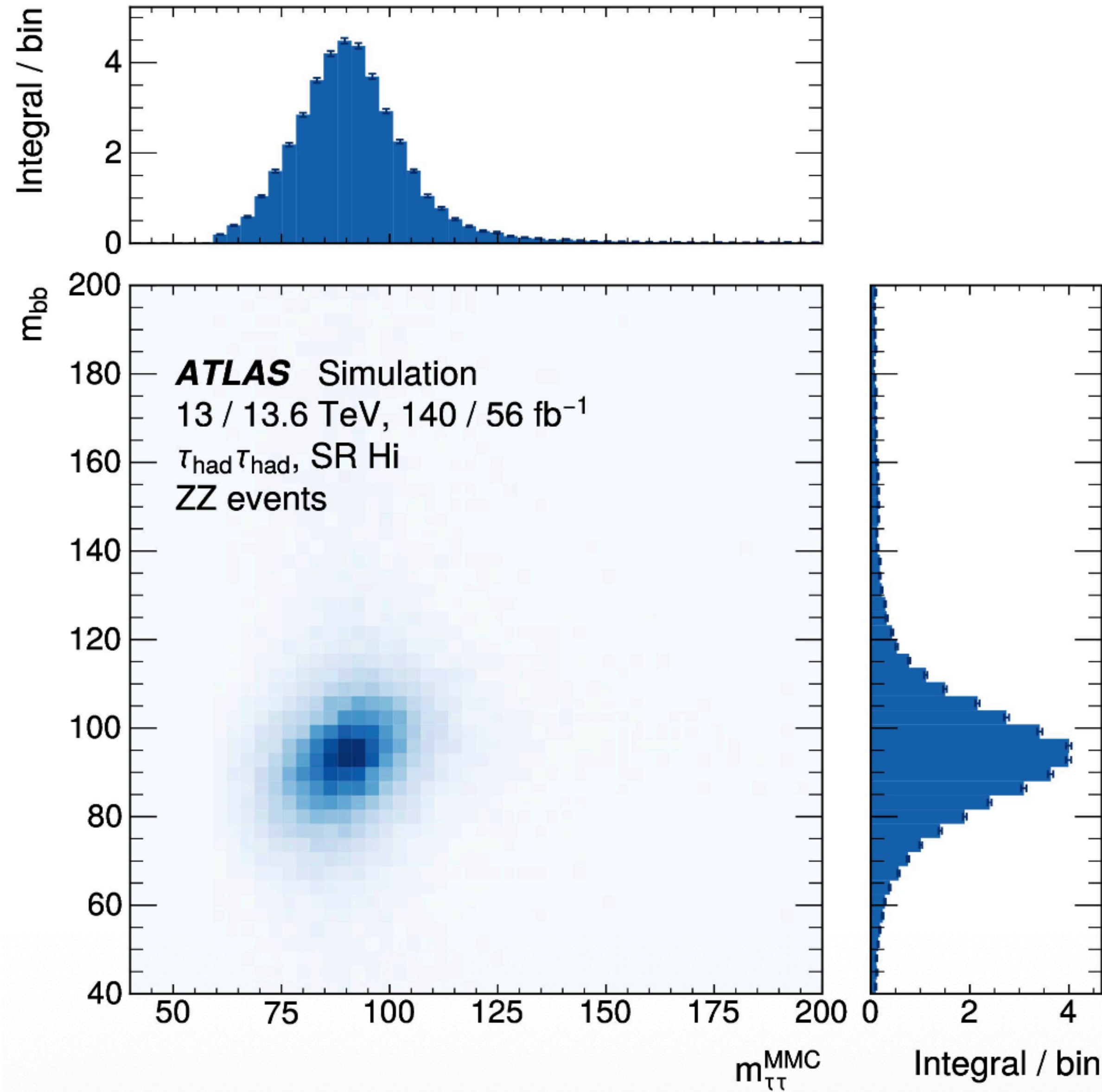
Process	SR Hi Run 2	SR Hi Run 3	SR Lo Run 2	SR Lo Run 3	SR VBF Run 2	SR VBF Run 3
Multijet	1550 ± 160	1153 ± 74	970 ± 140	5670 ± 160	382 ± 29	973 ± 29
$t\bar{t}$	1343 ± 100	563 ± 43	722 ± 48	666 ± 39	206 ± 24	114 ± 12
tW	96 ± 45	34 ± 13	21 ± 18	20 ± 11	6.8 ± 4.4	2.6 ± 1.3
Fake- τ_{had} ($t\bar{t}$)	1338 ± 210	855 ± 100	1352 ± 180	2581 ± 200	194 ± 43	269 ± 47
Lepton-fake- τ_{had} ($t\bar{t}$)	713 ± 48	329 ± 26	497 ± 42	564 ± 40	93.9 ± 9.6	69 ± 11
Z+HF	753 ± 62	346 ± 33	515 ± 42	379 ± 33	52.4 ± 9.2	32.3 ± 5.7
Single Higgs boson	57 ± 12	26.7 ± 5.4	23.2 ± 3.8	21.9 ± 3.1	3.8 ± 1.1	2.58 ± 0.69
Other	150 ± 34	76 ± 18	78 ± 18	88 ± 18	24 ± 13	18.6 ± 6.7
Total background	5995 ± 77	3382 ± 57	4182 ± 70	9992 ± 99	963 ± 30	1481 ± 36
Observed	6007	3394	4190	10000	976	1502
ggF HH	16.3 ± 6.4	7.4 ± 3.0	1.74 ± 0.72	2.10 ± 0.85	0.30 ± 0.12	0.171 ± 0.070
VBF HH	0.192 ± 0.082	0.083 ± 0.036	0.033 ± 0.014	0.035 ± 0.015	0.34 ± 0.14	0.179 ± 0.077
Signal	16.5 ± 6.5	7.5 ± 3.0	1.78 ± 0.73	2.14 ± 0.87	0.64 ± 0.26	0.35 ± 0.14



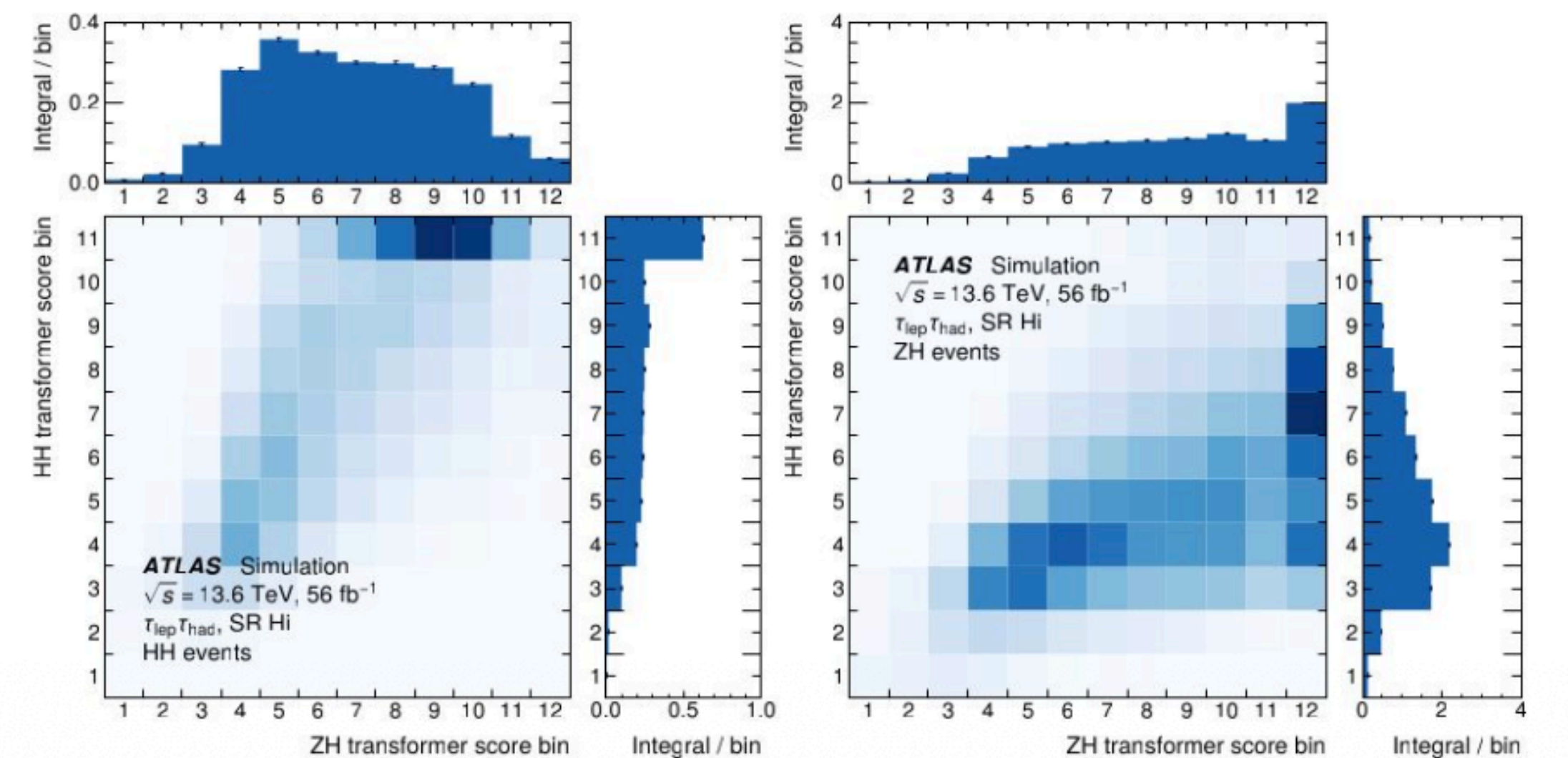
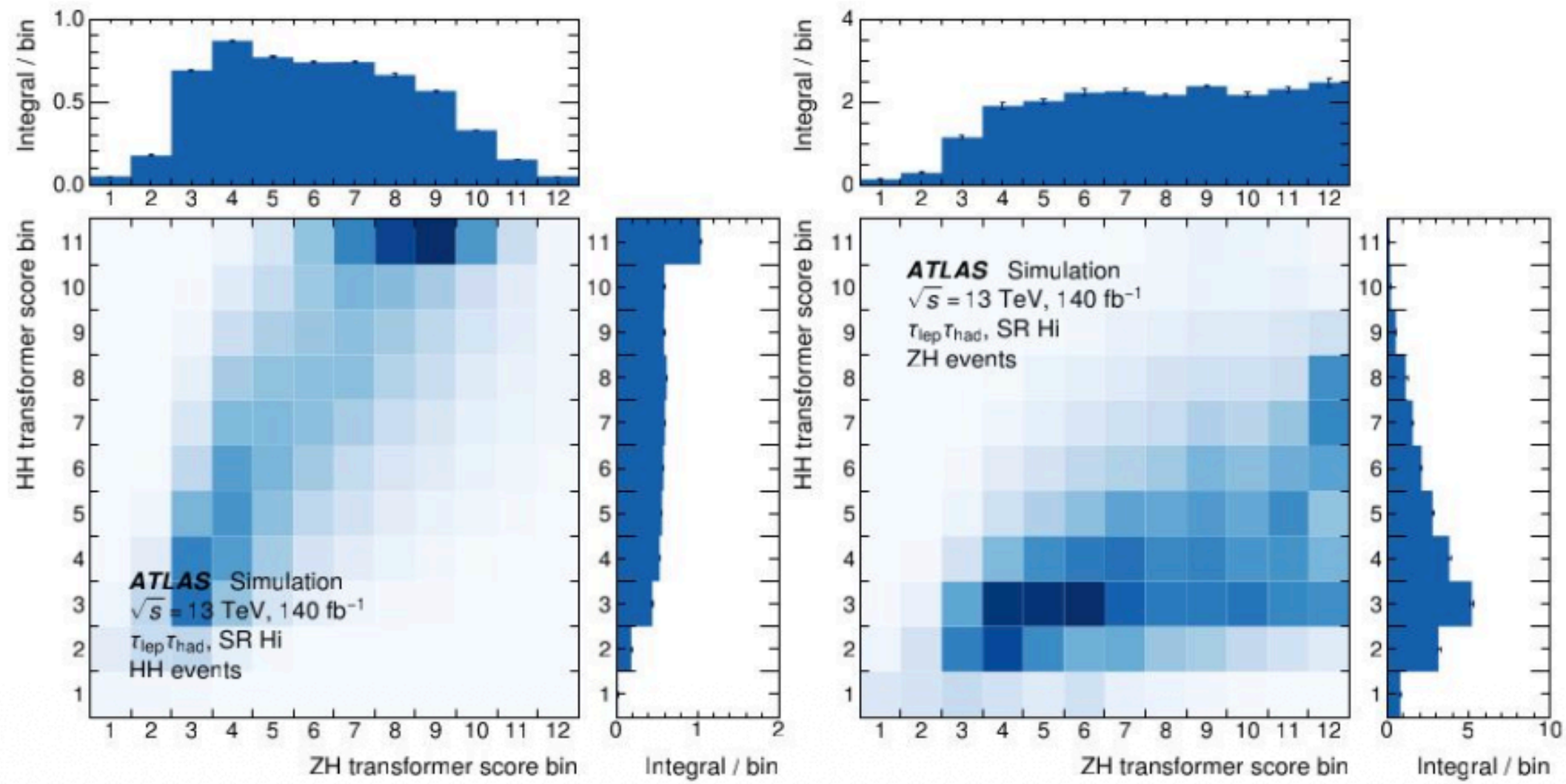
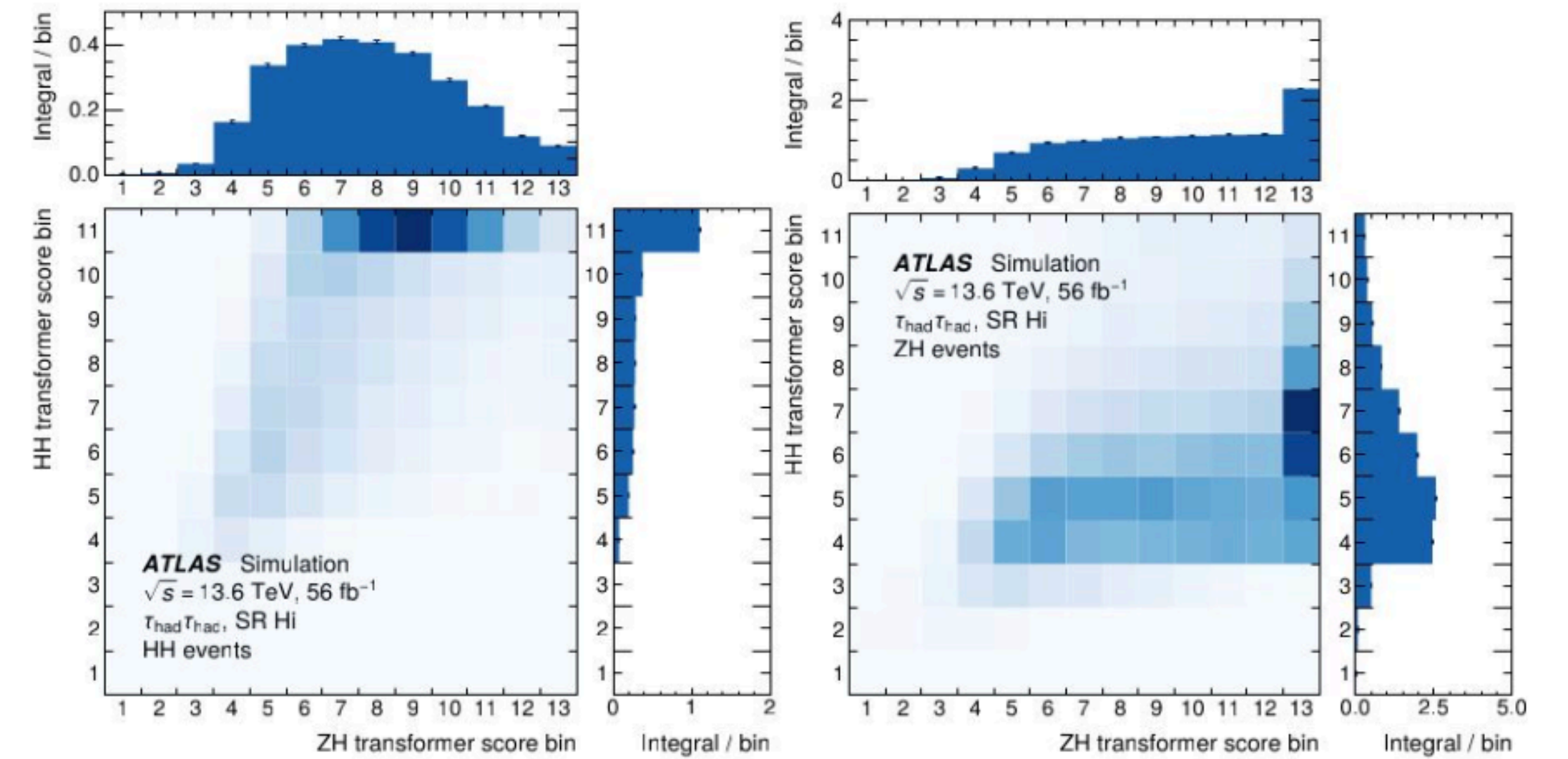
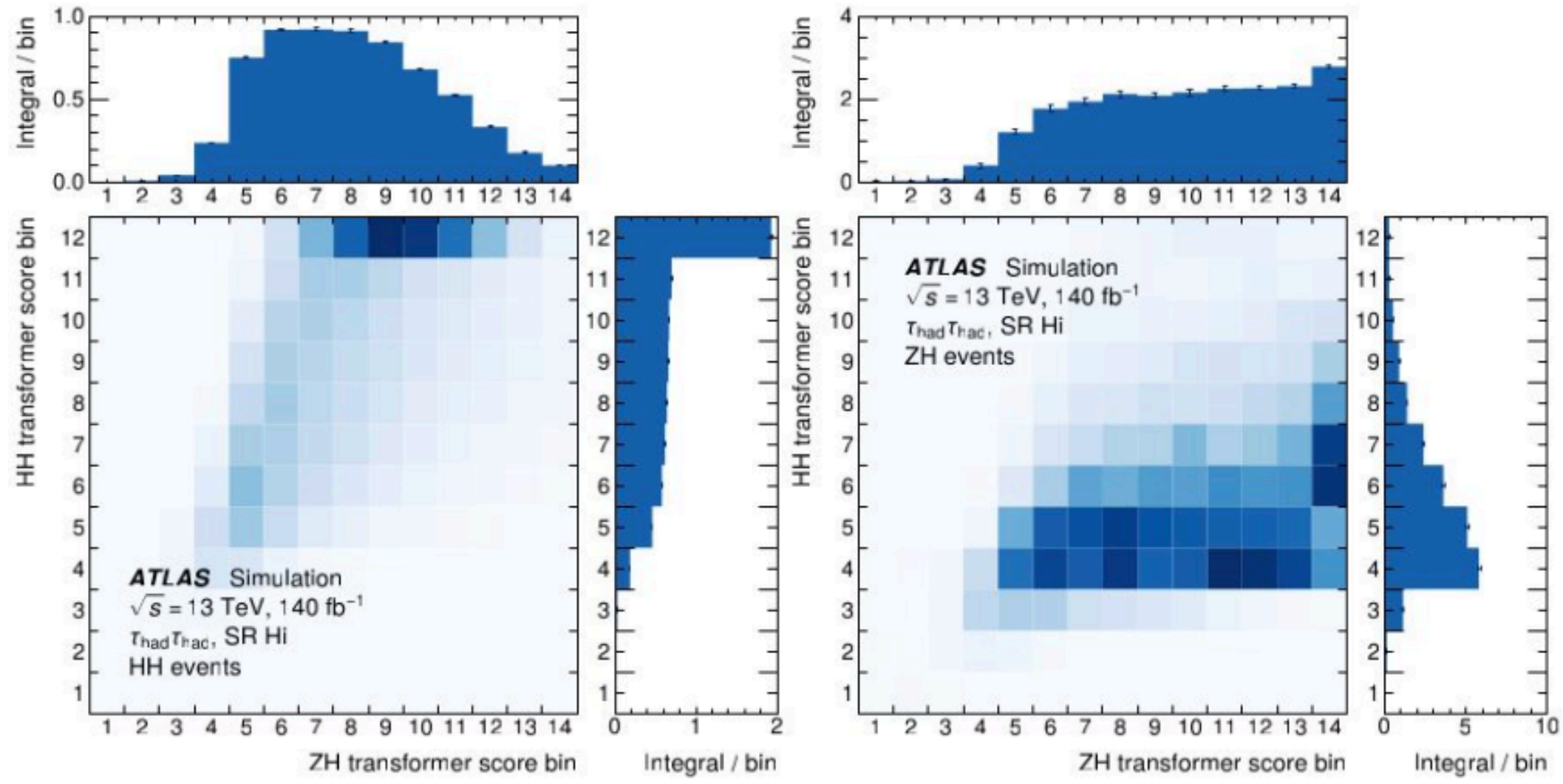
$m_{bb} - m_{\tau\tau}$ 2D plots: ZH events



$m_{bb} - m_{\tau\tau}$ 2D plots: ZZ events



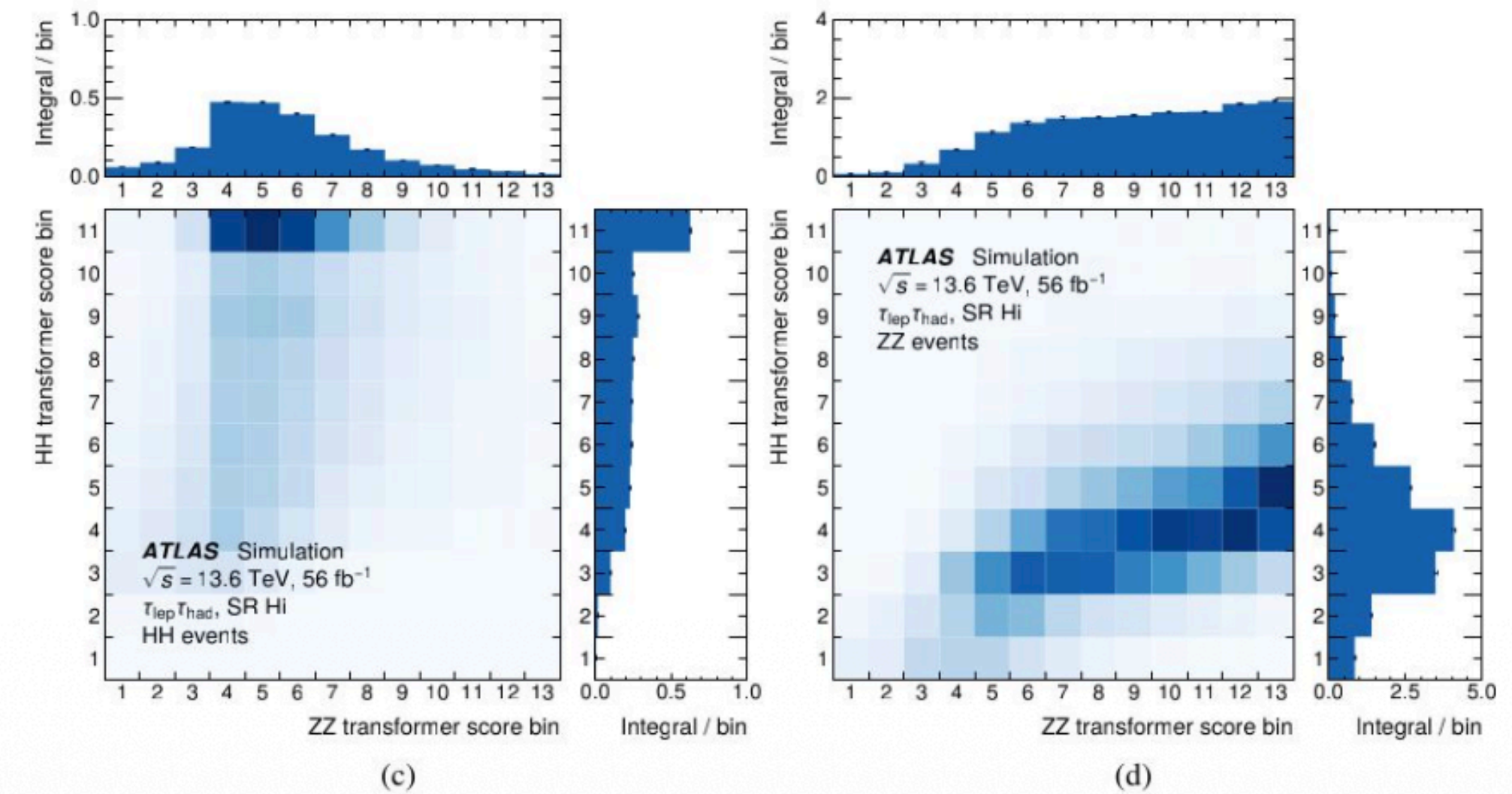
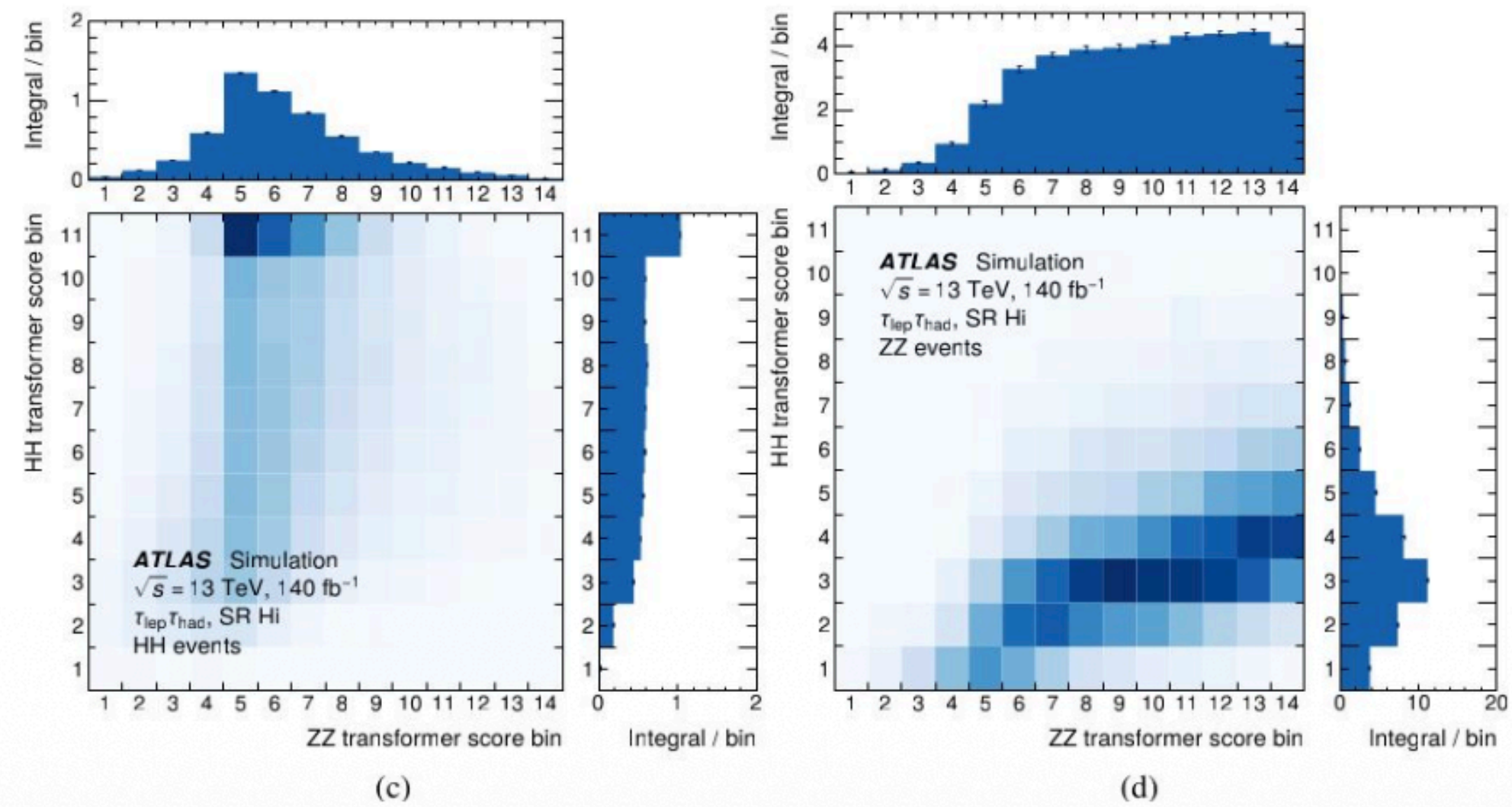
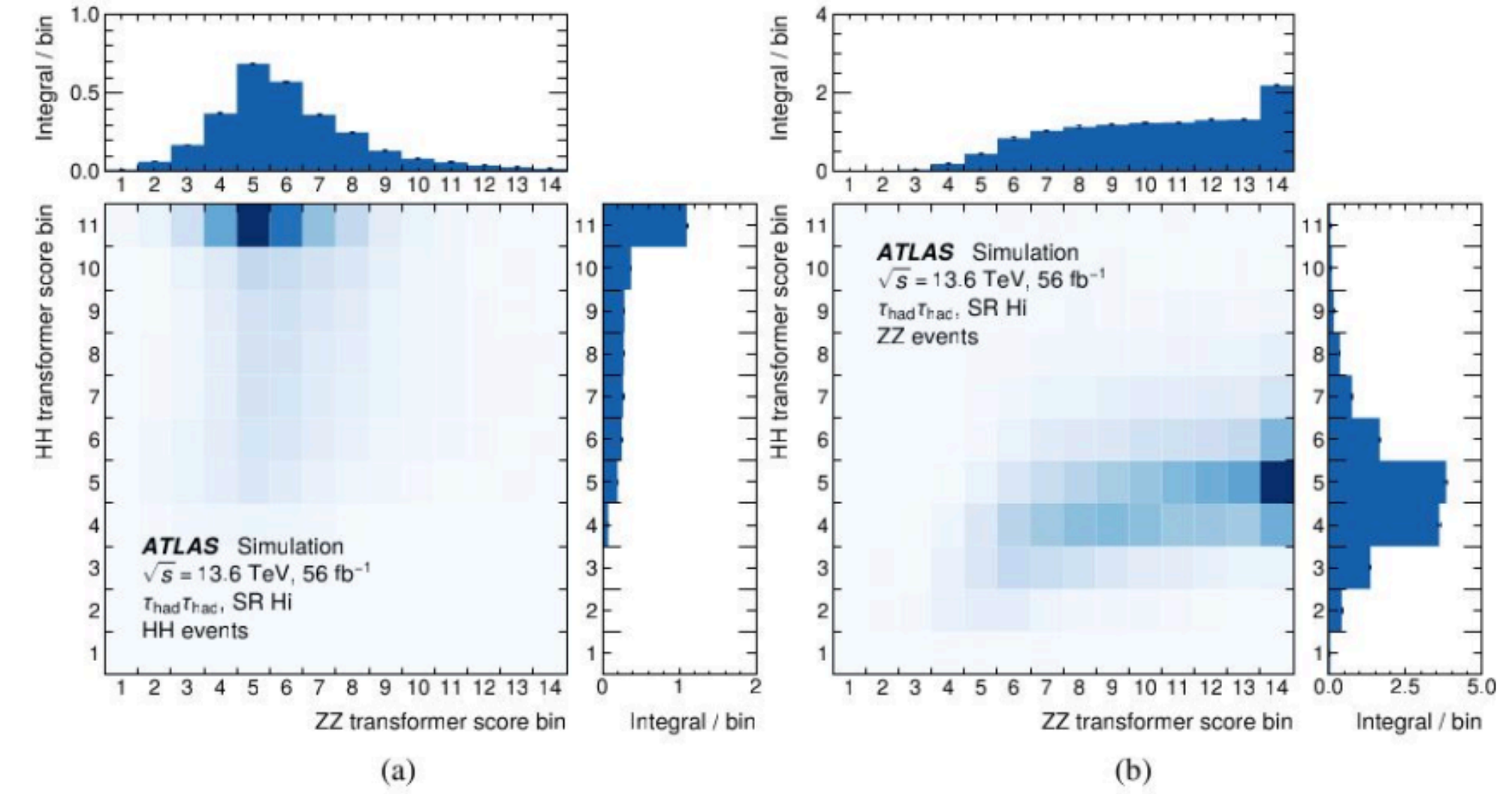
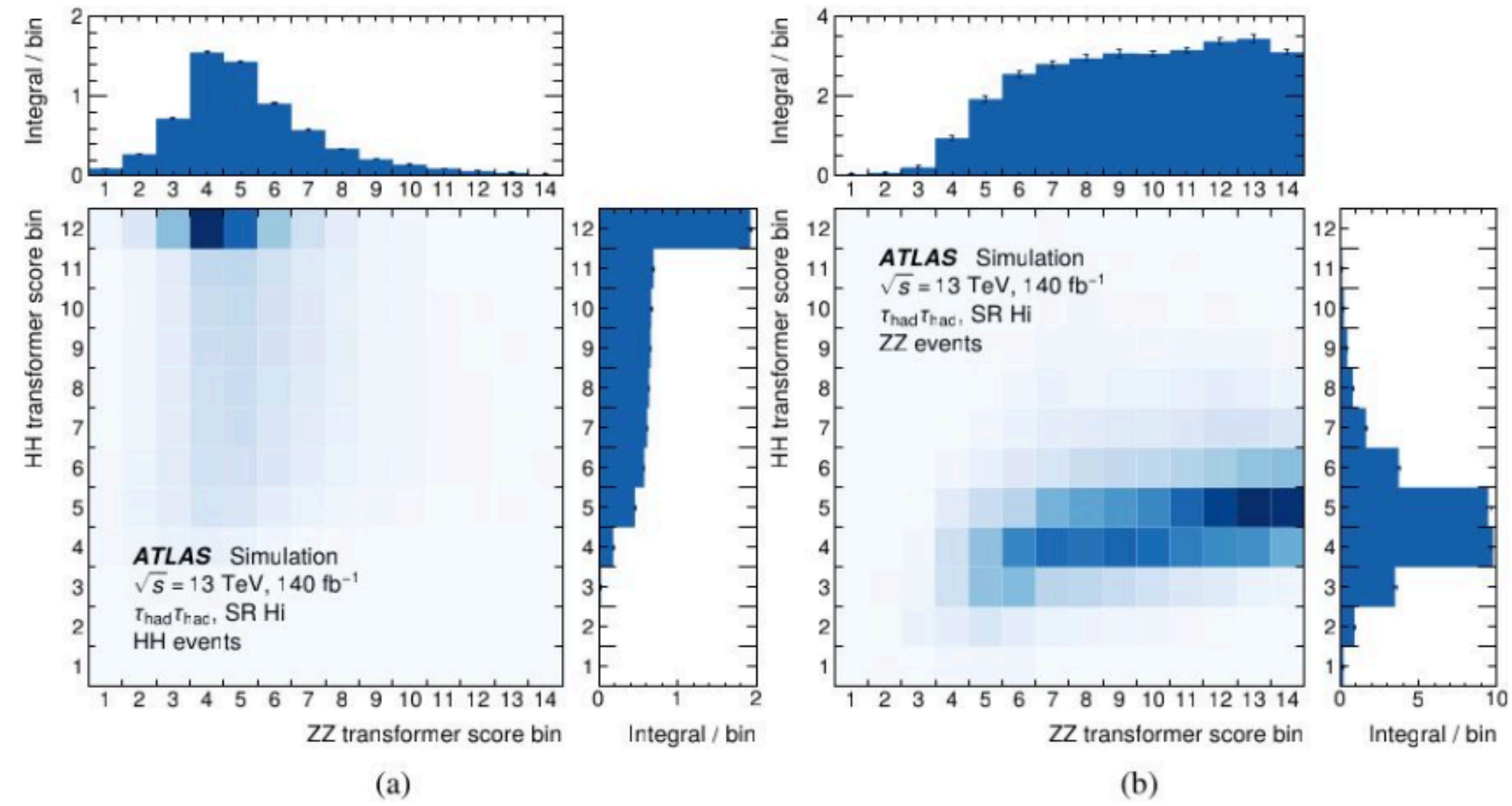
ZH-HH correlation



RUN2

RUN3

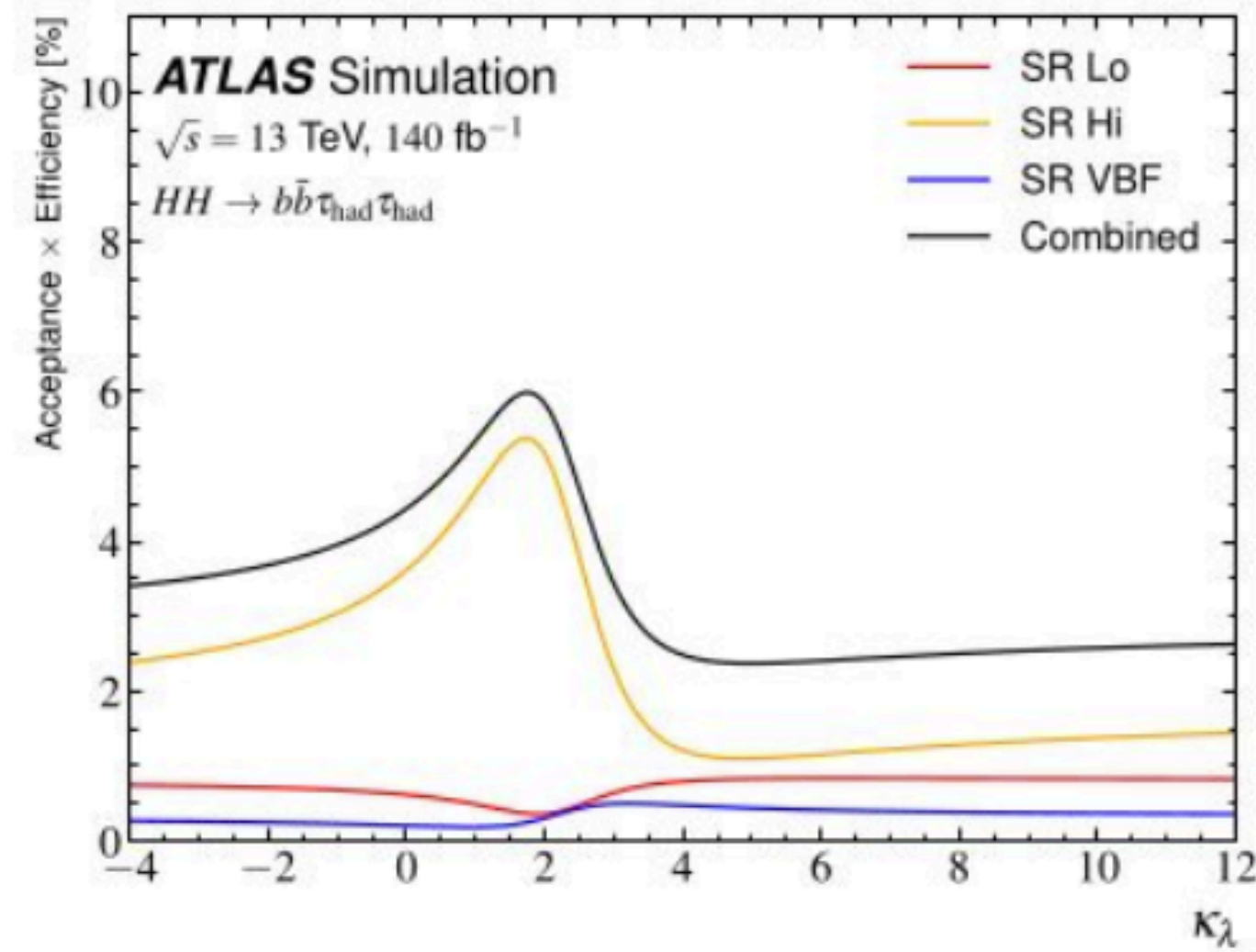
ZZ-HH correlation



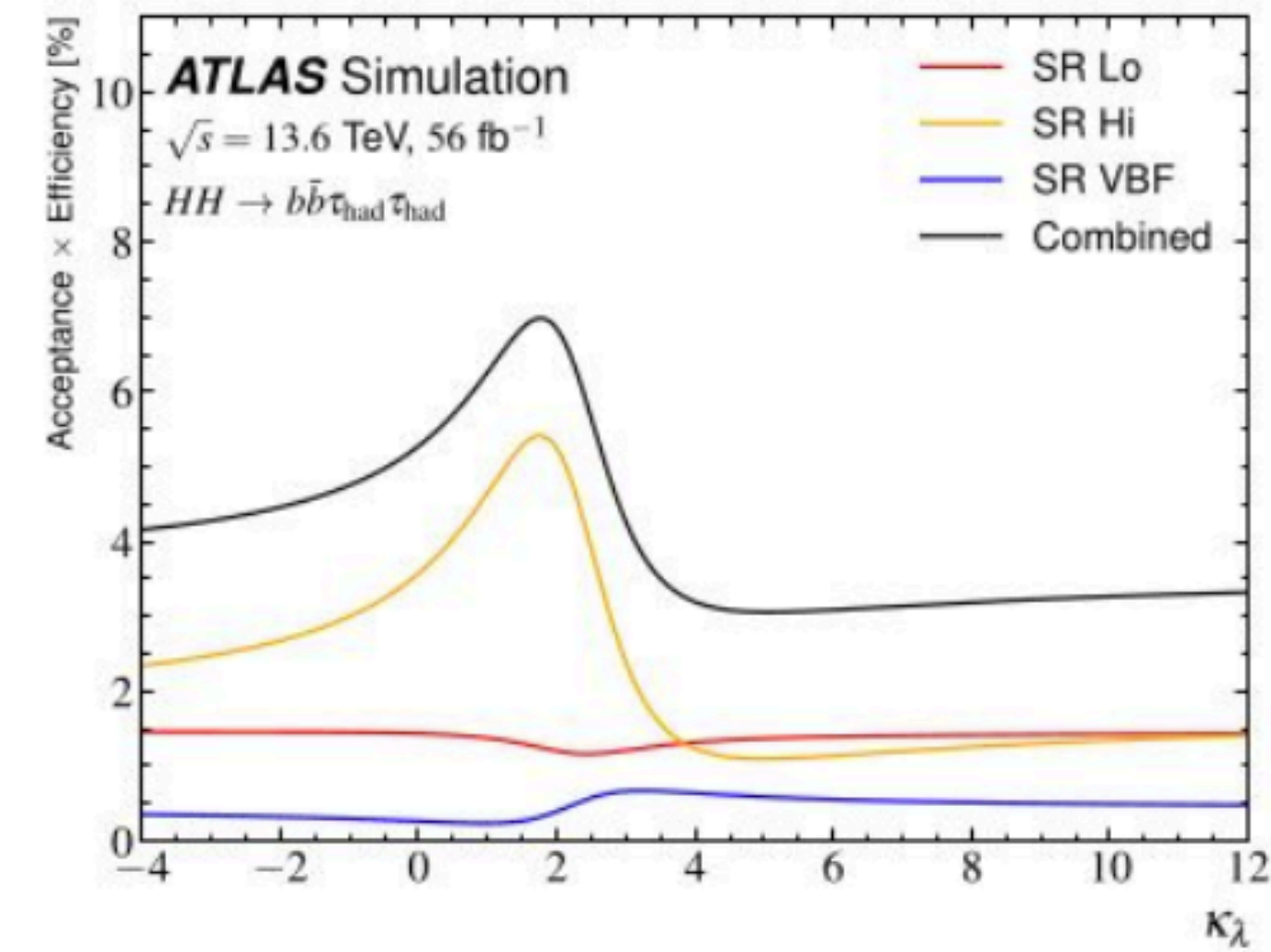
RUN2

RUN3

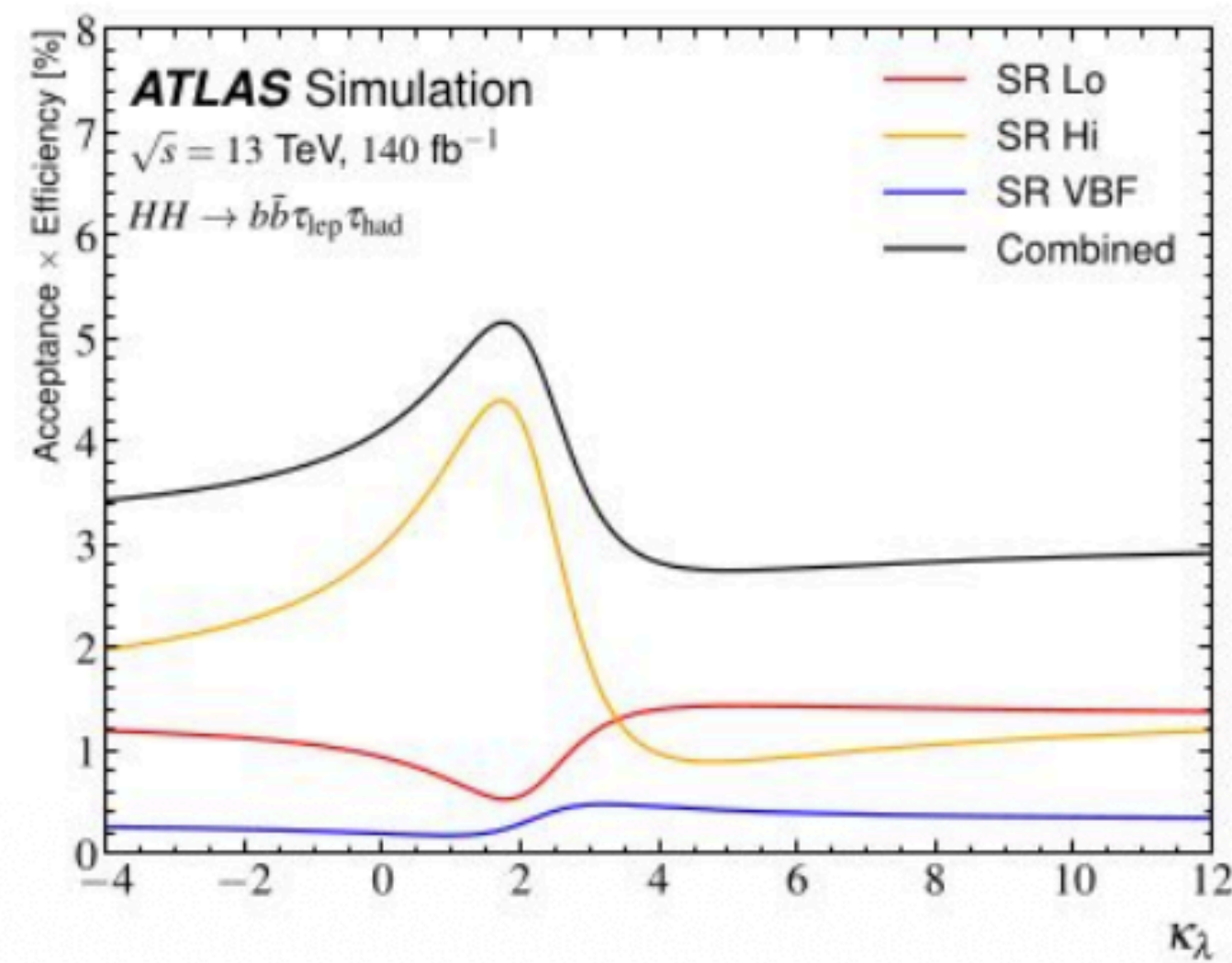
HH acceptance x efficiency



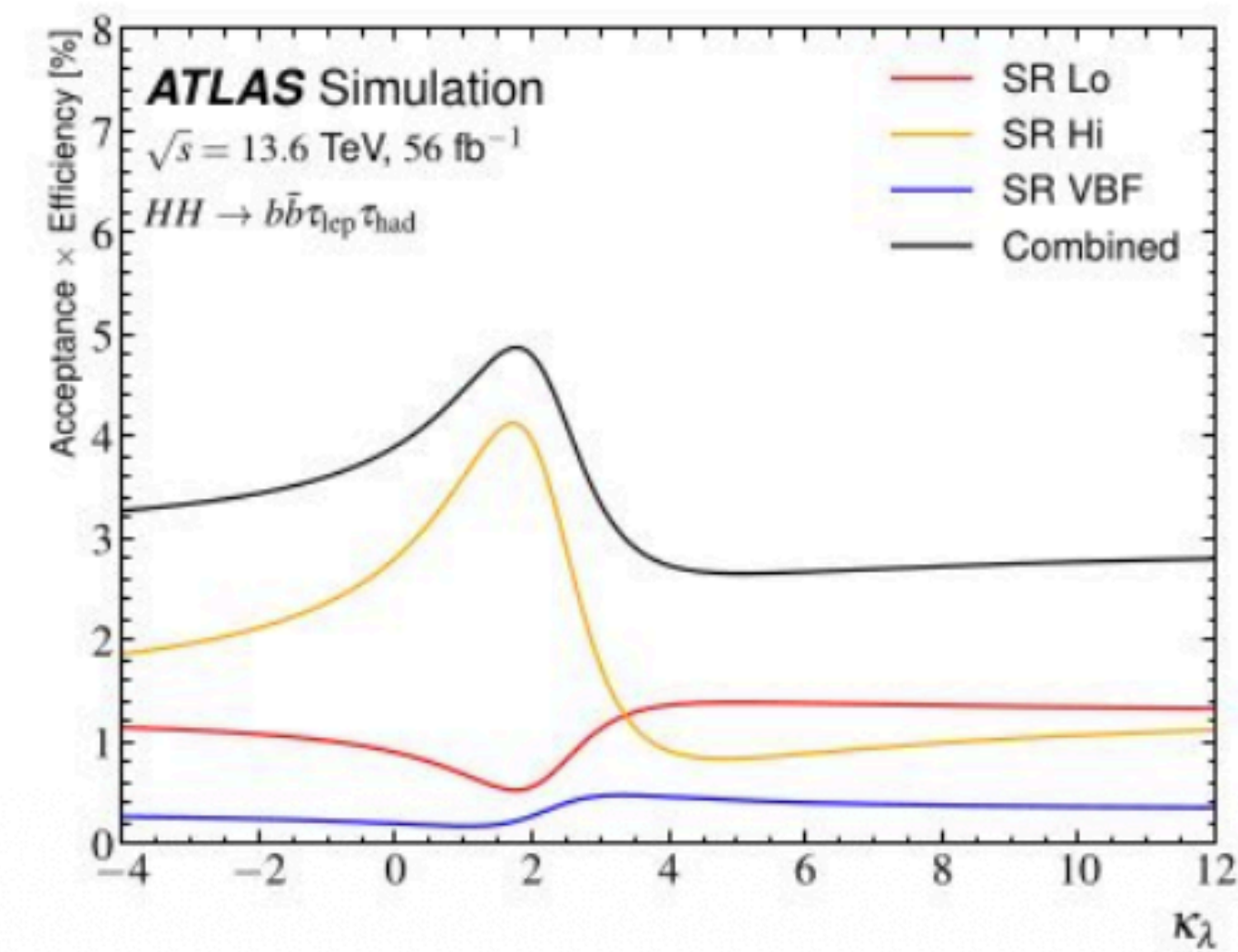
(a)



(b)

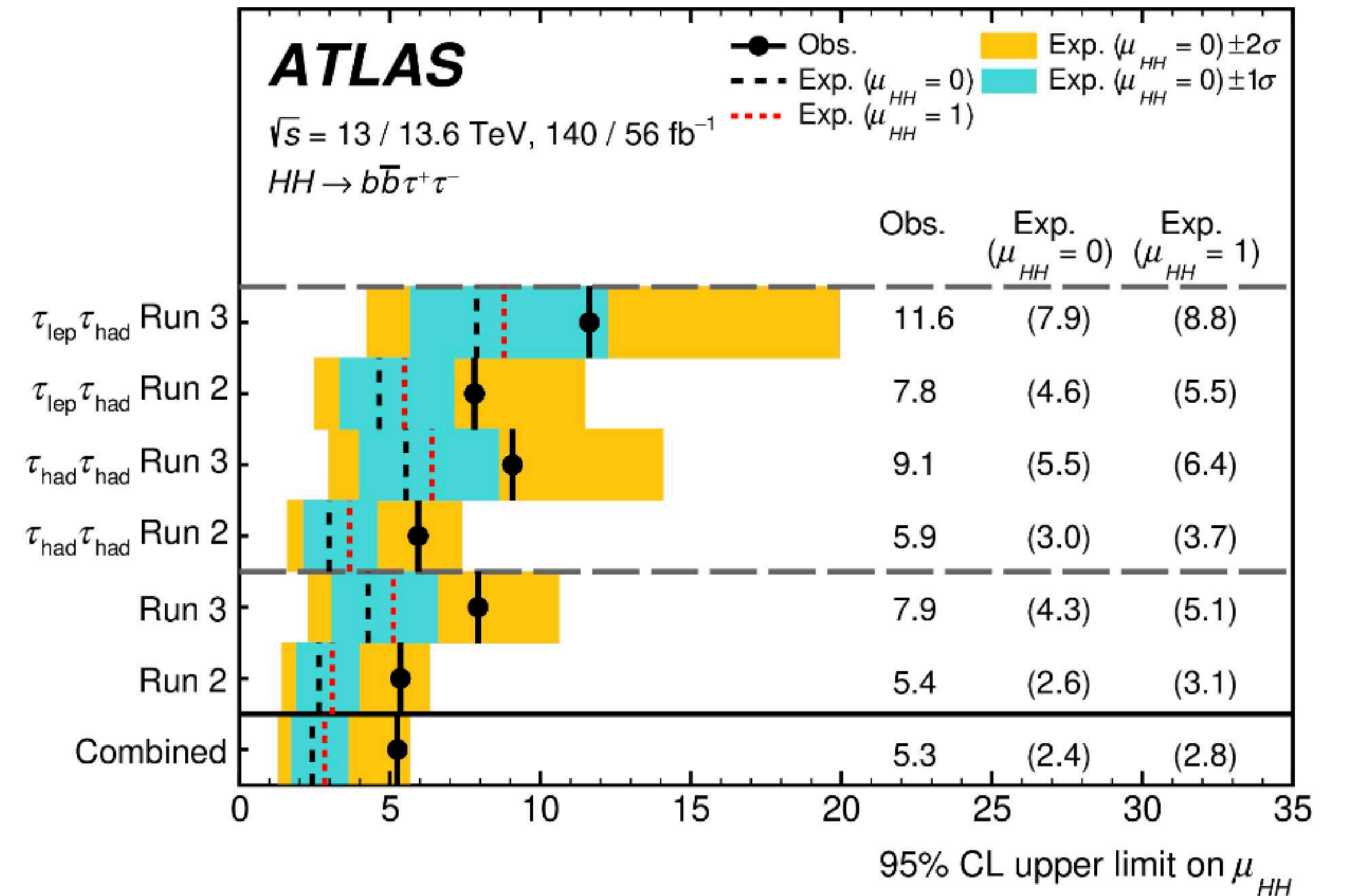
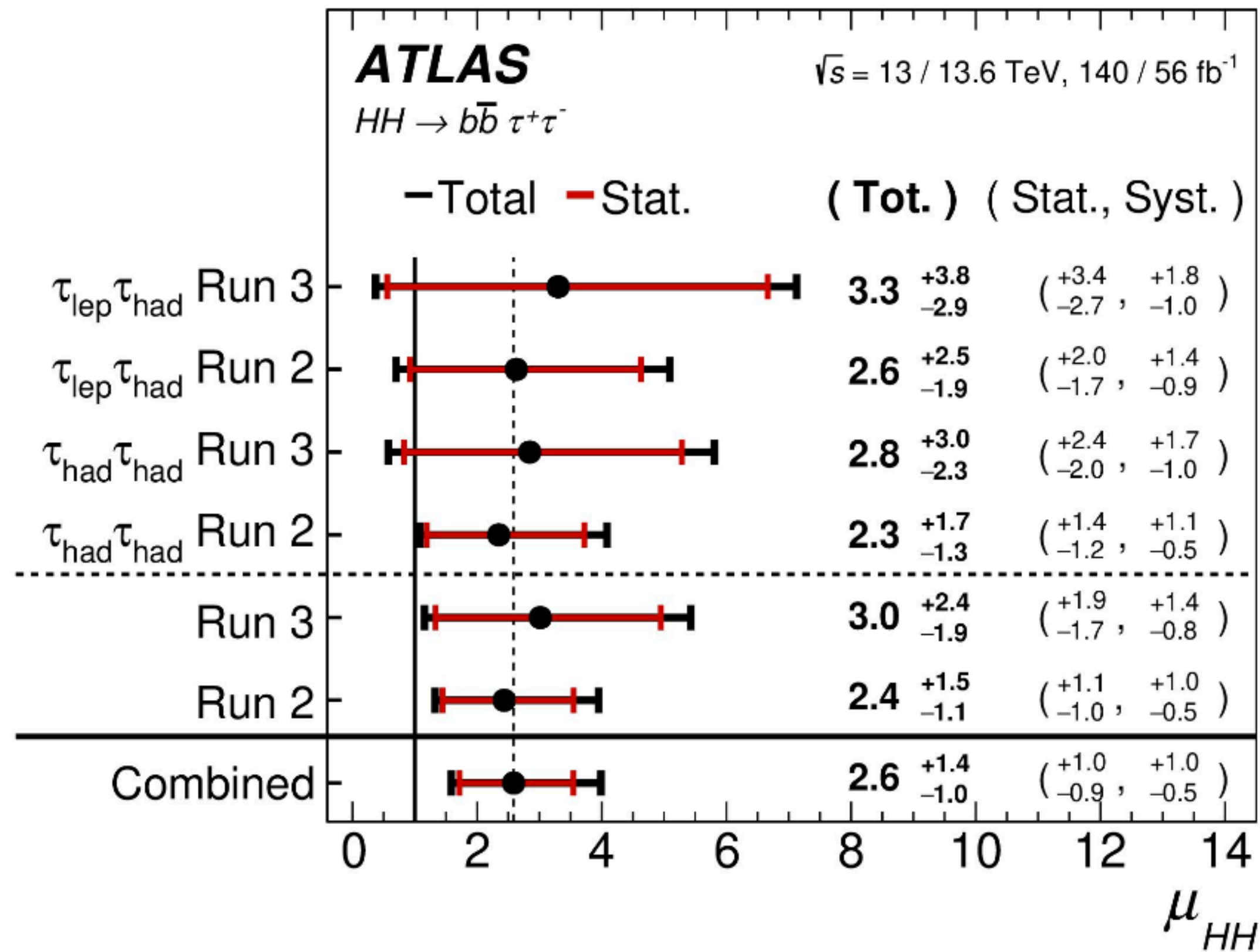


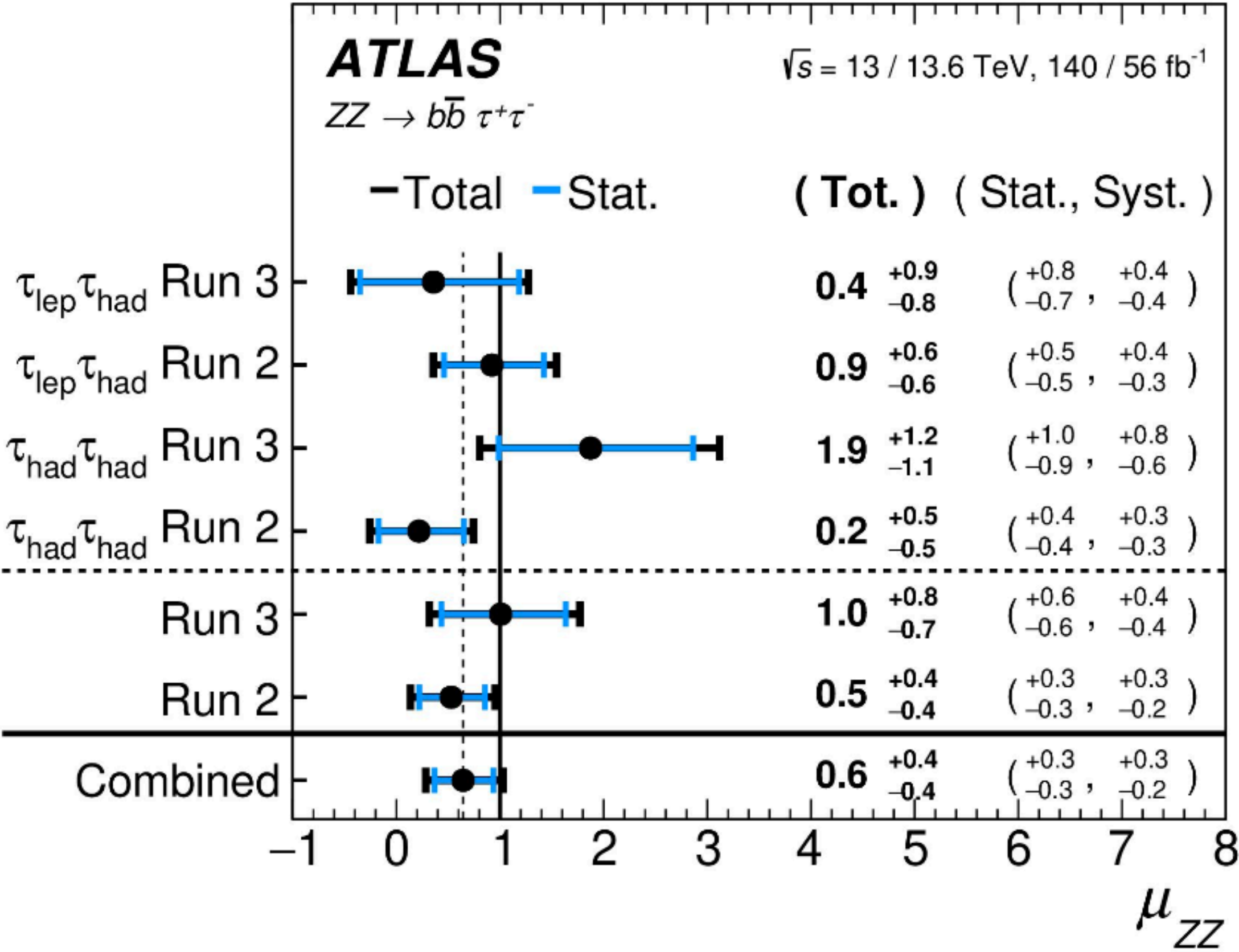
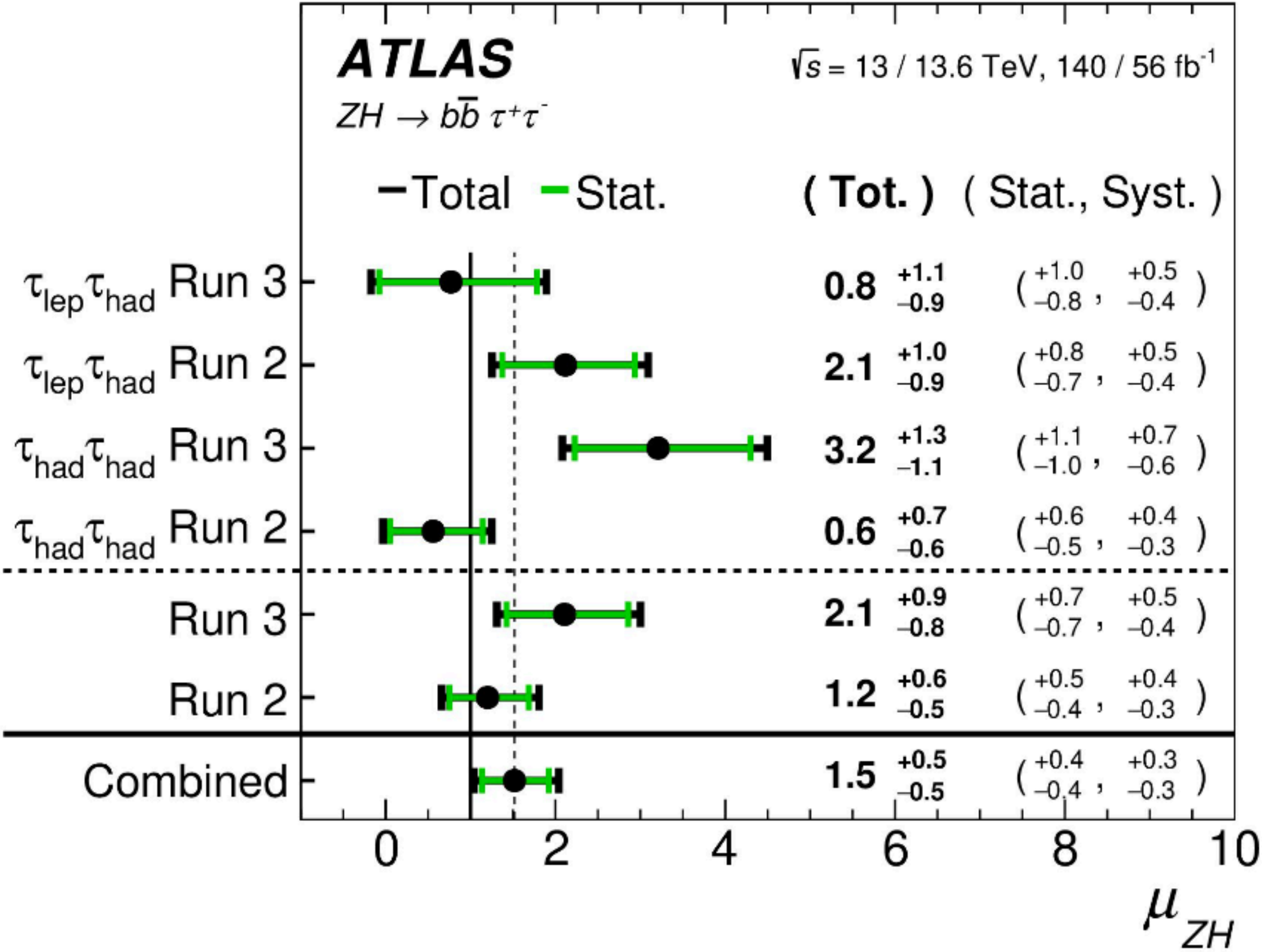
(c)



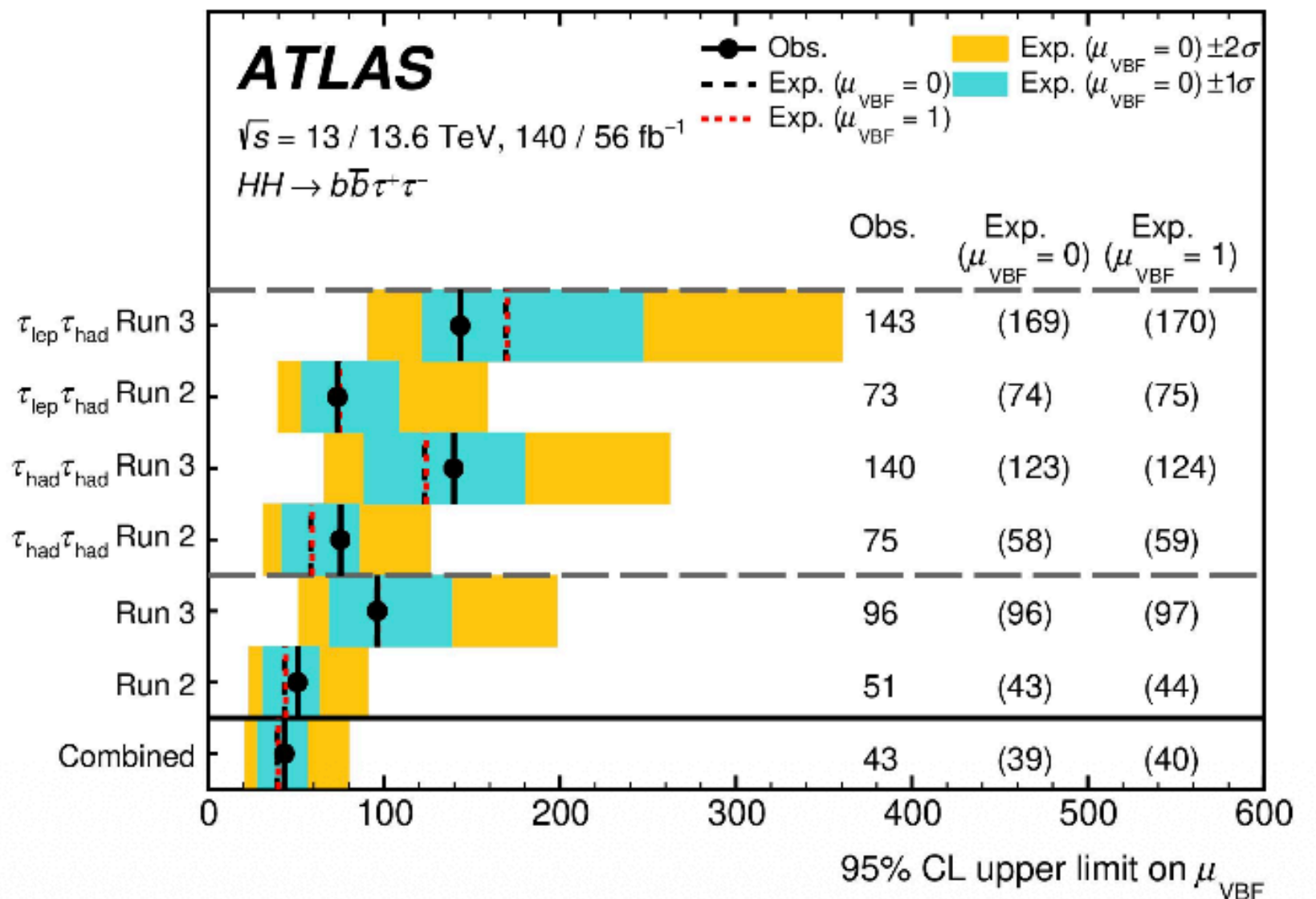
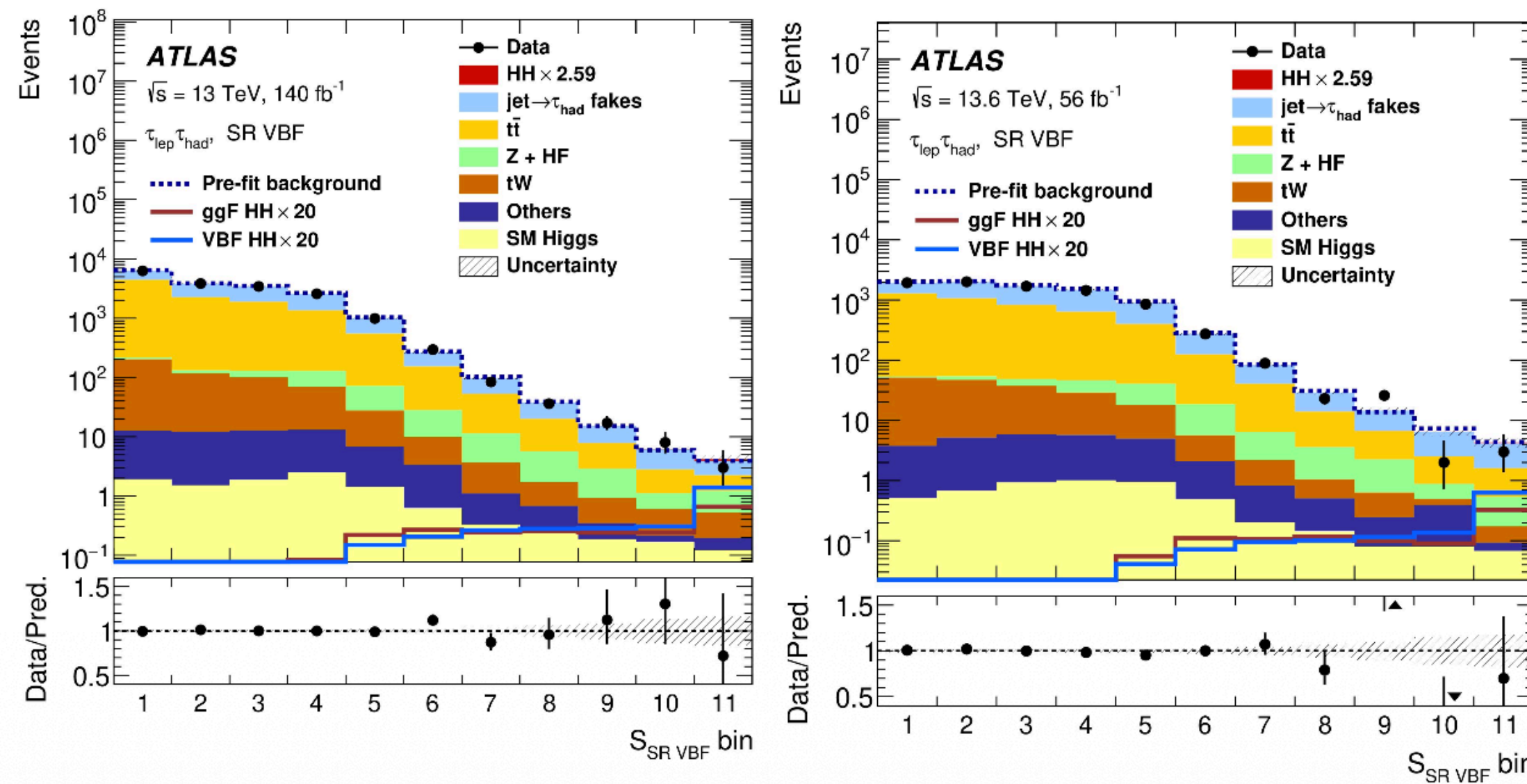
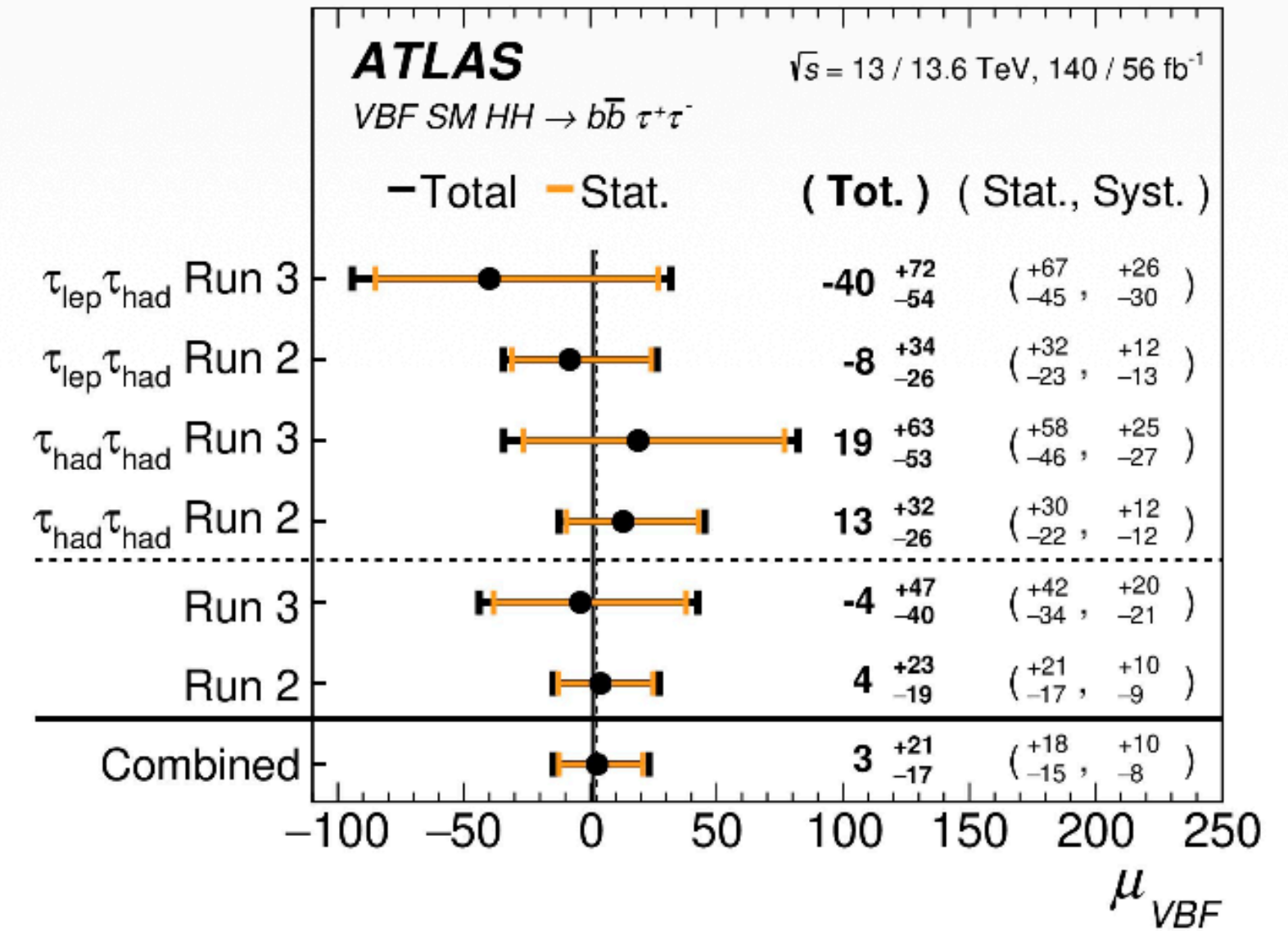
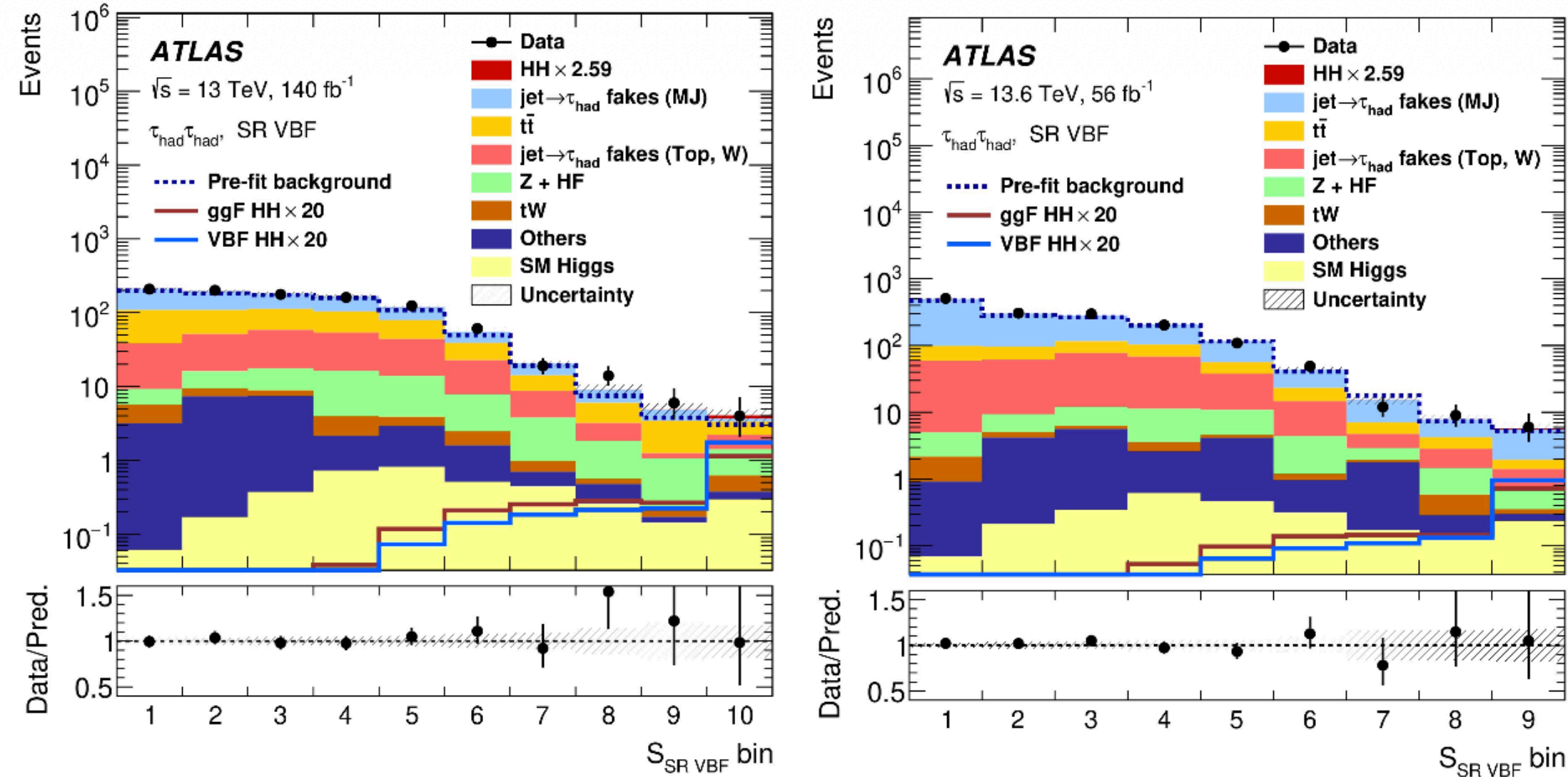
(d)

HH POI decorrelation and upper limit



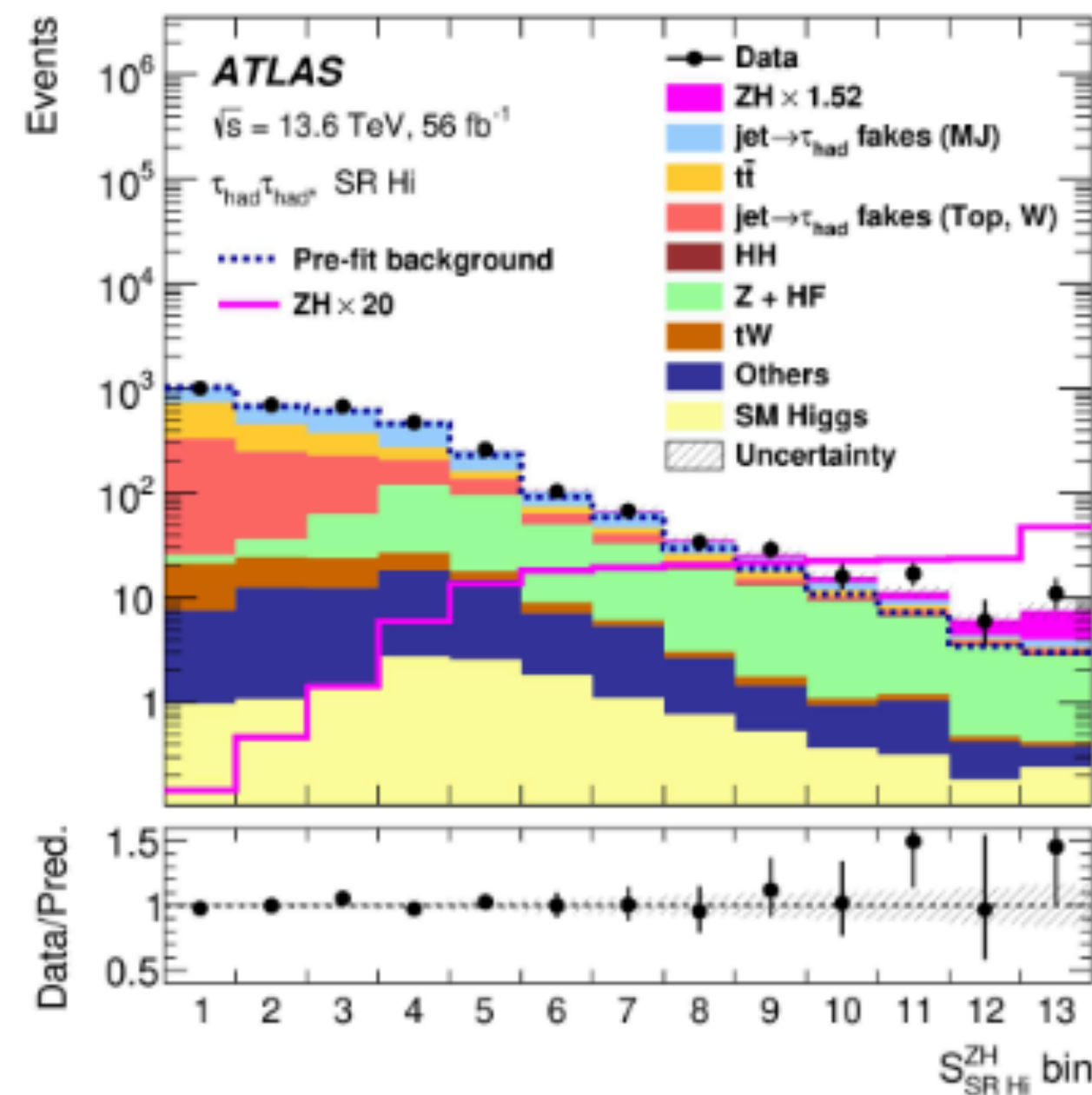
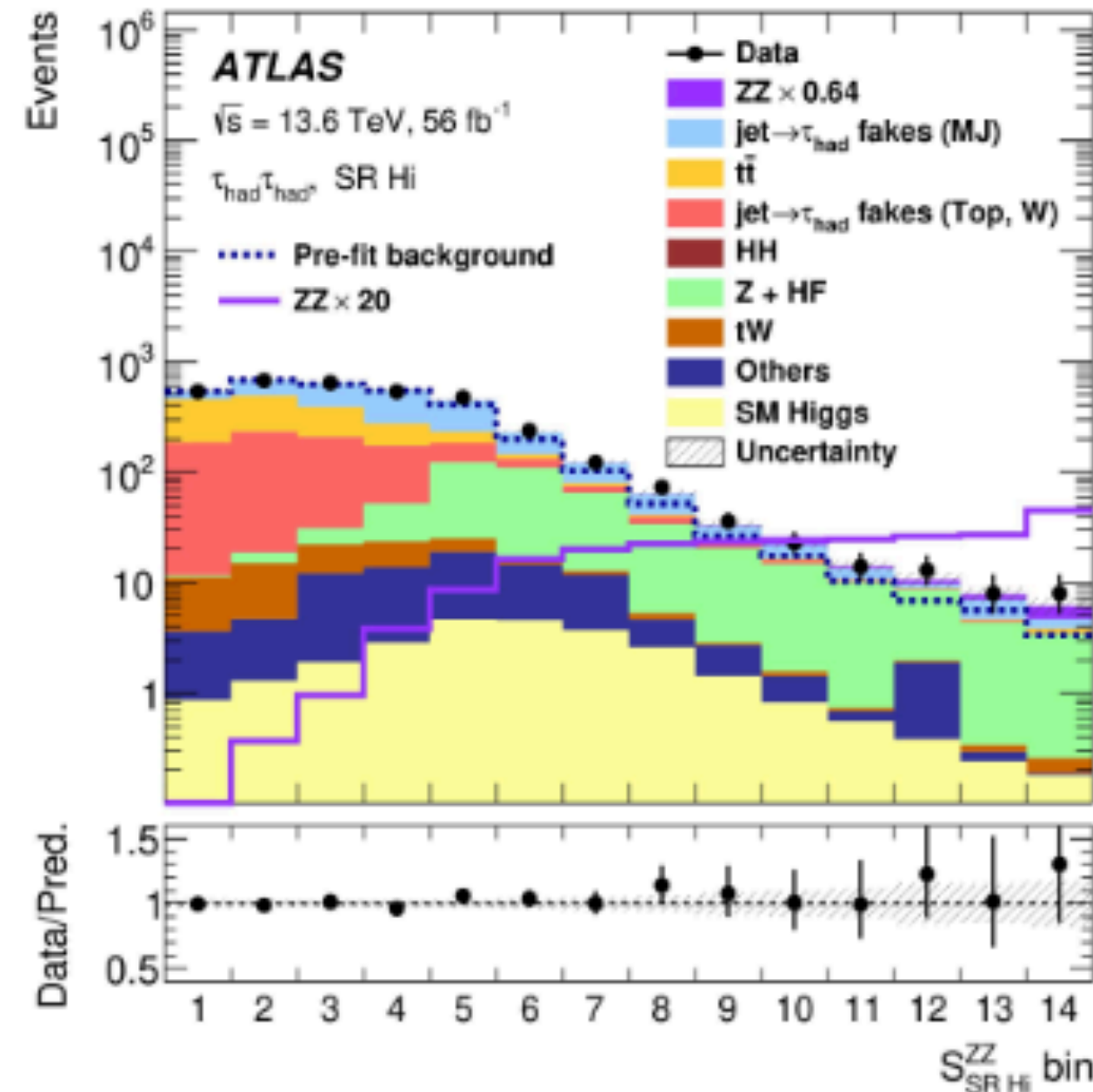


VBF Results



Observed (expected $\mu_{\text{VBF}} = 0$) $\mu_{\text{VBF}} < 43$ (39) @95% CL

		μ_{HH}	μ_{ggF}	μ_{VBF}	$\mu_{ggF} (\mu_{VBF}=1)$	$\mu_{VBF} (\mu_{ggF}=1)$
$\tau_{lep}\tau_{had}$ Run 3	observed	11.6	12.5	135	12.1	143
	expected	7.9	8.1	176	8.0	169
$\tau_{lep}\tau_{had}$ Run 2	observed	7.8	8.2	69	8.1	73
	expected	4.6	4.8	76	4.7	74
$\tau_{had}\tau_{had}$ Run 3	observed	9.1	9.2	134	9.2	140
	expected	5.5	5.7	127	5.6	123
$\tau_{had}\tau_{had}$ Run 2	observed	5.9	6.0	70	6.0	75
	expected	3.0	3.1	61	3.0	58
Run 3	observed	7.9	8.4	89	8.1	96
	expected	4.3	4.4	99	4.3	96
Run 2	observed	5.4	5.5	46	5.5	51
	expected	2.6	2.7	45	2.7	43
Combined	observed	5.3	5.5	41	5.4	43
	expected	$2.4^{+1.2}_{-0.7}$	$2.5^{+1.2}_{-0.7}$	39^{+18}_{-11}	$2.4^{+1.2}_{-0.7}$	39^{+17}_{-11}



- $ZH/ZZ \rightarrow b\bar{b}\tau^+\tau^-$, measurements are used to validate the HH analysis chain.
- In High-SR, the **HH** classifier is replaced by dedicated **ZZ/ZH** discriminants.
- Keeping the same analysis strategy and MVA setup.
- Both measurements are compatible with SM prediction:

$$\mu_{ZZ} = 0.64^{+0.39}_{-0.36} = 0.64 \pm 0.28 \text{ (stat.)}_{-0.28}^{+0.25} \text{ (syst.)}$$

$$\mu_{ZH} = 1.52^{+0.52}_{-0.48} = 1.52 \pm 0.40 \text{ (stat.)}_{-0.28}^{+0.33} \text{ (syst.)}$$

- Observed (expected) significance:

$$ZZ : 1.8 (2.7)\sigma, \quad ZH : \boxed{3.5} (2.4)\sigma$$

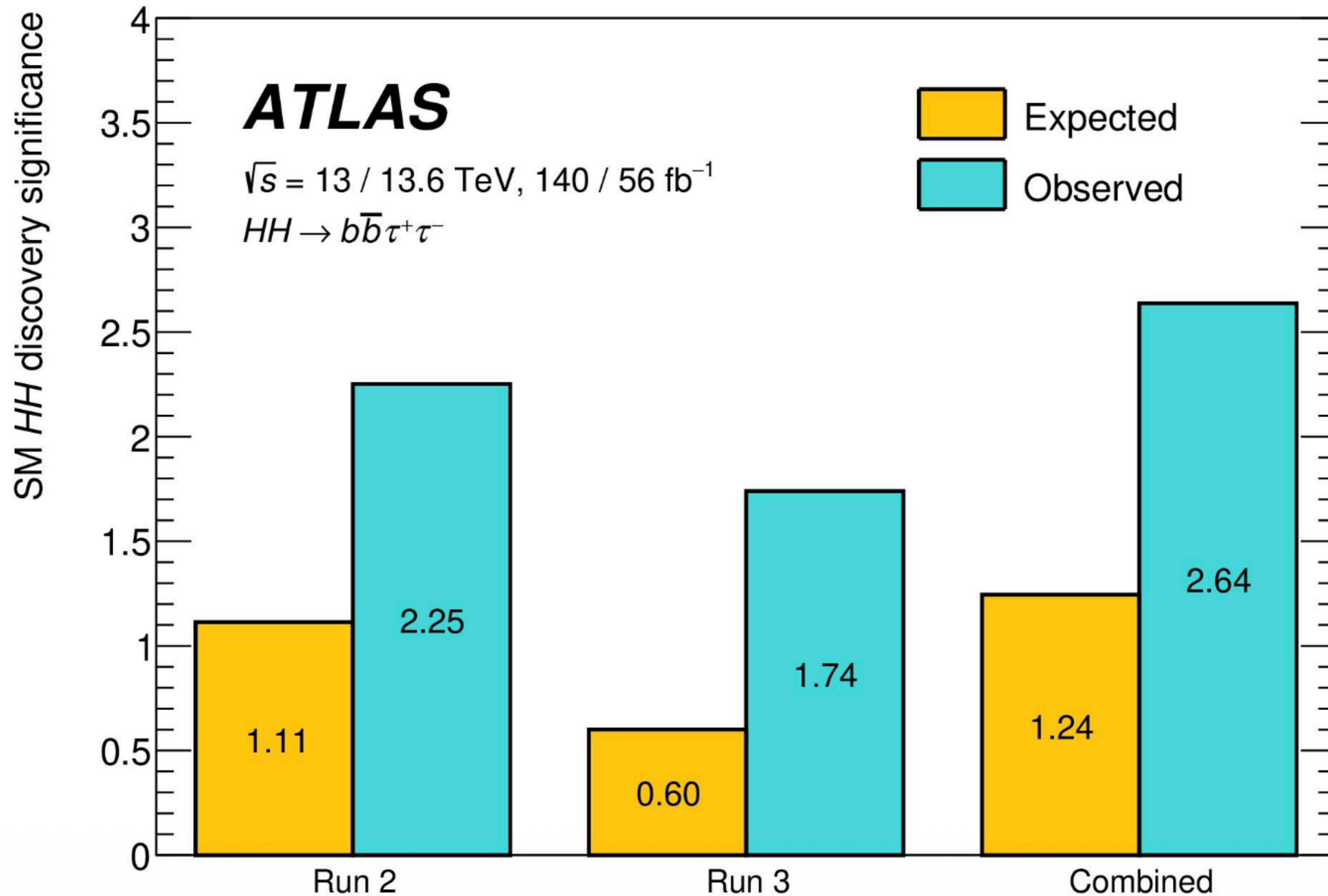
First evidence for $ZH \rightarrow b\bar{b}\tau^+\tau^-$ at 3.5σ .

$\mu_{HH}, \mu_{ZH}, \mu_{ZZ}$ uncertainty breakdown

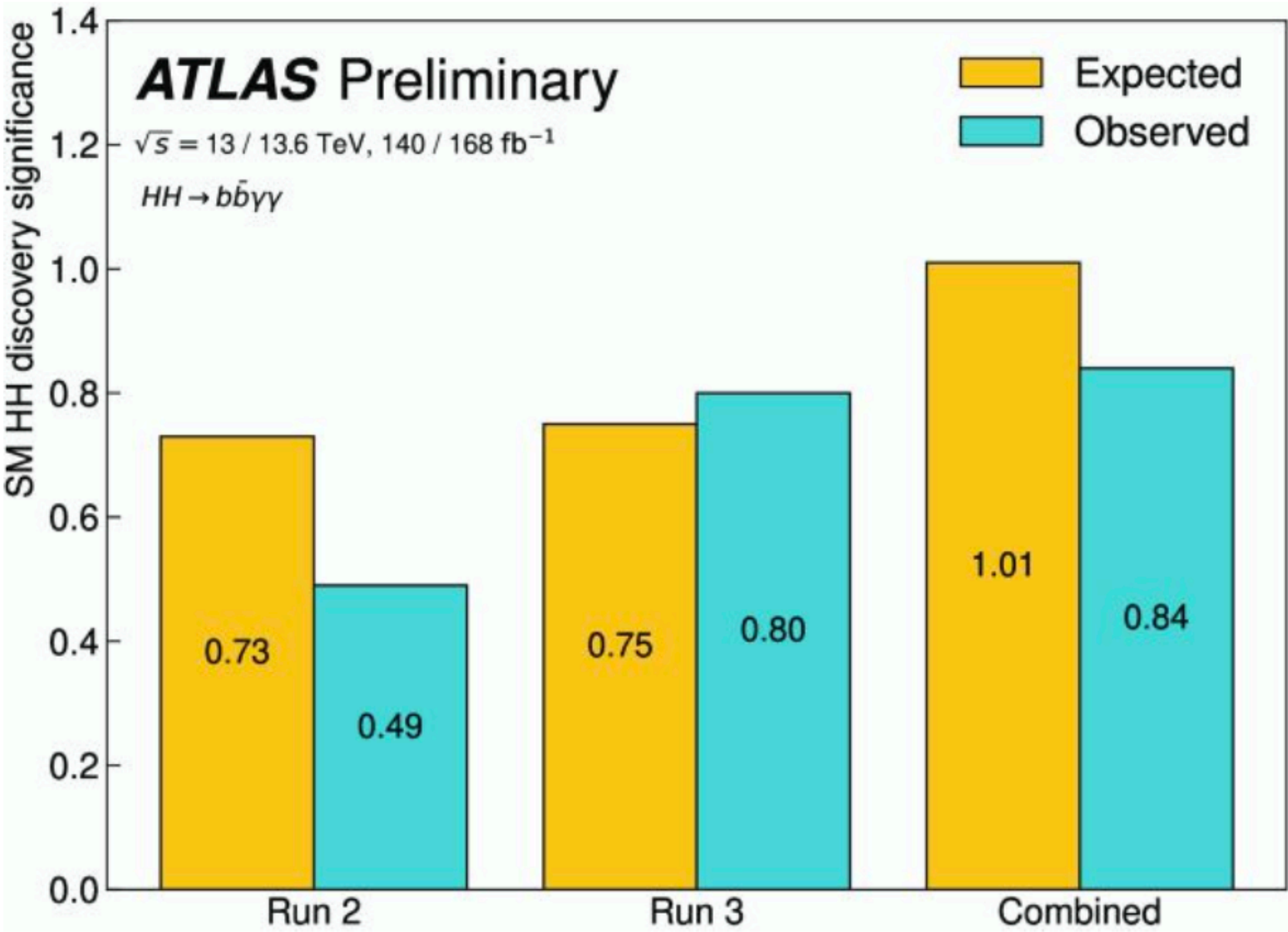
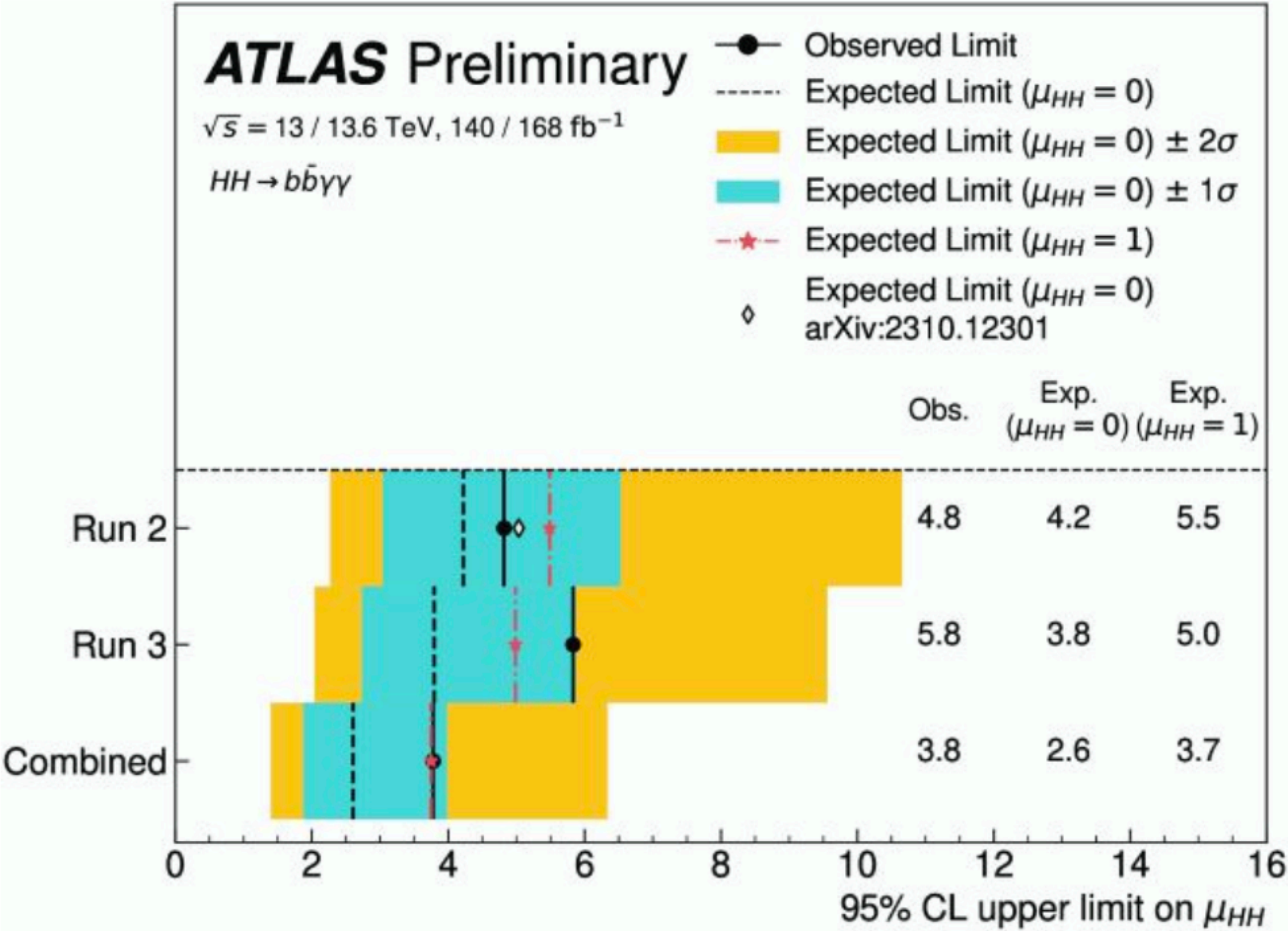
Source of uncertainty	$\sigma_{\mu_{HH}}$
Total	1.20
Statistical	0.91
Systematic	0.76
Experimental uncertainties	0.20
Electron and muon	0.01
τ_{had}	0.13
$E_{\text{T}}^{\text{miss}}$	0.03
Jet	0.14
Flavour tagging	0.04
Pile-up	0.01
Luminosity	0.03
Modelling uncertainties	0.71
Background template statistical	0.21
HH	0.54
ZH	0.02
ZZ	<0.01
Other SM Higgs	0.25
Z+jets	0.07
tW	0.21
Top	0.12
jet $\rightarrow \tau_{\text{had}}$ fakes	0.07
Others	0.01

Source of uncertainty	$\sigma_{\mu_{ZH}}$	$\sigma_{\mu_{ZZ}}$
Total	0.50	0.37
Statistical	0.39	0.28
Systematic	0.30	0.24
Experimental uncertainties	0.14	0.12
Electron and muon	0.02	0.02
τ_{had}	0.05	0.03
$E_{\text{T}}^{\text{miss}}$	0.02	0.02
Jet	0.13	0.10
Flavour tagging	0.02	0.02
Pile-up	0.01	0.01
Luminosity	0.01	0.01
Modelling uncertainties	0.26	0.21
Background template statistical	0.10	0.09
HH	0.01	<0.01
ZH	0.09	<0.01
ZZ	<0.01	0.04
Other SM Higgs	0.11	<0.01
Z+jets	0.14	0.17
tW	0.06	0.03
Top	0.07	0.05
jet $\rightarrow \tau_{\text{had}}$ fakes	0.03	0.03
Others	<0.01	0.04

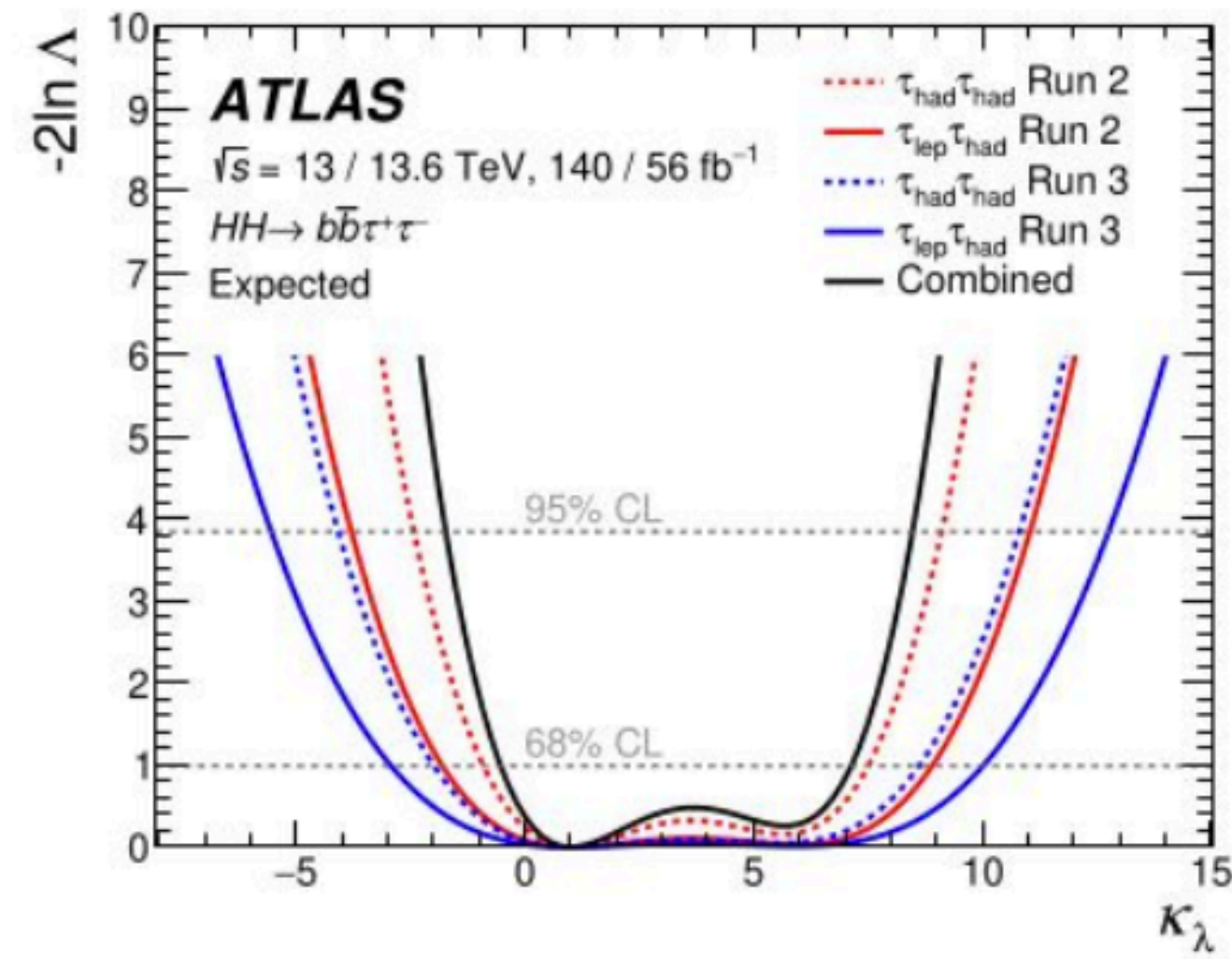
Source of uncertainty	$\sigma_{\mu_{VBF}}$
Total	18.88
Statistical	16.61
Systematic	8.96
Experimental uncertainties	2.17
Electron and muon	0.17
τ_{had}	0.55
$E_{\text{T}}^{\text{miss}}$	0.25
Jet	1.96
Flavour tagging	0.50
Pile-up	0.23
Luminosity	0.16
Modelling uncertainties	8.67
Background statistical uncertainty	5.61
HH	0.81
ZH	0.06
ZZ	0.12
Other SM Higgs	5.14
Z+jets	1.92
tW	1.18
Top	3.38
jet $\rightarrow \tau_{\text{had}}$ fakes	1.01
Others	0.17



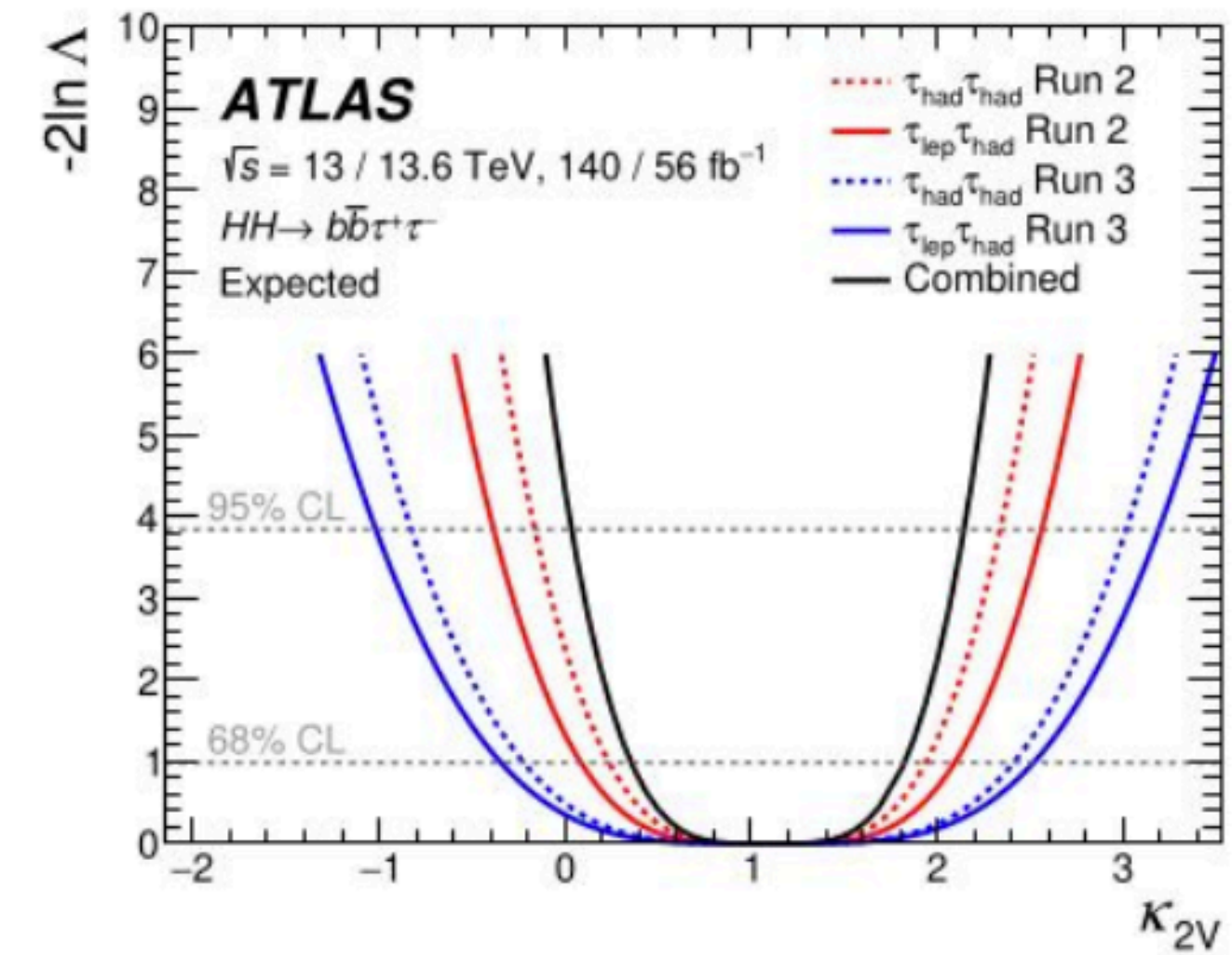
Phys. Lett. B 876 (2026) 140280



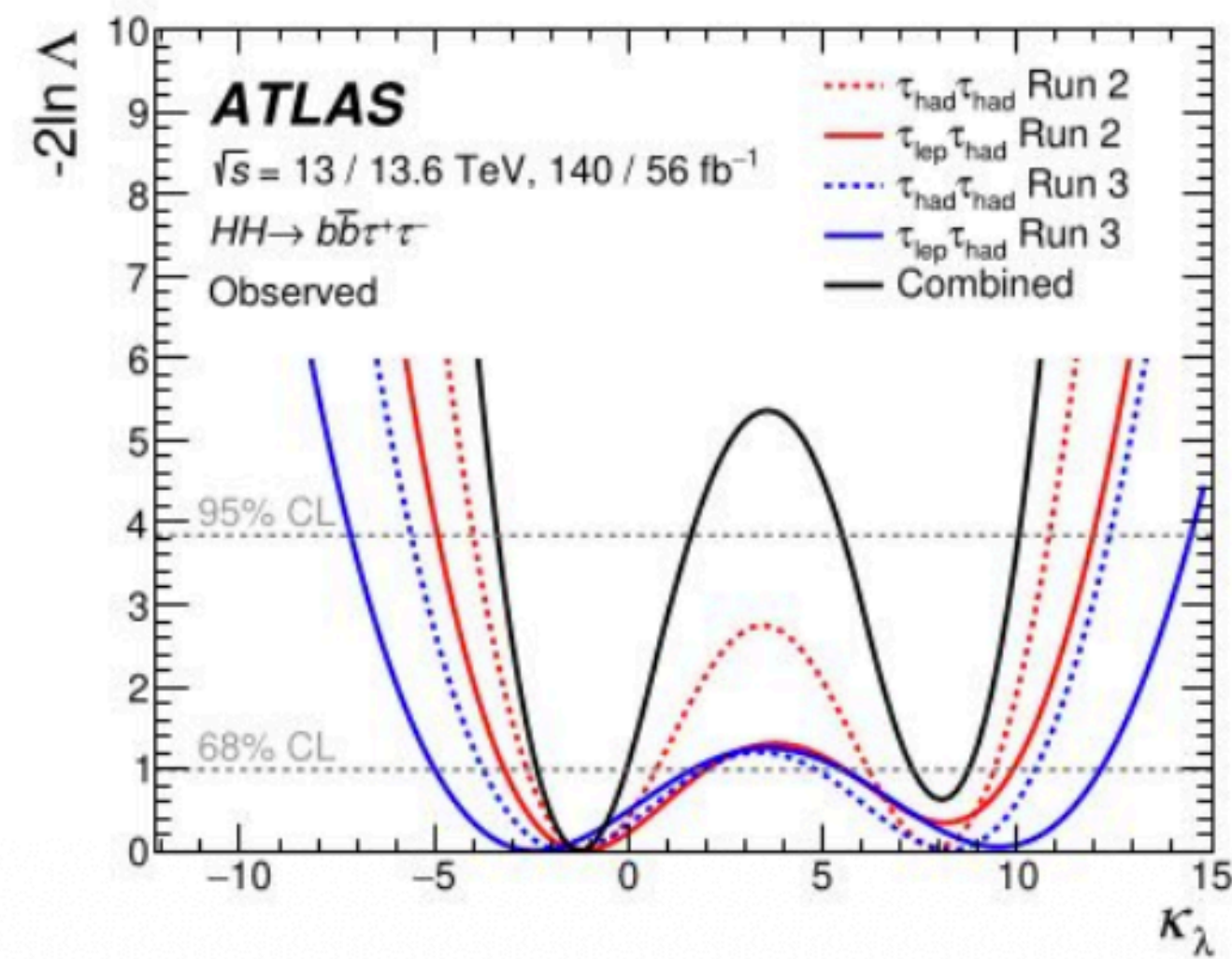
κ_λ , κ_{2V} expected/observed scans



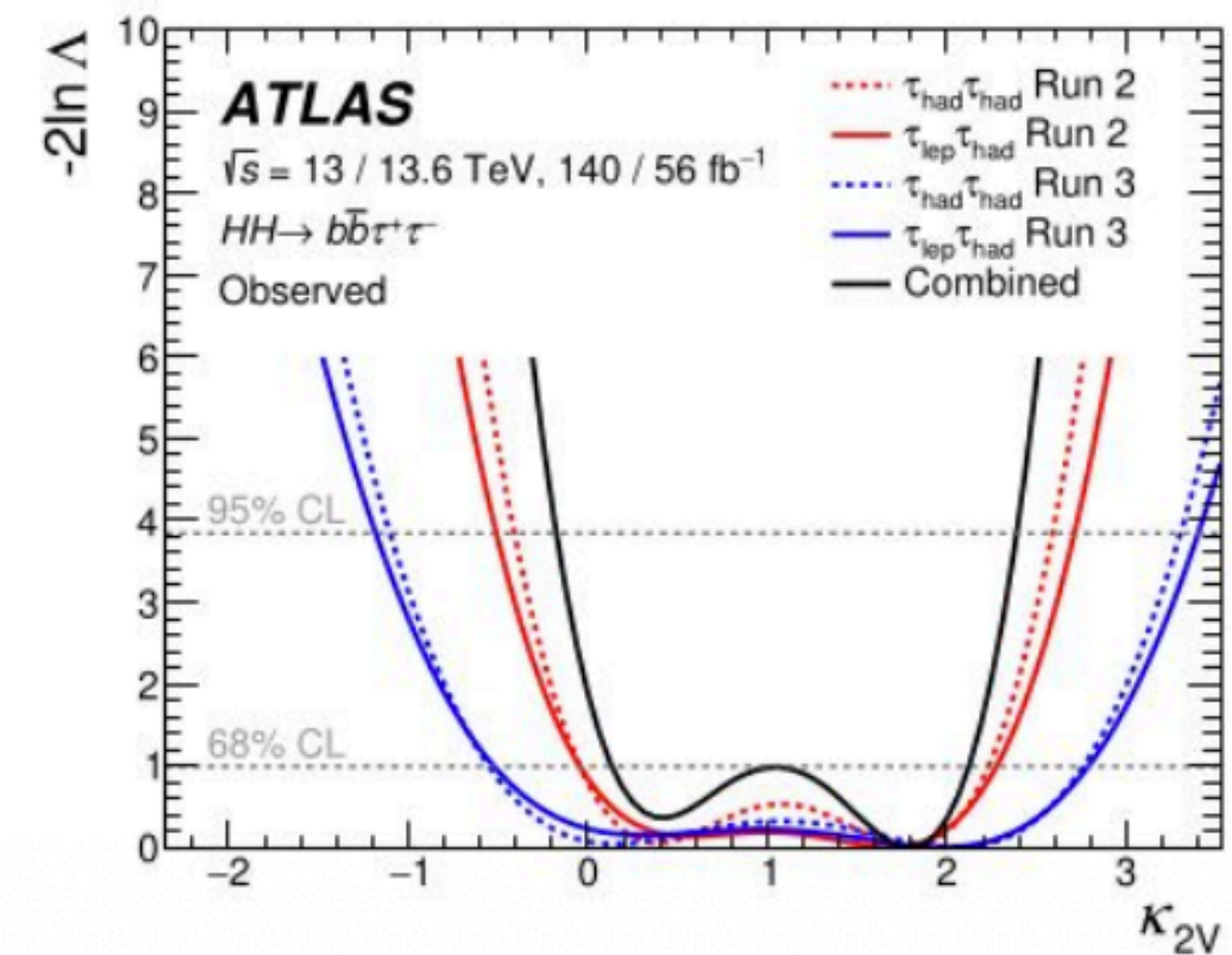
(a)



(b)

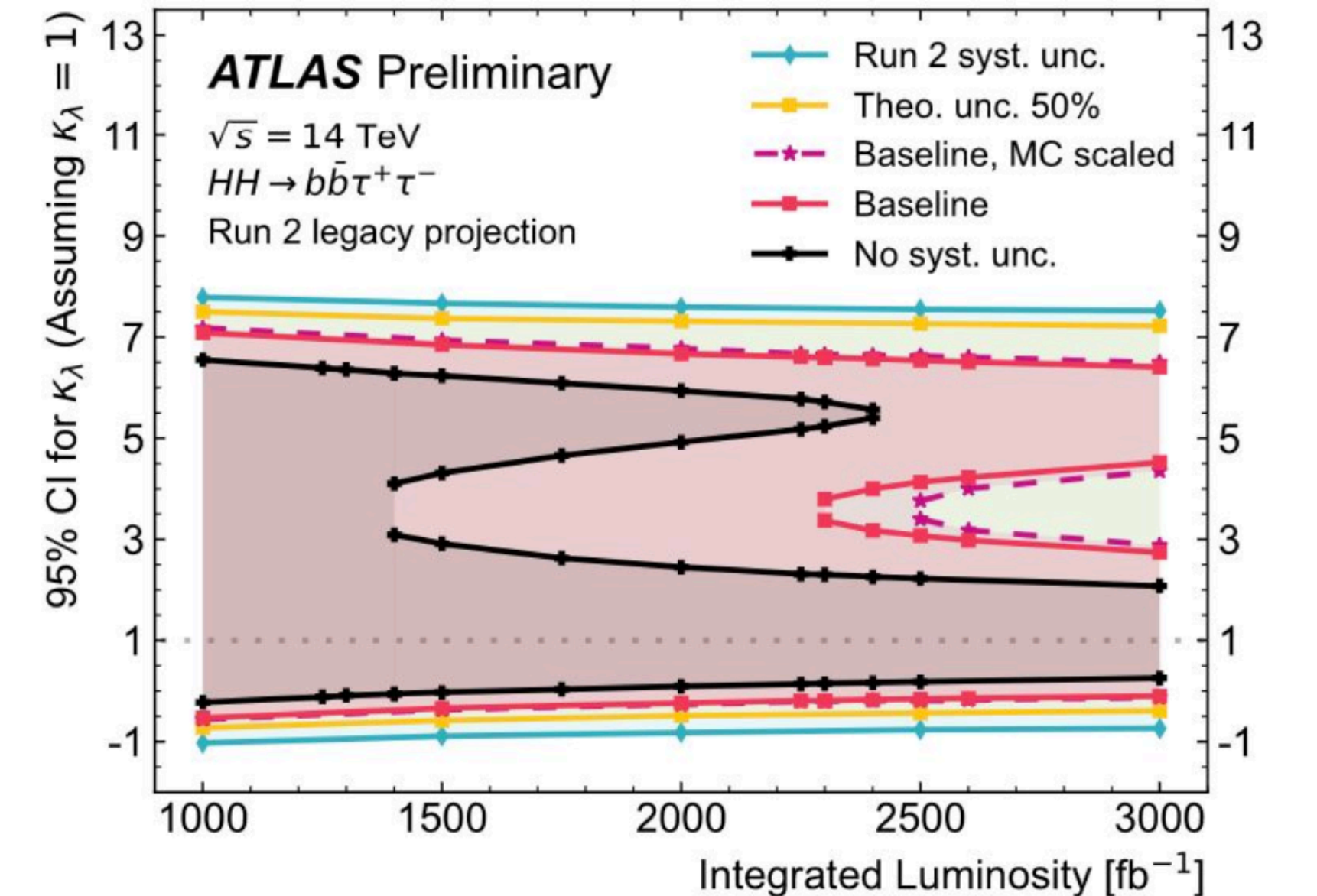
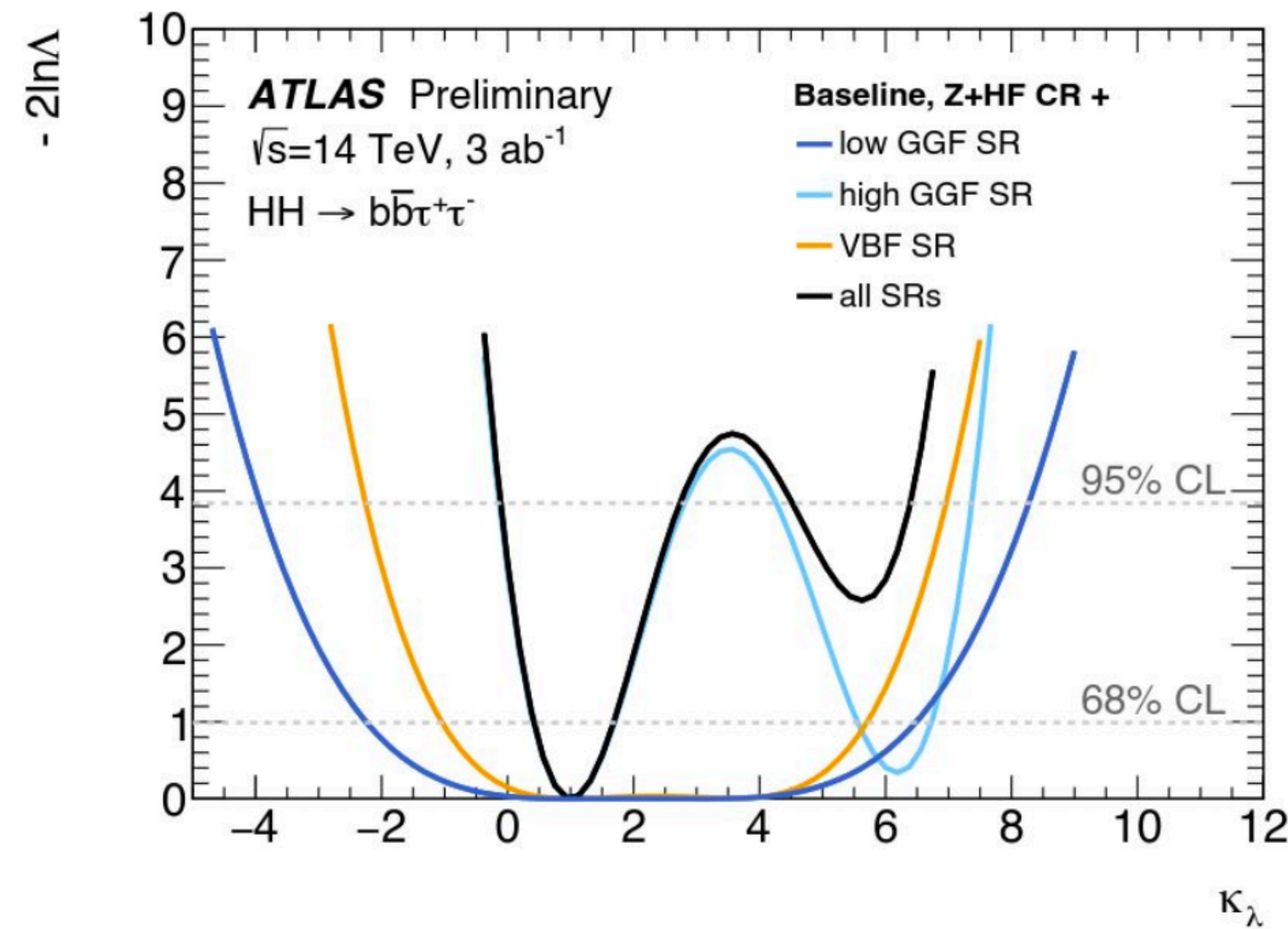
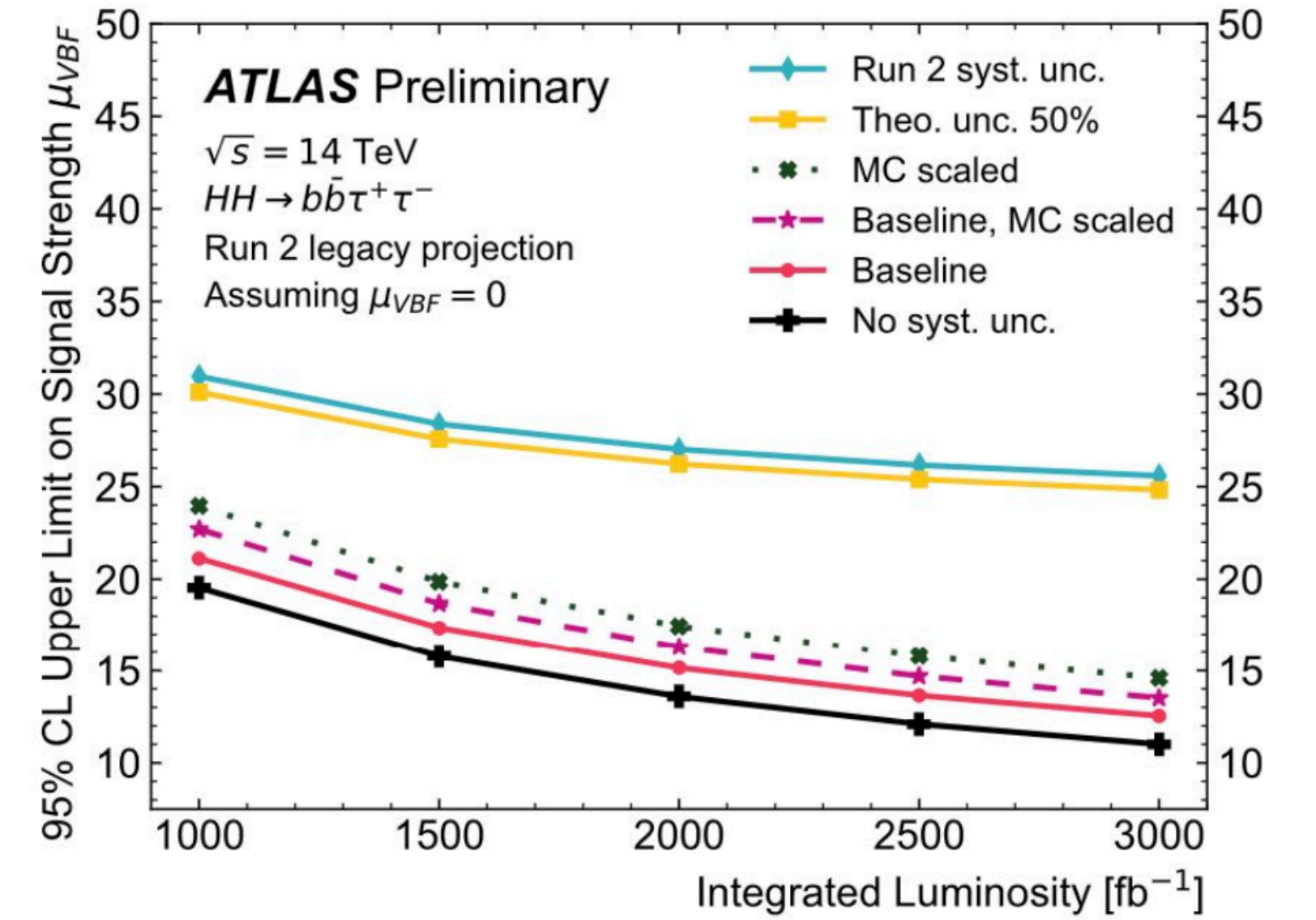
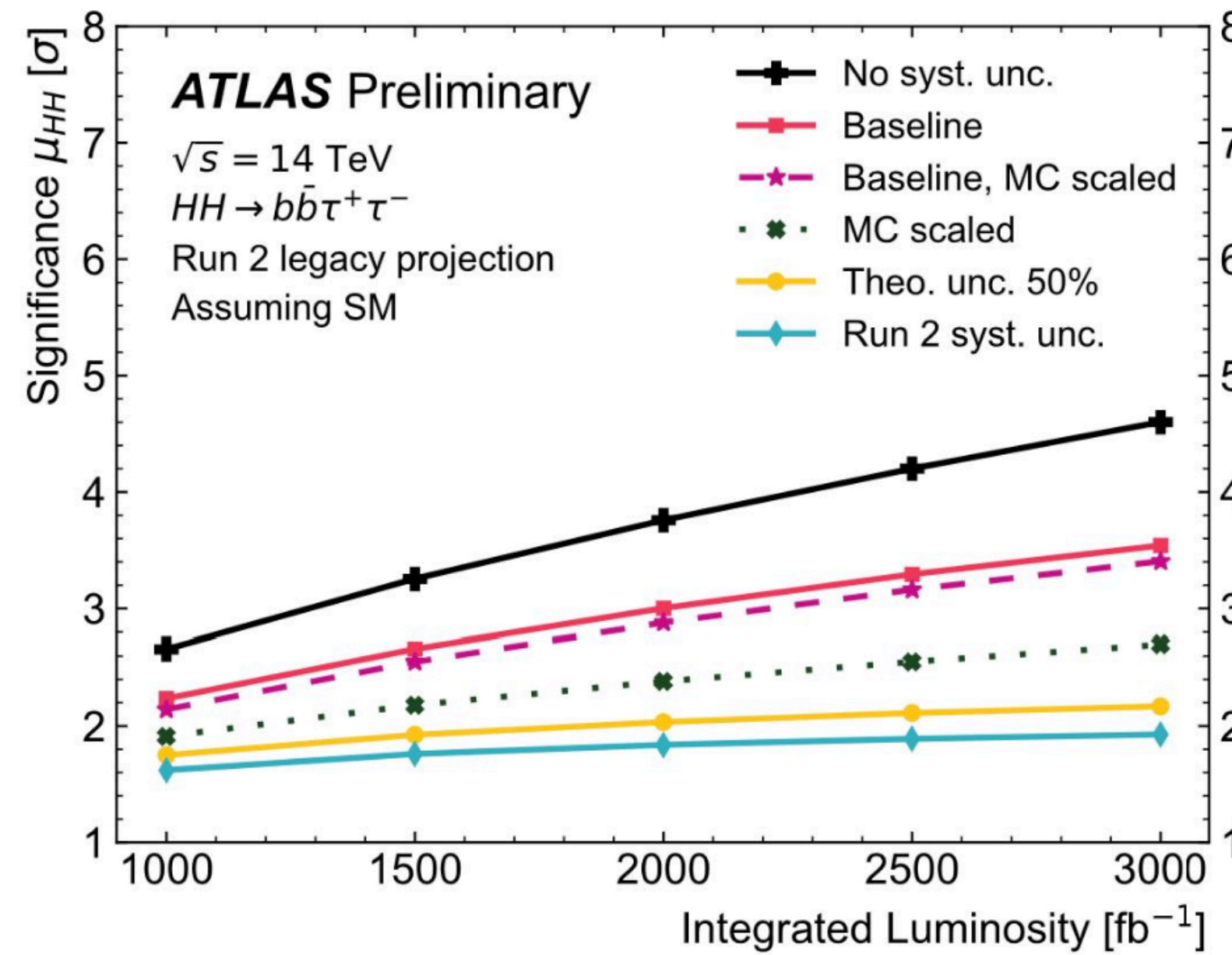


(c)

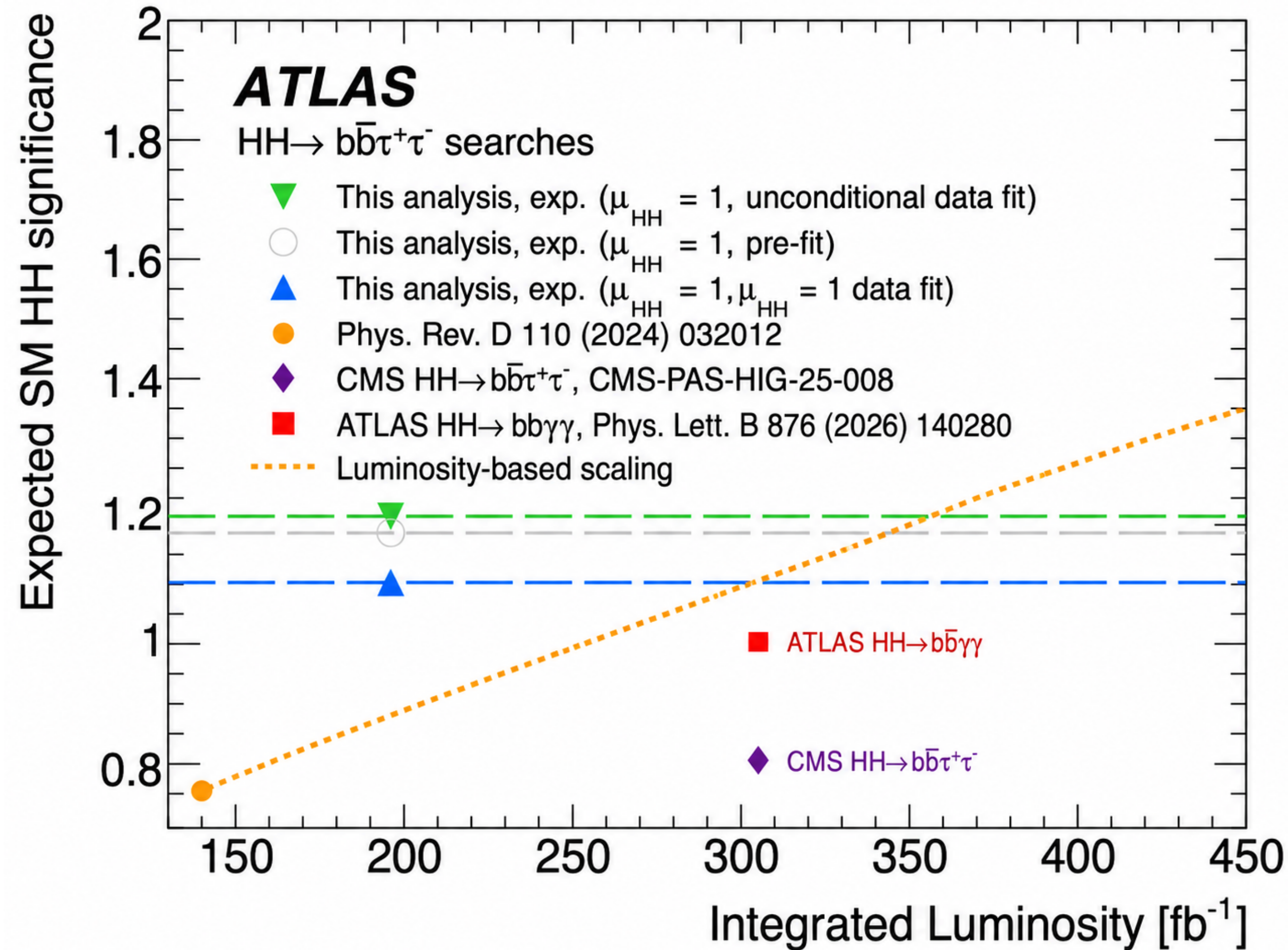


(d)

$HH \rightarrow b\bar{b}\tau^+\tau^-$ luminosity projections



[ATL-PHYS-PUB-2024-016](#)



- The expected μ_{HH} limit of **2.4** reaches approximately the sensitivity of **the full ATLAS Run-2 HH combination**.
- **50%** higher expected significance than CMS $HH \rightarrow b\bar{b}\tau^+\tau^-$, with **~37%** less luminosity.
- **19%** higher expected significance than ATLAS $HH \rightarrow b\bar{b}\gamma\gamma$, with **~36%** less luminosity.
- Sensitivity equivalent to **$\sim 230 \text{ fb}^{-1}$** of additional Run-2 data — about **164%** of the Run-2 luminosity.