Search for non-resonant Higgs boson pair production in $bb\tau\tau$ final state with the ATLAS detector

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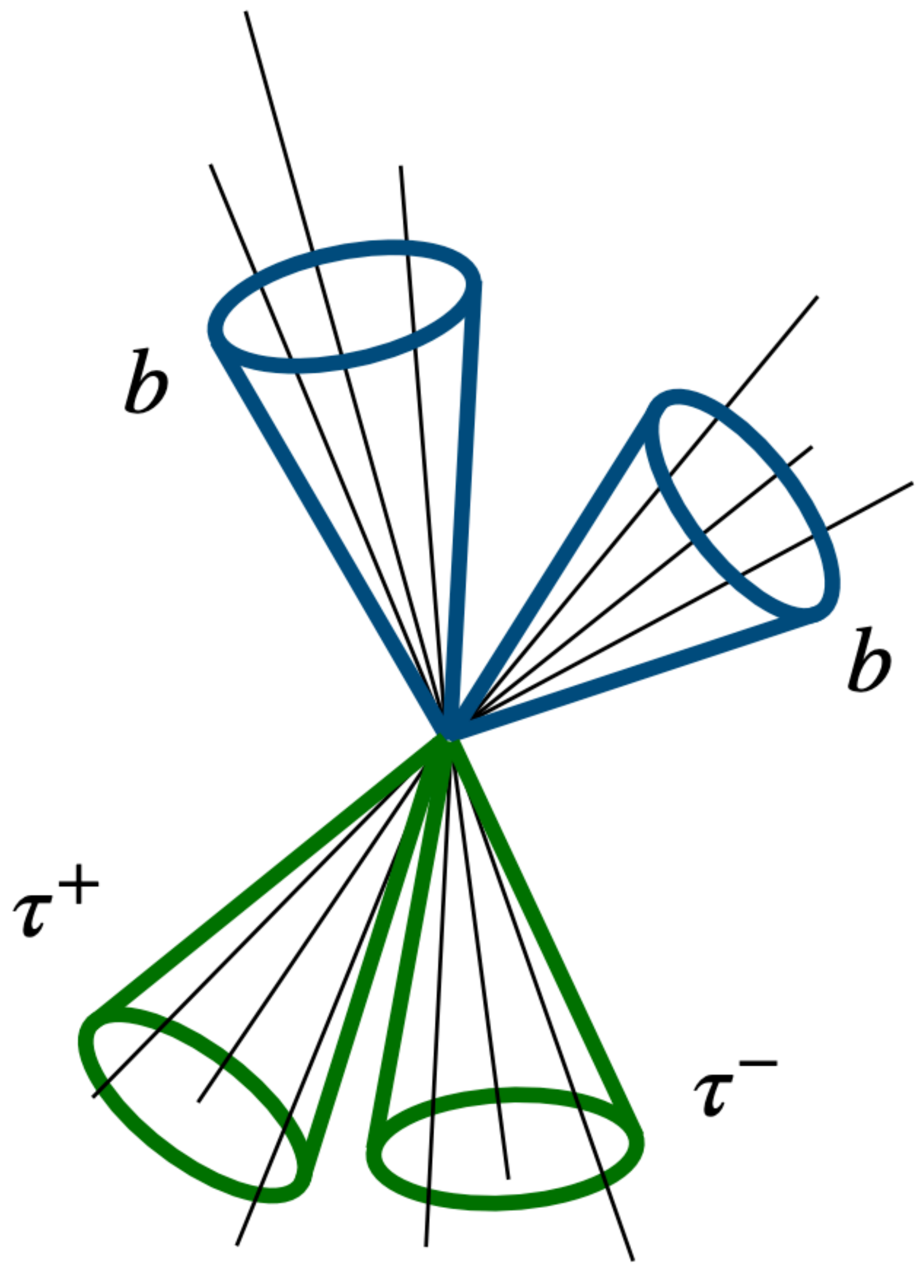
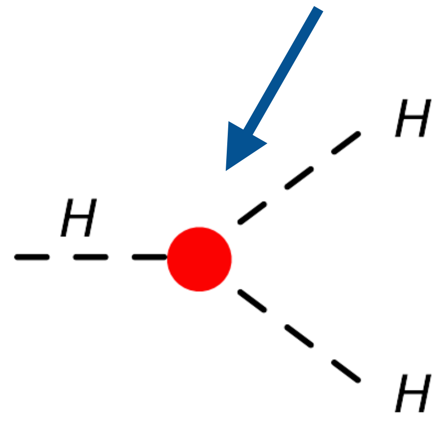
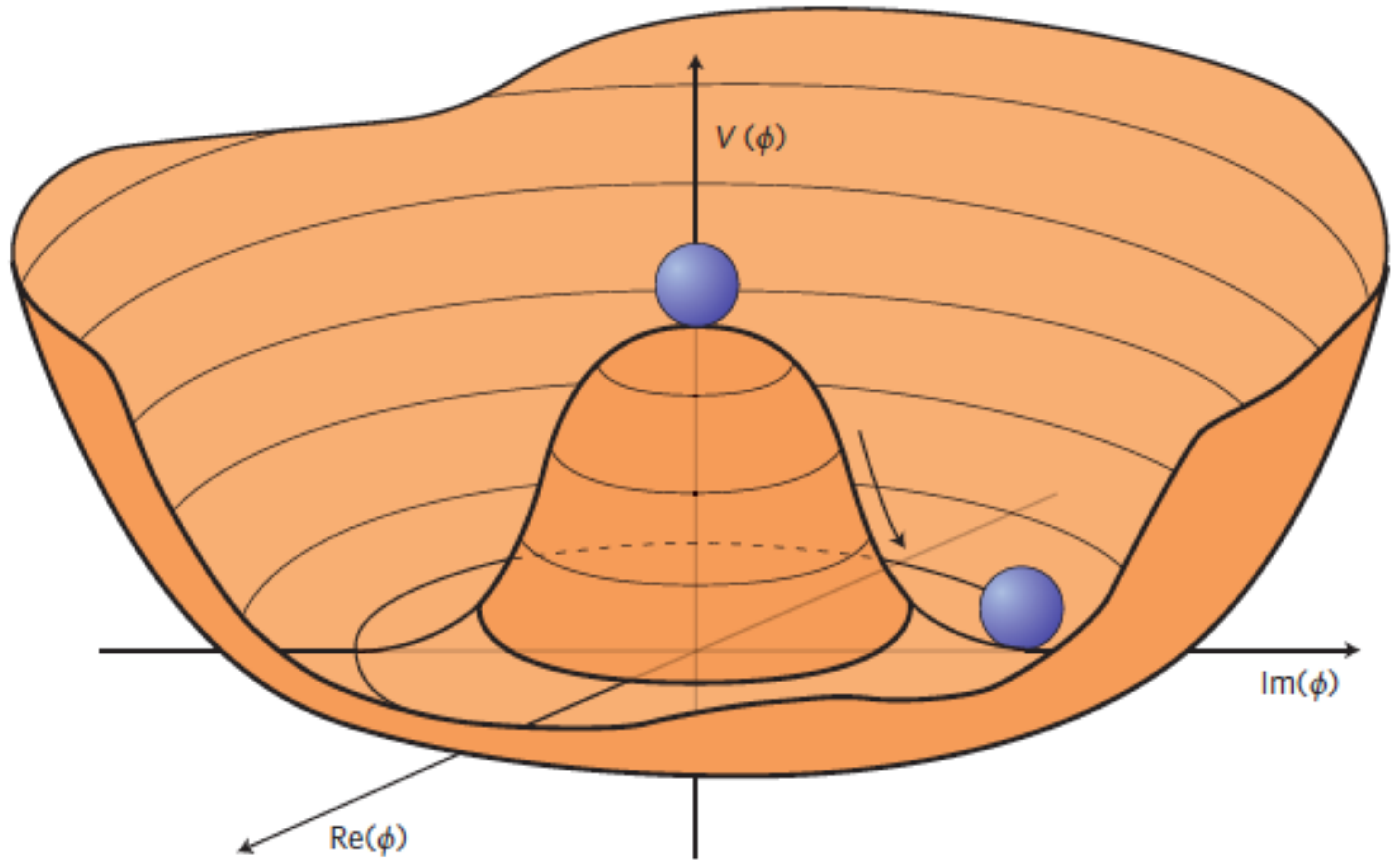


Motivation

→ After Higgs boson discovery, only a portion of Higgs potential has been measured.

$$V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$
$$= \frac{1}{2}m_H^2 H^2 + \boxed{\lambda v H^3} + \frac{\lambda}{4}H^4, \quad \boxed{m_H^2 = 2\lambda v^2}$$





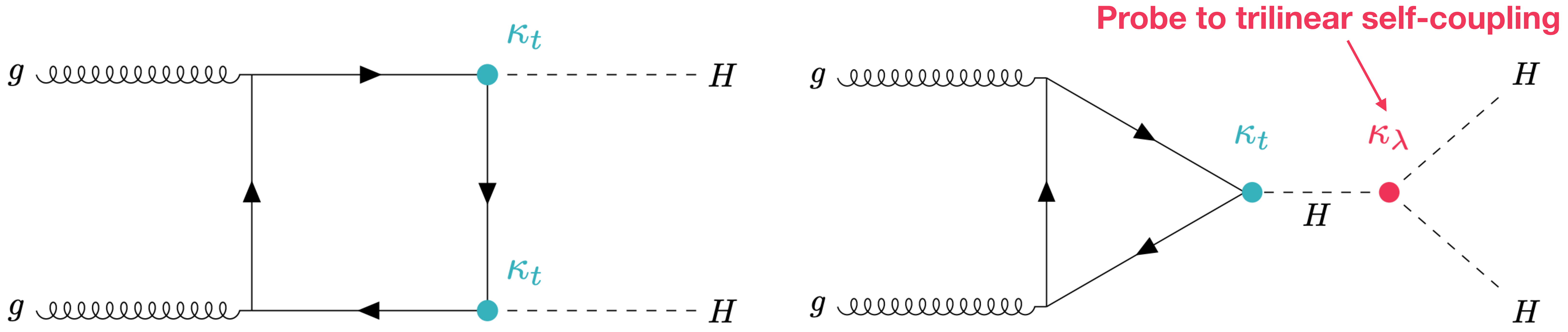
→ Higgs boson trilinear self-coupling

- The shape of Higgs potential
- Better understanding of Higgs mechanism and electroweak symmetry breaking
- Experimentally accessed by studying Higgs boson pair (HH) production
- Any deviation from the self-coupling predicted by the SM —> a sign of new physics

Non-resonant HH Production in SM

→ Very small cross-section! ~3 orders of magnitude smaller than single H production

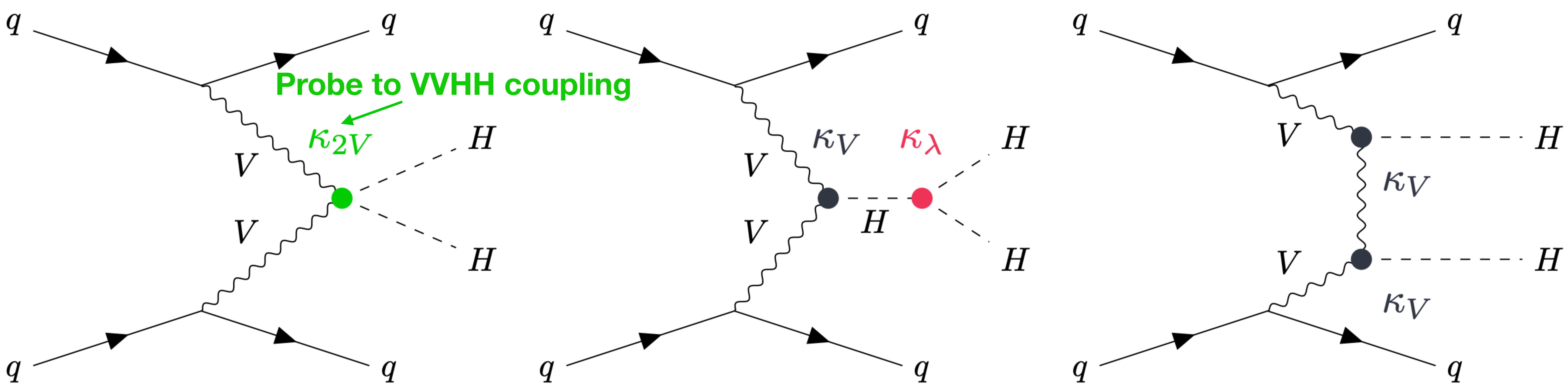
- Gluon-gluon fusion: $\sigma^{SM}_{ggF} = 31.05\ fb\ @13TeV$



$$Modifier:\ \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}_{HHH}}$$

$$\kappa_\lambda = 1,\ in\ the\ case\ of\ SM$$

- Vector-boson fusion: $\sigma^{SM}_{VBF} = 1.73\ fb\ @13TeV$



- Other production modes (e.g. VHH, ttHH) have even smaller cross-section.

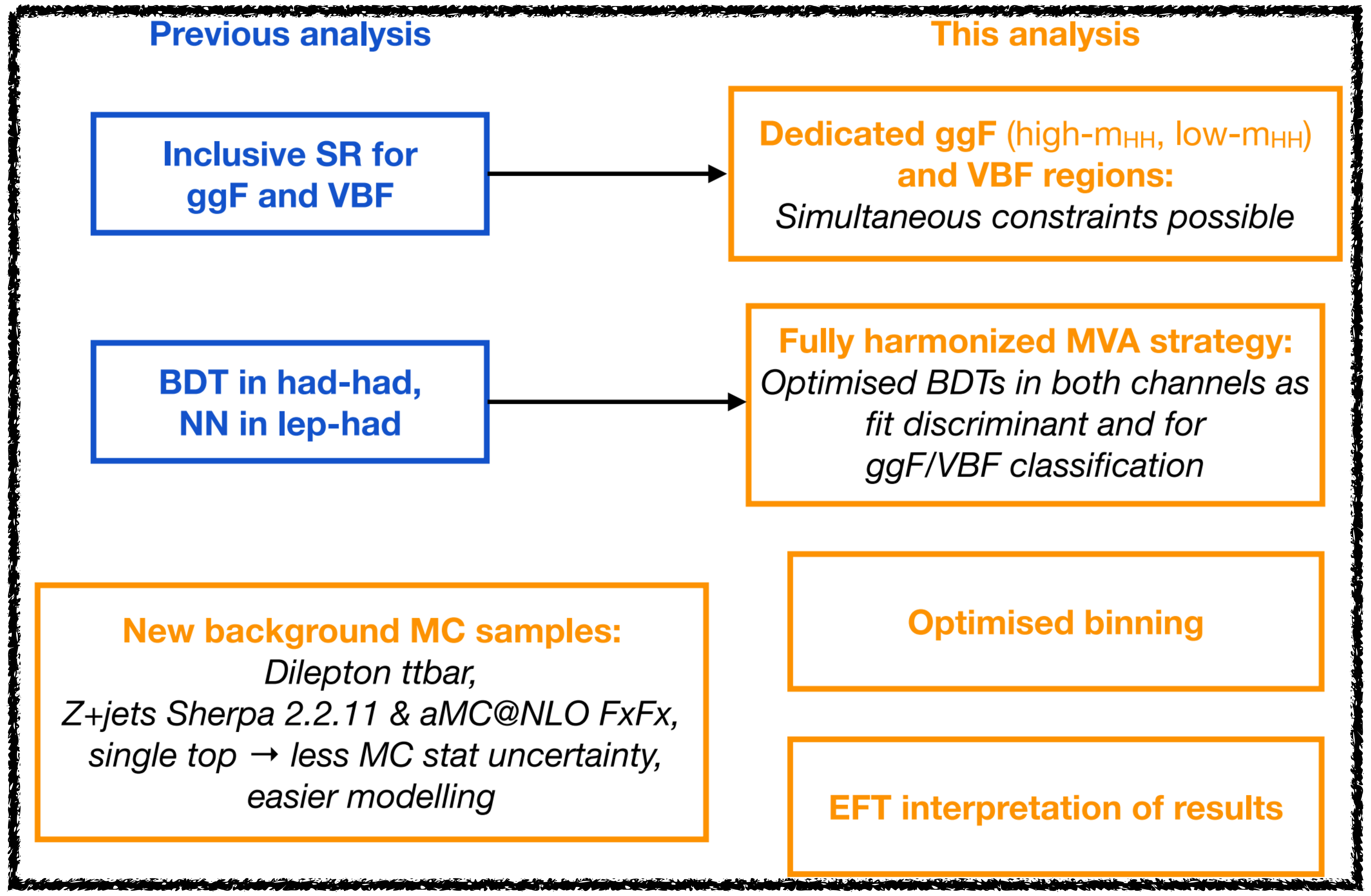
Overview of analysis strategy

→ **Re-analysis of the full Run 2 dataset inherited from previous analysis to improve the Higgs boson self-coupling measurement!**

Legacy Analysis inherited from previous analysis:
- Object selection and identification
- Trigger strategy
- Overall event selection (except Z CR)

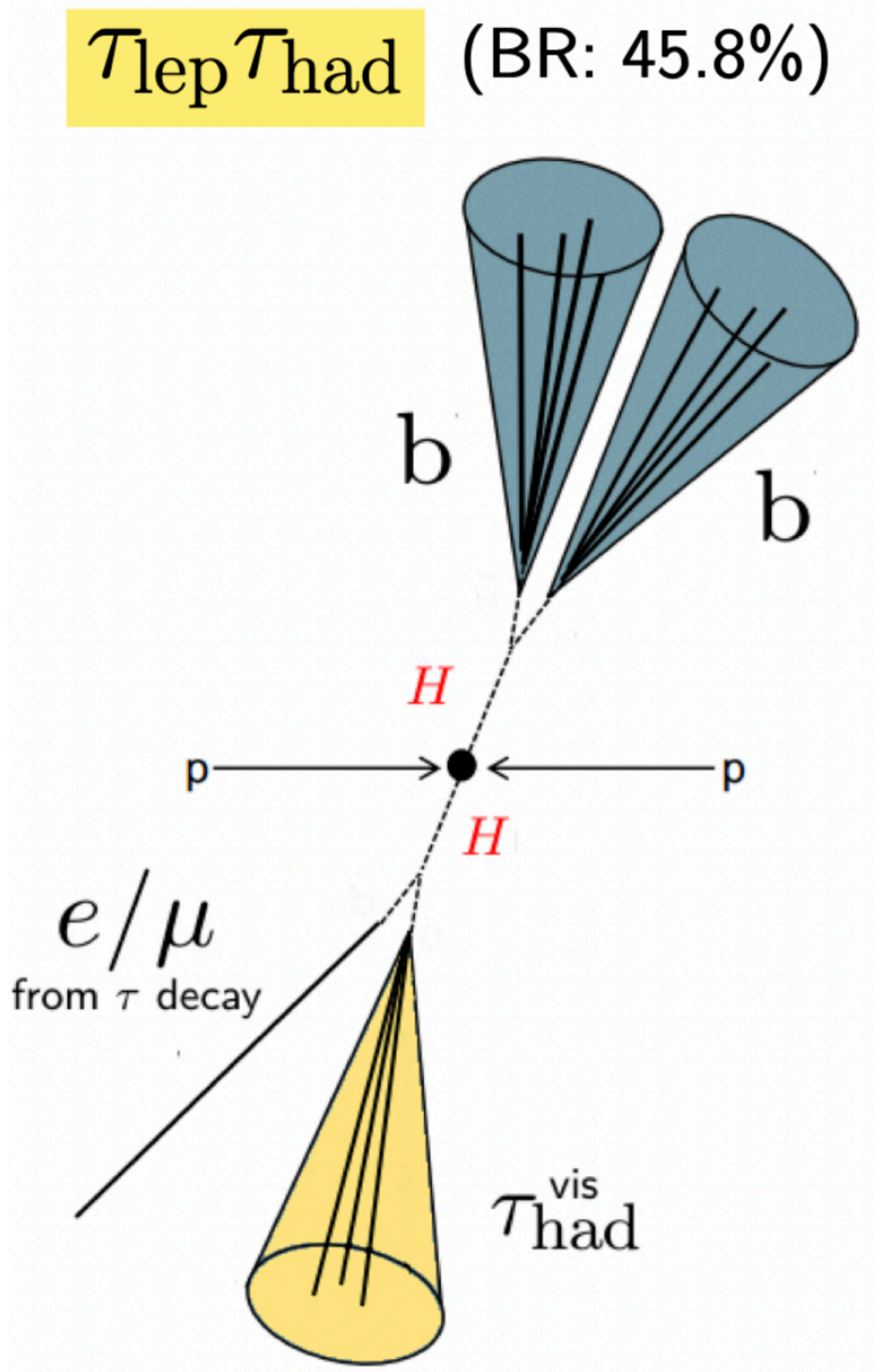
What we changed/included for achieving the figure of merits:
- Event categorisation: dedicated VBF SR and mHH split
- Increase MC statistics (for background)
  - **dilepton** $t\bar{t}$ (DSID 410472) is combined with **non-all-hadronic**
  - New **Sherpa2.2.11** samples for **V+jets**
- Re-optimisation of MVA approach: variables / hyperparam / binning
- Partial re-definition of CR
- More interpretations: EFT

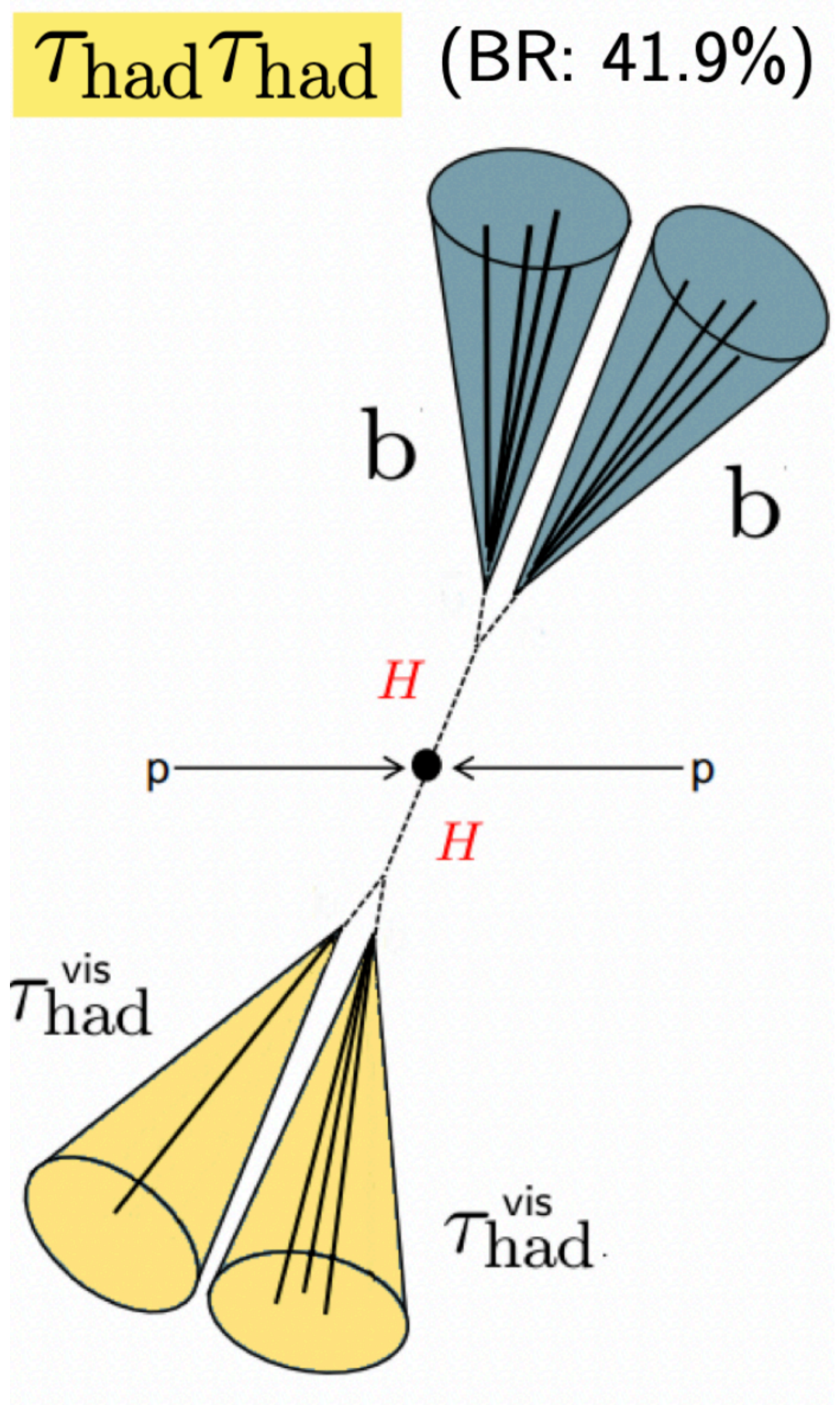
Harmonisation of the frameworks:
- Unlike previous analysis
  - Choose common framework (CxAOD Reader) for sub-channels
- Common codes for MC modelling evaluation and MVA trainings



Overview of analysis strategy

→ Targeting at non-resonant HH—>bbtautau signal (2 b-tagged jets + OS tau-leptons)





two analysis channels: lephad and hadhad

→ Events further categorized by triggers

hadhad	Single-tau triggers (STT) + Di-tau triggers (DTT)	High purity
lephad SLT	Single-lepton triggers (SLT)	High acceptance, large ttbar background
lephad LTT	Lepton + tau triggers (LTT)	Lower p_T^l increases low mass sensitivity

Data and MC Samples

Data:

- Full run2 dataset with integrated luminosity of 140 fb^{-1}

MC samples

- **Signals**:
  - gg→HH samples at NLO (ggF. with $\kappa_\lambda = 1, 10$): **Powheg Box v2**
  - qq→HH samples at LO (VBF with varied κ_λ, κ_{2V}, κ_V): **MadGraph5_aMC@NLO 2.7.3**

Background samples:

- $t\bar{t}$ **and single top**: Powheg + Pythia8, $t\bar{t}$ using NNLO + NNLL X.S* and single top using NLO
  - $t\bar{t}$ norm freely floating as determined from data by the fit
- **V (W,Z) + jets**: **Sherpa 2.2.11**, **Di-boson** (semi-leptonic): Sherpa 2.2.1. V + jets using NNLO X.S and Di-boson NLO
  - Z + HF jets norm freely floating as determined by the Z + HF CR (≈ shared by HH → bbll group)
- **ttV**: Sherpa 2.2.1 for **ttZ** and Sherpa 2.2.8 for ttW, both at NLO
- **Single SM Higgs**: Powheg+Pythia8, NLO: **tth**, NNLO(QCD) + NLO(EW): qqZh, Wh, ggFh, VBFh, NLO+NLL: ggZh

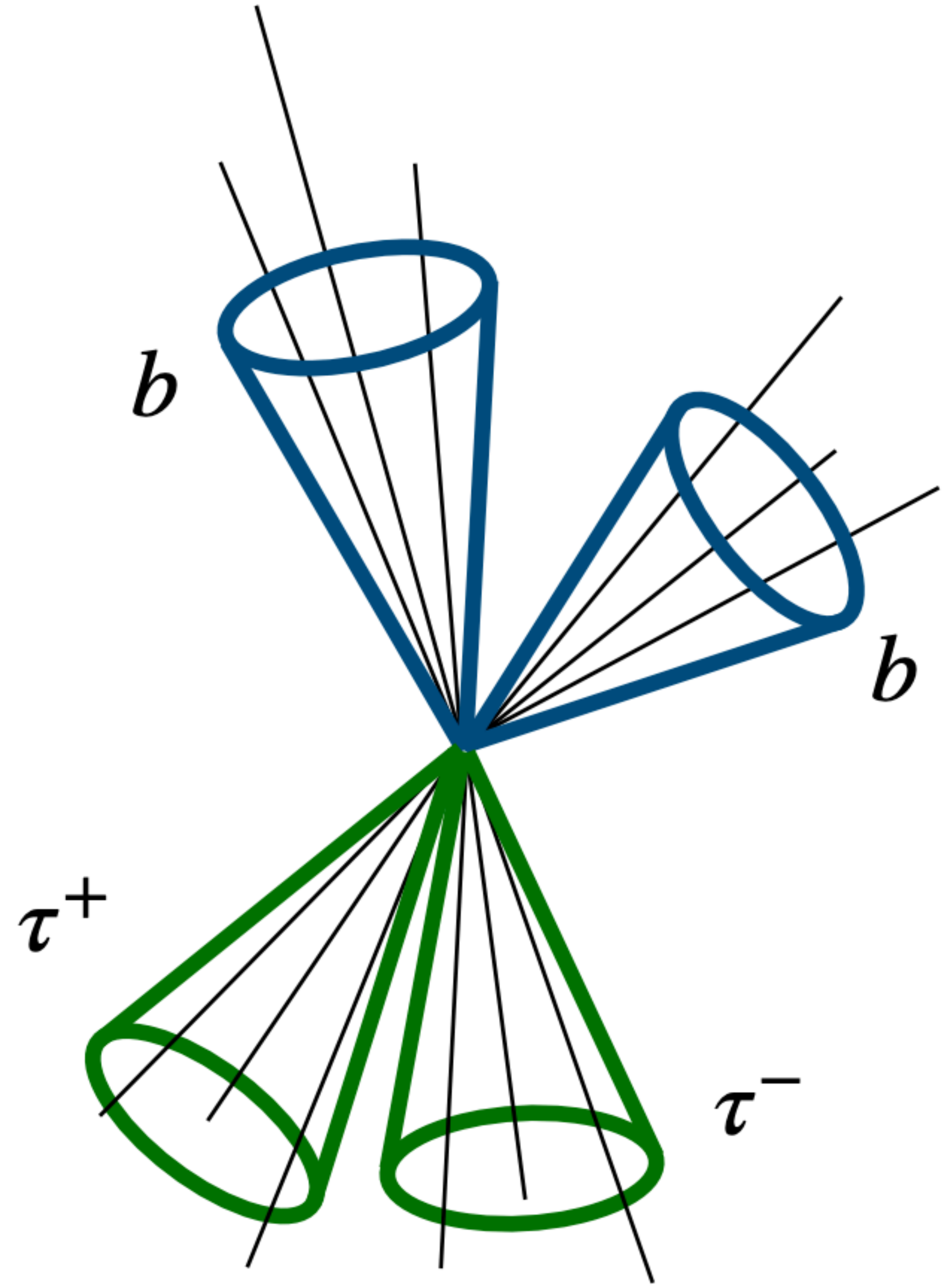
Background due to a τ_{had} is fake by a jet, which is estimated by (semi-) data driven method

- τ_{had} fake by a lepton is taken from MC

Event selection $HH -> bb\tau\tau$

→ **Search for HH with bbtautau final states**

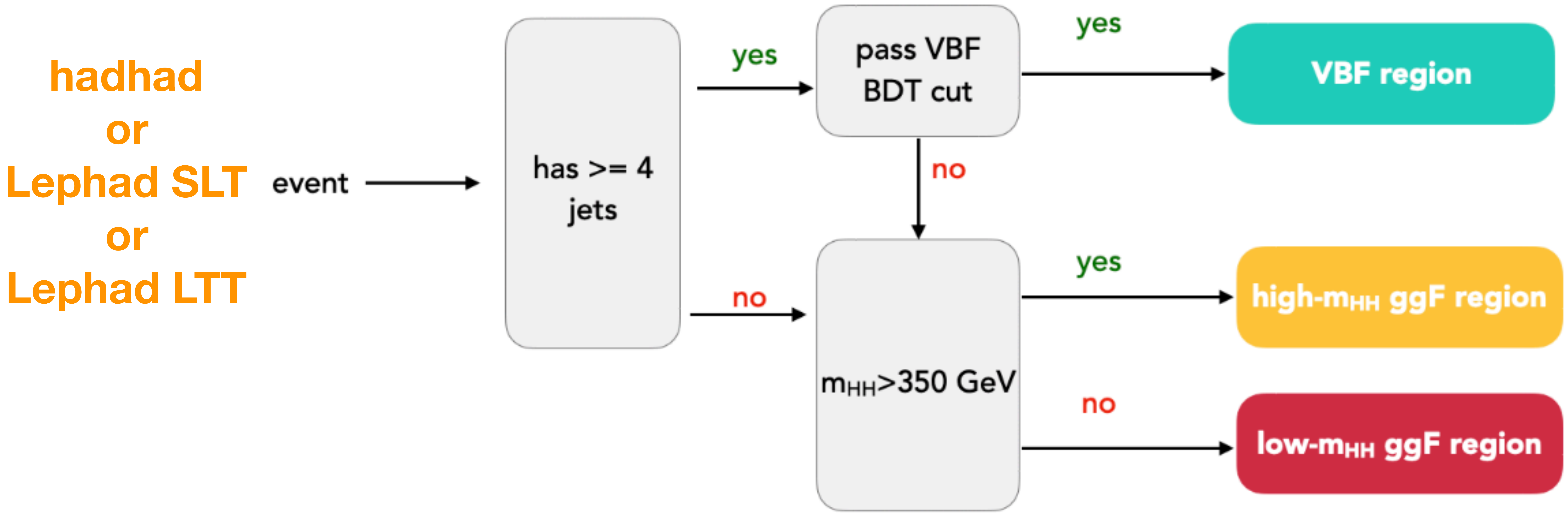
	$\tau_{lep}\tau_{had}$	$\tau_{had}\tau_{had}$
Triggers	Single Lepton (e/μ) triggers (SLT)	Single τ_{had} triggers (STT)
	Or Lepton + τ_{had} triggers (LTT)	Or Di-τ_{had} triggers (DTT)
	Offline Requirements Passed	Offline Requirements Passed
Event Selection	$m_{\tau\tau}^{MMC}$ [*] > 60 GeV	$m_{\tau\tau}^{MMC}$ [*] > 60 GeV
	Opposite-sign of e/μ/τ_{had} and τ_{had}	Opposite-sign of e/μ/τ_{had} and τ_{had}
	Exactly two b-tagged jets	Exactly two b-tagged jets
	One (tight) e or (medium) μ	No loose e/μ
	One (loose) τ_{had}	Two (loose) τ_{had}
	M_{bb} < 150 GeV	



Categorization

→ **In each sub-channel (hadhad, lephad SLT, lephad LTT), events passing all the selection are further divided into 3 Signal Regions (SR):**

- VBF region High-mHH ggF region Low-mHH ggF region



Categorization

→ 9 Signal Regions + 1 Control Region

3 channels per di-τ decays

different background composition

HadHad	LepHad	
$\tau_{had}\tau_{had}$	$\tau_{lep}\tau_{had}$ SLT	$\tau_{lep}\tau_{had}$ LTT
single-$\tau_{had\text{-}vis}$-trigger + di-$\tau_{had\text{-}vis}$ trigger	single-lepton-trigger	lepton-plus-$\tau_{had\text{-}vis}$ trigger

⊗

3 regions

per production mode + m_{HH} split

improve coupling modifier constraints

ggF m_{HH}< 350 GeV	ggF m_{HH} ≥ 350 GeV	VBF

⊕

1 control region

improve modelling of major backgrounds

m_{ll} CR

Background estimation

→ **Use the same strategy with last round analysis. Verified for this round!**

→ **Main backgrounds:**

- Top-quark, Z+jets, W+jets, diboson, single Higgs boson and multi-jet production
  - Fake tau-had is estimated by data-driven method
    1. backgrounds with tau-had mis-identified by quark-/gluon-initiated jet
  - Other backgrounds are estimated by MC simulation

→ **Normalizations of simulated ttbar and Z+HF are determined by data in the ZCR fit**

- ZCR: bbll trigger selection
  Exactly 2 muons or 2 electrons with opposite-sign charges
  Exactly 2 b-tagged jets
  mll window 75-110 GeV (select Z mass peak)
  mBB < 40 GeV or mBB > 210 GeV (to ensure orthogonality to bbll SR)
- Typical norm factors

Z+HF	**1.35 ± 0.1**
ttbar	**0.96 ± 0.04**

Background estimation — Fake tau-had in lephad channel

→ Two sources: Multi-jet process and ttbar process

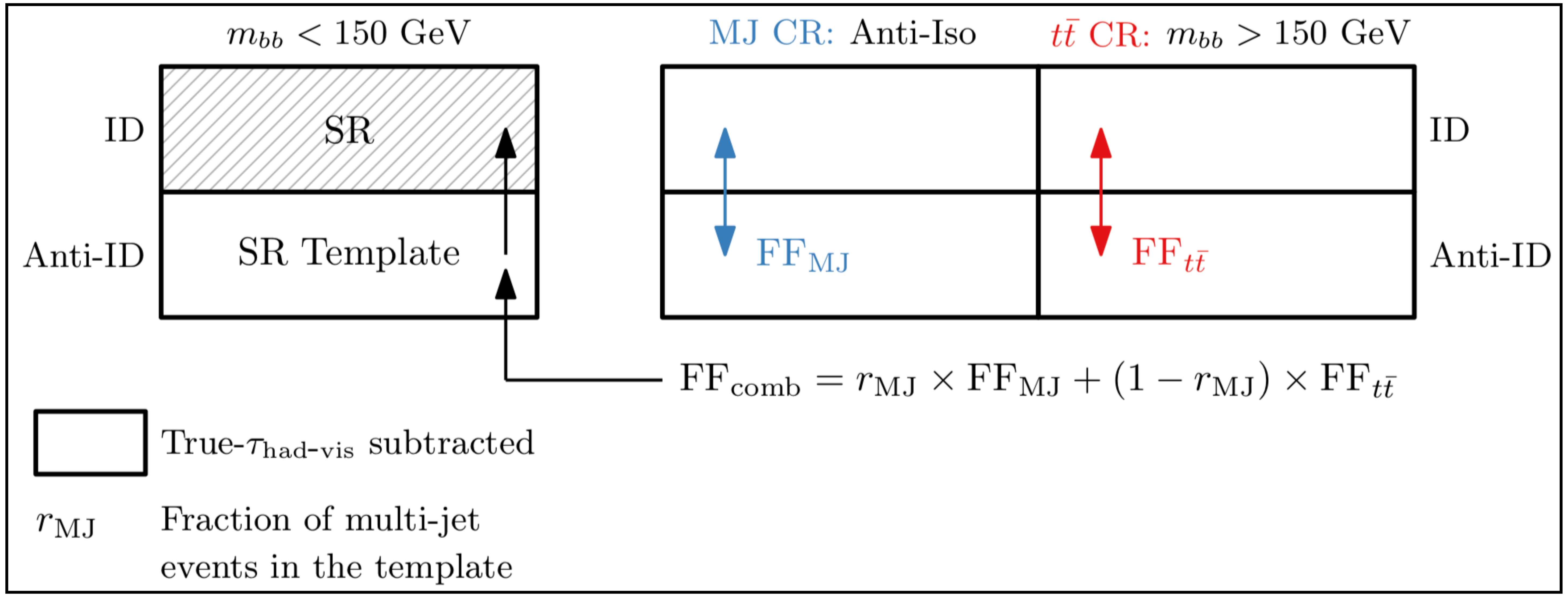
→ Fake factor (FF) method

- Define Multi-jet (MJ) CR and ttbar CR respectively for deriving FF_{MJ} and $FF_{t\bar{t}}$

$$\mathrm{FF} = \frac{\mathrm{N_{ID}}}{\mathrm{N_{Anti-ID}}},\ \mathrm{N} = \mathrm{N(data)} - \mathrm{N(non-Fake)}$$

- The fraction of multi-jet events in the template $r_{MJ} = \frac{N(data) - N(true+fake\ \tau_{had}, MC)}{N(data) - N(true\ \tau_{had}, MC)}$

- The combined FF applied to the SR template to estimate fake tau-had in SR

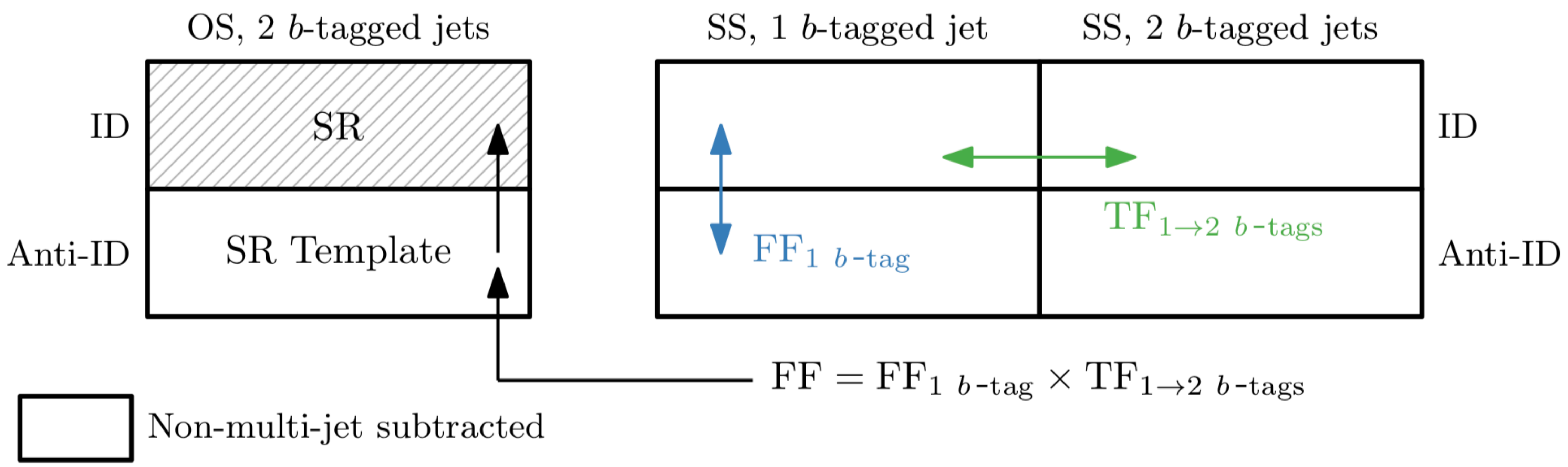


Background estimation — Fake tau-had in hadhad channel

→ **Two sources: Multi-jet process and ttbar process**

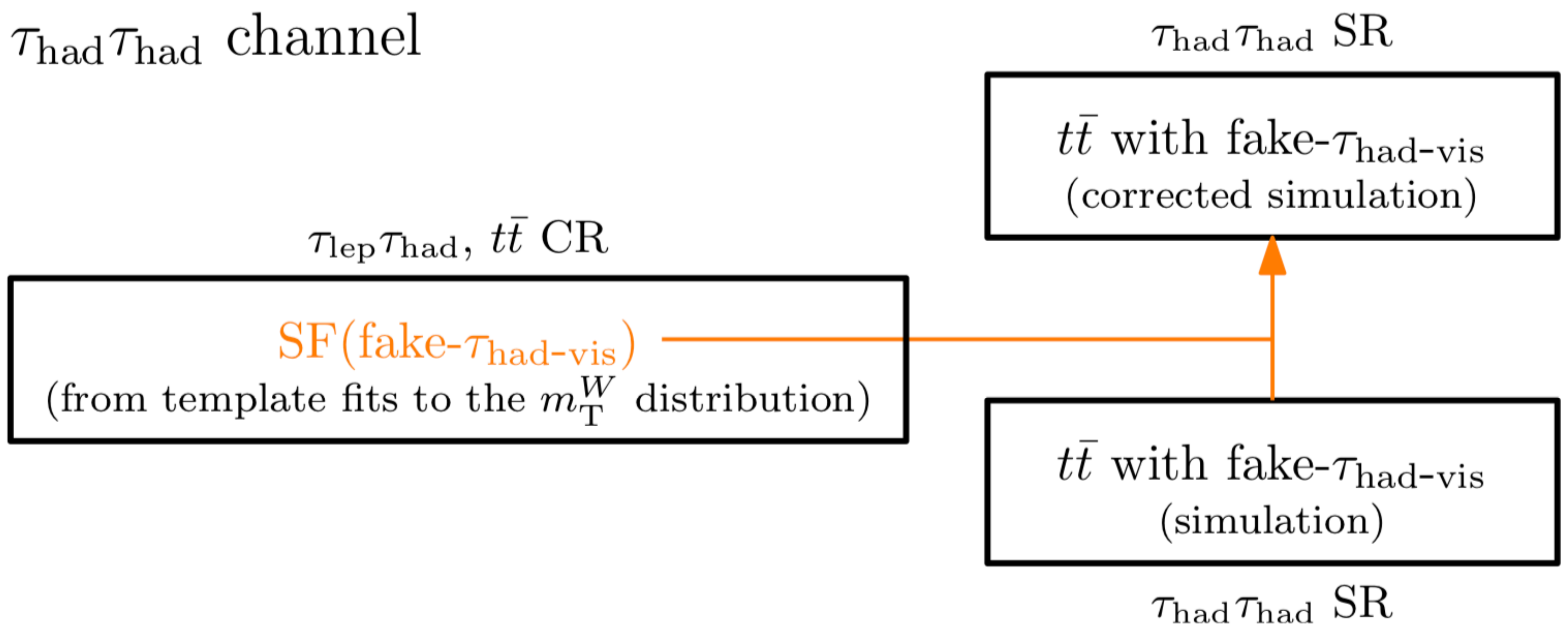
→ **Fake tau-had from multi-jet: FF method**

- FFs are derived in 1 b-tag SS control region
- Extrapolated to 2 b-tag SS control region by a transfer factors (TFs)



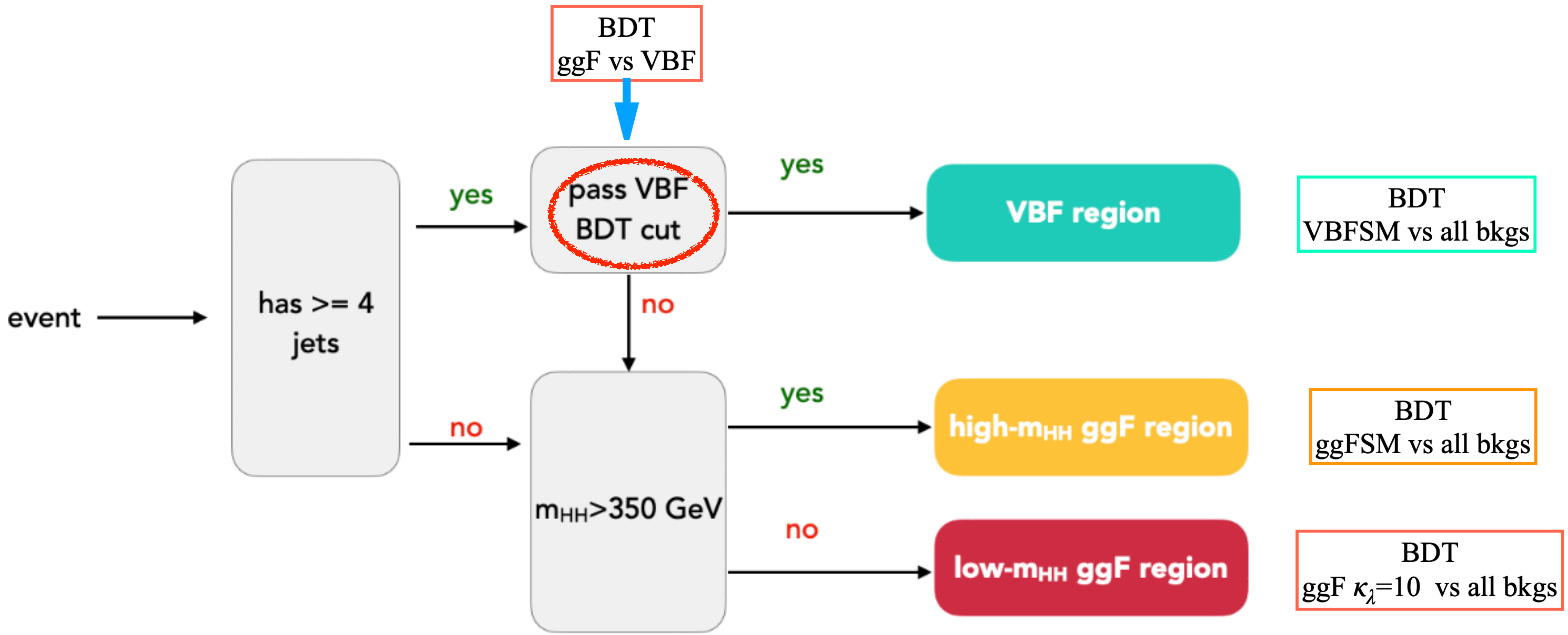
→ **Fake tau-had from ttbar: Fake scale factors**

- Fake tau-had Scale factors (SF)
- Measured in the lephad ttbar CR by fitting m_T^W to data
- Applied to simulated fake-tau ttbar in SR



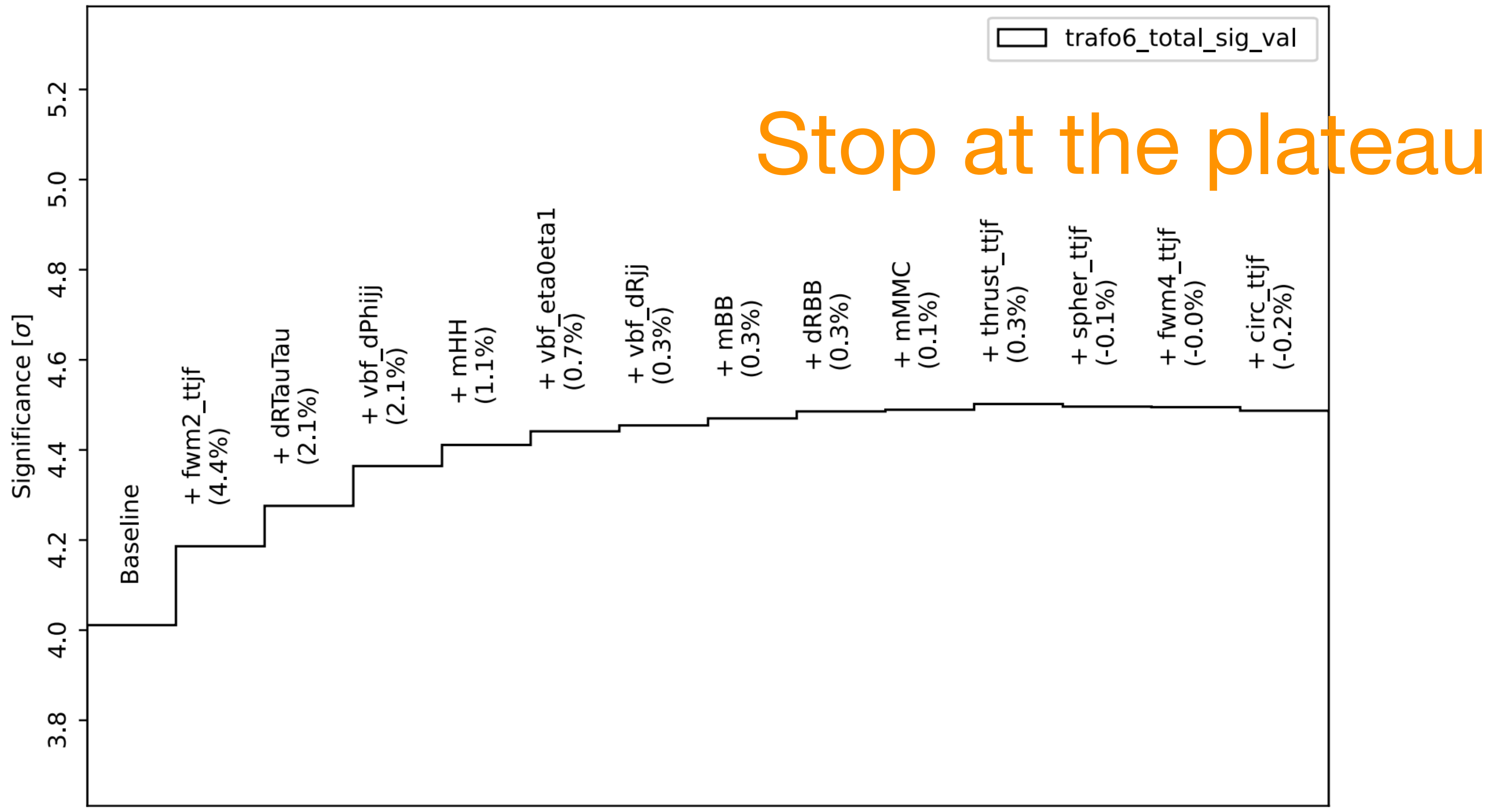
Signal extraction: Boosted Decision Tree (BDT)

→ **In each sub-channel (hadhad, lephad SLT, lephad LTT), train:**
3 different signal-vs-background BDTs
1 ggF/VBF separation BDT



Signal extraction: Boosted Decision Tree (BDT)

→ Input variables selection



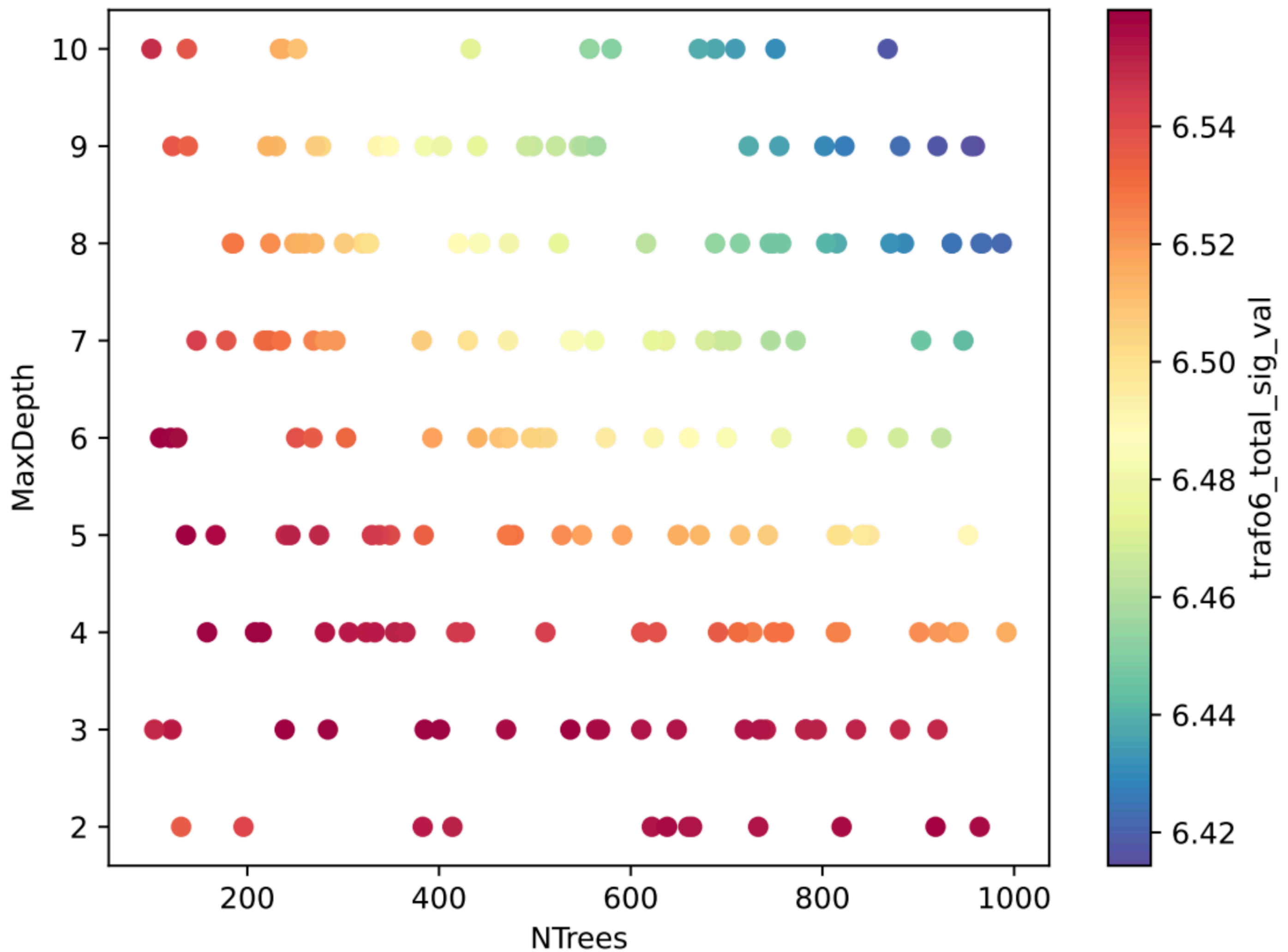
→ 3-fold training

- Divide events into 3 folds based on the event number
- Train 3 BDTs on each fold, and optimized and applied on other folds

Model	Fold 0 event_number %3 = 0	Fold 1 (event_number %3 = 1)	Fold 2 (event_number %3 = 2)
BDT 0	Training	Validation	Testing
BDT 1	Testing	Training	Validation
BDT 2	Validation	Testing	Training

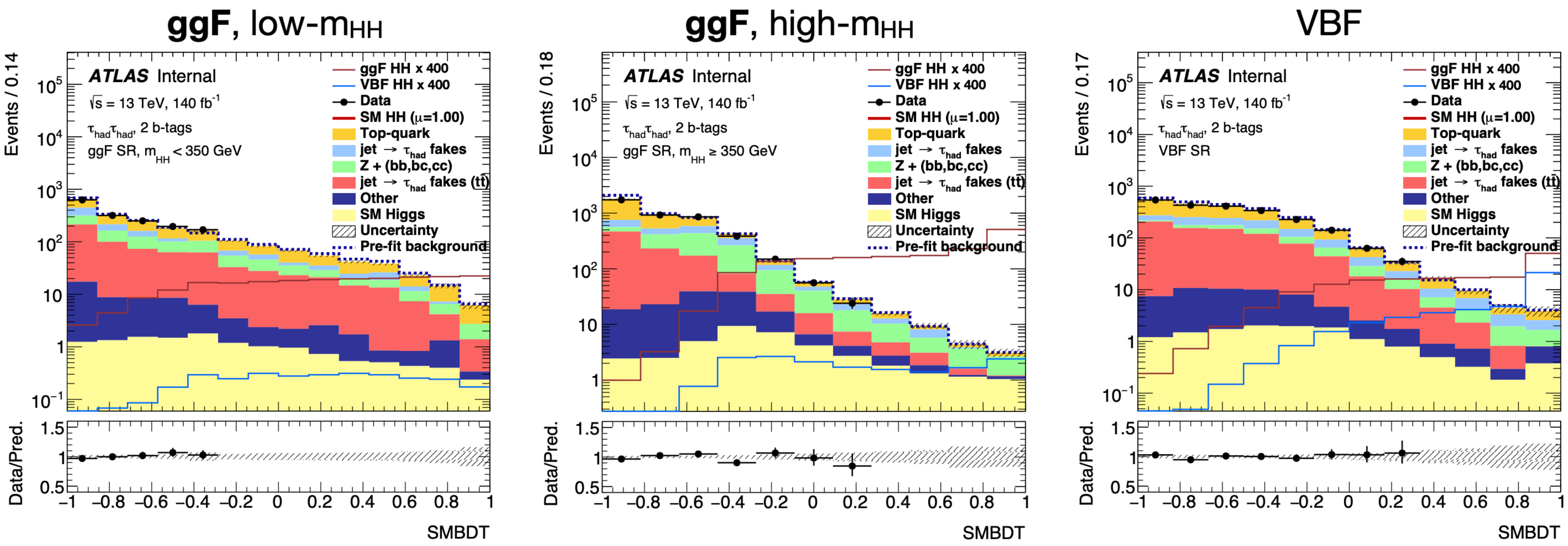
→ Hyperparameter optimization (on validation folds)

MinNodeSize	1%
BoostType	Grad
Shrinkage	0.2
IgnoreNegWeightsInTraining	True



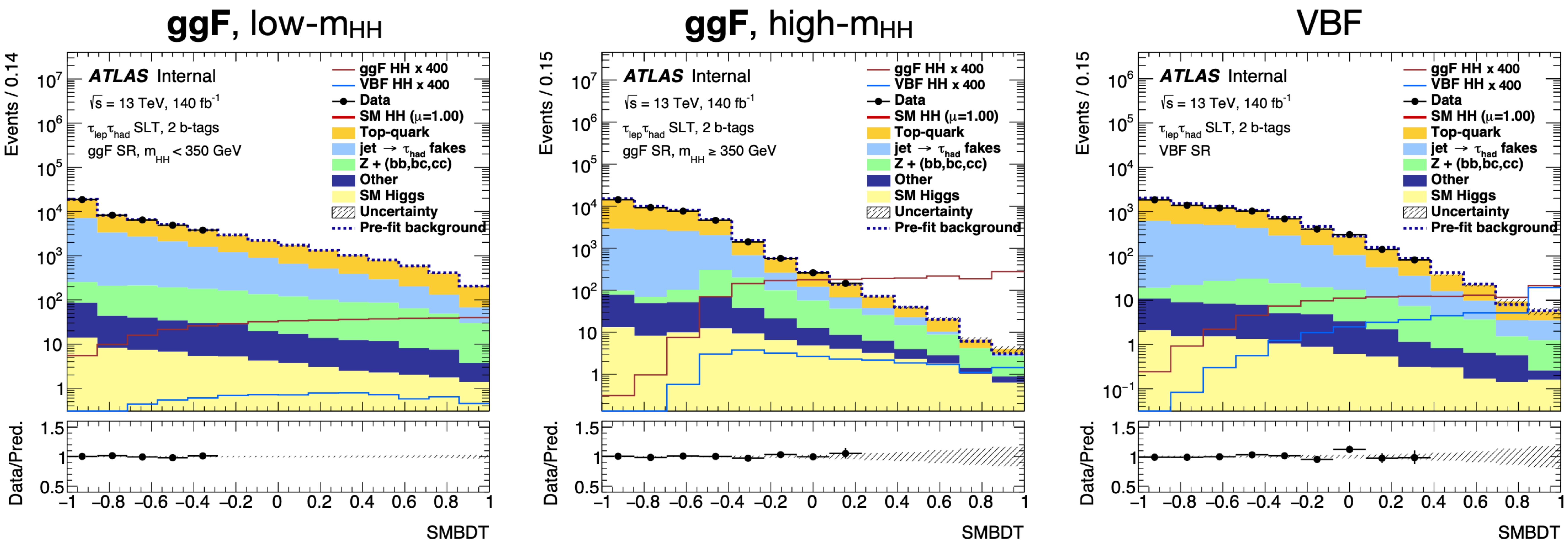
BDT output distributions

- hadhad channel



The binning is determined by an algorithms to optimize sensitivity while ensuring valid background stats.

- lephad SLT channel



Preliminary results (expected)

➔ Expected upper limit on the HH signal strength

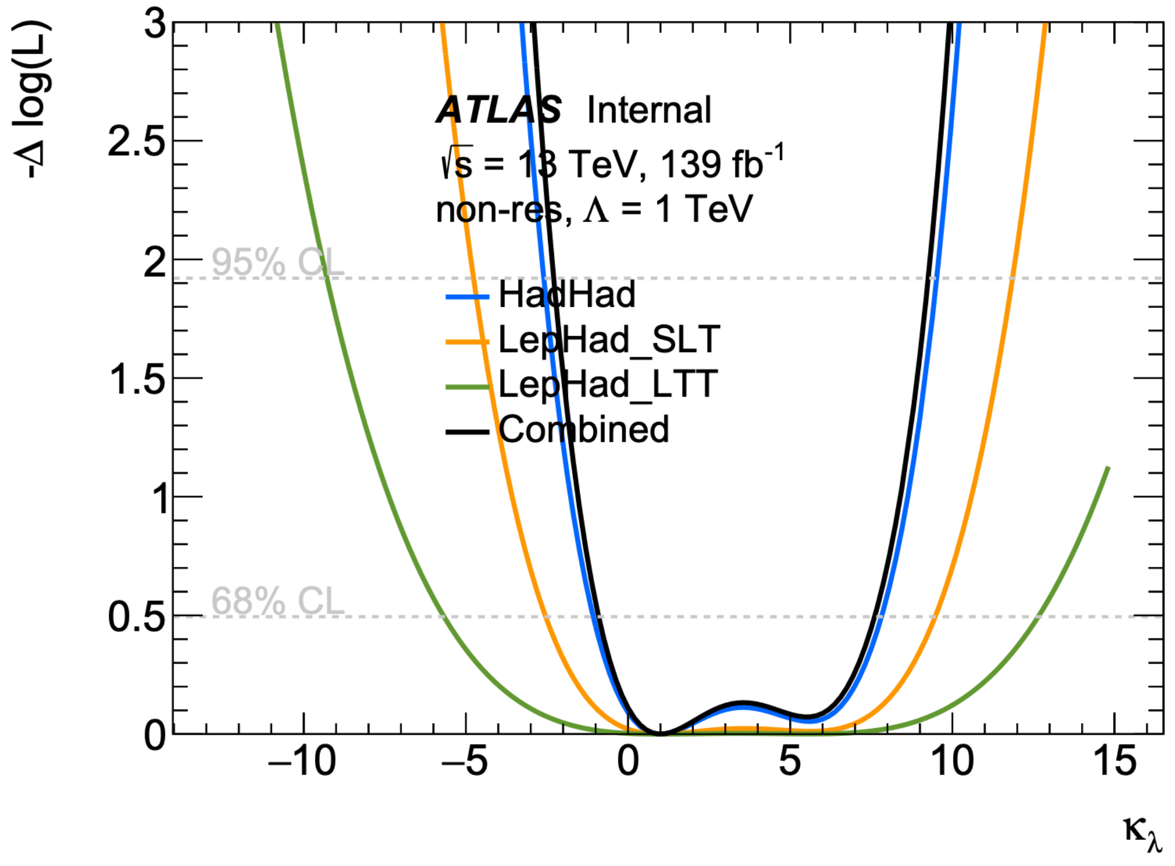
- Upper limit HH (ggF+VBF), as well as separately for each production mode

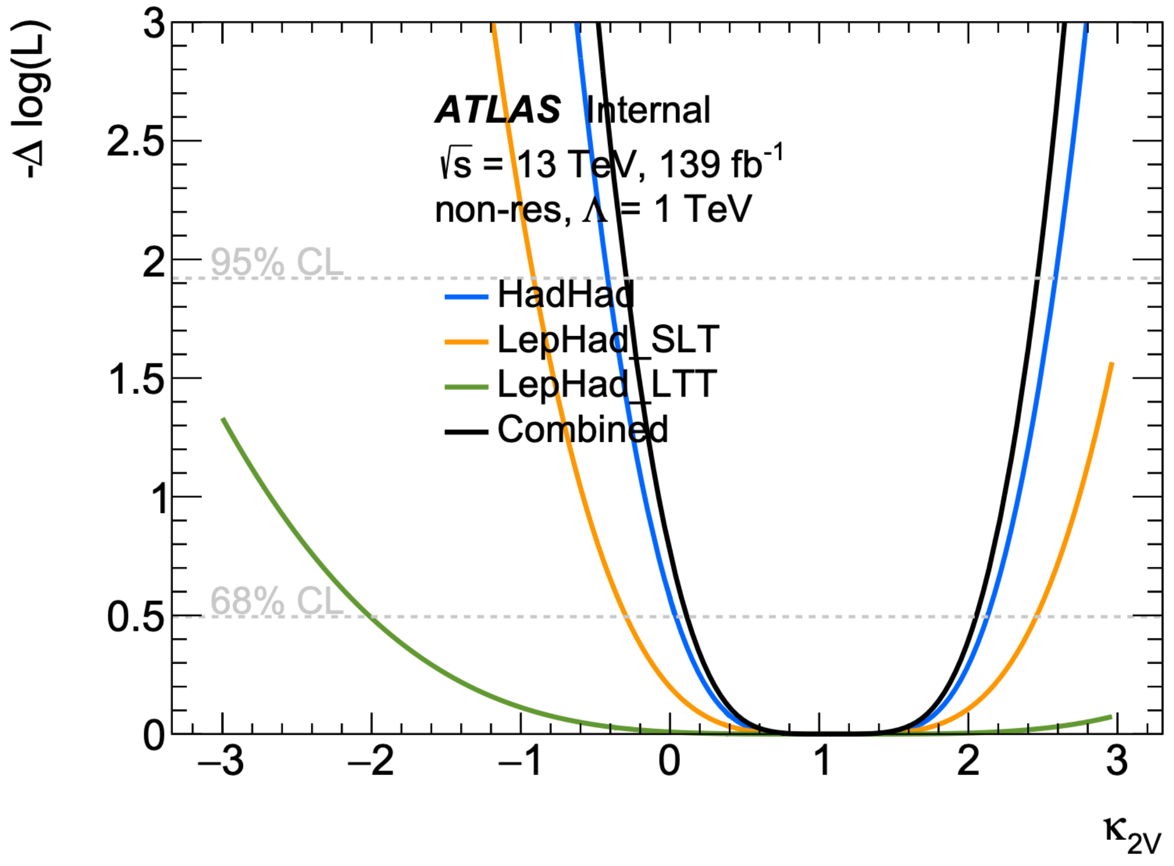
95% CL upper limits on	μ_{HH}	μ^{1D}_{ggF}	μ^{1D}_{VBF}	μ^{2D}_{ggF}	μ^{2D}_{VBF}
Baseline w/o systs	2.84	2.89	189	9.24	572
Baseline w/ systs	3.61	3.68	241	13.2	777
Legacy w/o systs	2.49	2.52	80	2.61	84
Legacy w/ systs	3.03	3.08	86	3.13	88
Rel. improvement w/o systs	12.3%	12.8%	57.7%	71.8%	85.3%
Rel. improvement w/ systs	16.1%	16.3%	64.3%	76.3%	88.7%

- 1D fit of μ_{ggF} (μ_{VBF}) While fixing the other to 1
- Simultaneous 2D fit of μ_{ggF} *and* μ_{VBF}

➔ Constraint on coupling modifiers

	95% CI for κ_λ	95% CI for κ_{2V}
Baseline w/o systs	[-2.35, 9.19]	[-0.42, 2.55]
Baseline w/ systs	[-2.97, 10.1]	[-0.50, 2.63]
Legacy w/o systs	[-2.01, 8.59]	[-0.25, 2.41]
Legacy w/ systs	[-2.28, 9.26]	[-0.29, 2.46]
Rel. improvement w/o systs	8.1%	10.4%
Rel. improvement w/ systs	11.7%	12.1%





Summary

→ A general overview of the Legacy Run 2 HH—>bbtautau analysis

→ Expected results

- Upper limit on the HH signal strength: ~16% improvement
- Constraint on coupling modifier κ_λ: 11.7% improvement
- Constraint on coupling modifier κ_{2V} : 12% improvement

→ Changes that lead to the improvement

- Dedicated ggF and VBF regions
- Improved background modeling
- Fully harmonized and optimized MVA strategy
- Optimized binning

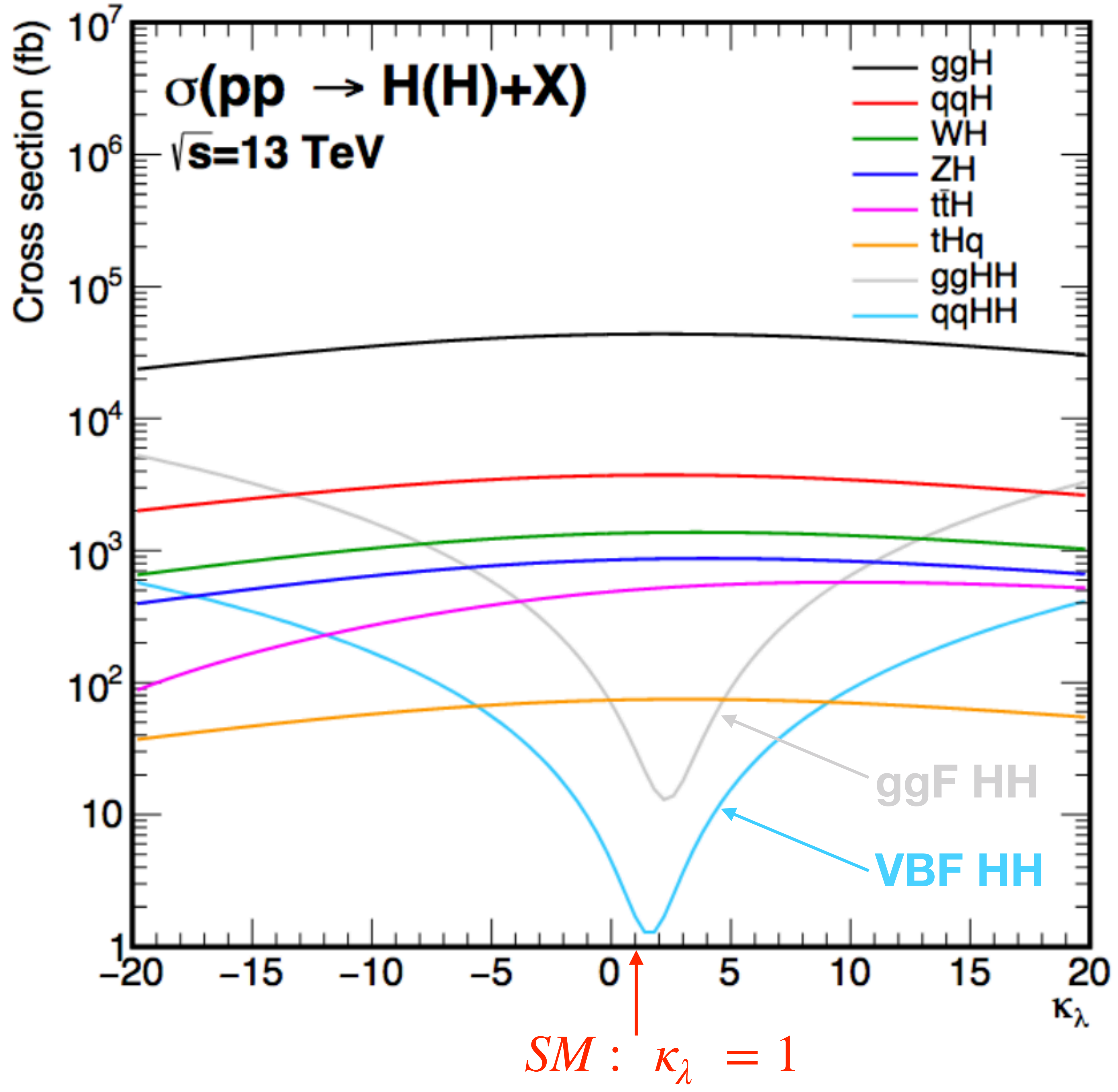
Thanks for your attention!

Back up

Non-resonant enhancement to HH production

→ Varying the value of κ_λ or κ_{2V}

- Lead to significant enhancement to HH production
- Allowed in many BSM scenarios, which makes it possible to probe new physics



HH decay modes

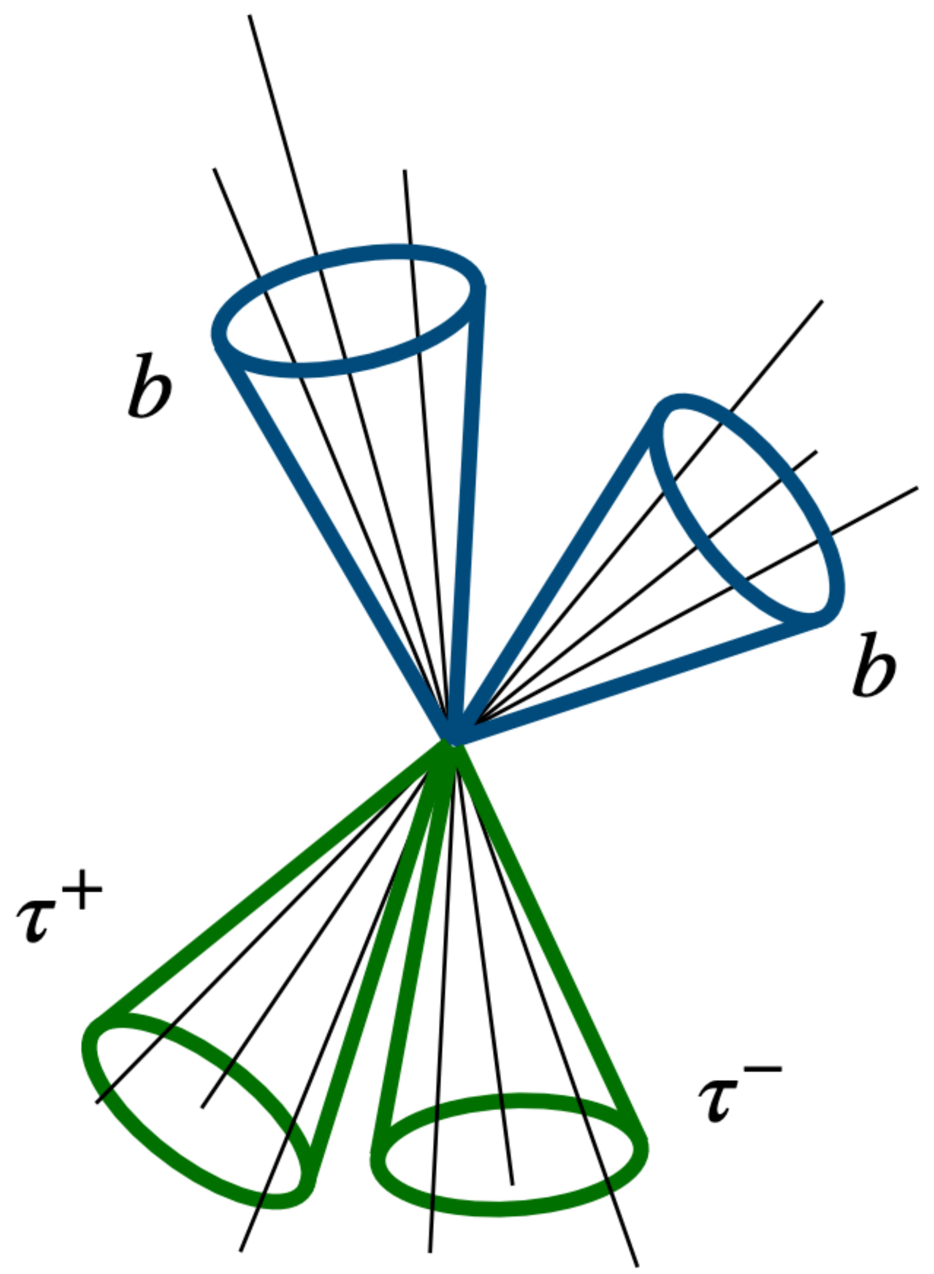
Large branching ratio

Clean final state

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

→ HH —> bbtautau final state

- One of the most sensitive channels
- Medium branch ratio and S/B



Data and MC Samples

→ Data samples

- full Run 2 dataset @ 13TeV with L = 140 fb^{-1} collected by ATLAS detector

→ Monte Calo (MC) Samples

- Signal samples generation:

A representative number of samples

↓

Sample combination technique

↓

Samples with a fine grid in plane (κ_λ, $\kappa 2v$)

- Improved bkg samples:

Considering Dilepton ttbar, Sherpa 2.2.11
V+jets —> reduction of stat. Unc by 30~50%

→ Results

- Upper limit on $\mu_{ggF+VBF}$, μ_{ggF}, μ_{VBF}
- 95% CL interval for modifier $\kappa_\lambda, \kappa 2v$

Targeting at 10~20% improvement!

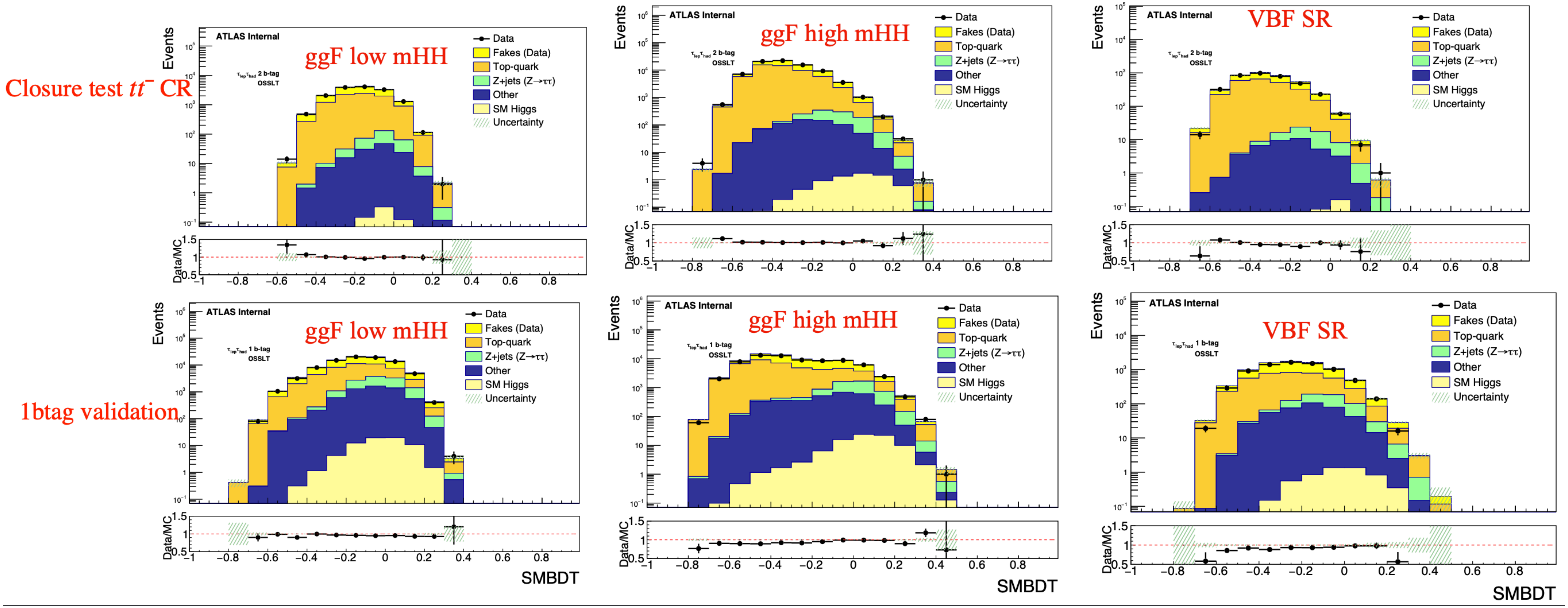
Process	ME generator	ME QCD order
Signal		
$gg \to HH$ (ggF with $\kappa_\lambda = 1, 10$)	Powheg Box v2	NLO
$qq \to qqHH$ (VBF with varied $\kappa_\lambda, \kappa_{2V}, \kappa_V$)	MadGraph5_aMC@NLO 2.7.3	LO
Top-quark		
$t\bar{t}$	Powheg Box v2	NLO
t-channel	Powheg Box v2	NLO
s-channel	Powheg Box v2	NLO
Wt	Powheg Box v2	NLO
$t\bar{t}Z$	Sherpa 2.2.1	NLO
$t\bar{t}W$	Sherpa 2.2.8	NLO
Vector boson + jets		
W/Z+jets	Sherpa 2.2.11	NLO ($\leq$ 2 jets) LO (3,4,5 jets)
Diboson		
WW, WZ, ZZ	Sherpa 2.2.1	NLO ($\leq$ 1 jet) LO (2,3 jets)
Single Higgs boson		
ggF	Powheg Box v2	NNLO
VBF	Powheg Box v2	NLO
$qq \to WH$	Powheg Box v2	NLO
$qq \to ZH$	Powheg Box v2	NLO
$gg \to ZH$	Powheg Box v2	NLO
$t\bar{t}H$	Powheg Box v2	NLO

Overview of analysis strategy

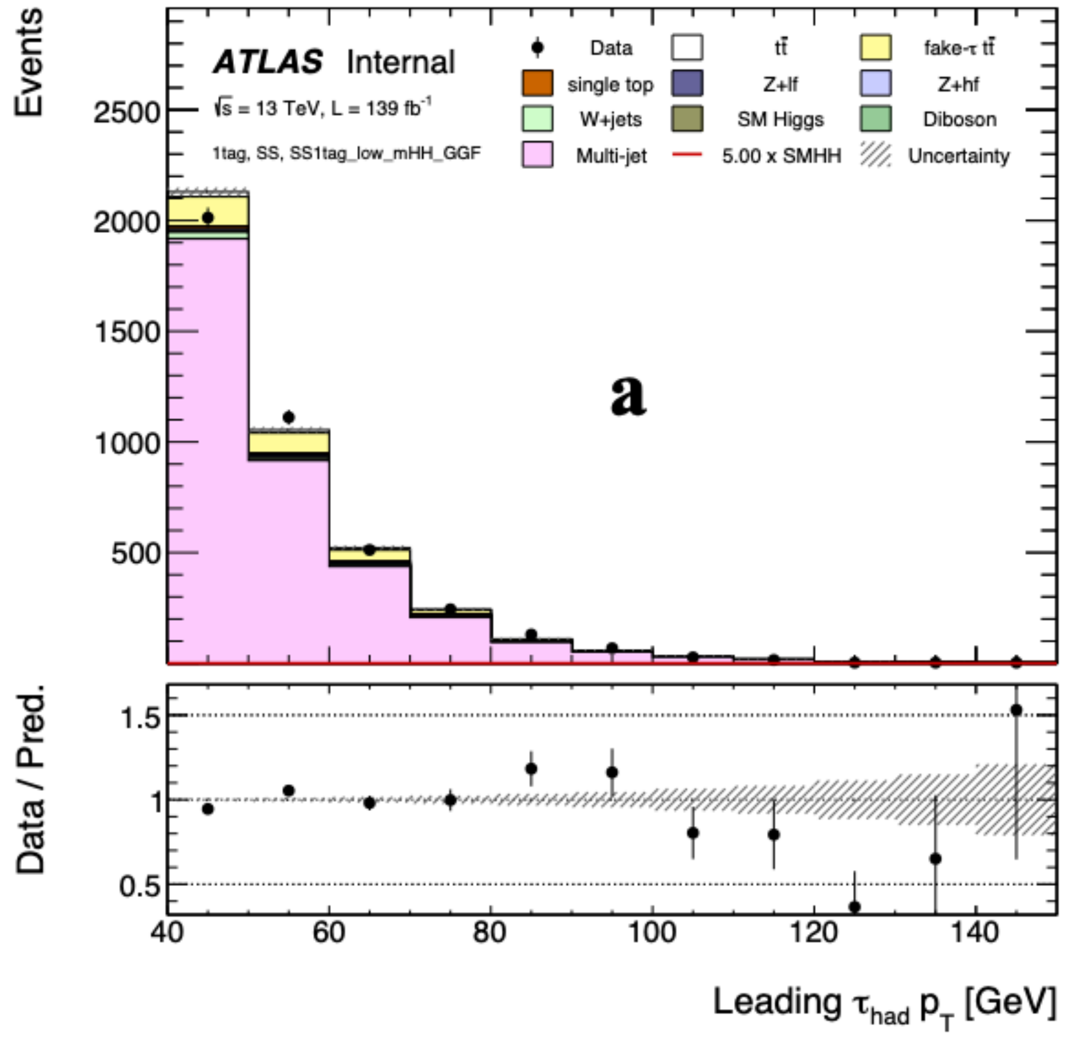
→ A sketch depicting the analysis strategy

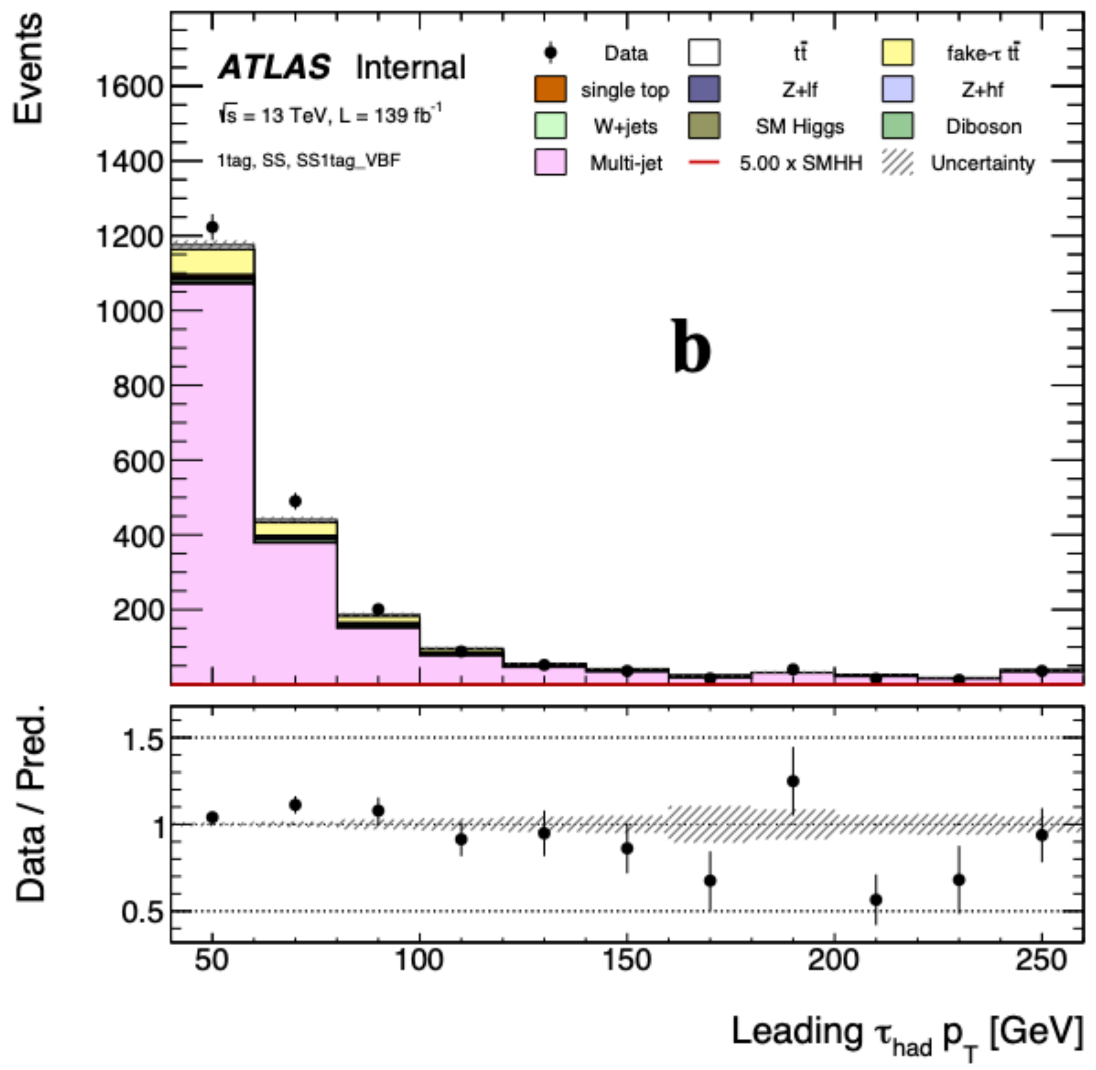
Background Estimation: Fake τ_{had} in LepHad validation

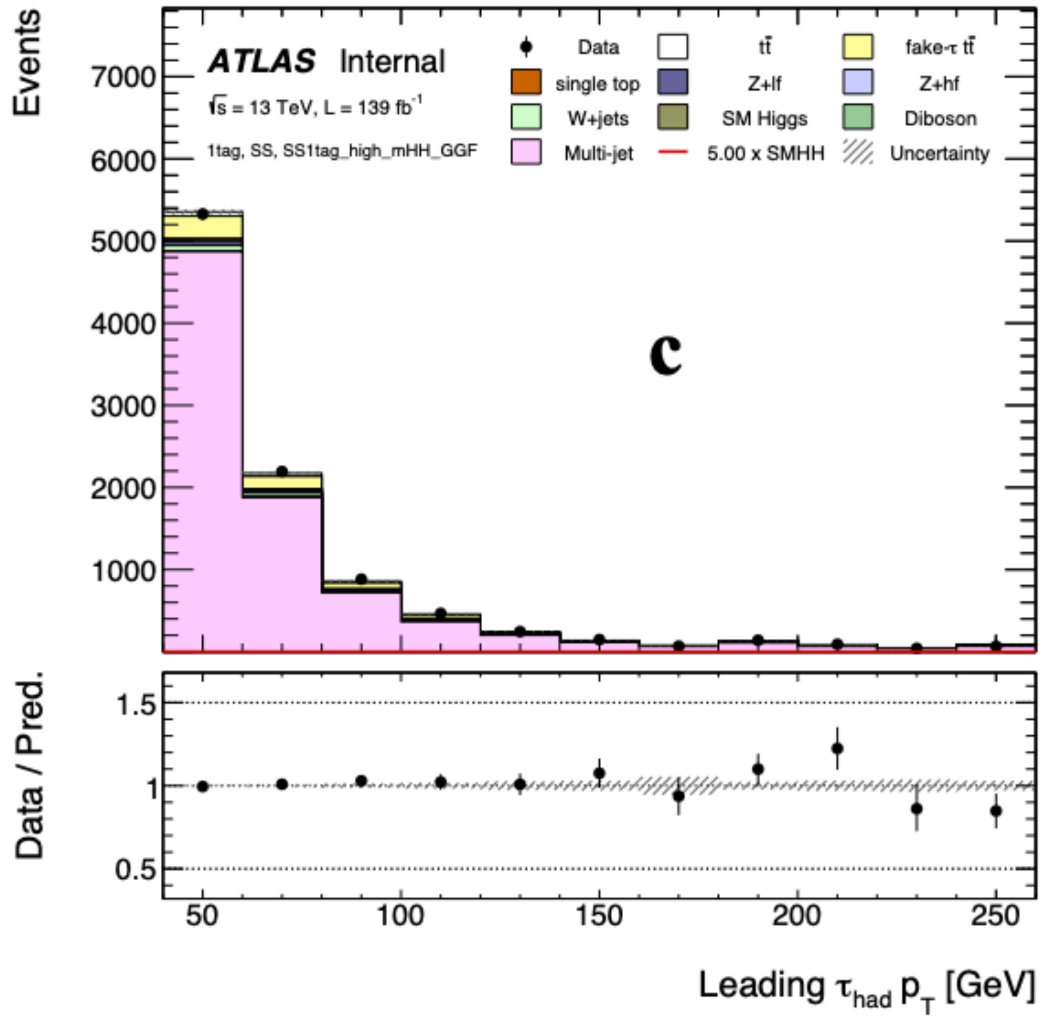
- To validate the ability of the combined fake factor method to describe the MVA shape (**plots shown only for SLT, LTT similar behaviour**)
  - The combined FFs were applied to multi-jet control region (1btag) and $t\bar{t}$ control region (mBB > 150)



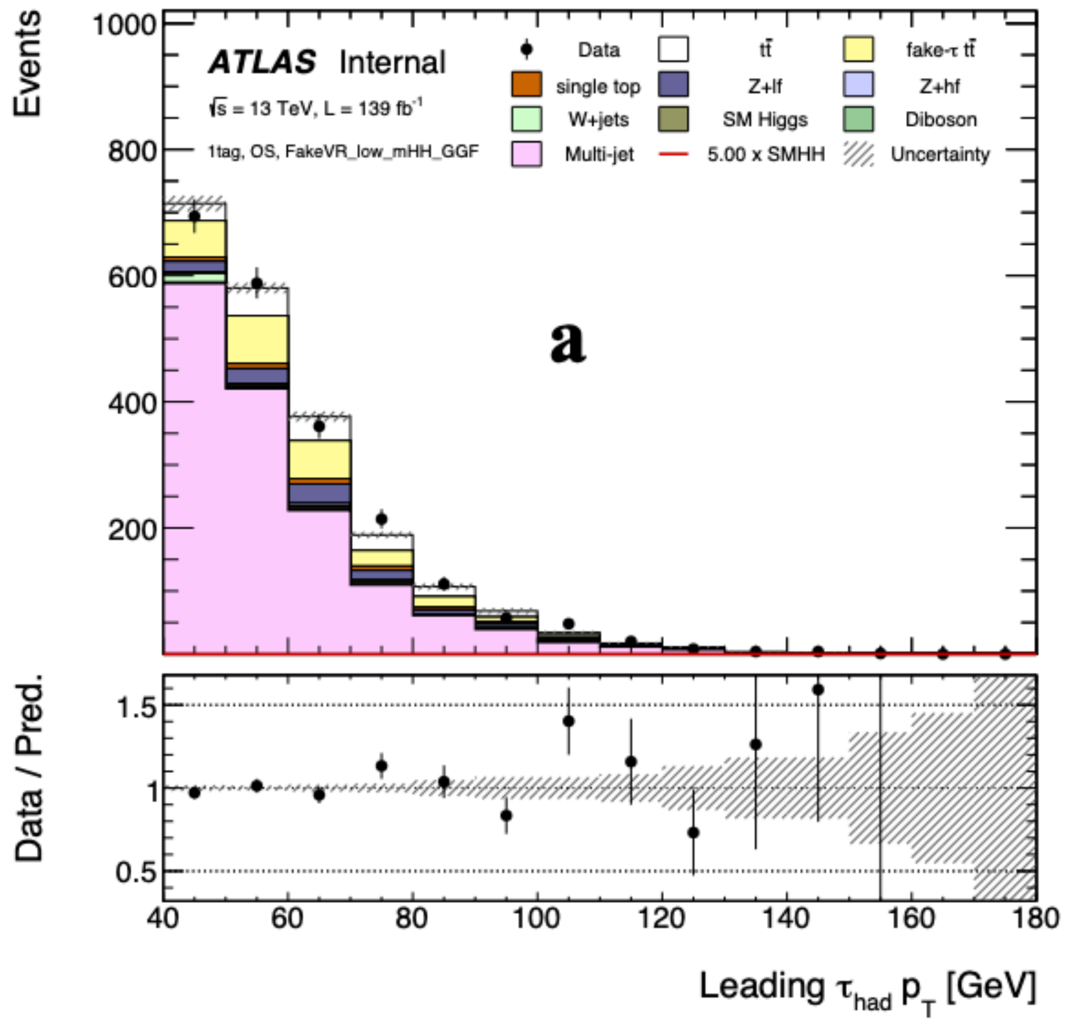
Background Estimation: Fake τ_{had} in HadHad validation

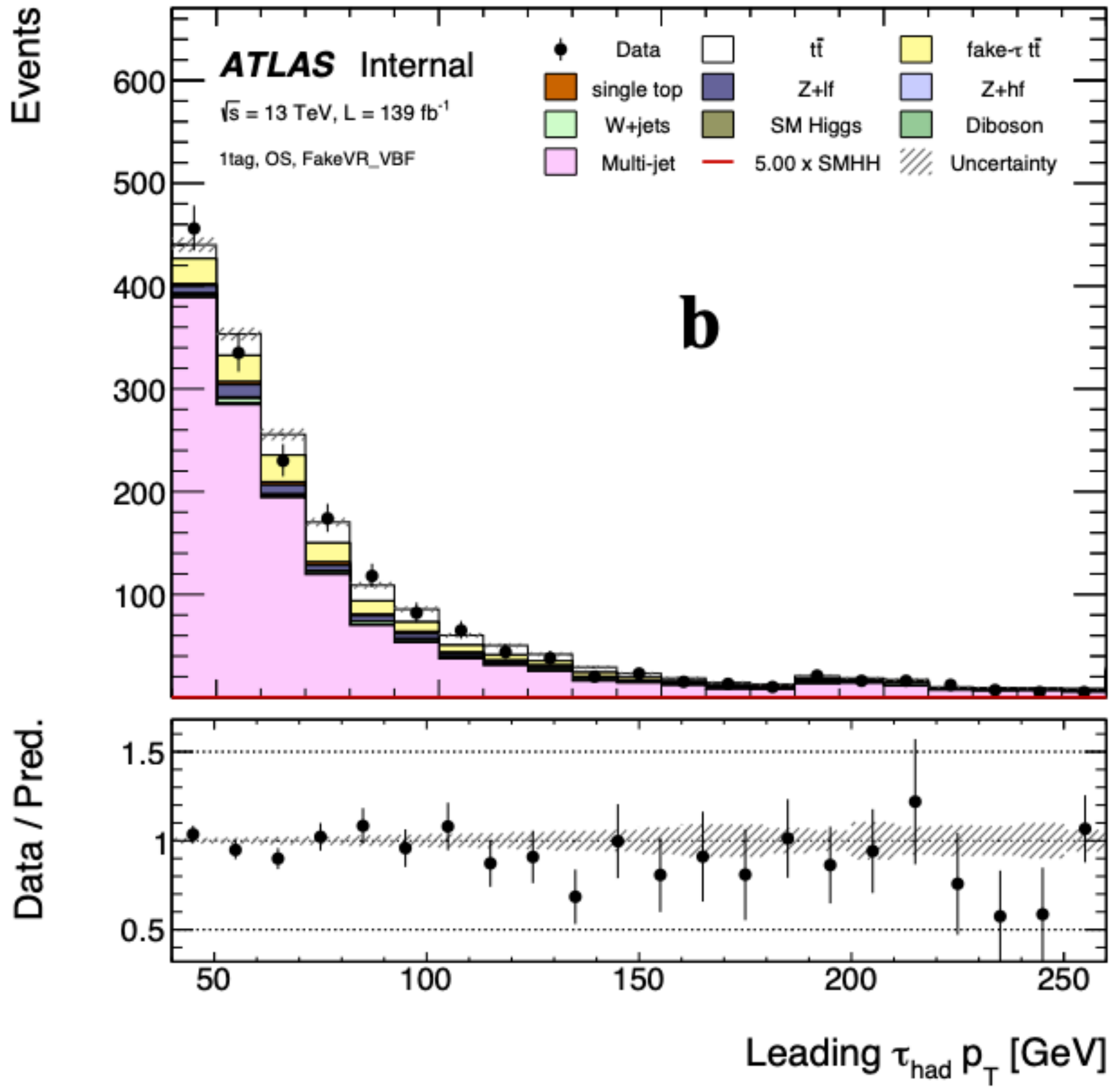


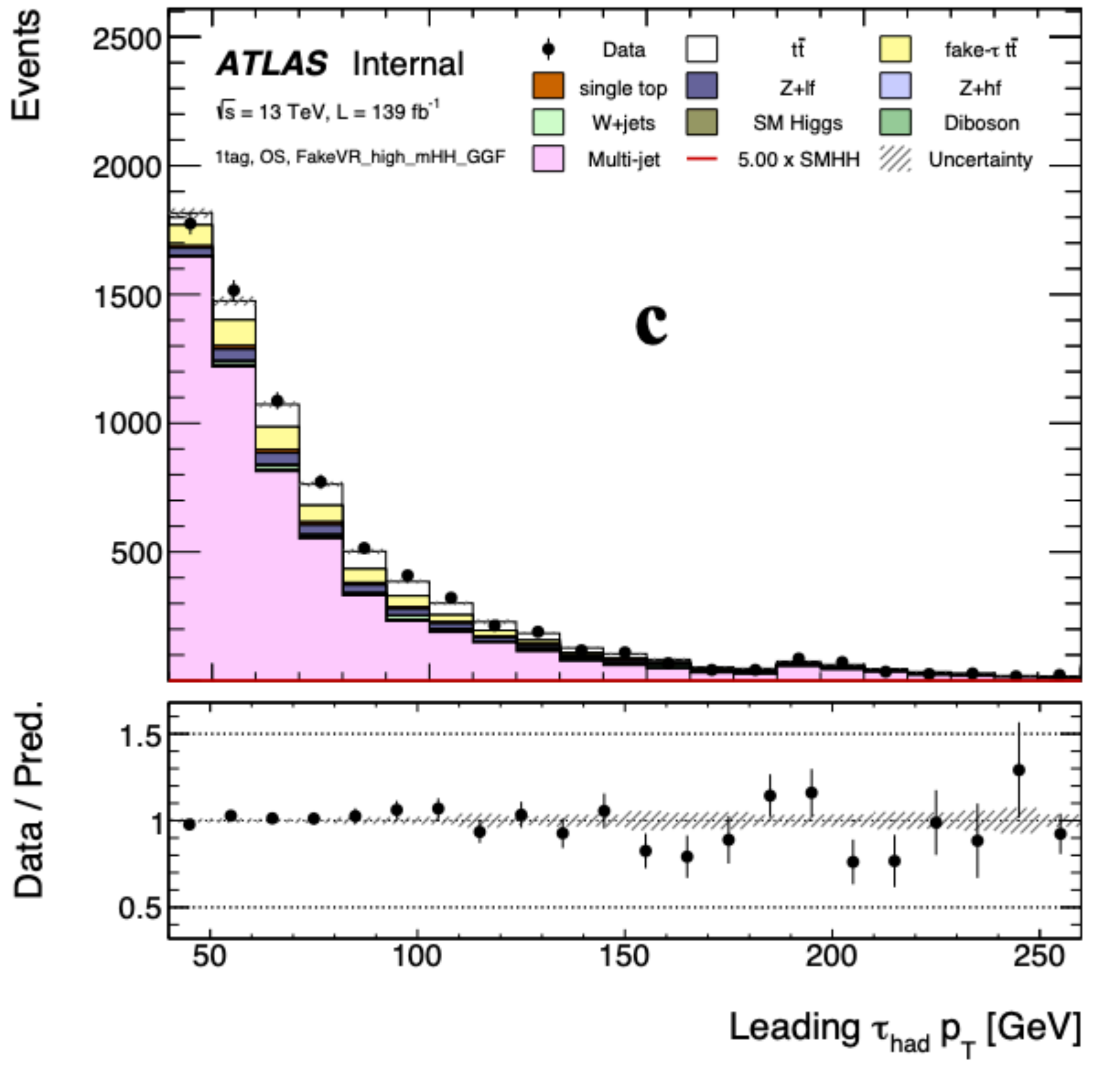




Closure check of the fake factor method in 1-btag SS ID-region showing the leading τ_{had} p_T distributions for the (**a**) low-mHH ggF, (**b**) high-mHH ggF and (**c**) VBF categories in the $\tau_{had}\tau_{had}$ channel







Validation of the multi-jet estimate in the 1-btag OS multi-jet validation region showing the leading τ_{had} p_T distributions for the (**a**) low-mHH ggF, (**b**) high-mHH ggF and (**c**) VBF categories in the $\tau_{had}\tau_{had}$ channel.

Systematic uncertainties

→ Considering the uncertainties from:

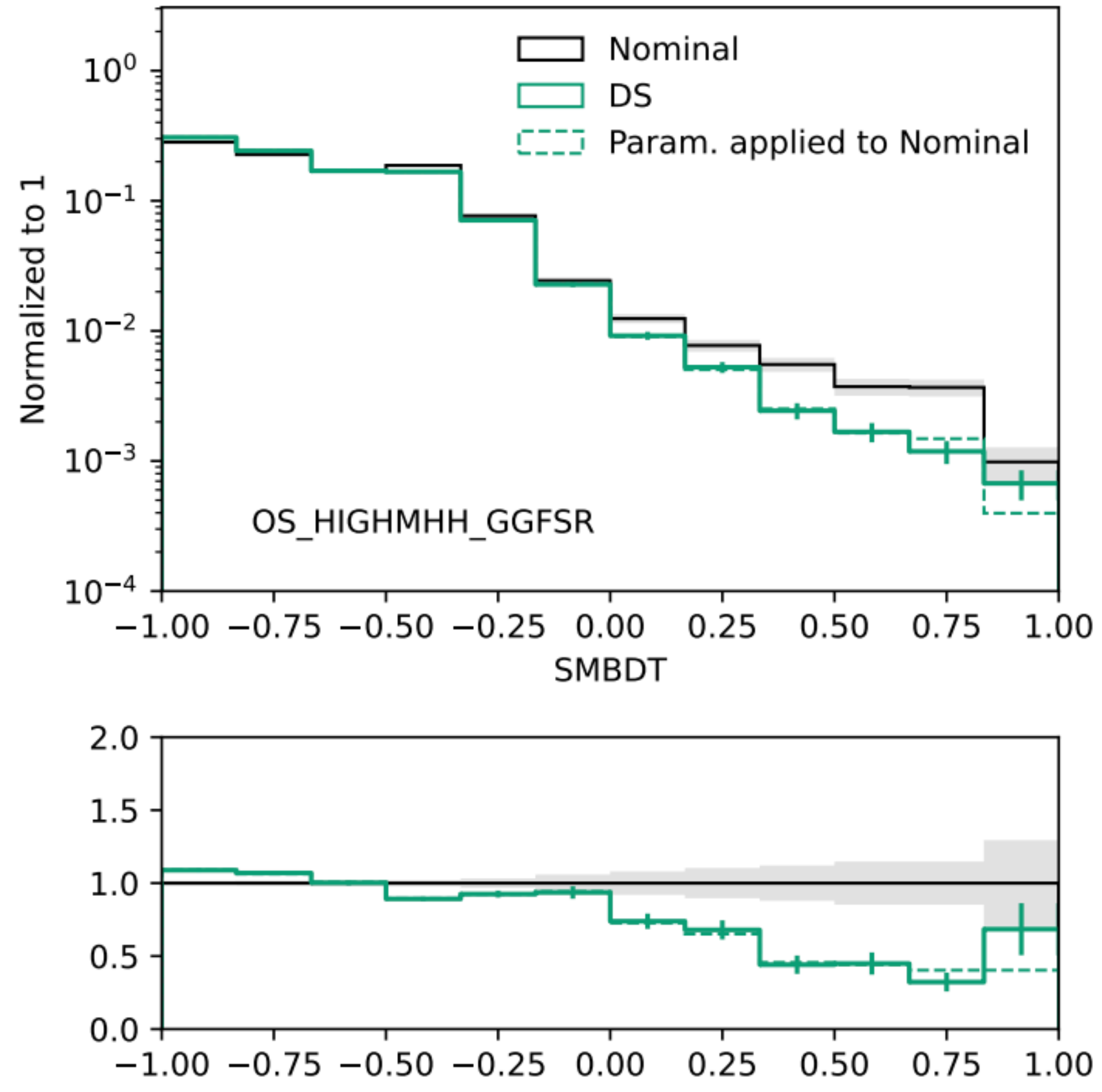
- Experimental uncertainties
- Background modeling for MC-based processes: ttbar, Z+HF, single-top, single Higgs
- Background modeling for data-driven processes: fake-tau in lephad and hadhad
- Signal modeling: ggF HH, VBF HH

→ Modeling uncertainties (take the difference between nominal and alternative)

- Acceptance: event yield variation in SRs due to imperfect modeling
- Shape: shape variation in SRs due to imperfect modeling

Table 67: Relative acceptance uncertainties obtained for the single top Wt in each $\tau_{lep}\tau_{had}$- SLT SR and inclusively.

Region	low-m_{HH} ggF SR	high-m_{HH} ggF SR	VBF SR	Inclusive SR
Interference	up: 6.7%	up: −22.9%	up: −14.0%	up: −9.8%
PS	up: −4.5%	up: −4.6%	up: 1.7%	up: −4.2%
ME	up: 6.2%	up: 3.0%	up: 20.3%	up: 5.3%
FSR	up: 5.1%, down: −4.9%	up: 2.7%, down: −5.7%	up: 12.7%, down: −7.8%	up: 4.3%, down: −5.4%
ISR	up: 1.2%, down: −1.2%	up: 4.0%, down: −3.1%	up: 12.0%, down: −10.5%	up: 3.2%, down: −2.6%
PDF	up: 1.1%	up: 1.4%	up: 0.4%	up: 0.9%



(h) high-m_{HH} ggF SR (**Interference**)

Statistical model

→ Binned likelihood

$$L(\mu,\tau,\theta,\gamma) = \prod_{i\in \mathrm{bins}} \mathrm{Po}(N_i \,|\, \nu_i(\mu,\tau,\theta,\gamma)) \times \prod_k \exp\left(-\frac{\theta_k^2}{2}\right) \times \prod_{i\in \mathrm{bins}} f(\gamma_i)$$

Model prediction (ν_i) — *Obs. data* (N_i)

Poisson term for every bin
Compares fit model prediction for bin i to observed event count

Constrained nuisance parameters
Systematic uncertainties

"Beeston-Barlow -gammas"
Statistical uncertainties in MC templates

Event yield in each bin as a linear combination of histogram templates

$$\nu_i(\mu,\tau,\theta,\gamma) = \mu \sum_{j\in \mathrm{signal}} h_{i,j}(\theta) + \gamma_i \sum_{j\in \mathrm{bkg}} \tau_j\, h_{i,j}(\theta)$$

→ Implementation

- The fit model is defined in terms of python/C++ code based on the Root HistFactory
- In this analysis, WSMaker is used.

Breakdown of the improvements

→ Hadhad channel

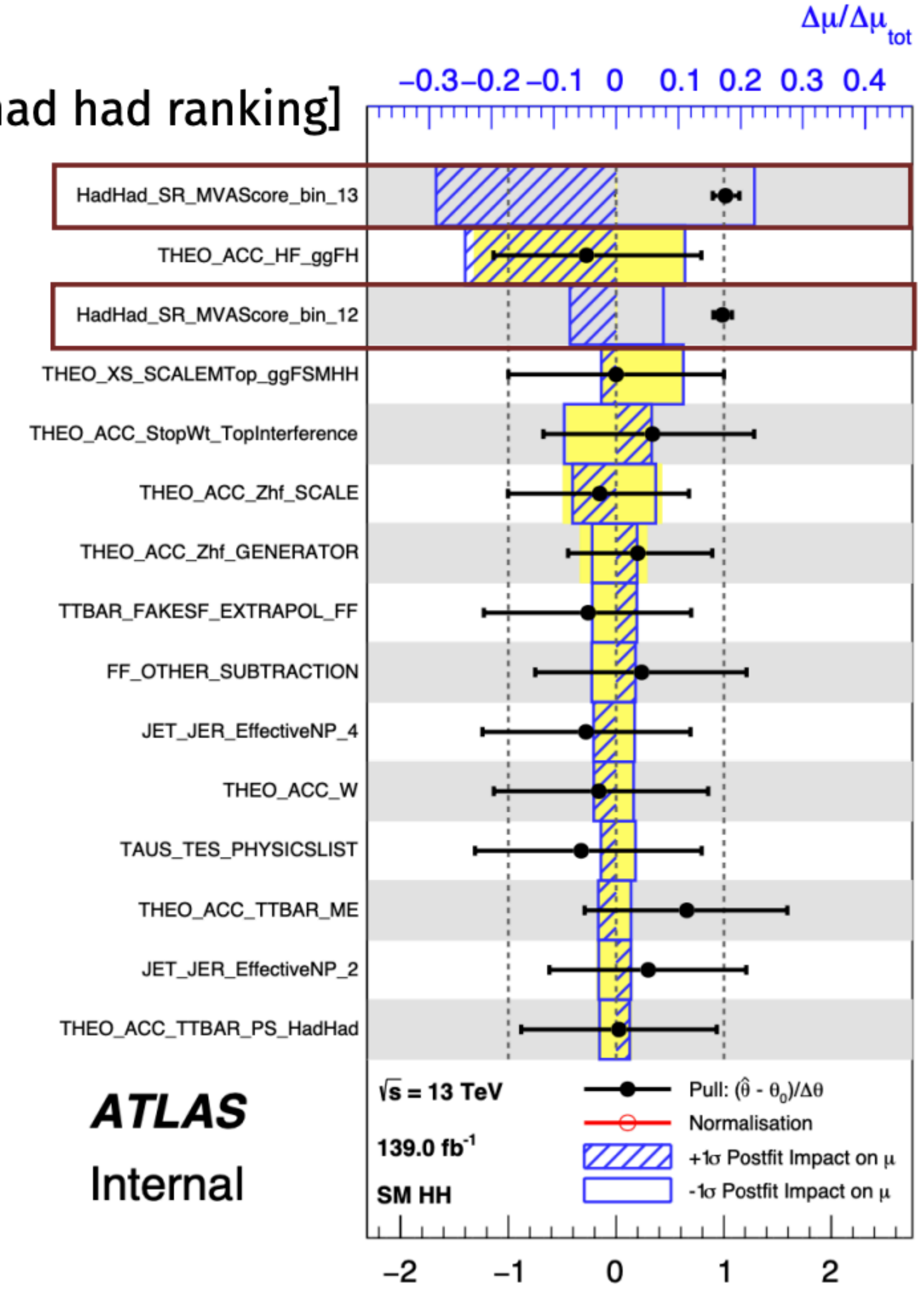
- For upper limit on HH signal strength, the improvement equally comes from new BDT binning, the usage of improved samples, the new optimized BDT
- For κ_λ interval, the new optimized BDT brings largest relative improvement
- For $\kappa 2v$ interval, the introduction of a dedicated VBF SR brings largest relative improvement

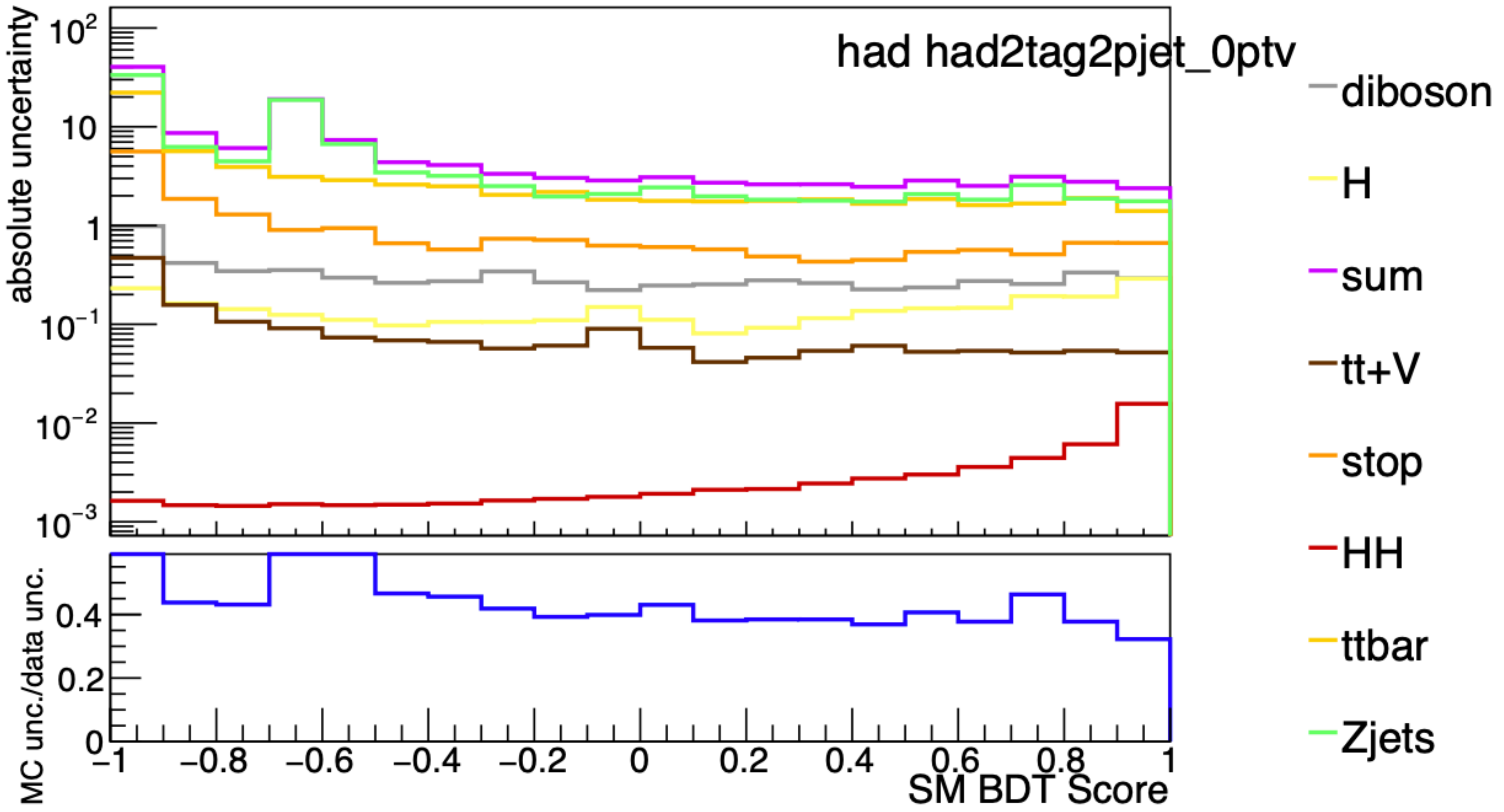
			simultaneous fit							
MCStat+Float Fit	Upper limit on μ_{HH}		Upper limit on μ_{VBF}		Upper limit on μ_{ggF}		*95% Confidence interval for κ_λ*		*95% Confidence interval for κ_{2V}*	
Baseline *(previous analysis)* ***without systematics***	3.46		778		12.5		[-2.79, 9.58]		[-0.58, 2.71]	
Baseline with new BDT output transformation *(trafo60, ≥ 1 bkg evt/bin)*	3.28	-5.2%	713	-8%	11.3	-10%	[-2.73, 9.56]	-0.6%	[-0.51, 2.64]	-4.3%
Moving to Sherpa 2.2.11, extending the ttbar sample	3.09	-10.7%	747	-4%	11.9	-5%	[-2.64, 9.49]	-1.9%	[-0.48, 2.60]	-6.4%
New BDT (architecture + variables) w/ one inclusive SR	2.94	-15.0%	630	-19%	9.51	-24%	[-2.31, 9.01]	-8.5%	[-0.52, 2.66]	-3.3%
High m_{HH}, low m_{HH} categorisation for ggF SR + VBF SR (each with own BDT)	2.92	-15.6%	90	-88%	3.04	-76%	[-2.34, 8.85]	-9.5%	[-0.34, 2.51]	-13.4%

Improved description of backgrounds

- MC statistical uncertainty currently very high ranked (but result is stat. limited)

[had had ranking]





- had had channel as example:
  - total MC stat uncertainty dominated by Z+jets and ttbar

5

Usage of dilepton ttbar sample

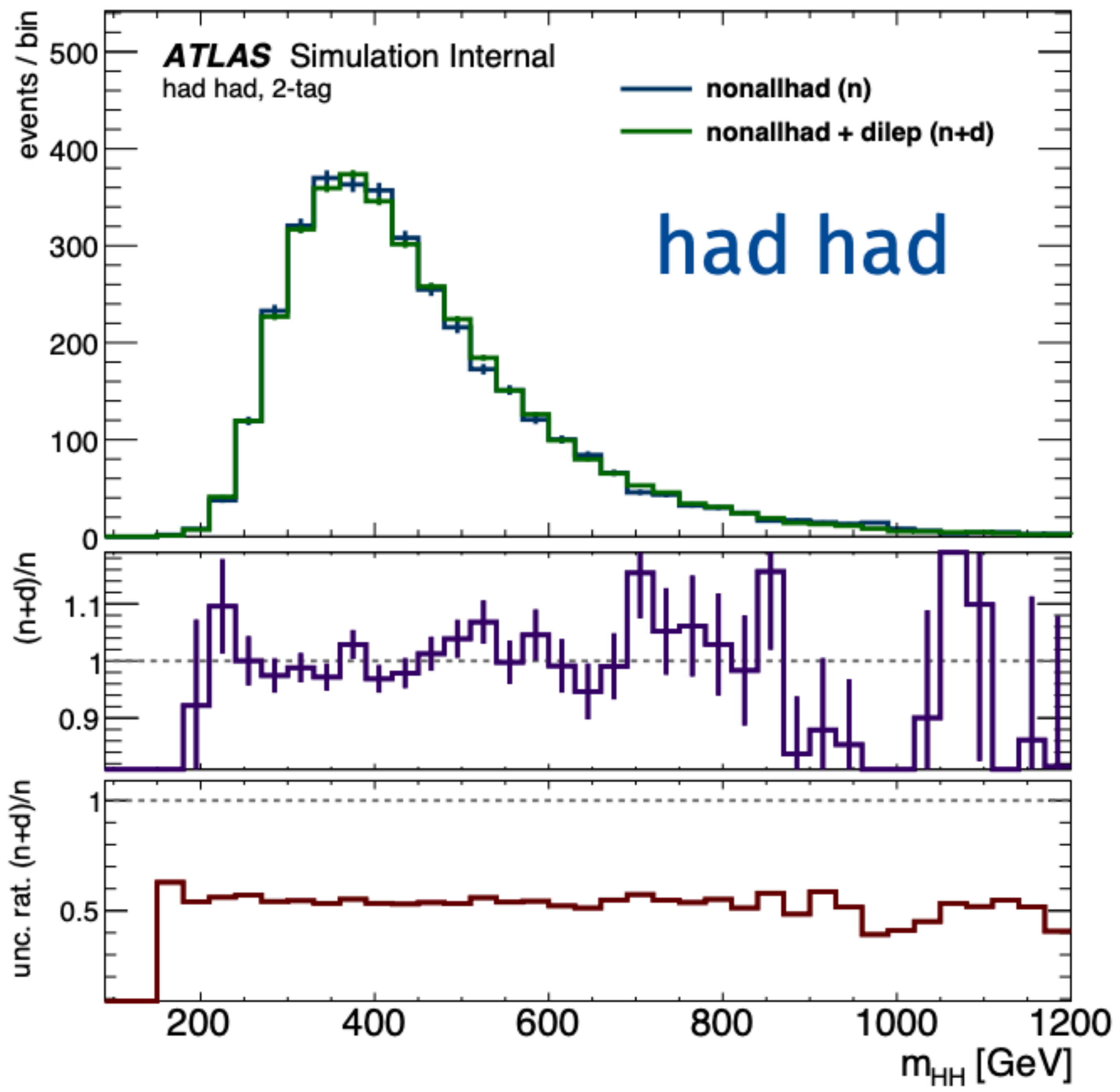
- For the previous round, only the nonallhad ttbar sample (DSID=410470) was used
  → add dedicated dilepton ttbar sample (and remove overlap)

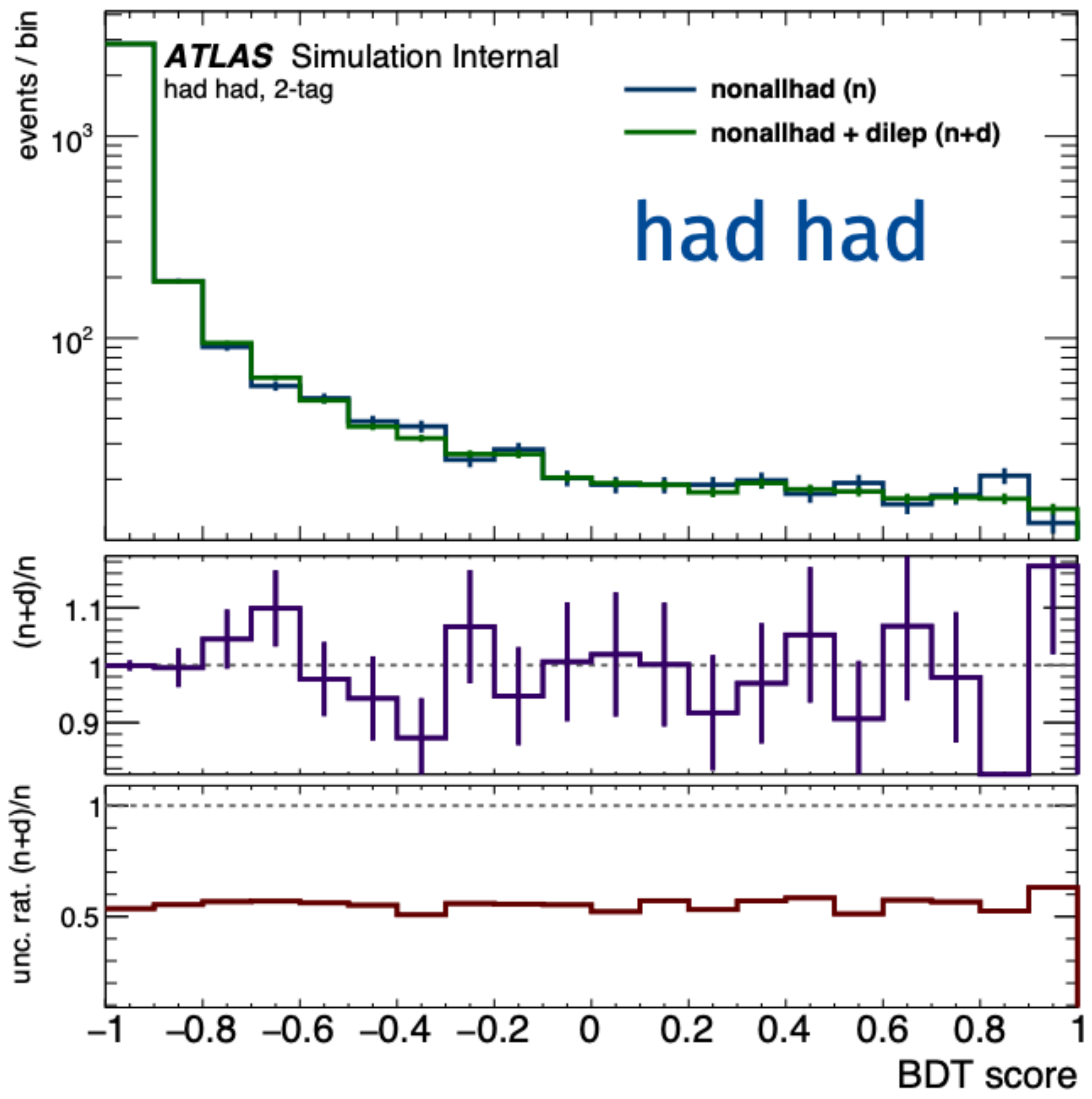
	dilepton	nonallhad	ratio
mc16a	80 M	119 M	67 %
mc16d	99 M	149 M	67 %
mc16e	139 M	199 M	70 %
∑	319 M	468 M	68 %

nonallhad = 1L + 2L ⟶ 4/5 1L and 1/5 2L

BR: 4/9 1/9

reduction of unc. to $1/\sqrt{5 \cdot 0.68} \sim 0.54$





← normalisation and shape comparison

← ratio (nonallhad + dilep)/nonallhad

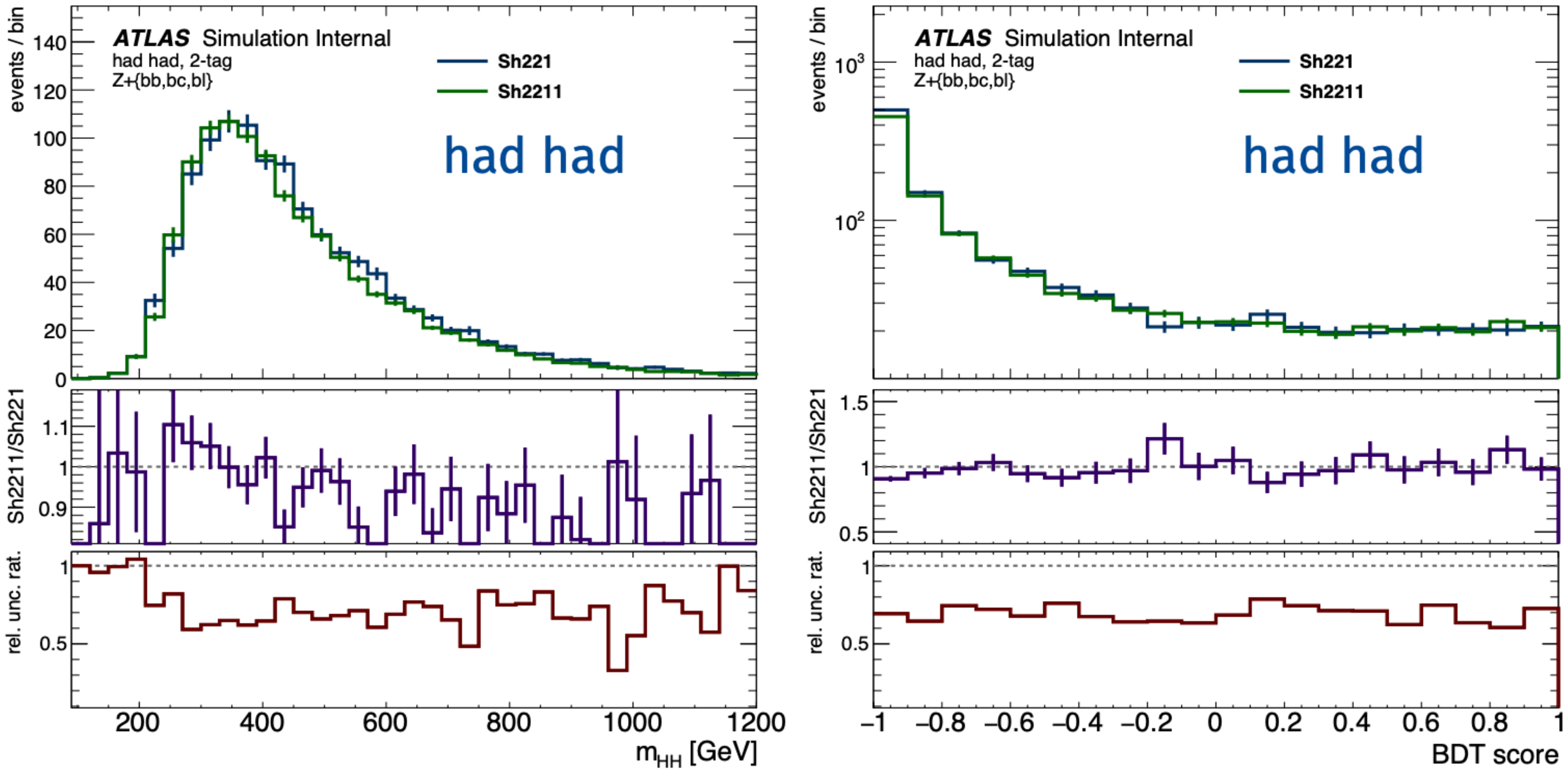
← reduction in MCStat uncertainty/bin

similar studies ongoing in lep had channel

6

Sherpa 2.2.11 vs. Sherpa 2.2.1

- Compared new Sherpa 2.2.11 V+jets samples to baseline Sherpa 2.2.1 in had had channel



Reasonable closure in the shapes [Sherpa 2.2.11 is a different generator after all]

Reduction of MC stat. unc. by ~ 35% (~ x2 more events)

Similar studies in the lep had channel ongoing

(also need to migrate sample in Z+hf CR to Sherpa 2.2.11)

- CxAOD production with systematic uncertainties ~ 80% complete [here]
- Requested aMC@NLO+Pythia 8 FxFx derivations for NLO vs. NLO generator comparison [here]
- Sherpa 2.2.11 EVNT will be further extended by a factor 2 [here]

8

ZCR re-definition

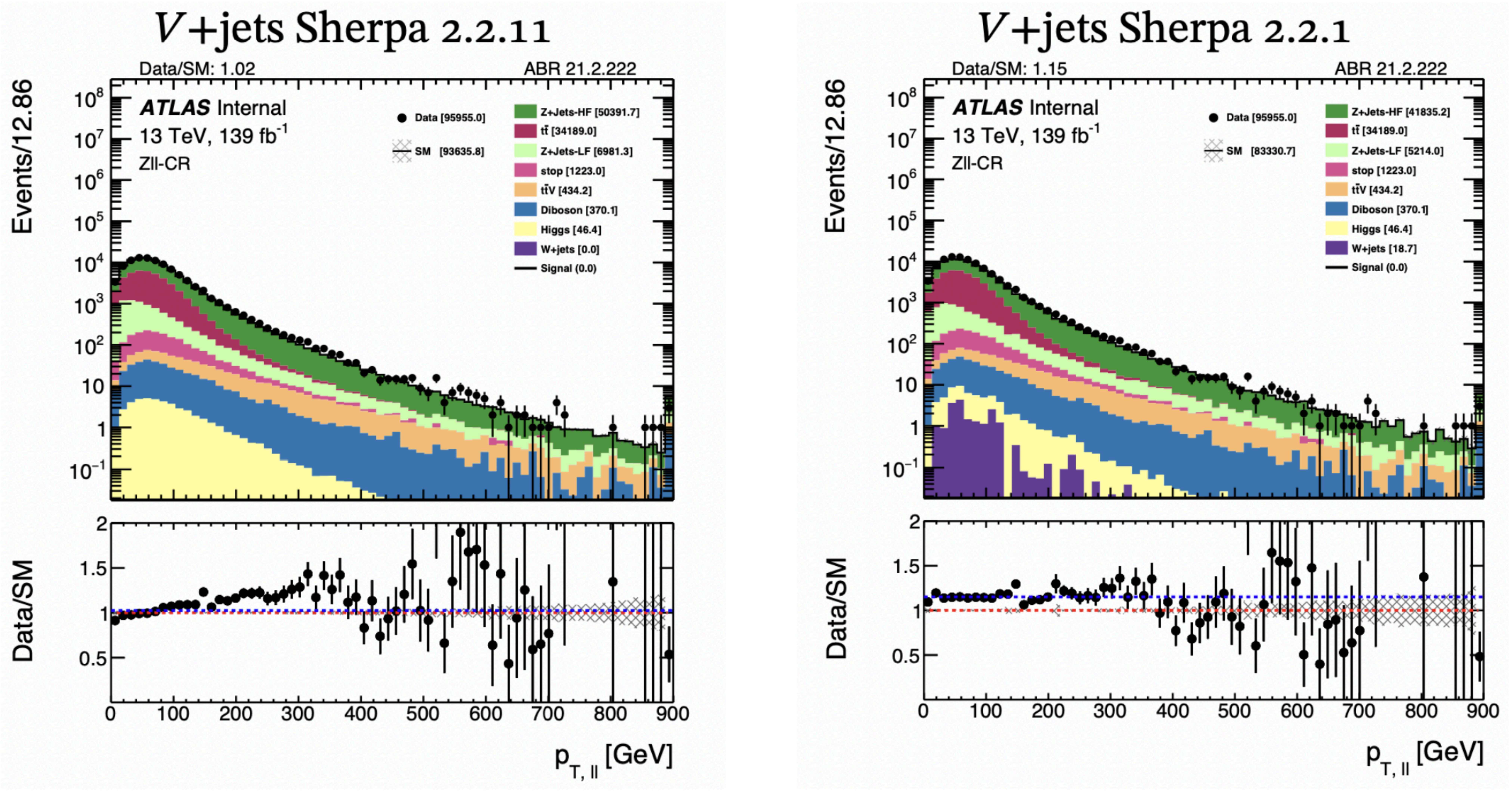


Figure 29: Data/MC comparison in the old $Z + HF$ control region, before adjustment of the cuts.

ZCR re-definition

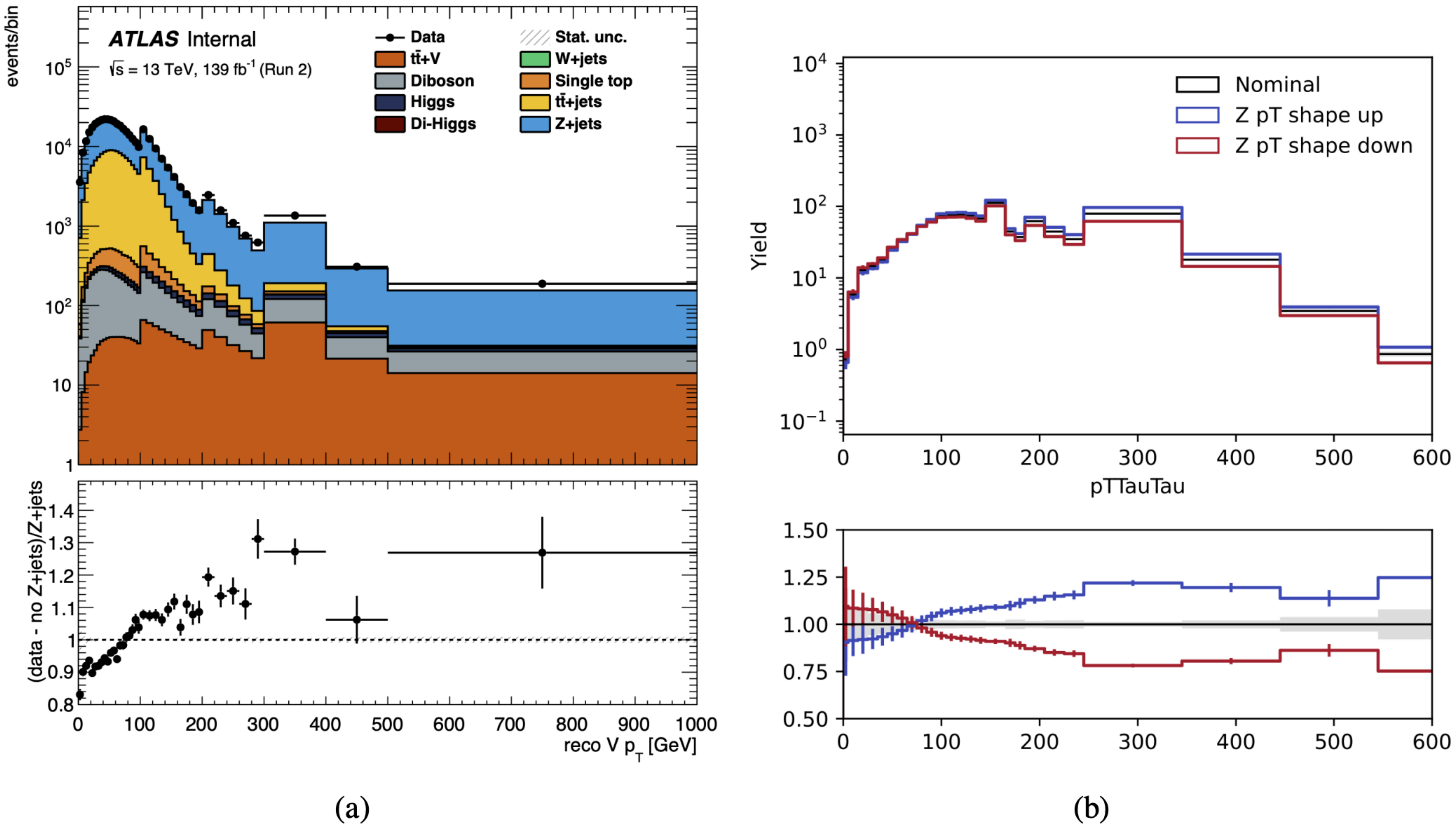
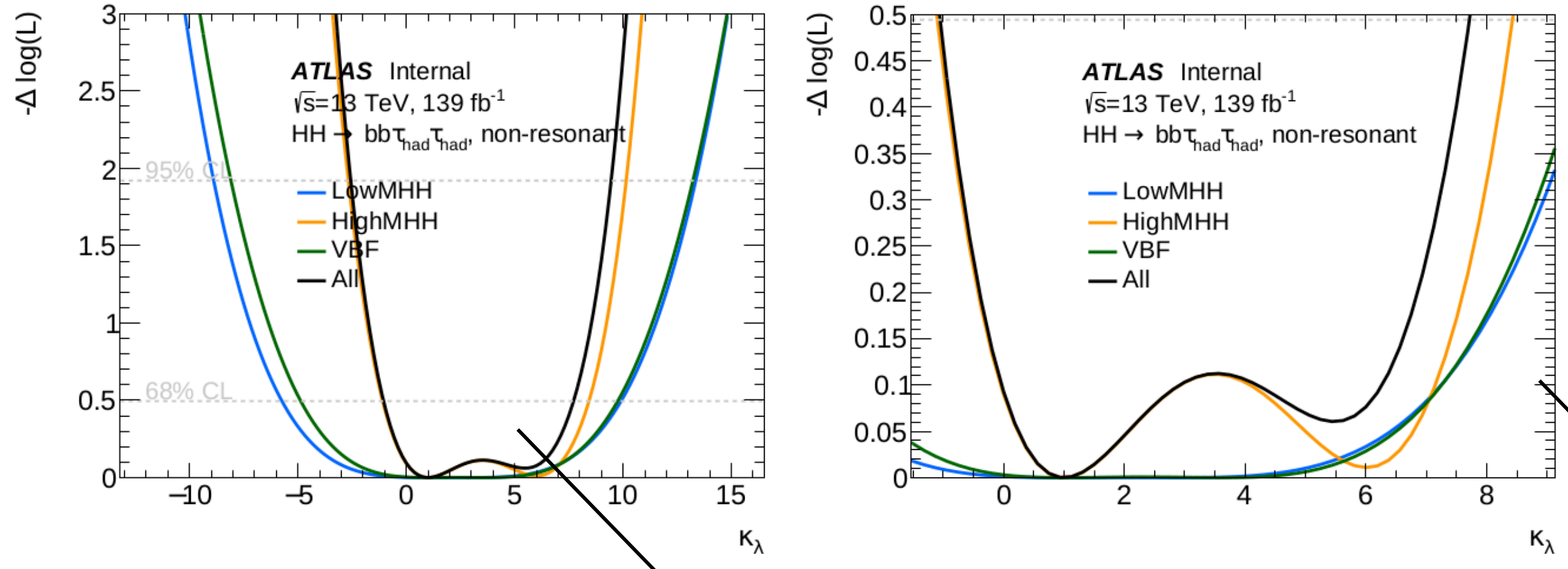


Figure 35: **a** Definition of the $V\ p_{\mathrm{T}}$ shape uncertainty covering the full difference between the data and the nominal MC prediction in the Z CR. **b** Resulting binned parameterization of the shape uncertainty.

Event selection

$\tau_{had}\tau_{had}$ category		$\tau_{lep}\tau_{had}$ categories	
STT	DTT	SLT	LTT
e/μ selection			
No loose e/μ		Exactly one loose e/μ	
		e (μ) must be tight (medium and have $\|\eta\| < 2.5$)	
		$p_T^e > 25, 27$ GeV	18 GeV $< p_T^e <$ SLT cut
		$p_T^\mu > 21, 27$ GeV	15 GeV $< p_T^\mu <$ SLT cut
$\tau_{had\text{-}vis}$ selection			
Two loose $\tau_{had\text{-}vis}$		One loose $\tau_{had\text{-}vis}$	
		$\|\eta\| < 2.3$	
$p_T >$ 100, 140, 180 (25) GeV	$p_T > 40$ (30) GeV		$p_T > 30$ GeV
Jet selection			
≥ 2 jets with $\|\eta\| < 2.5$			
Leading jet $p_T > 45$ GeV	Trigger dependent	Leading jet $p_T > 45$ GeV	Trigger dependent
Event-level selection			
Trigger requirements passed			
Collision vertex reconstructed			
$m_{\tau\tau}^{MMC} > 60$ GeV			
Opposite-sign electric charges of $e/\mu/\tau_{had\text{-}vis}$ and $\tau_{had\text{-}vis}$			
Exactly two b-tagged jets			
		$m_{bb} < 150$ GeV	

The plot further motivate the mHH splitting

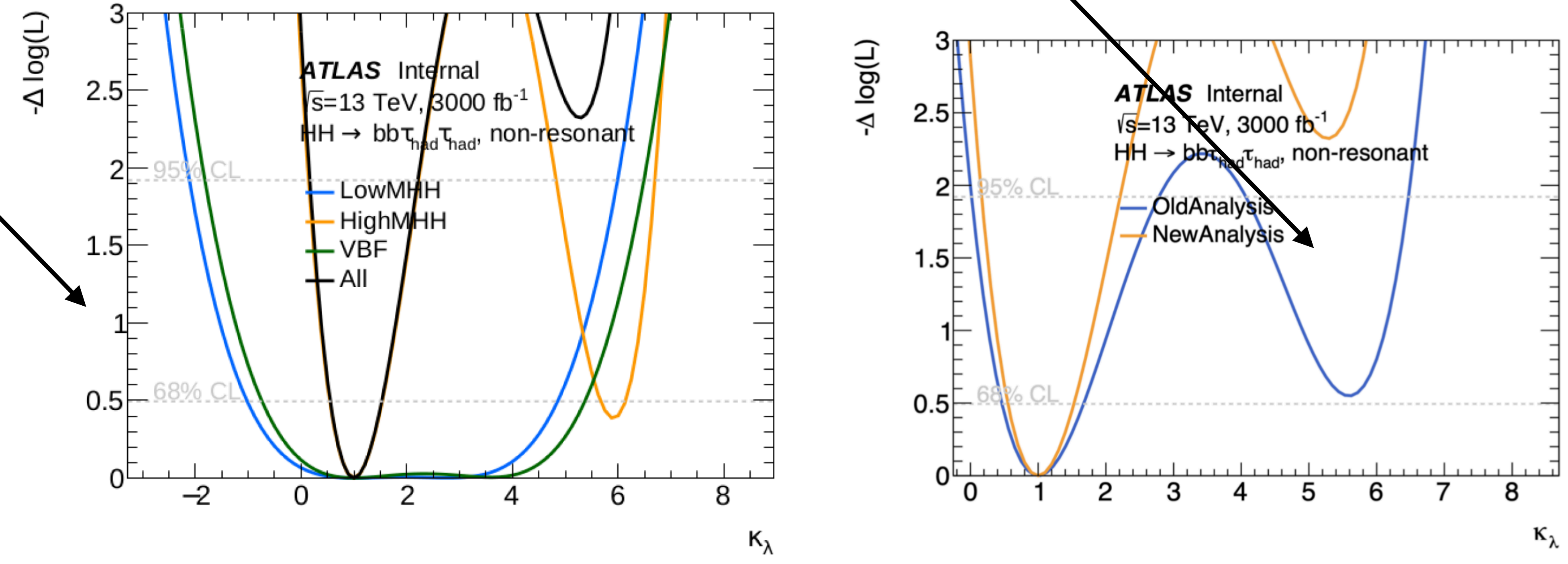


(a) (b) zoomed y-axis

Previous analysis projected to HL-LHC

Figure 157: Negative logarithm of the likelihood ratio comparing different κ_λ hypotheses to an Asimov dataset constructed under the SM hypothesis in the $\tau_{had}\tau_{had}$ channel. All the other couplings are fixed to their SM prediction. The intersections of the solid curves with the horizontal dashed lines indicate the 68% and 95% CL intervals. Subfigure (b) shows the scan zoomed in the y-axis.

Current analysis projected to HL-LHC



(a) (b)

Figure 158: Negative logarithm of the likelihood ratio comparing different κ_λ hypotheses to an Asimov dataset constructed under the SM hypothesis in the $\tau_{had}\tau_{had}$ channel projected at HL-LHC. Subfigure (b) compares the old analysis sensitivity to the one of the new legacy analysis strategy at HL-LHC.