HH->bbtautau final state with Run 3 data with the ATLAS experiment

Davide Fiacco

davide.fiacco@cern.ch

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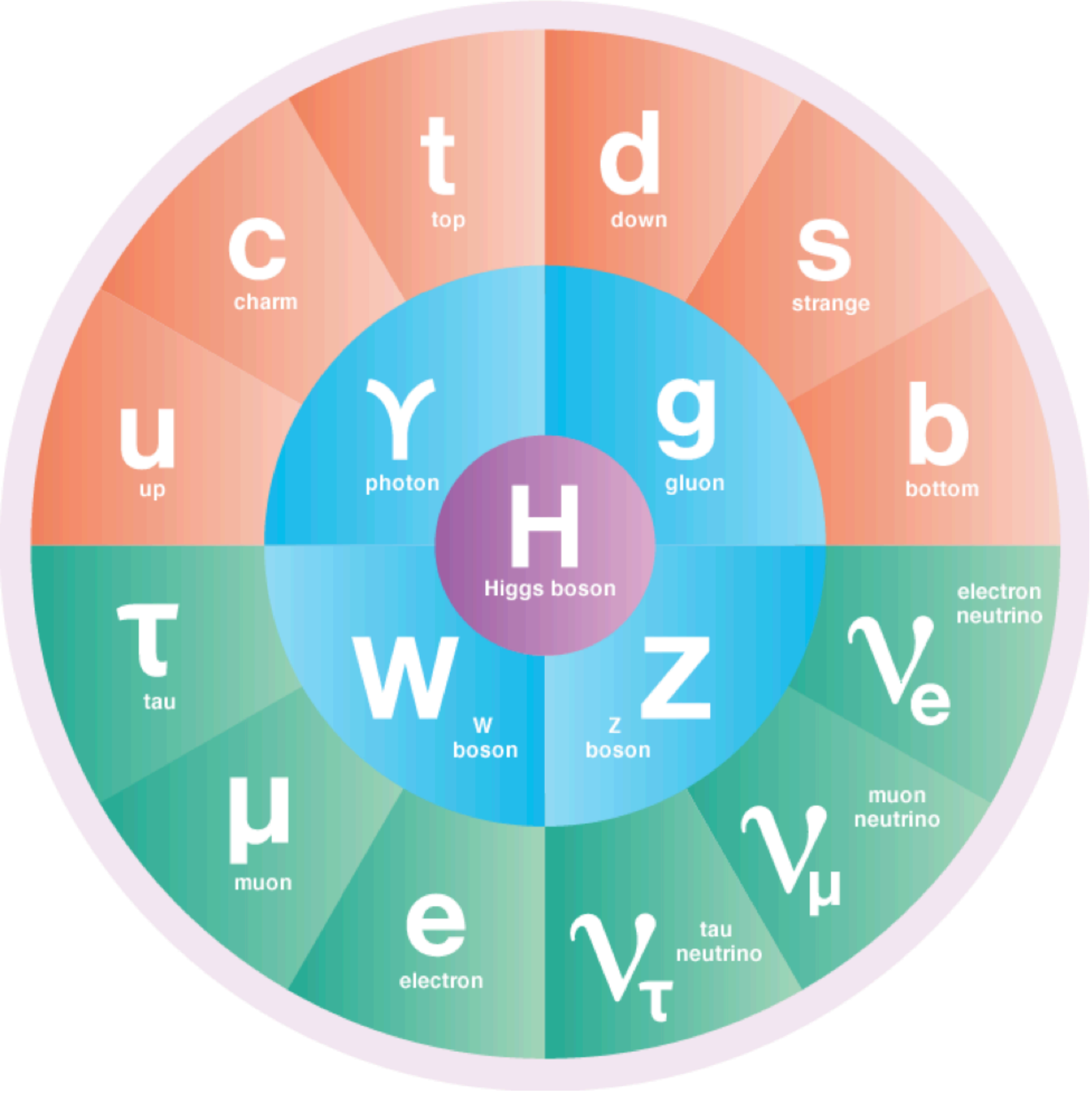
Why we care of Di-Higgs ?

Source for theoretical part of the talk of Patrick Meade

Standard Model introduction

It is an experimental model able to describe with great accuracy interactions between particles.



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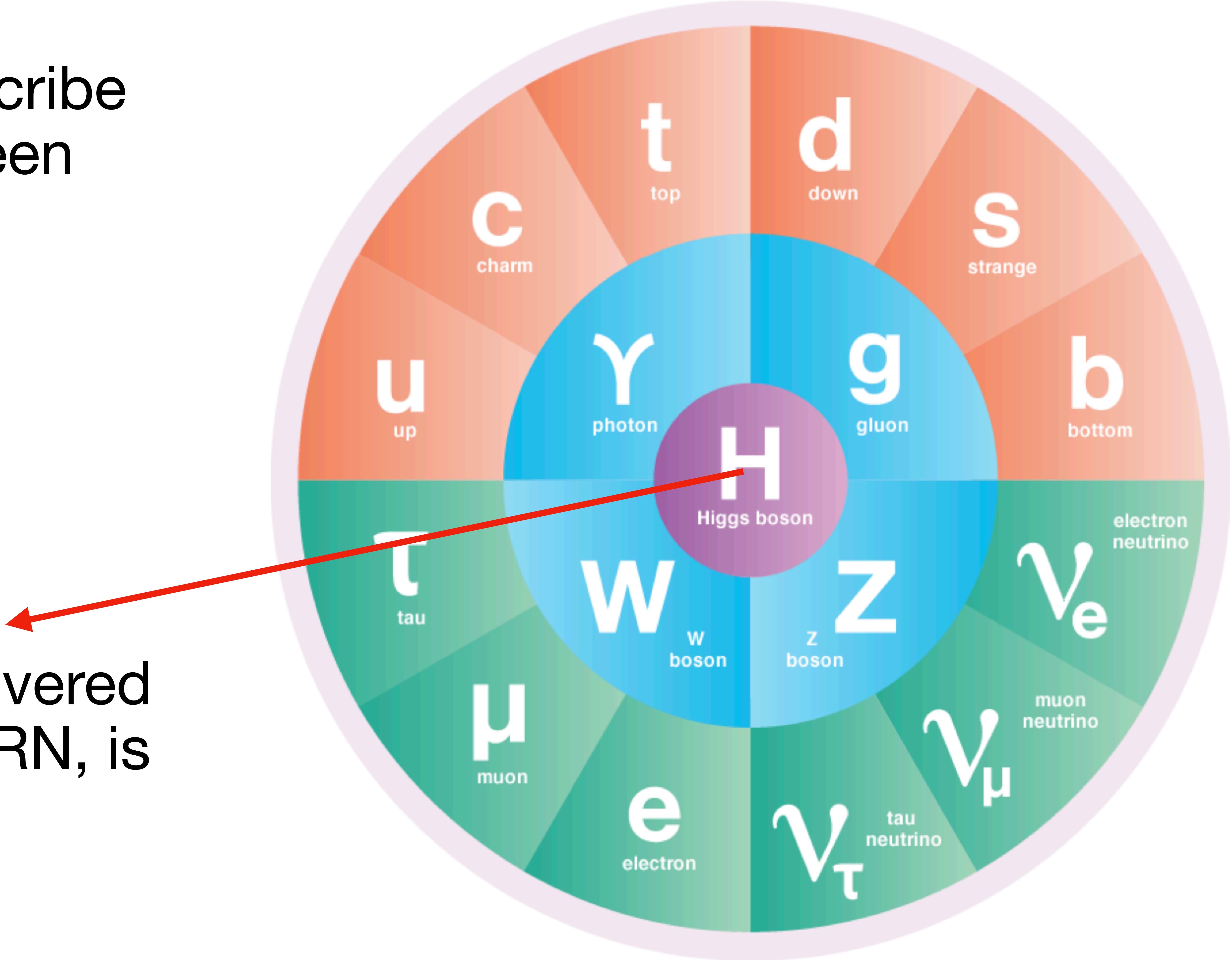


The Higgs Boson, experimentally discovered in 2012 at Large Hadron Collider at CERN, is the most fundamental piece.

Standard Model introduction

Looking at the parameters of the SM:

g_1, g_2, g_3 3 gauge couplings

+QCD vacuum angle θ_{QCD}

θ_{ij}, δ_{CP} 3 CKM angles +1 phase

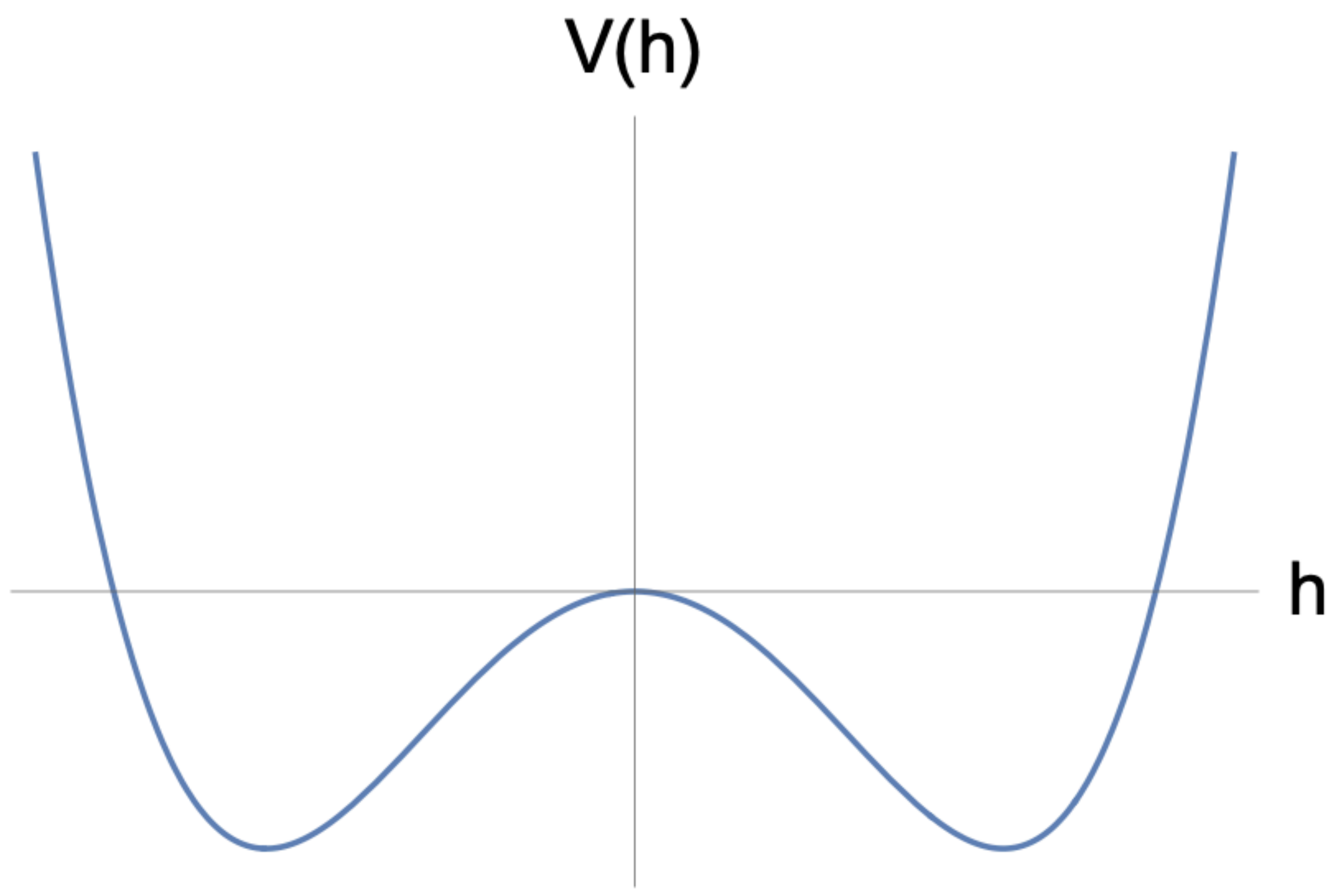
m_{q_i}, m_{l_j} 6 quark masses+3 charged leptons

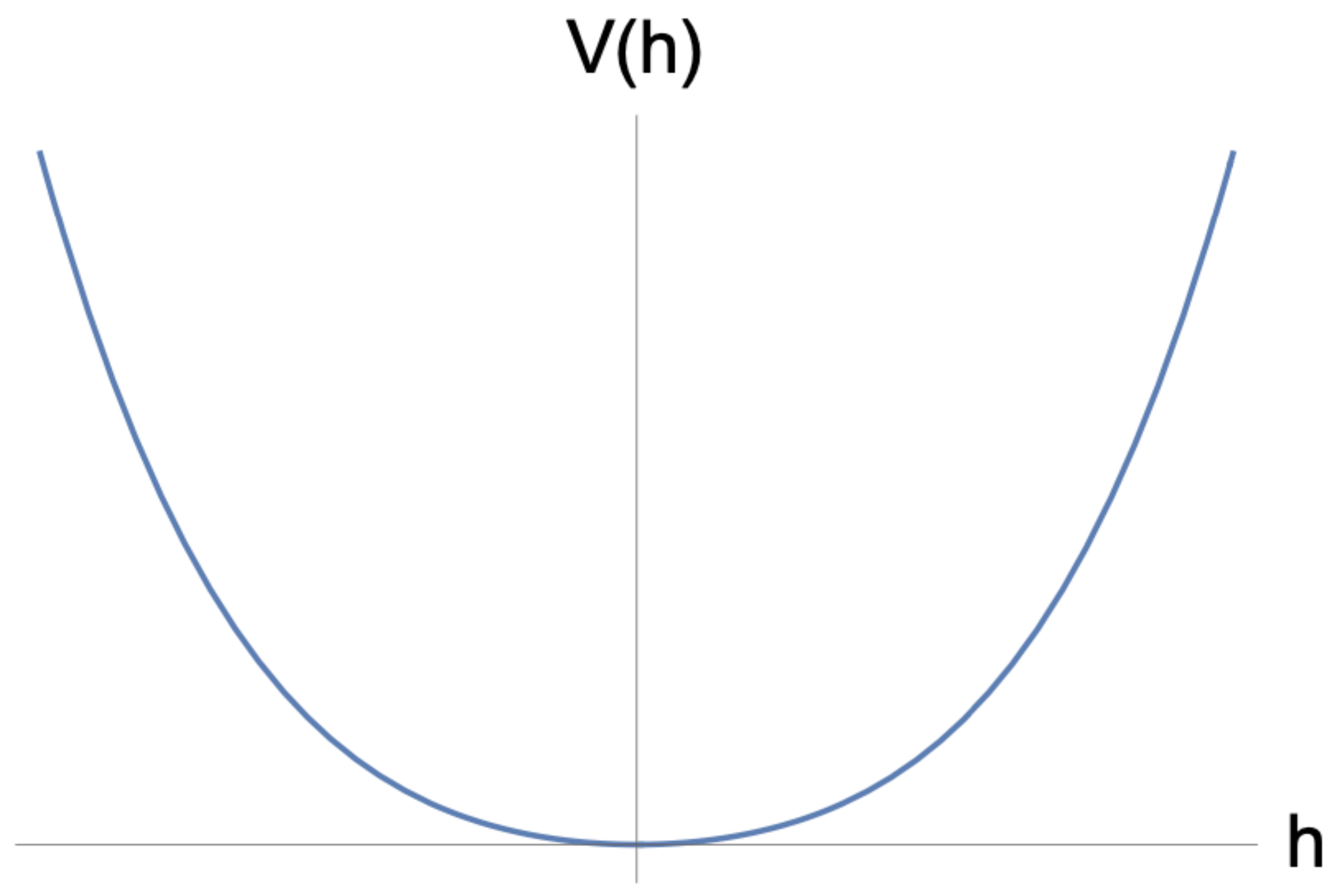
m_h, v Higgs mass and VEV

15 of 19 parameters depends on the Higgs field!

Higgs Potential

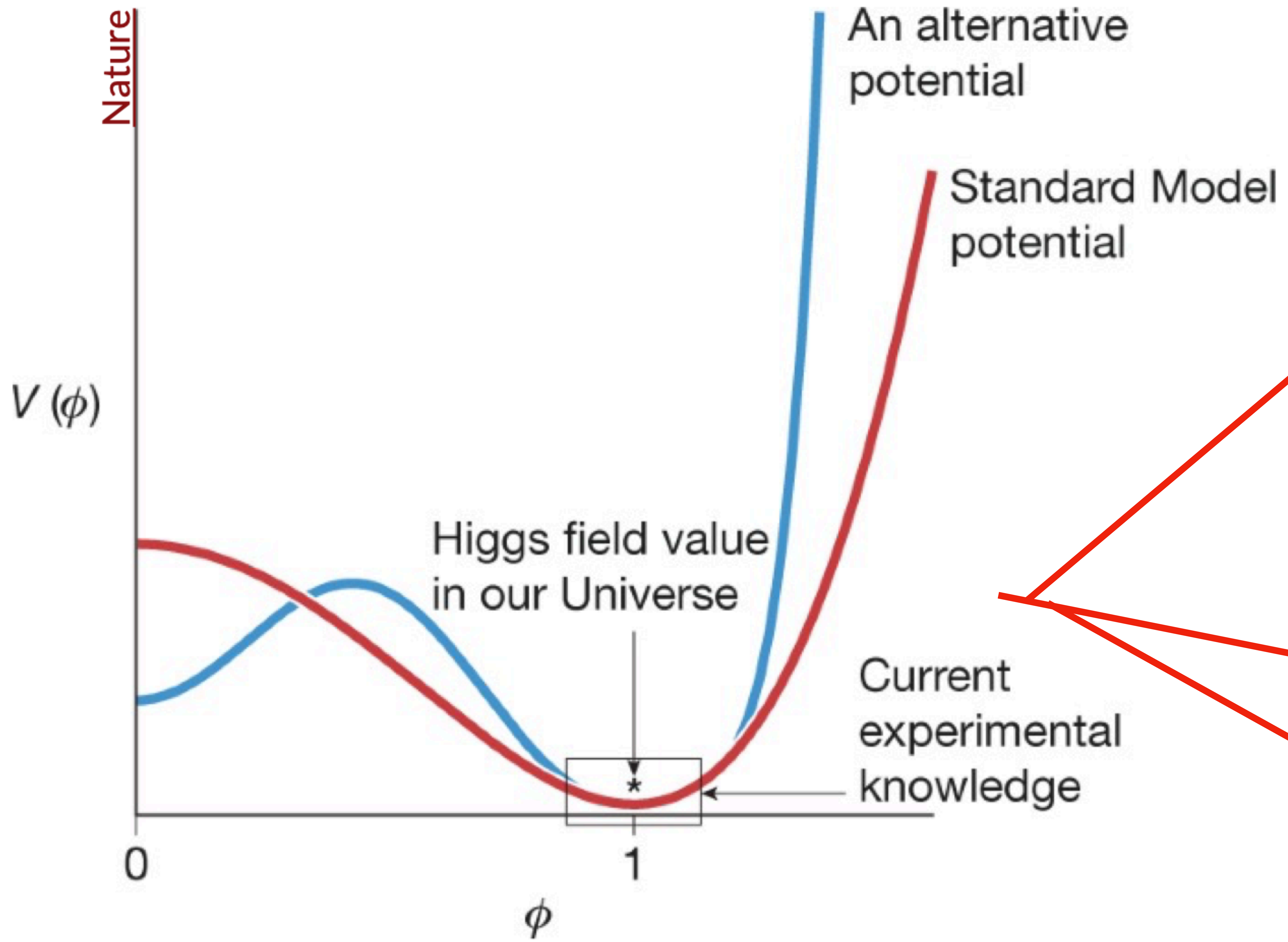
It is the cause of the E-W Spontaneus Symmetry Breaking, and the reason the SM particles have mass!





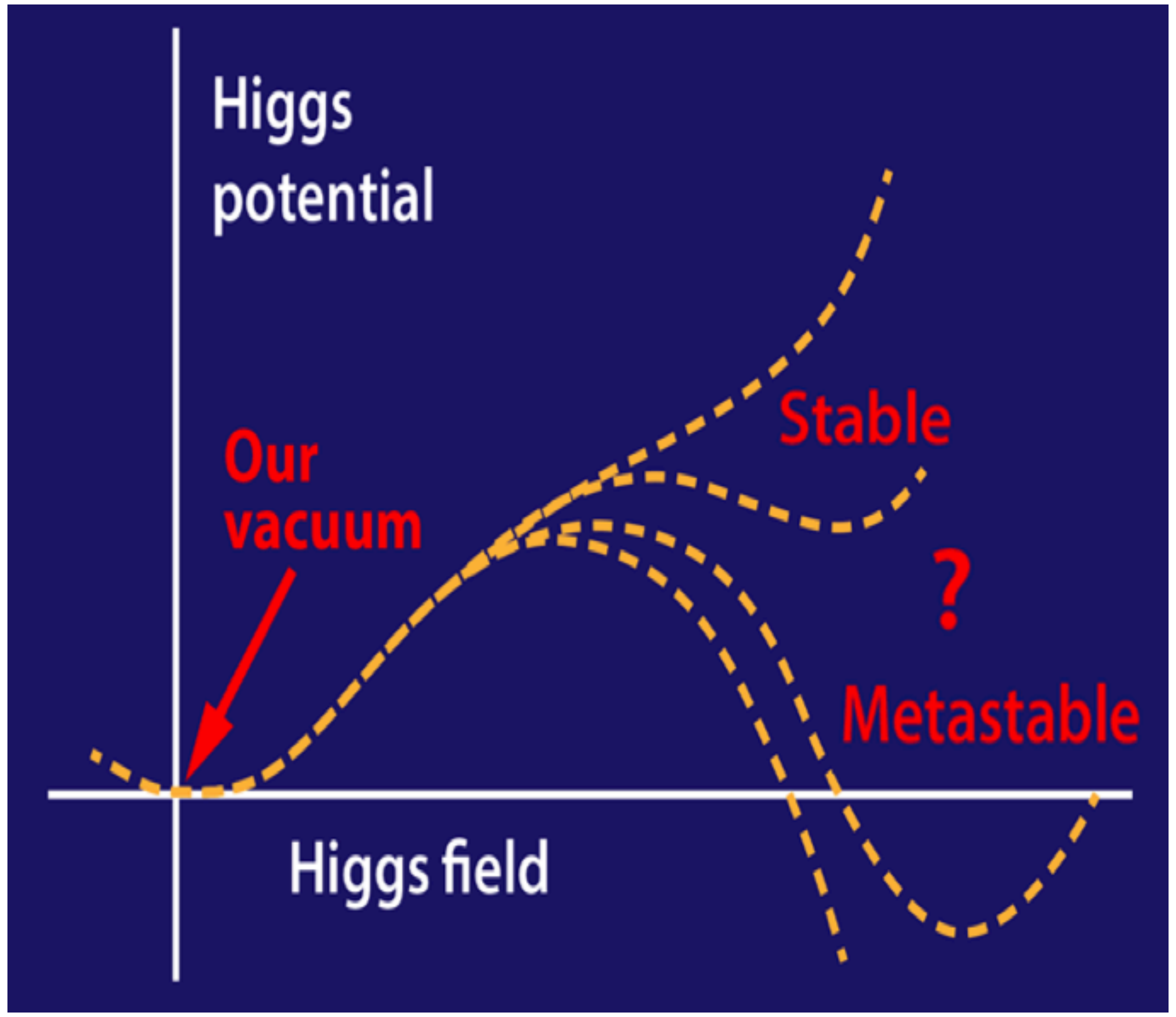
But we don’t know exactly it’s shape…

Higgs Potential



$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$

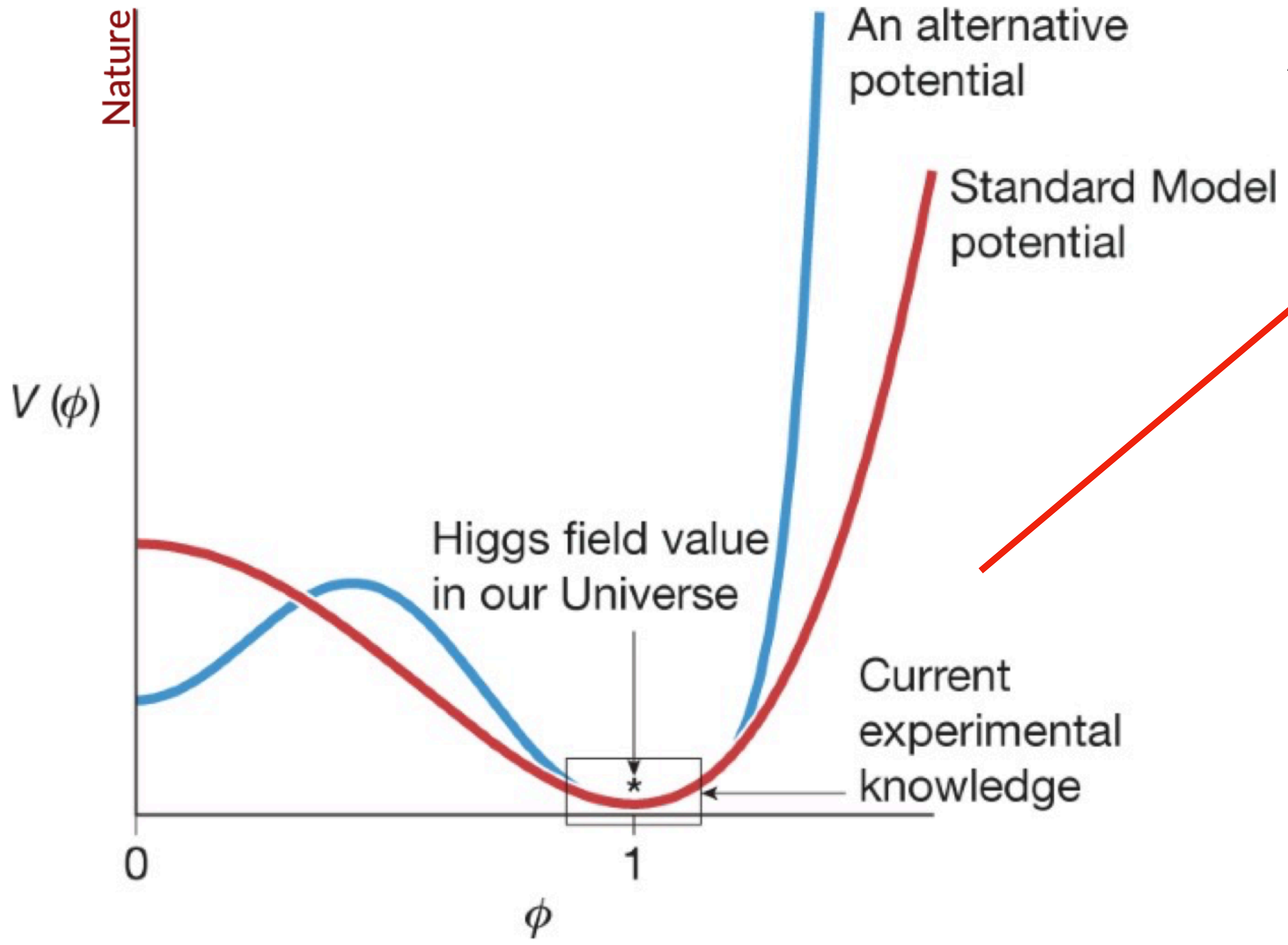
Stability of universe



Fundamental or composite Higgs?

Higgs portal to hidden sectors

Higgs Potential



$$V(h) \sim \lambda v h^3 + \frac{1}{4}\lambda h^4$$

A way to study the potential is to look at self interactions:

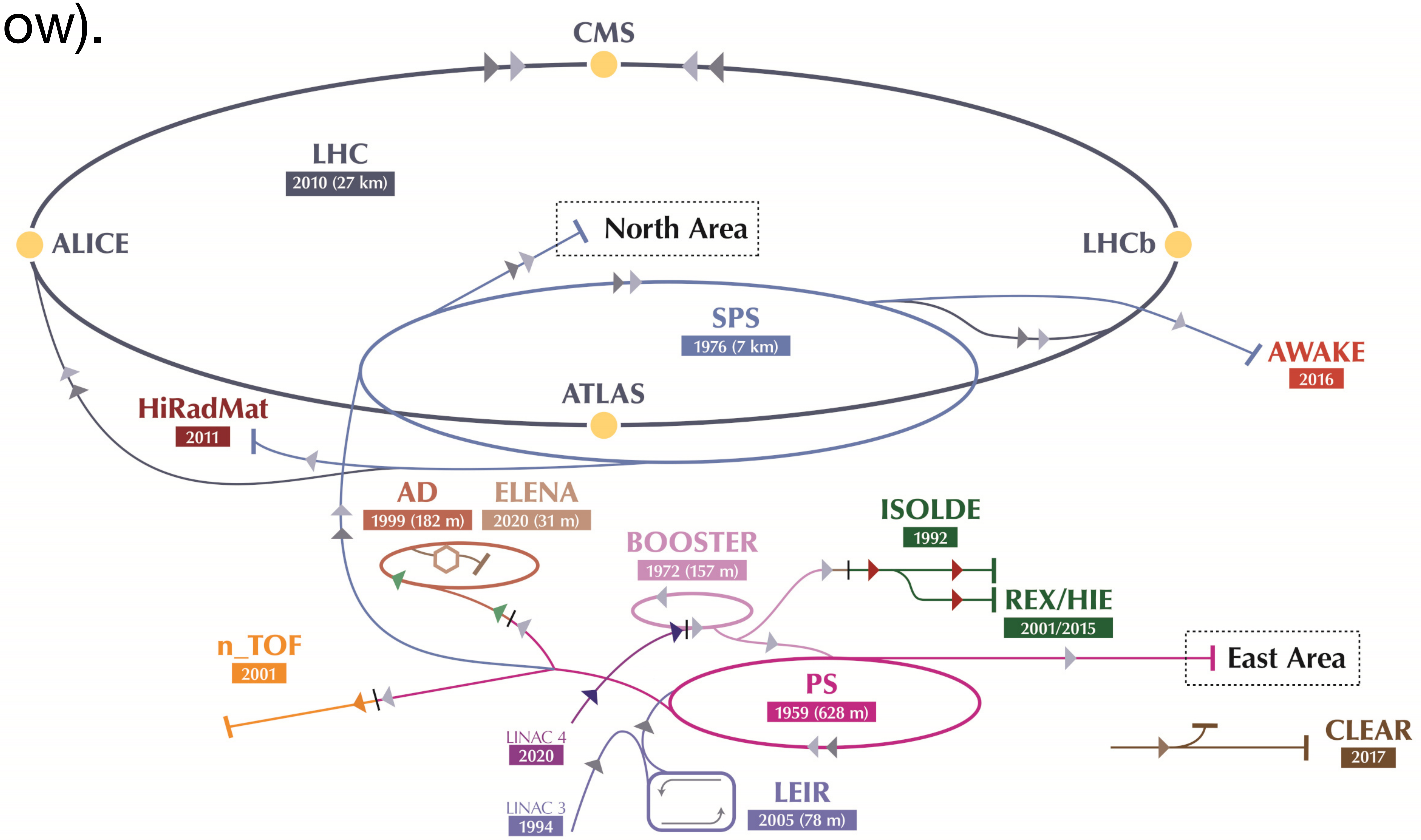
$$\lambda_{hhh} \sim \lambda v \qquad \lambda_{hhhh} \sim \lambda$$

Studying these processes we measure the self-couplings, and then we can extract the Higgs potential shape!

HH production at LHC

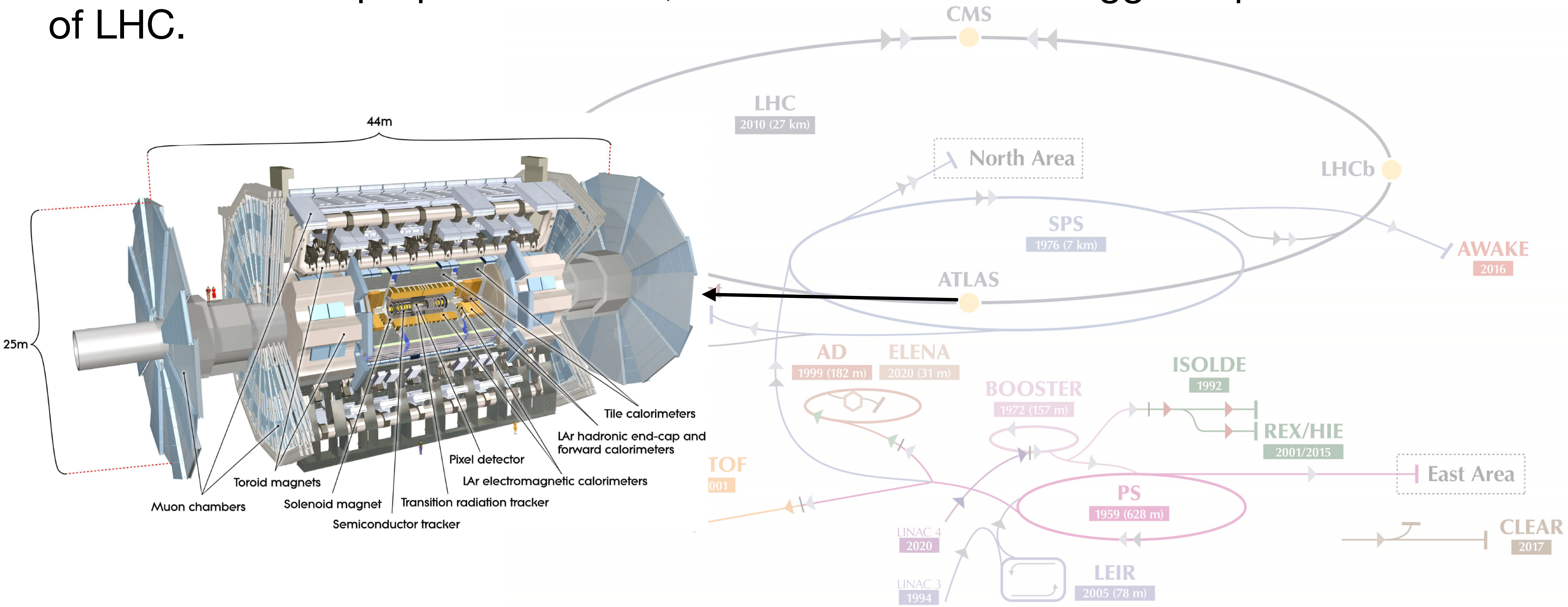
Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator (until now).



ATLAS Experiment

ATLAS is a multi-purpose detector, and it is one of the 4 bigger experiments of LHC.



HH Production (non-resonant)

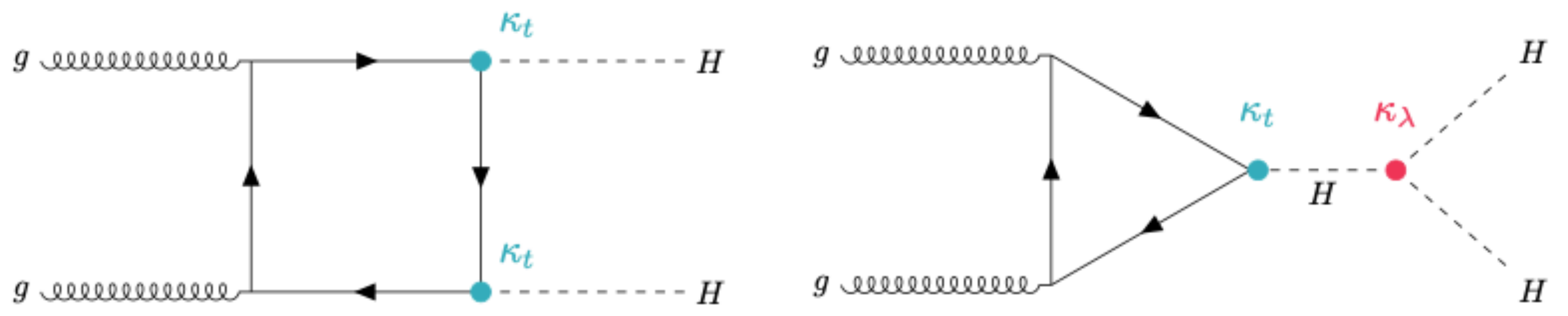
$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$$

LHC is a pp collider, and the available production channels at 13 TeV are:

gluon-gluon Fusion (ggF)

$\sim \kappa_\lambda$

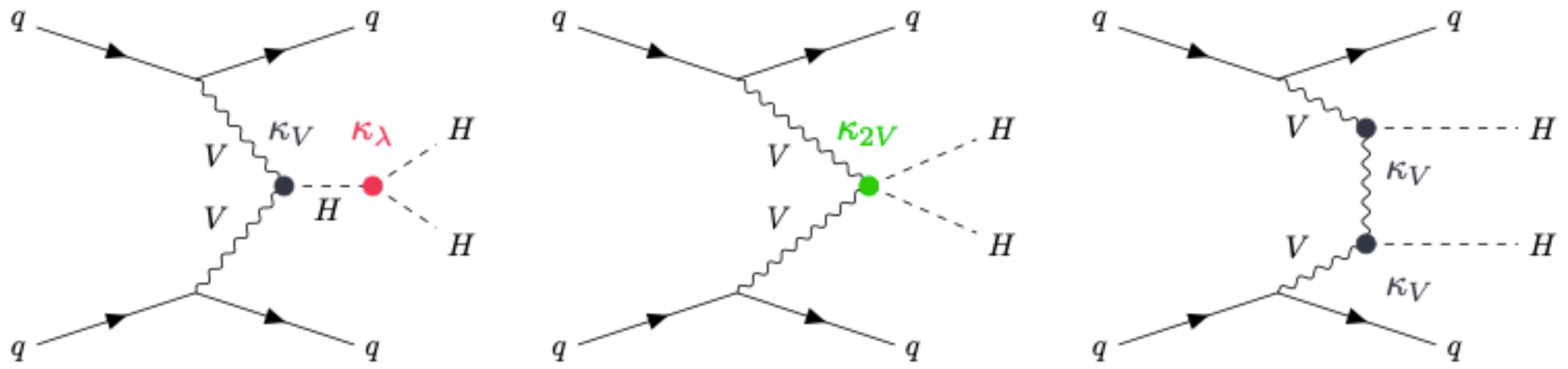
$\sigma \sim 31.0$ fb



Vector Boson Fusion (VBF)

$\sim \kappa_\lambda, \kappa_{2V}$

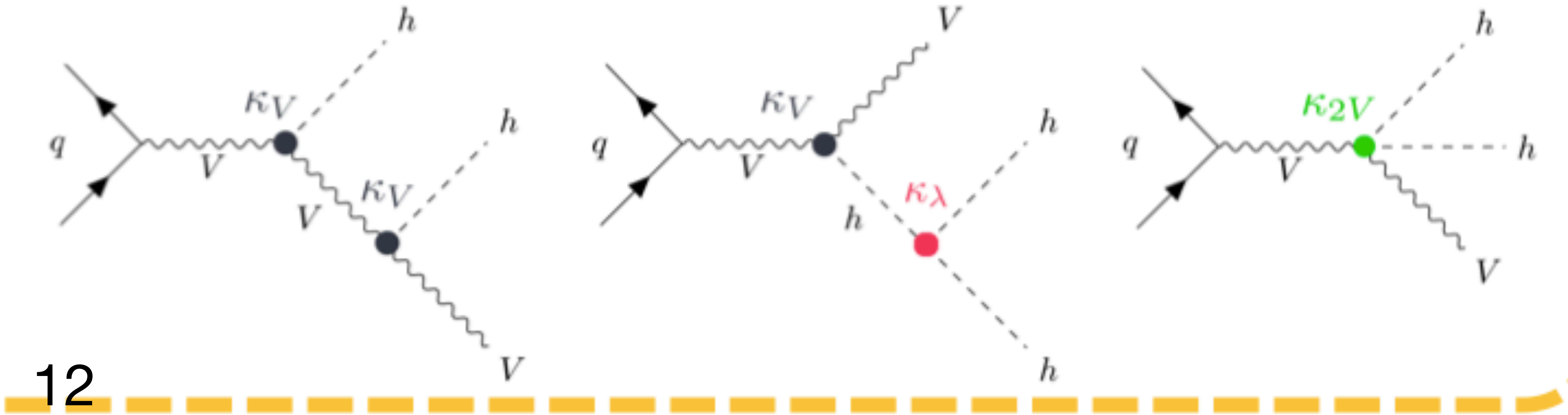
$\sigma \sim 1.72$ fb



Vector Boson Associated (VHH)

$\sim \kappa_\lambda, \kappa_{2V}$

$\sigma \sim 0.86$ fb



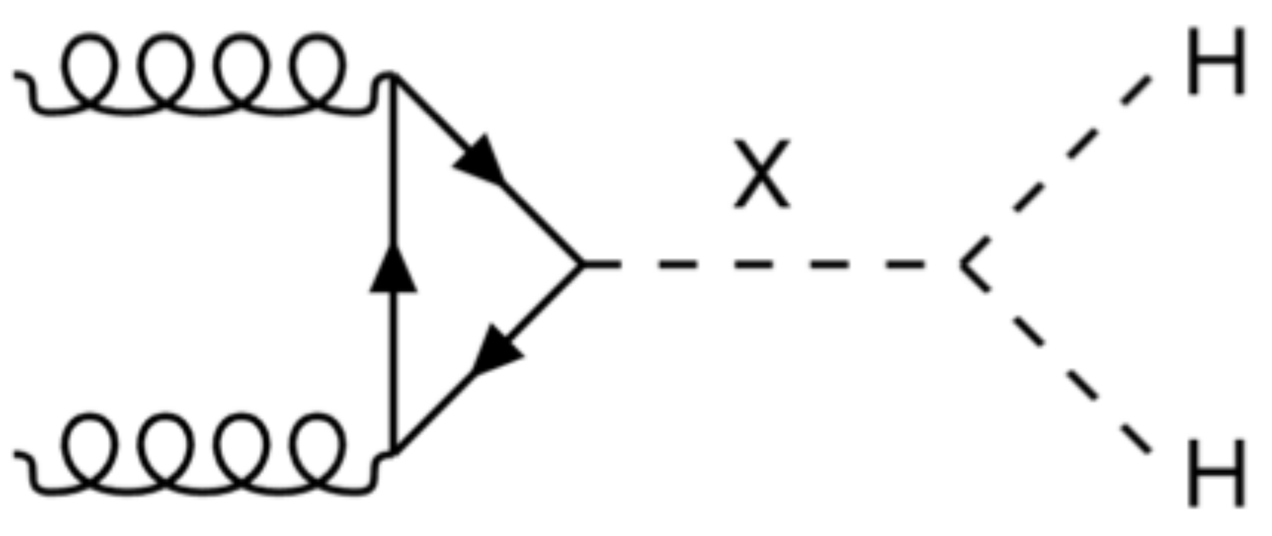
HH Production (resonant)

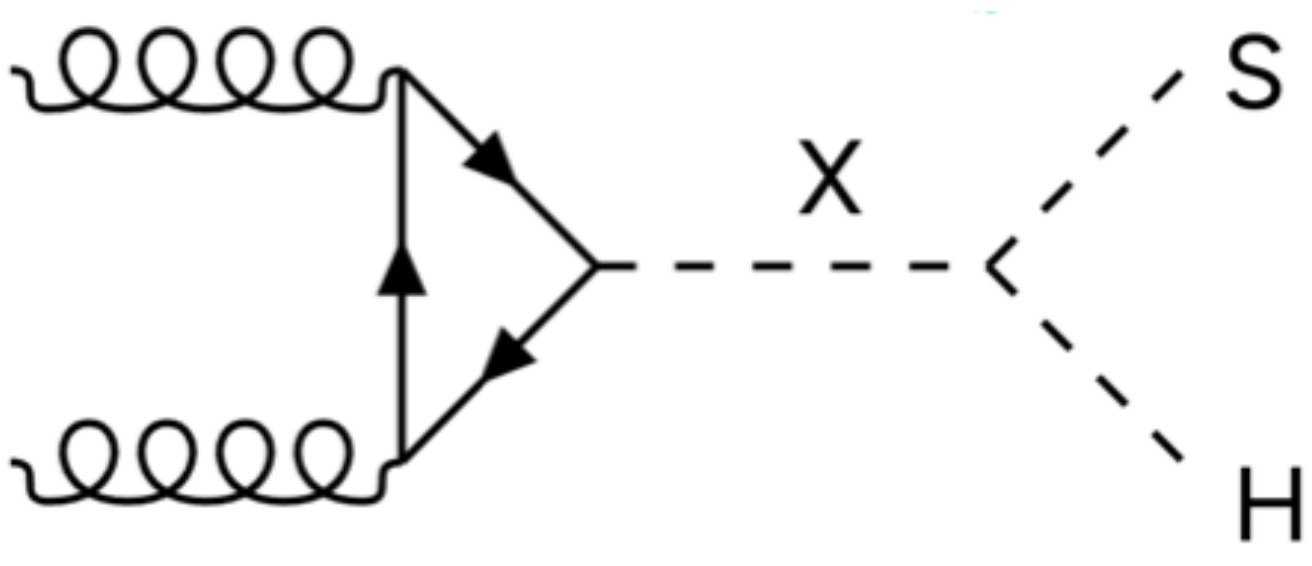
Several BSM predict the existence of an additional scalars to the SM, e. g., 2-Higgs Doublet Model (2HDM), two real singlet model (TRSM), minimal supersimmetryc SM (MSSM),…

Depending on the masses of the scalar two approaches are used:

- $m_X \leq E_{LHC}$, resonant searches;
- $m_X > E_{LHC}$, EFT interpretation.

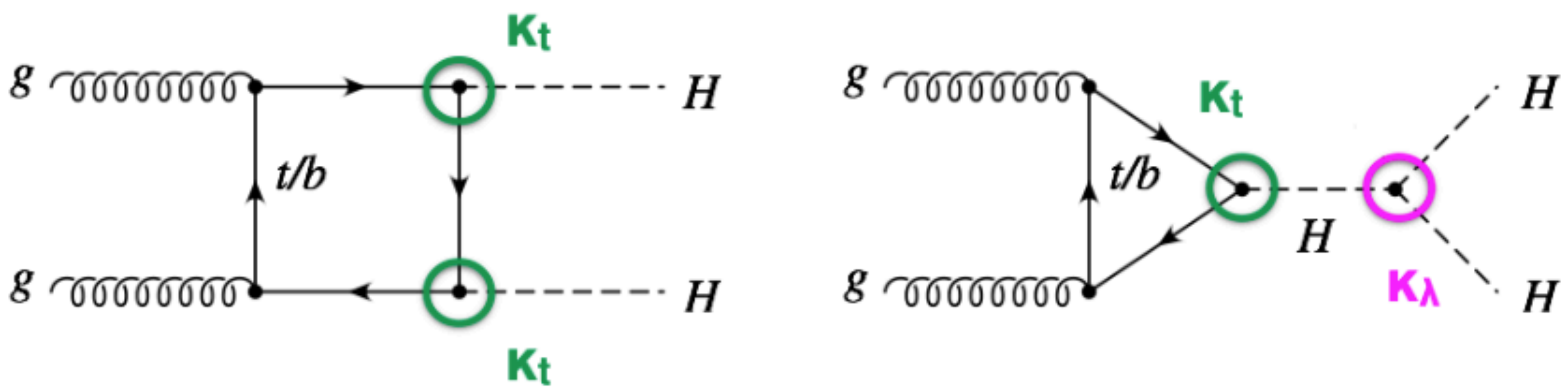
→ None of them will be traded today



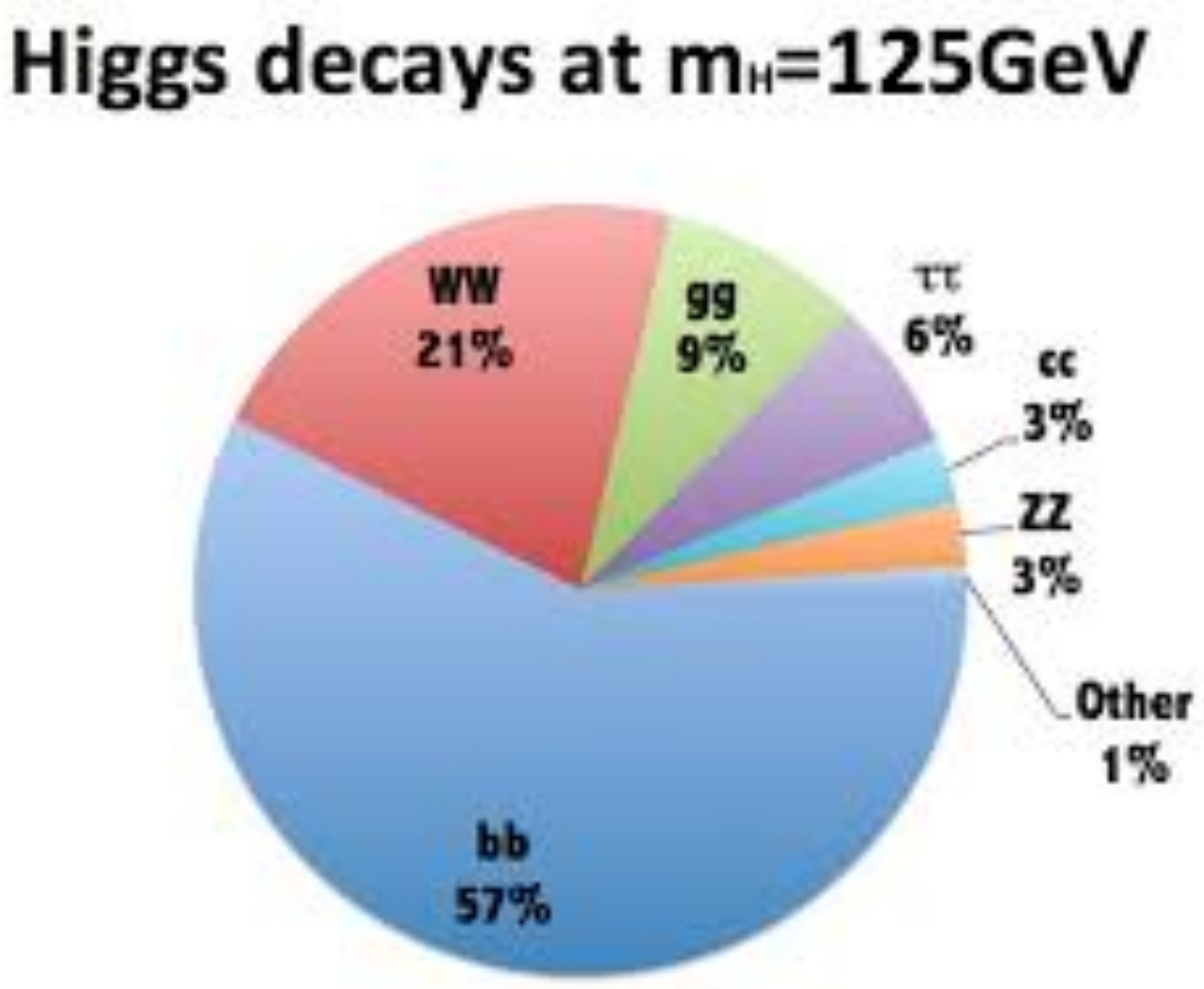


HH Search

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$$



Once produced the event has to be detected, and so we need to re-build the Higgs from its decays:



X 2 ⟶

	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 Search

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ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

→

Main final states:

- HH-> $b\bar{b}b\bar{b}$
- HH->$b\bar{b}\tau^+\tau^-$
- HH->$b\bar{b}\gamma\gamma$
- HH->$b\bar{b}W^+W^-$
- HH->Multilepton

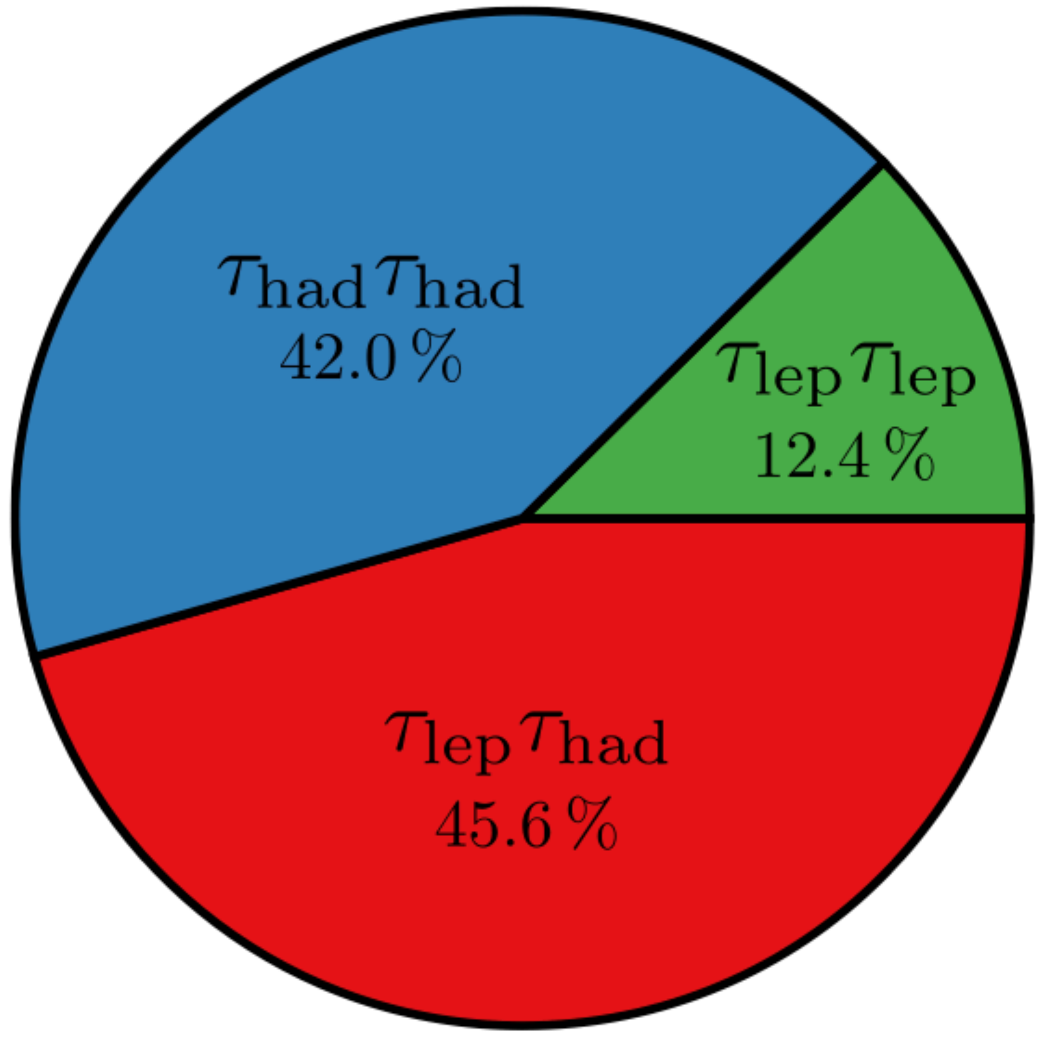
…

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

The tau lepton decay before to interact with the detector [lifetime = $(2.903\pm0.005)\times10^{-13}$ s].

The tau decays in lighter leptons (~35%, labelled as τ_{lep}) or in pions (~65%, labelled as τ_{had})

Di-Tau Branching Ratios



BR from PDG

Two final states as target:

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

Overview of Run2 HH->bbtautau analysis

HH -> $b\bar{b}\tau^+\tau^-$ Run 2 trigger strategy

The Run 2 trigger strategy focused on select the two taus of the final state.

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

  Single tau trigger (STT)

  Di-tau trigger (DTT)

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

  Single lepton trigger (SLT)

  Lepton+tau trigger (LTT)

HH -> $b\bar{b}\tau^+\tau^-$ Run 2 offline selection strategy

After the trigger selections, also called "online", the events are saved in ATLAS database.

On the saved events it's possible to apply more accurate (and slow) algorithms, called "offline".

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

Exactly two τ_{had} identified with opposite charge,

Lepton veto

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

Exactly one lepton and one τ_{had} with opposite charge

Exactly two identified b-jets

More detailed table in backup

HH -> $b\bar{b}\tau^+\tau^-$ Run 2 Background estimation

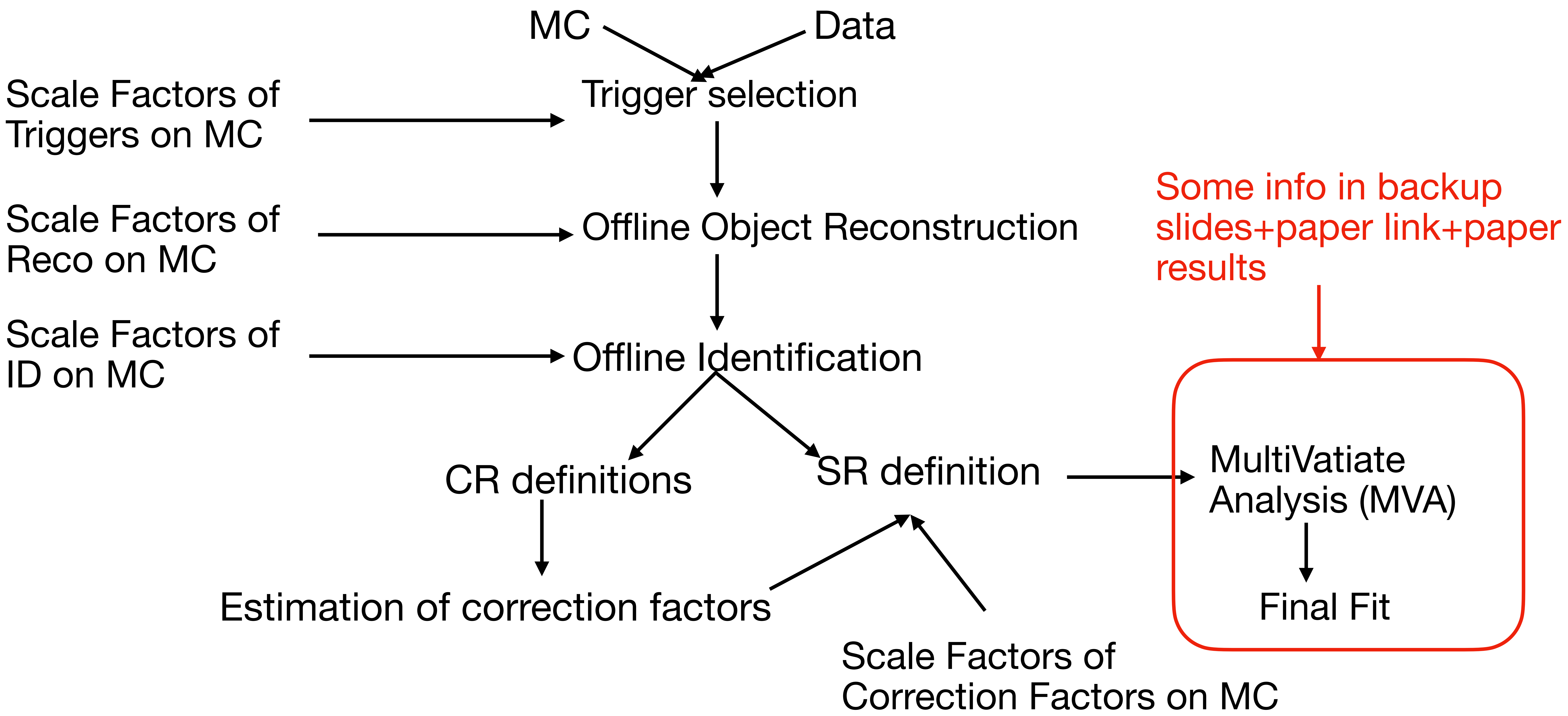
This kind of analysis rely heavily on MC.

MC are used to generate SM non-resonant signal, BSM resonant signal and SM background contributions.

Table of used MC for Run2 in backup

Background	$\tau_{had}\tau_{had}$-channel	$\tau_{lep}\tau_{had}$-channel
$t\bar{t}$	Simulation (normalized in fit)	Simulation (normalized in fit)
Z+jets	Simulation (normalized in fit – dedicated CR)	Simulation (normalized in fit – dedicated CR)
jet $\rightarrow \tau_{had}$ fakes ($t\bar{t}$)	Simulation (data-driven mis-ID eff.)	Combined fake-factor method
jet $\rightarrow \tau_{had}$ fakes (multi-jet)	Fake-factor method	Combined fake-factor method
SM Higgs / Other	Simulation	Simulation

HH -> $b\bar{b}\tau^+\tau^-$ cut flow



What can we improve for Run 3

Run 3 person power

All HH researches are considered very 'hot topics' and they have, especially in Run3, a very huge participation:

> 30 institutes declared interested only for HH->$b\bar{b}\tau^+\tau^-$

> 100 (potential) participants!

This huge person power is used also for software upgrades and collaboration with combined performance groups of ATLAS

HH->$b\bar{b}\tau^+\tau^-$ uses all physics objects, except for photons

Trigger options

Trigger only on the taus seems suboptimal, (which is great for my PhD!)

Trigger on two objects allows to require smaller energy for single object (rate requirements!)

We have 3 possible “type” of trigger that we can use:

Trigger options

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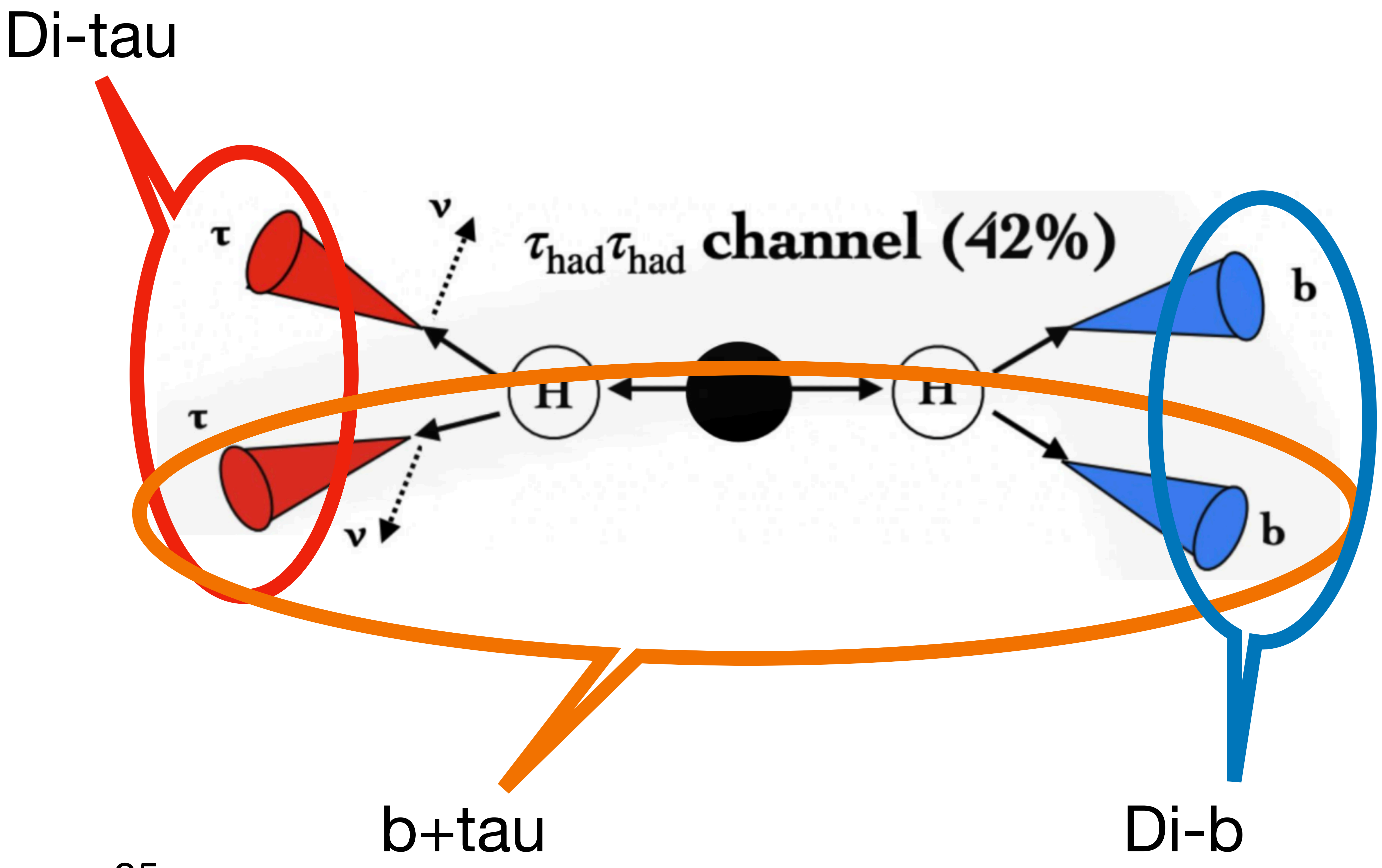


Trigger optiomization and development for $\tau_{had}\tau_{had}$

For the Run2 were used Di-tau triggers in the $\tau_{had}\tau_{had}$ channel

Respect the Run2, the Run3 offers a new delayed stream, in which events are saved in extra buffers, and are processed when there are available resources.

↓

It’s possible to develop triggers with a bigger rate

[The amount of events can be saved is limited by cost and resources, so the total available rate of each trigger is limited.]

Trigger optiomization and development for $\tau_{had}\tau_{had}$

For trigger developing we are interested on their efficiency on the signal

↓

We produce ggF MC of non-resonant signal sample.

↓

We apply offline selections to emulate the impact of the analysis

↓

We estimate the efficiency of different trigger configurations, varying kinematic cuts

↓

Then we estimate their rate on the data, and check if it’s possible to implement them

Di-tau and Di-b Triggers (kL=1)

Lower pt thresholds triggers for Run3 [from (35,25) GeV to (30,20)GeV] (activated during 2023).

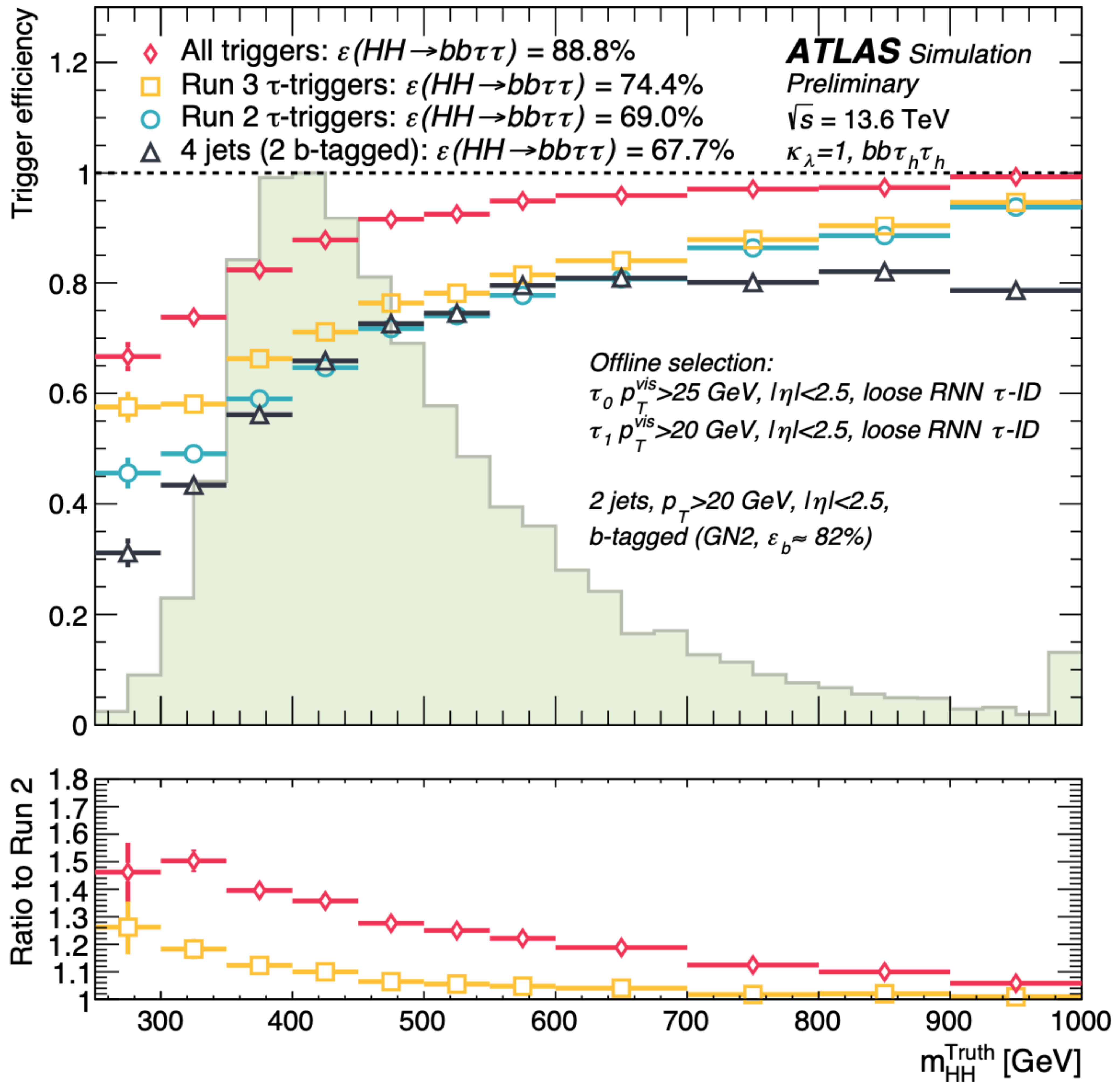
There are two di-tau triggers actually, and their rates go from 23->38Hz and 40->80Hz

Delayed Di-b trigger developed by HH->bbbb (activated during 2022) of 178 Hz

[What really care is the overlap with all other triggers of the Trigger Menu of ATLAS, and it's not something that is easily estimated. So the most reasonable trigger is implemented in the menu, and during the data-taking it will be adapted]

Di-tau and Di-b Triggers (kL=1)

Efficiency gain for new Di-tau and Di-b triggers:



Public plot link

	ε kl=1	Gain	Gain w/out offline selection
Di-tau Run2	0.69		
Di-tau Run3	0.74	7%	10%
Di-b	0.68		
Di-tau Run3 OR Di-b	0.89	29%	~60%

New Identification algorithms

Tau and b-jets need of an identification step to reject mis-reconstructed jets, the so called ‘fake’ contributions. New models based on Graph NNs give promising results.

↓

We produce dataset of true taus (from Z->tau tau) and jets from QCD

↓

We Train our models in a supervised way (supervised = we know each object if is a tau or not)

↓

We estimate our performances on a test dataset

New Identification algorithms

The ROC curve is a way to judge and compare different models

↓

In a 2-classification problem (as tau ID) we vary the threshold on the discrimination value, and compute efficiency on signal and background

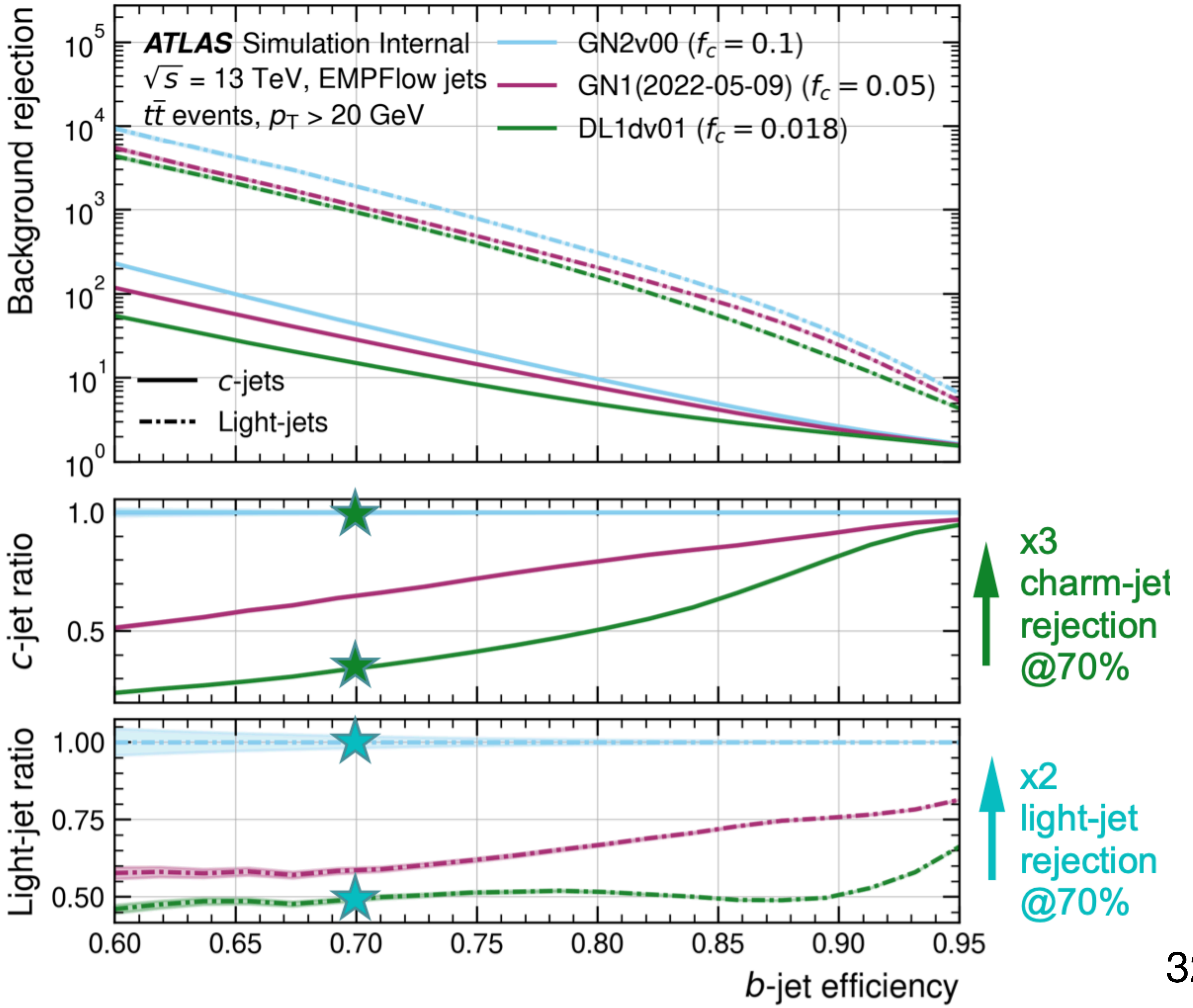
↓

$$\text{Rejection Power} = \frac{1}{\text{background selection efficiency}}$$

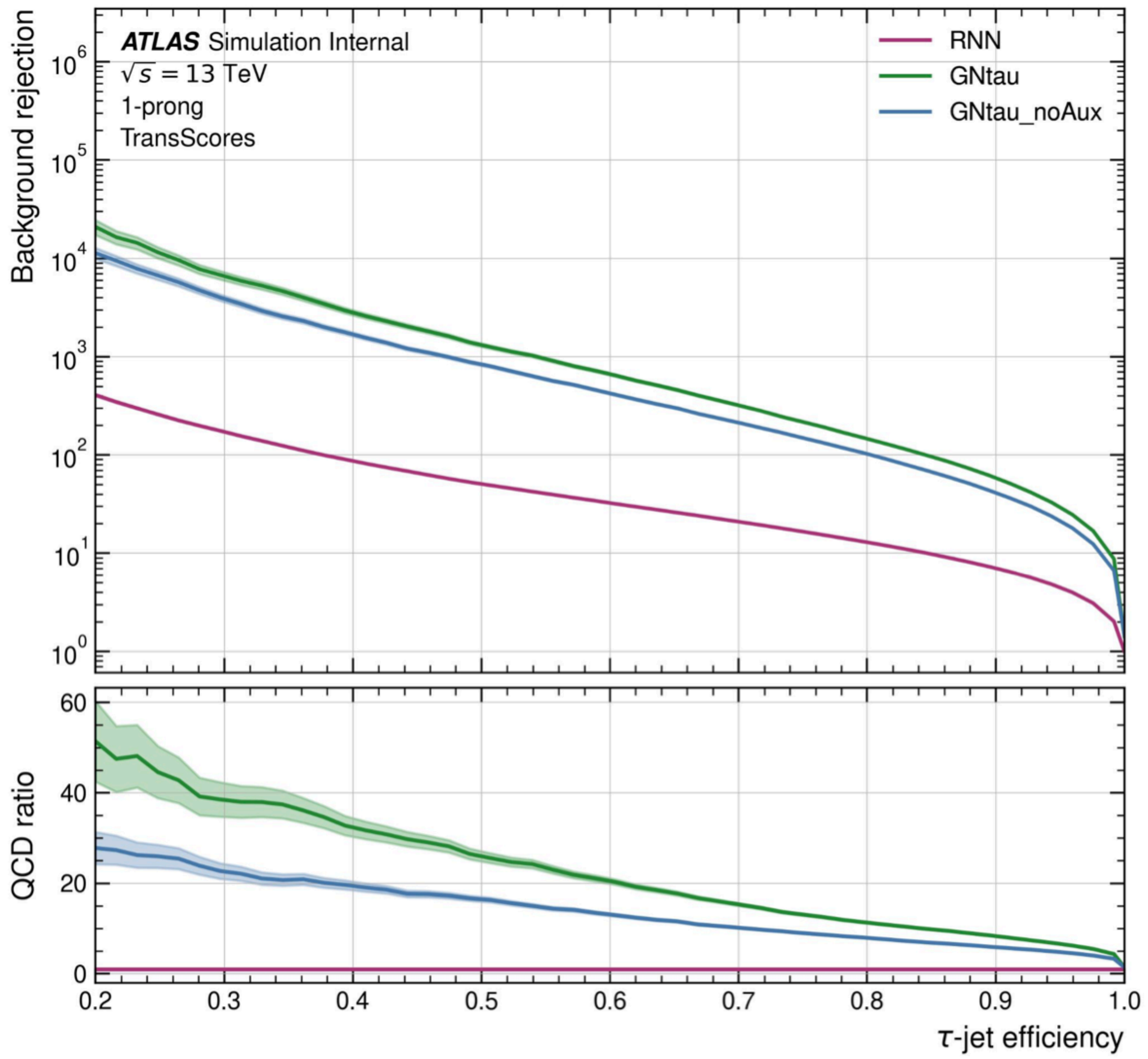
New Identification algorithms

New promising results for b-jets and tau ID

GN1 already implemented in 2023 Di-b trigger



GNtau is still under study

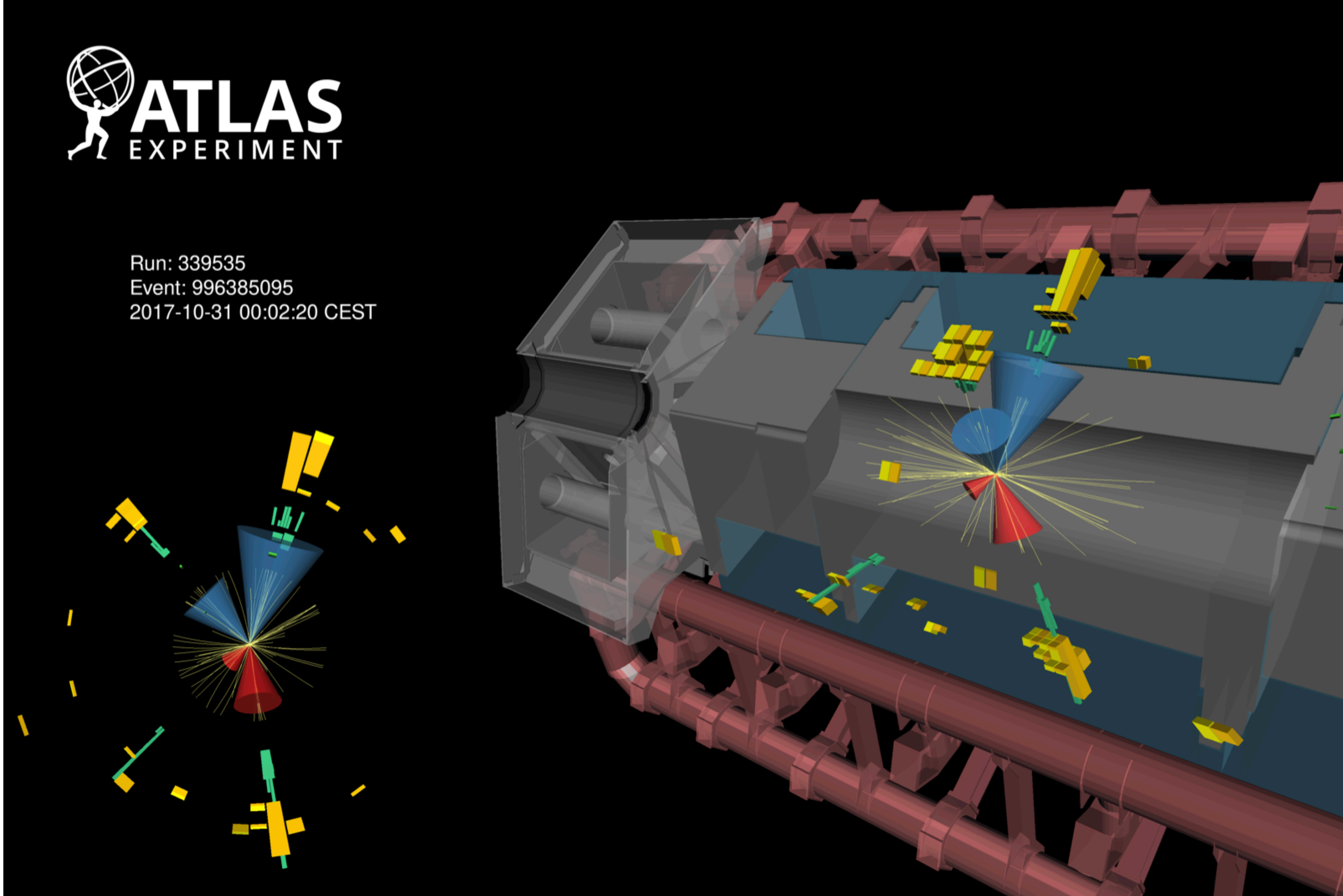


Conclusions

- We see an overview of a complex particle physics analysis as a HH research could be;
- For the Run3 it has been obtained a 60% improvement on the absolute efficiency for the first years of Run 3 (~30% with Off cuts);
- New b-jets ID and Tau ID algorithms will improve the background selections!
- Ongoing studies to further improvements also for the next years, stay tuned!!

Thank you!

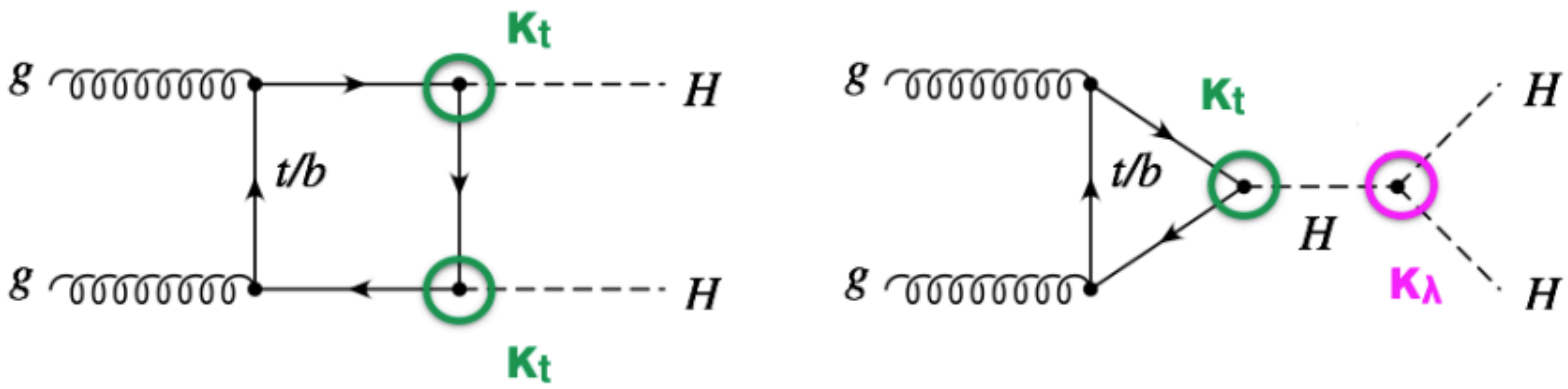
$HH \rightarrow b\bar{b}\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ candidate event



Amplitude of ggF->HH

$$\kappa_\lambda \equiv \frac{\lambda_{hhh}}{\lambda_{hhh}^{SM}}$$

The available production channels at 13 TeV:



Amplitude:

$$A(\kappa_t, \kappa_\lambda) = \kappa_t^2 A_1 + \kappa_t \kappa_\lambda A_2$$

Cross section:

$$\sigma(\kappa_t, \kappa_\lambda) \approx |A(\kappa_t, \kappa_\lambda)|^2 = |\kappa_t^2 A_1 + \kappa_t \kappa_\lambda A_2|^2 = \kappa_t^2 \kappa_\lambda^2 |A_2|^2 + \kappa_t^3 \kappa_\lambda |A_1 A_2 + A_2 A_1| + \kappa_t^4 |A_1|^2 =$$
$$\kappa_t^4 [(\kappa_\lambda/\kappa_t)^2 |A_2|^2 + (\kappa_\lambda/\kappa_t) |A_1 A_2 + A_2 A_1| + |A_1|^2]$$

Triggers and Event Preselection requirements

$\tau_{\text{had}}\tau_{\text{had}}$ category		$\tau_{\text{lep}}\tau_{\text{had}}$ categories	
STT	DTT	SLT	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	

MC generators for signal and background

Process	ME generator	ME PDF	PS and hadronisation	UE model tune	Cross-section order
Signal					
non-resonant $gg \to HH$ (ggF)	Powheg-Box v2	PDF4LHC15 NLO	Pythia 8.244	A14	NNLO FTApprox
non-resonant $qq \to qqHH$ (VBF)	MadGraph5_aMC@NLO v2.7.3	NNPDF3.0NLO	Pythia 8.244	A14	N3LO(QCD)
resonant $gg \to X \to HH$	MadGraph5_aMC@NLO v2.6.1	NNPDF2.3LO	Herwig v7.1.3	H7.1-Default	–
Top-quark					
$t\bar{t}$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NNLO+NNLL
t-channel	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NLO
s-channel	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NLO
Wt	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NLO
$t\bar{t}Z$	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO[(‡)]
$t\bar{t}W$	Sherpa 2.2.8	NNPDF3.0NNLO	Sherpa 2.2.8	Default	NLO[(‡)]
Vector boson + jets					
W+jets	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Z+jets	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NNLO
Diboson					
WW	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO[(‡)]
WZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO[(‡)]
ZZ	Sherpa 2.2.1	NNPDF3.0NNLO	Sherpa 2.2.1	Default	NLO[(‡)]
Single Higgs boson					
ggF	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	N3LO(QCD)+NLO(EW)
VBF	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \to WH$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NNLO(QCD)+NLO(EW)
$qq \to ZH$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NNLO(QCD)+NLO(EW)[(†)]
$gg \to ZH$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.212	AZNLO	NLO+NLL
$t\bar{t}H$	Powheg-Box v2	NNPDF3.0NLO	Pythia 8.230	A14	NLO

HH -> $b\bar{b}\tau^+\tau^-$ Run 2 MVA

Link to the analysis paper

Once obtained the SRs, and all scale factors are applied, a MultiVatiate Analysis (MVA) for signal extraction is taken using a Boosted Decision Tree (BDT) for $\tau_{had}\tau_{had}$ channel, and a Neural Network for the $\tau_{had}\tau_{lep}$ channel.

During training the sum of all backgrounds normalized to their respective cross-sections is used.

It has been trained by the Toolkit for MVA based on ROOT.

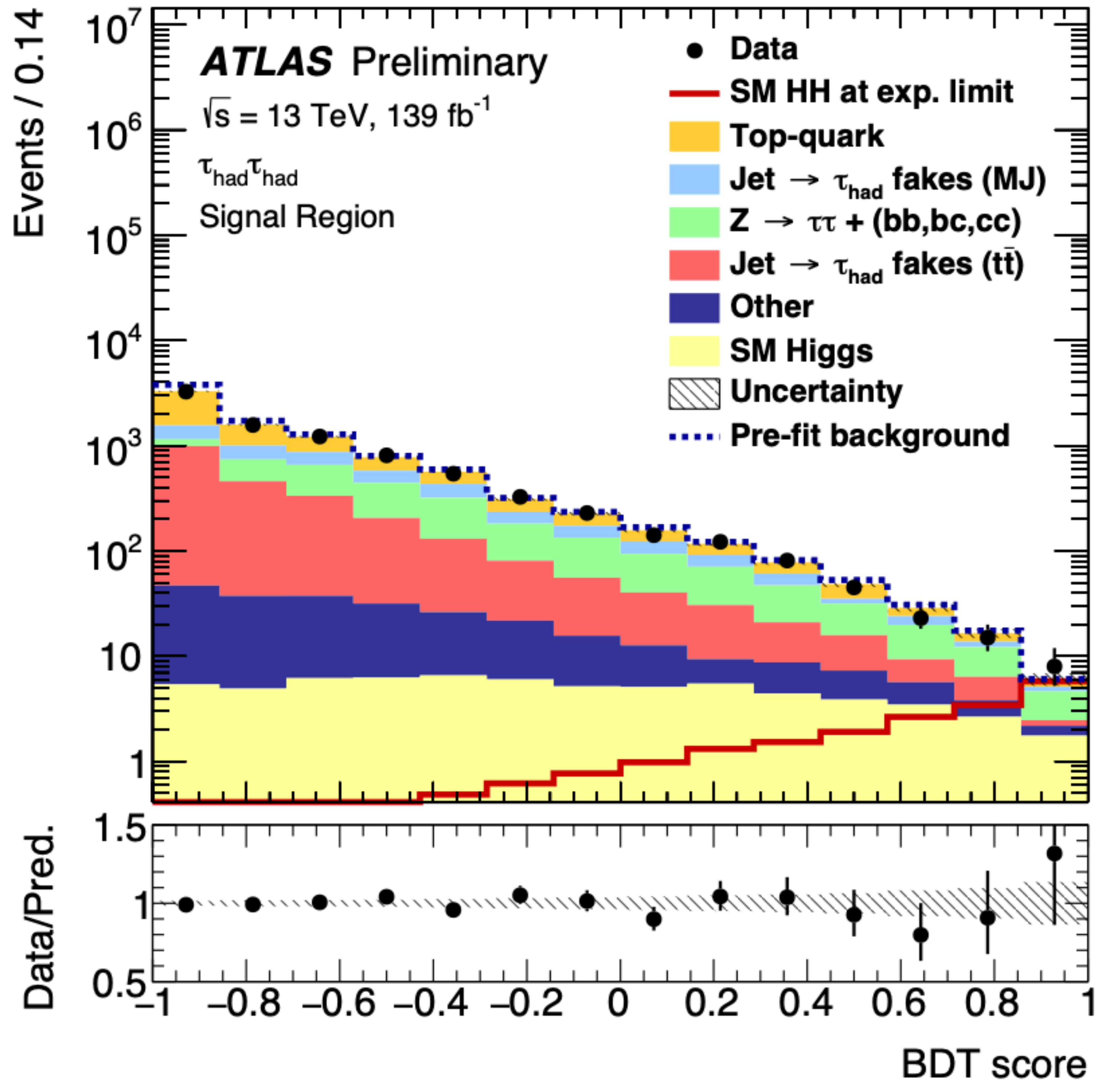
Variable	$\tau_{\text{had}}\tau_{\text{had}}$	$\tau_{\text{lep}}\tau_{\text{had}}$ SLT	$\tau_{\text{lep}}\tau_{\text{had}}$ LTT
m_{HH}	✓	✓	✓
$m_{\tau\tau}^{\text{MMC}}$	✓	✓	✓
m_{bb}	✓	✓	✓
$\Delta R(\tau,\tau)$	✓	✓	✓
$\Delta R(b,b)$	✓	✓	
$\Delta p_{\text{T}}(\ell,\tau)$		✓	✓
Sub-leading b-tagged jet p_{T}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

HH -> $b\bar{b}\tau^+\tau^-$ Run 2 MVA

Link to the analysis paper

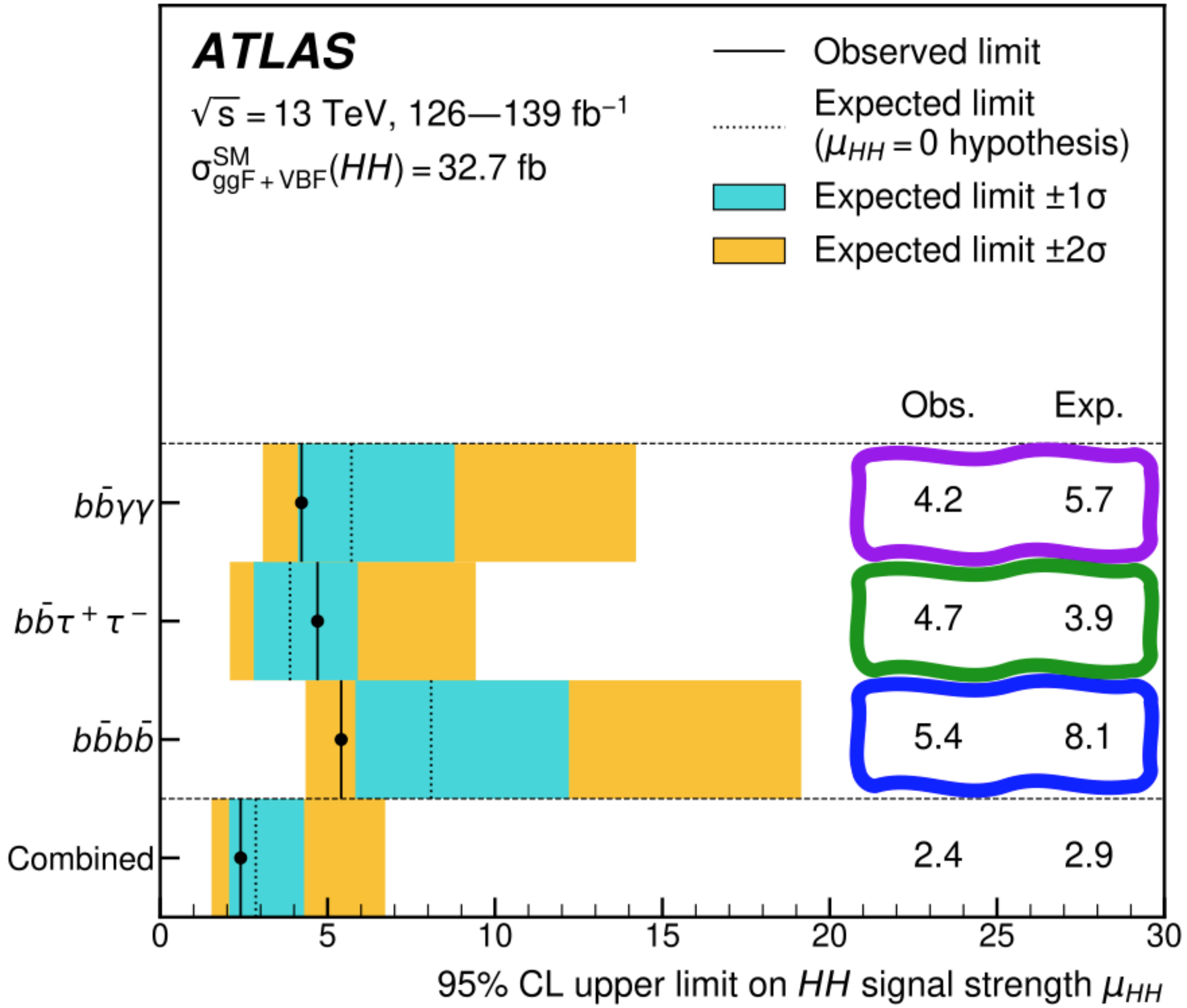
The HH signal yields are estimated from data using a simultaneous binned maximum-likelihood fit to the MVA output distributions.

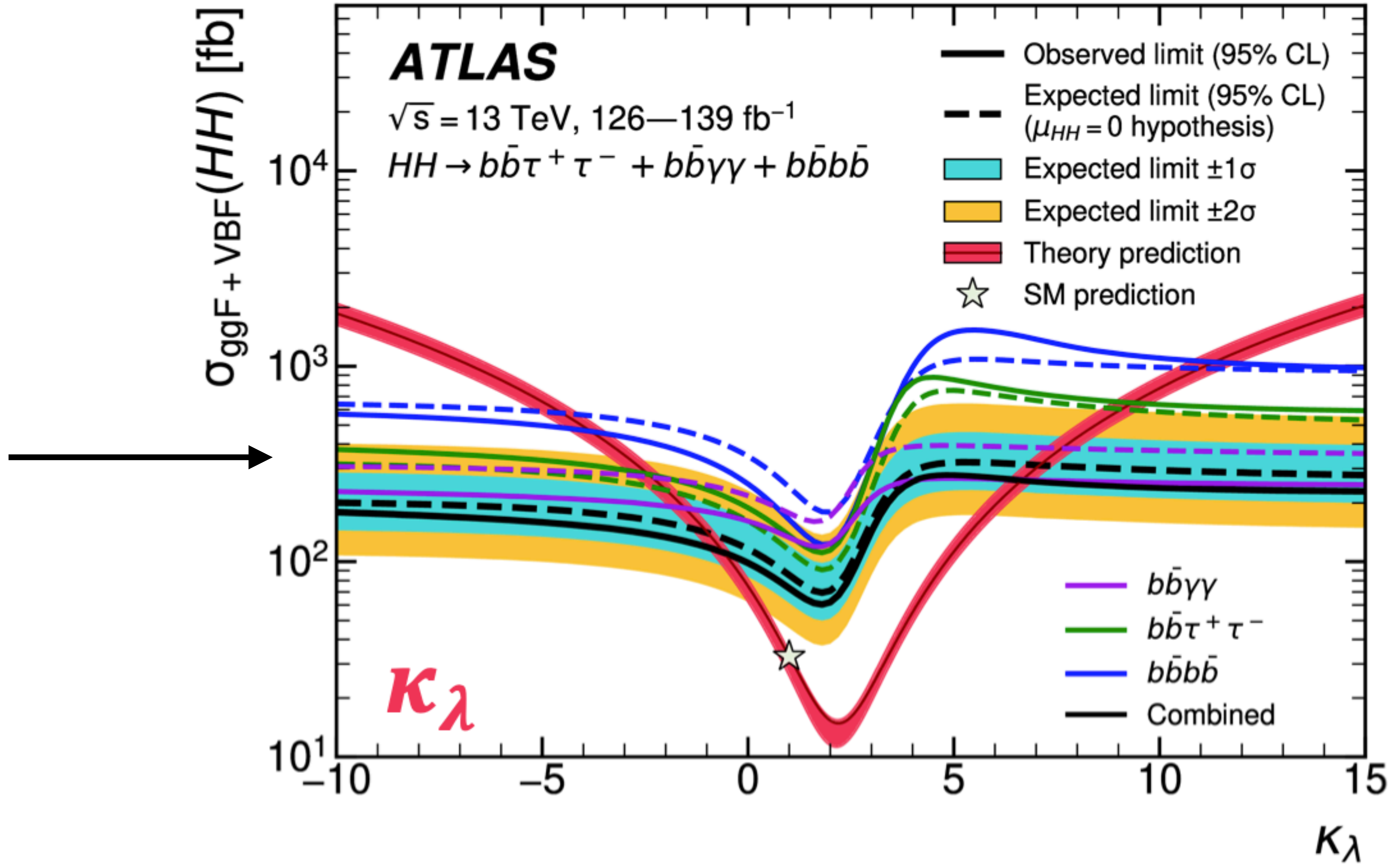
The background normalization of $t\bar{t}$ and Z+Heavy Flavour jets (HF) are free parameters, contained by the background-only bins of MVA and by the CR of the Z+HF.



Run 2 final results

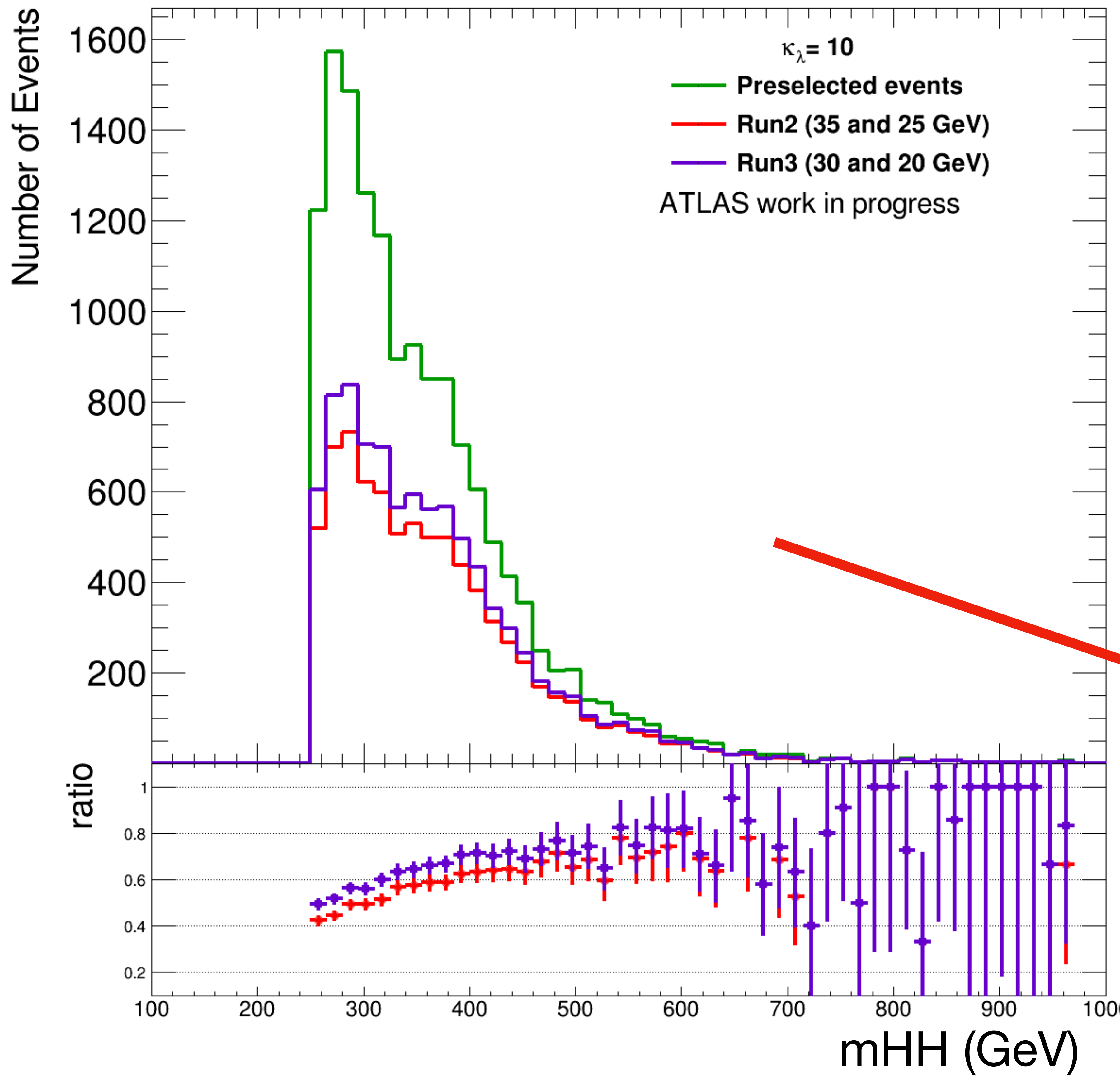
ATLAS final results, and their combination

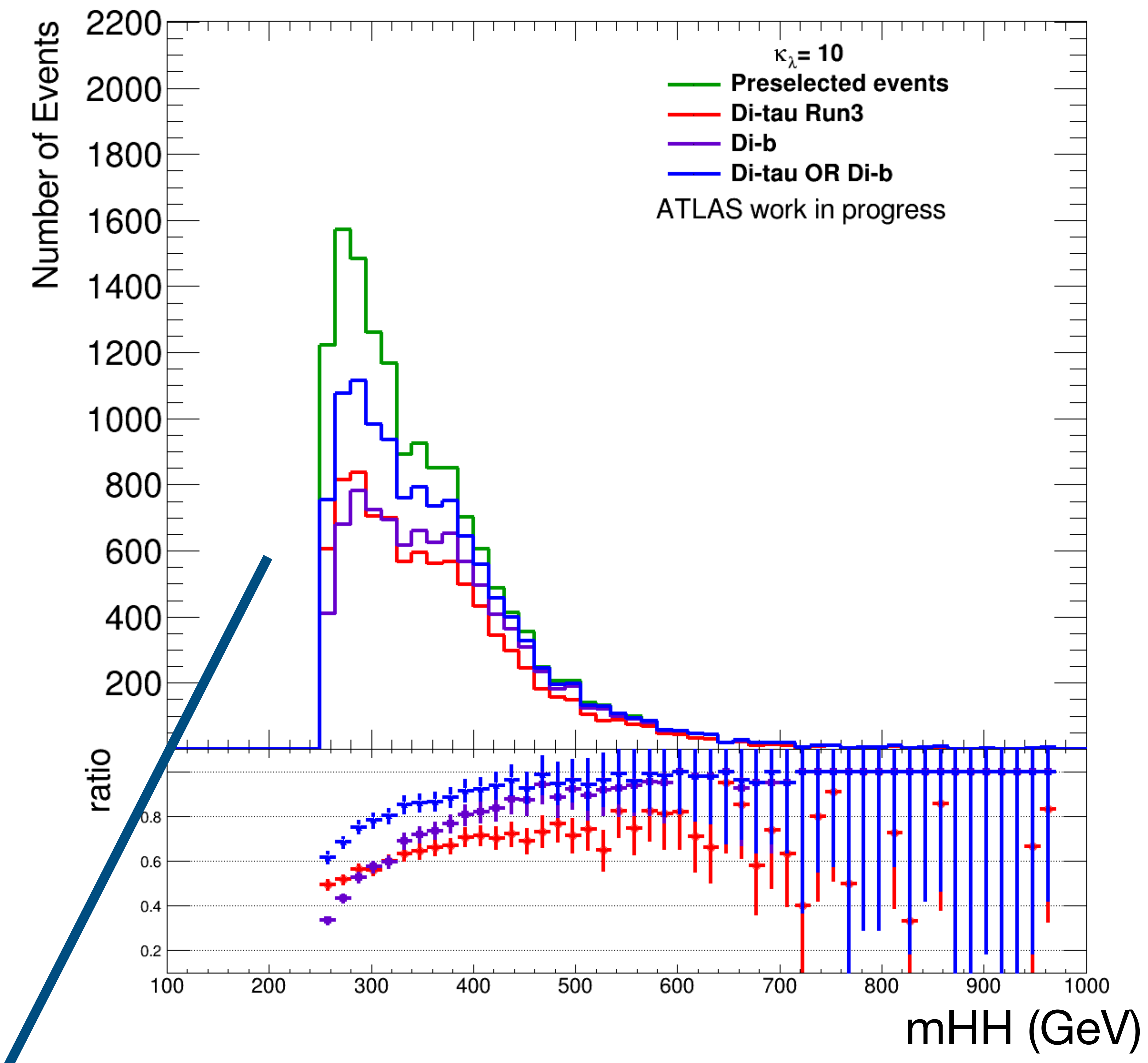




Di-tau and Di-b Triggers (kL=10)

- Lower pt thresholds triggers for Run3 [from (35,25) GeV to (30,20)GeV] (activated during 2023)
- Delayed Di-b trigger developed by HH->bbbb (activated during 2022)

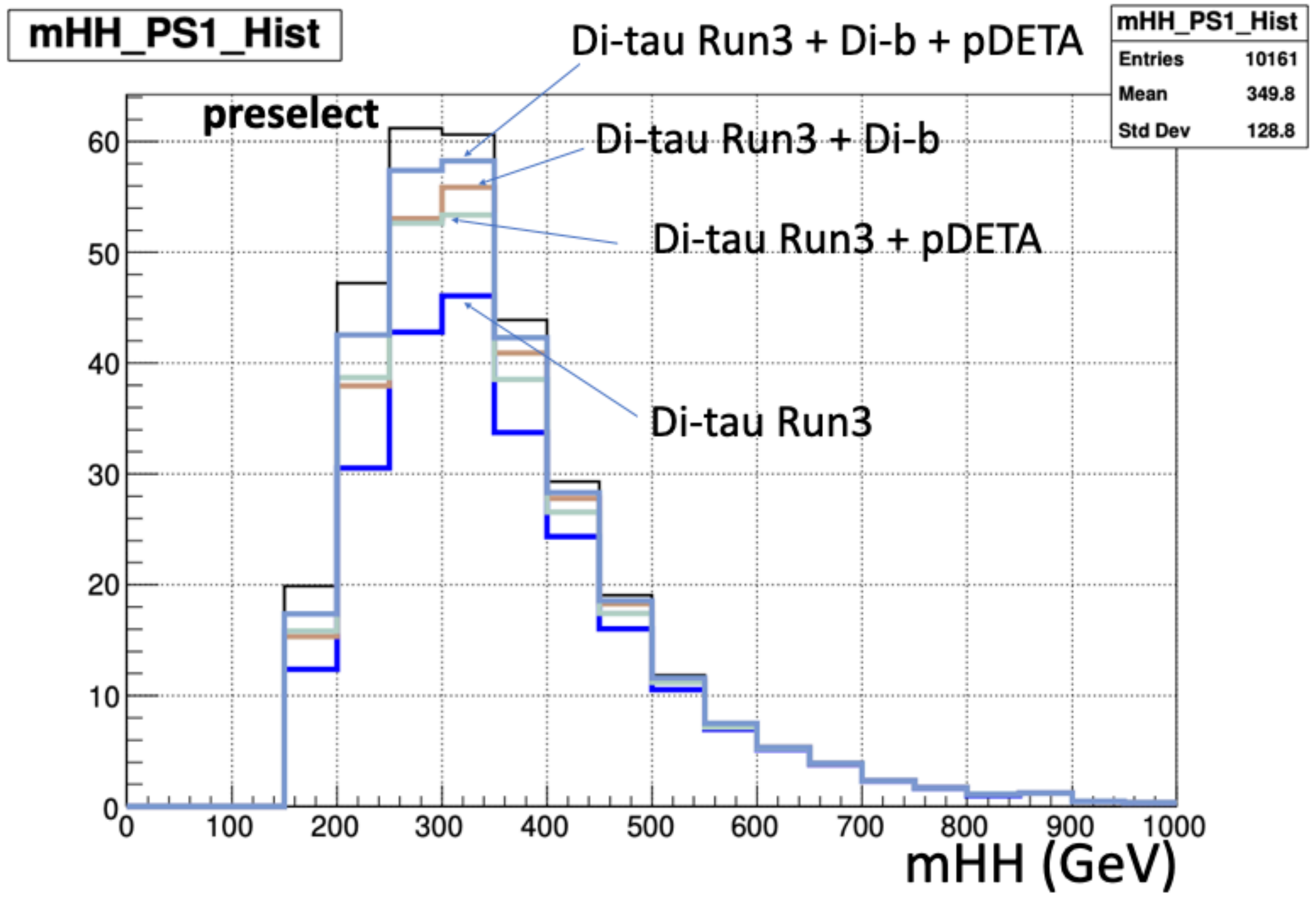


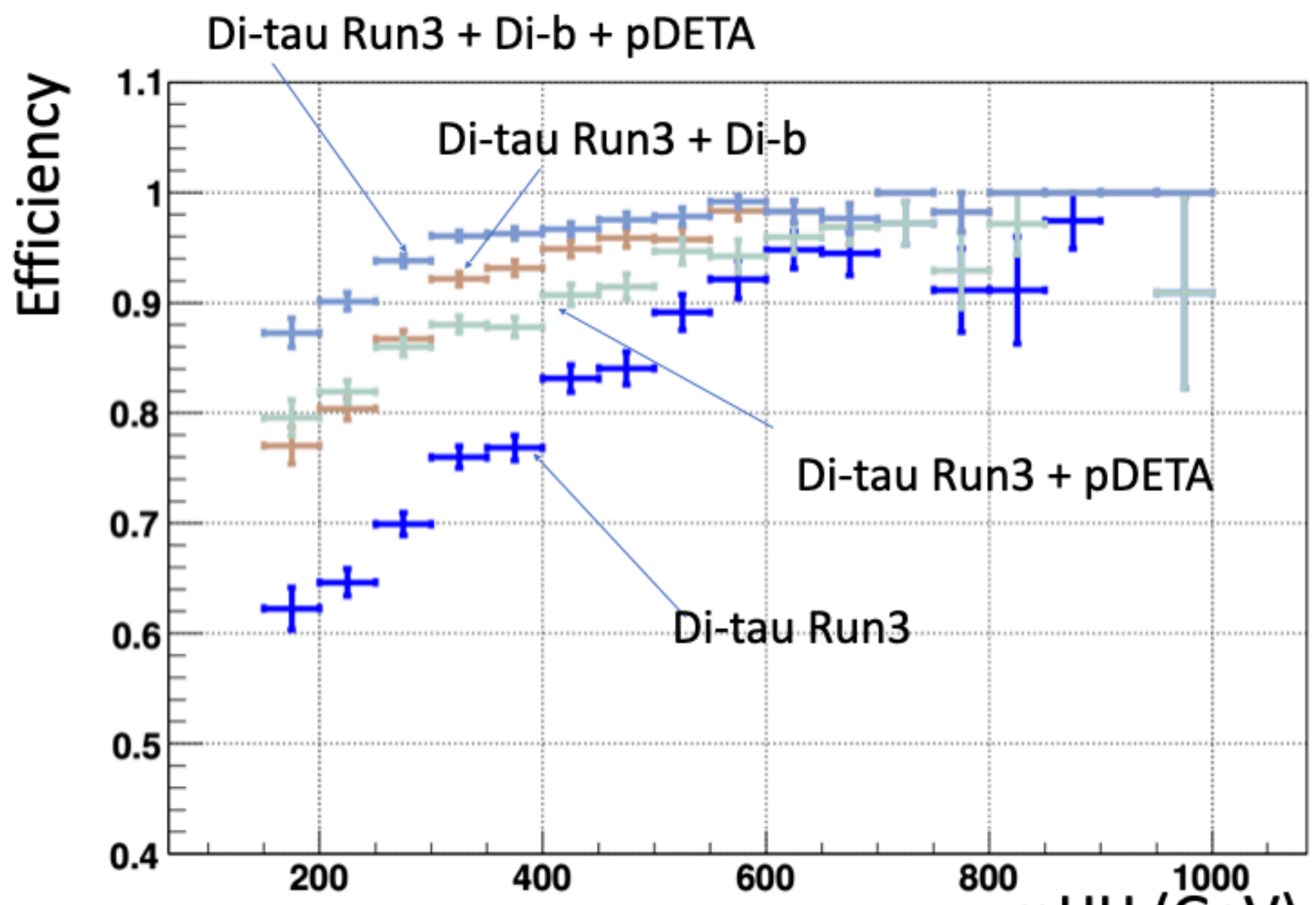


	ε kl=10	Gain	Gain w/out offline cuts
Di-tau Run2	0.55		
Di-tau Run3	0.62	13%	15%
Di-b	0.47		
Di-tau Run3 OR Di-b	0.76	38%	~65%

Di-tau Triggers (ongoing study)

- New di-tau trigger using another L1 (Labelled here as pDETA)



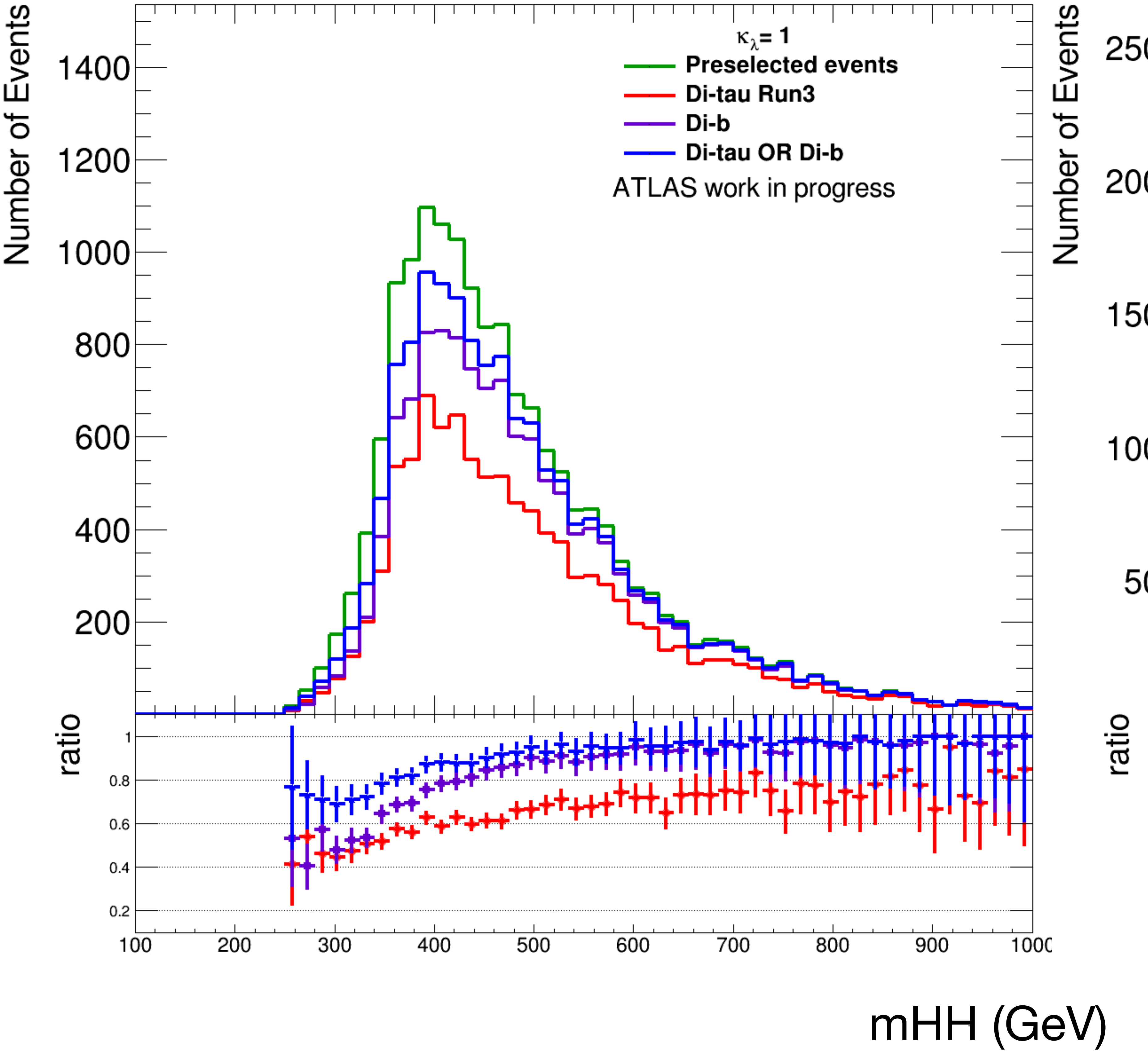


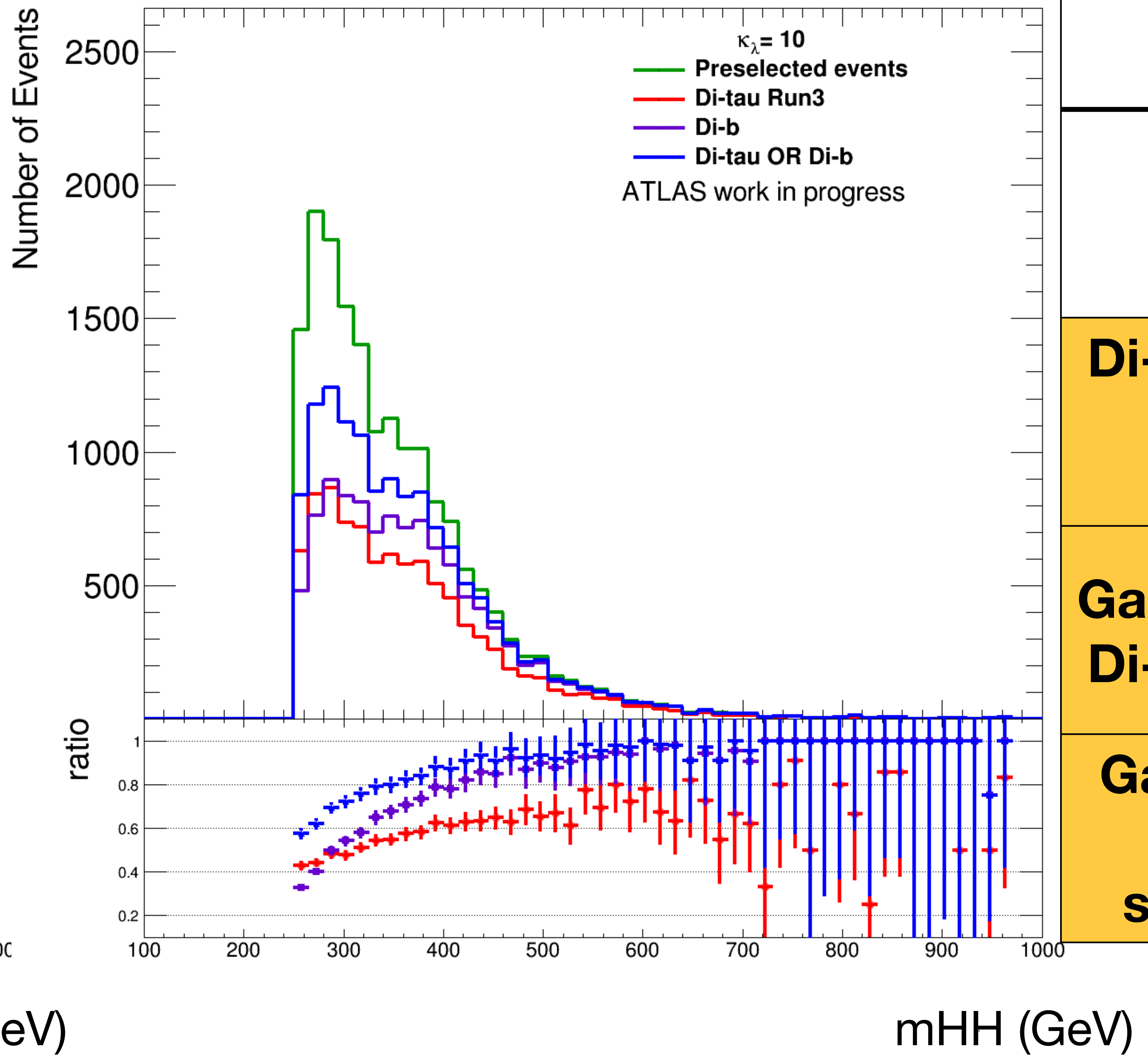
(Efficiency w.r.t. pre-selected events)

Kiran Farman and Song-Ming Wang

b+tau Triggers (ongoing study)

- The b+tau trigger has combinatorial advantage from the identification point of view;
- Very good tradeoff between efficiency on the signal and rate on data
- Included in 2024 Trigger Menu



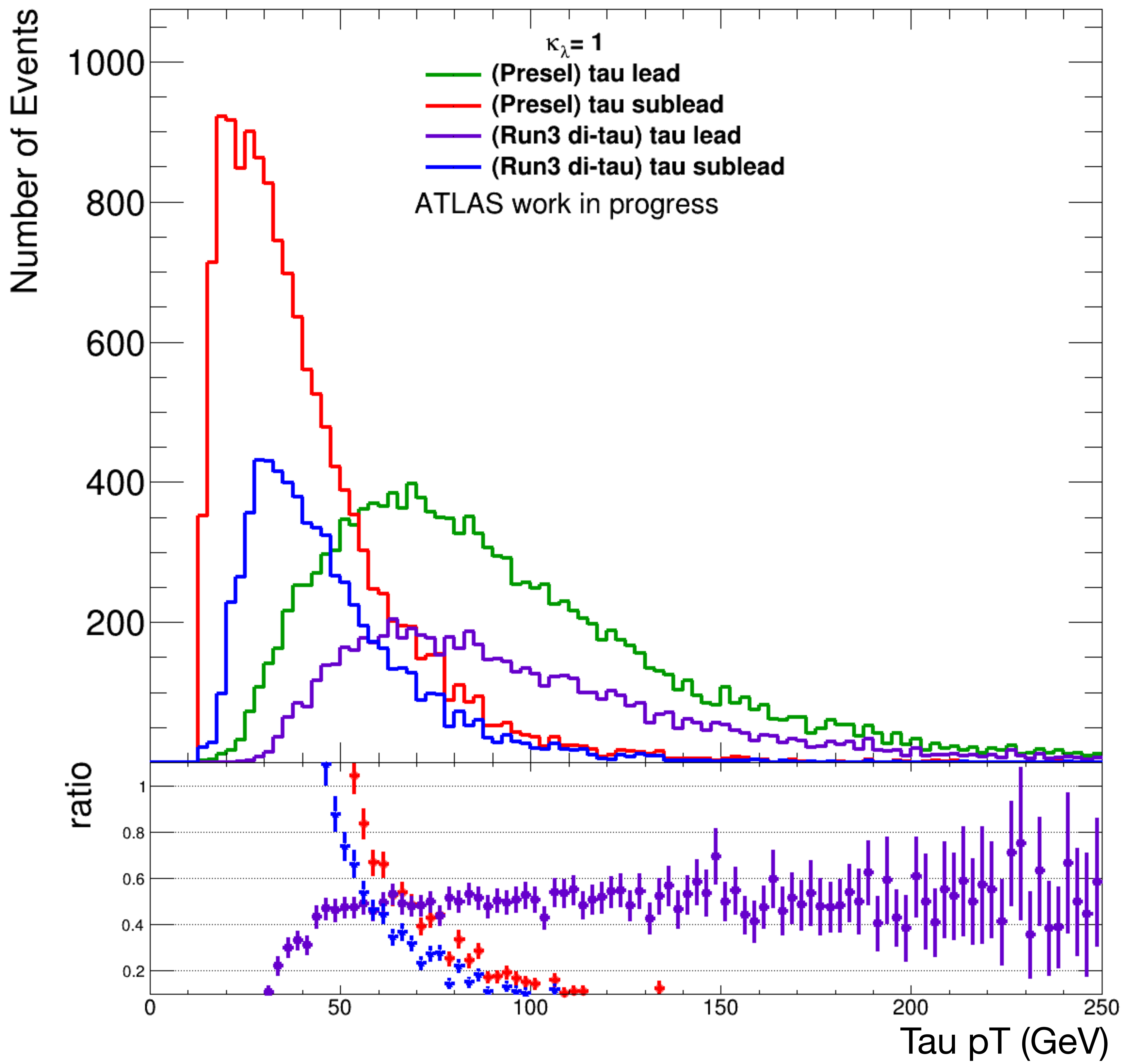


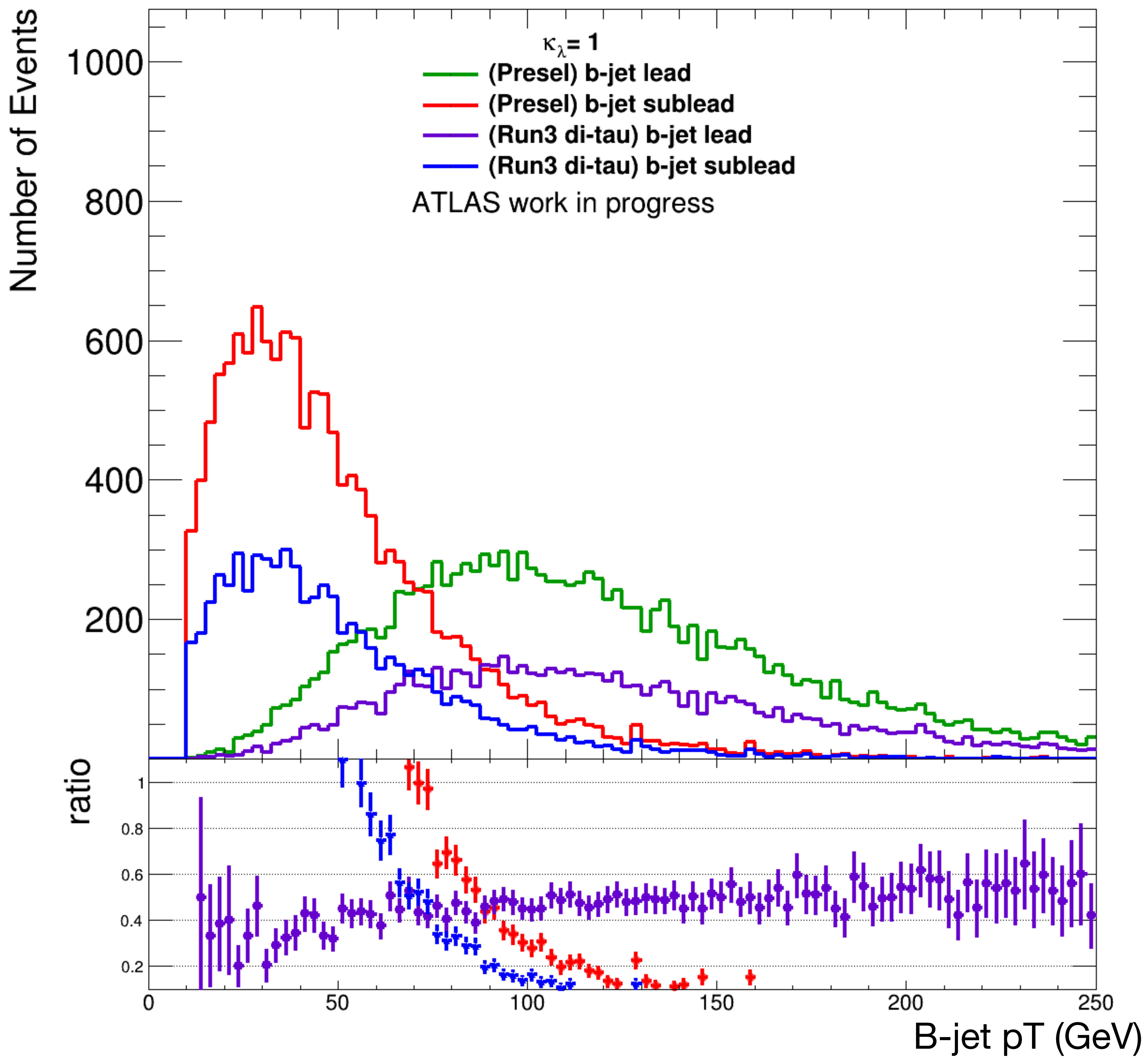
	ε kl=1	ε kl=10
b+tau	0.84	0.66
Di-tau Run3 OR b+tau	0.93	0.82
Gain respect Di-tau Run2	35%	49%
Gain w/out offline selection	~90%	~95%

b+tau Triggers

- The b+tau trigger has combinatorial advantage from the identification point of view;
- Very good tradeoff between efficiency on the signal and rate on data

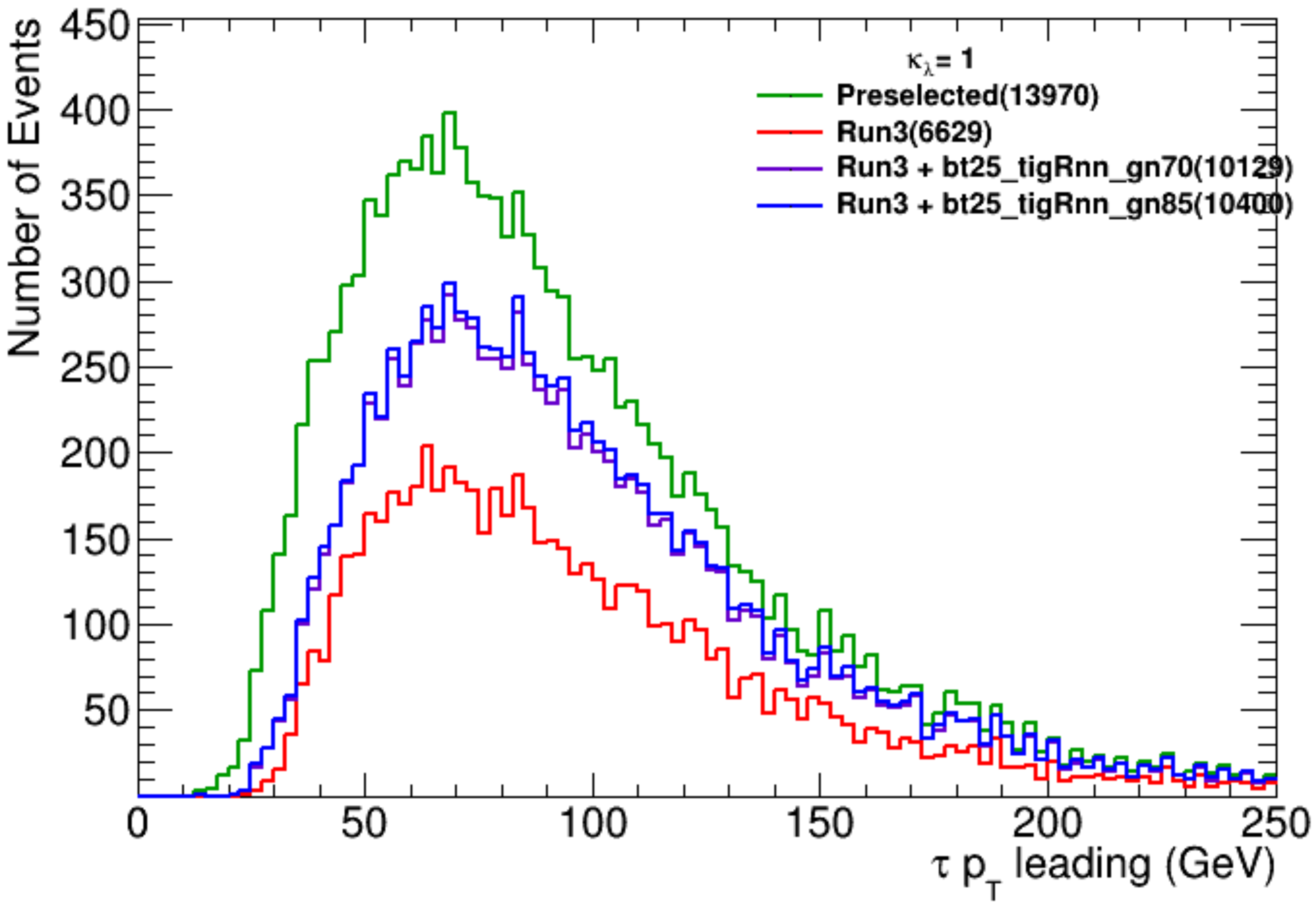
Kinematics of Di-tau Triggers

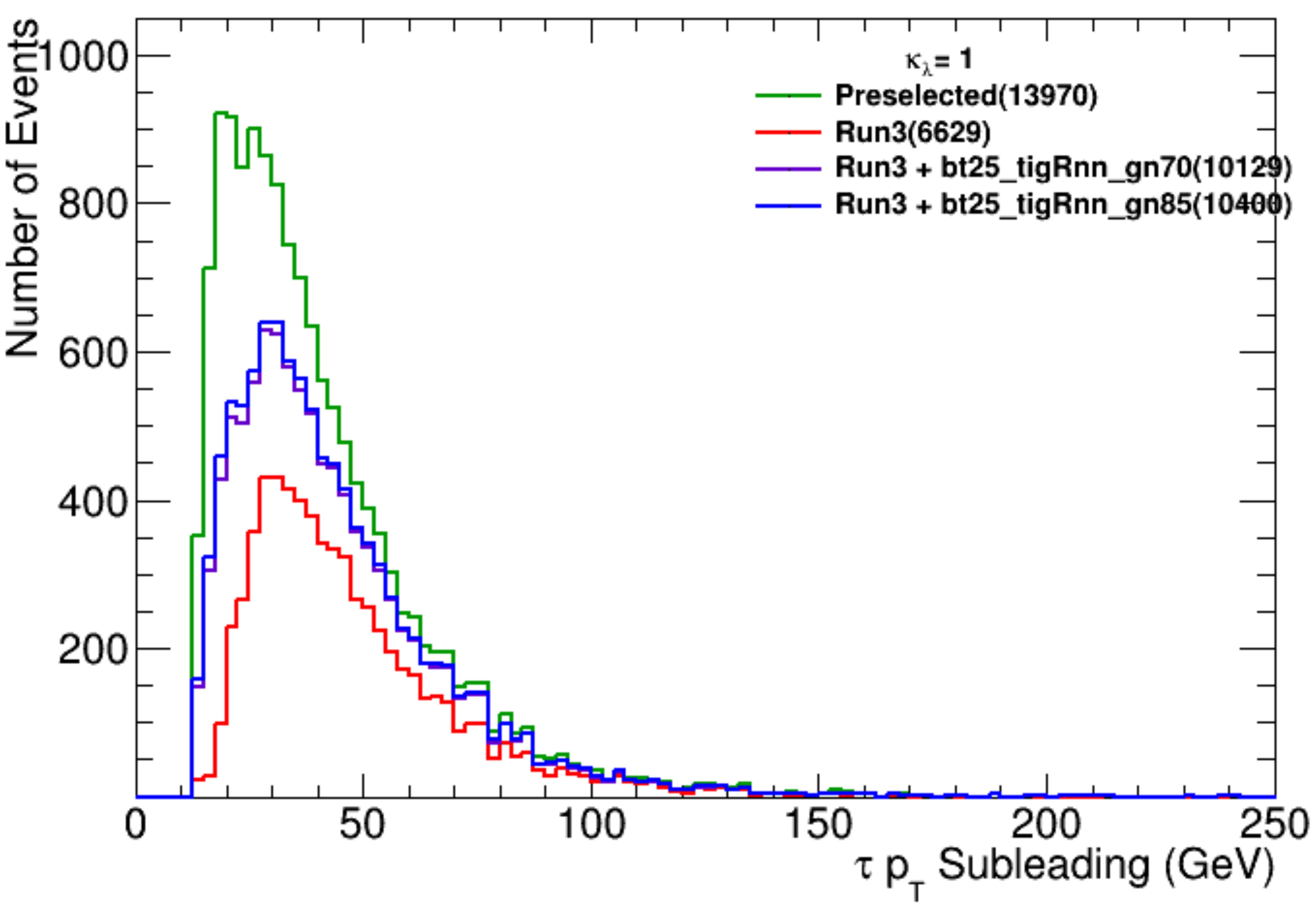




Why b+* gives so much improvements?

- It comes from low-pt tau, mostly subleasing, which are not triggered, probably because of ID.





Overlap between Di-b and b+tau

- b+tau and di-b are orthogonal from the rate point of view, because of the Tau ID.