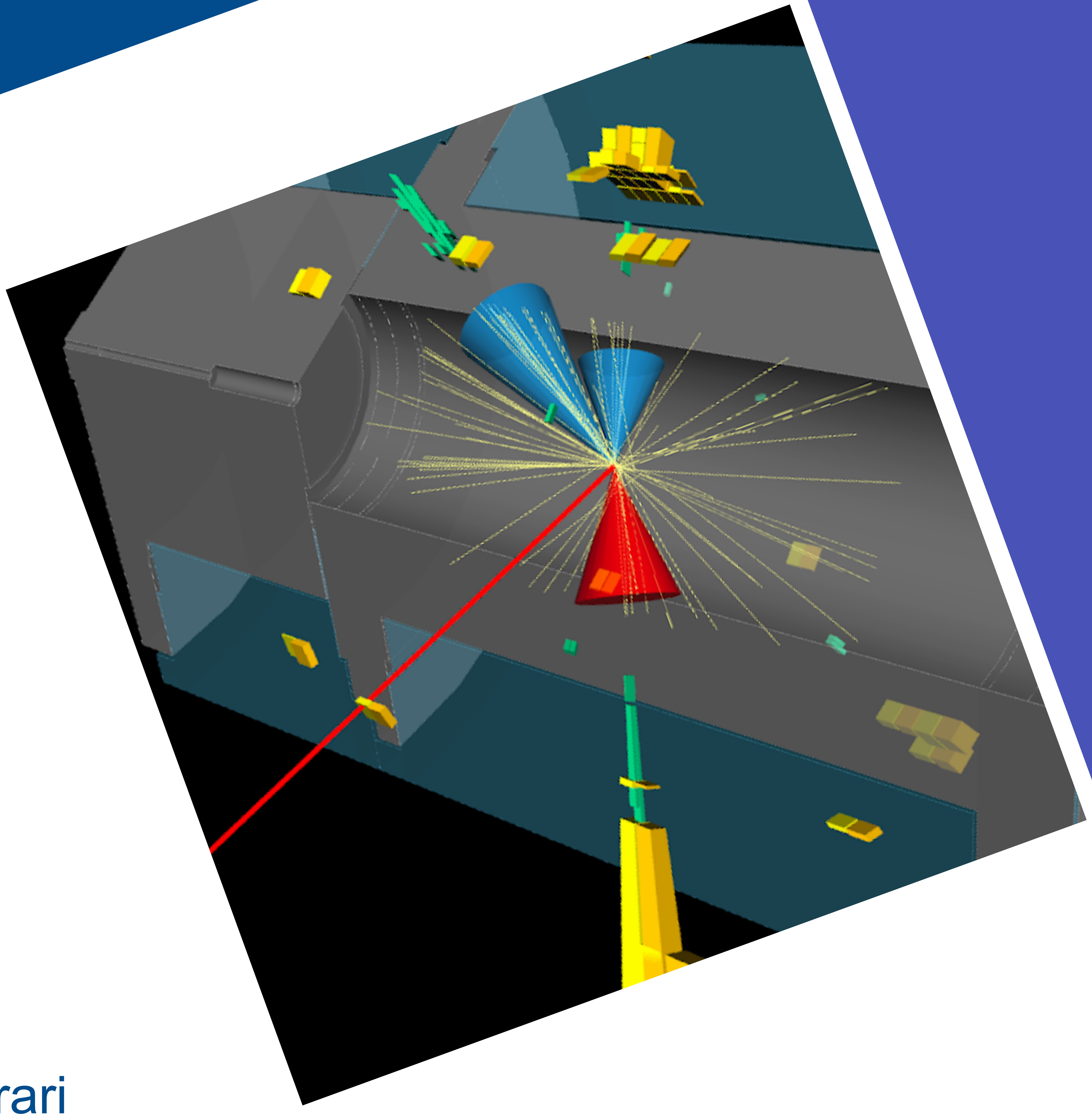
Probing the Higgs Sector: $H(bb)H(\tau\tau)$ At ATLAS

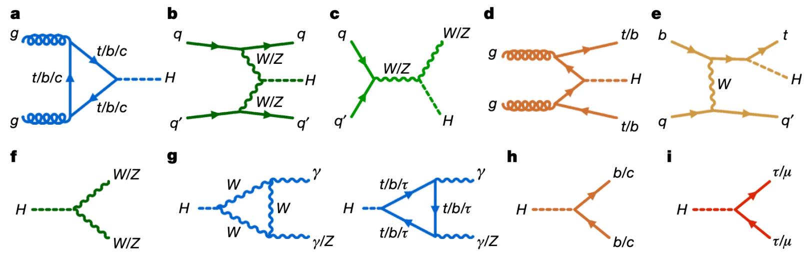


Osama Karkout

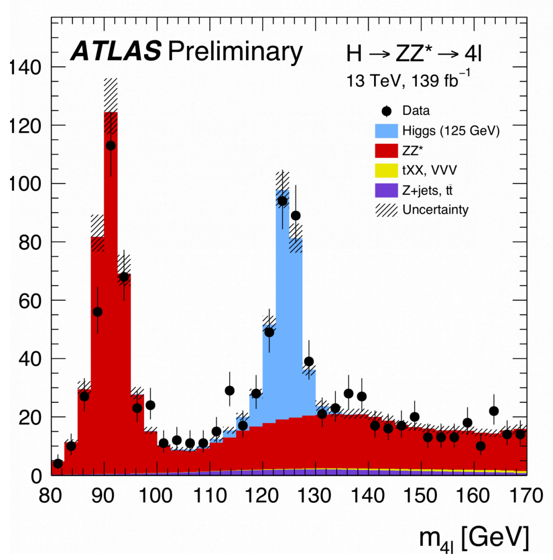
Supervised by Tristan du Pree and Pamela Ferrari

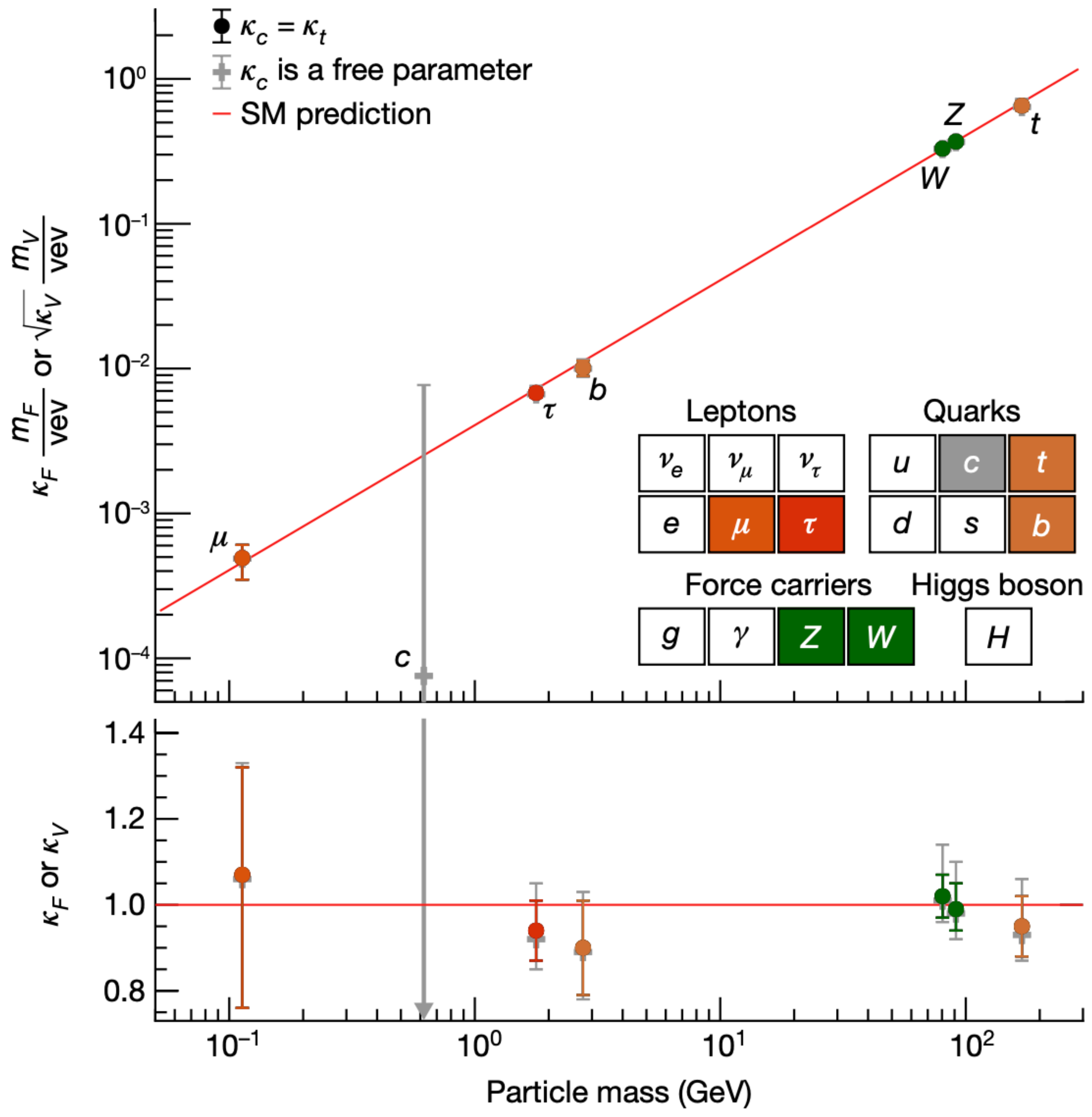
The experimentalist mug

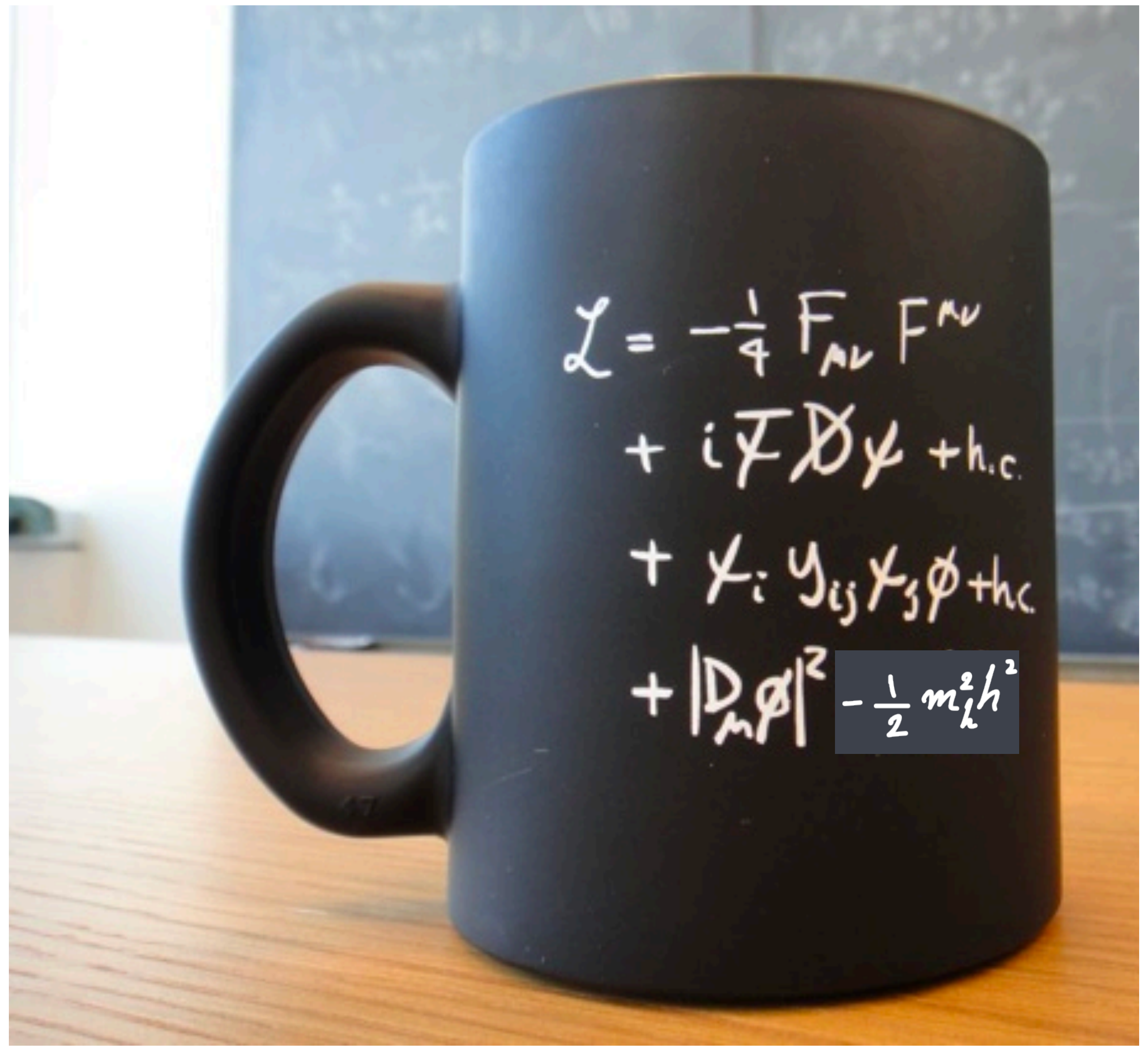
We discovered the Higgs boson, and studied its properties…
Gathered enough information to fill this experimentalist mug



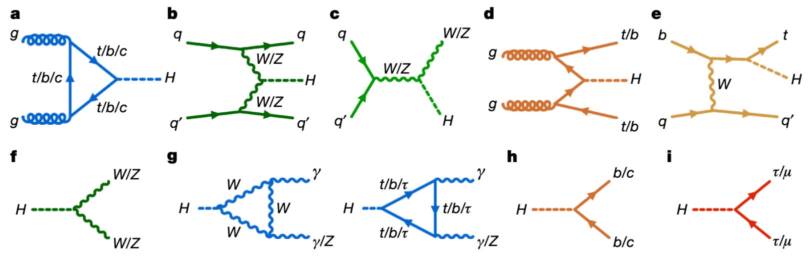
scalar
m=125 GeV



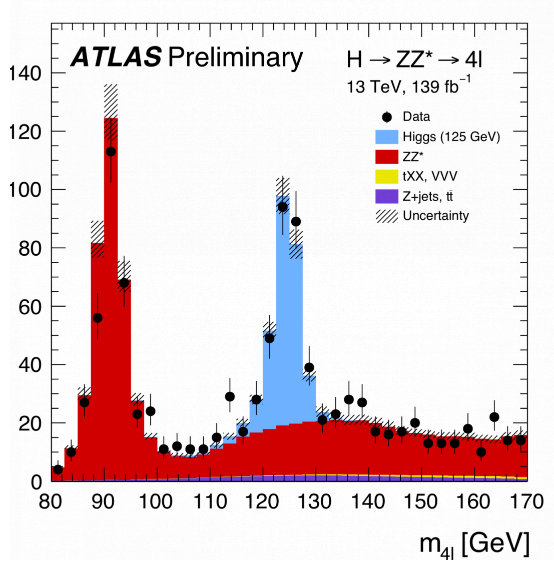


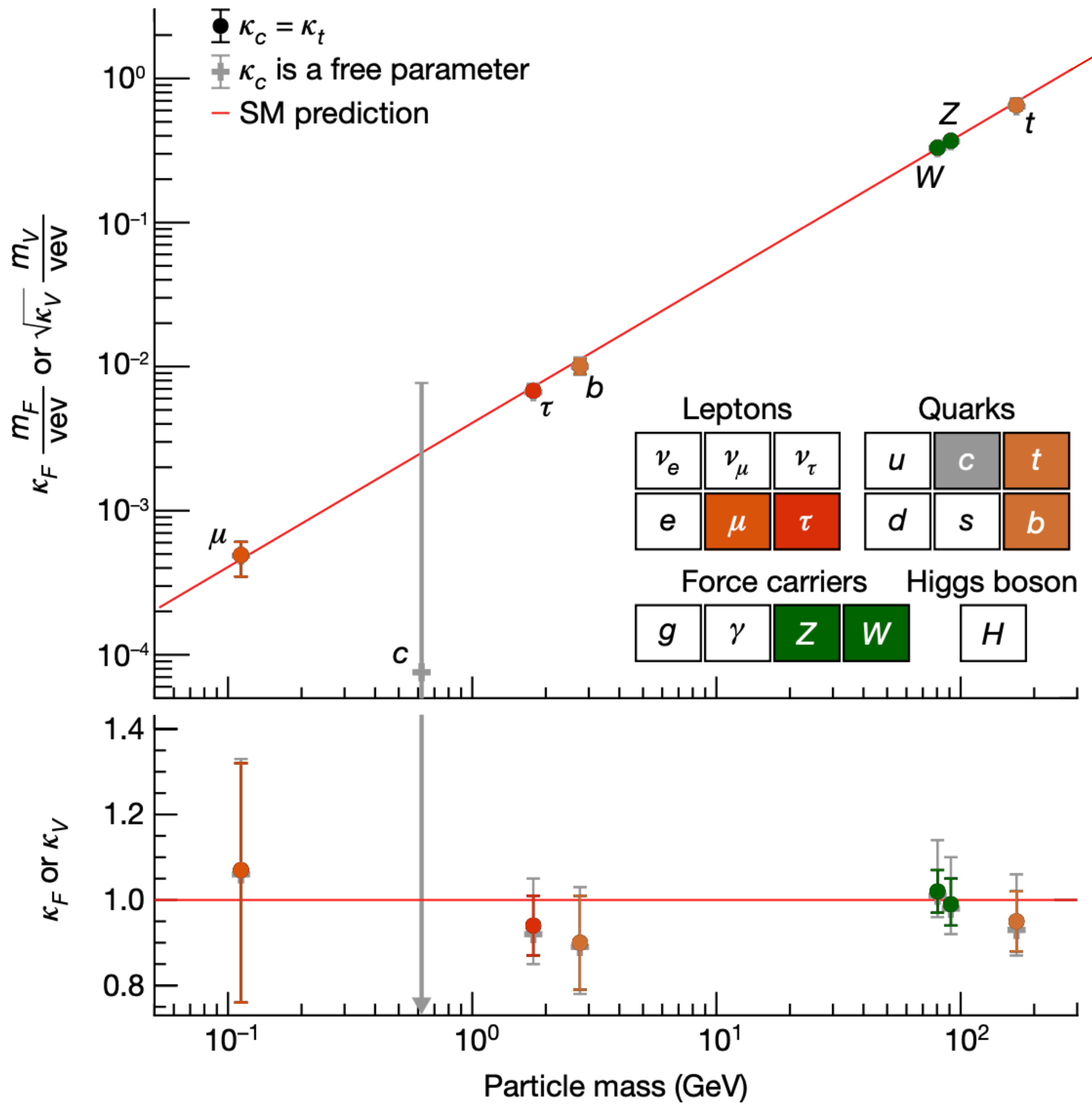


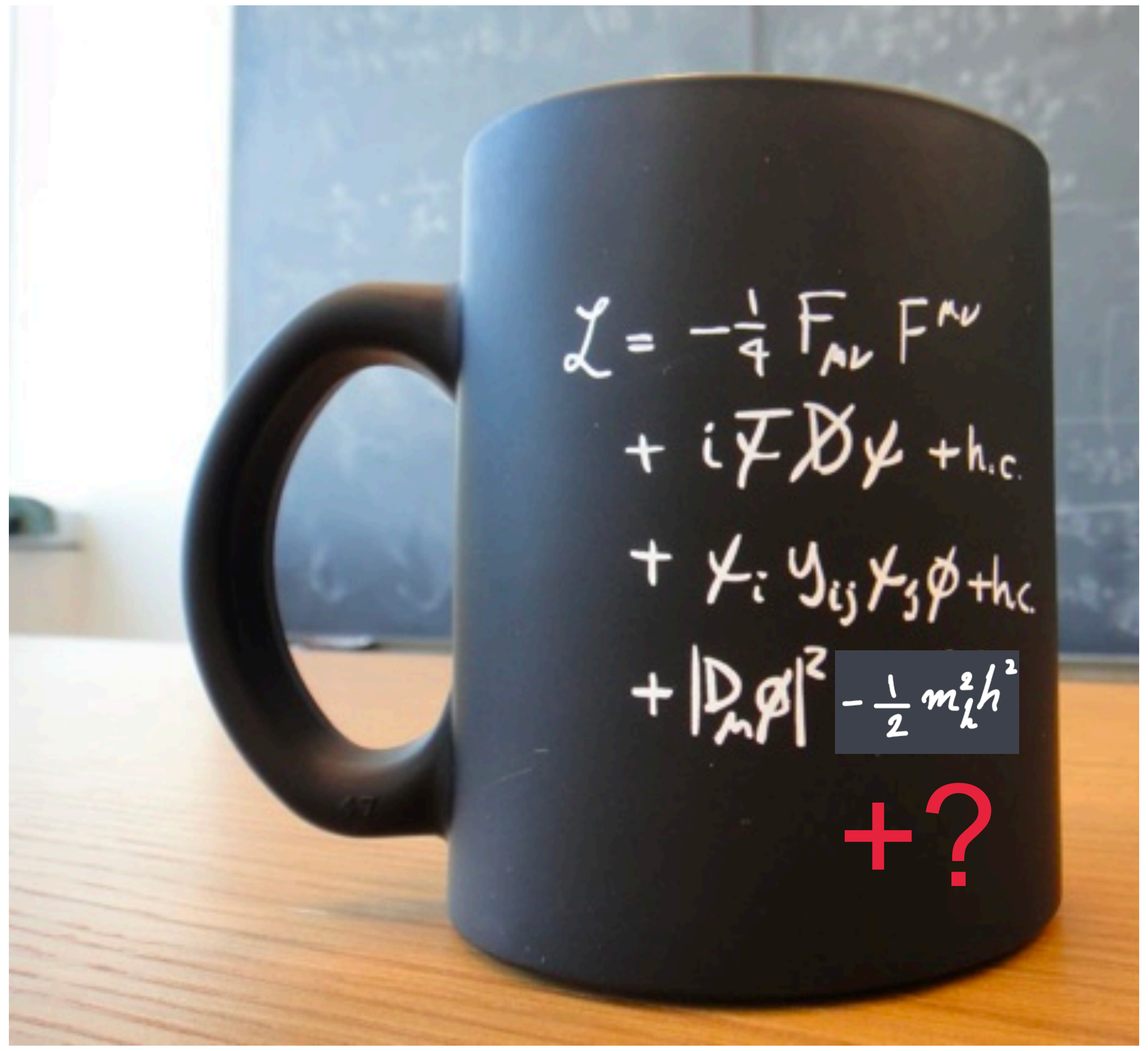
The experimentalist mug



scalar
m=125 GeV

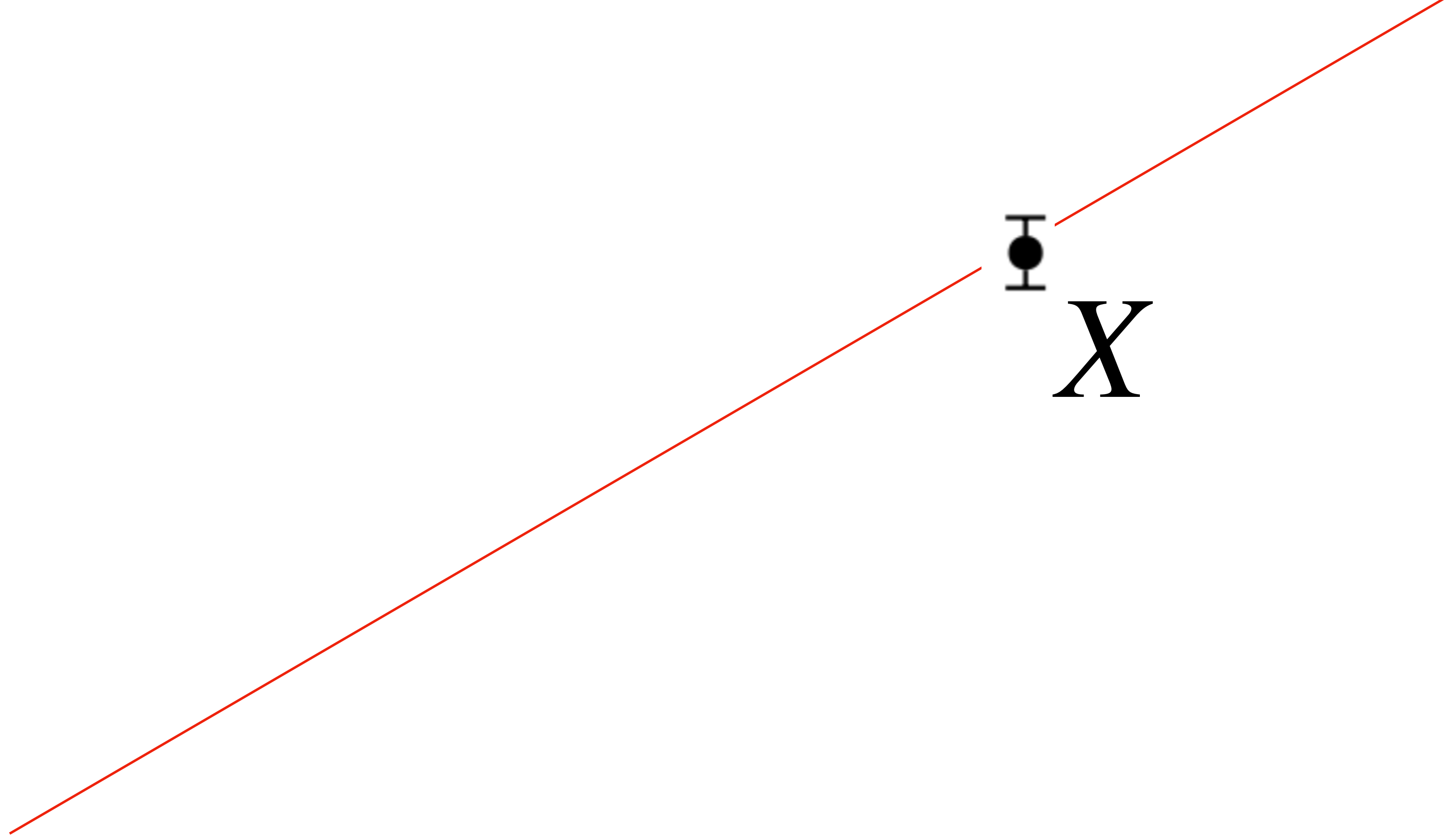






The Higgs can give mass to particles still not found

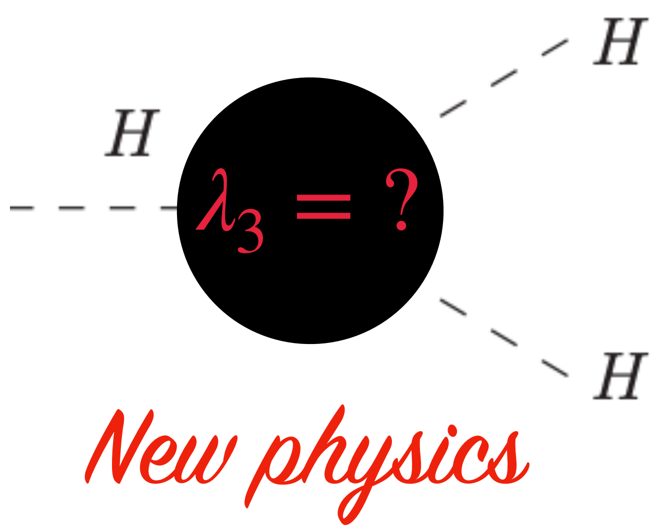
The Higgs sector

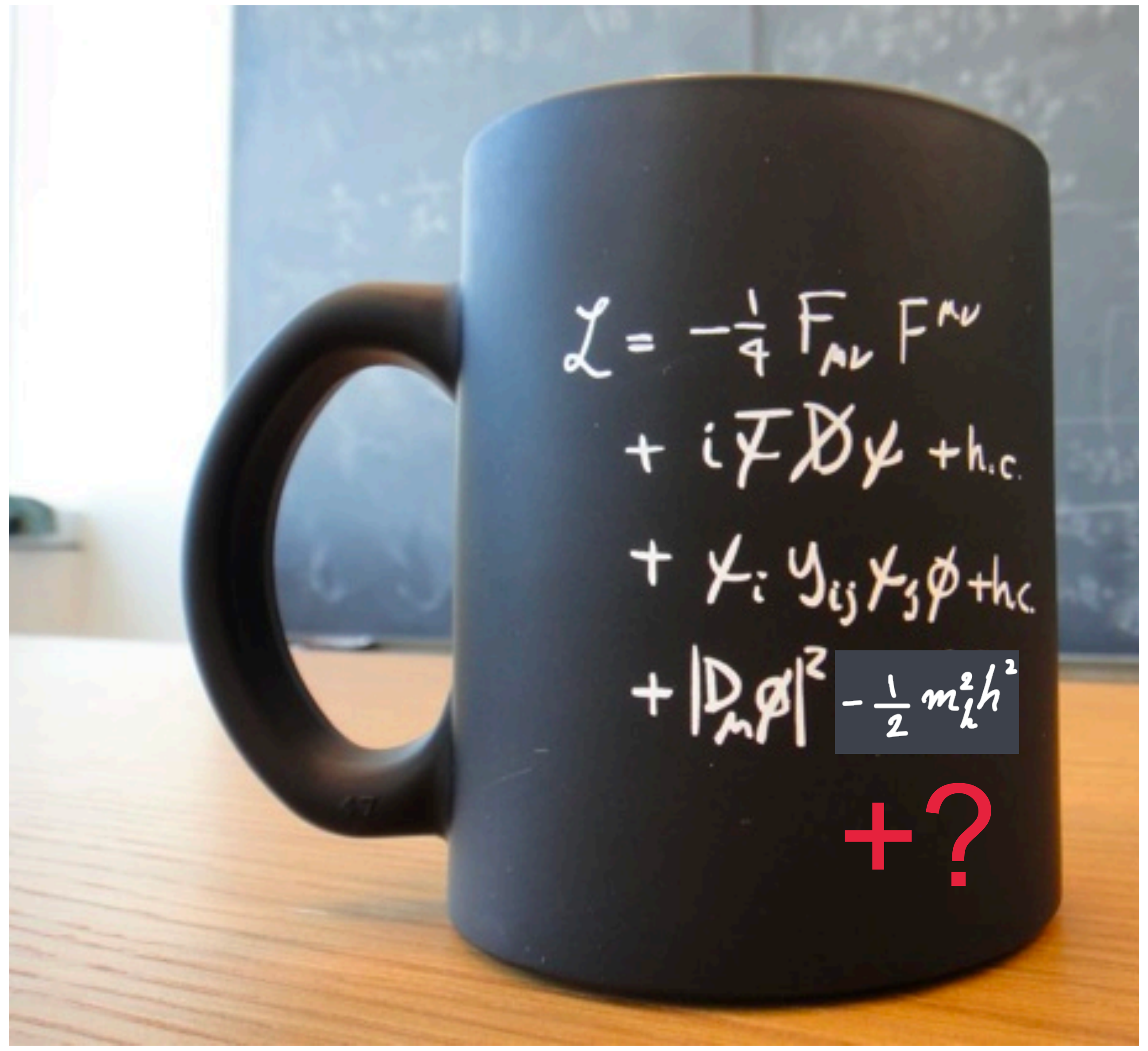


$$\mathscr{L}_{Nature} \in -\frac{1}{2}m_h^2h^2 - \frac{1}{2}X^2h^2 - \frac{1}{2}m_X^2X^2 + \ldots$$

We cannot create X but we can probe its effect on the Higgs field

$$\mathscr{L}_{EFT} \in -\frac{1}{2}m_h^2h^2 - \lambda_3 v h^3 + \ldots$$

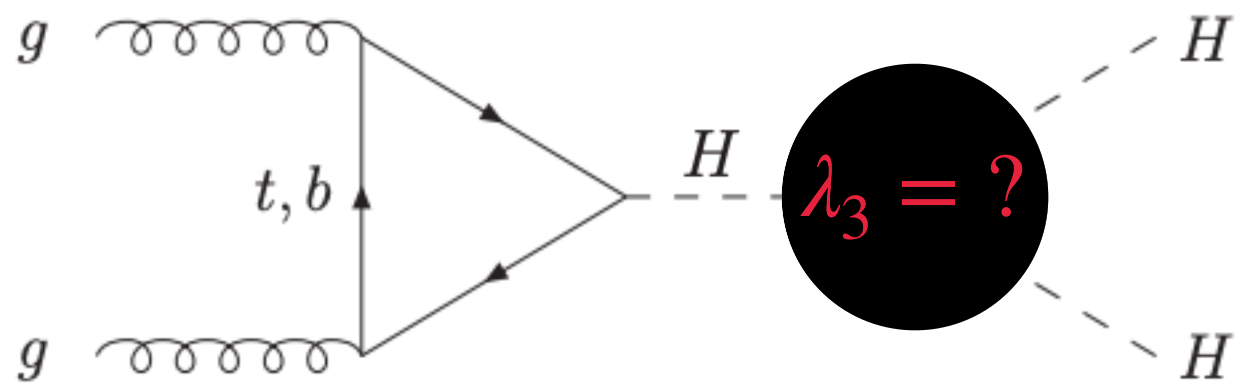




HH production at LHC

proton

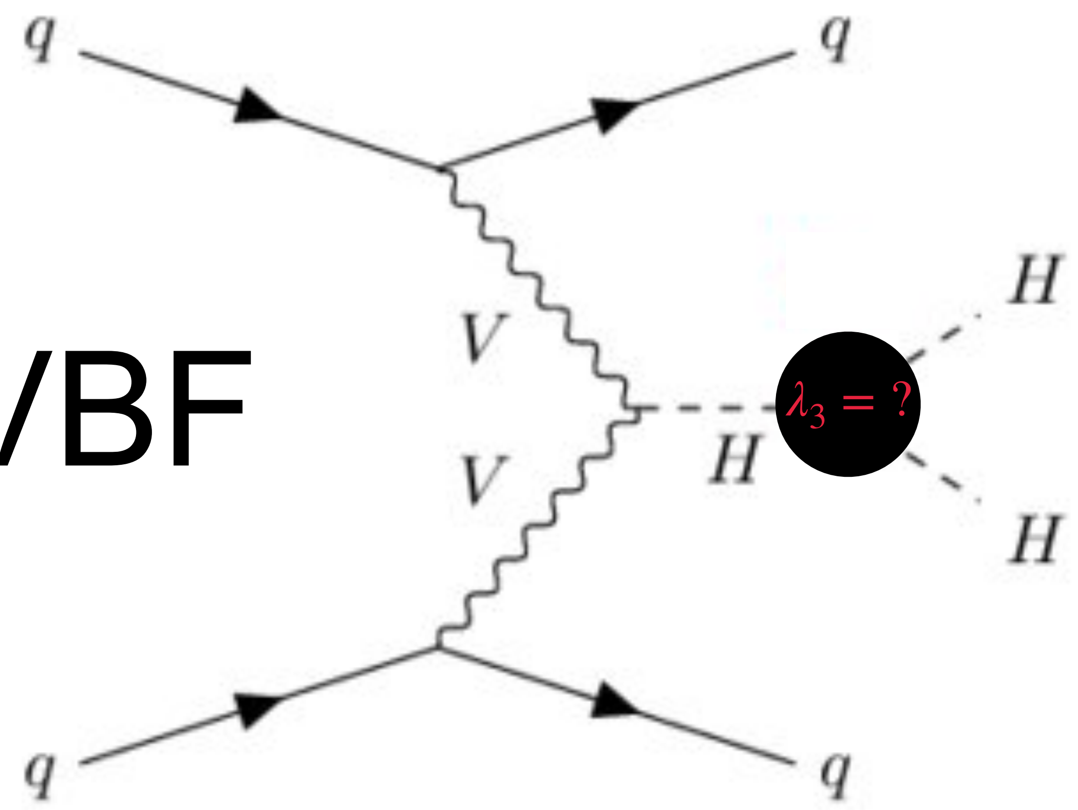
$SM : \lambda_3 = \lambda_{SM} \sim 0.13$



ggF

proton

+ VBF

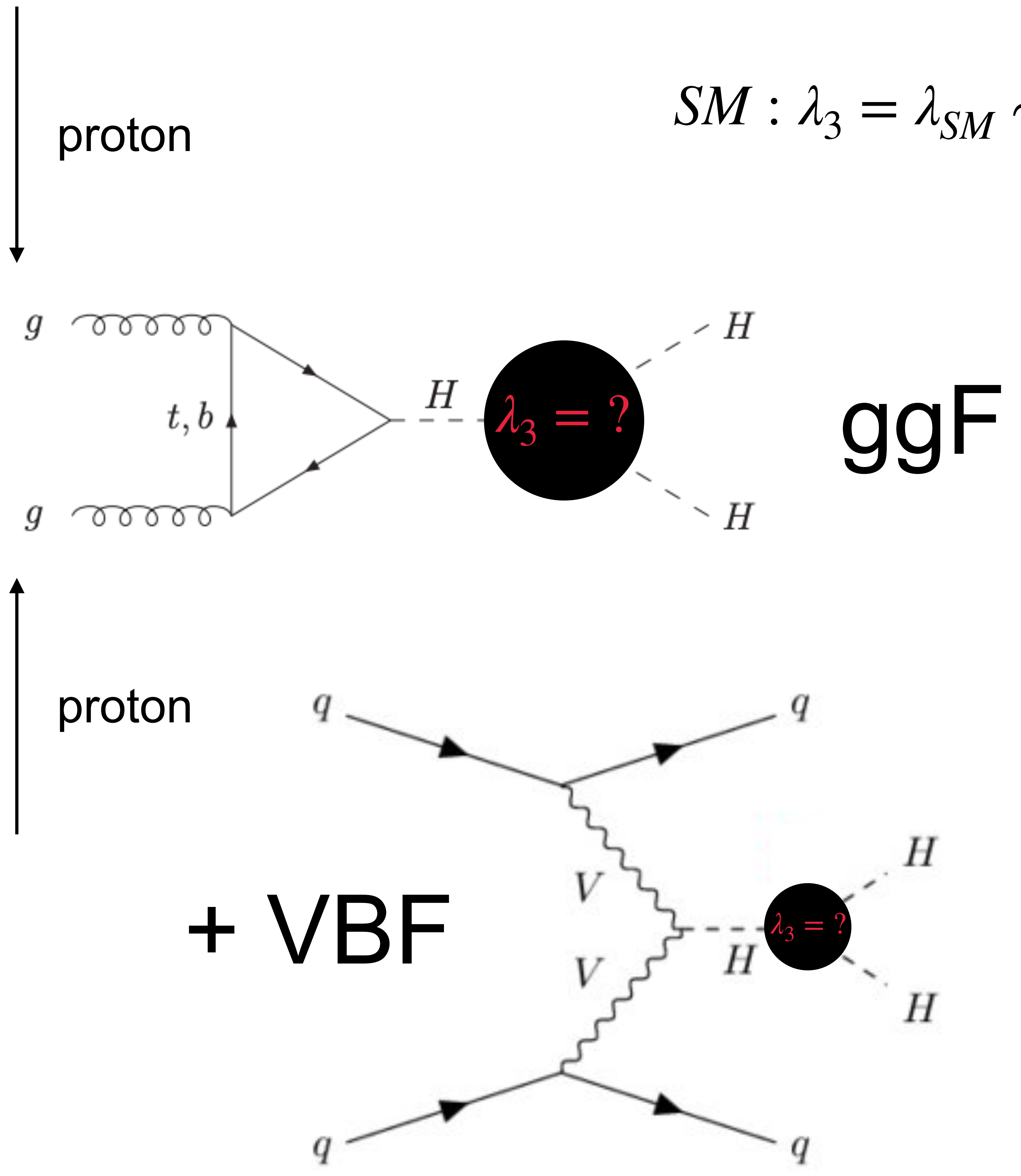


$SM : \sigma_{HH} \sim 40\ fb$

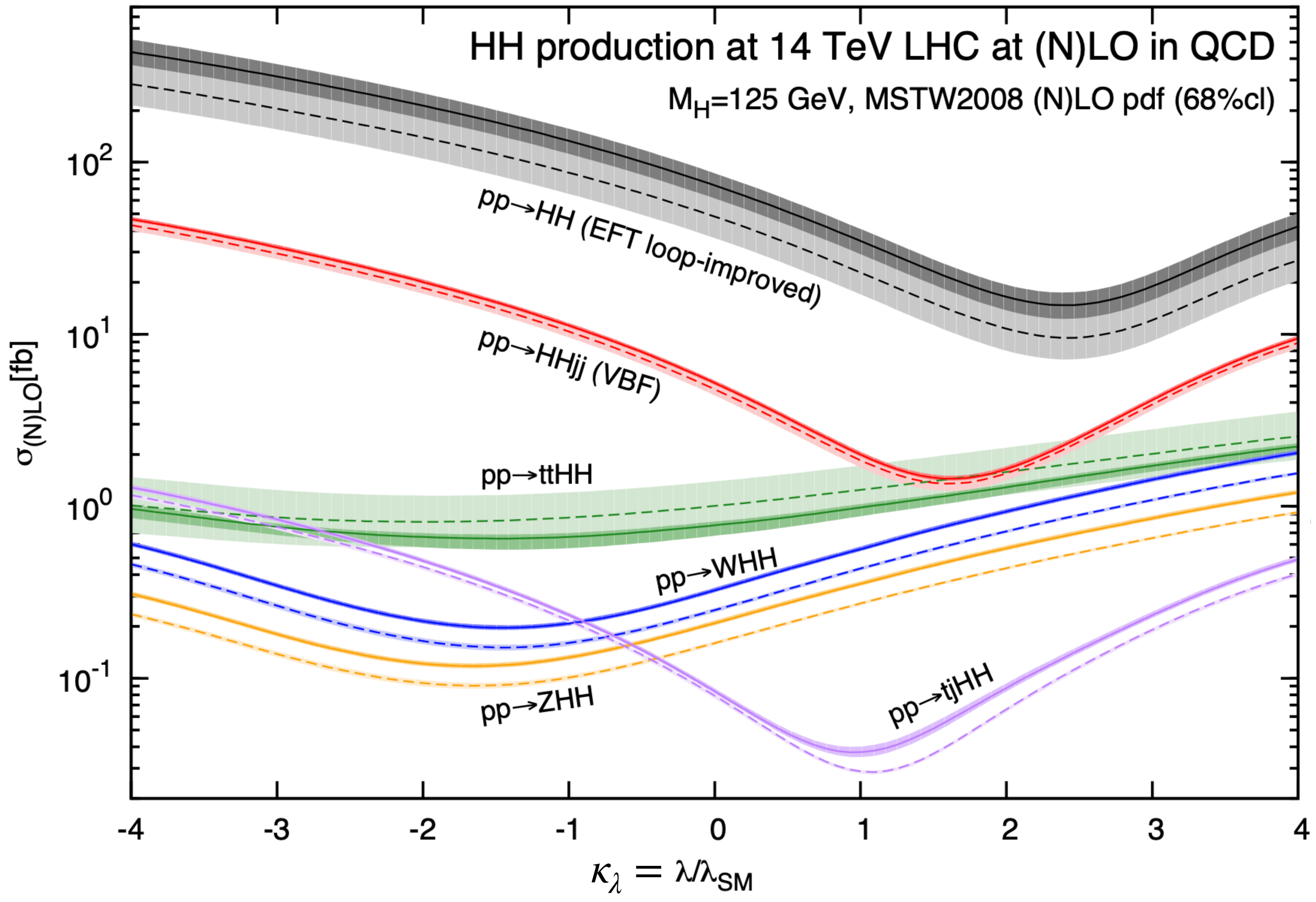
ATLAS run-2 data $\sim 140\ fb^{-1} \Rightarrow \sim$ 5000 events

HH production at LHC

$SM : \lambda_3 = \lambda_{SM} \sim 0.13$



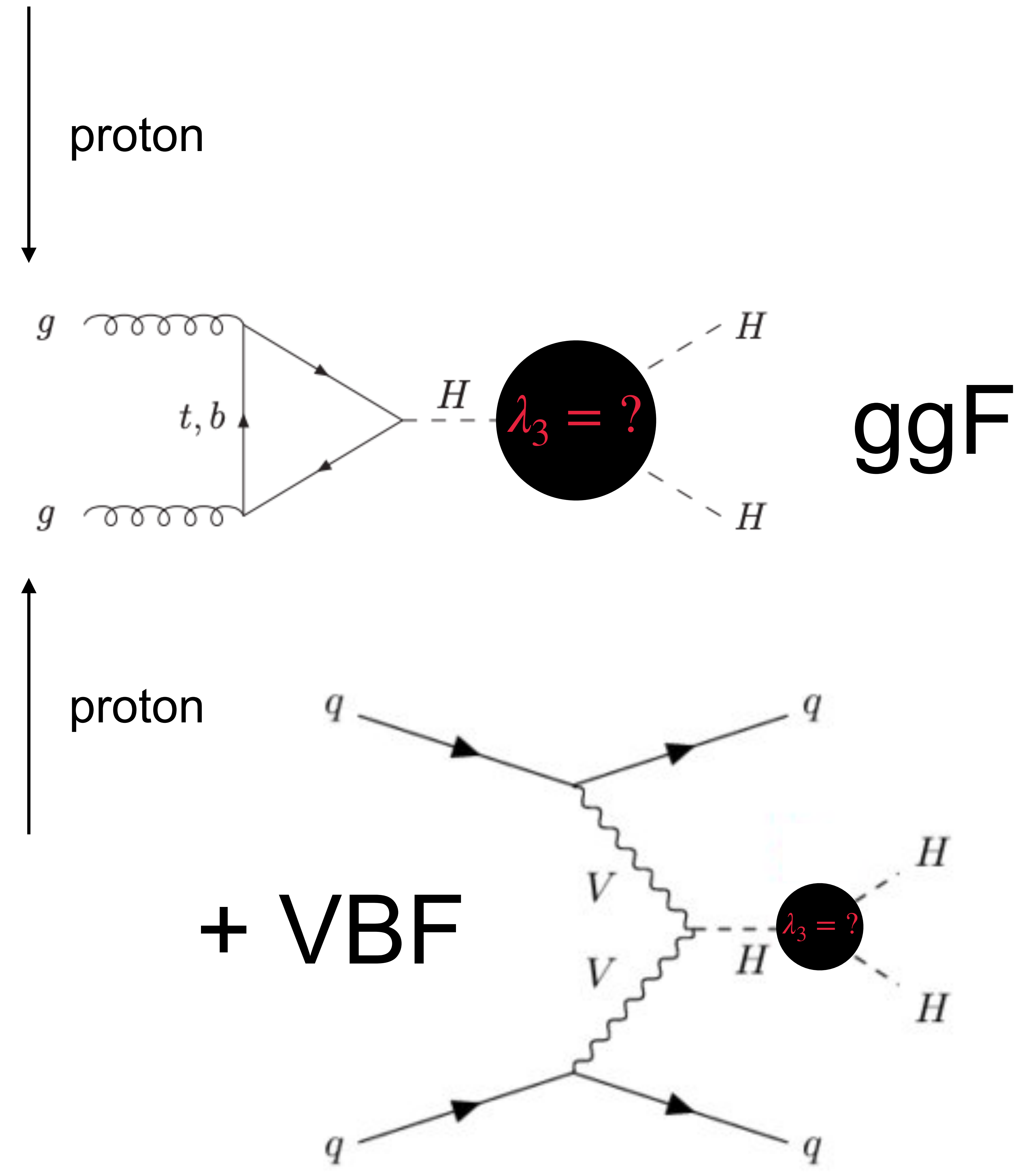
Changing $\kappa_\lambda = \lambda_3/\lambda_{SM}$ changes how many events we see… so we count



$SM : \sigma_{HH} \sim 40\, fb$

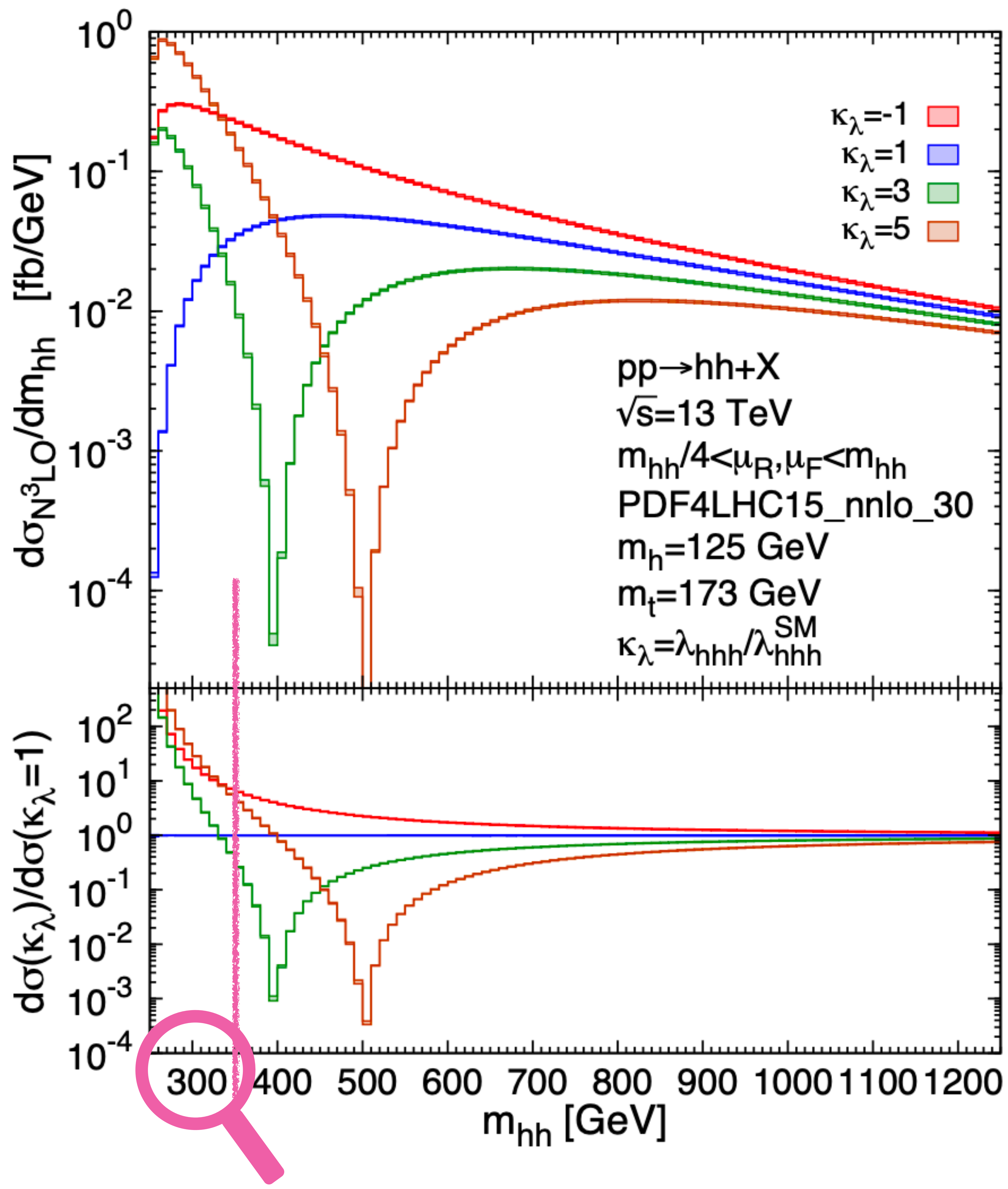
ATLAS run-2 data $\sim 140\, fb^{-1} \Rightarrow \sim 5000$ events

HH production at LHC



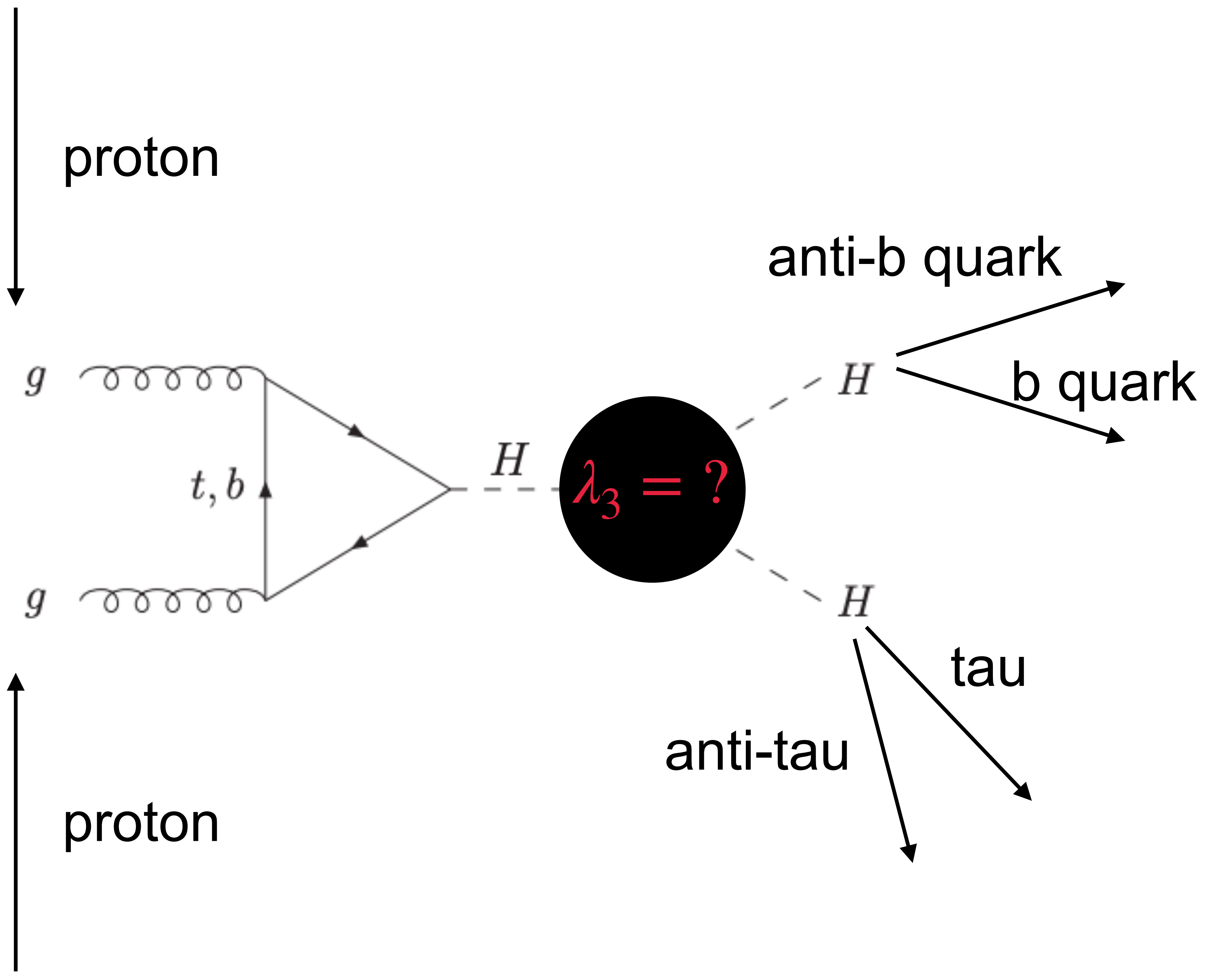
$\sim$ 5000 events

Not only counting: changing $\kappa_\lambda = \lambda_3/\lambda_{SM}$ changes kinematics



$m_{HH} < 350\ GeV$ sensitive to κ_λ

HHiggs self coupling at LHC



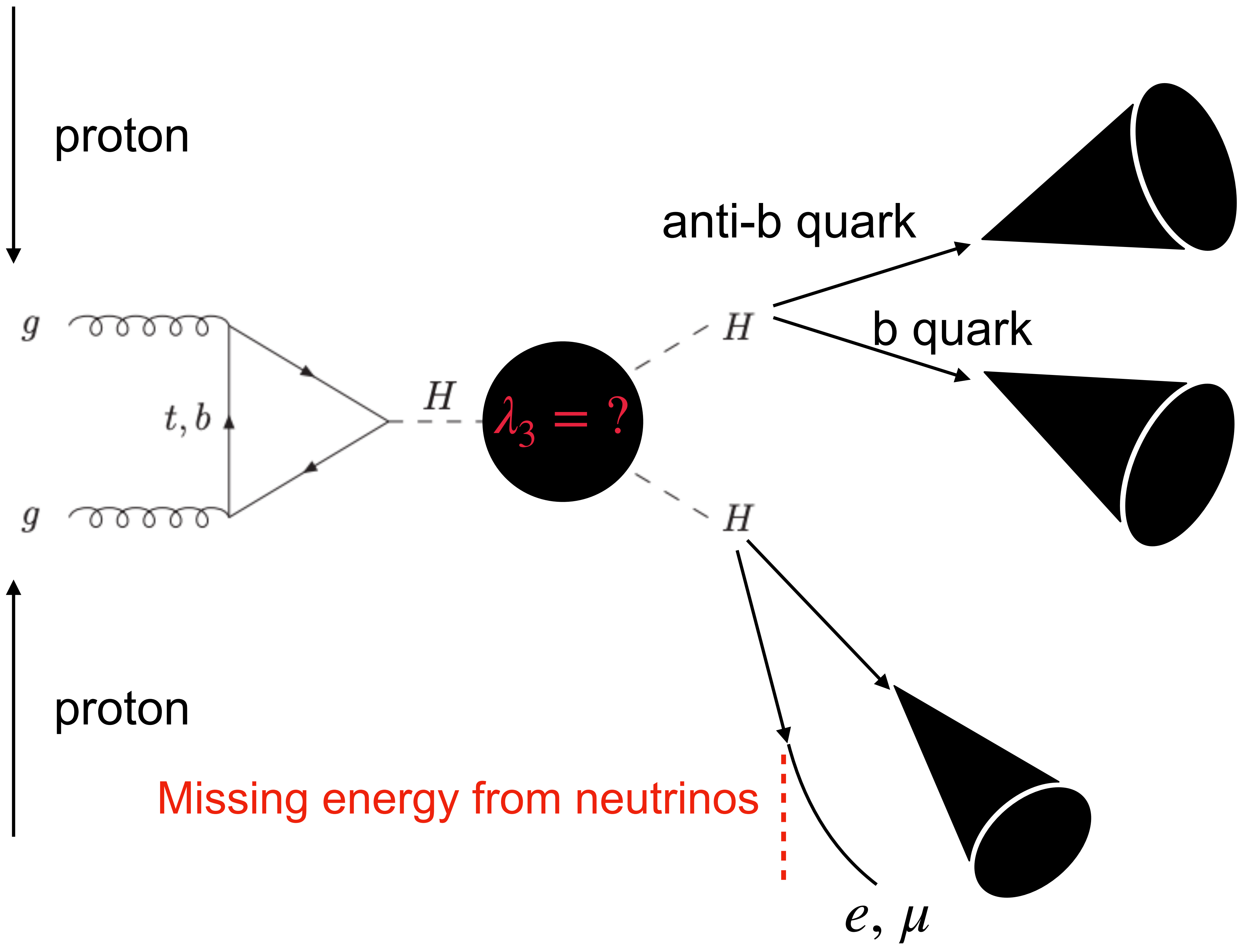
more events ⟷ clean signal

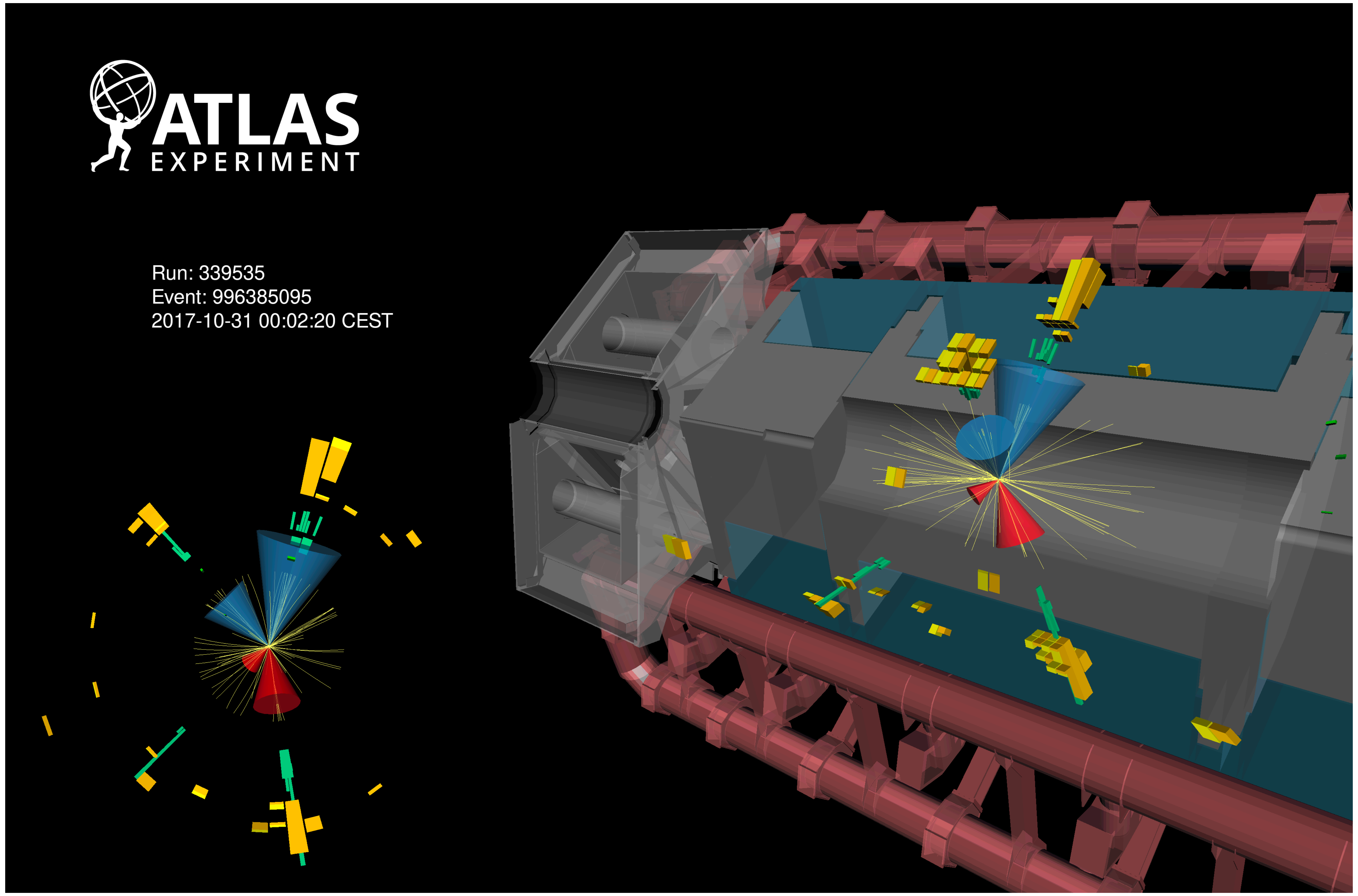
	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
γγ	0.26 %	0.10 %	0.028 %	0.012 %	0.0005 %

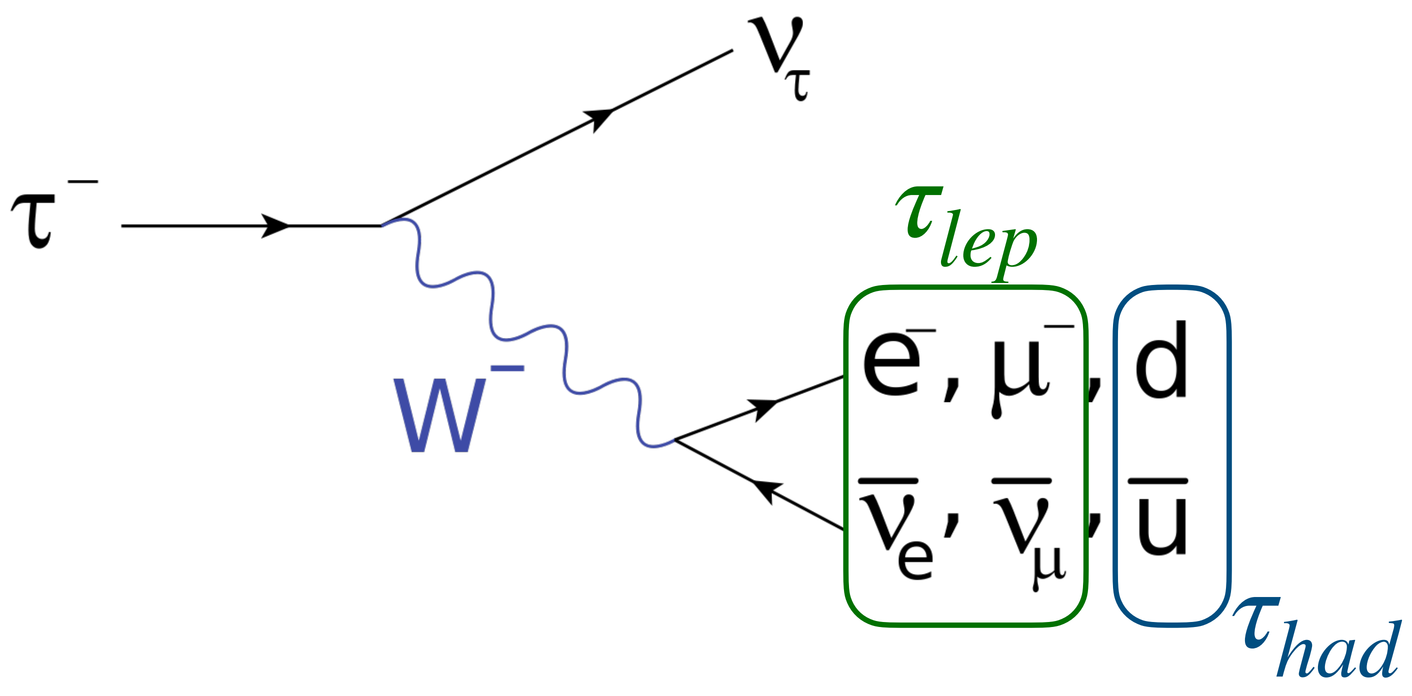
~ 350 events

Fine…

$HH \rightarrow bb\tau\tau$ event and objects







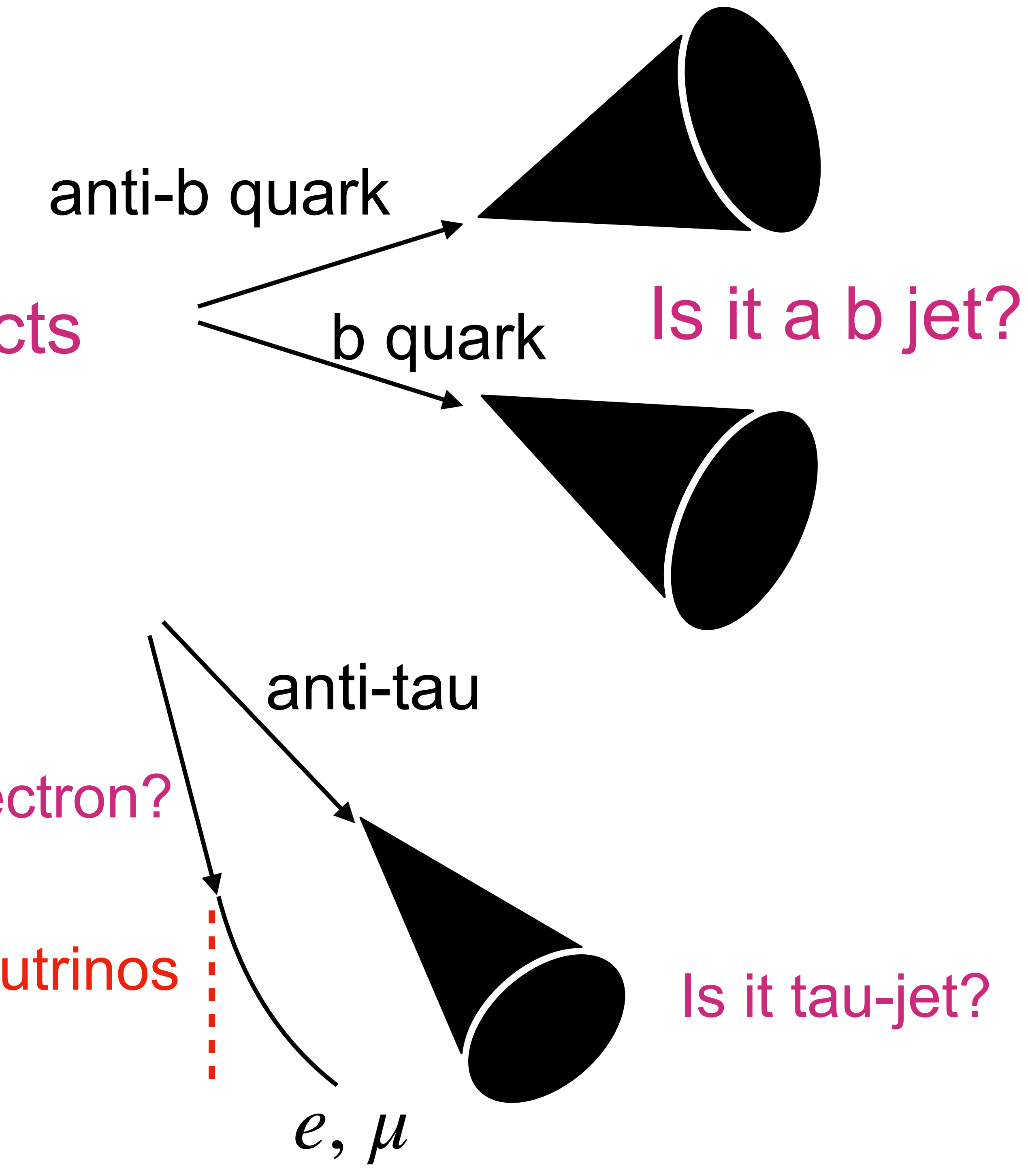
$\tau_{had}\tau_{had}$ channel ~ 140 events

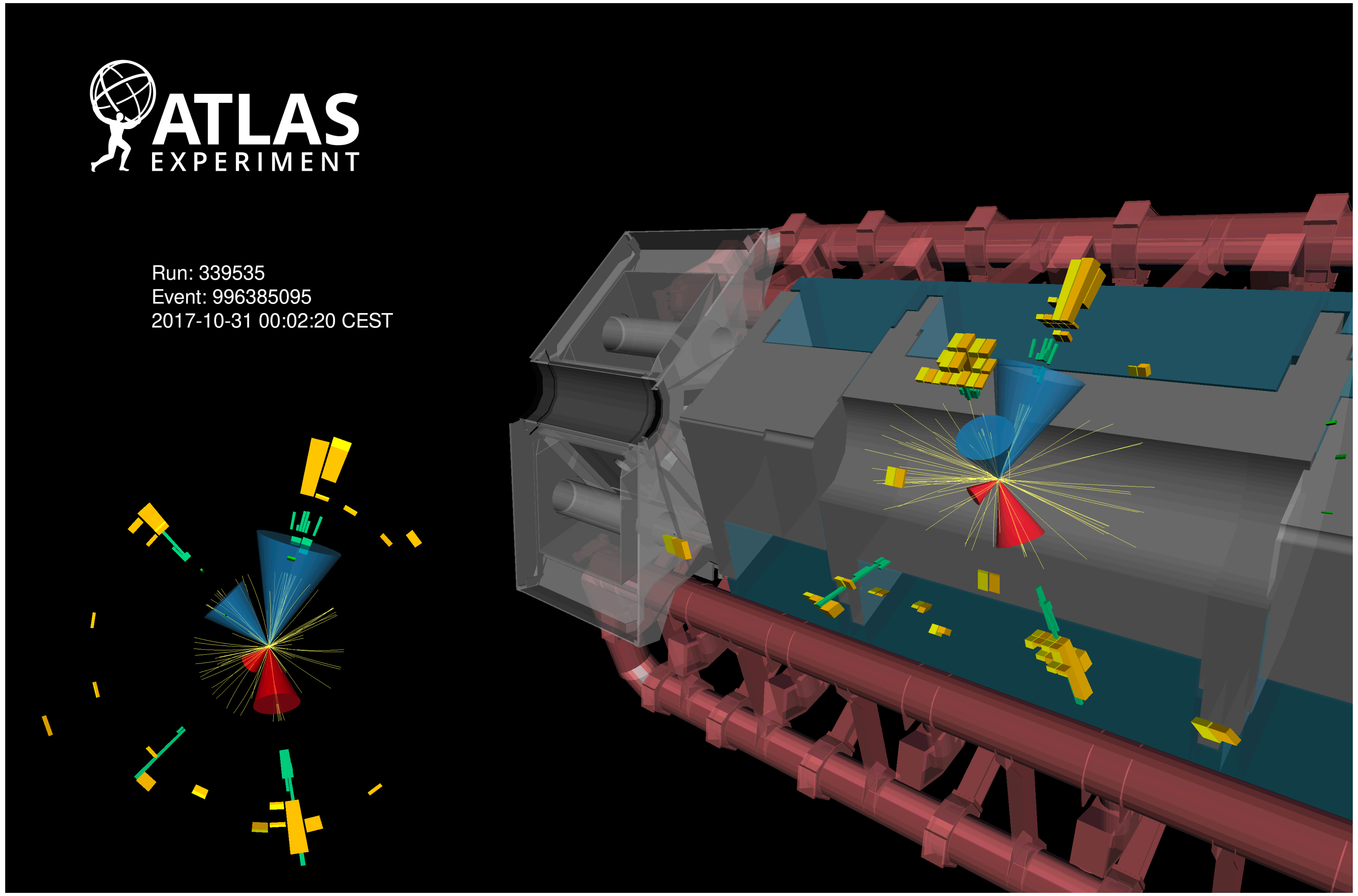
$\tau_{lep}\tau_{had}$ channel ~ 150 events

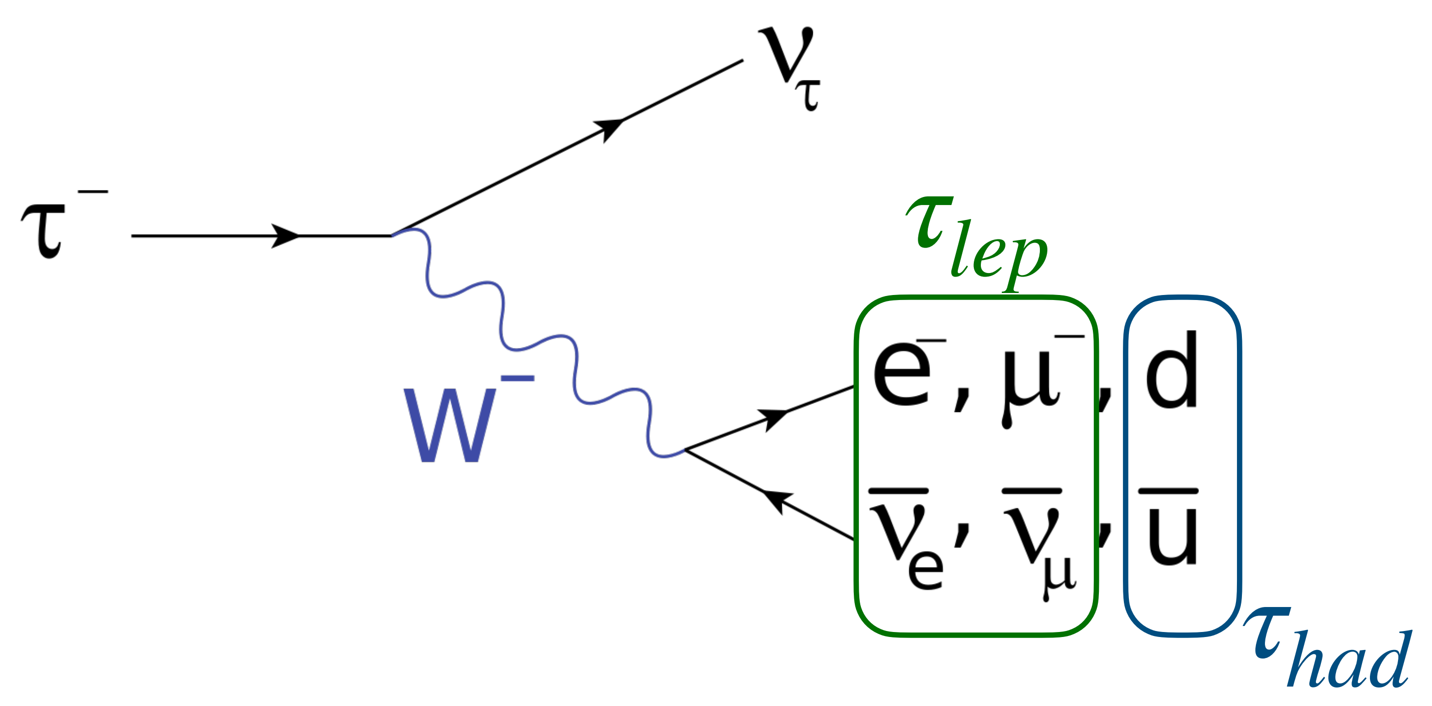
ok…

$HH \rightarrow bb\tau\tau$ event and objects

+ cuts for quality of objects
+ Triggers
+ cuts to select objects
+ cuts to isolate signal





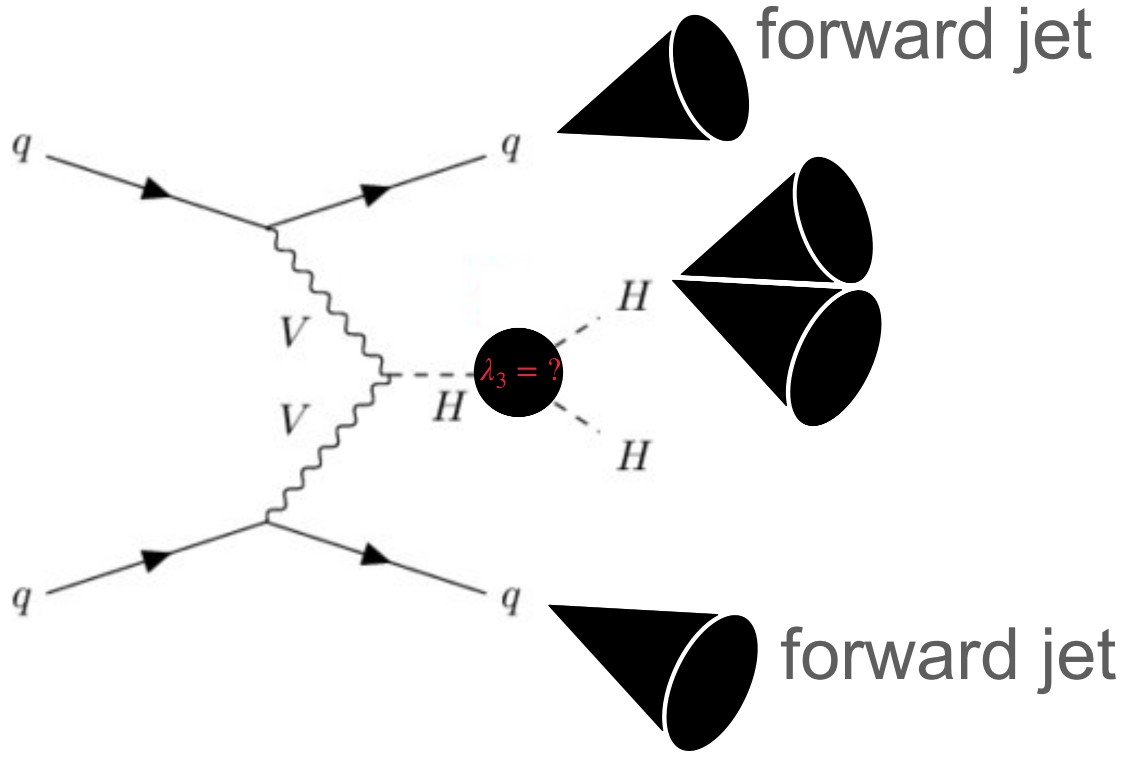


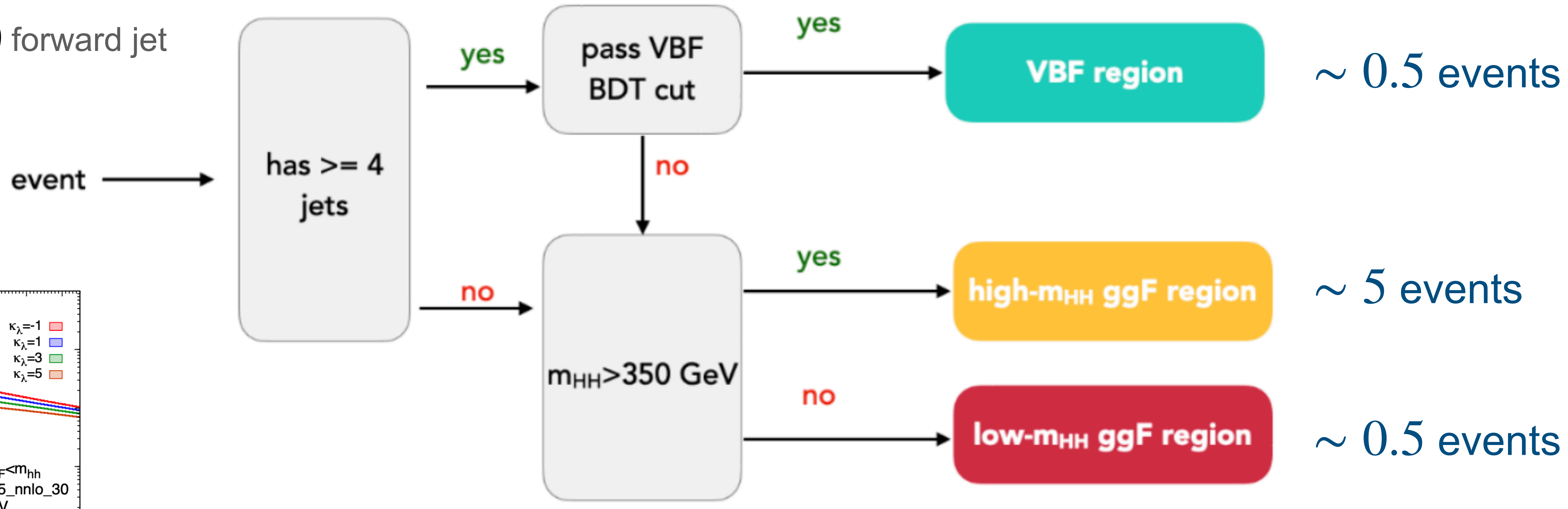
$\tau_{had}\tau_{had}$ channel ~ 140 events $\rightarrow 6$ events

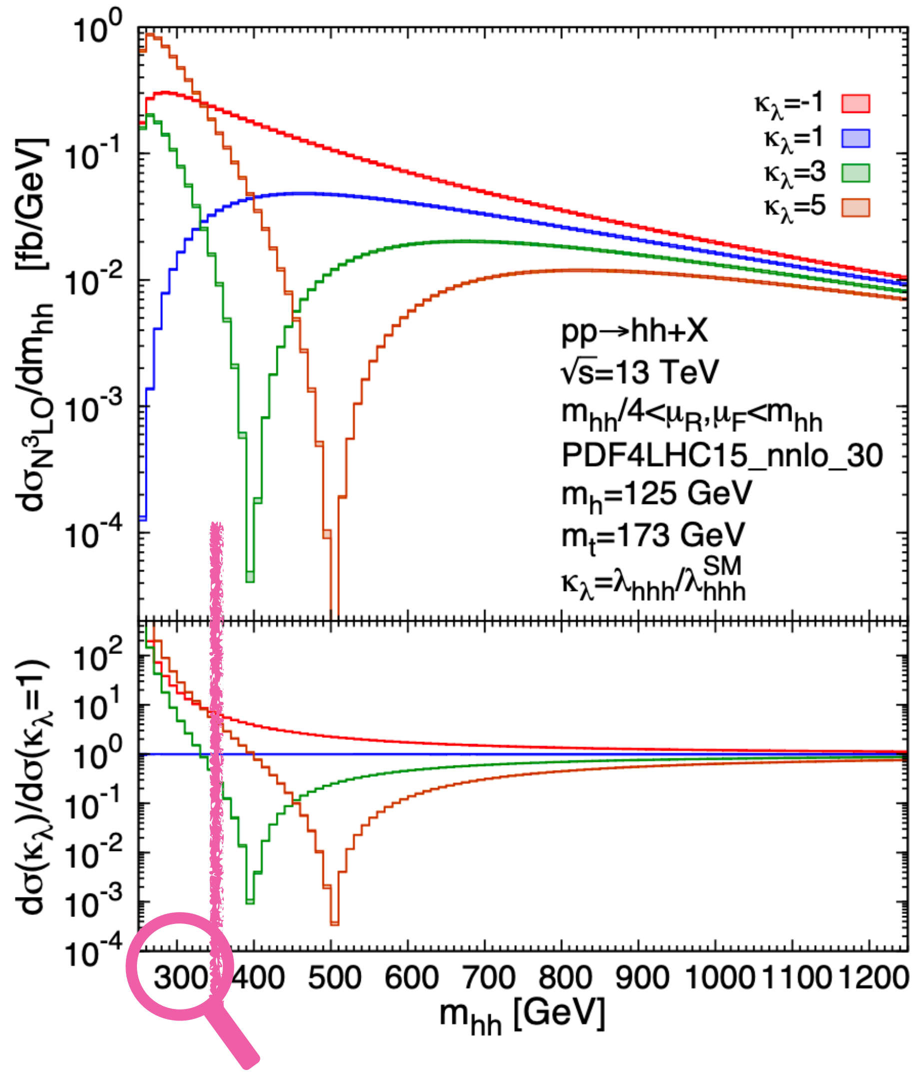
$\tau_{lep}\tau_{had}$ channel ~ 150 events $\rightarrow 7$ events

ok…

$HH \rightarrow bb\tau\tau$ at ATLAS: event categorisation

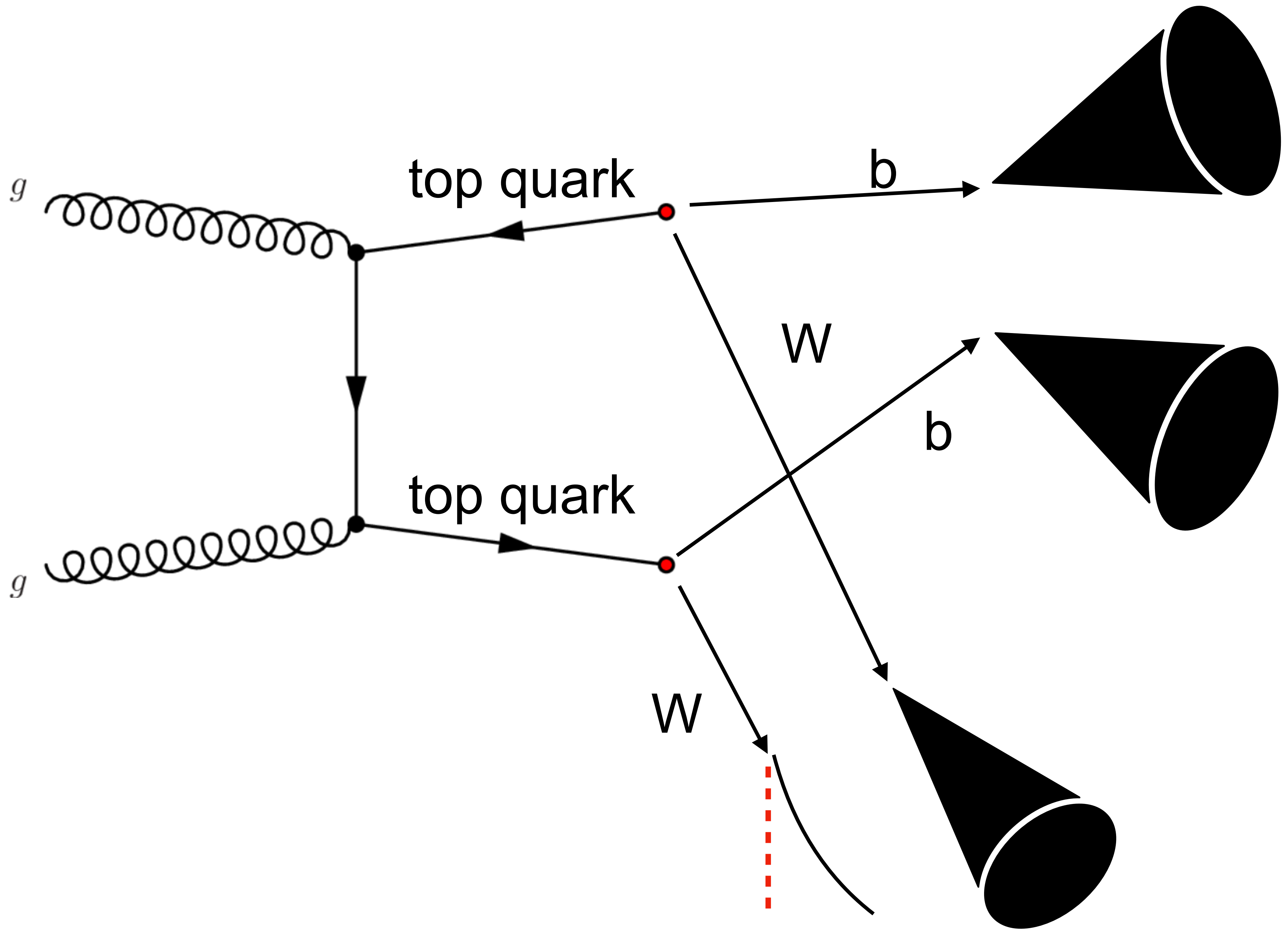


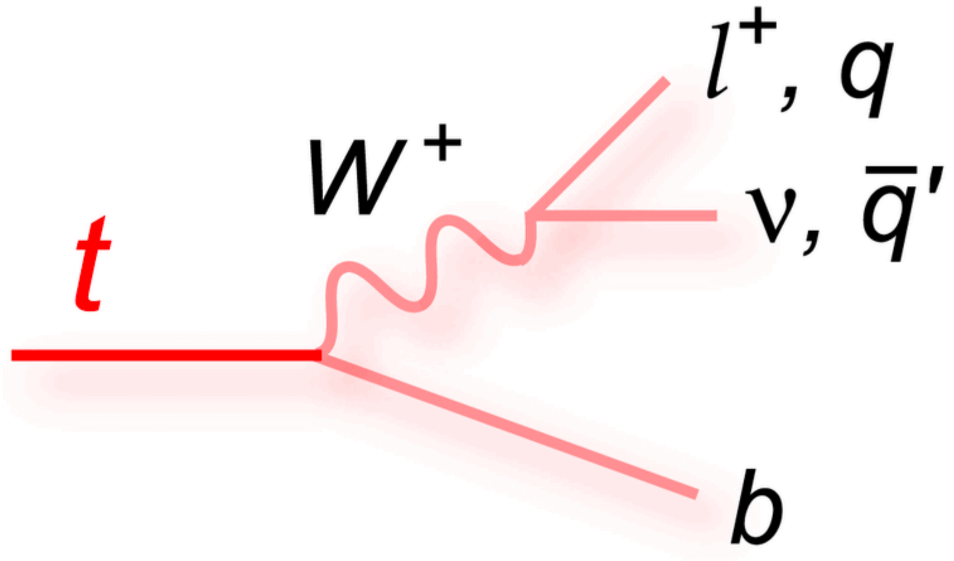




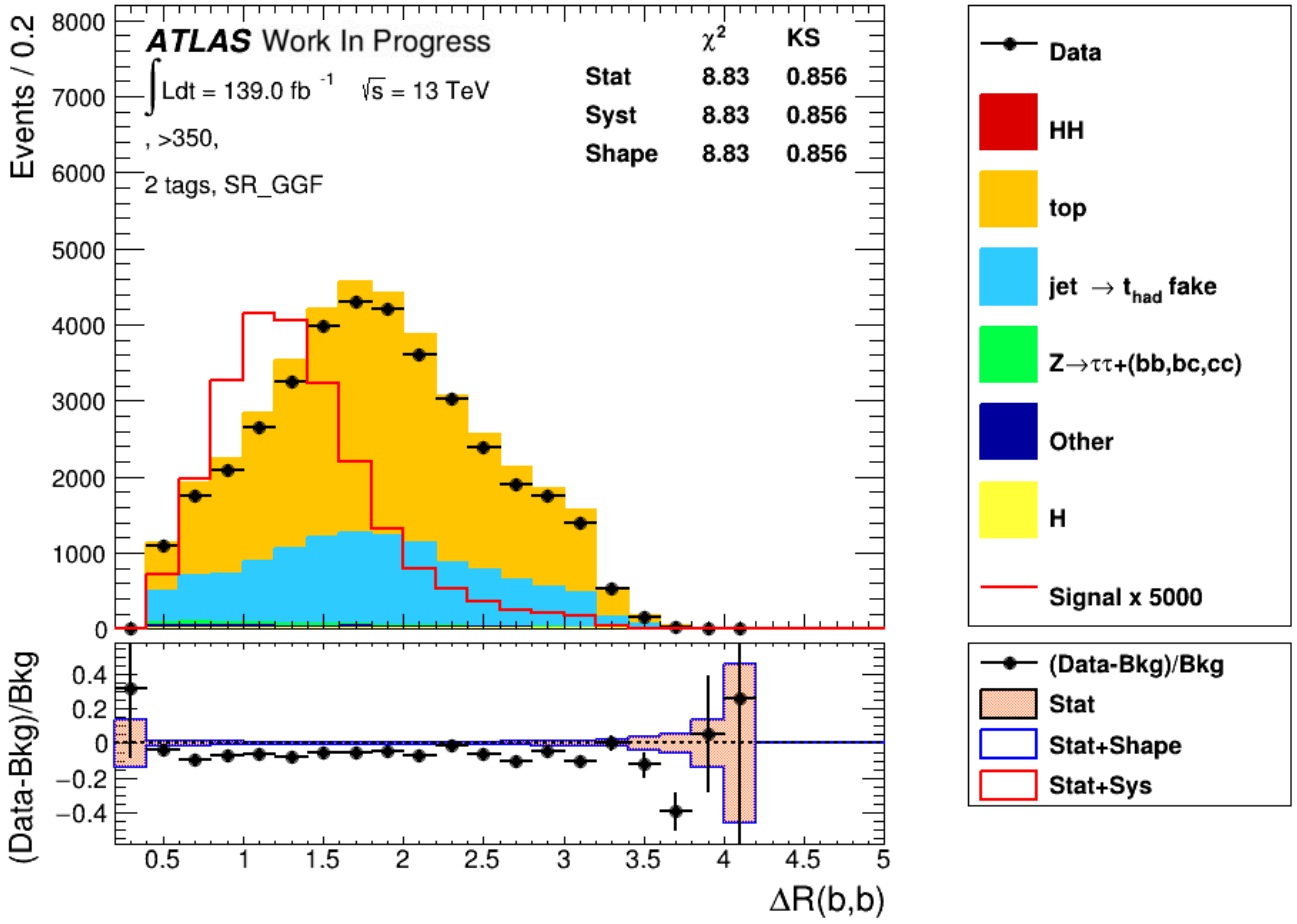
:') no bkg?

$HH \rightarrow bb\tau\tau$ background



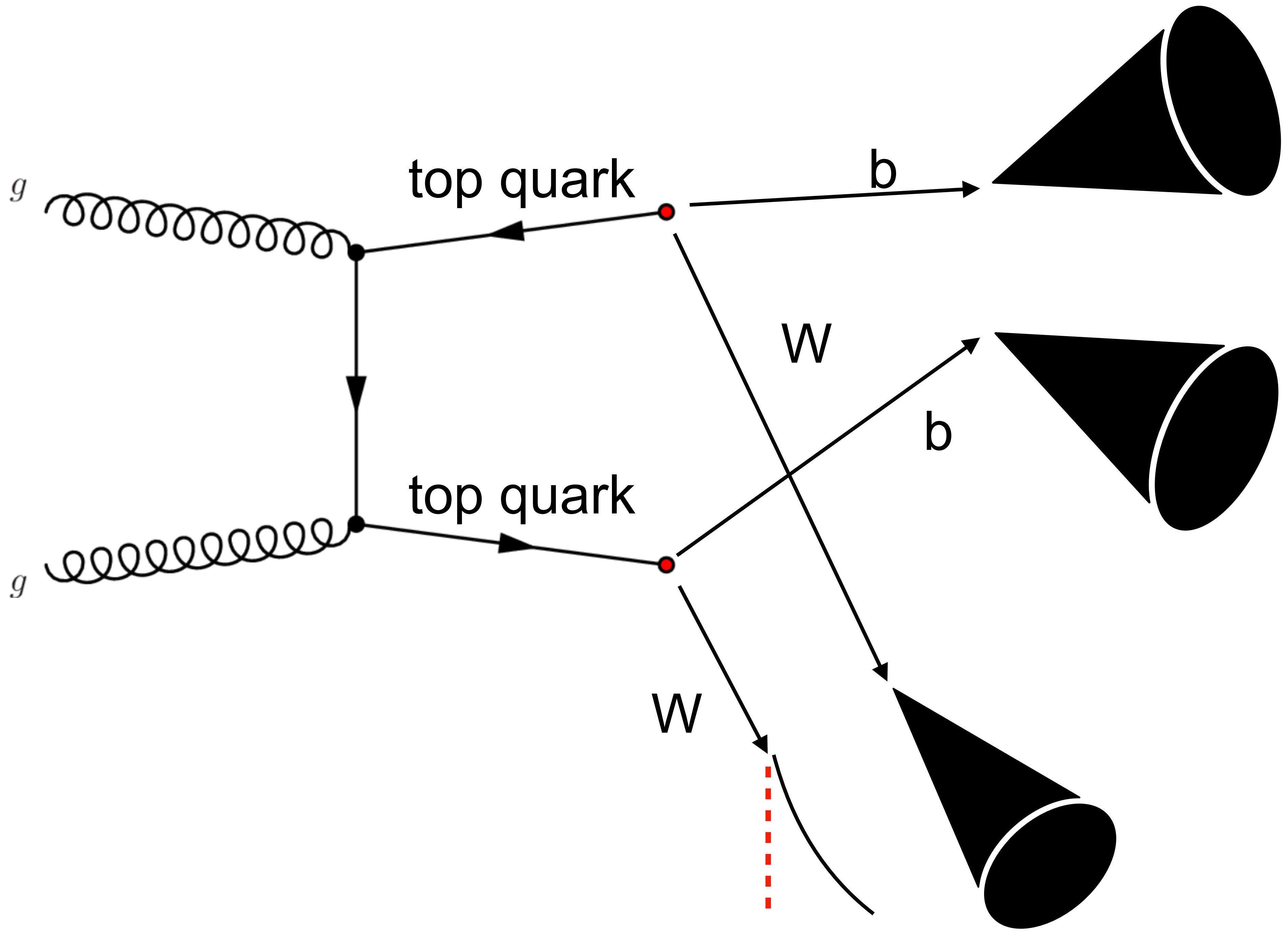


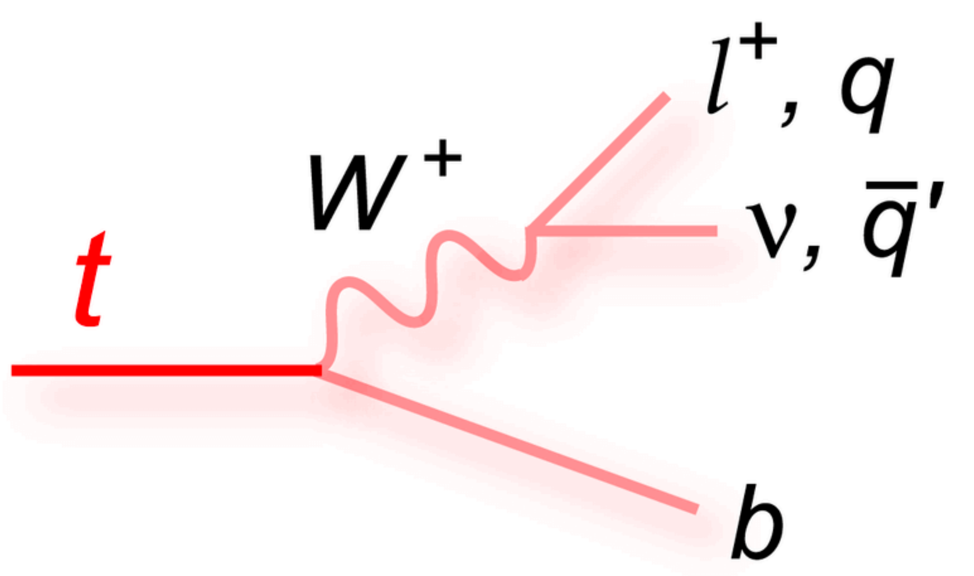
Low signal, so much more background!



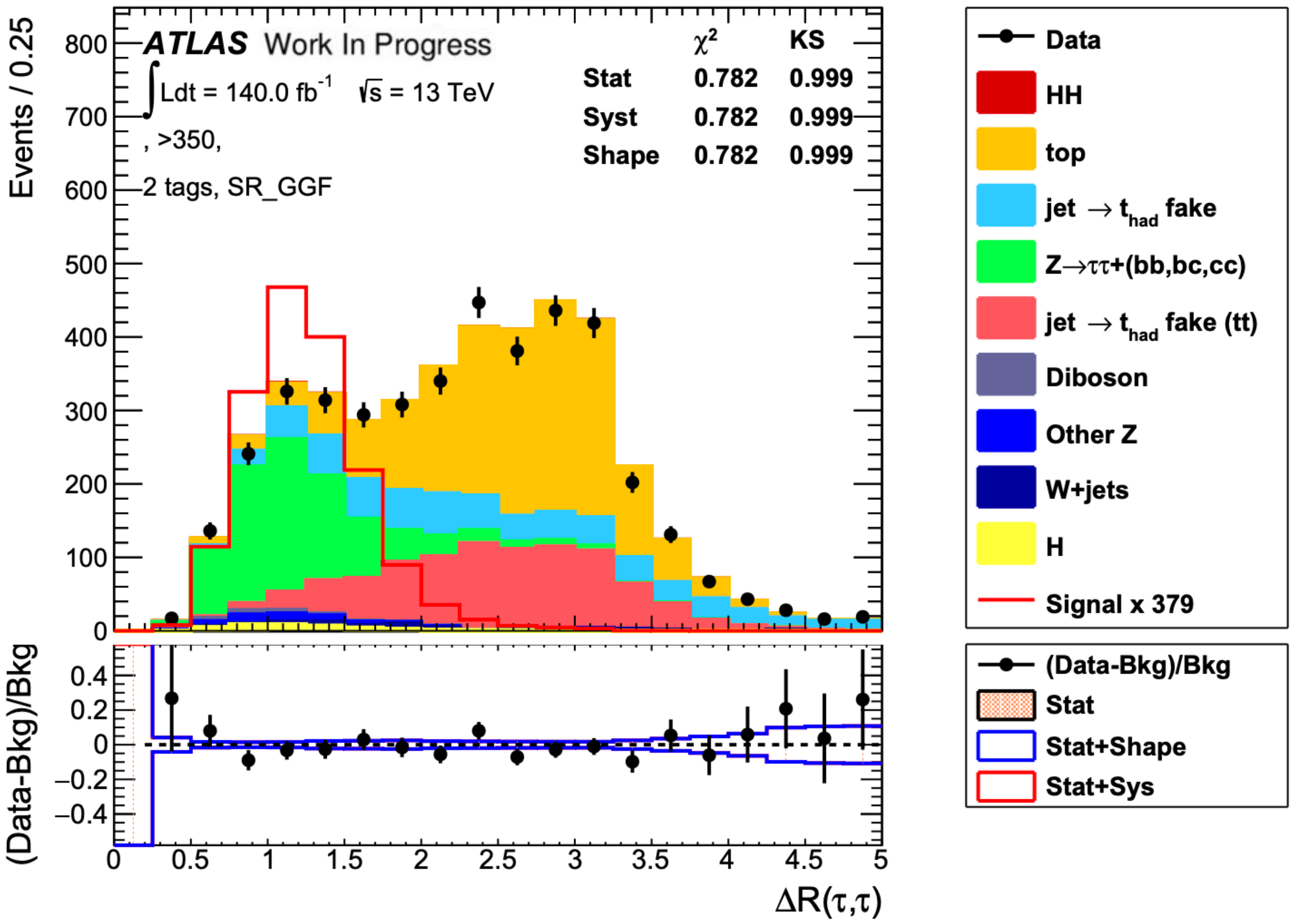
$\tau_{lep}\tau_{had}$ channel, ggF high-mHH

$HH \rightarrow bb\tau\tau$ background





We will use multivariate analysis (MVA)



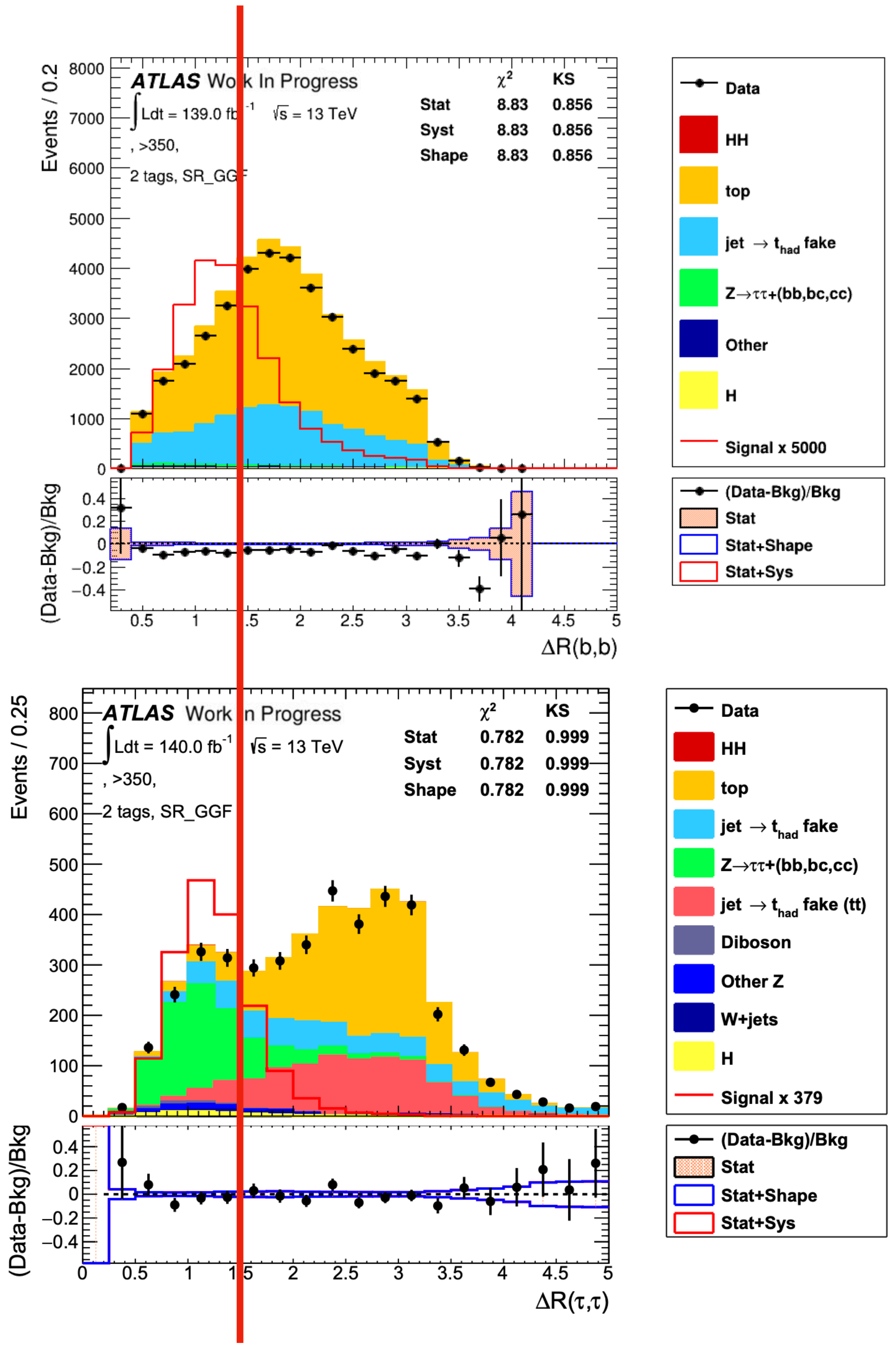
$\tau_{had}\tau_{had}$ channel, ggF high-mHH

$HH \to bb\tau\tau$ Mulitivariate Analysis

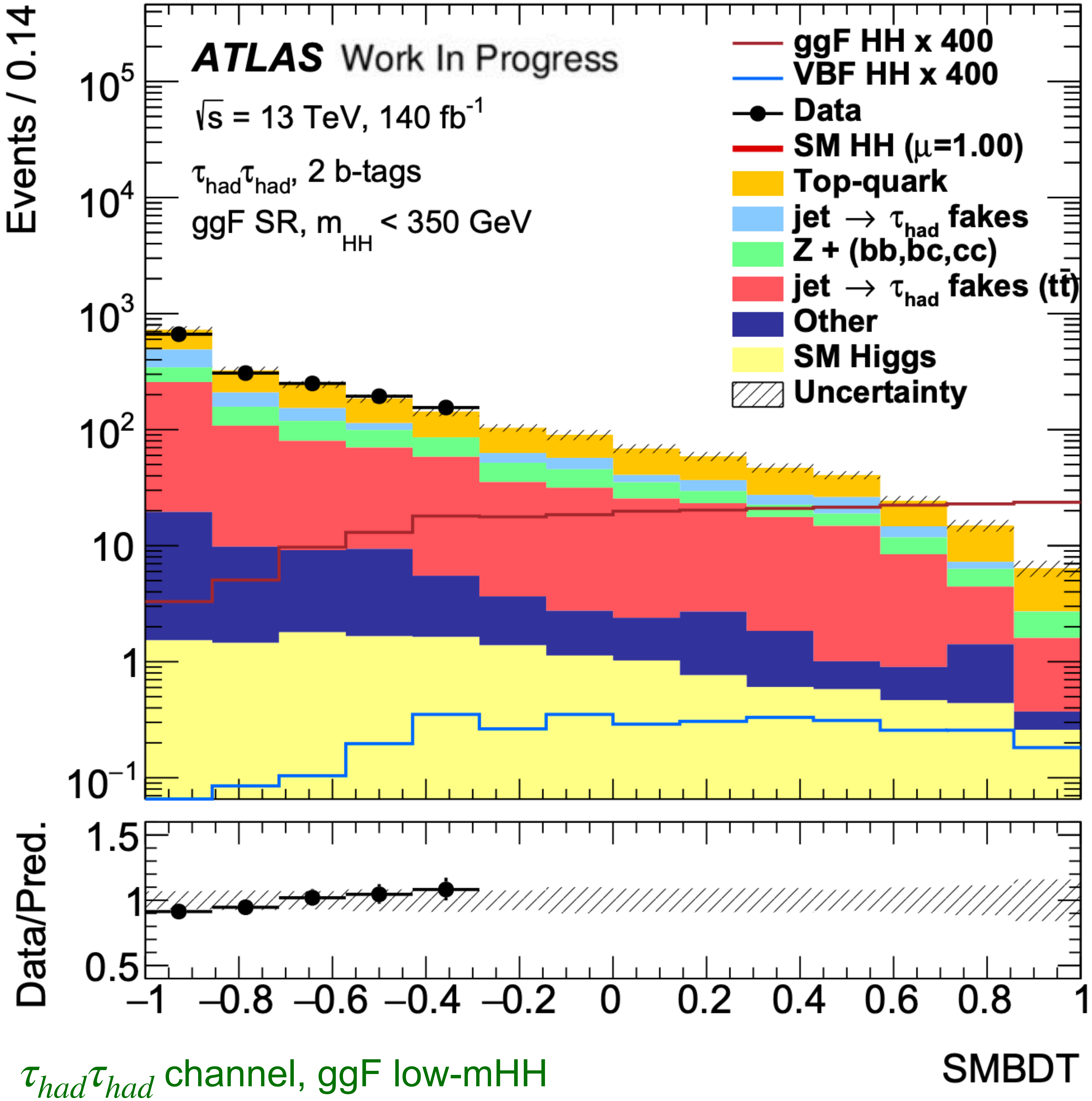
inputs

m_{HH}
$m_{\tau\tau}$
m_{bb}
$\Delta R(b, b)$
$\Delta R(\tau, \tau)$
+ …

Boosted Decision Tree (BDT)



Train the BDT on Monte Carlo samples, apply it to data



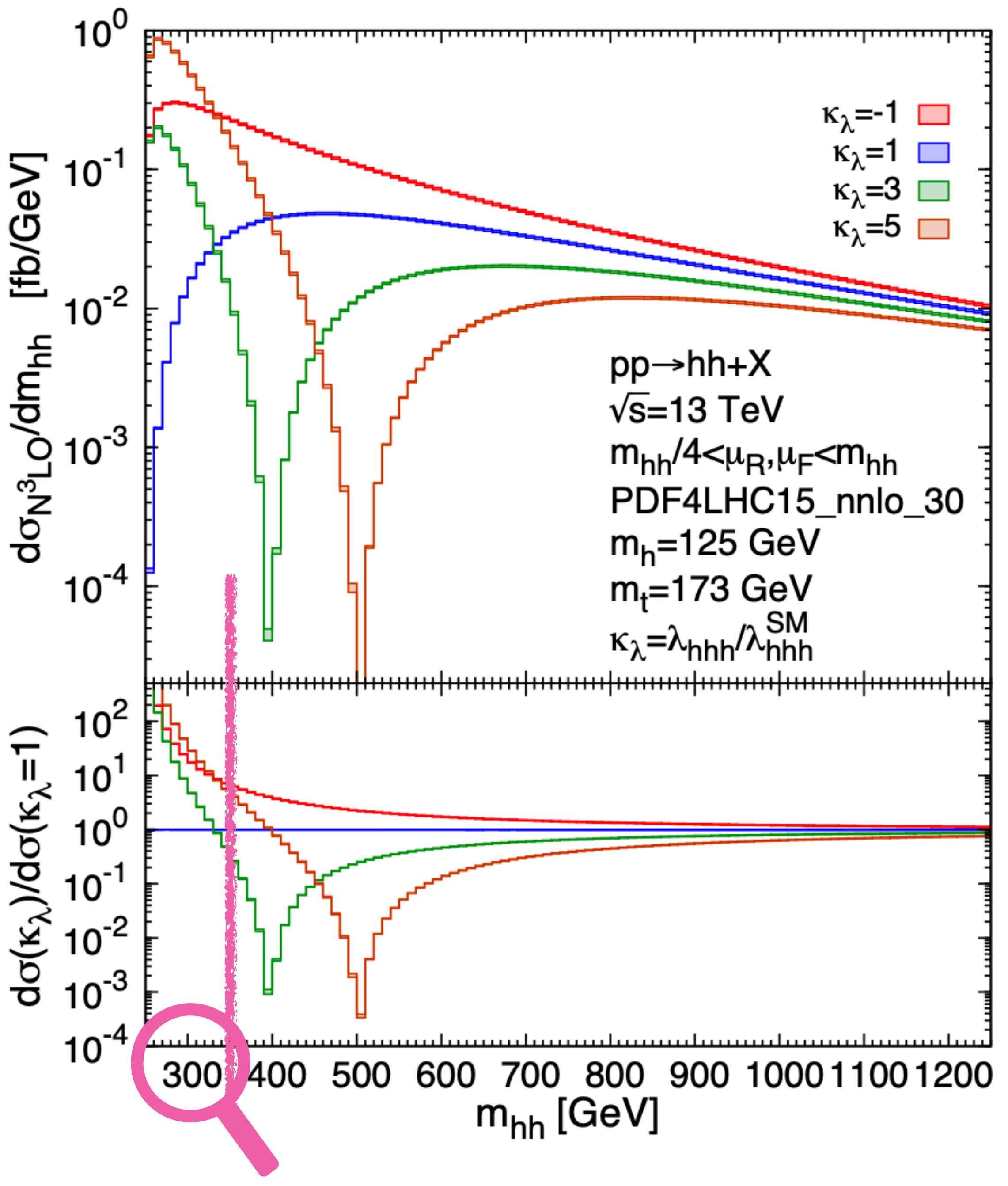
$\tau_{had}\tau_{had}$ channel, ggF low-mHH

$HH \to bb\tau\tau$ Mulitivariate Analysis

inputs

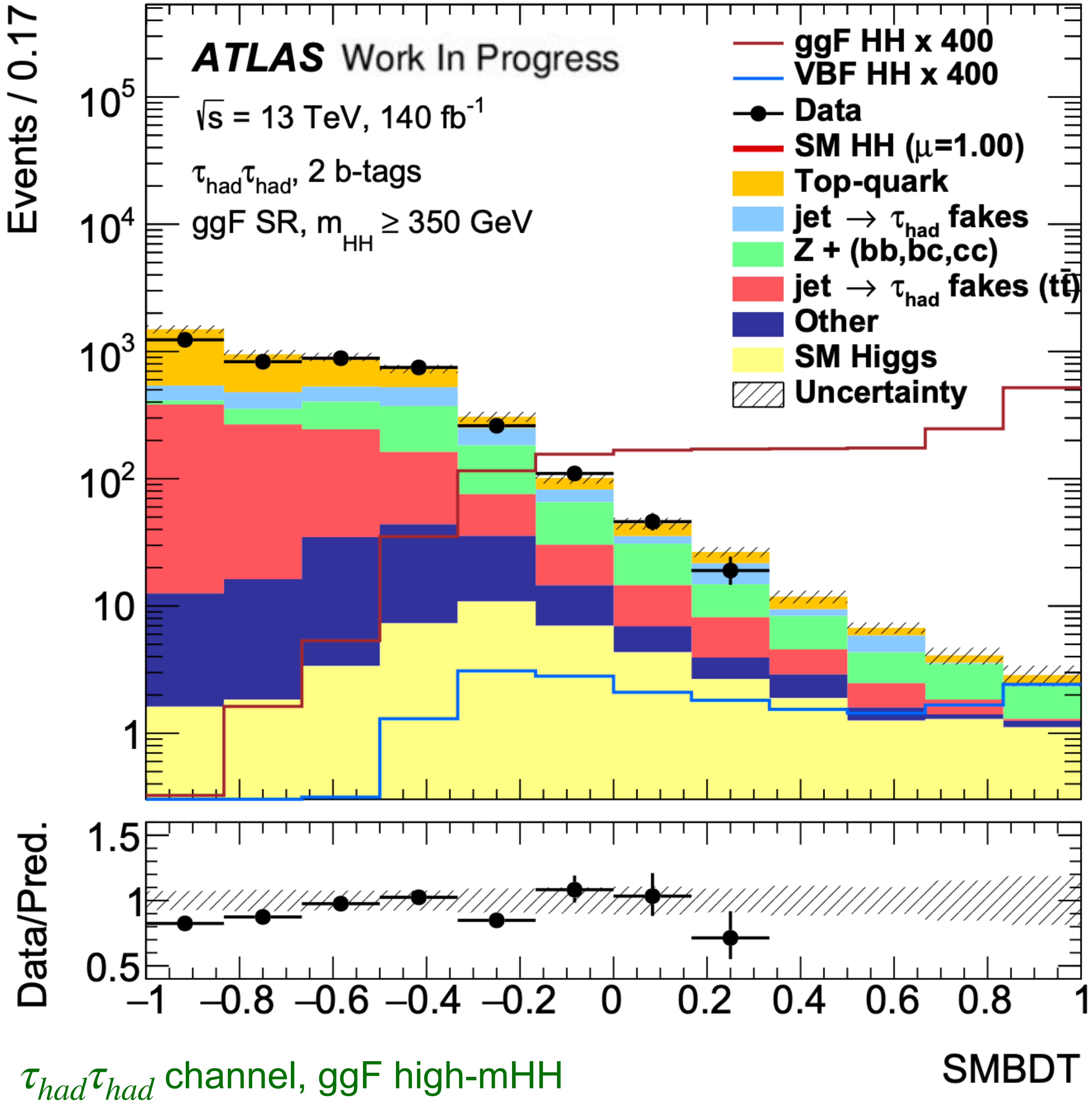
m_{HH}
$m_{\tau\tau}$
m_{bb}
$\Delta R(b, b)$
$\Delta R(\tau, \tau)$
$+ \ldots$

Boosted Decision Tree (BDT) →



Train on:
$\kappa_\lambda = 10$ for low-mHH
$\kappa_\lambda = 1$ for low-mHH

Train the BDT on Monte Carlo samples, apply it to data



$\tau_{had}\tau_{had}$ channel, ggF high-mHH

$HH \to bb\tau\tau$ fit to data

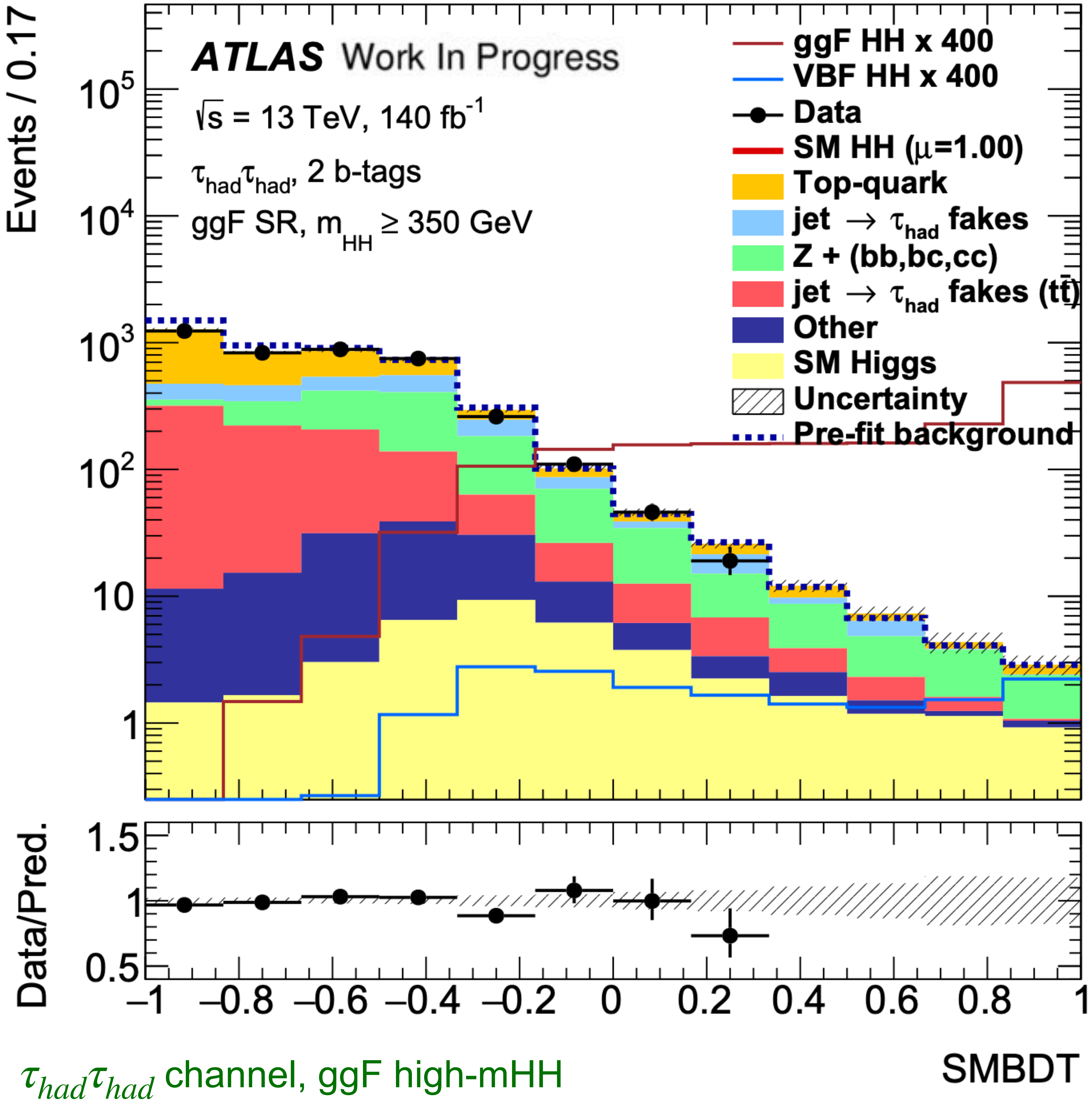
$$\mathcal{L}(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) = \prod_{c=1}^{N_{\text{cats}}} \mathcal{L}_c(\boldsymbol{\mu}, \boldsymbol{\theta}; \text{data}) \prod_{k \in \text{constraint NPs}} f_k(\theta_k)$$

Z background scaled up: $\times 1.33$

Top background scaled down $\times 0.96$

Ready to unblind?

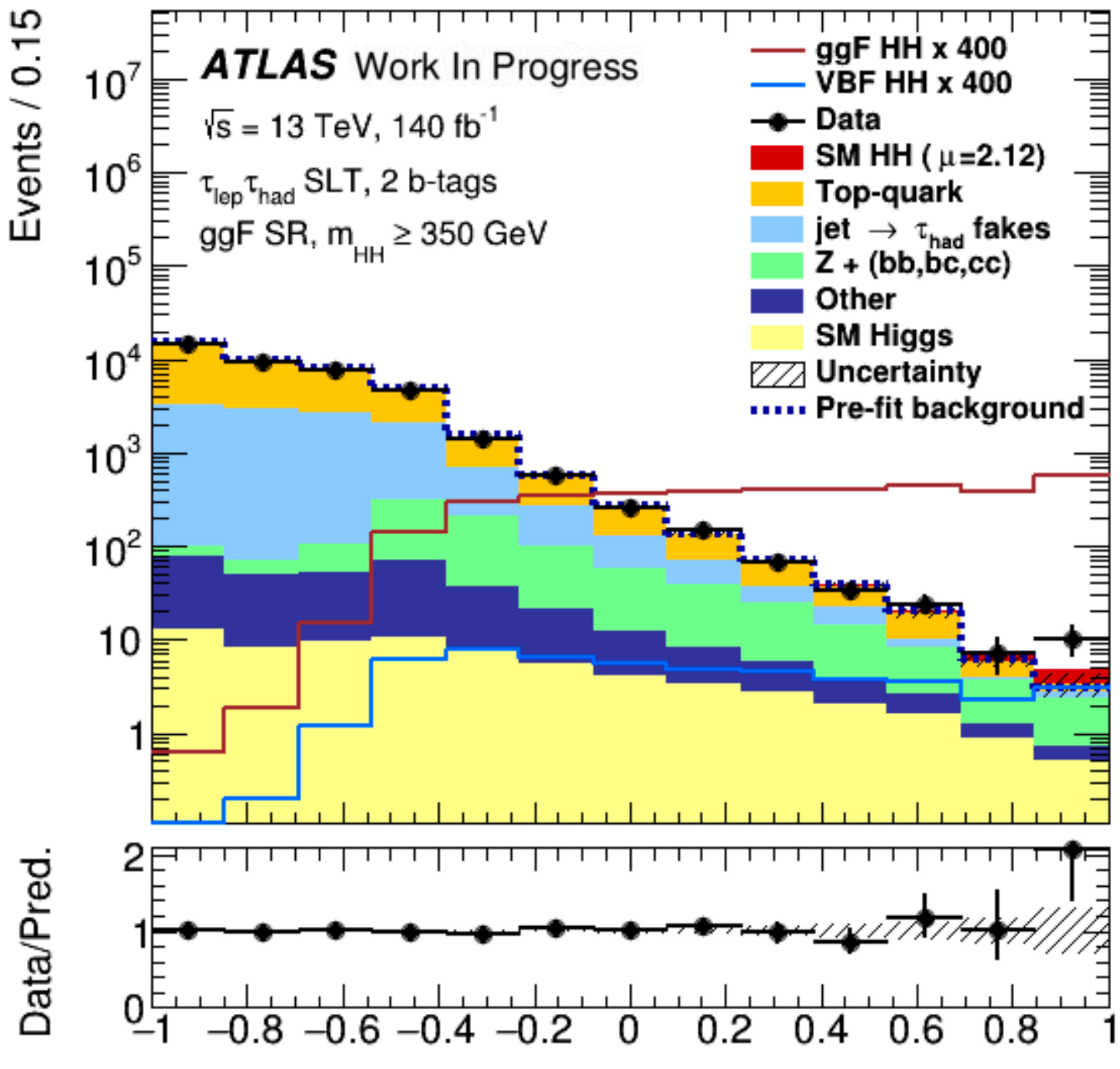
Fit the BDT distributions to data! Fit scales background



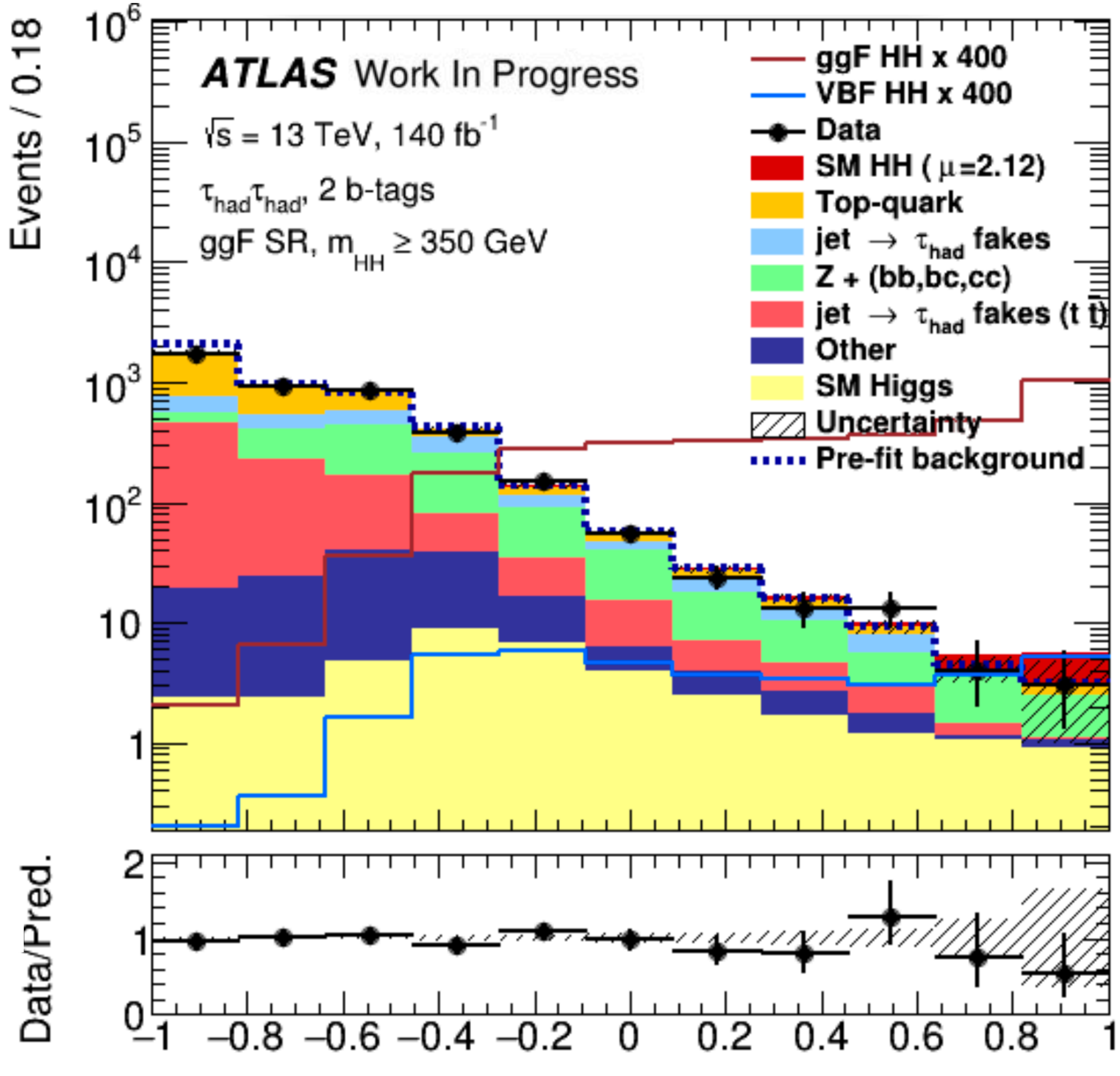
$\tau_{had}\tau_{had}$ channel, ggF high-mHH

$HH \rightarrow bb\tau\tau$

signal strength $\mu_{HH} = \sigma_{obs}/\sigma_{SM} = 2.1 \pm 1.6$



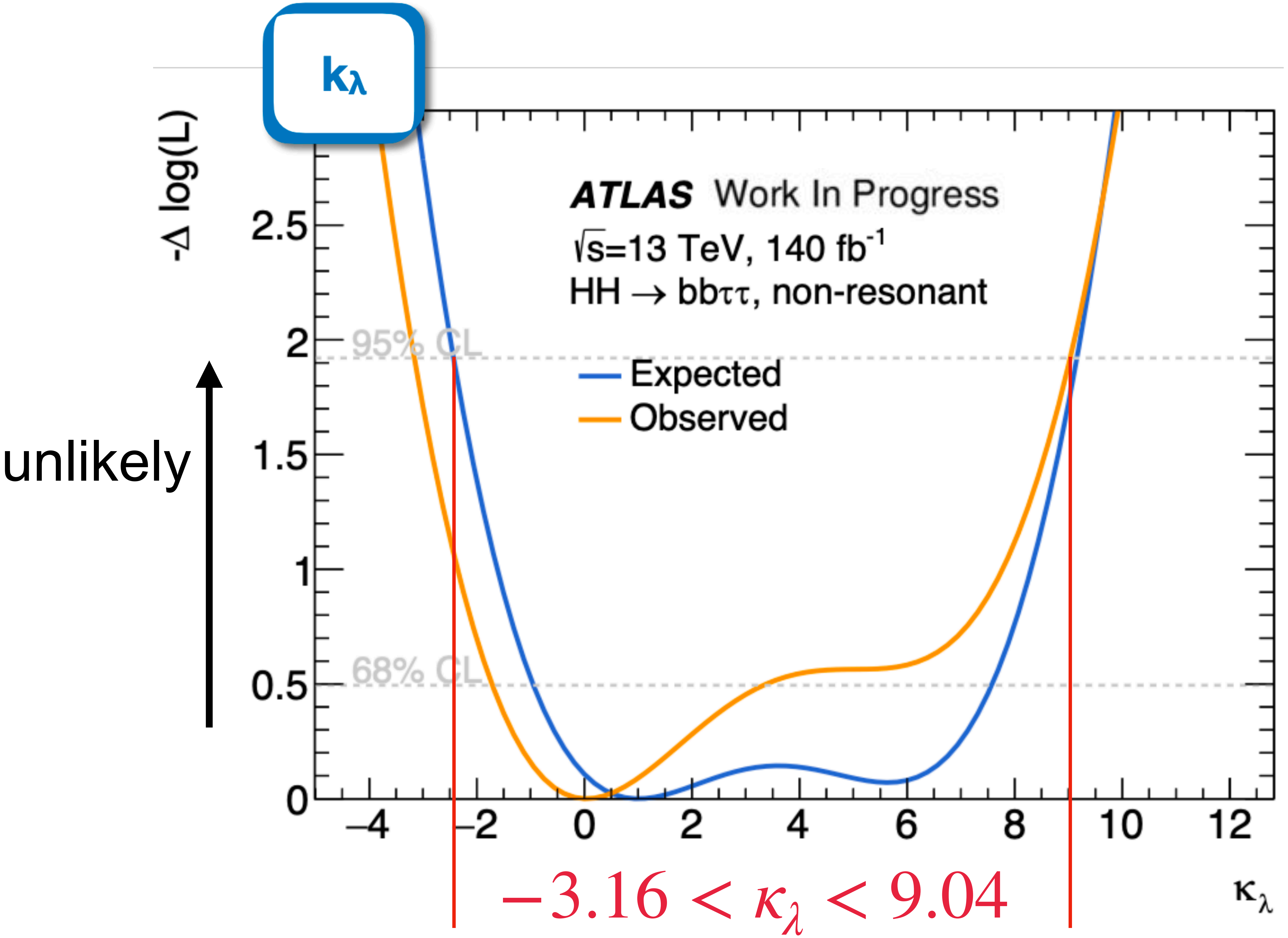
$\tau_{lep}\tau_{had}$ channel, ggF high-mHH



$\tau_{had}\tau_{had}$ channel, ggF high-mHH

$HH \rightarrow bb\tau\tau$

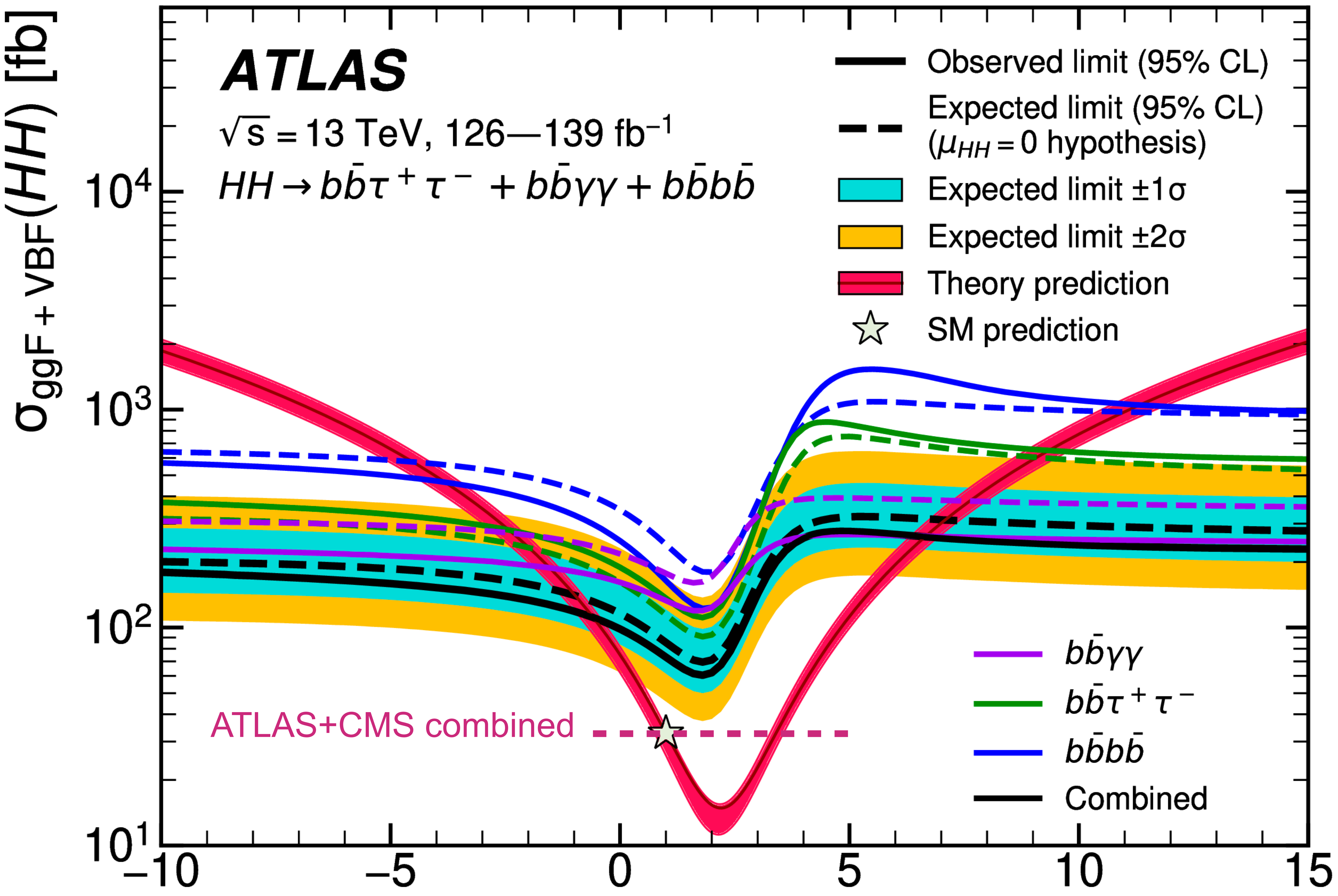
signal strength $\mu_{HH} = \sigma_{obs}/\sigma_{SM} = 2.1 \pm 1.6$



$-3.16 < \kappa_\lambda < 9.04$

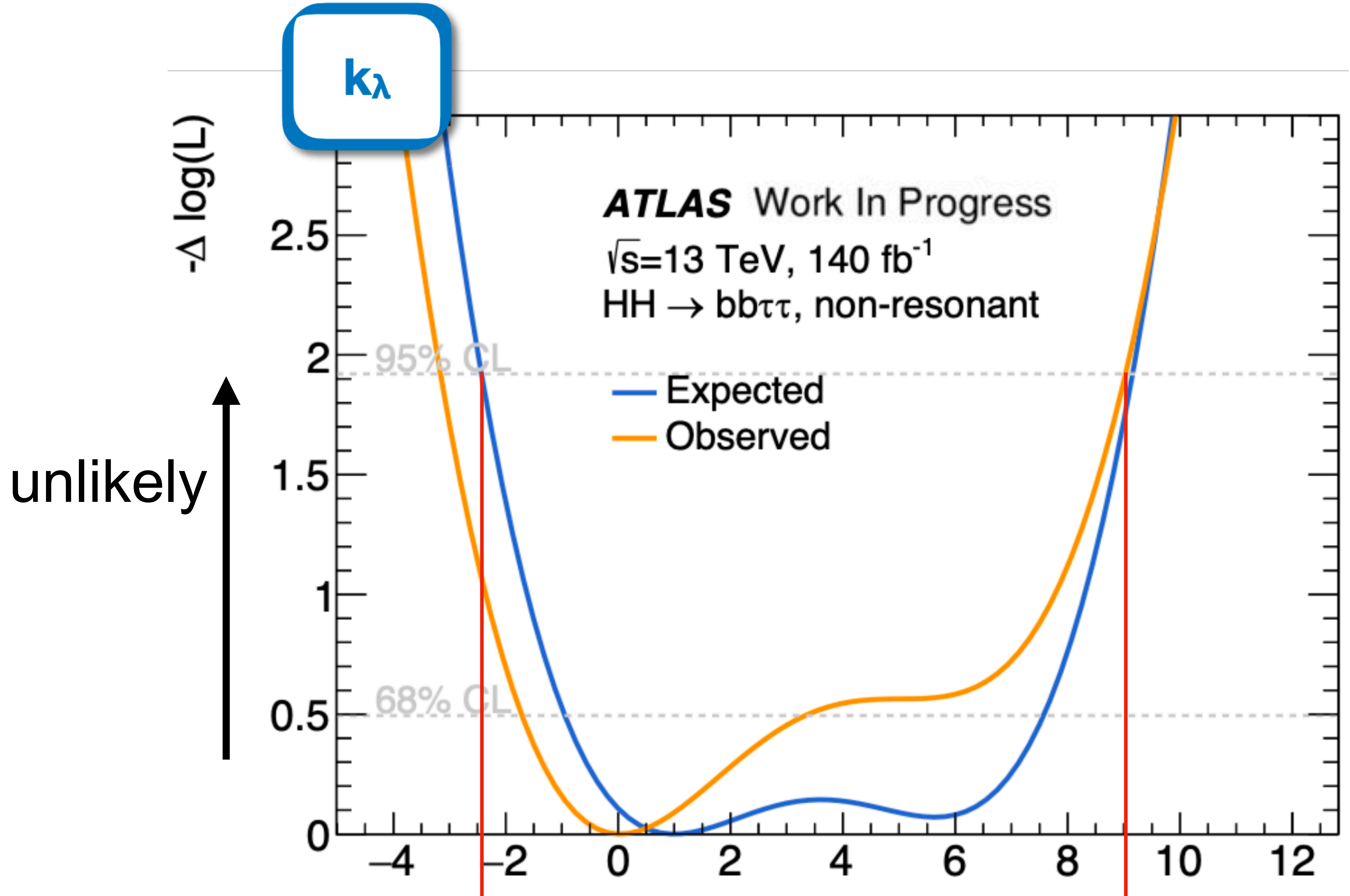
$b \rightarrow up$

$HH \to bb\tau\tau$ future



$1 < \kappa_\lambda < 3$

$HH \rightarrow bb\tau\tau$

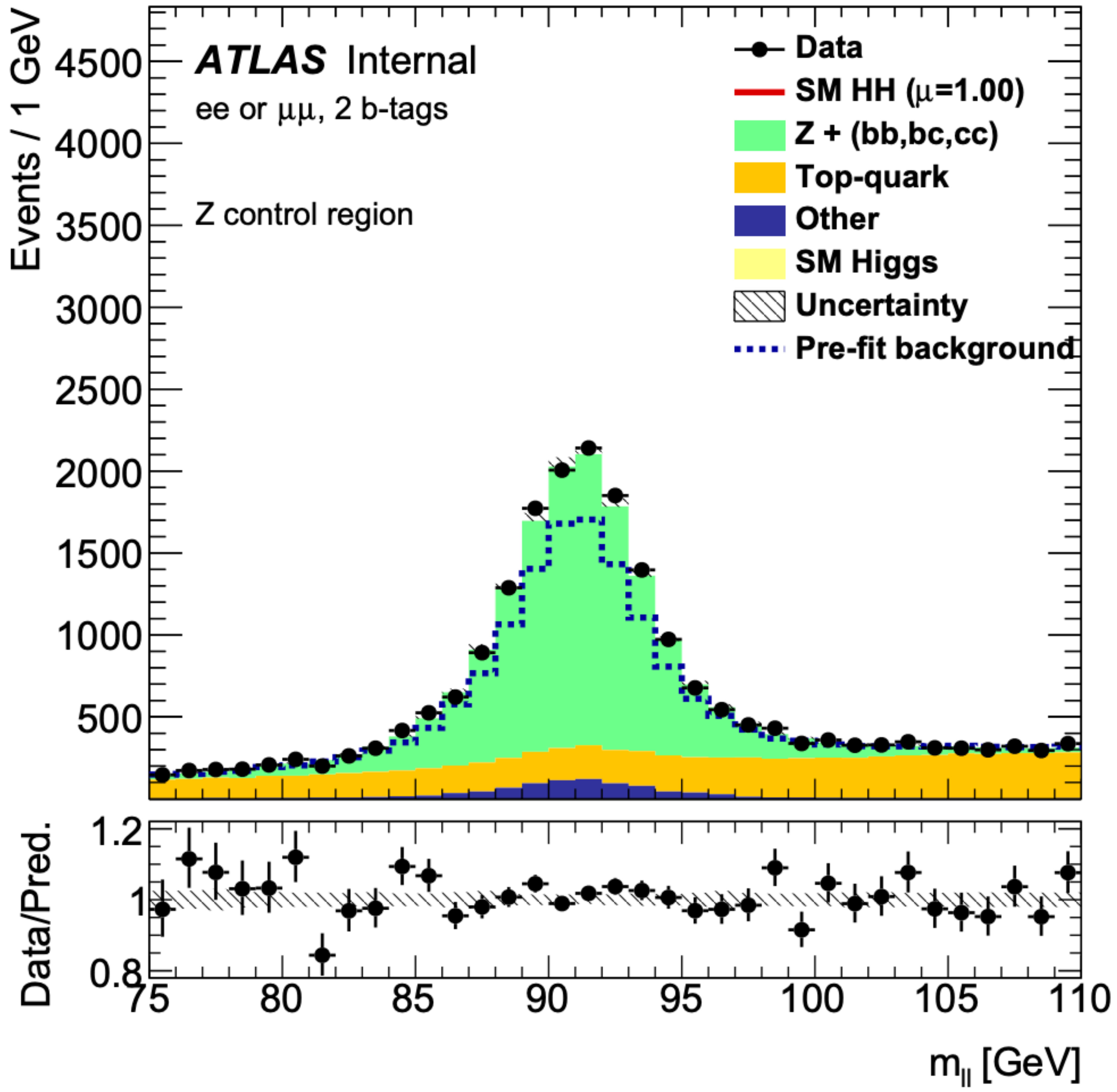


$-3.16 < \kappa_\lambda < 9.04$

Upper limit on signal strength

$\mu_{HH} = \sigma_{obs}/\sigma_{SM} = 5.8$

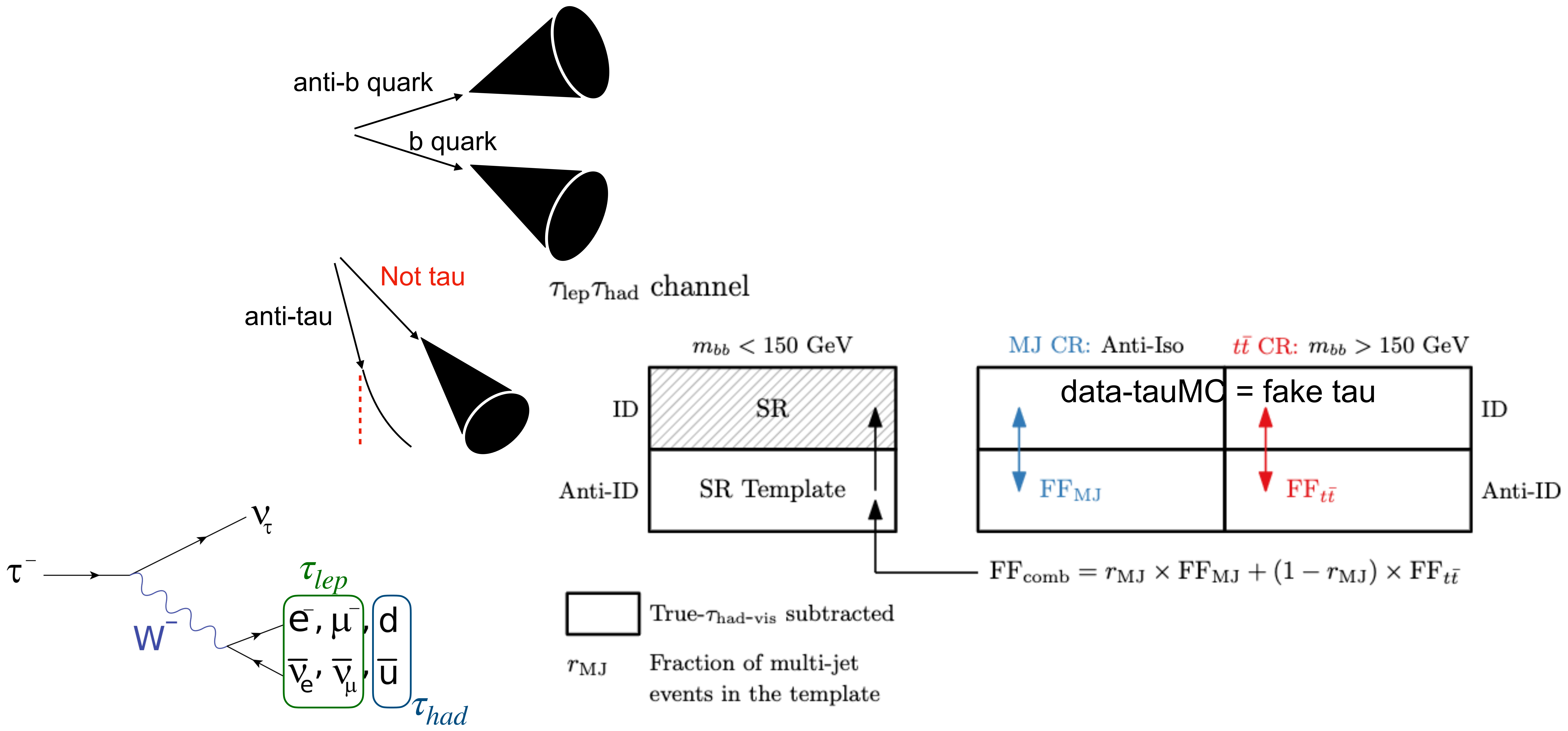
$HH \to bb\tau\tau$ something is wrong: Z+HF norm is off.



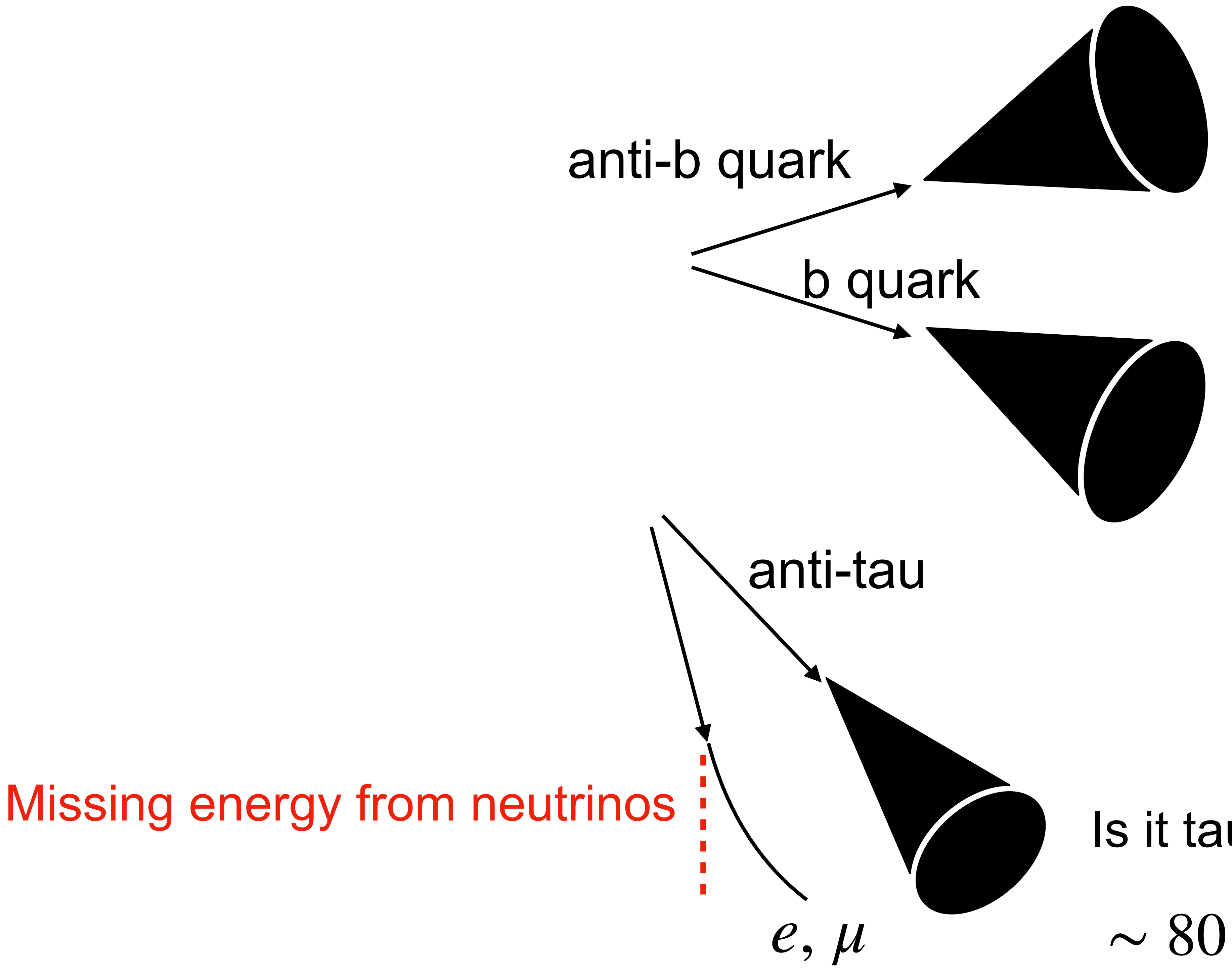
- Events selected with $bb\ell\ell$ trigger selection using single-lepton and di-lepton triggers (see Section 3.1 of Ref. [72]);
- Exactly two muons or two electrons with opposite-sign charges;
- Exactly two b-tagged jets (using DL1r tagger and 77% working point);
- 75 GeV < $m_{\ell\ell}$ < 110 GeV (select Z mass peak);
- m_{bb} < 40 GeV or m_{bb} > 210 GeV (to veto Higgs mass peak and to ensure orthogonality to $bb\ell\ell$ signal region);
- leading b-jet p_T > 45 GeV;
- lepton p_T > 40 GeV.

$HH \rightarrow bb\tau\tau$ fake tau-had

ID: $\tau_{had-vis}$ passed RNN 'loose' WP
Anti-ID: $\tau_{had-vis}$ failed RNN 'loose' WP & RNN score > 0.01
$\tau_{had-vis}$: reconstructed τ_{had} candidate with BDT on track vars.

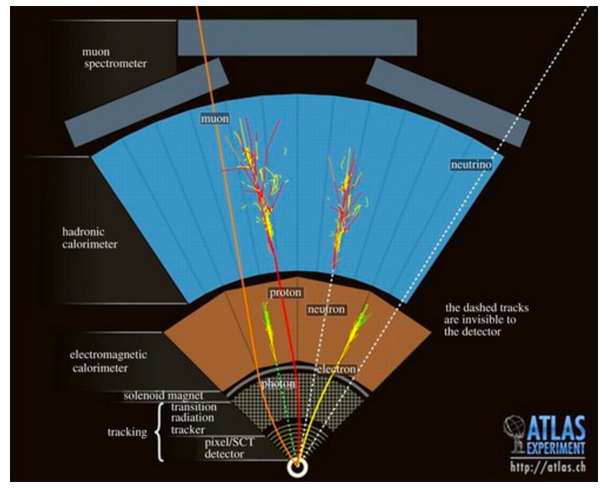


$HH \to bb\tau\tau$ event and objects



Is it b-jet? DL1r (deep learning algorithm)

b-tagging cut: 77% are accepted

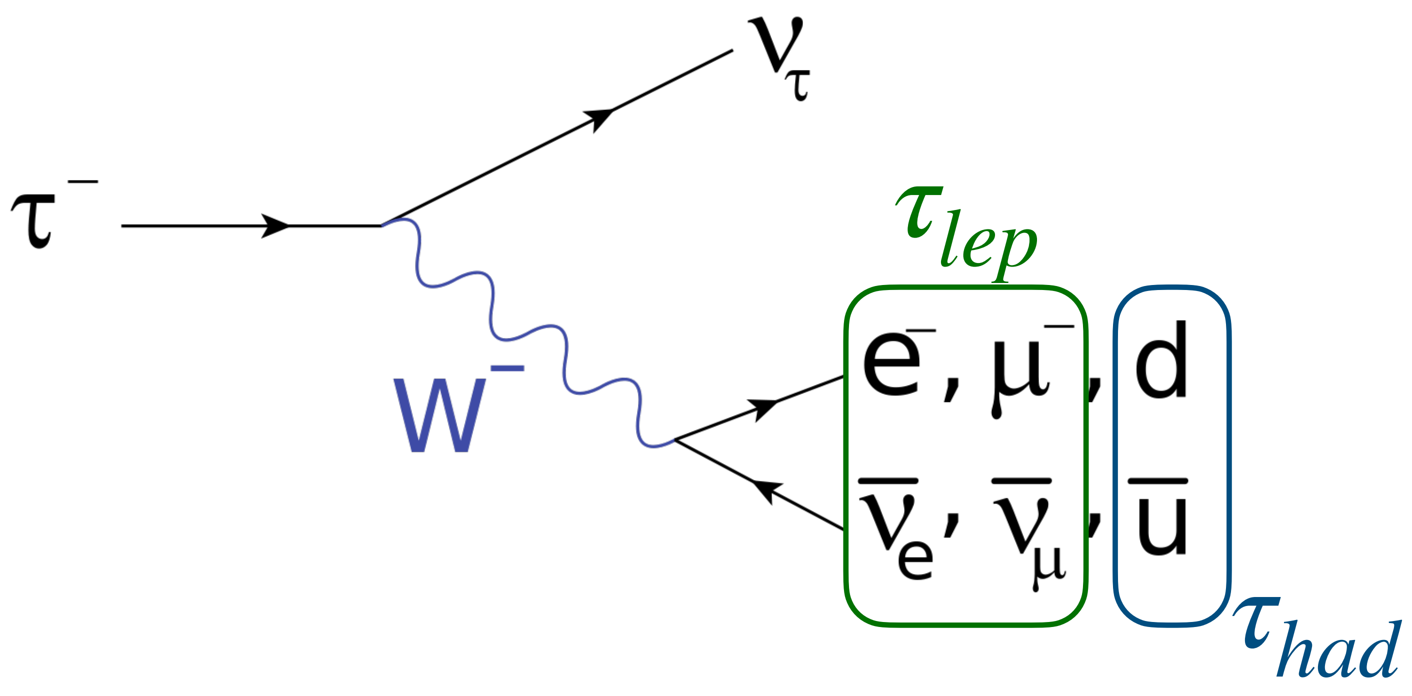


- \+ cuts for quality of objects (p_T, η)
- \+ Triggers: (STT, DTT, SLT, LTT)
- \+ cuts to reduce background:

$m_{\tau\tau} > 60\ GeV$, $m_{bb} < 150\ GeV$

Is it tau-jet? $\sim 80\,\%$ tau jets are accepted

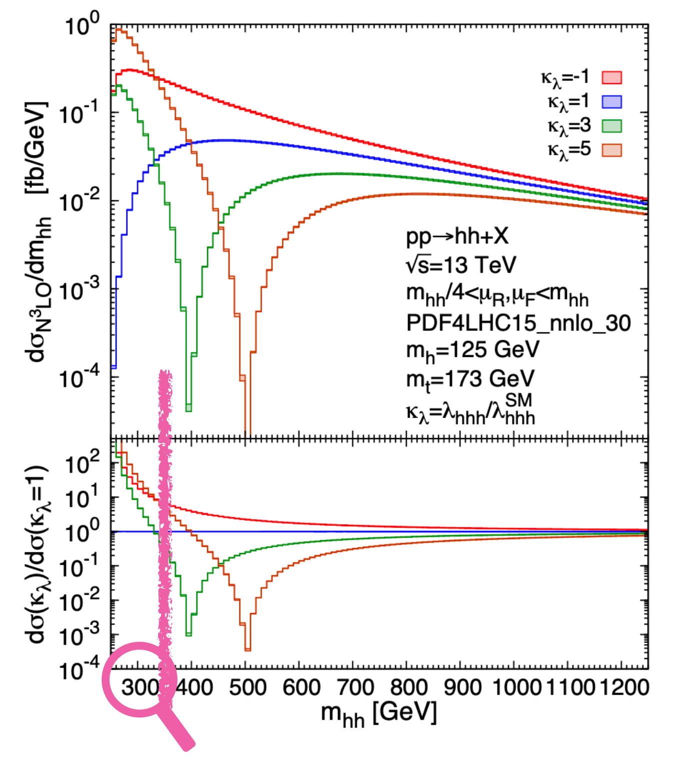
$\sim 80\,\%$ of electrons are accepted



$\tau_{had}\tau_{had}$ channel	~ 140 events	$\to 6$ events
$\tau_{lep}\tau_{had}$ channel	~ 150 events	$\to 7$ events

ok…

$HH \to bb\tau\tau$ MVA analysis



Train the BDT on Monte Carlo samples.
Train on $\kappa_\lambda = 10$ for low-mHH, and $\kappa_\lambda = 1$ for low-mHH

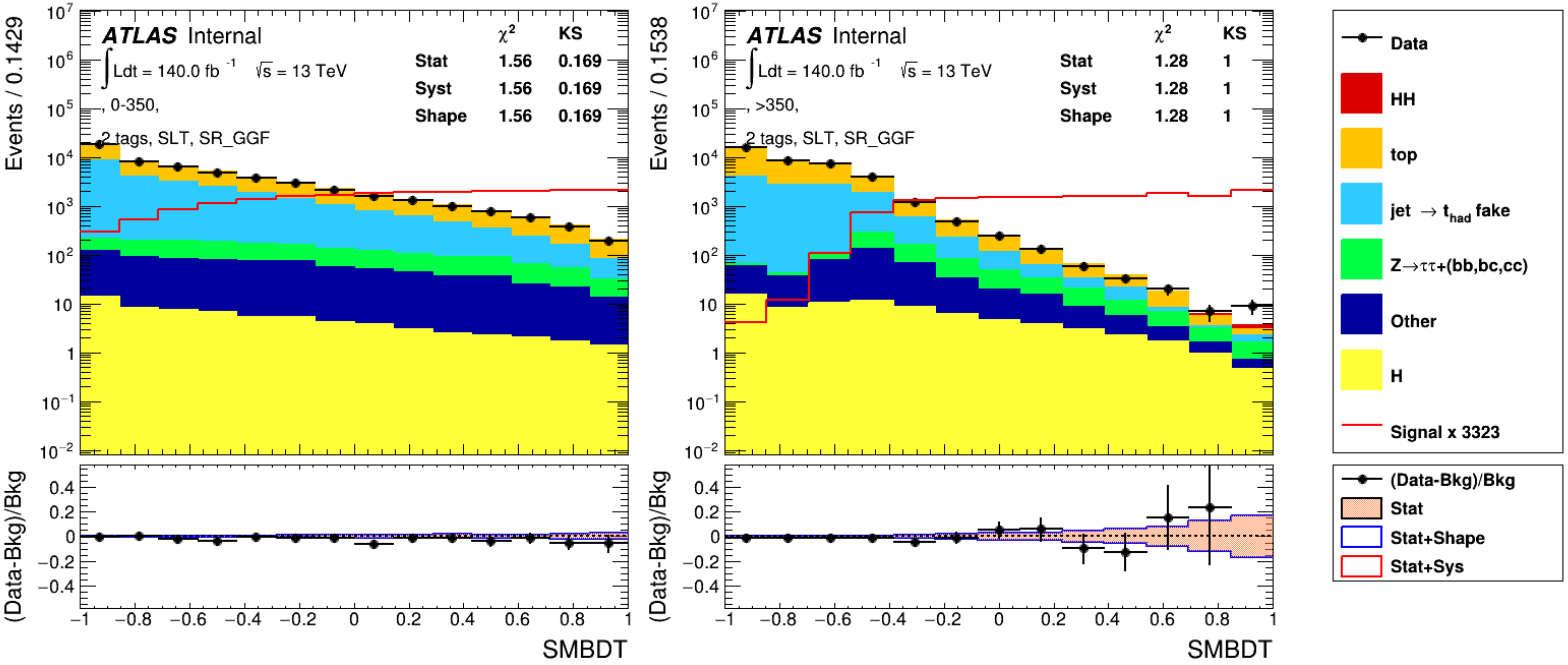
inputs

m_{HH}
$m_{\tau\tau}$
m_{bb}
$\Delta R(b, b)$
$\Delta R(\tau, \tau)$
+ ...

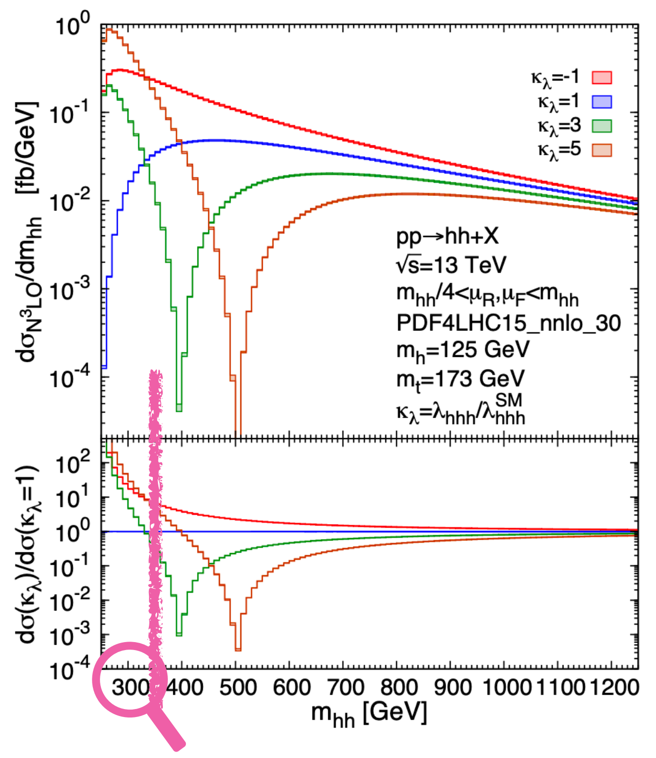
Boosted Decision Tree (BDT)

$\tau_{lep}\tau_{had}$ channel, ggF low-mHH

$\tau_{lep}\tau_{had}$ channel, ggF high-mHH



$HH \rightarrow bb\tau\tau$ MVA analysis



inputs

m_{HH}

$m_{\tau\tau}$

m_{bb}

$\Delta R(b, b)$

$\Delta R(\tau, \tau)$

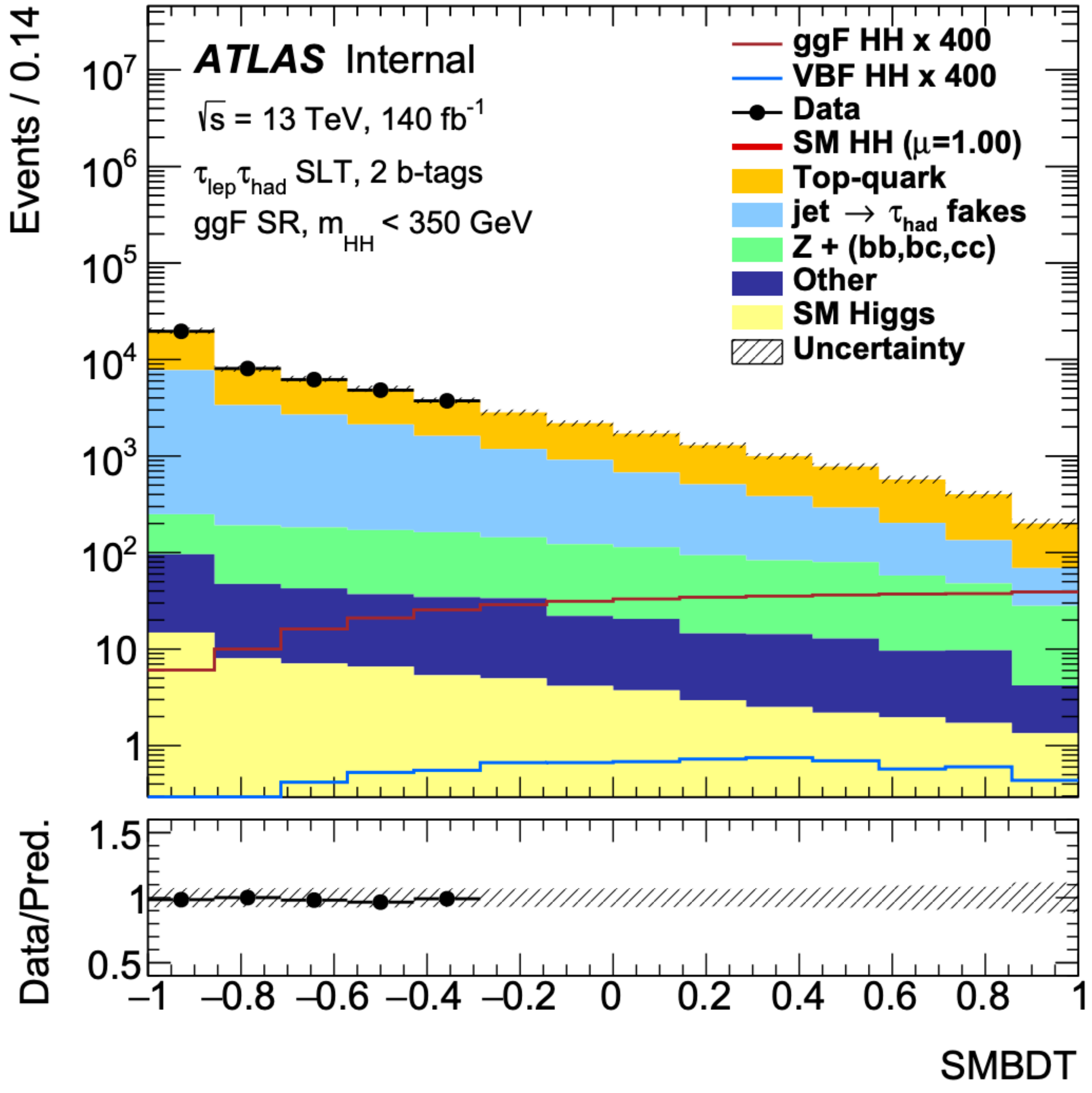
$+ \ldots$

Boosted Decision Tree (BDT) →

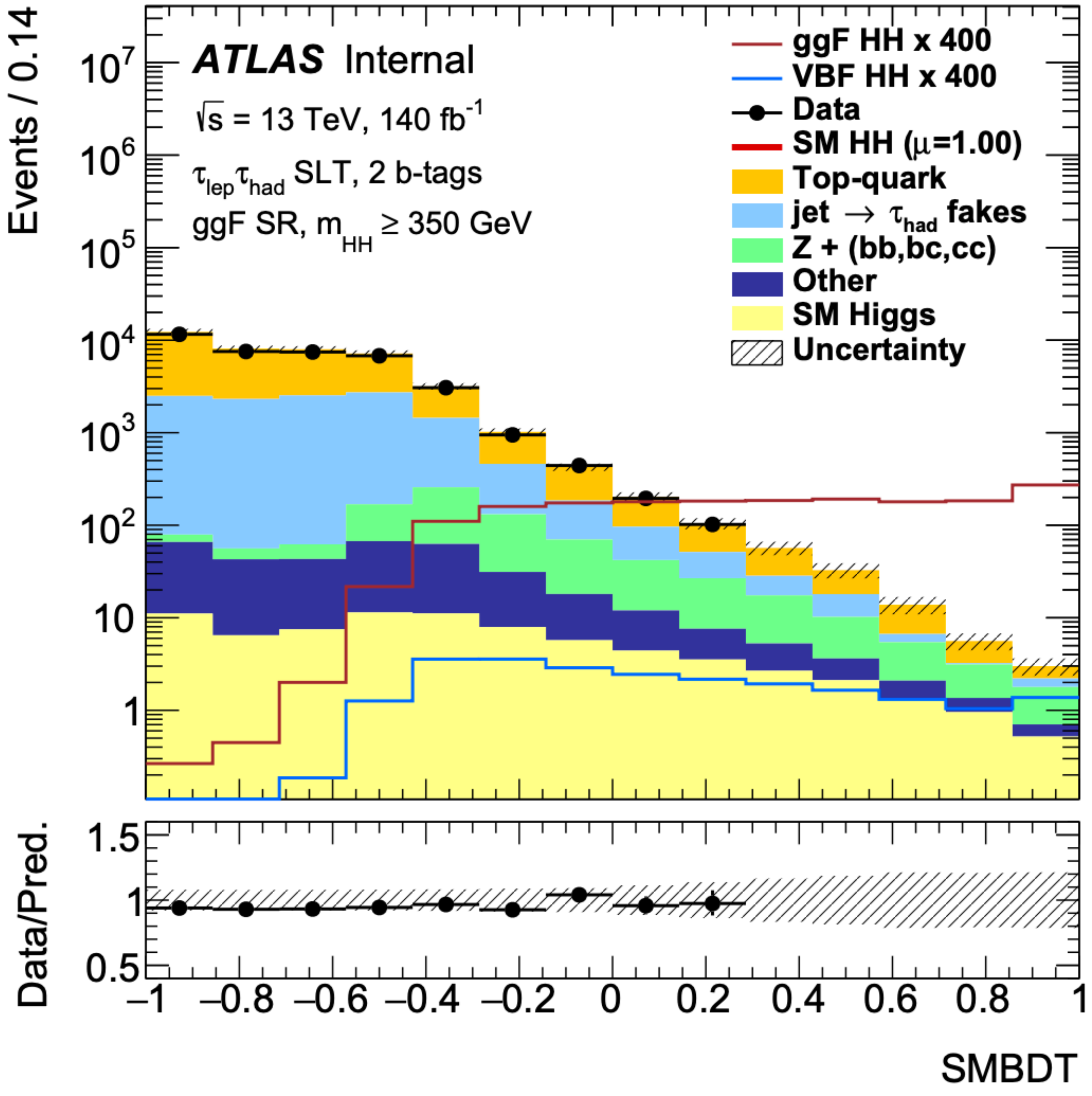
Train the BDT on Monte Carlo samples.

Train on $\kappa_\lambda = 10$ for low-mHH, and $\kappa_\lambda = 1$ for low-mHH

$\tau_{lep}\tau_{had}$ channel, ggF low-mHH



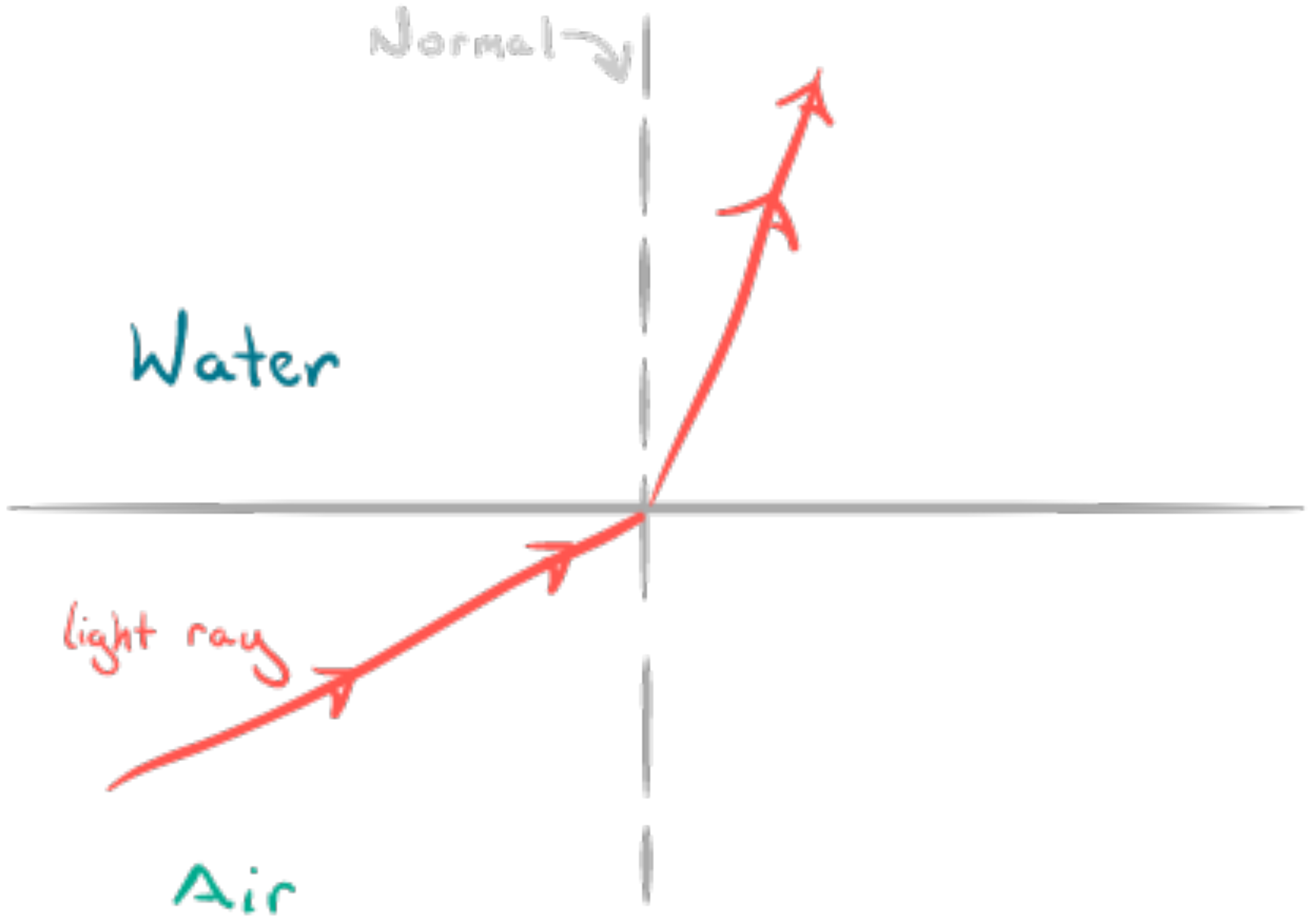
$\tau_{lep}\tau_{had}$ channel, ggF high-mHH



$HH \to bb\tau\tau$ bdt distributions

$HH \to bb\tau\tau$ fit on bdt distributions!

Massive Z particles? Add Higgs ;)



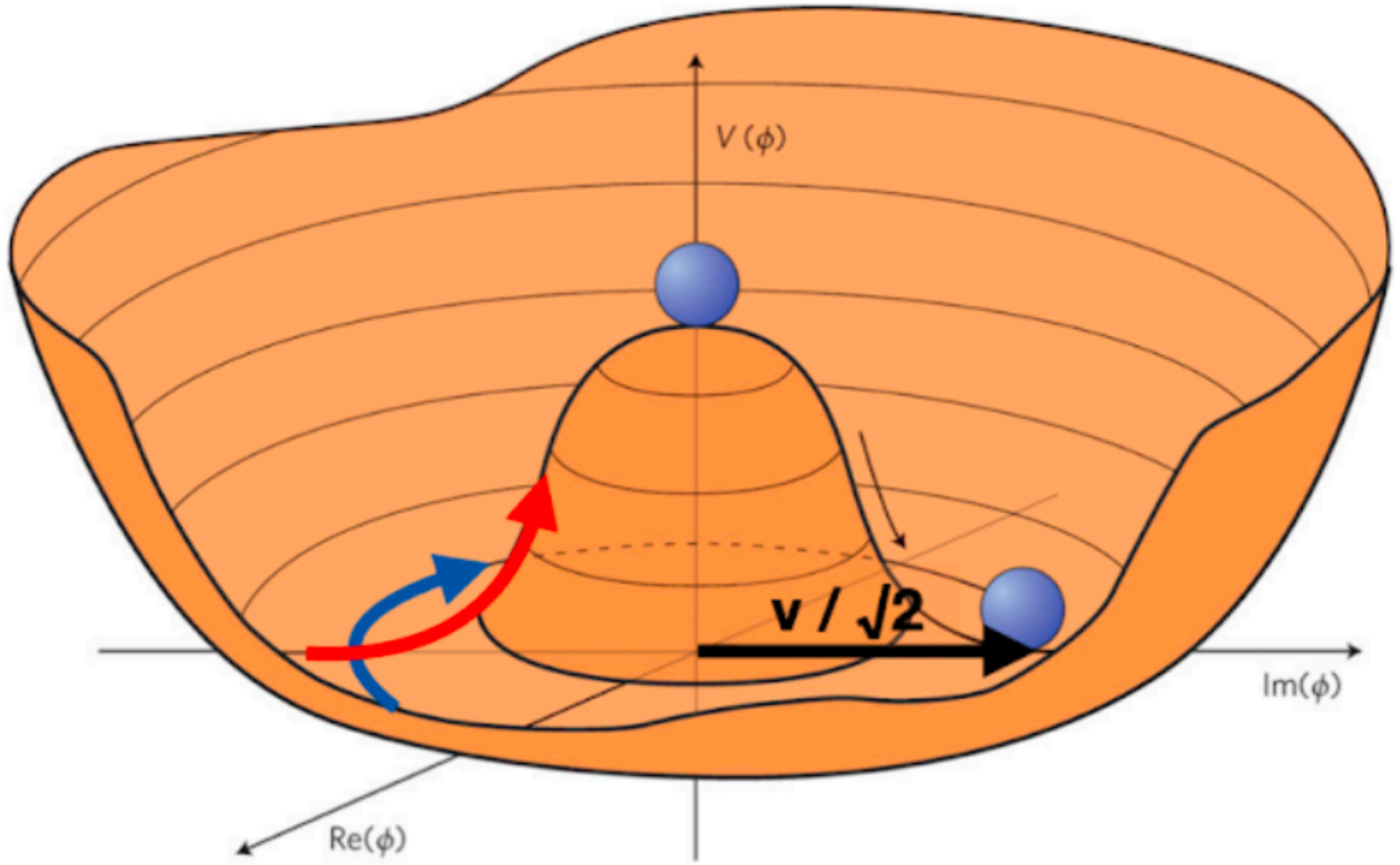
Bosons

Interact with Higgs

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi)$$

$$\Phi \neq 0$$

Massive Z particles? Add Higgs ;)



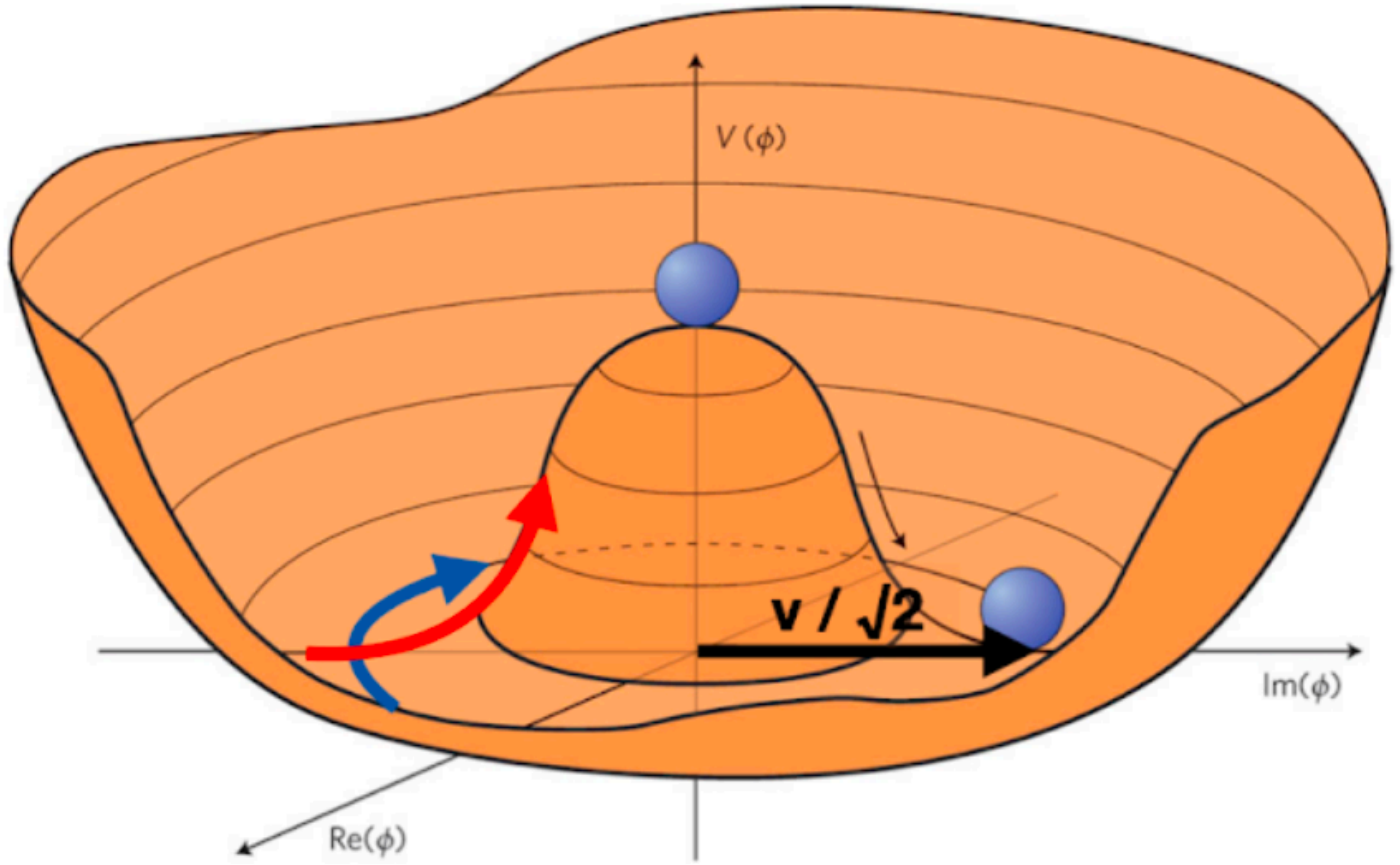
Bosons — Interact with Higgs — Higgs potential

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi)$$

$$\Phi \neq 0$$

Shape of Higgs

Standard Model: simplest shape that works.



$V(\Phi) =$

$+?$

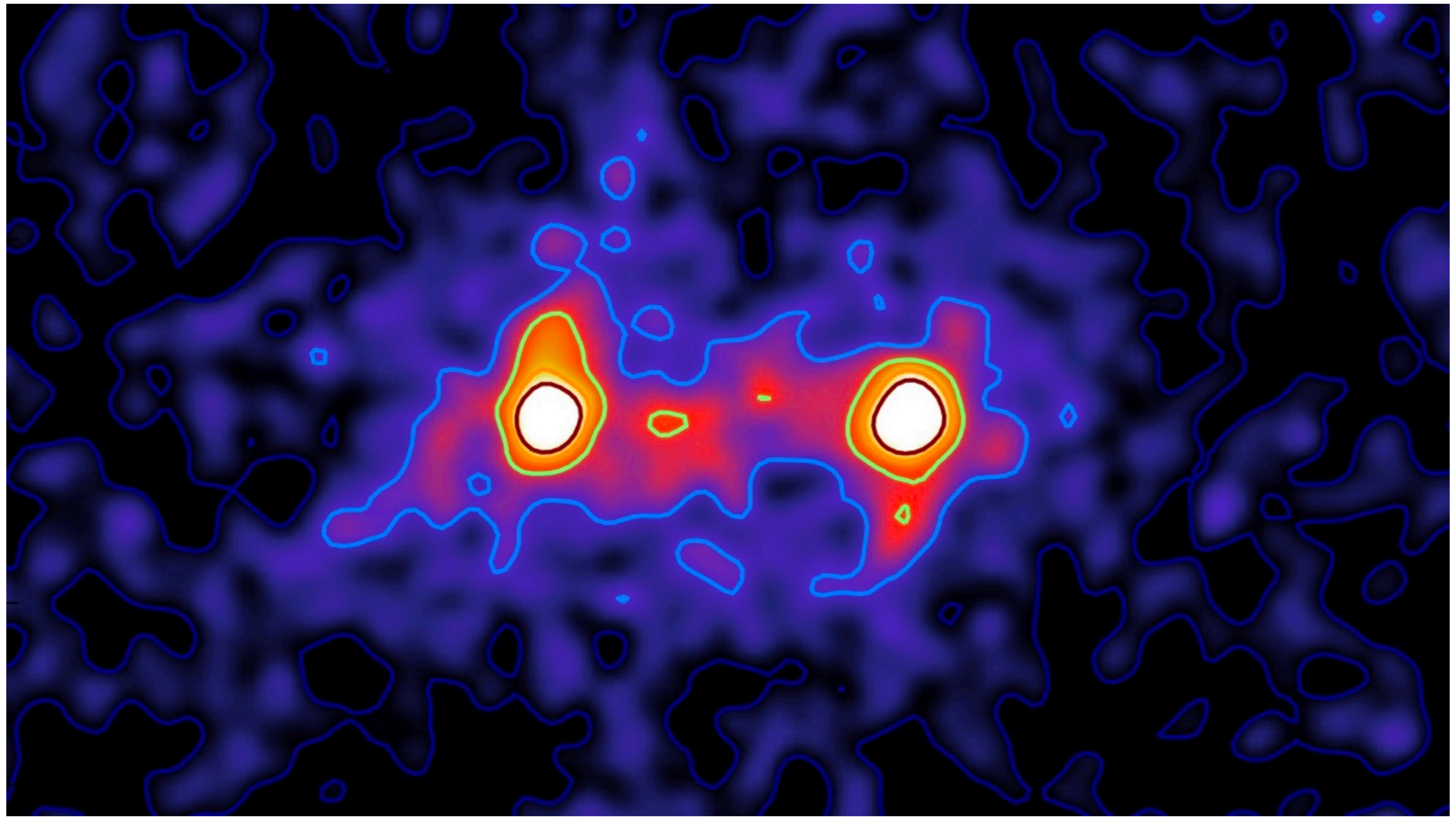
Shape of Higgs

Standard Model: simplest shape that works.

Many reasons to believe there's more:

- Need new massive particles to explain Dark Matter

$V(\Phi) =$  $+?$



+ *Dark matter interacting with Higgs?*

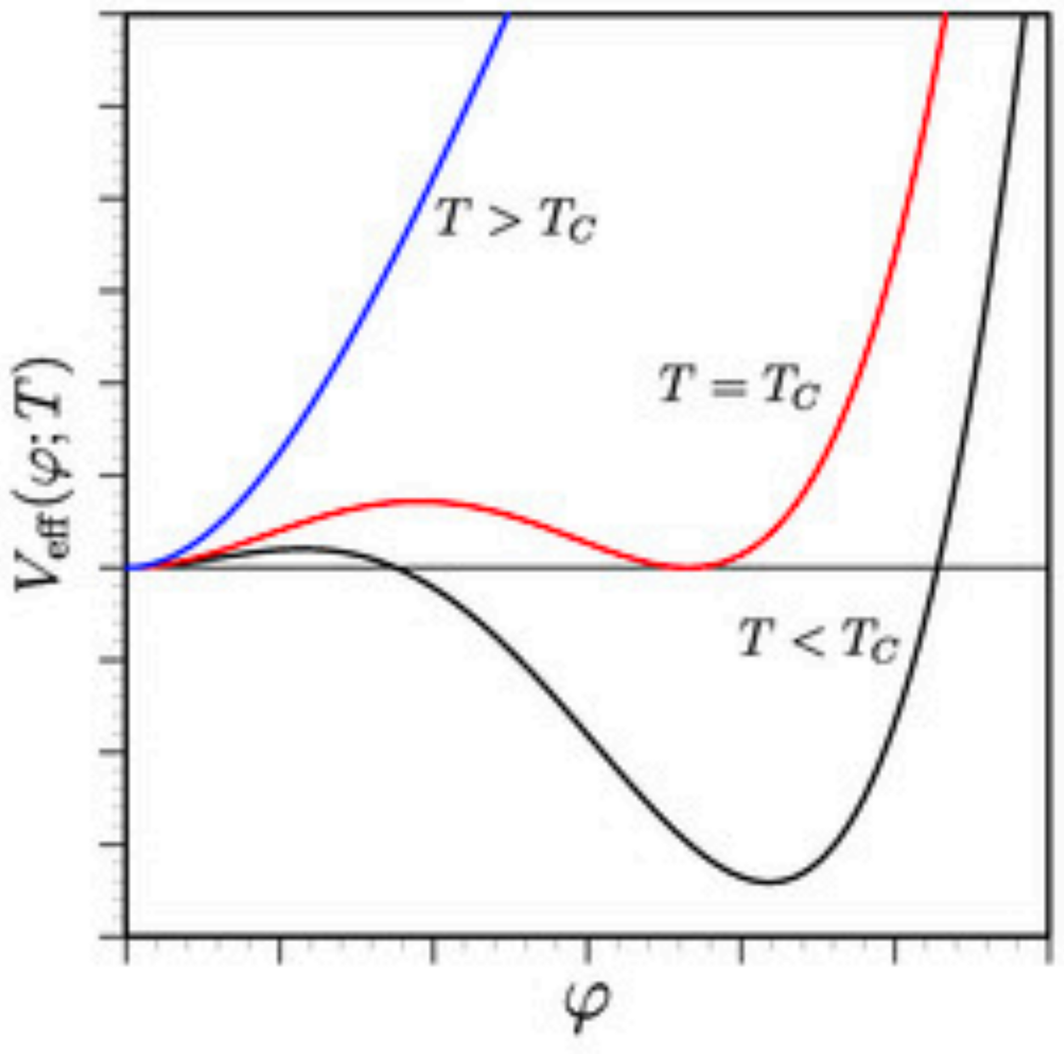
Shape of Higgs

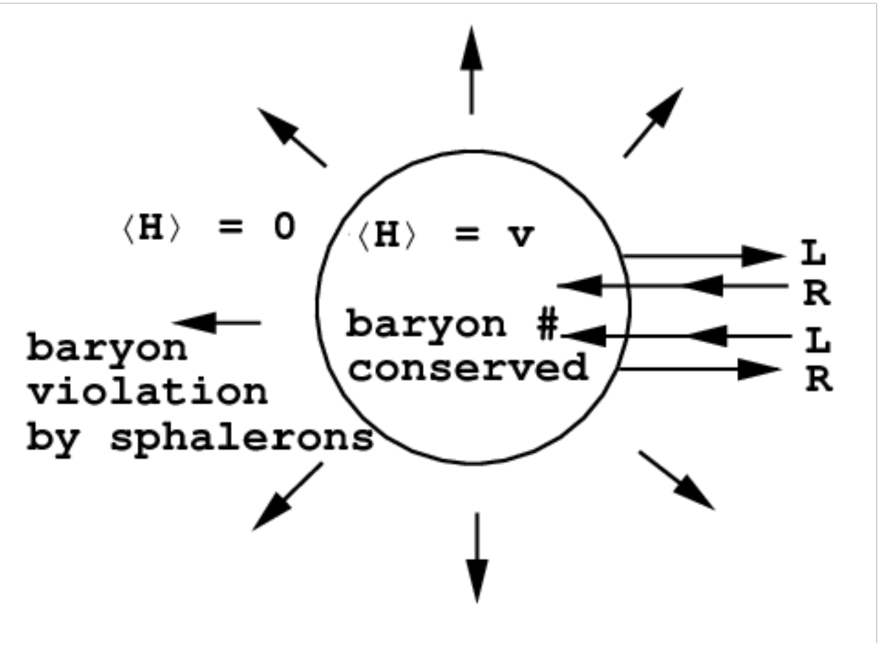
Standard Model: simplest shape that works.

Many reasons to believe there's more:

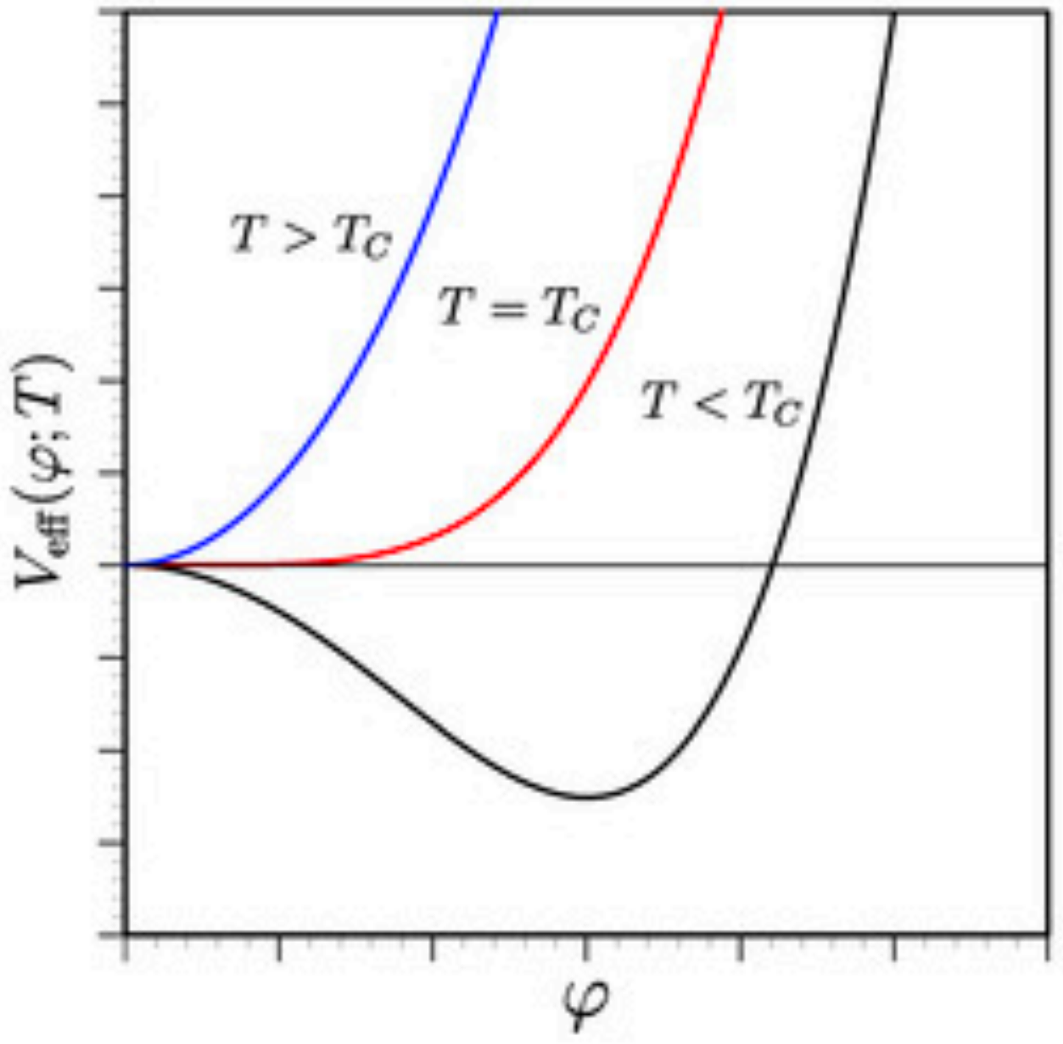
- Need new massive particles to explain Dark Matter
- Matter-antimatter asymmetry

$V(\Phi) =$  $+ ?$



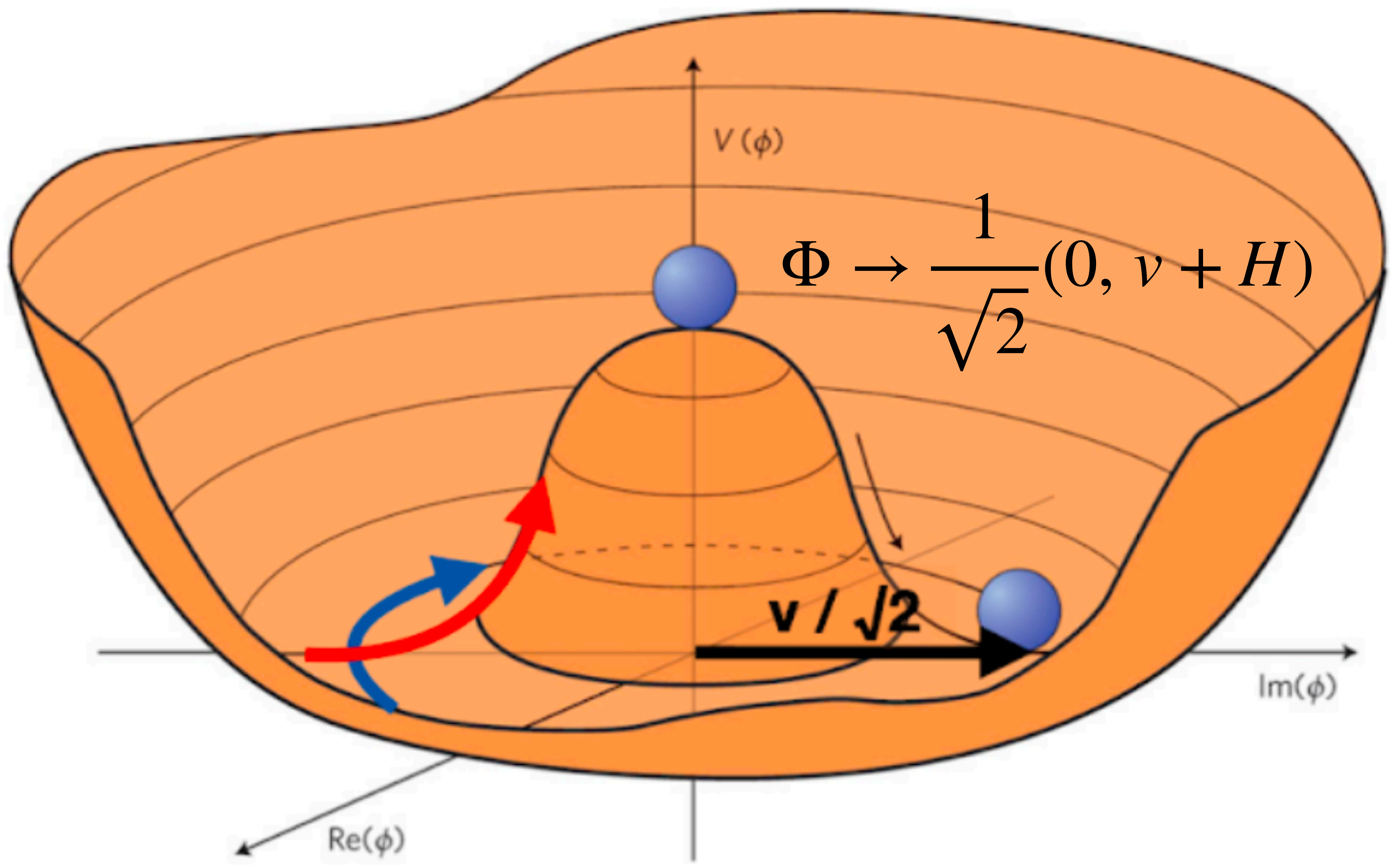


+ new interactions?



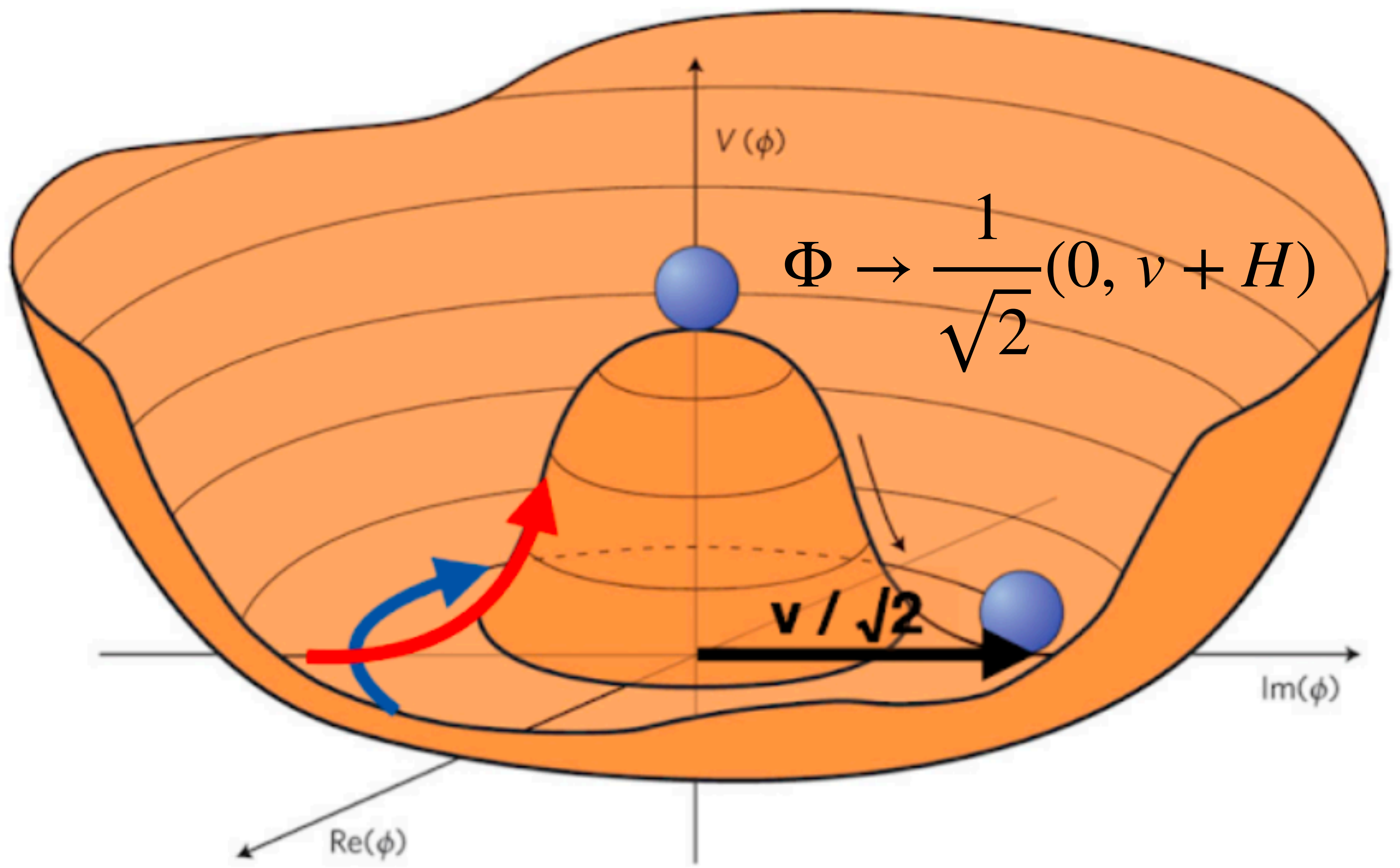
Standard Model
No bubbles
No matter

Why look for 2 Higgs particles

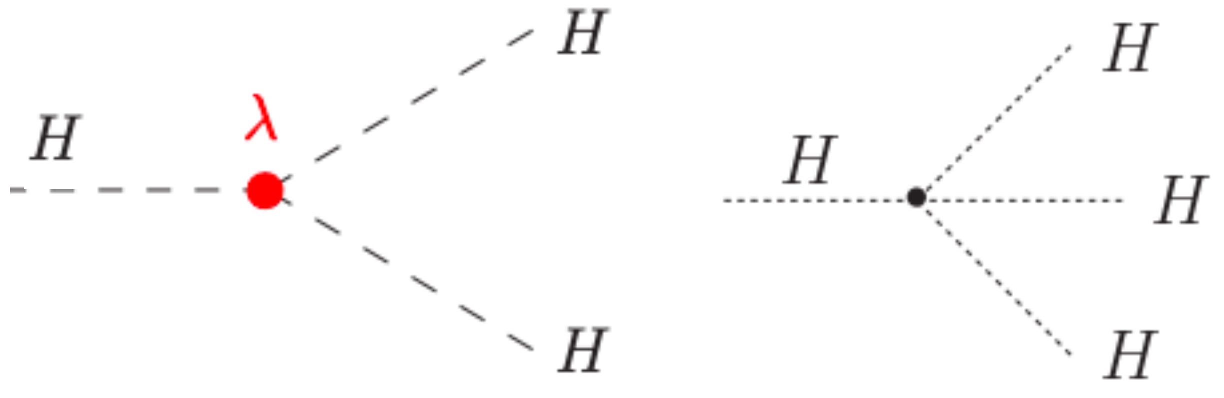


$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4$$

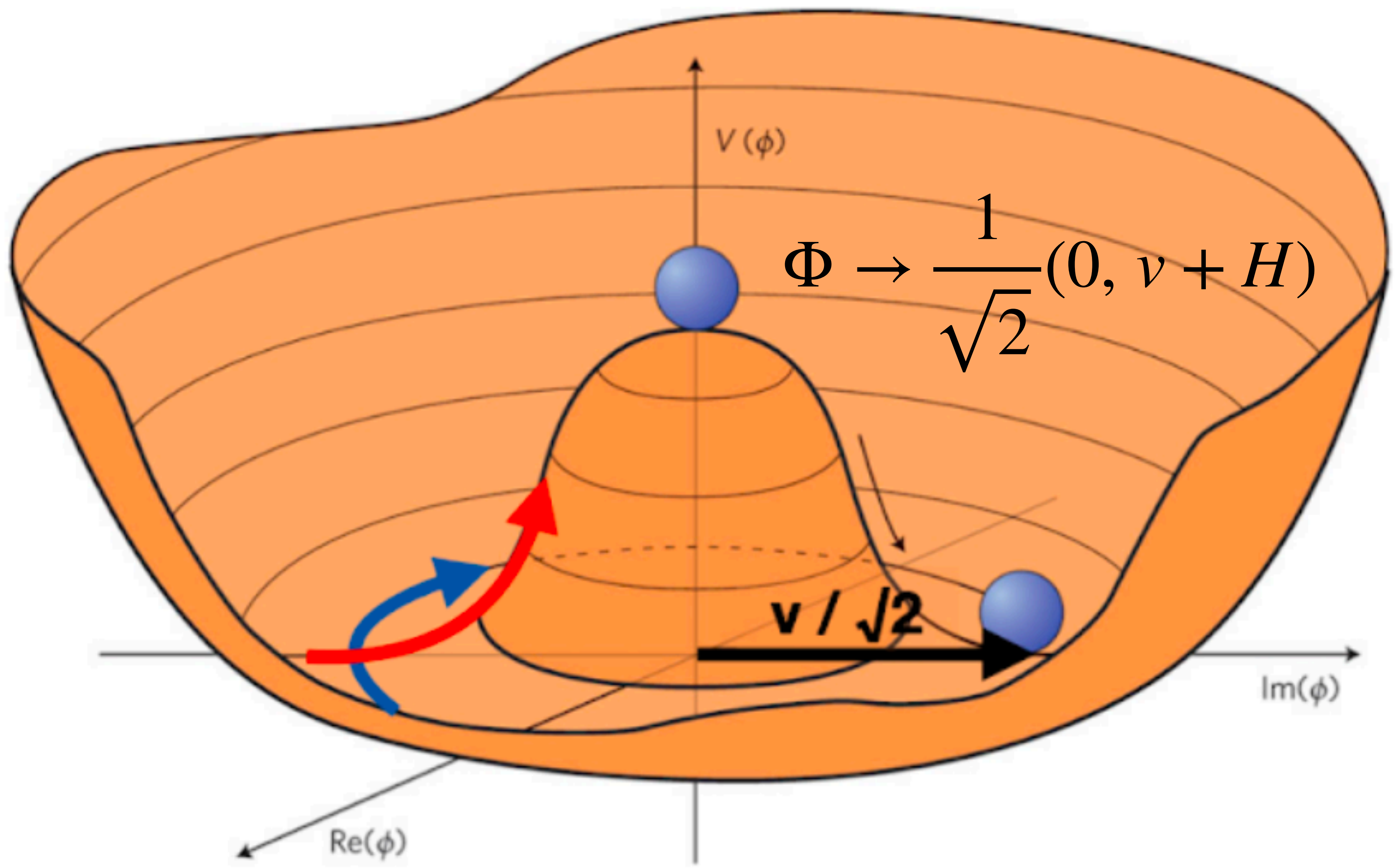
Why look for 2 Higgs particles



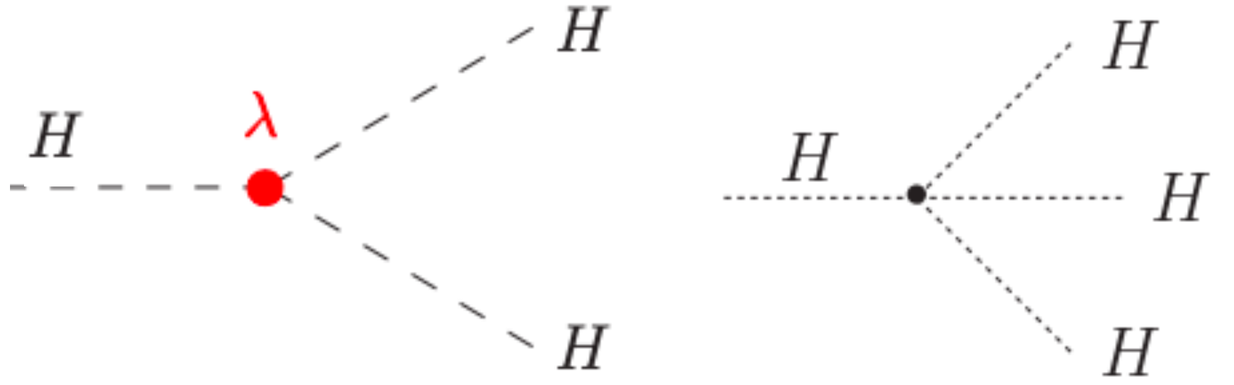
$$V(H) = \frac{1}{2} m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4} \lambda_{\mathrm{HHHH}} H^4$$

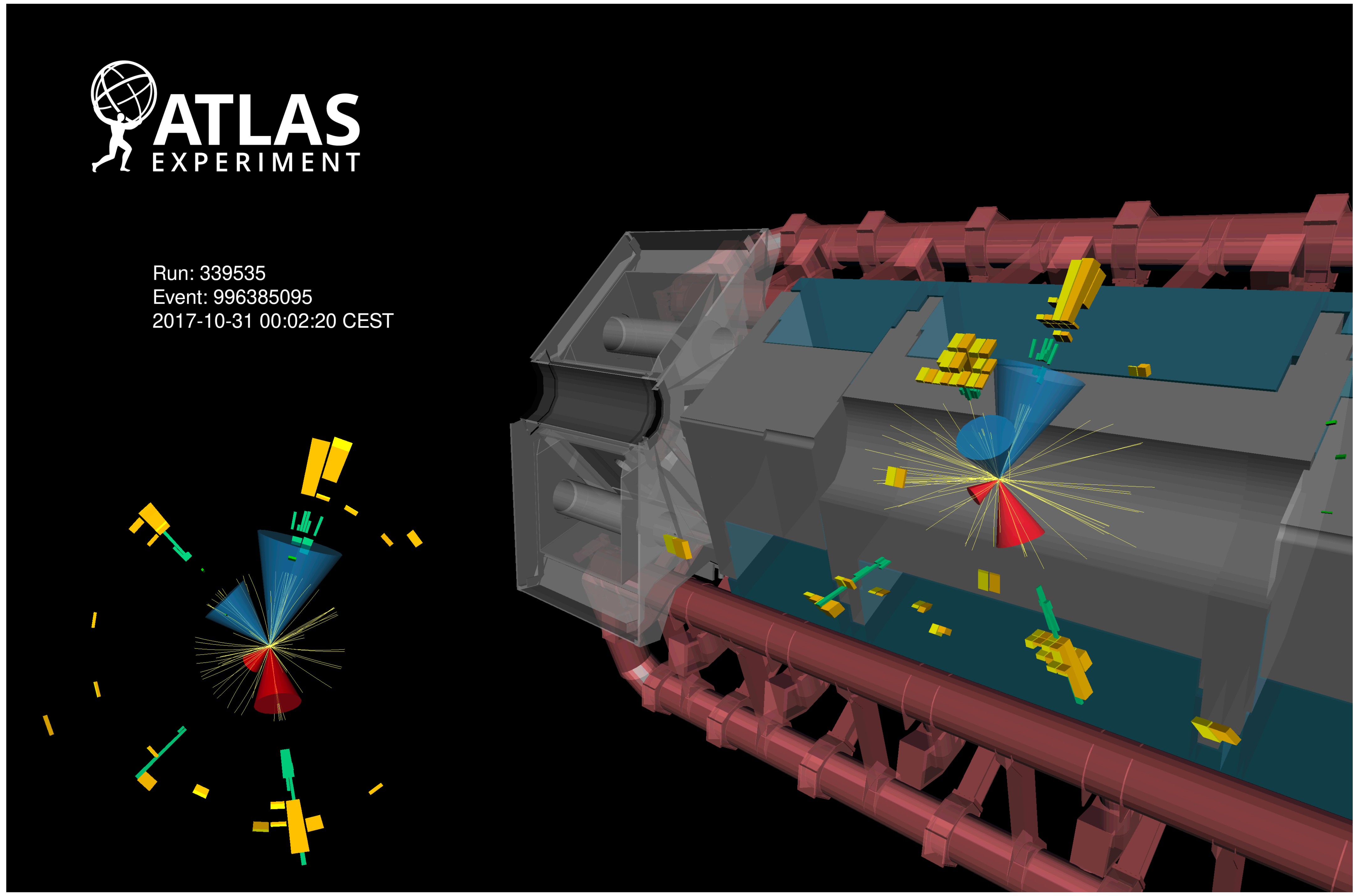


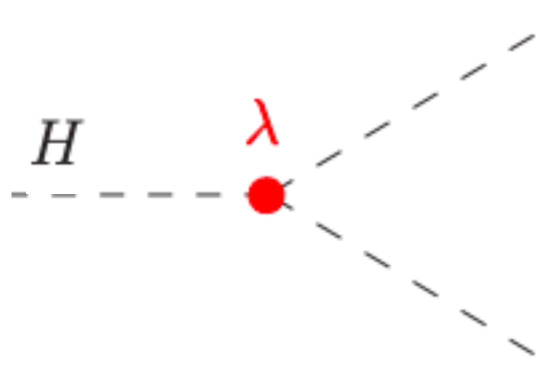
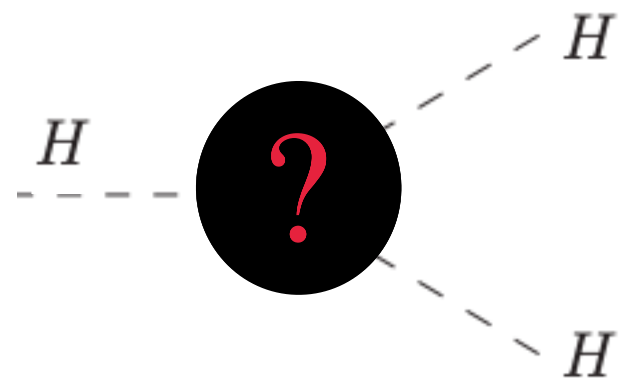
Why look for 2 Higgs particles



$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4$$

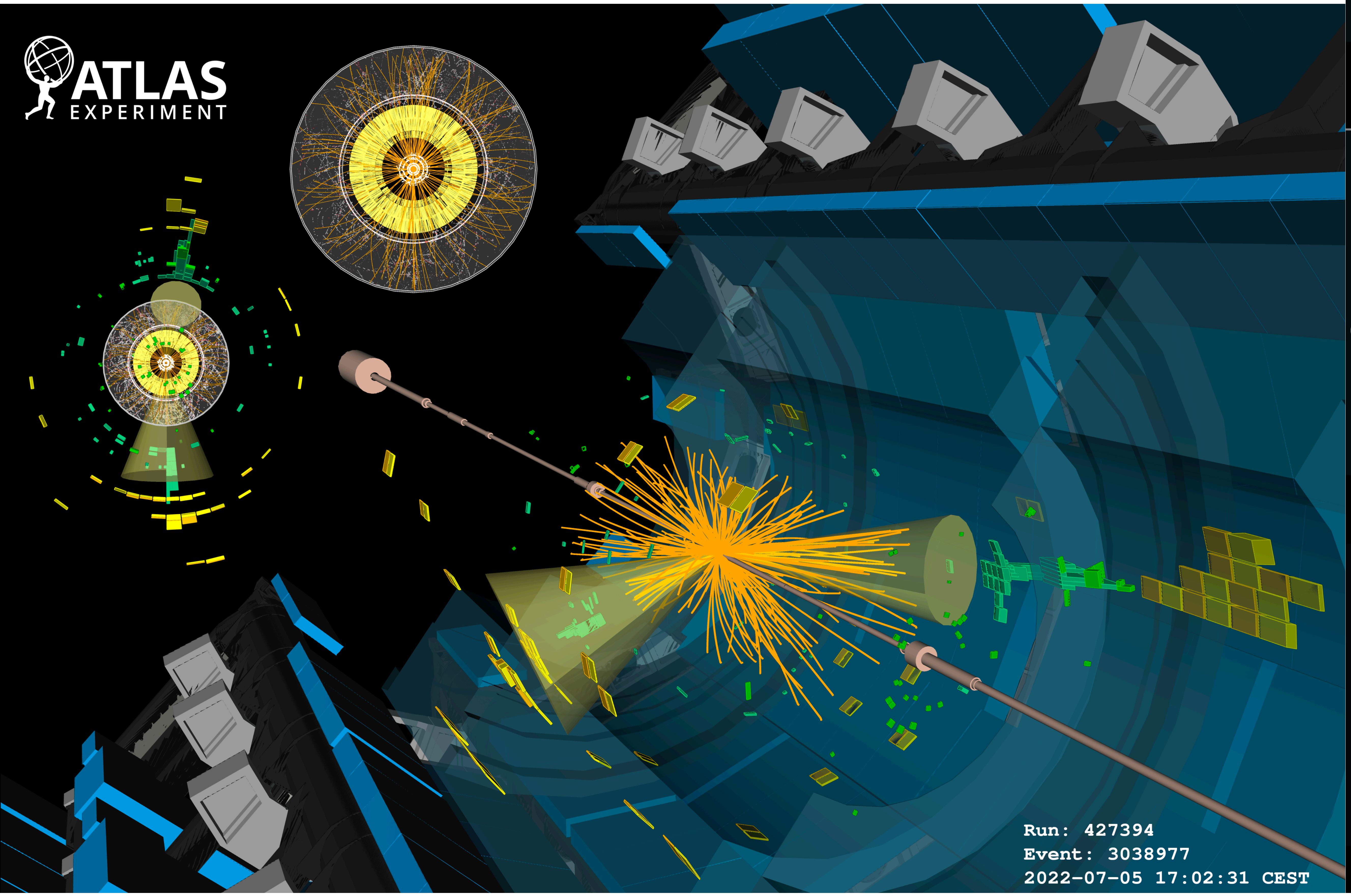


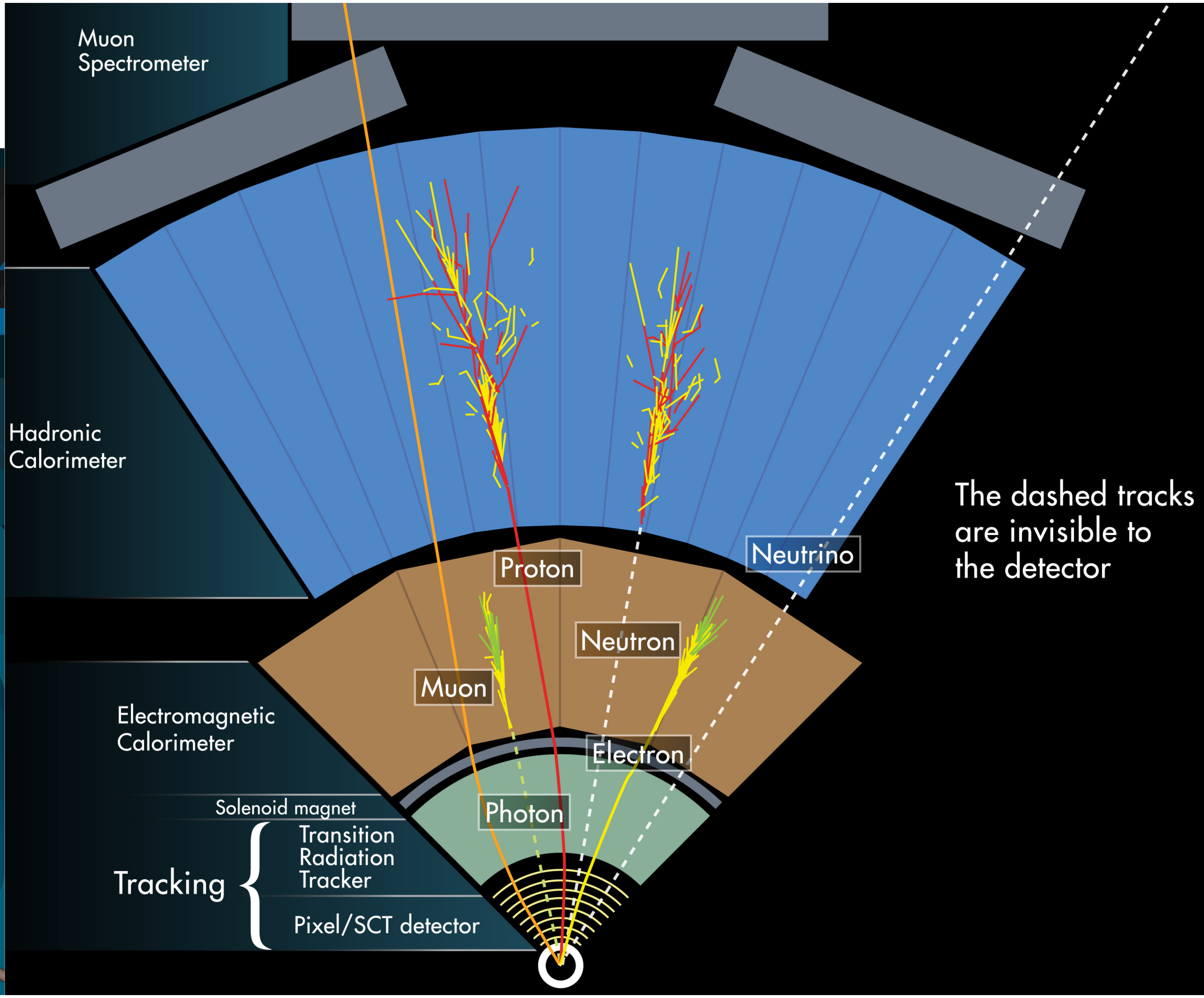


λ_{HHH} =  + 

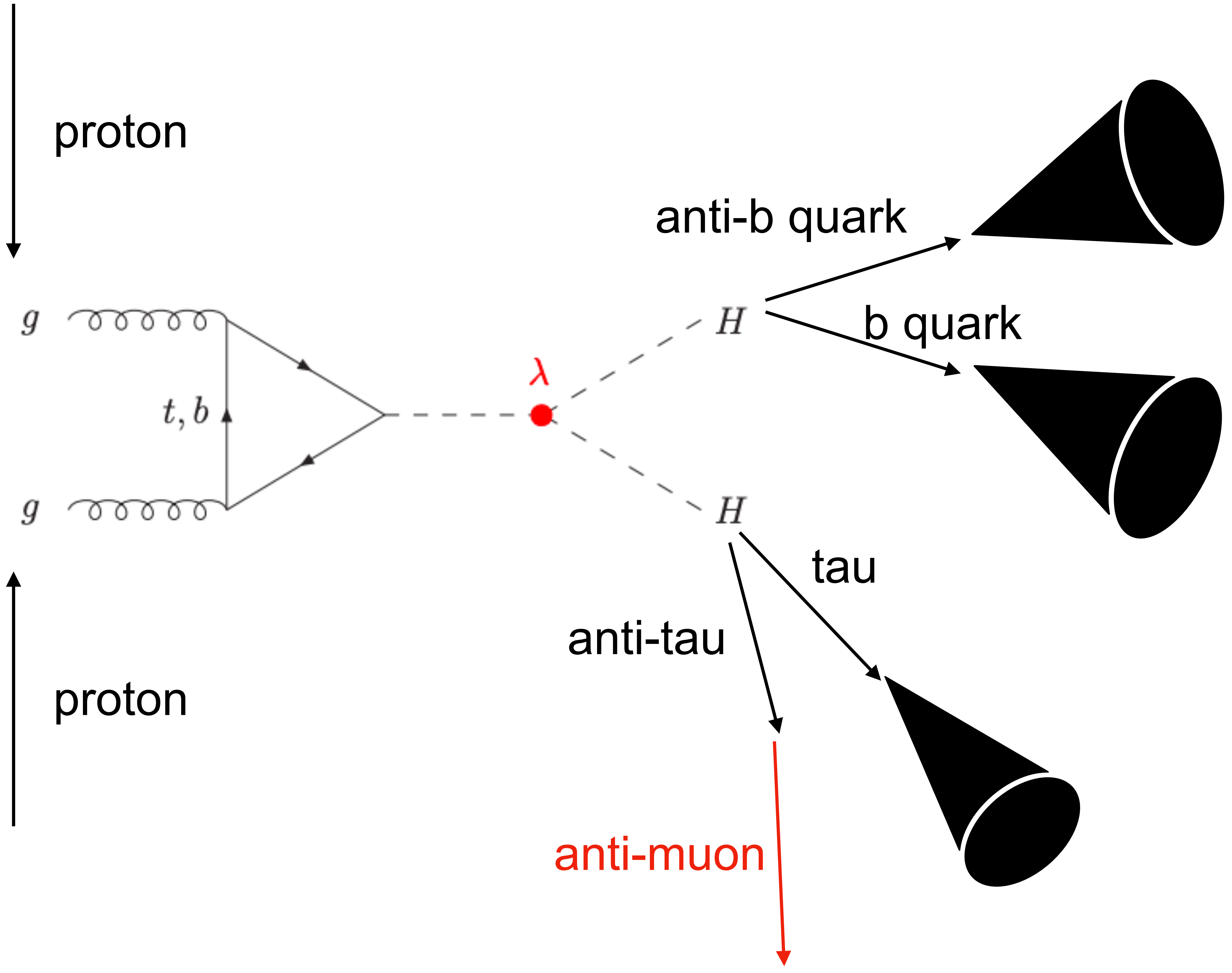
Measurement *Standard Model* *New physics*

LHC and ATLAS





2 Higgs in ATLAS



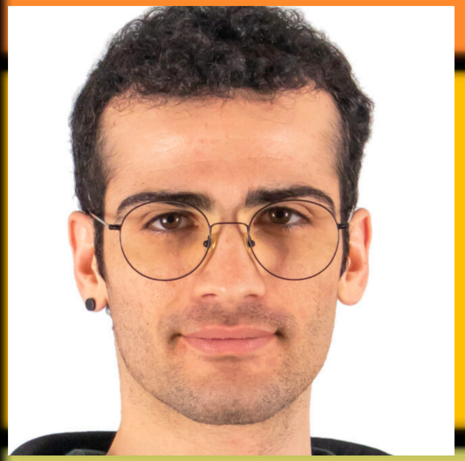
Large branching ratio ⟷ Clean final state

	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 %

2 Higgs at Nikhef





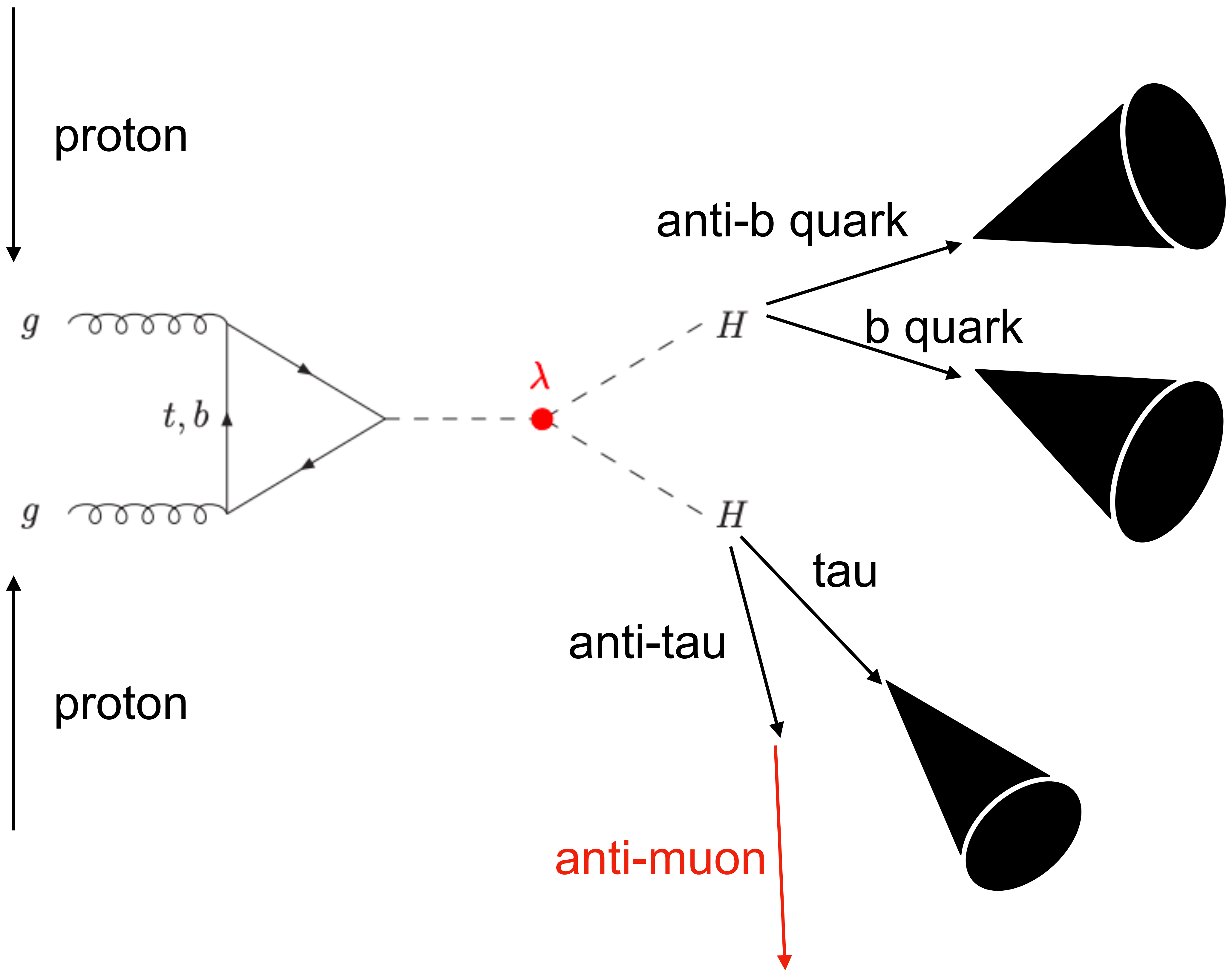


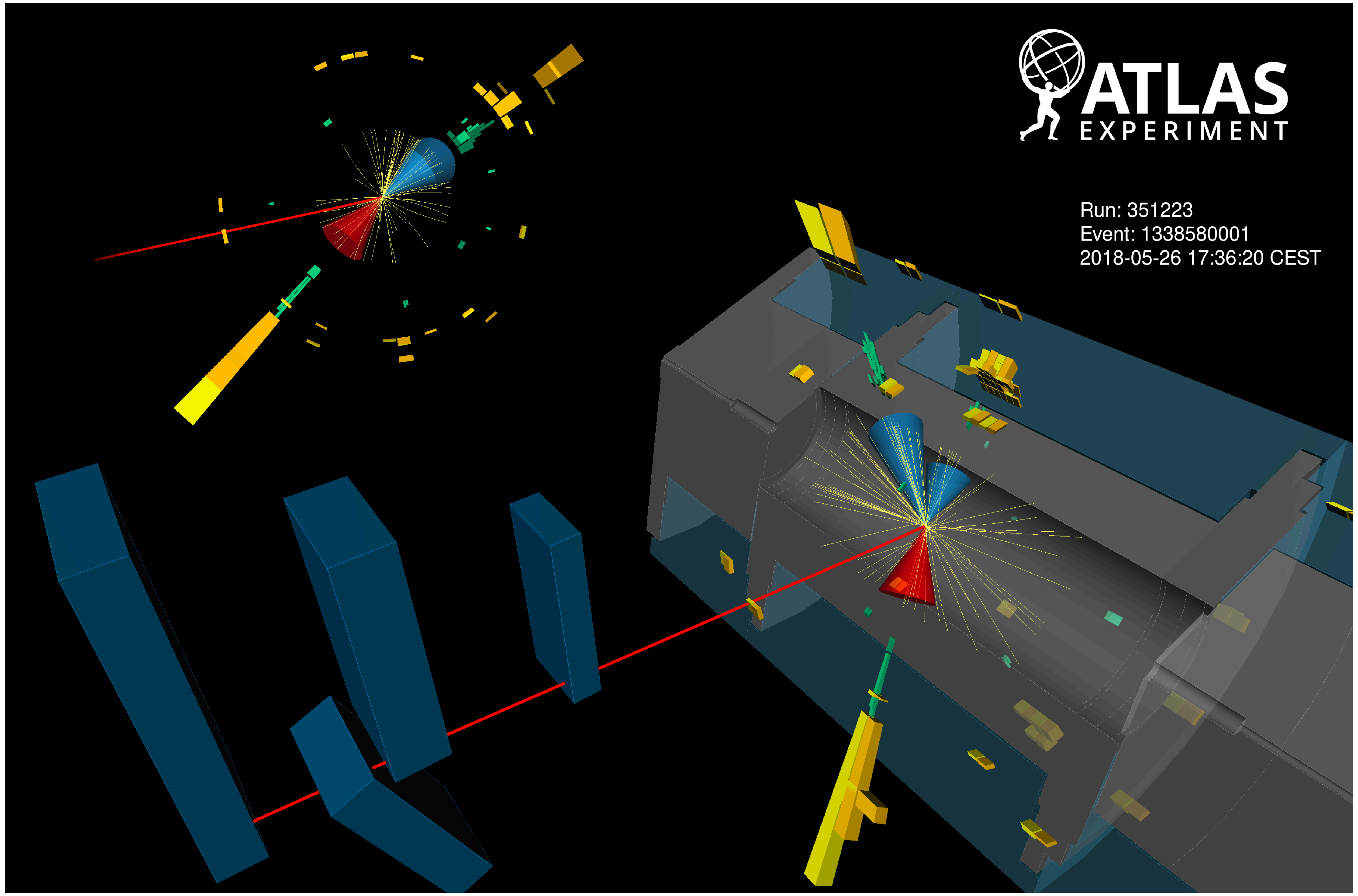

	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	[illegible] %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
γγ	[illegible] %	0.10 %	0.028 %	0.012 %	0.0005 %

2 Higgs in ATLAS

How we treat events: (examples)

1. Trigger: high-energy muon -> save the data!

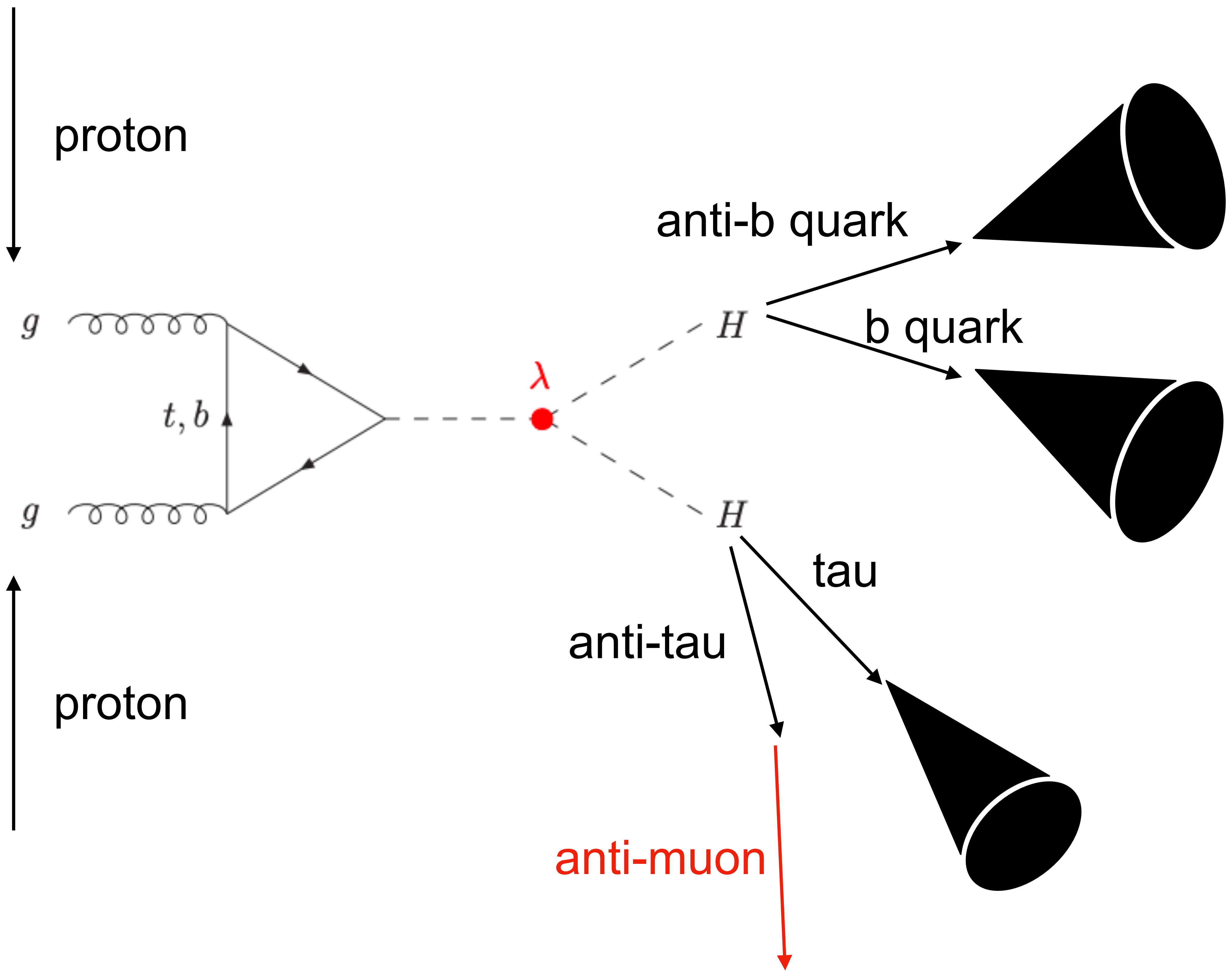


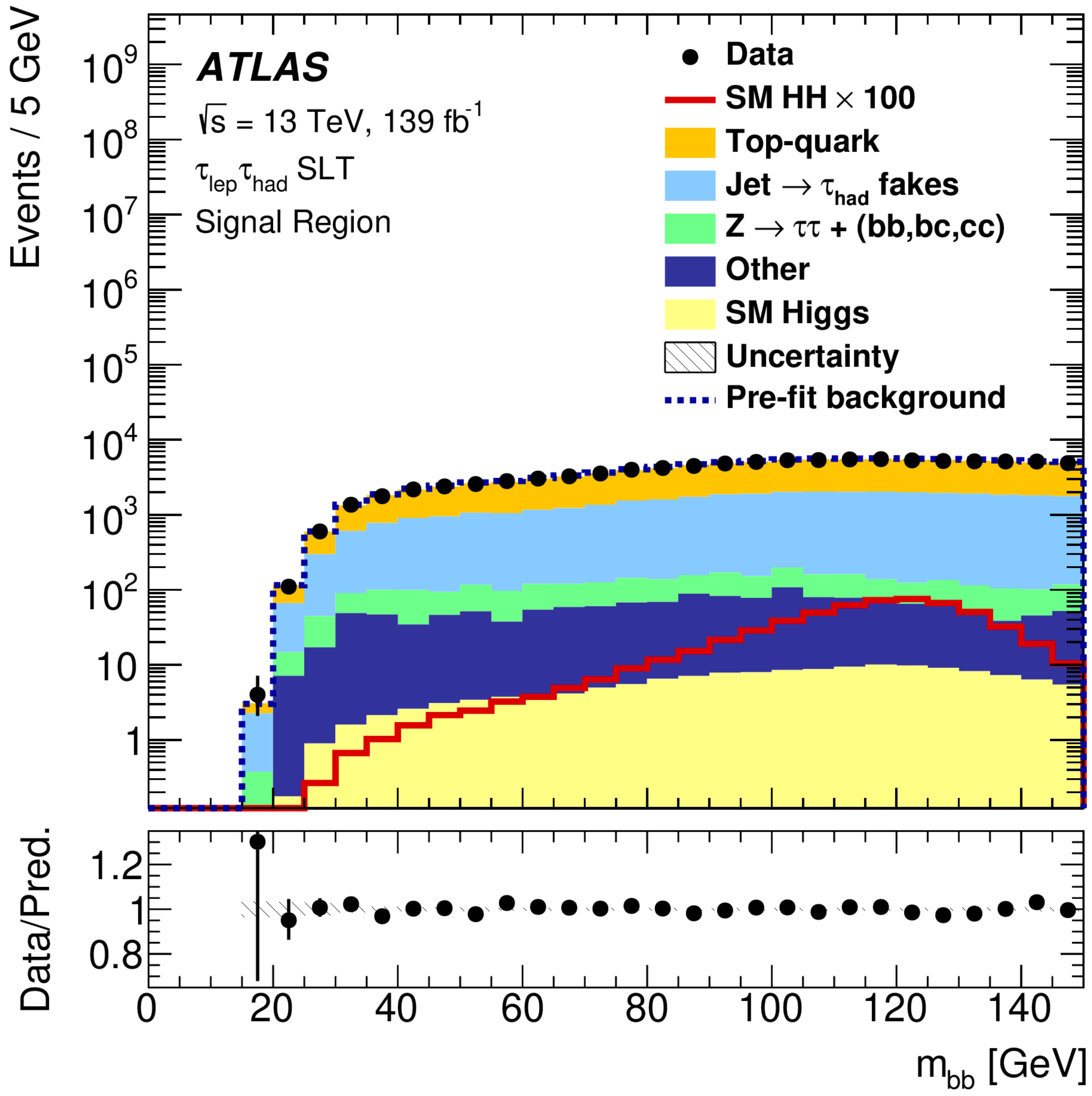


2 Higgs in ATLAS

How we treat events: (examples)

1. Trigger: high-energy muon -> save the data!
2. Event selection: 2 b-jets of combined mass < 150 GeV

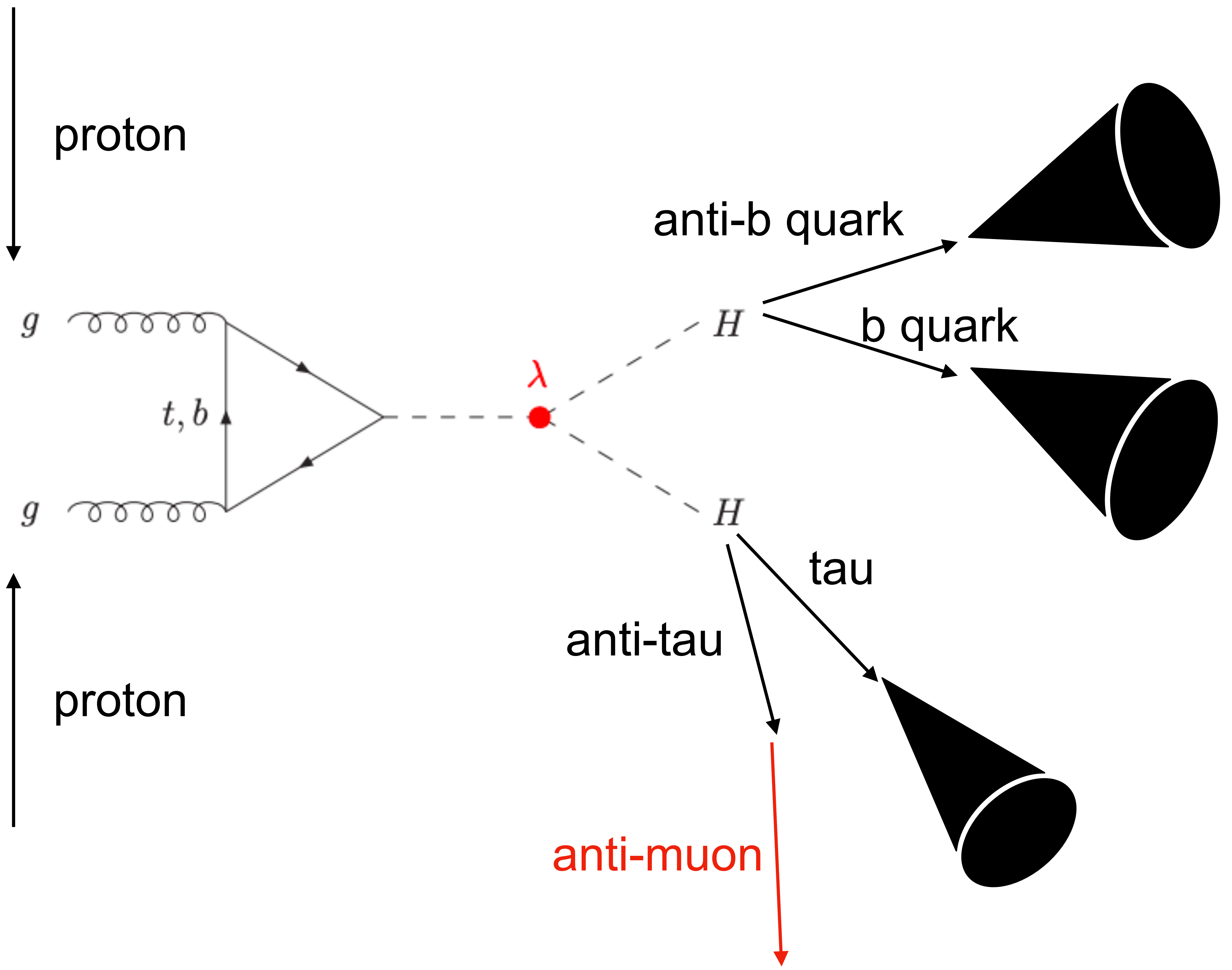


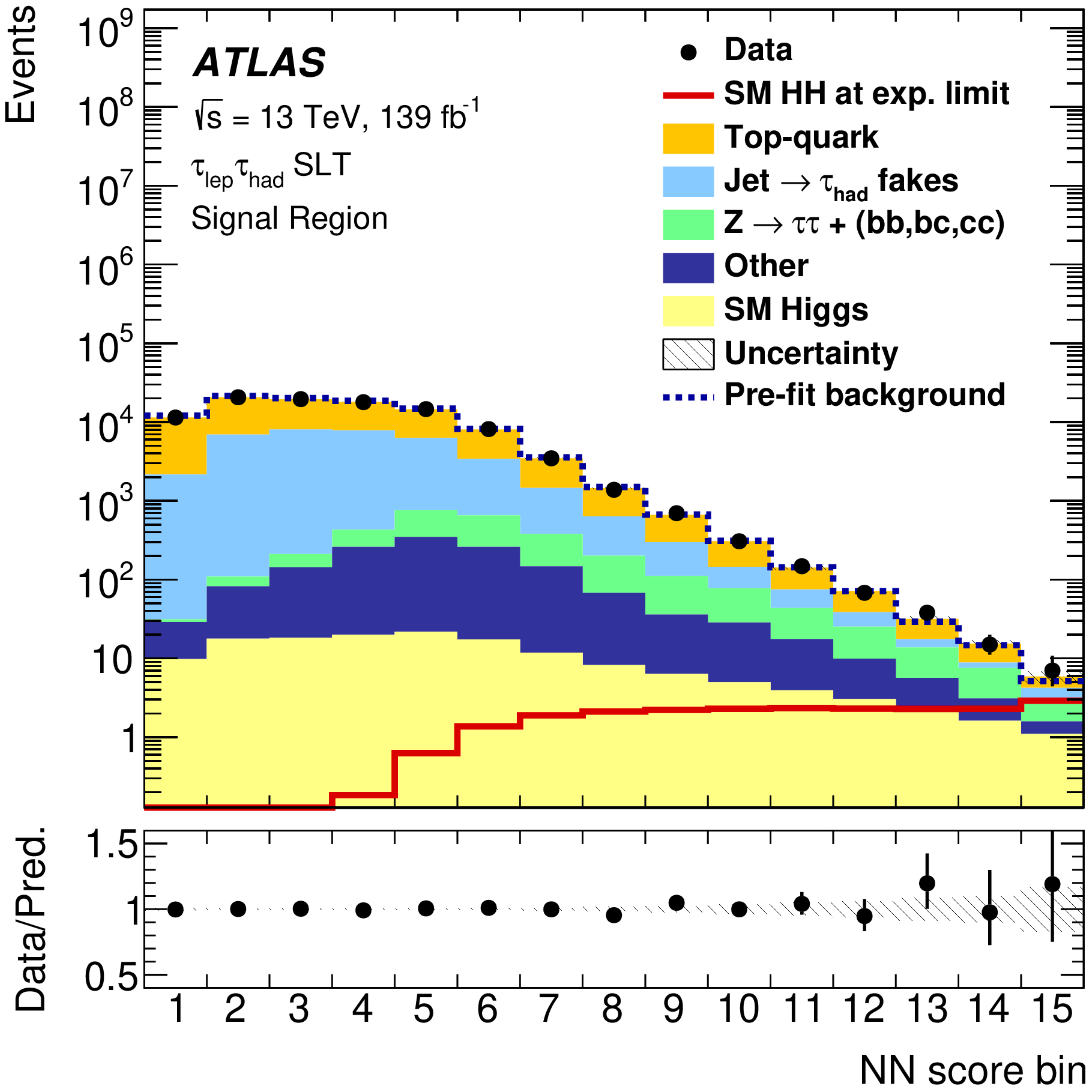


2 Higgs in ATLAS

How we treat events: (examples)

1. Trigger: high-energy muon -> save the data!
2. Event selection: 2 b-jets of combined mass < 150 GeV
3. Use machine learning to separate signal from background



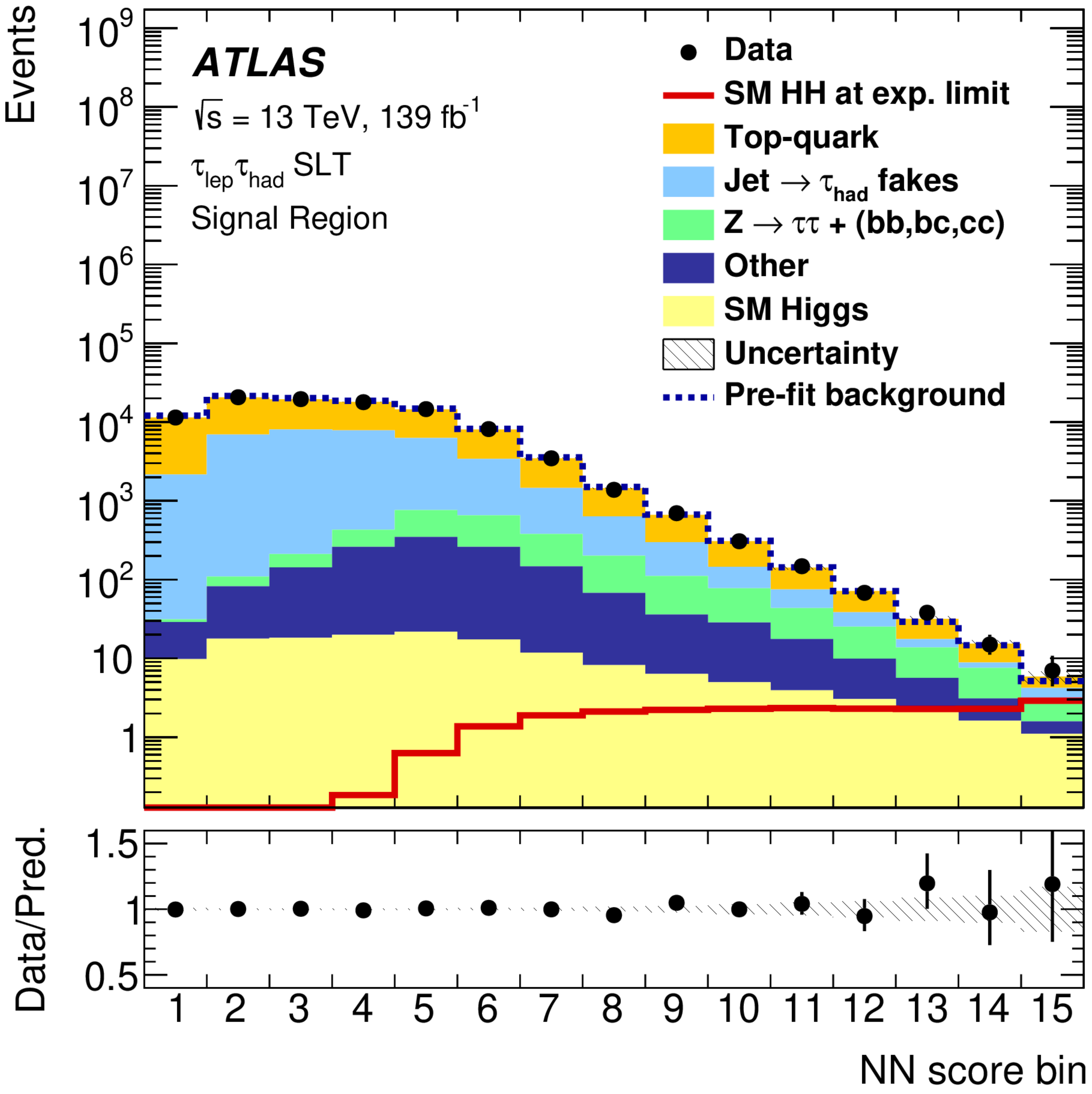


2 Higgs in ATLAS

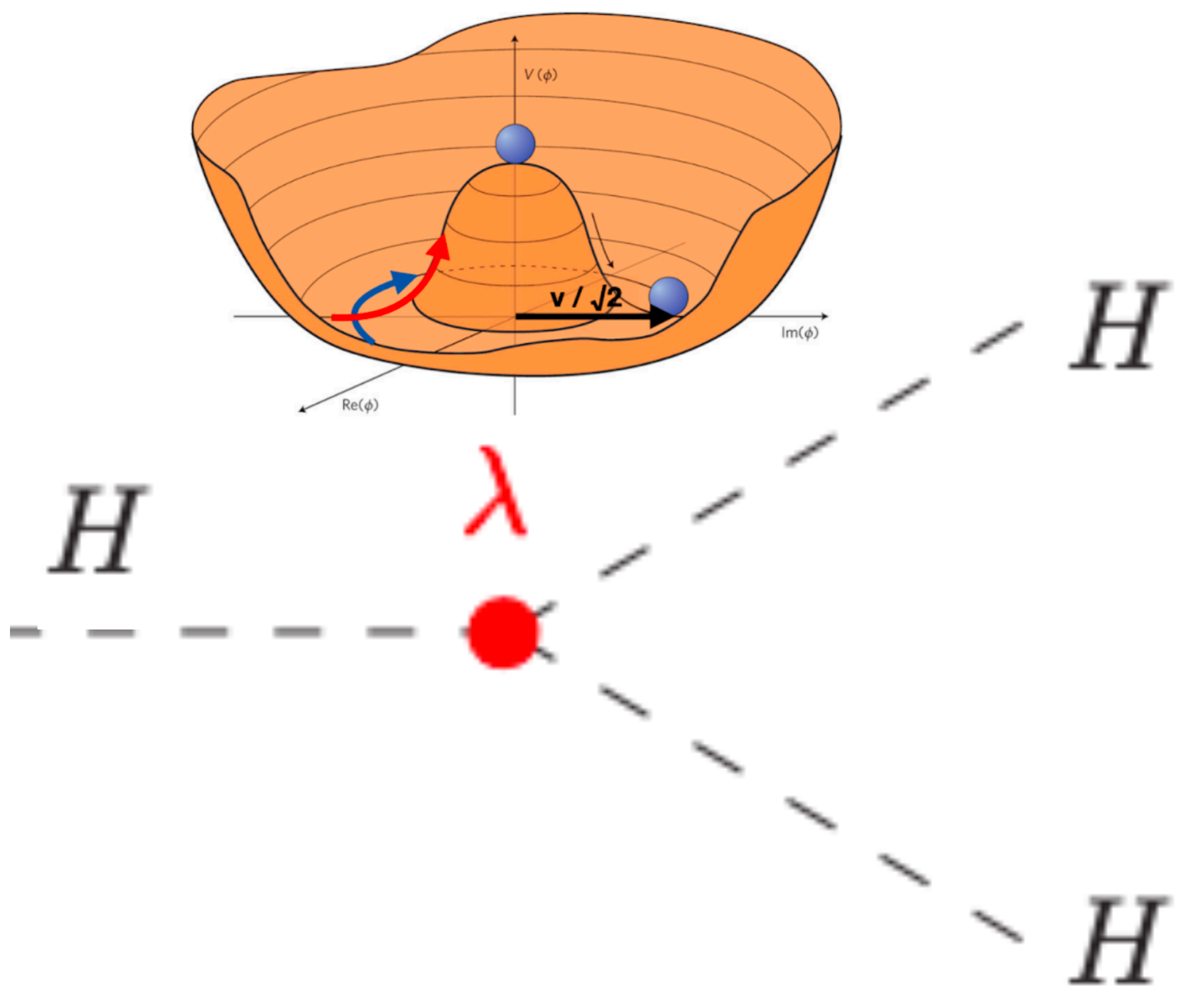
How we treat events: (examples)

1. Trigger: high-energy muon -> save the data!
2. Event selection: 2 b-jets of combined mass < 150 GeV
3. Use machine learning to separate signal from background
4. Statistical fit signal strength to data

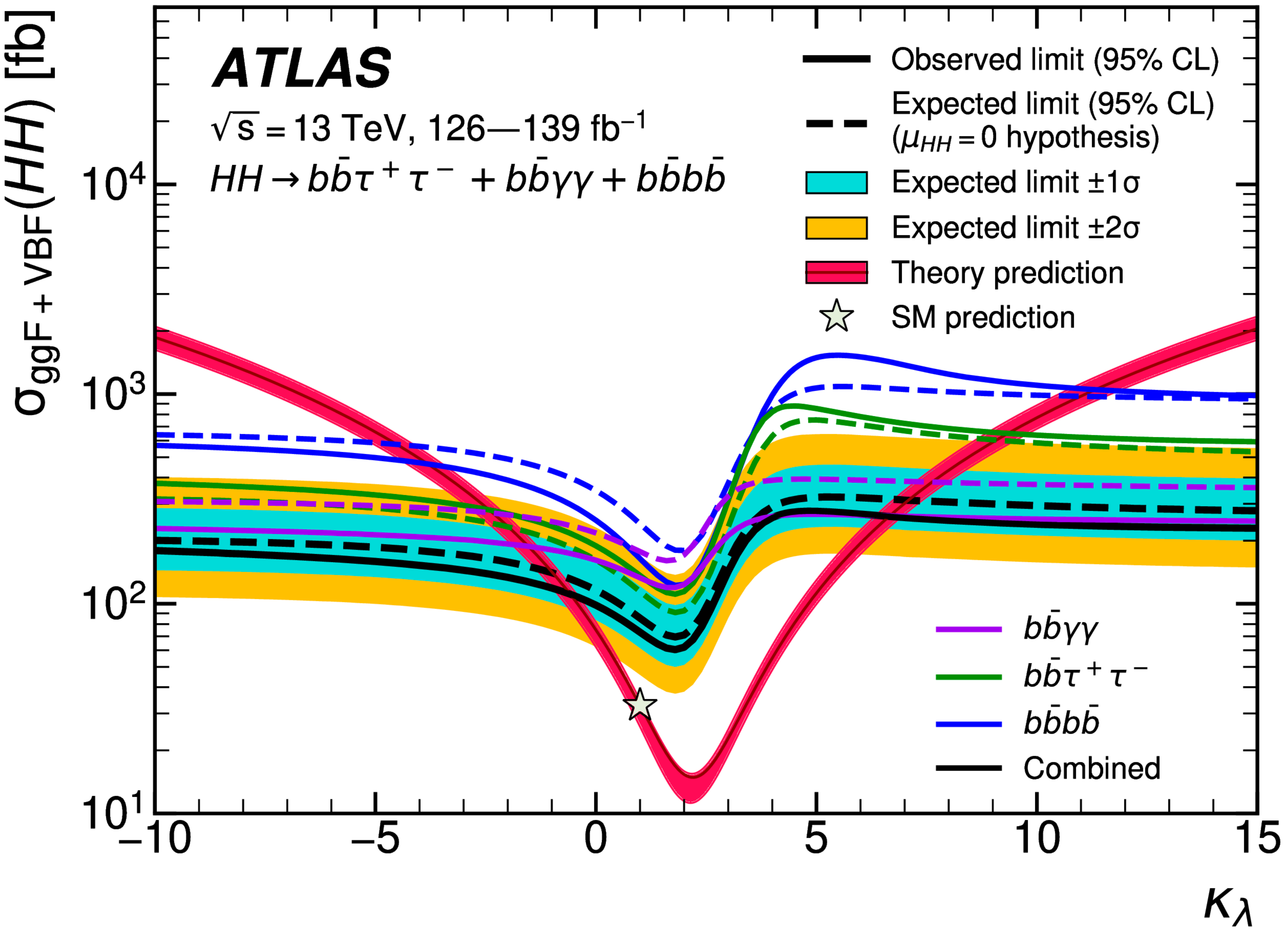
$$\mu_{HH} = \frac{\sigma_{HH}}{\sigma_{HH}^{SM}} < 2.4$$



2 Higgs in ATLAS



$$-1 < \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}} < 6$$



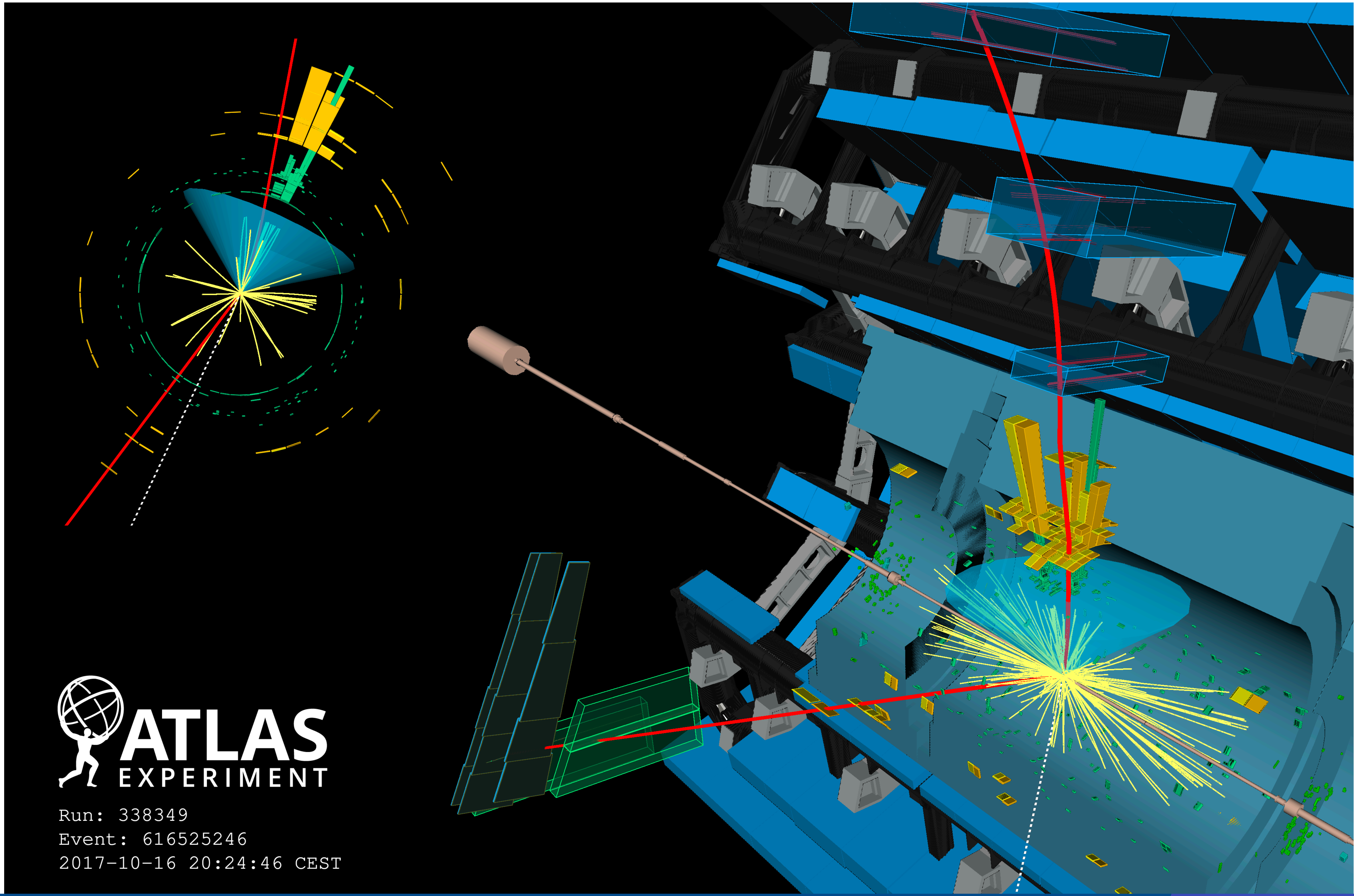
We will discover Double-Higgs production!

We do more at Nikhef

- Algorithms for object reconstruction (and more) at ATLAS:

What is this Large jet?

A. Higgs to 2 b-quarks
B. Top quark decay
C. QCD process

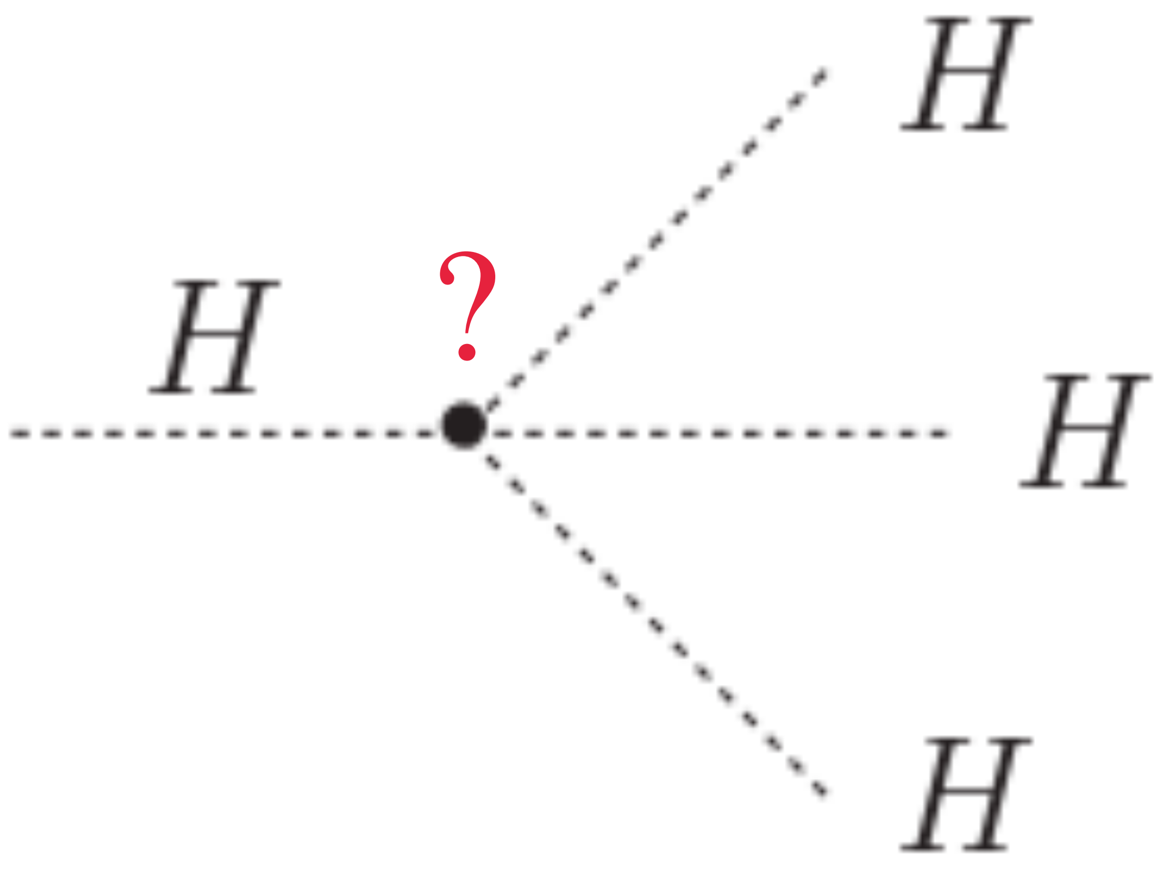


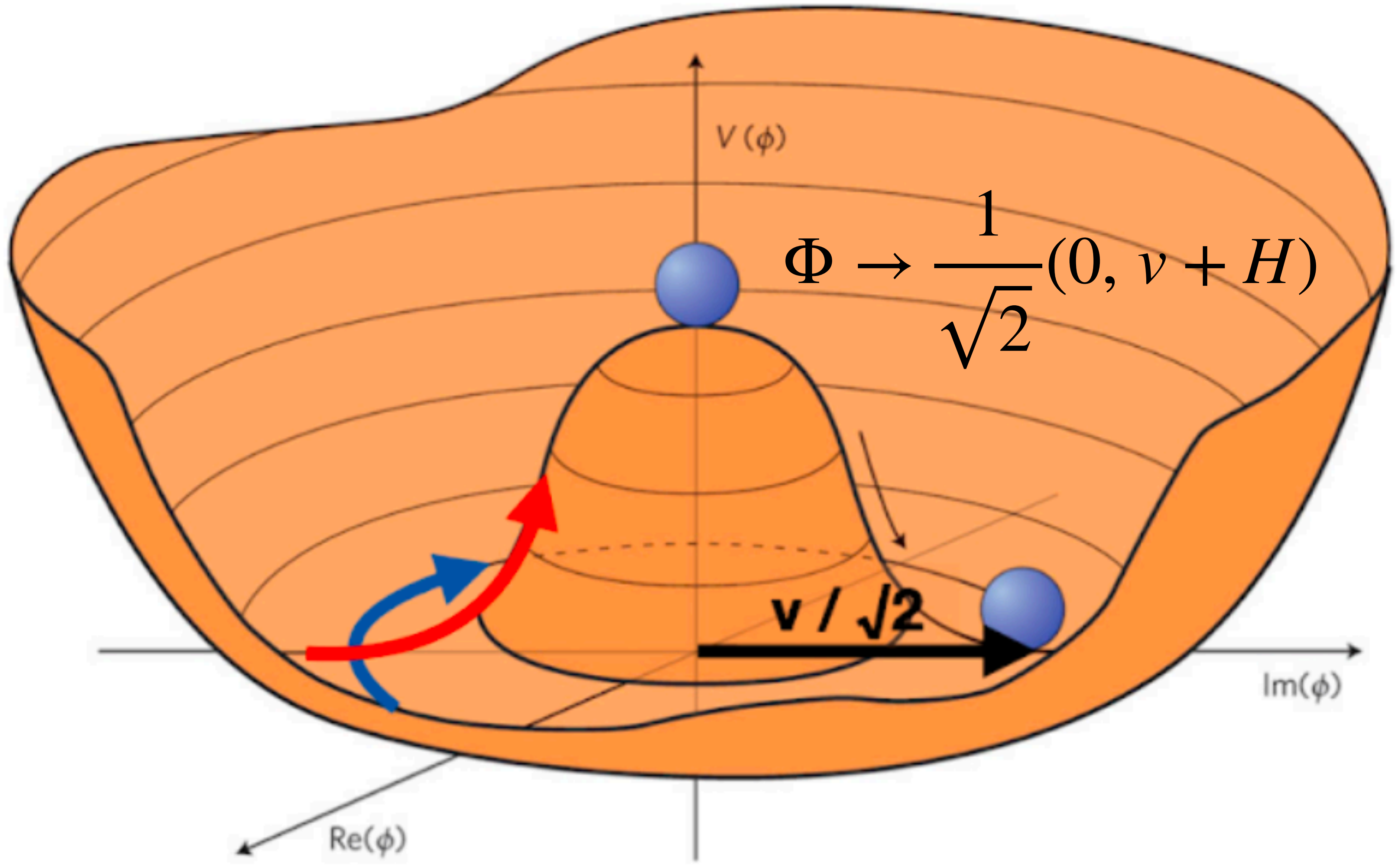
We use modern AI tools:

- Graph Neural Networks
- Transformers
- Multi-headed attention

We do more at Nikhef

- Algorithms for object reconstruction (and more) at ATLAS
- First look at Triple-Higgs production



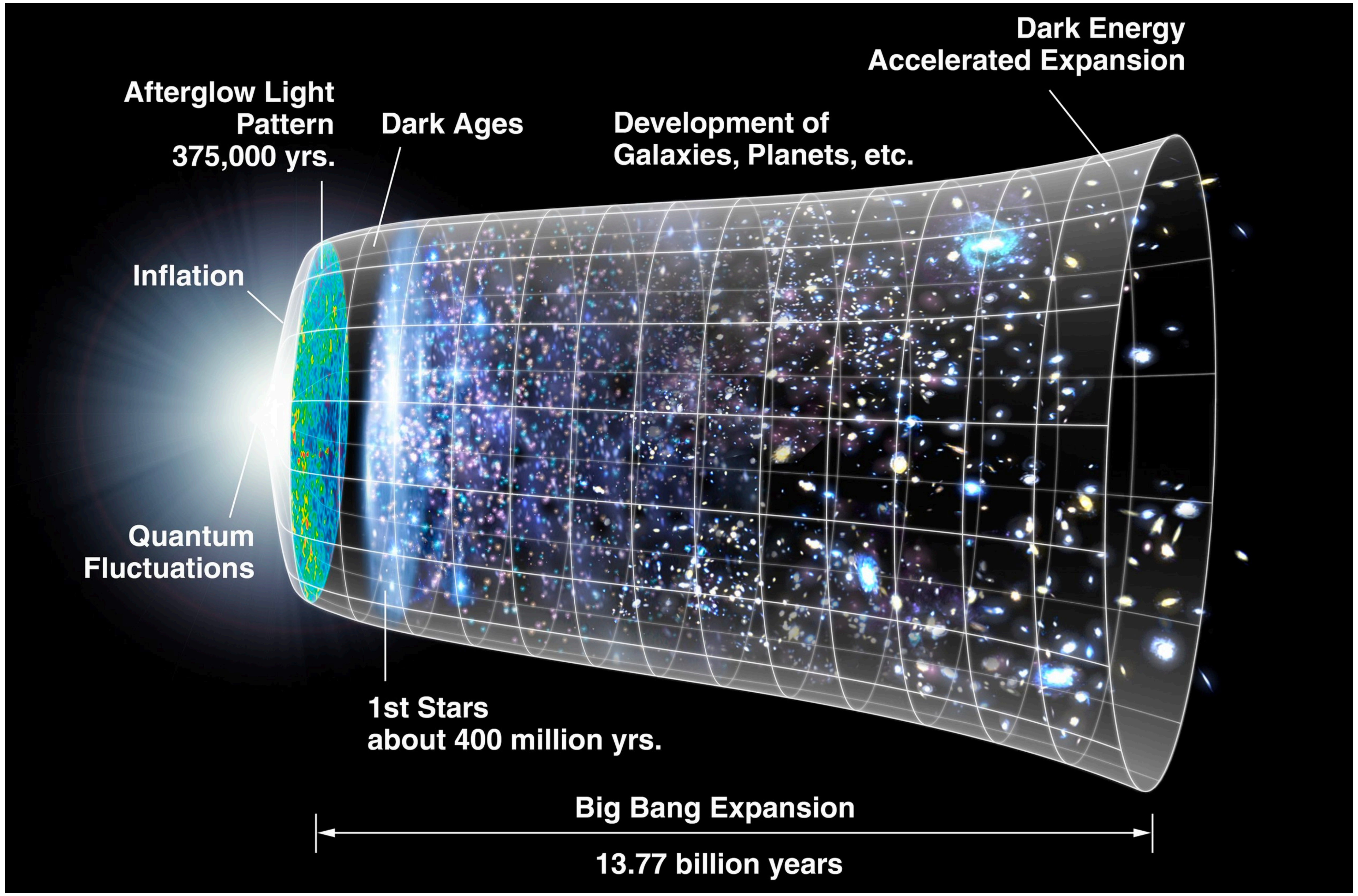


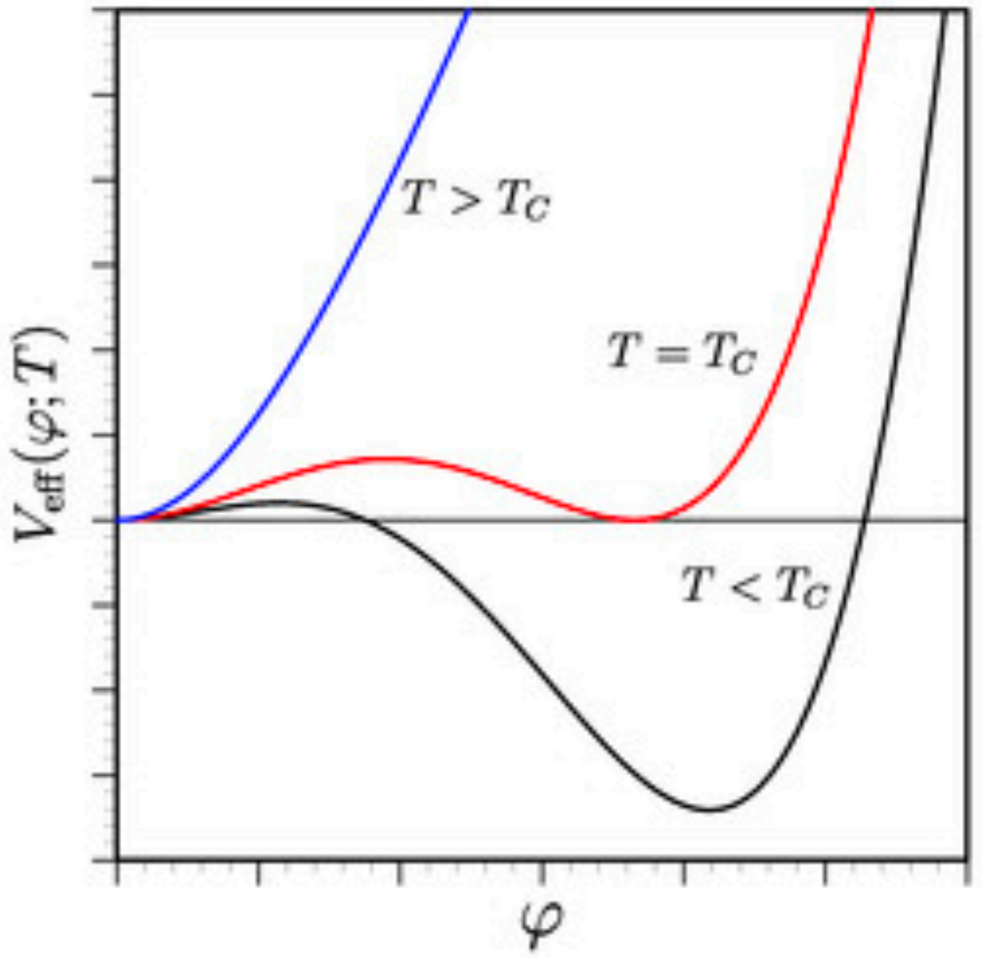
$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4$$

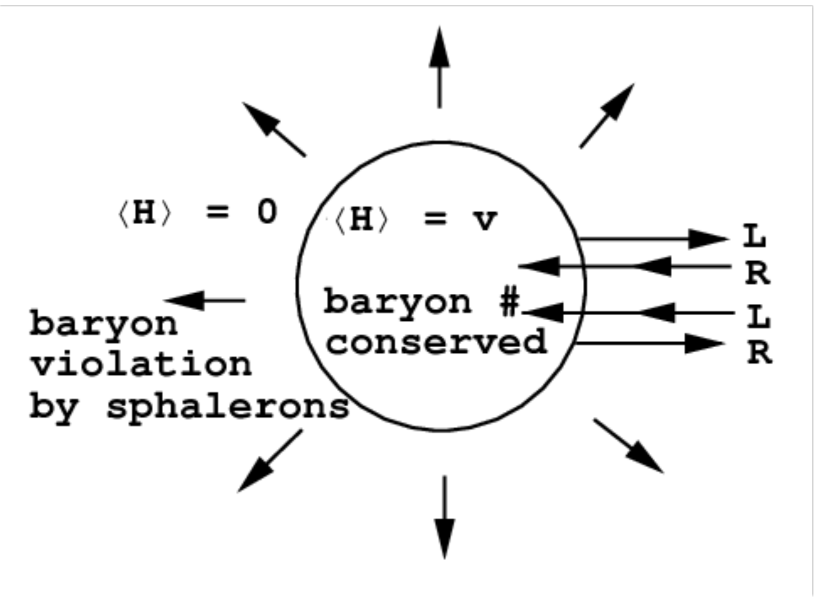
?

We do more at Nikhef

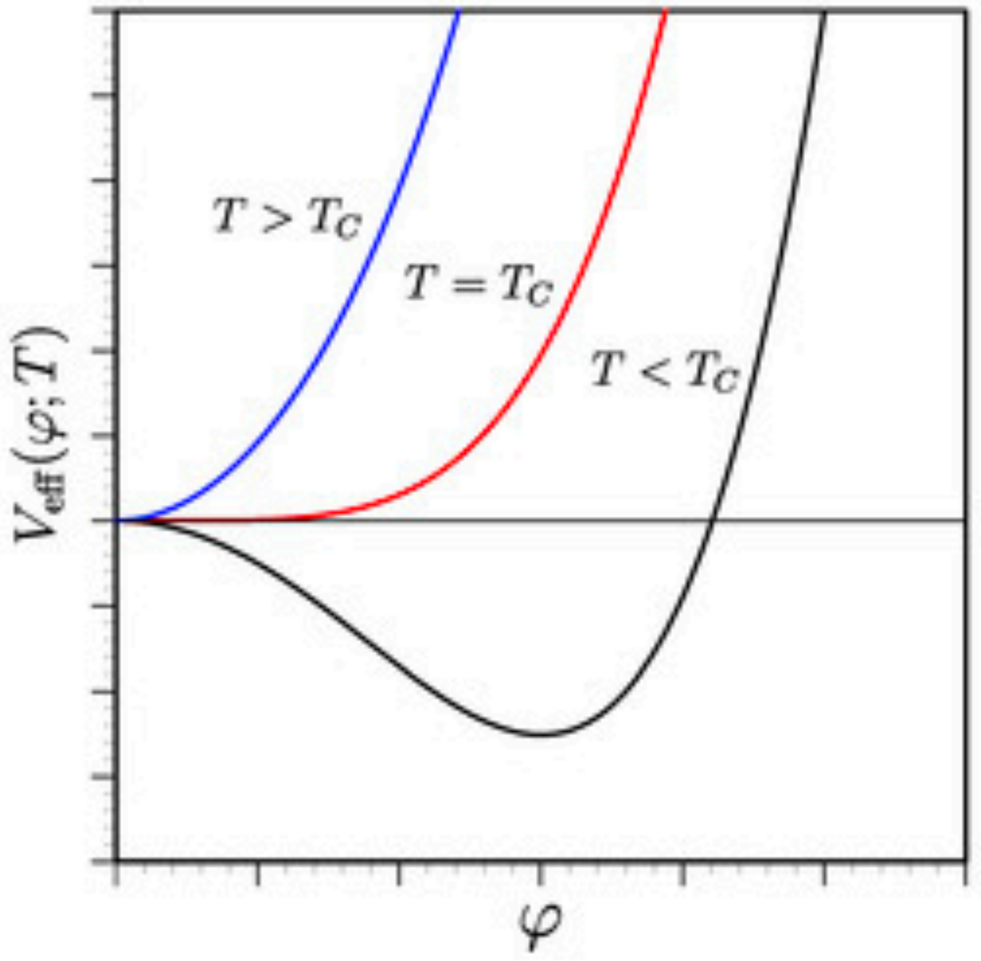
- Algorithms for object reconstruction (and more) at ATLAS
- First look at Triple-Higgs production
- Connecting to big questions: matter antimatter asymmetry?







+ new interactions?



Standard Model
No bubbles
No matter

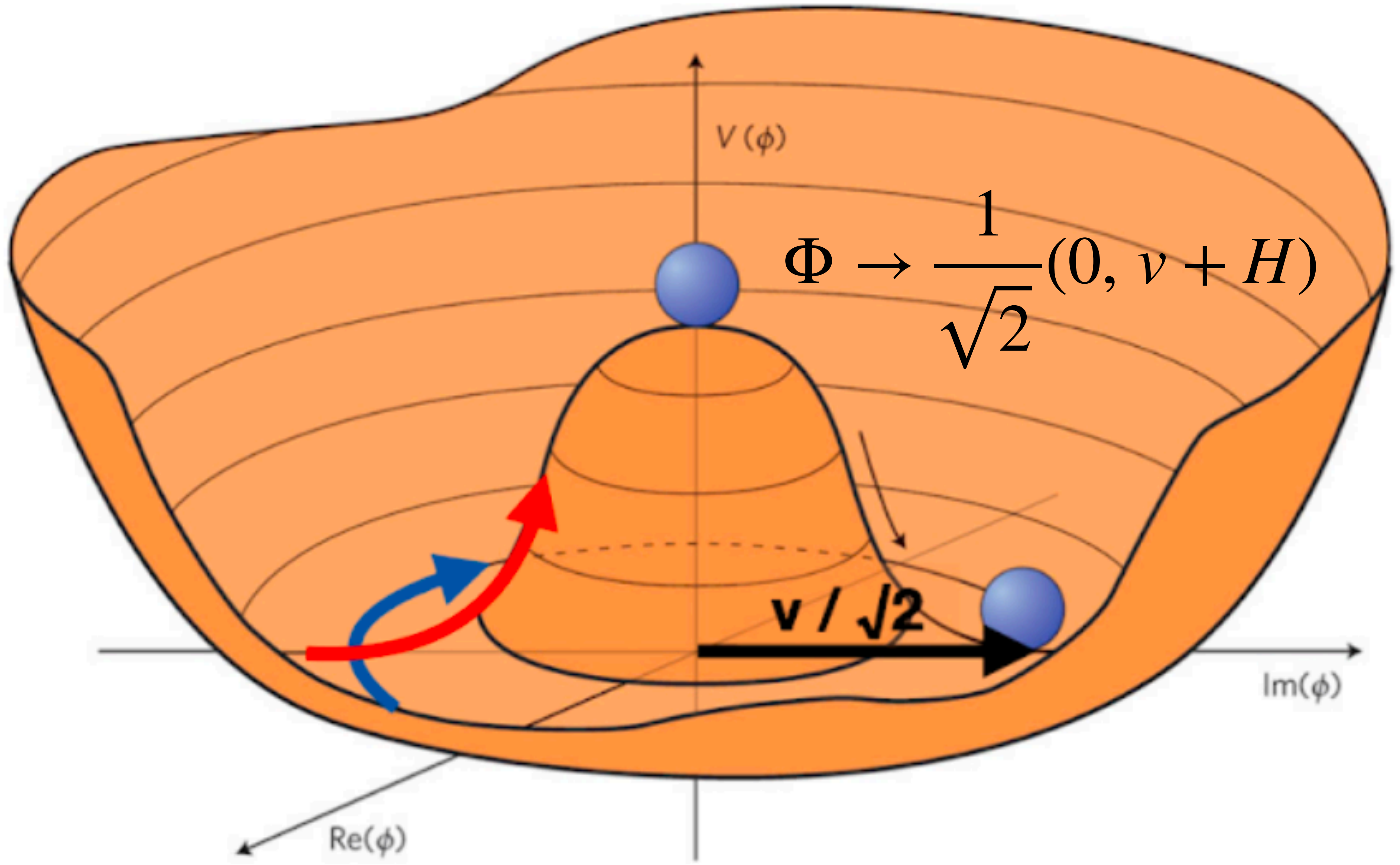
WARNING: unreadable slides ahead

We do more at Nikhef

First look at Triple-Higgs production

Challenges:

- Too few events (according to Standard Model)
- How to match decay products to Higgs particles!



$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4$$

?

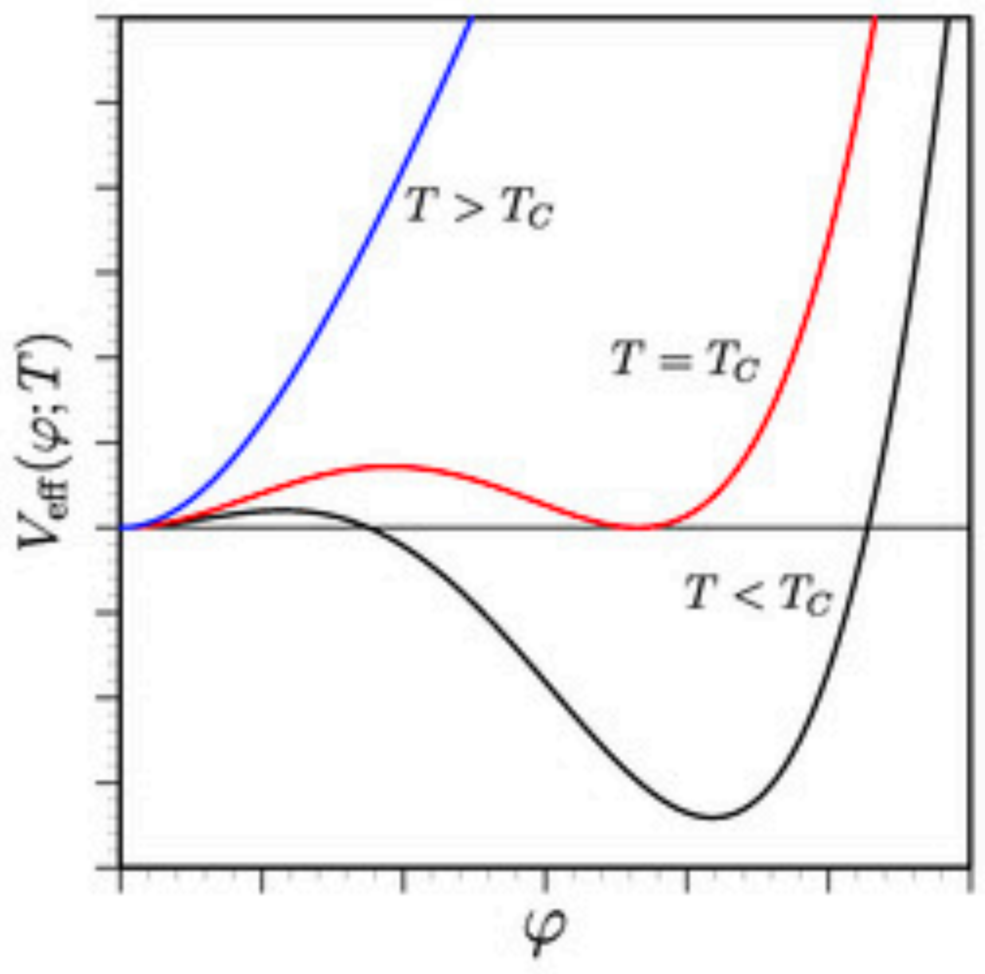
We do more at Nikhef

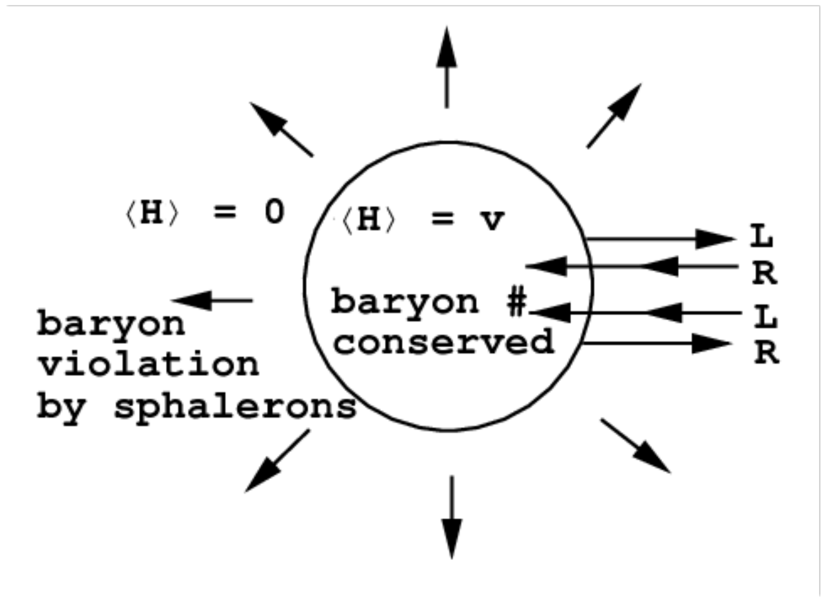
Connecting to big questions: matter antimatter asymmetry?

Recipe for matter:

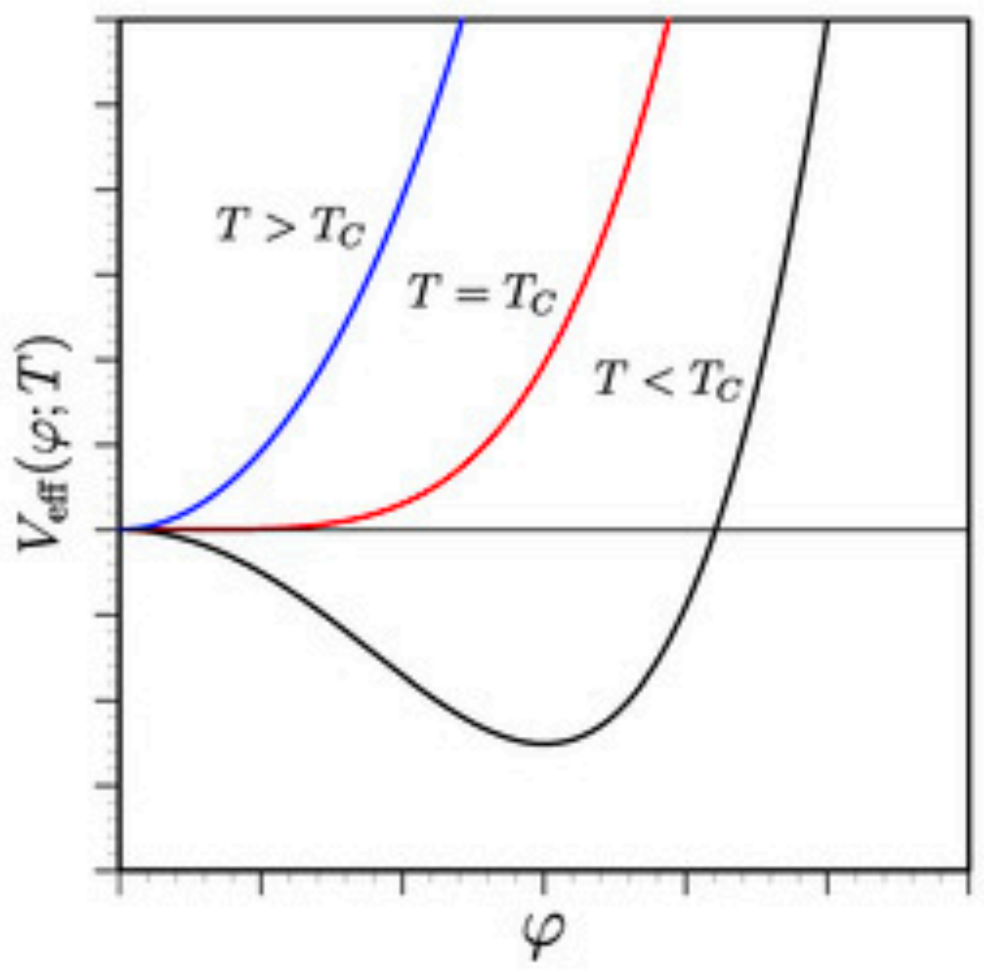
1. Baryon number violation
2. C and CP violation
3. Out of thermal equilibrium

- Out of equilibrium we get from a first order phase transition in the Higgs field (like water boiling)
- Bubbles expand,
- …





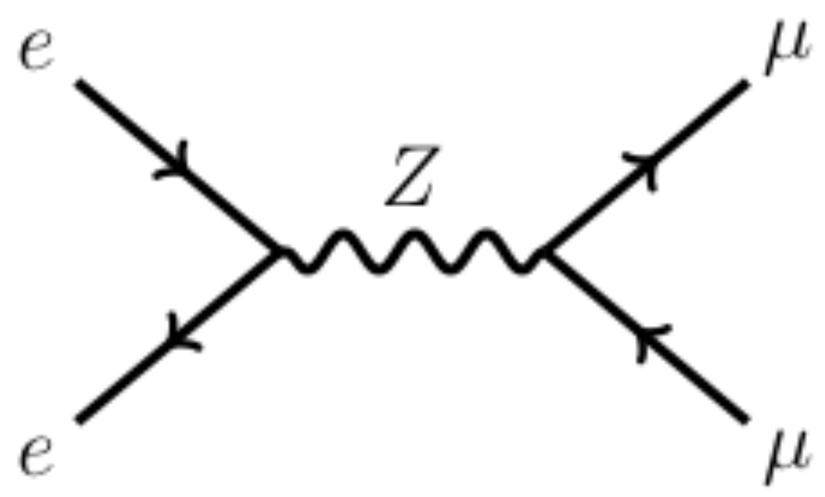
+ new interactions?



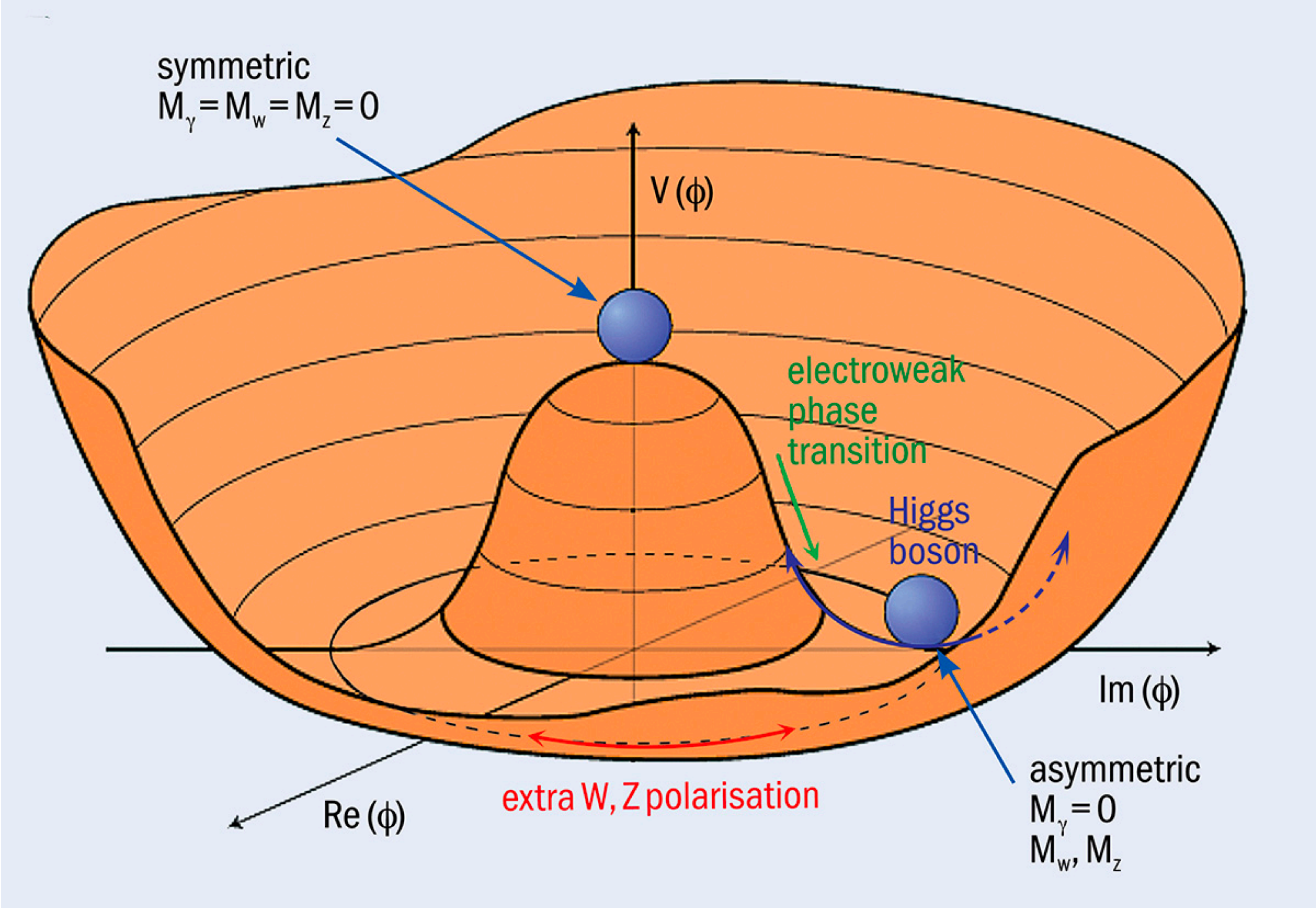
Standard Model
No bubbles
No matter

What gives the Z bosons mass?

- In nature we observe massive particles (fields)
- Massive Z bosons? Add Higgs field!



$$m_Z = 91\ GeV$$



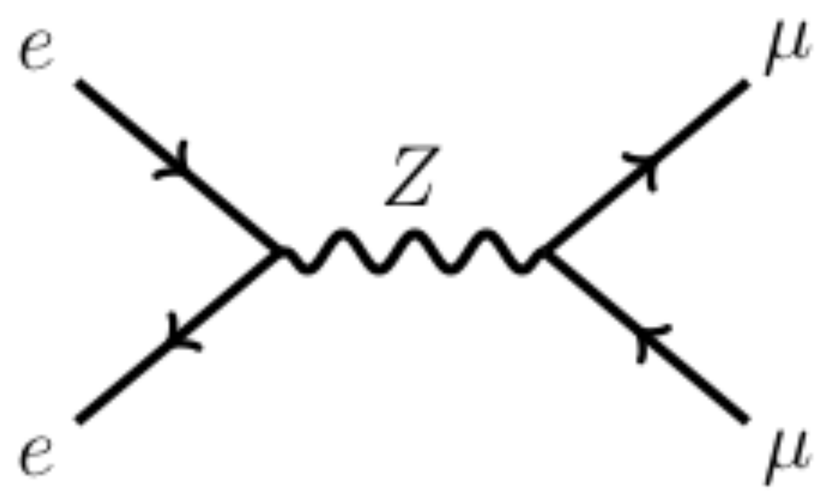
$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (D_\mu\Phi)^\dagger(D^\mu\Phi) - V(\Phi)$$

Bosons *Interact* *Higgs potential*

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$

Why Higgs? Mass without the mess

- In nature we observe massive particles (fields)
- Gauge fields cannot have fundamental mass!



$$m_Z = 91\ GeV$$

light

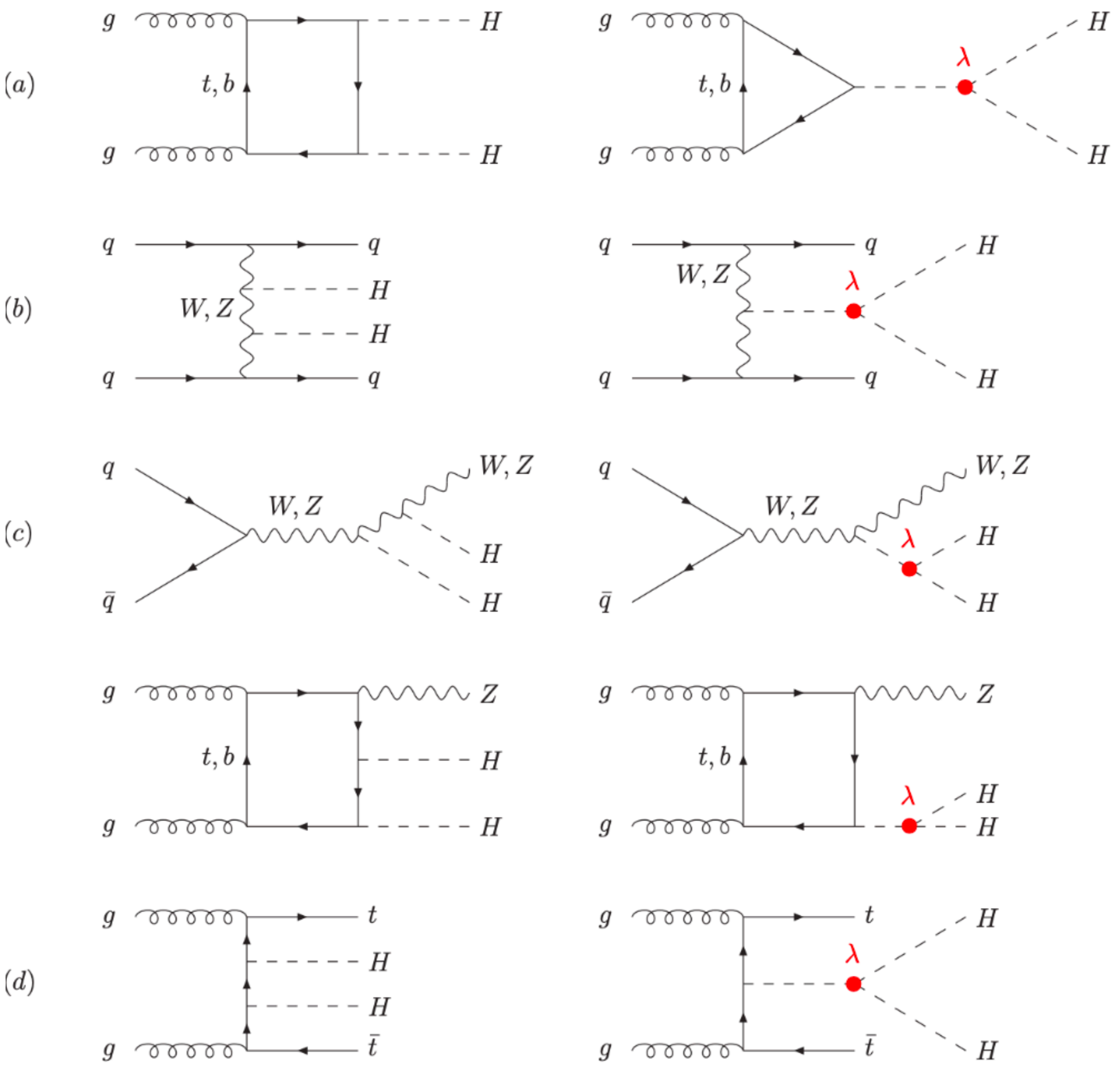
$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$A_\nu \rightarrow A_\nu + \partial_\nu \xi \quad \Rightarrow \quad \mathscr{L} \rightarrow \mathscr{L} + mess$$

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + ?$$

Higgs Self-Coupling: HH production



Large branching ratio

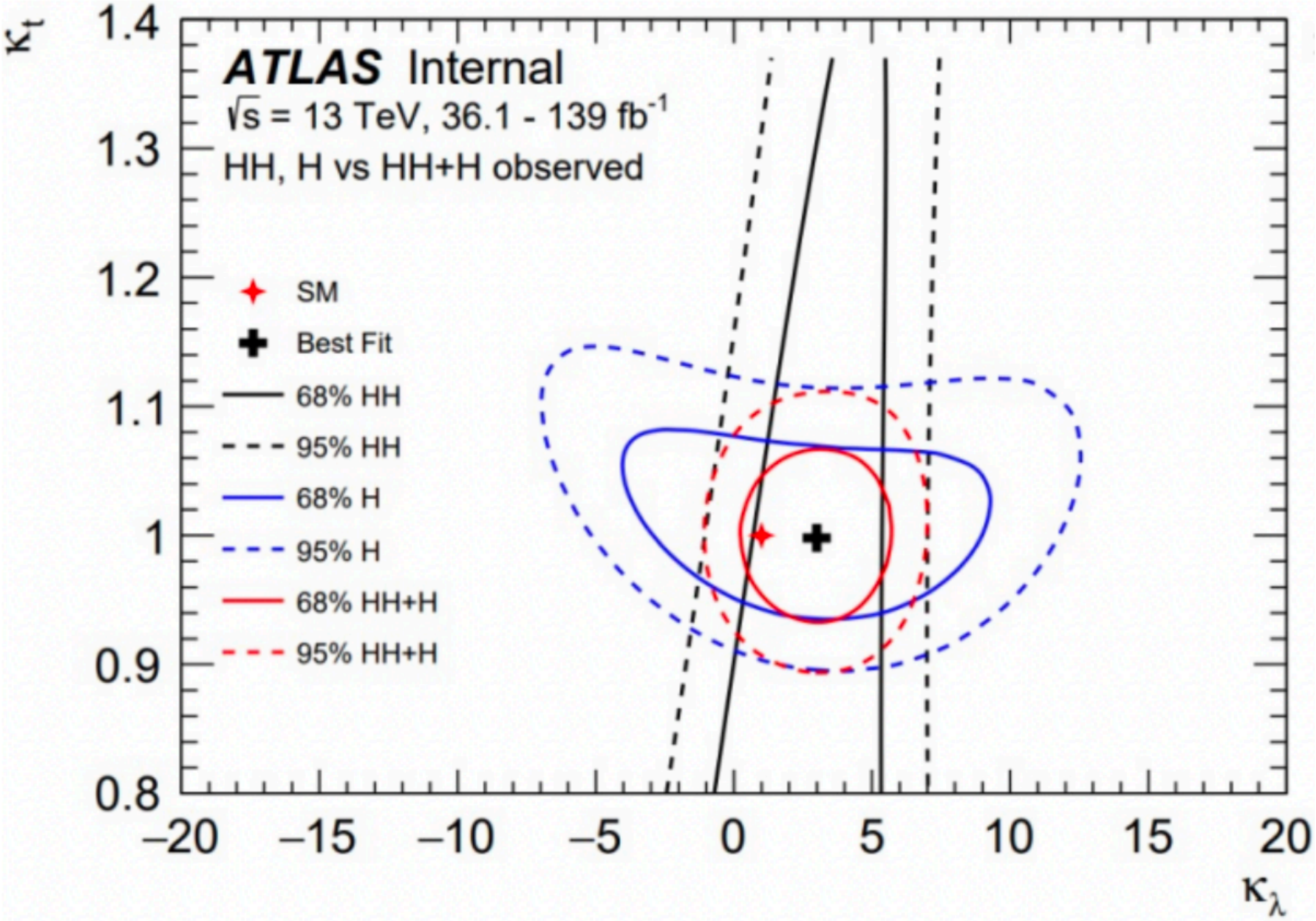
Clean final state

	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 %

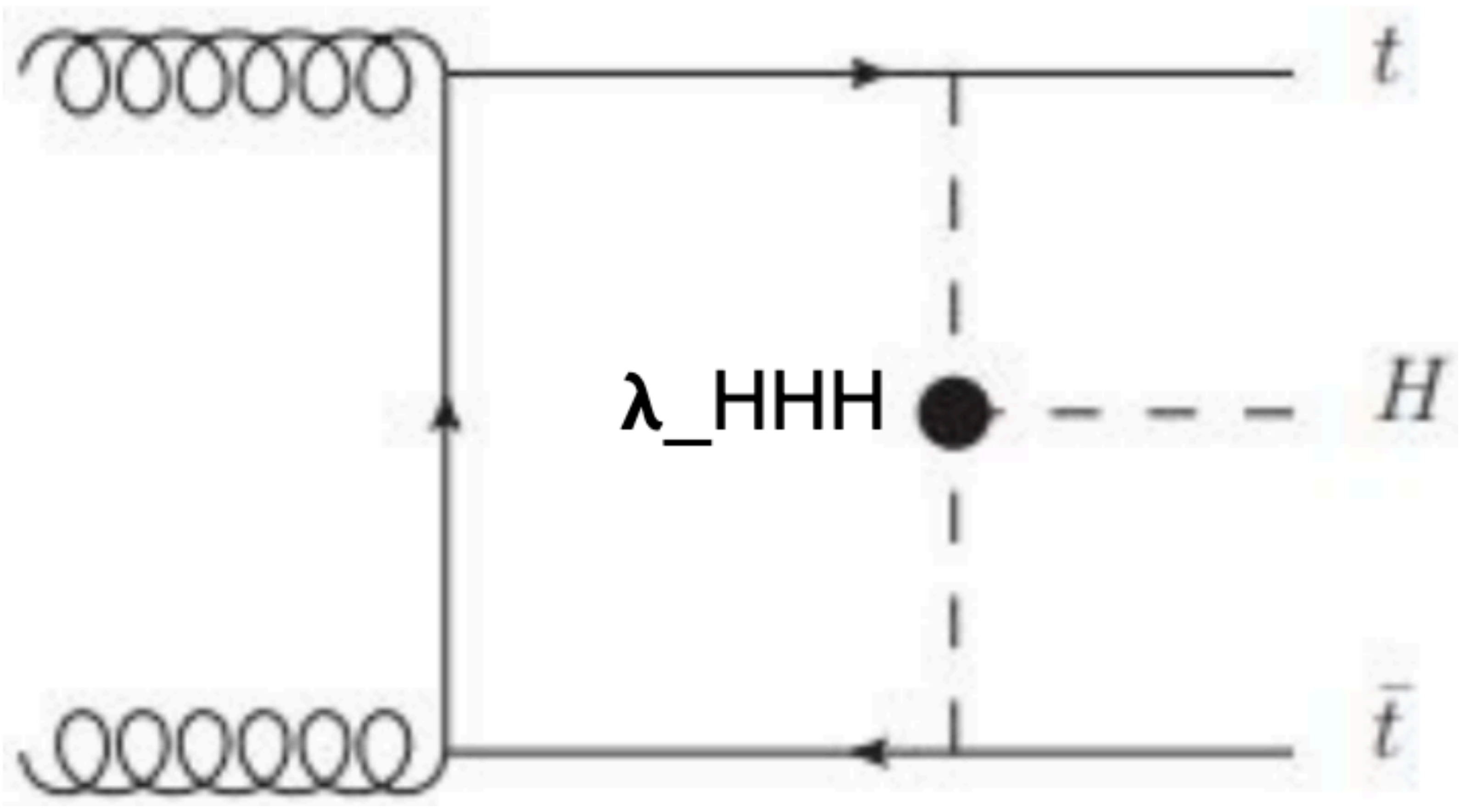
Combination +Single H

(and complementarity) of various final states fundamental for observation!

Higgs Self-Coupling: Single-H production



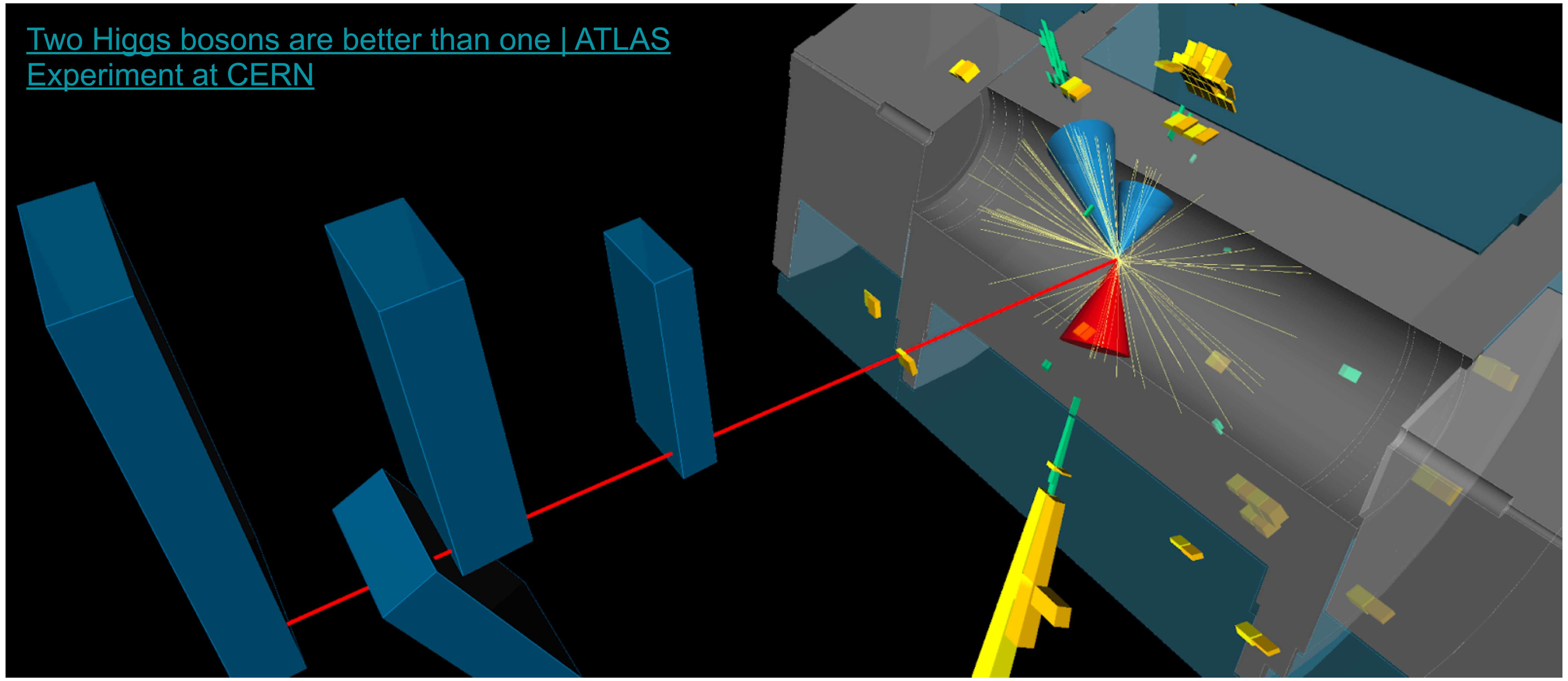
Example of EW correction to single-H



bbττ H(→bb good stat.), H(→ττ clean channel)

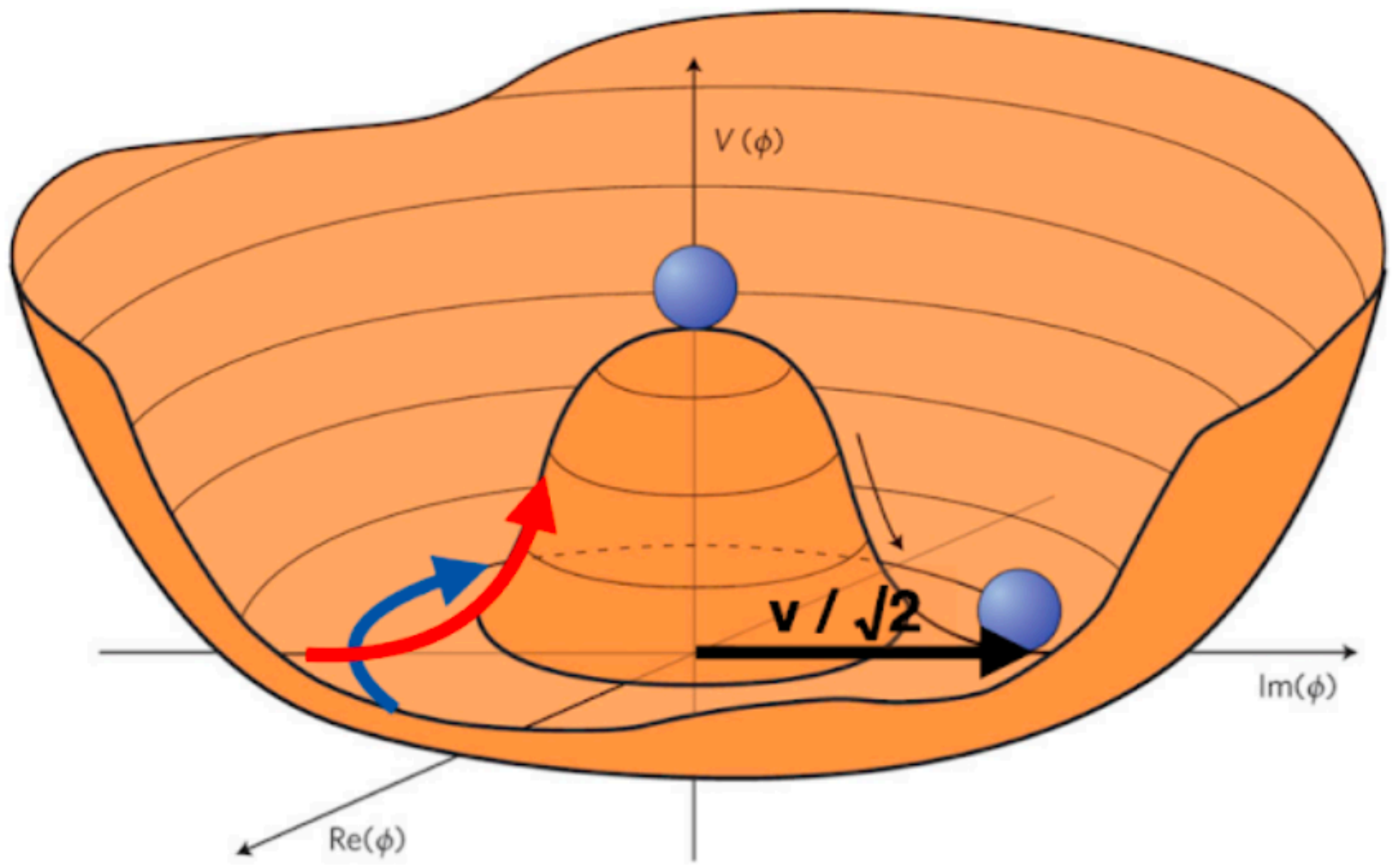
Challenges:

- HH low xsec: 1000 times less that H production.
- Reconstruction of b-jets and τ with neutrino final states.
- Backgrounds: single-H, ttbar, Z+heavy flavour, τ fakes.
- Large modelling uncertainties for H and ttbar bg.
- Recent ~2x improvement: reconstruction, MVA, τ fakes.

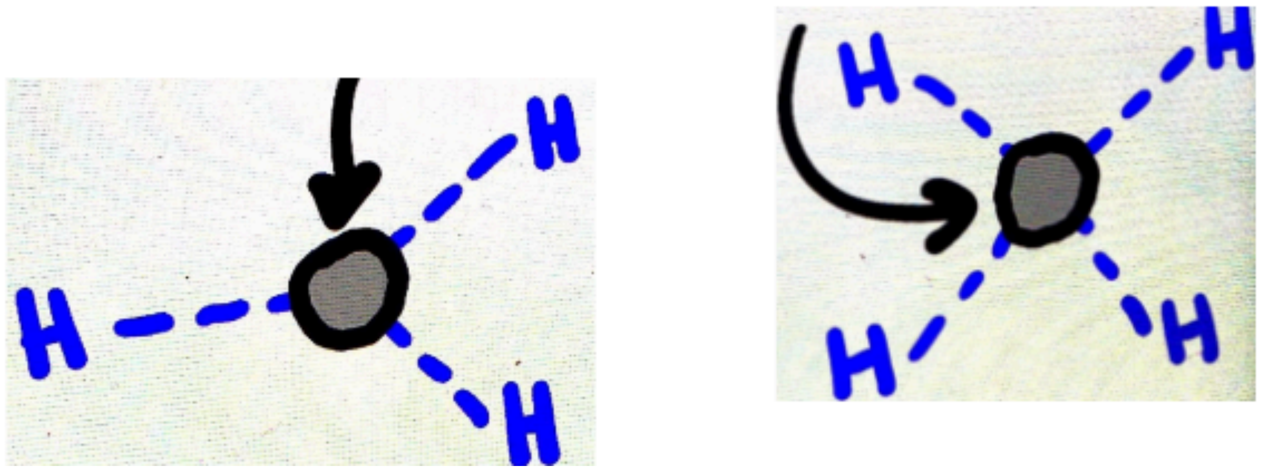


Higgs inflation via non-minimal Higgs-gravity coupling

$$V(\Phi^\dagger\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



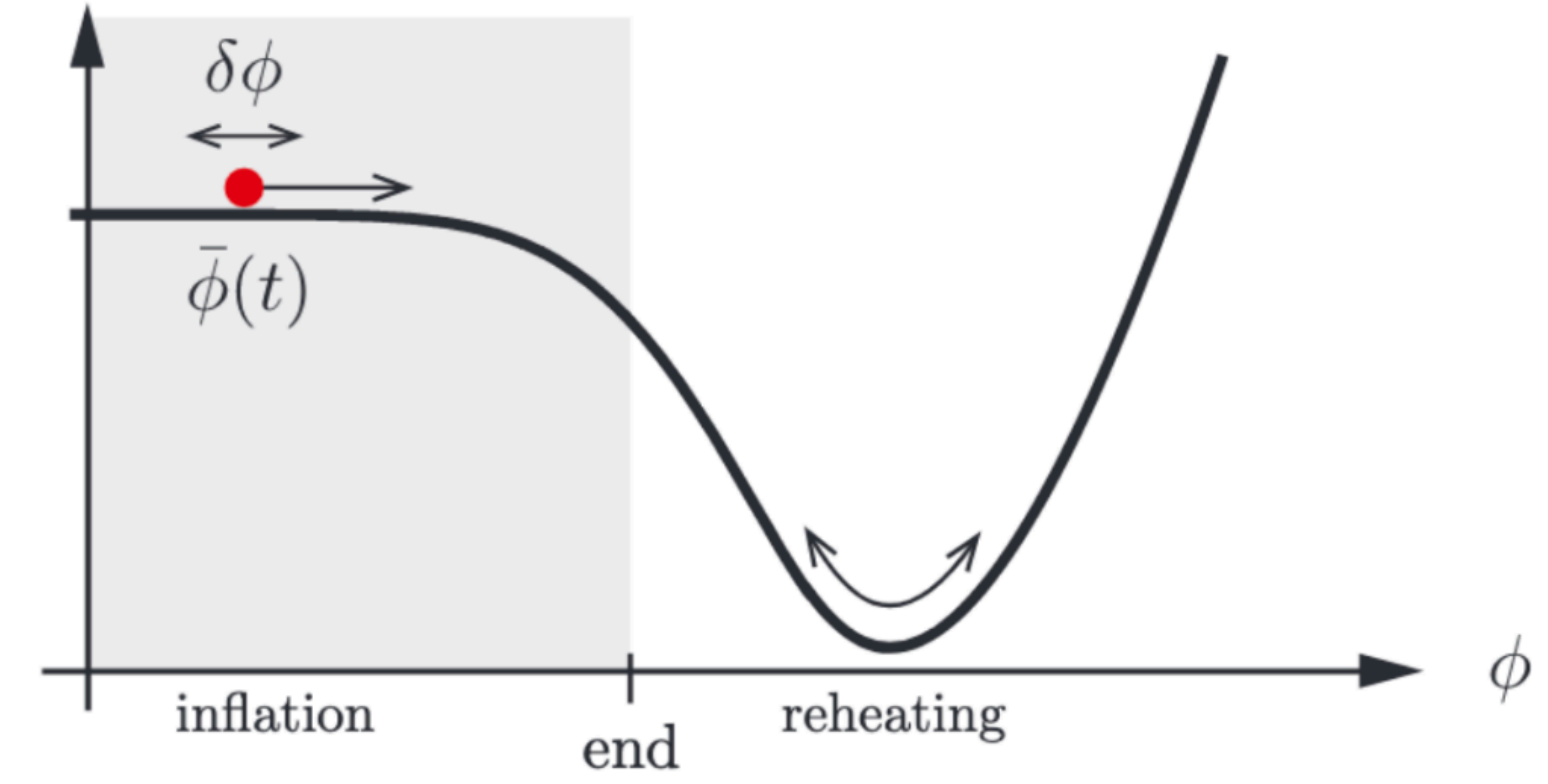
$$V(H) = \frac{1}{2}m_{\mathrm{H}}^2 H^2 + \lambda_{\mathrm{HHH}} v H^3 + \frac{1}{4}\lambda_{\mathrm{HHHH}} H^4$$



Higgs Inflation? 1807.02376

Non-minimal coupling is ruled out at 4σ for the SM potential: 1805.02160

baumann.pdf (wintherscoming.no)



$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R + \xi H^\dagger H R + \mathcal{L}_{\mathrm{SM}}\right]$$

$$\xi \simeq 47200\sqrt{\lambda}\,.$$

Shape of Higgs

Standard Model: simplest shape that works.
Some problems:

- Hierarchy problem: Higgs mass could have been much higher!
- New massive particles to explain Dark Matter
- Matter-antimatter asymmetry

$V(\Phi) =$  $+?$

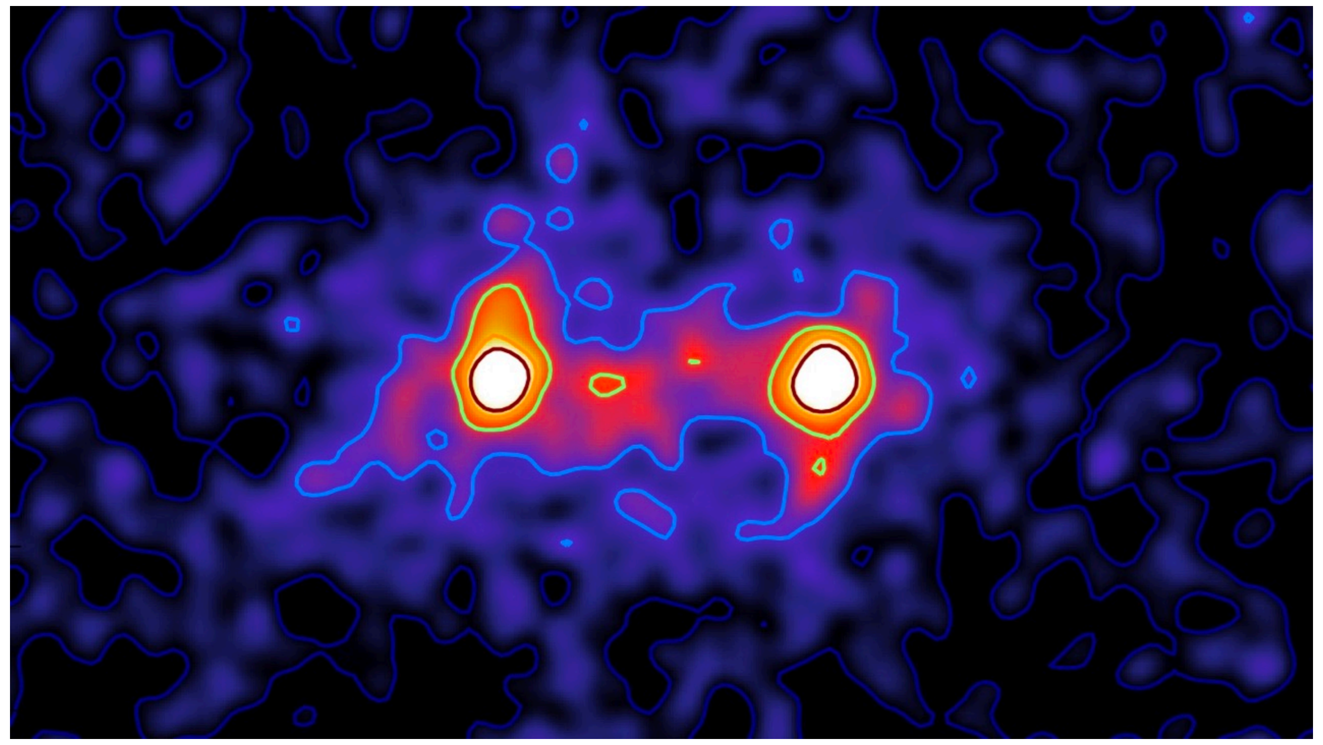
$$m_{Planck} = 1.2 \times 10^{19}\ GeV$$

+ string theory?

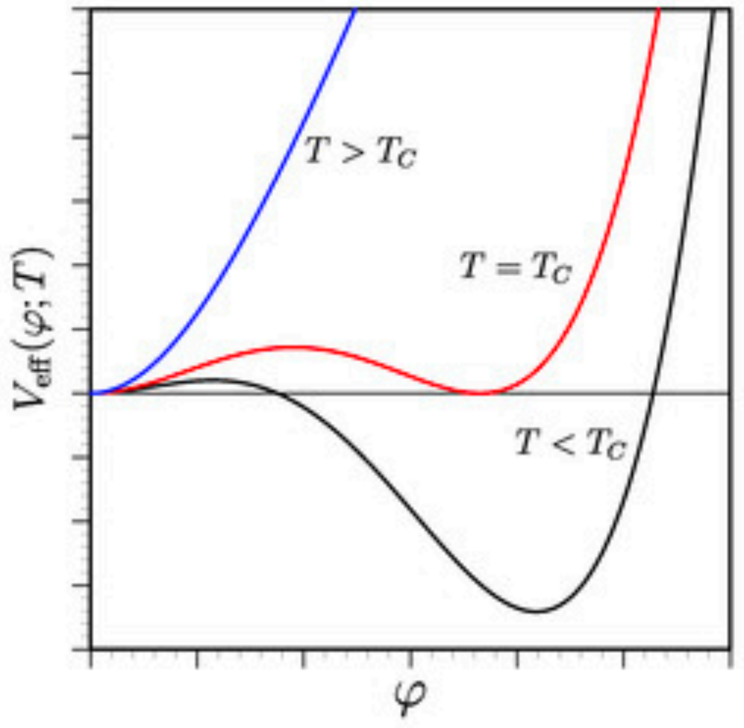
+ supersymmetry?

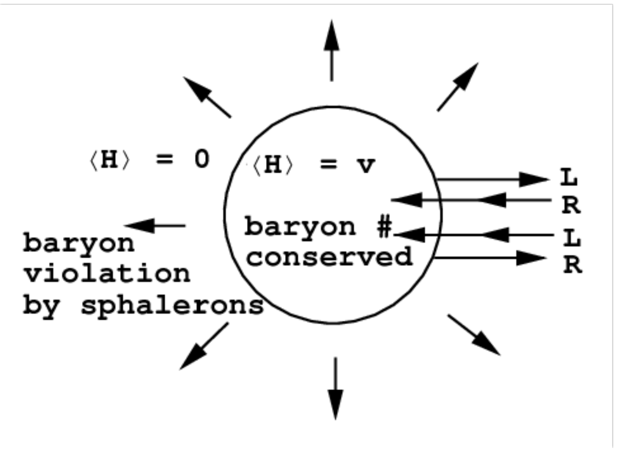
+ new particles within Higgs?

$m_H = 125\ GeV$

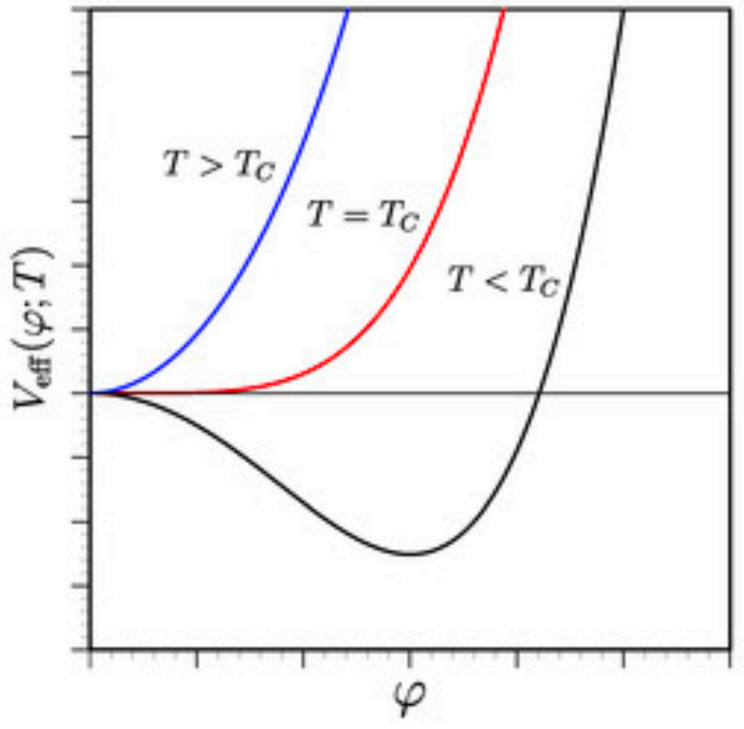


+ Dark matter interacting with Higgs?





+ new interactions?

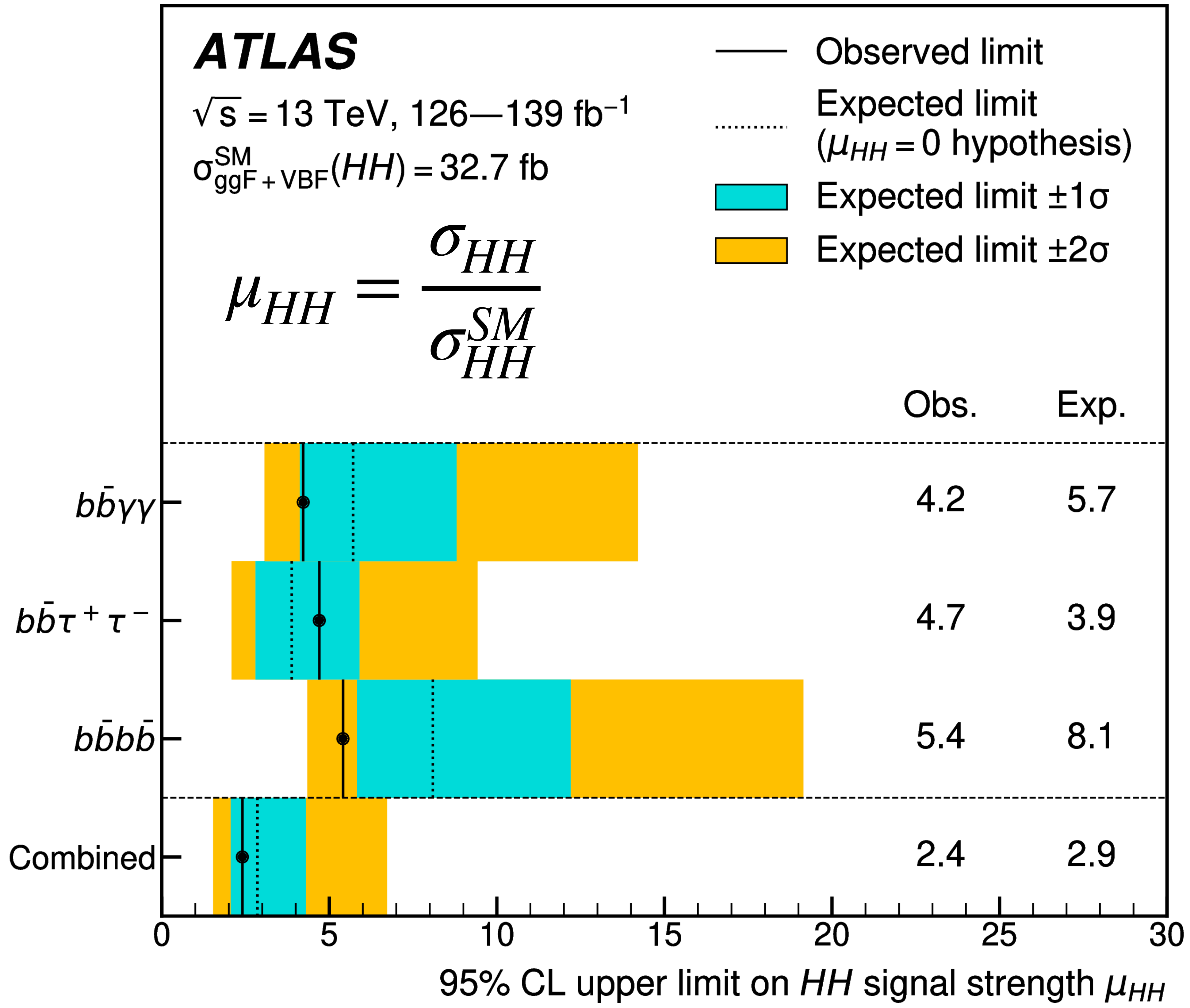


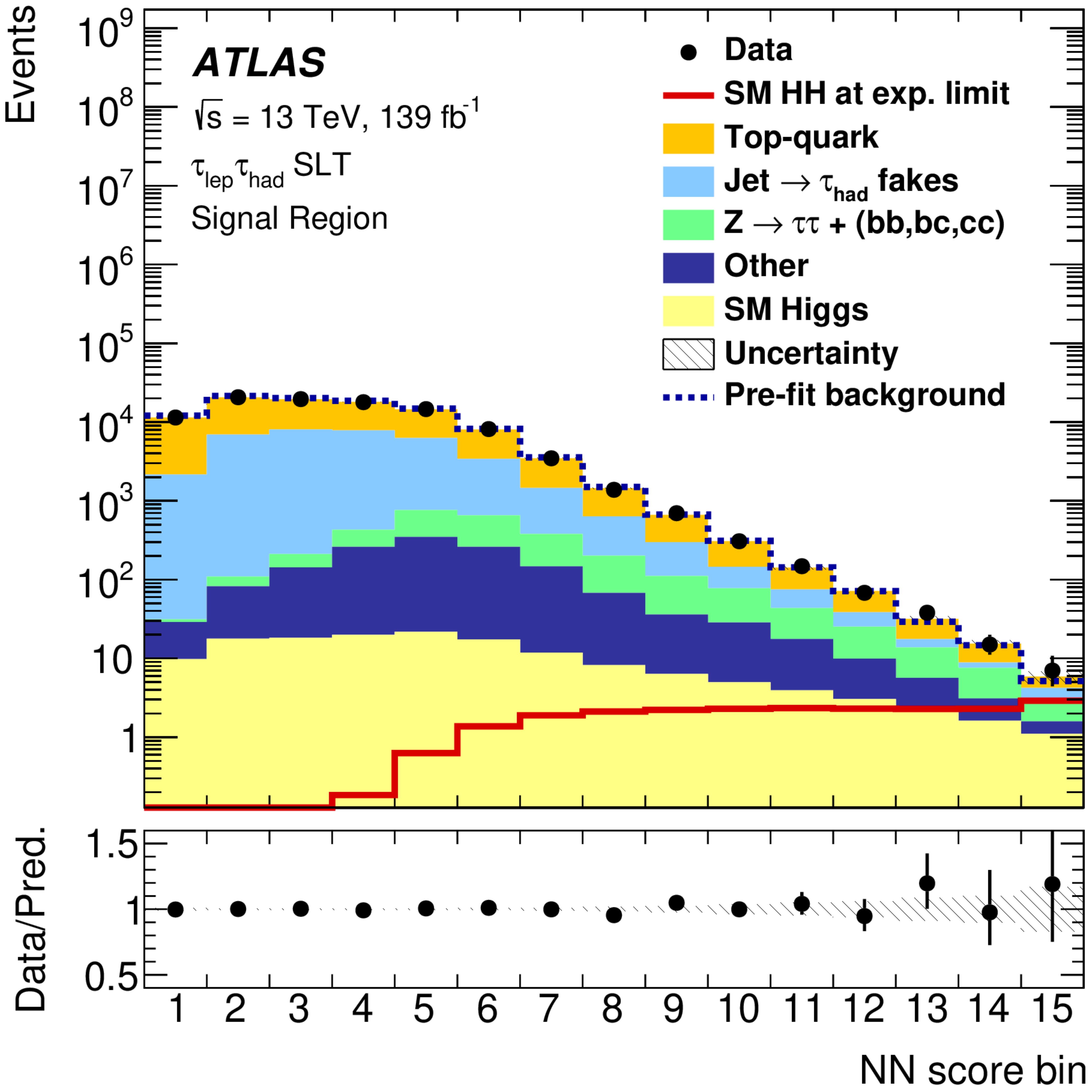
Standard Model
No bubbles
No matter

Di-Higgs in ATLAS

How we treat events: (examples)

1. Trigger: high-energy muon -> save the data!
2. Event selection: 2 b-jets of combined mass < 150 GeV
3. Use machine learning to separate signal from background
4. Statistical fit signal strength to data

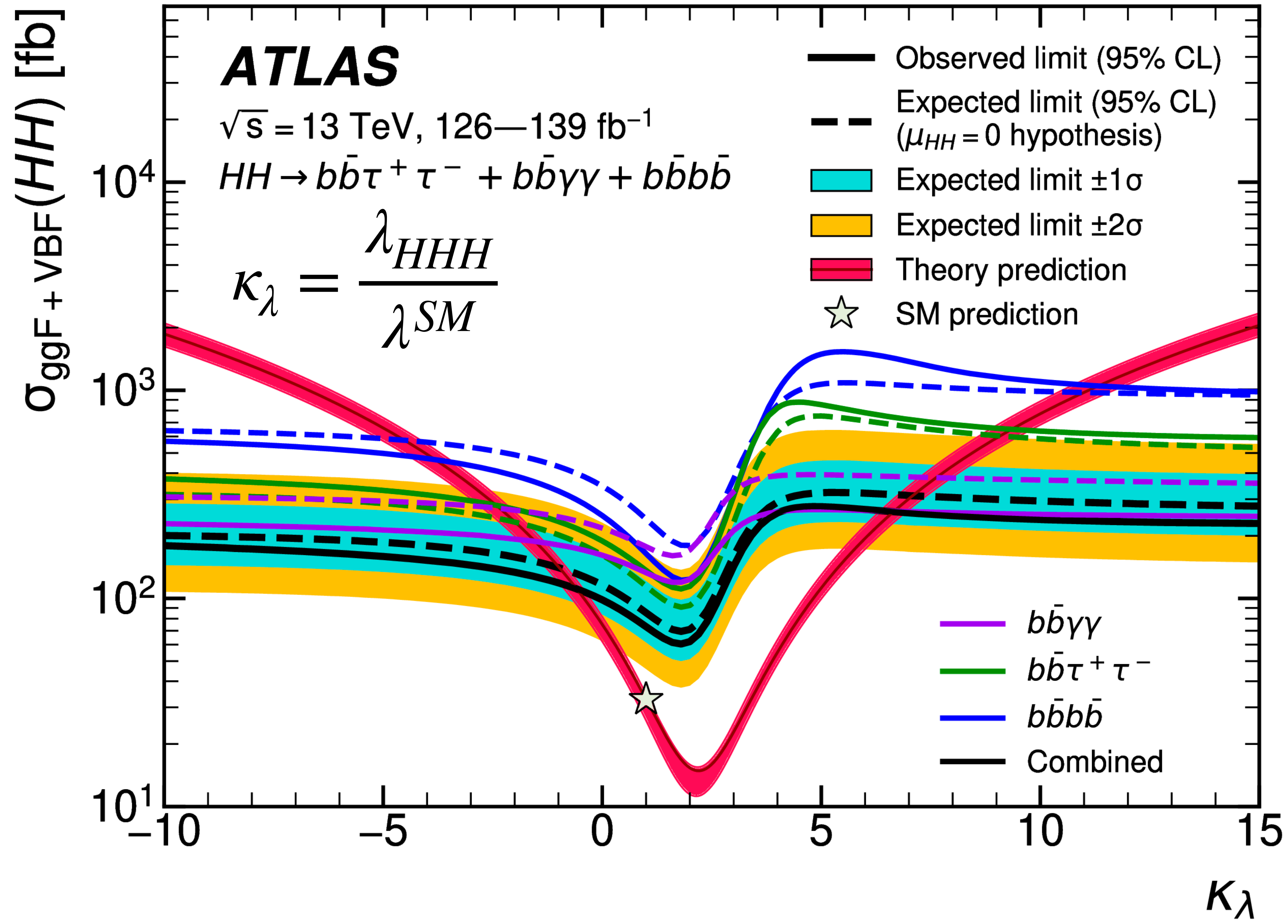


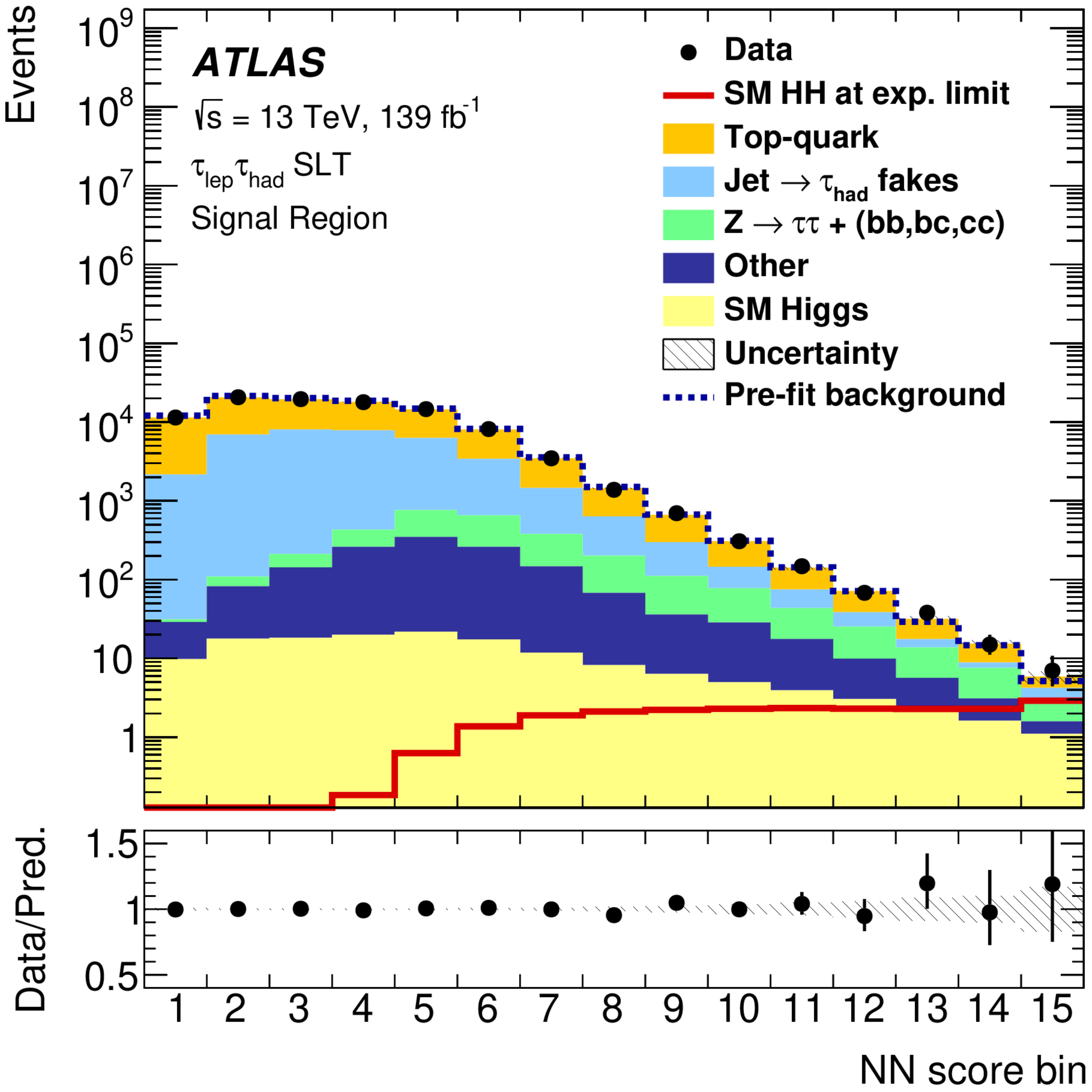


Di-Higgs in ATLAS

How we treat events: (examples)

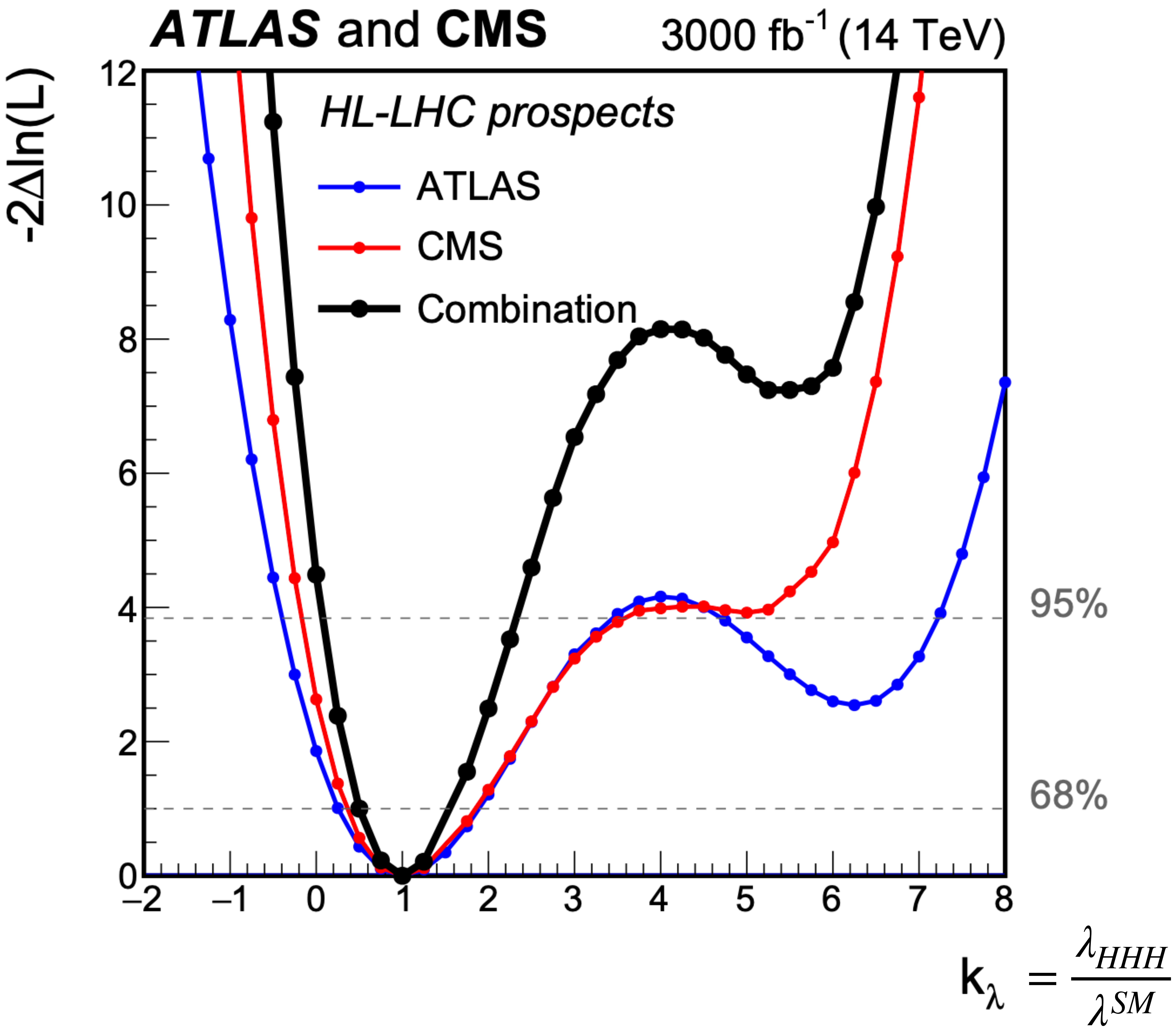
1. Trigger: high-energy muon -> save the data!
2. Event selection: 2 b-jets of combined mass < 150 GeV
3. Use ML to separate background from signal
4. Statistical fit signal strength to data





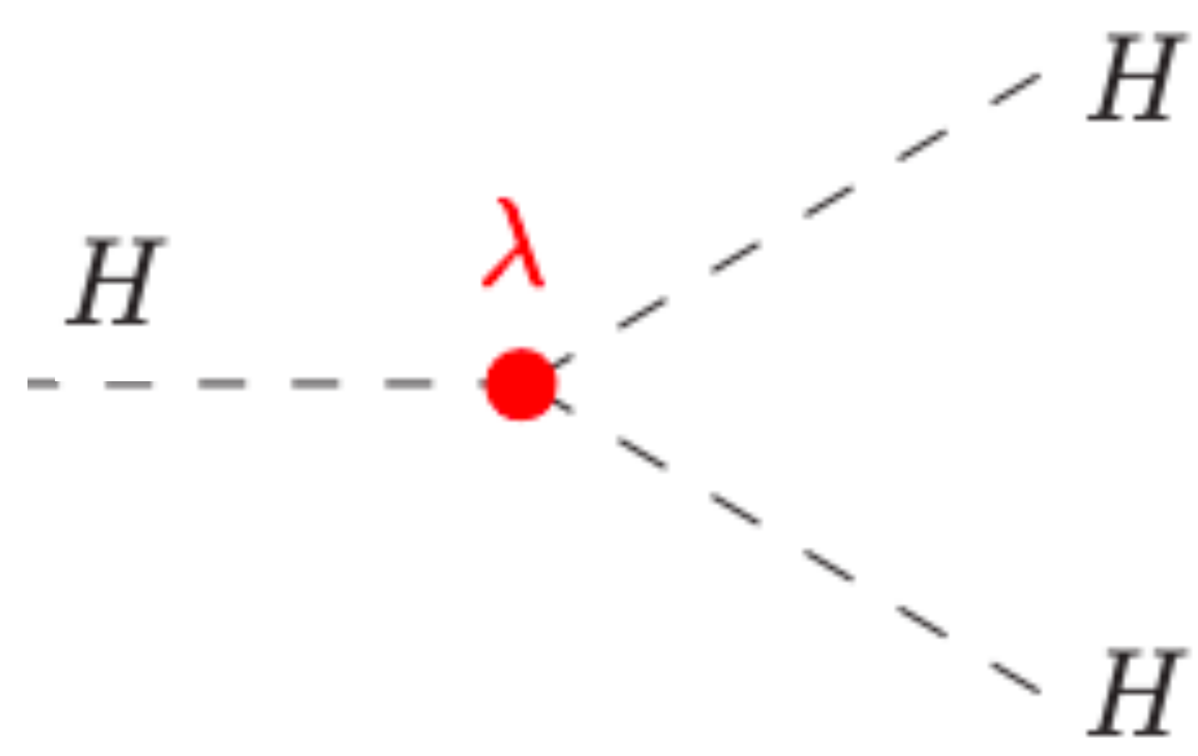
Di-Higgs in ATLAS

High Luminosity LHC coming!
X10 more data!
Launch round 2030

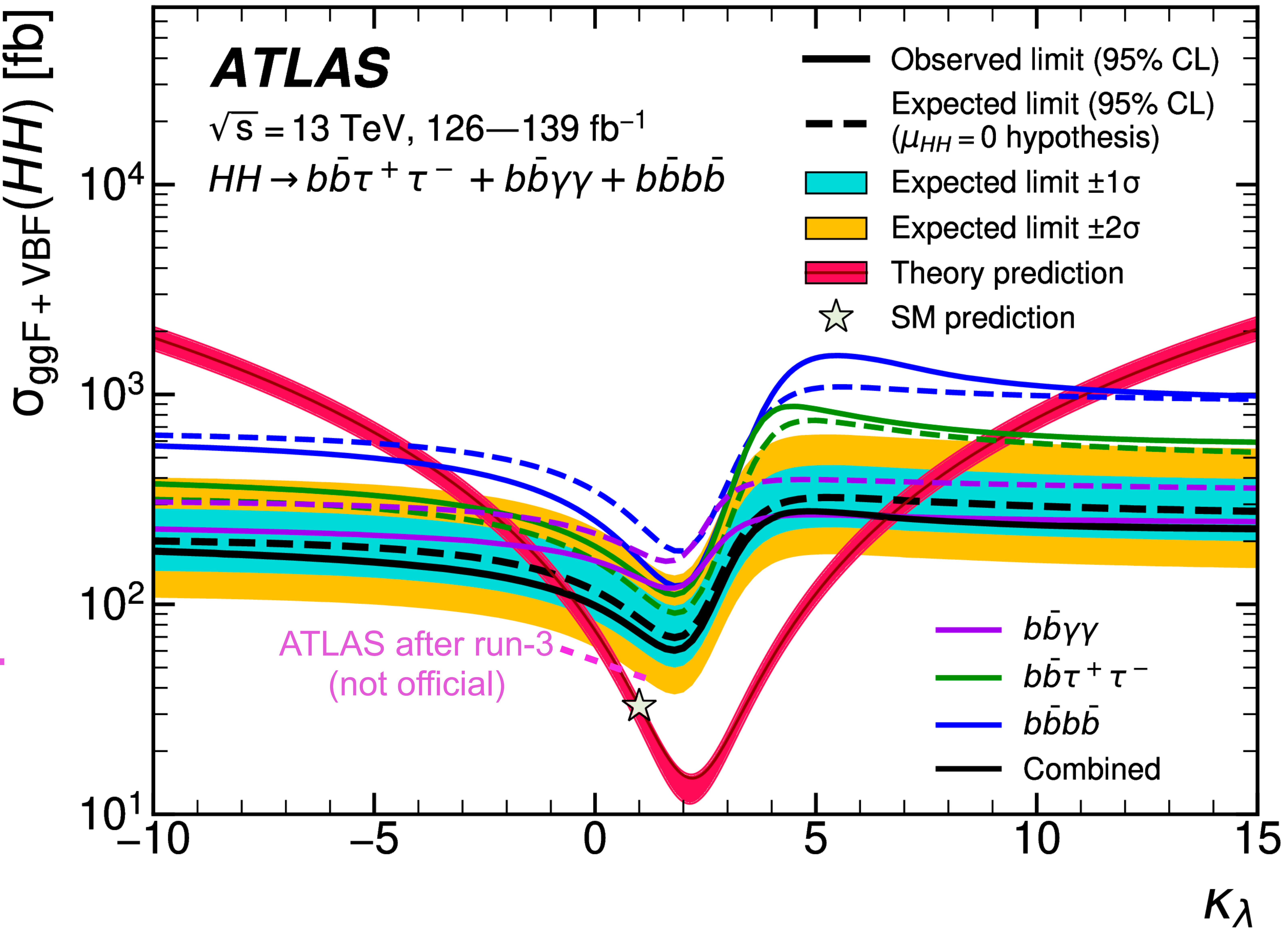


Di-Higgs in ATLAS after run 3: **Discover Di-Higgs**!!

Shape of Higgs?

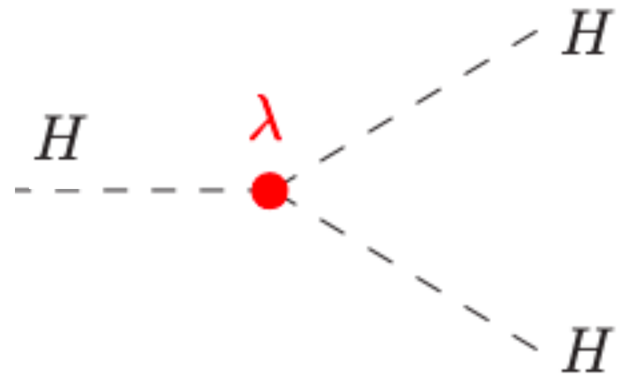


$$0 < \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}}$$



Di-Higgs with High Lumi LHC (~2030) (10 x data)

Shape of Higgs?



$$0.5 < \kappa_\lambda = \frac{\lambda_{HHH}}{\lambda^{SM}} < 1.5$$

New Physics?!