CERN-EP-2025-059

The Higgs boson’s lifetime measurement via off-shell decays to W-bosons

MoriondEW, 29-03-2025, La Thuile

Zef Wolffs,
on behalf of the ATLAS collaboration
Nikhef, University of Amsterdam

The lifetime and the width

- The lifetime of the Higgs boson is $\sim 10^{-22} s$, but is closely related to its **decay rate**

$$\Gamma = \frac{\hbar}{\tau}$$

- The **decay rate is the width of the Breit-Wigner peak! Let's measure it**

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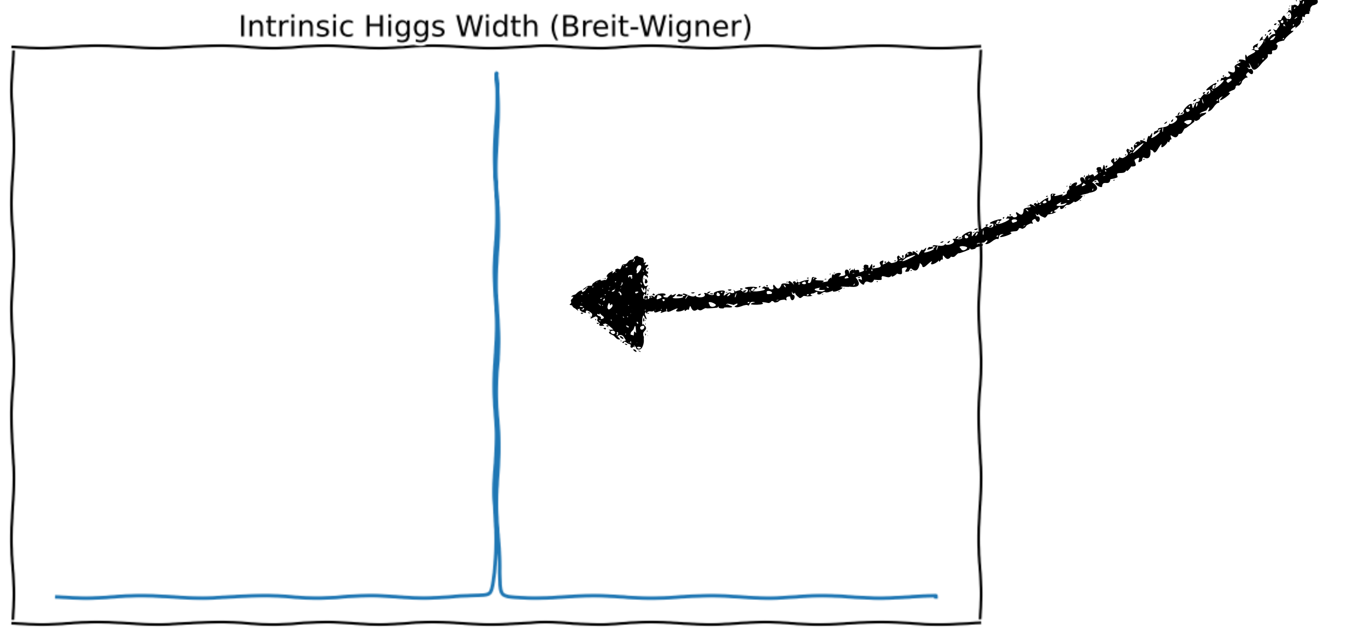
Intrinsic Higgs width 4.1 MeV in standard model



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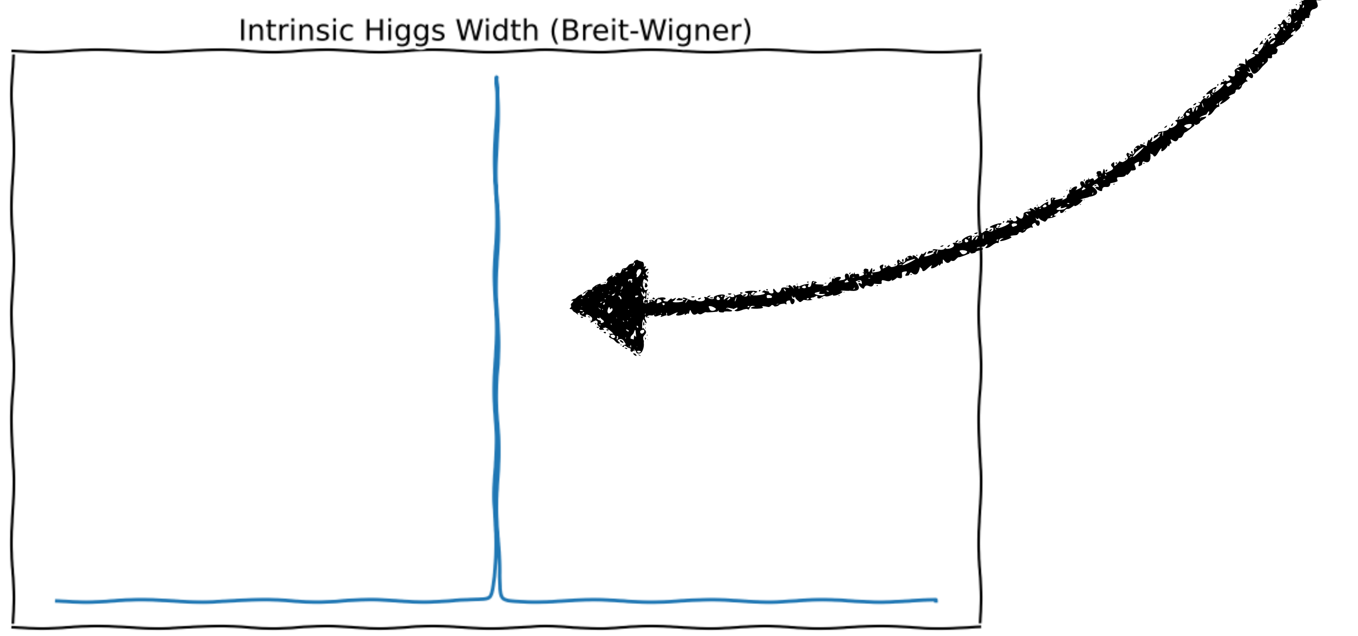

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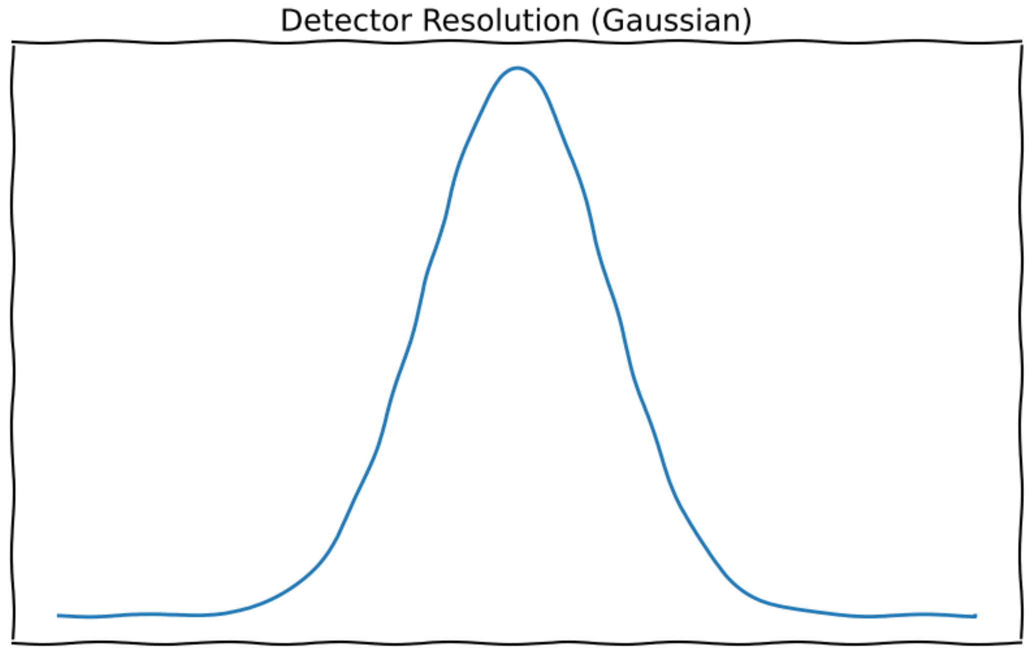

Detector resolution ~1000 MeV in ATLAS detector

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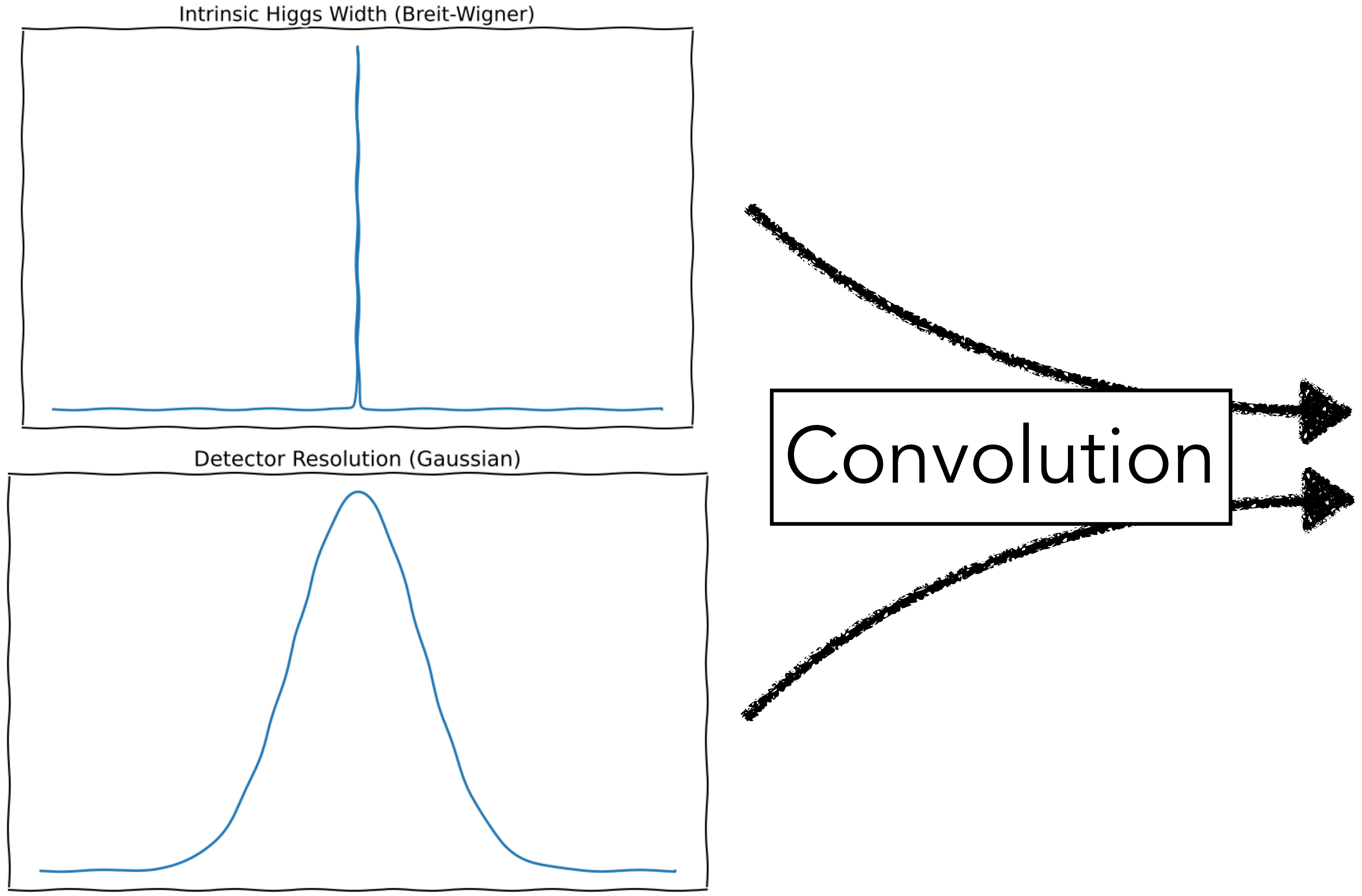
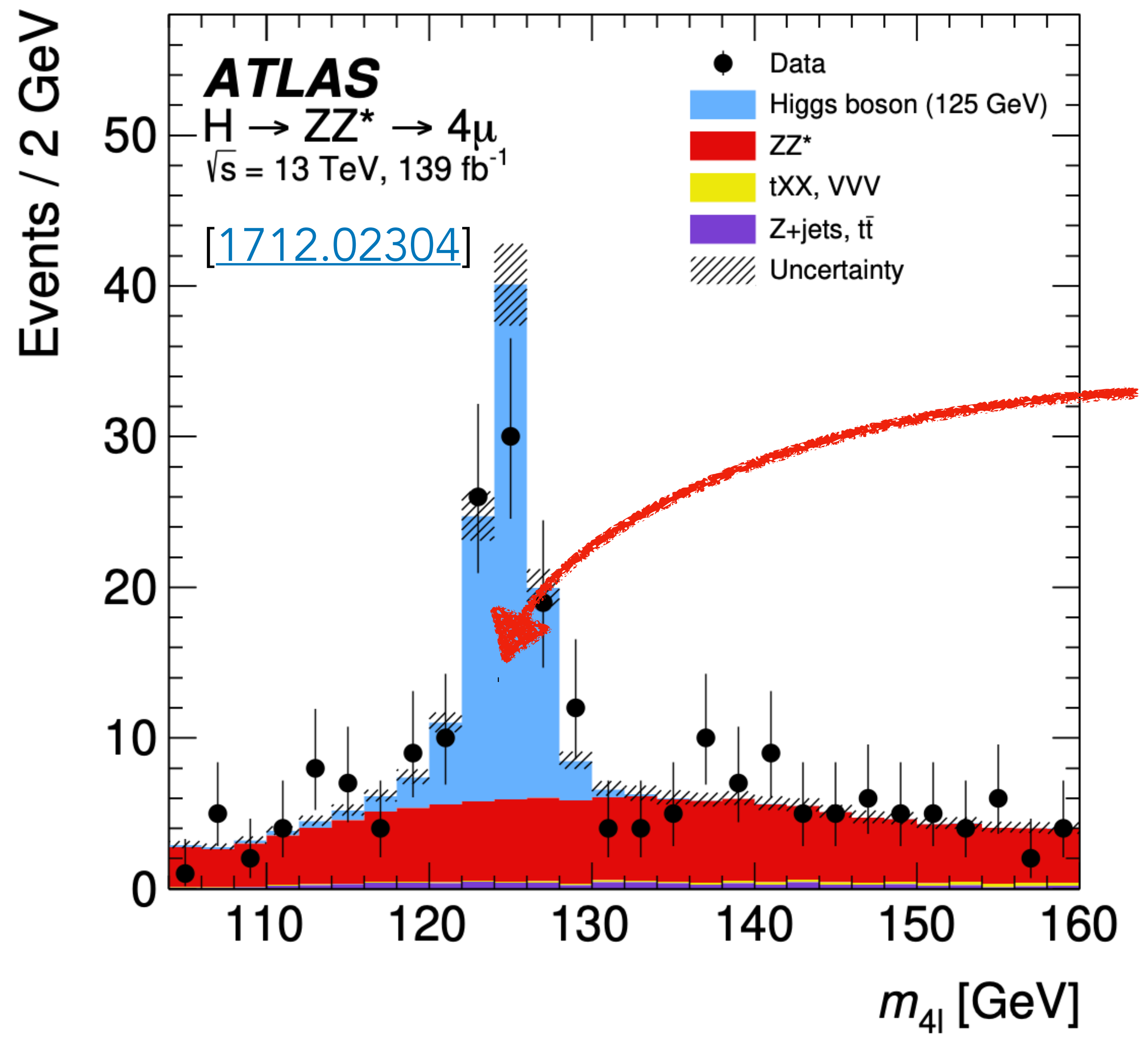


Convolution

What we see in the detector:



This dot has a width of 250 MeV

The lifetime and the width

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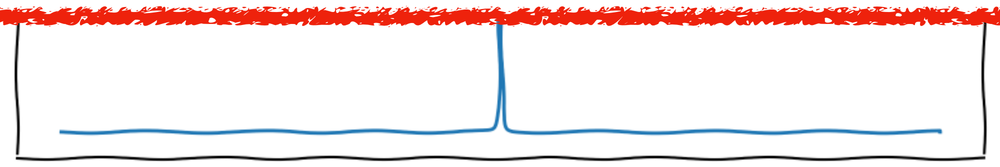
$$\Gamma = \frac{\hbar}{\tau}$$

- The **decay rat** **e it** n the detector:

The CMS collaboration did try the direct approach, and achieved a constraint of ~60 MeV

→ pretty impressive given the situation, but still not close to the actual SM value (~4 MeV) [HIG-21-019]

Intrinsic Higgs width 4.1 MeV in standard model



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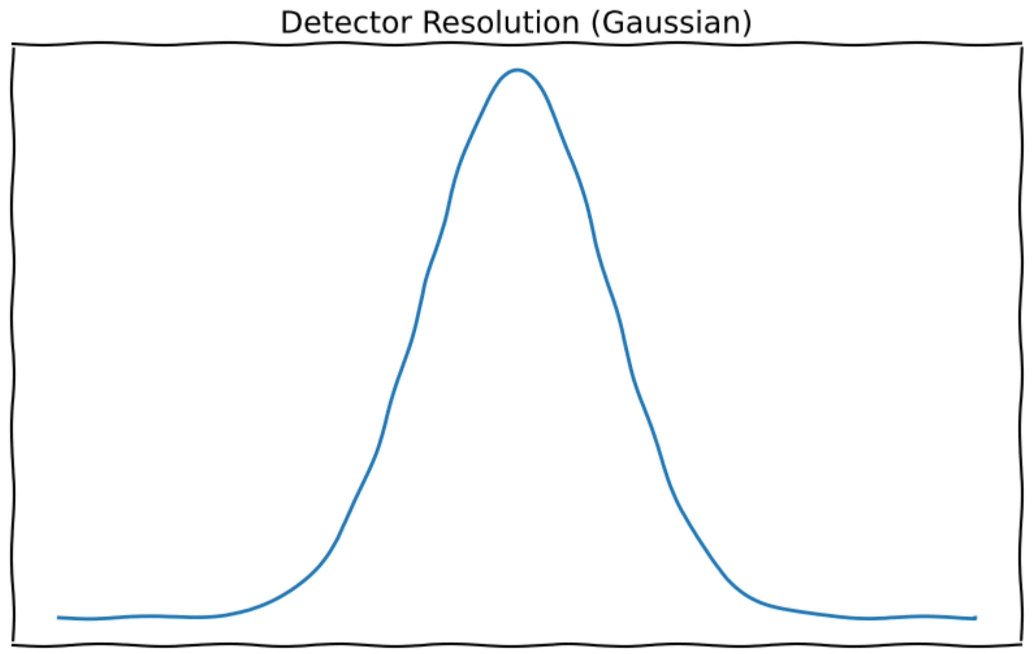

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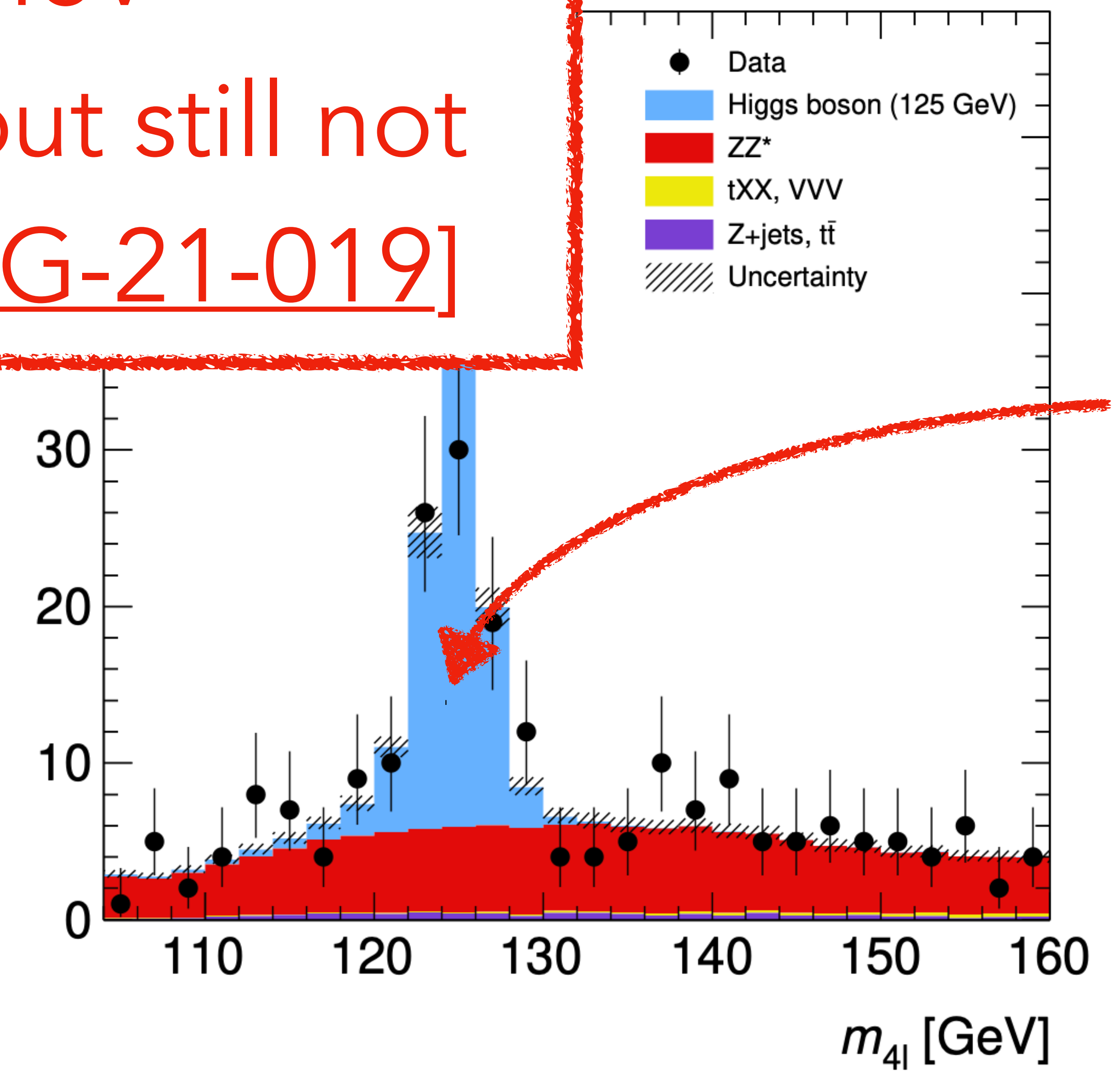

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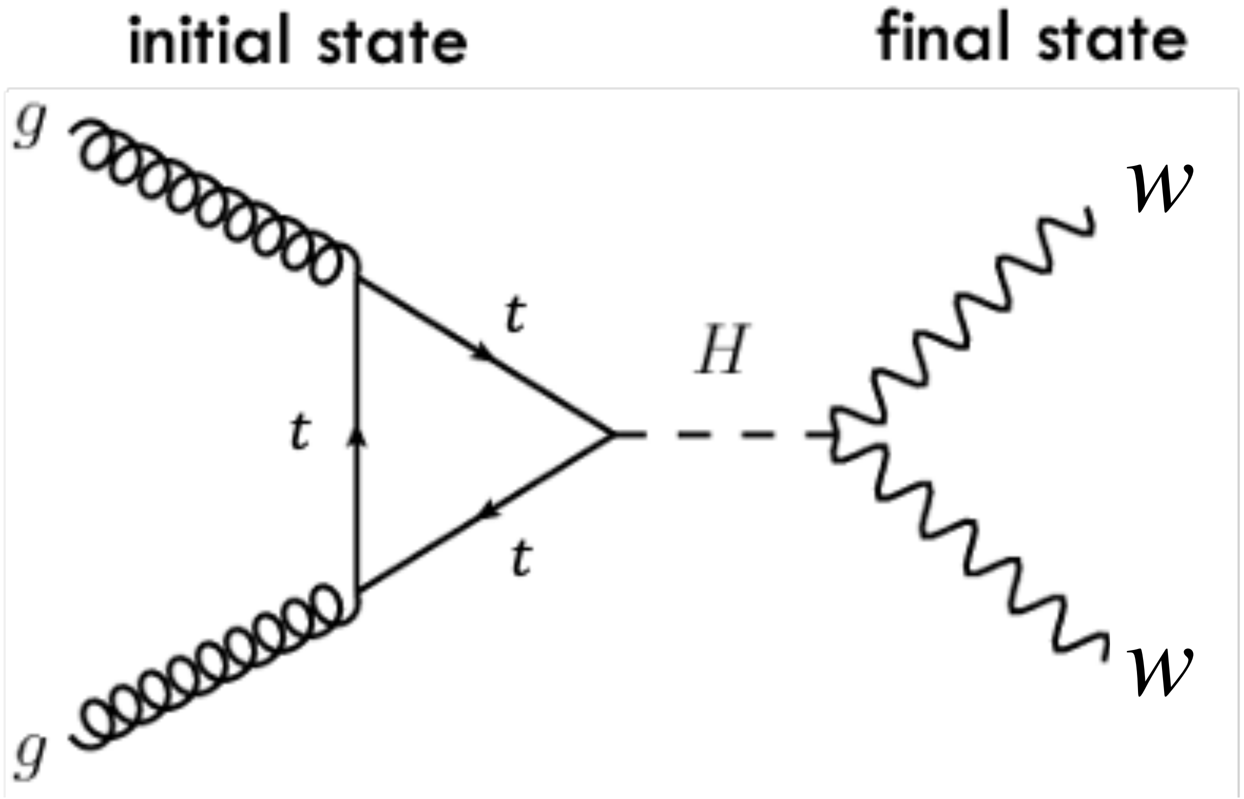
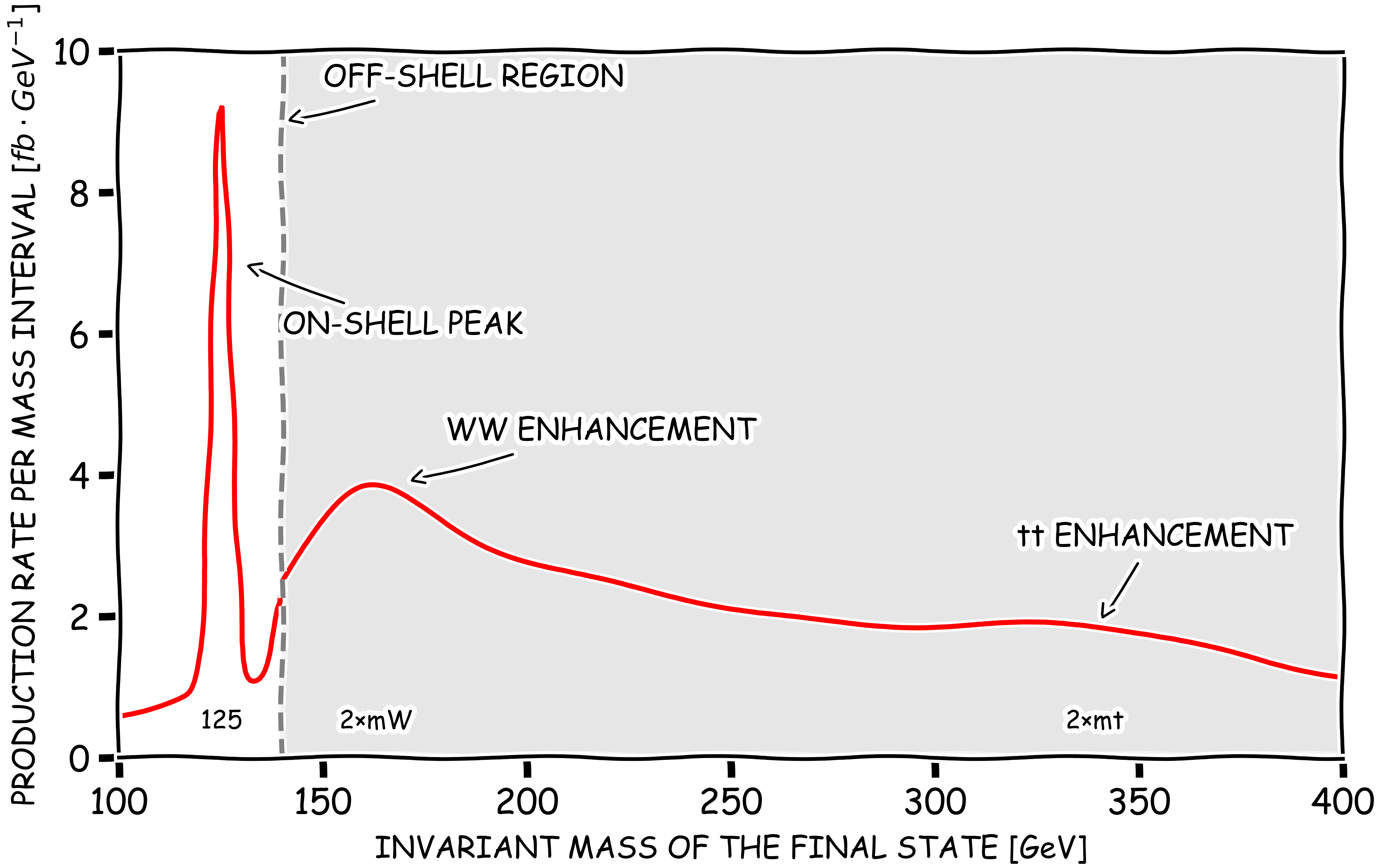
Another strategy to measure the Higgs width

- Caola and Melnikov [1307.4935] propose another strategy to measure the Higgs width





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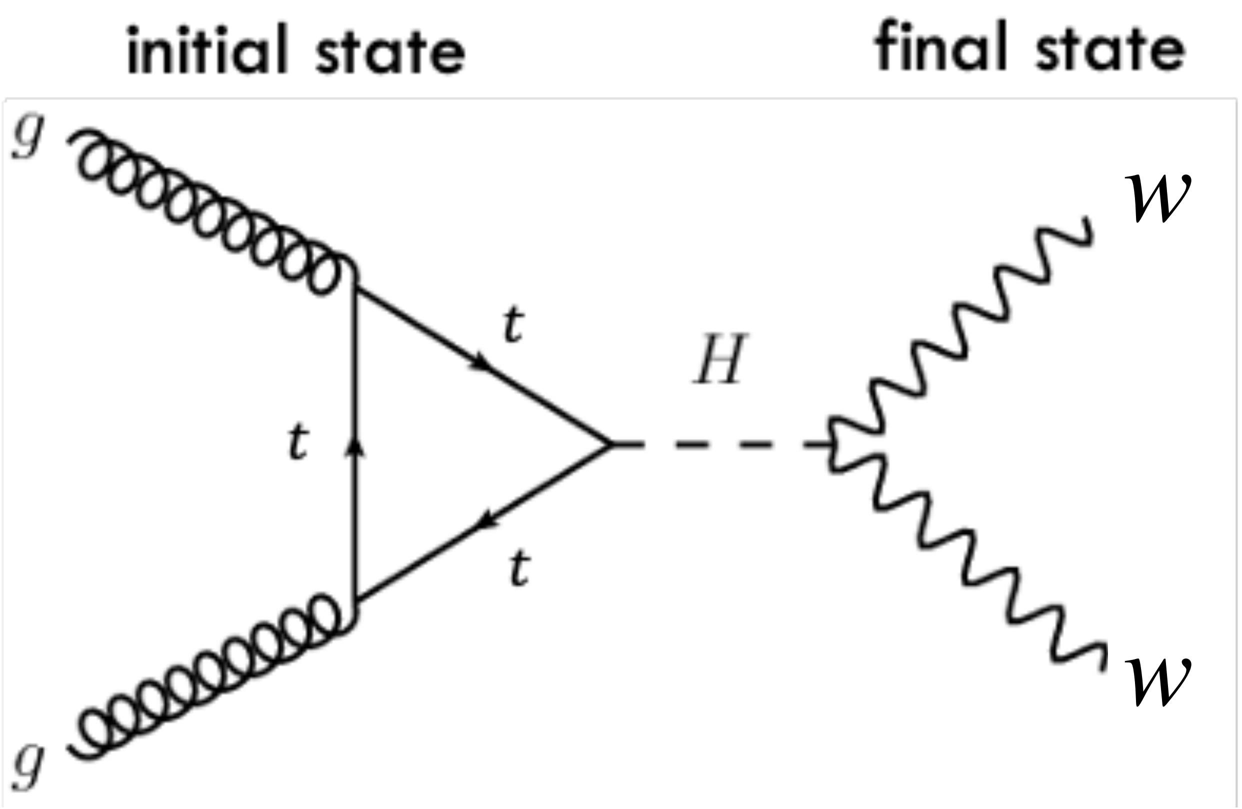

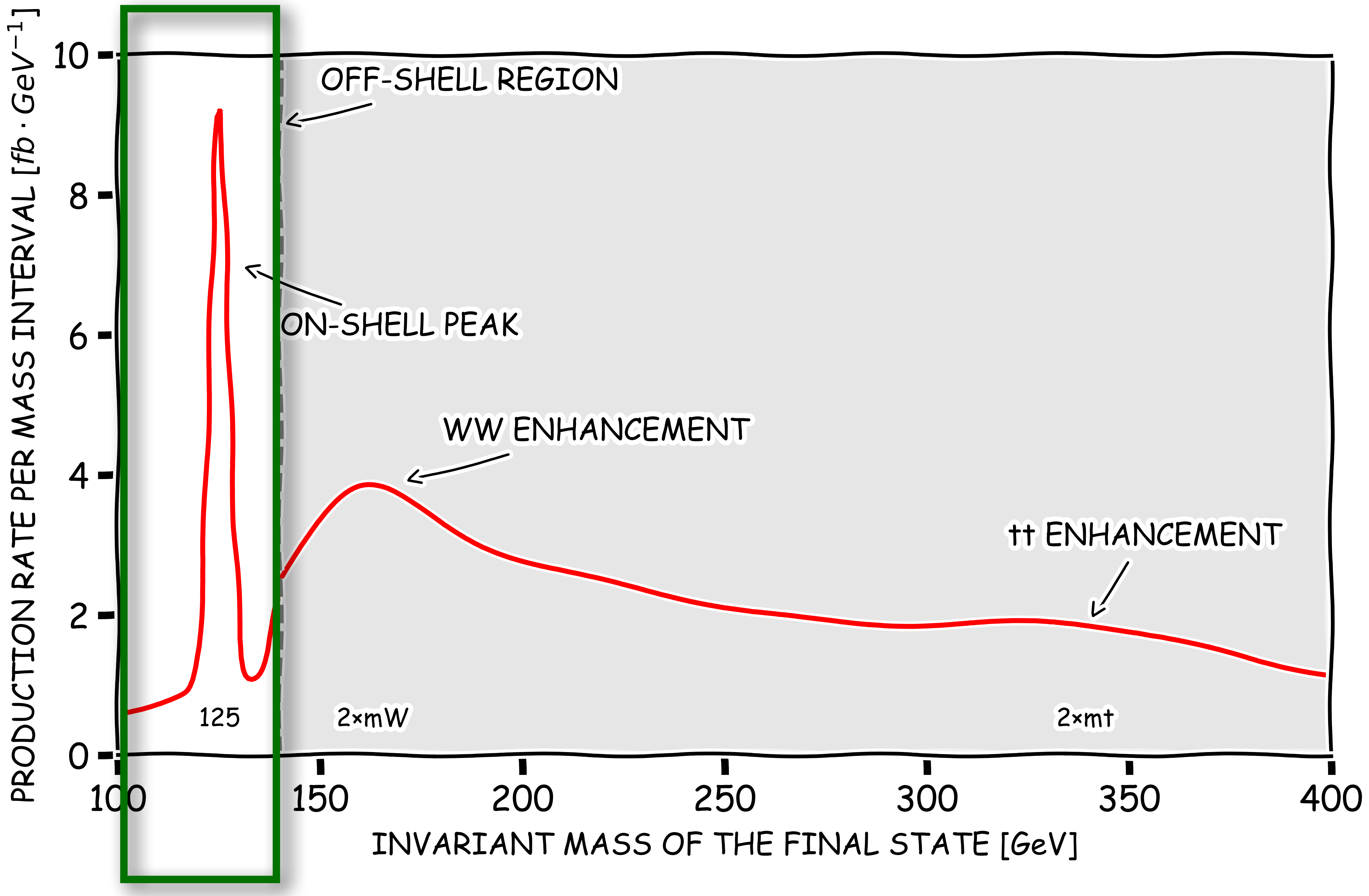

$$\frac{d\sigma_{i\to H\to f}}{dM_f^2} \sim \frac{g_i^2 g_f^2}{\boxed{m_H^2\Gamma_H^2} + (\cancel{M_f^2 - m_H^2})^2}$$

Dominant term
for the on-shell region

Degeneracy between couplings
and the width in onshell regime!

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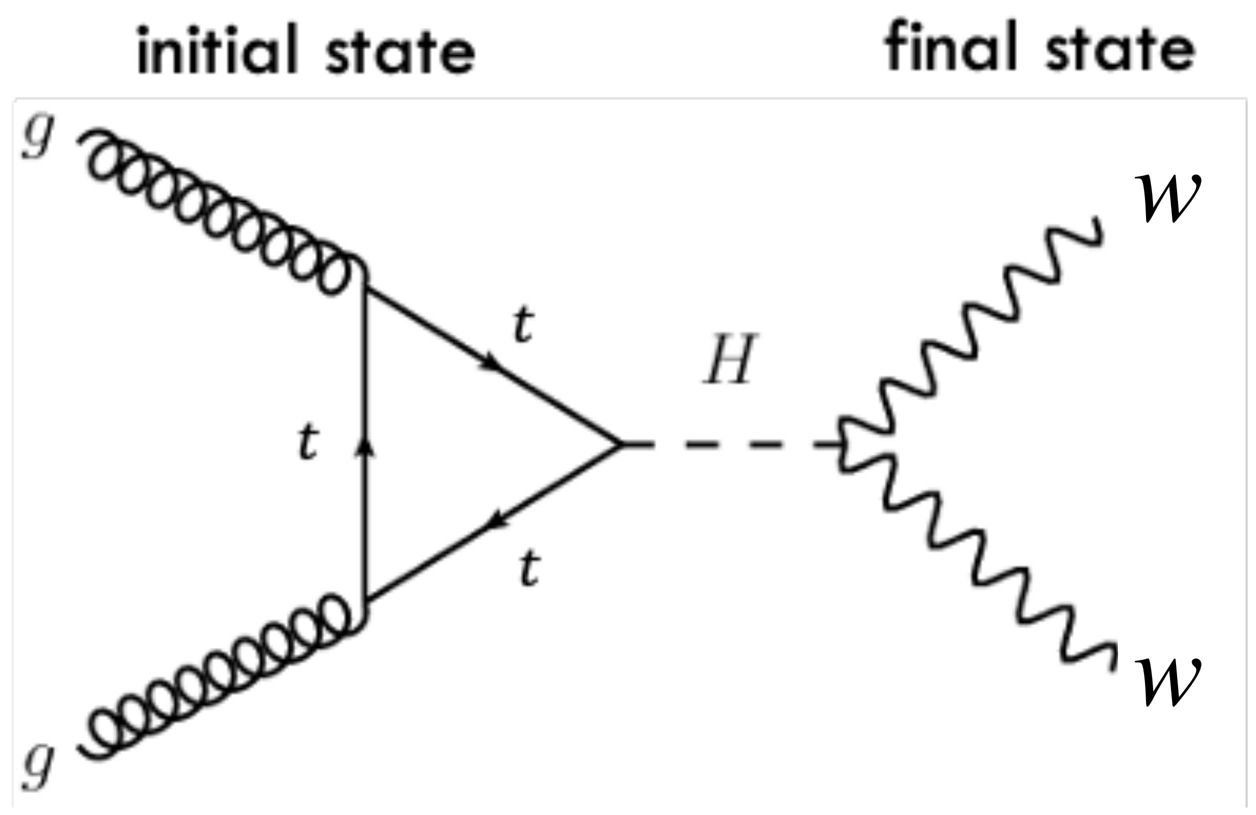

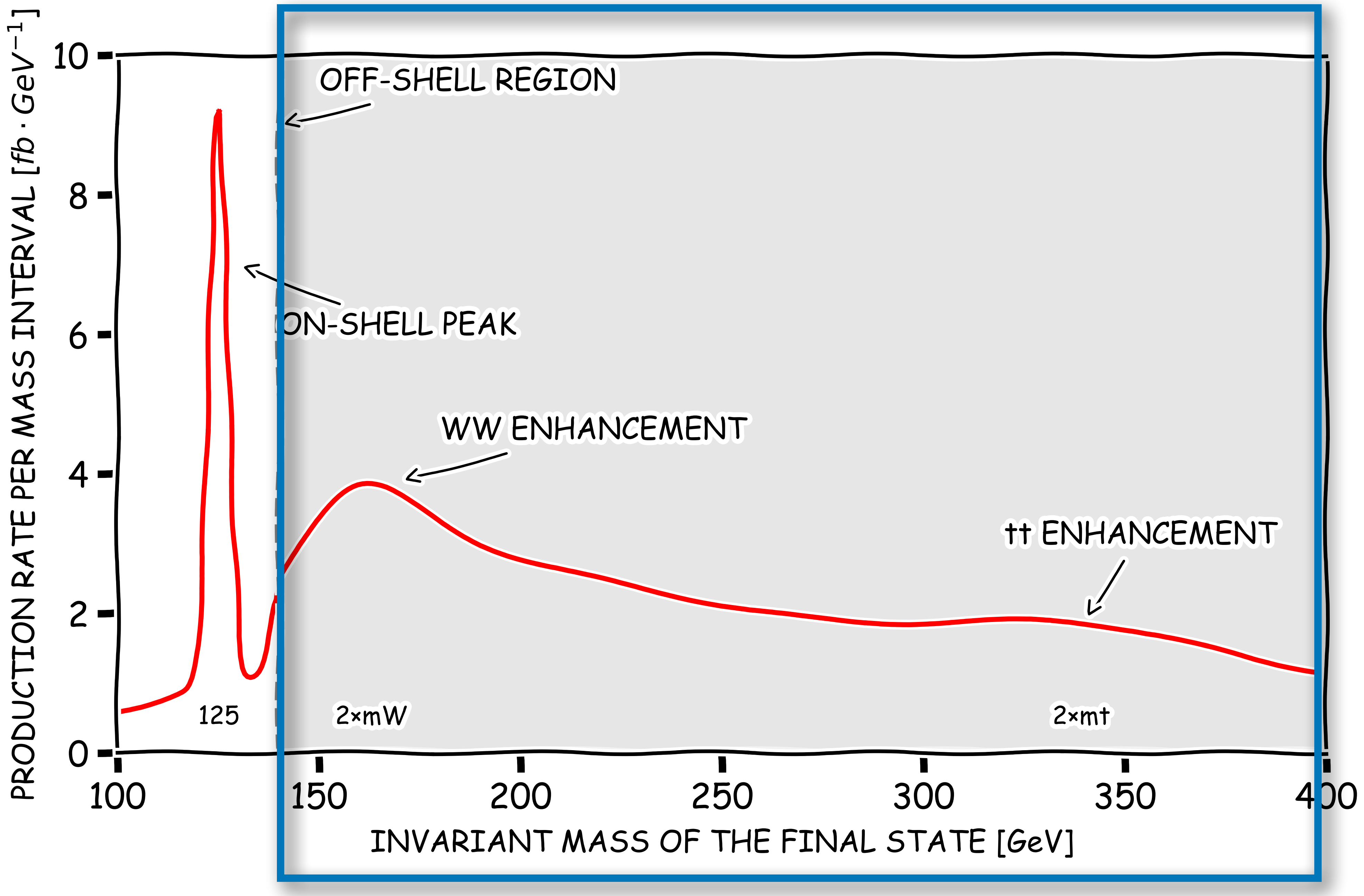

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Degeneracy resolved in offshell regime!

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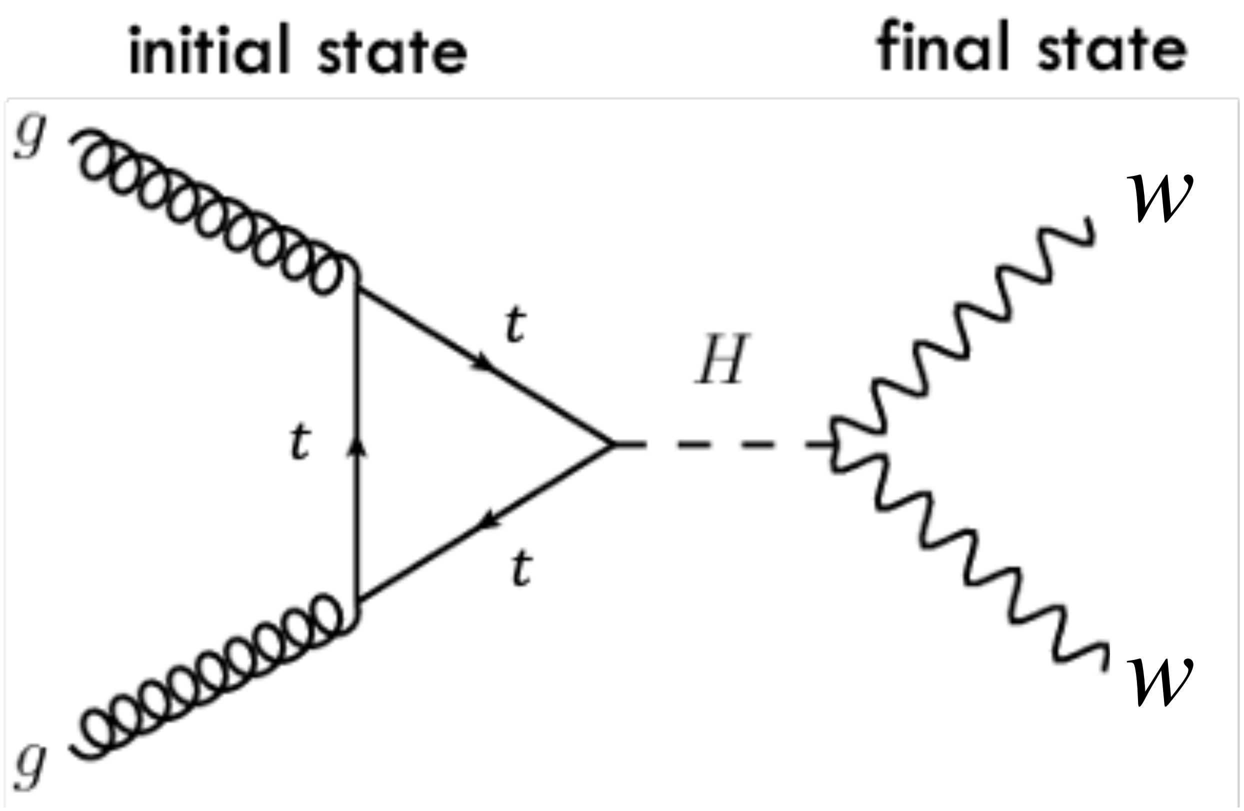

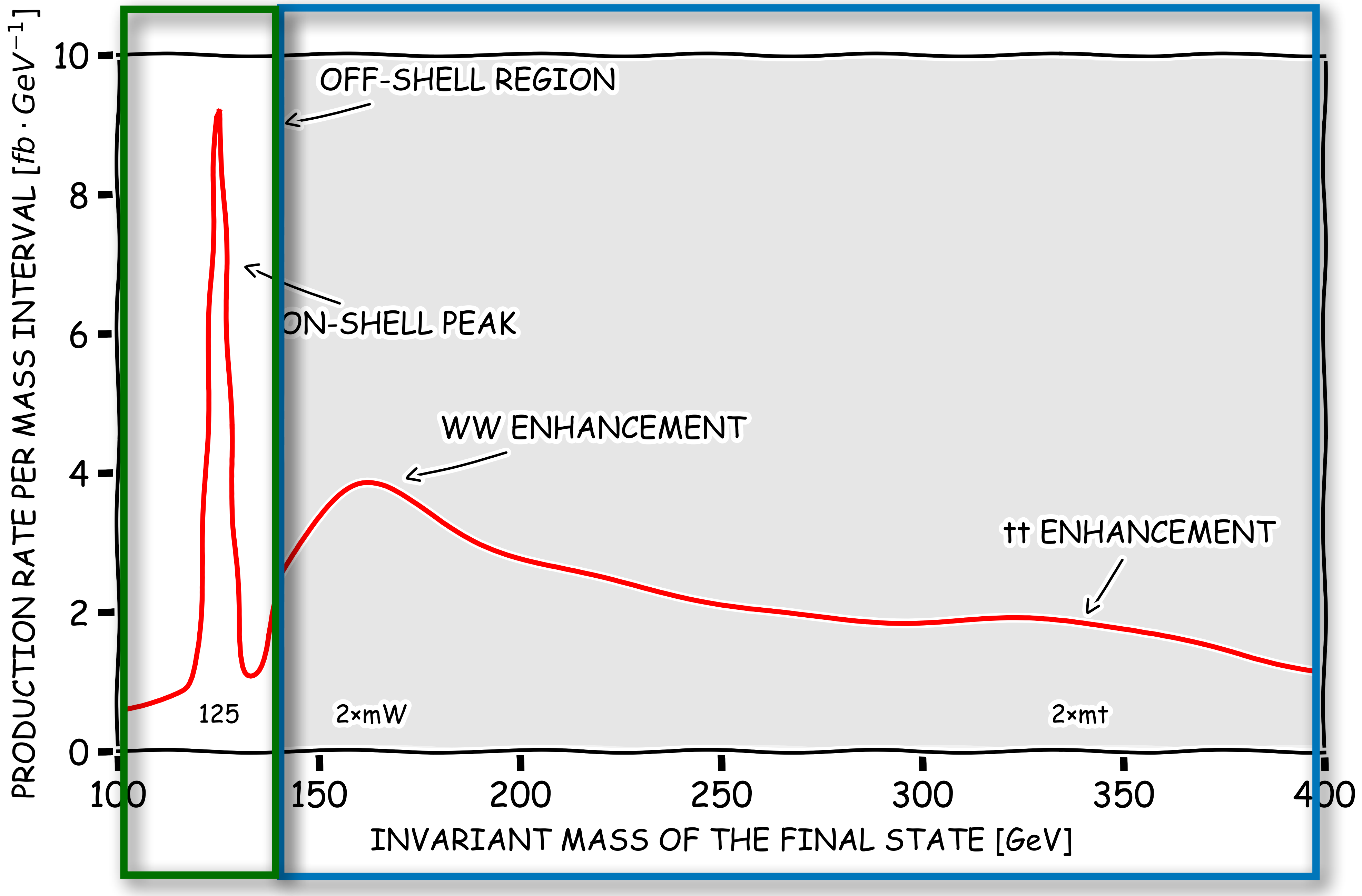

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$$\Gamma_H \propto \frac{\boxed{\sigma^{off-shell}_{i\to H\to f}}}{\boxed{\sigma^{on-shell}_{i\to H\to f}}}$$

Assuming couplings (kappas) cancel out in on- and off-shell regimes

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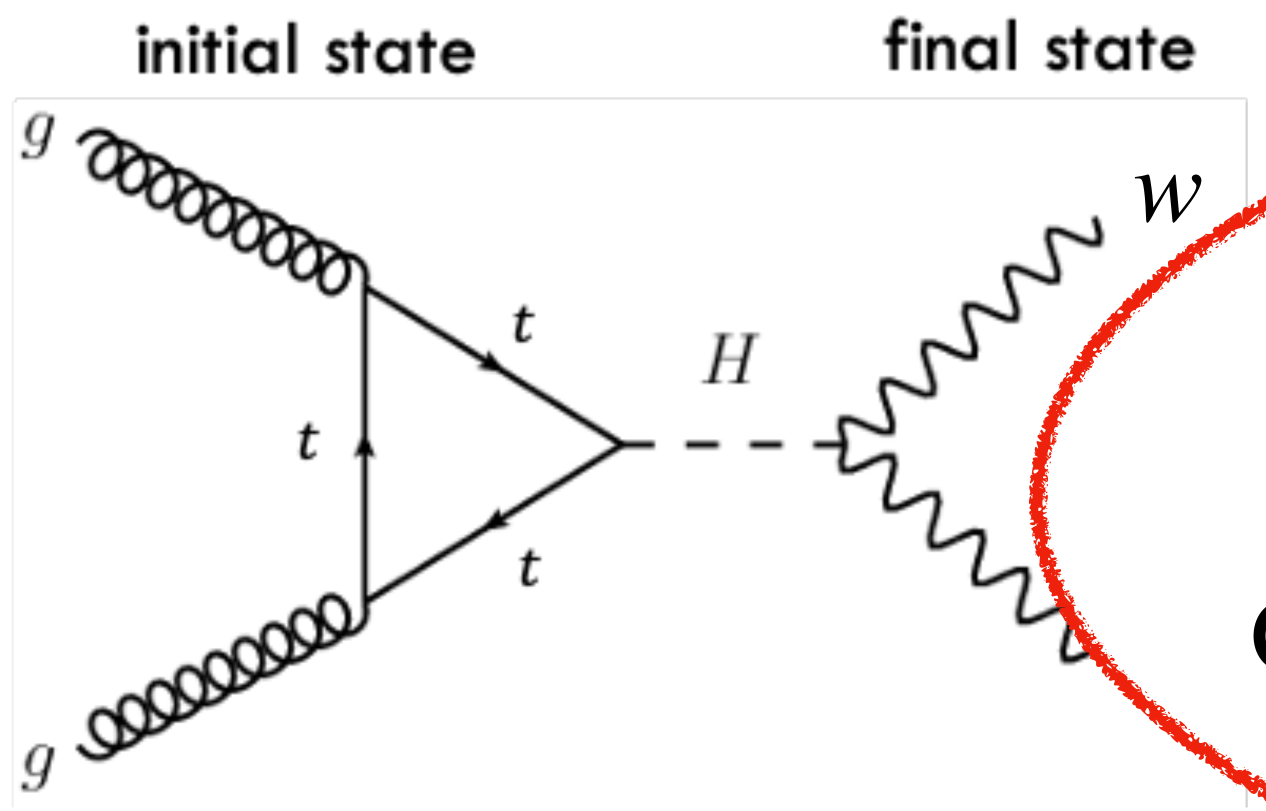

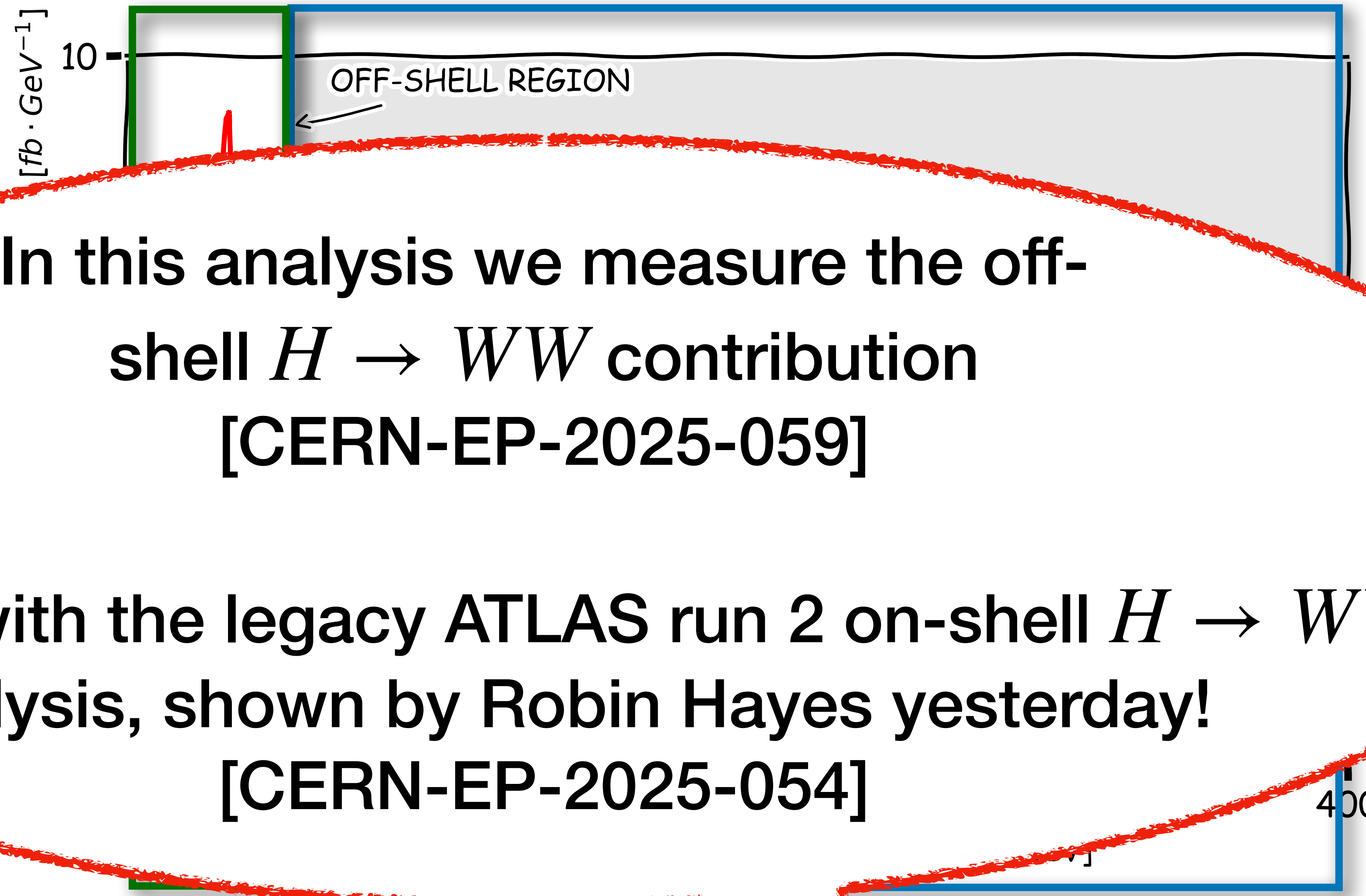

In this analysis we measure the off-shell $H \to WW$ contribution [CERN-EP-2025-059]

Combine with the legacy ATLAS run 2 on-shell $H \to WW$ analysis, shown by Robin Hayes yesterday! [CERN-EP-2025-054]

$$\frac{\mathrm{d}\sigma_{i\to H\to f}}{\mathrm{d}M_f^2} \sim \frac{g_i^2 g_f^2}{\underbrace{m_H^2\Gamma_H^2}_{\text{Dominant term for the on-shell region}} + \underbrace{(M_f^2 - m_H^2)^2}_{\text{Dominant term for the off-shell region}}}$$

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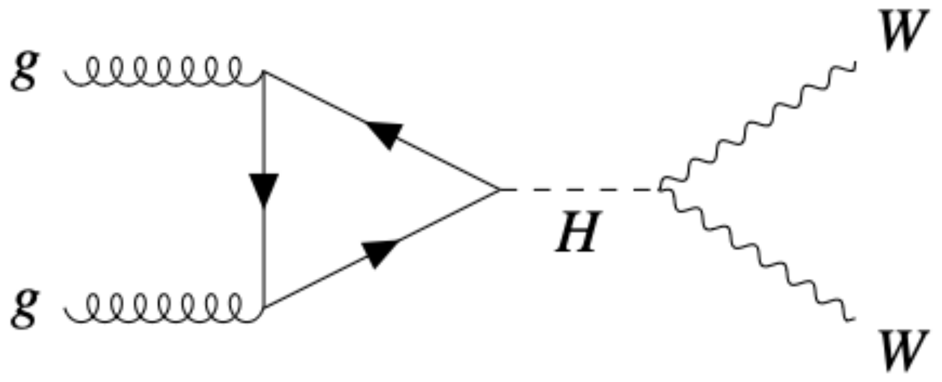
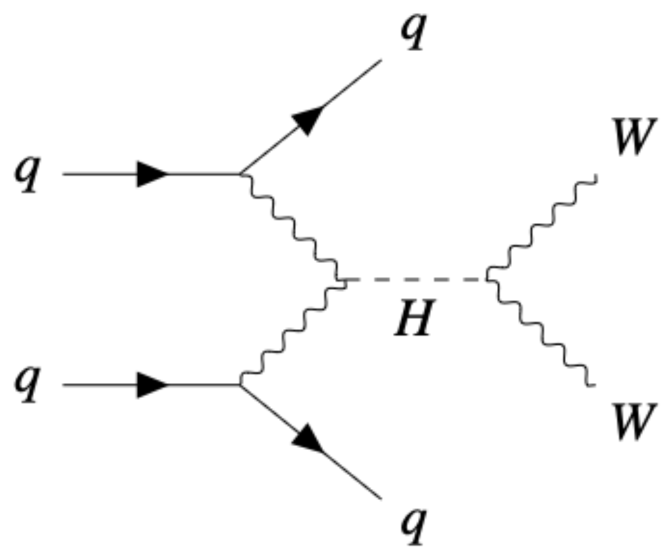
Analysis strategy

Dataset: Full LHC Run 2 collected by ATLAS experiment

Signal production modes: EW and ggF production of Higgs

- Split up into **three jet channels**, 0j focusing on ggF, 2j focusing on EW, 1j mixed

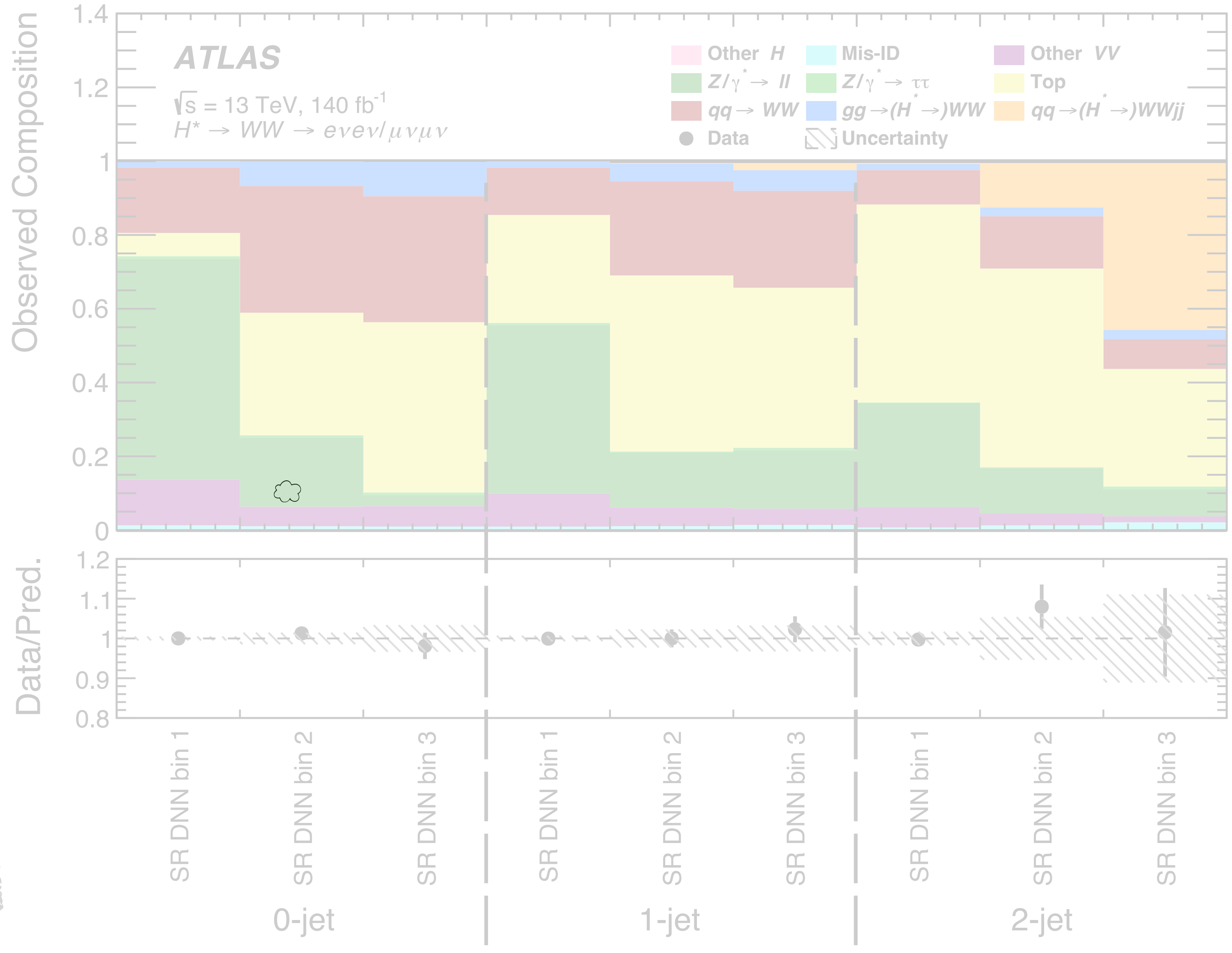


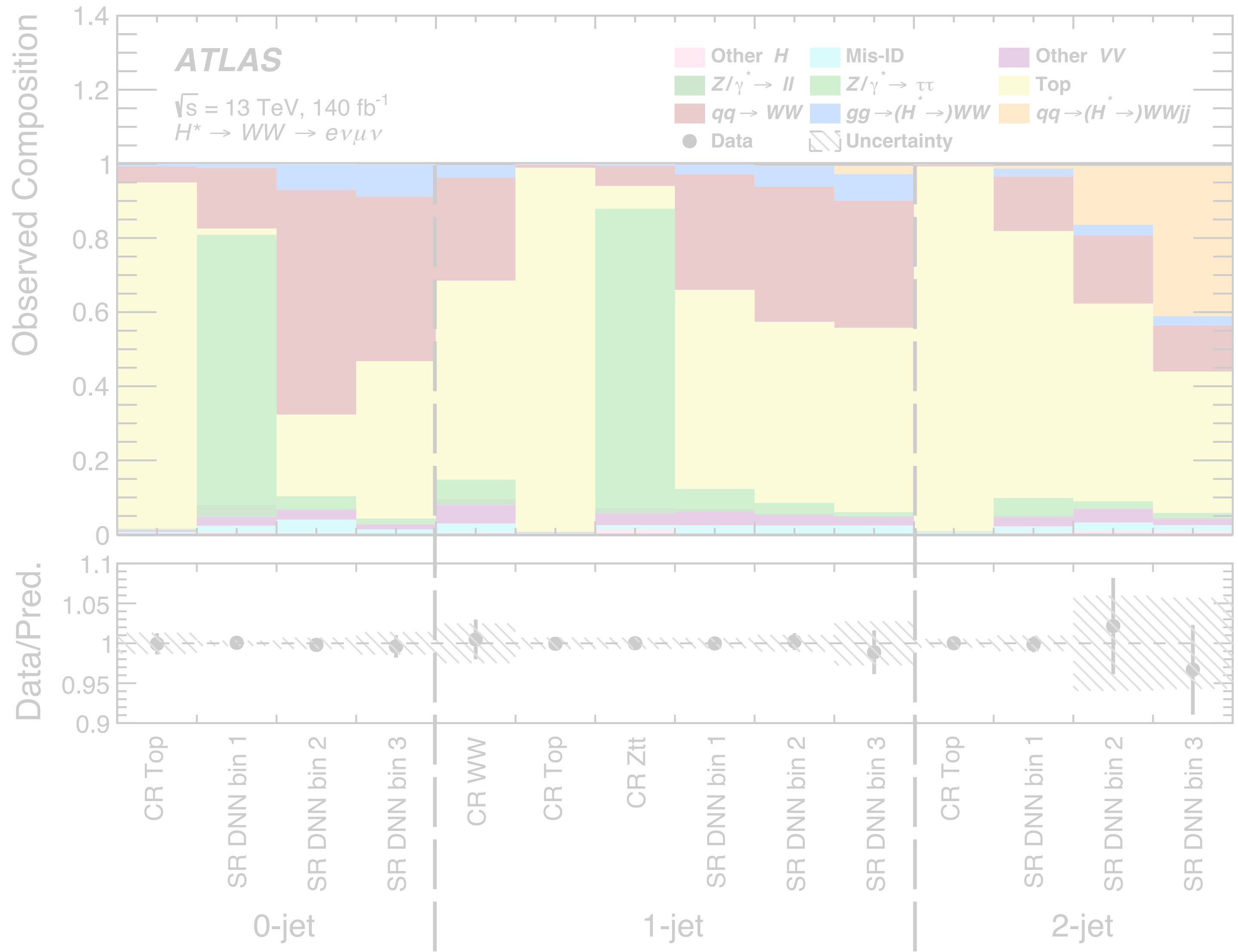


Two signal decay modes

- Same flavour $H \to WW$ decays ($WW \to e\nu e\nu/\mu\nu\mu\nu$)
- Different flavour $H \to WW$ decays ($WW \to e\nu\mu\nu$)

Three DNN bins per analysis region


same flavour regions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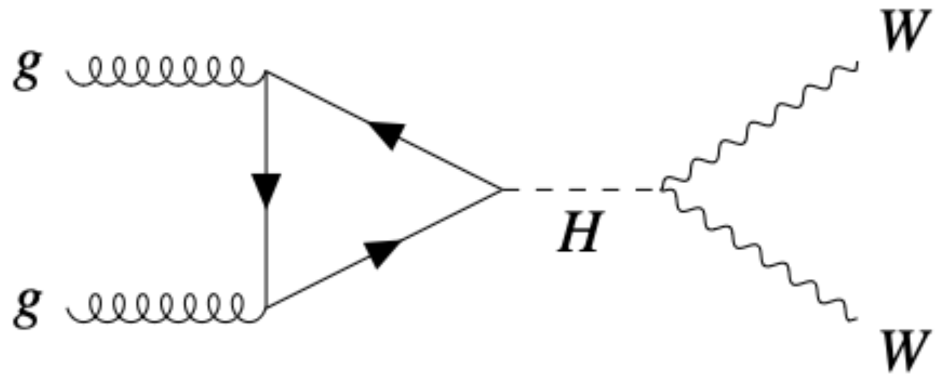

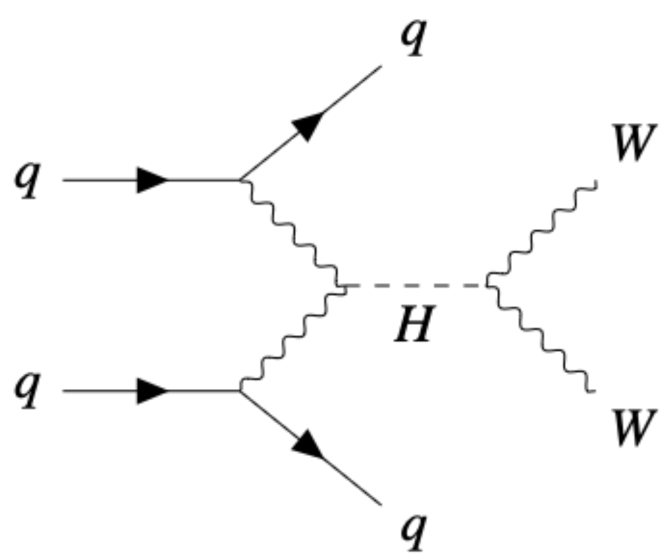

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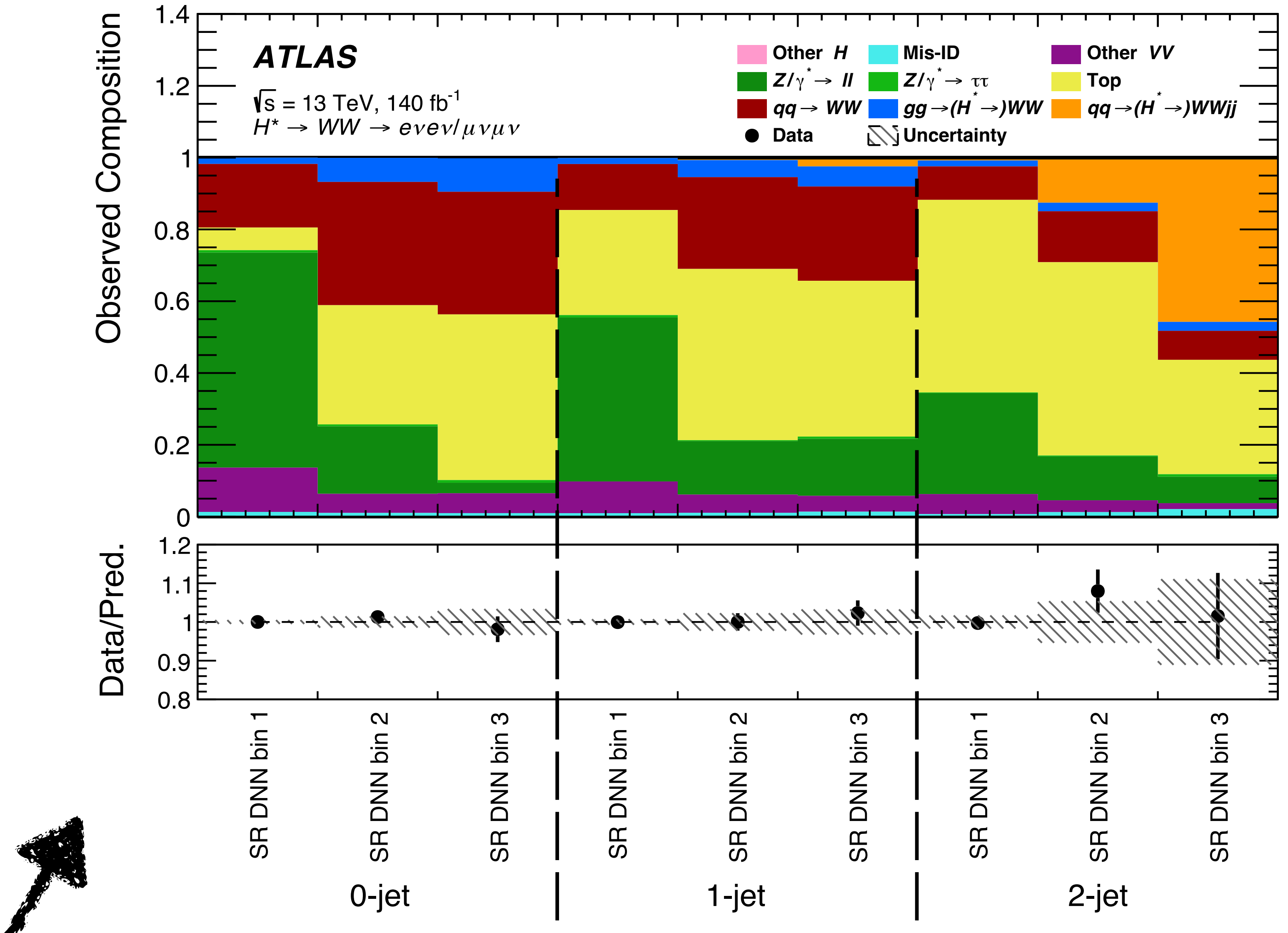

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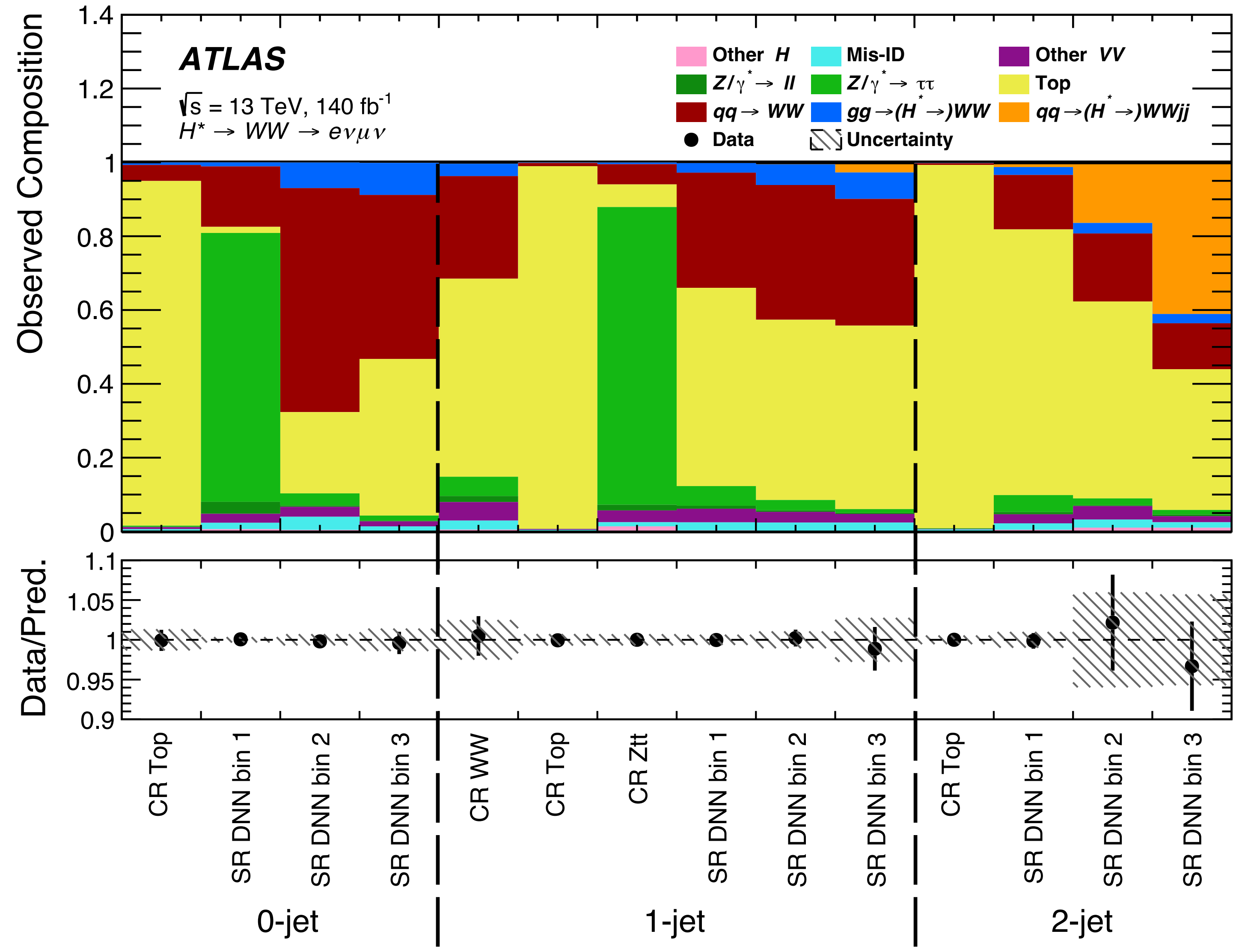
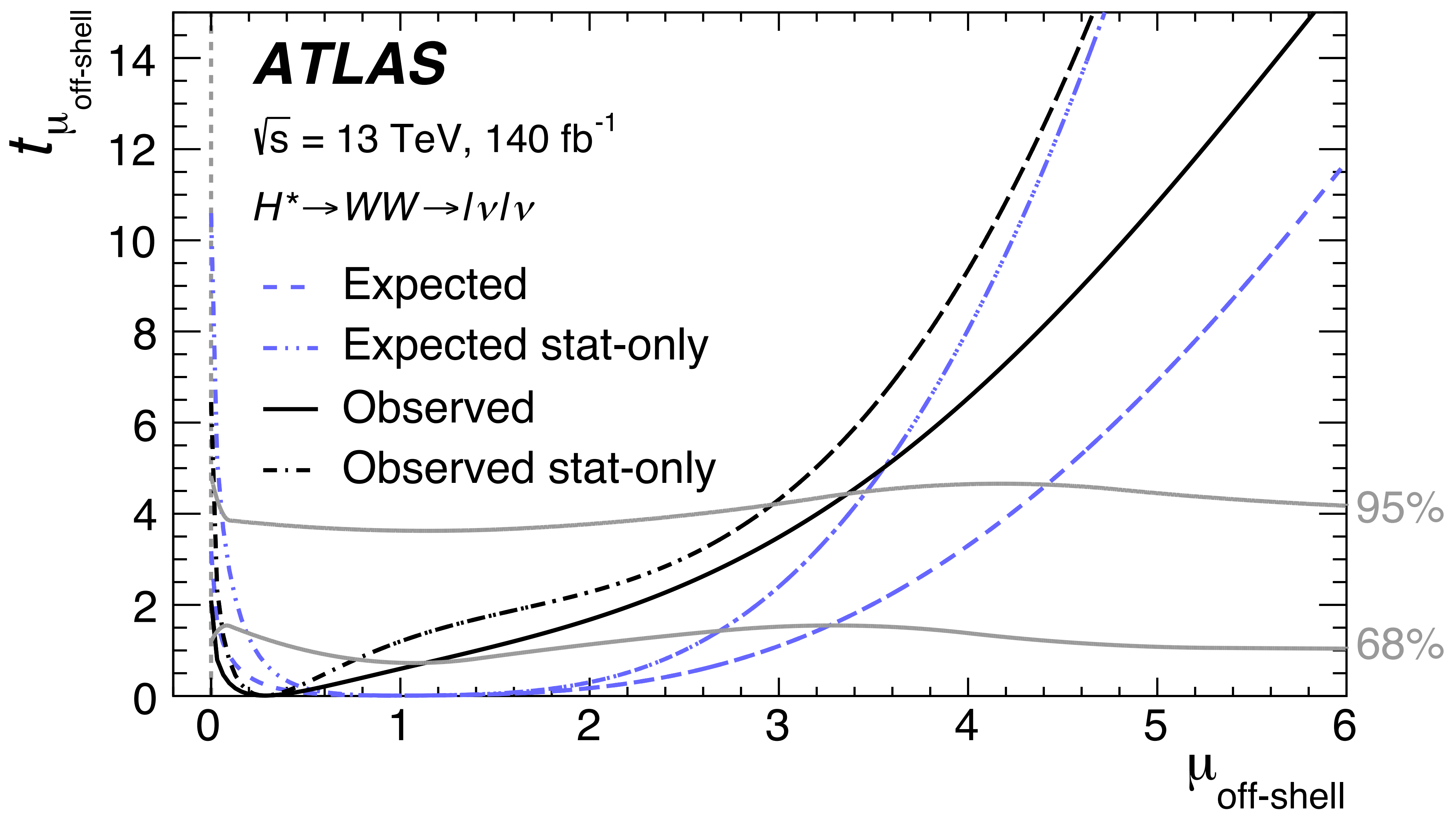


Results

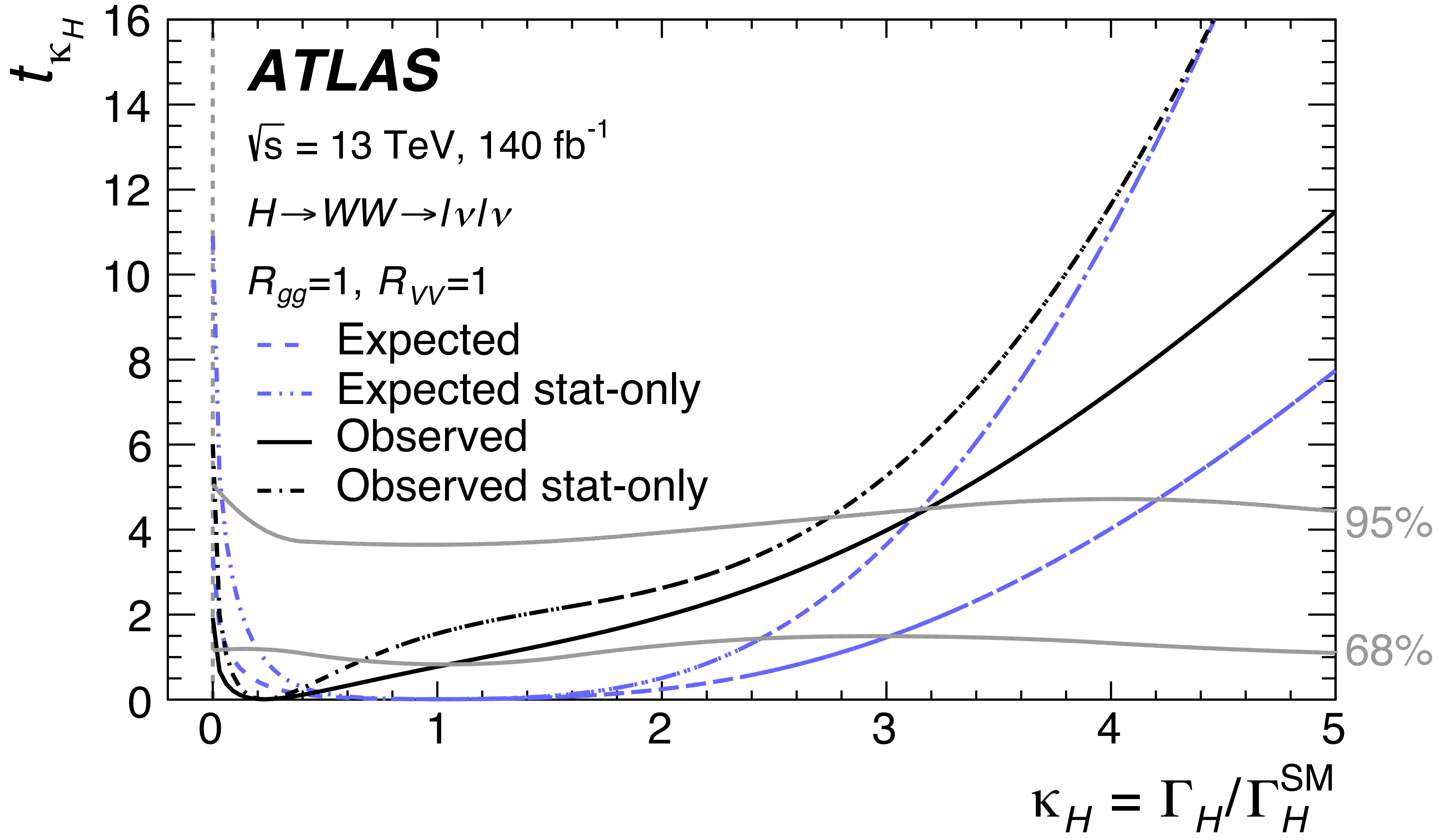
$H \to WW$ Off-shell signal strength parameter

- $\mu_{\text{off-shell}} = 0.3^{+0.9}_{-0.3}$ obs . $(1.0^{+2.3}_{-1.0}$ exp.)
- $\mu_{\text{off-shell}}$ < 3.4 obs. (4.4 exp.) @ 95% CL



The Higgs boson total width

- $\Gamma_H = 0.9^{+3.4}_{-0.9}$ MeV obs. $(4.1^{+8.3}_{-3.8}$ MeV exp.)
- Γ_H < 13.1 MeV obs. (17.3 MeV exp.) @ 95% CL

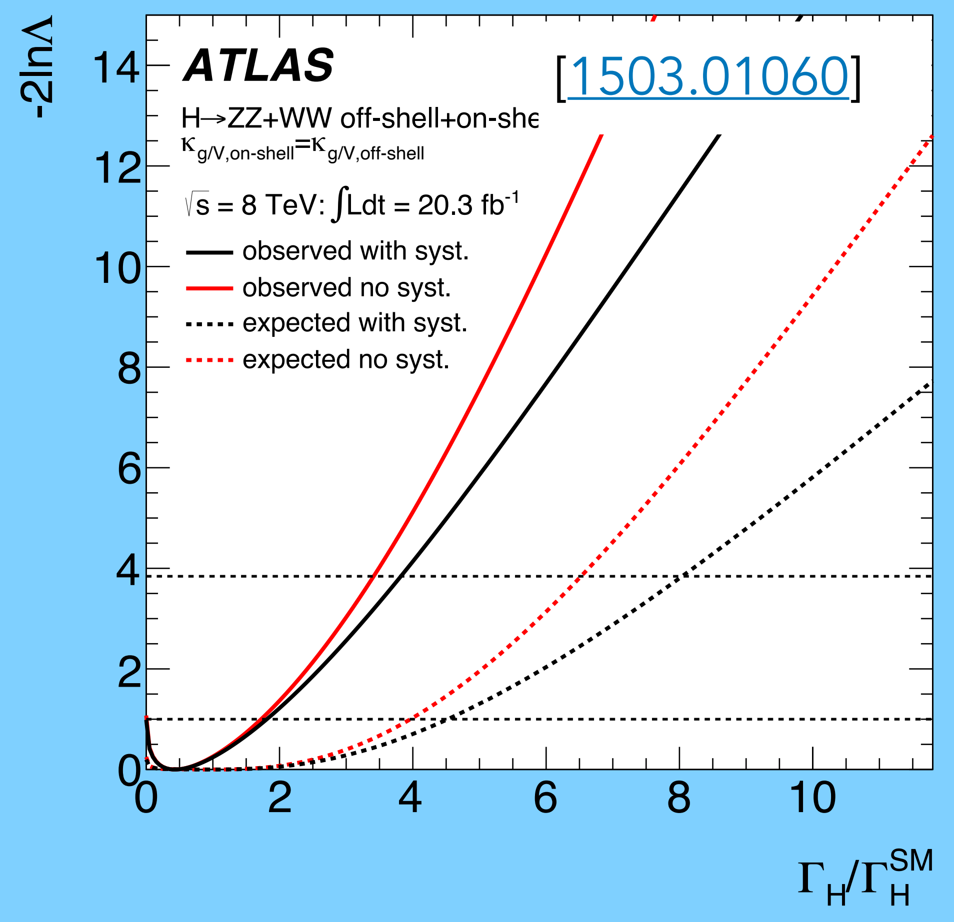


Conclusion

Presented the first ATLAS standalone $H \rightarrow WW$ width measurement!

ATLAS Run 1

$H \rightarrow ZZ$ & $H \rightarrow WW$

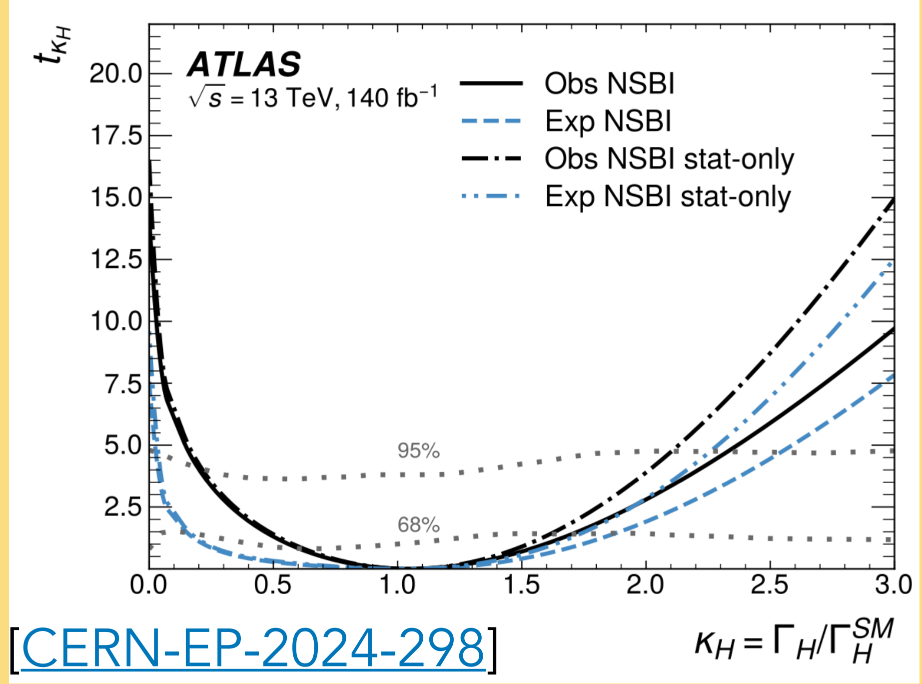


[1503.01060]

Γ_H < 22.7 MeV @95% CI

ATLAS Run 2

$H \rightarrow ZZ$



[CERN-EP-2024-298]

Γ_H < 9.7 MeV @95% CI

$H \rightarrow WW$

Before today

?

- Γ_H **competitive with state of the art**, also large improvement over run 1 ZZ & WW
- **Large improvement over run 1 $H \rightarrow WW$** standalone $\mu_{\text{off-shell}}$ measurement
  - 3.4 obs. (4.4 exp.) @ 95% CL versus 17.2 obs. (21.3 exp.) @ 95% CL
- **The lifetime** is $\tau_H = 7.0^{+82.1}_{-5.5} \times 10^{-22}\ s$ ($\tau = \hbar/\Gamma$)

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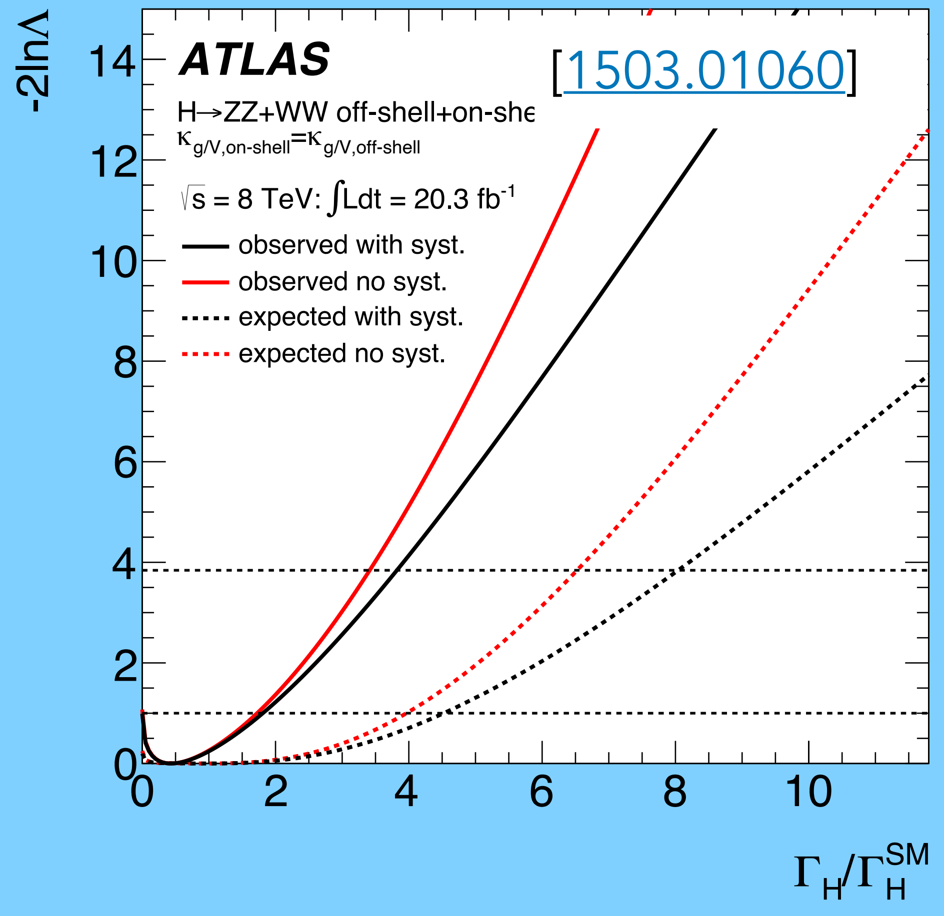

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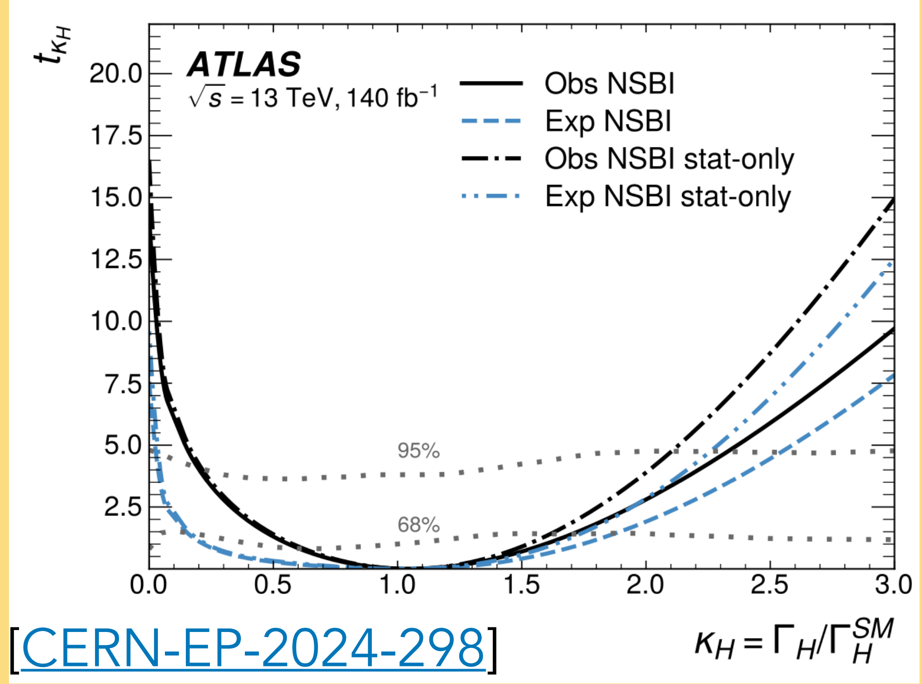

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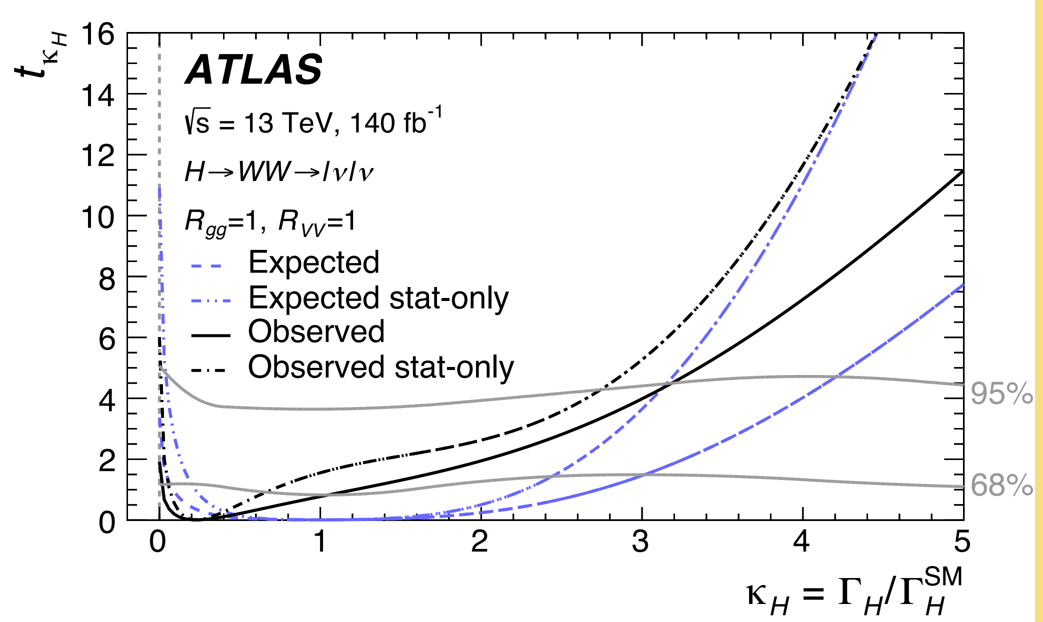

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Backup

Breakdown of uncertainties

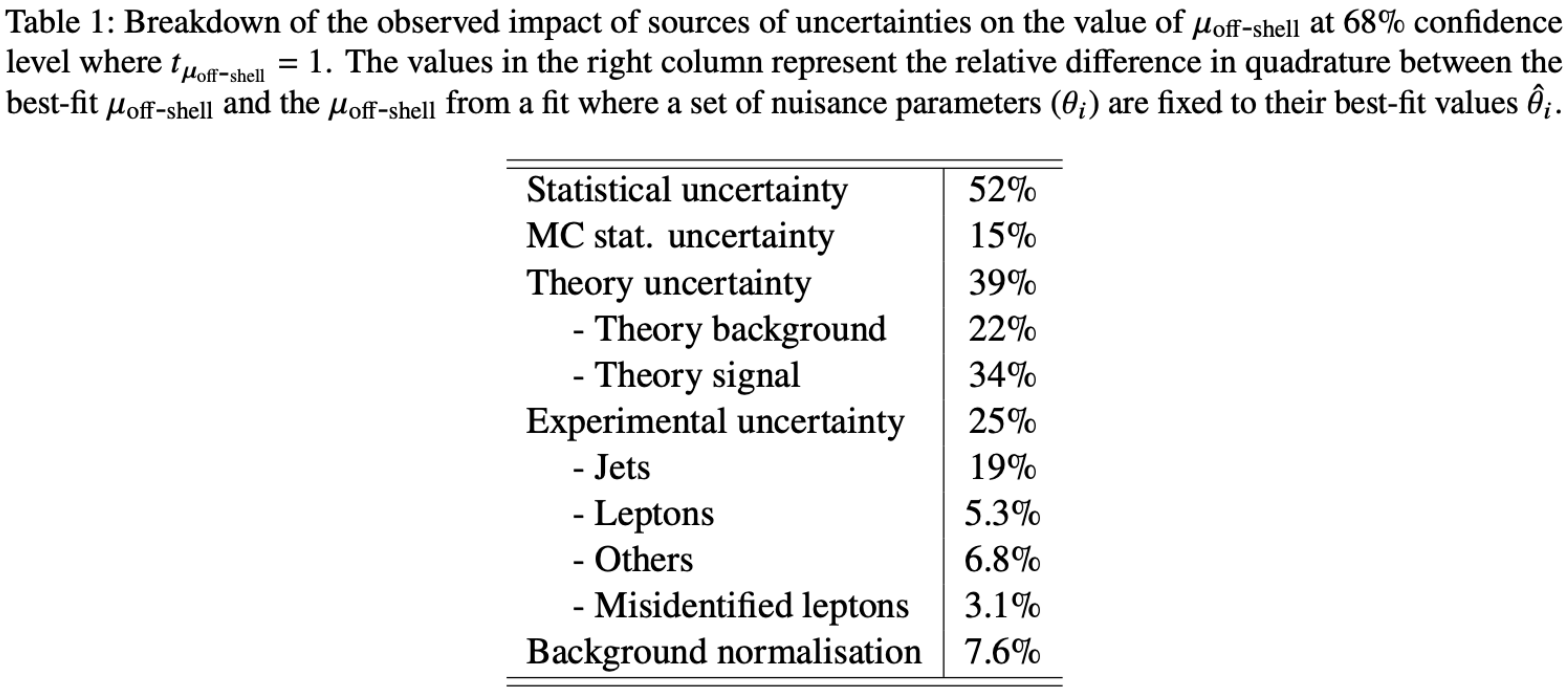


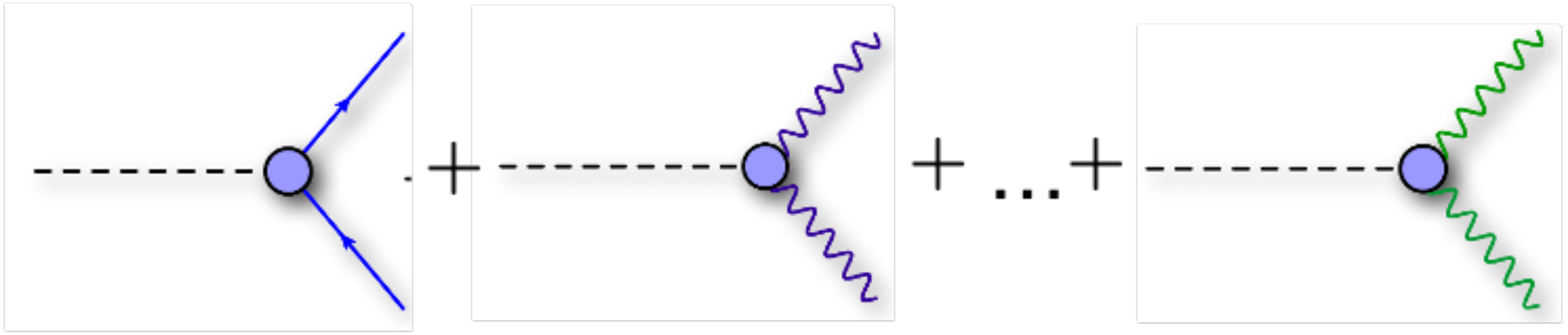
Table 1: Breakdown of the observed impact of sources of uncertainties on the value of $\mu_{\text{off-shell}}$ at 68% confidence level where $t_{\mu_{\text{off-shell}}} = 1$. The values in the right column represent the relative difference in quadrature between the best-fit $\mu_{\text{off-shell}}$ and the $\mu_{\text{off-shell}}$ from a fit where a set of nuisance parameters (θ_i) are fixed to their best-fit values $\hat{\theta}_i$.

Statistical uncertainty	52%
MC stat. uncertainty	15%
Theory uncertainty	39%
- Theory background	22%
- Theory signal	34%
Experimental uncertainty	25%
- Jets	19%
- Leptons	5.3%
- Others	6.8%
- Misidentified leptons	3.1%
Background normalisation	7.6%

Why measure the Higgs width?

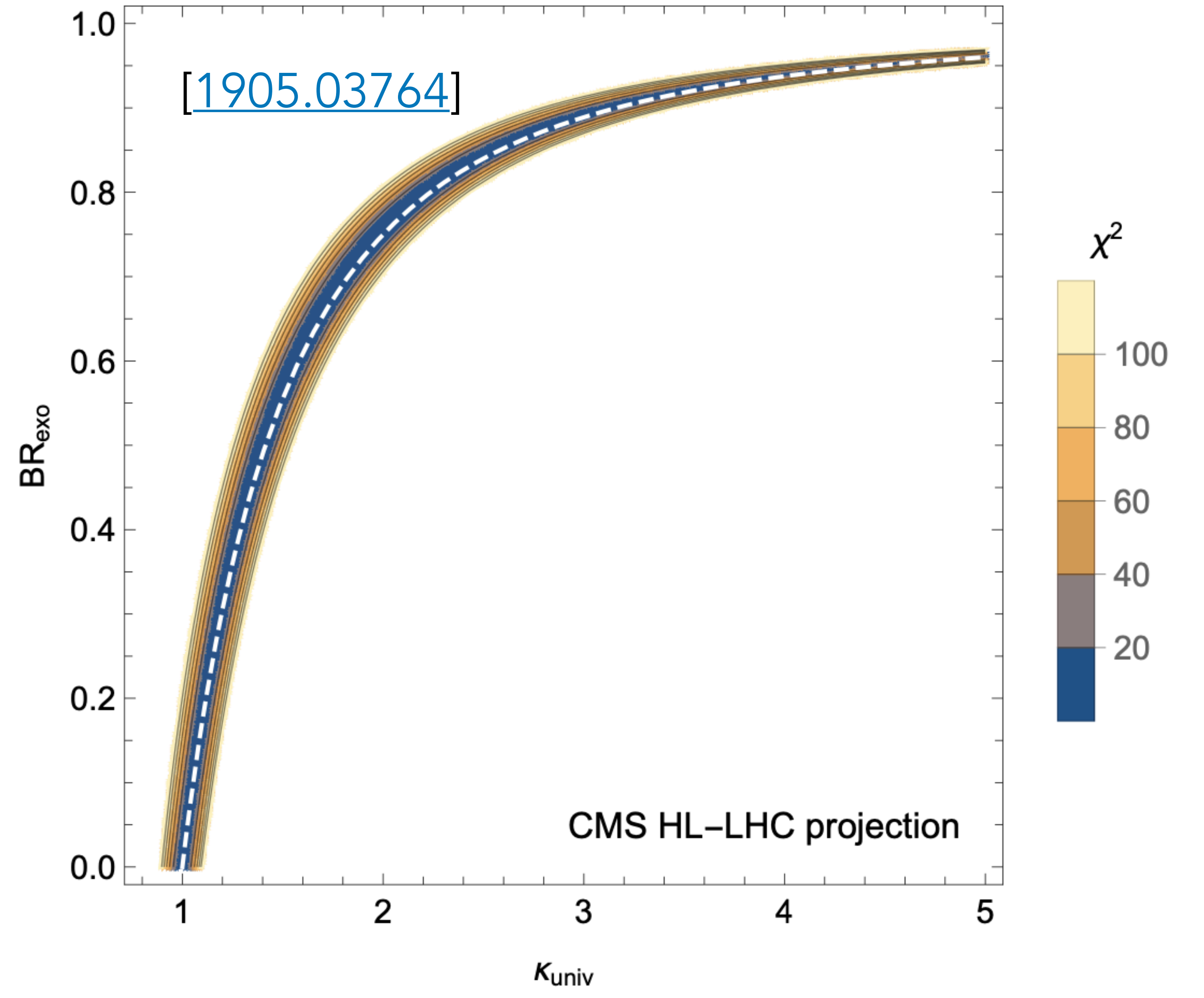
The Higgs decaying faster, or with **larger width, might indicate decay to undiscovered particles** [2107.08343]

$$\Gamma_H = \Gamma_{H\to bb} + \Gamma_{H\to WW} + ... + \Gamma^?_{BSM}$$



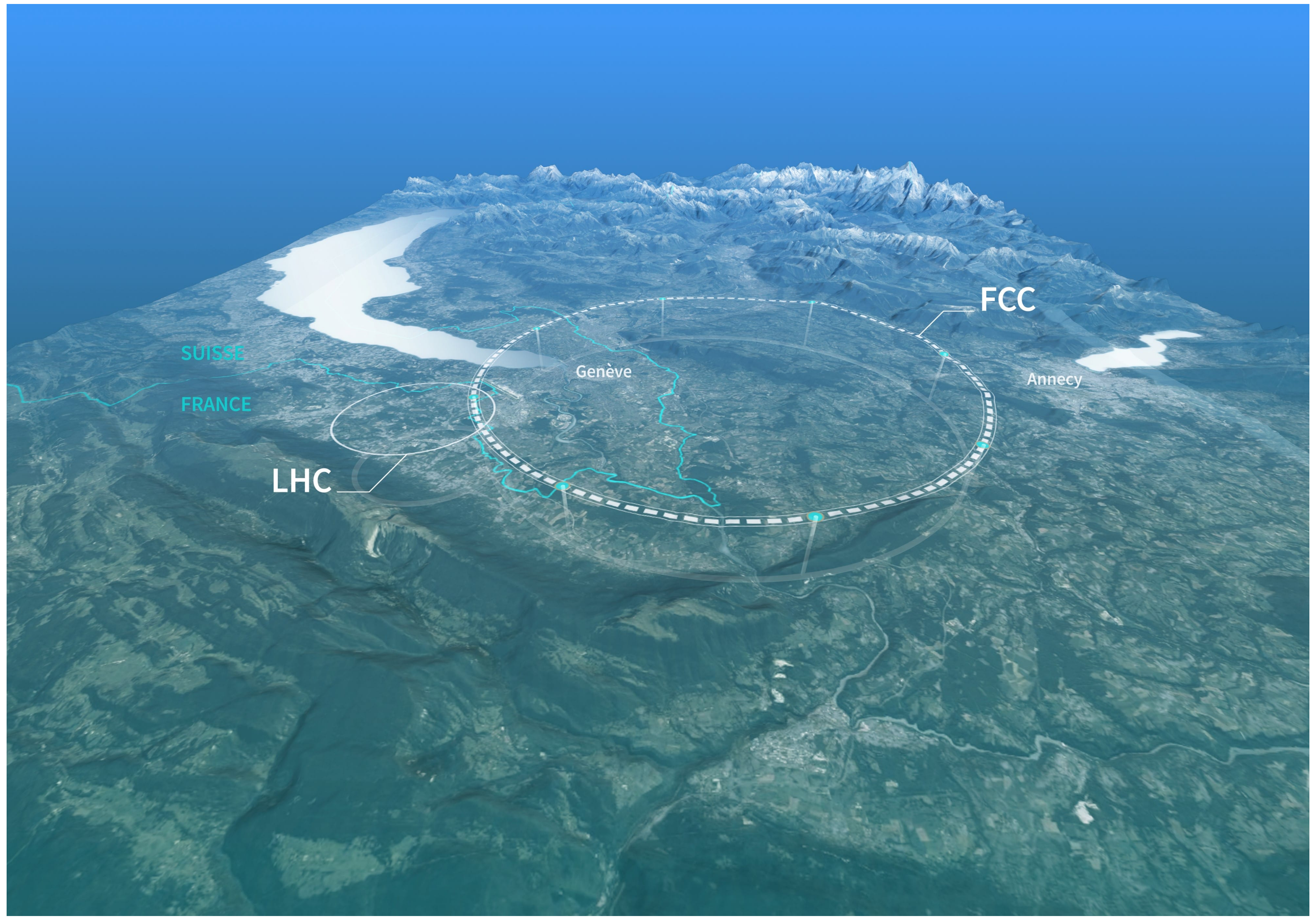
Measuring **off-shell Higgs boson production** is by itself important

- As shown before: $\sigma_{onshell} \propto g^4 \,/\, \Gamma_H \rightarrow$ **degeneracy** between couplings and width!
  - This can be **resolved in the offshell regime**! $\sigma_{offshell} \propto g^4$



Higgs width at the FCC-ee

One of the more realistic future colliders is the FCC, future circular collider



There are multiple options, but the FCC-ee would collide electrons, which generally comes with lower collision energy than hadronic colliders, but with the ability to more precisely tune the energy

Higgs width at the FCC-ee

With a lepton collider we can tune the beam energy to exactly $m_Z + m_H$ and produce the Higgsstrahlung process with a very high rate

Doing this we can target the Higgs width with minimal assumptions as follows

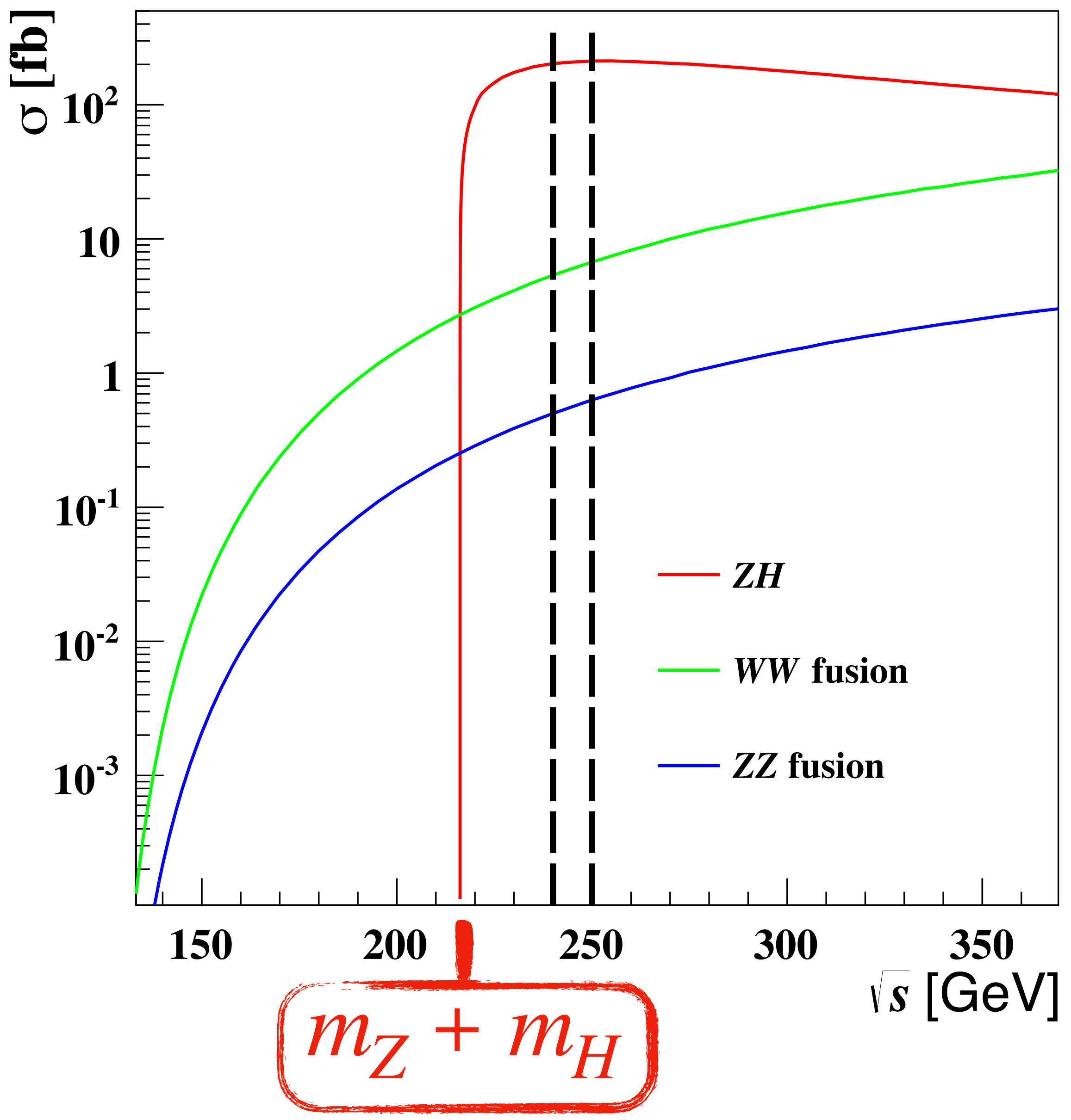
The cross section of the Higgsstrahlung process

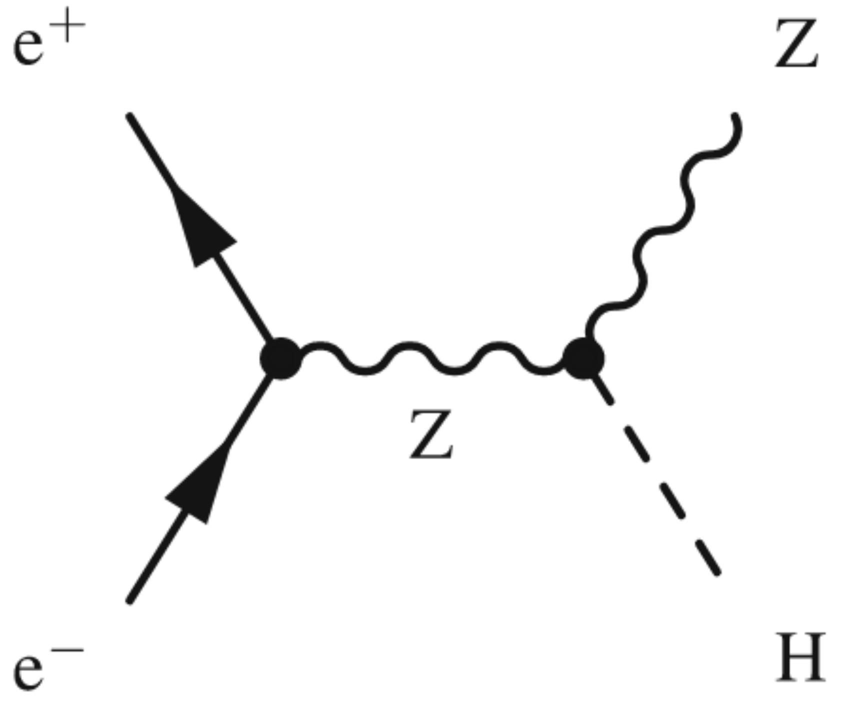
Left with an explicit dependence on the width

$$\frac{\sigma(e^+e^-\to ZH)}{\mathrm{BR}(H\to ZZ^*)} = \frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)/\Gamma_H} \simeq \left[\frac{\sigma(e^+e^-\to ZH)}{\Gamma(H\to ZZ^*)}\right]_{\mathrm{SM}} \times \Gamma_H$$

The branching ratio of $H \to ZZ$

Assume that new physics effects cancel in this ratio → SM!

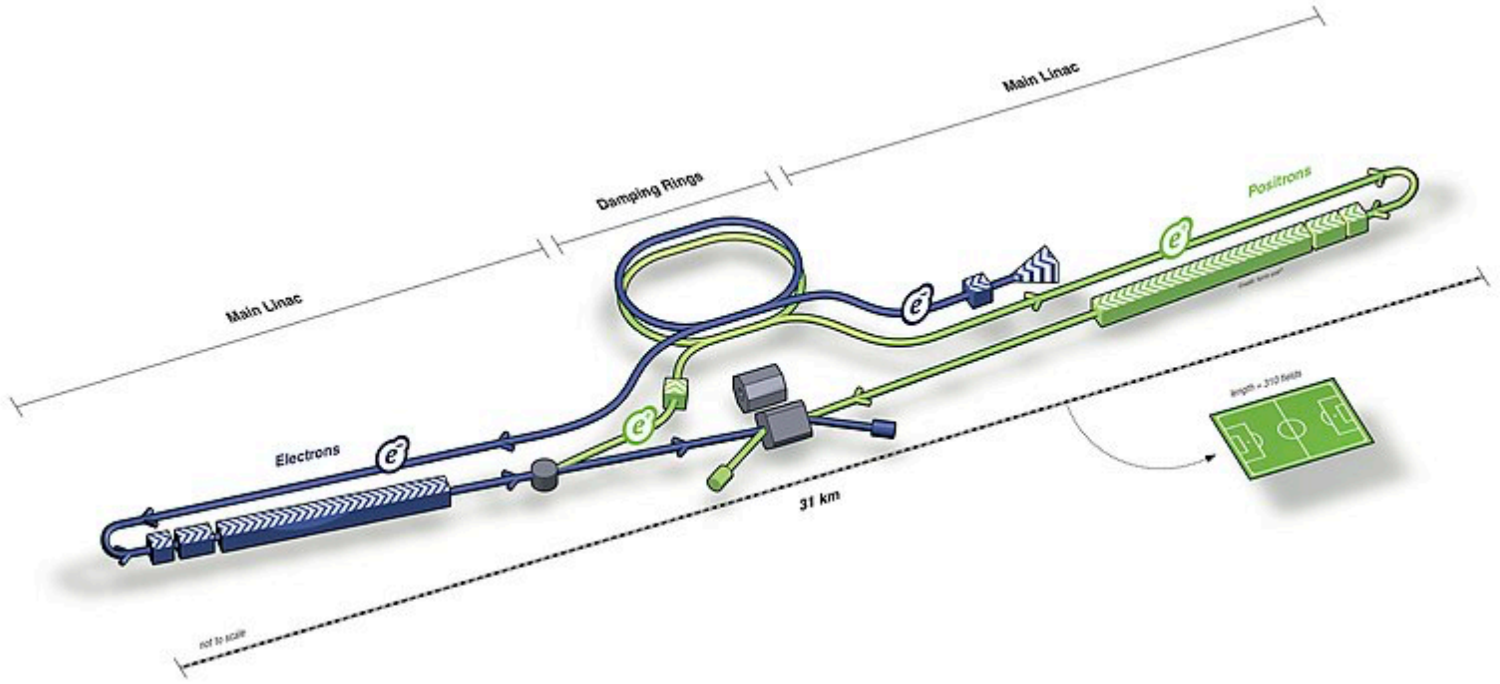




Higgsstrahlung, where the Higgs recoils off a Z boson

Higgs width at future (?) colliders

Takeaway is that few-percent level precision is achievable!

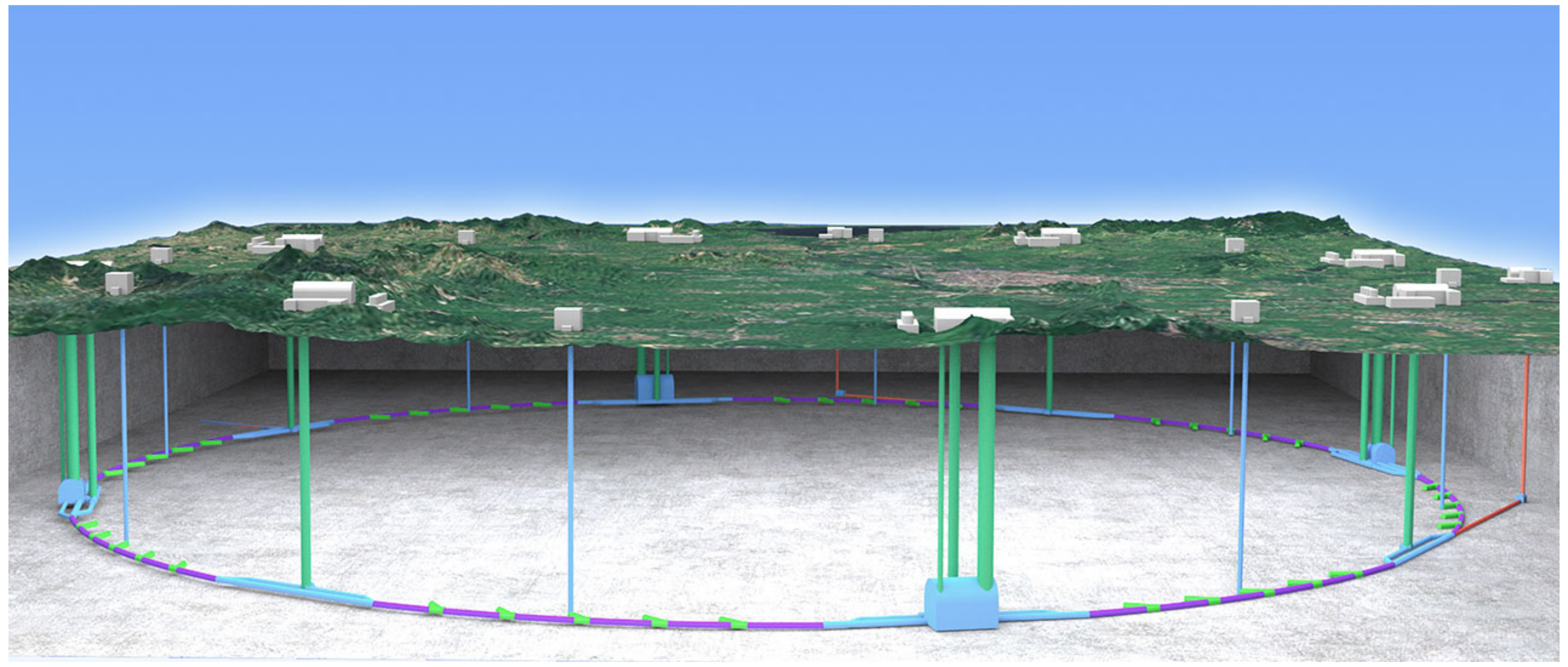


International linear collider

Compact linear collider

Collider	$\delta\Gamma_H$ [%] from Ref.
ILC_{250}	2.3
ILC_{500}	1.6
ILC_{1000}	1.4
CLIC_{380}	4.7
CLIC_{1500}	2.6
CLIC_{3000}	2.5
CEPC	2.8
FCC-ee_{240}	2.7
FCC-ee_{365}	1.3

[1905.03764]



Circular electron-positron collider (experiments in 2030?)

The future circular collider (ee)

A refresher: What is the width of a particle?

- The width, Γ, is defined as the decay rate $\Gamma = \frac{1}{\tau}$

- Take a wave function, add an exponentially decaying term

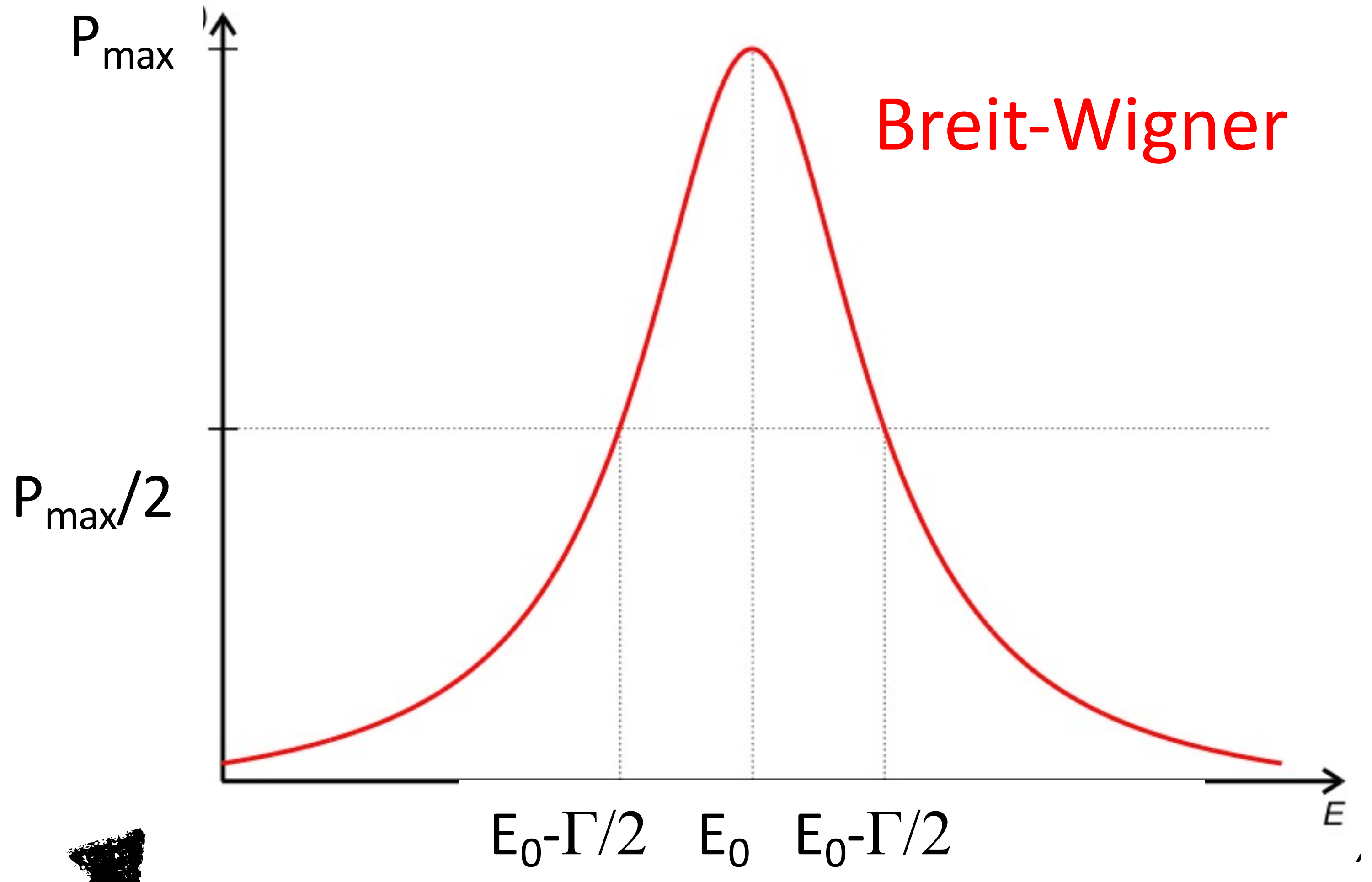
$$\psi(t) = \psi_0 e^{-iEt} \qquad \psi(t) = \psi_0 e^{-iEt} e^{-\frac{1}{2}\Gamma t}$$

- Fourier transform to energy domain

$$\Psi(E) = \Psi_0 \frac{i}{(E - E_0) + \frac{i}{2}\Gamma}$$

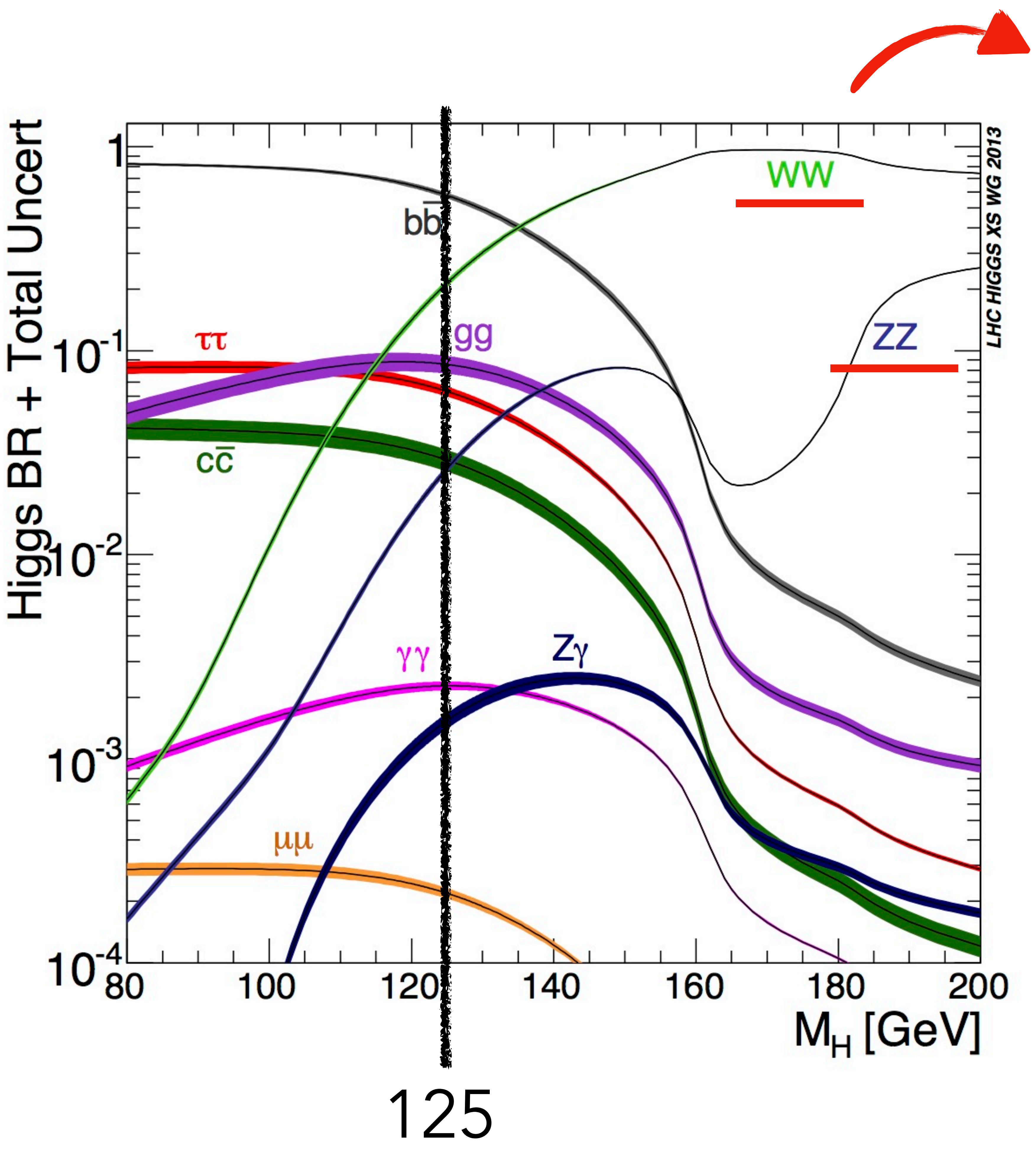
- Now ask, what is the probability to measure the particle with energy E?

$$\Psi(E)^* \Psi(E) = \Psi_0^* \Psi_0 \frac{1}{(E - E_0)^2 + \frac{1}{4}\Gamma^2}$$



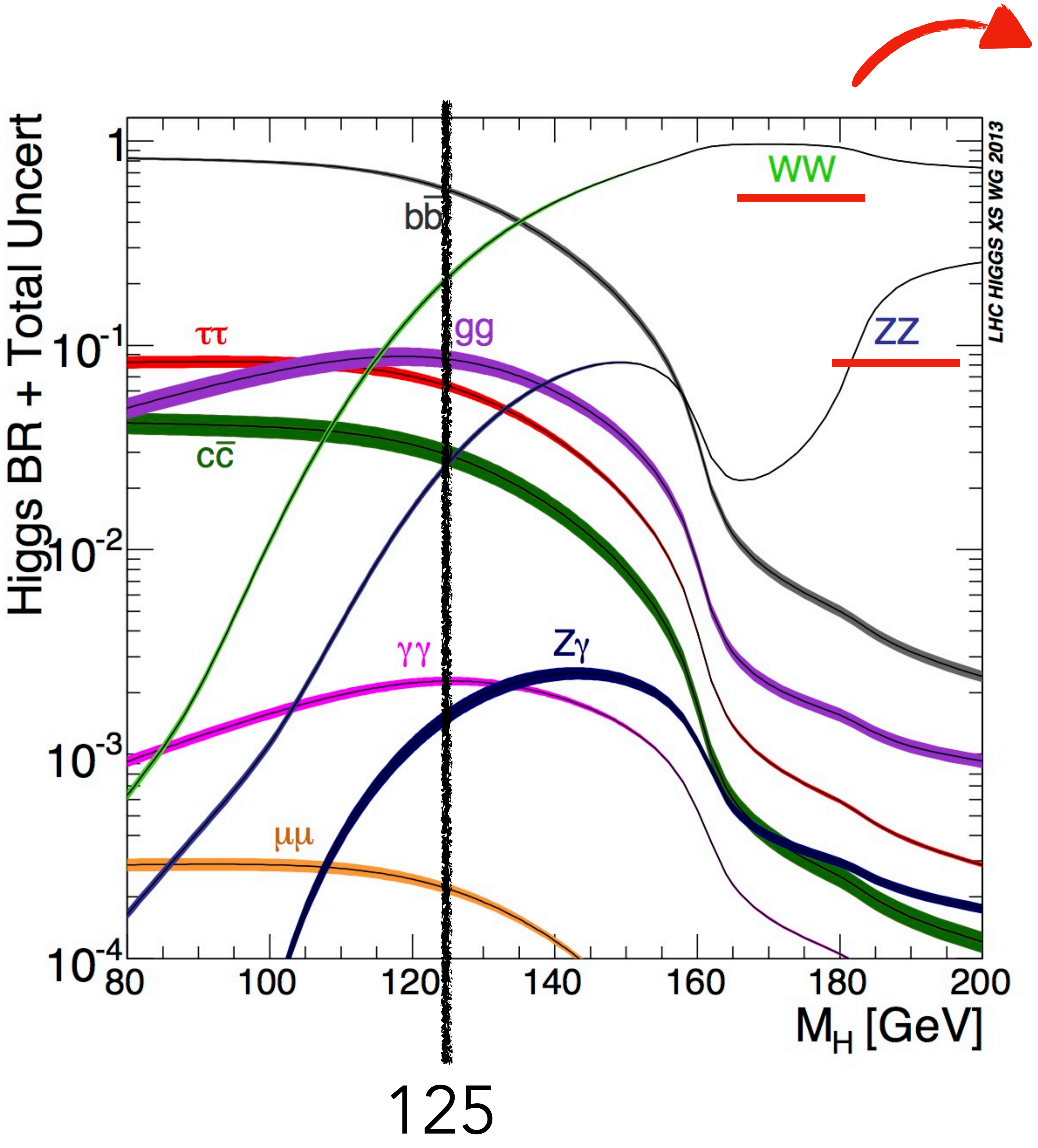
Width of the peak is intrinsically connected to the decay rate

The $H \rightarrow WW$ channel for width measurements



The **decay probability of the WW decay is significantly larger than** that of ZZ

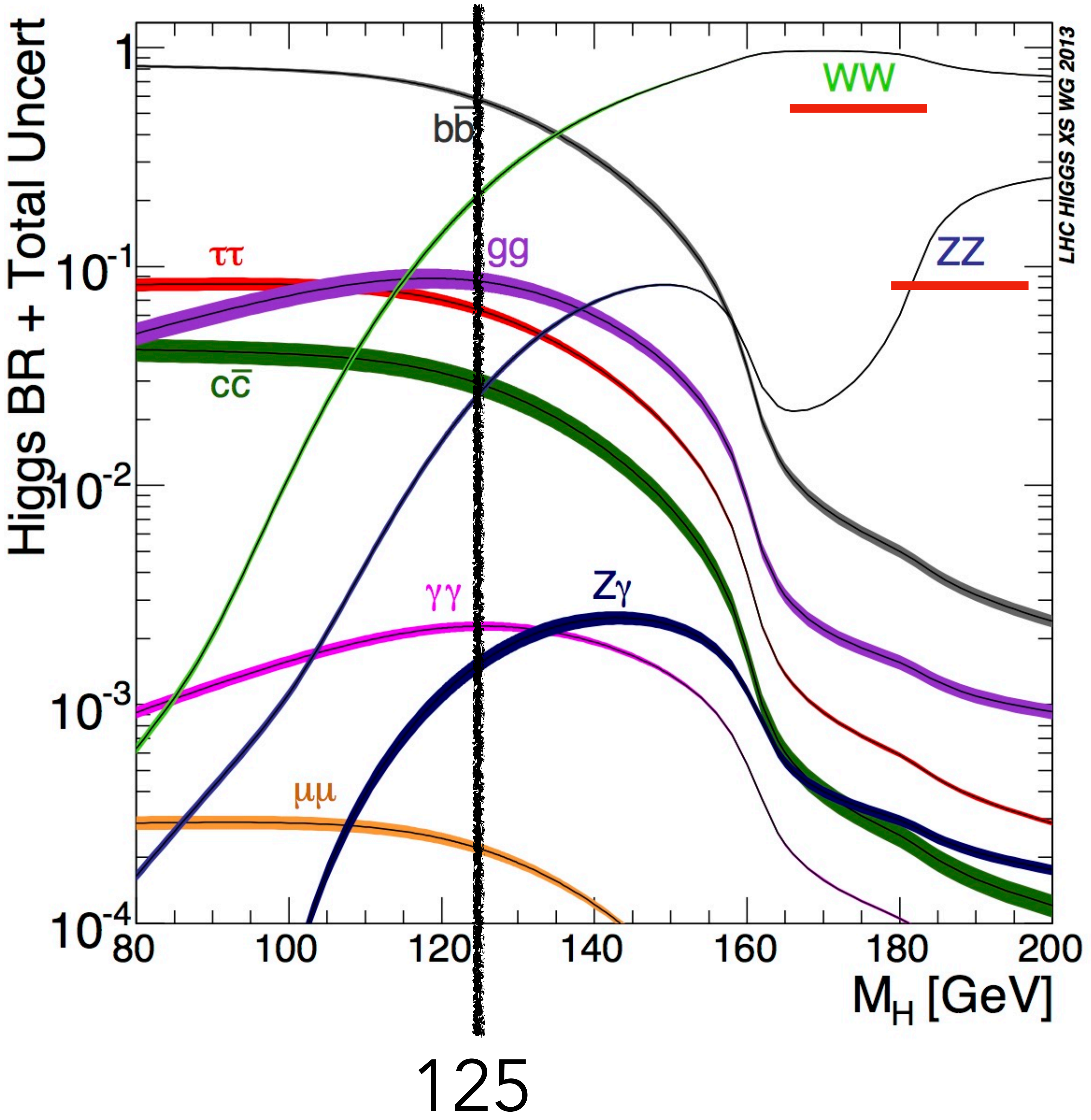
The $H \to WW$ channel for width measurements



The **decay probability of the WW decay is significantly larger than** that of ZZ

Expect more WW decays in LHC, so this channel **should be more sensitive**

The $H \rightarrow WW$ channel for width measurements



The **decay probability of the WW decay is significantly larger than** that of ZZ

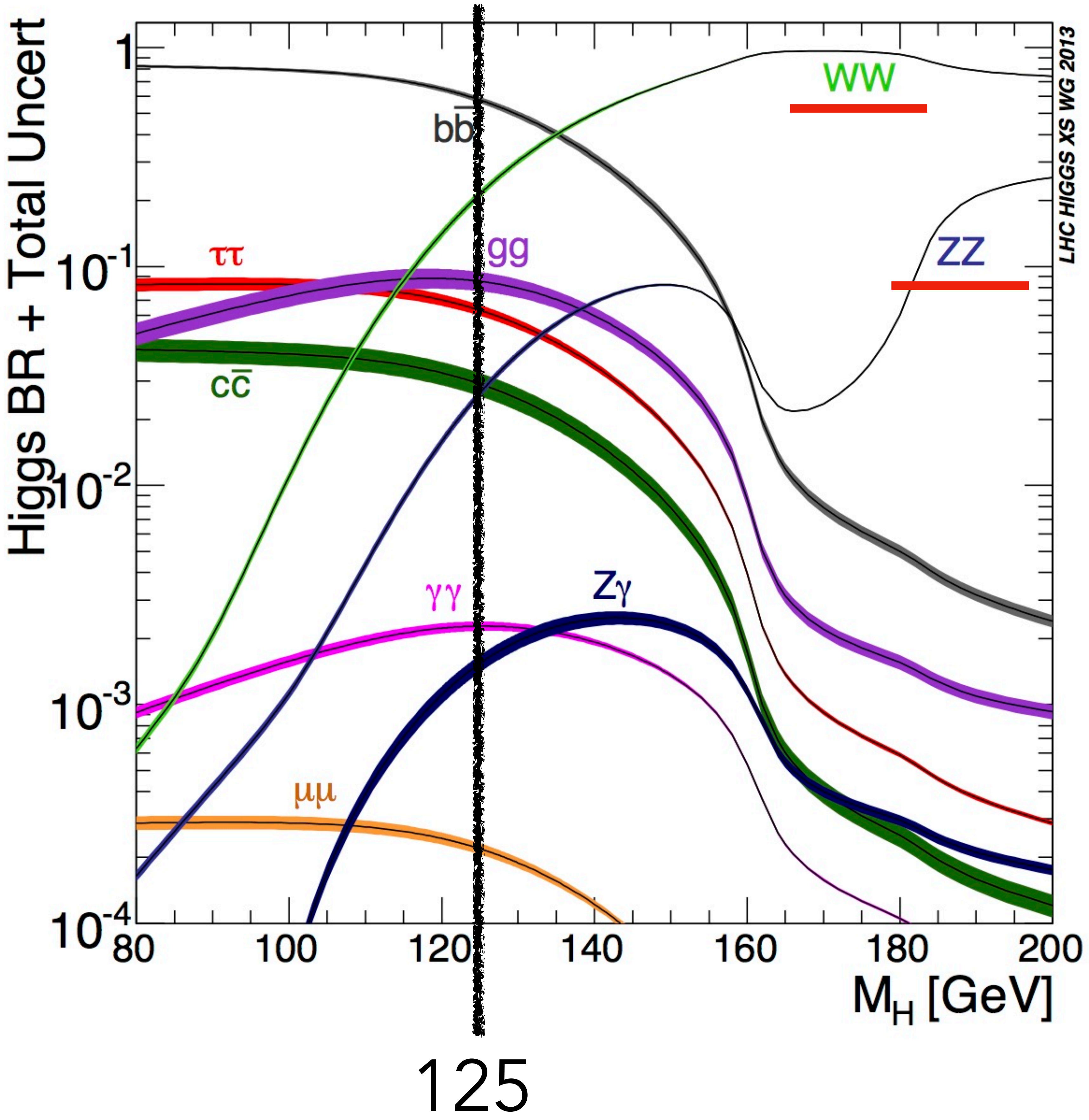
Expect more WW decays in LHC, so this channel **should be more sensitive**

However, **in practice WW is less sensitive** than the ZZ measurement?

Run 1: ZZ: $\Gamma_H \lessapprox 2\Gamma_H^{SM} @ 95\,\%$ CI

WW: $\Gamma_H \lessapprox 6\Gamma_H^{SM} @ 95\,\%$ CI

The $H \rightarrow WW$ channel for width measurements



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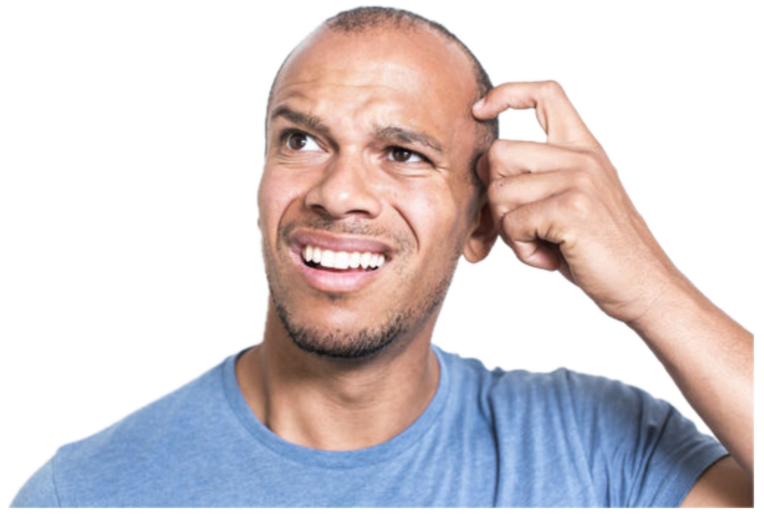
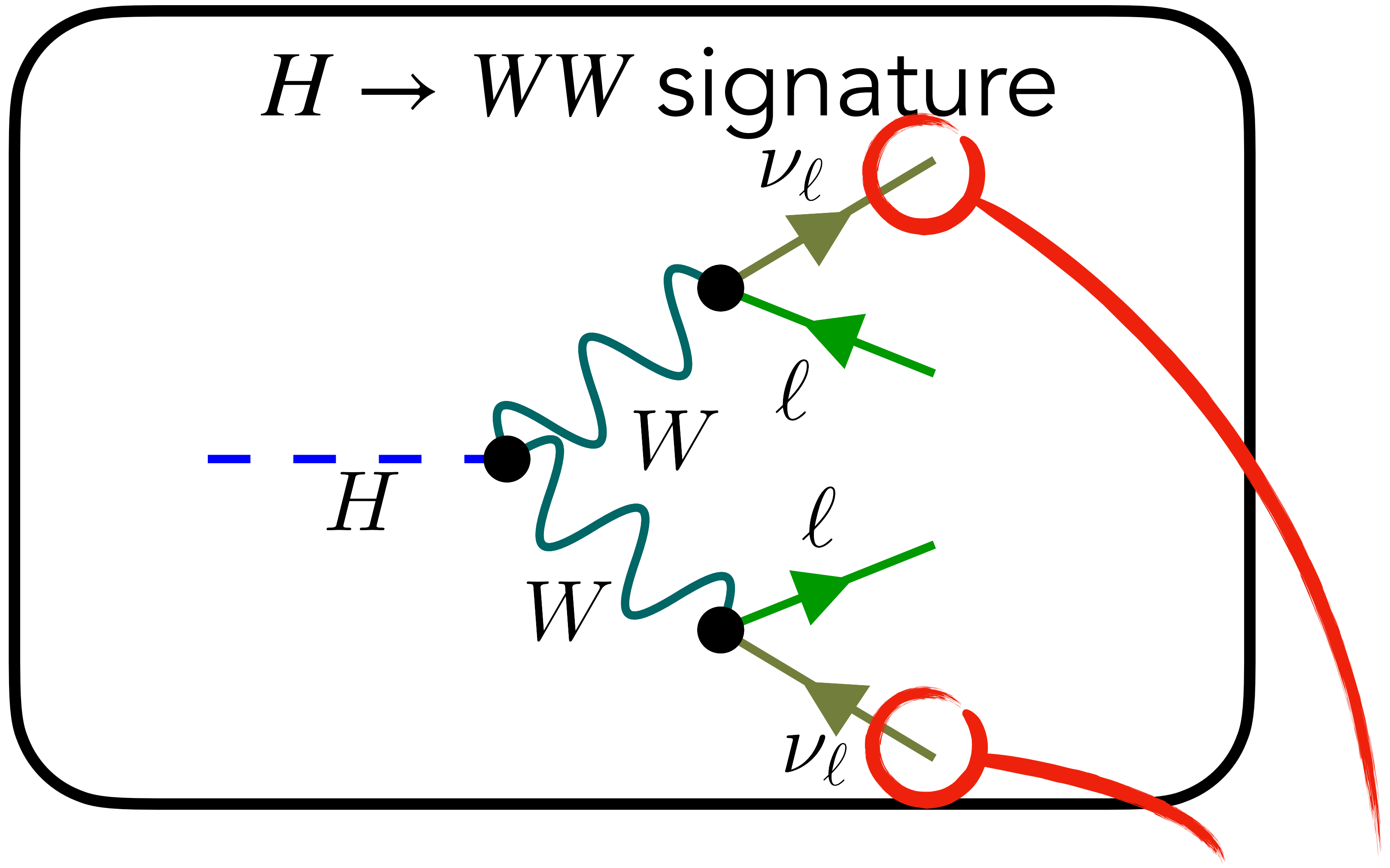
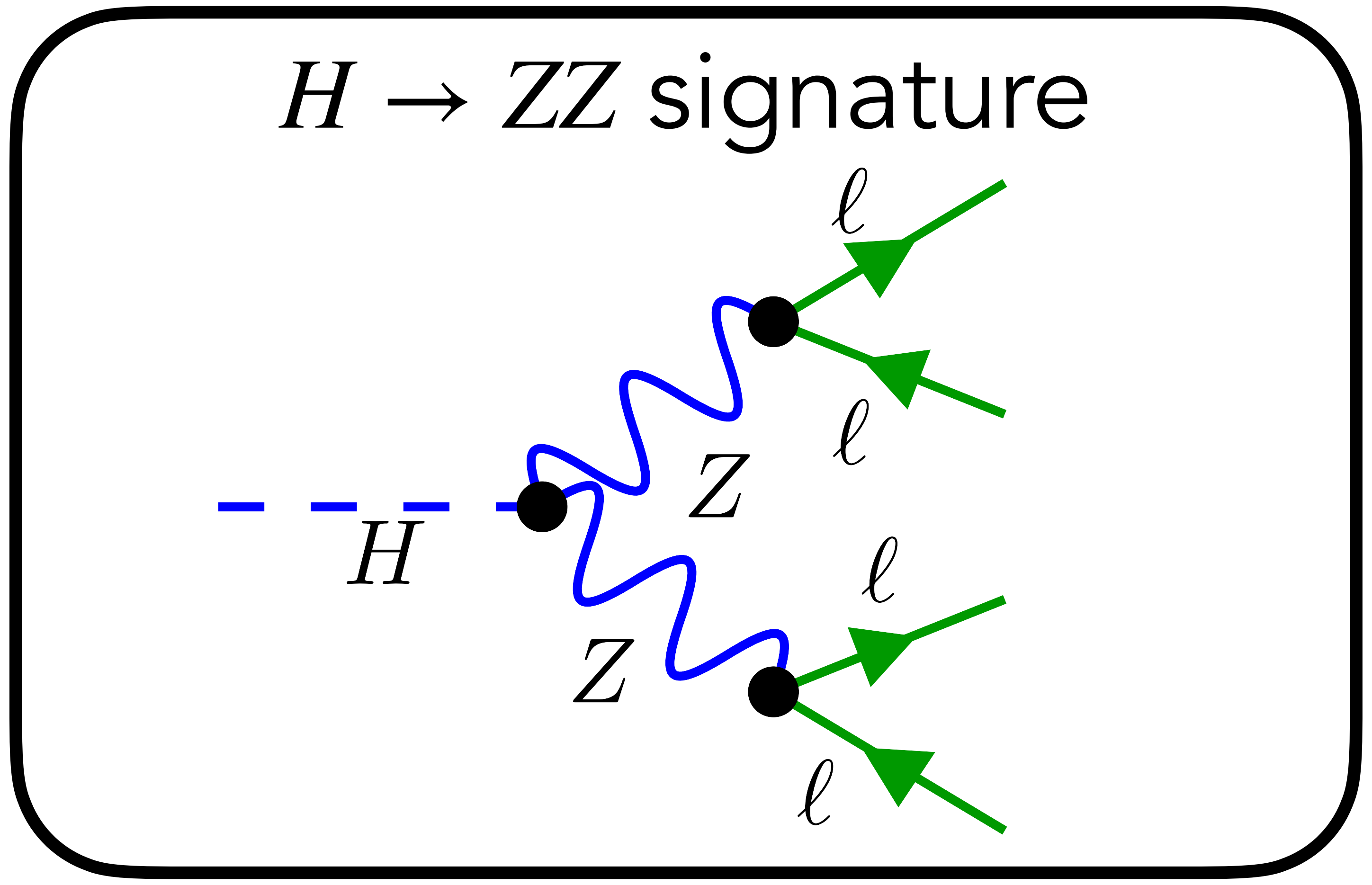


The $H \to WW$ channel for width measurements

W bosons decay into leptons and neutrinos

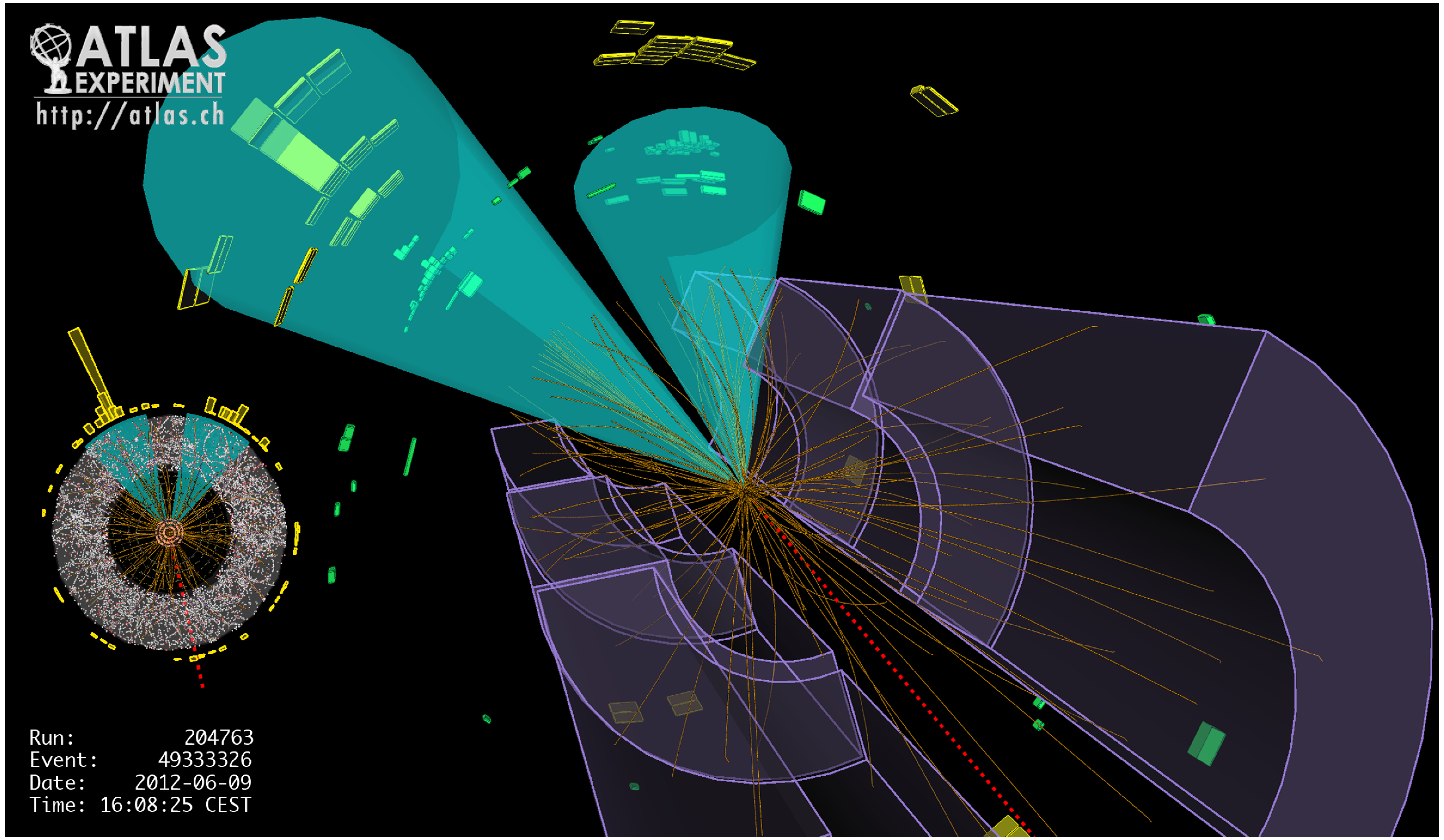




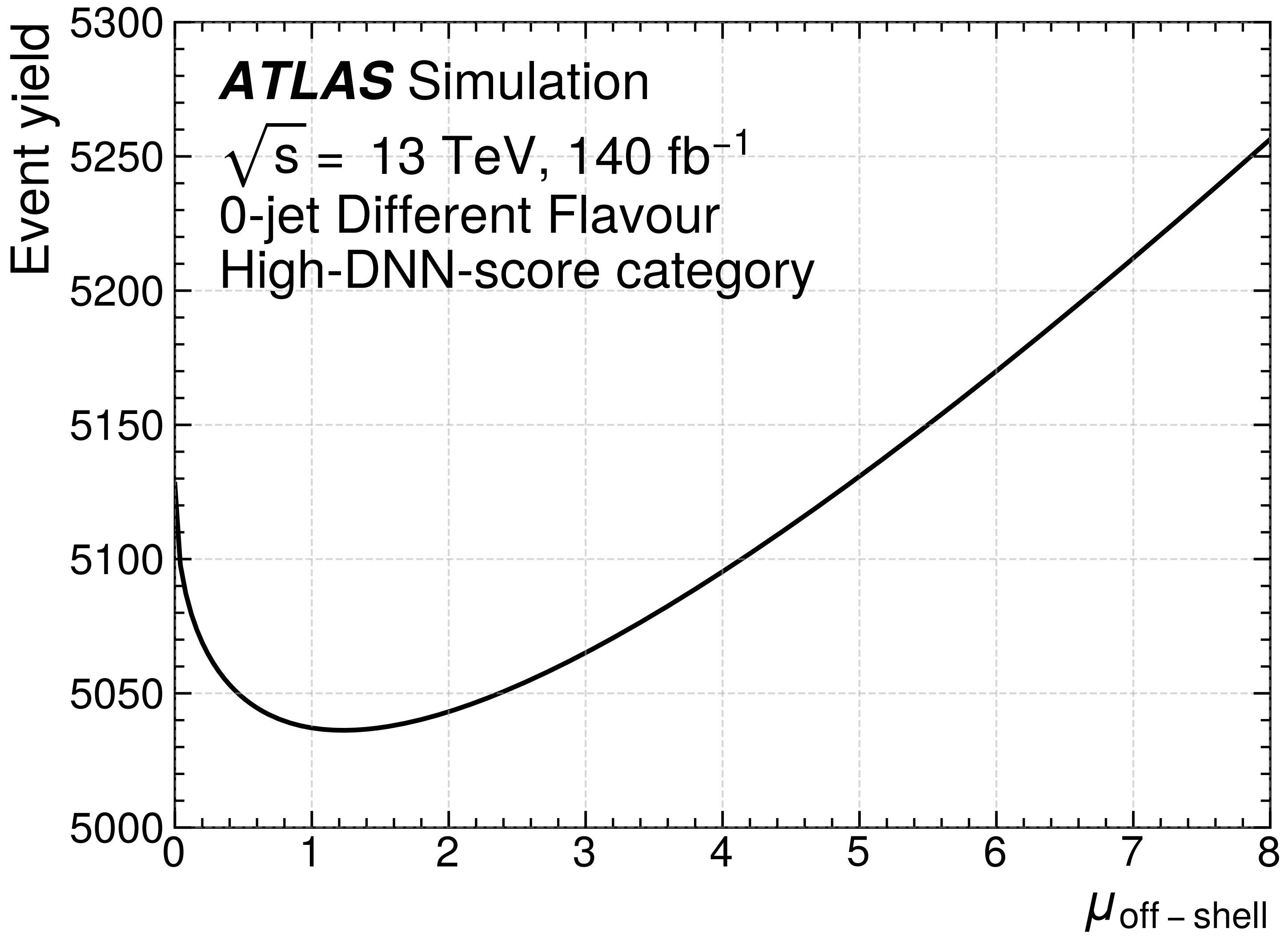
WW bosons decay to neutrino's
which cannot be detected
→ Results in "**missing energy**"
which is hard to reconstruct!

The $H \rightarrow WW$ channel for width measurements

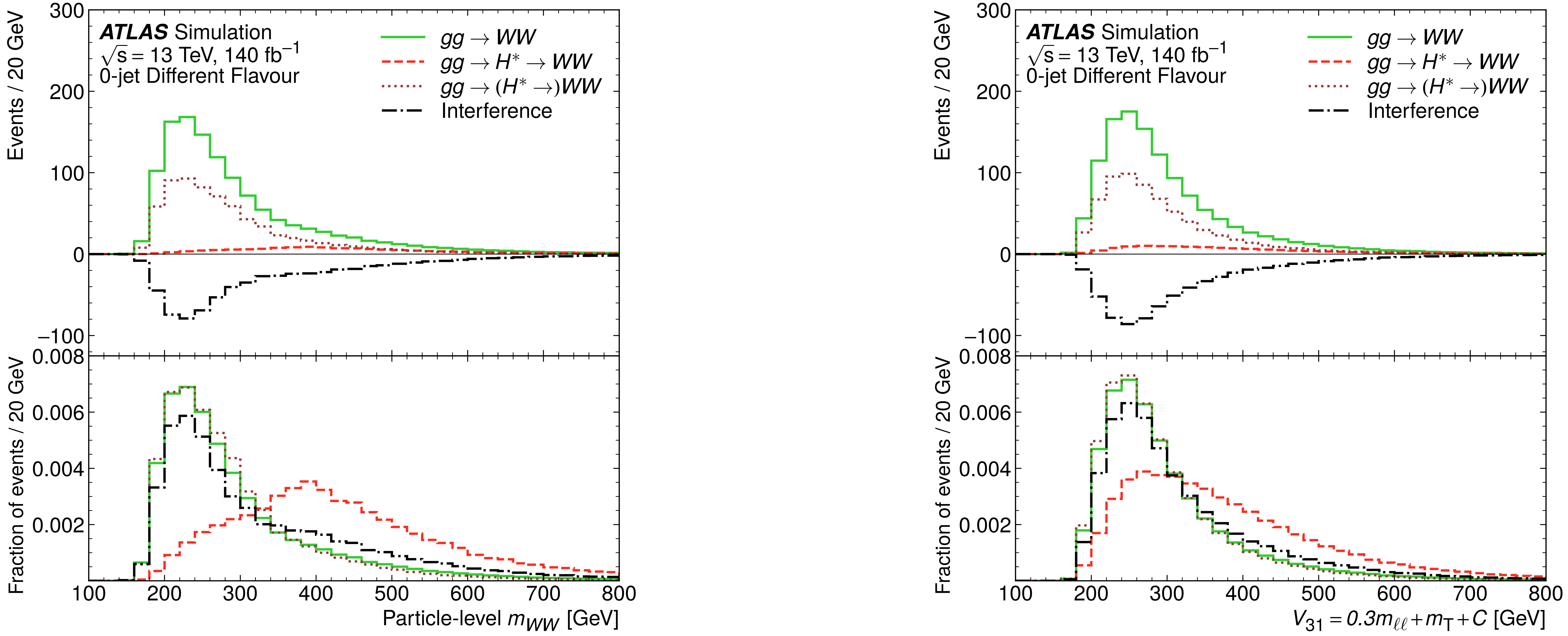
$H \rightarrow WW$ channel has **missing energy** caused by the final state neutrinos



Yield as a function of POI



M_{WW} and V_{31}


ATLAS Simulation
√s = 13 TeV, 140 fb⁻¹
0-jet Different Flavour
gg → WW
gg → H* → WW
gg → (H* →)WW
Interference
Events / 20 GeV
300
200
100
0
−100
Fraction of events / 20 GeV
0.008
0.006
0.004
0.002
100
200
300
400
500
600
700
800
Particle-level m_WW [GeV]
ATLAS Simulation
√s = 13 TeV, 140 fb⁻¹
0-jet Different Flavour
gg → WW
gg → H* → WW
gg → (H* →)WW
Interference
Events / 20 GeV
Fraction of events / 20 GeV
V_31 = 0.3m_ℓℓ + m_T + C [GeV]

R_{gg} and R_{VV}

mu_on and mu off width and couplings dependencies

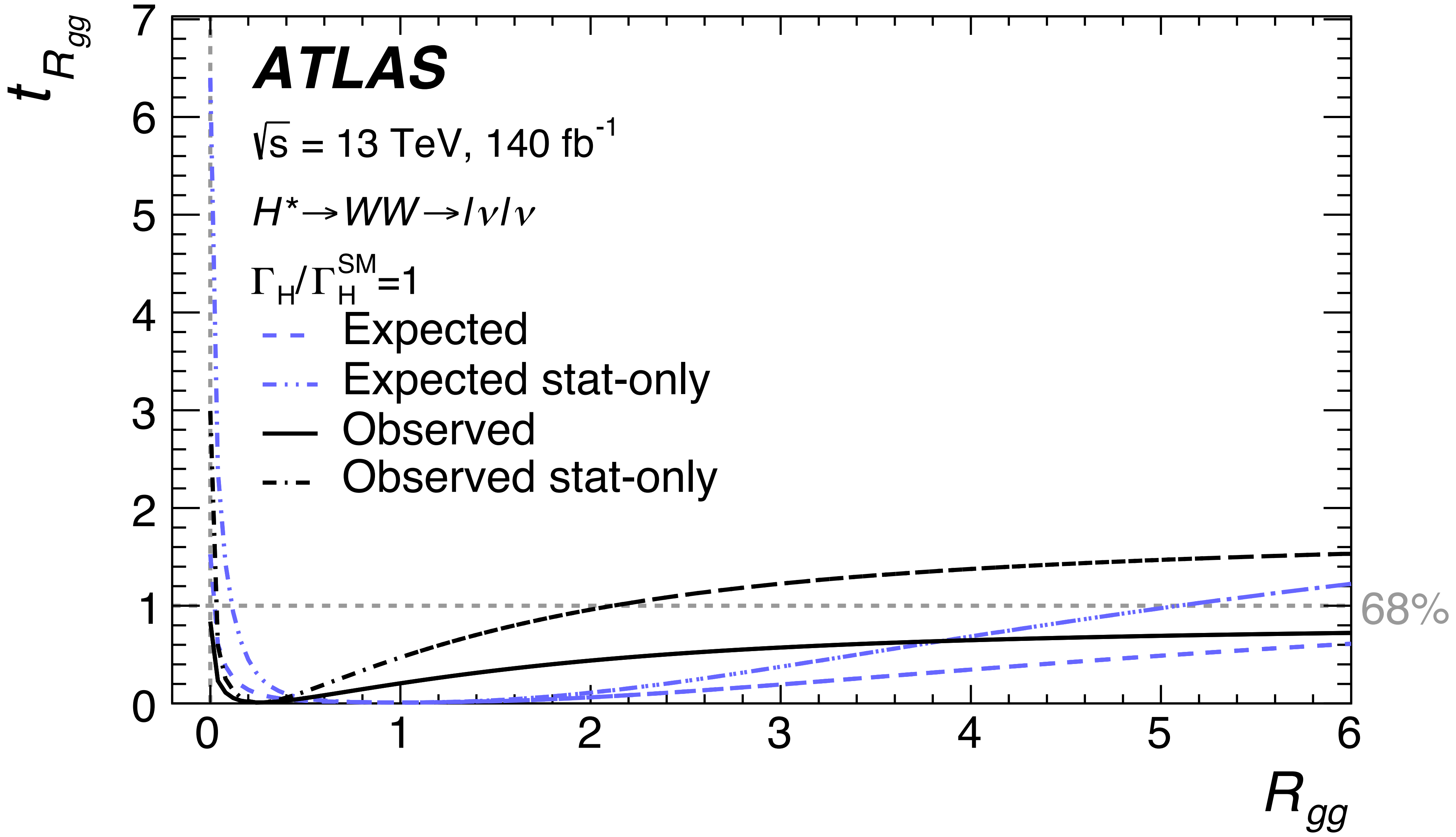
$$\mu^{ggF}_{off-shell} \propto g^2_{Hgg,off-shell} \cdot g^2_{HVV,off-shell}$$
$$\mu^{VBF}_{off-shell} \propto g^4_{HVV,off-shell}$$
$$\mu^{ggF}_{on-shell} \propto \frac{g^2_{Hgg,on-shell} \cdot g^2_{HVV,on-shell}}{\Gamma^H}$$
$$\mu^{VBF}_{on-shell} \propto \frac{g^4_{HVV,on-shell}}{\Gamma^H}$$

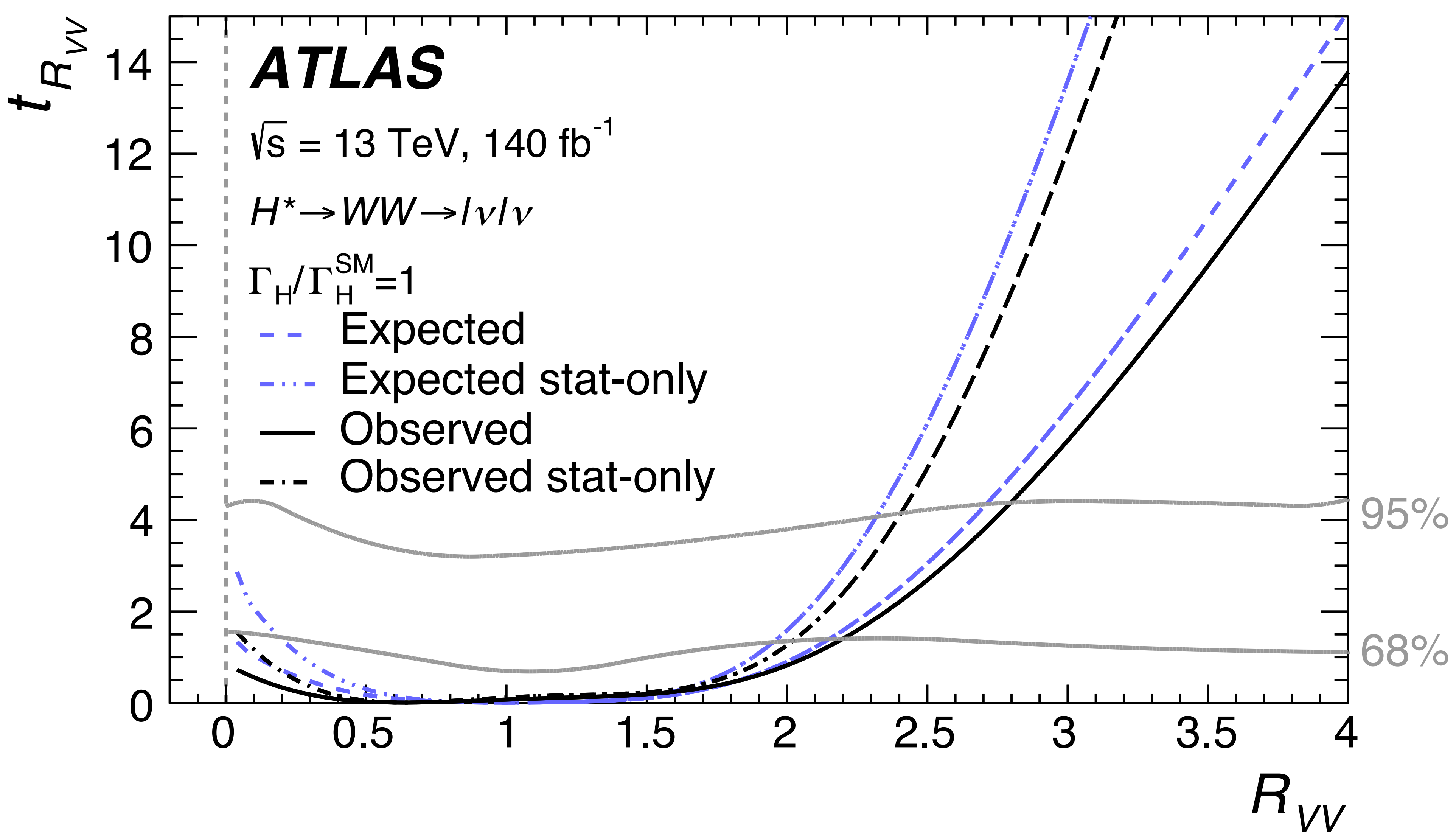
dividing mu_off by mu_on, and defining Rgg and Rvv:

$$R_{gg} \equiv \frac{g^2_{Hgg,off-shell}}{g^2_{Hgg,on-shell}}$$
$$R_{VV} \equiv \frac{g^2_{HVV,off-shell}}{g^2_{HVV,on-shell}}.$$

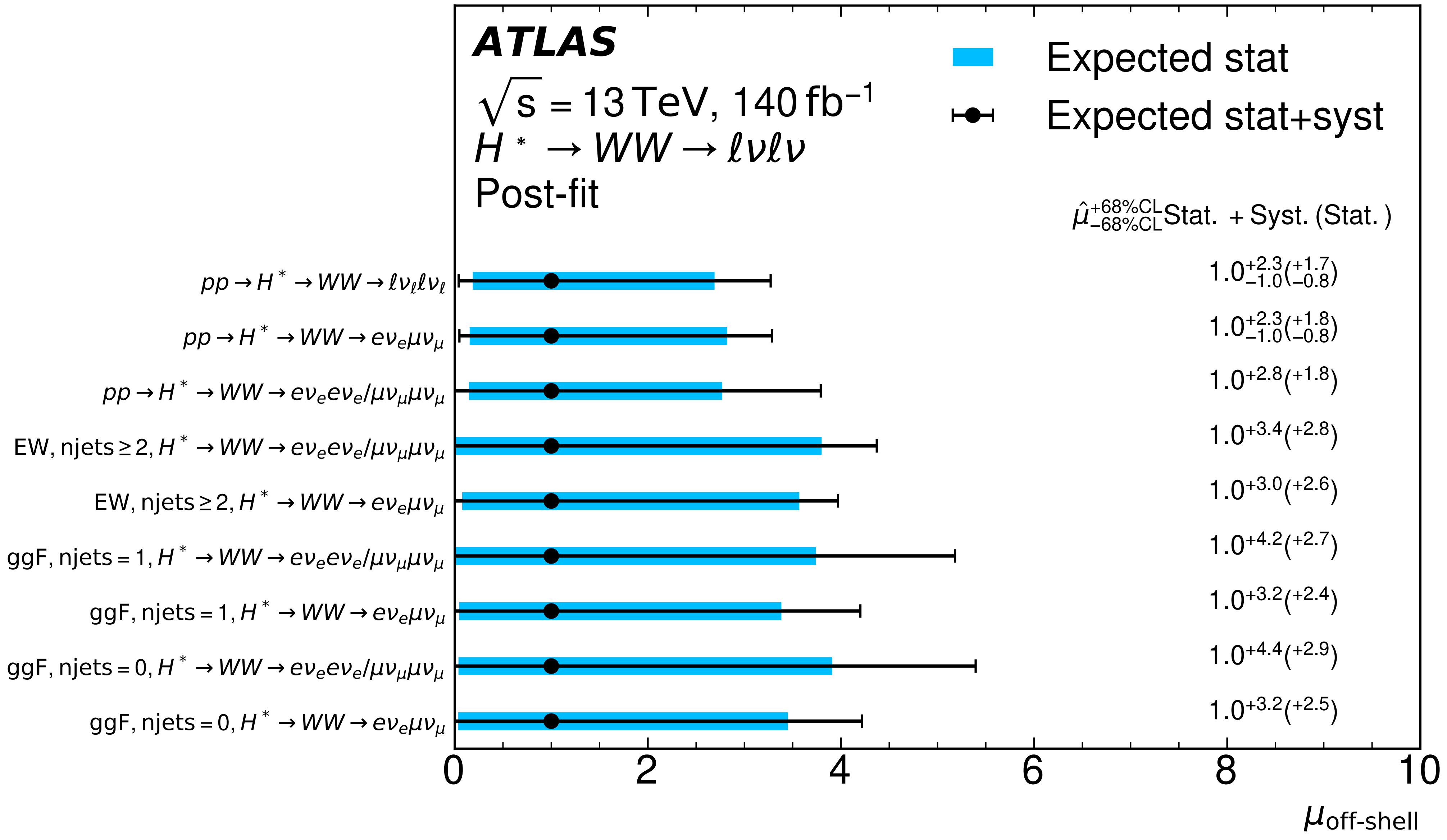
We get the following system of equations

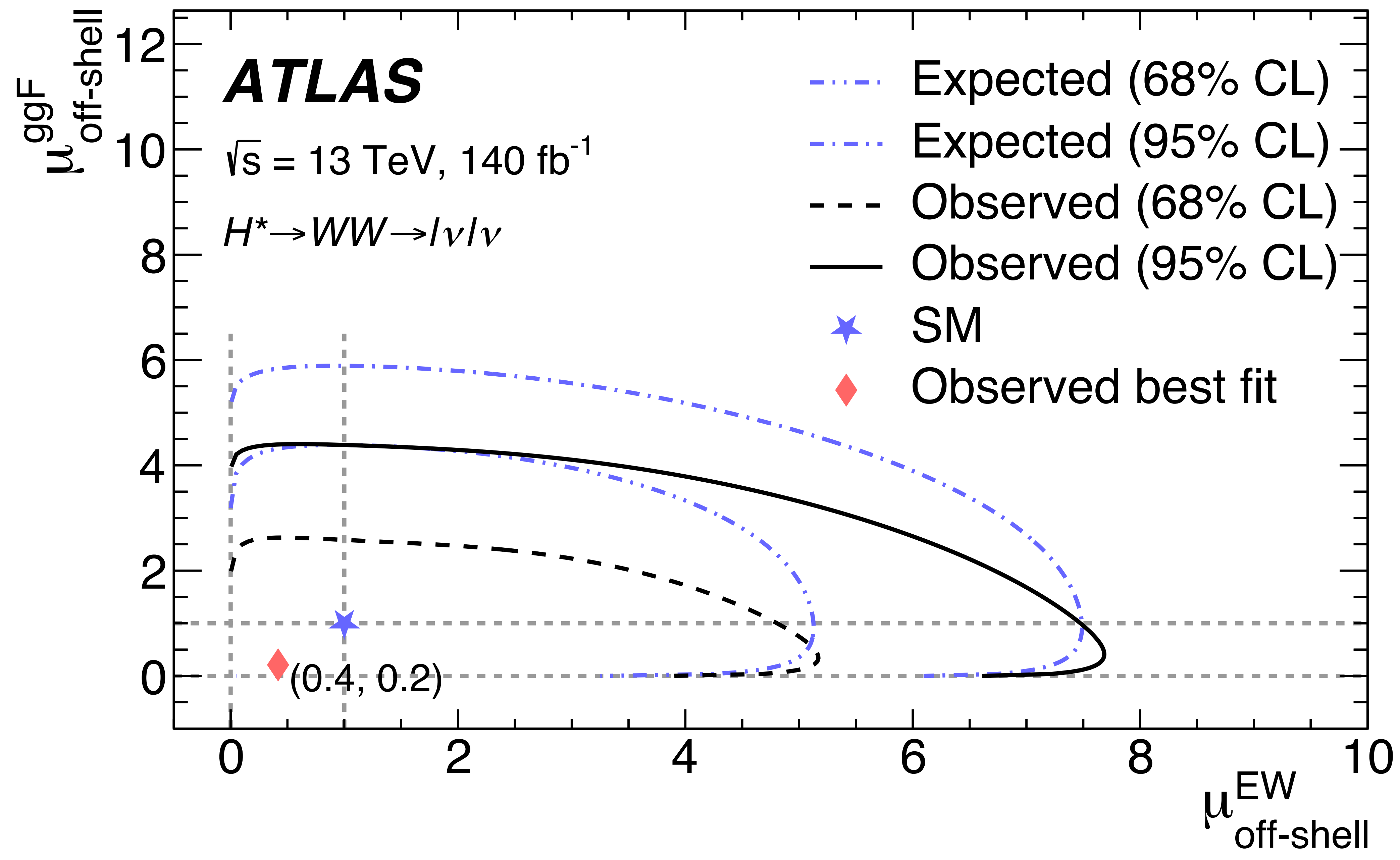
$$\mu^{ggF}_{off-shell} = R_{gg} \cdot R_{VV} \cdot \mu^{ggF}_{on-shell} \cdot \frac{\Gamma_H}{\Gamma_H^{SM}}$$
$$\mu^{VBF}_{off-shell} = R^2_{VV} \cdot \mu^{VBF}_{on-shell} \cdot \frac{\Gamma_H}{\Gamma_H^{SM}}.$$



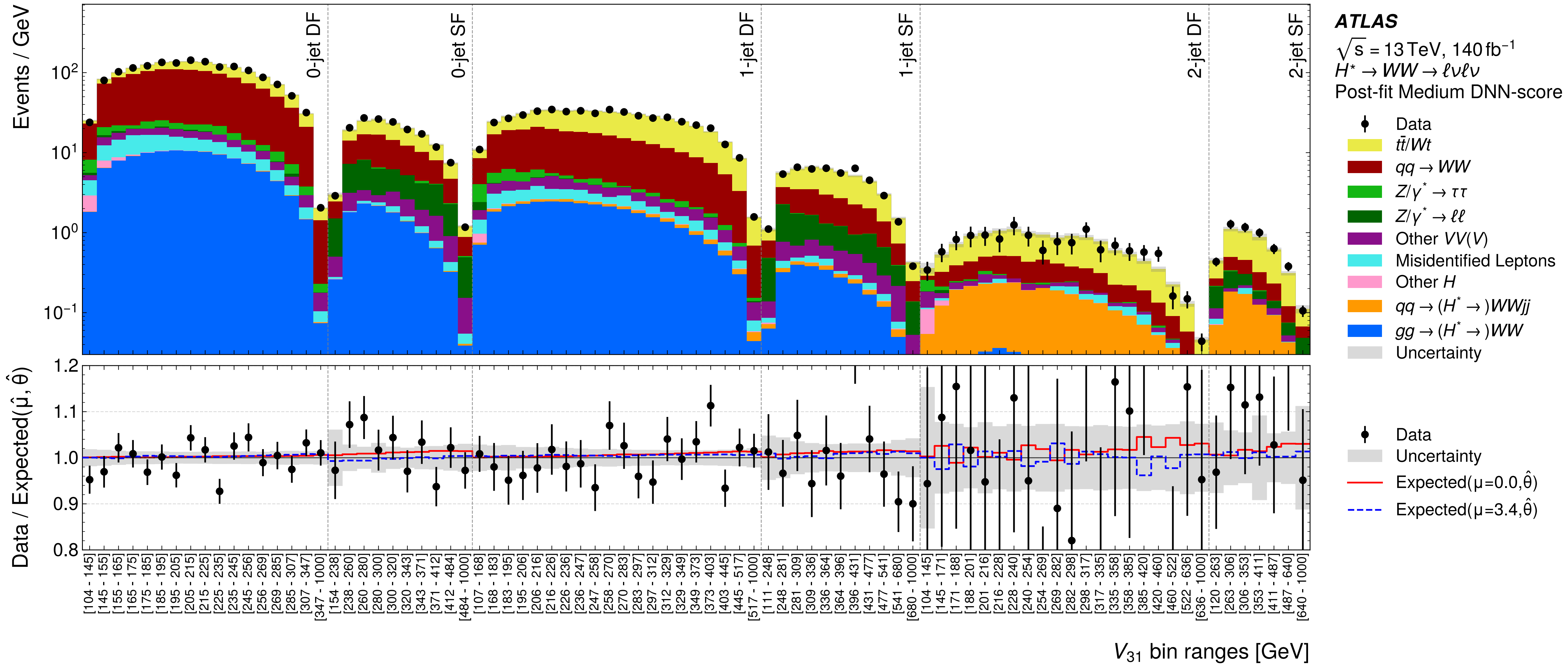


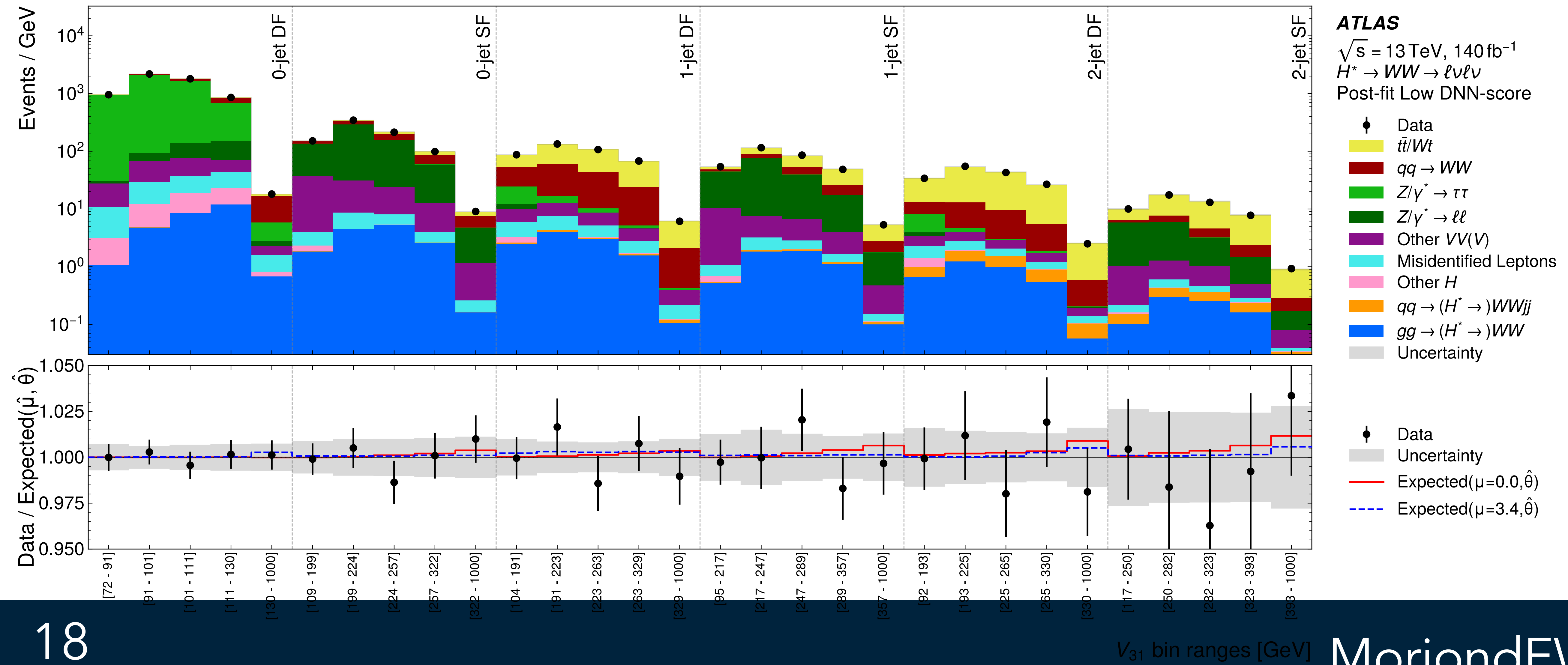
Multi-POI

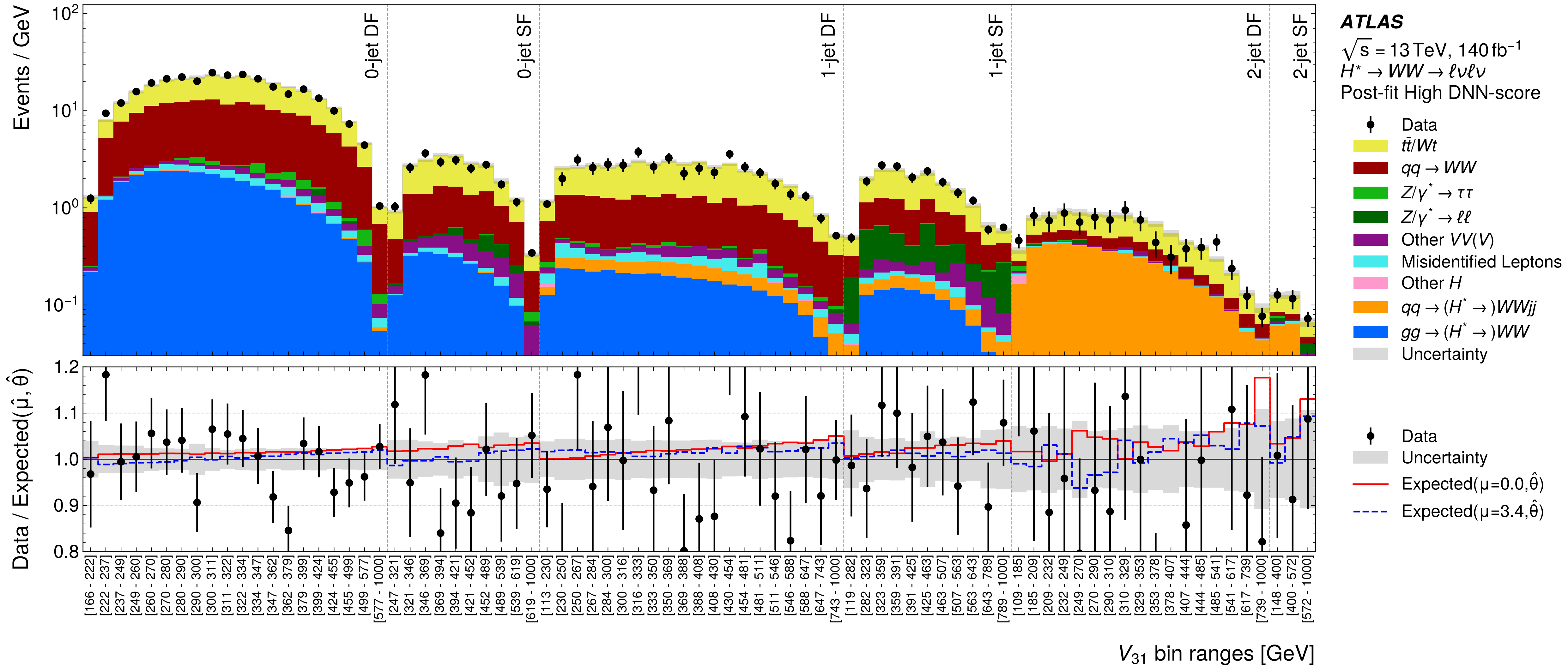

ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$H^* \rightarrow WW \rightarrow \ell\nu\ell\nu$
Post-fit
Expected stat
Expected stat+syst
$\hat{\mu}^{+68\%CL}_{-68\%CL}$Stat. + Syst. (Stat.)
$pp \rightarrow H^* \rightarrow WW \rightarrow \ell\nu_\ell\ell\nu_\ell$ $1.0^{+2.3}_{-1.0}(^{+1.7}_{-0.8})$
$pp \rightarrow H^* \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$ $1.0^{+2.3}_{-1.0}(^{+1.8}_{-0.8})$
$pp \rightarrow H^* \rightarrow WW \rightarrow e\nu_e e\nu_e/\mu\nu_\mu\mu\nu_\mu$ $1.0^{+2.8}(^{+1.8})$
EW, njets ≥ 2, $H^* \rightarrow WW \rightarrow e\nu_e e\nu_e/\mu\nu_\mu\mu\nu_\mu$ $1.0^{+3.4}(^{+2.8})$
EW, njets ≥ 2, $H^* \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$ $1.0^{+3.0}(^{+2.6})$
ggF, njets = 1, $H^* \rightarrow WW \rightarrow e\nu_e e\nu_e/\mu\nu_\mu\mu\nu_\mu$ $1.0^{+4.2}(^{+2.7})$
ggF, njets = 1, $H^* \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$ $1.0^{+3.2}(^{+2.4})$
ggF, njets = 0, $H^* \rightarrow WW \rightarrow e\nu_e e\nu_e/\mu\nu_\mu\mu\nu_\mu$ $1.0^{+4.4}(^{+2.9})$
ggF, njets = 0, $H^* \rightarrow WW \rightarrow e\nu_e\mu\nu_\mu$ $1.0^{+3.2}(^{+2.5})$
0
2
4
6
8
10
$\mu_{\text{off-shell}}$


ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$H^* \rightarrow WW \rightarrow l\nu l\nu$
Expected (68% CL)
Expected (95% CL)
Observed (68% CL)
Observed (95% CL)
SM
Observed best fit
(0.4, 0.2)
$\mu^{\text{ggF}}_{\text{off-shell}}$
12
10
8
6
4
2
0
0
2
4
6
8
10
$\mu^{\text{EW}}_{\text{off-shell}}$

All analysis signal regions





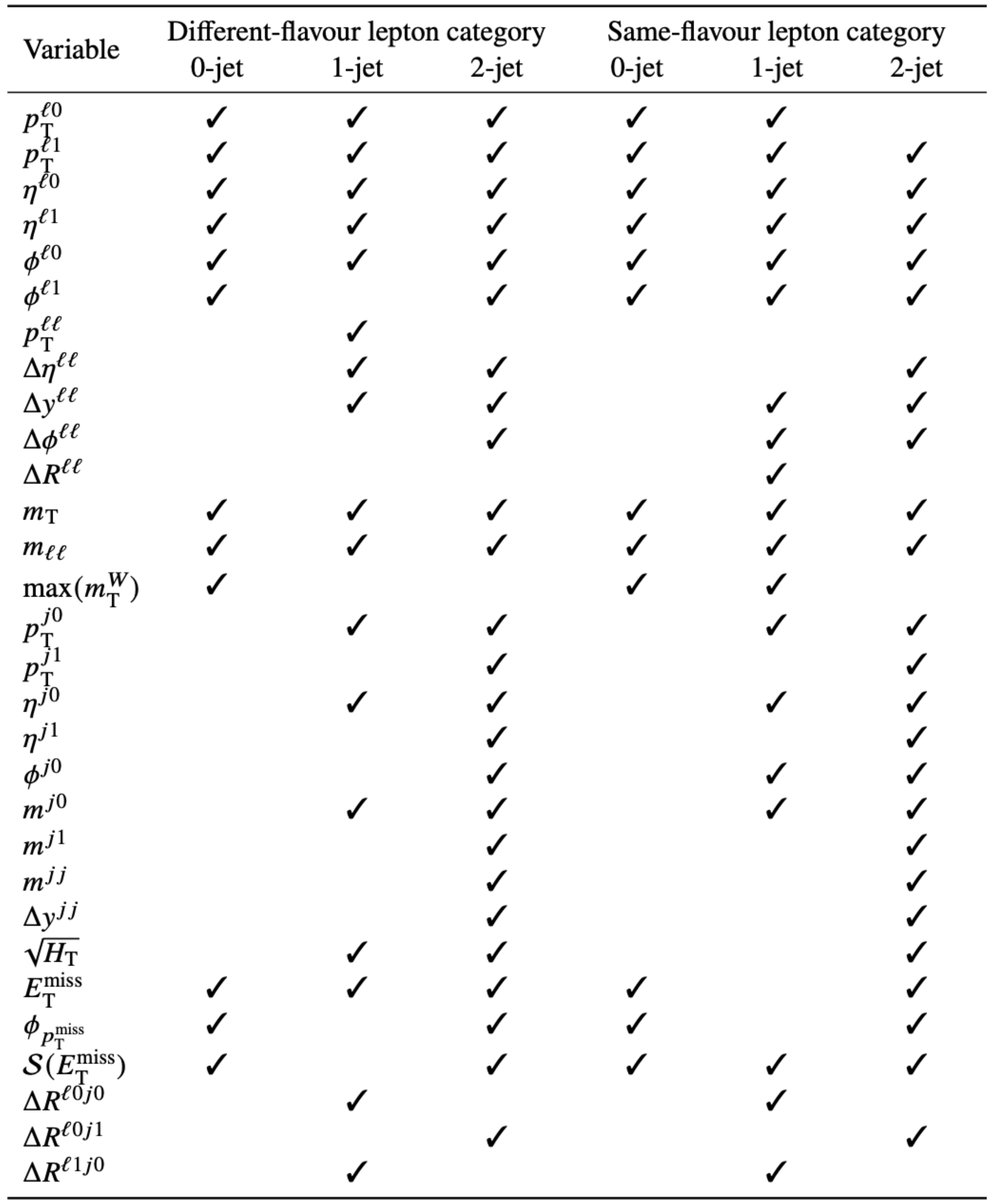


Neyman Construction for creating confidence intervals

- Neyman construction using toys can be used to correctly estimate the CI for the off-shell
- Three step procedure
  - 1] Profile dataset
    - Perform conditional fit (assuming particular injected value of POI) to data to obtain best fit values of nuisance parameters (NP)
  - 2] Generate toy datasets
    - Given the injected μ and NP, randomize the global observable according to the PDF and generate a toy dataset
  - 3] Perform unconditional and conditional fits for each toy to get test statistic distribution for each hypothesis (more info in the backup)

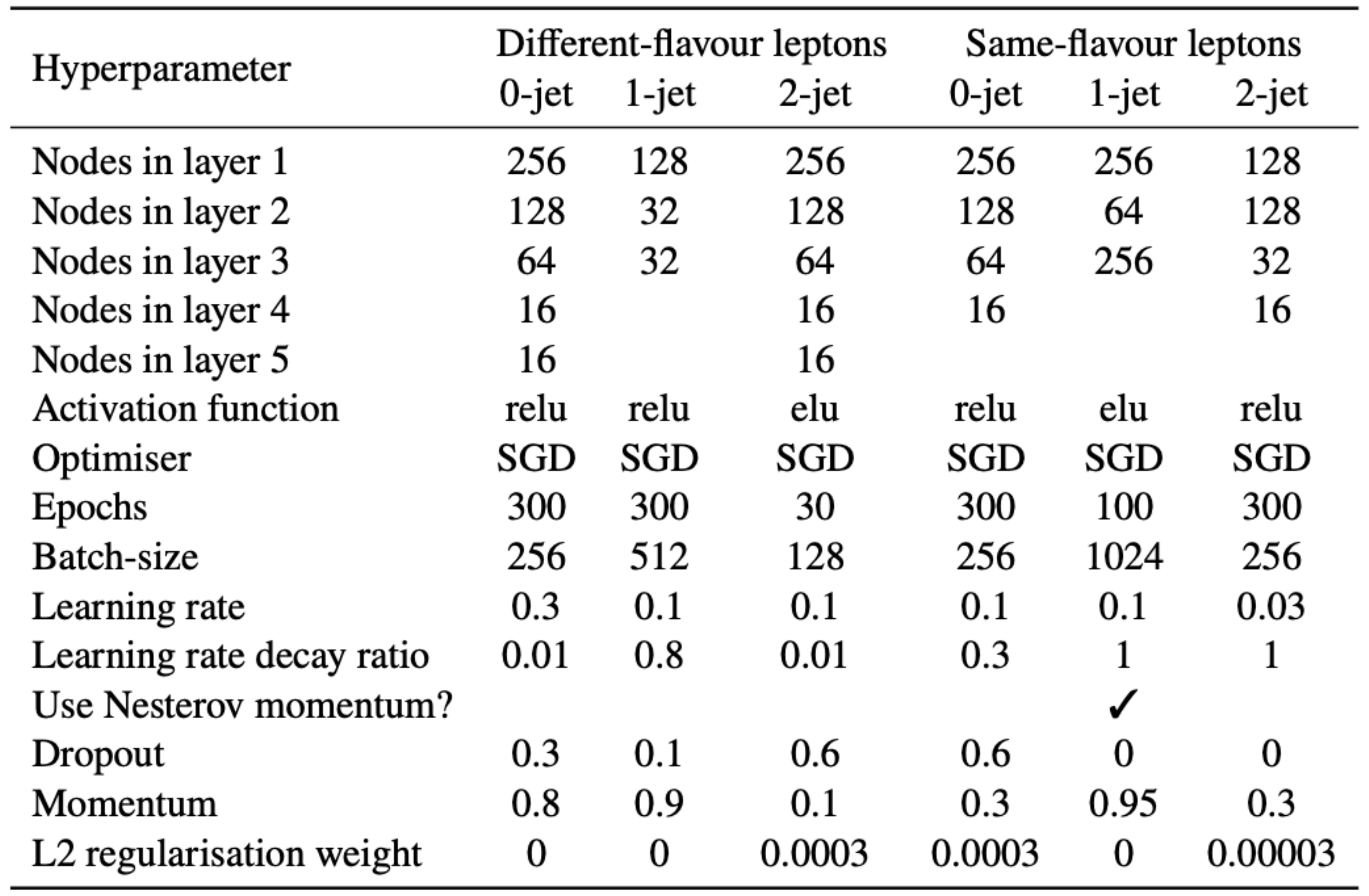
Tables

DNN inputs



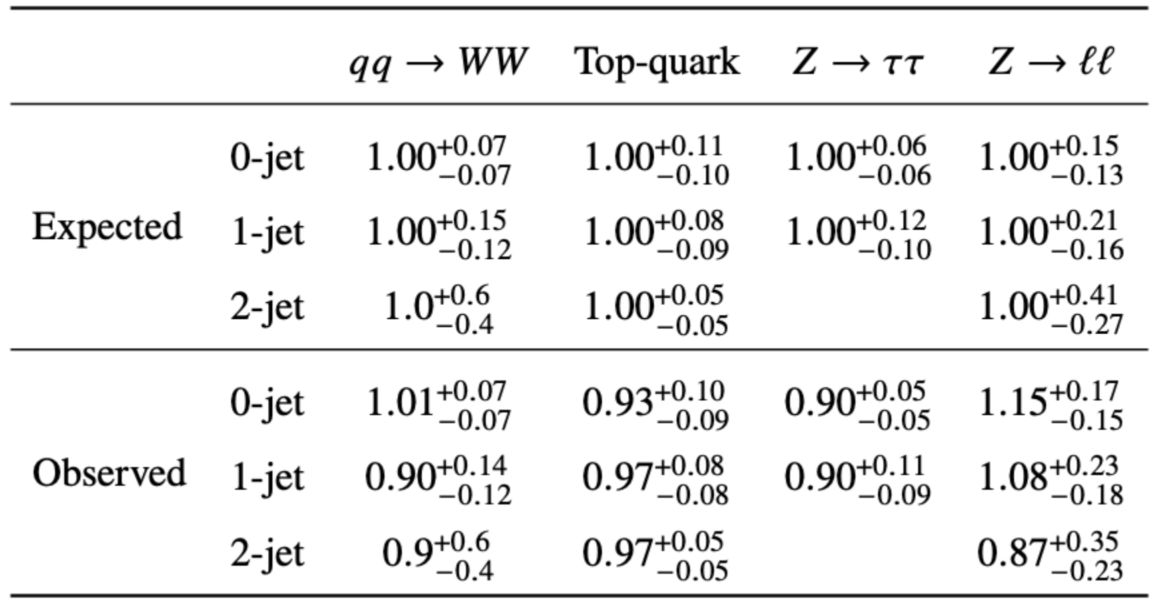
Variable	Different-flavour lepton category			Same-flavour lepton category		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
$p_{\mathrm{T}}^{\ell 0}$	✓	✓	✓	✓	✓	
$p_{\mathrm{T}}^{\ell 1}$	✓	✓	✓	✓	✓	✓
$\eta^{\ell 0}$	✓	✓	✓	✓	✓	✓
$\eta^{\ell 1}$	✓	✓	✓	✓	✓	✓
$\phi^{\ell 0}$	✓	✓	✓	✓	✓	✓
$\phi^{\ell 1}$	✓		✓	✓	✓	✓
$p_{\mathrm{T}}^{\ell\ell}$		✓				
$\Delta\eta^{\ell\ell}$		✓	✓			✓
$\Delta y^{\ell\ell}$		✓	✓		✓	✓
$\Delta\phi^{\ell\ell}$			✓		✓	✓
$\Delta R^{\ell\ell}$					✓	
m_{T}	✓	✓	✓	✓	✓	✓
$m_{\ell\ell}$	✓	✓	✓	✓	✓	✓
$\max(m_{\mathrm{T}}^{W})$	✓			✓	✓	
p_{T}^{j0}		✓	✓		✓	✓
p_{T}^{j1}			✓			✓
η^{j0}		✓	✓		✓	✓
η^{j1}			✓			✓
ϕ^{j0}			✓		✓	✓
m^{j0}		✓	✓		✓	✓
m^{j1}			✓			✓
m^{jj}			✓			✓
Δy^{jj}			✓			✓
$\sqrt{H_{\mathrm{T}}}$		✓	✓			✓
$E_{\mathrm{T}}^{\mathrm{miss}}$	✓	✓	✓	✓		✓
$\phi_{p_{\mathrm{T}}^{\mathrm{miss}}}$	✓		✓	✓		✓
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$	✓		✓	✓	✓	✓
$\Delta R^{\ell 0 j 0}$		✓			✓	
$\Delta R^{\ell 0 j 1}$			✓			✓
$\Delta R^{\ell 1 j 0}$		✓			✓	

Hyperparameters



Hyperparameter	Different-flavour leptons			Same-flavour leptons		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
Nodes in layer 1	256	128	256	256	256	128
Nodes in layer 2	128	32	128	128	64	128
Nodes in layer 3	64	32	64	64	256	32
Nodes in layer 4	16		16	16		16
Nodes in layer 5	16		16			
Activation function	relu	relu	elu	relu	elu	relu
Optimiser	SGD	SGD	SGD	SGD	SGD	SGD
Epochs	300	300	30	300	100	300
Batch-size	256	512	128	256	1024	256
Learning rate	0.3	0.1	0.1	0.1	0.1	0.03
Learning rate decay ratio	0.01	0.8	0.01	0.3	1	1
Use Nesterov momentum?					✓	
Dropout	0.3	0.1	0.6	0.6	0	0
Momentum	0.8	0.9	0.1	0.3	0.95	0.3
L2 regularisation weight	0	0	0.0003	0.0003	0	0.00003

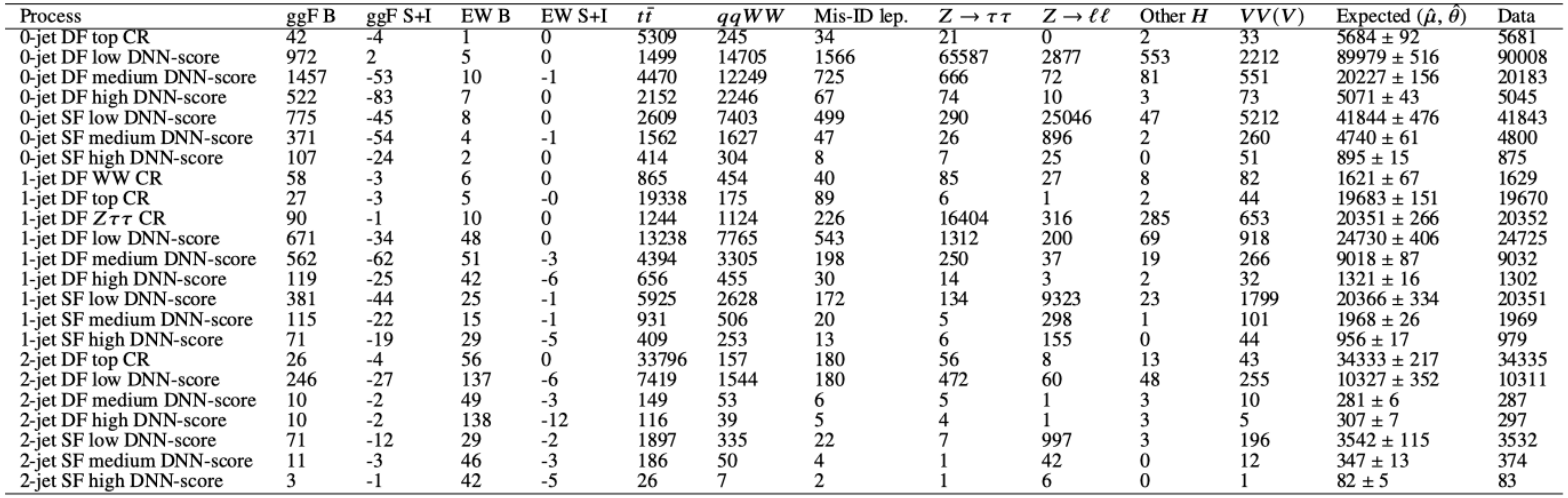
NFs



		$qq \to WW$	Top-quark	$Z \to \tau\tau$	$Z \to \ell\ell$
Expected	0-jet	$1.00^{+0.07}_{-0.07}$	$1.00^{+0.11}_{-0.10}$	$1.00^{+0.06}_{-0.06}$	$1.00^{+0.15}_{-0.13}$
	1-jet	$1.00^{+0.15}_{-0.12}$	$1.00^{+0.08}_{-0.09}$	$1.00^{+0.12}_{-0.10}$	$1.00^{+0.21}_{-0.16}$
	2-jet	$1.0^{+0.6}_{-0.4}$	$1.00^{+0.05}_{-0.05}$		$1.00^{+0.41}_{-0.27}$
Observed	0-jet	$1.01^{+0.07}_{-0.07}$	$0.93^{+0.10}_{-0.09}$	$0.90^{+0.05}_{-0.05}$	$1.15^{+0.17}_{-0.15}$
	1-jet	$0.90^{+0.14}_{-0.12}$	$0.97^{+0.08}_{-0.08}$	$0.90^{+0.11}_{-0.09}$	$1.08^{+0.23}_{-0.18}$
	2-jet	$0.9^{+0.6}_{-0.4}$	$0.97^{+0.05}_{-0.05}$		$0.87^{+0.35}_{-0.23}$

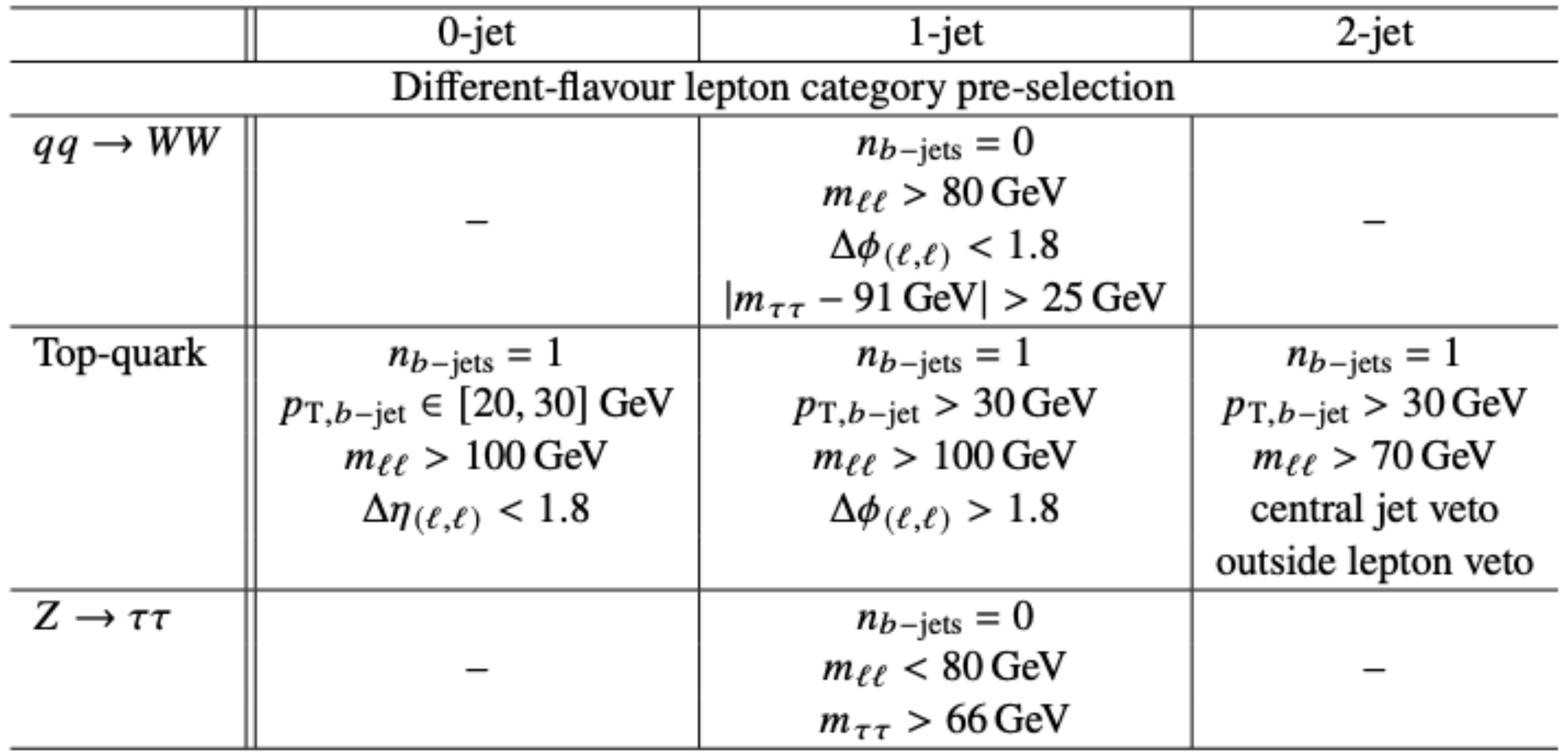
Tables

Yields



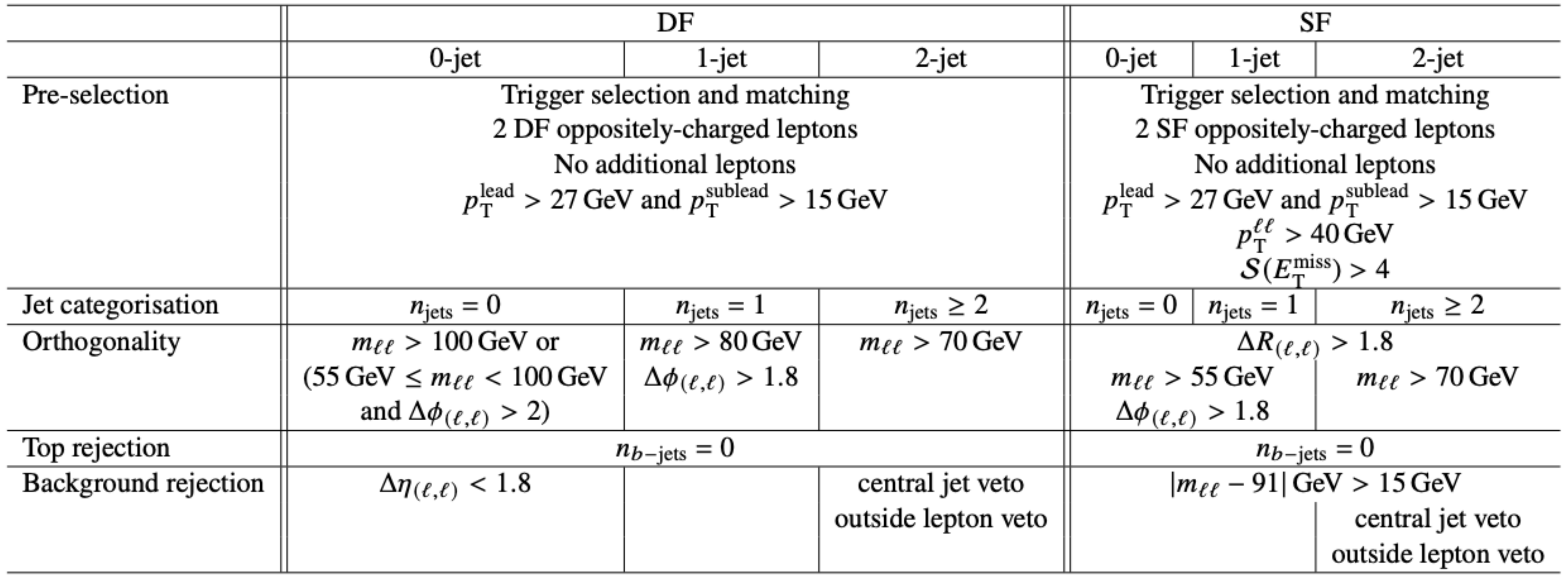
Process	ggF B	ggF S+I	EW B	EW S+I	$t\bar{t}$	$qqWW$	Mis-ID lep.	$Z \to \tau\tau$	$Z \to \ell\ell$	Other H	$VV(V)$	Expected ($\hat{\mu}$, $\hat{\theta}$)	Data
0-jet DF top CR	42	-4	1	0	5309	245	34	21	0	2	33	5684 ± 92	5681
0-jet DF low DNN-score	972	2	5	0	1499	14705	1566	65587	2877	553	2212	89979 ± 516	90008
0-jet DF medium DNN-score	1457	-53	10	-1	4470	12249	725	666	72	81	551	20227 ± 156	20183
0-jet DF high DNN-score	522	-83	7	0	2152	2246	67	74	10	3	73	5071 ± 43	5045
0-jet SF low DNN-score	775	-45	8	0	2609	7403	499	290	25046	47	5212	41844 ± 476	41843
0-jet SF medium DNN-score	371	-54	4	-1	1562	1627	47	26	896	2	260	4740 ± 61	4800
0-jet SF high DNN-score	107	-24	2	0	414	304	8	7	25	0	51	895 ± 15	875
1-jet DF WW CR	58	-3	6	0	865	454	40	85	27	8	82	1621 ± 67	1629
1-jet DF top CR	27	-3	5	-0	19338	175	89	6	1	2	44	19683 ± 151	19670
1-jet DF $Z\tau\tau$ CR	90	-1	10	0	1244	1124	226	16404	316	285	653	20351 ± 266	20352
1-jet DF low DNN-score	671	-34	48	0	13238	7765	543	1312	200	69	918	24730 ± 406	24725
1-jet DF medium DNN-score	562	-62	51	-3	4394	3305	198	250	37	19	266	9018 ± 87	9032
1-jet DF high DNN-score	119	-25	42	-6	656	455	30	14	3	2	32	1321 ± 16	1302
1-jet SF low DNN-score	381	-44	25	-1	5925	2628	172	134	9323	23	1799	20366 ± 334	20351
1-jet SF medium DNN-score	115	-22	15	-1	931	506	20	5	298	1	101	1968 ± 26	1969
1-jet SF high DNN-score	71	-19	29	-5	409	253	13	6	155	0	44	956 ± 17	979
2-jet DF top CR	26	-4	56	0	33796	157	180	56	8	13	43	34333 ± 217	34335
2-jet DF low DNN-score	246	-27	137	-6	7419	1544	180	472	60	48	255	10327 ± 352	10311
2-jet DF medium DNN-score	10	-2	49	-3	149	53	6	5	1	3	10	281 ± 6	287
2-jet DF high DNN-score	10	-2	138	-12	116	39	5	4	1	3	5	307 ± 7	297
2-jet SF low DNN-score	71	-12	29	-2	1897	335	22	7	997	3	196	3542 ± 115	3532
2-jet SF medium DNN-score	11	-3	46	-3	186	50	4	1	42	0	12	347 ± 13	374
2-jet SF high DNN-score	3	-1	42	-5	26	7	2	1	6	0	1	82 ± 5	83

CRs



	0-jet	1-jet	2-jet
Different-flavour lepton category pre-selection			
$qq \to WW$	–	$n_{b-\text{jets}} = 0$ $m_{\ell\ell} > 80\,\text{GeV}$ $\Delta\phi_{(\ell,\ell)} < 1.8$ $\lvert m_{\tau\tau} - 91\,\text{GeV}\rvert > 25\,\text{GeV}$	–
Top-quark	$n_{b-\text{jets}} = 1$ $p_{\text{T},b-\text{jet}} \in [20, 30]$ GeV $m_{\ell\ell} > 100\,\text{GeV}$ $\Delta\eta_{(\ell,\ell)} < 1.8$	$n_{b-\text{jets}} = 1$ $p_{\text{T},b-\text{jet}} > 30\,\text{GeV}$ $m_{\ell\ell} > 100\,\text{GeV}$ $\Delta\phi_{(\ell,\ell)} > 1.8$	$n_{b-\text{jets}} = 1$ $p_{\text{T},b-\text{jet}} > 30\,\text{GeV}$ $m_{\ell\ell} > 70\,\text{GeV}$ central jet veto outside lepton veto
$Z \to \tau\tau$	–	$n_{b-\text{jets}} = 0$ $m_{\ell\ell} < 80\,\text{GeV}$ $m_{\tau\tau} > 66\,\text{GeV}$	–

SRs



	DF			SF		
	0-jet	1-jet	2-jet	0-jet	1-jet	2-jet
Pre-selection	Trigger selection and matching 2 DF oppositely-charged leptons No additional leptons $p_{\text{T}}^{\text{lead}} > 27\,\text{GeV}$ and $p_{\text{T}}^{\text{sublead}} > 15\,\text{GeV}$			Trigger selection and matching 2 SF oppositely-charged leptons No additional leptons $p_{\text{T}}^{\text{lead}} > 27\,\text{GeV}$ and $p_{\text{T}}^{\text{sublead}} > 15\,\text{GeV}$ $p_{\text{T}}^{\ell\ell} > 40\,\text{GeV}$ $\mathcal{S}(E_{\text{T}}^{\text{miss}}) > 4$		
Jet categorisation	$n_{\text{jets}} = 0$	$n_{\text{jets}} = 1$	$n_{\text{jets}} \geq 2$	$n_{\text{jets}} = 0$	$n_{\text{jets}} = 1$	$n_{\text{jets}} \geq 2$
Orthogonality	$m_{\ell\ell} > 100\,\text{GeV}$ or $(55\,\text{GeV} \leq m_{\ell\ell} < 100\,\text{GeV}$ and $\Delta\phi_{(\ell,\ell)} > 2)$	$m_{\ell\ell} > 80\,\text{GeV}$ $\Delta\phi_{(\ell,\ell)} > 1.8$	$m_{\ell\ell} > 70\,\text{GeV}$	$\Delta R_{(\ell,\ell)} > 1.8$ $m_{\ell\ell} > 55\,\text{GeV}$ $\Delta\phi_{(\ell,\ell)} > 1.8$		$m_{\ell\ell} > 70\,\text{GeV}$
Top rejection	$n_{b-\text{jets}} = 0$			$n_{b-\text{jets}} = 0$		
Background rejection	$\Delta\eta_{(\ell,\ell)} < 1.8$		central jet veto outside lepton veto	$\lvert m_{\ell\ell} - 91\rvert\,\text{GeV} > 15\,\text{GeV}$		central jet veto outside lepton veto