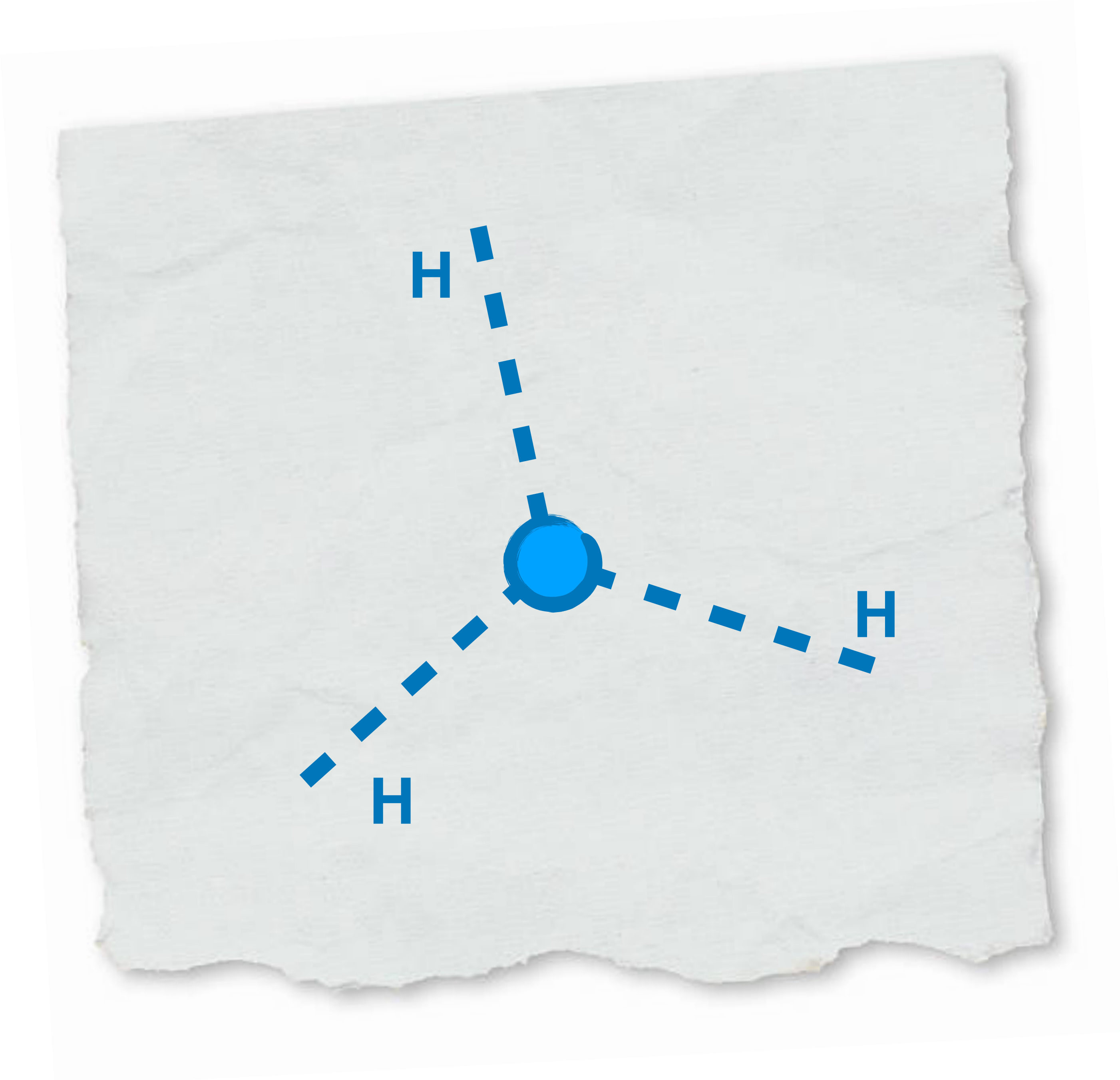
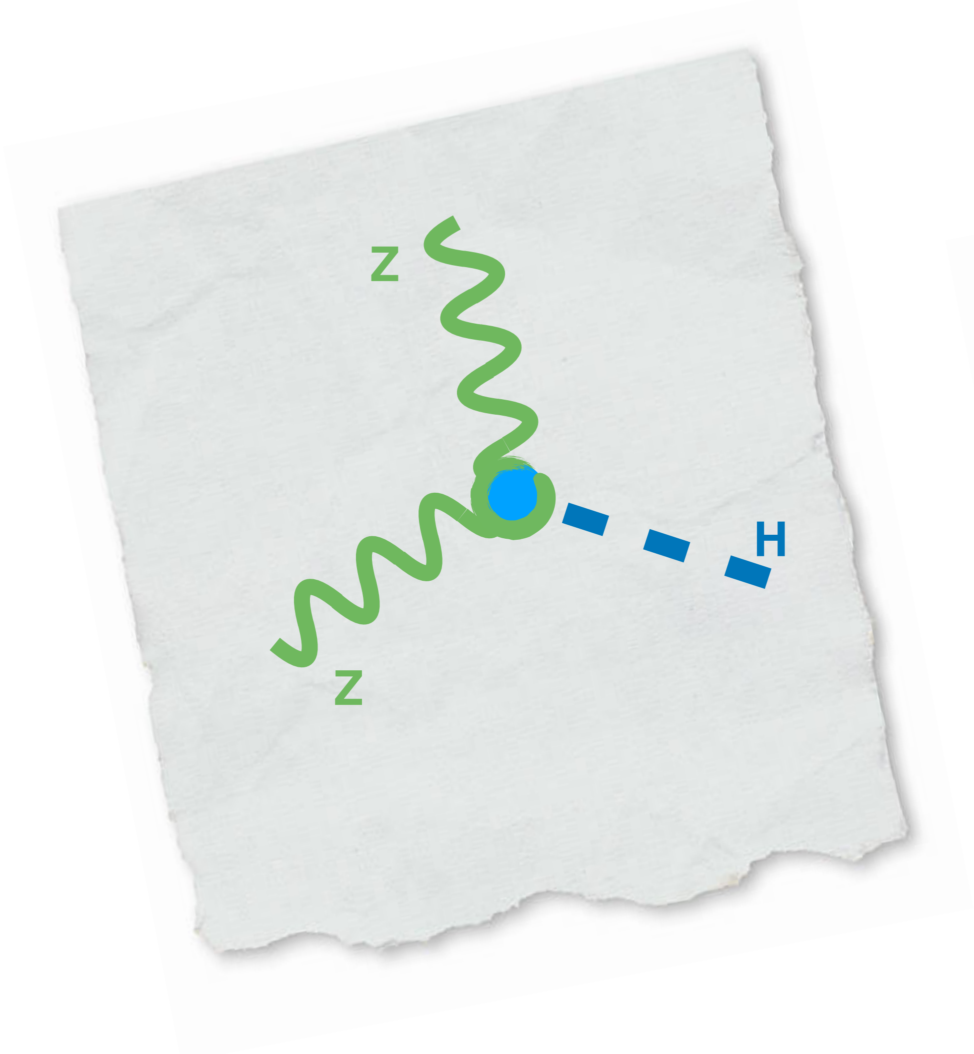
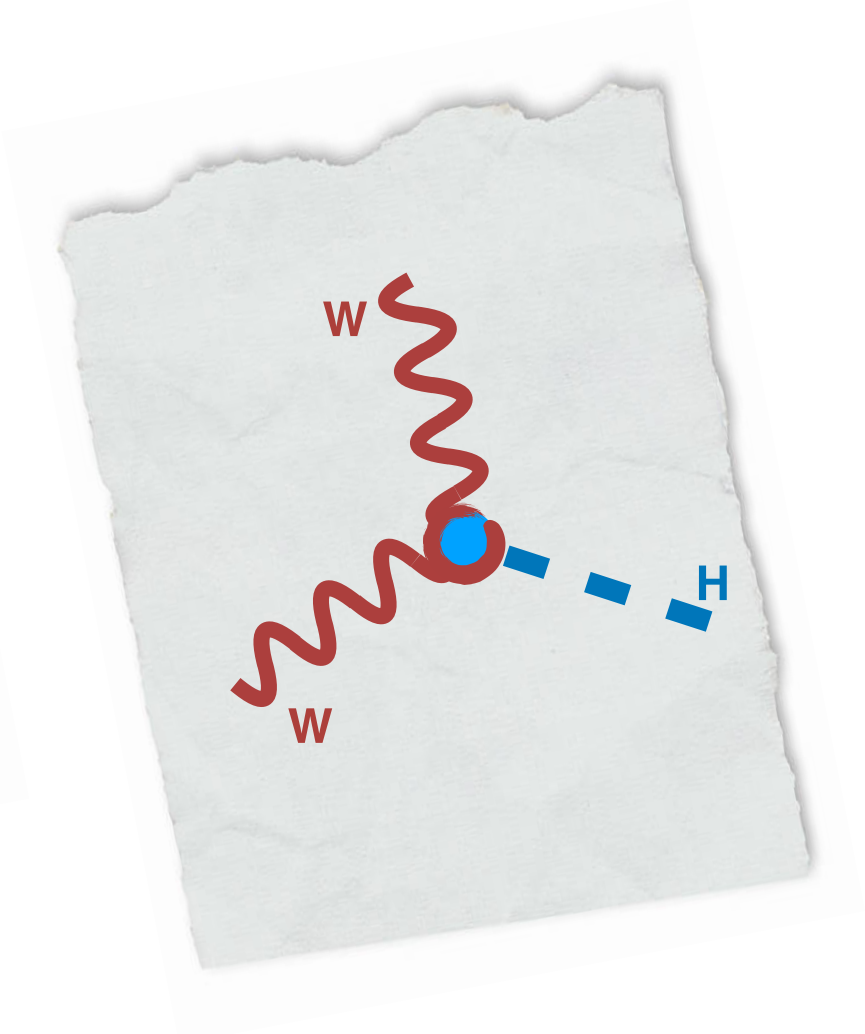
Higgs self-interactions



… and Higgs-gauge boson interactions





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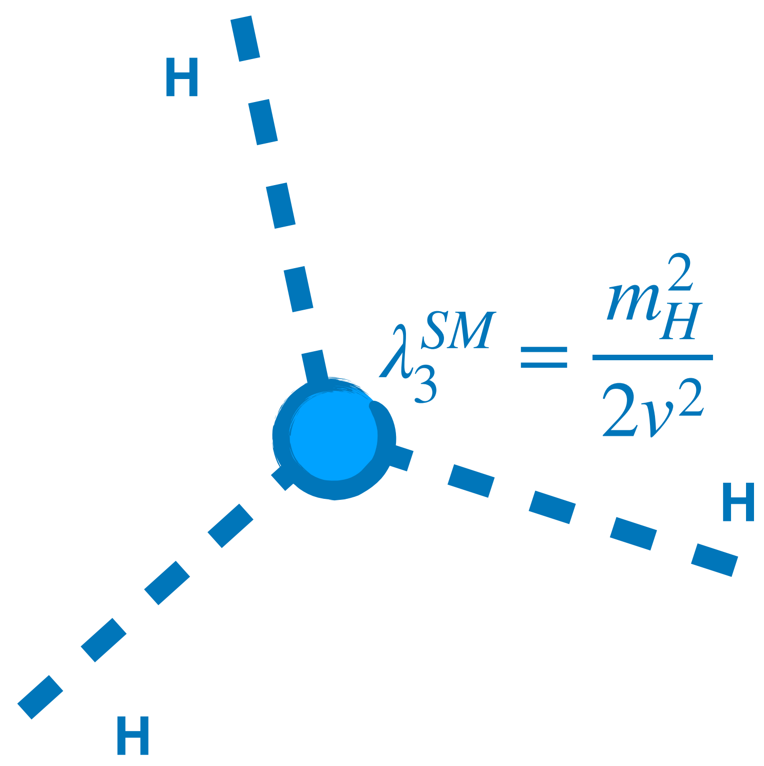
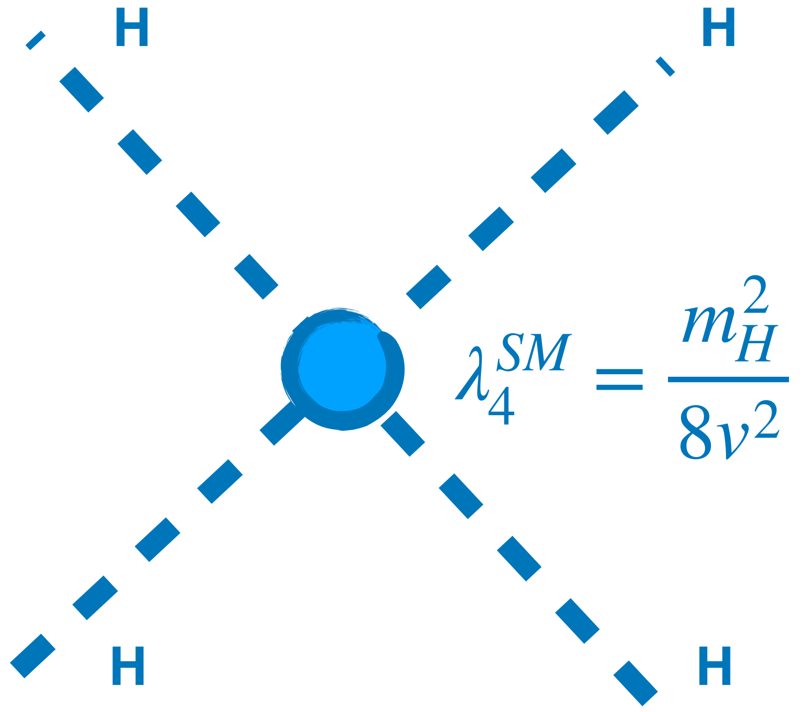
Does the Higgs interact with itself?

A self-interacting Higgs (as SM predicts) would be unlike anything yet seen in nature. All other interactions change particle identity.

The Higgs cubic (λ_3^{SM}) and quartic (λ_4^{SM}) couplings are the keys to investigate EWSB. The Higgs potential is :

$$\mathscr{L} \subset -\frac{m_h^2}{2}h^2 - \lambda_3^{SM} v h^3 - \lambda_4^{SM} h^4$$

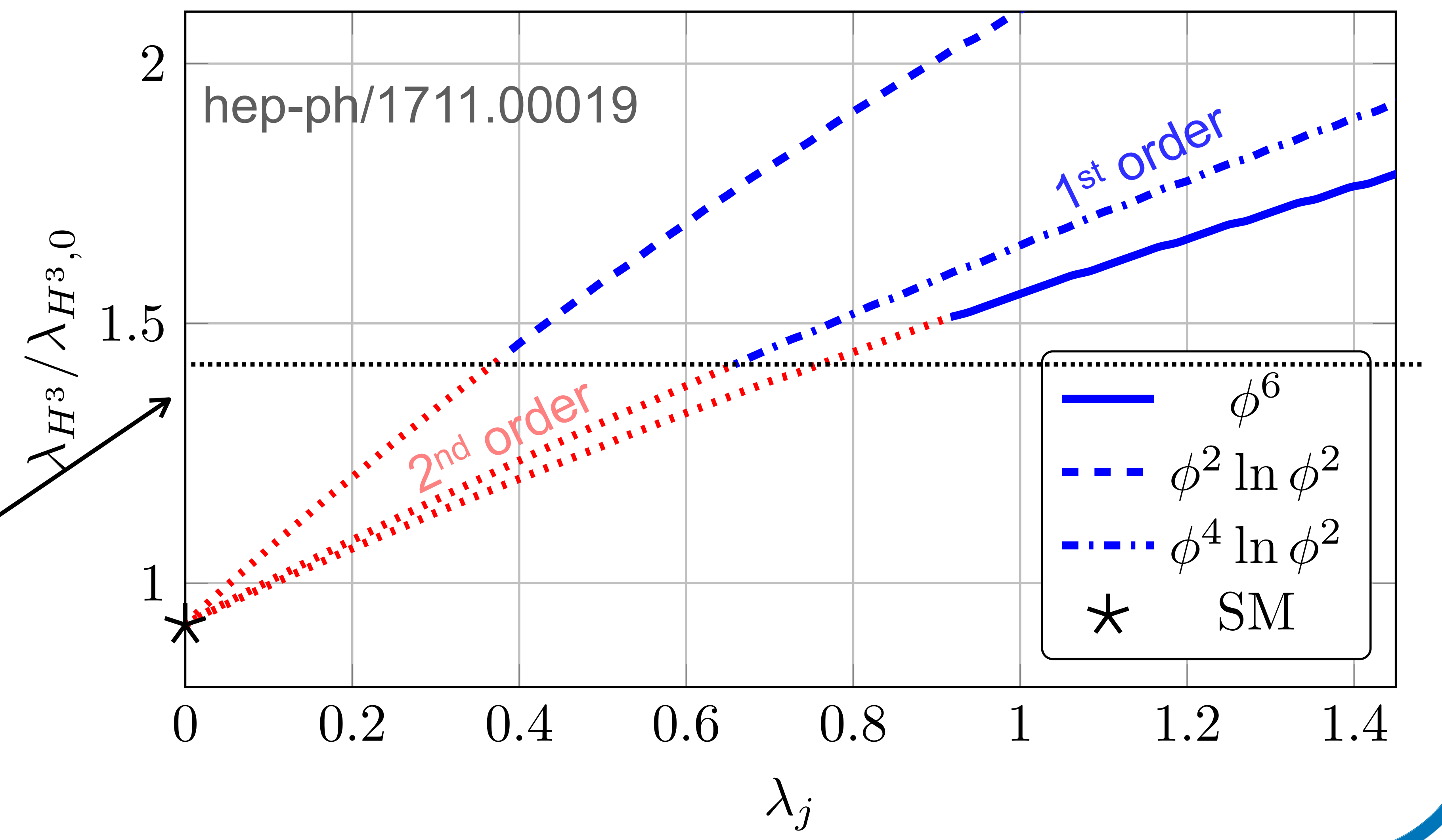




Link with cosmology

Deviations from SM Higgs self-coupling cause a modified potential that allows a **first-order electroweak phase transition** and hence an explanation of the observed matter vs anti-matter asymmetry

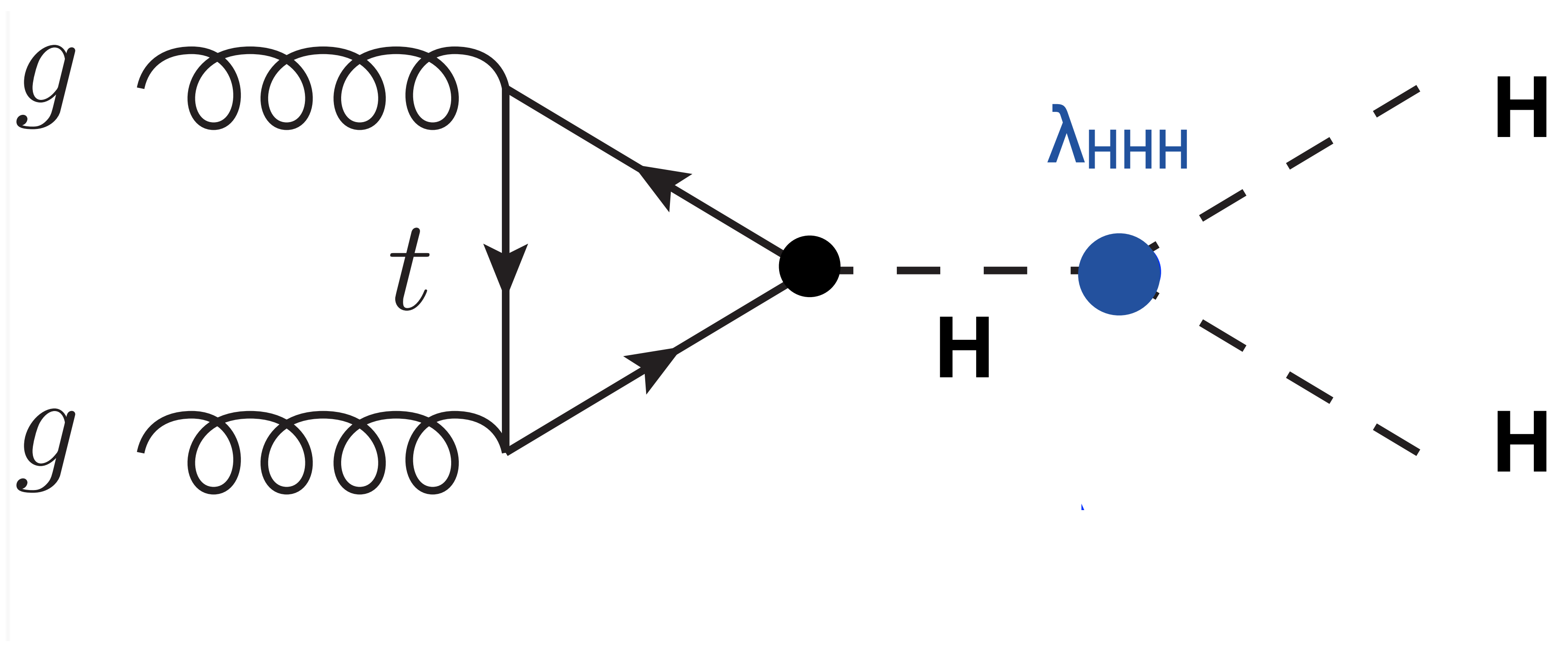
We need to probe size of modification down to 1.4,
the expected uncertainty of the measurement should be $\mathcal{O}(10\%)$



The Higgs self-coupling before FCC-ee

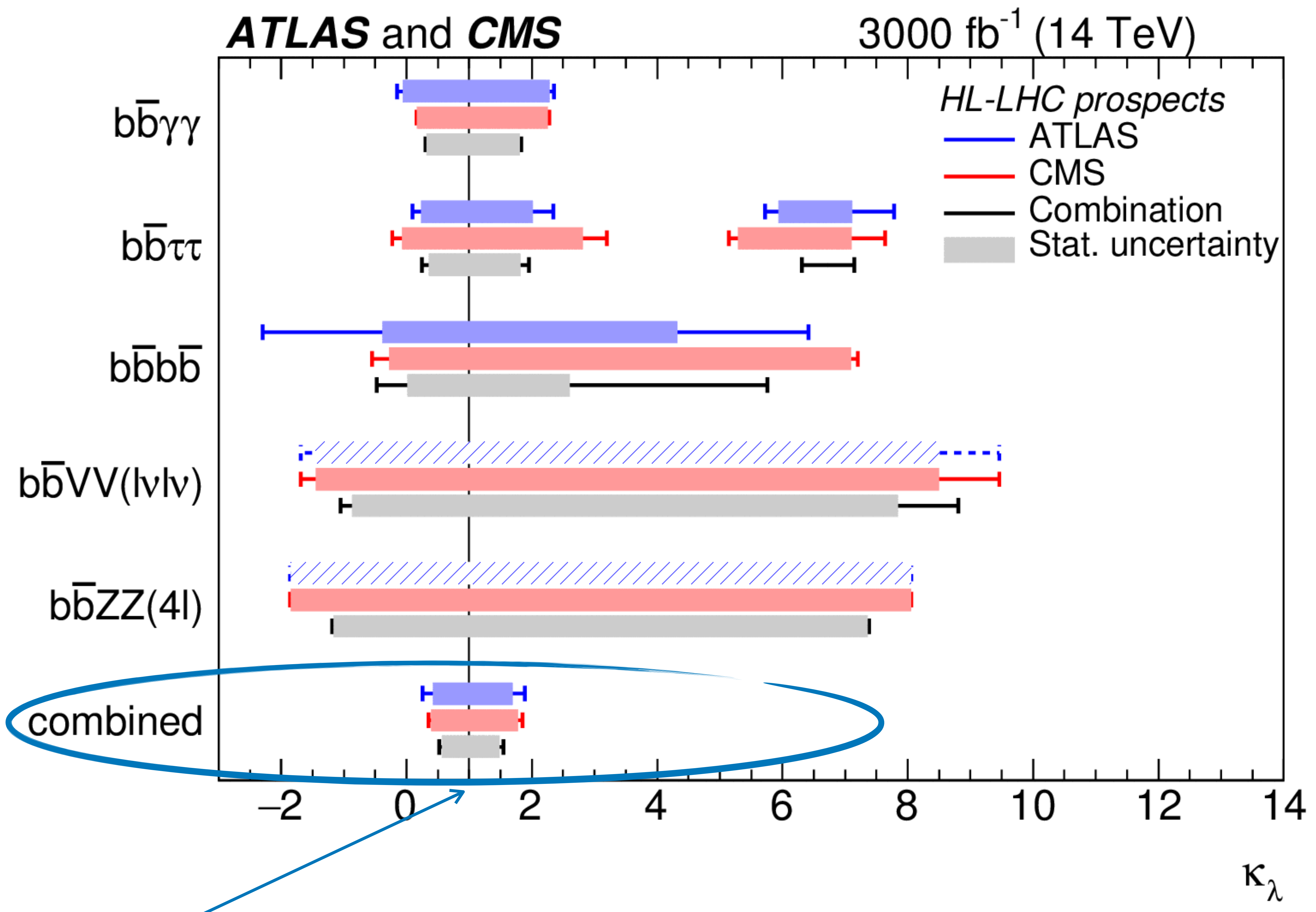
Direct measurements @ HL-LHC

On-shell production of two Higgs



- Theoretically clean
- Very rare process (σ~40fb @ 14TeV)
- Experimentally challenging

Expected results



arXiv:1902.00134

$\mathcal{O}(50\%)$ precision
2 experiments and various channels

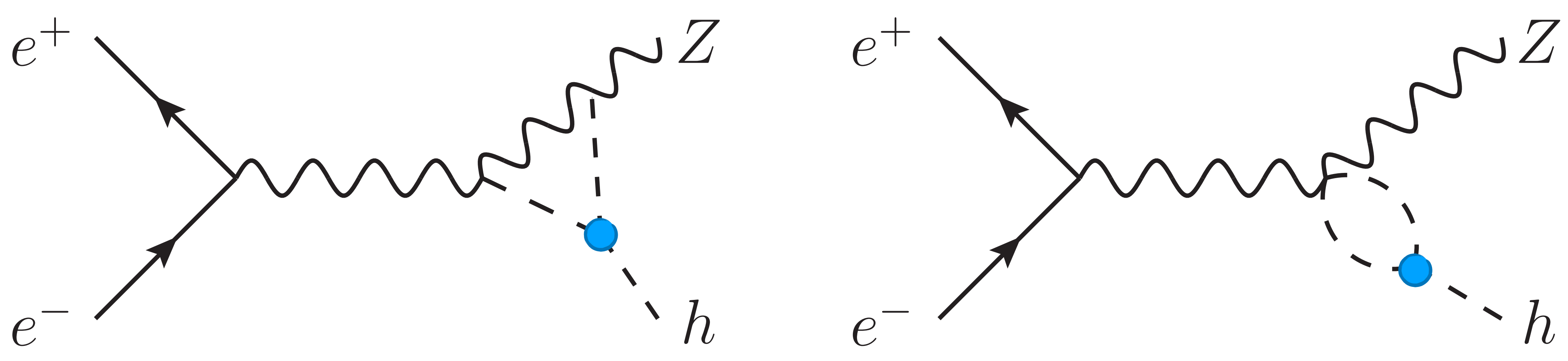
λ_3 @ FCC-ee

Higher-order corrections to single Higgs processes

λ_{HHH} does not enter single Higgs processes at LO but it affects both Higgs production and decay at NLO.

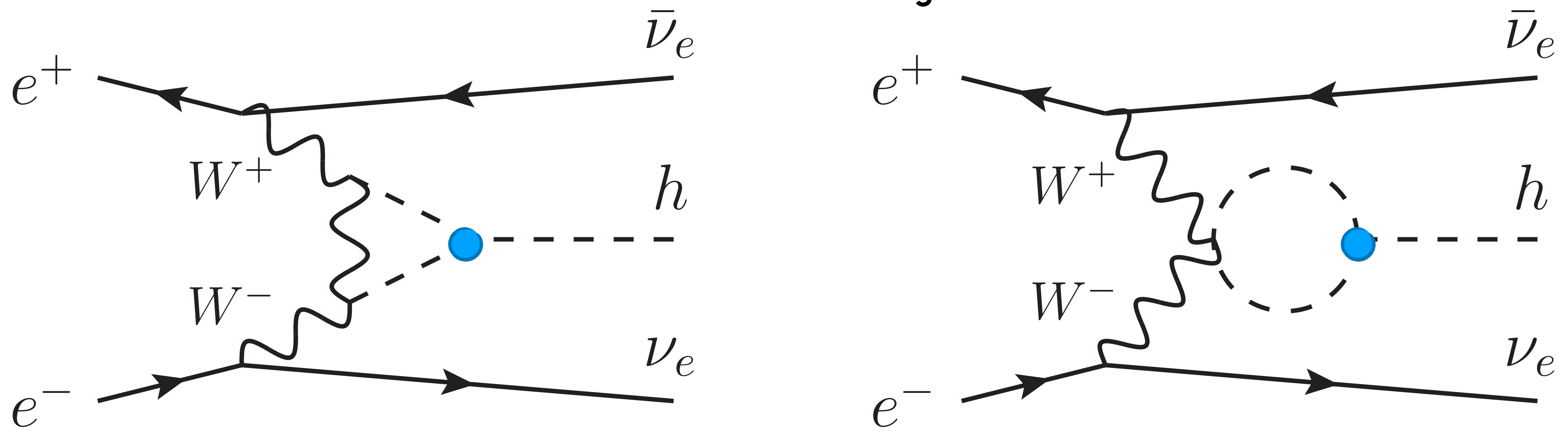
Vertex corrections (<u>linear</u> in k_λ)

ZH Higgsstrahlung



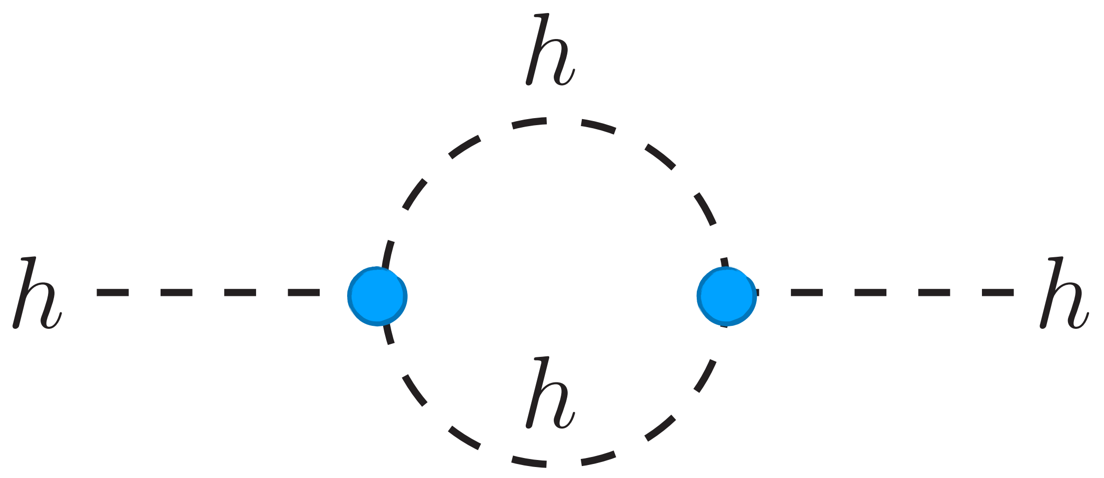
VBF processes

Both CC/NC diagrams



Higgs self-energy (<u>quadratic</u> in k_λ)

Universal modifications via wave function renormalisation



- Benefit of large single Higgs cross-section

λ_3 effect

The NLO corrections to an observable Σ

$$\Sigma_{\rm NLO} = Z_H \Sigma_{\rm LO}(1 + \kappa_\lambda C_1)$$

Z_H: Universal coefficient from wave function

C_1: Process and kinematic dependent coefficient

Decay modes

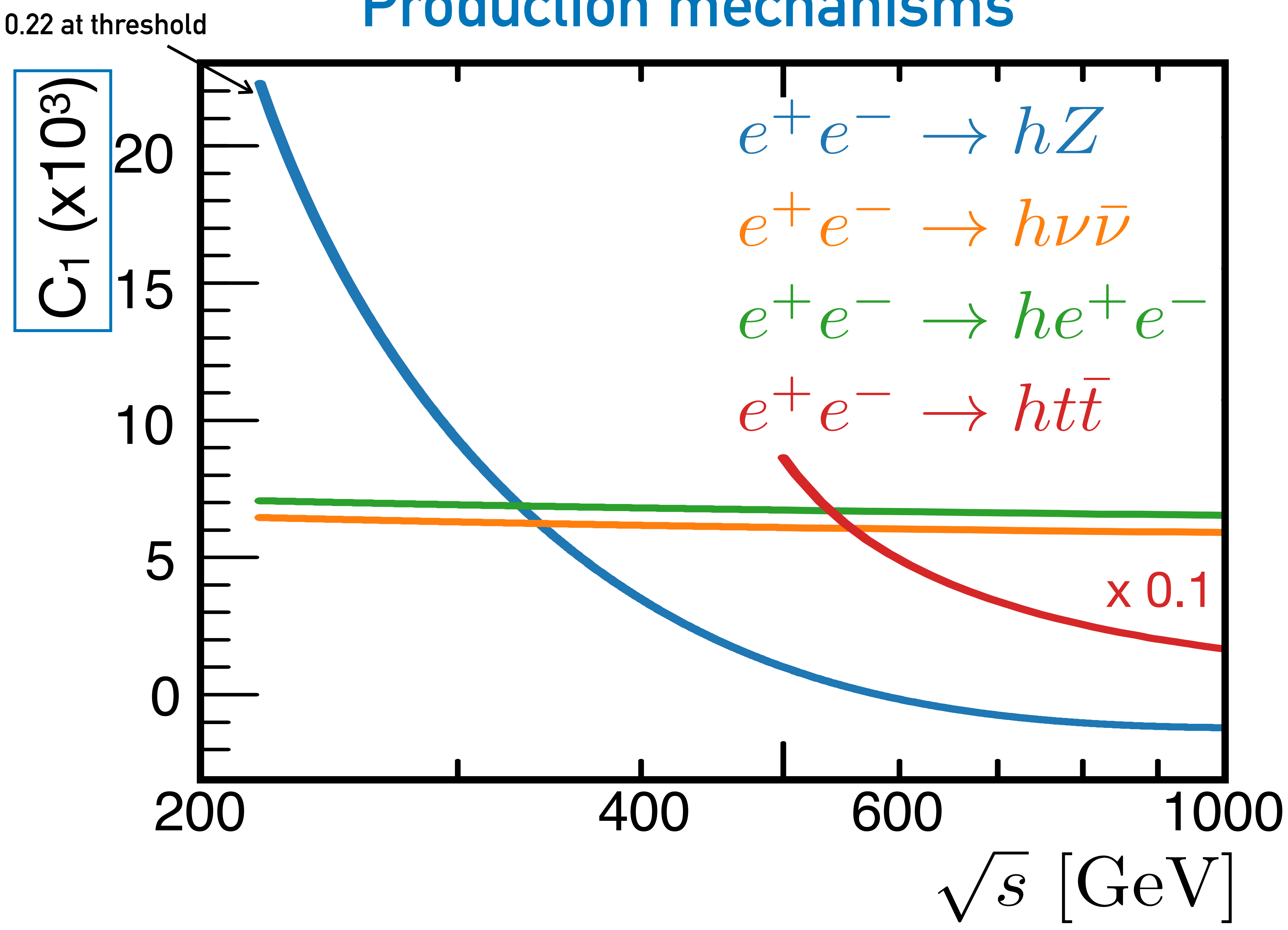
$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$$C_1^{\Gamma_{\rm tot}} \equiv \sum_j {\rm BR}^{\rm SM}(j) C_1^\Gamma(j) \sim 2.3\times10^{-3}$$

Close to SM predictions the BRs are sensitive to modified λ_{HHH}

$$\delta{\rm BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^\Gamma(i) - C_1^{\Gamma_{\rm tot}})}{1 + (\kappa_\lambda - 1)C_1^{\Gamma_{\rm tot}}}$$

Production mechanisms



Negligible impact of a modified λ_{HHH} on the angular asymmetries. At 1-loop C_1 for HZ, WW-boson fusion and ZZ-boson fusion are independent of the beam polarization.

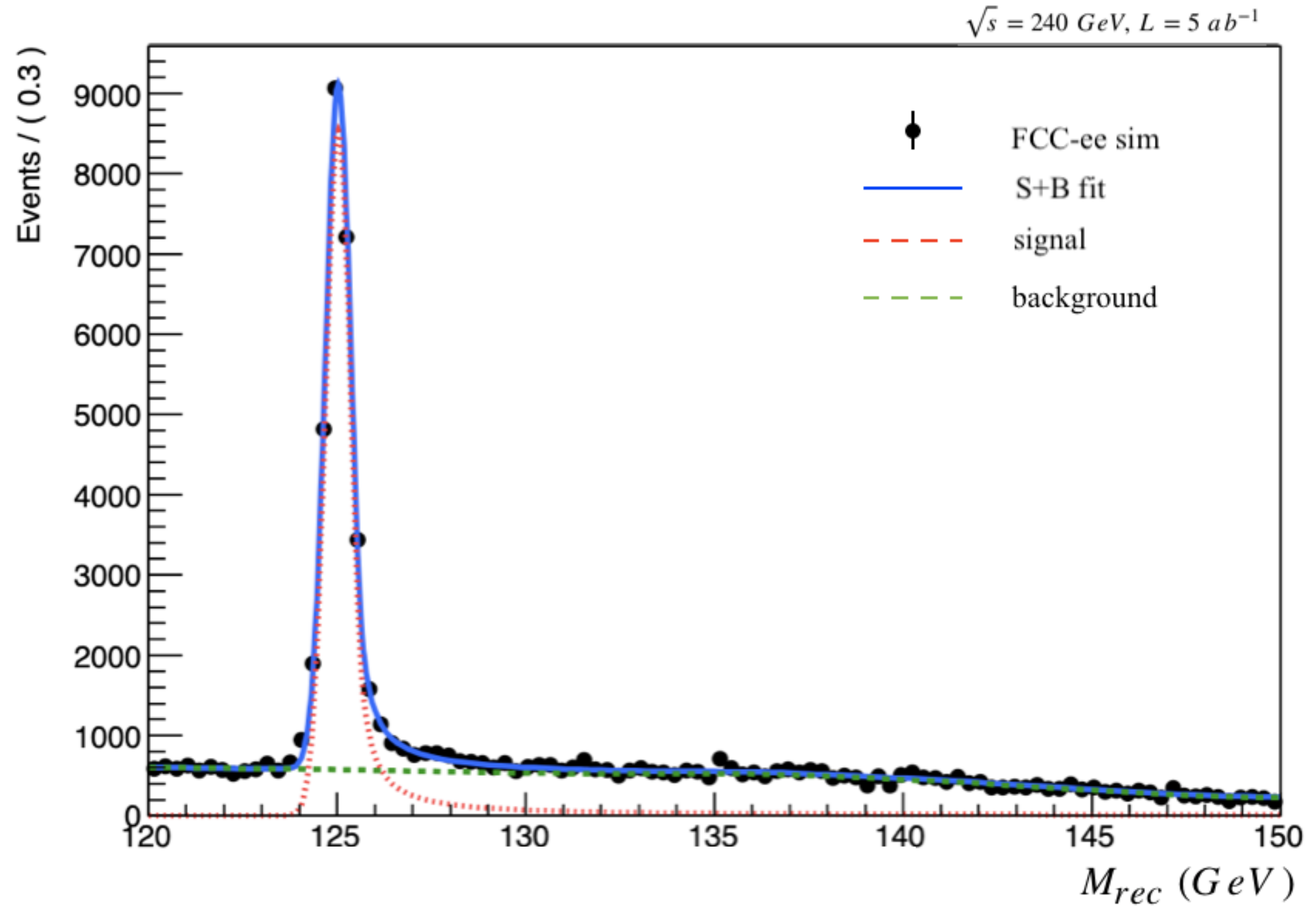
Great opportunity from the combination of inclusive or exclusive analyses and various production modes at two collision energies

Inclusive analyses @240 GeV

Exploited various Z decays, using the recoil techniques

Z(μμ)H

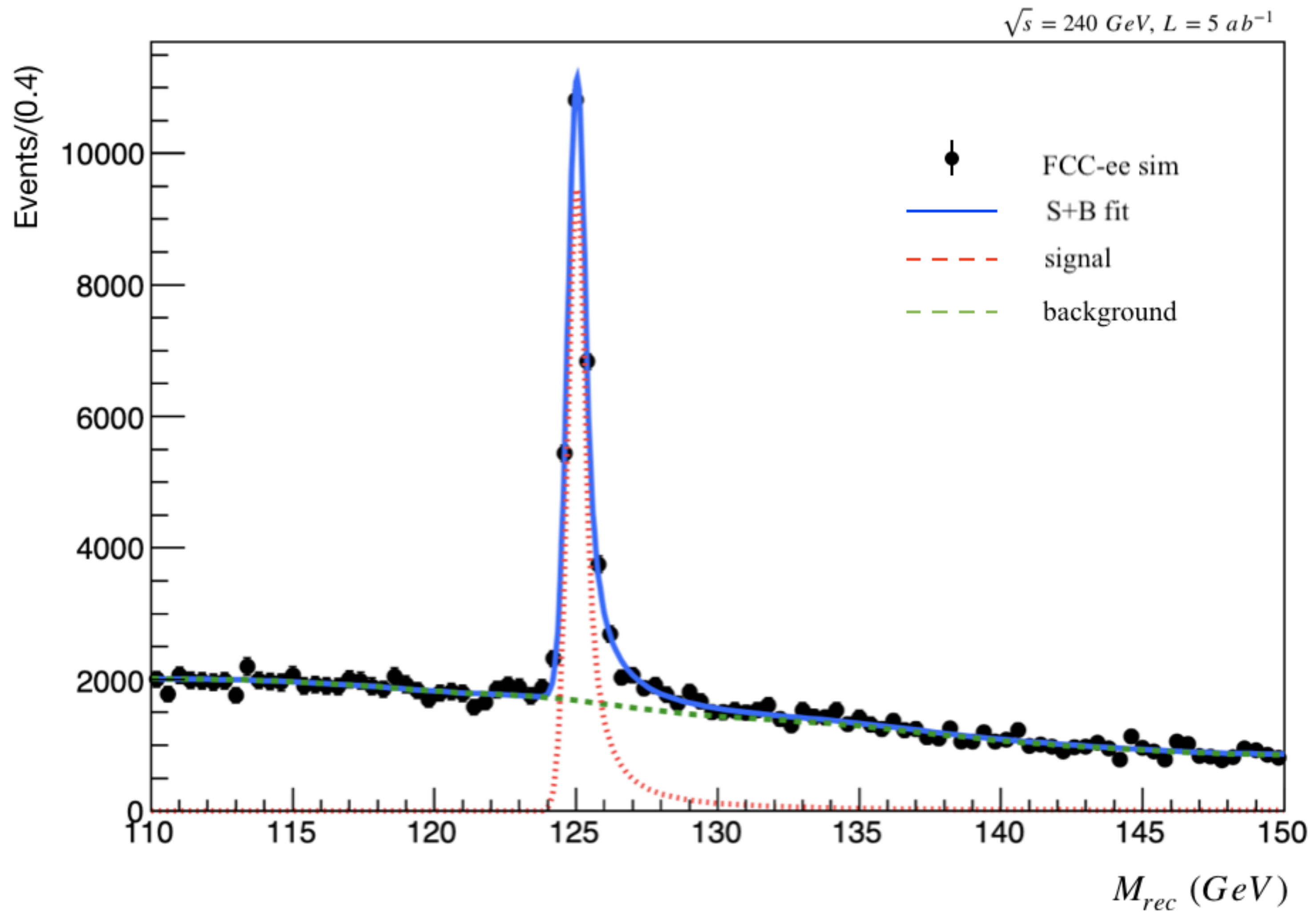
- $\mu^+\mu^-$ with $p_{T\mu 1} > 20$ GeV, $p_{T\mu 2} > 5$ GeV
- Minimum $|M_{\mu^+\mu^-} - M_Z|$
- $80 < M_{\mu^+\mu^-} < 100$ GeV



Golden channel

Z(ee)H

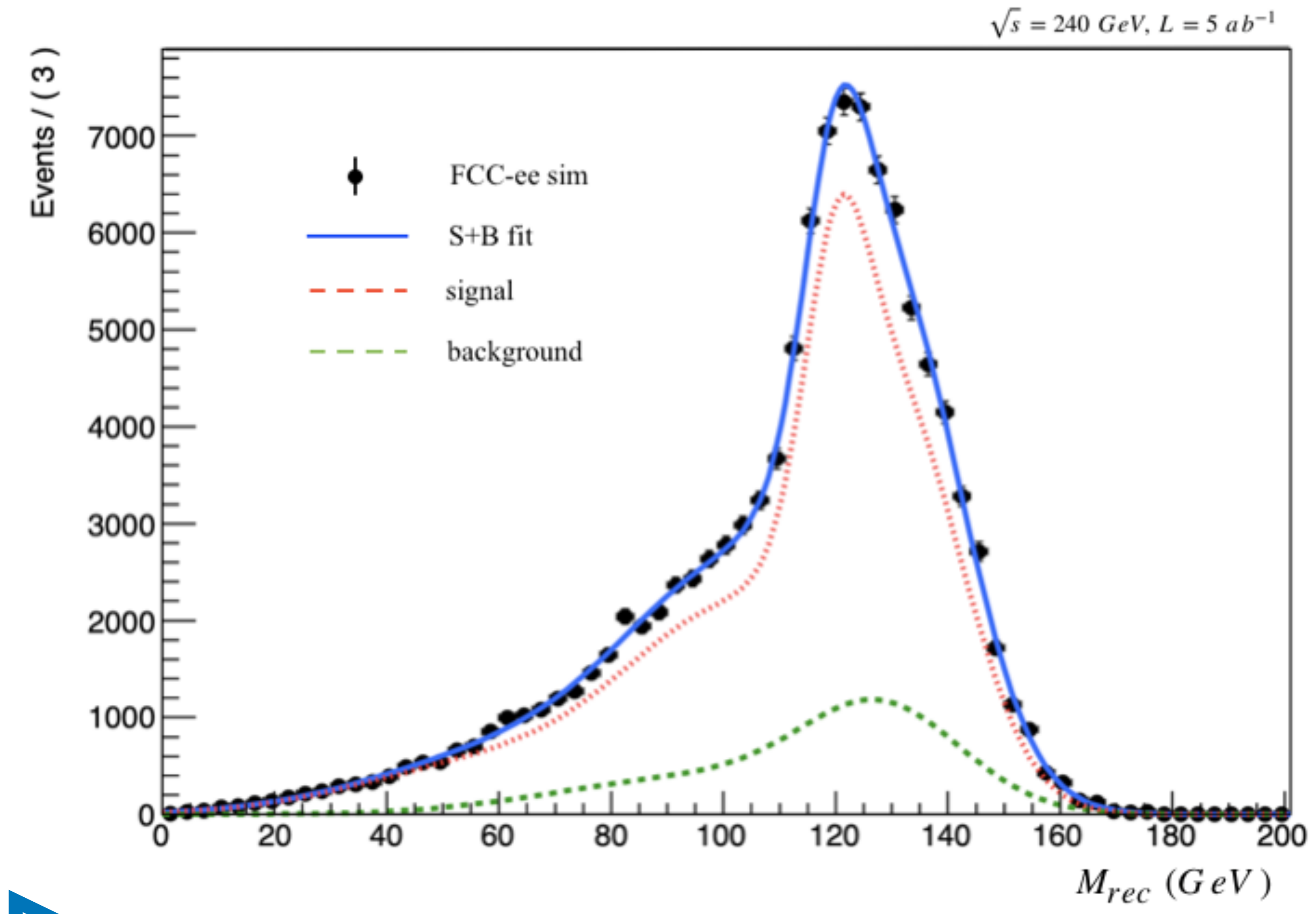
- e^+e^- with $p_{Te1} > 10$ GeV, $p_{Te2} > 5$ GeV
- Minimum $|M_{e^+e^-} - M_Z|$
- $60 < M_{e^+e^-} < 120$ GeV



Larger background

Z(bb)H

- ≥ 2 b-jets + $p_{Tjj} > 60$ GeV
- $M_{jj} > 45$ GeV
- $H_T > 10$ GeV
- BDT (17 variables)

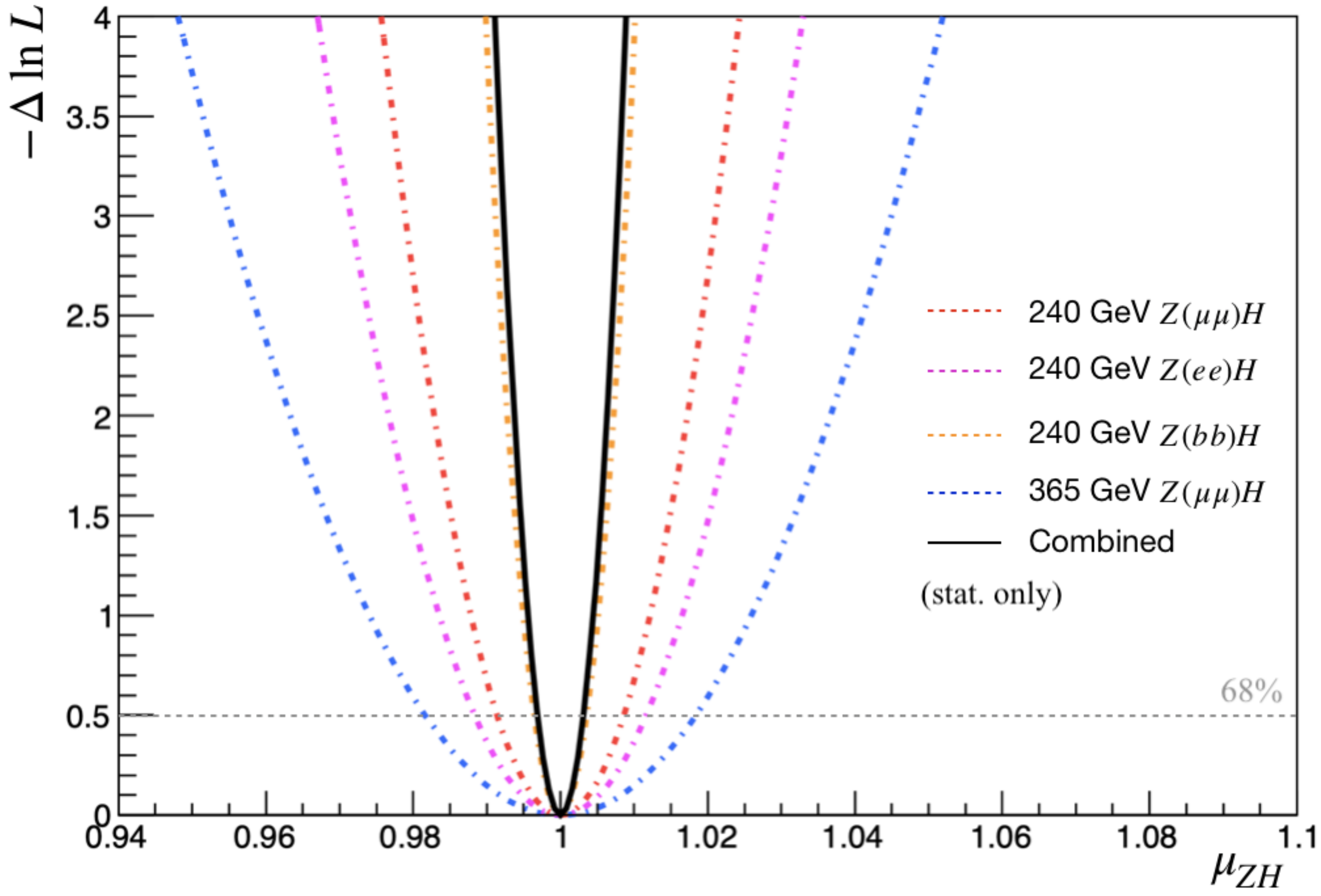


Broader resonant peak

Inclusive analyses @240 GeV

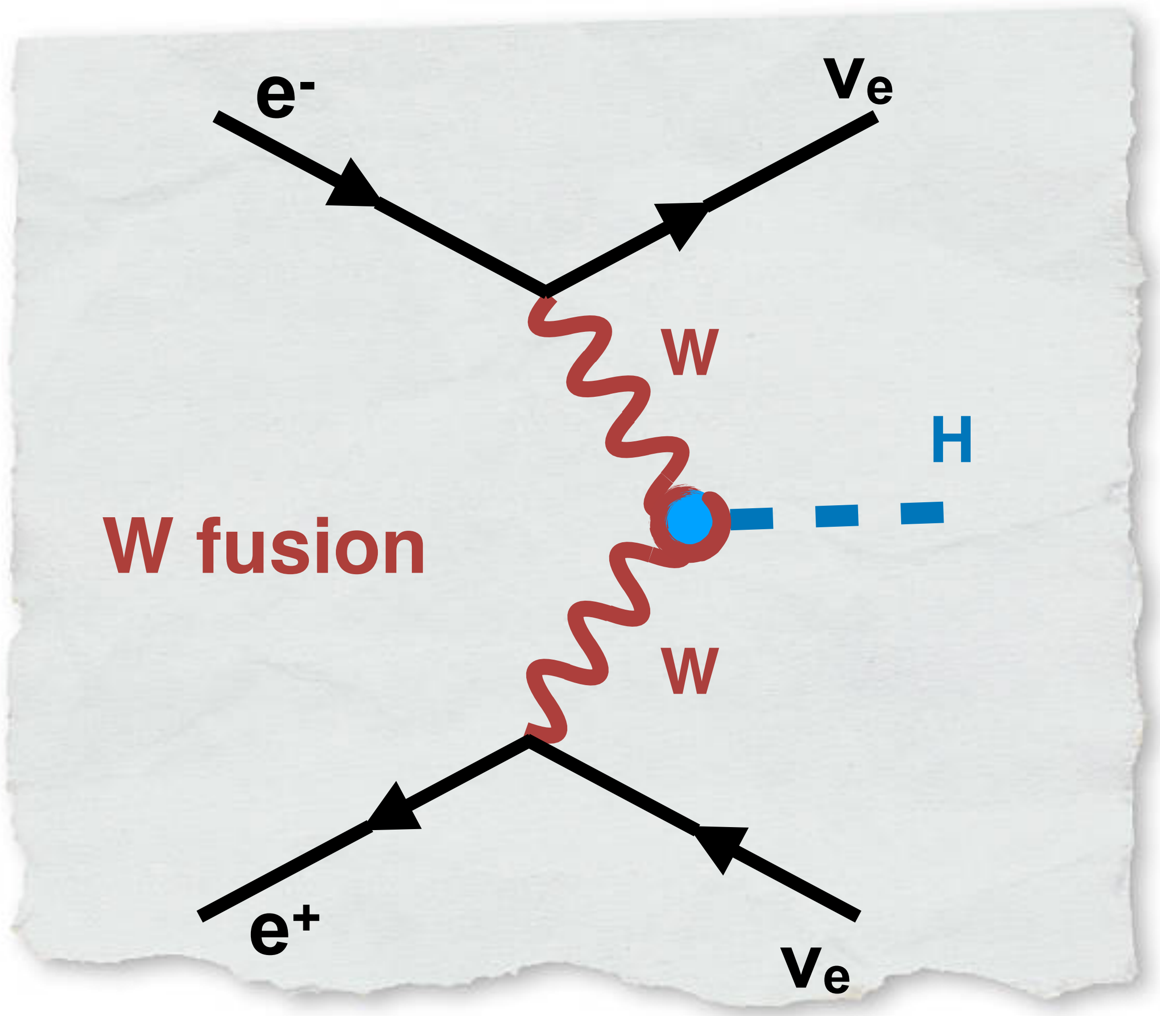
Exploited various Z decays, using the recoil techniques

Profile likelihood as a function of signal strength

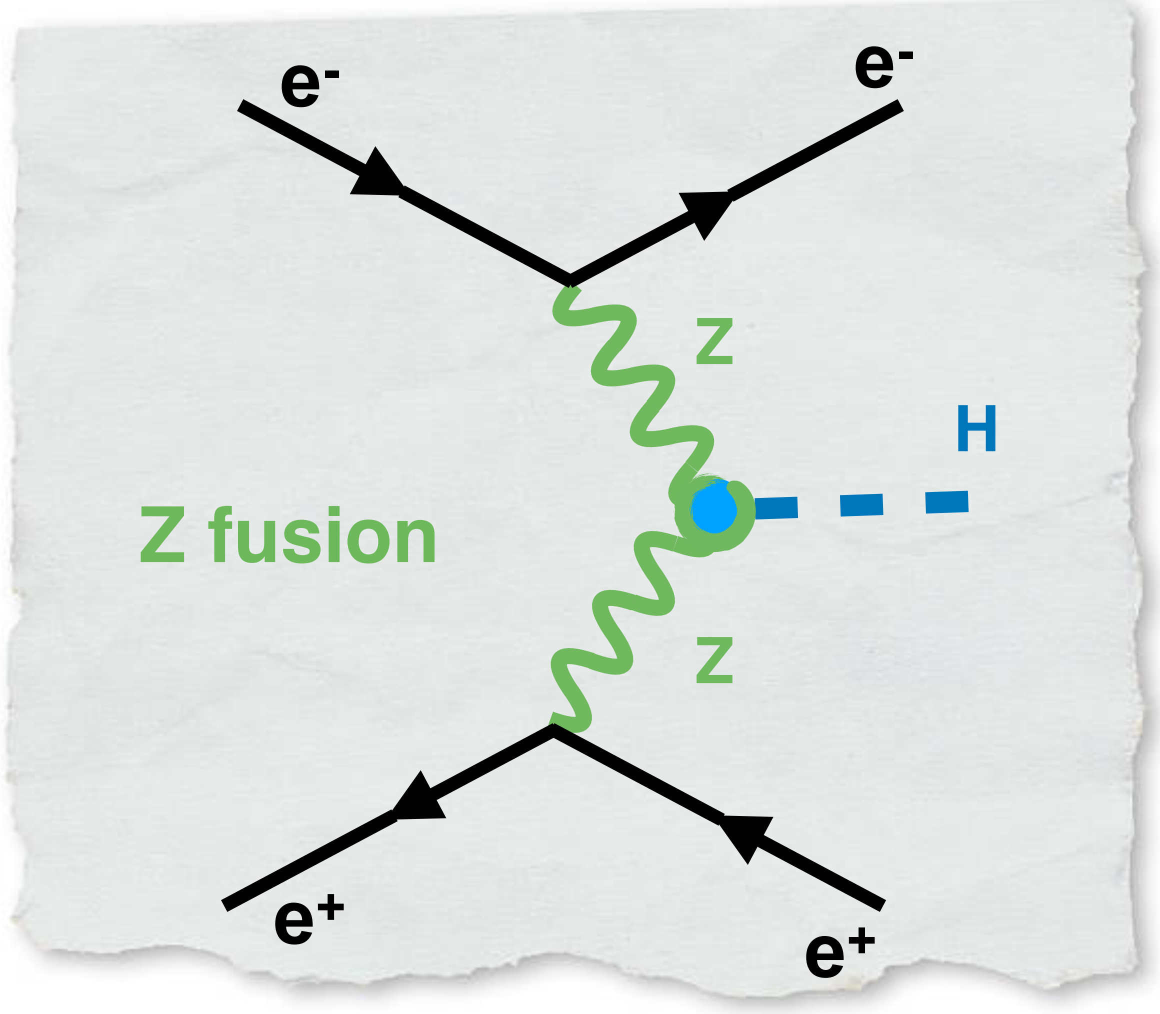


VBF production @365 GeV

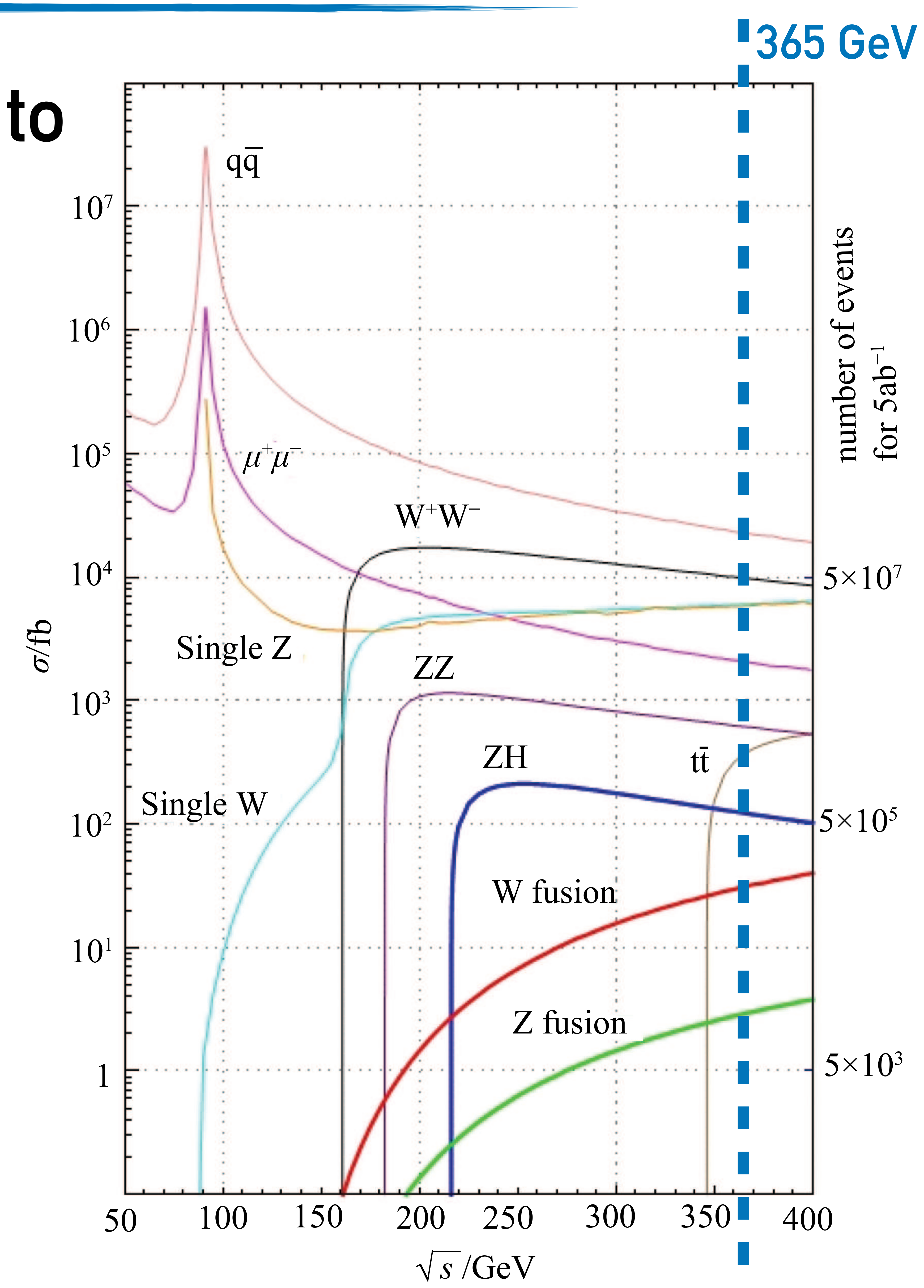
The production channel starts to become relevant due to the logarithmic rise ~$\ln^2(s/M_V^2)$ of the t-channel exchange of vector bosons



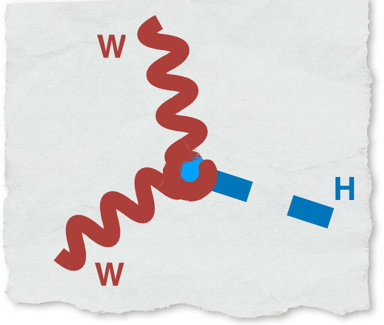
~50k H prod. @ 365 GeV (1.5 ab⁻¹)



~4k H prod. @ 365 GeV (1.5 ab⁻¹)



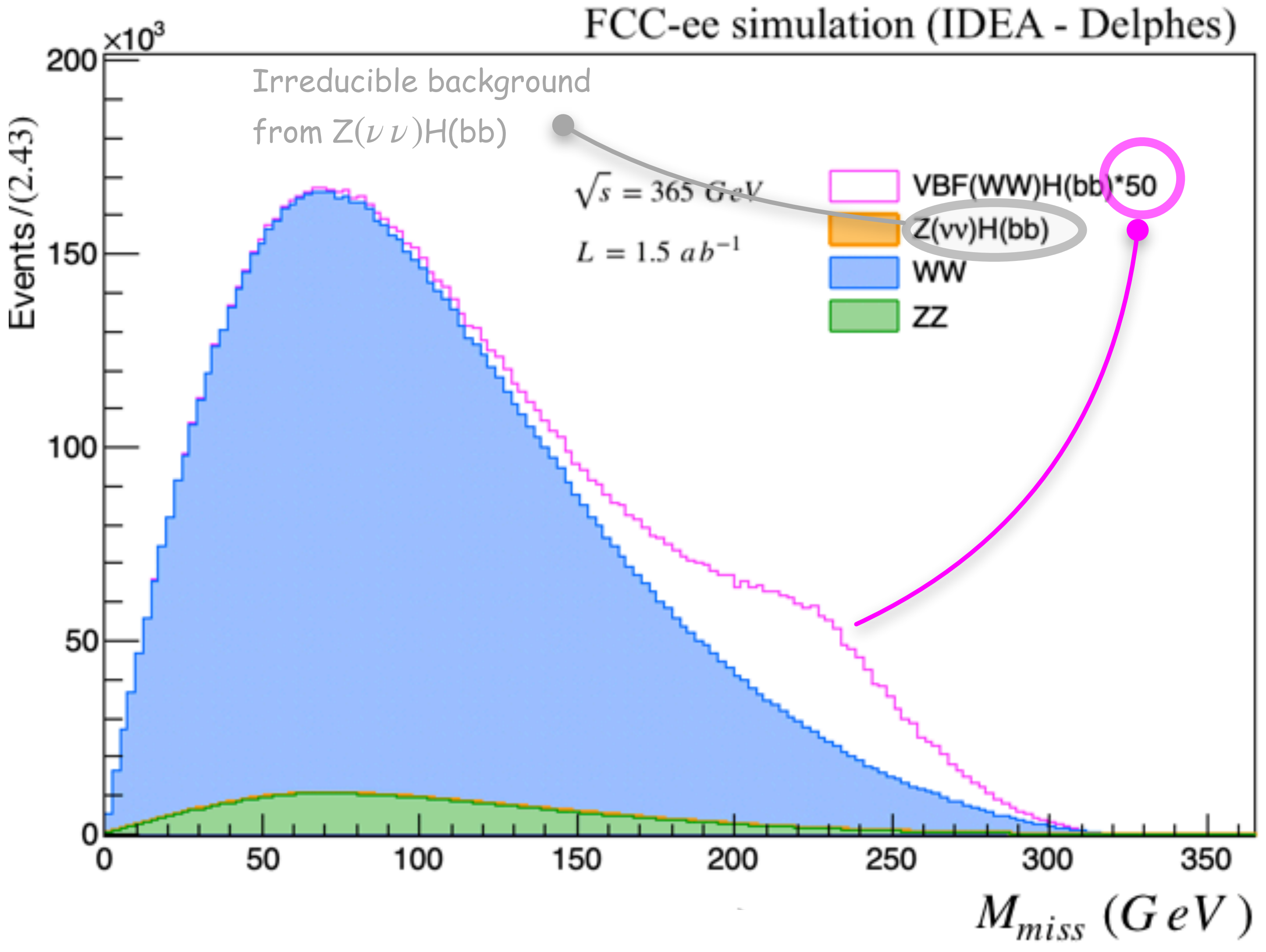
Production dominated by the W fusion because of larger charged currents



WW-boson fusion : ee→ννH(bb)

1. Preselection cuts

➔ 2 b-jets, $|\eta_{jj}|<3$
➔ H_T > 10 GeV
➔ MET > 10 GeV

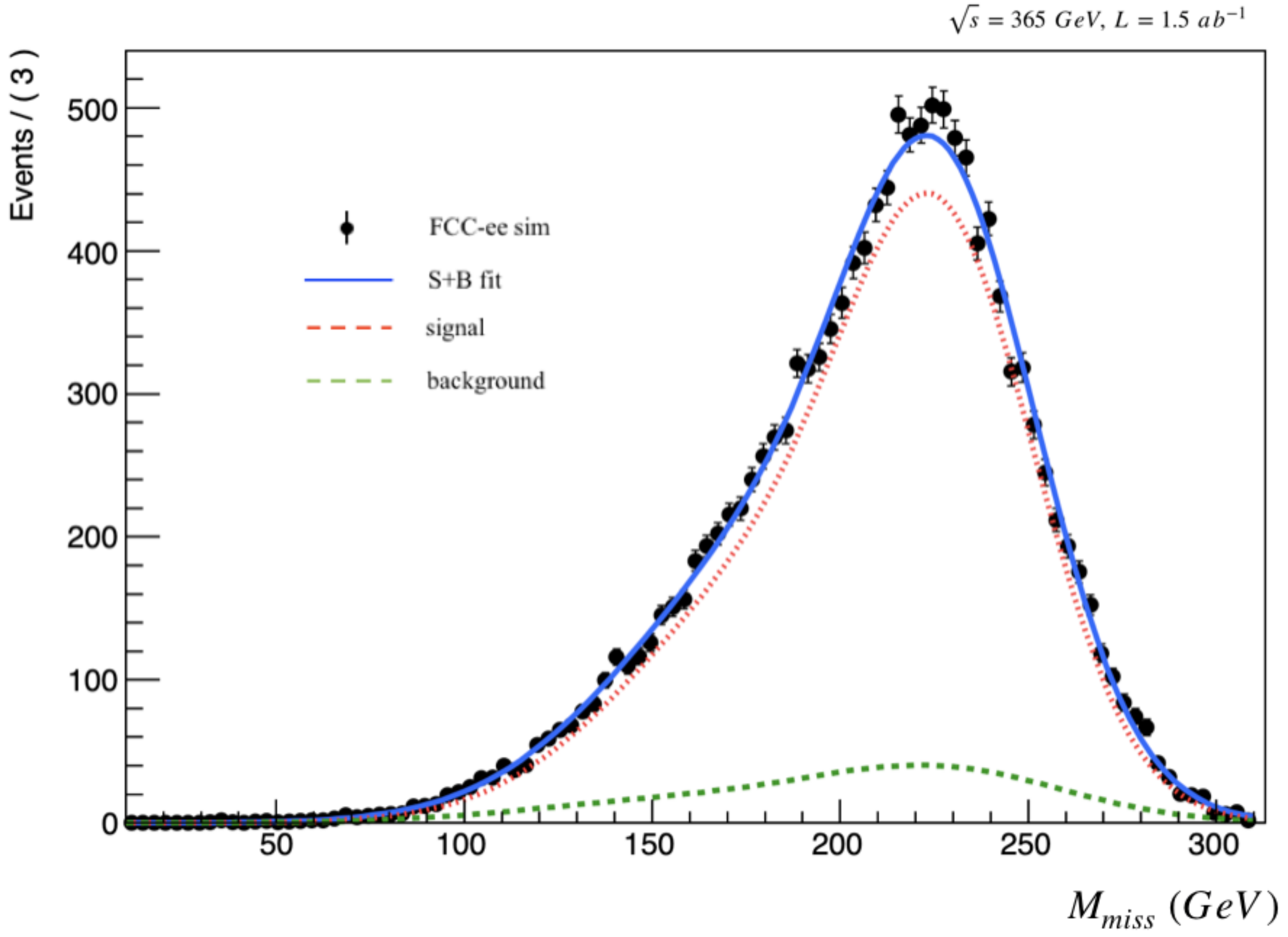


2. Adaptive BDT to reduce the backgrounds

➔ 17 input variables
➔ trained with a 20k sig. and 100k back. events
➔ 800 trees, min. node size of 1%, a max. depth of 3

MC samples	$\nu_e\bar{\nu}_e$H($b\bar{b}$)	Z($\nu\bar{\nu}$)H($b\bar{b}$)	WW	ZZ
Number of events (normalized)	$3.05 \cdot 10^4$	$2.06 \cdot 10^4$	$1.61 \cdot 10^7$	$9.49 \cdot 10^5$
$n_{bj} \geq 2$, $\lvert\Delta\eta\rvert < 3$, HT > 20, MET > 10 GeV	47%	48%	0.09%	5.5%
BDTAda response ≥ 0.12	42 %	3.4 %	0.002 %	0.06 %

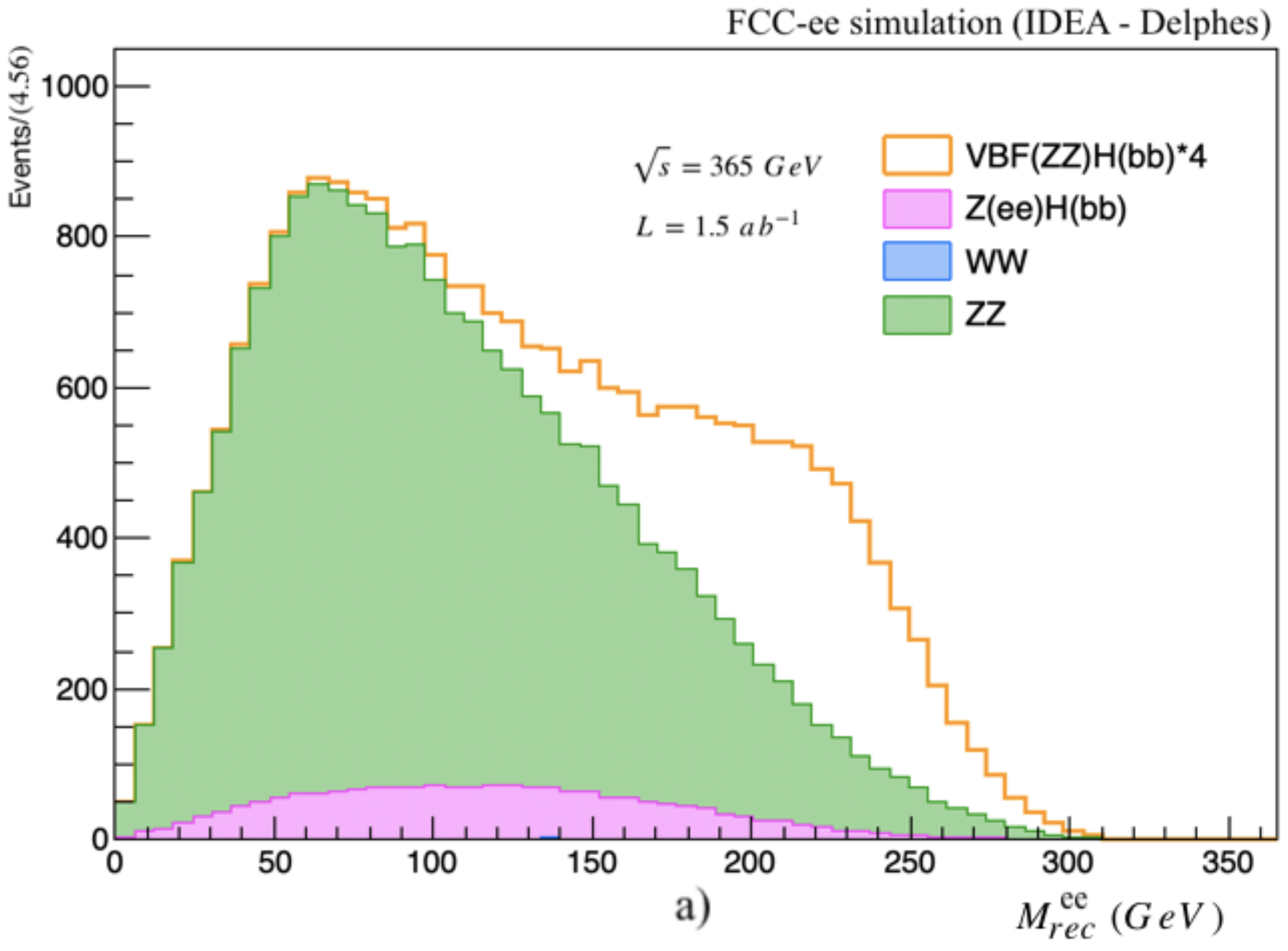
Fit to the recoil mass spectrum after the BDT



Signal (convolution of 2 Gaussians)
Irreducible background mainly from Z(νν)H(bb)

ZZ-boson fusion : ee→eeH(bb)

1. Preselection cuts
   - → 2 jets + 2 electrons
   - → m_{ee} > 80 GeV
   - → MET > 10 GeV

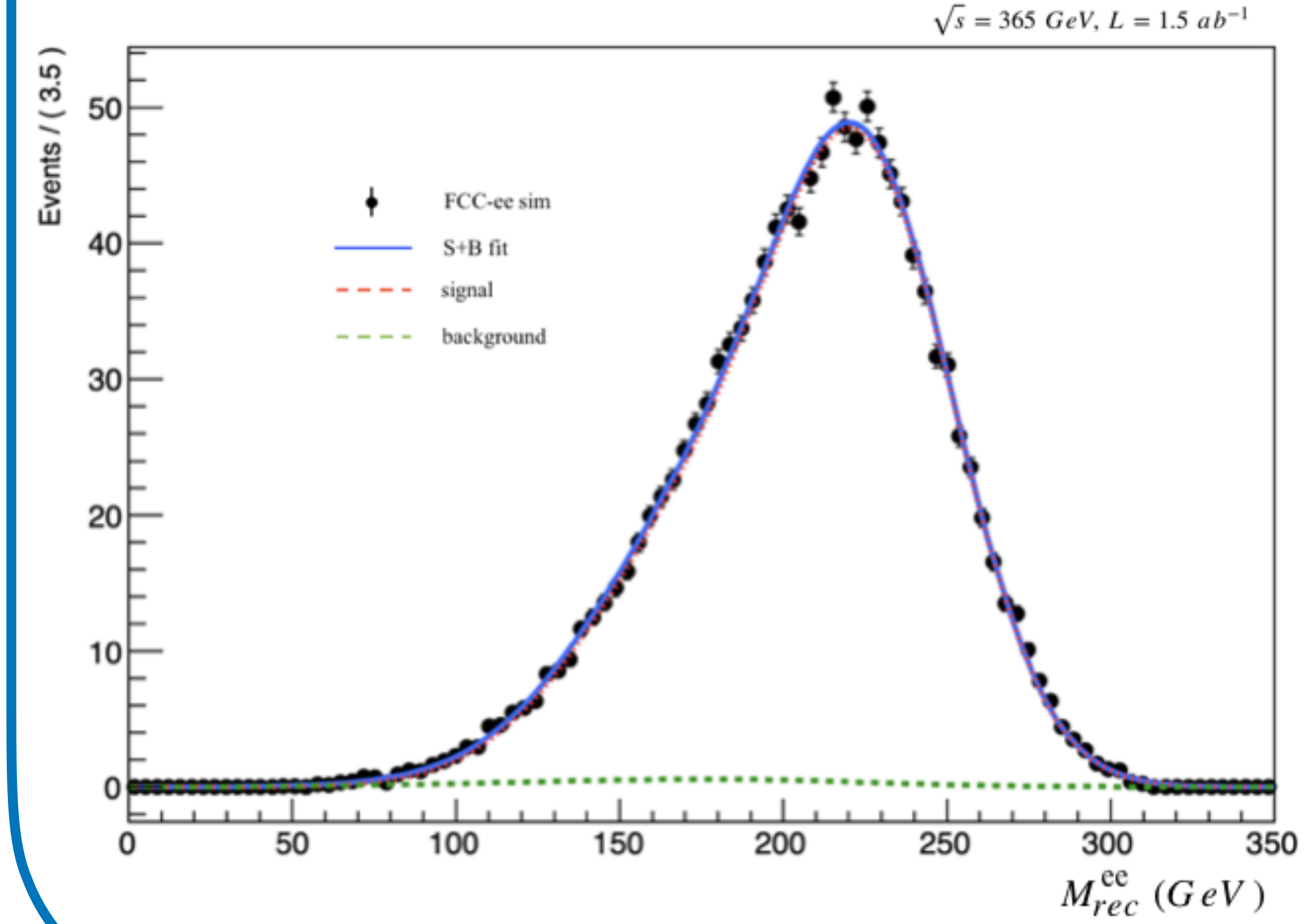


2. BDT to further reduce the backgrounds

Rank	Variable	Separation
1	$M_{e^+e^-}$	$9.1 \cdot 10^{-1}$
2	$acol_{e^+e^-}$	$7.1 \cdot 10^{-1}$
3	$acol_{jj}$	$7 \cdot 10^{-1}$
4	n_{bj}	$4.6 \cdot 10^{-1}$

Rank	Variable	Separation
5	M_{jj}	$3.8 \cdot 10^{-1}$
6	η_{e2}	$2.4 \cdot 10^{-1}$
7	E_{j1}	$2.1 \cdot 10^{-1}$
8	η_{j1}	$1.4 \cdot 10^{-1}$

Fit to the recoil mass spectrum after the BDT



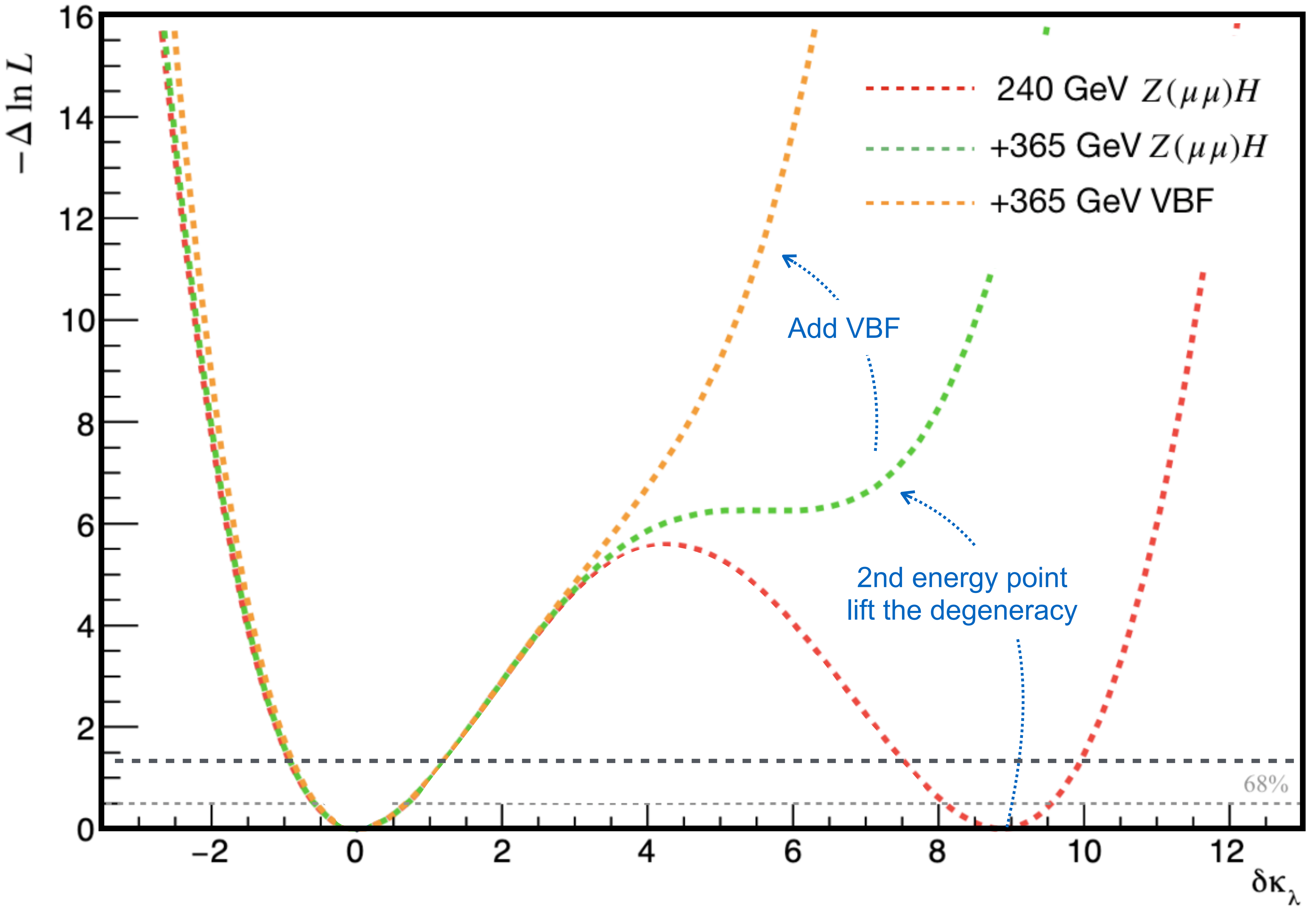
Higgs Self-Coupling

1D fit with only $\delta\kappa_\lambda$ floating

$$\kappa_\lambda = \frac{\lambda_3^{SM} + \delta\lambda_3}{\lambda_3^{SM}}$$

$$\Rightarrow \delta\kappa_\lambda = \kappa_\lambda - 1$$

Profile likelihood as function of $\delta\kappa_\lambda$



The secondary minimum easily excluded adding a 2nd energy point

Next Steps

The analysis chain has been put in place to measure the Higgs self-coupling from higher-order corrections (NLO) to single Higgs processes

The analyses are being redone (additional channels, improved selection, adding systematics, etc.) using the centrally produced samples within the FCCAnalyses framework.

Shown preliminary (optimistic) results but there are many caveats:

- We have only recently started to use the centrally produced samples
- Not all the systematic uncertainties are included
- Only main backgrounds are considered so less selection cuts included leading to higher signal efficiency

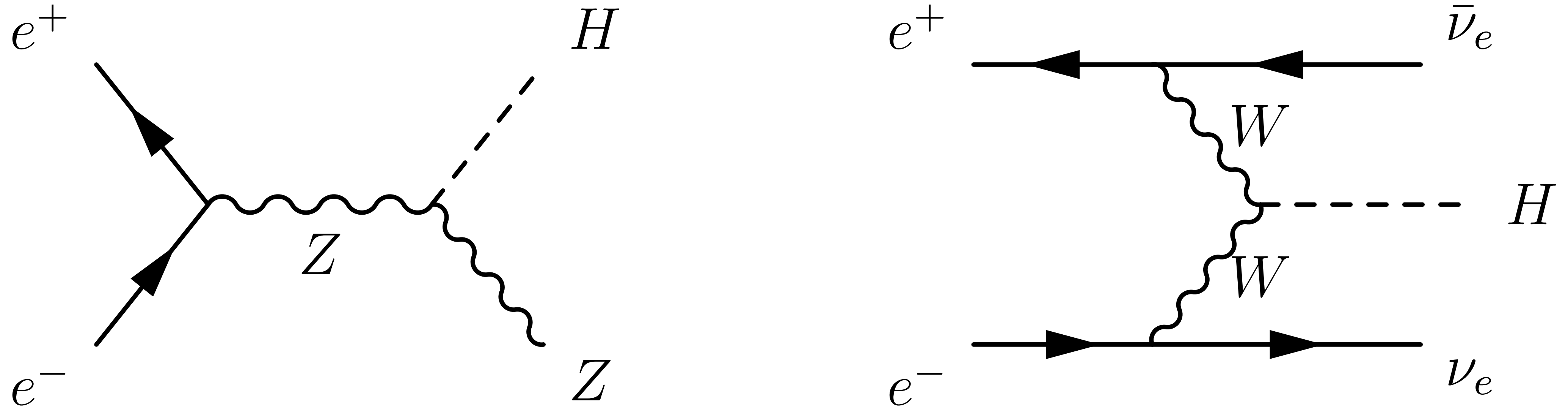
We plan to address these issues systematically and are currently working on:

- Hadronic Z decays in inclusive and exclusive reactions, e.g. efficient flavour tagging (bb, cc, etc.)
- Optimal jet angular and energy resolutions
- Angular distributions to better separate HZ and VBF channels

Backup

WW-boson fusion : $ee \rightarrow \nu\nu H(bb)$

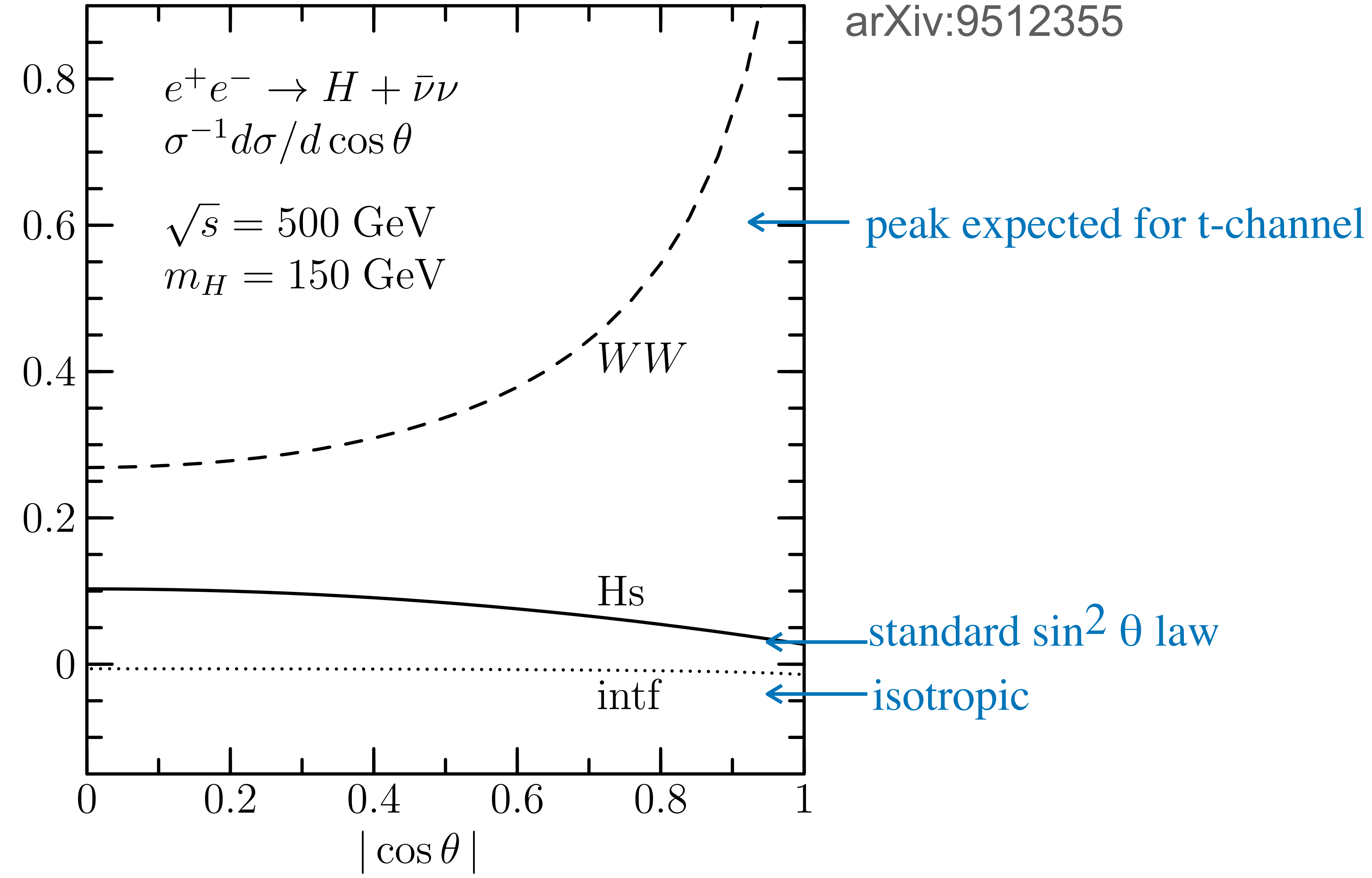
Two production mechanisms contribute



For $\nu_e \nu_{\bar{e}}$ decays of the Z boson, the two production amplitudes interfere.
Positive interference term of the same size as their individual cross sections

Need to exploit angular distributions to separate the processes

arXiv:9512355



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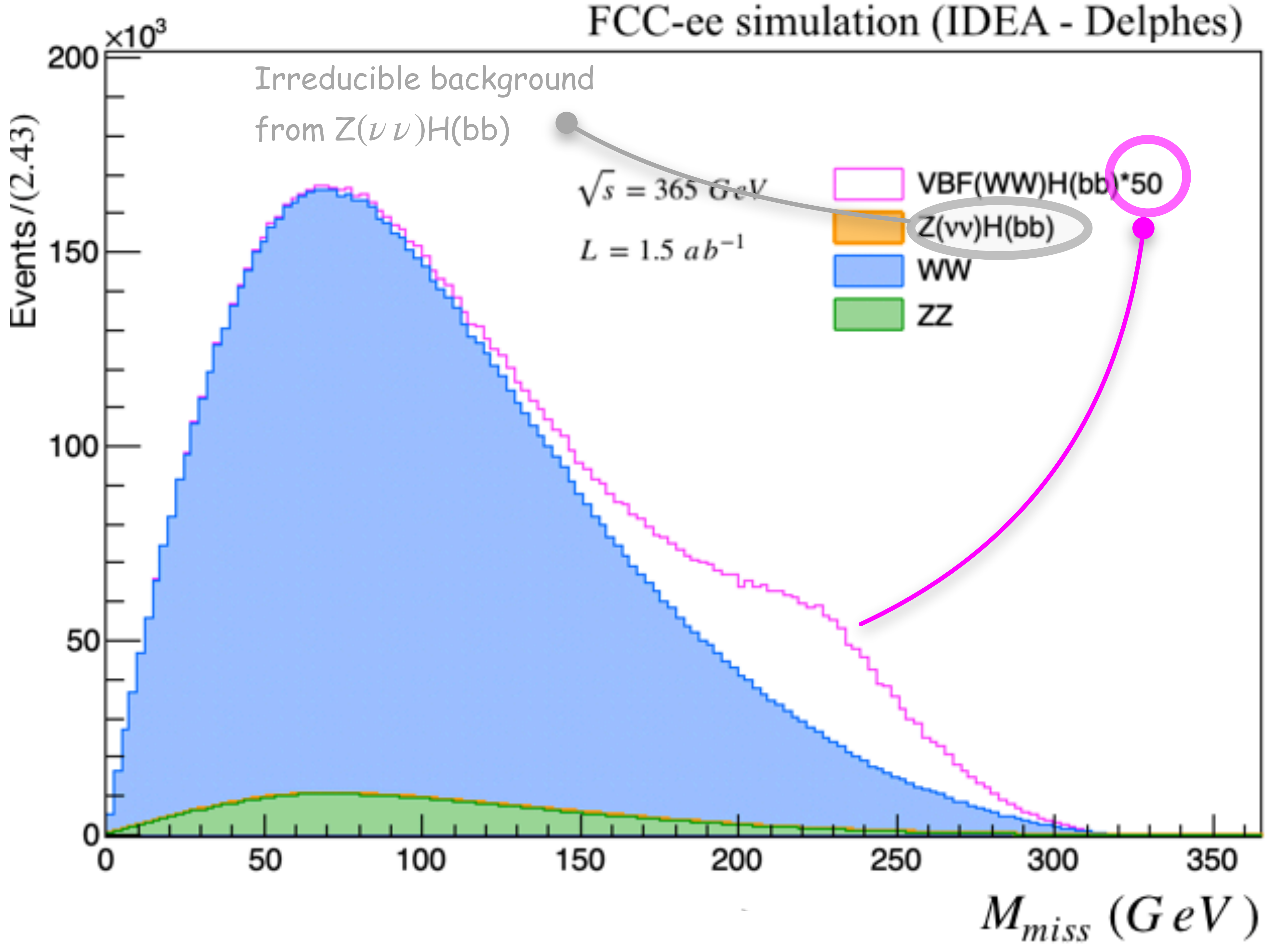
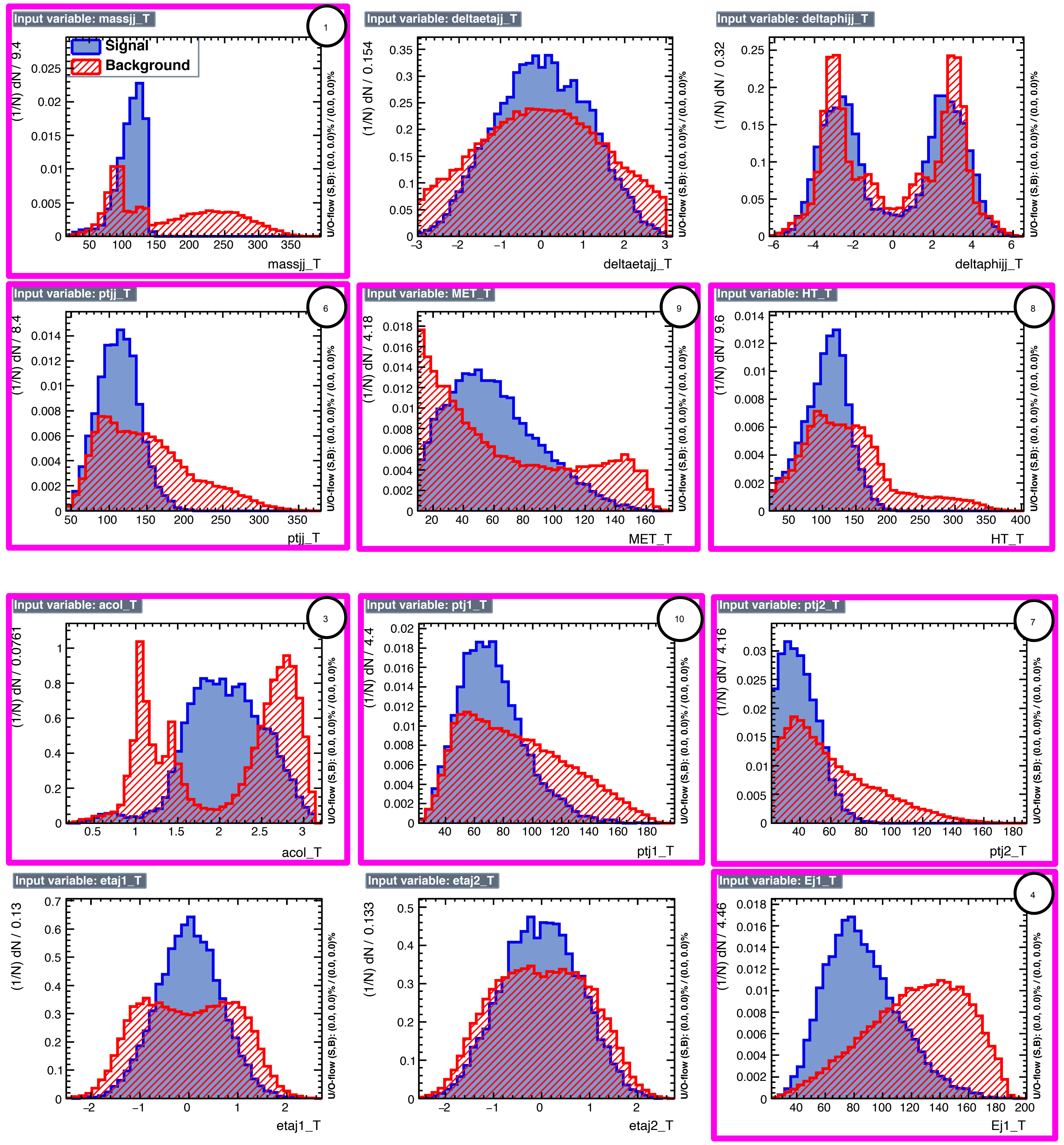
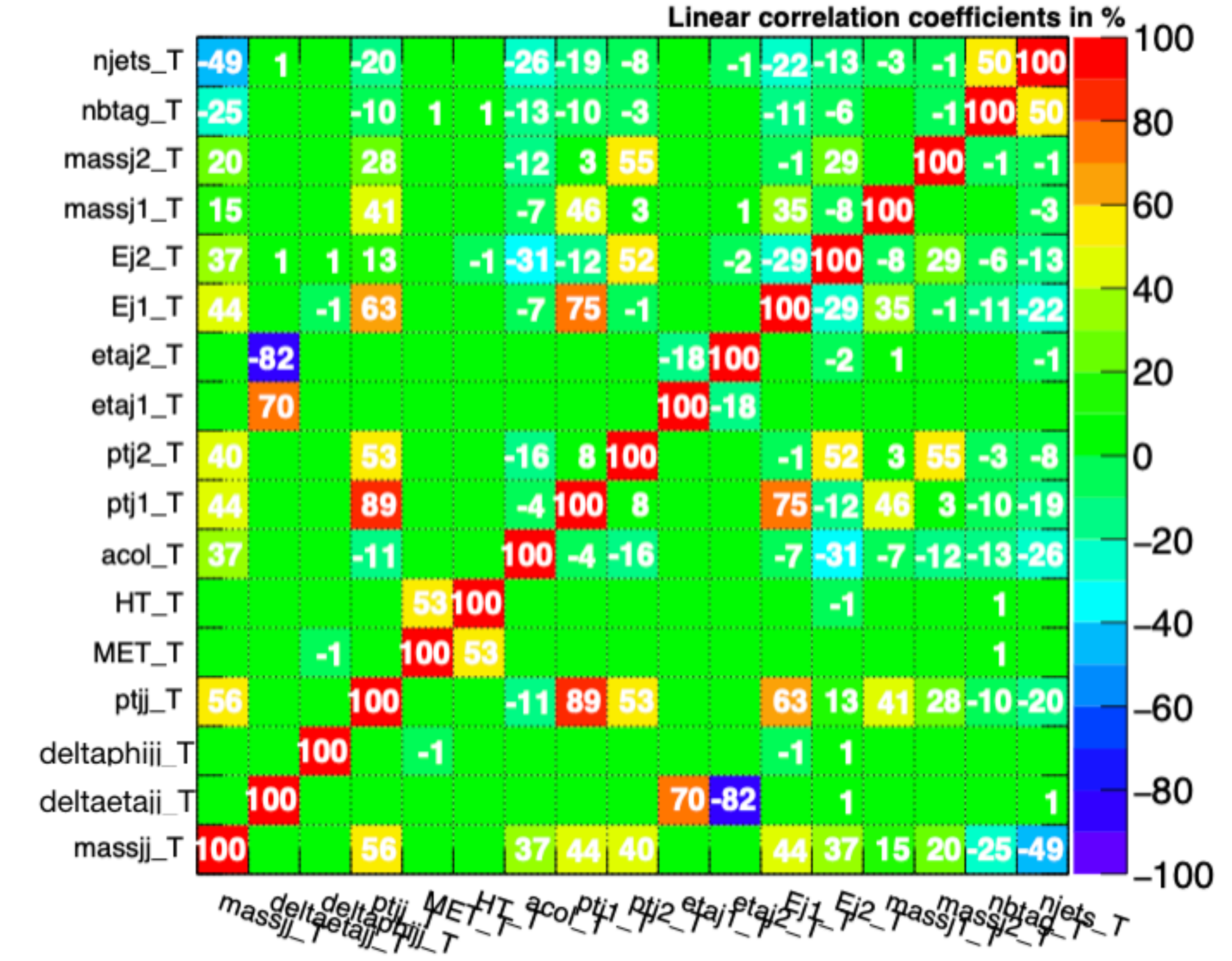


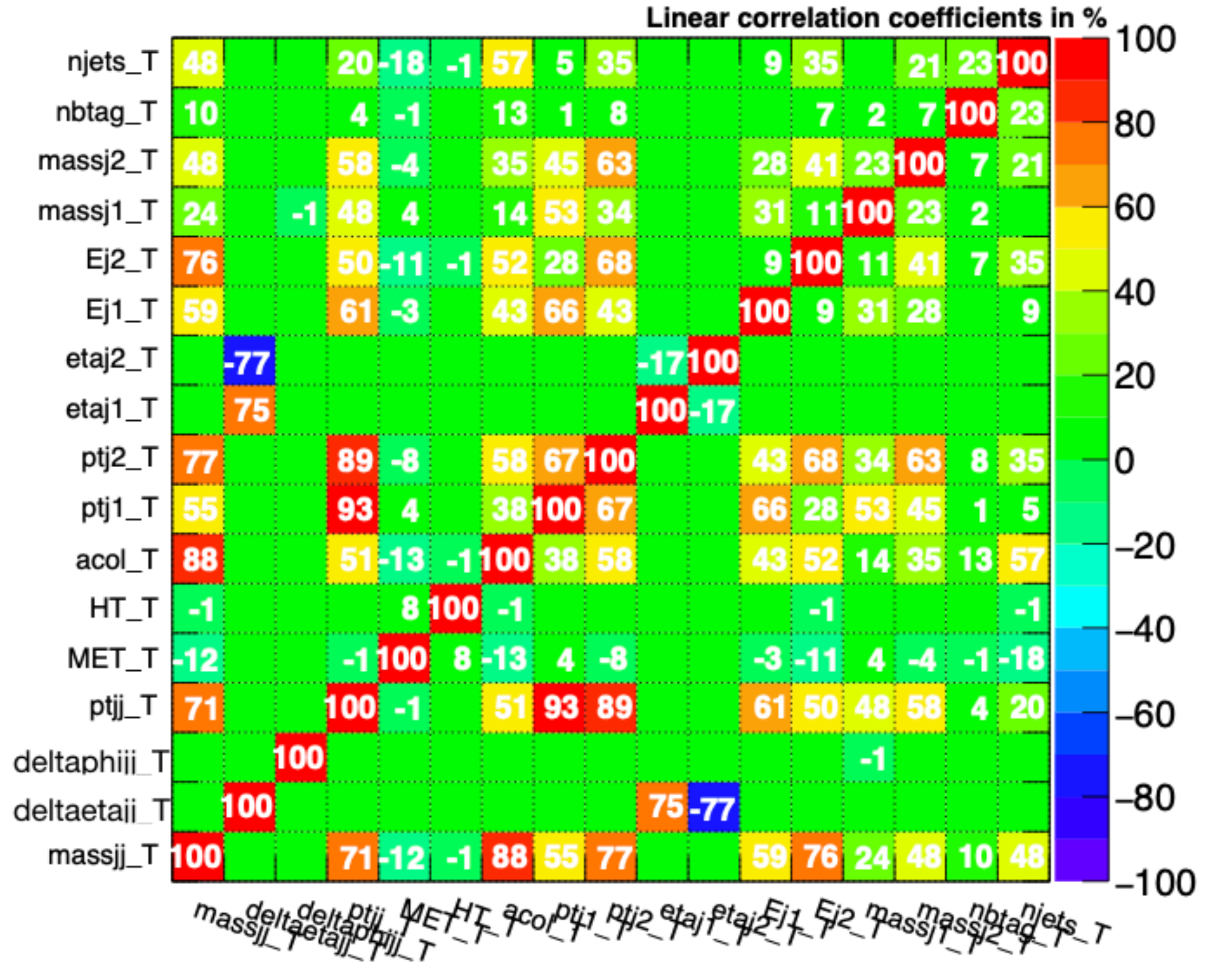
BDT variables and correlations



Correlation Matrix (signal)



Correlation Matrix (background)



Rank	Variable	Separation
1	M_{jj}	$4.6 \cdot 10^{-1}$
2	n_j	$3.7 \cdot 10^{-1}$
3	$acol_{jj}$	$3.5 \cdot 10^{-1}$
4	E_{j1}	$3 \cdot 10^{-1}$
5	E_{j2}	$2.7 \cdot 10^{-1}$

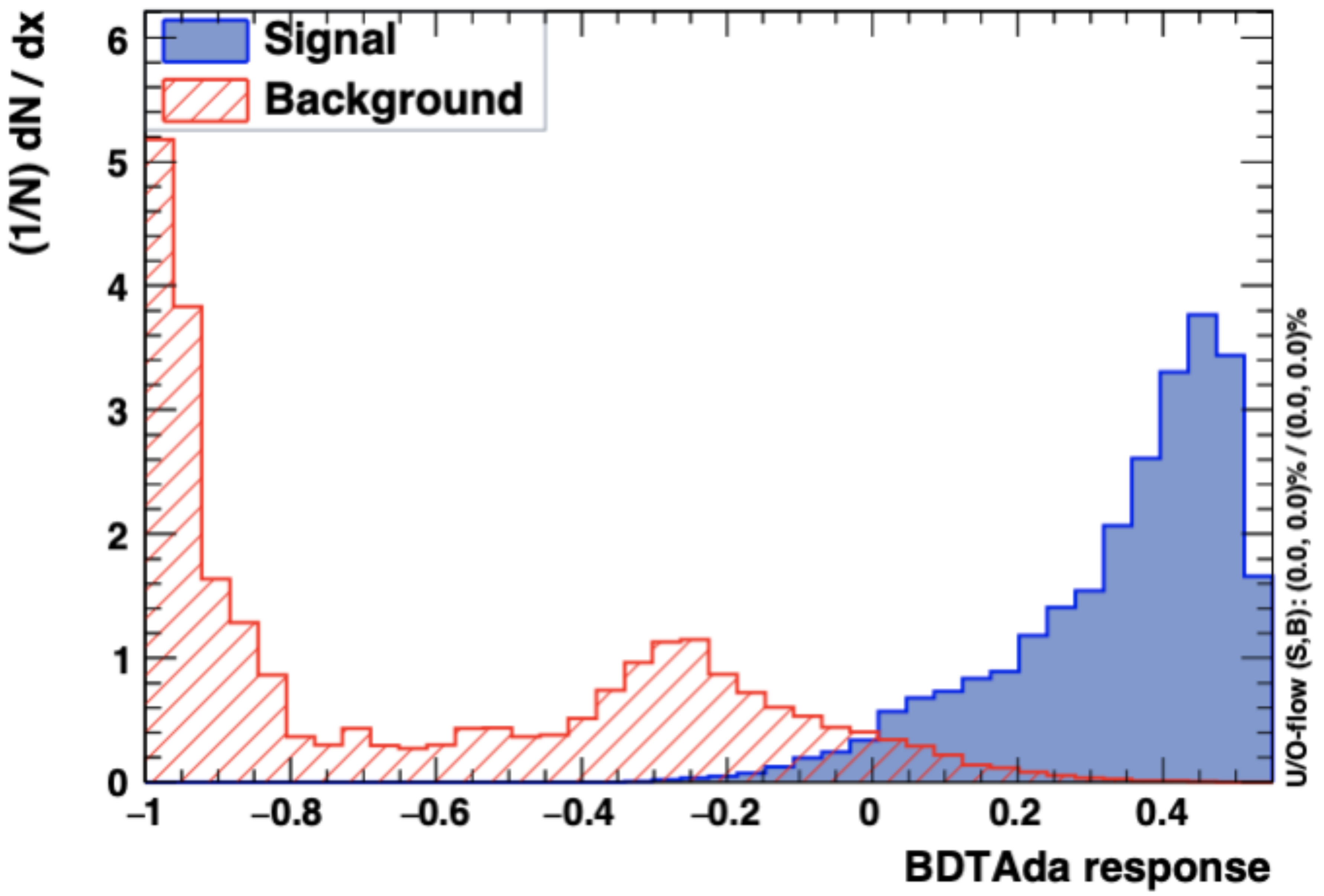
Rank	Variable	Separation
6	p_{Tjj}	$2 \cdot 10^{-1}$
7	p_{Tj2}	$1.9 \cdot 10^{-1}$
8	H_T	$1.6 \cdot 10^{-1}$
9	MET	$1.3 \cdot 10^{-1}$
10	p_{Tj1}	$1.1 \cdot 10^{-1}$

Separation integral: $$\langle S^2 \rangle = \frac{1}{2} \int dy \frac{(\hat{y}_S(y) - \hat{y}_B(y))^2}{(\hat{y}_S(y) + \hat{y}_B(y))}$$

Final discrimination variable

The missing mass after preselection and BDT cuts

BDT response



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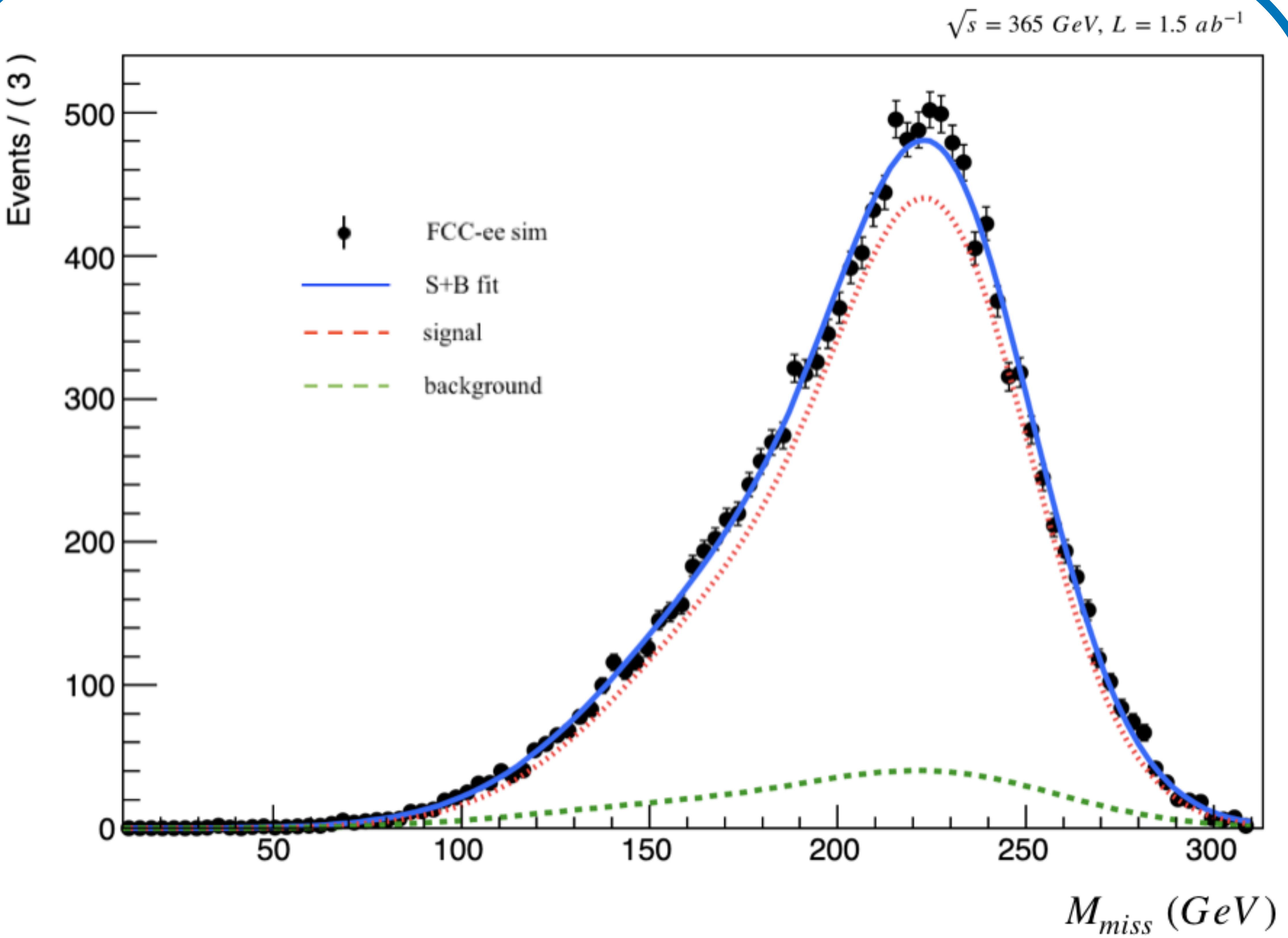

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Irreducible background mainly from Z(νν)H(bb)