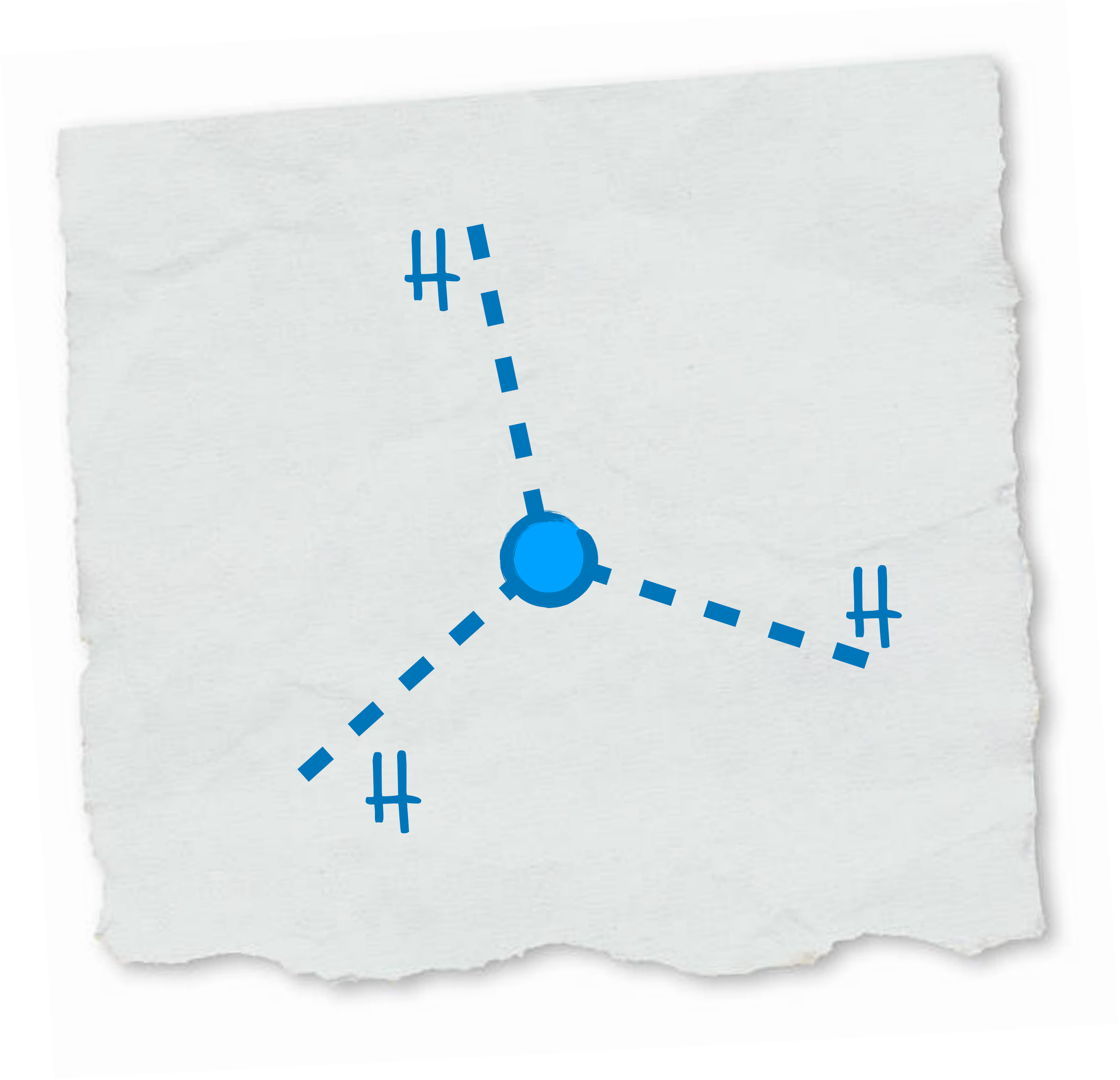
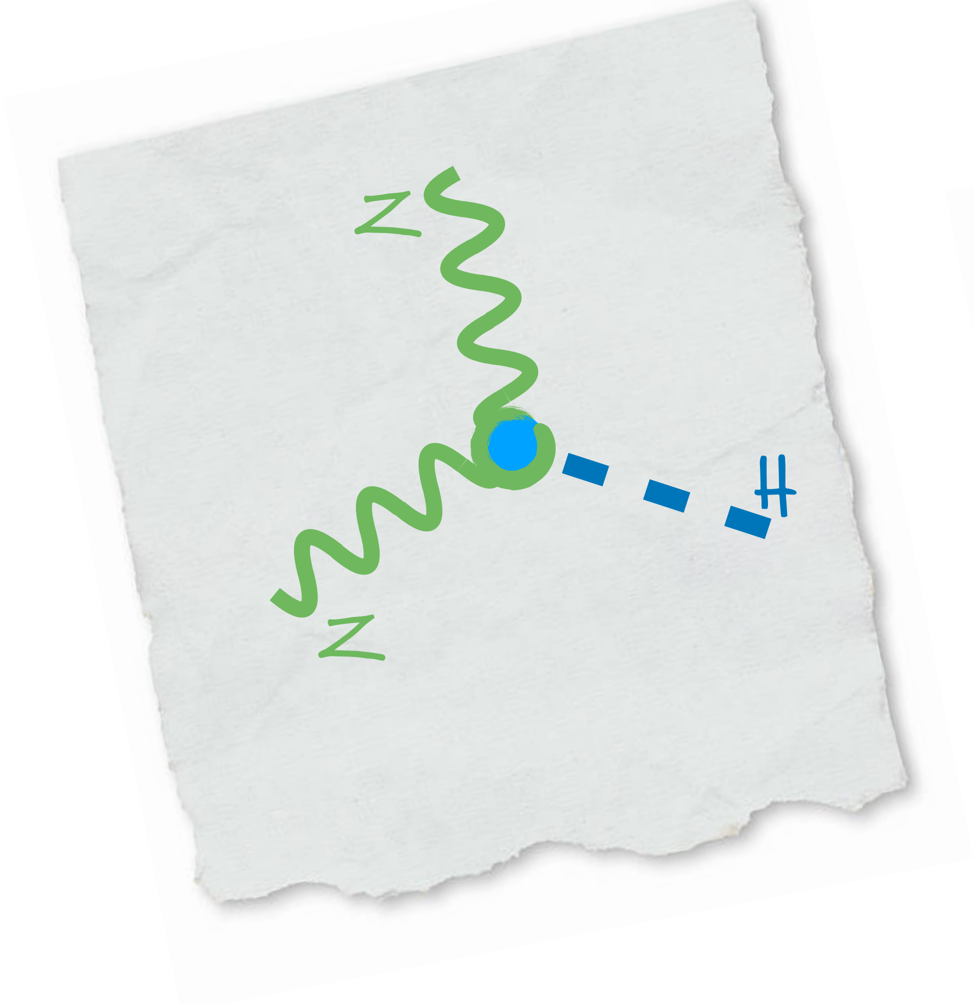
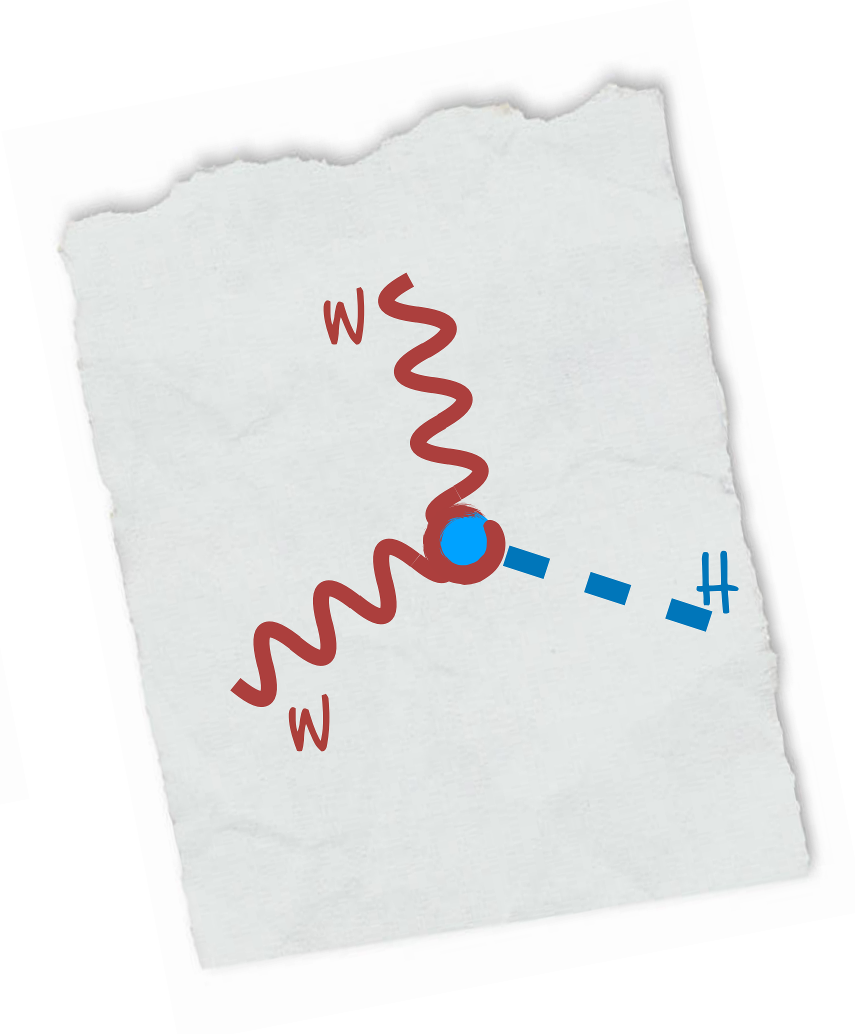
Higgs boson self-interactions



… and Higgs-gauge-boson interactions





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Foreword

These studies have been done in a contest of a 4 months M2 internship.
The goal was to put in place a full analysis chain from the generation of the samples through the selection of candidates to the statistical analysis.

There are many caveats (results are on the optimistic side)

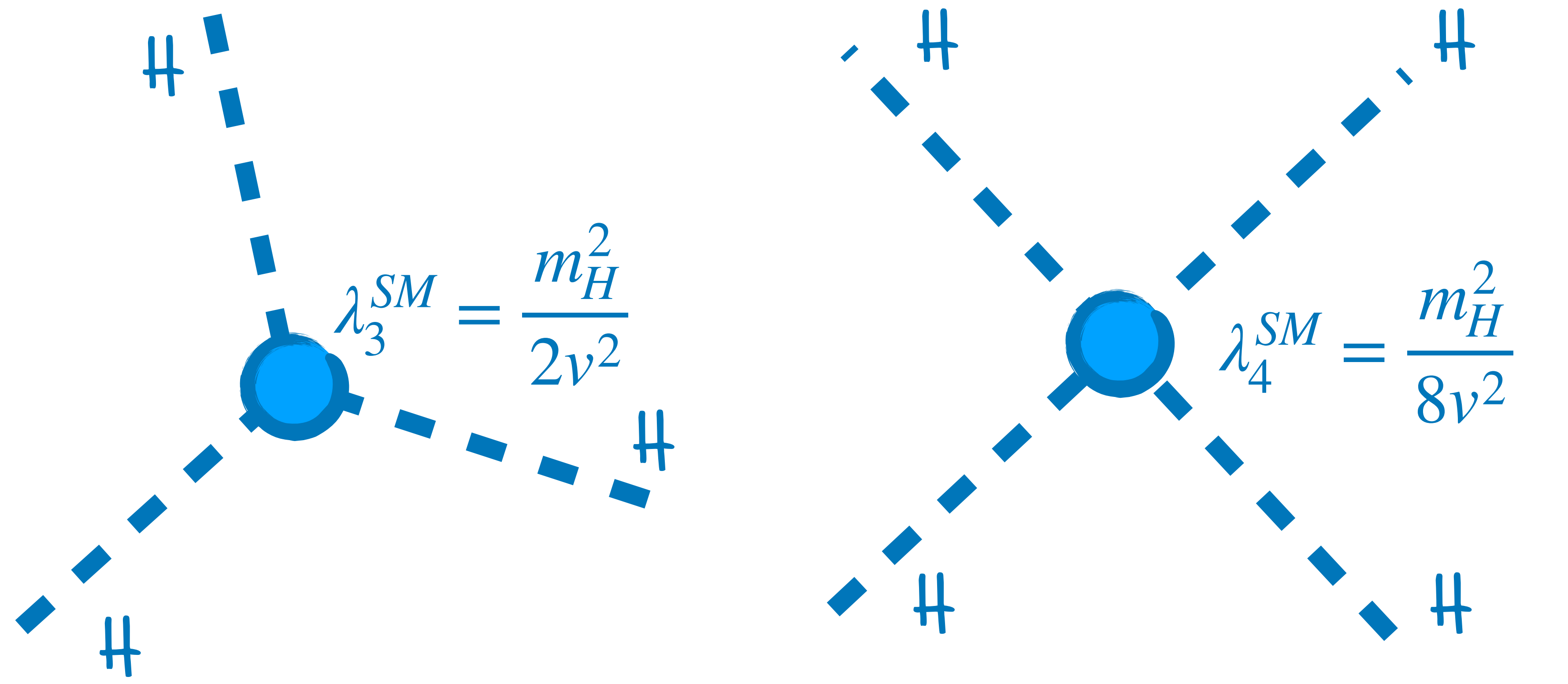
- ➔ The centrally produced samples are (yet) not used
- ➔ Not all the systematics uncertainties are included
- ➔ Only main backgrounds are considered so less selection cuts included leading to higher signal efficiency

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

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



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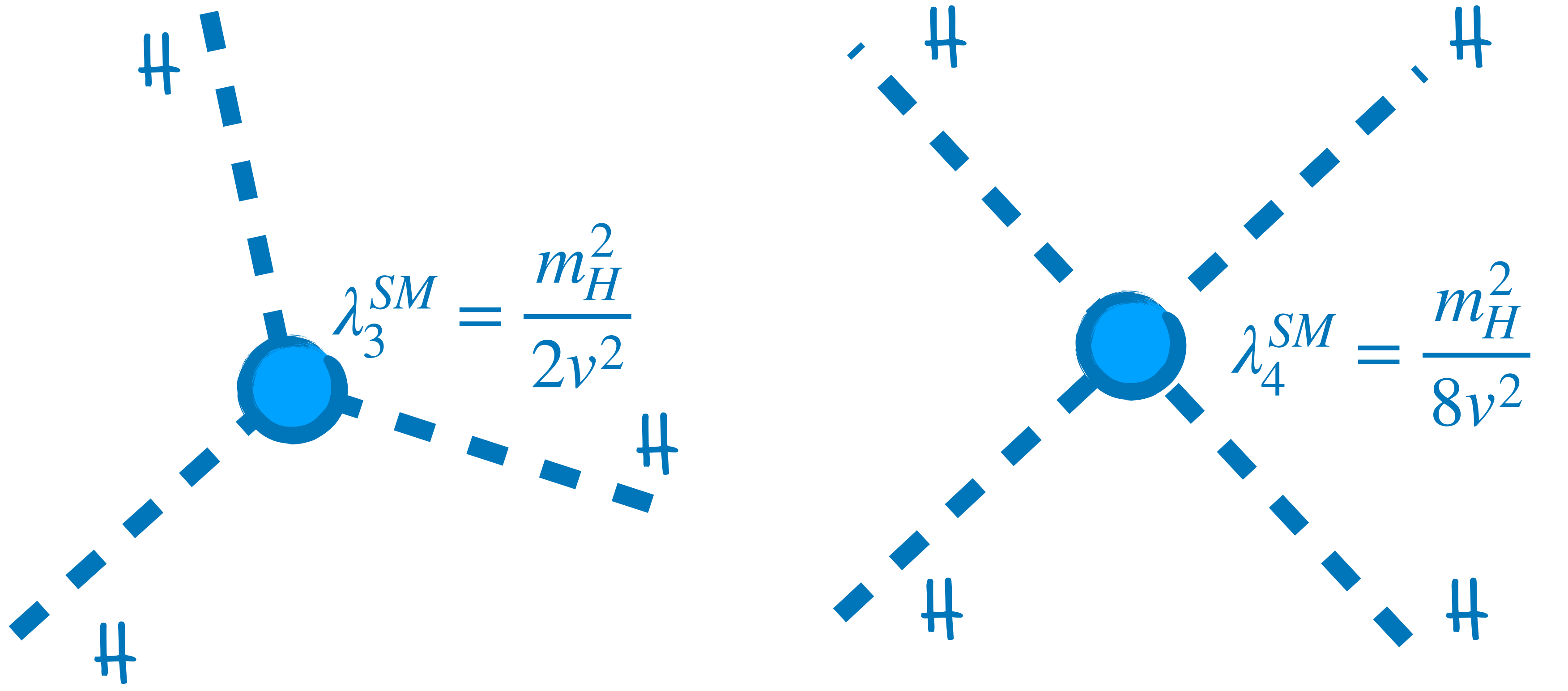
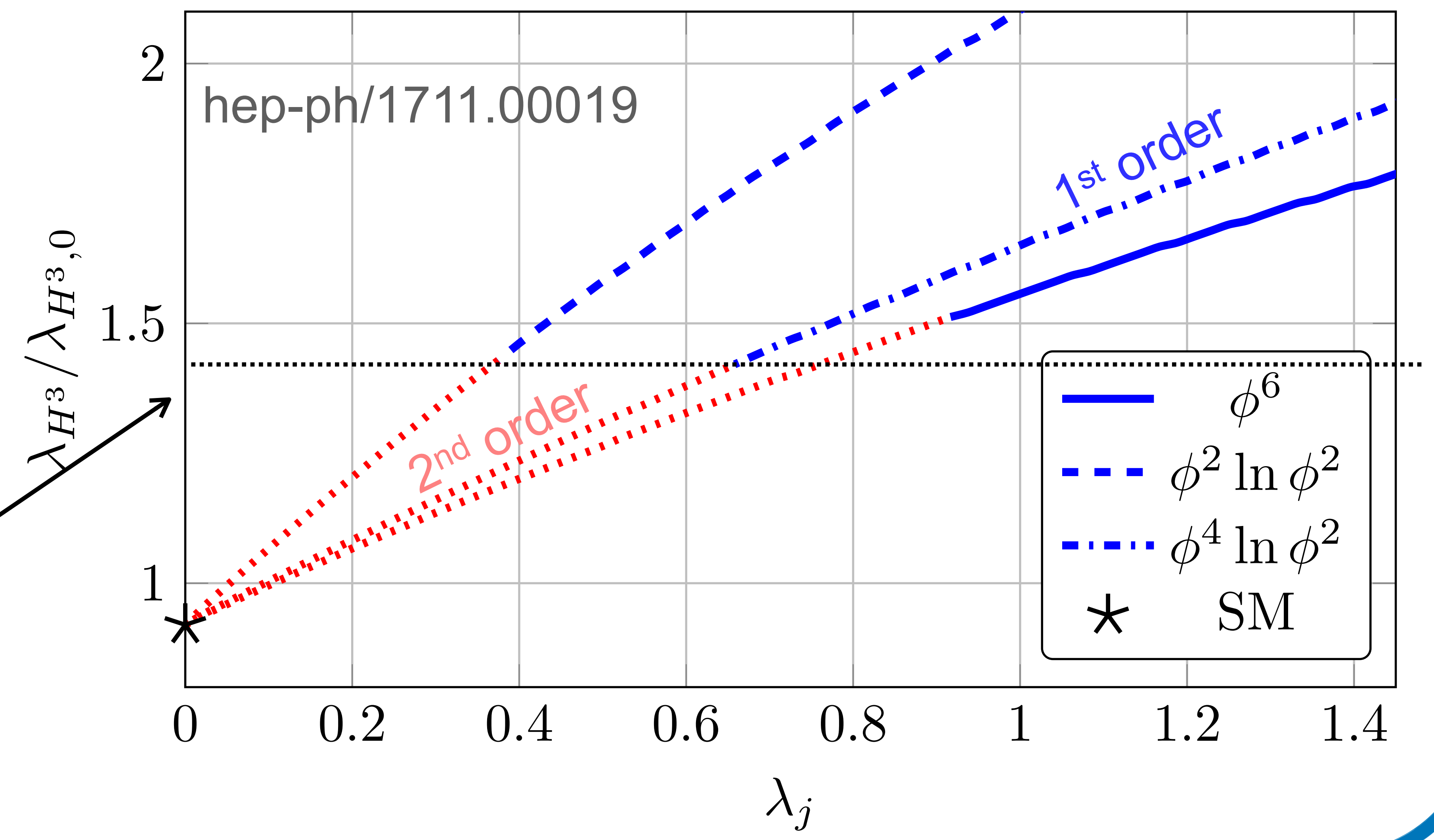


Link with the cosmology

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

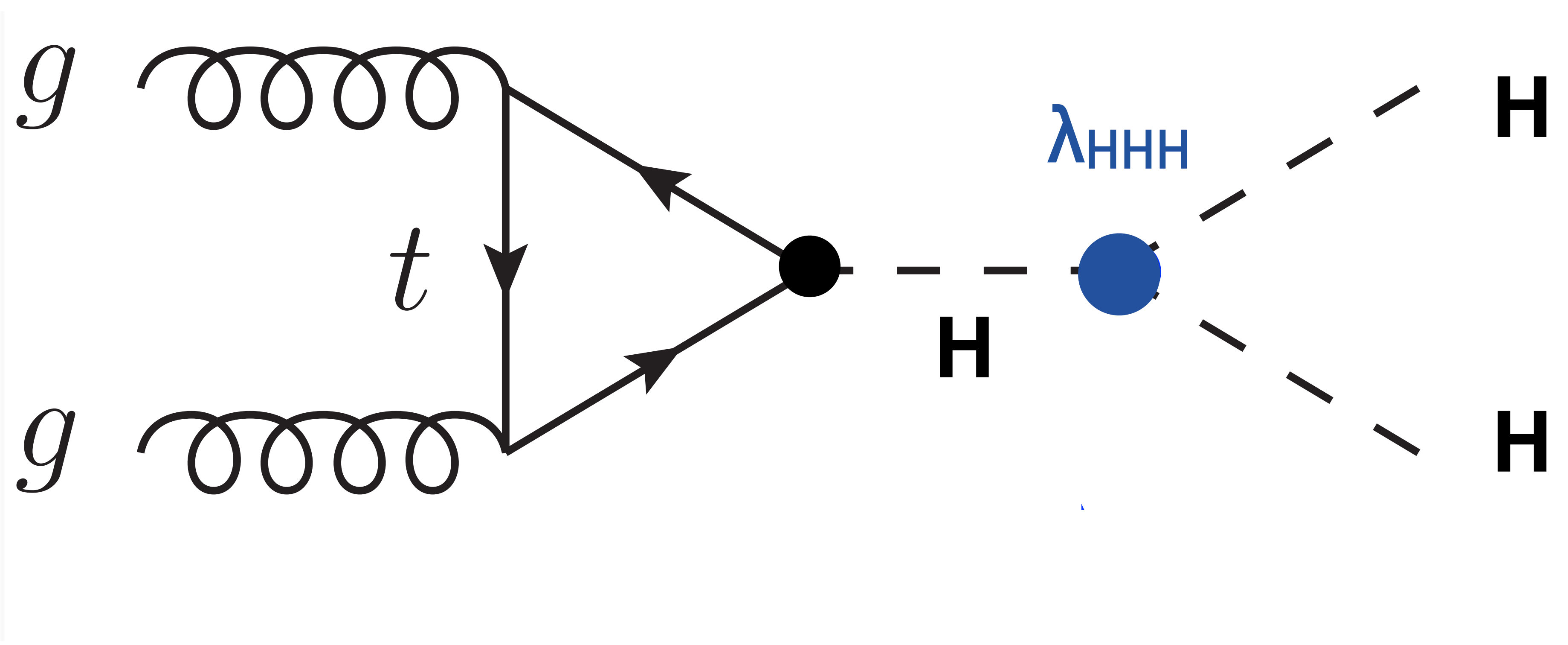
We need to probe size of modification down to 1.4, the expected uncertainty of the measurement should be $\mathcal{O}(10\%)$



The Higgs boson self-coupling before FCC-ee

Direct measurements @ HL-LHC

Profiting of on-shell production of two Higgs bosons



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

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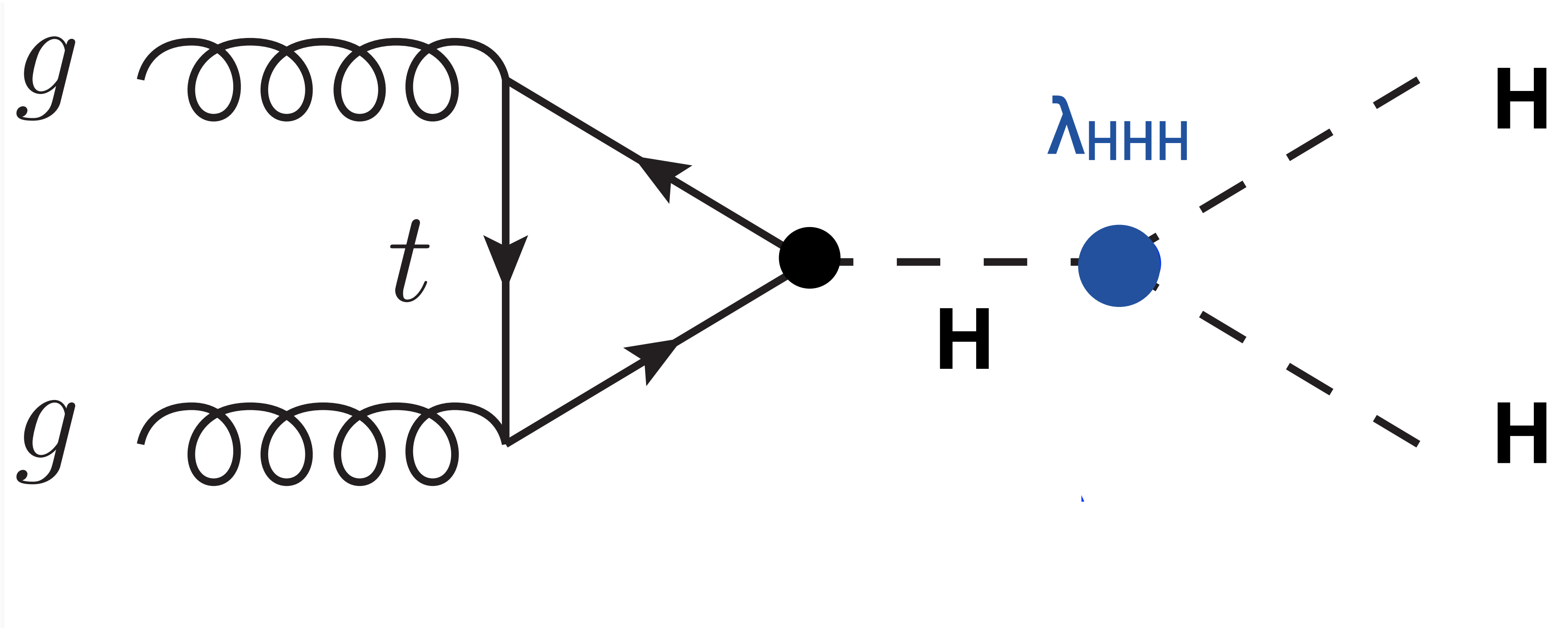

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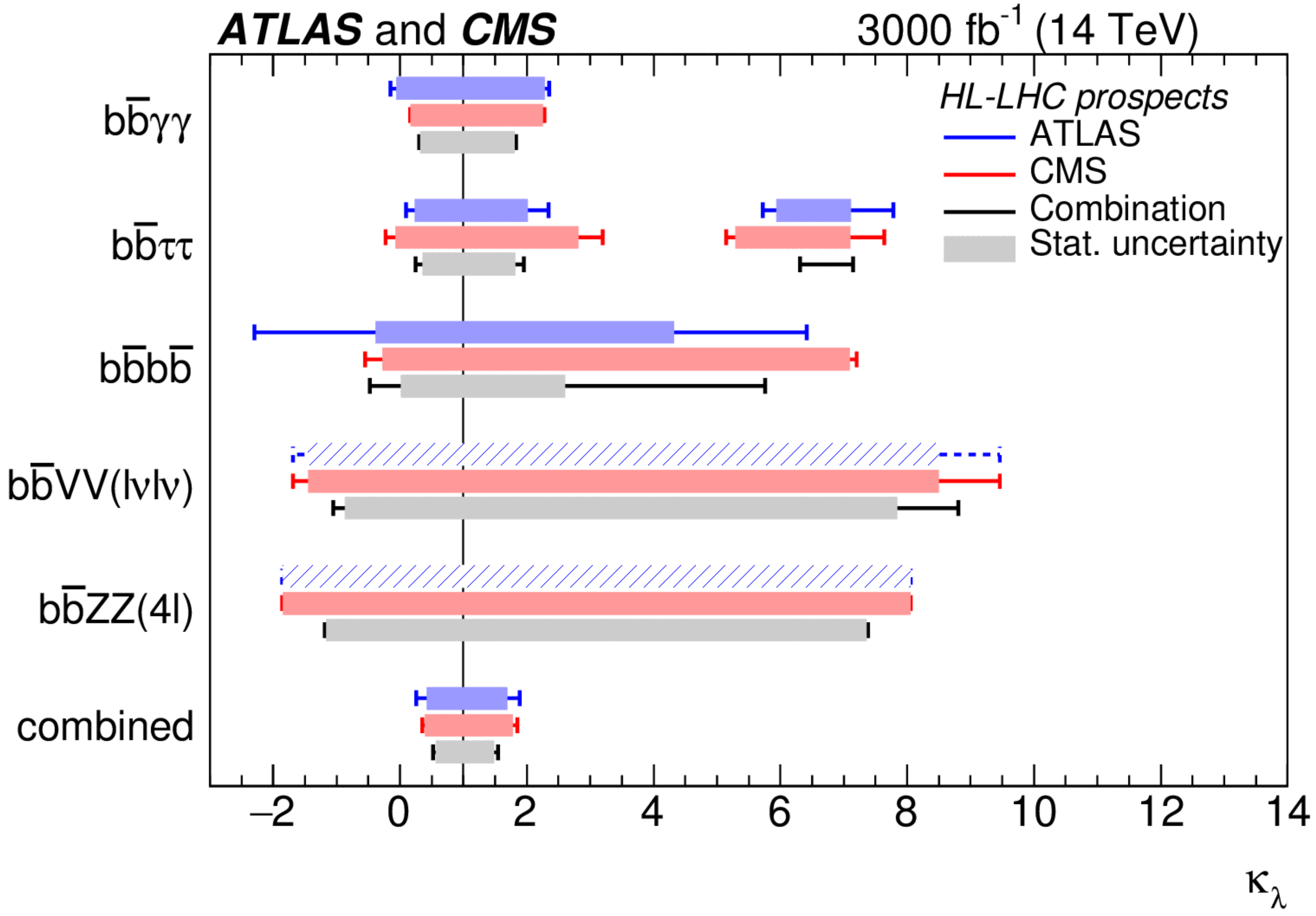
Expected results



arXiv:1902.00134

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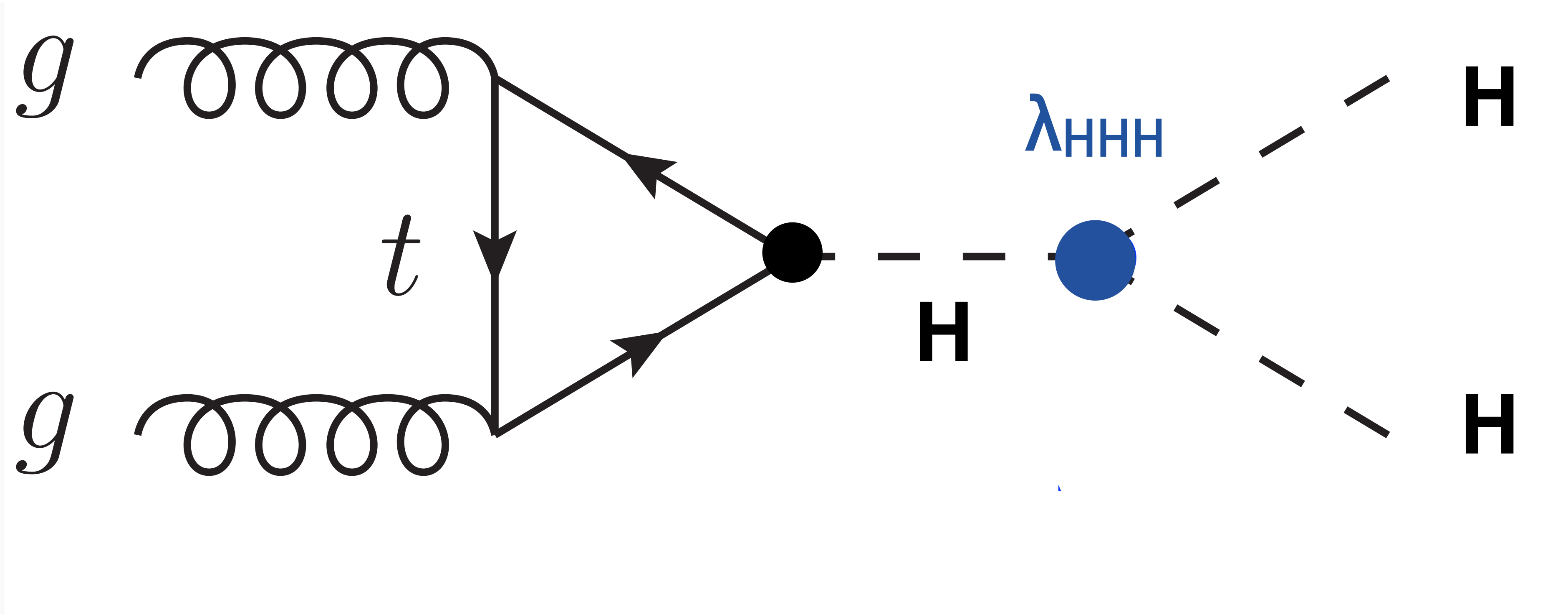

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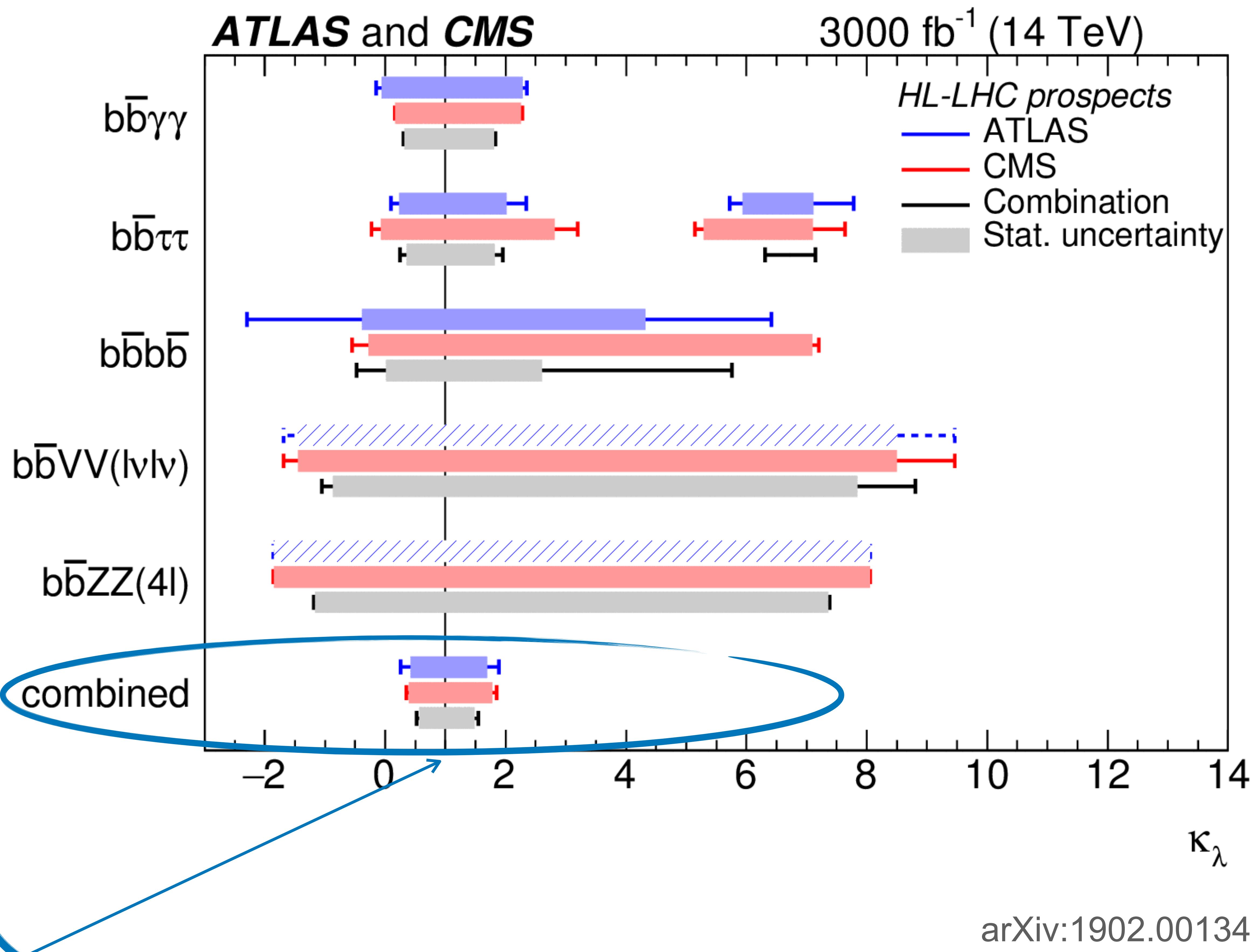

$\mathcal{O}(50\%)$ precision

2 experiments and various channels

λ_3 @ FCC-ee

Benefit of large single H cross section

Higher-order corrections to single-Higgs processes

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

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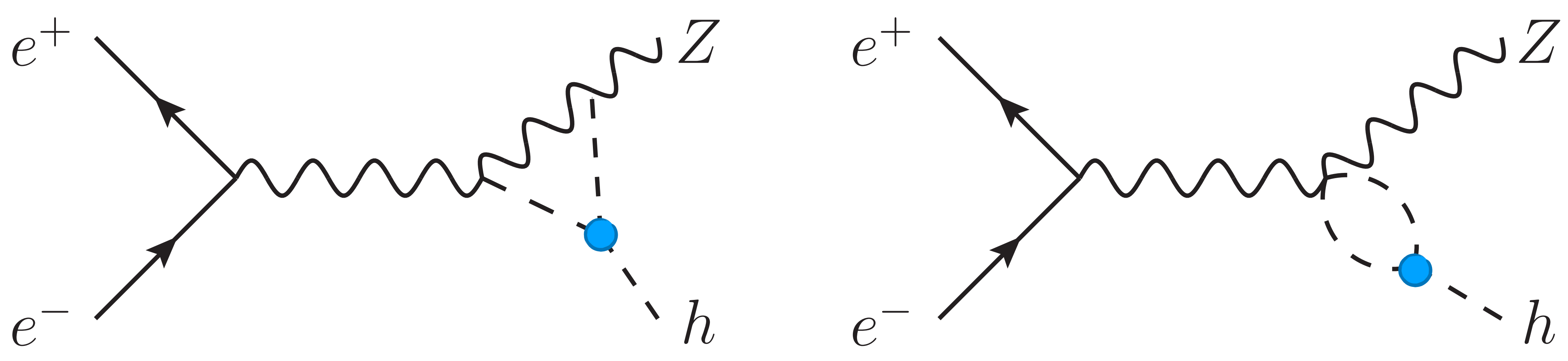
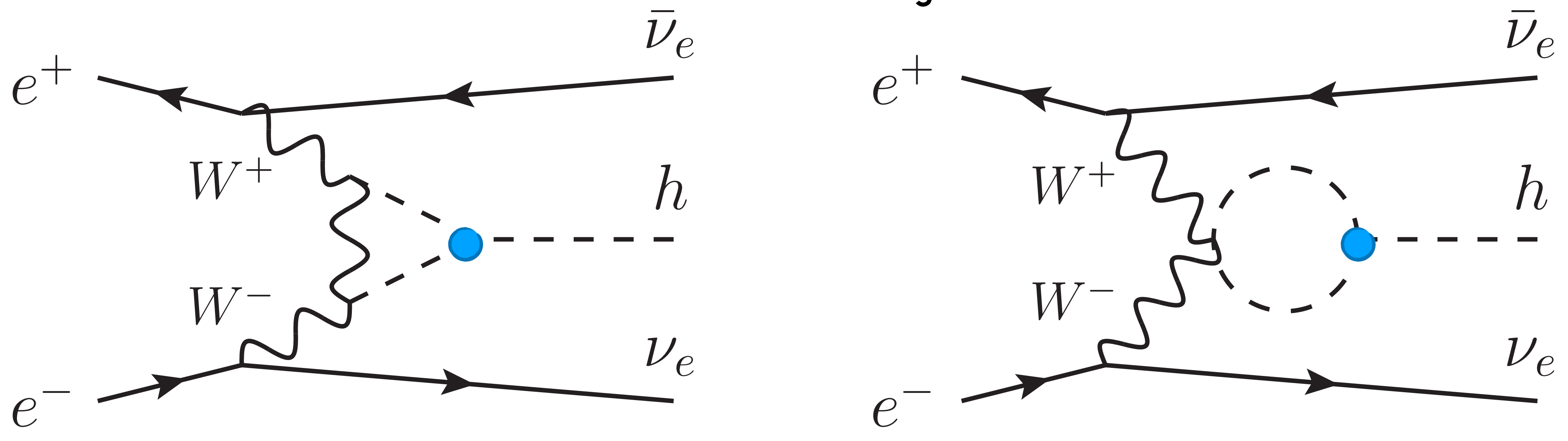
Vertex corrections (linear in k_λ)

ZH Higgsstrahlung



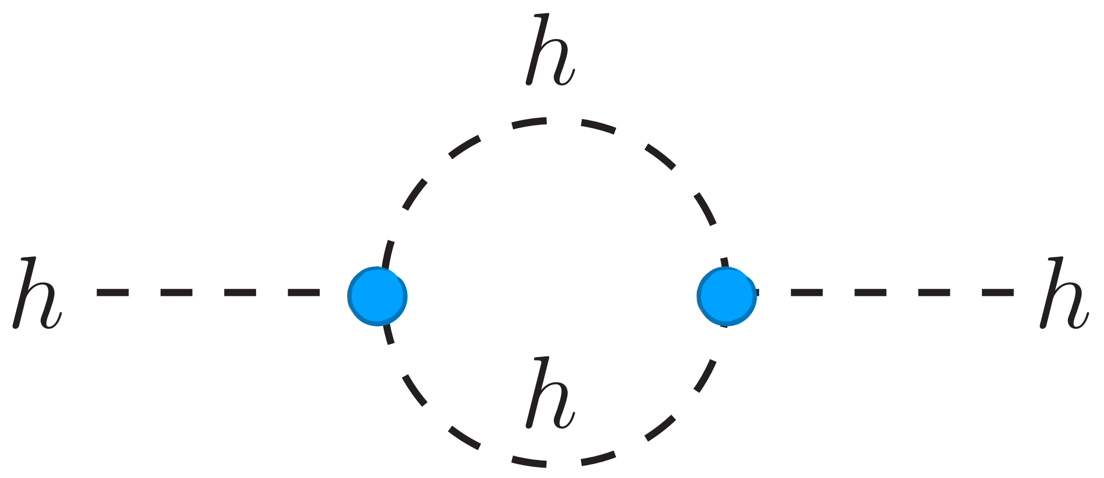
VBF processes

Both CC/NC diagrams



Higgs boson self-energy (quadratic in k_λ)

Universal modifications via wave function renormalisation



λ_3 effect

The NLO corrections to an observable Σ

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

Z_H: Universal coefficient from wave function

C_1: Process and kinematic dependent coefficient

arXiv:1607.04251
arXiv:1711.03978

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Universal coefficient from wave function (Z_H)

Process and kinematic dependent coefficient (C_1)

Decay modes

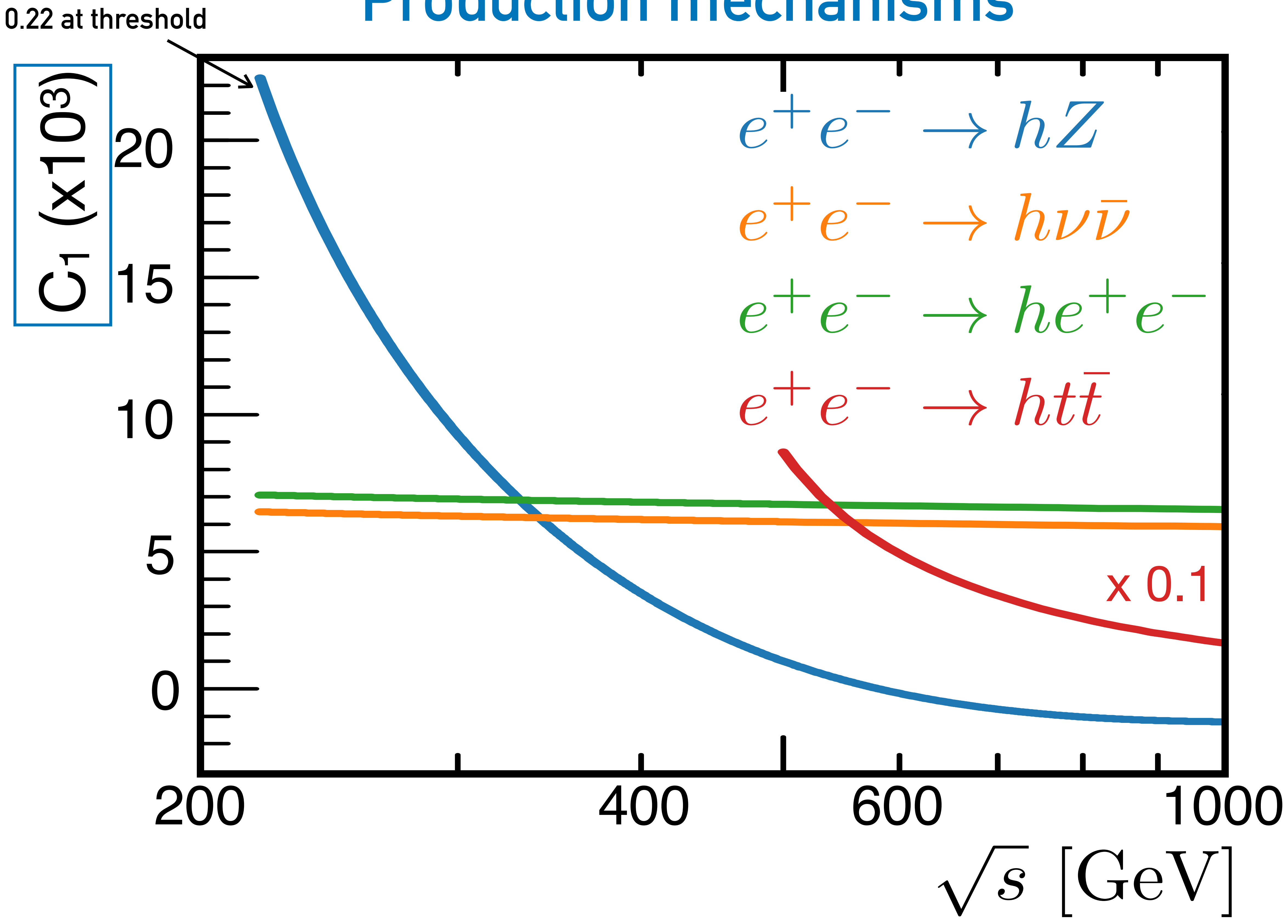
C_1^Γ[%]	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

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

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.

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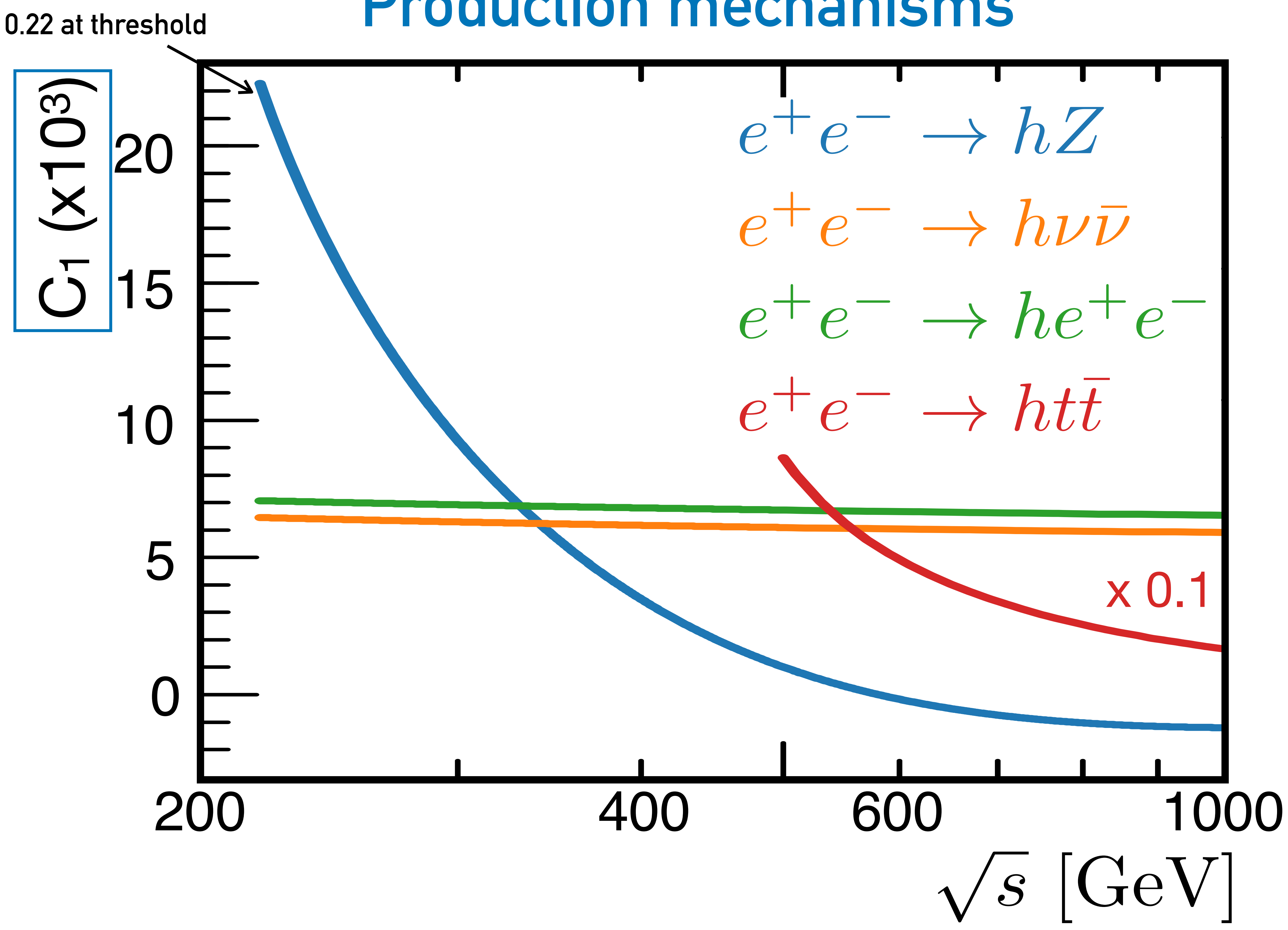

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Great opportunity from the combination of inclusive or exclusive analyses and various production modes at two collision energies

Inclusive analyses @240 GeV

Exploited various Z decays, using the recoil techniques

Z(μμ)H

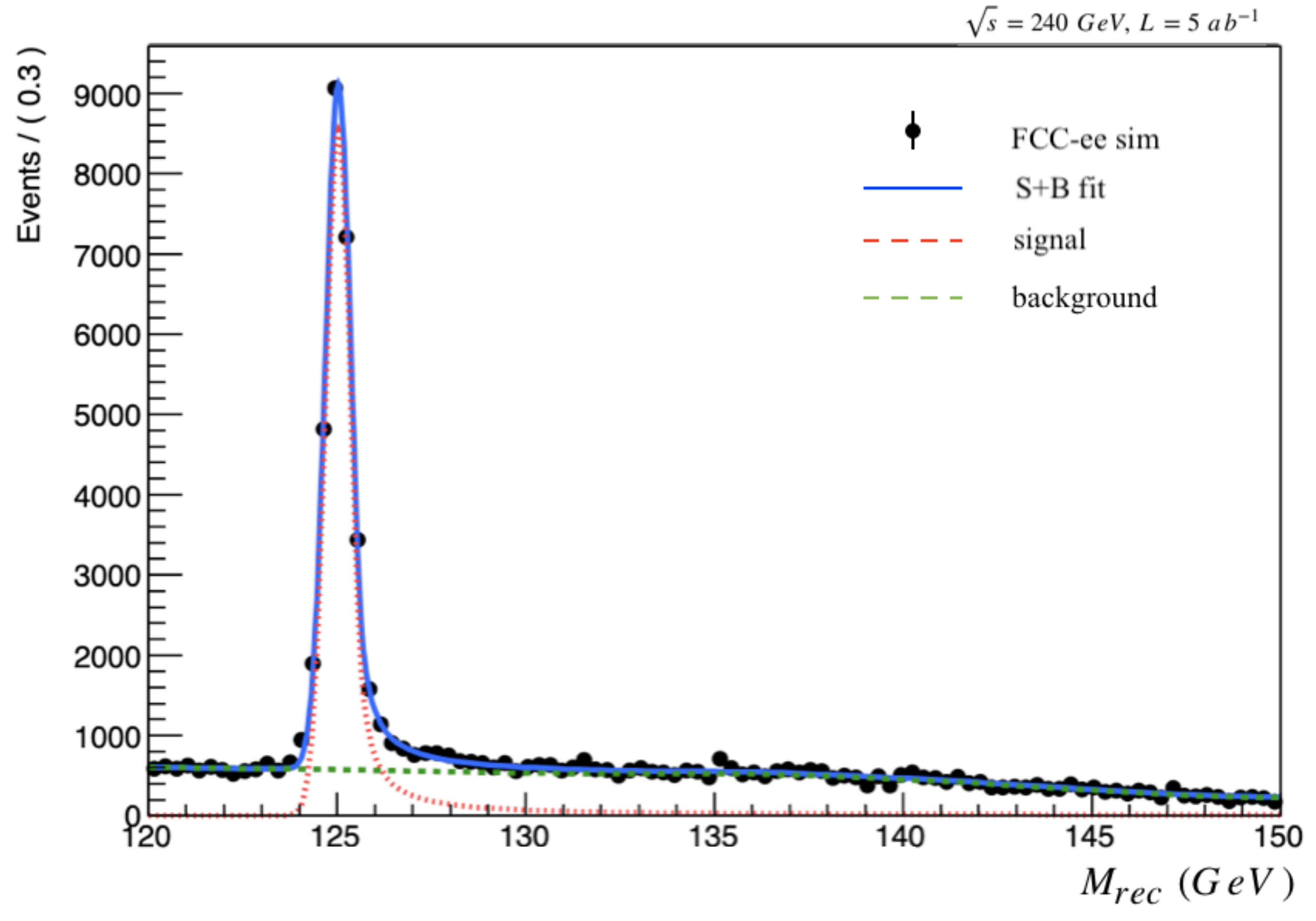
- $\mu^+\mu^-$ with $p_{T\mu 1} > 20$ GeV, $p_{T\mu 2} > 5$ GeV
- Minimum $|M_{\mu^+\mu^-} - M_Z|$
- $80 < M_{\mu^+\mu^-} < 100$ GeV

Z(ee)H

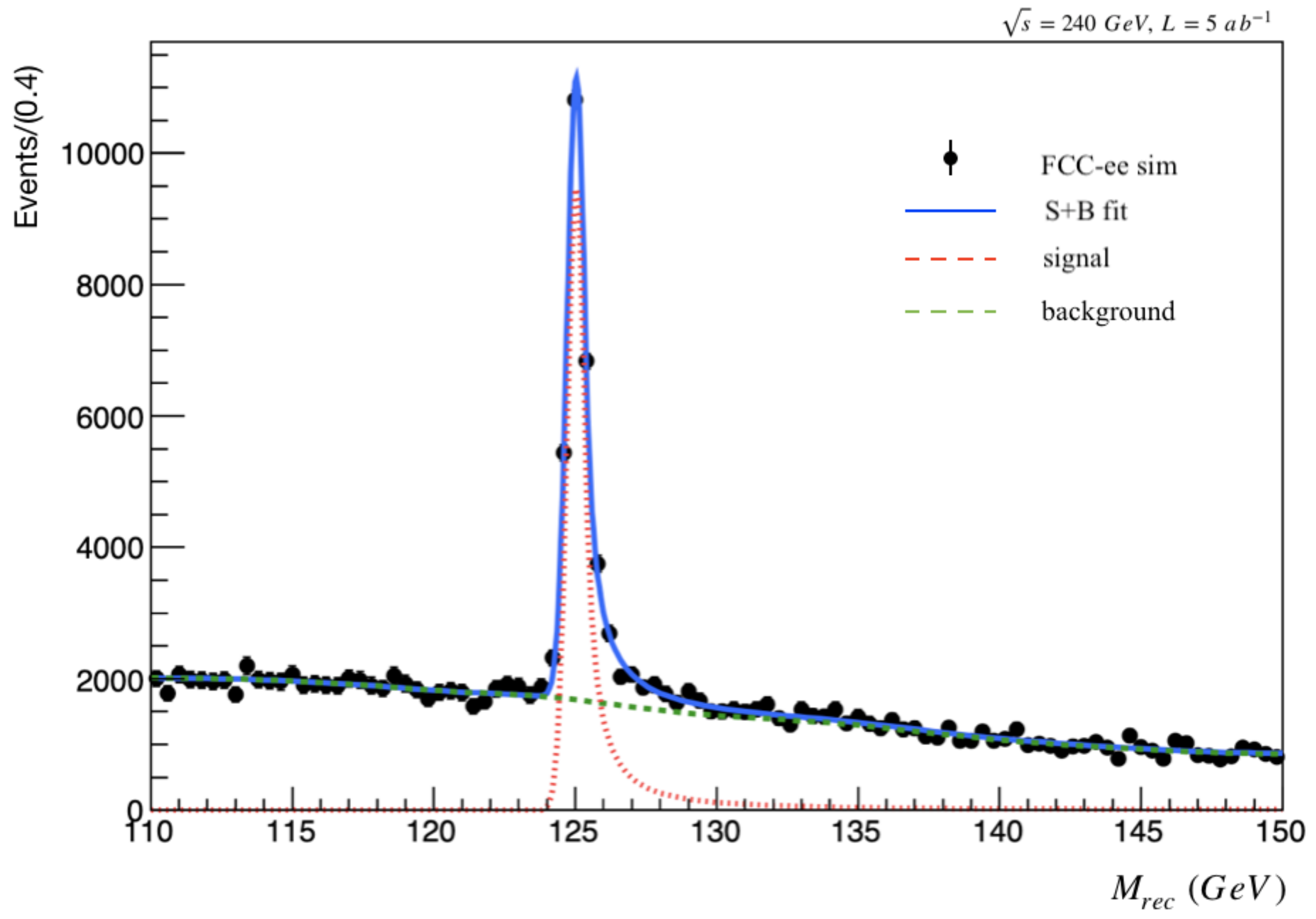
- e^+e^- with $p_{Te1} > 10$ GeV, $p_{Te2} > 5$ GeV
- Minimum $|M_{e^+e^-} - M_Z|$
- $60 < M_{e^+e^-} < 120$ GeV

Z(bb)H

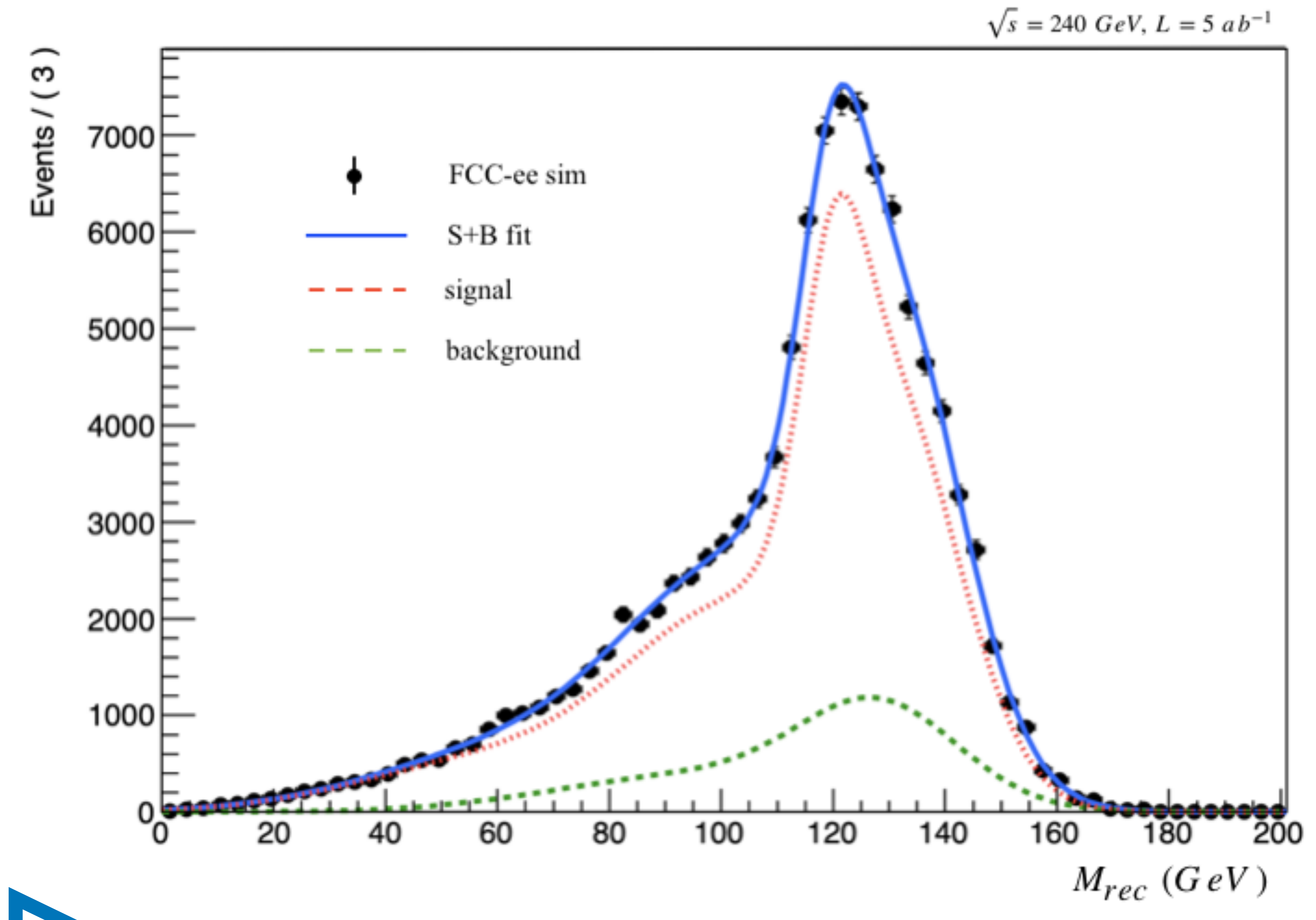
- ≥ 2 b-jets + $p_{Tjj} > 60$ GeV
- $M_{jj} > 45$ GeV
- $H_T > 10$ GeV
- BDT (17 variables)



Golden channel



Larger background



Broader resonant peak

Inclusive analyses @240 GeV

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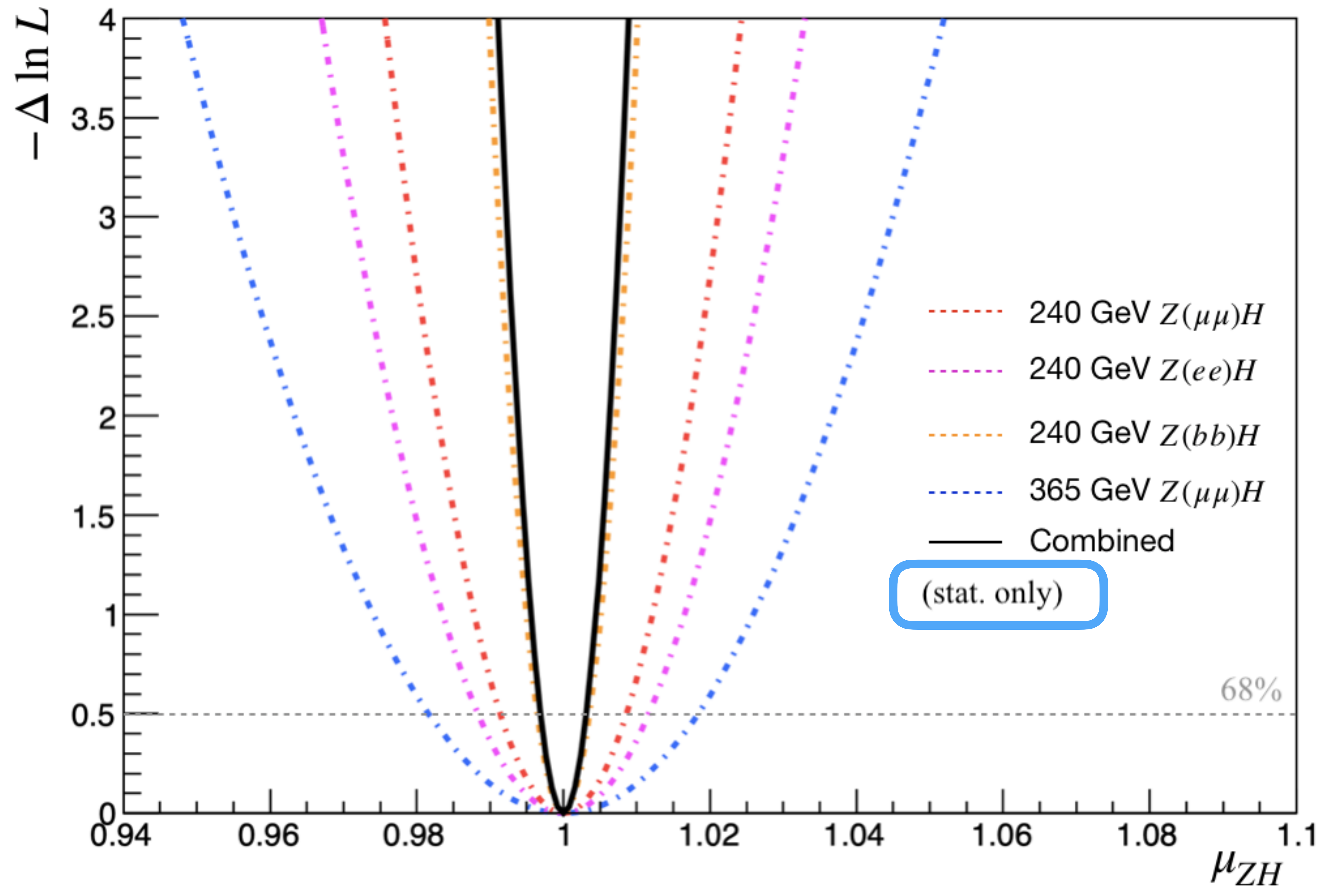
Golden char



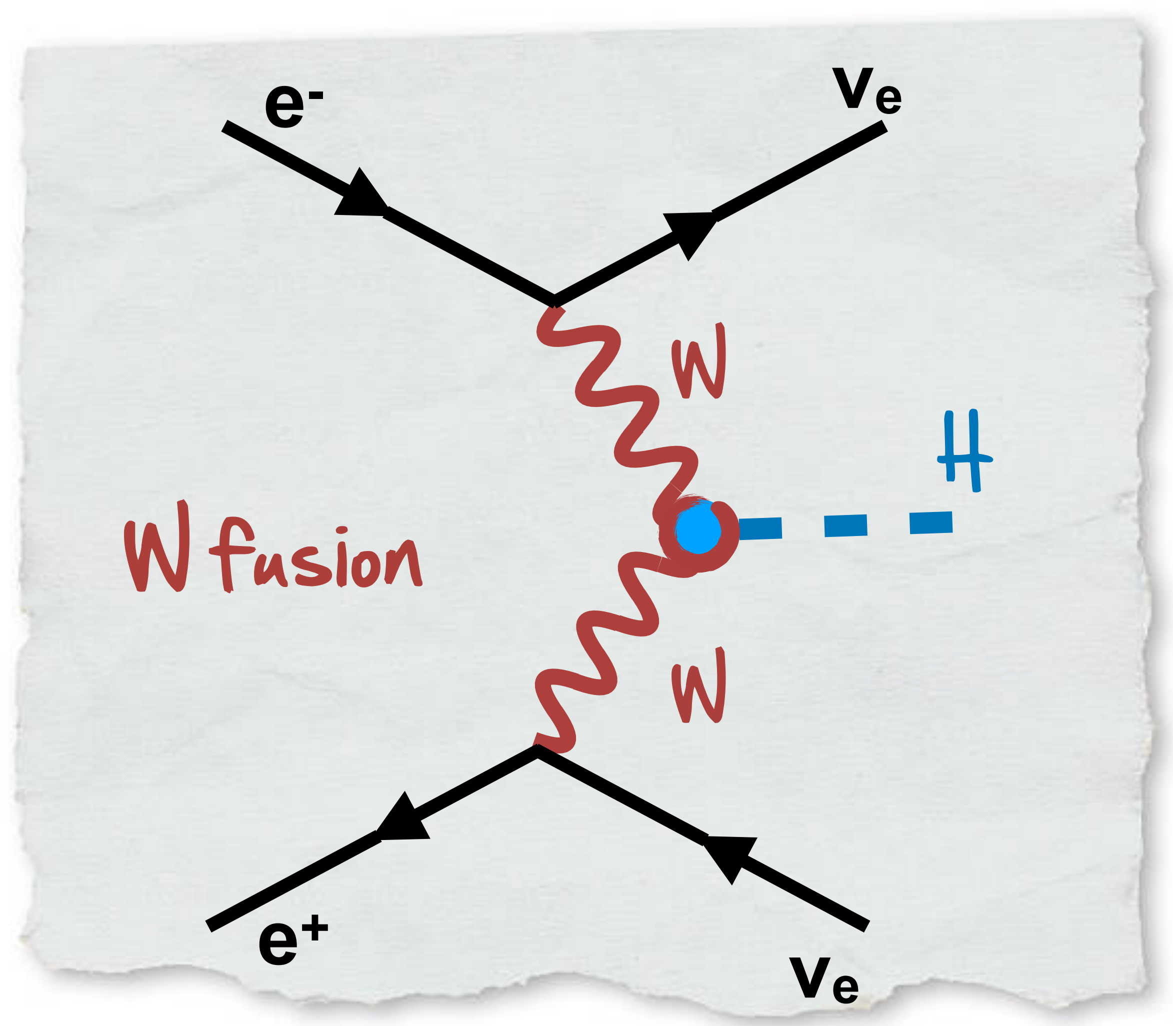
Z(bb)H

ets + $p_{Tjj} > 60$ GeV
5 GeV
) GeV
7 variables)

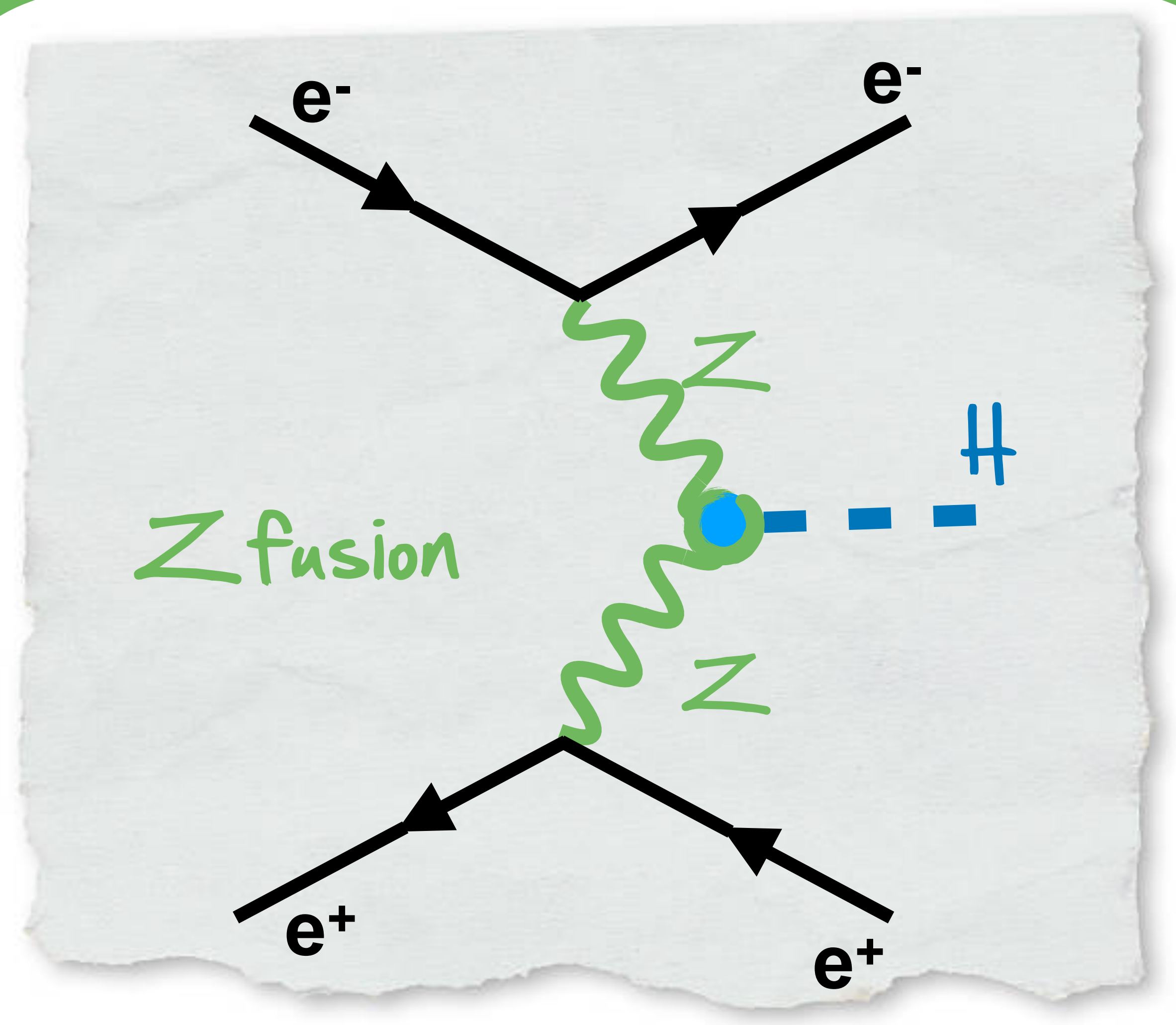
resonant peak

VBF production @365 GeV

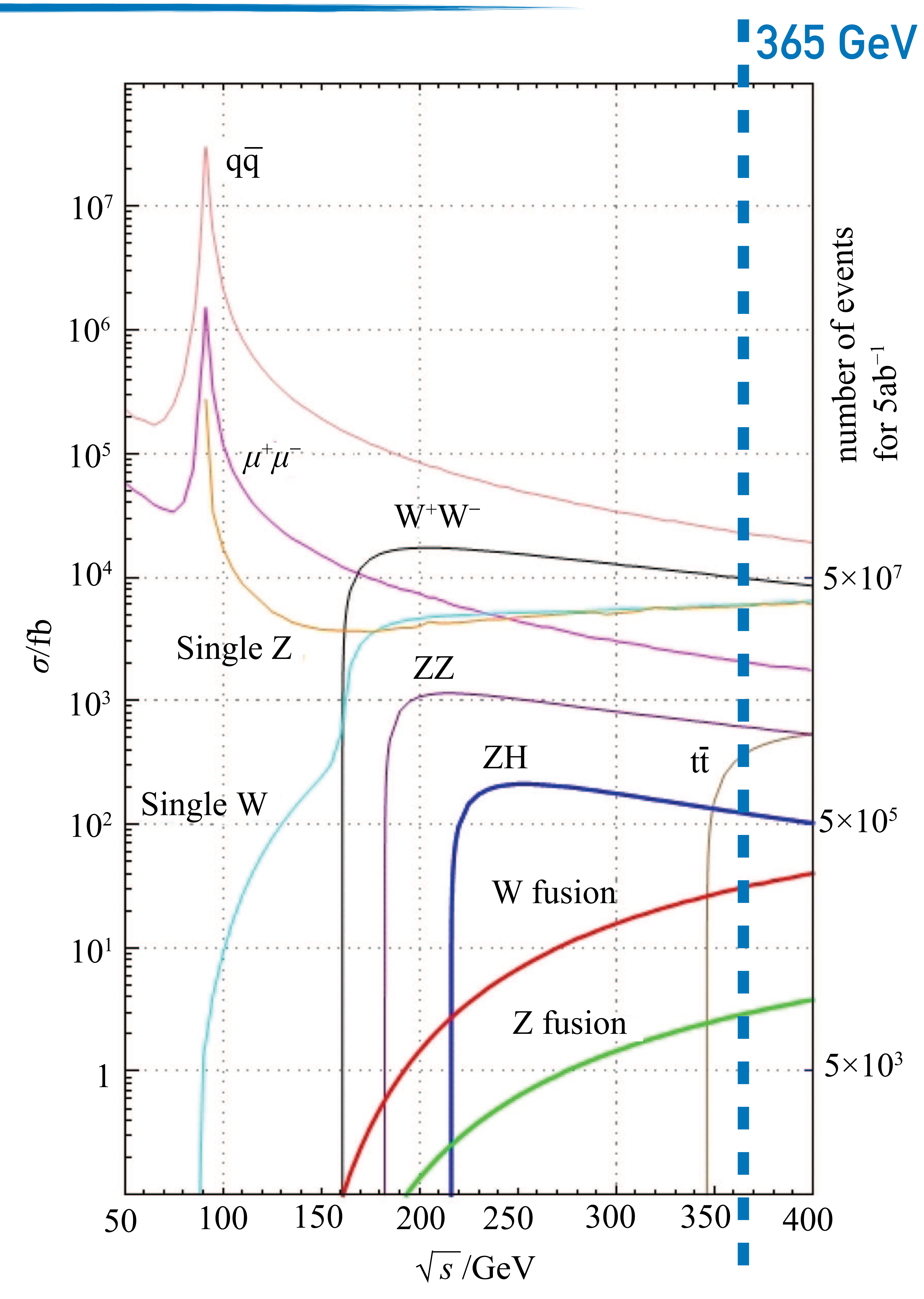
The production channel starts to become relevant due the logarithmic raise $\sim\ln^2(s/M_V^2)$ of the t-channel exchange of vector bosons



~50k H prod. @ 365 GeV (1.5 ab^{-1})



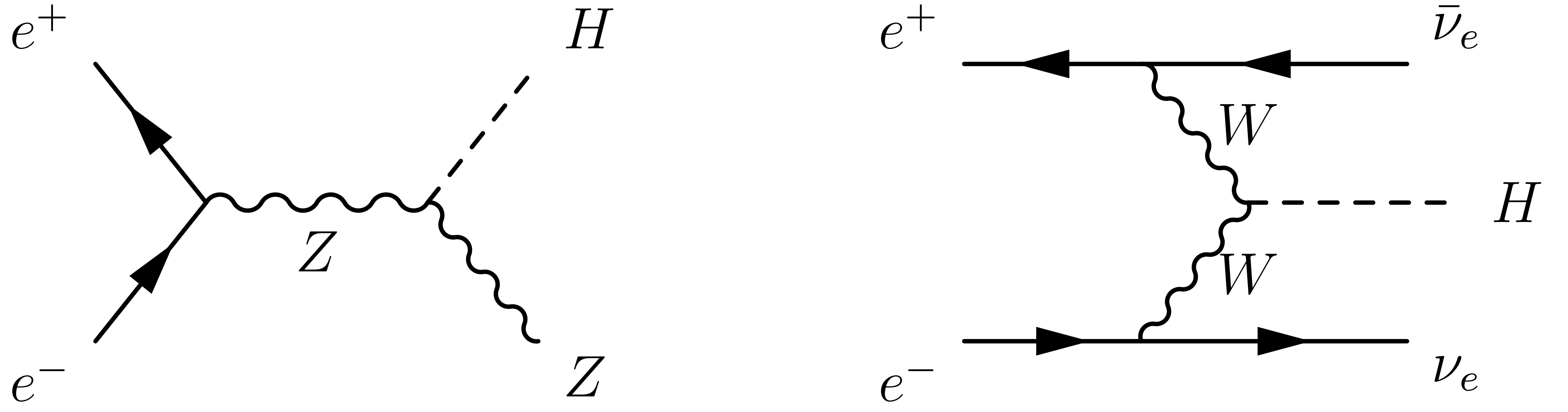
~4k H prod. @ 365 GeV (1.5 ab^{-1})



Production dominated by the W fusion because of larger charged currents

WW-boson fusion : ee→$\nu\nu H(bb)$

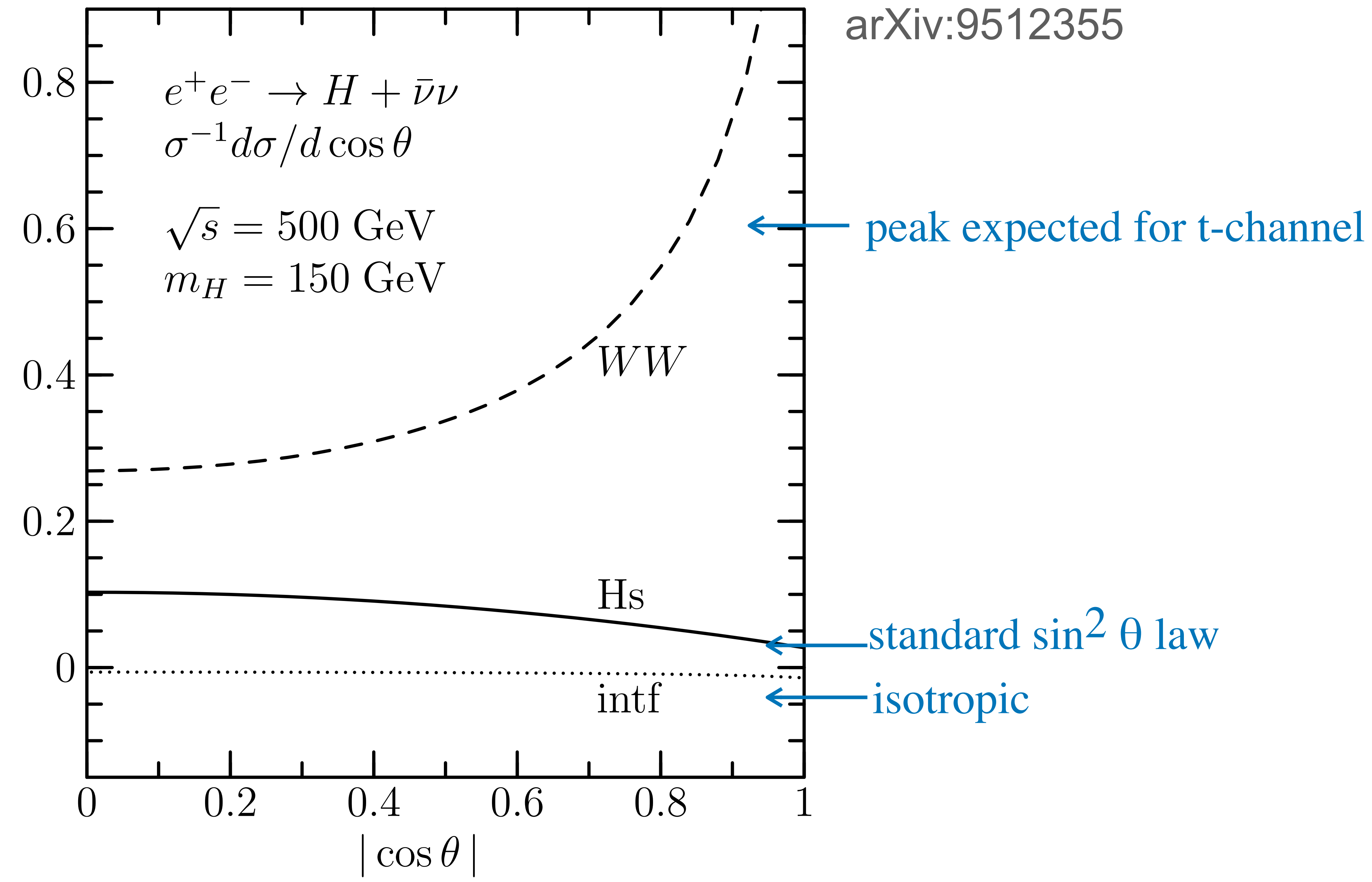
Two production mechanisms contribute

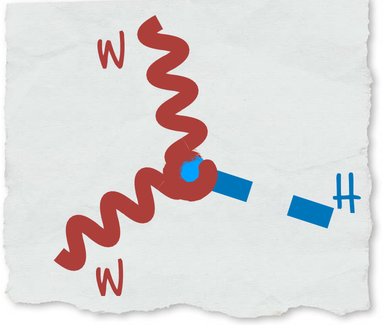


For $\nu_e\nu_{\bar{e}}$ decays of the Z boson, the two production amplitudes interfere

Positive interference term of the same size as their individual cross sections

Need to exploit angular distribution to separate the processes





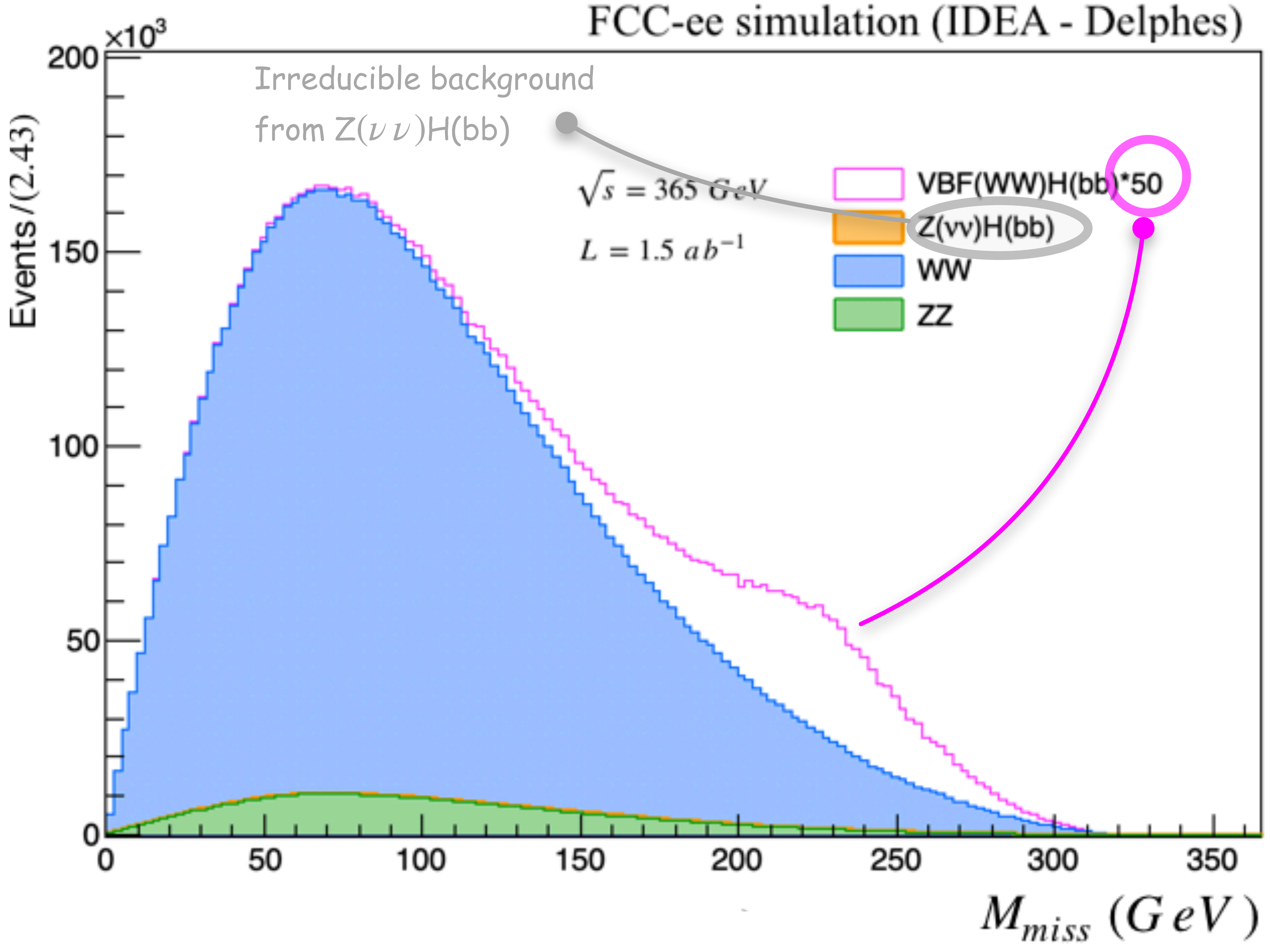
WW-boson fusion : ee→$\nu\nu H(bb)$

1. Preselection cuts

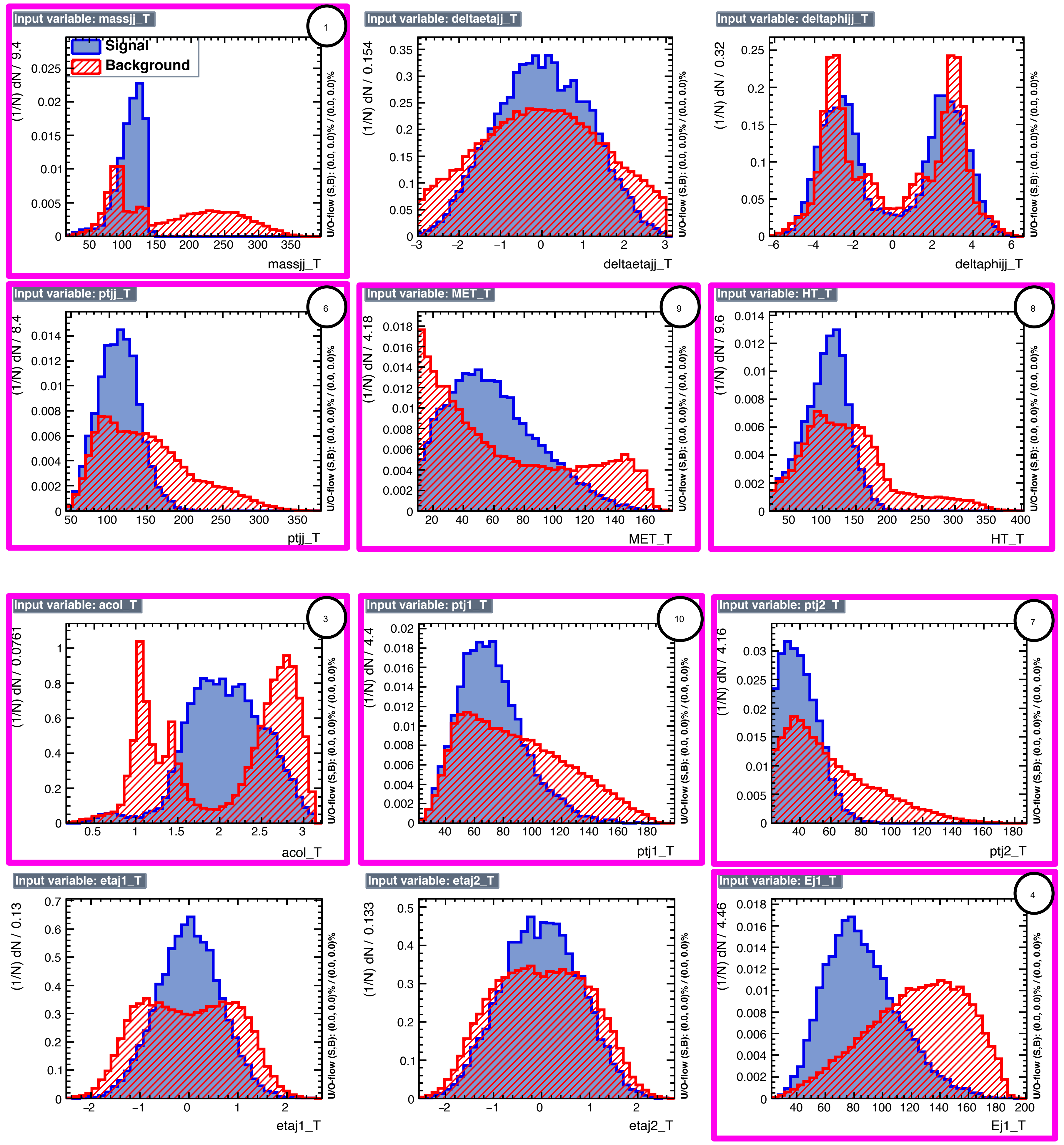
→ 2 b-jets, $|\eta_{jj}|<3$
→ H_T > 10 GeV
→ MET > 10 GeV

2. Adaptive BDT to reduce the backgrounds

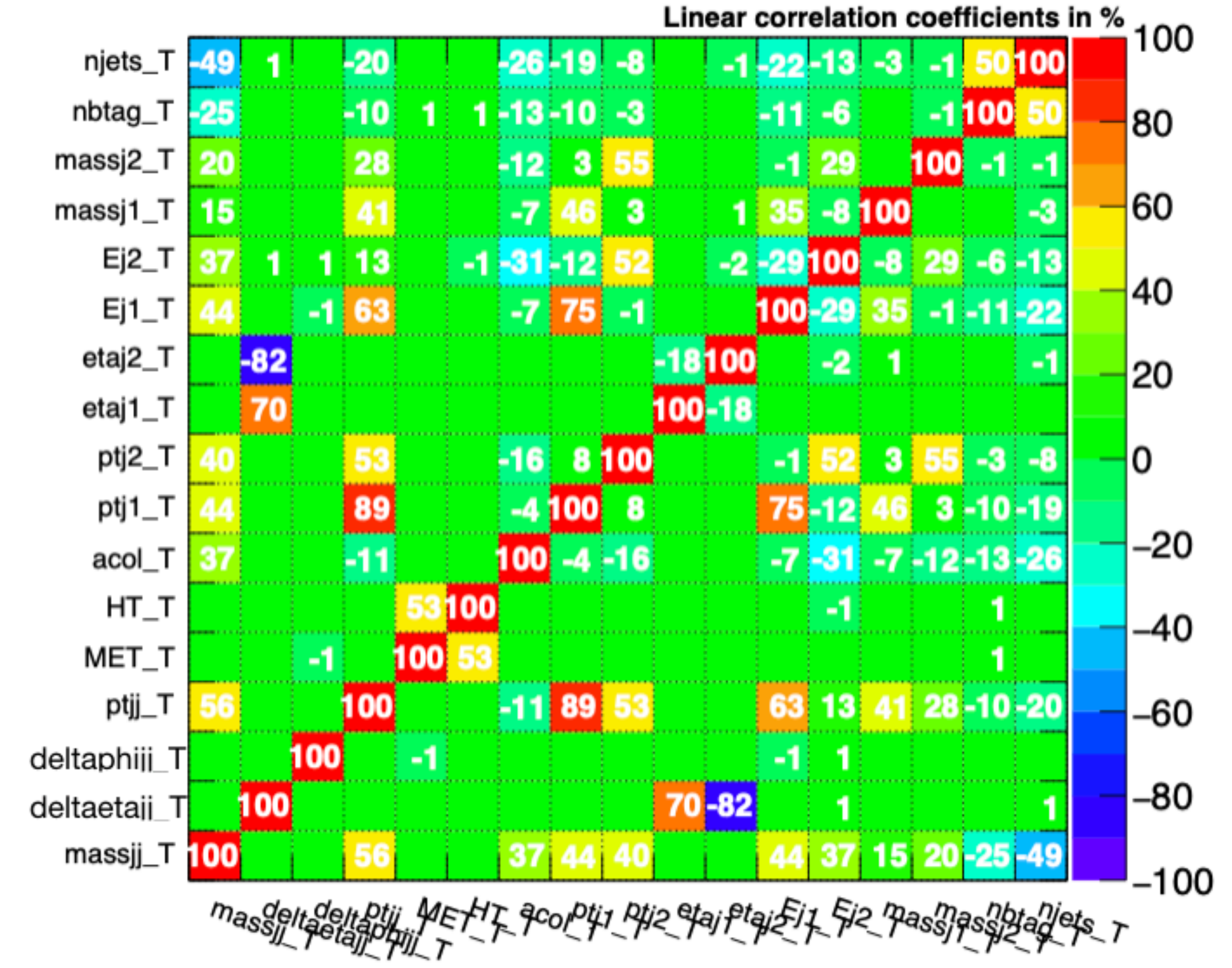
→ 17 input variables
→ trained with a 20k sig. and 100k back. events
→ 800 trees, min. node size of 1%, a max. depth of 3



BDT variables and correlations



Correlation Matrix (signal)

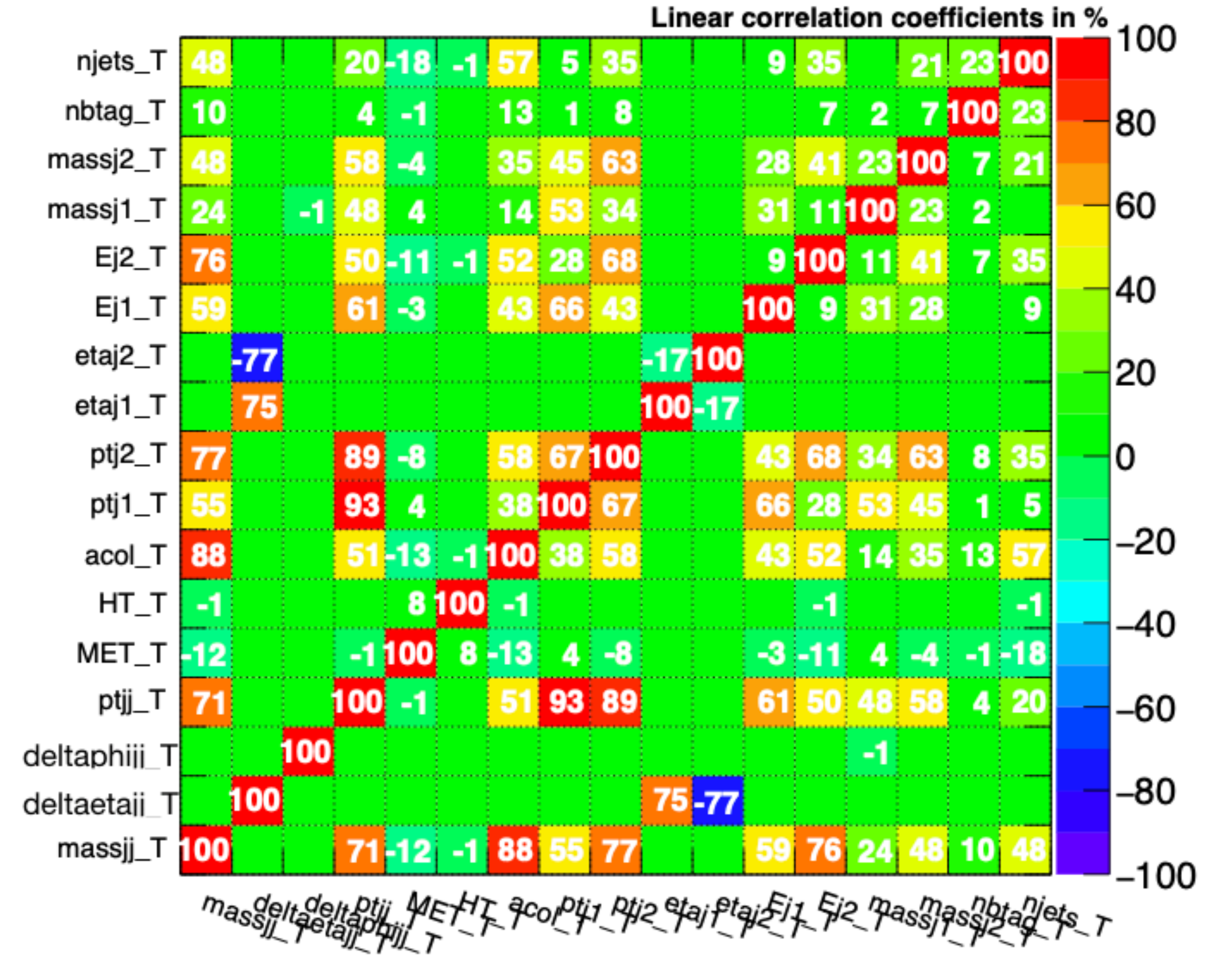


Rank	Variable	Separation
1	M_{jj}	$4.6 \cdot 10^{-1}$
2	n_j	$3.7 \cdot 10^{-1}$
3	$acol_{jj}$	$3.5 \cdot 10^{-1}$
4	E_{j1}	$3 \cdot 10^{-1}$
5	E_{j2}	$2.7 \cdot 10^{-1}$

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

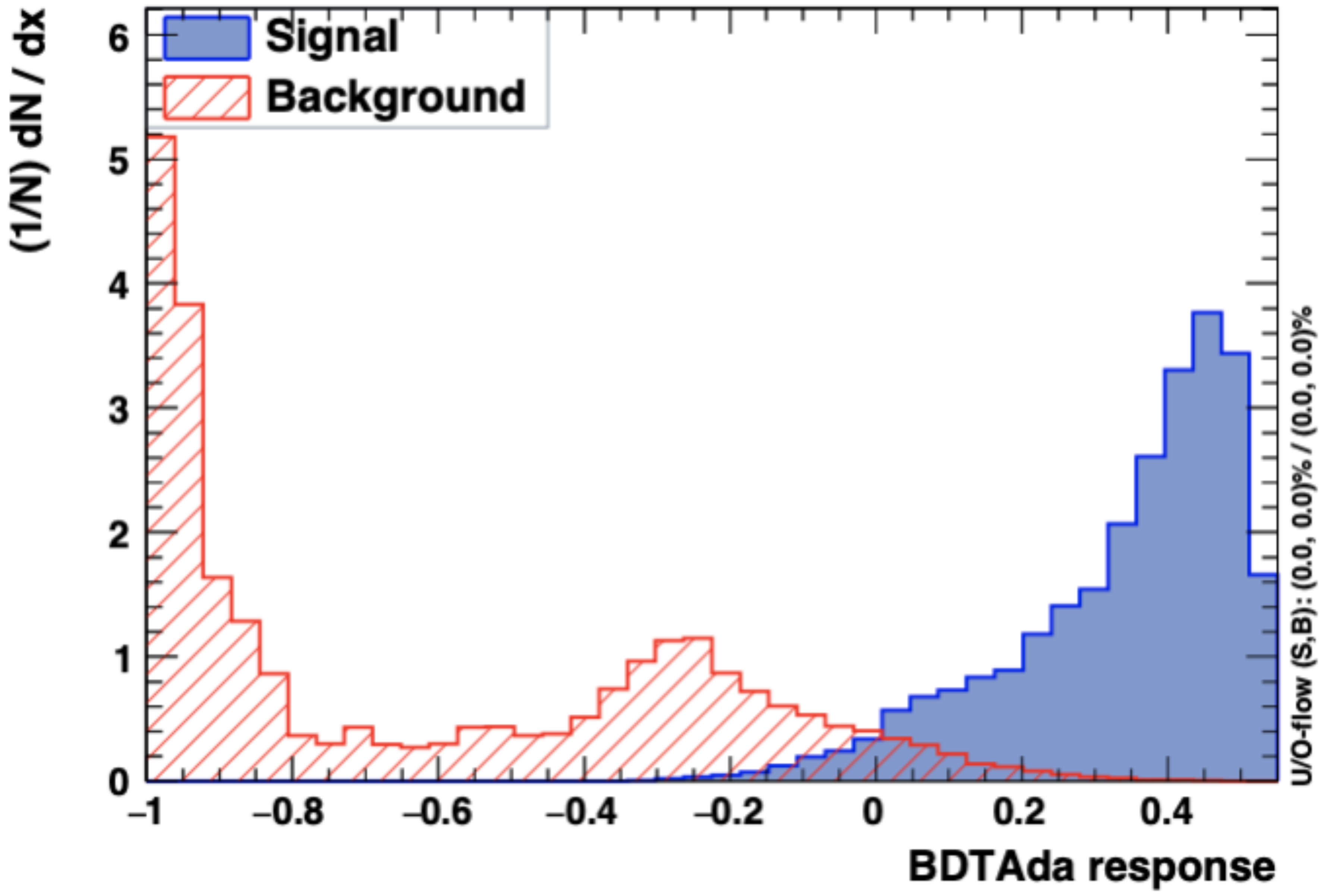
Correlation Matrix (background)

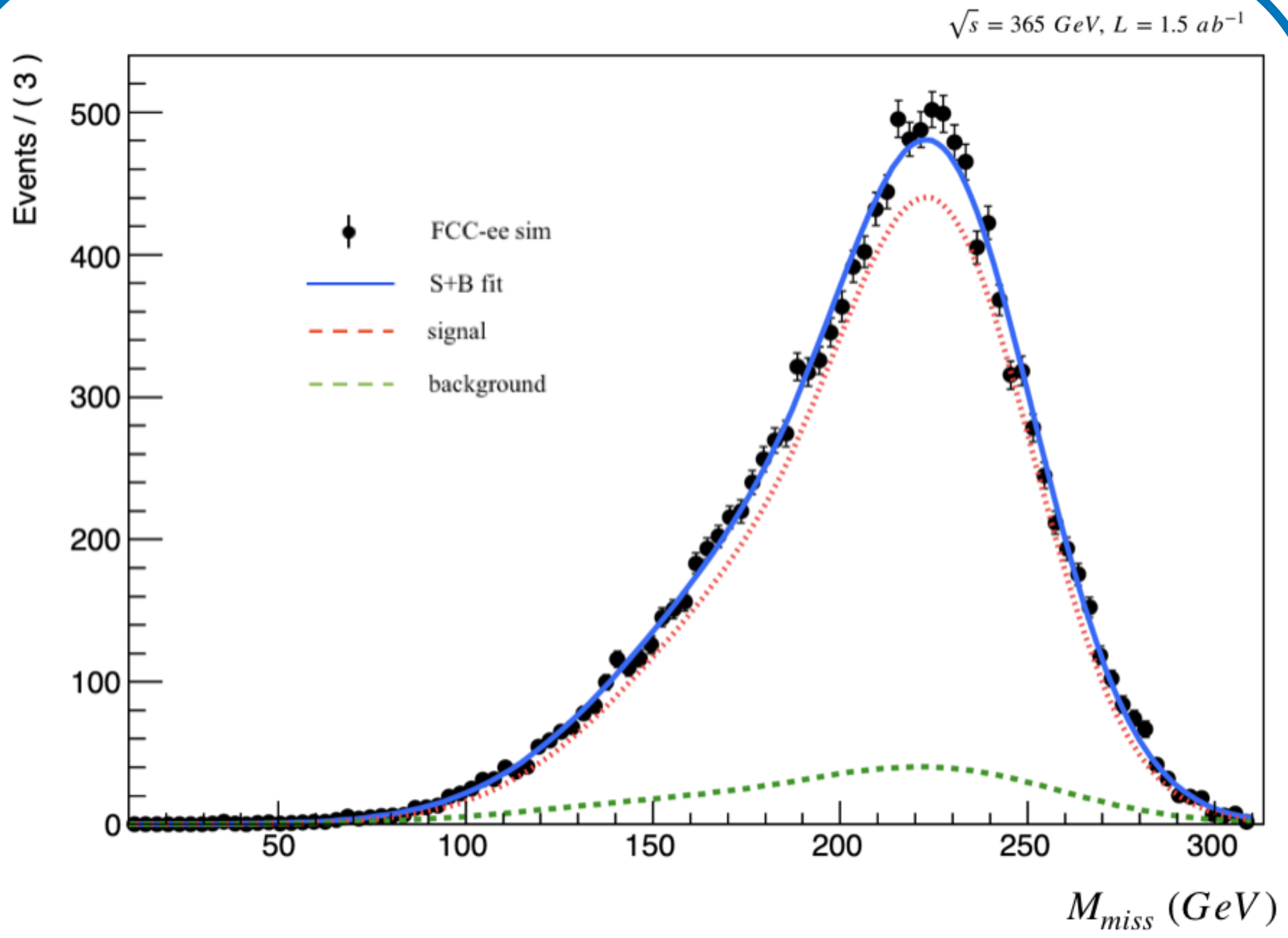


Final discrimination variable

The missing mass after preselection and BDT cuts

BDT response





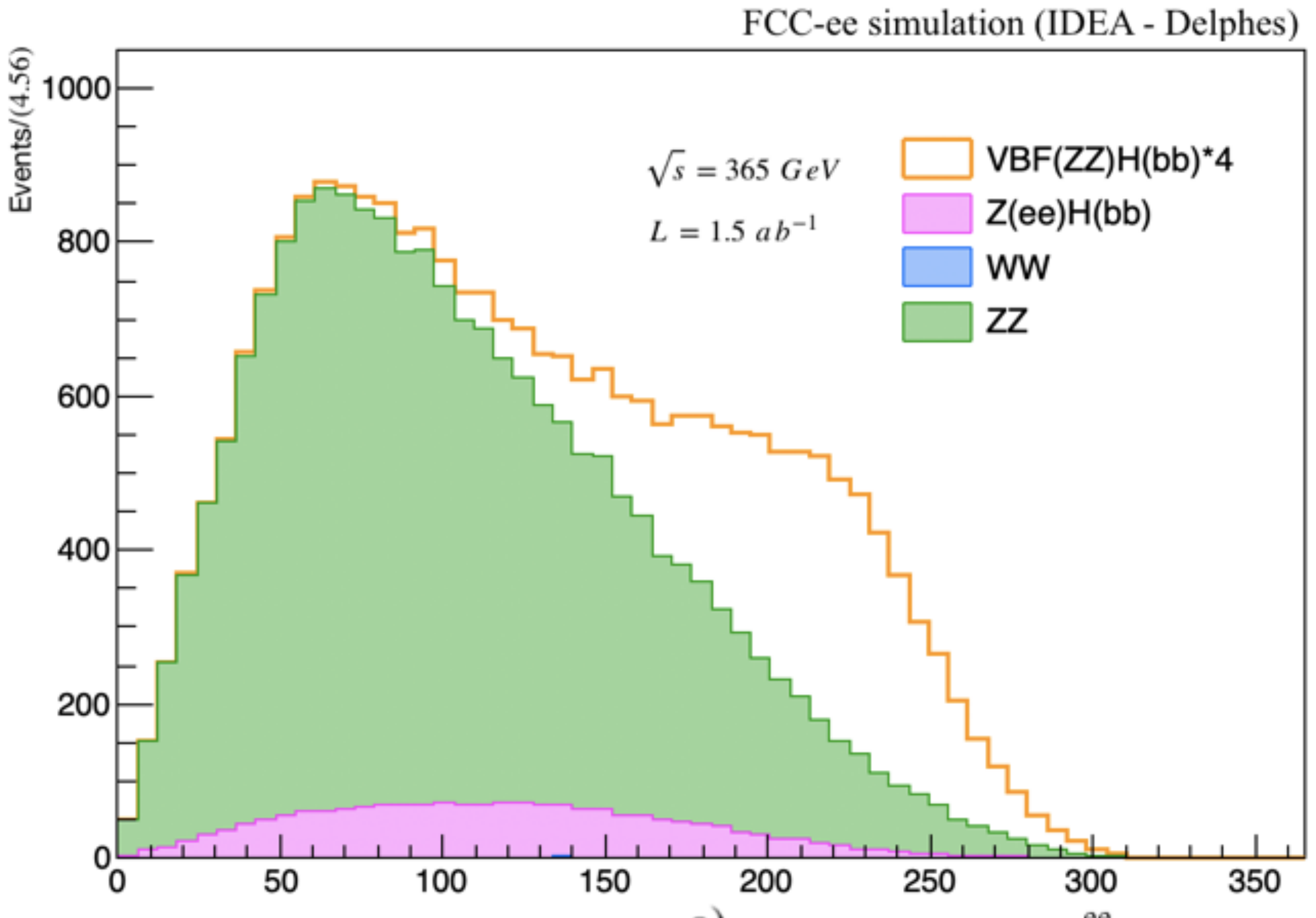
Signal (convolution of 2 Gaussians)

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

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)	$3.05 \cdot 10^4$	$2.06 \cdot 10^4$	$1.61 \cdot 10^7$	$9.49 \cdot 10^5$
$n_{bj} \geq 2$, $\vert\Delta\eta\vert < 3$, HT > 20, MET > 10 GeV	47%	48%	0.09%	5.5%
BDTAda response ≥ 0.12	42 %	3.4 %	0.002 %	0.06 %

ZZ-boson fusion : ee→eeH(bb)

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

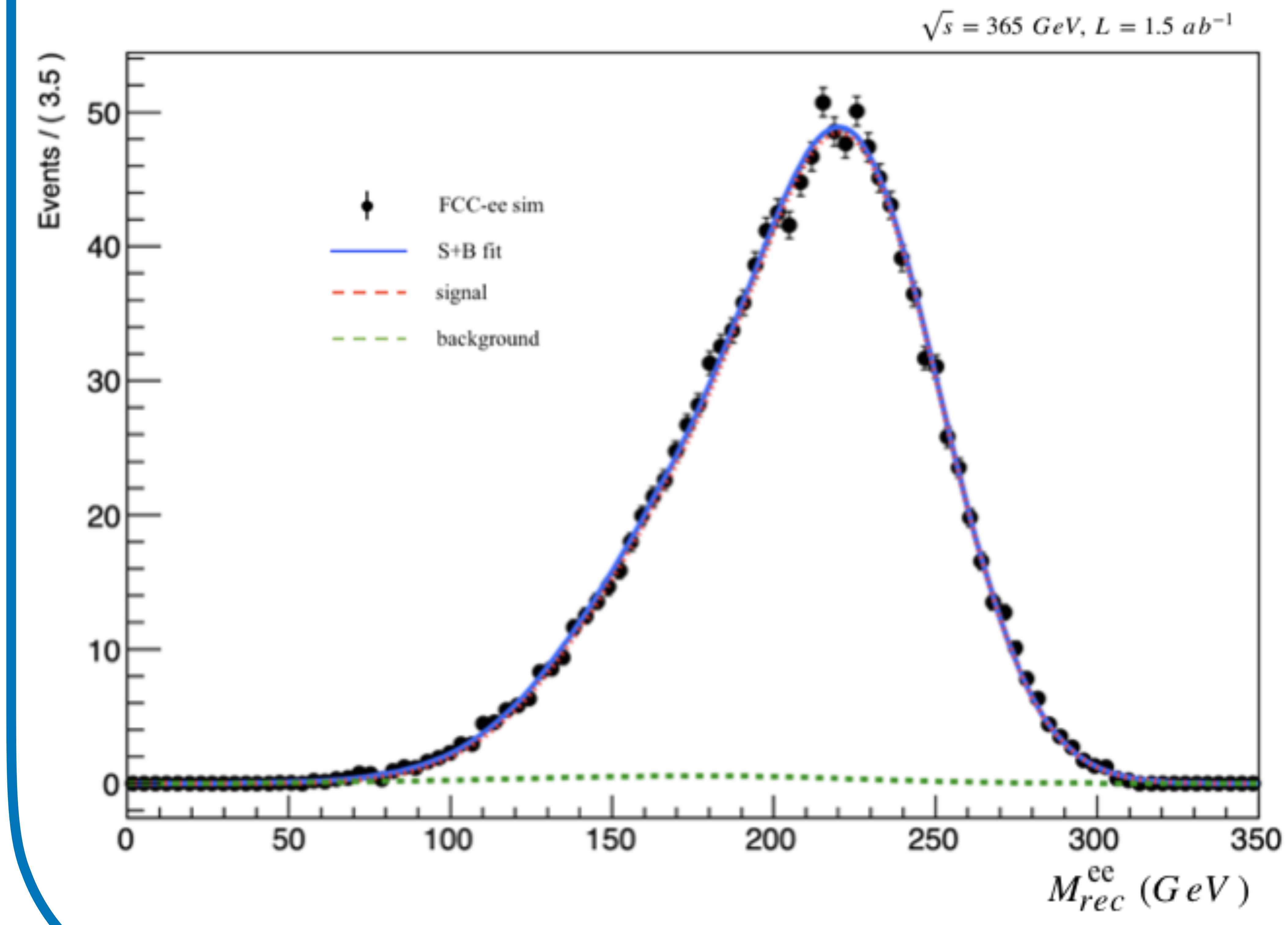


a)

2. BDT to further reduce the backgrounds

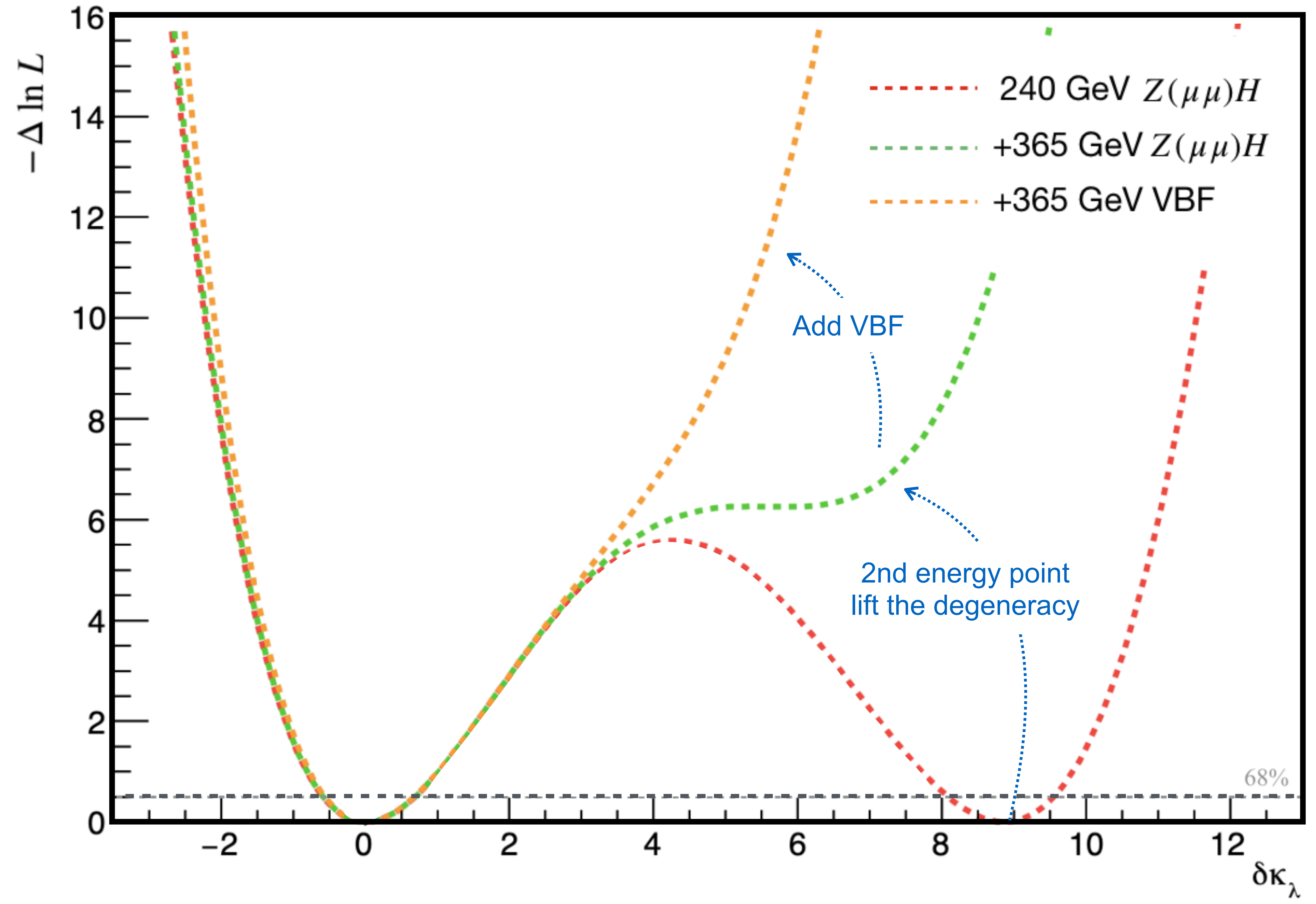
Rank	Variable	Separation	Rank	Variable	Separation
1	$M_{e^+e^-}$	$9.1 \cdot 10^{-1}$	5	M_{jj}	$3.8 \cdot 10^{-1}$
2	$acol_{e^+e^-}$	$7.1 \cdot 10^{-1}$	6	η_{e_2}	$2.4 \cdot 10^{-1}$
3	$acol_{jj}$	$7 \cdot 10^{-1}$	7	E_{j1}	$2.1 \cdot 10^{-1}$
4	n_{bj}	$4.6 \cdot 10^{-1}$	8	η_{j1}	$1.4 \cdot 10^{-1}$

Fit to the recoil mass spectrum in after the BDT



Putting all together

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



The secondary minimum easily excluded adding a 2nd energy point

Thoughts on "detector requirements"

Statistics is the essence of the Higgs boson self-coupling studies
Access to various production mechanisms and two energies points are great opportunities

We need to include
  -> hadronic Z decays in inclusive analyses
  -> highest H BR channel ($H \rightarrow bb$) in WW-fusion and ZZ-fusion channels
  -> exploit angular distribution(s) to better separate HZ and VBF channels
it means
  -> Efficient flavour tagging
  -> Optimal jet angular and energy resolutions

Conclusions

Preliminary results based on the work done during a M2 internship have been shown.

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

The analyses are going to be redone (improved selection, adding systematics, …) using the centrally produced samples within the FCCAnalyses framework.