FCC-ee
$H(jj)$ in the $Z(\nu\nu)$ final state

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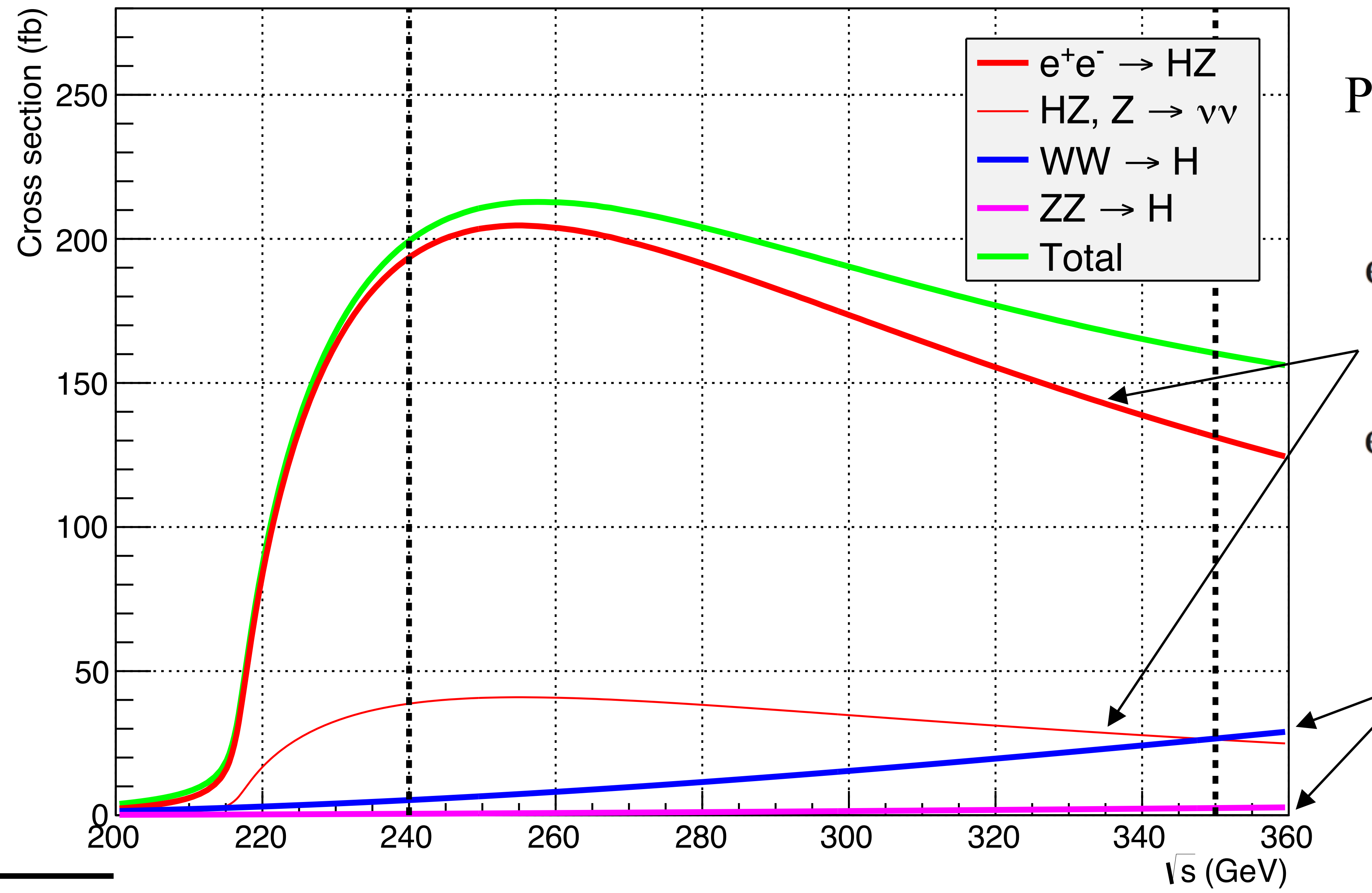
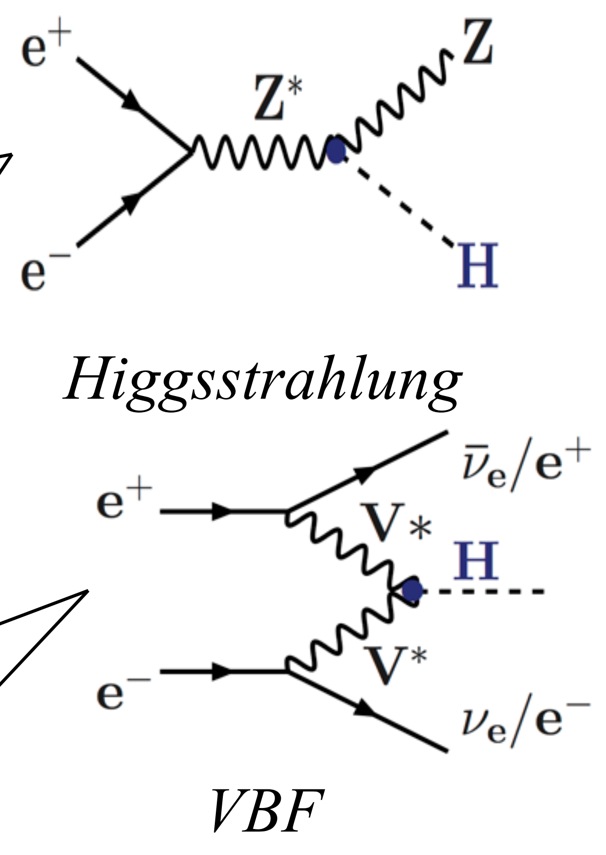
Motivation

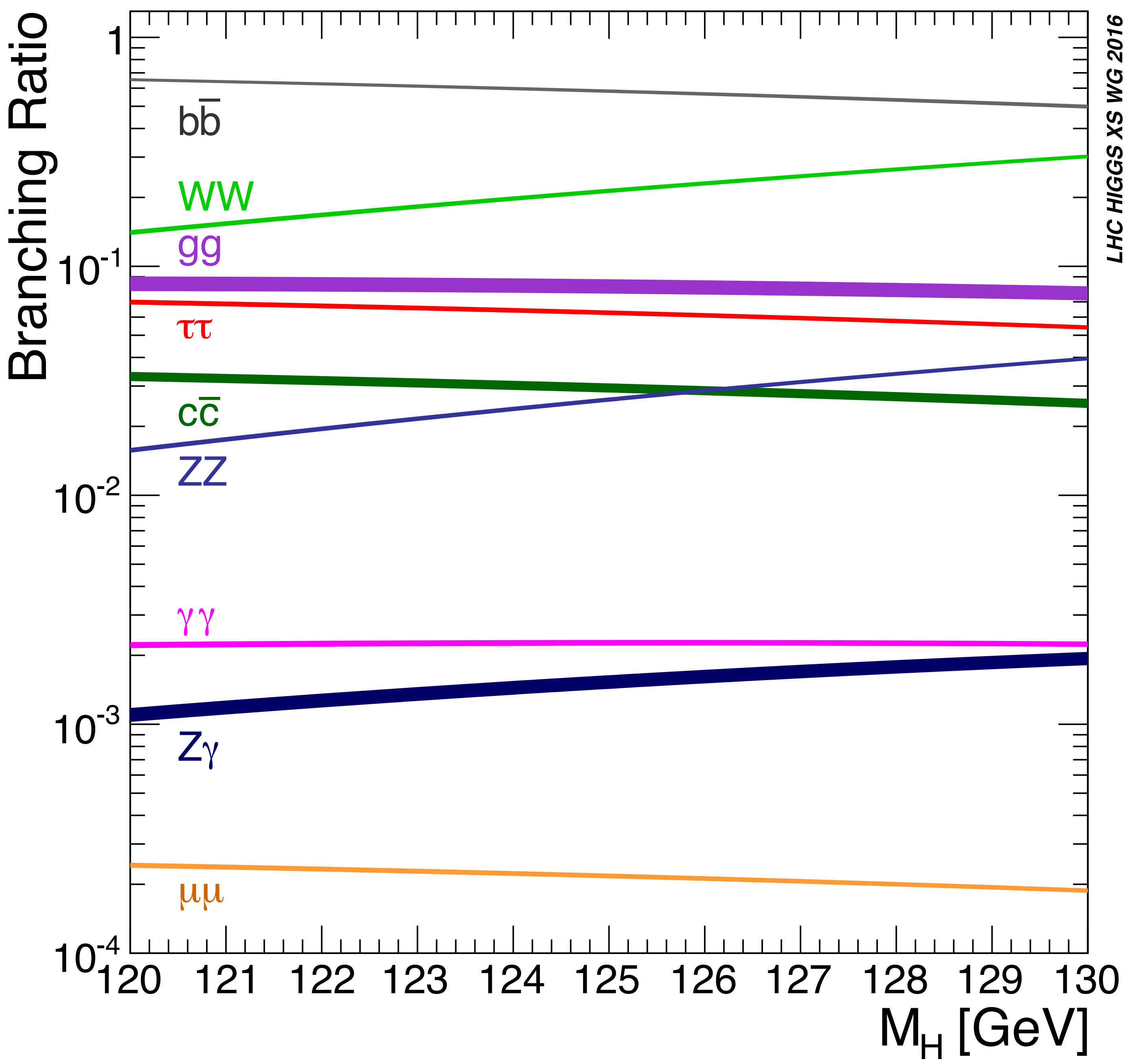
- At $\sqrt{s} = 240\,\text{GeV}$ Higgs boson is produced in association with a Z boson →measure couplings !
- Use the analysis to study and optimise the tracker design and performance





First Look at the Physics Case of TLEP
arXiv:1308.6176

Handbook of LHC Higgs cross sections
arXiv:1610.07922



H Decay	BR (%) $m_{\mathrm{H}} = 125.0\,\mathrm{GeV}$
$b\bar{b}$	58.24
$c\bar{c}$	2.891
$s\bar{s}$	0.016
gg	8.187
$\tau\bar{\tau}$	6.272

- BR($H \to s\bar{s}$) estimated as
  - ➡ $\mathrm{BR}\,[H \to s\bar{s}]_{\mathrm{SM}} \approx (m_s/m_c)^2 \cdot \mathrm{BR}\,[H \to c\bar{c}]_{\mathrm{SM}}$, PDG
  - ➡ $\mathrm{BR}\,[H \to s\bar{s}]_{\mathrm{SM}} \approx 0.024\,\%$ from theorists

	Process	Cross-section $[\mathrm{pb}^{-1}]$
Signal	ZH	0.2032195
	$Z(\nu\nu)H$	0.046191
	$e^+e^- \to Z(\nu\nu)H(b\bar{b})$	0.0269
	$e^+e^- \to Z(\nu\nu)H(c\bar{c})$	0.001335
	$e^+e^- \to Z(\nu\nu)H(gg)$	0.003782
	$e^+e^- \to Z(\nu\nu)H(s\bar{s})$	$1.109 \cdot 10^{-05}$
	$e^+e^- \to Z(\nu\nu)H(\tau\tau)$	0.002897
Background	$e^+e^- \to ZZ$	1.35899
	$e^+e^- \to W^+W^-$	16.4385
	$e^+e^- \to Z/\gamma^*(q\bar{q})$	52.6539
	$e^+e^- \to Z(\nu\nu)H(W^+W^-)$	0.00994
	$e^+e^- \to Z(\nu\nu)H(ZZ)$	0.00122
	$e^+e^- \to q\bar{q}H,\ q = u, d, s, c, b$	0.13635

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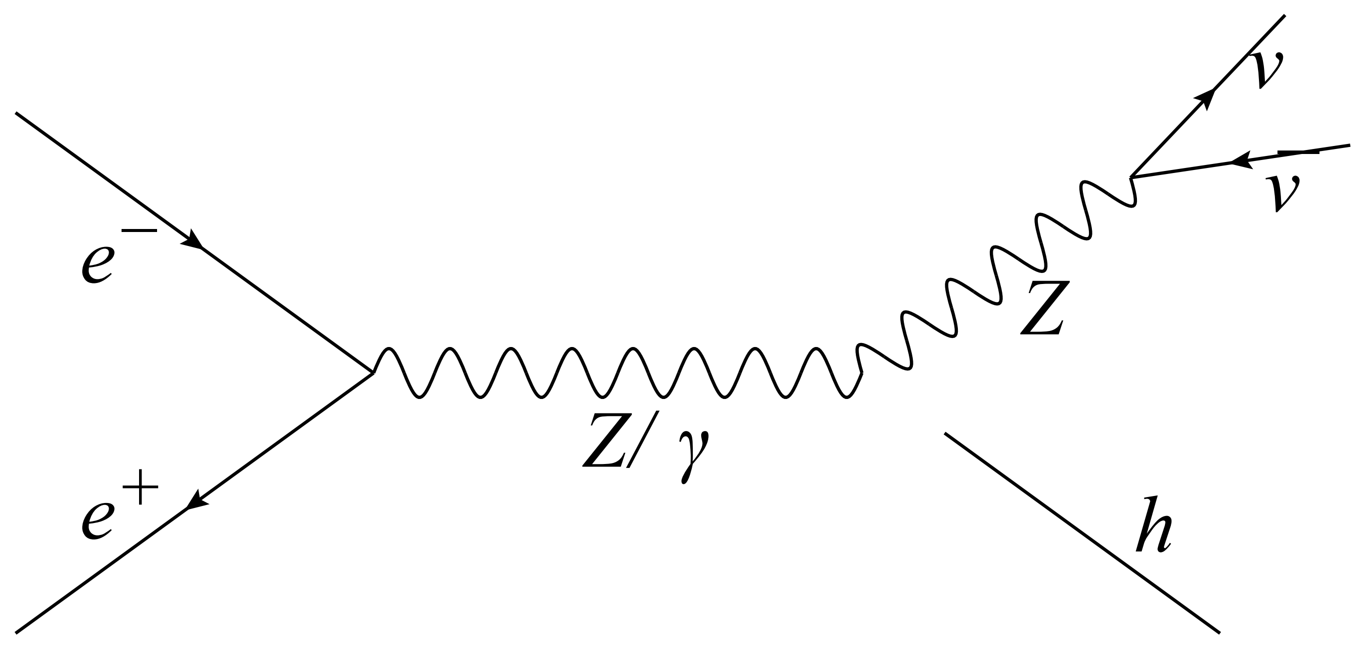
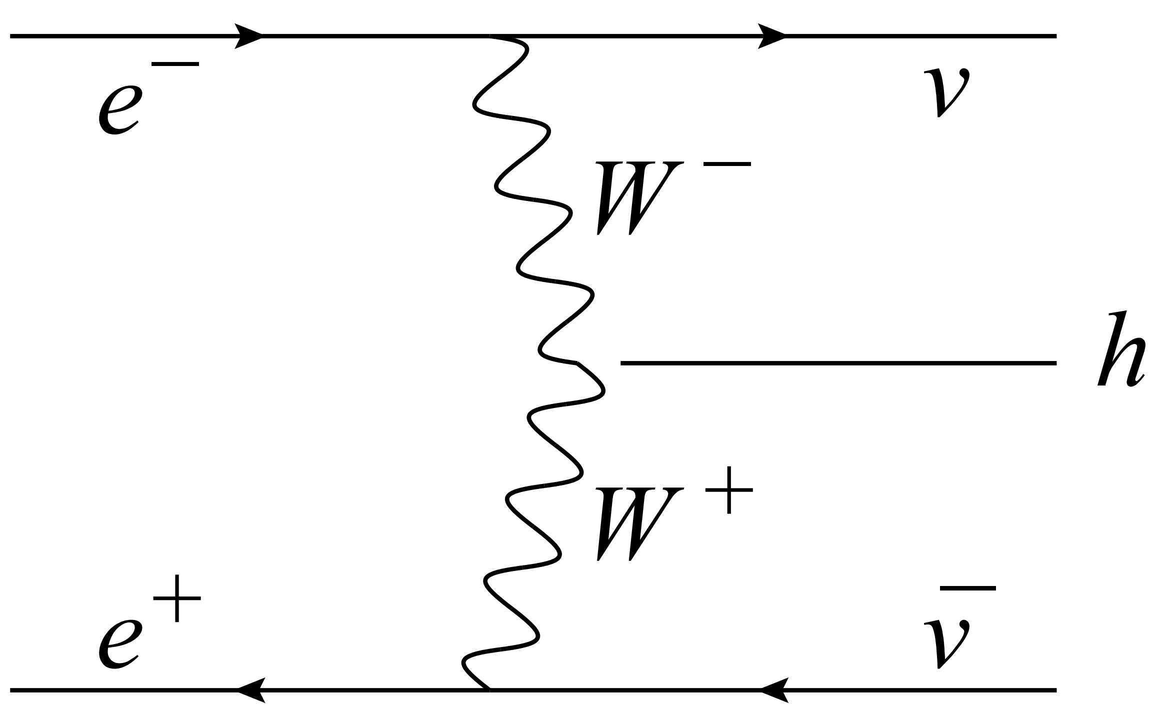
Recoil mass

- At lepton colliders, the recoil mass method can be used to reconstruct the mass of a particle without measuring its decay products
- Most of the $\nu\bar{\nu}H$ events are from ZH process with $Z \rightarrow \nu\bar{\nu}$, while the WW-fusion contributes about 13%
- The signal events have only the jets from the Higgs boson decay. Therefore, if the Higgs decay products are measured, the recoil mass can be turned around to reconstruct the Z mass

➡ $m_H^2 = E_H^2 - |\vec{p}_H|^2 = \left(\sqrt{s} - E_Z\right)^2 - |\vec{p}_Z|^2 = s - 2\sqrt{s}E_H + m_H^2$ and then the recoil mass: $m_{\text{recoil}}^2 = s - 2\sqrt{s}E_H^{\text{rec}} + \left(m_H^{\text{rec}}\right)^2$





- Offers a way to separate the Higgsstrahlung events with an invisible Z from the WW-fusion events
- Due to finite jet res. beam energy spread and other effects, the recoil mass distribution of the events has a rather large spread
- Can be improved by some jet energy corrections
- Take advance of different shapes of backgrounds to use Z recoil mass in the fit

Dataset

- FCCAnalysis framework used with some standalone analysis scripts
- IDEA Detector (delphes fast sim)
- Training using 9M jets and ParticleTransformer
- Winter2023 samples
  - model_dir = "/eos/experiment/fcc/ee/jet_flavour_tagging/**winter2023**/wc_pt_13_01_2022"
- tagger model_name = "fccee_flavtagging_edm4hep_wc_v1"

Sample	Generator	Events
$e^+e^- \to Z(\nu\nu)H(b\bar{b})$	wzp6	1,200,000
$e^+e^- \to Z(\nu\nu)H(c\bar{c})$	wzp6	1,100,000
$e^+e^- \to Z(\nu\nu)H(gg)$	wzp6	1,055,845
$e^+e^- \to Z(\nu\nu)H(s\bar{s})$	wzp6	1,008,052
$e^+e^- \to Z(\nu\nu)H(\tau\tau)$	wzp6	1,200,000
$e^+e^- \to ZZ$	p8	56,162,093
$e^+e^- \to W^+W^-$	p8	373,375,386
$e^+e^- \to Z/\gamma^*(q\bar{q})$	p8	100,559,248
$e^+e^- \to Z(\nu\nu)H(W^+W^-)$	wzp6	400,000
$e^+e^- \to Z(\nu\nu)H(ZZ)$	wzp6	200,000
$e^+e^- \to q\bar{q}H,\ q = u, d, s, c, b$	wzp6	5,400,000

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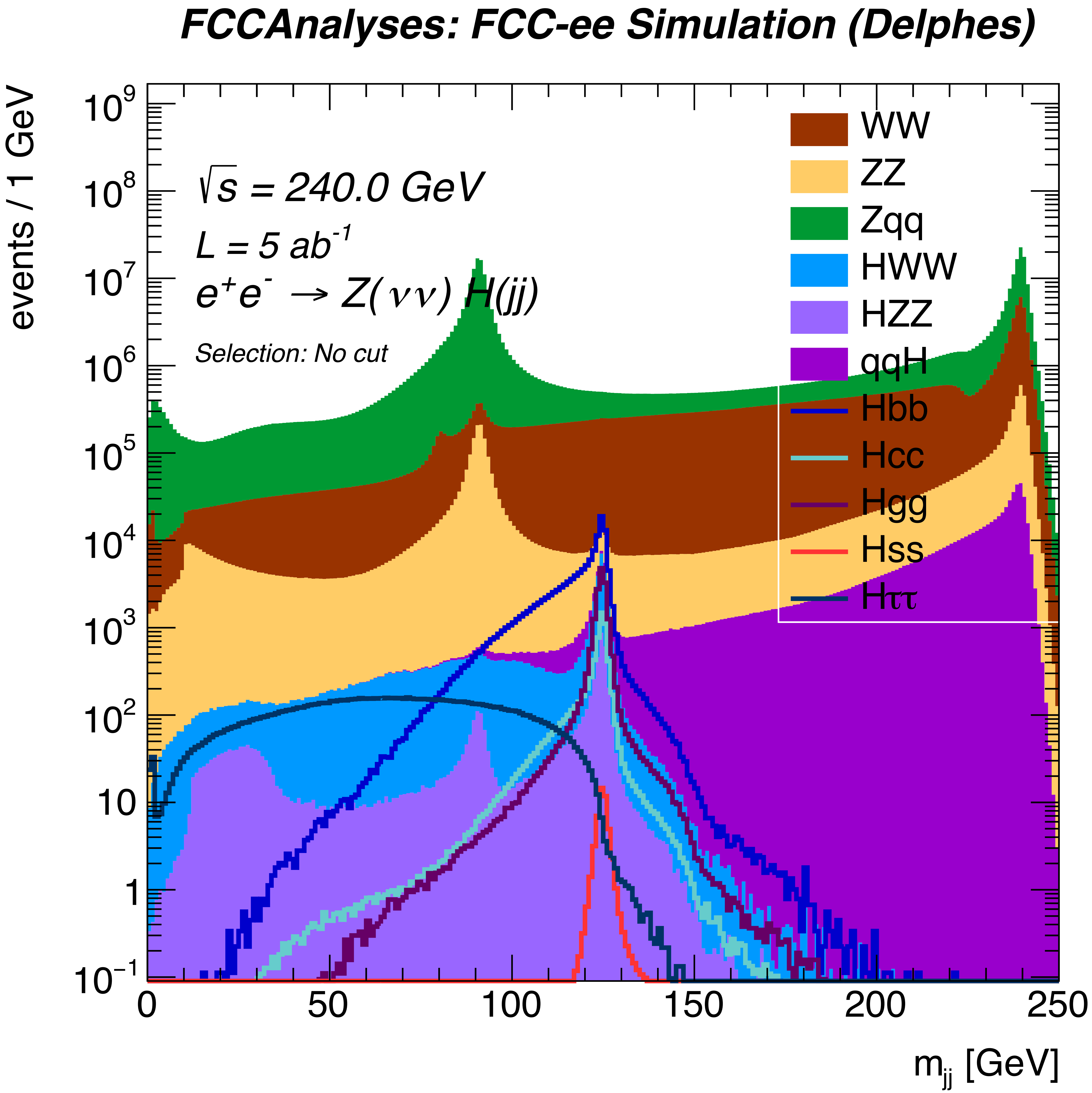
Analysis overview

- Signal: $H \to jj \quad (j = b, c, s, g, \tau)$
- Background:
  - $WW, ZZ, Zqq, qqH, HWW, HZZ$
- Jets reconstruction
  - N = 2 Durham kt exclusive algorithm
  - ParticleNet jet tagger (4 categories: b, c, s, g)
- Analysis
  - Events selection (orthogonal to with $Z(ll)H$)
  - Categorization based on tagger scores
  - Fit to extract uncertainties

Statistics

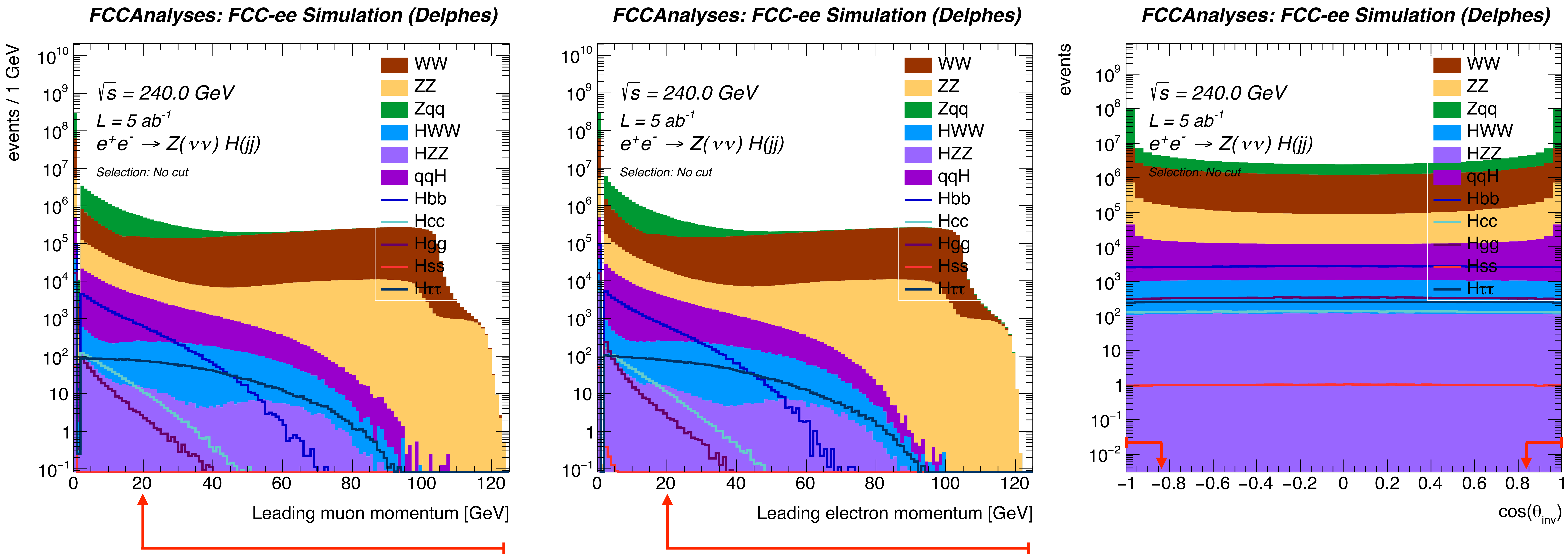
- Initial yield at (scaled for lumi): $\sqrt{s} = 240\,\text{GeV}, \mathscr{L} = 5\,\text{ab}^{-1}$

	Before selection
Hbb	1.34e+05
Hcc	6.68e+03
Hgg	1.66e+04
Hss	5.08e+01
Hττ	1.26e+04
HWW	4.80e+04
HZZ	5.77e+03
qqH	6.82e+05
WW	7.99e+07
ZZ	6.48e+06
Zqq	2.62e+08

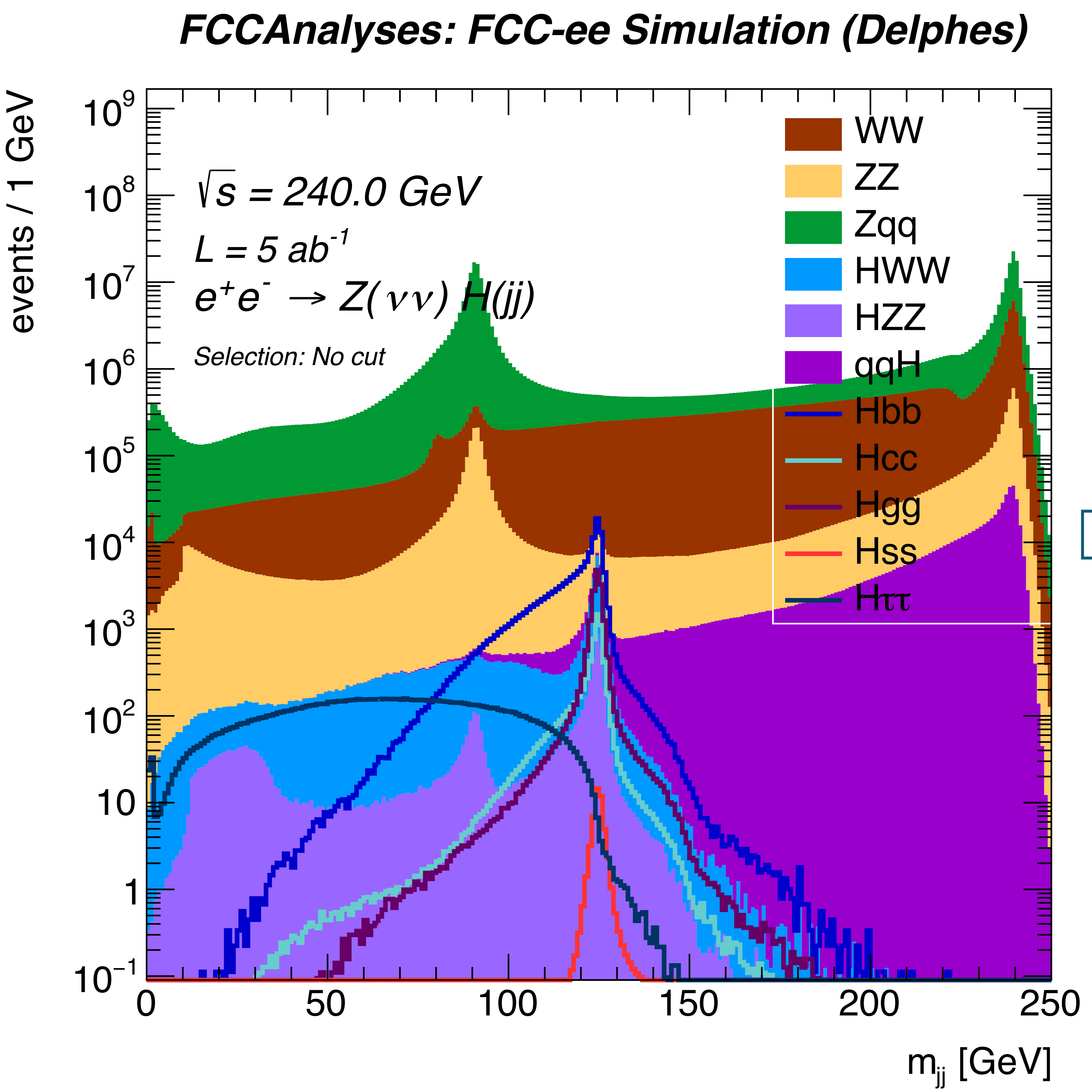


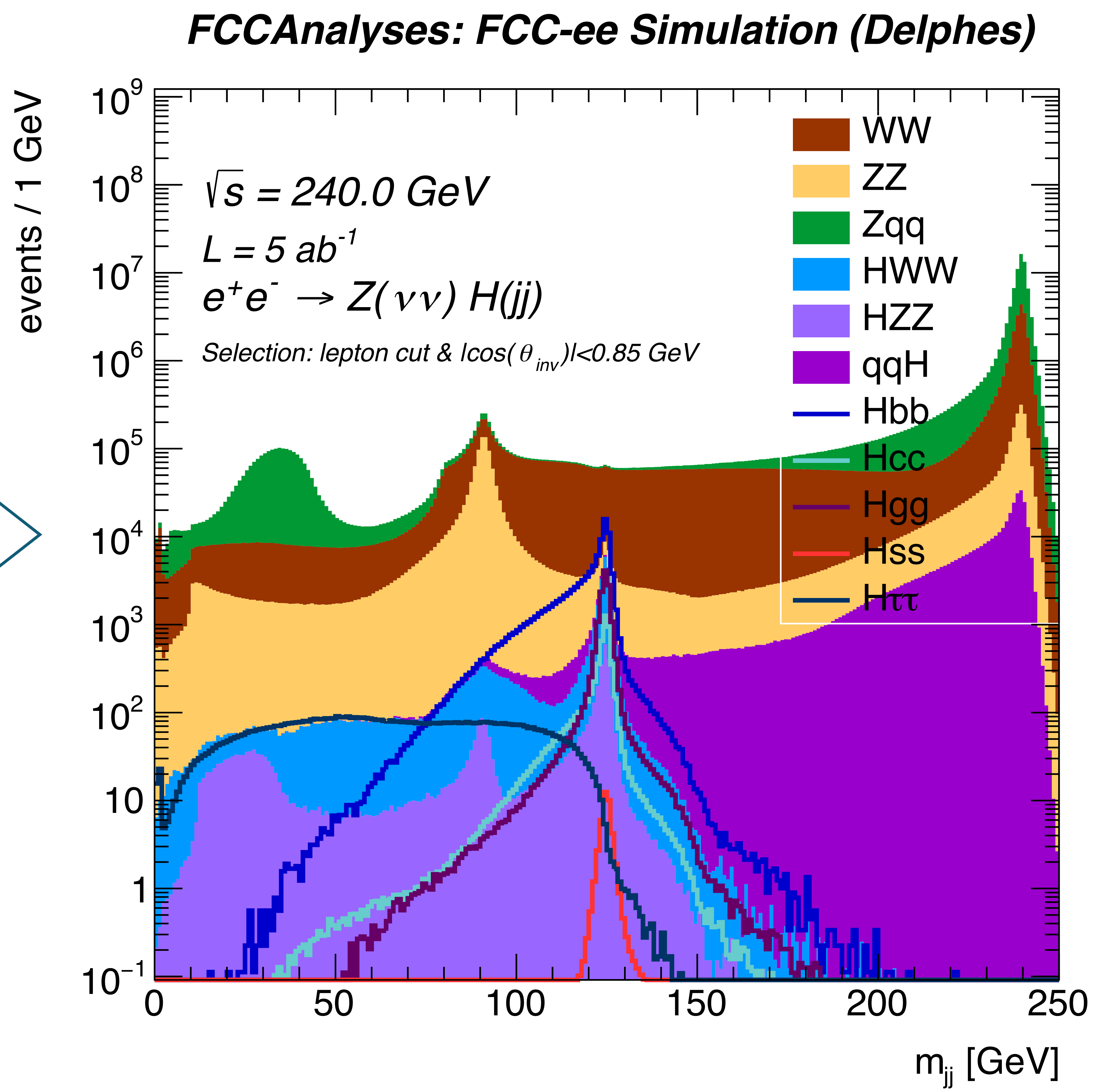
Cuts

- Cut on lepton p (<20GeV) (orthogonal to $Z(ll)$ analysis) and $|\cos(\theta_{inv})|<0.85$
  - ➡ Suppress leptonic and semi-leptonic and $\nu\bar{\nu}Z(Z \rightarrow q\bar{q})$ backgrounds



m_{jj} after initial cuts





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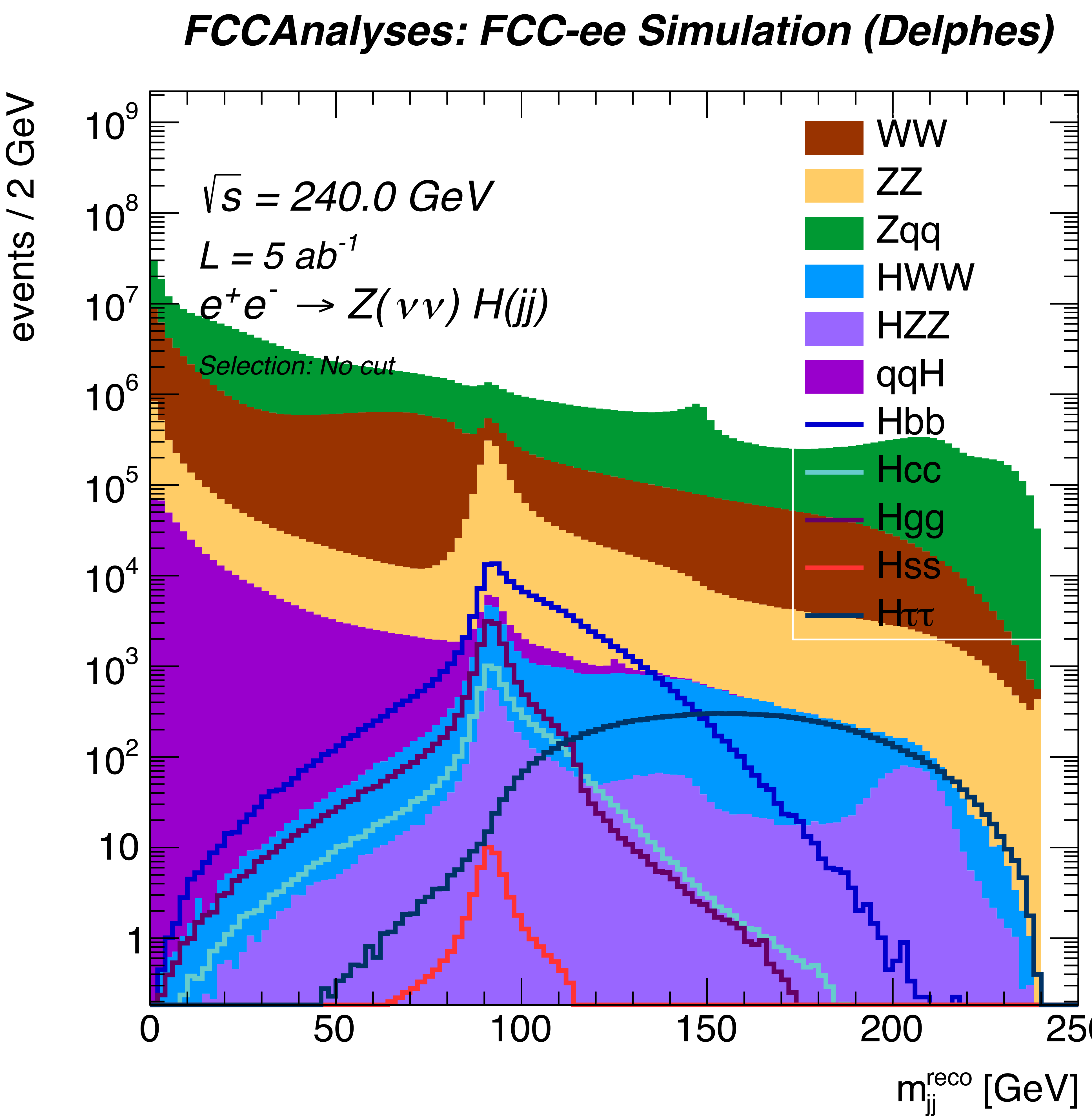
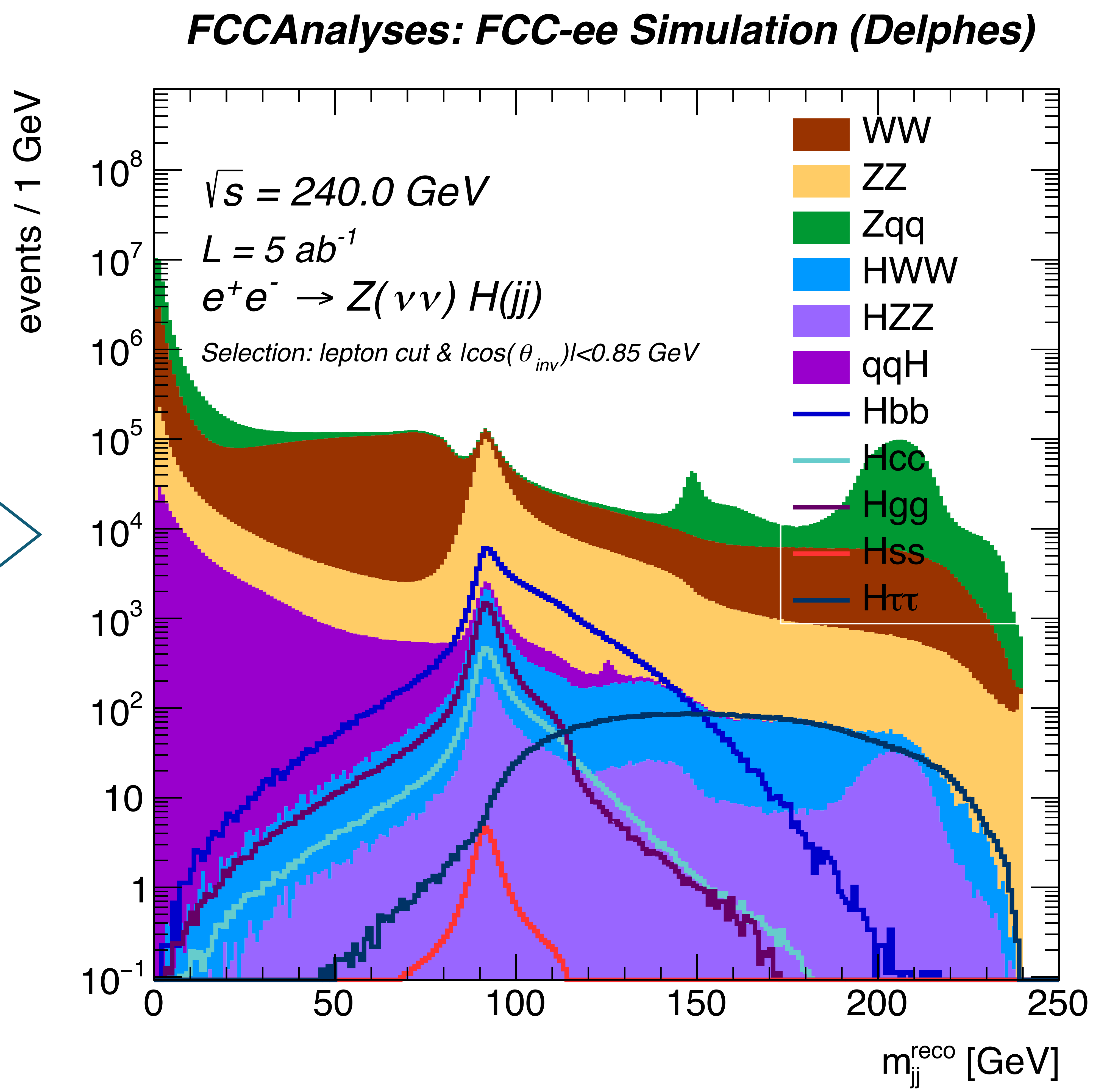
m^{recoil} after initial cuts





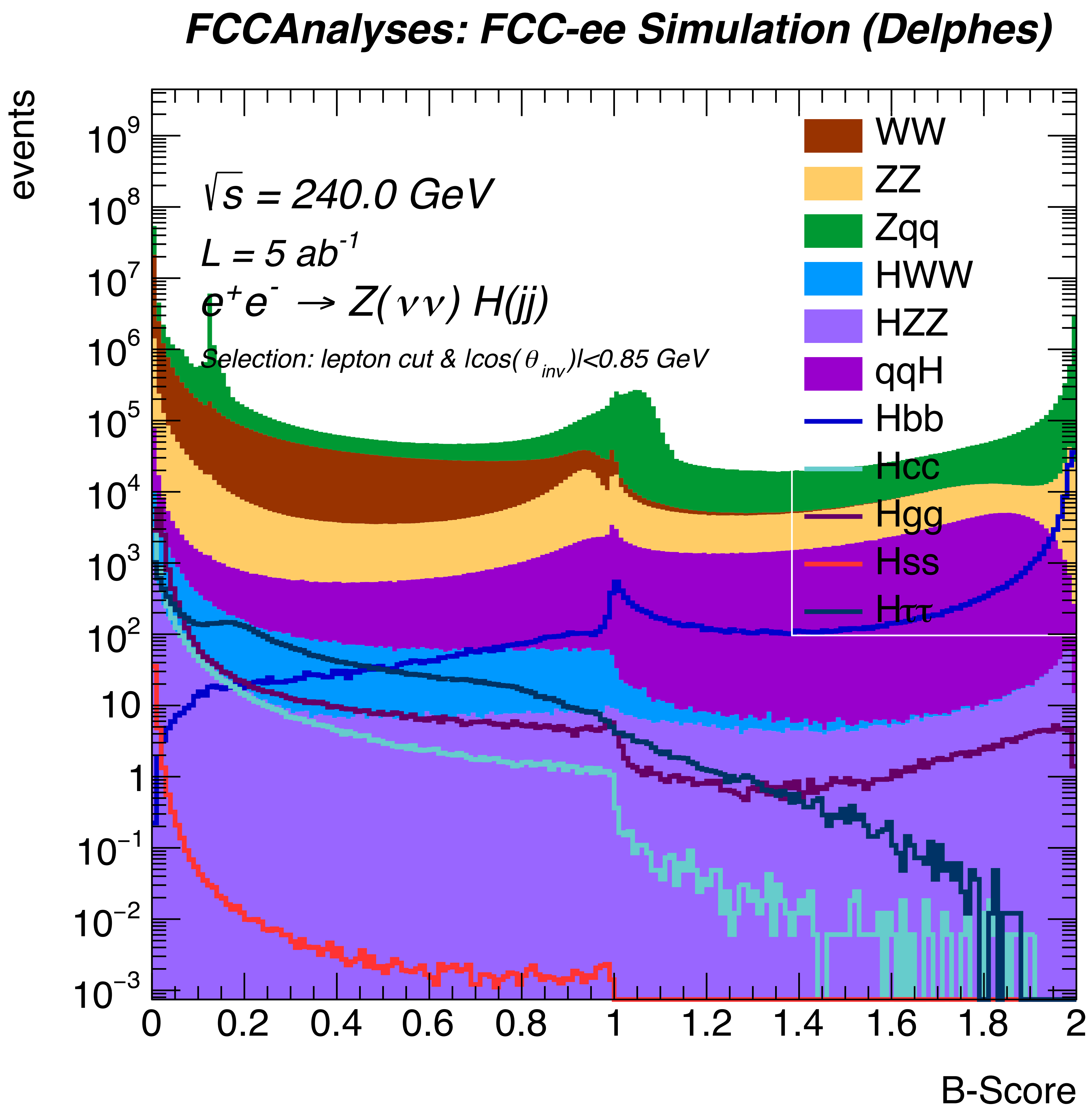
Yields & Cut-flow

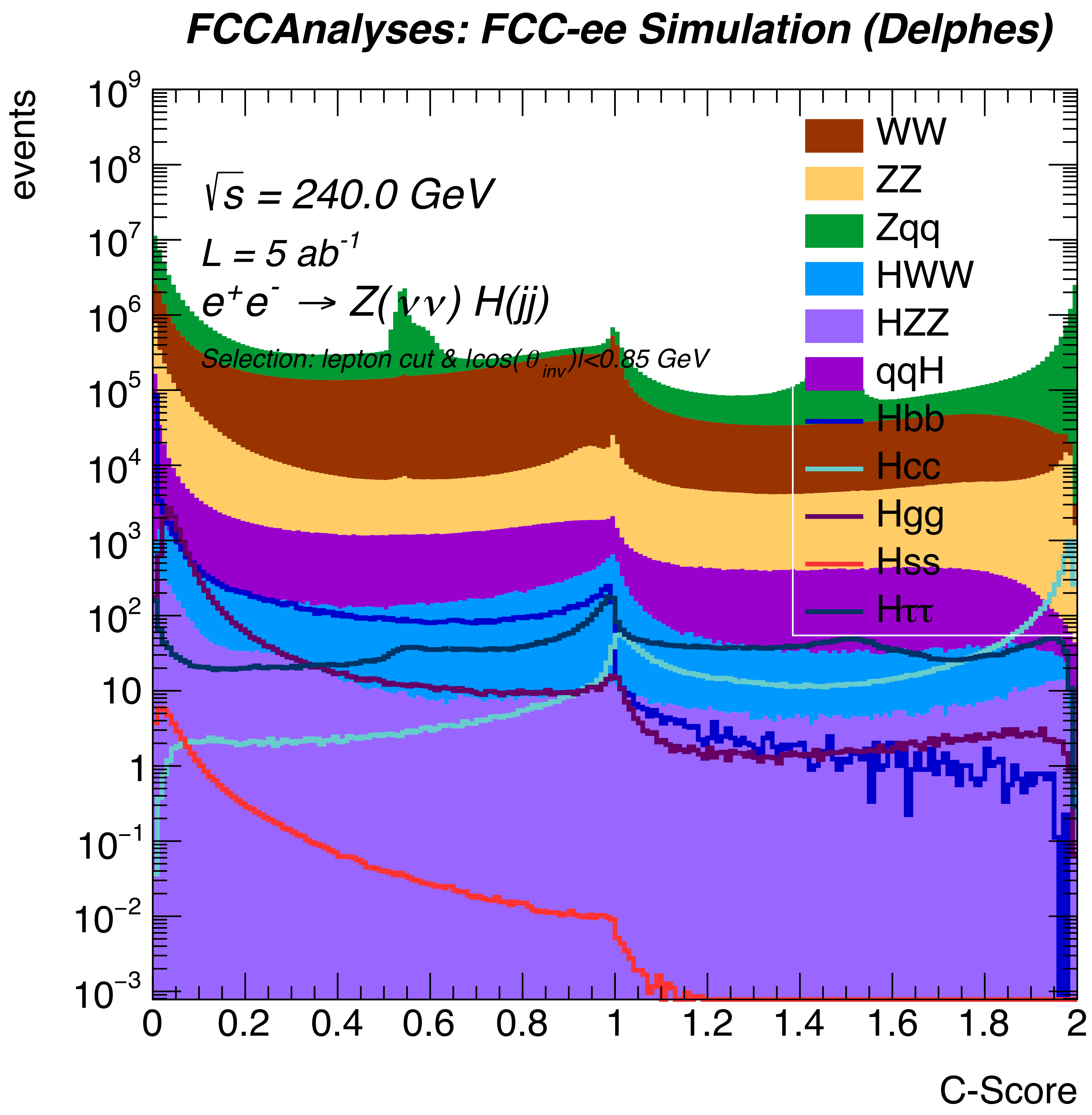
		Before selection	$p_\mu < 20\,GeV$	$p_e < 20\,GeV$	$\|cos(\theta_{inv})\| < 0.85$	efficiency
Hbb	Yield(10^5)	1.34	1.29	1.23	1.06	0.786
	Sig.	7.169921	7.119619	7.011417	10.945233	
Hcc	Yield(10^3)	6.68	6.60	6.53	5.59	0.837
	Sig.	0.357426	0.364260	0.372232	0.577206	
Hgg	Yield(10^4)	1.66	1.66	1.66	1.42	0.856
	Sig.	0.888214	0.916168	0.946256	1.466248	
Hss	Yield	51	51	51	44	0.856
	Sig.	0.002718	0.002804	0.002896	0.004492	
$H\tau\tau$	Yield(10^3)	12.6	10.8	9.11	7.75	0.613
	Sig.	0.674187	0.596061	0.519301	0.800241	
HWW	Yield(10^4)	4.80	4.08	3.40	2.92	0.607
HZZ	Yield(10^3)	5.77	5.43	5.08	4.34	0.752
qqH	Yield(10^5)	6.82	6.27	5.76	4.14	0.607
WW	Yield(10^7)	7.99	6.37	4.89	2.94	0.368
ZZ	Yield(10^6)	6.48	5.76	5.08	3.21	0.495
Zqq	Yield(10^7)	26.2	25.8	25.3	6.06	0.231

$S/\sqrt{S+B}$

Sum of dijet Scores from the tagger (I)

- B & C





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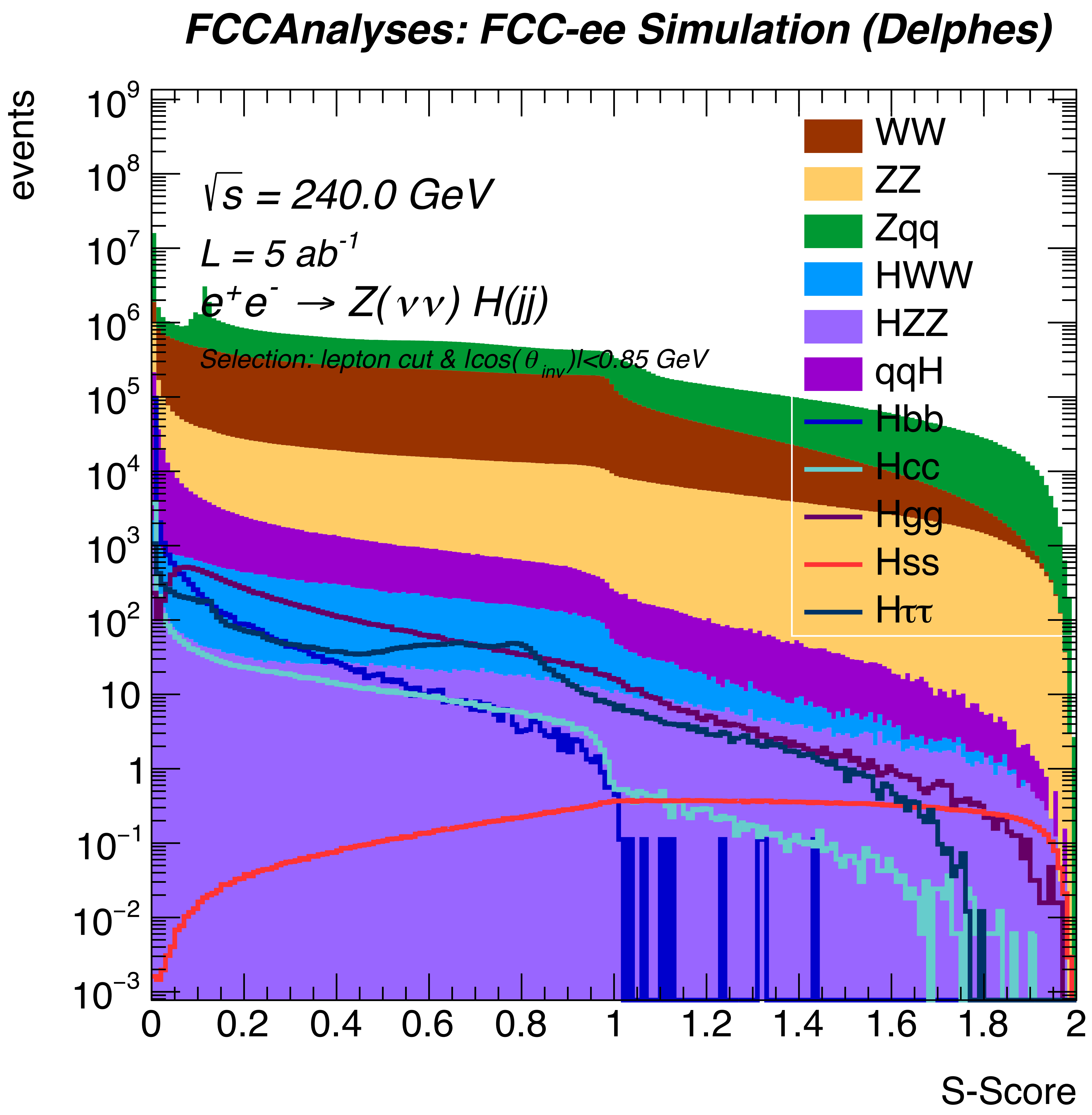
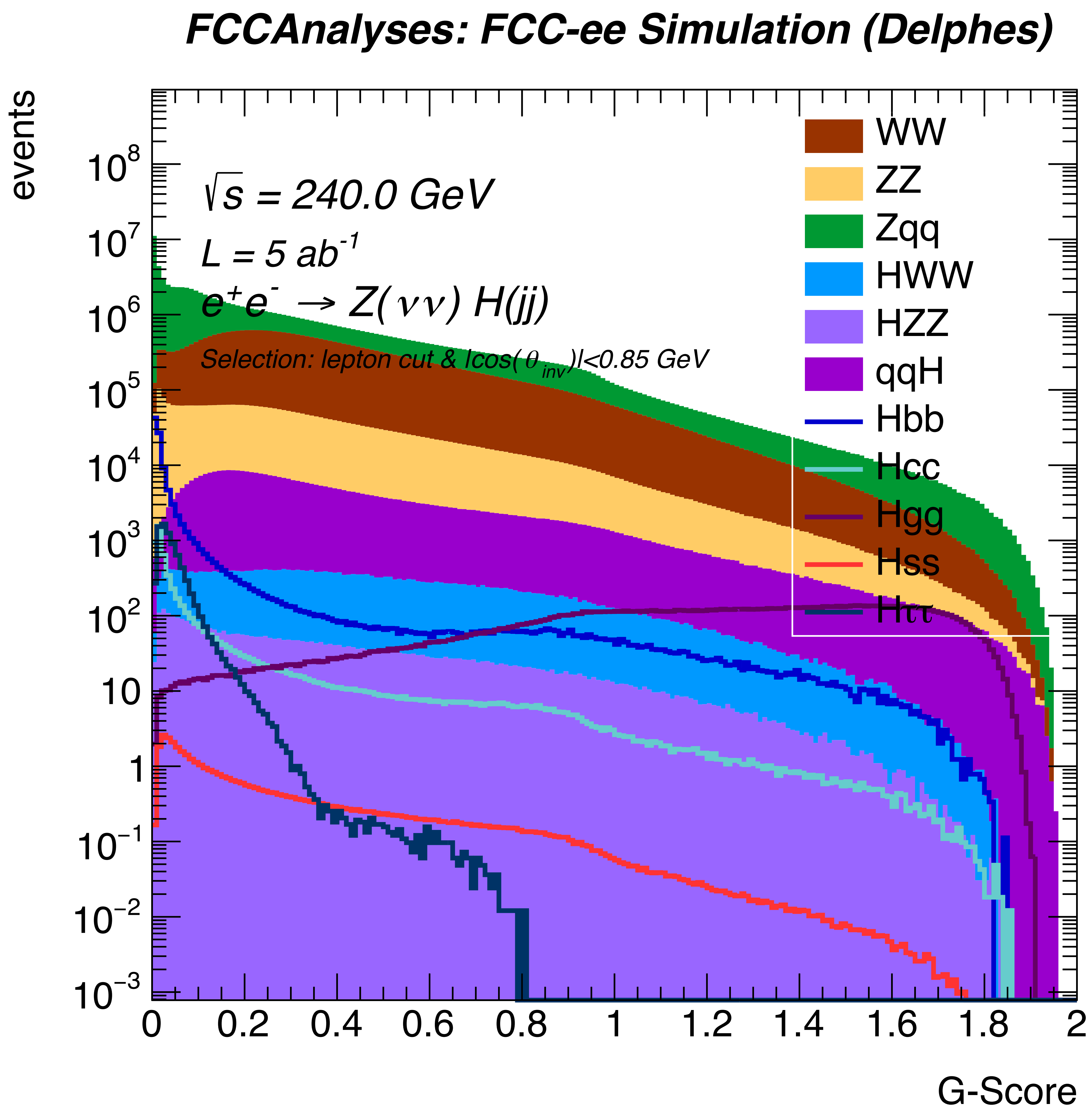
Sum of dijet Scores from the tagger (II)

- S & G





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Score Map

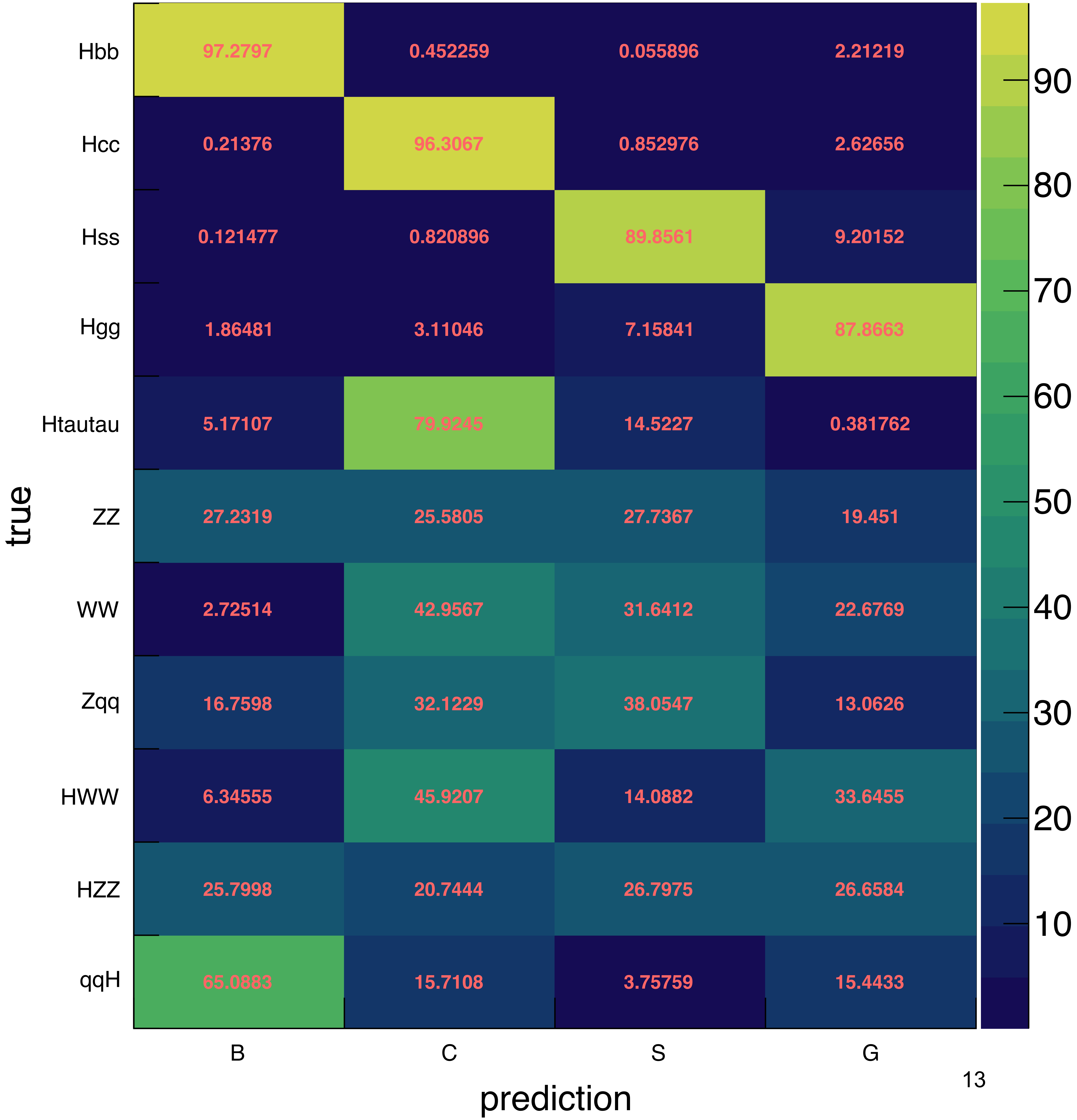
- Events are categorised from the sum of the two jets score

$$\forall \text{ event: } J_{12}^{score} = J_1^{score} + J_2^{score}, J = b, c, s, g$$

$$\text{eg. if: } J_1^{score} = b \;\&\; J_2^{score} = b \implies B_{like}^{score}$$

$$\text{if } B_{like}^{score} > C_{like}^{score} > S_{like}^{score} G_{like}^{score} \implies B_{like}^{event}$$

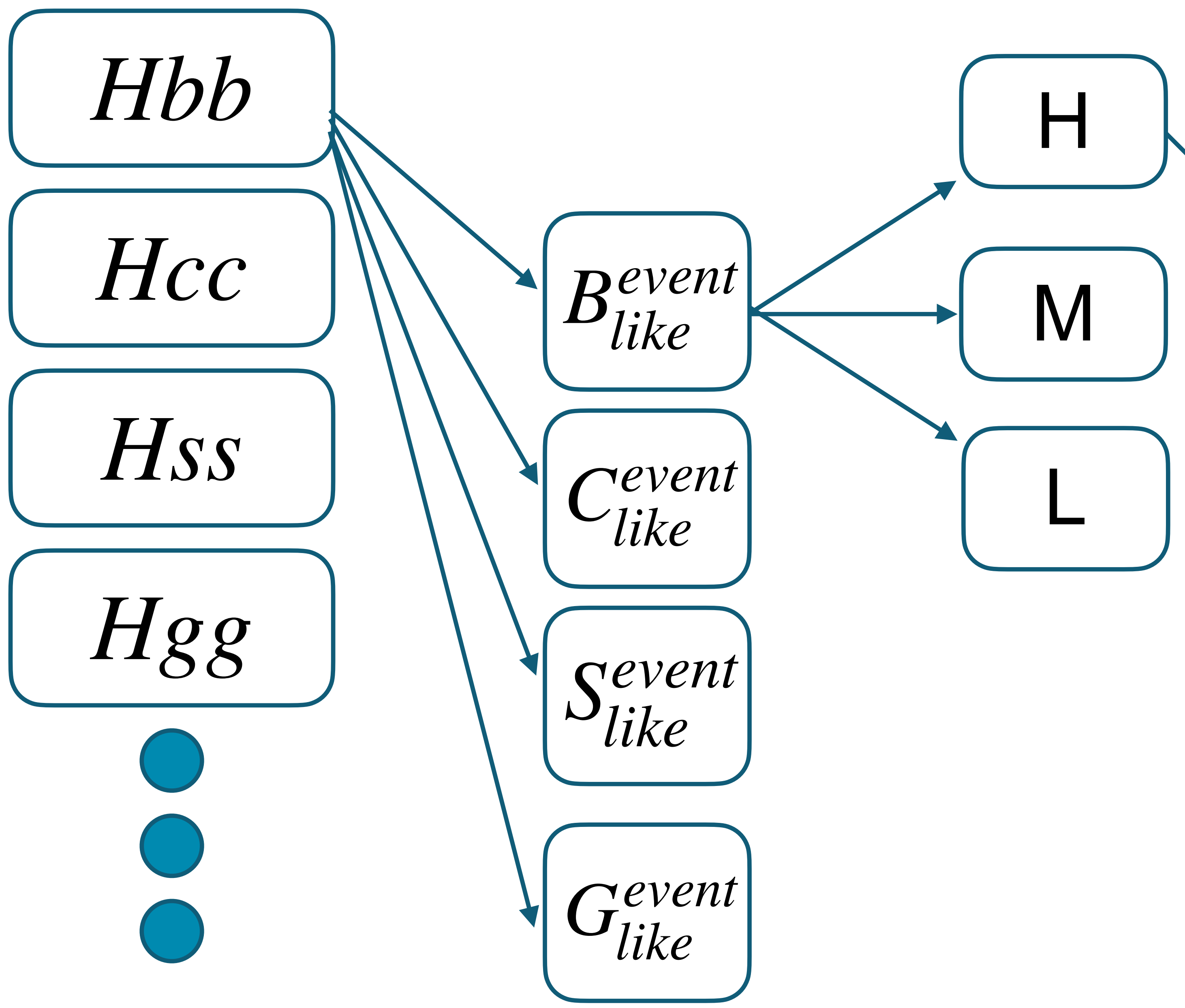
- Runs over the production processes and the jet categories



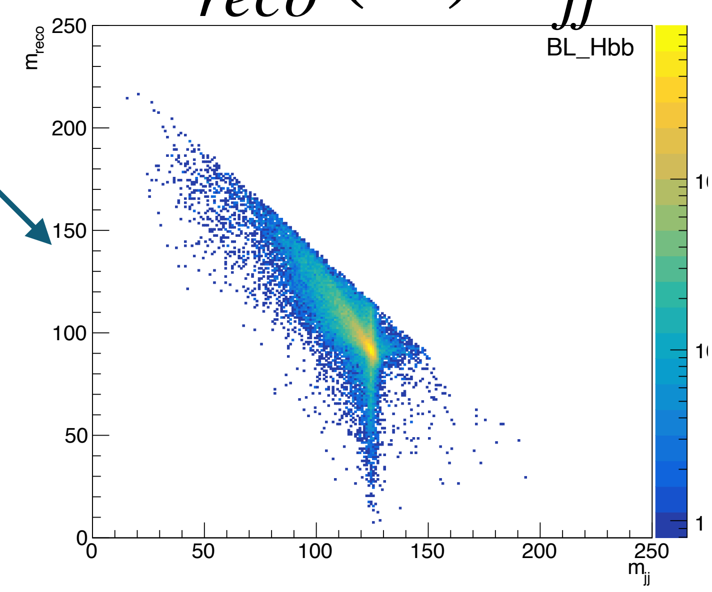
Categories

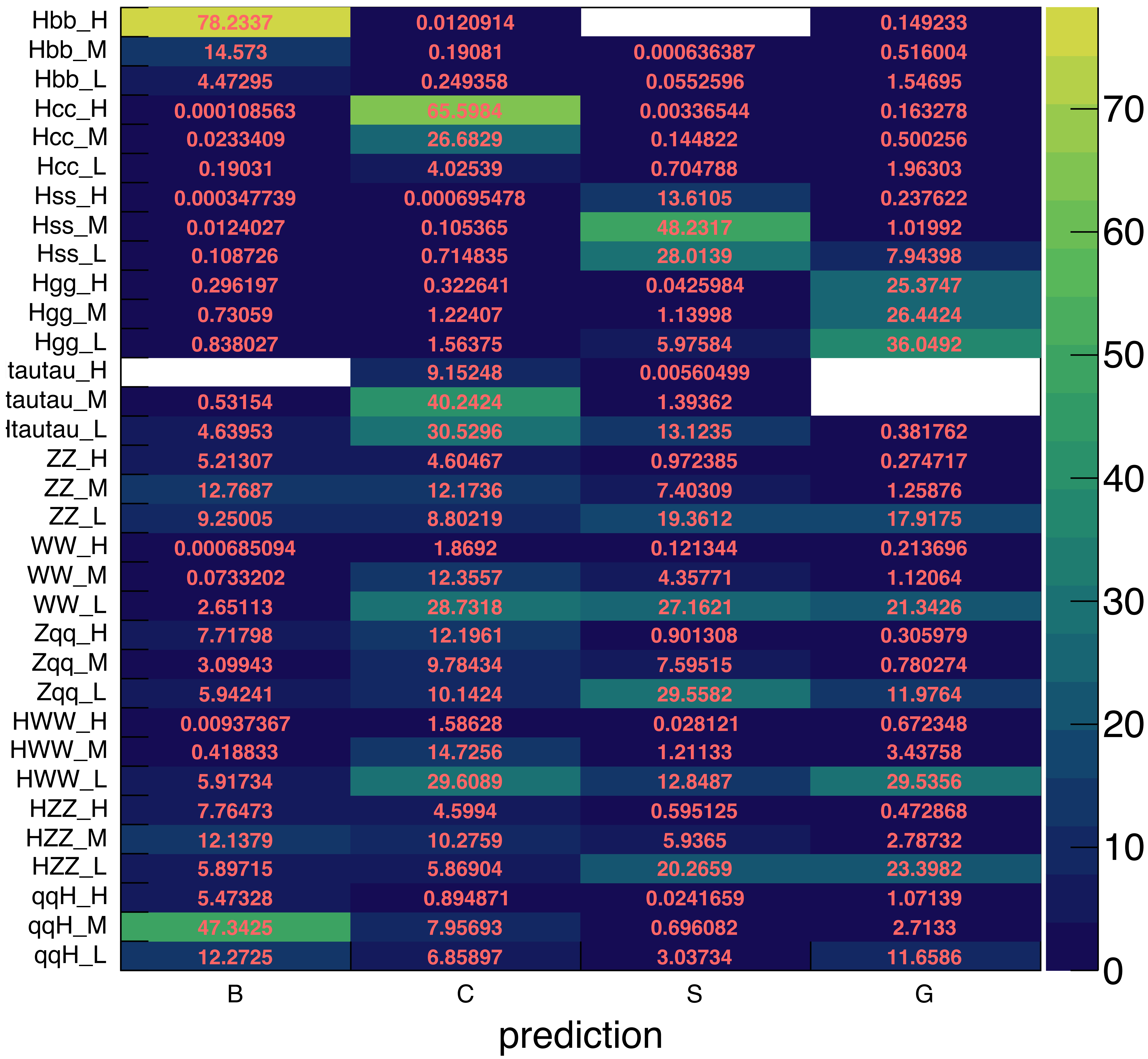
- Split the J_{like}^{score} in three bins of purity: Low, Medium, High

	B	C	S	G
L	< 1.1	< 1.0	< 1.1	< 1.2
M	$\in [1.1, 1.9]$	$\in [1.0, 1.8]$	$\in [1.1, 1.7]$	$\in [1.2, 1.5]$
H	> 1.9	> 1.8	> 1.7	> 1.5



$m_{reco}\,(vs)\,m_{jj}$





Tagger efficiency talk here

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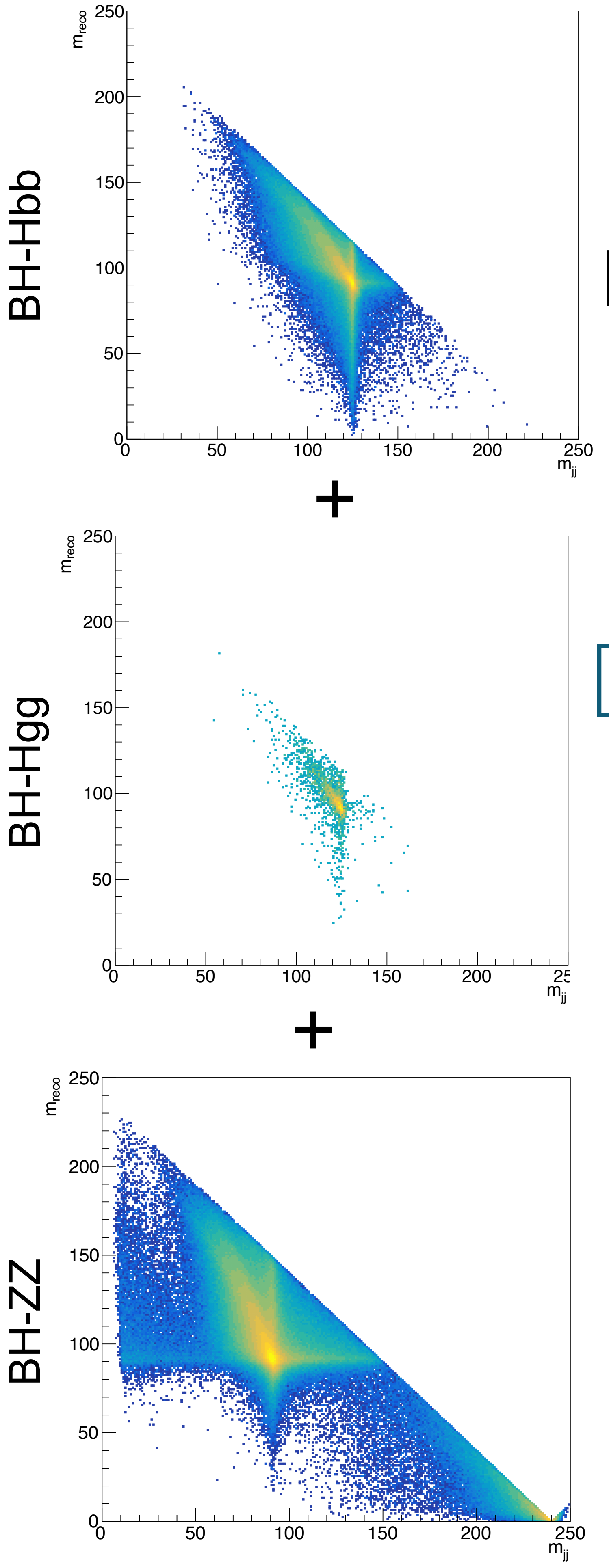
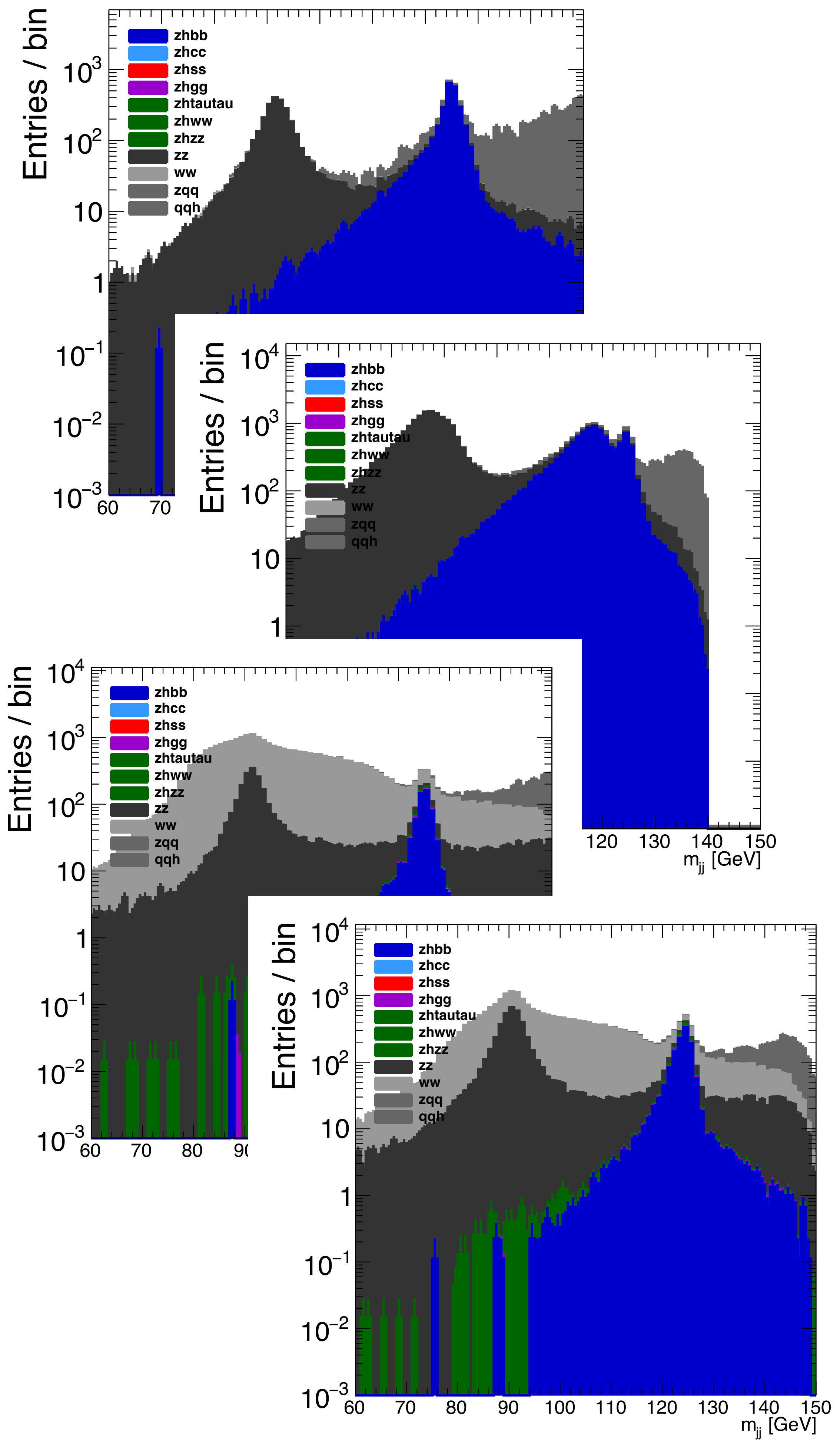
Fit Categories & Signal extraction

- For the fit the HiggsAnalysis-CombinedLimit was used (within CMSSW - http://cms-analysis.github.io/HiggsAnalysis-CombinedLimit/ (open access)) along with CombineHarvester (http://cms-analysis.github.io/CombineHarvester/)



Projection with 5 GeV bin on m_{recoil}



Shape-Combined fit for all S+B in the 12 categories

	Precision at 68 % CL
$r(Hgg)$	1.1 %
$r(Hs\bar{s})$	137 %
$r(Hc\bar{c})$	2.6 %
$r(Hb\bar{b})$	0.36 %

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Conclusions

- Able to reproduce the full analysis of $H(jj)$ in the $Z(\nu\nu)$ final state
  - Results look reasonable
- Looking forward to get some more experience with the tagger and study the performance in different categories (u,d is coming check here)
- Will be looking into the full hadronic final states
- We are interested to study the tracker performance in order to optimise the design and requirements for these physics cases
- We are looking for the best possible ways to collaborate and contribute to the existing effort