Measurement of hadronic Higgs boson branching ratios at FCC-ee with Z(ll)H events at $\sqrt{s}$=240 GeV

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Introduction

- **Goals**:
  - estimate sensitivity of FCC-ee to hadronic branching ratios of Higgs boson (bb / cc / gg) (=> couplings to b/c/g)
  - compare to estimates in FCC-ee CDR
  - longer term: assess impact of different b/c/g taggers or working points or different FCC-ee detector designs

- **Notes**:
  - Work done during **internships of two students in APC-Paris**, Paul Paquiez and Mariette Jolly, in March-July 2021.
    - **Only statistical uncertainties** for the time being, will consider systematic uncertainties only later
    - **Focus on Z(ll)H channel at $\sqrt{s}$=240 GeV**: use m_{recoil} distribution to estimate signal and background after selection
      - Method developed however should be extendable easily to Z($\nu\nu$)H and Z(qq)H
  - **Work performed on privately produced MC samples**: when we started, there weren't centrally-available tools or samples to implement some of the selections that we wanted (more details later)
    - Recently I've been able to port the analysis to the official FCC-ee "spring 2021" samples, using the FCC analysis code with some extensions that I developed for that purpose. The results are very preliminary. A 4-month intern student starting at the end of this month will further consolidate and extend them
  - **Assume an integrated luminosity of 5/ab**

Projections in FCC CDR

- Assuming **5/ab at 240 GeV**, the projected sensitivities at FCC-ee in the CDR (Eur. Phys. J. C 79, 474 (2019), Table 4.1) scaled to the Z(ll) channel alone (taking Z(ll)H/Z(ll+qq+vv)H from Table 6 of CEPC, https://arxiv.org/pdf/1810.09037.pdf):

Higgs decay mode	**Rel. unc. on σBR(bb) (%)**
bb	0.8
cc	5.3
gg	6.1

* Considering only background from ZZ and WW (background from ZH with other Higgs decays not considered)

Analysis strategy

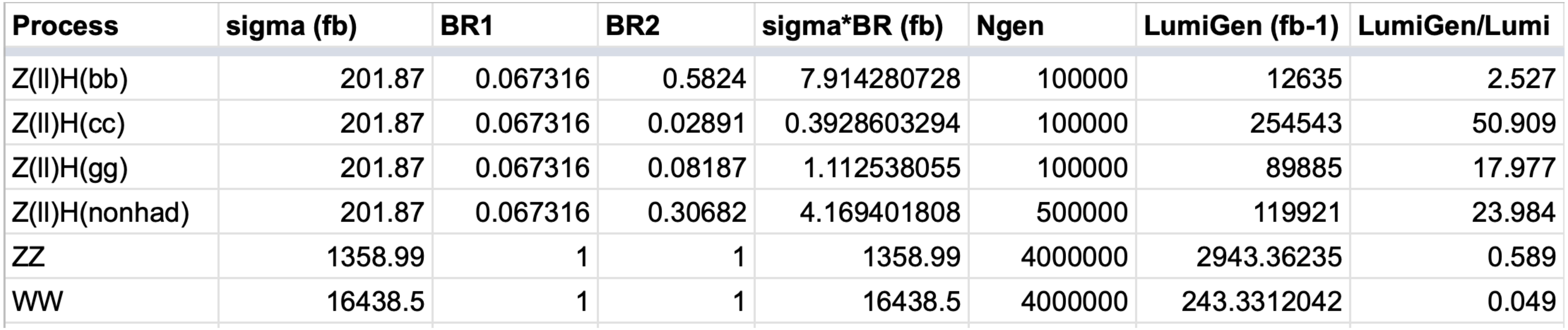
- The measurements proceeds in the following steps:
  - Event **reconstruction**: isolated leptons (and photons), jets and missing energy are reconstructed
  - Event **selection**: events consistent with the signature under study are kept
    - NOTE: So far optimised mainly for signal efficiency, should reoptimise for best BR sensitivity
  - Event **categorisation**: selected events are classified in categories based on # of b-, c- and (if applicable) g-tagged jets
  - **Fit** for BR measurement:
    - the signal yield in each category and for each Higgs decay mode (bb, cc, gg, non-hadronic) is extracted through a **simultaneous extended maximum likelihood fit to the recoil mass distribution of the various tagging categories**
    - Assuming tagging efficiencies for each flavour type to be known, the acceptance of each category for the various Z(ll)H(XX) is known and the system of equations relating the yields to the product σBR can be solved
    - In practice, in the likelihood the yields are expressed directly in terms of products of σBR times the acceptances and the fit returns σBR

Samples

- Signal and background samples were **privately generated** using the **FCC-ee software stack** for **Delphes+Pythia8**
- In Pythia8, **ISR and FSR** were turned **on**, while **beam energy spread** and **primary vertex smearing** were **off**
- The FCC-ee **IDEA Delphes card** (with track covariance) was **modified**
  - to implement **custom tagging efficiencies** (b/c/g)
  - to use a **different jet clustering algorithm (Valencia)** more adapted to ee collision than anti-k_t
  - to **remove isolated electrons, muons and photons from the list of EFlow objects used for jet clustering**

- **Signal samples**: Z(ll)H(bb), Z(ll)H(cc), Z(ll)H(gg), l=e+mu, generated separately and normalised using SM Higgs BRs
- **Background samples**: Z(ll)H(non-had), ZZ, WW
- **Cross sections** (ZH, ZZ and WW) taken from central FCC-ee json file

Samples (cont'd)

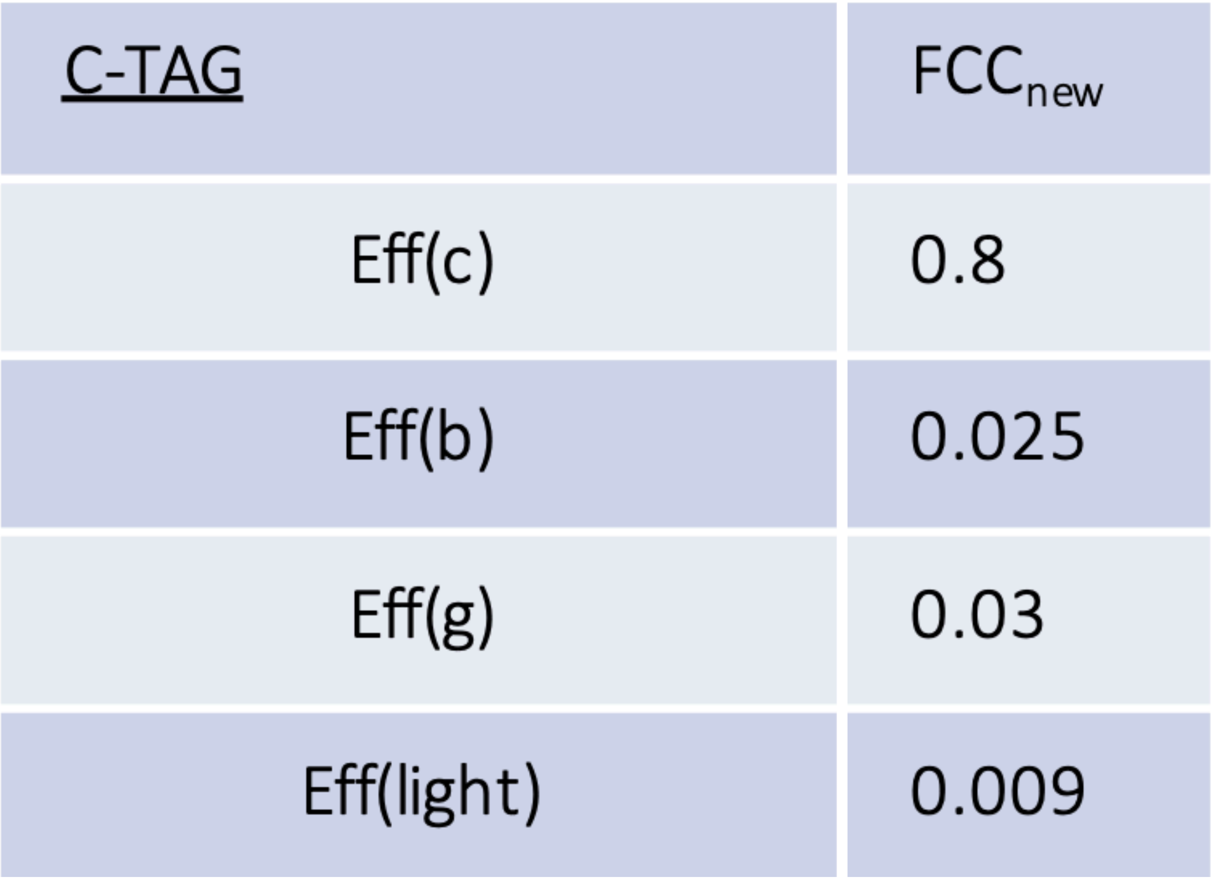


Process	sigma (fb)	BR1	BR2	sigma*BR (fb)	Ngen	LumiGen (fb-1)	LumiGen/Lumi
Z(ll)H(bb)	201.87	0.067316	0.5824	7.914280728	100000	12635	2.527
Z(ll)H(cc)	201.87	0.067316	0.02891	0.3928603294	100000	254543	50.909
Z(ll)H(gg)	201.87	0.067316	0.08187	1.112538055	100000	89885	17.977
Z(ll)H(nonhad)	201.87	0.067316	0.30682	4.169401808	500000	119921	23.984
ZZ	1358.99	1	1	1358.99	4000000	2943.36235	0.589
WW	16438.5	1	1	16438.5	4000000	243.3312042	0.049

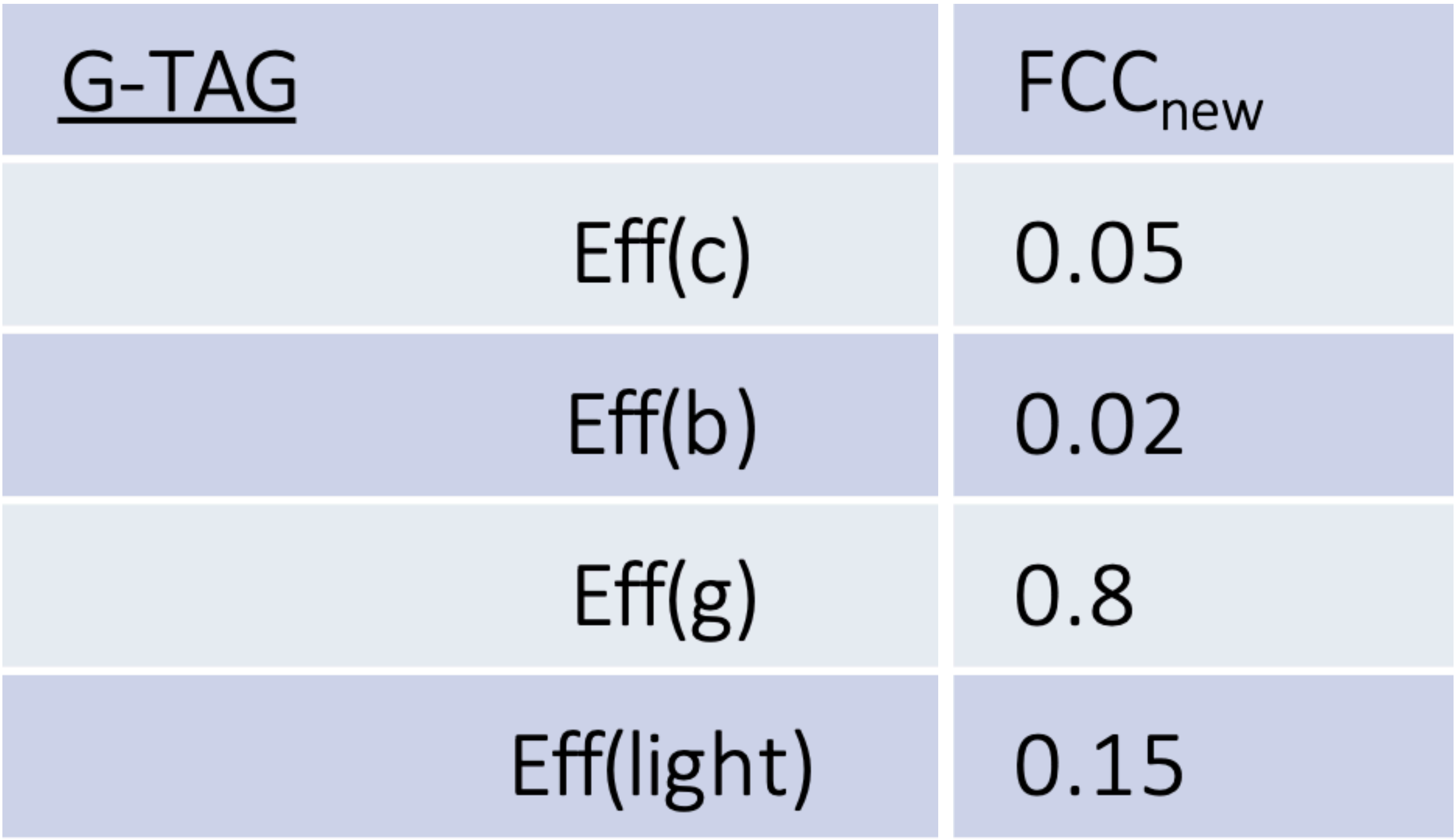
Flavour tagging

- Flavour tagging is implemented via basic Delphes modules, where a **jet is tagged according to whether there is a MC b, c or gluon within a given DeltaR to the jet and based on efficiency tables vs the jet true flavour**
- The work presented here uses the numbers presented at the June 2021 FCC week: https://indico.cern.ch/event/995850/contributions/4415991/attachments/2273135/3861058/flavour_tagging_fccee.pdf

B-TAG	FCCnew
Eff(b)	0.8
Eff(c)	0.004
Eff(g)	0.007
Eff(light)	<0.001 (*)



C-TAG	FCC_{new}
Eff(c)	0.8
Eff(b)	0.025
Eff(g)	0.03
Eff(light)	0.009



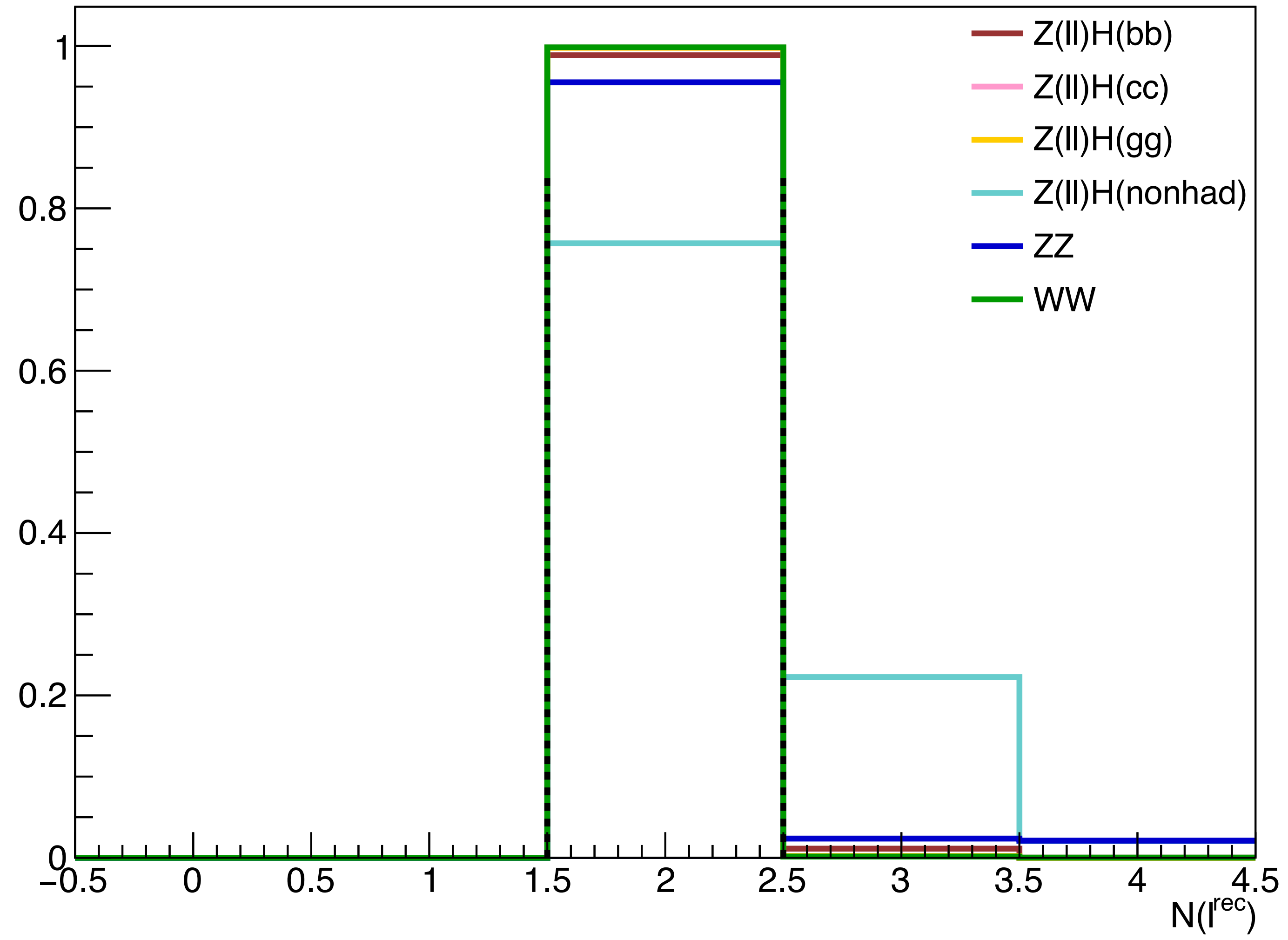
G-TAG	FCC_{new}
Eff(c)	0.05
Eff(b)	0.02
Eff(g)	0.8
Eff(light)	0.15

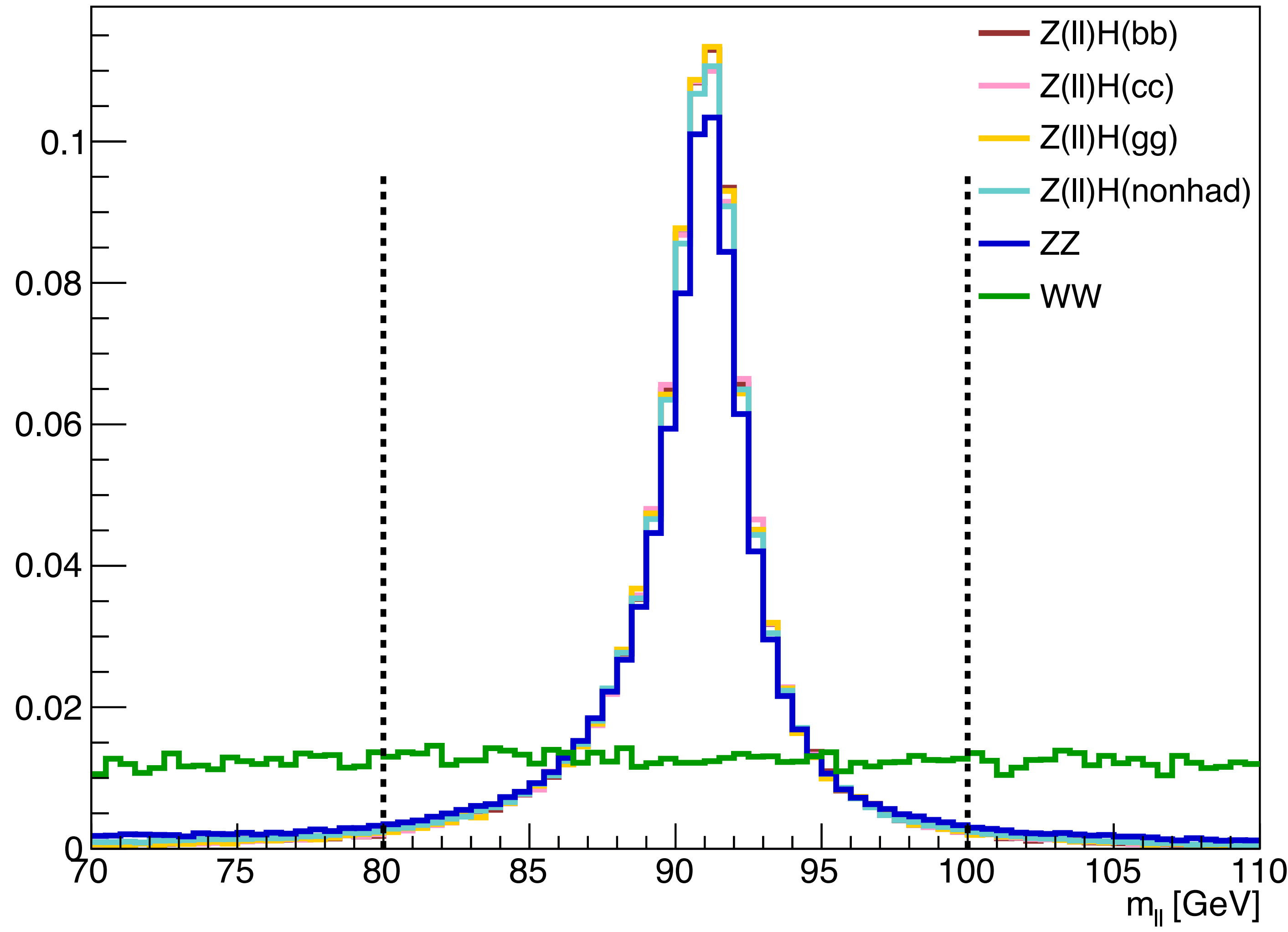
- I will first show results without gluon tagging, and then compare them to those with g-tagging

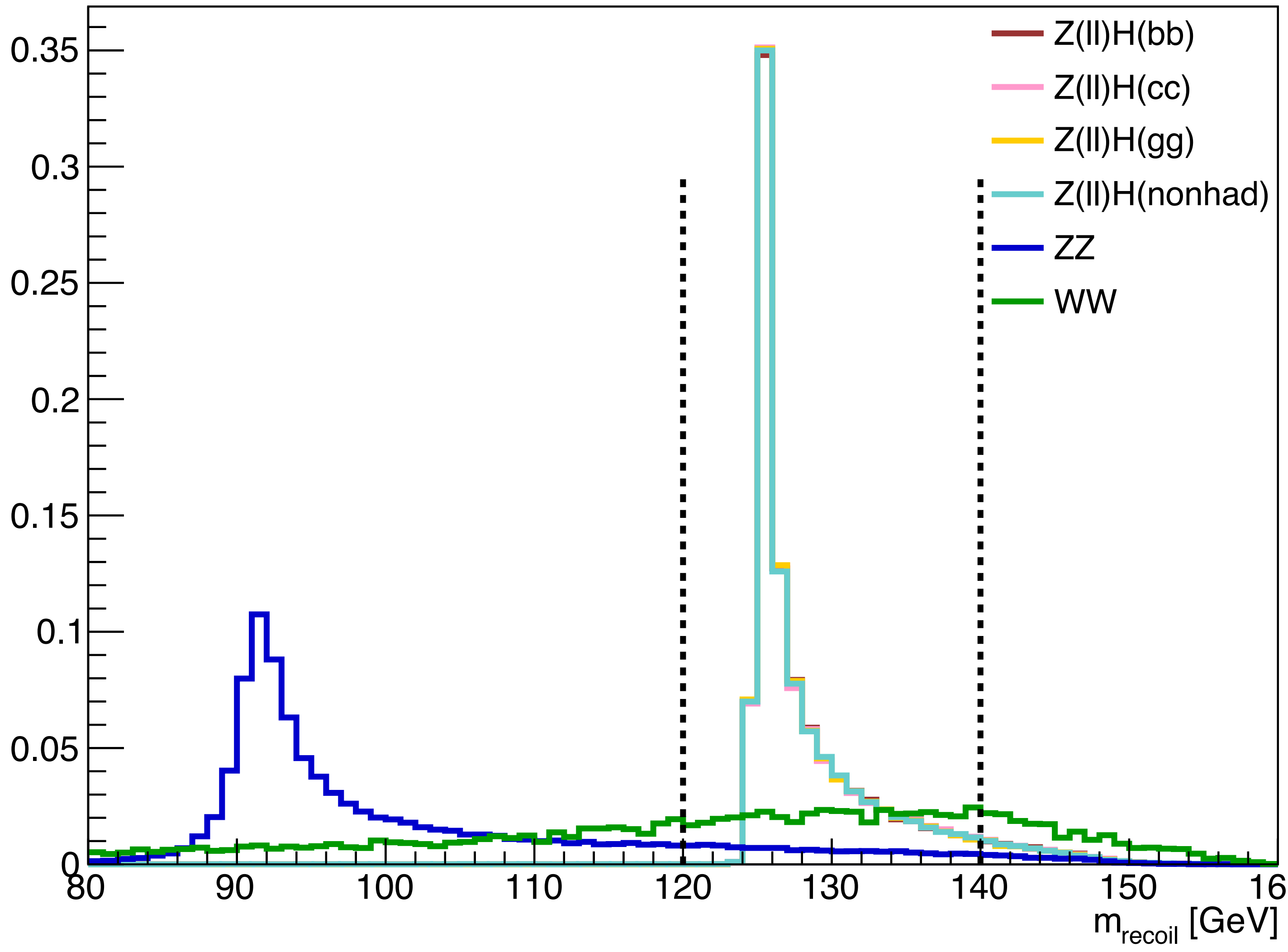
(*) due to a bug, a value of 1% was used instead of 0.1%

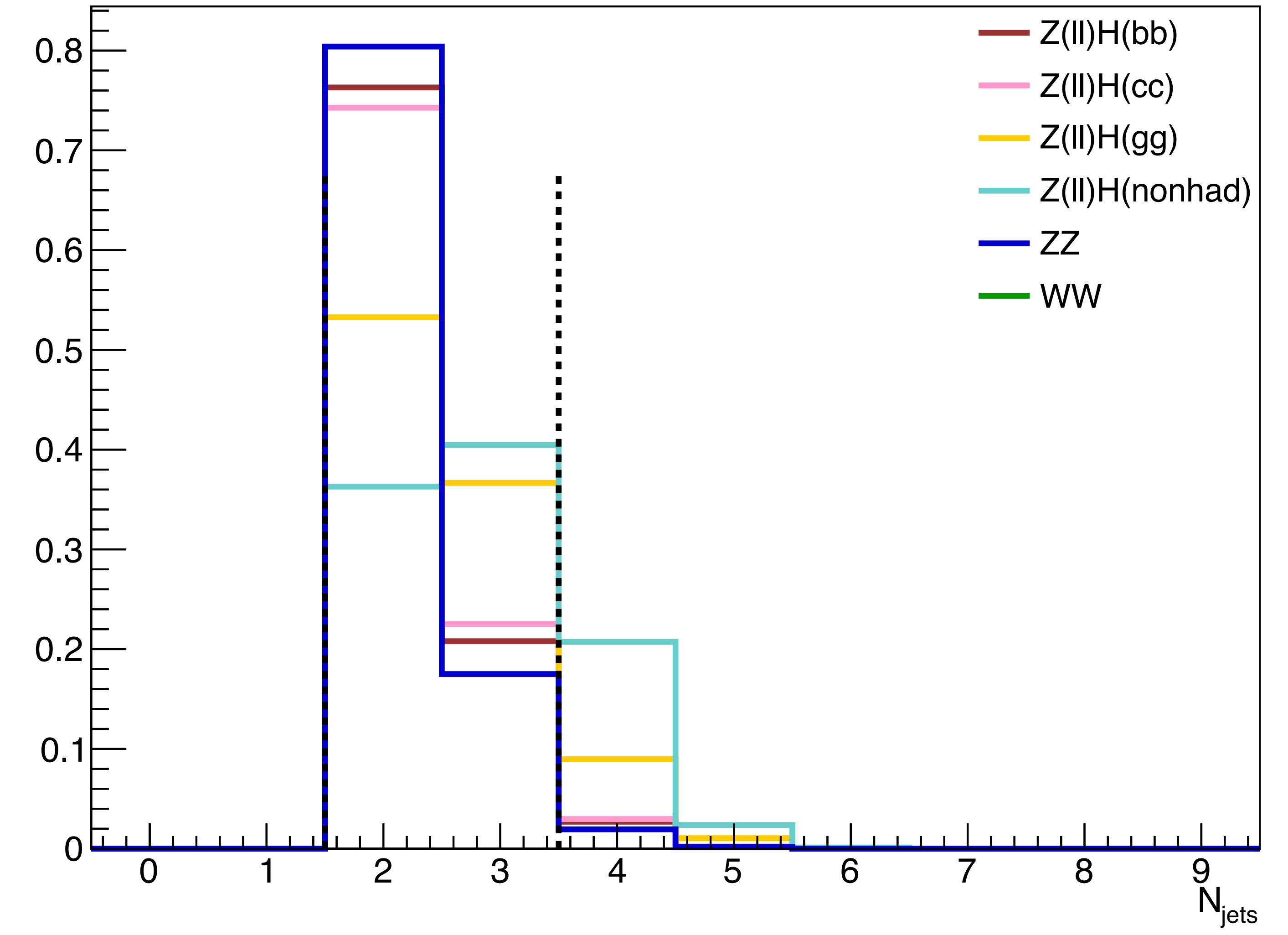
Event selection

- **Z->ll selection:**
  - Exactly 2 isolated electrons or muons, Q=0
  - No additional leptons
  - Lepton momenta between 20 and 80 GeV
  - Dilepton invariant mass in 80-100 GeV
  - |cos(Polar angle of dilepton pair)|<0.8
- **Recoil and jet selection:**
  - Recoil mass in 120-140 GeV
  - Jet momentum in 10-100 GeV
  - Hadronic mass (all jets): long tail, require only m<140 GeV
  - Missing energy < 35 GeV
  - <=3 jets (could actually apply a different #jet cut depending on tagging

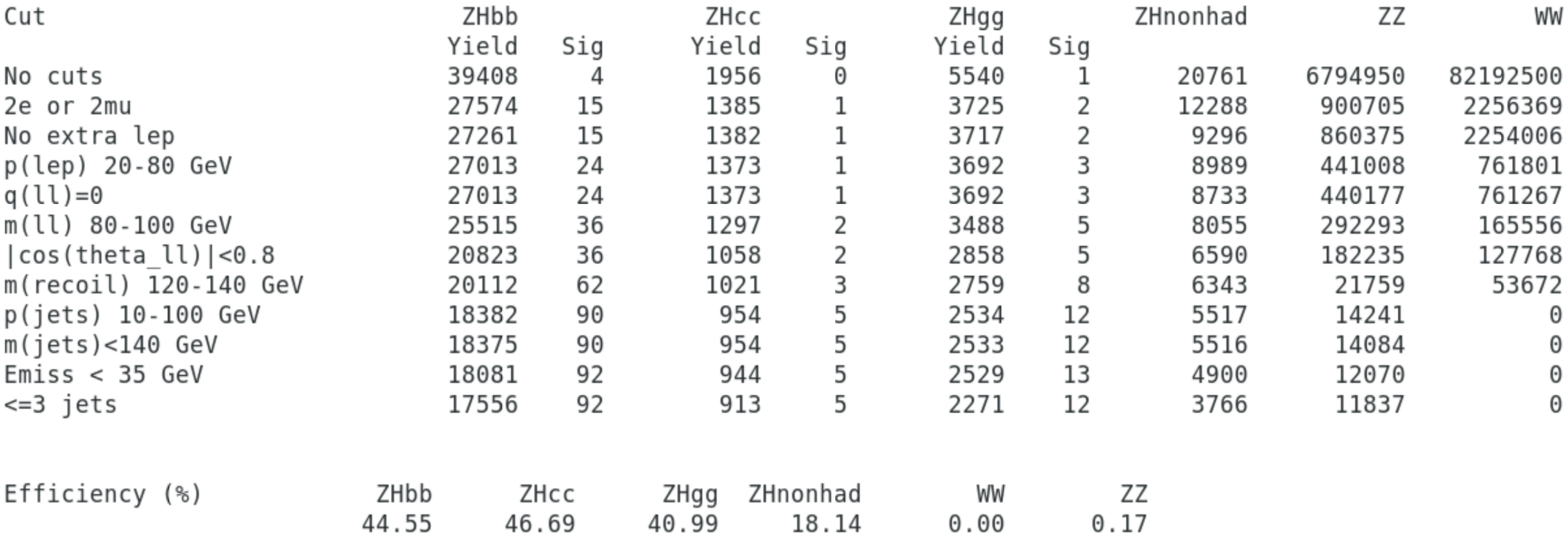








Cutflow, expected yields, efficiency



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Cut                              ZHbb               ZHcc               ZHgg        ZHnonhad          ZZ          WW
                                Yield   Sig        Yield   Sig        Yield   Sig
No cuts                         39408     4         1956     0         5540     1        20761     6794950    82192500
2e or 2mu                       27574    15         1385     1         3725     2        12288      900705     2256369
No extra lep                    27261    15         1382     1         3717     2         9296      860375     2254006
p(lep) 20-80 GeV                27013    24         1373     1         3692     3         8989      441008      761801
q(ll)=0                         27013    24         1373     1         3692     3         8733      440177      761267
m(ll) 80-100 GeV                25515    36         1297     2         3488     5         8055      292293      165556
|cos(theta_ll)|<0.8             20823    36         1058     2         2858     5         6590      182235      127768
m(recoil) 120-140 GeV           20112    62         1021     3         2759     8         6343       21759       53672
p(jets) 10-100 GeV              18382    90          954     5         2534    12         5517       14241           0
m(jets)<140 GeV                 18375    90          954     5         2533    12         5516       14084           0
Emiss < 35 GeV                  18081    92          944     5         2529    13         4900       12070           0
<=3 jets                        17556    92          913     5         2271    12         3766       11837           0


Efficiency (%)             ZHbb      ZHcc      ZHgg  ZHnonhad        WW        ZZ
                          44.55     46.69     40.99     18.14      0.00      0.17
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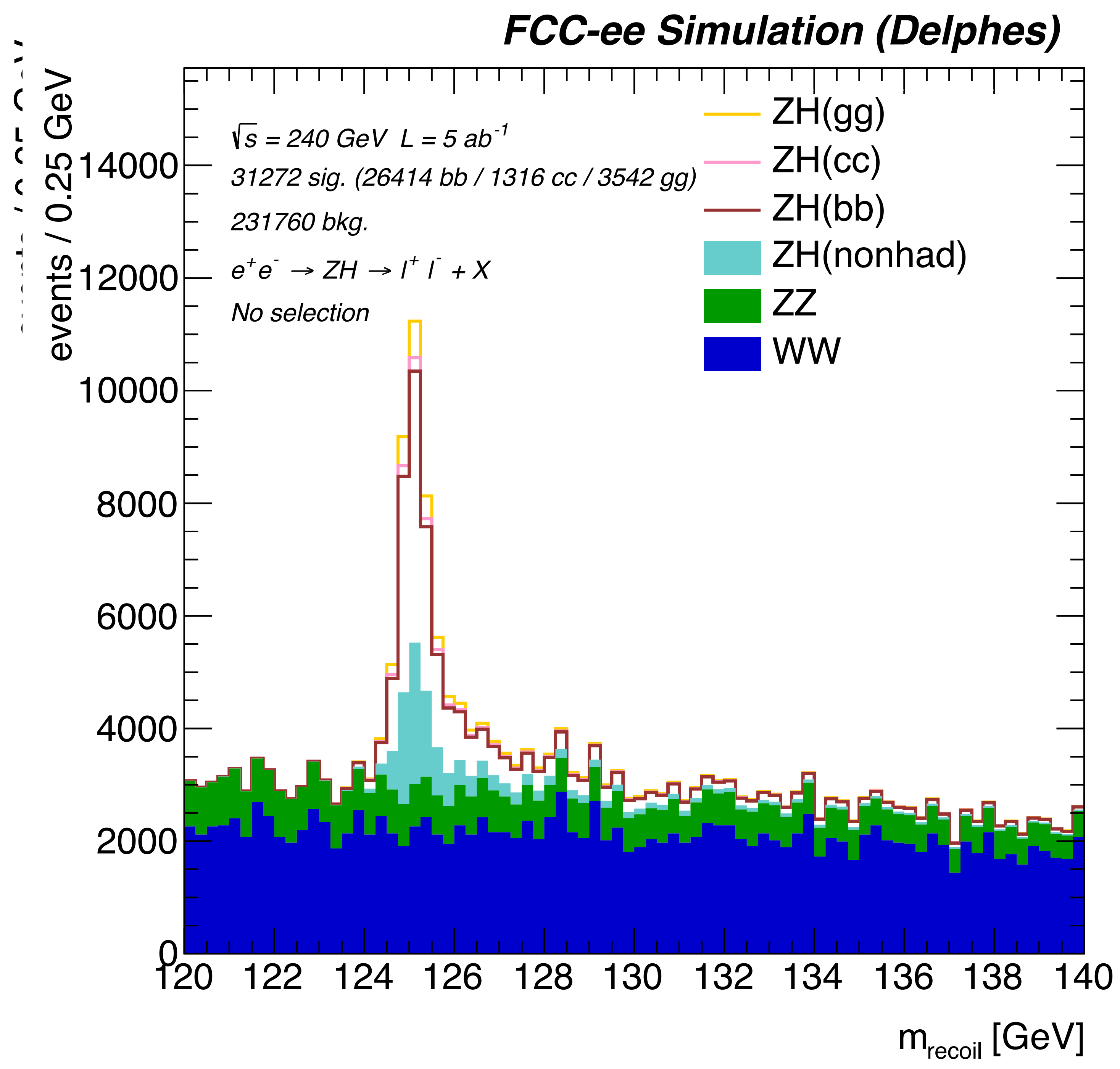
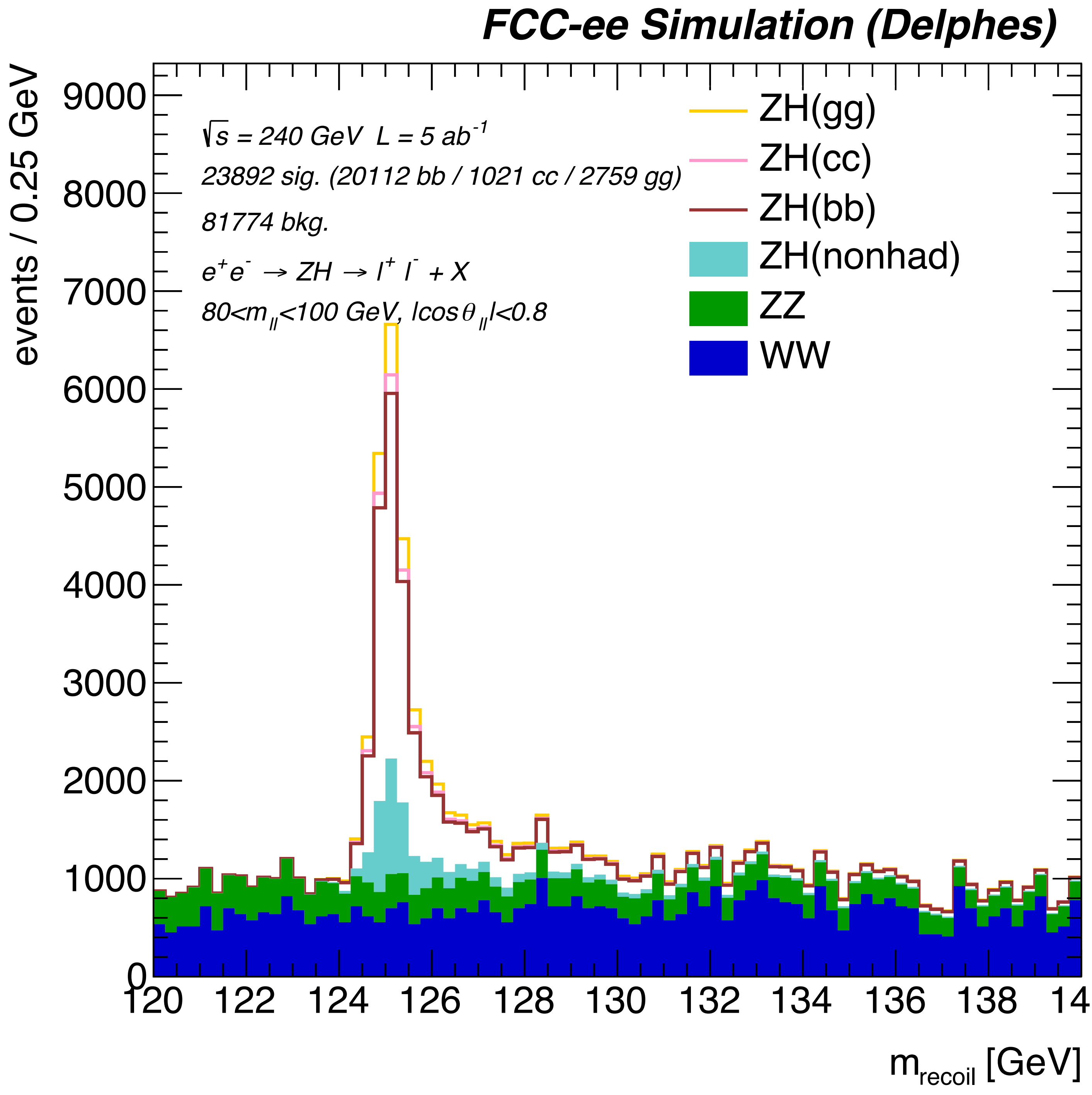
Evolution of the m_{recoil} distribution after the selection steps

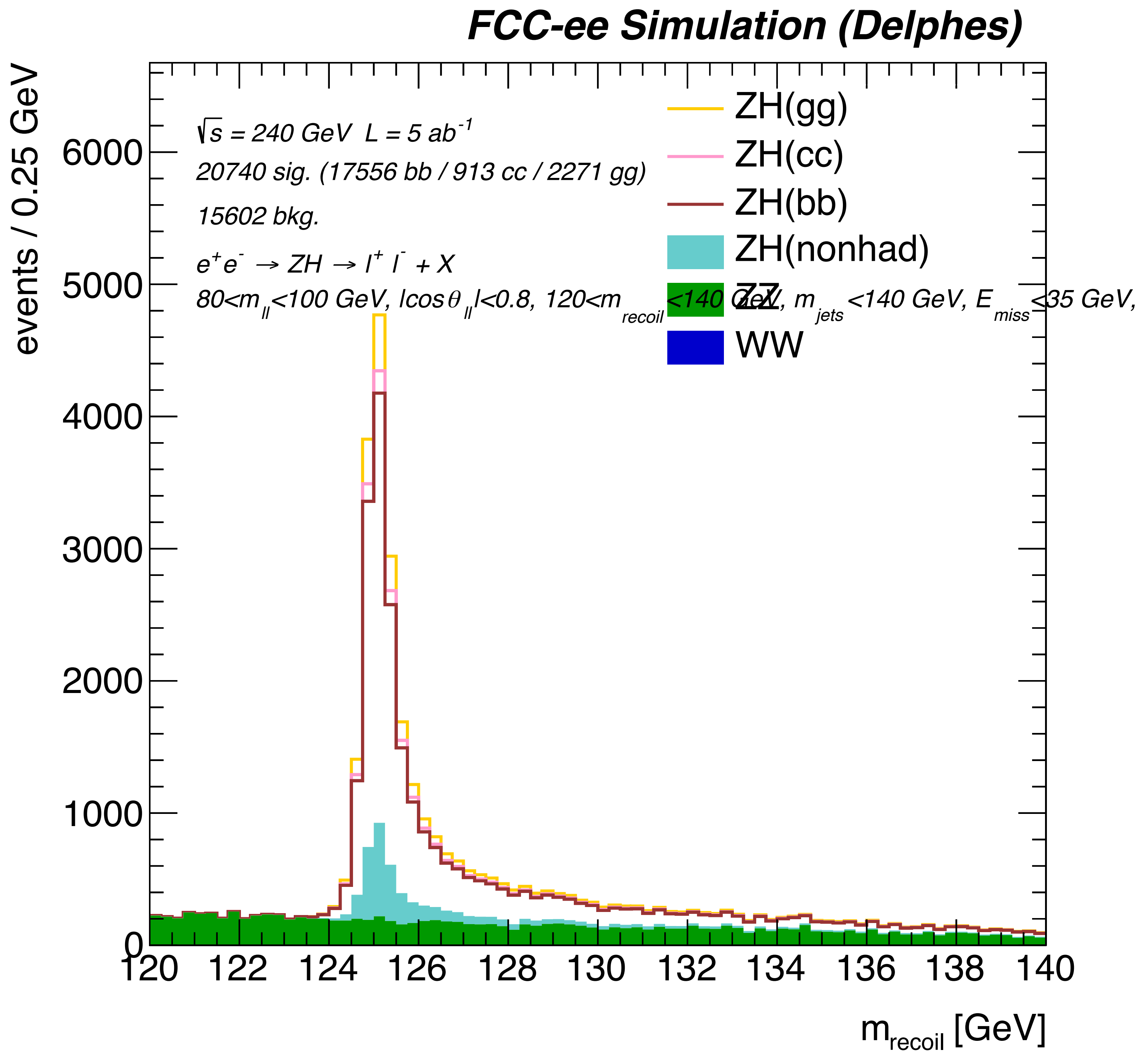
After reconstruction



After Z selection

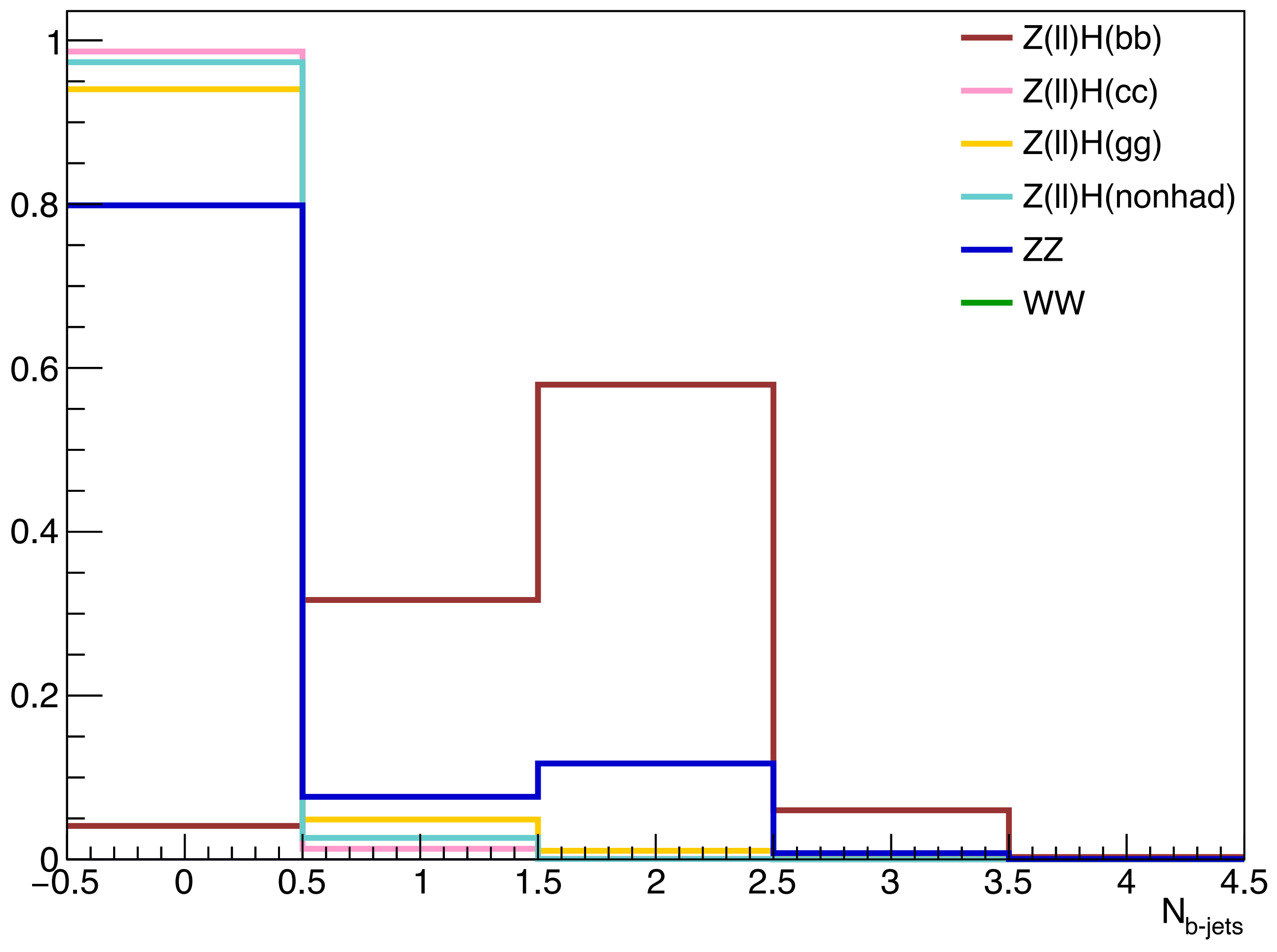


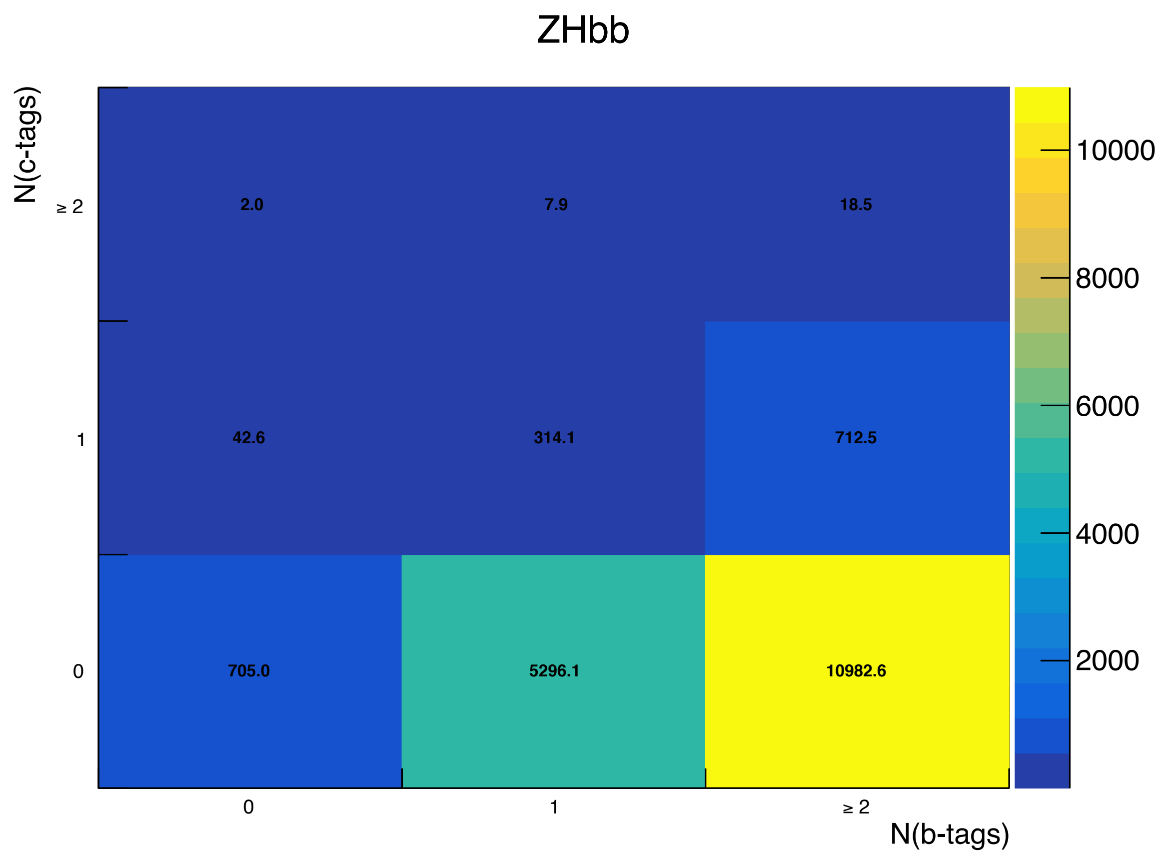
After recoil, jets, Emiss selection

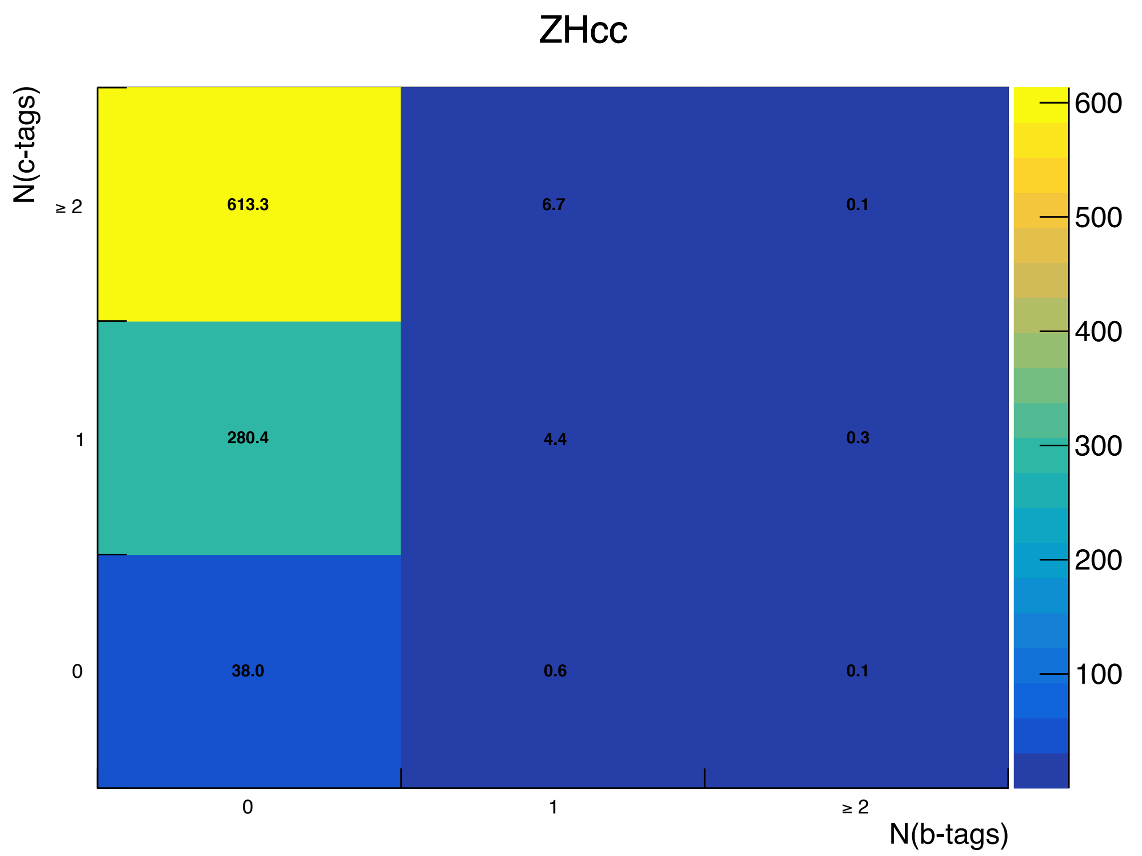


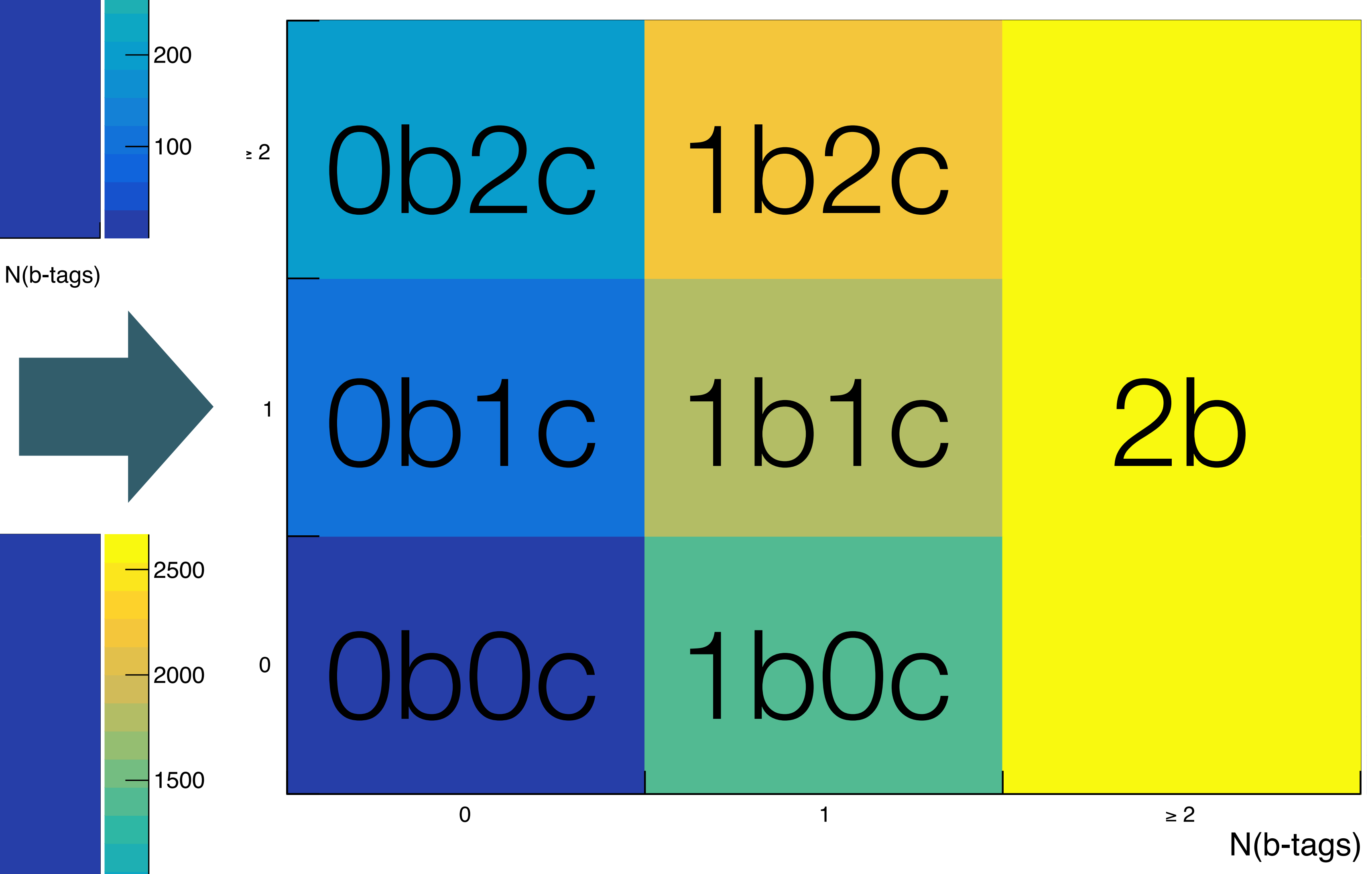
Event categorisation

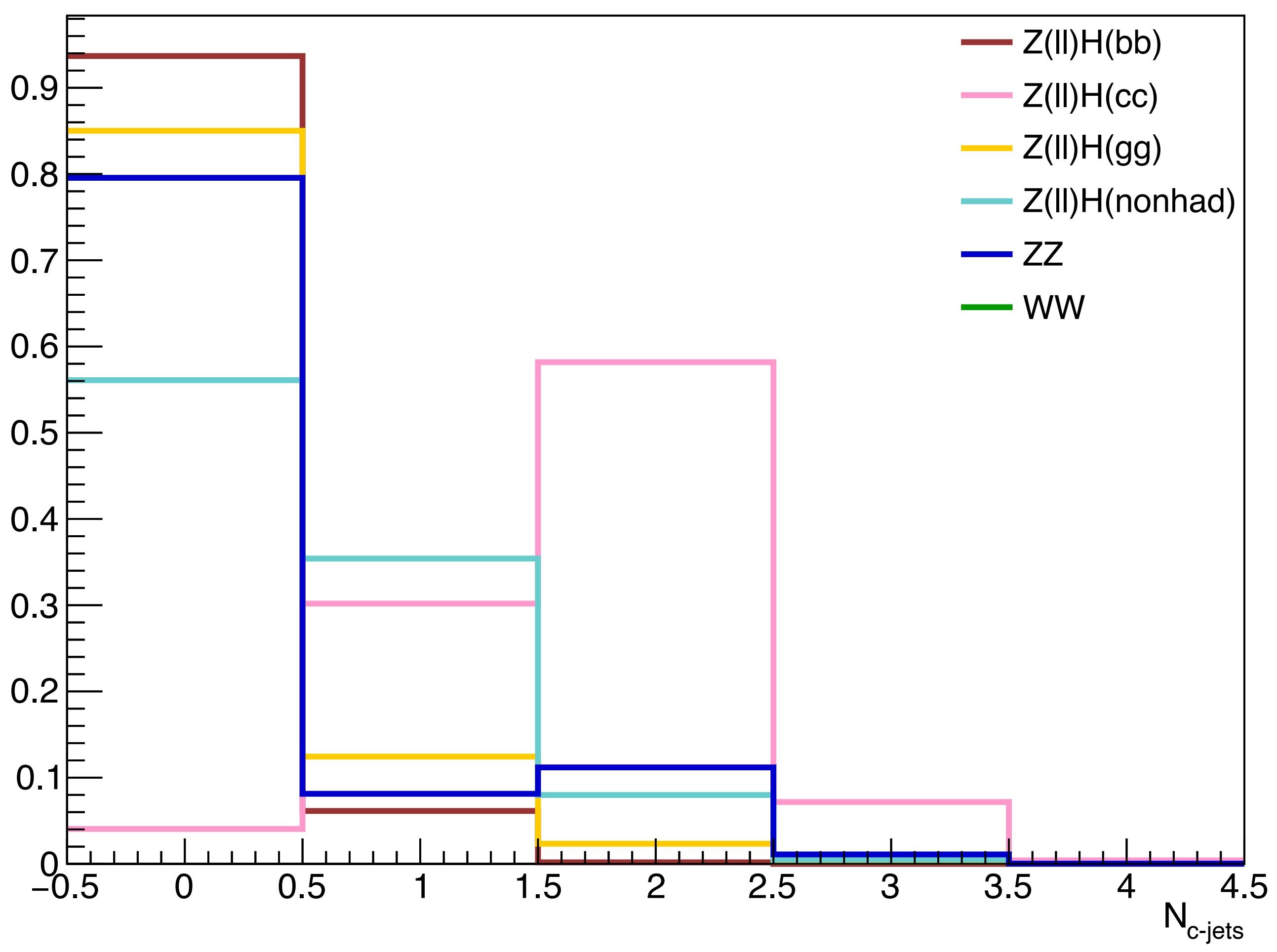
- Events are classified in mutually orthogonal categories based on the number of b- and c- tags

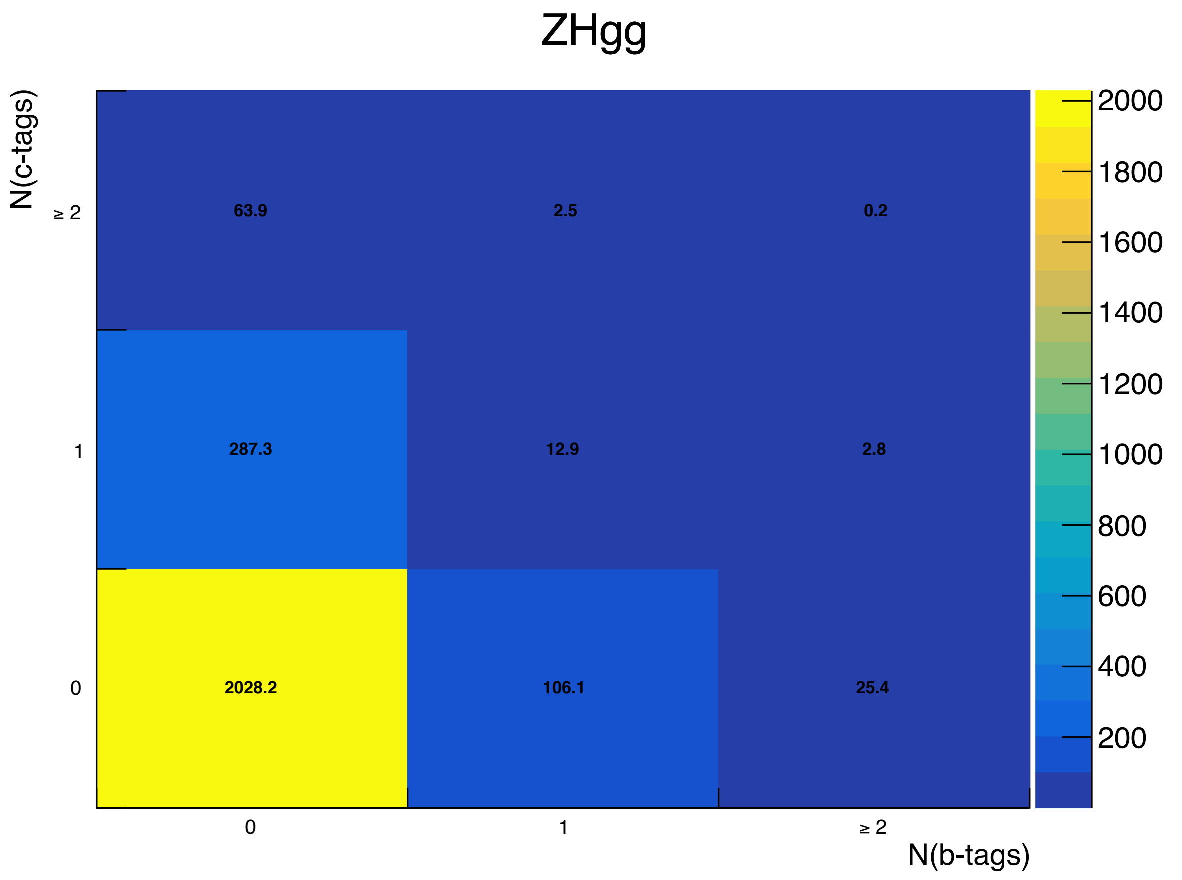


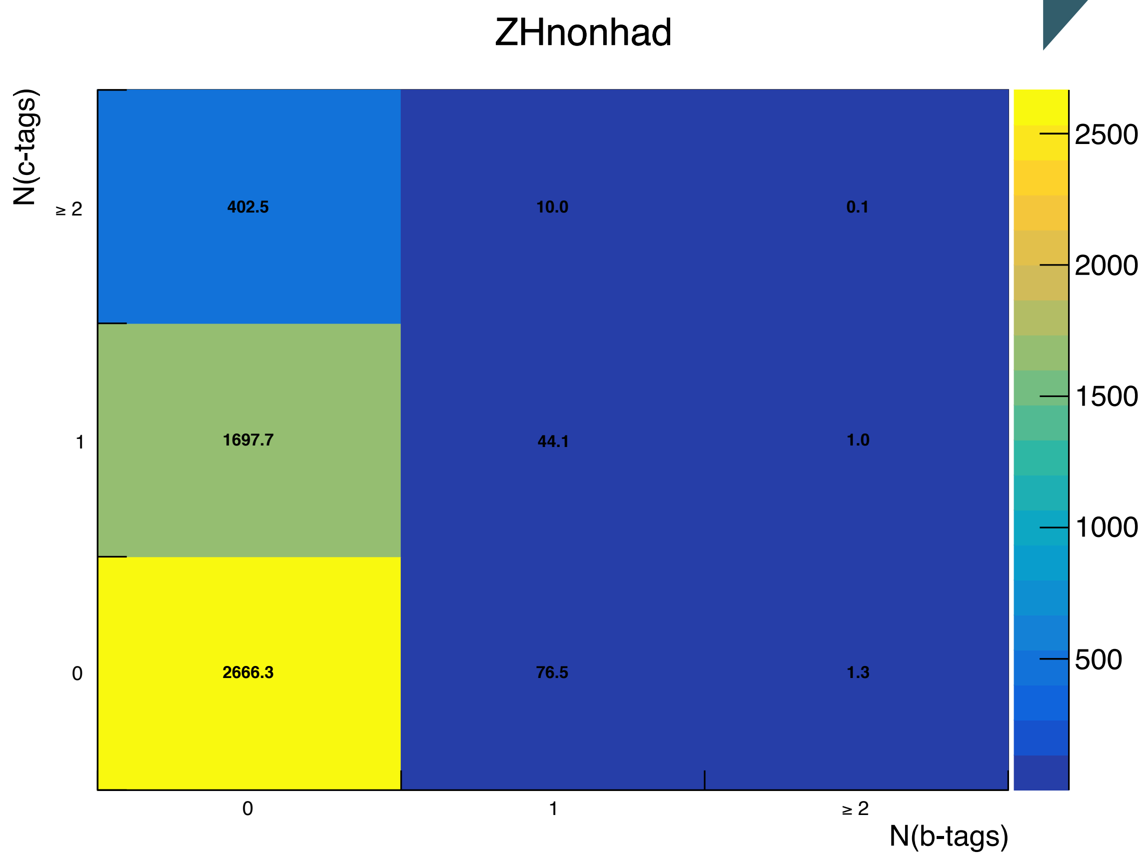




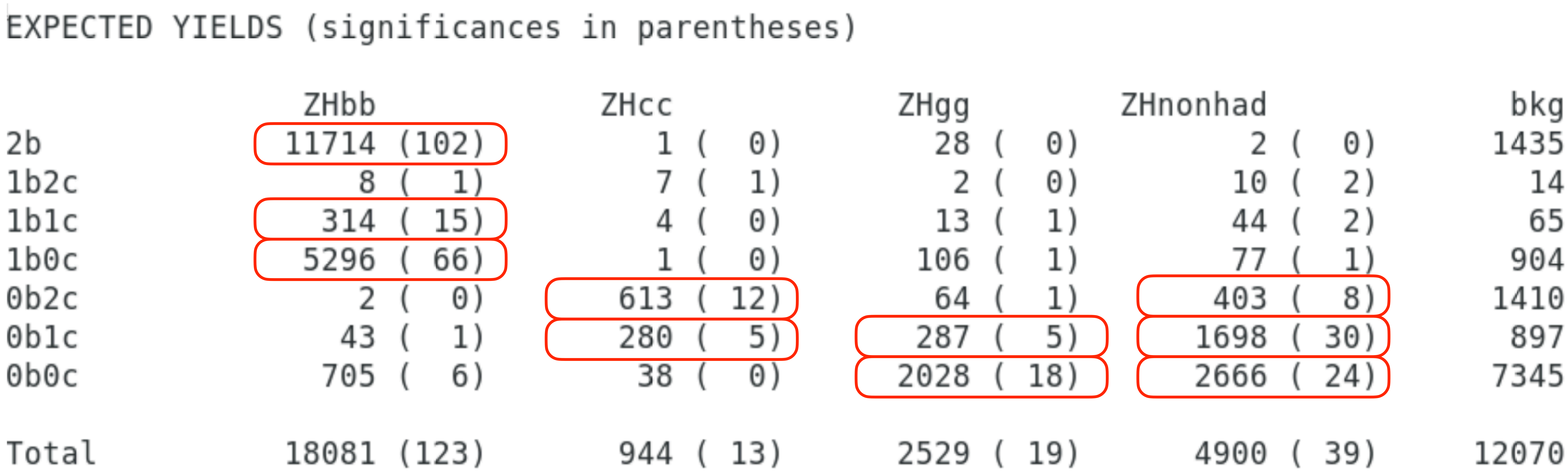








Event categorisation - expected events per category



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EXPECTED YIELDS (significances in parentheses)

                ZHbb            ZHcc            ZHgg        ZHnonhad             bkg
2b             11714 (102)         1 (  0)        28 (  0)         2 (  0)      1435
1b2c               8 (  1)         7 (  1)         2 (  0)        10 (  2)        14
1b1c             314 ( 15)         4 (  0)        13 (  1)        44 (  2)        65
1b0c            5296 ( 66)         1 (  0)       106 (  1)        77 (  1)       904
0b2c               2 (  0)       613 ( 12)        64 (  1)       403 (  8)      1410
0b1c              43 (  1)       280 (  5)       287 (  5)      1698 ( 30)       897
0b0c             705 (  6)        38 (  0)      2028 ( 18)      2666 ( 24)      7345

Total          18081 (123)       944 ( 13)      2529 ( 19)      4900 ( 39)     12070
```

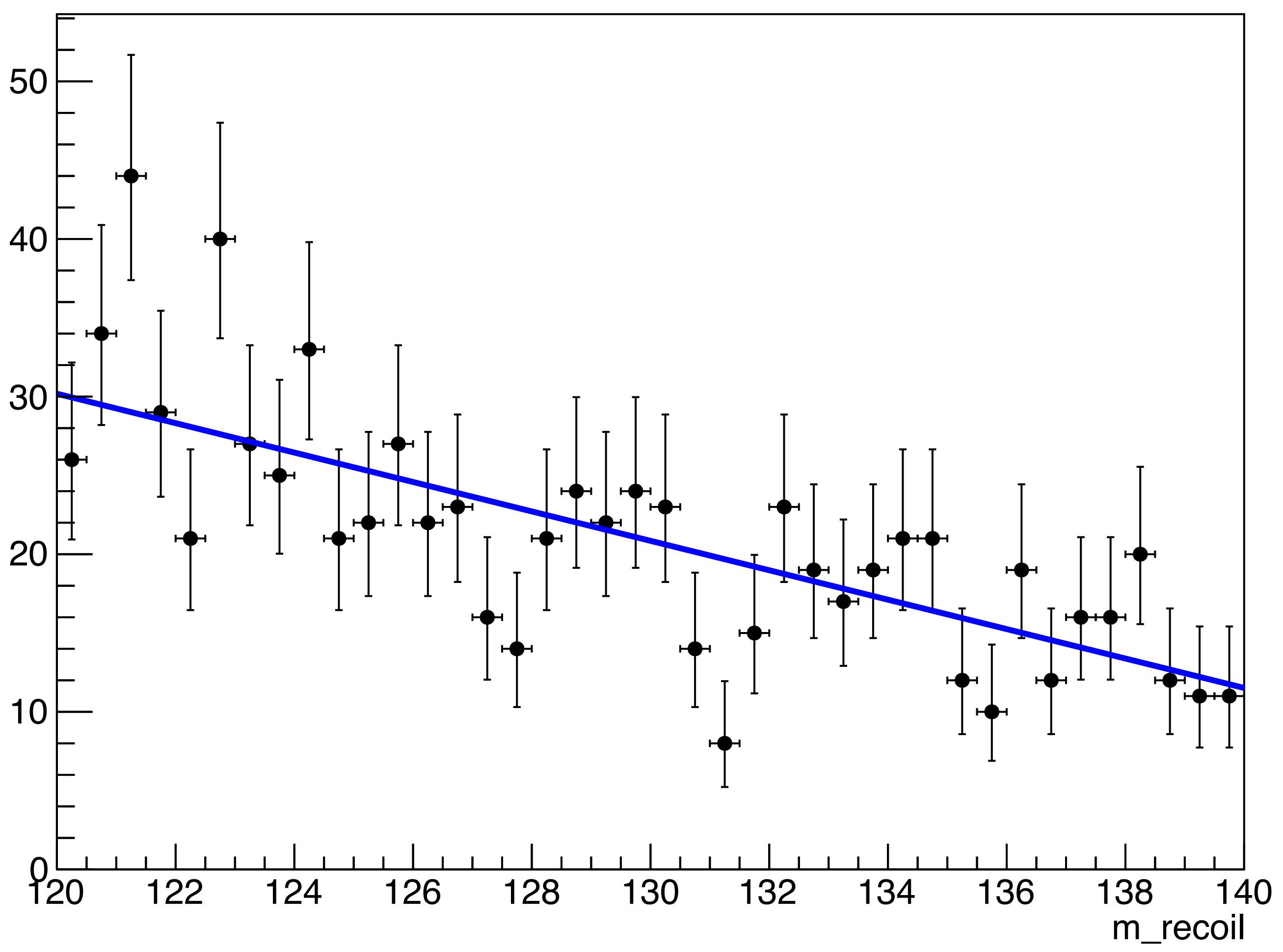
Fit - likelihood model

- **Simultaneous S+B fit to the recoil mass** of the event categories
- **Background** model: simple functions (**polynomials**, exponentials) with **floating parameters** in each category
- **Signal** model: **Crystal Ball** function with same parameters in each category
  - **peak position = mH + constant** (checked with MC samples w/ different mH)
  - Tail parameters and peak-mH are fixed, **m_H and resolution are floating**
- Signal yield in each category = function of the efficiencies for the various Z(ll)H(->XX) processes in each category (fixed, from simulation) and of σ_H*BR(H->XX):

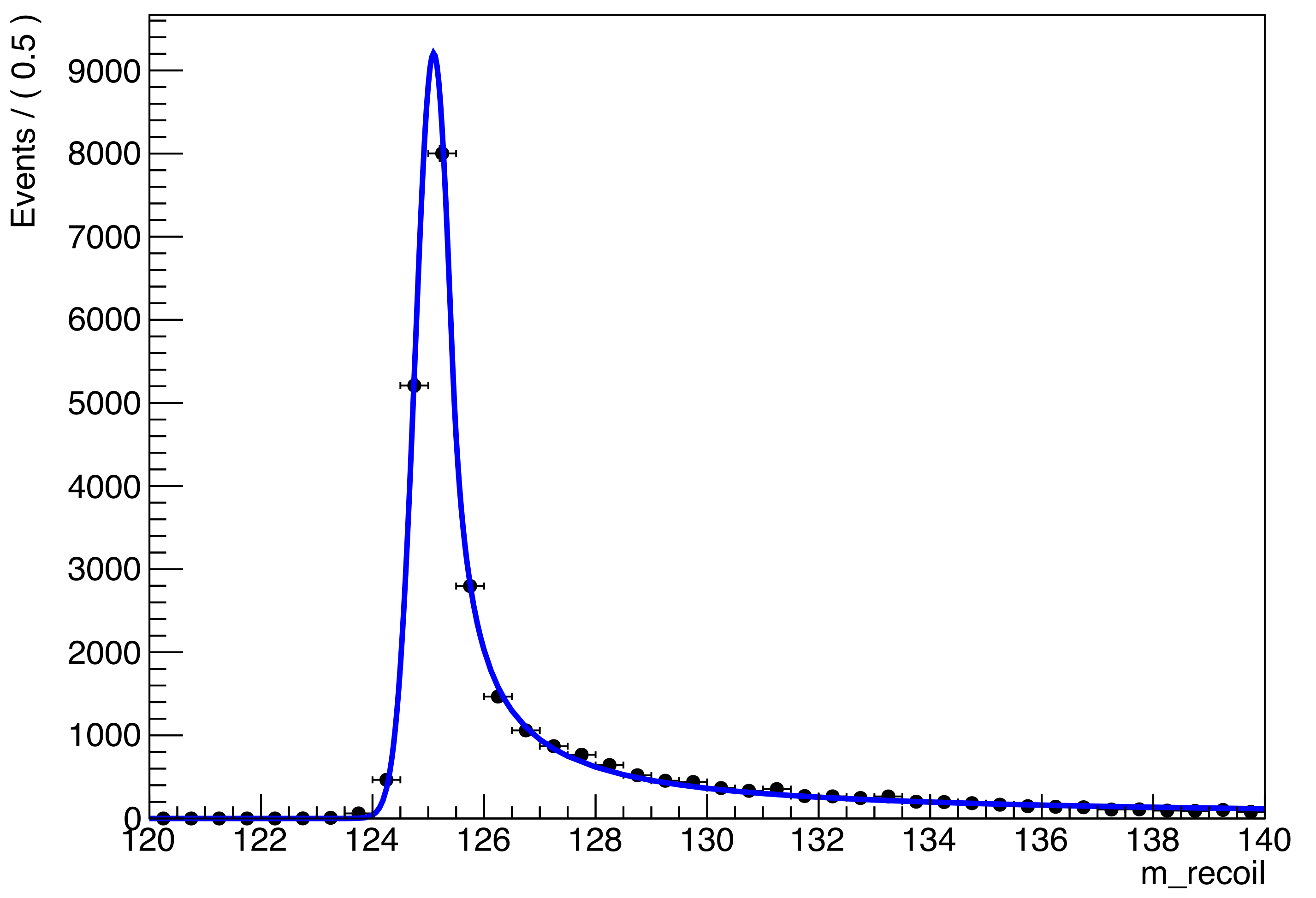
$$N_i = L \times \sigma(ee \to ZH) \times BR(Z \to ll) \times \left(BR(H \to b\bar{b})\epsilon_i^{b\bar{b}} + BR(H \to c\bar{c})\epsilon_i^{c\bar{c}} + BR(H \to gg)\epsilon_i^{gg} + BR(H \to nonhad)\epsilon_i^{nh} \right).$$

- In fit, **σ*BR(H->XX) = (σ*BR(H->XX))$_{SM}$*K$_{XX}$** => **parameters of interest = {K$_{XX}$}**
- Fit the output of the Pythia+Delphes simulation (not an Asimov sample generated from the nominal models) => statistical deviations from expected values k$_{XX}$=1 are expected
- The fit is **binned**, in the m$_{recoil}$ range **120-140 GeV**

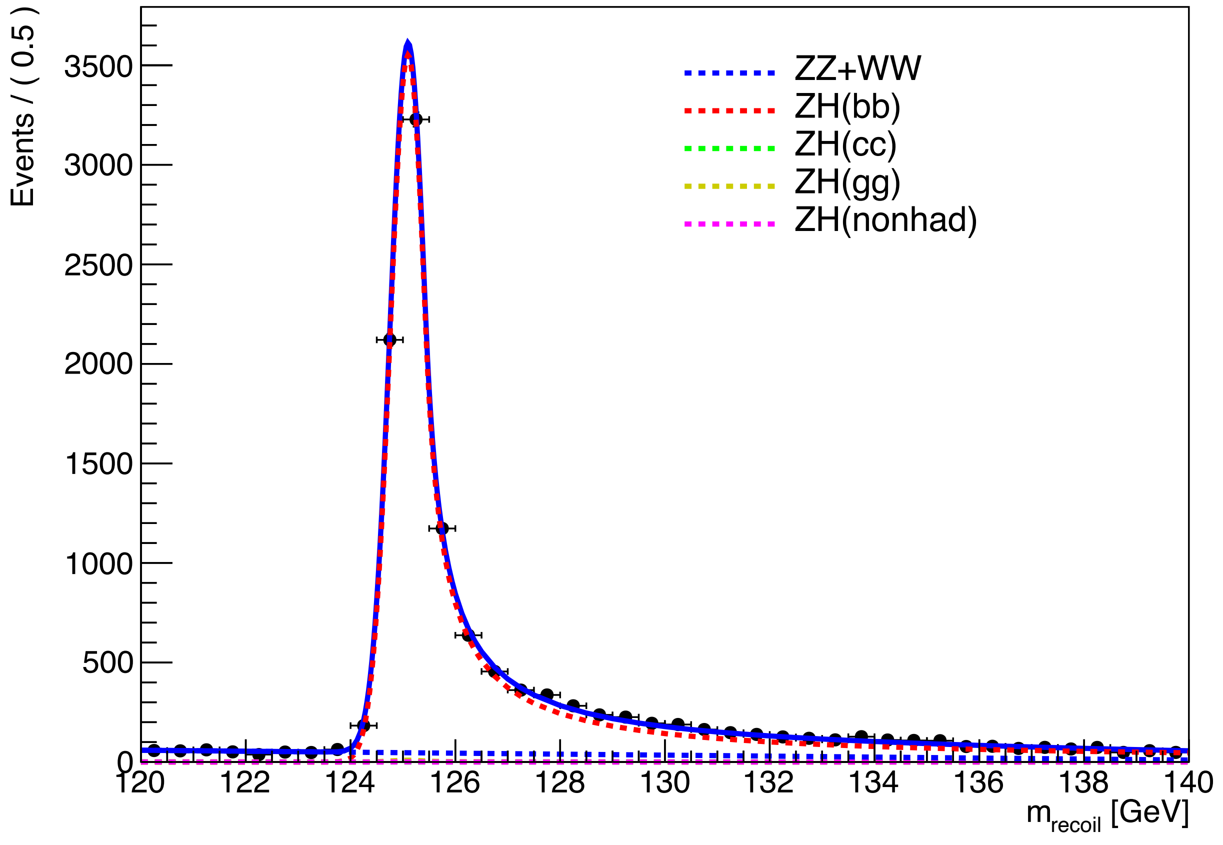
ee -> ZZ 2b

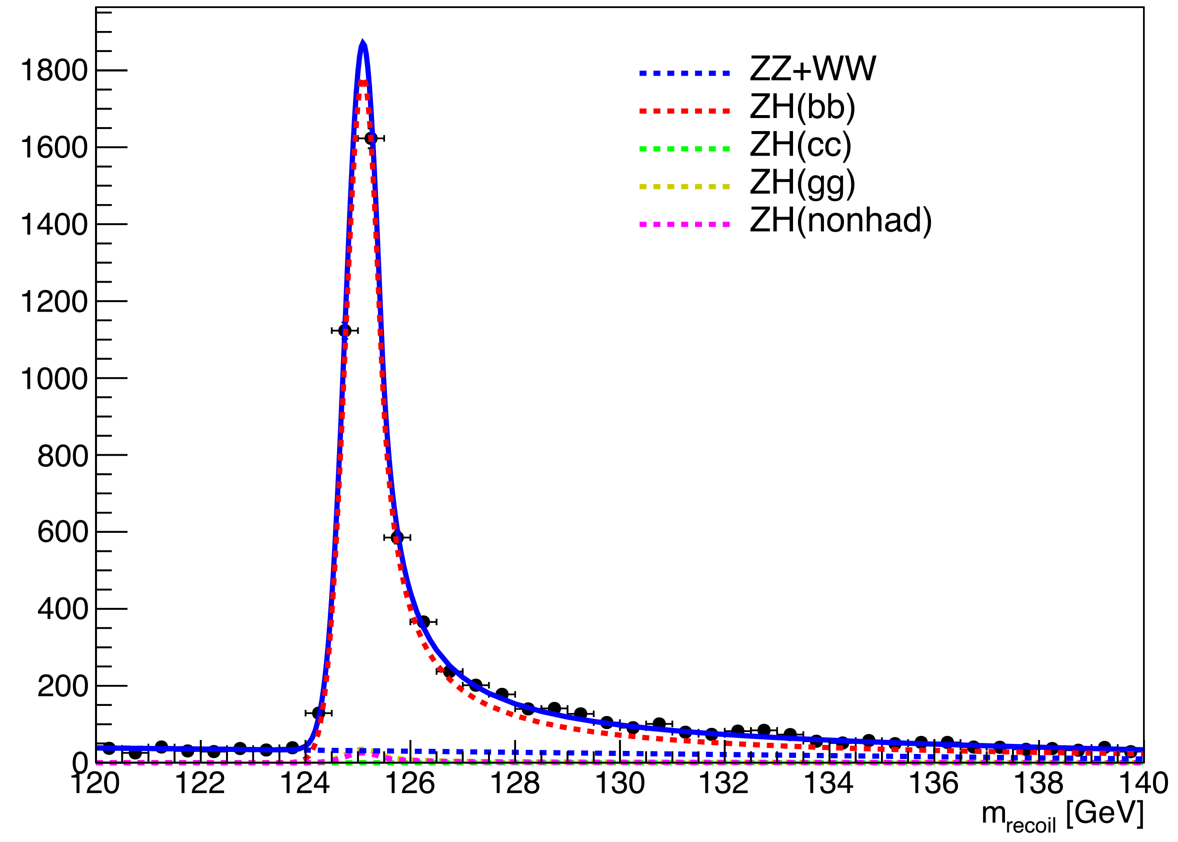


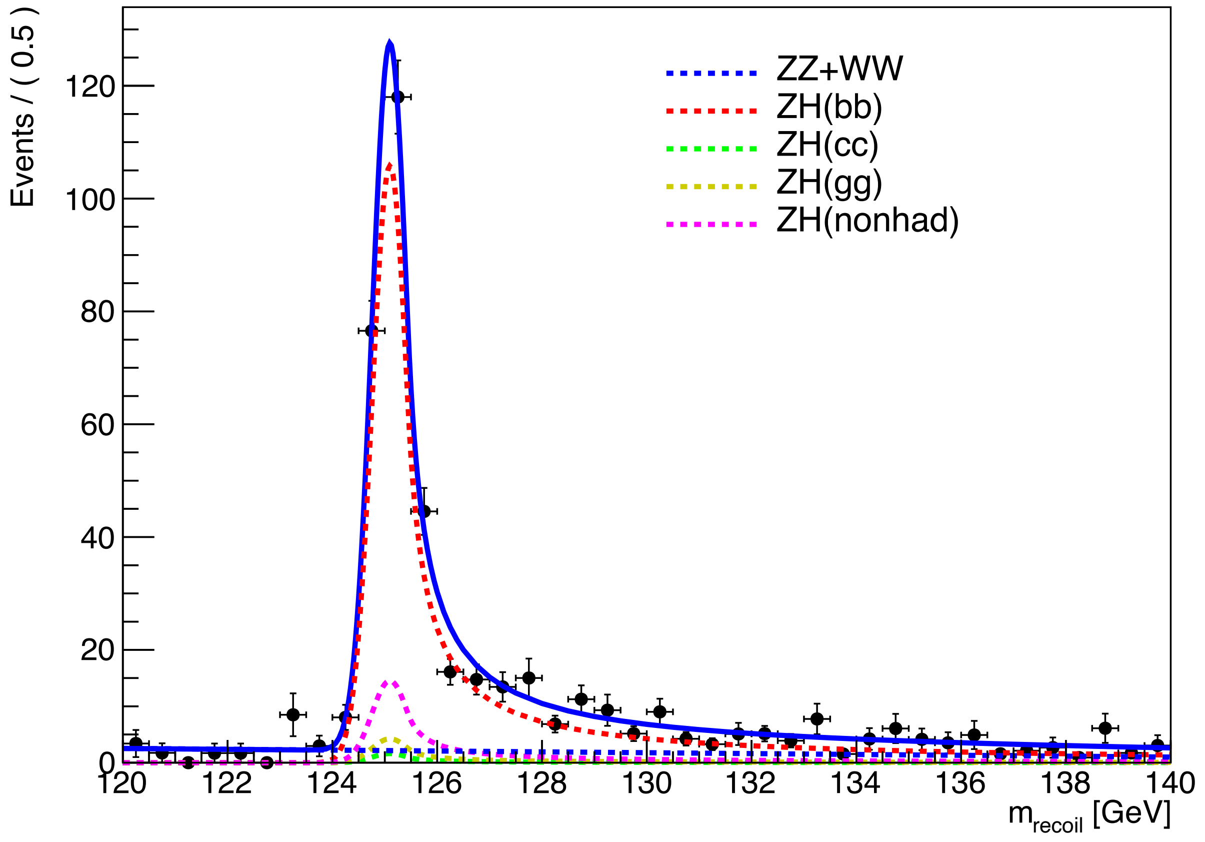
ee -> ZHbb 2b

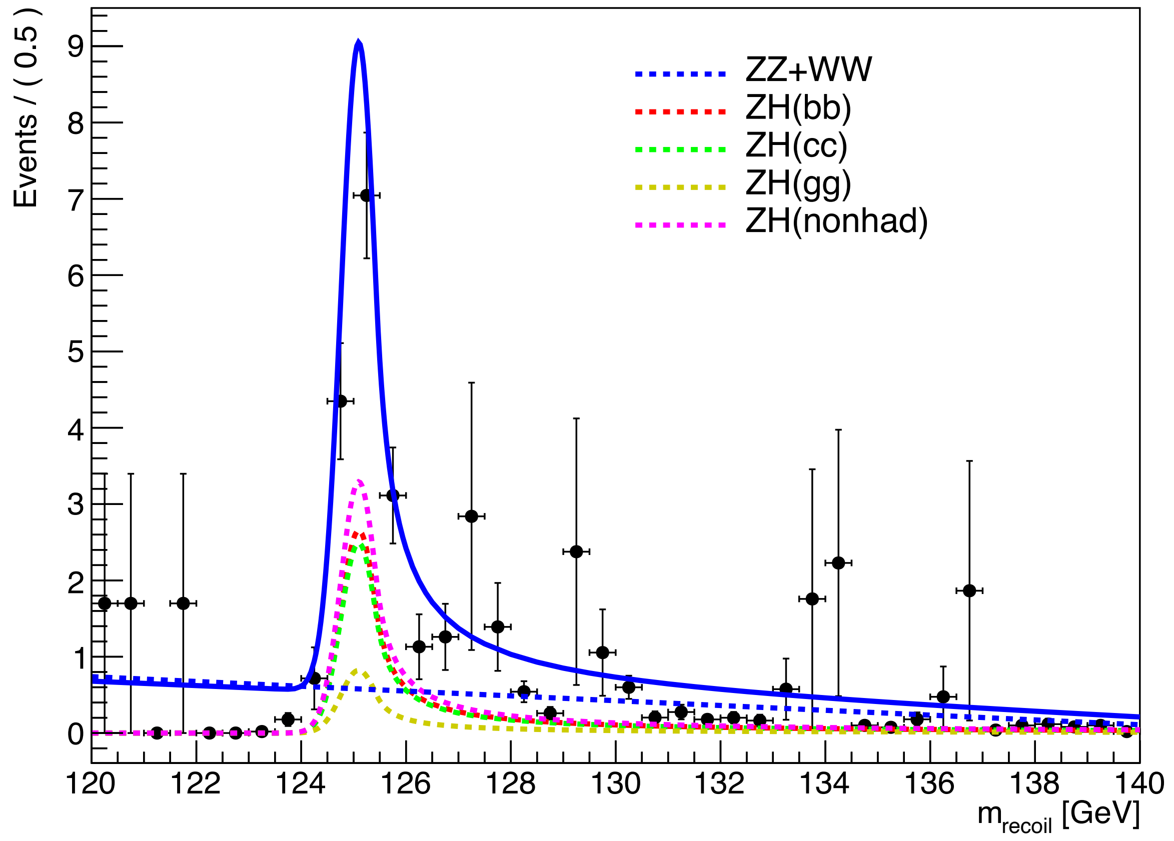


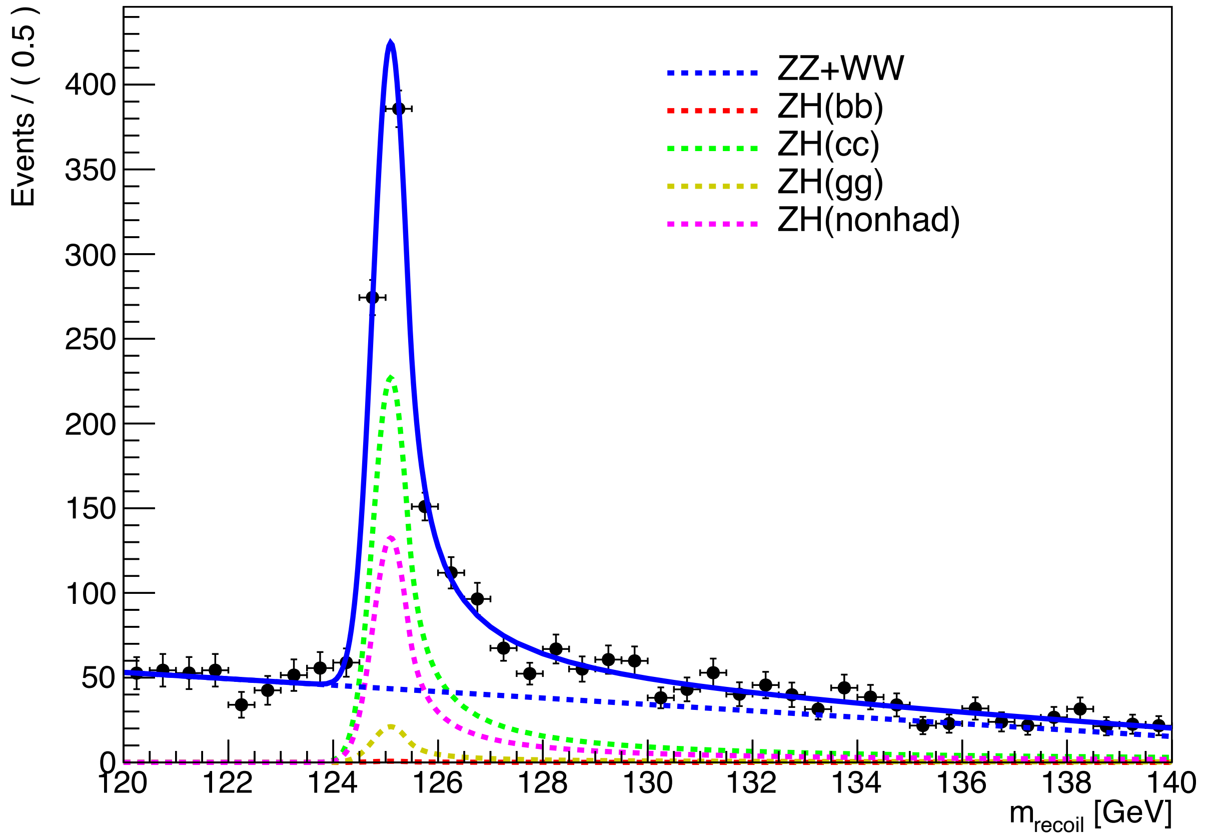
Results

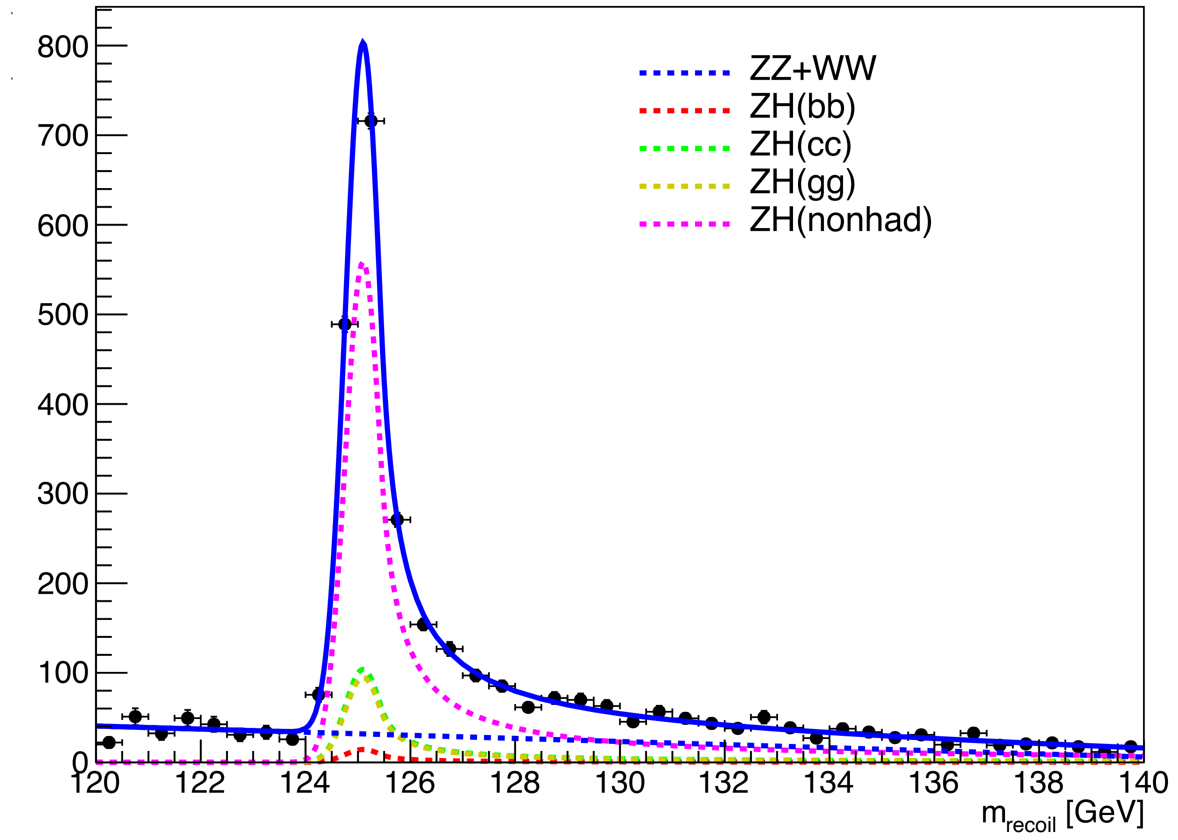

ee -> ZH, WW, ZZ, 2b

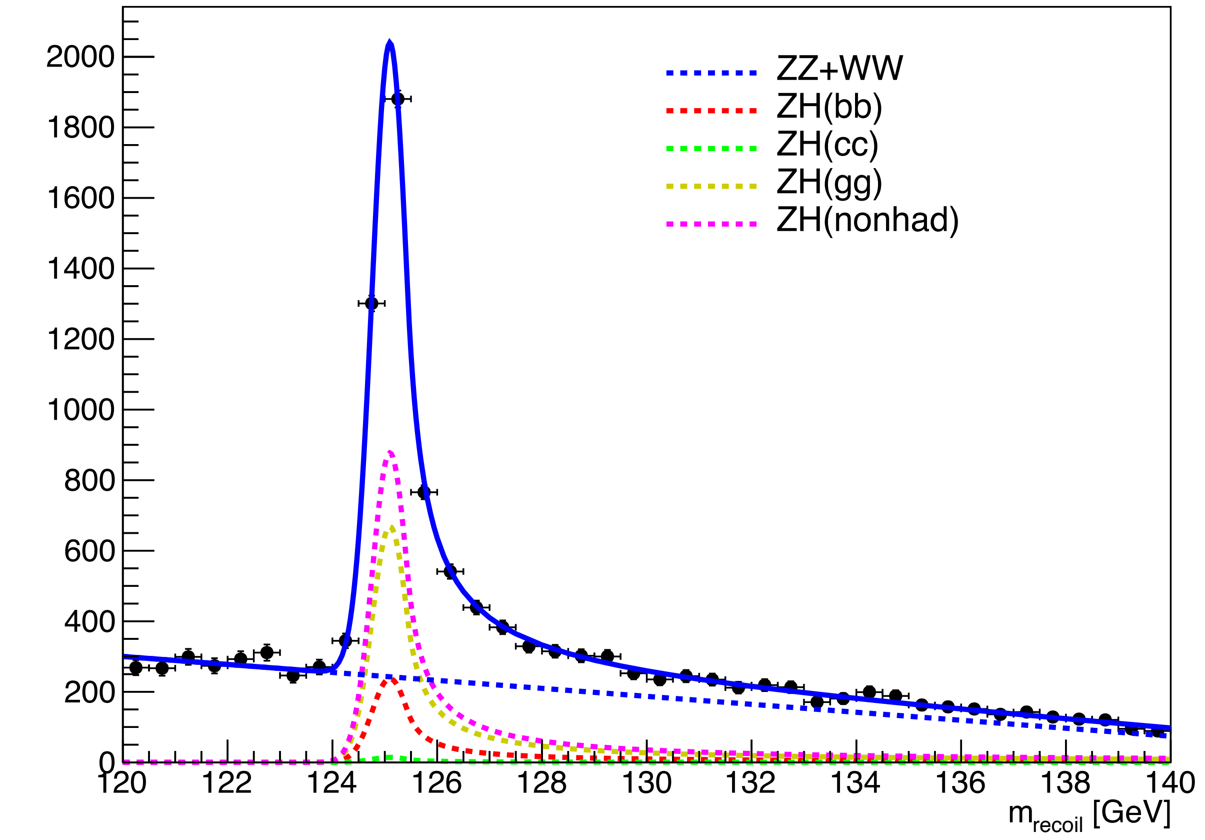

ee -> ZH, WW, ZZ, 1b0c


ee -> ZH, WW, ZZ, 1b1c


ee -> ZH, WW, ZZ, 1b2c


ee -> ZH, WW, ZZ, 0b2c


ee -> ZH, WW, ZZ, 0b1c

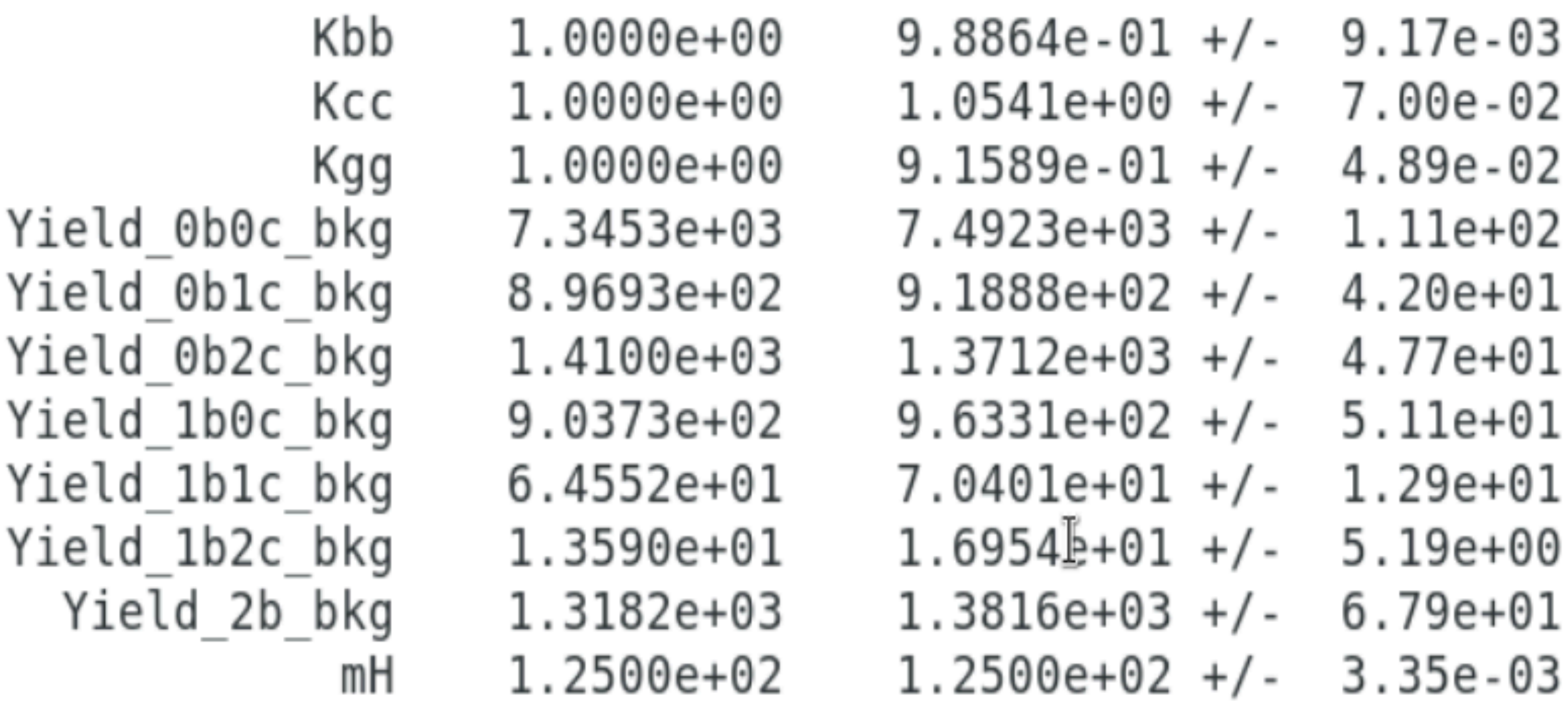

ee -> ZH, WW, ZZ, 0b0c

```
             Kbb    1.0000e+00    9.8842e-01 +/-  9.18e-03
             Kcc    1.0000e+00    1.0860e+00 +/-  8.68e-02
             Kgg    1.0000e+00    9.6729e-01 +/-  9.36e-02
         Knonhad    1.0000e+00    9.6564e-01 +/-  5.37e-02
  Yield_0b0c_bkg    7.3453e+03    7.4855e+03 +/-  1.11e+02
  Yield_0b1c_bkg    8.9693e+02    9.3080e+02 +/-  4.61e+01
  Yield_0b2c_bkg    1.4100e+03    1.3672e+03 +/-  4.81e+01
  Yield_1b0c_bkg    9.0373e+02    9.6276e+02 +/-  5.11e+01
  Yield_1b1c_bkg    6.4552e+01    7.0688e+01 +/-  1.29e+01
  Yield_1b2c_bkg    1.3590e+01    1.6957e+01 +/-  5.19e+00
   Yield_2b_bkg    1.3182e+03    1.3818e+03 +/-  6.79e+01
              mH    1.2500e+02    1.2500e+02 +/-  3.35e-03
```

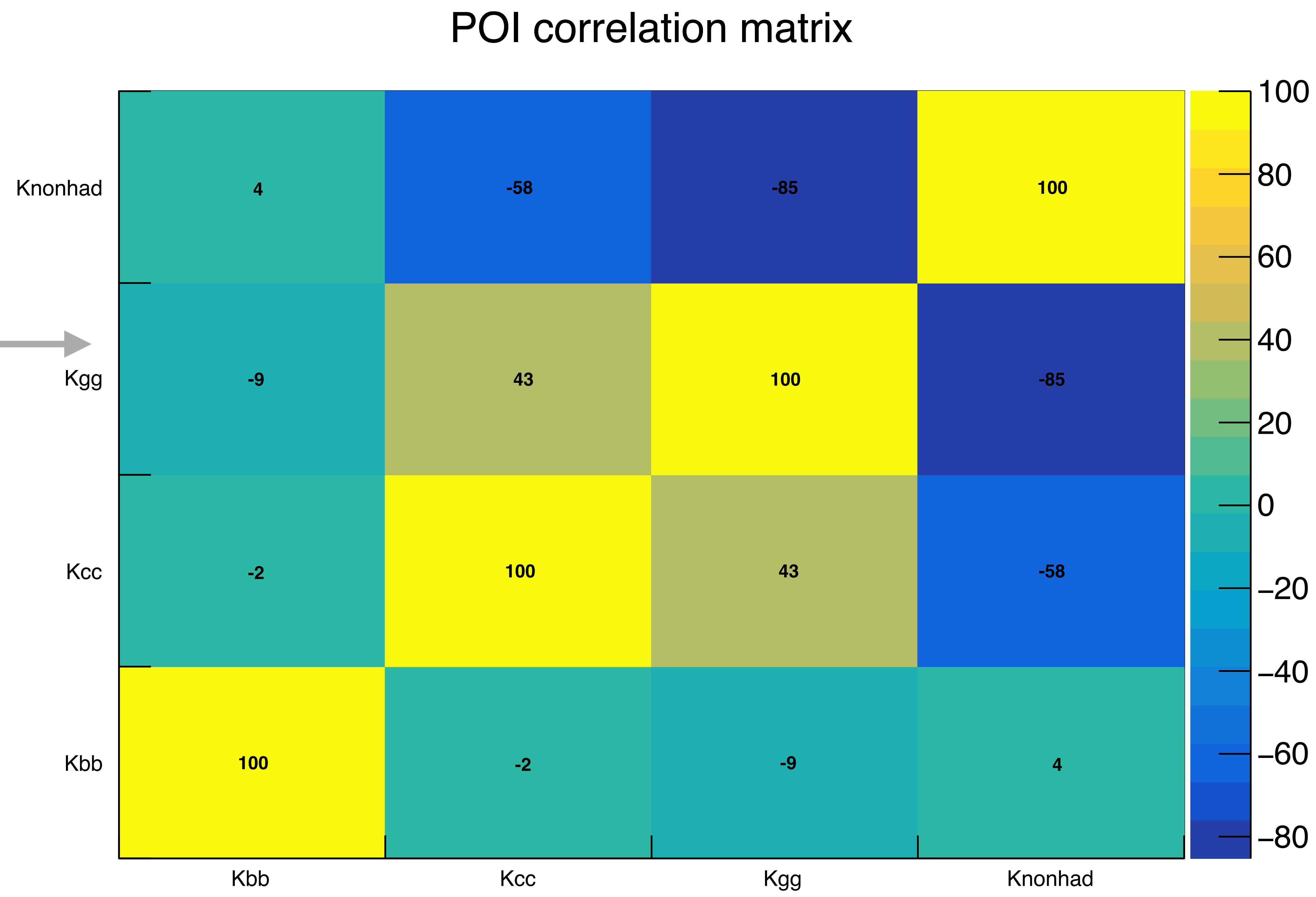
- Relative error on Kbb: 0.9%
- Relative error on Kcc: 8.0%
- Relative error on Kgg: 9.7%
- Relative error on Knonhad: 5.6%

Results with non-hadronic Higgs decays BR fixed

- Categories enriched in H→cc, gg have non negligible contamination from non-hadronic Higgs decays (mainly WW & ττ with hadronic W or τ decays)
- **Uncertainties in BR(cc) and BR(gg) are affected by uncertainty in BR(nonhad), to which they are largely anti correlated**
- In principle H(WW) and H(ττ) will be well measured by means of dedicated studies, we can profile them in the fit (or do a global fit)
- **Here we estimate what happens if we just fix BR(nonhad) to the SM:**

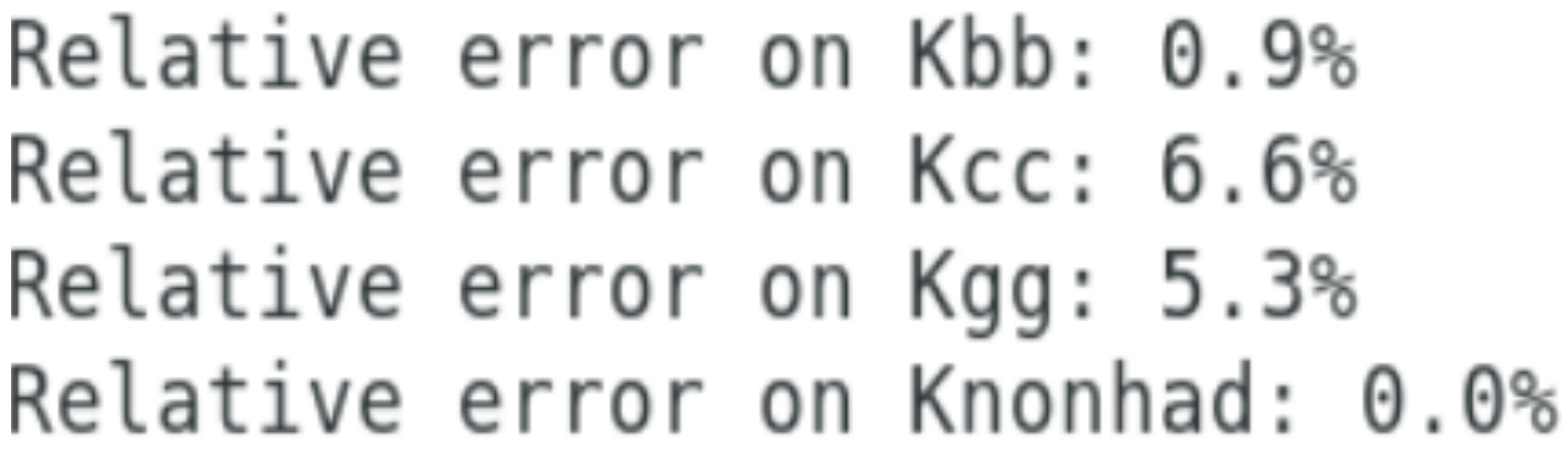


```
          Kbb    1.0000e+00    9.8864e-01 +/-  9.17e-03
          Kcc    1.0000e+00    1.0541e+00 +/-  7.00e-02
          Kgg    1.0000e+00    9.1589e-01 +/-  4.89e-02
Yield_0b0c_bkg   7.3453e+03    7.4923e+03 +/-  1.11e+02
Yield_0b1c_bkg   8.9693e+02    9.1888e+02 +/-  4.20e+01
Yield_0b2c_bkg   1.4100e+03    1.3712e+03 +/-  4.77e+01
Yield_1b0c_bkg   9.0373e+02    9.6331e+02 +/-  5.11e+01
Yield_1b1c_bkg   6.4552e+01    7.0401e+01 +/-  1.29e+01
Yield_1b2c_bkg   1.3590e+01    1.6954e+01 +/-  5.19e+00
  Yield_2b_bkg   1.3182e+03    1.3816e+03 +/-  6.79e+01
            mH   1.2500e+02    1.2500e+02 +/-  3.35e-03
```



POI correlation matrix

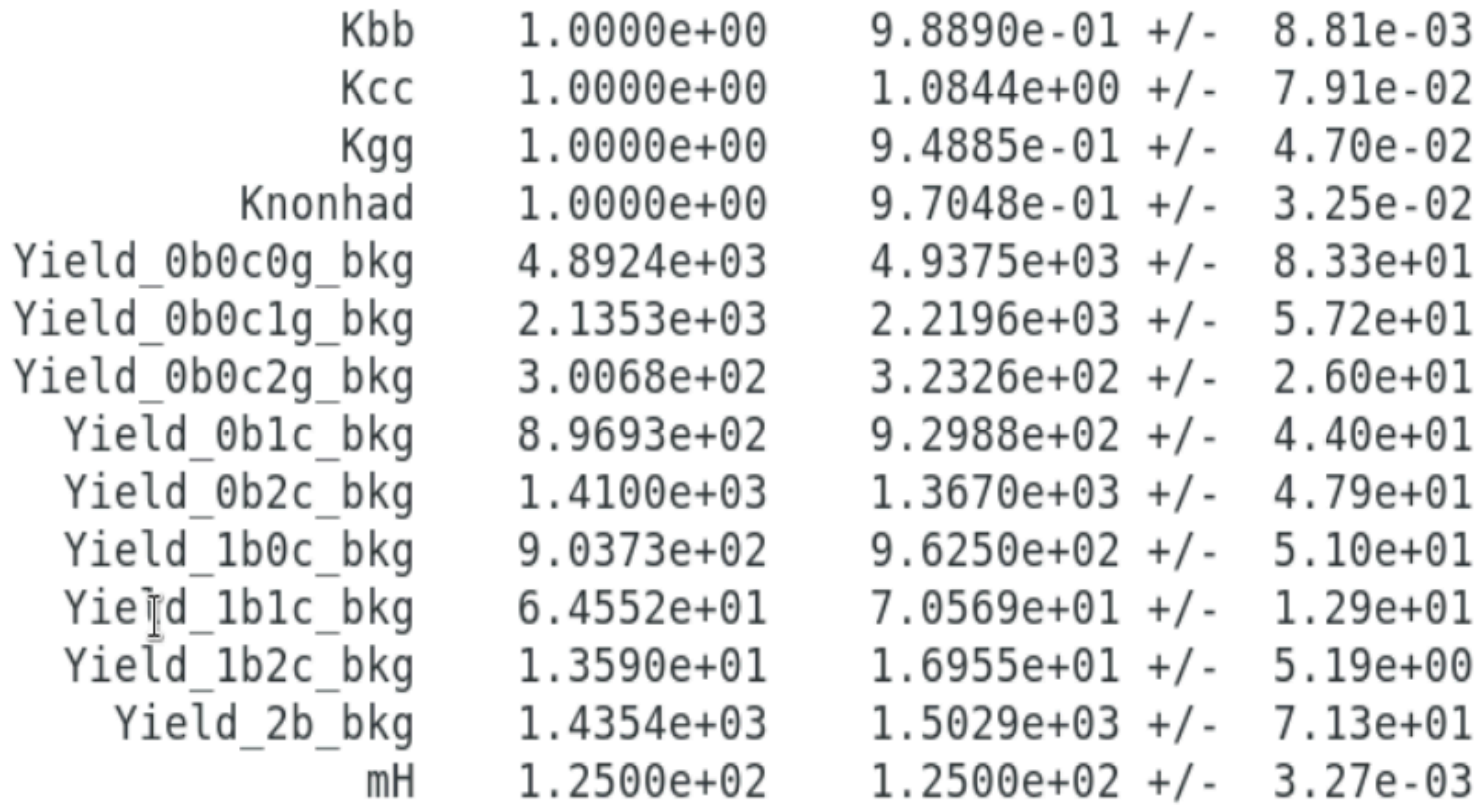
	Kbb	Kcc	Kgg	Knonhad
Knonhad	4	-58	-85	100
Kgg	-9	43	100	-85
Kcc	-2	100	43	-58
Kbb	100	-2	-9	4



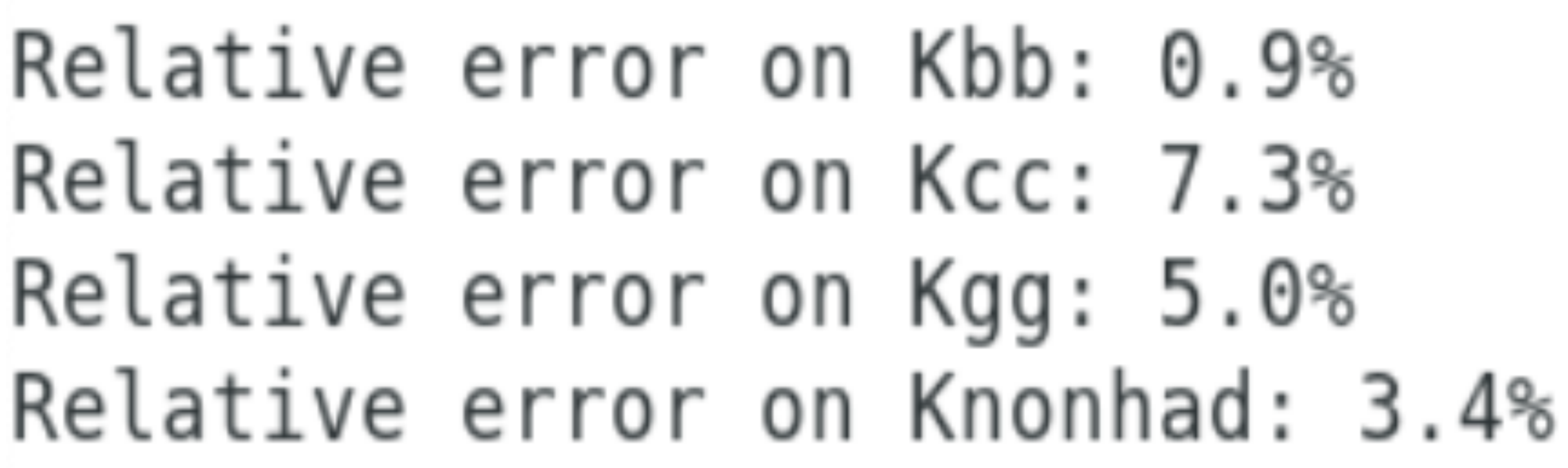
```
Relative error on Kbb: 0.9%
Relative error on Kcc: 6.6%
Relative error on Kgg: 5.3%
Relative error on Knonhad: 0.0%
```

Impact of gluon tagging

- If gluon tagging is available => **split the 0b0c category into 0b0c0g, 0b0c1g, 0b0c2g**
- This leads to improved results (mainly on Kgg) thanks to the rejection of quark jets from W and tau decays from the Higgs



```
             Kbb    1.0000e+00    9.8890e-01 +/-  8.81e-03
             Kcc    1.0000e+00    1.0844e+00 +/-  7.91e-02
             Kgg    1.0000e+00    9.4885e-01 +/-  4.70e-02
         Knonhad    1.0000e+00    9.7048e-01 +/-  3.25e-02
Yield_0b0c0g_bkg    4.8924e+03    4.9375e+03 +/-  8.33e+01
Yield_0b0c1g_bkg    2.1353e+03    2.2196e+03 +/-  5.72e+01
Yield_0b0c2g_bkg    3.0068e+02    3.2326e+02 +/-  2.60e+01
  Yield_0b1c_bkg    8.9693e+02    9.2988e+02 +/-  4.40e+01
  Yield_0b2c_bkg    1.4100e+03    1.3670e+03 +/-  4.79e+01
  Yield_1b0c_bkg    9.0373e+02    9.6250e+02 +/-  5.10e+01
  Yield_1b1c_bkg    6.4552e+01    7.0569e+01 +/-  1.29e+01
  Yield_1b2c_bkg    1.3590e+01    1.6955e+01 +/-  5.19e+00
    Yield_2b_bkg    1.4354e+03    1.5029e+03 +/-  7.13e+01
              mH    1.2500e+02    1.2500e+02 +/-  3.27e-03
```



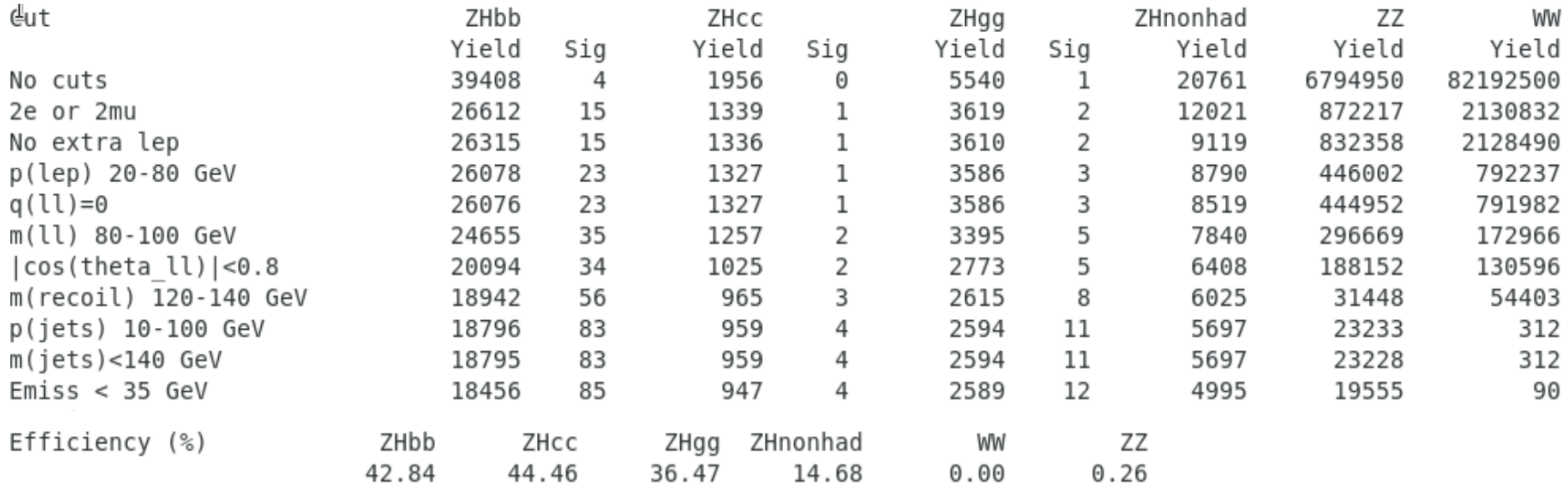
```
Relative error on Kbb: 0.9%
Relative error on Kcc: 7.3%
Relative error on Kgg: 5.0%
Relative error on Knonhad: 3.4%
```

Updated results with official FCC samples

- Recently I was able to run the analysis on the FCC-ee “spring21” samples with a little coding effort to implement some missing features.
- For comparison to previous study I tried to keep things as close as possible to the past:
  - Same event generator (Pythia8), same detector (IDEA), same list of signal and background processes, same jet clustering algorithm (Valencia inclusive), same selection criteria and categories
  - Main differences:
    - beam energy spread and vertex smearing on
  - Modifications with respect to the standard FCC-ee analysis code:
    - Modify flavour tagging code to allow for non-zero mistag rate
    - Modify parton-level truth labelling of jets to allow also matching to gluons
    - Introduce routine to remove selected leptons from particles used for jet clustering
- Samples used (Pythia 8):
  - ZZ and WW (central production, 10M each, x2.5 wrt past)
  - Z(ll)H(XX) produced privately with same settings as official production, in order to normalise separately the Higgs samples independently of the Pythia H(XX) branching ratios

New results (w/o gluon tagging)

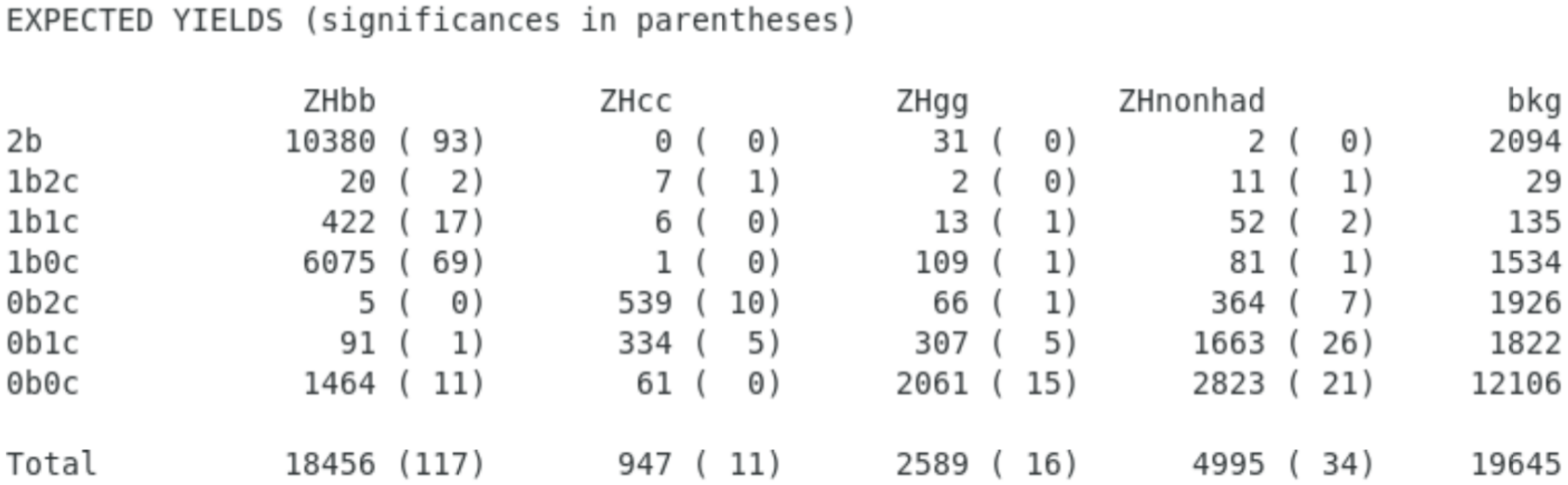
- **Cutflow**:



```
Cut                       ZHbb            ZHcc            ZHgg        ZHnonhad       ZZ          WW
                         Yield   Sig     Yield   Sig     Yield   Sig     Yield      Yield       Yield
No cuts                  39408     4      1956     0      5540     1     20761    6794950    82192500
2e or 2mu                26612    15      1339     1      3619     2     12021     872217     2130832
No extra lep             26315    15      1336     1      3610     2      9119     832358     2128490
p(lep) 20-80 GeV         26078    23      1327     1      3586     3      8790     446002      792237
q(ll)=0                  26076    23      1327     1      3586     3      8519     444952      791982
m(ll) 80-100 GeV         24655    35      1257     2      3395     5      7840     296669      172966
|cos(theta_ll)|<0.8      20094    34      1025     2      2773     5      6408     188152      130596
m(recoil) 120-140 GeV    18942    56       965     3      2615     8      6025      31448       54403
p(jets) 10-100 GeV       18796    83       959     4      2594    11      5697      23233         312
m(jets)<140 GeV          18795    83       959     4      2594    11      5697      23228         312
Emiss < 35 GeV           18456    85       947     4      2589    12      4995      19555          90

Efficiency (%)        ZHbb      ZHcc      ZHgg  ZHnonhad        WW        ZZ
                     42.84     44.46     36.47     14.68      0.00      0.26
```

- **Yields vs category**:

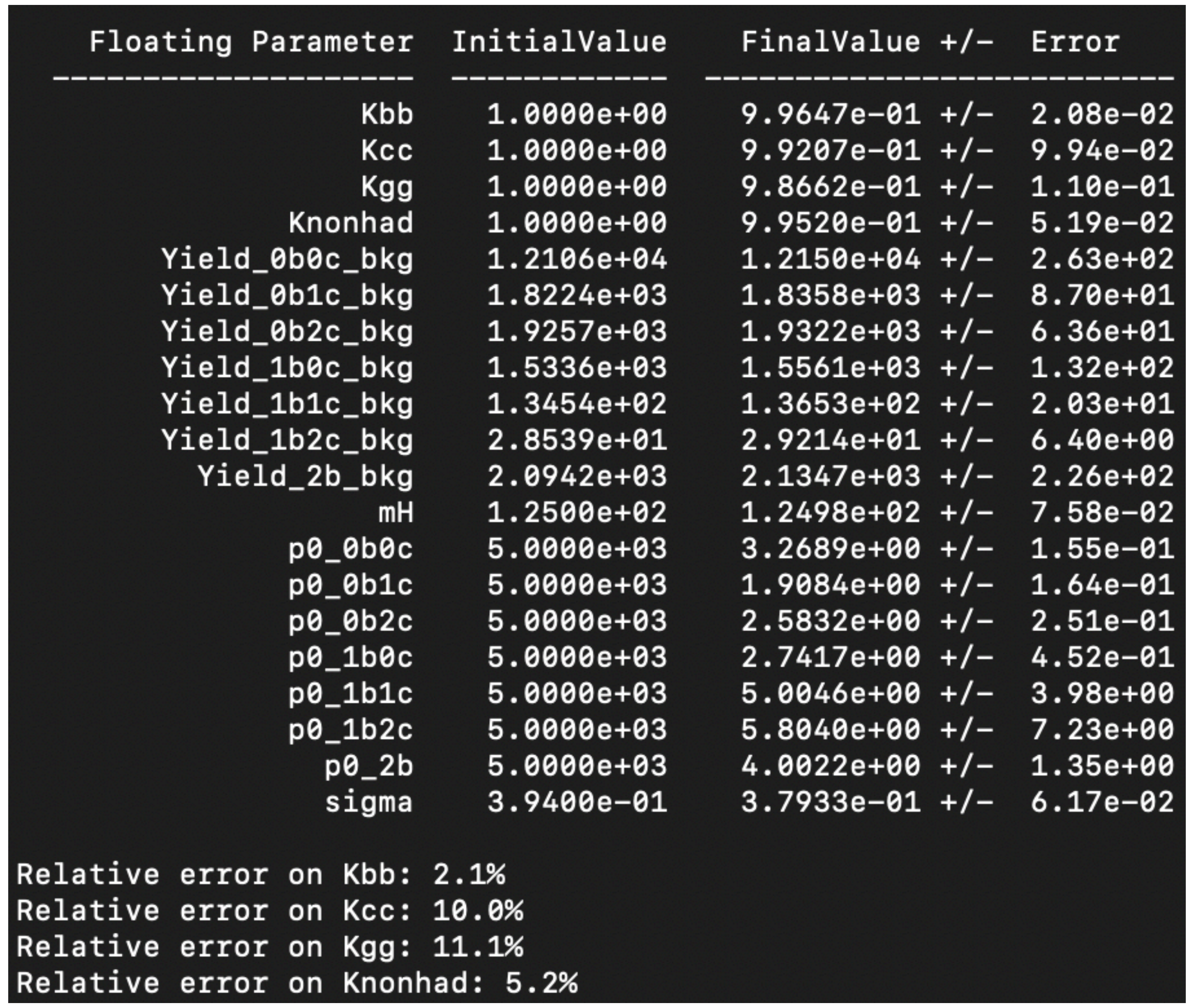


```
EXPECTED YIELDS (significances in parentheses)


              ZHbb            ZHcc            ZHgg         ZHnonhad          bkg
2b           10380 ( 93)         0 (  0)        31 (  0)        2 (  0)       2094
1b2c            20 (  2)         7 (  1)         2 (  0)       11 (  1)         29
1b1c           422 ( 17)         6 (  0)        13 (  1)       52 (  2)        135
1b0c          6075 ( 69)         1 (  0)       109 (  1)       81 (  1)       1534
0b2c             5 (  0)       539 ( 10)        66 (  1)      364 (  7)       1926
0b1c            91 (  1)       334 (  5)       307 (  5)     1663 ( 26)       1822
0b0c          1464 ( 11)        61 (  0)      2061 ( 15)     2823 ( 21)      12106

Total        18456 (117)       947 ( 11)      2589 ( 16)     4995 ( 34)      19645
```

- **Fit results**:



```
  Floating Parameter  InitialValue    FinalValue +/-  Error
  ------------------  ------------  --------------------------
                 Kbb   1.0000e+00    9.9647e-01 +/-  2.08e-02
                 Kcc   1.0000e+00    9.9207e-01 +/-  9.94e-02
                 Kgg   1.0000e+00    9.8662e-01 +/-  1.10e-01
             Knonhad   1.0000e+00    9.9520e-01 +/-  5.19e-02
      Yield_0b0c_bkg   1.2106e+04    1.2150e+04 +/-  2.63e+02
      Yield_0b1c_bkg   1.8224e+03    1.8358e+03 +/-  8.70e+01
      Yield_0b2c_bkg   1.9257e+03    1.9322e+03 +/-  6.36e+01
      Yield_1b0c_bkg   1.5336e+03    1.5561e+03 +/-  1.32e+02
      Yield_1b1c_bkg   1.3454e+02    1.3653e+02 +/-  2.03e+01
      Yield_1b2c_bkg   2.8539e+01    2.9214e+01 +/-  6.40e+00
        Yield_2b_bkg   2.0942e+03    2.1347e+03 +/-  2.26e+02
                  mH   1.2500e+02    1.2498e+02 +/-  7.58e-02
             p0_0b0c   5.0000e+03    3.2689e+00 +/-  1.55e-01
             p0_0b1c   5.0000e+03    1.9084e+00 +/-  1.64e-01
             p0_0b2c   5.0000e+03    2.5832e+00 +/-  2.51e-01
             p0_1b0c   5.0000e+03    2.7417e+00 +/-  4.52e-01
             p0_1b1c   5.0000e+03    5.0046e+00 +/-  3.98e+00
             p0_1b2c   5.0000e+03    5.8040e+00 +/-  7.23e+00
               p0_2b   5.0000e+03    4.0022e+00 +/-  1.35e+00
               sigma   3.9400e-01    3.7933e-01 +/-  6.17e-02

Relative error on Kbb: 2.1%
Relative error on Kcc: 10.0%
Relative error on Kgg: 11.1%
Relative error on Knonhad: 5.2%
```

- Similar signal yields but B +60%
  ➡ larger uncertainties on σBR (2x for Kbb)!
- Need to re-optimise selection to account for BES and vertex smearing and of course validate more thoroughly new code (esp. flavour labelling of jets)

Conclusions

- **Preliminary study of sensitivity to hadronic Higgs BR with Z(ll)H shows <% uncertainty on H→bb and 5-10% uncertainty on H→cc and H→gg**
  - Depending on various scenarios (BR H→WW and ττ measured separately, gluon tagging, …)
  - Various caveats: no BES and vertex smearing, only stat. uncertainties, sub-leading backgrounds not included..
  - Very recent update with official samples shows worse performance (2% on Kbb) with same analysis => need to consolidate results and (re)optimise selection criteria

- Several things remain to be done
  - Investigate **other event generators and more backgrounds**
  - Investigate impact of **alternative detector designs** (and of new algorithms) affecting **flavour tagging**
  - **Systematic uncertainties**
  - **Fit** (binned vs unbinned / range / signal model parameters that can / can't be correlated across categories / Asimov ..)
  - Improve **hadronic mass resolution** (correct for missing energy from neutrinos ..) to improve discrimination between signal and background

Backup

Event reconstruction - custom Delphes sequence

```
set ExecutionPath {
  ParticlePropagator

  ChargedHadronTrackingEfficiency
  ElectronTrackingEfficiency
  MuonTrackingEfficiency

  TrackMergerPre
  TrackSmearing
  TrackMerger

  Calorimeter
  EFlowMerger

  PhotonEfficiency
  PhotonIsolation

  ElectronFilter
  ElectronEfficiency
  ElectronIsolation

  MuonFilter
  MuonEfficiency
  MuonIsolation

  EFlowFilter

  NeutrinoFilter
  GenJetFinder

  FastJetFinderAntiKt
  FastJetFinderVLC_inclusive
  FastJetFinderVLC_N2
  FastJetFinderVLC_N4

  JetEnergyScaleAntiKt
  JetEnergyScaleVLC_inclusive
  JetEnergyScaleVLC_N2
  JetEnergyScaleVLC_N4

  MissingET
  GenMissingET

  JetFlavorAssociationAntiKt
  JetFlavorAssociationVLC_inclusive
  JetFlavorAssociationVLC_N2
  JetFlavorAssociationVLC_N4

  BTaggingAntiKt
  BTaggingVLC_inclusive
  BTaggingVLC_N2
  BTaggingVLC_N4

  CTaggingAntiKt
  CTaggingVLC_inclusive
  CTaggingVLC_N2
  CTaggingVLC_N4

  GTaggingAntiKt
  GTaggingVLC_inclusive
  GTaggingVLC_N2
  GTaggingVLC_N4

  ScalarHT
  TreeWriter
}
```

Tracking

Calorimetry

Identification of isolated e, μ, γ

Remove e, μ, γ from EFlow objects for jet clustering

Truth-level jet clustering

Detector-level jet clustering (anti-kt, Valencia inclusive and 2- and 4-jet exclusive algorithms)

Jet energy scale

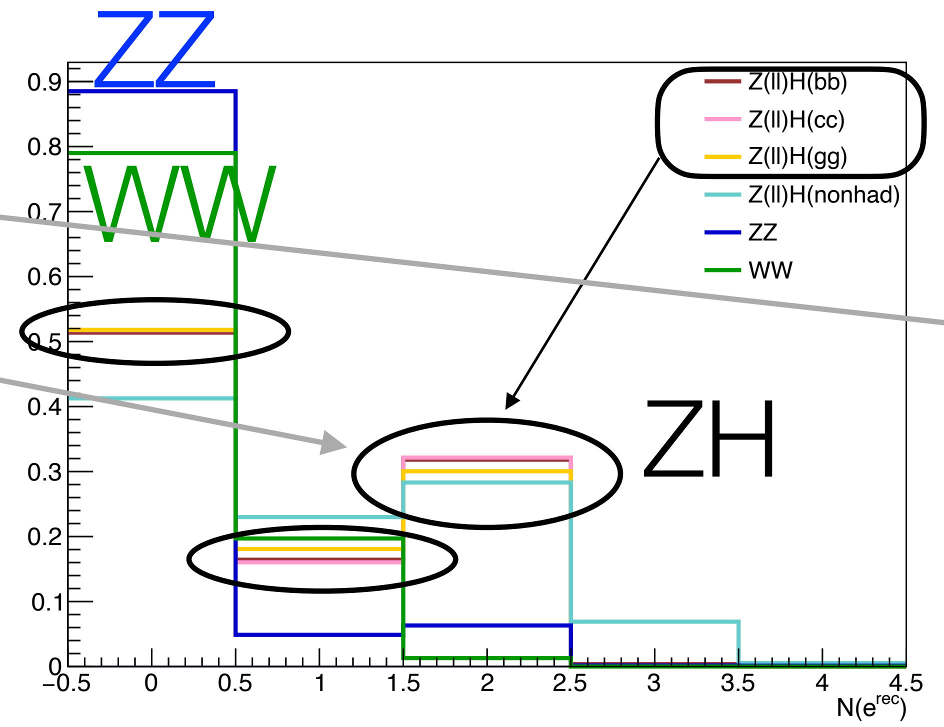
Missing energy (true and reconstructed)

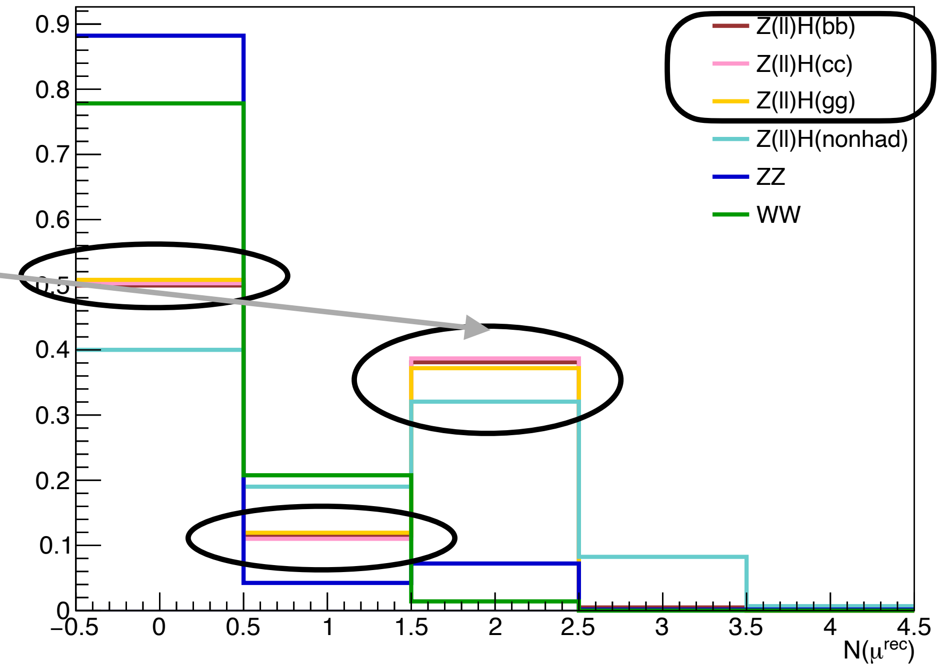
Jet flavour labelling and flavour tagging

H_T

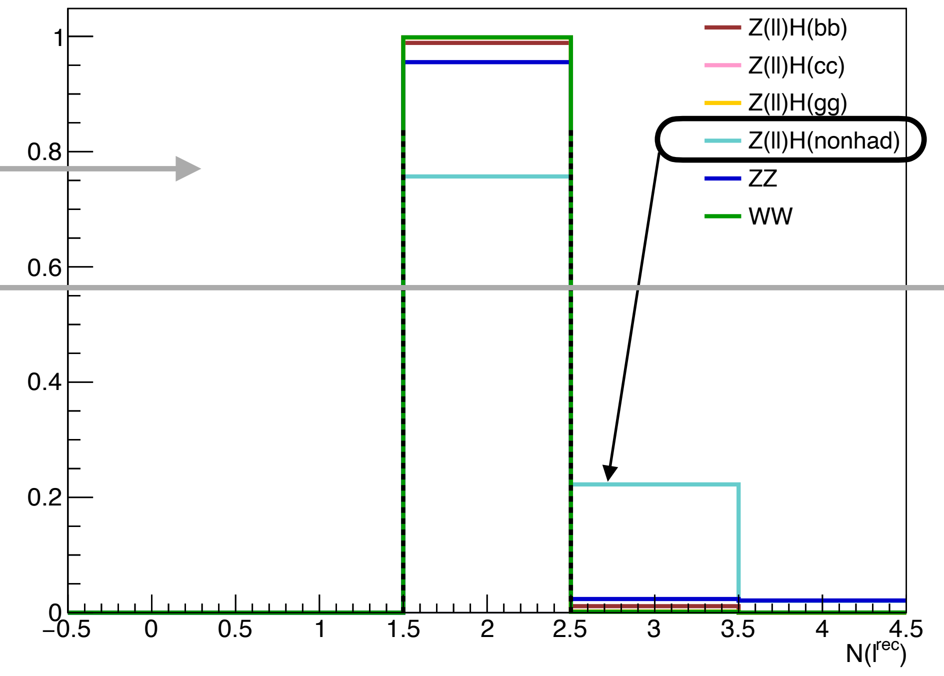
Event selection - Z->ll

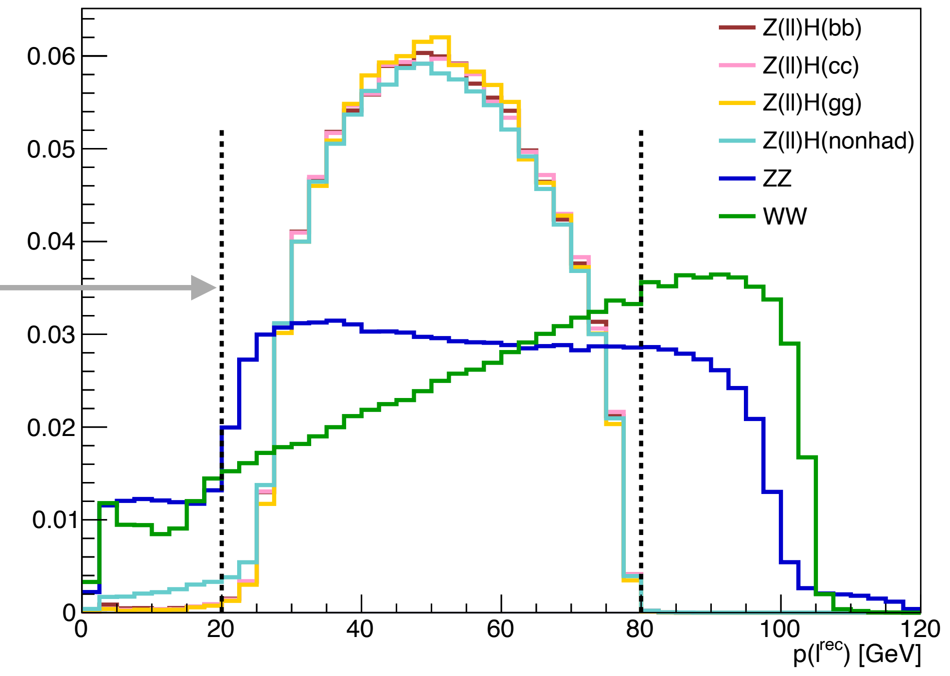
- Exactly 2 isolated electrons or muons



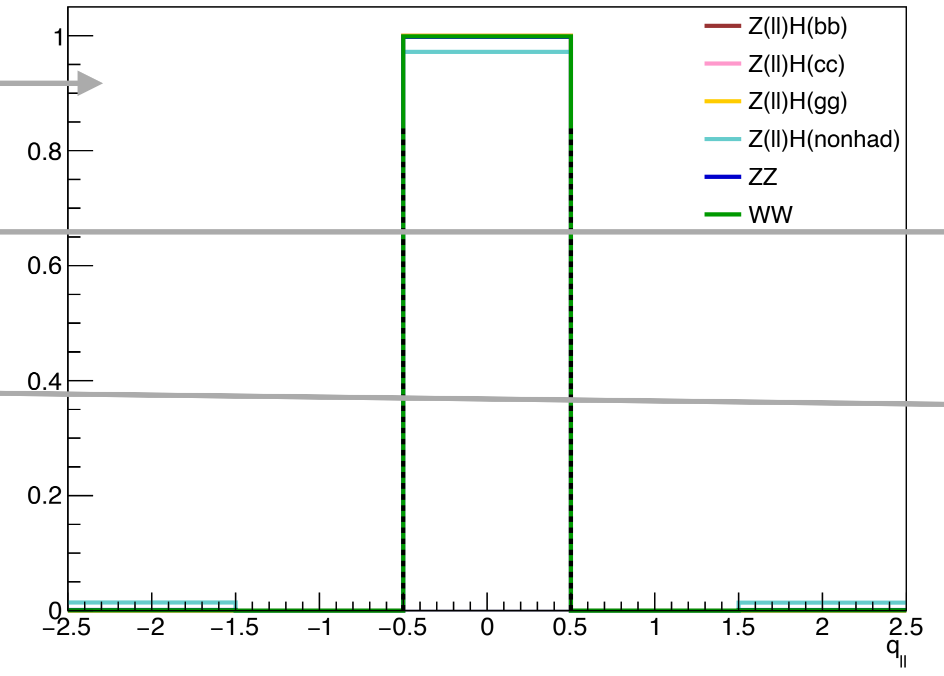


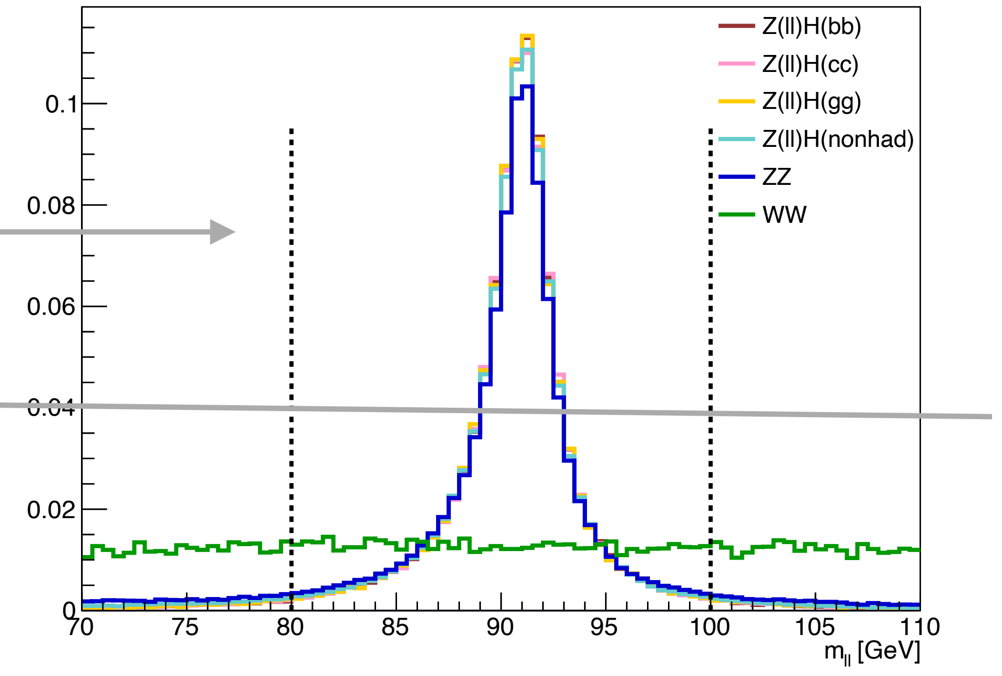
- No additional leptons
- Lepton momenta between 20 and 80 GeV

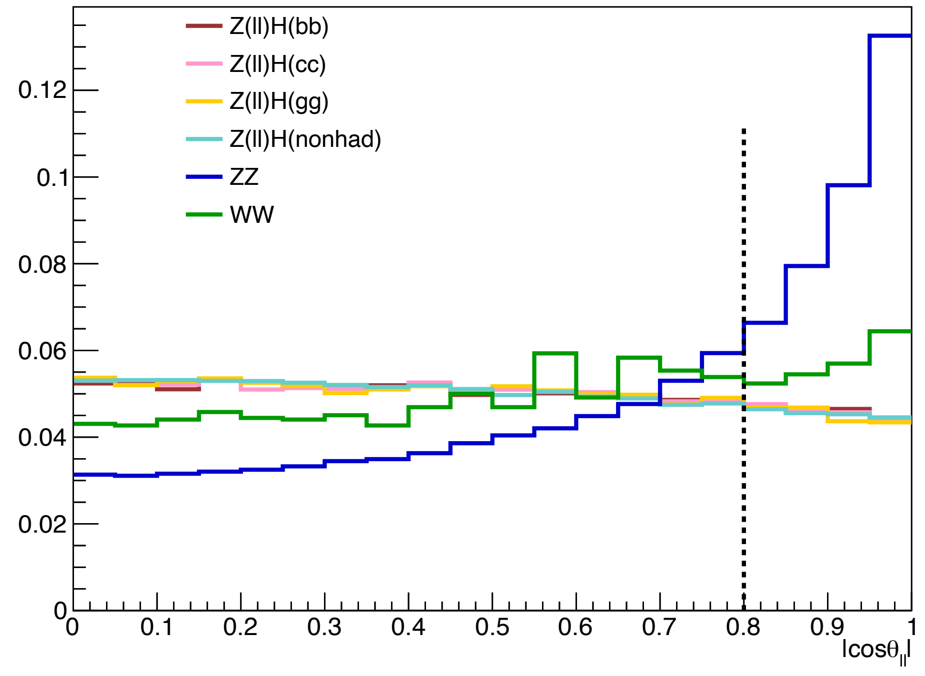




- Dilepton charge = 0
- Dilepton invariant mass in 80-100 GeV
- |cos(Polar angle of dilepton pair)|<0.8

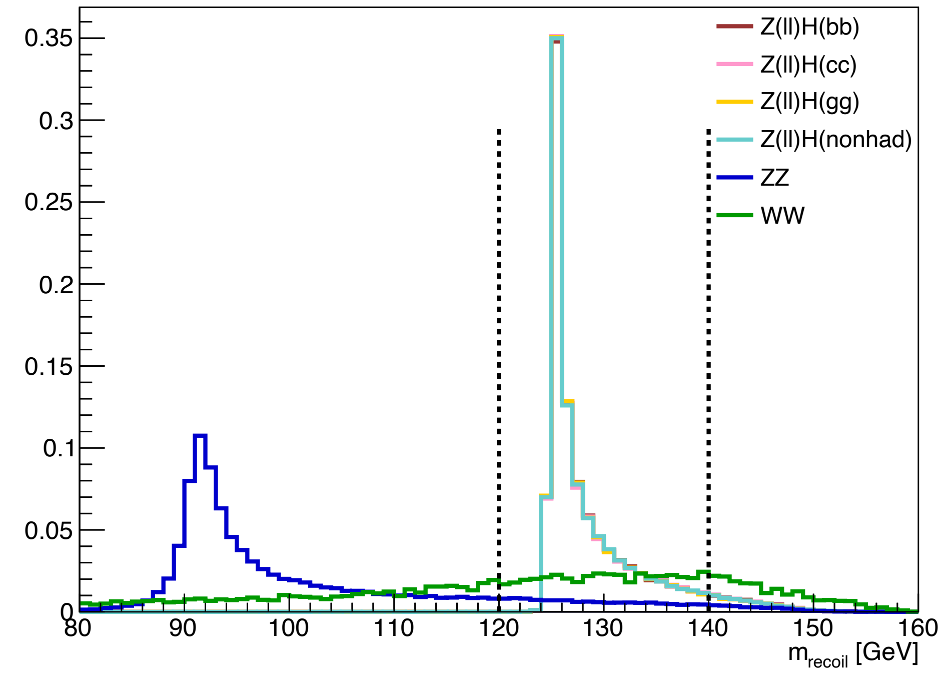




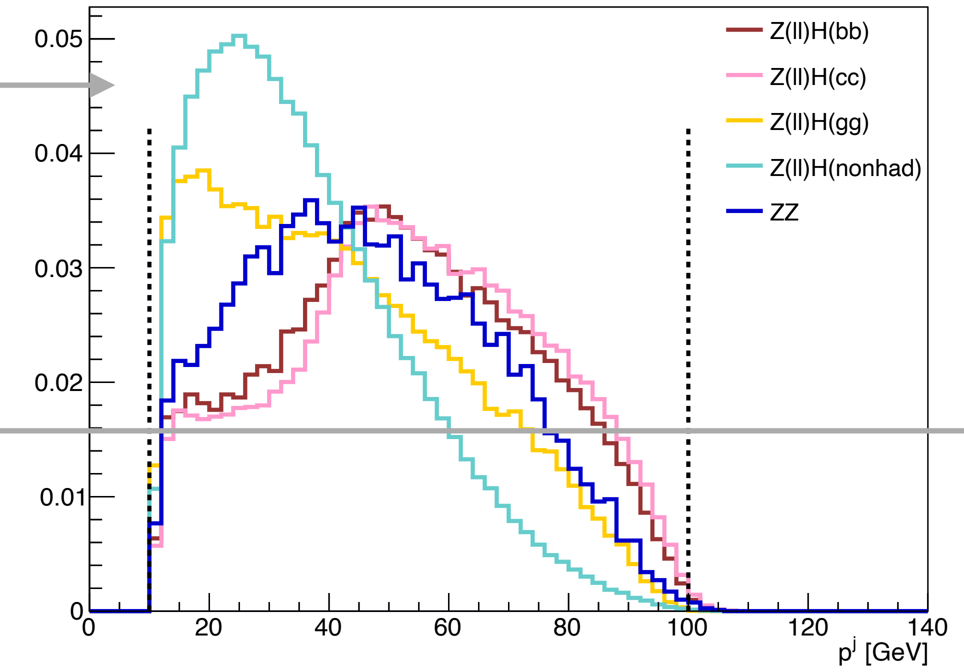


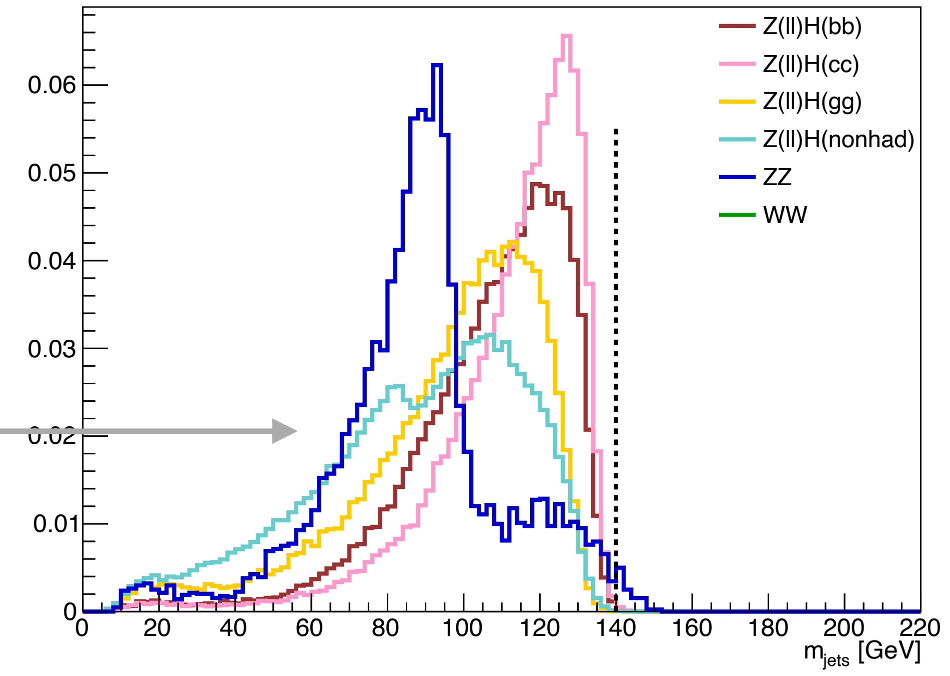
Event selection - recoil, jets

- Recoil mass in 120-140 GeV

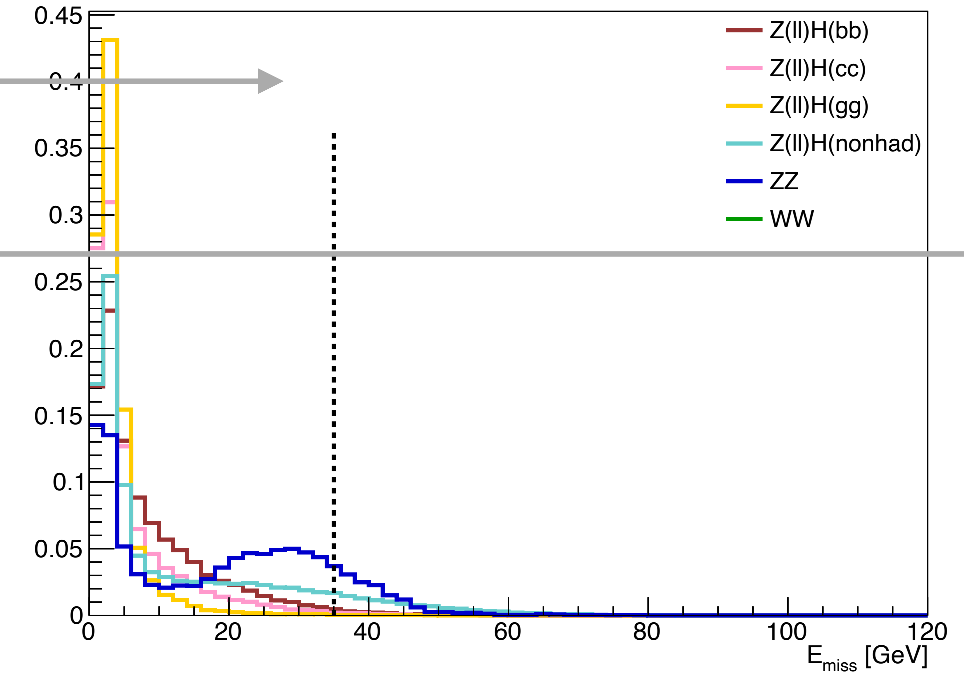


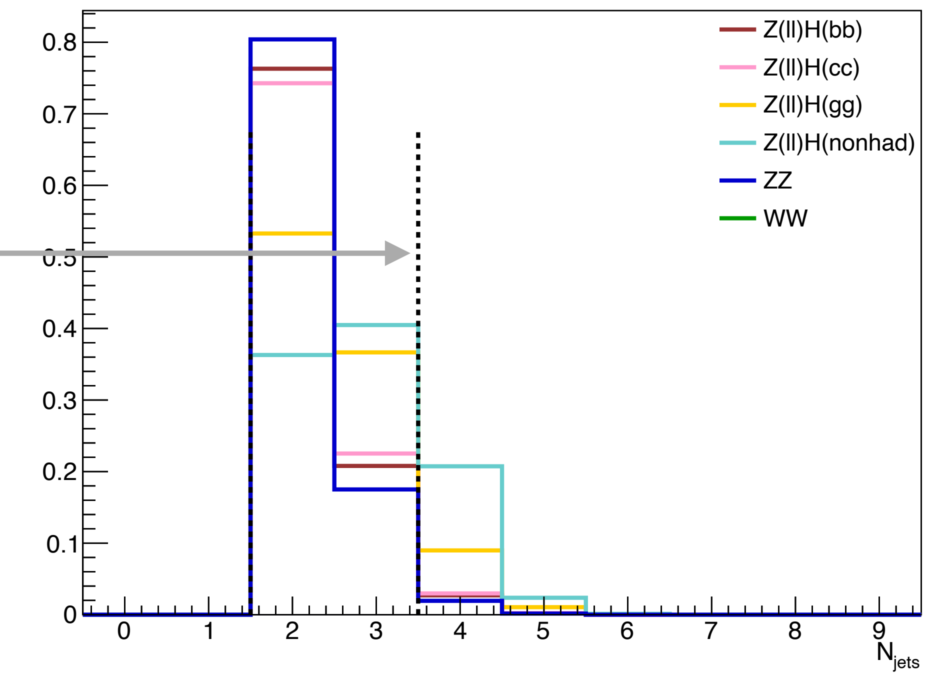
- Jet momentum in 10-100 GeV
- Hadronic mass: long tail, require only m<140 GeV



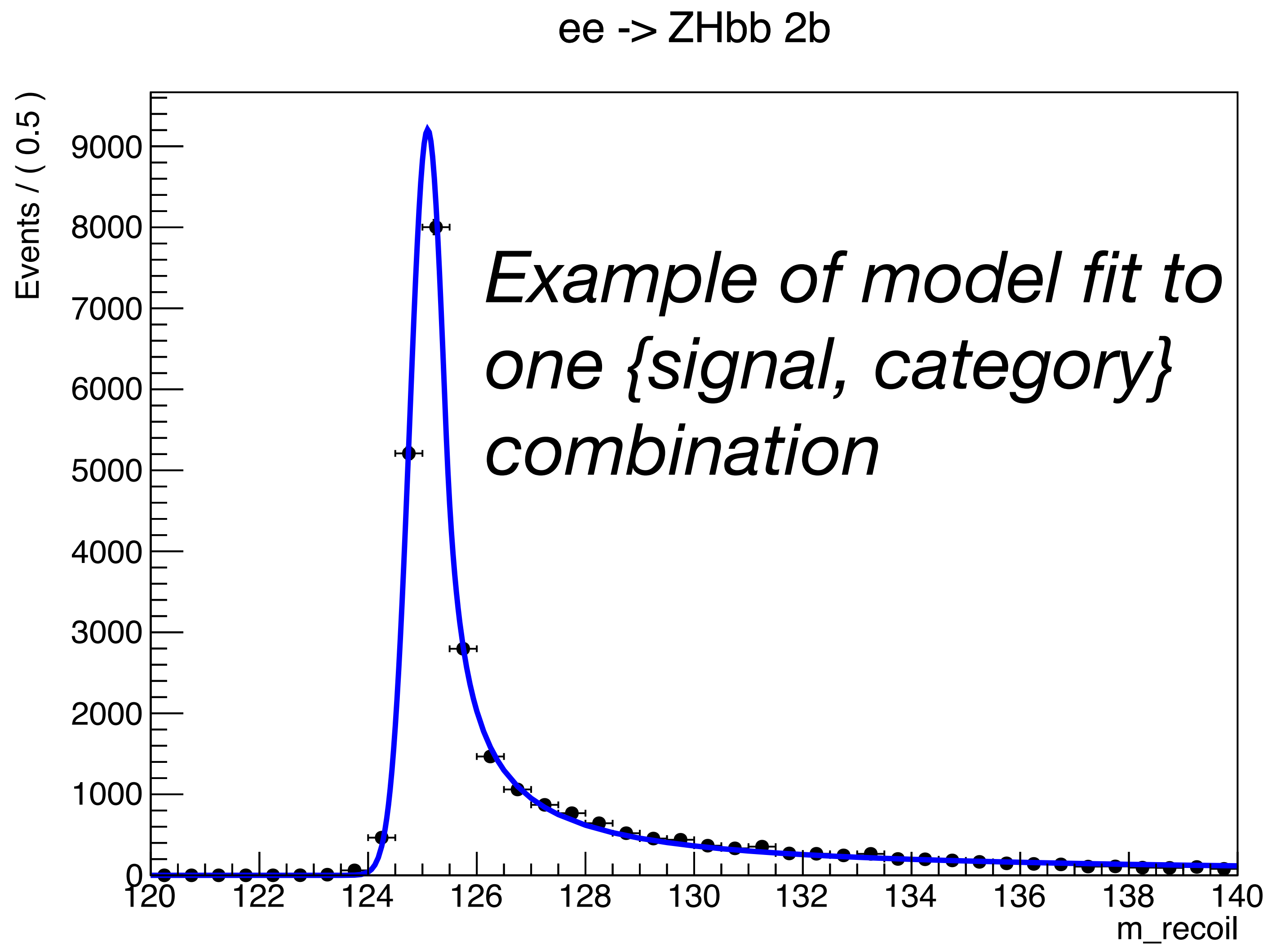


- Missing energy < 35 GeV
- <=3 jets (could actually apply a different #jet cut depending on tagging

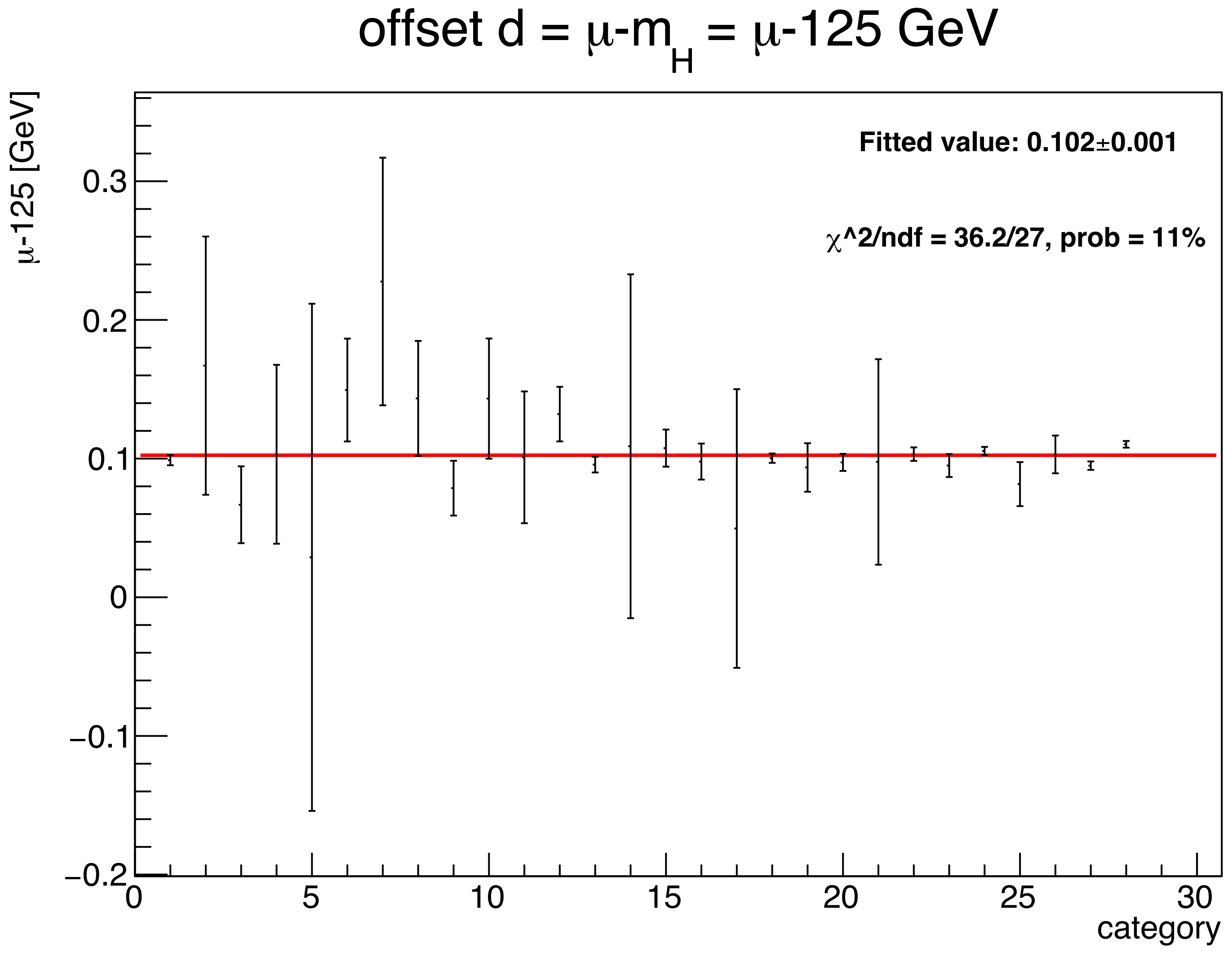


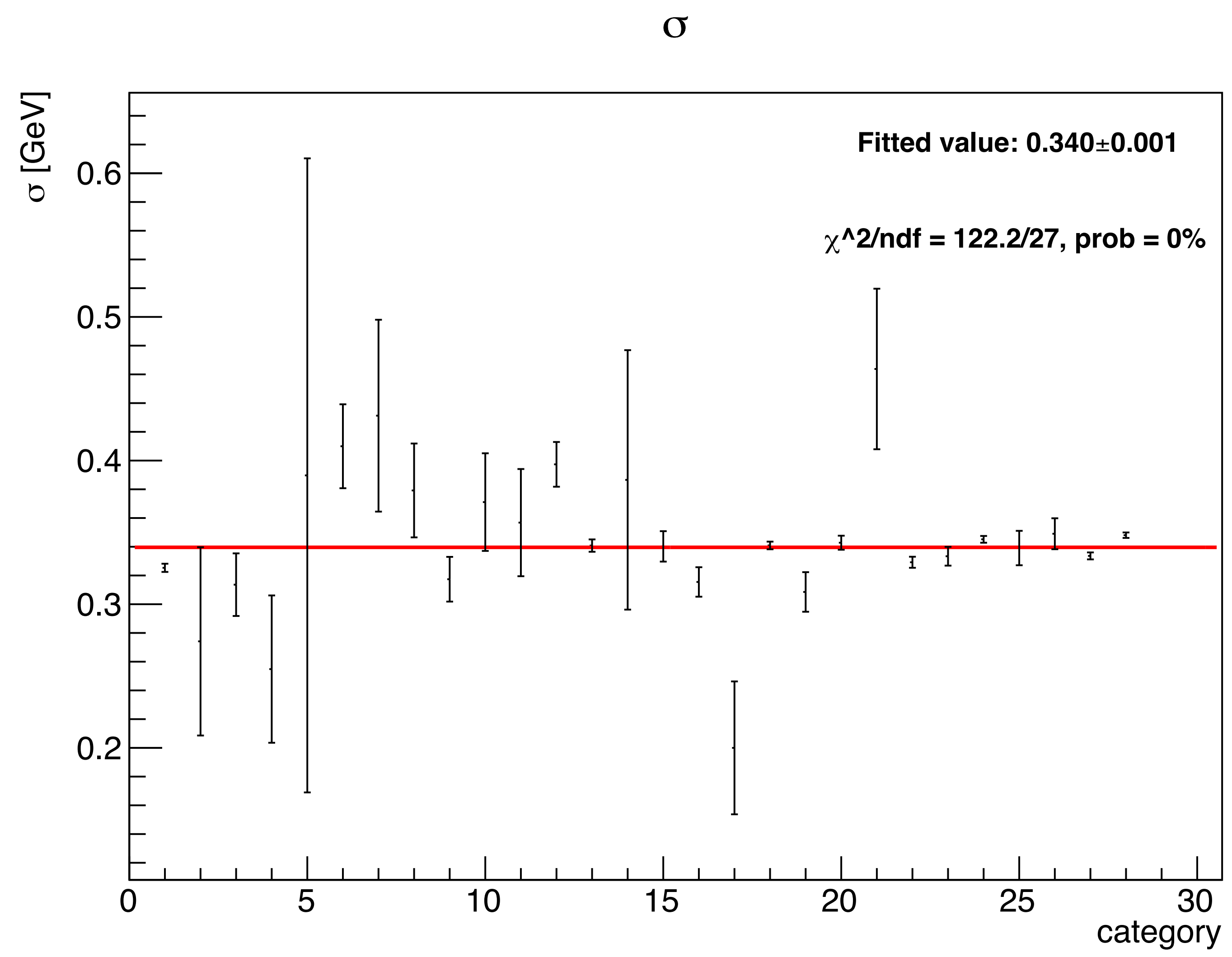


Fit - signal model



Example of model fit to one {signal, category} combination





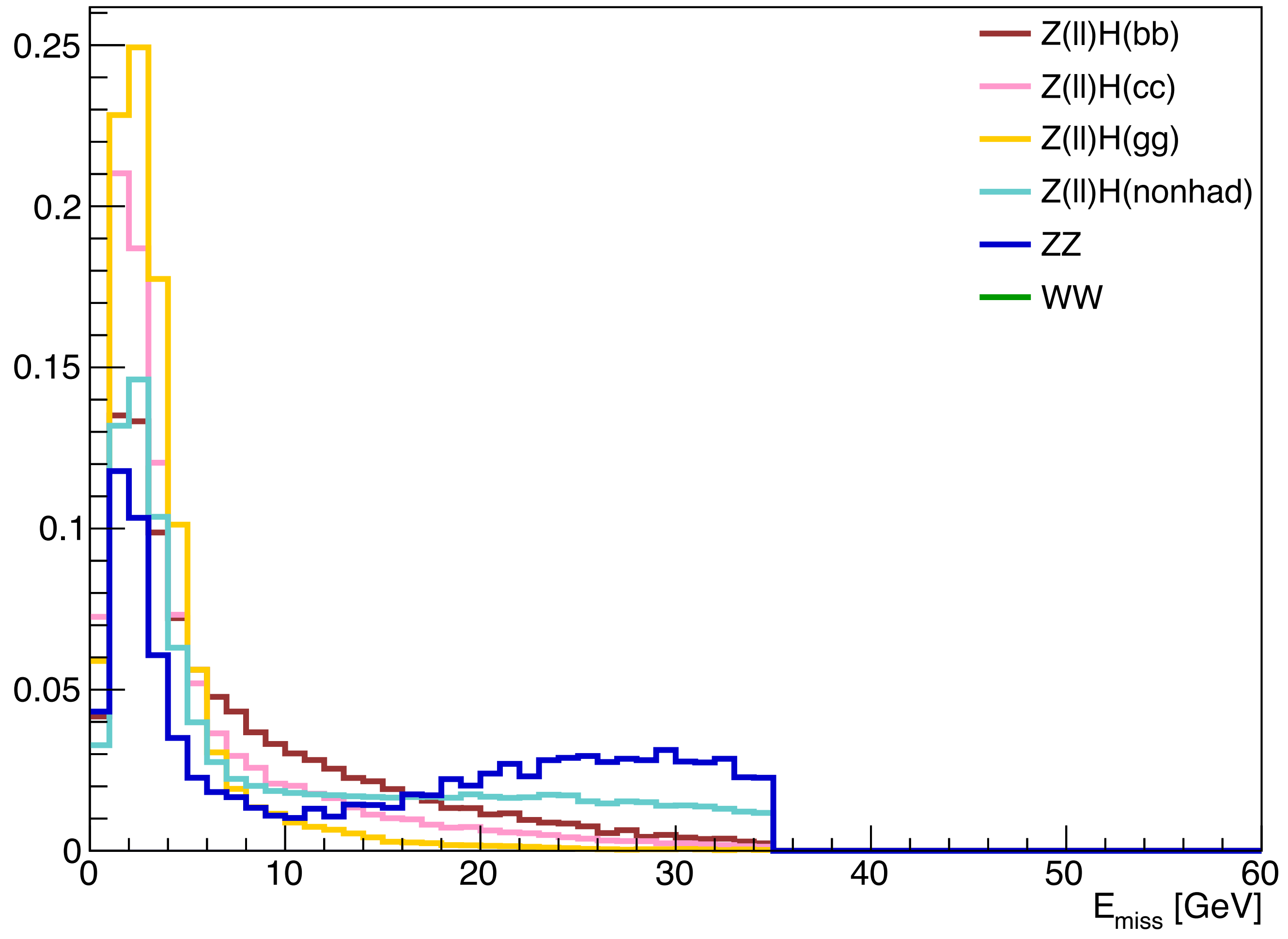
- Parameters are in decent agreement across categories, some tension for the width, seems affected by some very-low stat categories where fit is artificially too narrow - to be further investigated

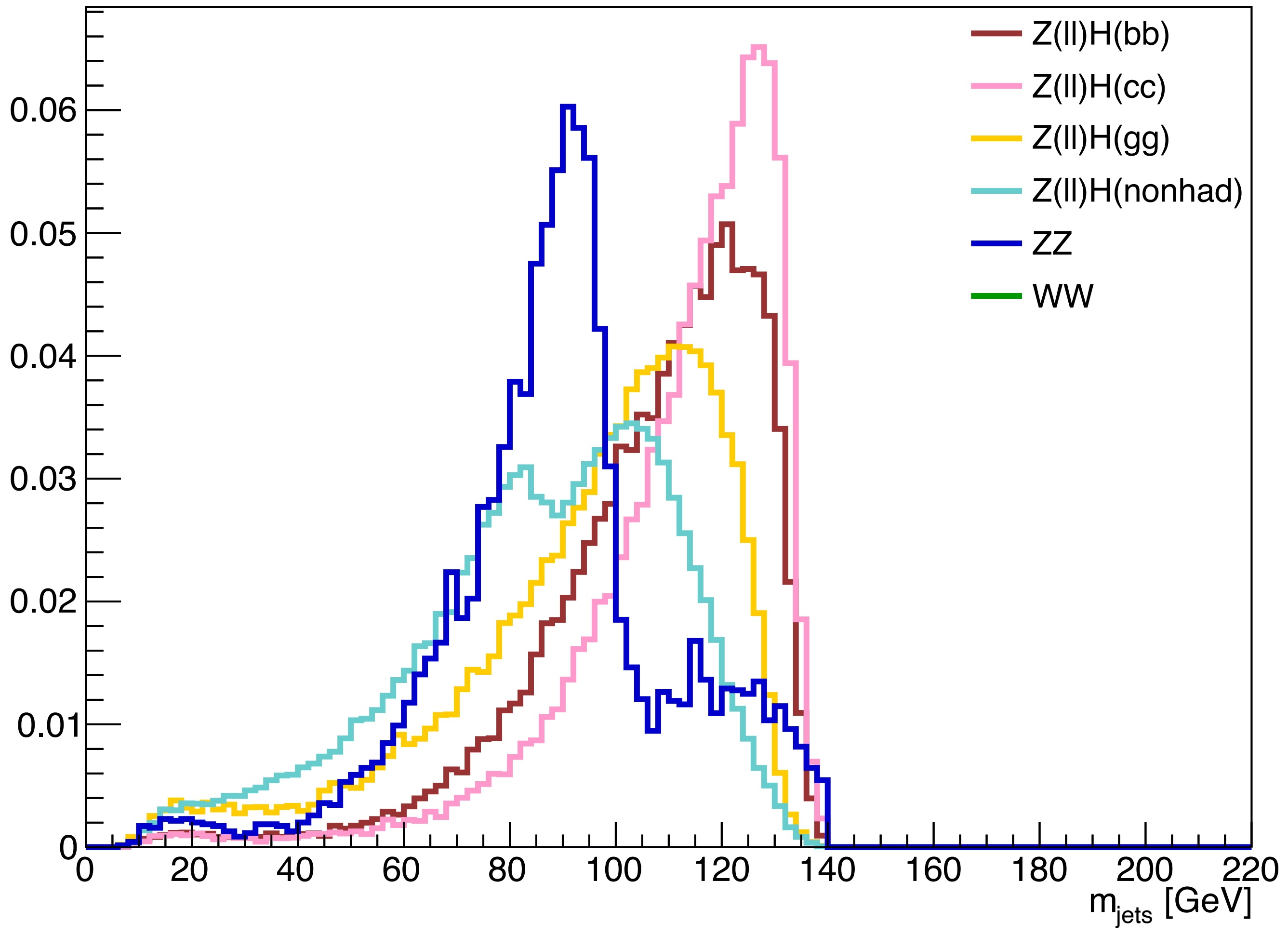
Fit - background model

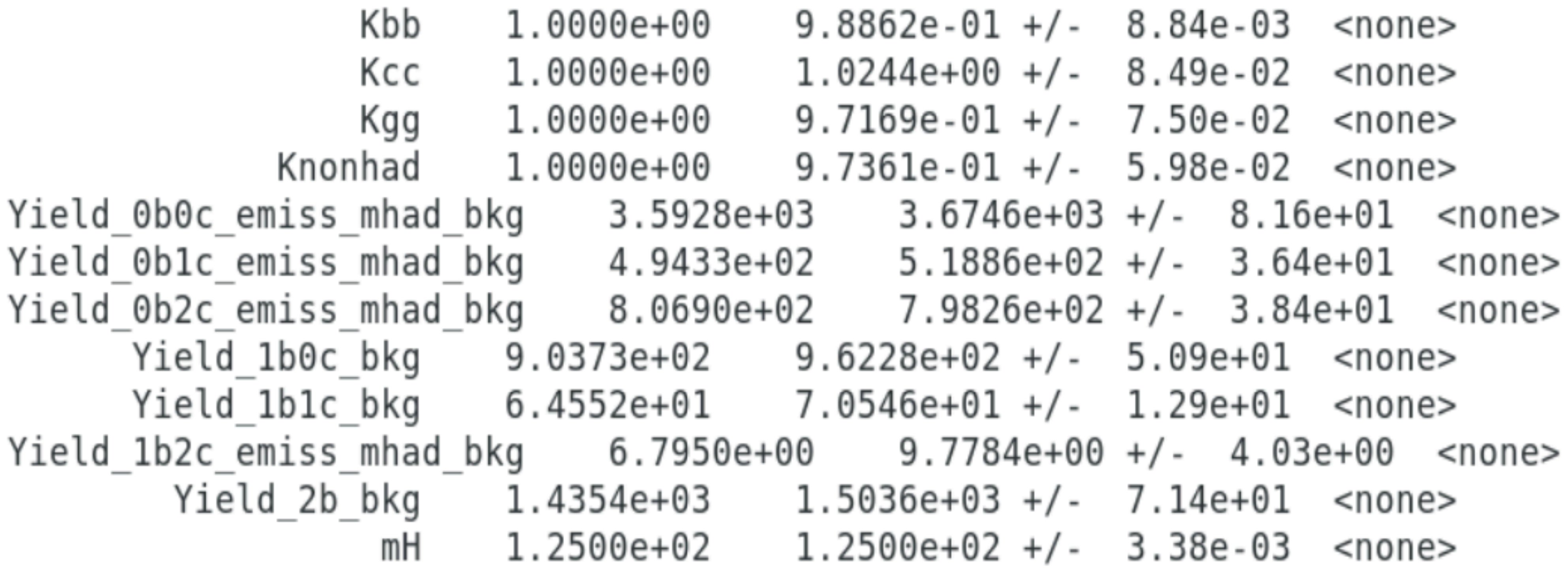
- Simple 1st order polynomial seems OK at first glance given low level of bkg

Suppressing ZH(nonhad) with Emiss, m(jets) cuts

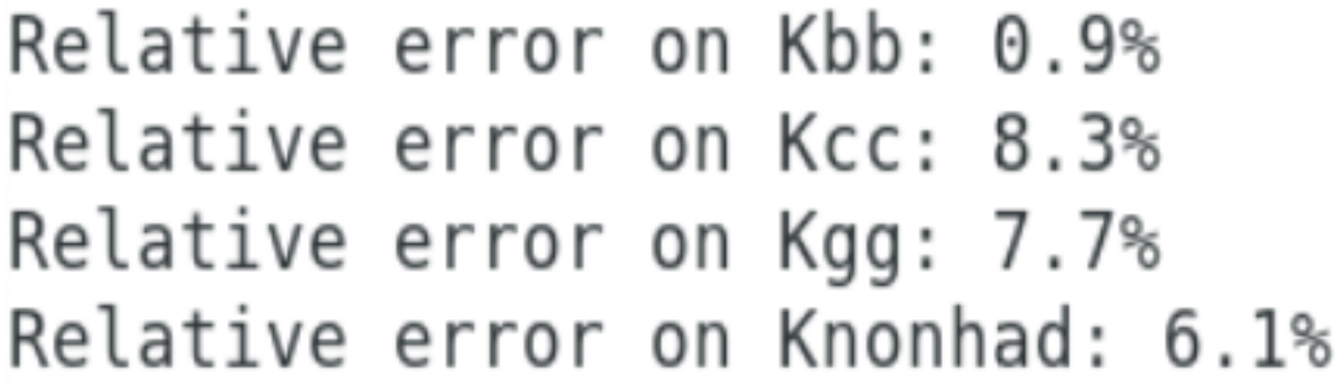
- H(gg) and H(cc) have lower missing energy than H(bb) and H(nonhad) -> tighter cut on Emiss in 0b0c category (15 GeV) and 0b1c, 0b2c, 1b2c categories (25 GeV)
- H(gg) and H(cc) have larger m(jets) than H(nonhad) -> tighter cut on m(jets) in 0b0c category (60 GeV) and 0b1c, 0b2c, 1b2c categories (80 GeV)







```
                Kbb    1.0000e+00    9.8862e-01 +/-  8.84e-03  <none>
                Kcc    1.0000e+00    1.0244e+00 +/-  8.49e-02  <none>
                Kgg    1.0000e+00    9.7169e-01 +/-  7.50e-02  <none>
            Knonhad    1.0000e+00    9.7361e-01 +/-  5.98e-02  <none>
Yield_0b0c_emiss_mhad_bkg    3.5928e+03    3.6746e+03 +/-  8.16e+01  <none>
Yield_0b1c_emiss_mhad_bkg    4.9433e+02    5.1886e+02 +/-  3.64e+01  <none>
Yield_0b2c_emiss_mhad_bkg    8.0690e+02    7.9826e+02 +/-  3.84e+01  <none>
       Yield_1b0c_bkg    9.0373e+02    9.6228e+02 +/-  5.09e+01  <none>
       Yield_1b1c_bkg    6.4552e+01    7.0546e+01 +/-  1.29e+01  <none>
Yield_1b2c_emiss_mhad_bkg    6.7950e+00    9.7784e+00 +/-  4.03e+00  <none>
         Yield_2b_bkg    1.4354e+03    1.5036e+03 +/-  7.14e+01  <none>
                 mH    1.2500e+02    1.2500e+02 +/-  3.38e-03  <none>
```

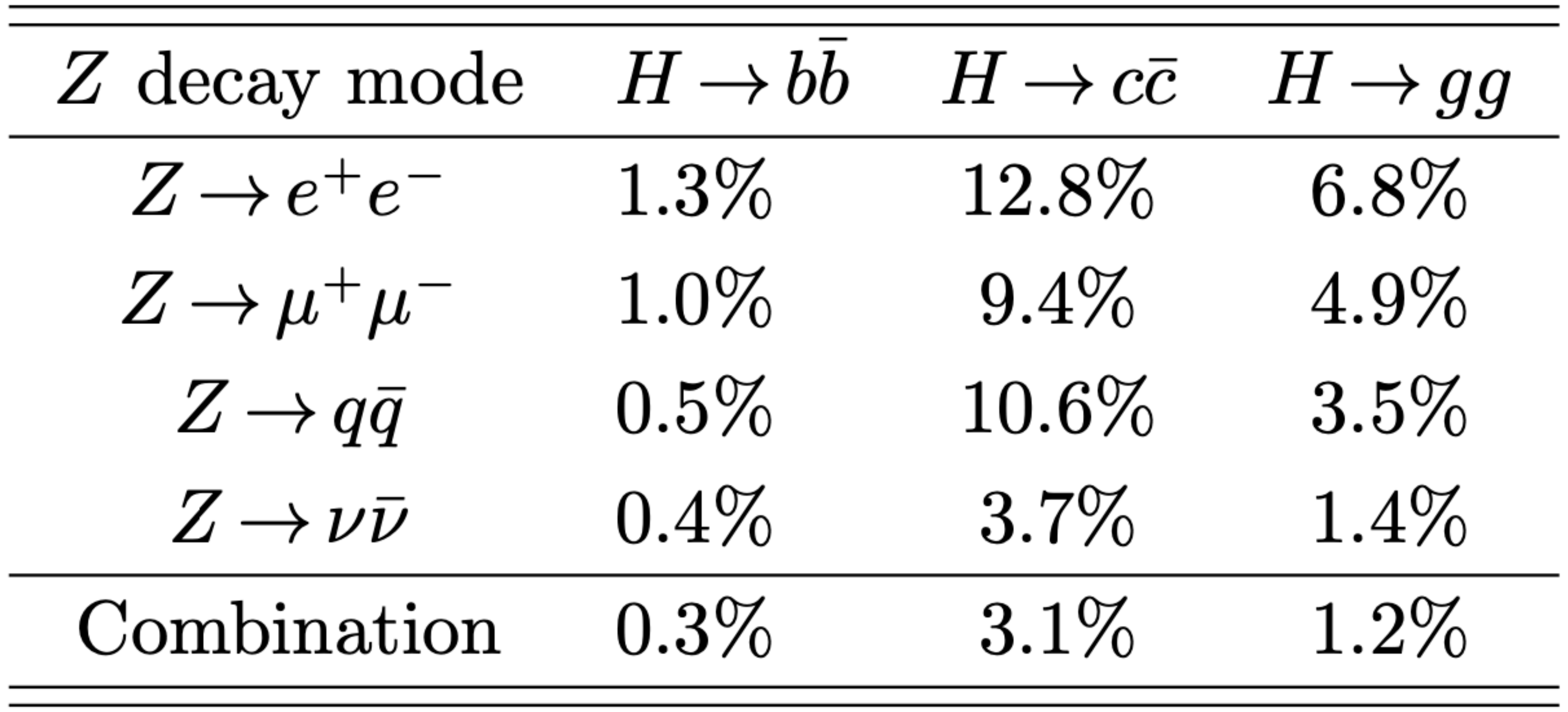


```
Relative error on Kbb: 0.9%
Relative error on Kcc: 8.3%
Relative error on Kgg: 7.7%
Relative error on Knonhad: 6.1%
```

- Error on Kgg decreases (9.7->7.7%) but on Kcc goes up a bit (8.0->8.3%)
  - Need optimisation of the criteria

CEPC projections

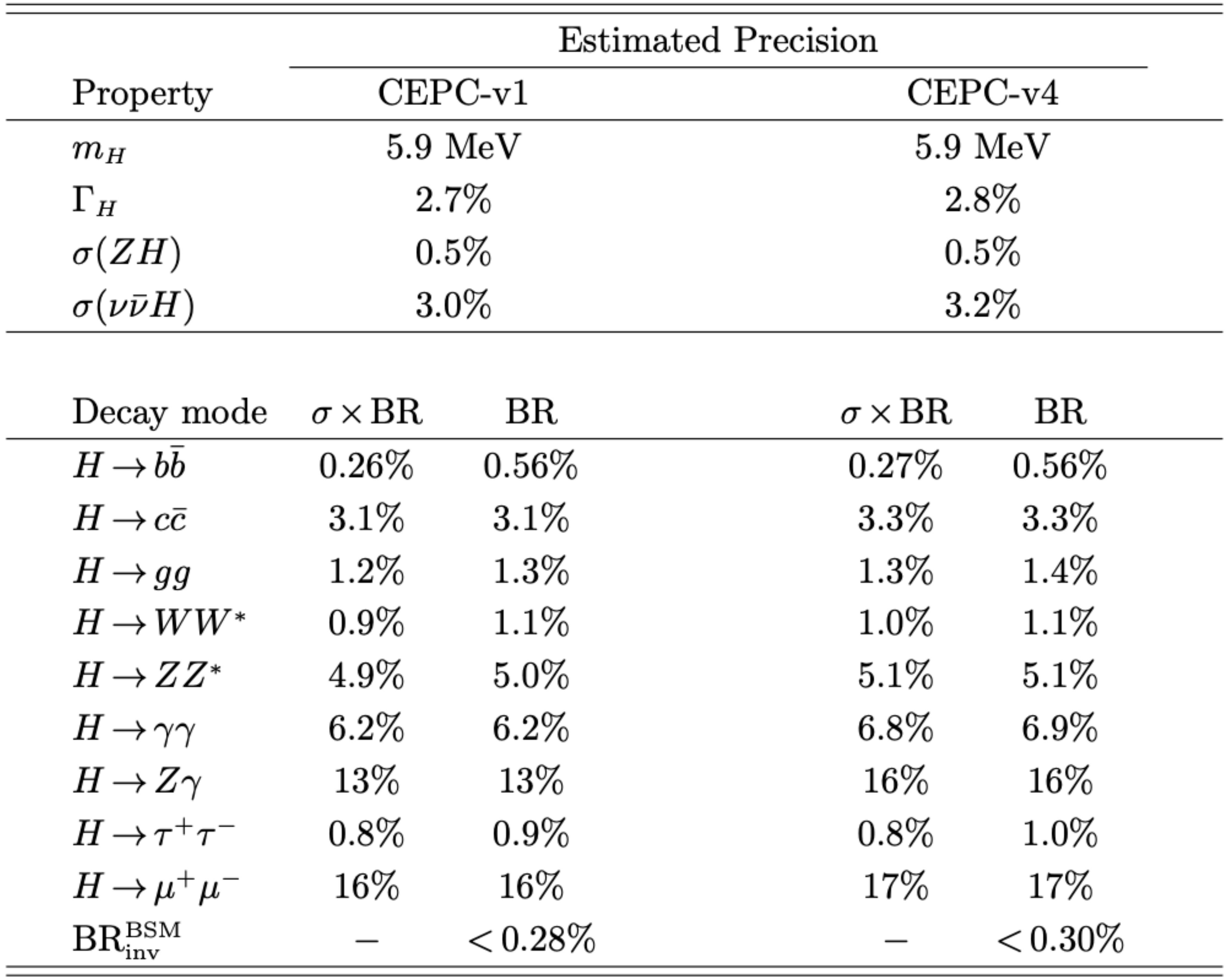
- CEPCv1 (5.6/ab at 250 GeV, B=3.5T)



Z decay mode	$H\to b\bar{b}$	$H\to c\bar{c}$	$H\to gg$
$Z\to e^+e^-$	1.3%	12.8%	6.8%
$Z\to \mu^+\mu^-$	1.0%	9.4%	4.9%
$Z\to q\bar{q}$	0.5%	10.6%	3.5%
$Z\to \nu\bar{\nu}$	0.4%	3.7%	1.4%
Combination	0.3%	3.1%	1.2%

- ~5% worse results for CEPCv4 vs v1

- CEPCv1 vs CEPCv4 (5.6/ab at 240 GeV, B=3T)



	Estimated Precision			
Property	CEPC-v1		CEPC-v4	
m_H	5.9 MeV		5.9 MeV	
Γ_H	2.7%		2.8%	
$\sigma(ZH)$	0.5%		0.5%	
$\sigma(\nu\bar{\nu}H)$	3.0%		3.2%	
Decay mode	$\sigma\times$BR	BR	$\sigma\times$BR	BR
$H\to b\bar{b}$	0.26%	0.56%	0.27%	0.56%
$H\to c\bar{c}$	3.1%	3.1%	3.3%	3.3%
$H\to gg$	1.2%	1.3%	1.3%	1.4%
$H\to WW^*$	0.9%	1.1%	1.0%	1.1%
$H\to ZZ^*$	4.9%	5.0%	5.1%	5.1%
$H\to \gamma\gamma$	6.2%	6.2%	6.8%	6.9%
$H\to Z\gamma$	13%	13%	16%	16%
$H\to \tau^+\tau^-$	0.8%	0.9%	0.8%	1.0%
$H\to \mu^+\mu^-$	16%	16%	17%	17%
$\mathrm{BR}_{\mathrm{inv}}^{\mathrm{BSM}}$	–	$<0.28\%$	–	$<0.30\%$

FCCee CDR projections

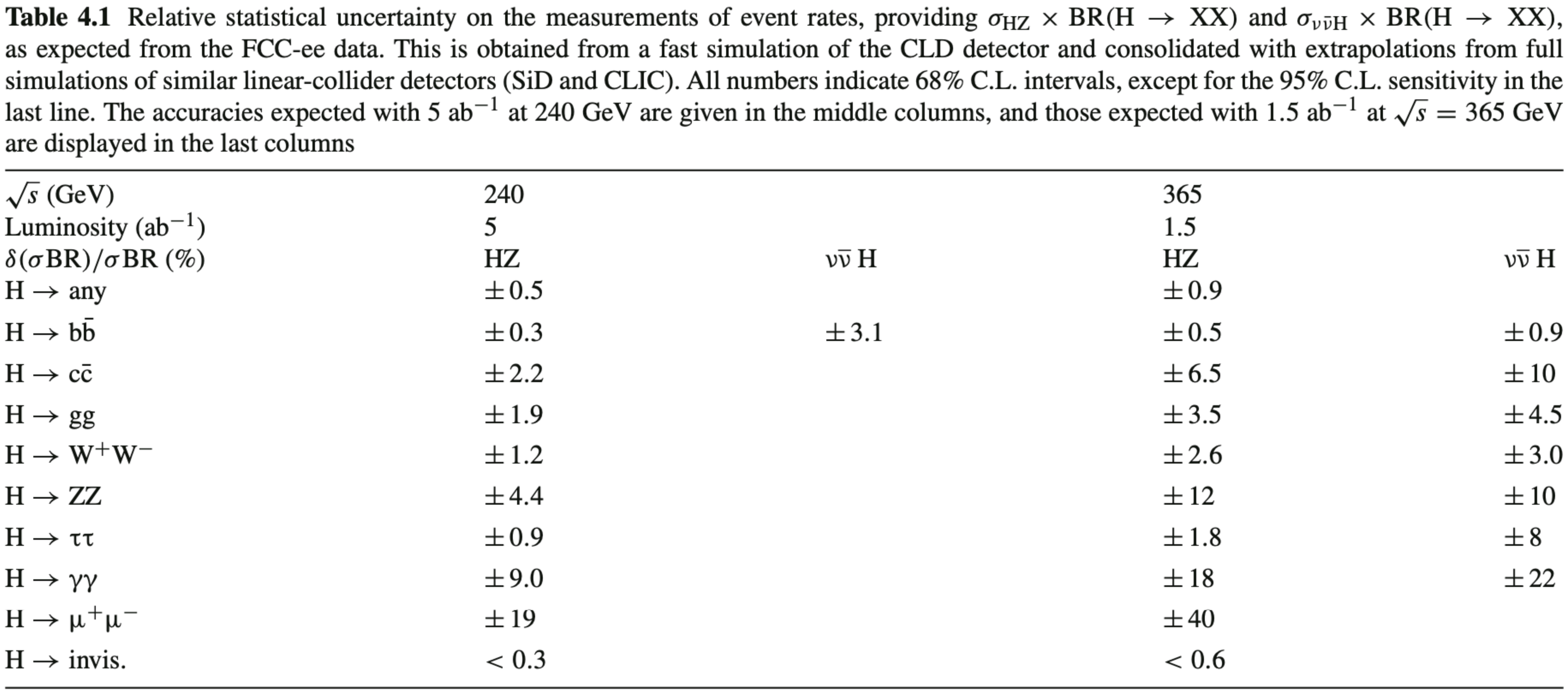


Table 4.1 Relative statistical uncertainty on the measurements of event rates, providing $\sigma_{HZ} \times BR(H \rightarrow XX)$ and $\sigma_{\nu\bar{\nu}H} \times BR(H \rightarrow XX)$, as expected from the FCC-ee data. This is obtained from a fast simulation of the CLD detector and consolidated with extrapolations from full simulations of similar linear-collider detectors (SiD and CLIC). All numbers indicate 68% C.L. intervals, except for the 95% C.L. sensitivity in the last line. The accuracies expected with 5 ab^{-1} at 240 GeV are given in the middle columns, and those expected with 1.5 ab^{-1} at $\sqrt{s} = 365$ GeV are displayed in the last columns

$\sqrt{s}$ (GeV)	240		365	
Luminosity (ab^{-1})	5		1.5	
$\delta(\sigma BR)/\sigma BR$ (%)	HZ	$\nu\bar{\nu}$ H	HZ	$\nu\bar{\nu}$ H
$H \rightarrow$ any	± 0.5		± 0.9	
$H \rightarrow b\bar{b}$	± 0.3	± 3.1	± 0.5	± 0.9
$H \rightarrow c\bar{c}$	± 2.2		± 6.5	± 10
$H \rightarrow gg$	± 1.9		± 3.5	± 4.5
$H \rightarrow W^+W^-$	± 1.2		± 2.6	± 3.0
$H \rightarrow ZZ$	± 4.4		± 12	± 10
$H \rightarrow \tau\tau$	± 0.9		± 1.8	± 8
$H \rightarrow \gamma\gamma$	± 9.0		± 18	± 22
$H \rightarrow \mu^+\mu^-$	± 19		± 40	
$H \rightarrow$ invis.	< 0.3		< 0.6	