# Lepton Flavour Violating Higgs Boson decays in the Compact Linear Collider CLIC

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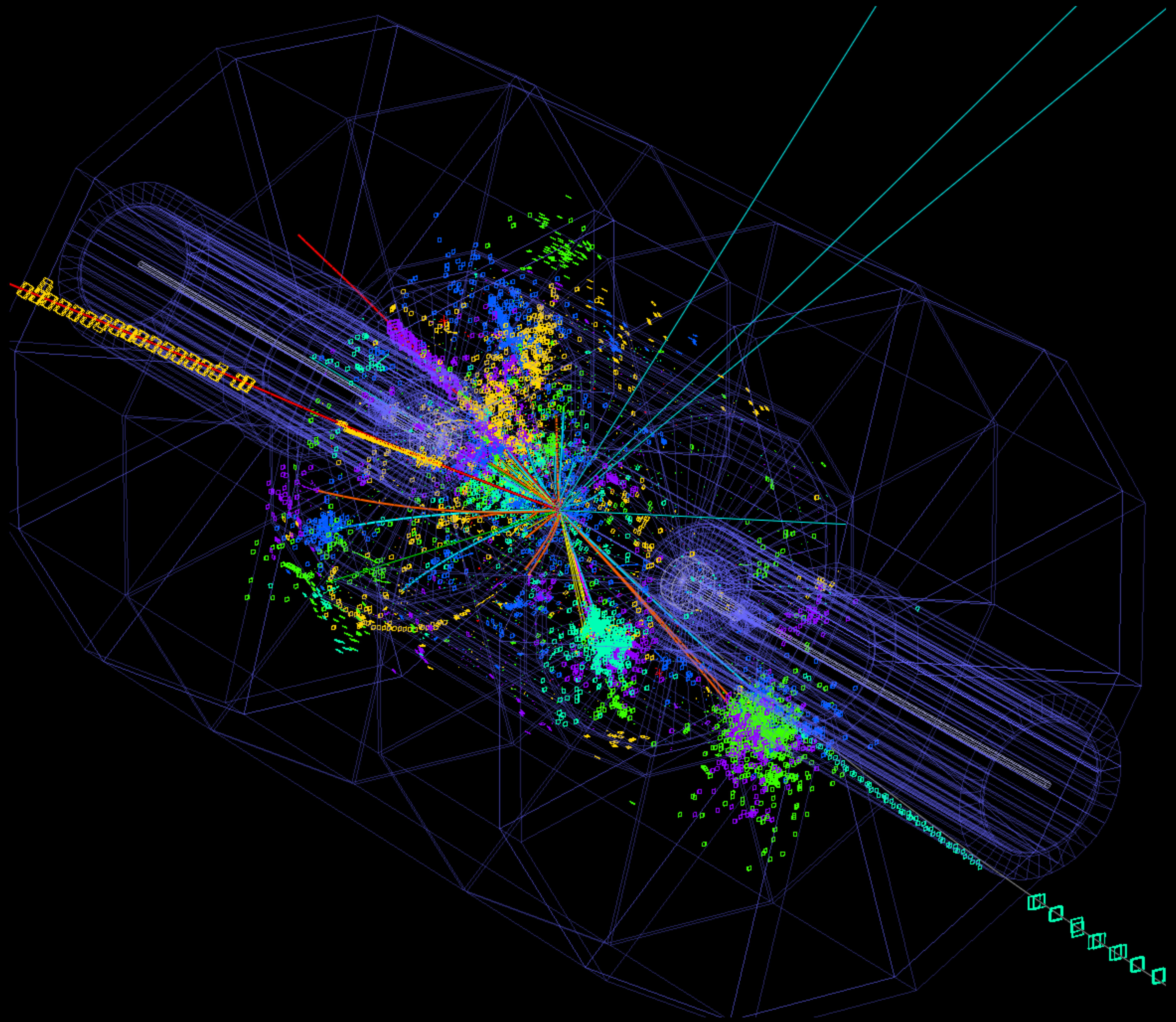
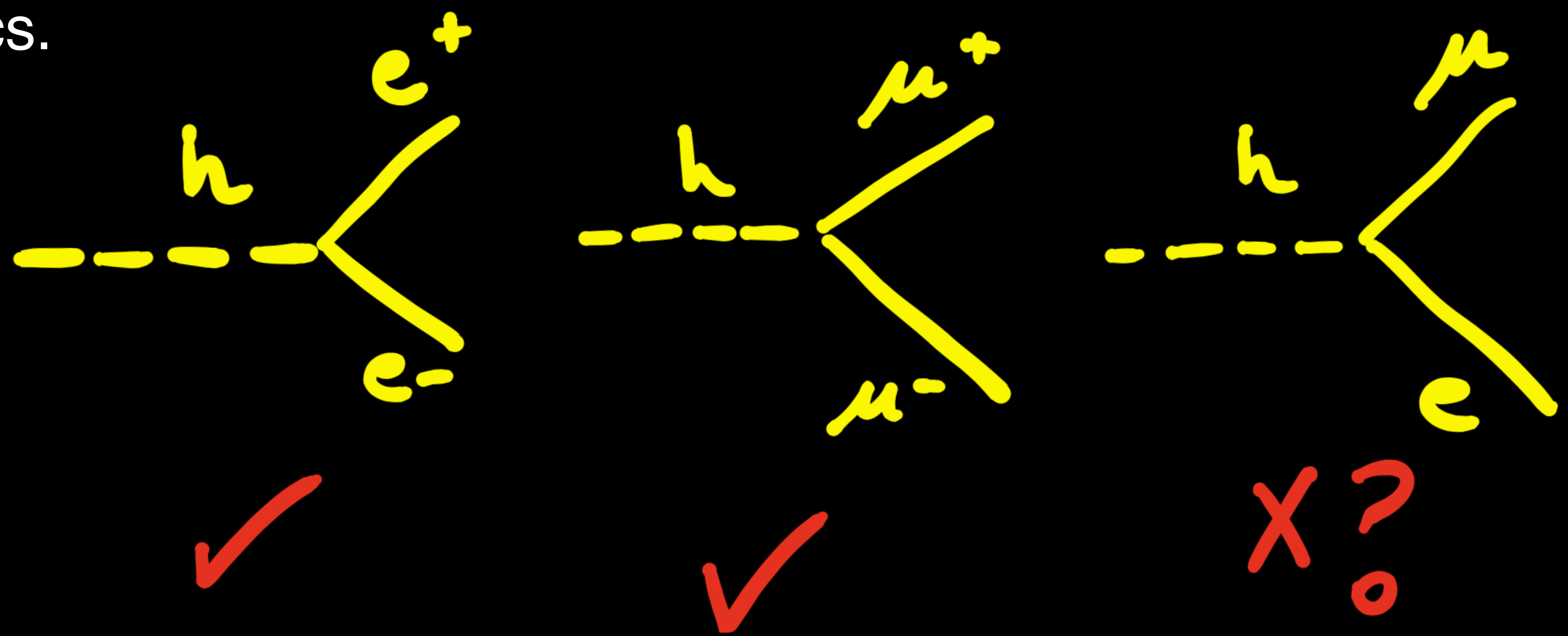


# Lepton Flavour Violation: motivation

- Both ATLAS and CMS collaborations have study Higgs Boson properties and found no significant deviations from SM predictions.
- Experimental data (neutrino oscillations) indicate that Lepton flavour is not an exact symmetry
- In the SM, the lepton flavour violating Higgs decays, $h \to \tau\mu$, $h \to \tau e$, and $h \to \mu e$ are suppressed by the tiny neutrino masses and thus below any imaginable experimental sensitivity
- Observation of a flavour violating Higgs decay would therefore clearly indicate the presence of new physics.

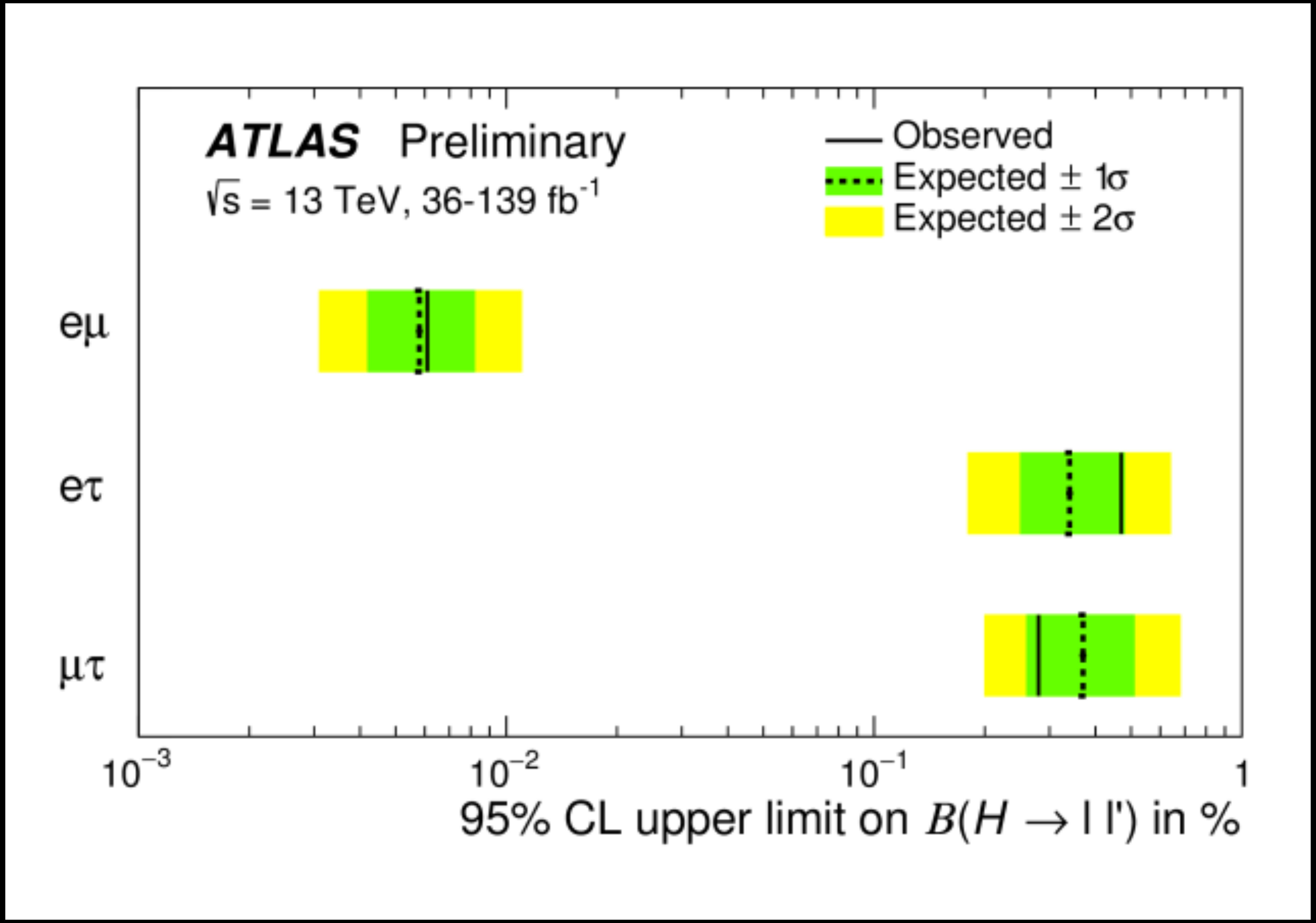


# Previous results

Previous studies have set upper limits (at 95% CL) on LFV Higgs decay branching ratios:

- Searches:
  - ✓ ATLAS: BR(h→τμ(e)) < 0.28%(0.47%) (13 TeV, L = 36.1 $fb^{-1}$, see arXiv:1907.06131 [hep-ex], 2019), BR(h→μe) < $6.1x10^{-3}$ %, see (13 TeV, L = 139 $fb^{-1}$, see ATLAS-CONF-2019-037)
  - ✓ CMS: BR(h→τμ(e)) < 0.25%(0.37%) (13 TeV, L=35.9 $fb^{-1}$, see arXiv:1712.07173 [hep-ex], 2018)

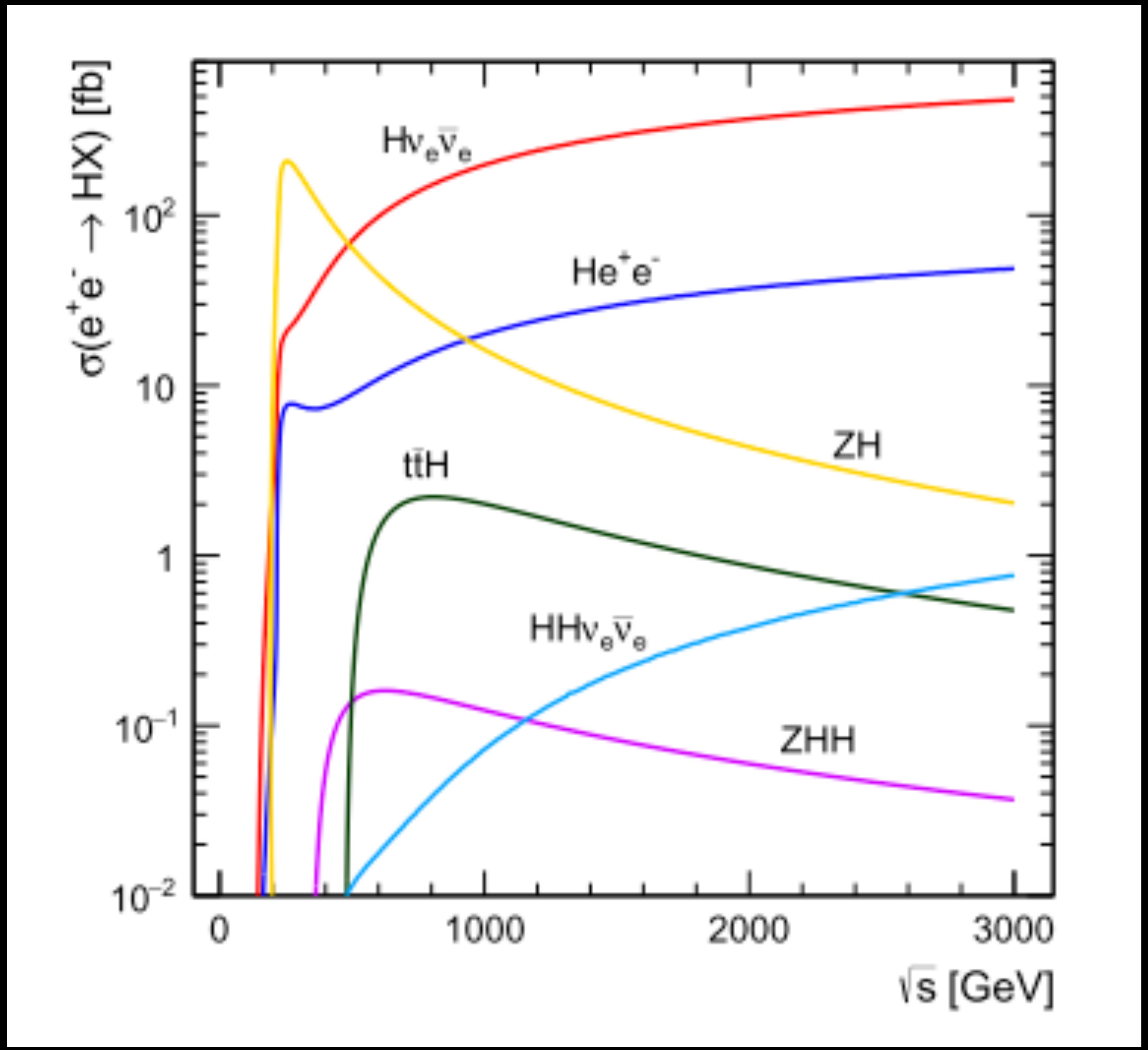
[hep-ex], 2018)



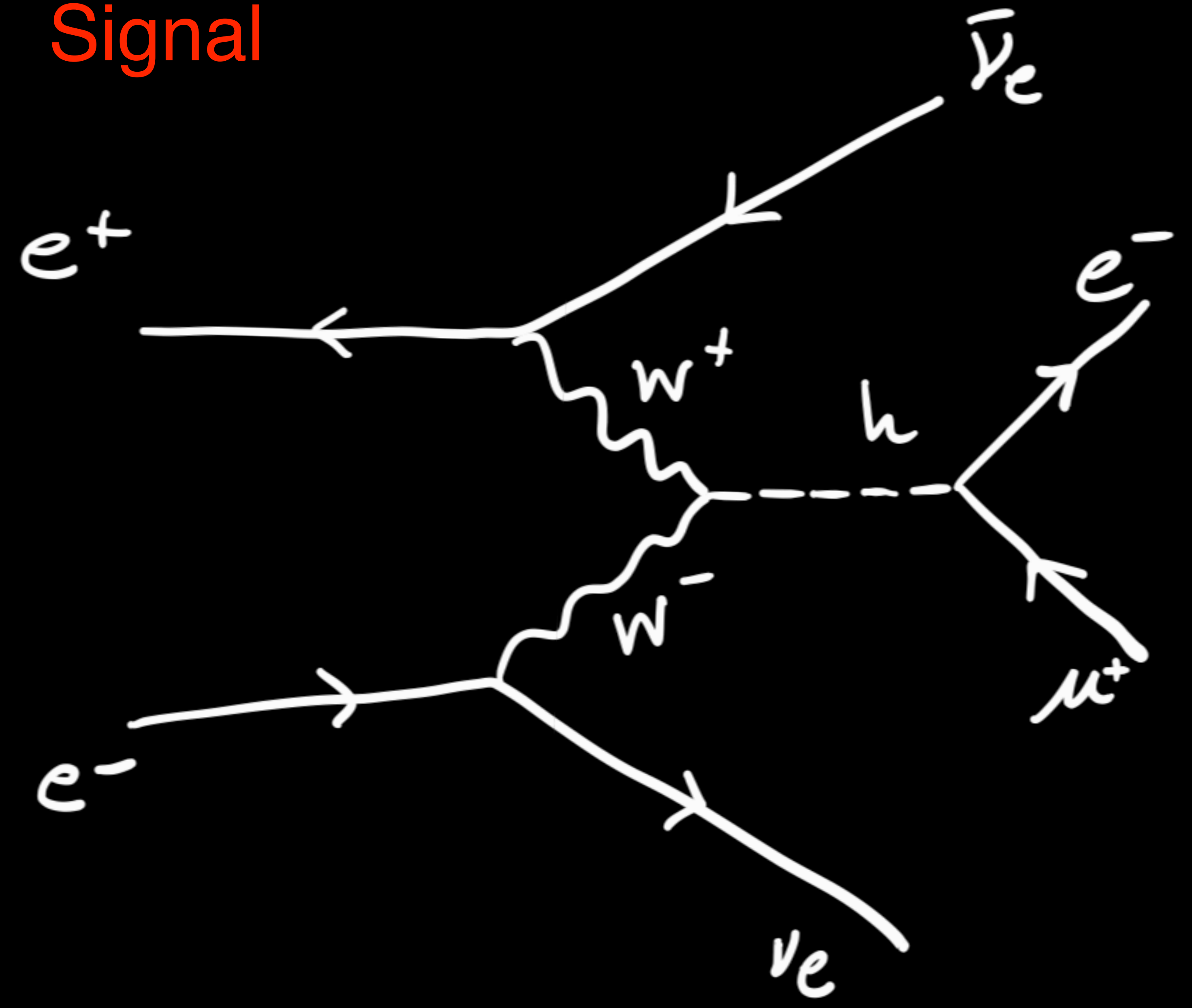
# Our analysis

Lepton Flavour Violating Higgs decays

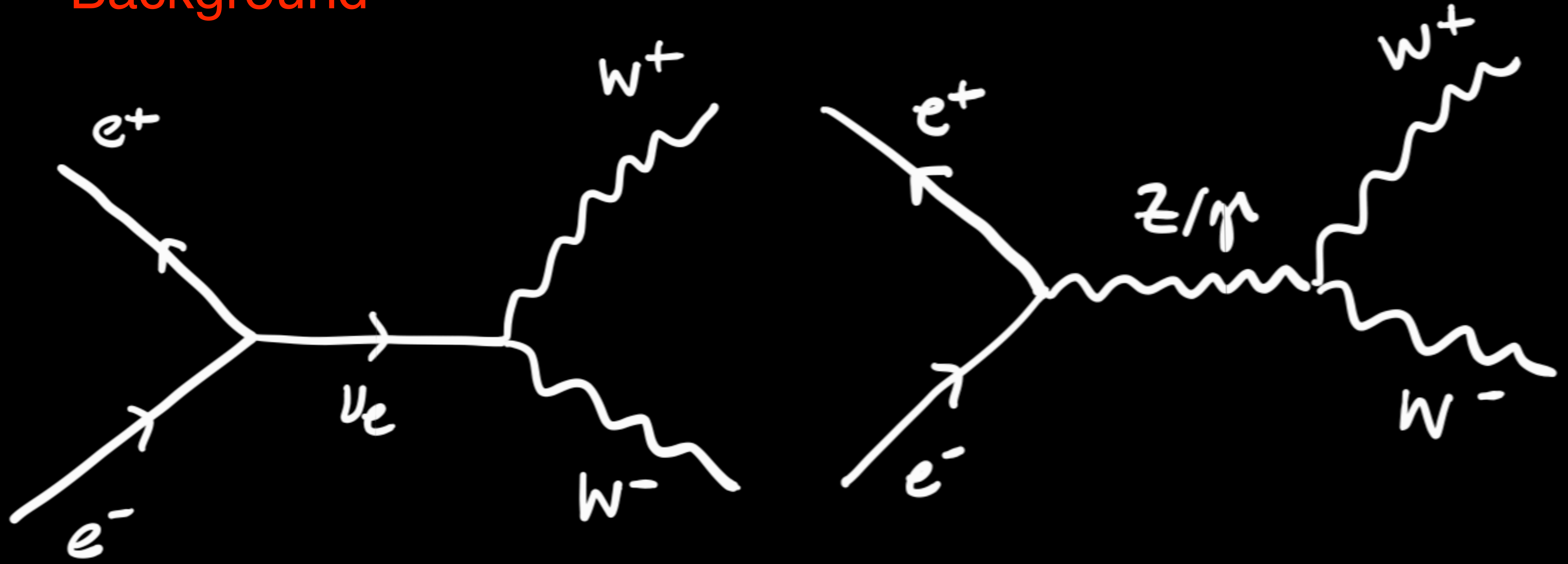
$H \rightarrow e\mu$
$H \rightarrow e\tau$
$H \rightarrow \mu\tau$




Signal




Background




We want to calculate limits on the branching ratios and improve significance using MVA techniques

# MC samples

- The signal ee→hνν and background ee→llνν processes were simulated using Whizard 1.95
- The effects of Beamstrahlung and ISR were included
- The Higgs mass was set to 126 GeV and unpolarised beams were assumed
- Then the events were passed to Pythia for (hadronisation and) decays (LFV added into decay table)
- The detector simulation and reconstruction chain with the CLIC_ILD detector model
- Pileup from γγ→hadrons interactions was overlaid to the physics events
- The cross-section for the signal sample is σ = 244 fb and for the background sample is σ = 978.5 fb
- The center of mass energy was assumed at 1.4 TeV

| Type | Energy | Detector | ProdID | Events planned | Events produced | σ [fb] | Comments |
|---|---|---|---|---|---|---|---|
| ee->hvv, h->emu | 1.4 TeV | CLIC_ILD | 8217 | 10000 | 10000 | 244.0 (1) | m(h) = 126 GeV |
| ee->hvv, h->etau | 1.4 TeV | CLIC_ILD | 11145 | 10000 | 10000 | 244.0 (2) | m(h) = 126 GeV NEW |
| ee->hvv, h->mutau | 1.4 TeV | CLIC_ILD | 11148 | 10000 | 10000 | 244.0 (3) | m(h) = 126 GeV NEW |
| ee->llvv | 1.4 TeV | CLIC_ILD | 8234 | 1500000 | 1570800 | 978.5 | l = e,μ,τ; v = v_e,v_μ,v_τ; 5° < Θ(l) < 5°; m(l,l) > 50 GeV, m(h) = 12 TeV |

# Cuts and selected events

- Two opposite sign leptons with different flavour (e, μ)
- $E_e > 8$ GeV
- 105 GeV < $m_{e\mu}$ <140 GeV

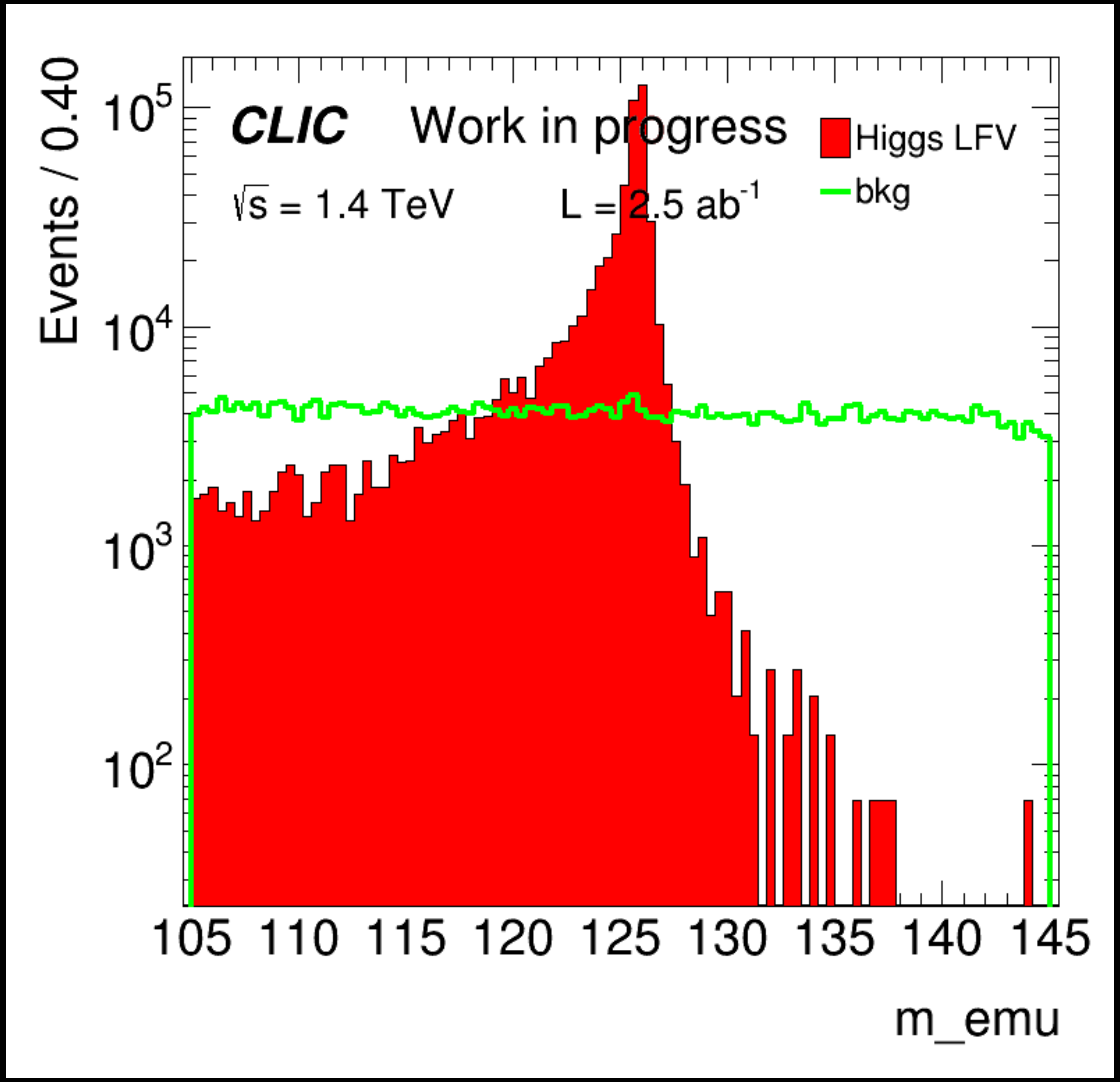
| | Number of events | $\varepsilon_{presel}$ | Expected events |
|---|---|---|---|
| Signal | | | |
| Tot events | 9900 | 100% | |
| ee→hνν, h→eμ | 8430 | 85.1% | 32 |
| Background | | | |
| Tot. Events | 1574397 | 100% | |
| ee→llνν | 59306 | 3.76% | 91979 |

Table 1: Number of generated events in signal and background samples before and after selection cuts. Last row shows the number of expected events assuming a L = 2.5 $ab^{-1}$, σ(ee→hνν)=244 fb and BR(h→eμ) = $6.1\times10^{-5}$ for signal and σ(ee→llνν) = 978.5 fb

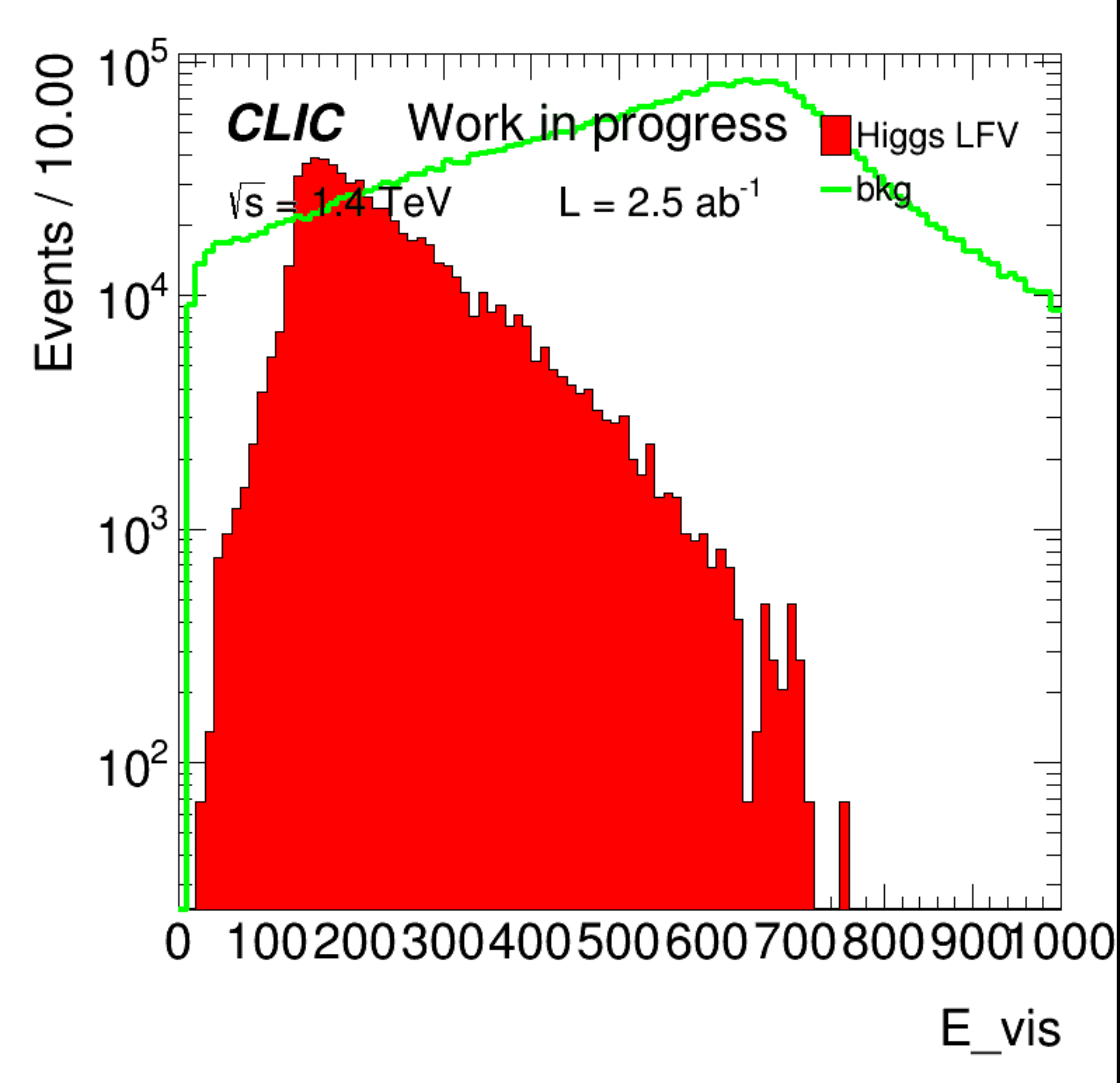
# Variables

The variables that are being studied are:

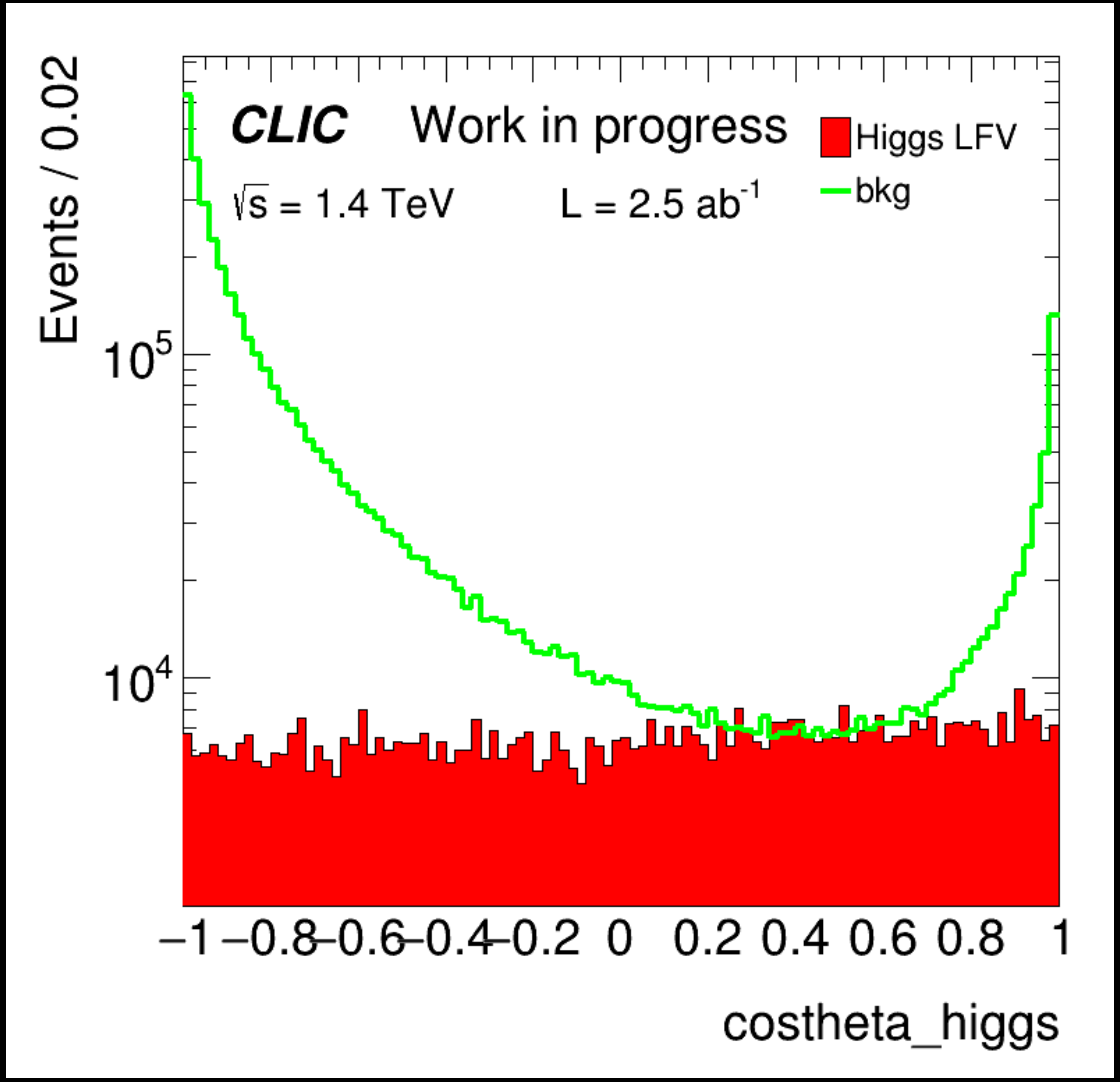
- Invariant mass: $m_{e\mu}$
- Sum of transverse momenta: $p_T(e)+p_T(\mu)$
- Transverse momenta: $p_T(e\mu)$
- Angles: $\theta(e\mu)$ and $\phi(e\mu)$
- The boost: $\beta_{e\mu}$
- Cosine of the helicity angle: $\cos(\theta^*)$
- Visible energy: $E_{vis}$
- Angular distance: $\nabla R_{e\mu}$




Invariant mass distribution for 104 GeV < $m_{e\mu}$ <145 GeV. Distribution is scaled to L = 2.5 $ab^{-1}$, $\sigma(ee\rightarrow h\nu\nu)$=244 fb and $BR(h\rightarrow e\mu)$ = 100% for signal and $\sigma(ee\rightarrow ll\nu\nu)$ = 978.5 fb




$E\_vis = E_e + E_\mu$ distribution between the final state particles

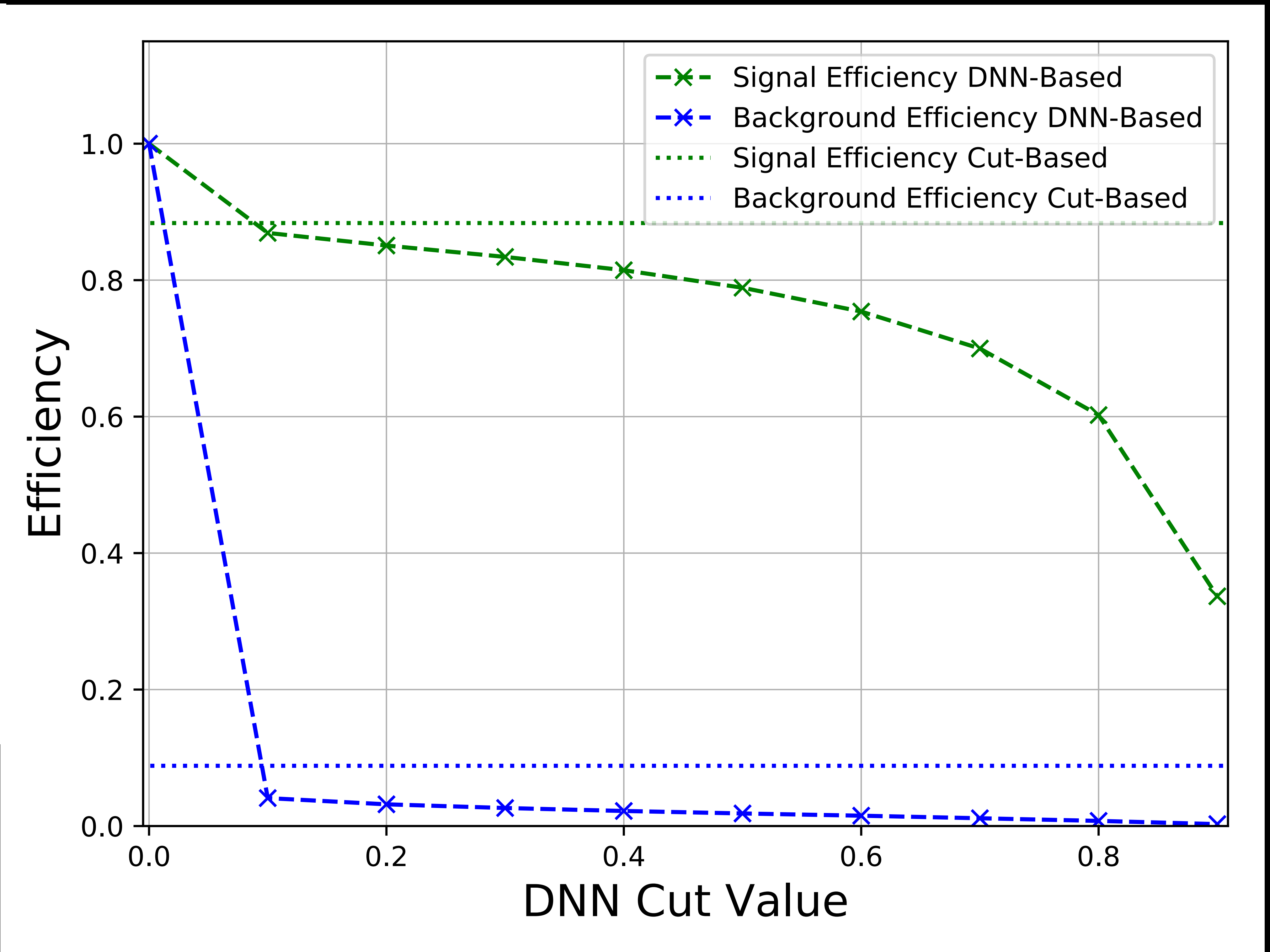


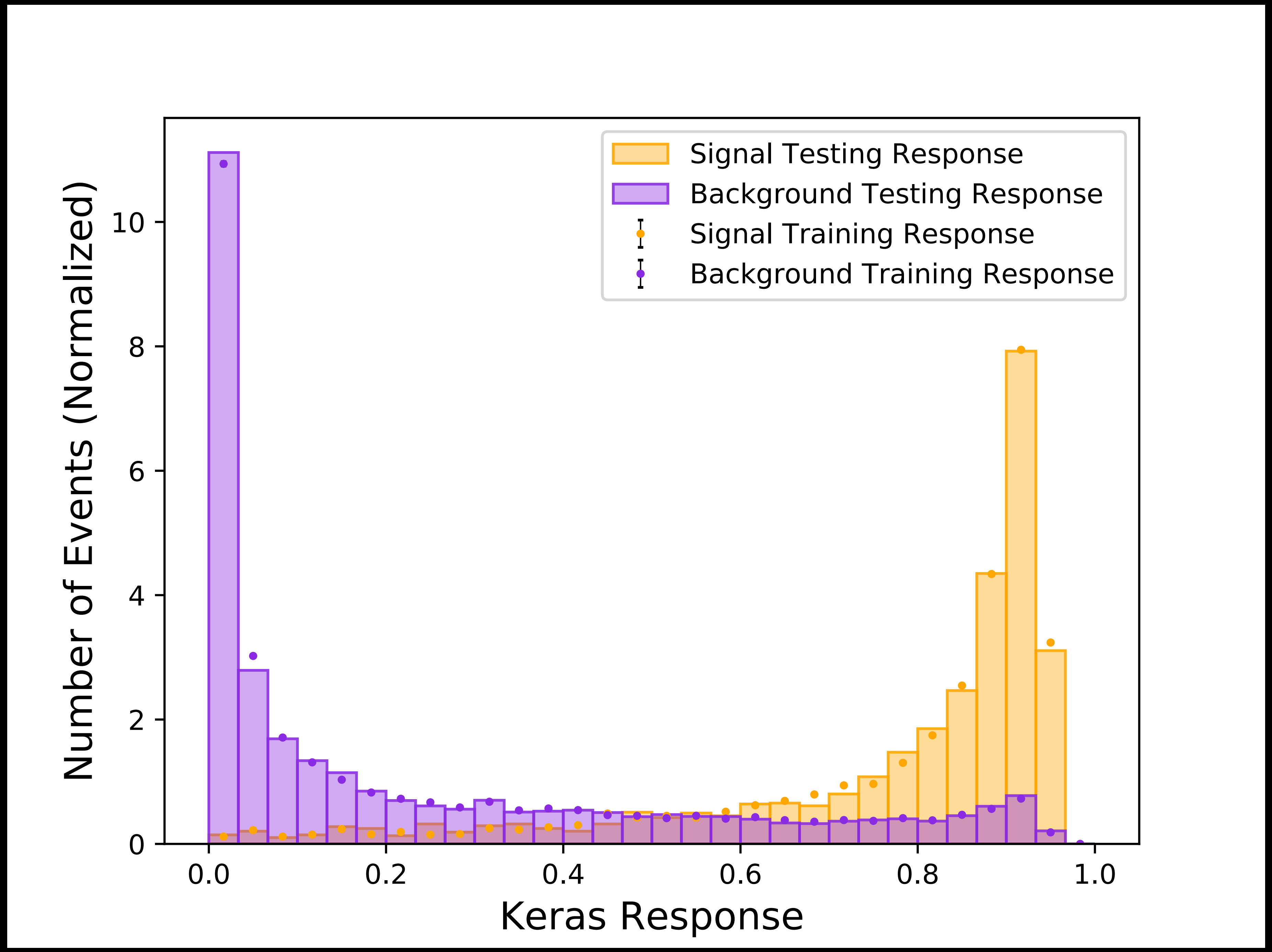

Cosine of the helicity angle, $\cos(\theta^*)$

# BDT and DNN

- We want to compare cut-based, Deep Neural Networks (DNN) and Boosted Decision Trees (BDT) to obtain the best cut with the best significance.
- The software is working for both models, but we still need to do a lot of studies

```
================
  First Input
================
     m_emu
costheta_higgs
   missing_pT
     pT_emu
   pT_eplusmu
   beta_higgs
     E_vis
  delta_r_emu
 angle_emu_phi
angle_emu_theta
================
```

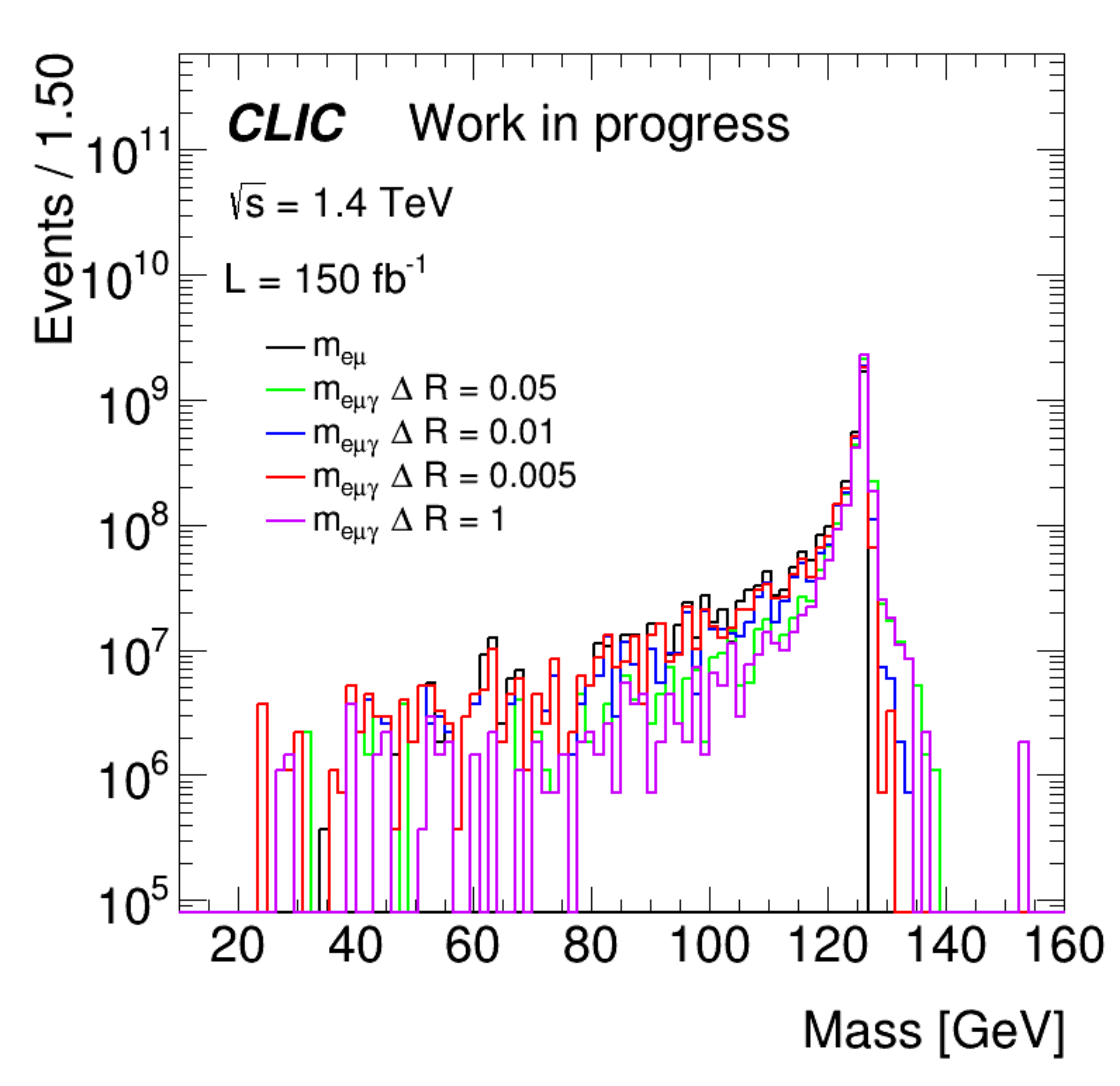



Just an example:

| DNN > 0.8<br>Sig = 0.24 | Efficiency | Expected events |
|---|---|---|
| Background | 0.282% | 7851 |
| Signal | 60.231% | 21.58 |

# Final state radiation (FSR) photons



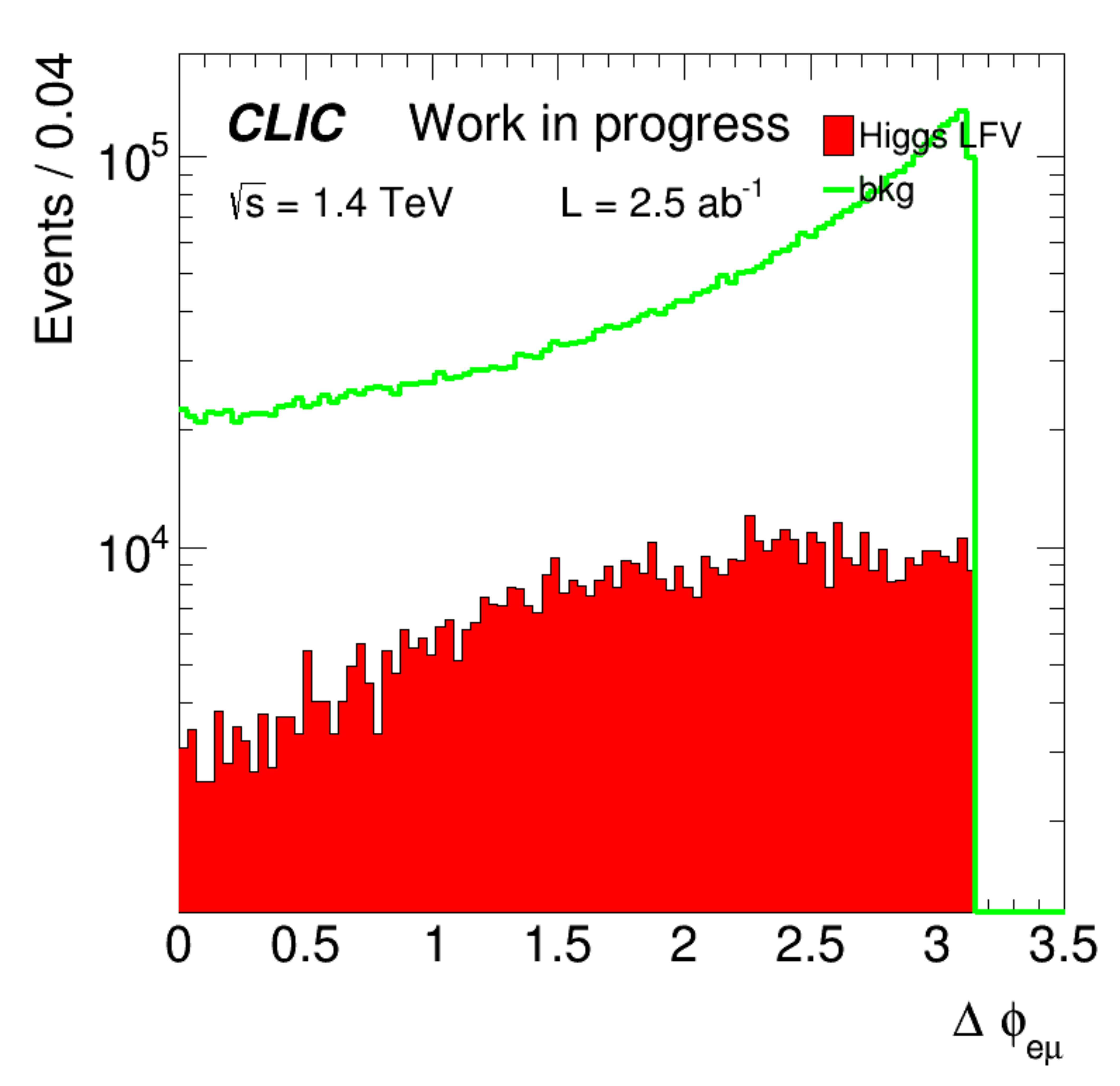

- Studying the possibility to improve the invariant mass by adding FSR photons to final state electrons
- Adding all photons inside a cone of $\Delta R < 0.005$, 0.01, 0.05 and 1
- The bremsstrahlung effect leads to a tail at lower values on the invariant mass
- This loss can be recovered by adding FSR photons
- The tail of the distribution seems to be improved (events shifted toward larger values)
- At large opening angles, the recovery leads to wider distribution at higher masses.
- TO DO: This can be further improved by choosing the $\Delta R$ that give an invariant mass closest to the Higgs Boson mass

# Conclusion

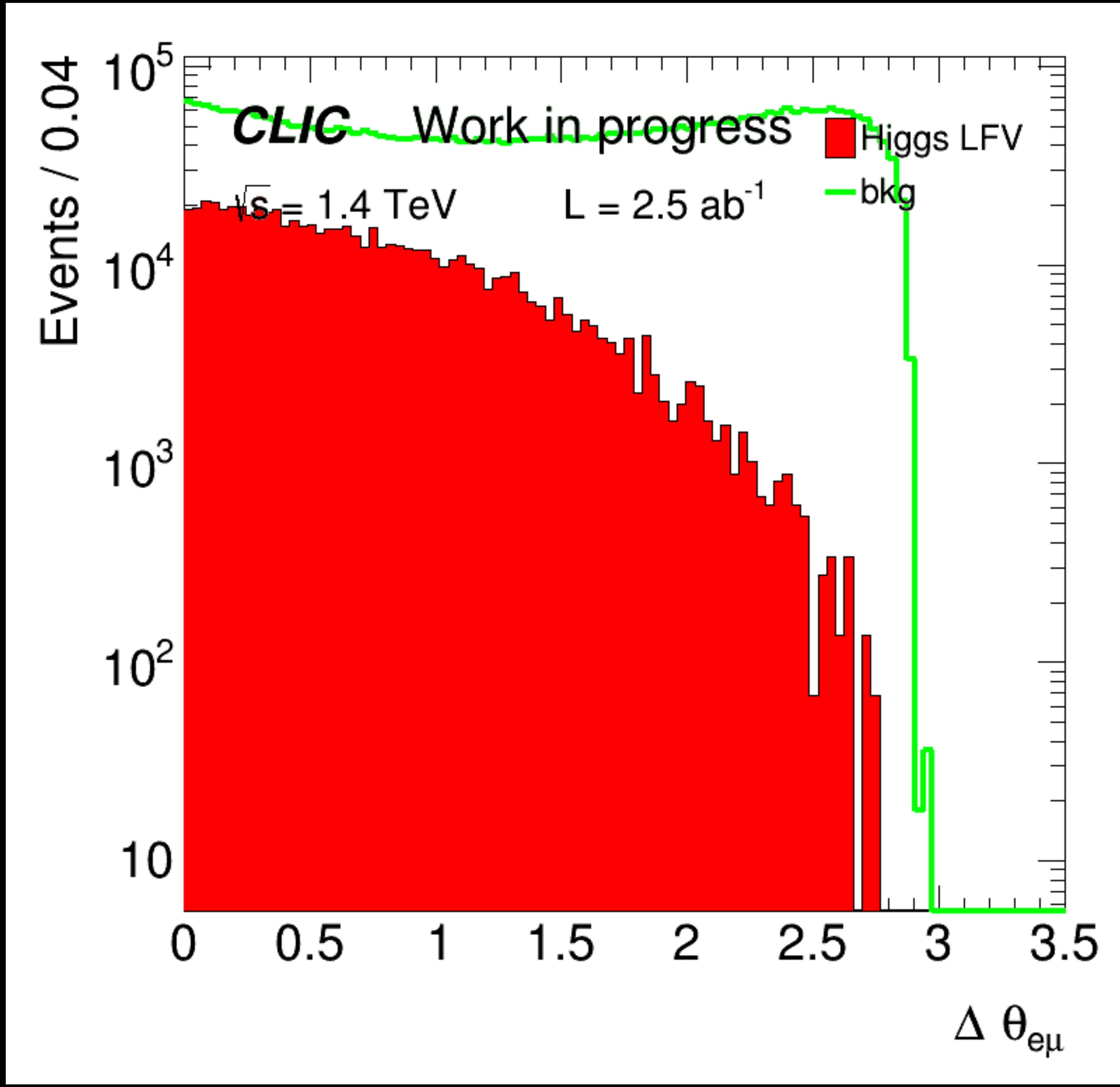
- ✓ The analysis for H→eμ is ongoing
- ✓ TO DO:
  - We want to add final state radiation (FSR) photons to the invariant mass distribution
  - The machinery is all working (Selection and MVA techniques). Now we have to play with it
- ✓ Once the analysis for H→eμ is done, we will move to H→τμ and H→τe channels.

Analysis team:
Francisca Garay
Philipp Rholloff
Bárbara Cid (student)
Raimundo Hoppe (student)

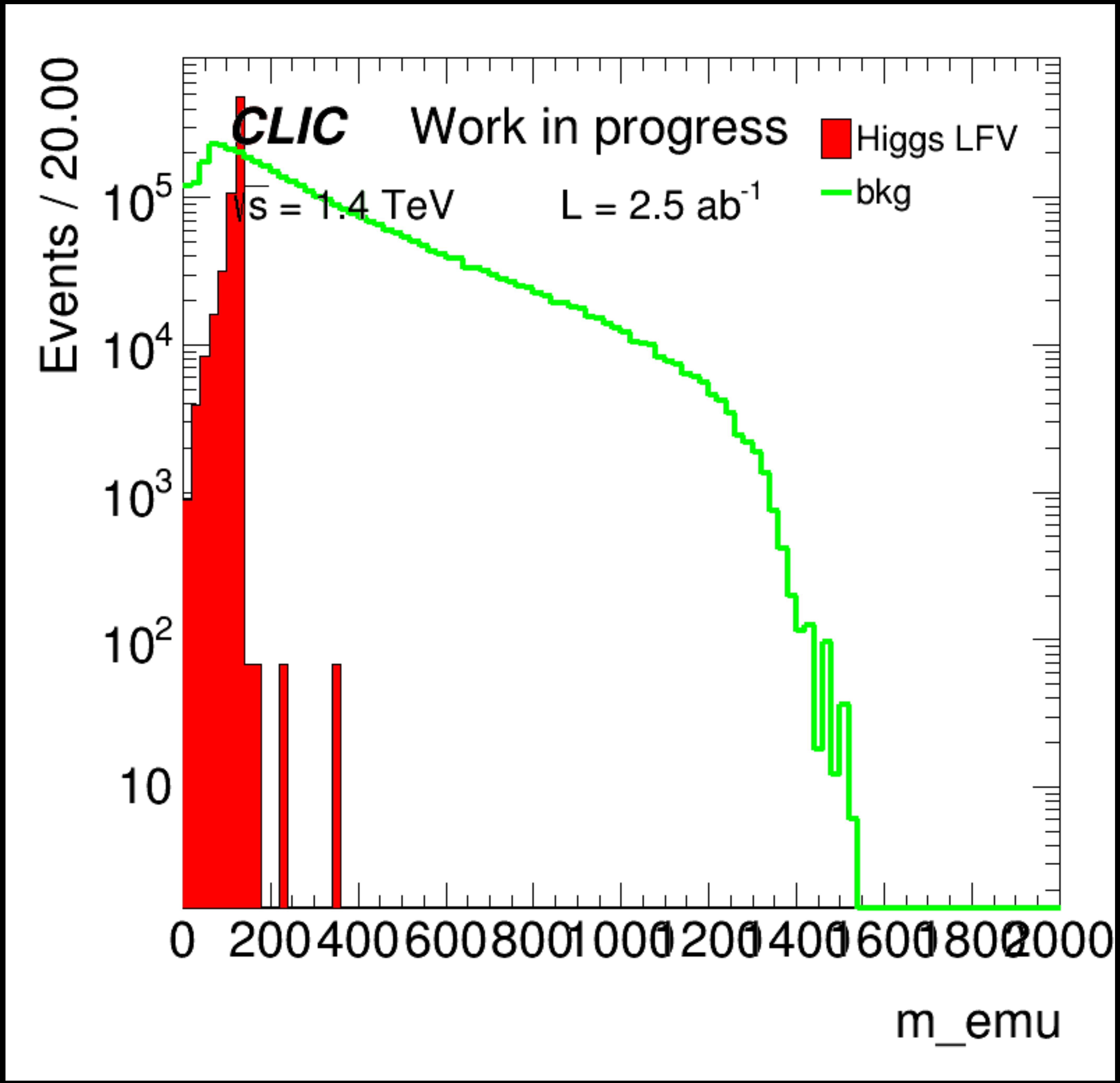
Thank you!

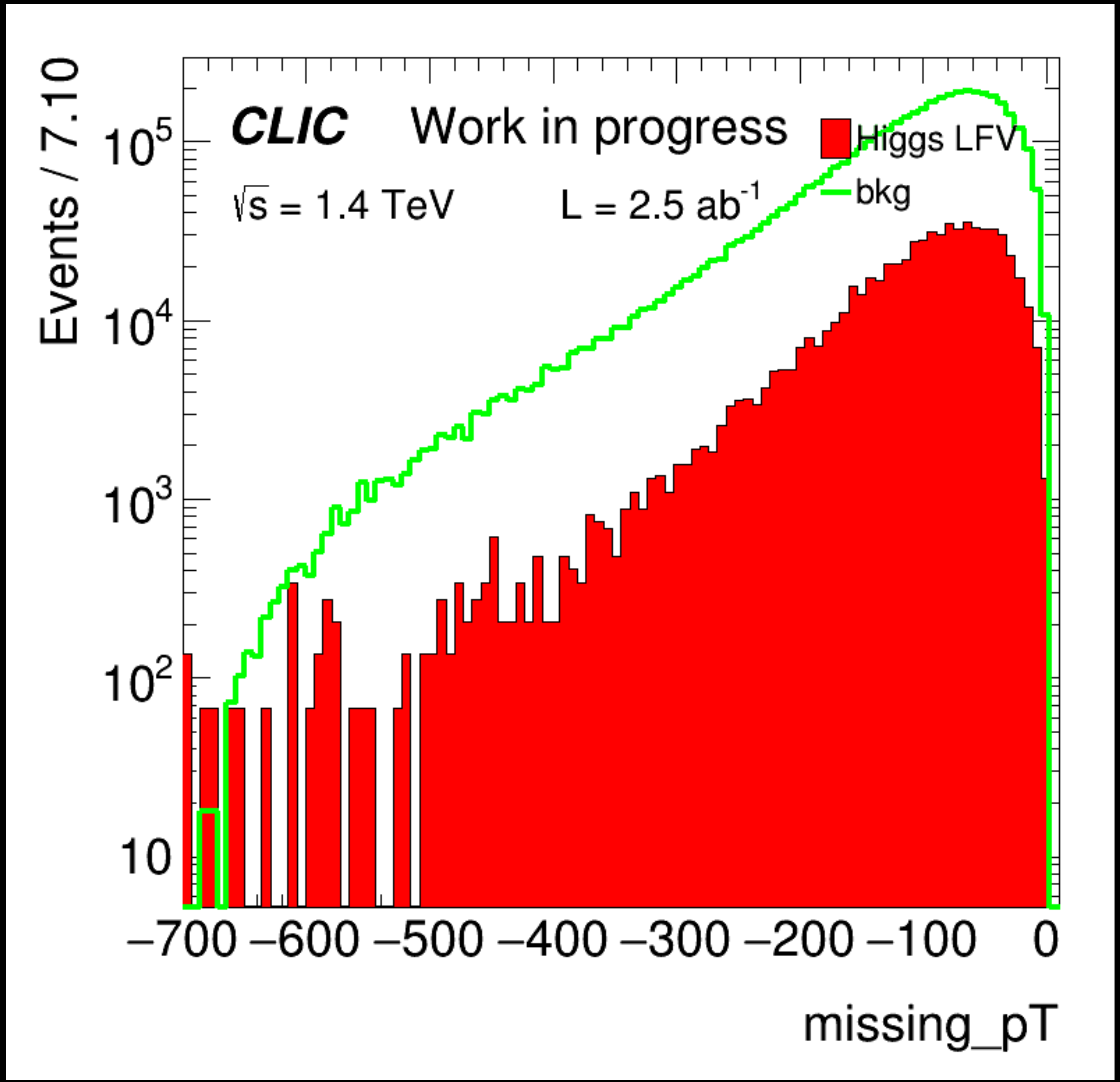


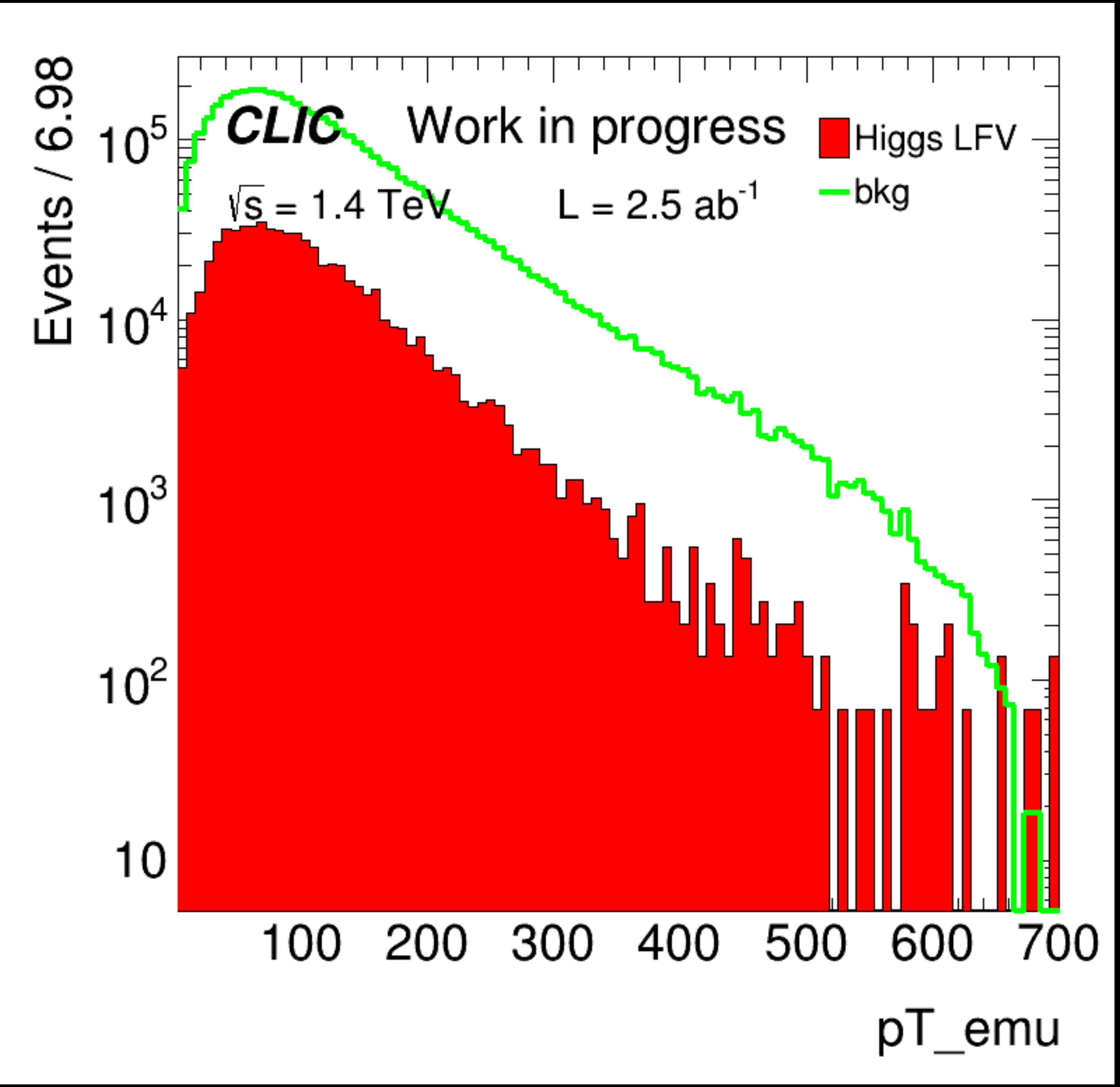
CLIC Work in progress
√s = 1.4 TeV
L = 2.5 ab-1
Higgs LFV
bkg
Events / 0.04
Δ φeμ

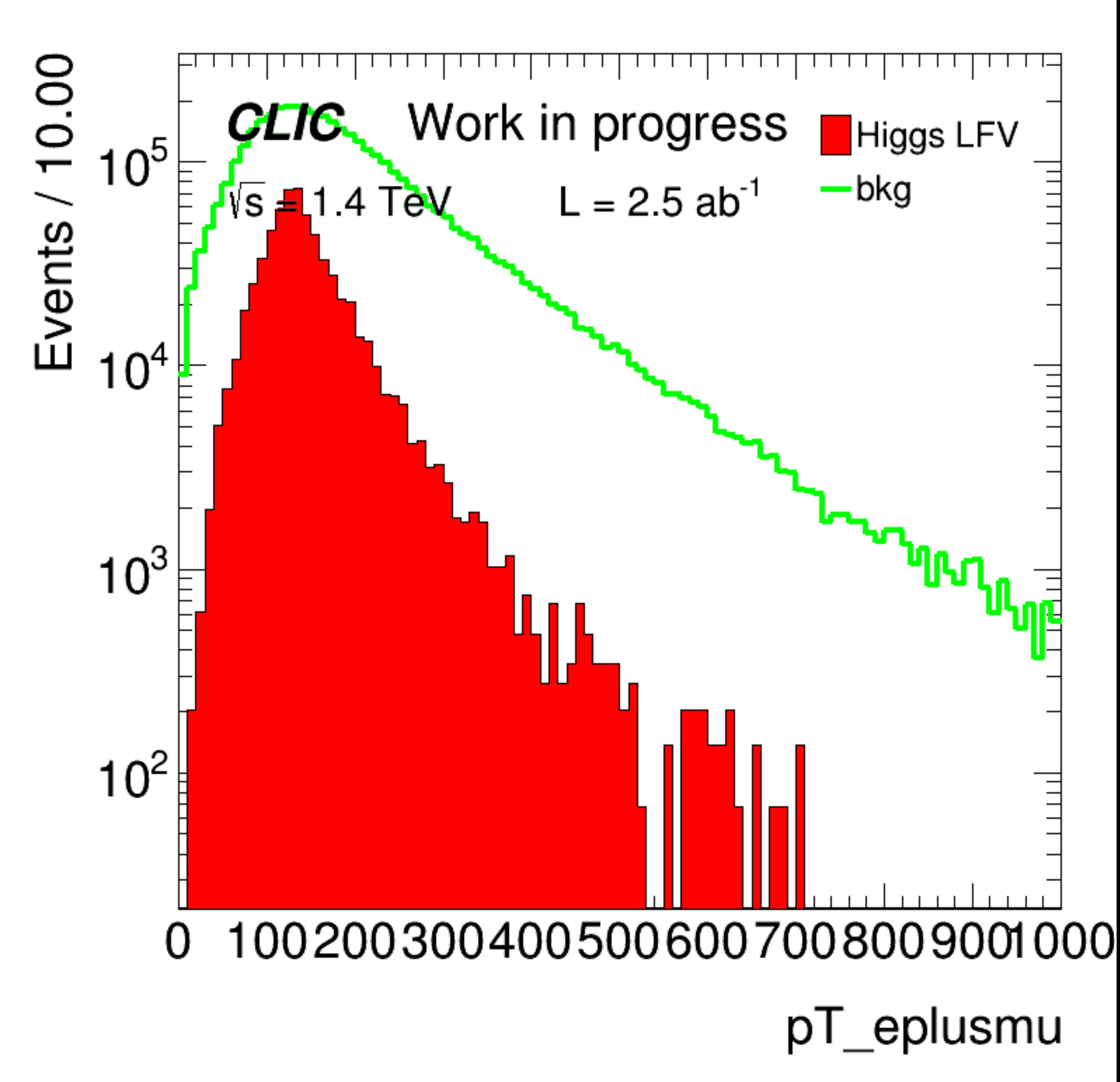



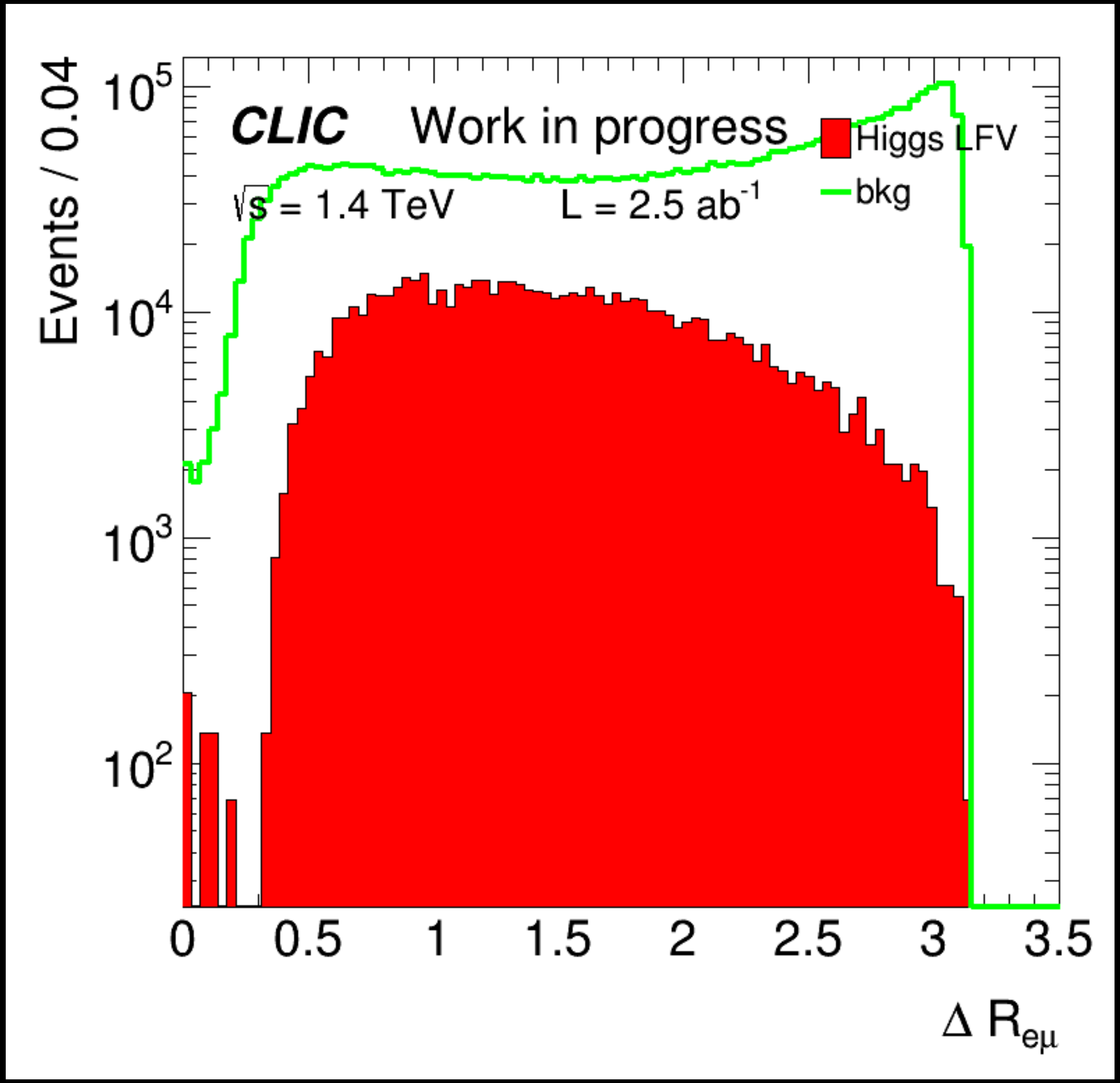
CLIC Work in progress
√s = 1.4 TeV
L = 2.5 ab-1
Higgs LFV
bkg
Events / 0.04
Δ θeμ


CLIC
Work in progress
Higgs LFV
bkg
√s = 1.4 TeV
L = 2.5 ab-1
Events / 20.00
m_emu


CLIC
Work in progress
Higgs LFV
bkg
√s = 1.4 TeV
L = 2.5 ab-1
Events / 7.10
missing_pT


CLIC Work in progress
√s = 1.4 TeV
L = 2.5 ab-1
Higgs LFV
bkg
Events / 6.98
pT_emu
100 200 300 400 500 600 700


CLIC Work in progress
√s = 1.4 TeV
L = 2.5 ab-1
Higgs LFV
bkg
Events / 10.00
pT_eplusmu
0 100 200 300 400 500 600 700 800 900 1000

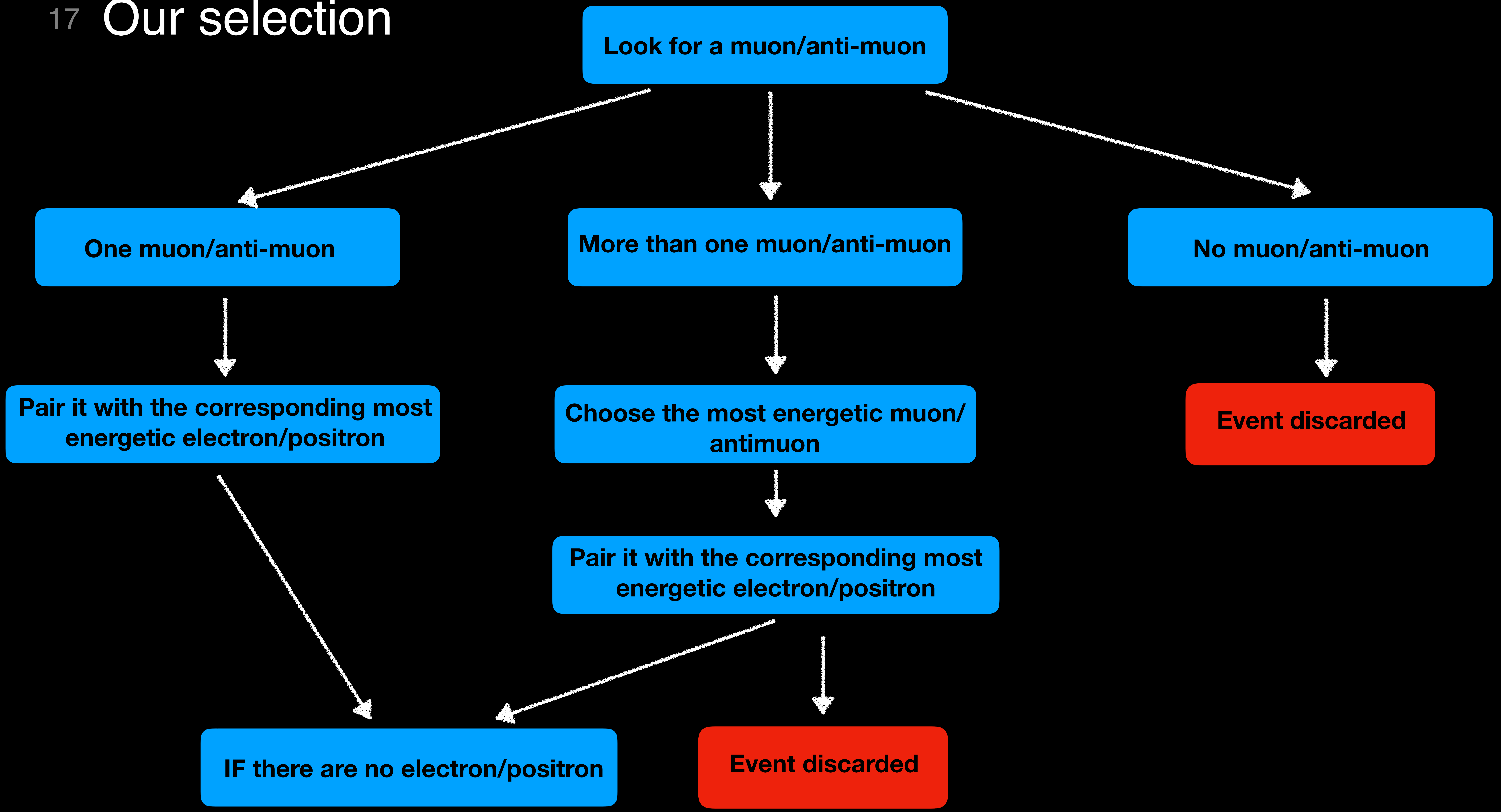



$\nabla R_{e\mu}$ distribution between the final state particles

| | Number of events | Percent | Expected events |
|---|---|---|---|
| Signal | | | |
| Tot events | 9900 | 100% | |
| ee→hνν, h→eμ | 8935 | 90.25% | 33.4 |
| Background | | | |
| Tot. Events | 1574397 | 100% | |
| ee→llνν | 405979 | 25.78% | 611563 |

Table 1: Number of generated events in signal and background samples before and after selection cuts. Last row shows the number of expected events assuming a L = 2.5 $ab^{-1}$, σ(ee→hνν)=244 fb and BR(h→eμ) = $6.1 \times 10^{-5}$ for signal and σ(ee→llνν) = 978.5 fb

# Our selection



```
Results:

Efficiency:
Mass Point/CutVal      Cut-Based      0.1      0.2      0.3      0.4      0.5      0.6      0.7      0.8      0.9
-------------------  -----------  -------  -------  -------  -------  -------  -------  -------  -------  -------
Background                 4.094%   3.183%   2.642%   2.208%   1.843%   1.515%   1.141%   0.754%   0.282%
treeLFV_sgn_ntuple        88.365%  86.918%  85.073%  83.407%  81.457%  78.889%  75.398%  69.979%  60.231%  33.669%
Average

Yields:
Mass Point/CutVal   Initial    Cut-Based        0.1        0.2        0.3        0.4        0.5        0.6        0.7        0.8
0.9
------------------- ---------  ----------- ---------  ---------  ---------  ---------  ---------  ---------  ---------  ---------
---------
Background         1.042e+06   9.198e+04  4.265e+04  3.315e+04  2.752e+04  2.300e+04  1.920e+04  1.579e+04  1.188e+04  7.851e+03
2.933e+03
treeLFV_sgn_ntuple 3.584e+01   3.167e+01  3.115e+01  3.049e+01  2.989e+01  2.919e+01  2.827e+01  2.702e+01  2.508e+01  2.158e+01
1.207e+01

Significance:
Mass Point/CutVal      Cut-Based        0.1        0.2        0.3        0.4        0.5        0.6        0.7        0.8
0.9
-------------------  -----------  ---------  ---------  ---------  ---------  ---------  ---------  ---------  ---------  --------
-
treeLFV_sgn_ntuple     1.044e-01  1.508e-01  1.674e-01  1.802e-01  1.925e-01  2.040e-01  2.151e-01  2.300e-01  2.436e-01  2.228e-
01
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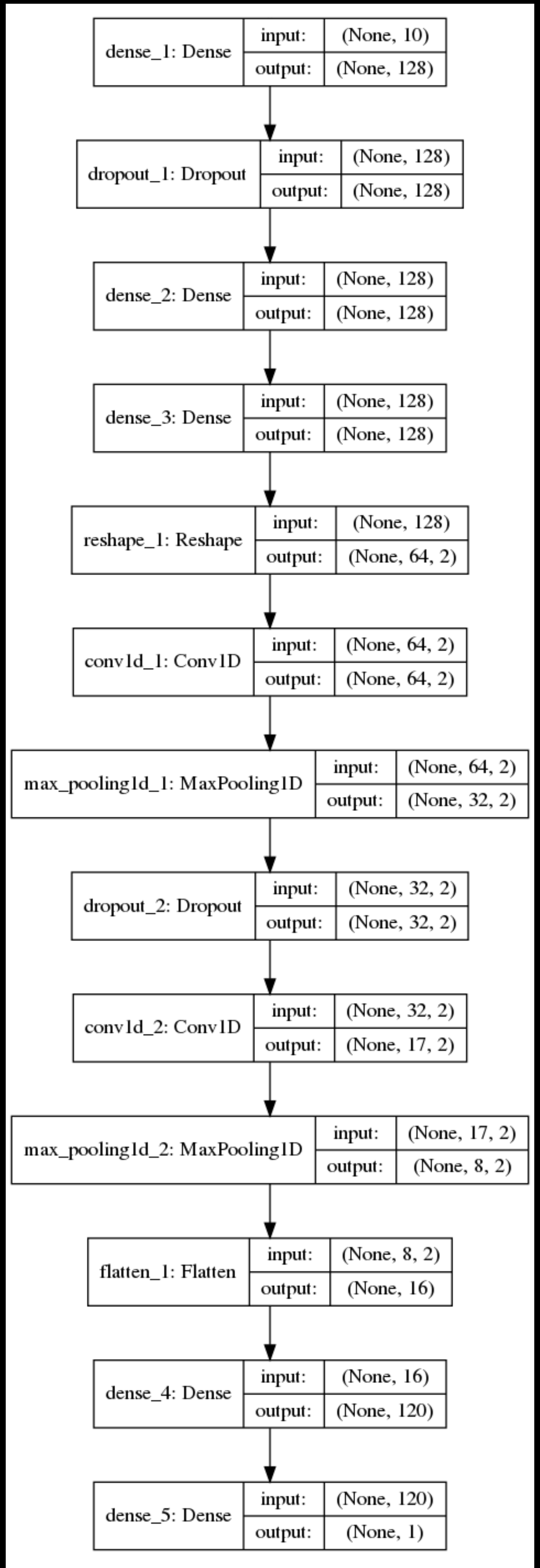

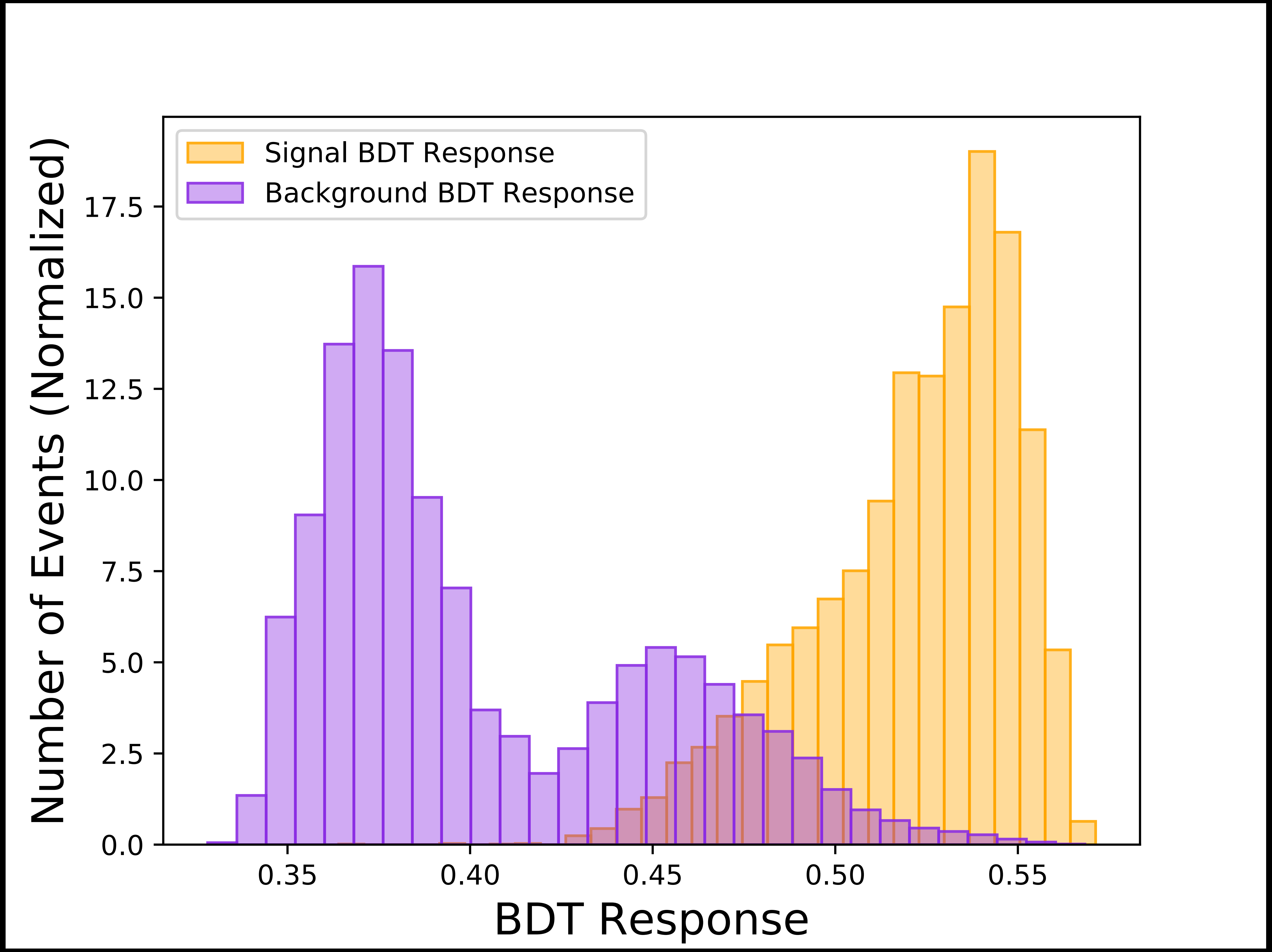

Signal BDT Response
Background BDT Response
Number of Events (Normalized)
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
0.35
0.40
0.45
0.50
0.55
BDT Response