Measurement of the Higgs couplings to b- and c- quarks and to gluons at 350 GeV, 1.4 TeV and 3 TeV CLIC

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on behalf of the CLIC Detector and Physics Study

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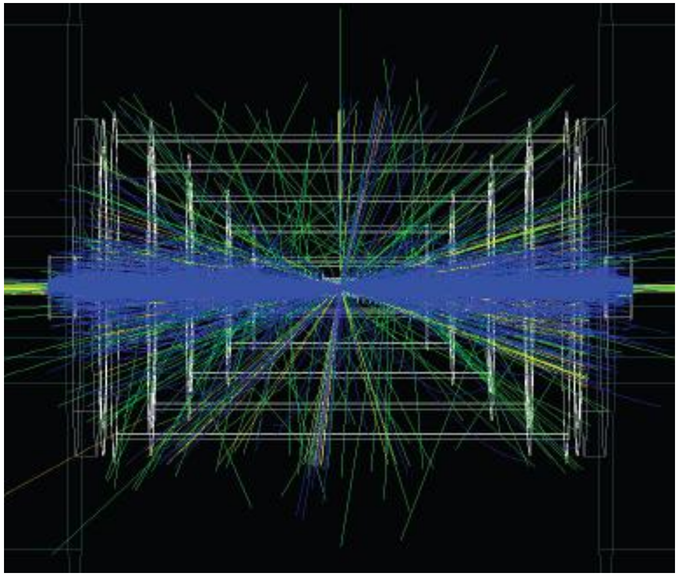
CLIC ENVIRONMENT

THE CLIC ACCELERATOR ENVIRONMENT

Center of mass energy	350 (500) GeV	1.4 TeV	3 TeV
Accumulated luminosity	500 fb^{-1}	1.5 ab^{-1}	2 ab^{-1}
Bunch spacing	0.5 ns	0.5 ns	0.5 ns
Bunches per train	354	312	312
Train repetition rate	50 Hz	50 Hz	50 Hz
$\gamma\gamma \rightarrow$ hadrons per BX	0.3	1.3	3.2

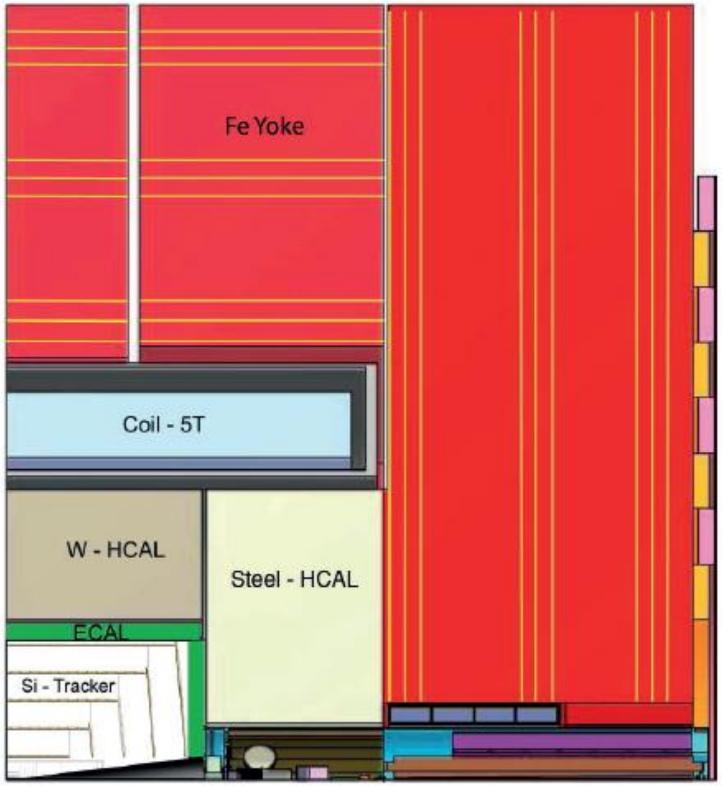
- Challenging environment
- $\gamma\gamma$ overlay $\rightarrow$ 19TeV visible energy @ 3 TeV
  - Reduced by a factor of 16 in 10ns readout window.
  - Requires to employ "LHC-style" jet reconstruction algorithms (typically FastJet k_T).



The CLIC detectors

- CLIC_SiD and CLIC_ILD
  - based on SiD and ILD detector concepts for ILC Letters of Intent.
    - CLIC_SiD used in the following studies.
  - Full simulation and reconstruction of events.
    - 60 $\gamma\gamma \rightarrow$hadrons events overlaid per BX
  - Event generation: WHIZARD 1.95
  - Hadronization: PYTHIA 6.4
  - Full event simulation: GEANT4 via SLIC (CLIC_SiD)
  - Full event reconstruction
    - PFA with PANDORAPFA
  - Flavour tagging: LCFI package

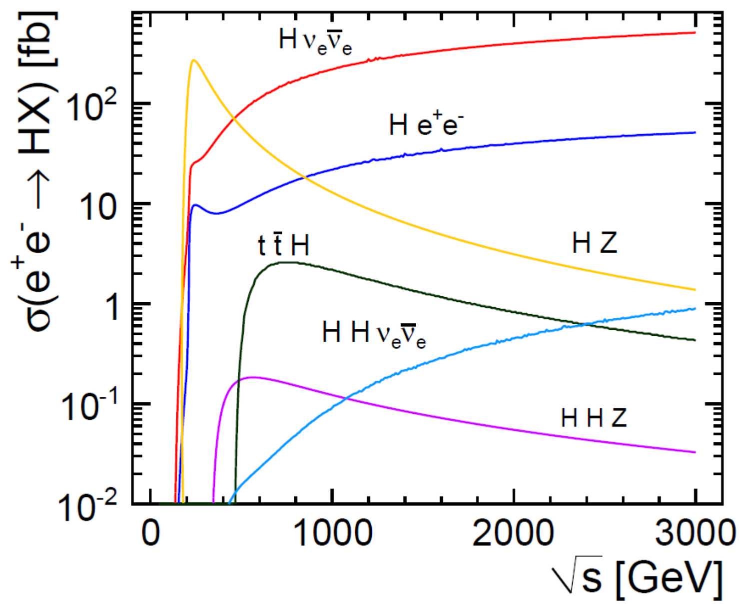
CLIC_SiD



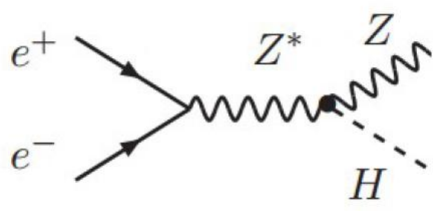
Higgs branching ratio analyses

Higgs Production

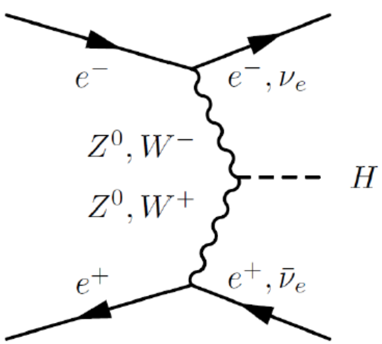
- m_H = 126 GeV
- Higgs production at e^+e^- collider
  - At √s < 500 GeV mostly via Higgs-strahlung
  - Above 500 GeV via vector boson fusion



- Final states
  - 350 GeV:
    - leptonic channel (2 leptons + 2 jets) ←
    - fully hadronic channel (4 jets)
  - 1.4 TeV and 3 TeV
    - 2 jets + missing energy ($H\nu\bar{\nu}$) ←
    - 2 jets + e^+e^- (Z-boson fusion)



Higgs-strahlung



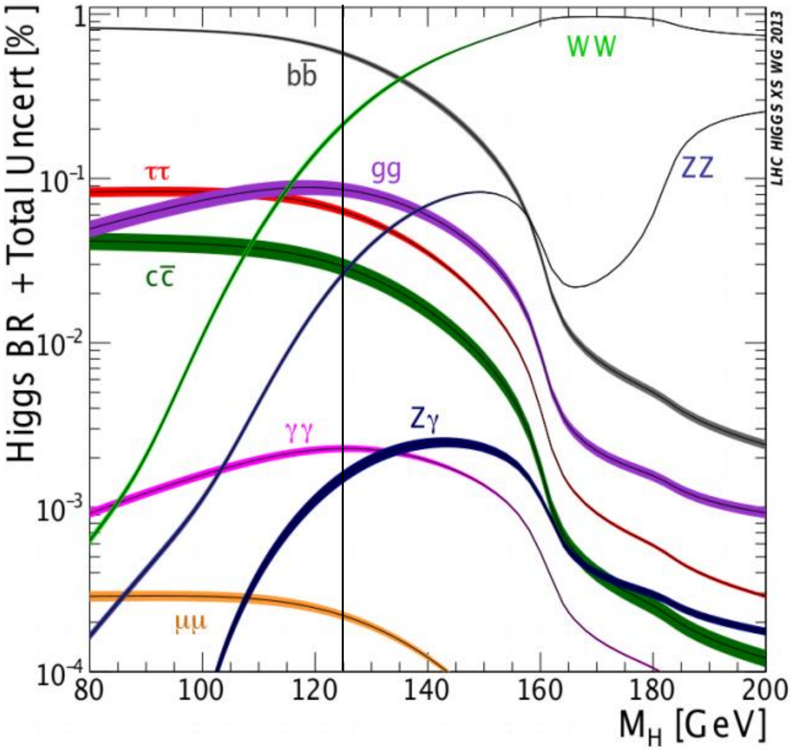
VB fusion

Higgs decay channels

- $H \rightarrow b\bar{b}$
  - Largest BR in the Standard Model (56.1 %)
  - Efficient b-flavour tagging
  - Easy channel, high precision measurement

- $H \rightarrow c\bar{c}$
  - Small BR in the Standard Model (2.83 %)
  - Difficult c-flavour tagging
  - Relatively challenging channel

- $H \rightarrow gg$
  - 3x larger BR than the $H \rightarrow c\bar{c}$ channel (3rd largest BR in SM: 8.38 %)

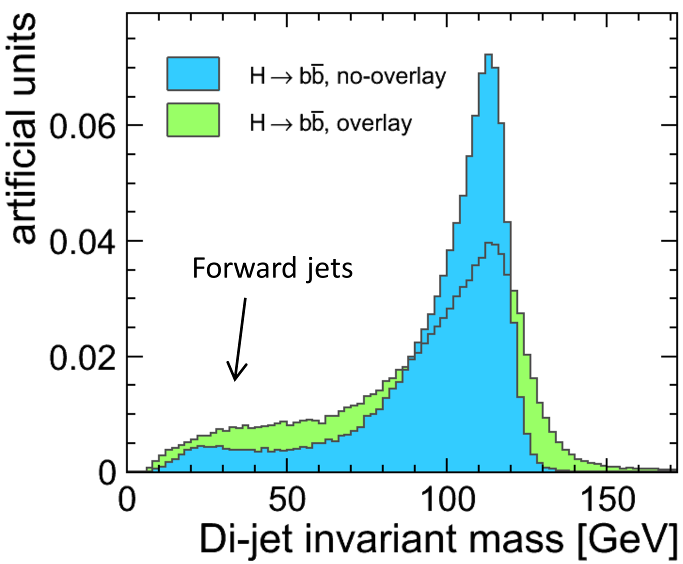


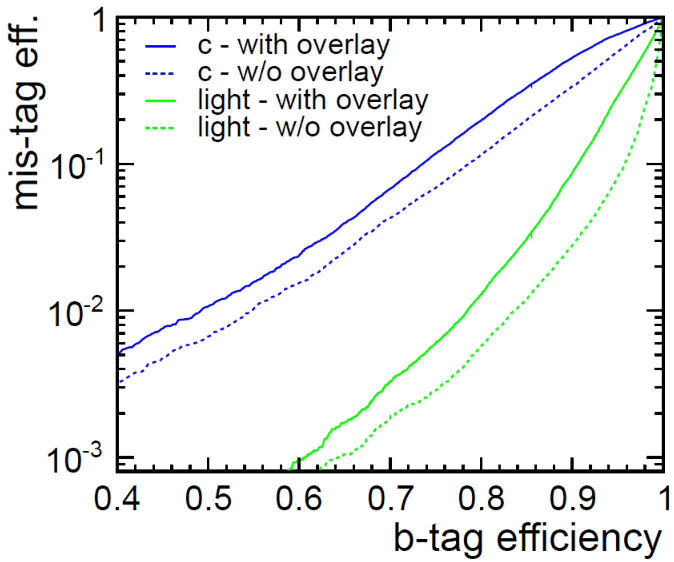
Event Reconstruction and Analysis Strategy

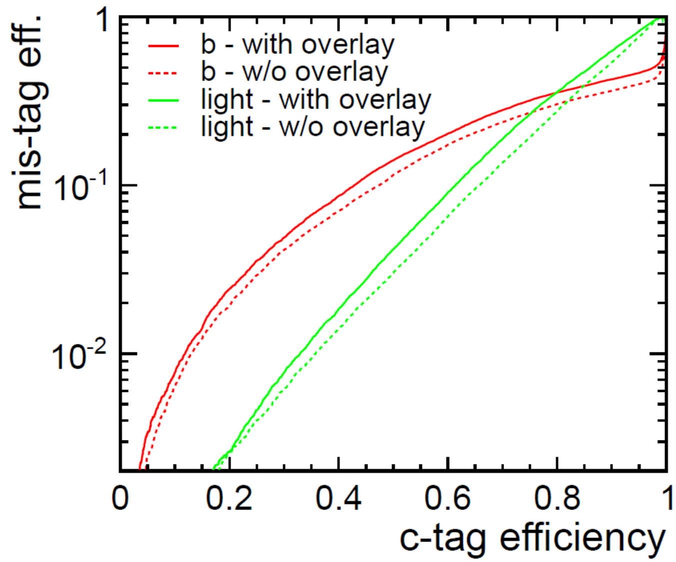
- Full simulation of signal and background
  - 60 BX of γγ→hadrons overlaid over each event
- Discard hits in physics events offline – out of 10 ns window (100 ns in HCAL)
  - Three scenarios in PandoraPFO: Loose, Standard, Tight selection
- Isolated lepton finder (MarlinReco)
- FastJet k_T algorithm used to force events into 2 jets
  - and to reject particles assigned to the beam-jet
- Event classification
  - FANN (Fast Artificial Neural Network library) trained including event weights.
  - Sophisticated approach addressing
    - noise in signal and background samples via using a poll of independent nets;
    - re-mapping of the neural net classifier output.

Jet flavour tagging with γγ overlay (3 TeV)

- **LCFIVertex package**
  - ZVTOP vertex reconstruction algorithm
  - FANN neural net package used throughout the Higgs analyses both for the flavour tag and the event selection.
  - Presence of γγ overlay (60BX considered) degrades both the jet-finding and the jet flavour tag quality (shown for di-jet events).







NEURAL NET INPUTS

Jet pair invariant mass
Sums of LCFI flavour tag outputs:
b-tag, c(b)-tag, c-tag and b(light)-tag
Distance of jets in η-φ plane
Acoplanarity
Visible energy in jets and missing transverse energy E_t
y_{min} and y_{max} from FastJet
p_t^{min}, p_t^{max} of jets
#leptons, #isolated leptons and #photons in event
max(|η_i|) of jet pseudorapidities η_i

Evaluation of Cross Section Uncertainty

1. Cut-and-count method

$$\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{S+B}}{S}$$

where S and B are the numbers of signal and background events above a particular cut on the NN classifier

2. Whole classifier spectrum

a) Fitting signal and background templates to simulated measurements

Generate many experiments – $O(10^4 - 10^6)$

Can be directly generalized to simultaneous 2D and 3D evaluation

b) Sum up uncertainties per-bin

For 1D identical results to a)

$$x_i = \frac{\sqrt{S_i + B_i}}{S_i}$$

$$\frac{\Delta\sigma}{\sigma} = \sqrt{\frac{1}{\sum_i \frac{1}{x_i^2}}}$$

Simultaneous Extraction – 2D and 3D Fits

- In 1D per-channel evaluation of CS uncertainties we implicitly assume that other Higgs channels uncertainties are known to a much better precision than the studied one and/or the correlation is negligible. This is not entirely correct.
  - One exception may be the b-channel, therefore it may be separated from c- and g-channels which can be evaluated simultaneously (2D).
  - Eventually all three channels should be evaluated simultaneously (3D).
  - It turns out that the inter-channel separation is rather good and therefore results for 1D, 2D and 3D are very similar.

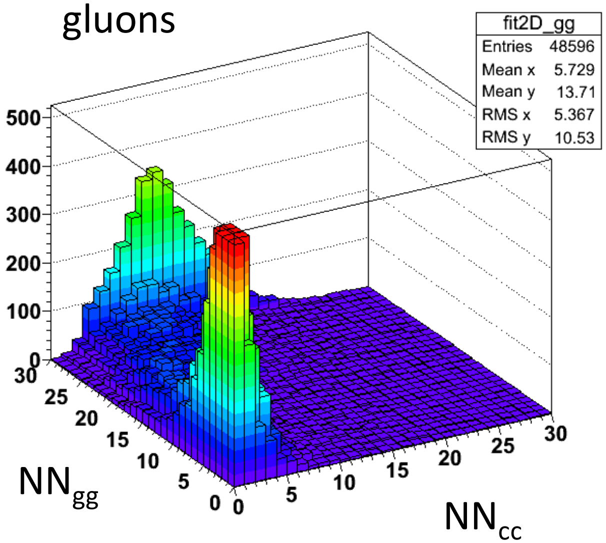
- It should be pointed out, however, that all these methods depend on the binning of NN classifiers.
  - The finer the binning the better the result (more information but more template noise).
  - Work in progress…

Simultaneous Extraction – 2D and 3D Fits

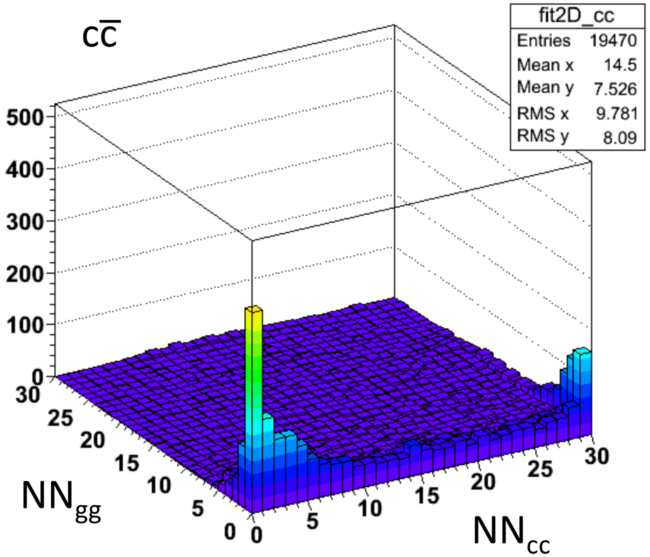
- In 2D picture $H \to c\bar{c}$ signal is well separated from $H \to gg$.
- Illustration at 1.4 TeV, for a single neural network out of a poll of 50 nets.
  - In fact, for all templates we re-map the NN poll output to provide flat output distribution for the signal.

2D templates for

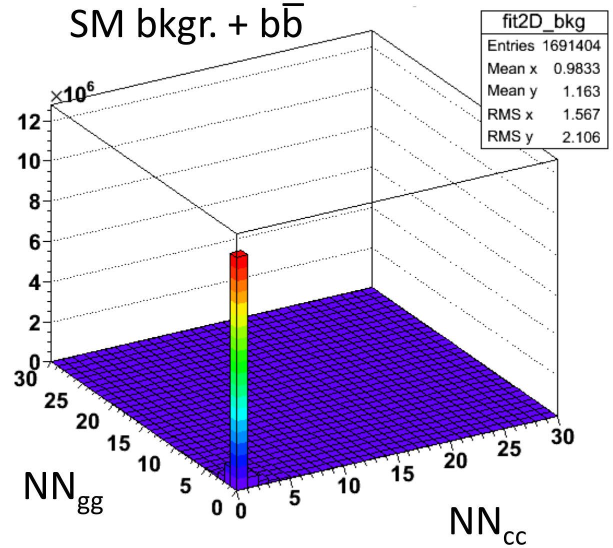
gluons



$c\bar{c}$



SM bkgr. + $b\bar{b}$



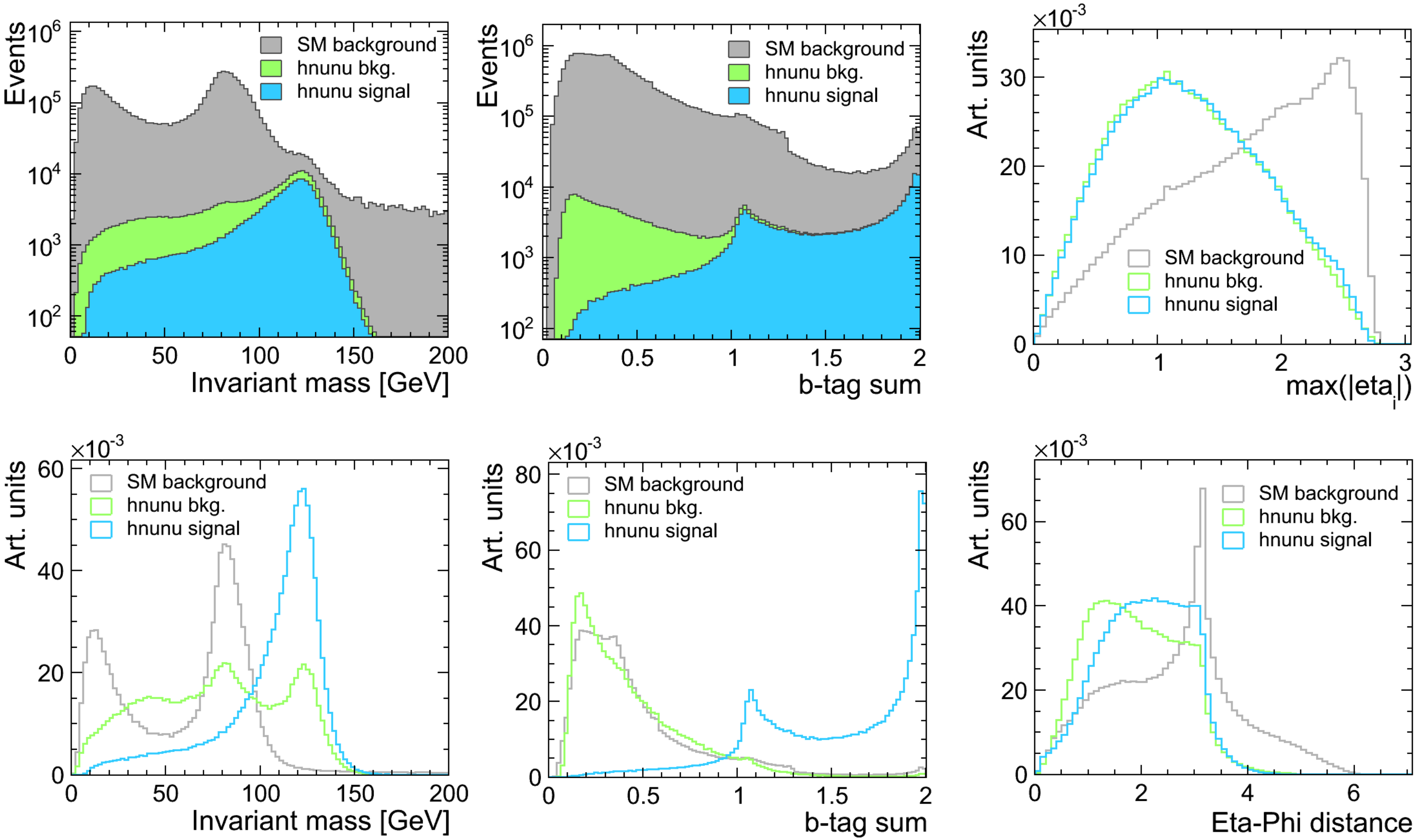
$H \rightarrow \{b\bar{b}, c\bar{c}, gg\}$ @ $\sqrt{s}$=1.4 TeV

DATA SAMPLES @ 1.4 TEV

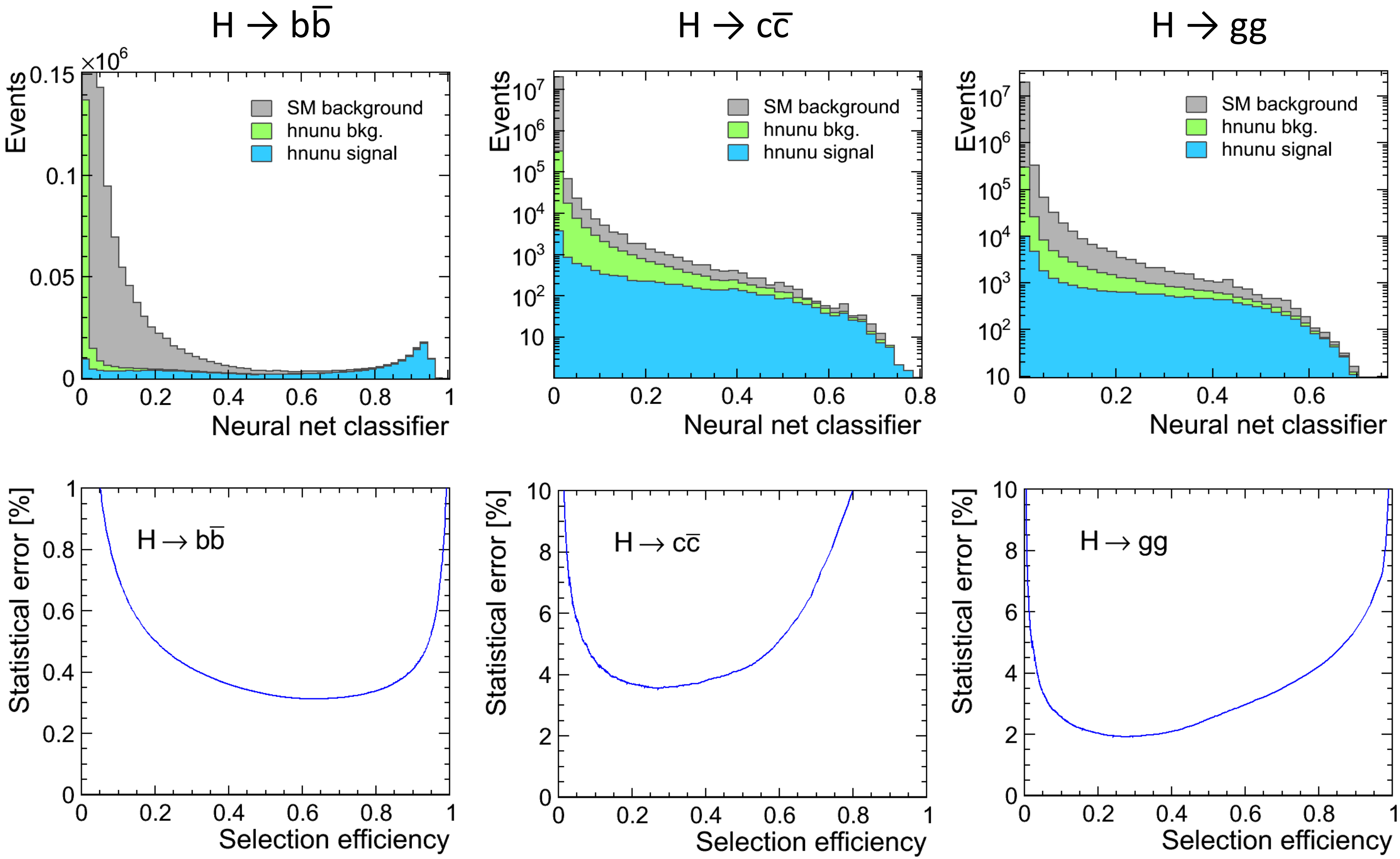
- Accumulated luminosity: 1500 fb^{-1}
- Isolated lepton finder
- FastJet k_T jet clustering
  - R = 1.0
  - Loose PFO selection: LooseSelectedPandoraPFOCollection

Sample	σ [fb]	Events in 1.5 ab^{-1}
$e^+e^- \rightarrow H\nu\nu$ inclusive	244.1	366k
$e^+e^- \rightarrow q\bar{q}\nu\nu$	788	1.2M
$e^+e^- \rightarrow q\bar{q}$	4008.8	6M
$e^+e^- \rightarrow q\bar{q}l\nu$	4312.9	6.5M
$e^+e^- \rightarrow q\bar{q}ll$	2726.7	4M
$e^+e^- \rightarrow q\bar{q}q\bar{q}\nu\nu$	24.72	37k
$e^+e^- \rightarrow q\bar{q}q\bar{q}$	1325	2M
$e^+e^- \rightarrow q\bar{q}q\bar{q}ll$	71.68	107k

Control Plots @ 1.4 TeV (for the b-channel signal)



NEURAL NET CLASSIFICATION @ 1.4 TEV



RESULTS @ 1.4 TEV

	$H \rightarrow b\bar{b}$	$H \rightarrow c\bar{c}$	$H \rightarrow gg$
$\sigma_{h\nu\nu}$ uncertainty	**0.31 %**	**3.55 %**	**1.92 %**
Signal efficiency	63 % (128k)	27 % (2.8k)	28 % (8.7k)
Signal purity	80 %	29 %	31 %

[1)] Full spectrum	0.29 %	2.9 %	1.6 %
Simultaneous 2D	-	2.8 %	1.8 %
Simultaneous 3D	**0.30 %**	**2.9 %**	**1.8 %**

Modest decrease in $H \rightarrow gg$ uncertainty in 2D/3D simultaneous fits attributed to influence of remaining decay channels of $H\nu\bar{\nu}$.

$H \rightarrow \{b\bar{b}, c\bar{c}, gg\}$ @ $\sqrt{s}$=3 TeV

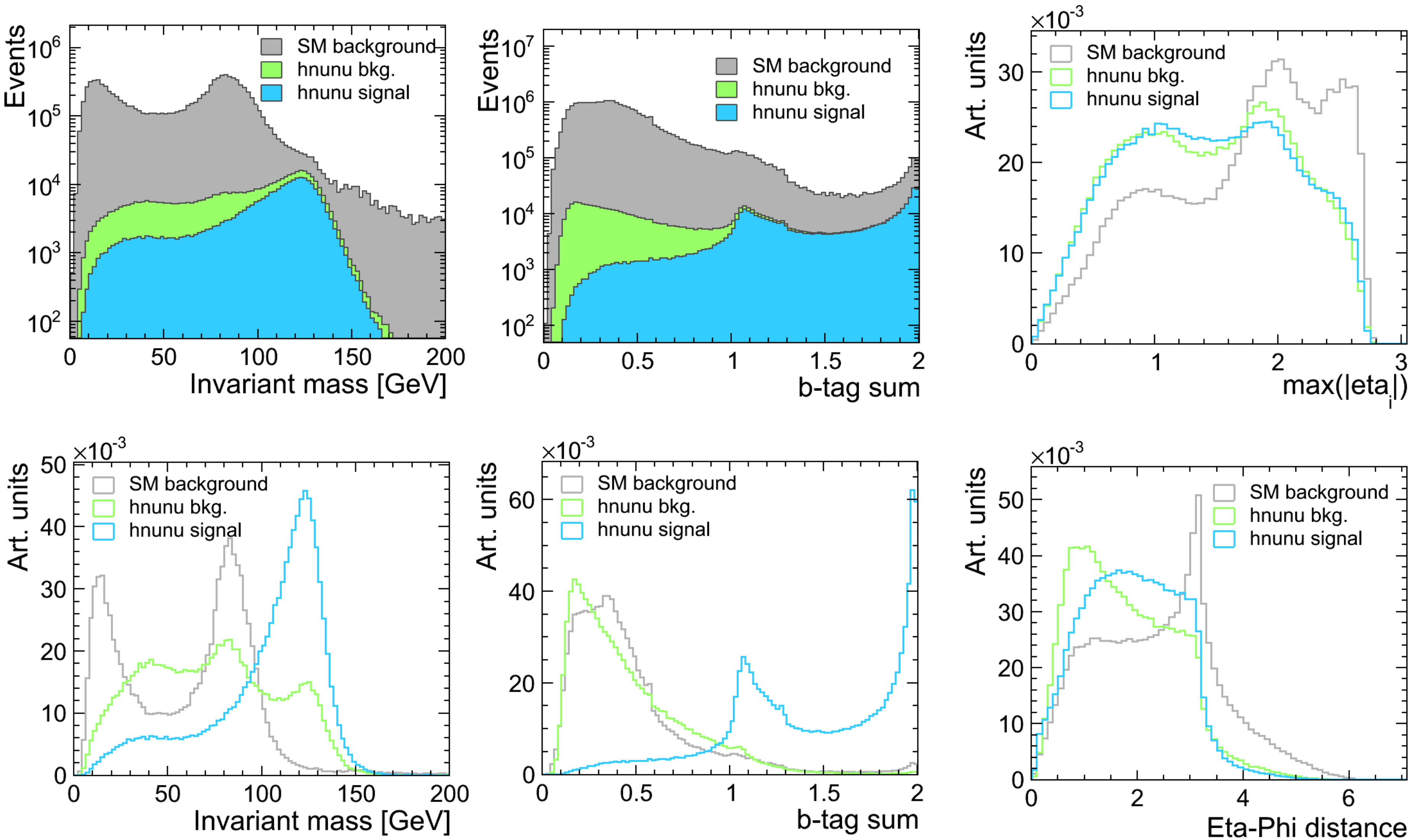
Data samples @ 3 TeV

- Accumulated luminosity: 2000 fb^{-1}
- Update of published CDR analysis for m_H = 120 GeV and $H \to c\bar{c}$, $H \to b\bar{b}$:
  - C. Grefe, T. Lastovicka and J. Strube, Eur. Phys. J. C (2013) **73**: 2290

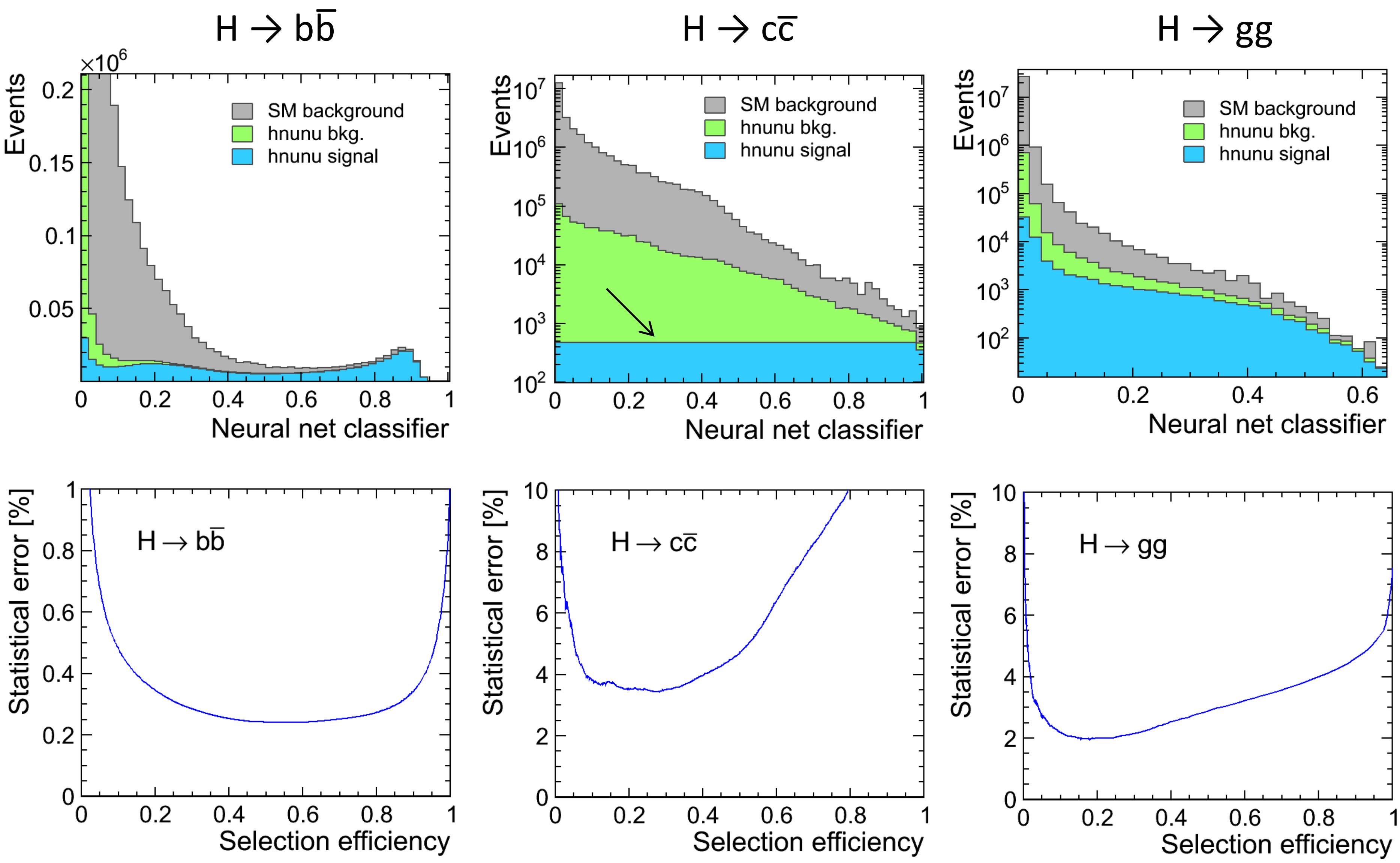
- Isolated lepton finder
- FastJet k_T jet clustering
  - R = 0.7
  - Loose PFO selection: LooseSelectedPandoraPFOCollection

Sample	σ [fb]	Events in 2 ab^{-1}
ee → hνν inclusive	415.3	831k
ee → qqνν	1305	2.6k
ee → qq	3076	6M
ee → qqνe	5255	10M
ee → qqee	3341	6.7M
ee → qqqq	593	1.2M

CONTROL PLOTS (FOR THE B-CHANNEL SIGNAL)



Neural Net Classification @ 3 TeV



RESULTS @ 3 TEV

	$H \to b\bar{b}$	$H \to c\bar{c}$	$H \to gg$
σ_{hvv} uncertainty	**0.24 %**	**3.42 %**	**1.97 %**
Signal efficiency	53 % (248k)	27 % (6.4k)	18% (12.6k)
Signal purity	70 %	13.4 %	20.5 %

Full spectrum	0.22 %	2.7 %	1.55 %
Simultaneous 2D	-	2.5 %	1.7 %
Simultaneous 3D	**0.22 %**	**2.7 %**	**1.8 %**

Modest decrease in $H \to gg$ uncertainty in 2D/3D simultaneous fits attributed to influence of remaining decay channels of $H\nu\bar{\nu}$.
Lower purities in $H \to c\bar{c}$ and $H \to gg$ channels compared to 1.4 TeV, but higher stats.

SUMMARY

The statistical accuracy of $\sigma(e^+e^- \rightarrow H\nu_e\nu_e)\times BR(H \rightarrow X\bar{X})$ could be determined to

X = b: 0.3 % at 1.4 TeV and to 0.22 % at 3 TeV.

X = c: 2.9 % at 1.4 TeV and to 2.7 % at 3 TeV.

X = g: 1.8 % at 1.4 TeV and to 1.8 % at 3 TeV.

for m_H = 126 GeV and accumulated luminosities of 1.5 ab^{-1} and 2 ab^{-1} for 1.4 TeV and 3 TeV, respectively.

The study was performed with full simulation and reconstruction in CLIC_SiD detector, realistic beam spectrum, ISR, γγ overlay… and with unpolarized beams.

Analysis at 350 GeV is in progress.