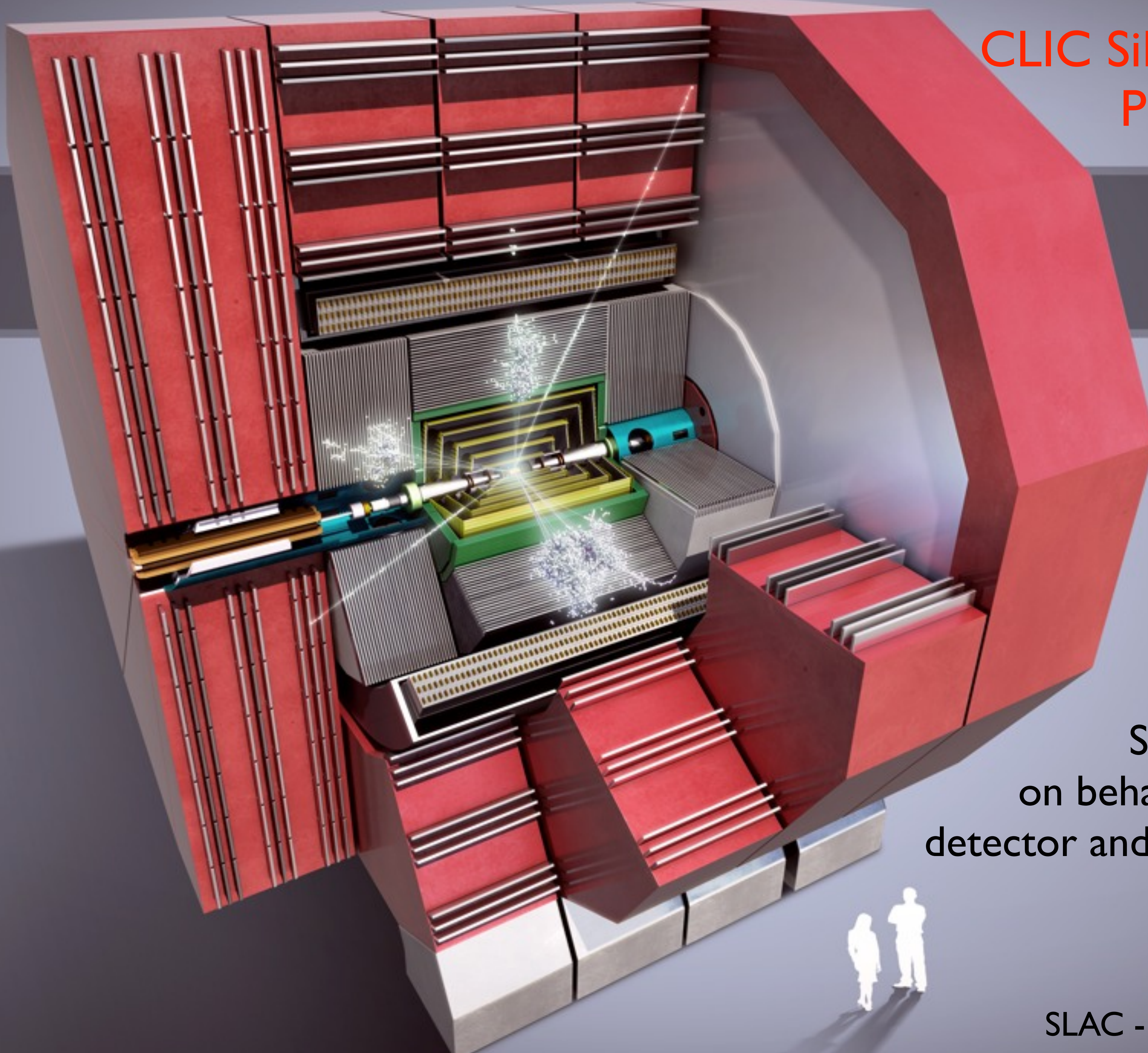
CLIC SiD Benchmark Physics Studies



Sophie Redford
on behalf of the CLIC detector and physics group

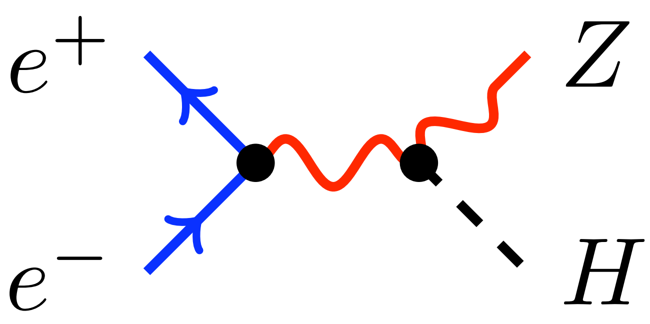
SiD workshop
SLAC - 14 October 2013

Outline

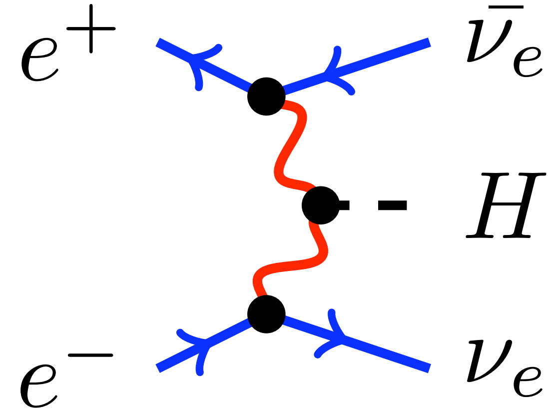
1) Higgs production and decay modes at CLIC
2) Current status: Snowmass white paper
3) CLIC_SiD benchmark processes:
   - $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ at 1.4 TeV
   - $H \rightarrow bb$, $H \rightarrow cc$ and $H \rightarrow gg$ at 1.4 TeV and 3 TeV
   - Higgs self coupling at 1.4 TeV and 3 TeV
   - Top Yukawa coupling at 1.4 TeV

Nobel Prize in Physics for the Higgs mechanism - 8.10.13

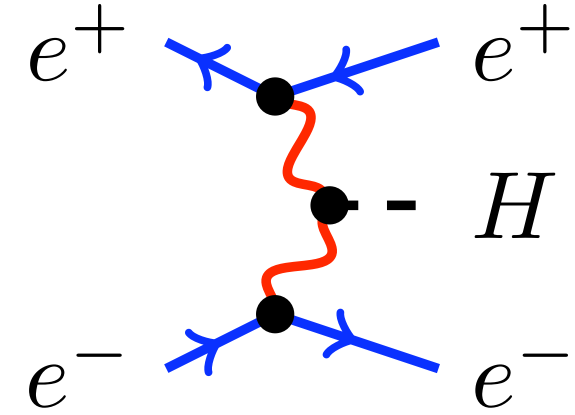
Higgs production at CLIC: dominant modes



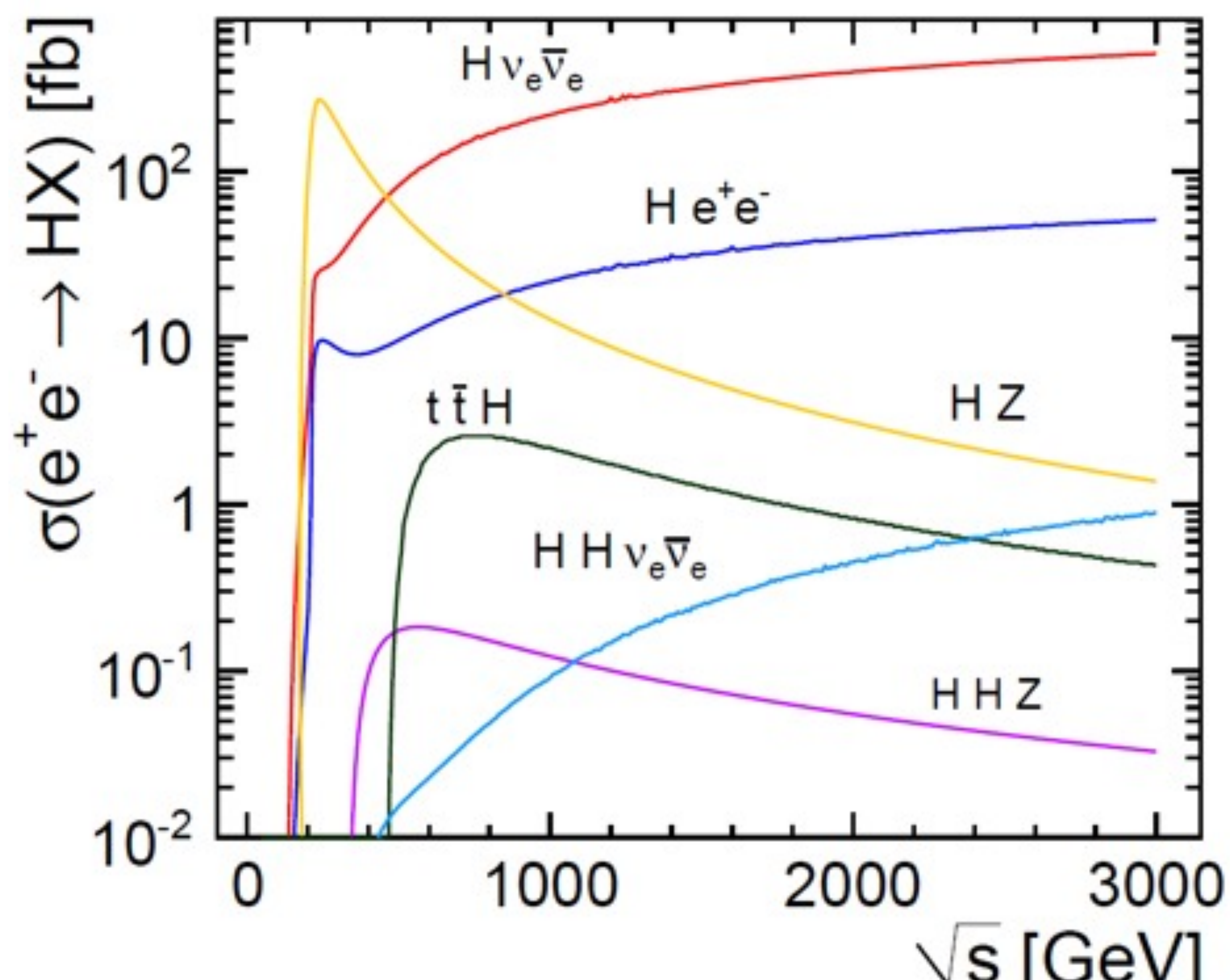
Higgsstrahlung
Dominates at $\sqrt{s}$ ~ 350 GeV
σ ~ 1/s



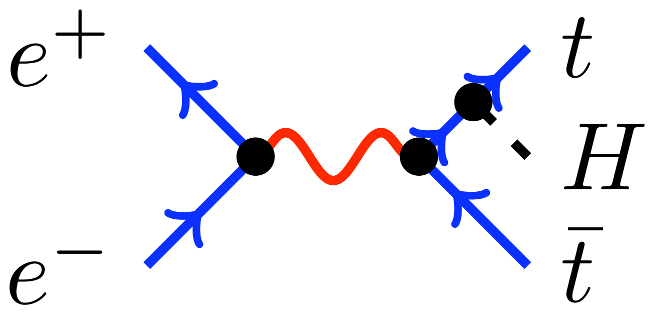
WW fusion
Dominates at $\sqrt{s}$ > 500 GeV
σ ~ log(s)



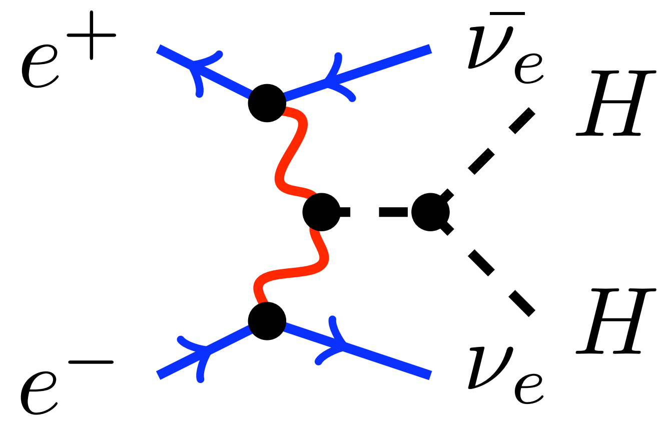
ZZ fusion
One order lower than WW
σ ~ log(s)



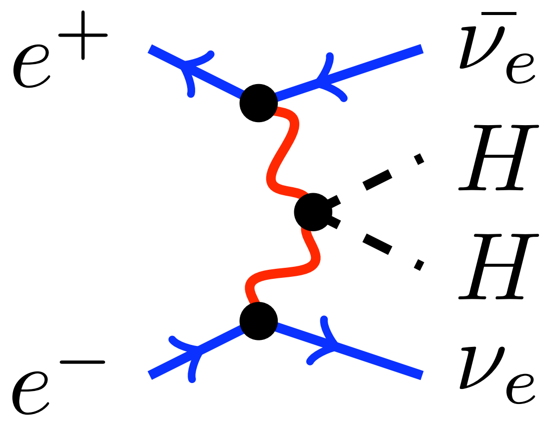
Higgs production at CLIC: rarer modes



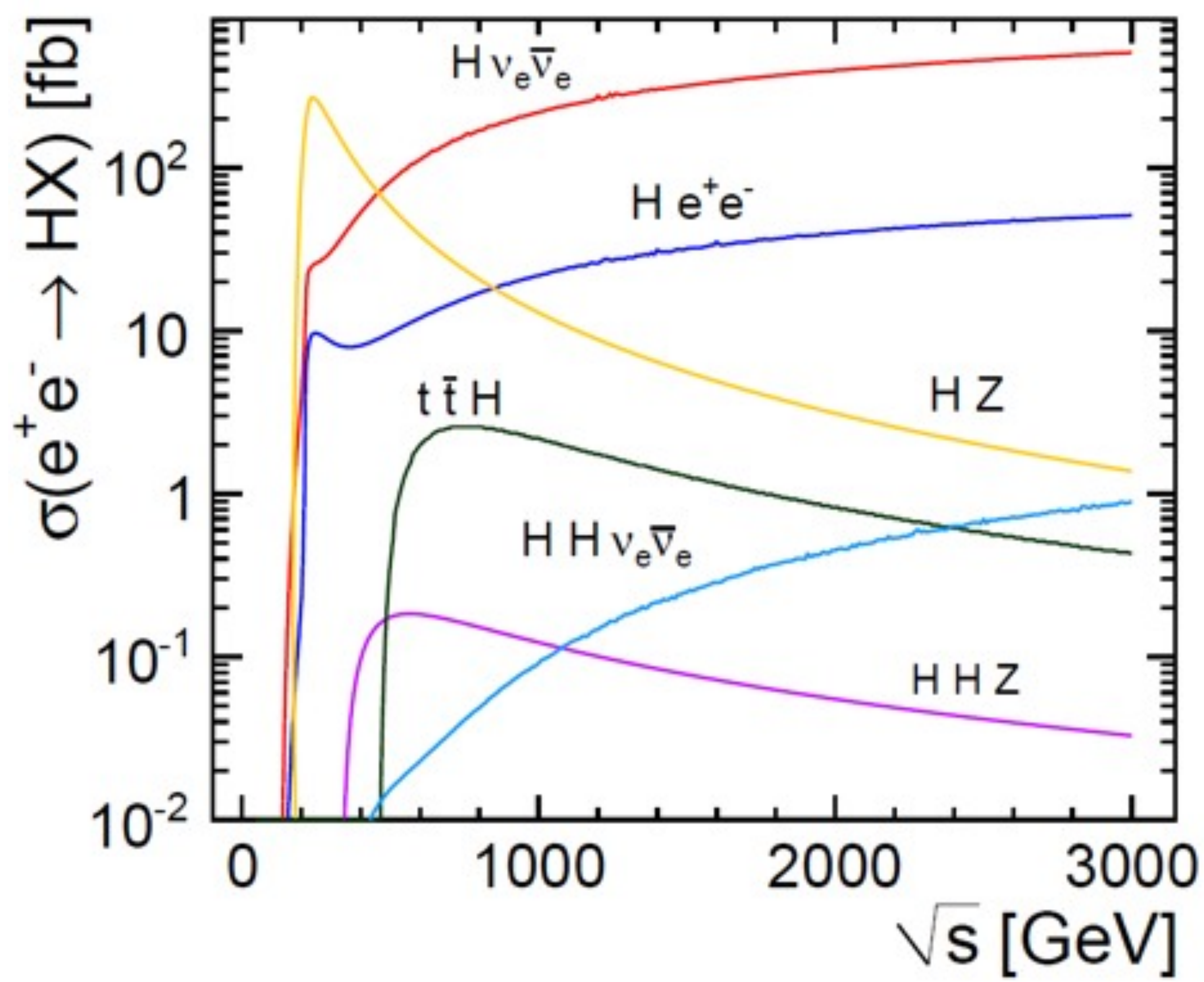
ttH production
Maximum at $\sqrt{s}$ ~ 800 GeV



Double Higgs production
Tri-linear self coupling



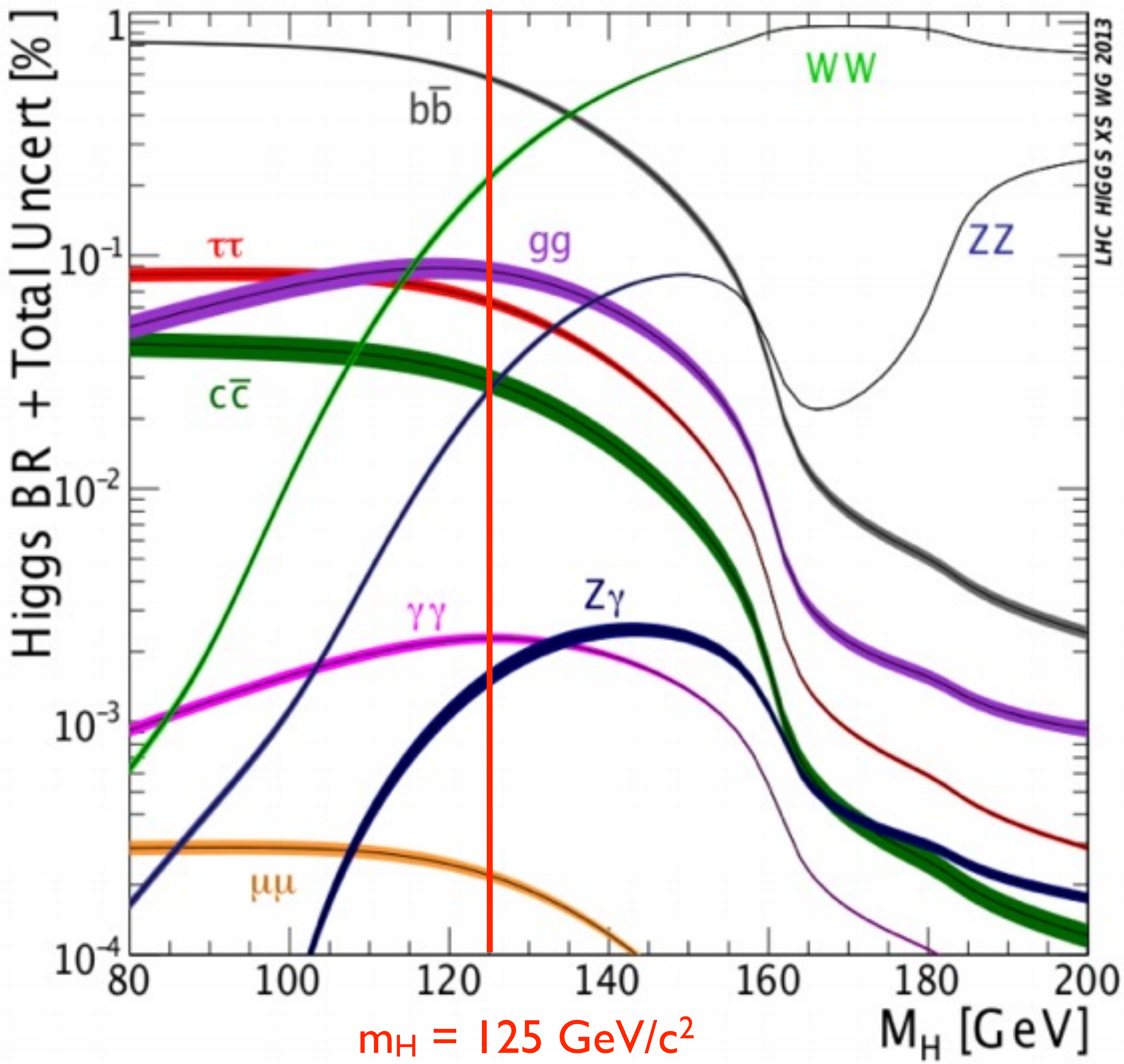
Quartic coupling
Requires high energy



Today: focus on high-energy
1.4 TeV and 3 TeV

Higgs decay modes

Decay	Branching ratio
H → bb	56.1%
H → WW	23.1%
H → gg	8.48%
H → ττ	6.16%
H → ZZ	2.89%
H → cc	2.83%
H → γγ	0.228%
H → Zγ	0.162%
H → μμ	0.0214%



Simulation: assumptions and numbers

Unpolarised cross sections for m_H = 125 GeV including ISR:

	350 GeV	1.4 TeV	3 TeV
$\sigma(e^+e^- \to ZH)$	134 fb	9 fb	2 fb
$\sigma(e^+e^- \to H\nu_e\bar{\nu}_e)$	52 fb	279 fb	479 fb
$\sigma(e^+e^- \to He^+e^-)$	7 fb	28 fb	49 fb

Numbers of events including ISR & Beam-strahlung:

	350 GeV	1.4 TeV	3 TeV
L_{int}	500 fb^{-1}	1500 fb^{-1}	2000 fb^{-1}
# ZH events	68'000	20'000	11'000
# $H\nu_e\bar{\nu}_e$ events	26'000	370'000	830'000
# He^+e^- events	3'700	37'000	84'000

Number of $e^+e^- \to H\nu\bar{\nu}$ events significantly enhanced with polarisation

Polarization	Enhancement factor	
$P(e^-) : P(e^+)$	$e^+e^- \to ZH$	$e^+e^- \to H\nu_e\bar{\nu}_e$
unpolarized	1.00	1.00
−80% : 0%	1.18	1.80
−80% : +30%	1.48	2.34

Simulation and reconstruction

- Full simulation of signal and bkg, 60 BX of $\gamma\gamma \to$ hadrons overlaid on each event
- Time and momentum hits - discard hits out of 10 ns window (100 ns in HCAL)

Current status: Snowmass white paper

Channel	Measurement	Observable	Statistical precision 350 GeV $500\ \mathrm{fb}^{-1}$	1.4 TeV $1.5\ \mathrm{ab}^{-1}$	3.0 TeV $2.0\ \mathrm{ab}^{-1}$
ZH	Recoil mass distribution	m_H	120 MeV	–	–
ZH	$\sigma(HZ) \times BR(H \to \text{invisible})$	Γ_{inv}	tbd	–	–
ZH	$H \to b\bar{b}$ mass distribution	m_H	tbd	–	–
$H\nu_e\bar{\nu}_e$	$H \to b\bar{b}$ mass distribution	m_H	–	40 MeV*	33 MeV*
ZH	$\sigma(HZ) \times BR(Z \to \ell^+\ell^-)$	g^2_{HZZ}	4.2%	–	–
ZH	$\sigma(HZ) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	1%†	–	–
ZH	$\sigma(HZ) \times BR(H \to c\bar{c})$	$g^2_{HZZ}g^2_{Hcc}/\Gamma_H$	5%†	–	–
ZH	$\sigma(HZ) \times BR(H \to gg)$		6%†	–	–
ZH	$\sigma(HZ) \times BR(H \to \tau^+\tau^-)$	$g^2_{HZZ}g^2_{H\tau\tau}/\Gamma_H$	5.7%	–	–
ZH	$\sigma(HZ) \times BR(H \to WW^*)$	$g^2_{HZZ}g^2_{HWW}/\Gamma_H$	2%†	–	–
ZH	$\sigma(HZ) \times BR(H \to ZZ^*)$	$g^2_{HZZ}g^2_{HZZ}/\Gamma_H$	tbd	–	–
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to b\bar{b})$	$g^2_{HWW}g^2_{Hbb}/\Gamma_H$	3%†	0.3%	0.2%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to c\bar{c})$	$g^2_{HWW}g^2_{Hcc}/\Gamma_H$	–	2.9%	2.7%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to gg)$		–	1.8%	1.8%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \tau^+\tau^-)$	$g^2_{HWW}g^2_{H\tau\tau}/\Gamma_H$	–	3.7%	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \mu^+\mu^-)$	$g^2_{HWW}g^2_{H\mu\mu}/\Gamma_H$	–	29%*	16%
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to \gamma\gamma)$		–	15%*	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to Z\gamma)$		–	tbd	tbd
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to WW^*)$	g^4_{HWW}/Γ_H	tbd	1.1%*	0.8%*
$H\nu_e\bar{\nu}_e$	$\sigma(H\nu_e\bar{\nu}_e) \times BR(H \to ZZ^*)$	$g^2_{HWW}g^2_{HZZ}/\Gamma_H$	–	3%†	2%†
He^+e^-	$\sigma(He^+e^-) \times BR(H \to b\bar{b})$	$g^2_{HZZ}g^2_{Hbb}/\Gamma_H$	–	1%†	0.7%†
$t\bar{t}H$	$\sigma(t\bar{t}H) \times BR(H \to b\bar{b})$	$g^2_{Htt}g^2_{Hbb}/\Gamma_H$	–	8%	tbd
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	g_{HHWW}	–	7%*	3%*
$HH\nu_e\bar{\nu}_e$	$\sigma(HH\nu_e\bar{\nu}_e)$	λ	–	28%	16%
$HH\nu_e\bar{\nu}_e$	with −80% e$^-$ polarization	λ	–	21%	12%

arXiv:1307.5288
Final update: 01/10/2013

† : estimate
*: preliminary

Several updates since the summer

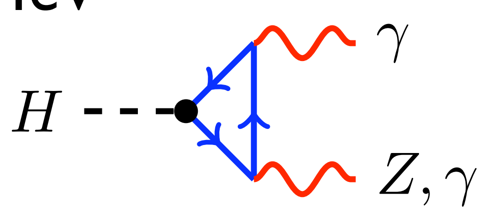
Today: focus on studies performed with CLIC_SiD

CLIC_SiD benchmark processes

Purpose of the benchmark studies: to demonstrate overall capability of the detector concept to deliver precision physics measurements in the CLIC environment

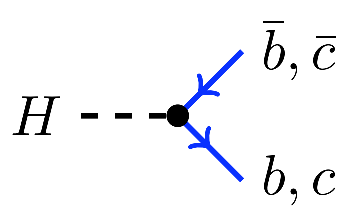
- H→γγ and H→Zγ at 1.4 TeV

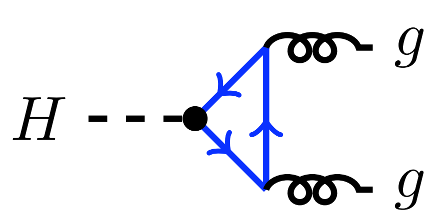
  Christian Grefe
  Eva Sicking



- H→bb, cc, gg at 1.4 TeV and 3 TeV

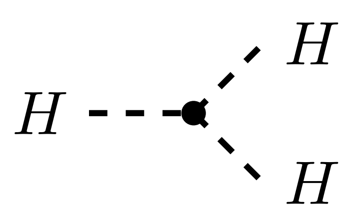
  Tomas Lastovicka
  Jan Strube





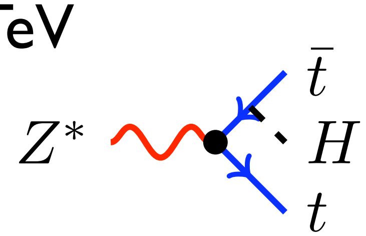
- Higgs self-coupling at 1.4 TeV and 3 TeV

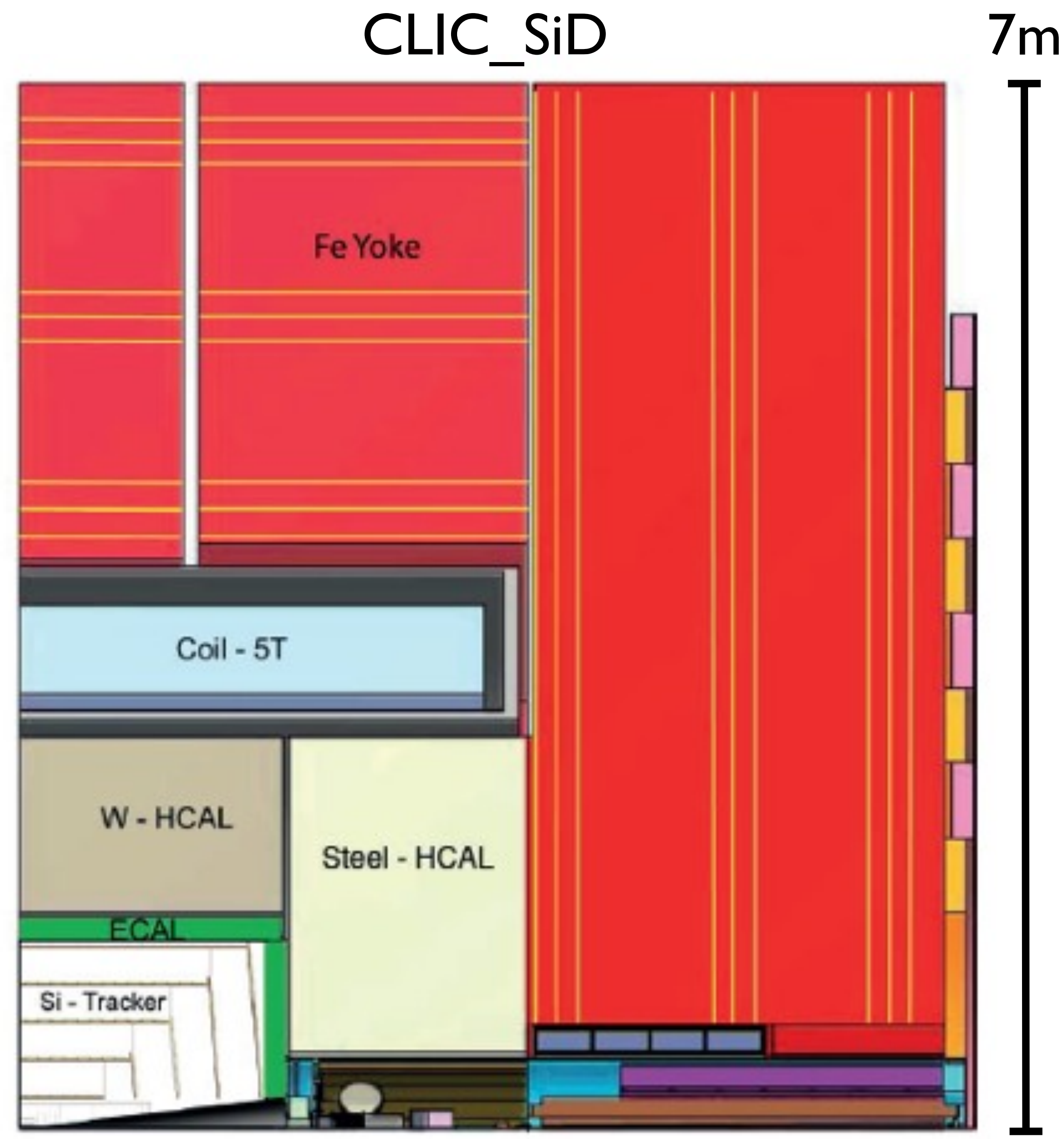
  Tomas Lastovicka
  Jan Strube



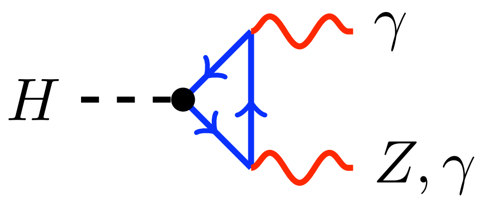
- Top Yukawa coupling at 1.4 TeV

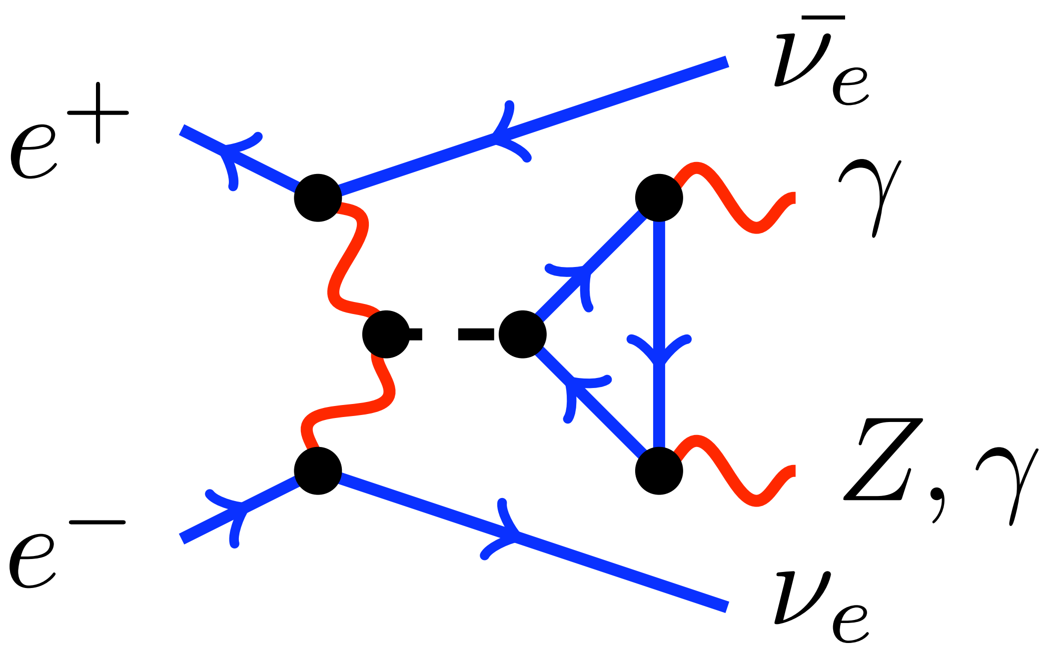
  Sophie Redford
  Philipp Roloff
  Marcelo Vogel





$H \to \gamma\gamma$ and $H \to Z\gamma$ at 1.4 TeV





Higgs produced via WW fusion

- Missing transverse momentum

Higgs decay to $\gamma\gamma/Z\gamma$ via fermion loop

- Sensitive to BSM physics in the loop
- Benchmark of photon reconstruction

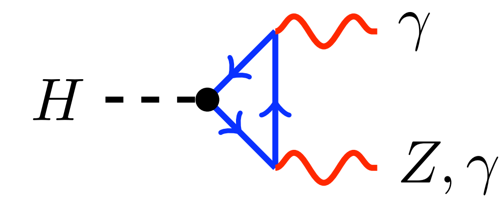
$H \to \gamma\gamma$

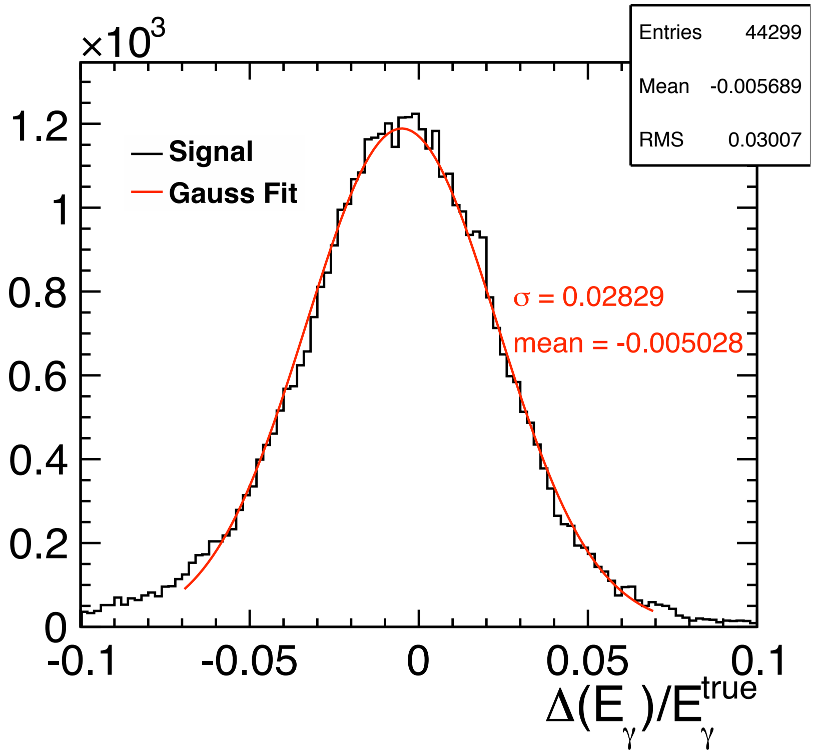
- σxBR = 0.56 fb
- Expect 840 signal events in 1.5 ab^{-1}
- Complete analysis
- Significance 6.8

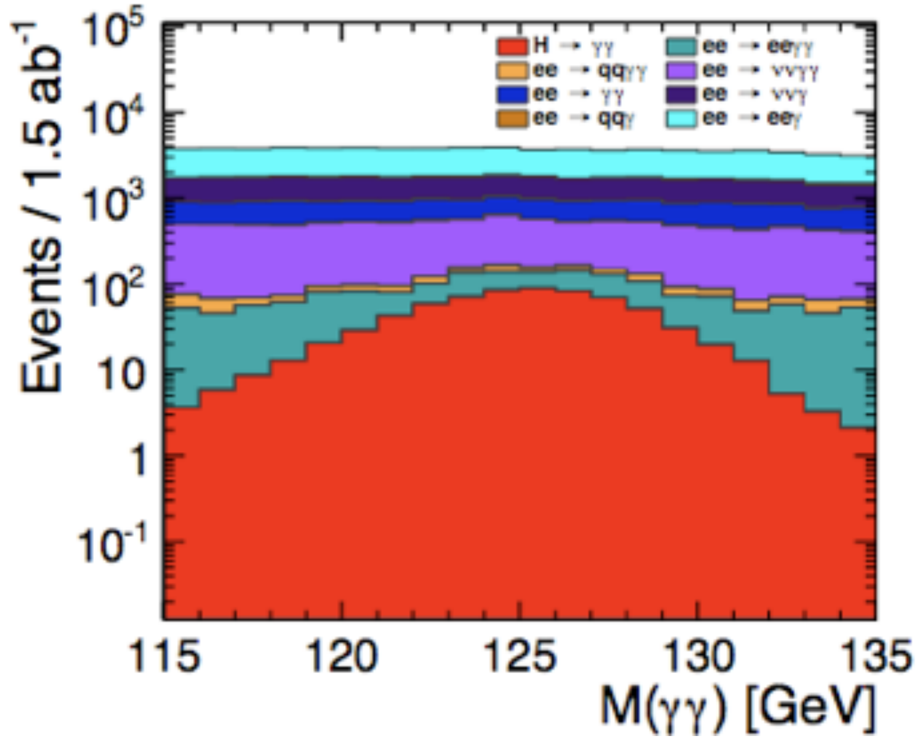
$H \to Z\gamma$

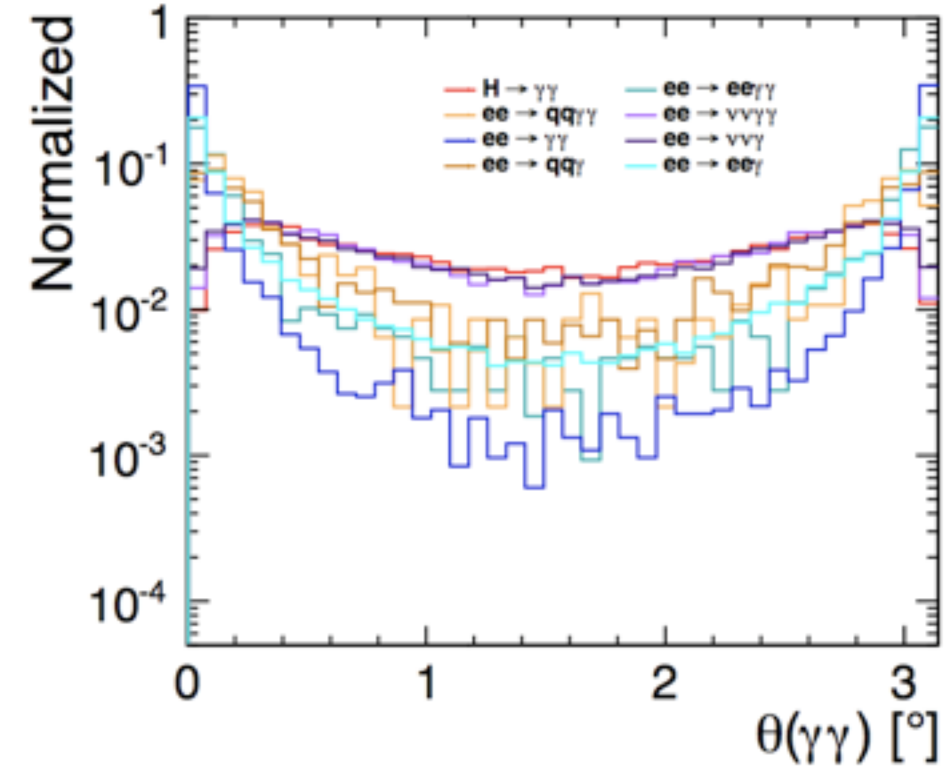
- σxBR = 0.39 fb
- Split by Z decay channel
- Expect 409 hadronic, 21 e/μ signal evt
- Some background samples have big weights, some eγ samples are missing
- Current combined significance 1.88

H → γγ analysis steps







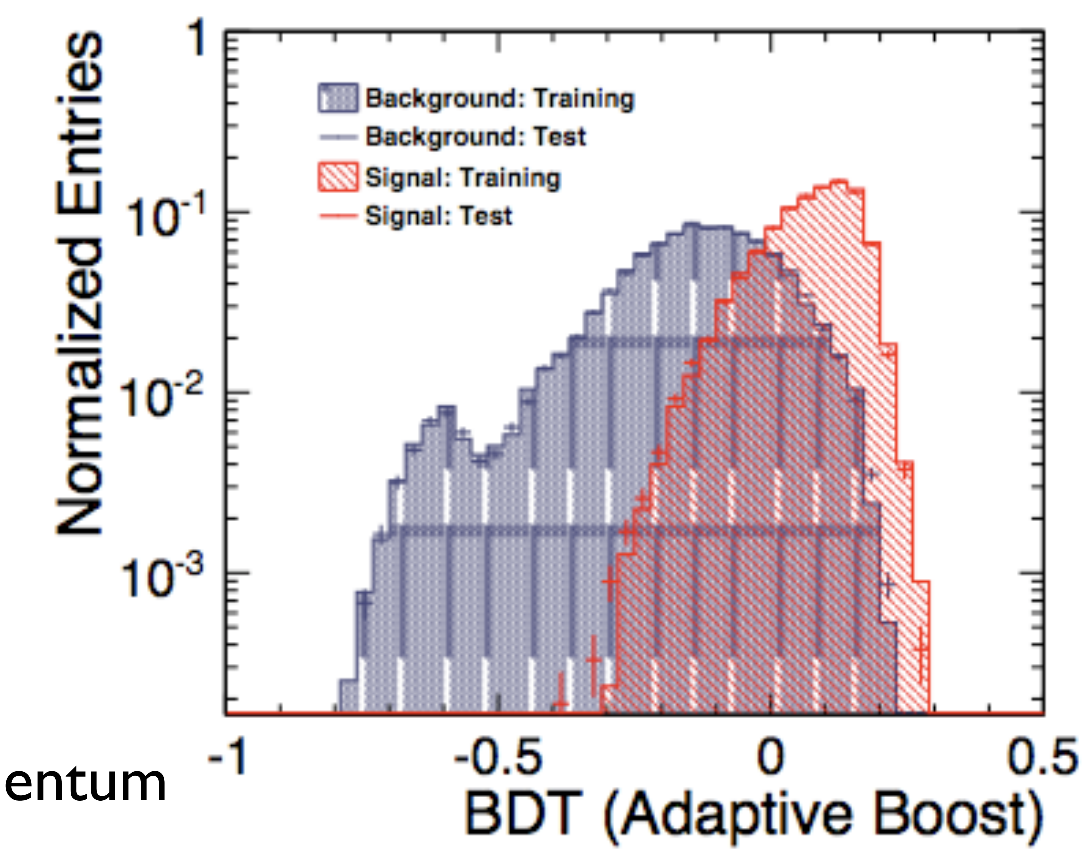


Pre-selection

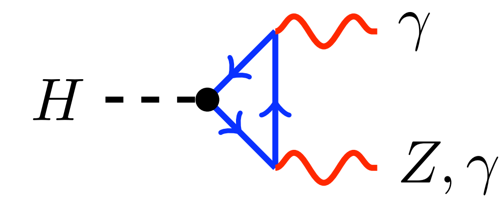
- Two high energy photons
- Invariant mass close to Higgs mass
- Isolation from charged particles
- Low remaining visible energy

Multi-variate selection

- BDT adaptive boost in TMVA
- Kinematic variables, Higgs and photon angles, momentum

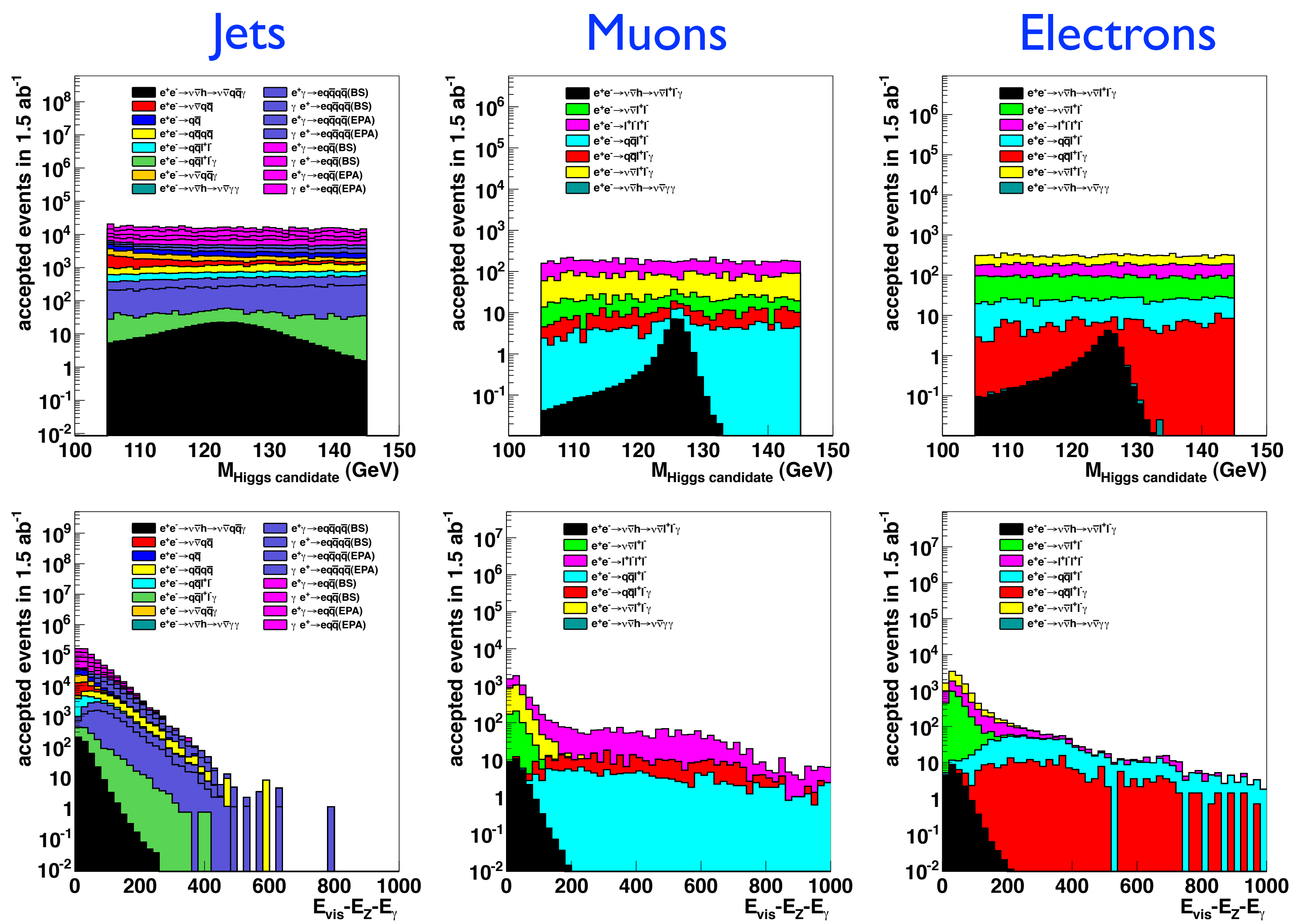


H → Zγ analysis steps



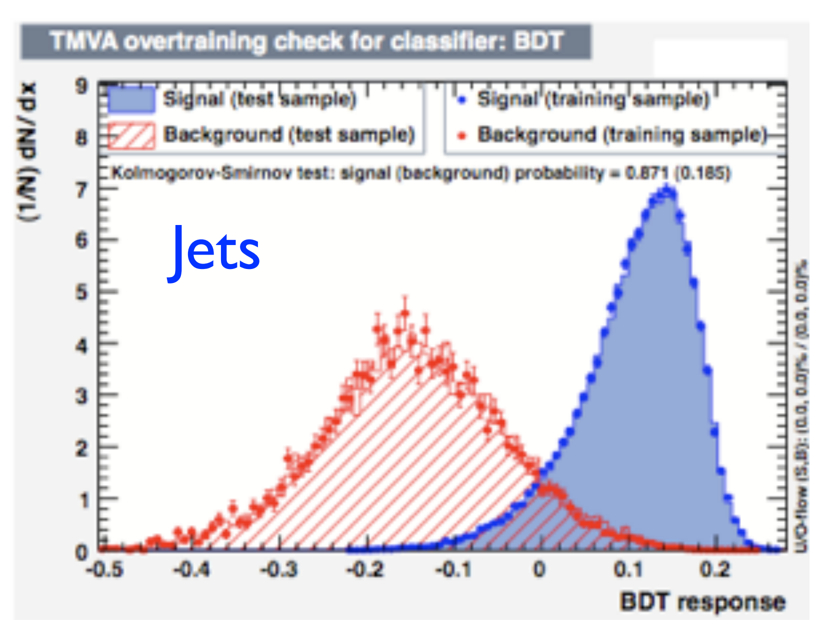
Pre-selection

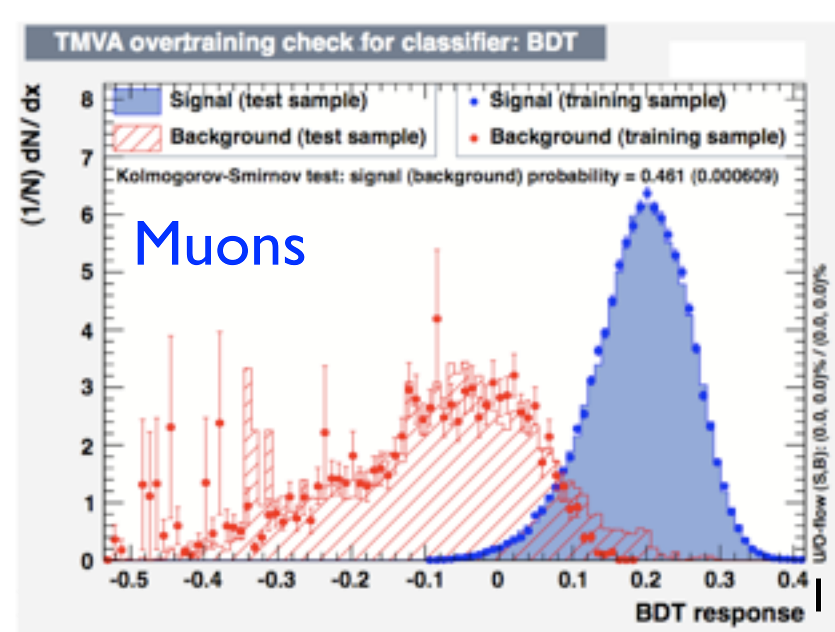
- High energy photon and leptons / jets
- Invariant mass close to Higgs mass
- Two jets (k_T algorithm) with >5 particles



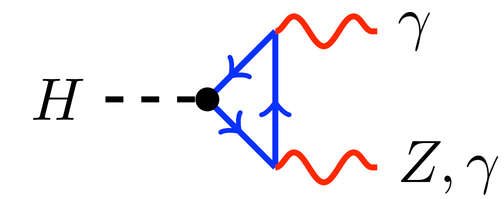
Multi-variate selection

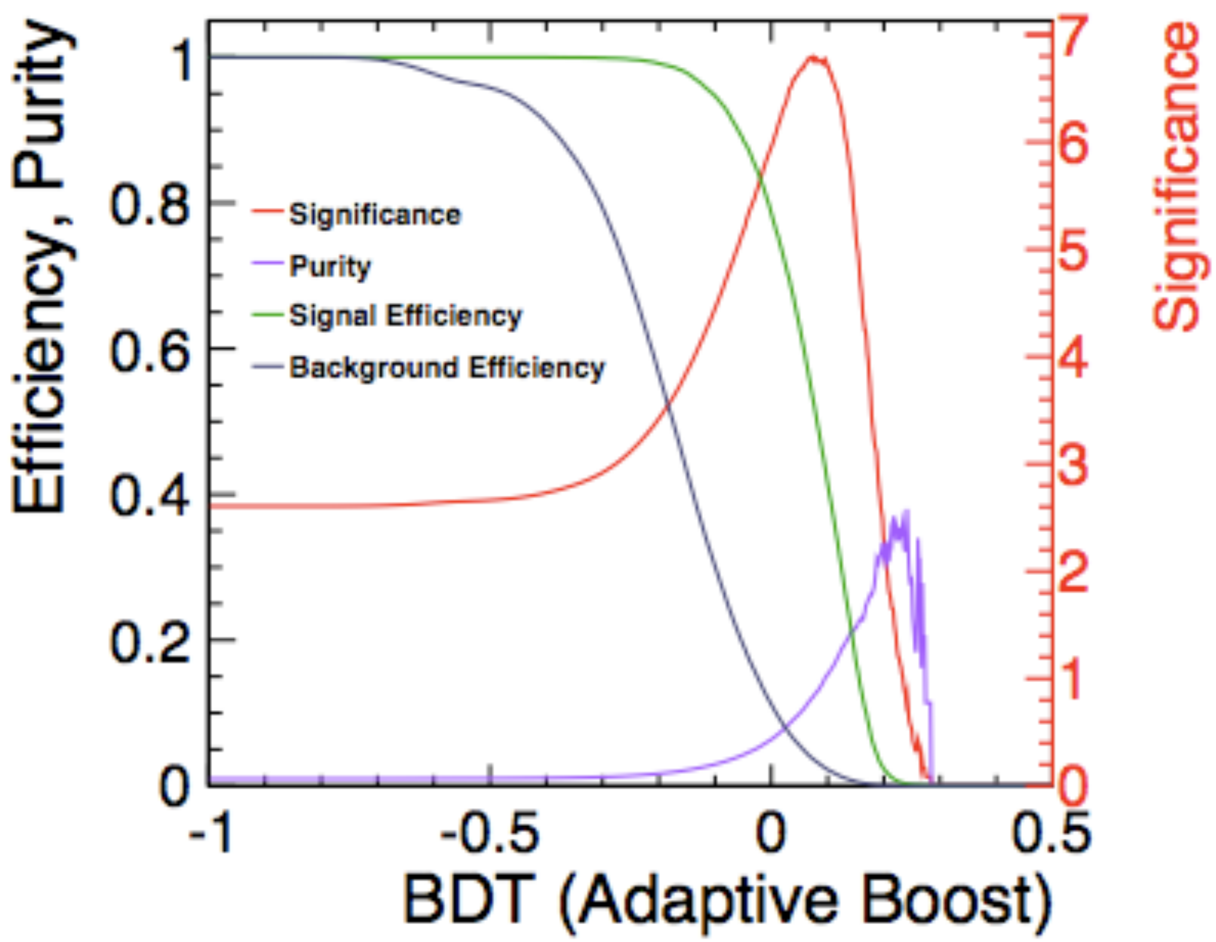
- BDT adaptive boost in TMVA
- Kinematic variables, event variables, jet variables

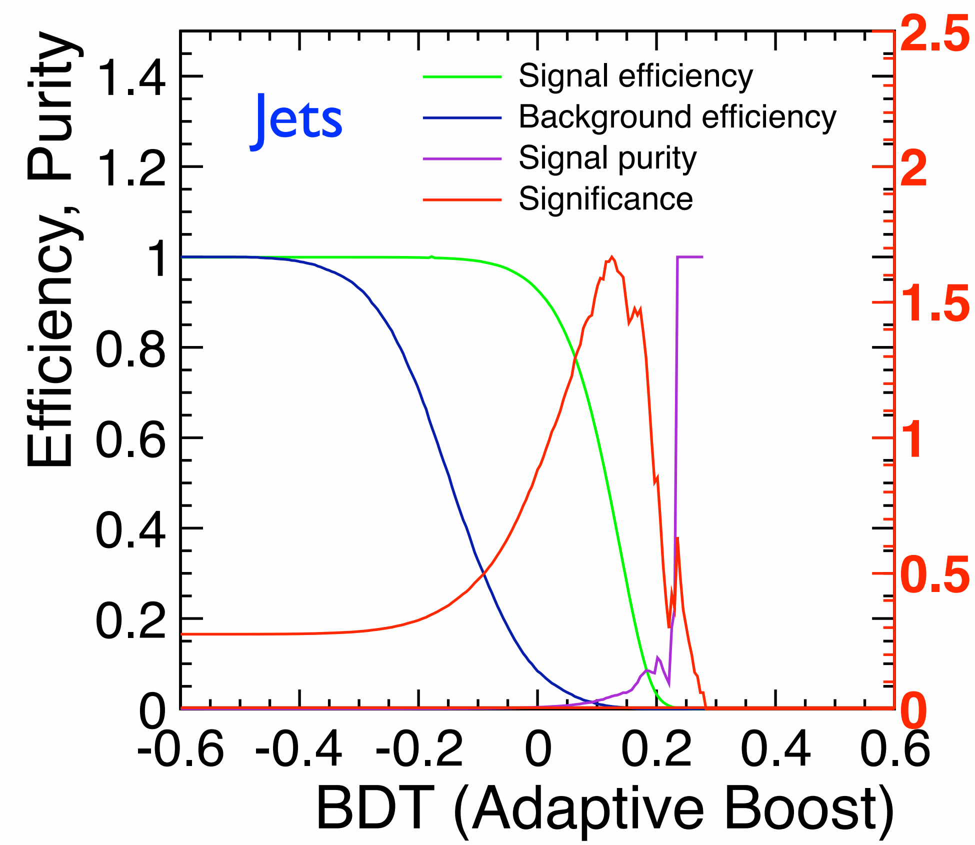




H → γγ and H → Zγ results







H → γγ

- Significance = 6.8
- δ(σxBR) = 14.7%
- Signal efficiency 44.1%
- 367 signal events selected

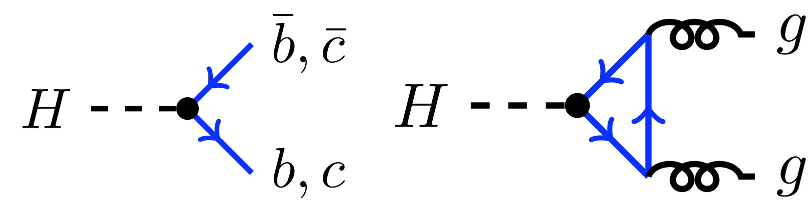
H → Zγ

- Current combined significance 1.88

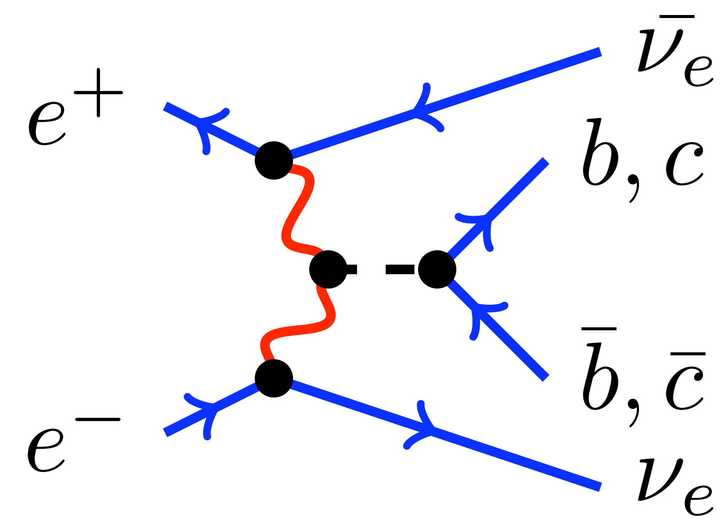
	Significance	Signal eff.	Evt.
Jets	1.667	25%	100
Muons	0.771	28%	6
Electrons	0.410	28%	6

- Additional bkg, stats needed

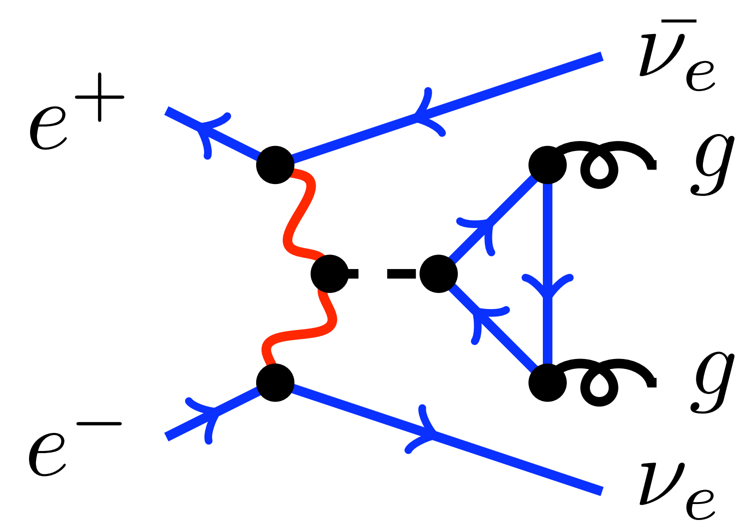
H → bb, cc, gg at 1.4, 3 TeV



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

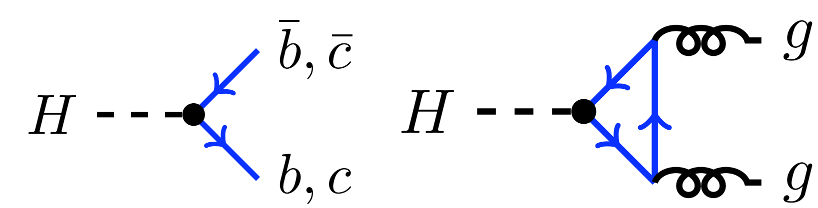


- H → $c\bar{c}$
  - Small BR in the Standard Model: 2.83 %
  - Difficult c-flavour tagging
  - Relatively challenging channel

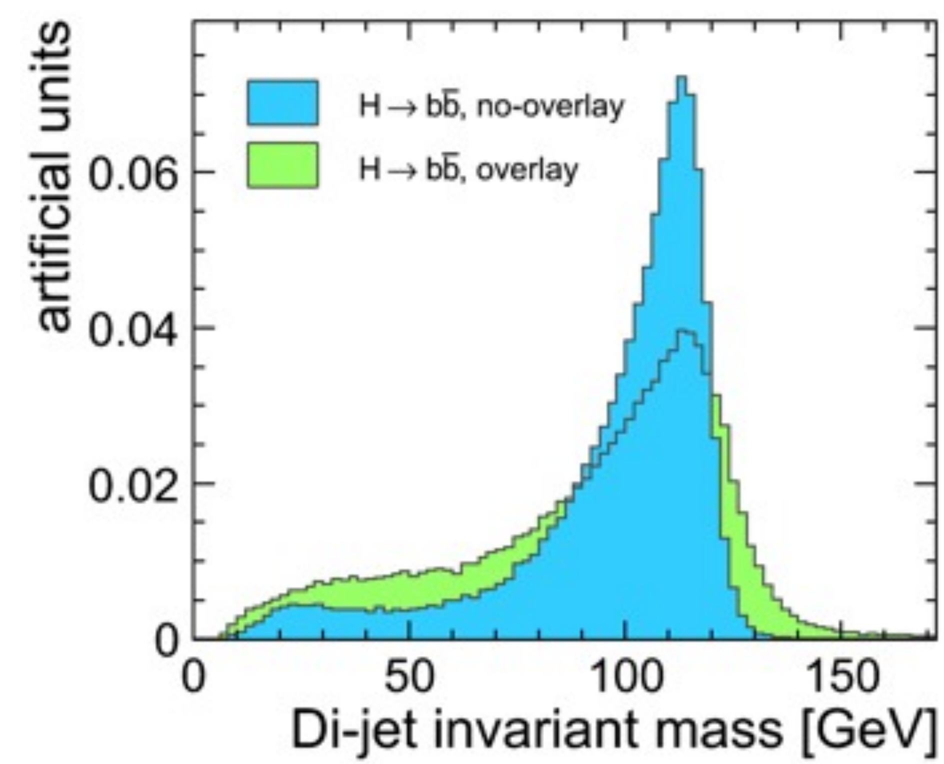


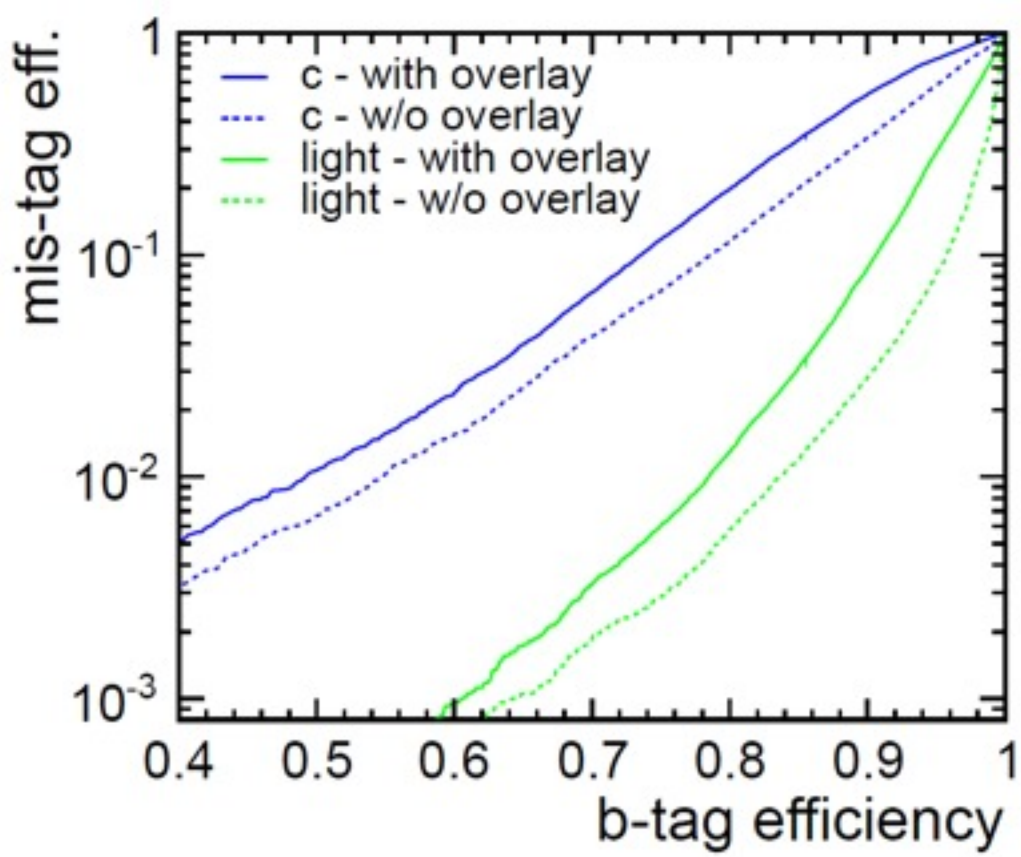
- H → gg
  - 3rd largest BR in the Standard Model: 8.38 %

Flavour tagging jets at 3 TeV

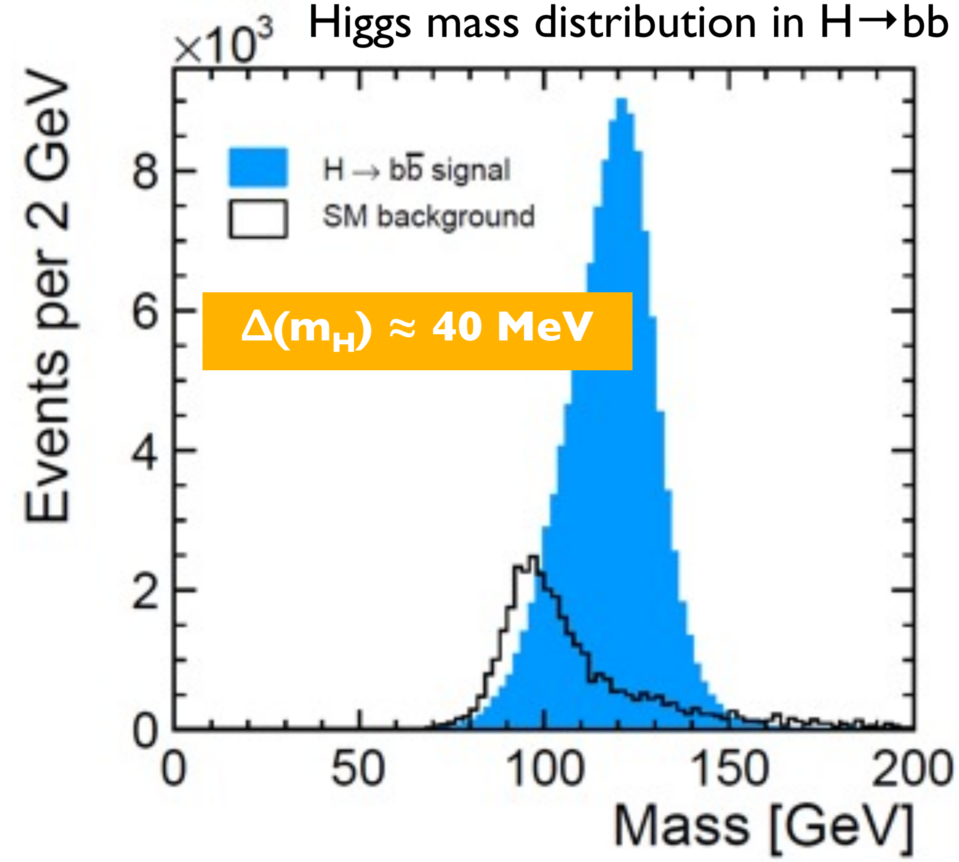


- FastJet k_T algorithm used to force events into 2 jets
- Reject particles assigned to the beam-jet
- LCFIVERTEX package for flavour tagging
- Presence of γγ overlay (60 BX considered) degrades the jet finding and the jet flavour tag quality

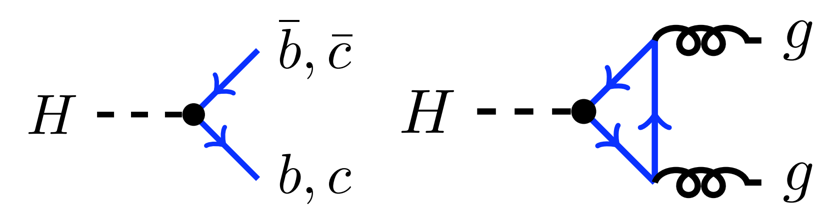




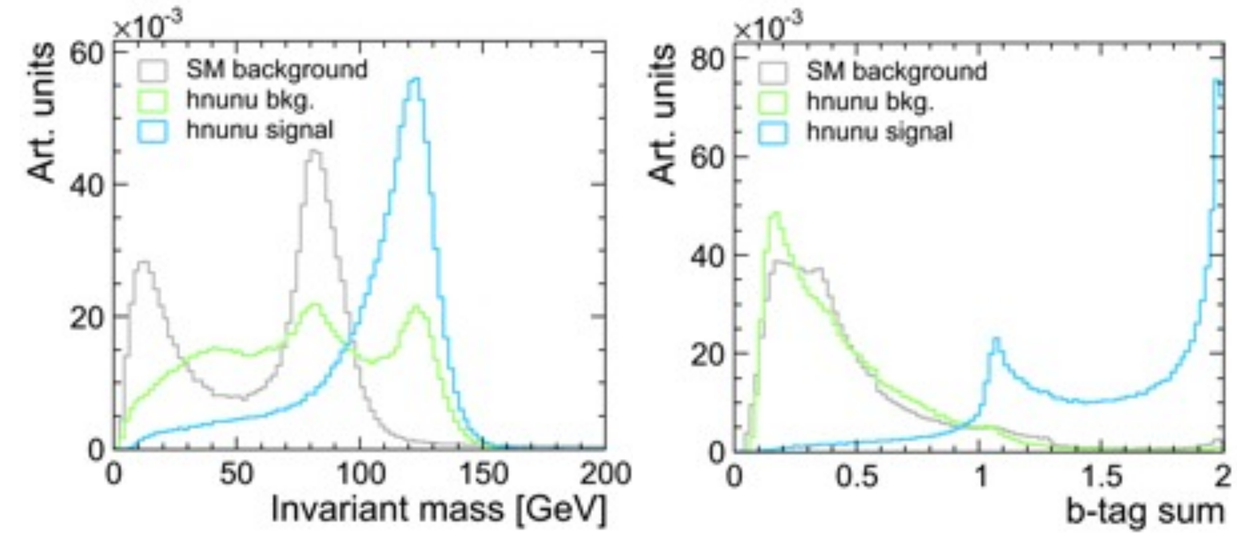
Higgs mass distribution in H→bb̄



Neural net at 1.4 TeV

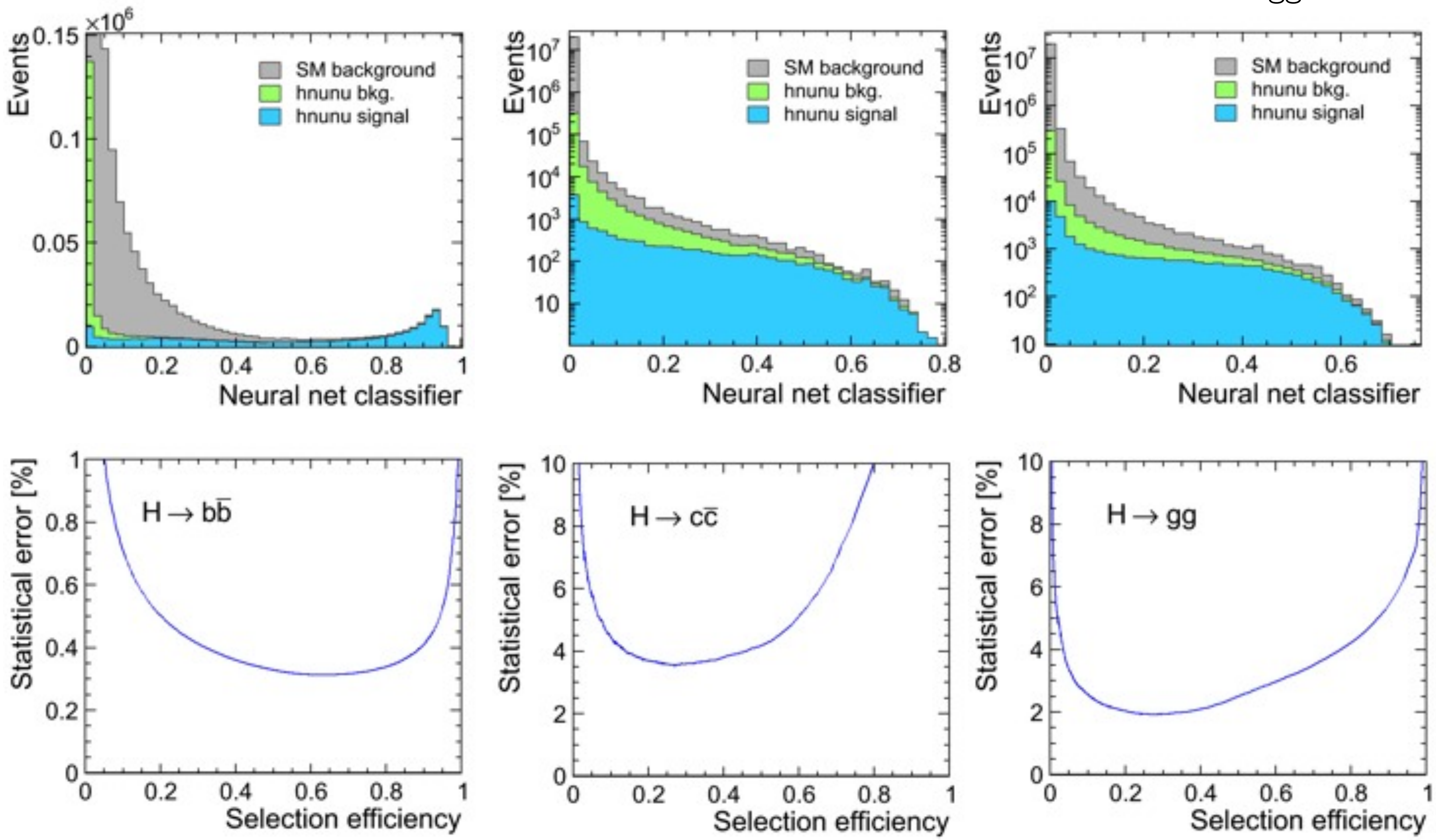


- Control plots for $H \rightarrow b\bar{b}$:
  - $H\nu\nu$ bkg - non signal H decay
  - SM bkg - 2q and 4q

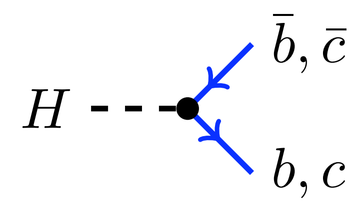


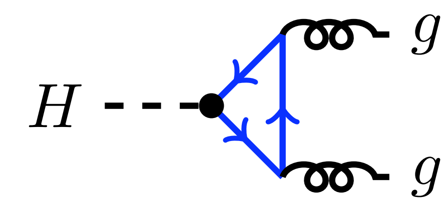
- Neural net results at 1.4 TeV:

$H \rightarrow b\bar{b}$ $H \rightarrow c\bar{c}$ $H \rightarrow gg$



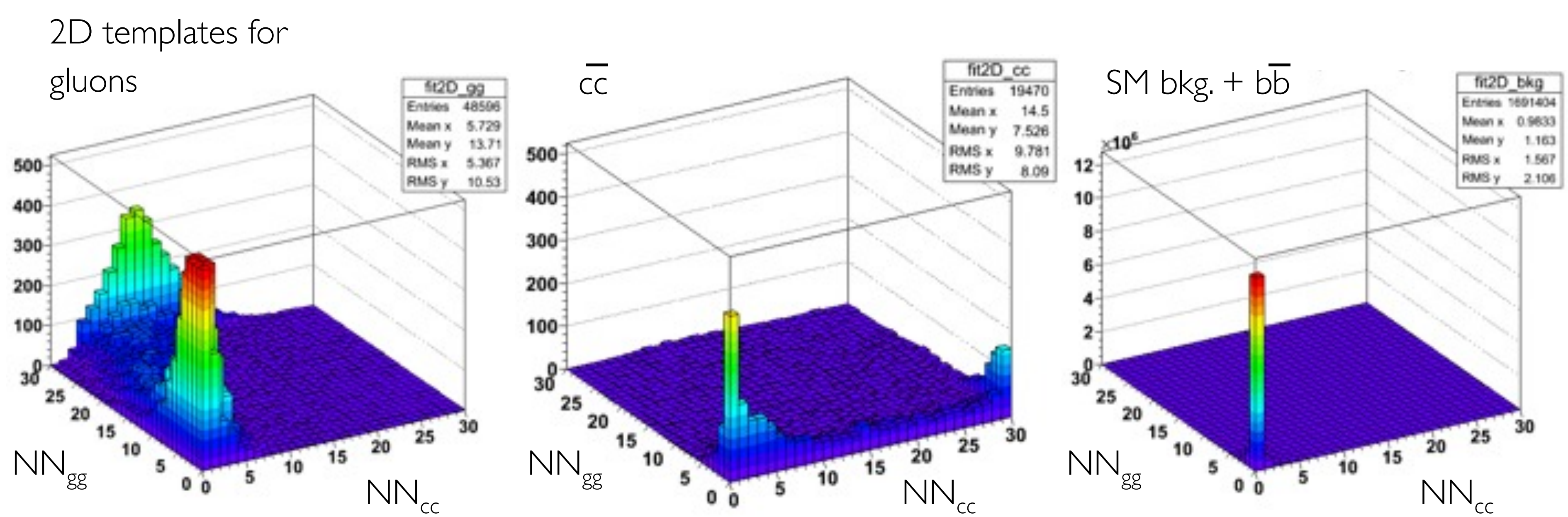
H → bb, cc, gg results





Results achieved using a simultaneous extraction - 2D fit (3D in future)

- Takes into account other channel uncertainties and correlations between channels
- b-channel may be separated from c- and g- channels (2D)
- It turns out that the inter-channel separation is rather good and therefore results for 1D, 2D and 3D are very similar



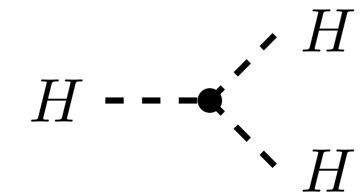
The statistical accuracy of $\sigma(e^+e^- \rightarrow H\nu_e\nu_e)\times BR(H \rightarrow X\bar{X})$:

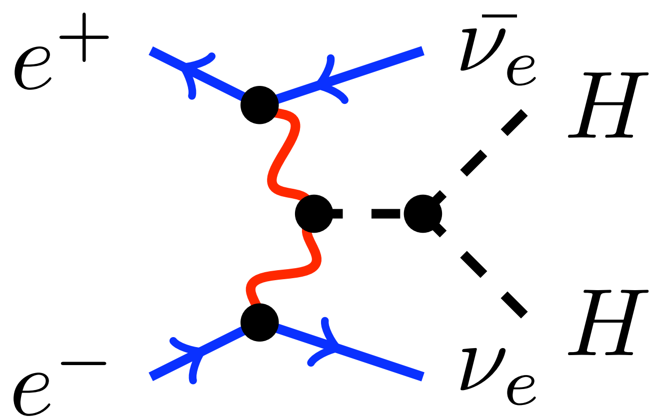
X = b: 0.3 % at 1.4 TeV and to 0.22 % at 3 TeV

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

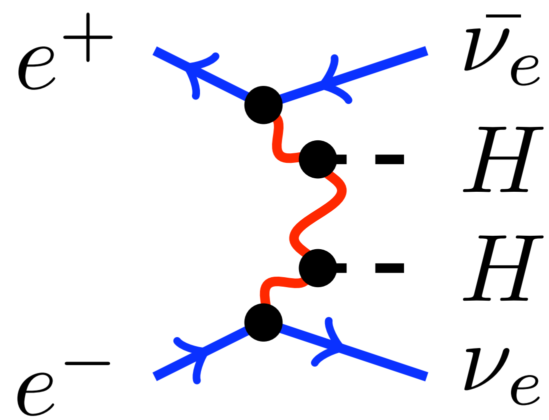
X = g: 1.8 % at 1.4 TeV and to 1.8 % at 3 TeV

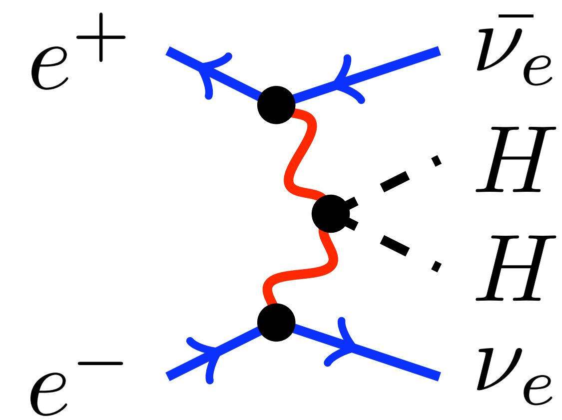
Higgs tri-linear self-coupling at 1.4, 3 TeV





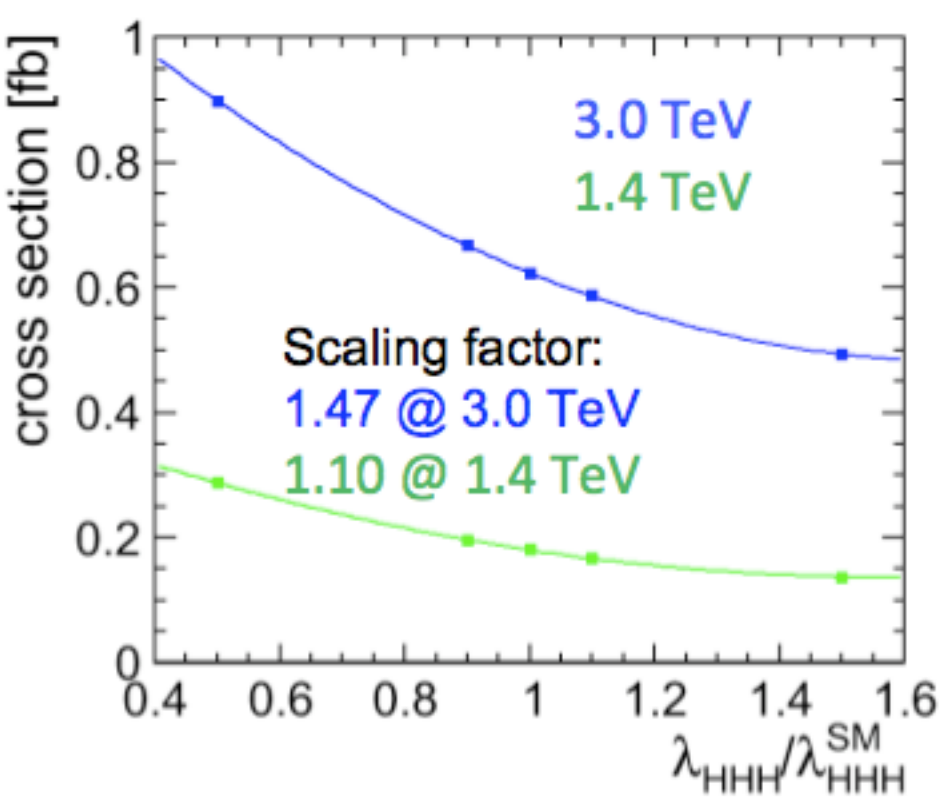
Higgs tri-linear self-coupling: λ_{HHH}





Higgs quartic coupling: λ_{HHWW}

- Goal: measure the rate of double Higgs production and relate it to λ_{HHH}
- Destructive interference between diagrams: larger λ_{HHH} means fewer double Higgs events
- To relate the measured uncertainty on the cross section to the uncertainty on λ_{HHH} :

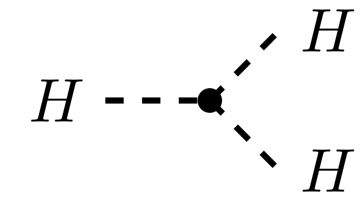


$$\frac{\partial \lambda_{HHH}}{\lambda_{HHH}} = K \frac{\partial \sigma_{hh\nu\nu}}{\sigma_{hh\nu\nu}}$$

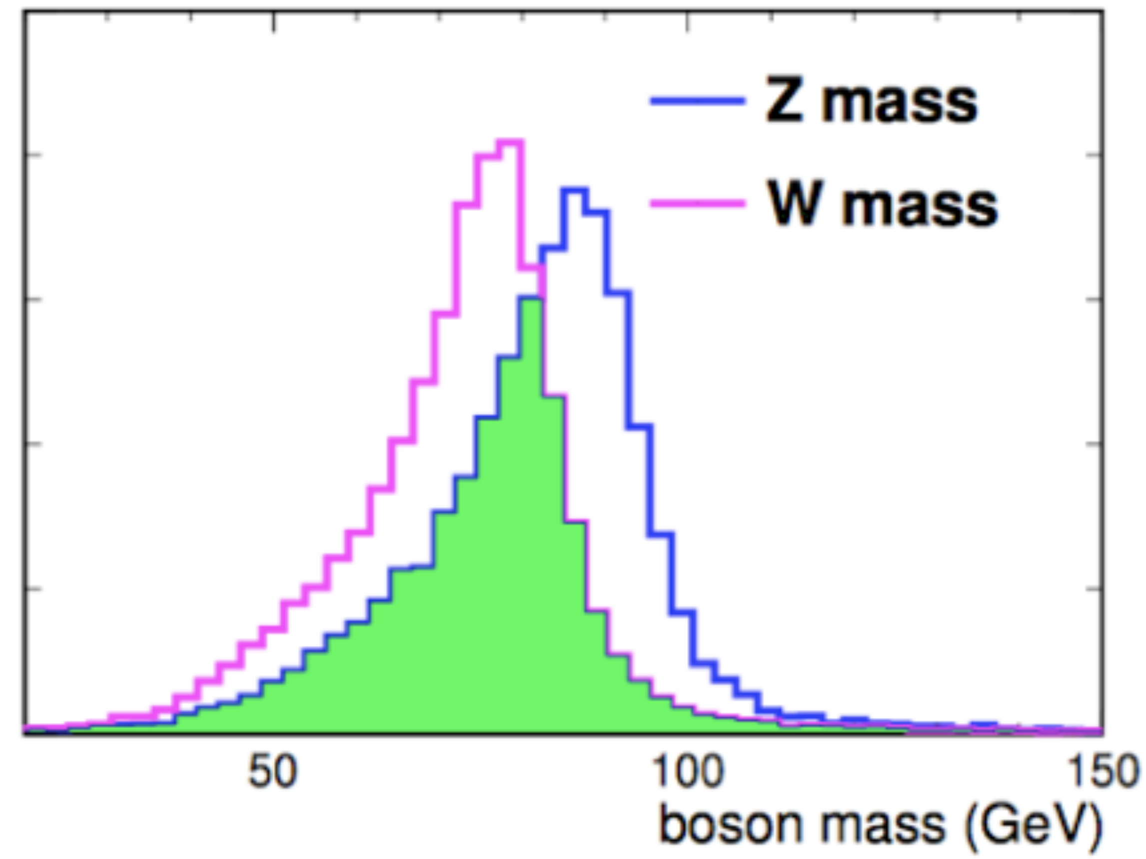
$$K = 1.10 \text{ at } 1.4 \text{ TeV}$$

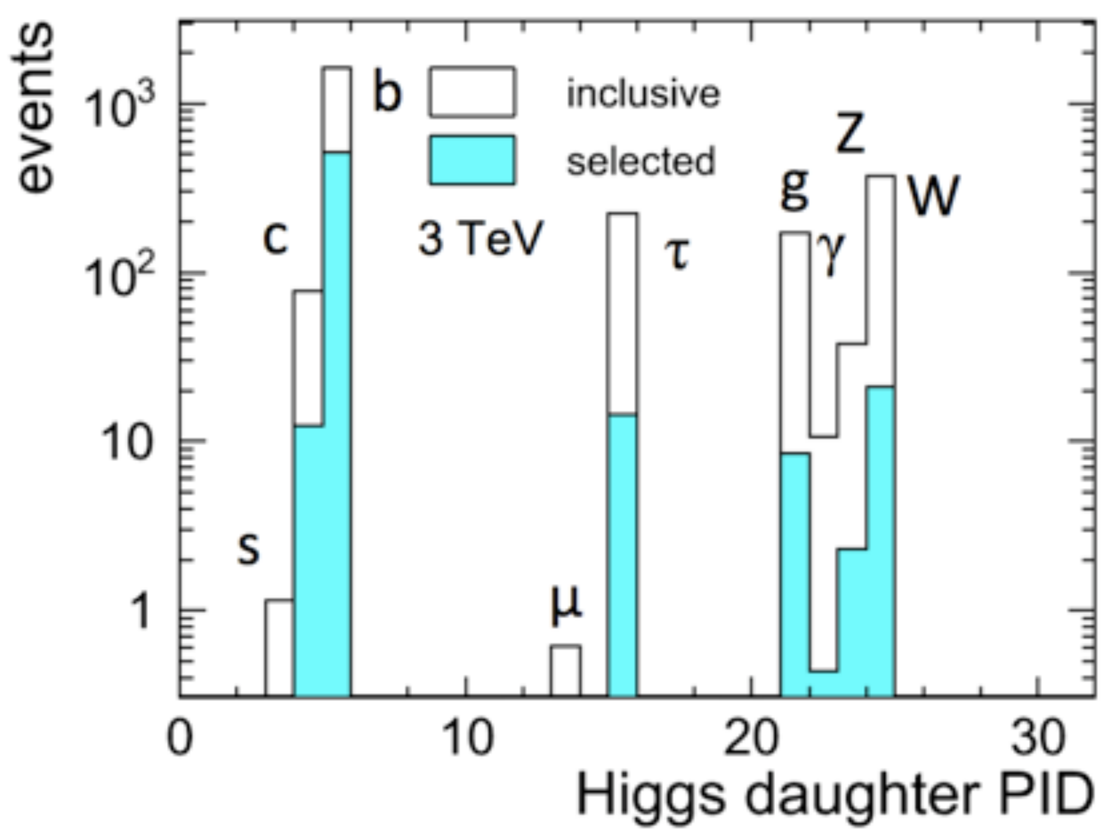
$$K = 1.47 \text{ at } 3.0 \text{ TeV}$$

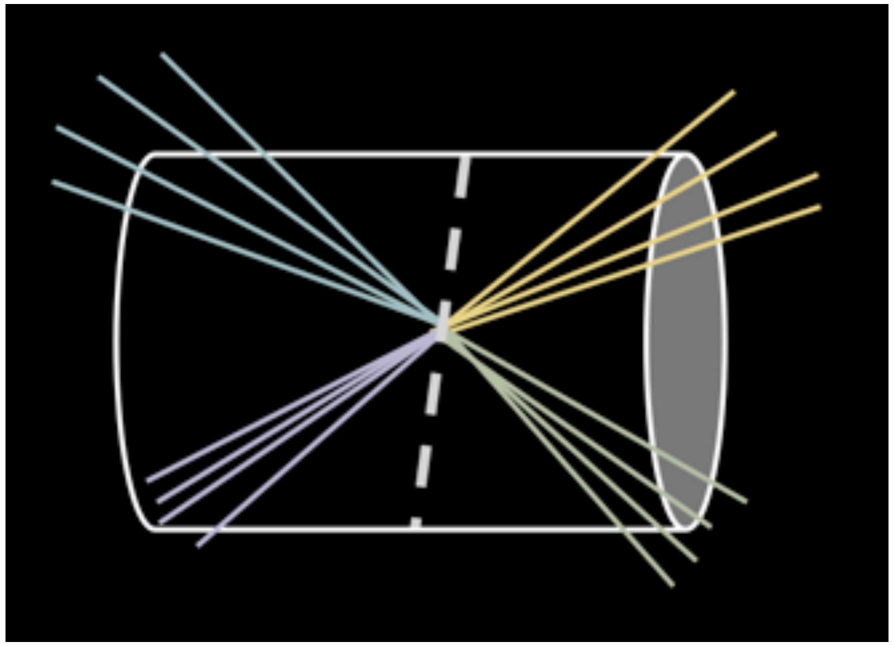
Analysis details



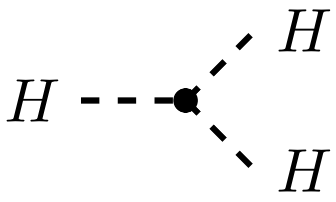
- All final states of H considered
- Jet radius and timing cuts chosen to minimise the overlap
- 4 jets are paired by hemisphere if possible, otherwise kinematics
- Neural network distinguishes between signal and background







Results with m_H = 120 GeV



- The HHνν cross section is sensitive to the Higgs self coupling and the quartic coupling
  - σ(HHvv) = 0.15 fb at 1.4 TeV
  - σ(HHvv) = 0.59 fb at 3 TeV

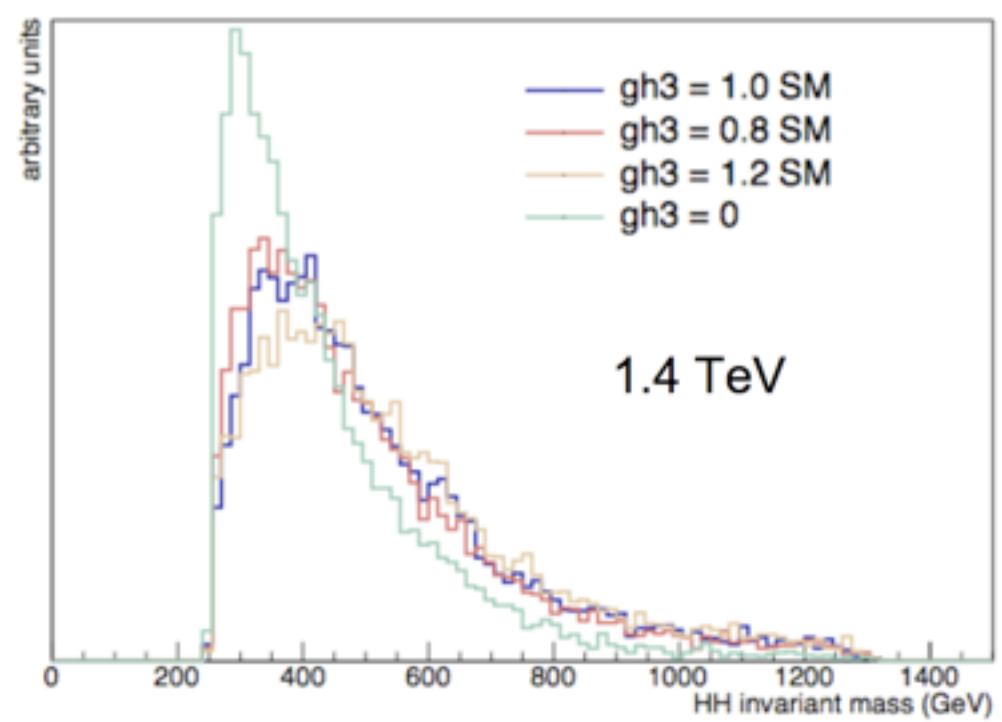
  (high energy and luminosity crucial)

Measurement	1.4 TeV	3 TeV
$\Delta\lambda_{HHWW}$	7%	3%
$\Delta\lambda_{HHH}$	28%	16%
$\Delta\lambda_{HHH}$ P(e-) = -80%	21%	12%

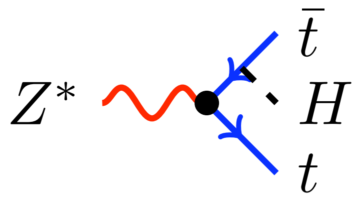
Future of the m_H = 126 GeV analysis

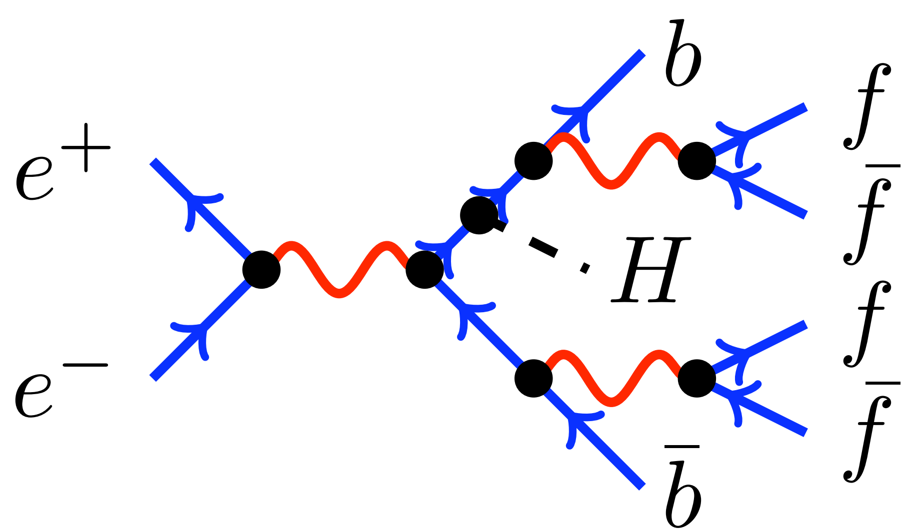
- Production of remaining backgrounds
- Train neural net
- Possible simultaneous extraction of λ_{HHH} and λ_{HHWW}
  - Needs samples with range of λ_{HHWW} values

The shape of the invariant mass of the Higgs pair changes with the value of the self-coupling



Top Yukawa coupling at 1.4 TeV





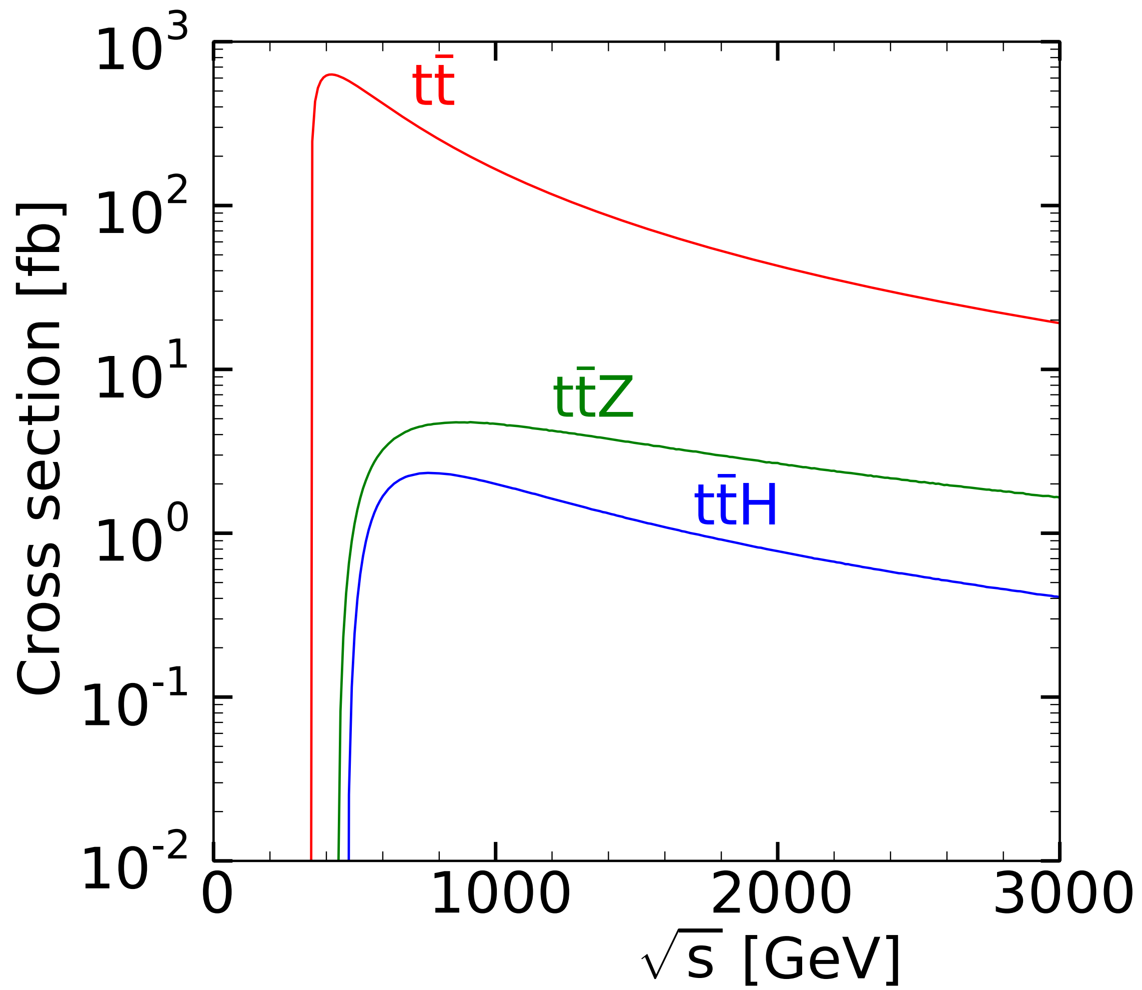
Higgs radiates from top quark

- Sensitive to top Yukawa coupling

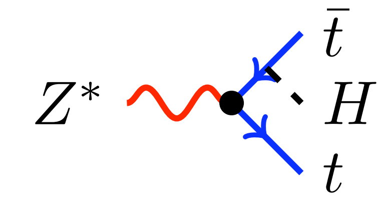
Higgs decay to bb

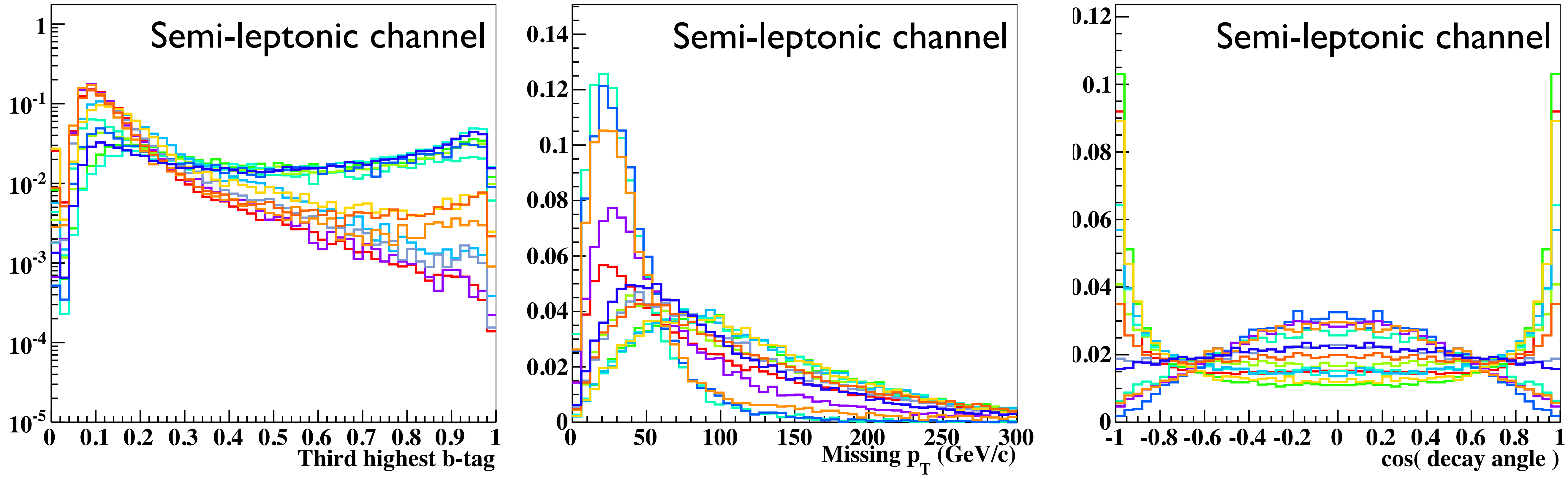
- Eight fermion final state
- Four b jets

- Top: heaviest SM particle, couples most strongly to the Higgs field
- New Physics: could induce sizeable deviation from SM expectation
- Benchmark analysis: final state requires many reconstruction tools, hence comprehensive check of analysis chain and detector performance



Analysis details





Semi-leptonic and fully hadronic channels considered

1) Lepton finding
2) Jet clustering
3) Flavour tagging: 4 b jets!
4) Jet pairing: choose permutation with smallest chi^2:

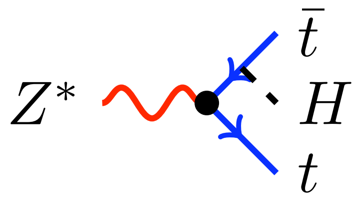
$$\chi^2 = \frac{(M_{12} - M_W)^2}{\sigma_W^2} + \frac{(M_{123} - M_t)^2}{\sigma_t^2} + \frac{(M_{45} - M_h)^2}{\sigma_h^2}$$

5) BDT selection based on discriminating variables

Event samples

- ttH semi-leptonic signal
- tt
- ttbb fully leptonic
- ttbb fully hadronic
- ttbb semi-leptonic
- ttH fully leptonic
- ttH fully leptonic (no bb)
- ttH fully hadronic
- ttH fully hadronic (no bb)
- ttH semi-leptonic (no bb)
- ttZ fully leptonic
- ttZ fully hadronic
- ttZ semi-leptonic

Results and coupling precision

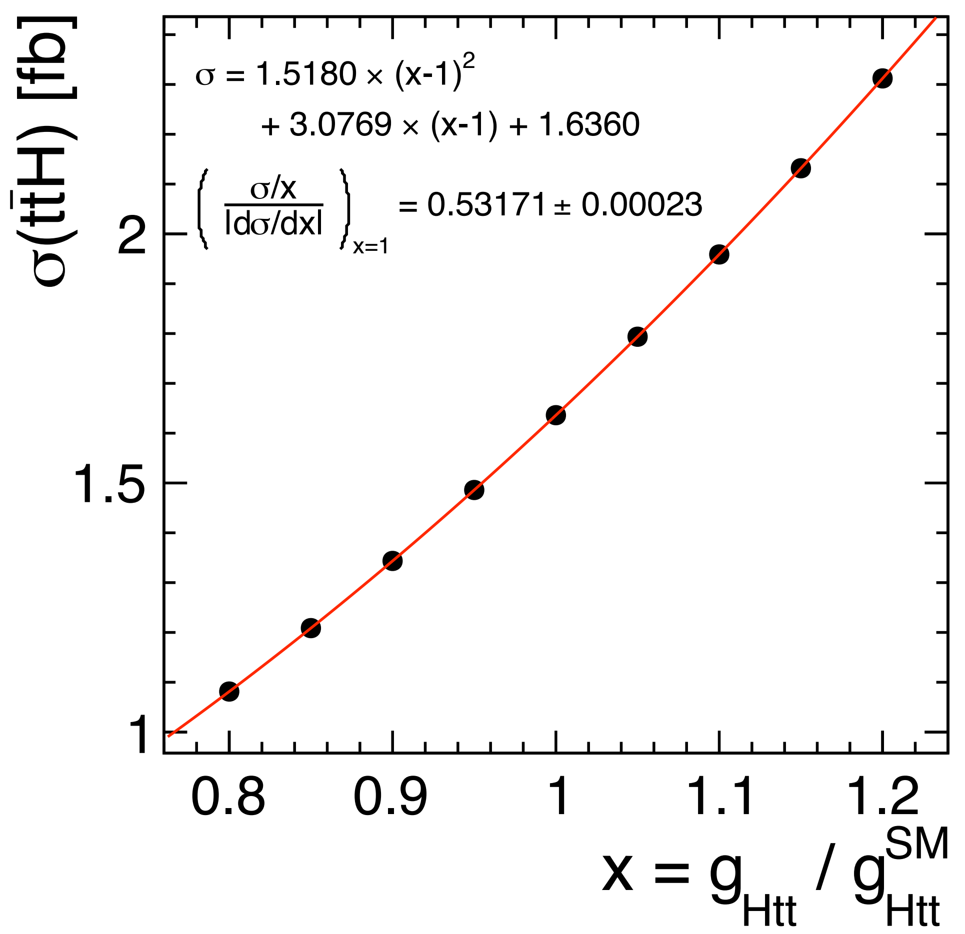


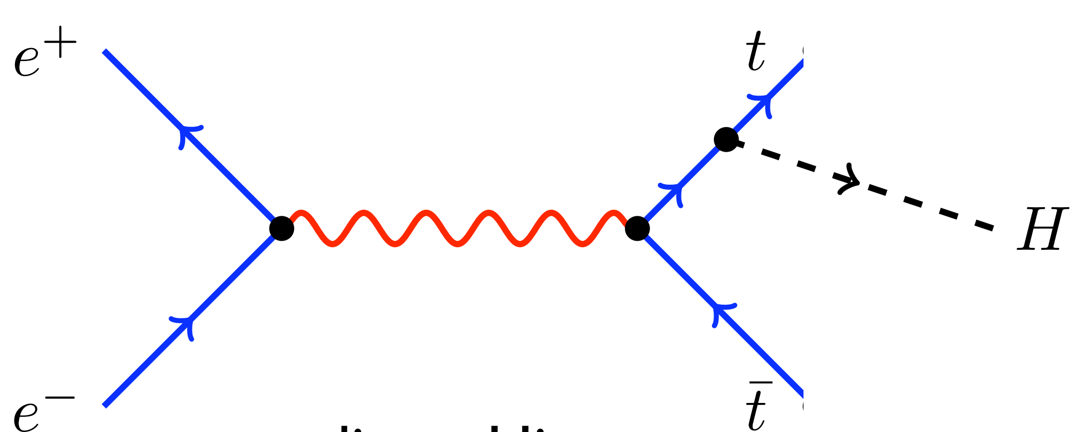
The ttH cross section can be measured with a precision of:

- $\Delta\sigma/\sigma$ = 12.9% in the semi-leptonic channel
- $\Delta\sigma/\sigma$ = 10.4% in the fully hadronic channel
- $\Delta\sigma/\sigma$ (combined) = 8.1% (independent samples)

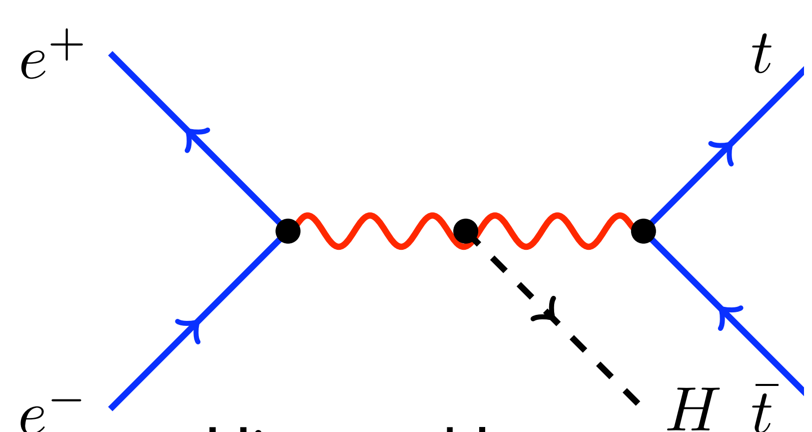
Linear relation between the uncertainty in the cross section and the uncertainty in the top Yukawa coupling:

- $\Delta g_{ttH}/g_{ttH} = 0.53\ \Delta\sigma/\sigma$
- $\Delta g_{ttH}/g_{ttH}$ = 4.3% precision on top Yukawa coupling



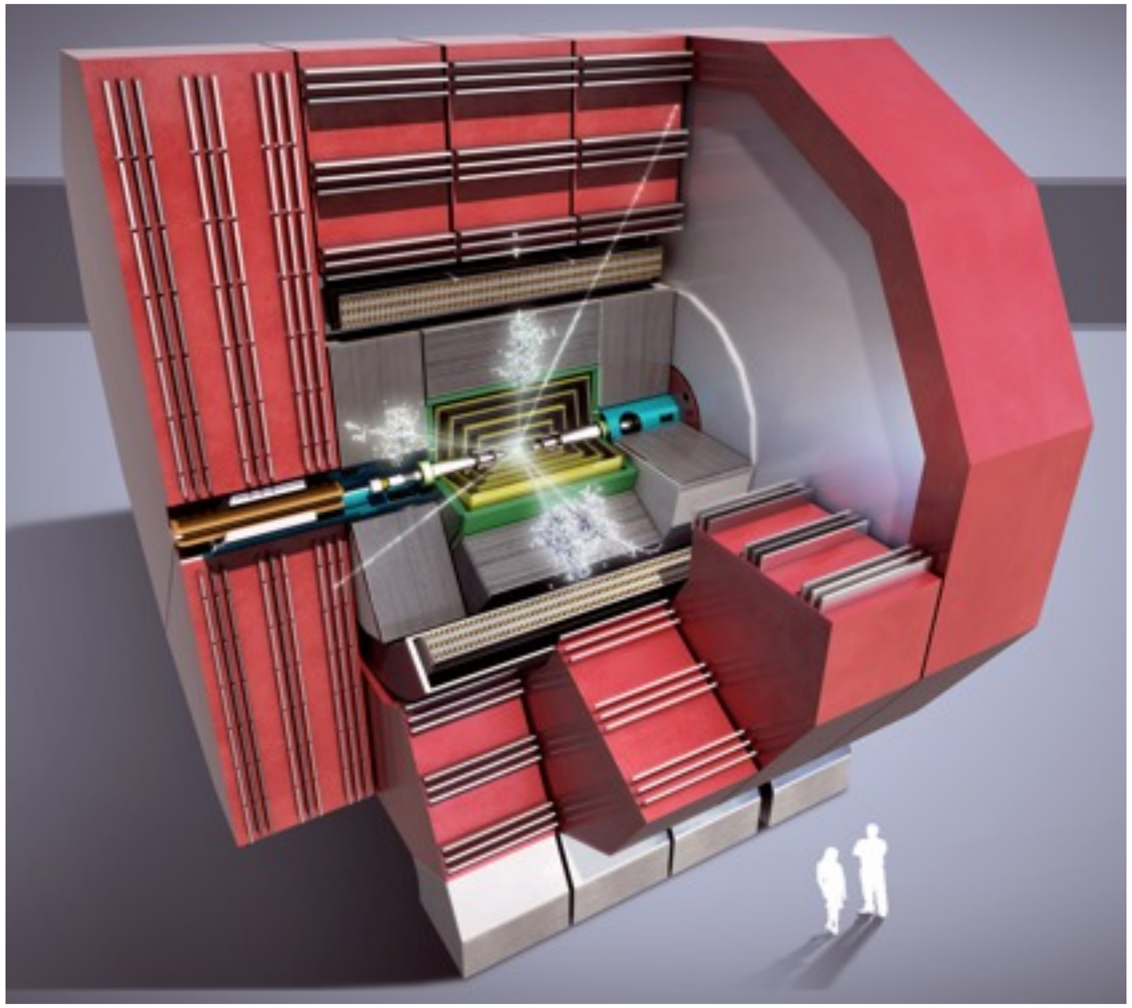


t radiates Higgs
sensitive to top Yukawa coupling



Higgsstrahlung
not sensitive to top Yukawa coupling

Summary



Fully leptonic ttH event in
the CLIC_SiD detector

- ☑ Higgs physics: major area of recent research
- ☑ Contribution to Snowmass submitted
- ☑ CLIC_SiD benchmark processes
- Higgs paper

title

- text

tikz

```
\begin{tikzpicture}
\coordinate (a) at (0,0.4);
\coordinate (b) at (0.6,0.4);
\coordinate (c) at (1,0.8);
\coordinate (d) at (1,0);
\coordinate (e) at (1.6,0.8);
\coordinate (f) at (1.6,0);
\coordinate (g) at (1,0.8);

\draw[higgs] (a) -- (b);
\draw[higgs] (b) -- (c);
\draw[higgs] (b) -- (d);
%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (b) circle (2pt);

\node at ($(a)$) [label={[label distance=-1.5mm] left:$H$}] {};
\node at ($(c)$) [label={[label distance=-1.5mm] right:$H$}] {};
\node at ($(d)$) [label={[label distance=-1.5mm] right:$H$}] {};

\end{tikzpicture}
```

```
% higgsstrahlung
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,0.8);
\coordinate (c) at (0.4,0.4);
\coordinate (d) at (1.0,0.4);
\coordinate (e) at (1.4,0.8);
\coordinate (f) at (1.4,0);
\coordinate (g) at (1.4,0.4);
\coordinate (h) at (1.2,0.6);

\draw[particle] (a) -- (c);
\draw[antiparticle] (b) -- (c);
\draw[photon] (c) -- (d);
\draw[photon] (d) -- (e);
\draw[higgs] (d) -- (f);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);
\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);

\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(e)$) [label={[label distance=-1.5mm] right:$Z$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$H$}] {};

\end{tikzpicture}
```

```
% tth
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,0.8);
\coordinate (c) at (0.4,0.4);
\coordinate (d) at (1.0,0.4);
\coordinate (e) at (1.4,0.8);
\coordinate (f) at (1.4,0);
\coordinate (g) at (1.4,0.4);
\coordinate (h) at (1.2,0.6);

\draw[particle] (a) -- (c);
\draw[antiparticle] (b) -- (c);
\draw[photon] (c) -- (d);
\draw[particle] (d) -- (h);
\draw[particle] (h) -- (e);
\draw[antiparticle] (d) -- (f);
\draw[higgs] (h) -- (g);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);
\fill [black] (h) circle (2pt);
\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(e)$) [label={[label distance=-1.5mm] right:$t$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$\bar{t}$}] {};
\node at ($(g)$) [label={[label distance=-1.5mm] right:$H$}] {};
\end{tikzpicture}
```

```
% WW fusion
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,1.2);
\coordinate (c) at (0.4,0.2);
\coordinate (d) at (0.4,1);
\coordinate (e) at (0.6,0.6);
\coordinate (f) at (1,1.2);
\coordinate (g) at (1,0);
\coordinate (h) at (1,0.6);

\draw[particle] (a) -- (c);
\draw[particle] (c) -- (g);
\draw[antiparticle] (b) -- (d);
\draw[antiparticle] (d) -- (f);
\draw[photon] (c) -- (e);
\draw[photon] (d) -- (e);
\draw[higgs] (e) -- (h);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);
\fill [black] (e) circle (2pt);
\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$\bar{\nu}_{e}$}] {};
\node at ($(g)$) [label={[label distance=-1.5mm] right:$\nu_{e}$}] {};
\node at ($(h)$) [label={[label distance=-1.5mm] right:$H$}] {};
\end{tikzpicture}
```

```
% triple higgs
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,1.2);
\coordinate (c) at (0.4,0.2);
\coordinate (d) at (0.4,1);
\coordinate (e) at (0.6,0.6);
\coordinate (f) at (1,1.2);
\coordinate (g) at (1,0);
\coordinate (h) at (1,0.6);
\coordinate (i) at (1.4,1);
\coordinate (j) at (1.4,0.2);

\draw[particle] (a) -- (c);
\draw[particle] (c) -- (g);
\draw[antiparticle] (b) -- (d);
\draw[antiparticle] (d) -- (f);
\draw[photon] (c) -- (e);
\draw[photon] (d) -- (e);
\draw[higgs] (e) -- (h);
\draw[higgs] (h) -- (i);
\draw[higgs] (h) -- (j);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);
\fill [black] (e) circle (2pt);
\fill [black] (h) circle (2pt);
\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$\bar{\nu}_{e}$}] {};
\node at ($(g)$) [label={[label distance=-1.5mm] right:$\nu_{e}$}] {};
\node at ($(i)$) [label={[label distance=-1.5mm] right:$H$}] {};
\node at ($(j)$) [label={[label distance=-1.5mm] right:$H$}] {};
\end{tikzpicture}
```

```
% quartic higgs
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,1.2
\coordinate (c) at (0.4,0
\coordinate (d) at (0.4,1
\coordinate (e) at (0.6,0
\coordinate (f) at (1,1.2
\coordinate (g) at (1,0);
\coordinate (h) at (1,0.6
\coordinate (i) at (1.4,1
\coordinate (j) at (1.4,0
\coordinate (k) at (1,0.8
\coordinate (l) at (1,0.4

\draw[particle] (a) -- (c
\draw[particle] (c) -- (g
\draw[antiparticle] (b) -
\draw[antiparticle] (d) -
\draw[photon] (c) -- (e);
\draw[photon] (d) -- (e);
\draw[higgs] (e) -- (k);
\draw[higgs] (e) -- (l);

%\draw[antiparticle] (d)
%\draw[particle] (d) -- (
%\draw[photon] (o) -- (e)

\fill [black] (c) circle
\fill [black] (d) circle
\fill [black] (e) circle

\node at ($(a)$) [label={
\node at ($(b)$) [label={
\node at ($(f)$) [label={
\node at ($(g)$) [label={
\node at ($(k)$) [label={
\node at ($(l)$) [label={
\end{tikzpicture}
```

```
\usepackage{tikz}
\usetikzlibrary{decorations.pathreplacing,decorations.pathmorphing,decorations.markings,trees,calc,patterns,snakes}
\tikzset{
photon/.style={decorate, decoration={snake}, draw=red},
particle/.style={draw=blue, postaction={decorate},decoration={markings,mark=at position .5 with {\arrow[draw=blue]{>}}}},
antiparticle/.style={draw=blue, postaction={decorate},decoration={markings,mark=at position .5 with {\arrow[draw=blue]{<}}}},
gluon/.style={decorate, draw=black,decoration={snake,amplitude=4pt, segment length=5pt}},
```

tikz2

```
% gamma gamma
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,1.2);
\coordinate (c) at (0.4,0.2);
\coordinate (d) at (0.4,1);
\coordinate (e) at (0.6,0.6);
\coordinate (f) at (1.6,1.4);
\coordinate (g) at (1.6,-0.2);
\coordinate (h) at (1,0.6);
\coordinate (i) at (1.4,1);
\coordinate (j) at (1.4,0.2);
\coordinate (m) at (1.8,1);
\coordinate (n) at (1.8,0.2);

\draw[particle] (a) -- (c);
\draw[particle] (c) -- (g);
\draw[antiparticle] (b) -- (d);
\draw[antiparticle] (d) -- (f);
\draw[photon] (c) -- (e);
\draw[photon] (d) -- (e);
\draw[higgs] (e) -- (h);
\draw[particle] (h) -- (i);
\draw[antiparticle] (h) -- (j);
\draw[antiparticle] (j) -- (i);
\draw[photon] (i) -- (m);
\draw[photon] (j) -- (n);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);
\fill [black] (e) circle (2pt);
\fill [black] (h) circle (2pt);
\fill [black] (i) circle (2pt);
\fill [black] (j) circle (2pt);

\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$\bar{\nu_{e}}$}] {};
```

```
% h to bb, cc
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,1.2);
\coordinate (c) at (0.4,0.2);
\coordinate (d) at (0.4,1);
\coordinate (e) at (0.6,0.6);
\coordinate (f) at (1.6,1.4);
\coordinate (g) at (1.6,-0.2);
\coordinate (h) at (1,0.6);
\coordinate (i) at (1.4,1);
\coordinate (j) at (1.4,0.2);
\coordinate (m) at (1.8,1);
\coordinate (n) at (1.8,0.2);

\draw[particle] (a) -- (c);
\draw[particle] (c) -- (g);
\draw[antiparticle] (b) -- (d);
\draw[antiparticle] (d) -- (f);
\draw[photon] (c) -- (e);
\draw[photon] (d) -- (e);
\draw[higgs] (e) -- (h);
\draw[particle] (h) -- (i);
\draw[antiparticle] (h) -- (j);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);
\fill [black] (e) circle (2pt);
\fill [black] (h) circle (2pt);

\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$\bar{\nu_{e}}$}] {};
\node at ($(g)$) [label={[label distance=-1.5mm] right:$\nu_{e}$}] {};
\node at ($(i)$) [label={[label distance=-1.5mm] right:$b$}] {};
\node at ($(j)$) [label={[label distance=-1.5mm] right:$\bar{b}$}] {};
\end{tikzpicture}
```

```
% two H final state
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,1.2);
\coordinate (c) at (0.4,0.2);
\coordinate (d) at (0.4,1);
\coordinate (e) at (0.6,0.6);
\coordinate (f) at (1,1.2);
\coordinate (g) at (1,0);
\coordinate (h) at (1,0.6);
\coordinate (i) at (1.4,1);
\coordinate (j) at (1.4,0.2);
\coordinate (k) at (1,0.8);
\coordinate (l) at (1,0.4);
\coordinate (o) at (0.6,0.8);
\coordinate (p) at (0.6,0.4);
\coordinate (q) at (1,0.8);
\coordinate (r) at (1,0.4);

\draw[particle] (a) -- (c);
\draw[particle] (c) -- (g);
\draw[antiparticle] (b) -- (d);
\draw[antiparticle] (d) -- (f);
\draw[photon] (c) -- (p);
\draw[photon] (p) -- (o);
\draw[photon] (o) -- (d);
\draw[higgs] (o) -- (q);
\draw[higgs] (p) -- (r);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);

\fill [black] (c) circle (2pt);
\fill [black] (d) circle (2pt);
\fill [black] (o) circle (2pt);
\fill [black] (p) circle (2pt);

\node at ($(a)$) [label={[label distance=-1.5mm] left:$e^{-}$}] {};
\node at ($(b)$) [label={[label distance=-1.5mm] left:$e^{+}$}] {};
\node at ($(f)$) [label={[label distance=-1.5mm] right:$\bar{\nu_{e}}$}] {};
\node at ($(g)$) [label={[label distance=-1.5mm] right:$\nu_{e}$}] {}
```

```
% tth 8 fermions
\begin{tikzpicture}
\coordinate (a) at (0,0);
\coordinate (b) at (0,0.8);
\coordinate (c) at (0.4,0.4);
\coordinate (d) at (1.0,0.4);
\coordinate (e) at (1.4,0.8);
\coordinate (f) at (1.4,0);
\coordinate (g) at (1.6,0.4);
\coordinate (h) at (1.2,0.6);
\coordinate (i) at (1.8,1.2);
\coordinate (j) at (2.0,0.8);
\coordinate (k) at (2.0,0.6);
\coordinate (l) at (2.0,0.2);
\coordinate (m) at (2.0,0);
\coordinate (n) at (1.8,-0.4);
\coordinate (o) at (2.4,1);
\coordinate (p) at (2.4,0.6);
\coordinate (q) at (2.4,0.2);
\coordinate (r) at (2.4,-0.2);

\draw[particle] (a) -- (c);
\draw[antiparticle] (b) -- (c);
\draw[photon] (c) -- (d);
\draw[particle] (d) -- (h);
\draw[particle] (h) -- (e);
\draw[antiparticle] (d) -- (f);
\draw[higgs] (h) -- (g);
\draw[particle] (e) -- (i);
\draw[photon] (e) -- (j);
\draw[antiparticle] (f) -- (n);
\draw[photon] (f) -- (m);
%\draw[particle] (g) -- (k);
%\draw[antiparticle] (g) -- (l);
\draw[particle] (j) -- (o);
\draw[antiparticle] (j) -- (p);
\draw[particle] (m) -- (q);
\draw[dntiparticle] (m) -- (r);

%\draw[antiparticle] (d) -- (f);
%\draw[particle] (d) -- (o);
%\draw[photon] (o) -- (e);
```