H→WW* at 1.4 TeV

and a first look at HZ→Hqq at 350 GeV

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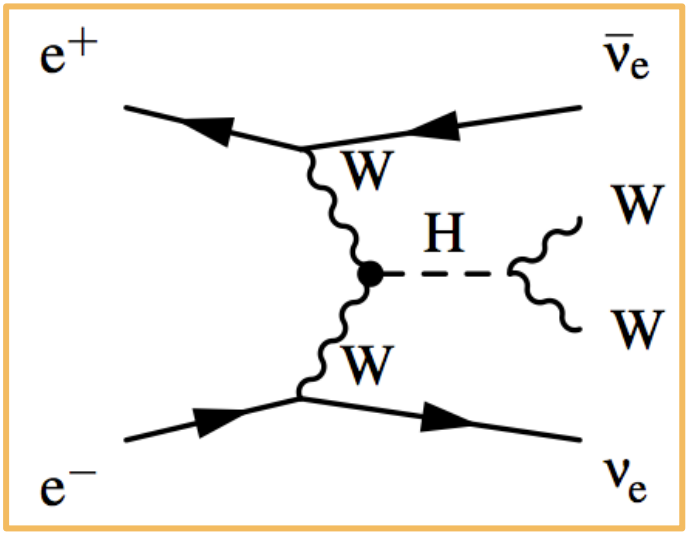
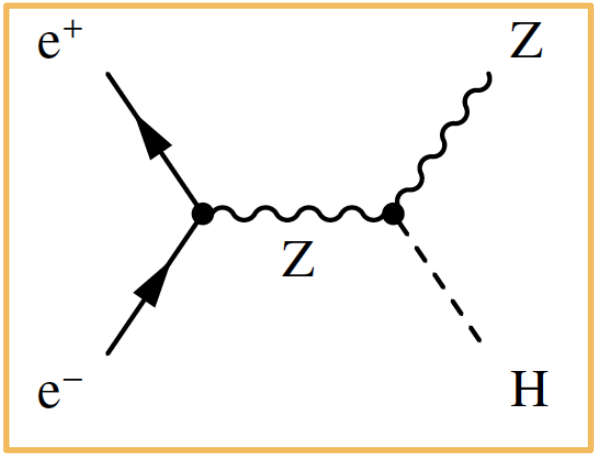
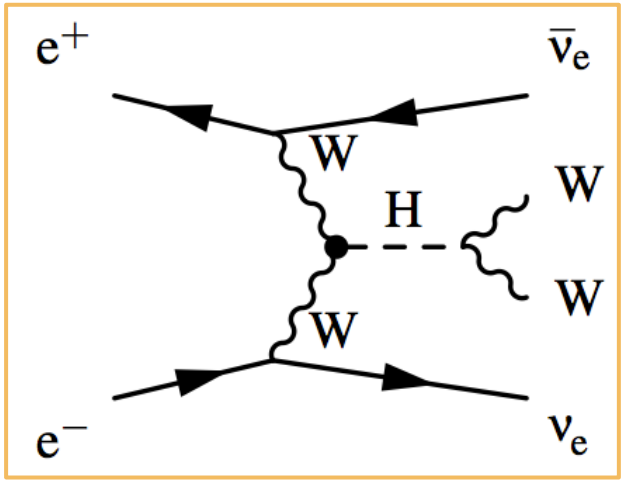




Introduction

★ **Study fusion process** $e^+e^- \to \nu_e\bar{\nu}_e H \to \nu_e\bar{\nu}_e WW$ **at 1.4 TeV**



- **Sensitive to**

$$\sigma \propto g^4_{HWW}/\Gamma_H$$

- **Both W-bosons quite soft, typically 50-400 GeV and 20-200 GeV**

★ **Three possible WW decay topologies:**

$WW \to \ell\nu\ell\nu$ **~10 %**

$WW \to qq\ell\nu$ **~45 %**

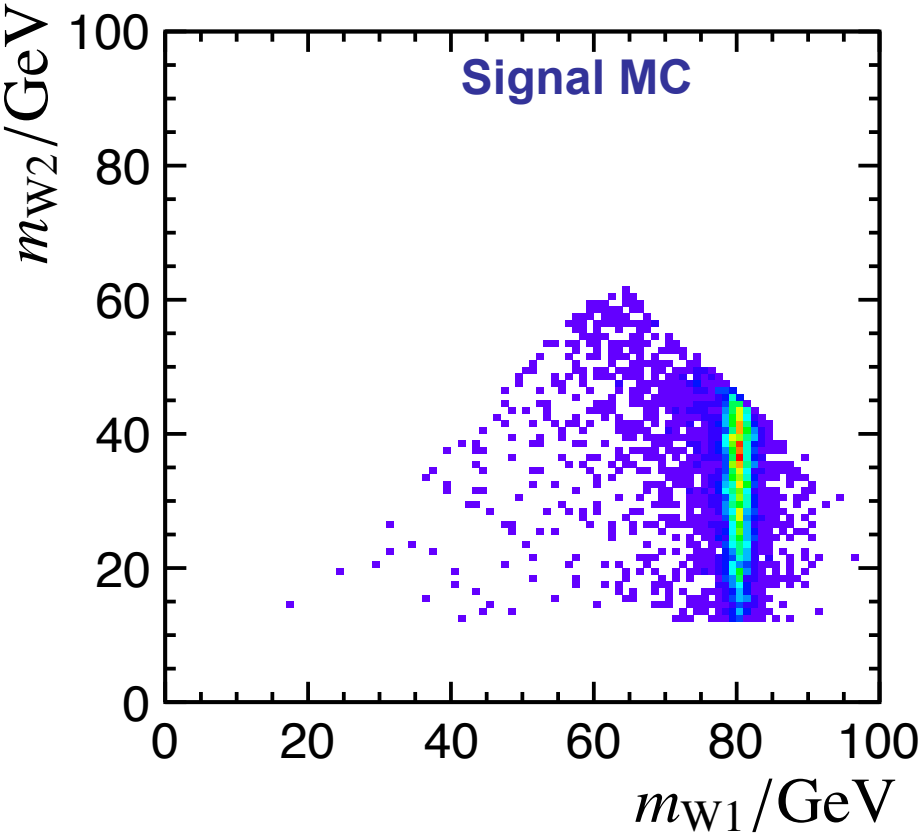
$WW \to qqqq$ **~45 %**

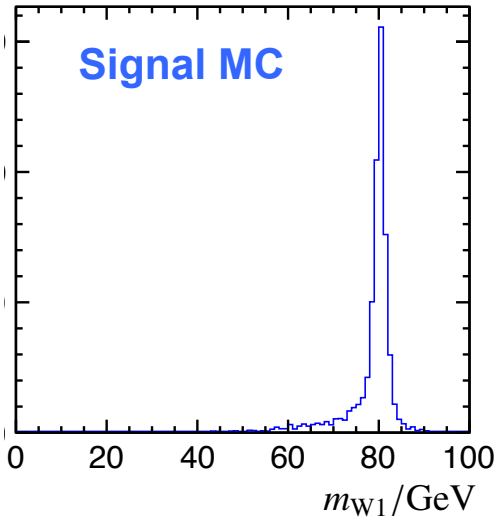
★ **Here only consider fully-hadronic final state**

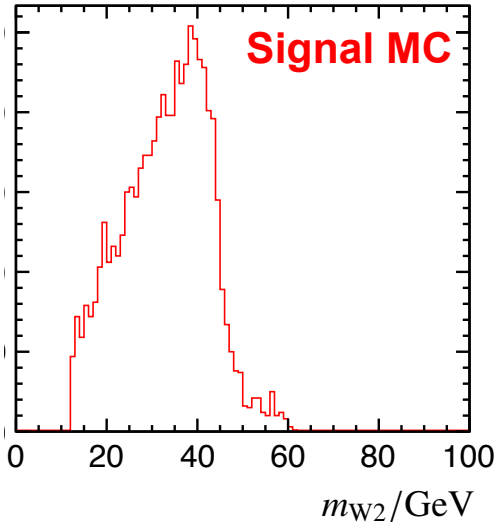
- **Favourable BR and relatively clear topology**

MC Invariant Masses

- **Signal : 4 jets – can reconstruct masses of both Ws** $H \to WW^*$
  - **But one is off-shell**
    - **not so useful in selection**

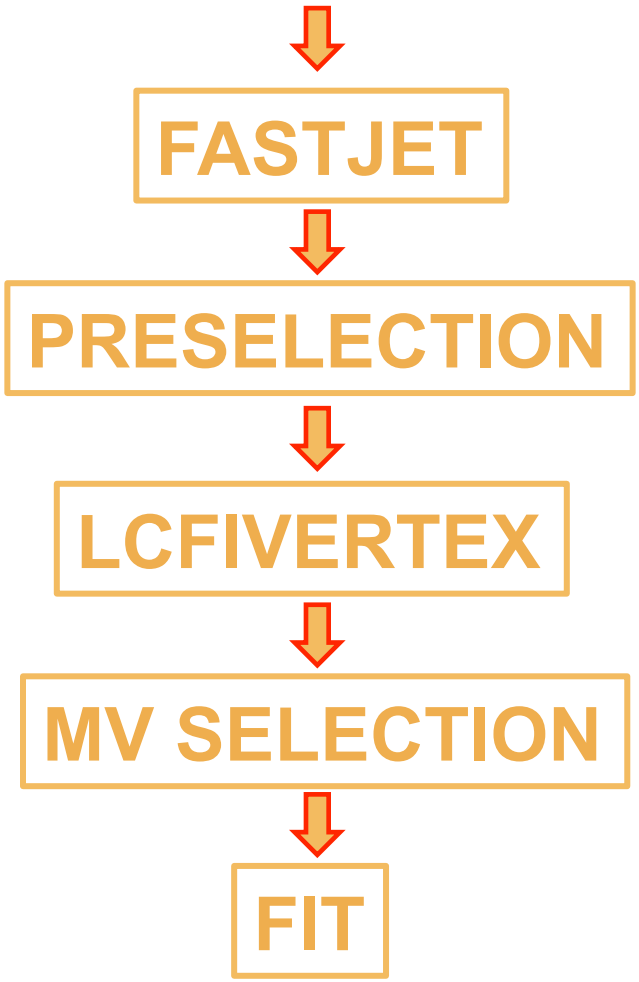






Analysis Strategy

★ **Analysis proceeds in several distinct steps**



- **Force events into 2 and 4 jet**
- **k_T exclusive, SELECTEDPFOs, R=1.0**

- **Cuts to reject large cross section backgrounds, e.g. qq & qqqq**

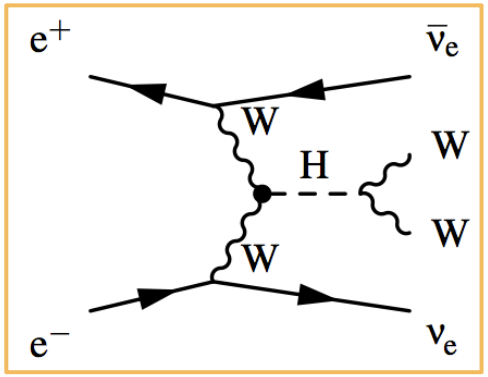
- **Apply b-tag/c-tag to 2 jet hypothesis**
- **NNs not yet trained on specific sample**

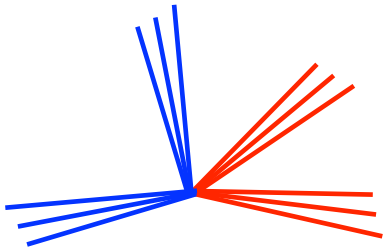
- **Multivariate analysis. Likelihood based (using uncorrelated variables)**

- **TMinuit fit to extract cross section x BR**

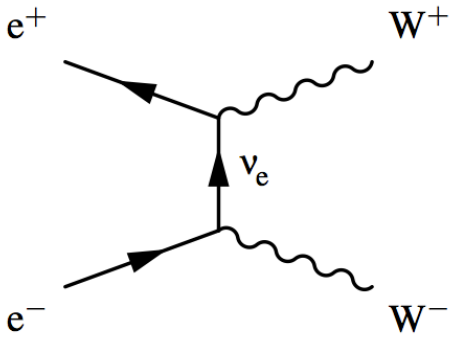
Preselection

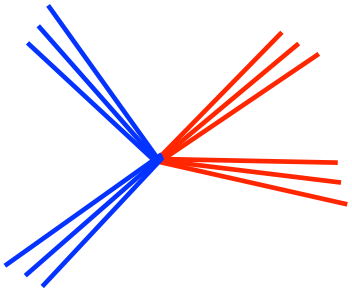
★ **Preselection targeted at main background processes**

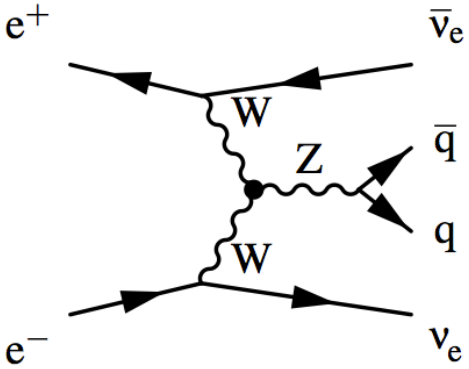


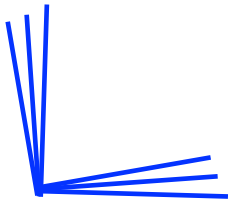


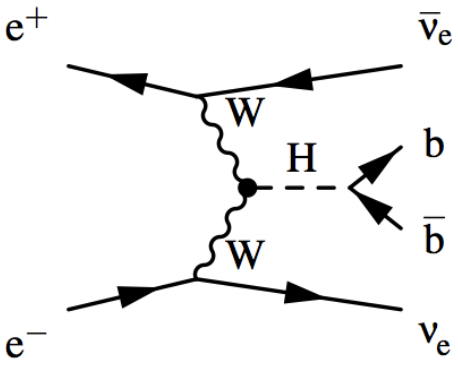
Signal

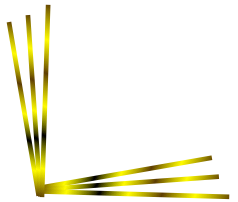








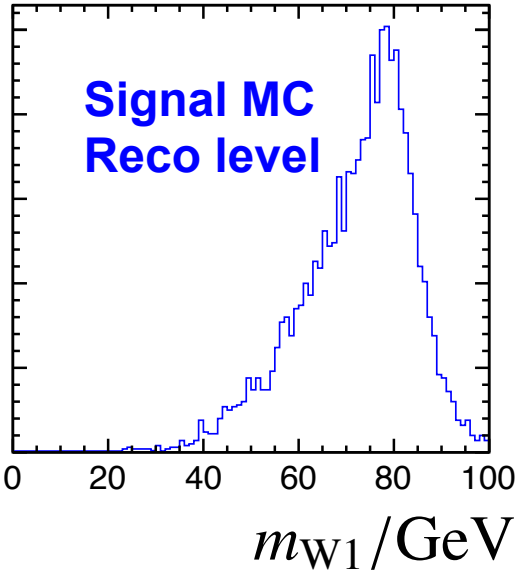


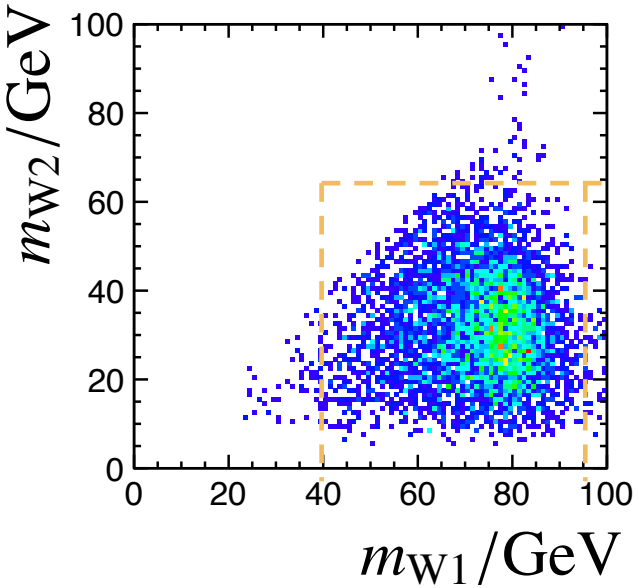


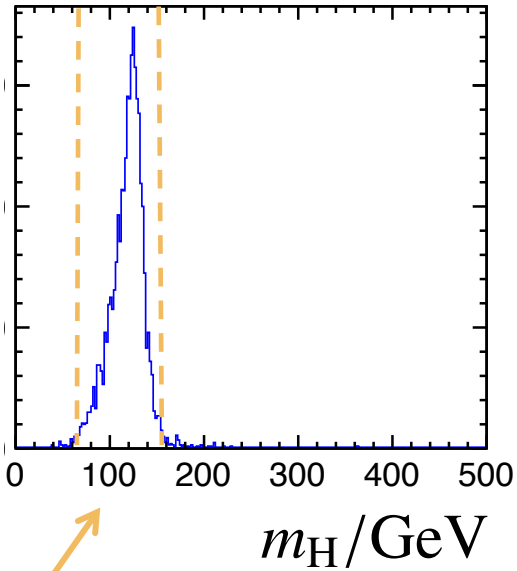
Higgs background

W-mass and H-mass

- **W mass reconstruction not trivial**
  - **Soft & forward jets**
  - **Event boosted, so jets from different Ws overlap**







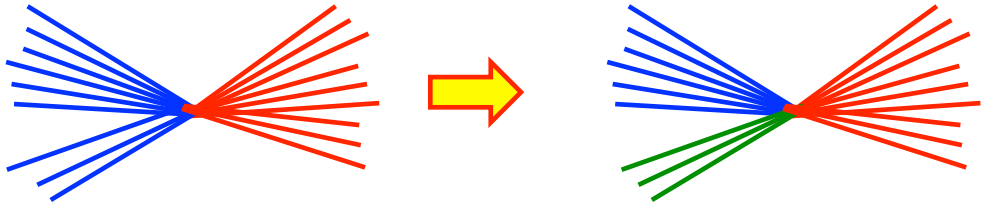
$$40\,\text{GeV} < m_{W1} < 95\,\text{GeV}$$

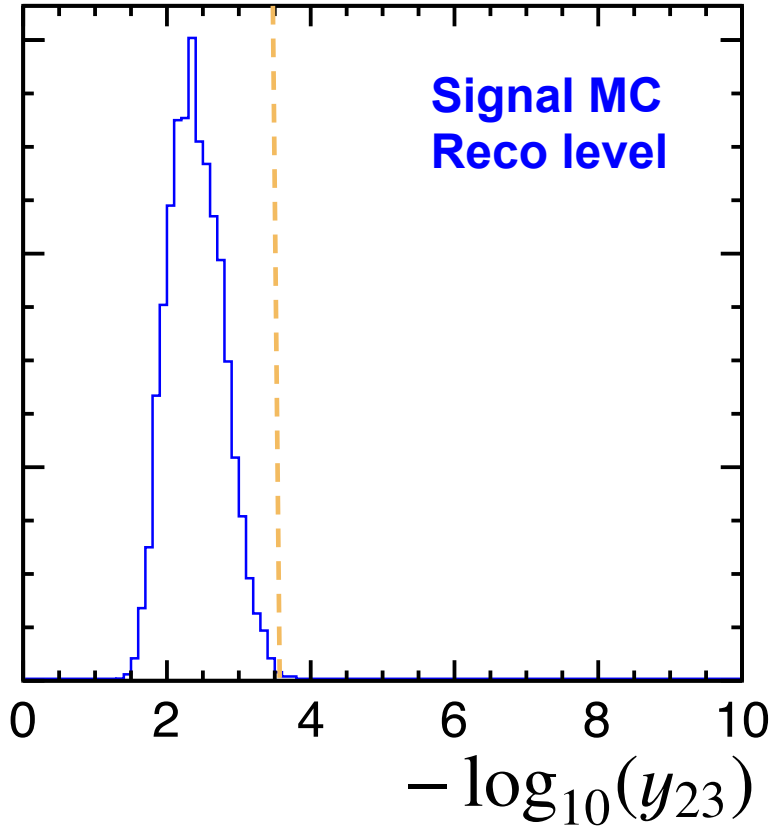
$$m_{W2} < 65\,\text{GeV}$$

$$65\,\text{GeV} < m_H < 155\,\text{GeV}$$

Number of Jets

★ Require event to have more than two jets
- cut on y_{23}: the k_T value at which the event transitions from 2 jets to 3 jets





★ Also use y_{34}, the k_T value at which the event transitions from 3 jets to 4 jets

$$-\log_{10}(y_{23}) < 2.75$$

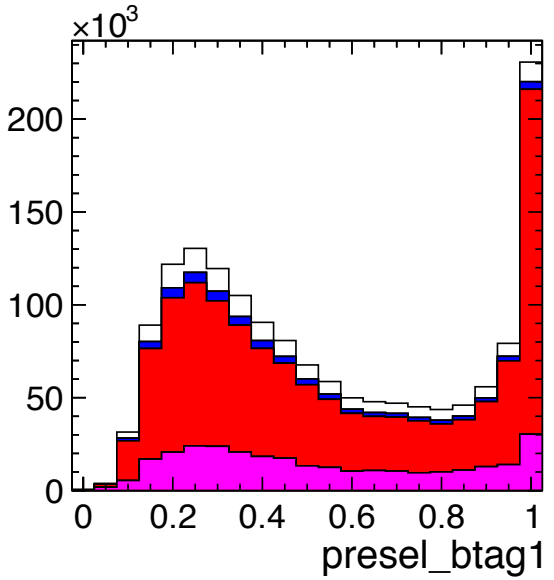
$$-\log_{10}(y_{34}) < 3.5$$

B-tagging

- Trying to reject **H → bb** decays
  - Force event into two jets and cut on b-tag probabilities for both jets
- Reject events with
  - At least one clear b-tagged jet

$$P(\mathrm{b})_{\mathrm{jet}\,1} < 0.95$$

$$P(\mathrm{b})_{\mathrm{jet}\,2} < 0.95$$



+ $100\,\mathrm{GeV} < E_{\mathrm{vis}} < 600\,\mathrm{GeV}$

$|\cos\theta_{\mathrm{mis}}| < 0.99$

$p_{\mathrm{T}} > 40\,\mathrm{GeV}$

$E_{\mathrm{lepton}} < 30\,\mathrm{GeV}$

After Preselection

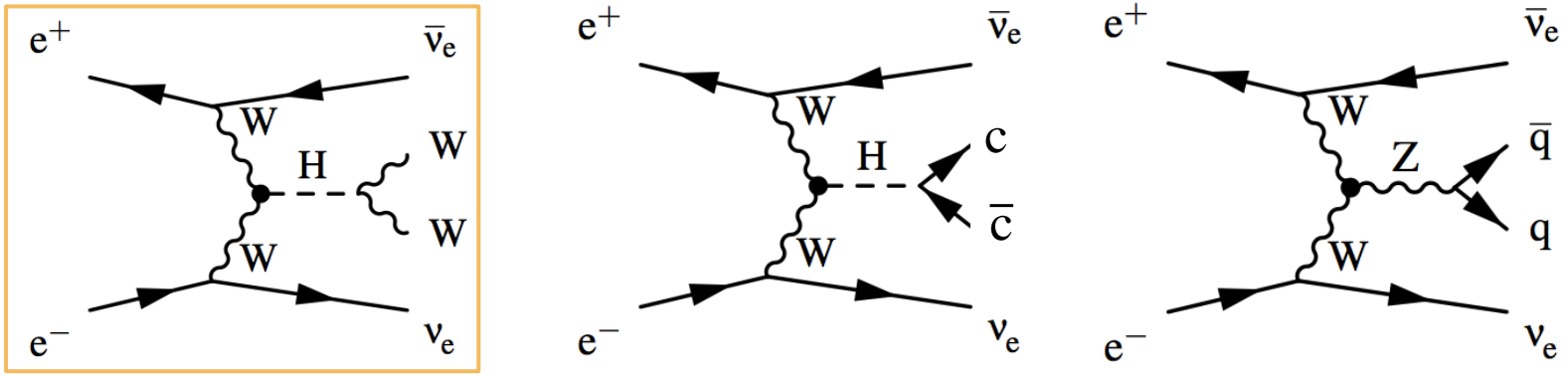
Process	ID	σ/fb	Presel	σ_{PRE}/fb
Hvv WW*	2022	27.6	59 %	16.2
Hvv Back.	2022	216.5	9.0 %	19.5
qq	2091	4009.5	0.1 %	3.5
qqqq	2163	1328.1	0.2 %	2.9
qqqqll	2166	71.7	0.5 %	0.4
qqqqlv	2169	115.3	0.2 %	0.2
qqqqvv	2152	24.7	1.7 %	0.4
qqvv	2199	788.0	13 %	99.7

★ **Main backgrounds:**

- **Hvv → cc vv and Hvv → gg vv**
- **qqvv which is dominated by Zvv → qq vv**

Event Selection

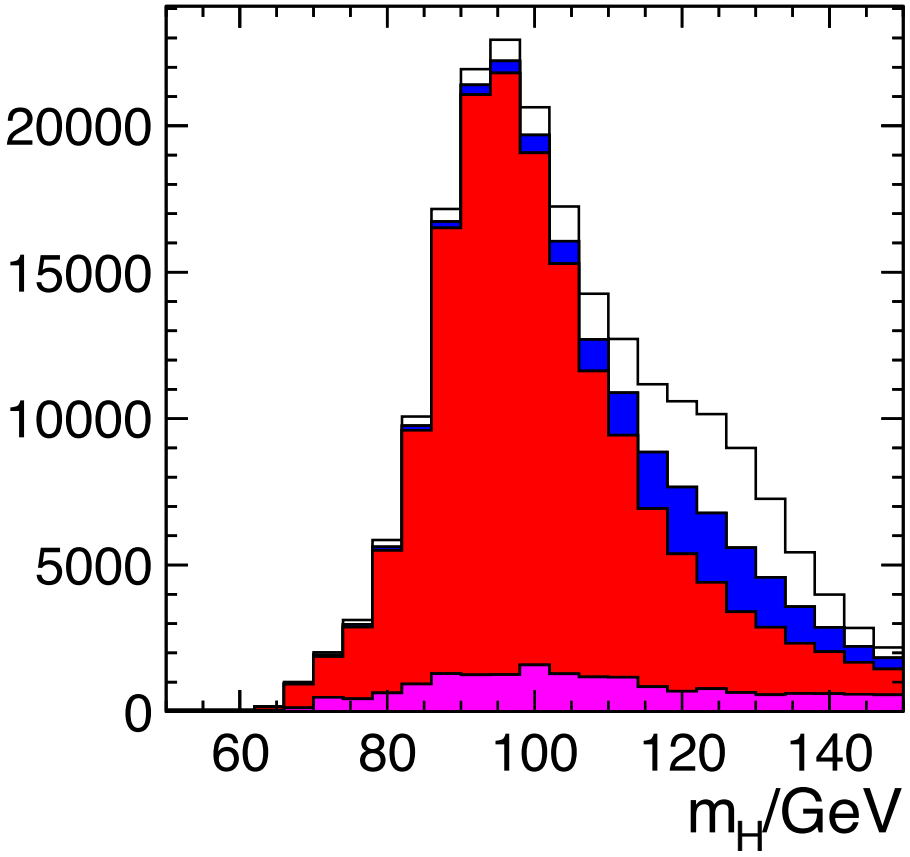
- ★ After preselection most difficult backgrounds are
  - Hνν → qqνν
  - qqνν which is dominated by Zνν → qqνν
- ★ Kinematically almost identical to signal
  - e.g. same/similar E_{vis} and p_T distributions

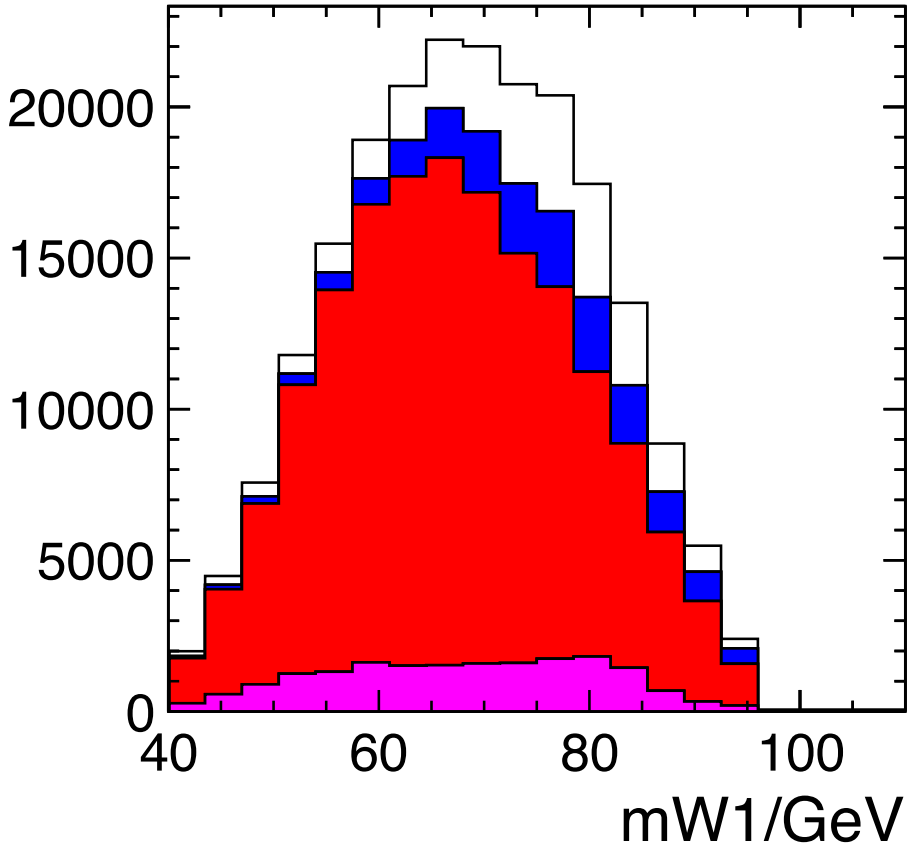


- ★ Selection based on just a few variables
  - m_H and m_W
  - 4-jet likeness, y_{23} and y_{34}
  - b-tagging: $P(b)_1$ and $P(b)_2$

Input variables: e.g. mass

★ **NOTE: plots normalised to 1.5 ab^{-1}**





WHITE = SIGNAL, BLUE = Higgs background, RED = qqvv, MAGENTA = other

Relative Likelihood

- ★ Use relative likelihood selection
- ★ Input variables
  - m_{H} *vs.* m_{W_1}
  - y_{23} *vs.* y_{34}
  - $P(\mathrm{b})_1$ *vs.* $P(\mathrm{b})_2$

Calculate absolute likelihood for given event type

$$L = P(m_{\mathrm{H}}, m_{\mathrm{W}}) \times P(y_{23}, y_{34}) \times P(b_1, b_2)$$

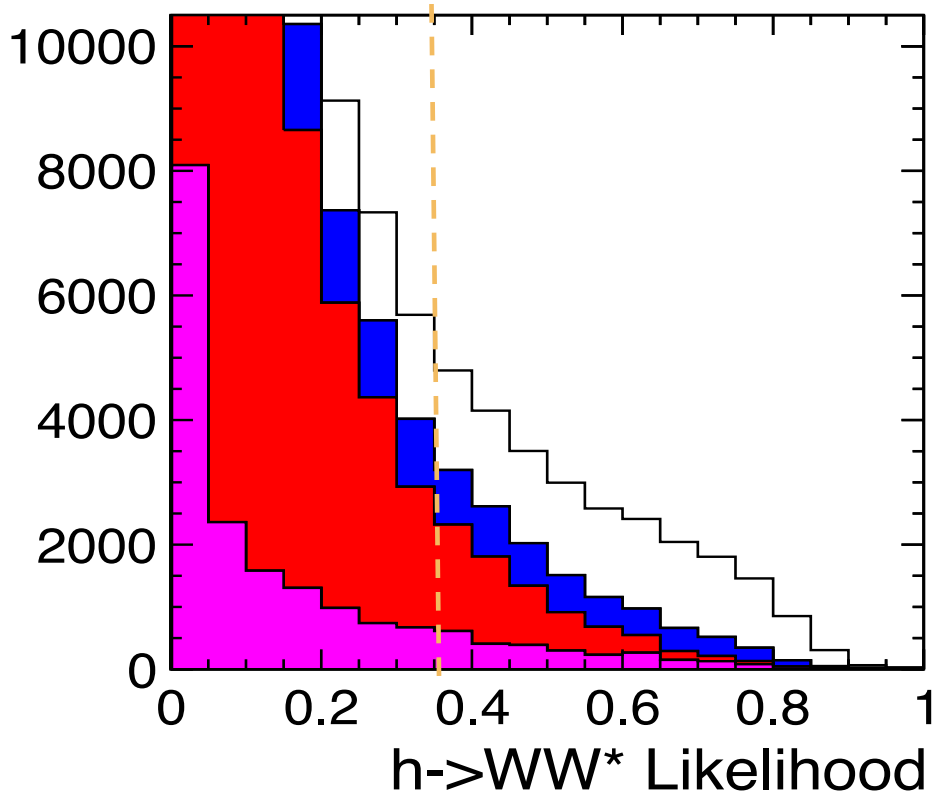
NOTE: 2D distributions – include main correlations

- ★ Absolute likelihoods calculated for four main event types:
- ★ Combined into relative likelihood

$$\mathcal{L}(\mathrm{H} \to \mathrm{WW}^*) = \frac{L(\mathrm{WW}^*)}{L(\mathrm{WW}^*) + L(\mathrm{c\bar{c}}) + L(\mathrm{gg}) + L(\mathrm{q\bar{q}\nu\bar{\nu}})}$$

Putting it all together

$$\mathcal{L}(\mathrm{H} \to \mathrm{WW}^*) = \frac{L(\mathrm{WW}^*)}{L(\mathrm{WW}^*) + L(\mathrm{c\bar{c}}) + L(\mathrm{gg}) + L(\mathrm{q\bar{q}\nu\bar{\nu}})}$$



WHITE = SIGNAL,
BLUE = Higgs back,
RED = qqvv,
MAGENTA = other

- ★ **If a cut were used…**
- ★ **Optimal value**
  - **L > 0.35**

Simple L>0.35 Selection

Process	ID	σ/fb	Presel	σ_{PRE}/fb	σ_{CUT}/fb
Hvv WW*	2022	27.6	59 %	16.2	8.5
Hvv Back.	2022	216.5	9.0 %	19.5	4.5
qq	2091	4009.5	0.1 %	3.5	0.1
qqqq	2163	1328.1	0.2 %	2.9	0.6
qqqqll	2166	71.7	0.5 %	0.4	0.2
qqqqlv	2169	115.3	0.2 %	0.2	0.1
qqqqvv	2152	24.7	1.7 %	0.4	0.2
qqvv	2199	788.0	13 %	99.7	3.8

★ **For this cut value**

- **S/N = 1:1**
- **Main backgrounds qqvv and other Higgs decay**

But… Higgs backgrounds

H Decay	σ/fb	Presel	σ_{PRE}/fb	σ_{CUT}/fb
WW* (qqqq)	27.6	59 %	16.19	8.54
ZZ*	7.4	24 %	1.81	0.65
WW* (qqlv/lvlv)	32.5	13 %	4.36	0.51
qq	141.0	5 %	6.85	1.27
gg	16.4	36 %	5.90	1.99
$\gamma\gamma/\tau\tau$	19.2	3 %	0.57	0.07

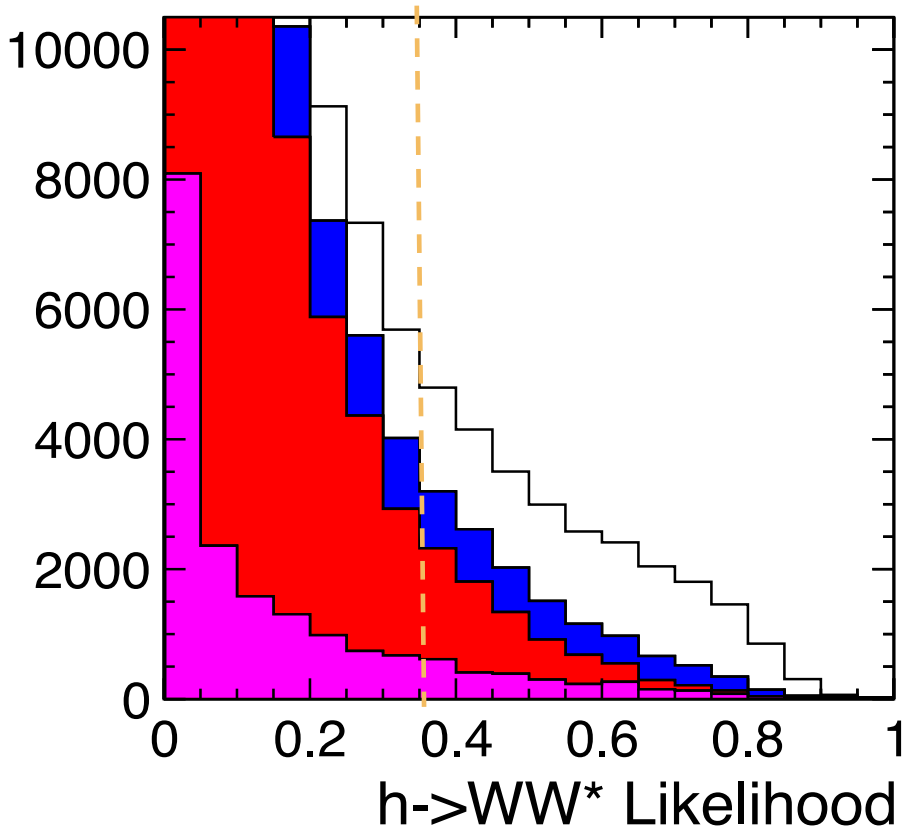
★ **A few important things to note**

- **ZZ* → qqqq is almost indistinguishable from WW* → qqqq (efficiency not all that different 24 % c.f. 31 %)**
- **Overall selection also sensitive to Higgs BRs to cc and gg**

Need to allow other Higgs decays to vary in BR extraction

Fitting

- **Rather than a simple cut**
  - **Fit likelihood distribution, varying contributing components**



WHITE = SIGNAL,
BLUE = Higgs back,
RED = qqvv,
MAGENTA = other

- **NOTE: Signal and Higgs background shapes not so different**

Constrained Fit

- ★ **Since signal and Higgs background shapes not so different**
  - **Need additional information**
- ★ **Constrain Higgs to qq and gg BRs using results from 1.4 TeV Higgs to bb, cc, gg analysis**

$$\chi^2 \to \chi^2 + \frac{(1-s_{gg})^2}{\sigma^2_{gg}} + \frac{(1-s_{c\bar{c}})^2}{\sigma^2_{c\bar{c}}} + \frac{(1-s_{b\bar{b}})^2}{\sigma^2_{b\bar{b}}}$$

$$\sigma^2_{gg} = 1.8\,\%$$
$$\sigma^2_{c\bar{c}} = 2.9\,\%$$
$$\sigma^2_{b\bar{b}} = 0.3\,\%$$

FIT

	σ x BR
WW*	**1.1 %**
gg	1.8 %
cc	2.9 %
bb	0.3 %
back	0.3 %

Largely uncorrelated

WW* Summary

- ★ Analysis mostly complete
- ★ Still need to include $e\gamma$ backgrounds

★ For Snowmass: sensitivity at 3 TeV is an extrapolation of 1.4 TeV study using updated cc, bb, gg BRs

★Results:

1.5 fb^{-1} @ 1.4 TeV

$$\frac{\Delta\sigma}{\sigma} = 1.1\,\%$$

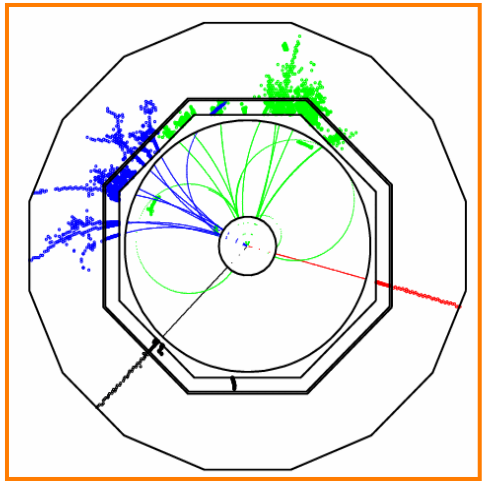
2.0 fb^{-1} @ 3.0 TeV

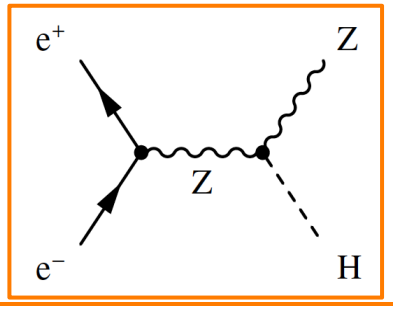
$$\frac{\Delta\sigma}{\sigma} \sim 0.8\,\%$$

Towards a Nearly Model Independent Higgs Recoil Analysis

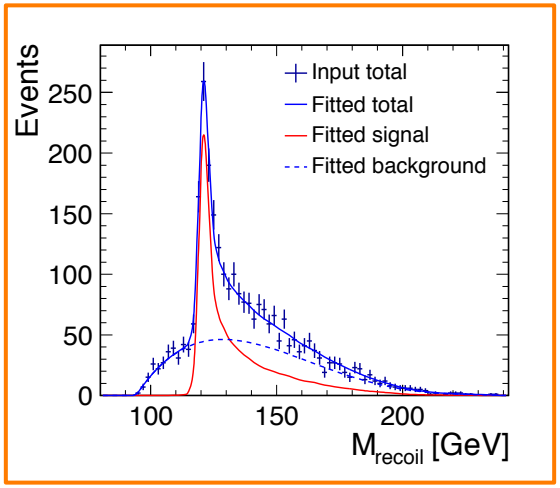
Recall Recoil Mass Method

★ Identify HZ events from decay of Z to leptons alone





★ **Model independent analysis**
- Select Higgs from mass recoiling against leptonically decaying Z
- Measure Higgs BRs



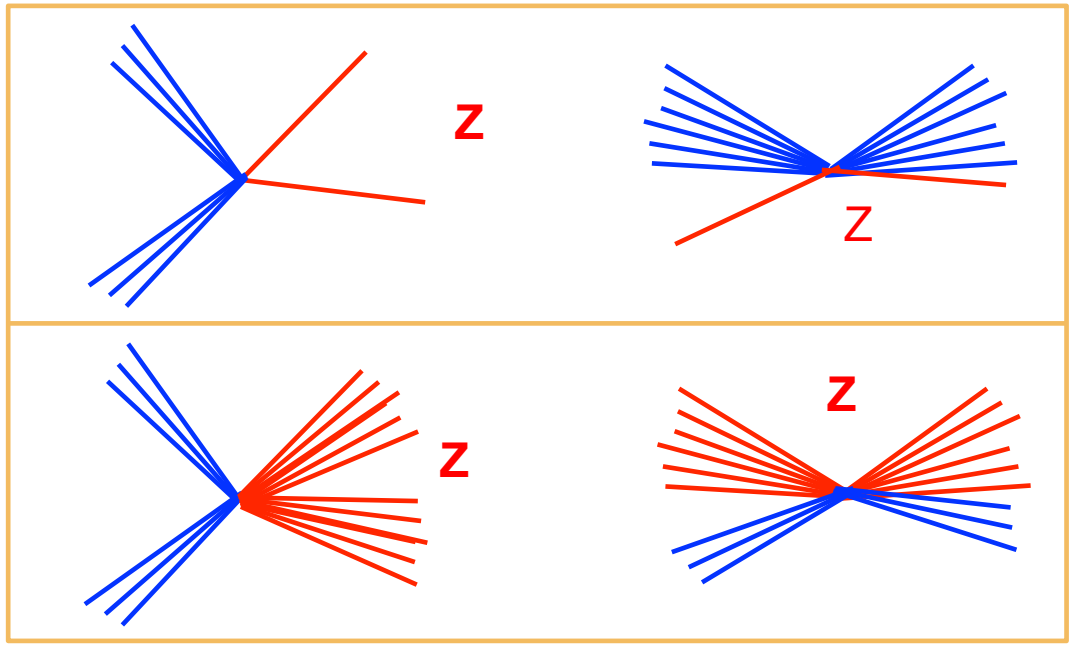
★ Measure Higgs production cross section independent of Higgs decay
- Sensitive to invisible Higgs decay modes
- Absolute measurement of HZ coupling

★ e.g. 350 fb^{-1} at $\sqrt{s}$ = 350 GeV

$$\frac{\Delta(\sigma)}{\sigma} \sim 4\,\% \quad \Rightarrow \quad \frac{\Delta(g_{HZZ})}{g_{HZZ}} \sim 2\,\%$$

But…

- ★ Only done (possible?) for $Z \to \mu\mu$ and $Z \to ee$
- ★ Statistical precision limited by BRs of 3.5 % and 3.5 %
- ★ Extend to $Z \to qq$ ~ 60 % of Z decays
- ★ Strategy – identify $Z \to qq$ decays and look at recoil mass
- ★ Can never be truly model independent:
  - unlike for $Z \to \mu\mu$ can't cleanly separate H and Z decays



Muons "always" obvious

Here jet finding blurs separation between H and Z

Different efficiencies for different Higgs decays

Carry on regardless…

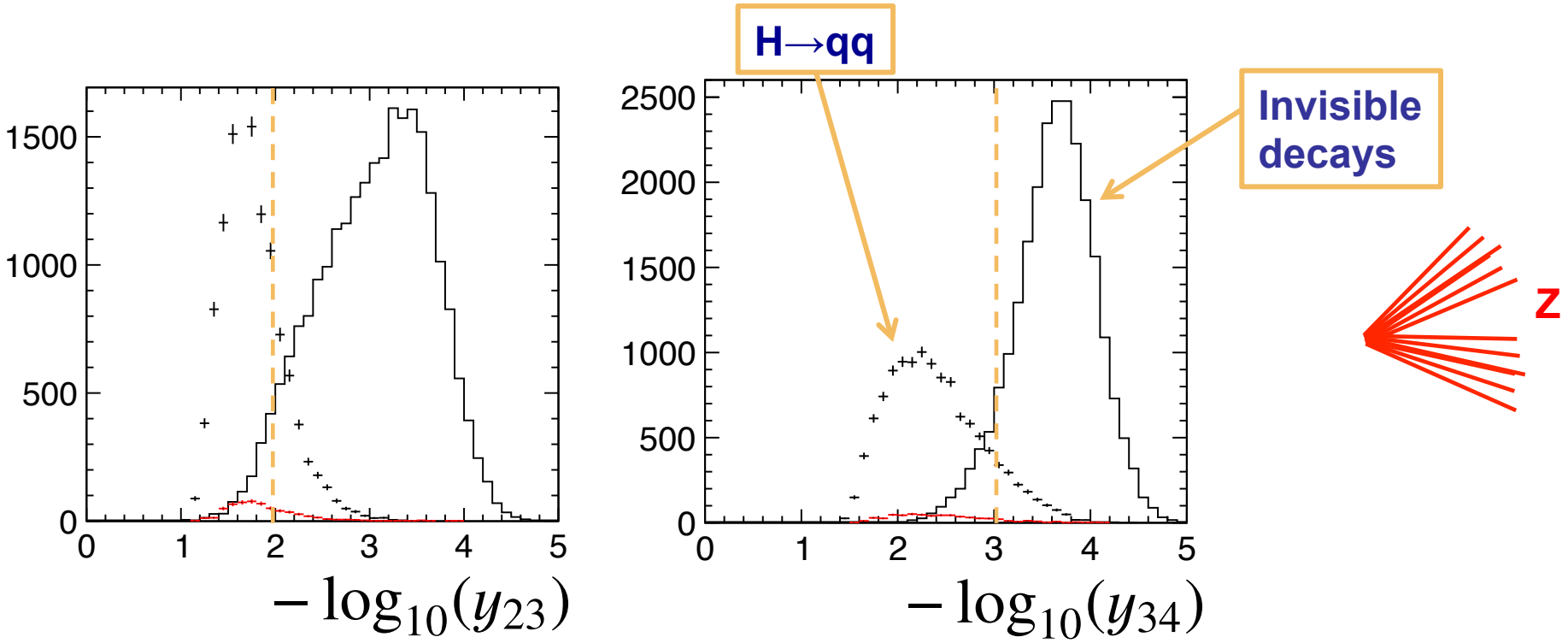
- ★ Important point, Higgs can either decay invisibly or visibly
- ★ For Z→qq decays either
  - two jets or two jets + at least two other particles

Analysis strategy:

- ★ Force events into 2-, 3-, 4-, 5- and 6- "jet" topologies (R=1.5)
  - For each topology:
    - find two jets (> 3 tracks) most consistent with Z mass
    - determine mass of system recoiling against the candidate Z

First divide into candidate invisible and visible Higgs decays

Invisible Higgs Decays



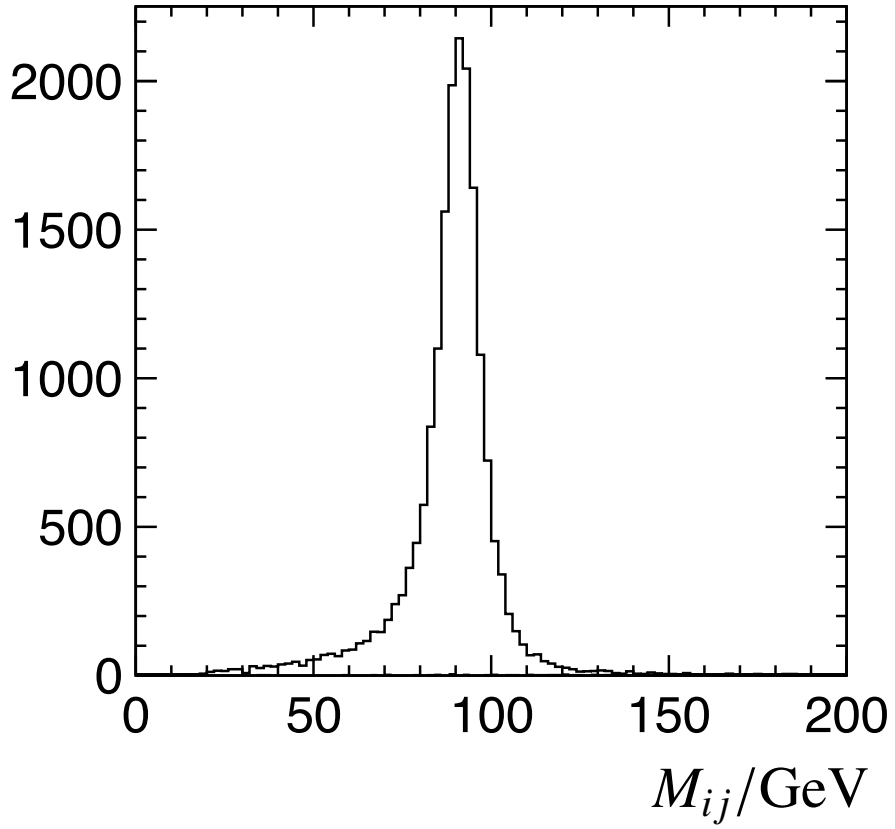
$$-\log_{10}(y_{23}) > 2$$
$$-\log_{10}(y_{34}) > 3$$

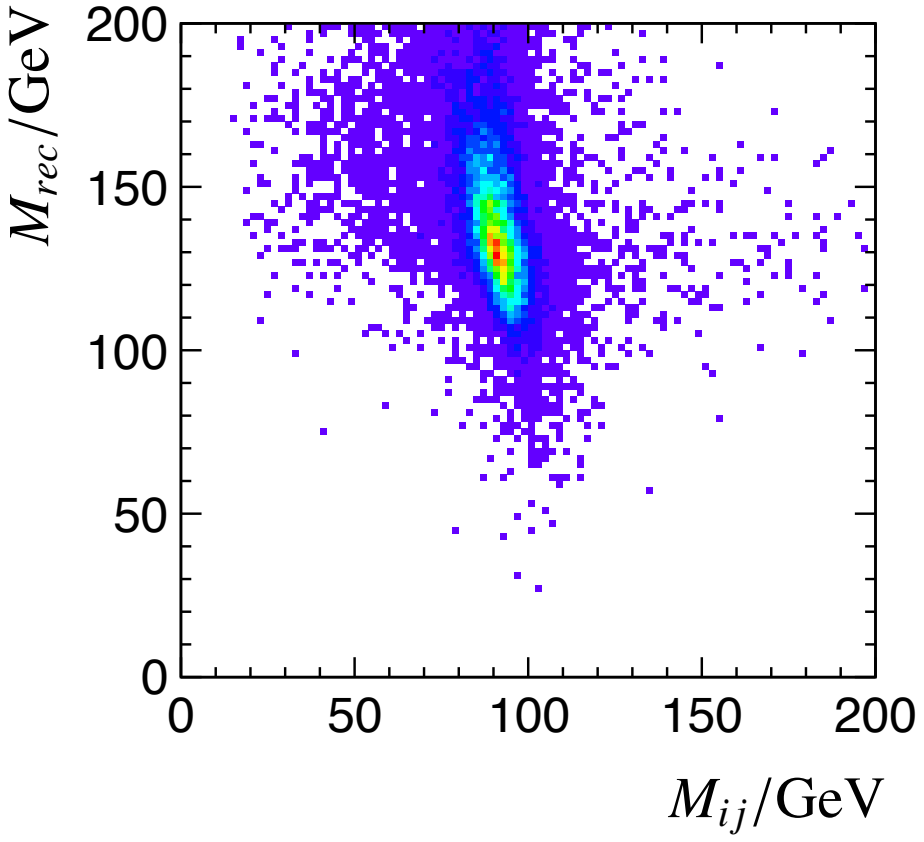
Selects clear two-jet topologies

(require each jet to have > 3 tracks)

Invisible Higgs Decays

- ★ Cuts remove ~all Higgs background (except H→ZZ*→νννν)
- ★ Cut on di-jet mass (Z) and recoil mass (H) to select events





- ★ Not looked at non-Higgs backgrounds yet, next step…

Visible Higgs Decays

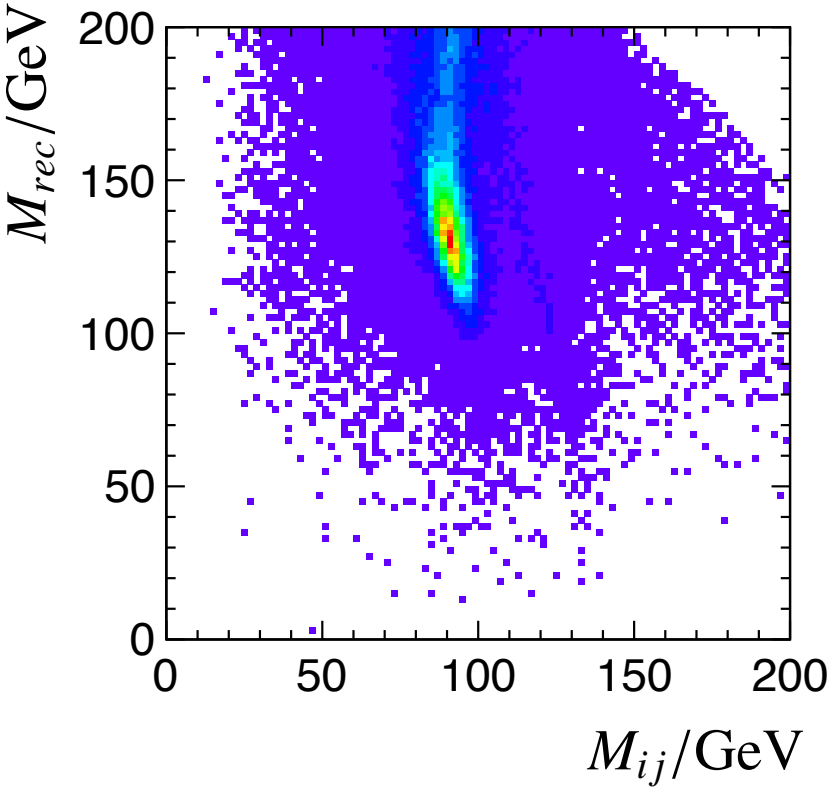
- Have two jets from Z + Higgs decay products:
  - $H \to q\bar{q}$: 4 quarks = 4 "jets"
  - $H \to \gamma\gamma$: 2 quarks + 2 photons = 4 "jets"
  - $H \to \tau\tau$: 2 quarks + 2 taus = 4 "jets"
  - $H \to WW^* \to l\nu l\nu$: 2 quarks + 2 leptons = 4 "jets"
  - $H \to WW^* \to q\bar{q}l\nu$: 4 quarks + 1 lepton = 5 "jets"
  - $H \to WW^* \to q\bar{q}q\bar{q}$: 6 "jets"
  - $H \to ZZ^* \to \nu\nu\nu\nu$: 2 "jets" (invisible analysis)
  - $H \to ZZ^* \to \nu\nu q\bar{q}$: 2 quarks = 4 "jets"
  - $H \to ZZ^* \to q\bar{q}ll$: 4 quarks + 2 leptons = 6 "jets"
  - $H \to ZZ^* \to q\bar{q}q\bar{q}$: 6 quarks = 6 "jets"

4, 5 or 6 ?

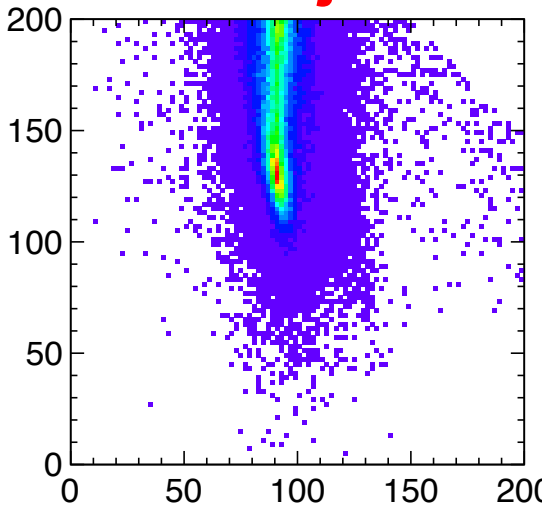
e.g. H→qq

- ★ Force event into 4-, 5-, 6- jet topologies
- ★ For each, choose Z di-jet combination closest to Z mass

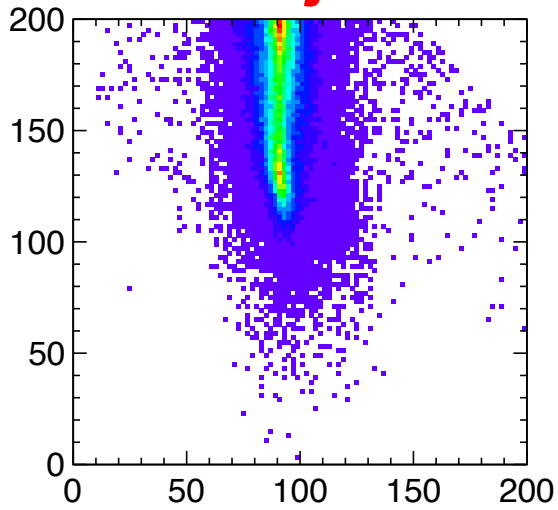
as 4-jets



as 5-jets



as 6-jets

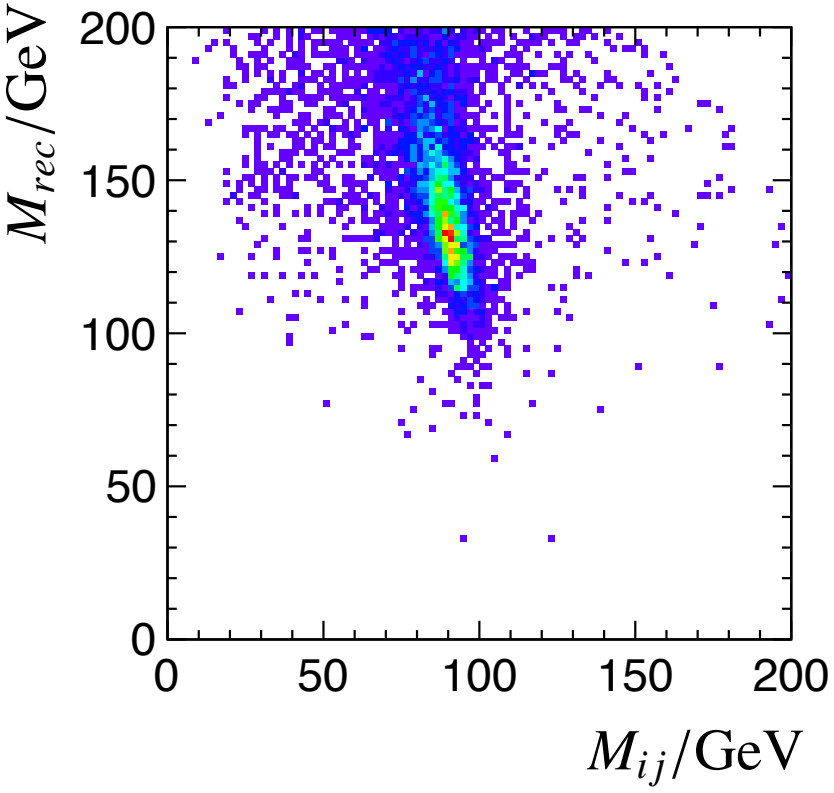


- ★ Clear Z and H signature in 4-jet reconstruction…

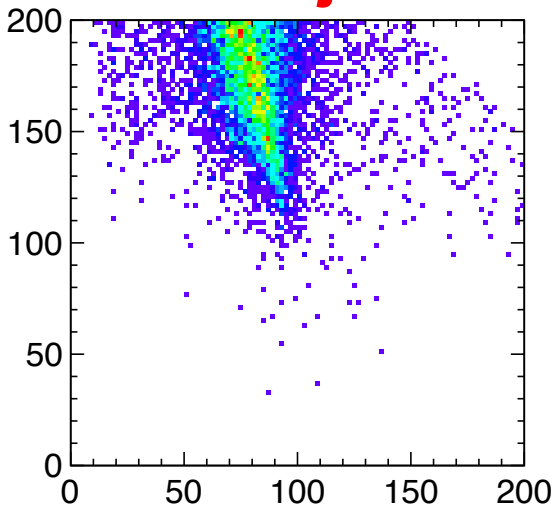
e.g. H→ττ

- ★ Force event into 4, 5, 6 jets
- ★ For each, choose Z di-jet combination closet to Z mass

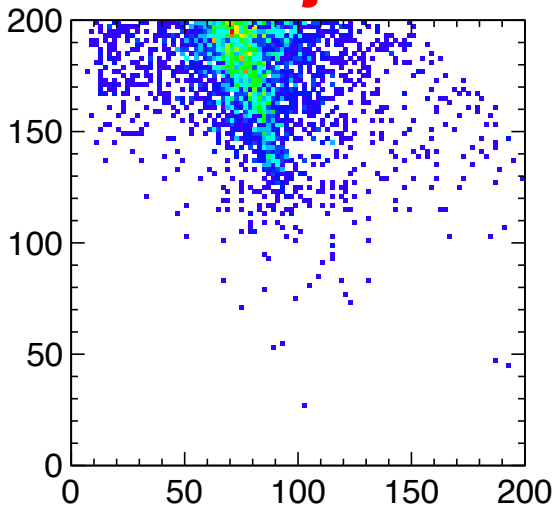
as 4-jets



as 5-jets



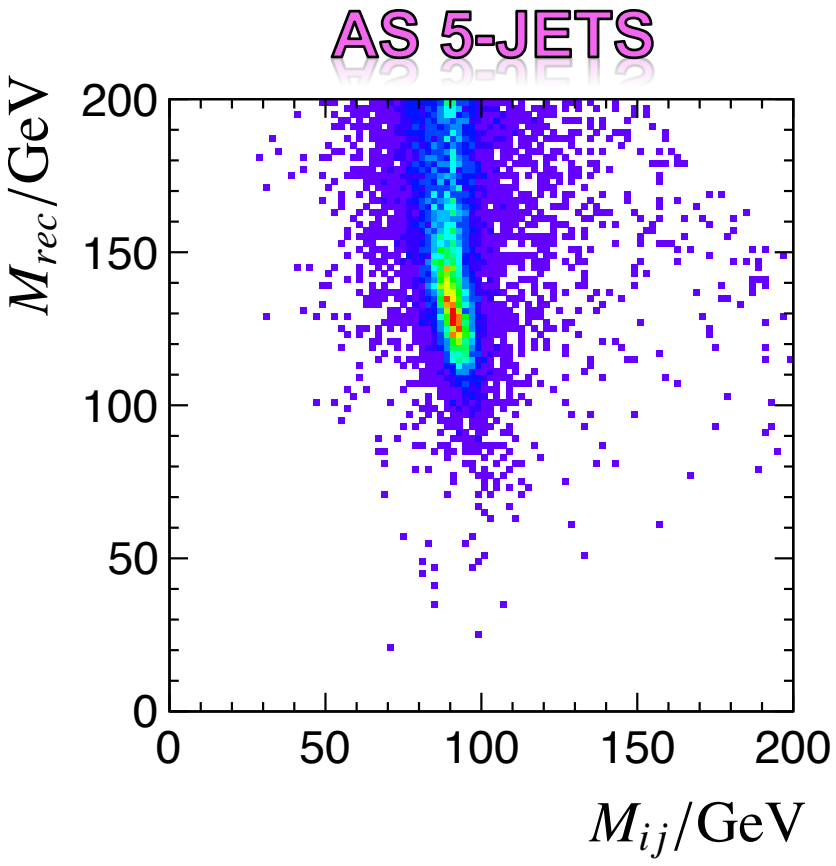
as 6-jets

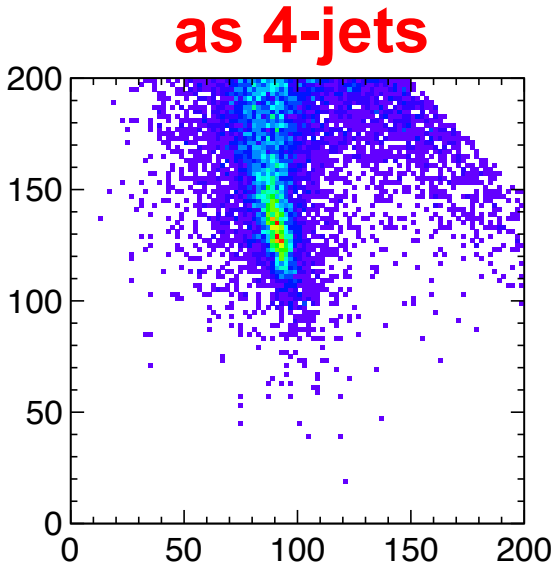


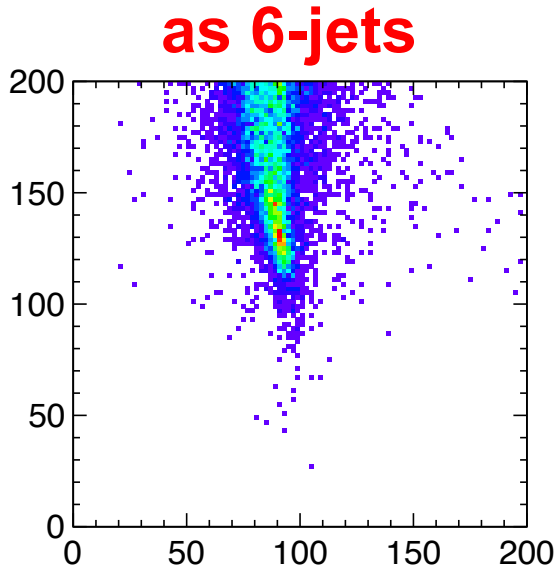
- ★ In 4-jet reconstruction – similar "peaks" to H→qq

e.g. H→WW*→qqlν

- ★ Force event into 4, 5, 6 jets
- ★ For each, choose Z di-jet combination closet to Z mass







- ★ In 5-jet reconstruction – similar "peaks" to H→qq

Watch this space…

- ★ "Similar quality" of Z mass and Higgs recoil mass reconstruction in all Higgs visible decay topologies
- ★ Potential for grouping all VISIBILE decay modes in a single analysis … "nearly model independent"
- ★ Need an event-by-event algorithm for deciding whether an event is reconstructed as 4-, 5- or 6-jet
- ★ Then look at backgrounds
- ★ Then add in "invisible" measurements

⇒ **"Essentially model-independent HZ cross section measurement"**