Visible and Invisible Higgs Decays at 350 GeV

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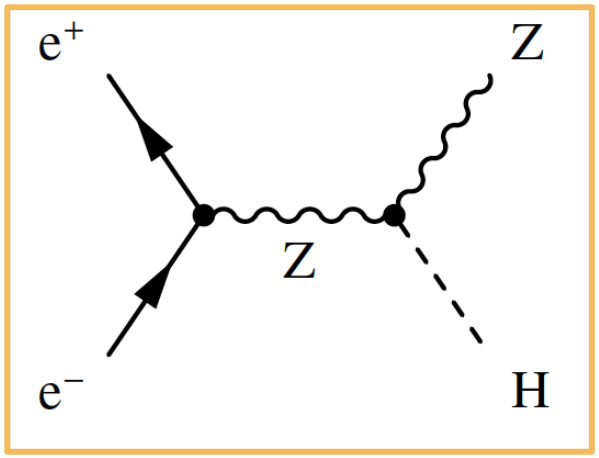

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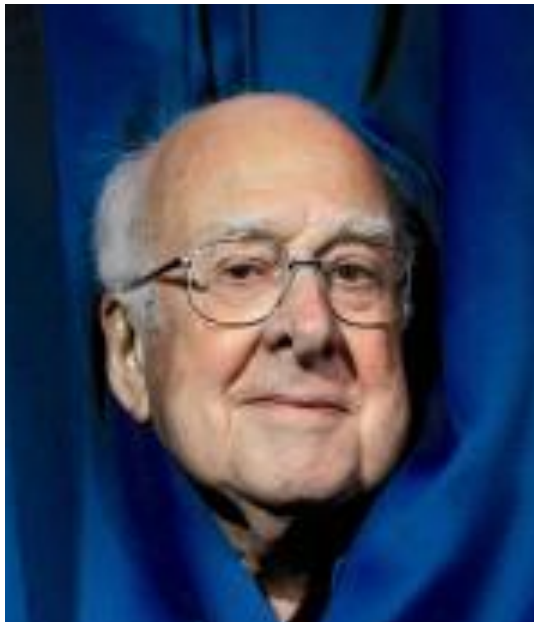

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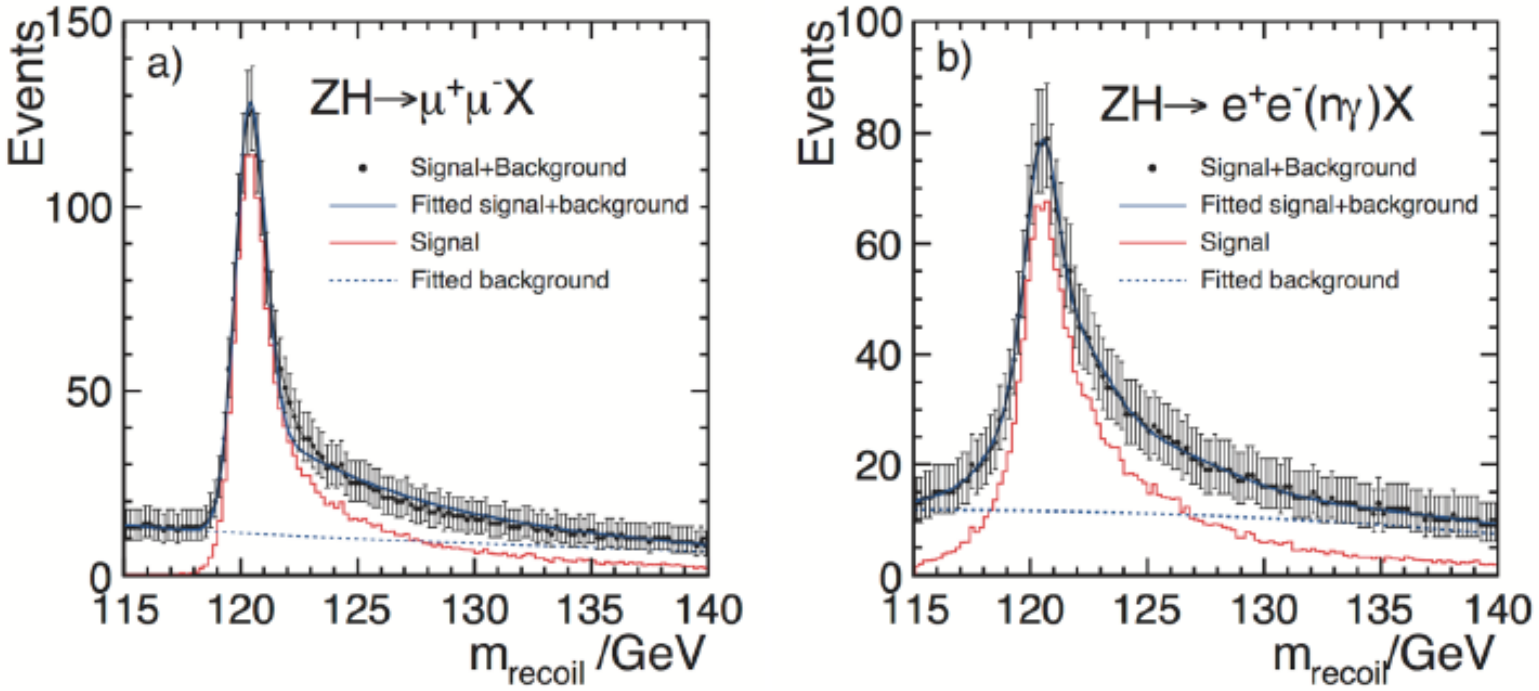
Recall Recoil

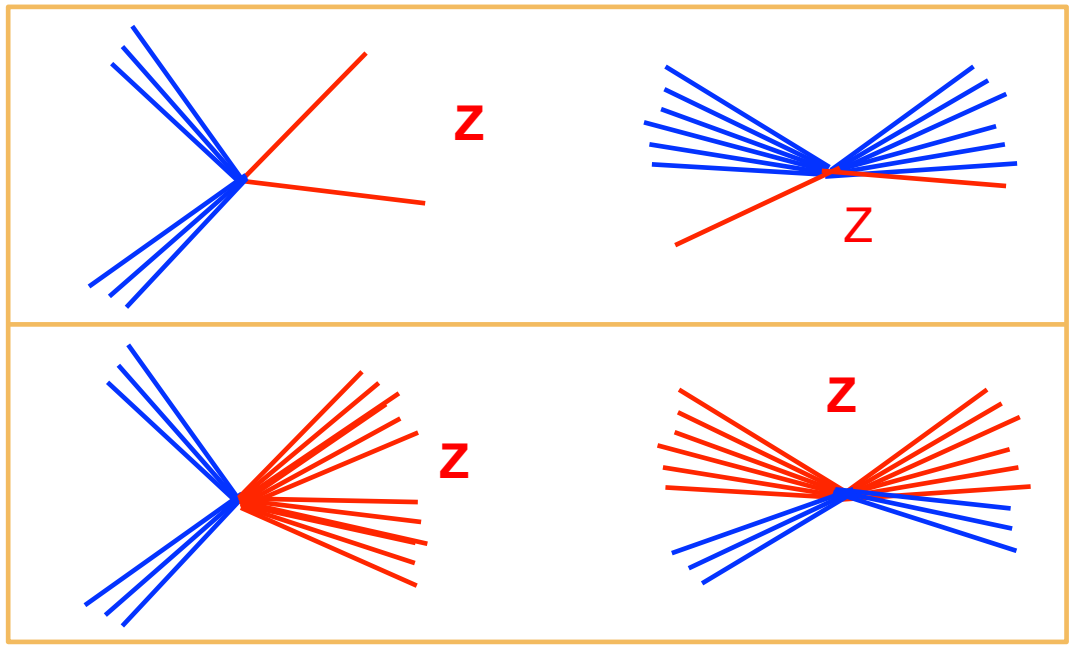
- ★ Can identify Higgs-strahlung (ZH) events by tagging of Z decays and looking at recoil mass
- ★ So far - only performed (possible?) for $Z \to \mu\mu$ and $Z \to ee$



- ★ Selection independent of Higgs decay mode
  ⇨ model indep. measurement of ZH cross section

Recoil Mass

- ★ To date, most studies only use $Z \to \mu\mu$ and $Z \to ee$
- ★ Statistical precision limited by leptonic BRs of 3.5 %
- ★ Here: extend to $Z \to qq$ ~ 70 % 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

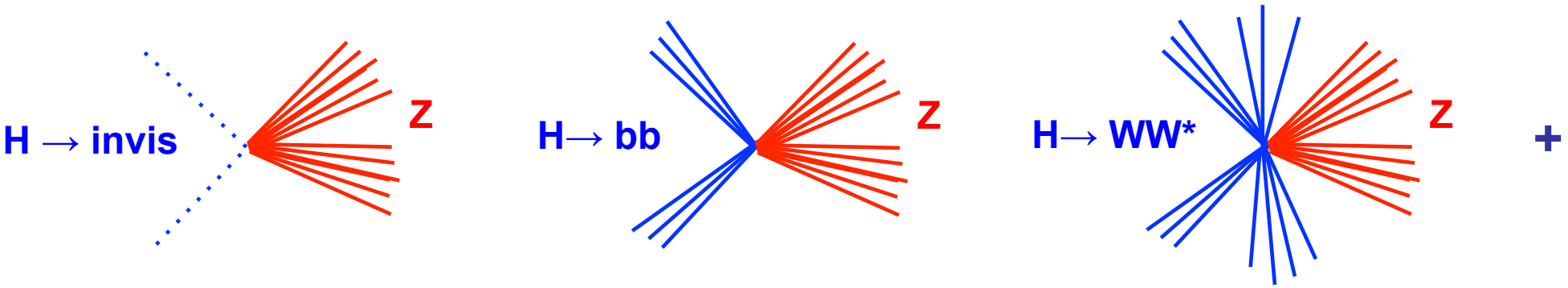
Different efficiencies for different Higgs decays

Study details

- ★ CLIC 350 GeV beam spectrum
- ★ CLIC_ILD detector model
- ★ Full simulation with overlayed background
- ★ 500 fb^{-1} unpolarised beams
- ★ "First look" – further optimisation possible

Analysis Strategy

- ★ Identify a two-jet system consistent with Z→ qq
- ★ Higgs can either decay invisibly or visibly
- ★ For Z→qq decays ⇨
  - two jets or two jets + at least two other particles



- ★ ZH signatures: Z + nothing or Z + other visible particles

First divide into candidate invisible and visible Higgs decays

- ★ Aim for same selection efficiency for all Higgs decays
  - ⇨ for model independence

Analysis Strategy

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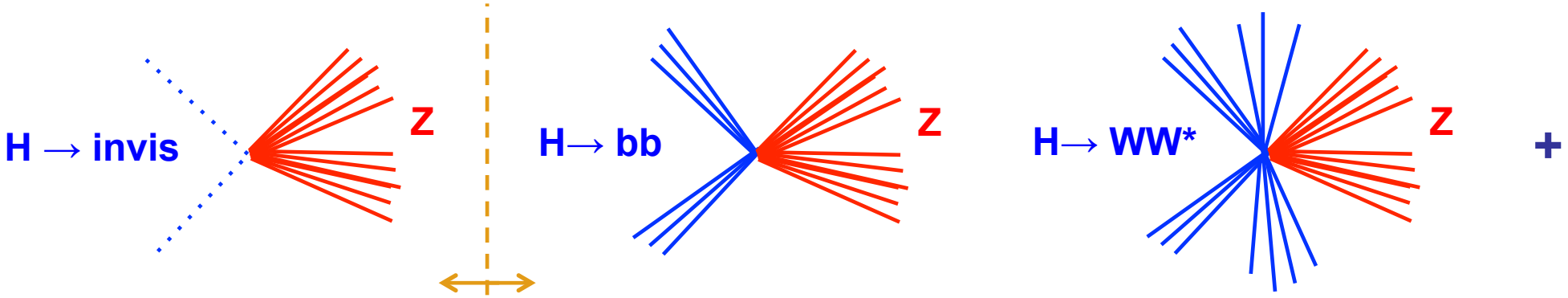


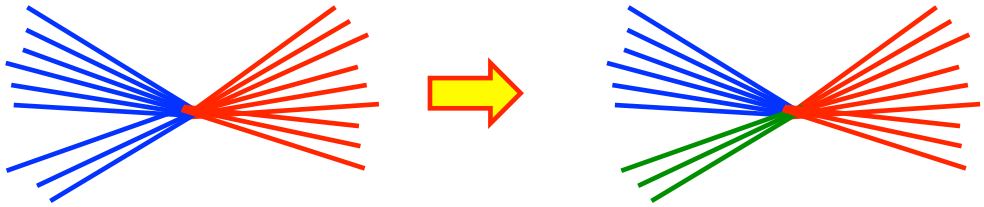
- ★ Force events into:
  - 2-jets: invisible decays
  - 3-, 4-, 5- and 6- "jet" topologies (R=1.5)

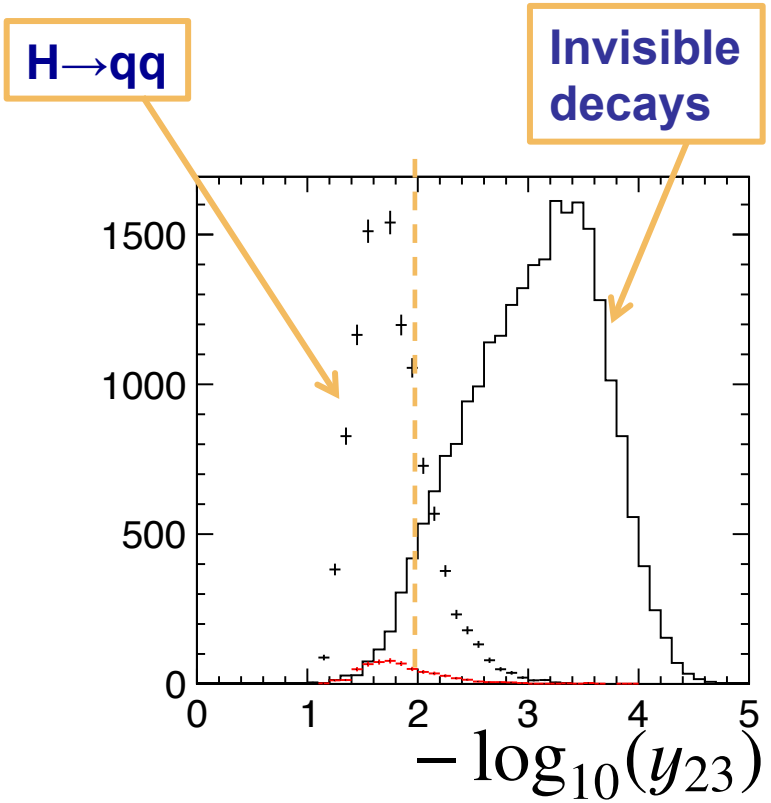
For each event will choose one topology

  - For each of these six topologies:
    - find two jets (> 3 tracks) most consistent with Z
    - determine mass of system recoiling against this "Z"

2 jets vs >2 jets

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



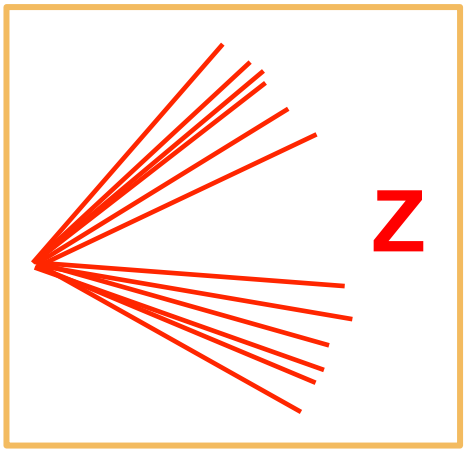


★ Also use y_{34}, the k_T value at which the event transitions from 3 jets to 4 jets

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

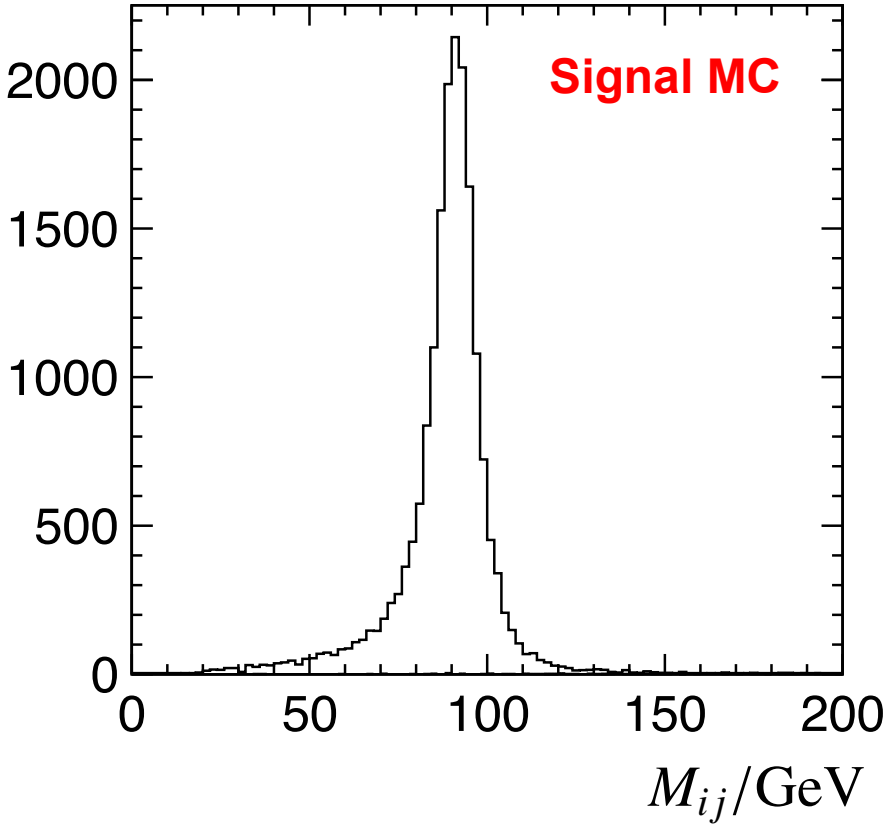
★ *All* events categorised in one of these two samples

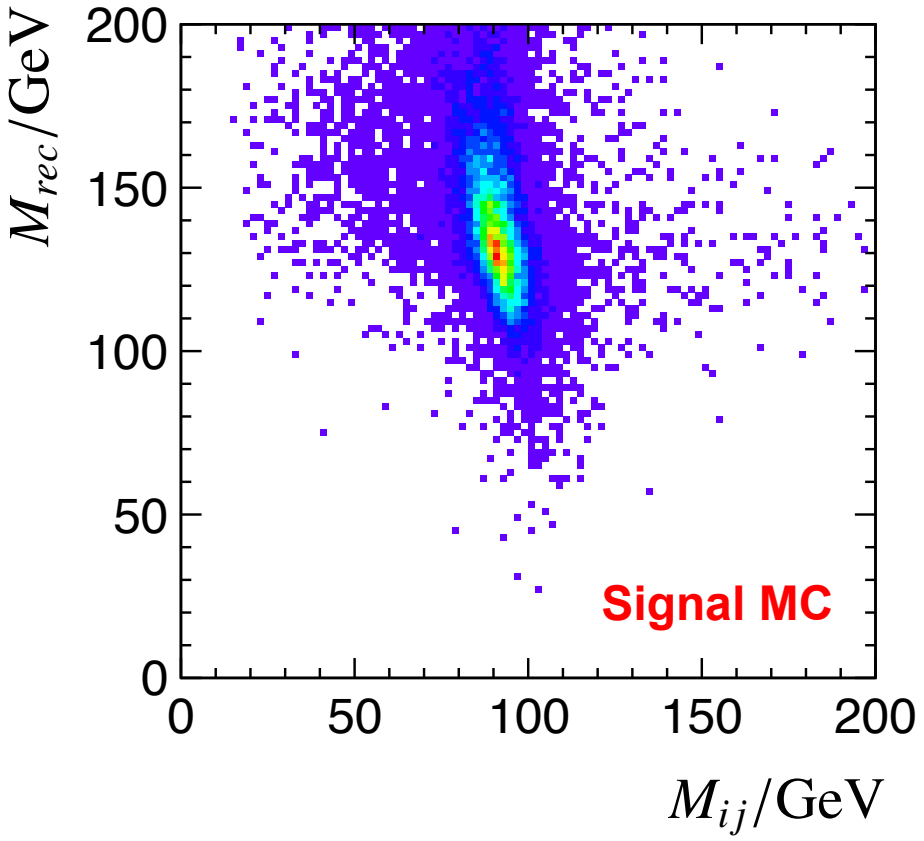
Invisible Decays



Invisible Higgs Decays

- ★ Start from 2-jet sample: essentially removes ~all Higgs "background" (except H→ZZ*→νννν and a little H→ττ)
- ★ Cut on di-jet mass (Z) and recoil mass (H) to select events





That's about it !

$$|\cos\theta^{1,2}_{\text{jet}}| < 0.95$$

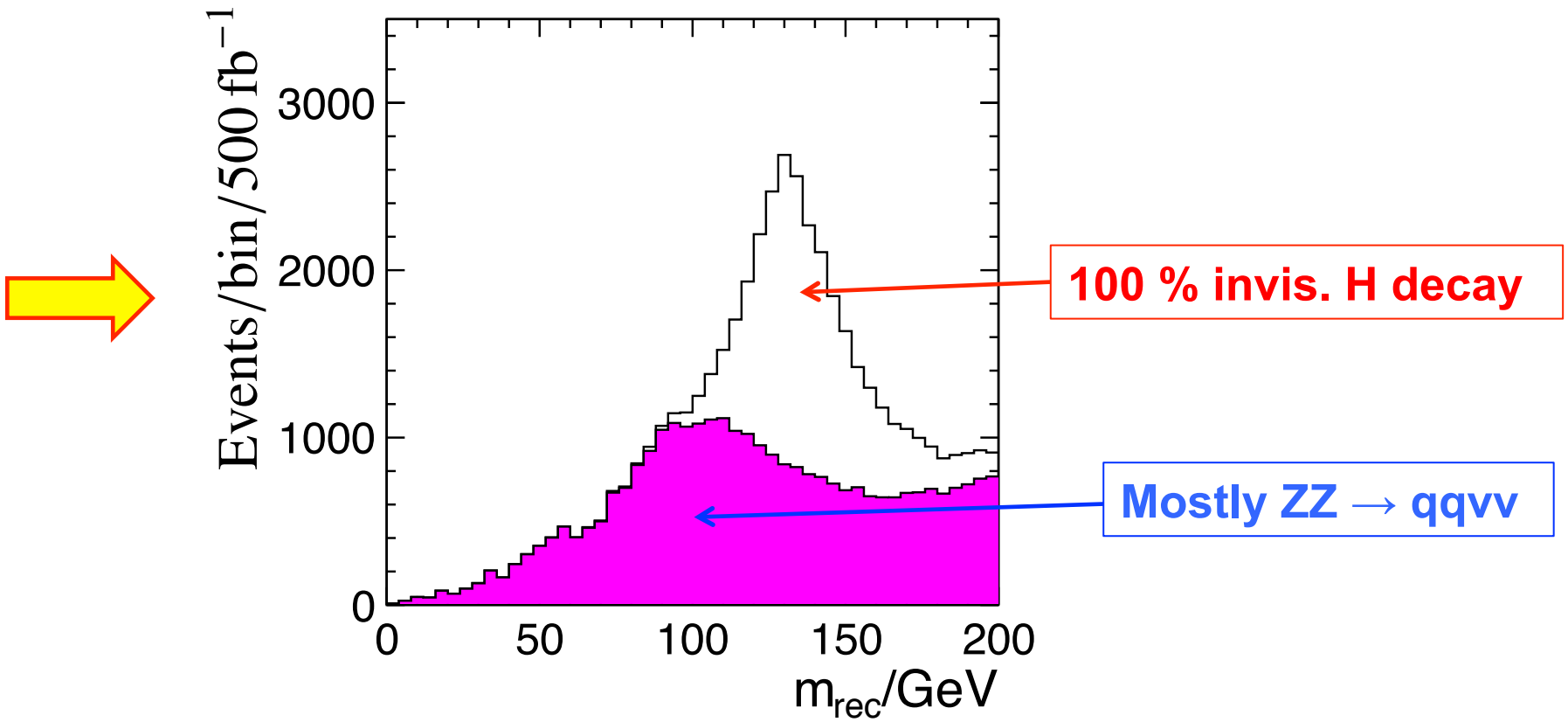
$$84\,\text{GeV} < m_{\text{qq}} < 104\,\text{GeV}$$

$$|\cos\theta_{\text{Z}}| < 0.7$$

Both jets well measured (hopefully)

Looks like Z

Z produced centrally



Relative Likelihood

- ★ Use relative likelihood selection MVA (will try others)
- ★ Input variables
  - m_{qq} *vs.* m_{rec}
  - $|\cos\theta_{\mathrm{Z}}|$
  - [..more to come]

Calculate absolute likelihood for given event type

$$L = P(m_{\mathrm{qq}}, m_{\mathrm{rec}}) \times P(|\cos\theta_{\mathrm{Z}}|)$$

NOTE: 2D mass distribution includes main correlations

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

$$\mathcal{L}(\mathrm{H} \to \mathrm{invis.}) = \frac{L(\mathrm{H} \to \mathrm{invis.})}{L(\mathrm{H} \to \mathrm{invis.}) + L(\mathrm{back})}$$

Preliminary Results

★ Preliminary results (optimal L cut)

Channel	Efficiency
Z H → qq qq	-
Z H → qq ZZ	1.4 %
Z H → qq WW	0.1 %
Z H → qq γγ	0.2 %
Z H → qq ττ	0.4 %
Z H → qq invis.	27.7 %

Backgrounds

Channel	Efficiency	Events
qq	0	0
qqqq	0	0
qqlv	0.065 %	1900
qqll	0.002 %	20
qqvv	2.6 %	4250

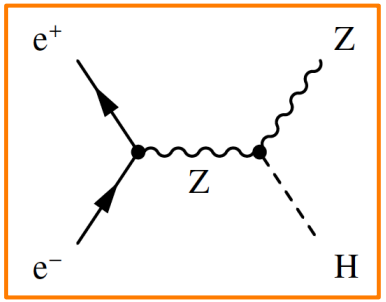
★ Assuming no invisible decays (1 sigma stat. error):

$$\Rightarrow \quad \Delta\sigma_{\text{invis}} = \pm 0.6\,\%$$

(CLIC beam spectrum, 500 fb^{-1} @ 350 GeV, no polarisation)

Visible Decays

Visible Higgs Decays

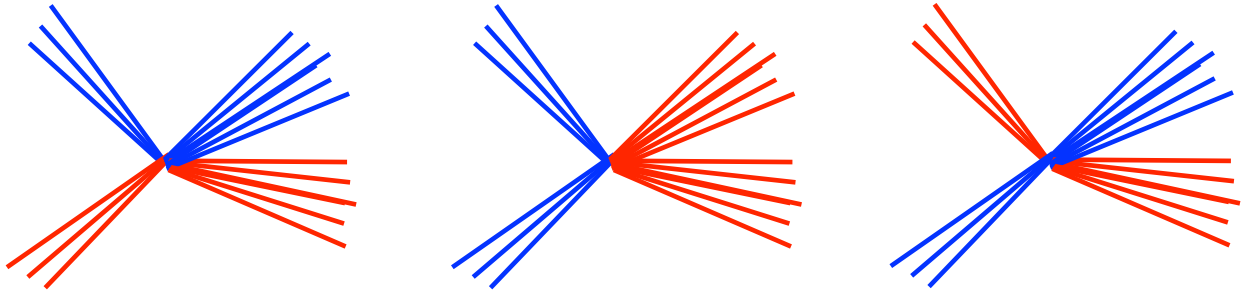


- ★ Have two jets from Z + Higgs decay products:
  - ★ H→qq : 4 quarks = 4 "jets"
  - ★ H→γγ : 2 quarks + 2 photons = 4 "jets"
  - ★ H→ττ : 2 quarks + 2 taus = 4 "jets"
  - ★ H→WW*→lνlν : 2 quarks + 2 leptons = 4 "jets"
  - ★ H→WW*→qqlν : 4 quarks + 1 lepton = 5 "jets"
  - ★ H→WW*→qqqq : 6 "jets"
  - ★ H→ZZ*→νννν : 2 "jets" (invisible analysis)
  - ★ H→ZZ*→ννqq : 2 quarks = 4 "jets"
  - ★ H→ZZ*→qqll : 4 quarks + 2 leptons = 6 "jets"
  - ★ H→ZZ*→qqqq: 6 quarks = 6 "jets"

4, 5 or 6 ?

Visible Higgs Decays

- ★ Force event into 4-, 5-, 6- jet topologies
- ★ For each, look at all jet combinations, e.g. for 4-jet topology



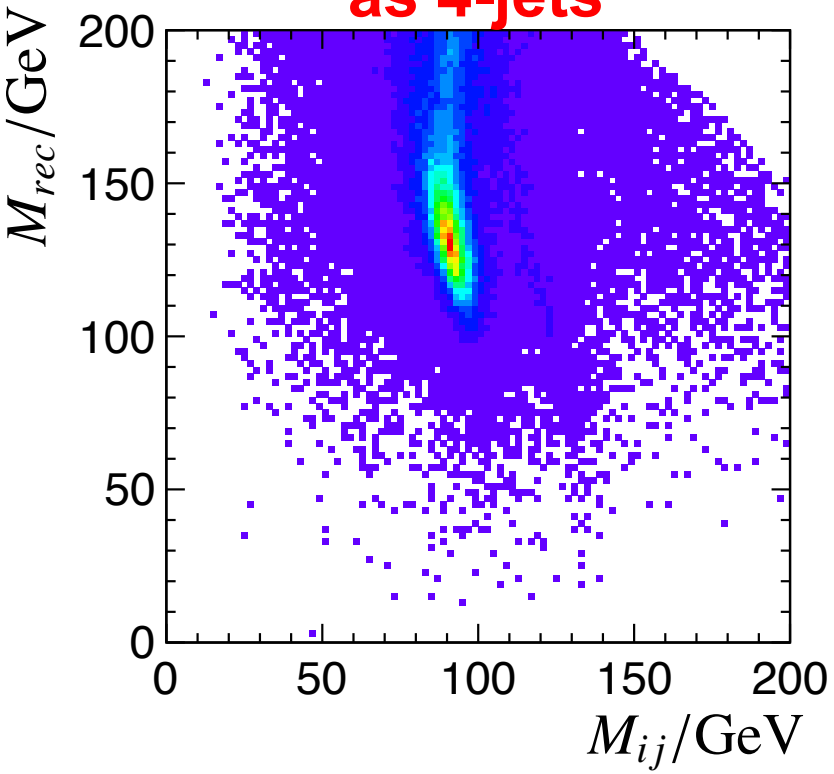
- ★ "Z" candidate = is the di-jet combination closest to Z mass from all three jet combinations, i.e. one per event

- ★ Repeat for 5- and 6-jet topologies…

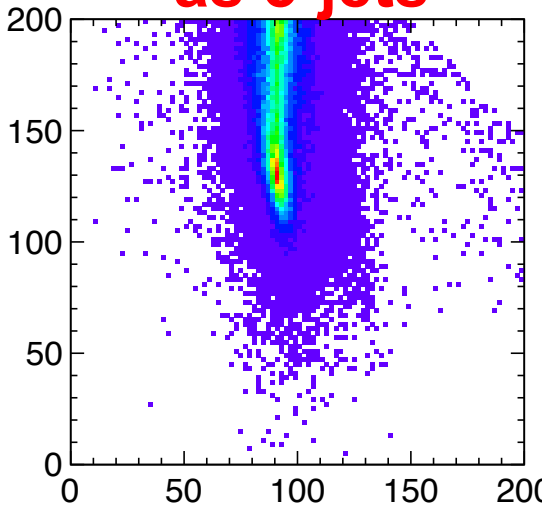
e.g. H→qq

- ★ For example, consider genuine ZH→qqqq decays
- ★ Plot mass of "candidate Z" vs. recoil mass for 4-, 5-, 6-jet hypotheses

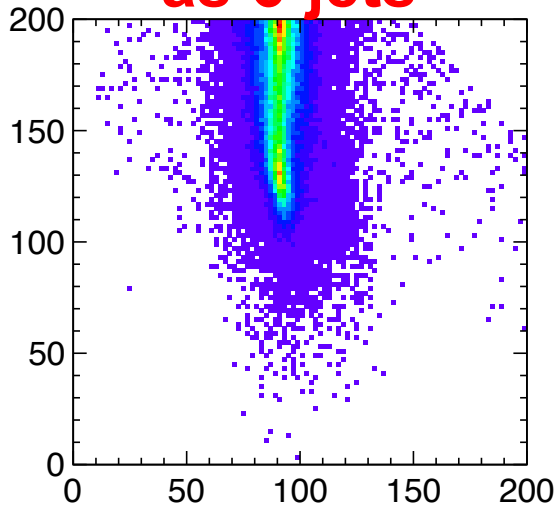
as 4-jets



as 5-jets



as 6-jets

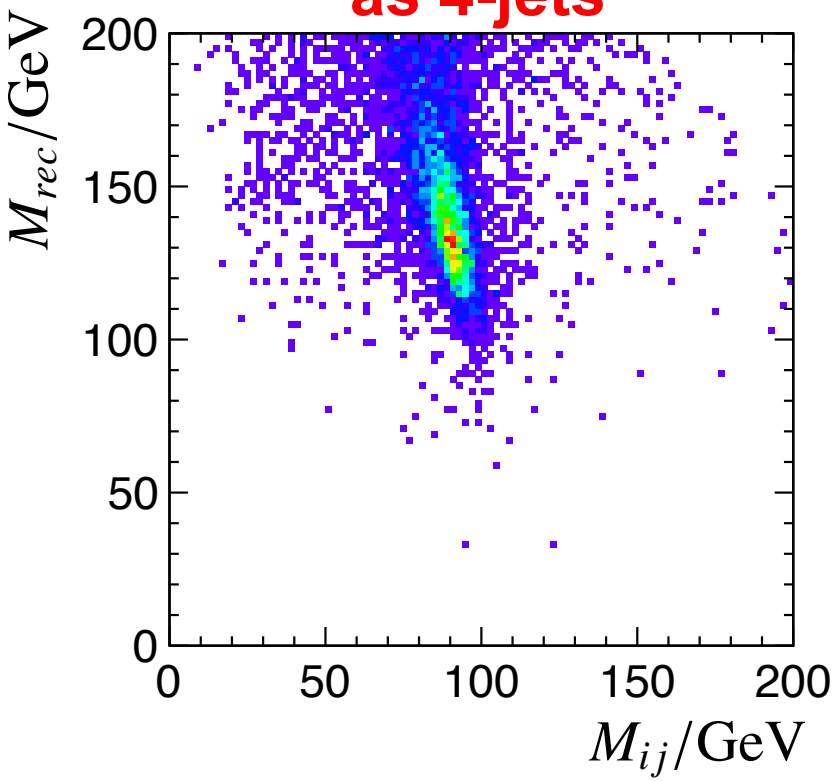


- ★ Clear Z and H signature in 4-jet reconstruction…

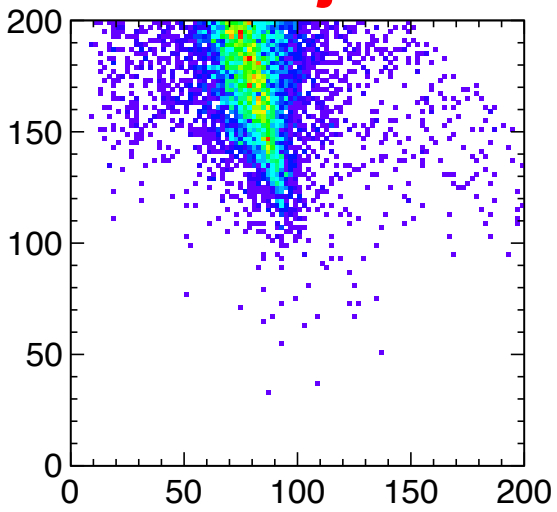
e.g. H→ττ

★ Similarly for ZH→qqττ

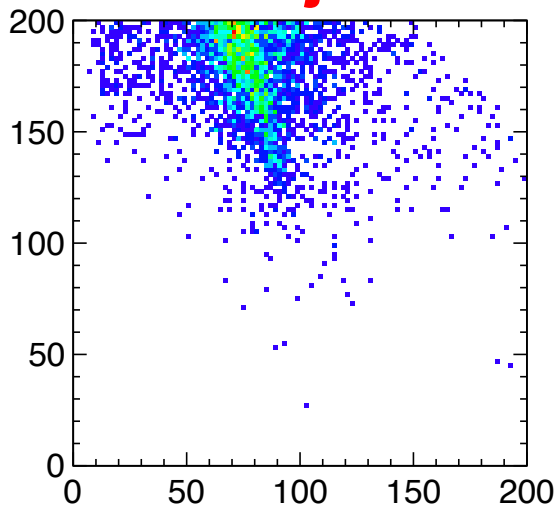
as 4-jets



as 5-jets



as 6-jets

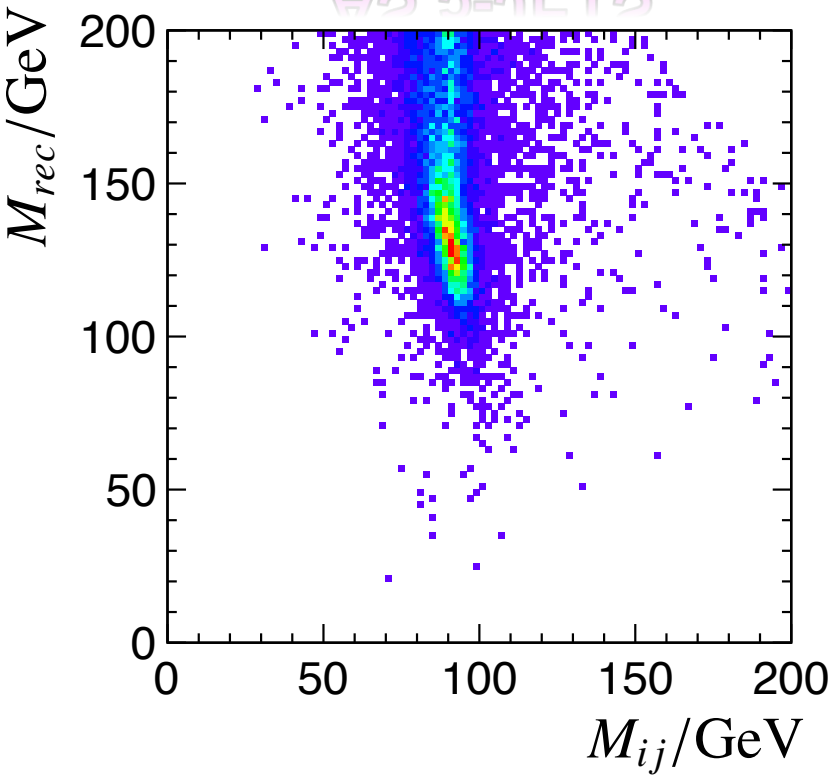


★ In 4-jet reconstruction – similar "peaks" to H→qq

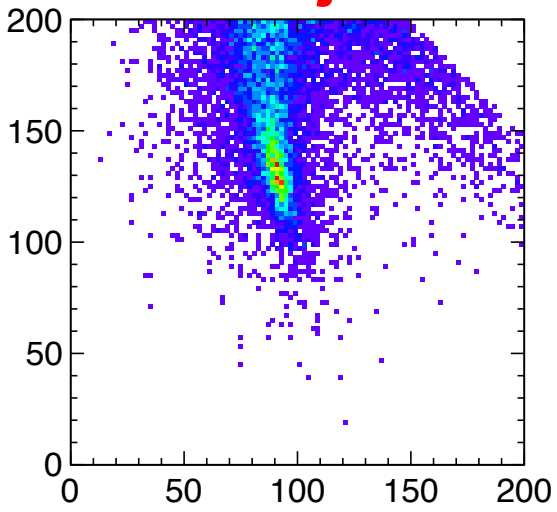
e.g. H→WW*→qqlν

★ Similarly for ZH→qqWW* → qqqqlν

AS 5-JETS



as 4-jets



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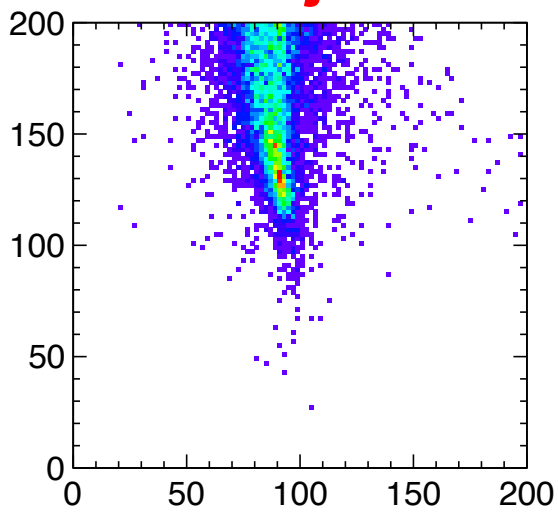


★ In 5-jet reconstruction – similar "peaks" to H→qq

A number of challenges

- ★ How many jets to use ?
- ★ Background suppression cuts ?
- ★ MVA variables ?

- ★ Nothing particularly hard here…

A number of challenges

- ★ How many jets to use ?
- ★ Background suppression cuts ?
- ★ MVA variables ?

- ★ Nothing particularly hard here…

BUT

HARD ?

- ★ Don't want to bias RELATIVE efficiencies for different Higgs decays
- ★ Otherwise – not truly MI

A simple plan

First….

Kill background

with targeted cuts

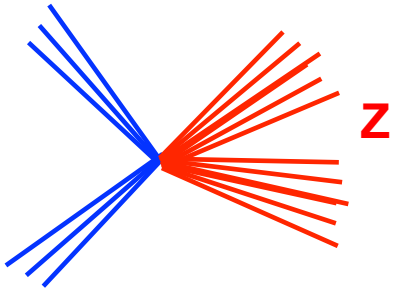
(as far as possible)

★ **Main backgrounds are large cross section processes:**

- **ZZ**
- **WW**
- **qq**

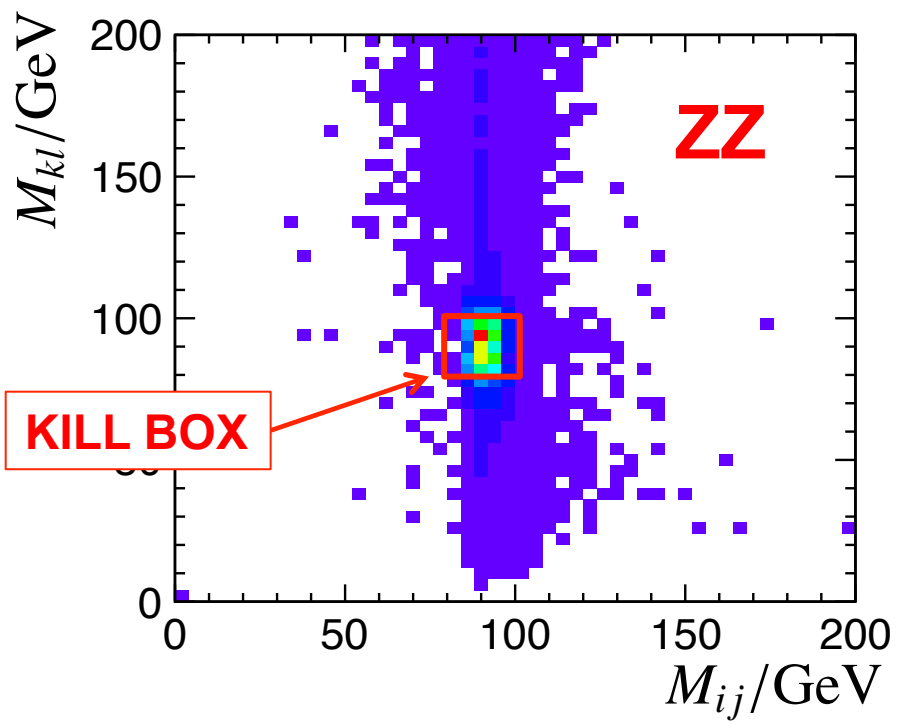
In each case reconstruct event assuming it is the background – then use invariant mass…

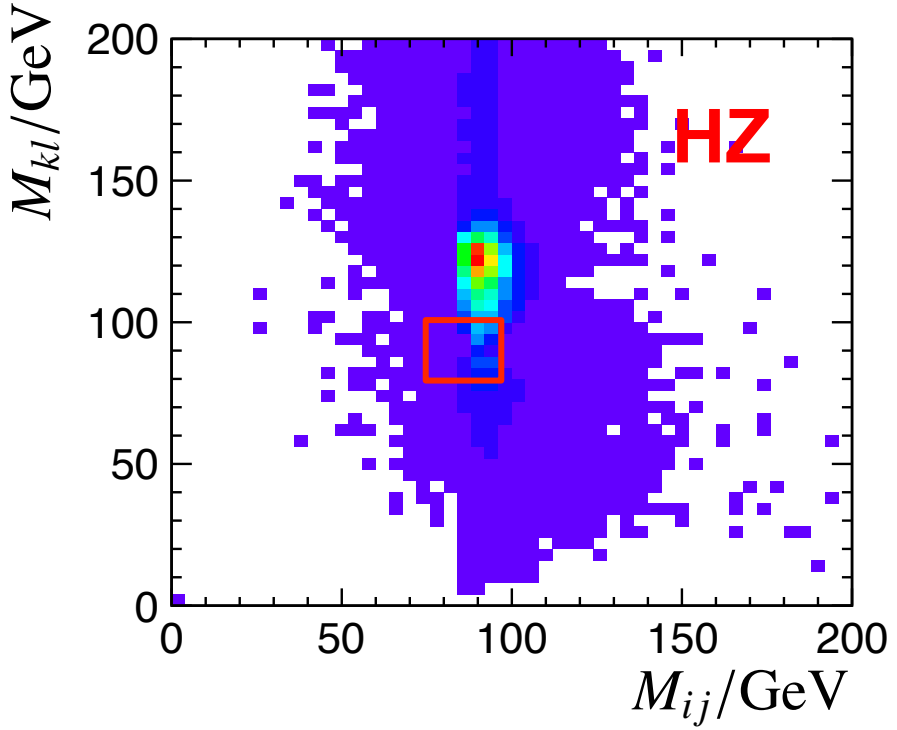
e.g. ZZ → qqqq



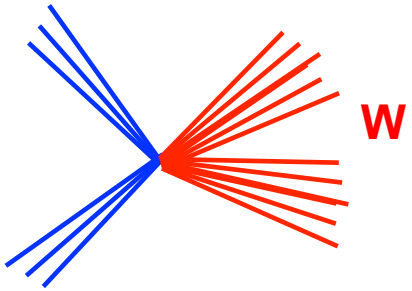
- Assume each event is ZZ → qqqq
- Therefore: force into 4 jets
- Choose jet pairing (12)(34), (13)(24) or (14)(23) with single jet-pair mass closest to Z mass

★ Cut on reconstructed di-jet masses (not recoil mass)





e.g. WW → qqqq



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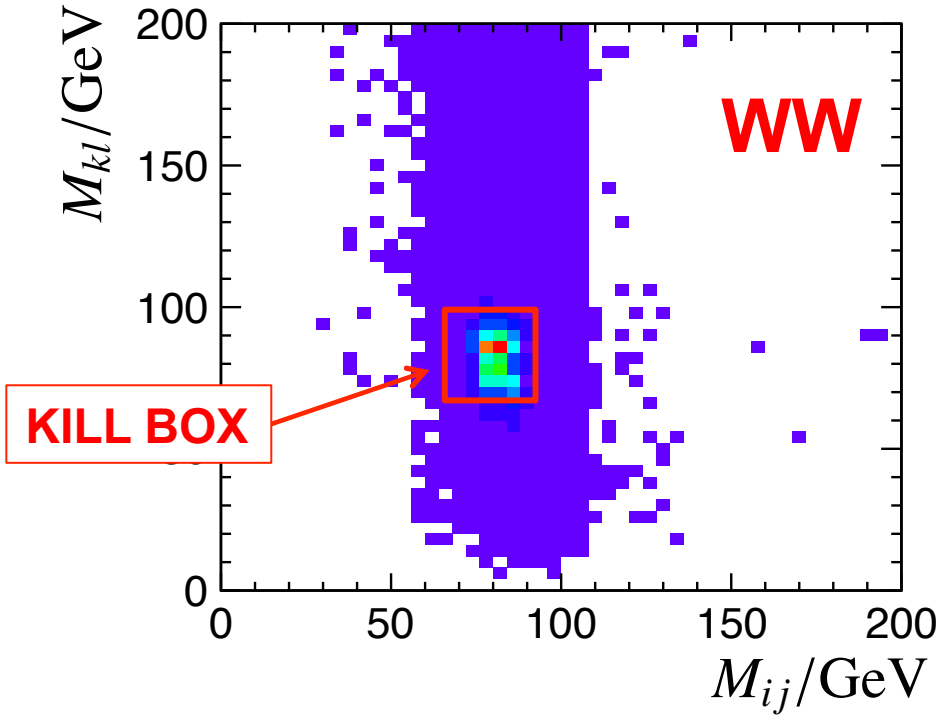
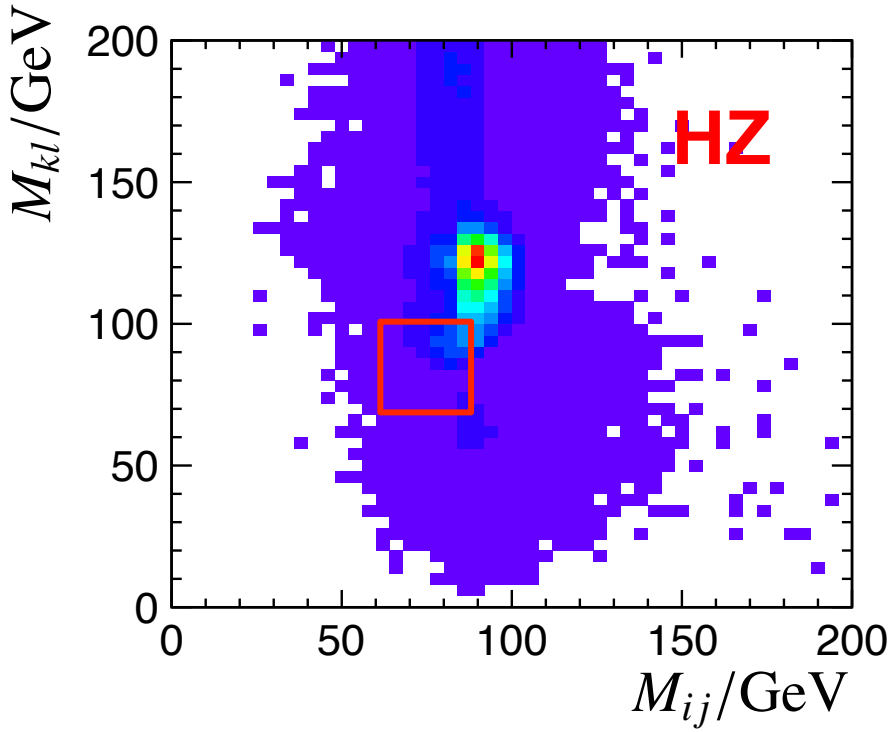
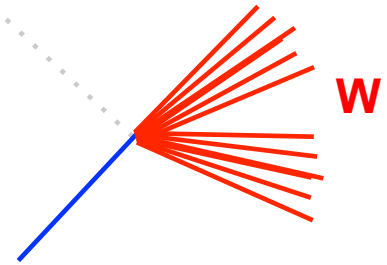
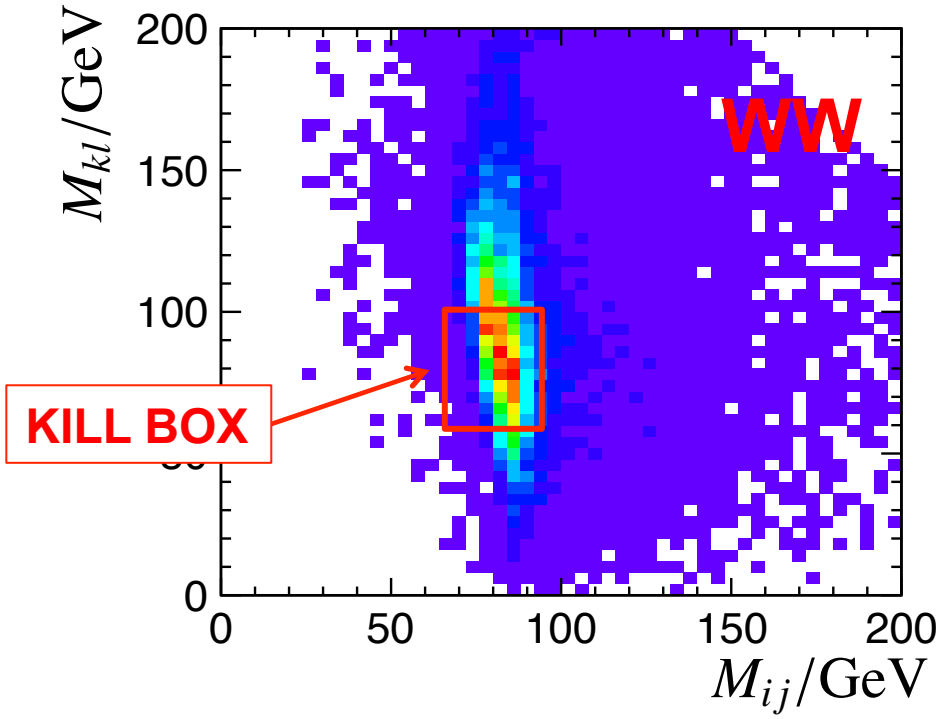


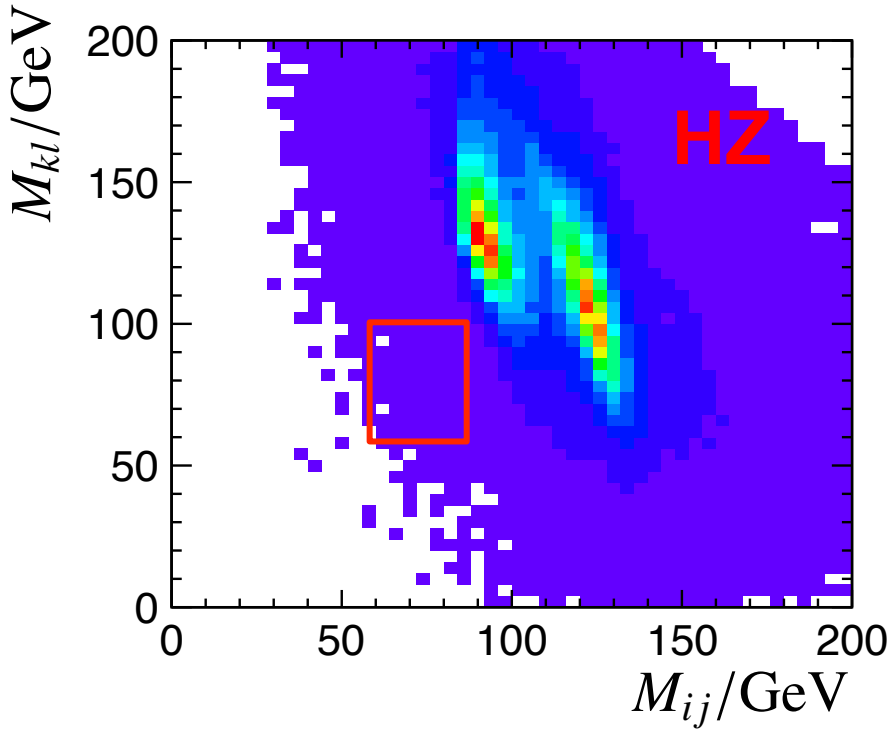


e.g. WW → qqlv



- Assume event is WW → qqlv
- Therefore: force into 3 jets
- Choose jet pairing (12) (13) (23) closest to W mass, only consider jets with >2 track





Now treat as ZH→qq X

4, 5, or 6 jets?

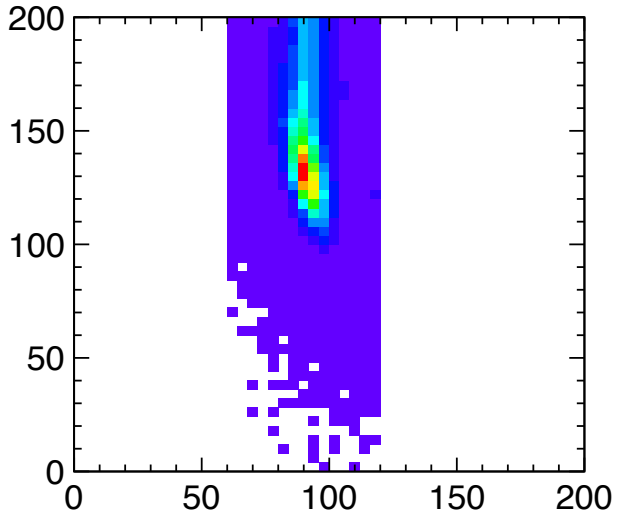
- ★ **Find that it rarely helps going from 5 → 6:**
  even if a 6-jet final state, provided reconstruct two "hard" jets from Z decay OK

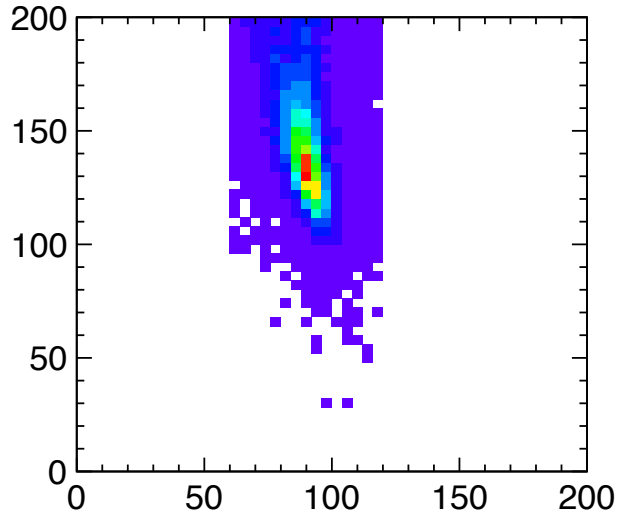
So choose between 4 or 5 jet topology:

- ★ **Default is to treat as 4-jets**
- ★ **Reconstruct as 5-jets only if:**
  - $-\log_{10}(y_{45}) < 3.5$ **AND**
  - **5-jet reconstruction gives "better" Z mass and "better" Higgs recoil mass**
    "better" = closer to true masses

Signal m_{qq} vs m_{rec}

H→qq

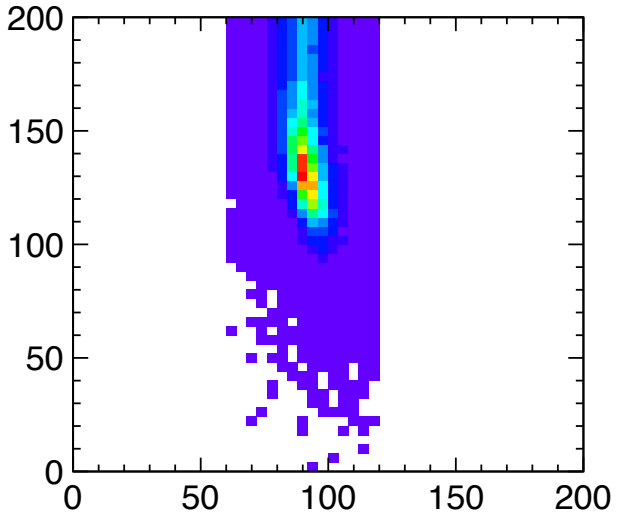


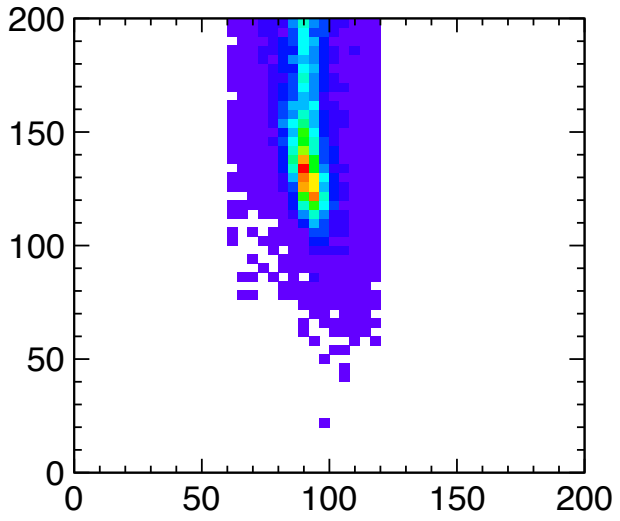


H→ττ

M_{rec}/GeV

H→WW*

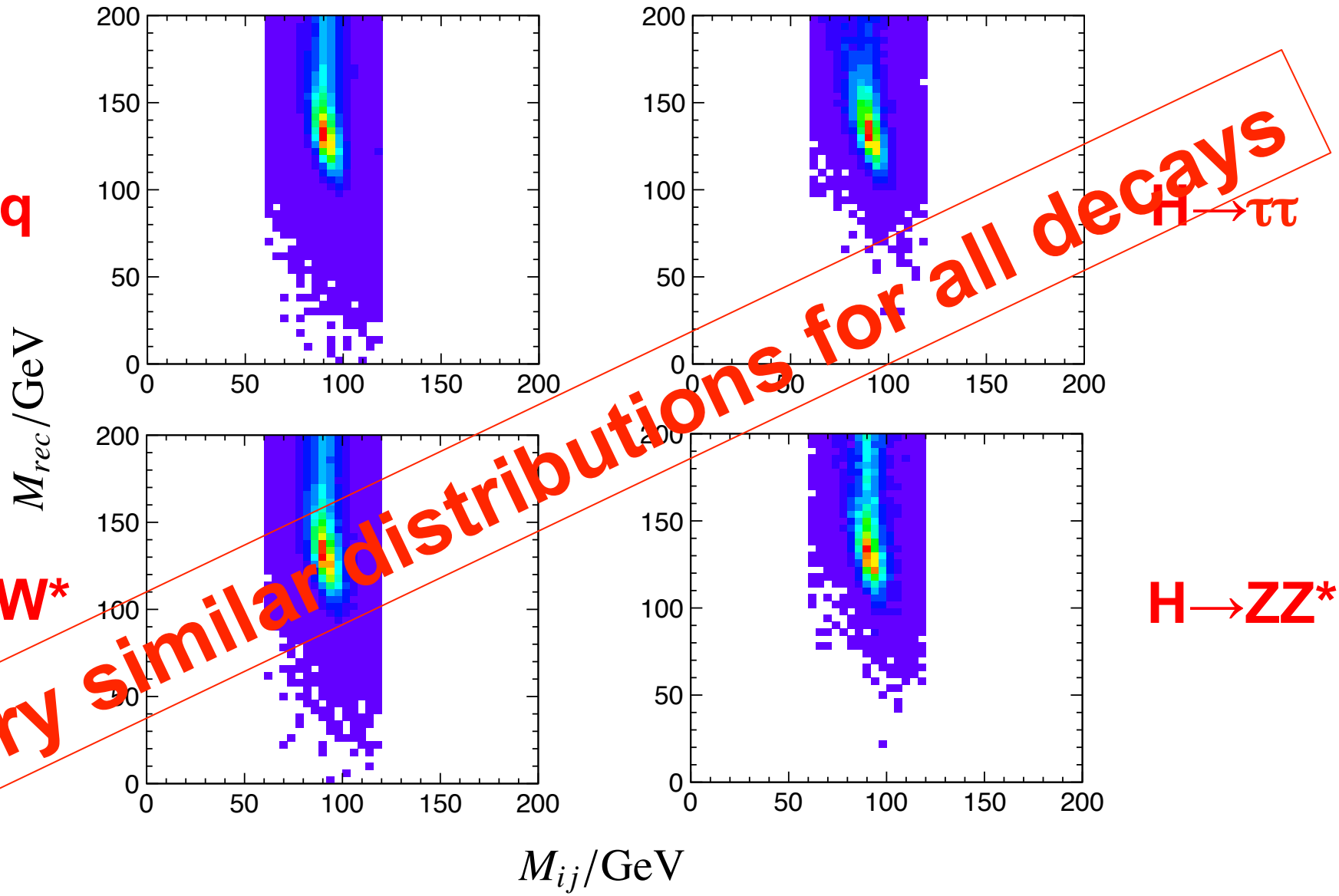




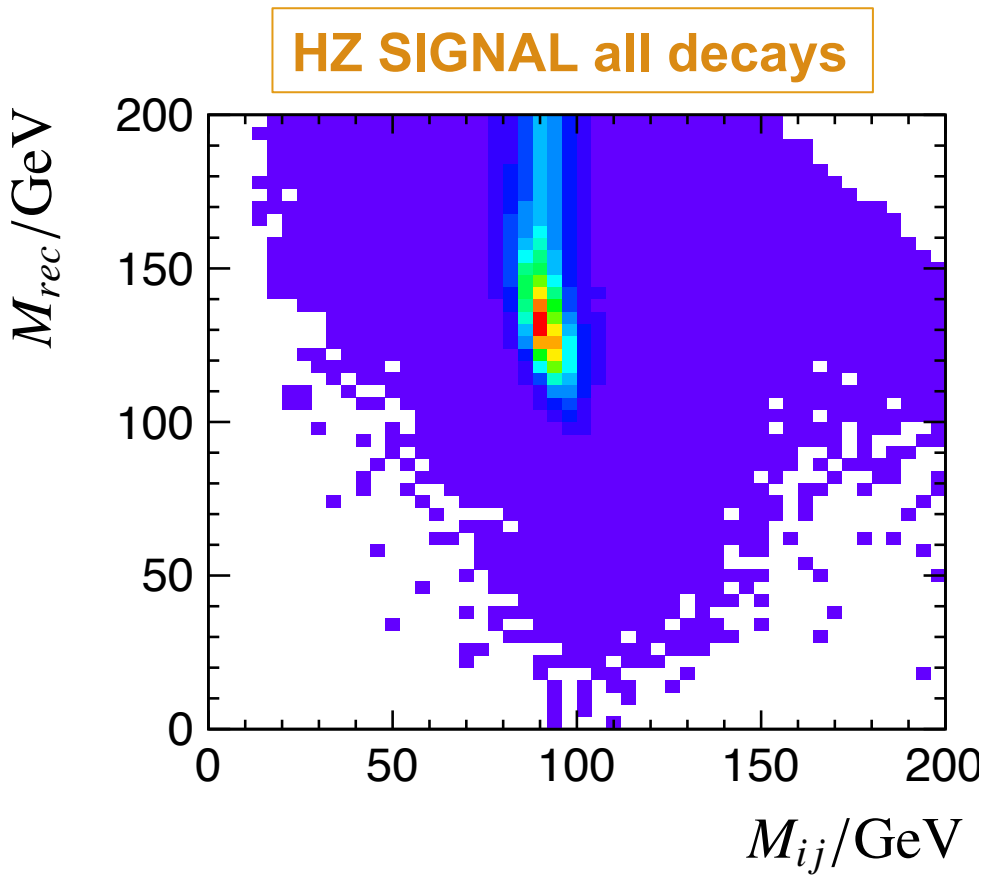
H→ZZ*

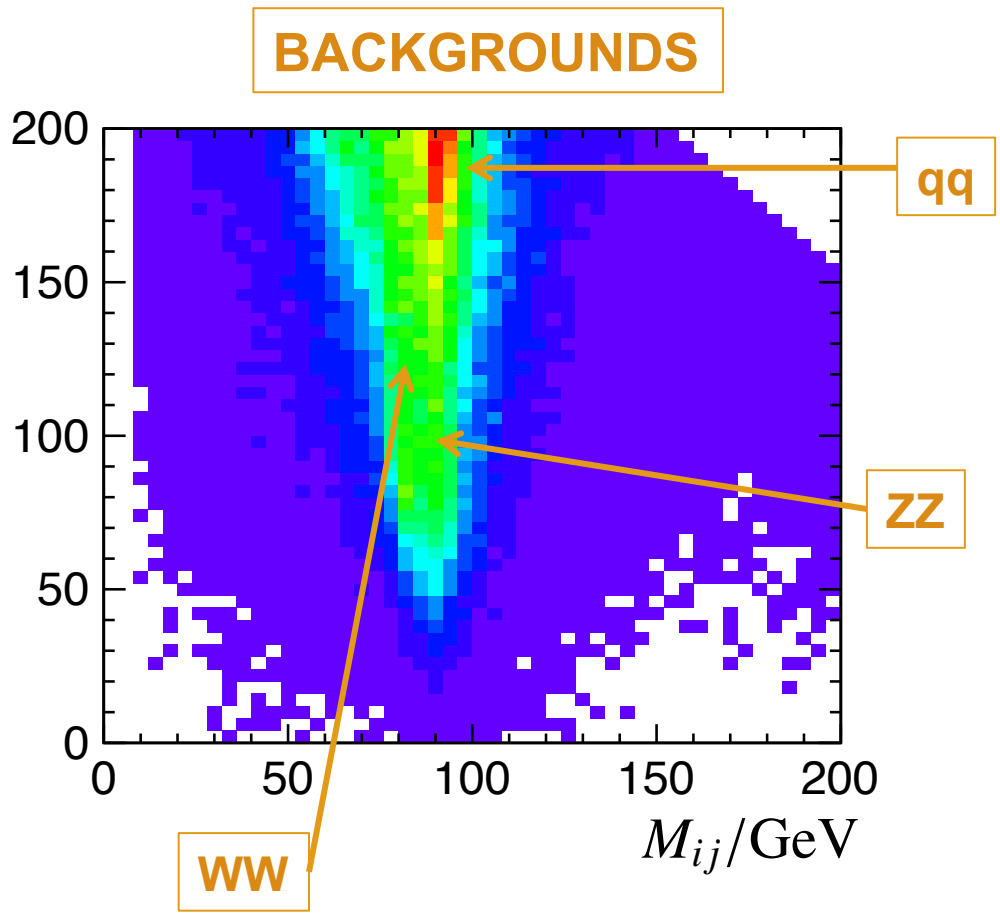
M_{ij}/GeV

Signal m_{qq} vs m_{rec}

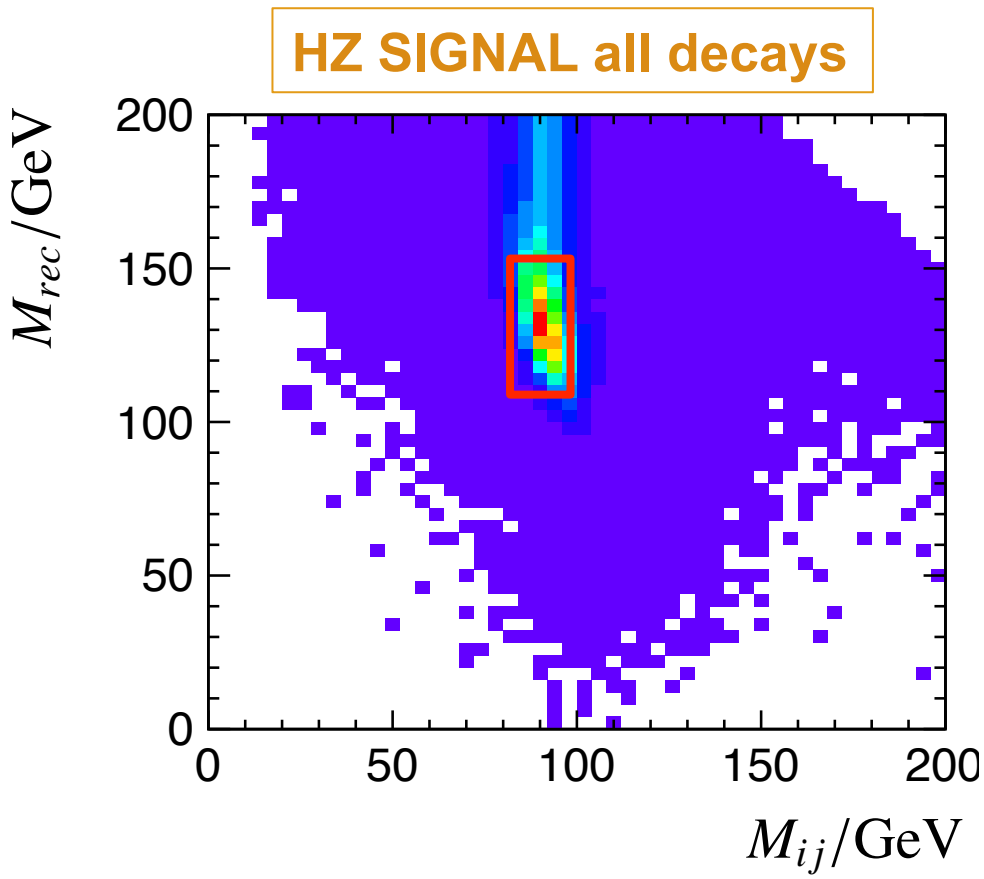


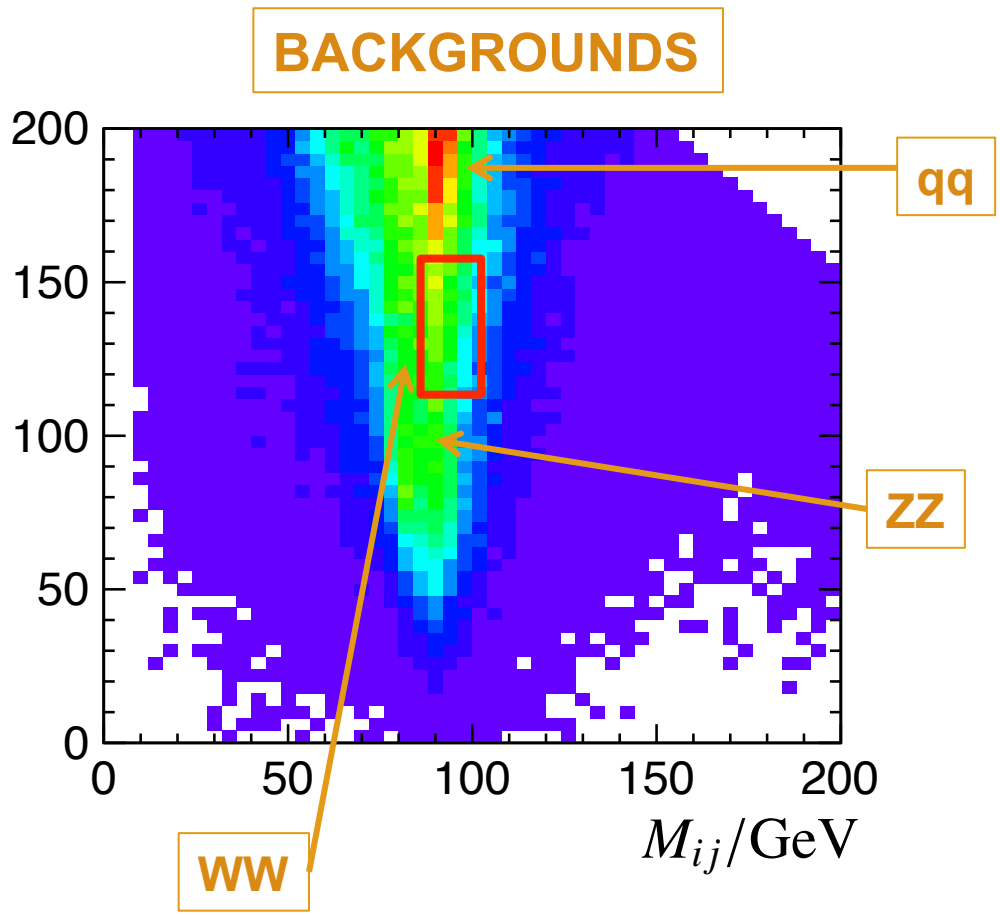
Signal vs Background





Signal vs Background





★ **Signal region clearly separated from background**

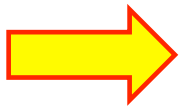
That's about it !

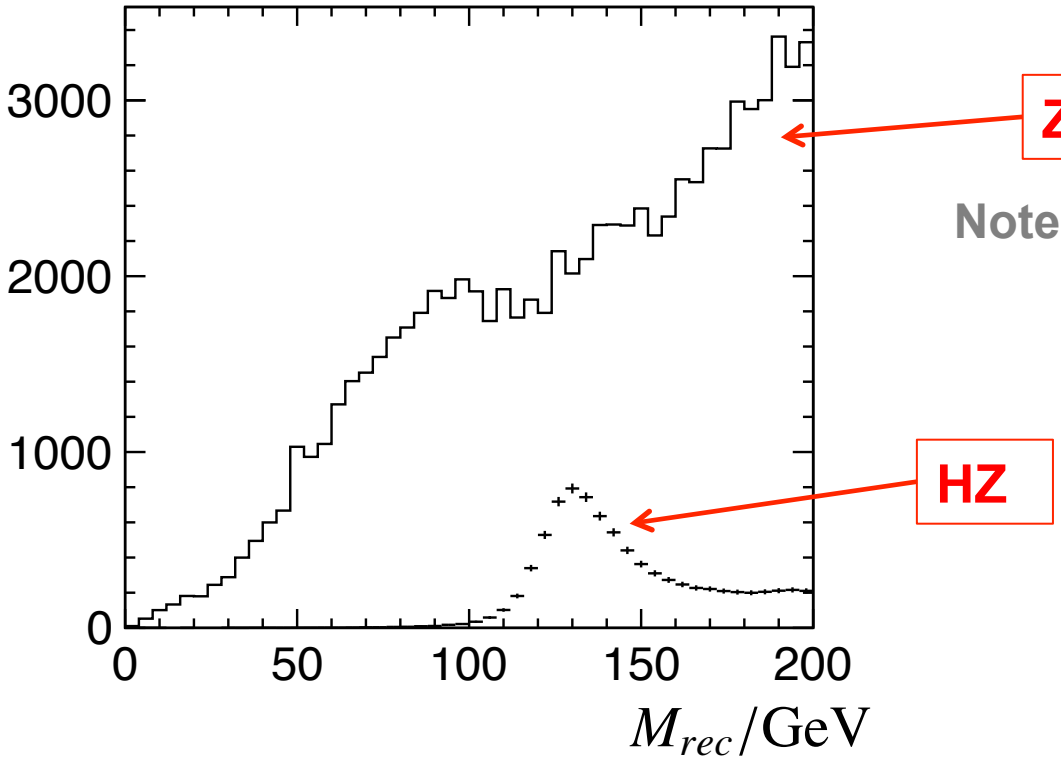
$$|\cos\theta^{1,2}_{\text{jet}}| < 0.95$$
$$84\,\text{GeV} < m_{\text{qq}} < 108\,\text{GeV}$$
$$|\cos\theta_{\text{Z}}| < 0.7$$

Both jets well measured (hopefully)

Looks like Z

Z produced centrally





ZZ, WW and qq

Note more qq MC required

HZ

Clear Higgs "peak": just a projection, clearer in 2D

Relative Likelihood

- ★ Use relative likelihood selection
- ★ Input variables
  - m_{qq} *vs.* m_{rec}
  - $|\cos\theta_Z|$
  - [..more to come]

Calculate absolute likelihood for given event type

$$L = P(m_{qq}, m_{rec}) \times P(|\cos\theta_Z|)$$

NOTE: 2D mass distribution includes main correlations

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

$$\mathcal{L}(\mathrm{HZ}) = \frac{L(\mathrm{HZ})}{L(\mathrm{HZ}) + L(\mathrm{back})}$$

Preliminary Results

Channel	Events	Effic.
Z H → qq qq	8145	27.0 %
Z H → qq ZZ	330	23.6 %
Z H → qq WW	2836	24.6 %
Z H → qq γγ	64	27.6 %
Z H → qq ττ	791	23.2 %
Z H → qq inv.	0	0
qq	18686	0.14 %
qqqq	27988	0.96 %
qqlv	4843	0.17 %
qqvv	53	0.03 %
qqll	2362	0.27 %

★ For optimal likelihood cut
- signal ~12k events
- background ~ 50k events

Efficiencies same to ~10 % !!!

almost model independent

Combined Sensitivity

$$\Delta\left(\sigma_{HZ}\frac{\Gamma_{vis}}{\Gamma}\right) = \pm 2.1\,\%$$ + $$\Delta\left(\sigma_{HZ}\frac{\Gamma_{invis}}{\Gamma}\right) = \pm 0.6\,\%$$

$$\Rightarrow \Delta(\sigma_{HZ}) = \pm 2.2\,\%$$

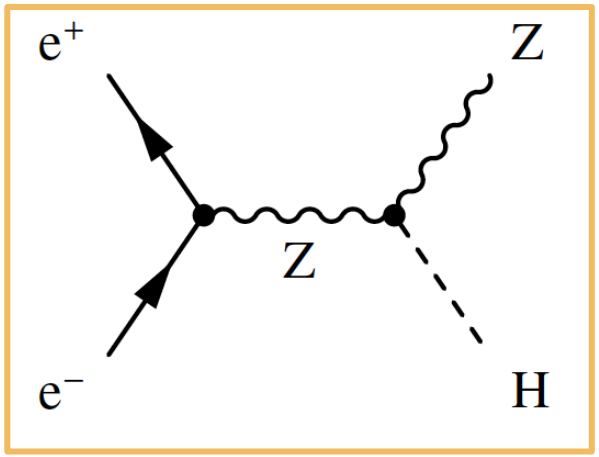
(CLIC beam spectrum, 500 fb^{-1} @ 350 GeV, no polarisation)

★ **Combined with leptonic recoil mass**

$$\Rightarrow \Delta(g_{HZZ}) \approx \pm 1.0\,\%$$

"almost model independent"

Summary



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- ★ Preliminary results look encouraging
- ★ Need to think about interpretation
  - how the results enter a combined fit
  - Systematic
- ★ This is a CLIC study, but applicable to ILC