Visible and Invisible Higgs Decays at 350 GeV

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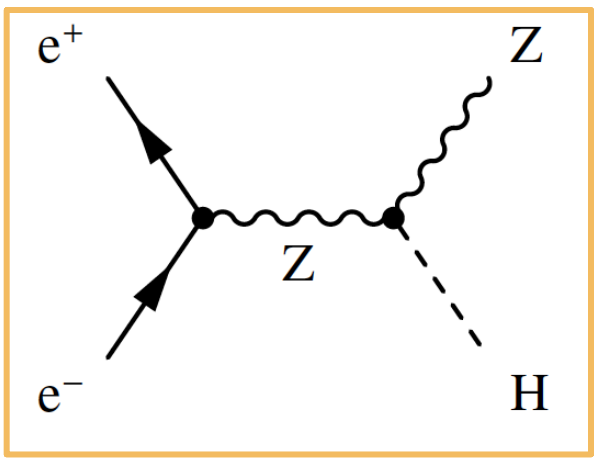

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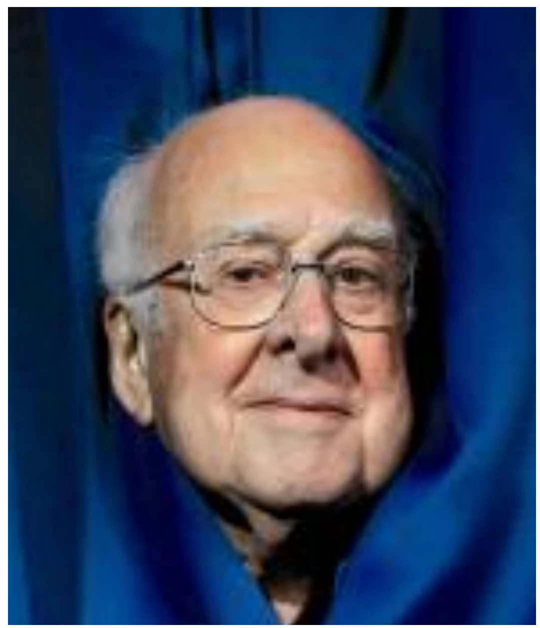

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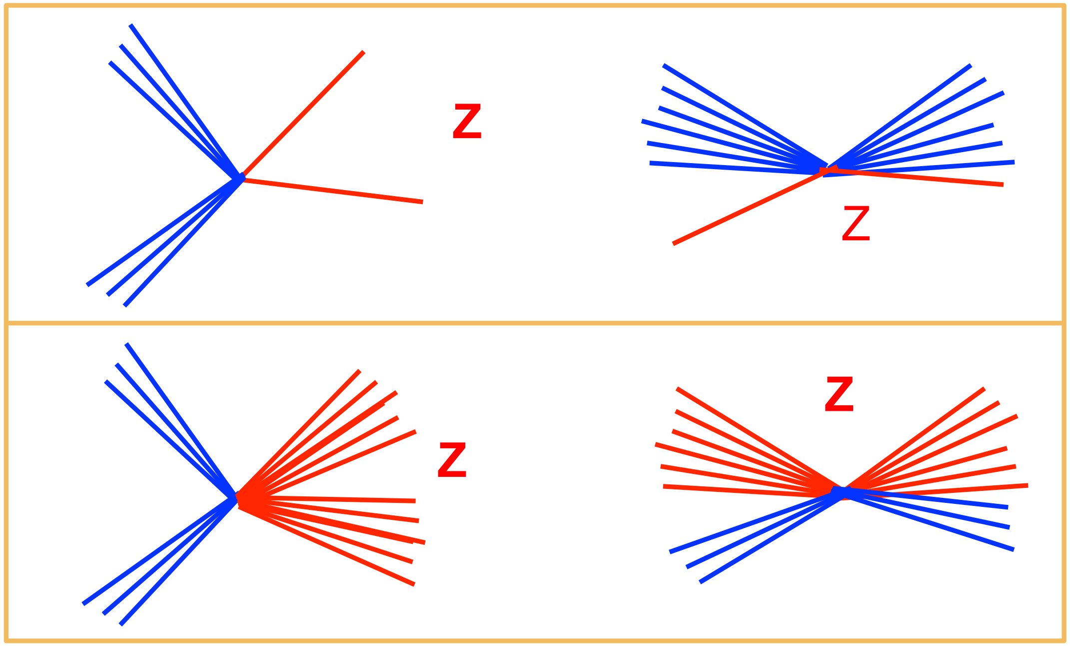
Recoil Mass

- ★ 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

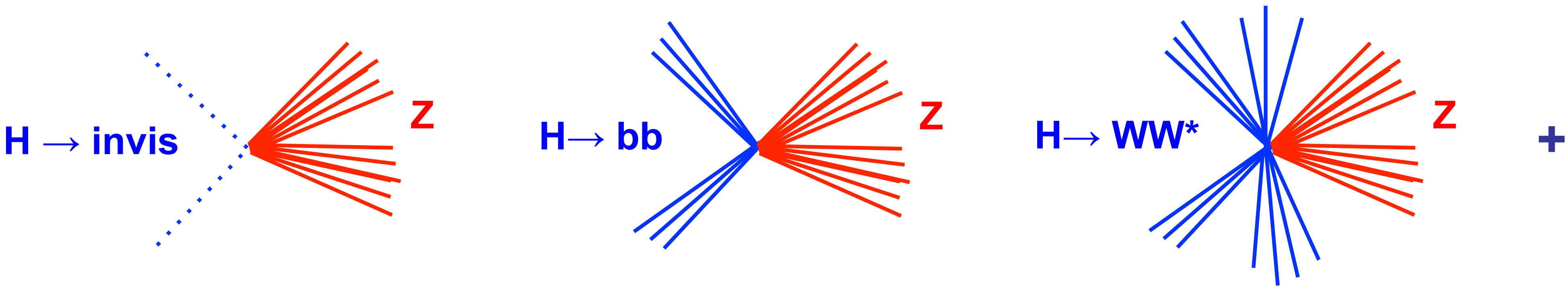
⇒ **Different efficiencies for different Higgs decays**

Study details

- ★ CLIC 350 GeV beam spectrum
- ★ CLIC_ILD detector model
- ★ Full simulation with overlayed background
- ★ 500 fb^{-1} unpolarised beams
- ★ Results from new optimised analysis

Analysis Strategy

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



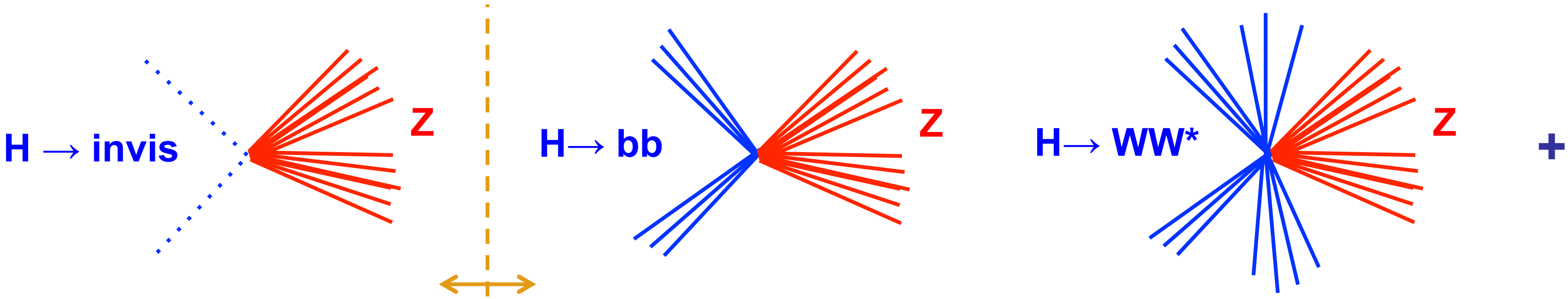
- ★ ZH signatures: Z + nothing or Z + other visible particles

First divide into candidate invisible and visible Higgs decays

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

Analysis Strategy

- ★ 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



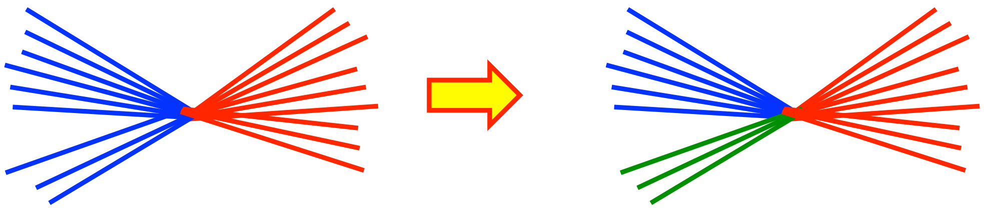
- ★ Force events into:
  - 2-jets: invisible decays [Kelvin's talk]
  - 3-, 4-, 5- and 6- "jet" topologies (R=1.5)

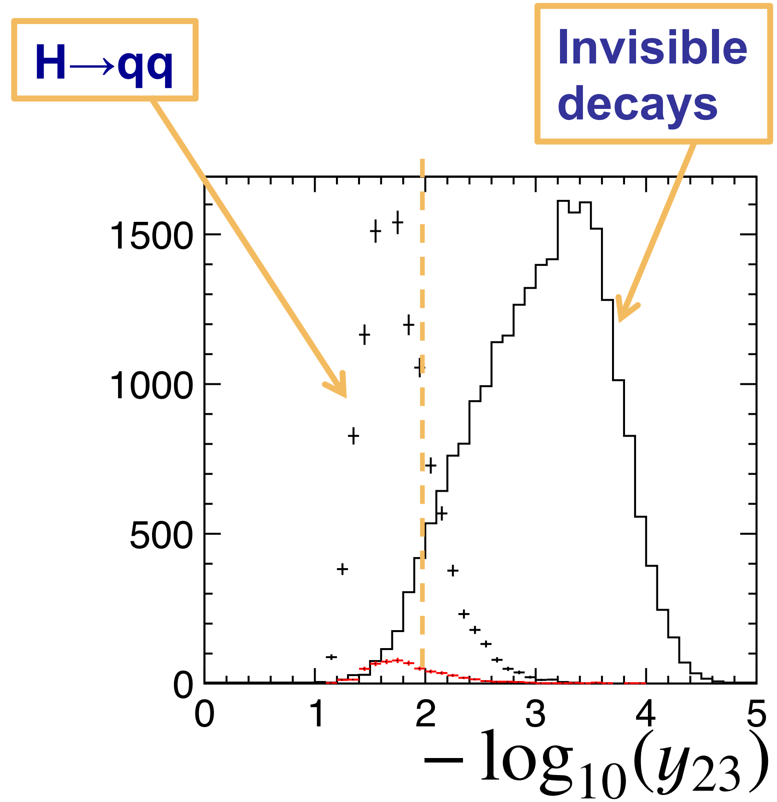
For each event will choose one topology

- 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

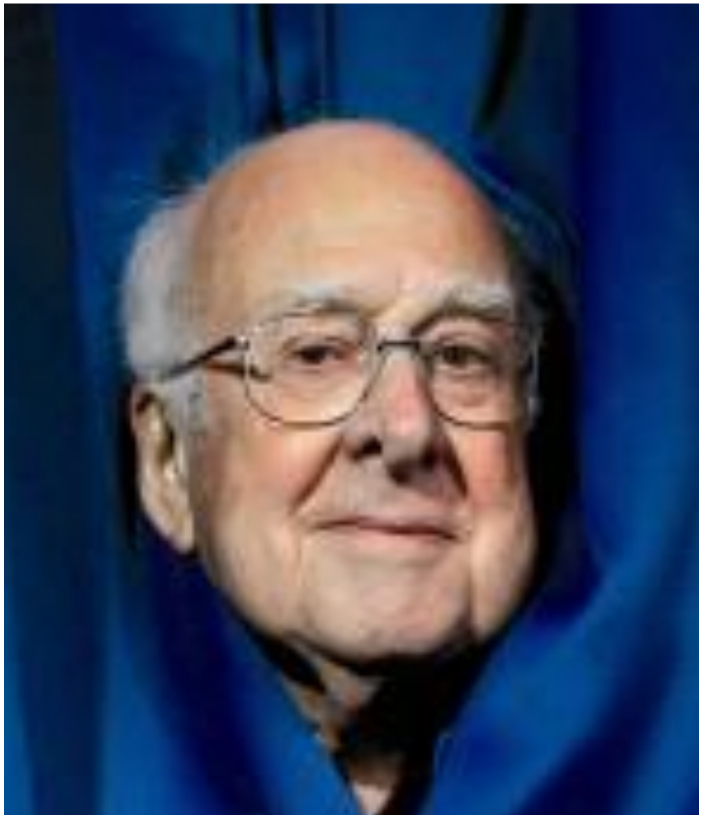




- ★ Also use y_{34}, the k_T value at which the event transitions from 3 jets to 4 jets

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

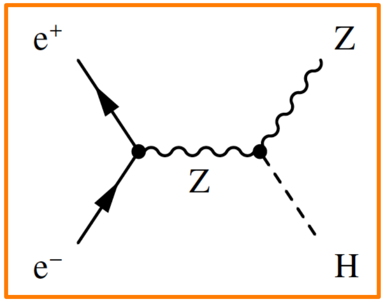
★ *All* events categorised in one of these two samples



Visible Decays

(> 2 jets)

Visible Higgs Decays

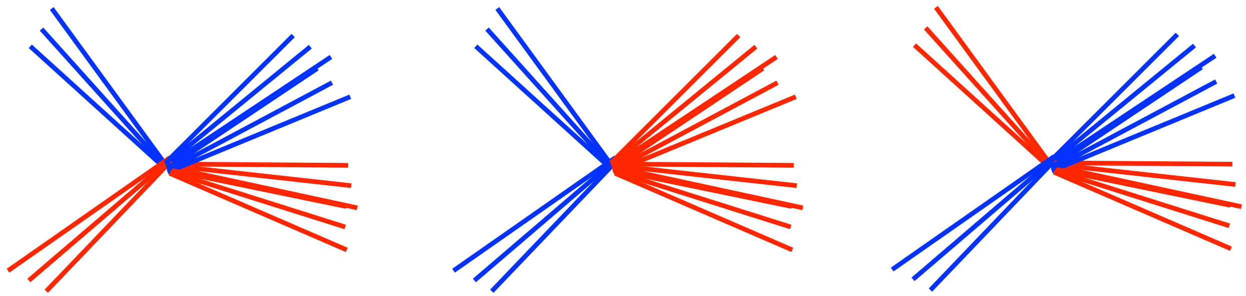


- ★ Have two jets from Z + Higgs decay products:
  - ★ H→qq : 4 quarks = 4 “jets”
  - ★ H→γγ : 2 quarks + 2 photons = 4 “jets”
  - ★ H→ττ : 2 quarks + 2 taus = 4 “jets”
  - ★ H→WW*→lνlν : 2 quarks + 2 leptons = 4 “jets”
  - ★ H→WW*→qqlν : 4 quarks + 1 lepton = 5 “jets”
  - ★ H→WW*→qqqq : 6 “jets”
  - ★ 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



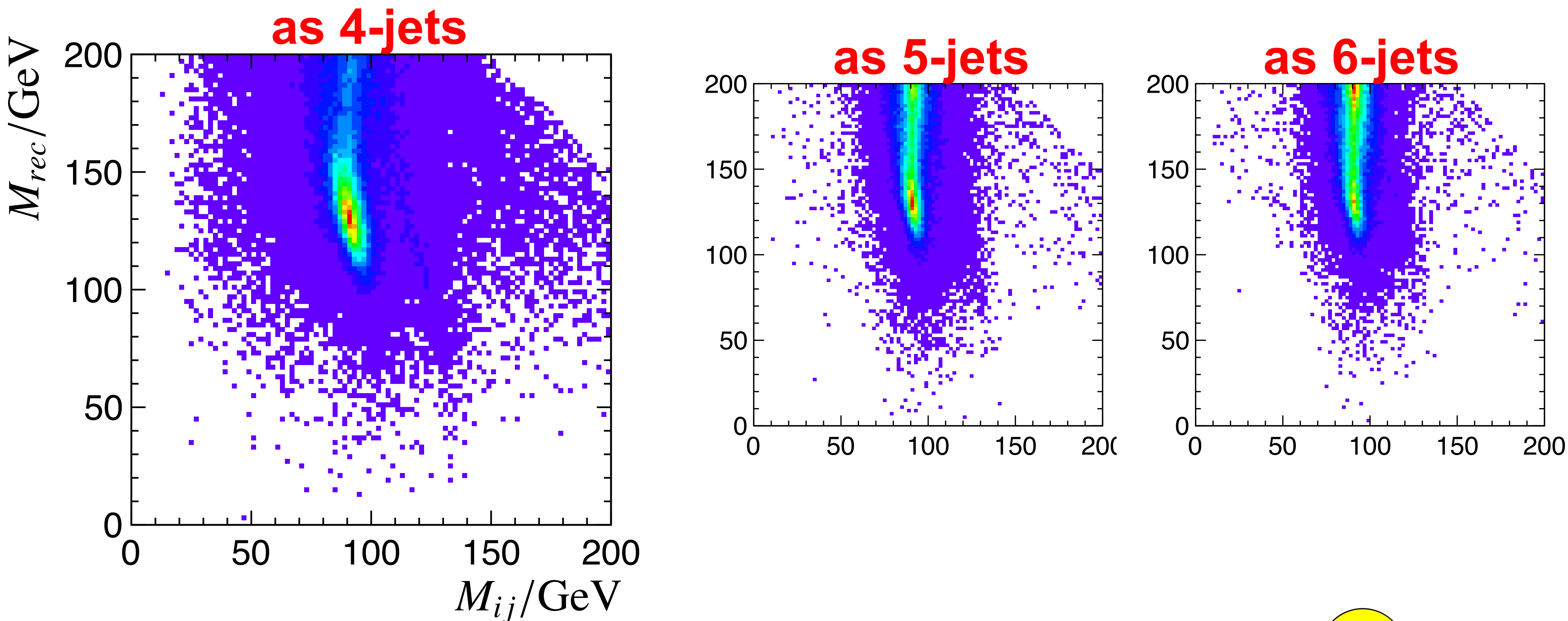
- ★ "Z" candidate = is the di-jet combination closest to Z mass from all three jet combinations, i.e. one per event

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

e.g. H→qq

★ For example, consider genuine ZH→qqqq decays

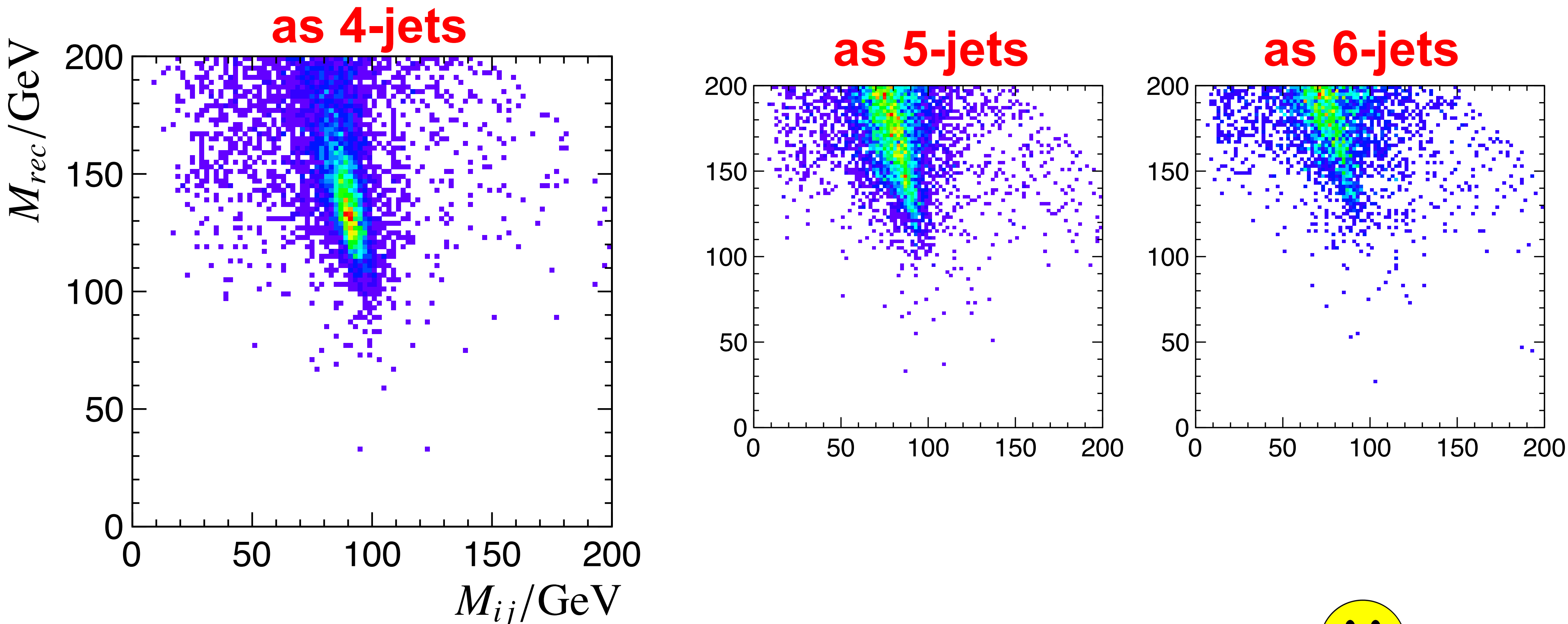
★ Plot mass of "candidate Z" vs. recoil mass for 4-, 5-, 6-jet hypotheses



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

e.g. H→ττ

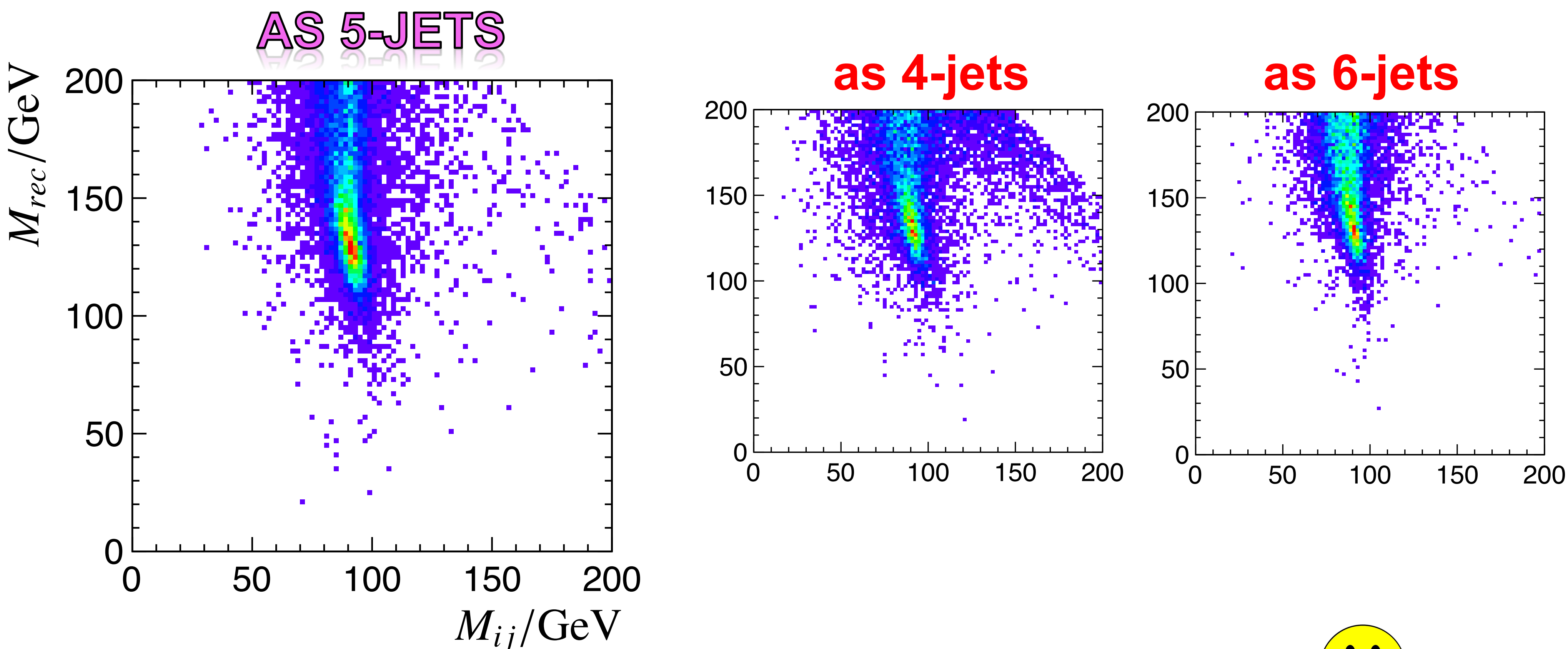
★ **Similarly for ZH→qqττ**



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

e.g. H→WW*→qqlν

★ **Similarly for ZH→qqWW* → qqqqlν**



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

Preselection

★ **Preselection now greatly simplified**

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

Not two-jet like

$$70\,\mathrm{GeV} < m_{\mathrm{q\bar{q}}} < 130\,\mathrm{GeV}$$
$$80\,\mathrm{GeV} < m_{\mathrm{recoil}} < 200\,\mathrm{GeV}$$

Very loose mass cuts

★ **Targeted background cuts for:**

$\mathrm{q\bar{q}}$

$\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}}\ell\nu$

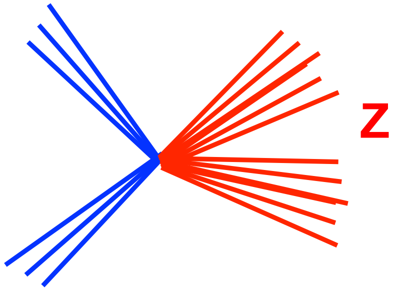
$\mathrm{W^+W^-} \rightarrow \mathrm{q\bar{q}q\bar{q}}$

$\mathrm{ZZ} \rightarrow \mathrm{q\bar{q}}\ell^+\ell^-$

$\mathrm{ZZ} \rightarrow \mathrm{q\bar{q}q\bar{q}}$

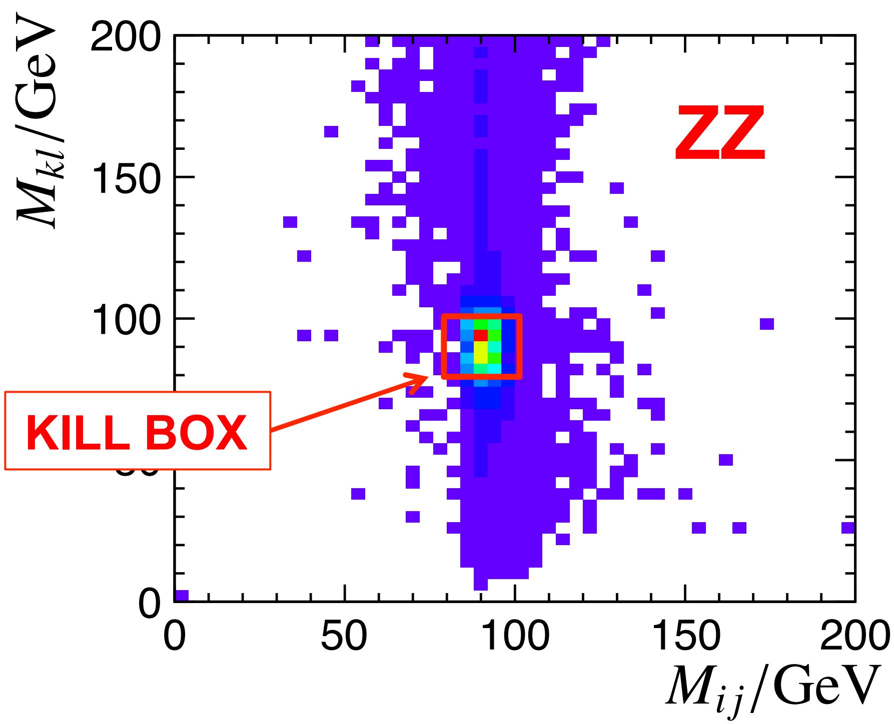
New:
- ★ Simplified
- ★ Optimised

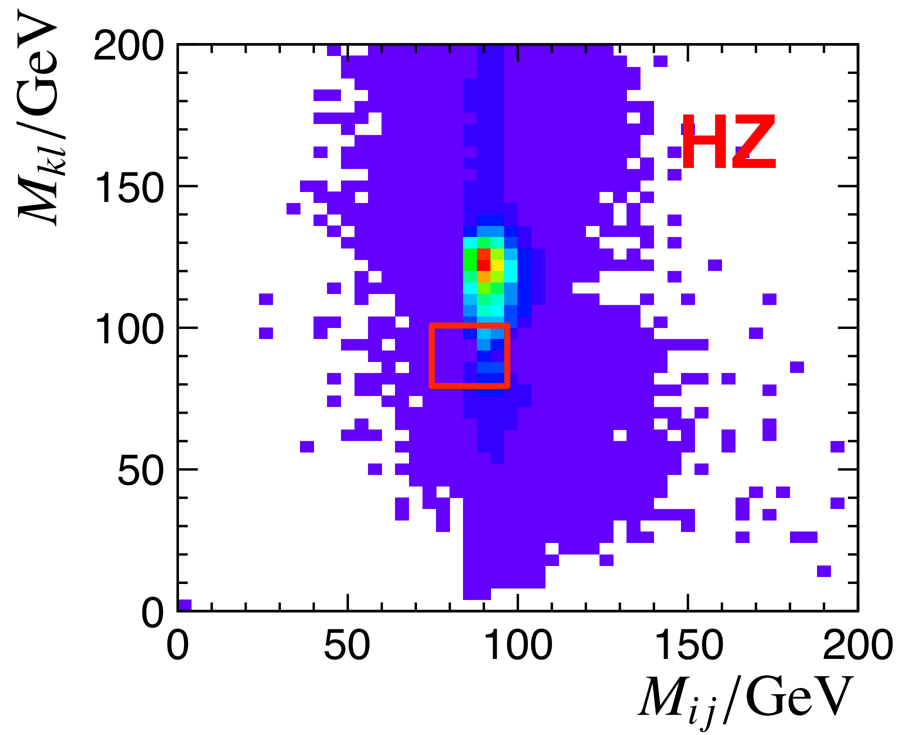
e.g. ZZ → qqqq



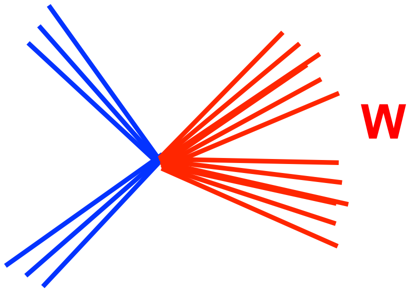
- **Assume each event is ZZ → qqqq**
- **Therefore: force into 4 jets**
- **Choose jet pairing (12)(34), (13)(24) or (14)(23) with single jet-pair mass closest to Z mass**

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

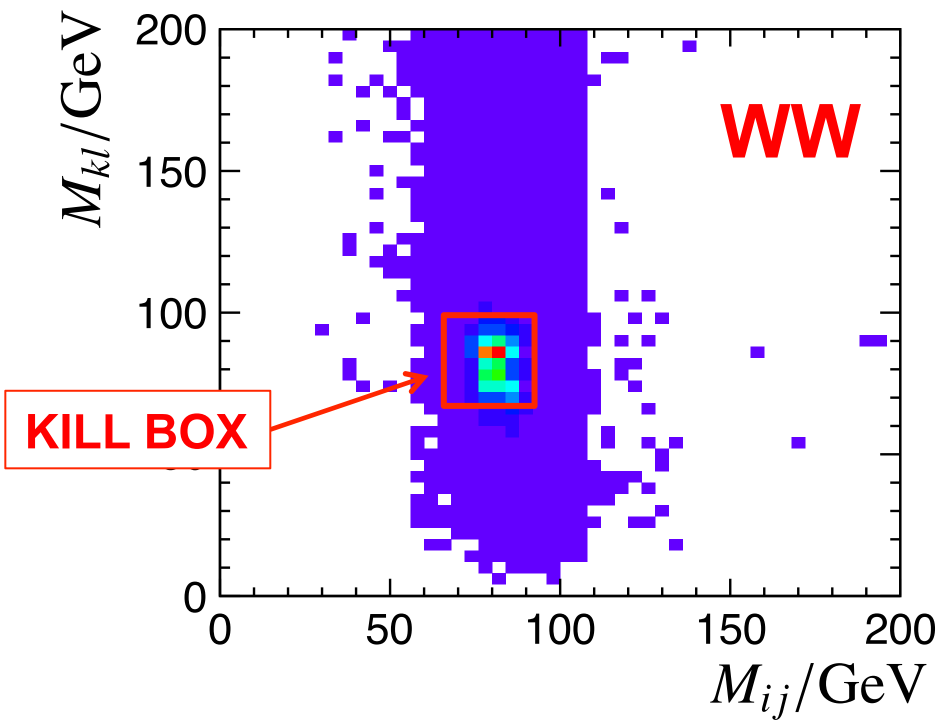


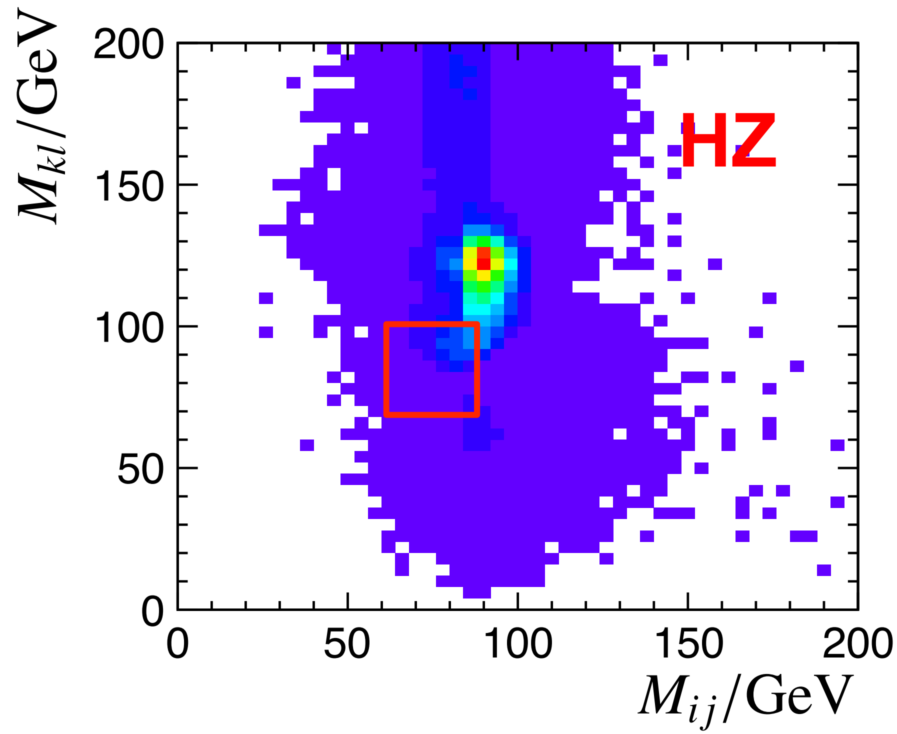


e.g. WW → qqqq

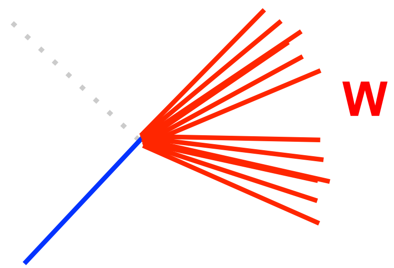


- Assume event is WW → qqqq
- Therefore: force into 4 jets
- Choose jet pairing (12)(34), (13)(24) or (14)(23) with single jet-pair mass closest to W mass

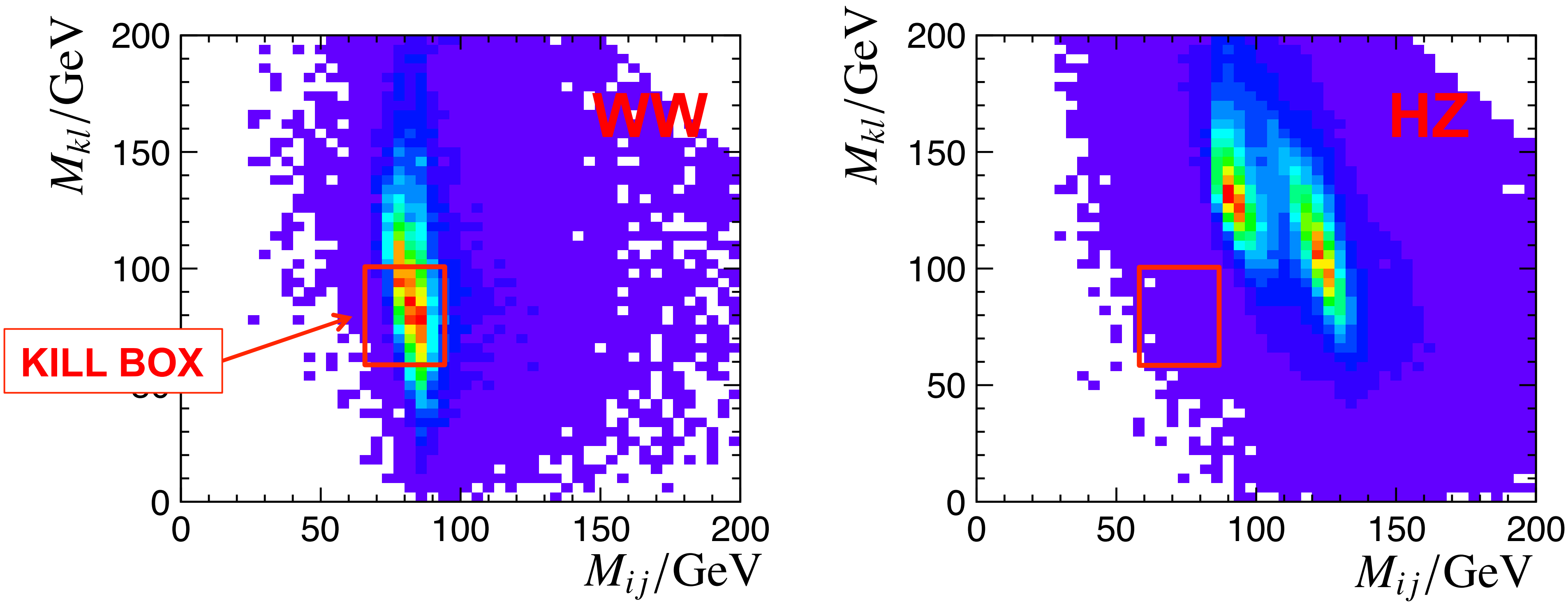




e.g. WW → qqlv



- 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?

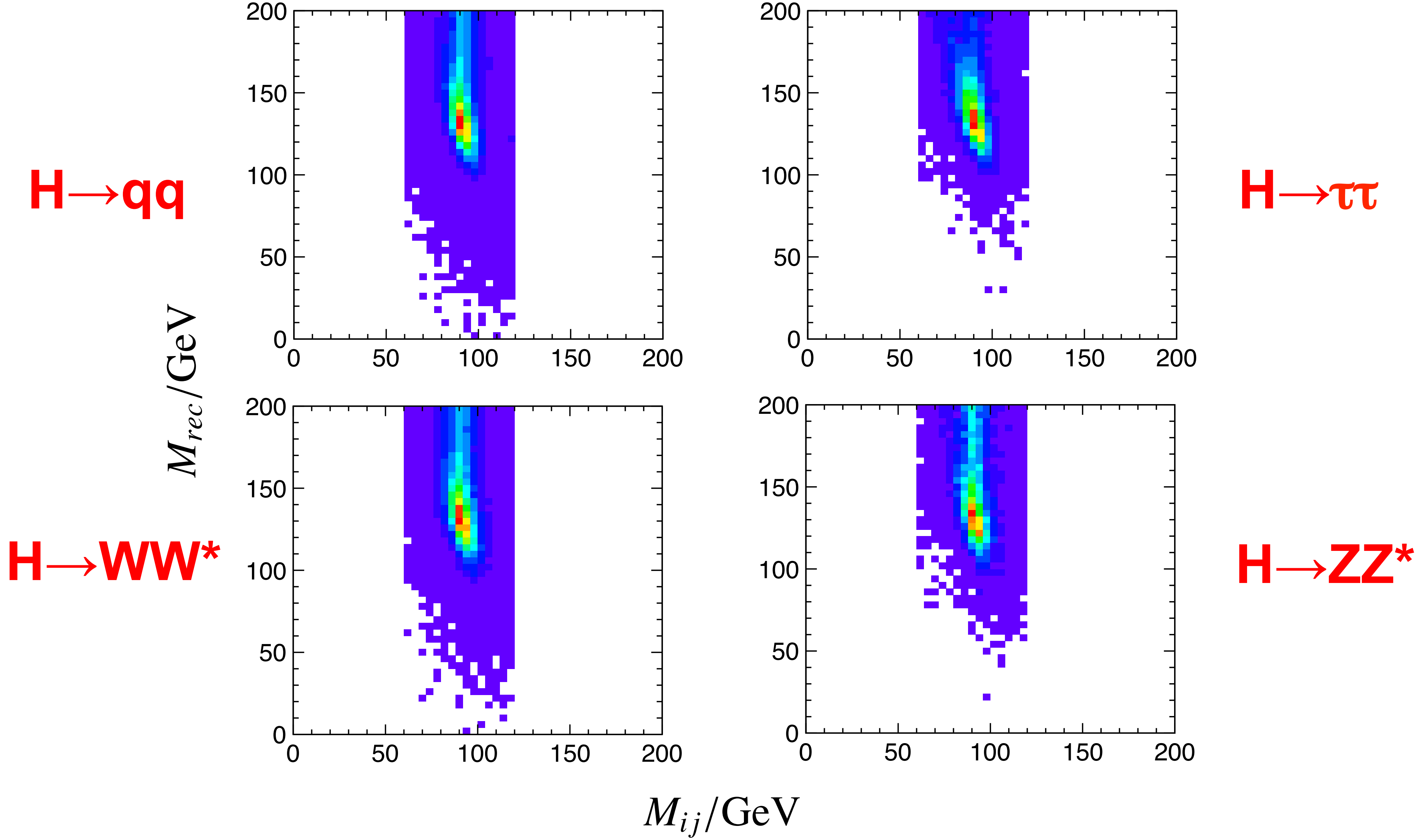
★ Find that it rarely helps going from 5 → 6:
   even if a 6-jet final state, provided reconstruct two "hard" jets from Z decay OK

So choose between 4 or 5 jet topology:

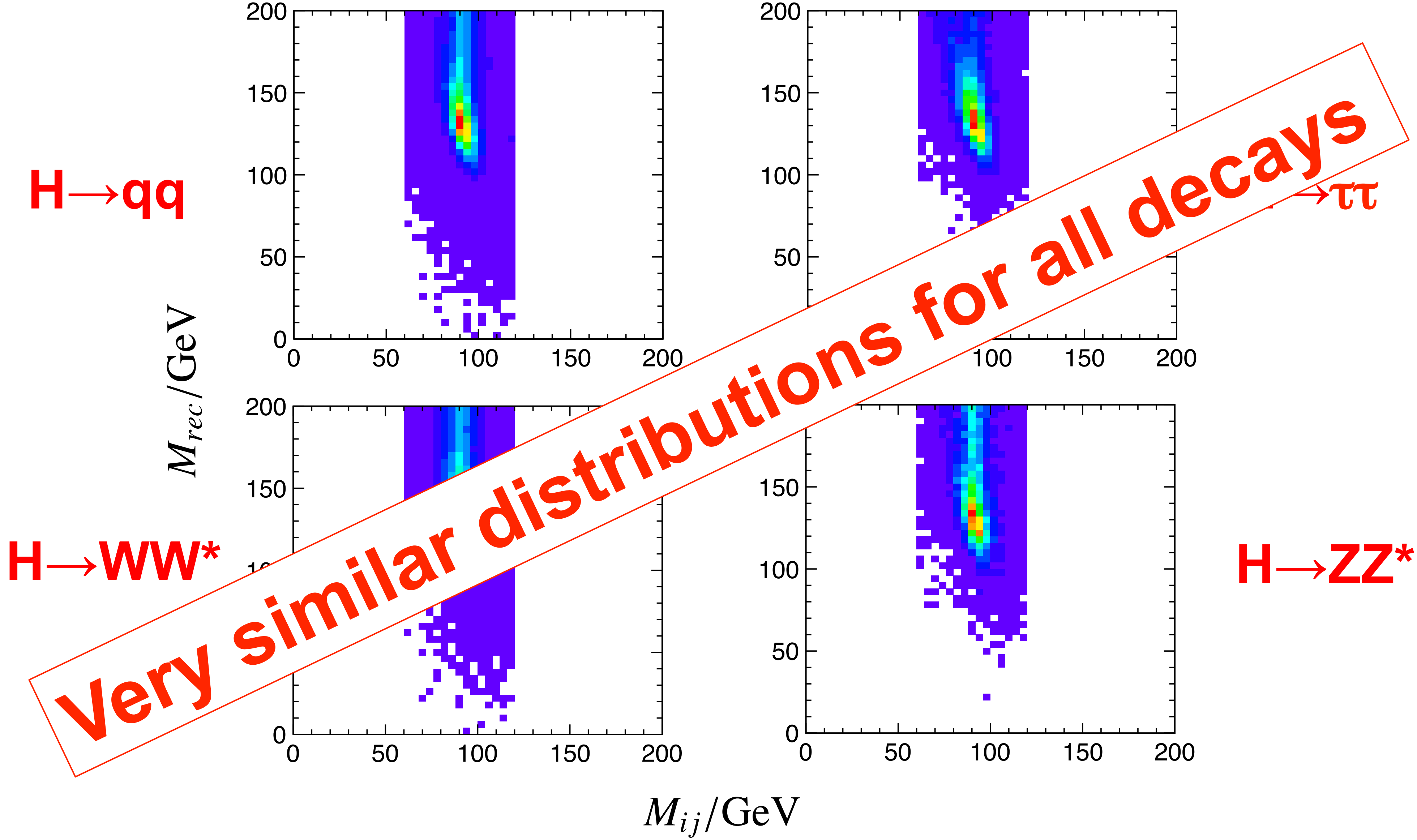
★ Default is to treat as 4-jets
★ Reconstruct as 5-jets only if:
   - $-\log_{10}(y_{45}) < 3.5$ **AND**
   - 5-jet reconstruction gives "better" Z mass and "better" Higgs recoil mass

     "better" = closer to true masses

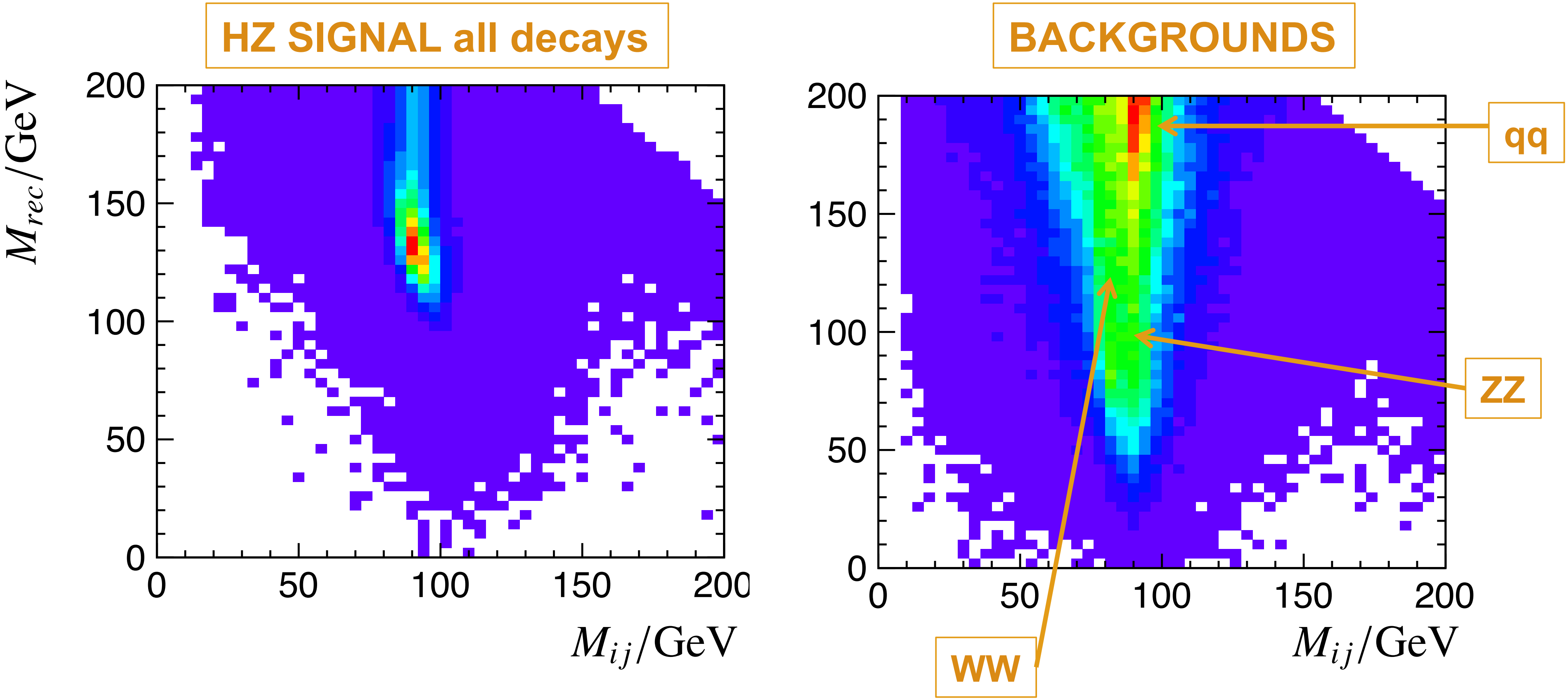
Signal m_{qq} vs m_{rec}



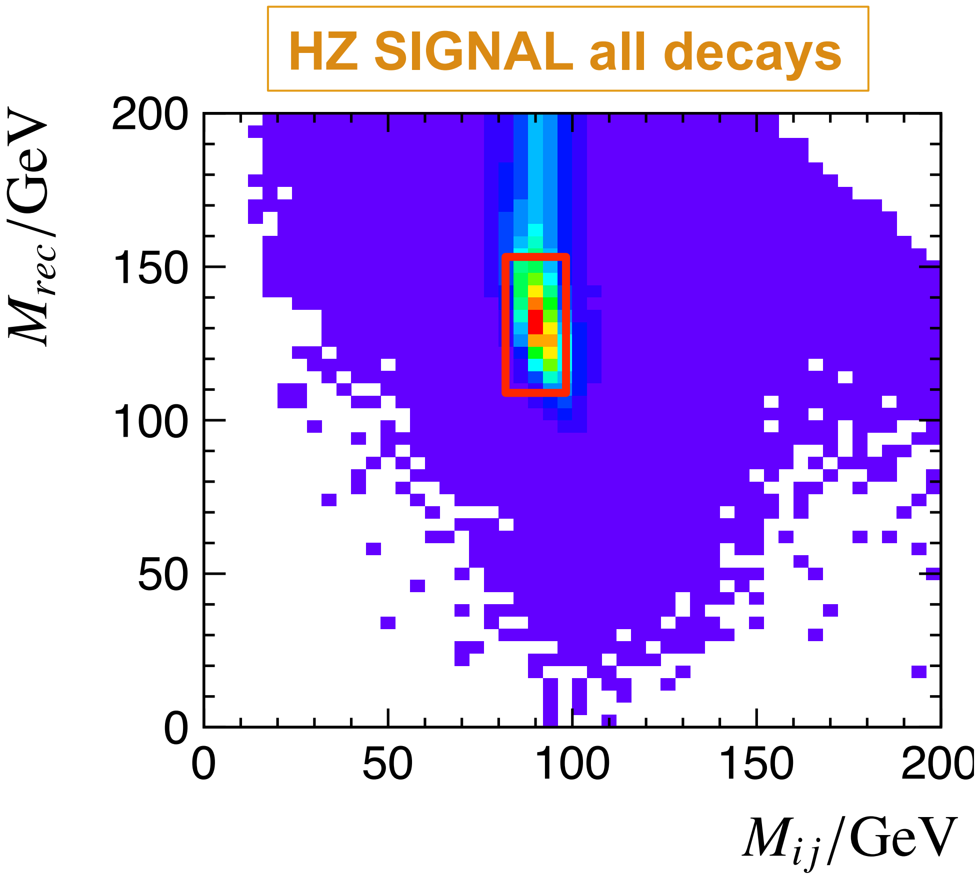
Signal m_{qq} vs m_{rec}

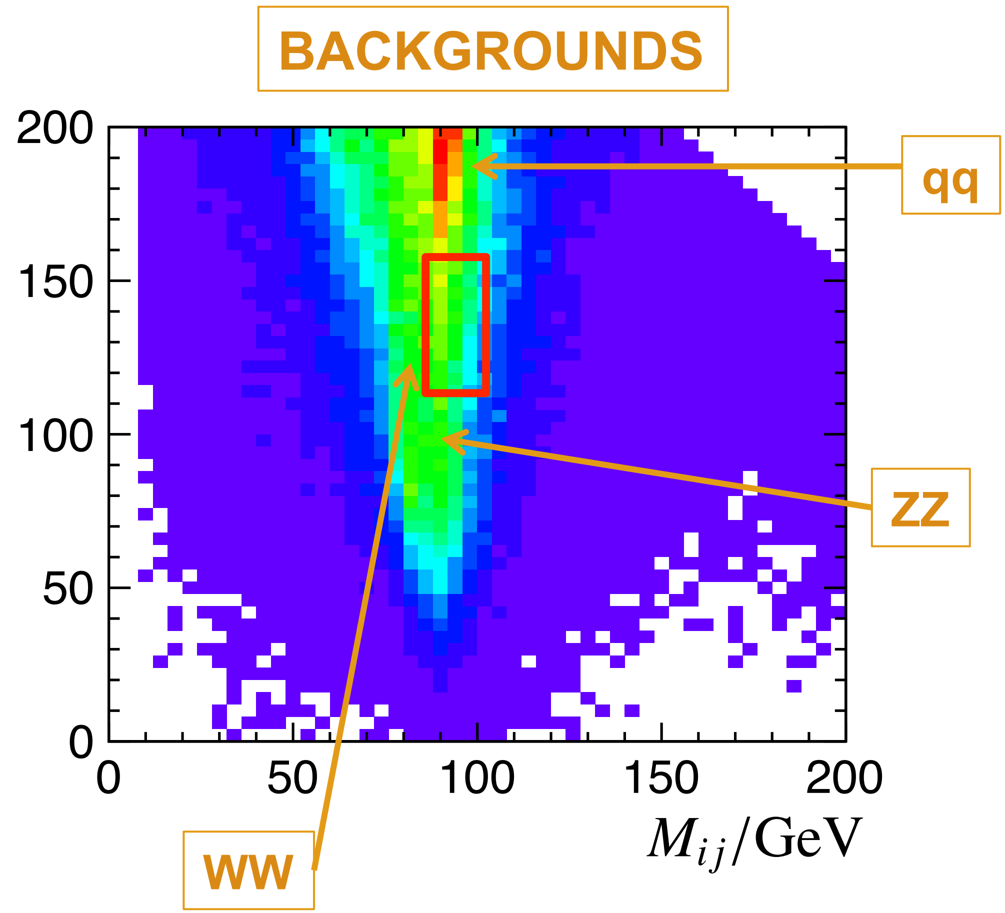


Signal vs Background



Signal vs Background





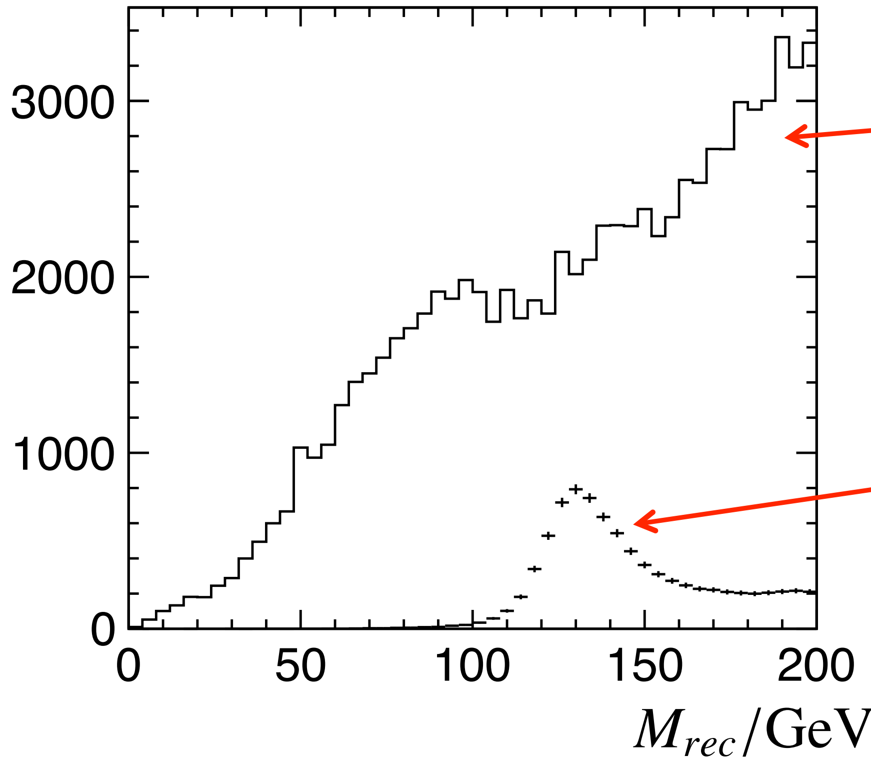
★ **Signal region clearly separated from background**

That's about it !

$$|\cos\theta_{\rm jet}^{1,2}| < 0.95$$ Both jets well measured (hopefully)

$$84\,{\rm GeV} < m_{\rm qq} < 108\,{\rm GeV}$$ Looks like Z

$$|\cos\theta_{\rm Z}| < 0.7$$ Z produced centrally



Note more qq MC required

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

Relative Likelihood

- Use relative likelihood selection
- Input variables
  - m_{qq} *vs.* m_{rec}
  - $|\cos\theta_Z|$
  - $|\cos\theta_q^*|$

Calculate absolute likelihood for given event type

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

NOTE: 2D mass distribution includes main correlations

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

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

Final(?) Results

Process	σ/fb	ε_{presel}	$\varepsilon_{\mathcal{L}>0.70}$	$N_{\mathcal{L}>0.70}$
$q\bar{q}$	25180	0.5 %	<0.1 %	6211
$q\bar{q}l\nu$	5914	6.4 %	0.1 %	3895
$q\bar{q}q\bar{q}$	5847	4.2 %	0.4 %	10818
$q\bar{q}ll$	1704	1.2 %	0.1 %	1218
$q\bar{q}\nu\bar{\nu}$	325	0.6 %	<0.1 %	35
$H\nu_e\bar{\nu}_e$		- %		
HZ	93.4	44.0 %	20.3 %	9493
$H \to$ invis.		0.6 %	<0.1 %	–
$H \to q\bar{q}/gg$		43.5 %	20.6 %	6211
$H \to WW^*$		44.7 %	19.5 %	2240
$H \to ZZ^*$		40.0 %	18.1 %	254
$H \to \tau^+\tau^-$		47.6 %	21.4 %	738
$H \to \gamma\gamma$		42.8 %	22.1 %	32
$H \to Z\gamma$		41.8 %	17.6 %	17
$H \to \mu^+\mu^-$		39.5 %	20.6 %	3

★ **For optimal cut**
- signal ~9.5k events
- background ~ 19k events

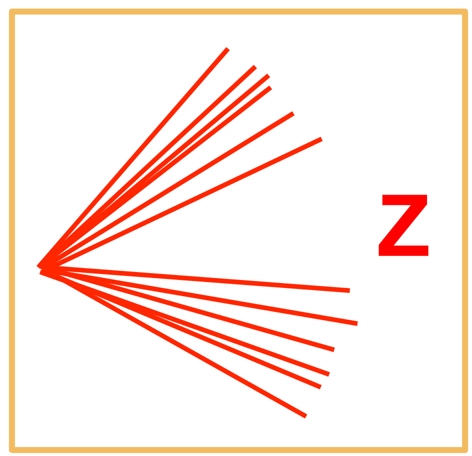
15 % improvement c.f. LCWS analysis

Efficiencies same to ~10 % !!!

almost model independent

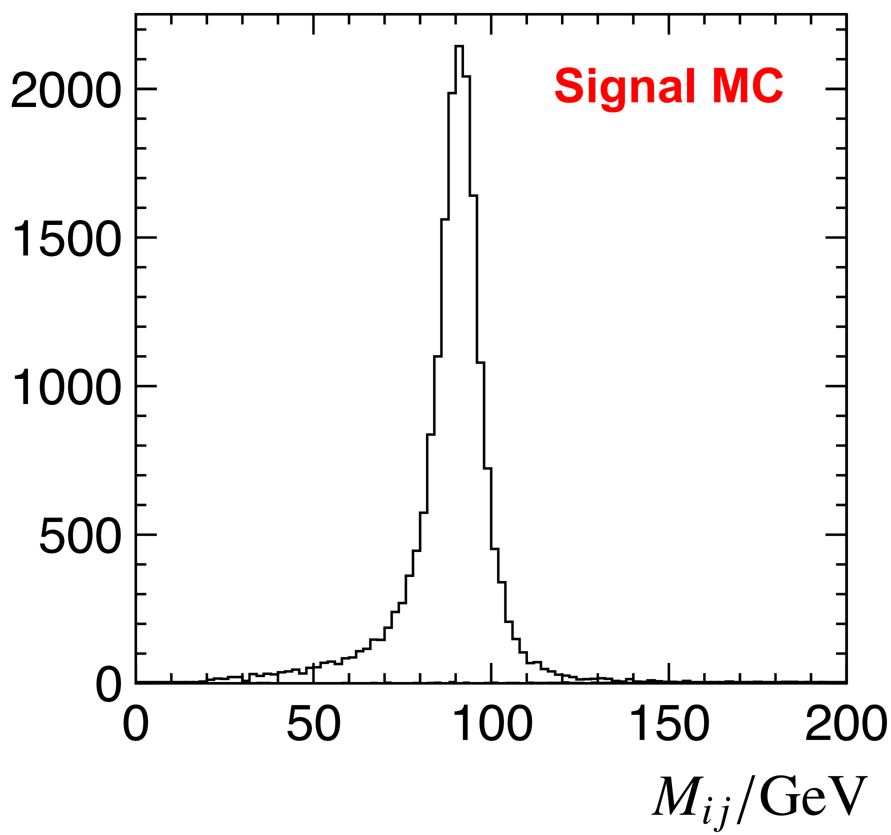
Analysis performed by:
Kelvin Mei

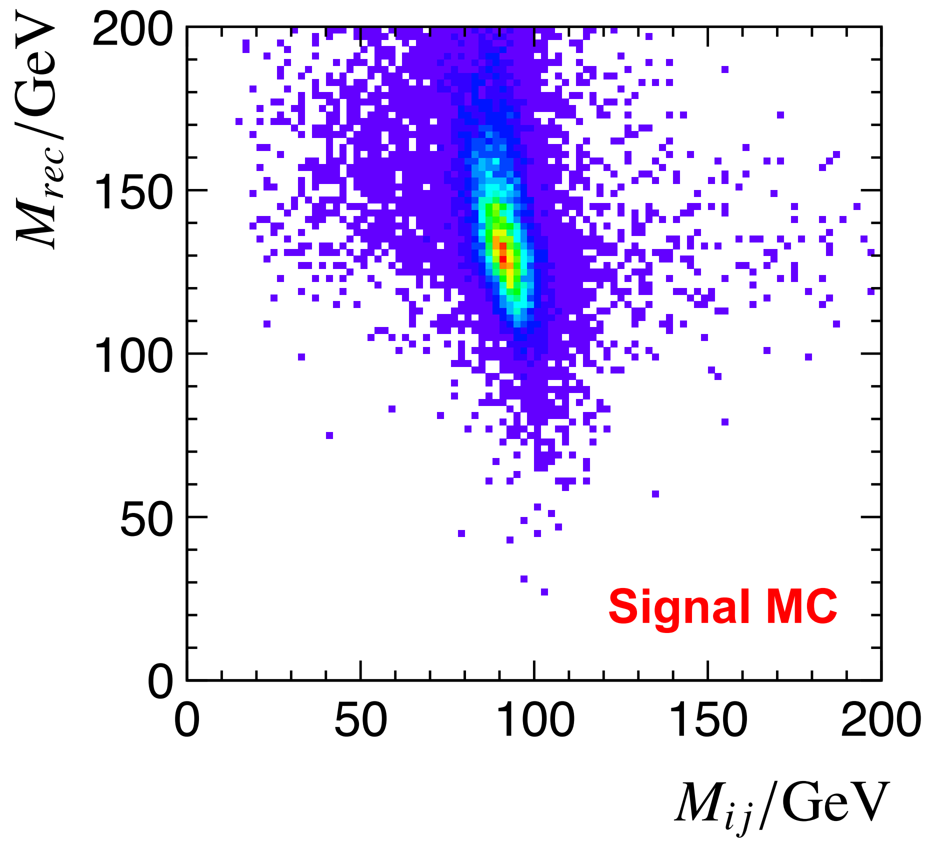
Invisible Decays



Invisible Higgs Decays

- Start from **2-jet** sample: essentially removes ~all Higgs "background" (except $H \to ZZ^* \to \nu\nu\nu\nu$ and a little $H \to \tau\tau$)
- Cut on di-jet mass (Z) and recoil mass (H) to select events





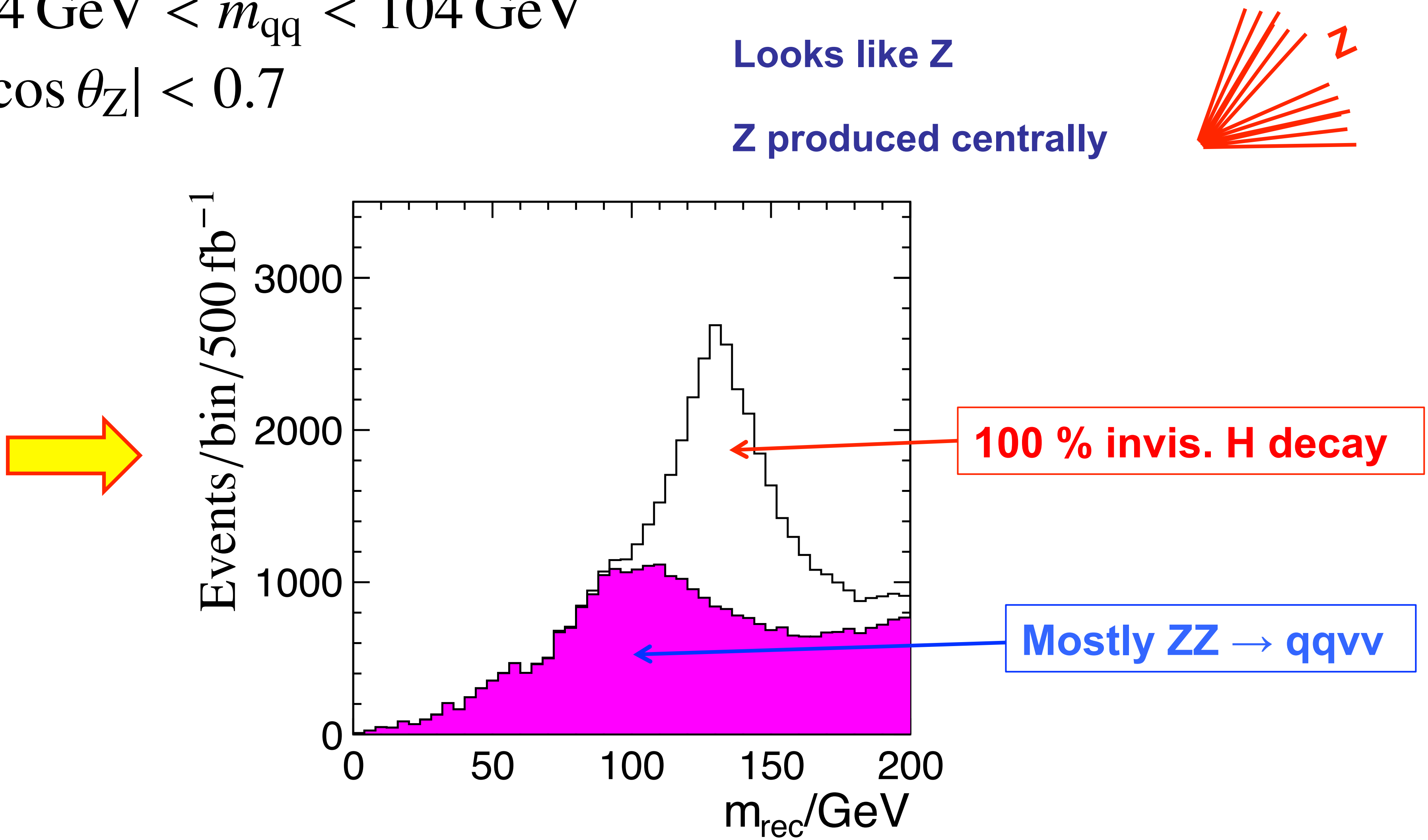
That's about it !

$$84\,\text{GeV} < m_{qq} < 104\,\text{GeV}$$
$$|\cos\theta_Z| < 0.7$$

Both jets well measured (hopefully)

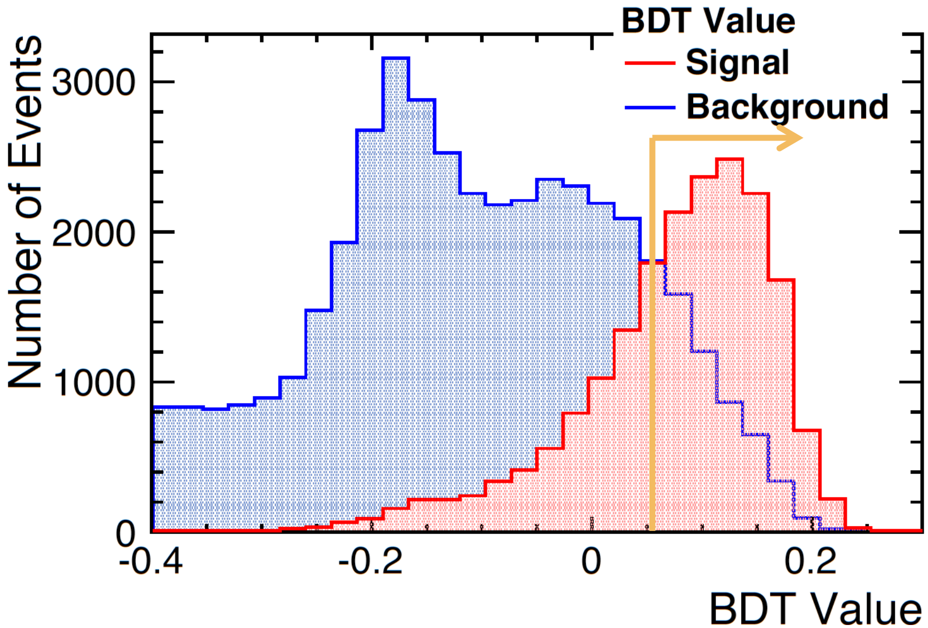
Looks like Z

Z produced centrally



BDT Selection

★ **Preliminary results (7 variable BDT selection)**



Signal

Channel	Efficiency
Z H → qq invis.	20.7 %

Backgrounds

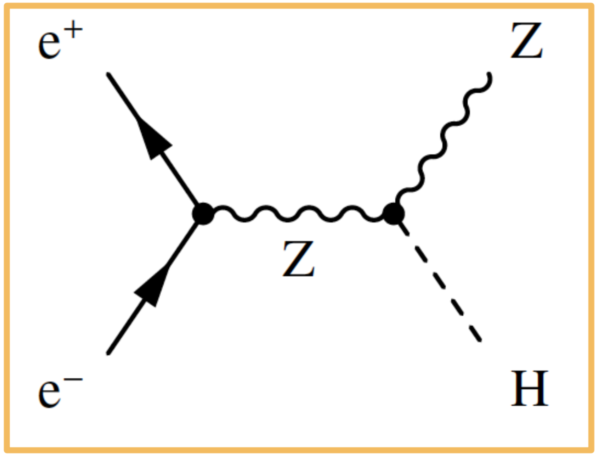
Channel	Efficiency	Events
qqlv	<0.1 %	900
qqll	<0.1 %	4
qqvv	1.5 %	2414

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

$$\Rightarrow \quad \Delta\sigma_{invis} = \pm 0.57\,\%$$

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

Model Independence



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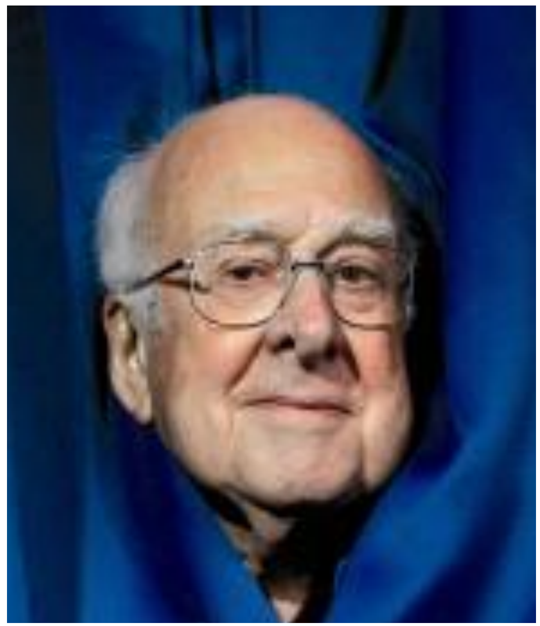

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Model Indepedence

- ★ Combining visible + invisible analysis: wanted M.I.
  - i.e. efficiency independent of Higgs decay mode

Decay mode	$\varepsilon^{\text{vis}}_{\mathscr{L}>0.70}$	$\varepsilon^{\text{invis}}_{\text{BDT}>0.08}$	$\varepsilon^{\text{vis}} + \varepsilon^{\text{invis}}$
$H \to$ invis.	<0.1 %	20.7 %	20.7 %
$H \to q\bar{q}/gg$	20.6 %	<0.1 %	20.6 %
$H \to WW^*$	19.5 %	<0.1 %	19.8 %
$H \to ZZ^*$	18.1 %	0.9 %	19.0 %
$H \to \tau^+\tau^-$	21.4 %	0.1 %	21.5 %
$H \to \gamma\gamma$	22.1 %	<0.1 %	22.1 %
$H \to Z\gamma$	17.6 %	<0.1 %	17.1 %
$H \to \mu^+\mu^-$	20.6 %	<0.1 %	20.6 %

Very similar efficiencies

Model Indepedence

- Combining visible + invisible analysis: wanted M.I.
  - i.e. efficiency independent of Higgs decay mode

Decay mode	$\varepsilon^{\mathrm{vis}}_{\mathscr{L}>0.70}$	$\varepsilon^{\mathrm{invis}}_{\mathrm{BDT}>0.08}$	$\varepsilon^{\mathrm{vis}} + \varepsilon^{\mathrm{invis}}$
$\mathrm{H} \to \mathrm{invis.}$	<0.1 %	20.7 %	20.7 %
$\mathrm{H} \to \mathrm{q\bar{q}/gg}$	20.6 %	<0.1 %	20.6 %
$\mathrm{H} \to \mathrm{WW}^*$	19.5 %	<0.1 %	19.8 %
$\mathrm{H} \to \mathrm{ZZ}^*$	18.1 %	0.9 %	19.0 %
$\mathrm{H} \to \tau^+\tau^-$	21.4 %	0.1 %	21.5 %
$\mathrm{H} \to \gamma\gamma$	22.1 %	<0.1 %	22.1 %
$\mathrm{H} \to \mathrm{Z}\gamma$	17.6 %	<0.1 %	17.1 %
$\mathrm{H} \to \mu^+\mu^-$	20.6 %	<0.1 %	20.6 %
$\mathrm{H} \to \mathrm{WW}^* \to \mathrm{q\bar{q}q\bar{q}}$	19.3 %	<0.1 %	19.3 %
$\mathrm{H} \to \mathrm{WW}^* \to \mathrm{q\bar{q}l\nu}$	19.6 %	<0.1 %	19.6 %
$\mathrm{H} \to \mathrm{WW}^* \to \mathrm{q\bar{q}\tau\nu}$	19.9 %	<0.1 %	19.9 %
$\mathrm{H} \to \mathrm{WW}^* \to \mathrm{l\nu l\nu}$	22.0 %	0.3 %	22.3 %
$\mathrm{H} \to \mathrm{WW}^* \to \mathrm{l\nu\tau\nu}$	16.7 %	0.3 %	17.0 %
$\mathrm{H} \to \mathrm{WW}^* \to \tau\nu\tau\nu$	12.2 %	1.3 %	13.6 %

Very similar efficiencies

Look at wide range of WW topologies

Combined Sensitivity

$$\Delta\left(\sigma_{HZ}\frac{\Gamma_{vis}}{\Gamma}\right) = \pm 1.7\,\%$$ **+** $$\Delta\left(\sigma_{HZ}\frac{\Gamma_{invis}}{\Gamma}\right) = \pm 0.6\,\%$$

$$\Rightarrow \Delta(\sigma_{HZ}) = \pm 1.8\,\%$$

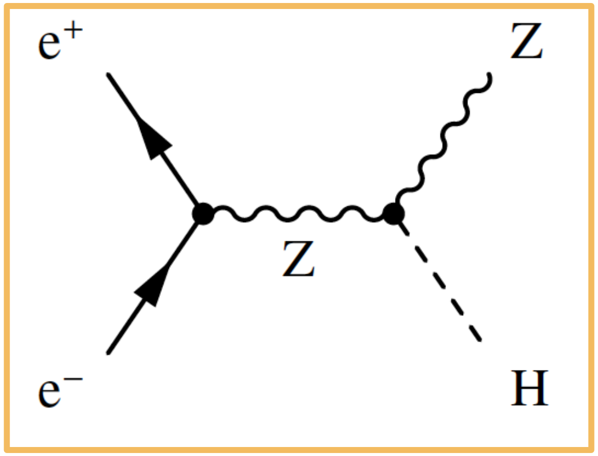
(CLIC beam spectrum, 500 fb^{-1} @ 350 GeV, no polarisation)

★ **Combined with leptonic recoil mass**

$$\Rightarrow \Delta(g_{HZZ}) \approx \pm 0.8\,\%$$

"almost model independent"

Summary



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★ **Results now "final" ?**

★ **0.8 % statistical sensitivity to g_{HZZ}**