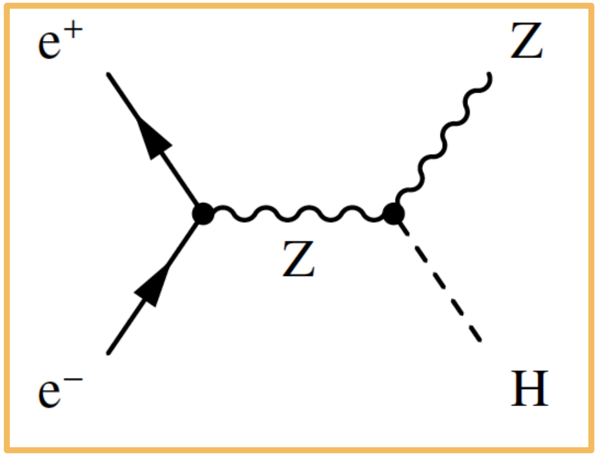
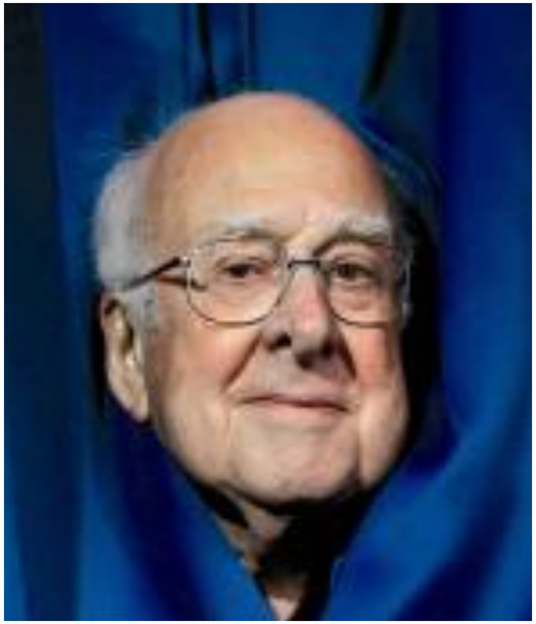
Visible and Invisible Higgs Decays at 350 GeV

Mark Thomson
University of Cambridge



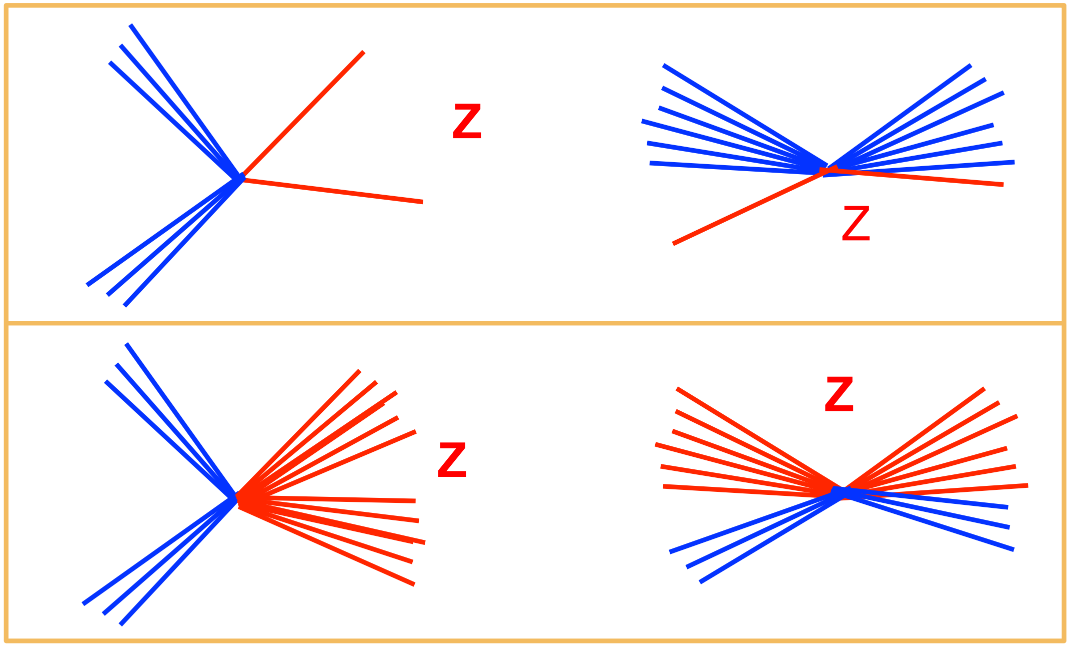
=



+

Recall

- ★ 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**

Model Indepedence

- Status as of May 2015 (AWLC14)
  - ~M.I. but some weaknesses…

Decay mode	$\varepsilon^{\text{vis}}_{\mathcal{L}>0.70}$	$\varepsilon^{\text{invis}}_{\text{BDT}>0.08}$	$\varepsilon^{\text{vis}}+\varepsilon^{\text{invis}}$
$H\to$ 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 %
$H\to WW^*\to q\bar{q}q\bar{q}$	19.3 %	<0.1 %	19.3 %
$H\to WW^*\to q\bar{q}l\nu$	19.6 %	<0.1 %	19.6 %
$H\to WW^*\to q\bar{q}\tau\nu$	19.9 %	<0.1 %	19.9 %
$H\to WW^*\to l\nu l\nu$	22.0 %	0.3 %	22.3 %
$H\to WW^*\to l\nu\tau\nu$	16.7 %	0.3 %	17.0 %
$H\to WW^*\to\tau\nu\tau\nu$	12.2 %	1.3 %	13.6 %

Very similar efficiencies

Look at wide range of WW topologies

Re-evaluation

★ Major re-evaluation

★ Aim to:

- Reduce model dependence
- Increase robustness
- Simplify analysis

★ Major re-structuring

- Use non-optimal invisible analysis
- Likelihood fit based signal extraction
- Proper assessment of M.I.

1) Common Preselection

★ **Previously:**
- Different preselection cuts for visible & invisible decays

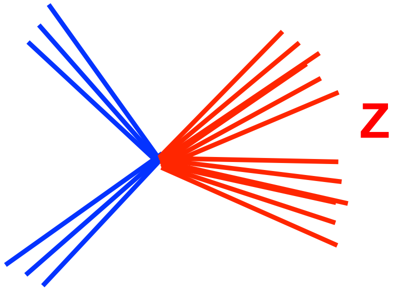
⇩

★ **Now:**
- Common preselection – simplifies analysis
- Veto events clearly consistent with:
  - $ZZ \rightarrow qqqq$
  - $ZZ \rightarrow qqll$
  - $WW \rightarrow qqqq$
  - $e^+e^- \rightarrow qq$
  - $WW \rightarrow qql\nu$

Only applied if p_T < 25 GeV (ZZ → qqqq, ZZ → qqll, WW → qqqq, e⁺e⁻ → qq)

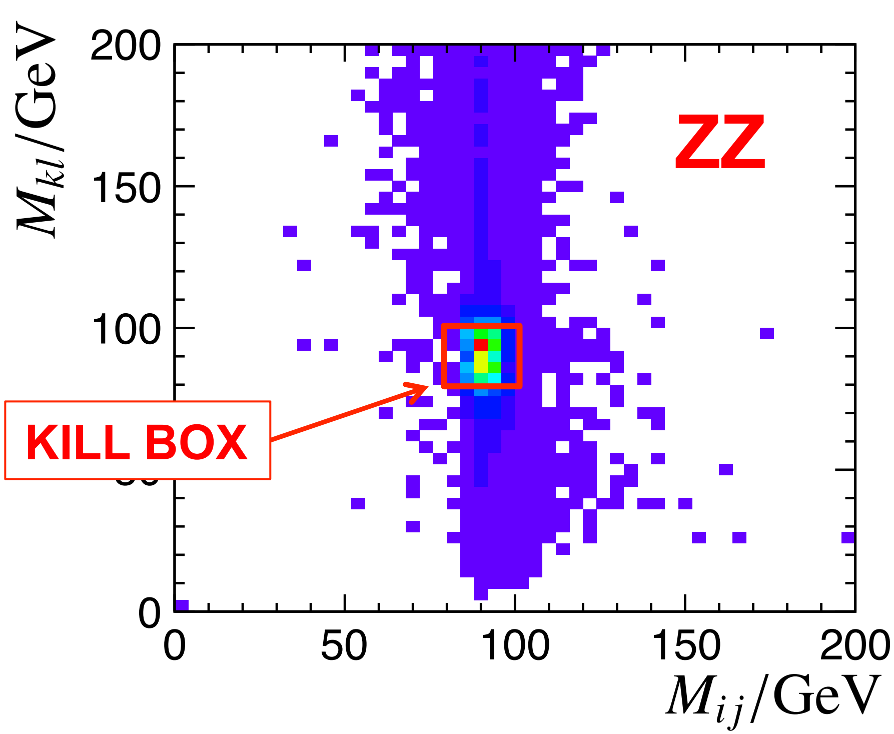
Only applied if p_T > 25 GeV (WW → qqlν)

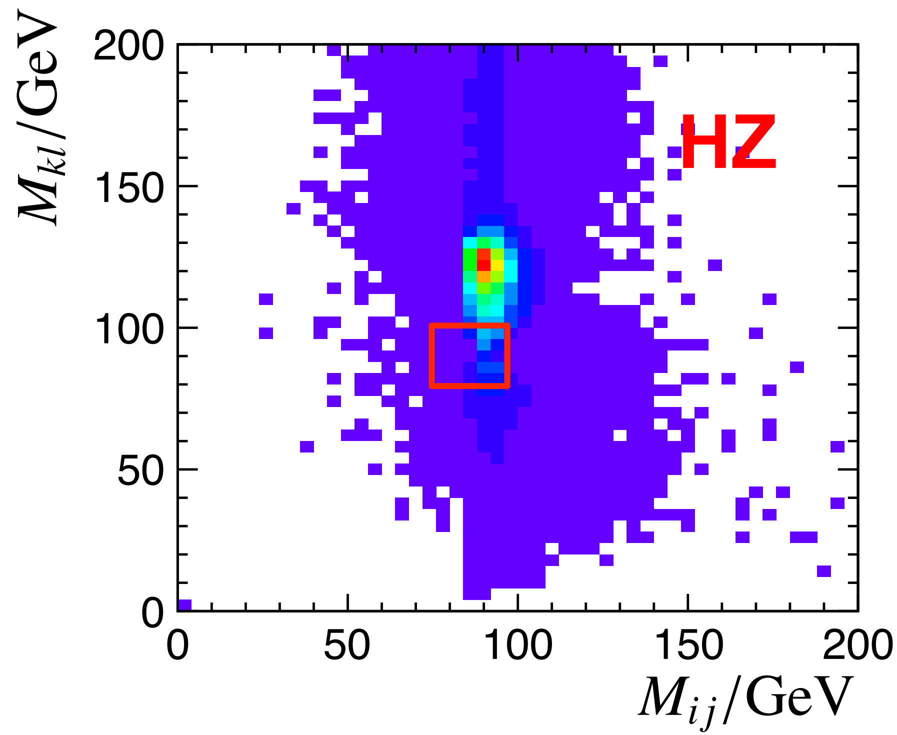
e.g. ZZ → qqqq



- 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

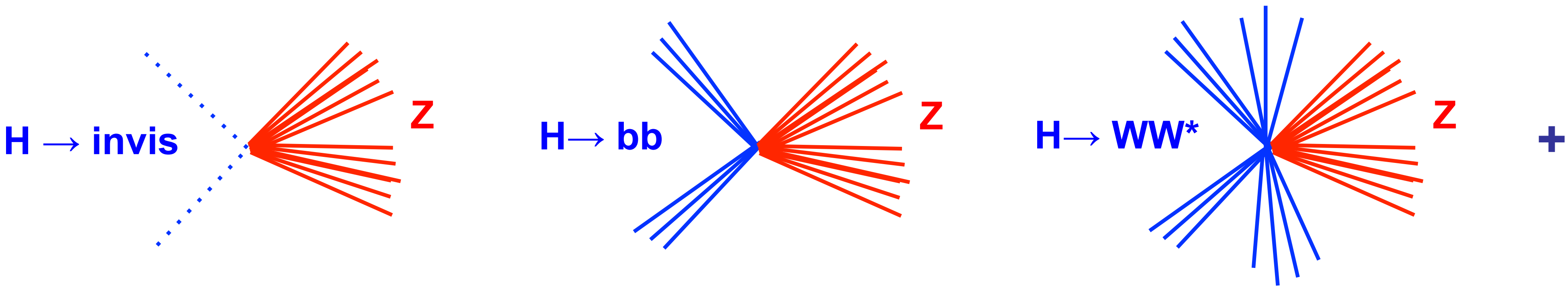
★ Cut on reconstructed di-jet masses





2) Jet Reconstruction

- ★ 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

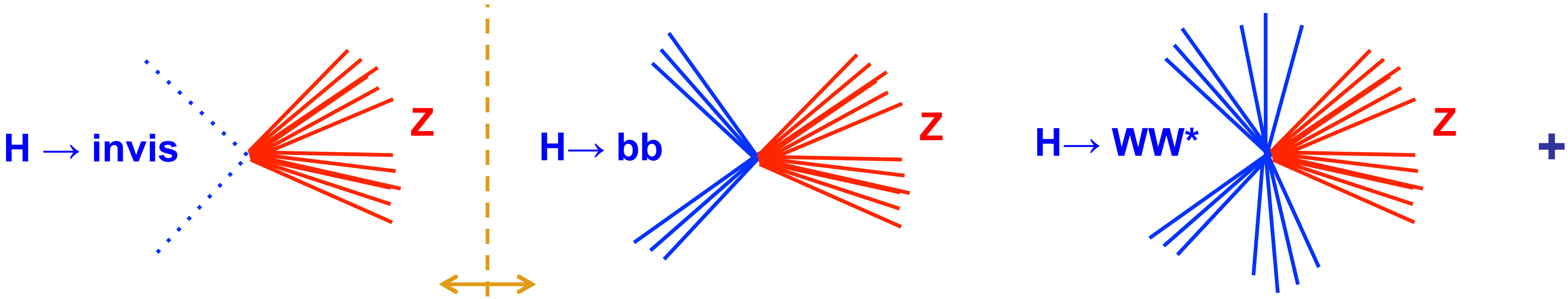
Divide into candidate invisible and visible Higgs decays

- ★ Aim for same selection efficiency for all Higgs decays

  ⇨ for model independence

2) Jet Reconstruction

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



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

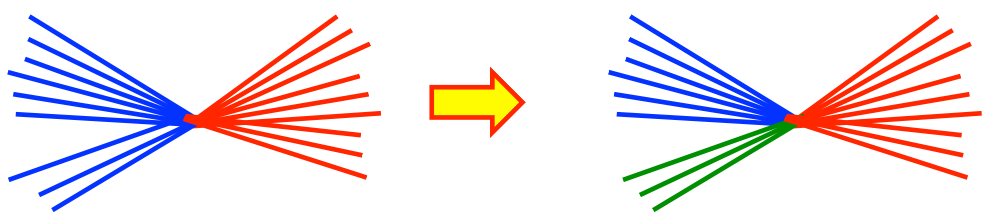
  For each event will choose one topology

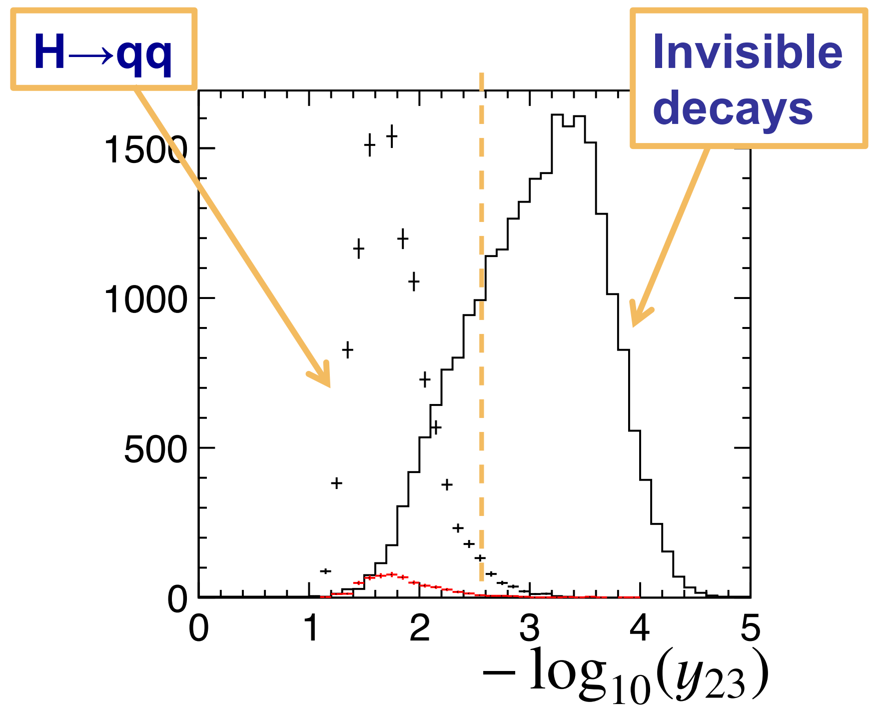
  - For each of these six topologies:
    - find two jets (> 3 tracks) most consistent with Z
    - determine mass of system recoiling against this "Z"

2 jets vs >2 jets

★ **Divide sample into: two "jets" or > two "jets"**

- **cut on y_{23}: the k_T value at which the 2 jets → 3 jets**

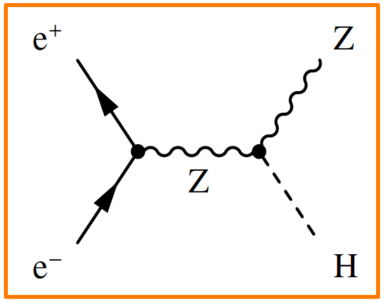




IF $-\log_{10}(y_{23}) > 2$ **&** $-\log_{10}(y_{34}) > 3$ ⇨ **Cand. invisible decay**

Visible Higgs Decays

IF $-\log_{10}(y_{23}) < 2$ OR $-\log_{10}(y_{34}) < 3$ Cand. visible decay



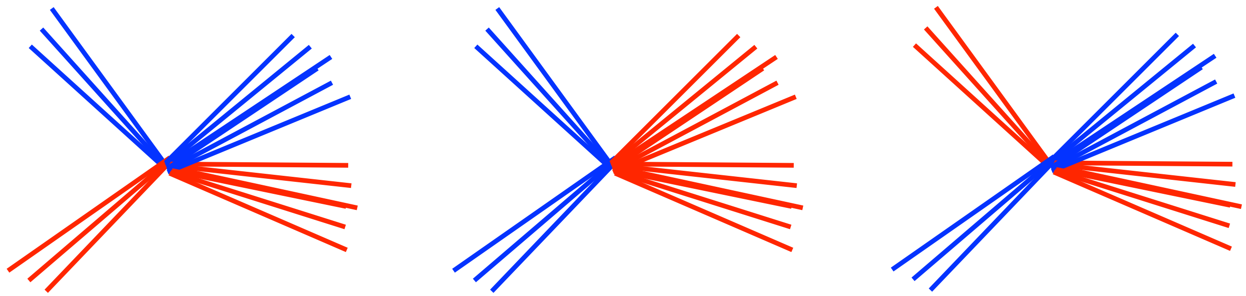
★ Candidate two jets from Z + Visible Higgs decay

- 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 jets ?

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…

Visible Higgs Decays

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

Recap

★ **To this point have:**

- Applied event type preselection
  - Based on reconstructed di-jet masses etc
- Separated remaining sample: visible/invisible
  - Based on jetiness: y_{23} and y_{34}
- Decided on # of “jets” for use in subsequent analysis
  - Invisible: 2 jets
  - Visible: either 4 or 5 jets

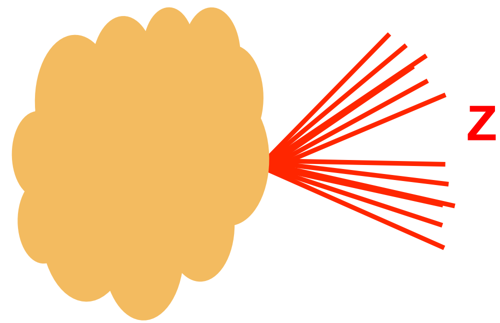
★ **Now:**

- Use ONLY properties of $Z \rightarrow qq$ decay
- Never again look at recoiling “Higgs” system

Final Preselection Cuts

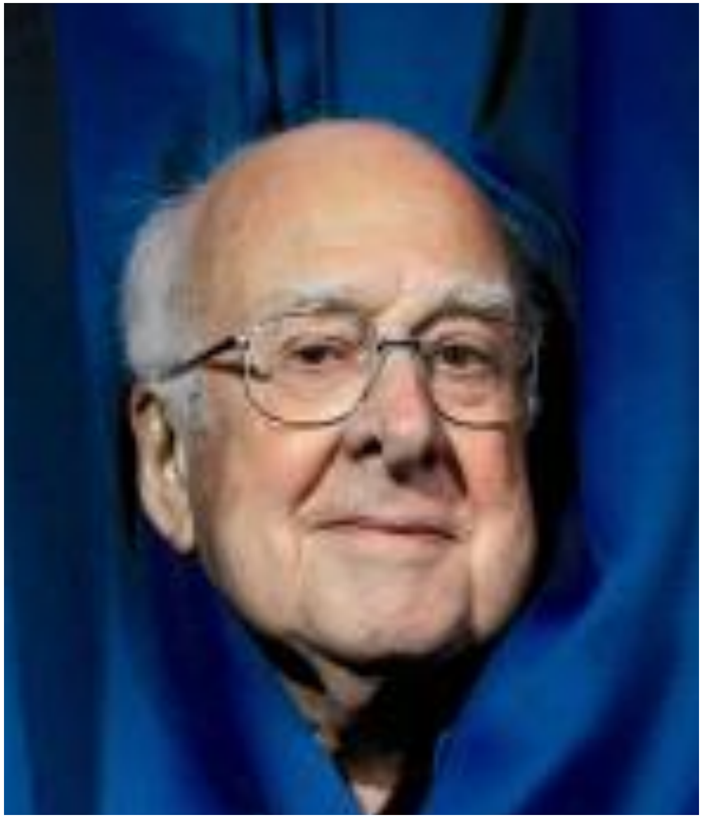
★ Using "best" jet hypothesis and best $Z \to qq$ candidate:

$$70\,\mathrm{GeV} < m_{q\bar{q}} < 110\,\mathrm{GeV}$$
$$80\,\mathrm{GeV} < m_{\mathrm{recoil}} < 200\,\mathrm{GeV}$$



$$|\cos\theta_Z| < 0.9 \quad \mathrm{(vis.)}$$
$$|\cos\theta_Z| < 0.7 \quad \mathrm{(invis.)}$$

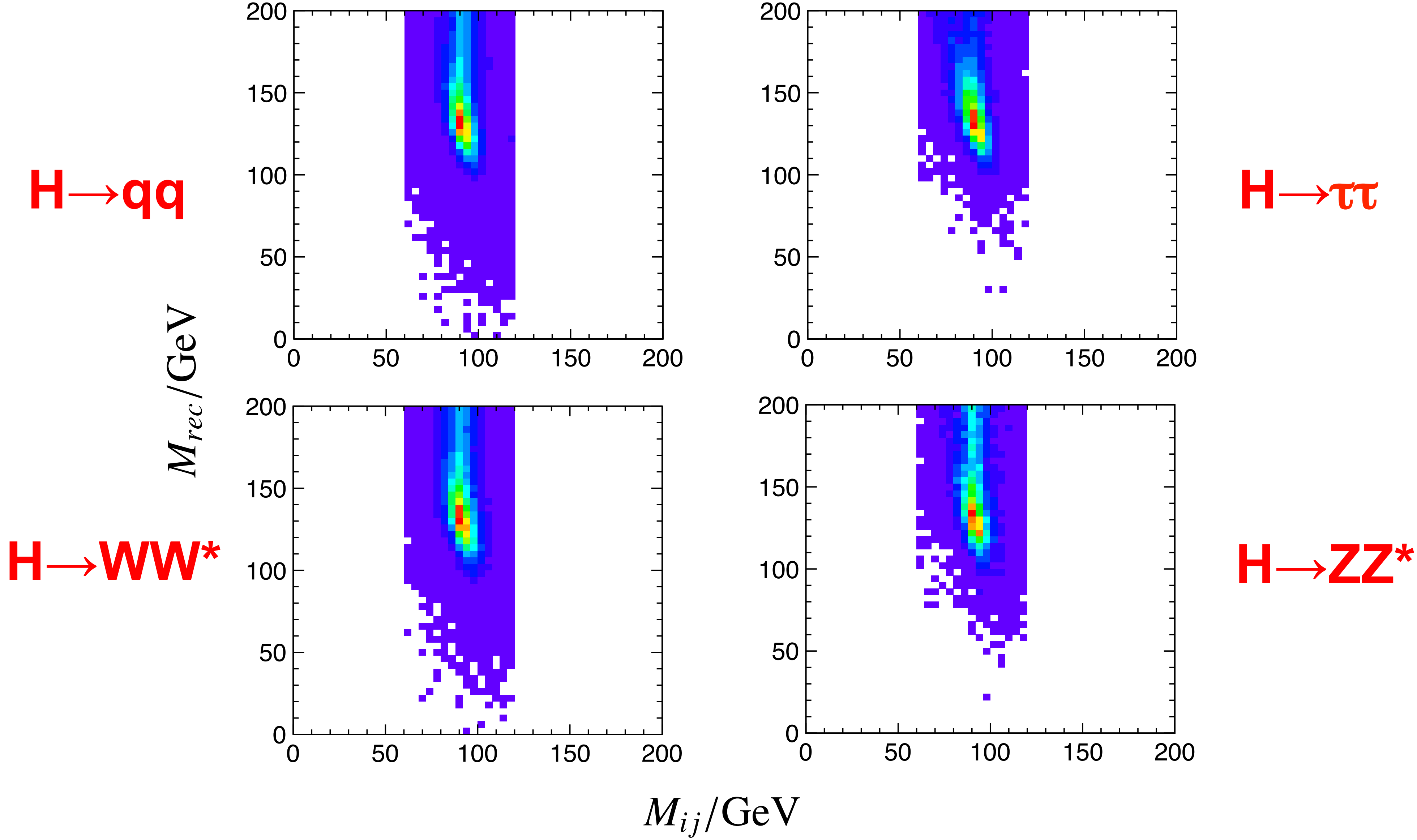
★ **Two likelihood based selections**
- Visible hypothesis
- Invisible hypothesis



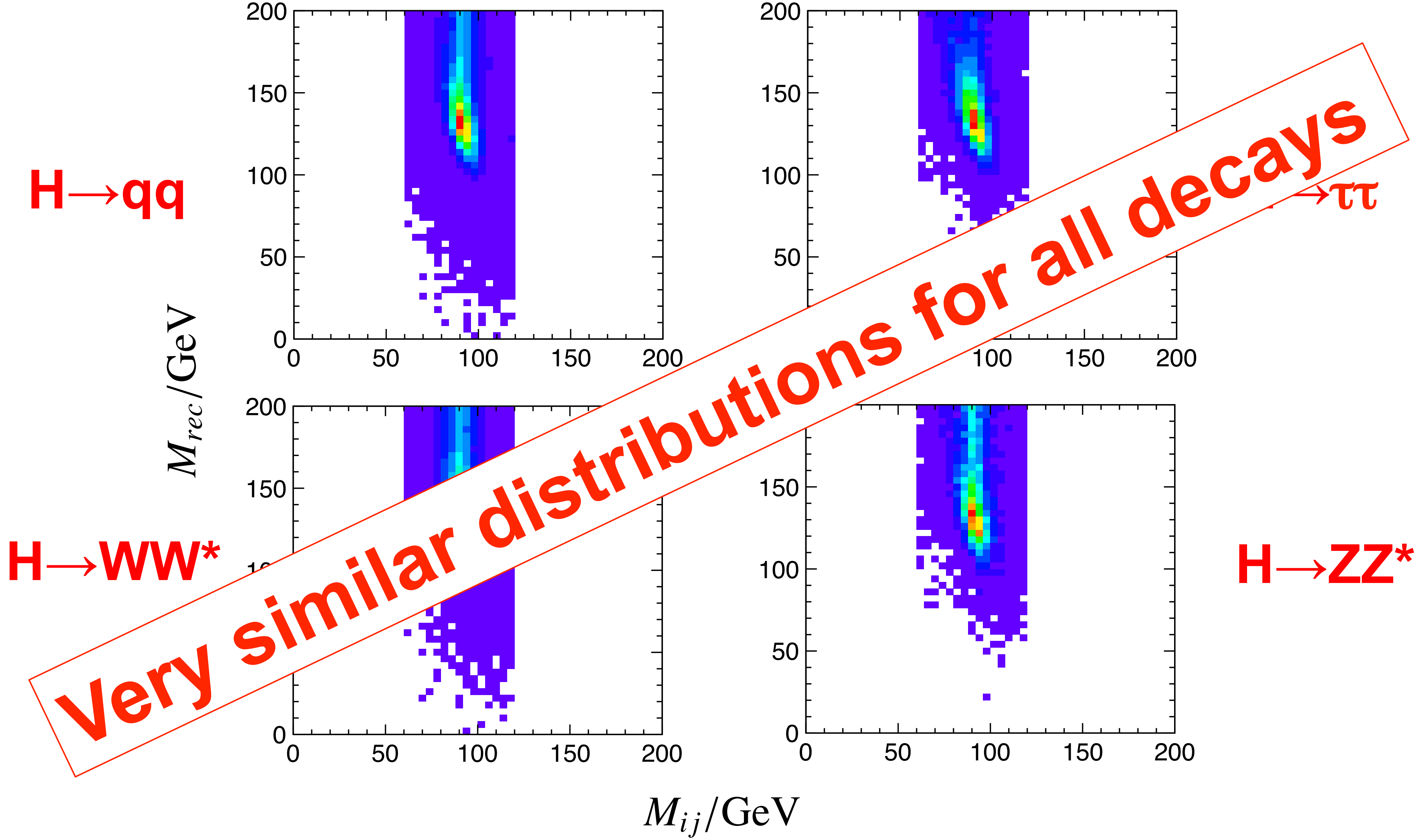
Visible Decays

(> 2 jets)

Signal m_{qq} vs m_{rec}



Signal m_{qq} vs m_{rec}



That's about it !

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

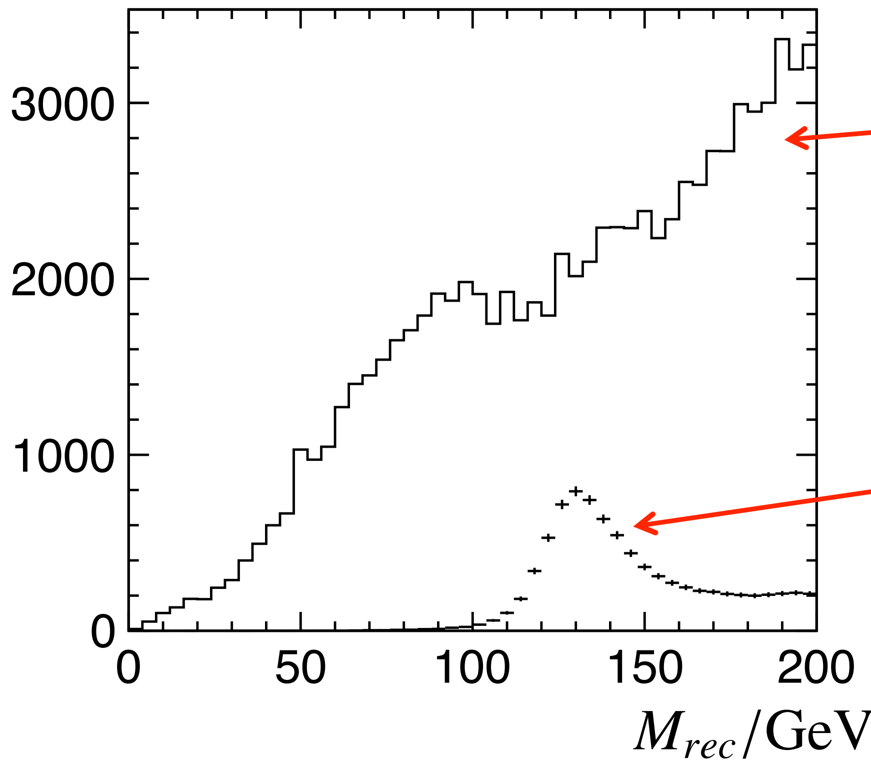
$$84\,\mathrm{GeV} < m_{\mathrm{qq}} < 108\,\mathrm{GeV}$$

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

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}
  - $|\cos\theta_Z|$
  - $|\cos\theta^*_q|$

Calculate absolute likelihood for given event type

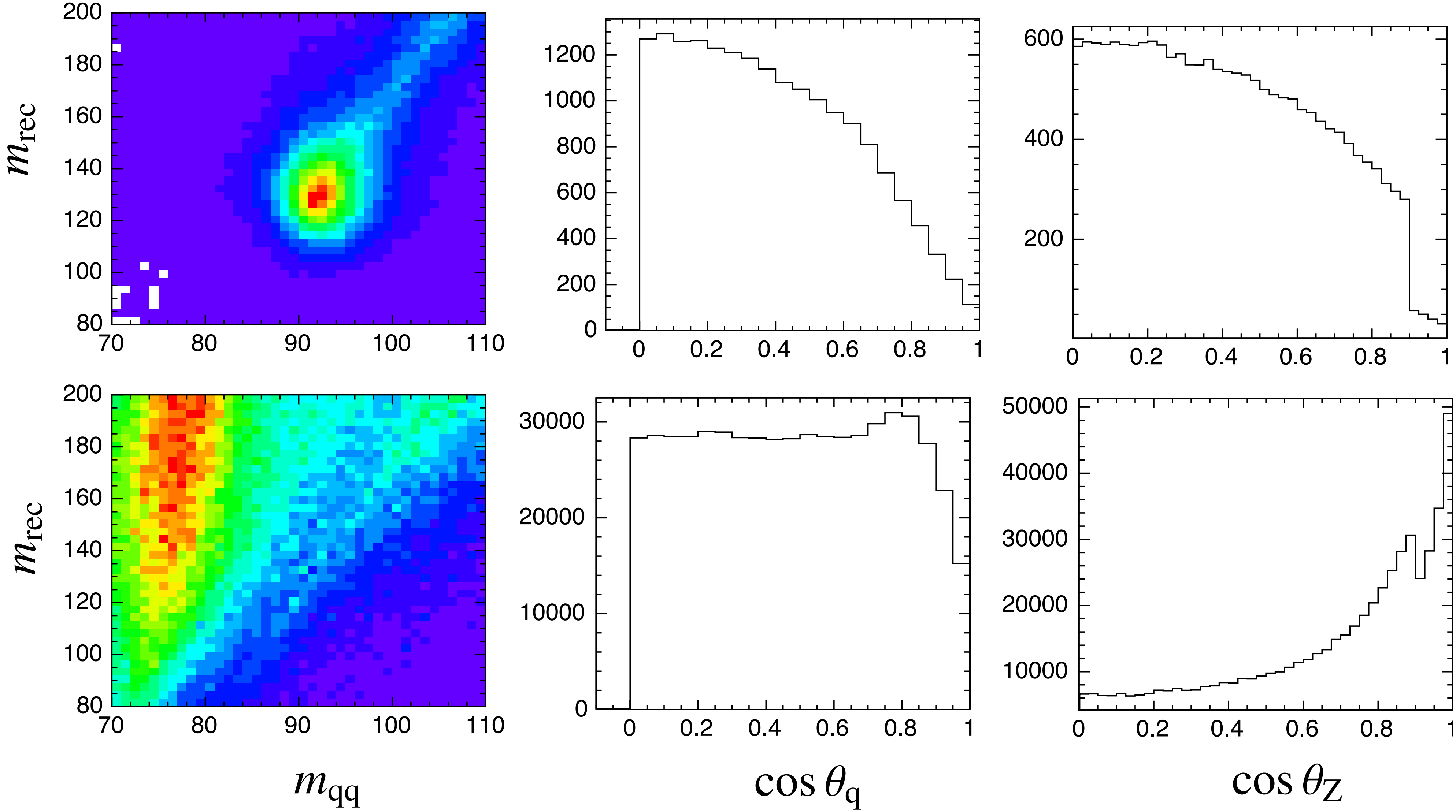
$$L = P(m_{qq}, m_{rec}) \times P(|\cos\theta_Z|) \times P(|\cos\theta^*_q|)$$

NOTE: 2D mass distribution includes main correlations

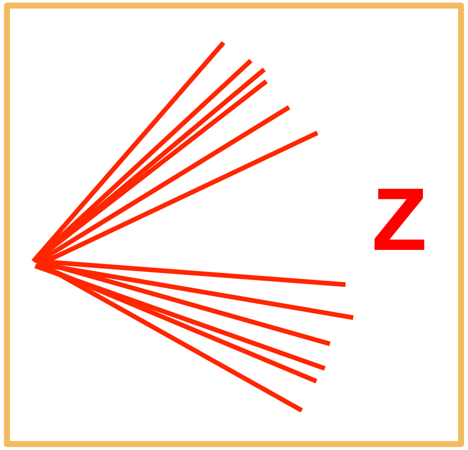
- ★ Absolute likelihoods calculated for two main event types:
- ★ Combined into relative likelihood

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

Input distributions (vis.)



Invisible Decays



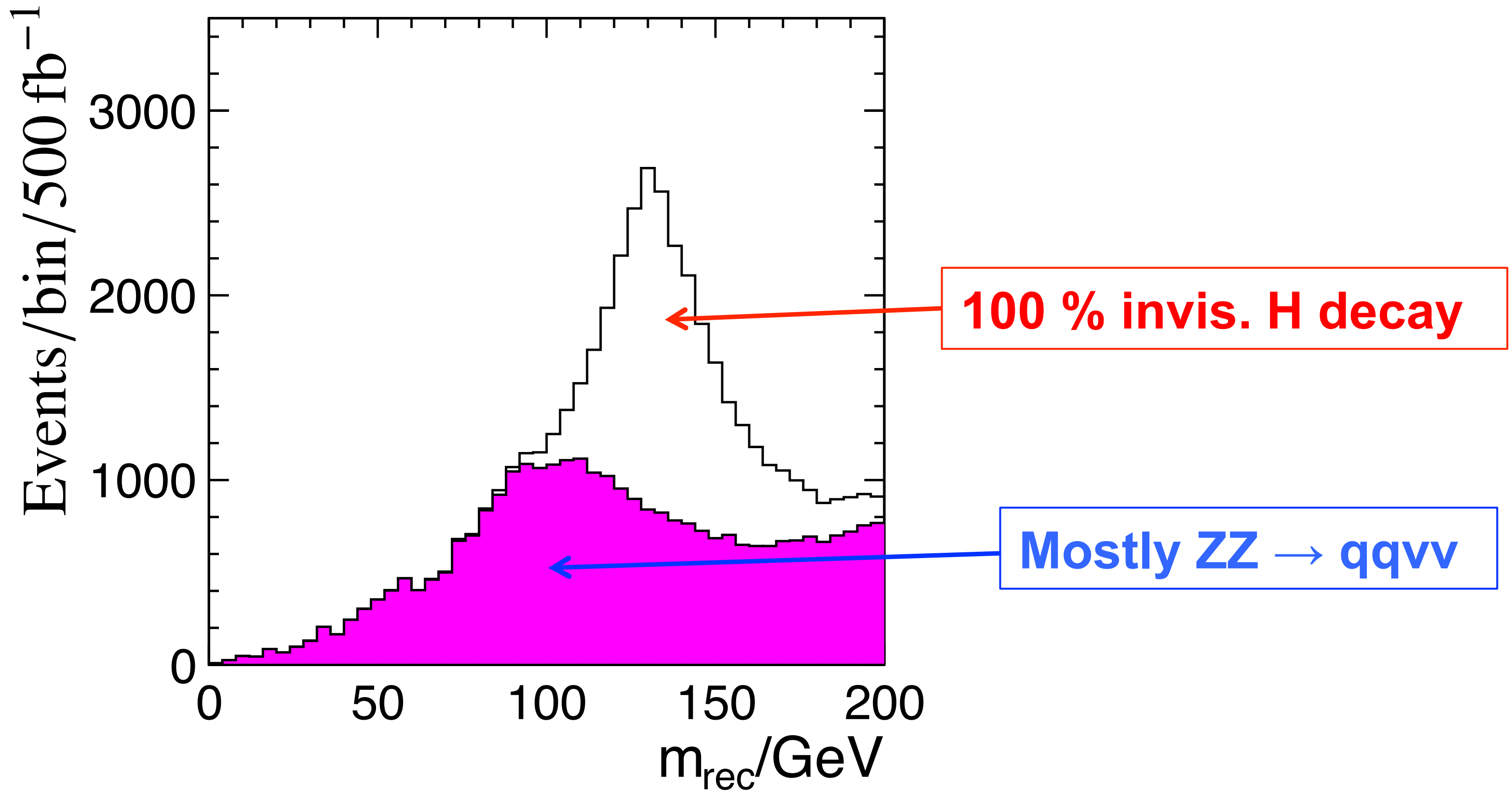
Single fairly clear, e.g.

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

Both jets well measured (hopefully)

Looks like Z

Z produced centrally



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

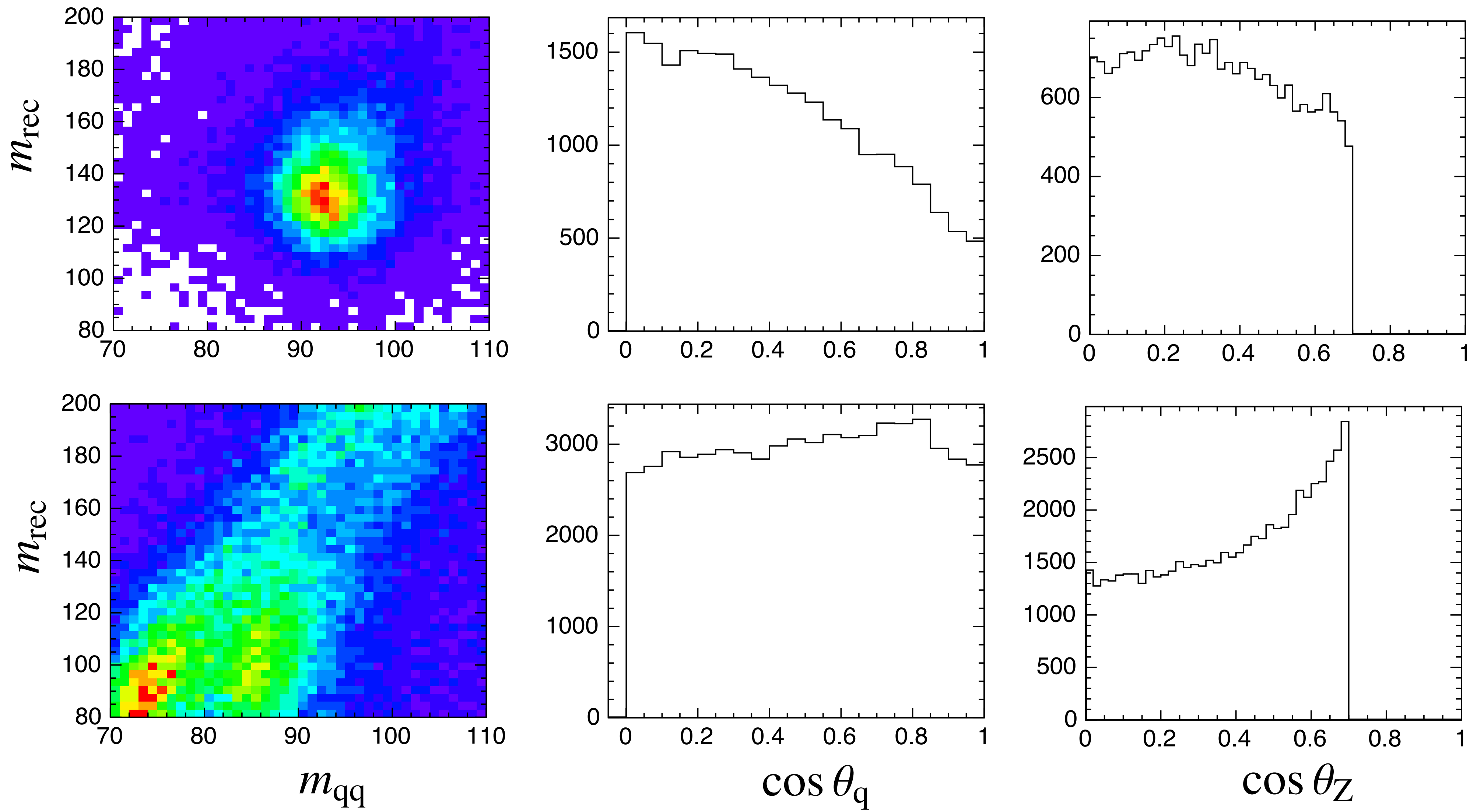
$$L = P(m_{qq}, m_{rec}) \times P(|\cos\theta_Z|) \times P(|\cos\theta_q^*|)$$

NOTE: 2D mass distribution includes main correlations

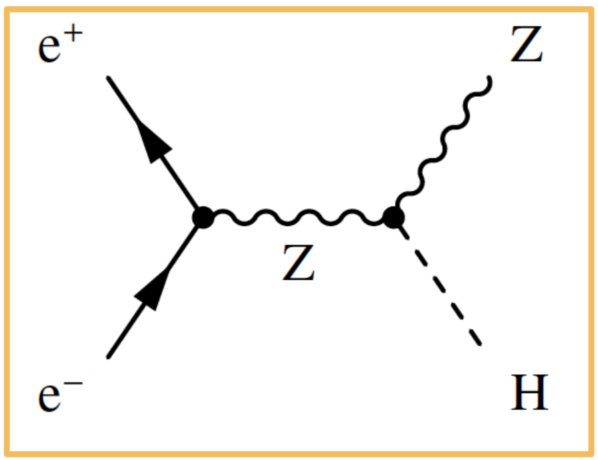
- ★ Absolute likelihoods calculated for two main event types:
- ★ Combined into relative likelihood

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

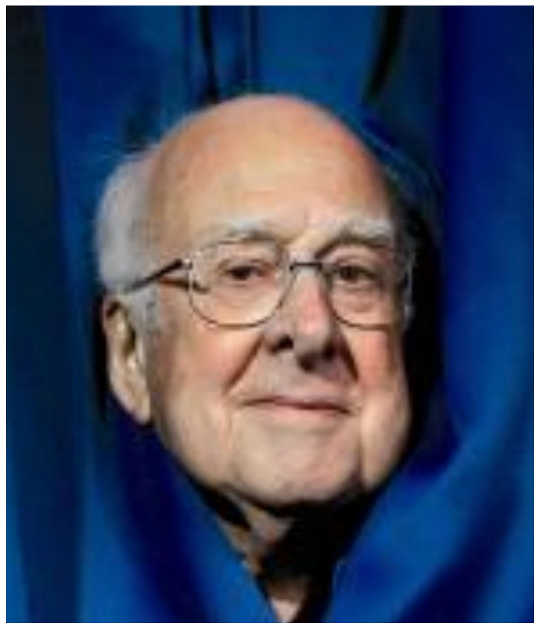
Input distributions (invis.)



Model Independence



=



+

Model Indepedence: I

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

Decay mode	$\varepsilon^{\text{vis}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{vis}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis}} + \varepsilon^{\text{invis}}$
$\mathrm{H} \to$ invis.	<0.1 %	22.0 %	22.0 %
$\mathrm{H} \to \mathrm{q\bar{q}/gg}$	22.2 %	<0.1 %	22.2 %
$\mathrm{H} \to \mathrm{WW}^*$	21.6 %	0.1 %	21.7 %
$\mathrm{H} \to \mathrm{ZZ}^*$	20.2 %	1.0 %	21.2 %
$\mathrm{H} \to \tau^+\tau^-$	24.7 %	0.3 %	24.9 %
$\mathrm{H} \to \gamma\gamma$	25.8 %	<0.1 %	25.8 %
$\mathrm{H} \to \mathrm{Z}\gamma$	18.5 %	0.3 %	18.8 %

Very similar efficiencies

Model Indepedence

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

Decay mode	$\varepsilon^{vis}_{\mathscr{L}>0.65}$	$\varepsilon^{vis}_{\mathscr{L}>0.60}$	$\varepsilon^{vis} + \varepsilon^{invis}$
$H \to$ invis.	<0.1 %	22.0 %	22.0 %
$H \to q\bar{q}/gg$	22.2 %	<0.1 %	22.2 %
$H \to WW^*$	21.6 %	0.1 %	21.7 %
$H \to ZZ^*$	20.2 %	1.0 %	21.2 %
$H \to \tau^+\tau^-$	24.7 %	0.3 %	24.9 %
$H \to \gamma\gamma$	25.8 %	<0.1 %	25.8 %
$H \to Z\gamma$	18.5 %	0.3 %	18.8 %
$H \to WW^* \to q\bar{q}q\bar{q}$	21.3 %	<0.1 %	21.3 %
$H \to WW^* \to q\bar{q}l\nu$	21.9 %	<0.1 %	21.9 %
$H \to WW^* \to q\bar{q}\tau\nu$	22.1 %	<0.1 %	22.1 %
$H \to WW^* \to l\nu l\nu$	24.8 %	0.1 %	25.0 %
$H \to WW^* \to l\nu\tau\nu$	20.5 %	0.8 %	22.1 %
$H \to WW^* \to \tau\nu\tau\nu$	16.4 %	2.5 %	18.9 %

Very similar efficiencies

Look at wide range of WW topologies

Extracting σ(ZH)

- Fit likelihood distributions…

- **Visible decays**
  - float background normalisation
  - float HZ normalisation (assume SM BRs)
  - assume no non-SM invisible decays

- **Invisible decays**
  - float background normalisation
  - fix SM HZ normalisation to visible decay fit result
    - note only a very small contribution $H \rightarrow ZZ^* \rightarrow \nu\nu\nu\nu$
  - float non-SM invisible decays normalisation

Combined Sensitivity

★ **Average fit results**

$$\frac{\sigma^{\mathrm{vis}}}{\sigma^{\mathrm{SM}}_{\mathrm{HZ}}} = 1.000 \pm 0.017$$

$$\frac{\sigma^{\mathrm{invis}}}{\sigma^{\mathrm{SM}}_{\mathrm{HZ}}} = 0.000 \pm 0.006$$

$$\frac{\sigma^{\mathrm{vis}} + \sigma^{\mathrm{invis}}}{\sigma^{\mathrm{SM}}_{\mathrm{HZ}}} = 1.000 \pm 0.018$$

$$\Delta\left(g_{\mathrm{HZZ}}\right) \approx \pm 0.9\,\%$$

"almost model independent"

Model Independence: II

★ **New fit procedure gives better handle on MI**

- investigated by reweighting HZ MC events to different Higgs Brs, e.g. + 5 % absolute
- e.g. BR($H\rightarrow bb$) = 64.5 % → 69.5 %
- Fit uses likelihood distributions based on SM BRs
- Determine average bias in fitted total HZ cross section

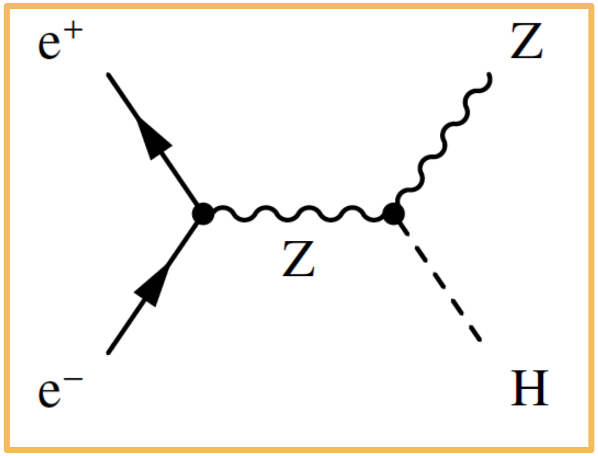
Decay mode	Δ(BR)	$\sigma^{vis} + \sigma^{vis}$ Bias
$H \rightarrow$ invis.	+5 %	-0.02 %
$H \rightarrow q\bar{q}$	+5 %	+0.03 %
$H \rightarrow WW^*$	+5 %	-0.19 %
$H \rightarrow ZZ^*$	+5 %	-0.33 %
$H \rightarrow \tau^+\tau^-$	+5 %	+0.64 %
$H \rightarrow \gamma\gamma$	+5 %	+0.89 %
$H \rightarrow Z\gamma$	+5 %	-0.57 %
$H \rightarrow WW^* \rightarrow \tau\nu\tau\nu$	+5 %	-0.96 %

c.f. 1.8 % statistical error

★ For extreme changes

$$\text{bias} \lesssim \frac{1}{2}\ \text{stat. error}$$

Summary



=

+

- ★ **Results now final**
- ★ **Aim to write paper**
- ★ **0.9 % statistical sensitivity to g_{HZZ}**