ILC Higgs Physics: Where are we and what is missing?

Mark Thomson
University of Cambridge

ILC Higgs Physics: a personal View

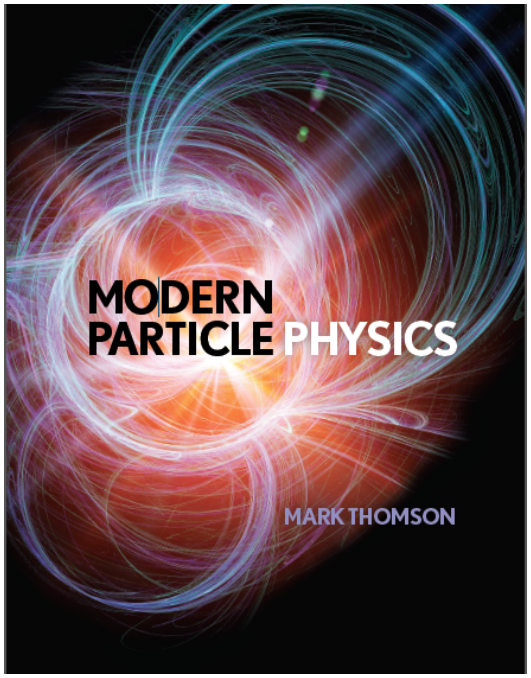
Mark Thomson
University of Cambridge

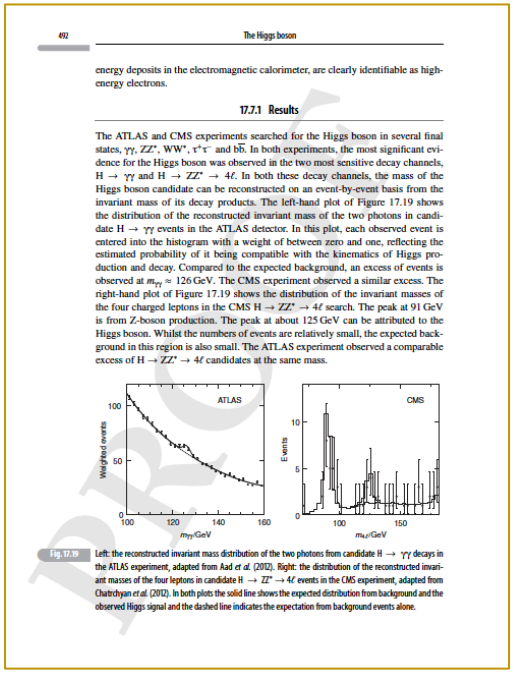
Was asked to be provocative…

…the Higgs is out there

★ **the Higgs is now standard textbook* physics**

*apologies for the gratuitous plug

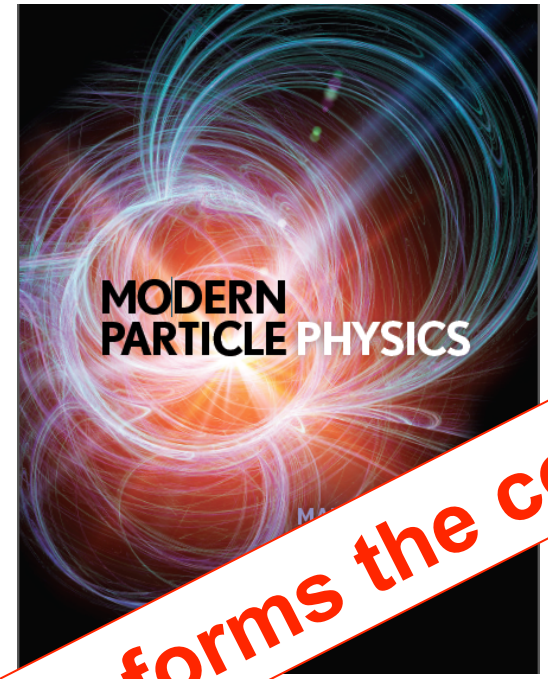


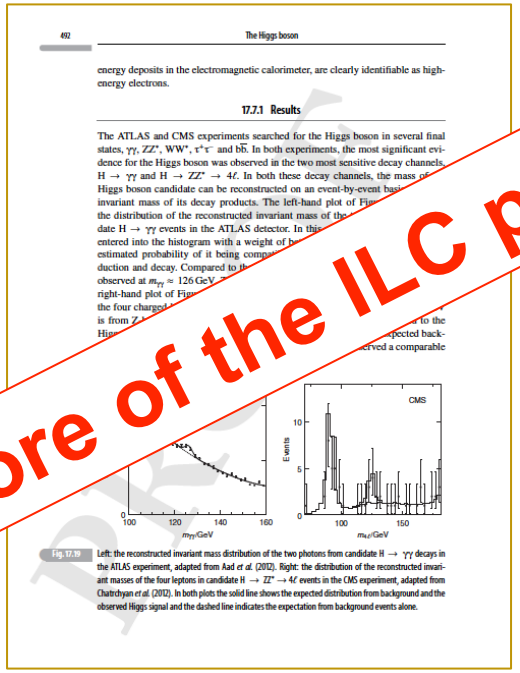


★ **The ILC is THE machine to study the Higgs**
★ **It is not the only physics motivation for the ILC, but …**
★ **… without the discovery of a low mass Higgs – I doubt we would be in this room today**

…the Higgs is out there

★ the Higgs is now standard textbook* physics





Higgs physics forms the core of the ILC physics case

★ The I machine to study the Higgs

★ I he only physics motivation for the ILC, but …

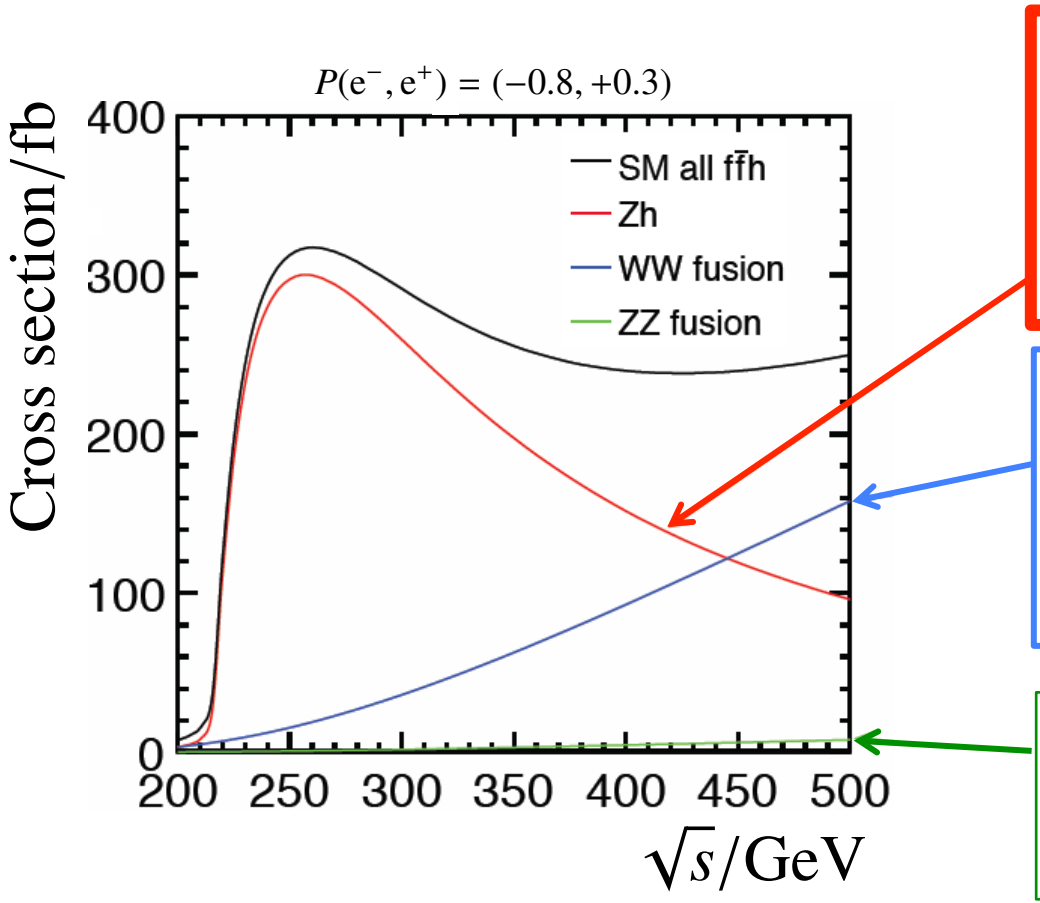
without the discovery of a low mass Higgs – I doubt we would be in this room today

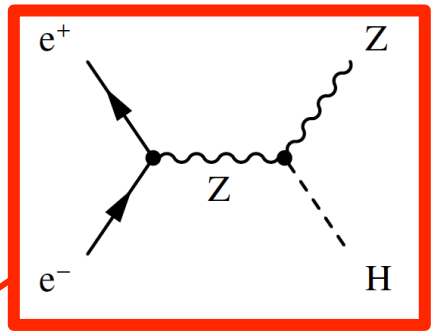
In this talk – only focus on:
physics arguments/questions…

NOT: a review of ILC Higgs physics !

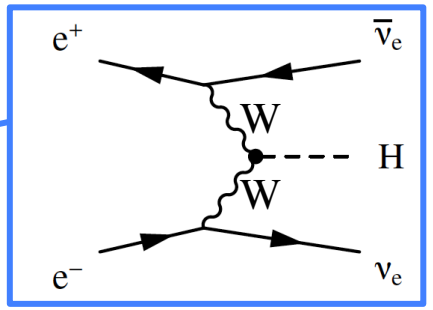
Higgs at $\sqrt{s}$ < 500 GeV

★ **How to best exploit the Higgs at the ILC ?**



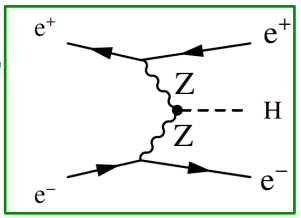


g_{HZZ}



+

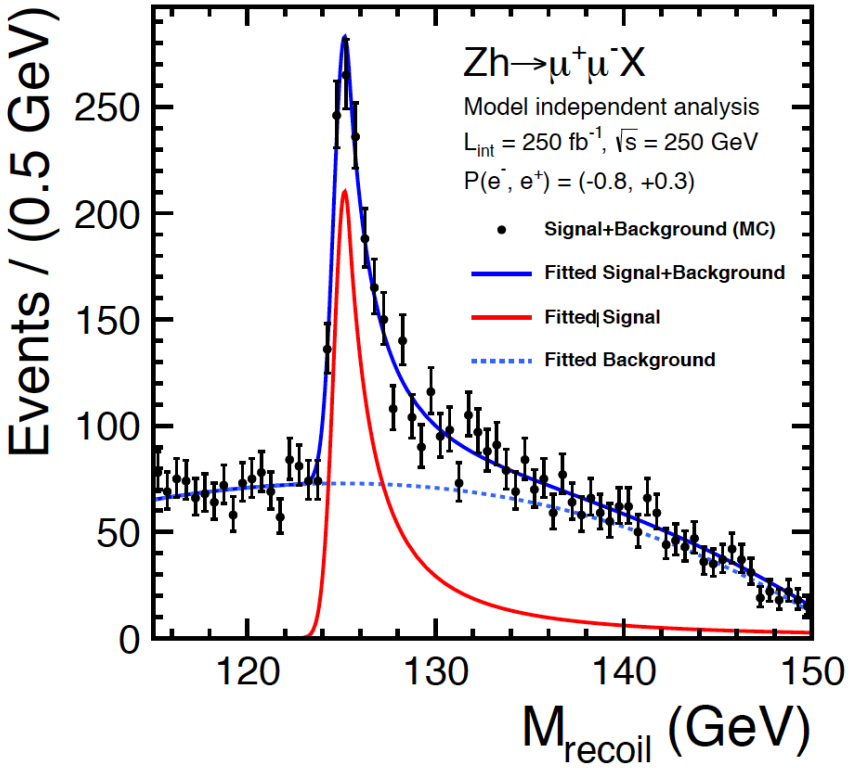
g_{HWW} , Γ_H , ...



★ **For M.I. measurements (inc. Γ_H) need HZ and Hvv production**

The case for $\sqrt{s}$ = 250 GeV

★ **The main argument for $\sqrt{s}$ = 250 GeV: Higgs recoil mass**



- **Exploit** $Z \to \mu^+\mu^-$ **decays***

$$m^2 = (\sqrt{s} - E_{\mu\mu})^2 - \mathbf{p}_{\mu\mu}^2$$

$$\Delta g_{HZZ} \sim 2.6\,\%$$

$$\Delta m_H \sim 35\,\text{MeV}$$

- **Apart from** $H \to b\bar{b}$ **other σ x BR measurements at >5 % level**

*Also have contributions from $Z \to e^+e^-$

Heretical View

HERESY: THE OBSTINATE POST-BAPTISMAL DENIAL OF SOME TRUTH WHICH MUST BE BELIEVED WITH DIVINE AND CATHOLIC FAITH, OR IT IS LIKEWISE AN OBSTINATE DOUBT CONCERNING THE SAME. (CATECHISM OF THE CATHOLIC CHURCH, 2089)

★ **Should be willing to ask the difficult questions, without fear of eternal damnation…**

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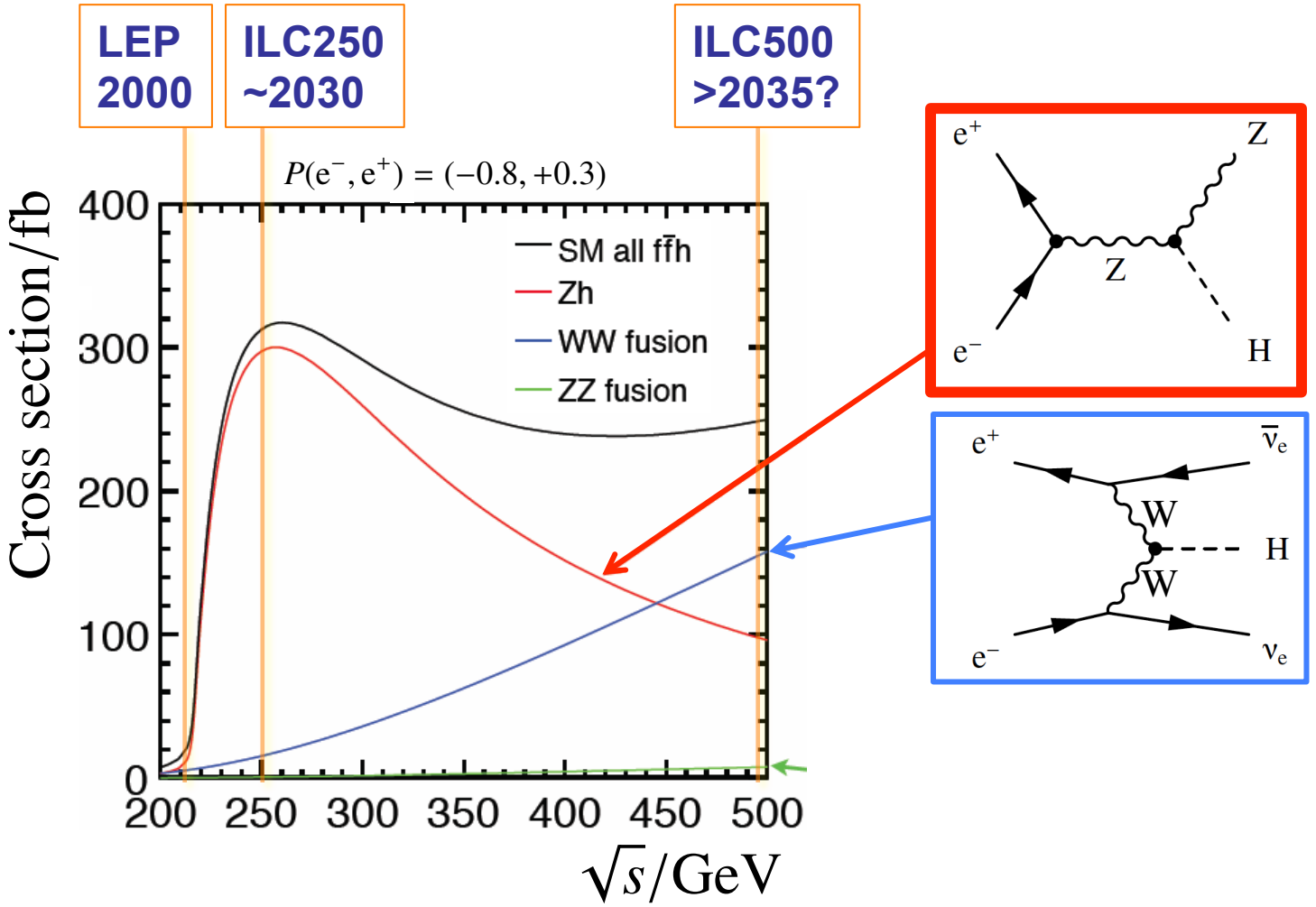
★ **Should be willing to ask the difficult questions, without fear of eternal damnation…**

★ **Is the first stage of the ILC at 250 GeV [alone] a truly transformative physics programme ?**

Why not start at 250 GeV?



★ **Only scratch the surface of ILC physics until (maybe) 2035…**

Case against 250 GeV

★ Only scratch the surface of ILC physics until (maybe) > 2035…

★ Higgs physics at 250 GeV
- Limited due to lack of WW-fusion

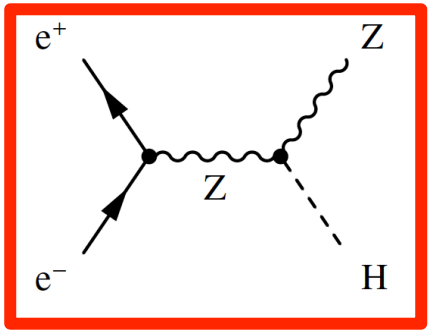
★ Other physics at 250 GeV:
- Rather limited:
  - below top threshold
  - energy reach only 20 % > than LEP
  - …

The Big Question ?

Do we <u>need</u>
250 GeV operation ?

that depends…

★ **HZ is essential for unique Model Independent Higgs programme at the ILC**



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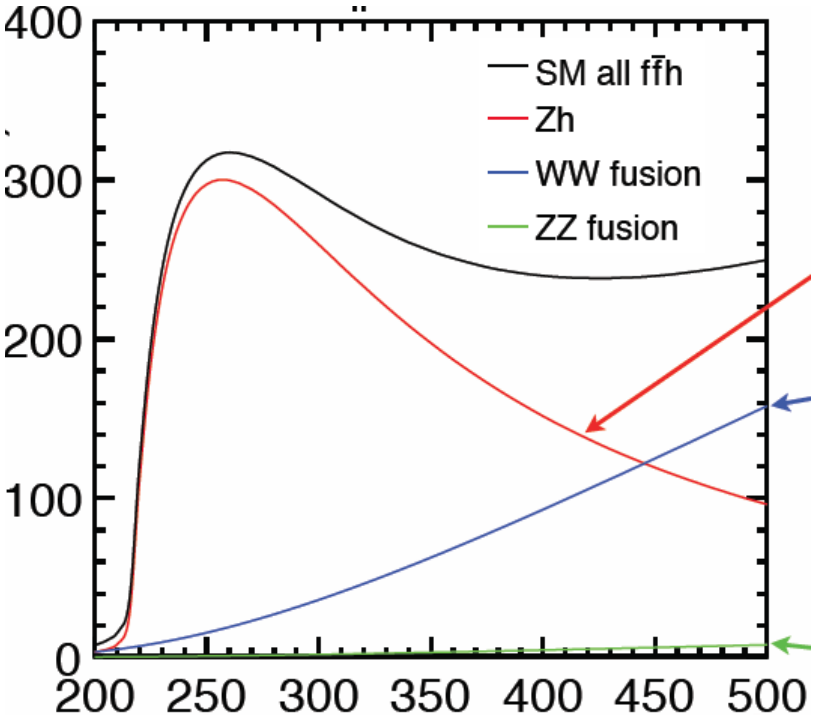

★ **No need to run at peak of cross section**

- **Event rate** $\propto \sigma \times \mathcal{L}$
- $\mathcal{L} \propto \gamma_e \propto \sqrt{s}$

that depends…

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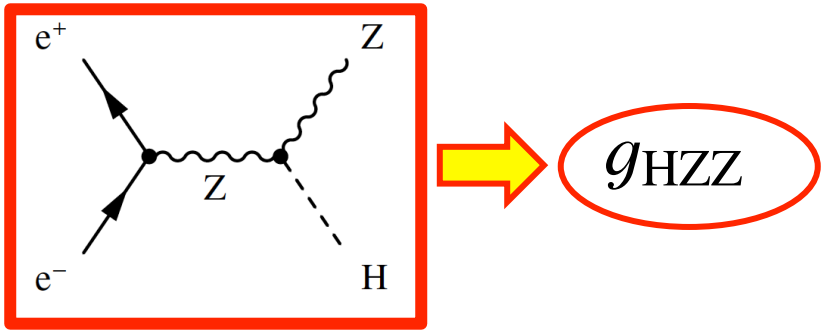
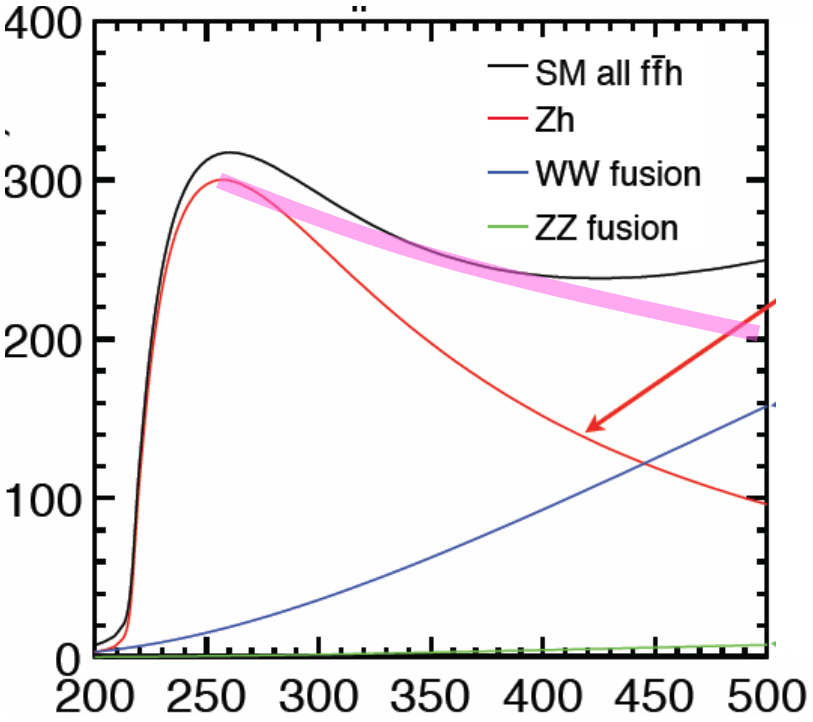




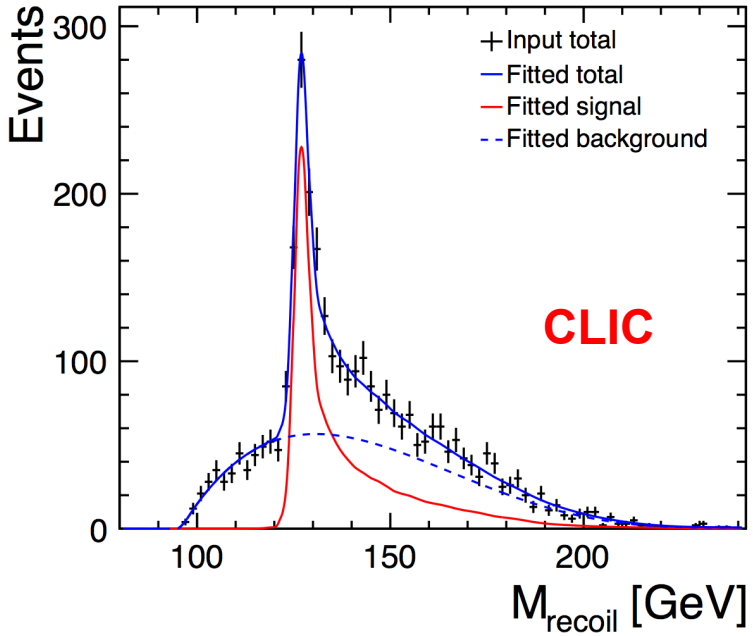
★ **No need to run at peak of cross section**

- **Event rate** $\propto \sigma \times \mathcal{L}$
- $\mathcal{L} \propto \gamma_e \propto \sqrt{s}$

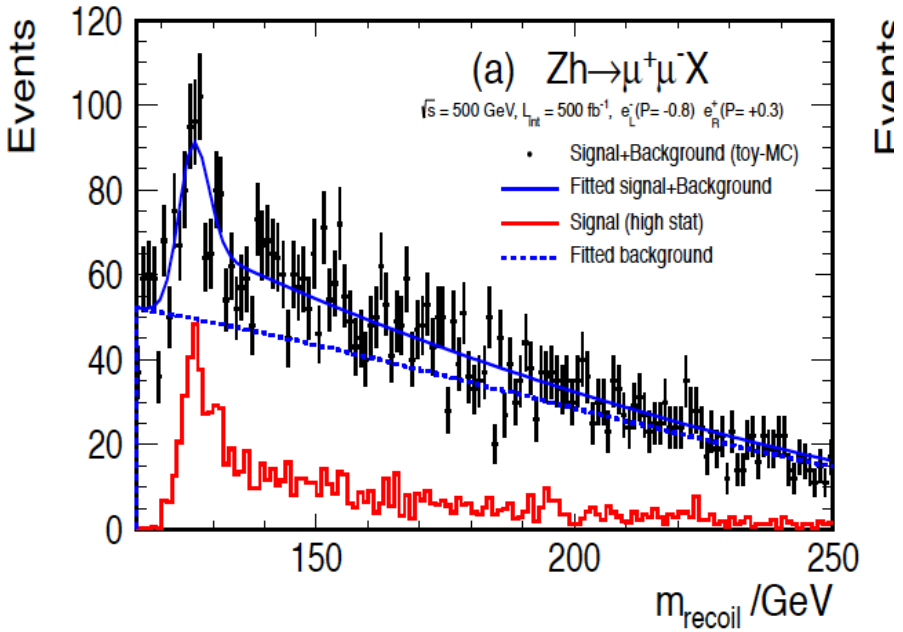
★ **Can we make a M.I. measurement of s(HZ) at** $\sqrt{s} > 250\,\text{GeV}$ **?**

Leptonic Recoil Mass

$500\,\mathrm{fb}^{-1} @ \sqrt{s} = 350\,\mathrm{GeV}$



$500\,\mathrm{fb}^{-1} @ \sqrt{s} = 500\,\mathrm{GeV}$



$$\frac{\Delta\sigma}{\sigma} = 4.7\,\%$$ ⟸ μμ only ⟹ $$\frac{\Delta\sigma}{\sigma} = 6.5\,\%$$

★ **Not competitive – limited by momentum resolution**

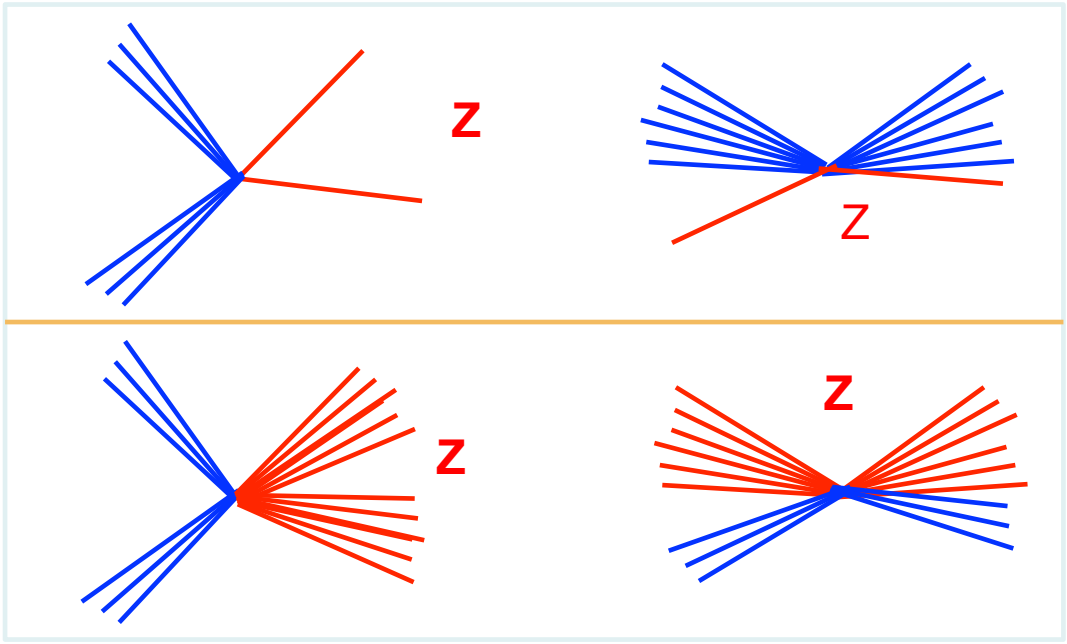
- **a challenge to the tracker ?**

HZ Hadronic Recoil

★ **Argument hinges on ability to exploit HZ production: $Z \rightarrow qq$**

- **Much larger branching ratio:**
  - **60 %** $Z \rightarrow qq$
  - **3.5 %** $Z \rightarrow \mu\mu$

★ **But model independence is the issue…**



Muons "always" obvious

Here jet finding blurs separation between H and Z

Different efficiencies for different Higgs decays

HZ Hadronic Recoil

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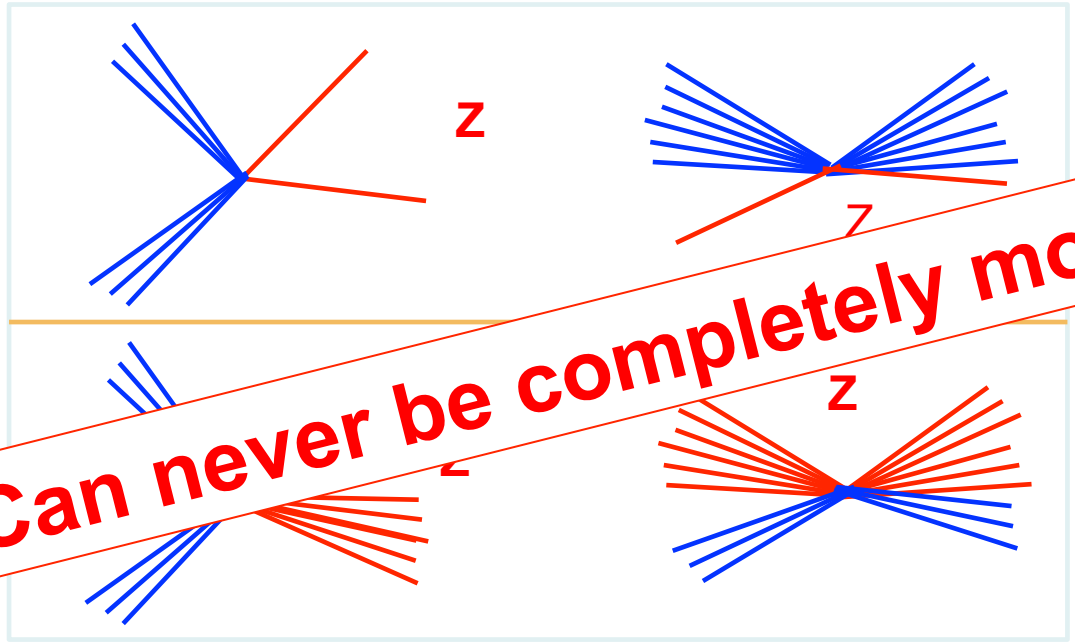


Can never be completely model independent

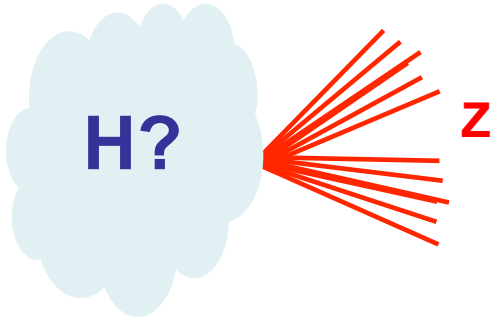
Here jet finding blurs separation between H and Z

Different efficiencies for different Higgs decays

e.g. CLIC @ 350 GeV

★ **Base selection on variables from observed Z→qq**

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



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

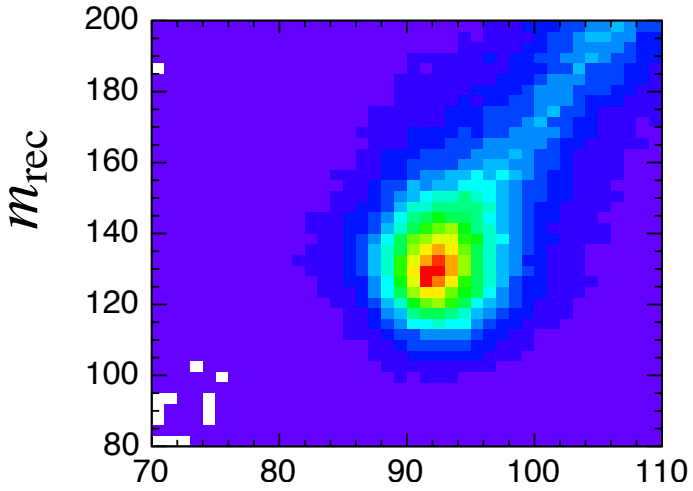
★ **Two likelihood based selections**
- **Visible hypothesis (> 2 jets)**
- **Invisible hypothesis (2 jets)**

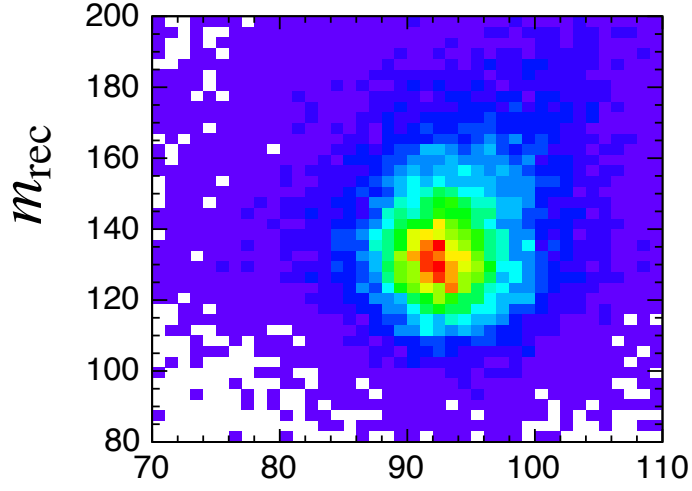
Visible Higgs Decays

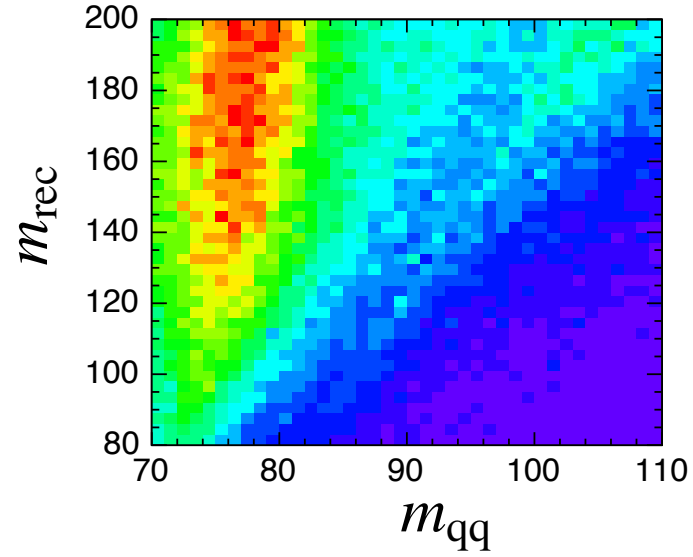
Invisible Higgs Decays

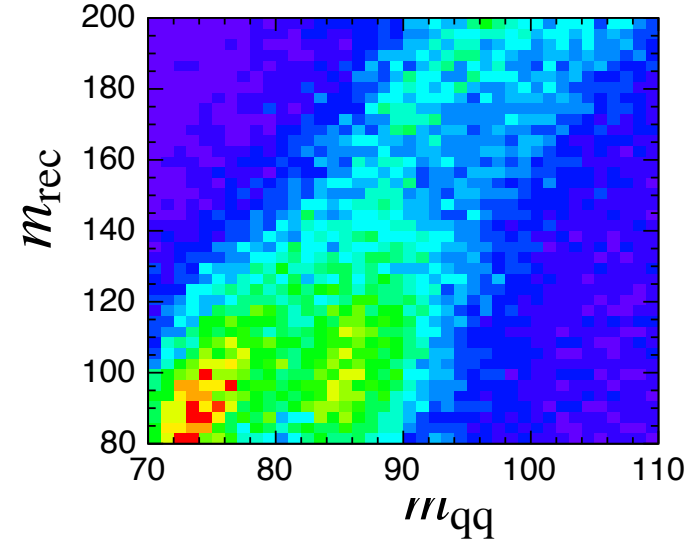
SIGNAL

SM Back.









Model Independent?

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

Decay mode	$\varepsilon^{\text{vis}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{vis}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis}} + \varepsilon^{\text{invis}}$
$H \to \text{invis.}$	<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 %

Very similar efficiencies

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$H \to Z\gamma$	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

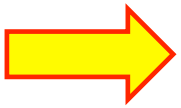
Look at wide range of WW topologies

Combined Sensitivity

★ Average fit results

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

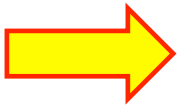
$$\frac{\sigma^{\text{invis}}}{\sigma^{\text{SM}}_{\text{HZ}}} = 0.000 \pm 0.006$$



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

CLIC: 500 fb^{-1} at 350 GeV no polar.

★ Repeated for ILC 350 GeV samples



$$\frac{\sigma^{\text{vis}} + \sigma^{\text{invis}}}{\sigma^{\text{SM}}_{\text{HZ}}} = 1.000 \pm 0.017$$

ILC: 350 fb^{-1} at 350 GeV -80%, + 30%

★ **Leptonic recoil at 250 GeV:**

$$\frac{\Delta\sigma}{\sigma} = 2.6\,\%$$

ILC: 250 fb^{-1}

★ **Hadronic recoil at 350 GeV:**

$$\frac{\Delta\sigma}{\sigma} = 1.7\,\%$$

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★ **Leptonic recoil at 250 GeV:**

$$\frac{\Delta\sigma}{\sigma} = 2.6\,\%$$

★ **Hadronic recoil at 350 GeV:**

$$\frac{\Delta\sigma}{\sigma} = 1.7\,\%$$

BIG QUESTION 1: is this "model independent"?

or is this sufficiently MI?

★ **What is the issue?**

- investigated by reweighting HZ MC events to different Higgs Brs, e.g. + 5 % absolute
- e.g. BR(H→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
$H \to$ invis.	+5 %	-0.02 %
$H \to q\bar{q}$	+5 %	+0.03 %
$H \to WW^*$	+5 %	-0.19 %
$H \to ZZ^*$	+5 %	-0.33 %
$H \to \tau^+\tau^-$	+5 %	+0.64 %
$H \to \gamma\gamma$	+5 %	+0.89 %
$H \to Z\gamma$	+5 %	-0.57 %
$H \to WW^* \to \tau\nu\tau\nu$	+5 %	-0.96 %

c.f. 1.7 % statistical error

★ **For extreme changes**

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

Suppose we accept MI…

BIG QUESTION 2: Is there any physics argument for 250 GeV operation?

Other arguments: BRs

σ x BR	HZ	HZ + WW	HZ + WW
	250 @ 250 GeV	350 @ 350 GeV	500 @ 500 GeV
ZH Z->ll	2.6 %	3.8 % ???	4.6% ?
bb	1.2 %	0.9 %	0.6 %
cc	8.3 %	7.9 %	5.6 %
gg	7.0 %	5.6 %	3.8 %
WW*	6.4 %	4.0 %	2.3 %
ττ	4.2 %	4.5 %	4.6 %
ZZ*	19.0%	13.4 %	7.8 %

★ **Almost always better at higher centre-of-mass energies**

Other arguments: BRs

σ x BR	HZ	HZ + WW	HZ + WW
	250 @ 250 GeV	350 @ 350 GeV	500 @ 500 GeV
ZH Z->ll	2.6 %	3.8 % ???	4.6% ?
ZH Z->qq	???	1.7 %	?
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σ x BR	HZ	HZ + WW	HZ
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WW*		4.0 %	2.3 %
		4.5 %	4.6 %
	.0%	13.4 %	7.8 %

BIG QUESTION 3: How do precisions from hadronic recoil mass analysis compare for: 250, 350, 500 GeV ?

...almost always better at higher centre-of-mass energies

Other arguments: mass

★ **Higgs boson mass uncertainty is an important parametric uncertainty in SM Higgs BRs**

[see Jenny's talk yesterday and Tsumura-san's talk]

- **ultimately require**

$$\Delta m_{\mathrm{H}} < 50\,\mathrm{MeV}$$

★ **Leptonic recoil at 250 GeV (250 fb^{-1}) gives:**

$$\Delta m_{\mathrm{H}} \sim 30\,\mathrm{MeV}$$

Other arguments: mass

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★ **Leptonic recoil at 350 GeV (350 fb^{-1}) gives (estimated):**

$$\Delta m_{\mathrm{H}} \sim 110\,\mathrm{MeV}$$

Not good enough…

Other arguments: mass

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[see Jenny's talk yesterday and Tsumura-san's

- **ultimately require**

$$\Delta m_{\mathrm{H}} < 50\,\mathrm{MeV}$$

★ **Leptonic recoil at 250 GeV (25 ves:**

Δm MeV

★ **Leptonic rec GeV (350 fb^{-1}) gives (estimated):**

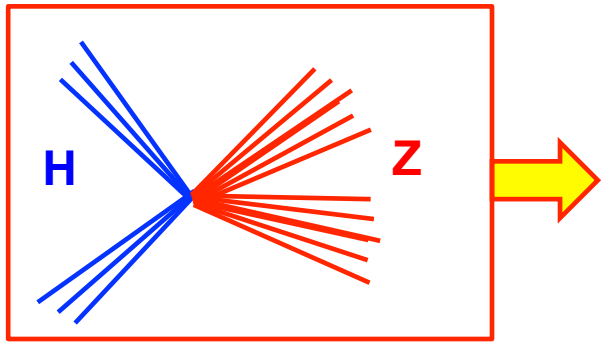
$$\Delta m_{\mathrm{H}} \sim 110\,\mathrm{MeV}$$

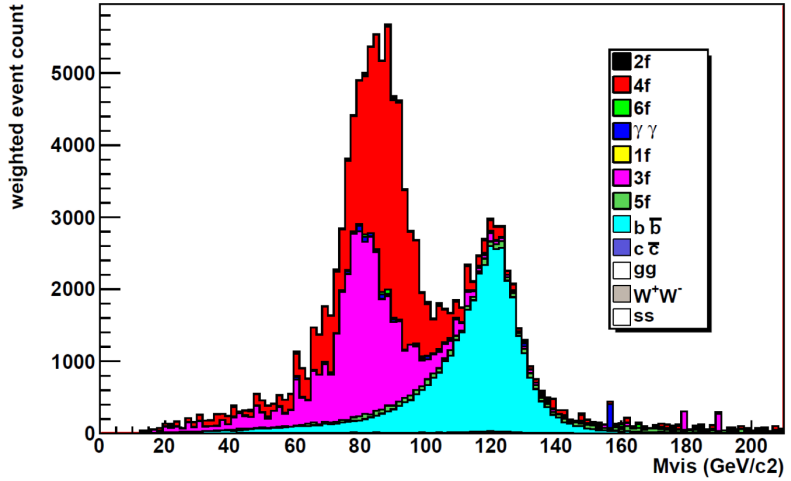
Not good enough…

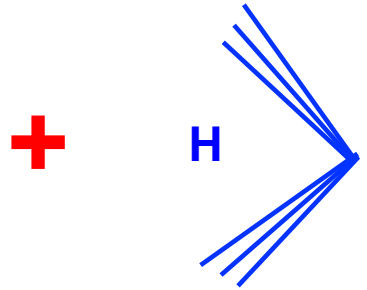
Is this a strong argument for 250 GeV operation ?

Probably not…

★ Direct reco. of visible mass in HZ and vvH with H→bb







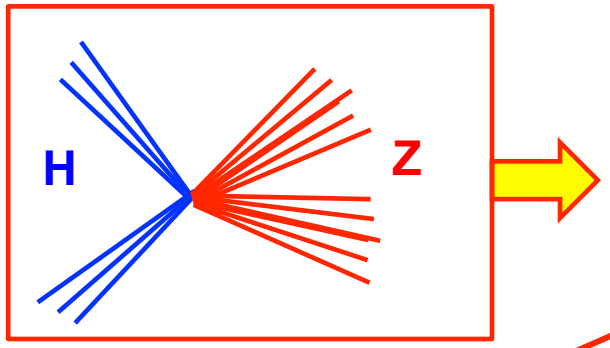
★ What precision can be achieved?

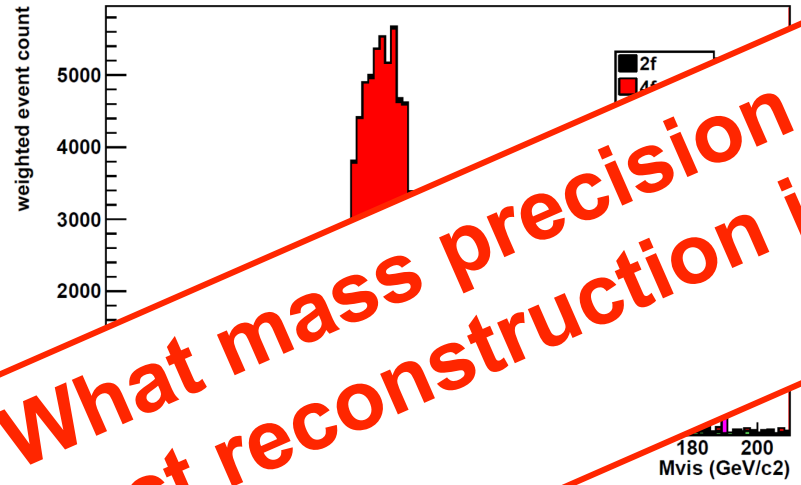
- Event-by-event mass resolution **~7 GeV**
- with **~100000** events, suggests $\Delta m_{\mathrm{H}} < 50\,\mathrm{MeV}$ is achievable but no (?) recent ILD studies

Probably good enough…

Probably not…

★ Direct reco. of visible mass in HZ and ννH with H→bb





BIG QUESTION 4: What mass precision can be achieved from direct reconstruction including systematics?

★ What pr

olution ~7 GeV

s, suggests $\Delta m_{\mathrm{H}} < 50\,\mathrm{MeV}$ is achievable

cent ILD studies

my (current) bias

- ★ **H Physics case can be summarised as:**

my (current) bias

★ H Physics case can be summarised as:

250 GeV circular collider:

- **Very limited physics**
  - no WW fusion

my (current) bias

★ **H Physics case can be summarised as:**

TLEP:

- **solid physics**
- **but...**

my (current) bias

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★ H Physics case for ILC can be summarised as:

TLEP:
- solid physics
- but...

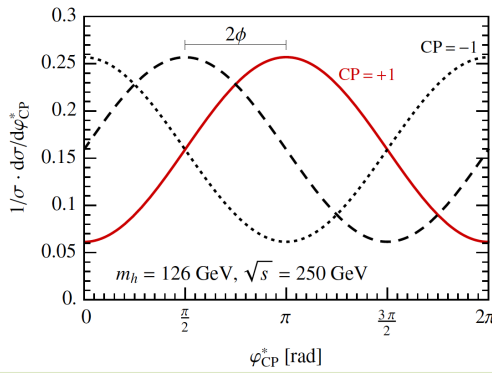
ILC 250:
- good physics
- not transform-ative from day 1

ILC 350/500:
- strong Higgs
- strong top
- BSM reach
- from DAY 1

★ **BUT**, need to understand whether there is a real scientific case for 250 GeV operation…

Other Higgs Topics

★ CP properties of Higgs $H \to \tau^+\tau^-$



- Update to recent ILD model
- Compare 250, 350, 500 GeV
- Compare HZ to Hνν

★ Higgs self-coupling

- Measurements at < 30 % precision may not be interesting
- Need 30 % for ~3σ signature for $\lambda = 0$
- Almost certainly not achievable $\sqrt{s} = 500\,\mathrm{GeV}$
- This is part of the physics for ILC 1 TeV…

★ ttH

- 500 vs 550 GeV – what is the gain in precision
- How does this compare to **3 ab^{-1}** HL-LHC?

Conclusions

★ If we can convince ourselves of:

- Model independence of hadronic recoil mass
- Direct reconstruction of m_H

⇨ May be a strong scientific argument for starting the ILC at > 250 GeV

★ An ILC with

- HZ, Hvv and top-pair production from day 1 is an compelling and attractive

★ A much simpler and clearer scientific case

Conclusions

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BIG QUESTION 5: Does this make any sense?

Thank you