Search of resonant s-channel Higgs production at FCC-ee

FCC-ee Vidyo Meeting

Geneva, 28th July 2014

David d'Enterria, G. Wojcik (CERN)
R. Aleksan (Saclay)

CERN

Resonant s-channel $e^+e^- \to H$ production

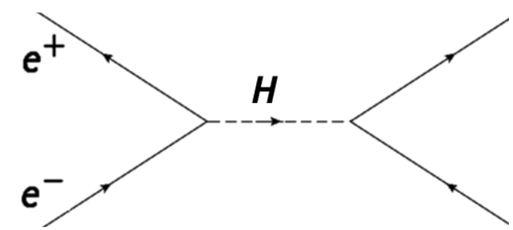
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H)$ ~ 70 pb. Tiny g_{Hee} Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee\to H)$

$$\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$$

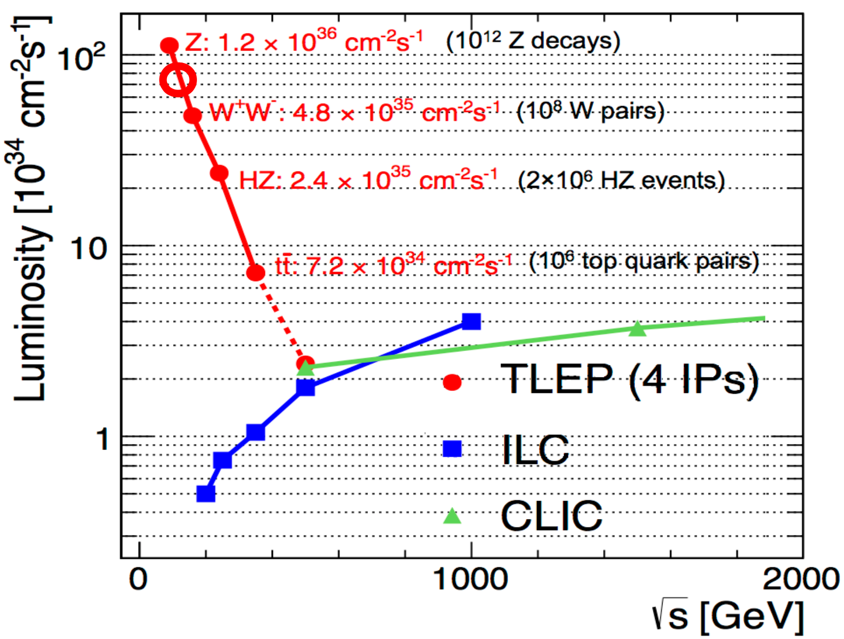
BR($H\to e^+e^-$)~$5.3\cdot10^{-9}$ (decay unobservable)

$$\sigma(e^+ e^- \to H) = \frac{4\pi\Gamma_H^2 Br(H \to e^+ e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2}$$

~ 1.64 fb (m_H=125 GeV, Γ_H=4.2 MeV)



- Huge luminosities available at FCC-ee:



In theory, with L_{int}~6 ab^{-1} (4 exps./year) FCC-ee running at H pole mass would produce O(10.000) H bosons.

With reduced beam energy spread & with reduced backgrounds:

→ Electron Yukawa coupling measurable?

→ Higgs width measurable (threshold scan)?

→ Separation of possible nearly-degen. H's?

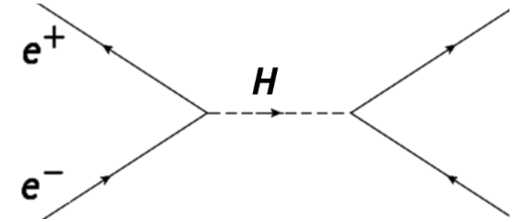
Resonant s-channel $e^+e^- \to H$ production

- Resonant Higgs production considered so far only for muon collider:
  $\sigma(\mu\mu\to H)$ ~ 70 pb. Tiny g_{Hee} Yukawa coupling ⇒ Tiny $\sigma(ee\to H)$

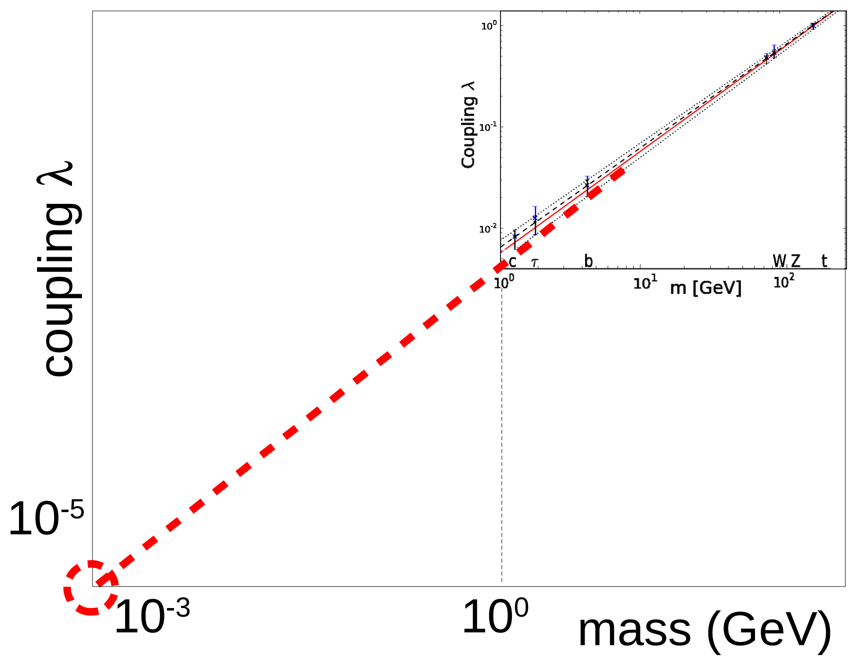
$$\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$$

$BR(H\to e^+e^-)$~$5.3\cdot10^{-9}$ (decay unobservable)

$$\sigma(e^+e^- \to H) = \frac{4\pi\Gamma_H^2 Br(H\to e^+e^-)}{(\hat{s}-M_H^2)^2+\Gamma_H^2 M_H^2}$$ ~ 1.64 fb (m_H=125 GeV, Γ_H=4.2 MeV)



- Huge luminosities available at FCC-ee:



In theory, with L_{int}~6 ab^{-1} (4 exps./year) FCC-ee running at H pole mass would produce O(10.000) H bosons.

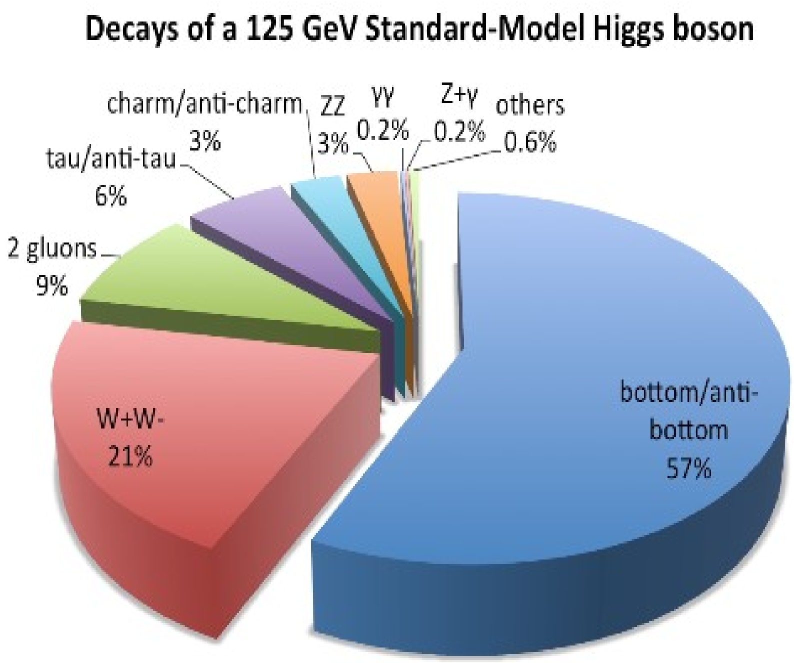
With reduced beam energy spread & with reduced backgrounds:

→ Electron Yukawa coupling measurable?

→ Higgs width measurable (threshold scan)?

→ Separation of possible nearly-degen. H's?

Visible Higgs decays at FCC-ee(H/2)



Considered Channels:

- WW*(2j,lν) (σ = 166 ab), continuum background σ~O(20 fb)
- WW*(2l2ν) (σ = 39 ab), continuum background σ~O(5 fb)
- WW*(4j) (σ = 173 ab), qqbar background σ~O(100 pb)
- ZZ*(2j2ν) (σ = 14 ab), continuum background σ~O(270 ab)
- bb(2j) (σ = 922 ab) continuum background σ~O(20 pb)
- Other 2-jet final-states (cc,gg) swamped by $e^+e^- \to Z^*,\gamma^* \to$ qqbar σ~O(100pb)
- Other 4-jet final-state (ZZ*) swamped by $e^+e^- \to Z^*,\gamma^* \to$ qq(gg), σ~O(1pb), $e^+e^- \to$ WW*,ZZ*, σ~O(20fb)
- τ-τ and rare decays swamped by backgrounds and/or have ~0 counts.

$e^+e^- \rightarrow H(WW^*) \rightarrow 2l2\nu$

- PYTHIA8 for signal & backgrounds at $\sqrt{s} = m_H = 125$ GeV.

  Final state: 2 isolated ($\Sigma E<0.75$ GeV, $\Delta R<0.25$) leptons e,μ,τ(e),τ(μ) +Miss.En.

  no unisolated leptons or final state hadrons, within $|\eta|<5$ (acceptance). This retains 60% of the σ(WW*(2l2nu)) = 39 ab.

- Kinematic Cuts: Sphericity > 0.03 ¬ Kills tautau

  ΔR(l,ME) > 1.5 ¬ Kills tautau

  $\cos(\theta_{l1l2})>-0.6$ ¬ Kills tautau

- We can exploit different lepton angular correlations from spin-0 decays into $W^-(l_L\nu_L)W^+(l_R\nu_L)$ and continuum to reduce the latter. MVA across kinematic and angular variables reduces WW* continuum.

- Signal & backgrounds before kinematics/MVA (left) and after (right):

H(WW*):	σ = 23 ab	$\Rightarrow$	σ(after cuts) ~ 13 ab
qqbar:	σ ~ 0* pb	$\Rightarrow$	σ(after cuts) ~ 0 ab
τ-τ:	σ ~ 1.3 pb	$\Rightarrow$	σ(after cuts) ~ 1 ab
WW:*	*σ = 3.4 fb*	$\Rightarrow$	*σ(after cuts) ~ 651 ab*
ZZ*:	σ = 29 ab	$\Rightarrow$	σ(after cuts) ~ 1.5 ab

*preselection kills this channel entirely

For L_{int}=1 ab^{-1}

$S/\sqrt{B} \sim 13/\sqrt{654} \sim 0.5$

Significance~0.5

BR(Hee) < $6\times BR_{SM}$ (3σ)

$g_{hee} < 2.6 \times g_{Hee,SM}$ (3σ)

$e^+e^- \rightarrow H(WW^*) \rightarrow l\nu jj$

- PYTHIA8 for signal & backgrounds at $\sqrt{s} = m_H = 125$ GeV.

  Final state: 1 isolated ($\Sigma E<0.75$ GeV, $\Delta R<0.25$) lepton e,μ,τ(e),τ(μ) + Miss.En. + 2 jets at most one tau lepton with 0.75% tau mistag rate, within $|\eta|<5$ (acceptance). Retains 80% of the $\sigma(WW^*(l\nu jj)) = 166$ ab.
- Kinematic Cuts: $m_{neutrinos} < 0.4$ GeV/c^2 ¬ kills tautau
  $E_{j1} < 52$ GeV ¬ Kills qqbar
  $E_{j2} < 45$ GeV ¬ Kills qqbar
  $m_{w(l\nu)} > 12$ GeV/c^2 ¬ Kills qqbar
- Signal & backgrounds before kinematics (left) and after (right):

H(WW*):	$\sigma = 136$ ab	$\Rightarrow$	σ(after cuts) ~ 78 ab
qqbar:	$\sigma \sim 5$ pb	$\Rightarrow$	σ(after cuts) ~ 93 ab
τ-τ:	$\sigma \sim 61$ fb	$\Rightarrow$	σ(after cuts) ~ 0 ab
WW:*	*$\sigma = 19$ fb*	$\Rightarrow$	*σ(after cuts) ~ 10.8 fb*

For $L_{int}=1$ ab^{-1}
$S/\sqrt{B} \sim 78/\sqrt{10900} \sim 0.75$
Significance~0.75

$BR(Hee) < 4 \times BR_{SM}$ (3σ)
$G_{hee} < 2 \times g_{Hee,SM}$ (3σ)

$e^+e^- \to H(ZZ^*) \to 2j2\nu$

- PYTHIA8 for signal & backgrounds at $\sqrt{s} = m_H = 125$ GeV.

  Final state: 0 isolated ($\Sigma E<0.75$ GeV, $\Delta R<0.25$) leptons e,μ,τ(e),τ(μ) + Miss.En.>30 GeV + 2 jets, 0 tau leptons in the event with 0.75% tau mistag rate, within $|\eta|<5$ (acceptance). This retains 75% of the $\sigma(WW^*(2j2\nu)) = 14$ ab.

- Kinematic Cuts: $\cos(\Delta\theta_{MEj2}) < 0.9$ ¬ Kills tautau

  $|Q_{jet}| < 0.66e$ ¬ Kills tautau

  $M_{ME} > 10$ GeV/c^2 ¬ Kills WW*

- Signal & backgrounds after cuts:

H(WW*):	$\sigma = 14$ ab	⇒	σ(after cuts) ~ 10 ab
τ-τ:	$\sigma \sim 178$ ab	⇒	σ(after cuts) ~ 5 ab
ZZ:*	*$\sigma = 214$ ab*	⇒	*σ(after cuts) ~ 196 ab*
WW*:	$\sigma = 543$ ab	⇒	σ(after cuts) ~ 50 ab

For $L_{int} = 1$ ab^{-1}

$S/\sqrt{B} \sim 10/\sqrt{251} \sim 0.6$

Significance~0.6

$BR(Hee) < 5 \times BR_{SM}$ (3σ)

$g_{hee} < 2.2 \times g_{Hee,SM}$ (3σ)

$e^+e^- \rightarrow H(WW^*) \rightarrow 4j$

- PYTHIA8 for signal & backgrounds at $\sqrt{s} = m_H = 125$ GeV.

Final state: 0 isolated ($\Sigma E<0.75$ GeV, $\Delta R<0.25$) leptons $e,\mu,\tau(e),\tau(\mu)$ +
+ 4jets 0 taus (with0.75% tau mistag rate), 0 b's (with 70% b tagging efficiency, 5% charm mistag rate, 1.5% light quark mistag rate). within $|\eta|<5$ (acceptance), This retains 78% of the $\sigma(WW^*(4j)) = 173$ ab.

- Kinematic Cuts: Sphericity > 0.018, Aplanarity > 0.004 (excludes 2-jet events)
- Signal & backgrounds after state definition:

$H(WW^*)$:	$\sigma=135$ pb $\Rightarrow \sigma= 108$ ab
qqbar:	$\sigma=74$ pb $\Rightarrow \sigma\sim 6.4$ pb
τ-τ:	$\sigma= 573$ ab $\Rightarrow \sigma\sim 0.11$ ab
WW:*	$\sigma=19$ fb $\Rightarrow \sigma=14.4$ fb
ZZ*:	$\sigma=234$ ab $\Rightarrow \sigma=134$ ab

For $L_{int}=1$ ab^{-1}

$S/\sqrt{B}\sim 108/\sqrt{6.4*10^6}\sim 0.04$

Significance~0.04

$BR(Hee) < 75\times BR_{SM}$ (3σ)

$g_{Hee} < 8.66 \times g_{Hee,SM}$ (3σ)

- This channel still under investigation... (add different-flavor requirements: < 2 b-jets and <2 c-jets, to kill b-bbar, c-cbar).

$e^+e^- \to H(bb) \to jj$

- PYTHIA8 for signal & backgrounds at $\sqrt{s} = m_H = 125$ GeV.

  Final state: 0 isolated ($\Sigma E<0.75$ GeV, $\Delta R<0.25$) leptons $e,\mu,\tau(e),\tau(\mu)$ + 2 jets both jets are b-tagged (70% efficiency, 5% charm mistag rate, 1.5% light quark mistag rate), 0 taus (0.75% tau mistag rate) and within $|\eta|<5$ (acceptance). This keeps ~50% of the original signal.
- Kinematic Cuts: None, after the final-state, nothing found yet to kill The dominant bbar continuum
- Signal & backgrounds:

  H(WW*): $\sigma = 451.6$ ab

  qqbar: $\sigma \sim 9.56$ pb

  τ-τ: $\sigma \sim 572$ ab

For $L_{int}=1$ ab^{-1}

$S/\sqrt{B} \sim 451/\sqrt{9.56*10^6} \sim 0.15$

Significance~0.15

$BR(Hee) < 7\times BR_{SM}$ (3σ)

$g_{Hee} < 4.4 \times g_{Hee,SM}$ (3σ)

- Clearly, this channel merits further investigation to improve signal purity.

Improvements to be made

- WW*(4j) and bb(jets) have HUGE backgrounds (). Clearly, further investigation into methods to reduce these backgrounds is needed. particularly interesting areas include:
  - distinguishing between gluon jets (emitted by the qqbar background in the WW*(4j) case) and jets from quarks (which all 4 jets will be in the signal for this channel)
  - finding methods to distinguish between s-channel and t-channel processes in 2-body decays (which I'll need to kill the continuum in the bb channel).
- Less urgently, it would be useful to find effective methods to distinguish signal from continuum background for the WW*(lvjj) and ZZ*(2vjj) channels, which would boost significance in these channels.

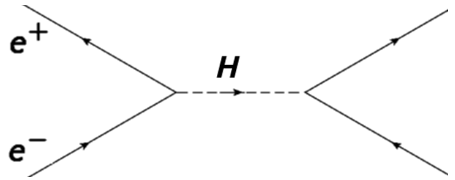
Multi-Channel Combination (Significance)

- Clearly, no channel has high significance alone. It is therefore necessary to combine significances.
- The below table was generated using the Roostats-based statistics tools for Higgs analysis. These numbers are the asymptotic significances here (for smaller numbers of events, the Monte Carlo toys method is more precise, but the difference between the outcomes is small enough here that the asymptotic significances can be instructive.

Channel	Significance (1 ab^{-1})	Significance (6 ab^{-1})	Significance (10 ab^{-1})
WW->lvjj	0.75	1.84	2.37
WW->2l2v	0.5	1.22	1.58
ZZ->2j2v	0.60	1.47	1.89
bb	0.15	0.36	0.46
WW->4j	0.04	0.10	0.13
Combined	1.09	2.68	3.46

Conclusions

- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):



$\sigma(e^+e^- \to H)_{B\text{-}W}$ ~ 1.64 fb (m_H=125 GeV, Γ_H=4.2 MeV)

(potentially visible thanks to huge FCC-ee lumi)

- Cleanest channels: WW*(2j,lν) (σ = 166 ab), WW*(2l2ν) (σ = 39 ab), WW*(4j) (σ = 173 ab), ZZ*(2j2ν) (σ = 14 ab), and bb(2j) (σ = 922 ab)
- Preliminary analysis yields significances of

  For L_{int} = 1 ab^{-1}, 1.08

  ⇒ BR(Hee) < 4.6×BR_{SM} (5σ), g_{hee} < 2.14 × $g_{Hee,SM}$ (5σ)

  For L_{int} = 6 ab^{-1}, 2.64

  ⇒ BR(Hee) < 1.87×BR_{SM} (5σ), g_{hee} < 1.37 × $g_{Hee,SM}$ (5σ)

  For L_{int} = 10 ab^{-1}, 3.41

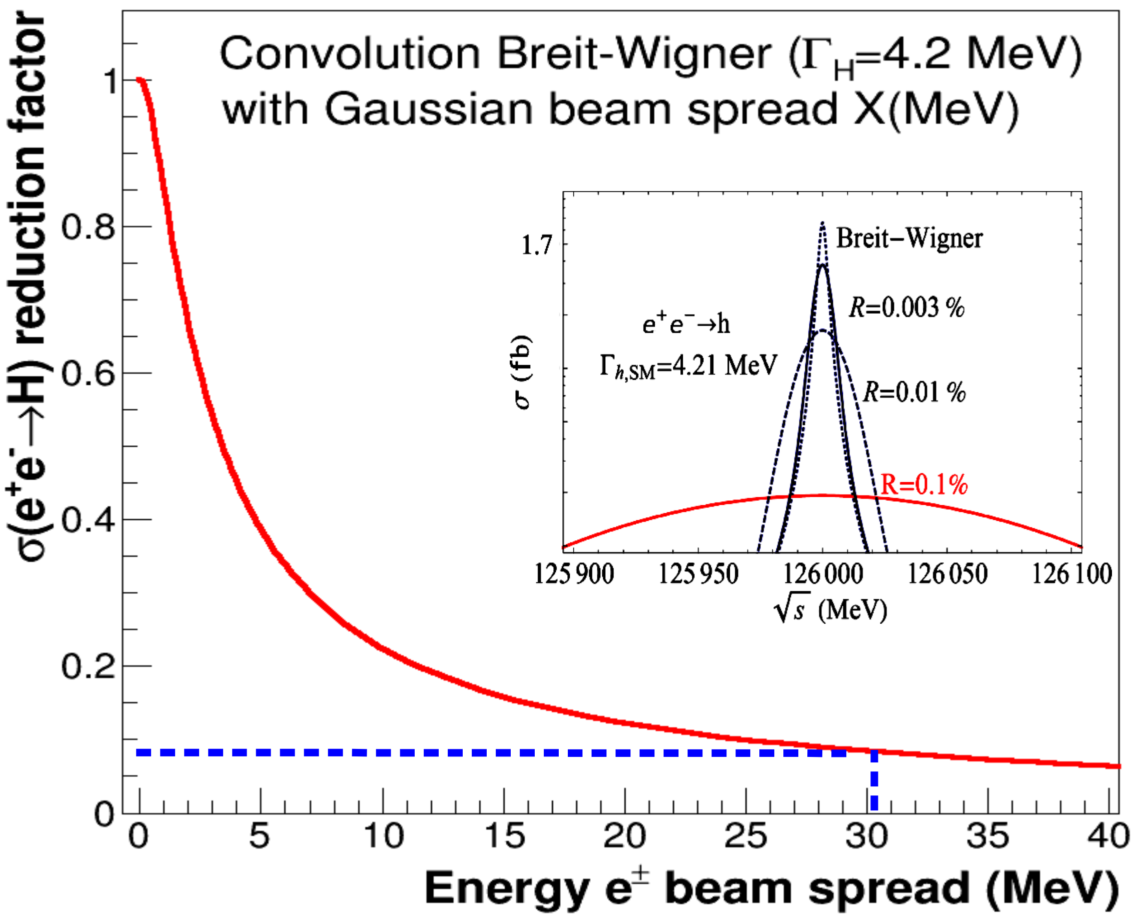
  ⇒ BR(Hee) < 1.4×BR_{SM} (5σ), g_{hee} < 1.19 × $g_{Hee,SM}$ (5σ)

- Fundamental & unique physics accessible if measurement feasible:
  - → Electron Yukawa coupling
  - → Higgs width measurable (“natural” threshold scan)
- Note: Significance reduction expected due to: (I) ISR (~60%), (ii) Beam spread (~50% for E_spread~Gamma_H~4.2MeV

Backup slides

$e^+e^- \to H$ x-section: Beam energy spread

- $\sigma(e^+e^-\to H)$ considered so far is for B.-W. with natural 4.2 MeV width...
- Convolution of increasing Gaussian energy spread of each $e^\pm$ beam with Higgs B.W. results on a (Voigtian) effective cross-section decrease:



$E_{spread} \sim \Gamma_H \sim$ 4.2 MeV:

Reduction factor: 45%

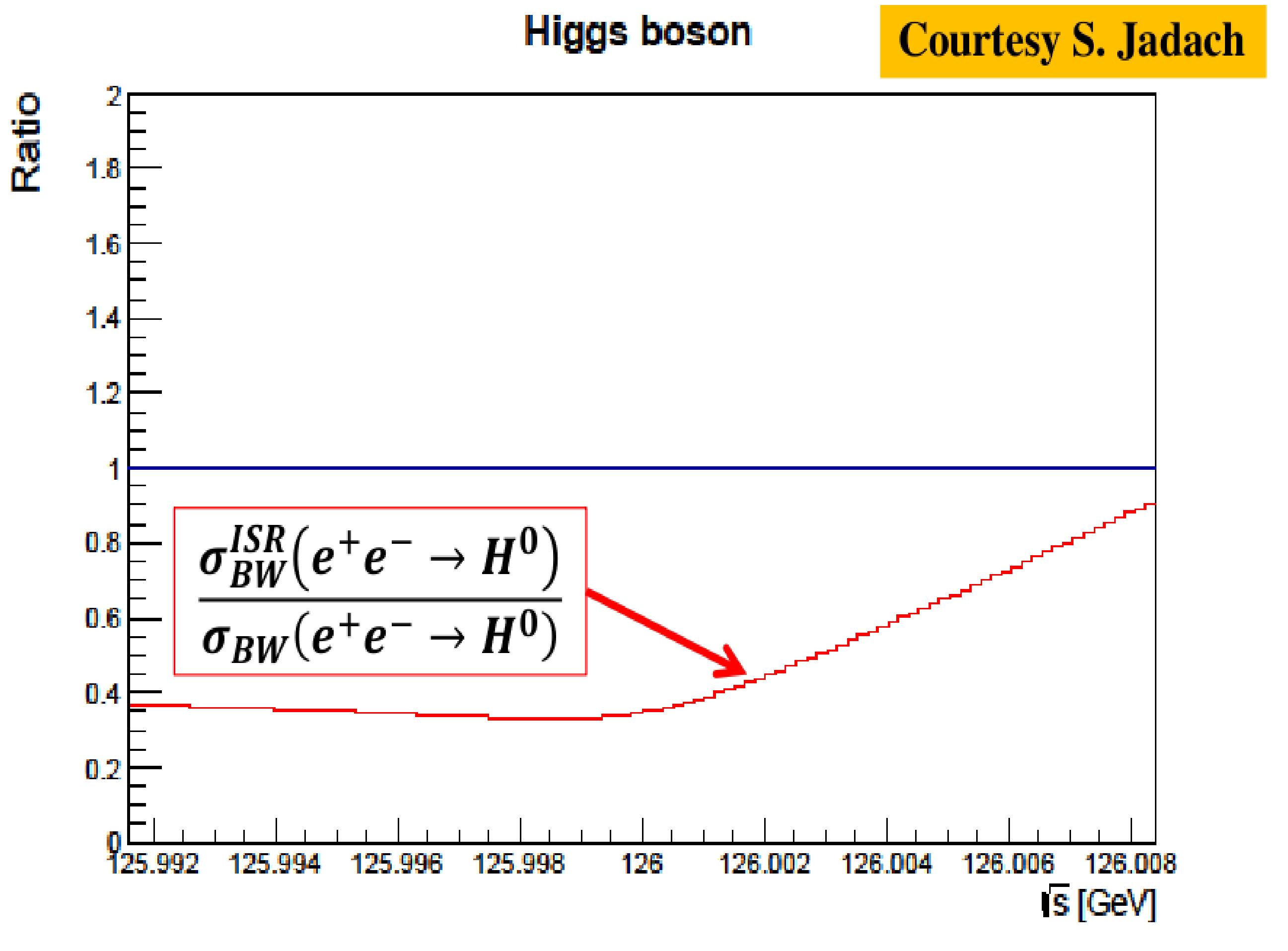
Current FCC-ee nominal ($\Delta E_{beam}/E_{beam} \sim 0.05\%$):

$E_{spread} \sim$ 30 MeV:

Reduction factor: 8%

$e^+e^- \rightarrow H$ x-section: ISR reduction factor

- Extra ~40% reduction in $\sigma(e^+e^- \rightarrow H)$ due to initial state radiation:



$e^+e^- \rightarrow H(WW^*) \rightarrow 4j$ (Discussion)

- The 4-jet final state WW*(4j) presents interesting challenges.
- The qqbar background σ ~O(100 pb) produces mainly 2-jet events, which can be killed by cutting on event shape variables (sphericity & aplanarity), but ~6 pb remains from quarks that radiate gluons to produce 4-jet events.
- Tagging b-jets (which are produced ~20% of the time in the qqbar background and ~5% of the time in the signal) and removing events with any b-tagged jets provides marginal improvement in separation, but the qqbar background still dominates and washes out the signal almost entirely
- Unfortunately, attempts to reconstruct W mass to apply cuts met with little success (low discriminating power)