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

8th FCC-ee Physics Workshop

Paris, 27th–29th October 2014

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

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

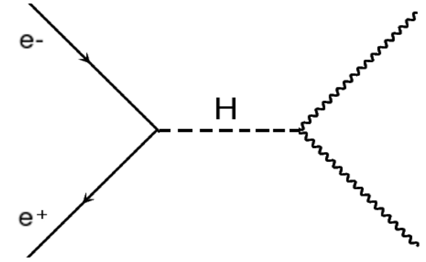
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu \rightarrow H) \sim 70$ pb. Tiny g_{Hee} Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee \rightarrow H)$

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

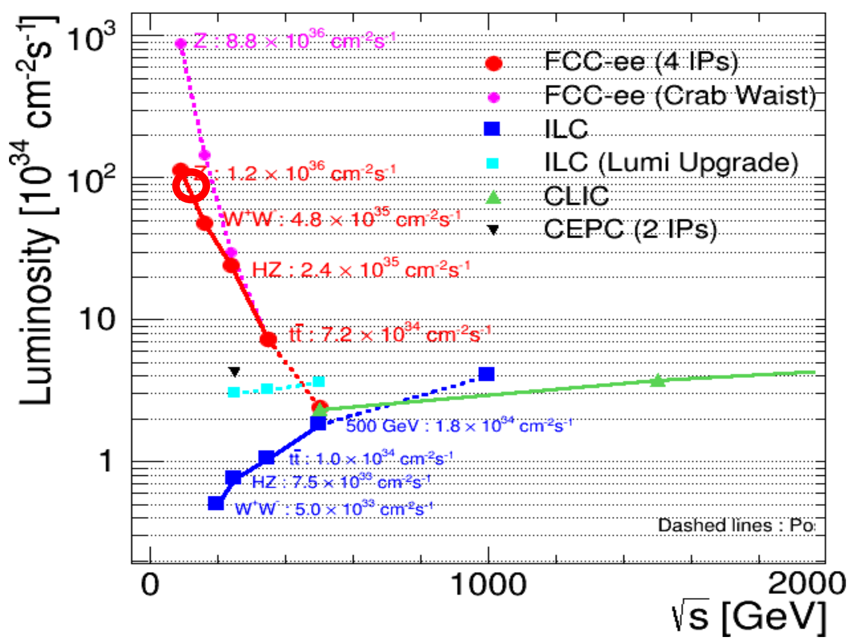
BR($H \rightarrow e^+e^-$)~$5.3 \cdot 10^{-9}$ (decay unobservable)

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

= 1.64 fb (m_H=125 GeV, Γ_H=4.2 MeV)



- Huge luminosities available at FCC-ee:



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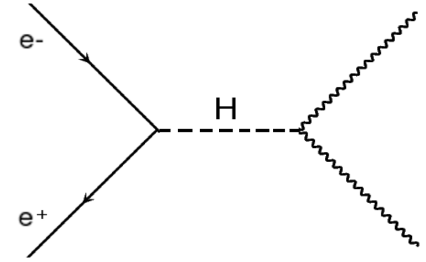

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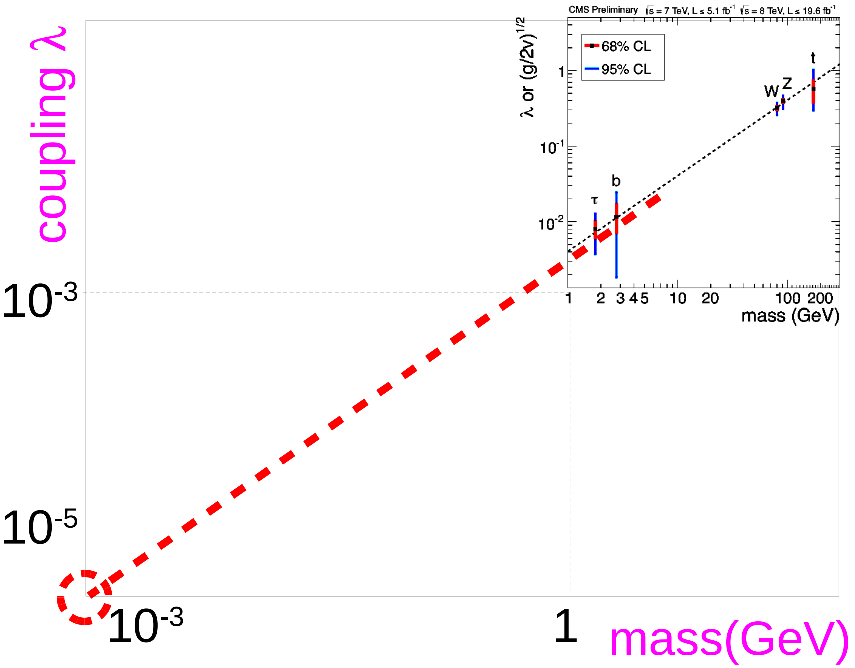


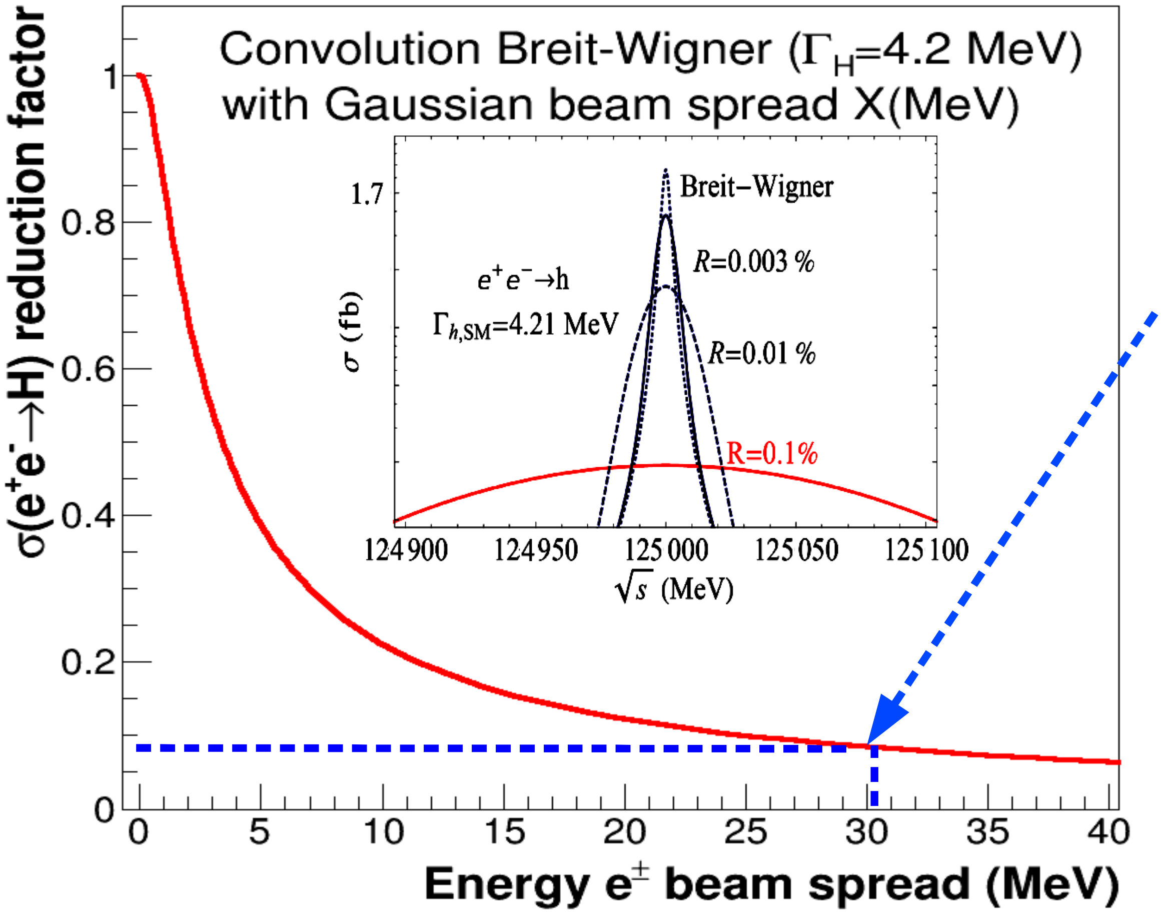
In theory,FCC-ee (L_{int}~10 ab^{-1}/yr) running at H-pole mass would produce O(16.000) H's

IFF we can handle: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds...

→ Electron Yukawa coupling measurable?
→ Higgs width measurable (threshold scan)?
→ Separation of possible nearly-degen. H's?

$\sigma(e^+e^- \to H)$ reduction: Beam energy spread

- $\sigma(e^+e^- \to H)$ = 1.64 fb for Breit-Wigner with Γ_H = 4.2 MeV width. Higgs production greatly suppressed off resonant peak.
- Convolution of Gaussian energy spread of each $e^\pm$ beam with Higgs B.-W. results on a (Voigtian) effective cross-section decrease:



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

E_{spread}~ 30 MeV:

Reduction factor: ×1/12

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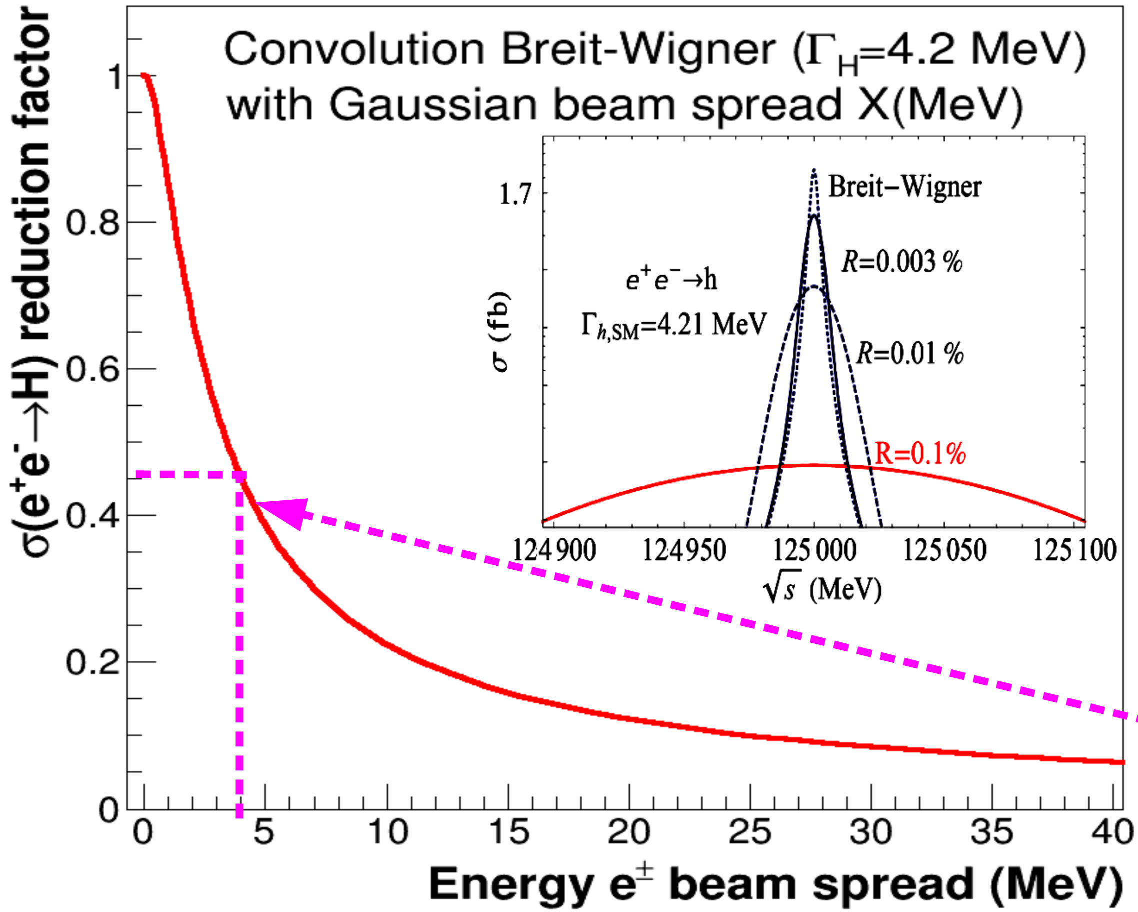


Current FCC-ee nominal ($\Delta E_{beam}/E_{beam}$~0.05%):

E_{spread} ~ 30 MeV:

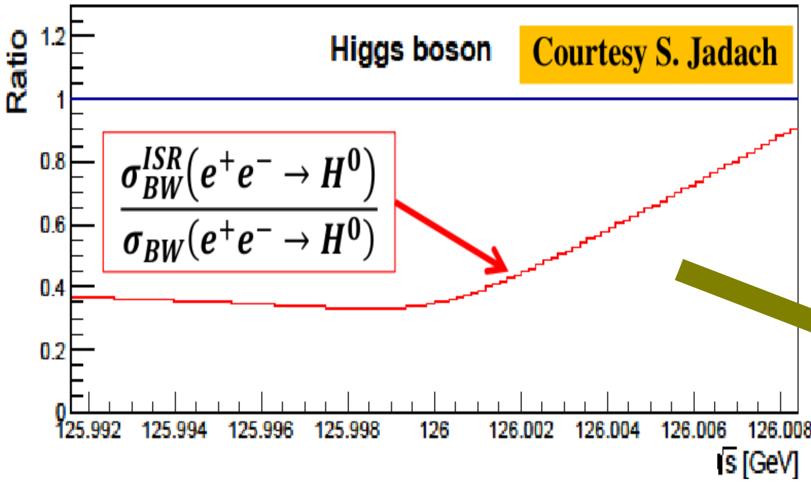
Reduction factor: ×1/12

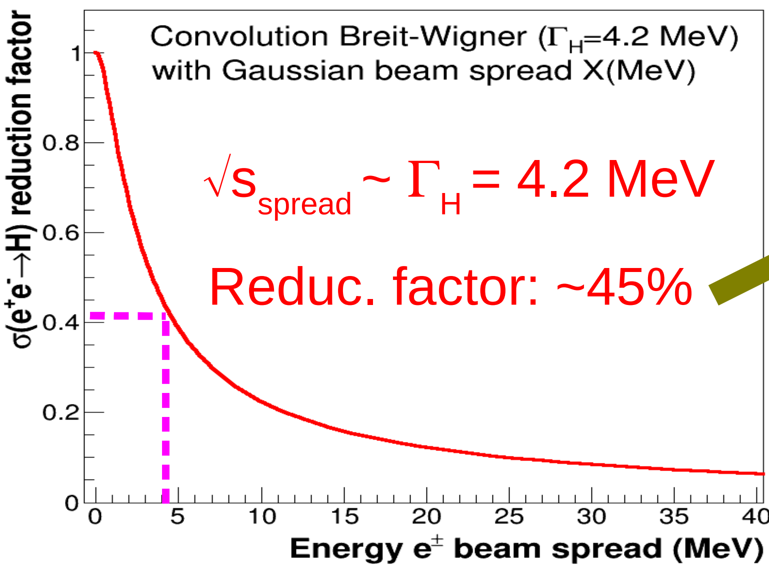
$\sqrt{s}_{spread} \sim \Gamma_H$ = 4.2 MeV (monochromatization?):

Reduction factor: ~45%

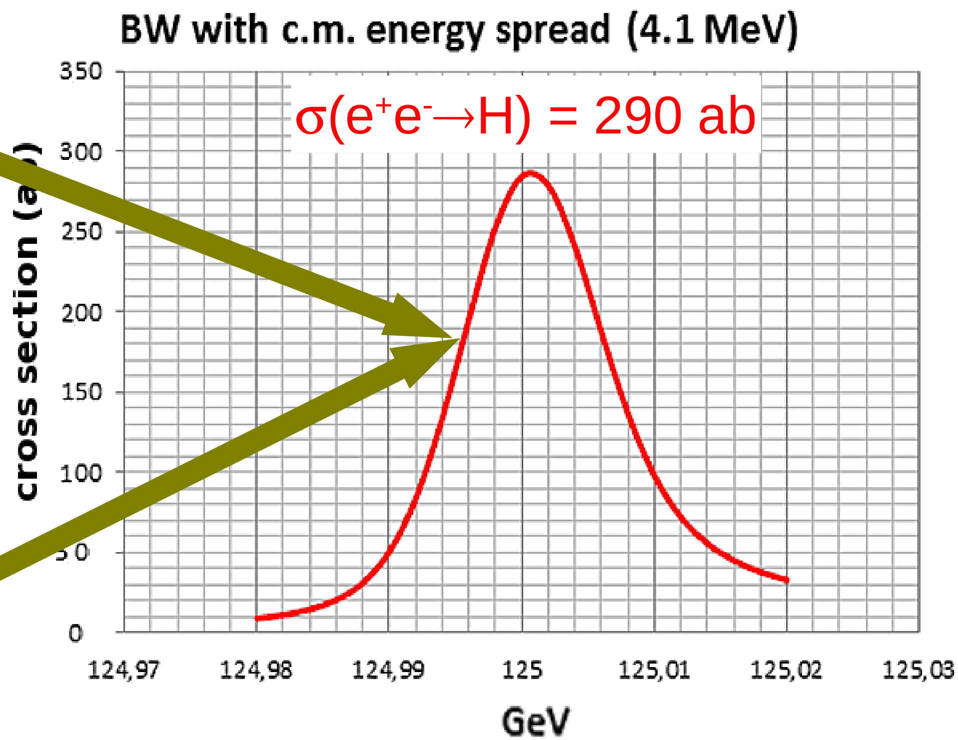
$\sigma(e^+e^- \to H)$ reduction: Beam energy spread + ISR

- Extra ~40% reduction also due to initial state radiation:





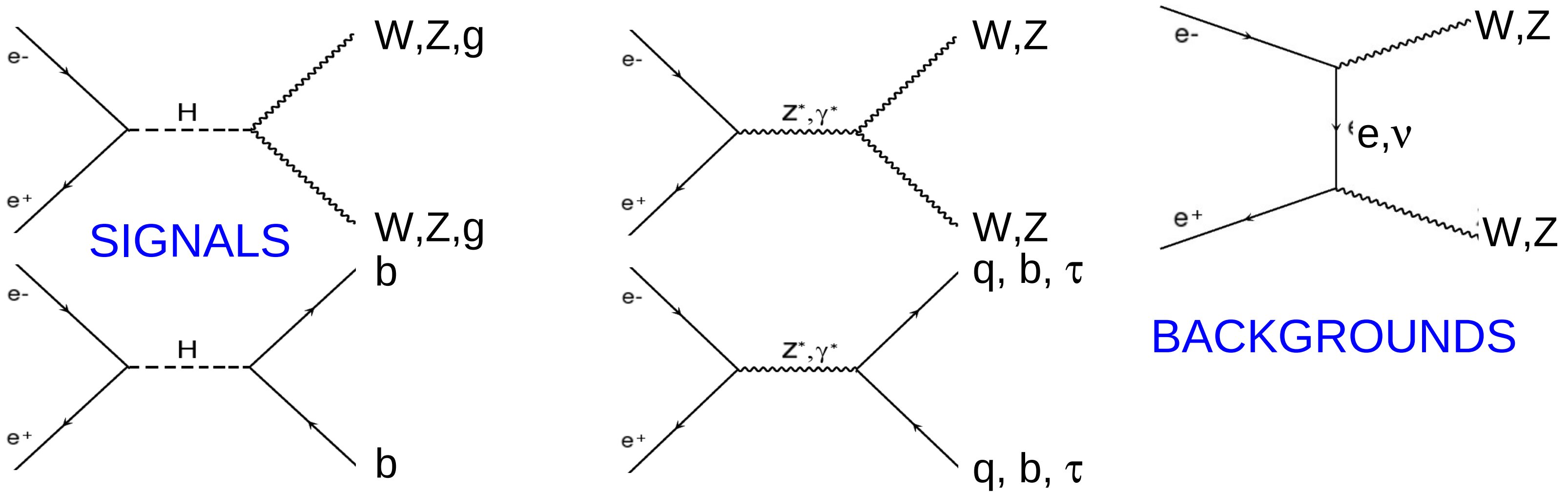
- Combined reduction factors:



$\sigma_{beam\text{-}spread+ISR}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H)$

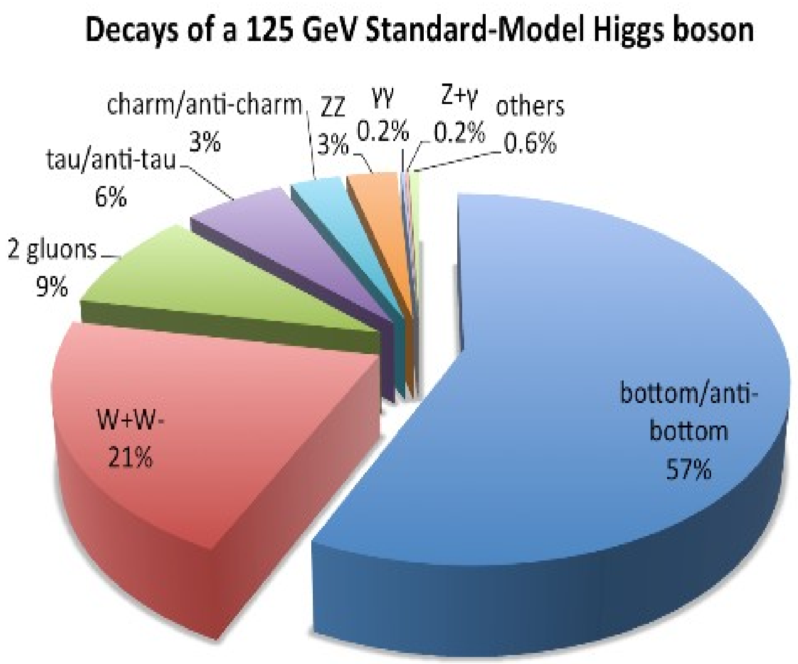
Theoretical setup

- PYTHIA8 at $\sqrt{s} = m_H = 125$ GeV for s-channel Higgs plus 5 backgrounds ($e^+e^- \to WW^*, ZZ^*, \tau\tau$, qqbar, gg):



- FastJet package: exclusive e^+e^- (2,4) jet algorithm.
- ISR automatically included. Beam energy spread included as scaling factor to match final computed ~0.17 suppression.
- ISR events tagged via 2 methods (depending on ν's in final state):
  - (1) Cut on the ME vector. ISR photons mostly emitted along beam axis: Large missing energy (ME) but low transverse missing energy (MET). constructed with sum of all particles outside of acceptance (|η|<5).
  - (2) Cut on Etotal (computed without isolated ISR photons within |η|<5): Isolated photons ($\Sigma E<1$ GeV, $\Delta R<0.25$) with E>5 GeV omitted: $E_{total} > 120$ GeV

7 visible Higgs decays at FCC-ee(62.5 GeV)



PYTHIA8 (ISR+beam-spread) for signal & backgrounds at $\sqrt{s} = m_H = 125$ GeV:

1) WW* (2jlν): σ = 28 ab
Dominant bckgd (ee→WW*): σ=20 fb (S/B~10^{-3})

2) WW* (2l2ν): σ = 6.7 ab
Dominant bckgd (ee→WW*): σ=5 fb (S/B~10^{-3})

3) ZZ* (2j2ν): σ = 2.3 ab
Dominant bckgd (ee→ZZ*): σ=213 ab (S/B~10^{-2})

4) ZZ* (2l2j): σ = 1.14 ab
Dominant bckgd (ee→ZZ*):σ=114 ab (S/B~10^{-2})

5) bb (2 b-jets): σ = 156 ab
Dominant bckgd (ee→bb): σ=90 pb (S/B~10^{-6})

6) gg (2 jets): σ = 24 ab
Domin. bckgd (ee→"gg"): σ=0.9 pb (S/B~10^{-4})

7) WW* (4j): σ = 29.5 ab
Dominant bckgd (ee→4j): σ=16 fb (S/B~10^{-3})

- Other 2-jet final-state (cc) swamped by $e^+e^- \rightarrow Z^*,\gamma^* \rightarrow qq$ (390 pb)
- Other 4-jet final-state (ZZ*) swamped by $e^+e^- \rightarrow Z^*,\gamma^* \rightarrow qq\,gg$ (1 pb), $e^+e^- \rightarrow WW^*,ZZ^*$ (20 fb)
- τ-τ and rare decays swamped by backgrounds and/or have ~0 counts.
- Note: H s-channel measurement = Counting experiment over many channels

Channel 1: $e^+e^- \to H(WW^*) \to l\nu jj$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):
  1 isolated ($\Sigma E<1$ GeV, $\Delta R<0.25$) lepton e, μ, $\tau(e)$, $\tau(\mu)$ + ME>2 GeV + 2 jets
  Retains 80% of $\sigma(WW^*(l\nu jj))$ = 28 ab.
- Kinematic cuts:

  $E_{j1,j2} < 52,45$ GeV ¬ Kills qqbar
  $m_{w(l\nu)} > 12$ GeV/c^2 ¬ Kills qqbar
  $E_{lepton} > 10$ GeV ¬ Kills qqbar
  ME > 20 GeV ¬ Kills qqbar
  m(ME) < 3 GeV/c^2 ¬ Kills τ-τ

For L_{int}=10 ab^{-1}
$S/\sqrt{B} \sim 80/\sqrt{27000} \sim 0.5$
Significance~0.5

BR(Hee) < 6.1×BR_{SM} (3σ)
$g_{hee} < 2.47 \times g_{Hee,SM}$ (3σ)

- Boosted Decision Tree across angular variables & 4-vectors (MELA) applied to remove WW* continuum.
- Signal & backgrounds before & after kinematics+MVA:

H(WW*):	σ = 23 ab	⇒	σ(after cuts) ~ 8 ab
WW*:	σ = 16.3 fb	⇒	σ(after cuts) ~ 2.7 fb
qqbar:	σ = 22 pb	⇒	σ(after cuts) ~ 4 ab
τ-τ:	σ = 1 pb	⇒	σ(after cuts) ~ 2.6 ab

Channel 2: $e^+e^- \to H(WW^*) \to 2l2\nu$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):
  2 isolated ($\Sigma E<1$ GeV, $\Delta R<0.25$) leptons e,μ,τ(e),τ(μ) + ME>2 GeV
  + no unisolated leptons or final state hadrons.
  This retains 60% of the $\sigma(WW^*(2l2\nu))$ = 7 ab.

- Kinematic cuts (Preselection kills qqbar entirely):

  $\cos(\theta_{l1l2})>-0.6$ ¬ Kills τ-τ
  $\Delta R(l_2,E_{miss}) > 1.5$ ¬ Kills τ-τ
  $E_{l1,l2} > 3$ GeV ¬ Kills τ-τ
  ME > 20 GeV ¬ Kills τ-τ
  + BDT MVA ¬ Kills WW*

For L_{int}=10 ab^{-1}
S/√B~21/√5063~0.3
Significance~0.3

BR(Hee) < 10.3×BR_{SM} (3σ)
$g_{hee} < 3.2 \times g_{Hee,SM}$ (3σ)

- Signal & backgrounds before & after kin. & MVA cuts:

H(WW*):	σ = 4 ab	⇒	σ(after cuts) ~ 2.1 ab
WW*:	σ = 2.9 fb	⇒	σ(after cuts) ~ 454 ab
τ-τ:	σ = 3.1 pb	⇒	σ(after cuts) ~ 51 ab
qqbar:	σ ~ 0 pb	⇒	σ(after cuts) ~ 0 ab
ZZ*:	σ = 24 ab	⇒	σ(after cuts) ~ 0.4 ab

Channel 3: $e^+e^- \to H(ZZ^*) \to 2j2\nu$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):

  0 isolated ($\Sigma E<1$ GeV, $\Delta R<0.25$) leptons e,μ,τ(e),τ(μ) + ME >30 GeV +

  2 jets (exclusive 2-jet algo) + 0 τ's in event (0.75% τ mistag rate).

  This retains 75% of the $\sigma(WW^*(2j2\nu))$ = 2.3 ab

- Kinematic cuts:

  $\min(|m_{ME}-m_Z|,|m_{jj}-m_Z|)<10$ GeV ¬ Kills qqbar,τ-τ

  $E_{total} > 120$ GeV ¬ Kills qqbar, τ-τ

  $M_{ME} > 60$ GeV/c^2 ¬ Kills qqbar, τ-τ

  $\cos(\Delta\theta_{ME,j2}) < 0.8$ ¬ Kills τ-τ

  $|\eta_{jj}| < 2$ ¬ Kills qqbar, τ-τ

  $E_{jj} > 14$ GeV ¬ Kills τ-τ

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

S/√B~3.7/√316~0.21

Significance~0.21

BR(Hee) < 14.3×BR_{SM} (3σ)

$g_{hee} < 3.78 \times g_{Hee,SM}$ (3σ)

- Signal & backgrounds before & after kin. cuts:

H(WW*):	σ = 1.75 ab	⇒	σ(after cuts) ~ 0.37 ab
ZZ*:	σ = 179 ab	⇒	σ(after cuts) ~ 25 ab
qqbar:	σ = 963 fb	⇒	σ(after cuts) ~ 4 ab
τ-τ:	σ = 471 ab	⇒	σ(after cuts) ~ 2 ab
WW*:	σ = 526 ab	⇒	σ(after cuts) ~ 0 ab

Channel 4: $e^+e^- \to H(ZZ^*) \to 2l2j$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):
  2 isolated ($\Sigma E<1$GeV,$\Delta R<0.25$) opposite-charge leptons $e,\mu,\tau(e),\tau(\mu)$ +
  2 jets (exclusive 2-jet algo)
  This retains 73% of the $\sigma(WW^*(2l2\nu))$ = 1.14 ab
- Kinematic cuts:
  $\min(|M_{ll}-M_Z|,|M_{jj}-M_Z|)< 20$ GeV ¬ Kills qqbar, τ-τ
  ME < 10 GeV ¬ Kills τ-τ
  $E_{lepton}> 6$ GeV ¬ Kills qqbar
  $E_{l1}+E_{l2}> 20$ GeV ¬ Kills qqbar
  $M_{ll} > 20$ GeV/c^2 ¬ Kills qqbar
  $M_{jj} > 10$ GeV/c^2 ¬ Kills τ-τ

For L_{int}=10 ab^{-1}
$S/\sqrt{B}\sim 2.7/\sqrt{296}\sim 0.16$
Significance~0.16

$BR(Hee) < 19\times BR_{SM}$ (3σ)
$G_{hee} < 4.35 \times g_{Hee,SM}$ (3σ)

- Signal & backgrounds before & after kin. cuts:

H(WW*):	σ = 0.84 ab	⇒	σ(after cuts) ~ 0.27 ab
ZZ*:	σ = 87 ab	⇒	σ(after cuts) ~ 23 ab
τ-τ:	σ ~ 0.8 pb	⇒	σ(after cuts) ~ 2.5 ab
WW*:	σ = 3.1 fb	⇒	σ(after cuts) ~ 0.04 ab
qqbar:	σ = 17 pb	⇒	σ(after cuts) ~ 4 ab

Channel 5: $e^+e^- \rightarrow H(bb) \rightarrow jj$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):
  2 jets (exclusive 2-jet algo) + 1 b-jet tagged (70% effic., 5% charm mistag rate, 1.5% light-q mistag rate) + 0 taus (0.75% tau mistag rate).
  This keeps ~90% of the original signal of σ = 156 ab

- Kinematic cuts:
  None. Final-state selection + MVA applied to kill dominant bbar continuum

For L_{int}=10 ab^{-1}
S/√B~1310/√1.7e+8~0.1
Significance~0.1

BR(Hee) < 30×BR_{SM} (3σ)
g_{Hee} < 5.44 × $g_{Hee,SM}$ (3σ)

- Signal & backgrounds before & after MVA cuts:
  H(bb): σ = 142 ab ⇒ σ (after cuts) ~ 131 ab
  qqbar: σ = 87 pb ⇒ σ (after cuts) ~ 17 pb
  τ–τ: σ = 607 ab ⇒ σ (after cuts) ~ 375 ab

Channel 6: $e^+e^- \to H(gg) \to jj$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):
  0 isolated ($\Sigma E<1$ GeV, $\Delta R<0.25$) leptons $e,\mu,\tau(e),\tau(\mu)$ +
  2 gluon-tagged jets (60% efficiency, 5% quark mistagging rate) +
  0 taus (0.75% τ mistag rate).
  This keeps ~30% of the original signal of σ = 24 ab.

- Kinematic cuts:
  E_{total} > 124 GeV ¬ Kills part of $\tau\tau$,WW,ZZ

For L_{int}=10 ab^{-1}
$S/\sqrt{B} \sim 39.1/\sqrt{1.9*10^5} \sim 0.09$
Significance~0.09

BR(Hee) < 32×BR_{SM} (3σ)
g_{Hee} < 5.66 × $g_{Hee,SM}$ (3σ)

- Signal & backgrounds before & after kin. cuts:

H(gg):	σ=7.34 ab	⇒	σ (after cuts) = 3.91 ab
qqbar:	σ=0.86 pb	⇒	σ (after cuts) = 18.7 fb
$\tau-\tau$:	σ = 607 ab	⇒	σ (after cuts) = 257 ab
WW*:	σ = 44.6 ab	⇒	σ (after cuts) = 26 ab
ZZ*:	σ = 0.74 ab	⇒	σ (after cuts) = 0.26 ab

Channel 7: $e^+e^- \to H(WW^*) \to 4j$

- Final state (all objects reconstructed within $|\eta|<5$ acceptance):

  0 isolated ($\Sigma E<1$ GeV, $\Delta R<0.25$) leptons $e,\mu,\tau(e),\tau(\mu)$ + 0 taus (0.75% tau mistag rate) +4 jets (exclusive 4 jet algo)+ 0 b-jets (70% b tagging effic., 5% charm mistag rate, 1.5% light-q mistag rate) +
  0 gluon jets (60% q-tagging efficiency, 5% gluon mistag rate) +
  jet pairs around m_W must not both be c-tagged (80% c-tagging rate, 18% b mistagging rate, 2% light-q mistag rate) + >=1 jet c-tagged jet

  This retains 9% of the $\sigma(WW^*(4j))$ = 29 ab.

- Kinematic cuts:

  $-\ln(y_{j3,jet4})>5.$, $E_{total}>110$ GeV
  $\max(M_{jj})$= 60–85 GeV/c^2
  $|\Delta\Phi_{Z\ decay\ planes}|<1.$

- Signal & backgrounds before & after kin. cuts:

H(WW*):	σ = 2.75 ab	$\Rightarrow$	σ(after cuts) = 1.4 ab
qqbar:	σ = 15.7 fb	$\Rightarrow$	σ(after cuts) ~ 2 fb
WW*:	σ = 1.4 fb	$\Rightarrow$	σ(after cuts) = 810 ab
τ–τ:	σ= 0 ab	$\Rightarrow$	σ(after cuts) ~ 0 ab
ZZ*:	σ = 4 ab	$\Rightarrow$	σ(after cuts) = 1.38 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B}\sim14/\sqrt{29000}\sim0.08$
Significance~0.08

$BR(Hee) < 36\times BR_{SM}$ (3σ)
$g_{Hee} < 6 \times g_{Hee,SM}$ (3σ)

Multi-Channel Combination (Significance)

- Channels combination using Roostats-based statistics tool for LHC Higgs analyses: ProfileLikelihood & HybridNew all give ~identical results, which are also very close to naive S/√B expectation (no background uncertainty).

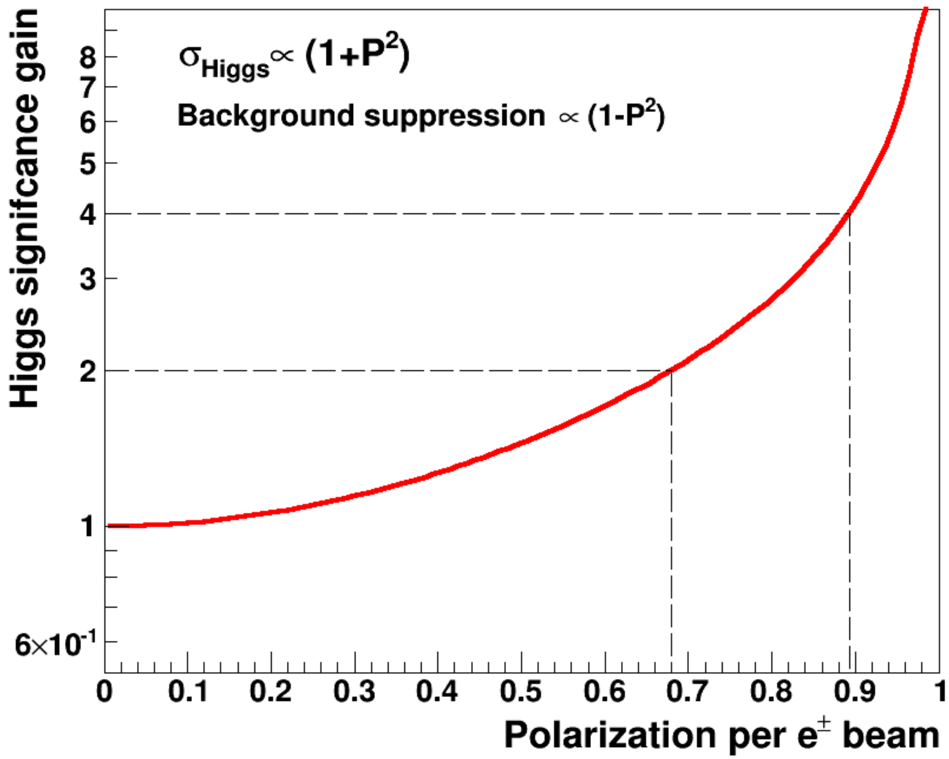
Channel	Significance ($1\ ab^{-1}$)	Significance ($6\ ab^{-1}$)	Significance ($10\ ab^{-1}$)
$WW \to l\nu jj$	0.15	0.38	0.49
$WW \to 2l2\nu$	0.09	0.23	0.29
$ZZ \to 2j2\nu$	0.07	0.16	0.21
$ZZ \to 2l2j$	0.05	0.12	0.16
bb	0.03	0.08	0.1
gg	0.03	0.07	0.09
$WW \to 4j$	0.03	0.06	0.08
Combined	**0.2**	**0.5**	**0.65**

- For 10 ab^{-1}: 3σ limit of 4.6*BR(H→ ee) for SM branching ratio
  3σ limit of 2.15*$g_{Hee,SM}$ for the H-e Yukawa coupling

Possible significance gains ?

- $L_{int} = L\times\Delta t = 10^{36}\ cm^{-2}s^{-1} \times$ 10Ms (8 months,50%) = 10 ab^{-1} (4 exps)
- Crab waist upgrade would result in ×6 more lumi at $\sqrt{s}=m_H$
  i.e. ×2.5 improve in significance: S=1.65σ, 3σ limit of 1.35*g_{Hee}(SM).
- Polarization of beams would enhance the signal (~1+P^2) & suppress background (1-P^2) but this would limit the lumi. Realistic polarization estimates (P=20-30%) are however clearly insufficient.

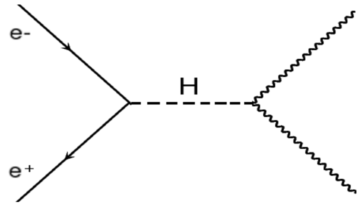
  P~0.7: ×2 significance
  P~0.9: ×4 significance



- Evidence (observation?) will require important improvements in large-BR (huge background) jet-channels: H→ bb, H → WW → 4j

Conclusions

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



$\sigma(e^+e^-\to H)_{B\text{-}W} \sim 1.64$ fb

$\sigma(e^+e^-\to H)_{visible} \sim 280$ ab (ISR + $E_{beam\text{-}spread} \sim \Gamma_H = 4.2$ MeV)

- Signal + backgrounds study for 7 decay channels:
  WW*(2j,lν) (σ = 28 ab), WW*(2l2ν) (σ = 6.7 ab),
  WW*(4j) (σ = 29.5 ab), ZZ*(2j2ν) (σ = 2.3 ab), ZZ*(2l2j) (σ = 1.14 ab),
  bb (2j) (σ = 156 ab), gg (2j) (σ = 24 ab)

- Preliminary analysis:
  $L_{int} = 10\ ab^{-1}$, S=0.65: $BR(Hee) < 4.63\times BR_{SM}$ (3σ), $g_{hee} < 2.15 \times g_{Hee,SM}$ (3σ)
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: $H\to bb$, $H \to WW \to 4j$

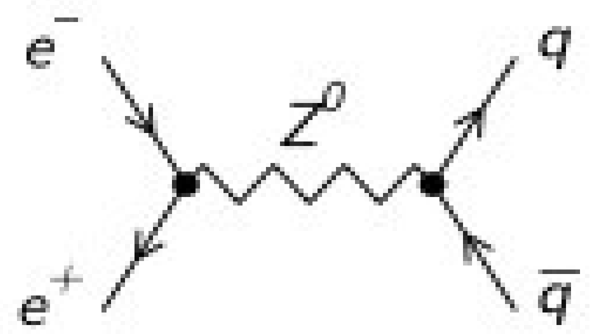
- Challenging accelerator conditions: mono-chromatization, huge lumi

- Fundamental & unique physics accessible if measurement feasible:
  → Electron Yukawa coupling
  → Higgs width measurable ("natural" threshold scan)

Backup slides

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

- 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
- Attempts to reconstruct W mass to apply cuts met with little success (low discriminating power). Try hemisphere separation ...

Other channels

- WW*(4j) and bb(jets) have HUGE backgrounds. Clearly, further investigation into methods to reduce these backgrounds is needed. particularly interesting areas include:
  (1) 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)
  (2) 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.