Resonant s-channel Higgs production at FCC-ee

FCC-ee Higgs Workshop

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

(*) Now SLAC/Stanford

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

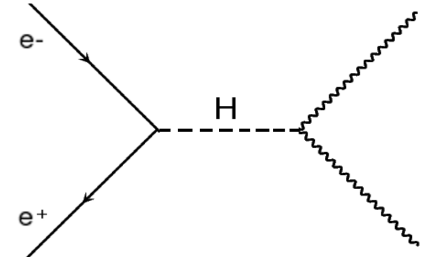
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \sim 70$ pb. Tiny g_{Hee} Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee\to H)$

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

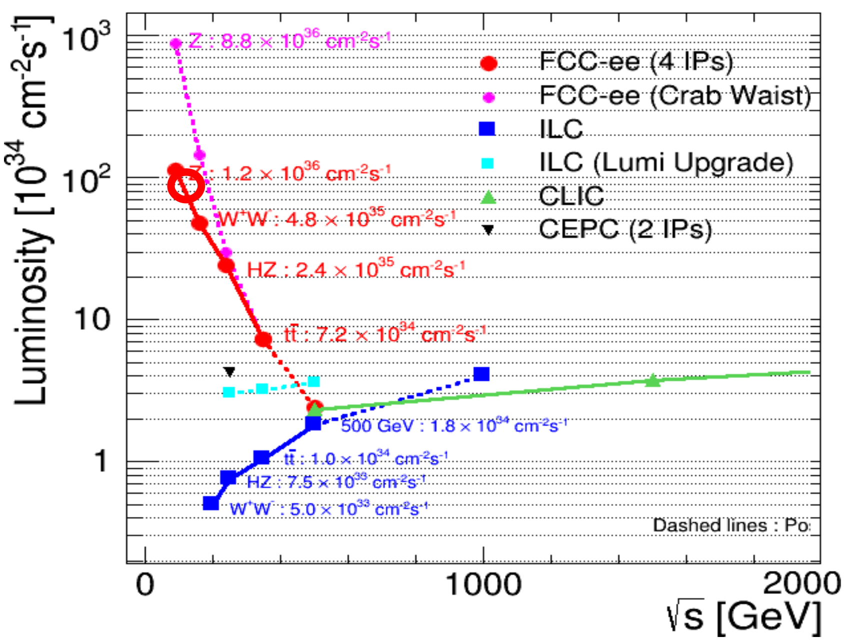
BR($H\to e^+e^-$)~$5.3\cdot 10^{-9}$ (decay unobservable)

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

= 1.64 fb (m_H=125 GeV, Γ_H=4.2 MeV)



- Huge luminosities available at FCC-ee:



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

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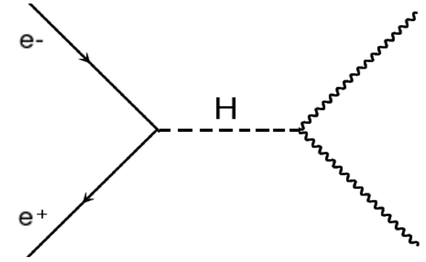

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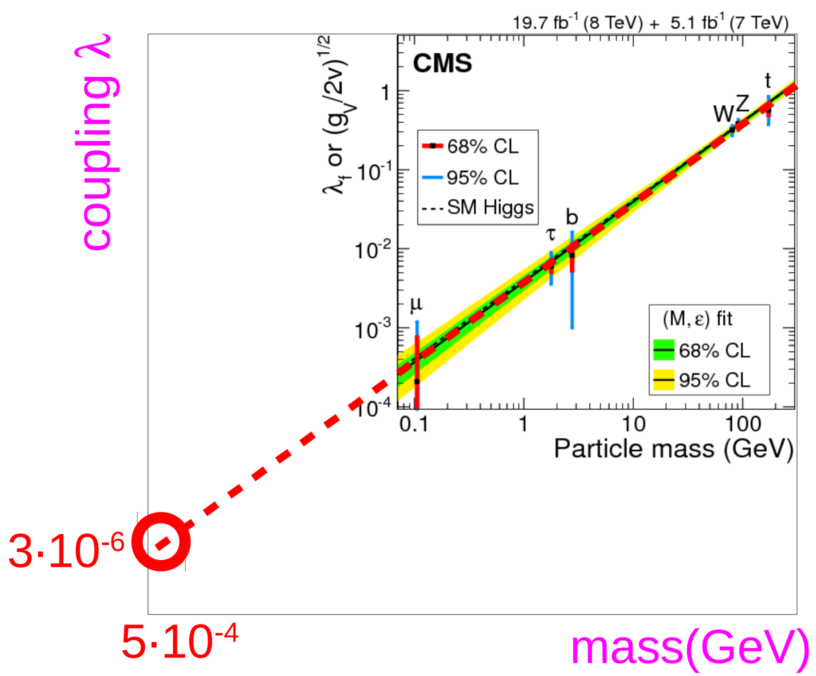


In theory, FCC-ee running at H pole-mass L_{int}~10 ab^{-1}/yr would produce O(16.000) H's

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

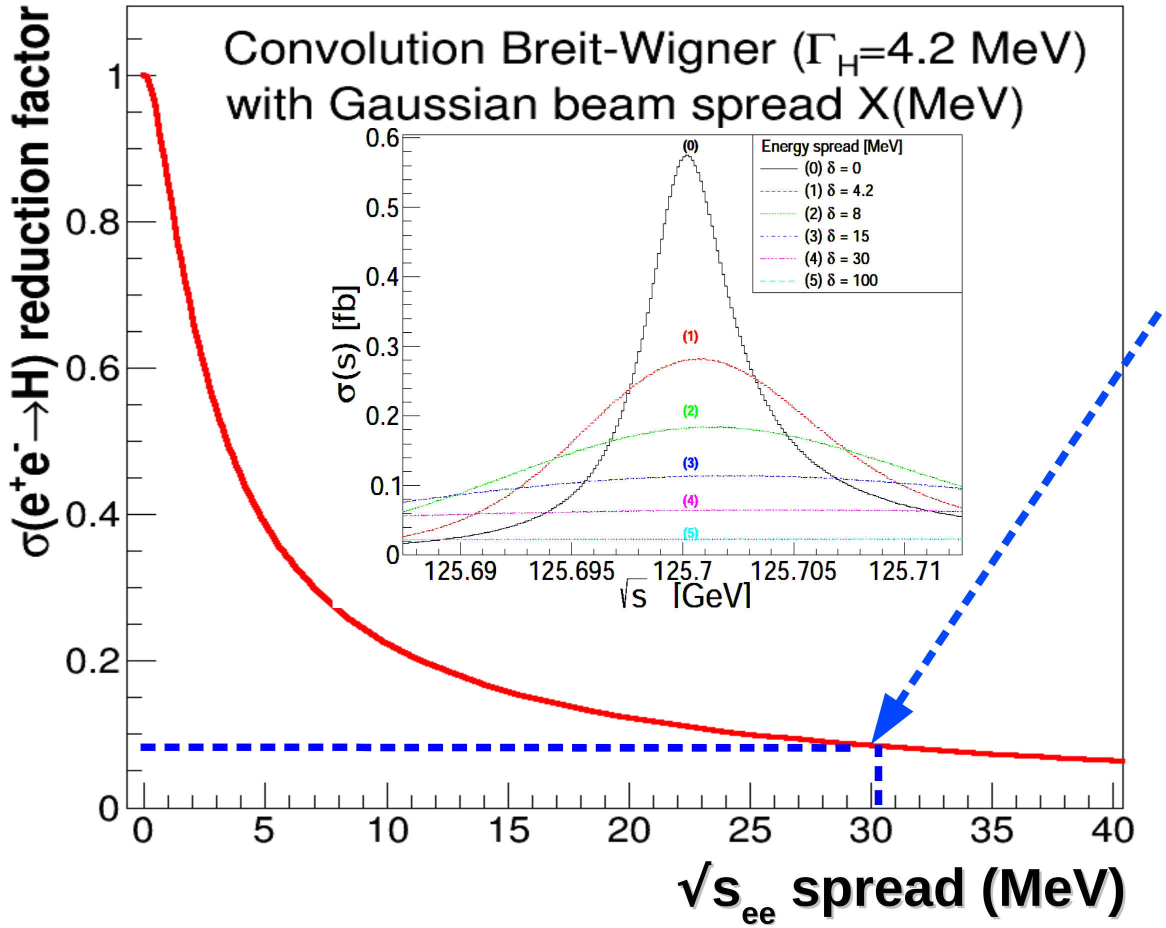
→ Electron Yukawa coupling measurable?

→ Higgs width measurable (threshold scan)?

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

σ(e⁺e⁻→H) reduction: √s 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

σ($e^+e^-\to$H) reduction: √s spread

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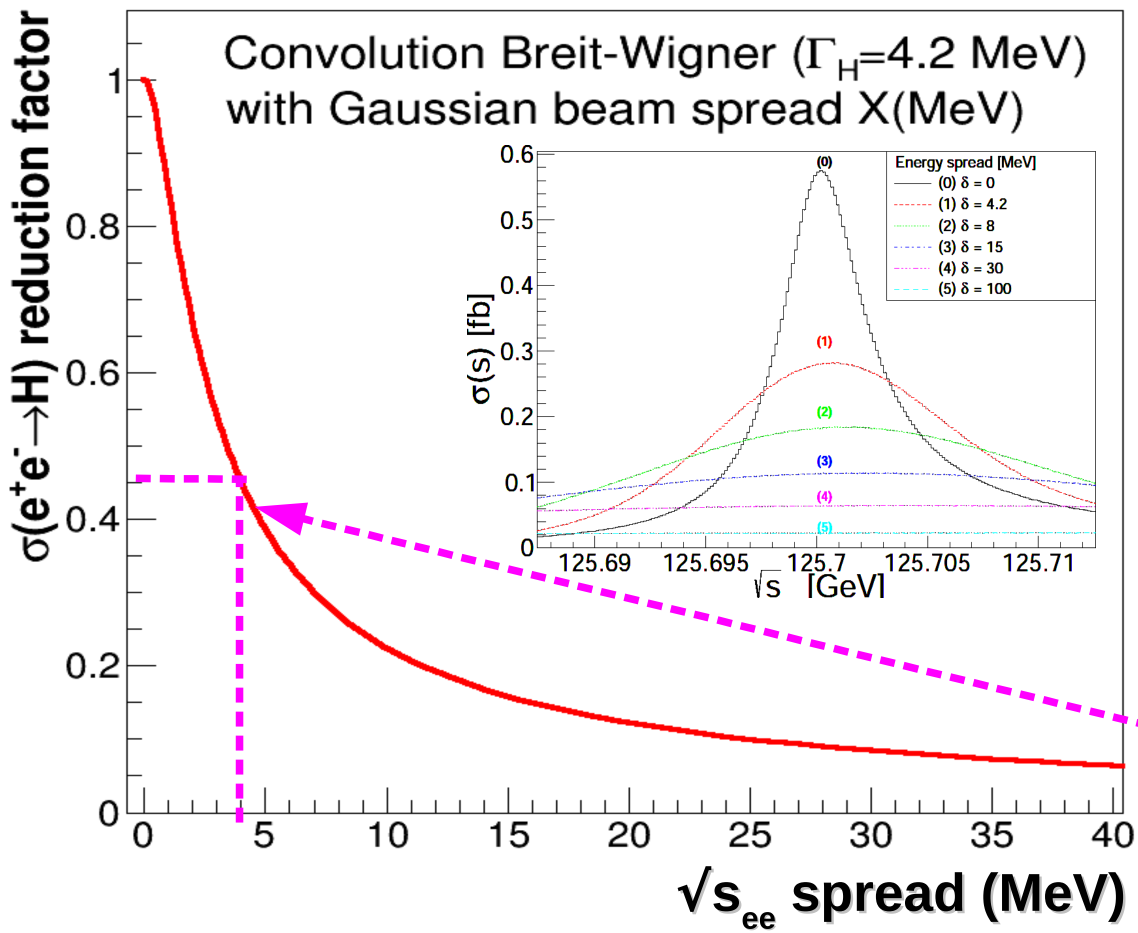


Current FCC-ee nominal ($\Delta E_{beam}/E_{beam}$~0.05%):

E_{spread}~ 30 MeV:

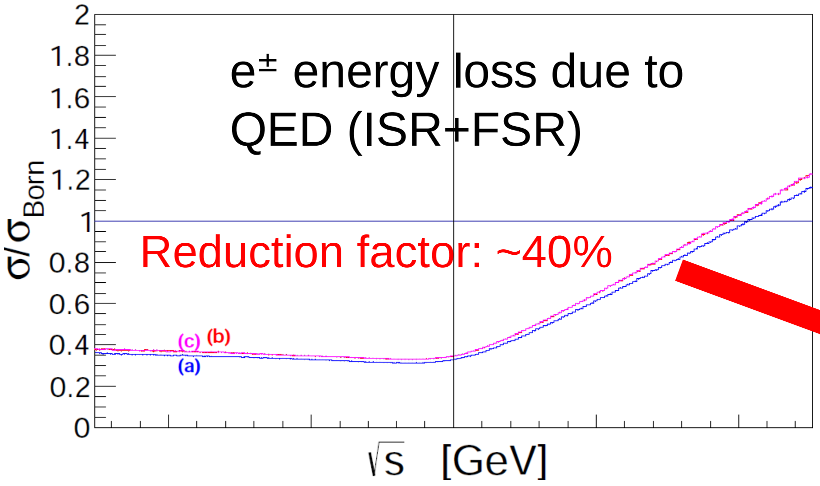
Reduction factor: ×1/12

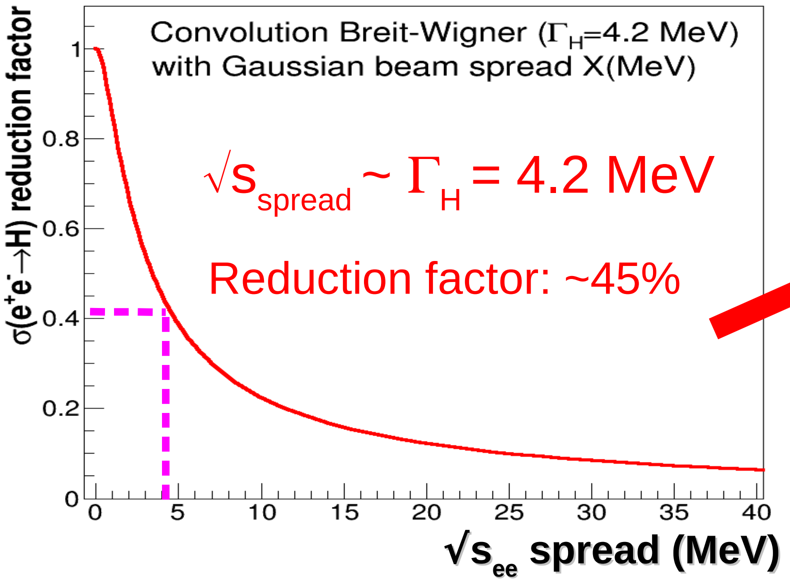
$\sqrt{s}_{spread} \sim \Gamma_H$ = 4.2 MeV (monochromatization?):

Reduction factor: ~45%

$\sigma(e^+e^-\to H)$ reduction: $\sqrt{s}$ spread + ISR

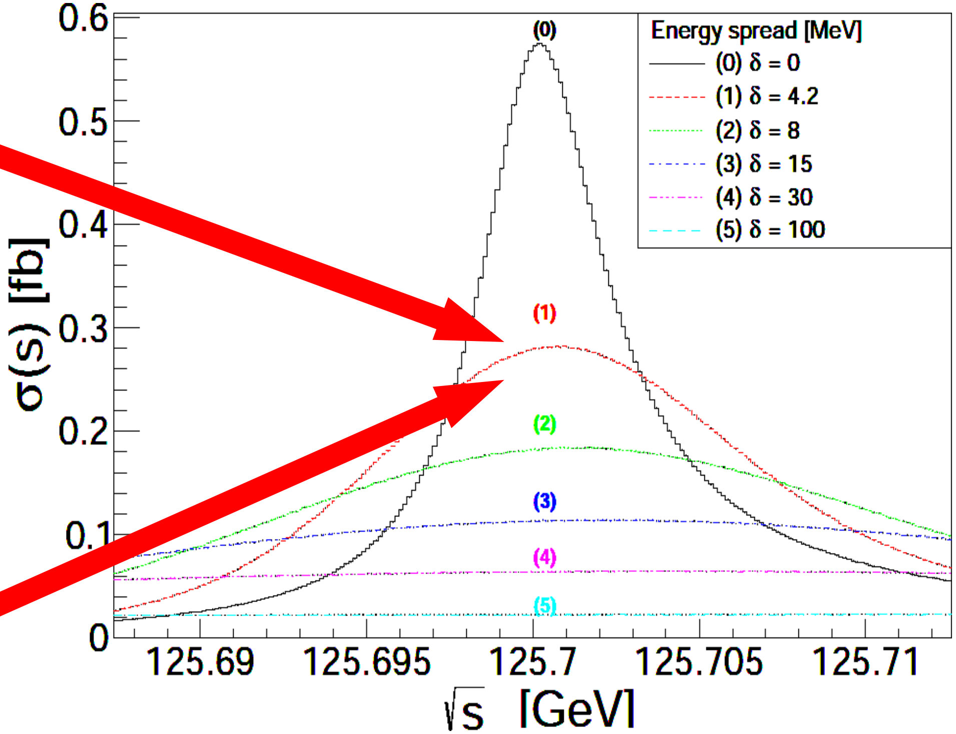
- Extra ~40% reduction also due to initial state radiation:





- Full convolution of both effects:

Jadach et. al. arXiv:1509.02406



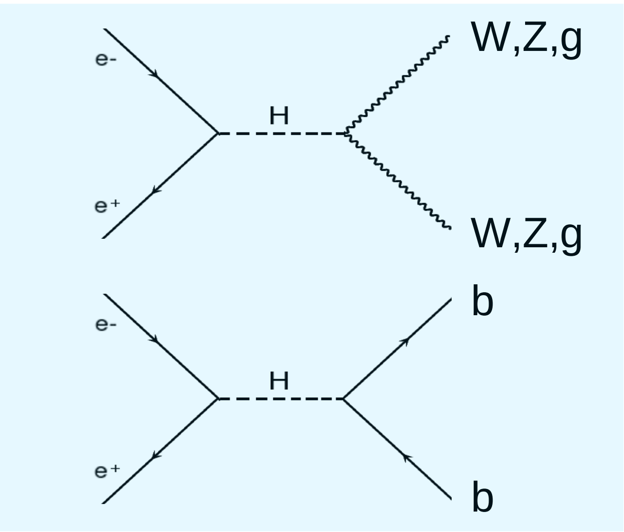
For $\sqrt{\sigma_{spread}} \sim \Gamma_H = 4.2$ MeV

$\sigma_{spread+ISR}(e^+e^-\to H) = 0.17 \times \sigma(e^+e^-\to H) = 290$ ab

Theoretical setup

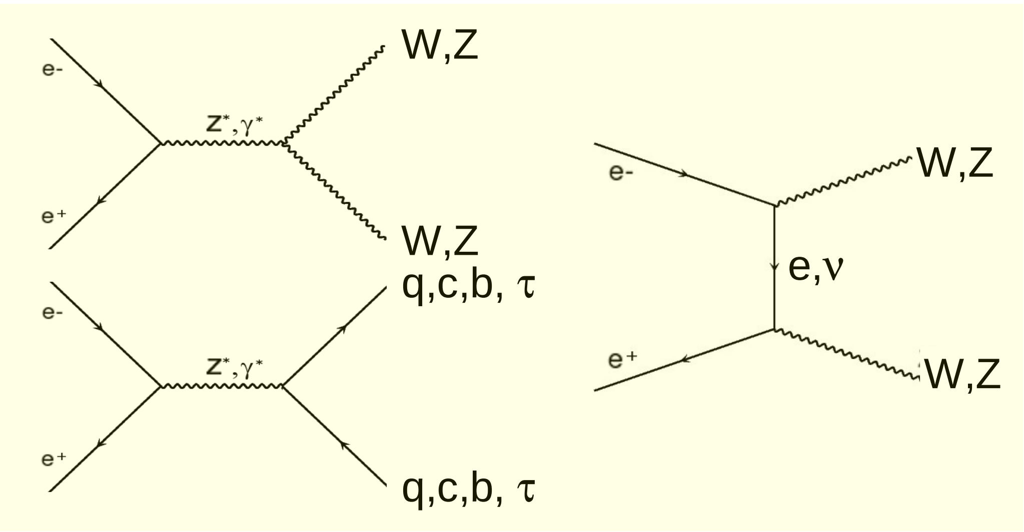
- PYTHIA8 at $\sqrt{s} = m_H = 125$ GeV to generate final-states for Higgs signal plus 7 backgrounds ($e^+e^- \rightarrow WW^*, ZZ^*, \tau\tau$, bbar, ccbar, qqbar, gg):

SIGNALS



+

BACKGROUNDS

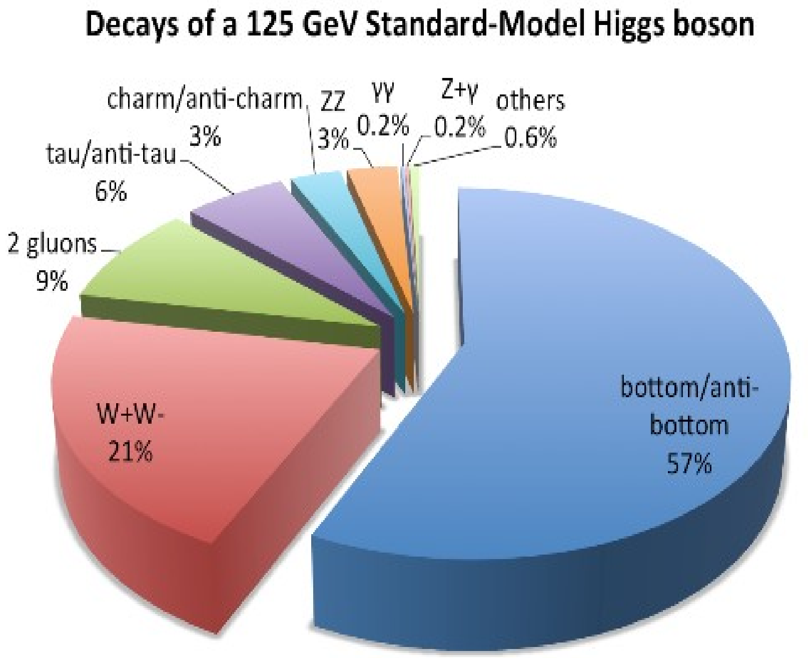


(other SM loop-induced $e^+e^- \rightarrow H$ found negligible)

- YFSWW/ZZ calculator to cross-check WW*, ZZ* background x-sections.
- FastJet package: Exclusive e^+e^- (2,4) jet algorithm.
- Event-shape variables: Webber 2007.
- ISR switched-on in PY8, and beam energy spread included as final scaling factor to match theoretical $\sigma(e^+e^- \rightarrow H) = 290$ ab.

Higgs measurement at FCC-ee(62.5 GeV)

- Higgs s-channel measurement = Counting experiment over 7 channels:



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 ($Z\rightarrow\tau\tau$) and/or have ~0 counts.*

Multi-variables, efficiencies & cuts

- Single & pair jets, leptons kinematical variables:

  $p_{T,i}$, η_i, ϕ_i, $mass_i$, $charge_i$, ΔR_{isol} (Isolation: $\Sigma E<1$ GeV, $\Delta R<0.25$)
  $p_{T,max}$, $p_{T,min}$, η_{max}, η_{min}, ϕ_{max}, ϕ_{min} (All objects reconstructed within $|\eta|<5$ acceptance)
  m_{inv}, $\cos(\theta_{ij})$, $\Delta\eta_i$, $\Delta\phi_i$, H_T

- Global event variables:

  E_{tot}, missing energy vector (ME, m_{ME})
  Sphericity, aplanarity, thrust min, thrust max,...

  – Kinematics cuts applied to reducible backgrounds.
  – MVA BDT applied to (dominant) irreducible continuum.

- Jet/tau reconstruction efficiencies:

  b-jet tagging effic. = 70%
  charm-jet mistag rate = 5%
  light-q mistag rate = 1.5%
  τ-mistag rate = 0.75%

  c-jet tagging effic. = 80%
  b-jet mistag rate = 18%
  light-q mistag rate = 2%

  g-tagging effic. = 60%
  light-q mistag rate = 5%

- ISR events tagged via 2 methods (depending on ν's in final state):

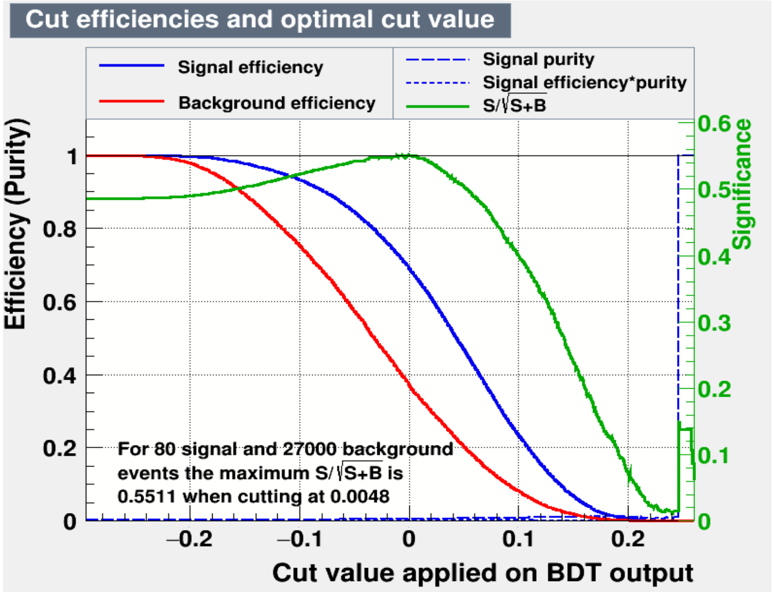
  (1) Cut on the ME vector. ISR photons mostly emitted along beam axis:
  Large missing energy (ME) but low transverse missing energy (MET).
  (2) Cut on E_{tot} (computed without isolated ISR photons within $|\eta|<5$):
  Isolated photons with E>5 GeV omitted: E_{total} > 120 GeV

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

- Final state definition (retains 80% of $\sigma(WW^*(l\nu jj))$ = 28 ab):
  1 isolated lepton e,μ,τ(e),τ(μ) + ME > 2 GeV + 2 jets (exclusive)

- 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
  + BDT MVA ¬ Kills WW* continuum
  (exploits opposite W± polarizations in H decay)



- Signal & backgrounds before/after kinematics+MVA:

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

For L_{int}=10 ab^{-1}
S/√B~80/√27000~0.5
Significance~0.5

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

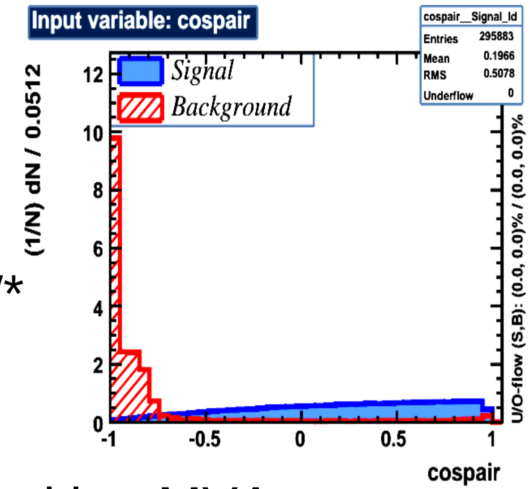
Channel 2: $e^+e^- \to H(WW^*) \to 2l2\nu$

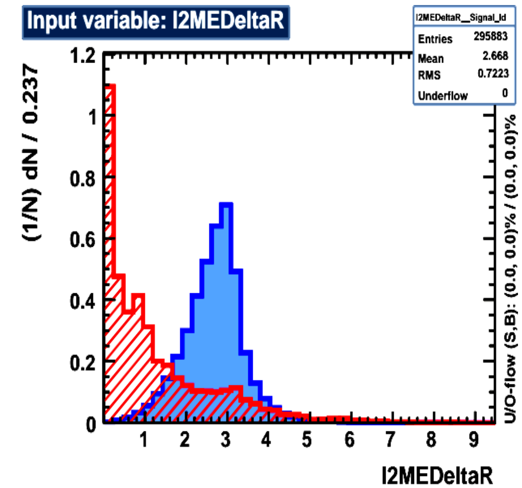
- Final state definition (retains 60% of the $\sigma(WW^*(2l2\nu))$ = 7 ab):
  2 isolated e,μ,τ(e),τ(μ) + ME>2 GeV + 0 non-isolated leptons or ch.had.

- Kinematic cuts (Preselection kills qqbar entirely):

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

(indicative distributions only: normalized to 1)





- Signal & backgds before/after kin.+MVA cuts:

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

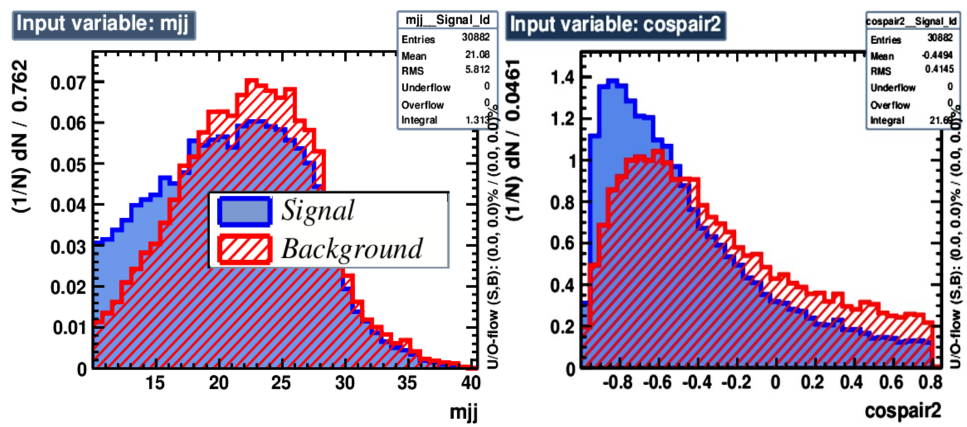
For L_{int}=10 ab^{-1}
S/√B~21/√5063~0.3
Significance~0.3

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

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

- Final state definition (retains 75% of the $\sigma(WW^*(2j2\nu))$ = 2.3 ab):
  2 jets (excl.) + ME > 30 GeV + 0 isolated leptons $e,\mu,\tau(e),\tau(\mu)$ + 0 τ(had)

- Kinematic cuts:
  $\min(|m_{ME}-m_Z|,|m_{jj}-m_Z|)<10$ GeV ¬ Kills qqbar,τ-τ *(indicative distributions only: normalized to 1)*
  $E_{tot} > 120$ 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



- Signal & backgrounds before/after kin. cuts:
  H(WW*): σ = 1.75 ab $\Rightarrow$ σ(after cuts) ~ 0.37 ab
  ZZ*: σ = 179 ab $\Rightarrow$ σ(after cuts) ~ 25 ab
  qqbar: σ = 963 fb $\Rightarrow$ σ(after cuts) ~ 4 ab
  τ-τ: σ = 471 ab $\Rightarrow$ σ(after cuts) ~ 2 ab
  WW*: σ = 526 ab $\Rightarrow$ σ(after cuts) ~ 0 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B}\sim 3.7/\sqrt{316}\sim 0.21$
Significance~0.21

BR(Hee) < 14.3×BR_{SM} (3σ)
$g_{hee} < 3.78 \times g_{Hee,SM}$ (3σ)

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

- Final state definition (retains 73% of the $\sigma(WW^*(2l2j))$ = 1.14 ab):
  2 isolated opposite-charge leptons e,μ,τ(e),τ(μ) + 2 jets (exclusive)

- Kinematic cuts:

(indicative distributions only: normalized to 1)

$\min(|M_{ll}-M_Z|,|M_{jj}-M_Z|) < 20$GeV

¬ Kills qqbar, τ-τ

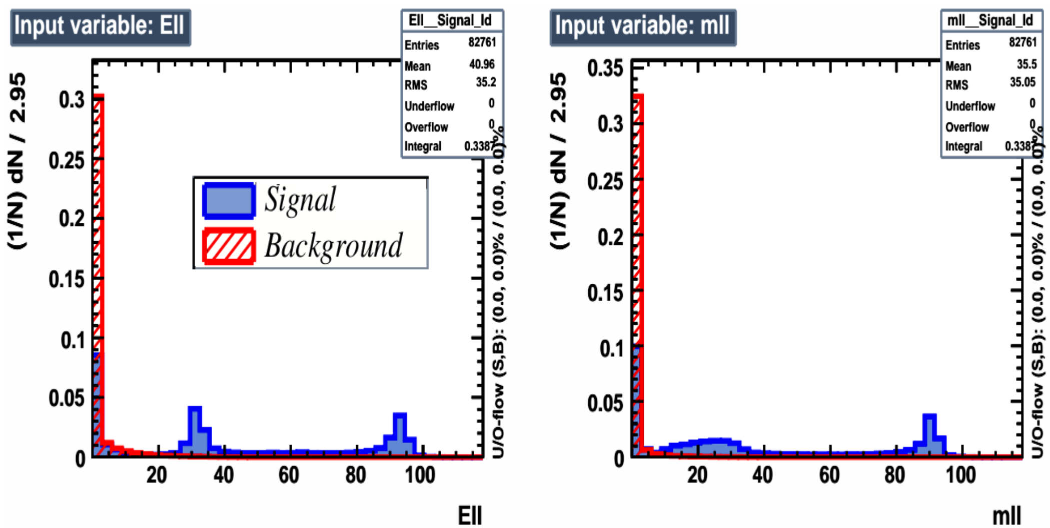
ME < 10 GeV ¬ Kills τ-τ

$E_{lepton} > 6$ 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



- Signal & backgrounds before/after kin. cuts:

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

For L_{int}=10 ab^{-1}
S/√B~2.7/√296~0.16
Significance~0.16

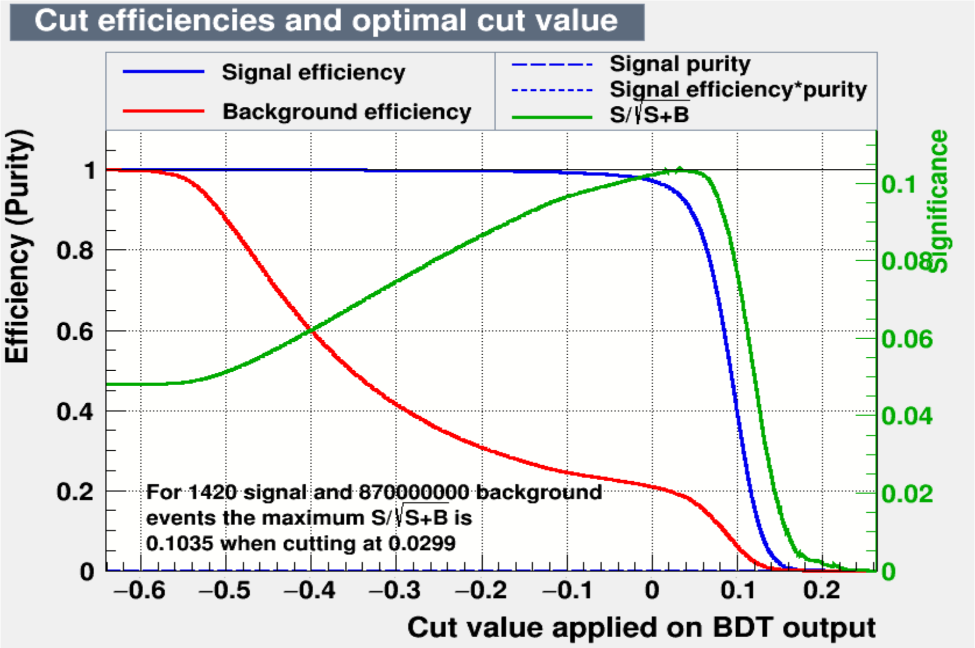
BR(Hee) < 19×BR_{SM} (3σ)
G_{hee} < 4.35 × $g_{Hee,SM}$ (3σ)

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

- Final state definition (retains 90% of the σ(bb) = 156 ab):
  2 jets (exclusive) + 1 b-jet tagged + 0 τ(had)

- Kinematic cuts:
  None.

  MVA BDT applied to reduce dominant $Z^*\gamma^*\to$bbar continuum



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

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)

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

- Final state definition (retains 30% of the $\sigma(gg)$ = 24 ab):

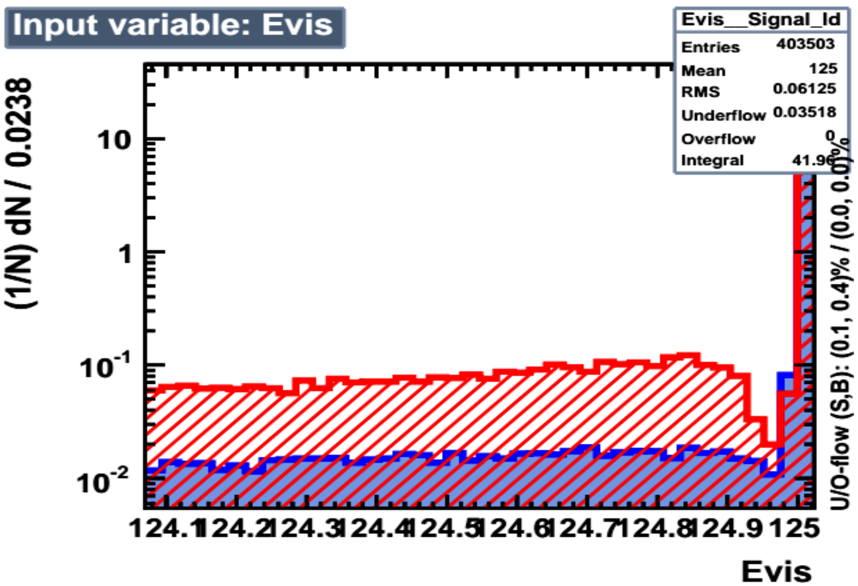
  2 gluon-tagged jets + 0 isolated leptons e,μ,τ(e),τ(μ) + 0 τ(had)

(indicative distributions only: normalized to 1)

- Kinematic cuts:

  E_{tot} > 124 GeV

  Kills part of $\tau\tau$,WW,ZZ



- Signal & backgrounds before/after kin. cuts:

H(gg):	σ=7.34 ab	$\Rightarrow$ σ (after) =	3.91 ab
qqbar:	σ=0.86 pb	$\Rightarrow$ σ (after) =	18.7 fb
τ–τ:	σ = 607 ab	$\Rightarrow$ σ (after) =	257 ab
WW*:	σ = 44.6 ab	$\Rightarrow$ σ (after) =	26 ab
ZZ*:	σ = 0.74 ab	$\Rightarrow$ σ (after) =	0.26 ab

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

S/$\sqrt{}$B~39.1/$\sqrt{}$1.9*10^5~0.09

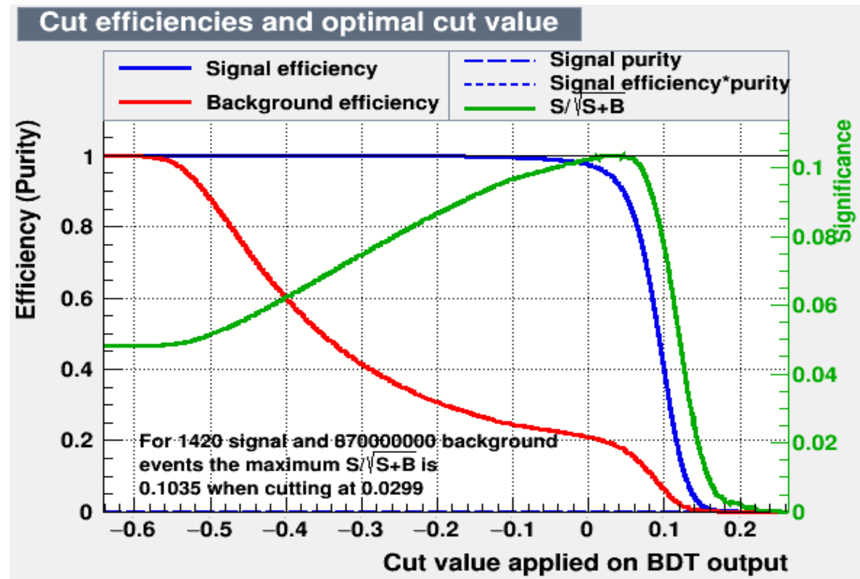
Significance~0.09

BR(Hee) < 32×BR_{SM} (3σ)

g_{Hee} < 5.66 × $g_{Hee,SM}$ (3σ)

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

- Final state (retains 9% of the σ(WW*(4j)) = 29 ab):
  4 jets (exclusive) + >=1 jet c-tagged jet + 0 b-jets + 0 g-jets
  Jets with $m_{j1j2} \sim m_W$ not both c-tagged + 0 τ(had) + 0 isolated e,μ,τ(e),τ(μ)



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

- Signal & backgrounds before/after kin. cuts:

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

For L_{int}=10 ab^{-1}
$S/\sqrt{B} \sim 14/\sqrt{29000} \sim 0.08$
Significance~0.08

BR(Hee) < 36×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).

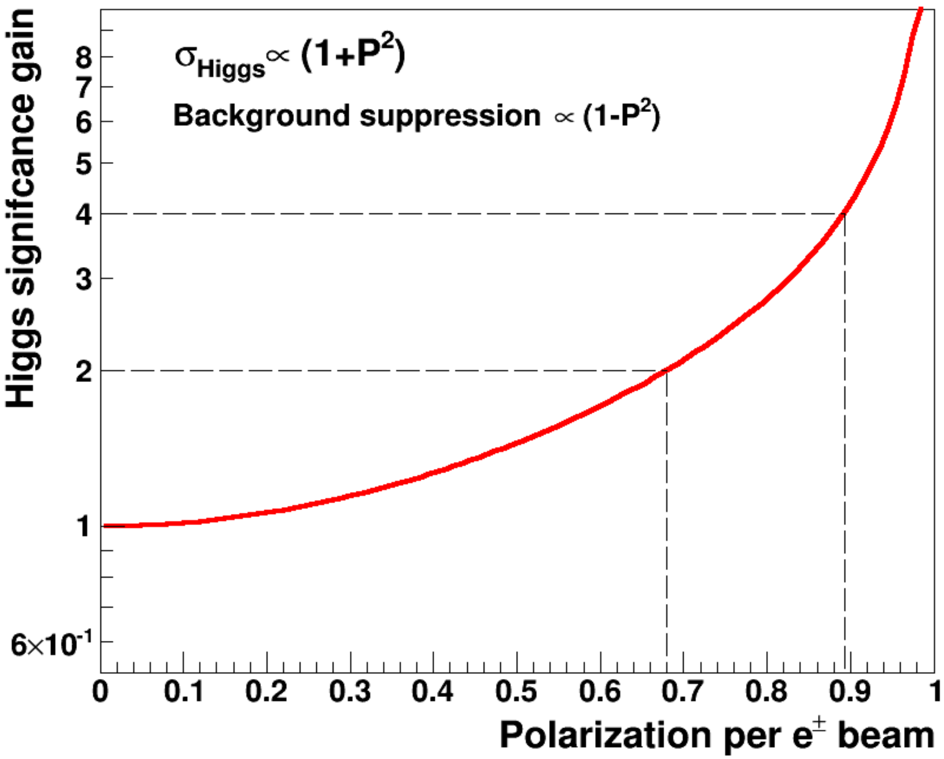
Channel	Significance (1 ab^{-1})	Significance (6 ab^{-1})	Significance (10 ab^{-1})
$WW \to l\nu jj$	0.15	0.38	0.49
$WW \to 2l2\nu$	0.09	0.23	0.29
$ZZ \to 2j2\nu$	0.07	0.16	0.21
$ZZ \to 2l2j$	0.05	0.12	0.16
bb	0.03	0.08	0.10
gg	0.03	0.07	0.09
$WW \to 4j$	0.03	0.06	0.08
Combined	**0.2**	**0.5**	**0.65**

- For 10 ab^{-1}: 95% CL limit for SM branching ratio $BR(H \to ee) < 3*BR_{SM}(H \to ee)$
  95% CL limit for SM Yukawa $g_{eH} < 1.75*g_{eH,SM}$

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, 95% CL limit of $g_{eH} < 1.1*g_{eH,SM}$
- Polarization of beams would enhance the signal (~1+P^2) & suppress background (1-P^2) Realistic polarization estimates (P=20-30%) are however clearly insufficient. Higher Pol. would reduce lumi

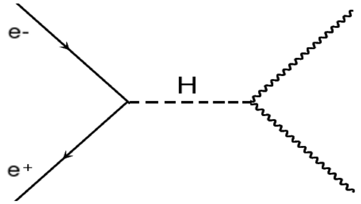
  P~0.7: ×2 significance
  P~0.9: ×4 significance



- Evidence (observation?) requires 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):



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

$\sigma(e^+e^-\rightarrow H)_{visible} \sim 290$ ab (ISR + $\sqrt{s}_{spread} \sim \Gamma_H = 4.2$ 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) < 3×BR_{SM} (95% CL), $g_{eH} < 1.75\times g_{eH,SM}$ (95% CL)
  Evidence (observation?) will require further improvements in large-BR (huge background) jet channels: H→ bb, H → WW → 4j

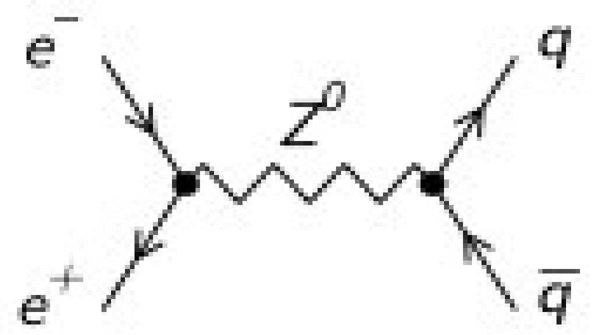
- Challenging performances: Mono-chromatization to achieve $\sqrt{s}_{spread} \sim \Gamma_H$

- 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.