Electron Yukawa from s-channel Higgs production at FCC-ee

FCC-ee Physics Workshop

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

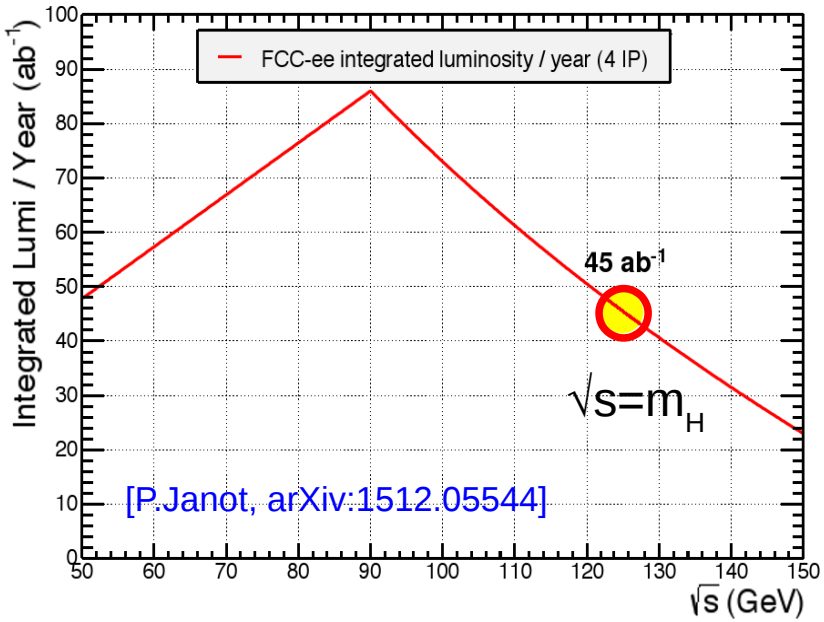
- Resonant Higgs production considered so far only for muon collider:
  $\sigma(\mu\mu \rightarrow H) \approx 70$ pb. Tiny g_{eH} Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee \rightarrow H)$

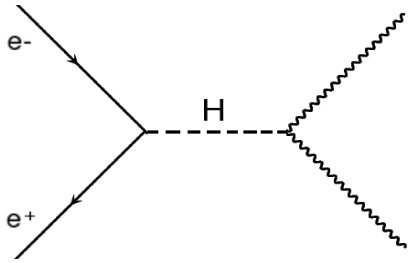
$$\frac{g_{H\mu\mu}}{g_{Hee}} \propto \frac{m_\mu^2}{m_e^2} = 4.28 \times 10^4$$

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

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

- Huge luminosities available at FCC-ee:





In theory, FCC-ee running at H pole-mass
$L_{int} \approx 45$ ab^{-1}/yr would produce O(75.000) H's

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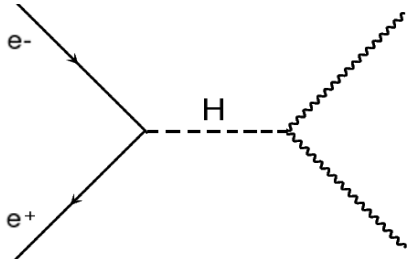

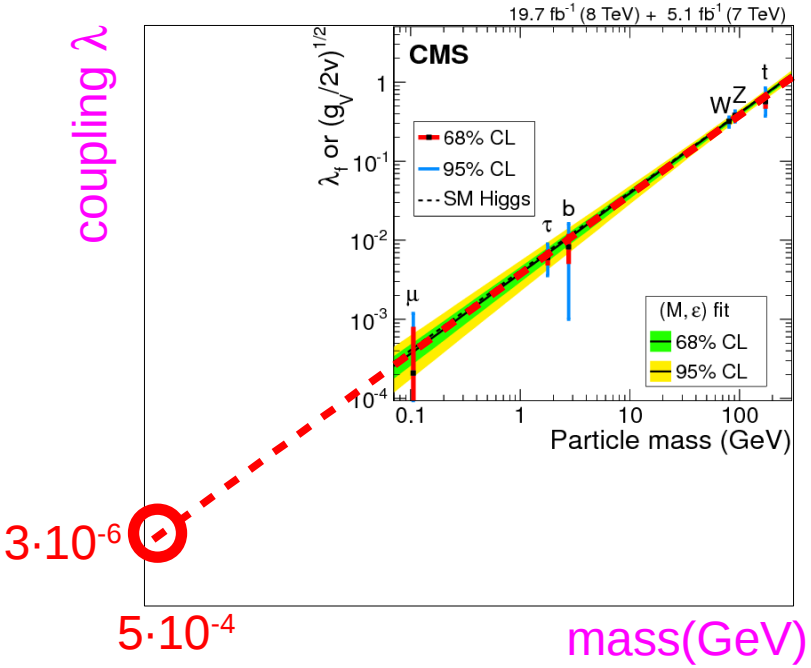

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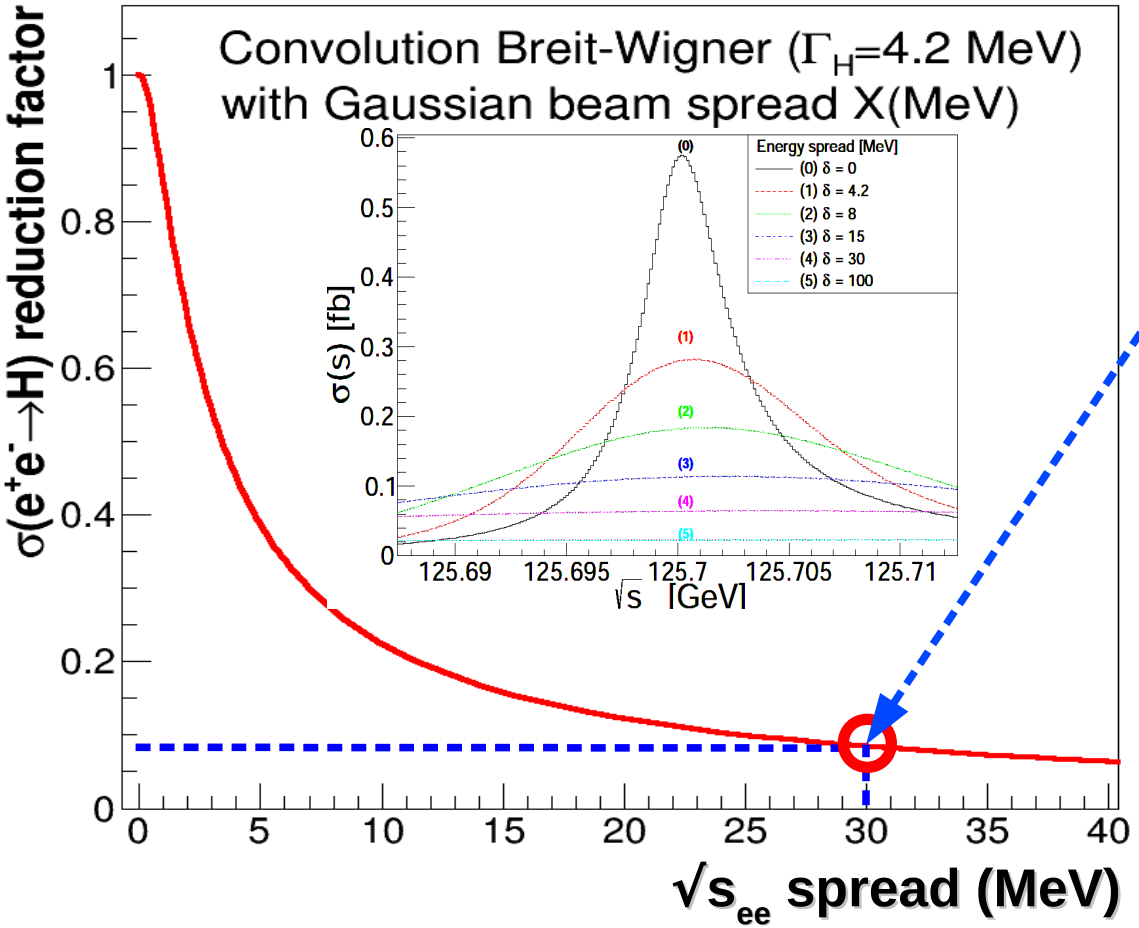
IFF we can handle: (i) beam-energy spread, (ii) ISR, and (iii) huge backgrounds, then:

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

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



For $\sqrt{s}_{spread} \approx 30$ MeV:

Reduction factor: $\times 1/12$

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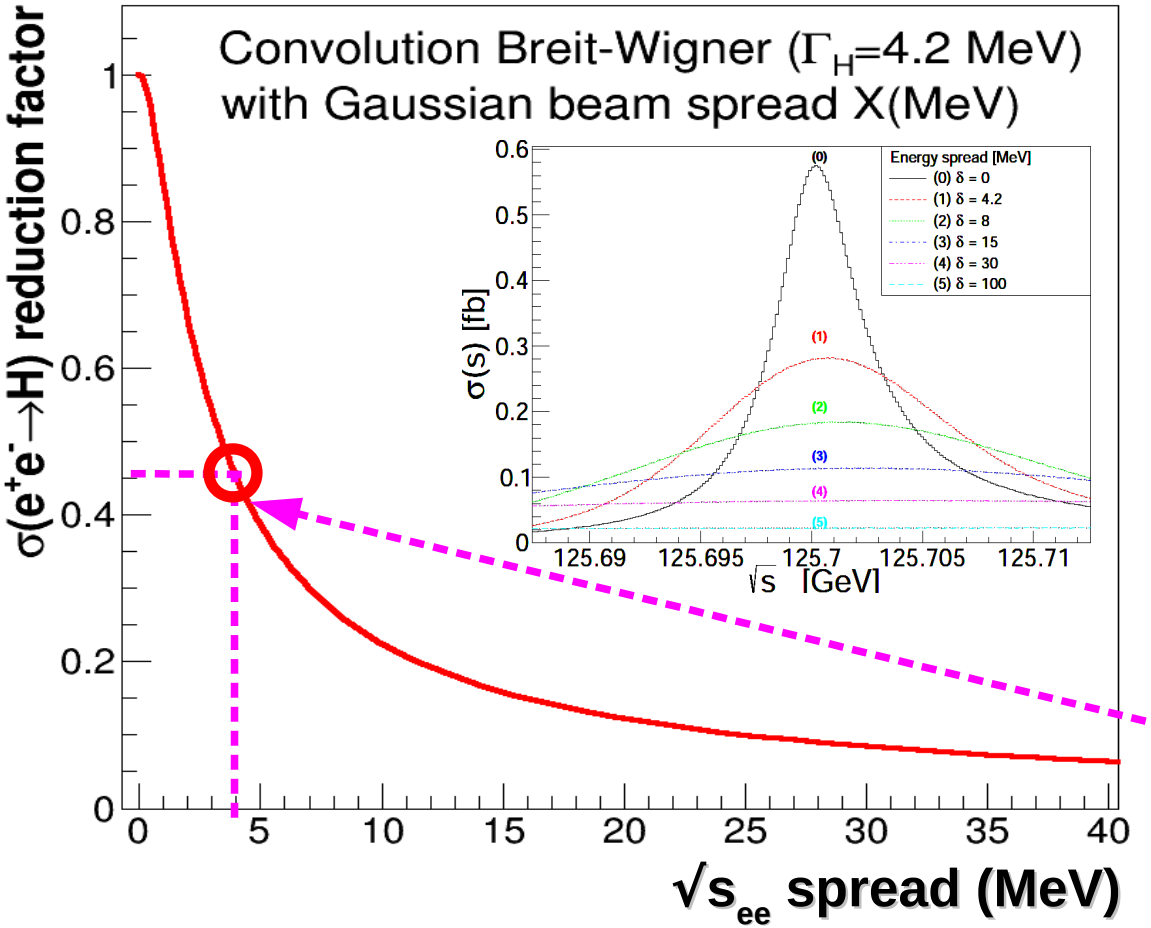
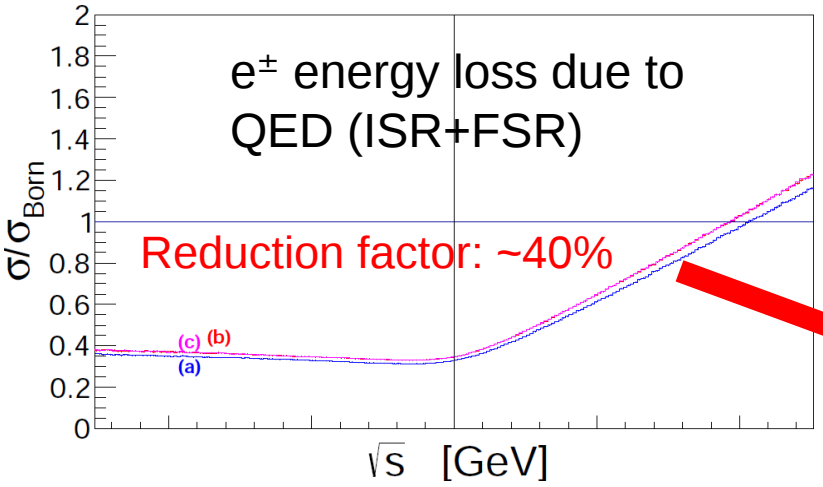


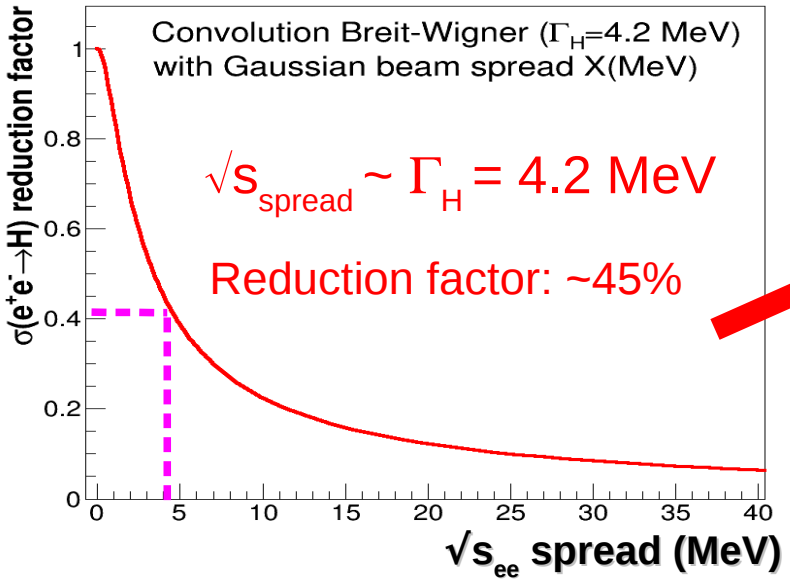
For $\sqrt{s}_{spread} \approx$ 30 MeV:
Reduction factor: ×1/12

$\sqrt{s}_{spread} = \Gamma_H$ = 4.2 MeV (monochromatization?):
Reduction factor "only" of ~45%

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

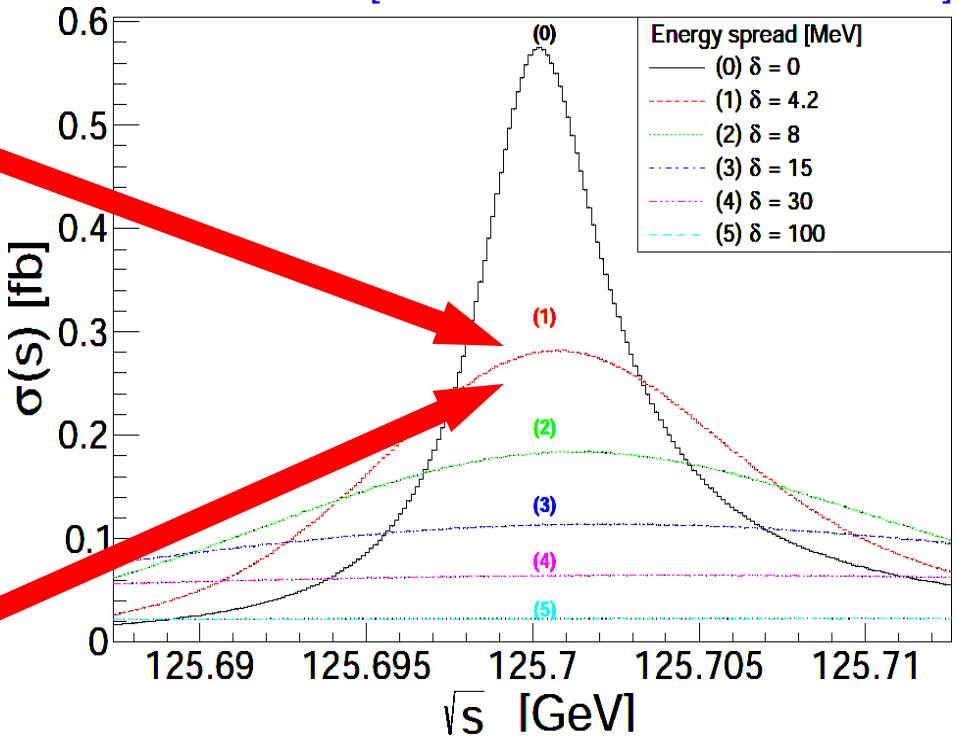
- Extra ~40% reduction also due to initial state radiation:





- Full convolution of both effects:

[S.Jadach et. al. arXiv:1509.02406]



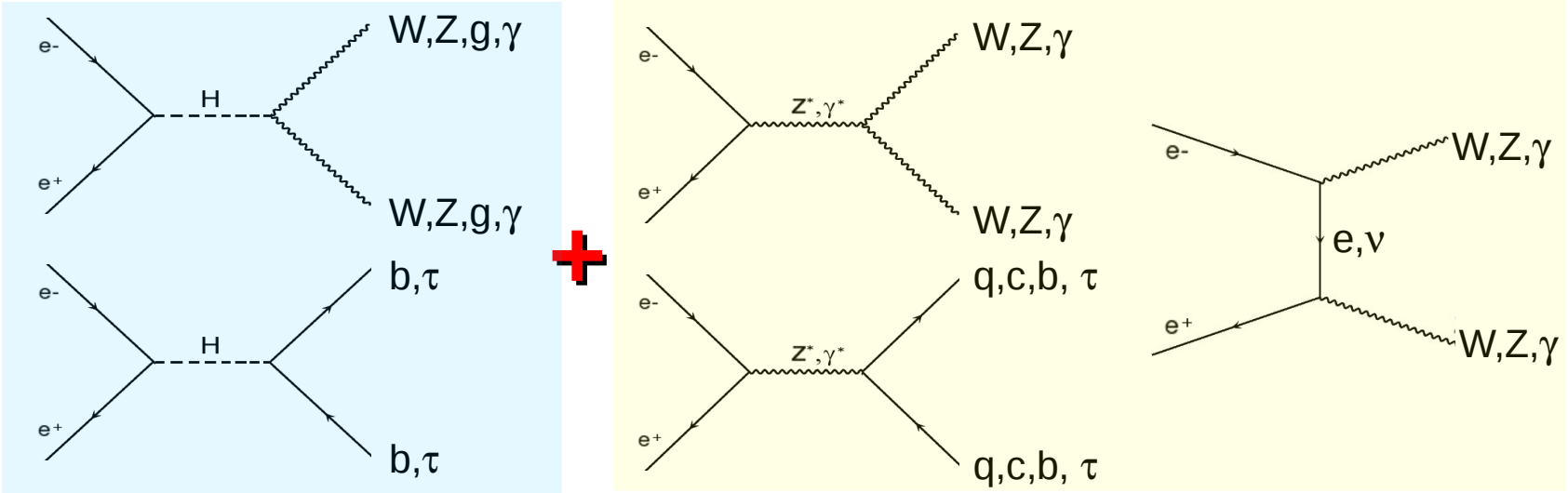
For $\sqrt{}\sigma_{spread} \approx \Gamma_H = 4.2$ MeV

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

Theoretical setup

- PYTHIA8 e^+e^- at $\sqrt{s} = m_H = 125$ GeV to generate 10 final-states for Higgs signal plus backgrounds ($e^+e^- \to WW^*, ZZ^*, \gamma\gamma$, gg, $\tau\tau$, bbar, ccbar, qqbar):

SIGNALS **BACKGROUNDS**

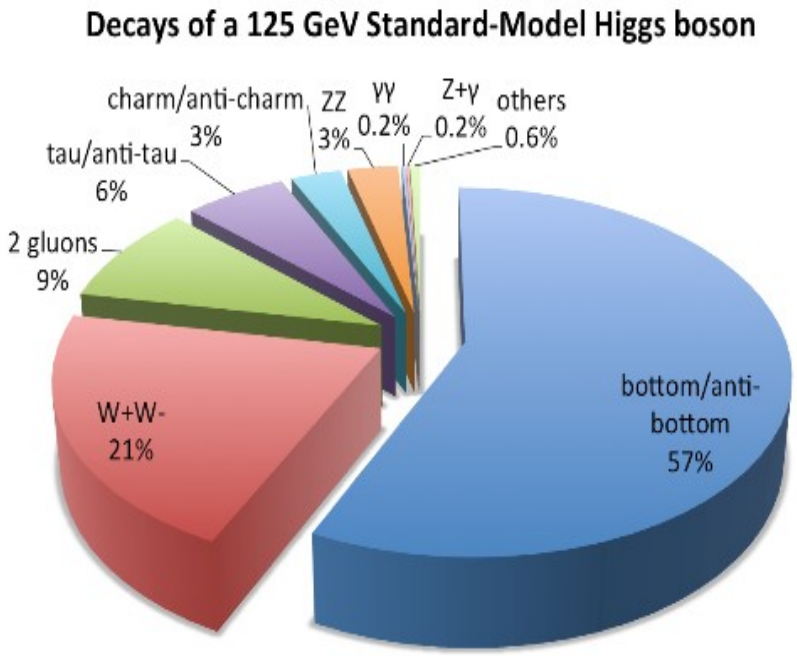


(other SM loop-induced $e^+e^- \to H$ found negligible)

- HDECAY: State-of-the-art Higgs boson decay branching ratios
- YFSWW/ZZ/MG5 calculators cross-check PYTHIA8 x-sections
- FastJet package: Exclusive e^+e^- (2,4) jet algorithm (incl. València algo).
- Event-shape variables: [Webber 2007].
- ISR switched-on in PY8, $\sqrt{s}_{spread}$ via scaling to match $\sigma(e^+e^- \to H)$=290 ab

Higgs measurement at FCC-ee(62.5 GeV)

- Counting experiment over 10 decay channels:



- *Other 2-jet final-state (cc) swamped by $e^+e^- \to Z^*,\gamma^* \to cc$ (20 pb)*
- *Other 4-jet final-state (ZZ*) swamped by $e^+e^- \to Z^*,\gamma^* \to qq$ (100 pb), $e^+e^- \to WW^*,ZZ^*$ (20 fb)*
- *Rarer decays (4ℓ) have ~0 counts.*

1) bb (2 b-jets): σ = 156 ab
Dominant bckgd (ee→bb): σ=20 pb (S/B~10^{-5})

2) WW* (4j): σ = 28 ab
Dominant bckgd (ee→4j): σ=16 fb (S/B~10^{-3})

3) WW* (2jlν): σ = 27 ab
Dom. bckgd (ee→WW*): σ=20 fb (S/B~10^{-3})

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

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

6) ττ (2 τ-jets): σ = 7.5 ab
Dom. bckgd (ee→ττ): σ=10 pb (S/B~10^{-7})

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

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

9) ZZ* (2l2ν): σ = 0.34 ab
Dominant bckgd (ee→ττ):σ=10 pb (S/B~10^{-8})

10) γγ (2 isolated γ): σ = 0.65 ab
Dominant bckgd (ee→γγ): σ=36 pb (S/B~10^{-8})

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

  – Kinematics cuts applied to reducible backgrounds.

  – MVA BDT applied to (dominant) irreducible continuum.

- Global event variables:

  E_{tot}, missing energy vector (ME, m_{ME})

  Sphericity, aplanarity, thrust min, thrust max,...

- Jet/tau reconstruction efficiencies:

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

  c-jet tagging effic. = 80%
  b-jet mistag rate = 18%
  light-q mistag rate = 2%
  e-γ mistag rate = 0.3%

  g-tagging effic. = 60%
  light-q mistag rate = 5%
  τ-tagging rate = 80%
  τ-mistag rate = 0.75%

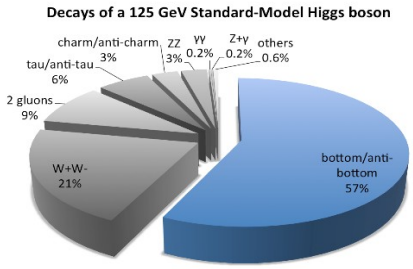
- ISR events tagged via 2 methods (depending on ν's in final state):

  (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: $e^+e^- \rightarrow H(bb) \rightarrow$ 2 b-jets

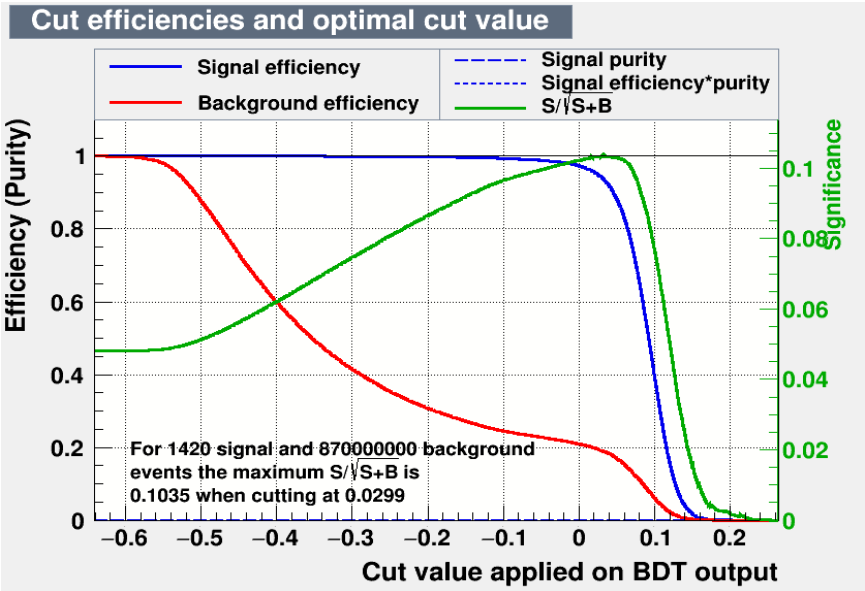
- Final state (retains 90% of σ(bb) = 156 ab):
  2 jets (exclusive) + 1 b-jet tagged + 0 τ(had)



- Analysis cuts:

  ✓ Kinematics: None.

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



- Signal & backgds before/after MVA cuts:

  H(bb): σ = 142 ab ⇒ σ (after) = 131 ab

  qqar: σ ≈ 20 pb ⇒ σ (after) = 17 pb

  τ–τ: σ = 607 ab ⇒ σ (after) = 375 ab

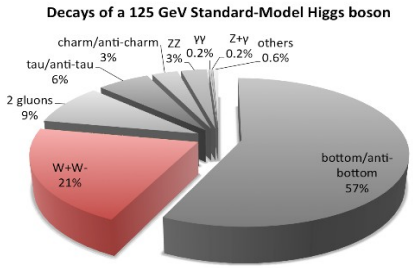
For L_{int}=10 ab^{-1}

$S/\sqrt{B} = 1310/\sqrt{1.7e+8} \approx 0.1$

Significance ≈ 0.1

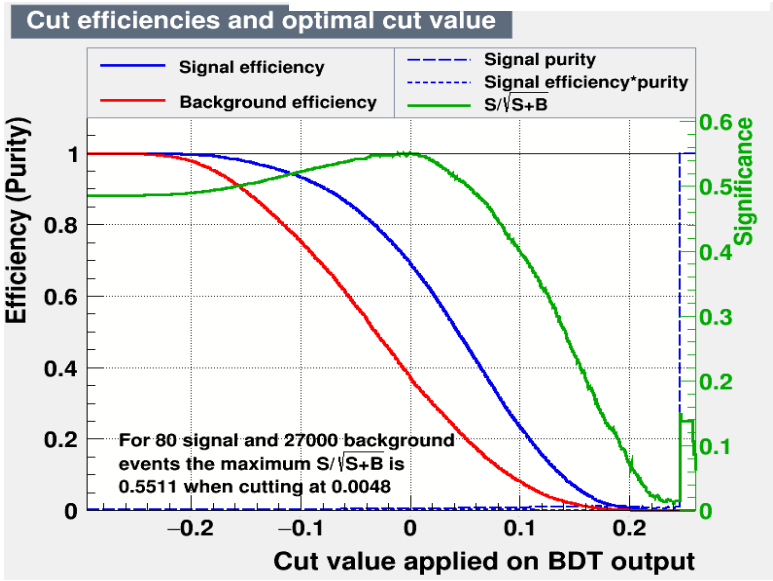
Channel 2: $e^+e^- \rightarrow H(WW^*) \rightarrow l\nu jj$

- Final state (retains 80% of σ(WW*(lνjj)) = 28 ab):
  1 isolated e,μ,τ(e),τ(μ) + ME>2 GeV + 2 jets (excl.)



- Analysis cuts:
  - ✓ $E_{j1,j2} < 52,45$ GeV ¬ Kills qqbar
  - ✓ $m_{w(l\nu)} > 12$ GeV/c² ¬ Kills qqbar
  - ✓ $E_{lepton} > 10$ GeV ¬ Kills qqbar
  - ✓ ME > 20 GeV ¬ Kills qqbar
  - ✓ $m_{ME} < 3$ GeV/c² ¬ Kills τ-τ
  - ✓ BDT MVA ¬ Kills WW* continuum

  (exploits opposite W± polarizations in H decay)



- Signal & backgrounds before/after cuts:

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}

$S/\sqrt{B} = 80/\sqrt{27.e3} \approx 0.5$

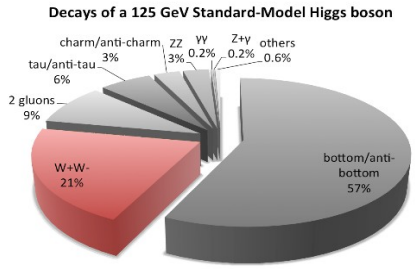
Significance ≈ 0.5

Channel 3: $e^+e^- \rightarrow H(WW^*) \rightarrow 2l2\nu$

- Final state (retains 60% of $\sigma(WW^*(2l2\nu)) = 7$ ab):

  2 isolated $e,\mu,\tau(e),\tau(\mu)$ + ME > 2 GeV

  + 0 non-isolated leptons or ch.had.



- Analysis cuts (Preselection kills qqbar entirely):

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

  ✓ $\Delta R(l_2,ME) > 1.5$ ¬ Kills τ-τ

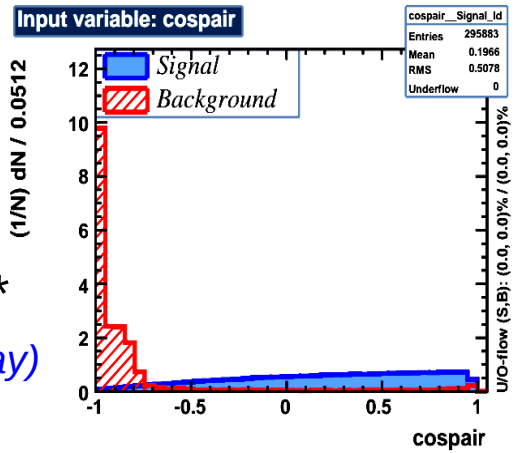
  ✓ $E_{l1,l2} > 3$ GeV ¬ Kills τ-τ

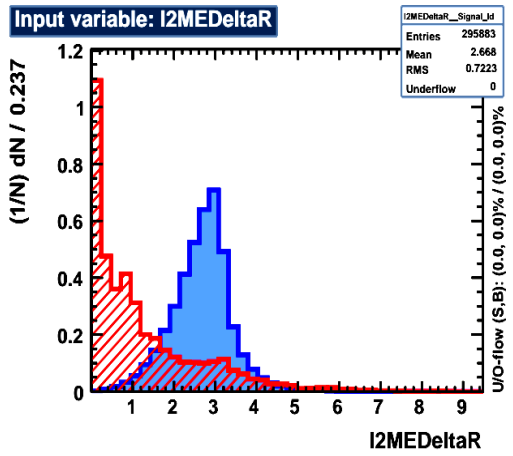
  ✓ ME > 20 GeV ¬ Kills τ-τ

  ✓ BDT MVA ¬ Kills WW*

  (exploits opp. $W^\pm$ polarizations in H decay)

(indicative distributions only: normalized to 1)





- Signal & backgds before/after cuts:

  H(WW*): $\sigma = 4$ ab $\Rightarrow \sigma$(after) = 2.1 ab

  WW*: $\sigma = 2.9$ fb $\Rightarrow \sigma$(after) = 454 ab

  τ-τ: $\sigma = 3.1$ pb $\Rightarrow \sigma$(after) = 51 ab

  qqbar: $\sigma \sim 0$ pb $\Rightarrow \sigma$(after) = 0 ab

  ZZ*: $\sigma = 24$ ab $\Rightarrow \sigma$(after) = 0.4 ab

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

$S/\sqrt{B} = 21/\sqrt{5000} \approx 0.3$

Significance ≈ 0.3

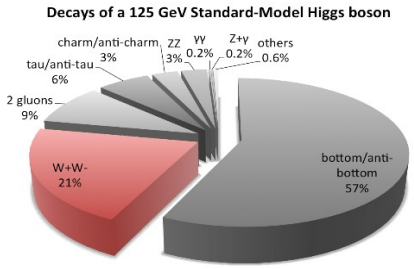
Channel 4: $e^+e^- \rightarrow H(WW^*) \rightarrow 4j$

- Final state (retains 9% of σ(WW*(4j)) = 29 ab):

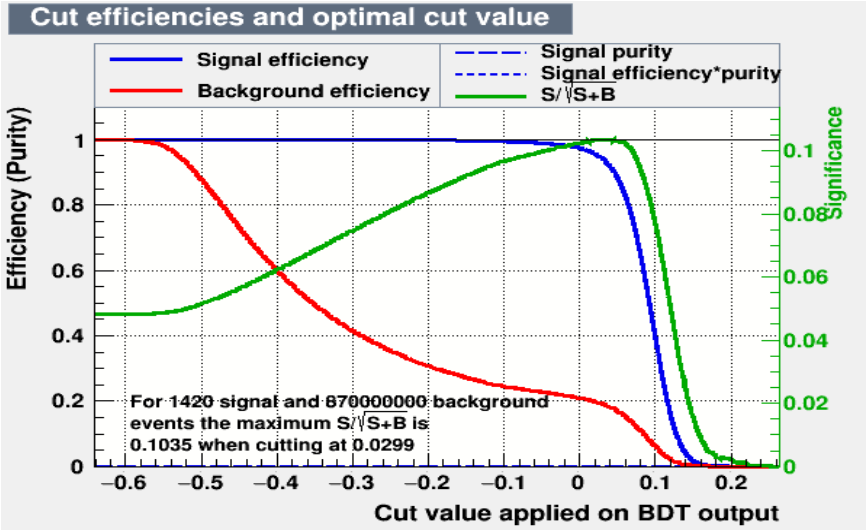
  4 jets (excl.) + >=1 jet c-tagged jet + 0 b-jets + 0 g-jets

  Jets with $m_{j1j2} \sim m_W$ not both c-tagged + 0 τ(had)

  + 0 isolated e,μ,τ(e),τ(μ)



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



- Signal & backgrounds before/after 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

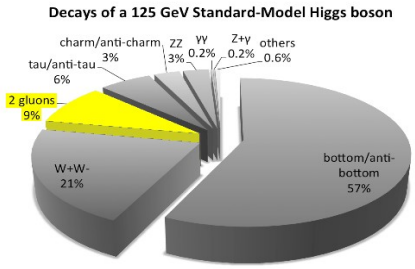
For $L_{int} = 10$ ab^{-1}

$S/\sqrt{B} = 14/\sqrt{29.e3} \approx 0.08$

Significance ≈ 0.08

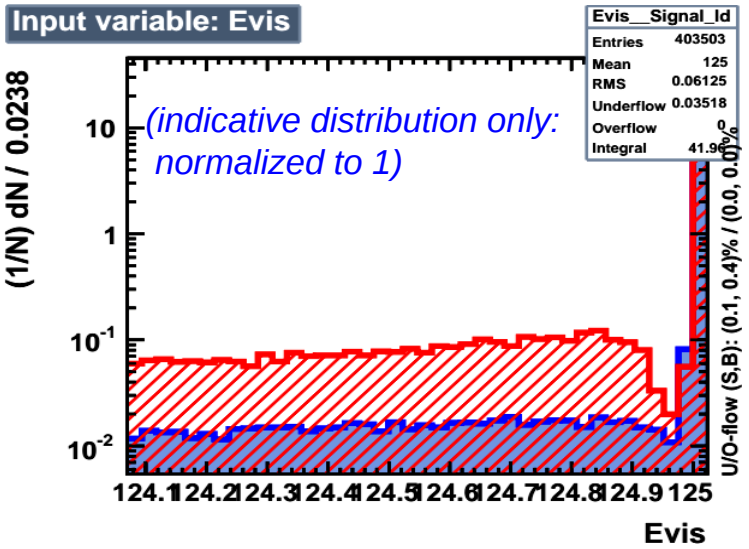
Channel 5: $e^+e^- \rightarrow H(gg) \rightarrow jj$

- Final state (retains 30% of σ(gg) = 24 ab):
  2 gluon-tagged jets
  + 0 isolated e,μ,τ(e),τ(μ) + 0 τ(had)



- Analysis cuts:

  ✓ $E_{tot} > 124$ GeV
  Kills part of ττ,WW,ZZ



- Signal & backgrounds before/after kin. cuts:

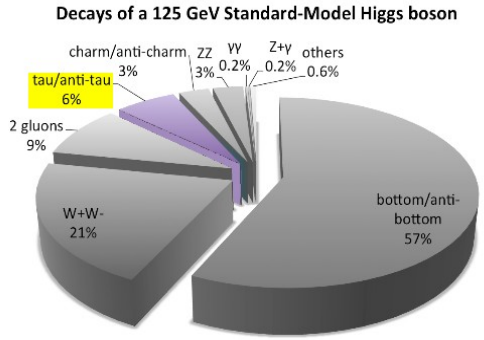
H(gg): σ=7.34 ab ⇒ σ (after) = 3.91 ab
qqbar: σ=0.86 pb ⇒ σ (after) = 18.7 fb
τ–τ: σ = 607 ab ⇒ σ (after) = 257 ab
WW*: σ = 44.6 ab ⇒ σ (after) = 26 ab
ZZ*: σ = 0.74 ab ⇒ σ (after) = 0.26 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 39.1/\sqrt{1.9e5} \approx 0.09$
Significance ≈ 0.09

Channel 6: $e^+e^- \to H \to \tau_{had}\tau_{had}$

- Final state (retains 65% of $\sigma(\tau\tau)$ = 7.4 ab):

  2 jets (exclusive) + 2 tau-jet tagged
  + 0 isolated final-state leptons



- Analysis cuts:

  ✓ Kinematics cuts: None

  ✓ MVA BDT applied to reduce dominant $Z^*/\gamma^* \to \tau\tau$ continuum.

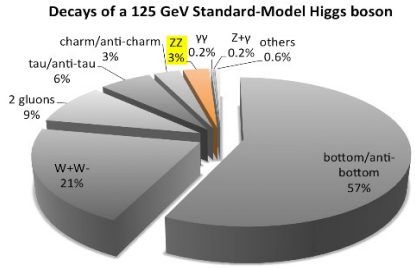
- Signal & backgds before/after MVA cuts:

  H($\tau\tau$): σ = 7.4 ab $\Rightarrow$ σ (after) = 1.5 ab
  qqbar: σ = 87 pb $\Rightarrow$ σ (after) = 75 ab
  τ–τ: σ = 10 pb $\Rightarrow$ σ (after) = 100 fb

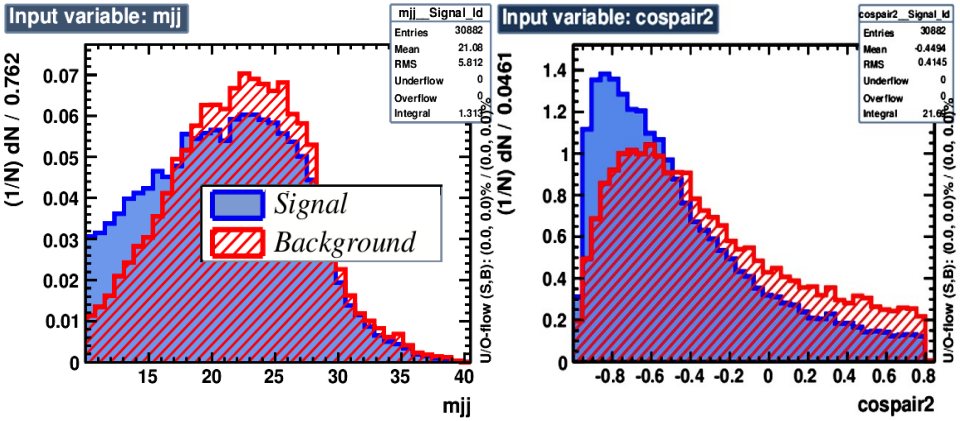
For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 15/\sqrt{1e+6} \approx 0.02$
Significance $\approx$ 0.02

Channel 7: $e^+e^- \rightarrow H(ZZ^*) \rightarrow 2j2\nu$

- Final state (retains 75% of σ(WW*(2j2ν)) = 2.3 ab):
  2 jets (excl.) + ME > 30 GeV
  + 0 isolated e,μ,τ(e),τ(μ) + 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

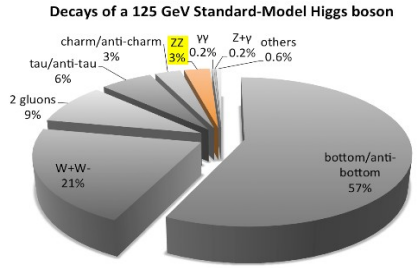


- Signal & backgrounds before/after cuts:
  H(ZZ*): σ = 1.75 ab ⇒ σ(after cuts) = 0.37 ab
  ZZ*: σ = 179 ab ⇒ σ(after cuts) = 25 ab
  qqbar: σ = 963 fb ⇒ σ(after cuts) = 4 ab
  τ-τ: σ = 471 ab ⇒ σ(after cuts) = 2 ab
  WW*: σ = 526 ab ⇒ σ(after cuts) = 0 ab

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

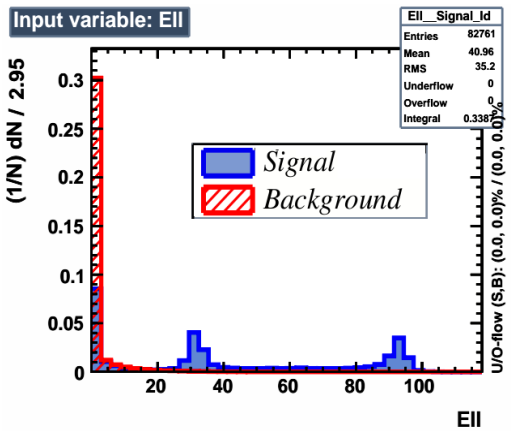
Channel 8: $e^+e^- \rightarrow H(ZZ^*) \rightarrow 2l2j$

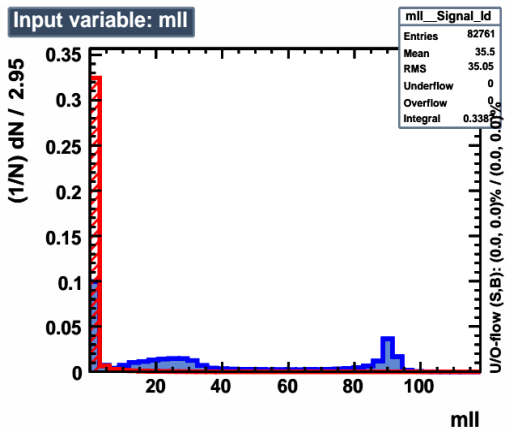
- Final state (retains 73% of σ(WW*(2l2j)) = 1.14 ab):
  2 isolated opposite-charge leptons e,μ,τ(e),τ(μ)
  + 2 jets (exclusive)



- 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/c² ¬ Kills qqbar
  - ✓ $M_{jj} > 10$ GeV/c² ¬ Kills τ-τ

(indicative distributions only: normalized to 1)





- Signal & backgrounds before/after cuts:

H(ZZ*):	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

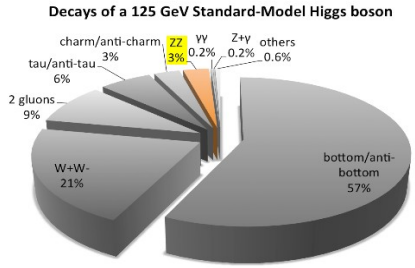
For $L_{int}=10$ ab^{-1}
$S/\sqrt{B} = 2.7/\sqrt{296} \approx 0.16$
Significance ≈ 0.16

Channel 9: $e^+e^- \rightarrow H(ZZ^*) \rightarrow 2l2\nu$

- Final state (retains 60% of $\sigma(ZZ^*(2l2\nu)) = 0.34$ ab):

  2 isolated $e,\mu,\tau(e),\tau(\mu)$ + ME>2 GeV

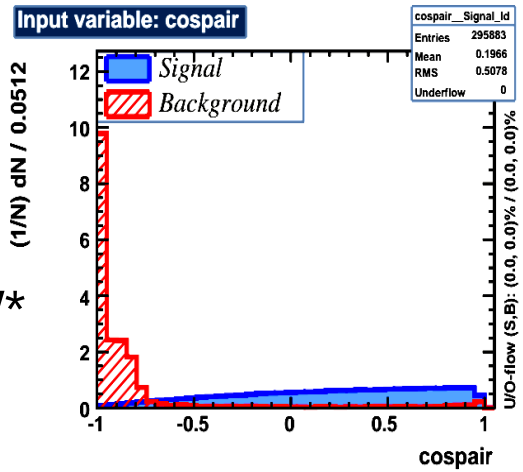
  + 0 non-isolated leptons or ch.had.

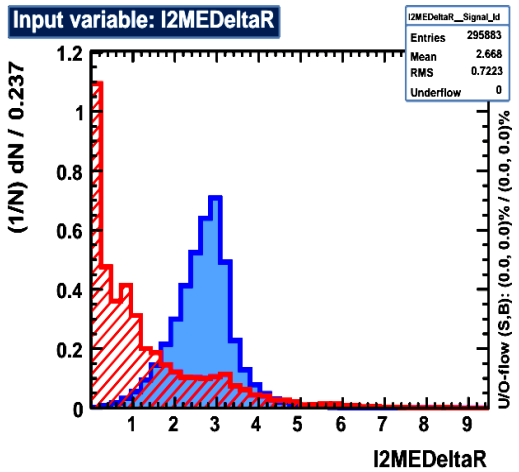


- Analysis cuts (Preselection kills qqbar entirely):

(indicative distributions only: normalized to 1)

- ✓ $\cos(\theta_{l1l2})$>-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*





- Signal & backgds before/after cuts:

H(ZZ*): σ = 0.2 ab $\Rightarrow \sigma$(after) = 0.04 ab

WW*: σ = 29 fb $\Rightarrow \sigma$(after) = 144 ab

τ-τ: σ = 3.1 pb $\Rightarrow \sigma$(after) = 51 ab

qqbar: σ ~ 0 pb $\Rightarrow \sigma$(after) = 0 ab

ZZ*: σ = 24 ab $\Rightarrow \sigma$(after) = 9 ab

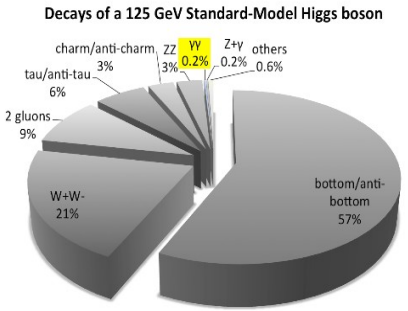
For L_{int}=10 ab^{-1}

$S/\sqrt{B} = 0.4/\sqrt{2000} \approx 0.01$

Significance ≈ 0.01

Channel 10: $e^+e^- \to H \to \gamma\gamma$

- Final state (retains 95% of the $\sigma(\tau\tau)$ = 0.64 ab):
  2 isolated photons (exclusive) + nothing else



- Analysis cuts:

  ✓ $E_\gamma > 60$ GeV reduces diphoton continuum &
  Bhabha scatt. backgd where e^+e^- mis'id for γ with P≈0.35%.

  ✓ MVA BDT doesn't improve result

- Signal & backgds before/after cuts:

  $H(\gamma\gamma)$: σ = 0.61 ab $\Rightarrow$ σ (after) = 0.3 ab
  $\gamma\gamma$: σ = 25 pb $\Rightarrow$ σ (after) = 900 fb
  e^+e^-: σ = 2.3 pb $\Rightarrow$ σ (after) = 59 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 30/\sqrt{1.e4} \approx 0.01$
Significance ≈ 0.01

Significance: Multi-Channel Combination

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

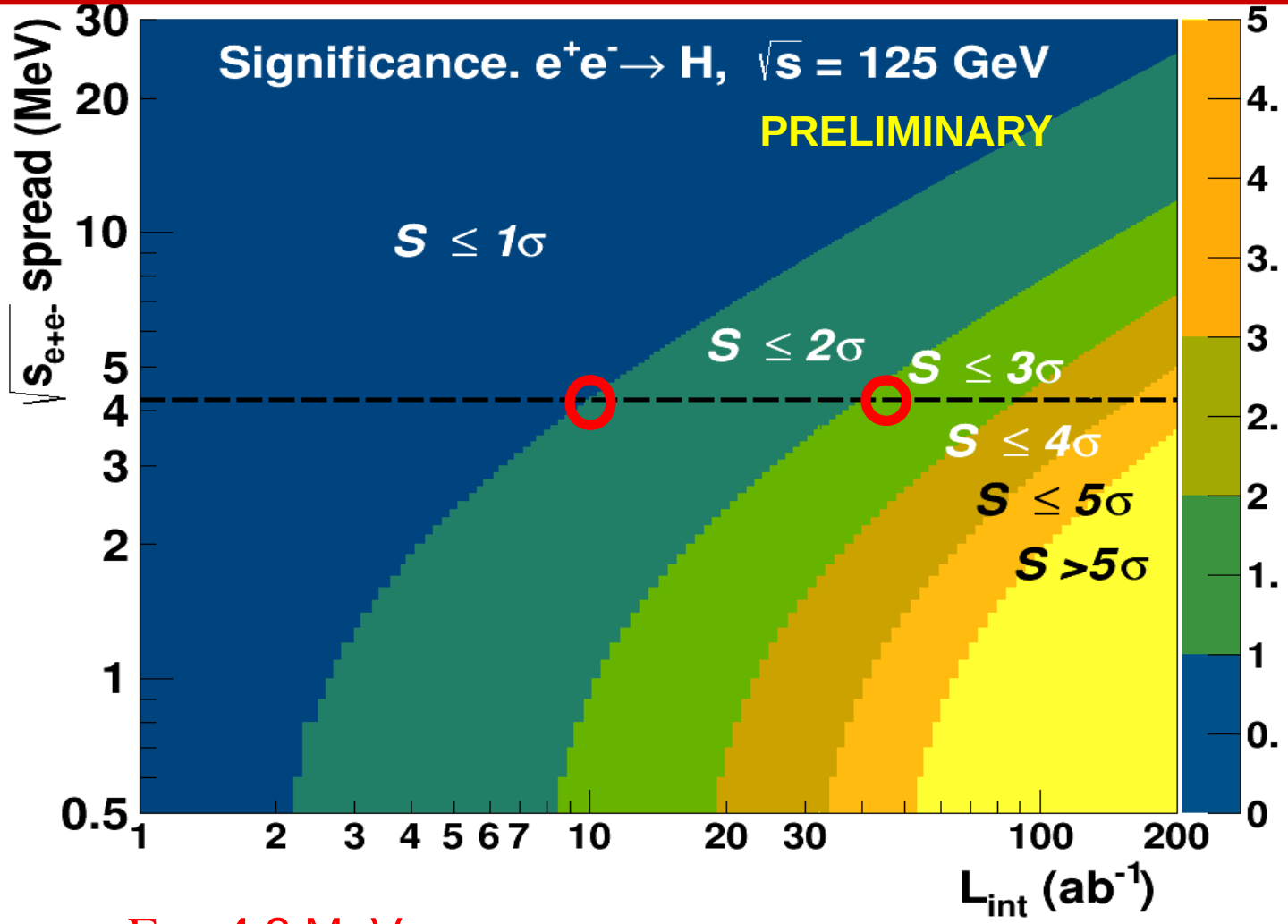
Channel	Significance (1 ab^{-1})	Significance (10 ab^{-1})
WW→lν2j,2l2ν,4j	0.15⊕0.09⊕0.03	0.50⊕0.30⊕0.08
ZZ→2j2ν,2l2j,2l2ν	0.07⊕0.05⊕0.01	0.21⊕0.16⊕0.03
bb	0.03	0.10
gg	0.03	0.09
ττ	–	0.02
γγ	–	0.01
Combined	**0.2**	**0.7**

- For 10 ab^{-1}: Significance ≈ 0.7 (preliminary, optimizations under study)

  Limit (95% CL) for branching ratio: $BR(H\rightarrow ee) < 2.8\times BR_{SM}(H\rightarrow ee)$

  Limit (95% CL) for SM Yukawa: $g_{eH} < 1.7\times g_{eH,SM}$

Significance vs. L_{int} & $\sqrt{s}_{spread}$

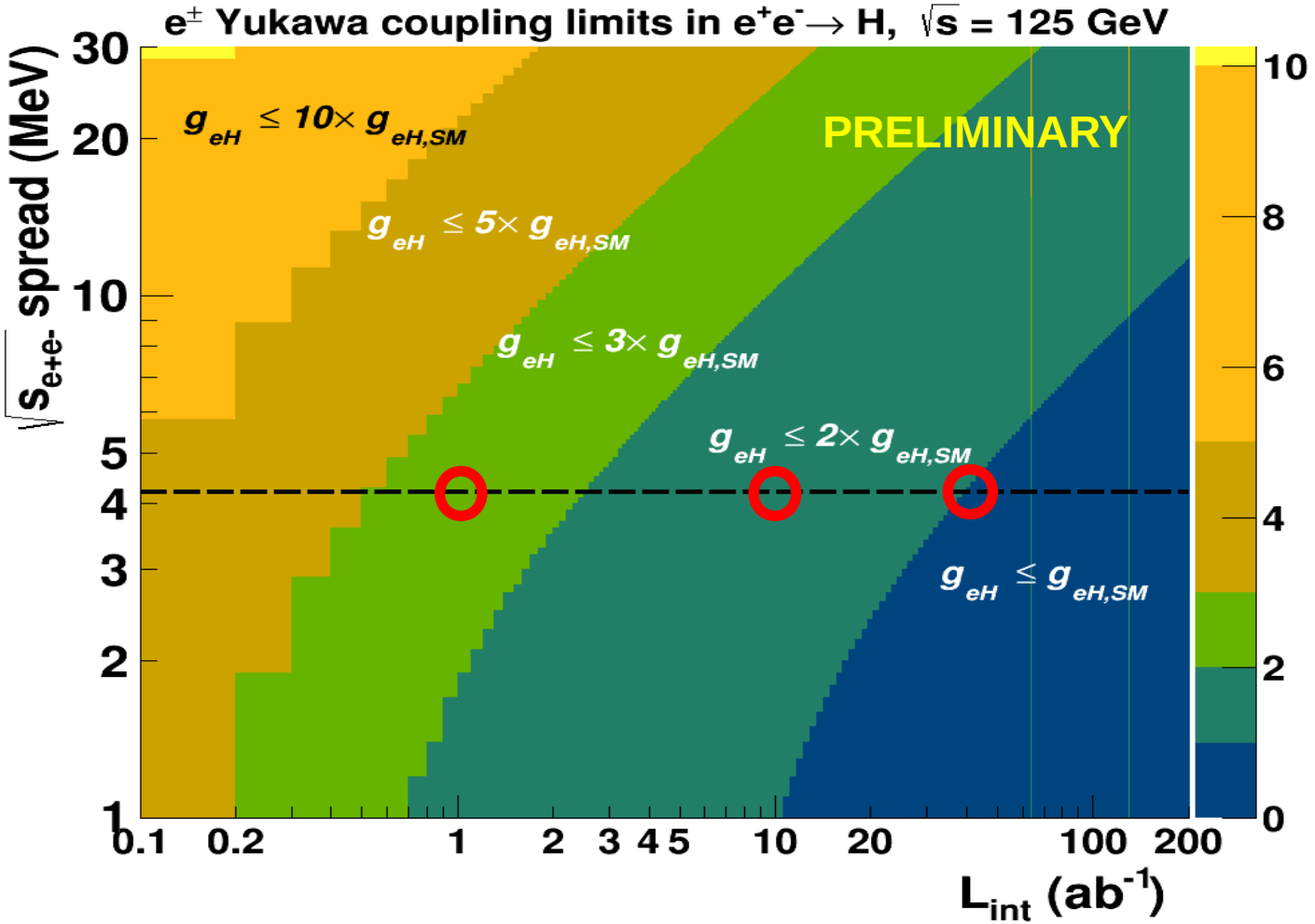


- If $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV:

  L_{int}=10 ab^{-1}: Signif. = 1σ. Target L_{int} = 45 ab^{-1} (crab waist, 4 IPs): Signif. = 2.1σ

  3σ evidence would require 2 yrs running at Higgs pole with target luminosity.

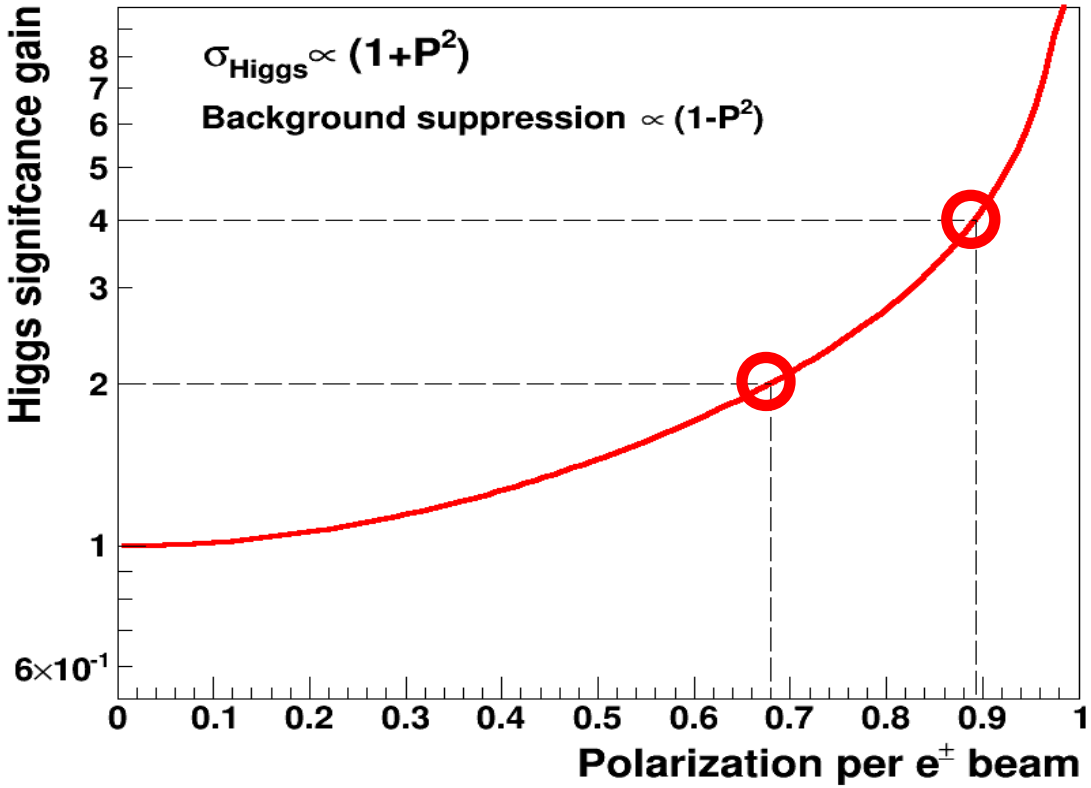
g_{eH} Yukawa limits vs. L_{int} & $\sqrt{s}_{spread}$



- For low lumis (L_{int}<1 ab^{-1}) & $\sqrt{s}_{spread}$=4–30 MeV: $g_{eH} < (3–10) \times g_{eH,SM}$ (95% CL)
- For L_{int} = 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: $g_{eH} < 1.7 \times g_{eH,SM}$ (95% CL)
- For L_{int}=45 ab^{-1} (crab waist, 4 IPs) & $\sqrt{s}_{spread} = \Gamma_H$: $g_{eH} < 1.1 \times g_{eH,SM}$ (95% CL)

Significance increase with polarized beams

- Polarization of beams would enhance the signal by $(1+P^2)$ & suppress background by $(1-P^2)$. However, realistic polarization estimates (P=20-30%) are clearly insufficient and higher polarizations would reduce luminosity...



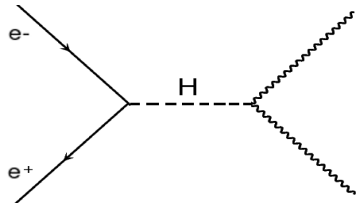
- Significance increase:

  P = 68%: ×2 significance

  P = 90%: ×4 significance

Conclusions

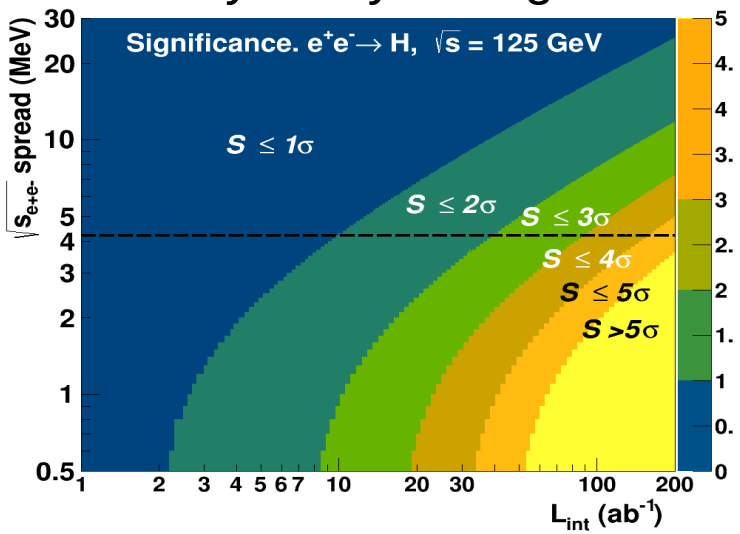
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):

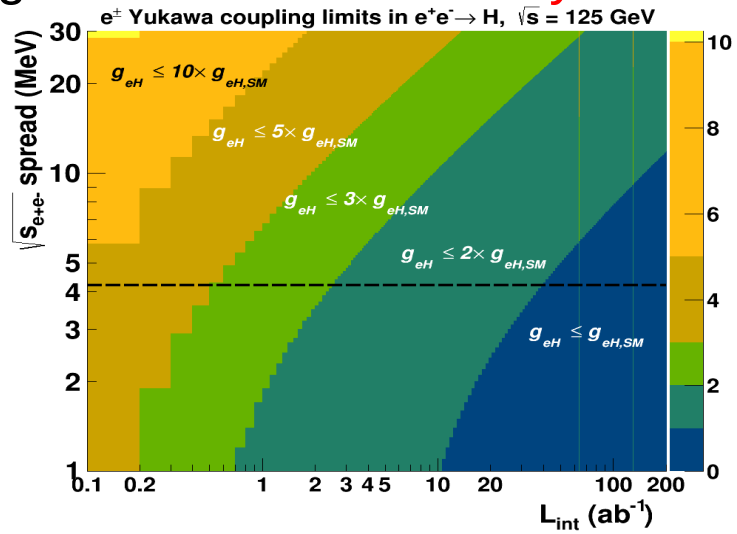


$\sigma(e^+e^- \to H)_{B\text{-}W} = 1.64$ fb

$\sigma(e^+e^- \to H)_{visible} = 290$ ab (ISR + $\sqrt{s}_{spread} = \Gamma_H = 4.2$ MeV)

- Preliminary study for signal + background for "all" 10 decay channels.





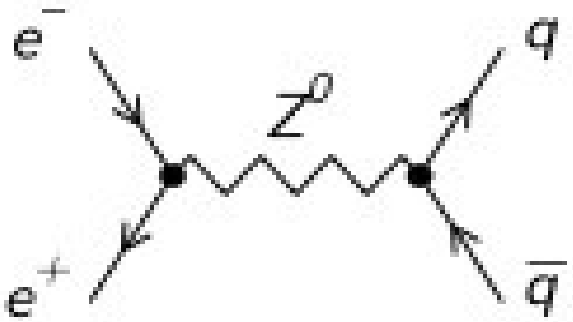
$\sqrt{s}_{spread} = \Gamma_H$, $L_{int} = 10$ ab^{-1}: $S \approx 0.7$, $BR(Hee) < 2.8 \times BR_{SM}$, $g_{eH} < 1.7 \times g_{eH,SM}$ (95% CL)

- Challenging performances: Mono-chromatization to achieve $\sqrt{s}_{spread} \sim \Gamma_H$
- Fundamental & unique physics accessible:
  - → Electron Yukawa coupling
  - → Higgs width measurable ("natural" threshold scan)?

Backup slides

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

- 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 ...