Resonant $e^+e^- \to$ Higgs at FCC-ee: Unrivaled probe of the $e^\pm$ Yukawa

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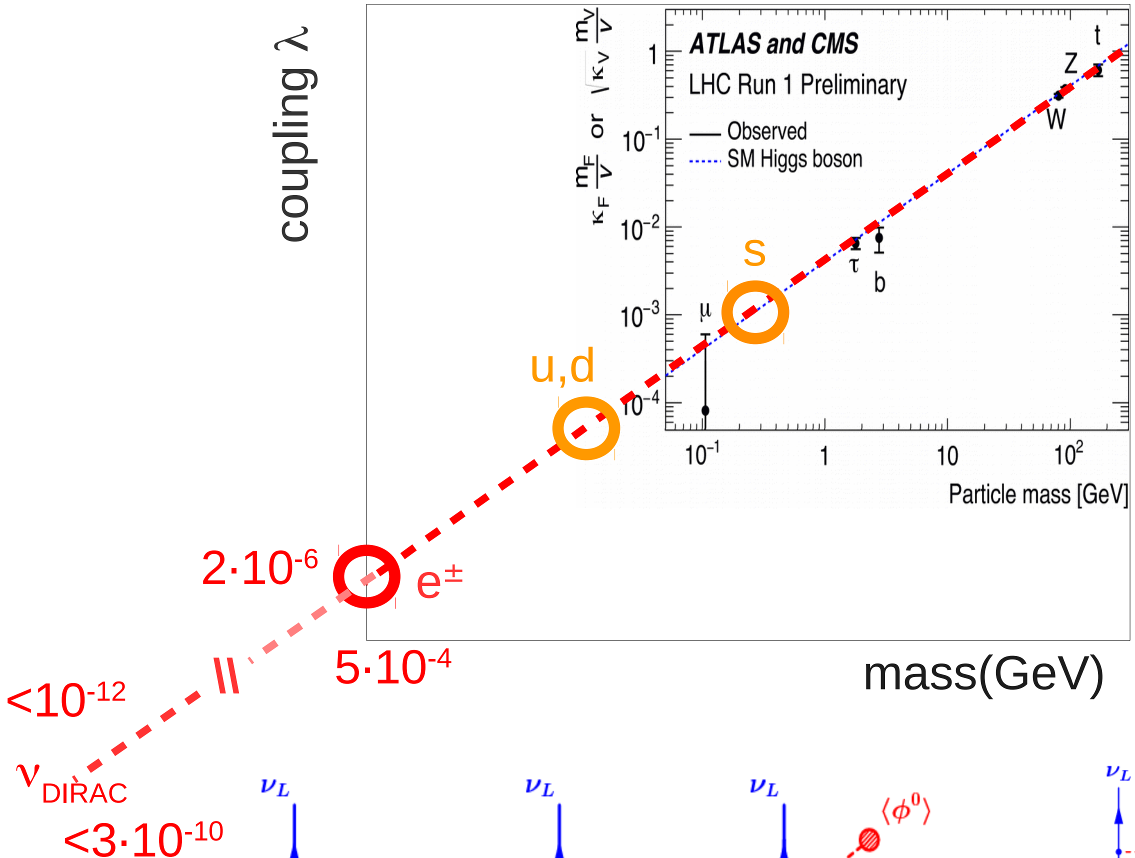
David d'Enterria (CERN)

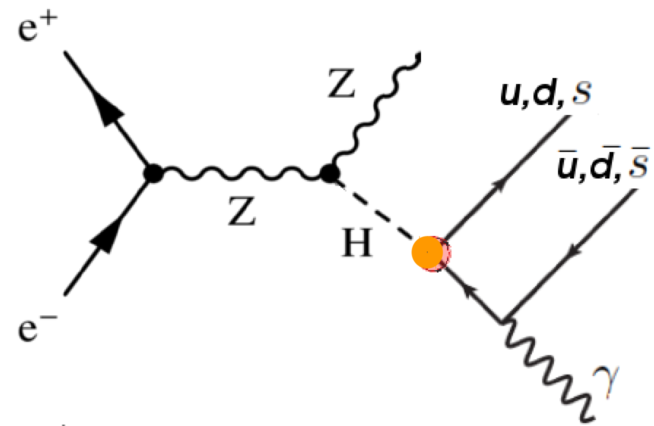
A. Poldaru (Tallin)

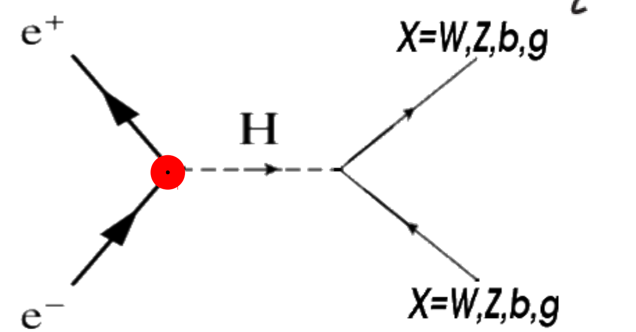
G. Wojcik (SLAC)

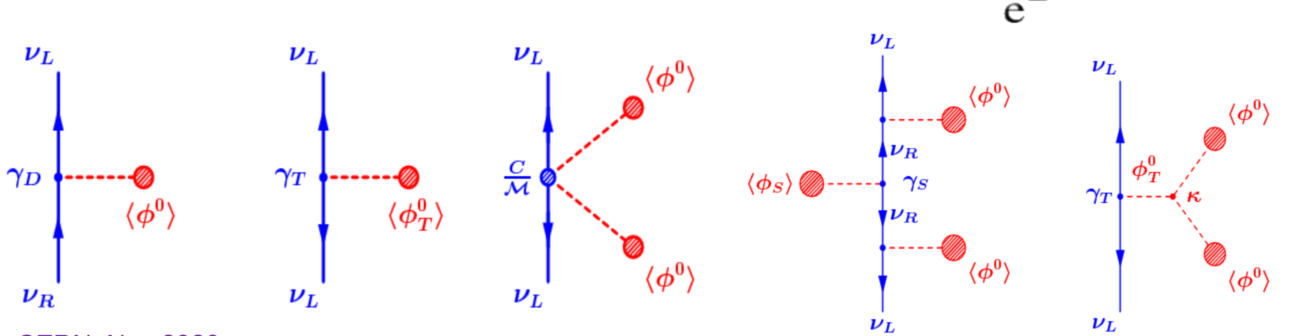
Generation of lightest fermion masses?

- LHC can only measure 3rd (plus a few 2nd)-generation Yukawas.
- Can we prove mass generation for stable (u,d,e,ν) matter in the Universe?





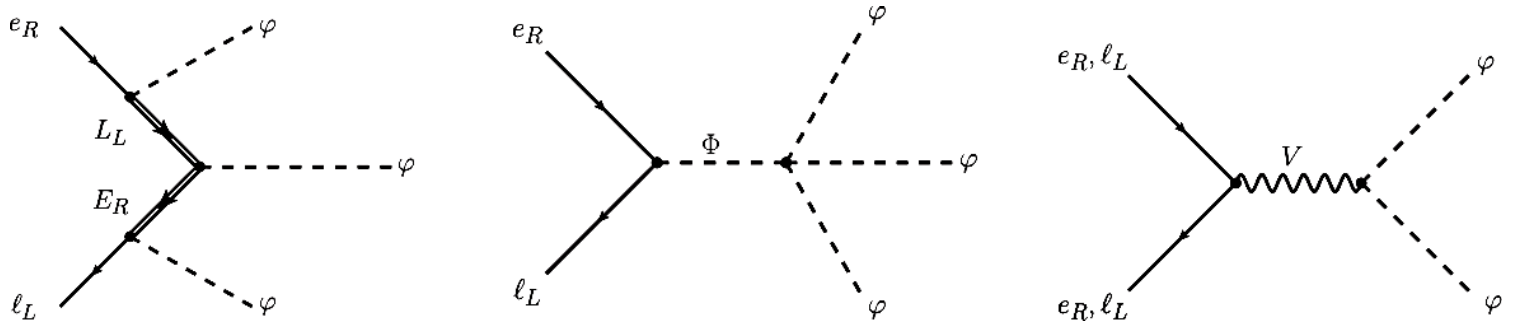




BSM electron Yukawa

- Lowest order dim-6 operators with BSM electron Yukawa:

[W. Altmannshofer et al. JHEP 05 (2015) 125]



mixing e w/ heavy vector-like leptons

mixing of SM Higgs doublet w/ heavy scalar doublet coupled to e

exchange of a heavy vector

- Modified Higgs-electron coupling (k_e indicates modification wrt. k_e^{SM}=1):

$$g_{eeh} = \kappa_e \frac{\sqrt{2} m_e}{v},$$

Upper bound on k_e translates into lower bound on M_{BSM} scale:

$$\kappa_e \approx 1 + v^3/(\sqrt{2} m_e M^2)$$

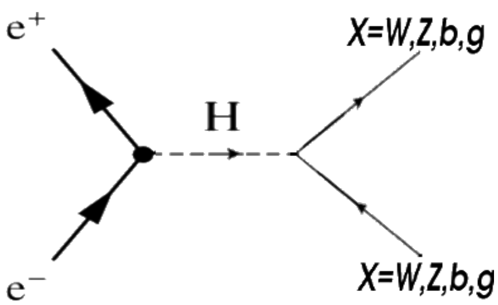
$h \to e^+e^-$	LHC8 (25/fb)	$\lvert\kappa_e\rvert \lesssim 600$	$M \gtrsim 6$ TeV
	LHC14 (300/fb)	$\lvert\kappa_e\rvert \sim 260$	$M \sim 9$ TeV
	LHC14 (3/ab)	$\lvert\kappa_e\rvert \sim 150$	$M \sim 12$ TeV
	100 TeV (3/ab)	$\lvert\kappa_e\rvert \sim 75$	$M \sim 17$ TeV
$e^+e^- \to h$	LEP II	$\lvert\kappa_e\rvert \lesssim 2000$	$M \gtrsim 3$ TeV
	FCC-ee (100/fb)	$\lvert\kappa_e\rvert \sim 10$	$M \sim 50$ TeV
$(g-2)_e$	current	$\mathrm{Re}\,\kappa_e \lesssim 3000$	$M \gtrsim 2.5$ TeV
	future	$\mathrm{Re}\,\kappa_e \sim 300$	$M \sim 8$ TeV

- Note: Unsuppressed dim-10 BSM operators also possible.

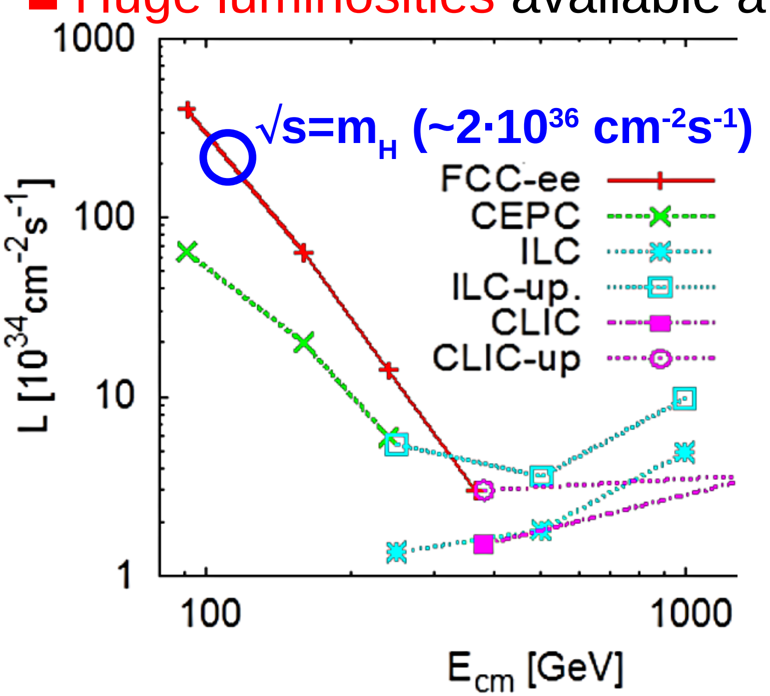
e Yukawa via s-channel $e^+e^- \to H$ production

- Higgs decay to e^+e^- is unobservable: BR($H\to e^+e^-$) $\propto m_e^2 \approx 5\cdot10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu\to H) \approx 70$ pb. Tiny κ_e Yukawa coupling $\Rightarrow$ Tiny $\sigma(ee\to H)$:

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



- Huge luminosities available at FCC-ee:



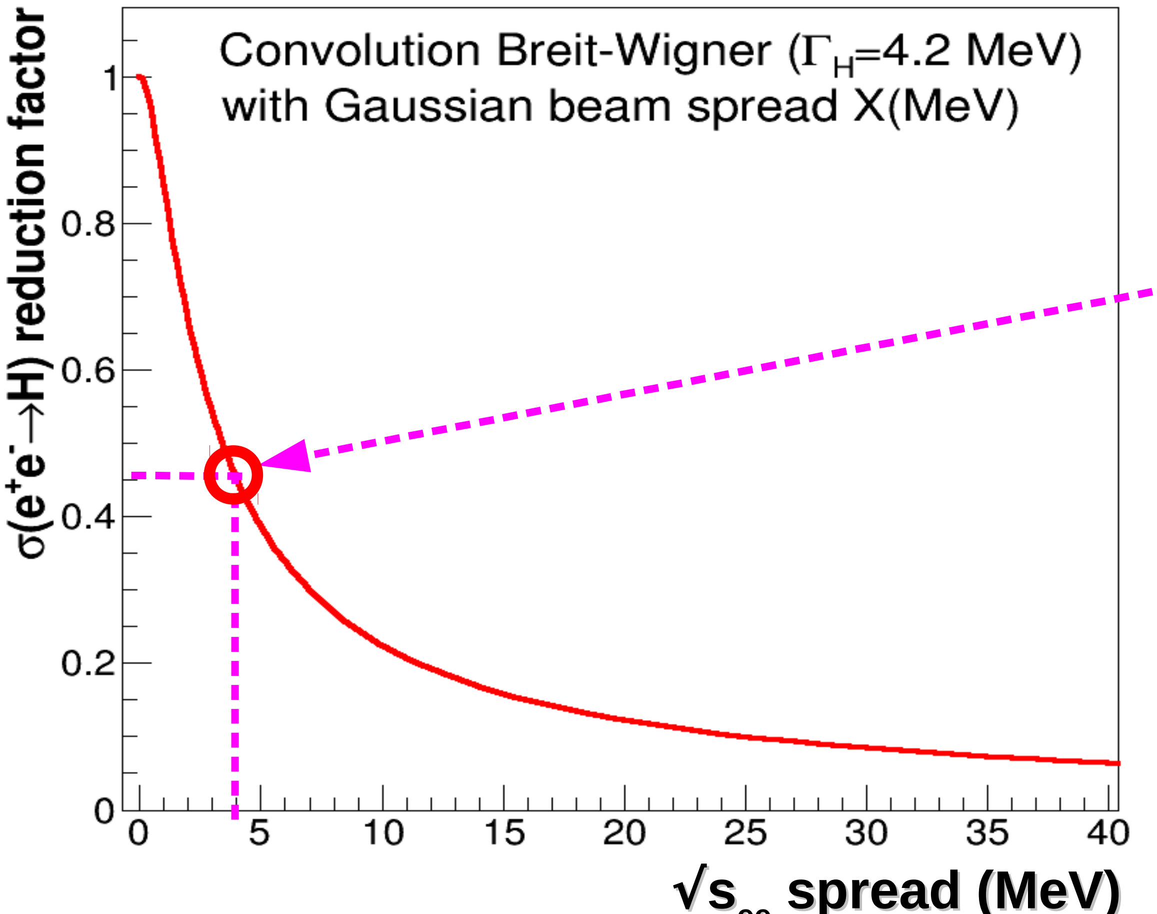
In theory, FCC-ee running at H pole-mass L_{int} ≈20 ab^{-1}/yr would produce O(30.000) H's

IFF we can control: (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?

"Actual" s-channel $e^+e^- \rightarrow H$ cross section

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



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

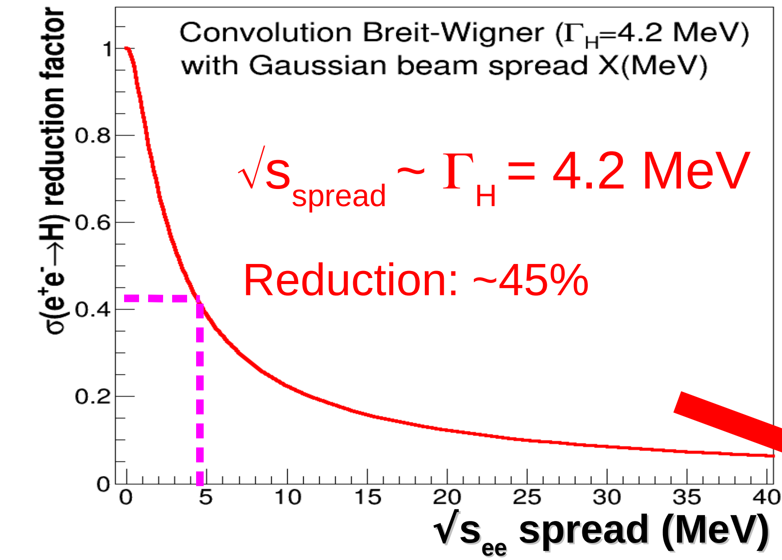
~45% x-section reduction

Reachable with beams monochromatization? (opposite sign dispersion using magnetic lattice)

What luminosity loss price?

[F.Zimmermann, A.Valdivia:
JACoW-IPAC2017-WEPIK015
JACoW-IPAC2019-MOPMP035]

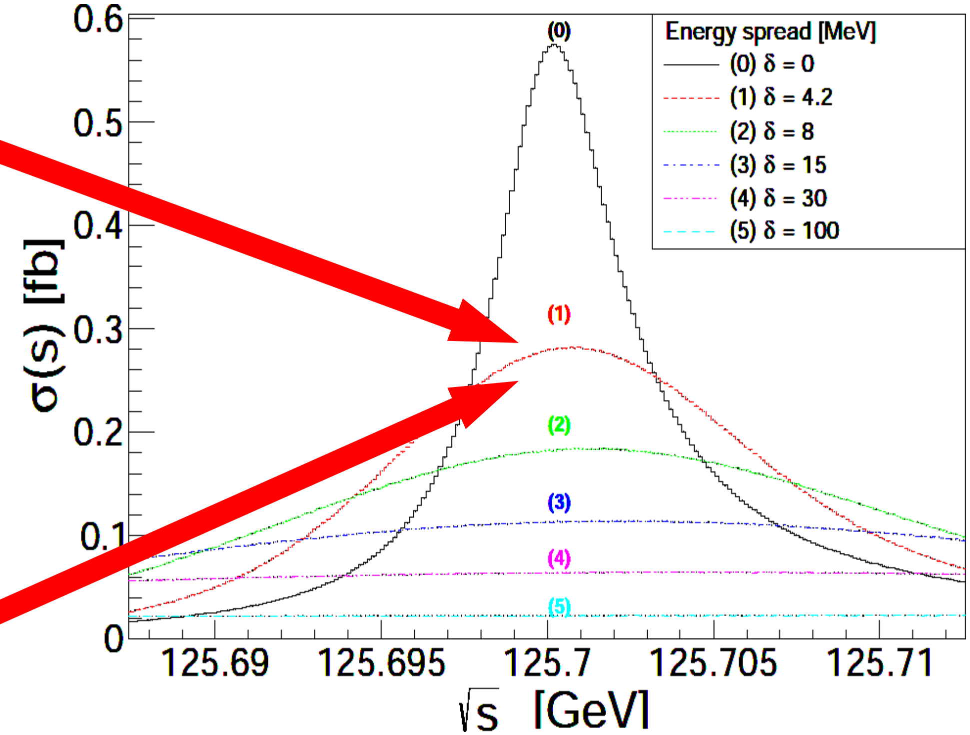
“Actual” s-channel $e^+e^- \to H$ cross section



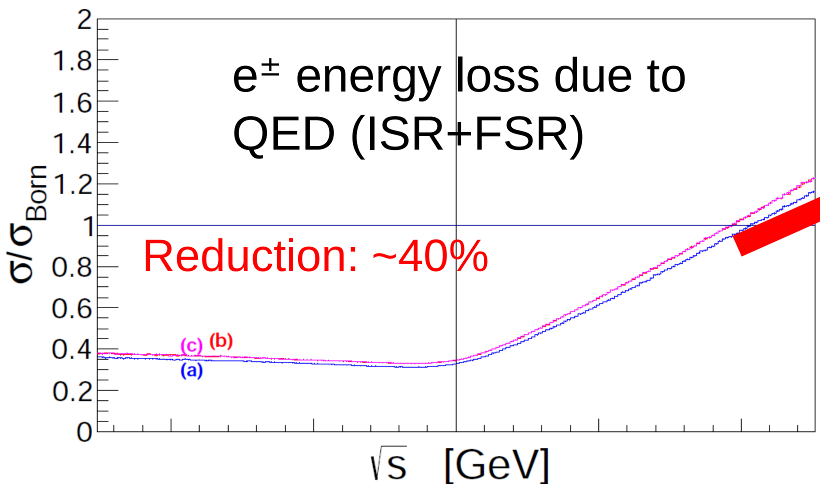
Assume monochromatization ref. point:
$\sqrt{s}_{spread} \approx \Gamma_H = 4.2$ MeV

- Full convolution of both effects:

[S.Jadach, R. Kycia, PLB755 (2016) 58]



- Extra ~40% reduction due to QED radiation:



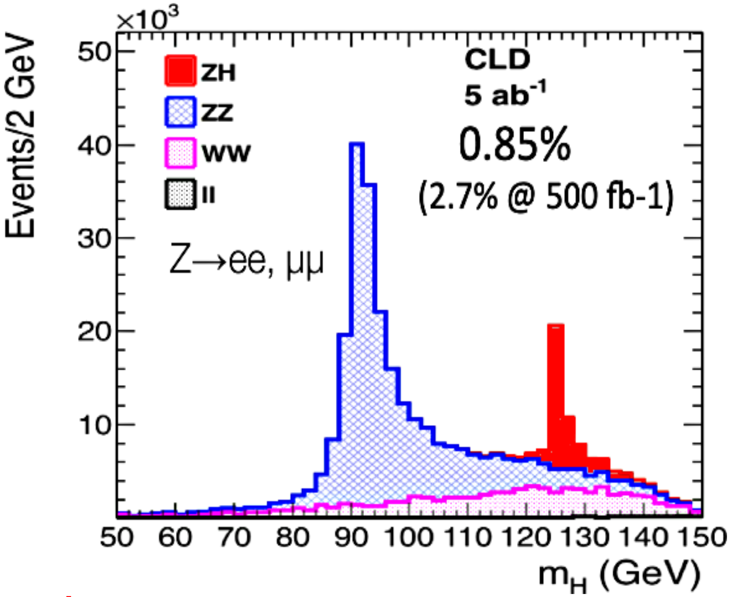
$\sigma_{spread+ISR}(e^+e^- \to H) = 0.17 \times \sigma(e^+e^- \to H) = 290$ ab

Accurate m_H needed to run at resonant peak

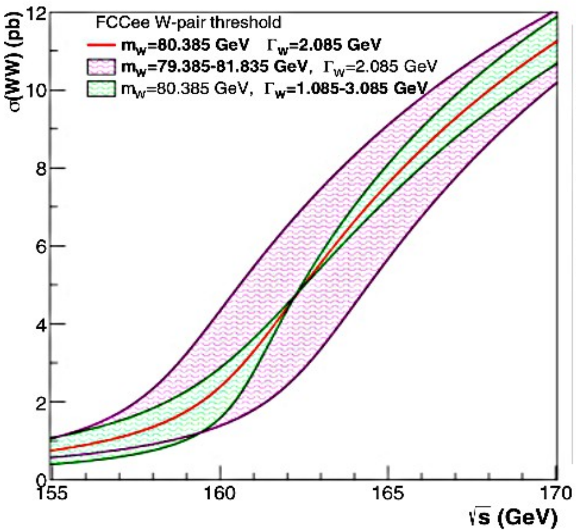
- $e^+e^- \to H\ Z(l^+l^-)$ recoil method: allows Higgs mass reconstruction with δm_H = 8 MeV in $Z \to \mu^+\mu^-$

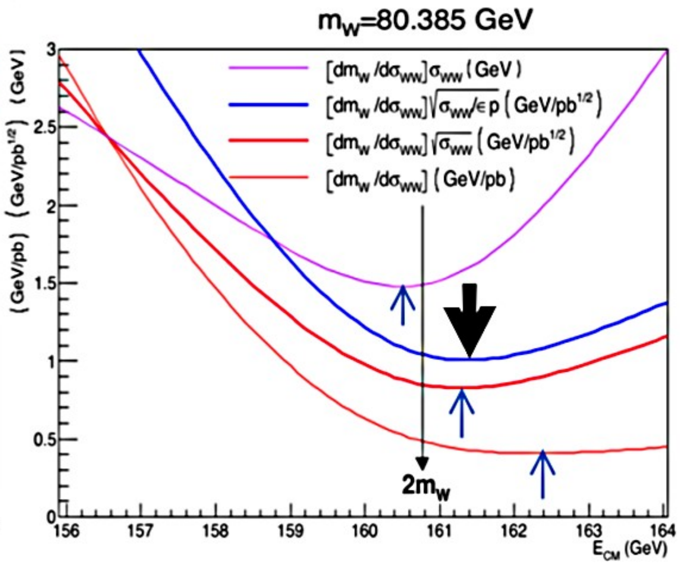
$$m^2_{\rm recoil} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

(δm_H = ±5 MeV adding other decays)



- Can m_H be accurately reconstructed via σ(HZ) line shape scan? Like done for m_W via $e^+e^- \to W^+W^-$...





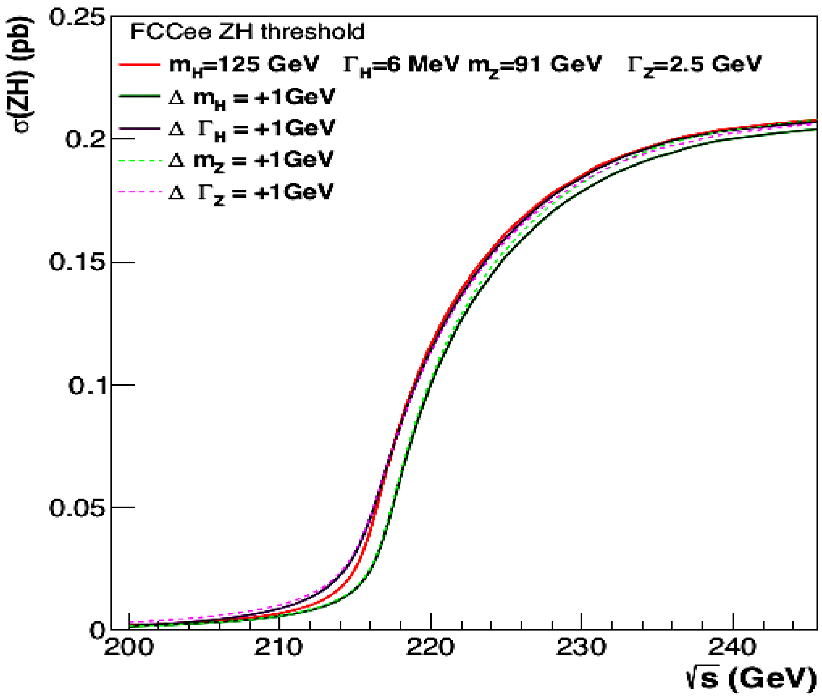
With 7/ab @ 162.6 GeV: δm_W(stat)= ±0.5 MeV

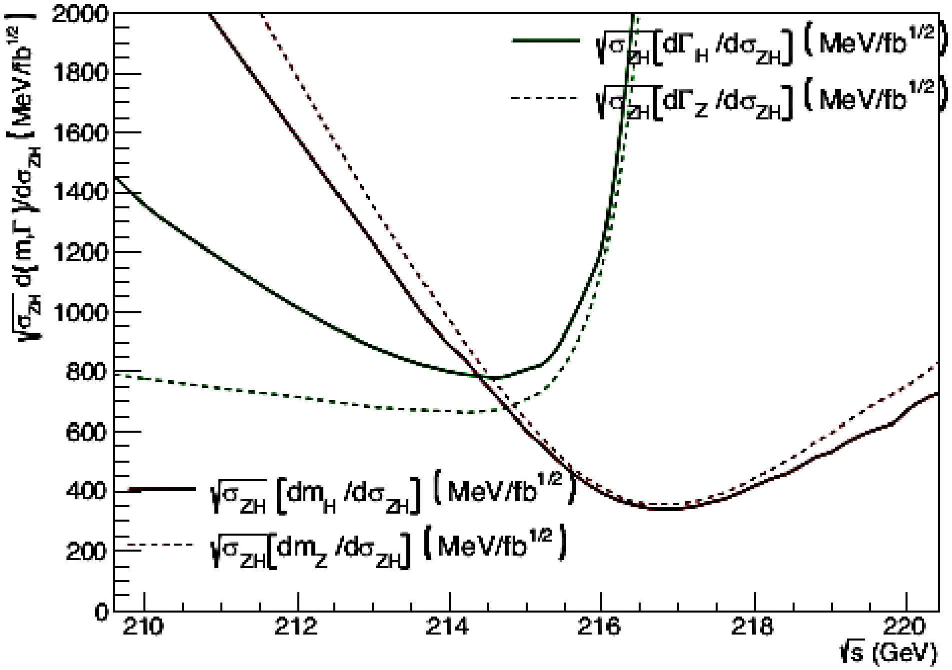
Need systematics control:
- δE_{beam}<0.5 MeV ($6\cdot10^{-6}$)
- $\delta\varepsilon/\varepsilon$, $\delta L/L < 2\cdot10^{-4}$)
- $\delta\sigma_B$ <1 fb ($2\cdot10^{-3}$)

[arXiv:1703.01626 arXiv:1909.12245]

Accurate m_H needed to run at resonant peak

- Can m_H be accurately reconstructed via σ(HZ) line shape scan?
- Preliminary MG5@NLO studies by Paolo Azzurri:





- Optimal data-taking point for min Δm_H(stat): $\sqrt{s} \simeq$ mZ+mH–0.2 $\simeq$ 217 GeV
- $\sqrt{\sigma_{ZH}}(dm_H/d\sigma_{ZH})_{min}$=350 MeV/$\sqrt{fb}$ With 5/ab @ 217 GeV: $\delta m_H = \pm 5$ MeV

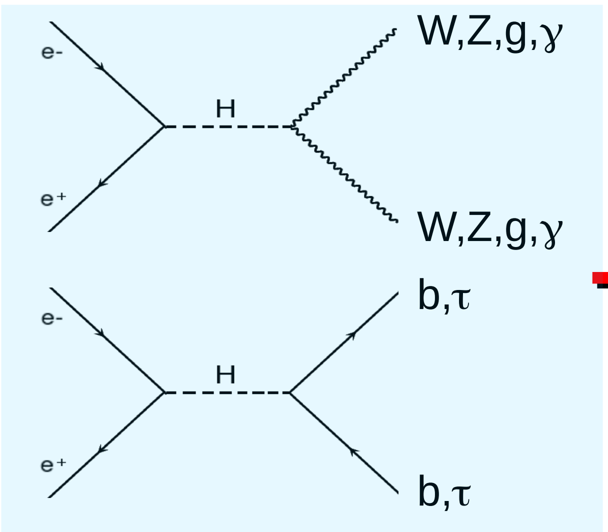
  Need systematics control: δE_{beam} < 5 MeV ($5\cdot 10^{-5}$), $\delta\varepsilon/\varepsilon$, $\delta L/L < 10^{-3}$, $\delta\sigma_B$ <0.1 fb (~10^{-3})

- Combining threshold HZ x-section with m_{HZ}(recoil) should give: $\delta m_H = \pm 3.5$ MeV

Signal & backgrounds simulation

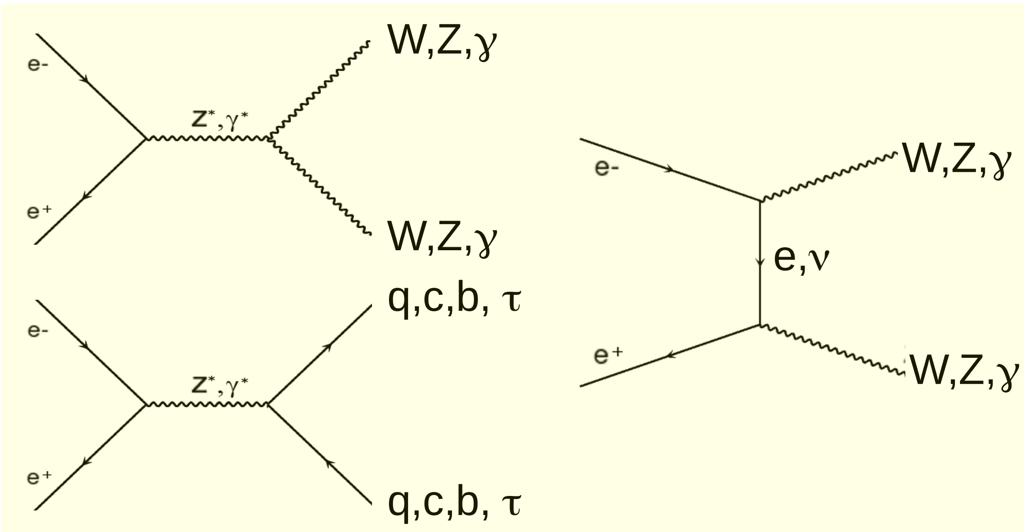
- PYTHIA8 e^+e^- at $\sqrt{s} = m_H = 125$ GeV to generate 10 final-states for Higgs signal plus backgrounds ($e^+e^- \to WW^*, ZZ^*, \gamma\gamma$, gg, $\tau\tau$, bbar, ccbar, qqbar):

SIGNAL



+

BACKGROUNDS (s-channel Z/γ, all t-channels)

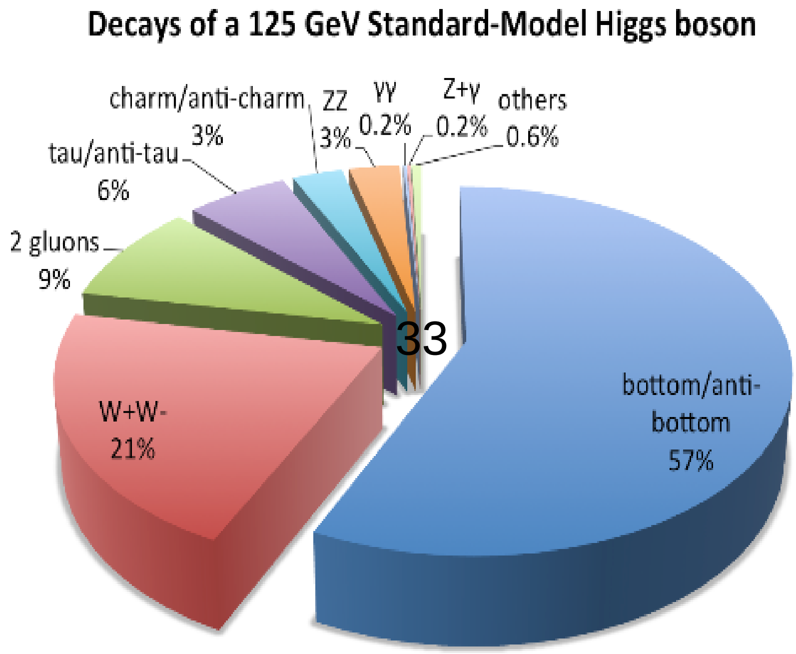


(other SM loop-induced $e^+e^- \to H$ found negligible)

- HDECAY: Higgs boson decay NLO branching ratios
- YFSWW/ZZ/MG5 calculators to cross-check PYTHIA8 x-sections
- FastJet package: Exclusive e^+e^- (N_j=2,4) jet algorithm
- Event-shape variables: thrust, sphericity, T, oblateness,... [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(125 GeV)

- Very-rare counting experiment over 10 decay channels:



Higgs decay channel	BR	σ× BR (ISR⊗spread incl.)
$H \to b\bar{b}$	58.2%	164 ab
$H \to gg$	8.2%	23 ab
$H \to \tau\tau$	6.3%×60%×60%	6.5 ab
$H \to c\bar{c}$	2.9%	8 ab
$H \to WW \to \ell\nu\, 2j$	21.4%×67.6%×32.4%×2	26 ab
$H \to WW \to 2\ell\, 2\nu$	21.4%×32.4%×32.4%	6.3 ab
$H \to WW \to 4j$	21.4%×67.6%×67.6%	28 ab
$H \to ZZ \to 2j\, 2\nu$	2.6%×70.%×20.%×2	2 ab
$H \to ZZ \to 2\ell\, 2j$	2.6%×70.%×10.%×2	1 ab
$H \to ZZ \to 2\ell\, 2\nu$	2.6%×20.%×10.%×2	0.3 ab
$H \to \gamma\gamma$	0.23%	0.65 ab

Background process	σ × BR	
$e^+e^- \to bb$	19 pb	(S/B~10^{-5})
$e^+e^- \to q\bar{q}$	61 pb	(S/B~10^{-3} w/ $\varepsilon_{q\text{-}g,mistag}$~1%)
$e^+e^- \to \tau\tau$	10 pb	(S/B~10^{-6})
$e^+e^- \to c\bar{c}$	22 pb	(S/B~10^{-7})
$e^+e^- \to WW \to \ell\nu\, 2j$	23 fb	(S/B~10^{-3})
$e^+e^- \to WW \to 2\ell\, 2\nu$	5.6 fb	(S/B~10^{-3})
$e^+e^- \to WW \to 4j$	24 fb	(S/B~10^{-3})
$e^+e^- \to ZZ \to 2j\, 2\nu$	273 ab	(S/B~10^{-2})
$e^+e^- \to ZZ \to 2\ell\, 2j$	136 ab	(S/B~10^{-2})
$e^+e^- \to ZZ \to 2\ell\, 2\nu$	39 ab	(S/B~10^{-2})
$e^+e^- \to \gamma\gamma$	79 pb	(S/B~10^{-8})

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

Event selection variables & efficiencies

- Single & pair kinematical variables for jets, leptons :
  $p_{T,i}$, 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,...

- Jet(s)/tau reconstruction performances:

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

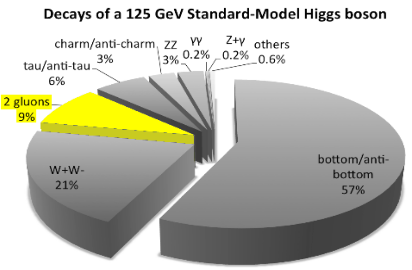
b-jet tagging effic. = 70%
charm-jet mistag rate = 5%
light-q mistag rate = 1.5%

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

g-tagging effic. = 70%
light-q mistag rate = 1%
τ-tagging rate = 80%
τ-mistag rate = 0.75%

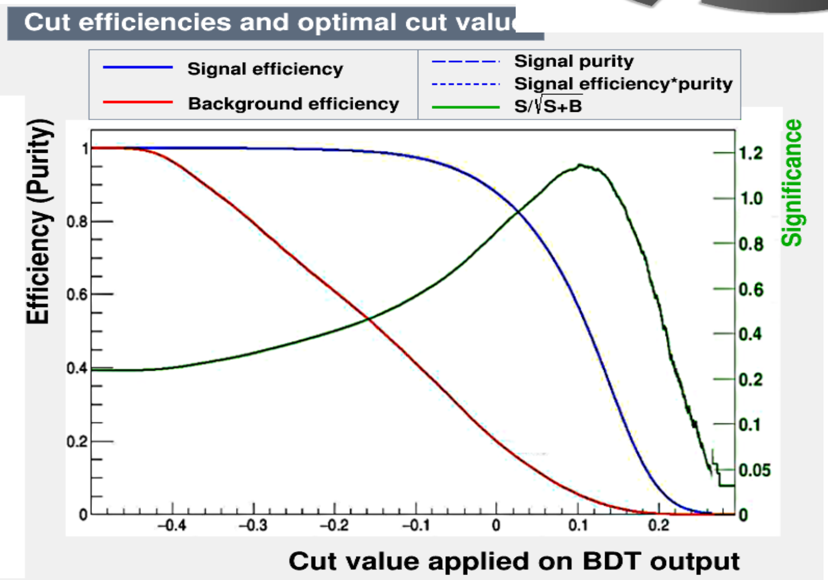
- ISR events tagged via 2 methods (depending on ν's in final state):
  (1) Cut on the ME vector. ISR photons mostly emitted along beam axis:
  Large missing energy (ME) but low transverse missing energy (MET).
  (2) Cut on E_{tot} (computed without isolated ISR photons within $|\eta|<5$):
  Isolated photons with E>5 GeV omitted: E_{total} > 120 GeV

Most significant channel: $e^+e^- \rightarrow H(gg) \rightarrow jj$



- Final state definition (retains 30% of σ(gg) = 24 ab):

  2 gluon-tagged jets (with 70% effic. each)
  Light-q mistagging rate: ~1%
  Challenging, not impossible:
  Dedicated QCD studies needed
  (reco&PID of ALL hadrons in jets).



- MVA result:

  Signal reduction ~50%
  Backgd. reduction: x20

- Signal & backgrounds cross sections after each effic./cuts/MVA:

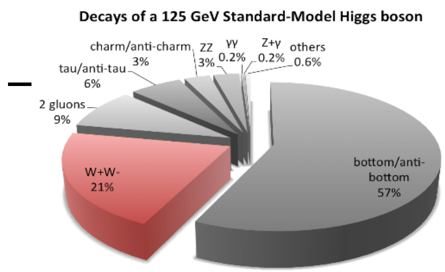
Process	Events	Passes	+ cuts	+ MVA	raw σ	Tagrate	Pass+Tag	+ Cut	Final σ
Hgg	100000	85315	80350	45440	25 ± 0 ab	$70\%^2$	10 ab	9.7 ab	5.5 ± 0.0 ab
bb	199981	140057	12532	1331	81 ± 0 pb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb
cc	200000	174120	28282	1984	73 ± 0 pb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb
qq	200000	186171	36888	2015	237 ± 0 pb	$1.0\%^2$	22 fb	4.4 fb	239 ± 5 ab
ZZ	99999	75095	49798	14261	224 ± 0 fb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb
tautau	20000	0	0	0	26 ± 0 pb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb
WW	20000	16959	12783	5413	21 ± 0 fb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb

Total bckg: 244 ab, $S/\sqrt{S+B} = 1.0973$, training data 1.1843, from MVA 1.1101

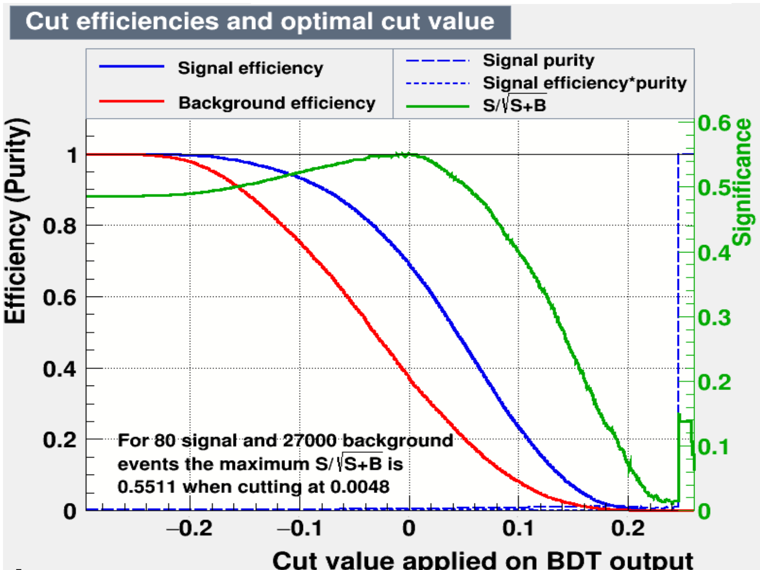
For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 55/\sqrt{2.3e3} \approx 1.2$
Significance ≈ 1.2

2^{nd} most significant channel: $e^+e^- \to H(WW^*) \to l\nu jj$

- Final state (retains 80% of $\sigma(WW^*(l\nu jj))$ = 27 ab):
  1 isolated e,μ,τ(e),τ(μ) + ME>2 GeV + 2 jets (excl.)



- Analysis cuts:
  - ✓ $E_{j1,j2}$ < 52,45 GeV $\Longleftarrow$ Kills $e^+e^- \to q\bar{q}$
  - ✓ $m_{w(l\nu)}$ > 12 GeV/c^2 $\Longleftarrow$ Kills $e^+e^- \to q\bar{q}$
  - ✓ E_{lepton} > 10 GeV $\Longleftarrow$ Kills $e^+e^- \to q\bar{q}$
  - ✓ ME > 20 GeV $\Longleftarrow$ Kills $e^+e^- \to q\bar{q}$
  - ✓ m_{ME} < 3 GeV/c^2 $\Longleftarrow$ Kills $e^+e^- \to \tau\tau$
  - ✓ BDT MVA ← Kills $e^+e^- \to WW^*$ continuum
    (exploits opposite $W^\pm$ polarizations in H decay)



- Signal & backgrounds after each cuts/MVA:

Process	Events	Passes	+ cuts	+ MVA	raw σ	Tagrate	Pass+Tag	+ Cut	Final σ
HWWjjlν	400000	174534 144336	66399	44797	27 ± 0 ab	$100\%^2$	23 ab	10 ab	7.0 ± 0.0 ab
WW	400000	174809 145026	55955	16886	46 ± 0 fb	$100\%^2$	17 fb	6.4 fb	1.9 ± 0.0 fb
bb	999898	0 200961	2	0	81 ± 0 pb	$100\%^2$	16 pb	161 ab	0 ± 81 ab
cc	1000000	0 63844	0	0	73 ± 0 pb	$100\%^2$	4.7 pb	0 pb	0 ± 73 ab
qq	1000000	0 7675	0	0	237 ± 0 pb	$100\%^2$	1.8 pb	0 pb	0 ± 237 ab
tautau	20000	0 8359	0	0	26 ± 0 pb	$0.75\%^2$	605 ab	0 pb	0 ± 72 zb

Total bckg: 1.9 fb, $S/\sqrt{S+B}$ = 0.5025, training data 0.5352, from MVA 0.5033

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

$e^+e^- \rightarrow H$ significance: Multi-channel combination

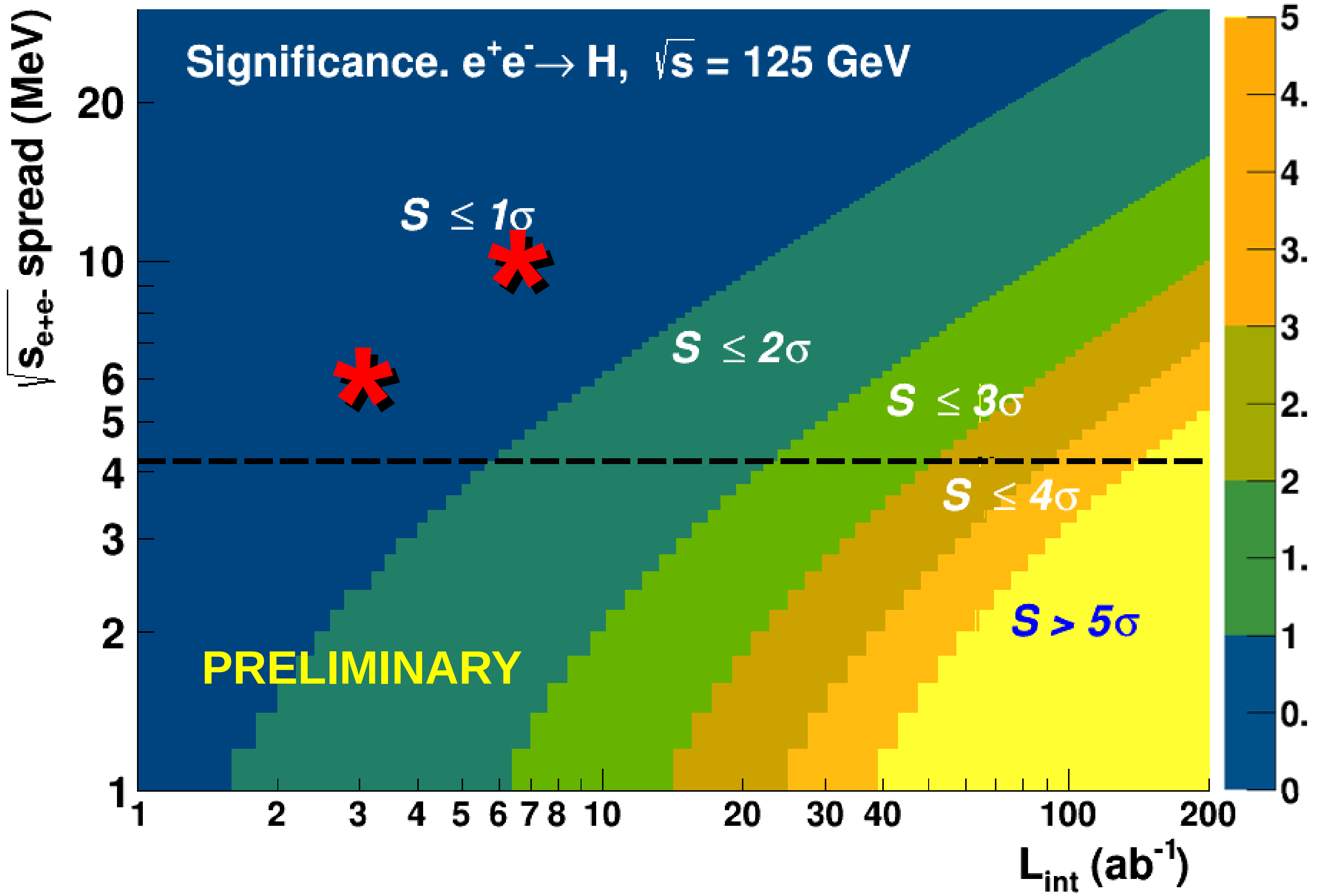
- Channels combination using RooStats-based tool for LHC Higgs analyses: Profile likelihood & hybrid significances give ~identical results, which are also very close to naive S/√B expectation (no background uncertainty).

Channel	Significance (1 ab^{-1})	Significance (10 ab^{-1})
$WW \rightarrow l\nu 2j, 2l2\nu, 4j$	$0.15 \oplus 0.09 \oplus 0.03$	$0.50 \oplus 0.32 \oplus 0.13$
$ZZ \rightarrow 2j2\nu, 2l2j, 2l2\nu$	$0.07 \oplus 0.05 \oplus 0.01$	$0.25 \oplus 0.20 \oplus 0.03$
bb	0.04	0.13
gg	0.34	1.11
$\tau\tau$	–	0.02
$\gamma\gamma$	–	0.01
Combined	**0.4**	**1.3**

- For 10 ab^{-1}: Significance ≈ 1.3σ (preliminary, ongoing optimizations)

Limit (95% CL) for SM Yukawa: $\kappa_e < 1.6 \times \kappa_{e,SM}$ $\sigma_{sig}(e^+e^- \rightarrow h \rightarrow X\bar{X}) \simeq |\kappa_e|^2$

$e^+e^- \to H$ significance vs. L_{int} & $\sqrt{s}_{spread}$

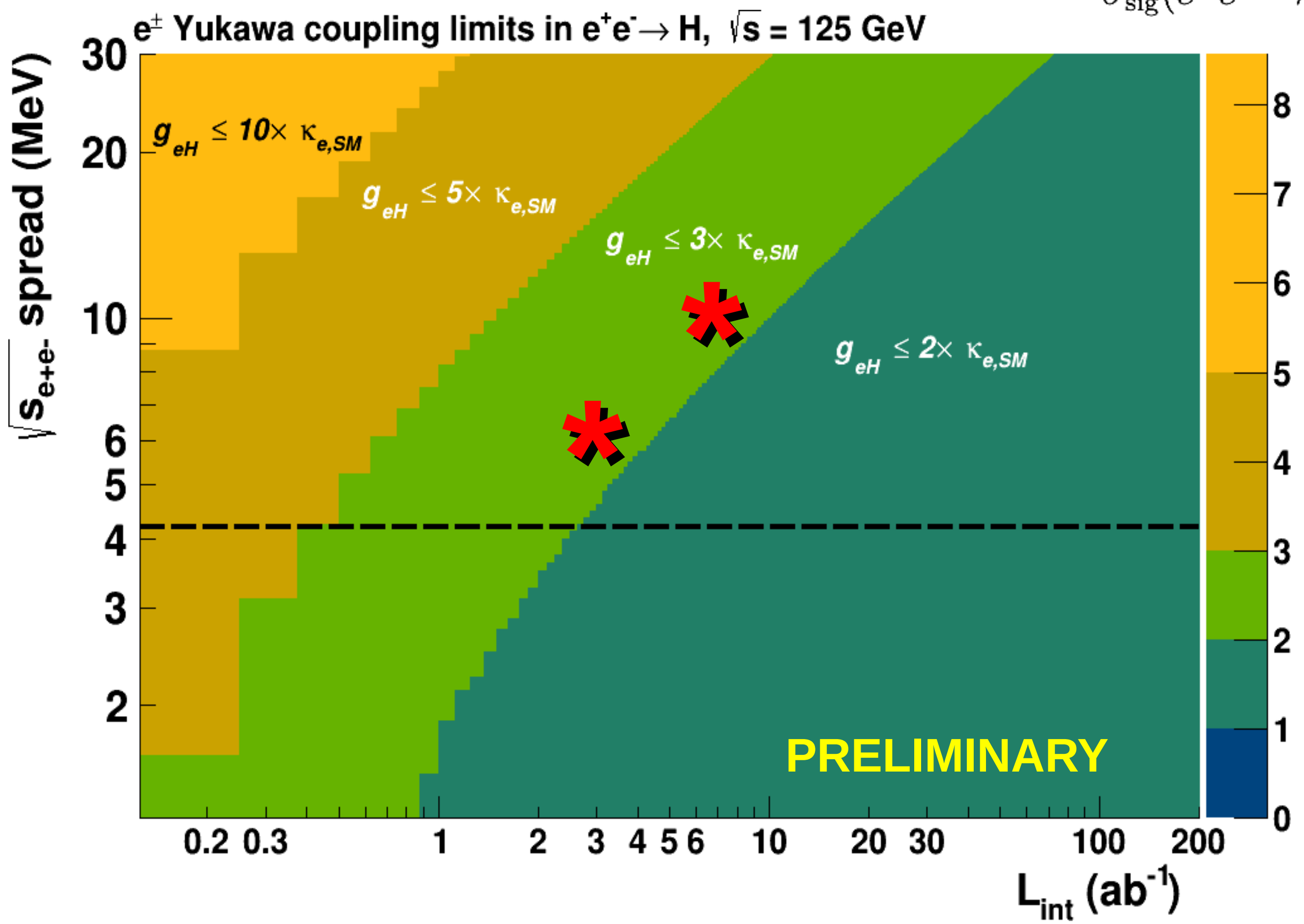


[Monochromatization WP: Valdivia-Zimmermann]

- Baseline monochromatization ($\sqrt{s}_{spread}$ = 6 MeV, L_{int} = 3 ab^{-1}) : Signif. = 0.5σ
- Optimized monochromatization ($\sqrt{s}_{spread}$ = 10 MeV, L_{int} =7 ab^{-1}) : Signif. = 0.6σ

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

$\sigma_{sig}(e^+e^- \to h \to X\bar{X}) \simeq |\kappa_e|^2$

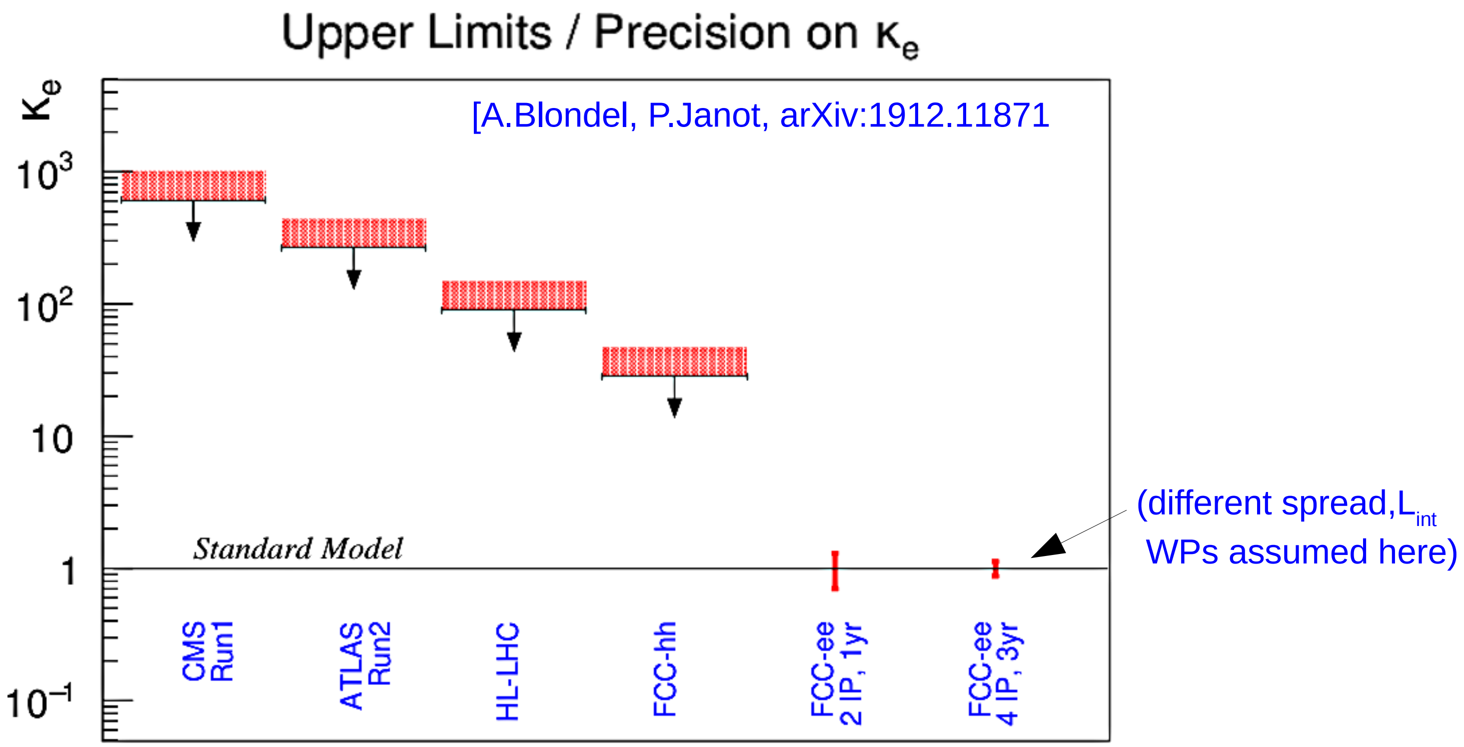


[Monochromatization WP: Valdivia-Zimmermann]

- Baseline monochrom. ($\sqrt{s}_{spread}$ = 6 MeV, 3 ab^{-1}): $\kappa_e < 2.2\times\, \kappa_{e,SM}$ (95% CL)
- Optimized monochrom. ($\sqrt{s}_{spread}$ = 10 MeV, 7 ab^{-1}): $\kappa_e < 2.1\times\, \kappa_{e,SM}$ (95% CL)

κ_e Yukawa limits at various machines

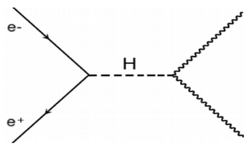
- Hadron machines can very loosely constrain κ_e via $H \to e^+e^-$ searches on top of huge DY (and $H \to \gamma\gamma$) backgrounds:



- Combining 2, 4 exps. (depend. on monochrom. WP, yrs) we are at SM κ_e values.
- Limits on κ_e are ✕100 (✕30) better than at HL-LHC (FCC-hh).

Conclusions

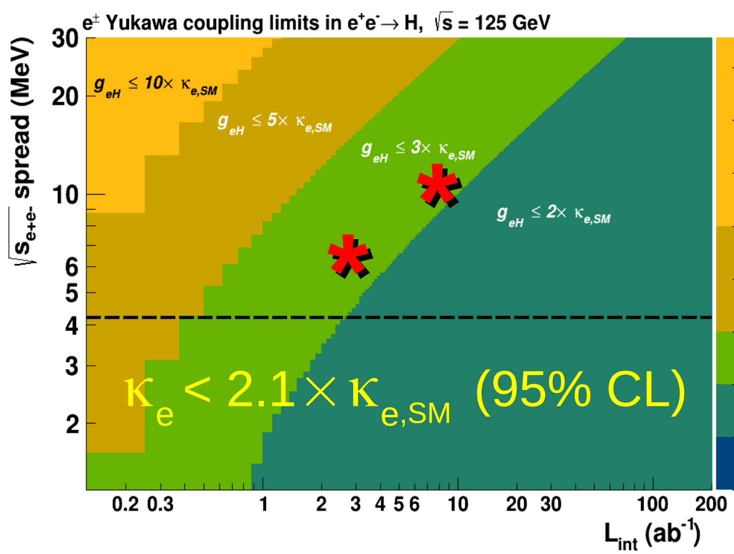
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125 GeV):



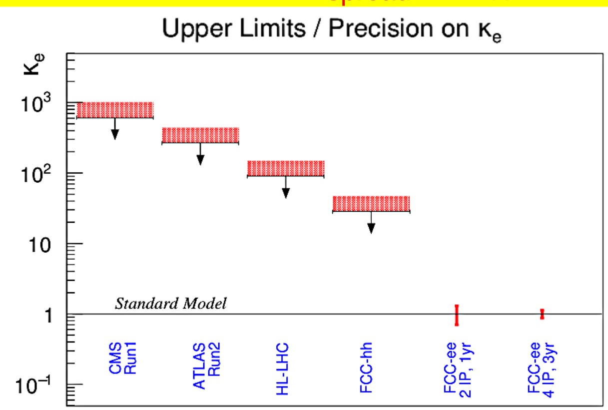
$\sigma(e^+e^- \to H)_{B\text{-}W}$ = 1.64 fb

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

- Prerequisite: Higgs mass extraction $\delta m_H = \pm 3.5$ MeV via HZ @ 240,217 GeV
- Preliminary study for signal + backgrounds for 10 decay channels:
  Most significant channels: H→gg (for light-q mistag ~1%!), H→WW*→l+jets



For 10 ab^{-1} & $\sqrt{s}_{spread} = \Gamma_H$: Signif ≈ 1.3σ

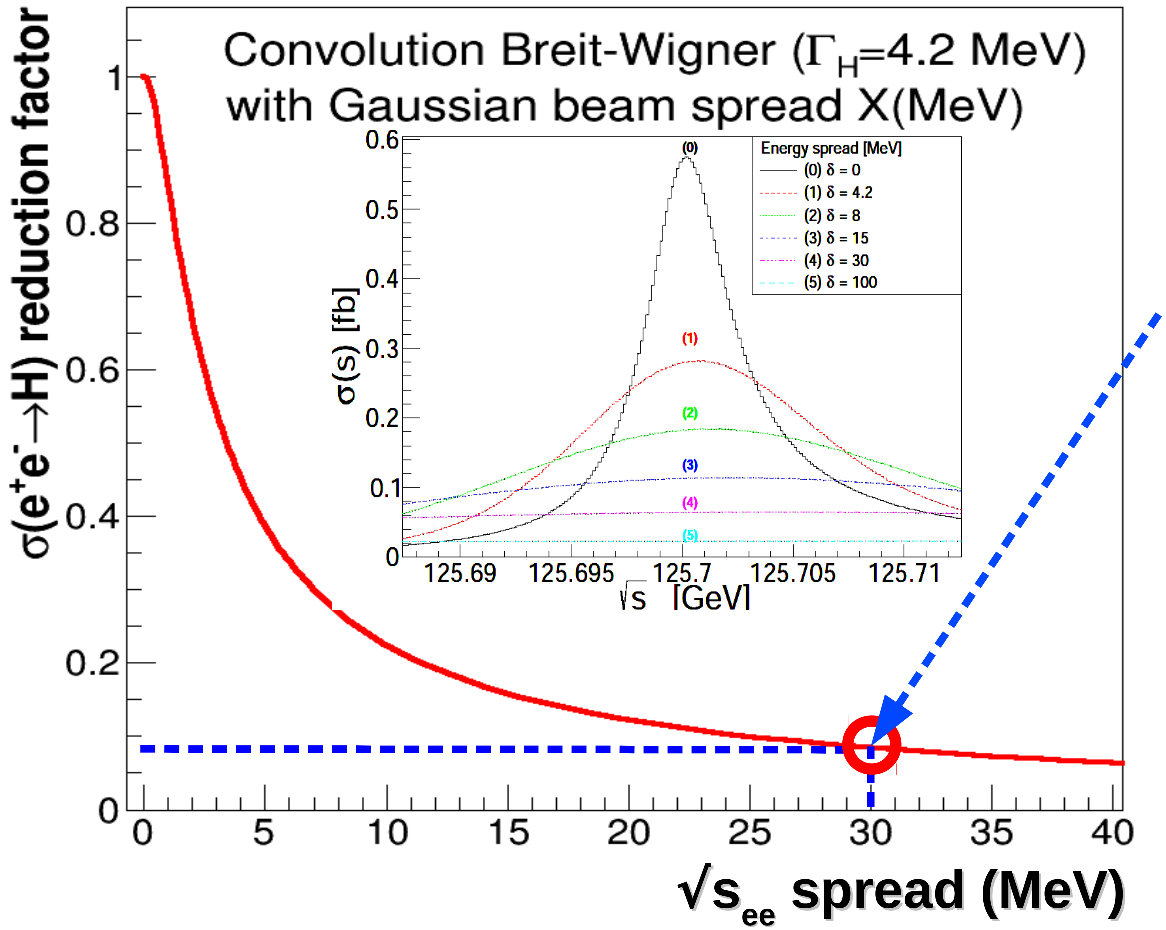


- Need to determine best monochromatization $\sqrt{s}_{spread}$, L_{int} working point.
- Fundamental unique physics accessible:
  → Electron Yukawa coupling: Limits ×100 (×30) better than HL-LHC (FCC-hh)
  → BSM electron Yukawa? Separation of BSM nearly-degen. H's?

Backup slides

“Actual” s-channel $e^+e^- \to H$ cross section

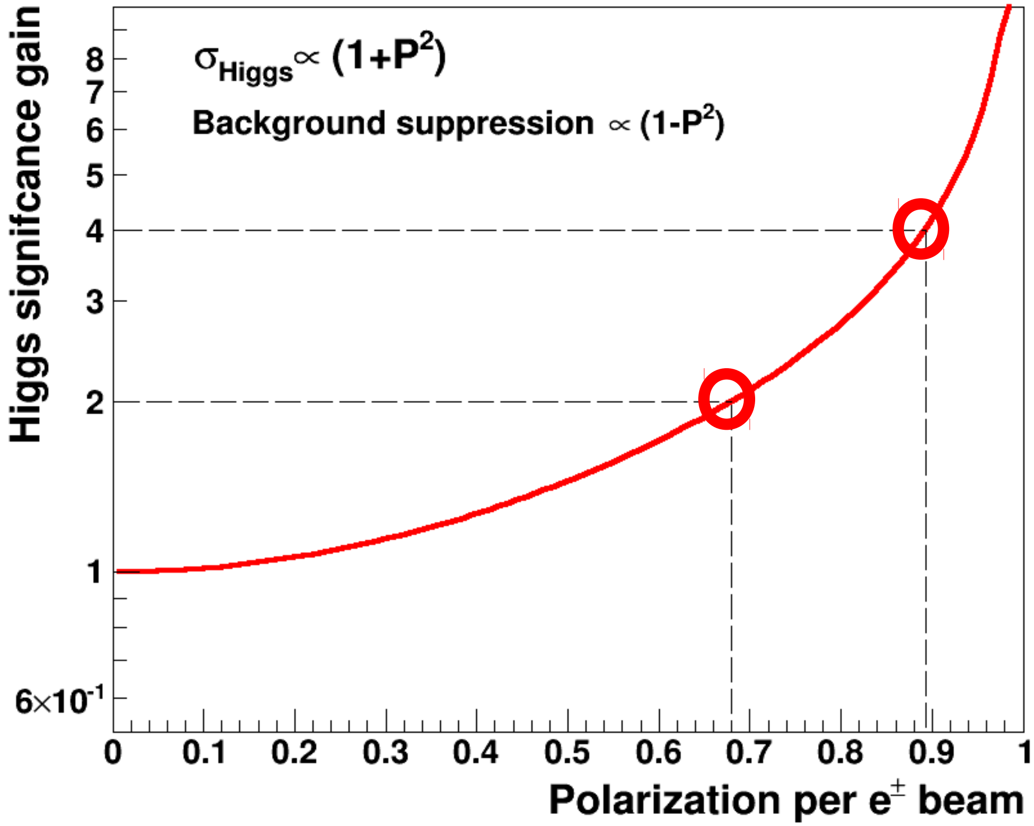
- $\sigma(e^+e^- \to H)$ = 1.64 fb for Breit-Wigner with natural Γ_H = 4.2 MeV width. But Higgs production greatly suppressed off resonant peak.
- Convolution of Gaussian energy spread of each $e^\pm$ beam with Higgs Breit-Wigner results on a (Voigtian) effective cross-section decrease:



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

Significance increase with polarized beams?

- Polarization of beams would enhance the signal by (1+Pol²) and suppress background by (1-Pol²). However, realistic longit. polarization estimates (Pol=20-30%) are clearly insufficient and higher polarizations would reduce luminosity...

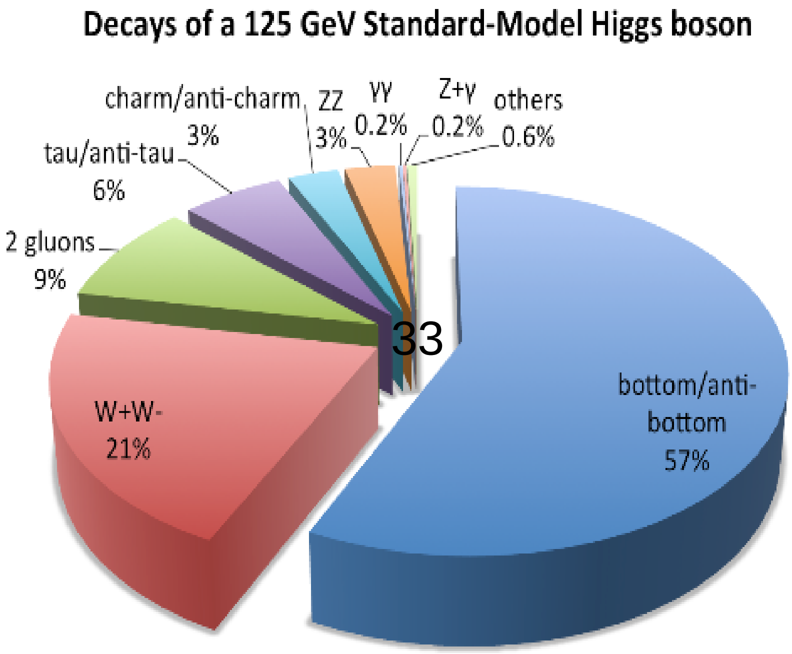


- Significance increase:

  Pol. = 68%: ×2 significance
  Pol. = 90%: ×4 significance

Higgs measurement at FCC-ee(125 GeV)

- Very-rare counting experiment over 10 decay channels:

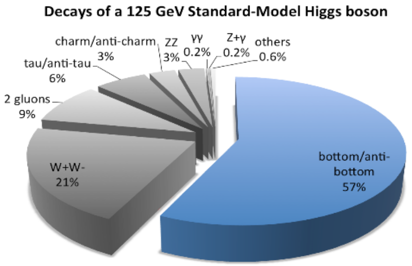


- *Other 2-jet final-state ($c\bar{c}$) swamped by $e^+e^- \to Z^*,\gamma^* \to cc$ (20 pb)*
- *Other 4-jet final-state (ZZ^*) swamped by $e^+e^- \to Z^*,\gamma^* \to q\bar{q}$ (100 pb), $e^+e^- \to WW^*,ZZ^*$ (20 fb)*
- *Rarer decays (4ℓ) have ~0 counts.*

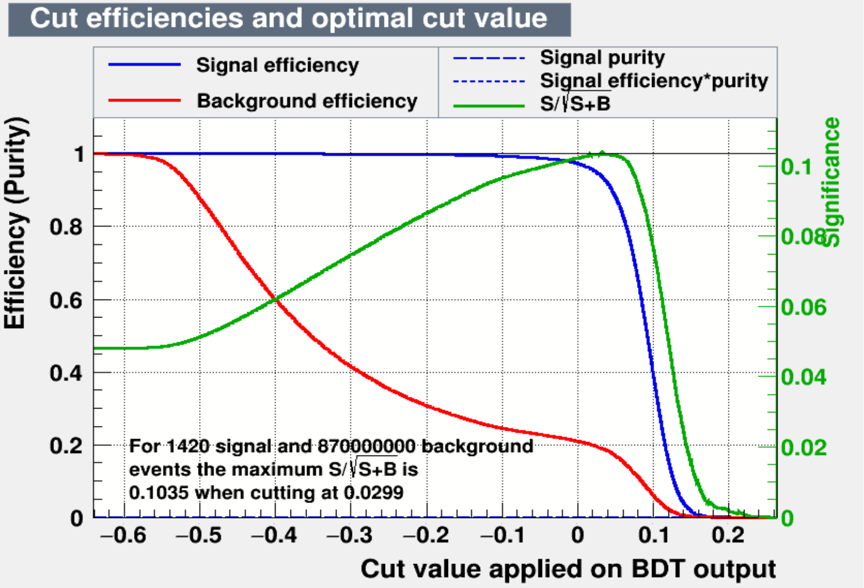
1) **$b\bar{b}$ (2 b-jets)**: σ = 156 ab
   Dominant bckgd (ee→$b\bar{b}$): σ=20 pb (S/B~10^{-5})
2) **WW* (4j)**: σ = 28 ab
   Dominant bckgd (ee→4j): σ=16 fb (S/B~10^{-3})
3) **WW* (2jlν)**: σ = 27 ab
   Dom. bckgd (ee→WW*): σ=20 fb (S/B~10^{-3})
4) **WW* (2l2ν)**: σ = 6.7 ab
   Dom. bckgd (ee→WW*): 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})

Channel 1: $e^+e^- \to H(bb) \to 2$ 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*γ*→bbar continuum



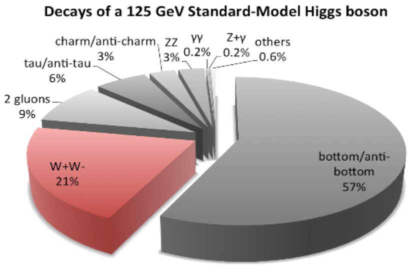
- Signal & backgds before/after MVA cuts:

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/√1.7e+8≈0.1
Significance ≈ 0.1

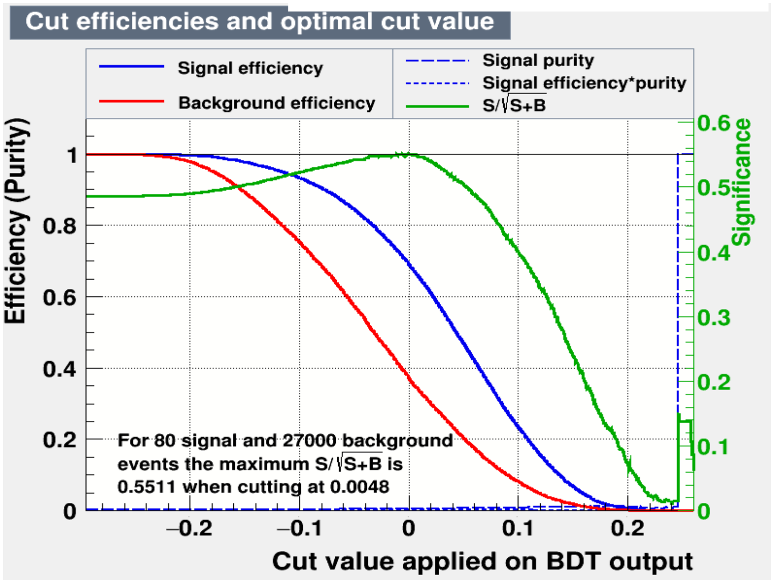
Channel 2: $e^+e^- \to H(WW^*) \to l\nu jj$

- 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/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 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/√B = 80/√27.e3 ≈ 0.5
Significance ≈ 0.5

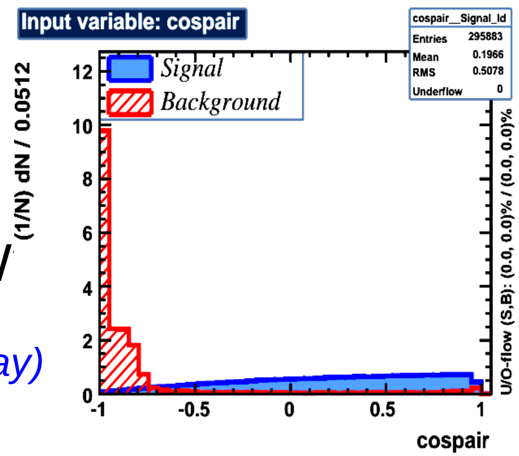
Channel 3: $e^+e^- \to H(WW^*) \to 2l2\nu$

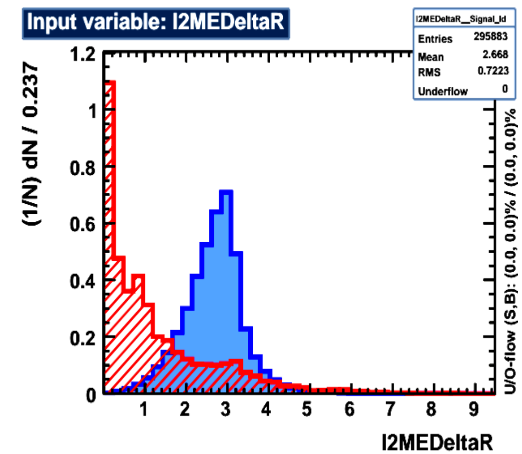
- Final state (retains 60% of $\sigma(WW^*(2l2\nu))$ = 7 ab):
  2 isolated $e,\mu,\tau(e),\tau(\mu)$ + ME > 2 GeV
  + 0 non-isolated leptons or ch.had.

- 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:

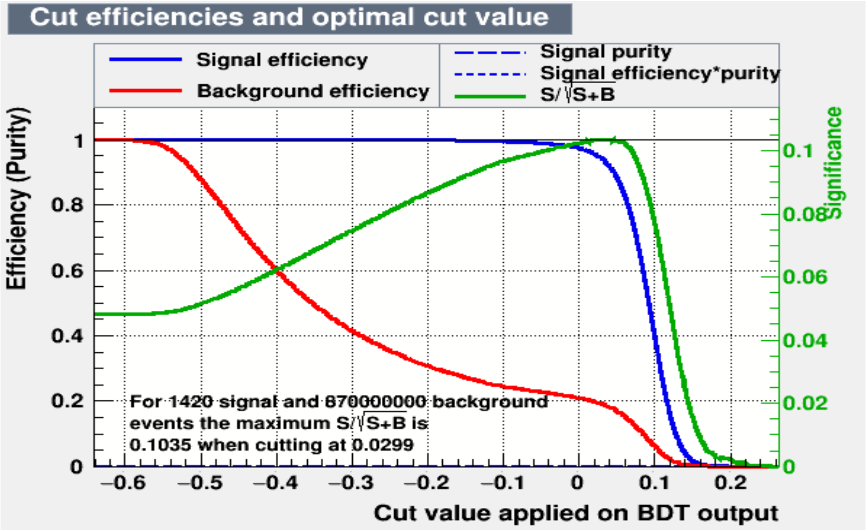
H(WW*):	σ = 4 ab	⇒ σ(after) = 2.1 ab
WW*:	σ = 2.9 fb	⇒ σ(after) = 454 ab
τ-τ:	σ = 3.1 pb	⇒ σ(after) = 51 ab
qqbar:	σ ~ 0 pb	⇒ σ(after) = 0 ab
ZZ*:	σ = 24 ab	⇒ σ(after) = 0.4 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 21/\sqrt{5000} \approx 0.3$
Significance ≈ 0.3

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

- Final state (retains 9% of $\sigma(WW^*(4j))$ = 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
  - ✓ $|\Delta\phi_{Z\ decay\ planes}| < 1.$
  - ✓ BDT MVA



- Signal & backgrounds before/after cuts:

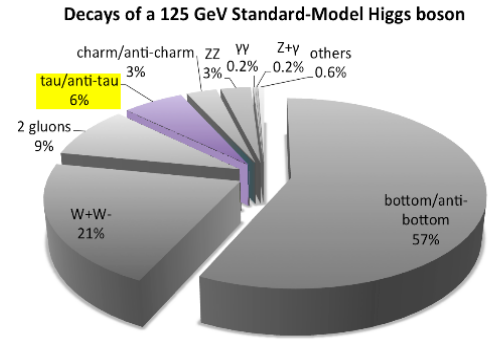
H(WW*):	σ = 2.75 ab ⇒	σ(after) = 1.4 ab
qqbar:	σ = 15.7 fb ⇒	σ(after) = 2 fb
WW*:	σ = 1.4 fb ⇒	σ(after) = 810 ab
τ-τ:	σ= 0 ab ⇒	σ(after) = 0 ab
ZZ*:	σ = 4 ab ⇒	σ(after) = 1.38 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 14/\sqrt{29.e3} \approx 0.08$
Significance $\approx$ 0.08

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

- 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 $Z^*/\gamma^* \rightarrow \tau\tau$ continuum.

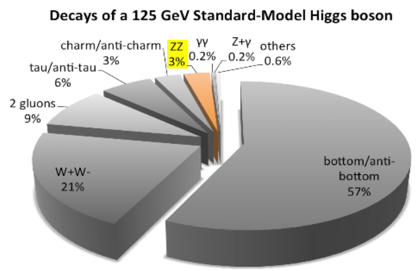
- Signal & backgds before/after MVA cuts:

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

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

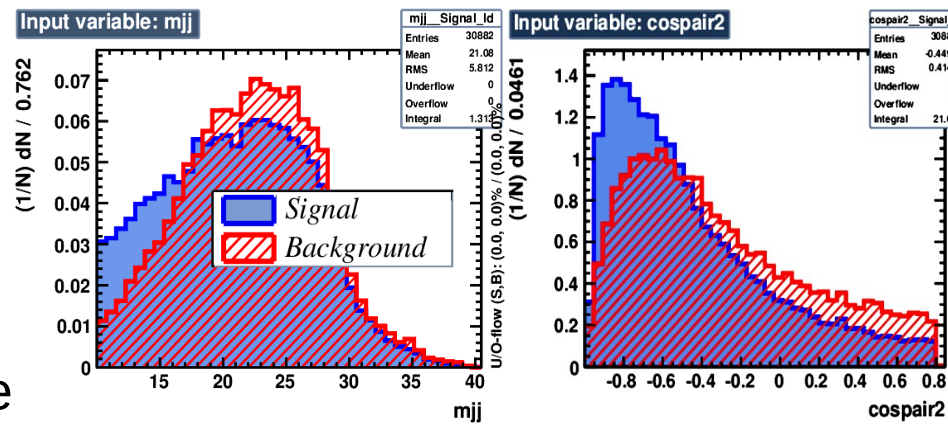
Channel 7: $e^+e^- \to H(ZZ^*) \to 2j2\nu$

- Final state (retains 75% of $\sigma(WW^*(2j2\nu))$ = 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
  - ✓ 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

(indicative distributions only: normalized to 1)



- Signal & backgrounds before/afte
  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

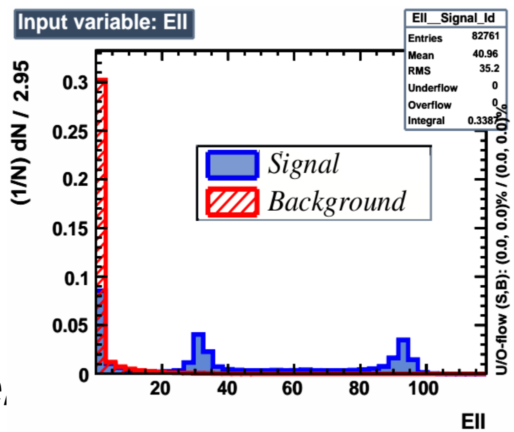
For $L_{int}=10\ ab^{-1}$
$S/\sqrt{B} = 3.7/\sqrt{316} \approx 0.21$
Significance ≈ 0.21

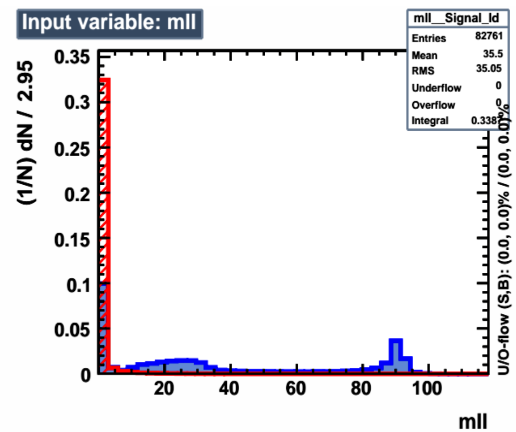
Channel 8: $e^+e^- \to H(ZZ^*) \to 2l2j$

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

- Kinematic cuts:
  ✓ min($|M_{ll}-M_Z|,|M_{jj}-M_Z|$)< 20GeV ← Kills qqbar, τ-τ
  ✓ ME < 10 GeV
  ✓ E_{lepton} > 6 GeV ← Kills τ-τ
  ✓ $E_{l1}+E_{l2}$ > 20 GeV ← Kills qqbar
  ✓ M_{ll} > 20 GeV/c^2 ← Kills qqbar
  ✓ M_{jj} > 10 GeV/c^2 ← Kills qqbar
  ← Kills τ-τ

(indicative distributions only: normalized to 1)





- Signal & backgrounds before

H(ZZ*):	σ = 0.84 ab	⇒	σ(after) = 0.27 ab
ZZ*:	σ = 87 ab	⇒	σ(after) = 23 ab
τ-τ:	$\sigma \sim$ 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

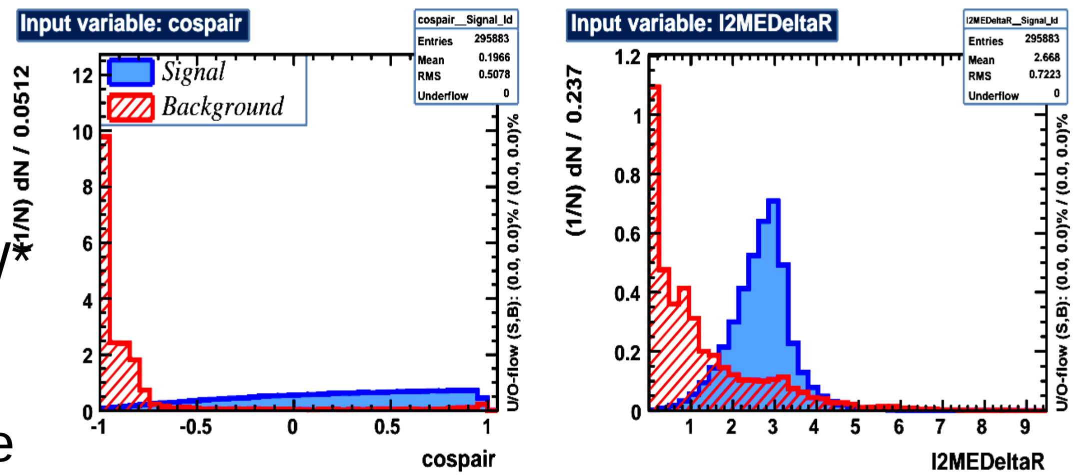
For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 2.7/\sqrt{296} \approx$ 0.16
Significance $\approx$ 0.16

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,μ,τ(e),τ(μ) + 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*

(indicative distributions only: normalized to 1)

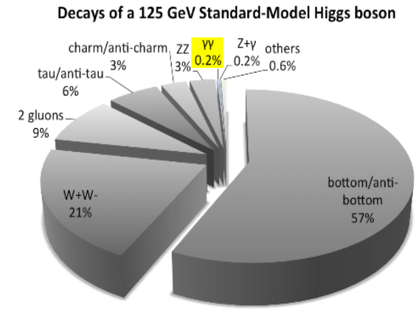


- Signal & backgds before/afte
  H(ZZ*): σ = 0.2 ab ⇒ σ(after) = 0.04 ab
  WW*: σ = 29 fb ⇒ σ(after) = 144 ab
  τ-τ: σ = 3.1 pb ⇒ σ(after) = 51 ab
  qqbar: σ ~ 0 pb ⇒ σ(after) = 0 ab
  ZZ*: σ = 24 ab ⇒ σ(after) = 9 ab

For L_{int}=10 ab^{-1}
$S/\sqrt{B} = 0.4/\sqrt{2000} \approx 0.01$
Significance ≈ 0.01

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

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



- Analysis cuts:

  ✓ E_γ > 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

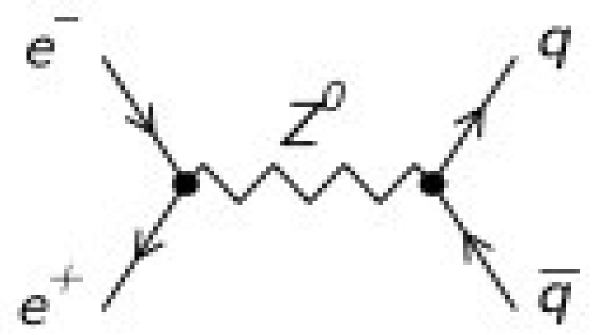
- Signal & backgds before/after cuts:

  H(γγ): σ = 0.61 ab ⇒ σ (after) = 0.3 ab
  γγ: σ = 25 pb ⇒ σ (after) = 900 fb
  e^+e^-: σ = 2.3 pb ⇒ σ (after) = 59 ab

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

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

- 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 ...