Electron Yukawa from s-channel $e^+e^- \to$ Higgs at FCC-ee

Snowmass Higgs EF01 WG

FNAL (online), 15th Sept. 2021

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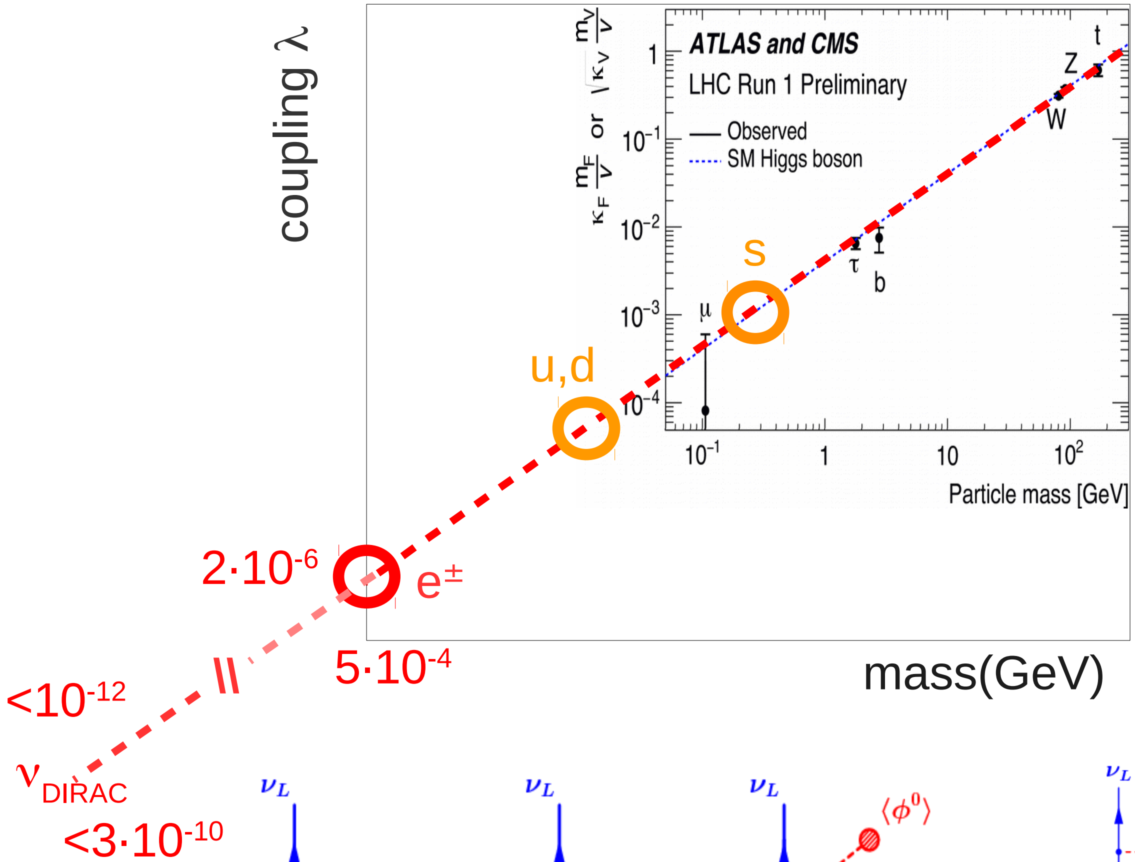
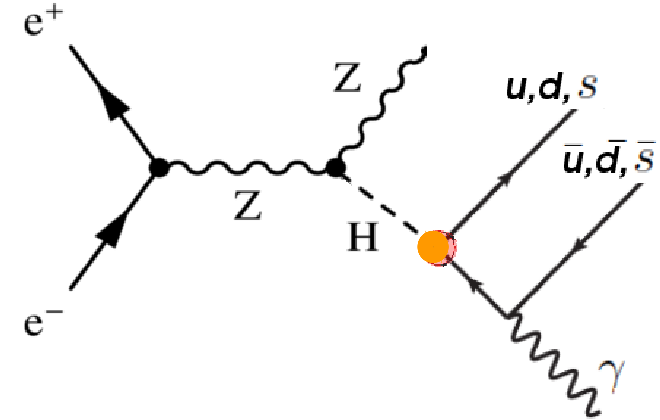
FCC

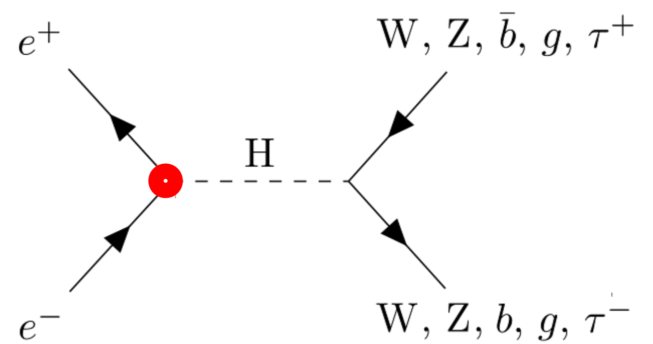
[More details in: arXiv:2107.02686]

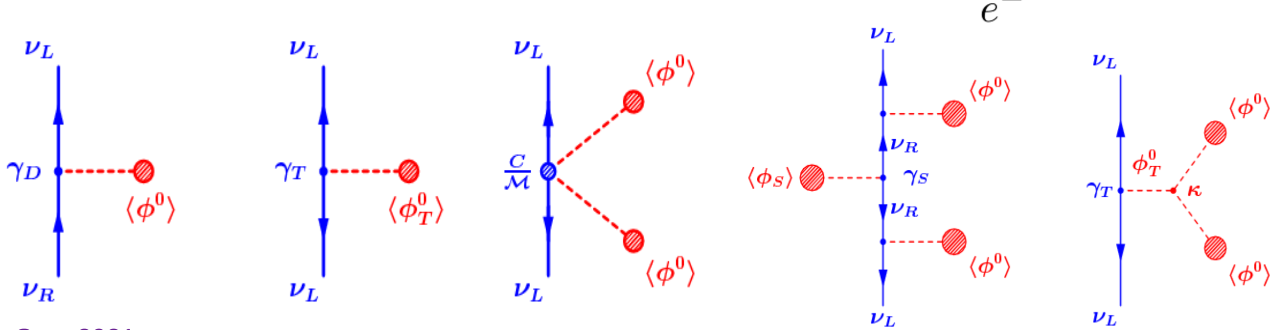
Generation of lightest fermion masses?

- 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?





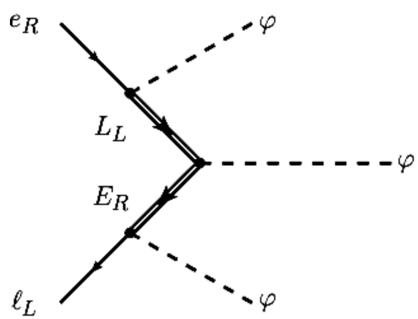




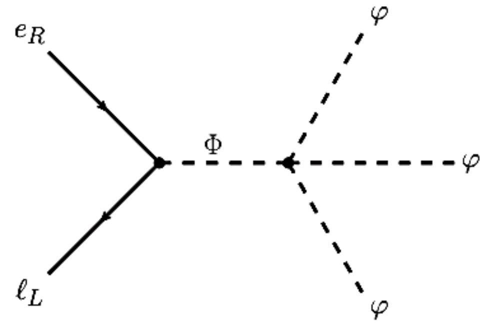
BSM electron Yukawa

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

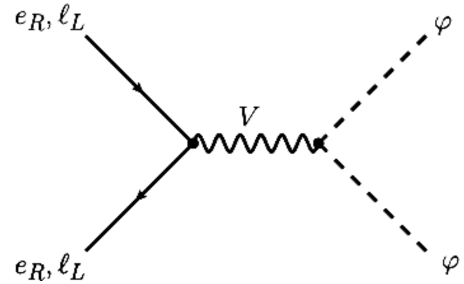
- Lowest order dim-6 operators with BSM electron Yukawa:



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:

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

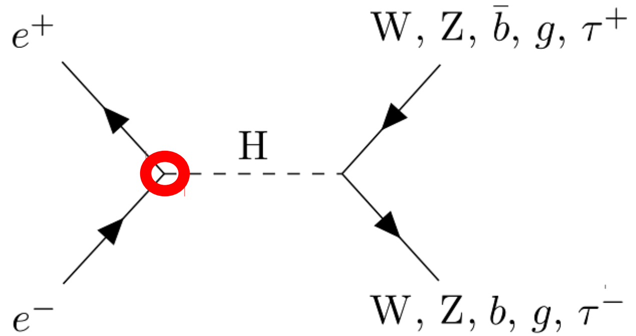
$h \to e^+e^-$	LHC8 (25/fb)	$\lvert\kappa_e\rvert \lesssim 600$	$M \gtrsim 6$ TeV
	LHC14 (300/fb)	$\lvert\kappa_e\rvert \sim 260$	$M \sim 9$ TeV
	LHC14 (3/ab)	$\lvert\kappa_e\rvert \sim 150$	$M \sim 12$ TeV
	100 TeV (3/ab)	$\lvert\kappa_e\rvert \sim 75$	$M \sim 17$ TeV
$e^+e^- \to h$	LEP II	$\lvert\kappa_e\rvert \lesssim 2000$	$M \gtrsim 3$ 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.

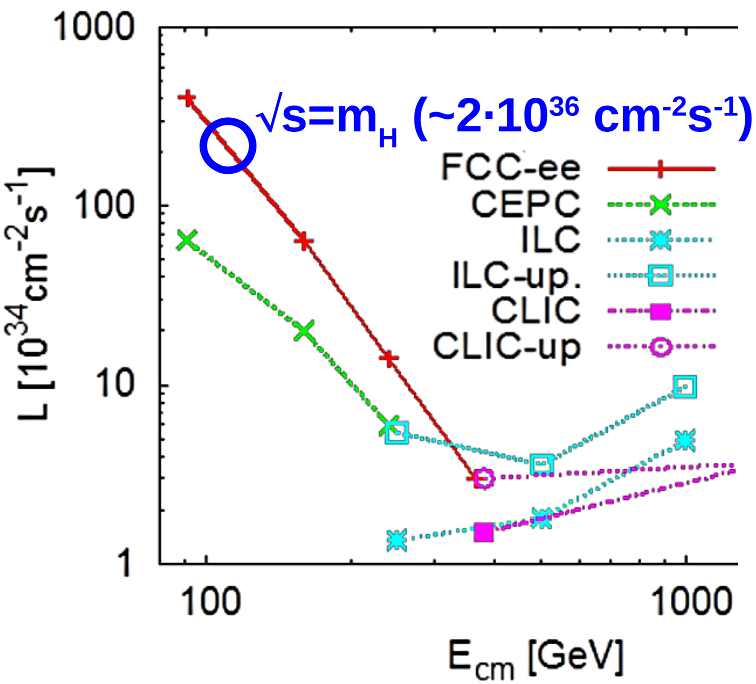
e Yukawa via s-channel $e^+e^- \to H$ production

- Higgs decay to e^+e^- is unobservable: $BR(H\to e^+e^-) \propto m_e^2 = 5.2\cdot 10^{-9}$
- 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=4.1 MeV)



- Huge luminosities available at FCC-ee:



In theory, FCC-ee running at H pole-mass $\mathcal{L}_{int}$ ≈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:

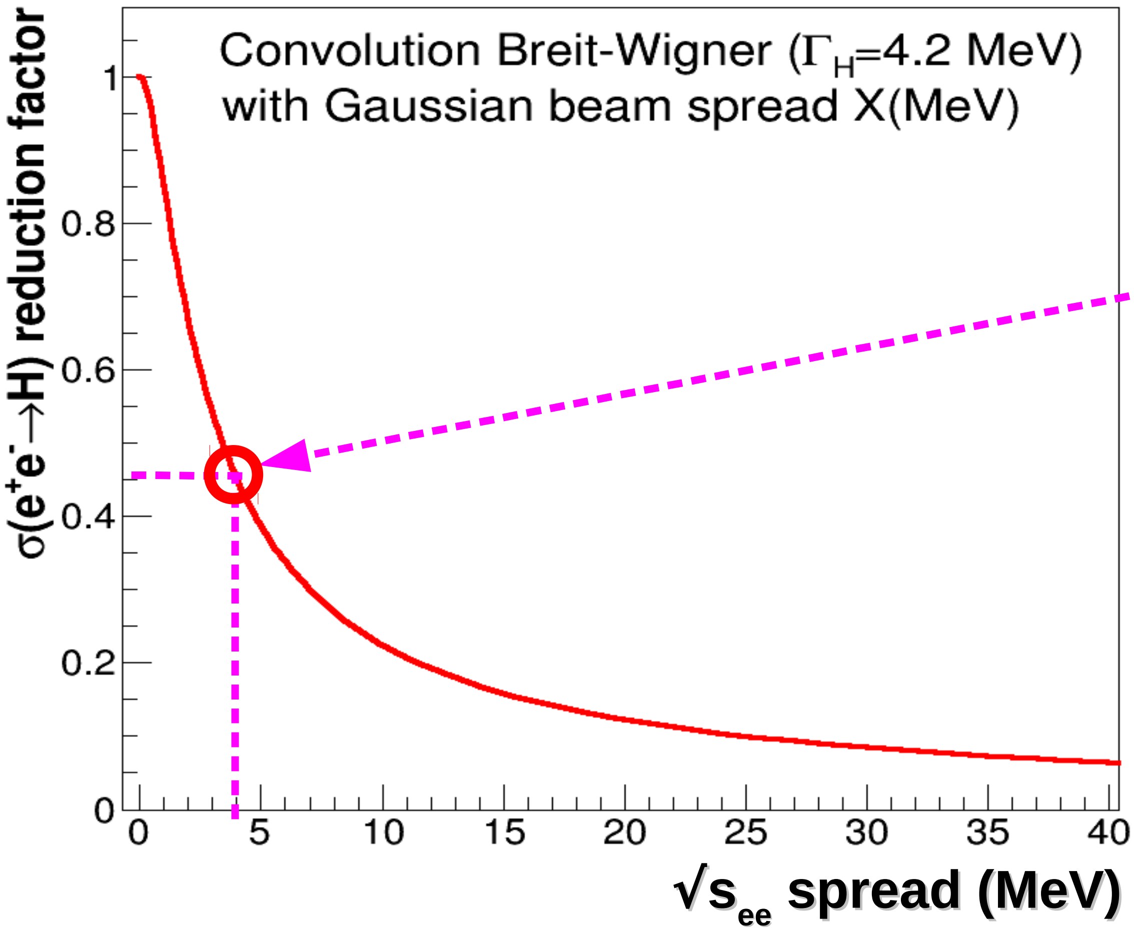
→ Electron Yukawa coupling measurable.

→ 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 = 4.1 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:



$\sqrt{s}_{spread} = \Gamma_H$ = 4.1 MeV

~45% x-section reduction

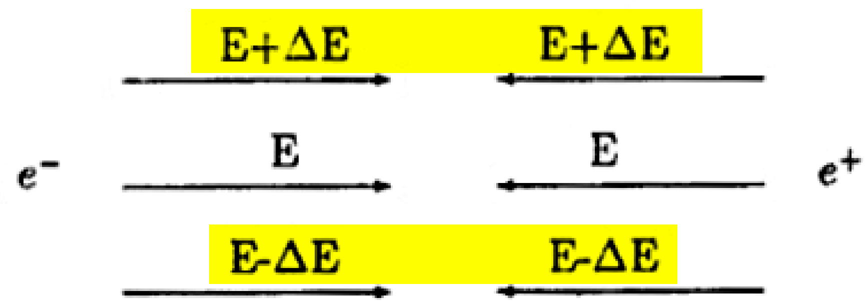
Reachable with beams monochromatization? (opposite sign dispersion using magnetic lattice) What luminosity loss price?

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

Beams monochromatization in e$^+$e$^-$ collisions

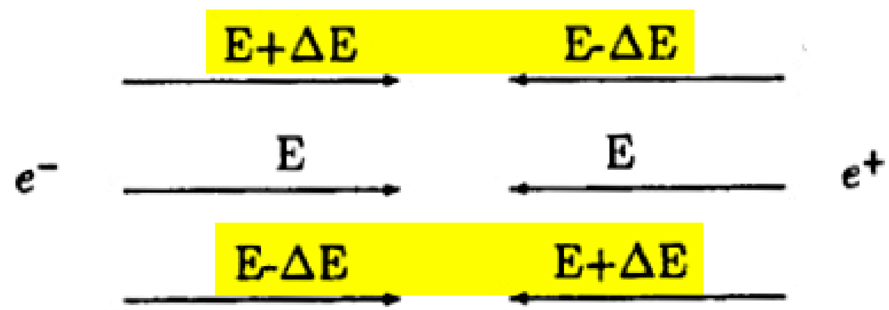
Standard collision:
dispersion has the same sign in the IP

$$w = 2\left(E_0 + \varepsilon\right)$$



Monochromatization:
dispersion has opposite sign in the IP

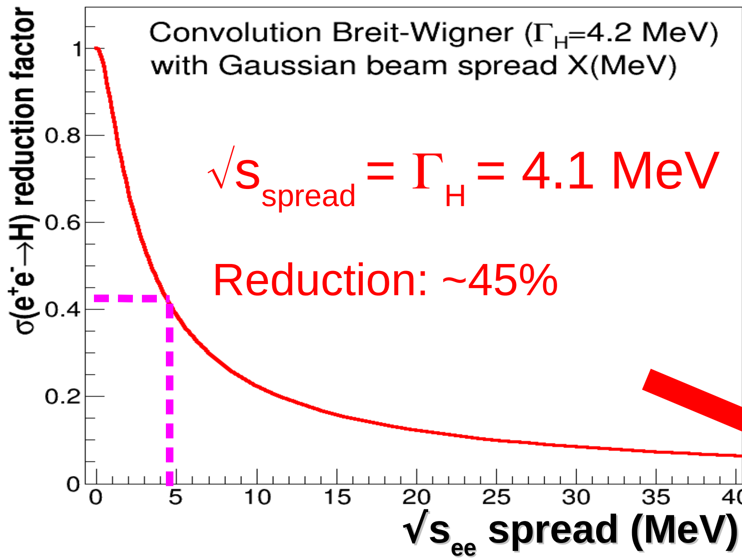
$$w = 2E_0 + 0(\varepsilon)^2$$



Enhancement of energy resolution, and sometimes increase of the relative frequency of the events at the centre of of the distribution.

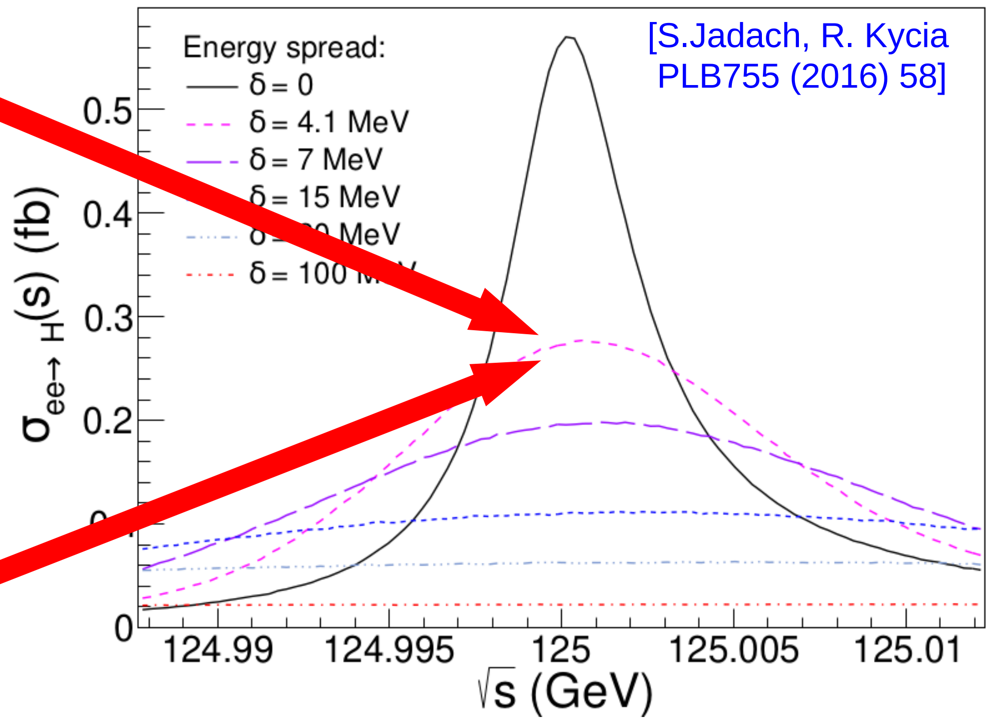
[F.Zimmermann, A.Valdivia:
JACoW-IPAC2017-WEPIK015
JACoW-IPAC2019-MOPMP035]

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

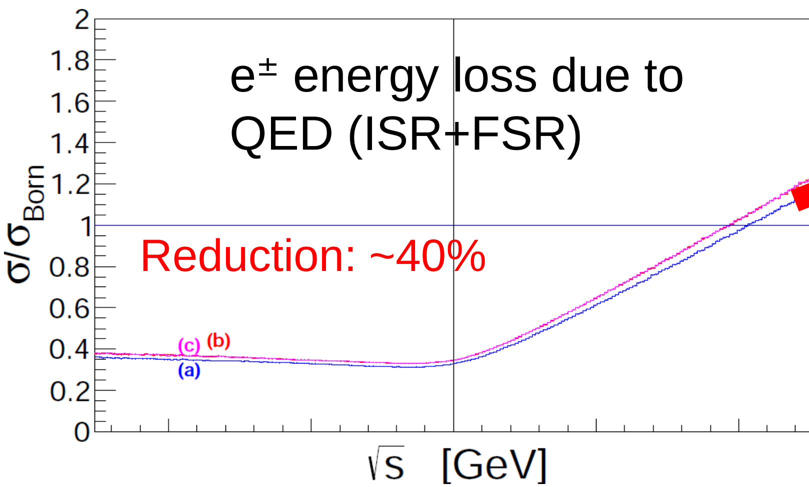


Assume monochromatization ref. point:
$\sqrt{s}_{spread} = \Gamma_H = 4.1$ MeV

- Full convolution of both effects:



- Extra ~40% reduction due to QED radiation:

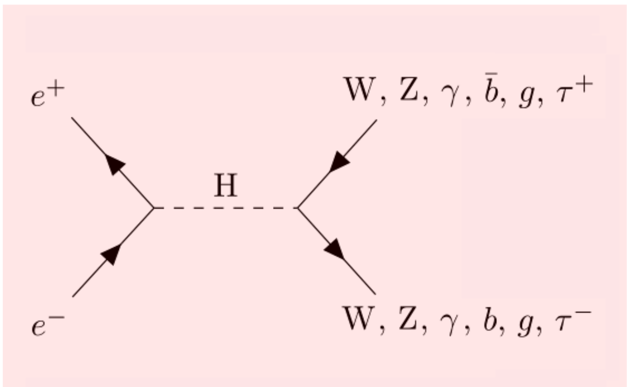


$\sigma_{spread+ISR}(e^+e^-\to H) = 0.17\times\sigma(e^+e^-\to H) = 280$ ab

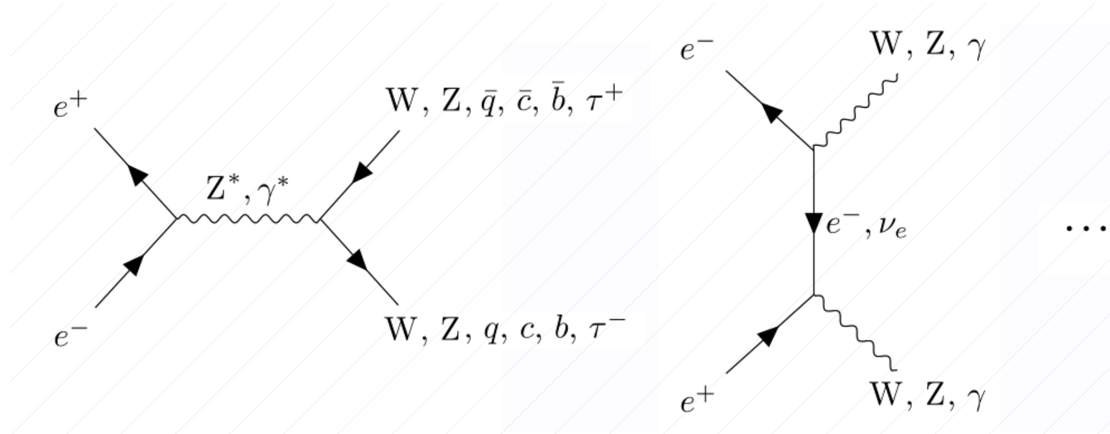
Signal & backgrounds simulation

- PYTHIA8 e^+e^- at $\sqrt{s} = m_H = 125$ GeV to generate 10 final-states for Higgs signal plus backgrounds:

SIGNALS



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

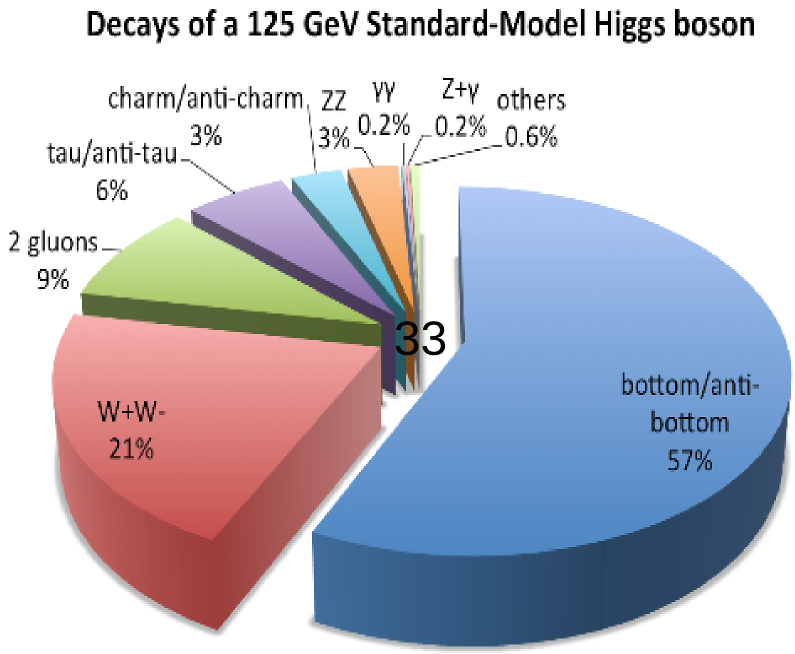


(other SM loop-induced $e^+e^- \rightarrow H$ found negligible)

- 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,...
- ISR switched-on in PY8, $\sqrt{s}_{spread}$ via scaling to match $\sigma(e^+e^- \rightarrow H)$=280 ab

Higgs measurement at FCC-ee(125 GeV)

- Very-rare counting experiment over 10 decay channels:



Higgs decay channel	BR	$\sigma\times$ 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

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

- *Other 4-jet final states, e.g. $H\to ZZ^*(4j)$ swamped by $e^+e^-\to Z^*,\gamma^*\to q\bar{q}$ (100 pb),*
- *Rarer decays (4ℓ) have ~0 counts.*

Event reconstruction, preselection, MVA

- Signal & backgd events showered/hadronized/decayed with PYTHIA8.
  Final-state particles acceptance: 5°< θ < 175°.
  Jet reco: k_T algorithm for N_j=2,4 exclusive jets. Isolation: ΣE<1 GeV, ΔR<0.25
- Assumed reconstruction (in)efficiencies for jets (uds, g, c, b), tau, γ, e:

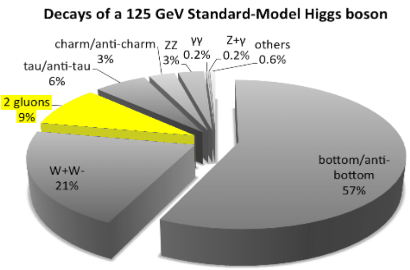
	b jets	c jets	gluon jets	$\tau_{\rm had}$ (hadron decays)	$\gamma, e^{\pm}$
reco/tagging efficiency (ε_i)	80%	70%	70%	80%	100%
mistagging rates ($\varepsilon_{j\to i}^{\rm mistag}$)	1% (for c jet)	5% (for b jet)	1% (for uds jets)	∼0% (for b,c-jets)	0.01% ($e^{\pm}$ for γ)
	0.01% (for $udsg$ jets)	0.1% (for $udsg$ jets)	0.001,0.01% (for b,c-jets)	∼0% (for $udsg$ jets)	

- Final-state Higgs signal definitions (preselection to eliminate reducible backgds):

Target Higgs decay	Final state definition	Signal presel. efficiency
$\mathrm{H}\to b\bar{b}$	2 (excl.) jets, 1 b-tagged jet, no $\tau_{\rm had}$	80%
$\mathrm{H}\to gg$	2 (excl.) gluon-tagged jets, 0 isolated $\ell^{\pm}$	50%
$\mathrm{H}\to \tau_{\rm had}\tau_{\rm had}$	Exactly 2 $\tau_{\rm had}$, 0 isolated $\ell^{\pm}$	65%
$\mathrm{H}\to c\bar{c}$	2 (excl.) jets, 1 c-tagged jet, no $\tau_{\rm had}$	70%
$\mathrm{H}\to \mathrm{WW}^*\to \ell\nu 2j$	1 isolated $\ell^{\pm}$, $E_{\rm miss}>2$ GeV, 2 (excl.) jets	∼100%
$\mathrm{H}\to \mathrm{WW}^*\to 2\ell 2\nu$	2 isolated opp.-charge $\ell^{\pm}$, $E_{\rm miss}>2$ GeV, 0 non-isol. $\ell^{\pm}$, 0 charged hadrons	∼100%
$\mathrm{H}\to \mathrm{WW}^*\to 4j$	4 (excl.) jets, ≥ 1 c-tag jets, 0 b-,g-tag jets; jets with $m_{j1j2}\approx m_{\rm W}$ not both c-tagged, 0 $\tau_{\rm had}$, 0 isolated $\ell^{\pm}$	70%
$\mathrm{H}\to \mathrm{ZZ}^*\to 2j2\nu$	2 (excl.) jets, $E_{\rm miss}>30$ GeV, 0 isolated $\ell^{\pm}$, 0 $\tau_{\rm had}$	∼100%
$\mathrm{H}\to \mathrm{ZZ}^*\to 2\ell 2j$	2 isolated opposite-charge $\ell^{\pm}$, 2 (excl.) jets, 0 $\tau_{\rm had}$	∼100%
$\mathrm{H}\to \mathrm{ZZ}^*\to 2\ell 2\nu$	2 isolated opp.-charge $\ell^{\pm}$, $E_{\rm miss}>2$ GeV, 0 non-isol. $\ell^{\pm}$, 0 charged hadrons	∼100%
$\mathrm{H}\to \gamma\gamma$	2 (excl.) isolated photons	∼100%

- MVA with O(50) variables for kinematical properties of each single, pair, (n-wise combinations) of physics objects, global event vars., MELA vars.,...

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

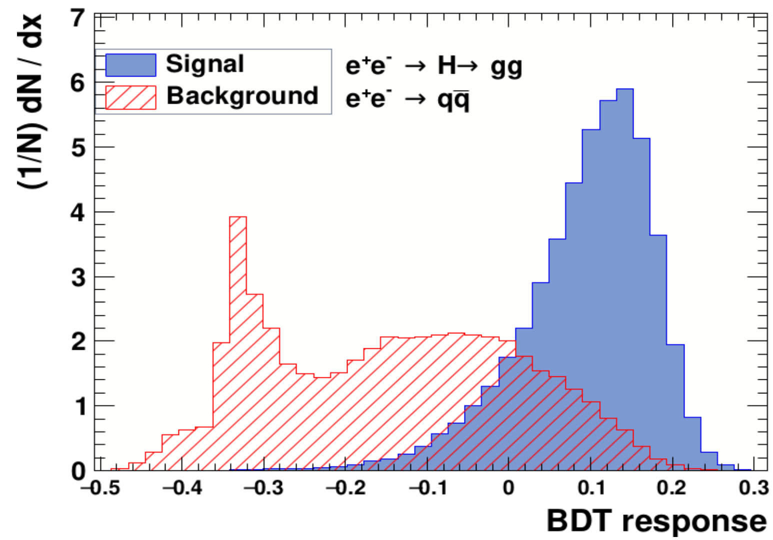


- Final state definition (retains 50% of σ(gg) = 24 ab):

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

- BDT MVA result (removing jet vars. potentially already used in g-uds discrimination):

  Signal reduction ~50%
  Backgd. reduction: x17



- Signal & backgrounds cross sections cut flow:

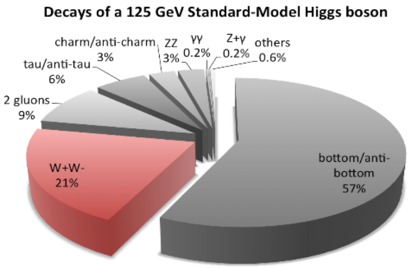
Process	Events	Passes	+ cuts	+ MVA	raw σ	Tagrate	Pass+Tag	+ Cut	Final σ
Hgg	100000	85315	80350	45440	25 ± 0 ab	$70\%^2$	10 ab	9.7 ab	5.5 ± 0.0 ab
bb	199981	140057	12532	1331	81 ± 0 pb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb
cc	200000	174120	28282	1984	73 ± 0 pb	$0.0\%^2$	0 pb	0 pb	0 ± 0 pb
qq	200000	186171	36888	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 $\mathscr{L}_{int}$=10 ab^{-1}
$S/\sqrt{B} = 55/\sqrt{2500} \approx 1.1$
Significance $\approx$ 1.1

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

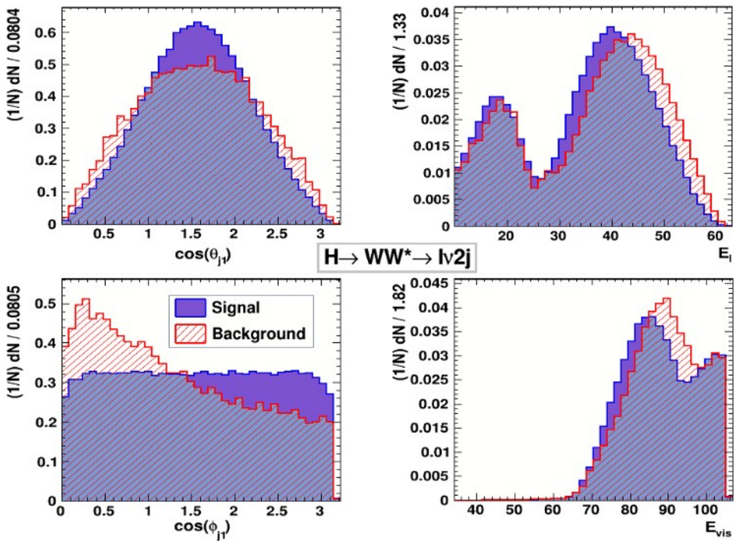
- Final state def. (retains ~100% of $\sigma(WW^*(l\nu jj))$ = 27 ab):
  1 isolated e,μ,τ(e),τ(μ) + ME>2 GeV + 2 jets (excl.)



- Analysis cuts (from MVA):

✓ $E_{j1,j2}$ < 52,45 GeV $\Longleftarrow$ Kills $e^+e^- \to q\bar{q}$
✓ $m_{w(l\nu)}$ > 12 GeV/c² $\Longleftarrow$ 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/c² $\Longleftarrow$ Kills $e^+e^- \to \tau\tau$

✓ BDT MVA ← Kills $e^+e^- \to WW^*$ continuum
(exploits opposite $W^\pm$ polarizations in H decay)



- Signal & backgrounds cross sections cut flow:

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 $\mathscr{L}_{int}$=10 ab^{-1}
$S/\sqrt{B} = 55/\sqrt{11000} \approx 0.5$
Significance $\approx$ 0.5

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

- Number of presel. & MVA events per channel for signal & backgrounds:

Table 4. Number of reconstructed events expected after preselection N(presel.) and BDT output N(MVA) cuts, for s-channel Higgs decay modes and associated dominant backgrounds in e^+e^- collisions at $\sqrt{s} = m_H$ ($\delta_{\sqrt{s}} = 4.1$ MeV and $\mathcal{L}_{\rm int} = 10\,{\rm ab}^{-1}$).

Channel	N(presel.)	N(MVA)	Channel	N(presel.)	N(MVA)	Channel	N(presel.)	N(MVA)
$H \to b\bar{b}$	1320	1220	$H \to gg$	110	55	$H \to \tau_{had}\tau_{had}$	48	13
$e^+e^- \to b\bar{b}$	$1.5 \cdot 10^8$	$1.1 \cdot 10^8$	$e^+e^- \to q\bar{q}$	61 000	2400	$e^+e^- \to \tau_{had}\tau_{had}$	$2.7 \cdot 10^7$	$3.8 \cdot 10^5$
$e^+e^- \to c\bar{c}$	$1.4 \cdot 10^6$	$9.4 \cdot 10^5$	$e^+e^- \to c\bar{c}$	220	$\sim$10			
$e^+e^- \to q\bar{q}$	$3.0 \cdot 10^4$	4800	$e^+e^- \to b\bar{b}$	20	$\sim$1			
$H \to WW^* \to \ell\nu 2j$	265	55	$H \to WW^* \to 2\ell 2\nu$	64	25	$H \to WW^* \to 4j$	180	27
$e^+e^- \to WW^* \to \ell\nu 2j$	$2.3 \cdot 10^5$	11 000	$e^+e^- \to WW^* \to 2\ell 2\nu$	$5.6 \cdot 10^4$	7600	$e^+e^- \to WW^* \to 4j$	$1.3 \cdot 10^5$	14 000
$e^+e^- \to b\bar{b}$	1100	–	$e^+e^- \to ZZ^* \to 2\ell 2\nu$	1360	$\sim$5	$e^+e^- \to ZZ^* \to 4j$	$4.7 \cdot 10^3$	20
$e^+e^- \to c\bar{c}, q\bar{q}$	150	–	$e^+e^- \to \tau\tau$	$1.2 \cdot 10^7$	–	$e^+e^- \to b\bar{b}, c\bar{c}$	$5 \cdot 10^5$	7 000
$H \to ZZ^* \to 2j 2\nu$	21	11	$H \to ZZ^* \to 2\ell 2j$	10	4	$H \to ZZ^* \to 2\ell 2\nu$	3	0.8
$e^+e^- \to ZZ^* \to 2j 2\nu$	2700	1000	$e^+e^- \to ZZ^* \to 2\ell 2j$	1000	500	$e^+e^- \to ZZ^* \to 2\ell 2\nu$	270	70
$e^+e^- \to WW^* \to 2j 2\nu$	6100	400	$e^+e^- \to WW^* \to 2\ell 2j$	$3.3 \cdot 10^4$	$\sim$1	$e^+e^- \to WW^* \to 2\ell 2\nu$	$3.3 \cdot 10^4$	260
$e^+e^- \to b\bar{b}, c\bar{c}, q\bar{q}$	7000	–	$e^+e^- \to b\bar{b}, c\bar{c}, q\bar{q}$	400	–	$e^+e^- \to b\bar{b}, c\bar{c}, q\bar{q}$	390	–
$e^+e^- \to \tau\tau$	1700	$\sim$2				$e^+e^- \to \tau\tau$	$3 \cdot 10^4$	–

- Channels significance & combination via RooStats-based LHC Higgs tool: Profile likelihood & hybrid significances give ~identical results, which are also very close to naive S/√B expectation (10^{-4} backgd. relative uncertainty):

$H \to gg$	$H \to WW^* \to \ell\nu\, 2j;\ 2\ell\, 2\nu;\ 4j$	$H \to ZZ^* \to 2j\, 2\nu;\ 2\ell\, 2j;\ 2\ell\, 2\nu$	$H \to b\bar{b}$	$H \to \tau_{had}\tau_{had};\ c\bar{c};\ \gamma\gamma$	Combined
1.1σ	$(0.53 \otimes 0.34 \otimes 0.13)\sigma$	$(0.32 \otimes 0.18 \otimes 0.05)\sigma$	0.13σ	$< 0.02\sigma$	1.3σ

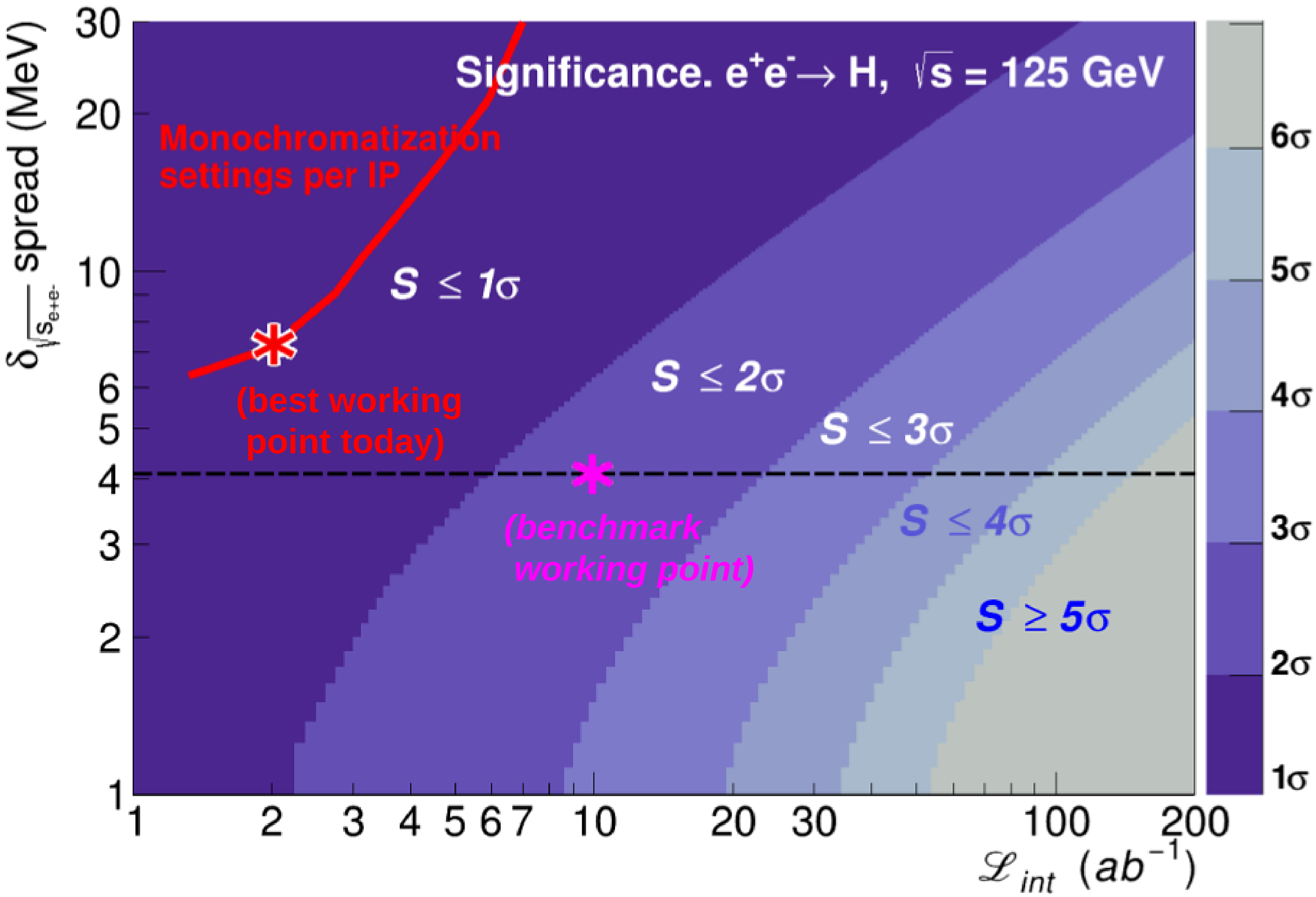
- For $\mathscr{L}_{\rm int}$ = 10 ab^{-1}: Significance ≈ 1.3σ

  Limit (95% CL) for SM Yukawa: $y_e < 1.6\times\, y_{e,SM}$

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

$e^+e^- \to H$ significance contours in ($\sqrt{s}_{spread}$, $\mathscr{L}_{int}$) plane

- Monochromatization working points ($\sqrt{s}_{spread}$ vs. $\mathscr{L}_{int}$ per IP/year):

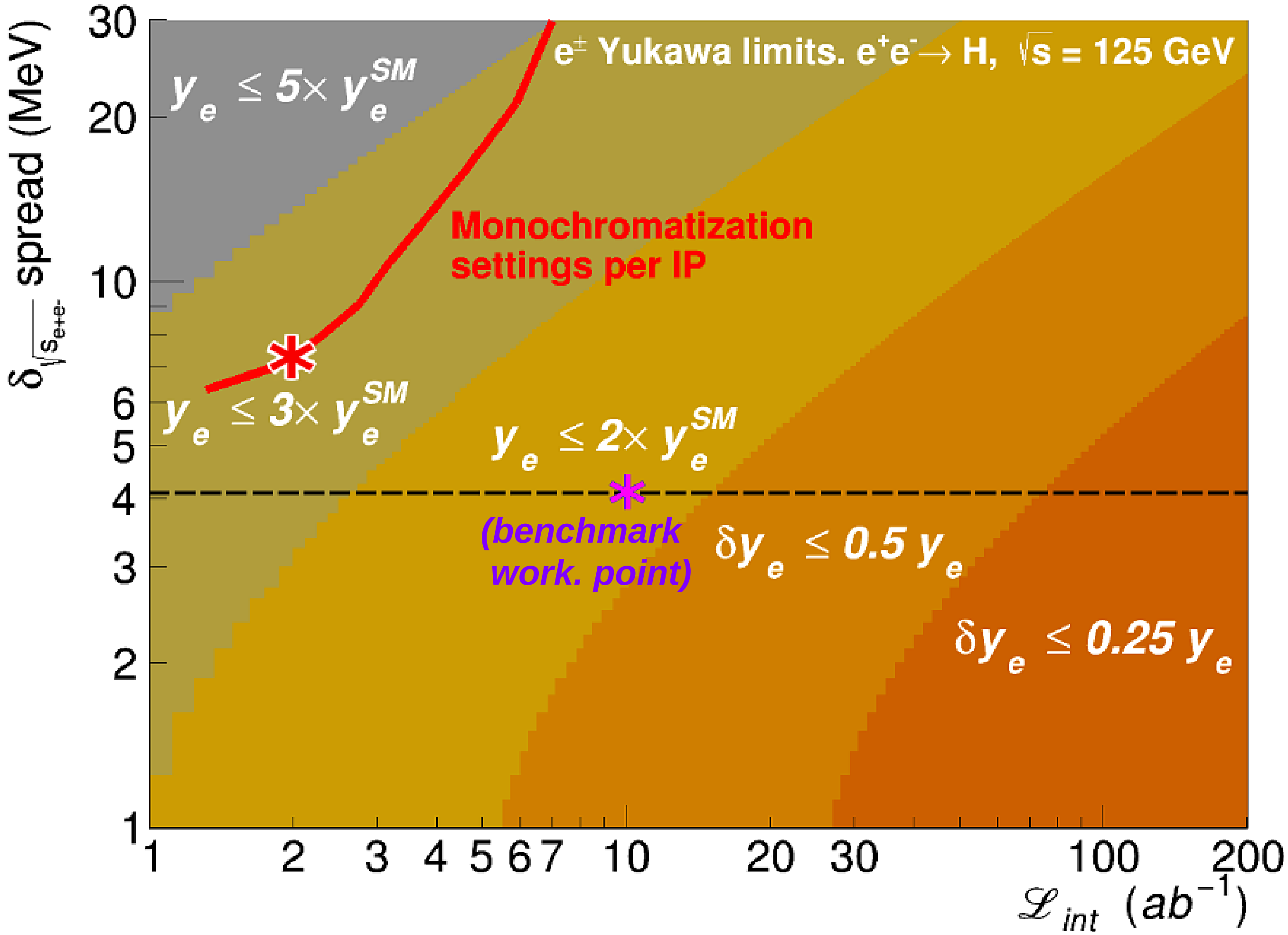


[Monochromatization studies: Valdivia-Zimmermann]

- Best significance ≈ 0.4σ in ($\sqrt{s}_{spread}$ = 7–10 MeV, $\mathscr{L}_{int}$=2–3 ab^{-1}) region.

Electron Yukawa limits in ($\sqrt{s}_{spread}$, $\mathscr{L}_{int}$) plane

- Monochromatization working points ($\sqrt{s}_{spread}$ vs. $\mathscr{L}_{int}$ per IP/year):

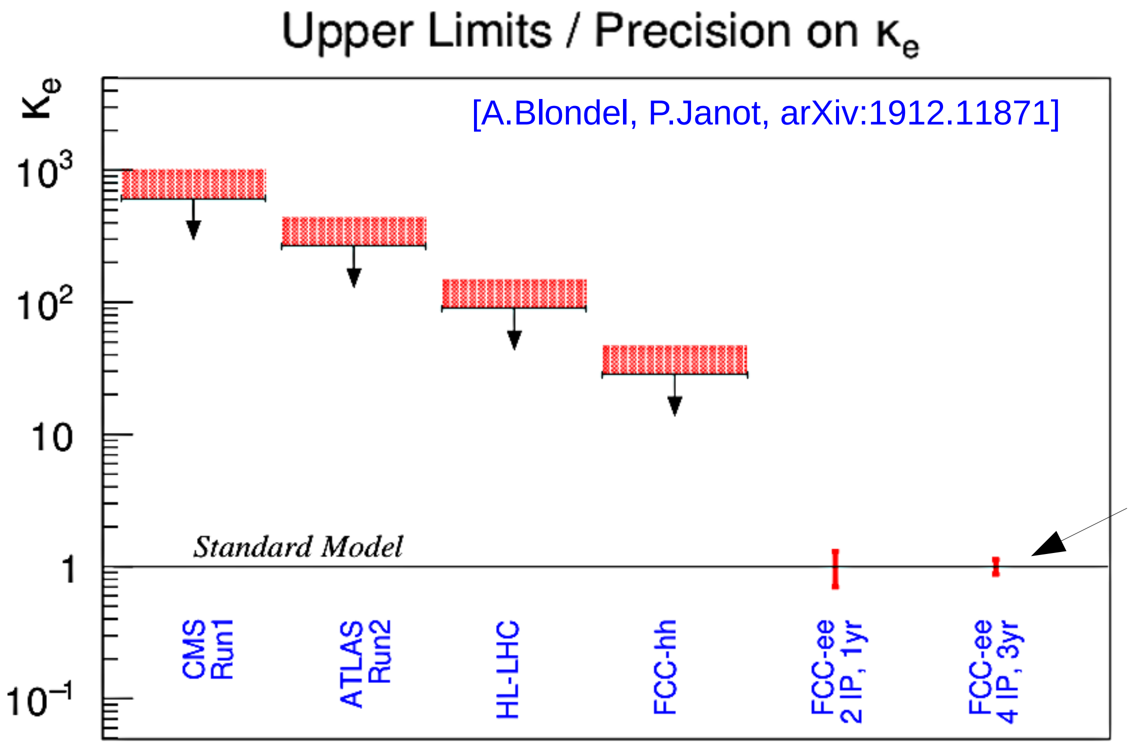


[Monochromatization studies: Valdivia-Zimmermann]

- Best limit: $y_e < 2.5 \times y_{e,SM}$ (95% CL) in ($\sqrt{s}_{spread}$ = 7–10 MeV, $\mathscr{L}_{int}$=2–3 ab^{-1}) region.

Electron Yukawa limits at various machines

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

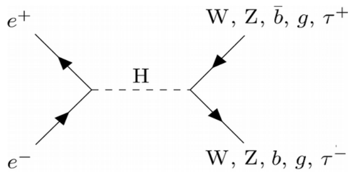


(Note: more optimistic $\sqrt{s}$ spread and $\mathscr{L}_{int}$ WP assumed here)

- Combining up to 4 IPs & running a few years we are at SM y_e values.
- Limits on y_e are ×100 (×30) better than at HL-LHC (FCC-hh).

Conclusions

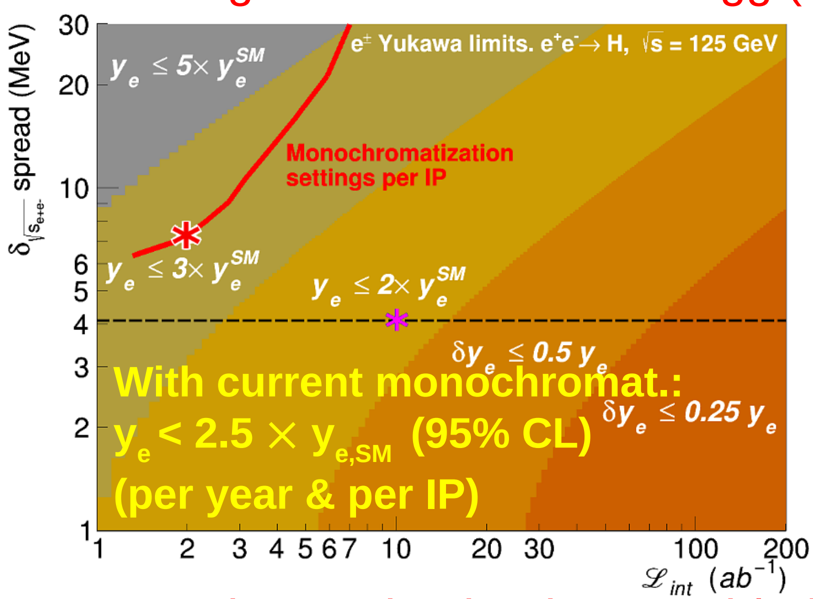
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s}$ = 125.00 GeV):



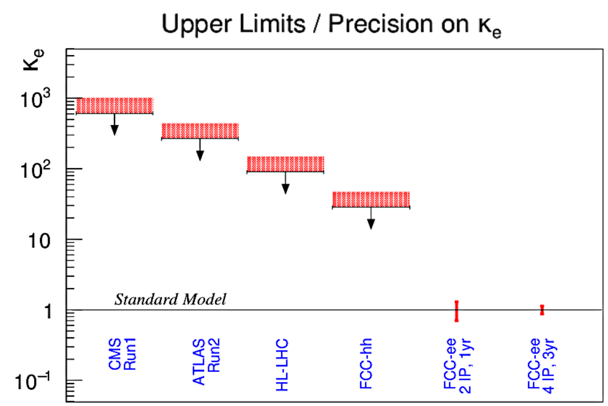
$\sigma(e^+e^-\to H)_{B\text{-}W}$ = 1.64 fb

$\sigma(e^+e^-\to H)_{spread}$ = 280 ab (ISR + $\sqrt{s}_{spread} = \Gamma_H$ = 4.2 MeV)

- Prerequisite: Higgs mass extraction $\delta m_H = O$(3 MeV) via HZ @ 240,217 GeV
- Generator-level 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



- Monochromatization improvable beyond ($\sqrt{s}_{spread}$, $\mathscr{L}_{int}$)≈(7 MeV, 2 ab^{-1})?
- Fundamental unique physics accessible:
  → Electron Yukawa coupling: Limits ×100 (×30) better than HL-LHC (FCC-hh)
  → BSM scale affecting e$^\pm$ Yukawa pushed up to Λ_{BSM} > 110 TeV

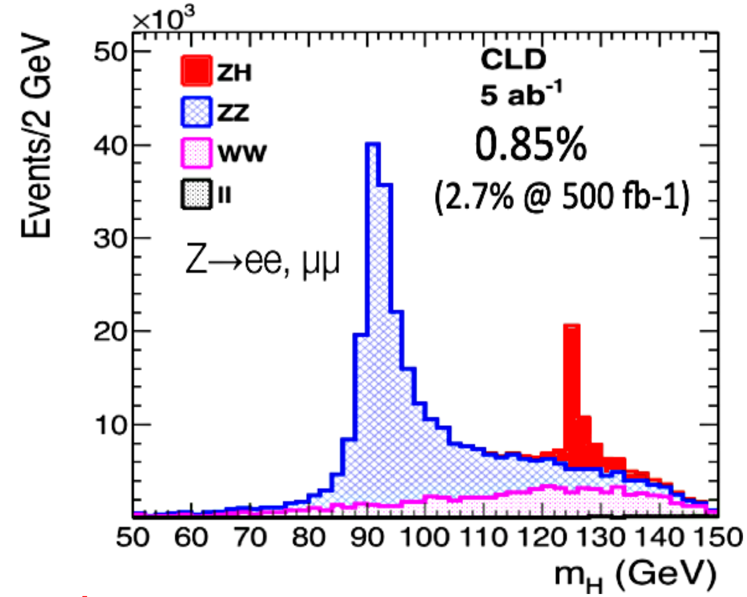
Backup slides

Accurate m_H needed to run at resonant peak

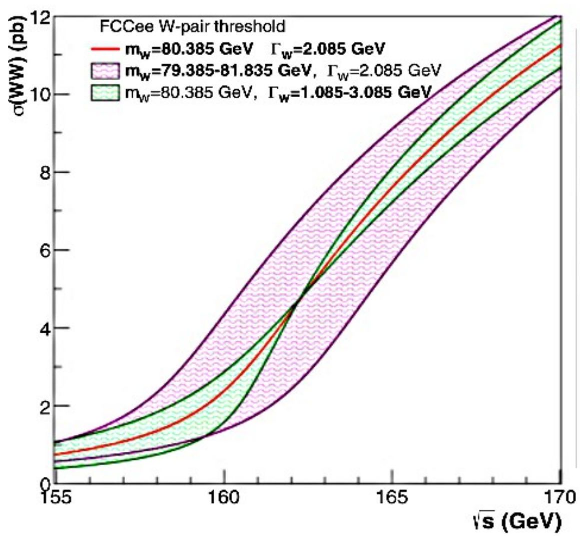
- $e^+e^- \to H$ Z(l^+l^-) recoil method: allows Higgs mass reconstruction with δm_H = 8 MeV in $Z \to \mu^+\mu^-$

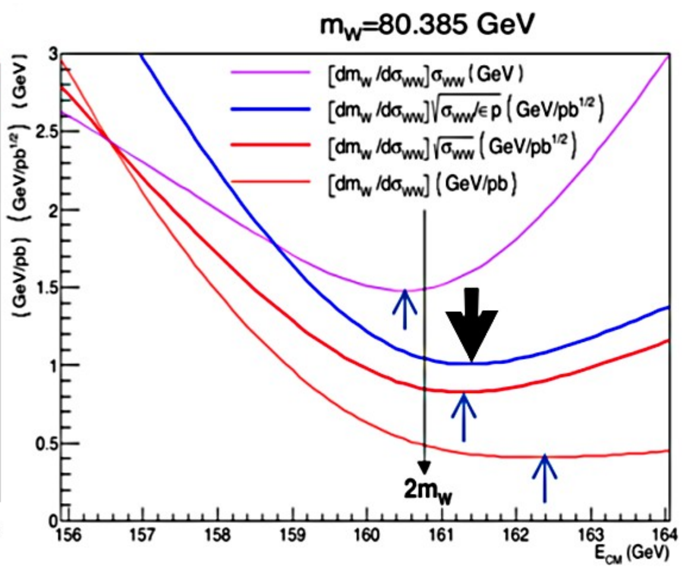
$$m^2_{\rm recoil} = (\sqrt{s} - E_{f\bar{f}})^2 - p^2_{f\bar{f}} = s - 2E_{f\bar{f}}\sqrt{s} + m^2_{f\bar{f}}$$

(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 $e^+e^- \to W^+W^-$...





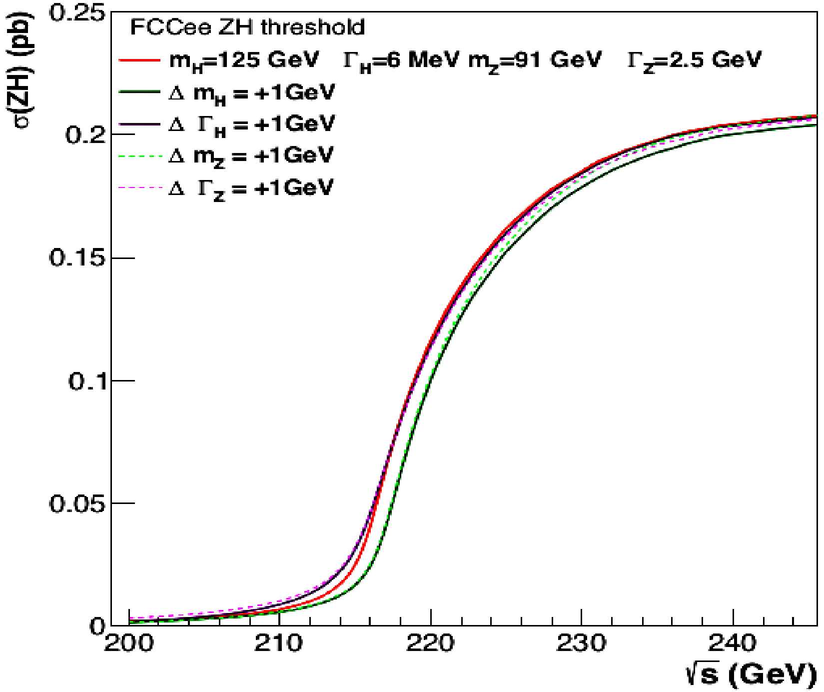
With 7/ab @ 162.6 GeV:
δm_W(stat)= ±0.5 MeV

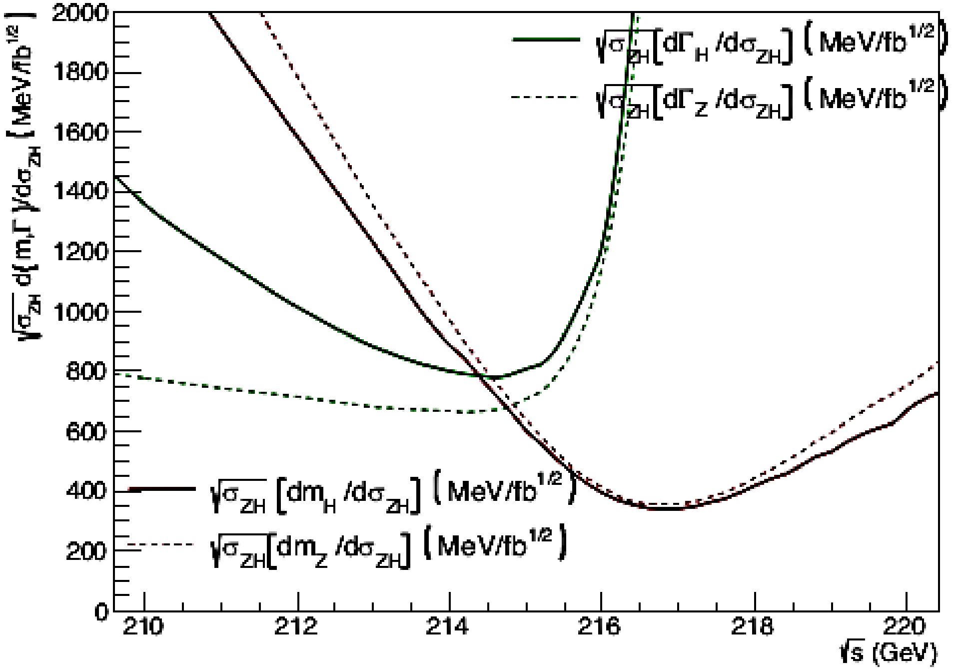
Need systematics control:
- δE_{beam}<0.5 MeV ($6\cdot10^{-6}$)
- $\delta\varepsilon/\varepsilon$, $\delta L/L$ < $2\cdot10^{-4}$)
- $\delta\sigma_B$ <1 fb ($2\cdot10^{-3}$)

[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 ≃ 217 GeV
- $\sqrt{\sigma_{ZH}}(dm_H/d\sigma_{ZH})_{min}$=350 MeV/√fb   With 5/ab @ 217 GeV: δm_H = ±5 MeV

  Need systematics control: δE_{beam}< 5 MeV ($5\cdot10^{-5}$), $\delta\varepsilon/\varepsilon$, $\delta L/L < 10^{-3}$, $\delta\sigma_B$ <0.1 fb (~10^{-3})

- Combining threshold HZ x-section with m_{HZ}(recoil) should give: δm_H = ±3.5 MeV

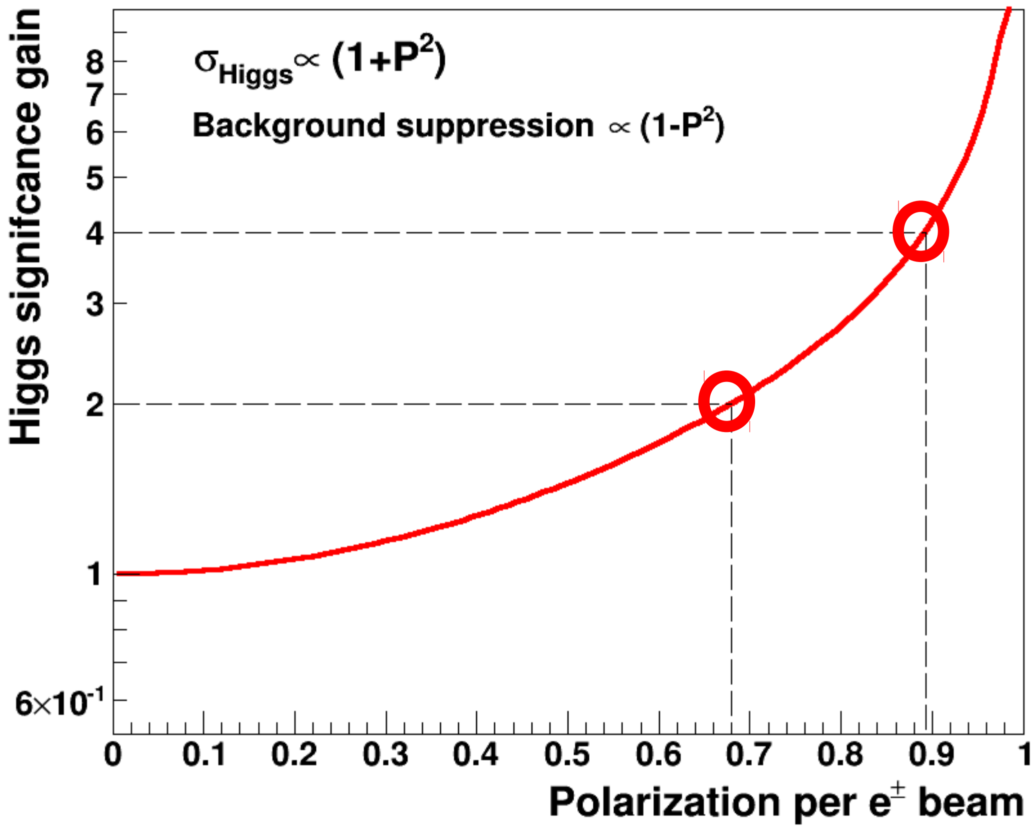
Example of BDT MVA vars. ($H \to WW^* \to l\nu jj$)

Table 5. Indicative list of BDT variables used in the $\mathrm{H} \to \mathrm{WW}^* \to \ell\nu\, 2j$ analysis, with their relative weight in the statistical significance for this channel.

$\cos\theta_{j1}$	E_ℓ	$p_{\mathrm{T}}(jj)$	$\cos\phi_{j1}$	m_{miss}	E_{vis}	p_{T}^{ℓ}	E_{miss}	$p_{\mathrm{T}}(jj\ell)$	$\cos\theta^*$
0.0446	0.0417	0.0409	0.0398	0.0341	0.0328	0.0308	0.03015	0.02726	0.02626
η_{miss}	η_{j1}	$\cos\theta_{j2}$	$\Delta\phi_{jj}$	$m_{\mathrm{T,miss}}$	$m_{\mathrm{W\ offsh.}}$	$E_{j,\mathrm{min}}$	$\Delta R_{\mathrm{min,j}\ell}$	$\min\Delta\eta_{j\ell}$	p_{T}^{j1}
0.0255	0.0238	0.0220	0.0215	0.0212	0.0212	0.0205	0.0204	0.0192	0.0189
$\max\cos(\ell j)$	η_ℓ	$m(\ell\nu)$	$\min\cos(\ell j)$	$\max\Delta\eta_{jj}$	$m_{\mathrm{W\ shell}}$	$m_{\mathrm{T}}(\ell j_1)$	$m_{\mathrm{T}}(jj\ell)$	$m(\ell j_1)$	m_{j2}
0.0189	0.0182	0.0179	0.0176	0.0165	0.0160	0.0160	0.0160	0.0156	0.0147
$\cos\phi_{j1,j2}$	p_{T}^{j2}	$\Delta R_{\mathrm{max,j}\ell}$	η_{j2}	lin.spher.	m_{j1}	$p_{\mathrm{T}}(\ell j2)$	$\Delta\theta_{jj}$	$m_{\mathrm{T}}(jj)$	ΔR_{jj}
0.0140	0.0136	0.0136	0.0136	0.0136	0.0134	0.0134	0.0132	0.0131	0.0127
$E_{j,\mathrm{max}}$	$m_{\mathrm{T}}(\ell j_2)$	sphericity	$p_{\mathrm{T}}(\ell j1)$	$\min\Delta\phi_{j\ell}$	$\mathrm{E}_{\mathrm{isol}}$	aplanarity	$\max\Delta\phi_{j\ell}$	$\phi(j_1)$	$m(jj\ell)$
0.0125	0.0121	0.0116	0.0103	0.0102	0.00998	0.00927	0.00914	0.00894	0.00764
$m(\ell j_2)$	m_{jj}	$\phi(j_2)$	lin.aplan.	ϕ^{ℓ}	$\cos\phi^*$		others (R_{min}, η_ℓ, ...)		
0.00680	0.00641	0.00565	0.00514	0.00512	0.00471		< 0.001		

Significance increase with polarized beams?

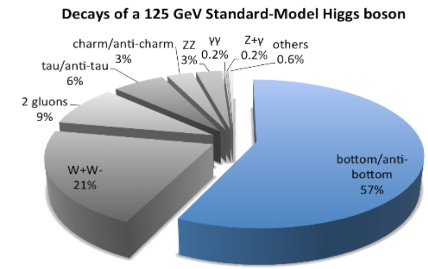
- Polarization of beams would enhance the signal by $(1+\text{Pol}^2)$ and suppress background by $(1-\text{Pol}^2)$. However, realistic longitud. polarization estimates (Pol=20-30%) are clearly insufficient and higher polarizations would reduce luminosity...



- Significance increase:

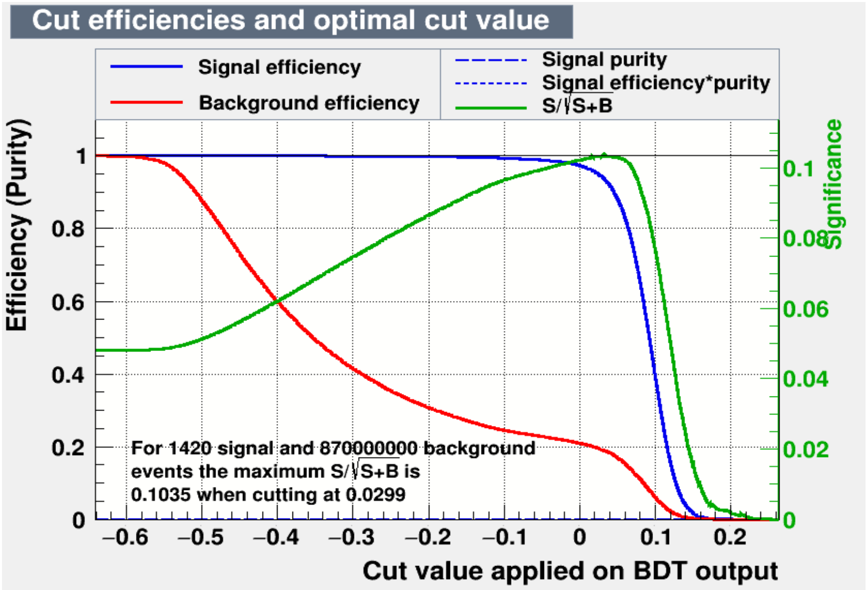
  Pol. = 68%: ×2 significance
  Pol. = 90%: ×4 significance

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 $Z^*\gamma^* \to$ bbar continuum

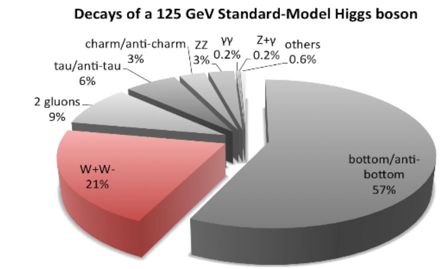


- Signal & backgds before/after MVA cuts:

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

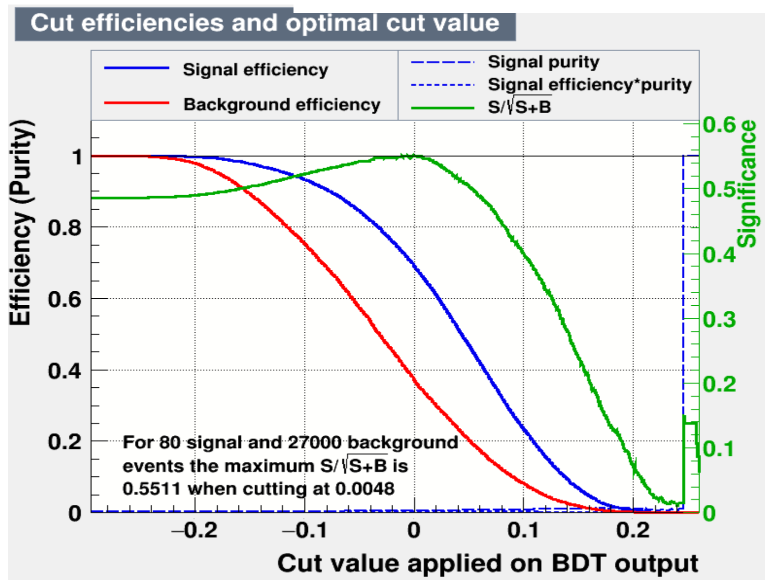


- Final state (retains 80% of $\sigma(WW^*(l\nu jj))$ = 28 ab):
  1 isolated e,μ,τ(e),τ(μ) + ME>2 GeV + 2 jets (excl.)

- 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

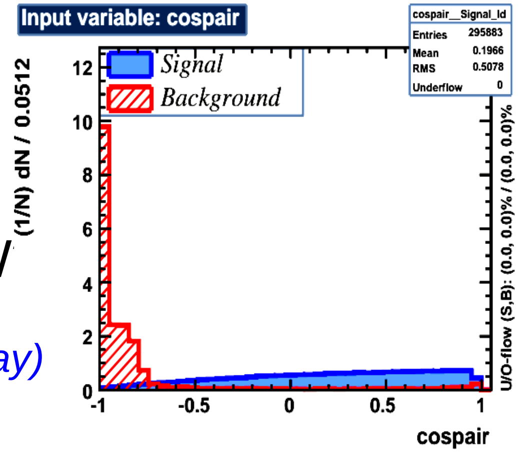
Channel 3: $e^+e^- \to H(WW^*) \to 2l2\nu$

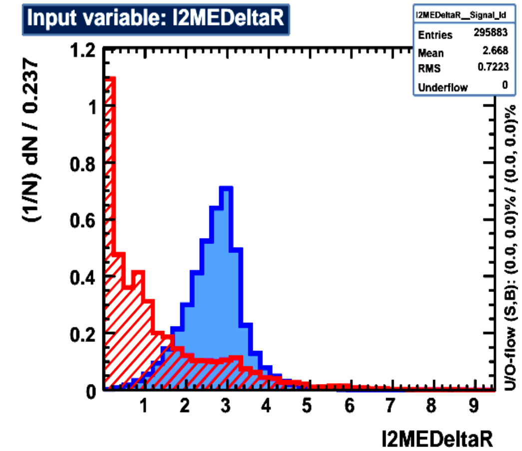
- Final state (retains 60% of $\sigma(WW^*(2l2\nu))$ = 7 ab):
  2 isolated e,μ,τ(e),τ(μ) + ME > 2 GeV
  + 0 non-isolated leptons or ch.had.

- 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

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

(indicative distributions only: normalized to 1)





- Signal & backgds before/after cuts:

H(WW*):	σ = 4 ab	$\Rightarrow \sigma$(after) = 2.1 ab
WW*:	σ = 2.9 fb	$\Rightarrow \sigma$(after) = 454 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) = 0.4 ab

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

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

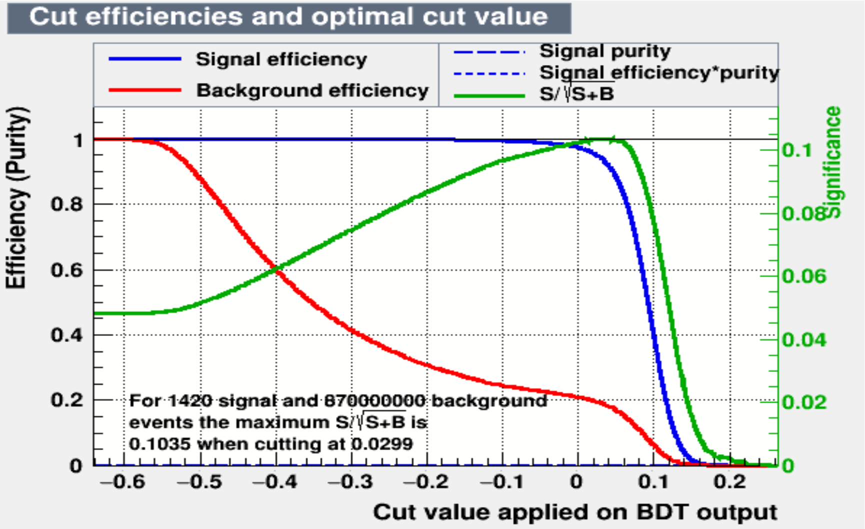
- Final state (retains 9% of $\sigma(WW^*(4j))$ = 29 ab):

  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),$\tau(\mu)$

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

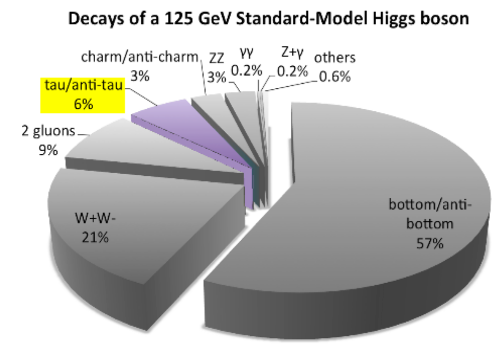
$S/\sqrt{B} = 14/\sqrt{29.e3} \approx 0.08$

Significance $\approx$ 0.08

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

- 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.

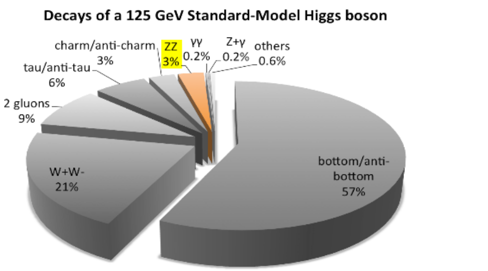
- Signal & backgds before/after MVA cuts:

  $H(\tau\tau)$: σ = 7.4 ab ⇒ 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

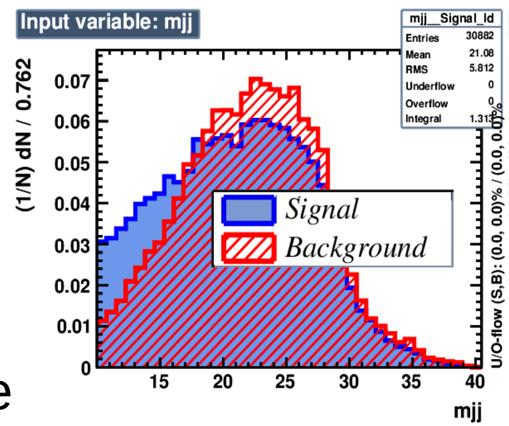
Channel 7: $e^+e^- \to H(ZZ^*) \to 2j2\nu$

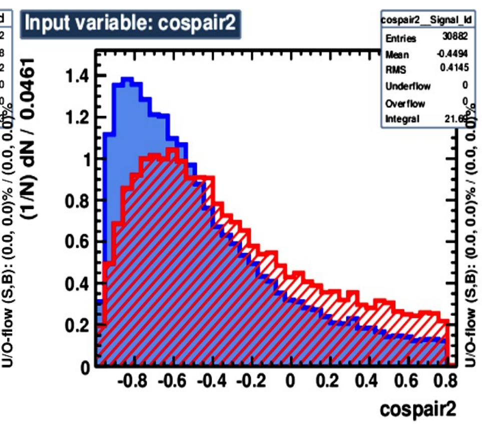
- Final state (retains 75% of $\sigma(WW^*(2j2\nu))$ = 2.3 ab):
  2 jets (excl.) + ME > 30 GeV
  + 0 isolated $e,\mu,\tau(e),\tau(\mu)$ + 0 τ(had)



- Kinematic cuts:
  - ✓ $\min(|m_{ME}-m_Z|,|m_{jj}-m_Z|)<10$ GeV ← Kills qqbar,τ-τ
  - ✓ 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 $\approx$ 0.21

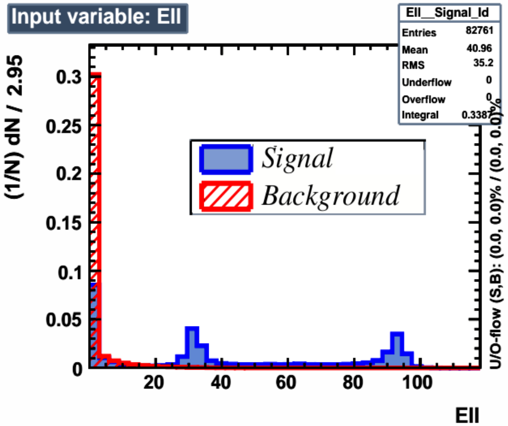
Channel 8: $e^+e^- \to H(ZZ^*) \to 2l2j$

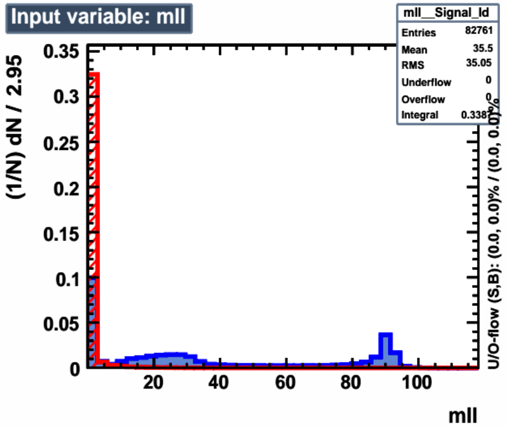
- Final state (retains 73% of $\sigma(WW^*(2l2j))$ = 1.14 ab):
  2 isolated opposite-charge leptons e,μ,τ(e),τ(μ)
  + 2 jets (exclusive)

- 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 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

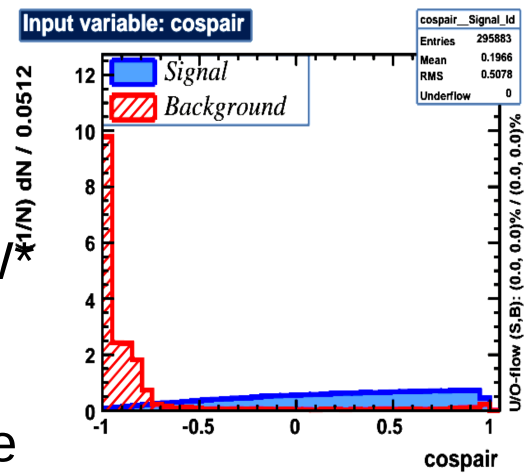
Channel 9: $e^+e^- \to H(ZZ^*) \to 2l2\nu$

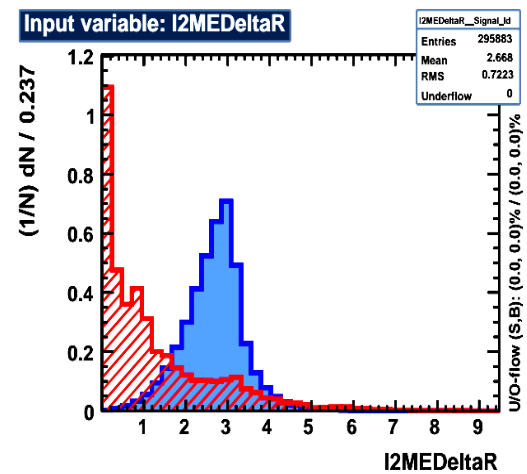
- Final state (retains 60% of $\sigma(ZZ^*(2l2\nu))$ = 0.34 ab):
  2 isolated e,μ,τ(e),τ(μ) + ME>2 GeV
  + 0 non-isolated leptons or ch.had.

- 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)



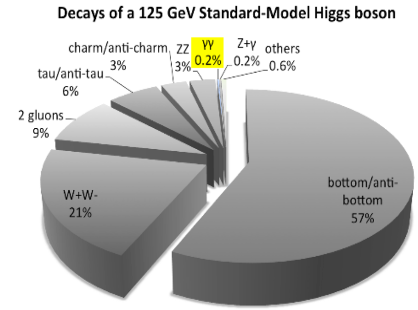


- Signal & backgds before/afte
  H(ZZ*): σ = 0.2 ab ⇒ σ(after) = 0.04 ab
  WW*: σ = 29 fb ⇒ σ(after) = 144 ab
  τ-τ: σ = 3.1 pb ⇒ σ(after) = 51 ab
  qqbar: σ ~ 0 pb ⇒ σ(after) = 0 ab
  ZZ*: σ = 24 ab ⇒ σ(after) = 9 ab

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

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

- 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 $P \approx 0.35\%$.

  ✓ MVA BDT doesn't improve result

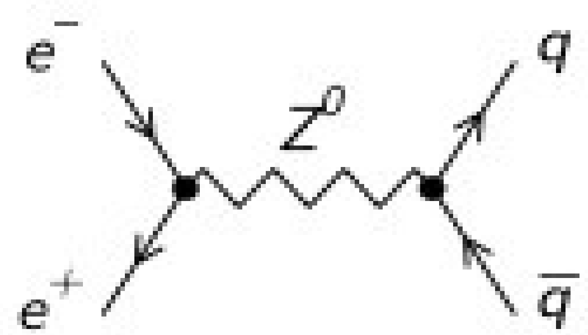
- Signal & backgds before/after cuts:

  $H(\gamma\gamma)$: 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 $\approx$ 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 ...