

s-channel $e^+e^- \rightarrow$ Higgs & electron Yukawa constraints at FCC-ee

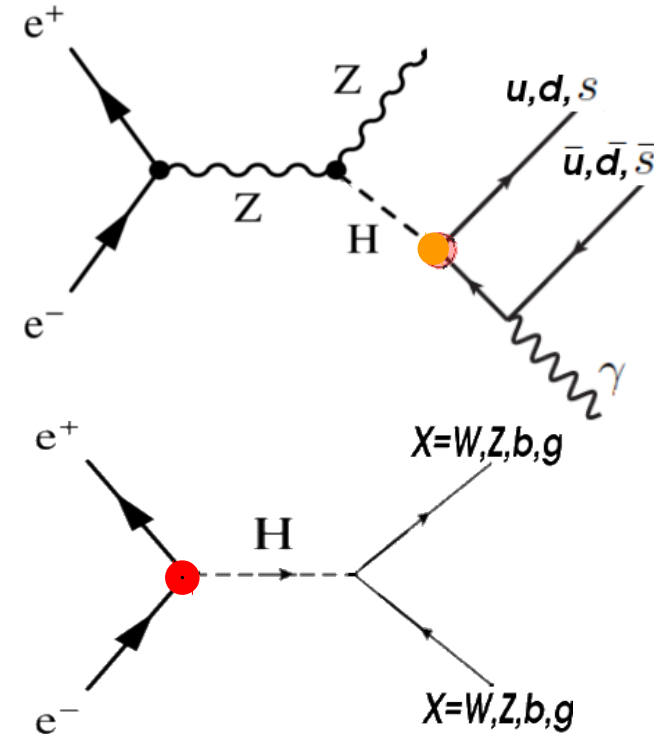
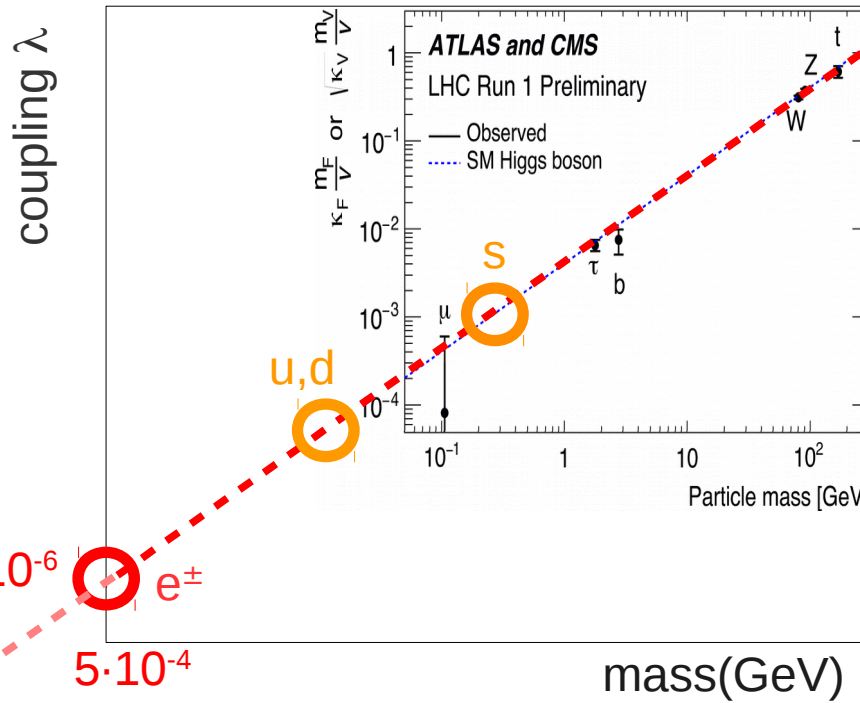
2nd FCC-France Workshop
Paris (Virtual), 20th–21st Jan. 2021

David d'Enterria (CERN)*

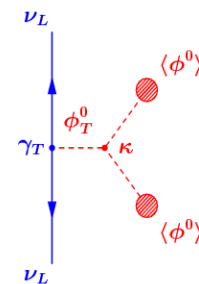
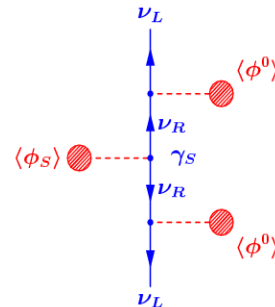
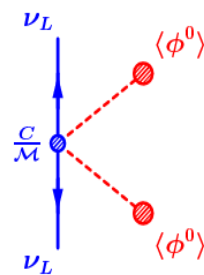
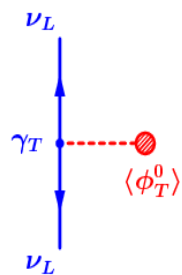
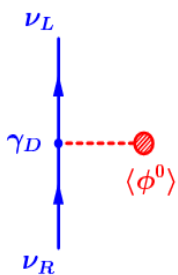
(*) Simulations/analysis help from: *A. Poldaru (Tallin), G. Wojcik (SLAC)*
FCC-ee monochromatization studies: *F. Zimmermann, M.A.Valdivia (CERN)*

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,v) matter** in the Universe?



$<10^{-12}$
 ν_{DIRAC}
 $<3 \cdot 10^{-10}$

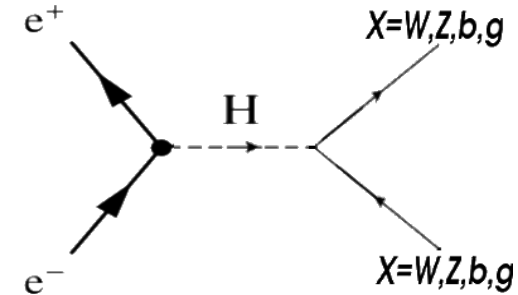
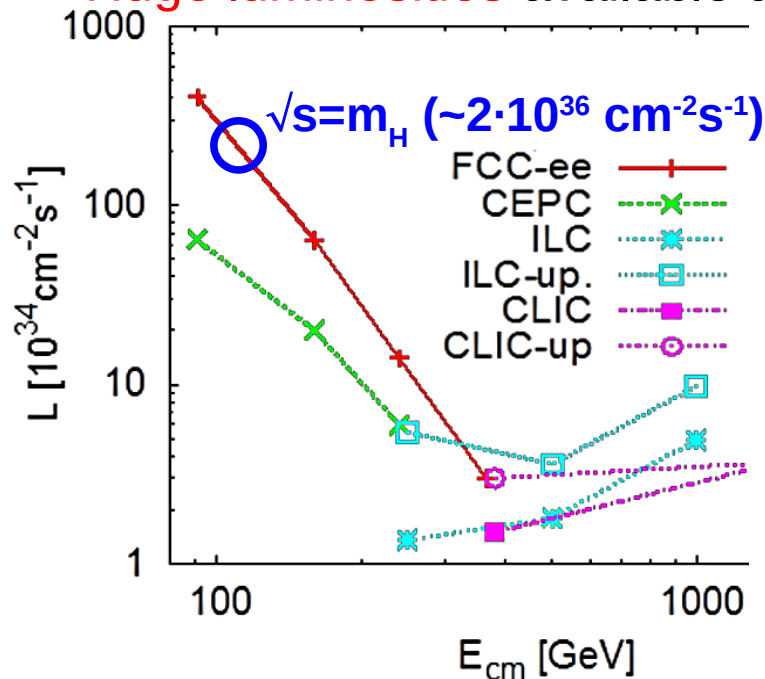


e Yukawa via s-channel $e^+e^- \rightarrow H$ production

- Higgs decay to e^+e^- is unobservable: $BR(H \rightarrow e^+e^-) \propto m_e^2 \approx 5 \cdot 10^{-9}$
- Resonant Higgs production considered so far only for muon collider: $\sigma(\mu\mu \rightarrow H) \approx 70$ pb. **Tiny κ_e Yukawa coupling** \Rightarrow Tiny $\sigma(ee \rightarrow H)$:

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

- **Huge luminosities** available at FCC-ee:



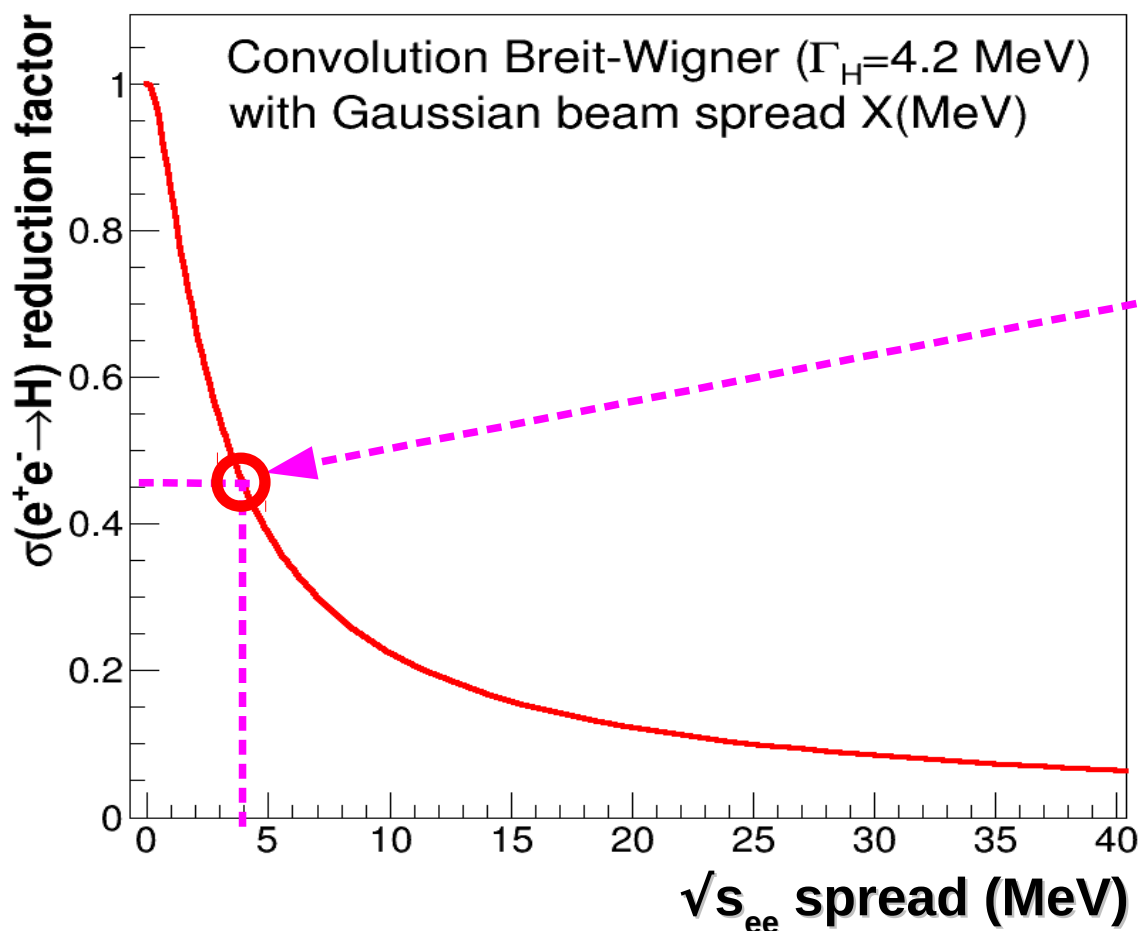
In theory, FCC-ee running at H pole-mass $L_{\text{int}} \approx 20 \text{ ab}^{-1}/\text{yr}$ would produce $O(30.000)$ H's

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

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

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

- $\sigma(e^+e^- \rightarrow H) = 1.64 \text{ fb}$ for Breit-Wigner with natural $\Gamma_H = 4.2 \text{ MeV}$ 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**:



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

~45% x-section reduction

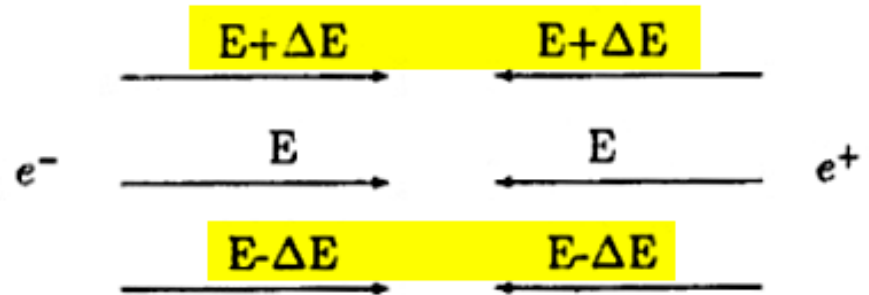
Reachable with beams **monochromatization?**
(opposite sign dispersion using magnetic lattice)
What luminosity loss price?

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

Beam monochromatization in e^+e^- collisions

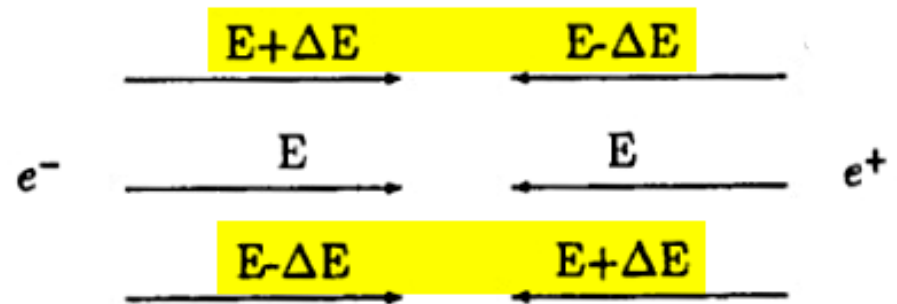
Standard collision:
dispersion has the same sign
in the IP

$$W = 2(E_0 + \varepsilon)$$



Monochromatization:
dispersion has opposite sign in
the IP

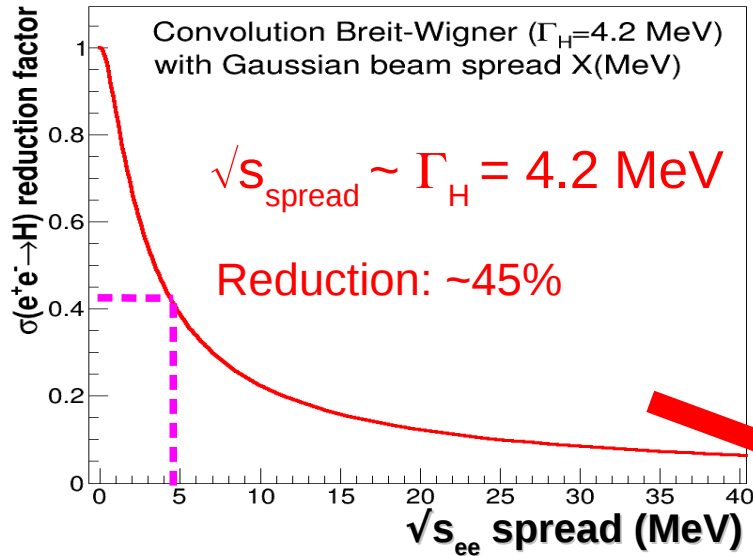
$$W = 2E_0 + 0(\varepsilon)^2$$



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

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

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

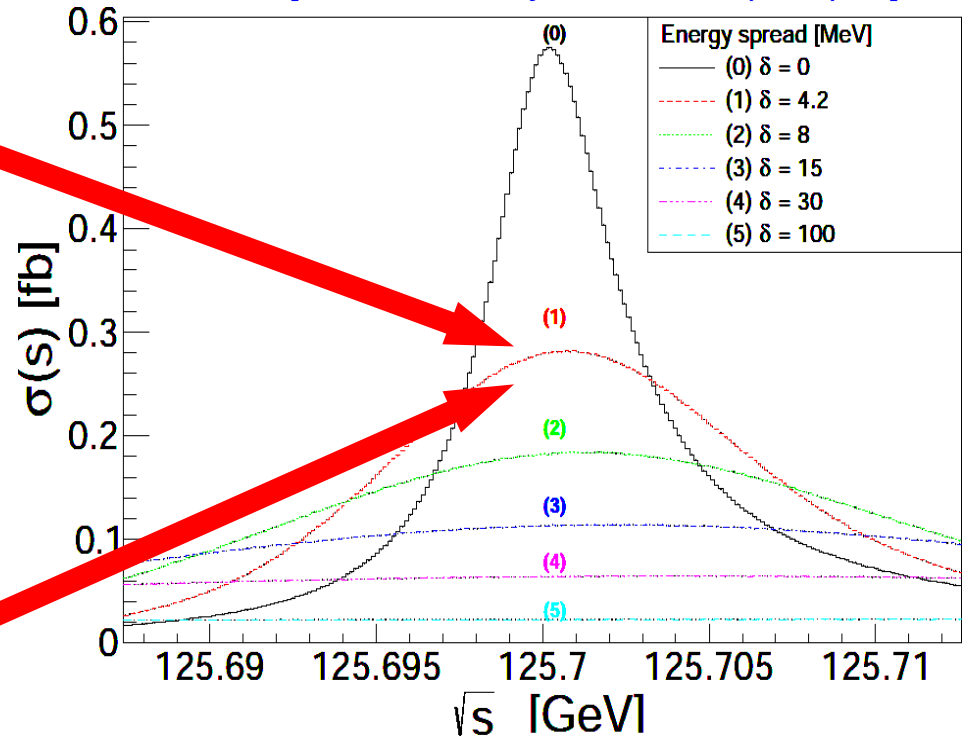


Assume monochromatization ref. point:

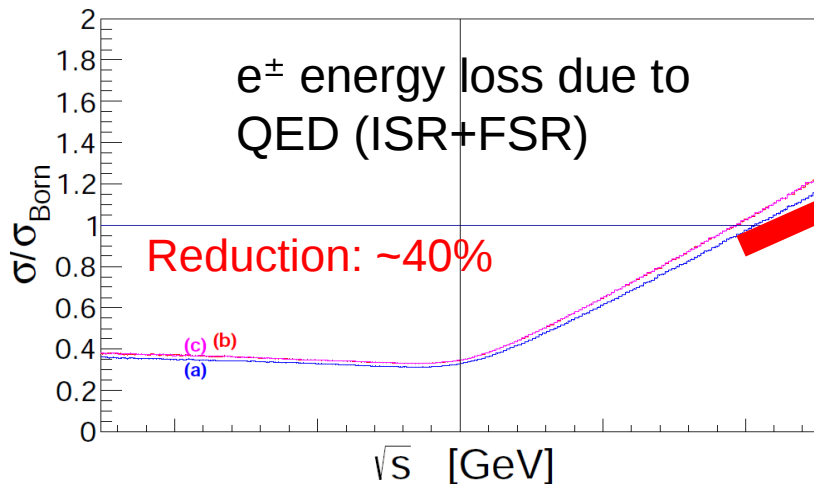
$$\sqrt{s}_{\text{spread}} \approx \Gamma_H = 4.2 \text{ MeV}$$

■ Full convolution of both effects:

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



■ Extra $\sim 40\%$ reduction due to QED radiation:

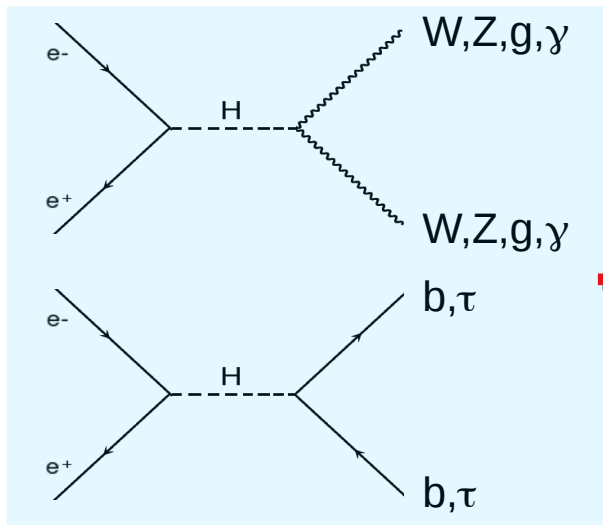


$$\sigma_{\text{spread+ISR}}(e^+e^- \rightarrow H) = 0.17 \times \sigma(e^+e^- \rightarrow H) = 290 \text{ ab}$$

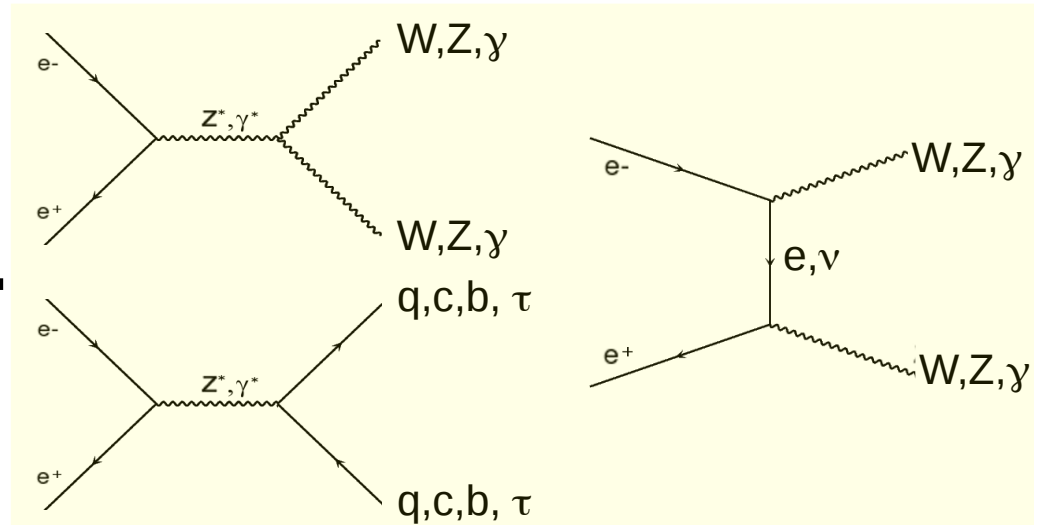
Signal & backgrounds simulation

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

SIGNAL



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



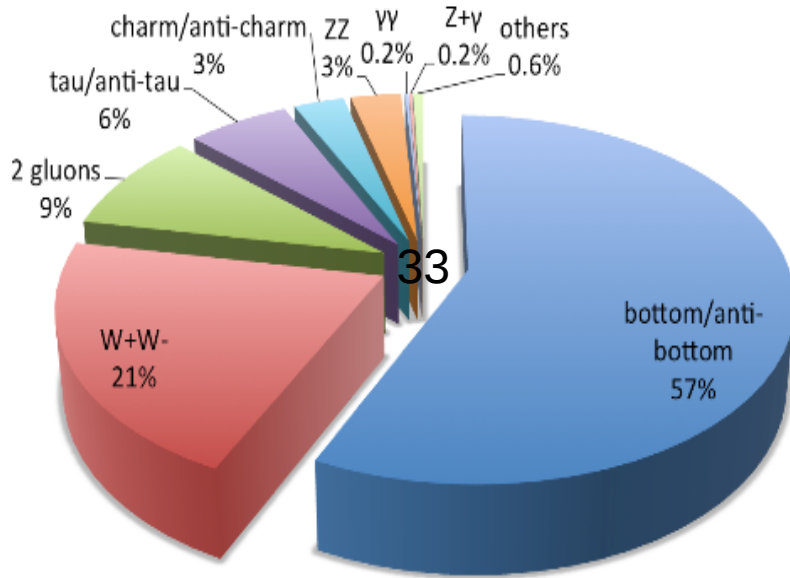
(other SM loop-induced $e^+e^- \rightarrow H$ found negligible)

- **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, ... [Webber 2007]
- **ISR switched-on in PY8**, \sqrt{s}_{spread} via scaling to match $\sigma(e^+e^- \rightarrow H) = 290$ ab

Higgs measurement at FCC-ee(125 GeV)

Very-rare counting experiment over 10 decay channels:

Decays of a 125 GeV Standard-Model Higgs boson



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

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

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

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:

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

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

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

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

2 gluon-tagged jets (with 70% effic. each)

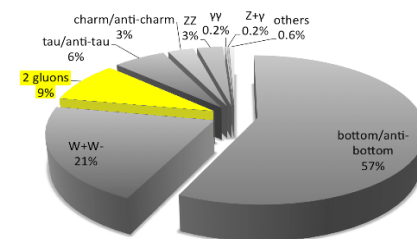
Light-q mistagging rate: $\sim 1\%$

Challenging, not impossible:

Dedicated QCD studies needed

(reco&PID of ALL hadrons in jets).

Decays of a 125 GeV Standard-Model Higgs boson

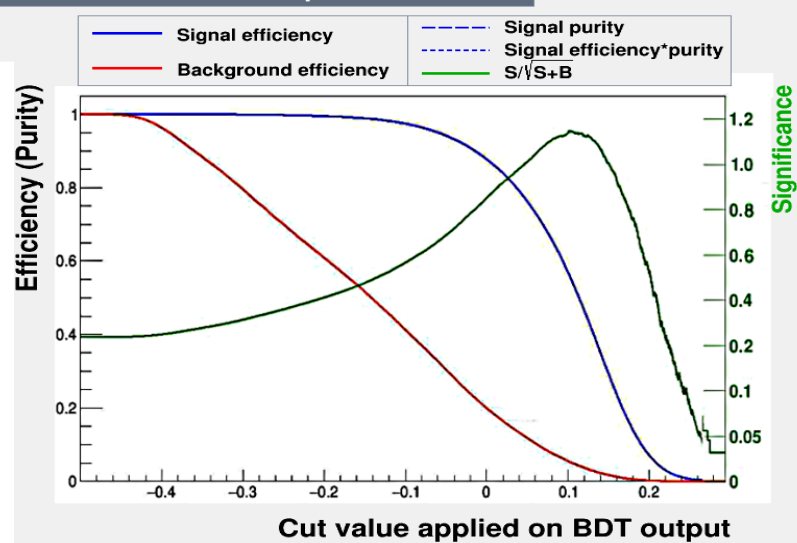


- MVA result:

Signal reduction $\sim 50\%$

Backgd. reduction: x20

Cut efficiencies and optimal cut value



- 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	$25 \pm 0 \text{ ab}$	$70\%^2$	10 ab	9.7 ab	$5.5 \pm 0.0 \text{ ab}$
bb	199981	140057	12532	1331	$81 \pm 0 \text{ pb}$	$0.0\%^2$	0 pb	0 pb	$0 \pm 0 \text{ pb}$
cc	200000	174120	28282	1984	$73 \pm 0 \text{ pb}$	$0.0\%^2$	0 pb	0 pb	$0 \pm 0 \text{ pb}$
qq	200000	186171	36888	2015	$237 \pm 0 \text{ pb}$	$1.0\%^2$	22 fb	4.4 fb	$239 \pm 5 \text{ ab}$
ZZ	99999	75095	49798	14261	$224 \pm 0 \text{ fb}$	$0.0\%^2$	0 pb	0 pb	$0 \pm 0 \text{ pb}$
tautau	20000	0	0	0	$26 \pm 0 \text{ pb}$	$0.0\%^2$	0 pb	0 pb	$0 \pm 0 \text{ pb}$
WW	20000	16959	12783	5413	$21 \pm 0 \text{ fb}$	$0.0\%^2$	0 pb	0 pb	$0 \pm 0 \text{ pb}$

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

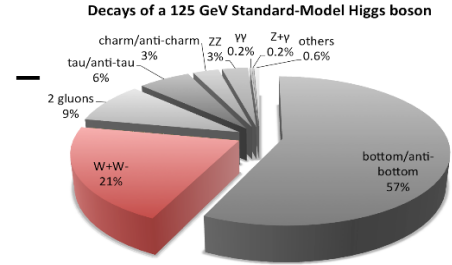
For $L_{\text{int}} = 10 \text{ ab}^{-1}$

$S/\sqrt{B} = 55/\sqrt{2.3e3} \approx 1.2$

Significance ≈ 1.2

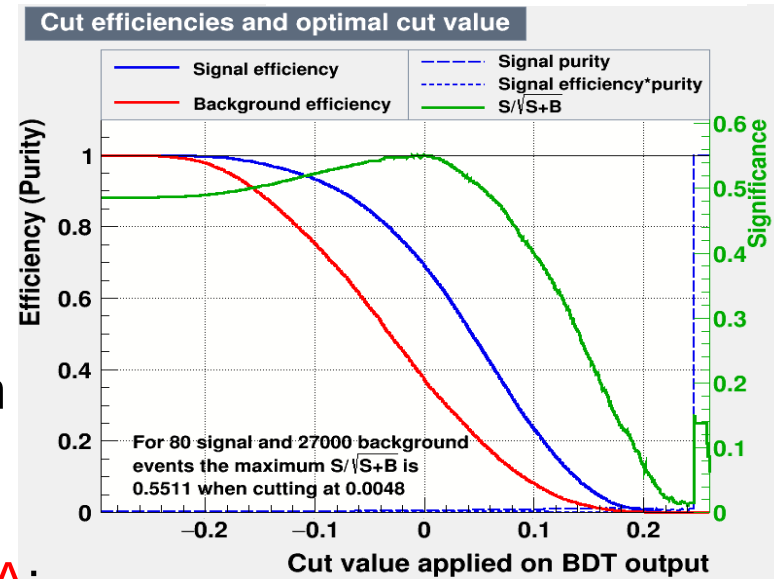
2nd most significant channel: $e^+e^- \rightarrow H(WW^*) \rightarrow l\nu jj$

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



- Analysis cuts:

- ✓ $E_{j1,j2} < 52,45$ GeV \Leftarrow Kills $e^+e^- \rightarrow q\bar{q}$
- ✓ $m_{w(l\nu)} > 12$ GeV/c² \Leftarrow Kills $e^+e^- \rightarrow q\bar{q}$
- ✓ $E_{lepton} > 10$ GeV \Leftarrow Kills $e^+e^- \rightarrow q\bar{q}$
- ✓ $ME > 20$ GeV \Leftarrow Kills $e^+e^- \rightarrow q\bar{q}$
- ✓ $m_{ME} < 3$ GeV/c² \Leftarrow Kills $e^+e^- \rightarrow \tau\tau$
- ✓ BDT MVA \Leftarrow Kills $e^+e^- \rightarrow WW^*$ 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
HW $Wjjl\nu$	400000	174534 144336	66399	44797	27 \pm 0 ab	100% ²	23 ab	10 ab	7.0 \pm 0.0 ab
WW	400000	174809 145026	55955	16886	46 \pm 0 fb	100% ²	17 fb	6.4 fb	1.9 \pm 0.0 fb
bb	999898	0 200961	2	0	81 \pm 0 pb	100% ²	16 pb	161 ab	0 \pm 81 ab
cc	1000000	0 63844	0	0	73 \pm 0 pb	100% ²	4.7 pb	0 pb	0 \pm 73 ab
qq	1000000	0 7675	0	0	237 \pm 0 pb	100% ²	1.8 pb	0 pb	0 \pm 237 ab
tautau	20000	0 8359	0	0	26 \pm 0 pb	0.75% ²	605 ab	0 pb	0 \pm 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 ≈ 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 \sim identical results, which are also very close to naive S/\sqrt{B} expectation (no background uncertainty).

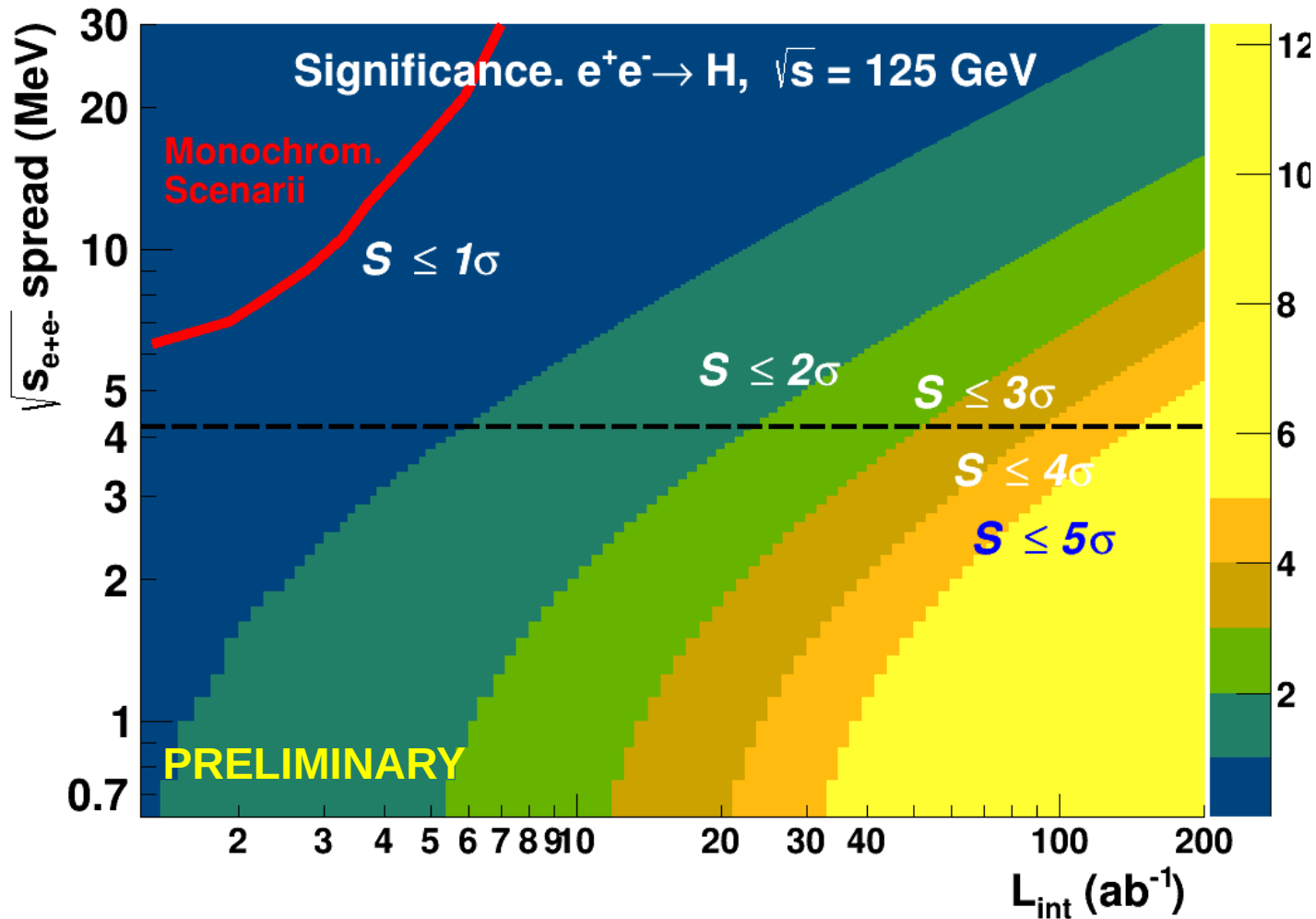
Channel	Significance (1 ab^{-1})	Significance (10 ab^{-1})
$WW \rightarrow l\nu 2j, 2l 2\nu, 4j$	$0.15 \oplus 0.09 \oplus 0.03$	$0.50 \oplus 0.32 \oplus 0.13$
$ZZ \rightarrow 2j 2\nu, 2l 2j, 2l 2\nu$	$0.07 \oplus 0.05 \oplus 0.01$	$0.25 \oplus 0.20 \oplus 0.03$
bb	0.04	0.13
gg	0.34	1.11
$\tau\tau$	–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

- For 10 ab^{-1} : Significance $\approx 1.3\sigma$ (preliminary, ongoing optimizations)

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

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

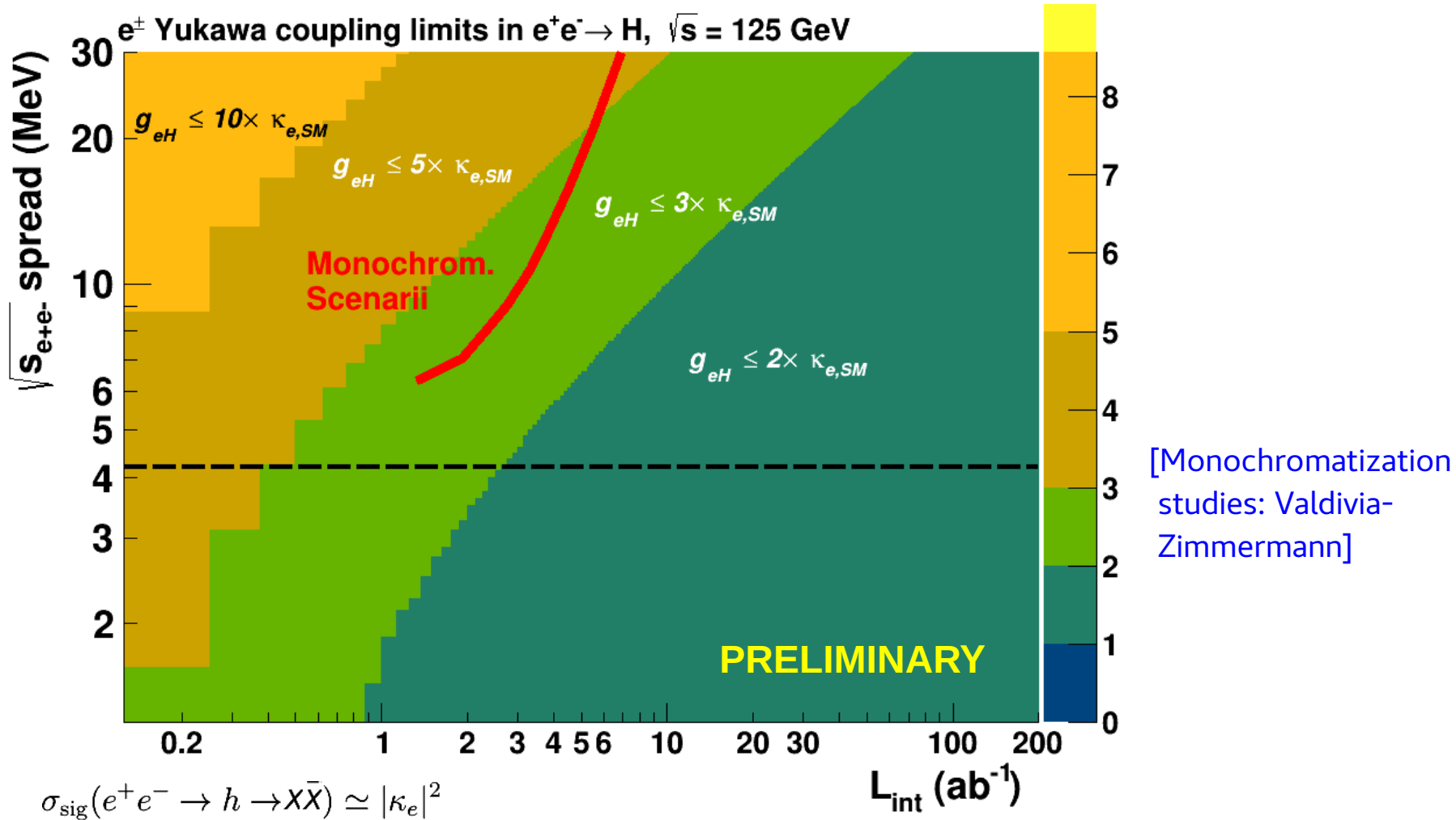
- Monochromatization working points (\sqrt{s}_{spread} vs. L_{int} per IP/year):



- Best significance $\approx 0.4\sigma$ around $\sqrt{s}_{\text{spread}} = 7\text{--}10$ MeV region.

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

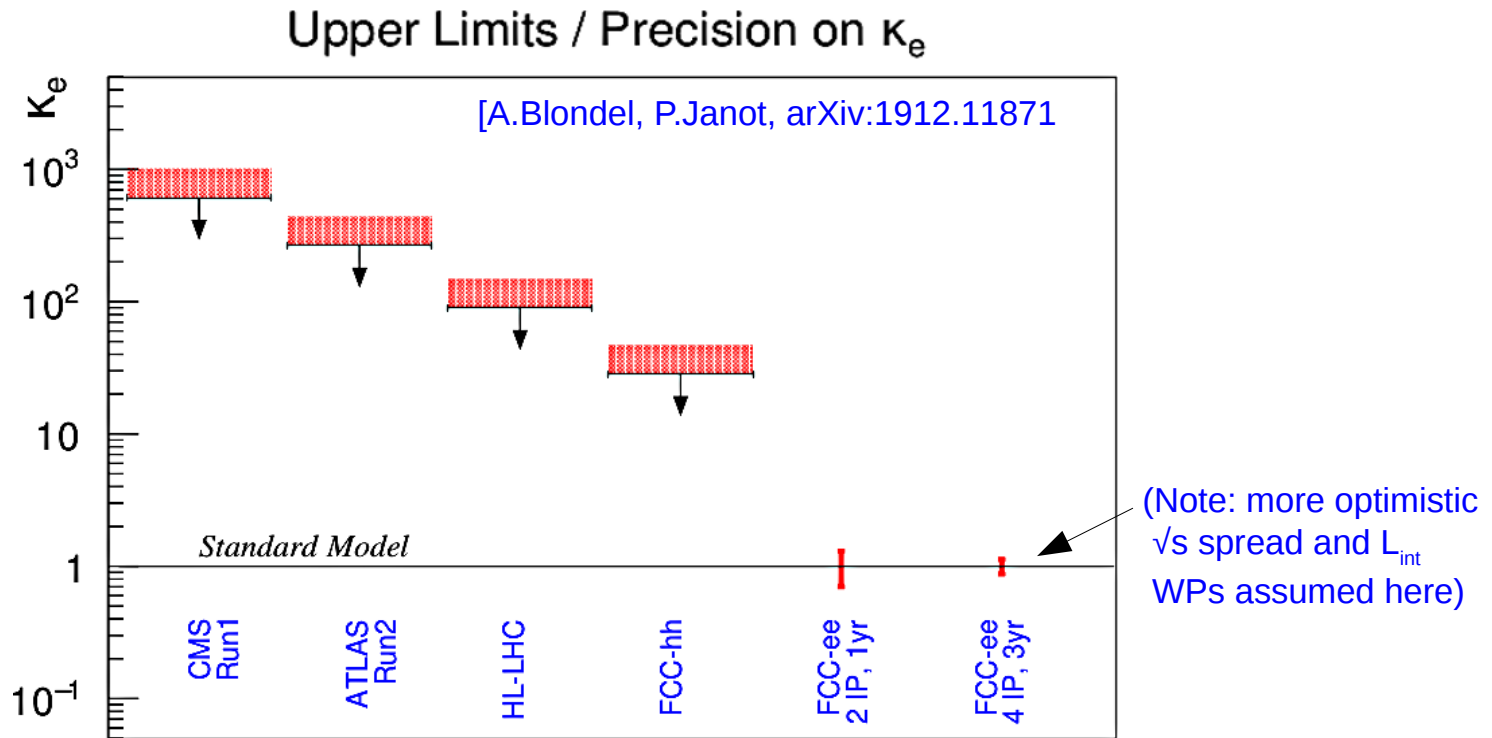
- Monochromatization working points (\sqrt{s}_{spread} vs. L_{int} per IP/year):



- Best limits: $\kappa_e < 2.6 \times \kappa_{e,SM}$ (95% CL) around $\sqrt{s}_{\text{spread}} = 7\text{--}10$ MeV region.

κ_e Yukawa limits at various machines

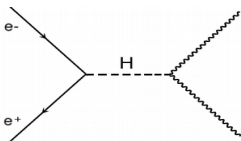
- Hadron machines can very loosely constrain κ_e via $H \rightarrow e^+e^-$ searches on top of huge DY (and $H \rightarrow \gamma\gamma$) backgrounds:



- Combining up to 4 exps. & running a few years we are at SM κ_e values.
- Limits on κ_e are $\times 100$ ($\times 30$) better than at HL-LHC (FCC-hh).

Conclusions

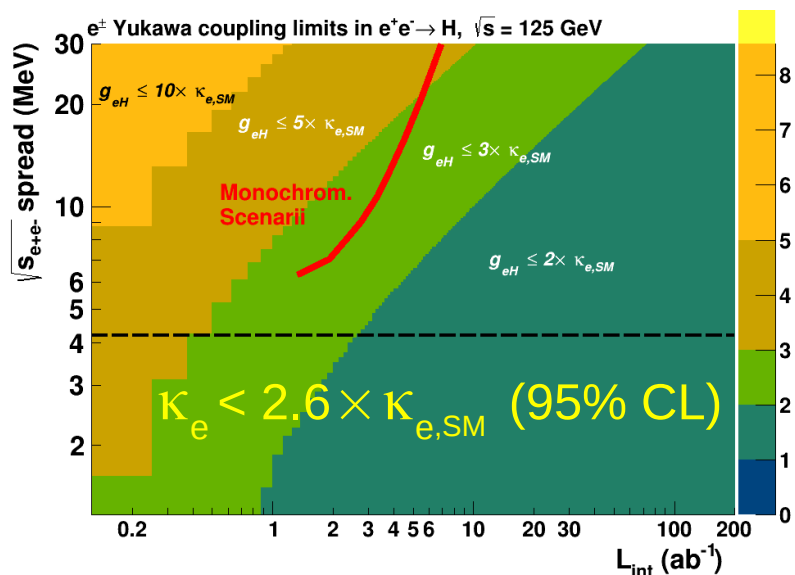
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s} = 125$ GeV):



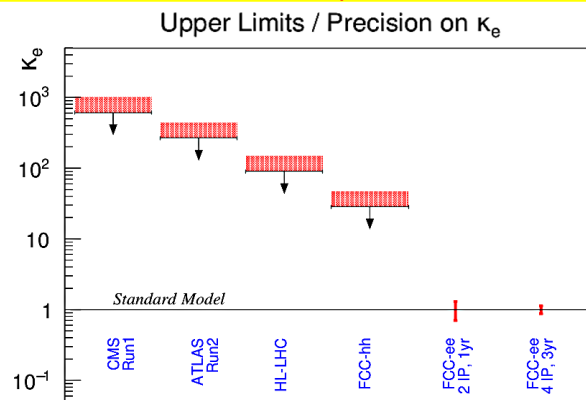
$$\sigma(e^+e^- \rightarrow H)_{B-W} = 1.64 \text{ fb}$$

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

- 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: $H \rightarrow gg$ (for light-q mistag $\sim 1\%$!), $H \rightarrow WW^* \rightarrow l+jets$



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



- Can we improve the **monochromatization** $\sqrt{s}_{\text{spread}}, L_{\text{int}}$ working points?
- Fundamental unique physics accessible:

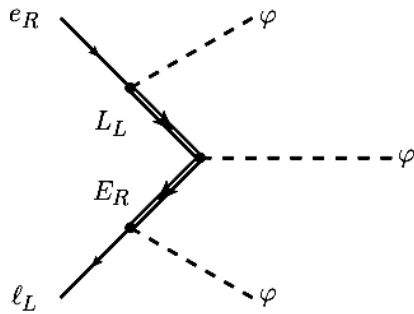
- **Electron Yukawa coupling: Limits $\times 100$ ($\times 30$) better than HL-LHC (FCC-hh)**
- BSM electron Yukawa? Separation of BSM **nearly-degen. H's?**

Backup slides

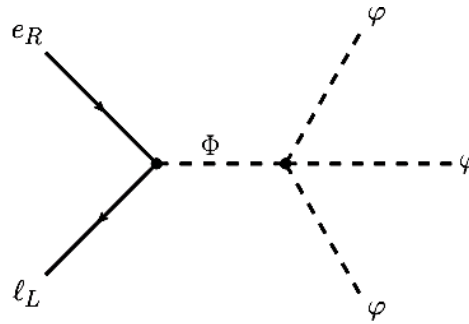
BSM electron Yukawa

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

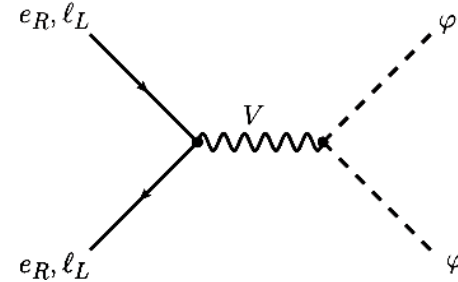
■ Lowest order **dim-6 operators** with BSM electron Yukawa:



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. $k_e^{\text{SM}}=1$):

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

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

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

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

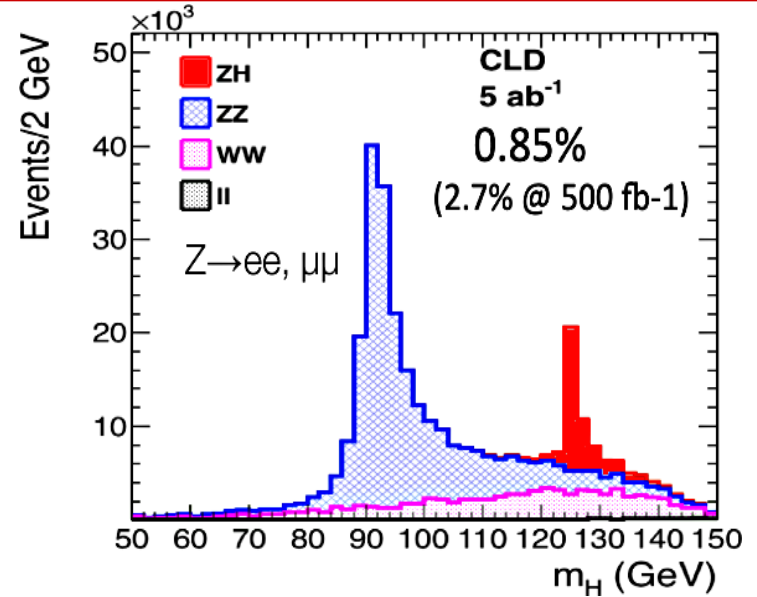
■ Note: Unsuppressed **dim-10 BSM operators** also possible.

Accurate m_H needed to run at resonant peak

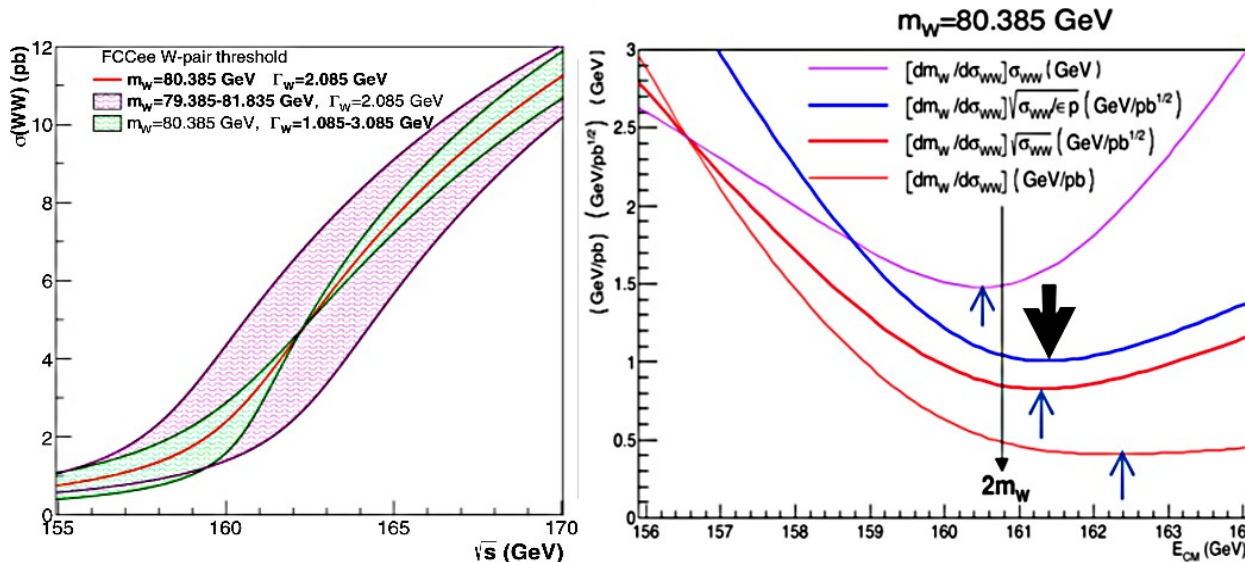
- $e^+e^- \rightarrow H Z(l^+l^-)$ recoil method:
allows Higgs mass reconstruction
with $\delta m_H = 8 \text{ MeV}$ in $Z \rightarrow \mu^+\mu^-$

$$m_{\text{recoil}}^2 = (\sqrt{s} - E_{f\bar{f}})^2 - p_{f\bar{f}}^2 = s - 2E_{f\bar{f}}\sqrt{s} + m_{f\bar{f}}^2$$

$(\delta m_H = \pm 5 \text{ MeV}$ adding other decays)



- Can m_H be accurately reconstructed via $\sigma(\text{HZ})$ line shape scan? Like done for m_W via $e^+e^- \rightarrow W^+W^- \dots$



With 7/ab @ 162.6 GeV:
 $\delta m_W(\text{stat}) = \pm 0.5 \text{ MeV}$

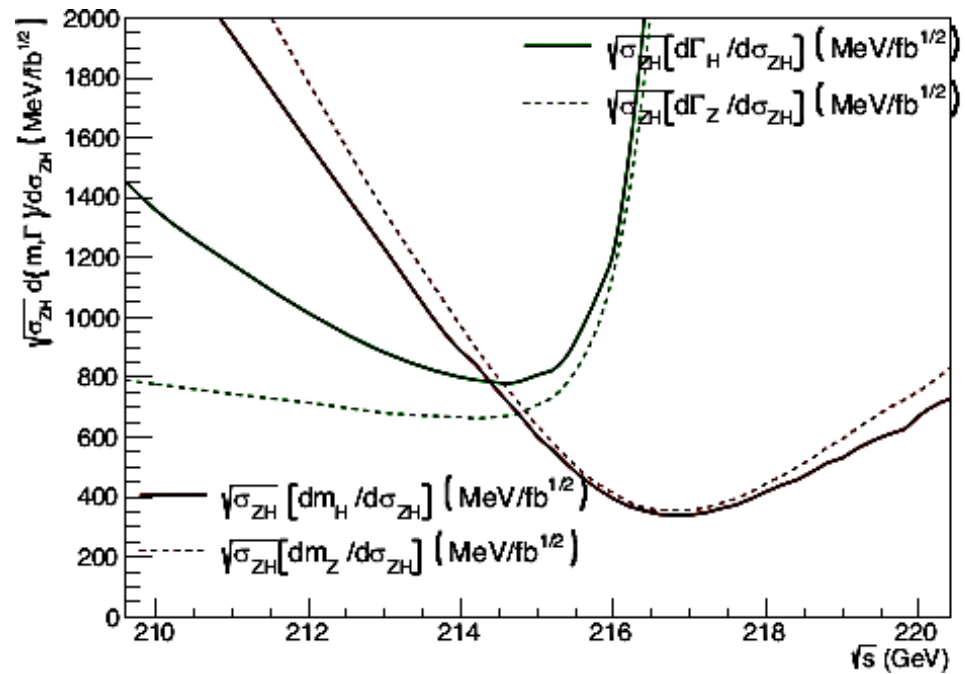
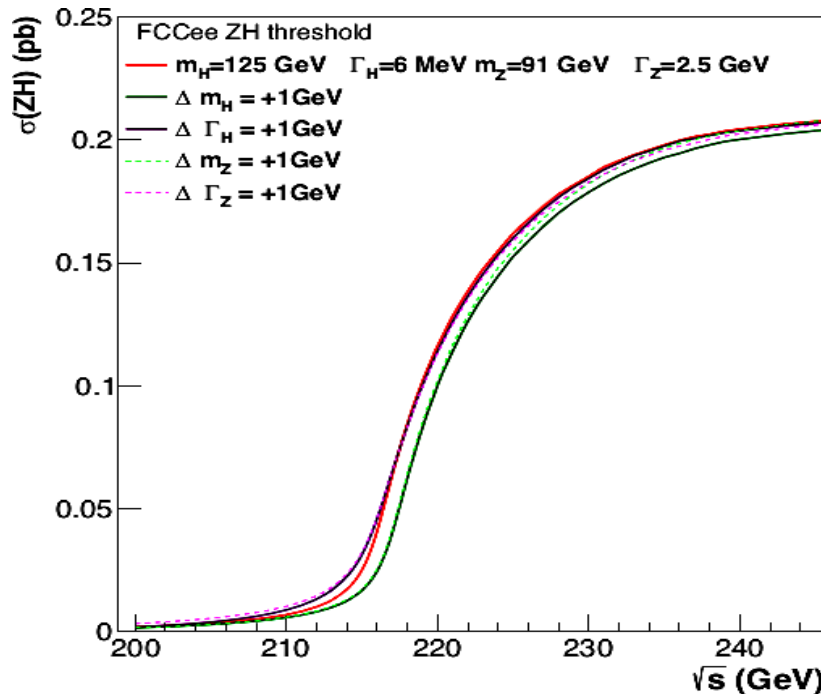
Need systematics control:

- $\delta E_{\text{beam}} < 0.5 \text{ MeV}$ ($6 \cdot 10^{-6}$)
- $\delta \epsilon/\epsilon, \delta L/L < 2 \cdot 10^{-4}$
- $\delta \sigma_B < 1 \text{ fb}$ ($2 \cdot 10^{-3}$)

[arXiv:1703.01626
arXiv:1909.12245]

Accurate m_H needed to run at resonant peak

- Can m_H be accurately reconstructed via $\sigma(\text{HZ})$ line shape scan?
- Preliminary MG5@NLO studies by Paolo Azzurri:



- Optimal data-taking point for min $\Delta m_H(\text{stat})$: $\sqrt{s} \approx m_Z + m_H - 0.2 \approx 217 \text{ GeV}$

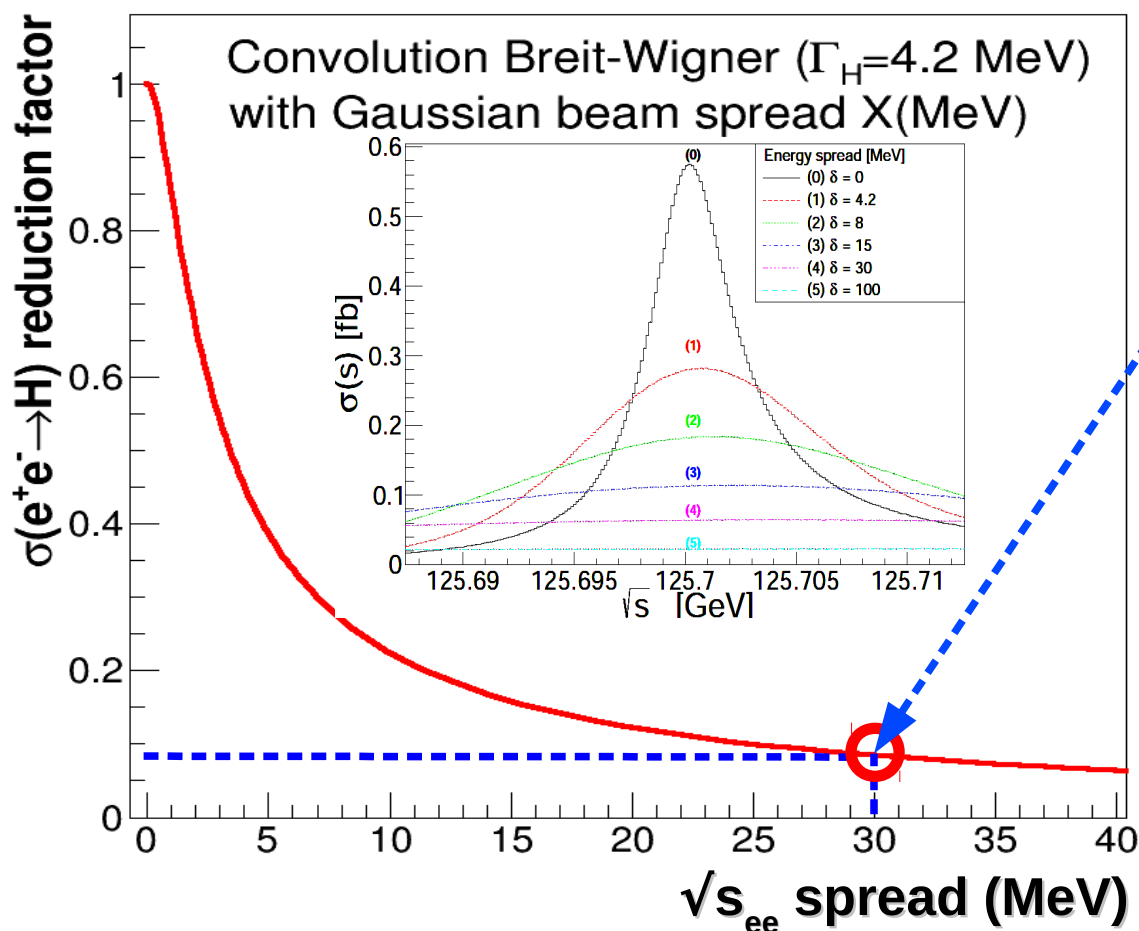
- $\sqrt{\sigma_{ZH}} (dm_H / d\sigma_{ZH})_{\min} = 350 \text{ MeV}/\sqrt{\text{fb}}$ With $5/\text{ab}$ @ 217 GeV: $\delta m_H = \pm 5 \text{ MeV}$

Need systematics control: $\delta E_{\text{beam}} < 5 \text{ MeV}$ ($5 \cdot 10^{-5}$), $\delta \epsilon / \epsilon$, $\delta L / L < 10^{-3}$, $\delta \sigma_B < 0.1 \text{ fb}$ ($\sim 10^{-3}$)

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

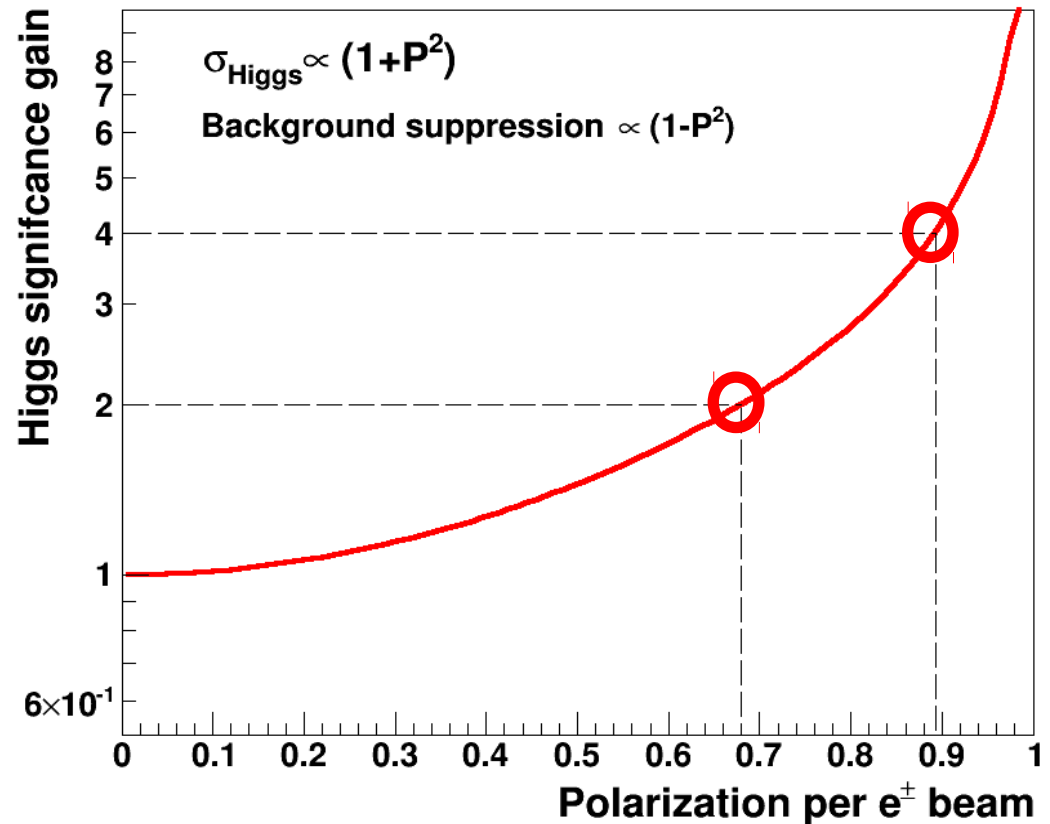
“Actual” s-channel $e^+e^- \rightarrow H$ cross section

- $\sigma(e^+e^- \rightarrow H) = 1.64 \text{ fb}$ for Breit-Wigner with natural $\Gamma_H = 4.2 \text{ MeV}$ 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**:



Significance increase with polarized beams?

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

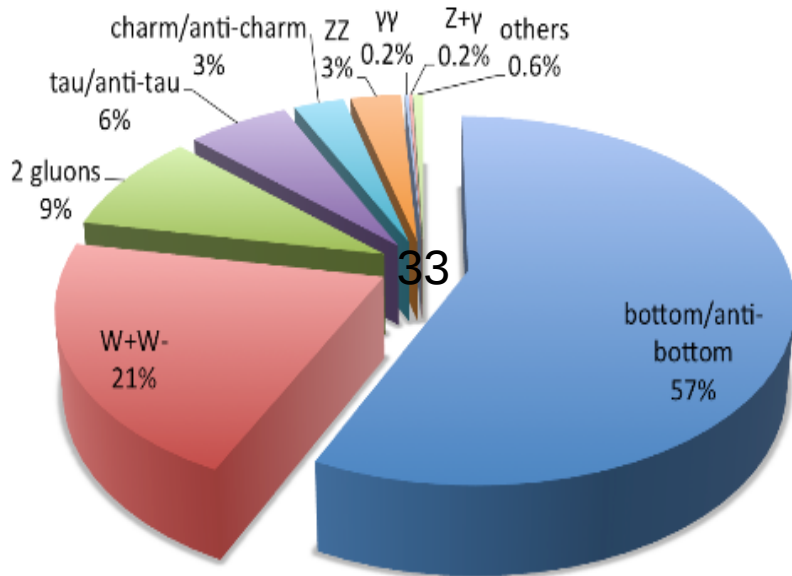


- Significance increase:
 - Pol. = 68%: $\times 2$ significance
 - Pol. = 90%: $\times 4$ significance

Higgs measurement at FCC-ee(125 GeV)

Very-rare counting experiment over 10 decay channels:

Decays of a 125 GeV Standard-Model Higgs boson



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

1) $b\bar{b}$ (2 b-jets): $\sigma = 156$ ab

Dominant bckgd ($ee \rightarrow b\bar{b}$): $\sigma = 20$ pb (S/B $\sim 10^{-5}$)

2) WW^* (4j): $\sigma = 28$ ab

Dominant bckgd ($ee \rightarrow 4j$): $\sigma = 16$ fb (S/B $\sim 10^{-3}$)

3) WW^* (2j1 ν): $\sigma = 27$ ab

Dom. bckgd ($ee \rightarrow WW^*$): $\sigma = 20$ fb (S/B $\sim 10^{-3}$)

4) WW^* (2l2 ν): $\sigma = 6.7$ ab

Dom. bckgd ($ee \rightarrow WW^*$): $\sigma = 5$ fb (S/B $\sim 10^{-3}$)

5) gg (2 jets): $\sigma = 24$ ab

Dom. bckgd ($ee \rightarrow "gg"$): $\sigma = 0.9$ pb (S/B $\sim 10^{-4}$)

6) $\tau\tau$ (2 τ -jets): $\sigma = 7.5$ ab

Dom. bckgd ($ee \rightarrow \tau\tau$): $\sigma = 10$ pb (S/B $\sim 10^{-7}$)

7) ZZ^* (2j2 ν): $\sigma = 2.3$ ab

Dom. bckgd ($ee \rightarrow ZZ^*$): $\sigma = 213$ ab (S/B $\sim 10^{-2}$)

8) ZZ^* (2l2j): $\sigma = 1.14$ ab

Dominant bckgd ($ee \rightarrow ZZ^*$): $\sigma = 114$ ab (S/B $\sim 10^{-2}$)

9) ZZ^* (2l2 ν): $\sigma = 0.34$ ab

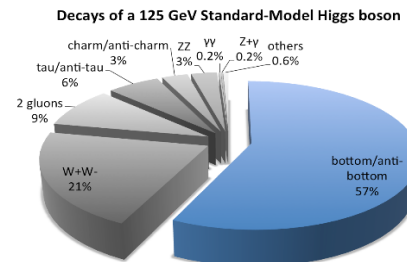
Dominant bckgd ($ee \rightarrow \tau\tau$): $\sigma = 10$ pb (S/B $\sim 10^{-8}$)

10) $\gamma\gamma$ (2 isolated γ): $\sigma = 0.65$ ab

Dominant bckgd ($ee \rightarrow \gamma\gamma$): $\sigma = 36$ pb (S/B $\sim 10^{-8}$)

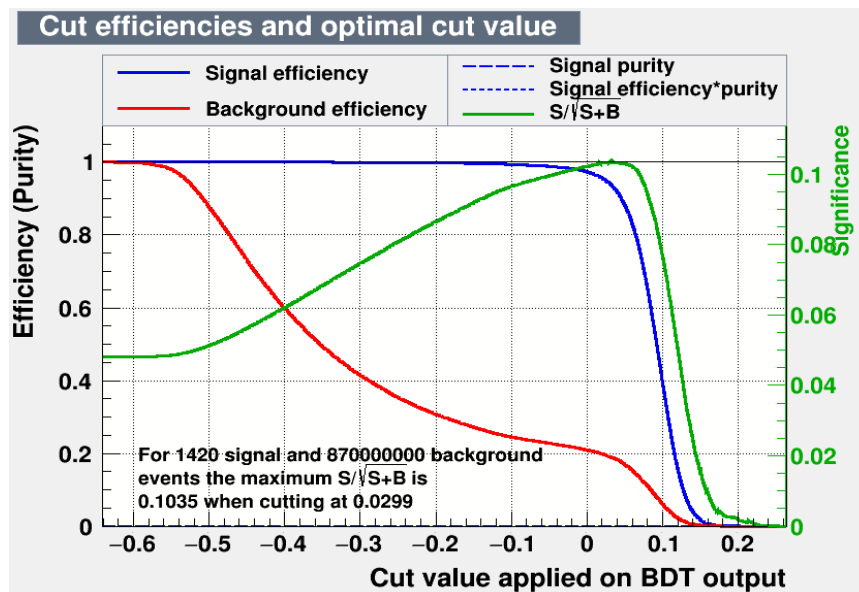
Channel 1: $e^+e^- \rightarrow H(bb) \rightarrow 2 \text{ b-jets}$

- Final state (retains 90% of $\sigma(bb) = 156 \text{ ab}$):
2 jets (exclusive) + 1 b-jet tagged + 0 $\tau(\text{had})$



- Analysis cuts:

- ✓ Kinematics: None.
- ✓ BDT MVA applied to reduce dominant $Z^*\gamma^* \rightarrow b\bar{b}$ continuum



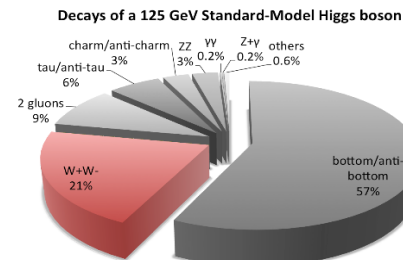
- Signal & backgds before/after MVA cuts:

$H(bb)$: $\sigma = 142 \text{ ab} \Rightarrow \sigma (\text{after}) = 131 \text{ ab}$
 $qqar$: $\sigma \approx 20 \text{ pb} \Rightarrow \sigma (\text{after}) = 17 \text{ pb}$
 $\tau\text{-}\tau$: $\sigma = 607 \text{ ab} \Rightarrow \sigma (\text{after}) = 375 \text{ ab}$

For $L_{\text{int}} = 10 \text{ ab}^{-1}$
 $S/\sqrt{B} = 1310/\sqrt{1.7e+8} \approx 0.1$
 Significance ≈ 0.1

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

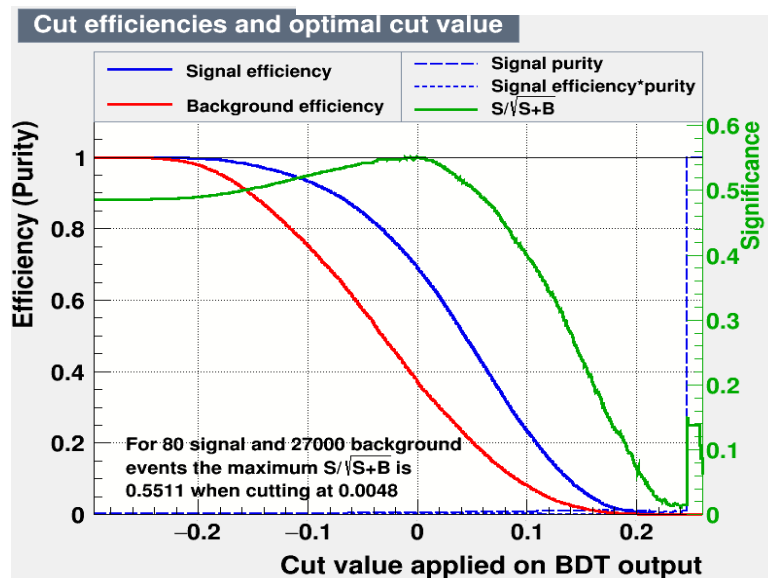
- Final state (retains 80% of $\sigma(WW^*(l\nu jj)) = 28$ ab):
1 isolated $e, \mu, \tau(e), \tau(\mu) + ME > 2$ GeV + 2 jets (excl.)



- 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 $\tau\text{-}\tau$
- ✓ BDT MVA ← Kills WW^* continuum

(exploits opposite W^\pm polarizations in H decay)



- Signal & backgrounds before/after cuts:

$H(WW^*)$: $\sigma = 23$ ab $\Rightarrow \sigma(\text{after}) = 8$ ab
 WW^* : $\sigma = 16.3$ fb $\Rightarrow \sigma(\text{after}) = 2.7$ fb
 qqbar: $\sigma = 22$ pb $\Rightarrow \sigma(\text{after}) = 4$ ab
 $\tau\text{-}\tau$: $\sigma = 1$ pb $\Rightarrow \sigma(\text{after}) = 2.6$ ab

For $L_{\text{int}} = 10$ ab⁻¹

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

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

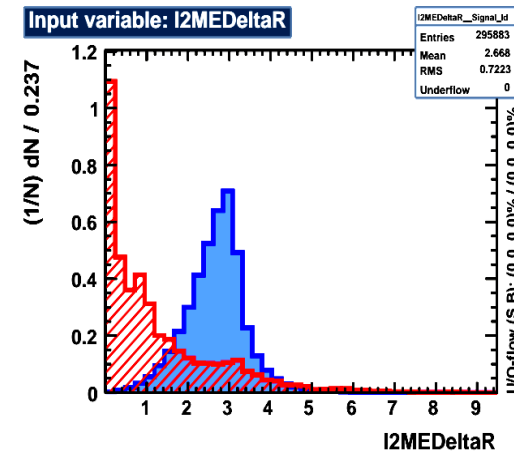
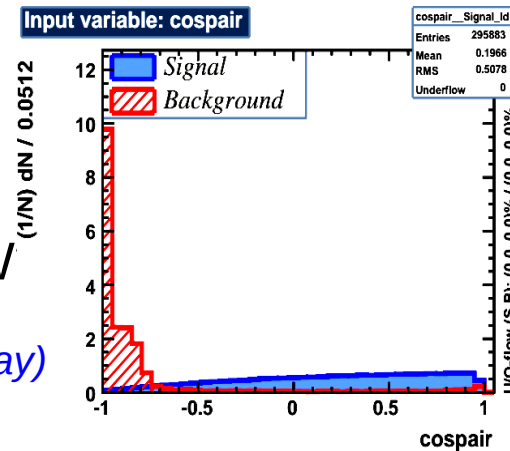
- Final state (retains 60% of $\sigma(WW^*(2l2\nu)) = 7$ ab):
 2 isolated $e, \mu, \tau(e), \tau(\mu) + ME > 2$ GeV
 + 0 non-isolated leptons or ch.had.

- Analysis cuts (Preselection kills qqbar entirely):

- ✓ $\cos(\theta_{l_1l_2}) > -0.6$ ← Kills $\tau\tau$
- ✓ $\Delta R(l_2, ME) > 1.5$ ← Kills $\tau\tau$
- ✓ $E_{l_1, l_2} > 3$ GeV ← Kills $\tau\tau$
- ✓ $ME > 20$ GeV ← Kills $\tau\tau$
- ✓ BDT MVA ← Kills WW

(indicative distributions only: normalized to 1)

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



- Signal & backgds before/after cuts:

$H(WW^*)$: $\sigma = 4$ ab $\Rightarrow \sigma(\text{after}) = 2.1$ ab

WW^* : $\sigma = 2.9$ fb $\Rightarrow \sigma(\text{after}) = 454$ ab

$\tau\tau$: $\sigma = 3.1$ pb $\Rightarrow \sigma(\text{after}) = 51$ ab

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

ZZ^* : $\sigma = 24$ ab $\Rightarrow \sigma(\text{after}) = 0.4$ ab

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

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

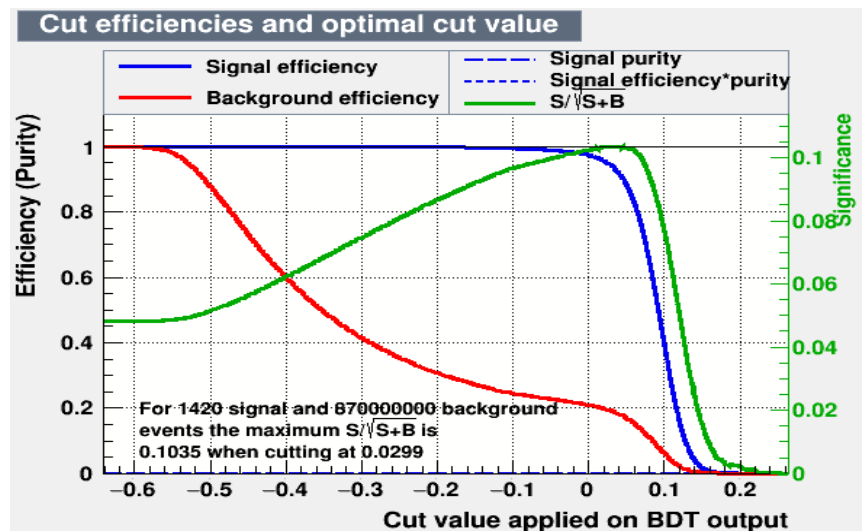
Significance ≈ 0.3

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 $e, \mu, \tau(e), \tau(\mu)$

Analysis cuts:

- ✓ $-\ln(y_{j3,jet4}) > 5.$, $E_{total} > 110$ GeV
- ✓ $\max(M_{jj}) = 60-85$ GeV/c²
- ✓ $|\Delta\phi_{Z \text{ decay planes}}| < 1.$
- ✓ BDT MVA



Signal & backgrounds before/after cuts:

$H(WW^*)$: $\sigma = 2.75$ ab \Rightarrow $\sigma(\text{after}) = 1.4$ ab
 $qq\bar{q}$: $\sigma = 15.7$ fb \Rightarrow $\sigma(\text{after}) = 2$ fb
 WW^* : $\sigma = 1.4$ fb \Rightarrow $\sigma(\text{after}) = 810$ ab
 $\tau\text{-}\tau$: $\sigma = 0$ ab \Rightarrow $\sigma(\text{after}) = 0$ ab
 ZZ^* : $\sigma = 4$ ab \Rightarrow $\sigma(\text{after}) = 1.38$ ab

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

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

- 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

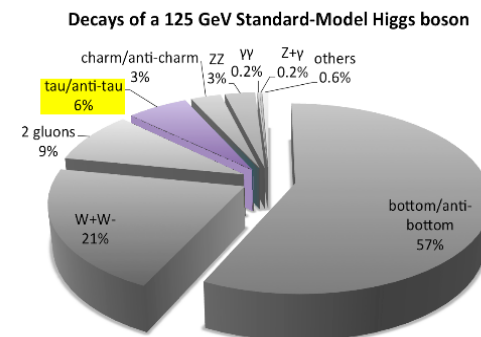
✓ MVA BDT applied to reduce dominant $Z^*/\gamma^* \rightarrow \tau\tau$ continuum.

- Signal & backgds before/after MVA cuts:

$H(\tau\tau)$: $\sigma = 7.4$ ab \Rightarrow σ (after) = 1.5 ab

qqbar: $\sigma = 87$ pb \Rightarrow σ (after) = 75 ab

τ - τ : $\sigma = 10$ pb \Rightarrow σ (after) = 100 fb



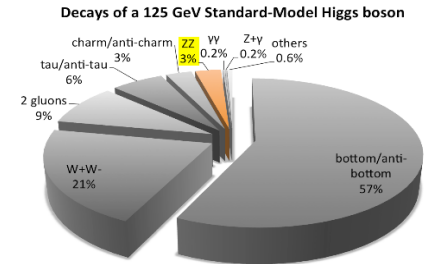
For $L_{\text{int}} = 10 \text{ ab}^{-1}$

$S/\sqrt{B} = 15/\sqrt{1e+6} \approx 0.02$

Significance ≈ 0.02

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

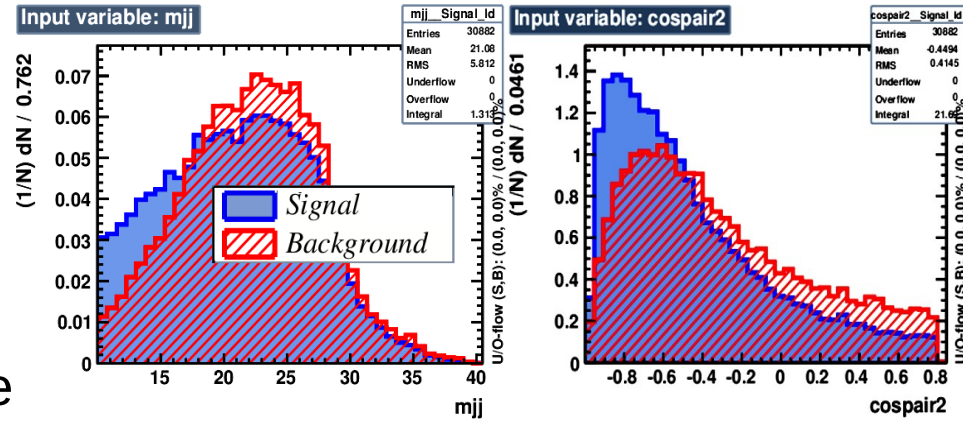
- Final state (retains 75% of $\sigma(WW^*(2j2\nu)) = 2.3$ ab):
 2 jets (excl.) + ME > 30 GeV
 + 0 isolated $e, \mu, \tau(e), \tau(\mu)$ + 0 $\tau(\text{had})$



Kinematic cuts:

- $\min(|m_{ME} - m_Z|, |m_{jj} - m_Z|) < 10$ GeV ← Kills qqbar, τ - τ
- $E_{\text{tot}} > 120$ GeV ← Kills qqbar, τ - τ
- $m_{ME} > 60$ GeV/c² ← 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/after

$H(ZZ^*)$: $\sigma = 1.75$ ab \Rightarrow $\sigma(\text{after cuts}) = 0.37$ ab

ZZ^* : $\sigma = 179$ ab \Rightarrow $\sigma(\text{after cuts}) = 25$ ab

qqbar: $\sigma = 963$ fb \Rightarrow $\sigma(\text{after cuts}) = 4$ ab

τ - τ : $\sigma = 471$ ab \Rightarrow $\sigma(\text{after cuts}) = 2$ ab

WW^* : $\sigma = 526$ ab \Rightarrow $\sigma(\text{after cuts}) = 0$ ab

For $L_{\text{int}} = 10$ ab⁻¹

$S/\sqrt{B} = 3.7/\sqrt{316} \approx 0.21$

Significance ≈ 0.21

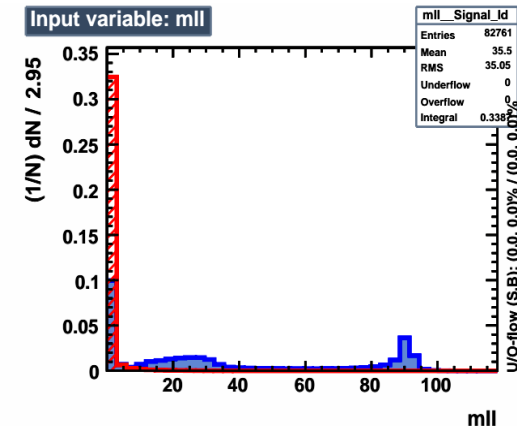
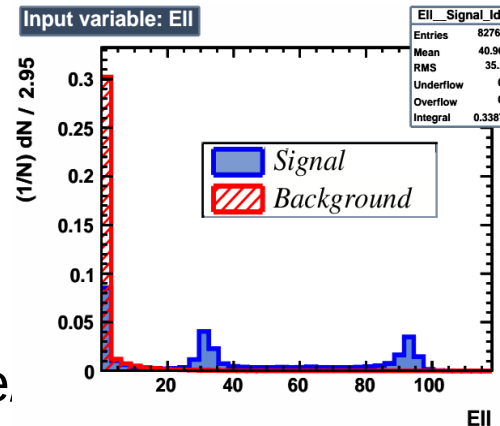
Channel 8: $e^+e^- \rightarrow H(ZZ^*) \rightarrow 2l2j$

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

Kinematic cuts:

- ✓ $\min(|M_{ll} - M_{Zl}|, |M_{jj} - M_{Zl}|) < 20 \text{ GeV}$ ← Kills qqbar, $\tau\text{-}\tau$
- ✓ $ME < 10 \text{ GeV}$
- ✓ $E_{\text{lepton}} > 6 \text{ GeV}$ ← Kills $\tau\text{-}\tau$
- ✓ $E_{l1} + E_{l2} > 20 \text{ GeV}$ ← Kills qqbar
- ✓ $M_{ll} > 20 \text{ GeV}/c^2$ ← Kills qqbar
- ✓ $M_{jj} > 10 \text{ GeV}/c^2$ ← Kills $\tau\text{-}\tau$

(indicative distributions only: normalized to 1)



Signal & backgrounds before

$H(ZZ^*)$: $\sigma = 0.84 \text{ ab} \Rightarrow \sigma(\text{after}) = 0.2 \text{ ab}$

ZZ^* : $\sigma = 87 \text{ ab} \Rightarrow \sigma(\text{after}) = 23 \text{ ab}$

$\tau\text{-}\tau$: $\sigma \sim 0.8 \text{ pb} \Rightarrow \sigma(\text{after}) = 2.5 \text{ ab}$

WW^* : $\sigma = 3.1 \text{ fb} \Rightarrow \sigma(\text{after}) = 0.04 \text{ ab}$

qqbar: $\sigma = 17 \text{ pb} \Rightarrow \sigma(\text{after}) = 4 \text{ ab}$

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

$S/\sqrt{B} = 2.7/\sqrt{296} \approx 0.16$

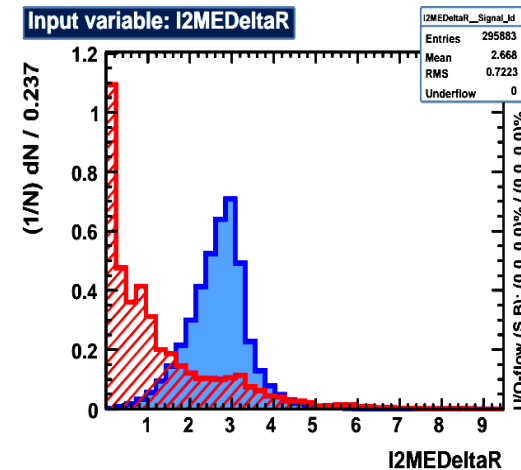
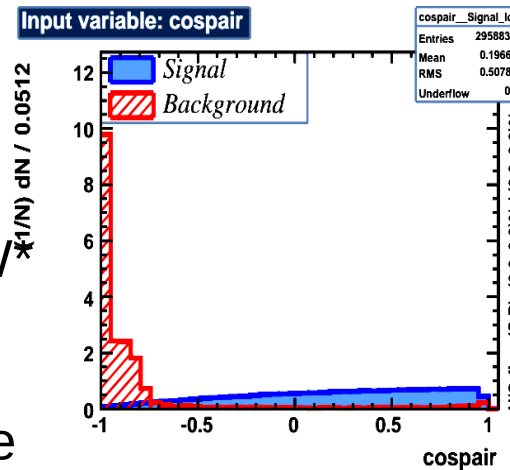
Significance ≈ 0.16

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):

- ✓ $\cos(\theta_{l1l2}) > -0.6$ ← Kills $\tau\text{-}\tau$
- ✓ $\Delta R(l_2, ME) > 1.5$ ← Kills $\tau\text{-}\tau$
- ✓ $E_{l1, l2} > 3$ GeV ← Kills $\tau\text{-}\tau$
- ✓ $ME > 20$ GeV ← Kills $\tau\text{-}\tau$
- ✓ BDT MVA ← Kills WW

(indicative distributions only: normalized to 1)



- Signal & backgds before/afte

H(ZZ*): $\sigma = 0.2$ ab $\Rightarrow \sigma(\text{after}) = 0.04$ ab

WW*: $\sigma = 29$ fb $\Rightarrow \sigma(\text{after}) = 144$ ab

$\tau\text{-}\tau$: $\sigma = 3.1$ pb $\Rightarrow \sigma(\text{after}) = 51$ ab

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

ZZ*: $\sigma = 24$ ab $\Rightarrow \sigma(\text{after}) = 9$ ab

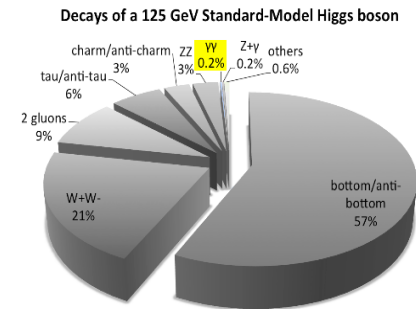
For $L_{\text{int}} = 10$ ab⁻¹

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

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:

✓ $E_\gamma > 60$ 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:

$H(\gamma\gamma)$: $\sigma = 0.61$ ab \Rightarrow σ (after) = 0.3 ab

$\gamma\gamma$: $\sigma = 25$ pb \Rightarrow σ (after) = 900 fb

e^+e^- : $\sigma = 2.3$ pb \Rightarrow σ (after) = 59 ab

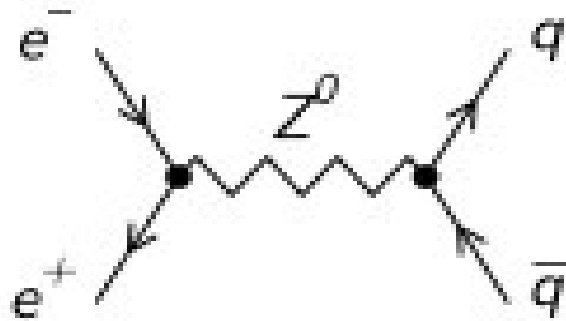
For $L_{\text{int}} = 10$ ab $^{-1}$

$S/\sqrt{B} = 30/\sqrt{1.e4} \approx 0.01$

Significance ≈ 0.01

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

- The $q\bar{q}$ background $\sigma \sim O(100 \text{ pb})$ produces mainly 2-jet events, which can be killed by cutting on event shape variables (sphericity & aplanarity), but $\sim 6 \text{ pb}$ remains from quarks that radiate gluons to produce 4-jet events.



- Tagging b-jets (which are produced $\sim 20\%$ of the time in the $q\bar{q}$ background and $\sim 5\%$ of the time in the signal) and removing events with any b-tagged jets provides marginal improvement in separation, but the $q\bar{q}$ 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 ...