

Physics & operational requirements for FCC-ee monochromatization

FCC EPOL workshop

CERN, 20th Sept. 2022

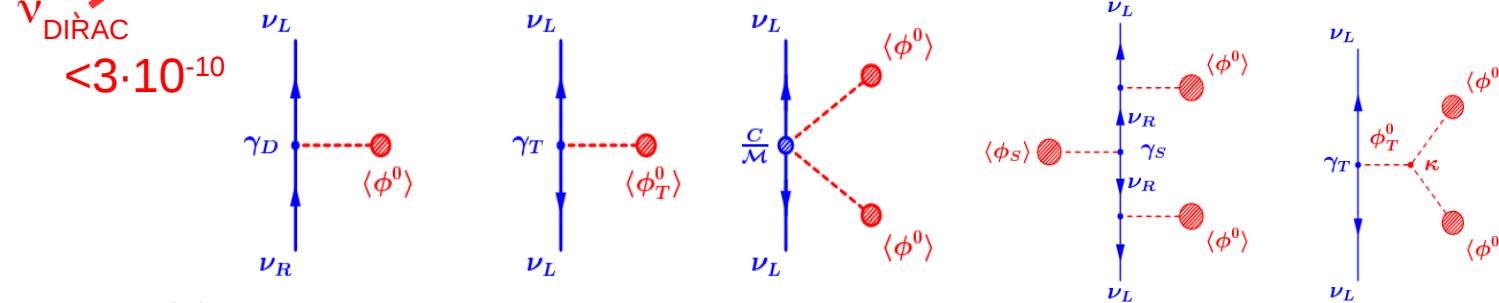
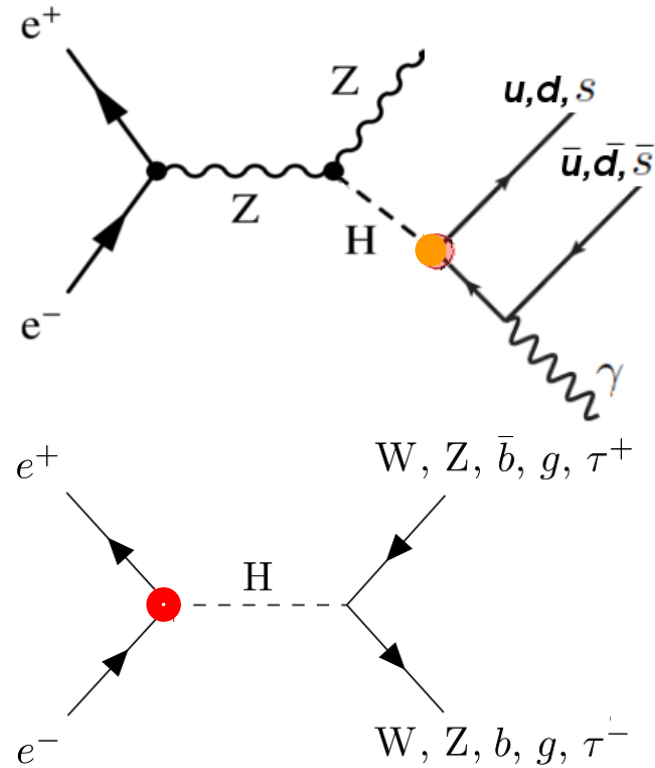
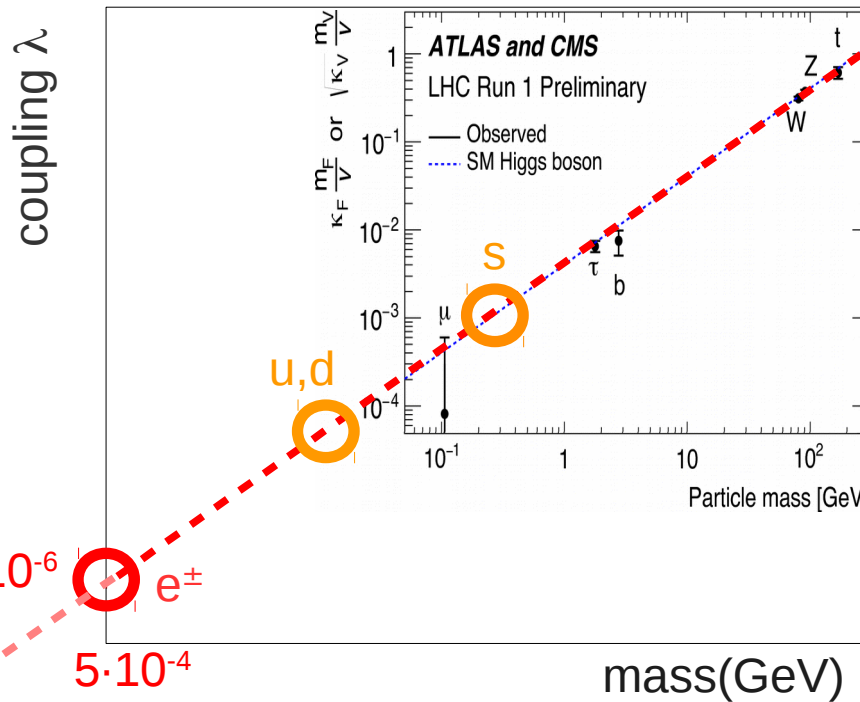
David d'Enterria (CERN)



[Details in: [arXiv:2107.02686](https://arxiv.org/abs/2107.02686)]

Generation of lightest fermion masses?

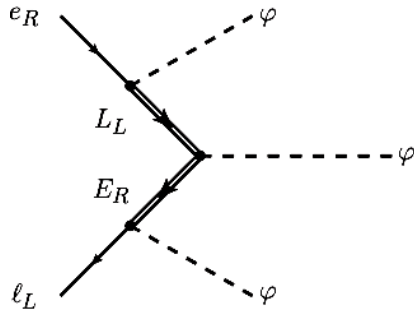
- LHC can only measure 3rd (plus a few 2nd) generation Yukawas.
- Can we **prove mass generation for stable (u,d,e,v) matter** in the Universe?



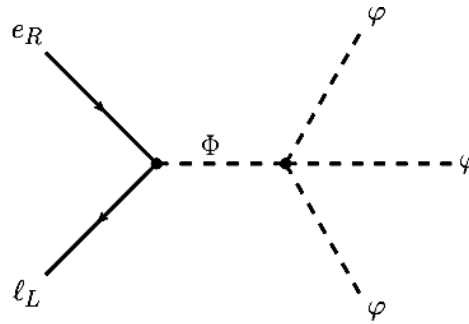
BSM electron Yukawa

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

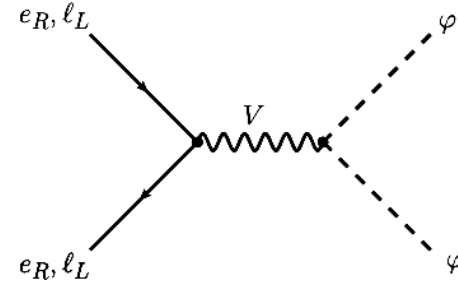
■ Lowest order **dim-6 operators** with BSM electron Yukawa:



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** (κ_e indicates modification wrt. $\kappa_e^{\text{SM}}=1$):

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

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

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

	LHC8 (25/fb)	$ \kappa_e \lesssim 600$	$M \gtrsim 6 \text{ TeV}$
$h \rightarrow e^+e^-$	LHC13 (130/fb)	$ \kappa_e \sim 260, 240$	$M \sim 9 \text{ TeV}$ (CMS)
	LHC14 (3/ab)	$ \kappa_e \sim 150$	$M \sim 12 \text{ TeV}$
	100 TeV (3/ab)	$ \kappa_e \sim 75$	$M \sim 17 \text{ TeV}$
	LEP II	$ \kappa_e \lesssim 2000$	$M \gtrsim 3 \text{ TeV}$
$e^+e^- \rightarrow h$	FCC-ee (100/fb)	$ \kappa_e \sim 10$	$M \sim 50 \text{ TeV}$
	current	$\text{Re } \kappa_e \lesssim 3000$	$M \gtrsim 2.5 \text{ TeV}$
$(g-2)_e$	future	$\text{Re } \kappa_e \sim 300$	$M \sim 8 \text{ TeV}$

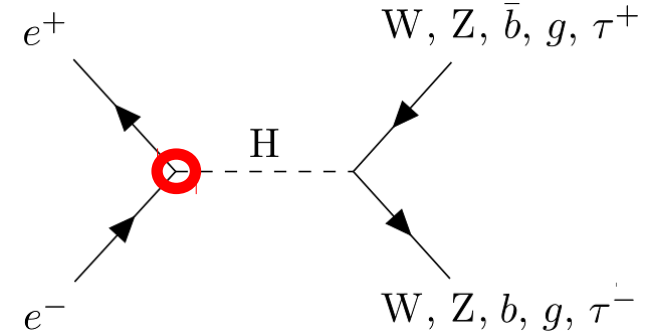
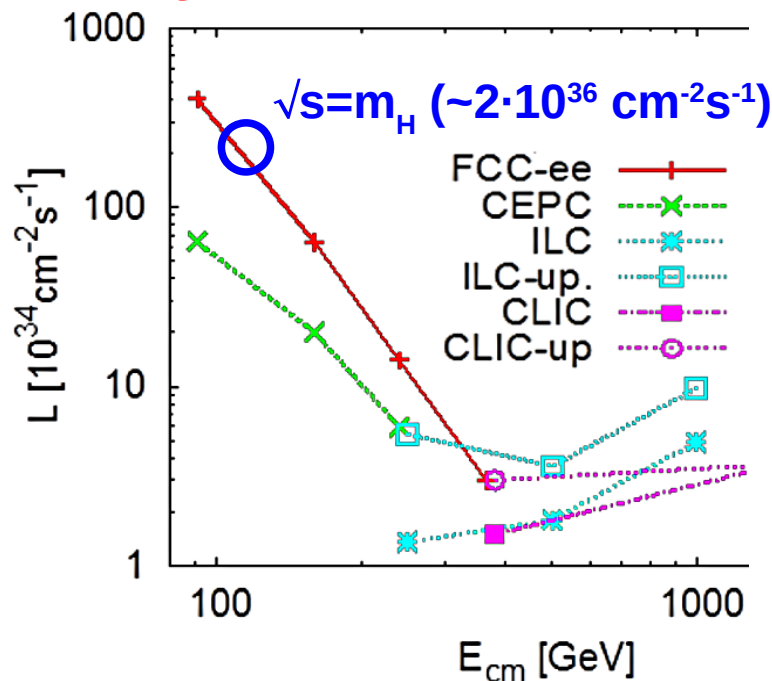
■ Note: Unsuppressed **dim-10 BSM operators** also possible.

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

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

$$\sigma(e^+e^- \rightarrow H) = \frac{4\pi\Gamma_H^2 Br(H \rightarrow e^+e^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2} = 1.64 \text{ fb } (m_H=125 \text{ GeV}, \Gamma_H=4.1 \text{ MeV})$$

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



In theory, FCC-ee running at H pole-mass

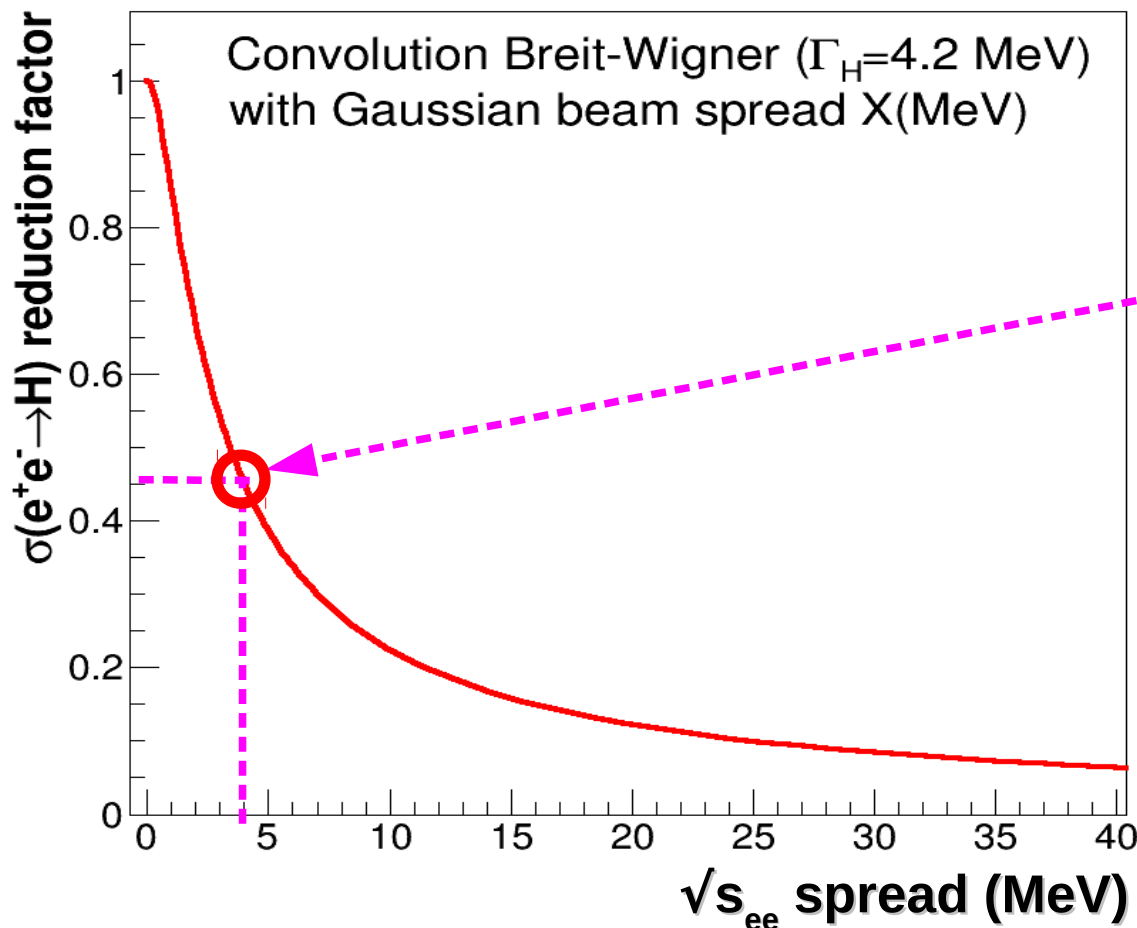
$\mathcal{L}_{int} \approx 20 \text{ ab}^{-1}/\text{yr}$ would produce $O(30.000)$ H's

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 $\Gamma_H = 4.1 \text{ MeV}$ 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**:



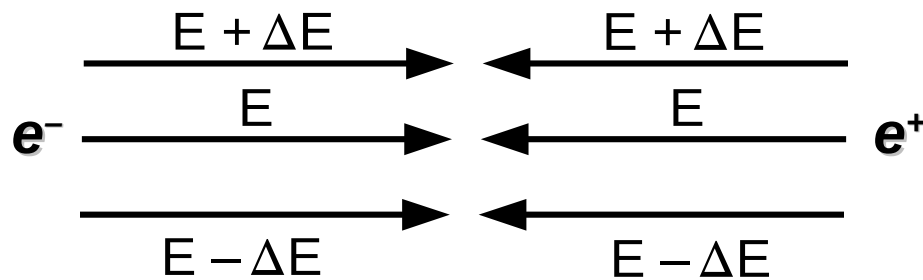
$\sqrt{s_{\text{spread}}} = \Gamma_H = 4.1 \text{ MeV}$
~45% x-section reduction

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

Beams monochromatization in e^+e^- collisions

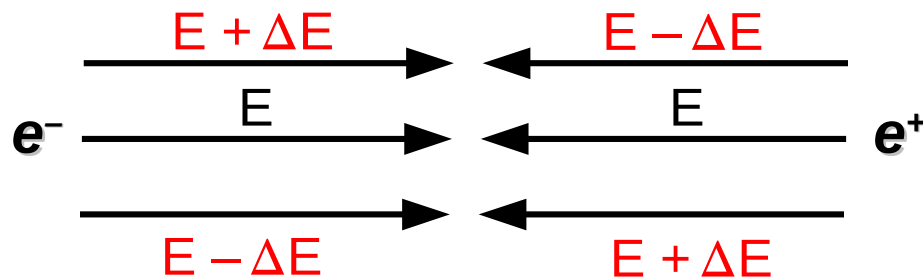
- **Standard** collision:
Dispersion has the **same** sign at the IP:

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



- **Monochromatization**:
Dispersion has **opposite** sign at the IP:

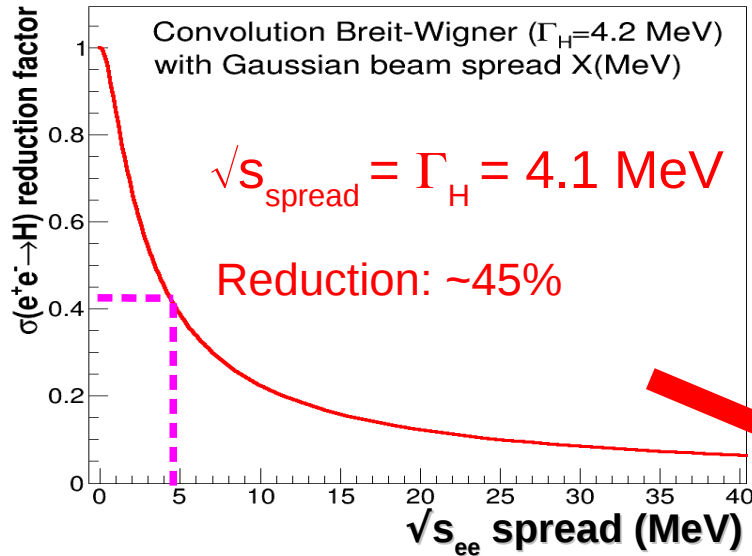
$$w = 2 E_0 + O(\varepsilon^2)$$



Enhanced c.m. energy resolution, and in some cases increase of the relative frequency of events at the centre of the distribution.

[F.Zimmermann, A.Valdivia: JACoW-IPAC2017-WEPIK015
JACoW-IPAC2019-MOPMP035
A.Faus-Golfe et al. EPJ+137(2022)]

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

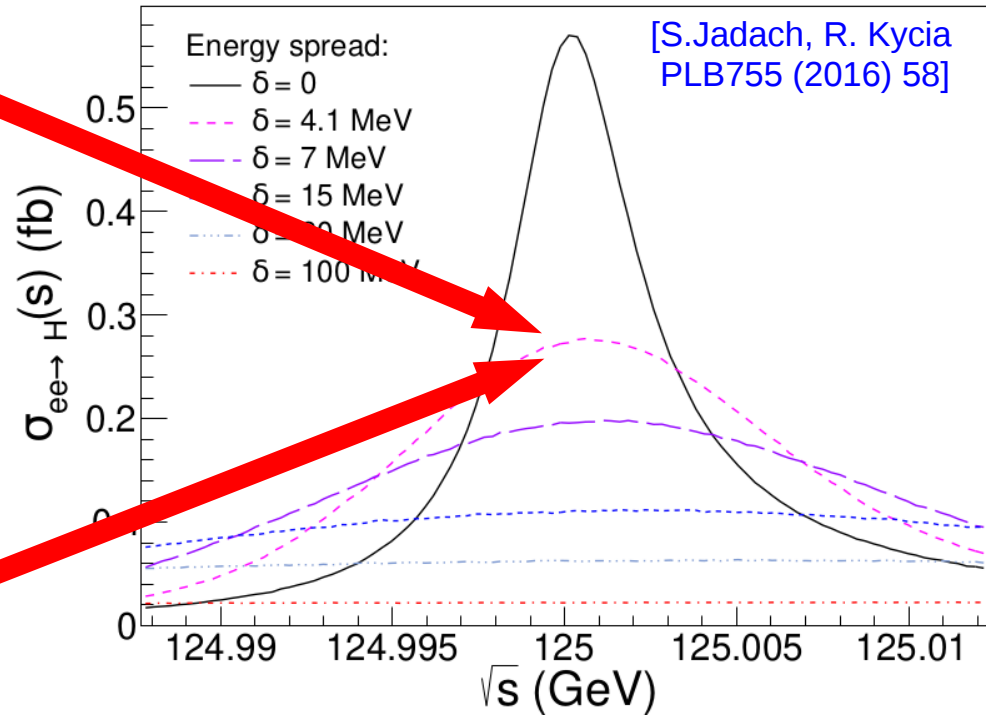
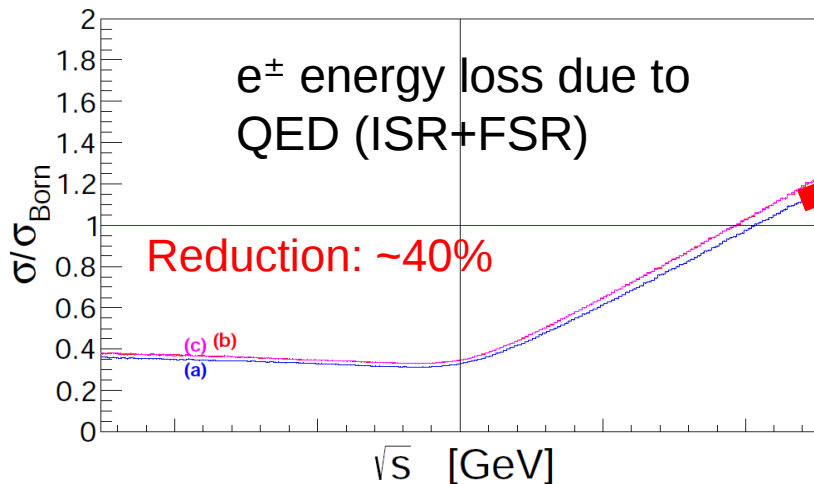


Assume monochromatization ref. point:

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

■ Full convolution of both effects:

■ Extra ~40% reduction due to QED radiation:

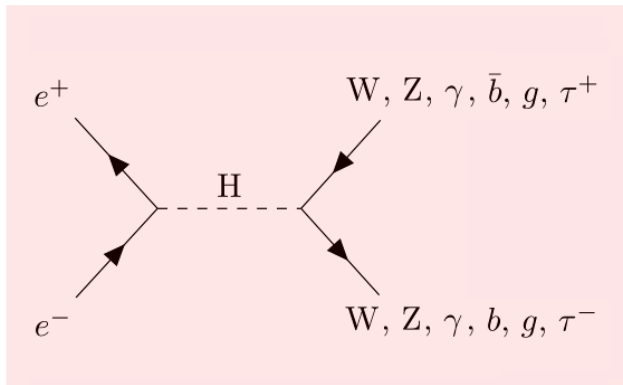


$$\sigma_{\text{spread+ISR}}(e^+e^- \rightarrow H) = 0.17 \times \sigma(e^+e^- \rightarrow H) = 280 \text{ ab}$$

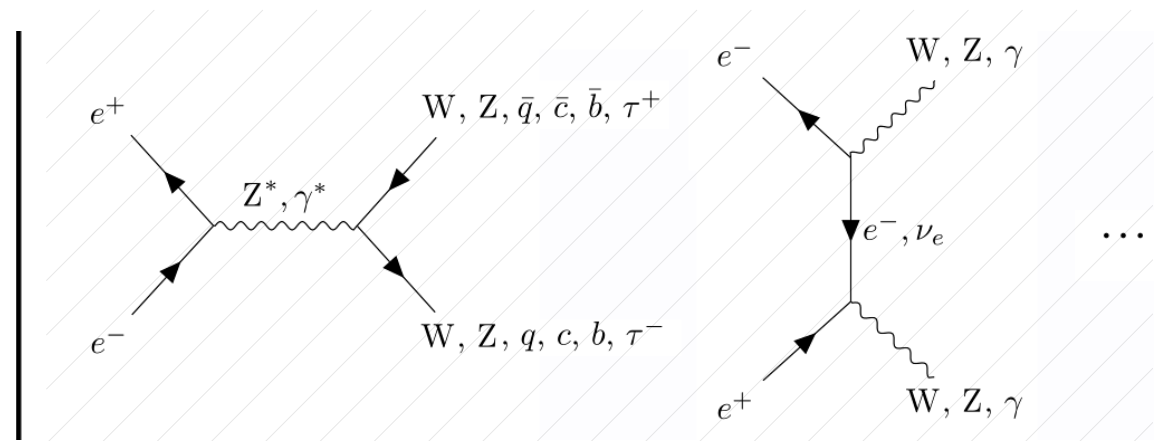
Signal & backgrounds simulation

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

SIGNALS



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



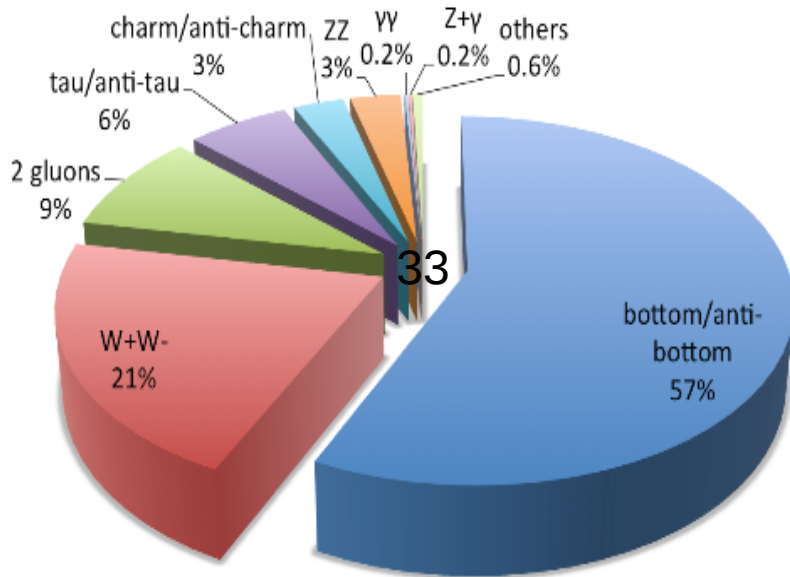
(other SM loop-induced $e^+e^- \rightarrow H$ found negligible)

- **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:

Decays of a 125 GeV Standard-Model Higgs boson



- Other 4-jet final states, e.g. $H \rightarrow ZZ^*(4j)$ swamped by $e^+e^- \rightarrow Z^*, \gamma^* \rightarrow q\bar{q}$ (100 pb),
- 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

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



Event reconstruction, preselection, MVA

- Signal & backgd events showered/hadronized/decayed with PYTHIA8. Final-state particles **acceptance**: $5^\circ < \theta < 175^\circ$.

Jet reco: k_T algorithm for $N_j=2,4$ exclusive jets. **Isolation**: $\Sigma E < 1$ GeV, $\Delta R < 0.25$

- Assumed **reconstruction (in)efficiencies** for jets (uds, g, c, b), tau, γ , e:

	<i>b</i> jets	<i>c</i> jets	gluon jets	τ_{had} (hadron decays)	γ, e^\pm
reco/tagging efficiency (ε_i)	80%	70%	70%	80%	100%
mistagging rates ($\varepsilon_{j \rightarrow i}^{\text{mistag}}$)	1% (for <i>c</i> jet)	5% (for <i>b</i> jet)	1% (for <i>uds</i> jets)	$\sim 0\%$ (for <i>b, c</i> -jets)	0.01% (e^\pm for γ)
	0.01% (for <i>uds</i> jets)	0.1% (for <i>uds</i> jets)	0.001, 0.01% (for <i>b, c</i> -jets)	$\sim 0\%$ (for <i>uds</i> jets)	

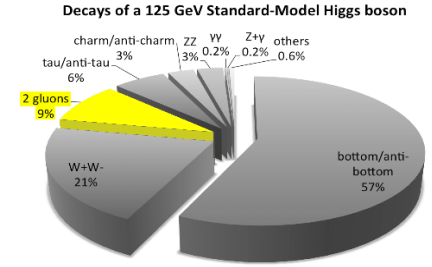
- Final-state **Higgs signal definitions (preselection to eliminate reducible backgds)**:

Target Higgs decay	Final state definition	Signal presel. efficiency
$H \rightarrow b\bar{b}$	2 (excl.) jets, 1 <i>b</i> -tagged jet, no τ_{had}	80%
$H \rightarrow gg$	2 (excl.) gluon-tagged jets, 0 isolated ℓ^\pm	50%
$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}$	Exactly 2 τ_{had} , 0 isolated ℓ^\pm	65%
$H \rightarrow c\bar{c}$	2 (excl.) jets, 1 <i>c</i> -tagged jet, no τ_{had}	70%
$H \rightarrow WW^* \rightarrow \ell\nu 2j$	1 isolated ℓ^\pm , $E_{\text{miss}} > 2$ GeV, 2 (excl.) jets	$\sim 100\%$
$H \rightarrow WW^* \rightarrow 2\ell 2\nu$	2 isolated opp.-charge ℓ^\pm , $E_{\text{miss}} > 2$ GeV, 0 non-isol. ℓ^\pm , 0 charged hadrons	$\sim 100\%$
$H \rightarrow WW^* \rightarrow 4j$	4 (excl.) jets, ≥ 1 <i>c</i> -tag jets, 0 <i>b, g</i> -tag jets; jets with $m_{j_1 j_2} \approx m_W$ not both <i>c</i> -tagged, 0 τ_{had} , 0 isolated ℓ^\pm	70%
$H \rightarrow ZZ^* \rightarrow 2j 2\nu$	2 (excl.) jets, $E_{\text{miss}} > 30$ GeV, 0 isolated ℓ^\pm , 0 τ_{had}	$\sim 100\%$
$H \rightarrow ZZ^* \rightarrow 2\ell 2j$	2 isolated opposite-charge ℓ^\pm , 2 (excl.) jets, 0 τ_{had}	$\sim 100\%$
$H \rightarrow ZZ^* \rightarrow 2\ell 2\nu$	2 isolated opp.-charge ℓ^\pm , $E_{\text{miss}} > 2$ GeV, 0 non-isol. ℓ^\pm , 0 charged hadrons	$\sim 100\%$
$H \rightarrow \gamma\gamma$	2 (excl.) isolated photons	$\sim 100\%$

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

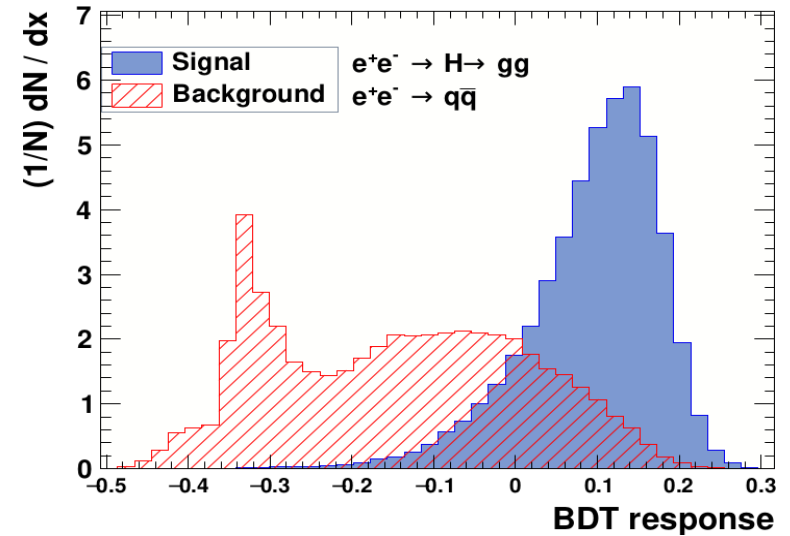
Most significant channel: $e^+e^- \rightarrow H(gg) \rightarrow jj$

- Final state definition (retains 50% of $\sigma(gg) = 24$ ab):
 - 2 gluon-tagged jets (with 70% effic. each)
 - Light-q mistagging rate: $\sim 1\%$
 - 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 vs. uds discrimination):

Signal reduction $\sim 50\%$
 Backgd. reduction: $\times 17$



- Signal & backgrounds cross sections cut flow:

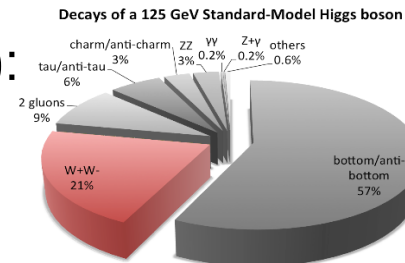
Process	Events	Passes	+ cuts	+ MVA	raw σ	Tagrate	Pass+Tag	+ Cut	Final σ
Hgg	100000	85315	80350	45440	25 ± 0 ab	70% ²	10 ab	9.7 ab	5.5 ± 0.0 ab
bb	199981	140057	12532	1331	81 ± 0 pb	0.0% ²	0 pb	0 pb	0 ± 0 pb
cc	200000	174120	28282	1984	73 ± 0 pb	0.0% ²	0 pb	0 pb	0 ± 0 pb
qq	200000	186171	36888	2015	237 ± 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 $\mathcal{L}_{int} = 10 \text{ ab}^{-1}$
 $S/\sqrt{B} = 55/\sqrt{2500} \approx 1.1$
 Significance ≈ 1.1

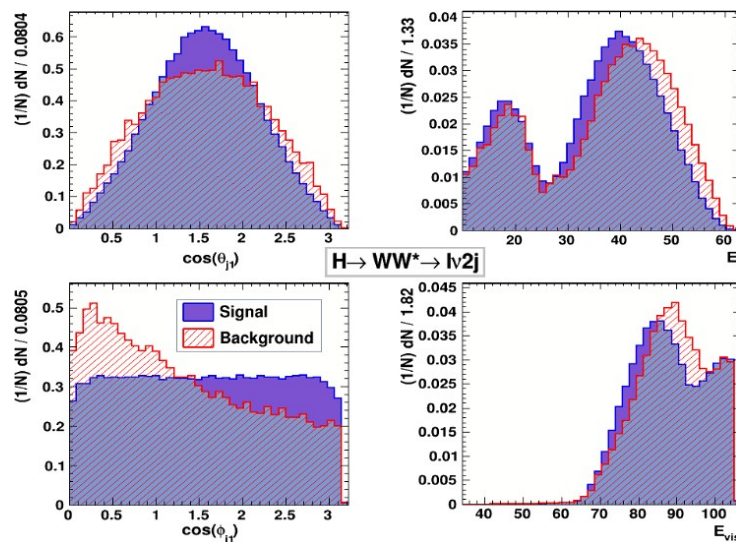
2nd most significant channel: $e^+e^- \rightarrow H(WW^*) \rightarrow l\nu jj$

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



- Analysis cuts (from MVA):

- ✓ $E_{j1,j2} < 52,45$ 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 cross sections **cut flow**:

Process	Events	Passes	+ cuts	+ MVA	raw σ	Tagrate	Pass+Tag	+ Cut	Final σ
HWWjjl ν	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	200961 ⁰	2	0	81 \pm 0 pb	100% ²	16 pb	161 ab	0 \pm 81 ab
cc	1000000	63844 ⁰	0	0	73 \pm 0 pb	100% ²	4.7 pb	0 pb	0 \pm 73 ab
qq	1000000	7675 ⁰	0	0	237 \pm 0 pb	100% ²	1.8 pb	0 pb	0 \pm 237 ab
tautau	20000	8359 ⁰	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 $\mathcal{L}_{int} = 10$ ab⁻¹
 $S/\sqrt{B} = 55/\sqrt{11000} \approx 0.5$
 Significance ≈ 0.5

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

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

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

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

- Channels significance & combination via **RooStats-based** LHC Higgs tool: **Profile likelihood** & hybrid **significances** give \sim identical results, which are also very close to naive S/\sqrt{B} expectation (due to 10^{-4} bckgd. relat. uncert.):

$H \rightarrow g\bar{g}$	$H \rightarrow WW^* \rightarrow \ell\nu 2j; 2\ell 2\nu; 4j$	$H \rightarrow ZZ^* \rightarrow 2j 2\nu; 2\ell 2j; 2\ell 2\nu$	$H \rightarrow b\bar{b}$	$H \rightarrow \tau_{\text{had}}\tau_{\text{had}}; c\bar{c}; \gamma\gamma$	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

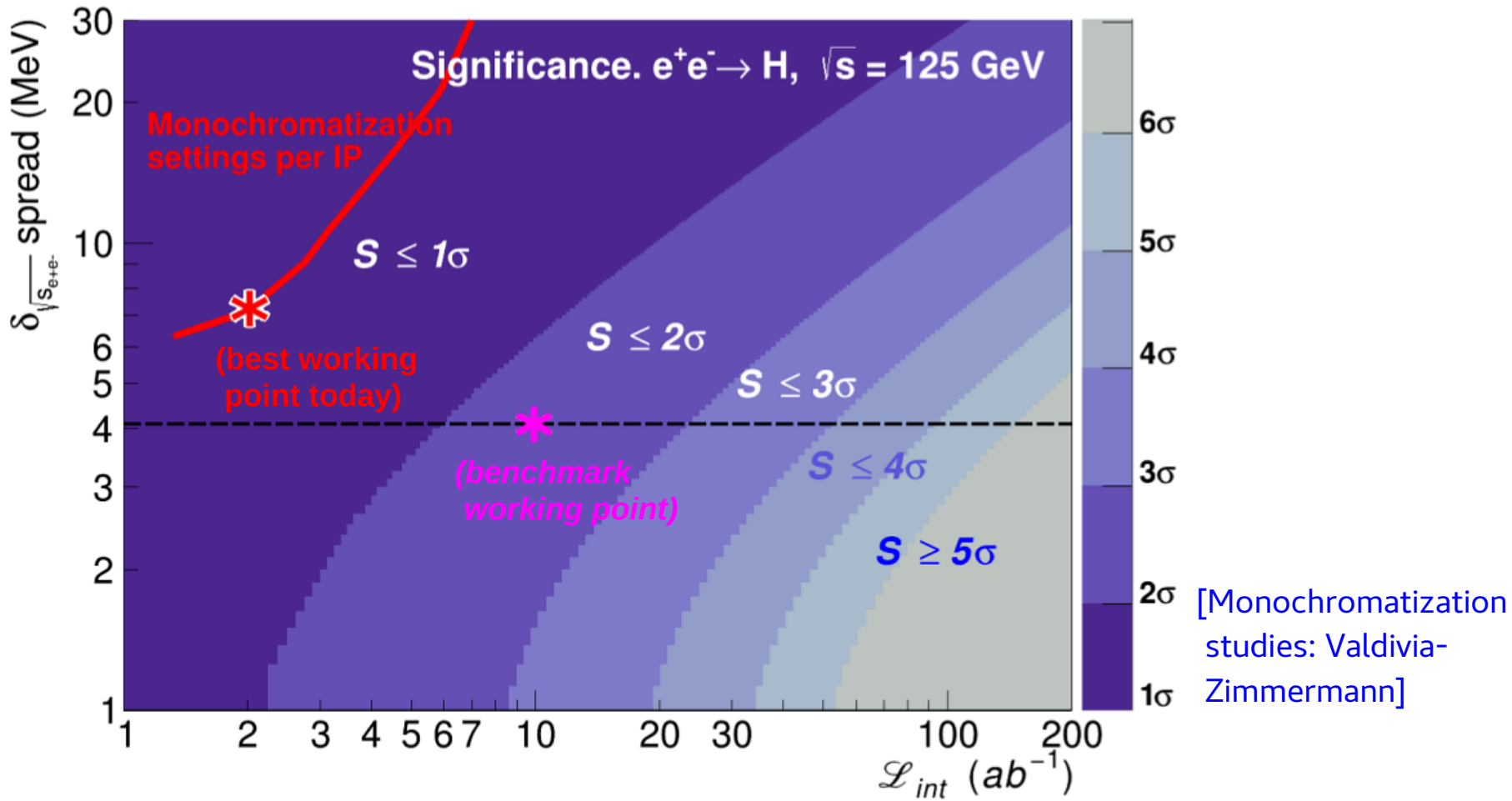
- For our benchmark $\sqrt{s}_{\text{spread}} = 4 \text{ MeV}$ & $\mathcal{L}_{\text{int}} = 10 \text{ ab}^{-1}$:

Significance $\approx 1.3\sigma$ \Rightarrow Limit (95% CL) for SM Yukawa: $y_e < 1.6 \times y_{e,\text{SM}}$

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

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

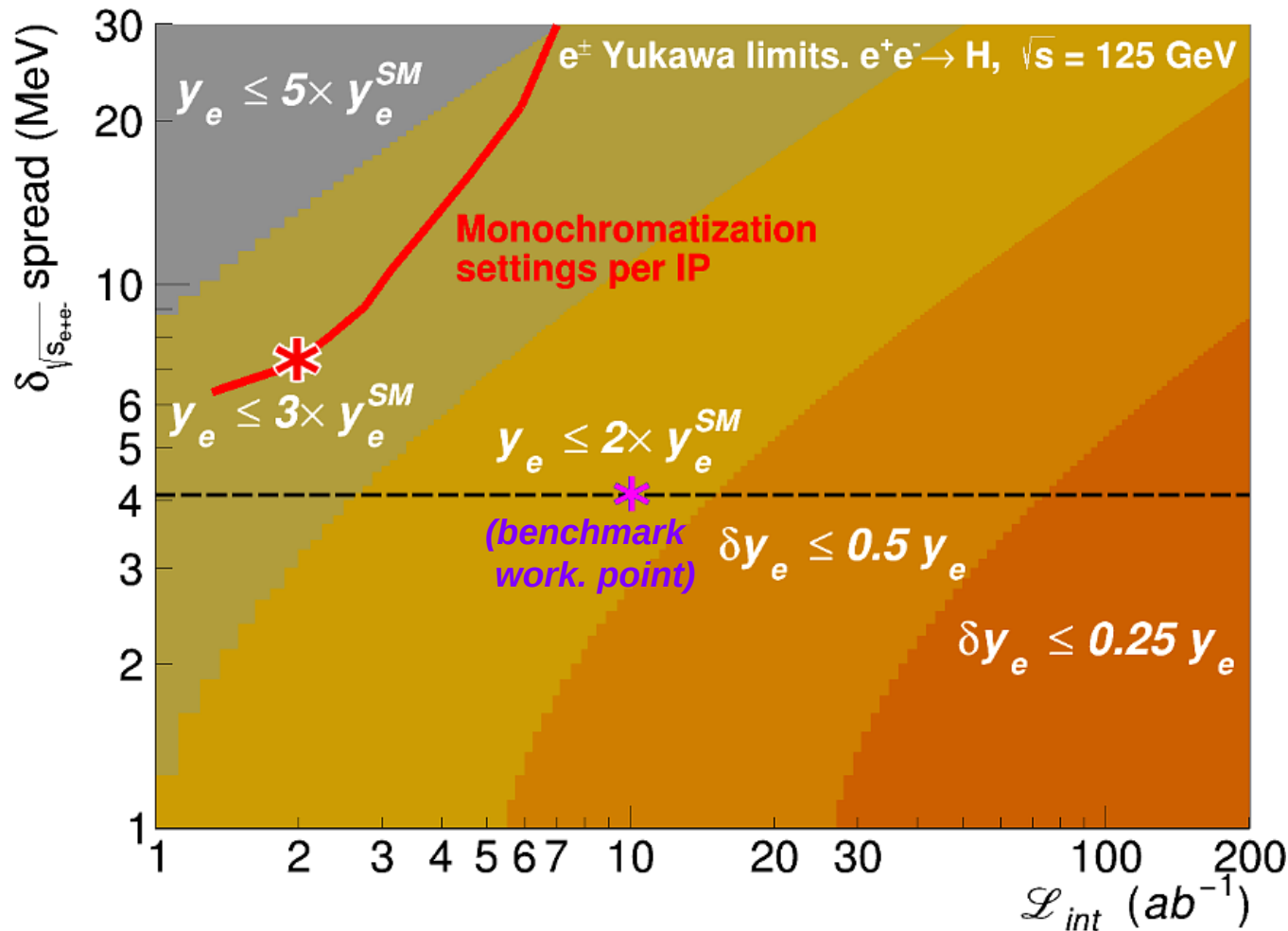
- Monochromatization working points (\sqrt{s}_{spread} vs. \mathcal{L}_{int} per IP/year):



- Best significance $\approx 0.4\sigma$ in $(\sqrt{s}_{\text{spread}} = 7\text{--}10$ MeV, $\mathcal{L}_{\text{int}} = 2\text{--}3$ ab^{-1}) region.

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

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

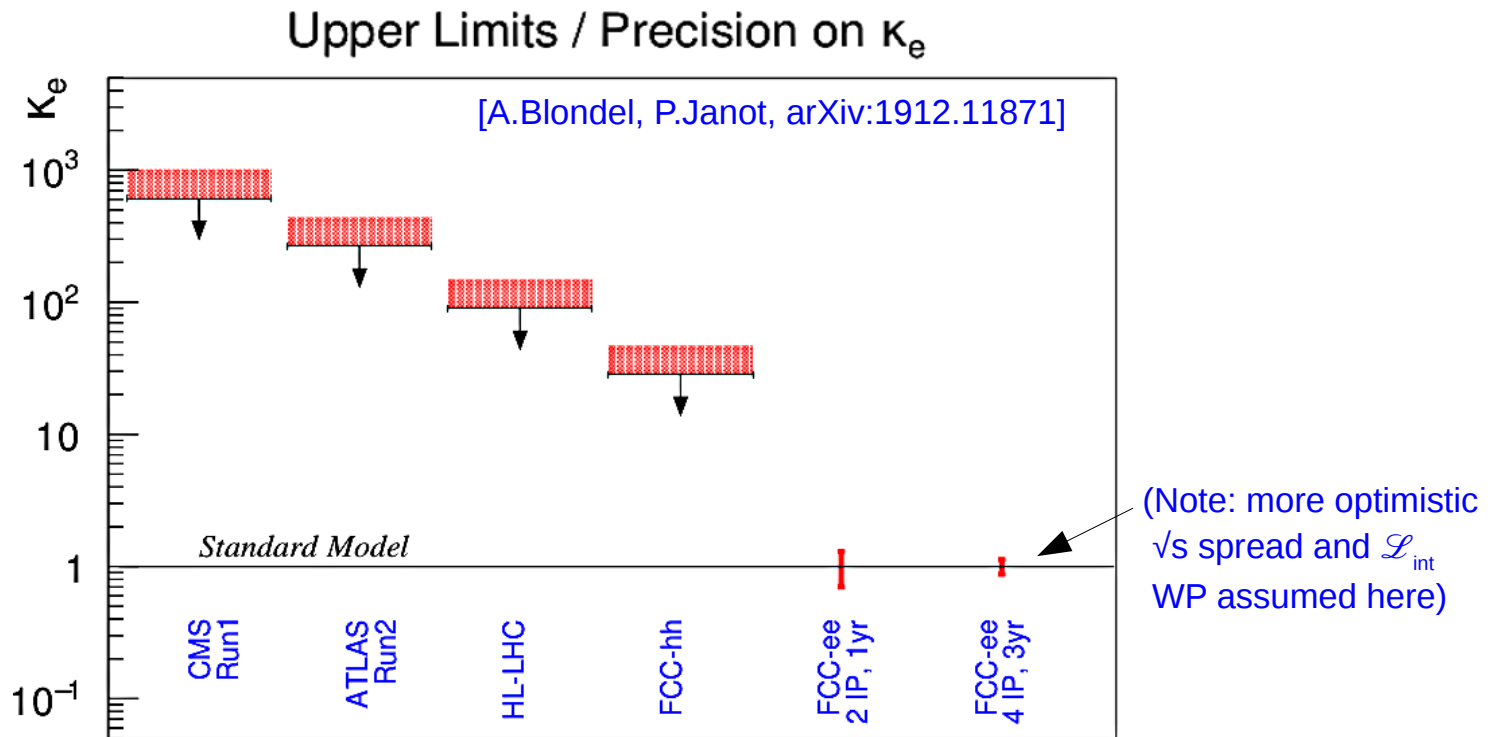


[Monochromatization studies: Valdivia-Zimmermann]

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

Electron Yukawa limits at various machines

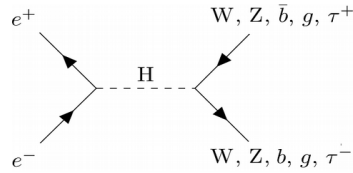
- Hadron machines can **very loosely constrain** y_e via $H \rightarrow e^+e^-$ searches on top of **huge DY (and $H \rightarrow \gamma\gamma$)** backgrounds:



- Combining up to 4 IPs & running a few years we are at SM y_e values.
- Limits on y_e are about **×100 (×20)** better than at HL-LHC (FCC-hh).

Conclusions

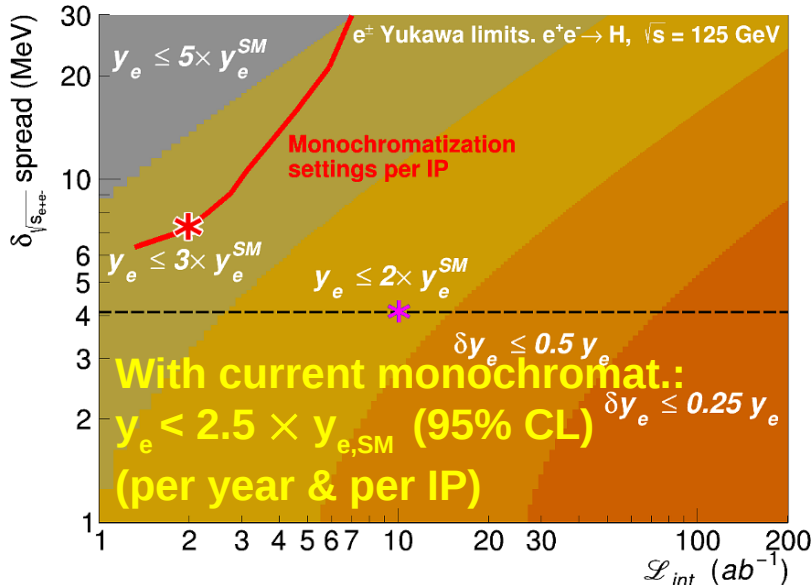
- Resonant s-channel Higgs production at FCC-ee ($\sqrt{s} = 125.00$ GeV):



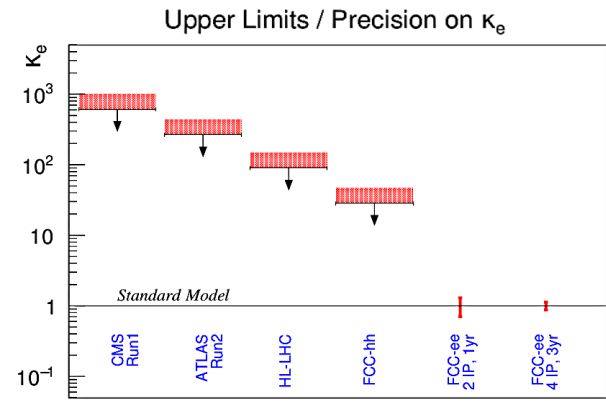
$$\sigma(e^+e^- \rightarrow H)_{B-W} = 1.64 \text{ fb}$$

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

- Prerequisite: Higgs mass extraction $\delta m_H = O(3 \text{ MeV})$ via HZ @ 240,217 GeV
- Generator-level 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} & $\sqrt{s}_{\text{spread}} = \Gamma_H$: $\text{Signif} \approx 1.3\sigma$



- Monochromatization improvable beyond $(\sqrt{s}_{\text{spread}}, \mathcal{L}_{\text{int}}) \approx (7 \text{ MeV}, 2 \text{ ab}^{-1})$?
- Fundamental unique physics accessible:
 - Electron Yukawa coupling: Limits $\times 100$ ($\times 20$) better than HL-LHC (FCC-hh)
 - BSM scale affecting e^\pm Yukawa pushed up to $\Lambda_{\text{BSM}} > 110 \text{ TeV}$

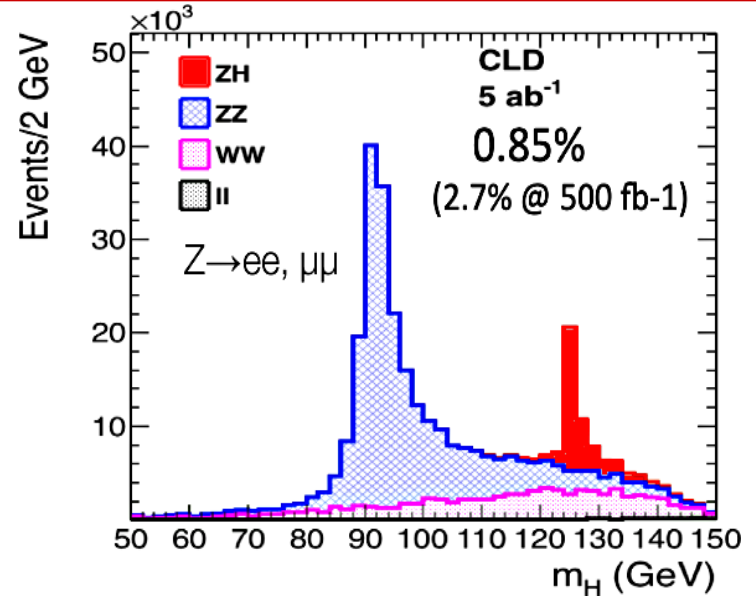
Backup slides

Accurate m_H needed to run at resonant peak

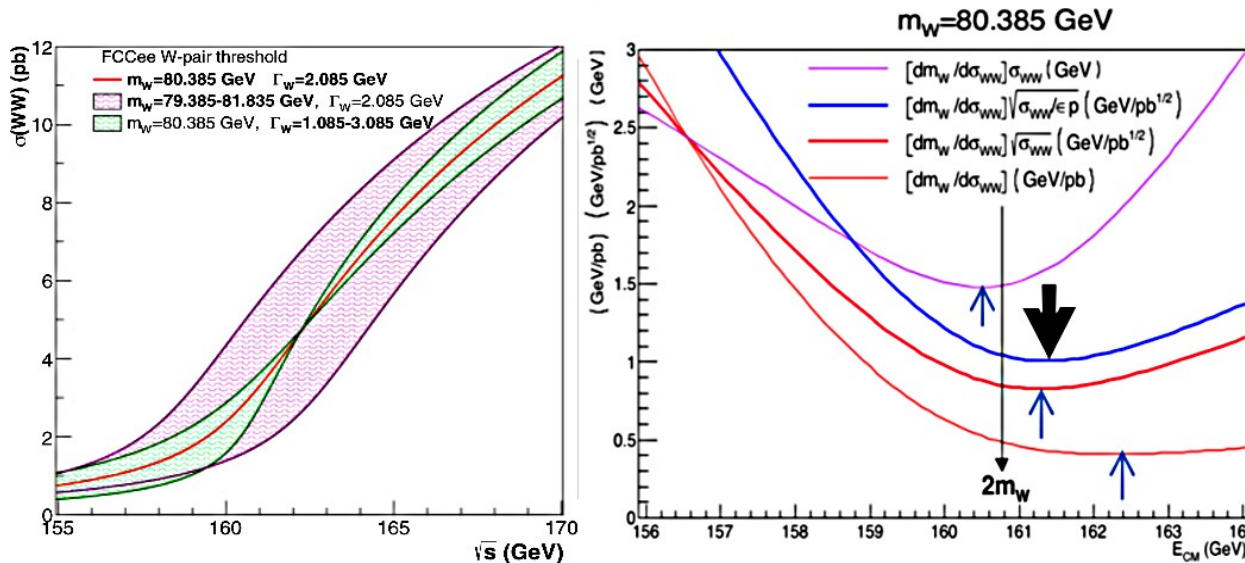
- $e^+e^- \rightarrow H Z(l^+l^-)$ recoil method:
allows Higgs mass reconstruction
with $\delta m_H = 8 \text{ MeV}$ in $Z \rightarrow \mu^+\mu^-$

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

$(\delta m_H = \pm 5 \text{ MeV}$ 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:
 $\delta m_W(\text{stat}) = \pm 0.5 \text{ MeV}$

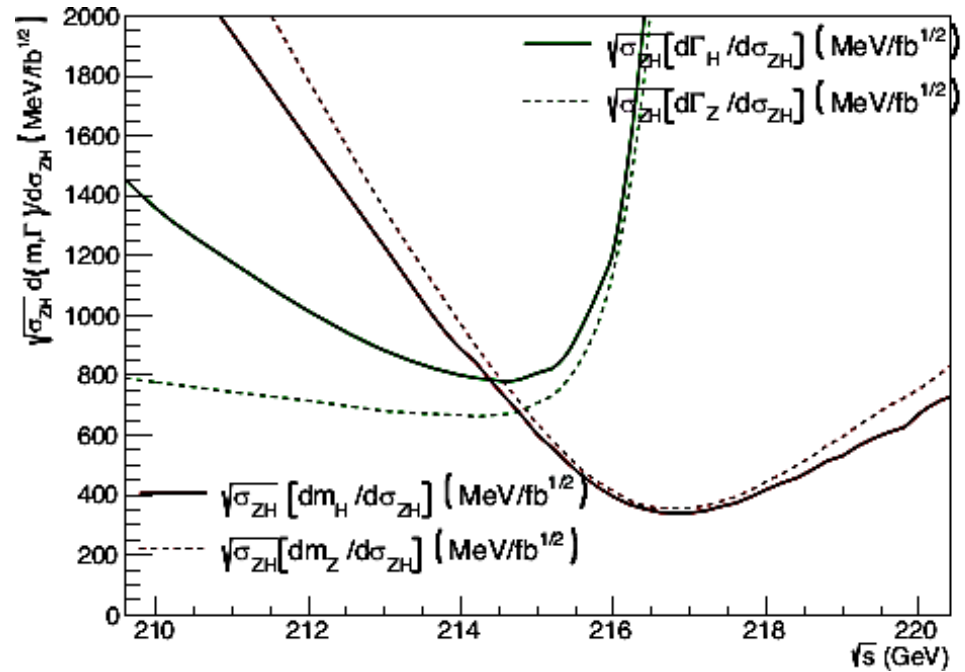
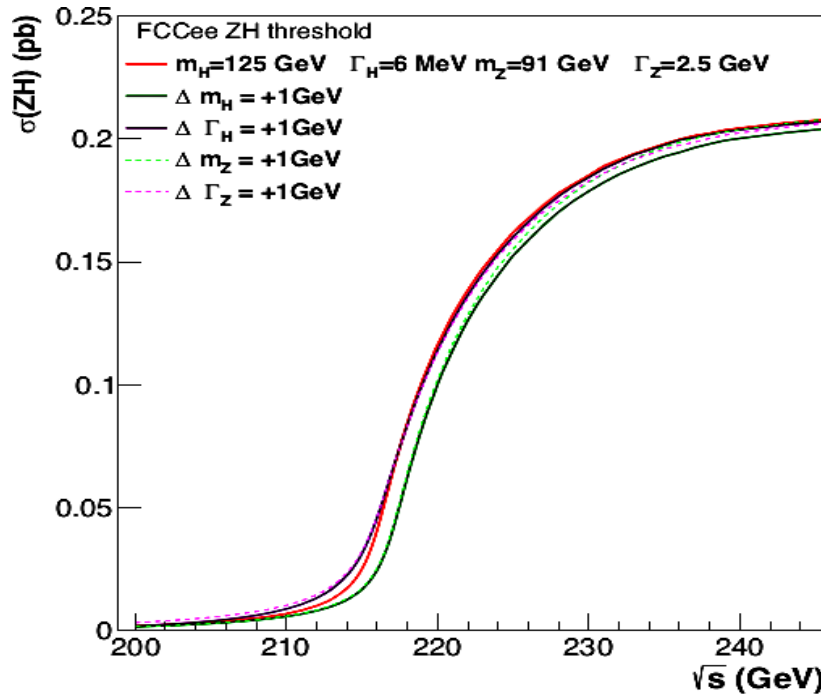
Need systematics control:

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

[arXiv:1703.01626
arXiv:1909.12245]

Accurate m_H needed to run at resonant peak

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



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

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

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

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

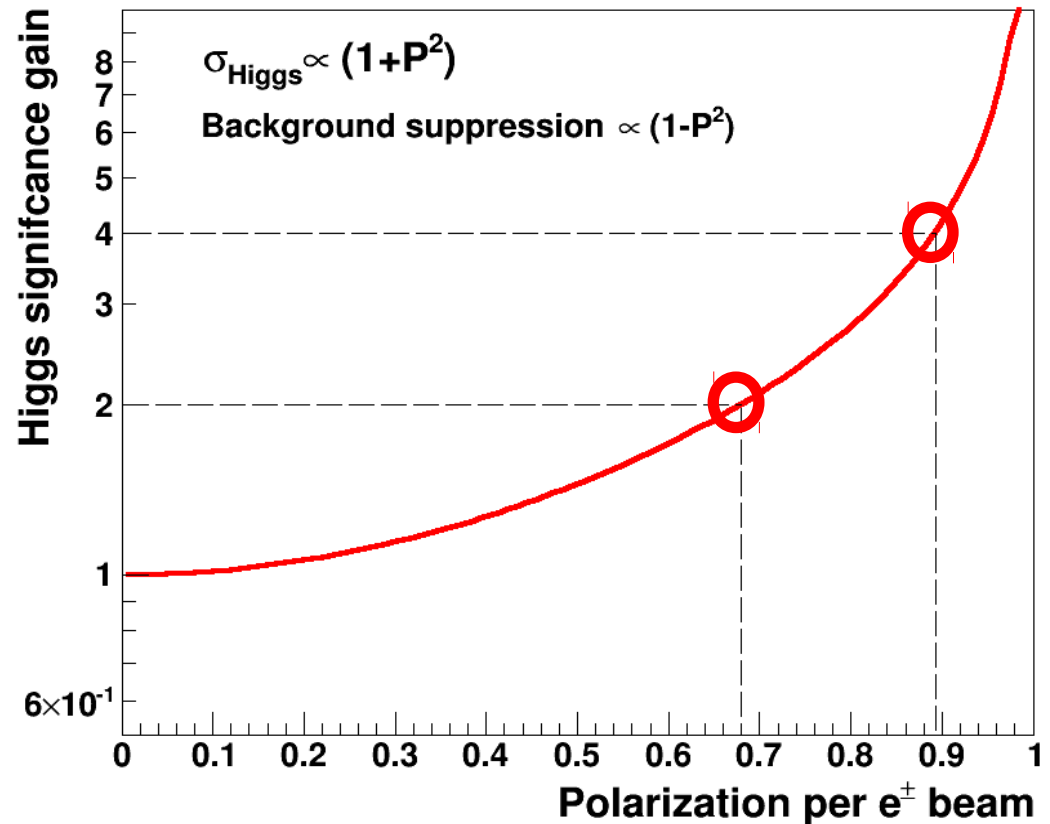
Example of BDT MVA vars. ($H \rightarrow WW^* \rightarrow l\nu jj$)

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

$\cos \theta_{j1}$	E_ℓ	$p_T(jj)$	$\cos \phi_{j1}$	m_{miss}	E_{vis}	p_T^ℓ	E_{miss}	$p_T(jj\ell)$	$\cos \theta^*$
0.0446	0.0417	0.0409	0.0398	0.0341	0.0328	0.0308	0.03015	0.02726	0.02626
η_{miss}	η_{j1}	$\cos \theta_{j2}$	$\Delta\phi_{jj}$	$m_{T,\text{miss}}$	$m_{W \text{ offsh.}}$	$E_{j,\text{min}}$	$\Delta R_{\text{min},j\ell}$	$\min \Delta\eta_{j\ell}$	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	$m(l\nu)$	$\min \cos(\ell j)$	$\max \Delta\eta_{jj}$	$m_{W \text{ shell}}$	$m_T(\ell j_1)$	$m_T(jj\ell)$	$m(\ell j_1)$	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}	$\Delta R_{\text{max},j\ell}$	η_{j2}	lin.spher.	m_{j1}	$p_T(\ell j_2)$	$\Delta\theta_{jj}$	$m_T(jj)$	ΔR_{jj}
0.0140	0.0136	0.0136	0.0136	0.0136	0.0134	0.0134	0.0132	0.0131	0.0127
$E_{j,\text{max}}$	$m_T(\ell j_2)$	sphericity	$p_T(\ell j_1)$	$\min \Delta\phi_{j\ell}$	E_{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 ($R_{\text{min}}, \eta_\ell, \dots$)			
0.00680	0.00641	0.00565	0.00514	0.00512	0.00471	< 0.001			

Significance increase with polarized beams?

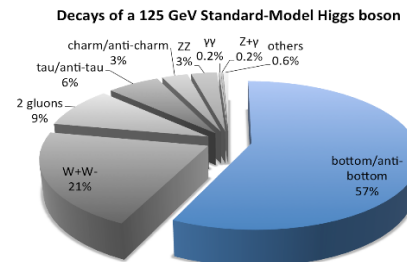
- Polarization of beams would **enhance the signal by $(1+Pol^2)$** and **suppress background by $(1-Pol^2)$** . However, realistic longitudinal polarization estimates ($Pol=20-30\%$) are clearly insufficient and higher polarizations would reduce luminosity...



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

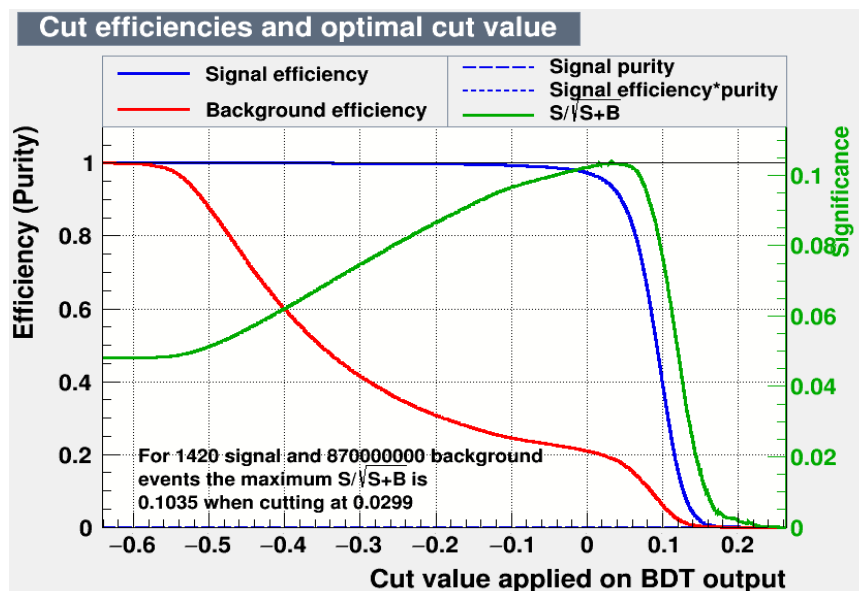
Channel 1: $e^+e^- \rightarrow H(bb) \rightarrow 2 \text{ b-jets}$

- 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



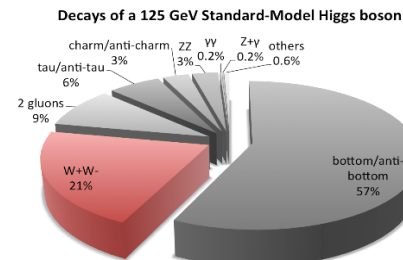
- Signal & backgds before/after MVA cuts:

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

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

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

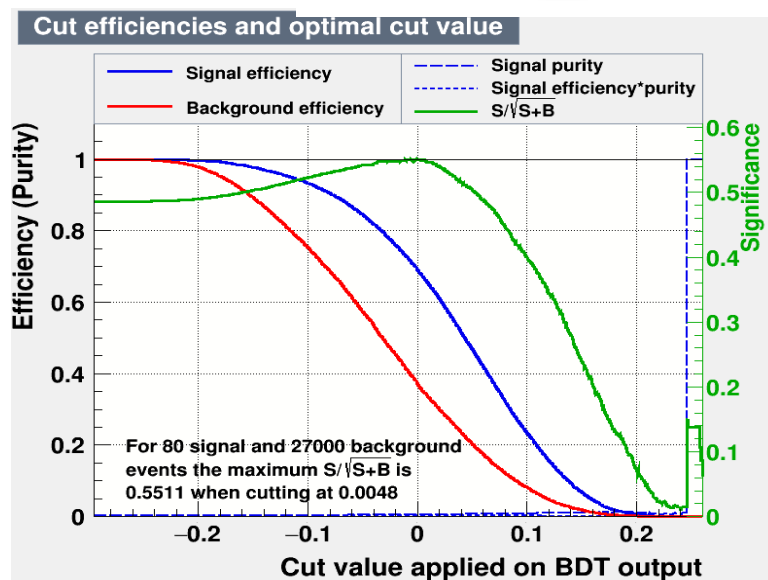
- Final state (retains 80% of $\sigma(WW^*(l\nu jj)) = 28$ ab):
1 isolated $e, \mu, \tau(e), \tau(\mu) + ME > 2$ GeV + 2 jets (excl.)



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

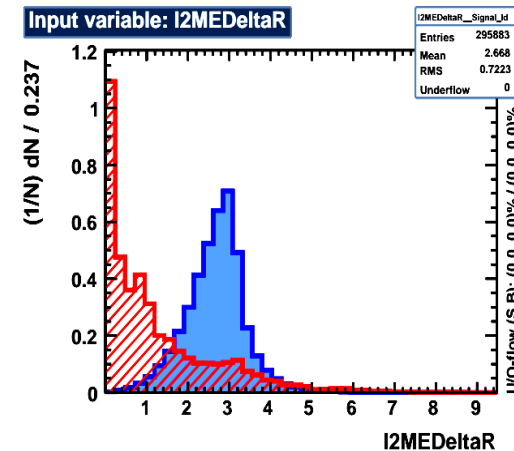
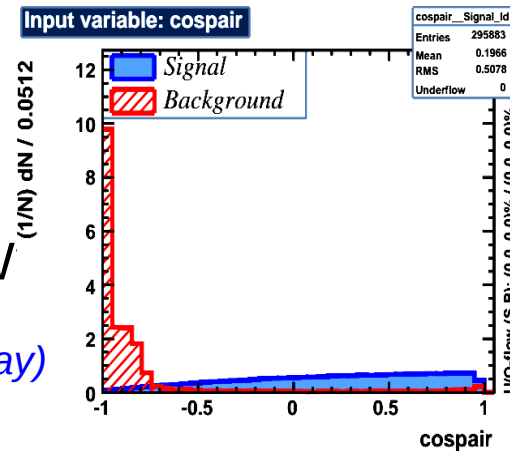
- Final state (retains 60% of $\sigma(WW^*(2l2\nu)) = 7$ ab):
 2 isolated $e, \mu, \tau(e), \tau(\mu) + ME > 2$ GeV
 + 0 non-isolated leptons or ch.had.

- Analysis cuts (Preselection kills qqbar entirely):

- ✓ $\cos(\theta_{l_1 l_2}) > -0.6$ ← 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

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

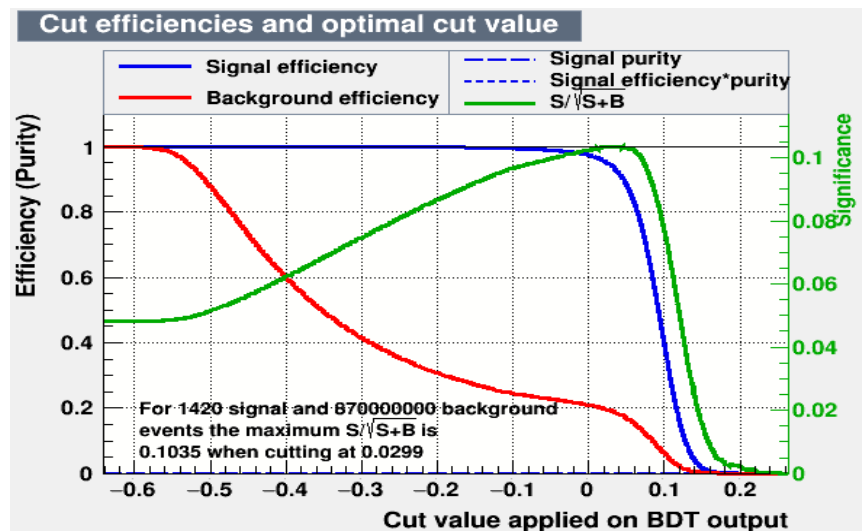
Significance ≈ 0.3

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
 qqbar: $\sigma = 15.7$ fb \Rightarrow $\sigma(\text{after}) = 2$ fb
 WW*: $\sigma = 1.4$ fb \Rightarrow $\sigma(\text{after}) = 810$ ab
 τ - τ : $\sigma = 0$ 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 $\sigma(\tau\tau) = 7.4 \text{ ab}$):

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

- Analysis cuts:

✓ Kinematics cuts: None

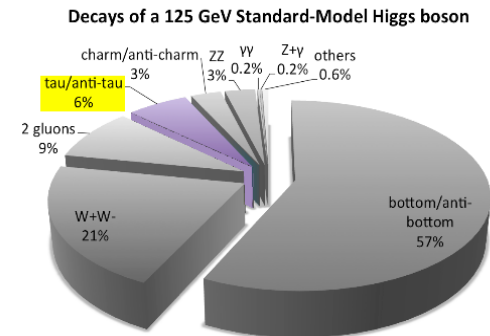
✓ MVA BDT applied to reduce dominant $Z^*/\gamma^* \rightarrow \tau\tau$ continuum.

- Signal & backgds before/after MVA cuts:

$H(\tau\tau)$: $\sigma = 7.4 \text{ ab} \Rightarrow \sigma (\text{after}) = 1.5 \text{ ab}$

$q\bar{q}$: $\sigma = 87 \text{ pb} \Rightarrow \sigma (\text{after}) = 75 \text{ ab}$

$\tau\text{-}\tau$: $\sigma = 10 \text{ pb} \Rightarrow \sigma (\text{after}) = 100 \text{ fb}$



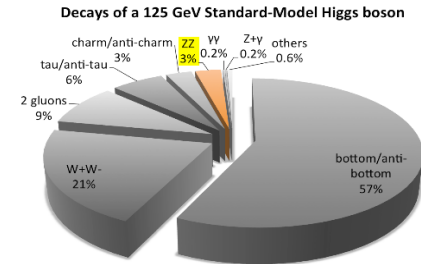
For $L_{\text{int}} = 10 \text{ ab}^{-1}$

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

Significance ≈ 0.02

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

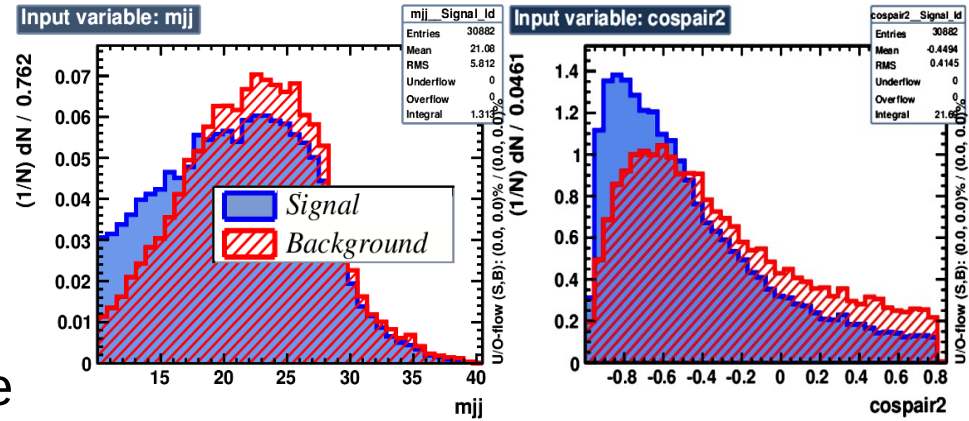
- Final state (retains 75% of $\sigma(WW^*(2j2\nu)) = 2.3$ ab):
 2 jets (excl.) + ME > 30 GeV
 + 0 isolated $e, \mu, \tau(e), \tau(\mu)$ + 0 $\tau(\text{had})$



Kinematic cuts:

- ✓ $\min(|m_{ME} - m_Z|, |m_{jj} - m_Z|) < 10$ GeV ← Kills qqbar, τ - τ
- ✓ $E_{tot} > 120$ 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 $L_{int} = 10$ ab⁻¹

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

Significance ≈ 0.21

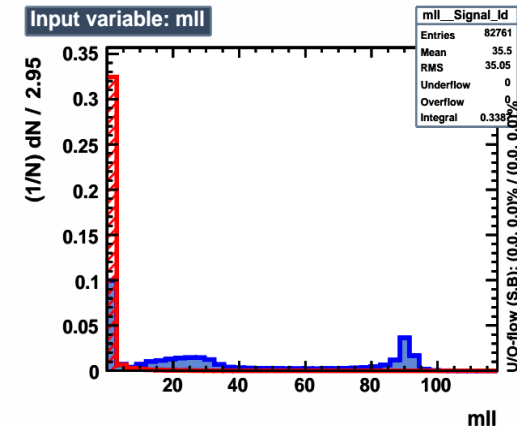
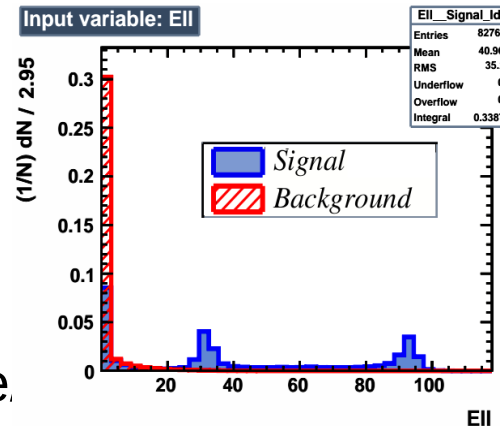
Channel 8: $e^+e^- \rightarrow H(ZZ^*) \rightarrow 2l2j$

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

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

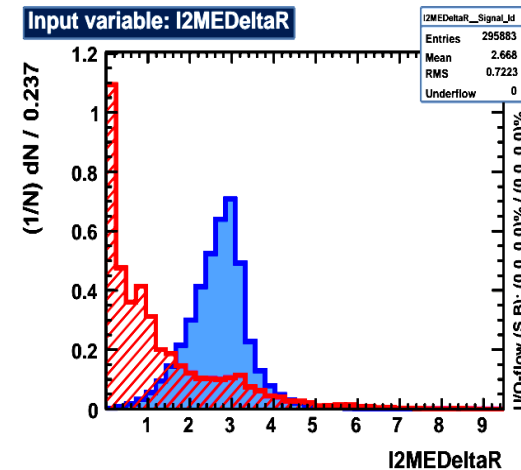
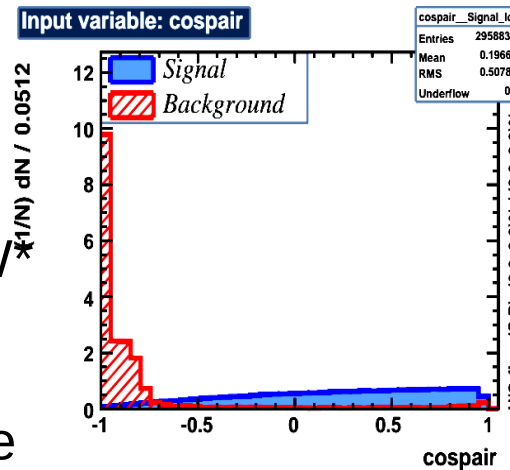
Significance ≈ 0.16

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

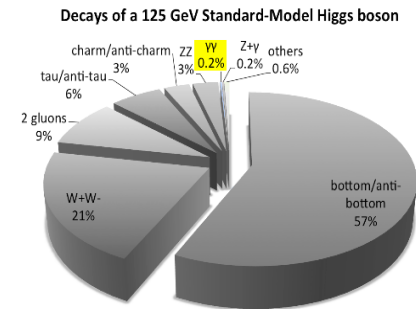
For $L_{\text{int}} = 10$ ab⁻¹

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

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

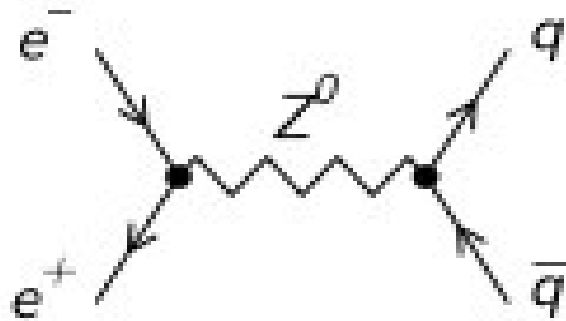
For $L_{\text{int}} = 10 \text{ ab}^{-1}$

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

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 ...