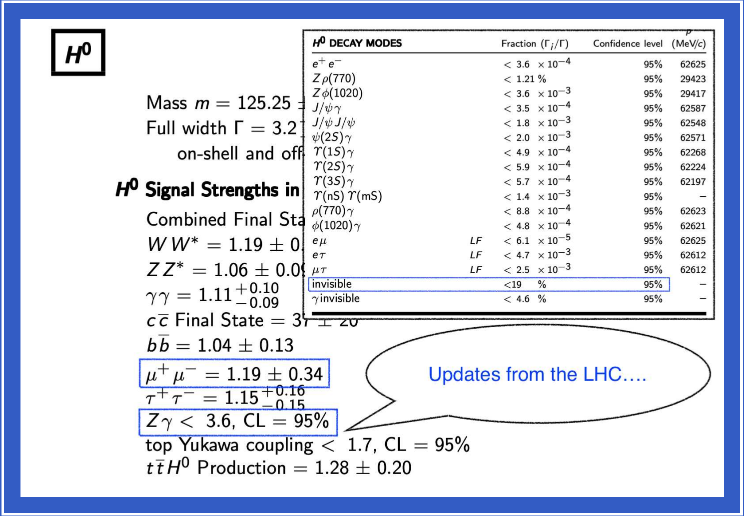
Higgs Invisible & Rare Decays at ILC



H^0

Mass $m = 125.25$ ...
Full width $\Gamma = 3.2$ ...
on-shell and off...

H^0 Signal Strengths in ...

Combined Final Sta...
$WW^* = 1.19 \pm 0.$...
$ZZ^* = 1.06 \pm 0.0$...
$\gamma\gamma = 1.11^{+0.10}_{-0.09}$
$c\bar{c}$ Final State $= 37 \pm 20$
$b\bar{b} = 1.04 \pm 0.13$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma < 3.6$, CL = 95%
top Yukawa coupling < 1.7, CL = 95%
$t\bar{t}H^0$ Production $= 1.28 \pm 0.20$

H^0 DECAY MODES		Fraction (Γ_i/Γ)	Confidence level	p (MeV/c)
e^+e^-		$< 3.6 \times 10^{-4}$	95%	62625
$Z\rho(770)$		< 1.21 %	95%	29423
$Z\phi(1020)$		$< 3.6 \times 10^{-3}$	95%	29417
$J/\psi\gamma$		$< 3.5 \times 10^{-4}$	95%	62587
$J/\psi J/\psi$		$< 1.8 \times 10^{-3}$	95%	62548
$\psi(2S)\gamma$		$< 2.0 \times 10^{-3}$	95%	62571
$\Upsilon(1S)\gamma$		$< 4.9 \times 10^{-4}$	95%	62268
$\Upsilon(2S)\gamma$		$< 5.9 \times 10^{-4}$	95%	62224
$\Upsilon(3S)\gamma$		$< 5.7 \times 10^{-4}$	95%	62197
$\Upsilon(nS)\Upsilon(mS)$		$< 1.4 \times 10^{-3}$	95%	–
$\rho(770)\gamma$		$< 8.8 \times 10^{-4}$	95%	62623
$\phi(1020)\gamma$		$< 4.8 \times 10^{-4}$	95%	62621
$e\mu$	LF	$< 6.1 \times 10^{-5}$	95%	62625
$e\tau$	LF	$< 4.7 \times 10^{-3}$	95%	62612
$\mu\tau$	LF	$< 2.5 \times 10^{-3}$	95%	62612
invisible		<19 %	95%	–
γ invisible		< 4.6 %	95%	–

Chris Potter
(on behalf of the ILC IDT WG on Physics and Detectors)

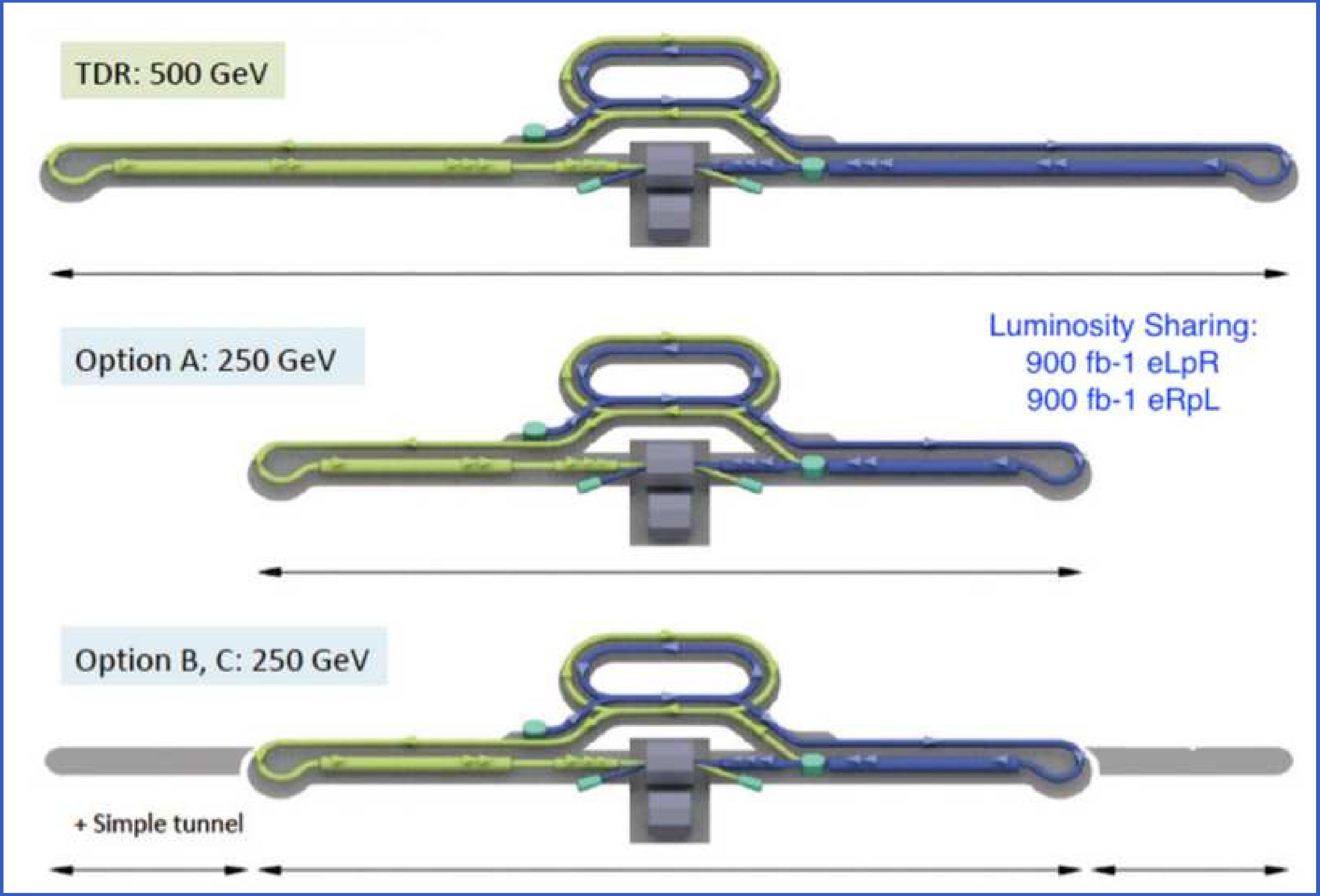
University of Oregon

The ILC International Development Team (IDT)

https://linearcollider.org/team/

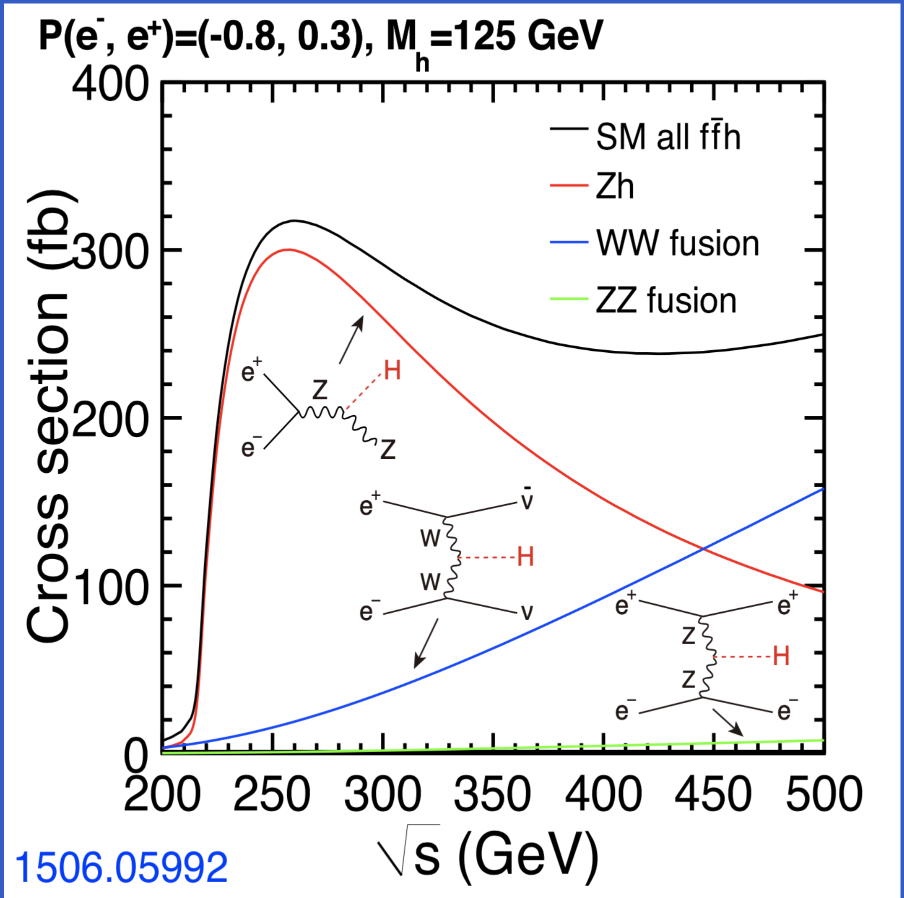
The ILC Higgs Factory: ILC TDR Volumes 1-4

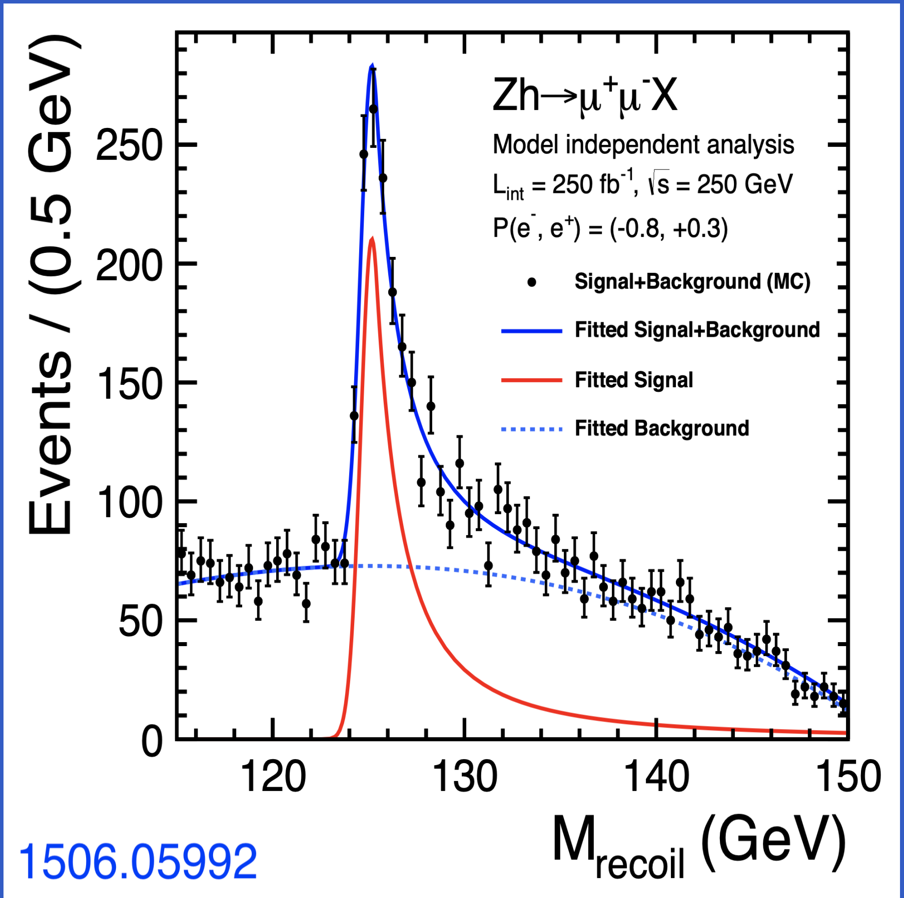
The operation of an e^+e^- collider at a CM energy of 250 GeV will yield a large sample of Higgs bosons that are tagged by recoil against an observed Z boson at a fixed laboratory energy.



By selecting these Z bosons and looking on the other side of the event, e^+e^- colliders will be sensitive to essentially all possible rare and exotic Higgs boson decay channels...

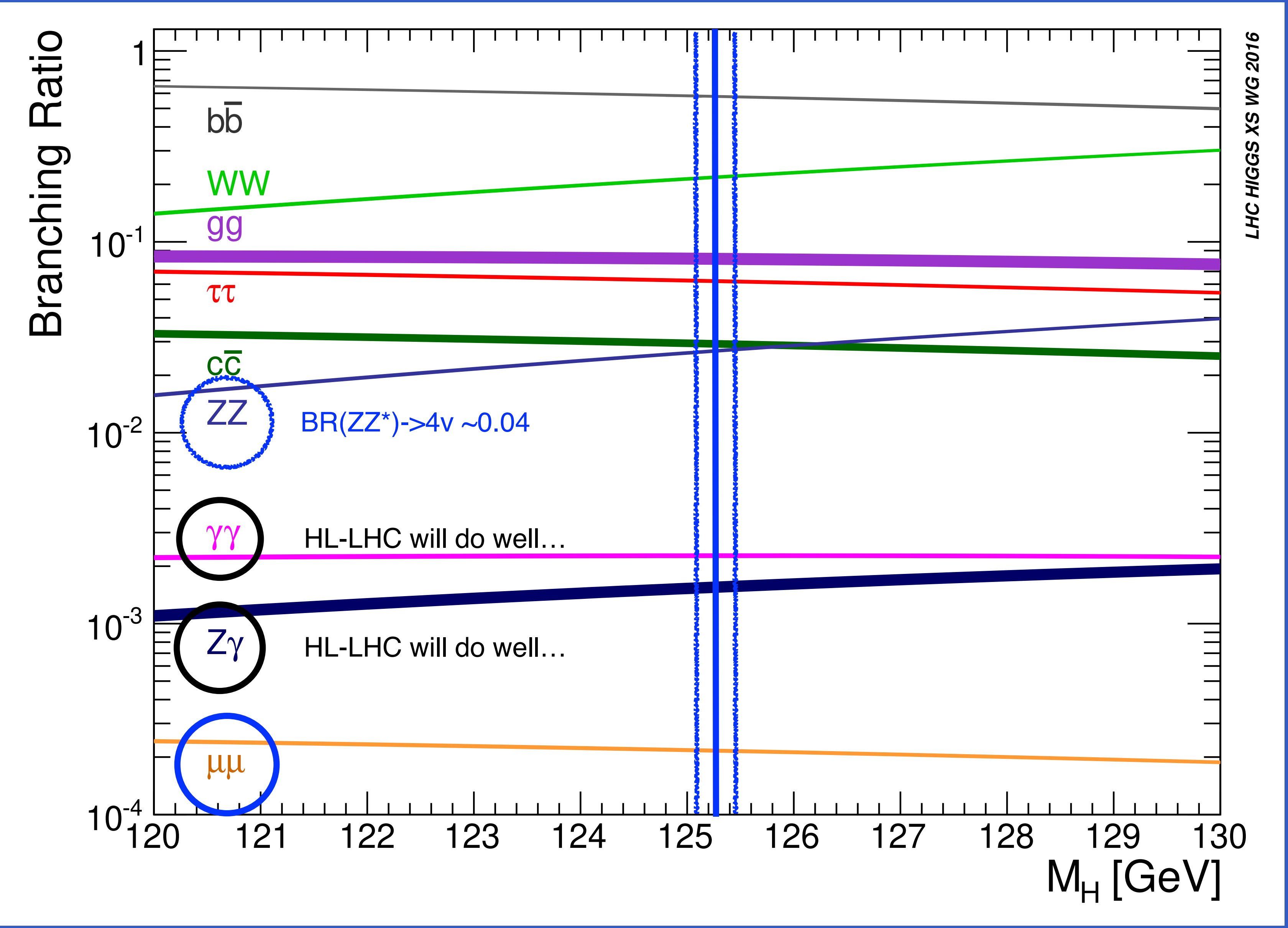
Higgs Boson Production at the ILC





At left, cross sections vs $\sqrt{s}$ for the three Higgs boson production modes. At right, the recoil mass distribution in simulation at $\sqrt{s} = 250$ GeV with $L = 250$ fb^{-1} assuming 80% lefthanded e^- and 30% righthanded e^+. This yields a *decay-independant* sample of Higgs bosons.

Rare Higgs Boson Decay in the Standard Model (SM)



Particle Data Group: Higgs Boson

H^0

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Full width $\Gamma = 3.2$

on-shell and off

H^0 Signal Strengths in

Combined Final Sta

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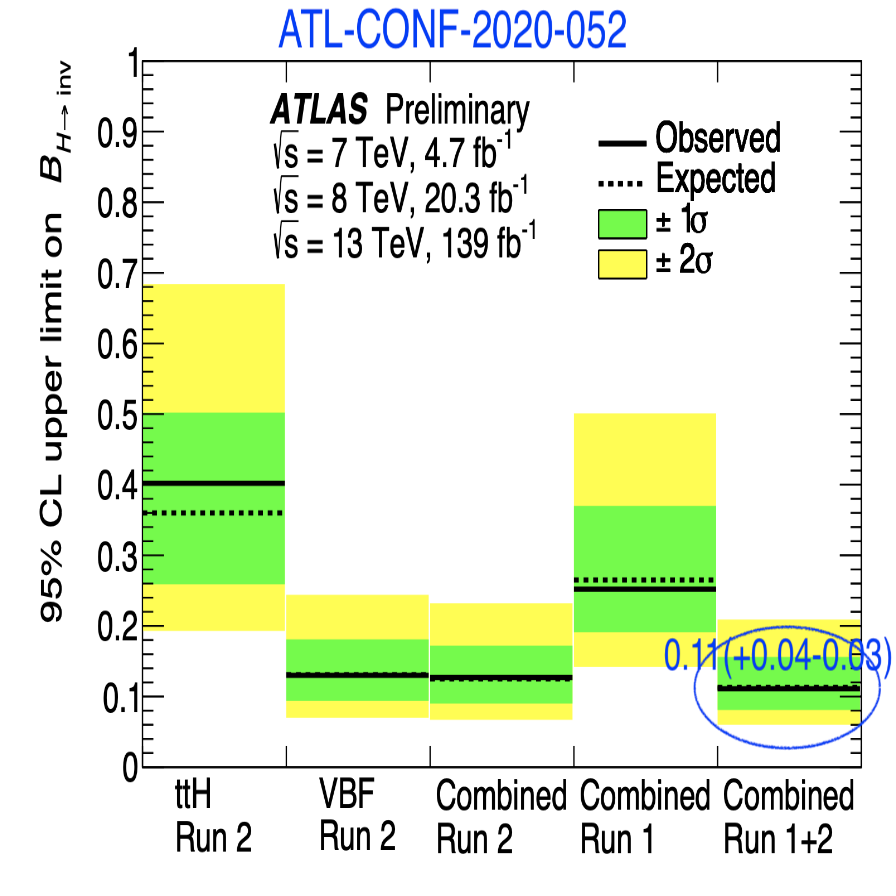
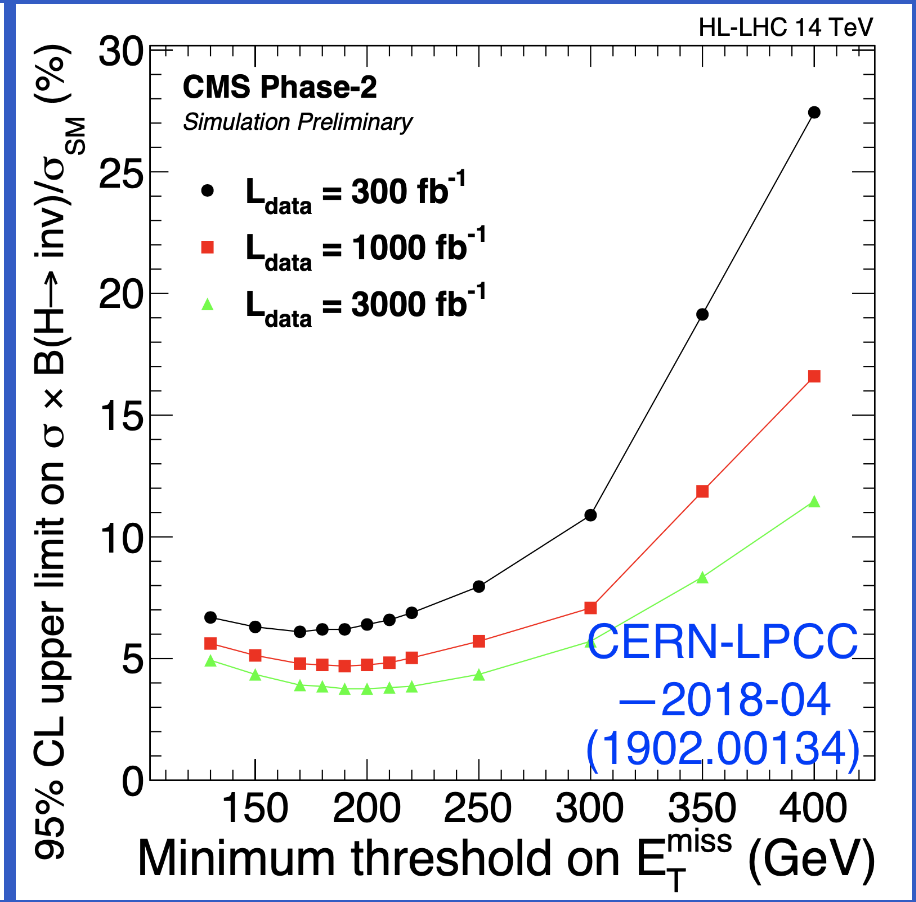
Updates from the LHC....

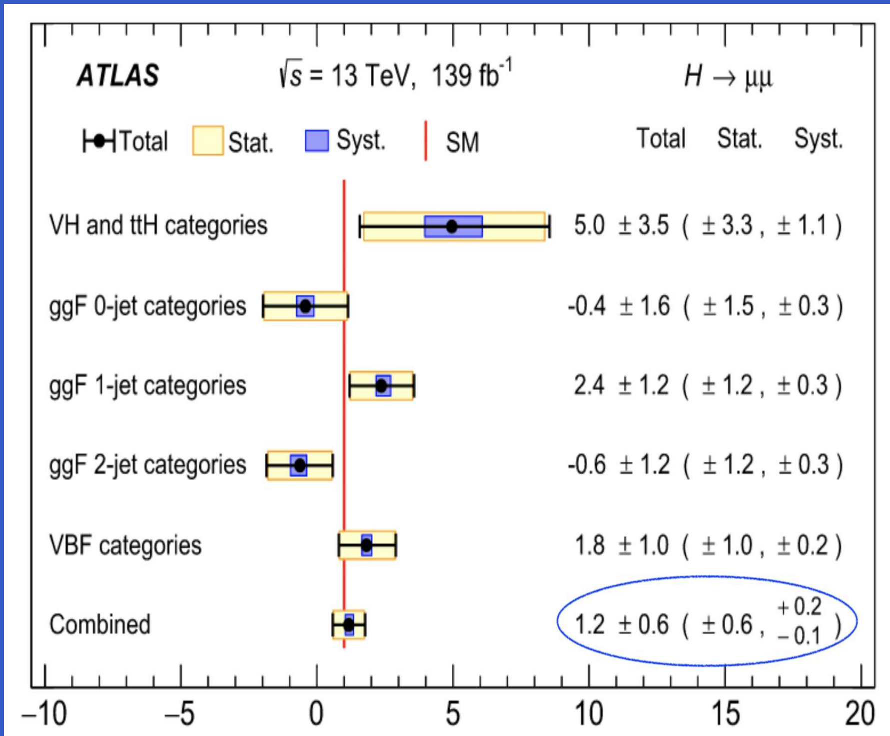
Current LHC and HL-LHC Expectations: $H \to$invisible





ATLAS upper limit on BR($H \to$inv.) is 11%, CMS expectation for the HL-LHC is 3-4%.

Current LHC and HL-LHC Expectations: $H \to \mu^+\mu^-$



PLB 812 (2021) 135980

Table 27: Expected precision on the signal strength measurement in the $H \to \mu^+\mu^-$ channels with 3000 fb^{-1} of HL-LHC data with the two systematic uncertainties scenarios. For the HL-LHC extrapolation, the improved ITk resolution has been emulated.

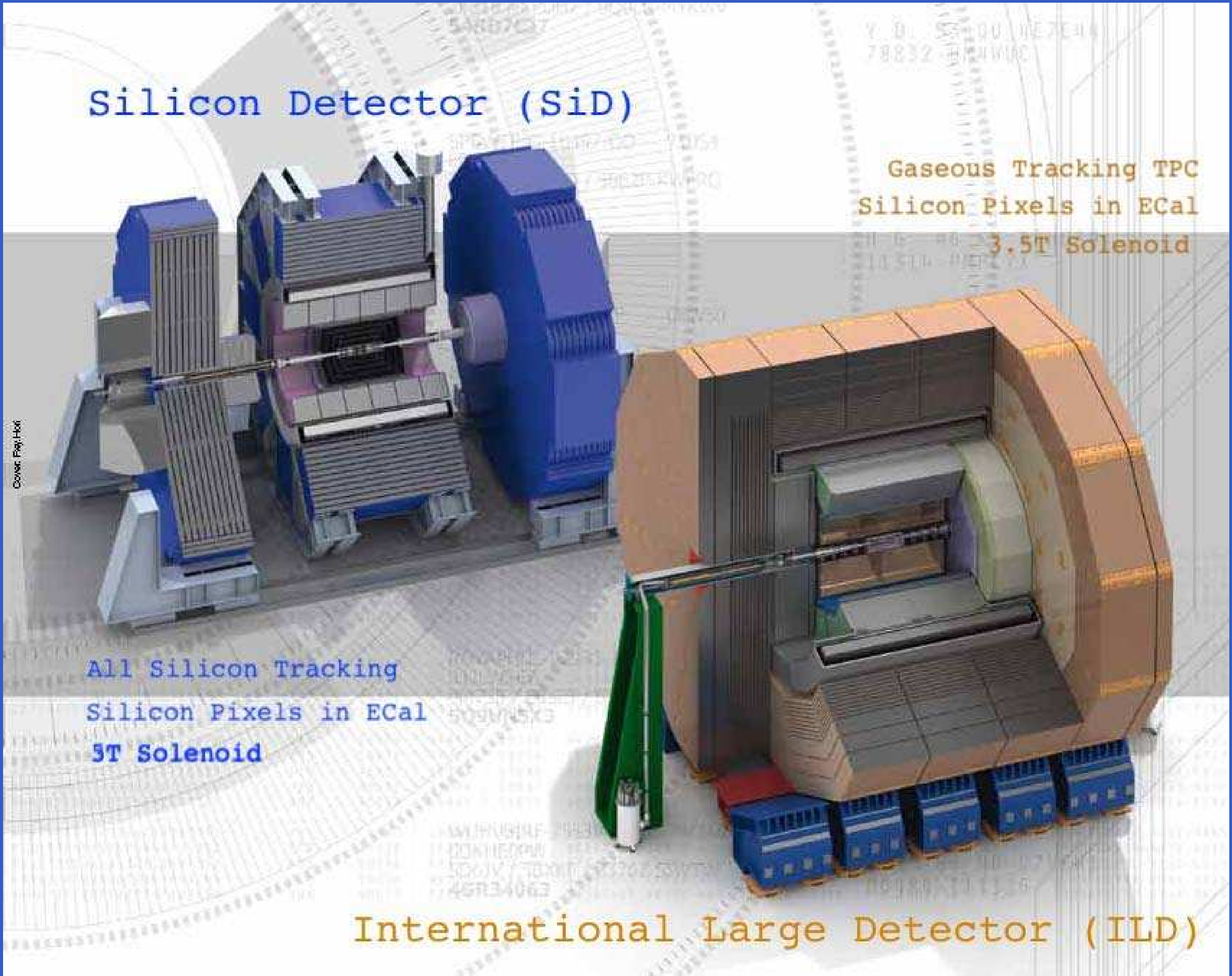
Experiment	ATLAS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	$^{+15\%}_{-14\%}$	$^{+13\%}_{-13\%}$
Statistical uncert.	$^{+12\%}_{-13\%}$	$^{+12\%}_{-13\%}$
Experimental uncert.	$^{+3\%}_{-3\%}$	$^{+2\%}_{-2\%}$
Theory uncer.	$^{+8\%}_{-5\%}$	$^{+5\%}_{-4\%}$

Experiment	CMS	
Process	Combination	
Scenario	S1	S2
Total uncertainty	13%	10%
Statistical uncert.	9%	9%
Experimental uncert.	8%	2%
Theory uncer.	5%	3%

CERN-LPCC —2018-04 (1902.00134)

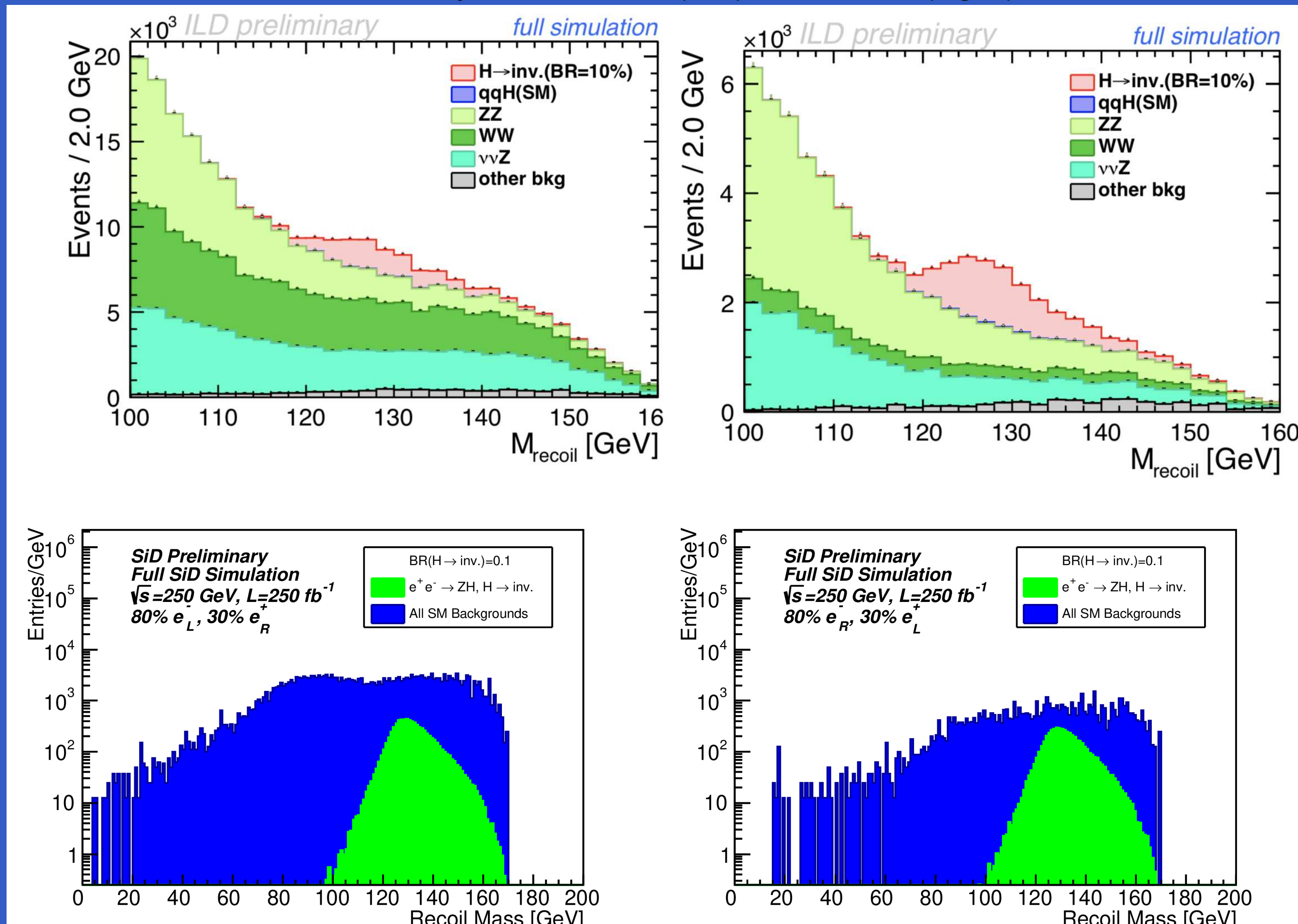
ATLAS uncertainty on the $H \to \mu^+\mu^-$ signal strength is 50%, CMS HL-LHC expectation is 10%.

SiD and ILD: ILC TDR Volume 4 (arXiv:1306.6329)



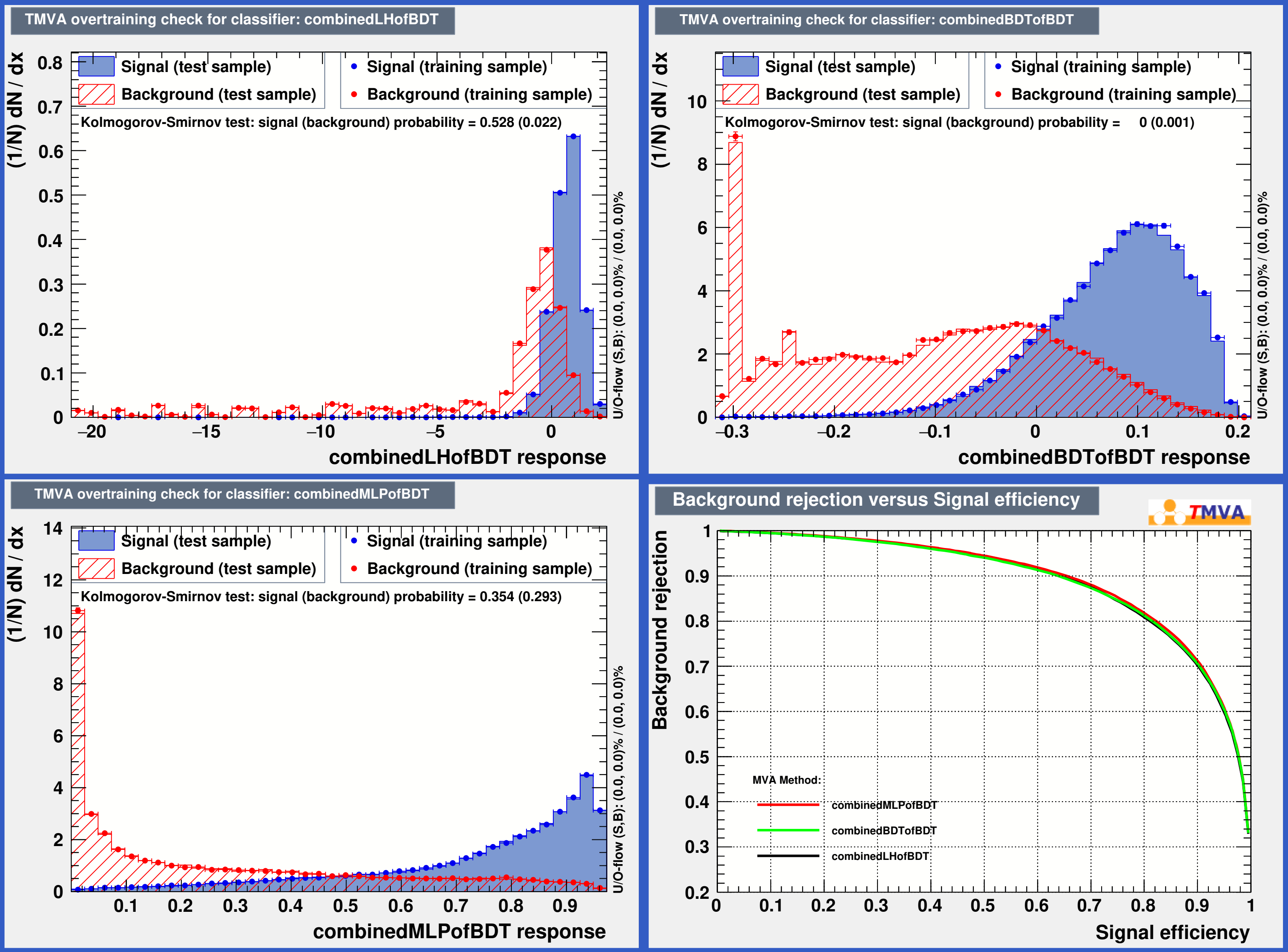
ILD/SiD at ILC: Higgs to Invisible (Hadronic Channel)

Luminosity is 900 fb^{-1} (left), 900 fb^{-1} (right)



ILD:"...95% C.L. UL on BR(H $\rightarrow$invisible) of 0.23%" (2002.12048)

SiD at ILC: Higgs to Invisible MVA (Hadronic Channel)



Preliminary multivariate analysis using separate Boosted Decision Trees (BDTs) for each background category should significantly improve sensitivity.

ILD at ILC: Higgs to Muon Pairs

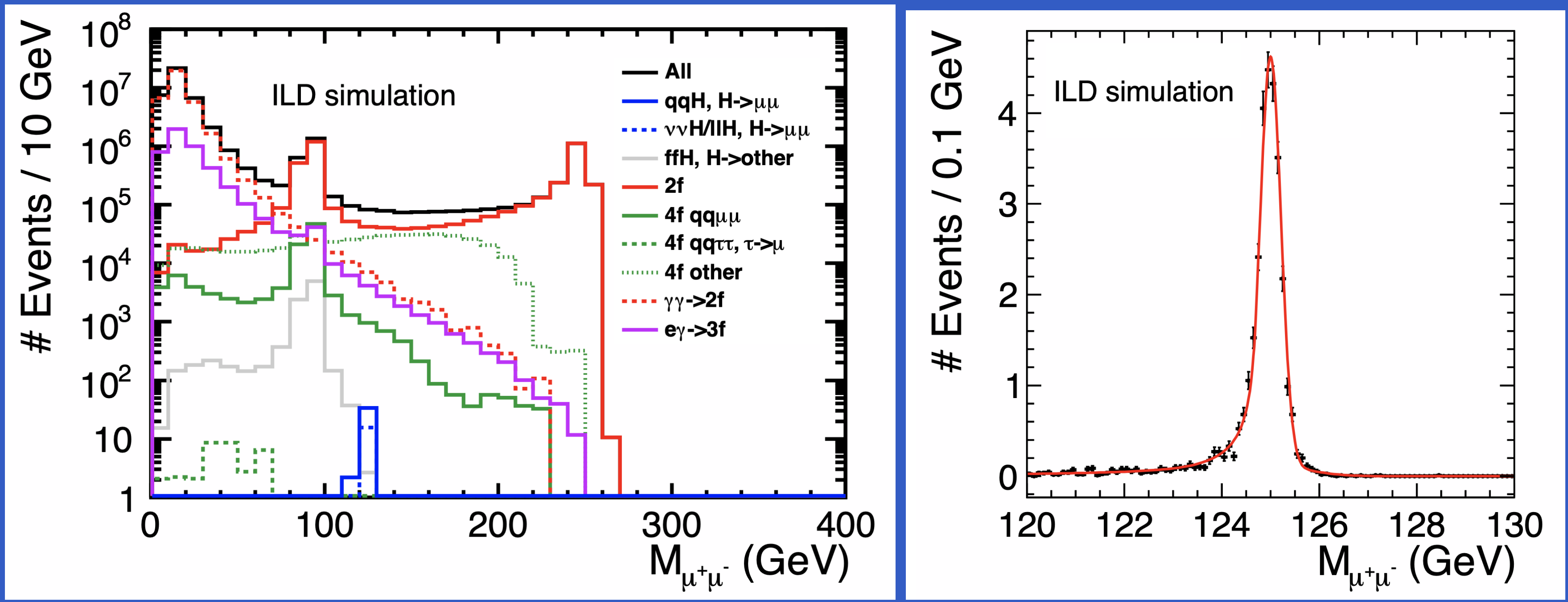


Table 10: Expected precisions on BF($H \to \mu^+\mu^-$) for $\sqrt{s} = 250$ GeV (ILC250), $\sqrt{s} = 500$ GeV (ILC500) and their combination (ILC250+500). The luminosities and polarisation sharing correspond to the standard ILC running scenario as detailed in Sec. 1.

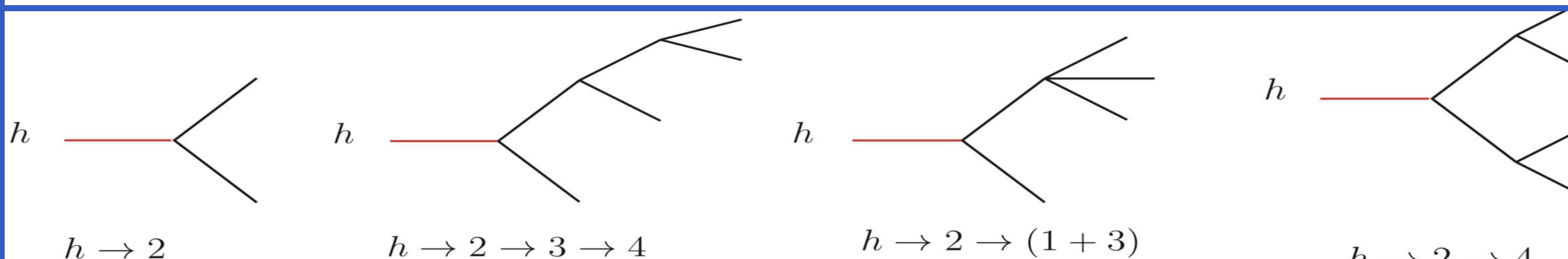
$\sqrt{s} = 250$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC250	ILC250+500
L	34%	113%	23%	
R	36%	111%		
$\sqrt{s} = 500$ GeV	$q\bar{q}H$	$\nu\bar{\nu}H$	ILC500	17%
L	43%	37%	24%	
R	48%	106%		

The study assumes 900 fb^{-1} (900 fb^{-1}) at $\sqrt{s} = 250$ GeV for LR (RL) polarization and 1600 fb^{-1}(1600 fb^{-1}) at $\sqrt{s} = 500$ GeV for LR (RL) polarization.

Exotic Higgs Decay in Beyond the SM (BSM)

Liu, Wang, Zhang — 1612.09284

Decay Mode	95% C.L. limit on Br: LHC	HL-LHC	CEPC	ILC	FCC-ee
$\not{E}_T$	0.23 [49, 50]	0.056 [12–14]	0.0028 [16]	0.0025 [17]	0.005 [18]
$(b\bar{b})+\not{E}_T$	–	[0.2]	1×10^{-4}	2×10^{-4}	5×10^{-5}
$(jj)+\not{E}_T$	–	–	5×10^{-4}	5×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)+\not{E}_T$	–	[1]	$8\times10^{-4}*$	1×10^{-3}	3×10^{-4}
$b\bar{b}+\not{E}_T$	–	[0.2] [39]	3×10^{-4}	4×10^{-4}	1×10^{-4}
$jj+\not{E}_T$	–	–	5×10^{-4}	7×10^{-4}	2×10^{-4}
$\tau^+\tau^-+\not{E}_T$	–	–	$8\times10^{-4}*$	1×10^{-3}	3×10^{-4}
$(b\bar{b})(b\bar{b})$	1.7 [51]	(0.2)	4×10^{-4}	9×10^{-4}	3×10^{-4}
$(c\bar{c})(c\bar{c})$	–	(0.2)	8×10^{-4}	1×10^{-3}	3×10^{-4}
$(jj)(jj)$	–	[0.1]	1×10^{-3}	2×10^{-3}	7×10^{-4}
$(b\bar{b})(\tau^+\tau^-)$	[0.1]* [52]	[0.15]	$4\times10^{-4}*$	6×10^{-4}	2×10^{-4}
$(\tau^+\tau^-)(\tau^+\tau^-)$	[1.2]* [53]	[0.2 ∼ 0.4]	$1\times10^{-4}*$	2×10^{-4}	5×10^{-5}
$(jj)(\gamma\gamma)$	–	[0.01]	1×10^{-4}	2×10^{-4}	3×10^{-5}
$(\gamma\gamma)(\gamma\gamma)$	$[7\times10^{-3}]$ [54]	$4\times10^{-4}*$	1×10^{-4}	1×10^{-4}	3×10^{-5}



SiD at ILC: Exotic Higgs to Four Taus

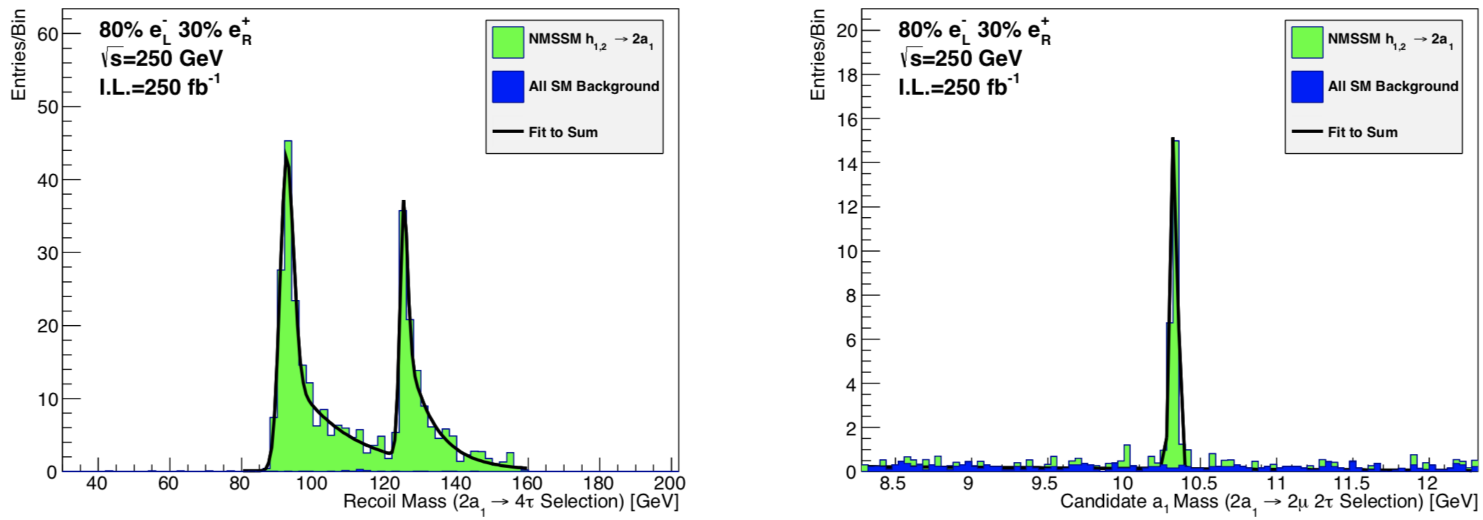


Figure 1: At left, the fit to the $h_{1,2}$ recoil mass distribution after full 4τ analysis selection. At right, the fit to the reconstructed $a_1 \to \mu^+\mu^-$ mass distribution after the full $2\mu2\tau$ selection. The plots assume $\sqrt{s} = 250$ GeV, 250fb^{-1} integrated luminosity, and 80% e_L^-, 30% e_R^+ beam polarization. 1309.0021

	Case I	Case II	Case III
S	121	182	302
B	0.4	1.3	1.7

Table 2: Signal (S) and background (B) yields for the h_2, h_1 and h_2+h_1 searches in early running at the ILC, respectively. The yields assume $\sqrt{s} = 250$ GeV, 250fb^{-1} integrated luminosity, and 80% e_L^-, 30% e_R^+ beam polarization. 1309.0021

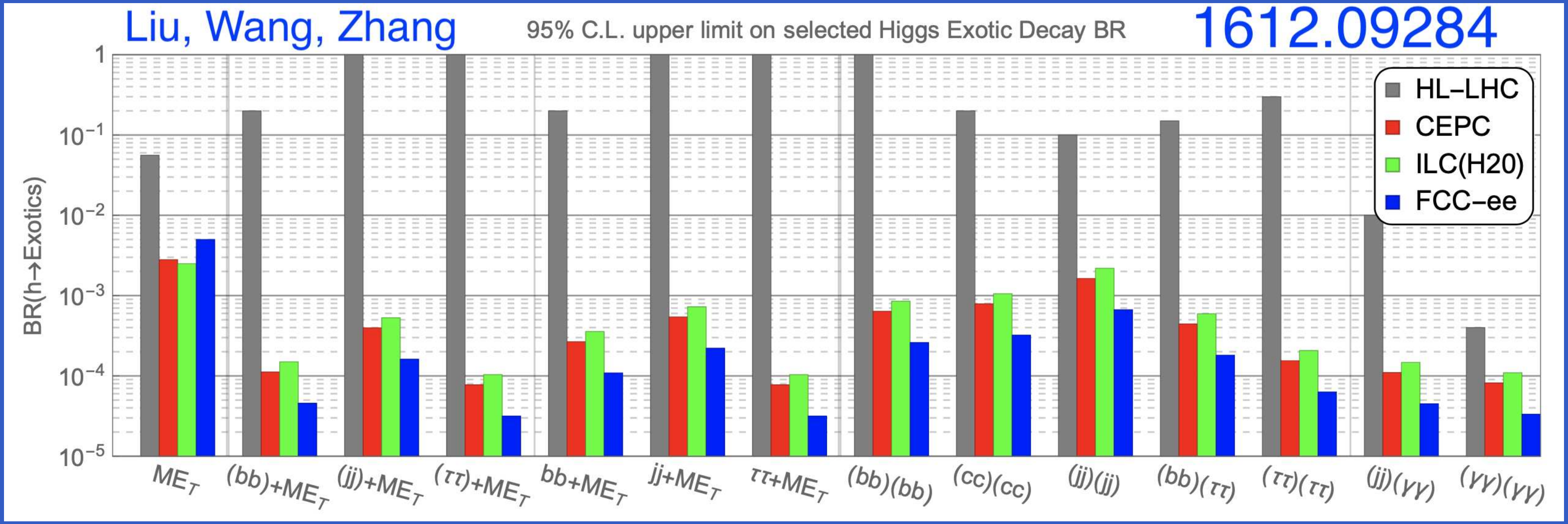
This study is motivated by the NMSSM and the LEPII excess near 96 GeV. See 1309.0021 for details. The $h_2 \to (\tau^+\tau^-)(\tau^+\tau^-)$ topology has minimal background.

Conclusion: ILC sharply improves on the HL-LHC!

Invisible and Rare SM Higgs Decays

Decay	LHC	HL-LHC	ILC
$H \to$inv	BR<11%	BR<3-4%	BR<0.2% [a]
$H \to \mu^+\mu^-$	$\Delta\mu/\mu \approx 50\%$	$\Delta\mu/\mu \approx 10\%$	$\Delta_{BR}/BR \approx 17\%$

Exotic BSM Higgs Decays



[a] Improvements expected with multivariate analysis.

Thank you for your attention.

Backup: Higgs to Invisible (Hadronic Channel)

Table 2: Selection table for $\sqrt{s} = 250$ GeV, $(P_{e^-}, P_{e^+}) = (-0.8, +0.3)$.

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	18917 (1.000)	1.417×10^8 (1.000)	1.59
$N_{lep} = 0$	18880 (0.998)	9.732×10^7 (0.687)	1.91
Pre-Cut	18202 (0.962)	3.358×10^6 (0.024)	9.91
$N_{pfo} > 15 \& N_{charged} > 6$	17918 (0.947)	2.539×10^6 (0.018)	11.2
$p_{T jj} \in (20, 80)$GeV	16983 (0.898)	1.368×10^6 (0.010)	14.4
$M_{jj} \in (80, 100)$GeV	14158 (0.748)	713194 (0.005)	16.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	13601 (0.719)	539921 (0.004)	18.3
$M_{recoil} \in (100, 160)$GeV	13585 (0.718)	244051 (0.002)	26.8

Table 3: Selection table for $\sqrt{s} = 250$ GeV, $(P_{e^-}, P_{e^+}) = (+0.8, -0.3)$.

cut condition	signal (efficiency)	all bkg (efficiency)	significance
No Cut	12776 (1.000)	7.785×10^7 (1.000)	1.45
$N_{lep} = 0$	12752 (0.998)	4.893×10^7 (0.628)	1.82
Pre-Cut	12270 (0.960)	1.329×10^6 (0.017)	10.6
$N_{pfo} > 15 \& N_{charged} > 6$	12067 (0.945)	852285 (0.011)	13.0
$p_{T jj} \in (20, 80)$GeV	11394 (0.892)	285847 (0.004)	20.9
$M_{jj} \in (80, 100)$GeV	9481 (0.742)	165798 (0.002)	22.6
$\lvert\cos\theta_{jj}\rvert < 0.9$	9126 (0.714)	130070 (0.002)	24.5
$M_{recoil} \in (100, 160)$GeV	9115 (0.713)	62979 (0.001)	33.9

Requirement (Full)	S(LR)	B(LR)	$\frac{S}{\sqrt{S+B}}$	S(RL)	B(RL)	$\frac{S}{\sqrt{S+B}}$
Track, lepton, PFO multiplicity requirements imposed (2105.00128)						
$20 \leq p_T^{vis} \leq 70$ GeV	1.25e+04	7.71e+06	4.48	8.84e+03	1.07e+06	8.53
$75 \leq m_{vis} \leq 105$ GeV	1.16e+04	1.79e+06	8.63	8.21e+03	3.14e+05	14.5
$N_{jet} = 2$	1.16e+04	1.79e+06	8.63	8.21e+03	3.14e+05	14.5
$-0.9 \leq \cos\theta_{jj} \leq -0.2$	1.08e+04	8.68e+05	11.5	7.65e+03	1.78e+05	17.7
$110 \leq m_{recoil} \leq 150$	1.03e+04	3.6e+05	17	7.33e+03	8.39e+04	24.2

Full simulation (ILCSoft v02-00-02, SID o2_v3) scaled from 250fb^{-1} to 900fb^{-1}.