Physics at Future Linear Colliders

Swathi Sasikumar

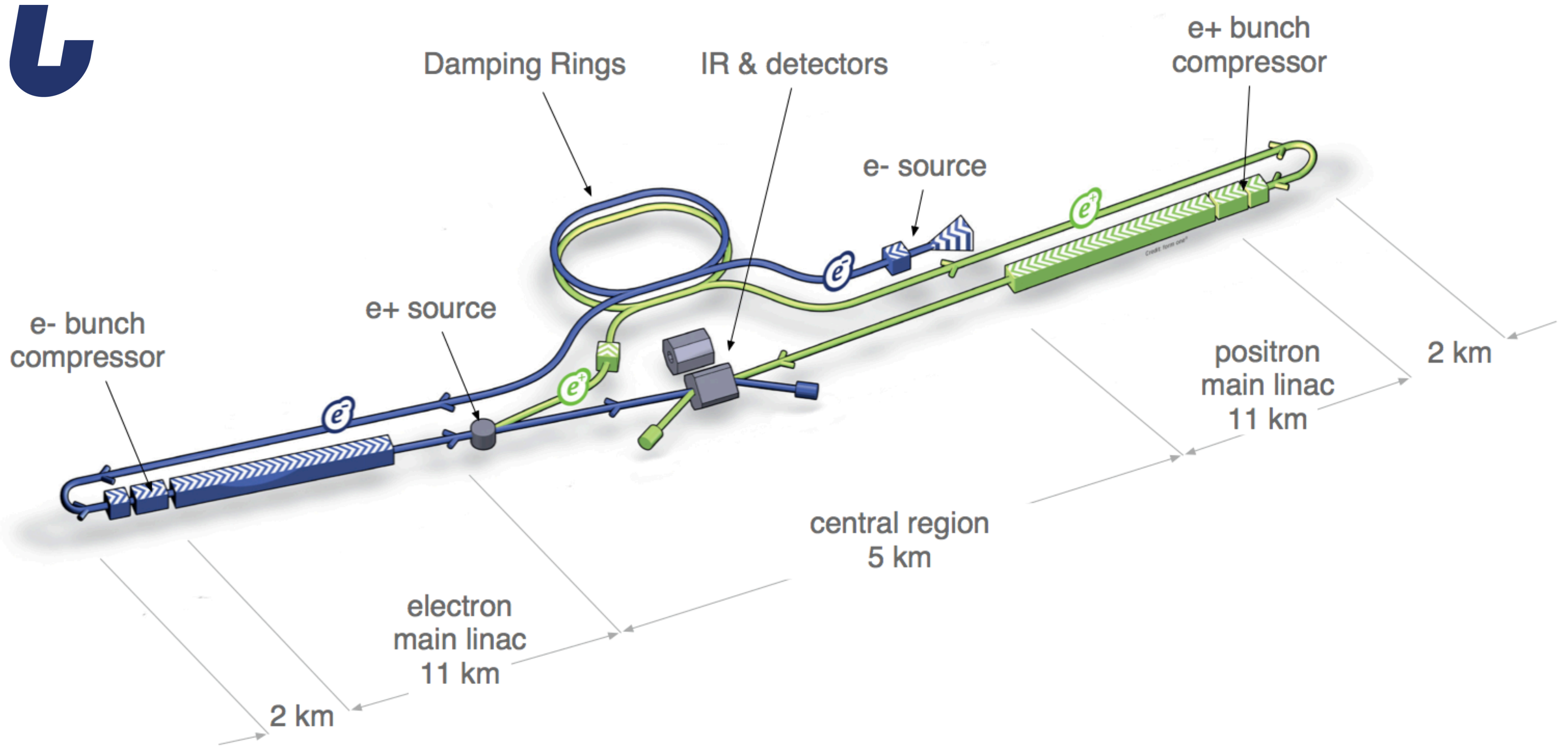
LFC 2022

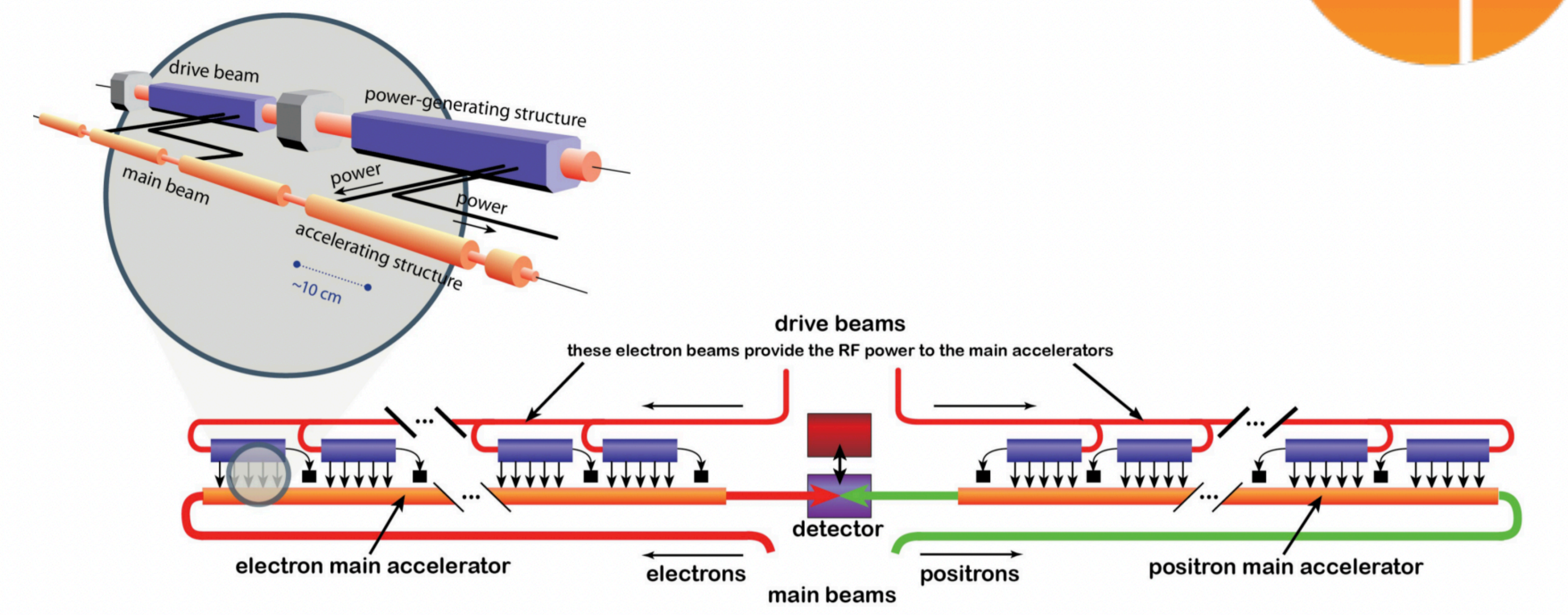
ECT* Trento

MAX-PLANCK-INSTITUT
FÜR PHYSIK

29th August 2022

Introduction





- Tunable centre-of-mass energy between 250 - 500 GeV (upgradable to 1 TeV)
- P(e-) = ±80%, P (e+) = ±30%
- Length - 20 km (250 GeV), 31 km(500 GeV)
- Superconducting RF cavities

- Centre-of-mass energy 380 GeV - 3 TeV
- P(e-) = ±80%
- Length - 11 km (380 GeV), 50 km (3 TeV)
- Based of 2-beam acceleration scheme

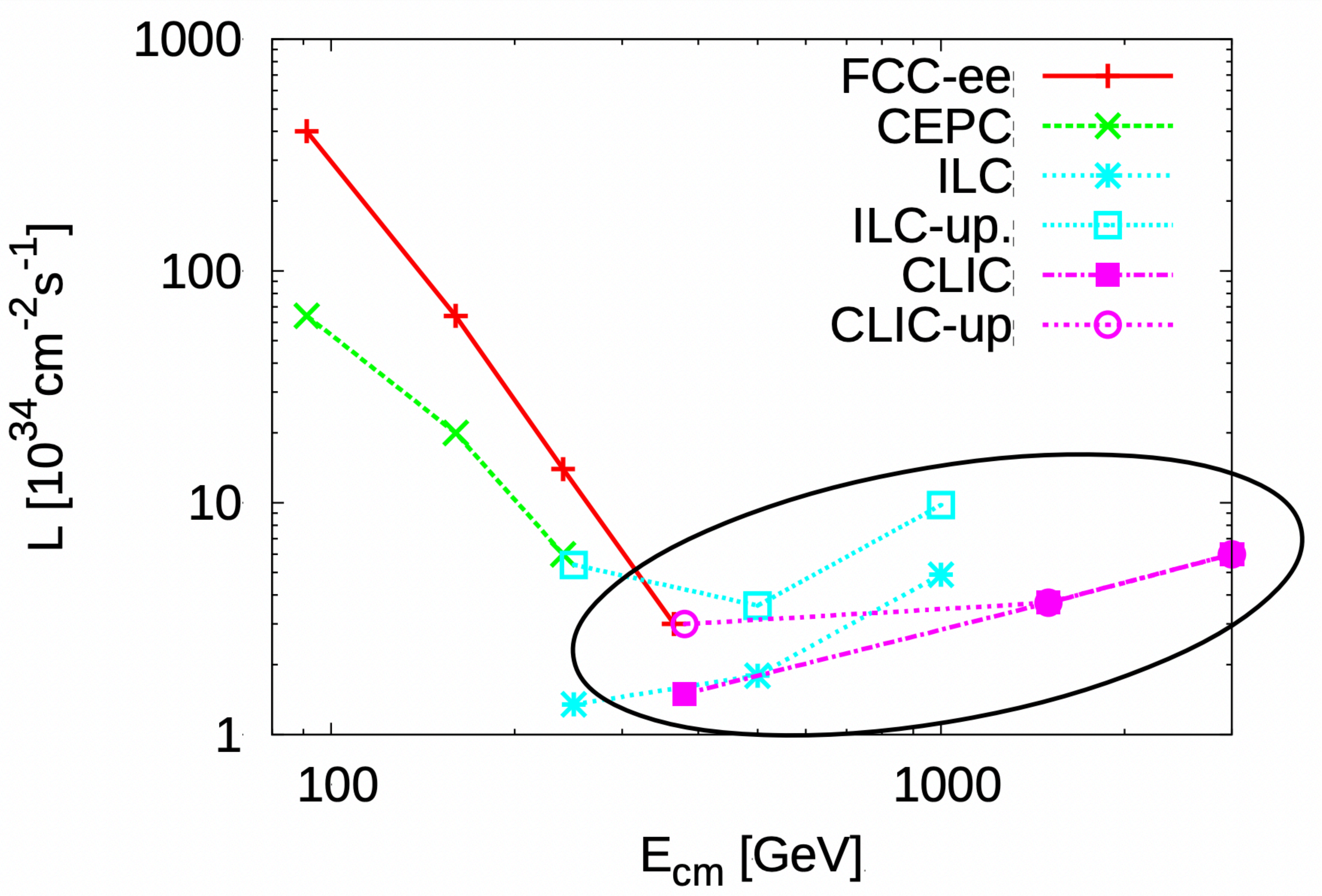
Advantages of a linear e^+e^- collider

- Being an e^+e^- collider ILC mainly has EW production and therefore a very clean physics environment
- No trigger required
- e^+e^- being fundamental particles: initial state known
- Detectors with 4π coverage
- Radiation hardness not required: only few % X_0 in front of calorimeters
- Planned to run for 22 years: 250 GeV @ $2ab^{-1}$ + 500 GeV @ $4ab^{-1}$
- Under political discussion in Japan for hosting

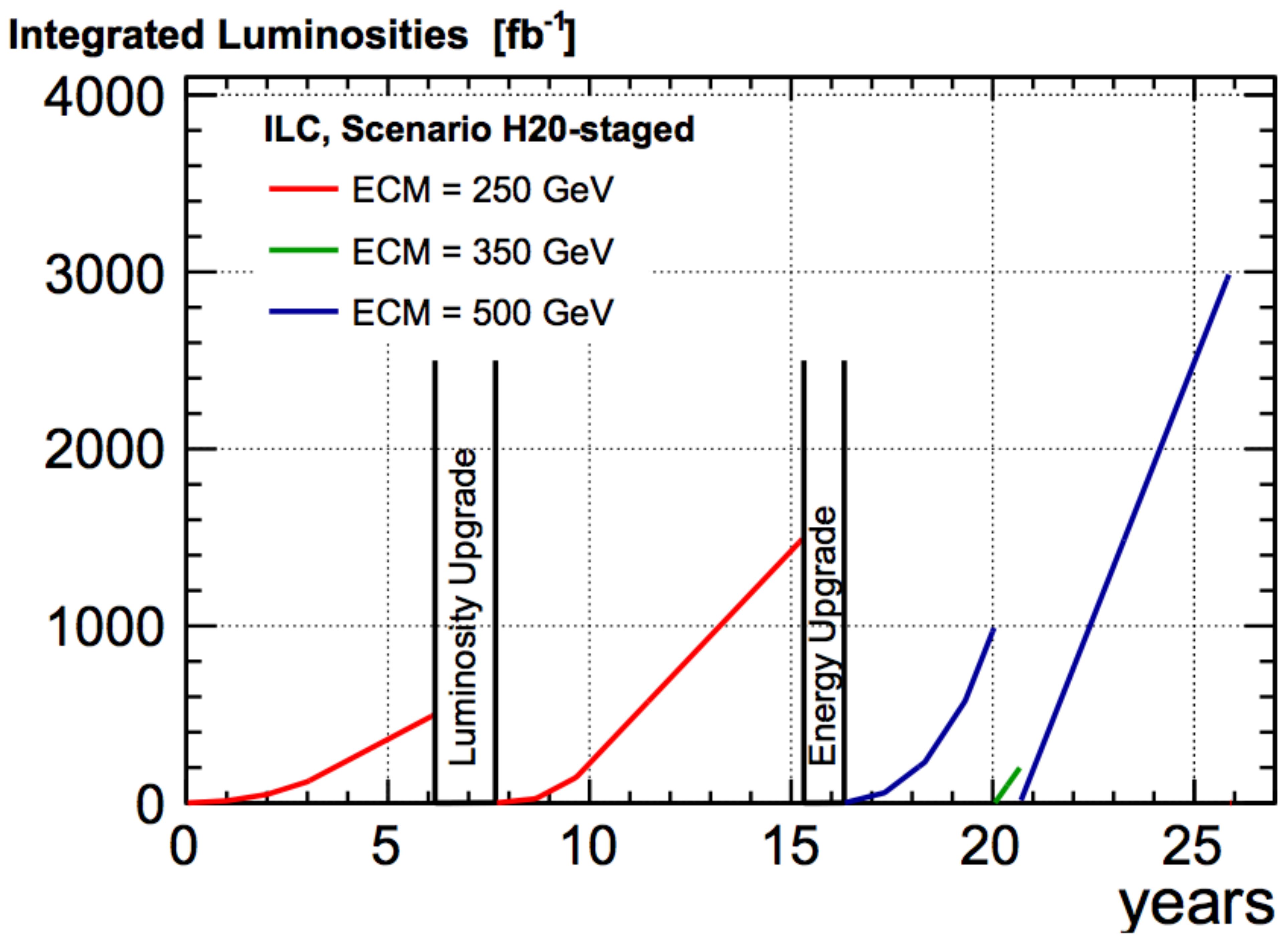
Comparison between linear and circular e+e− collider

- Linear Collider:
    - High energies can be achieved with more LINAC
    - Higher luminosity with higher energy
    - Beam polarisation at all energies

- Circular collider:
    - Higher luminosity at lower energies
    - Luminosity decreases with higher energy



ILC staged implementation

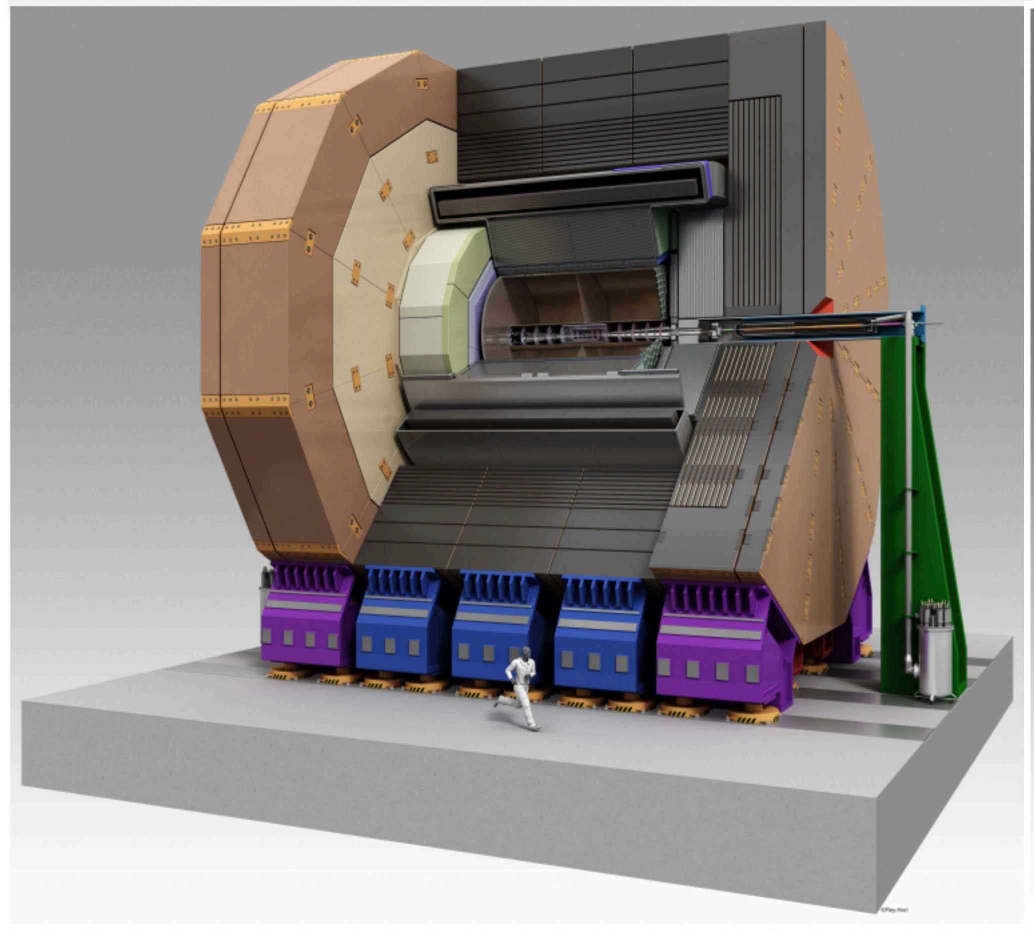


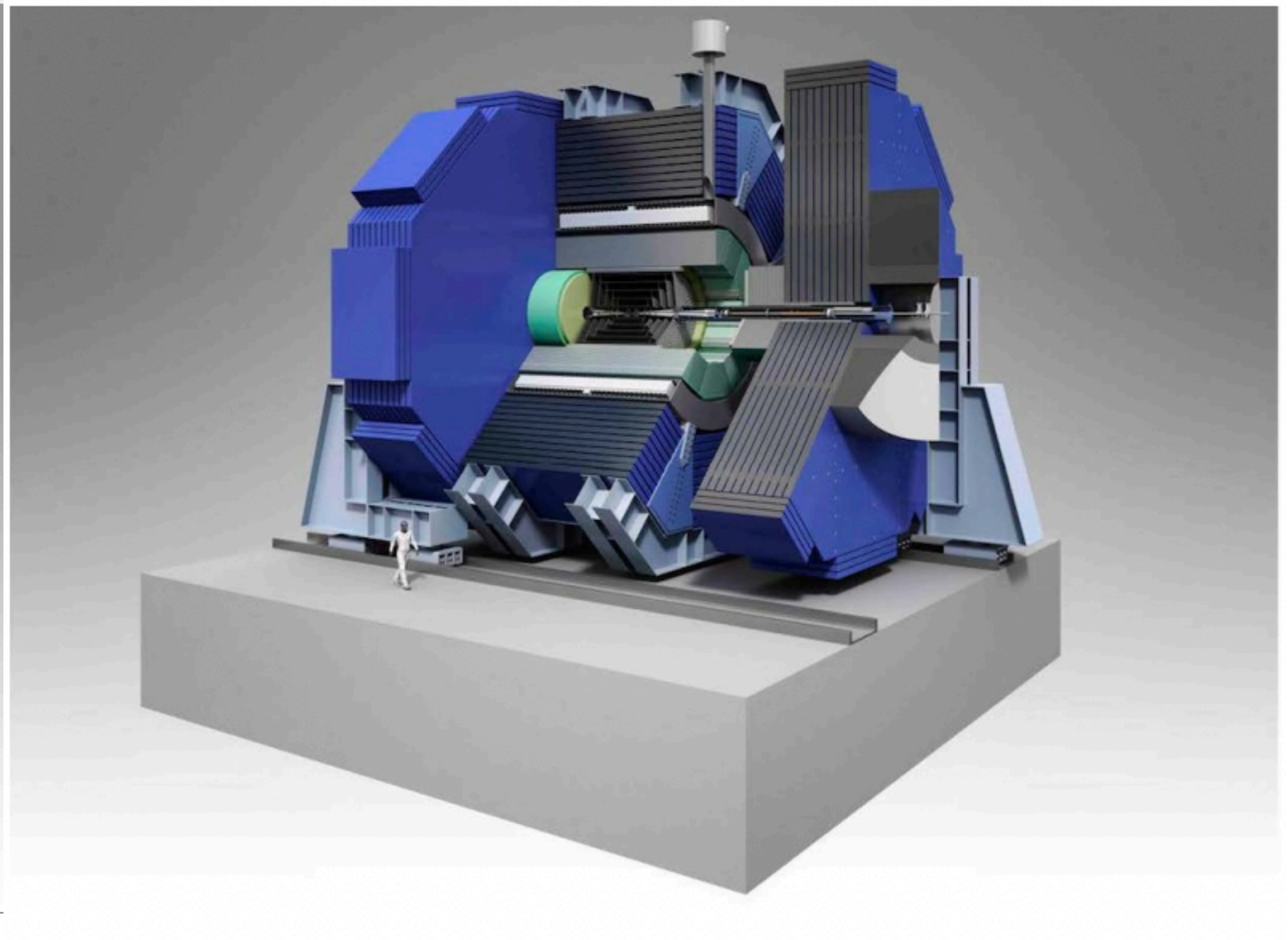
- The proposed staged design for ILC is given the figure
- First stage at 250 GeV with highest luminosity of 2 ab^{-1}
- Luminosity upgrade would require twice the number of bunches per pulse

	E_{CM} (GeV)	$\int \mathcal{L}$ (fb^{-1})	fraction with sign$(P(e^-), P(e^+)) =$ $(-+)$	$(+-)$	$(--)$	$(++)$
ILC250	250	2000	45%	45%	5%	5%
ILC350	350	200	67.5%	22.5%	5%	5%
ILC500	500	4000	40%	40%	10%	10%

ILC detector concept

International Large Detector





Silicon Detector

- Time Projection Chamber(dE/dx)
- Radius of tracker- 1.8m
- B field = 3.5 T

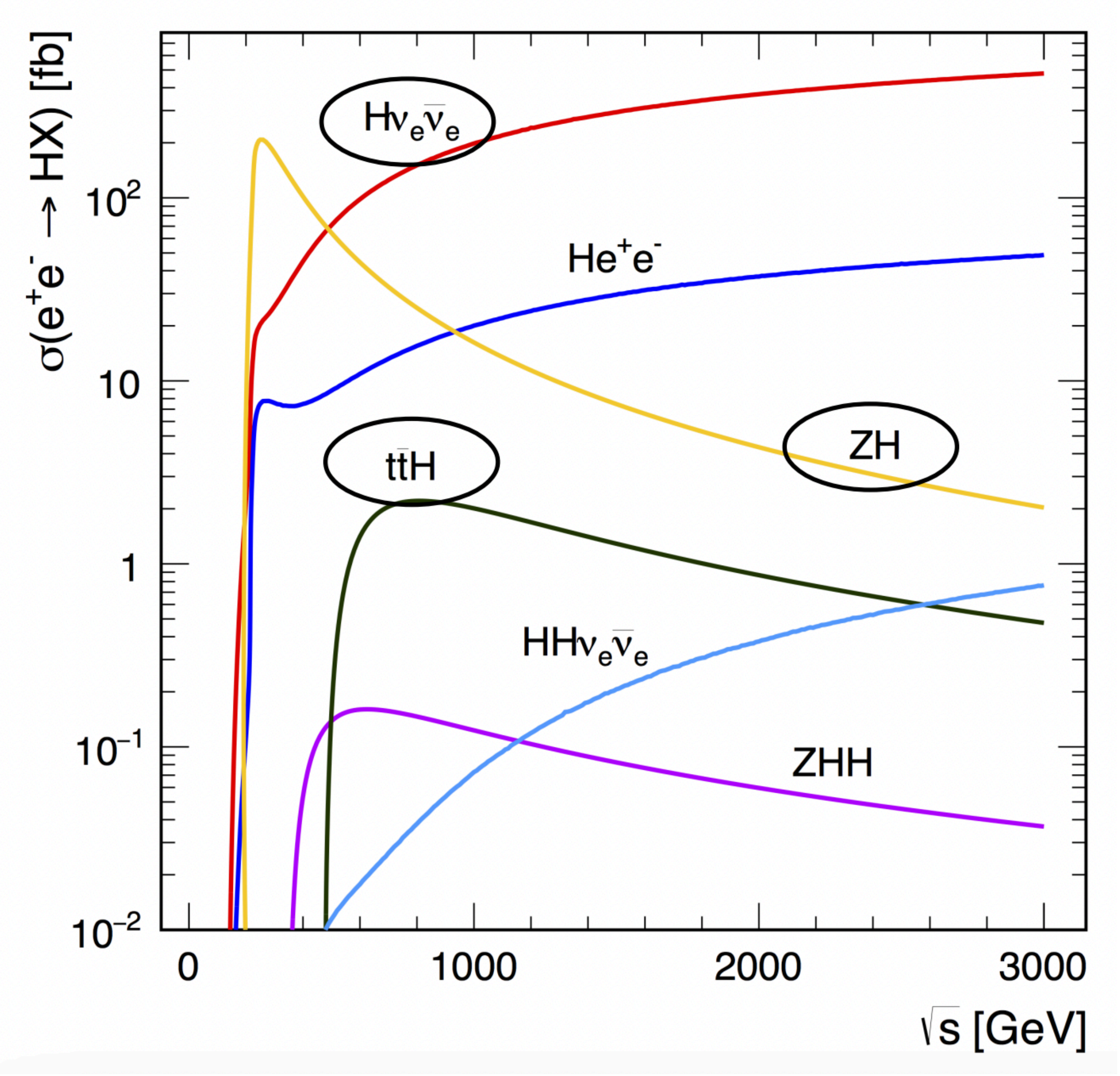
- Silicon tracker
- Radius of tracker - 1.2m
- B field = 5 T

- Particle flow concept to reconstruct particles
- Highly granular ECAL and HCAL

- ILD has a p_T resolution of $\sigma(1/p_T) = 2 \times 10^{-5}\mathrm{GeV}^{-1} \oplus 1 \times 10^{-3}/p_T \sin^{1/2}\theta \approx \mathrm{CMS}/40$
- Vertexing: $\sigma(d_0) < 5 \oplus 10/(p[\mathrm{GeV}]\sin^{3/2}\theta)\mu\mathrm{m} \approx \mathrm{CMS}/4$
- Jet energy resolution: 3-4 % $\approx$ ATLAS/2

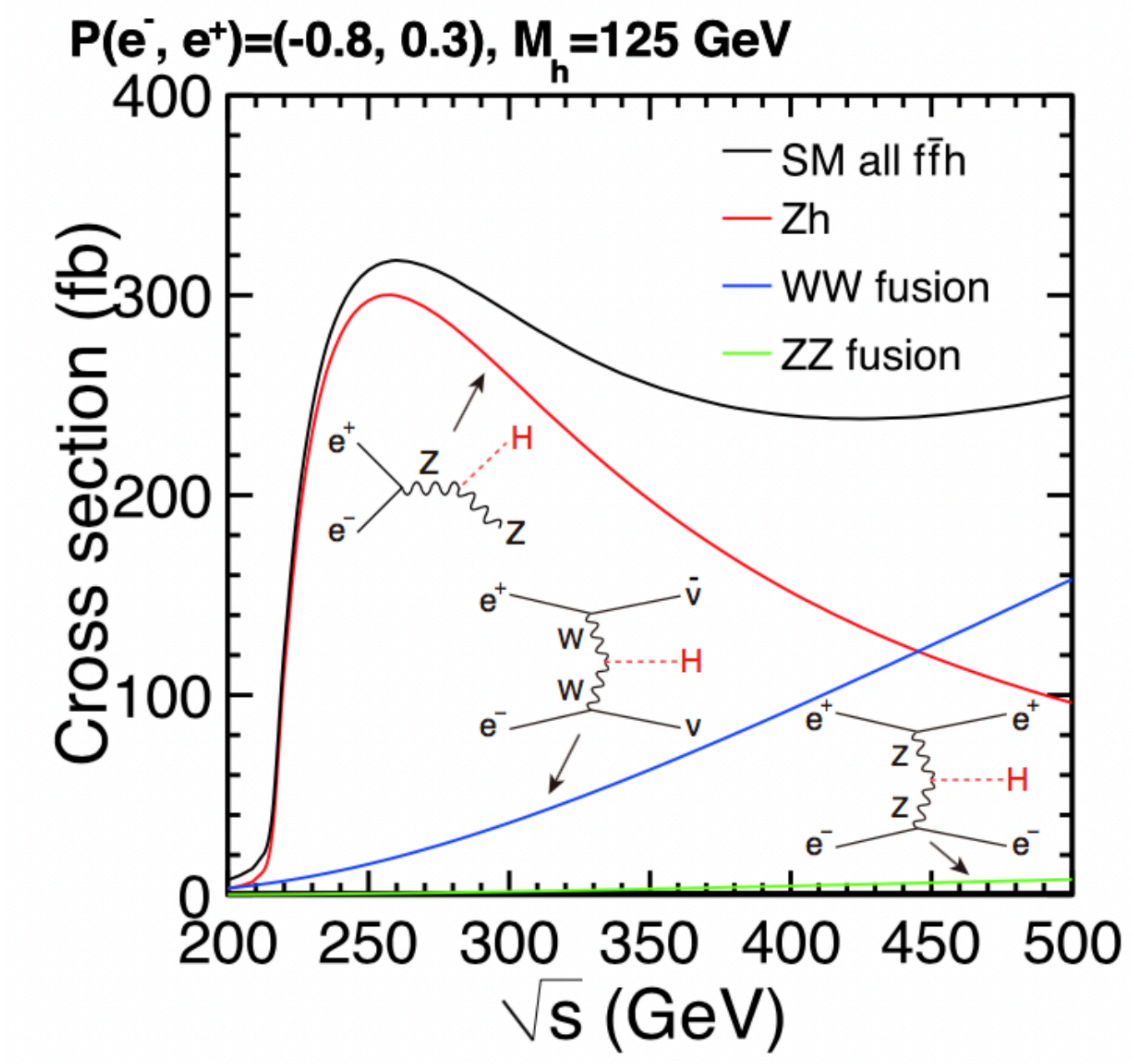
Single Higgs Production

- Higgstrahlung: ee ->ZH
  - highest cross-section upto 500 GeV
- WW fusion: ee ->$H\nu_e\nu_e$
  - dominant above 500 GeV
  - Large statistics at high energies
- ZZ fusion: ee->He^+e^-
  - Important above 500 GeV
- ttH production:
  - High cross-sections above 500 GeV
  - Direct extraction of top-Yukawa coupling



Single Higgs Production

- Higgstrahlung: ee ->ZH
  - highest cross-section upto 500 GeV
- WW fusion: ee ->$H\nu_e\nu_e$
  - dominant above 500 GeV
  - Large statistics at high energies
- ZZ fusion: ee->He^+e^-
  - Dominant above 500 GeV
- ttH production:
  - High cross-sections above 500 GeV
  - Direct extraction of top-Yukawa coupling



Recoil method for leptonic decays of Z

- Model-independent measurements of Higgs cross-section and M_H possible at ee colliders

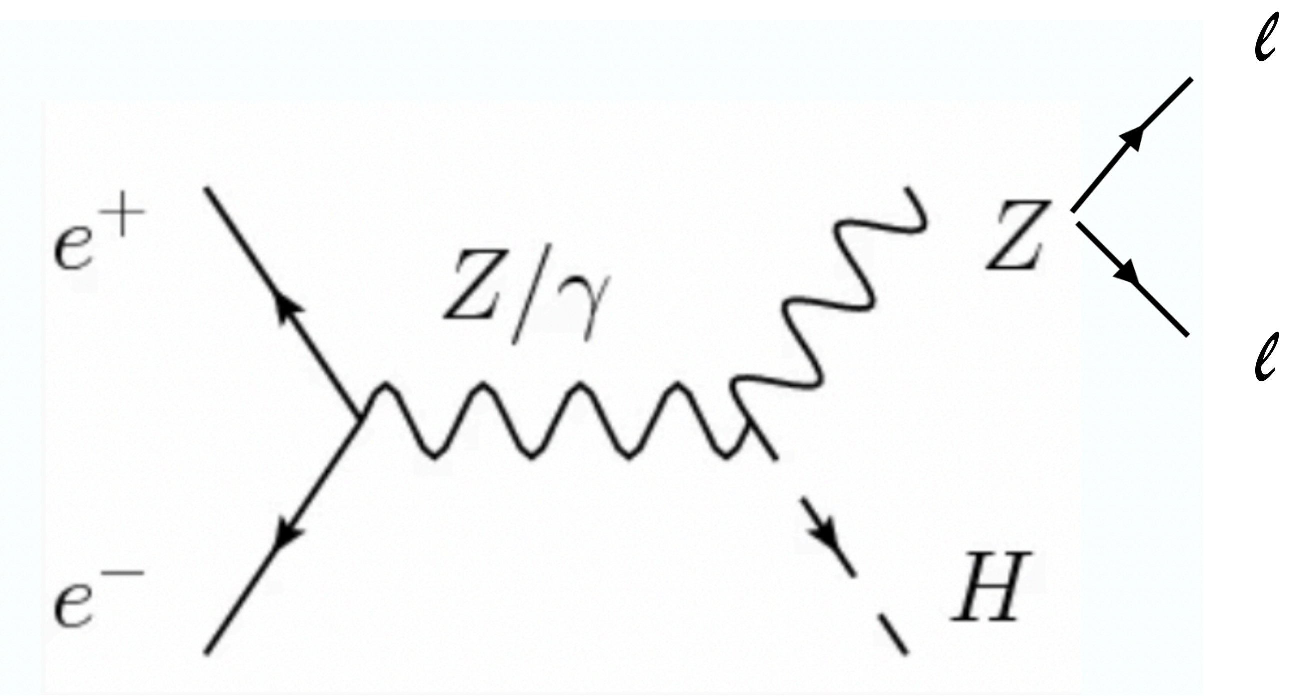
$$m_{rec}^2 = (\sqrt{s} - E_Z)^2 - p_Z^2$$

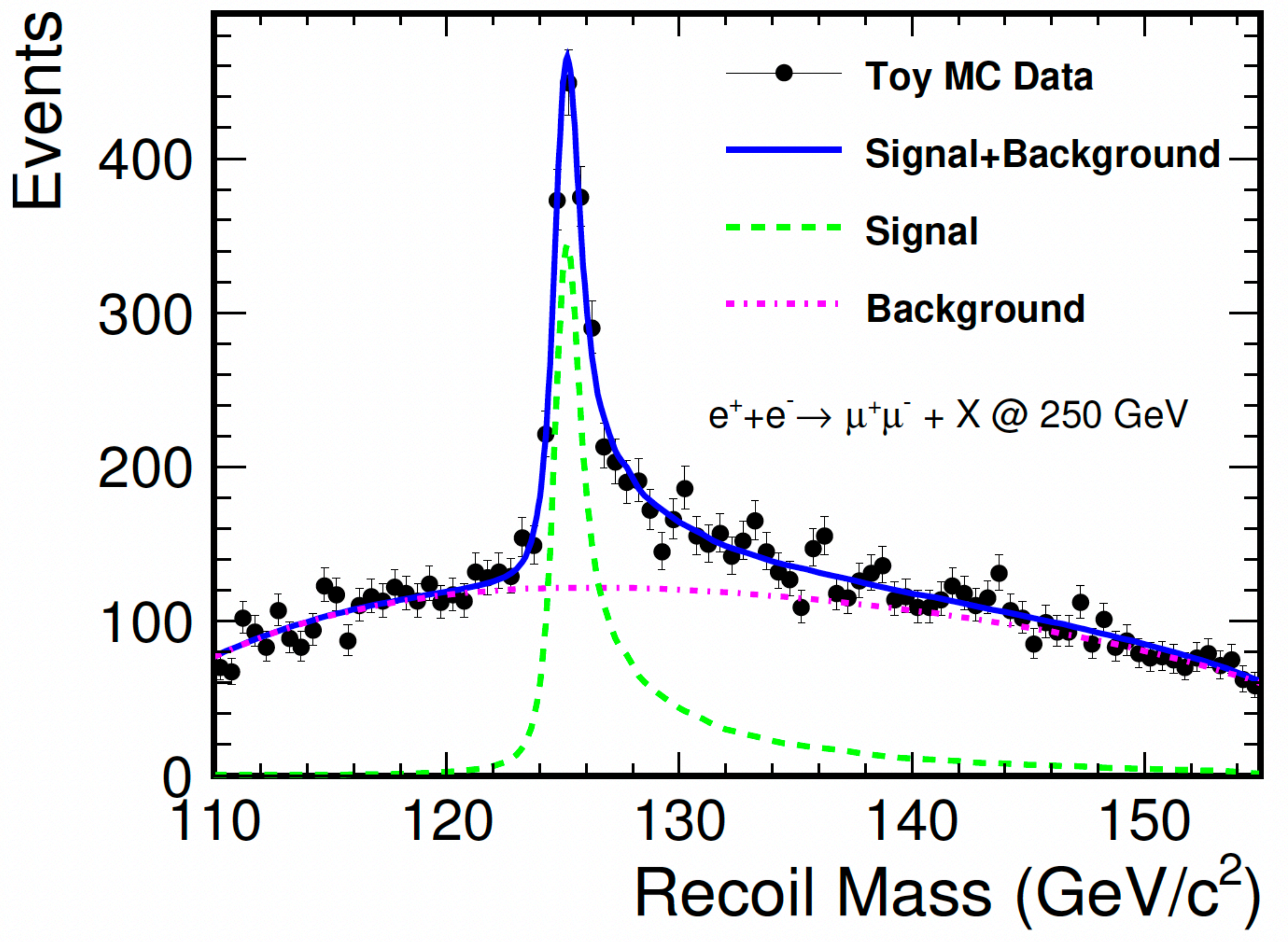
- Since $\sqrt{s}$ is known very well at lepton colliders
- With leptonic decays of Z, bigger backgrounds like ZZ and WW events not a problem
- Impact of beam energy spectrum and ISR is smaller

$$\sqrt{s} = 250\,\mathrm{GeV}, \mathrm{L} = 2\,\mathrm{ab}^{-1}$$

$$\Delta\sigma(\mathrm{HZ})/\sigma(\mathrm{HZ}) = 1.0\,\%$$

$$\Delta \mathrm{m_H} = 14\,\mathrm{MeV}$$





Phys. Rev. D 94, 113002 (2016)

Recoil method for leptonic decays of Z

- Model-independent measurements of Higgs cross-section and M_H possible at ee colliders

$$m_{rec}^2 = (\sqrt{s} - E_Z)^2 - p_Z^2$$

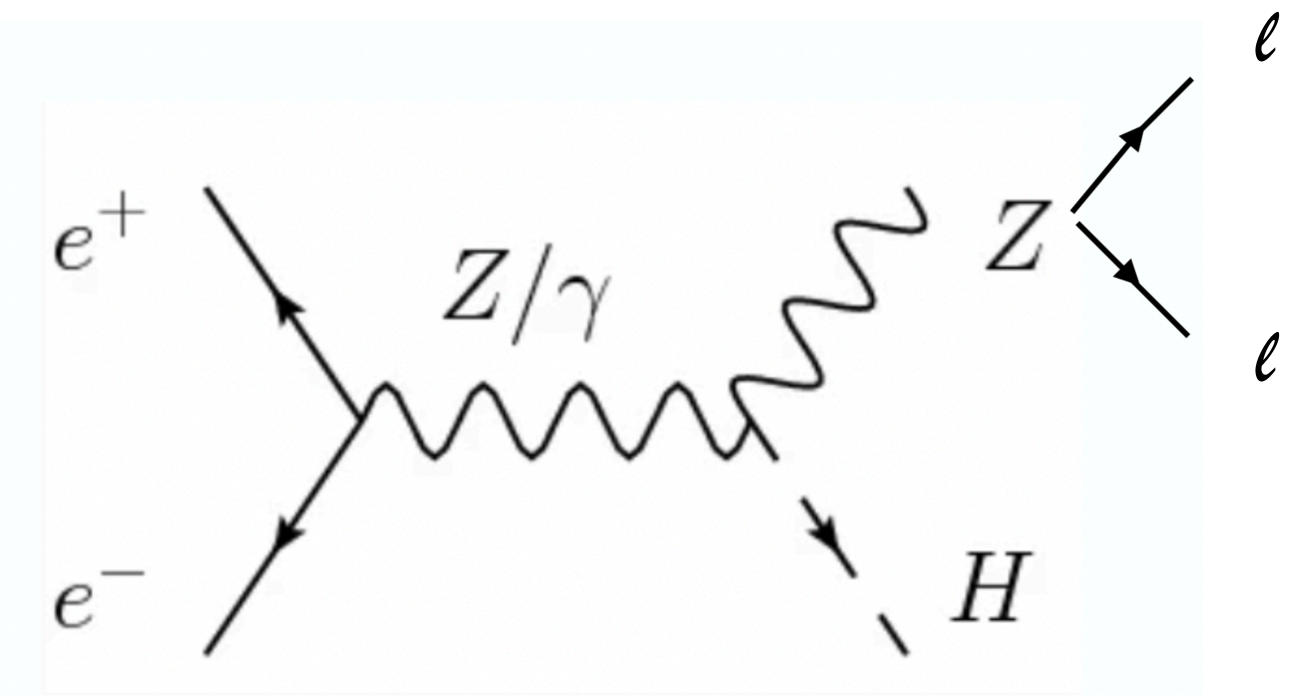
- Since $\sqrt{s}$ is known very well at lepton colliders
- With leptonic decays of Z, bigger backgrounds like ZZ and WW events not a problem
- Impact of beam energy spectrum and ISR is smaller

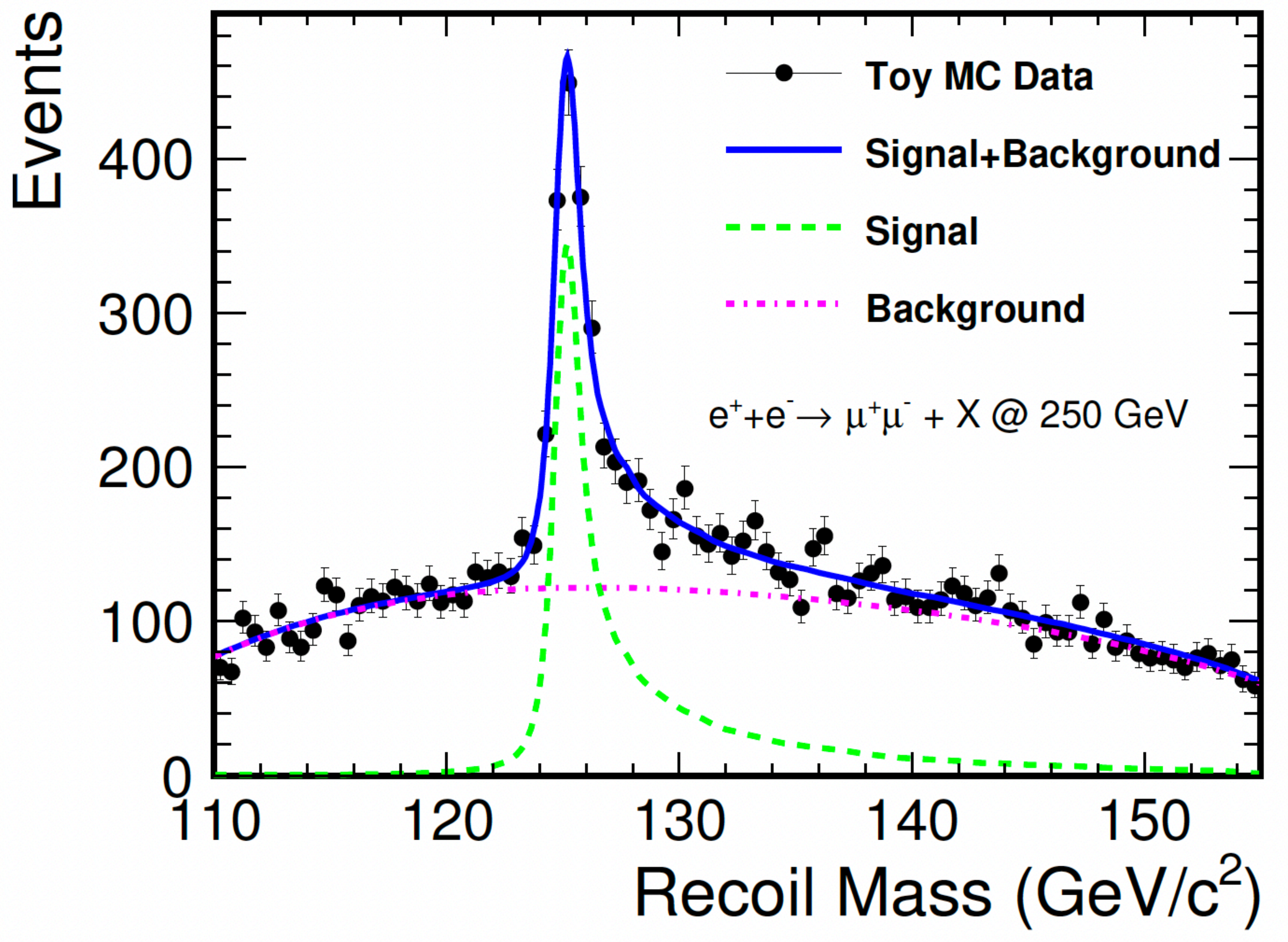
$$\sqrt{s} = 250\,\mathrm{GeV}, \mathrm{L} = 2\,\mathrm{ab}^{-1}$$

$$\Delta\sigma(\mathrm{HZ})/\sigma(\mathrm{HZ}) = 1.0\,\%$$

Value is used in other Higgs studies

$$\Delta m_{\mathrm{H}} = 14\,\mathrm{MeV}$$

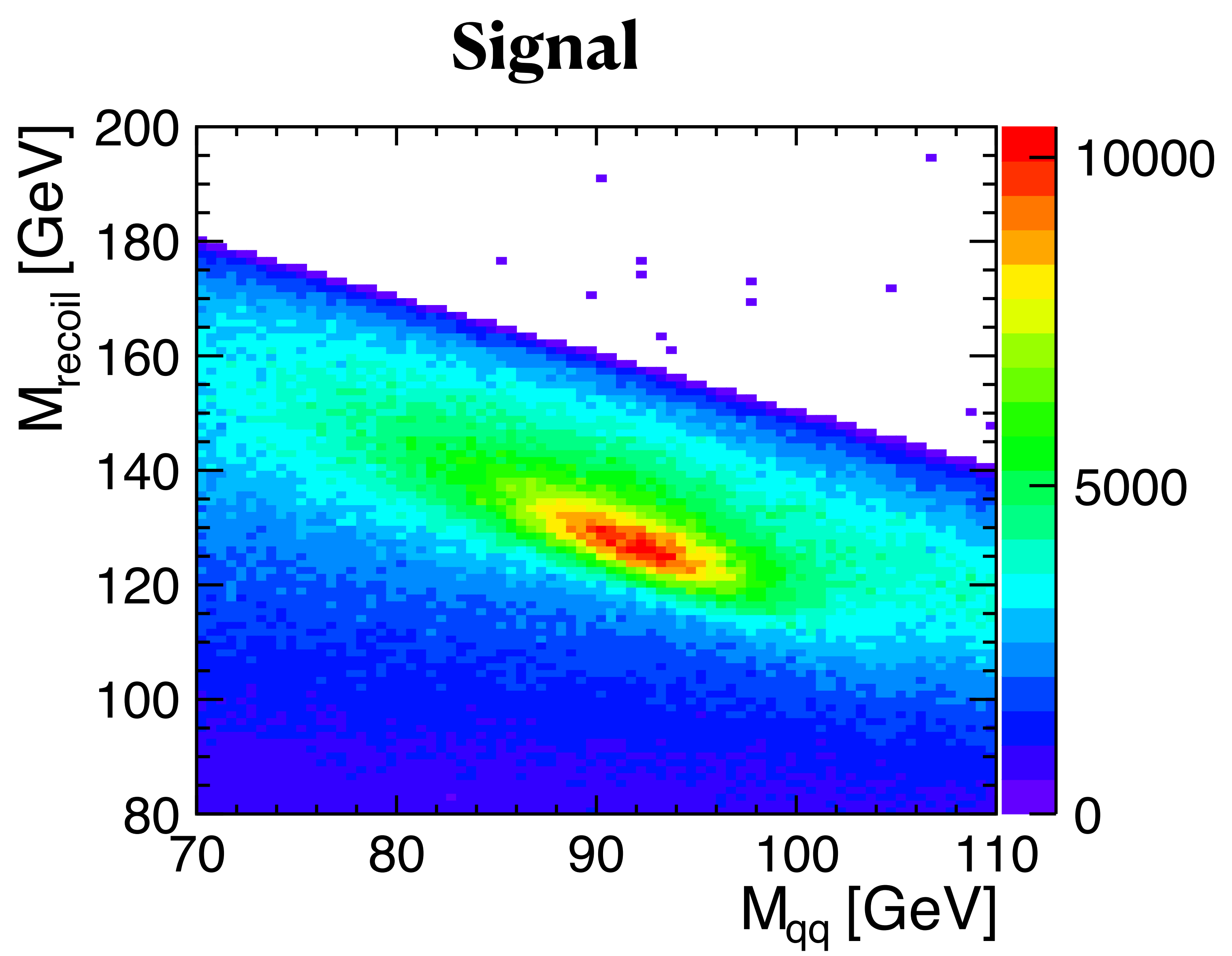


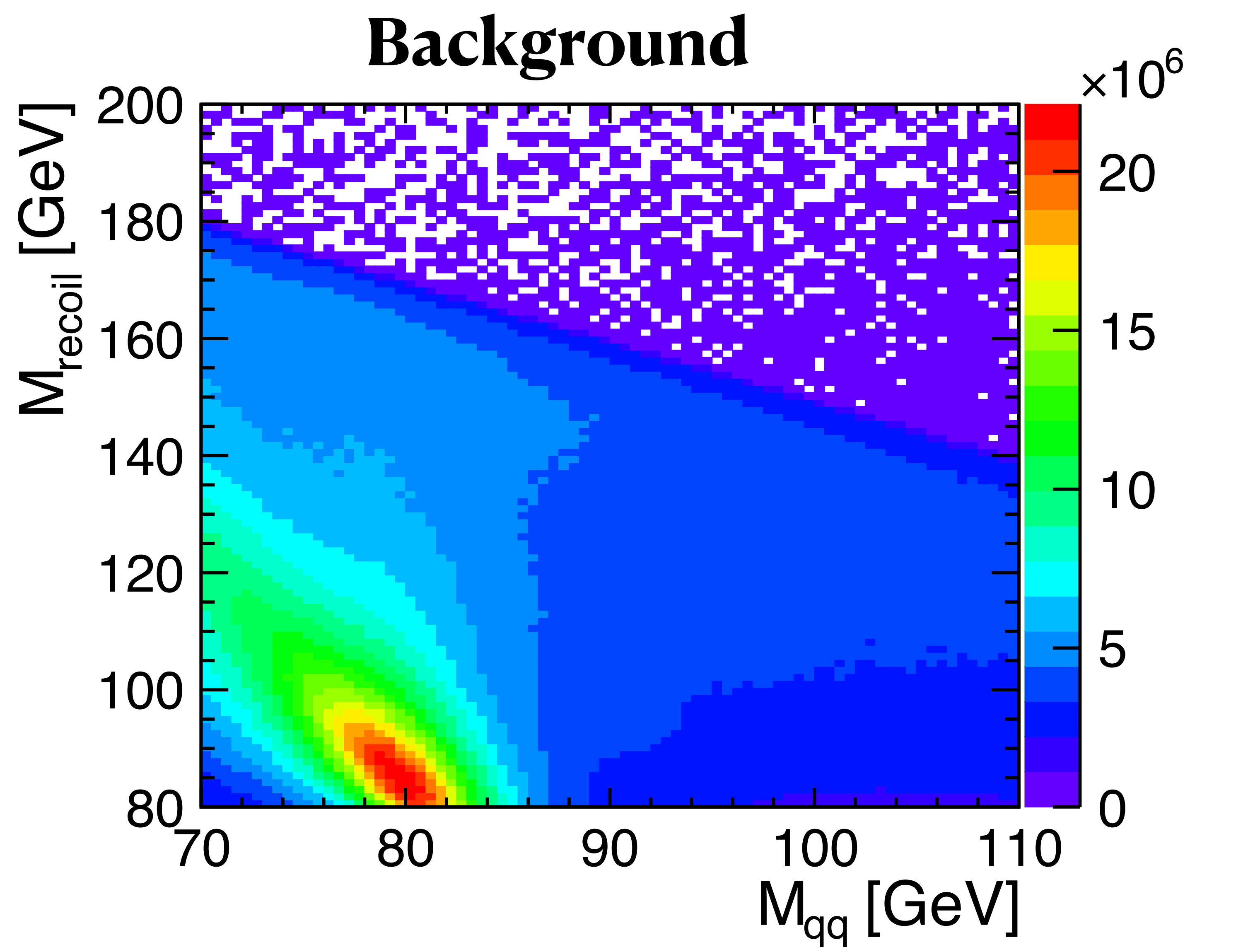


Phys. Rev. D 94, 113002 (2016)

Recoil method for hadronic decays of Z

- ee->Hqq have 10 times higher cross-section than leptonic decays
- However, at 250 GeV the HZ production is not far above threshold
- Recoil mass distribution is relatively closer to kinematic limit
- The region populated by huge backgrounds from processes like ee->qqqq (from ZZ or WW)
- Separation of signal and background very challenging especially when Higgs decay hadronically too ($H \rightarrow b\bar{b}$, WW)
- Recoil method for hadronic decays of Z can only be nearly model-independent

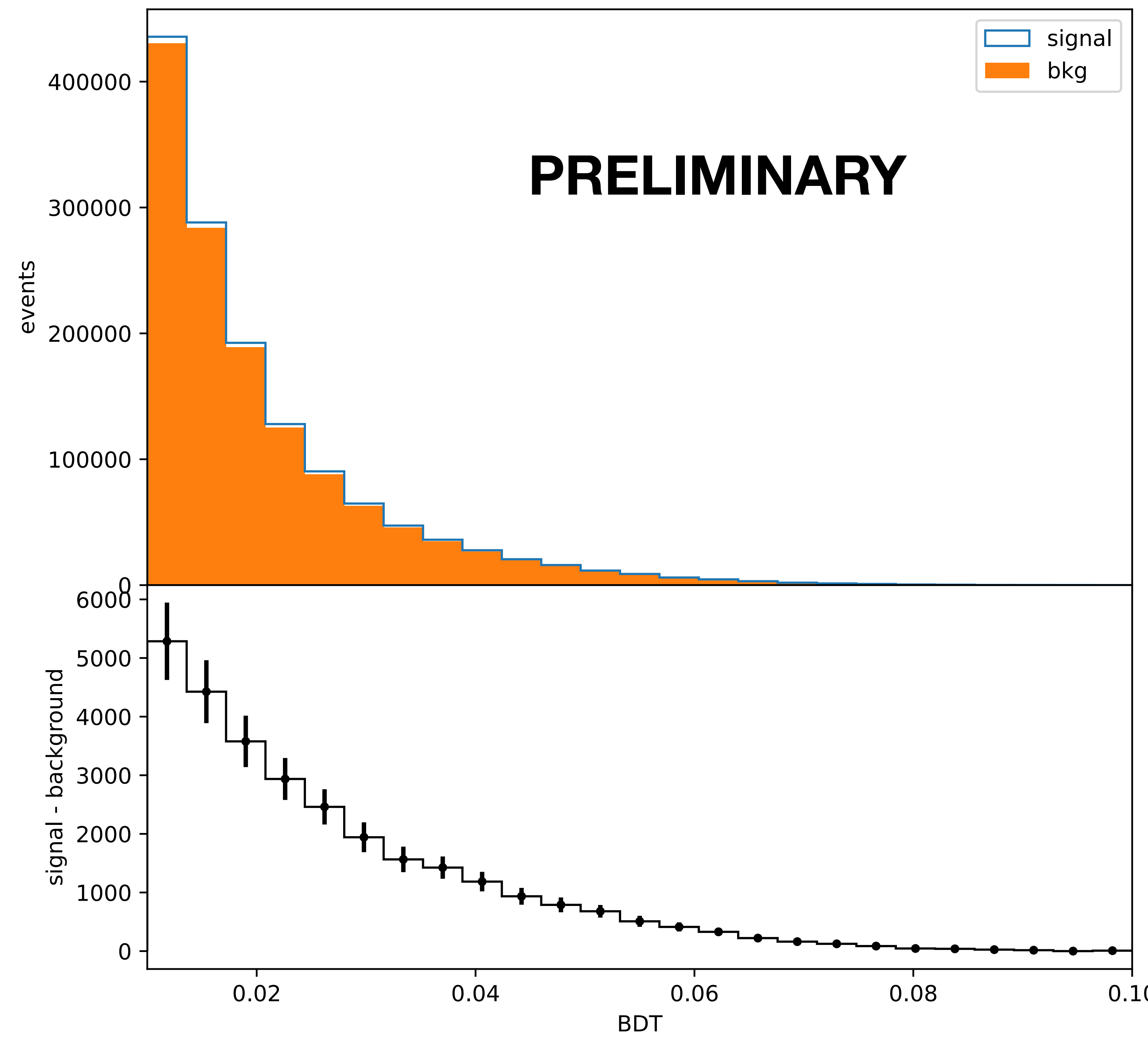




Recoil method for hadronic decays of Z

- At a study for CLIC it was found that hadronic Z decays provide best sensitivity at 350 GeV

$\sqrt{s}$ [GeV]	L_{int}[fb^{-1}]	σ (ZH)[fb]	$\Delta\sigma$(ZH)
250	1000	136	2.58%
350	1000	93	1.27%
420	1000	68	1.86%

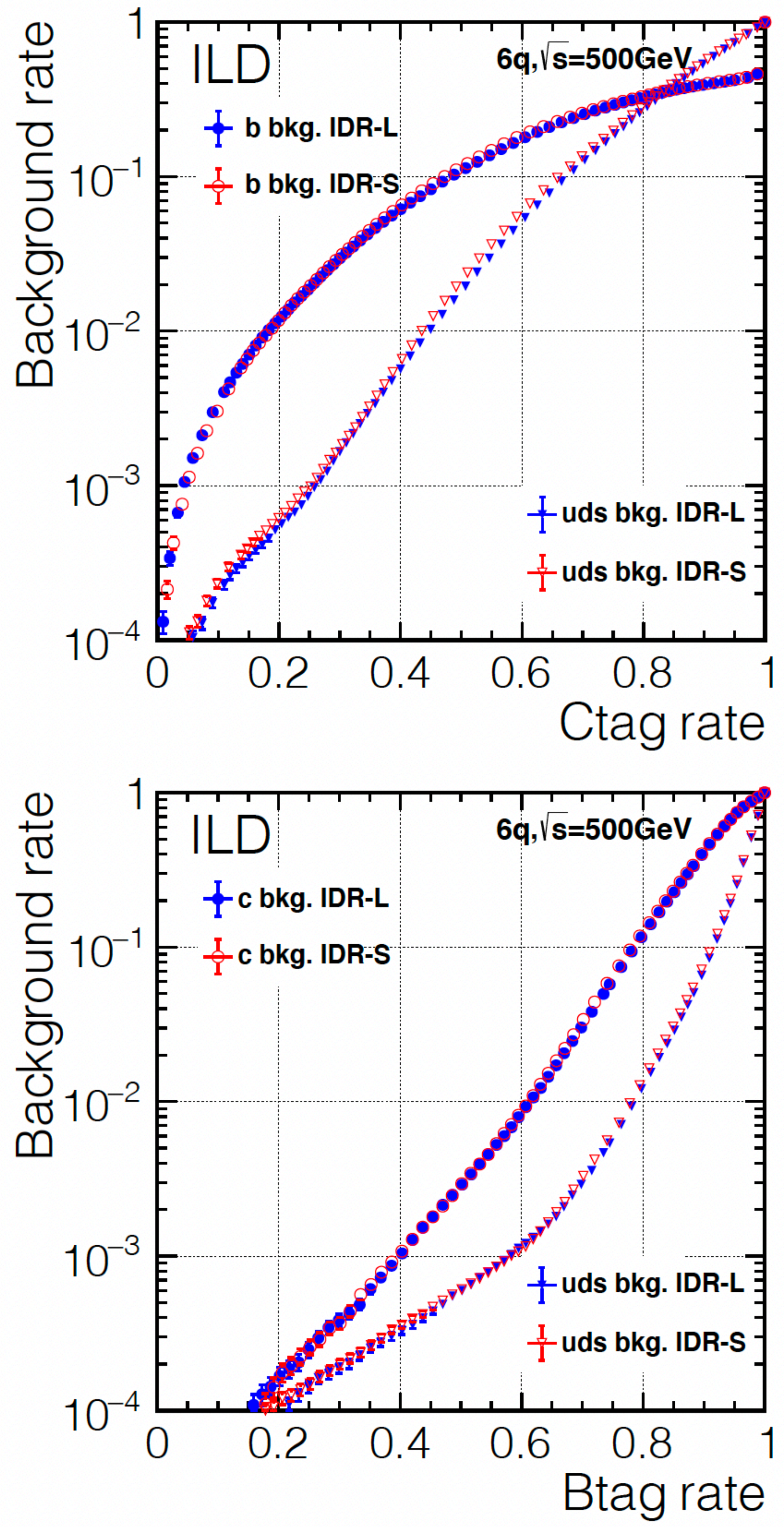


- A similar study at ILC being done at 250 GeV for a luminosity of 500 fb^{-1}
- The study confirms that 350 GeV is the best centre of mass energy to study Higgs using hadronic decays of Z

Eur. Phys. J. C 76, 72 (2016)

Hadronic decays of Higgs

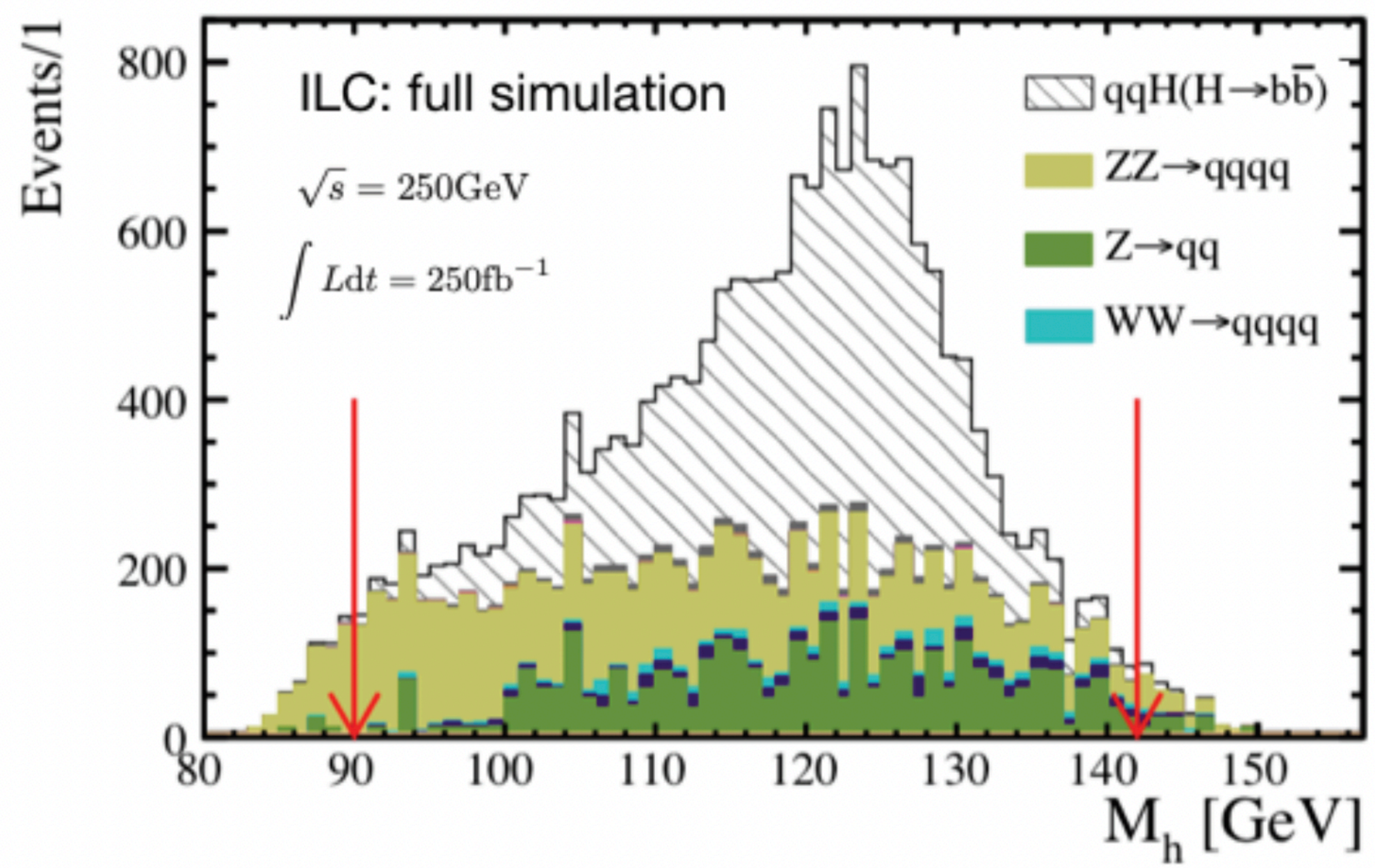
- Direct reconstruction of Higgs from its decay products
- Hadronic decays of Higgs, e.g H->bb, cc or gluons are dominant
- Flavour tagging very important for experimental separation of the jets
- Excellent c and b tagging performance achieved
- Moreover, only $\sigma \times$ BR can be measured at the hadron colliders like LHC whereas both σ and BR can be individually measured at ILC



arXiv:2003.01116v1

Hadronic decays of Higgs

- Direct reconstruction of Higgs from its decay products
- Hadronic decays of Higgs, e.g H->bb, cc or gluons are dominant
- Flavour tagging very important for experimental separation of the jets
- Excellent c and b tagging performance achieved

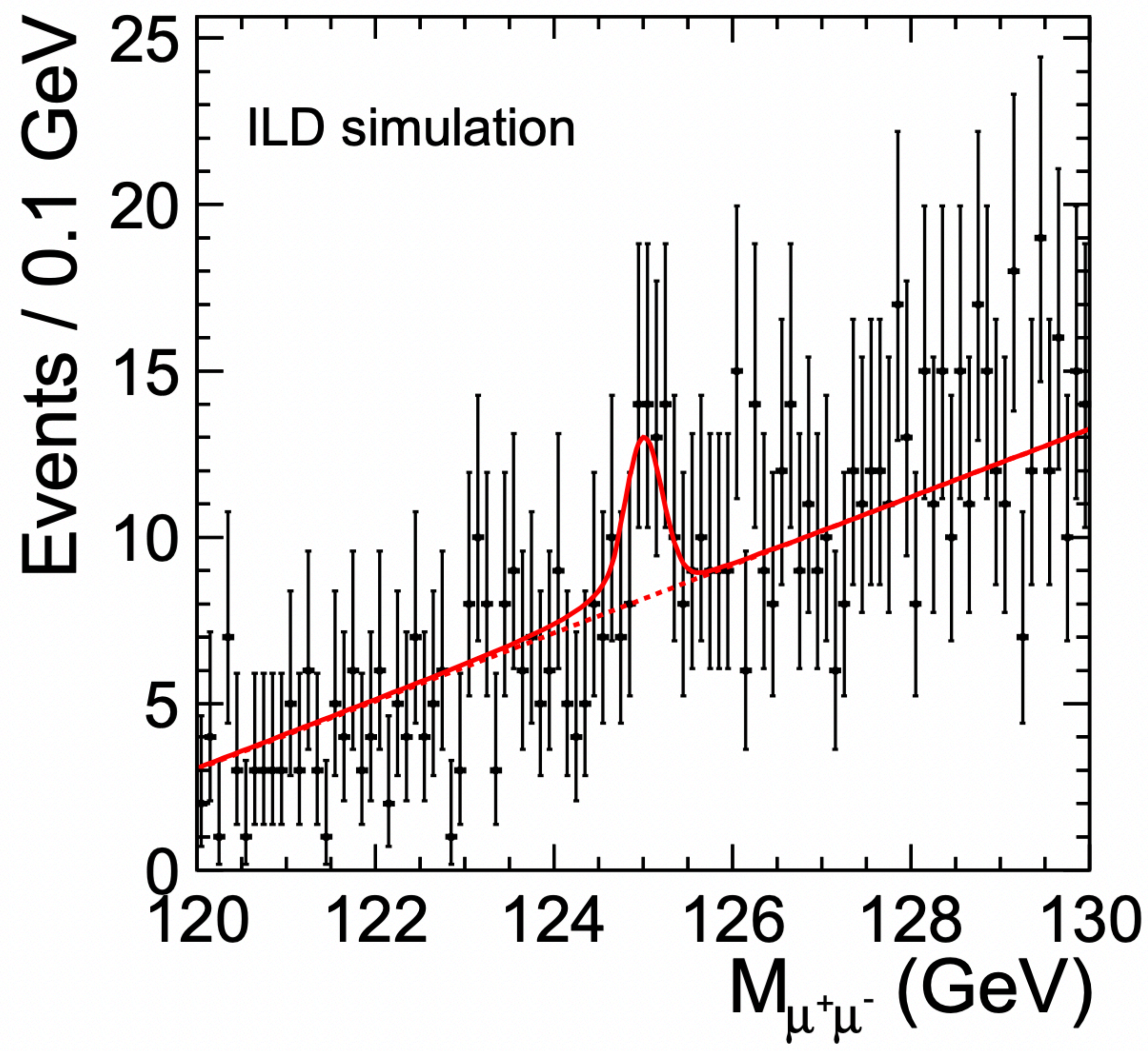


- $\sqrt{s}$ = 250 GeV, L = 2 ab^{-1}
- $\sigma(\mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \mathrm{b\bar{b}})$ measured at 0.7 % precision
- $\sigma(\mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \mathrm{c\bar{c}}, \mathrm{g\bar{g}})$ Measured at 4 % precision

Eur. Phys. J. C 73

Leptonic Decays of Higgs

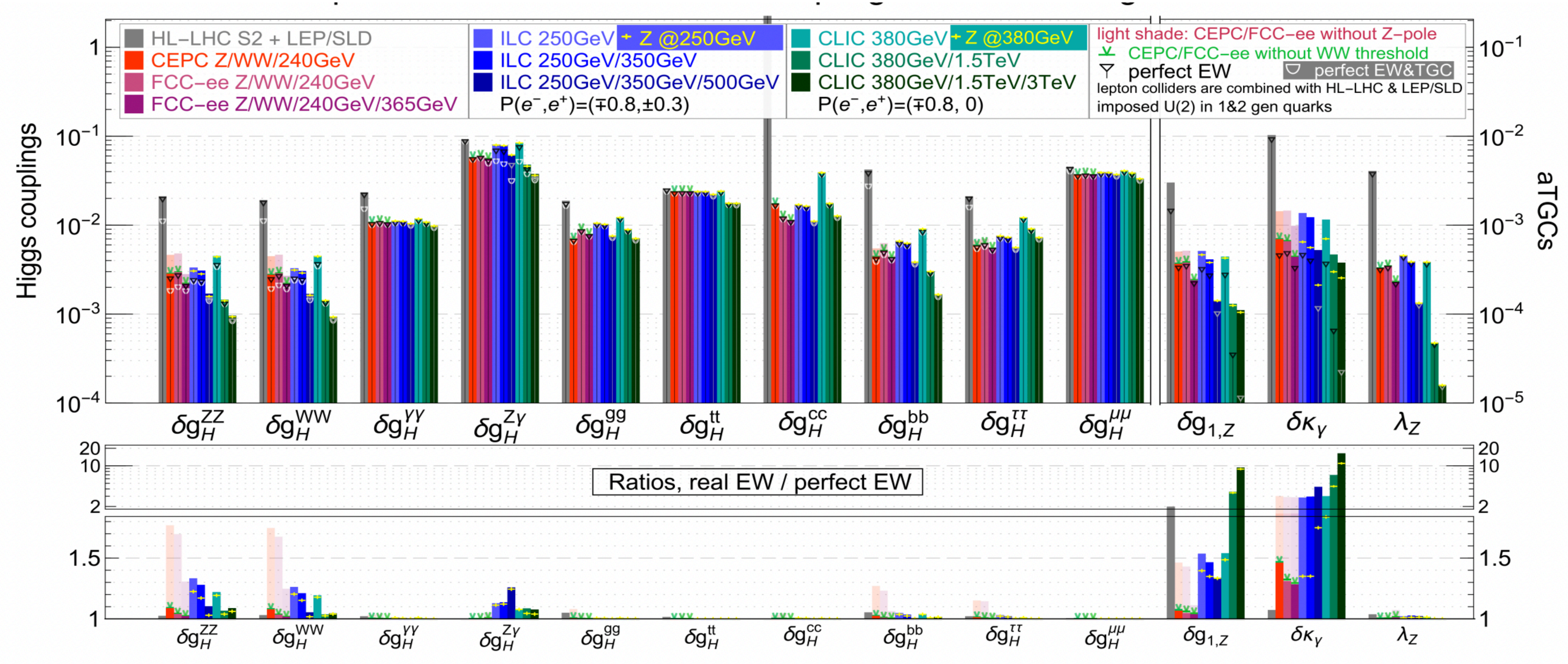
- Higgs decays to leptons can be measured if these BRs are similar to as predicted in SM
- The partial cross-section $\sigma(\mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \tau\tau)$ can be measured at ILC 250 with a precision less than 2%
- The small branching ratio of $\mathrm{H} \to \mu\mu$ limits the statistics available at ILC
- However, the partial cross-section $\sigma(\mathrm{ZH}) \times \mathrm{BR}(\mathrm{H} \to \mu\mu)$ still can be measured with a precision of 17 % for combined 250 GeV and 500 GeV results



Eur. Phys. J. C (2015) 75:617

Eur. Phys. J. C (2020) 80:1186

Higgs coupling sensitivity at different colliders



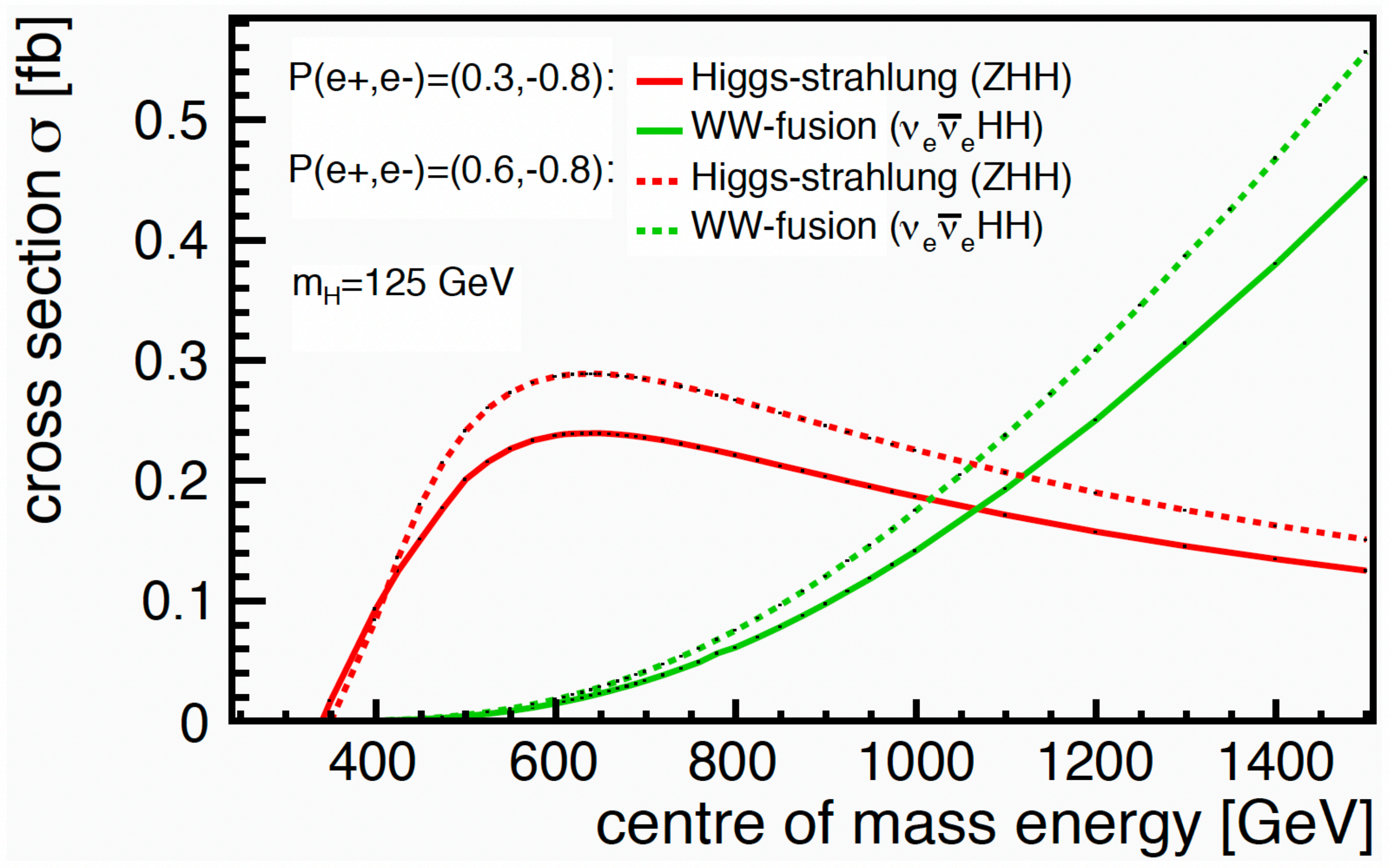
- ILC and CLIC are much more sensitive to Higgs couplings as compared to the HL-LHC
- Processes like $H \to c\bar{c}$ very challenging at hadron colliders

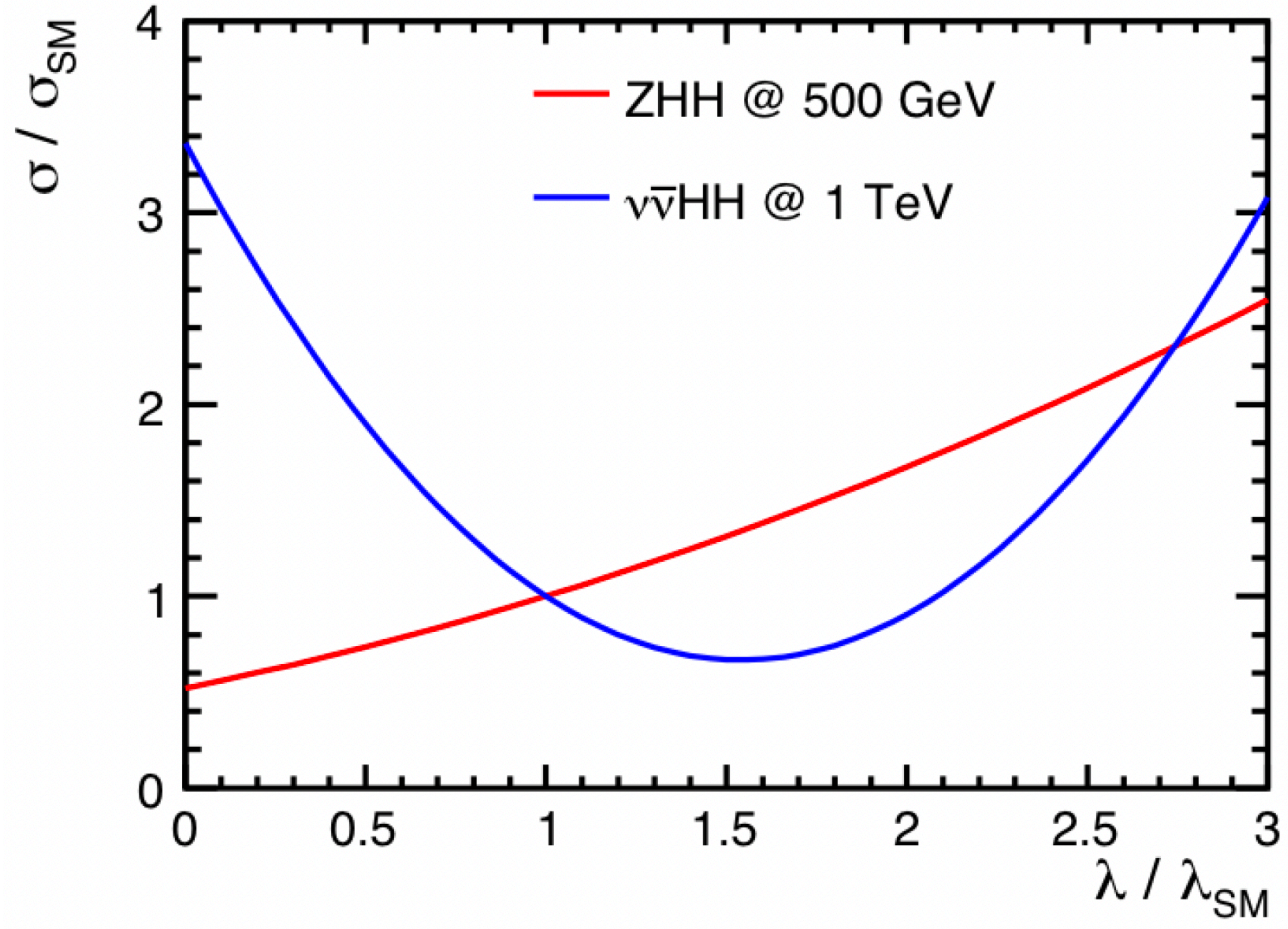
arXiv:1907.04311

Higgs self-coupling at ILC

DESY-THESIS-2016-027

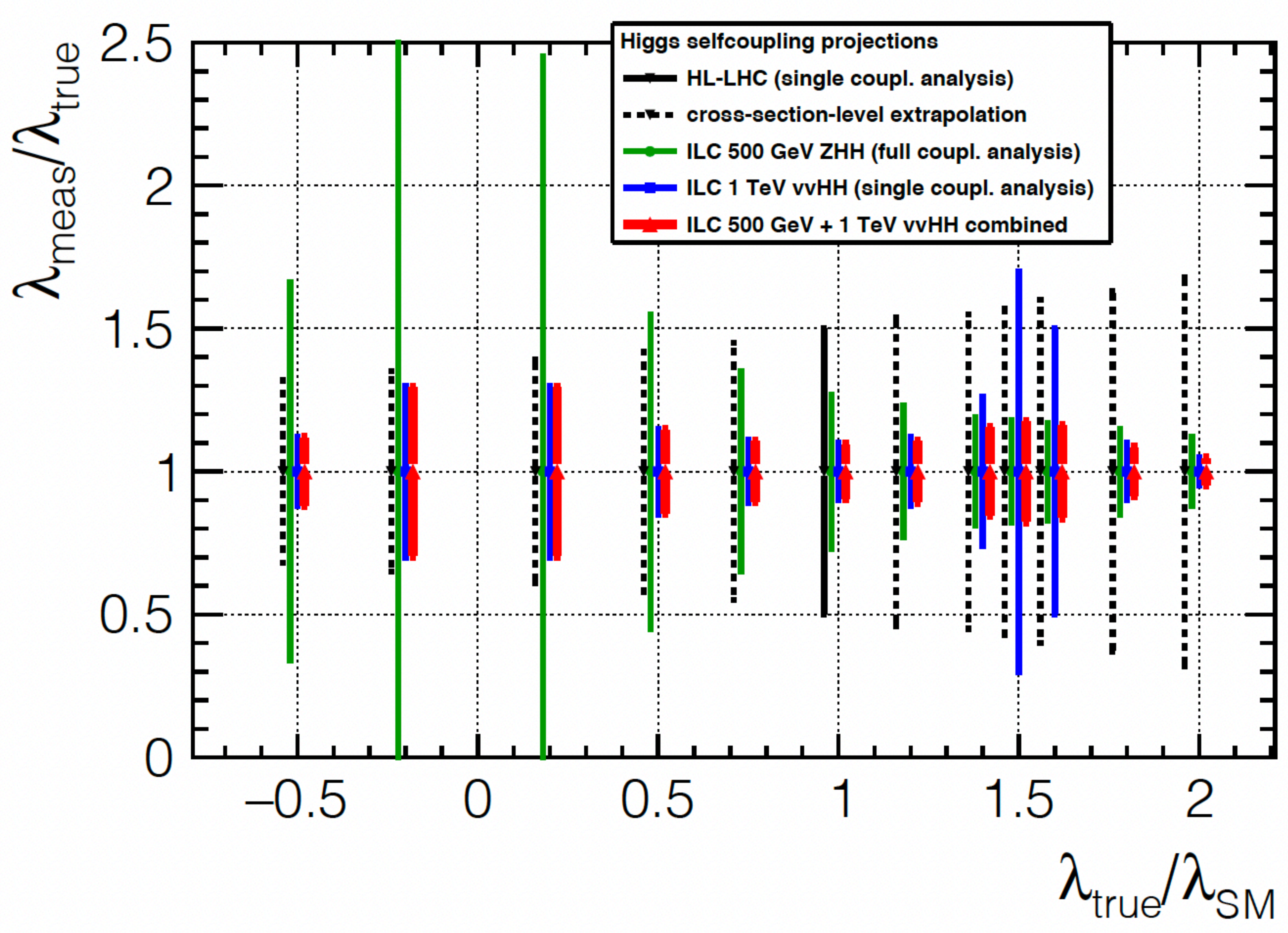
- Two relevant di-Higgs production $\mathrm{e^+e^- \to ZHH}$ and $\mathrm{e^+e^-} \to \nu\bar{\nu}\mathrm{HH}$ (WW fusion)
- Cross-section as a function of centre-of-mass energy:
  - double Higgsstrahlung around 500-600 GeV
  - WW fusion at and above 1 TeV
- If the Higgs coupling deviates from the SM, the two channels would interfere with the SM effects
- The cross-section for ZHH increases with increase in triple Higgs coupling (λ) whereas that for HH$\nu\bar{\nu}$ decreases
- With both increase or decrease in λ, one of the processes will give sensitivity to it at the ILC





Higgs self-coupling measurements

- The prospect of measuring Higgs self-coupling both at $\sqrt{s}$ = 500 GeV and 1 TeV studied
- At $\sqrt{s}$ = 500 GeV double higgstrahlung can be observed with a significance of 8σ
- Combined channels HH → $b\bar{b}b\bar{b}$ and HH → $b\bar{b}WW^*$
- Therefore obtaining a measurement precision of 27% on λ
- With addition of measurement at 1 TeV with the ILC upgrade, the precision improves to 10 %



DESY-THESIS-2016-027

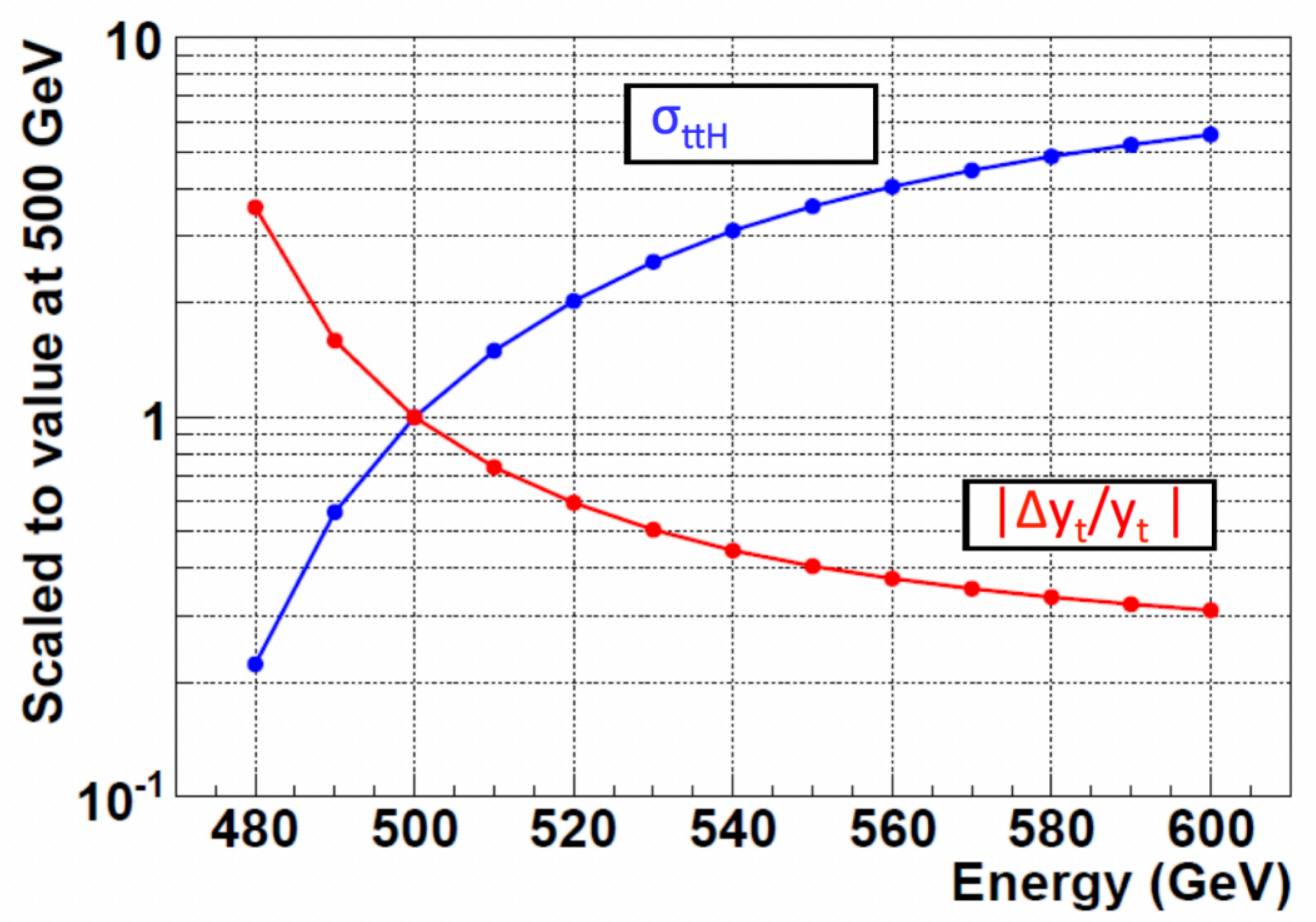
ATL-PHYS-PUB-2018-053

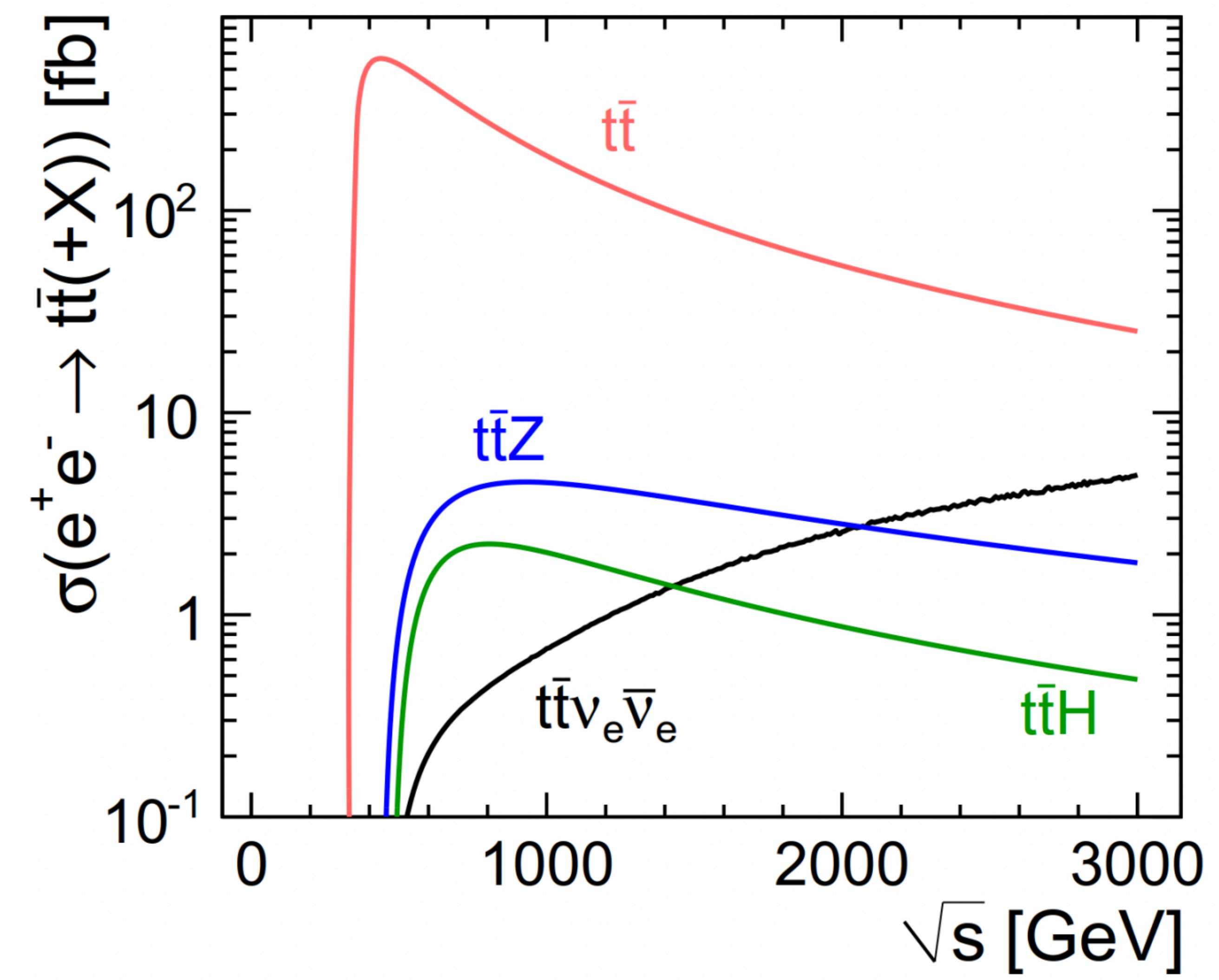
Top quark Yukawa Coupling

arXiv:1506.07830v1

- Main processes to access top:
  - $e^+e^- \rightarrow t\bar{t}$ (threshold at $2m_T$, 380-500 GeV)
  - $e^+e^- \rightarrow t\bar{t}H$ (maximum at 800 GeV)
  - $e^+e^- \rightarrow t\bar{t}\nu_e\bar{\nu}_e$ (at highest energies)
- The $t\bar{t}$ threshold scan offers an indirect measurement of top Yukawa coupling with a precision of 4 %
- The direct measurement using $e^+e^- \rightarrow t\bar{t}H$ process:
  - The cross sections for other $t\bar{t}$ events decreases at and above 500 GeV

$\sqrt{s}$ [GeV]	L_{int}[ab^{-1}]	precision [%]
550	4	2.8
1000	8	1



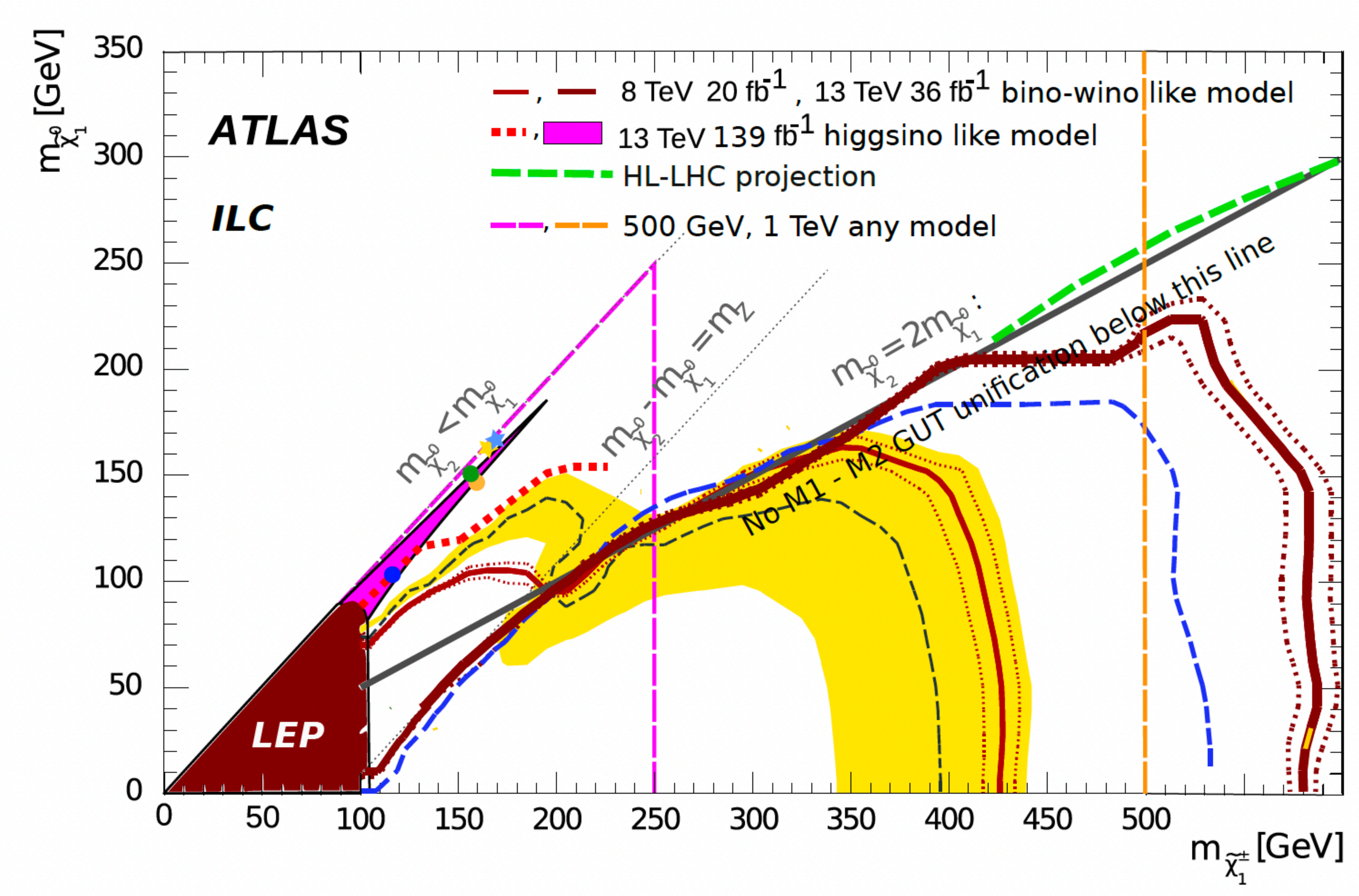


SUSY searches at ILC

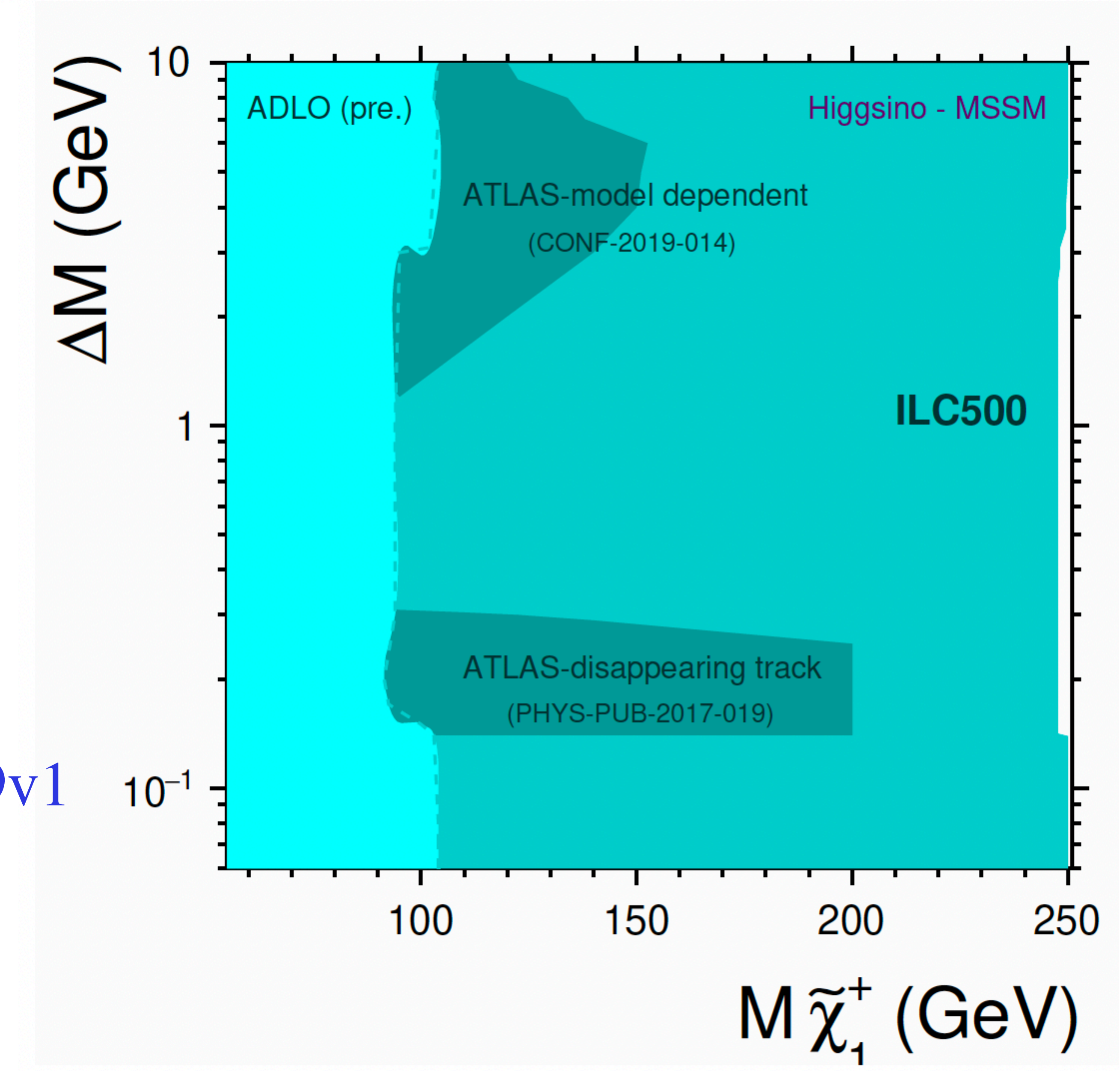
- ILC offers different angles to explore SUSY compared to LHC
- Loop-hole free searches and complete coverage of compressed spectra
- Light Higgsinos motivated by naturalness

$$m_Z^2 = 2\underbrace{\frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1}}_{\text{terms from SUSY breaking}} - \underbrace{2\mu^2}_{\text{higgsino mass parameter}}$$

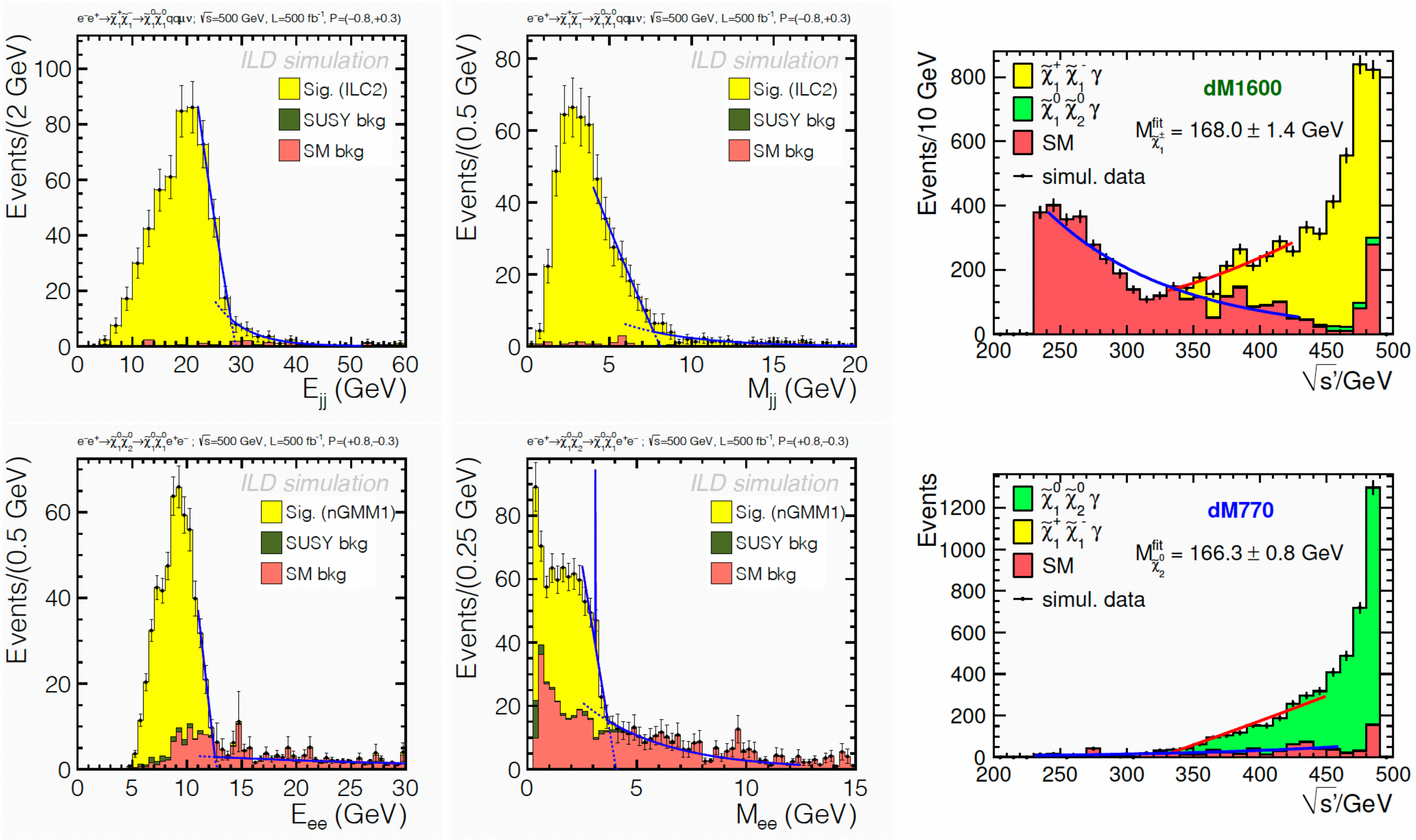
- Light Higgsinos expected in the electroweak scale



arXiv:2002.01239v1



Higgsinos with low ΔM



- Observables for three different Higgsino-LSP models

Models	Benchmark	$\Delta M_{\tilde{\chi}_1^\pm}$ [GeV]	$\Delta M_{\tilde{\chi}_1^0}$ [GeV]
NUHM1	ILC1	14.6	21.3
NUHM2	ILC2	10.2	9.7
Mixed guage-gravitation	dM770	0.77	1.04
	dM1600	1.6	2.7

- The Higgsinos masses for different scenarios can be measured at:

- The Higgsinos masses can be measured at an uncertainty 0.004 - 1% for different benchmark scenarios
- The $\sigma \times \mathrm{BR}$ could be measured at 1.6-5% uncertainty

arXiv:1912.06643

Eur. Phys. J. C (2013) 73:2660

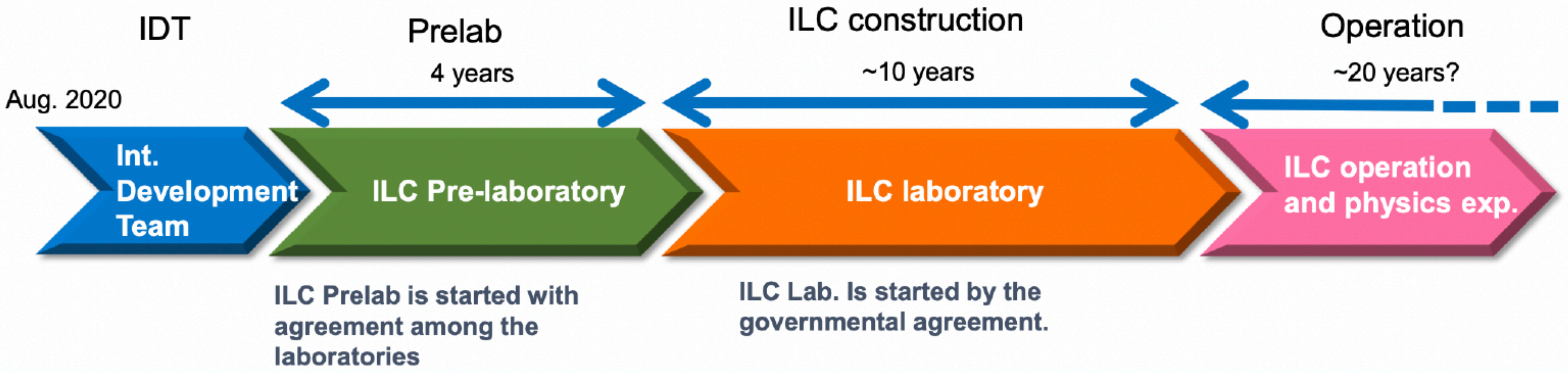
Summary

- Due to the highly clean physics environment and possibility to upgrade to higher energies gives the possibility to access process that are highly challenging at hadron colliders
- Substantial improvements with respect to the hadron colliders possible at ILC for the discussed topics
- Precise measurements of single Higgs and Higgs self-coupling possible especially the model-independent approach gives many higher possibilities
- Along with precision measurements, search for new particles in electroweak scale may also be possible at ILC

Backup Slides

Timeline

- European Strategy Output:
  - Electron positron collider as a Higgs factory highest priority
  - ILC timescale:



  - Timely realisation of ILC in Japan would be compatible with European strategy output, European particle physics community would wish to collaborate
  - The situation in Japan still very unclear - positive statements from MEXT, stressing need for international contributions