Higgs physics at future lepton colliders.

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- The discovery of the Higgs particle (H) has been a success of the SM, but is also demanding a detailed knowledge of its properties.

- ATLAS and CMS data are consistent with fermionic and bosonic couplings expected from a SM Higgs particle. Searches have been performed in several decay modes. From the available data it cannot be concluded yet that we have found the SM Higgs and not one of the scalars postulated within the possible extensions of the SM.

- Experimental energy resolutions have been so far much wider of the expected intrinsic Higgs width of about 4 MeV. A detailed study of the properties of this particle is mandatory. Will the ultimate LHC be enough?

New lepton and hadron colliders have been proposed.
Two possible future lepton alternatives:

- A muon collider, at $L > 10^{32}$ with a resonant s-channel H signal. Offers the unique opportunity of a precision study of the total and partial widths of H in the various decay channels.

- A e^+e^- collider, at $L > 10^{34}$ with a (Z + H) signal. FCCee/CEPC/ILC.

- The idea of muon colliders (MC) goes back to about middle ‘90s.
- Discovery and study of s-channel Higgs physics in the SM and beyond. D. Cline, ’94 , …
- V. Barger, M. Berger, J. Gunion and T. Han, Phys. Rept. 286 (1997)

(i) First MC at low c.m. energy (100-500 Gev) for Higgs discovery, $L \sim 2 \times 10^{33}$ $cm^{-2}\,s^{-1}$

(ii) Next MC at high c.m. energy (up to 4 Tev), for new phenomena, $L \sim 10^{35}$ $cm^{-2}\,s^{-1}$

- Muon Ionization Cooling is the key technology required to be able to realise a Muon Collider and a Neutrino Factory
- MICE

Novel approaches to MC after MICE:

"A complete demonstrator of a muon cooled Higgs factory."

C. Rubbia, arXiv: 1308.6612

- Muon cooling: a Higgs factory at CERN? C. Rubbia, 2015

→ The collider radius is about 50 m. The issue of muon cooling is essential for the luminosity and the energy spread of the beams. Higgs physics requires highly mono-chromatic beams (see later).

A new idea: **(LEMMA,** muon cooling not necessary)

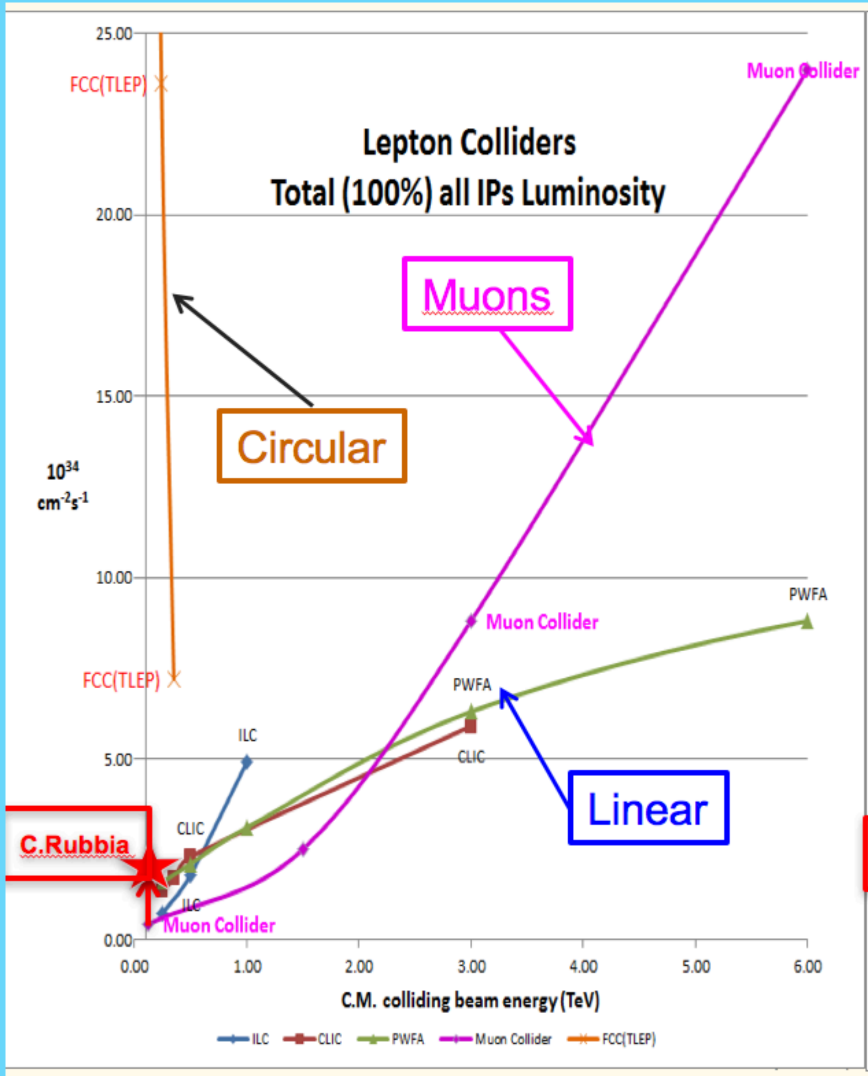
- Low emittance muon beams using positron beam on target.

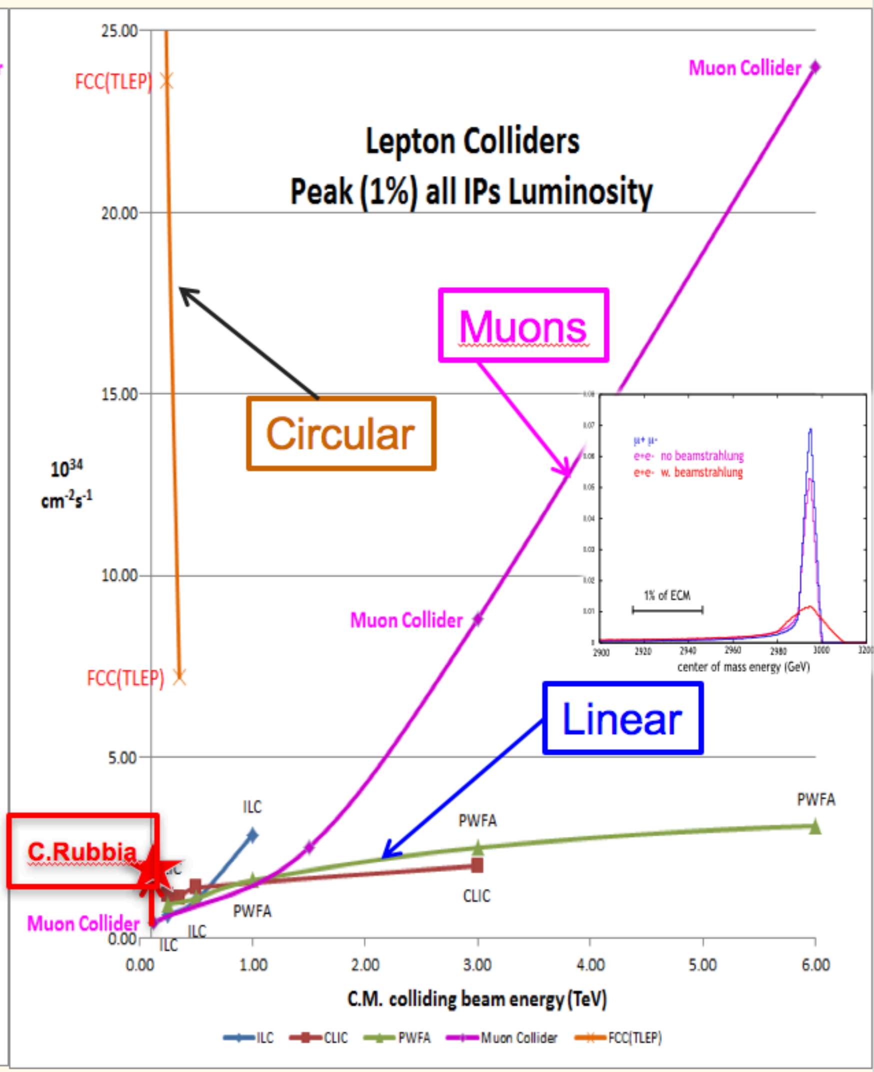
  M.Antonelli, P. Raimondi et al. Nucl.Instr.Meth. A807 (2016) 101

→ Process: $e^+ e^- \rightarrow \mu^+ \mu^-$ just above threshold.

$E(e^+) = 45$ GeV

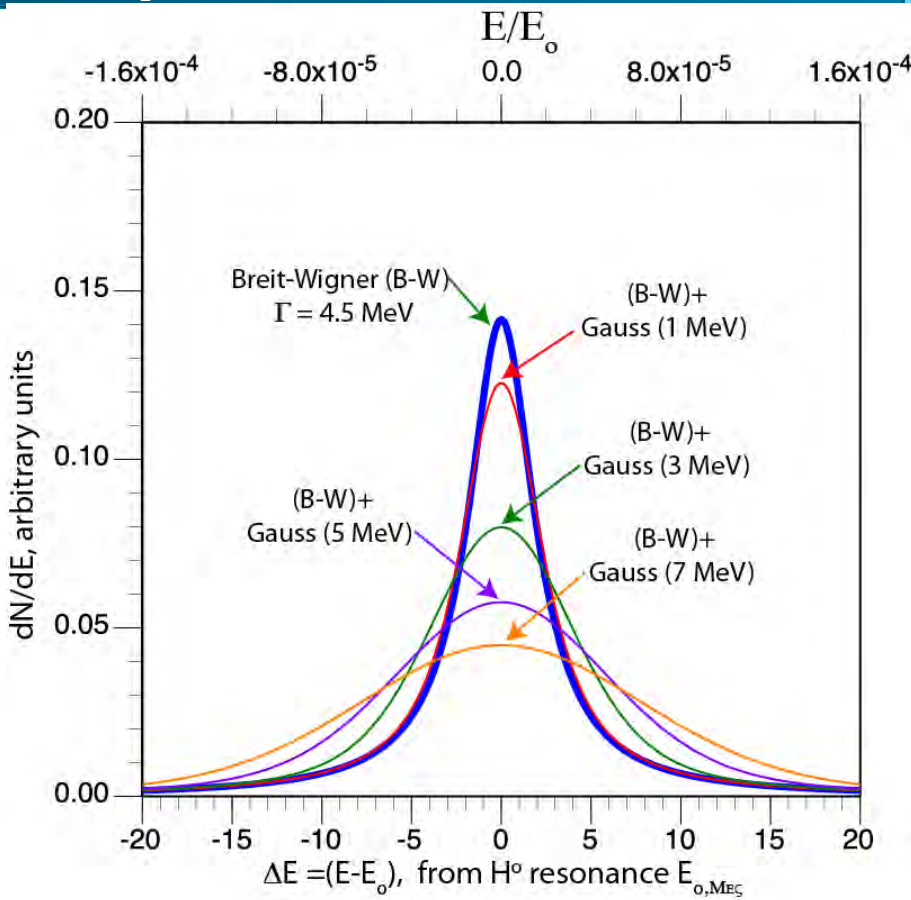
Muon Colliders potential Luminosities





The Higgs width according to the Standard Model

- Like in the case of the Zo, the determination of the H_o width will be crucial in the determination of the nature of the particle and the underlying theory
- Cross section is shown here, convoluted with a Gaussian beam distribution.
- Signal is not affected only if the rms beam energy width is ≤ a few MeV.



4.5 MeV wdth:A very demanding resolution R ≈ 0.003% is required

Venice,March.2015 Slide# : 6

C. Rubbia

No radiative corrections are included yet.

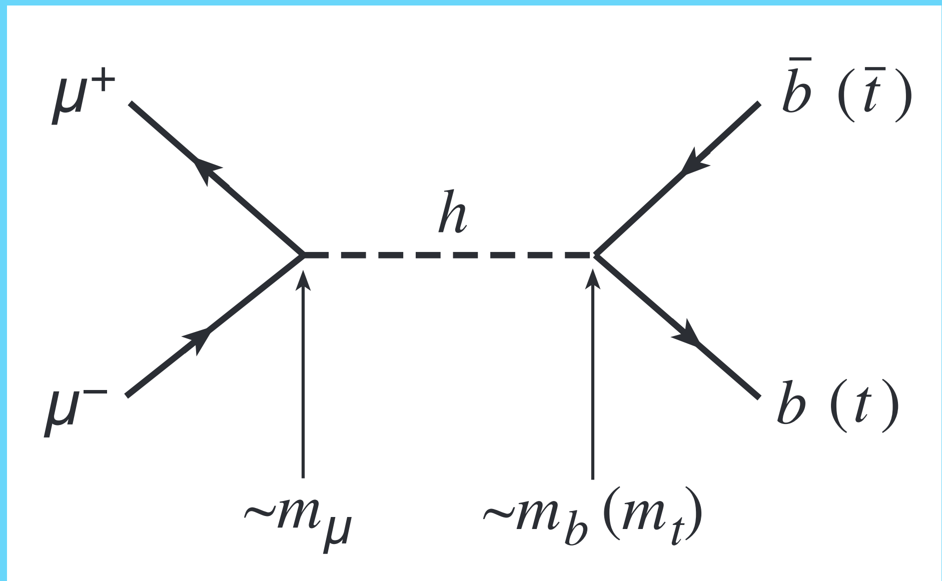
SUSY Extensions of the SM

- MSSM: the Higgs sector contains at least two Higgs doublets and the resulting spectrum of physical Higgs fields includes three neutral Higgs bosons, the CP-even h_0 and H_0 and the CP-odd A_0.
- The couplings of the MSSM Higgs bosons to fermions and vector bosons are determined by tan β and the mixing angle α between the neutral Higgs states h_0 and H_0.
- The Higgs boson widths are then crucial parameters, and for this study the muon collider is particularly suitable.
- Tests of lepton universality of Higgs couplings.
- Non minimal extensions of MSSM → neutral Higgs bosons.

→ Crucial role played by the beam energy resolution for study of the widths in the case of muon colliders.

Muon Collider

- The s-channel cross section is much higher and allows a direct and very precise measurement of the H total and partial widths. Tests of universality of H couplings.



- Possibility to detect and measure with precision more scalars, if any, and therefore to distinguish among the various extensions of the SM. Scalars close in mass.

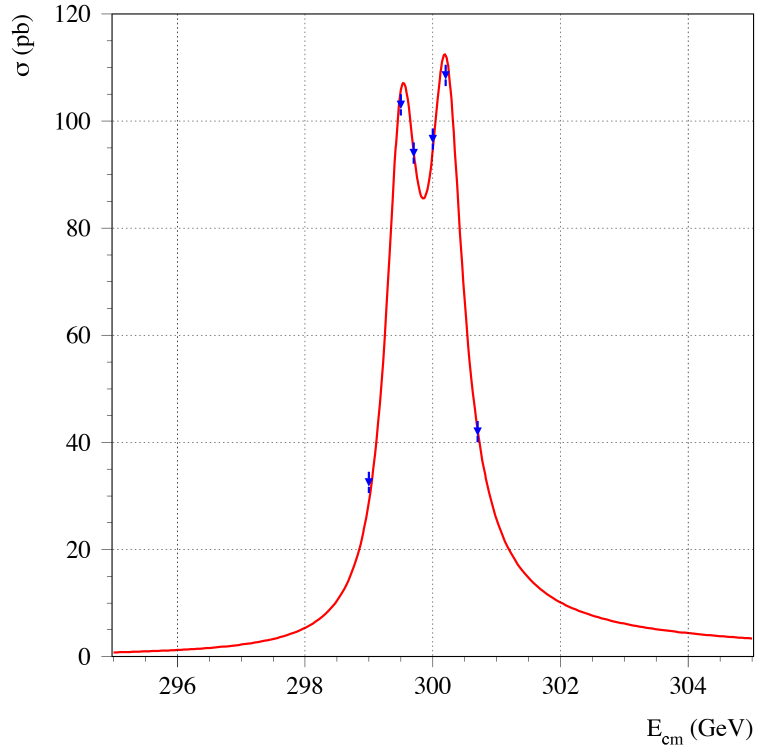


Fig. 39: Production cross-section of H and A via $\mu^+\mu^- \to \mathrm{H,A} \to \mathrm{b\bar{b}}$ as a function of the centre-of-mass energy for $m_\mathrm{A} = 300$ GeV/c^2 and $\tan\beta = 10$, with a centre-of-mass energy relative spread of 3×10^{-5}. The triangles with error bars represent a simulated six-energy-point scan, with 25 pb^{-1} per point.

B. Autin, A.Blondel and J. Ellis, CERN 99-02, 1999

However:

- Key role is played by the beam energy resolution.

- Great importance of QED radiative effects for a precision study of the line-shape and Sign/Backg ratio. Not enough emphasized in the past.

Radiative effects

- In the case of a Higgs factory through a muon collider, sizeable QED radiative effects - of order of 50% - must be carefully taken into account for a precise measurement of the leptonic and total widths of the Higgs particle.
- Those large effects do not apply in the case of Higgs production in electron-positron colliders (→ ZH, see later).
- ISR effects similar to J/Psi, Z, … production in e+e- annihilation, but not accounted for in previous studies.

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M. G. arXiv:1503.05046
S. Jadach, R. Kycia arXiv:1509.02406
M. G., T. Han, Z. Liu arXiv:1607.03210, **Phys.Lett. B763 (2016)**

The I S R effect

- Correction factor $\propto (\Gamma/M)^{(4\alpha/\pi)\log(2E/m)}$

  modifies the Born cross section for production of a narrow resonance by o(50%).

- By defining: $\beta_i = \frac{4\alpha}{\pi}\left[\log\frac{W}{m_i} - \frac{1}{2}\right]$,

$$\begin{aligned} y &= W - M \\ \tan\delta_R(W) &= \frac{1}{2}\Gamma/(-y) \end{aligned}$$

Infrared factor modifies Born cross section as:

M.G., Pancheri, Srivastava, Nucl. Phys. B101, 1975 and B171, 1980

M.C. Codes for LEP

$$C^{res}_{infra} = \left(\frac{y^2 + (\Gamma/2)^2}{(M/2)^2}\right)^{\beta_i/2}\left[1 + \beta_i\frac{y}{\Gamma/2}\delta_R\right]$$

to o(1-2 %) accuracy

→ Folding with beam energy resolution:

$$G(W' - W) = \frac{1}{\sqrt{2\pi\sigma}} e^{-(W'-W)^2/(2\sigma^2)}$$

$$\tilde{\sigma}(W) = \int G(W' - W) dW' \sigma(W')$$

the observed cross section at the peak is, to o(1%) accuracy:

$$\tilde{\sigma}(M) = \frac{2\pi^2 \Gamma_i \Gamma_f}{\sqrt{2}\pi\sigma M^2 \Gamma} \left(\frac{\Gamma}{M}\right)^{\beta_i} e^{\left(\frac{\Gamma}{2\sqrt{2}\sigma}\right)^2} \left\{ ercf\left(\frac{\Gamma}{2\sqrt{2}\sigma}\right) + \frac{1}{2}\beta_i E_1\left(\frac{\Gamma^2}{8\sigma^2}\right)\right\}$$

--> Numerical results for SM Higgs. The correction factor C is:

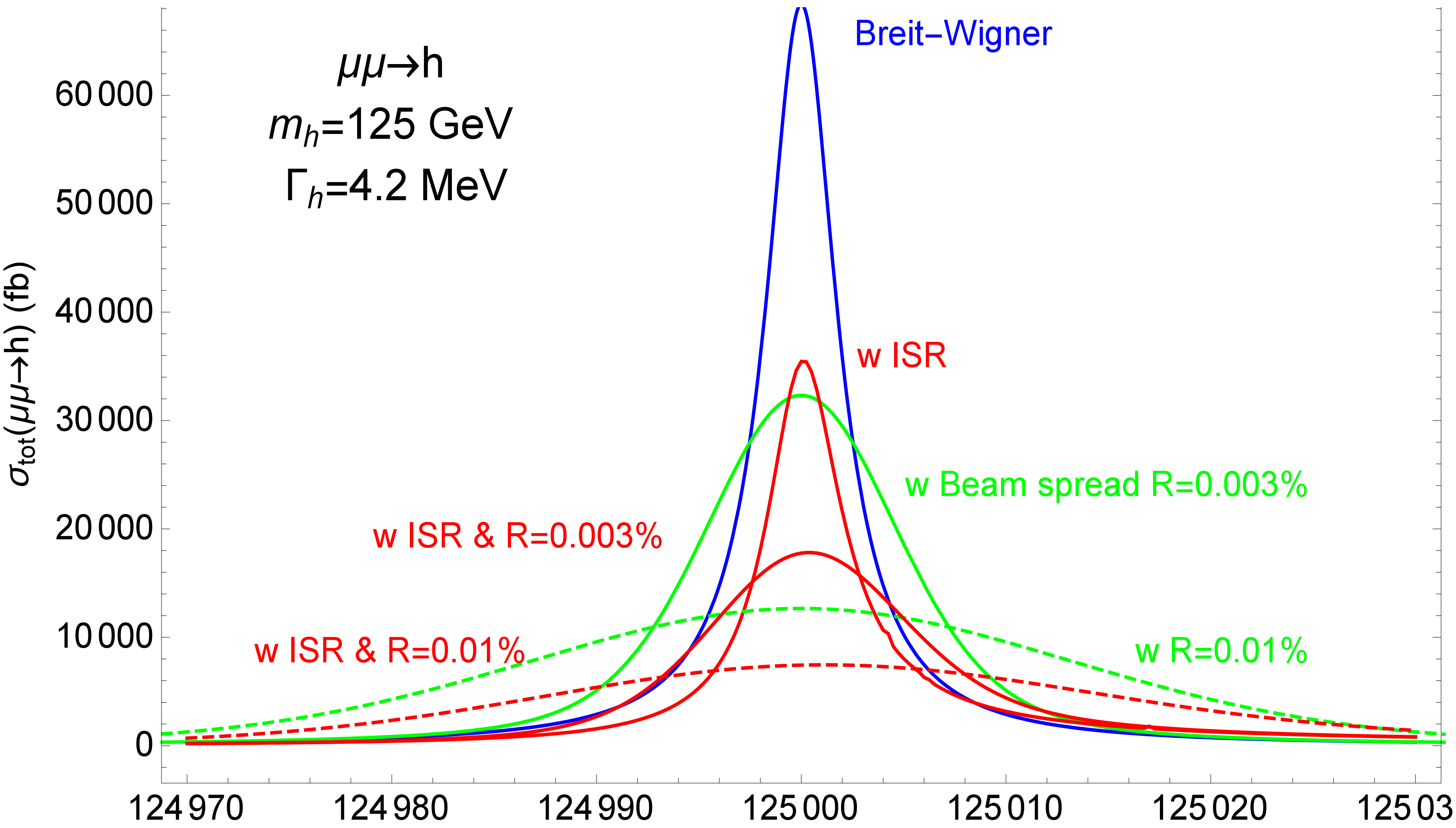
C = 0.47 , 0.37 , 0.30 , 0.20

for

$\sigma = 1$ MeV, 2 MeV, 3 MeV, 4 MeV,

-- > Important reduction of the Born Higgs signal.

Higgs line shape



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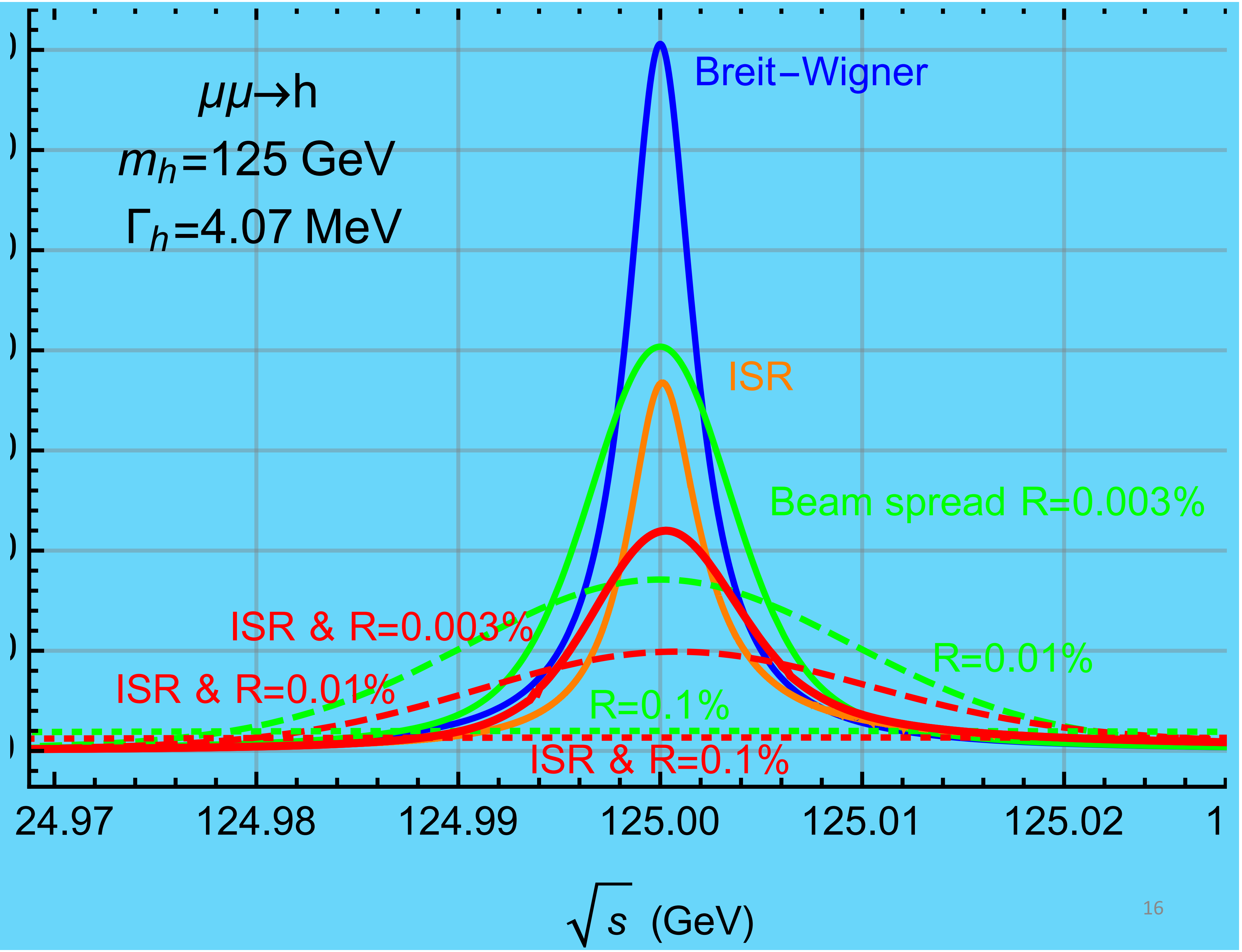
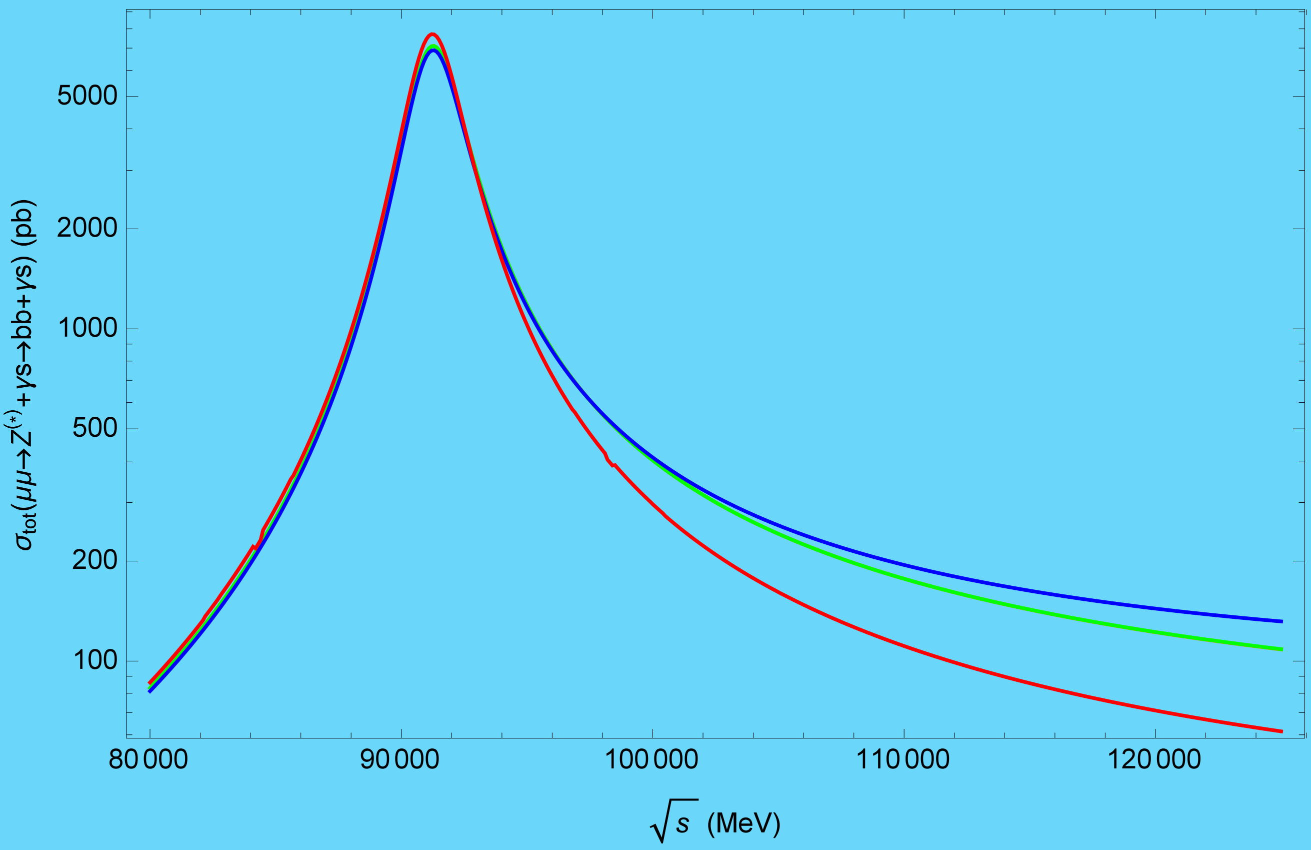


μμ→h
m_h=125 GeV
Γ_h=4.07 MeV
Breit−Wigner
ISR
Beam spread R=0.003%
ISR & R=0.003%
ISR & R=0.01%
R=0.01%
R=0.1%
ISR & R=0.1%
24.97
124.98
124.99
125.00
125.01
125.02
1
$\sqrt{s}$ (GeV)

Signal/Backg ratio is affected by r. c. and beam energy spread

- Background coming from Z radiative tail:



← Different accuracy in QED structure functs. of initial beams

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Signal/Background ratio

R (%)	$\mu^+\mu^- \to h$ σ_{eff} (pb)	$h \to b\bar{b}$ σ_{Sig}	$h \to b\bar{b}$ σ_{Bkg}	$h \to WW^*$ σ_{Sig}	$h \to WW^*$ σ_{Bkg}
0.01	7.3	3.4	20	1.7	0.051
0.003	17	8.0		2.5	

The bb background is shown with a 100 GeV m_bb cut applied to the signal and background.

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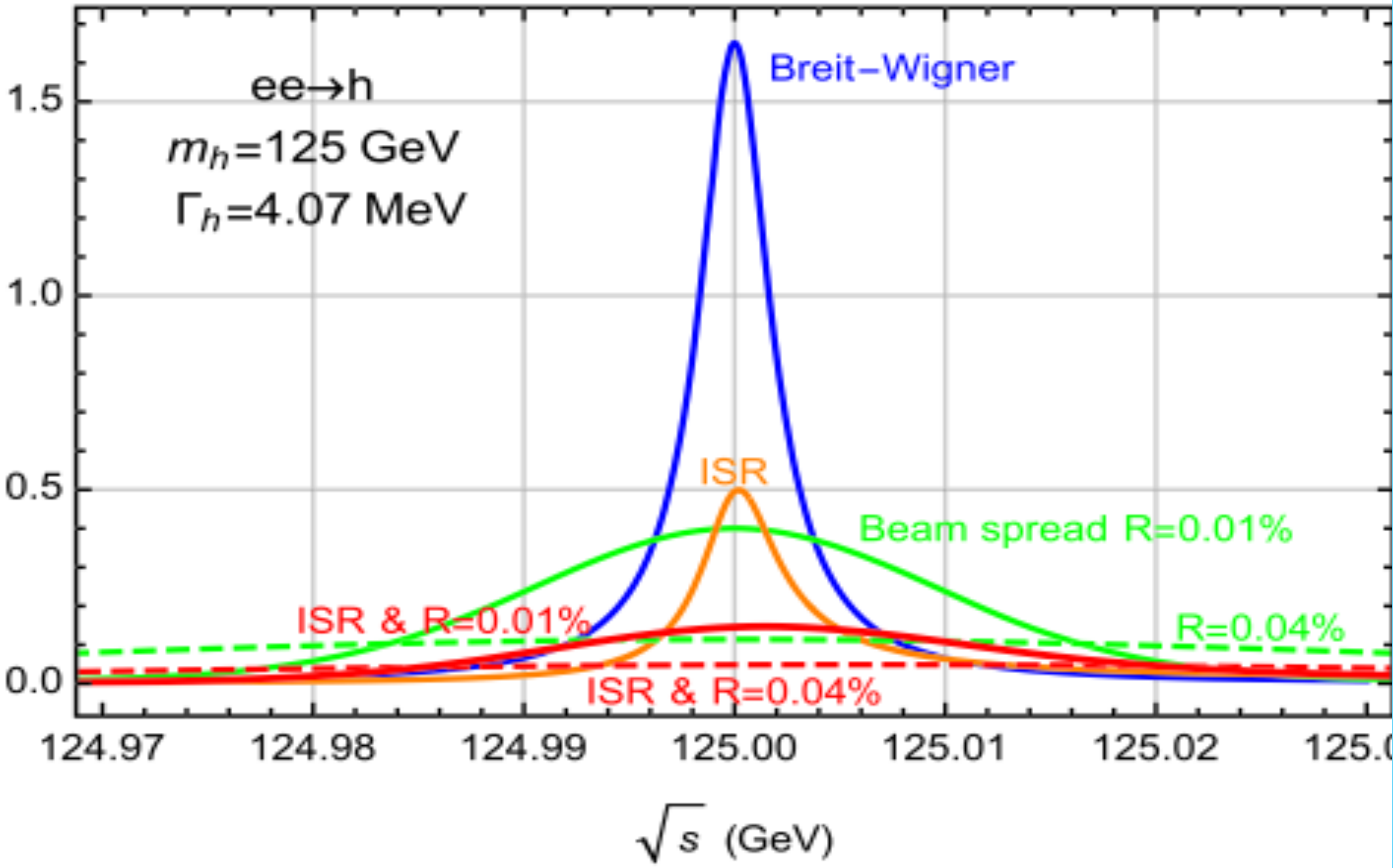
The energy spread plays a role on the Sign/Backg. ratio

FCC-ee H-resonant production



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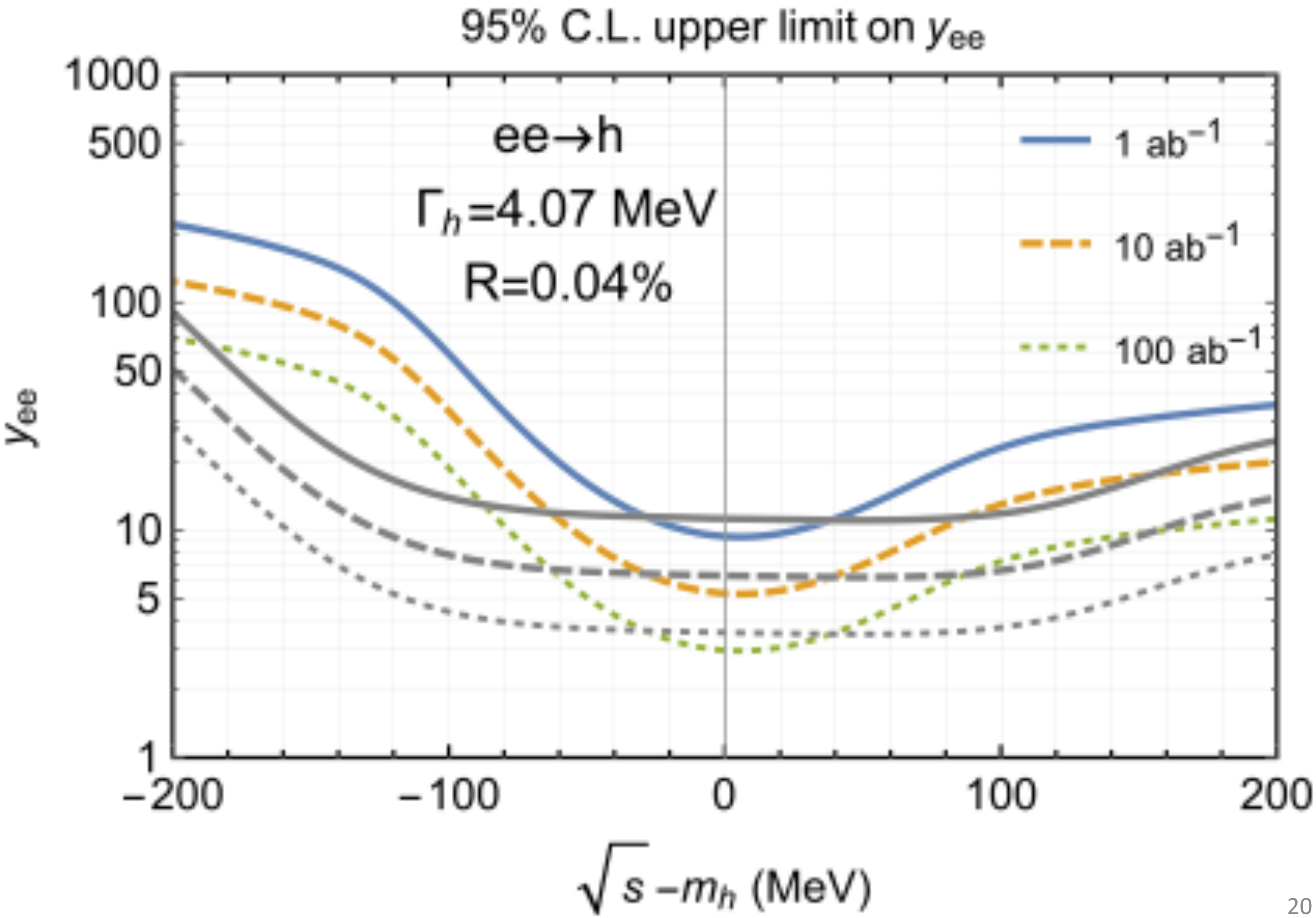
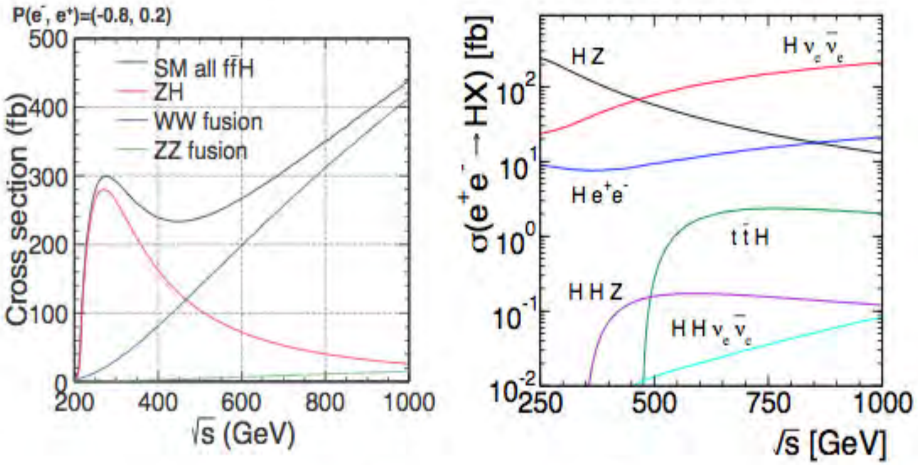
FCC-ee Limits for H-ee Yukawa coupl.

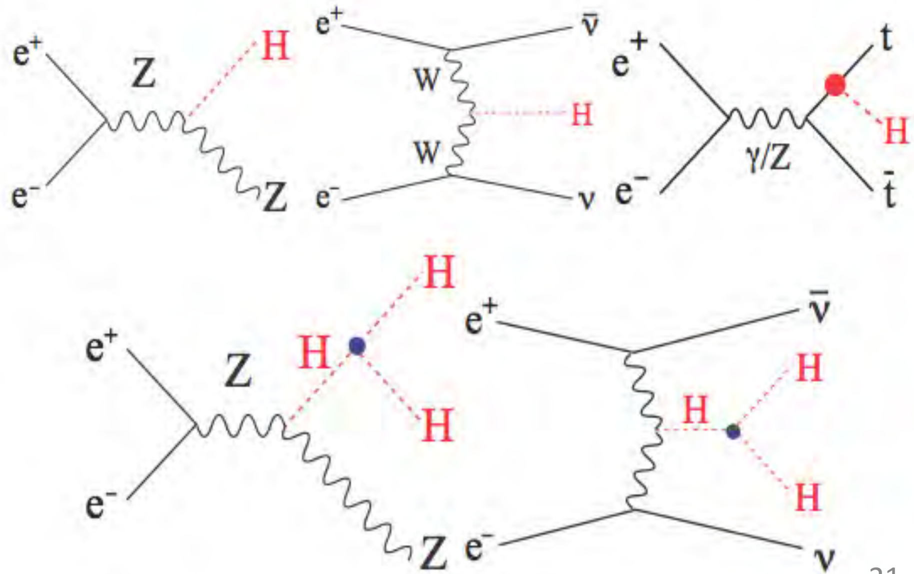


No similarly large effects for e^+e^- colliders at higher energies

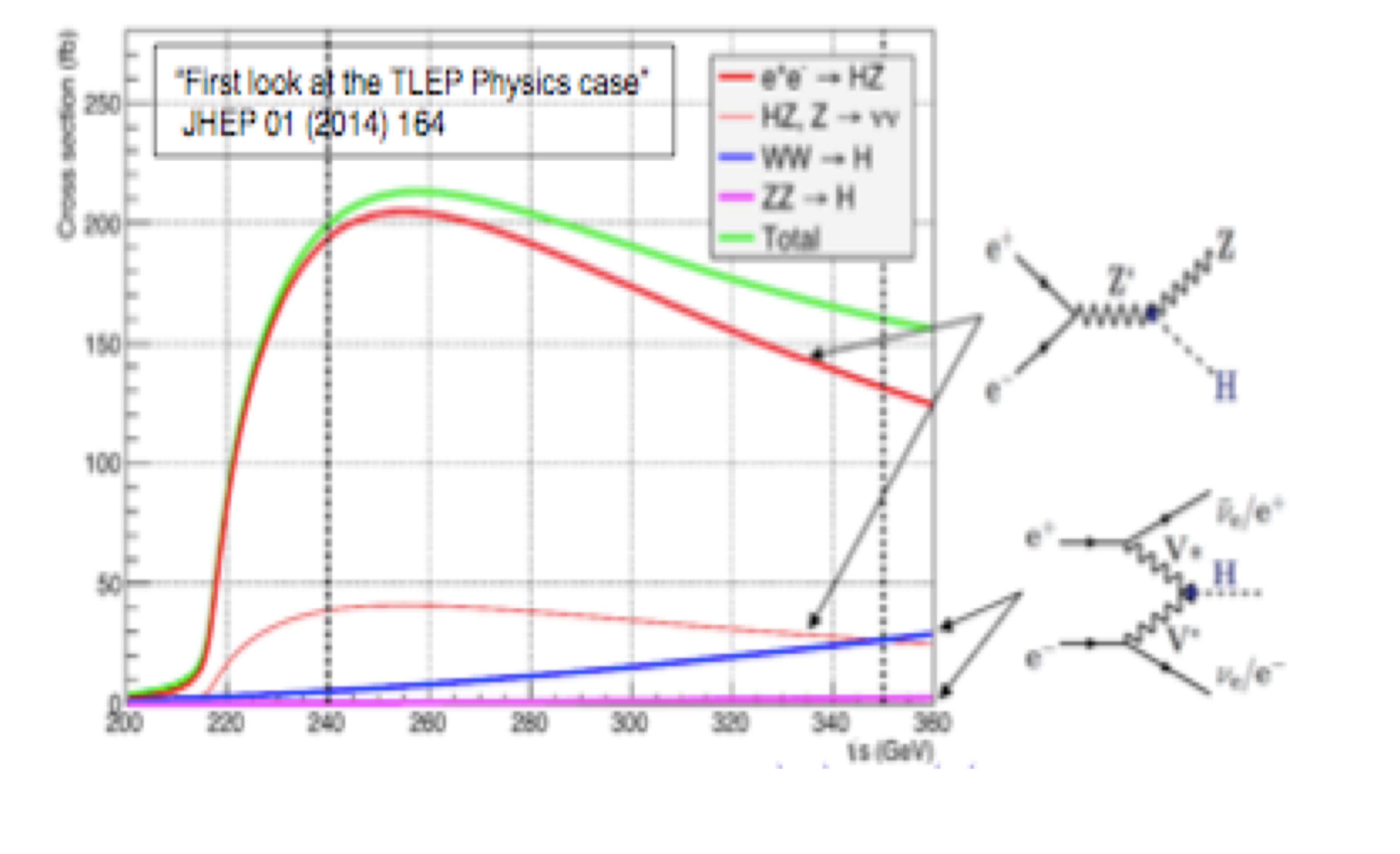
Production cross sections at the e+ e- collider

- The production cross sections of the Higgs boson with the mass of 125 GeV for e+-e- as a function of the energy $\sqrt{s}$.
- The cross sections of the production processes as a function of the $\sqrt{s}$ collision energy.
- The Higgs-strahlung diagram (Left), the W-boson fusion process (Middle) and the top-quark association (Right).
- Double Higgs boson diagrams via off-shell Higgs-strahlung (Left) and W-boson fusion (Right) processes





FCC-ee HZ-production experiments.



ISR effects not included

→ Very recent analysis of the production process e+e− → μ+μ−b̄b

"ISR corrections to associated HZ production at future Higgs factories"

M.G., Montagna, Nicrosini, Piccinini, Volpi, PL B777, 2018

Calculation:

$$\mathrm{d}\sigma(s) = \int \mathrm{d}x_1 \mathrm{d}x_2 D(x_1, s) D(x_2, s) \mathrm{d}\sigma_0(x_1 x_2 s) \Theta(\mathrm{cuts}).$$

- $D(x, s)$ *Electron structure functions (up to third order finite terms)*

- $\mathrm{d}\sigma_0$ *Tree-level differential c. s. for HZ signal + all backg.s*

Effect of kinematical cut on the b_bar invariant mass

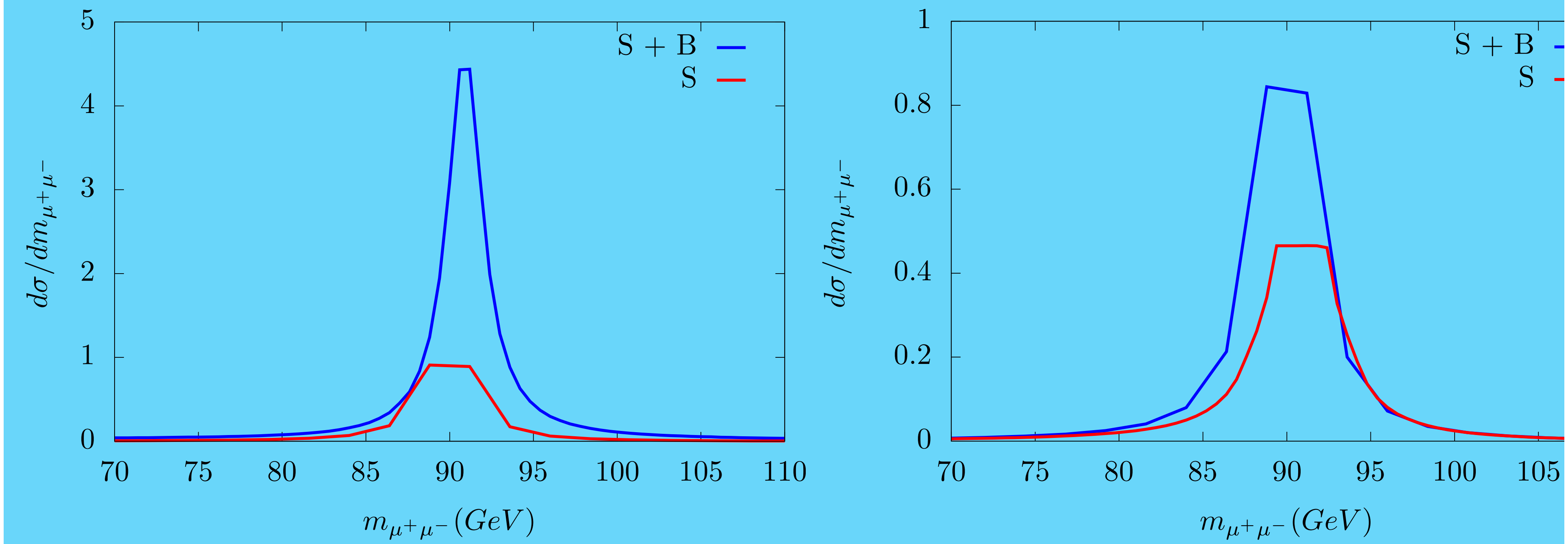
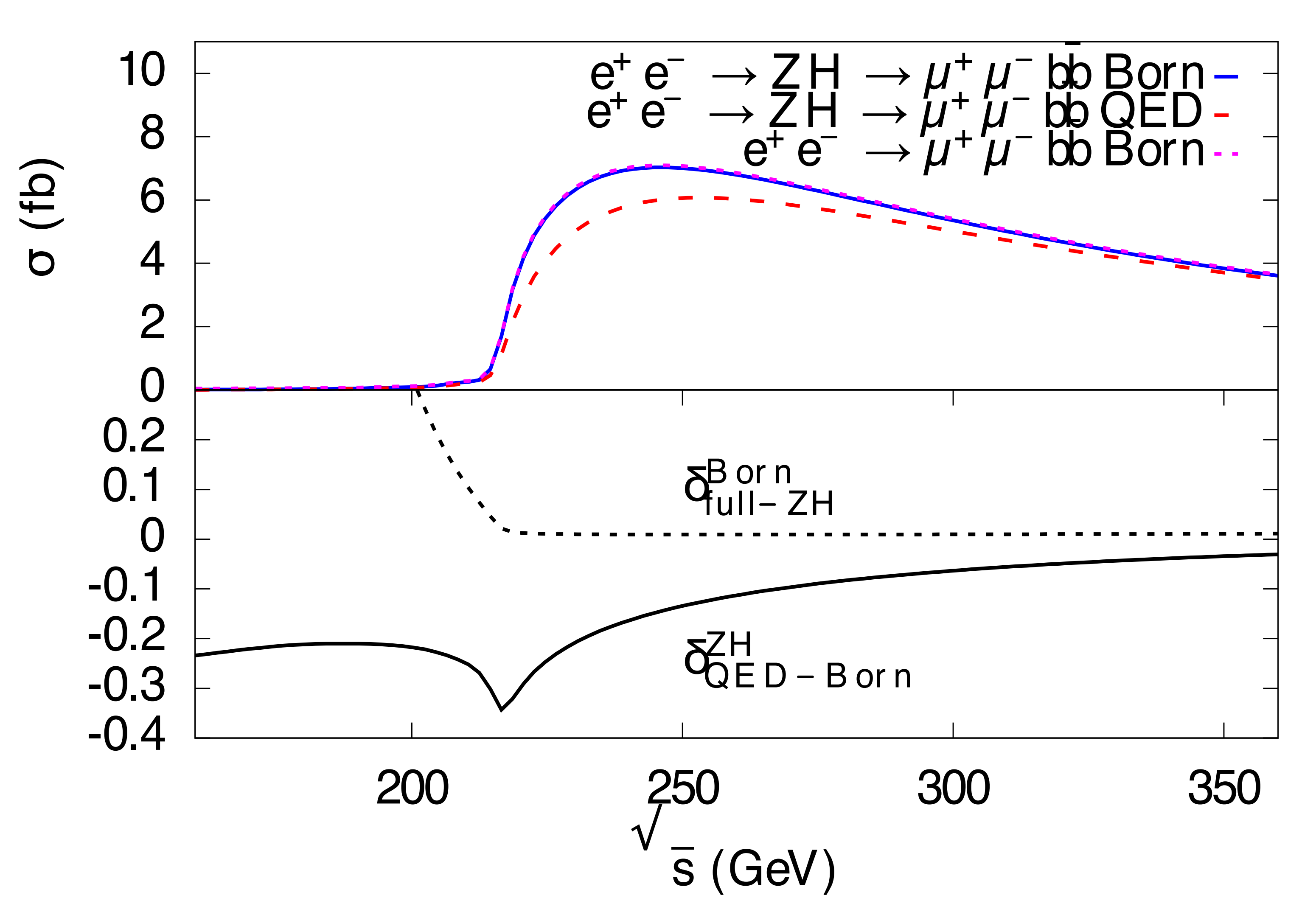


Figure 1: The $\mu^+\mu^-$ invariant mass distribution without (left panel) and with (right p
a cut on the invariant mass of the $b\bar{b}$ system $M_H - 3\text{GeV} \geq m_{b\bar{b}} \leq M_H + 3\text{GeV}$

Relevance of the ISR corrections particularly near threshold.



Conclusions

- Precision studies of the properties of the Higgs particle are mandatory.

- Various proposals of electron and muon colliders have been suggested.

- Muon Collider seems more appropriate for measuring the Higgs width and couplings, checking flavor universality, trying discover and investigate the scalar sector predicted in various extensions of the SM.
- Sizeable radiative effects – of order 50% or larger – must be carefully taken into account for high precision measurements.. In addition the energy spread of beams plays an important role.

- FCC-ee, CEPC, ILC: ISR effects are also relevant in associated HZ production. Possible effects on the expected degree of accuracy of relevant physical quantities.