Higgs physics and ISR at future lepton colliders.

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FCC Week 2019, Brussels, June 24-28, 2019

- Since the discovery of the Higgs particle (H) – a great success of the SM – ATLAS and CMS data are so far consistent with fermionic and bosonic couplings as expected from a SM Higgs particle. With the present experimental resolutions, much wider of the expected intrinsic Higgs width of about 4 MeV, we can't conclude we have found the SM Higgs and not one of the many scalars postulated within possible extensions of the SM.

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Supersimmetry

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 partial widths are crucial parameters.
- Test of lepton universality of Higgs couplings.
- Non minimal extensions of MSSM → neutral Higgs bosons.
- Neutral Higgs bosons could be very close.

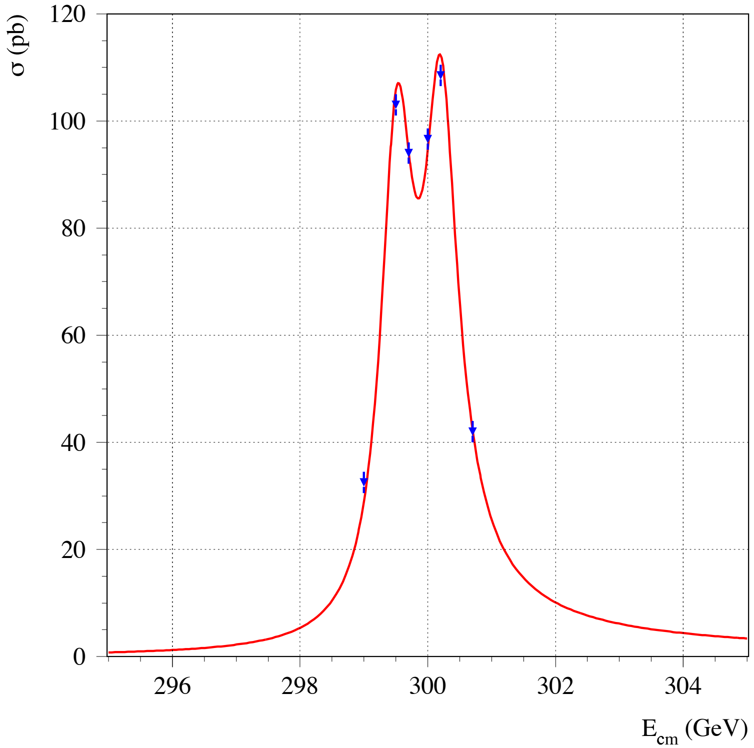

Fig. 39: Production cross-section of H and A via $\mu^+\mu^- \to$ H, A $\to$ b$\bar{\text{b}}$ as a function of the centre-of-mass energy for $m_A = 300$ GeV/c^2 and $\tan\beta = 10$, with a centre-of-mass energy relative spread of 3×10^{-5}. The triangles with error bars represent a simulated six-energy-point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

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

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Supersimmetry

Axion-like particles (ALP's) appear in many BSM scenarios.
Higgs decays into ALP's with branching ratios of order 10%.

Example: Exotic decay h → aa

- Higgs portal interaction and loop-mediated processes allow for ALP pair production in Higgs decay:

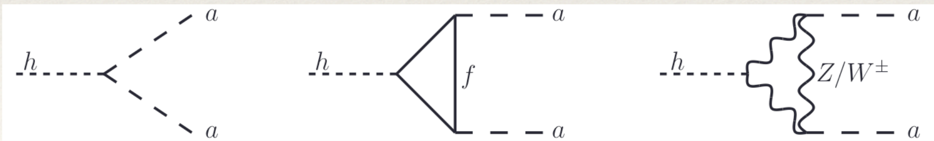
$$\Gamma(h \to aa) = \frac{|C_{ah}^{\rm eff}|^2}{32\pi} \frac{v^2 m_h^3}{\Lambda^4} \left(1 - \frac{2m_a^2}{m_h^2}\right) \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

with:

$$C_{ah}^{\rm eff} = C_{ah}(\mu) + \frac{N_c\, y_t^2}{4\pi^2}\, c_{tt}^2 \left[\ln \frac{\mu^2}{m_t^2} - g_1(\tau_{t/h})\right] + \dots$$

$$\approx C_{ah}(\Lambda) + 0.173\, c_{tt}^2 - 0.0025\, (C_{WW}^2 + C_{ZZ}^2)$$

- A 10% branching ratio is obtained for $|C_{ah}^{\rm eff}| \approx 0.62\, (\Lambda/\text{TeV})^2$



M. Neubert: Recent progress on ALPs (La Thuile 2019)

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Is the Higgs elementary or composite?

Higgs couplings measurements are mandatory!

Two possible future lepton alternatives:

- Muon collider (MC), at L > 10^{32} with a resonant s-channel H signal.

It could offer a unique opportunity of a precision study of the total and partial widths of H in various decay channels.

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

e+e- → HZ at √s = 240-250 GeV

Two novel approaches to MC after MICE:

(i) "A complete demonstrator of a muon cooled Higgs factory."
(Collider radius is about 50 m.)

C. Rubbia, arXiv: 1308.6612

(ii) "Low emittance muon beams using positron beam on target."

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

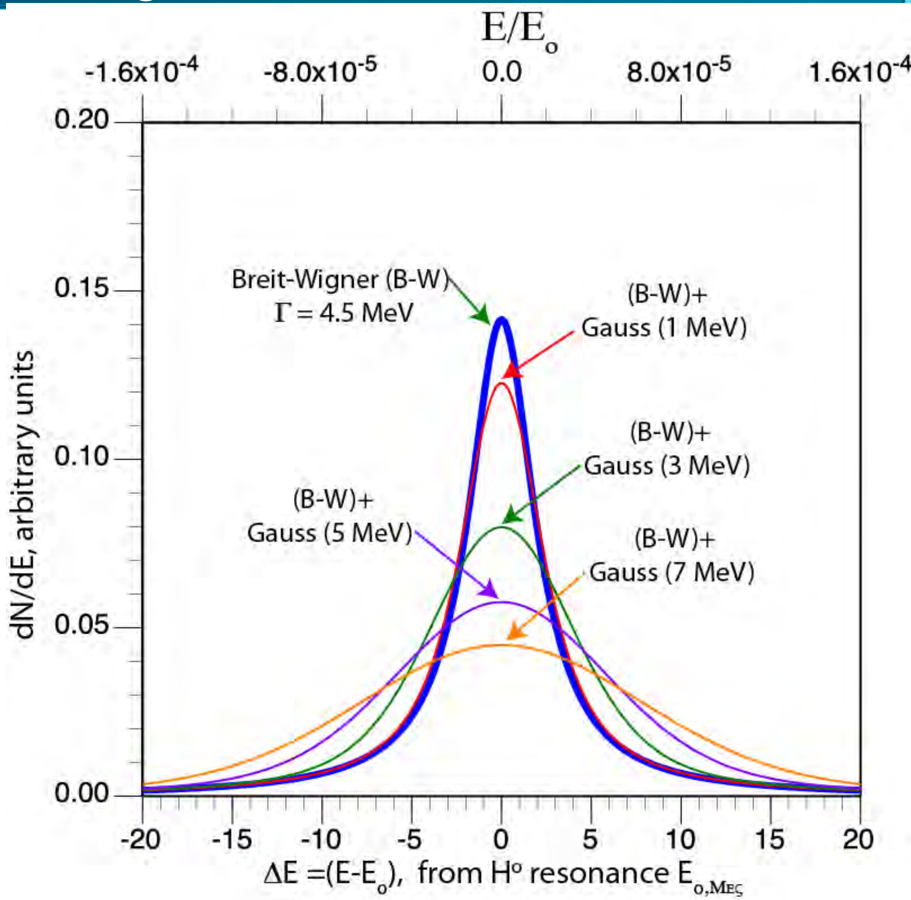
(Process: $e^+ e^- \rightarrow \mu^+ \mu^-$ just above threshold, $E(e^+) = 45$ GeV)

Measurements of m and Γ require excellent energy resolution !!!

- Key role is played by the beam energy spread.
- Great importance of QED radiative effects for a precision study of the line-shape and Sign/Backg ratio. Not enough emphasized in the past.

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.

I S R effects

- In the case of a Higgs factory through a muon collider, sizeable QED radiative effects - of order of 50% or larger- must be carefully taken into account for a precise measurement of the partial and total widths of the Higgs.
- Those large effects are not present 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 generally not accounted for in previous studies.

- 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 %) 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:

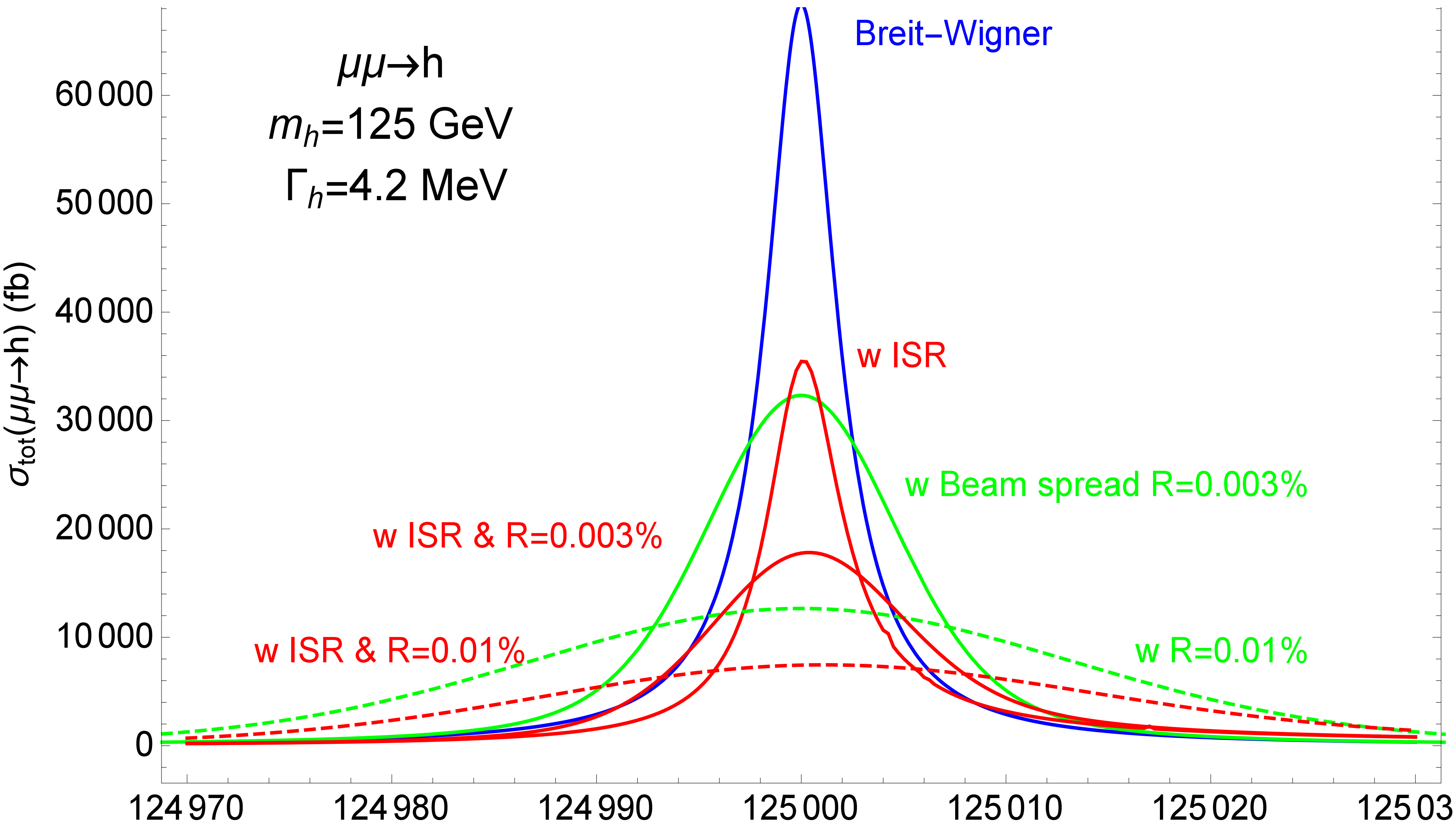
C = 0.47 , 0.37 , 0.30 , 0.20

for

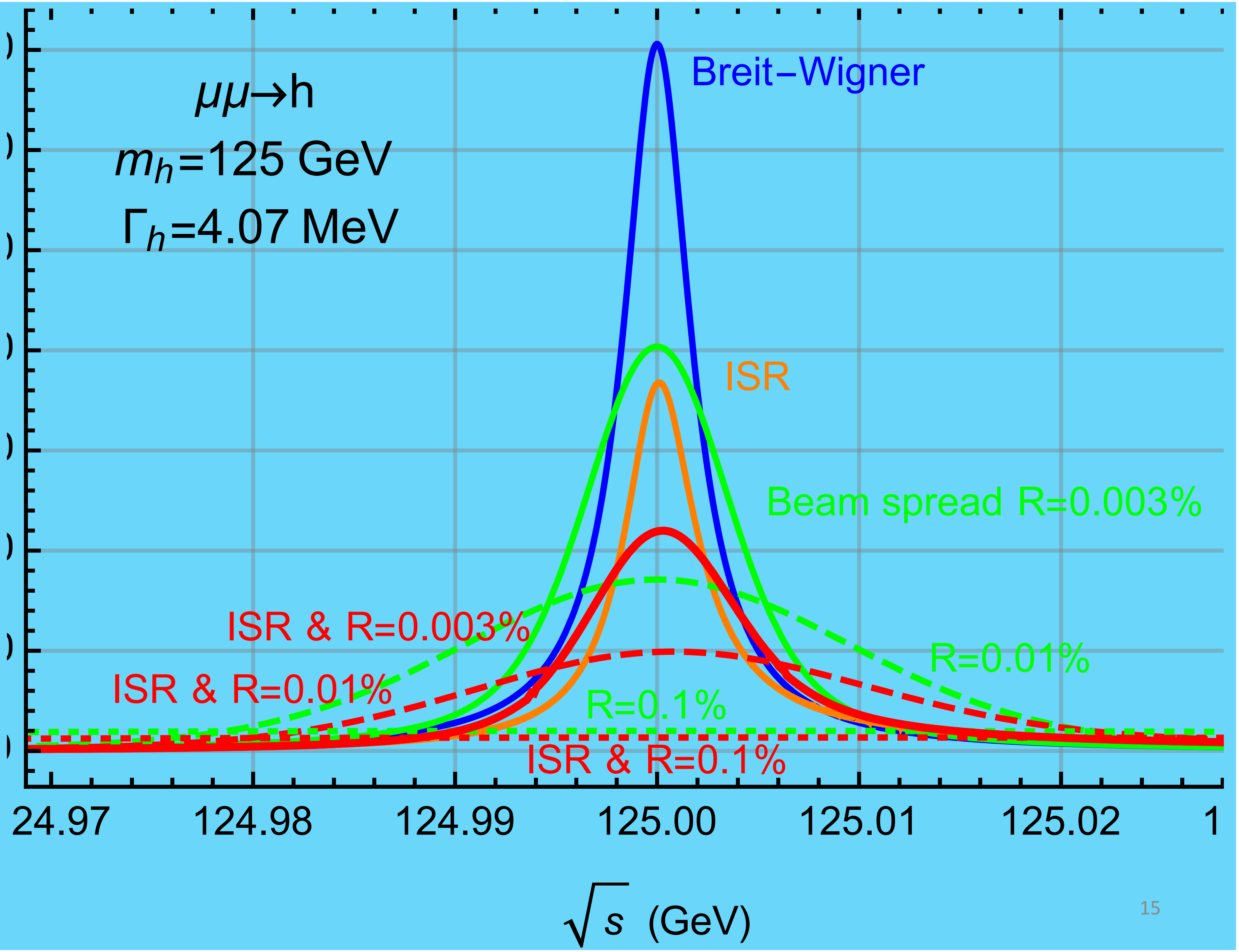
$\sigma = 1$ MeV, 2 MeV, 3 MeV, 4 MeV,

-- > Important reduction of the Born Higgs signal.

Higgs line shape



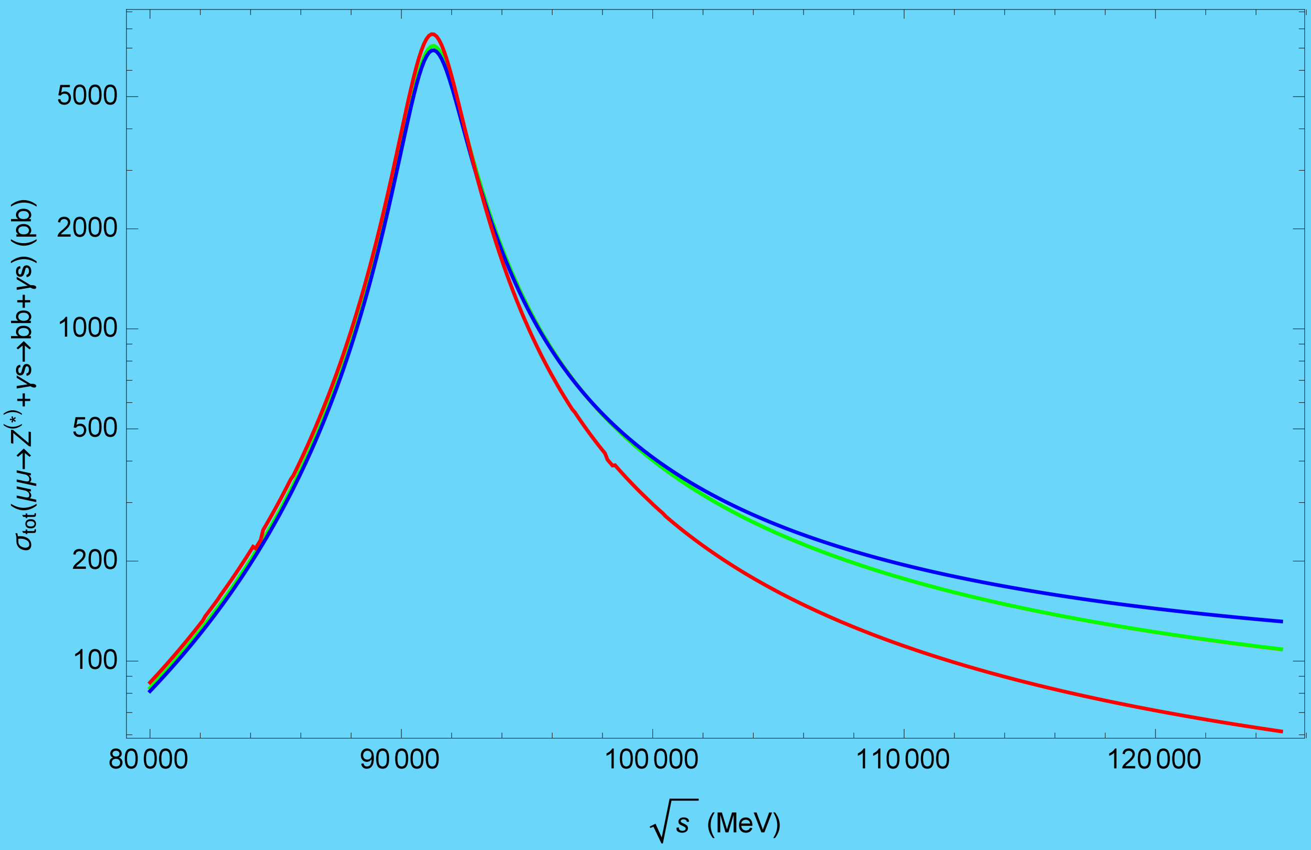
M.G., T. Han, Z. Liu



μμ→h
m_h=125 GeV
Γ_h=4.07 MeV
Breit−Wigner
ISR
Beam spread R=0.003%
ISR & R=0.003%
R=0.01%
ISR & 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 ISR 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)	$h \to b\bar{b}$		$h \to WW^*$	
		σ_{Sig}	σ_{Bkg}	σ_{Sig}	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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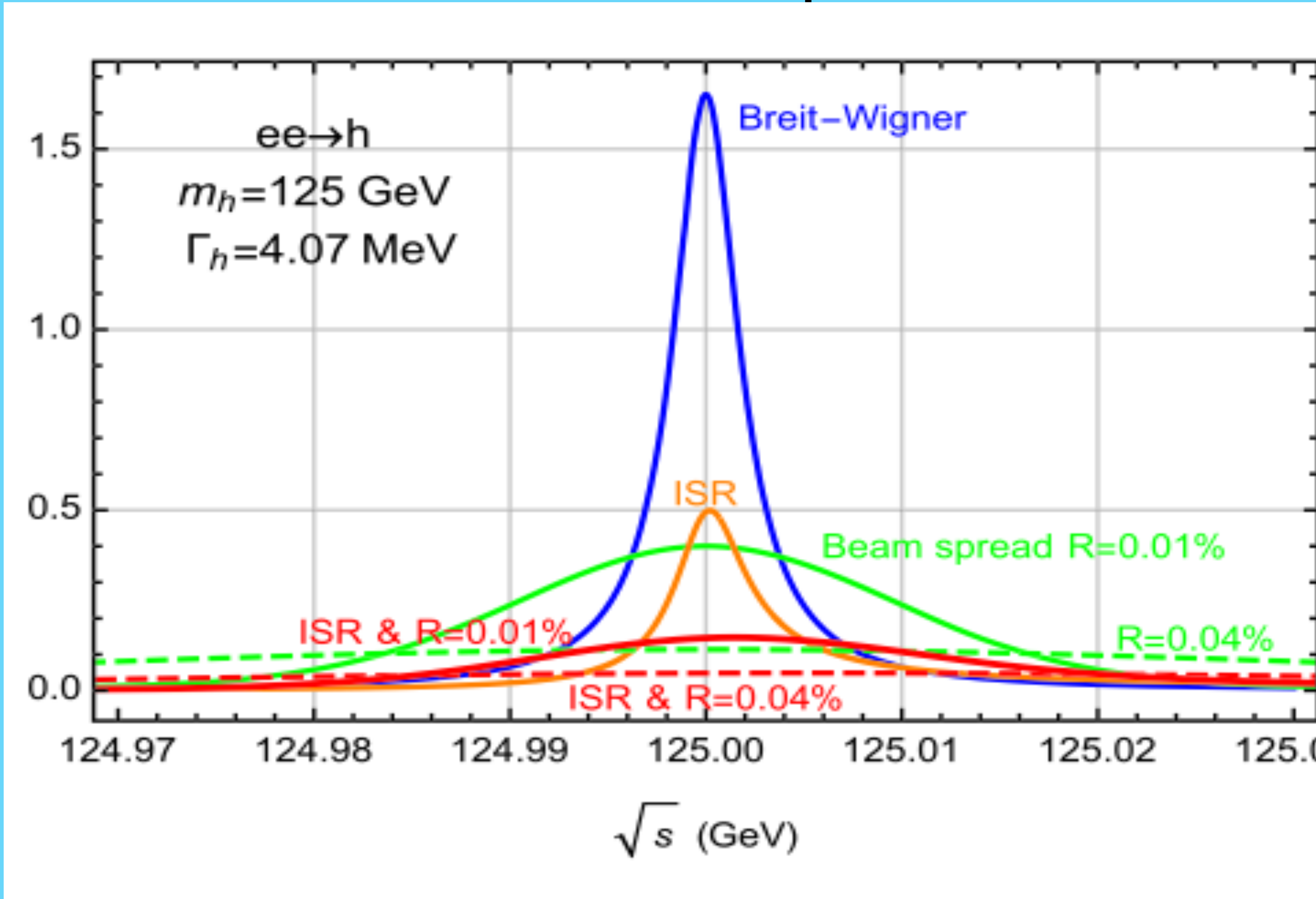
The energy spread plays a role also on the Sign/Backg. ratio

FCC-ee H-resonant production



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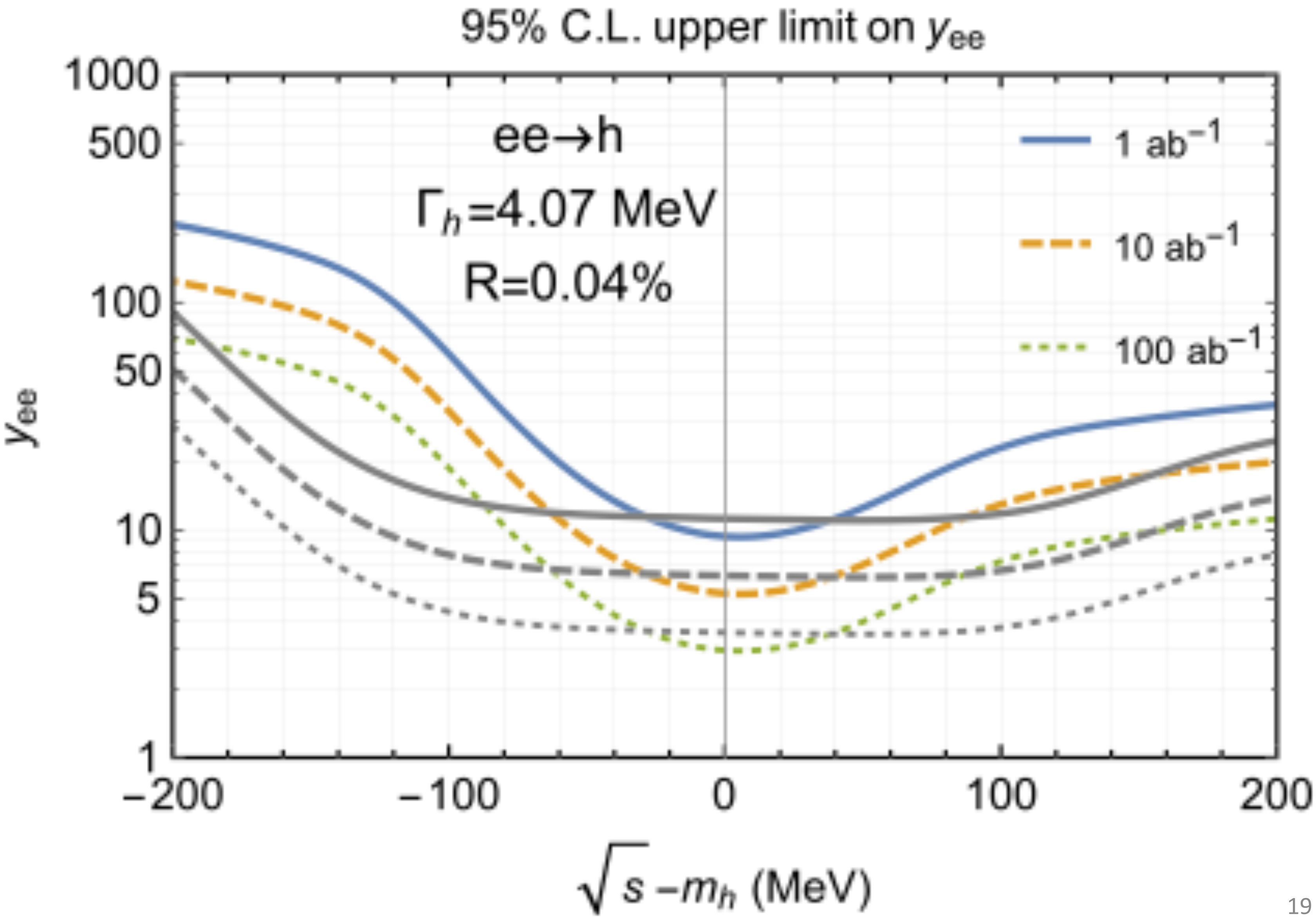
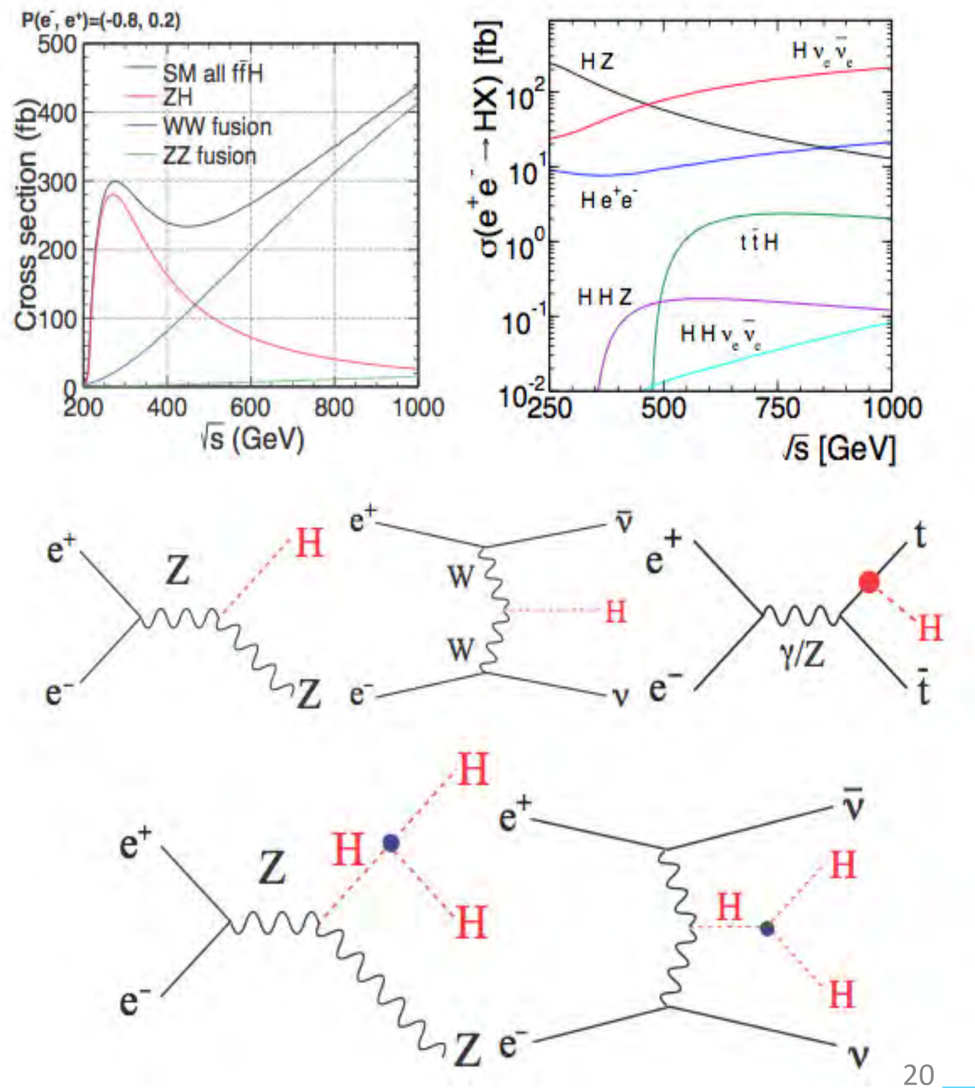
FCC-ee Limits for H-ee Yukawa coupl.



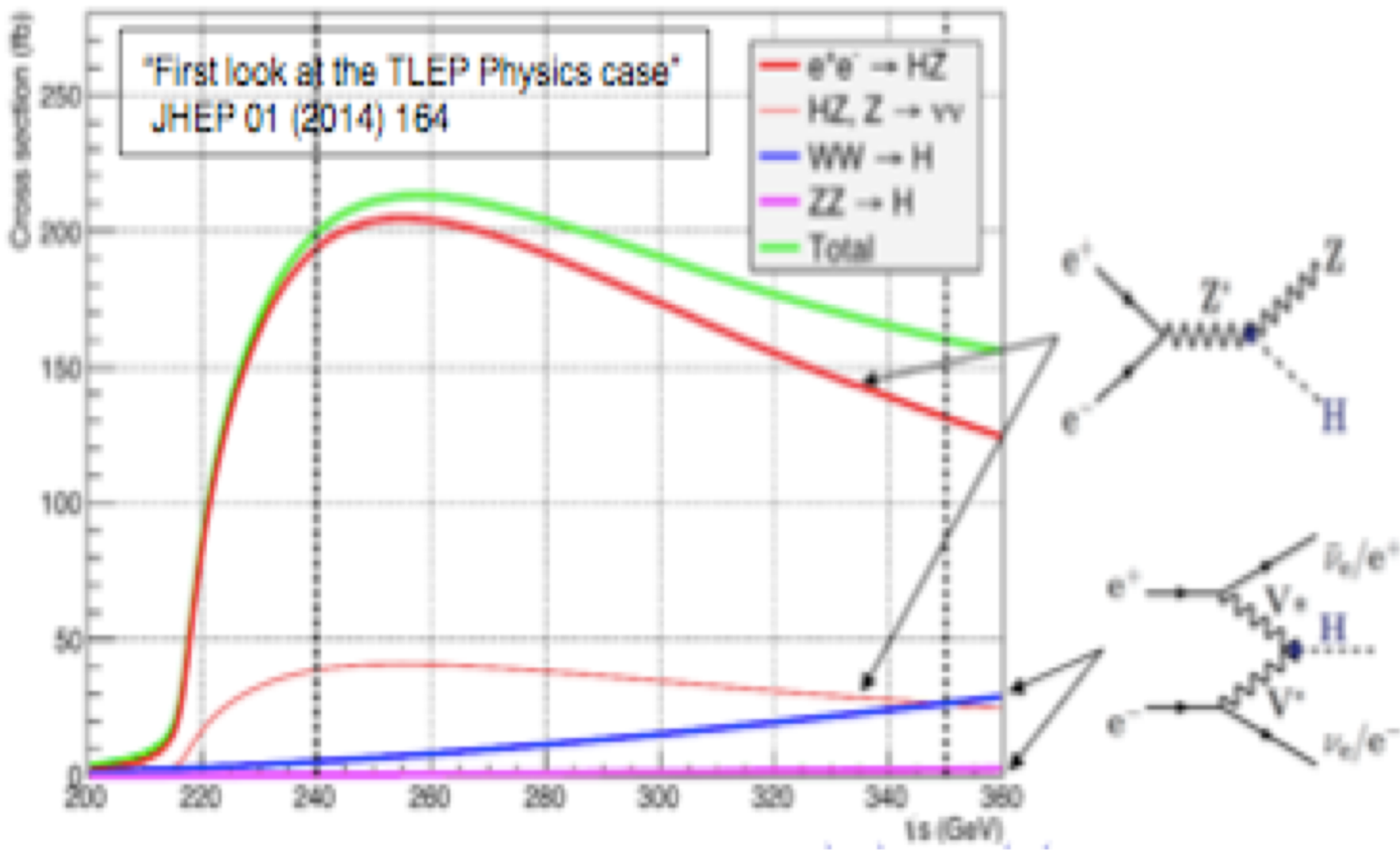
No similarly large effects for e^+e^- colliders at higher energies

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 √s.
- The cross sections of the production processes as a function of the √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.



Recent analysis of the HZ production process in $e^+e^- \to \mu^+\mu^- \bar{b} b$

"ISR corrections to associated HZ production at future Higgs factories"
M.G., Montagna, Nicrosini, Piccinini, Volpi, PL B777, 2018

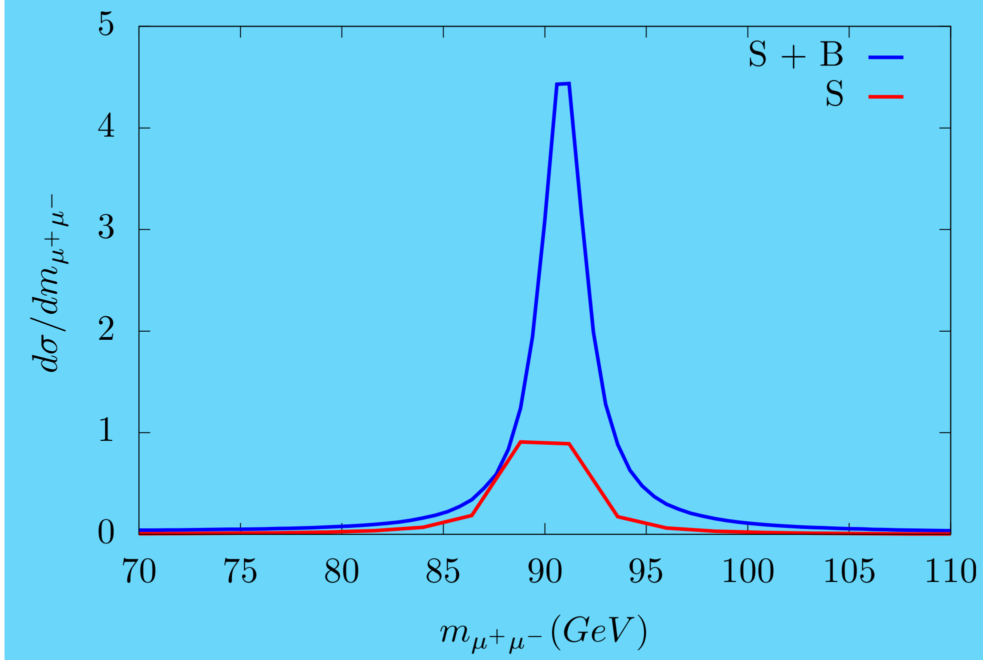
Calculation:

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

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

- $\mathrm{d}\sigma_0$ *Tree-level differential cross section for HZ signal +*
  + backg. (ZZ, γZ, γγ)

Effect of kinematical cut on the b_bar invariant mass



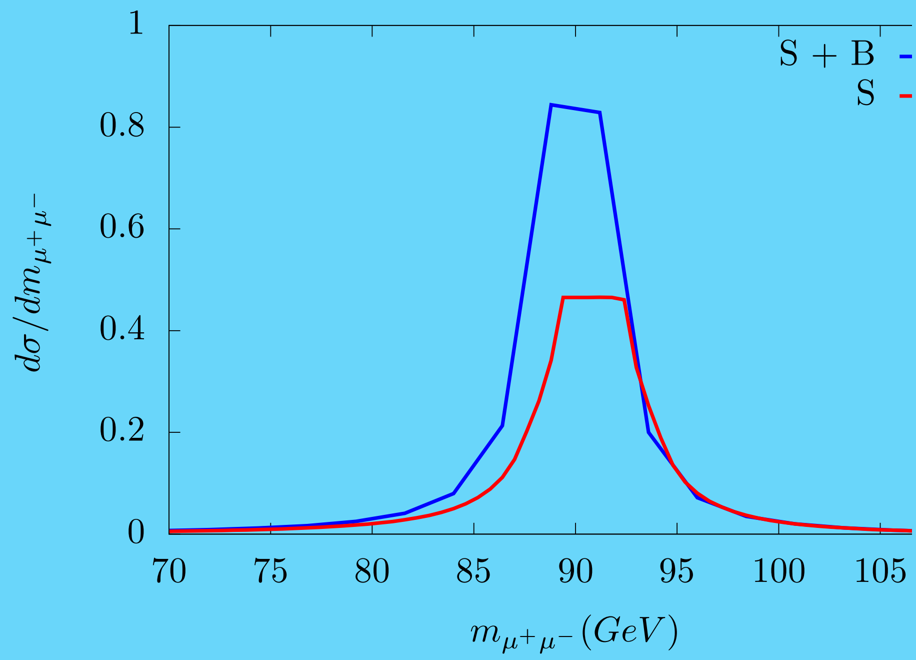
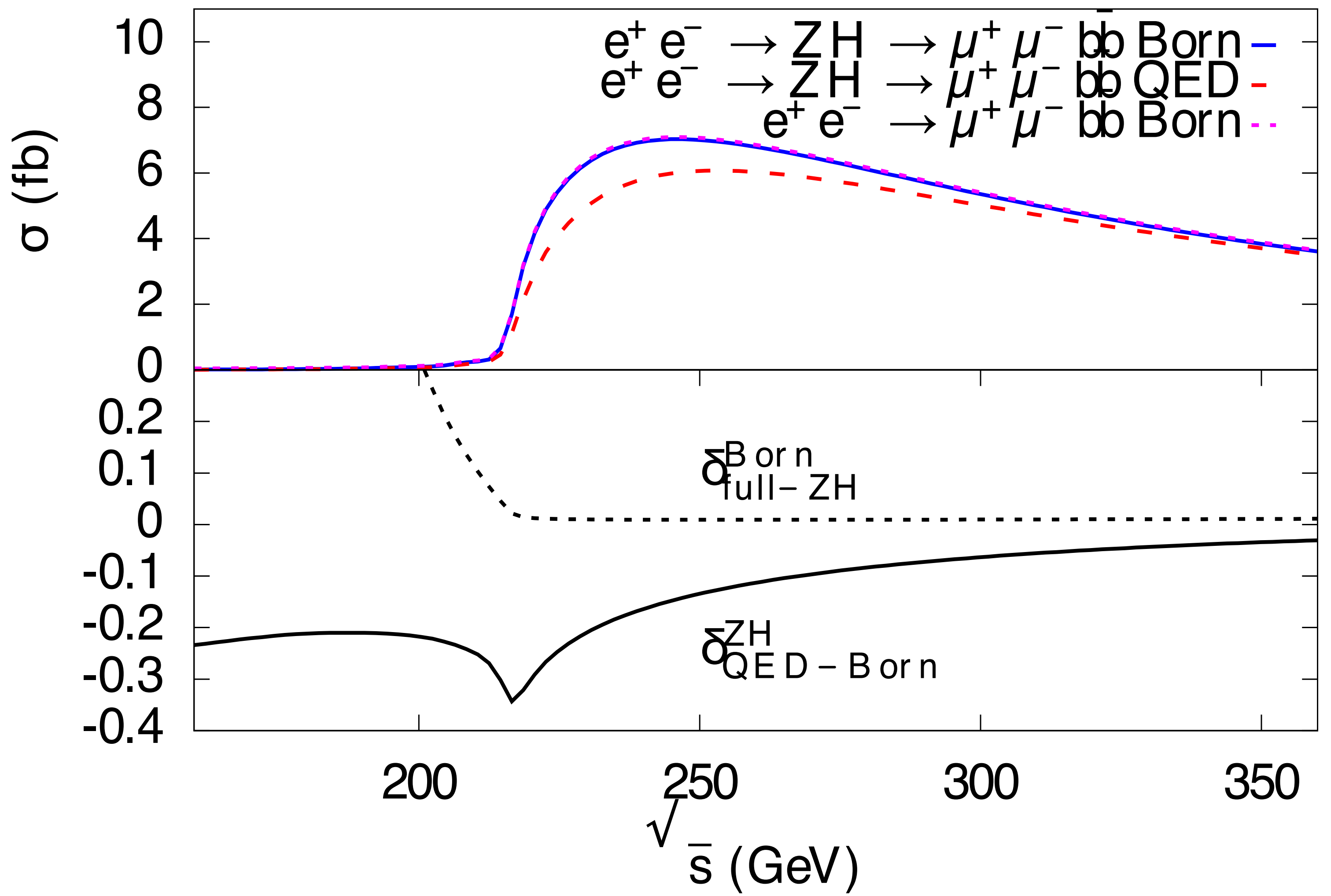


Figure 1: The $\mu^+\mu^-$ invariant mass distribution without (left panel) and with (right p
a cut on the invariant mass of the $b\bar{b}$ system $M_H - 3\text{GeV} \geq m_{b\bar{b}} \leq M_H + 3\text{GeV}$

Relevance of the ISR corrections particularly near threshold.



Relevance of the ISR corrections near threshold also for t-tbar production

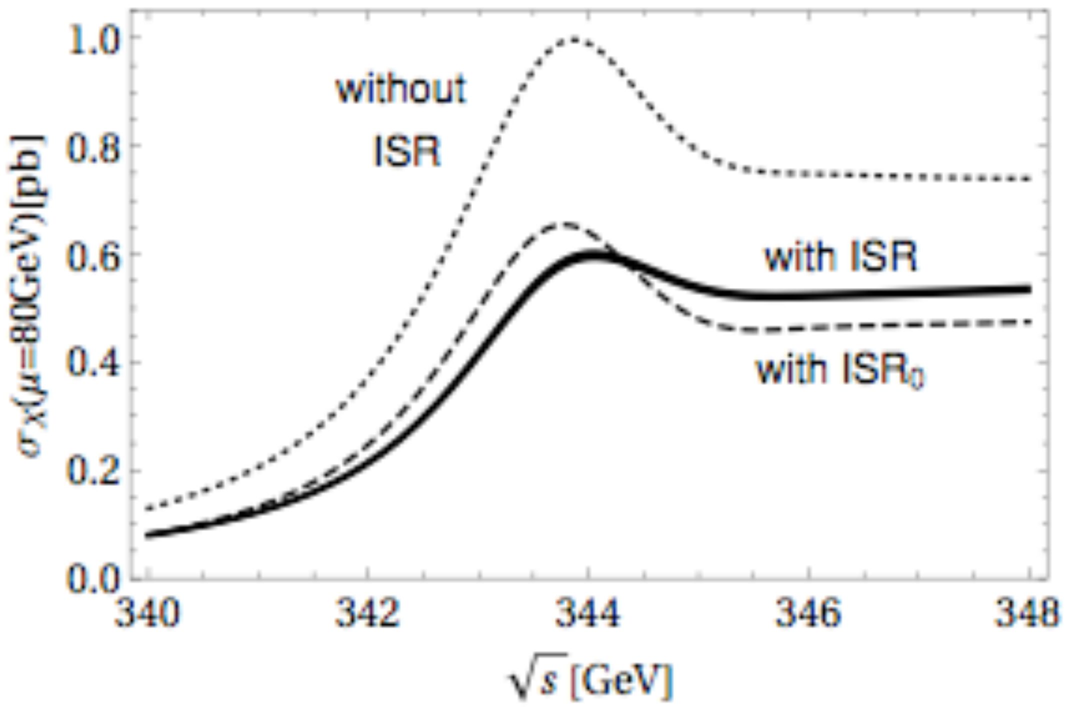


Figure 15: The effect of initial-state QED radiation on the cross section. The dotted curve shows the full result without ISR. The solid band (with ISR) is the envelope of results obtained by convoluting the full 'partonic' cross section with the structure

M. Beneke et al., **JHEP 1802 (2018) 125**

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 ISR effects – of order 50% or larger – must be carefully taken into account for high precision measurements.. In addition the energy spread of the initial beams plays an essential role.

- FCC-ee, CEPC, ILC: ISR effects are also relevant in associated HZ production, particularly near threshold. Possible effects on the expected degree of accuracy of the relevant physical quantities, if not taken into account with high precision. Relevance of similar effects in t-tbar production near threshold.