Physics potential and motivations for muon colliders.

Mario Greco
Univ. and INFN - Roma Tre

CERN, November 19th, 2015

Little of history

- 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 ~ 2 × 10(33) cm−2 s−1

(ii) Next MC at high c.m. energy (up to 4 Tev), for new phenomena, L ~ 10(35) cm−2 s−1

Neutrino Factories

- Neutrino beams from a high L muon storage ring (with a straight section pointing towards a desired experimental area)

S. Geer, '97

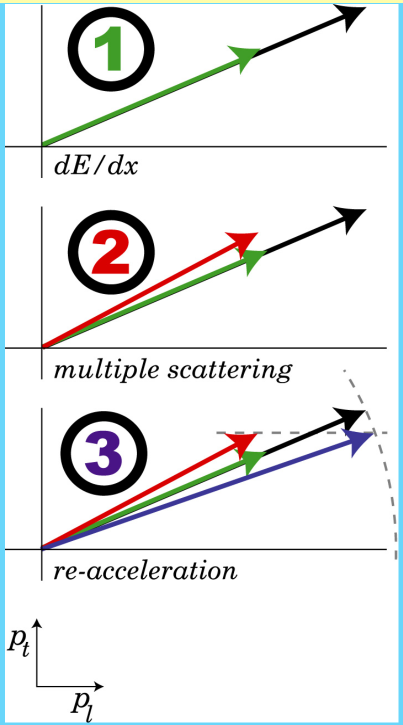
- Precision neutrino physics:
- Neutrino oscillations
- Neutrino mixing, Dirac vs. Majorana phases
- CP violation
- …..

See f. ex. P. Huber, '15

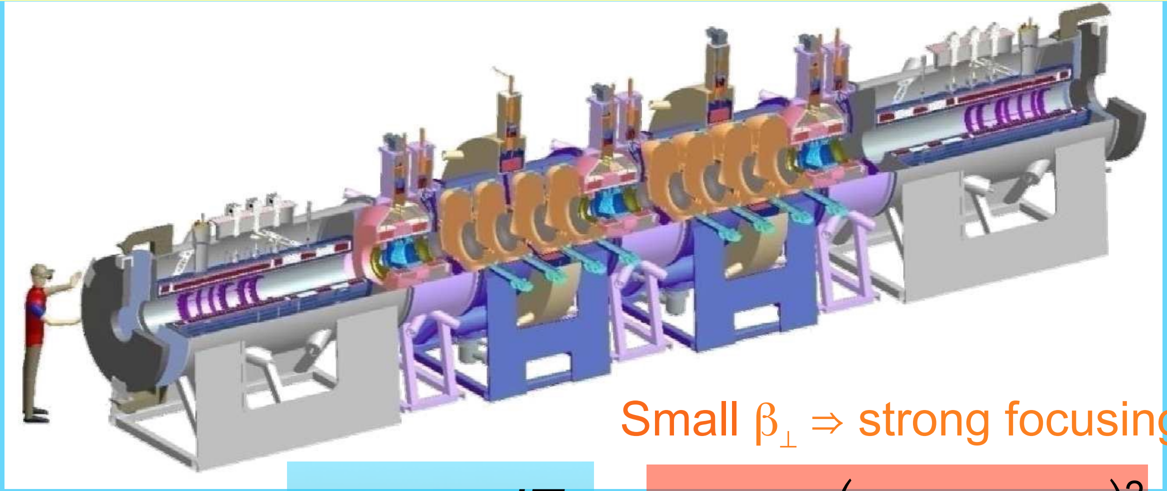
Muon Cooling

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

Principle



Practice



Small $\beta_\perp \Rightarrow$ strong focusing

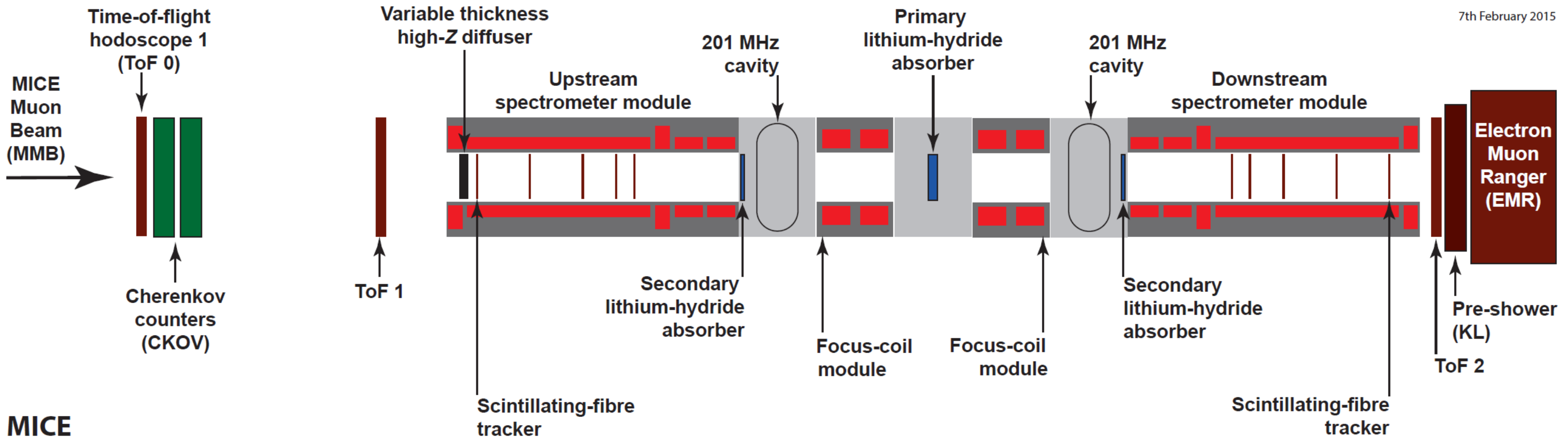
$$\frac{d\varepsilon}{dz} \approx -\frac{\varepsilon}{E_\mu \beta^2}\frac{dE_\mu}{dz} + \frac{\beta_\perp}{2m\beta^3}\frac{(13.6\,MeV)^2}{E_\mu X_0}$$

Ionization: cooling term

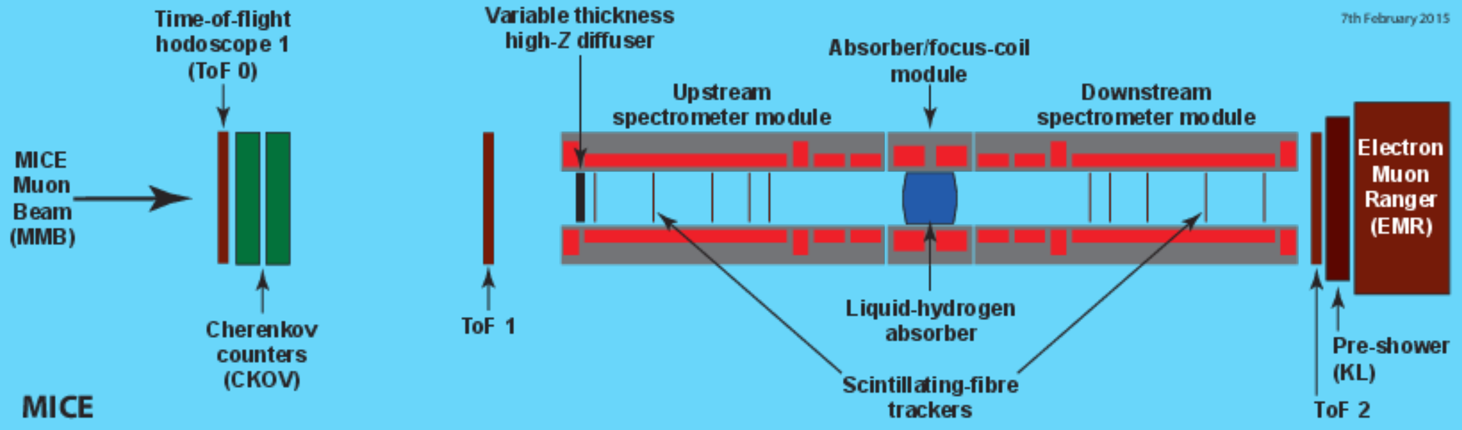
Multiple scattering: heating term

Muon Ionization Cooling Experiment

- ❑ Final MICE demonstration of ionization cooling was recently reconfigured after a detailed project review



- ❑ MICE Step IV: first chance to measure normalised transverse emittance reduction and explore ionization cooling parameters



New motivation

- The discovery of the Higgs particle (H) has been a success of the SM, but is also demanding a detailed knowledge of its properties.
- Among the various types of colliders which have been proposed, the muon collider offers the unique opportunity of a precision study of the total and partial widths of H in the various decay channels.
- In addition, all the Higgs bosons of the minimal Susy model (MSSM) are produced in sufficient abundance in s- channel $\mu^+\mu^-$ collisions to allow their detection for most of the model parameter space.

The LHC discovery of the Higgs at 125 GeV

- Atlas and CMS have observed a narrow line of high significance at about 125 GeV mass, compatible with the Standard Model Higgs boson.

- Their data are consistent with fermionic and bosonic couplings expected from a SM Higgs particle. Searches have been performed in several decay modes.

- ATLAS and CMS and CDF also exclude so far other SM-type Higgs bosons up to approximately 600 GeV.

- Experimental energy resolutions have been so far much wider of the expected intrinsic Higgs width of about 4 MeV.

- 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.

- In particular the Higgs width's measurement is essential to determine the couplings to fermions and bosons and their partial widths

- Therefore the detailed study of the properties of this particle is mandatory.

Q: Will LHC (14-Tev) be enough?

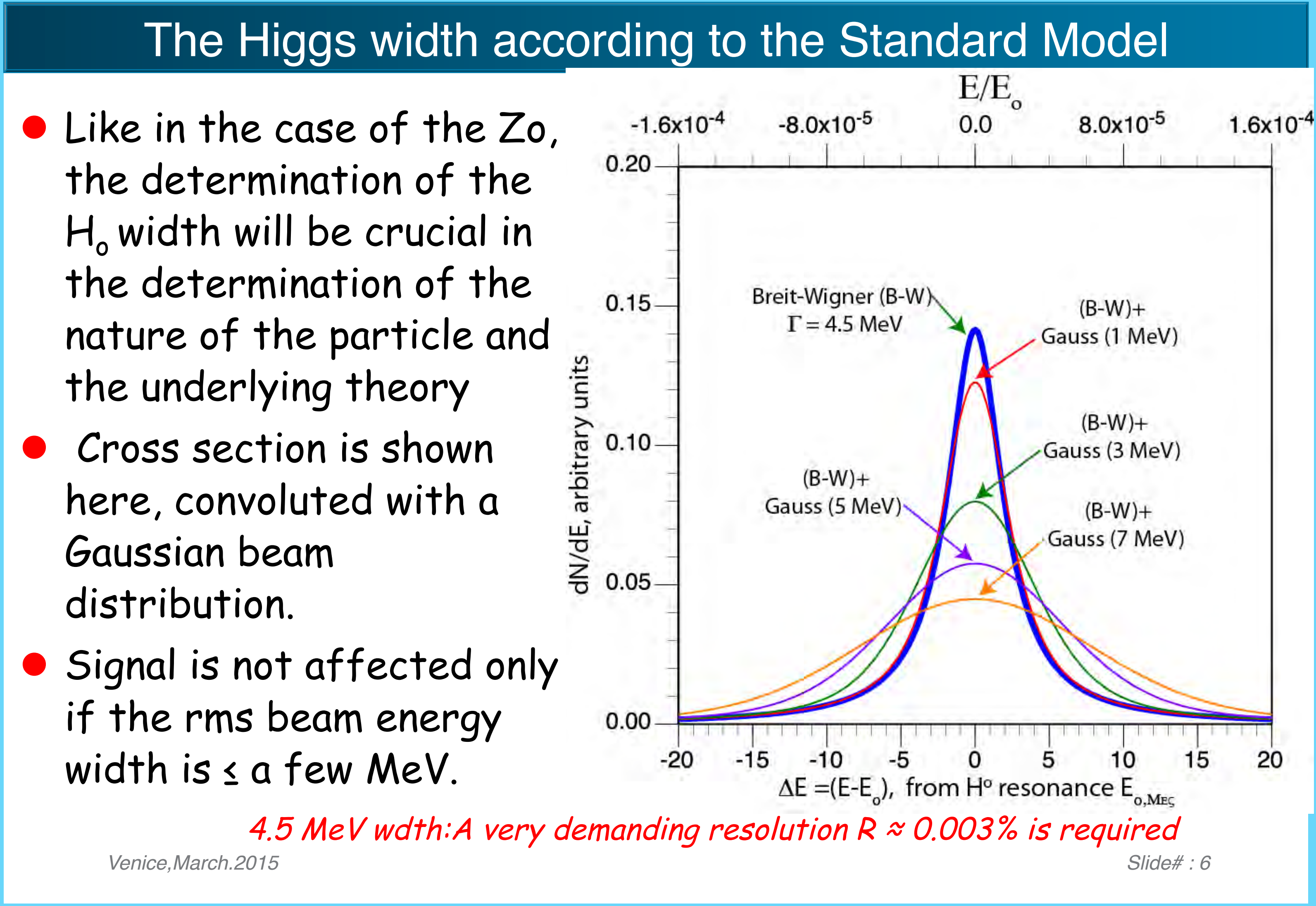
“A complete demonstrator of a muon cooled Higgs factory.”

C. Rubbia, arXiv: 1308.6612

- Muon cooling: a Higgs factory at CERN?

C.Rubbia, Frascati, Dec. ‘14, Venice, March 2015, Cern, April 2015

--> The issue of muon cooling is essential for the Luminosity and the energy spread of the beams. We need highly mono-chromatic beams.



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.

The need of a better precision

- What precision is needed in order to search for possible additional deviations from the SM, even under the assumption that there is no other additional “Higgs” state at the LHC ?
- Predicted ultimate LHC accuracies for “exotic” alternatives

R.S. Gupta et al.	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	$< 1\%$	3%	$10\%^a$,
LHC 14 TeV, $3\,\mathrm{ab}^{-1}$	8%	10%	15%

Ultimate at LHC

1 ab= 10^{-42} cm^2

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

SUSY tan(β)>5

$$\frac{g_{hff}}{g_{h_{SM}ff}} \quad \frac{g_{hVV}}{g_{h_{SM}VV}} \quad \simeq \quad 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

Composite Higgs

$$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

Top partners

- Sensitivity to “TeV” new physics for “5 sigma” discoveries may need 1 per-cent to sub 1-per-cent σ accuracies on rates.

arXiv:1206.3560v3 [hep-ph] 27 Sep 2012

C. Rubbia

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.

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

- Non minimal extensions of MSSM → neutral Higgs bosons.

The quest for Higgs Factories

- Two possible future lepton alternatives:

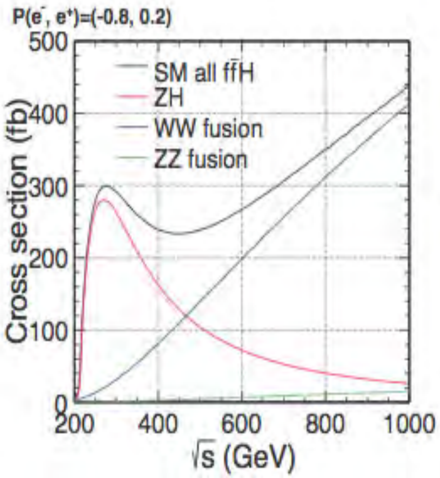
➢ A e^+e^- collider at $L > 10^{34}$ and a *$Z+H_o$ signal* of *≈ 200 fb.* The circumference of a new, LEP-like ring is of about ≈ 80 km or of a Linear Collider of 31 km.

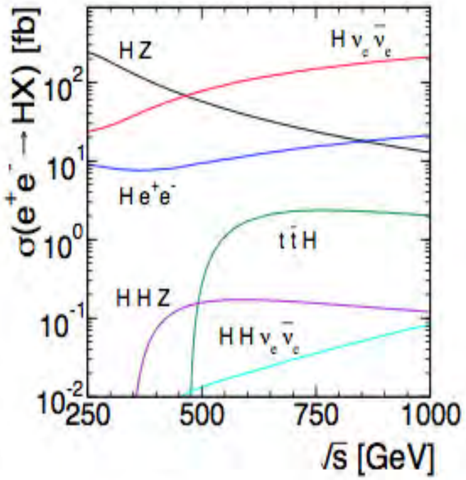
➢ A $\mu^+\mu^-$ collider at $L > 10^{32}$ and a *H_o signal in the s-state* of ≈ *20'000 fb*. The collider radius is much smaller, only ≈ 50 m, but the novel "muon cooling" facility is required.

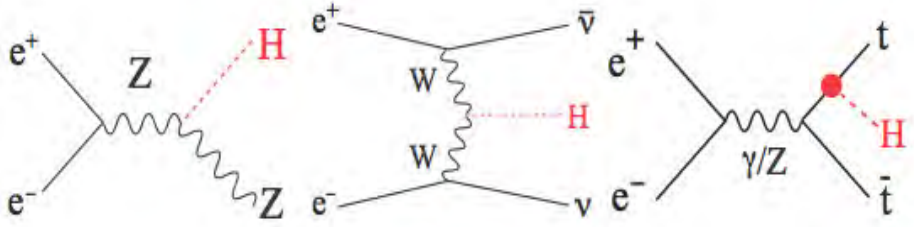
C. Rubbia

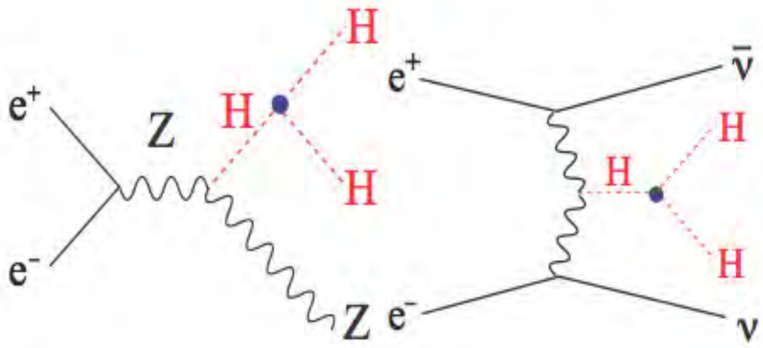
Production cross sections at the e+ e- collider

- 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



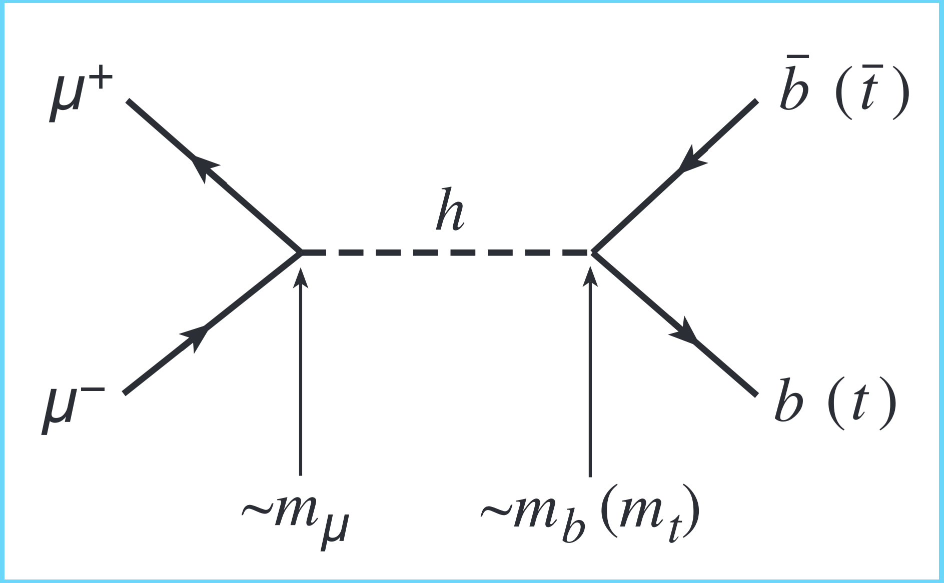






Muon Collider

- 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.

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

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 effects do not apply in the case of Higgs production in electron-positron colliders.
- ISR effects similar to J/Psi, Z, … production in e+e- annihilation, but not accounted for in previous studies.
-

M. G. arXiv:1503.05046
S. Jadach, R. Kycia arXiv:1509.**02406**

I S R effect

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

  modifies the lowest order cross section 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 (Zfitter,….)

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

to o(1-2 %) accuracy

- At W = 2E = M

$$\beta_i = 0.061$$

$$C^{res}_{infra} = (\Gamma/M)^{\beta_i} = 0.53,$$

→ The effect is very similar to the case of J/Psi, Z production in e+e- annihilation. Background situation is different.

→ Folding with beam energy resolution:

- Since the resonance is quite narrow, one has to integrate over the machine resolution

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

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

- Then 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:

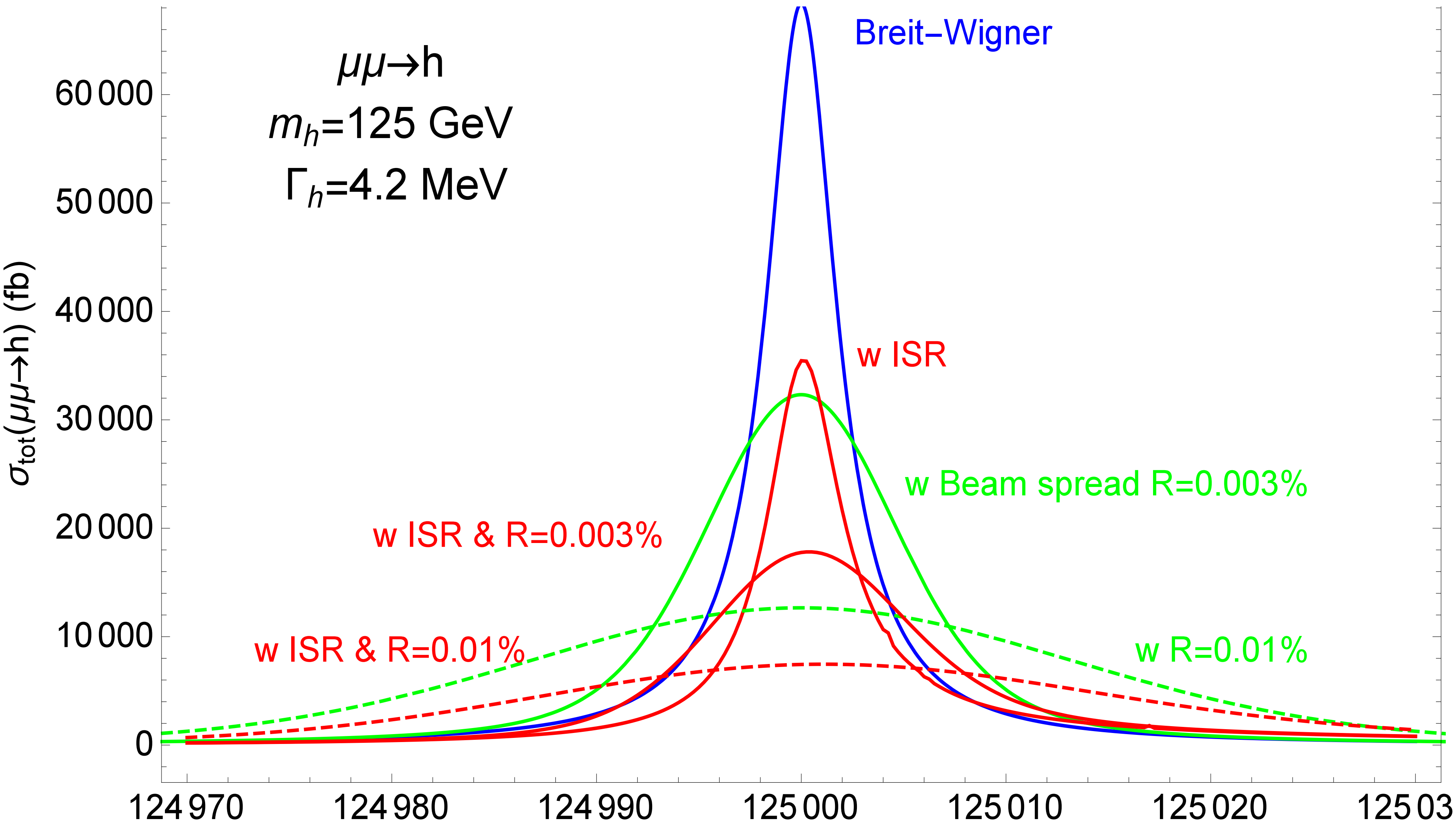
C = 0.47 , 0.37 , 0.30 , 0.20

for

$$\sigma = 1 \text{ MeV}, 2 \text{ MeV}, 3 \text{ MeV}, 4 \text{ MeV},$$

-- > Important reduction of the Born Higgs signal.

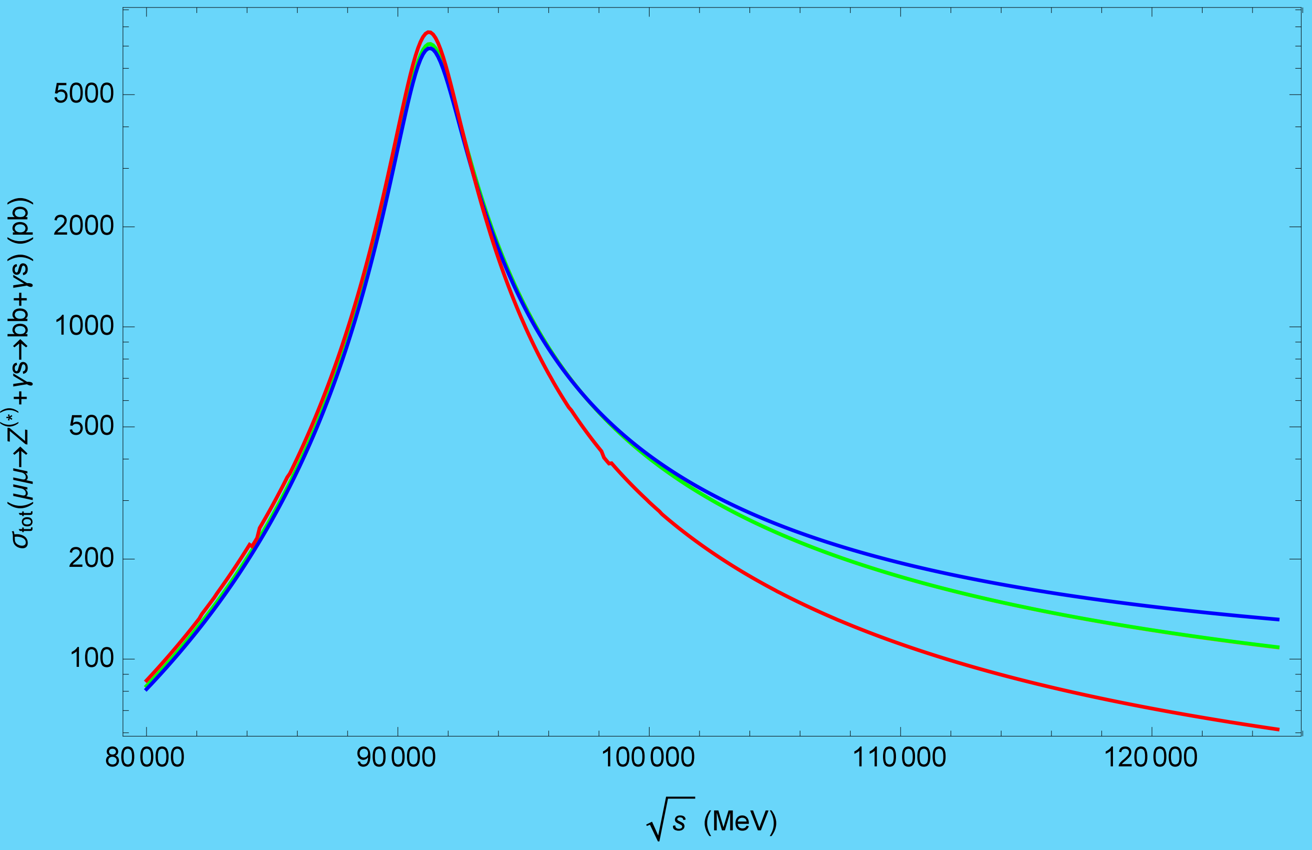
Higgs line shape



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

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

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

Previous Signal/Background studies:

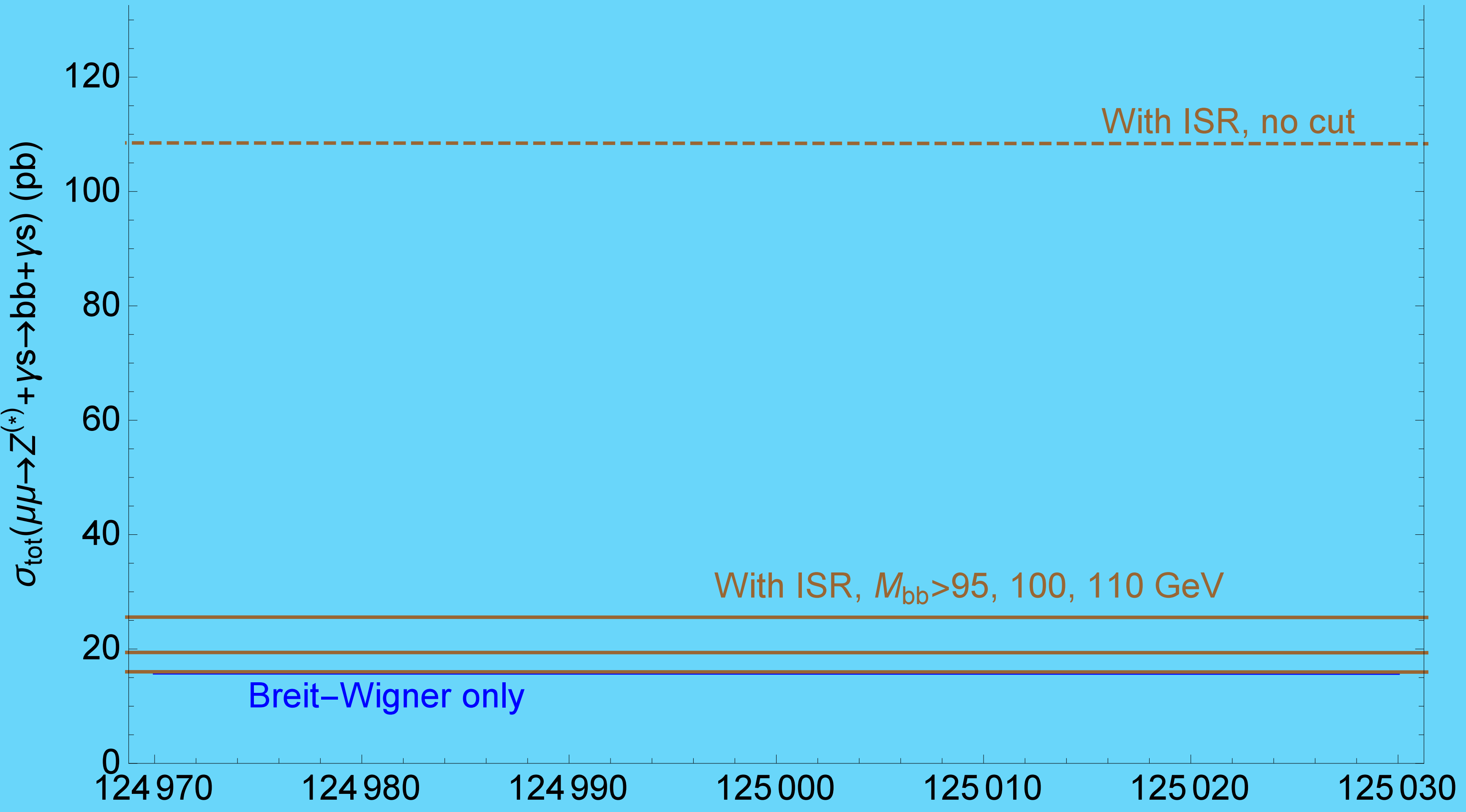
T. Han and Z. Liu (arXiv:1210.7803v2)

R (%)	$\mu^+\mu^- \to h$	$h \to b\bar{b}$		$h \to WW^*$	
	$\sigma_{\rm eff}$ (pb)	σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	16	7.6	15	3.7	0.051
0.003	38	18		5.5	

Effective cross sections (in pb) at the resonance for two choices of beam energy resolutions R and two leading decay channels, with the SM branching fractions.

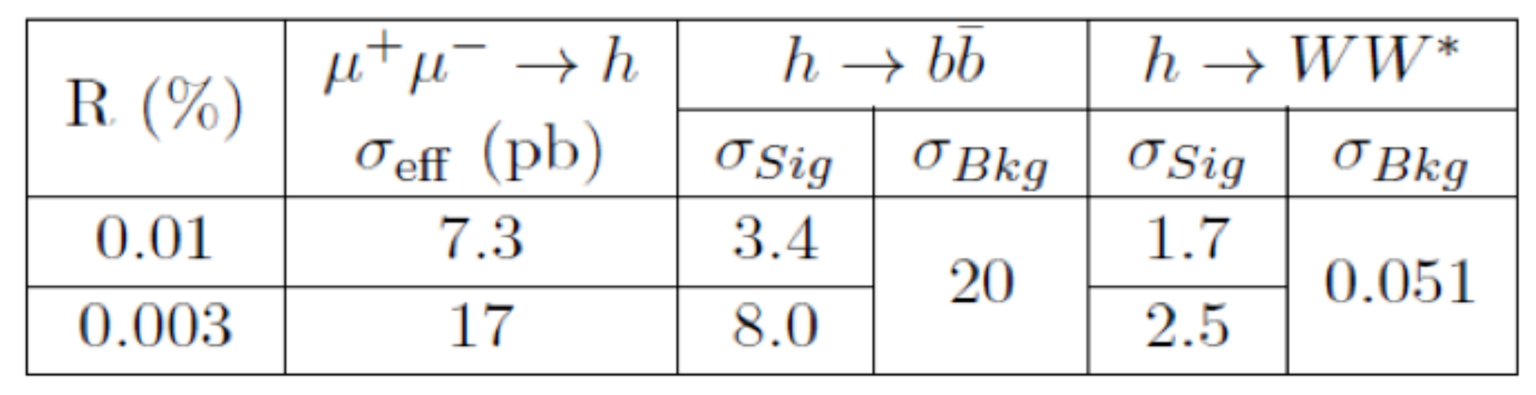
(No radiative effects included yet)

Backg. cross section vs. M_bb cuts



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

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.

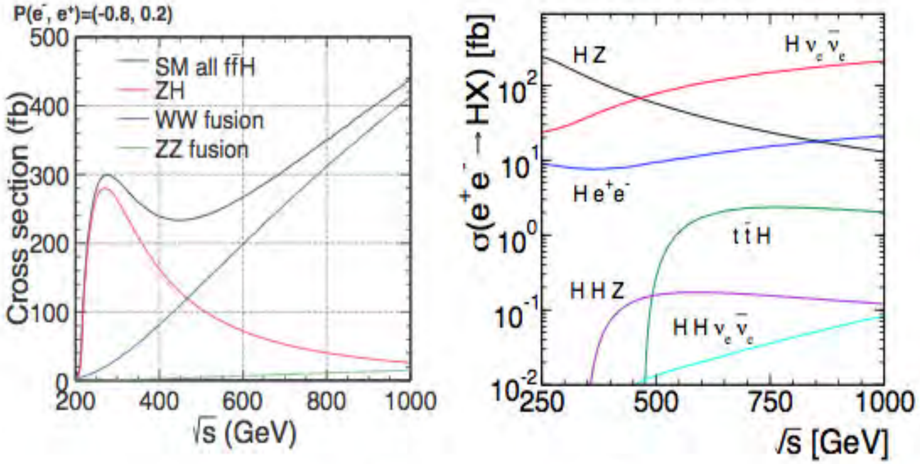
M.G., T. Han, Z. Liu

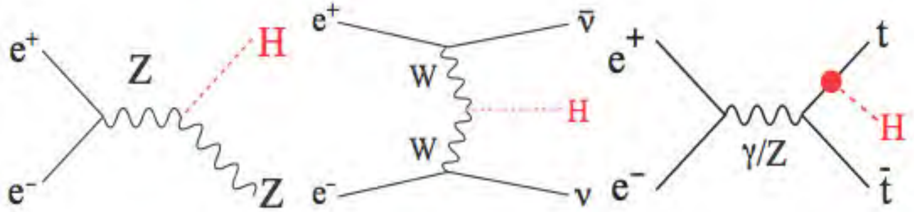
The energy spread plays a role on the Sign/Backg. ratio

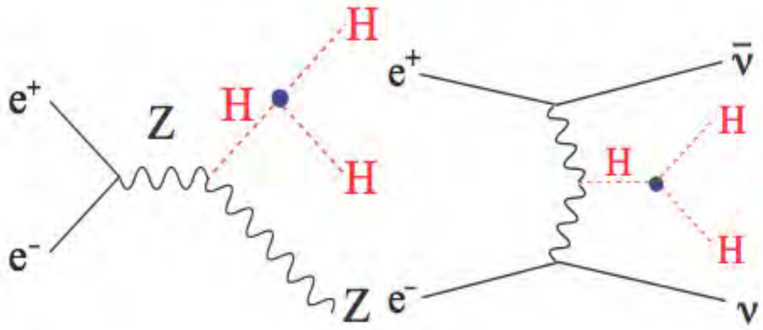
- No similar effects for e+e- colliders

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







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 flavour 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.

- The issue of muon cooling is really crucial. In addition to L the energy spread of beams plays an important role.