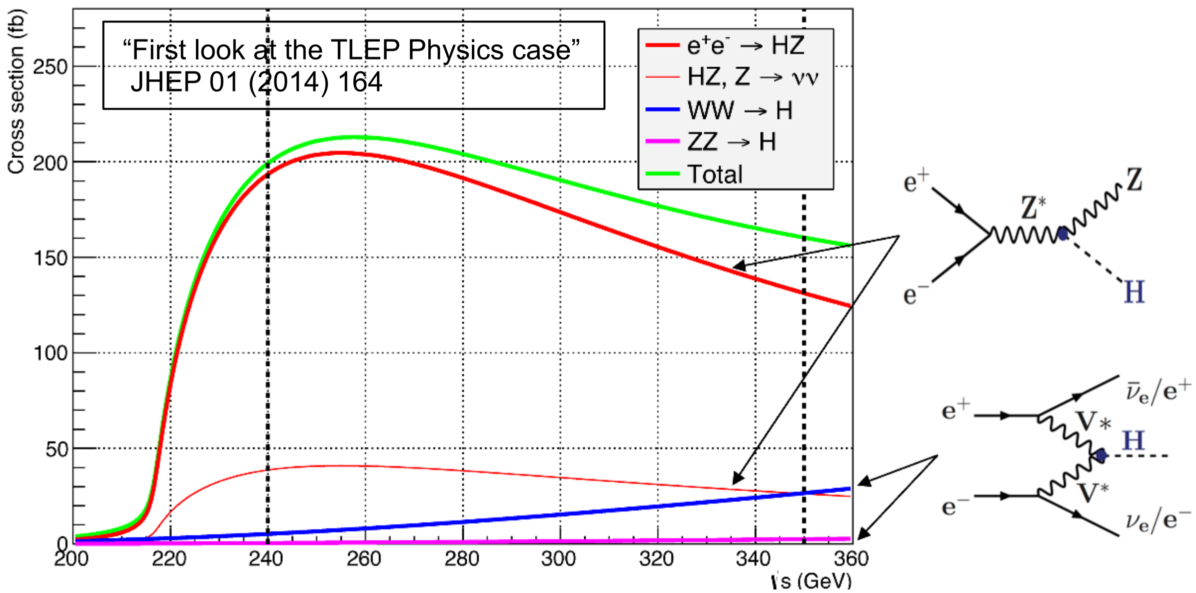
Muon Collider(s) & FCC-ee: Higgs physics

Outline

- Overview: Higgs boson production at lepton colliders
  - Processes
  - Energy
  - Luminosity
- Potential added value of muon colliders
  - Scan of the SM Higgs resonance
  - Beam energy and beam energy spread measurement
  - Additional Higgs bosons
- Summary

Higgs boson production (1)

- **Muons are leptons, like electrons**
  - Muon colliders can a priori do everything that e^+e^- colliders can do, e.g.:

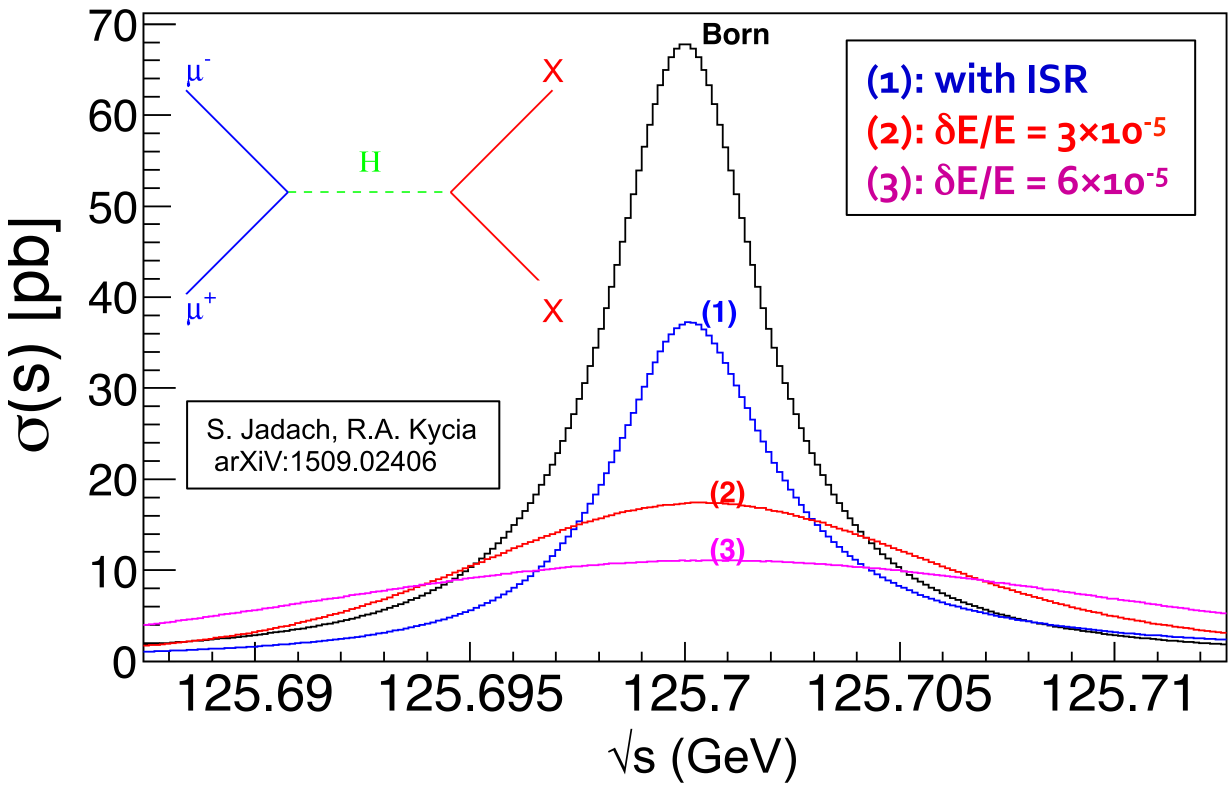


  - However, for a similar beam energy spread ($\delta E/E \sim 0.12\%$) at $\sqrt{s}$ = 240-350 GeV
    - FCC-ee luminosity: $0.5 - 1.1 \times 10^{35}$ $cm^{-2}s^{-1}$ / IP and up to 4 IPs
    - Muon collider luminosity: $0.4 - 1.5 \times 10^{33}$ $cm^{-2}s^{-1}$ / IP and only one IP (R ~ 50 m!)

  - Precision on branching ratios, couplings, width, mass, etc. , with 2 IPs
    - A factor 10 better at FCC-ee (and twice better at ILC) than at a muon collider

Higgs boson production (2)

- Muons are heavy, unlike electrons: $m_\mu/m_e \sim 200$
  - Large direct coupling to the Higgs boson: $\sigma(\mu^+\mu^- \rightarrow H) \sim 40{,}000 \times \sigma(e^+e^- \rightarrow H)$
  - Much less synchrotron radiation, hence potentially superb energy definition
    - $\delta E/E$ can be reduced to $3\text{-}4 \times 10^{-5}$ with more longitudinal cooling
      - ➨ Albeit with equivalent reduction of luminosity: $2 - 8 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

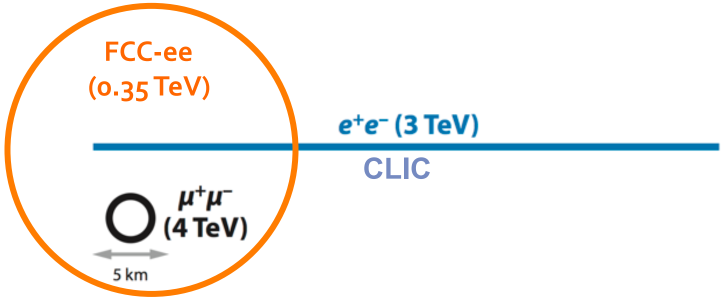


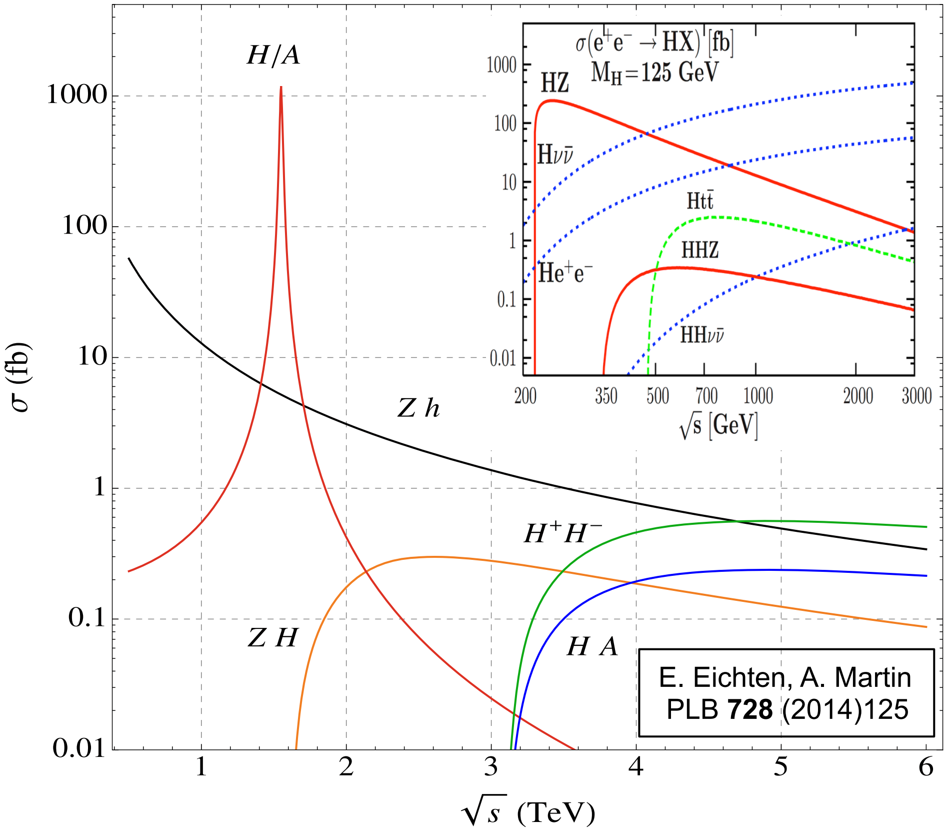
- $\sigma(\mu^+\mu^- \rightarrow H) \sim 15$ pb
  (ISR often forgotten: 28 pb)
- 200 – 800 pb^{-1} / yr
- 3000 – 12000 Higgs / yr

Reminder: At FCC-ee
400,000 to 800,000 Higgs/yr

Higgs boson production (3)

- **Muons are heavy, similar to protons**
  - Limited synchrotron radiation
    - Can reach very high energy in small rings





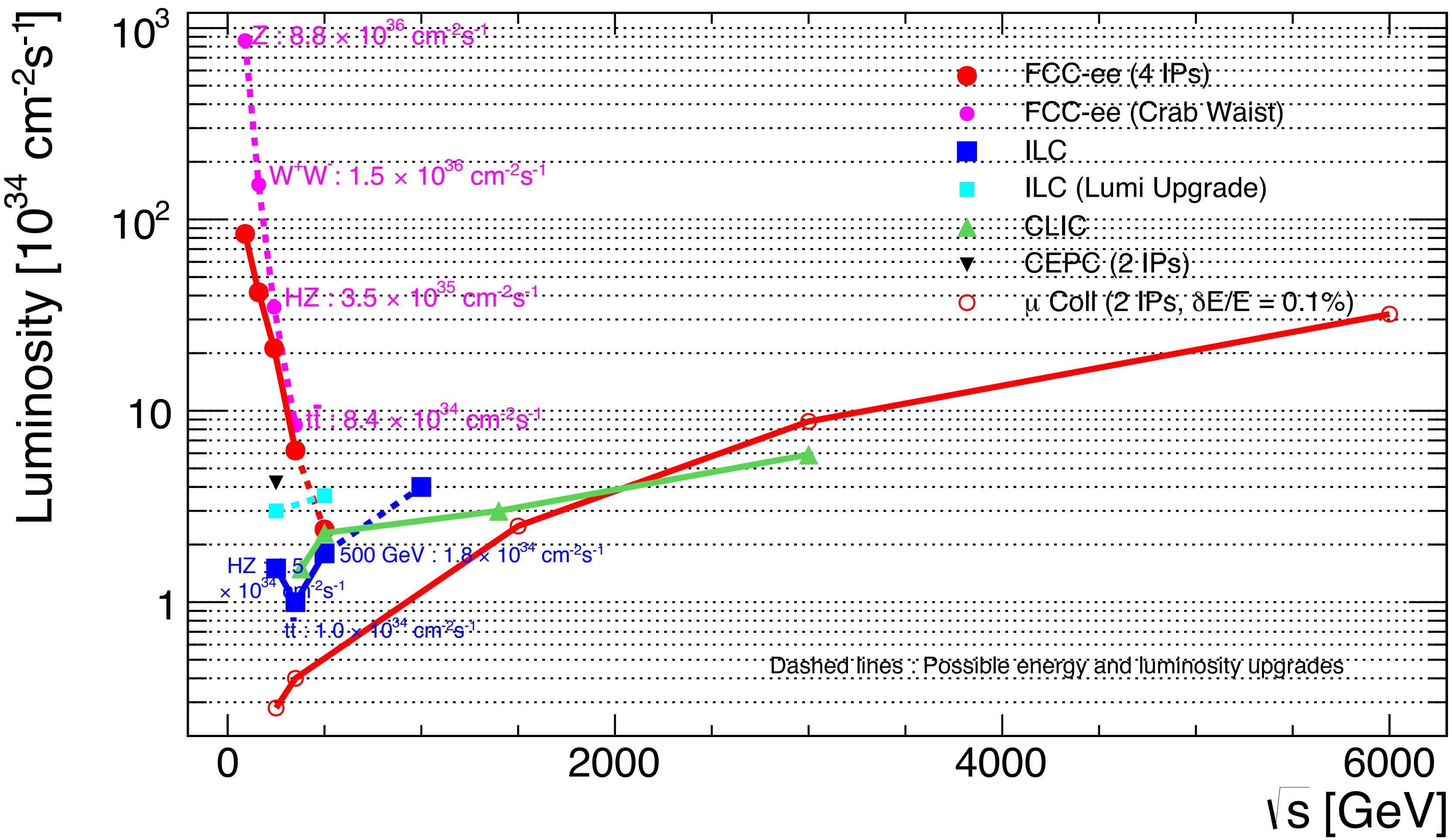
Luminosity
- Similar to linear colliders for $\sqrt{s} > 1$ TeV
  - HHH coupling with similar precision
    - (Also done at FCC-hh)

Energy
- Can go to higher energy
  - Advantage for 2HDM (e.g., SUSY)
    - Heavy Higgs with $\mu^+\mu^- \to$ H,A

- $\sqrt{s} \sim 6$ TeV possible in the Tevatron tunnel

Higgs boson production (4)

- Luminosity and energy at lepton colliders

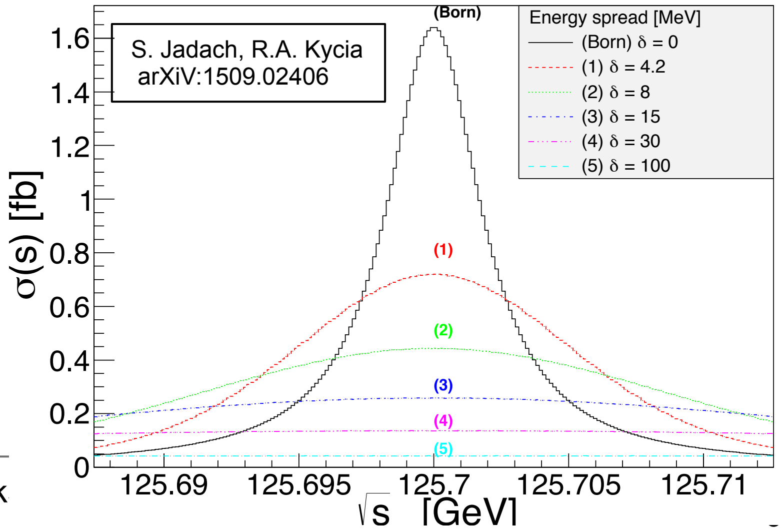


Higgs boson production (5)

- **When muon colliders try to do what the other collider do**
  - They do a factor 10 worse than FCC-ee, a factor 2 worse than ILC at $\sqrt{s} < 500$ GeV
  - They reach a performance similar to that of CLIC at 1.5 TeV < $\sqrt{s}$ < 3 TeV

- **Muon colliders are, however, unique on two aspects**
  - They can scan the Higgs resonance(s) by direct $\mu^+\mu^- \to H$ production (*)
  - They can reach $\sqrt{s} > 3$ TeV with reasonably-sized rings, and low power consumption
    - I focus on these specificities in the rest of the presentation

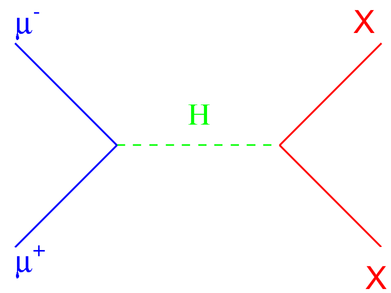
- **(*) Note: Scan of the SM Higgs resonance at FCC-ee with $e^+e^- \to H$**
  - $\sigma(e^+e^- \to H) \sim 50$ ab with nominal $\delta E/E$
    - 200- 500 ab with monochromators?
      - ➨ ~10,000 events/yr (40 ab^{-1}/yr)
      - ➨ S/B × 10^{-5} wrt muon collider
    - No way to study resonance parameters
      - ➨ See study from d'Enterria et al.
      - ➨ Optimistically expect ~2σ excess



Scan of the SM Higgs resonance (1)

Resonant production

$$\sigma(\mu^+\mu^- \to H^0) = \frac{4\pi\Gamma_H^2 Br(H^0 \to \mu^+\mu^-)}{(\hat{s} - M_H^2)^2 + \Gamma_H^2 M_H^2}$$



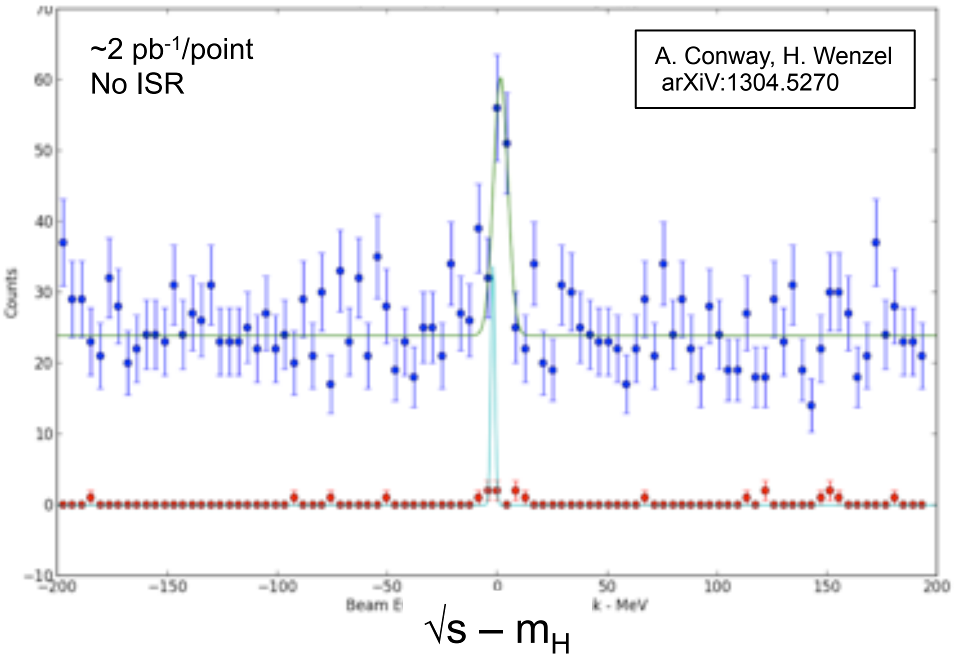
Major background:
$\mu^+\mu^- \to Z/\gamma^* \to XX$

- **Convoluted with**
  - **Beam energy spectrum**
  - **Initial state radiation (ignored in most studies)**

- **The measurement of the lineshape gives access to**
  - **The Higgs mass, m_H**
  - **The Higgs width, Γ_H**
  - **The branching ratio into $\mu^+\mu^-$, BR(H → μμ)**
    - ➨ **Hence, the coupling of the Higgs to the muon, $g_{H\mu\mu}$**
  - **Some branching fractions and couplings, with exclusive decays**

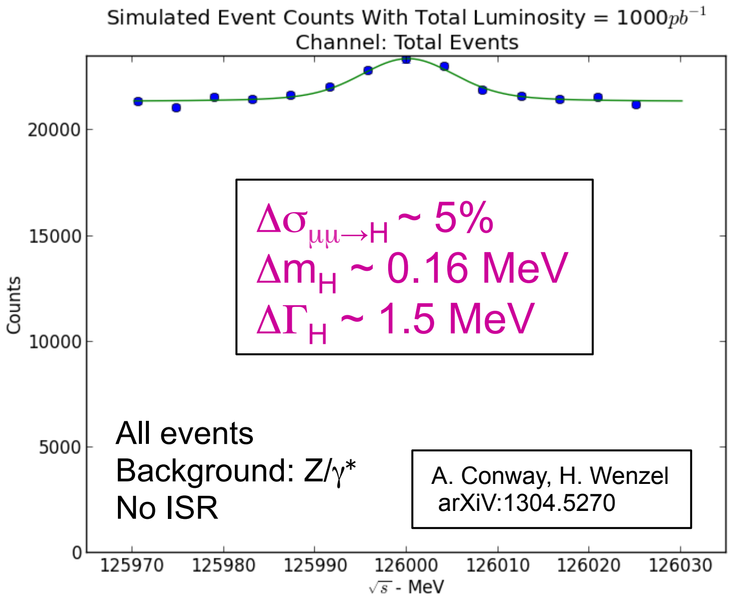
Scan of the SM Higgs resonance (2)

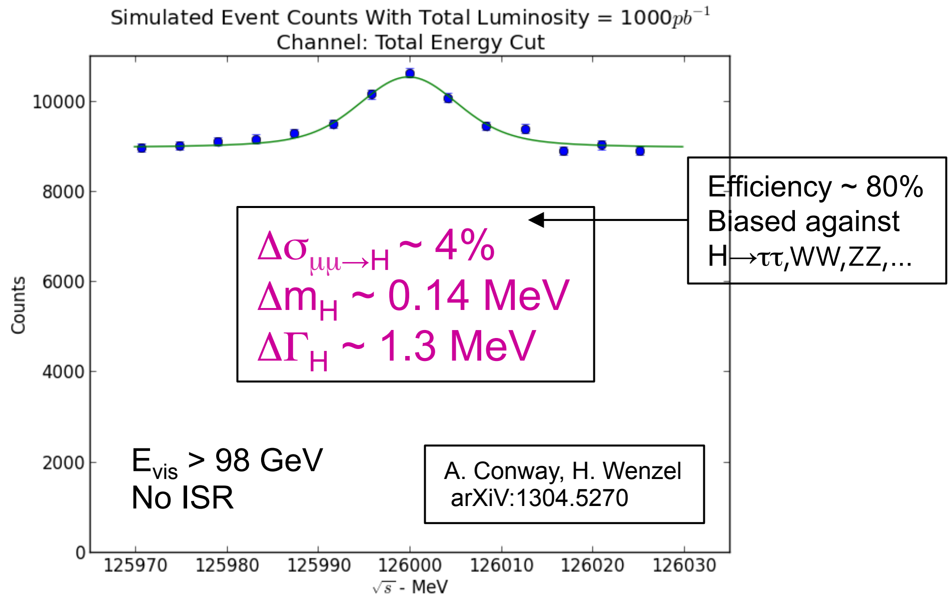
- **Finding the resonance (Γ_H = 4.2 MeV ~ δE)**
  - Today, m_H is known to ±250 MeV
    - Improves to ±100 MeV (LHC14), ±30 MeV (ILC), or ±8 MeV (FCC-ee)
  - Scan the √s region of interest in optimal bins of 4.2 MeV
    - Count the number of bb and semi-leptonic WW events (see next slides)
  - Without ISR, needs about 2 pb^{-1} / point for a 5σ significance
    - Reduced to 3σ when ISR is included
      - ➨ Probably enough
  - Total luminosity needed for 3σ
    - 300 pb^{-1} (1.5 yr) for ±300 MeV
    - 90 pb^{-1} (6 months) for ±90 MeV
    - 25 pb^{-1} (2 months) for ± 24 MeV
      - ➨ With L = 2×10^{31} $cm^{-2}s^{-1}$
  - Can be long …
    - … but feasible
      - ➨ Especially after ILC / FCC-ee



Scan of the SM Higgs resonance (3)

- **Measurement of the lineshape**
  - Assume 1 fb^{-1} (5 yrs at 2×10^{31} and ≥ 1 yr at 8×10^{31}) : 70 pb^{-1} / point around m_H
    - The detector is assumed to have the performance of an ILC detector
    - No beam background (e.g., from muon decays) is simulated
  - Count either all events, or only those with E_{vis} > 98 GeV [reject Z(γ) events]



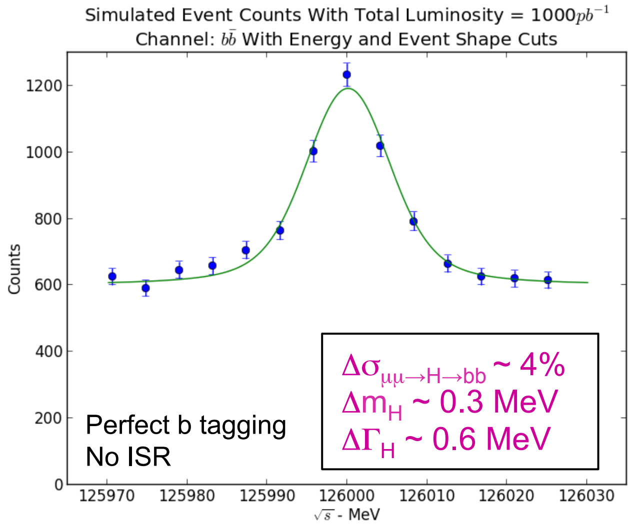


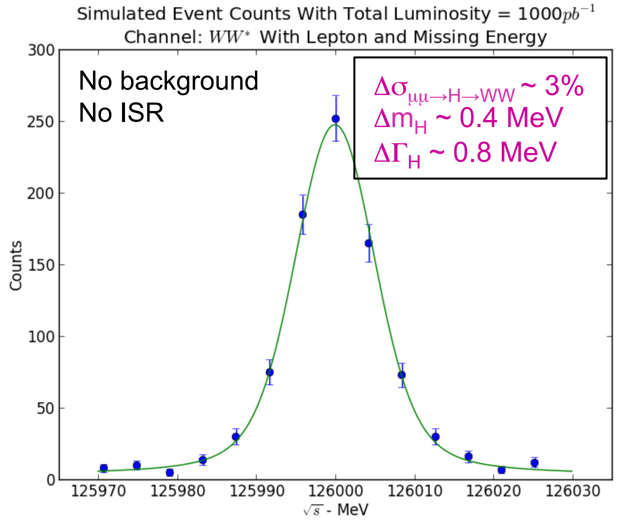
- ISR reduces the signal by a factor 2 (but not the background)
  - ➨ All errors to be increased by a factor 2
- m_H and Γ_H measurements require knowledge of E and δE with great precision

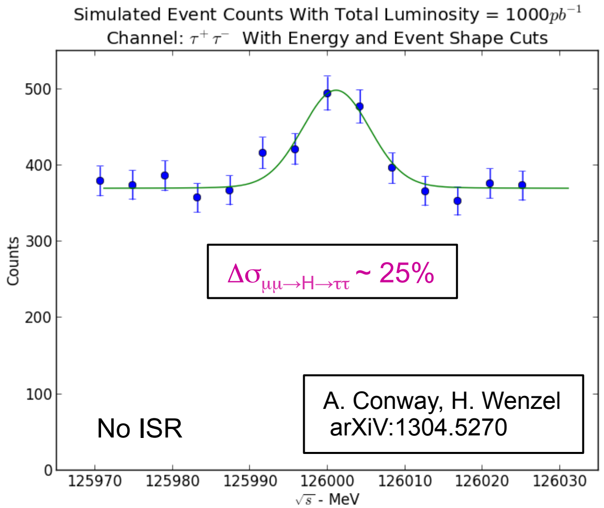
Scan of the SM Higgs resonance (4)

Exclusive decays

- $H \to bb$ — $H \to WW \to l\nu qq$ — $H \to \tau\tau$







- **Notes**
  - Some optimism in these numbers (perfect b tag, only Z bkgd, no beam bkgd…)
  - Errors to be increased anyway to account for ISR
  - A better scan strategy could be thought of (less in the sides, more in the peak)
  - The numbers are for 5 years at low luminosity, and 1.2 year after lumi upgrade
    - ➨ Combined numbers (next slide) given for 5 (low lumi) + 5 (upgrade) years.

Scan of the SM Higgs resonance (5)

- **Summary of precision measurements (after ~10 years of running)**

Error on	$\mu\mu$ Collider	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

Not sure of the practical use of such a precision on m_H

The Higgs width is best measured at ee colliders

These Higgs couplings are best measured at ee colliders

The SM Higgs coupling to muons is *the* added value of a $\mu\mu$ collider *

These Higgs couplings are *only* measured at ee colliders *

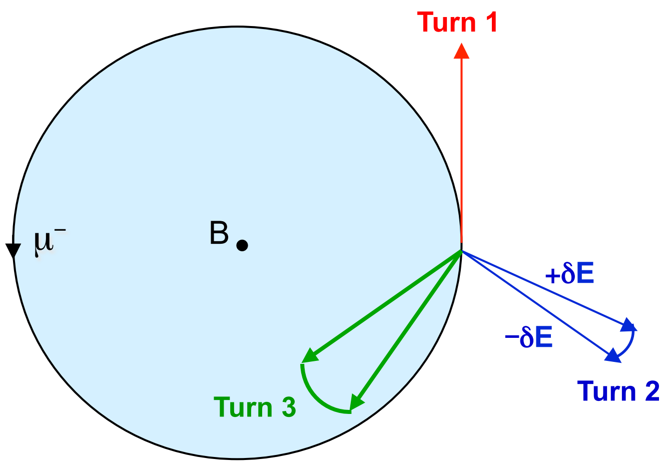
* pp colliders have their say, too

- **Note: BR($H \to \mu\mu$) can also be measured with % precision at FCC-hh. (Will be already 10% after LHC.)**

Beam energy and beam-energy spread (1)

- **Muons are naturally 100% polarized (from $\pi^{\pm}$ decays)**
  - **It is hoped that ~20% of this polarization can be kept in the collider ring**
    - Then, the spin precesses around B with a frequency ν_0
      - ➨ For m_H = 125 GeV, ν_0 = 0.68967593(35)
    - Without energy spread, P_L oscillates between -20% and +20%
    - With energy spread, P_L gets diluted turn after turn

$$\nu_0 = \frac{g_\mu - 2}{2} \times \frac{E_{\mathrm{Beam}}}{m_\mu}$$



$$P_L(T) = P_0 \int_0^\infty \cos(2\pi\nu T) S(\nu) \mathrm{d}\nu$$

- ➨ P_L(T) is the Fourier transform of S(ν)
- For example, with a Gaussian energy spread

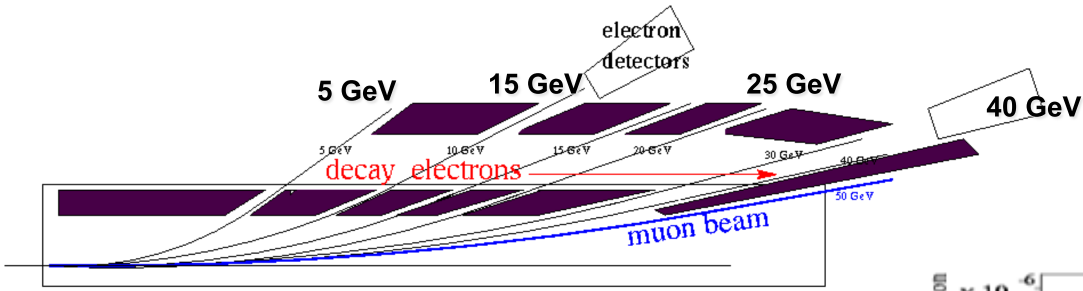
$$P_L(T) = P_0 \cos(2\pi\nu_0 T) \exp\left\{ -\frac{1}{2}\left[2\pi\nu_0 T \frac{\delta E}{E} \right]^2 \right\}$$

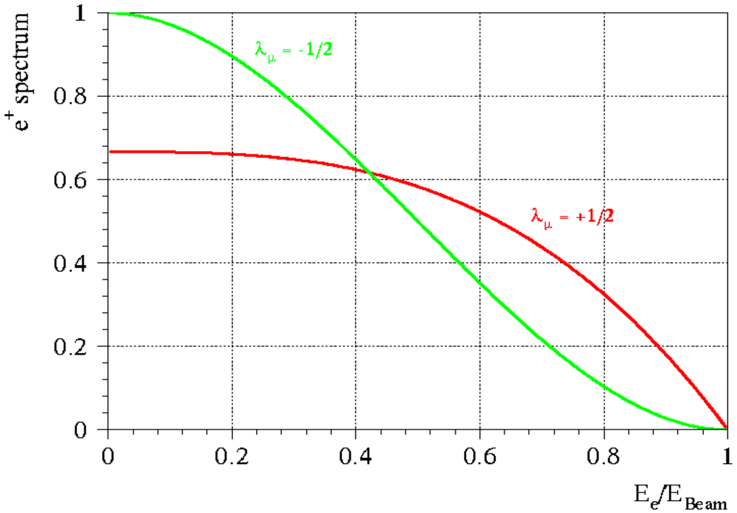
- Experimentally, measure P_L at each turn T
  - ➨ And deduce the complete beam energy spectrum by inverse Fourier transform

i.e., δE/E for a Gaussian energy spread

Beam energy and beam-energy spread (2)

- Use decay electrons to measure $P_L(T)$
  - Energy distribution depends on the muon helicity
    - $N_e(E) / N_{tot}$ oscillates according to P_L
      - ➨ Count electrons in the first dipole:

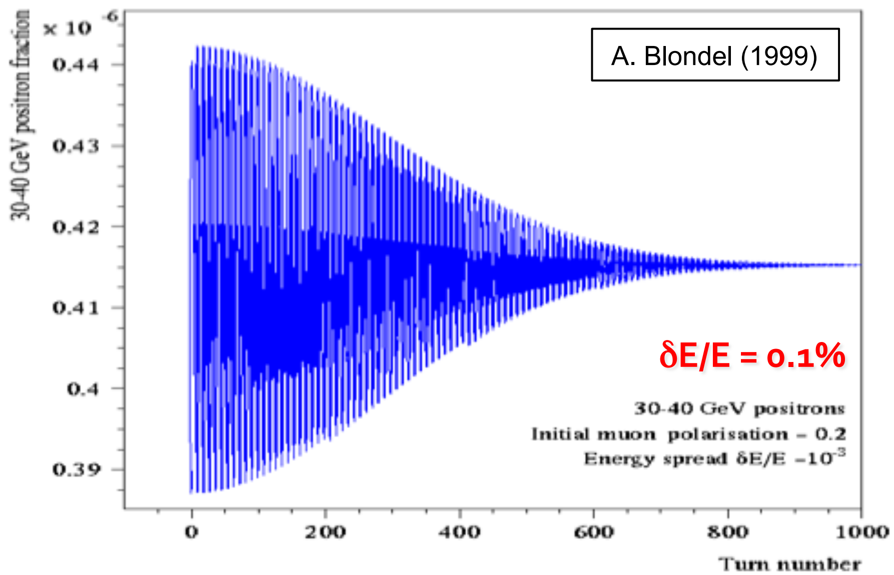




  - Fraction of e⁺ from 30 to 40 GeV

$$P_L(T) = P_0 \cos(2\pi\nu_0 T)\exp\left\{-\frac{1}{2}\left[2\pi\nu_0 T\,\frac{\delta E}{E}\right]^2\right\}$$

    - The amplitude gives P_0
    - The frequency gives ν_0 (E_{Beam})
    - The damping gives $\delta E/E$



Beam energy and beam-energy spread (3)

- **Expected statistical accuracy of the method**
  - For L = 2×10^{31} cm^{-2}s^{-1} and $\delta E/E = 3\times10^{-5}$, for each "fill" (i.e., 1000 turns)
    - 10^{-7} on the beam energy (6 keV)
      - Limited to 5×10^{-7} (30 keV) by the precision on $g_\mu - 2$ (!)
    - $3\cdot10^{-7}$ on the beam energy spread $\delta E/E$ (1%)
      - Corresponds to a systematic uncertainty of 0.5% on $\sigma(\mu\mu \to H)$
      - Corresponds to a systematic uncertainty of 50 keV on Γ_H
    - 10^{-4} on the polarization value
      - Negligible impact on $\sigma(\mu\mu \to H)$
  - These uncertainties are appropriately smaller than the statistical precision
    - On the Higgs mass (60 keV)
    - On the Higgs width (170 keV)
    - On the production cross section (1.5%)

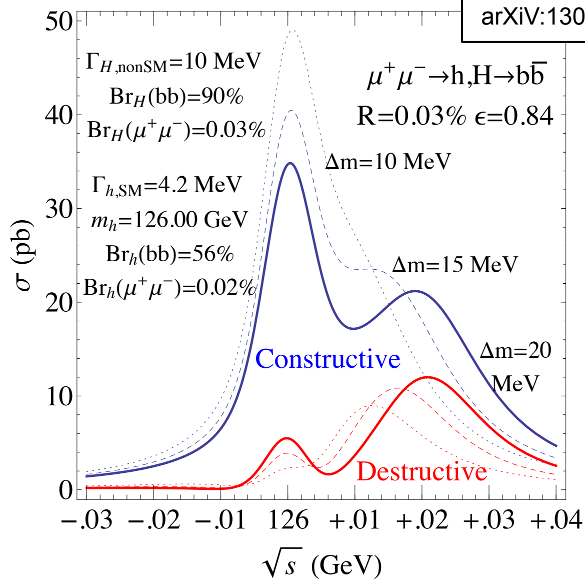
Additional Higgs bosons (1)

- **Is H(125) made of several quasi-degenerate Higgs bosons ?**
  - At LHC, the typical m_H resolution in the $H \to ZZ^* \to \mu\mu$ channel is ~1 GeV
    - Two quasi-degenerate Higgs bosons difficult to infer if ΔM < few 100 MeV
  - Would be a piece of cake at a muon collider
    - Examples shown for
      - ΔM = 10, 15, 20 MeV
      - Destructive/constructive interference
      - Similar coupling to muons and b quarks
    - Lineshape sensitive to ΔM ~ MeV
      - If both Higgs bosons couple to μ and b/W
  - Probably observable at FCC-ee via pair production with √s > 250 GeV (to be studied)
    - $e^+e^- \to hA$ present at tree level with large cross section (A pseudoscalar, m_A~m_h~m_H)
    - [$e^+e^- \to hH$ only at loop level with a few ab cross section (H scalar)]
      - A small mass difference is not measurable this way

… but the pair production proves the existence of two (three) states

Similar at FCC-ee (Recoil mass)

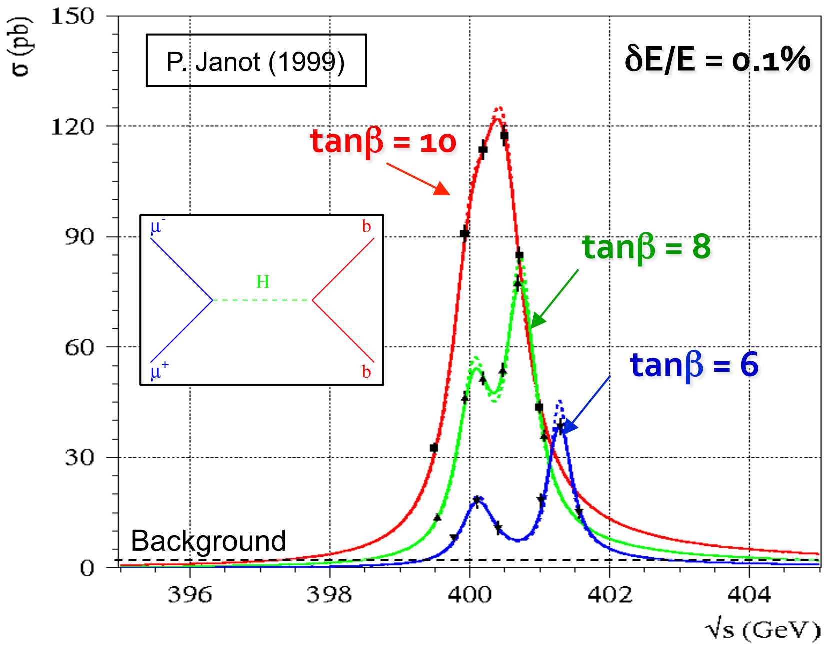
Snowmass 2013
arXiV:1308.2143

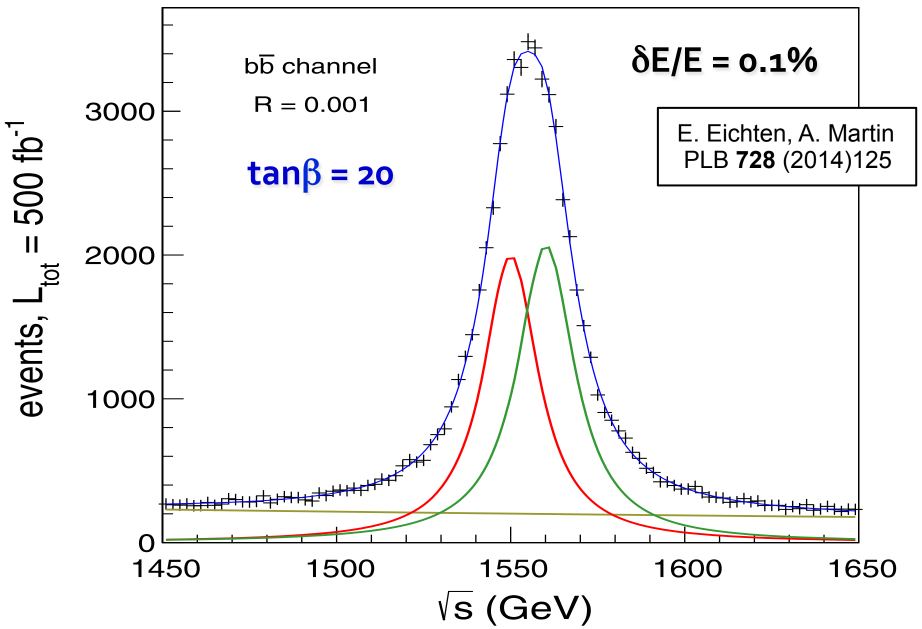


A. Djouadi et al.
PRD **54** (1996) 759

Additional Higgs bosons (2)

- **Can be applied to heavier H and A in 2HDM (e.g., from SUSY)**
  - **Example 1: m_A = 400 GeV** — **Example 2: m_A = 1.55 TeV**

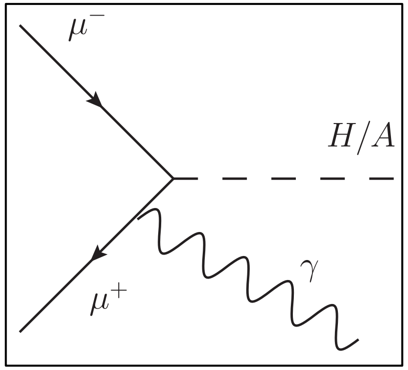




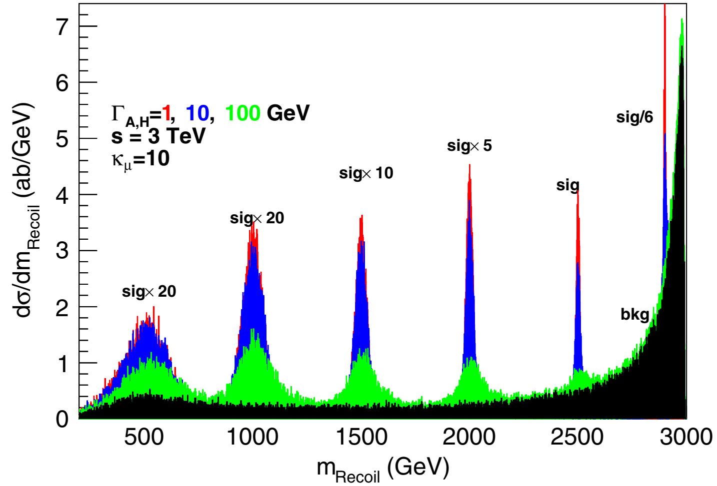
- **Notes:**
  - Higgs width of the order of 0.1 to 1% of the Higgs mass
    - ➨ δE/E ~ 0.1% enough, large integrated luminosities (100's fb^{-1} or ab^{-1}) possible
  - Each value of m_A correspond to a specific ring diameter
    - ➨ Need to know the mass beforehand

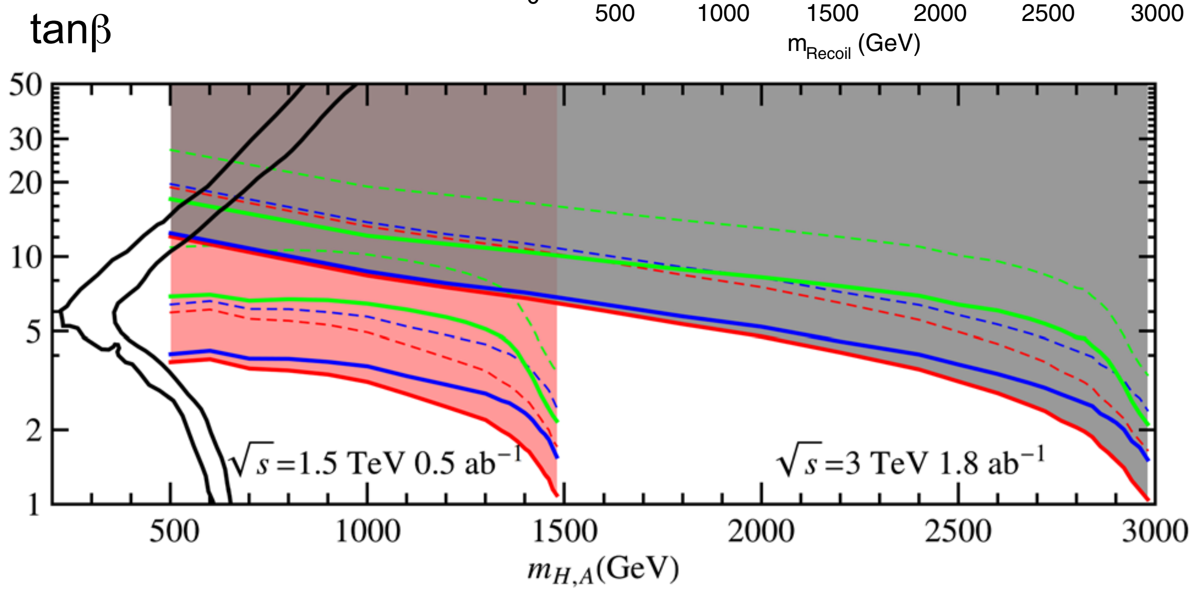
Additional Higgs bosons (3)

- **Automatic mass scan with radiative returns in $\mu\mu$ collisions**
  - Go to the highest energy first
    - $\sqrt{s}$ = 1.5, 3 or 6 TeV
  - Select event with an energetic photon
    - Check the recoil mass $m_{Recoil} = [s - 2E_\gamma\sqrt{s}]^{1/2}$



N. Chakrabarty et al.
PRD **91** (2015)015008

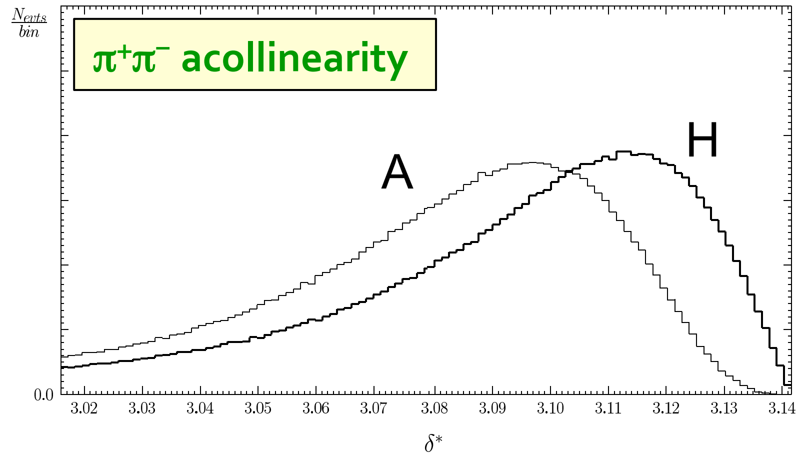


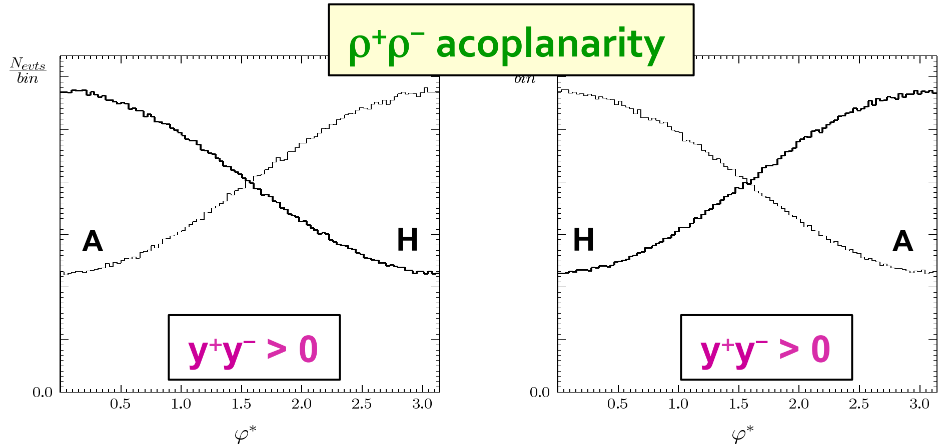


- Can “see” H and A
  - If tanβ > 5
- Build the next collider
  - At $\sqrt{s} \sim m_{A,H}$

Additional Higgs bosons (4)

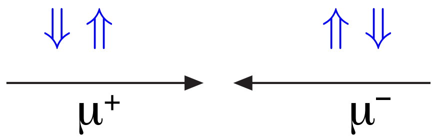
- **Unique CP (violation) and H/A mixing studies can start**
  - From H,A $\rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$
  - From H,A $\rightarrow \tau^+\tau^- \rightarrow \rho^+\rho^-\nu_\tau\nu_\tau$ with $\rho^\pm \rightarrow \pi^\pm\pi^0$





$y^\pm = E_{\pi\pm} - E_{\pi 0}$

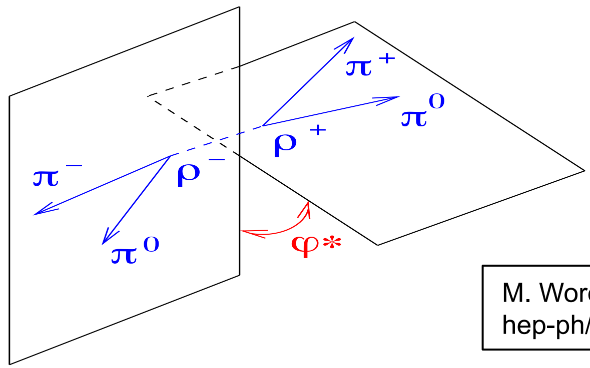
- From beam transverse polarization



Parallel spins: produces H
Antiparallel spins: produces A

- No idea of whether it is feasible or not…

F. Palhen et al.
JHEP 0808:030
JHEP 0801:017



M. Worek
hep-ph/0305082

Summary

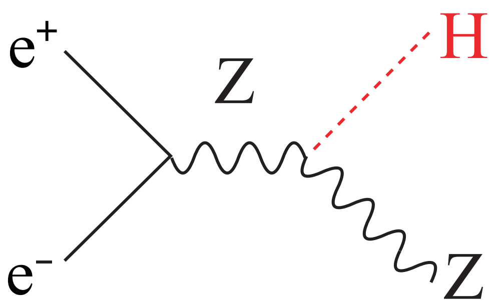
- A muon collider at $\sqrt{s}$ = 125 GeV is a pretty Higgs factory
  - But not necessarily the one we need
    - Only a few Higgs couplings are accessible (b, μ, W, τ) with a 2-5% precision
      - ➨ The Higgs total decay width can be measured with a 5% precision
    - If H is a single particle, we will know more from e^+e^- collisions at the FCC-ee
      - ➨ All Higgs couplings can be measured with 0.1 – 1% precision
      - ➨ Sensitive to the Higgs invisible branching fraction down to 0.1%
    - Important : e^+e^- colliders can measure the Higgs width very well
      - ➨ Precision of 0.9% at the FCC-ee (4% at the ILC)

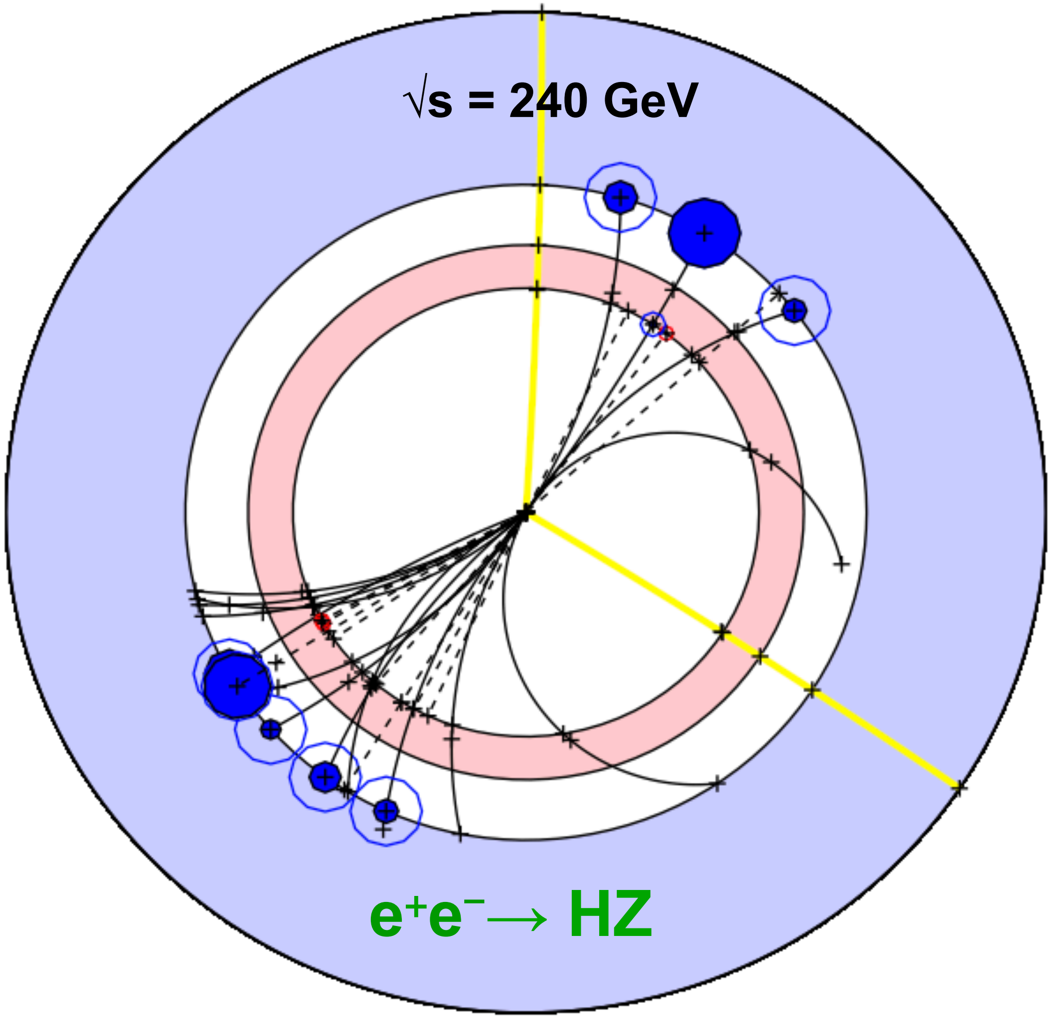
- Muon colliders may have a case if H(125) is formed by nearby peaks
  - Separated by less than few 100 MeV and by more than a few MeV
    - Can be observed via $e^+e^- \to$ hA at FCC-ee
    - A similar situation occurs for heavy H and A: requires $m_{H,A}$ to be known beforehand
    - Open the possibility of nice (and unique) CP studies

- Muon colliders may be the best way to reach $\sqrt{s}$ > 3 TeV with leptons
  - Much R&D remain to be done in cooling and acceleration

Backup: Higgs width at FCC-ee (1)

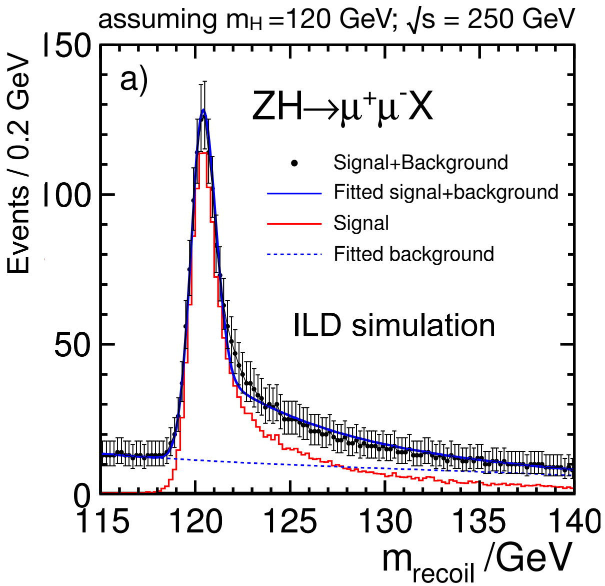
- Example of a Higgs boson event
  - Tagged with a Z boson
  - Very clean signature

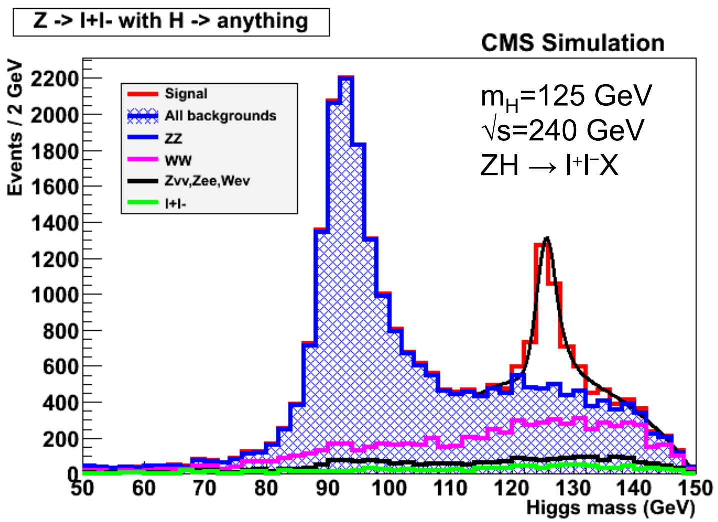




Backup: Higgs width at FCC-ee (2)

- **Example: Model-independent measurement of σ_{HZ} and κ_Z**
  - The Higgs boson in HZ events is tagged by the presence of the $Z \to e^+e^-, \mu^+\mu^-$
    - Select events with a lepton pair (e^+e^-, $\mu^+\mu^-$) with mass compatible with m_Z
    - No requirement on the Higgs decays: measure $\sigma_{HZ} \times BR(Z \to e^+e^-, \mu^+\mu^-)$
    - Apply total energy-momentum conservation to determine the "recoil mass"
      - ➨ $m_H^2 = s + m_Z^2 - 2\sqrt{s}\,(p_+ + p_-)$ Exercise !
    - Plot the recoil mass distribution – resolution proportional to momentum resolution

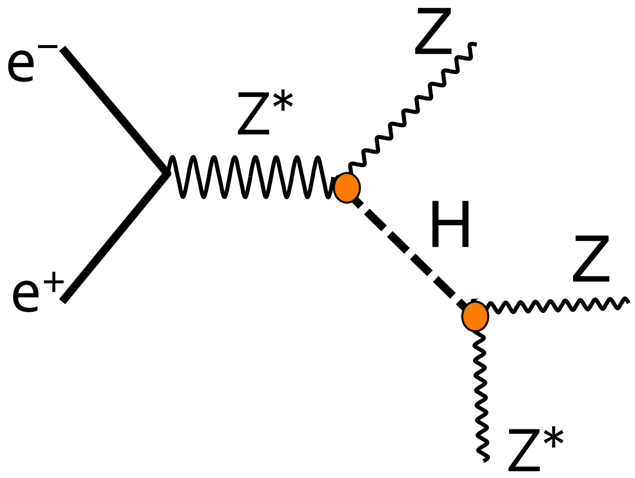




  - Provides an absolute measurement of κ_Z and set required detector performance

Backup: Higgs width at FCC-ee (3)

- Indirect determination of the total Higgs decay width
  - From a counting of HZ events with $H \to ZZ$ at $\sqrt{s} = 240$ GeV
    - Measure $\sigma_{HZ} \times BR(H \to ZZ)$



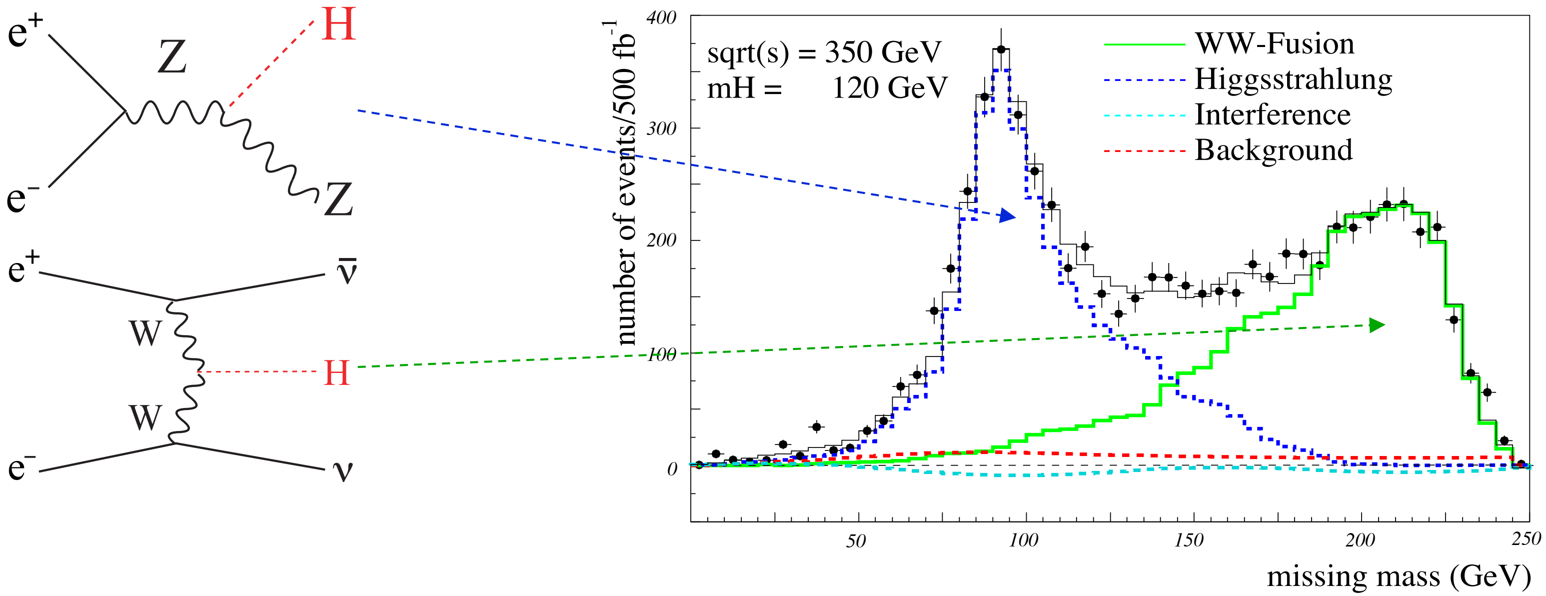
Final state with three Z's
Almost background free

Measured with the Hl^+l^- final state (see slide 21)

- σ_{HZ} is proportional to κ_Z^2
- $BR(H \to ZZ) = \Gamma(H \to ZZ) / \Gamma_H$ is proportional to κ_Z^2/Γ_H
  - ➨ $\sigma_{HZ} \times BR(H \to ZZ)$ is proportional to κ_Z^4 / Γ_H
- Infer the total width Γ_H

Backup: Higgs width at FCC-ee (4)

- **Indirect determination of the total Higgs decay width (cont'd)**
  - **From a counting WW→ H→ $b\bar{b}$ events at 350-500 GeV in the $b\bar{b}\nu\bar{\nu}$ final state:**



- **Measure σ(WW→ H→ bb)**
- **Take the branching ratios into WW and bb from σ_{HZ} and $\sigma_{HZ}\times$ BR(H → WW,bb)**
- **Infer the total width**

$$\boxed{\Gamma_H \propto \sigma_{WW\to H} / \mathrm{BR}(H\to WW) = \sigma_{WW\to H\to bb} / \mathrm{BR}(H\to WW) \times \mathrm{BR}(H\to bb)}$$