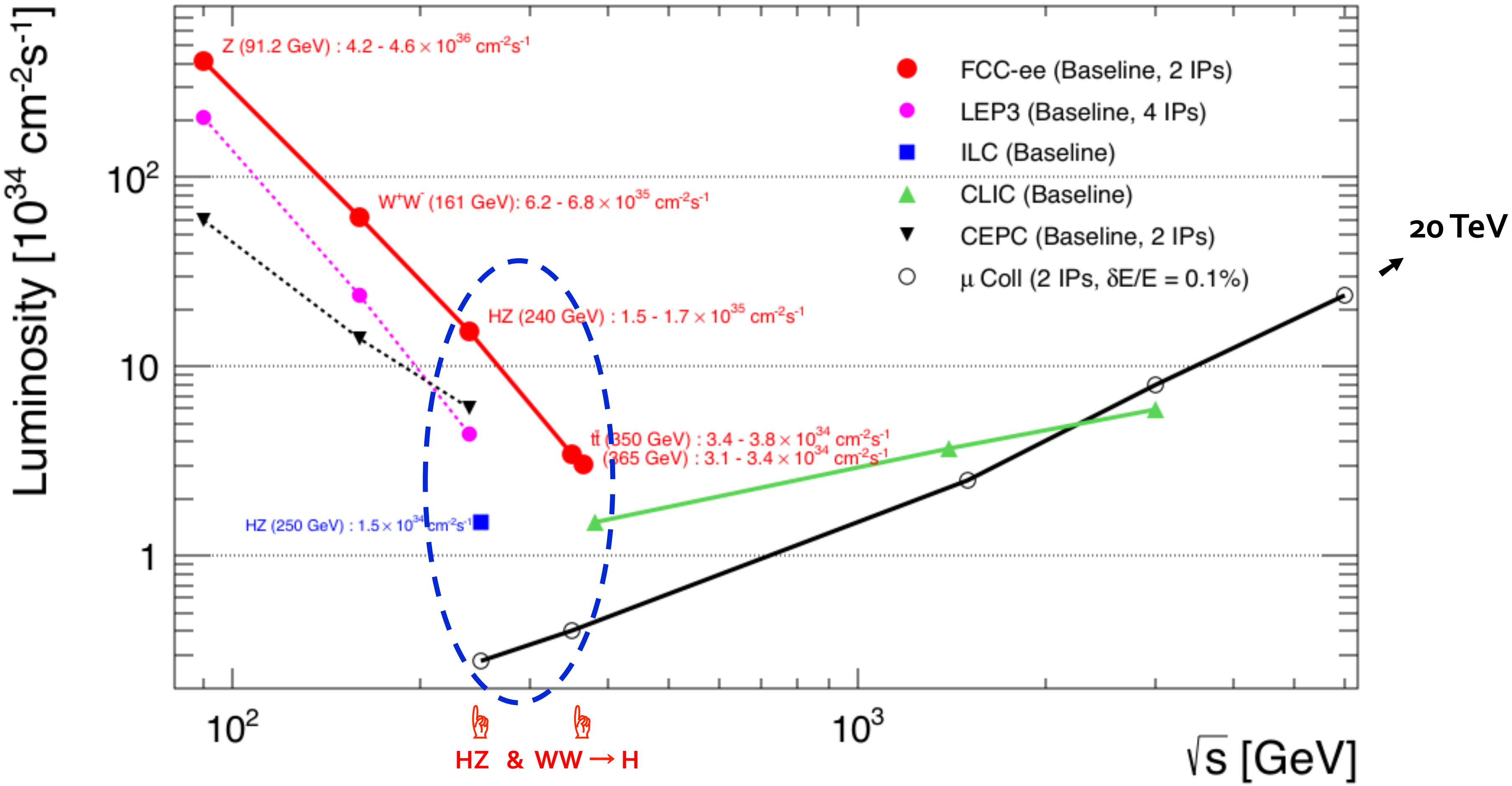
# Higgs Properties @ Circular Lepton Colliders

- **Outline**
  - Lepton colliders:  Overview
  - Muon circular Higgs factory at $\sqrt{s}$ = 125 GeV
  - Circular $e^+e^-$ circular colliders at the EW scale : FCC-ee, CEPC, LEP3
  - Access to the high energy frontier
  - Summary and outlook

Generic references
- Physics case of FCC-ee, arxiv:1308.6176 + FCC CDR
- Higgs program at CEPC, presentation from Manqi Ruan at IAS (2017)
- Muon collider Higgs factory for Snowmass 2013, arxiv:1308.2143
- Physics case for the 250 GeV ILC, arxiv:1710.07621, 1708.08912
- Higgs physics at CLIC, arxiv:1608.07538

# Lepton collider overview

- Six different lepton colliders cover the 240-380 GeV range (some partially)




- Significant differences in luminosity, access to the energy frontier, infrastructure, …

# Lepton collider overview (cont'd)

## In numbers

(+) With -80%/+30% polarization
(*) Infrastructure exists already

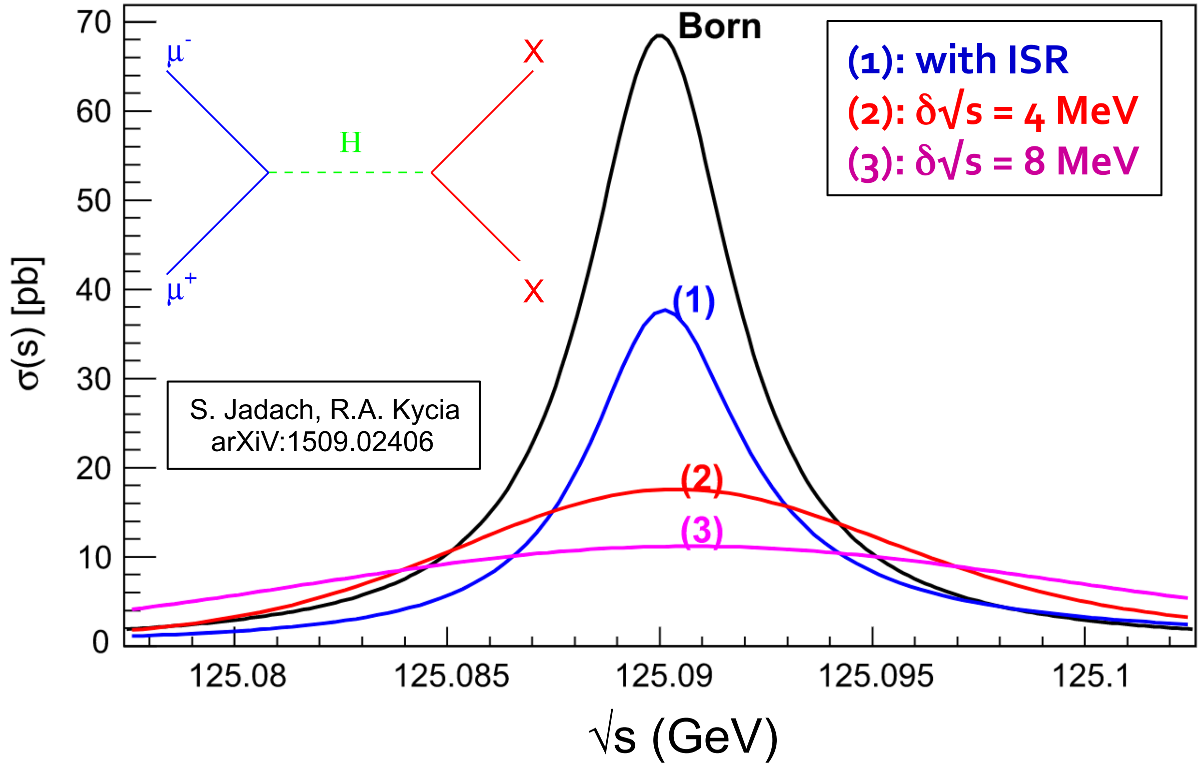
| Collider (#IPs) | Lumi ($10^{34}$ $cm^{-2}s^{-1}$) at … | | Time (yrs) for … | Length (km) | Energy frontier (TeV) |
|---|---|---|---|---|---|
| | 240-250 GeV | 350-380 GeV | $10^6$ HZ events | | |
| ILC (1) | 1.5 | – | $20^{(+)}$ | 23 | 0.35 – 0.5 (ILC?) |
| CLIC (1) | – | 1.5 | $30^{(+)}$ | 11 | 3 (CLIC) |
| LEP3 (4) | 4.4 | – | 10 | $27^{(*)}$ | 27 (HE-LHC) |
| CEPC (2) | 6.0 | – | 7 | 100 | 70 (SppC) |
| FCC-ee (2) | 17. | 3.4 | 2.5 | 100 | 100 (FCC-hh) |
| μColl (1-2) | 0.15 | 0.20 | 200 | 0.6 | 20 (FCC-μμ?) |

## General observations

- Higgs width and coupling precision ultimately limited by the $\sigma_{HZ}$ accuracy
  - Circular $e^+e^-$ colliders can get to 0.1% precision in a reasonable time
- Muons are leptons : muon colliders can do what $e^+e^-$ colliders can do
  - In much smaller rings (almost no synchrotron radiation because $m_\mu \sim 200\, m_e$)
  - But need much more time at low energy: 10 (100) times slower than linear (circular).

# Muon collider: s channel production at $\sqrt{s} \sim m_H$

- **Muons are heavy: $m_\mu/m_e \sim 200$**
  - Large direct coupling to the Higgs boson: $\sigma(\mu^+\mu^- \to H) \sim 40{,}000 \times \sigma(e^+e^- \to H) \sim 100\ \sigma_{HZ}$
  - Much less synchrotron radiation, hence potentially superb energy definition
    - Can/must reduce the beam energy spread from 0.1% to 0.004% ($\delta\sqrt{s} \sim \Gamma_H$)
      - ➨ Longitudinal ionization cooling further reduces luminosity: $2 - 8 \times 10^{31}\ cm^{-2}s^{-1}$




- $\sigma(\mu^+\mu^- \to H) \sim 18$ pb
  (ISR often forgotten: 38 pb)
- 200 – 800 $pb^{-1}$ / yr
- 3500 – 14000 Higgs / yr

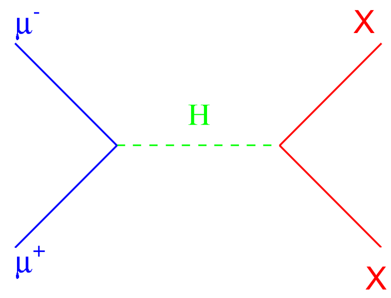
Reminder:
400,000 HZ/yr at FCC-ee
100,000 HZ/yr at LEP3
50,000 HZ/yr at ILC 250

**Not quite there, even within a factor 10**

# Scan of the Higgs resonance (1)

## Resonant production

$$\sigma(\mu^+\mu^- \to H \to XX) = \frac{4\pi\,\Gamma_H^2 Br(H\to\mu^+\mu^-)Br(H\to XX)}{(s-m_H^2)^2+\Gamma_H^2 m_H^2}$$




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

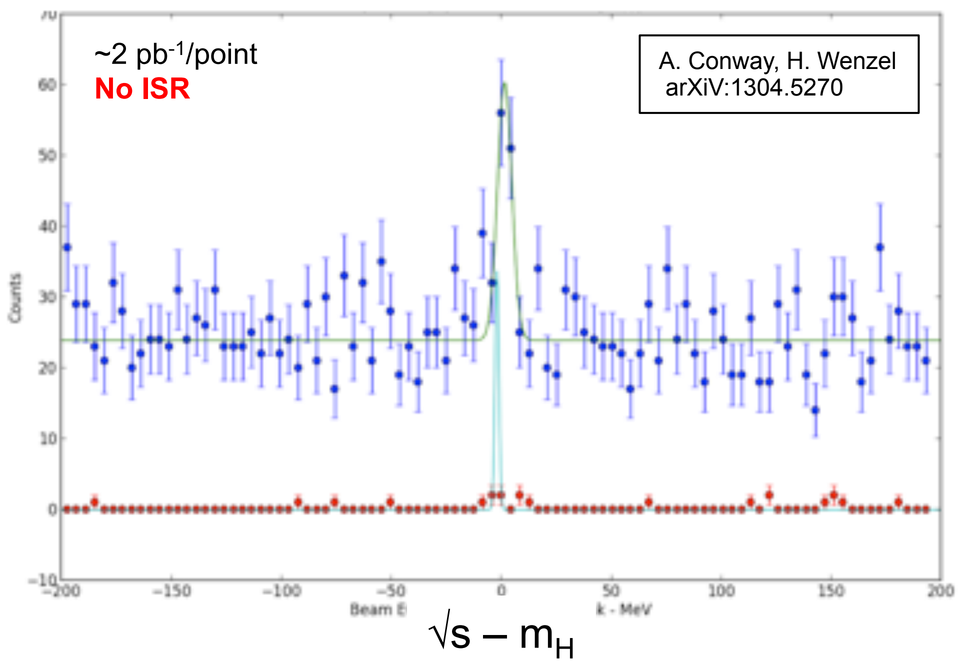
- Convoluted with
  - Beam energy spectrum
  - Initial state radiation (ignored in most studies)
- The measurement of the lineshape in any XX final state gives access to
  - The Higgs mass, $m_H$
  - The Higgs width, $\Gamma_H$
  - The product of the branching ratios $BR(H \to \mu\mu)\times BR(H \to XX)$
    - ➨ And $BR(H \to \mu\mu)$ with the inclusive lineshape if $BR(H\to invis)$ is neglected
- Note: only one IP in a very small ring (R = 50m)

# Scan of the Higgs resonance (2)

- **First, need to find the resonance ($\Gamma_H$ = 4.2 MeV ~ $\delta\sqrt{s}$)**
  - Today, $m_H$ is known to ±250 MeV with gg → H → γγ, ZZ at LHC
    - Will improve to ±100 MeV with full stat
  - Scan the $\sqrt{s}$ region of interest (±300 MeV ) in optimal bins of 4.2 MeV
    - Count the number of bb and semi-leptonic WW events (see next slides)
  - About 4 $pb^{-1}$ / point required for a 5σ significance

  - Total luminosity needed for 5σ
    - Up to 150 points in ±300 MeV
      - Up to 600 $pb^{-1}$
    - ~ 1.5 yr at $4\times10^{31}$ $cm^{-2}s^{-1}$
      - Used for commissioning

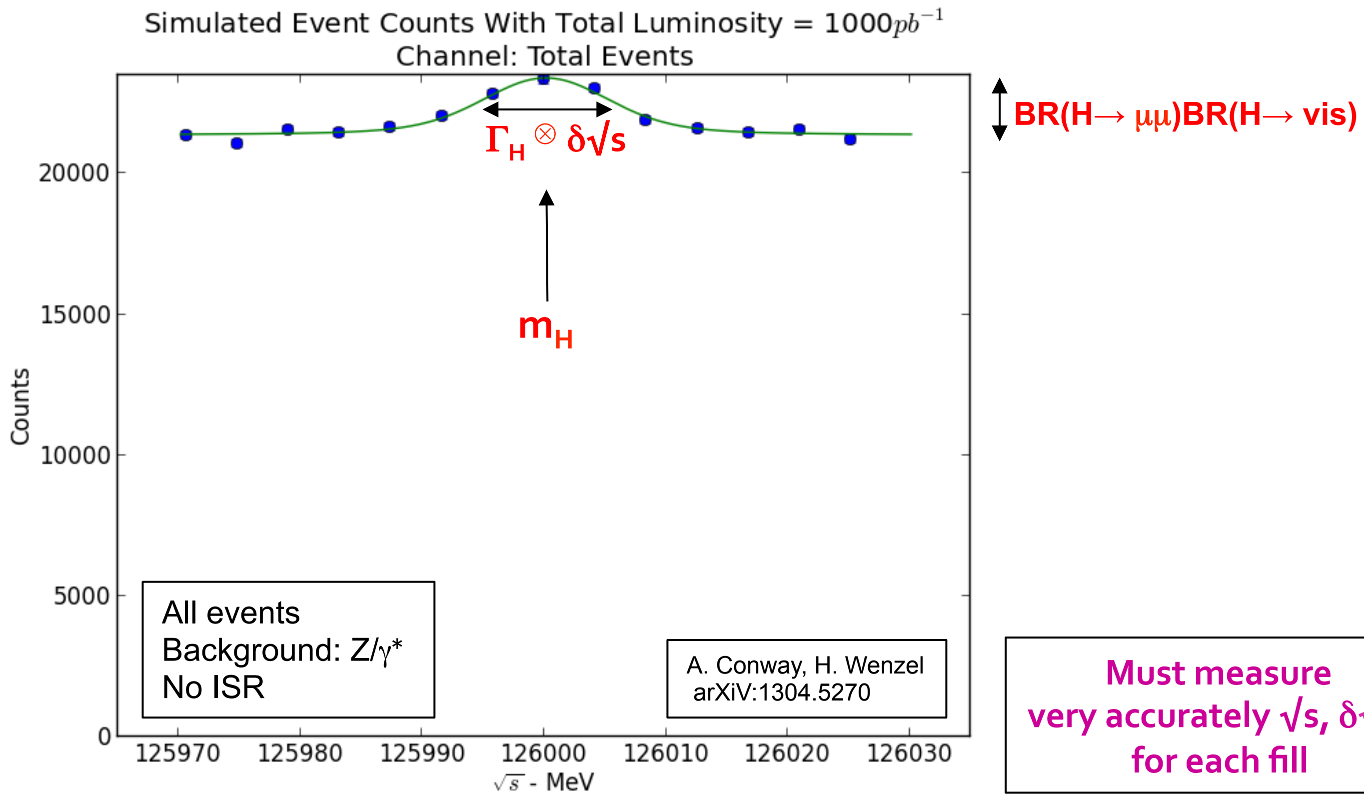
  - Can also be shorter
    - Either with some luck
    - Or after an $e^+e^-$ collider
      - $m_H$ known to 10-20 MeV



# Scan of the SM Higgs resonance (3)

- Then, proceed with a multi-point scan around the peak
  - Example: 14 points with 70 $pb^{-1}$ / point around $m_H$ (about one year at $8\times10^{31}$ $cm^{-2}s^{-1}$)
    - Count all events (except invisible decays of H or Z)

Must measure Luminosity

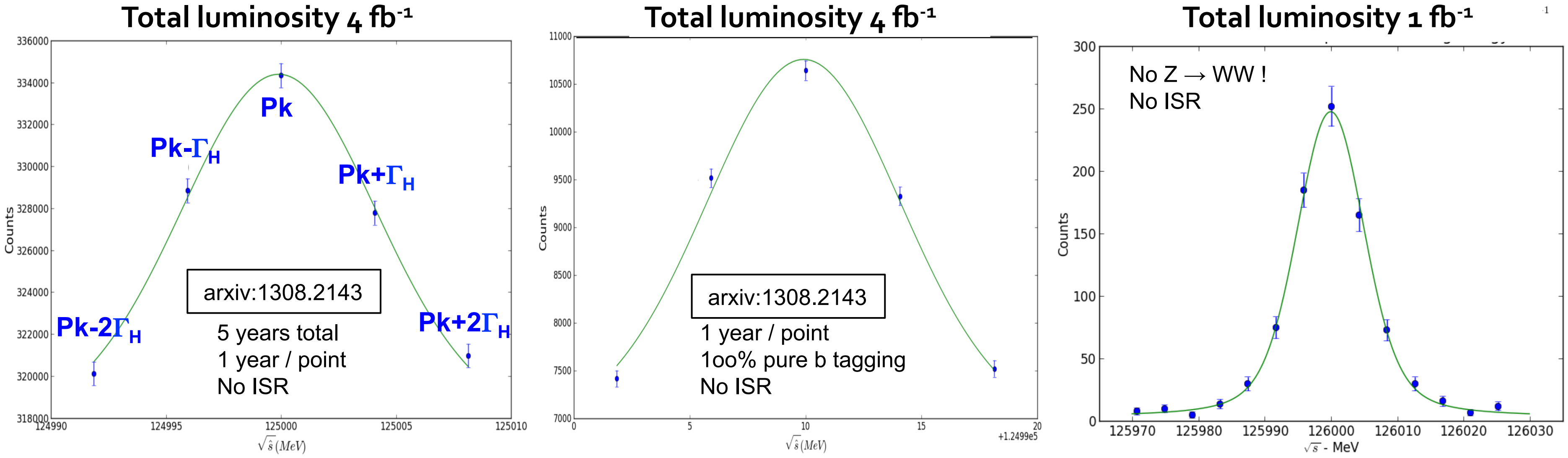



Must measure very accurately √s, δ√s, for each fill

Need reproducible √s at each "shot" for optimal use of luminosity

# Scan of the SM Higgs resonance (4)

- Five points suffice to determine $m_H$, $\Gamma_H$, $BR_{\mu\mu}BR_{XX}$, and background level
  - $H \rightarrow$ visible    $H \rightarrow bb$    $H \rightarrow WW \rightarrow l\nu qq$




- Fit to BW ⊗ Gaussian + linear background, with perfect knowledge of $\sqrt{s}$, $\delta\sqrt{s}$, and L
  - After 5 years of running at $8\times10^{31}$ cm$^{-2}$s$^{-1}$ and 1 year at half luminosity

| Obs. | $m_H$ (MeV) | $\Gamma_H$ (MeV) | $BR_{\mu\mu}BR_{vis}$ | $BR_{\mu\mu}BR_{bb}$ | $BR_{\mu\mu}BR_{WW}$ | $BR_{\mu\mu}BR_{\tau\tau}$ |
|---|---|---|---|---|---|---|
| Precision | 0.1 | 0.25 | 4% | 2.5% | 3% | 10% |

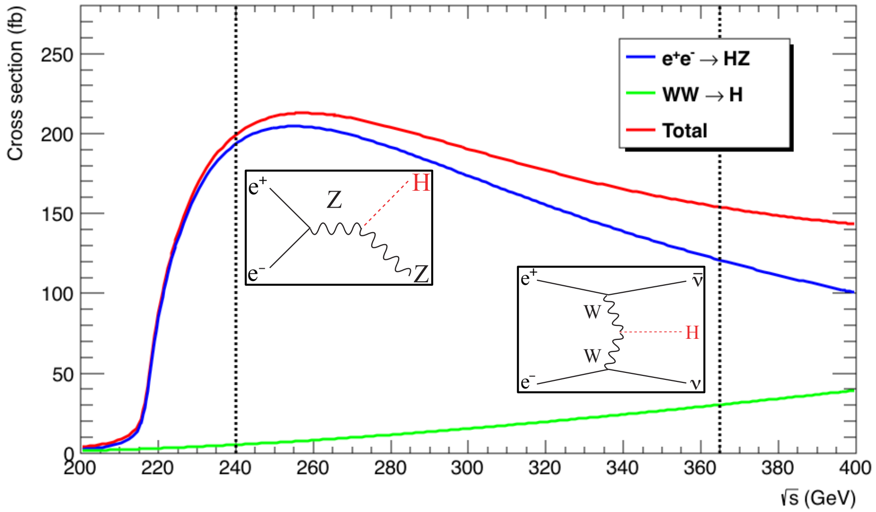
  - Note: $\Gamma_H$ = 4.2 MeV ⇒ 0.25 MeV precision corresponds to 6% relative.

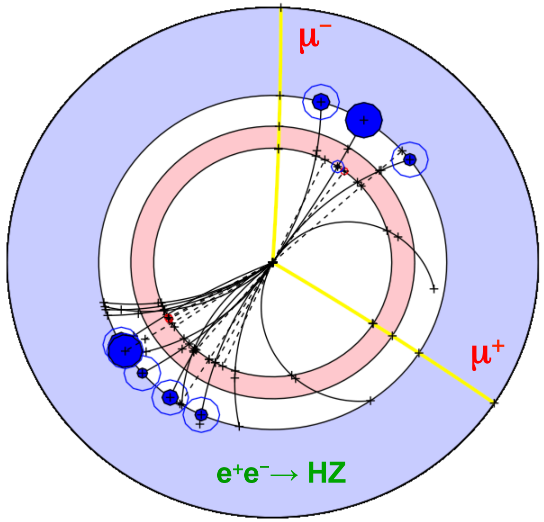
# Practical considerations

- The luminosity and bunch crossing frequency are such that
  - Pileup won't be a problem : situation better than LHC / CLIC / FCC-hh
- The main detector background come from $\mu \to e\nu_e\nu_\mu$ decays
  - $10^9$ $e^\pm$ per turn : lots of photons and neutrons shielded by 10-15° tungsten cones
    - Much work to do : situation worse than $e^+e^-$ colliders, but not than HL-LHC
    - Background not included in the studies presented in these slides
- Luminosity measured with 1% precision: low angle Mhamha $\mu\mu \to \mu\mu$ ?
  - Measurement to be done through the aforementioned shielding
    - Needs to be demonstrated
- Measurements of $m_H$ and $\Gamma_H$ requires excellent energy calibration
  - Muon natural polarization and decay provide beam energy and beam energy spread
    - With adequate precision (limited by $g_\mu$-2) : see backup slides
- Initial state radiation reduces the signal by a factor 2
  - … and increases the background in turn (radiative return towards the Z)
- $\mu^+\mu^- \to Z / \gamma^*$ is not always the dominant background
  - e.g. $\mu^+\mu^- \to \gamma\gamma$ is 1000 times larger than $\mu^+\mu^- \to H \to \gamma\gamma$
- Result of the coupling fit given together with that of $e^+e^-$ colliders
  - Only few couplings, need assumptions, 5% level precision to be expected (6% on $\Gamma_H$)

# Circular $e^+e^-$ colliders: FCC-ee, CEPC, LEP3

- **Basic measurements similar for all $e^+e^-$ colliders**
  - Some differences in experimental conditions




- $e^+e^- \rightarrow HZ$ at $\sqrt{s}$ = 240-250 GeV : Higgs boson are tagged with a Z and $m_{Recoil} = m_H$
  - Measure $\sigma_{HZ}$ ($\propto g_{HZ}^2$) independently of H decay: absolute determination of $g_{HZ}$
  - Measure $\sigma_{HZ} \times BR(H \rightarrow \text{invisible})$ and many exclusive decays $\sigma_{HZ} \times BR(H \rightarrow XX)$
  - Infer Higgs width $\Gamma_H$ from $\sigma_{HZ} \times BR(H \rightarrow ZZ)$ ($\propto g_{HZ}^4/\Gamma_H$)
  - Fit couplings $g_{HX}$ from $BR(H \rightarrow XX)$ and $\Gamma_H$ in a model-independent manner
- $e^+e^- \rightarrow HZ$ completed with WW fusion at $\sqrt{s}$ = 350-365 GeV at FCC-ee
  - Improves all precisions, especially on $g_{HW}$ and $\Gamma_H$
  - First glance at top Yukawa coupling $\lambda_t$ and Higgs self coupling $\lambda_H$ (next slides)

# Typical measurement precision (FCC-ee)

- **Detector performance similar at all colliders (SiD, CLIC, CLD, …)**
  - Statistical accuracy expected to evolve like $1/\sqrt{N}$, typically %-level or below for FCC-ee

| $\sqrt{s}$ (L) | 240 GeV (5 $ab^{-1}$) | | 365 GeV (1.5 $ab^{-1}$) | |
|---|---|---|---|---|
| BR × σ (%) | HZ | ννH | HZ | ννH |
| H → any | 0.5 | | 0.9 | |
| H → bb | 0.3 | 3.1 | 0.5 | 0.9 |
| H → cc | 2.2 | | 6.5 | 10 |
| H → gg | 1.9 | | 3.5 | 4.5 |
| H → WW | 1.2 | | 2.6 | 3.0 |
| H → ZZ | 4.4 | | 12 | 10 |
| H → ττ | 0.9 | | 1.8 | 8 |
| H → γγ | 9.0 | | 18 | 22 |
| H → μμ | 19 | | 40 | |
| H → inv. | < 0.3 | | < 0.6 | |

  - Experimental uncertainties much smaller ~ few $10^{-4}$ (regular high-luminosity Z runs)

Specific to circular colliders

# Result of the coupling (a.k.a. κ) fit

- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

| Collider | μ $Coll_{125}$ | $ILC_{250}$ | $CLIC_{380}$ | $LEP3_{240}$ | $CEPC_{250}$ | FCC-$ee_{240}$ | FCC-$ee_{365}$ | HL-LHC |
|---|---|---|---|---|---|---|---|---|
| Years | 6 | 15 | 7 | 6 | 7 | 3 | +4 | 25 |
| Lumi ($ab^{-1}$) | 0.005 | 2 | 0.5 | 3 | 5 | 5 | +1.5 | 3 |
| $\delta m_H$ (MeV) | 0.1 | 14 | 110 | 10 | 5 | 7 | 6 | 100 |
| $\delta\Gamma_H / \Gamma_H$(%) | 6.1 | 3.8 | 6.3 | 3.7 | 2.6 | 2.8 | 1.6 | 50 |
| $\delta g_{Hb} / g_{Hb}$ (%) | 3.8 | 1.8 | 2.8 | 1.8 | 1.3 | 1.4 | 0.68 | 8.2 |
| $\delta g_{HW} / g_{HW}$ (%) | 3.9 | 1.7 | 1.3 | 1.7 | 1.2 | 1.3 | 0.47 | 3.5 |
| $\delta g_{H\tau} / g_{H\tau}$(%) | 6.2 | 1.9 | 4.2 | 1.9 | 1.4 | 1.4 | 0.80 | 6.5 |
| $\delta g_{H\gamma} / g_{H\gamma}$ (%) | n.a. | 6.4 | n.a. | 6.1 | 4.7 | 4.7 | 3.8 | 3.6 |
| $\delta g_{H\mu} / g_{H\mu}$ (%) | 3.6 | 13 | n.a. | 12 | 6.2 | 9.6 | 8.6 | 5.0 |
| $\delta g_{HZ} / g_{HZ}$ (%) | n.a. | 0.35 | 0.80 | 0.32 | 0.25 | 0.25 | 0.22 | 3.5 |
| $\delta g_{Hc} / g_{Hc}$ (%) | n.a. | 2.3 | 6.8 | 2.3 | 1.8 | 1.8 | 1.2 | SM |
| $\delta g_{Hg} / g_{Hg}$ (%) | n.a. | 2.2 | 3.8 | 2.1 | 1.4 | 1.7 | 1.0 | 3.9 |
| $Br_{invis}$ $(\%)_{95\%CL}$ | SM | < 0.3 | < 0.6 | < 0.5 | < 0.15 | < 0.3 | < 0.25 | < 3 |
| $BR_{EXO}$ $(\%)_{95\%CL}$ | SM | < 1.8 | < 3.0 | < 1.6 | < 1.2 | < 1.2 | < 1.1 | SM |

(*) **Green = best**
**Red = worst**

# General considerations

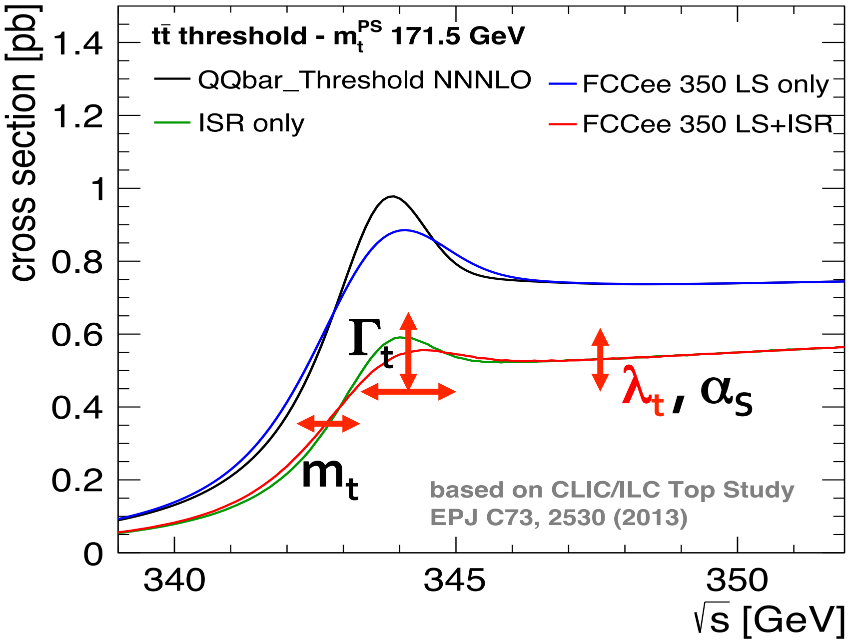
- **Despite common wisdom, $\Gamma_H$ is not best measured with a muon collider**
  - It would take 15-20 more luminosity to get to the FCC-ee level
    - Rubbia: use of parametric-resonance ionization cooling (PIC)?
      - ➨ May bring a factor 5 on paper – full experimental demonstration mandatory
  - A muon collider would allow to identify two almost degenerate Higgses at 125 GeV

Y. Derbenev et al arxiv:1205.3476

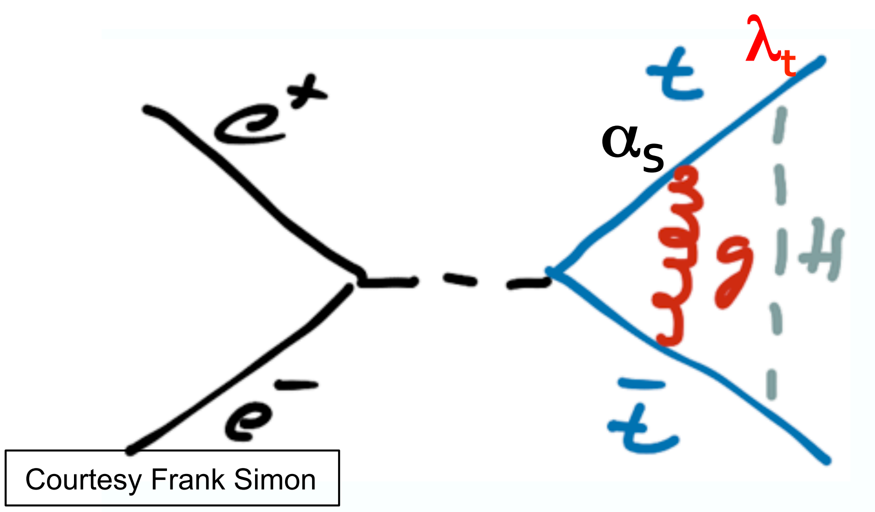
- **The $\kappa$ fit is almost model-independent for $e^+e^-$ colliders, but …**
  - Assumes SM value for the Higgs self coupling $\lambda_H$ (see next slides)
  - Assumes pure scalar state, no mixing, no CP violation (could change efficiencies)
  - Assumes that SM cross section predictions will significantly improve (×5)
- **15 years of ILC@250 lead to similar precision**
  - As 6 years of LEP3@240, at a ~ five times smaller cost
  - As 2 years of FCC-ee@240 GeV
- **The FCC-ee provides the best precision on all couplings (except $g_{H\mu}$)**
  - The FCC-ee improves model-dependent HL-LHC precisions by a factor 10
  - The add'l FCC-ee run at $\sqrt{s}$ = 365 GeV significantly helps : $\delta\Gamma_H / \Gamma_H$ ~ 1.6%
  - CEPC and LEP3 precision limited by running only at 240-250 GeV
    - Note: CLIC precision similarly limited by running only at 380 GeV
      - ➨ Access to high energy frontier : see next slides

# Additional value of FCC-ee (1)

- The FCC-ee operation model includes a short run (0.2 $ab^{-1}$) at $\sqrt{s}$ ~ 350 GeV
  - Eight-point scan, primarily to measure the top mass and width, but …



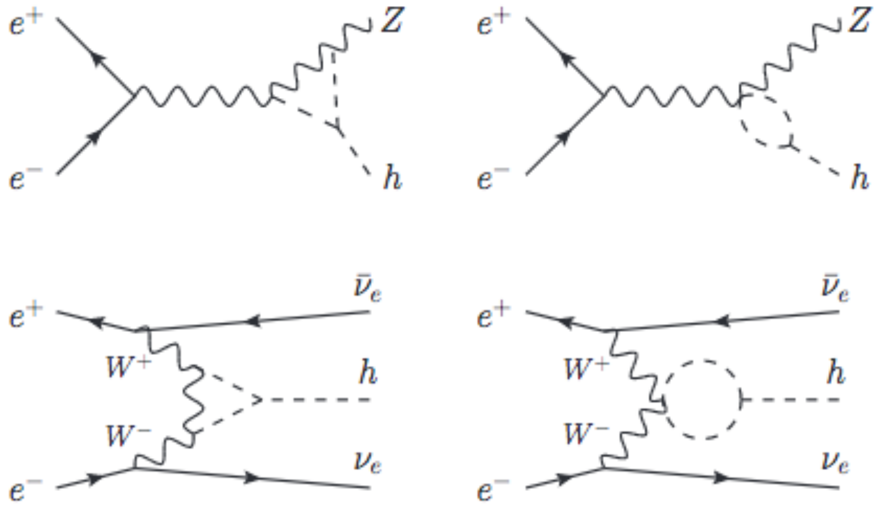

Small, correlated, sensitivity to $\lambda_t$ and $\alpha_S$

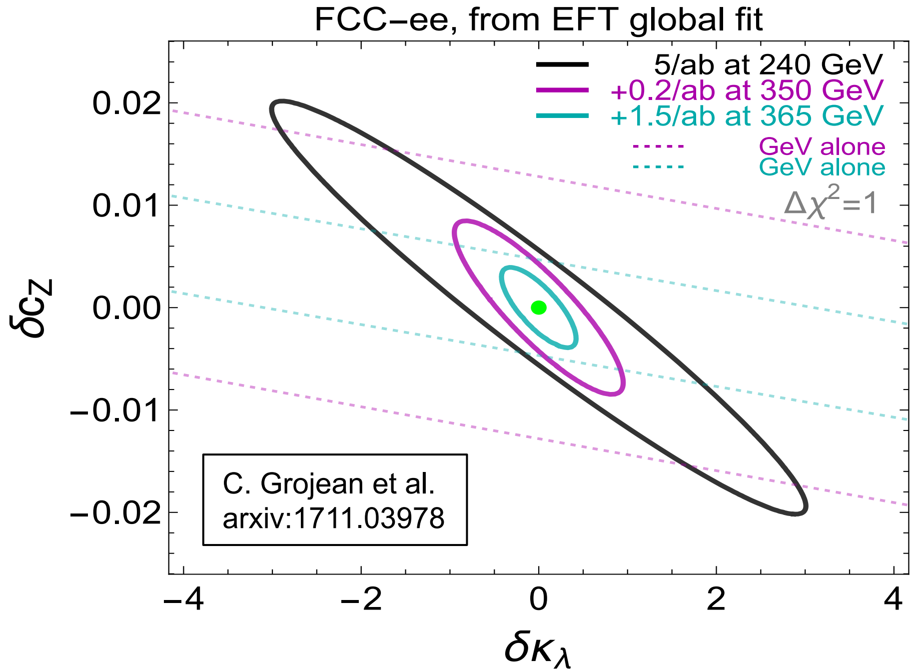



- The strong coupling constant will be measured with precision at FCC-ee ($\delta\alpha_S$ ~ 0.0001)
  - From the ratio of hadronic to leptonic branching ratios of the Z and the W
    - ➨ FCC-ee synergy between the Z pole, the WW threshold, and the top threshold
- Which in turn allows FCC-ee to infer the top Yukawa coupling $\lambda_t$ with a ~10% precision
  - Current uncertainty from higher orders ($N^4LO$) ~ 10% a – will decrease in future

# Additional value of FCC-ee (2)

- $\sqrt{s}$ dependence of the "effective" $g_{HZ}$ and $g_{HW}$ to the Higgs self-coupling
  - Accessible from the high-precision runs at 240, (350), and 365 GeV
    - Arising from Higgs-triangle and -loop diagrams

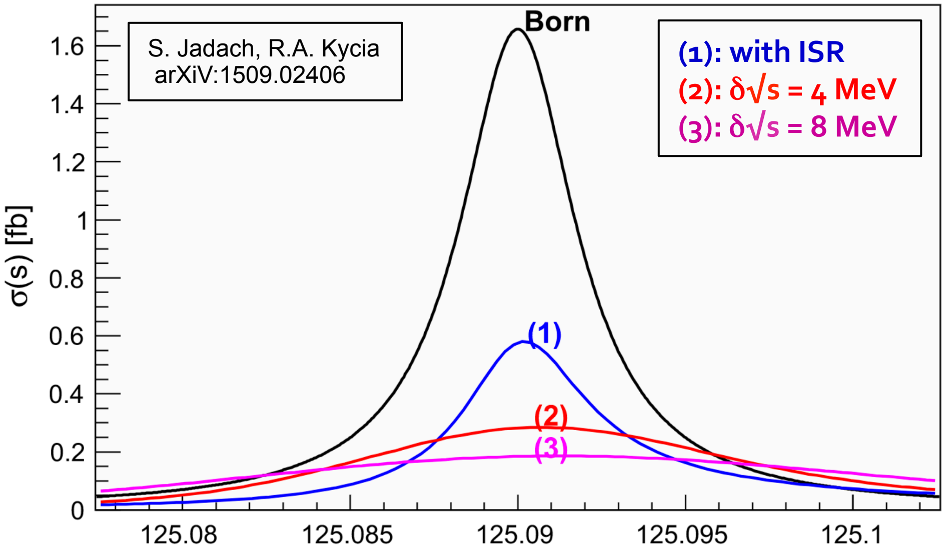



- Higgs self-coupling precision at FCC-ee : ~40%
  - Improved to ~20% if $g_{HZ}$ is fixed to its SM value
- Unique FCC-ee synergy between the runs at 240 and 365 GeV
  - Calls for the highest luminosity (4IP's ? Longer runs if schedule allows ?)

# Additional value of FCC-ee (3)

- **If schedule allows or calls for a prolongation of FCC-ee**
  - Few years at $\sqrt{s}$ = 125.09 GeV with high luminosity is an interesting addition
    - For s-channel production $e^+e^- \rightarrow H$ (a la muon collider, with $10^4$ higher lumi )




- **FCC-ee monochromatization setups**
  - Default: $\delta\sqrt{s}$ = 100 MeV, 25 $ab^{-1}$ / year
    - No visible resonance
  - Option 1: $\delta\sqrt{s}$ = 10 MeV, 7 $ab^{-1}$ / year
    - $\sigma(e^+e^- \rightarrow H) \sim$ 100 ab
  - Option 2: $\delta\sqrt{s}$ = 6 MeV, 2 $ab^{-1}$ / year
    - $\sigma(e^+e^- \rightarrow H) \sim$ 250 ab
  - Backgrounds much larger than signal
    - $e^+e^- \rightarrow q\bar{q}, \tau\tau, WW^*, ZZ^*, \gamma\gamma, \ldots$

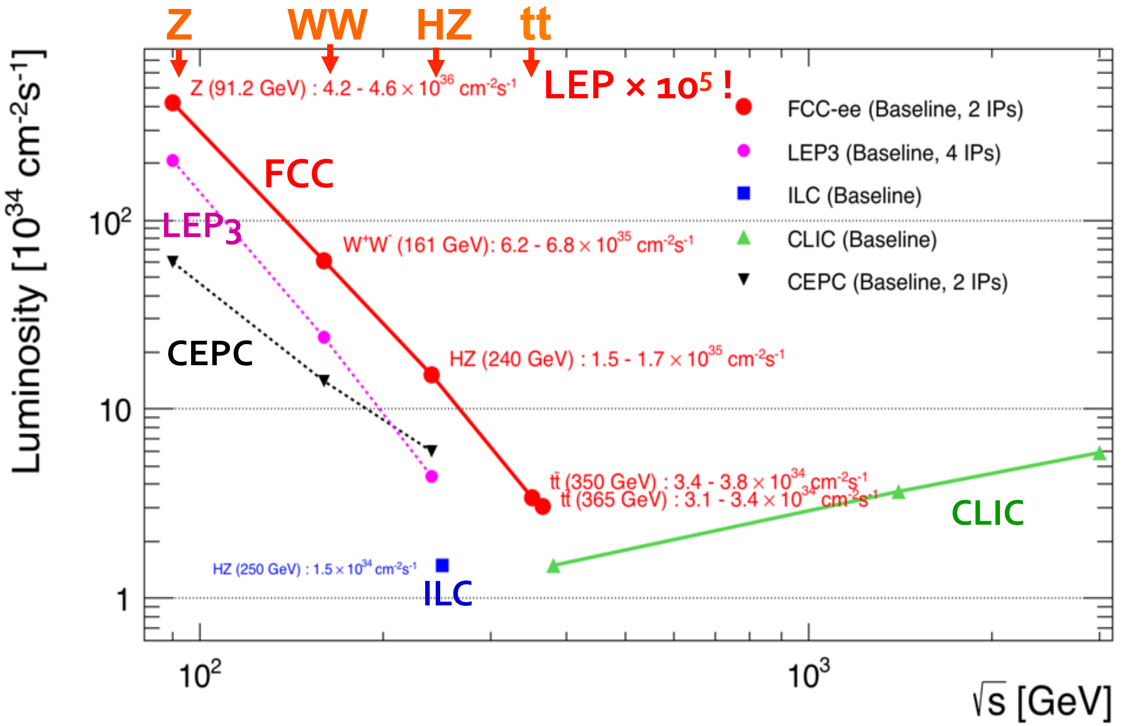
  - Expected signal significance of ~0.4σ / year in both option 1 and option 2
    - Set a electron Yukawa coupling upper limit : $\kappa_e < 2.5$ @ 95% C.L.
      - ➨ Constrain CP violating Higgs-top couplings from EDM measurements
    - Reaches SM sensitivity after five years
  - FCC-ee unique opportunity to constrain first generation Yukawa's

# The FCC-ee is much more than a Higgs factory

https://cds.cern.ch/record/1567258/

- Meet the recommendation from ESPP 2013

> There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.




- Ultimate precision @ FCC-ee :
  - 100 000 Z / second (!)
    - 1 Z / second at LEP
  - 10 000 W / hour
    - 20 000 W in 5 years at LEP
  - 1 500 Higgs bosons / day
    - 10 times more than ILC
  - 1 500 top quarks / day

... in each detector
  - In a clean exp'tal environment:
    - no pileup; beam backgrounds under control; E,p constraints

- The FCC-ee unique discovery potential is multiplied by the presence of the four heavy particles of the standard model in its energy range

# FCC-ee: Luminosity goals and operation model

- **The FCC-ee physics goals require <u>at least</u>**
  - 150 ab$^{-1}$ at and around the Z pole ($\sqrt{s}$~91.2 GeV)
  - 10 ab$^{-1}$ at the WW threshold ($\sqrt{s}$~161 GeV)
  - 5 ab$^{-1}$ at the HZ cross section maximum ($\sqrt{s}$~240 GeV)
  - 0.2 ab$^{-1}$ at the top threshold ($\sqrt{s}$~350 GeV) and 1.5 ab$^{-1}$ above ($\sqrt{s}$~365 GeV)

> $5\times10^{12}$ Z
> $10^8$ WW
> $10^6$ HZ
> $10^6$ $t\bar{t}$

- **Operation model (with 10% add'l safety margin) with two IPs**
  - 200 scheduled physics days per year (7 months – 13 days of MD / stops)
  - Hübner factor ~ 0.75 (lower than achieved with KEKB top-up injection, ~0.8)
  - Half the design luminosity in the first years of Z operation (~LEP1) and top operation
  - Machine configuration between WPs changed during Winter shutdowns (3 months/year)

| Working point | Z, years 1-2 | Z, later | WW | HZ | $t\bar{t}$ threshold | 365 GeV |
|---|---|---|---|---|---|---|
| Lumi/IP ($10^{34}$ cm$^{-2}$s$^{-1}$) | 100 | 200 | 31 | 7.5 | 0.85 | 1.5 |
| Lumi/year (2 IP) | 26 ab$^{-1}$ | 52 ab$^{-1}$ | 8.1 ab$^{-1}$ | 1.95 ab$^{-1}$ | 0.22 ab$^{-1}$ | 0.39 ab$^{-1}$ |
| Physics goal | 150 | | 10 | 5 | 0.2 | 1.5 |
| Run time (year) | 2 | 2 | 1 | 3 | 1 | 4 |

- **Total running time : 13 (+1) years (~ LEP)**

Longer shutdowns: install 196 RF CMs
LEP Record: 32 in one shutdown !

# FCC-ee: Discovery potential in a nutshell

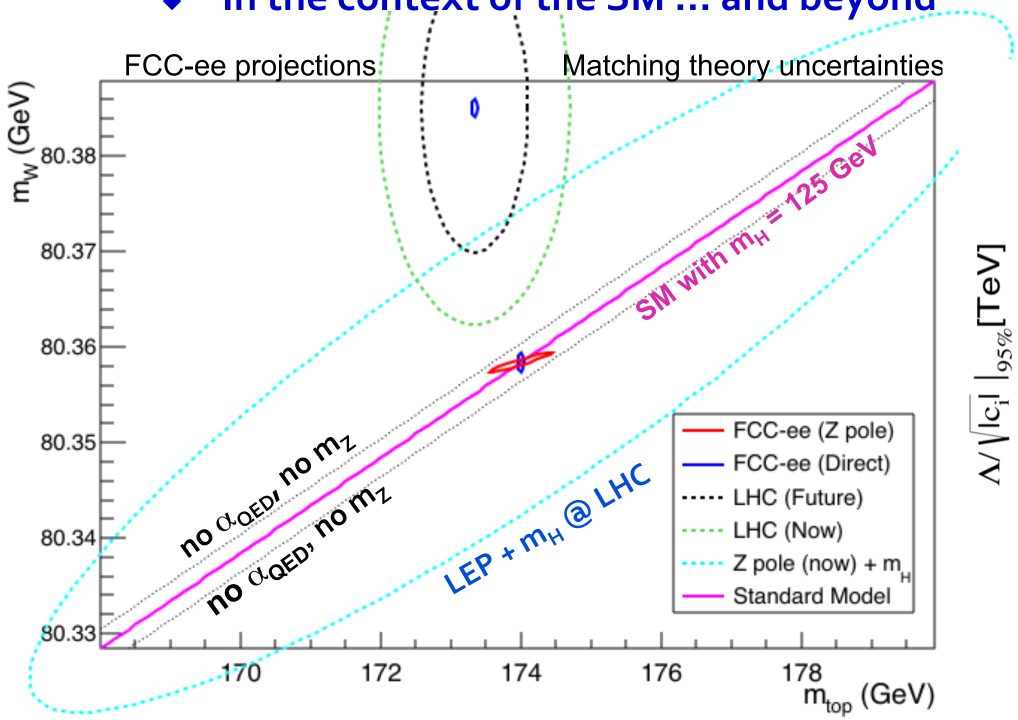
- **EXPLORE the 10-100 TeV energy scale**
  - With precision measurements of the properties of the Z, W, Higgs, and top particles
    - 20-50 fold improved precision on ALL electroweak observables (EWPO)
      - ➨ $m_Z$, $\Gamma_Z$, $m_W$, $m_{top}$, $\sin^2\theta_w^{eff}$, $R_b$, $\alpha_{QED}(m_z)$, $\alpha_s(m_z)$, top EW couplings …
    - 10 fold more precise Higgs couplings measurements
      - ➨ Break model dependence with $\Gamma_H$ accurate measurement
- **DISCOVER that the Standard Model does not fit**
  - Then extra weakly-coupled and Higgs-coupled particles exist
  - Understand the underlying physics through effects via loops
- **DISCOVER a violation of flavour conservation / universality**
  - e.g., with $B^0 \to K^{*0}\tau^+\tau^-$ or $B_S \to \tau^+\tau^-$ in $10^{12}$ $b\bar{b}$ events
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DISCOVER very weakly coupled particles in the 5-100 GeV mass range**
  - Such as right-handed neutrinos, dark photons, …
    - May help understand dark matter, universe baryon asymmetry, neutrino masses

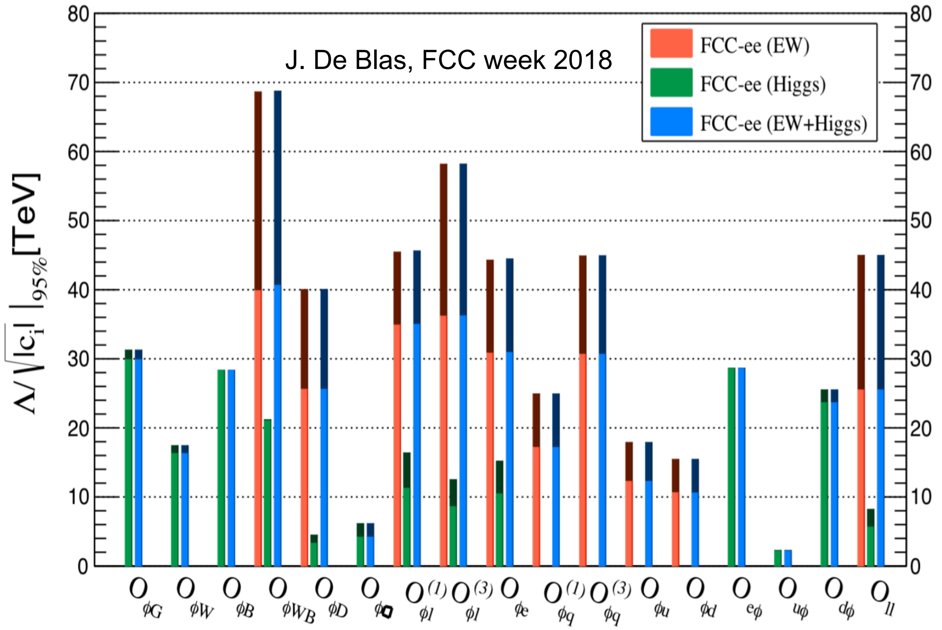
**Today, we do not know how nature will surprise us: other things may come up with FCC-ee**

# FCC-ee precision : Sensitivity to new physics

- **Combining all FCC-ee EW measurements**
  - In the context of the SM … and beyond

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i$$




**Requires 10-fold improved theory calculations**

- New physics: blue and red ellipses may not overlap
  - Or even better, data may not fit to the SM
- All ingredients are needed: $m_Z$, $\Gamma_Z$, $m_W$, $m_{top}$, $\sin^2\theta_W^{eff}$, $R_b$, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, $g_{HX}$, …

**Sensitivity 10-100 TeV**

# … and whose energy can be upgraded

- All EW-scale $e^+e^-$ projects provide access to the high energy frontier
  - Either using the same infrastructure (circular: pp) or extending it (linear: $e^+e^-$)
    - Which in turn provides direct measurement of top Yukawa and Higgs self couplings

| Collider → Energy frontier (TeV) | $\delta\lambda_t/\lambda_t$ | $\delta\lambda_H/\lambda_H$ | |
|---|---|---|---|
| $ILC_{250}$ → ILC : 0.5 (?) | X → 6% | X → 27% | arXiv:1506.05992 |
| $CLIC_{380}$ → CLIC : 1.4 – 3 | 15% → 4% | X → 19%(**) | arXiv:1608.07538 |
| $FCC\text{-}ee_{90\text{-}365}$ → FCC-hh : 100 | 10% → 0.4%(*) | 40% → 5% | FCC week 2018 |

(*) LHC precision on $\lambda_t$ today : ± 10%, after HL-LHC : ± 4.2%

(**) Unpublished 10-16% from Philip's slides

The SppC (70 TeV pp colliders in the CEPC tunnel) numbers are not available

  - The 100 TeV energy frontier of FCC-hh significantly pays off
    - FCC-hh is helped by the FCC-ee precision: ttZ couplings for $\lambda_\tau$, Higgs BR's
    - FCC-hh helps back FCC-ee model-independence (no assumption for $\lambda_H$)

**The FCC-ee complies best with the ESSP2013 statement on $e^+e^-$ colliders**

# Towards FCC-μμ ? (1)

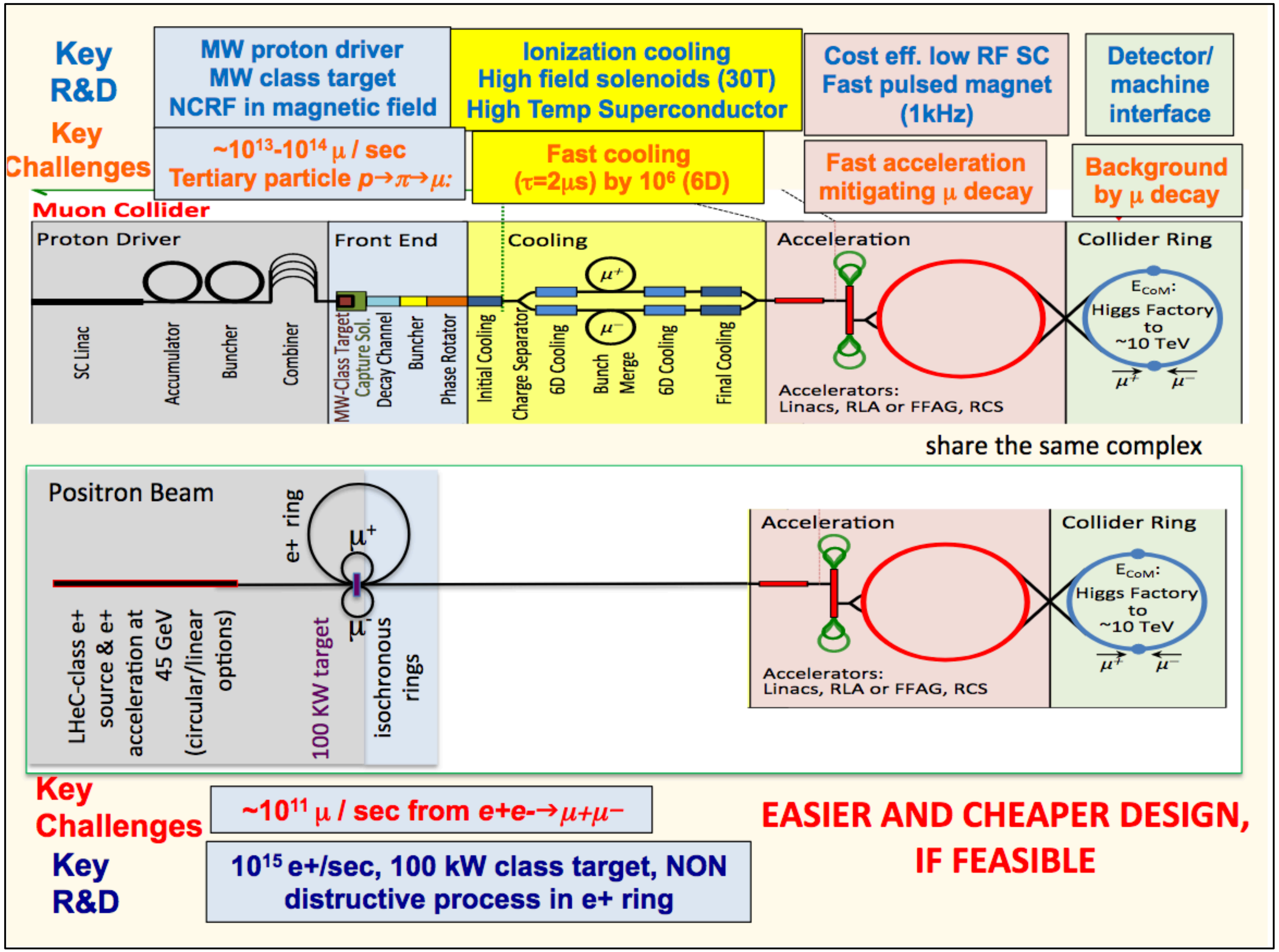
- Recently revived approach to muon collider : LEMMA

D. Kaplan, T. Hart, P. Allport
arXiV:0707.1546

- MAP
- LEMMA

M. Antonelli et al.
arXiV:1509.04454

Mario Antonelli
FCC Week 2016



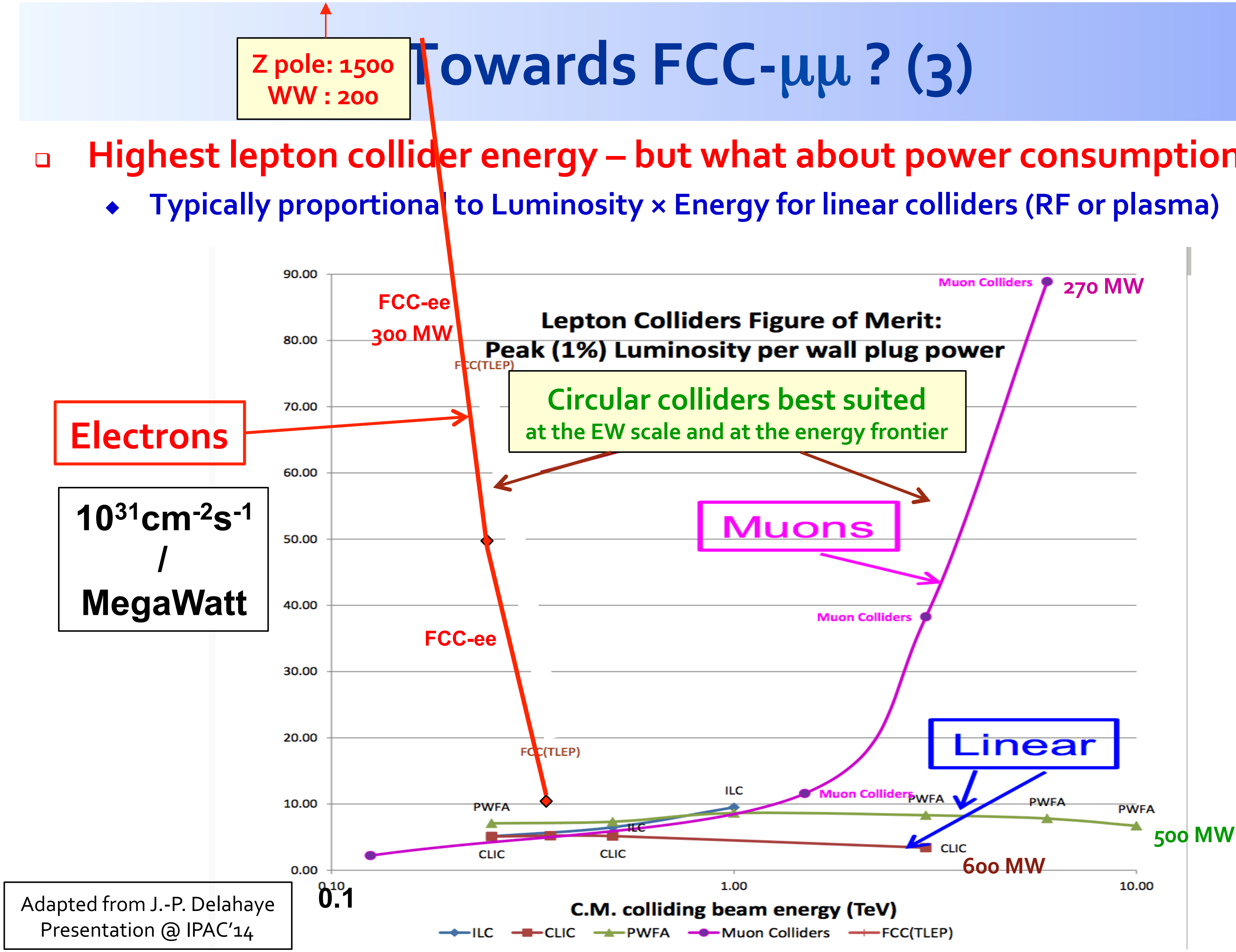
# Towards FCC-μμ ? (2)

- **Recently revived approach to muon collider : LEMMA**
  - Produce low emittance muon beams with $e^+e^- \rightarrow \mu^+\mu^-$ at production threshold
  - The threshold $e^+$ energy for $\mu^+\mu^-$ production on a thin target ($e^-$) is … 43.7 GeV !
    - Can use the FCC-ee/LEP3 $e^+$ ring / booster as internal accumulation and target ring
      - ➨ Requires an $e^+$ source at least 20 times more intense than FCC-ee / CLIC
        - Intense $e^+$ source and polarized $e^-$ target feasibility to be demonstrated
    - All muons are produced with ~ the same energy, in the same direction
      - ➨ No longitudinal muon cooling needed at high $\sqrt{s}$ ($\Delta E/E$ ~ 0.07% at $\sqrt{s}$ = 6 TeV)
      - ➨ Unfortunately not better suited for a 125 GeV Higgs factory ($\Delta E/E$ ~ 3%)
        - Would still require a three-order of magnitude longitudinal cooling
    - Transverse emittance 500 × smaller than with protons on target + cooling (MAP)
      - ➨ Two orders of magnitude less muons needed for same luminosity as MAP
        - Lower background from $e^\pm$ in the detector (from muon decays)
        - Lower radiation hazard from neutrino interactions at the surface
      - ➨ MAP was limited to $\sqrt{s}$ = 4 TeV to cope with regulations on CERN site

**LEMMA could go to $\sqrt{s}$ > 20 TeV (in the FCC or LEP tunnel) within the same regulations**

# Towards FCC-μμ ? (3)

- Highest lepton collider energy – but what about power consumption ?
  - Typically proportional to Luminosity × Energy for linear colliders (RF or plasma)



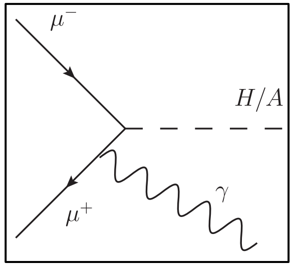

Adapted from J.-P. Delahaye Presentation @ IPAC'14

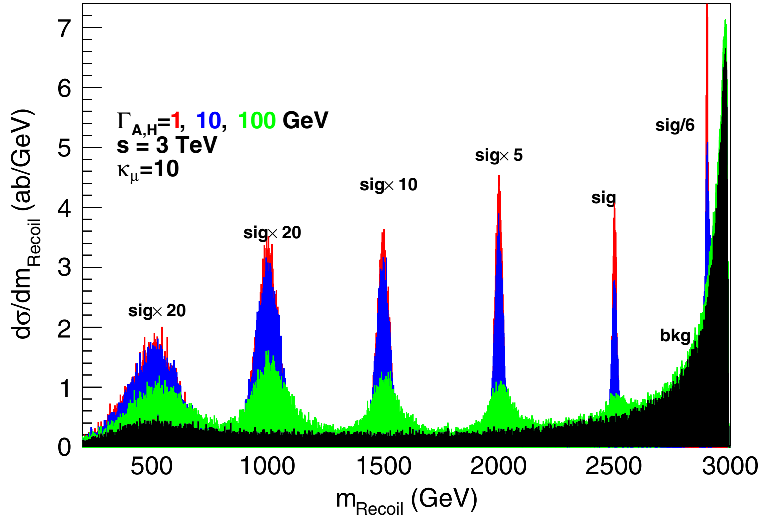
# Additional Higgs bosons at FCC-μμ

- **Automatic mass scan with radiative returns in μμ collisions**

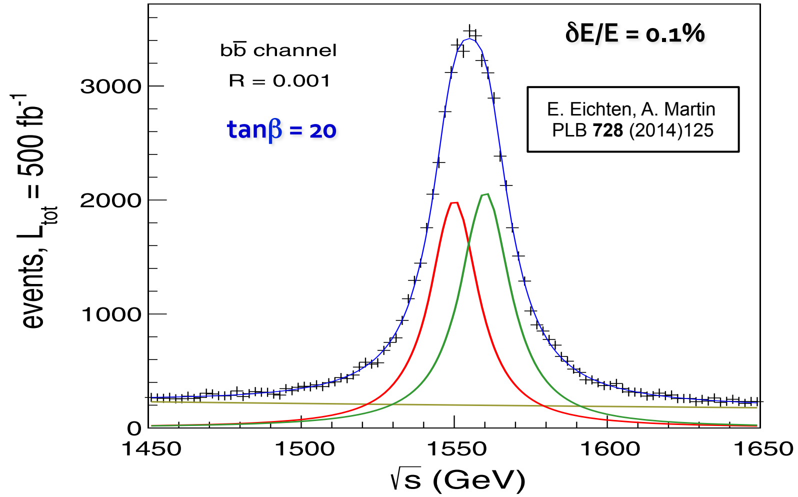
N. Chakrabarty et al.
PRD **91** (2015)015008

- Go to the highest energy first
  - $\sqrt{s}$ = 3, 6, or 20 TeV in LHC / FCC
- Select event with an energetic photon
  - Recoil mass distribution :




- Can also do the same as CLIC at 3 TeV
  - And much more at 6 or 20 TeV
- Then build the next muon collider
  - At $\sqrt{s} \sim m_{A,H}$ in the SPS
- Study H/A mixing, CP violation
  - With H/A → tt → $\pi^+\pi^-\nu_\tau\nu_\tau$, $\rho^+\rho^-\nu_\tau\nu_\tau$



# Summary

- A muon circular collider at $\sqrt{s}$ = 125 GeV is a pretty Higgs factory
  - But not necessarily the one we need – if we are after precision and new physics
- Circular $e^+e^-$ colliders deliver largest luminosities at $\sqrt{s}$ = 240-250 GeV
  - The FCC-ee delivers 10 times more luminosity at 240 GeV than the ILC250
  - The FCC-ee benefits from the ability to run at and above the top pair threshold
  - The Higgs width and coupling precision covers Higgs-coupled new physics up to 10-30 TeV
- Circular $e^+e^-$ colliders are much more than a better Higgs factory
  - The FCC-ee physics case is multiplied by the presence of the 4 heavy SM particles in its energy range. In a coherent programme of about 14 years:
    - It measures $m_Z$, $\Gamma_Z$, $m_W$, $m_{top}$, $\sin^2\theta_W^{eff}$, $R_b$, $\alpha_{QED}(m_Z)$, $\alpha_s(m_Z)$, EW top couplings, …, with unprecedented precision
    - It covers weakly-coupled new physics up to 10-100 TeV
    - It provides a unique direct discovery potential – with $5\times10^{12}$ Z decays, in particular
- Circular $e^+e^-$ colliders pave the way towards the highest energy frontier
  - The FCC tunnel can host a 100 TeV pp collider (FCC-hh), with many ee-hh synergies
    - In particular for Higgs precision physics (see next talk)
- Muon circular colliders may be the best way to reach $\sqrt{s}$ > 3 TeV with leptons
  - The FCC-ee ability to accelerate a very intense $e^+$ beam could be the first step
    - Much R&D remain to be done in (cooling), $e^+$ source, $e^-$ target, and acceleration

# A visionary strategy

PHYSICS WITH VERY HIGH ENERGY
$e^+e^-$ COLLIDING BEAMS

L. Camilleri, D. Cundy, P. Darriulat, J. Ellis, J. Field, H. Fischer, E. Gabathuler, M.K. Gaillard, H. Hoffmann, K. Johnsen, E. Keil, F. Palmonari, G. Preparata, B. Richter, C. Rubbia, J. Steinberger, B. Wiik, W. Willis and K. Winter

ABSTRACT

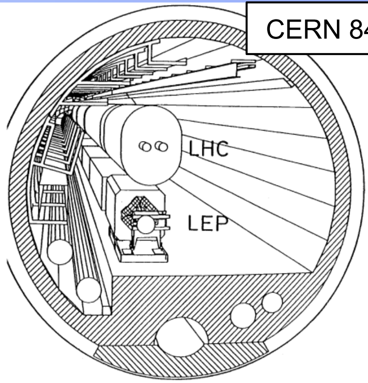
This report consists of a collection of documents produced by a Study Group on Large Electron-Positron Storage Rings (LEP). The reactions of

CERN 76-18
8 November 1976

$e^+e^-$ 1989-2000

pp 2009-2038

CERN 84-10




LARGE HADRON COLLIDER
IN THE LEP TUNNEL

Vol. I

- Did these people know that we would run HL-LHC in the same tunnel more than 60 years later ?

**Let's not be shy !**
**A visionary strategy based on a 100 km tunnel would provide**
**the most natural, broadest, and most ambitious scientific future**
**for CERN and for fundamental physics,**
**for many years to come,**
**with FCC-ee, FCC-hh, and maybe even FCC-μμ.**

**An early realization of FCC-ee (2035?) will materialize the chances to get the FCC-hh as soon as technically/financially possible**

# Backup material

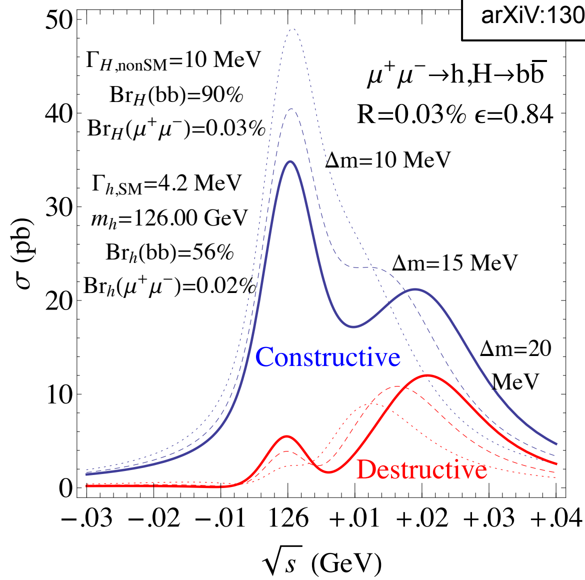
# Muon Higgs factory bonus

- **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 $\Delta M$ < few 100 MeV
  - Would be a piece of cake at a muon collider
    - Examples shown for
      - $\Delta M$ = 10, 15, 20 MeV
      - Destructive/constructive interference
      - Similar coupling to muons and b quarks
    - Lineshape sensitive to $\Delta M$ ~ MeV
      - If both Higgs bosons couple to $\mu$ and b/W
  - Probably observable at FCC-ee via pair production with $\sqrt{s}$ > 250 GeV (to be studied)
    - $e^+e^- \to hA$ present at tree level with large cross section (A pseudoscalar, $m_A \sim m_h \sim m_H$)
    - [$e^+e^- \to hH$ 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)

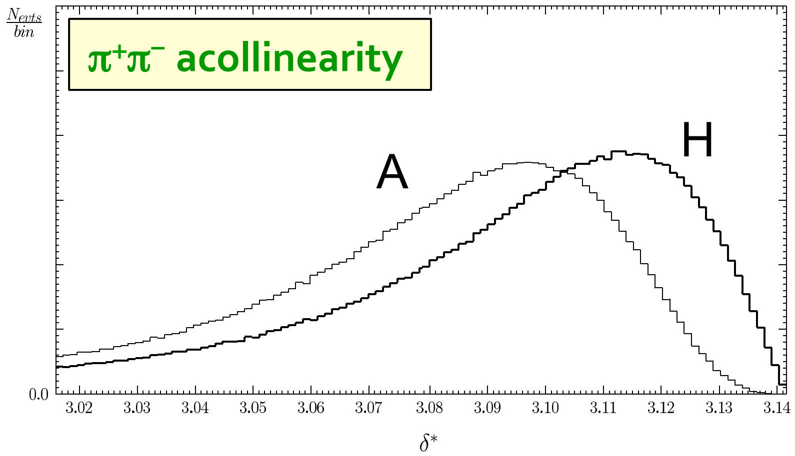
Snowmass 2013 arXiV:1308.2143

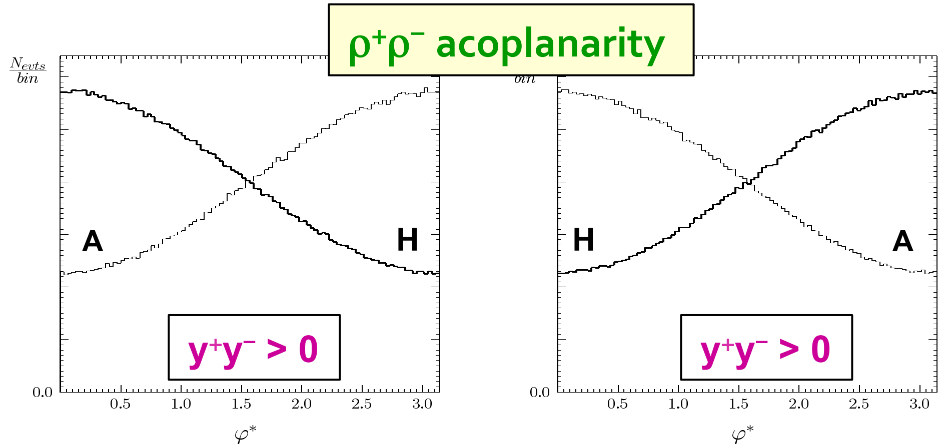



A. Djouadi et al. PRD **54** (1996) 759

# Higgs mixing and CP studies (muon coll.)

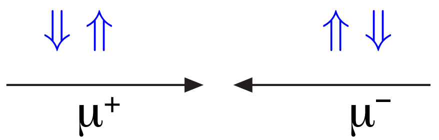
- **Unique CP (violation) and H/A mixing studies can start**
  - **From H,A $\to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$**  **From H,A $\to \tau^+\tau^- \to \rho^+\rho^-\nu_\tau\nu_\tau$ with $\rho^\pm \to \pi^\pm\pi^0$**



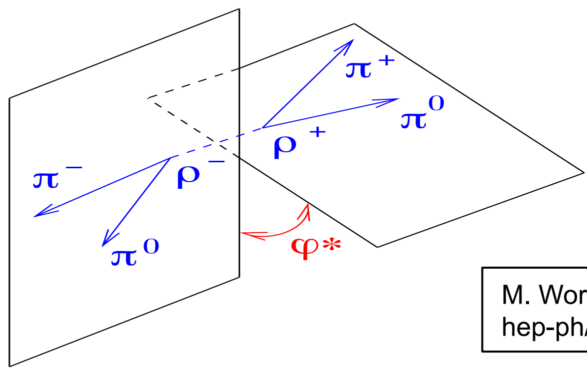




$y^\pm = E_{\pi\pm} - E_{\pi 0}$

  - **From beam transverse polarization**




Parallel spins: produces H
Antiparallel spins: produces A



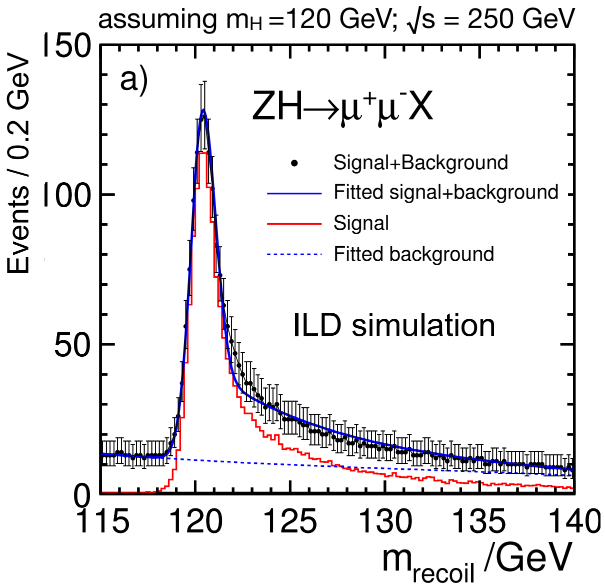

- **No idea of whether it is feasible or not…**

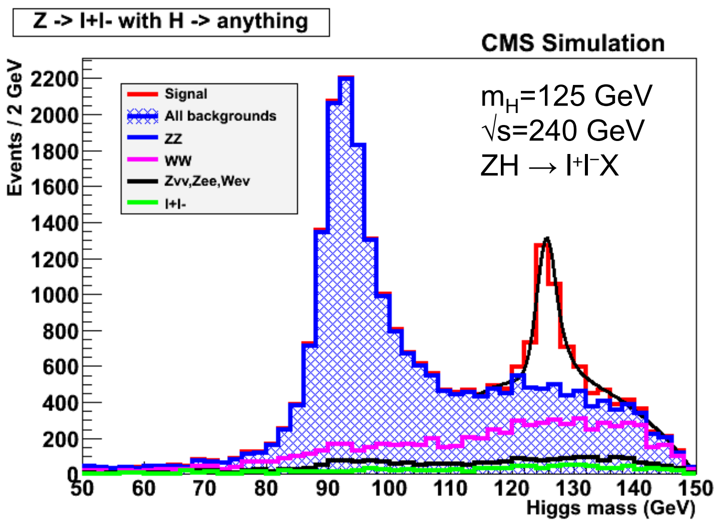
F. Palhen et al.
JHEP 0808:030
JHEP 0801:017

M. Worek
hep-ph/0305082

# Higgs width at FCC-ee (2)

- **Example: Model-independent measurement of $\sigma_{HZ}$ and $\kappa_Z$**
  - The Higgs boson in HZ events is tagged by the presence of the $Z \rightarrow e^+e^-, \mu^+\mu^-$
    - Select events with a lepton pair ($e^+e^-, \mu^+\mu^-$) with mass compatible with $m_Z$
    - No requirement on the Higgs decays: measure $\sigma_{HZ} \times BR(Z \rightarrow e^+e^-, \mu^+\mu^-)$
    - 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

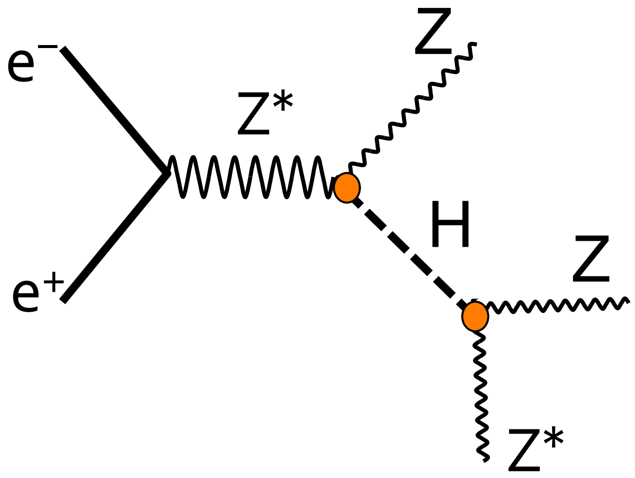



  - Provides an absolute measurement of $\kappa_Z$ and set required detector performance

# Backup: Higgs width at FCC-ee (3)

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



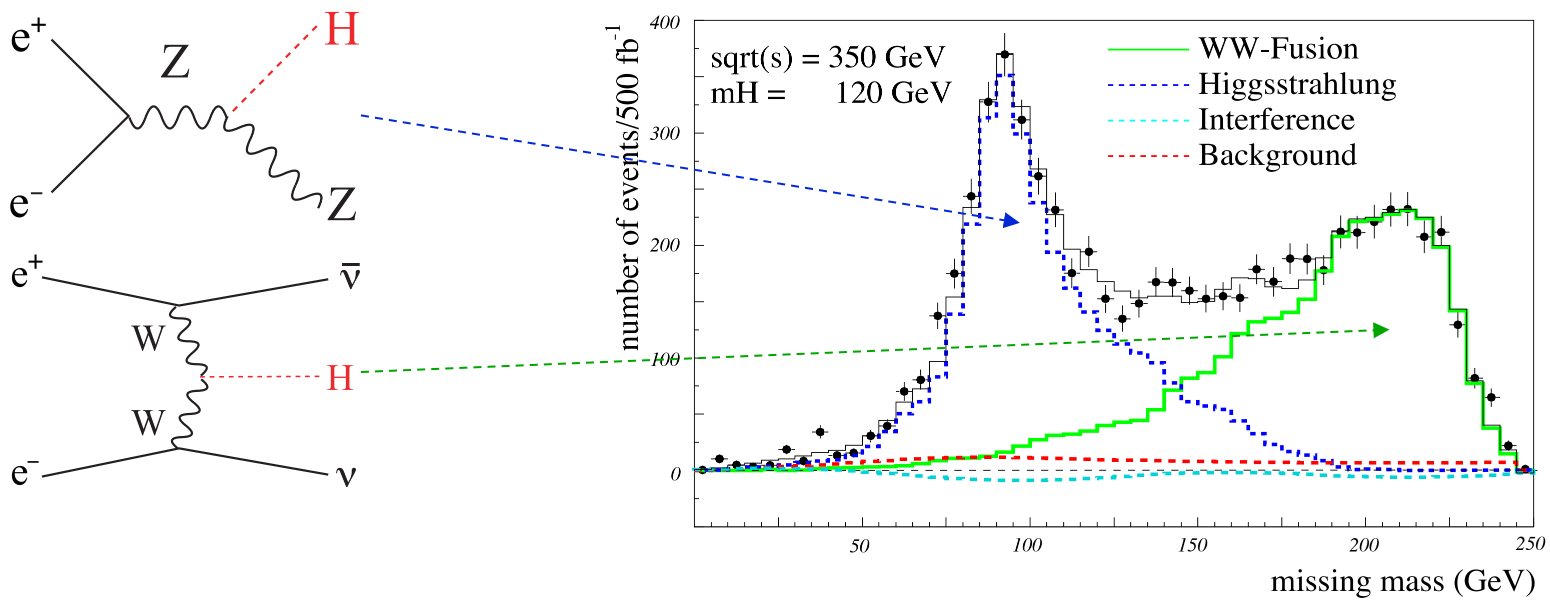

Final state with three Z's
Almost background free

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

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

# 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:**

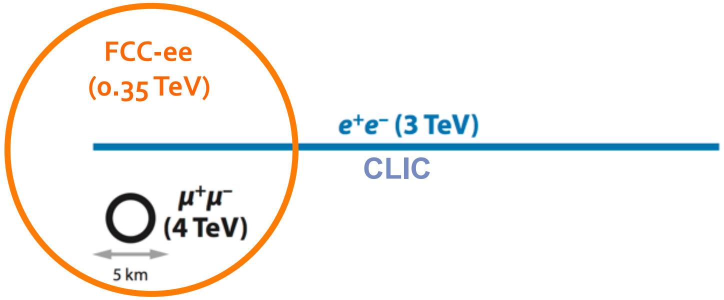


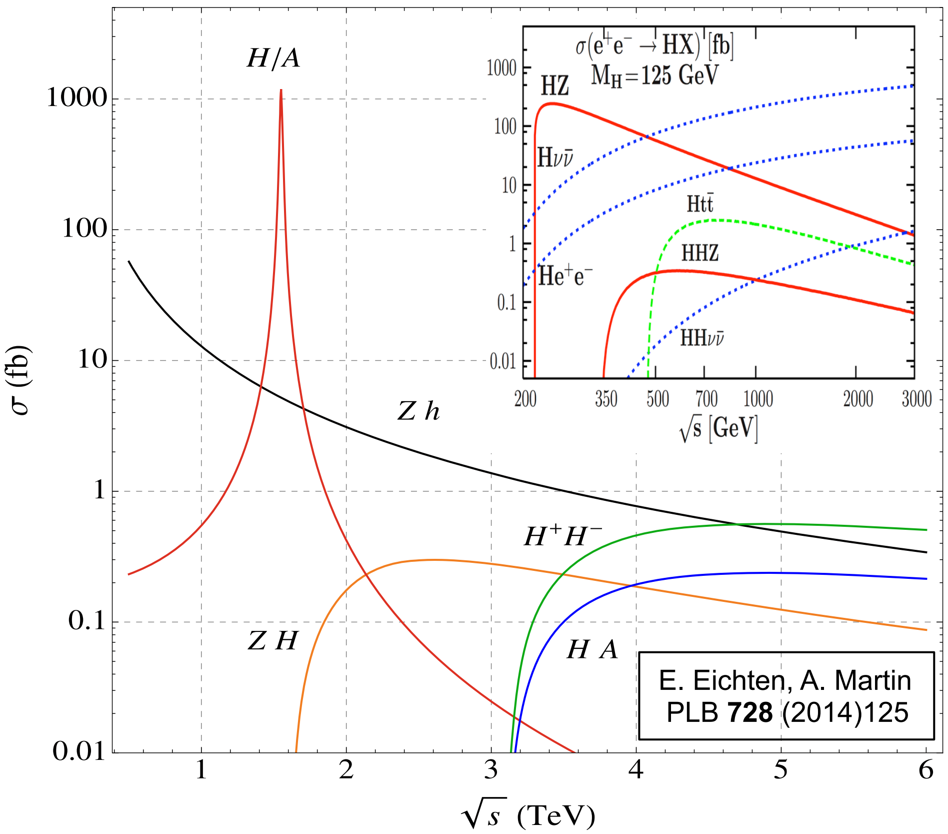

- **Measure σ(WW→ H→ bb)**
- **Take the branching ratios into WW and bb from $\sigma_{HZ}$ and $\sigma_{HZ}$× BR(H → WW,bb)**
- **Infer the total width**

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

# Higgs boson production at muon colliders

- **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**

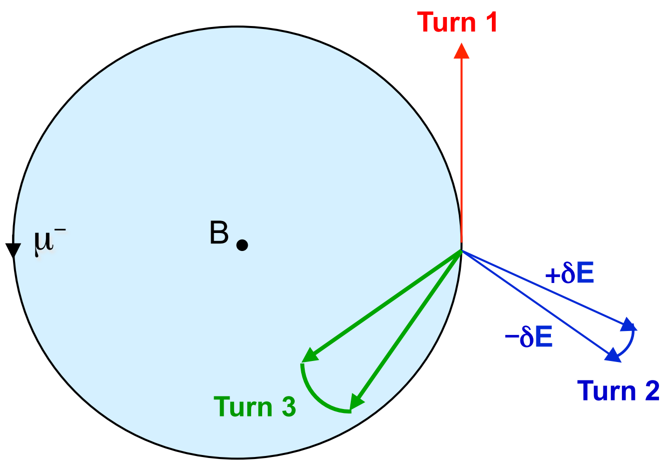
- Can go to higher energy
  - Advantage for 2HDM (e.g., SUSY)
    - Heavy Higgs with $\mu^+\mu^- \to$ H,A
- $\sqrt{s}$ ~ 6 TeV possible in the SPS tunnel
- $\sqrt{s}$ ~ 20 TeV possible in the LEP tunnel

# 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 $\nu_0$
      - ➨ For $m_H$ = 125 GeV, $\nu_0$ = 0.68967593(35)
    - Without energy spread, $P_L$ oscillates between -20% and +20%
    - With energy spread, $P_L$ gets diluted turn after turn

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

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




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

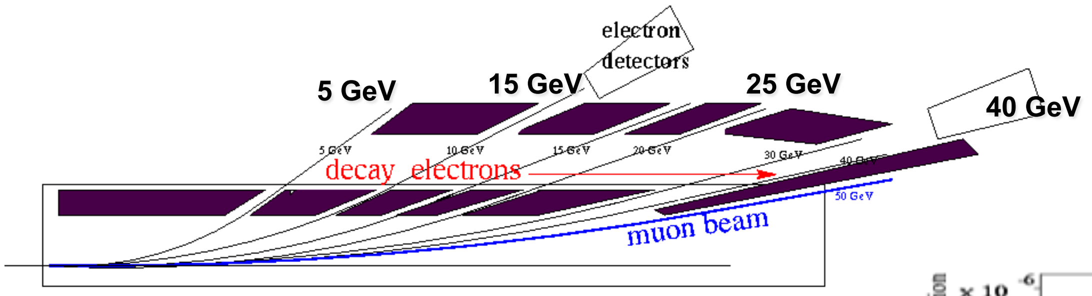
$$P_L(T) = P_0 \cos(2\pi\nu_0 T) \exp\left\{ -\frac{1}{2} \left[ 2\pi\nu_0 T \frac{\delta E}{E} \right]^2 \right\}$$

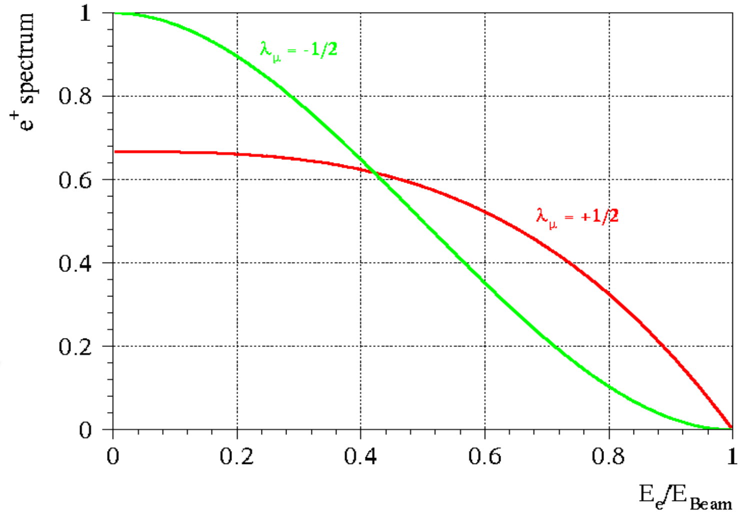
- Experimentally, measure $P_L$ at each turn T
  - ➨ And deduce the complete beam energy spectrum by inverse Fourier transform

**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:

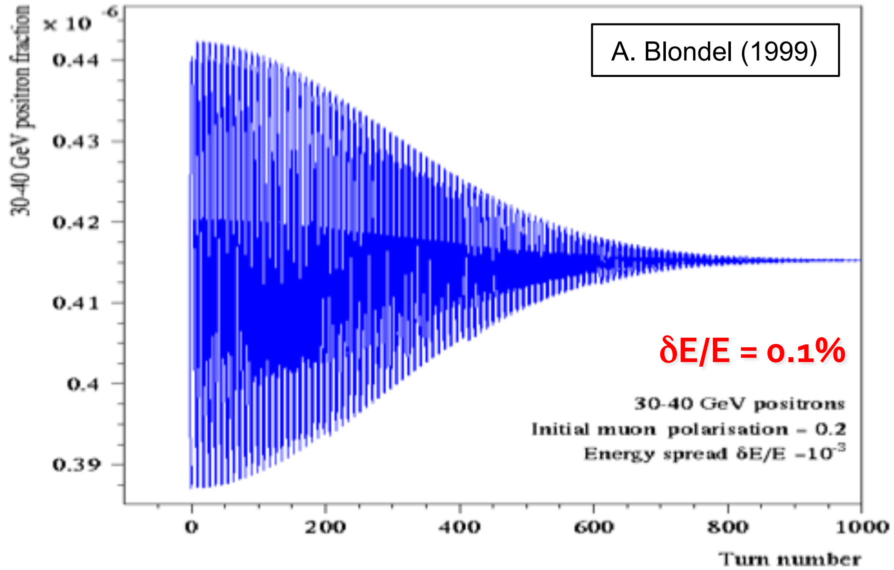



  - Fraction of e+ from 30 to 40 GeV

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

    - The amplitude gives $P_0$
    - The frequency gives $\nu_0$ ($E_{Beam}$)
    - The damping gives $\delta E/E$



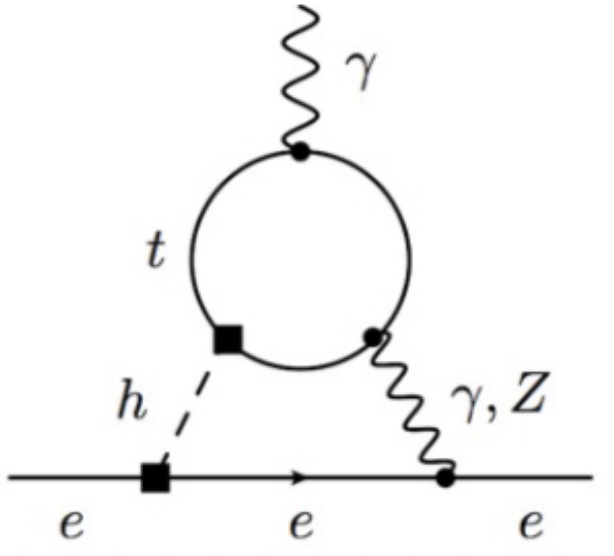
# Beam energy and beam-energy spread (3)

- **Expected statistical accuracy of the method**
  - For $L = 2\times10^{31}$ 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 $5\times10^{-7}$ (30 keV) by the precision on $g_\mu - 2$ (!)
    - $3{\cdot}10^{-7}$ 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 $\Gamma_H$
    - $10^{-4}$ 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 (0.1 MeV)
    - On the Higgs width (0.25 MeV)
    - On the production cross section (4%)

# EDM and electron Yukawa coupling

- **Electron EDM used to set constraint on CP violating top couplings**

J. Brod, U. Haisch, J. Zupan
arXiV:1310.1385




- **Assumes SM value for the electron Yukawa couplings**
  - **The FCC-ee constraint (upper limit of ~2) on $\kappa_e$ takes all its importance**