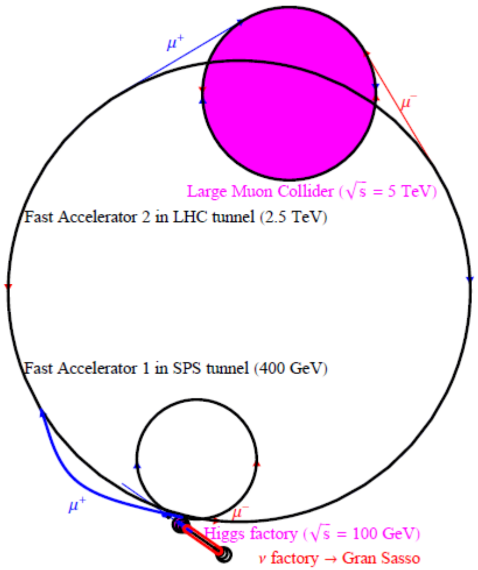
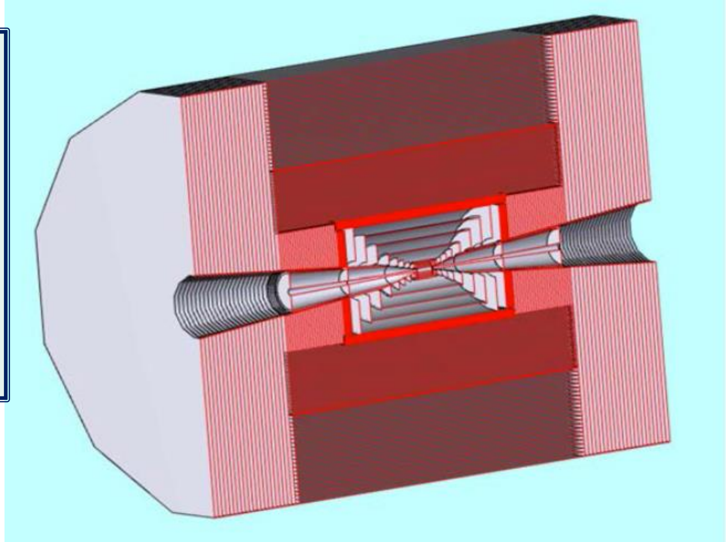
Experiments at Muon colliders

Alain Blondel

with great help from P. Janot, M. Palmer, C. Tully, and many others

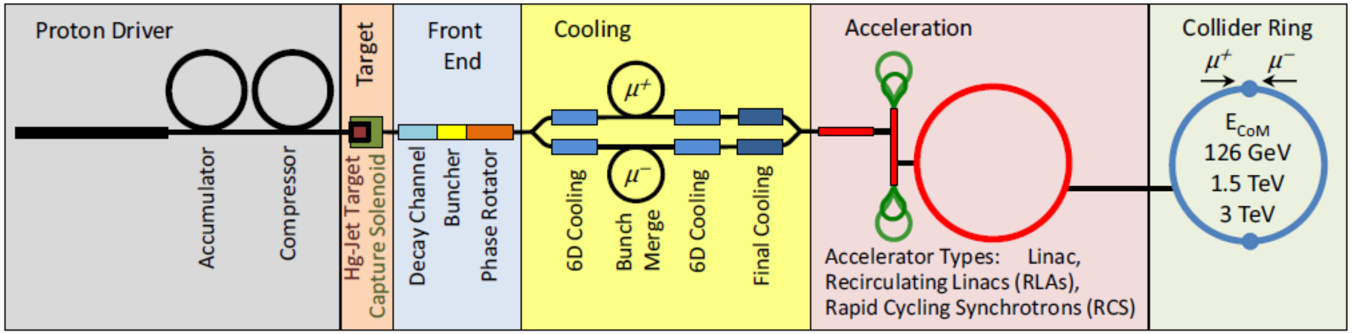


- Higgs physics
- Precision measurements
- Higher masses
- Experimental environment
- What can a muon collider do .... and not do?



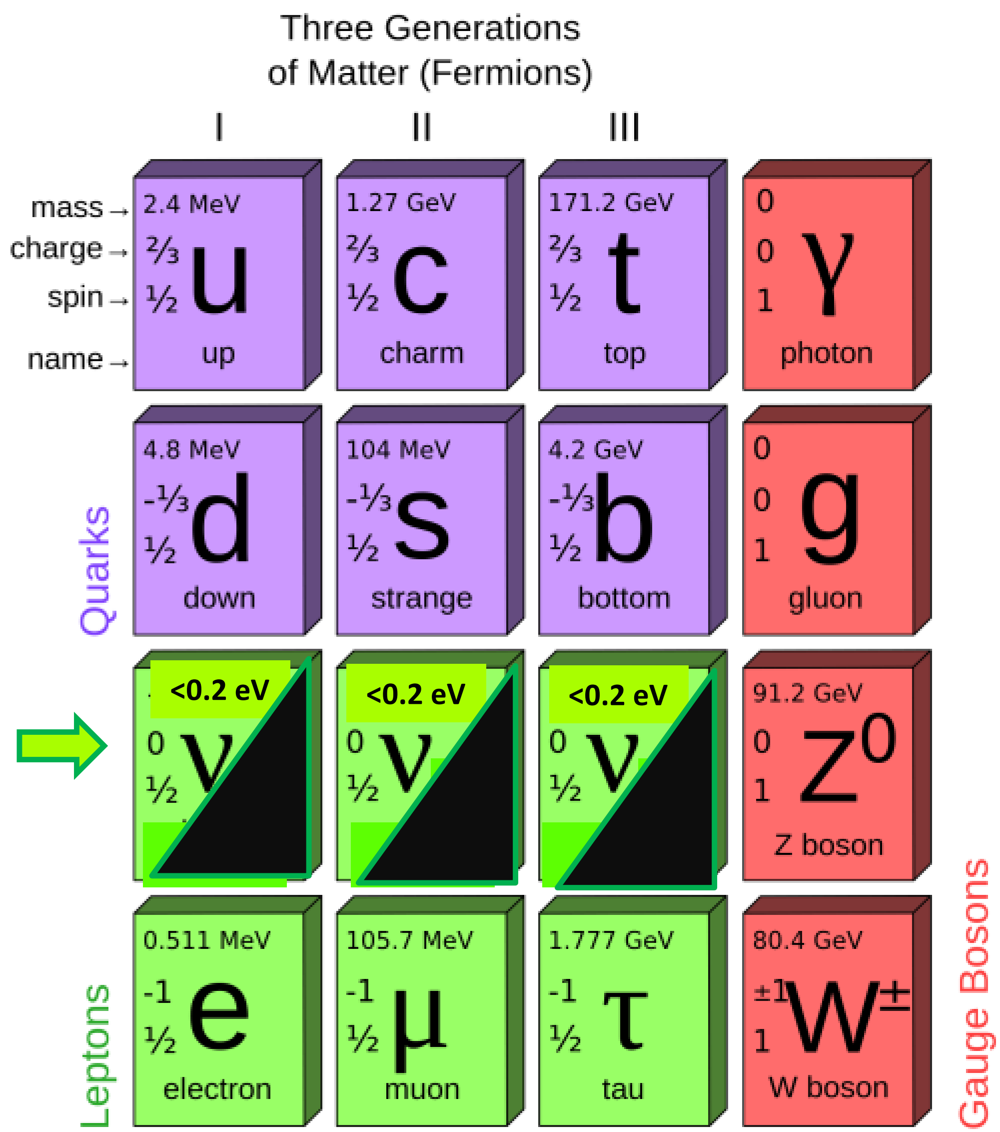
CERN-YELLOW-99-02, CERN-2004-002 ; ECFA-04-230

U.S. Muon Accelerator Program

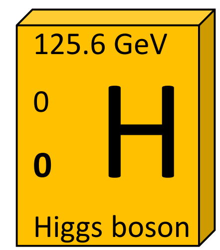


arxiv:1308.0494

THE STANDARD MODEL CONSTRUCTION

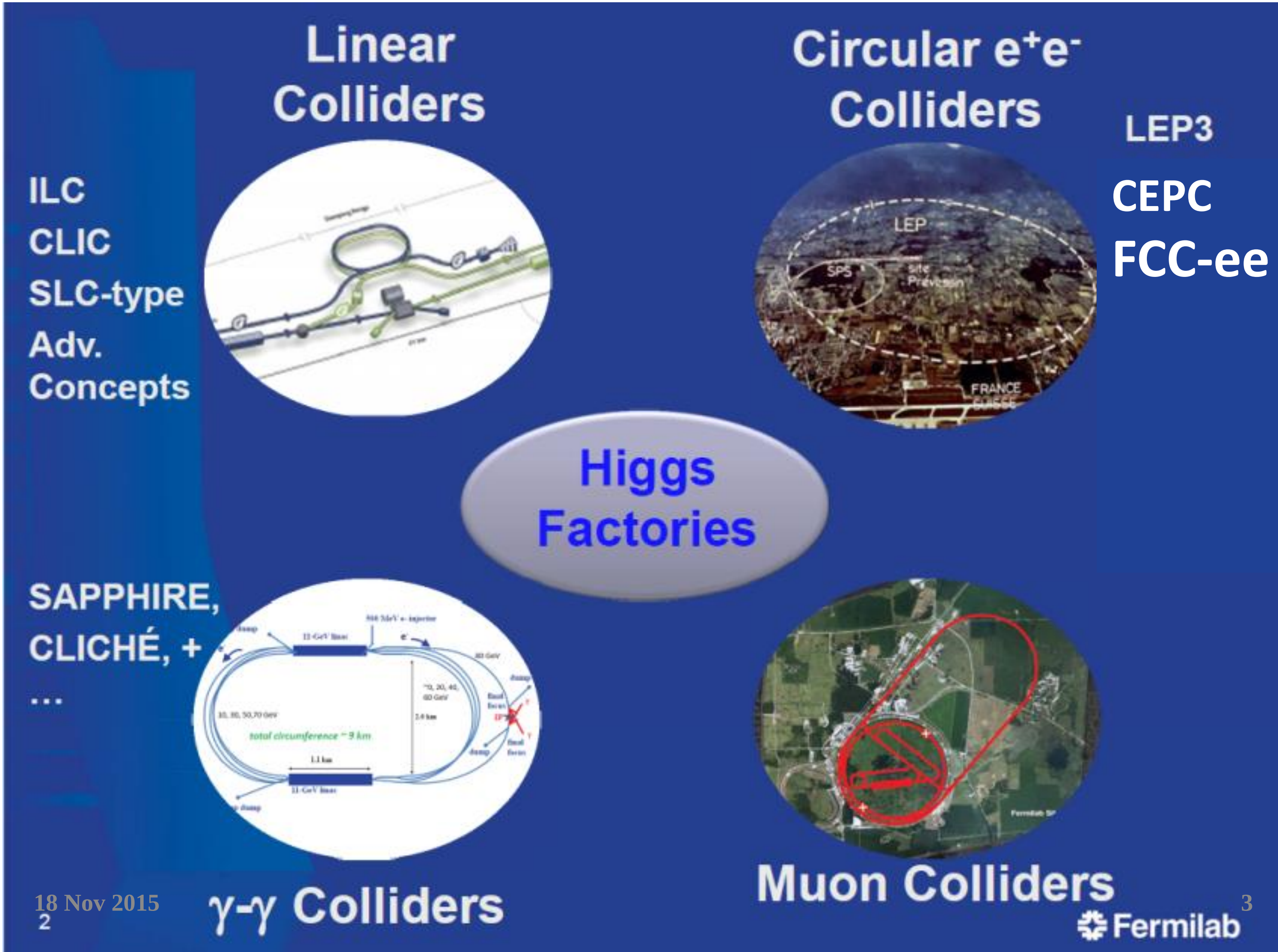


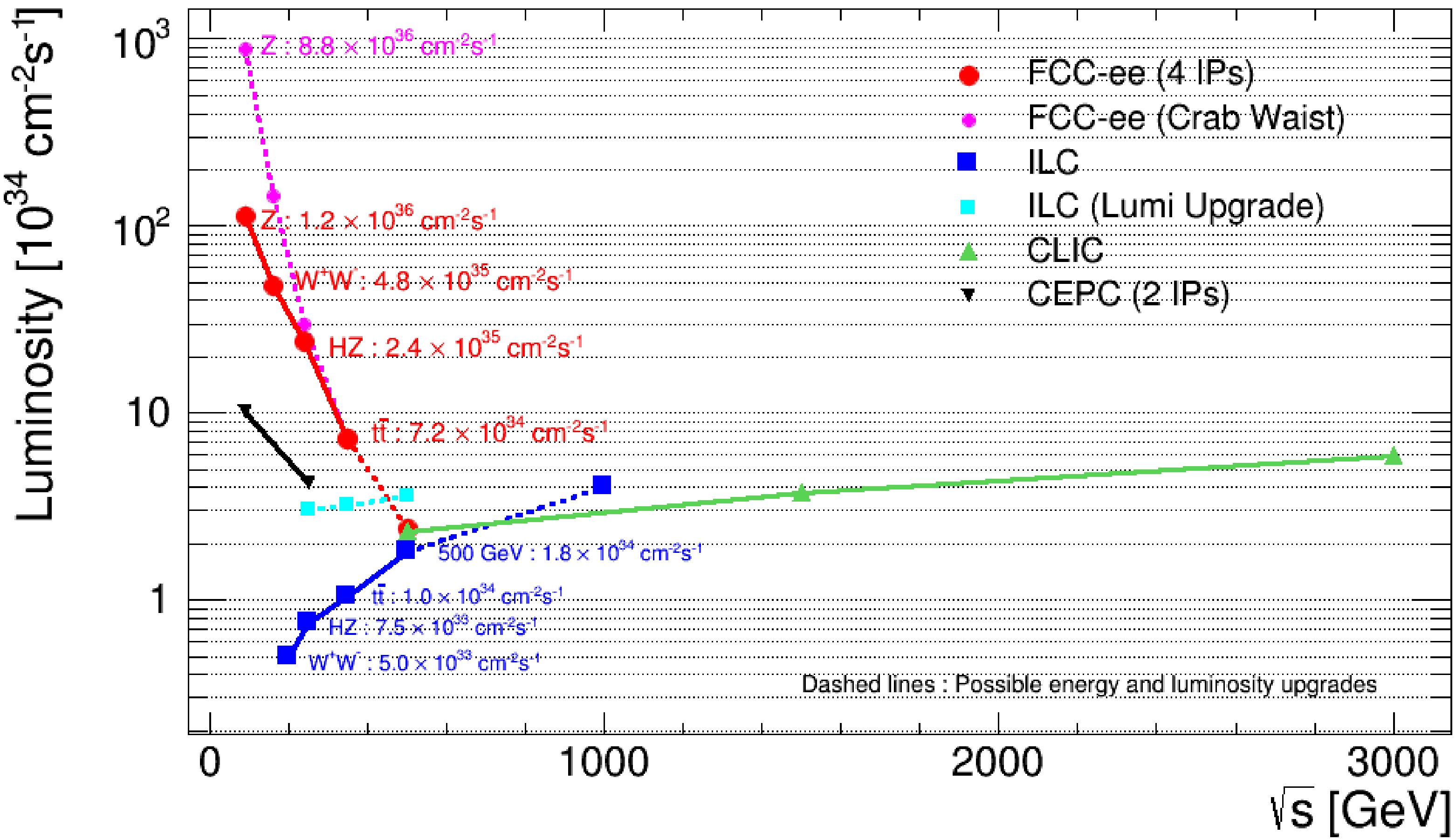
This part is not complete



This part is very new

LEPTON COLLIDERS





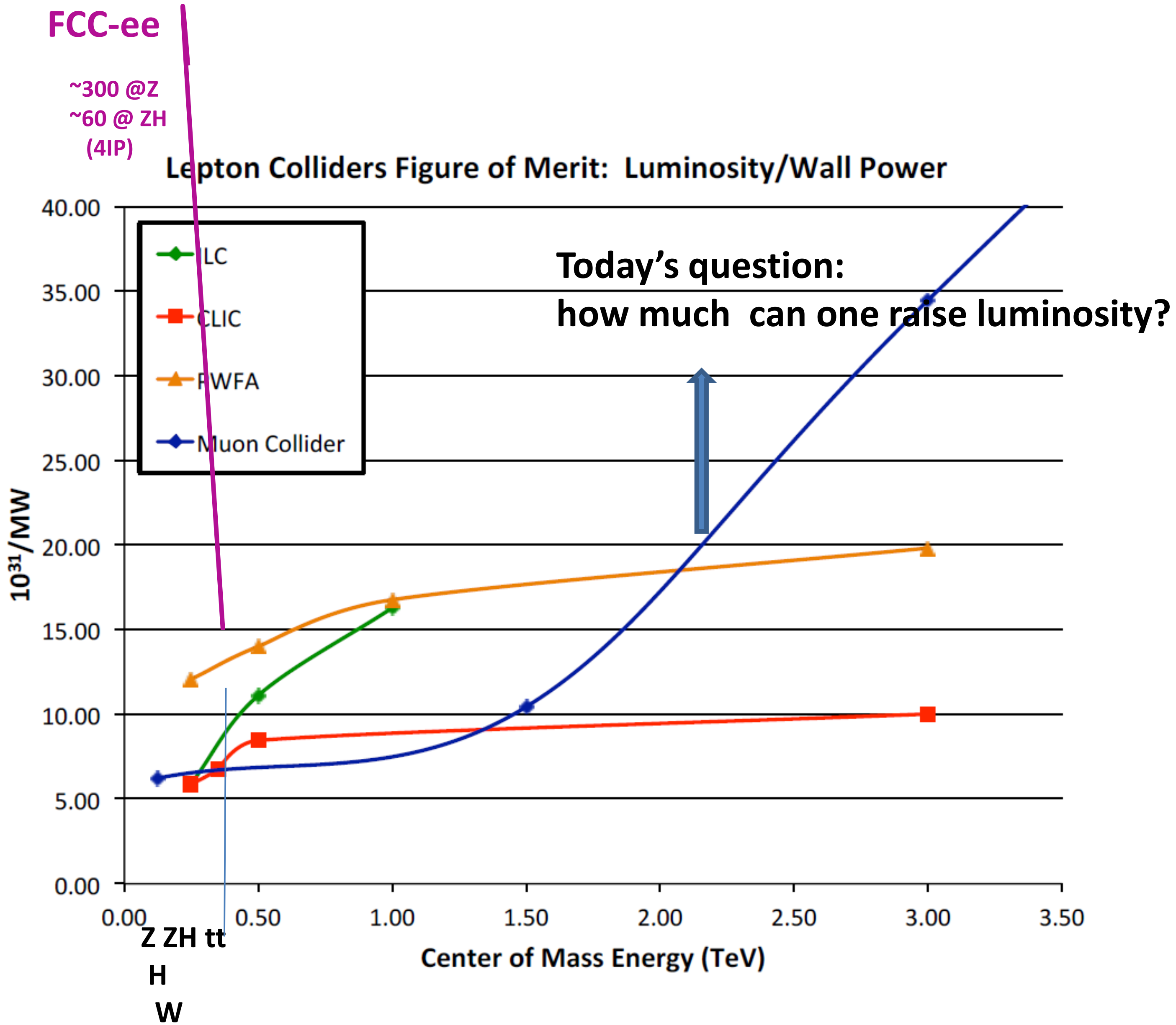
Overlap in Higgs/top region, but differences and complementarities between linear and circular e+e- machines:
Circ: High luminosity, experimental environment (up to 4 IP), E_{CM} calibration
Linear: higher energy reach, longitudinal beam polarization

1. Basic limitation from number of muons @ given proton driver power
2. Luminosity grows like E^2 for given muon source (normalized emittance) in optimized ring
   ! The winner for E.C.M. above 2 TeV !
   in a given ring it grows like E^3 :
   ex: top factory E_{CM}=350 GeV, L=6 10^{33} → @Z 10^{32} ; @WW 6 10^{32} ; @ZH 2 10^{33} ; @H 3 10^{31}
3. ! energy spread can be reduced to 3 10^{-5}
4. ! beam energy and beam energy spread calibration is exquisite
5. rep rate > 1μs , typically 15(fills)x10^3 (turns/fill) → no pile-up
6. large fraction of power in cooling!
   → wall power increases slowly with E_{CM}
7. muons decay ! 10^{12} muons : $\mu \rightarrow e\nu\nu$
   → e/γ background at IP

7'. ν from muon decay give radiation at point of exit → grows as E^4
   limits applicability to ~E_{CM}= 10 TeV

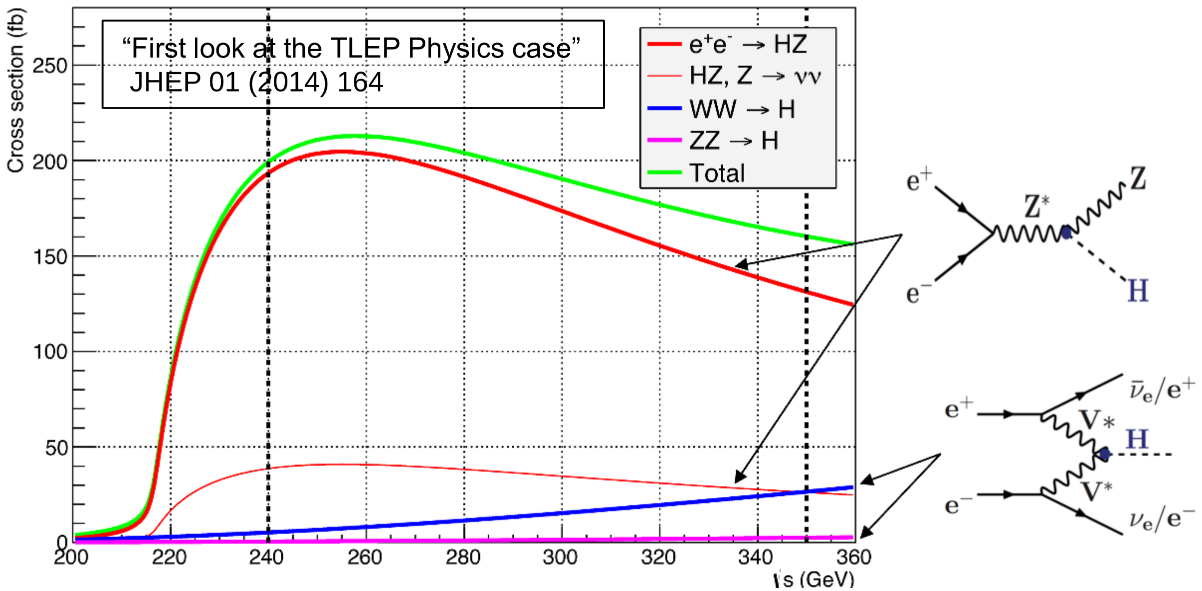
Muon Collider Baseline Parameters

Parameter	Units	Higgs Factory: Startup Operation	Higgs Factory: Production Operation	Multi-TeV Baselines	Multi-TeV Baselines
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Higgs/10^7sec		3,500	13,500	37,500	200,000
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
β*	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	10^{12}	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	70	70
Bunch Length, σ_s	cm	5.6	6.3	1	0.5
Beam Size @ IP	μm	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4[#]	4	4	4


FCC-ee
~300 @Z
~60 @ ZH
(4IP)
Lepton Colliders Figure of Merit: Luminosity/Wall Power
Today's question:
how much can one raise luminosity?
ILC
CLIC
PWFA
Muon Collider
10^31/MW
40.00
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0.00
0.50
1.00
1.50
2.00
2.50
3.00
3.50
Z ZH tt
H
W
Center of Mass Energy (TeV)

Higgs boson production (1)

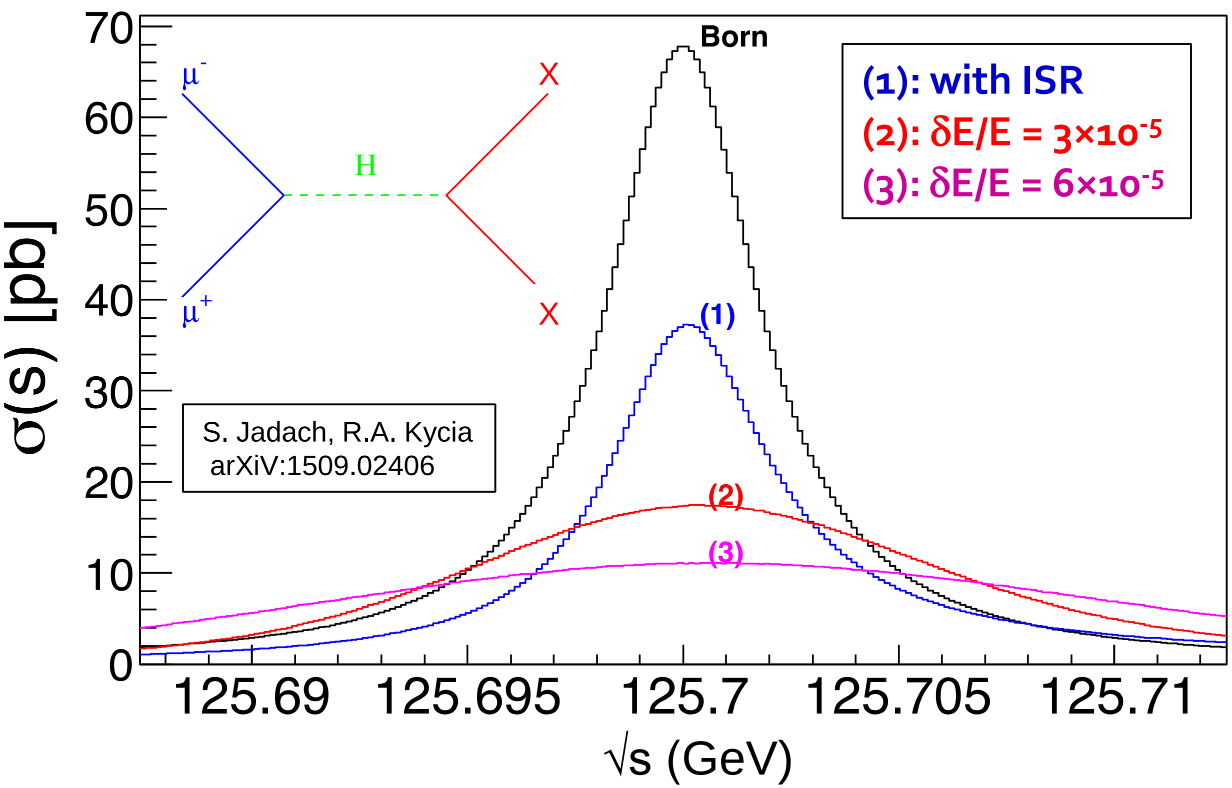
- **Muons are leptons, like electrons**
  - Muon colliders can a priori do everything that e^+e^- colliders can do, e.g.:



  - 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 × 10^{35} $cm^{-2}s^{-1}$ / IP and up to 4 IPs
    - Muon collider luminosity: few× 10^{33} $cm^{-2}s^{-1}$ / IP
  - 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: $2 – 8 \times 10^{31}$ cm^{-2}s^{-1}**



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

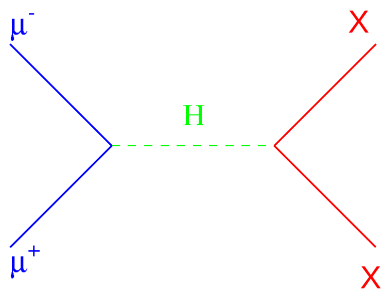
Reminder: At FCC-ee
400,000 to 800,000 Higgs/yr

Not quite there, even with factor 10

Scan of the SM Higgs resonance (1)

Resonant production

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



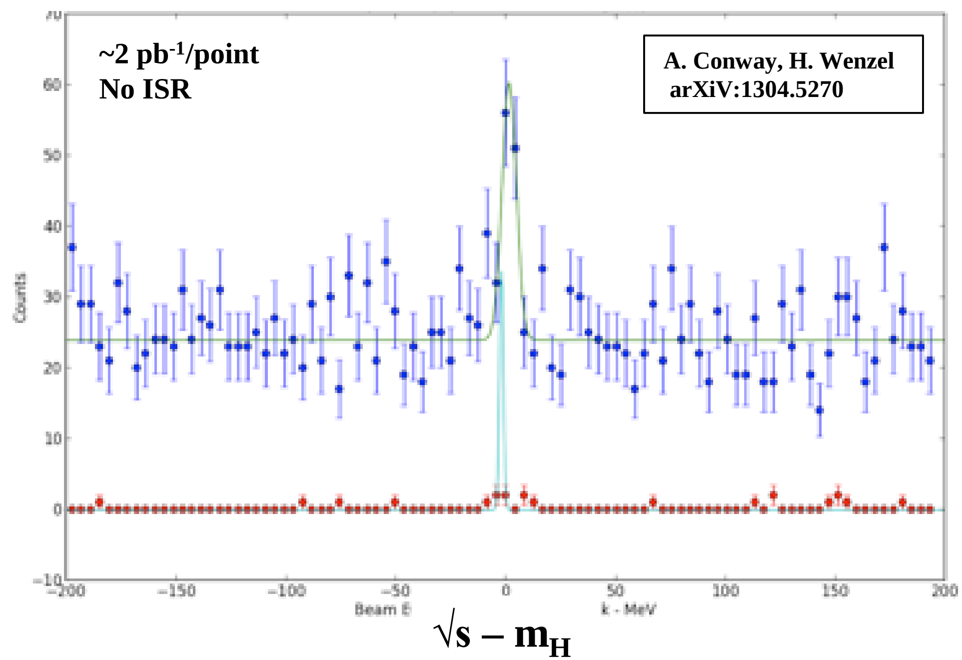
Major background:
$\mu^+\mu^- \to Z/\gamma^* \to XX$

- **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($H \to \mu\mu$)**
    - ➔ **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)

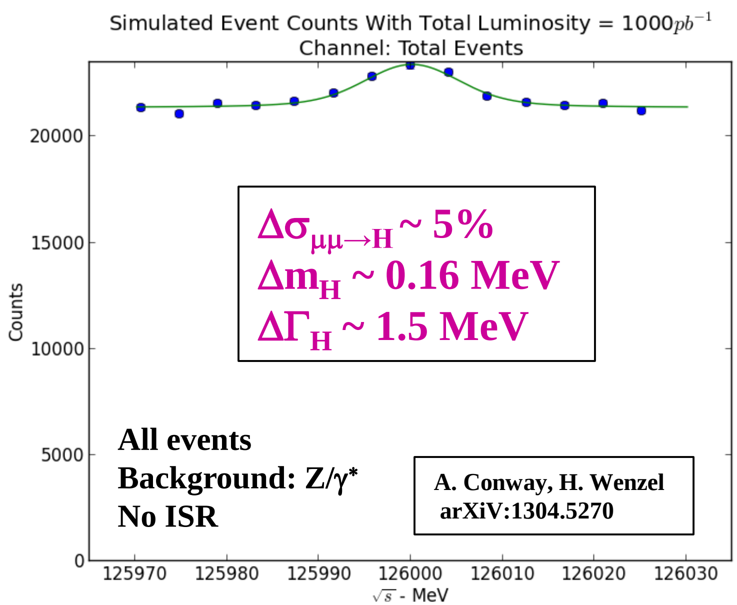
- Finding the resonance (Γ_H = 4.2 MeV ~ δE)
  - Today, m_H is known to ±250 MeV
    - Improves to ±100 MeV (LHC14), ±30 MeV (ILC), or ±8 MeV (FCC-ee)
  - Scan the √s region of interest in optimal bins of 4.2 MeV
    - Count the number of bb and semi-leptonic WW events (see next slides)
  - Without ISR, 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

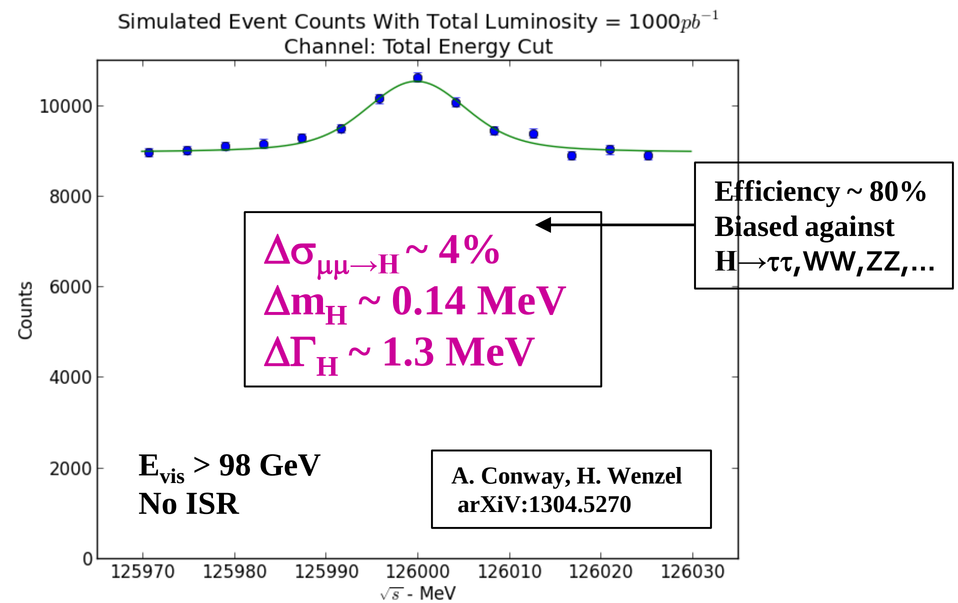


Scan of the SM Higgs resonance (3)

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) was simulated
- Count either all events, or only those with E_{vis} > 98 GeV [reject Z(γ) events]



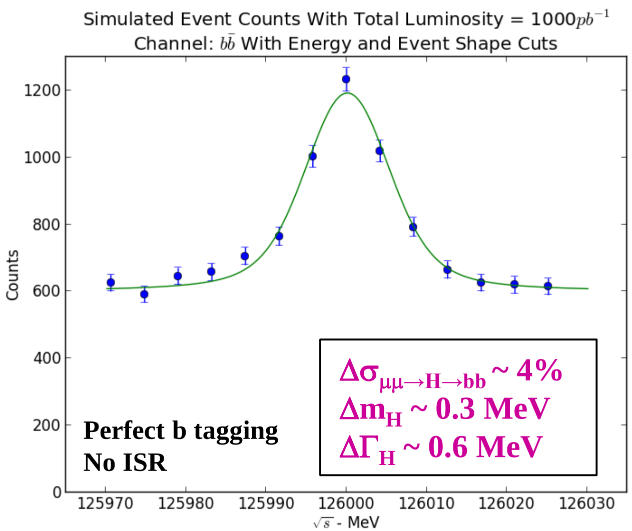


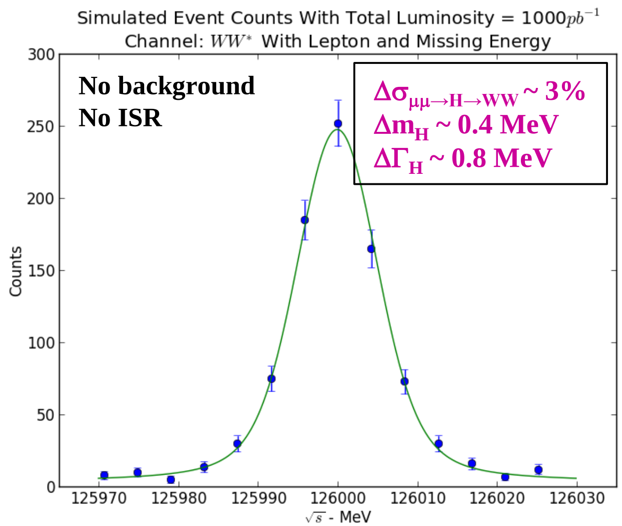
- ISR reduces the signal by a factor 2 (but not the background)
  - ➔ All errors to be increased by a factor 2
- m_H and Γ_H measurements require knowledge of E and δE with great precision

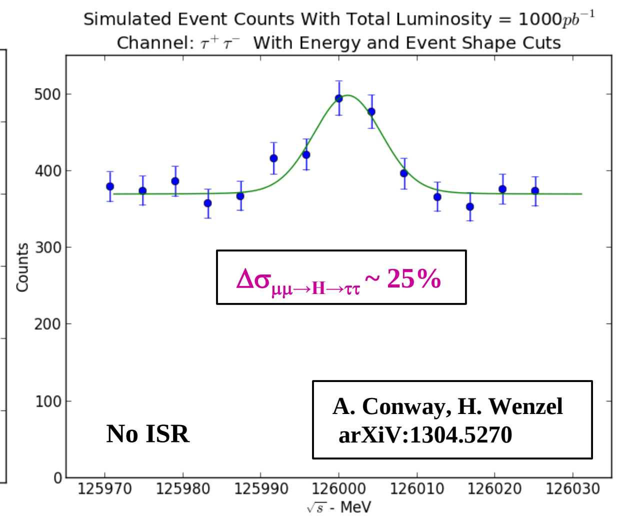
Scan of the SM Higgs resonance (4)

❑ Exclusive decays

◆ H ⟶ bb   H ⟶ WW ⟶ lνqq   H ⟶ ττ







◆ **Notes**

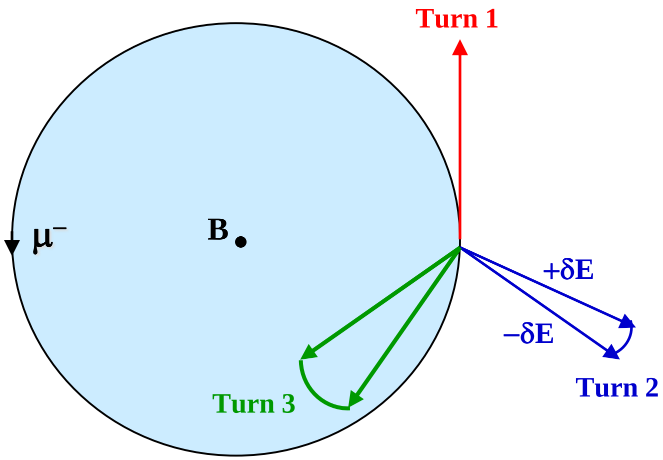
- Some optimism in these numbers (perfect b tag, only Z bkgd, no beam bkgd…)
- Errors to be increased to account for ISR
- A better scan strategy should be designed (less in the sides, more in the peak)
- The numbers are for 5 years at low luminosity, and 1.2 year after lumi upgrade
  - ➔ Combined numbers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

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 $S(\nu)$
- For example, with a Gaussian energy spread

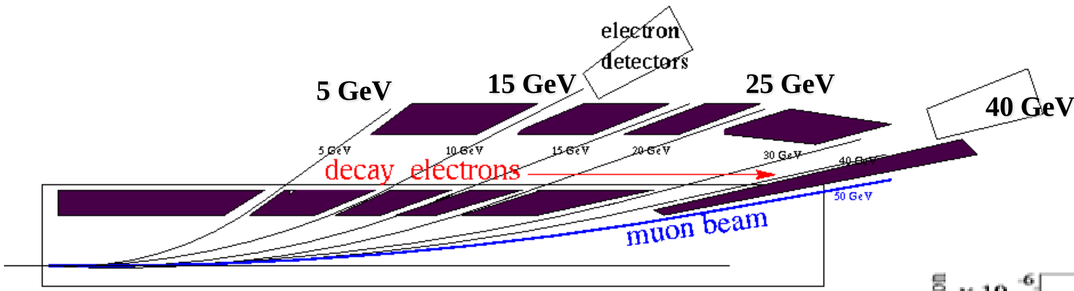
$$P_L(T) = P_0 \cos(2\pi\nu_0 T) \exp\left\{ -\frac{1}{2} \left[2\pi\nu_0 T \frac{\delta E}{E} \right]^2 \right\}$$

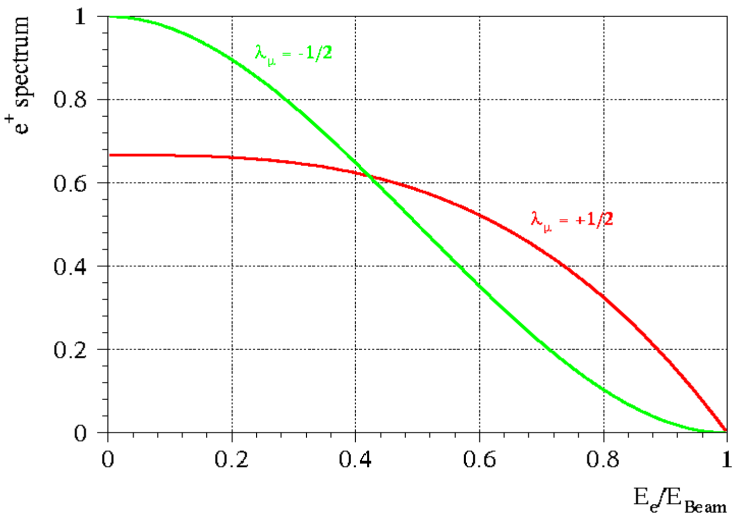
- Experimentally, measure P_L at each turn T
  - ➔ And deduce the complete beam energy spectrum by inverse Fourier transform

i.e., $\delta E/E$ 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:

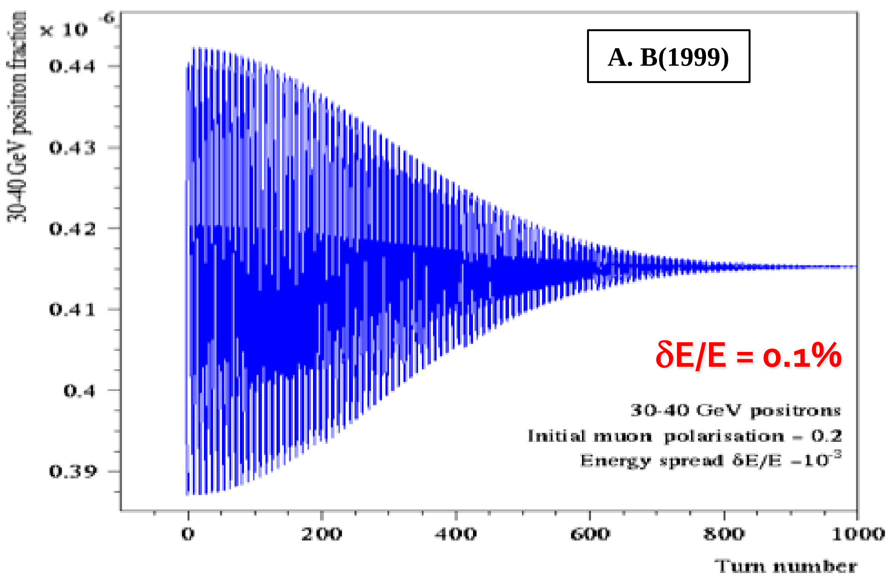




  - Fraction of e^+ from 30 to 40 GeV

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

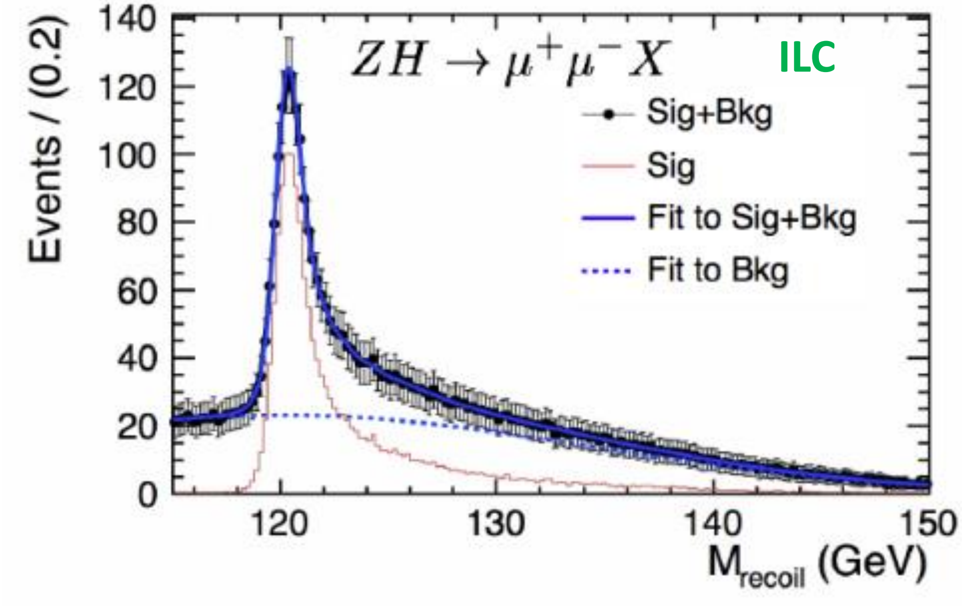
    - The amplitude gives P_0
    - The frequency gives ν_0 (E_{Beam})
    - The damping gives $\delta E/E$



Beam energy and beam-energy spread (3)

Expected statistical accuracy of the method

- For $L = 2\times10^{31}$ 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 5×10^{-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 $\sigma(\mu\mu\rightarrow H)$
    - ➔ Corresponds to a systematic uncertainty of 50 keV on Γ_H
  - 10^{-4} on the polarization value
    - ➔ Negligible impact on $\sigma(\mu\mu\rightarrow H)$
- 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%)



e+e- : Z – tagging by missing mass

total rate $\propto g_{HZZ}^2$

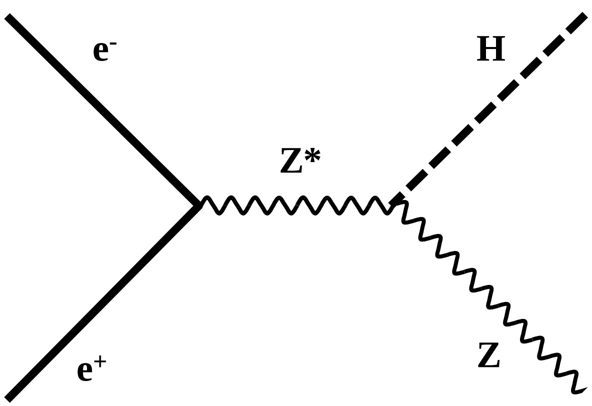
ZZZ final state $\propto g_{HZZ}^4 / \Gamma_H$

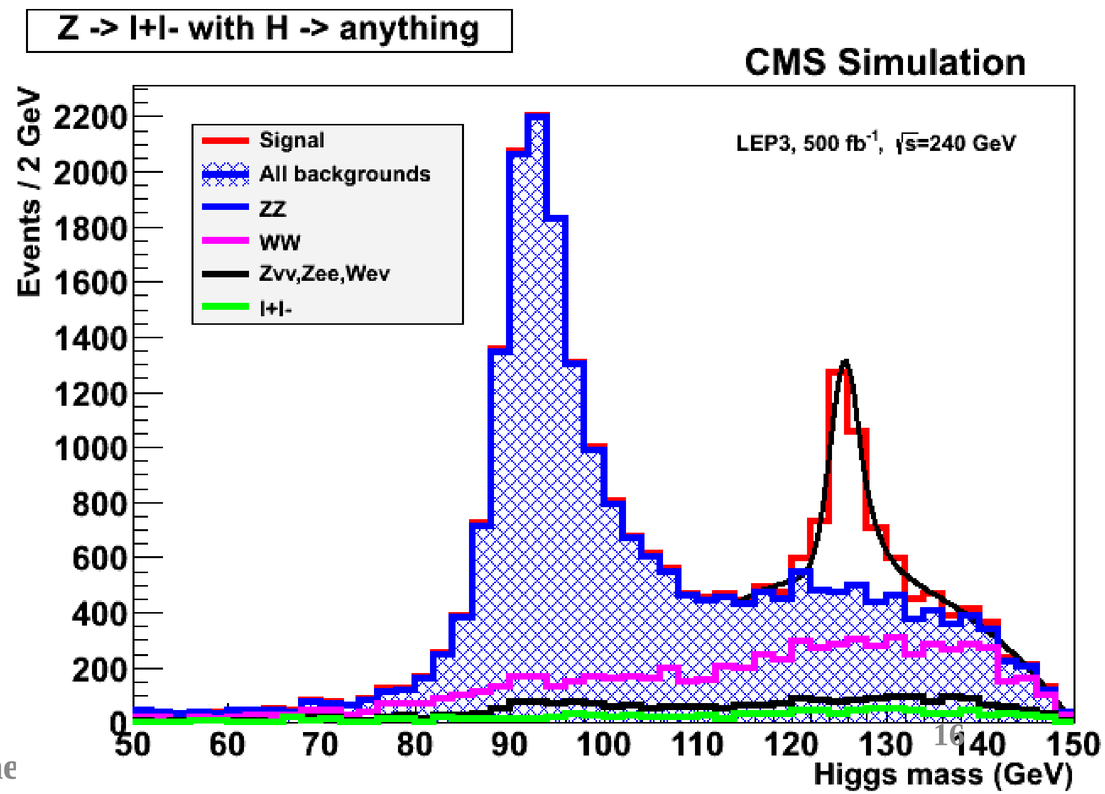
➔ measure total width Γ_H

empty recoil = invisible width

'funny recoil' = exotic Higgs decay

easy control below theshold





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

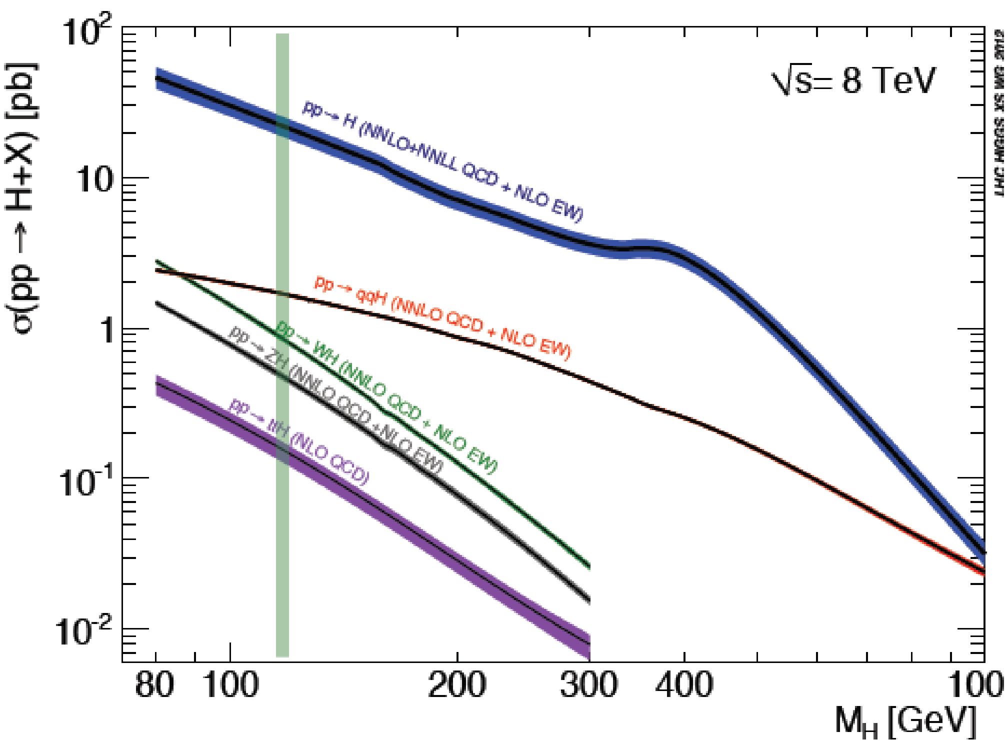
These Higgs couplings are best measured at ee colliders

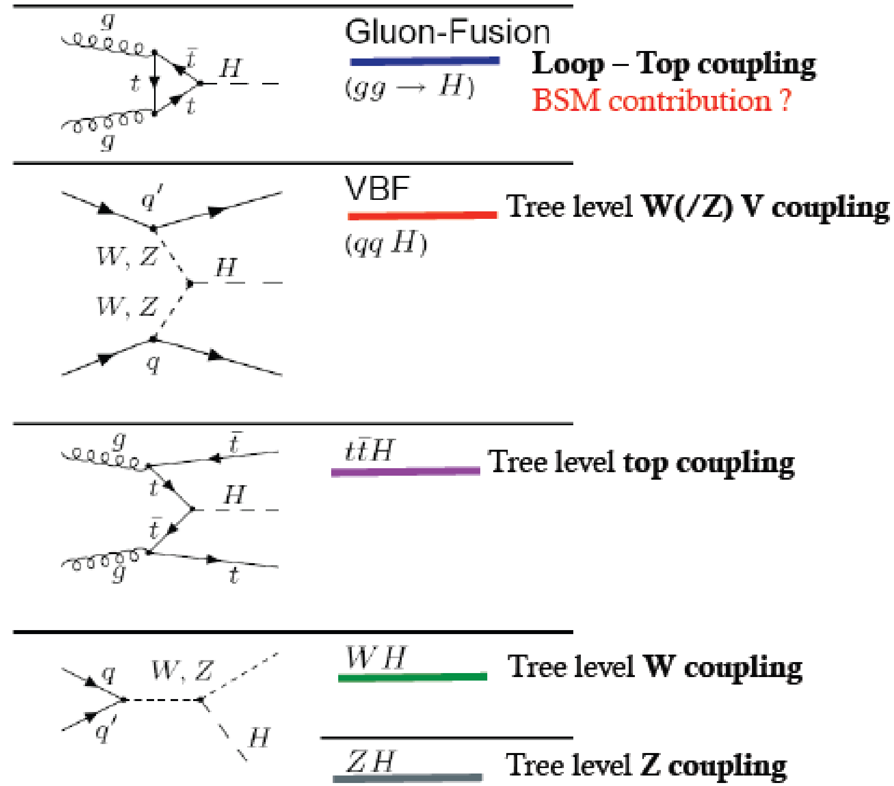
The SM Higgs coupling to muons is *the* added value of a $\mu\mu$ collider *

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

* pp colliders have their say, too

- FCC-hh best for g_{HHH} and g_{ttH} , perhaps $g_{H\mu\mu}$; FCC (ee, hh) for rare decays
  - BR($H\rightarrow \mu\mu$) can also be measured with % precision at FCC-hh. (Will be already 10% after LHC.)





THE LHC is a Higgs Factory

several Million Higgs already produced – more than most Higgs factory projects.
> 50 Higgs bosons / minute at 13 TeV

Difficulties: several production mechanisms to disentangle and significant systematics in the production cross-sections σ_{prod} .
Challenge will be to reduce systematics by measuring related processes.

$$\sigma_{i\to f}^{\ \ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$ → **couplings to known initial x final state, mod. total width.**

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 5×10^{-7} (30 keV) by the precision on $g_\mu - 2$ (!)
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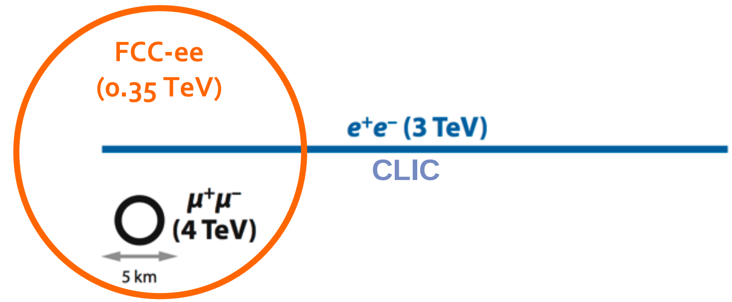
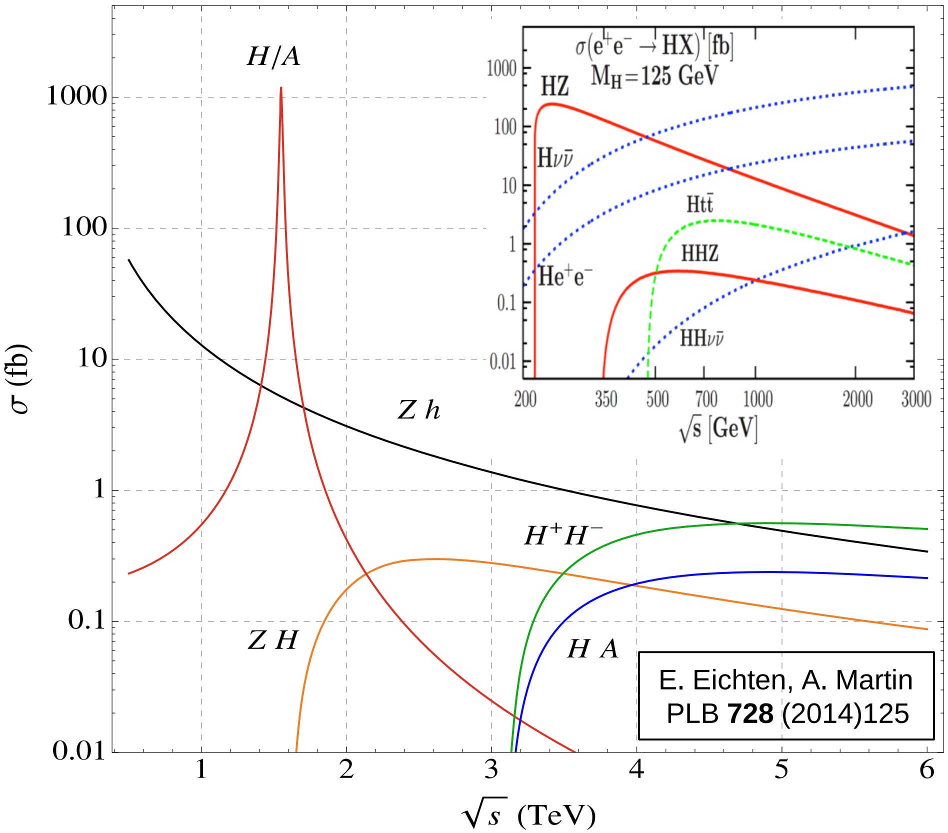
  - These uncertainties are appropriately smaller than the statistical precision
    - On the Higgs mass (60 keV)
    - On the Higgs width (170 keV)
    - On the production cross section (1.5%)

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 $\mu^+\mu^- \rightarrow$ H,A

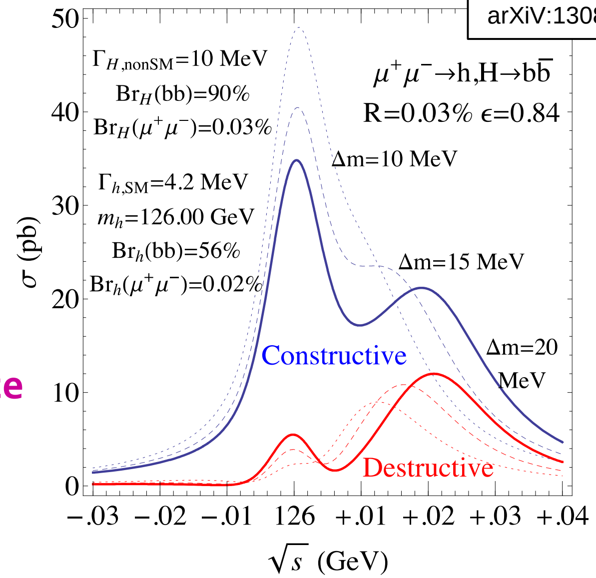
- $\sqrt{s}$ ~ 6 TeV possible in the Tevatron tunnel

Additional Higgs bosons (1)

- **Is H(125) made of several quasi-degenerate Higgs bosons ?**
  - At LHC, the typical m_H resolution in the H → ZZ* → μμ 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
      - ➔ might be visible at FCC-ee (ZH) by difference in recoil mass for different decay modes.
    - Lineshape sensitive to ΔM ~ MeV
      - ➔ If both Higgs bosons couple to μ and b/W
  - Probably observable at ILC FCC-ee via pair production with √s > 250 GeV (to be studied)
    - e^+e^- → hA present at tree level with large cross section (A pseudoscalar)
    - [e^+e^- → hH only at loop level with a few ab cross section (H scalar)]
      - ➔ A small mass difference is not measurable this way

Similar at FCC-ee (Recoil mass)

Snowmass 2013 arXiV:1308.2143

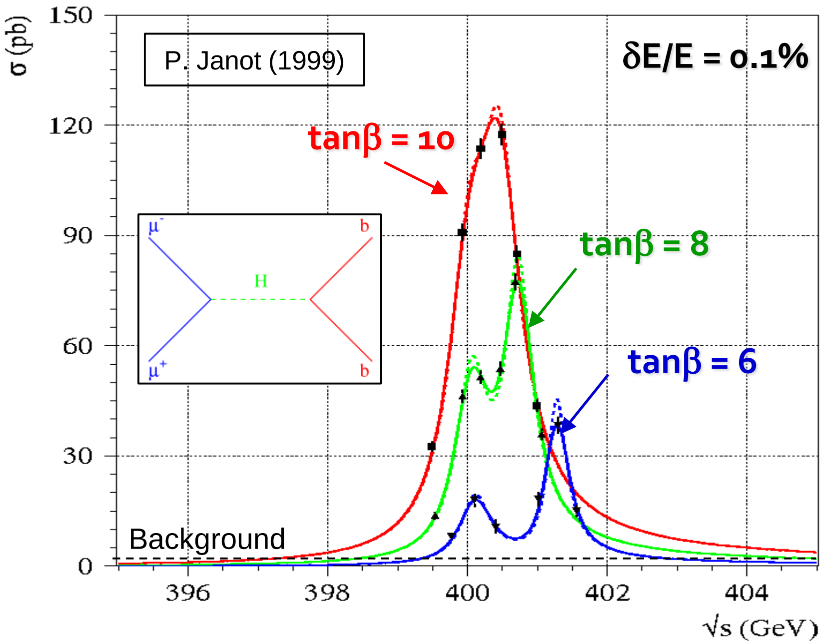


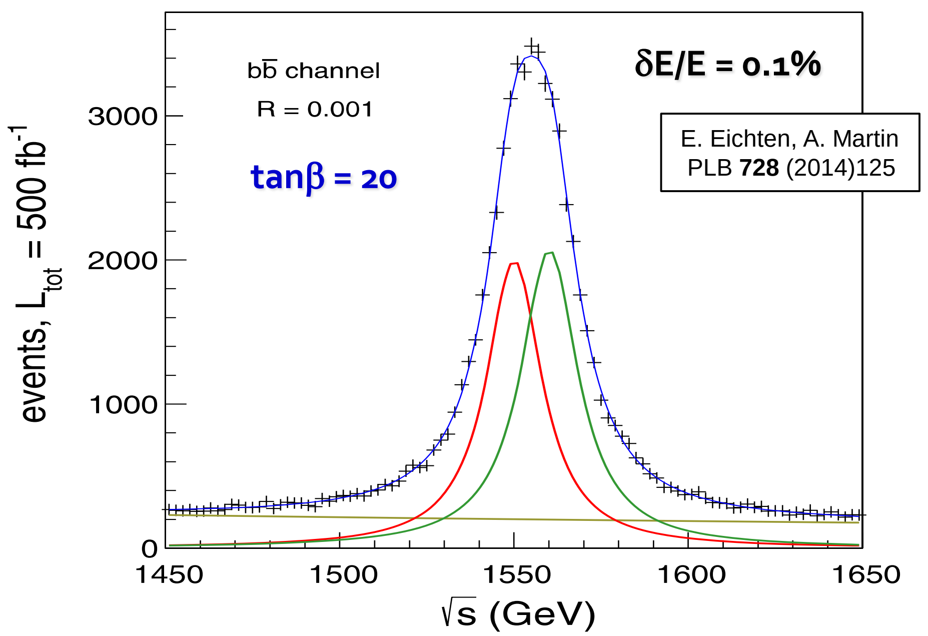
A. Djouadi et al. PRD **54** (1996) 759

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

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

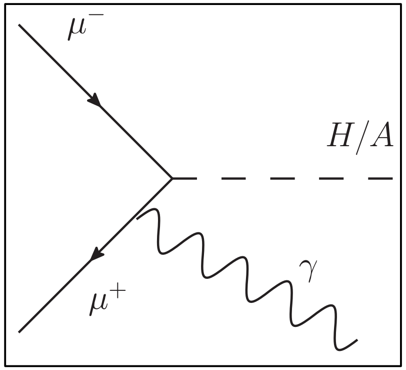




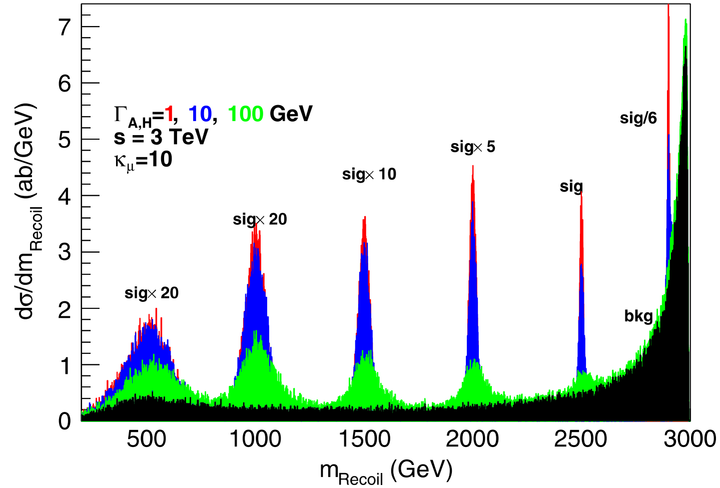
- Notes:
  - Higgs width of the order of 0.1 to 1% of the Higgs mass
    - ➔ δE/E ~ 0.1% enough, large integrated luminosities (100's fb^{-1} or ab^{-1}) possible
  - Each value of m_A correspond to a specific ring diameter
    - ➔ Need to know the mass before designing the ring!

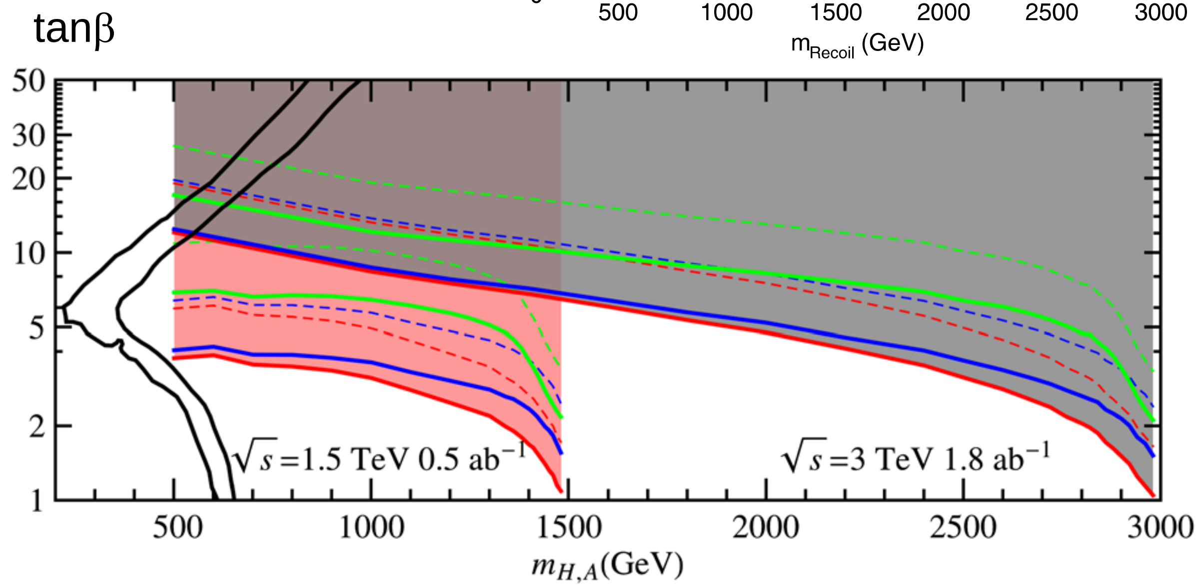
Additional Higgs bosons (3)

- **Automatic mass scan with radiative returns in μμ 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

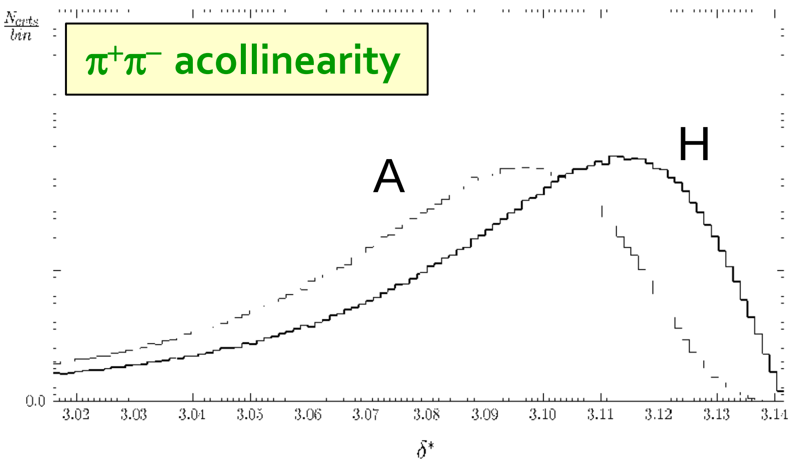




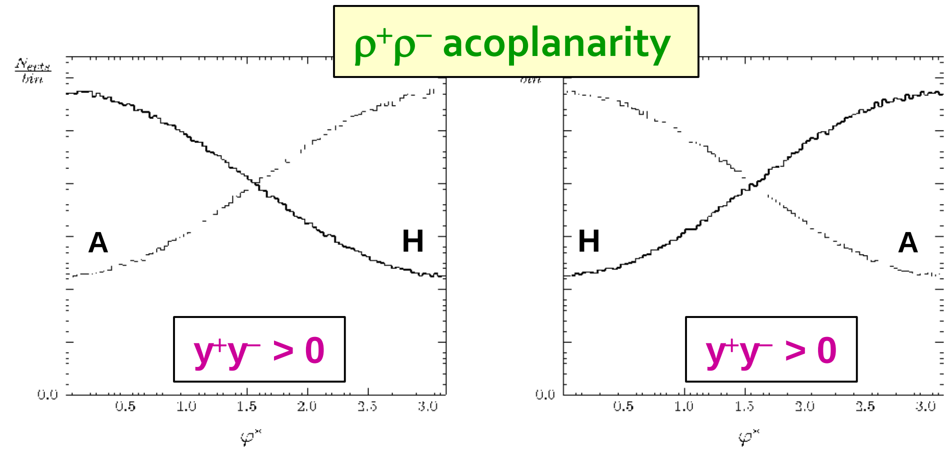
  - Can "see" H and A
    - If tanβ > 5
  - Build the next collider
    - At $\sqrt{s} \sim m_{A,H}$

Additional Higgs bosons (4)

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

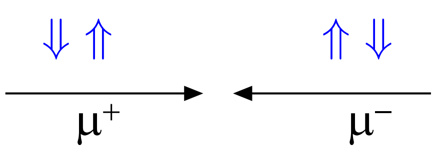


  - From H,A $\rightarrow \tau^+\tau^- \rightarrow \rho^+\rho^-\nu_\tau\nu_\tau$ with $\rho^\pm \rightarrow \pi^\pm\pi^0$



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

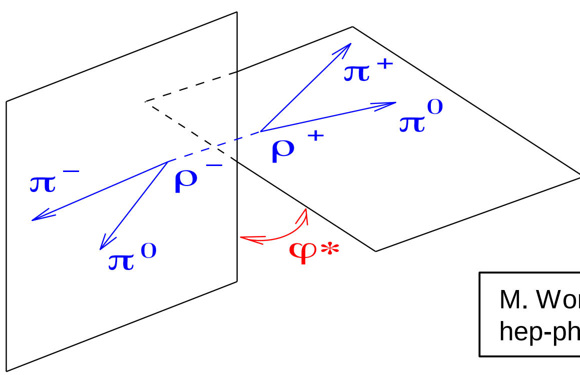
  - From beam transverse polarization



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

Experimental environment

1. the luminosity and frequency of crossings are such that
pile-up will not be a problem. Situation better than LHC/CLIC/FCC-hh

2. the main background arises from $\mu\rightarrow e\nu\nu$ decays with off momentum/axis electron radiate or hit material around the detector (low beta point is most achromatic)
10^{12} muons → 10^{9} $e^{\pm}$ produced per turn ➔ produce lots of photons and neutrons.

Shielding against these backgrounds is necessary. 10-15° cones of tungsten have been proposed seems OK. Never worse than the background at HL-LHC!
Much work to do. Situation worse than e+e- colliders.

3. luminosity measurement with $\mu\mu\rightarrow\mu\mu$ (muon equivalent to Bhabha scattering) has to be done through this shielding (probably OK, needs to be demonstrated)

4. HF design similar to that of ILC/CLIC detectors (beam constraint is more constraining)

5. High energy collider more similar to LHC

U.S. Muon Accelerator Program

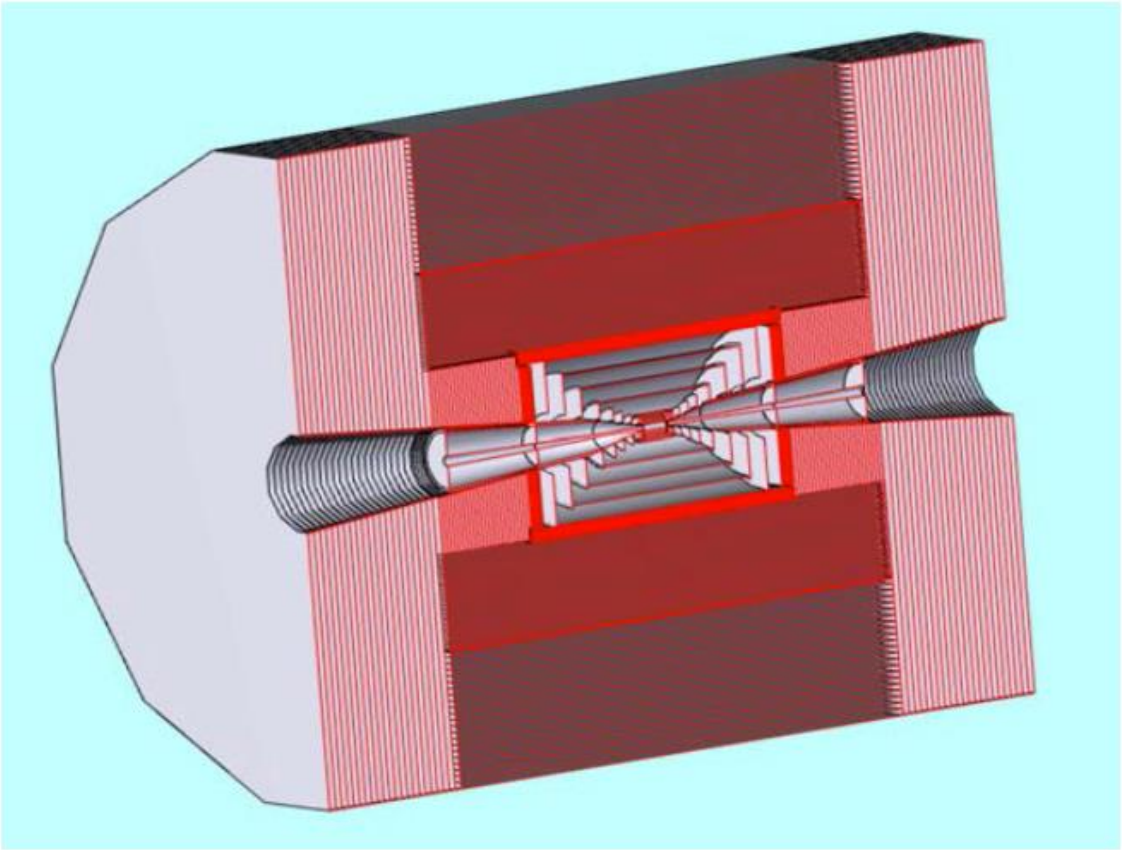


Figure 23: Cross sectional view of a possible Higgs Factory Muon Collider detector showing the tungsten cones shielding the detector from beam related backgrounds.

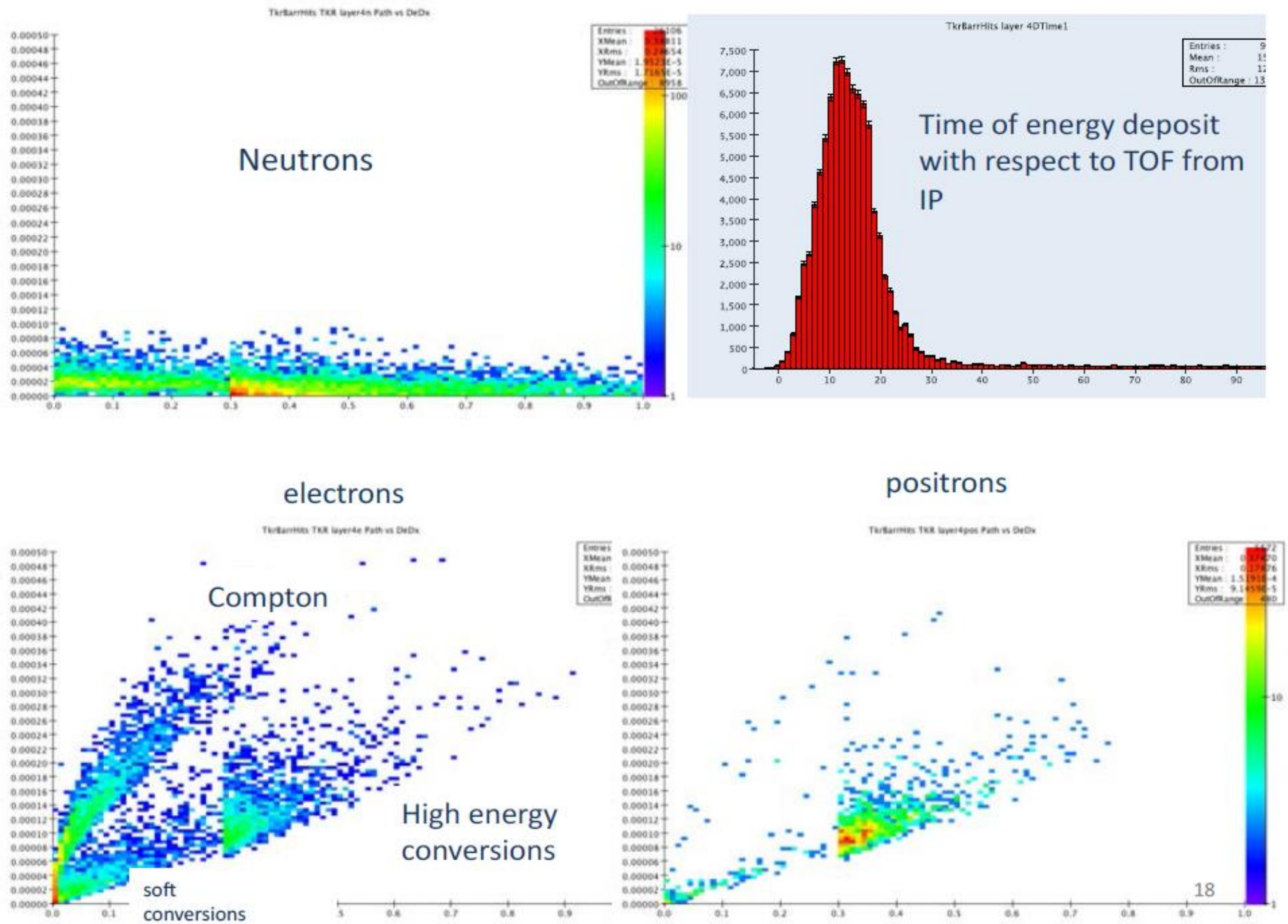


Figure 26: Contributions of various background components to signals in a barrel silicon detector layer

Silicon detectors with good spacial & timing resolution is excellent across-the-board R&D

Other physics of interest (questions)

-- What could a muon collider do for precision EW physics (Z, WW, tt)?
(broad search for physics beyond the standard model via loop corrections)
Certainly has the energy resolution. How about luminosity?

-- What could a muon collider do for right handed neutrinos?
-- neutrino counting, direct search?
possible at FCC-ee @Z w. 10^{13}Z or perhaps FCC-hh with 10^{13} W-> e,μ ν

-- Presently the case for a 'Z,W,H,top factory is quite clear,
the physics case fot higher energy (E> 400 GeV) lepton collider needs to be revisited

Summary

-- The ‘Higgs factory’ muon collider is a beautiful machine!
  -- being on s-channel is different from being at ZH threshold.
  -- However except perhaps for the case where there is a hint of some split Higgs
  with a small split (to be determined), the experimental precisions
  on Higgs parameter fall short of those of a dedicated e+e- ring.
  e+e- machines can measure the Higgs width!

-- The case of other precision measurements in muon collider should be revisited

-- There seems to be a unique case in a tow-higgs-doublet situation,
  and possible cases for Z’, new threshold to scan etc...

-- The muon collider is the best in town for high energy lepton collider up to?10TeV?
starting at a point that depends on achievable luminosity.
A factor 5 in Luminosity would make muon collider the winner from 400 GeV upwards
The physics case for lepton collider much above 400 GeV needs to be revisited

-- the experimental conditions are tough and should be carefully studied.
However things seem comparable than at LHC (easier because of bunch spacing)

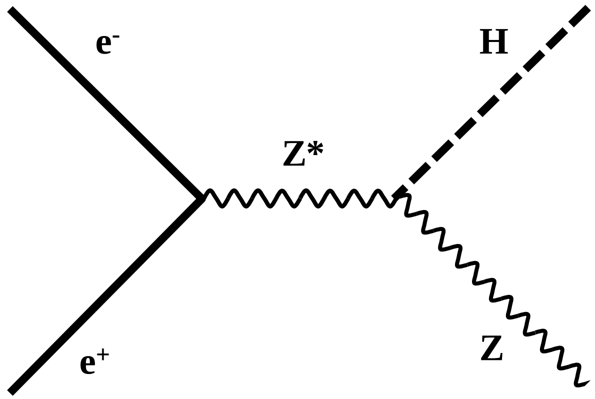
SPARES

e+ e- special Higgs production mechanism

“higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold ~200 fb

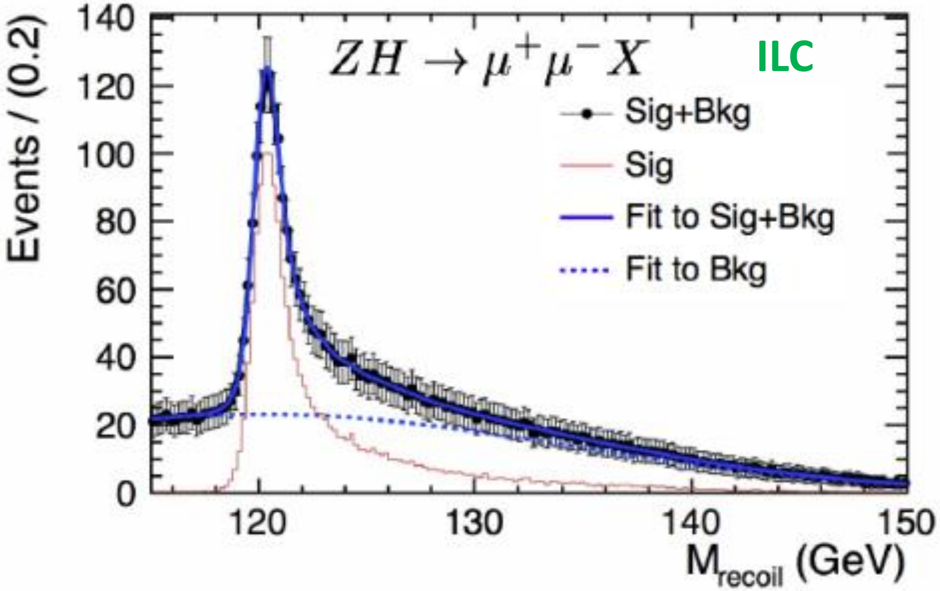
$10^{34}/cm^2/s$ ➔ 20’000 HZ events per year.



Z – tagging
by missing mass

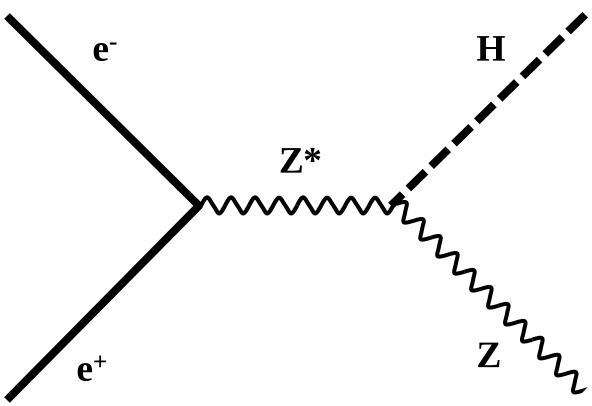
can do that with muon of course.

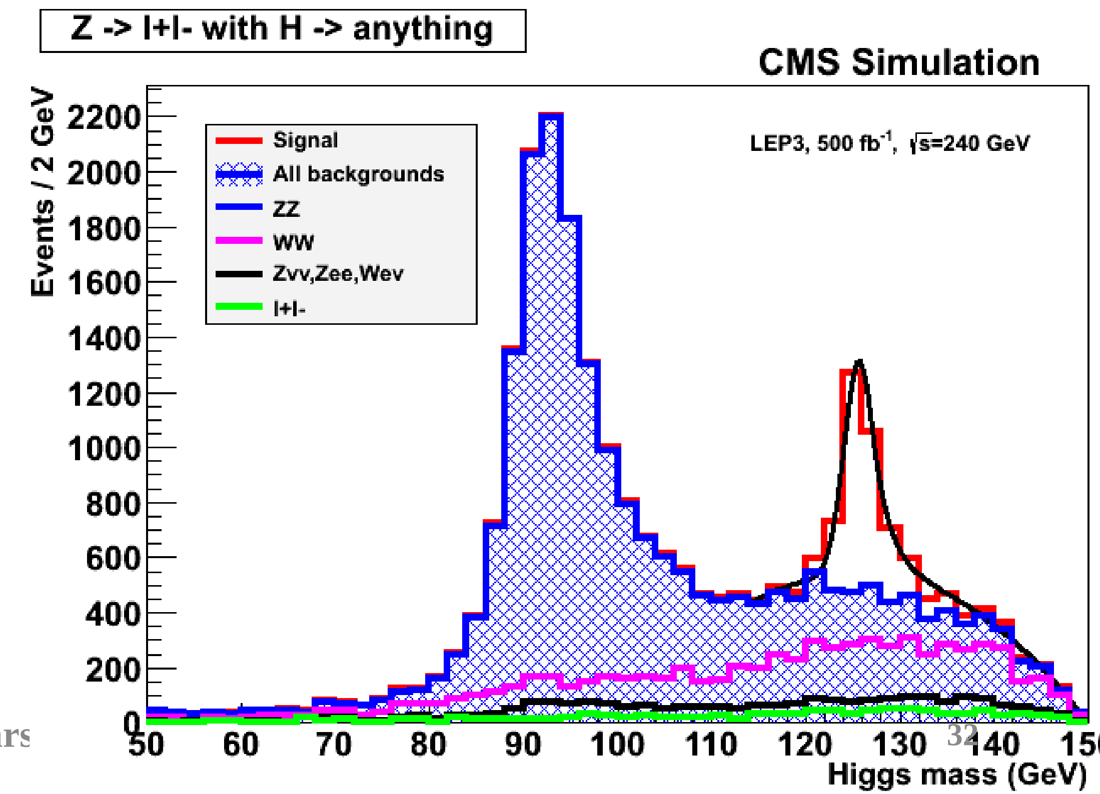
For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient
➔ kinematical constraint near threshold for high precision in mass, width, selection purity



Z – tagging
by missing mass

total rate ∝ g_{HZZ}^2
ZZZ final state ∝ g_{HZZ}^4 / Γ_H
➔ measure total width Γ_H
empty recoil = invisible width
'funny recoil' = exotic Higgs decay
easy control below theshold





FCC-ee as Higgs factory

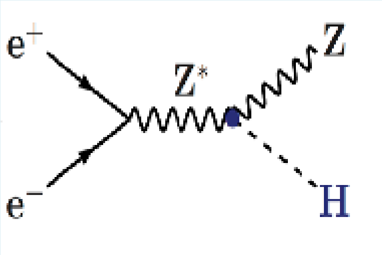
(constrained fit including 'exotic')

	4 IPs TLEP	(2 IPs)
g_{HZZ}	0.05%	(0.06%)
g_{HWW}	0.09%	(0.11%)
g_{Hbb}	0.19%	(0.23%)
g_{Hcc}	0.68%	(0.84%)
g_{Hgg}	0.79%	(0.97%)
$g_{H\tau\tau}$	0.49%	(0.60%)
$g_{H\mu\mu}$	6.2%	(7.6%)
$g_{H\gamma\gamma}$	1.4%	(1.7%)
BR_{exo}	0.16%	(0.20%)

→ *total width* <1%

HHH (best at FCC-hh) 28% → from HZ thresh

Htt (best at FCC-hh) 13% → from tt thresh



2 10^6 ZH events in 5 years

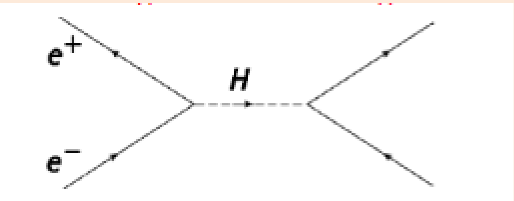
«A tagged Higgs beam».

sensitive to new physics in loops

incl. invisible = (dark matter?)
NB leptonic tag only.
Will improve with Hadronic Z tag

A big challenge:

Higgs s-channel production at $\sqrt{s} = m_H$



10^4 events per year. limits or signal?

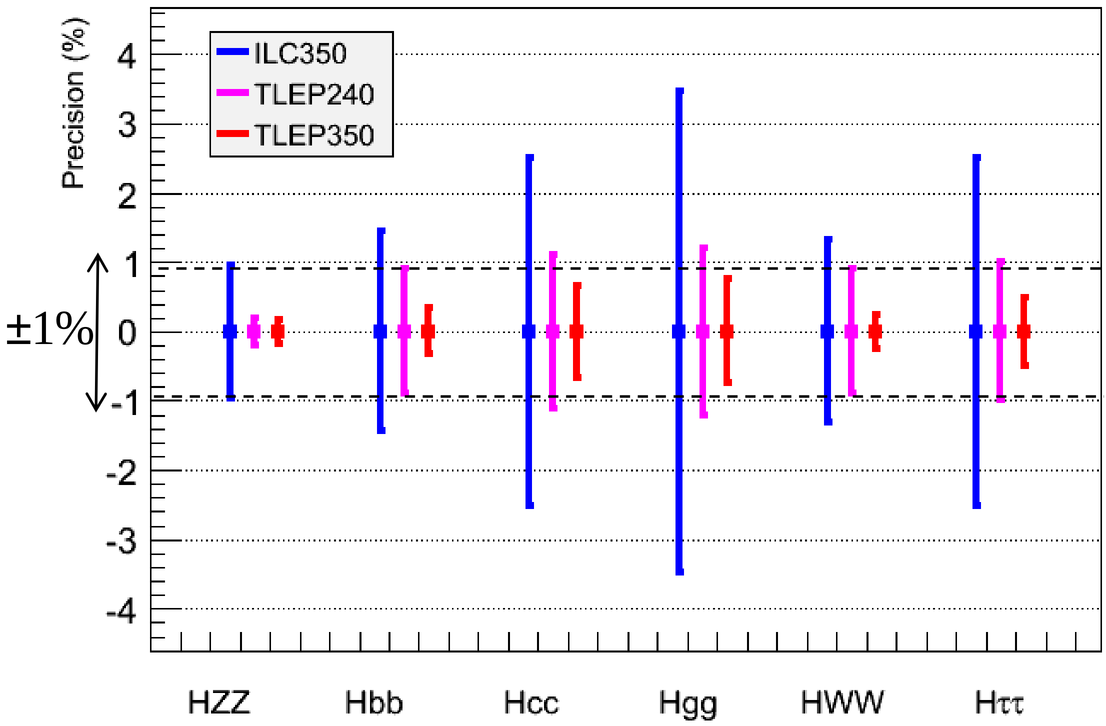
monochromators?

Aleksan, D'Enterria, Woijcik

Performance Comparison

$$\sigma_{HZ} \propto g^2_{HZZ}, \text{ and } \sigma_{HZ,WW\to H} \times \mathrm{BR}(H \to XX) \propto g^2_{HZZ,HWW}\, g^2_{HXX} / \Gamma_H$$

- Same conclusion when Γ_H is a free parameter in the fit

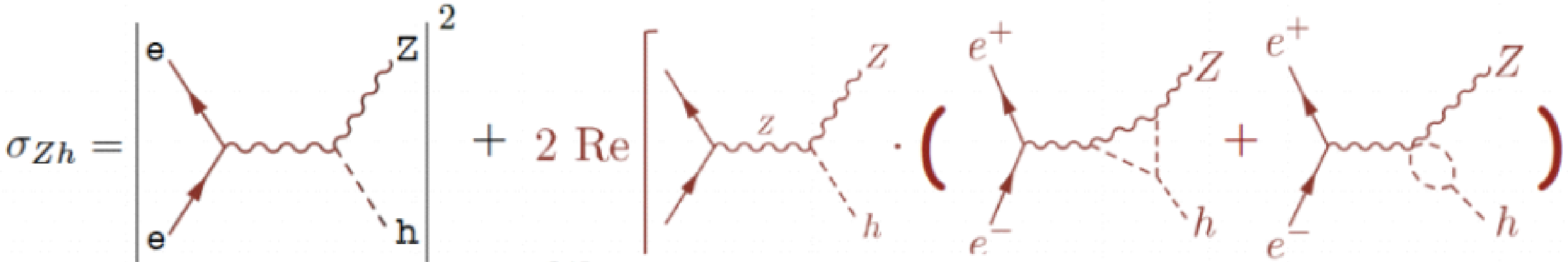


Expected precision on the total width

$\mu^+\mu^-$	ILC350	ILC1000	TLEP240	TLEP350
5%	5%	3%	2%	1%

TLEP : sub-percent precision, BSM Physics sensitivity beyond several TeV

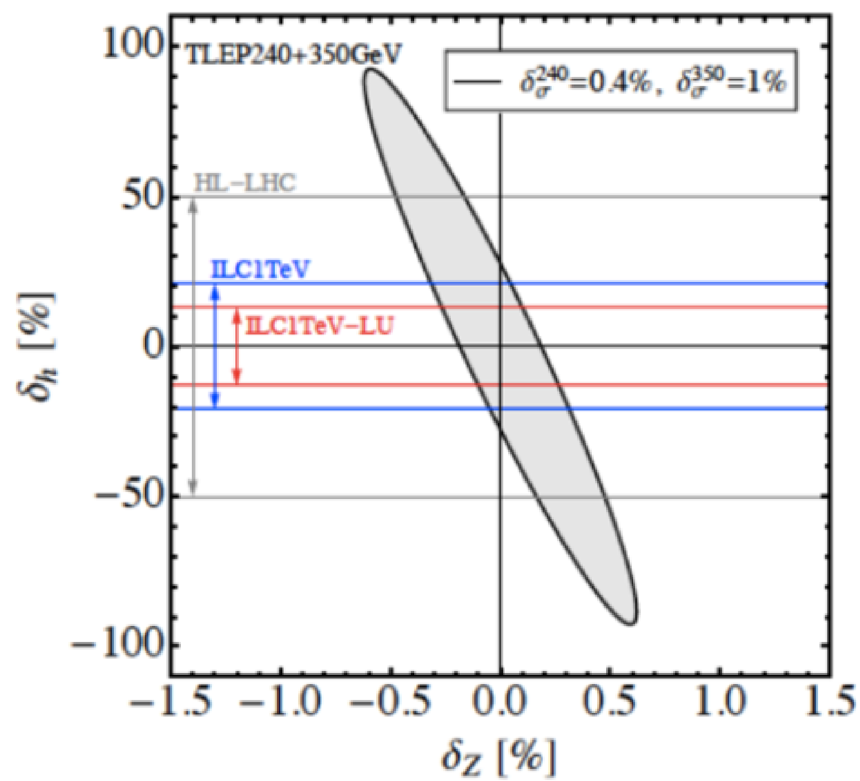
very accurate precision on threshold cross-section sensitive to loop corrections



$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$

arxiv:1312.3322

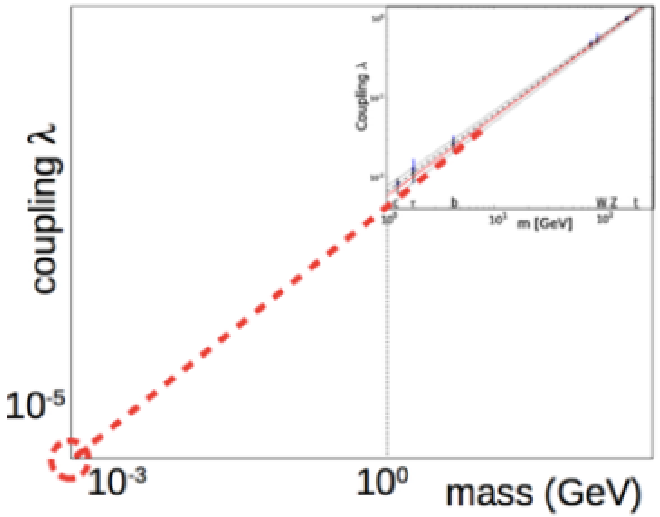
- ➡ Very large datasets at high energy allow extreme precision g_{ZH} measurements
- ➡ Indirect and model-dependent probe of Higgs self-coupling
- ➡ Note, the time axis is missing from the plot

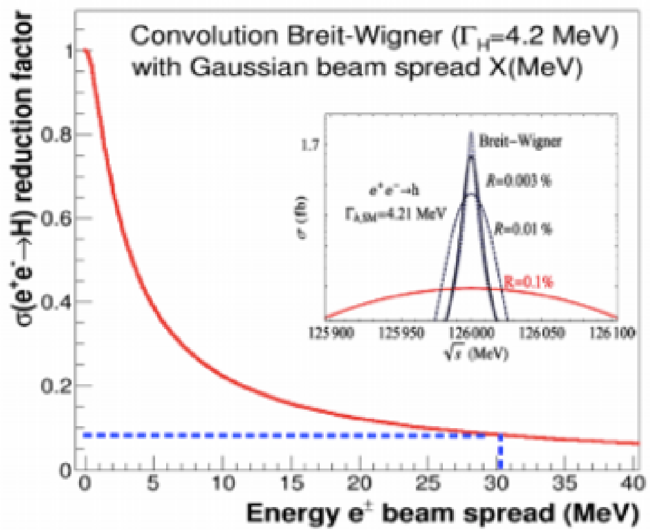


19

First generation couplings

- **s-channel Higgs production**
  - Unique opportunity for measurement close to SM sensitivity
  - Highly challenging; σ(ee→H) = 1.6fb; 7 Higgs decay channels studied





Preliminary Results

$L = 10\ ab^{-1}$

$\kappa_e < 2.2$ at 3σ

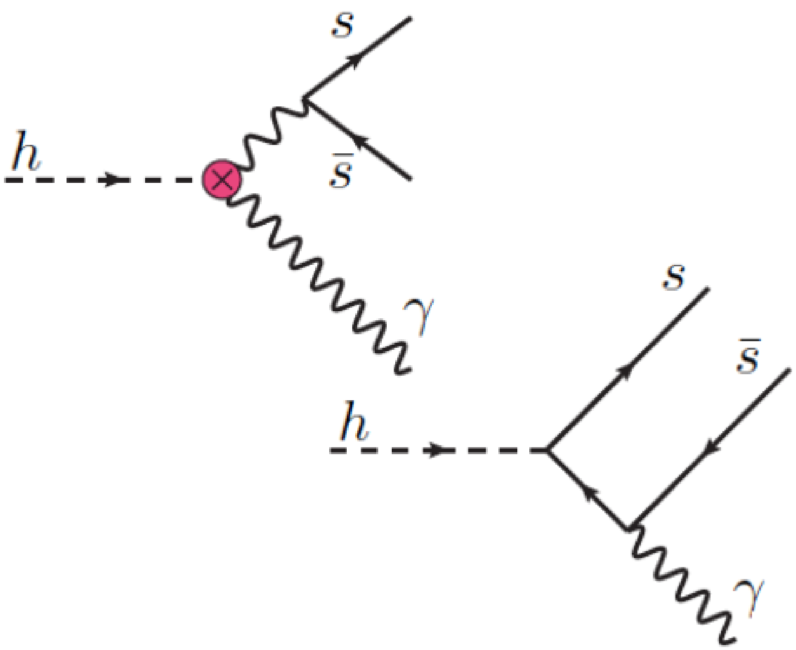
- **Work in progress**
  - How large are loop induced corrections? How large are BSM effects?
  - Do we need an energy scan to find the Higgs?
  - How much luminosity will be available for this measurement? By how much is the luminosity reduced by monochromators?

Exclusive Higgs boson decays

- ➡ First and second generation couplings accessible
  - Study of $\rho\gamma$ channel most promising; expect ~50 evts.
  - Sensitivity to u/d quark Yukawa coupling
  - Sensitivity due to interference

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times 10^{-5}$$

- ➡ Also interesting to FCC-hh program
- ➡ Alternative H→MV decays should be studied (V= γ, W, and Z)



H → J/Ψ γ ➡ y_c

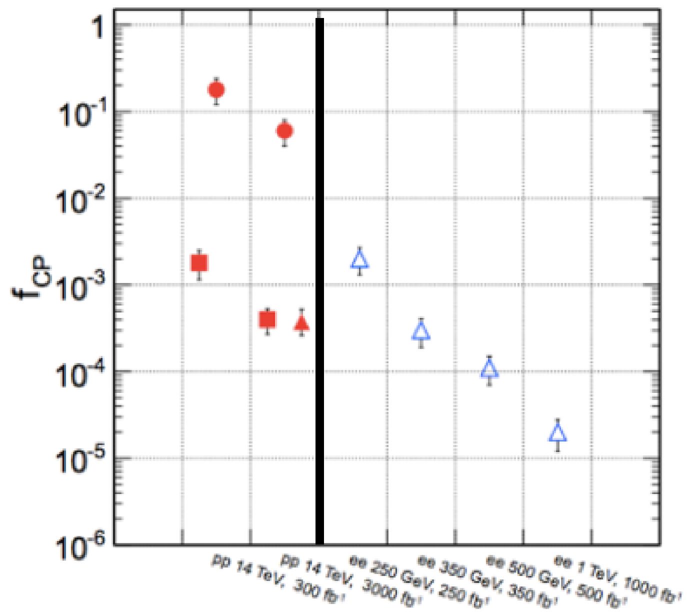
H → ϕ γ ➡ y_s

H → ρ γ, H → ω γ ➡ y_u, y_d

CP Measurements

- ➡ CP violation can be studied by searching for CP-odd contributions; CP-even already established
- ➡ Snowmass Higgs paper http://arxiv.org/abs/1310.8361
- ➡ Higgs to Tau decays of interest
- ➡ More detailed presentation by Felix Yu http://arxiv.org/abs/1308.1094

for HVV couplings



$$\mathcal{L}_{hff} \propto h\bar{f}(\cos\Delta + i\gamma_5 \sin\Delta) f$$

Colliders	LHC	HL-LHC	FCCee (1 ab^{-1})	FCCee (5 ab^{-1})	FCCee (10 ab^{-1})
Accuracy(1σ)	25°	8.0°	5.5°	2.5°	1.7°

Rare and Exotics Higgs Bosons

- 2,000,000 ZH events allow for detailed studies of rare and exotic decays
  - requires hadronic and invisible Z decays
  - set requirements for FCC-ee detector
- Coupling measurements have sensitivity to BSM decays
- Dedicated studies using specific final states improve sensitivity
- Example: Higgs to invisible, flavor violating Higgs, and many more
- Potential at the LHC (and HL-LHC) currently not fully explored
- Modes with of limited LHC sensitivity are of particular importance to FCC-ee program
  - currently under study
- FCC-ee might allow precision measurement of exotic Higgs decays
- Detailed discussion of exotic Higgs decays at Phys. Rev. D 90, 075004 (2014) More from David Curtin

$h \to \not{E}_T$

$h \to 4b$

$h \to 2b2\tau$

$h \to 2b2\mu$

$h \to 4\tau, 2\tau 2\mu$

$h \to 4j$

$h \to 2\gamma 2j$

$h \to 4\gamma$

$h \to ZZ_D, Za \to 4\ell$

$h \to Z_D Z_D \to 4\ell$

$h \to \gamma + \not{E}_T$

$h \to 2\gamma + \not{E}_T$

$h \to$ 4 ISOLATED LEPTONS $+ \not{E}_T$

$h \to 2\ell + \not{E}_T$

$h \to$ ONE LEPTON-JET + X

$h \to$ TWO LEPTON-JETS + X

$h \to b\bar{b} + \not{E}_T$

$h \to \tau^+\tau^- + \not{E}_T$

TERA-Z, Oku-W, Megatops

Precision tests of the closure of the Standard Model

Best-of ee-FCC/TLEP #2: Precision EW measts

Assets:

-- high luminosity ($10^{12/13}$ Z decays + 10^8 Wpairs + 10^6 top pairs)

-- exquiste energy calibration up and above WW threshold

target precisions

Quantity	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty
m_Z (keV)	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV
Γ_Z (keV)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV
R_ℓ	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001
N_ν	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004
N_ν	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001
R_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060
A_{LR}	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015
m_W (MeV)	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV
m_{top} (MeV)	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV

Also -- $\Delta\sin^2\theta_W$ eff ≈ 510^{-6} from $A_{FB}^{\mu\mu}$ at the Z pole.

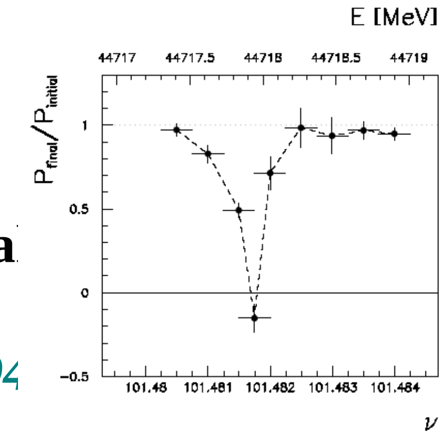
-- $\Delta\alpha_S$= 0.0001 from W and Z hadronic widths

-- $\Delta\alpha_{QED}$(Mz)= 0.00002 from Z line shape extended scan

-- orders of magnitude on FCNCs and rare decays etc. etc.

Design study to establish possibility of corresponding precision theoretical calculations.

Beam polarization and E-calibration @ FCC-ee



Precise meast of E_{beam} by resonant depolarization
~100 keV each time the meast is made

At LEP transverse polarization was achieved routinely at Z pea
instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in March 1994

FCC-ee: use 'single' bunches to measure the beam energy continuously
no interpolation errors due to tides, ground motion or trains etc…
but saw-toothing must be well understood! **require Wigglers to speed up pol. time**

At LEP beam energy spread destroyed polarization above 60 GeV
$\sigma_E \propto E^2/\sqrt{\rho}$ ➔ **At FCC-ee transverse polarization up to at least 80 GeV**
to go to much higher energies requires spin rotators and siberian snake

<< 100 keV beam energy calibration around Z peak and W pair threshold.
Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

Polarization in collisions was observed *(40% at BBTS = 0.04)*

Theoretical limitations

FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm \ldots 6_{m_t} \pm \ldots 6_{M_Z} \pm \ldots 8_{\Delta\alpha_{had}}$$
$$\pm \ldots 7_{\alpha_S} \pm \ldots 2_{M_H} \pm 0.0040_{theo}$$
$$= 80.359 \pm 0.011_{tot}$$

0.0005 (over m_t) **0.0001** (over M_Z) **0.0005?** (over $\Delta\alpha_{had}$)

0.0005? (over α_S) **0.0000** (over M_H)

0.0005 - 0.001

$$\sin^2\theta^{\ell}_{eff} = 0.231496 \pm \ldots 0_{m_t} \pm \ldots 5_{M_Z} \pm \ldots 35_{\Delta\alpha_{had}}$$
$$\pm \ldots 0_{\alpha_S} \pm \ldots 2_{M_H} \pm 0.000047_{theo}$$
$$= 0.23150 \pm 0.00010_{tot}$$

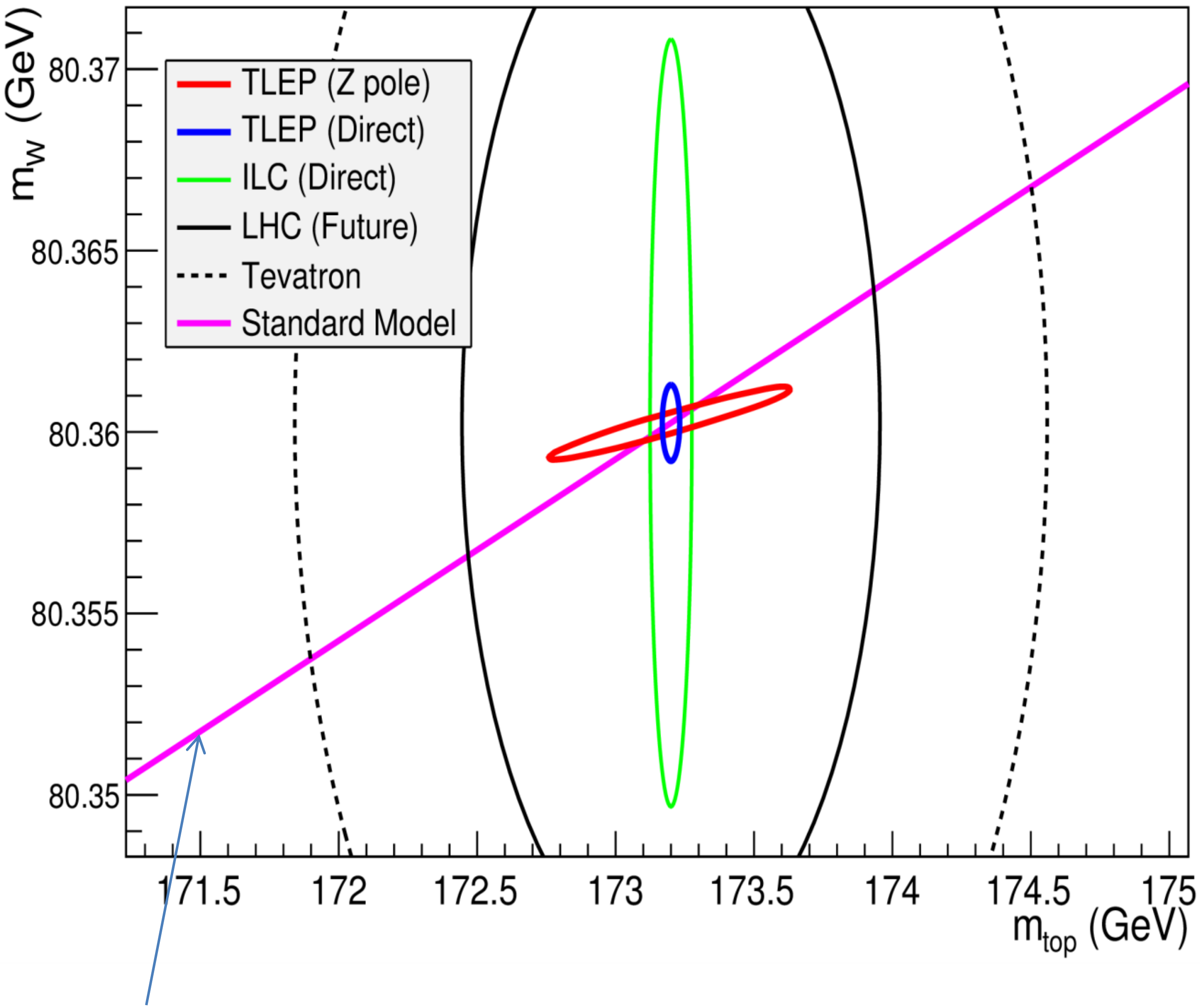
0.000003 (over m_t) **0.000001** (over M_Z) **0.000003?** (over $\Delta\alpha_{had}$)

0.000001? (over α_S) **0.000000** (over M_H)

0.000002

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.

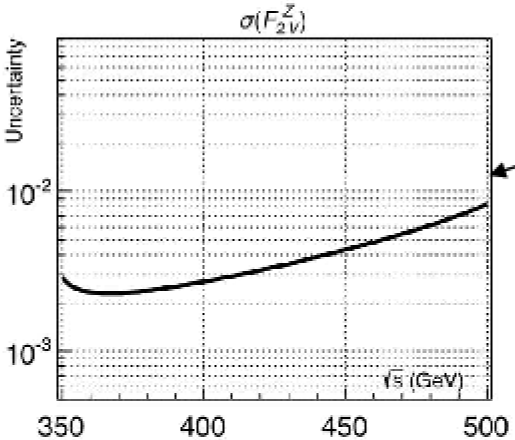
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!
Radiative correction workshop 13-14 July 2015



NB without TLEP the SM line would have a 2.2 MeV width

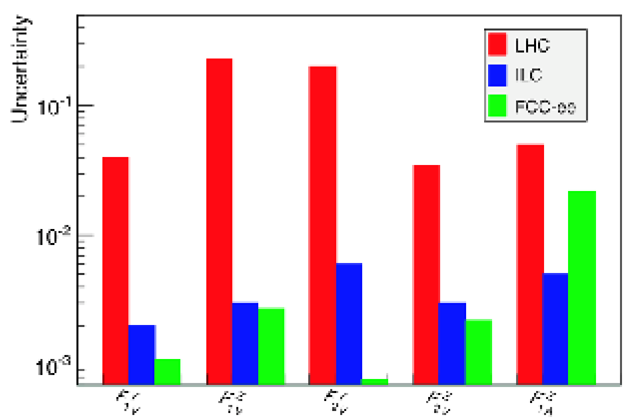
in other words .... $\Delta(\Delta\rho) = \pm\, 10^{-5}$ + several tests of same precision

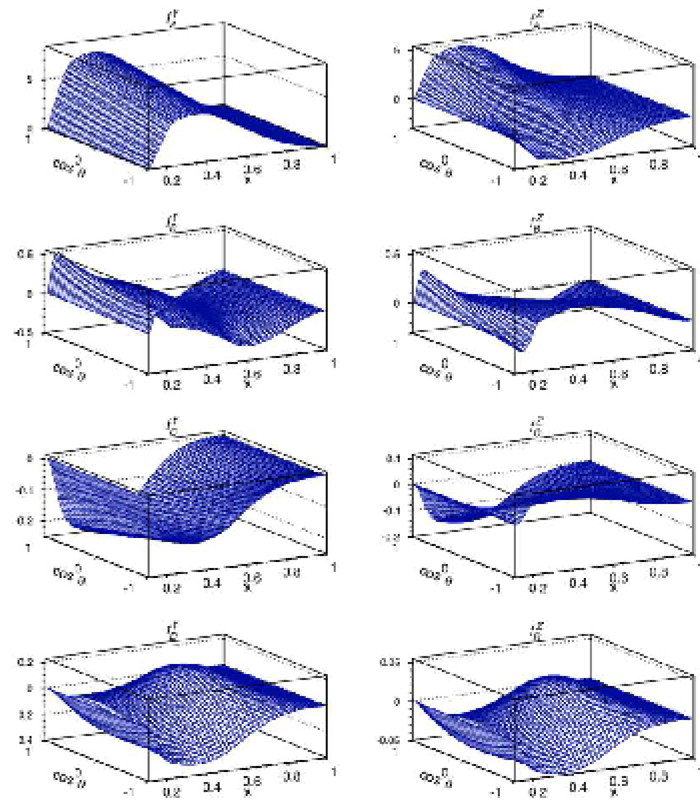
Determination of top-quark EW couplings via measurement of top-quark polarization.
In semileptonic decays, fit to lepton momentum vs scattering angle

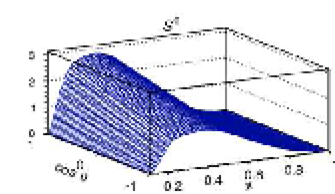


Typically best sensitivity just above production threshold

Momenta up to: 175 GeV







Patrick Janot
arXiv:1503.01325v2

Neutrino counting at TLEP

given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \rightarrow ee,\mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma e,\mu}\,(SM)}$$

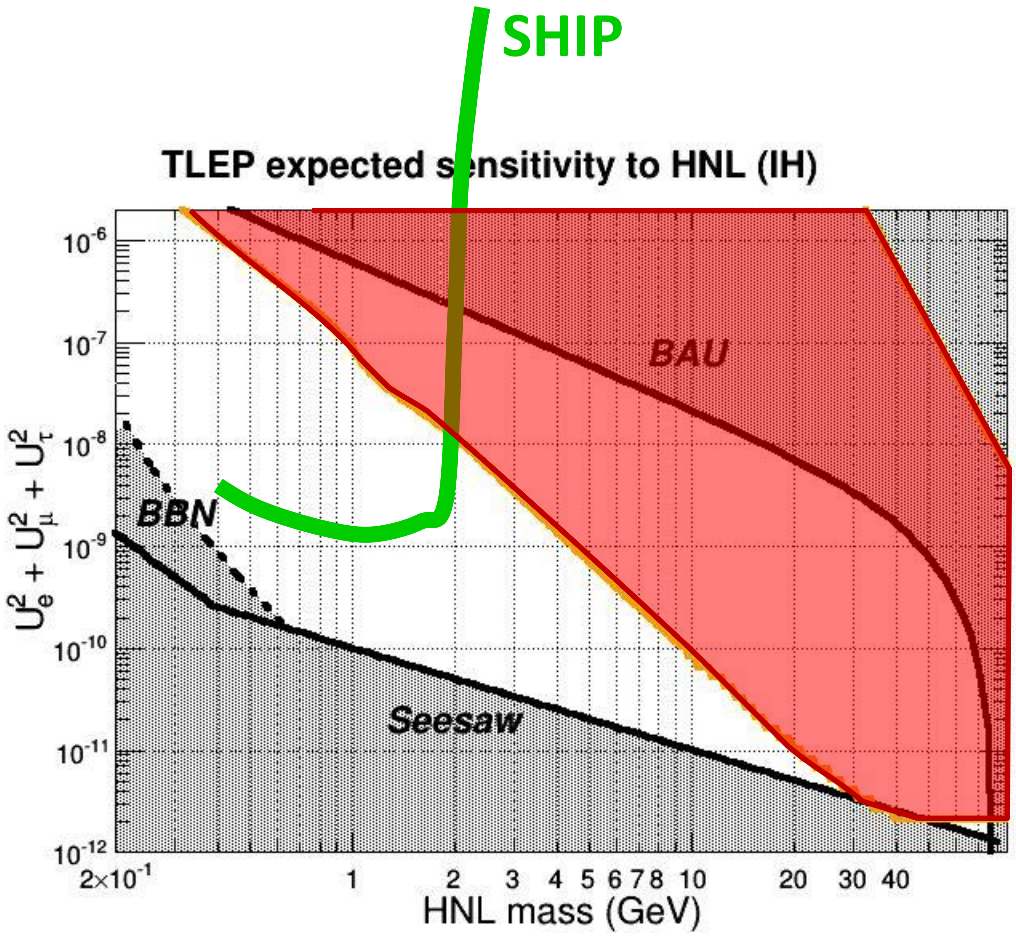
The common γ tag allows cancellation of systematics due to photon selection, luminosity etc. The others are extremely well known due to the availability of $O(10^{12})$ Z decays.

The full sensitivity to the number of neutrinos is restored , and the theory uncertainty on $\frac{\Gamma_\nu}{\Gamma_e}(SM)$ is very very small.

A good measurement can be made from the data accumulated at the WW threshold where σ (γ Z(inv)) ~4 pb for $|\cos\theta_\gamma| < 0.95$

161 GeV (10^7 s) running at $1.6\times10^{35}/cm^2/s$ x 4 exp ➔ 3×10^7 γ Z(inv) evts, ΔN_ν=0.0011
adding 5 yrs data at 240 and 350 GeV .... ΔN_ν=0.0008

A better point may be 105 GeV (20pb and higher luminosity) may allow ΔN_ν=0.0004?



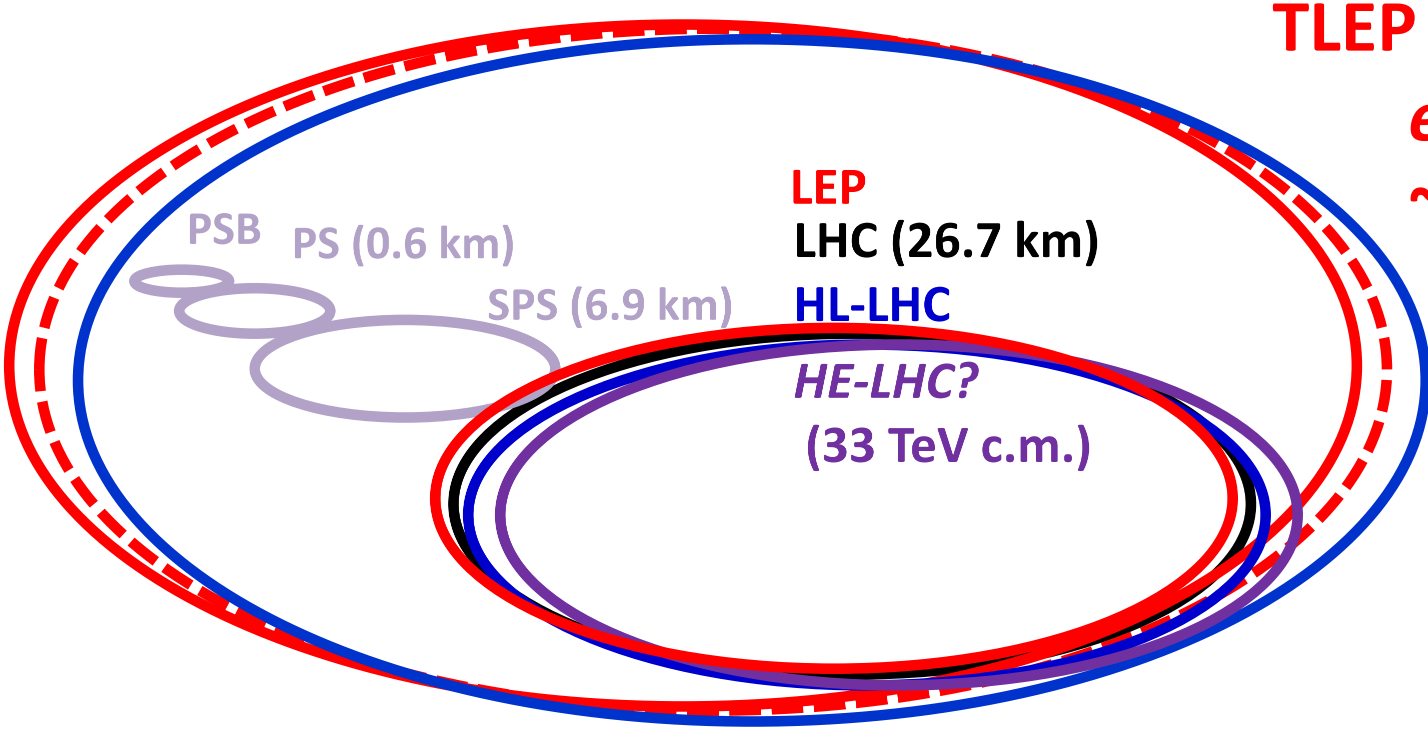
$N_Z = 10^{13}$ $100\mu m$ <L<5m

region of interest

FCC-ee sensitivity

NB very large detector caverns for FCC-hh may allow very large FCC-ee detector (R=15m?) leading to improved reach at lower masses.

possible long-term strategy



TLEP (80-100 km, e^+e^-, up to ~350 GeV c.m.)

VHE-LHC (*pp*, up to 100 TeV c.m.)

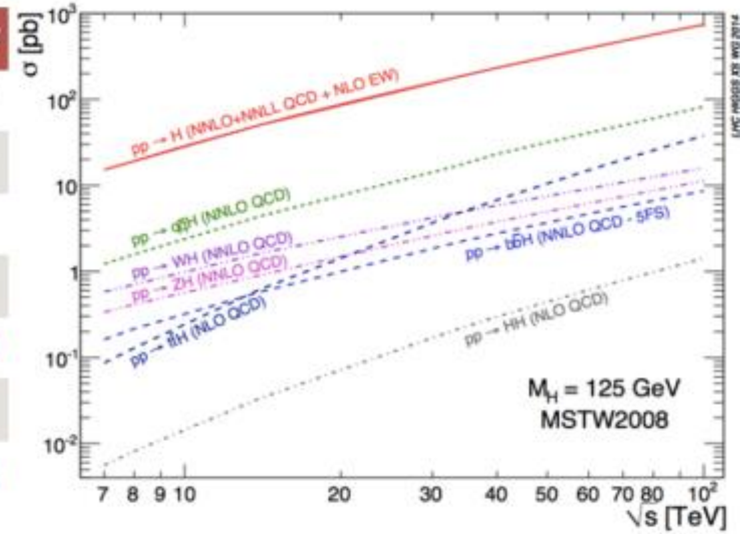
"same" detectors!?

& ***e***$^{\pm}$ **(120 GeV)–*p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC**)

≥60 years of e^+e^-, *pp*, *ep/A* physics at highest energies

HIGGS AT FCC-pp

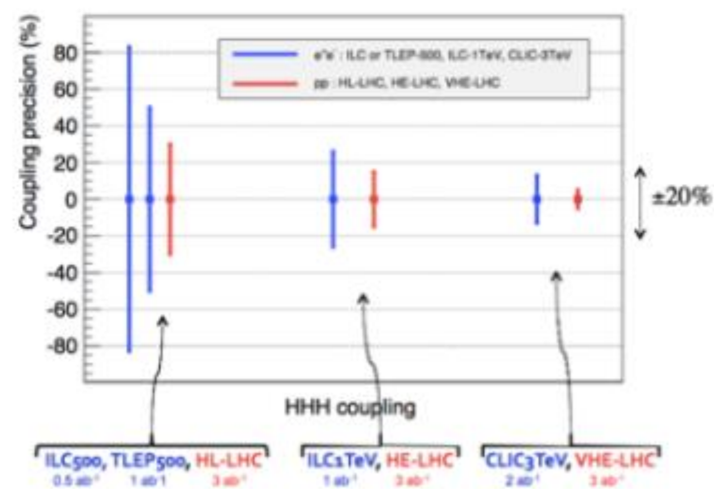
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Proton-proton Higgs datasets **LHC Run I** → x300-600 → **HL LHC** → x10-400 → **FCC pp**

	HL-LHC	HE-LHC	VLHC
$\sqrt{s}$ (TeV)	14	33	100
$\int \mathcal{L}dt$ (fb^{-1})	3000	3000	3000
$\sigma \cdot \text{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

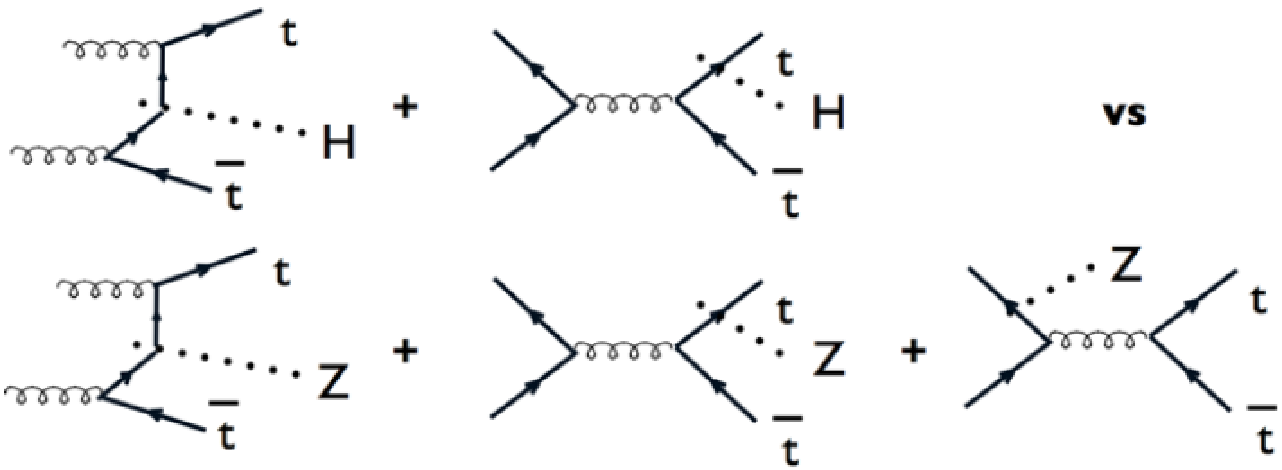
arXiv:1310.8361



10

➡ … but also new measurements not possible at the LHC/HL-LHC

ttH / ttZ



➡ Theoretical uncertainties cancel mostly

- PDF (CTEQ 6.6) ± 0.5%
- Missing higher orders ± 1.2%

➡ One can not conclude that one can measure the cross section ratio with ~2% ($\delta\lambda_{top} \cong$ 1%) precision. **More detailed studies are ongoing.**

➔ Lots of statistics and ideas for small systematics

Table from D. Curtin FCC workshop, Washington, 23-27 March 2015)

- Both lepton and 100 TeV pp colliders are vital for this effort!

Observables at Current + Future Colliders	100 TeV	ILC/TLEP
• producing extra higgs states (incl. superpartners)	✓	
• Exotic Higgs Decays	✓	✓
• Electroweak Precision Observables		✓
• Higgs coupling measurements	(✓)	✓
• Higgs portal direct production of new states	✓	
• Higgs self coupling measurements	✓	(✓)
• Zh cross section measurements		✓

Higgs invisible decays

Right handed Neutrinos
etc.. etc..

THE COMBINATION of FCC-ee and FCC-hh IS INVINCIBLE

There are a number of issues with the cooling rings as proposed:

1. Kickers! Injecting large beams into very focused ring requires very strong kickers
   -- this is the main reason for cooling rings to have been left aside since 2003.

2. Magnetic lattice and interference between solenoids

3. stability and other requirements for PIC method need to be asserted.

4. factor of 10 in emittance cooling leads to factor of 10 in luminosity

both constraints lead to larger, less focused rings for realistic set-ups
→ some loss of luminosity

Other issues with muon collider as Higgs factory

1. requires not only small energy spread but shot-to-shot reproducibility of energy at the level of 3 10^{-5} (monitoring OK)

2. Even with factor of 10 in luminosity (→23000 H), still 1(resp 2) orders of magnitude short of e+e- colliders like ILC (resp FCC-ee)