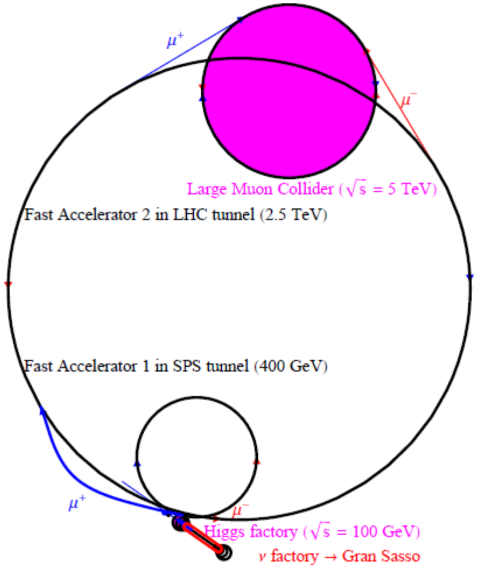
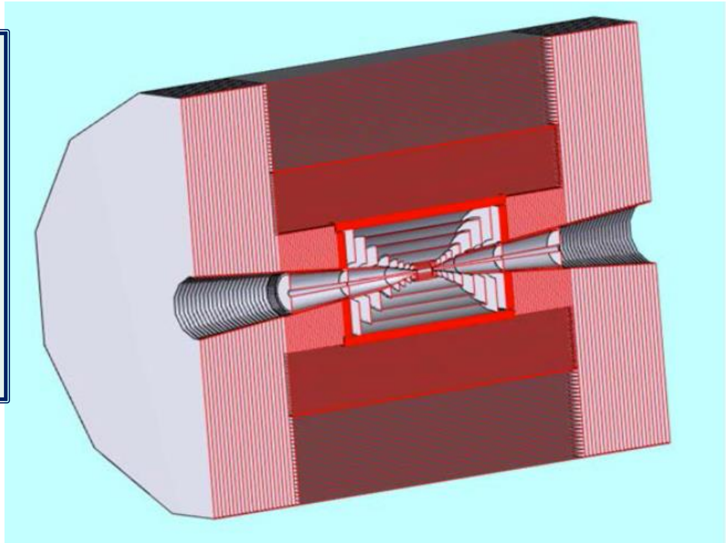
Experiments at Muon colliders
as Higgs Factories

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

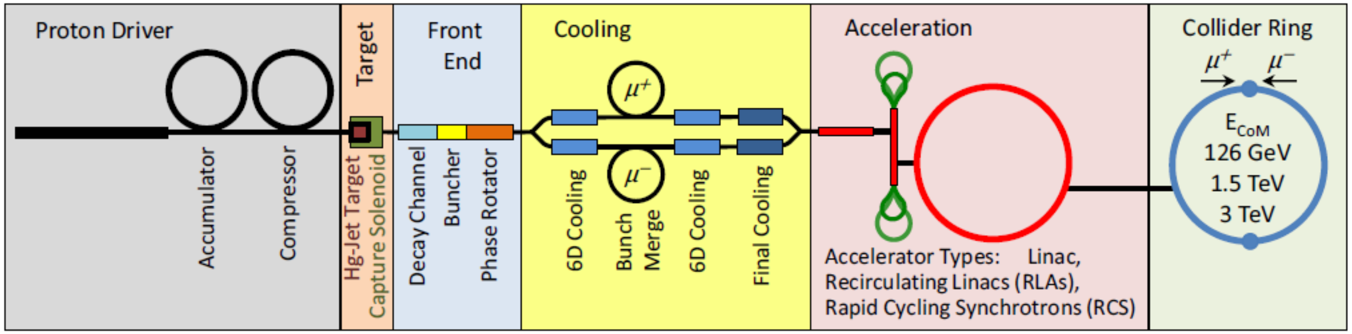


- Higgs physics
- Precision measurements
- Higher masses
- Experimental environment
- What can a muon collider do .... and not do?



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

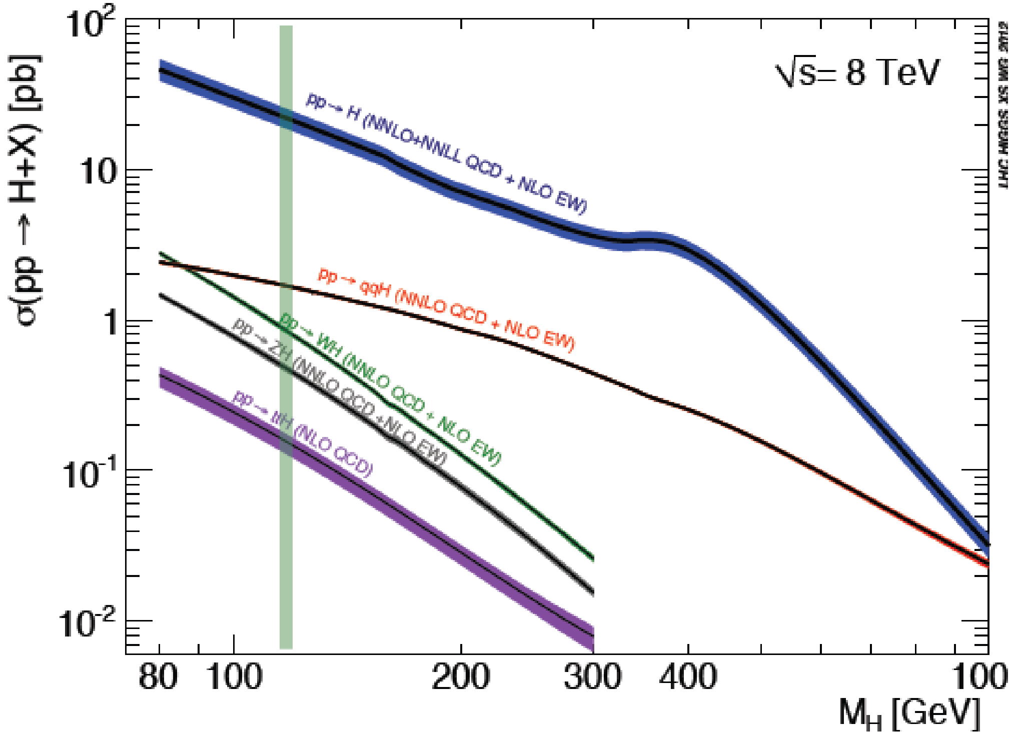
U.S. Muon Accelerator Program

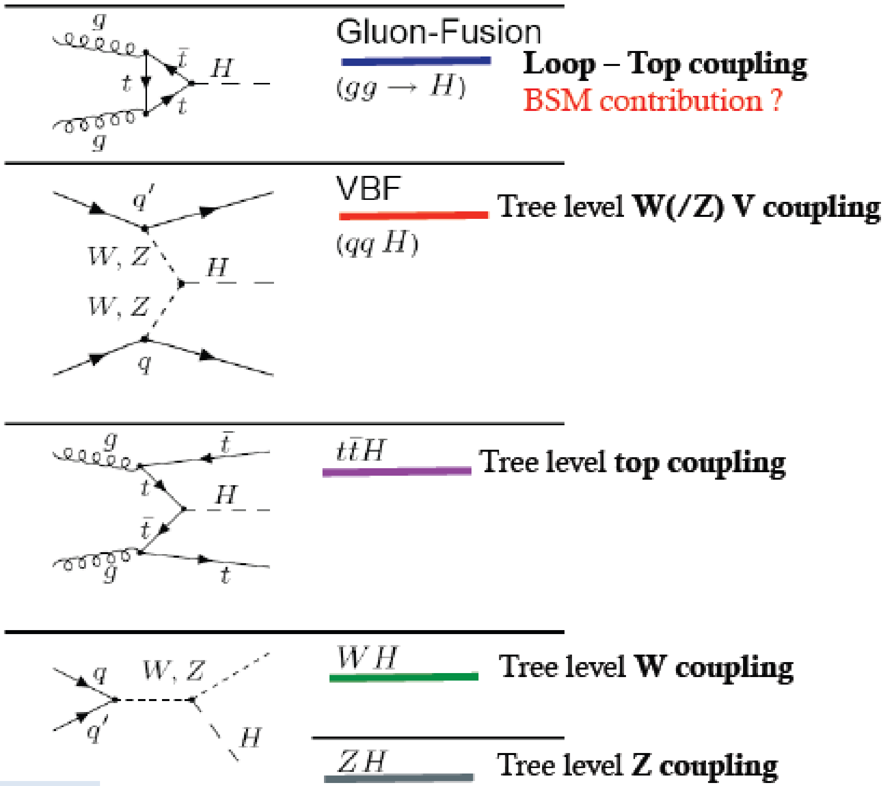


arxiv:1308.0494

HIGGS FACTORY

Higgs provides a very good reason why we need a lepton (e+e- or $\mu\mu$) collider





THE LHC is a Higgs Factory…BUT

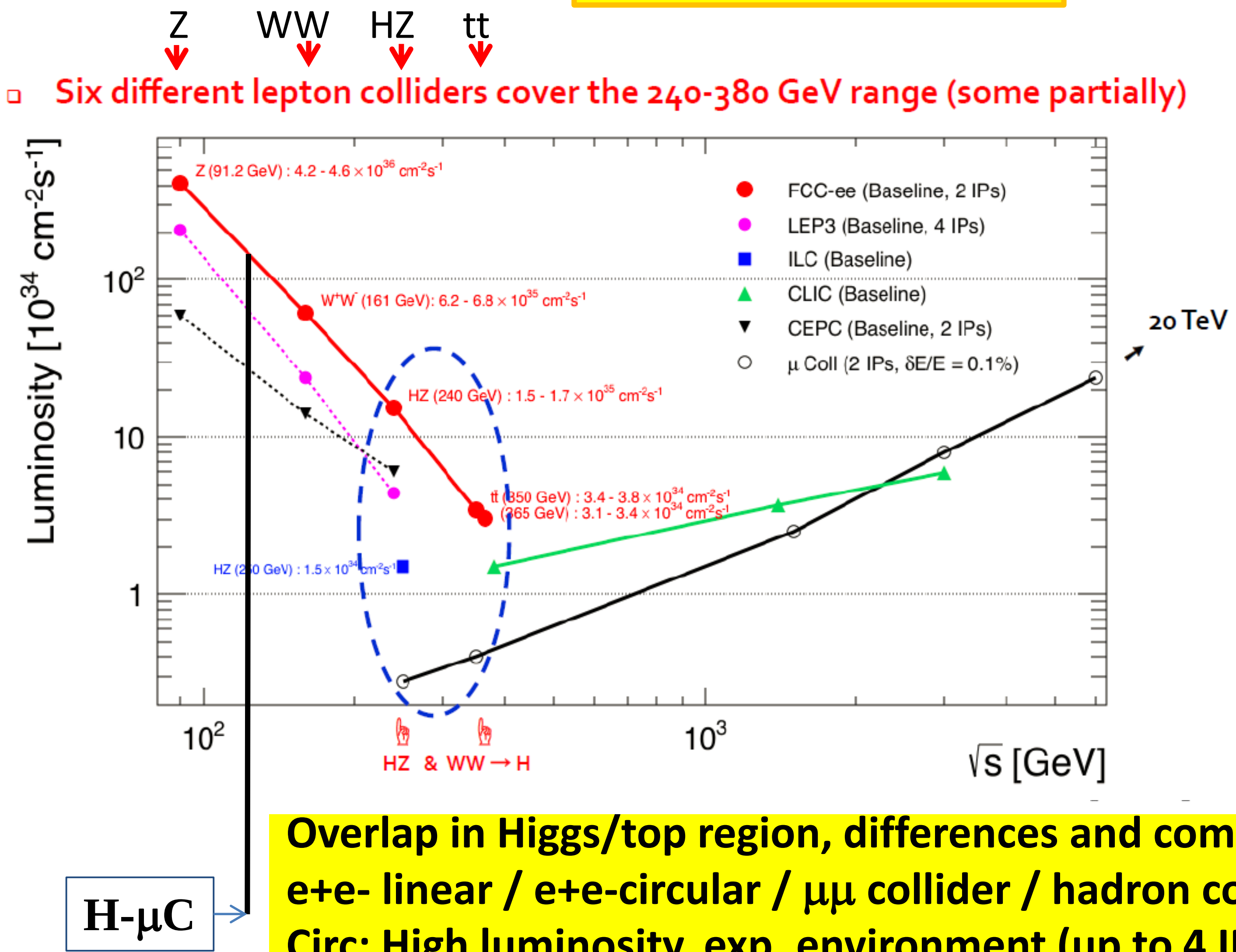
several tens of Million Higgs already produced… > than most Higgs factory projects.

$$\sigma_{i \to f}^{\ observed} \propto \sigma_{prod} \frac{(g_{Hi})^2 (g_{Hf})^2}{\Gamma_H}$$

relative error scales with 1/purity and 1/√efficiency of signal

difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels)
→ must do physics with ratios.

Higgs factories



Overlap in Higgs/top region, differences and complementarities
e+e- linear / e+e-circular / μμ collider / hadron collider
Circ: High luminosity, exp. environment (up to 4 IP), E_{CM} calibration
Linear: higher energy reach, longitudinal beam polarization
muon collider: s-channel production → line shape measurements
hadron collider: gg ttH W&Z production, lots of HH events for g_{Ht} g_{HH}

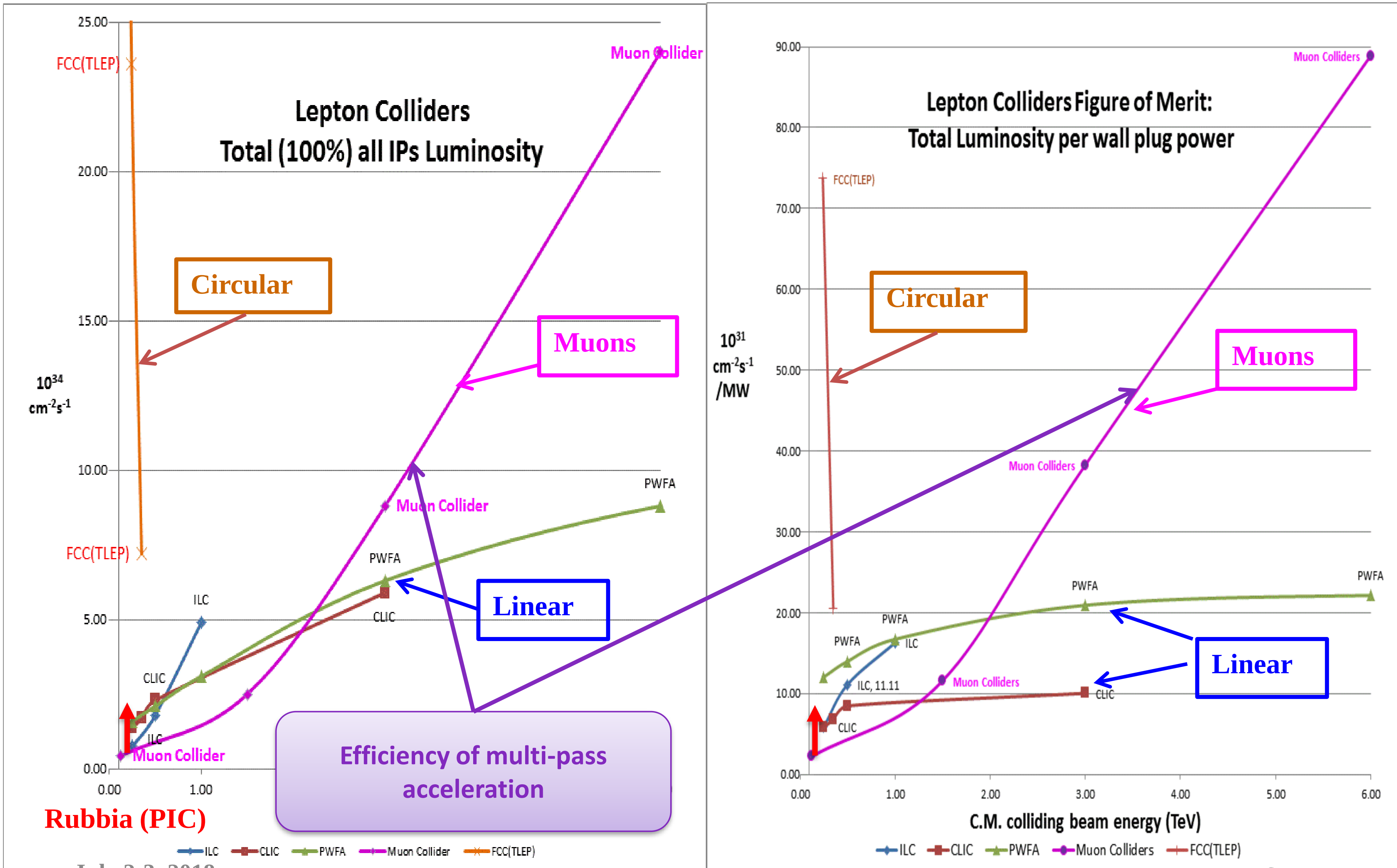
also: precision measurements

A sample of FCC-ee observables… the top quark mass is an essential input!

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_l	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g → bb
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	<0.000005 *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	<0.0002	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.6	< 0.6	EW Corr.
Γ_W (MeV)	Threshold scan	2085 ± 42	1.5	<1.5	EW Corr.
N_ν	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2.92 ± 0.05	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 ± 760 ± 500	20	<40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	<40	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 ± 0.3	0.08	< 0.05	QCD corr.
ttZ couplings	√s = 365 GeV	~30%	~2%	<2%	QCD corr

*** work to do: check if we cant improve**

Muon Colliders – Efficiency at the multi-TeV scale



Muon Collider Parameters

Muon Collider Parameters						
		Higgs	**Multi-TeV**			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
b*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, e_{TN}	p mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, e_{LN}	p mm-rad	1.5	70	70	70
Bunch Length, s_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts ⇨ several x 10^{32} [Rubbia proposal: $5x10^{32}$]

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

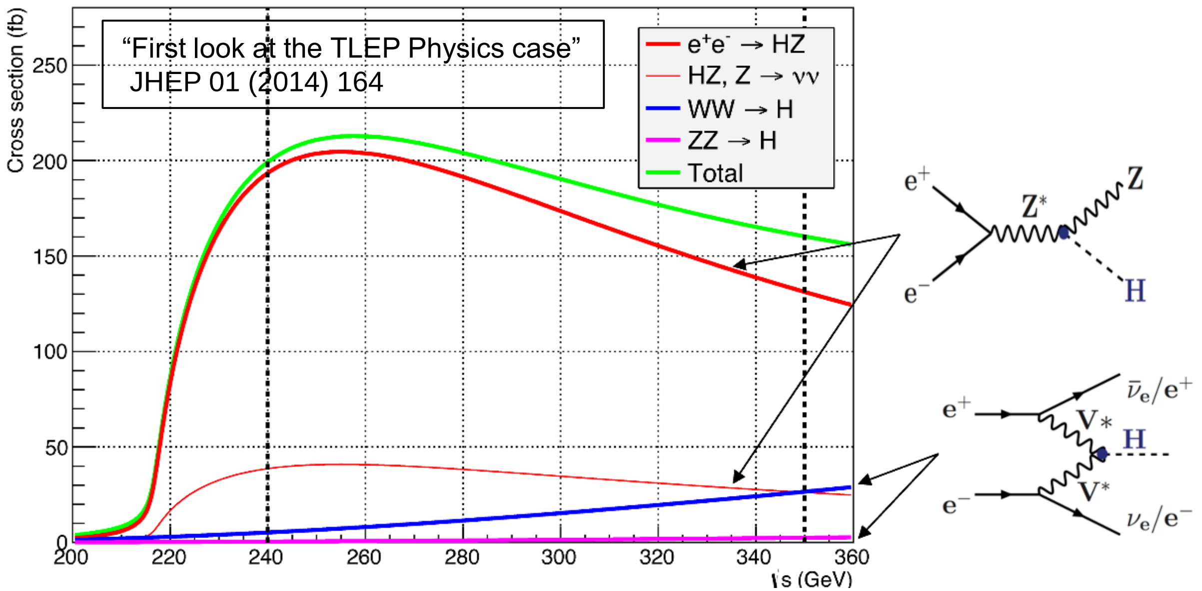
7'. ν from muon decay give radiation at point of exit → grows as E^4 limits applicability to ~E_{CM}=? 10 TeV mitigation is site-dependent.

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

Higgs boson production (1)

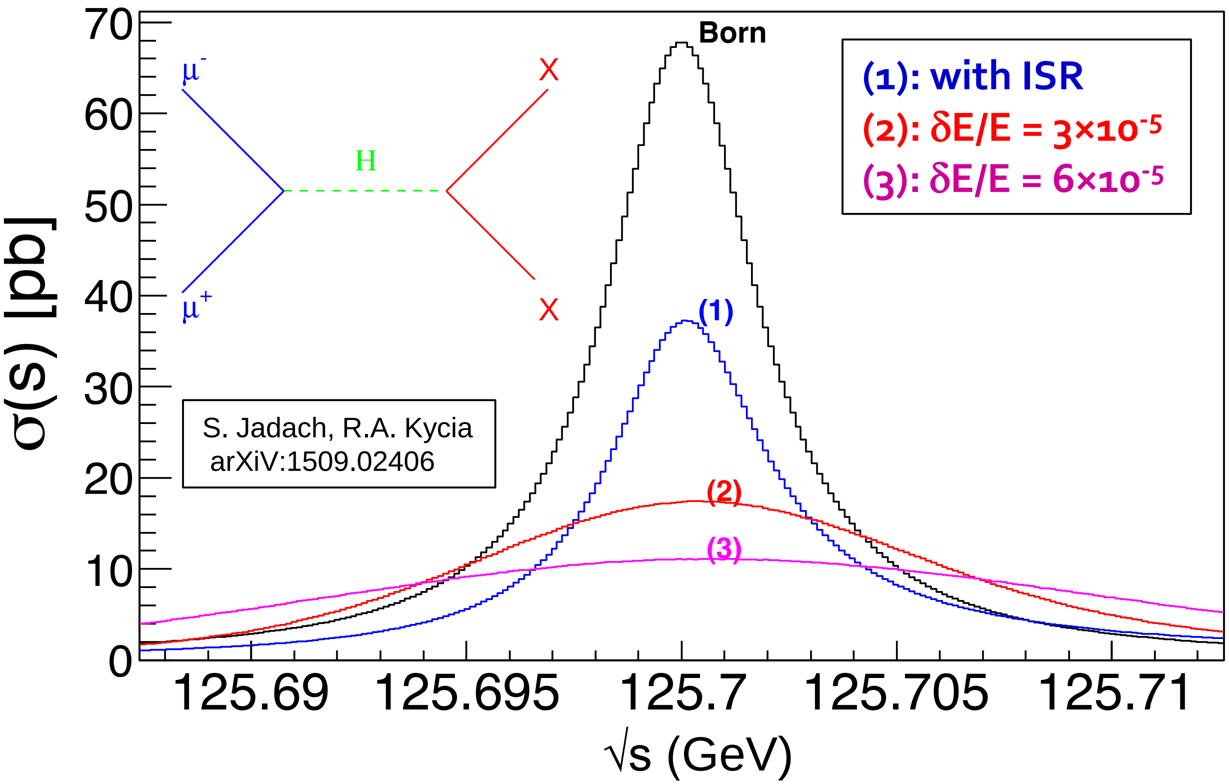
- **Muons are leptons, like electrons**
  - Muon colliders can a priori do everything that e^+e^- colliders can do, e.g.:



  - However, for a similar beam energy spread ($\delta E/E$ ~ 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

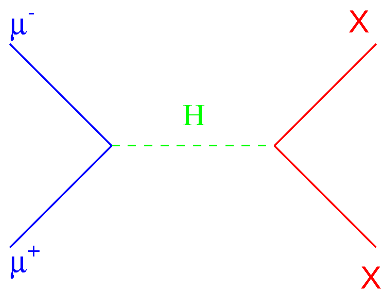
Reminder: At FCC-ee
400,000 to 800,000 Higgs/yr

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)

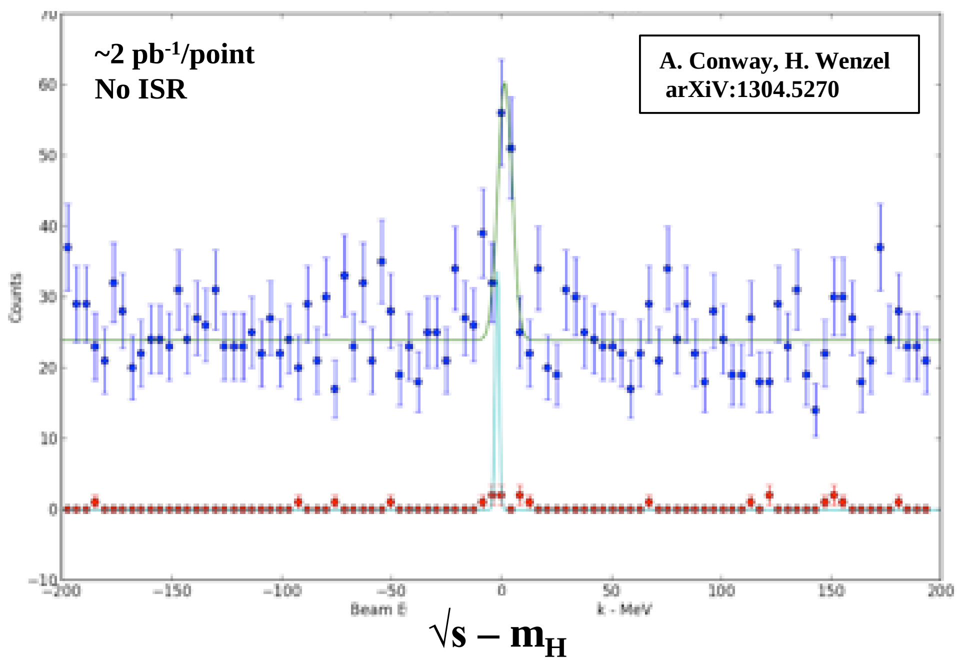
- The measurement of the lineshape gives access to
  - The Higgs mass, m_H
  - The Higgs width, Γ_H
  - The branching ratio into $\mu^+\mu^-$, BR($H \to \mu\mu$)
    - ➔ Hence, the coupling of the Higgs to the muon, $g_{H\mu\mu}$
  - Some branching fractions and couplings, with exclusive decays

Practical considerations

- The luminosity and BX frequency are such that
  - Pileup won't be a problem : situation better than LHC / CLIC / FCC-hh
- The main detector background come from $\mu \rightarrow e\nu_e\nu_\mu$ 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 $\mu\mu \rightarrow \mu\mu$?
  - Measurement to be done through the aforementioned shielding
    - Needs to be demonstrated
- Measurements of m_H and Γ_H requires excellent energy calibration
  - Muon natural polarization and decay provide beam energy and beam energy spread
    - With adequate precision (limited by g_μ-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)
- $\mu^+\mu^- \rightarrow Z / \gamma^*$ is not always the dominant background
  - e.g. $\mu^+\mu^- \rightarrow \gamma\gamma$ is 1000 times larger than $\mu^+\mu^- \rightarrow H \rightarrow \gamma\gamma$
- 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 Γ_H)

Scan of the SM Higgs resonance (2)

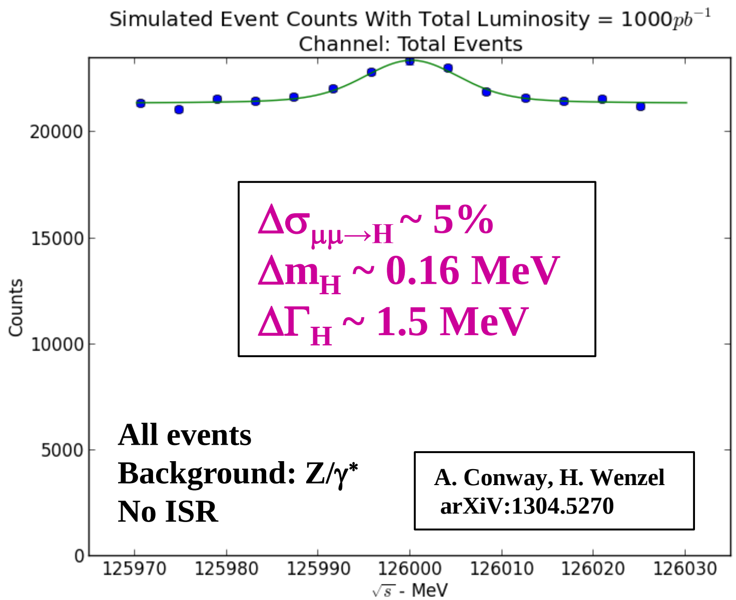
- **Finding the resonance (Γ_H = 4.2 MeV ~ δE)**
  - Today, m_H is known to ±250 MeV
    - Improves to ±100 MeV (LHC14), ±30 MeV (ILC), or ±8 MeV (FCC-ee)
  - Scan the $\sqrt{s}$ region of interest in optimal bins of 4.2 MeV
    - Count the number of bb and semi-leptonic WW events (see next slides)
  - 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

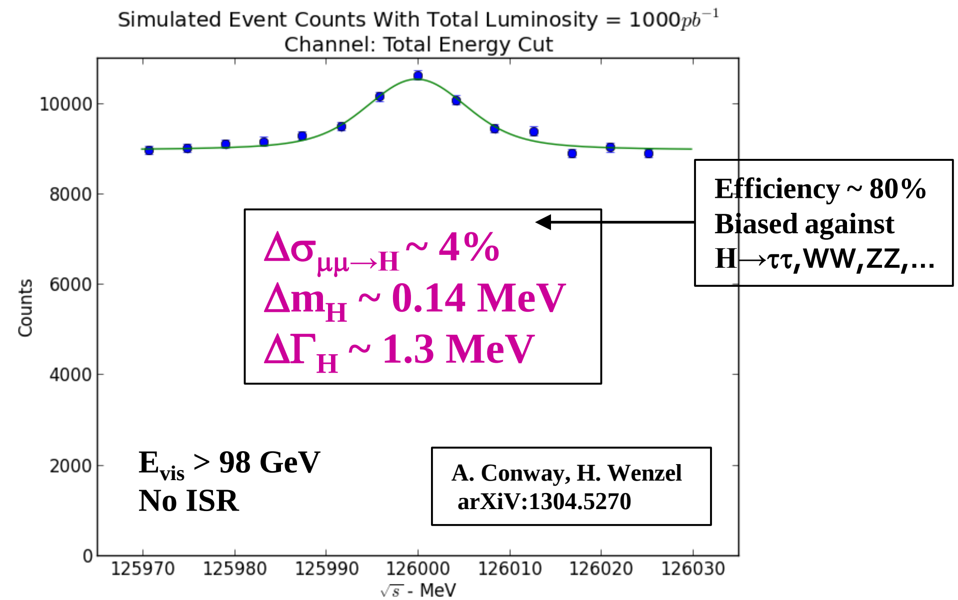


Scan of the SM Higgs resonance (3)

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]



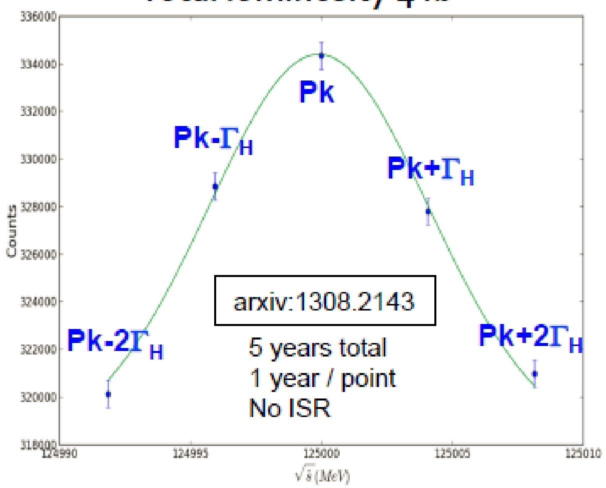


- ISR reduces the signal by a factor 2 (but not the background)
  - ➔ All errors to be increased by a factor 2
- m_H and Γ_H measurements require knowledge of E and δE with great precision

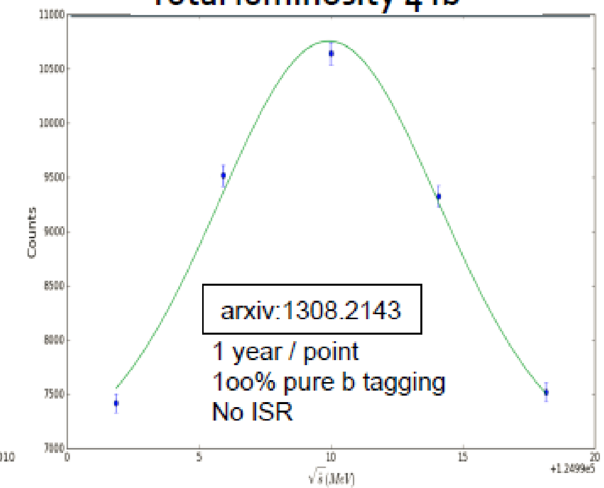
Scan of the SM Higgs resonance (4)

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

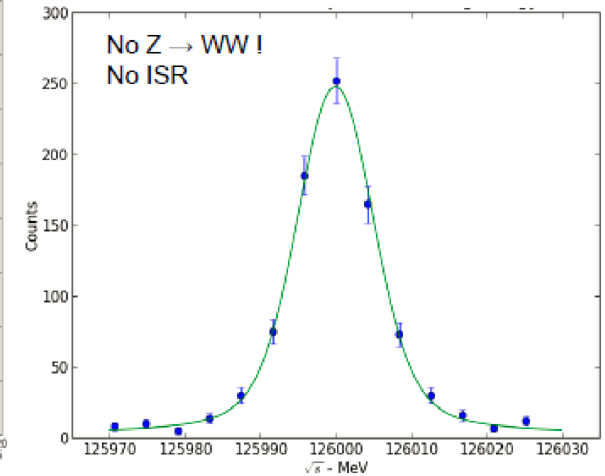
Total luminosity 4 fb^{-1}



Total luminosity 4 fb^{-1}



Total luminosity 1 fb^{-1}



- Fit to BW ⊗ Gaussian + linear background, with perfect knowledge of $\sqrt{s}$, $\delta\sqrt{s}$, and L
  - After 5 years of running at 8×10^{31} $cm^{-2}s^{-1}$ and 1 year at half luminosity

Obs.	m_H (MeV)	Γ_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%

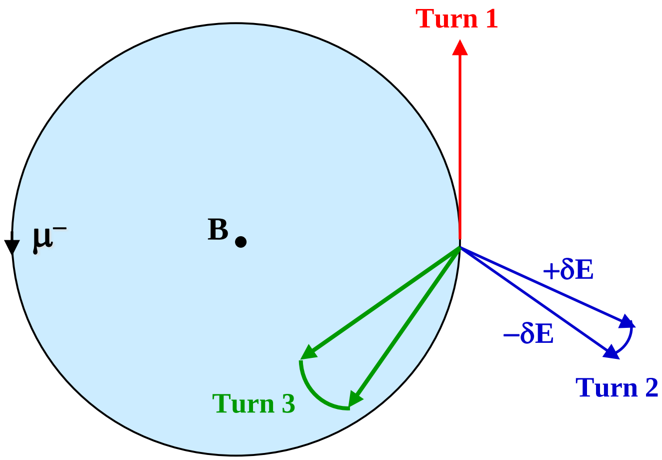
- Note: Γ_H = 4.2 MeV ⇒ 0.25 MeV precision corresponds to 6% relative.

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

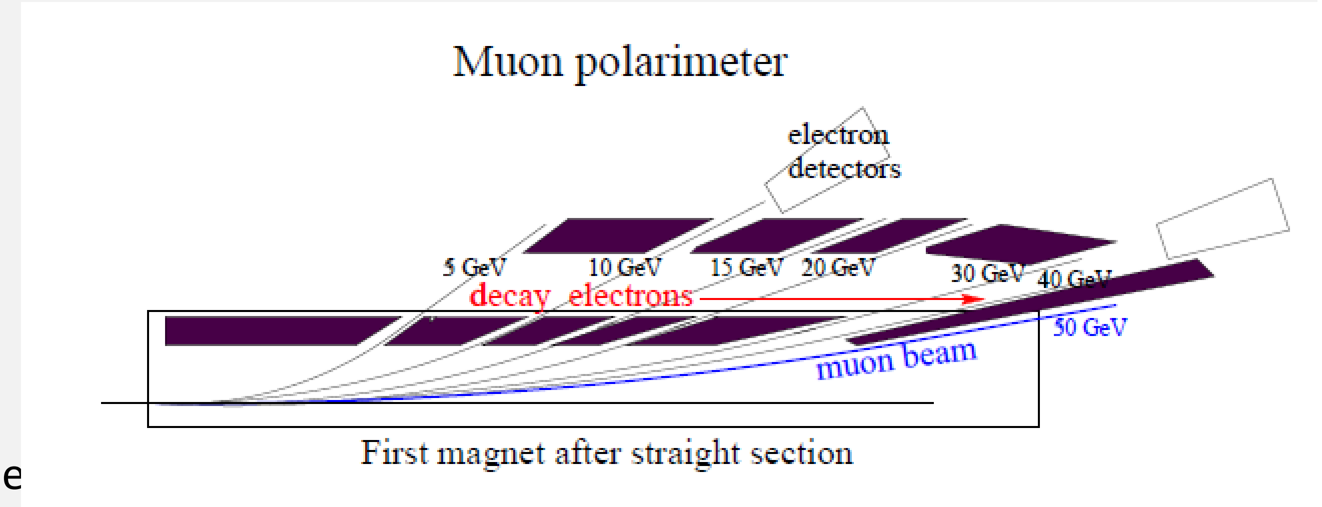
$$P_L(T) = P_0 \cos(2\pi \nu_0 T) \exp\left\{ -\frac{1}{2} \left[2\pi \nu_0 T \frac{\delta E}{E} \right]^2 \right\}$$

- 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

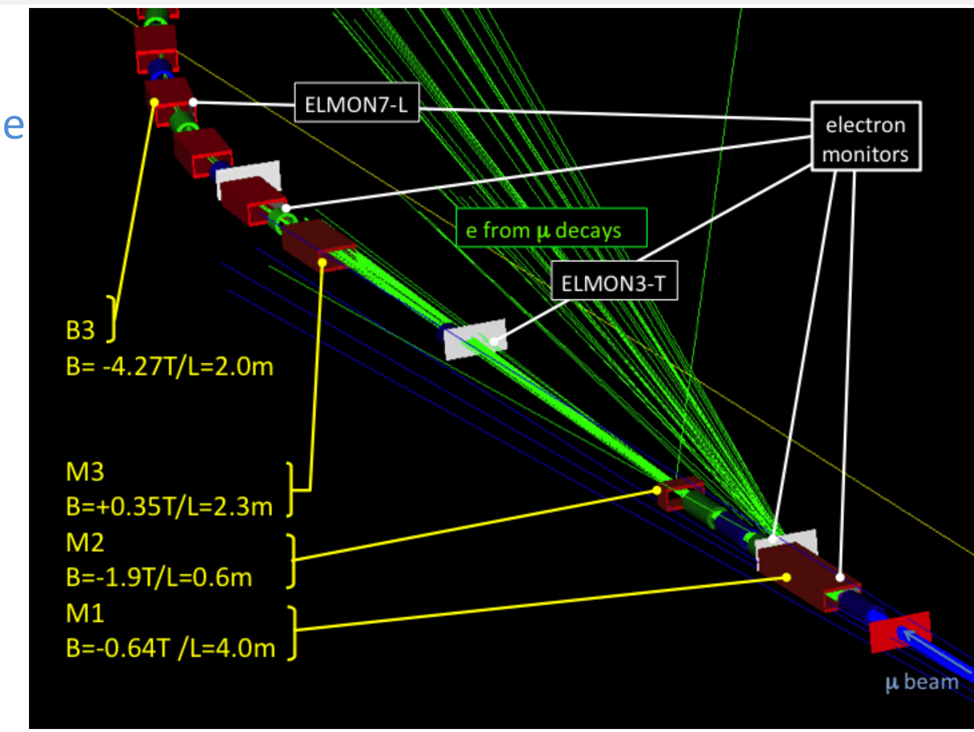
Example of a polarimeter (magnet is open on one side– or 'electron gaps' are foreseen) (AB) calculations of acceptance/statistics « by hand » and a fortran code simulating errors +minuit fit

Electrons originate from a straight section before the the bending magnet where the polarimeter is located.
The acceptance calculation is more reliable if the straight section is short
Detectors= gas CKOV+ calorime



Another possibility on the same principle

[Marco Apollonio]
This one was actually fully simulated, for the neutrino factory with the consequence that only 'small' statistics were accumulated.
NB: This one took the design of the storage ring 'as is'.
I think the measurement is so important that it deserves inclusion in Storage Ring desing from the start as in above.



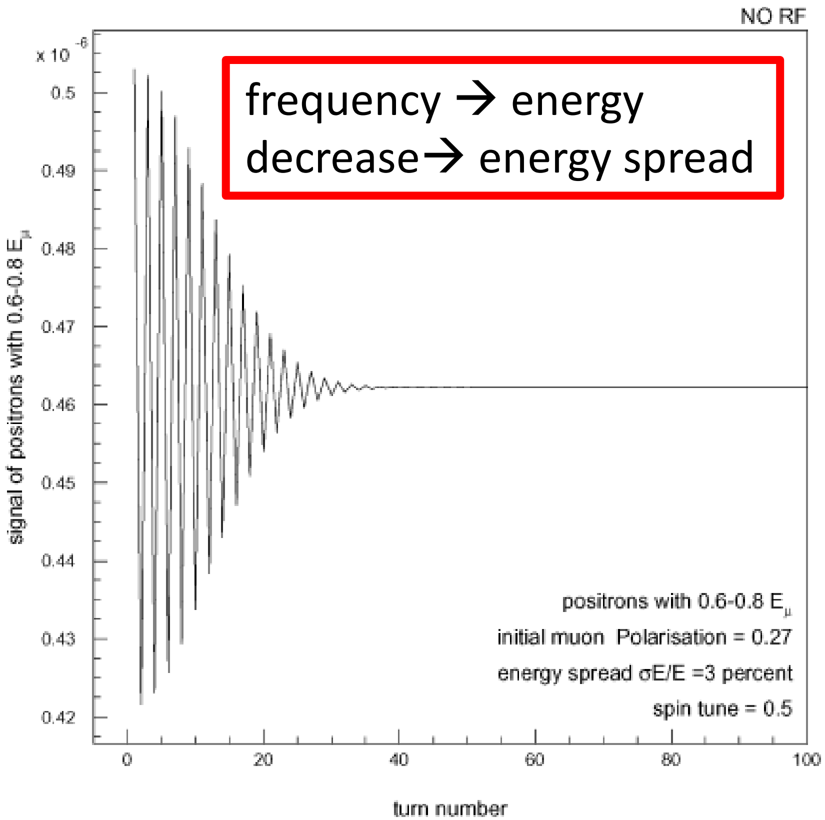
As muons circulate in the ring, the polarization precesses in the plane of the ring, so that, at turn T after injection,

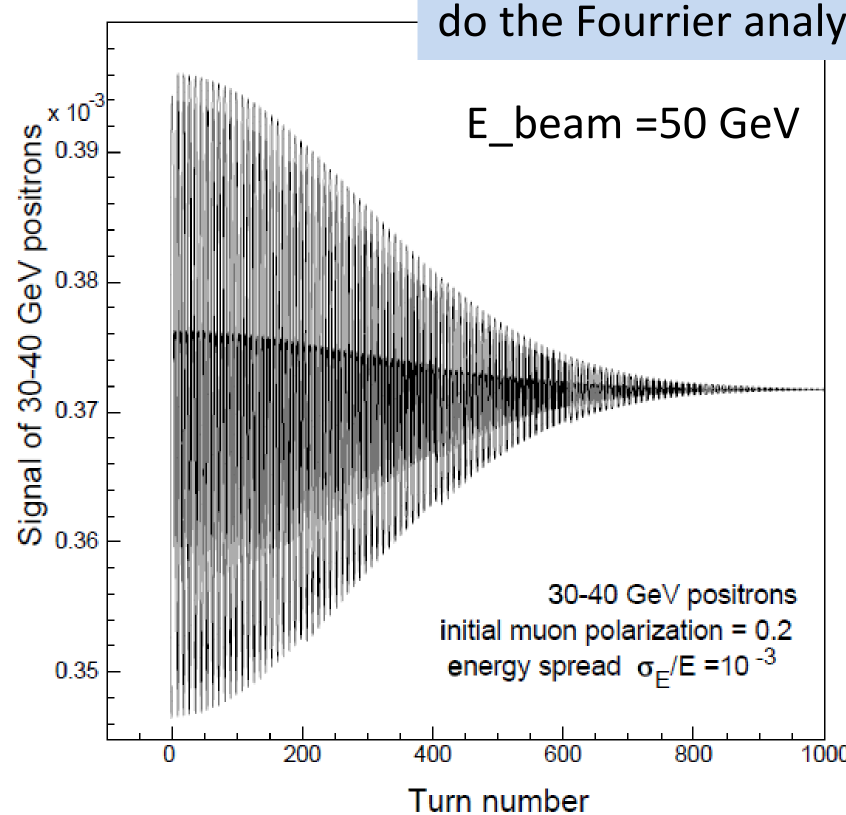
$$[P_L + iP_x](T) \propto \int e^{i2\pi\nu T} S(\nu) \mathrm{d}\nu \ ,$$

where $S(\nu)$ is the distribution of spin tunes (i.e. of energies) within the bunch of muons. One can see that the polarization analysis effectively provides *the Fourier transform of the muon beam-energy distribution.* For a Gaussian energy spread, the polarization decreases as

$$P(T) = P_{\text{init}} \ e^{-\frac{1}{2}(T 2\pi\nu \frac{\Delta E}{E})^2} \ ,$$

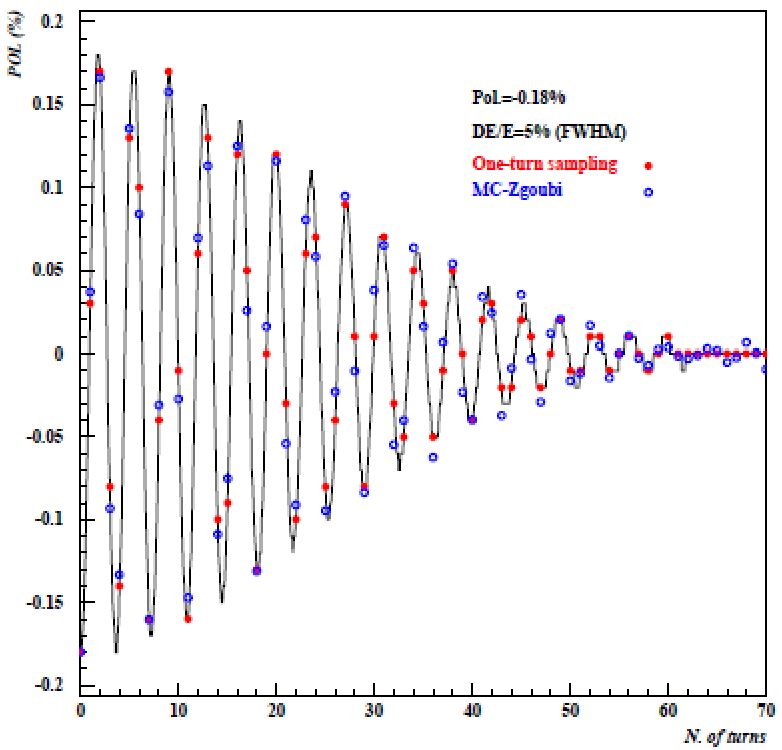
we dont have to make this Gaussian assumption, just do the Fourrier analysis.

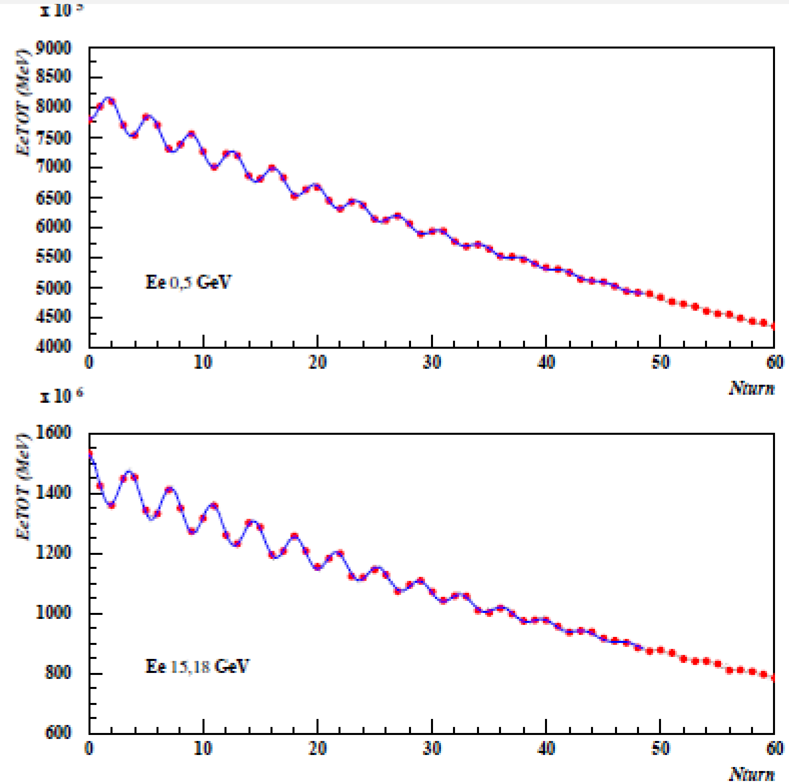




NB: in a muon collider operating at 15Hz, there is always enough turns!

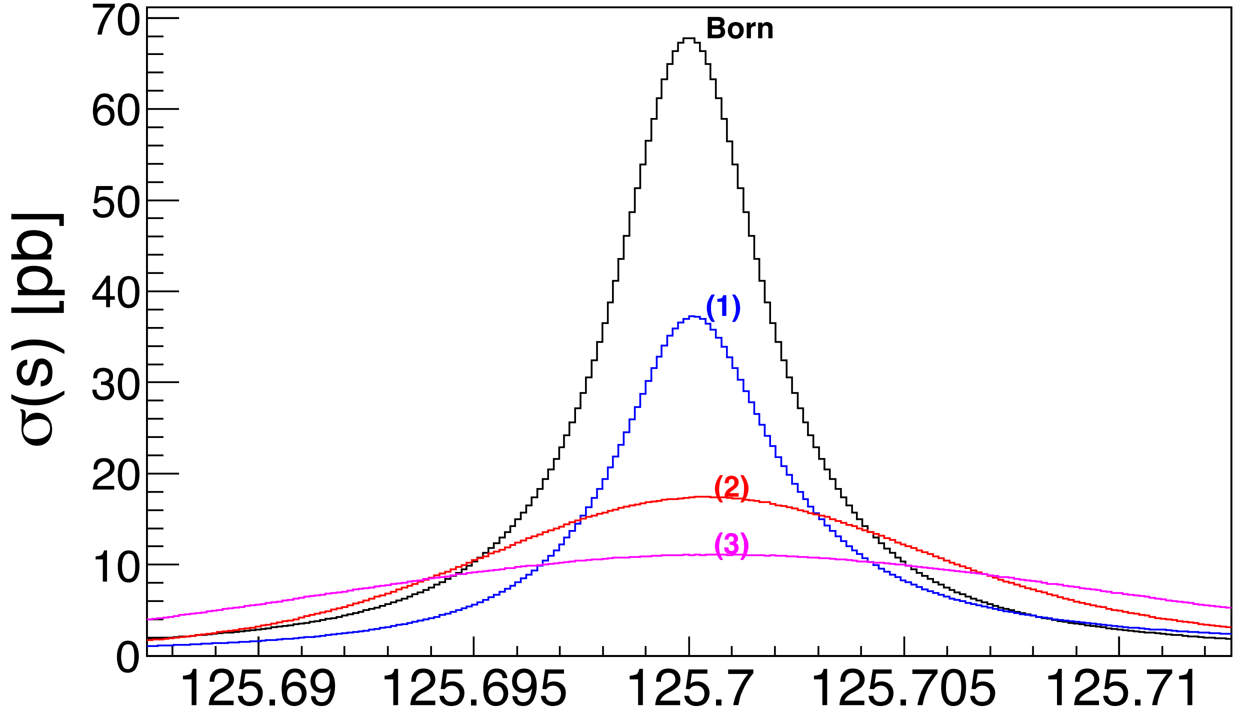
M. Apollonio, real simulation (NB simulated one of100 bunches of muons for 1 fill out of 50/s). Statistical errors are higher by corresponding factors)





In real life there are 10^{13} muons decaying per second and the only challenge in the estimate of errors is to understand the number of decay electrons that make it to the polarimeter. (typically 10^{9}-10^{11} per second, statistics is never a problem). Because the absolute value of the polarization is not relevant, and only frequencies are involved the systematic errors are very small (~5-100 keV) on both the beam energy and energy spread.

The scan performances given above assumes that there is no jitter in the beam energies at a level that is significant with respect to the energy spread.
While beam energies are measured on a fill by fill basis, (no wrong result) but it would lead to a large amount of data off the Higgs peak.
They also assume onlv one IP for the muon collider and two for FCC-ee

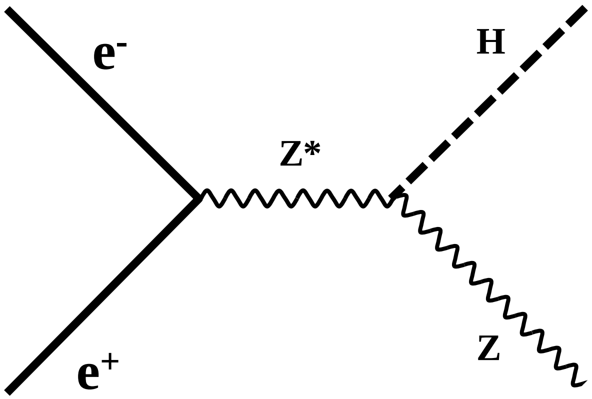


Higgs production mechanism

"higgstrahlung" process close to threshold

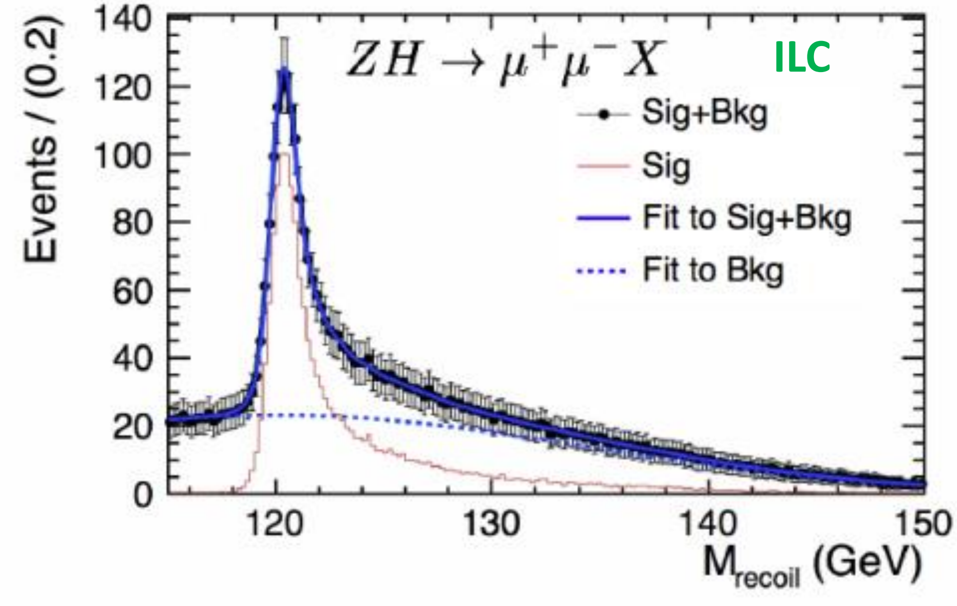
Production xsection has a maximum at near threshold ~200 fb

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



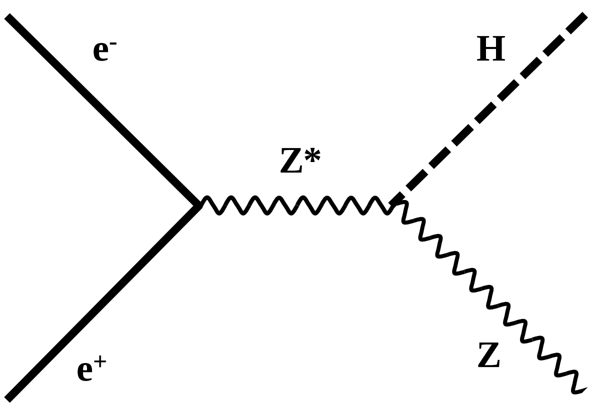
Z – tagging by missing mass

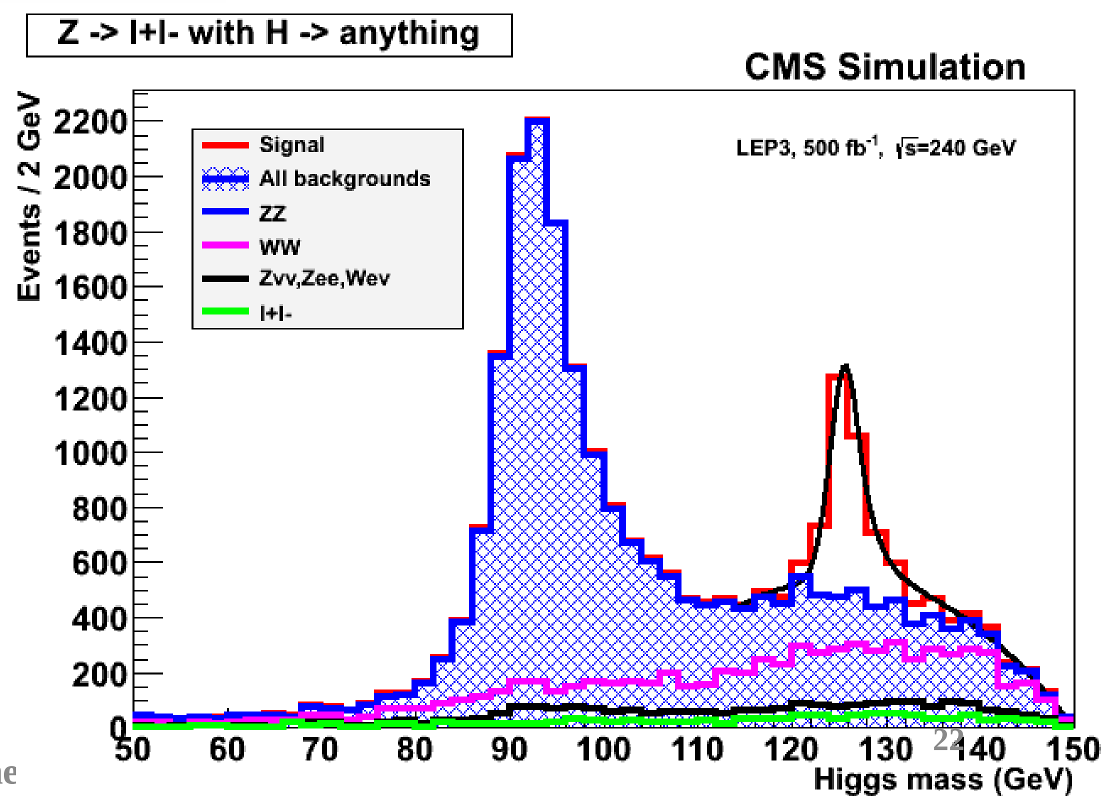
For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient
➔ kinematical constraint near threshold for high precision in mass, width, selection purity



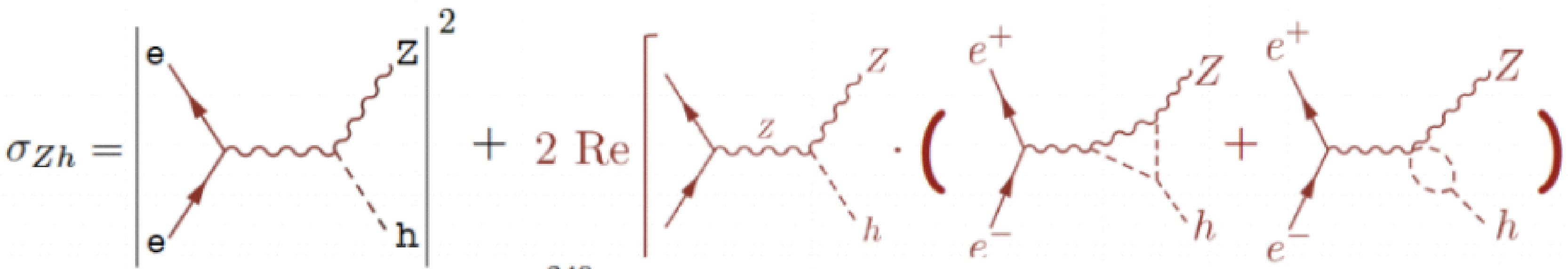
e+e- : Z – tagging by missing mass

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





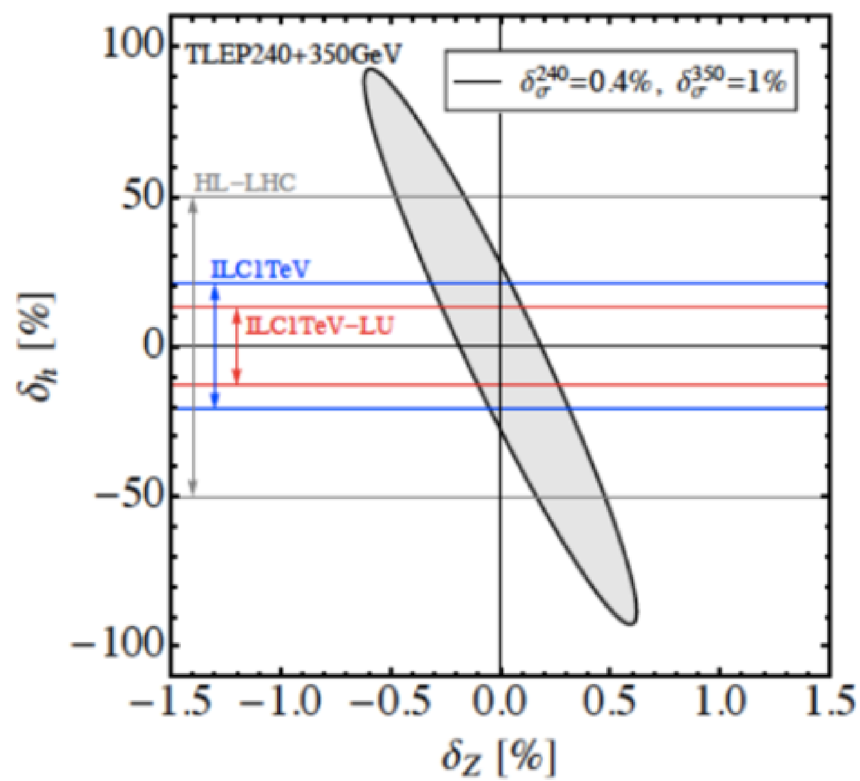
very accurate precision on threshold cross-section sensitive to loop corrections



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

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



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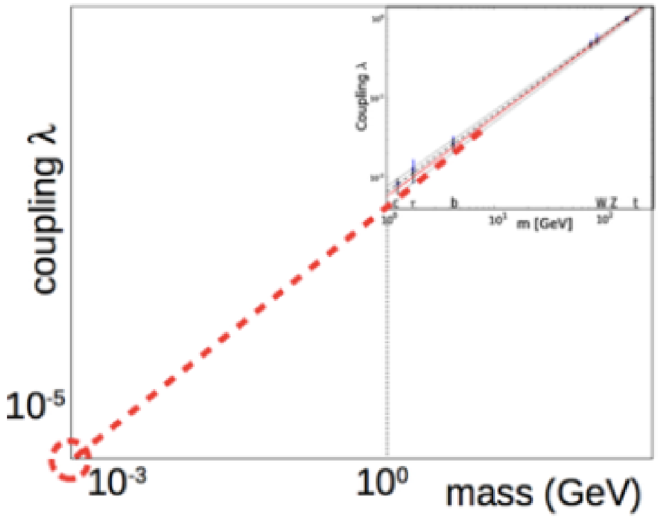
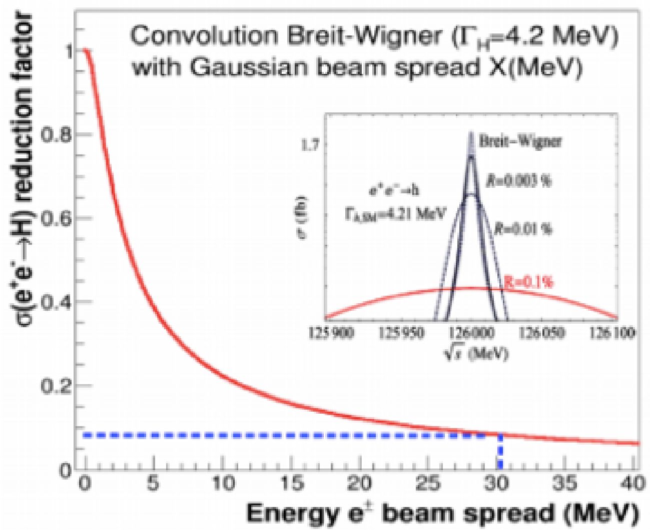
First generation couplings

➡ **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}

κ_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?

Result of the coupling (a.k.a. κ) fit

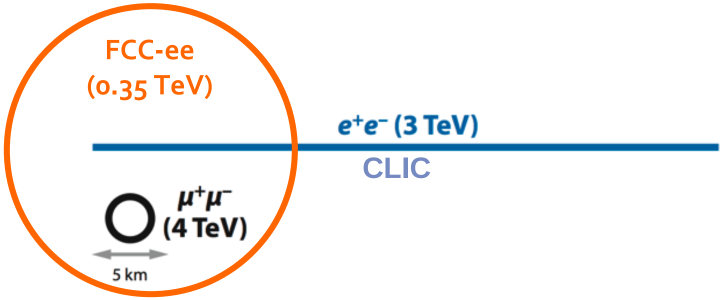
- Comparison(*) with other lepton colliders at the EW scale (up to 380 GeV)

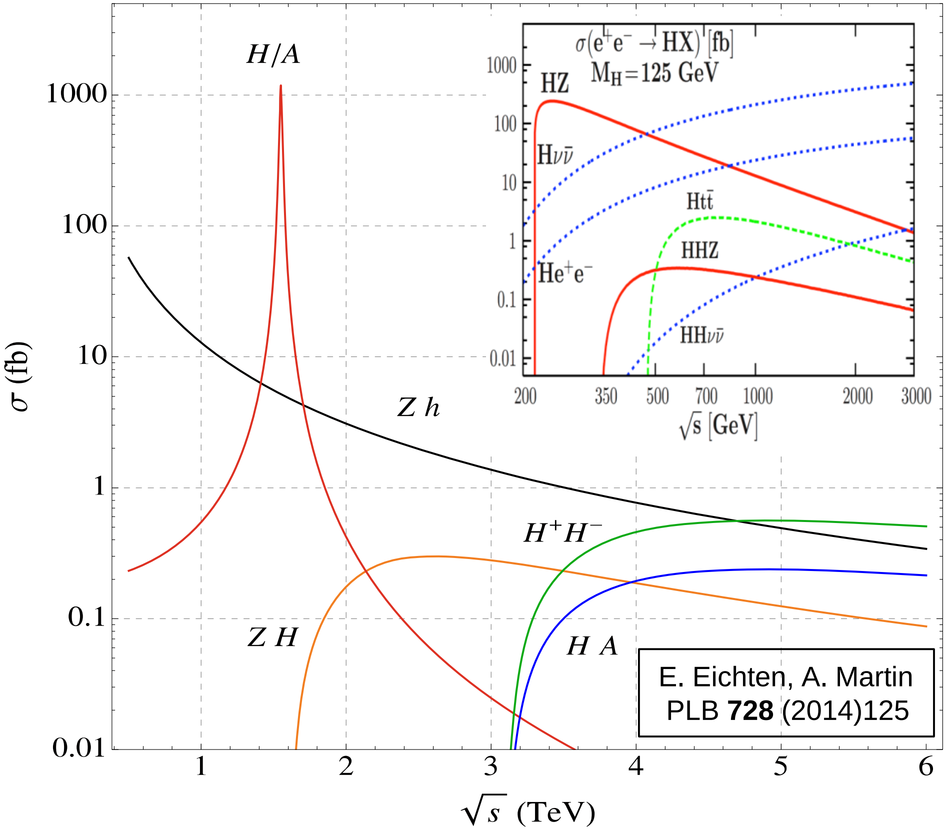
13	μ Coll$_{125}$	ILC$_{250}$	CLIC$_{380}$	LEP3$_{240}$	CEPC$_{250}$	FCC-ee$_{240}$	FCC-ee$_{365}$
Years	6	15	5	6	7	3	+4
Lumi (ab^{-1})	0.005	2	0.5	3	5	5	+1.5
δm_H (MeV)	0.1	t.b.a.	110	10	5	7	6
$\delta\Gamma_H / \Gamma_H$(%)	6.1	3.8	6.3	3.7	2.6	2.8	1.6
$\delta g_{Hb} / g_{Hb}$ (%)	3.8	1.8	2.8	1.8	1.3	1.4	0.70
$\delta g_{HW} / g_{HW}$ (%)	3.9	1.7	1.3	1.7	1.2	1.3	0.47
$\delta g_{H\tau} / g_{H\tau}$(%)	6.2	1.9	4.2	1.9	1.4	1.4	0.82
$\delta g_{H\gamma} / g_{H\gamma}$ (%)	n.a.	6.4	n.a.	6.1	4.7	4.7	4.2
$\delta g_{H\mu} / g_{H\mu}$ (%)	3.6	13	n.a.	12	6.2	9.6	8.6
$\delta g_{HZ} / g_{HZ}$ (%)	n.a.	0.35	0.80	0.32	0.25	0.25	0.22
$\delta g_{Hc} / g_{Hc}$ (%)	n.a.	2.3	6.8	2.3	1.8	1.8	1.2
$\delta g_{Hg} / g_{Hg}$ (%)	n.a.	2.2	3.8	2.1	1.4	1.7	1.0
Br_{invis} (%)$_{95\%CL}$	SM	<0.3	<0.6	<0.5	<0.15	<0.3	<0.25
BR_{EXO} (%)$_{95\%CL}$	–	<1.8	<3.0	<1.6	<1.2	<1.2	<1.1

Patrick Janot   Higgs properties @ Circular Lepton Colliders 1 June 2018   (*) Green = best Red = worst   12

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)

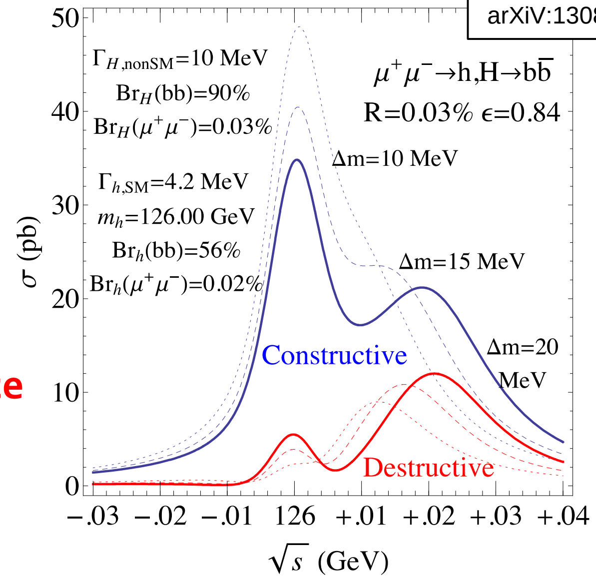
Energy
- Can go to higher energy
  - Advantage for 2HDM (e.g., SUSY)
    - Heavy Higgs with $\mu^+\mu^- \to$ H,A
- $\sqrt{s}$ ~ 6 TeV(?) possible in the Tevatron tunnel

Additional Higgs bosons (1)

- **Is H(125) made of several quasi-degenerate Higgs bosons ?**
  - At LHC, the typical m_H resolution in the $H \to ZZ^* \to \mu\mu$ 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
      - ➔ 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)
    - $e^+e^- \to hA$ present at tree level with large cross section (A pseudoscalar)
    - [$e^+e^- \to hH$ only at loop level with a few ab cross section (H scalar)]
      - ➔ A small mass difference is not measurable this way

Similar at FCC-ee (Recoil mass)

Snowmass 2013 arXiV:1308.2143

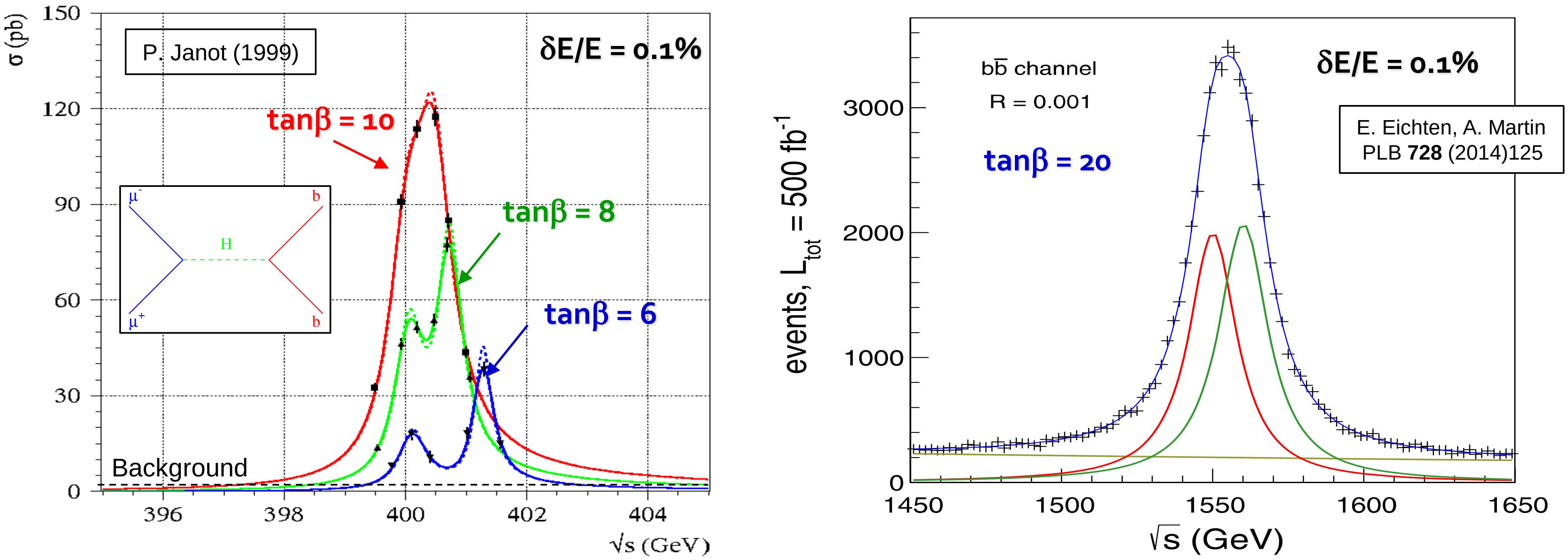


A. Djouadi et al. PRD **54** (1996) 759

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

Additional Higgs bosons (2)

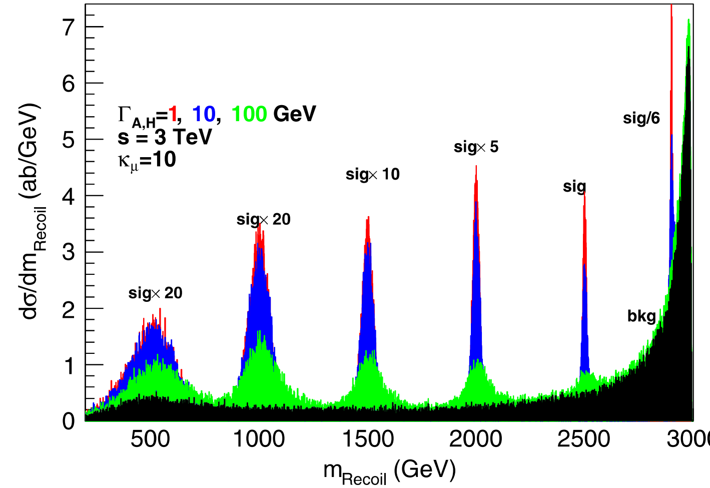
- **Can be applied to heavier H and A in 2HDM (e.g., from SUSY)**
  - Example 1: m_A = 400 GeV — Example 2: m_A = 1.55 TeV

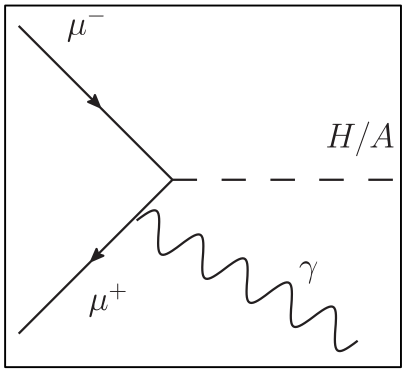


- Notes:
  - Higgs width of the order of 0.1 to 1% of the Higgs mass
    - ➔ δE/E ~ 0.1% enough, large integrated luminosities (100's fb^{-1} or ab^{-1}) possible
  - Each value of m_A correspond to a specific ring diameter
    - ➔ Need to know the mass before designing the ring!

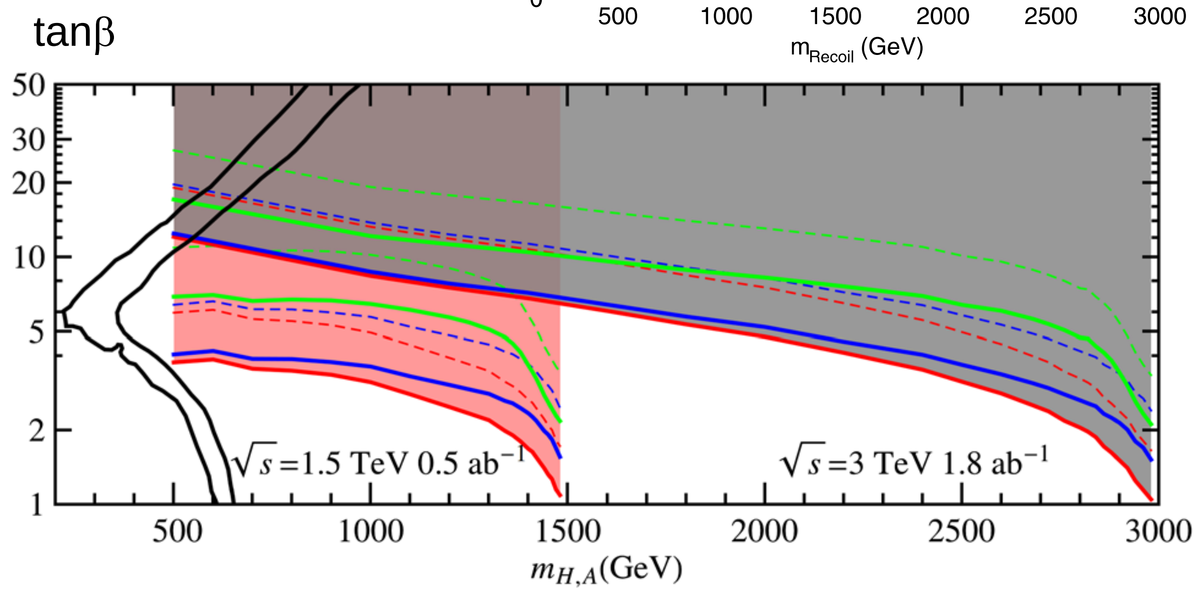
Additional Higgs bosons (3)

- **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 $m_{Recoil} = [s - 2E_\gamma\sqrt{s}]^{1/2}$





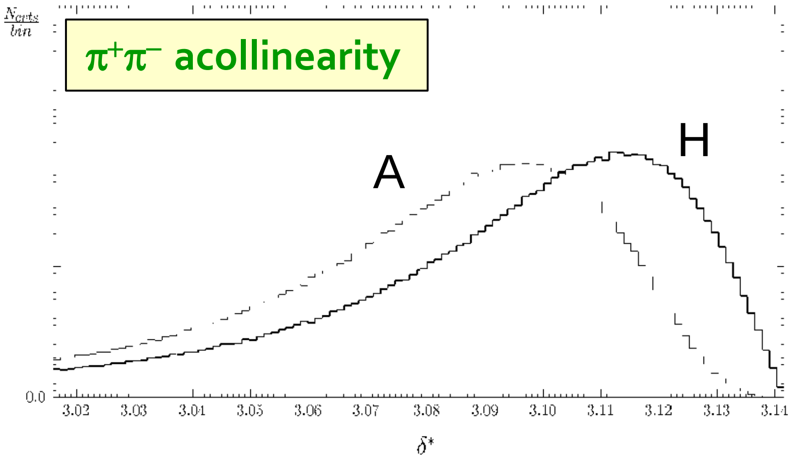
N. Chakrabarty et al.
PRD **91** (2015)015008

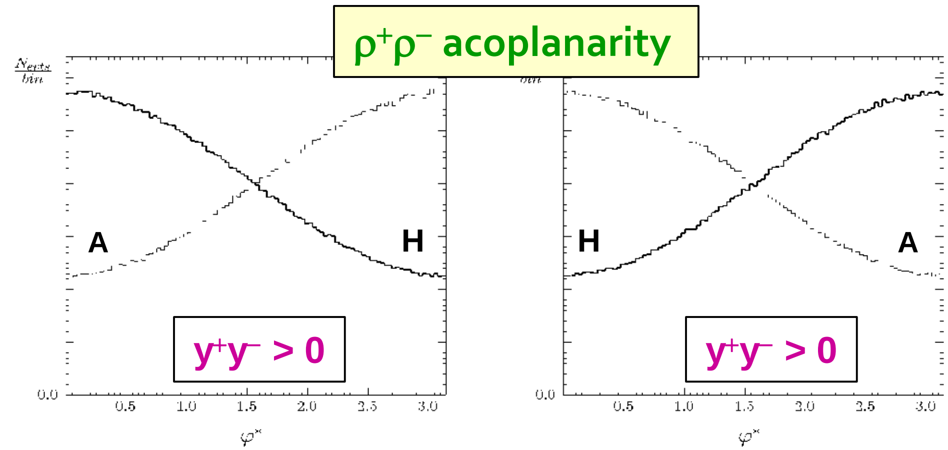


  - Can "see" H and A
    - If tanβ > 5
  - Build the next collider
    - At $\sqrt{s} \sim m_{A,H}$

Additional Higgs bosons (4)

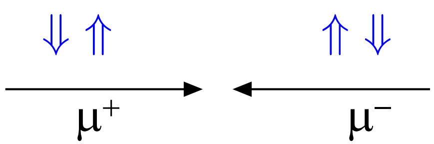
- **Unique CP (violation) and H/A mixing studies can start**
  - From $H,A \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$
  - From $H,A \rightarrow \tau^+\tau^- \rightarrow \rho^+\rho^-\nu_\tau\nu_\tau$ with $\rho^\pm \rightarrow \pi^\pm\pi^0$



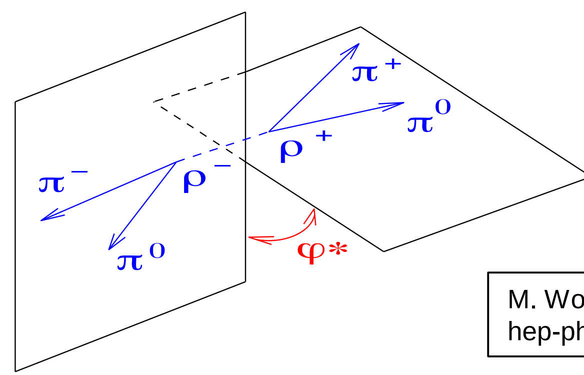


$y^\pm = E_{\pi\pm} - E_{\pi 0}$

- 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

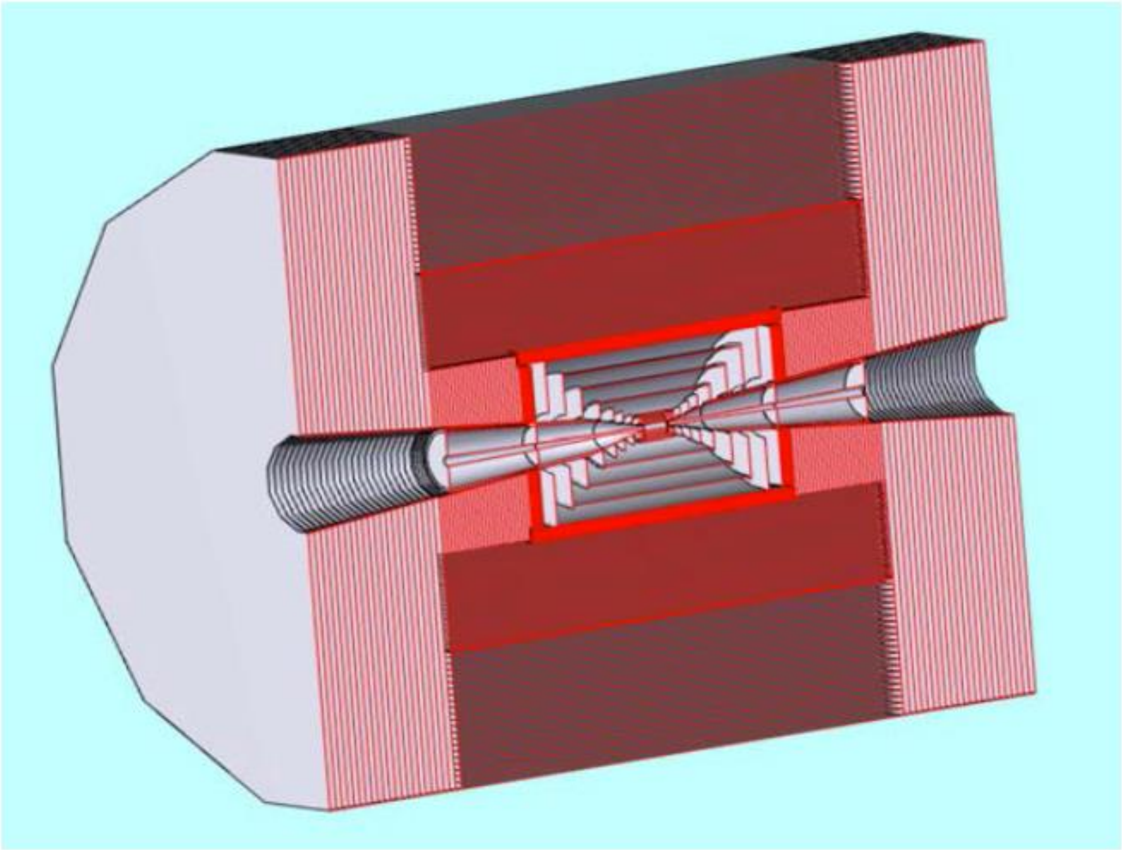


Figure 23: Cross sectional view of a possible Higgs Factory Muon Collider detector showing the tungsten cones shielding the detector from beam related backgrounds.

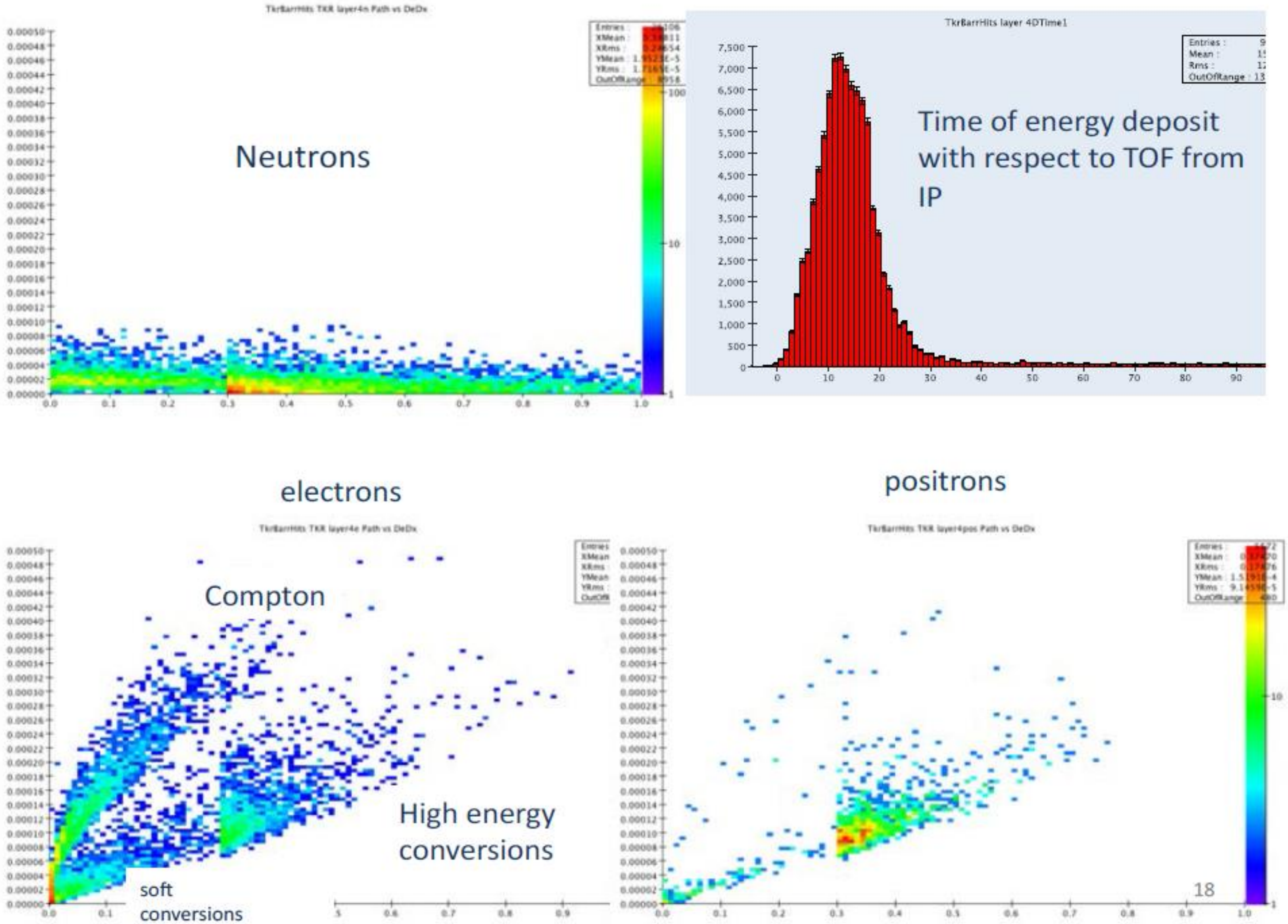


Figure 26: Contributions of various background components to signals in a barrel silicon detector layer

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- circular collider.
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 two-higgs-doublet situation, and possible cases for Z', new threshold to scan etc...

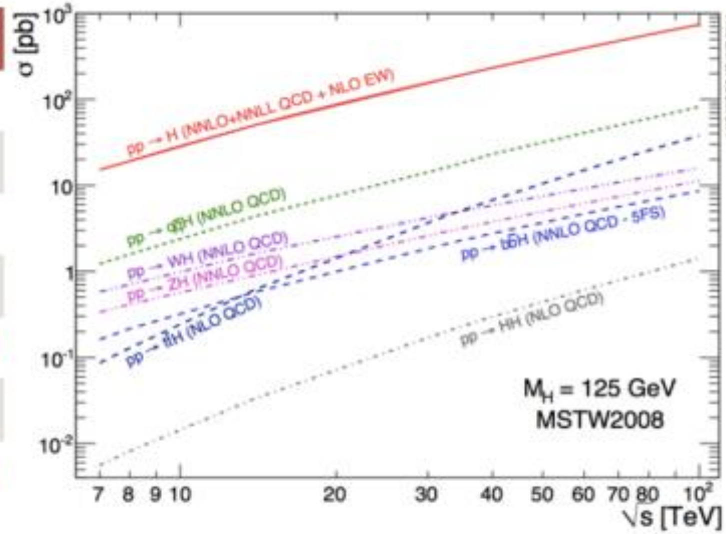
-- The muon collider is the best in town for high energy lepton collider up to?10(0)TeV?
starting at a point that depends on achievable luminosity.
A factor x5 in Luminosity →muon collider the winner from 400 GeV upwards.
The physics case for lepton collider much above 400 GeV needs to be revisited
Integration in a global study (FCC) would help for practical aspects

-- the experimental conditions are tough and should be more carefully studied.
However things seem comparable/easier than at LHC

SPARES

HIGGS AT FCC-pp

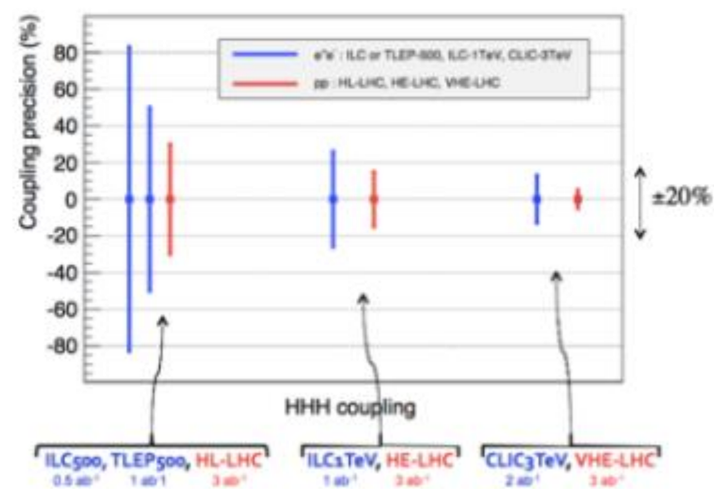
Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



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
$\sigma \cdot \mathrm{BR}(pp \to HH \to bb\gamma\gamma)$ (fb)	0.089	0.545	3.73
$S/\sqrt{B}$	2.3	6.2	15.0
λ (stat)	50%	20%	8%

arXiv:1310.8361



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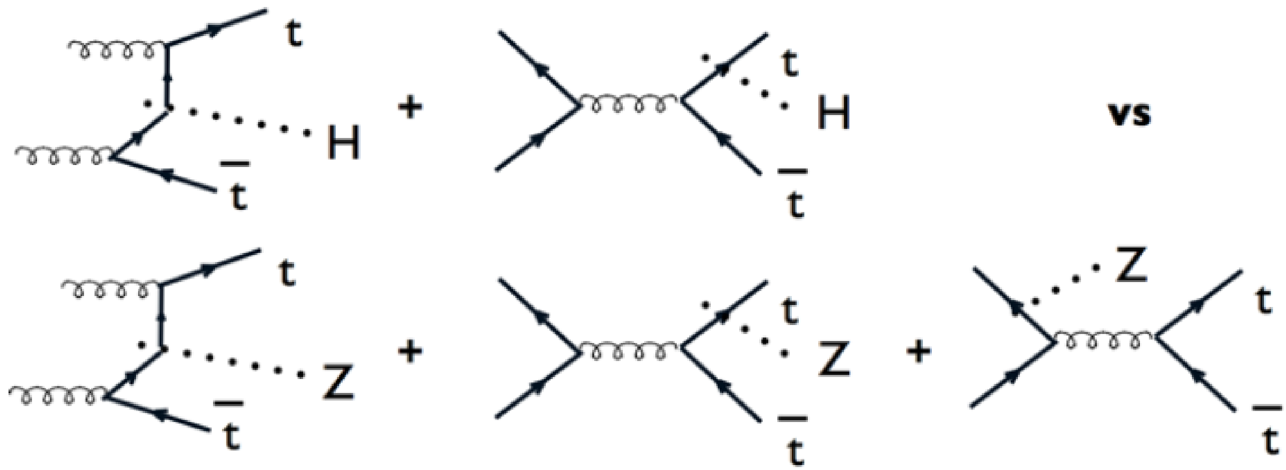
➡ … but also new measurements not possible at the LHC/HL-LHC

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