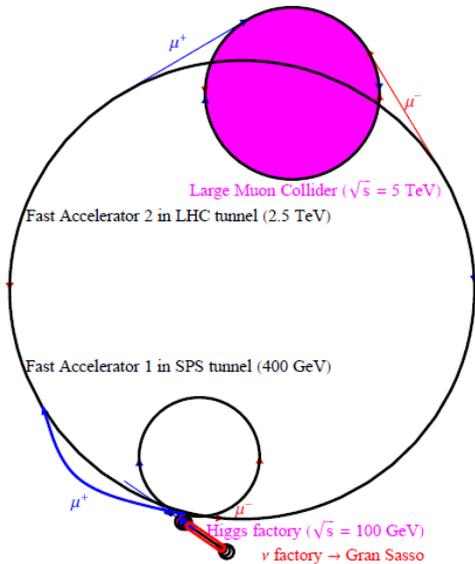


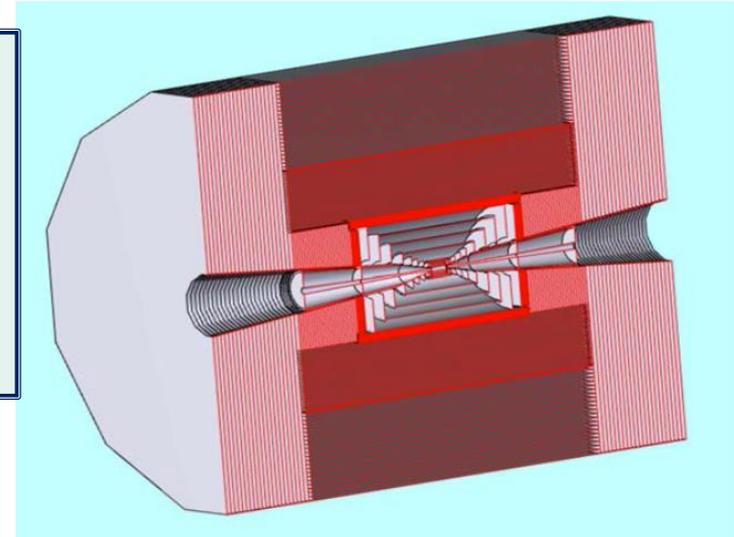
Experiments at Muon colliders

Alain Blondel

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

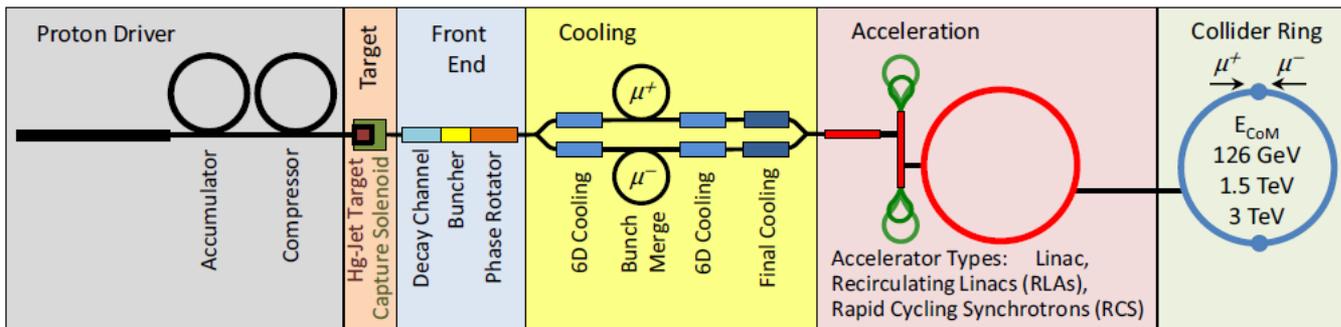


- Higgs physics
- Precision measurements
- Higher masses
- Experimental environment
- What can a muon collider do ... and not do?



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

U.S. Muon Accelerator Program



arxiv:1308.0494

18 Nov 2015

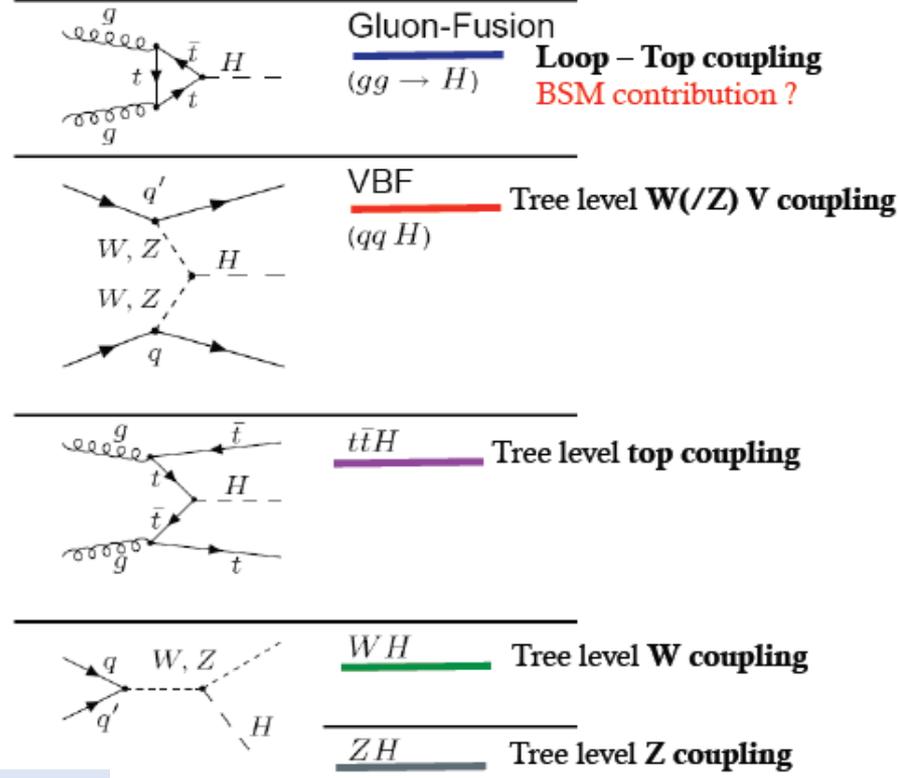
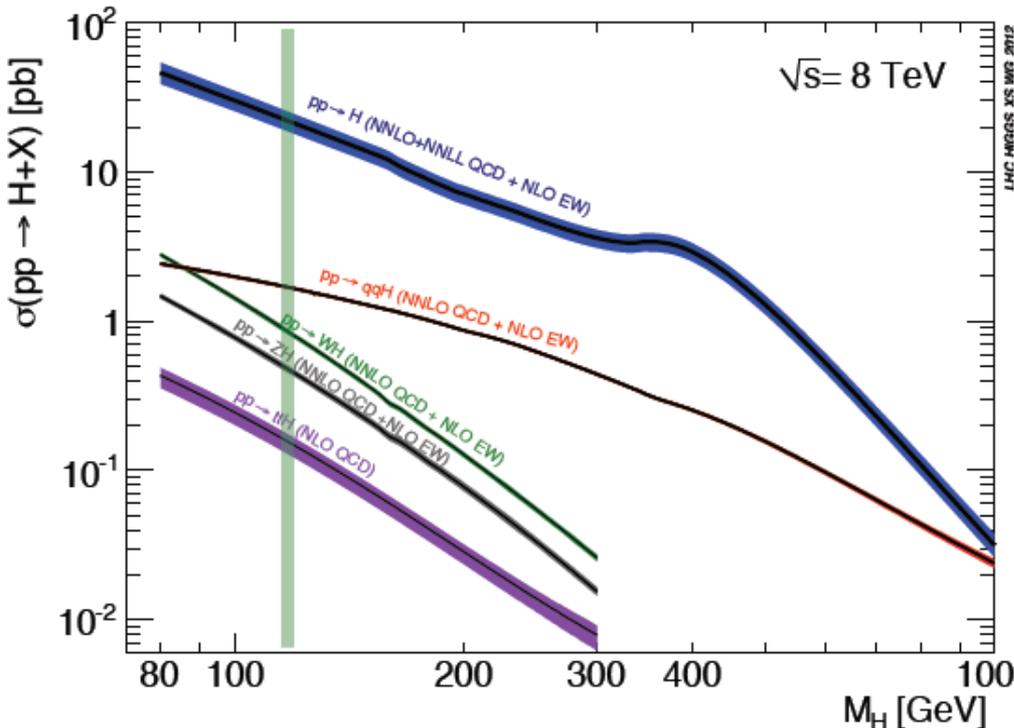
Alain Blondel Physics at muon colliders



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... more than most Higgs factory projects.

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

relative error scales with $1/\text{purity}$ and $1/\sqrt{\text{efficiency of signal}}$

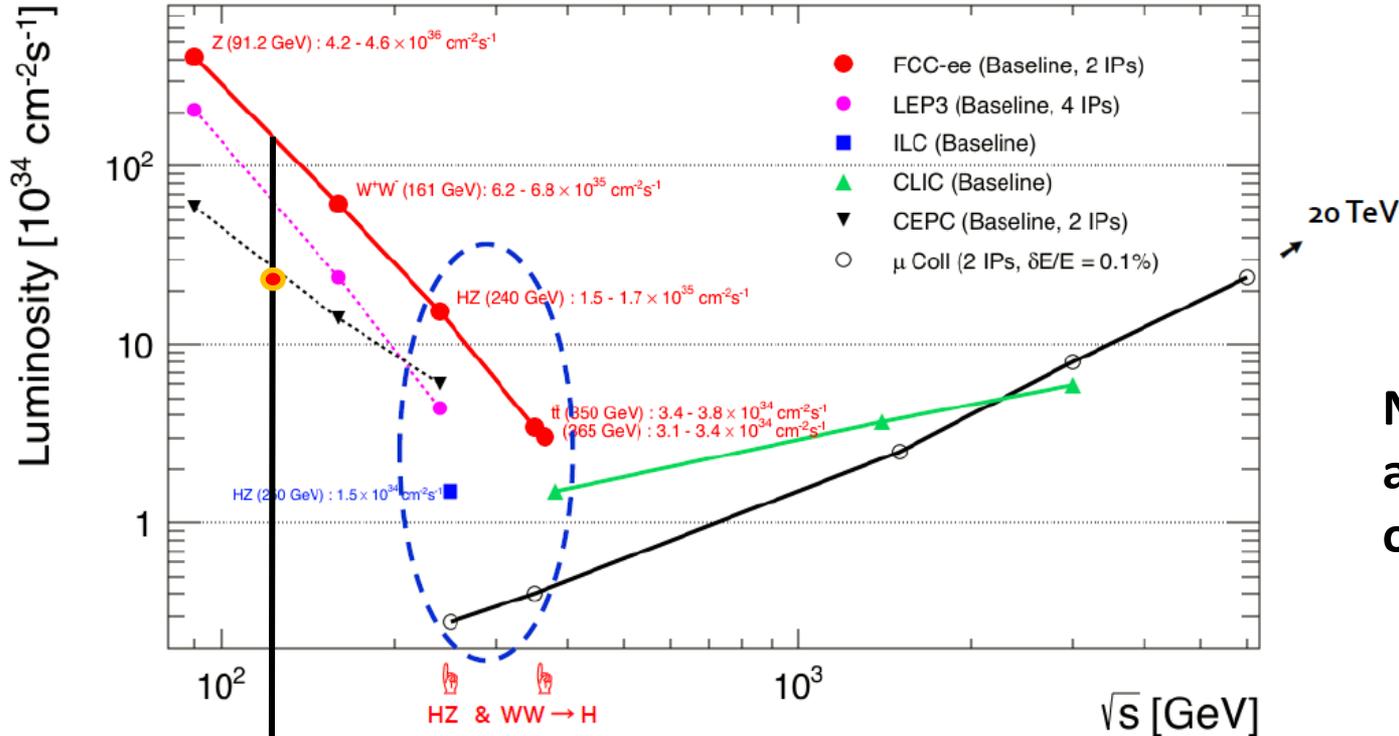
difficult to extract the couplings because σ_{prod} uncertain and Γ_H is unknown (invisible channels)
 → must do physics with ratios.



Higgs factories

Z
WW
HZ
tt

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



NB: the Z machine has a circulating current of 1.5 A ($10^{19} \text{ e}^+/\text{s}$)

H- μ C

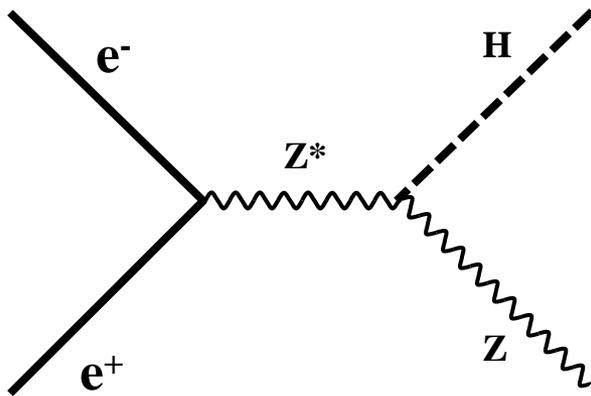
Overlap in Higgs/top region, differences and complementarities
 e+e- linear / e+e-circular / $\mu\mu$ collider / hadron collider
 Circ: High luminosity, exp. environment (up to 4 IP), E_{CM} calibration
 Linear: higher energy reach, longitudinal beam polarization
 muon collider: s-channel production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

Higgs production mechanism

“higgstrahlung” process close to threshold

Production xsection has a maximum at near threshold ~ 200 fb

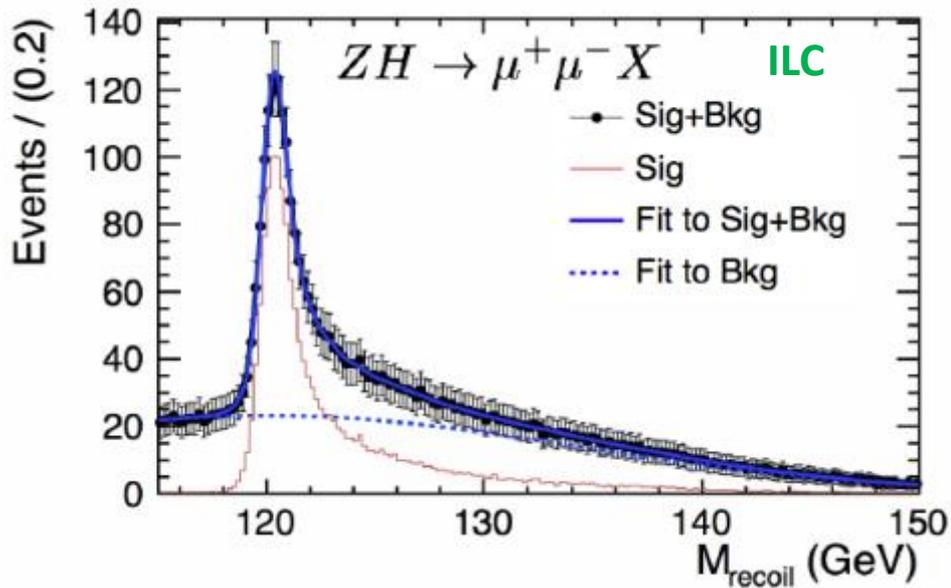
$10^{34}/\text{cm}^2/\text{s} \rightarrow 20'000$ HZ events per year.



**Z – tagging
by missing mass**

For a Higgs of 125GeV, a centre of mass energy of 240GeV is sufficient

\rightarrow kinematical constraint near threshold for high precision in mass, width, selection purity



e^+e^- : Z – tagging by missing mass

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

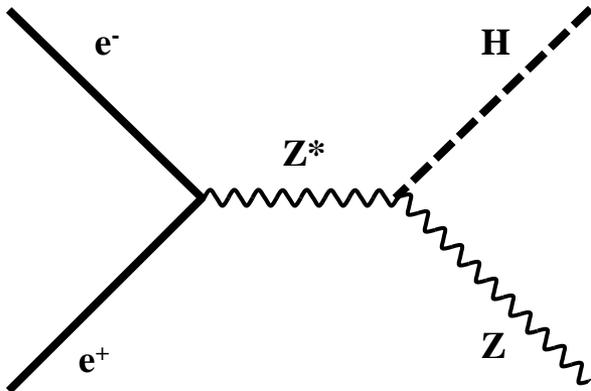
ZZZ final state $\propto g_{\text{HZZ}}^4 / \Gamma_{\text{H}}$

→ measure total width Γ_{H}

empty recoil = invisible width

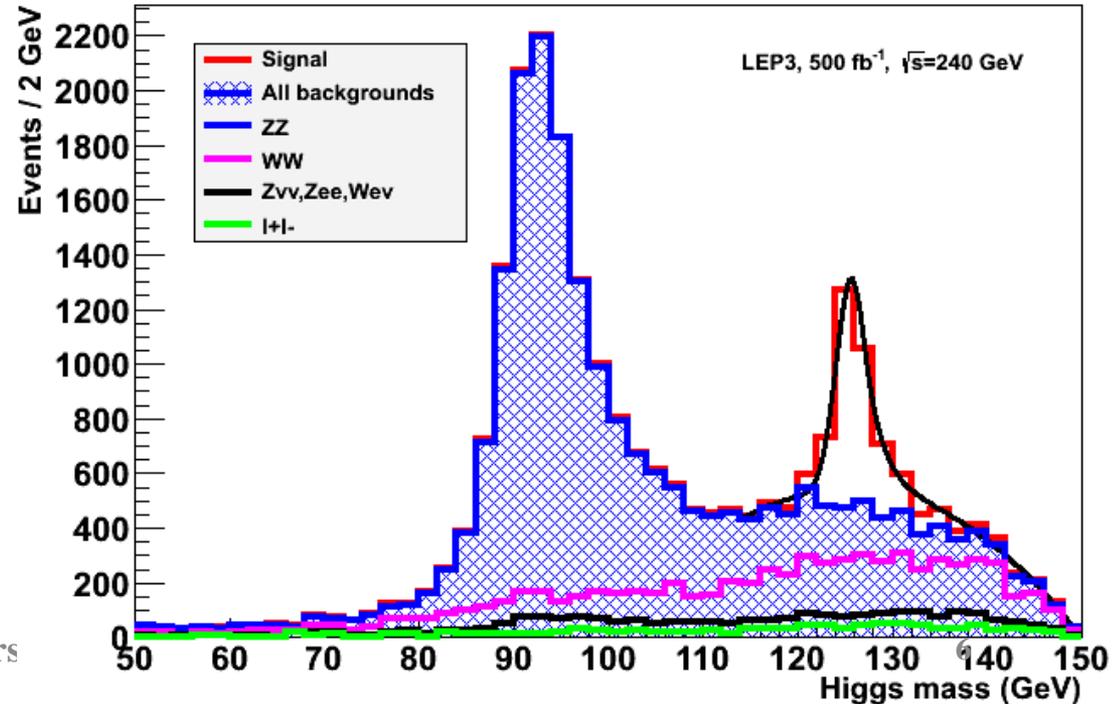
‘funny recoil’ = exotic Higgs decay

easy control below threshold



Z → l+l- with H → anything

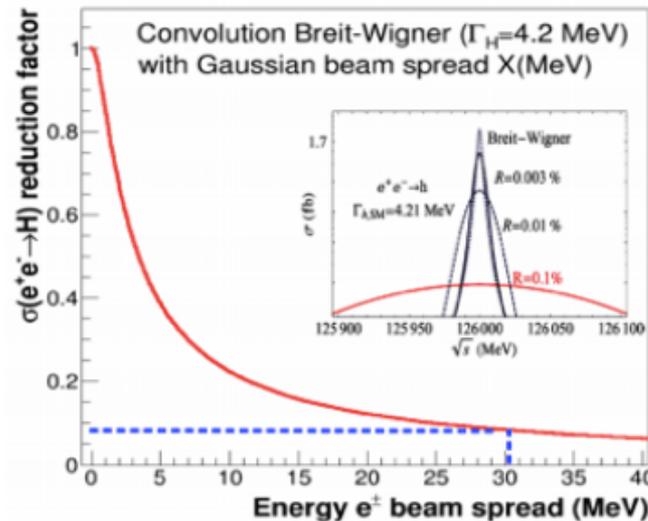
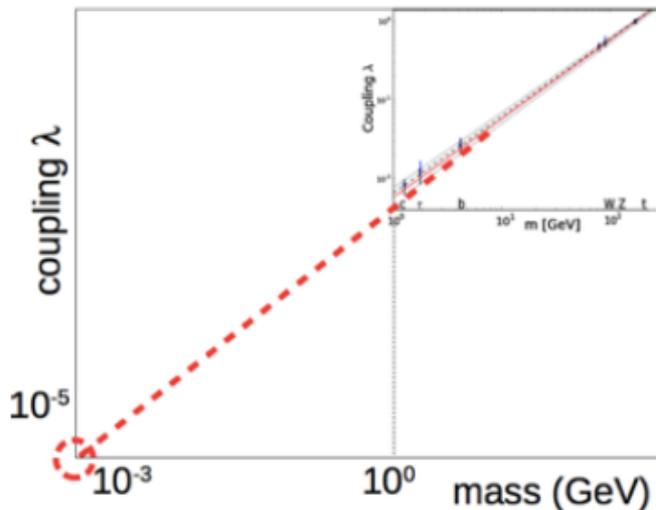
CMS Simulation



First generation couplings

→ s-channel Higgs production

- Unique opportunity for measurement close to SM sensitivity
- Highly challenging; $\sigma(ee \rightarrow H) = 1.6\text{fb}$; 7 Higgs decay channels studied



Preliminary Results

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

$\kappa_e < 2.2 \text{ at } 3\sigma$

→ 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?



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	0.0000003	< 0.00006	g → bb
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.001	Lumi meast
$\sin^2\theta_W^{\text{eff}}$	$A_{\text{FB}}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	< 0.000005 *	Beam energy
$1/\alpha_{\text{QED}}(m_z)$	$A_{\text{FB}}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_z)$	R_l	0.1196 ± 0.0030	0.00001	< 0.00015	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	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2.92 ± 0.05	0.0008	< 0.0001	?
$\alpha_s(m_w)$	$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_w$	$B_{\text{had}} = 67.41 \pm 0.27$	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	$\mu = 1.2 \pm 0.3$	0.08	< 0.05	QCD corr.
ttZ couplings	$\sqrt{s} = 365$ GeV	~30%	~2%	< 2%	QCD corr



Muon Collider Parameters

Muon Collider Parameters					
Parameter	Units	Higgs	Multi-TeV		
		Production Operation			Accounts for Site Radiation Mitigation
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/ 10^7 sec		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, ϵ_{TN}	$\mu \text{m-rad}$	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ϵ_{LN}	$\mu \text{m-rad}$	1.5	70	70	70
Bunch Length, σ_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

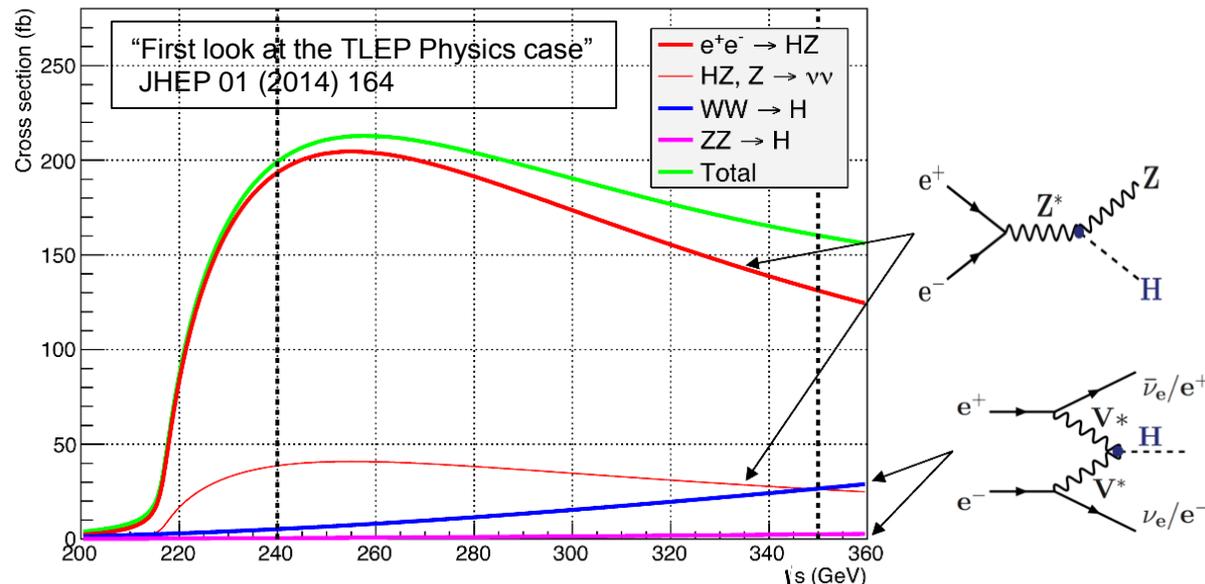
Success of advanced cooling concepts
 \Rightarrow several $\times 10^{32}$ [Rubbia proposal: 5×10^{32}]



Higgs boson production (1)

□ Muons are leptons, like electrons

- ◆ Muon colliders can a priori do everything that e^+e^- colliders can do, e.g.:

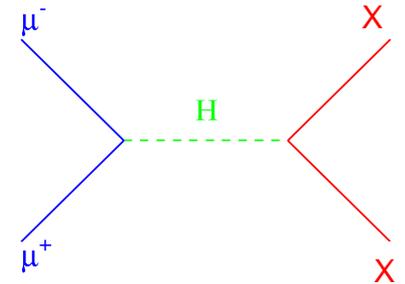


- ◆ However, for a similar beam energy spread ($\delta E/E \sim 0.12\%$) at $\sqrt{s} = 240\text{--}350$ GeV
 - FCC-ee luminosity: $0.5 - 1.1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ / IP and up to 4 IPs
 - Muon collider luminosity: $\text{few} \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ / IP
-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

Scan of the SM Higgs resonance (1)

□ Resonant production

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



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

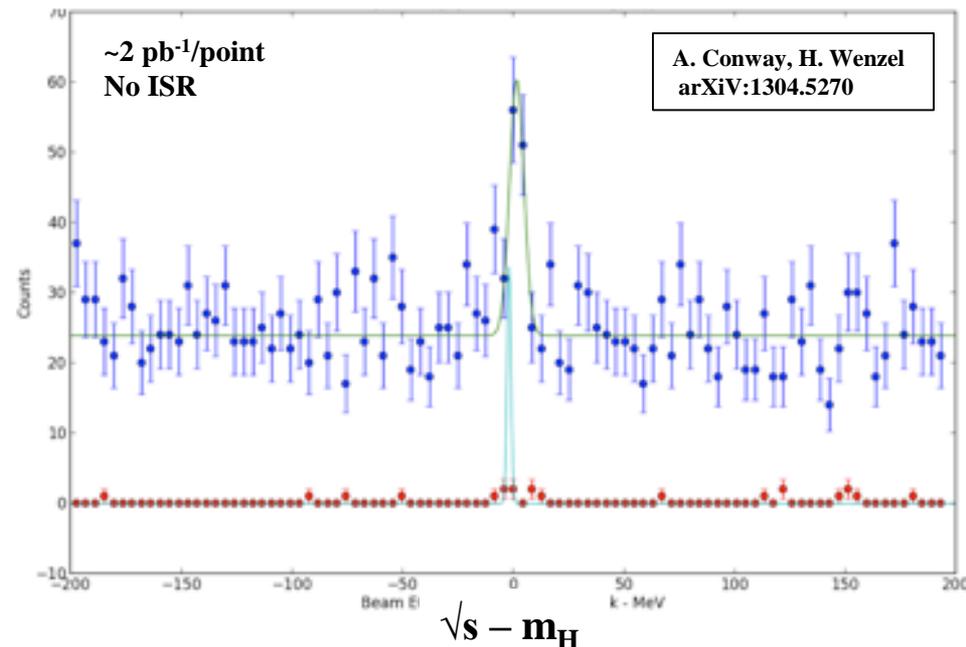
- ◆ Convolved with
 - Beam energy spectrum
 - Initial state radiation (ignored in most studies)
- ◆ The measurement of the lineshape gives access to
 - The Higgs mass, m_H
 - The Higgs width, Γ_H
 - The branching ratio into $\mu^+\mu^-$, $BR(H \rightarrow \mu\mu)$
 - Hence, the coupling of the Higgs 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 $g_\mu-2$) : see backup slides
- **Initial state radiation reduces the signal by a factor 2**
 - ◆ ... and increases the background in turn (radiative return towards the Z)
- **$\mu^+\mu^- \rightarrow Z / \gamma^*$ 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)

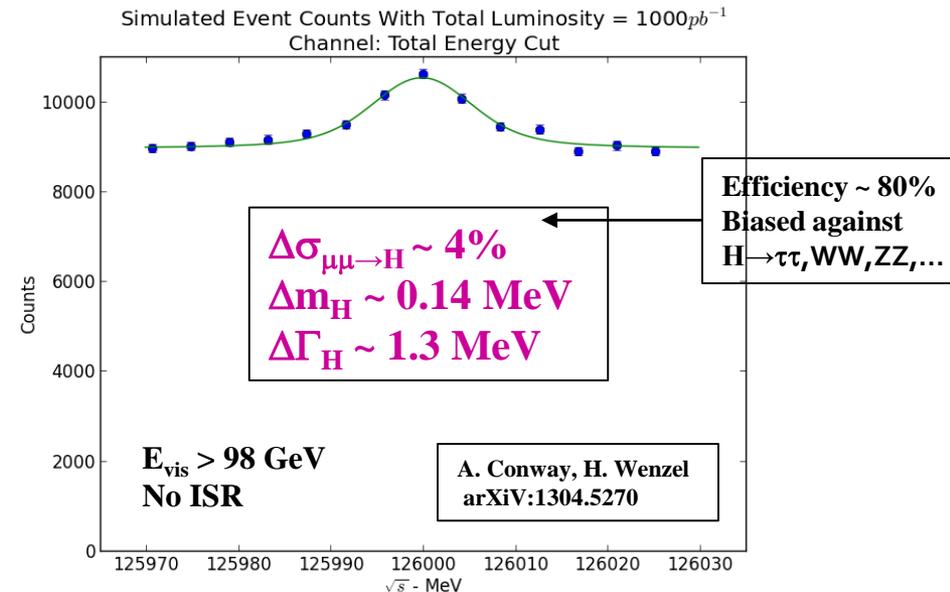
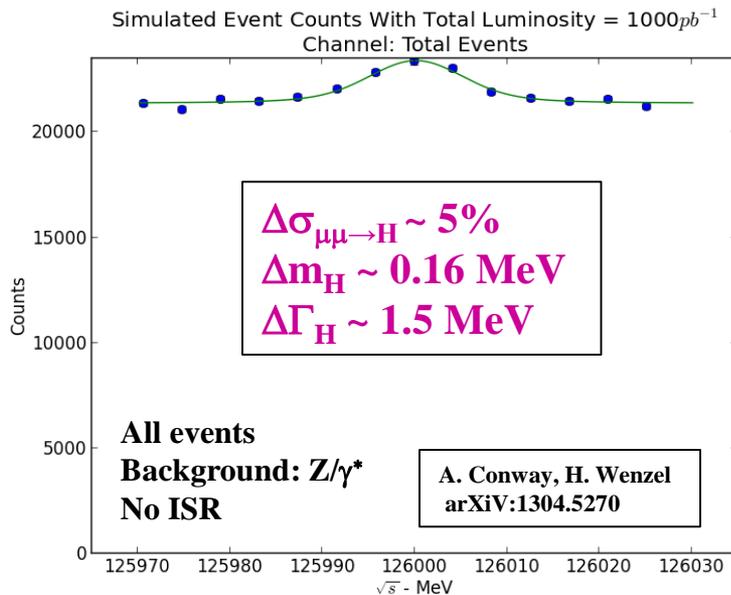
- Finding the resonance ($\Gamma_H = 4.2 \text{ MeV} \sim \delta E$)
 - ◆ Today, m_H is known to $\pm 250 \text{ MeV}$
 - Improves to $\pm 100 \text{ MeV}$ (LHC14), $\pm 30 \text{ MeV}$ (ILC), or $\pm 8 \text{ MeV}$ (FCC-ee)
 - ◆ Scan the \sqrt{s} region of interest in optimal bins of 4.2 MeV
 - Count the number of bb and semi-leptonic WW events (see next slides)
 - ◆ Without ISR, needs about $2 \text{ pb}^{-1} / \text{point}$ 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 $\pm 300 \text{ MeV}$
 - 90 pb^{-1} (6 months) for $\pm 90 \text{ MeV}$
 - 25 pb^{-1} (2 months) for $\pm 24 \text{ MeV}$
 - With $L = 2 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
 - ◆ 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 $\geq 1 \text{ yr}$ 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 $E_{\text{vis}} > 98 \text{ GeV}$ [reject $Z(\gamma)$ events]



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

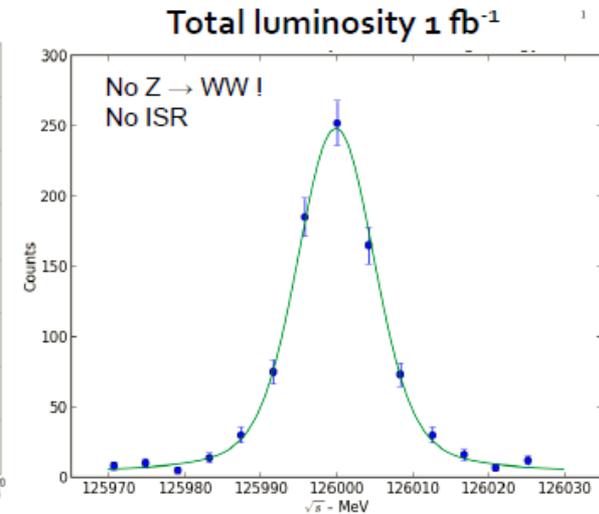
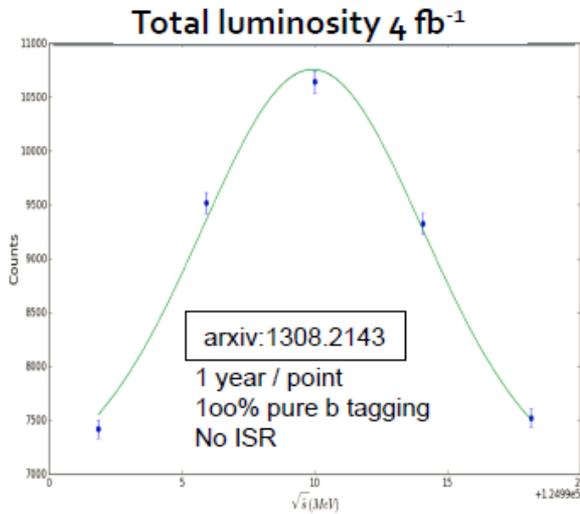
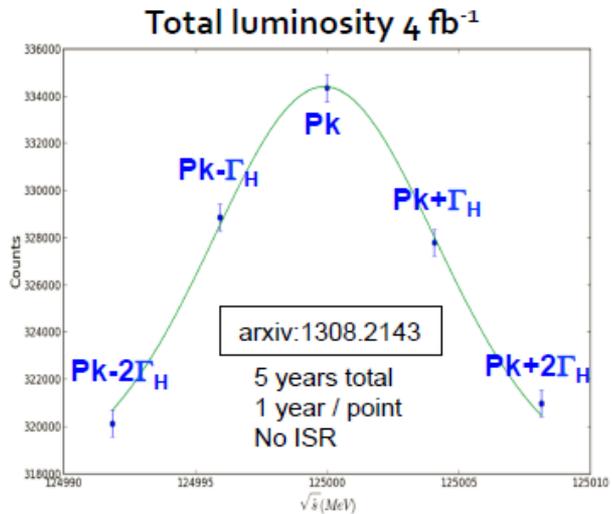
Scan of the SM Higgs resonance (4)

- Five points suffice to determine m_H , Γ_H , $BR_{\mu\mu}$, BR_{XX} , and background level

- $H \rightarrow \text{visible}$

- $H \rightarrow b\bar{b}$

- $H \rightarrow WW \rightarrow l\nu qq$



- Fit to BW \otimes Gaussian + linear background, with perfect knowledge of \sqrt{s} , $\delta\sqrt{s}$, and L

- After 5 years of running at $8 \times 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ and 1 year at half luminosity

Obs.	m_H (MeV)	Γ_H (MeV)	$BR_{\mu\mu} BR_{\text{vis}}$	$BR_{\mu\mu} BR_{b\bar{b}}$	$BR_{\mu\mu} BR_{WW}$	$BR_{\mu\mu} BR_{\tau\tau}$
Precision	0.1	0.25	4%	2.5%	3%	10%

- Note: $\Gamma_H = 4.2 \text{ MeV} \Rightarrow 0.25 \text{ MeV}$ precision corresponds to 6% relative.

Beam energy and beam-energy spread (1)

- **Muons are naturally 100% polarized (from π^\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, $\nu_0 = 0.68967593(35)$
 - Without energy spread, P_L oscillates between -20% and +20%
 - With energy spread, P_L gets diluted turn after turn

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

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

→ $P_L(T)$ is the Fourier transform of $S(\nu)$

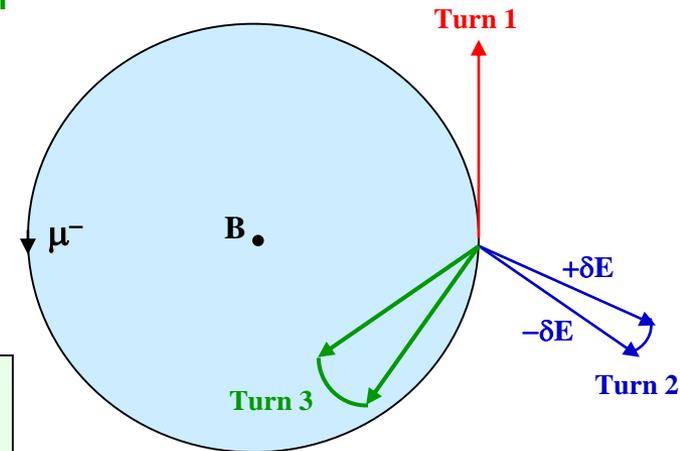
- For example, with a Gaussian energy spread

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

- Experimentally, measure P_L at each turn T

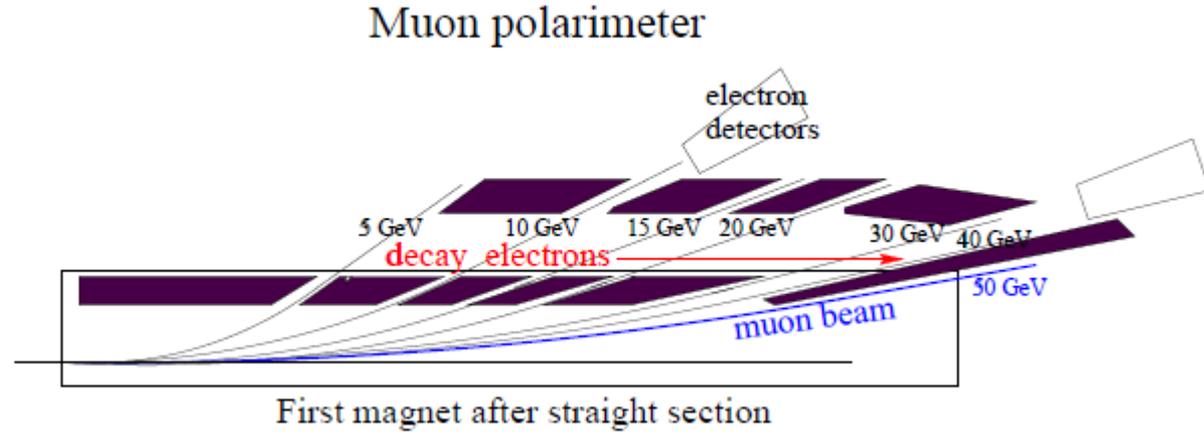
→ And deduce the complete beam energy spectrum by inverse Fourier transform

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

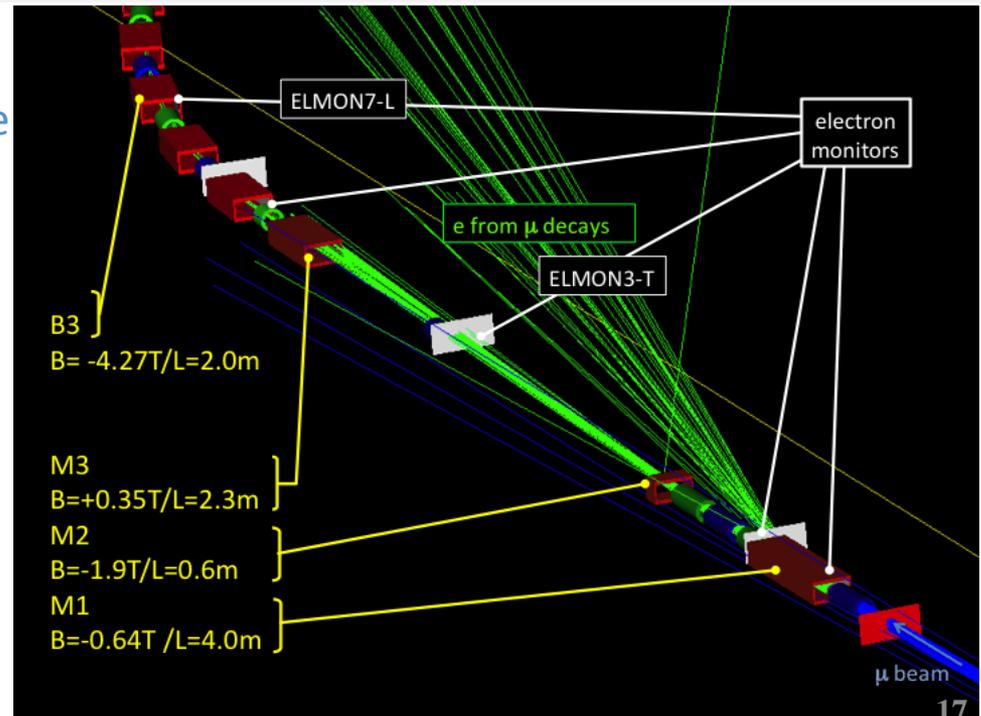


Another possibility on the same principle

[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.



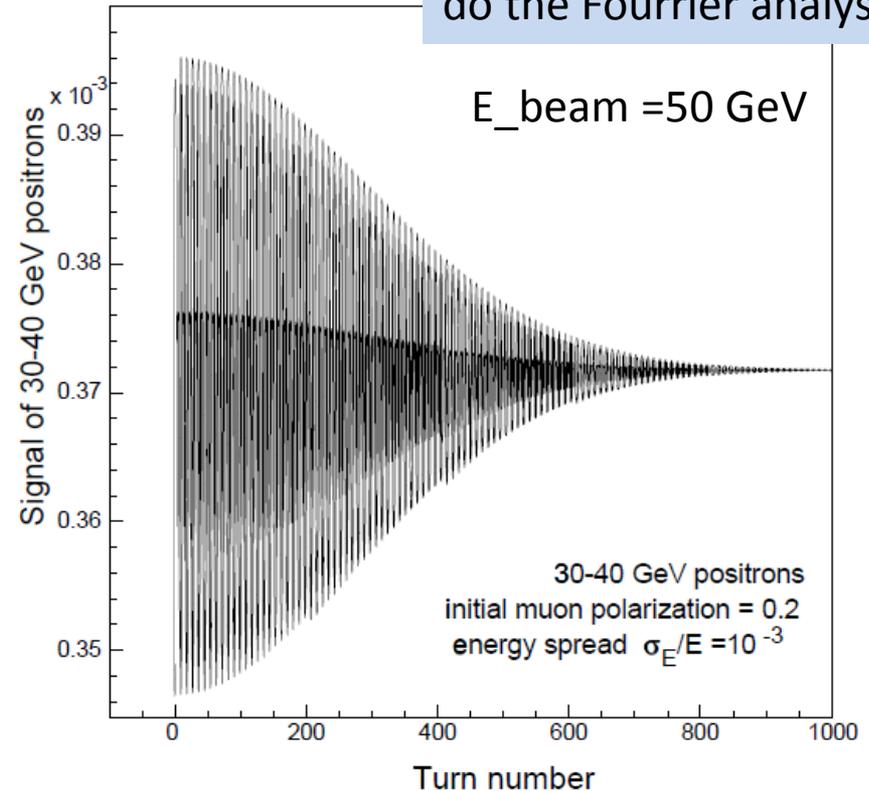
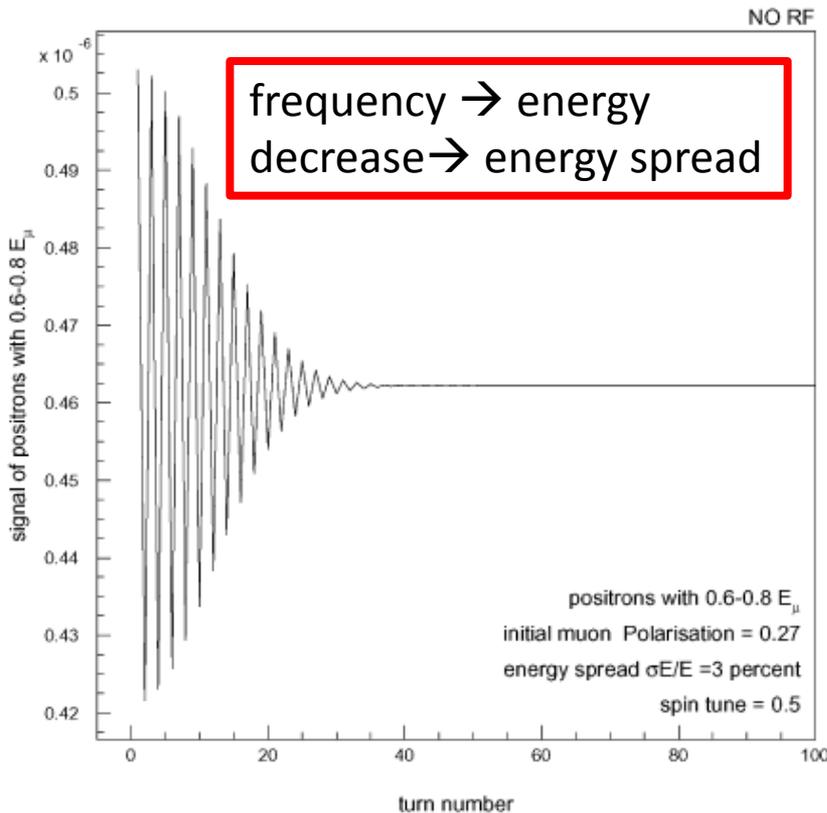
As muons circulate in the ring, the polarization precesses in the plane of the ring, so that, at turn T after injection,

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

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

$$P(T) = P_{\text{init}} e^{-\frac{1}{2}(T2\pi\nu\frac{\Delta E}{E})^2} ,$$

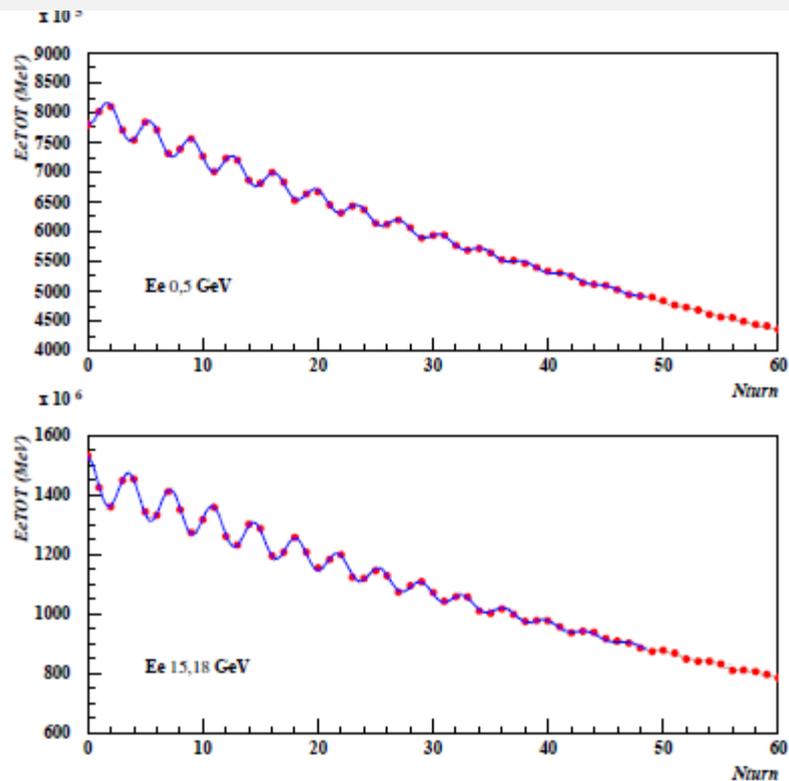
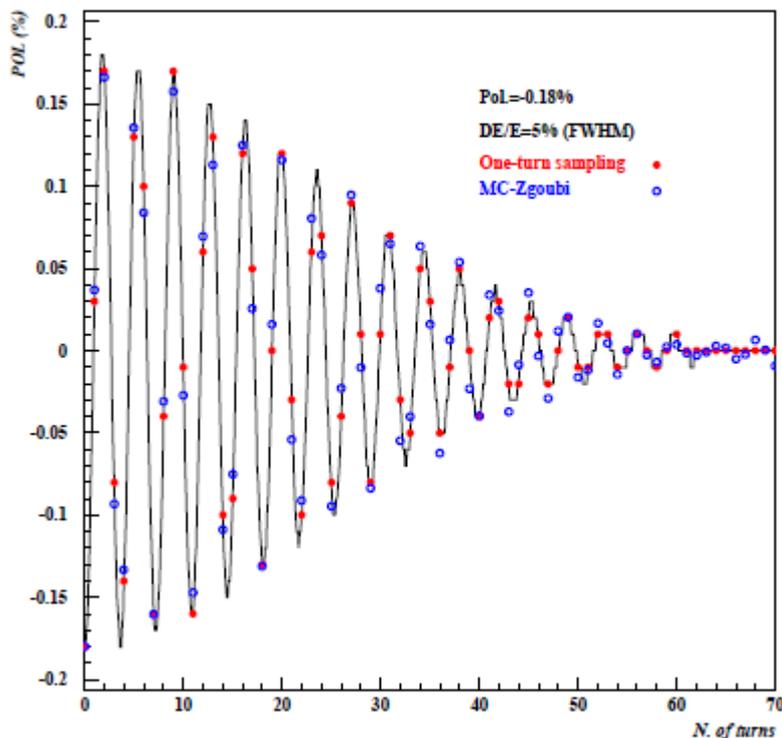
we don't have to make this Gaussian assumption, just do the Fourier analysis.



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



M. Apollonio, real simulation (NB simulated one of 100 bunches of muons for 1 fill out of 50/s).
 Statistical errors are higher by corresponding factors)

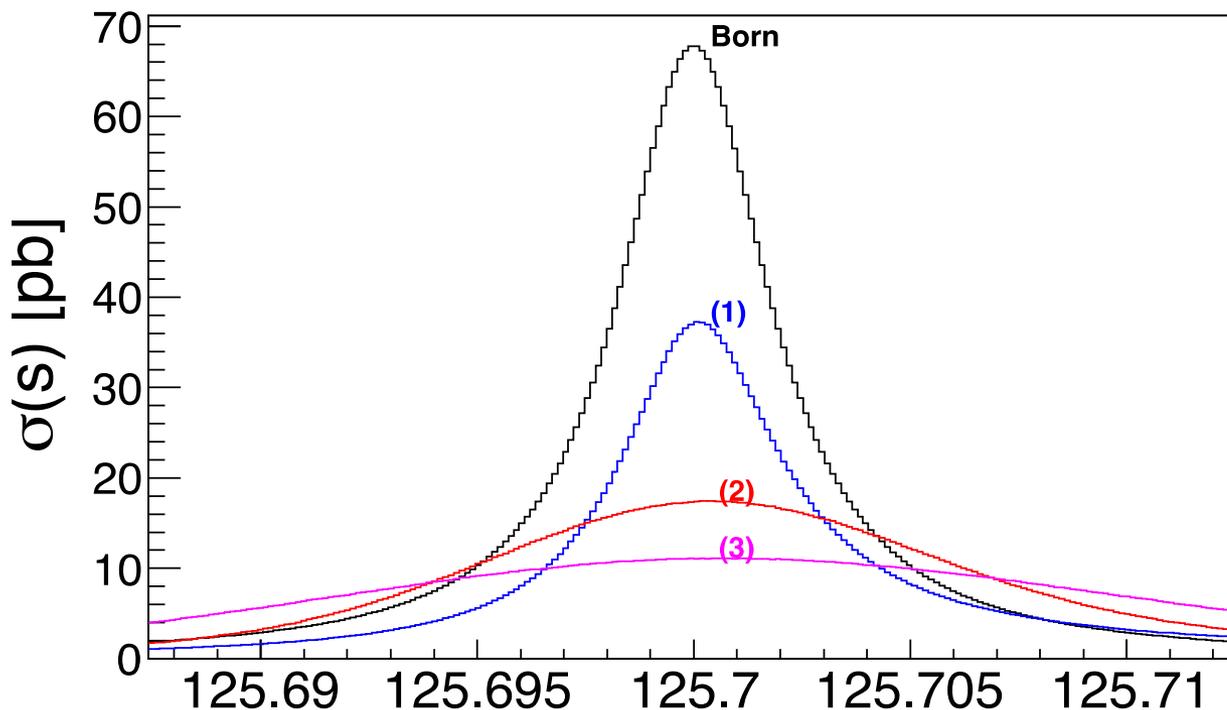


In real life there are 10^{13} muons decaying per second and the only challenge in the estimate of errors is to understand the number of decay electrons that make it to the polarimeter. (typically 10^9 - 10^{11} per second, statistics is never a problem). Because the absolute value of the polarization 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.

Beam energies are measured on a fill by fill basis, → no wrong result but it could lead to a large amount of data off the Higgs peak.

They also assume only one IP for the muon collider and two for FCC-ee



THE MUON COLLIDER IS UNIQUE BECAUSE IT ACCESSES THE HIGGS LINE SHAPE and tests for instance the theory of vdBij that there could be several nearby particles



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	LEP ₃₂₄₀	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

18 Nov 2015

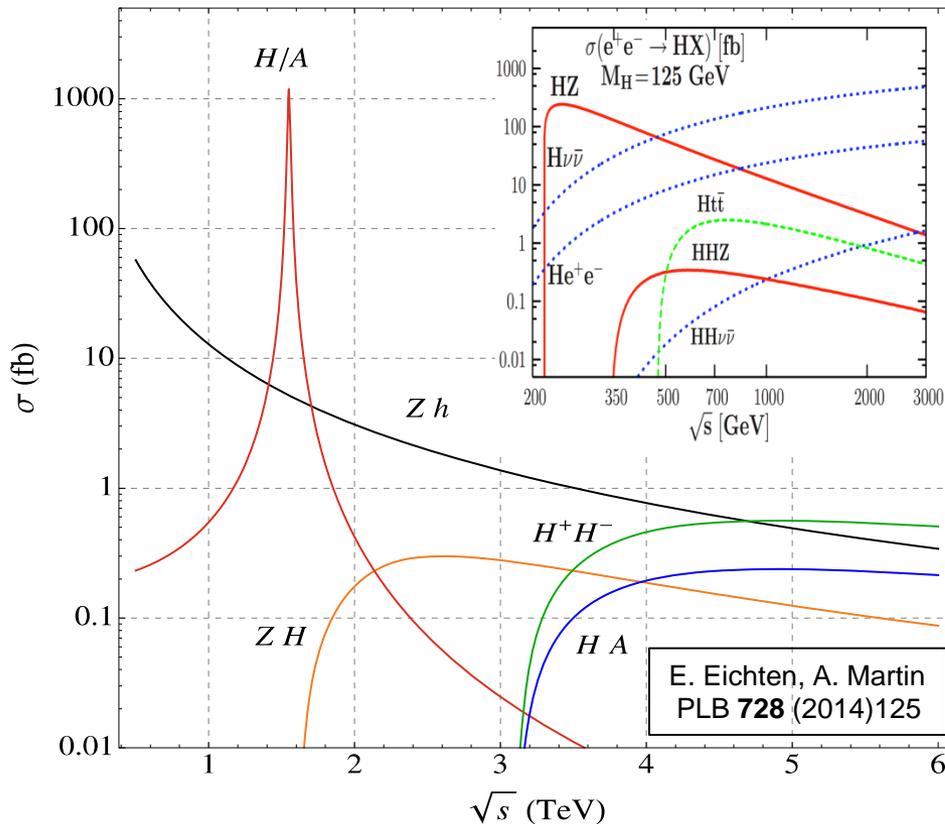
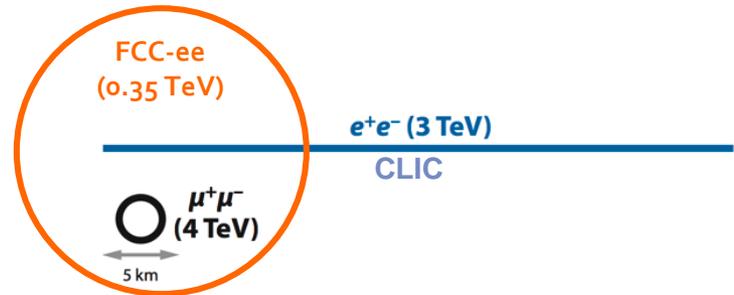
Alain Blondel Physics at muon colliders

21



High Energy muon collider

- 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 $\mu^+\mu^- \rightarrow H, A$
- $\sqrt{s} \sim 6$ TeV(?) possible in the Tevatron tunnel

Additional Higgs bosons (1)

□ Is H(125) made of several quasi-degenerate Higgs bosons ?

Similar at FCC-ee
(Recoil mass)

◆ At LHC, the typical m_H resolution in the $H \rightarrow ZZ^* \rightarrow \mu\mu$ channel is ~ 1 GeV

● Two quasi-degenerate Higgs bosons difficult to infer if $\Delta M < \text{few } 100 \text{ MeV}$

◆ Would be a piece of cake at a muon collider

● Examples shown for

→ $\Delta M = 10, 15, 20 \text{ MeV}$

→ 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 $\Delta M \sim \text{MeV}$

→ If both Higgs bosons couple to μ and b/W

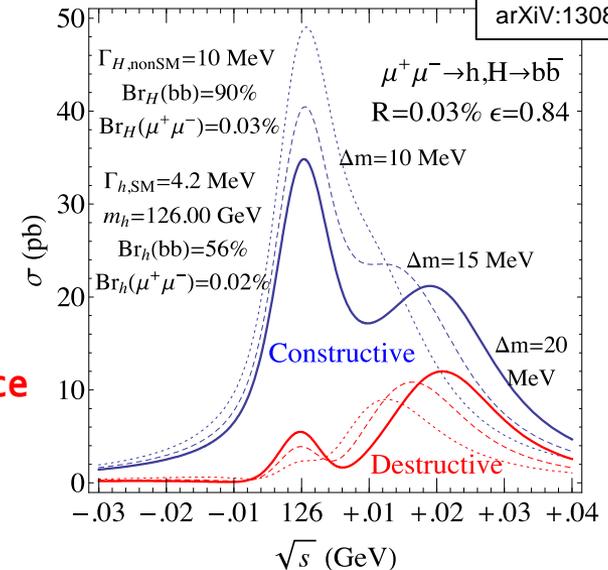
◆ Probably observable at ILC FCC-ee via pair production with $\sqrt{s} > 250 \text{ GeV}$ (to be studied)

● $e^+e^- \rightarrow hA$ present at tree level with large cross section (A pseudoscalar)

● $[e^+e^- \rightarrow hH \text{ only at loop level with a few ab cross section (H scalar)]$

→ A small mass difference is not measurable this way

Snowmass 2013
arXiv:1308.2143



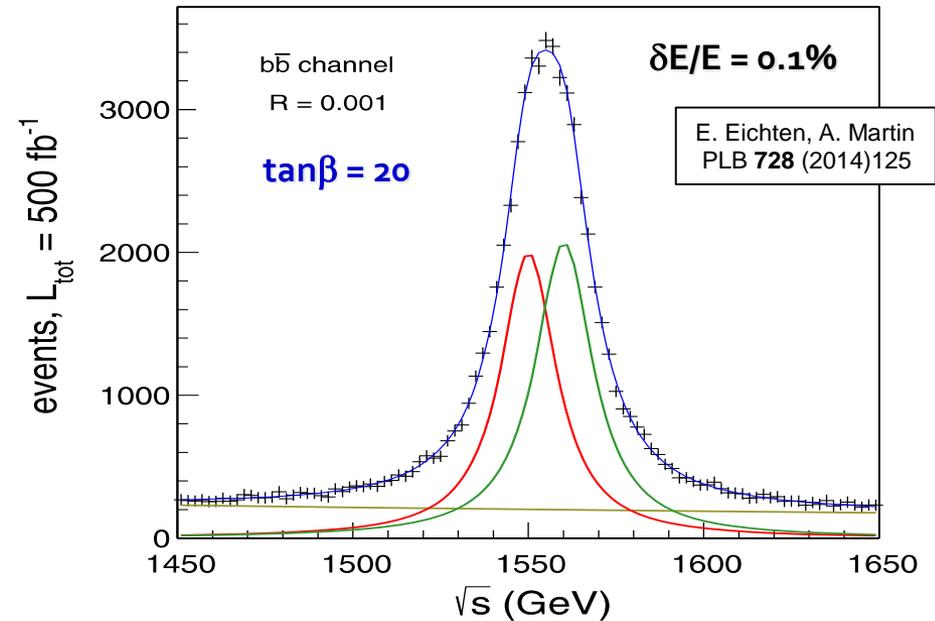
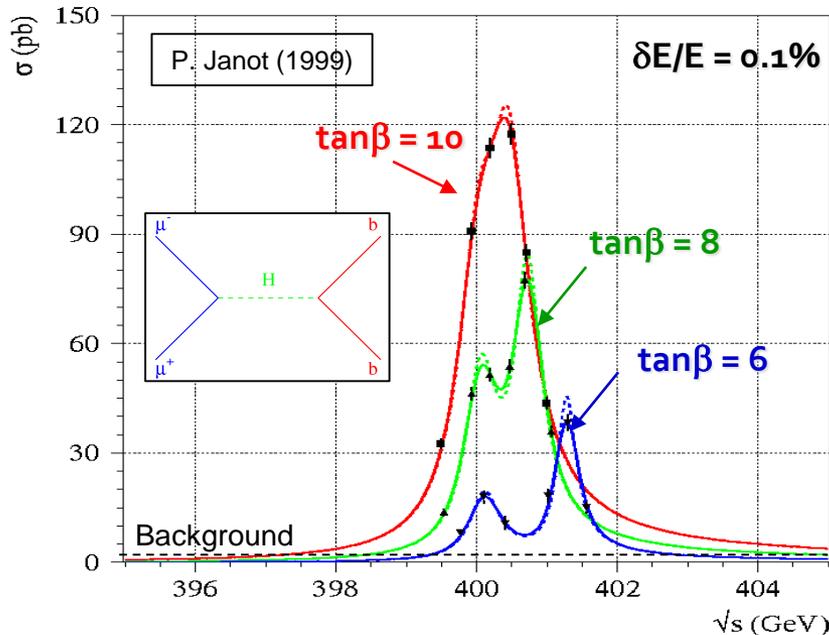
A. Djouadi et al.
PRD **54** (1996) 759

Additional Higgs bosons (2)

□ Can be applied to heavier H and A in 2HDM (e.g., from SUSY)

◆ Example 1: $m_A = 400$ GeV

Example 2: $m_A = 1.55$ TeV



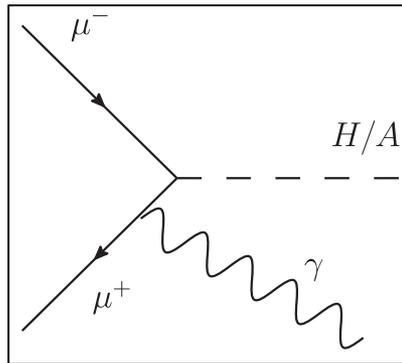
◆ Notes:

- Higgs width of the order of 0.1 to 1% of the Higgs mass
 → $\delta E/E \sim 0.1\%$ 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!

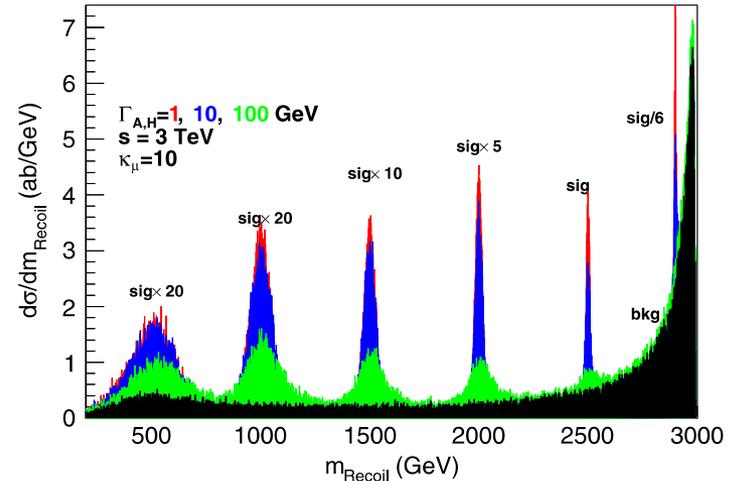
Additional Higgs bosons (3)

Automatic mass scan with radiative returns in $\mu\mu$ collisions

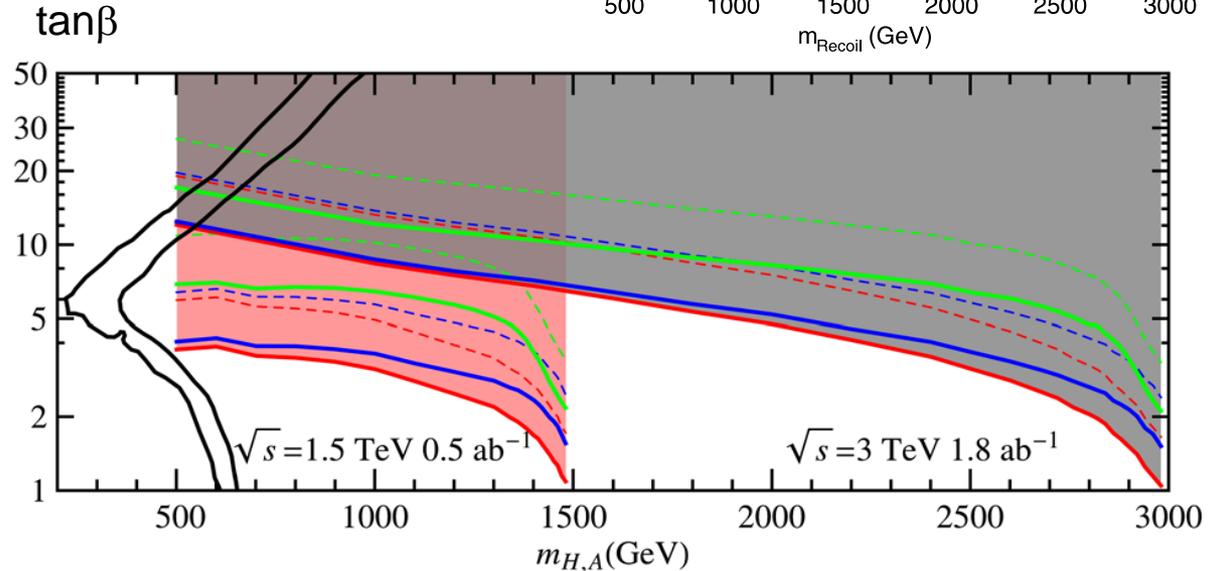
- ◆ Go to the highest energy first
 - $\sqrt{s} = 1.5, 3$ or 6 TeV
- ◆ Select event with an energetic photon
 - Check the recoil mass $m_{\text{Recoil}} = [s - 2E_\gamma\sqrt{s}]^{1/2}$



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



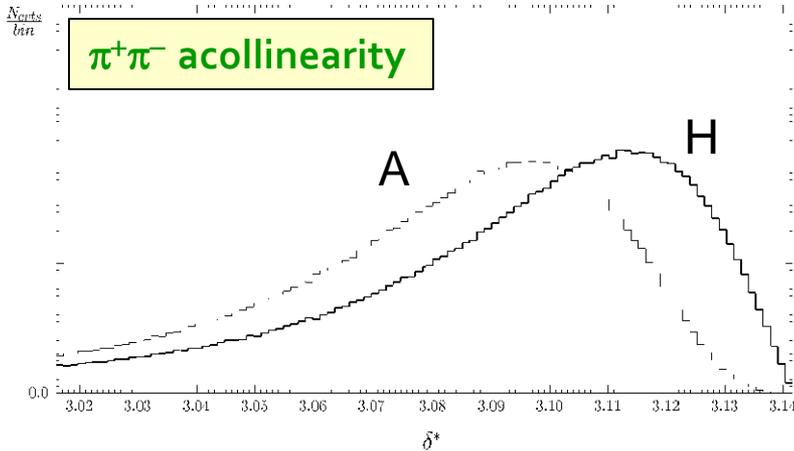
- ◆ Can "see" H and A
 - If $\tan\beta > 5$
- ◆ Build the next collider
 - At $\sqrt{s} \sim m_{A,H}$



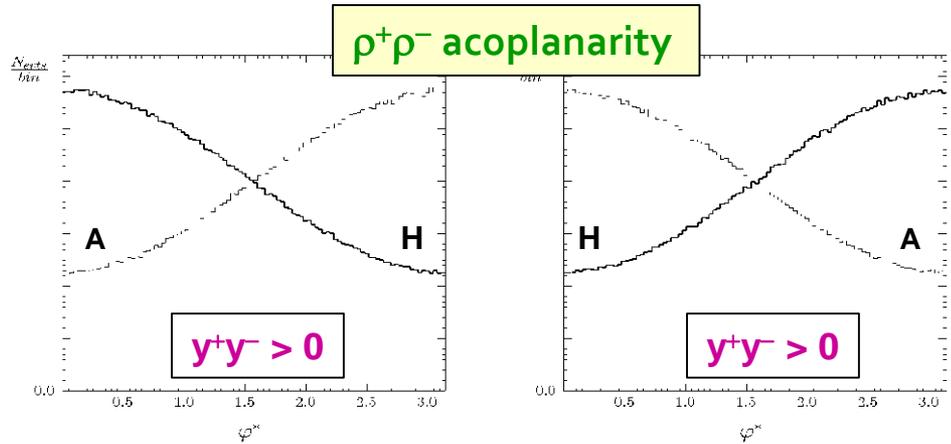
Additional Higgs bosons (4)

□ **Unique CP (violation) and H/A mixing studies can start**

◆ From $H, A \rightarrow \tau^+\tau^- \rightarrow \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$

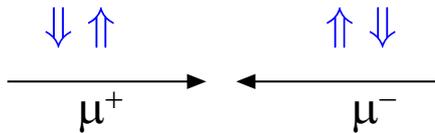


From $H, A \rightarrow \tau^+\tau^- \rightarrow \rho^+\rho^-\nu_\tau\nu_\tau$ with $\rho^\pm \rightarrow \pi^\pm\pi^0$



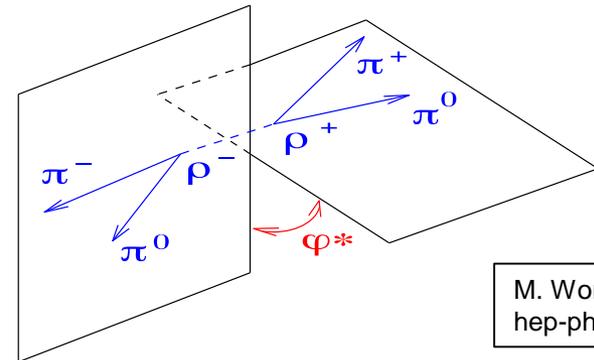
$$y^\pm = E_{\pi^\pm} - E_{\pi^0}$$

◆ 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 $\rightarrow 10^9 e^\pm$ produced per turn \rightarrow **produce lots of photons and neutrons.**

Shielding against these backgrounds is necessary. $10\text{-}15^\circ$ 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 $\mu\mu \rightarrow \mu\mu$ (Mhamha? 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

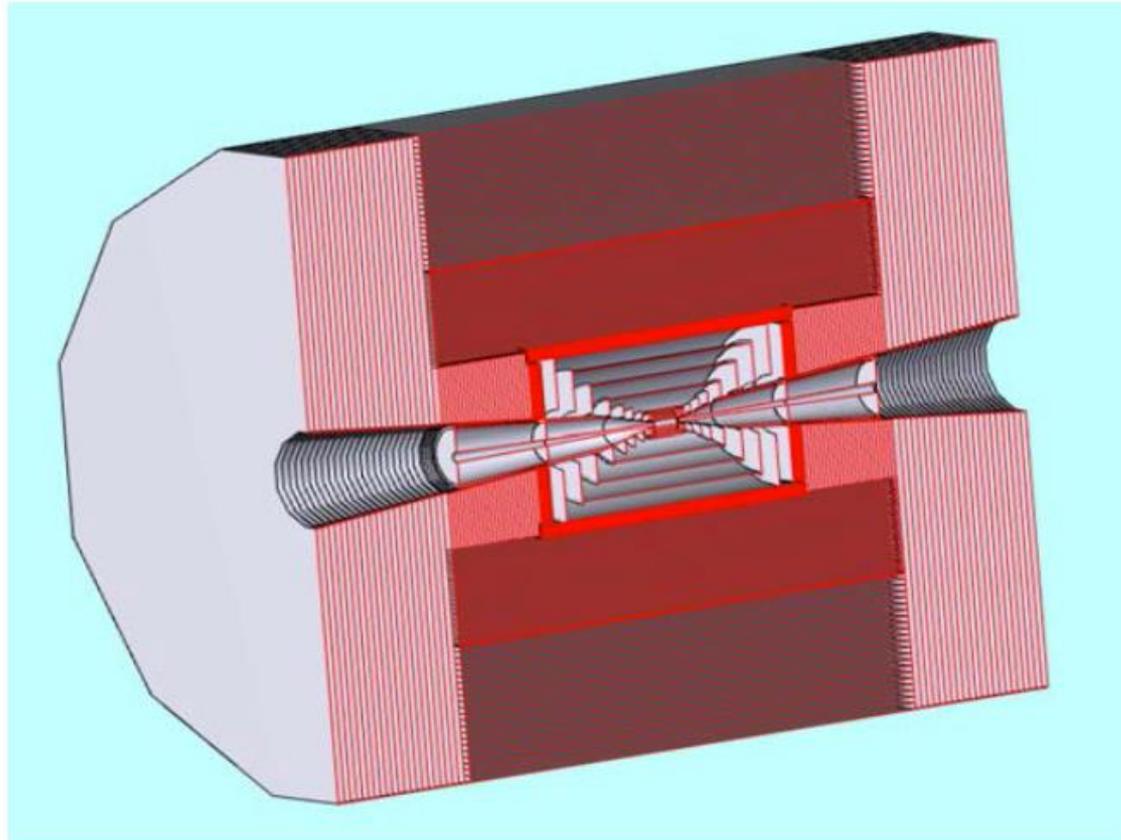


Figure 23: Cross sectional view of a possible Higgs Factory Muon Collider detector showing the tungsten cones shielding the detector from beam related backgrounds.

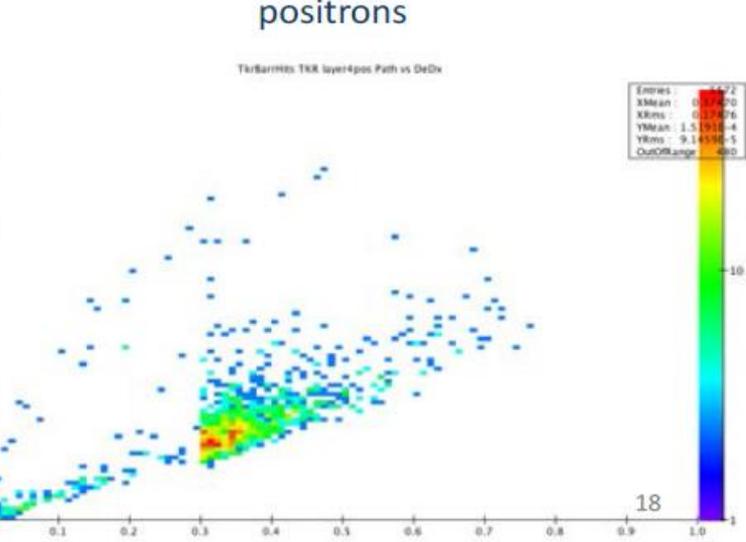
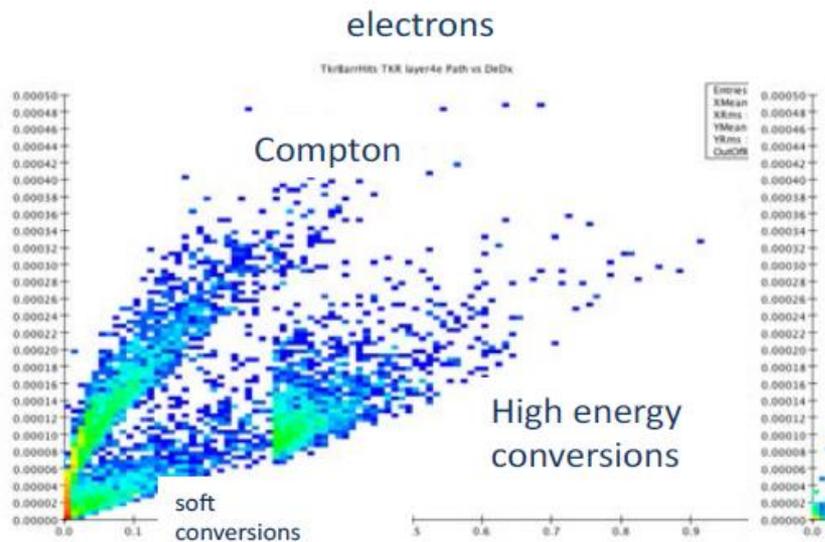
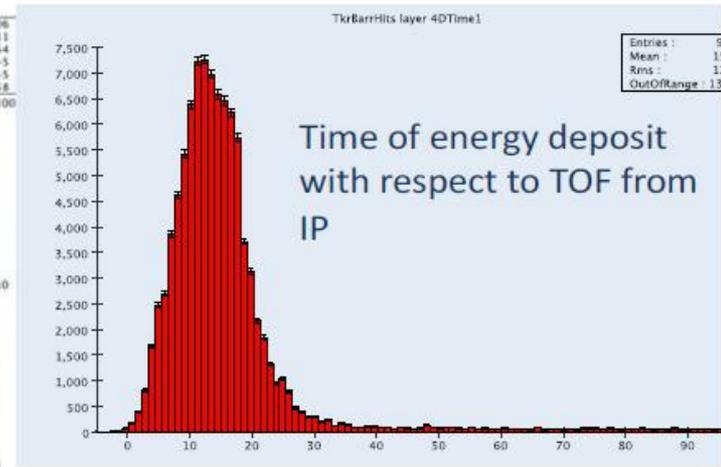
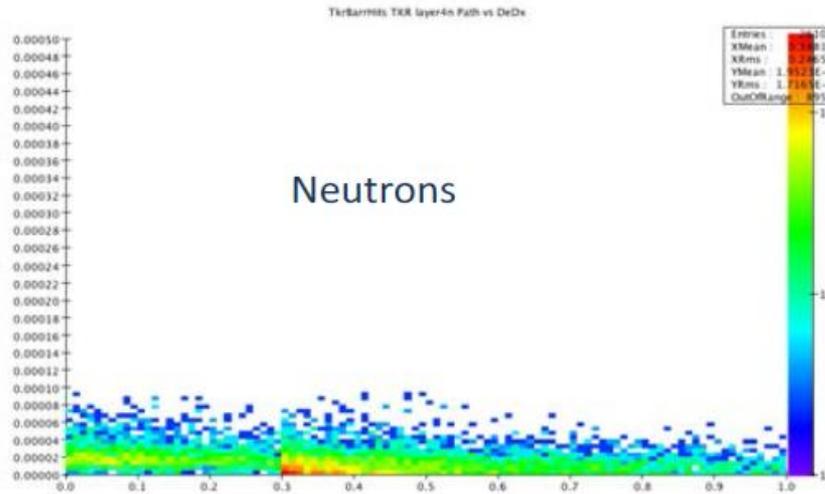


Figure 26: Contributions of various background components to signals in a barrel silicon detector layer

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 precision and 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 $10^{13} W \rightarrow e, \mu, \nu$
- Presently the case for a 'Z,W,H,top factory' is quite clear.

the physics case for higher energy ($E > 400$ GeV) lepton collider needs to be revisited in the light of LHC results



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! (and many other things)
- 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... flavour specific 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 \rightarrow 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 comparably easier than at LHC



SPARES



also: precision measurements

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

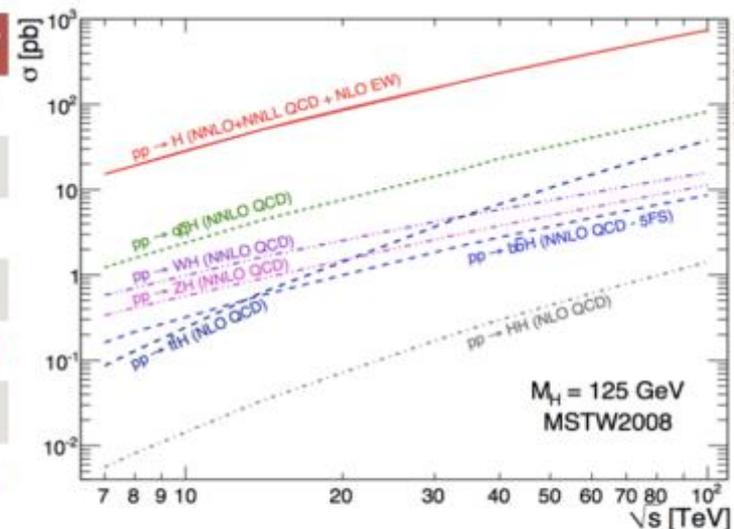
Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1 *	QED / EW
R_l	Peak	20.767 ± 0.025	0.001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.0000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.001	Lumi meas
$\sin^2\theta_W^{\text{eff}}$	$A_{\text{FB}}^{\mu\mu}$ (peak)	0.23148 ± 0.00016	0.000003	< 0.000005 *	Beam energy
$1/\alpha_{\text{QED}}(m_Z)$	$A_{\text{FB}}^{\mu\mu}$ (off-peak)	128.952 ± 0.014	0.004	< 0.004	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 ± 0.0030	0.00001	< 0.00015	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	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2.92 ± 0.05	0.0008	< 0.0001	?
$\alpha_s(m_W)$	$B_{\text{had}} = (\Gamma_{\text{had}}/\Gamma_{\text{tot}})_W$	$B_{\text{had}} = 67.41 \pm 0.27$	0.00018	< 0.0001	CKM Matrix
m_{top} (MeV)	Threshold scan	$173340 \pm 760 \pm 500$	20	< 40	QCD corr.
Γ_{top} (MeV)	Threshold scan	?	40	< 40	QCD corr.
λ_{top}	Threshold scan	$\mu = 1.2 \pm 0.3$	0.08	< 0.05	QCD corr.
ttZ couplings	$\sqrt{s} = 365$ GeV	~30%	~2%	< 2%	QCD corr

* work to do: check if we cant improve



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

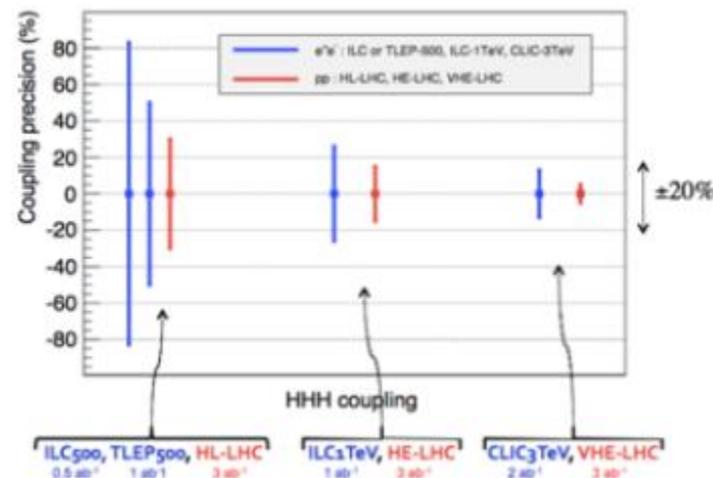
HL
LHC

➔
x10-400

FCC
pp

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

arXiv:1310.8361

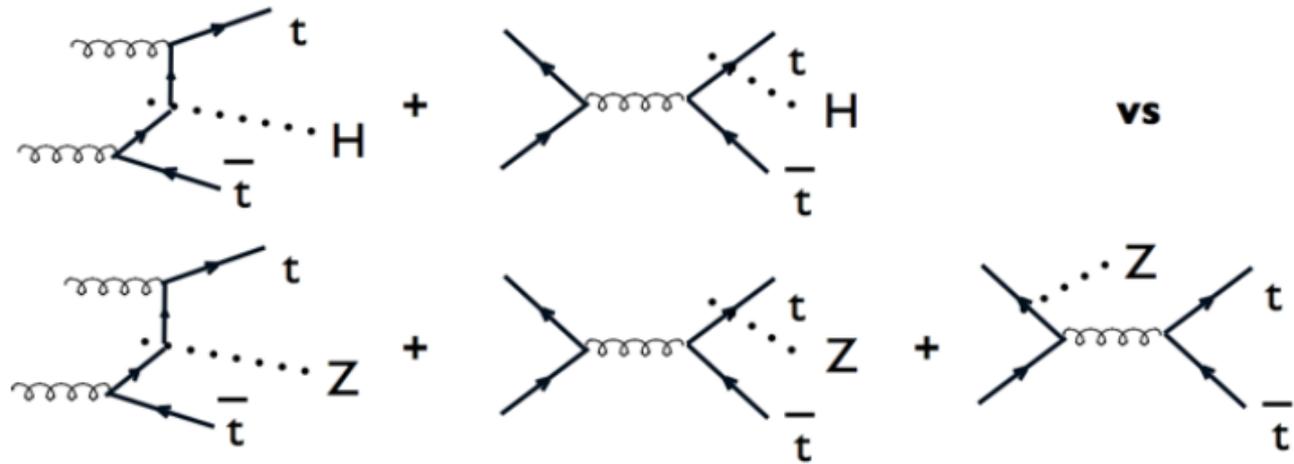


10



➔ ... but also new measurements not possible at the LHC/HL-LHC

ttH / ttZ



➔ Theoretical uncertainties cancel mostly

- PDF (CTEQ 6.6) $\pm 0.5\%$
- Missing higher orders $\pm 1.2\%$

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

➔ Lots of statistics and ideas for small systematics

