WORKING GROUP ON :

MUON COLLIDERS AT CERN

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20/09/99

OUTLINE

1.- AIM OF THE WORKING GROUP

2.- STATE OF THE ART

3.- WHAT IS TO BE DONE ?

4.- CONCLUSION

Plenary Meeting of the European Muon Study Group
CERN - 20 Sept. 1999

1.- AIM OF THE WORKING GROUP (AS I SEE IT)

* GLOBAL GOAL:

ASSESS THE PHYSICS OPPORTUNITIES OF A MUON COMPLEX AT CERN.

- ν - FACTORY
- INTENSE MUON BEAMS

→ WORKED OUT BY OTHER GROUPS

- PRECISION MUON COLLIDERS
- HIGH ENERGY MUON COLLIDER

→ PHYSICS PROGRAMME NOT OUSTANDINGLY DIFFERENT FROM THAT OF AN e^+e^- COLLIDER. NO EXTRA-NEED FOR MOTIVATIONS WHEN ALL THE REST IS DONE!

→ MAIN EMPHASIS FOR THE WORKING GROUP

* SEVERAL QUESTIONS TO BE TREATED IN DETAIL:

→ IS THE PHYSICS OUTCOME SUPERIOR TO THAT OF LHC / NLC / $\gamma\gamma$ COLLIDER?

(IF YES)
→ IS IT SUPERIOR ENOUGH TO JUSTIFY THE BUILDING OF PRECISION MUON COLLIDERS AFTER LHC (AND MAYBE NLC)?

(IF YES)
→ IS SUCH A COLLIDER FEASIBLE WITH THE SPECIFICATIONS (LUMINOSITY, ENERGY SPREAD...) IMPOSED BY THE ABOVE?

(IF YES)
→ IS IT AFFORDABLE? (COMPARE THE COST ADD'L TO THAT OF A ν FACTORY WRT NLC + $\gamma\gamma$ COLLIDER)

2.- STATE OF THE ART

ANSWER TO THE LAST THREE POINTS : MOSTLY UNKNOWN

COST : ?

FEASIBILITY : FOR THE COLLIDER: NOT MUCH DONE [EVOLVING FAST] → MOSTLY U.S. → (+ ECFA STUDY)

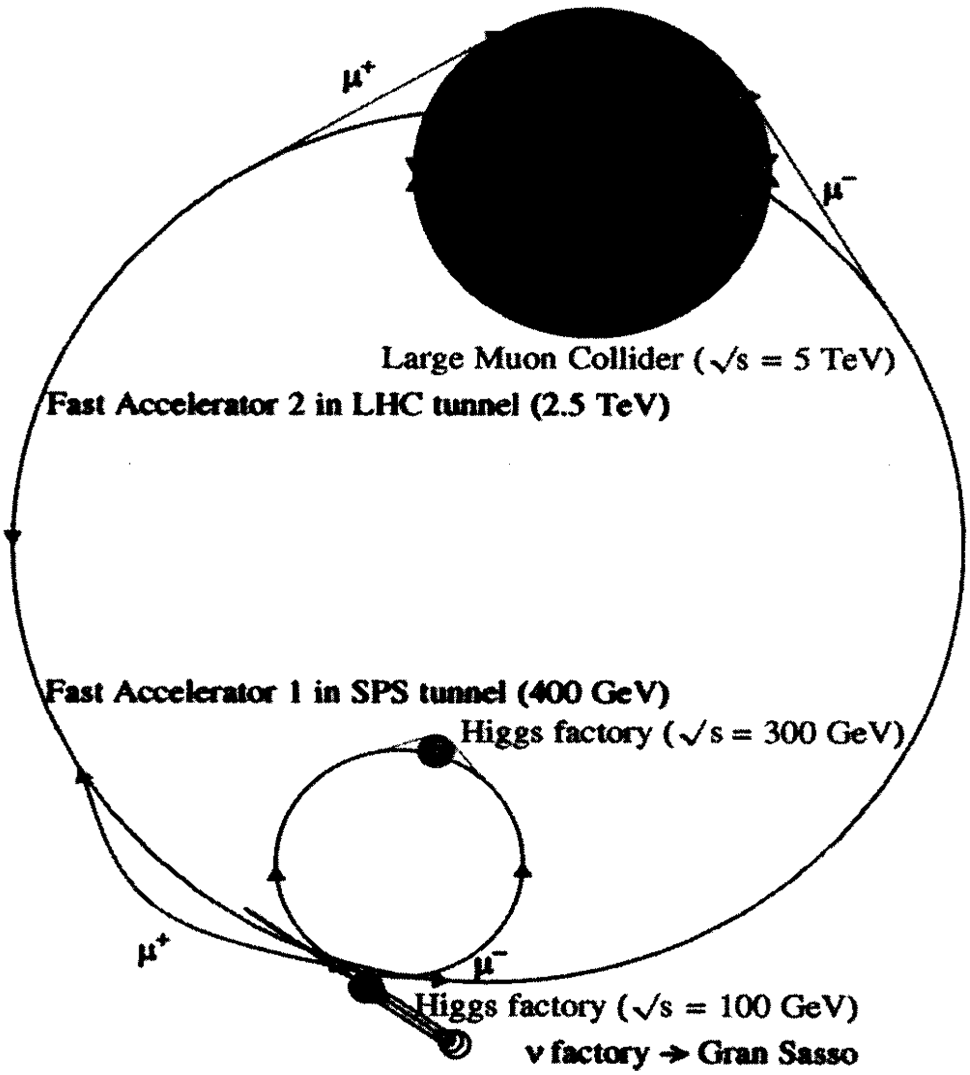
A FEW ISSUES ADDRESSED :
(BASIC PRINCIPLES + A COUPLE OF M.C. STUDIES)

- PROTON SOURCE
- TARGET
- π/μ COLLECTION
- MUON COOLING, BUNCHING
- MUON ACCELERATION TO ~ 20 GeV
- —"— —"— TO 50 GeV AND MORE
- COLLIDER
- FINAL FOCUS AND BACKGROUNDS

(BLUE : NEEDED FOR A ν- FACTORY
RED : SPECIFIC TO COLLIDERS)

→ MANY PROBLEMS TO BE UNDERSTOOD AND WORKED OUT

Possible Layout of a muon complex on the CERN site

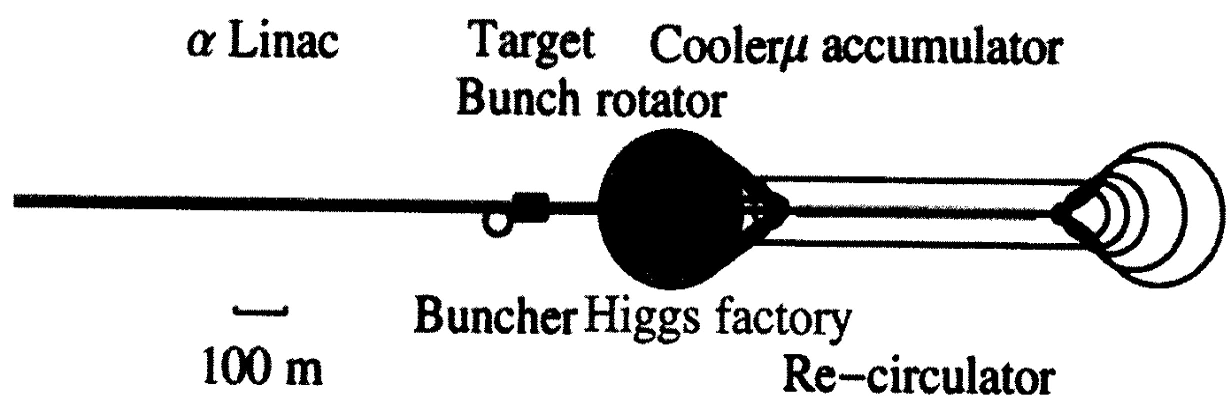


As anticipated:

- **the collider rings would be** small,
- **the accelerator complex would** fit nicely **in the CERN site,**
- **it would make an optimal use of the** existing facilities,
- **with a reasonable amount of** civil engineering.

Tentative Layout for the First Precision Muon Collider

(Higgs Factory)



Note: 10 arcs instead of 4...

... QUITE BASIC ⟶ A LOT TO DO !

PHYSICS MOTIVATIONS : THEY SEEM TO BE THERE !
(ESPECIALLY IF THE HIGGS BOSON EXISTS AND IS LIGHT...)

A $\mu^+\mu^-$ collider can do things that an e^+e^- collider cannot do.

- Larger coupling to Higgs bosons
  by a factor m_μ/m_e:

$$\sigma(\mu^+\mu^- \to h) \simeq 40\,000 \times \sigma(e^+e^- \to h).$$

⇒ Discovery/study of Higgs resonances (h, H, A).
(Would need several centre-of-mass energies, and therefore, several collider rings, but the acceleration/cooling stages and the rest of the infrastructure would remain the same.)

- No beamstrahlung, less Bremsstrahlung

⇒ Beam energy resolution can be excellent;
Down to $3\,10^{-5}$ ⇒ Precision Physics at the Z peak, at the WW threshold, at the $t\bar{t}$threshold, ...

- Muons decay and are naturally polarized

⇒ Almost infinitely precise energy calibration with decay electron monitoring;
The whole energy spectrum can be known.

(UNIQUE) Physics programme
for 2–3 decades

Requires vigorous R&D programme
to reach the desired performance

ECFA STUDY → "QUICK" OVERVIEW OF THE SUPERIOR PHYSICS CAPABILITIES OF PRECISION MUON COLLIDER

- **HIGGS FACTORY**

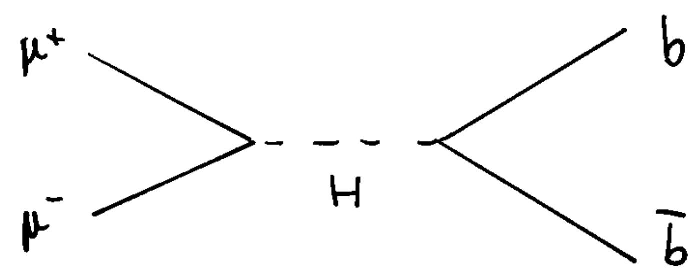
ASSUMED:

- → $\mathcal{L} \gtrsim 10^{31}\ cm^{-2} s^{-1}$
- → $\delta E/E \sim \Gamma_H/m_H \sim 3.10^{-5}$
- → NO DETECTOR BACKGROUNDS
- → EXCELLENT b-TAGGING CAPABILITIES
- → NO POLARIZATION

... AND $m_H \sim 110\ GeV/c^2$

⇓

HIGGS LINESHAPE MEASUREMENTS

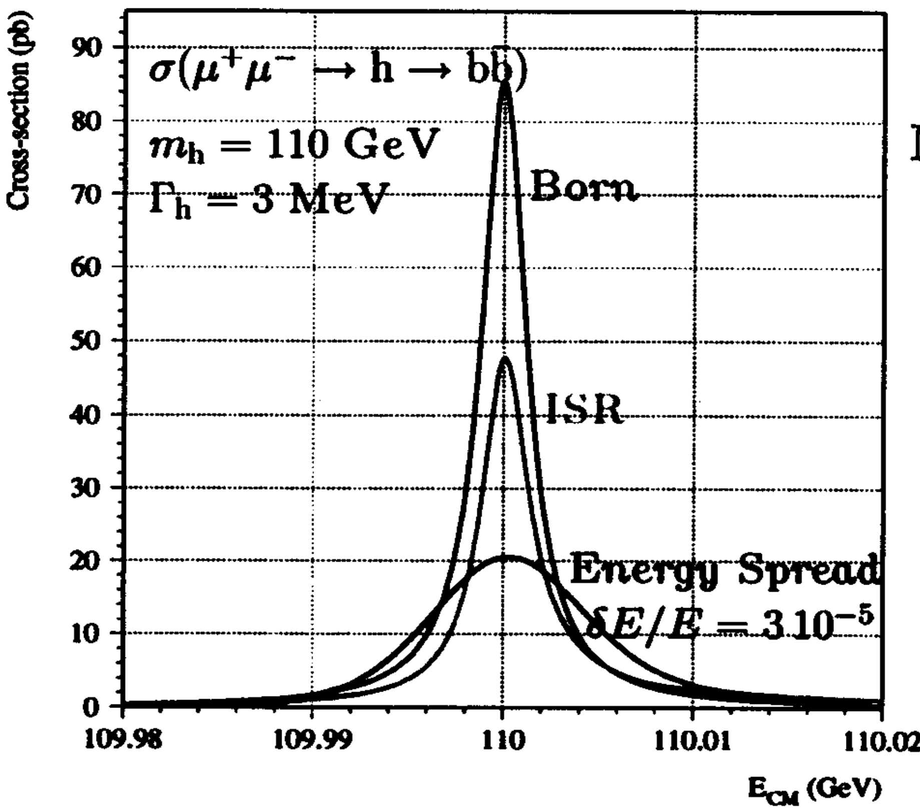


$m_H, \Gamma_H, \sigma^0_{peak}$
with a scan in $\sqrt{s}$
(FEW 1000's H / year)

SO WHAT ?

3.-Precision Muon Colliders

a. The Higgs Line Shape



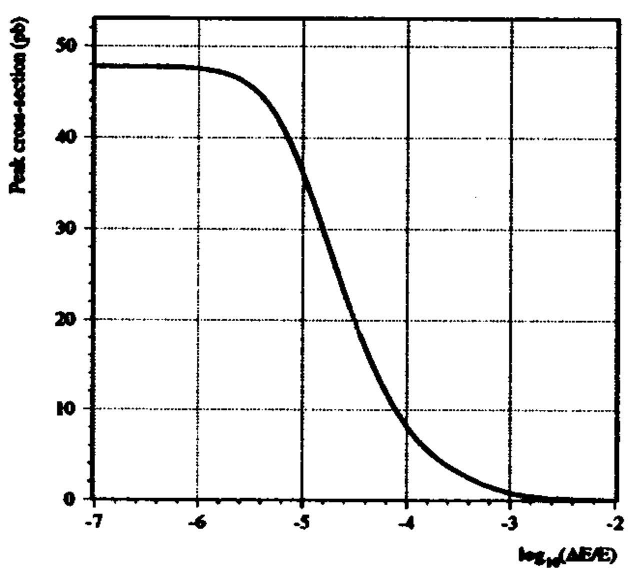
Measure:
(as for the Z)

1. The mass m_h;
2. The width Γ_h;
3. The cross section

$\sigma^0_{peak} = \frac{12\pi}{m_h^2} BR_{\mu\mu} BR_{bb}$;

⇒ Need to know with precision:

1. The beam energy;
   (for the mass)
2. The energy spread;
   (for the width, but also for the cross section)
3. The integrated luminosity;
   (for the line shape; not crucial, though)



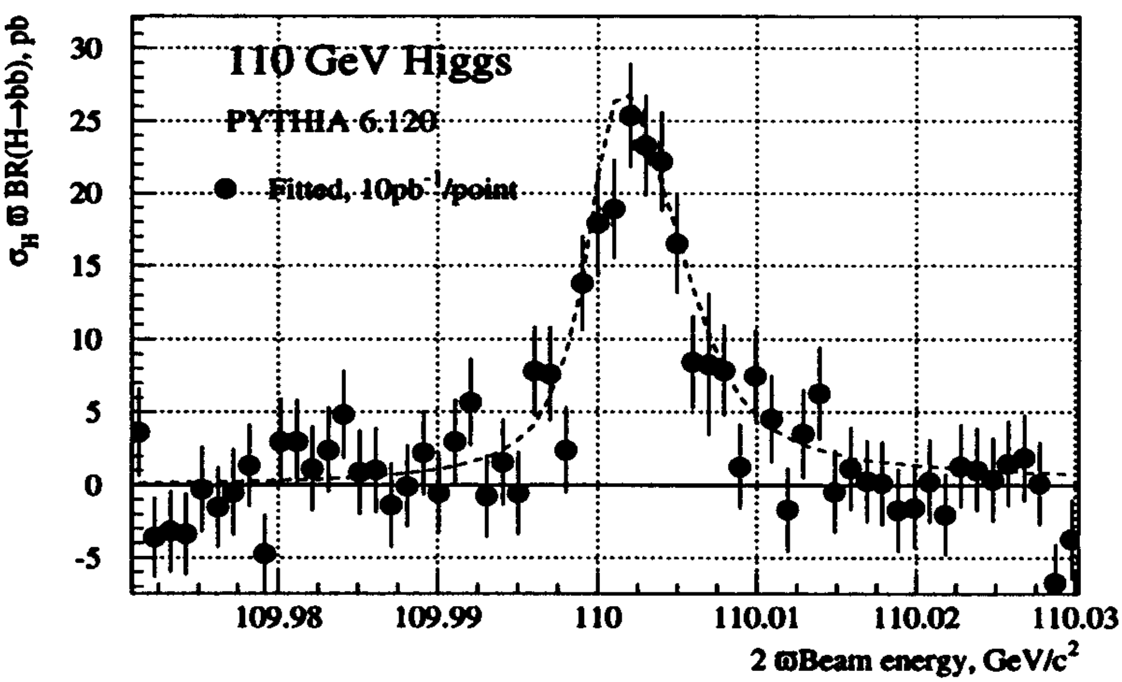
Results:

For a beam energy spread of $3\,10^{-5}$ and $4\,10^{12}$ muons per bunch, and for each muon fill (!), the following statistical accuracy can be reached:

- 10^{-7} on the beam energy (5 keV);
- $3\,10^{-7}$ on the energy spread (0.5% on $\sigma(\mu^+\mu^- \to \mathrm{h})$);
- 10^{-4} on the polarization;

and is limited by the uncertainty on $g_\mu - 2$...

A scan of the Higgs resonance would then give:



Observable	Accuracy	
σ_{peak}	$\pm 10\,\mathrm{pb}\ /\ \sqrt{\mathcal{L}}$	(5% for $100\,\mathrm{pb}^{-1}$)
m_{h}	$\pm 0.1\,\mathrm{MeV}/c^2$	
Γ_{h}	$\pm 0.5\,\mathrm{MeV}$	(20%)

(with a three-point scan only)

OUTSTANDING CONSEQUENCES:

✓ → PRECISION TESTS OF THE STANDARD MODEL

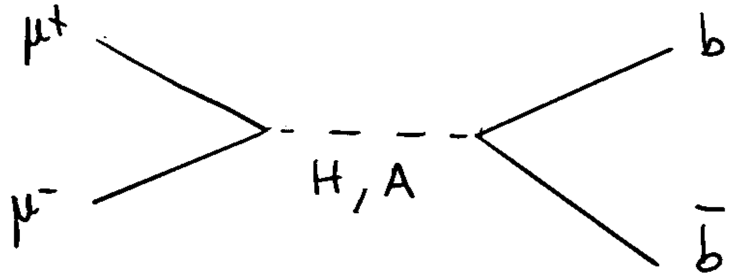
✓ → RELEVANT CONSTRAINTS ON THE MSSM (FOR INSTANCE)

?✓ → PREDICT m_A, IF NOT TOO HEAVY (IN THE MSSM FRAMEWORK)

⇓

GO FOR

- A SECOND HIGGS FACTORY ($\sqrt{s} \simeq m_H, m_A$)



? → PRECISION TESTS OF THE MSSM

? → PREDICT / MEASURE $\tan\beta$

? → CP VIOLATION STUDIES IN THE HIGGS SECTOR

- QUICK LOOK AT OTHER FACTORIES (Z, WW, $t\bar{t}$)

NO NEED FOR "OUTSTANDING" $\delta E/E$ } $\simeq$ FREE
HIGH LUMINOSITY
POLARIZATION } MORE STUDIES NEEDED

Implications in the MSSM

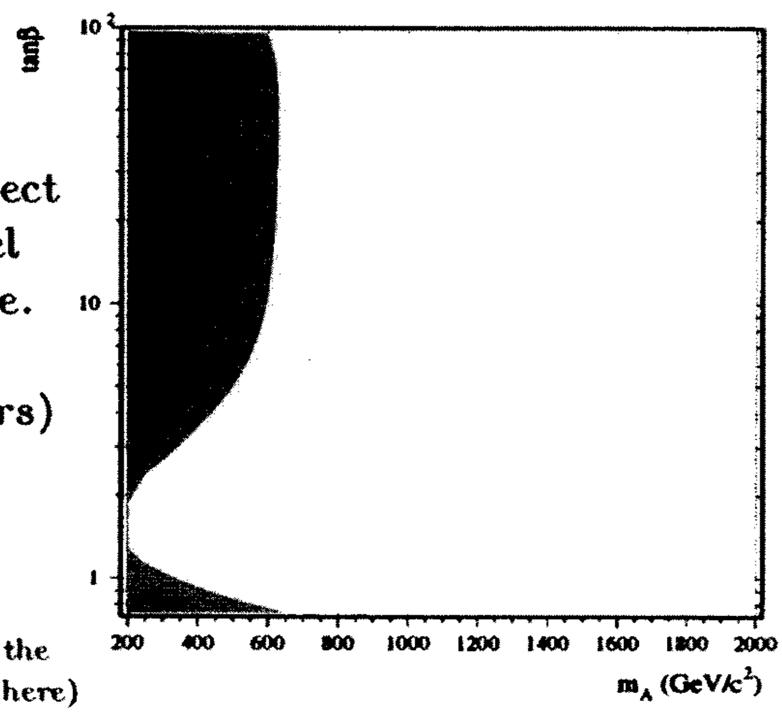
Assume that LHC found one standard-model-like Higgs boson (nothing else) and that an e^+e^- linear collider studied it with $500\,fb^{-1}$.

Observable	Accuracy
m_h	$\pm 100\,MeV/c^2$
$\sigma(gg \to h)BR(h \to \gamma\gamma)$	$\pm 7\,fb \equiv \pm 20\%$ (theory uncertainty on the cross section)
$\sigma(e^+e^- \to hZ)BR(h \to b\bar{b})$	$\pm 2.5\%$ (theory uncertainty the pole b quark mass)
$\sigma(e^+e^- \to hZ)$, with $Z \to \ell^+\ell^-$	$\pm 1\%$

Question: Is it the first sign of supersymmetry?

χ^2 of the LHC and LC **measurements with respect to the standard model in the $(m_A, \tan\beta)$ plane.**

(5σ, 4σ, 3σ, 2σ, contours)



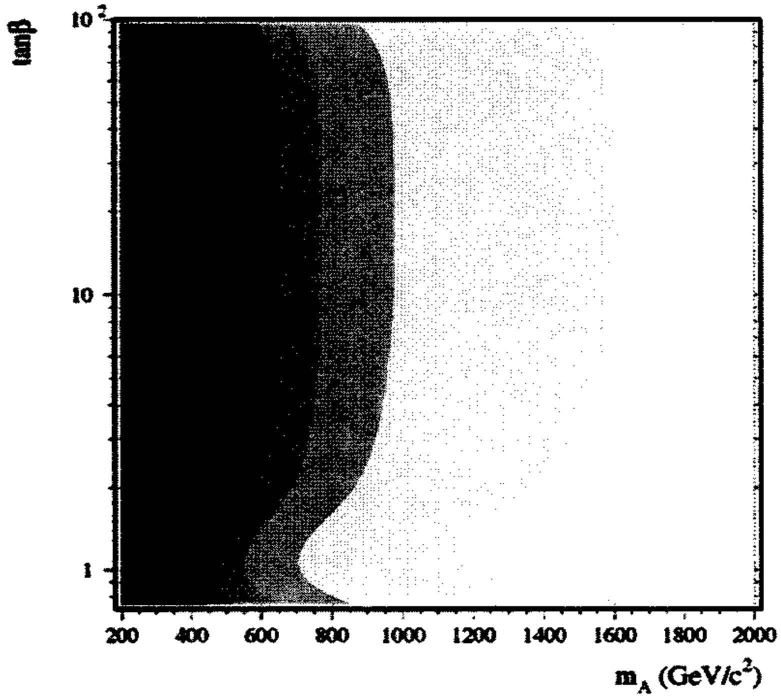
(Note: A Susy scale of 1 TeV and the maximal stop mixing were chosen here)

What a precision muon collider would bring:

1.- With $100\,\mathrm{pb}^{-1}$:

A 5% measurement does better than the 2.5% and 1% LC measurements!

Why?



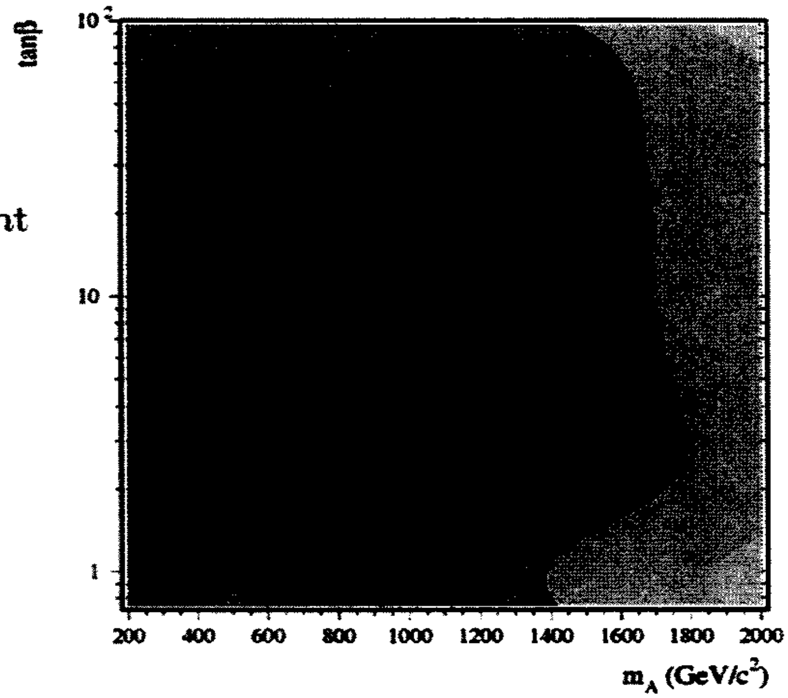
The $\mu^+\mu^- \to \mathrm{h} \to \mathrm{b\bar{b}}$ cross section varies much faster with the $\mathrm{hb\bar{b}}$ coupling than the $\mathrm{h} \to \mathrm{b\bar{b}}$ branching fraction $\Rightarrow$ Take more luminosity.

2.- With $10\,\mathrm{fb}^{-1}$:

Would need ten times more luminosity than in the present collider designs

$m_A < 2\,\mathrm{TeV}/c^2$ covered.

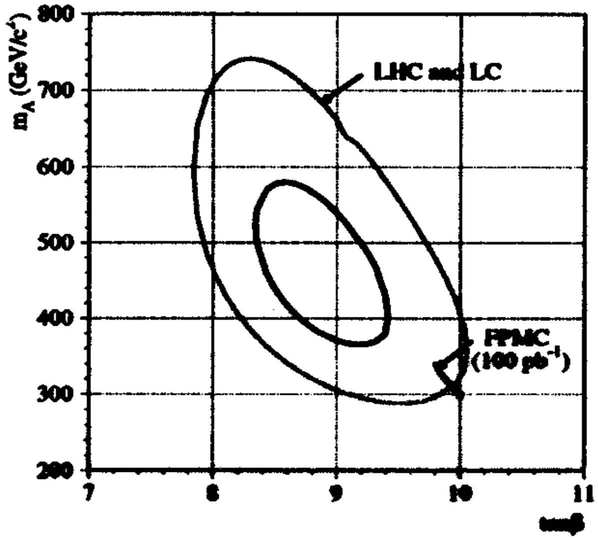
(No systematics due to m_b)

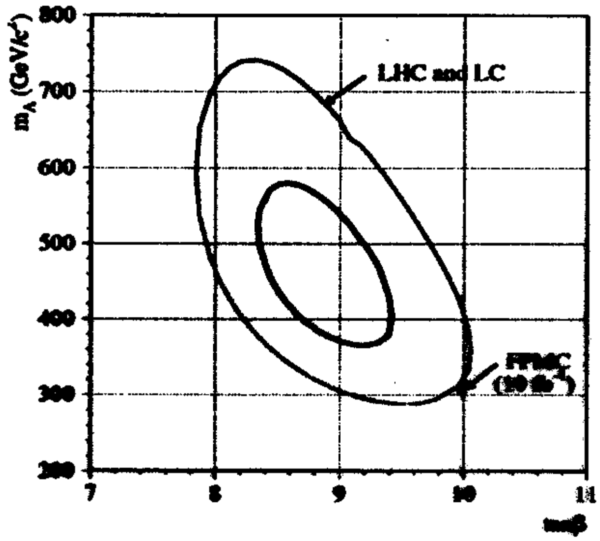


Two possibilities:

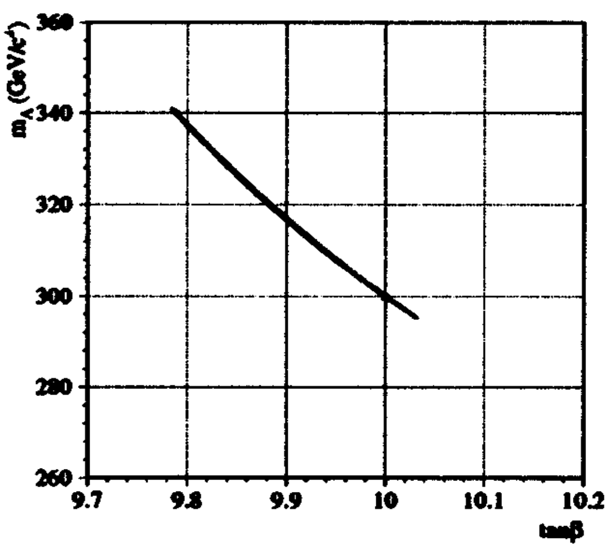
1. Put a lower limit on m_A if very high;
2. **Measure m_A if small enough!**

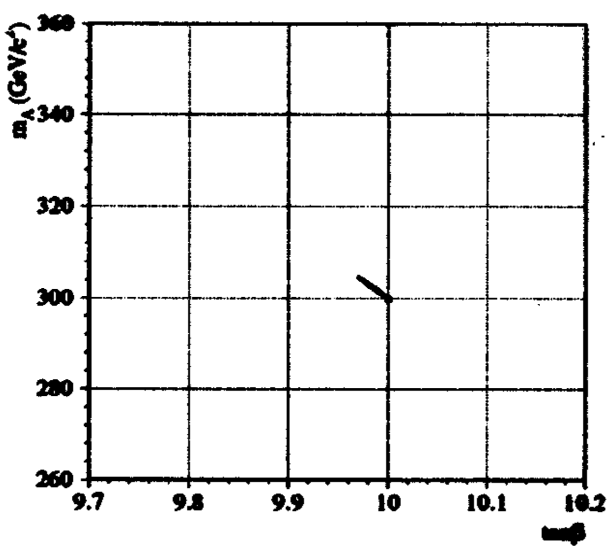
For instance, for $\tan\beta = 10$ and $m_A = 300\,\mathrm{GeV}/c^2$:





With $100\,\mathrm{pb}^{-1}$: **With $10\,\mathrm{fb}^{-1}$:**





m_A is very much correlated with $\tan\beta$, but also with the other parameters of the MSSM:

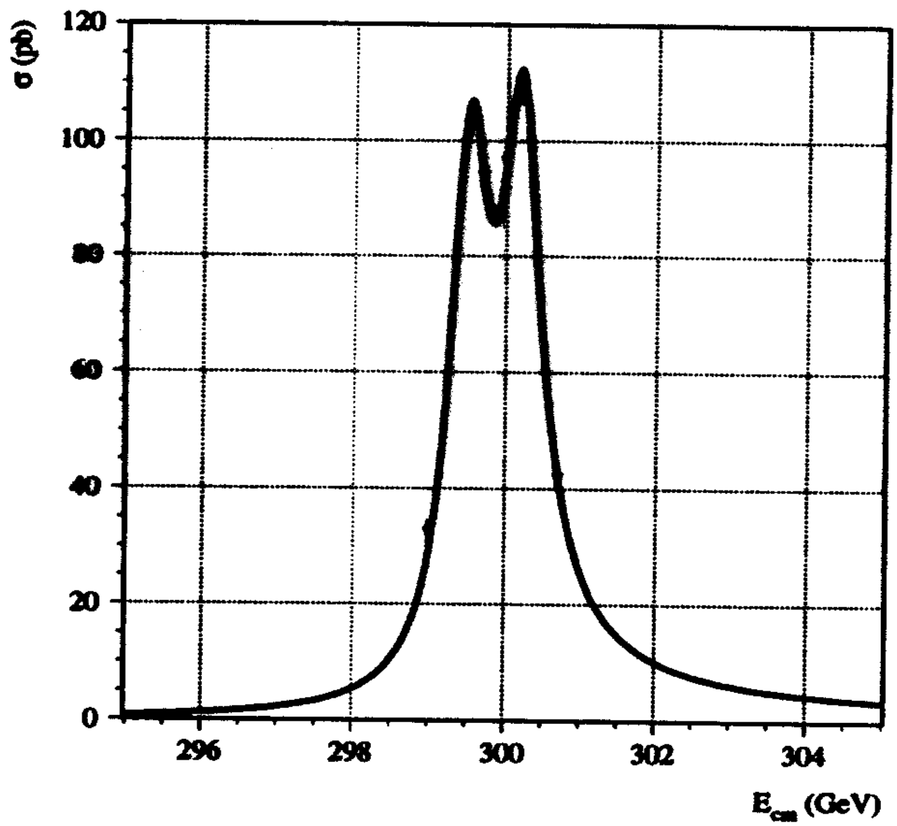
$$\Rightarrow \sigma_{m_A} = \pm 1\text{–}10\ (\text{stat.}) \pm 60\ (\text{syst.})\ \mathrm{GeV}/c^2$$

b. The Second Precision Muon Collider ($\sqrt{s} \simeq m_A$)

1. **No ones, no recirculator** (becomes too expensive), but fixed **field alternating gradient** accelerator in the SPS, and a new **collider ring**;

2. Scan ±60 GeV with 1 pb^{-1} per GeV; A beam energy spread of $3\,10^{-5}$ is not needed due to the larger A, H decay widths;

3. Perform a six-point scan, 25 pb^{-1} per point, to determine the lineshape of A, H.

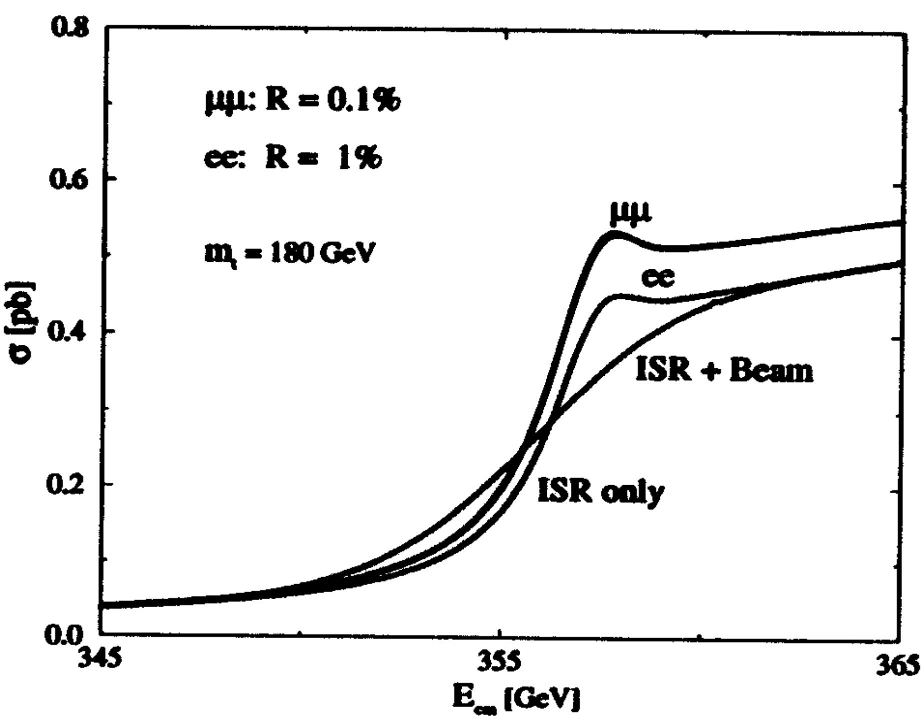


Observable	Accuracy
$\sigma_{\rm peak}^{\rm A,H}$	±1%
m_H, m_A	±10 MeV/c^2
$\Gamma_{\rm H,A}$	±50 MeV

c. Other precision collider rings

$\sqrt{s}$	Measurement	Accuracy	Comments
m_Z	Γ_Z	0.2 MeV	High lumi: 10^7 Z's
	R_ℓ	$\Delta\alpha_s = 0.0005$	E calibration
	A_{LR}	$\Delta \sin^2\theta_W = 0.00003$	Polarization
$2m_W$	m_W	7 MeV	E calibration
$2m_t$	m_t	Few MeV	No beamstrahlung
m_h	m_h	0.1 MeV	(See previous transp.)
	Γ_h	0.5 MeV	
	σ	1–2%	

For instance, the top threshold:



3.- WHAT REMAINS TO BE DONE? (≃ EVERYTHING!)

PHYSICS MOTIVATION : HIGGS FACTORY #1

MAKE DEFINITE STATEMENTS AS TO THE PHYSICS CAPABILITIES, AND THE NEEDS IN TERMS OF $\mathcal{L}$, $\delta E/E$, $\mathbb{P}$

⇒ PERFORM DETAILED STUDIES TO

a) ASCERTAIN / IMPROVE THE QUICK ECFA STUDY RESULTS

- OTHER MEASUREMENTS OF THE SAME OBSERVABLES
- OTHER OBSERVABLES
- HIGGS MASS RANGE ($m_H > 150$ GeV ?)
- RÔLE OF POLARIZATION
- ESTIMATE THEORY UNCERTAINTIES (m_b, m_t, α_s, ...) WHICH COULD SPOIL THE PREDICTING POWER OF THE MEASUREMENT

b) MAKE A FULL COMPARISON WITH COMPETITORS

- COMBINE ALL POSSIBLE OBSERVABLES FROM LHC, e^+e^- LC, $\gamma\gamma$ COLLIDER
- INCLUDING THEIR OWN THEORY UNCERTAINTIES

LEP 1 FOR THE Z ? | c) ESTABLISH THE PREDICTIVE POWER, e.g., IN THE WHOLE MSSM PARAMETER SPACE (m_A)

d) DETERMINE $\mathcal{L}$ NEEDS TO IMPROVE ON {LHC, NLC

PHYSICS MOTIVATIONS : HIGGS FACTORY #2

ONLY A QUICK LOOK IN THE ECFA STUDY

MAKE A SYSTEMATIC STUDY OF WHAT CAN BE DONE WITH THE H, A RESONANCE SCAN –

a) WHO IS H ? WHO IS A ? CP VALUES ?

b) CP VIOLATION IN THE HIGGS SECTOR

c) PRECISION TESTS OF THE MSSM

d) . . .

PHYSICS MOTIVATIONS : OTHER FACTORIES

ASCERTAIN THE FORMER – ROUGH – ESTIMATES WITH PROPER STUDIES

a) NEEDS IN
- $\mathcal{L}$
- POLARIZATION
- ENERGY CALIBRATION

b) CONSEQUENCES OF THE PRECISE MEASUREMENTS ON SM / MSSM.

MACHINE FEASIBILITY

WITH THE HELP / COLLABORATION FROM U.S. GROUP
+ ν-FACTORY STUDIES

DEFINE APPROPRIATE DESIGNS TO ACHIEVE THE REQUIRED $\mathcal{L}$, E, $\delta E/E$

- $\mathcal{L}$ → $10^{31} - 10^{32}$ (?)
- E → m_h, m_H, m_A
- $\delta E/E$ → $\lesssim \Gamma_h / m_h$ (TUNEABLE)

a) MUON PRODUCTION ($\mathcal{L} \propto N_\mu$; N_μ^2 ?)

- STUDY THE STORED MUON RATE AS A FUNCTION OF $E_{PROTONS}$, REP. RATE, TARGET, ...
- SYMMETRIC STORAGE/CAPTURE OF μ^+ AND μ^-

b) MUON BUNCHING

- DESIGN OF A MUON BUNCHER

c) MUON COOLING (TRANSVERSE ↑$\mathcal{L}$, LONGITUDINAL ↑$\delta E/E$)

- DESIGN OF A COOLING UNIT
  - → SEVERAL STAGES?
  - → CIRCULAR COOLING?
  - → OTHER THAN IONIZATION COOLING?

★ NOTE: dE/dx VS MULTIPLE SCATTERING?

d) ACCELERATION: ENERGY STABILITY AT EACH PULSE?

- h → RECIRCULATOR?
- H, A → OTHER?

e) COLLIDER + FINAL FOCUS DESIGN / OPTICS

- POLARIZATION?
- ○ ? ∞ ?
- BACKGROUNDS?

4 - CONCLUSION

THE CONCLUSION OF THE WORK OF THE GROUP SHOULD BE :

- A FIRM AND CONVINCING PHYSICS CASE
- A DEFINITE ASSESSMENT OF THE NEEDS IN $\mathcal{L}$, $(\delta E/E)$
- A LIST OF MACHINE PARAMETERS FROM PRELIMINARY DESIGN STUDIES
- A PRELIMINARY COST ESTIMATE

TIMESCALE ? (FOR THE HIGGS FACTORY)

TO BE DISCUSSED
- WORKING REPORT IN A YEAR FROM NOW ?
- meetings EVERY THREE MONTHS ?

MAN POWER ? (BARE MINIMUM FOR THE HIGGS FACTORY)

- A COUPLE OF THEORISTS - OR MORE
- A COUPLE OF EXPERIMENTALISTS - OR MORE
- SOME ACCELERATOR PHYSICISTS

LET'S HAVE A 10' "RESTRICTED" SESSION AFTER THIS MEETING.