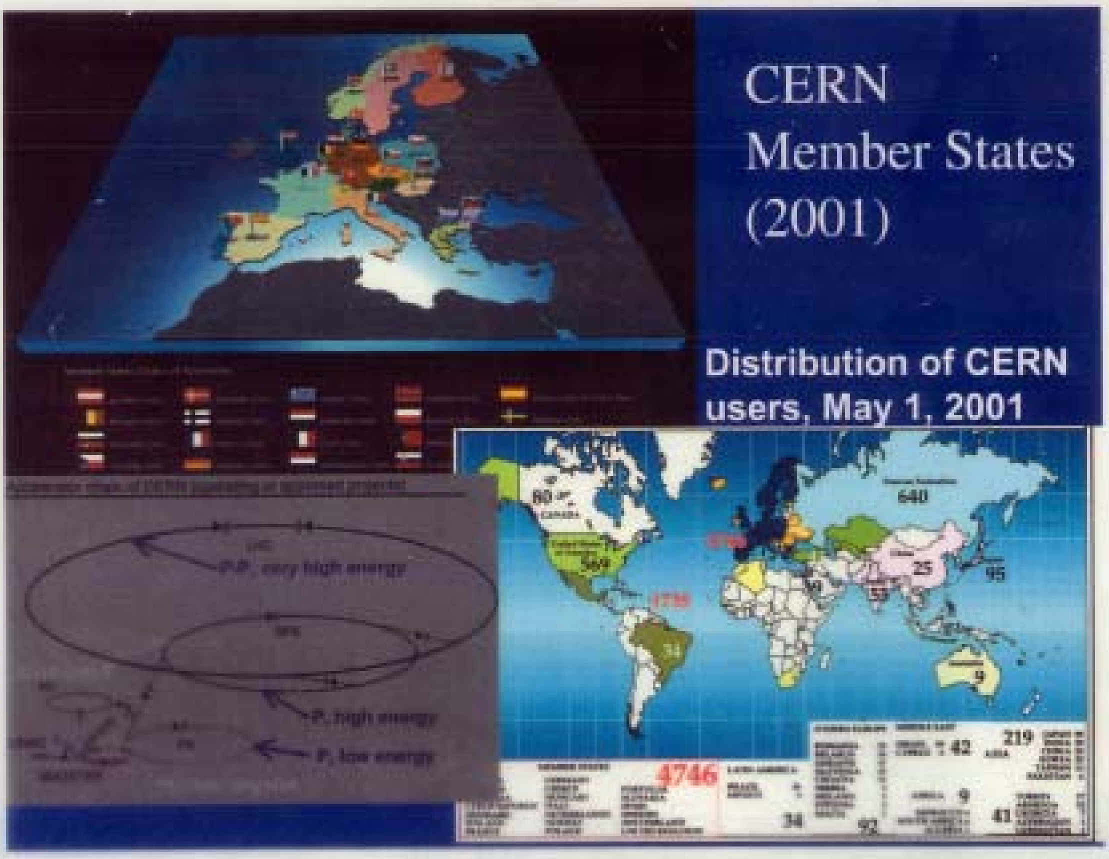


CERN Member States (2001)

Distribution of CERN users, May 1, 2001

Future Perspectives @ CERN

1 - Beyond the Standard Model

important open problems

2 - Approved projects

ν → Gran Sasso 2006

LHC 2007

3 - Possible projects beyond the LHC

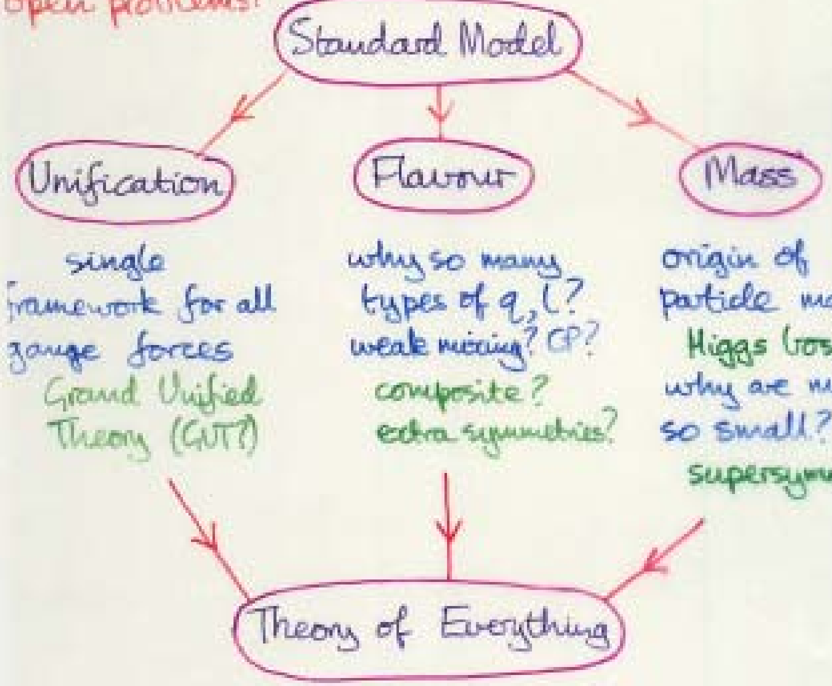
CLIC

ν factory

Roadmap to physics

- Beyond the Standard Model

open problems:



Standard Model

Unification

single framework for all gauge forces
Grand Unified Theory (GUT?)

Flavour

why so many types of q, l?
weak mixing? CP?
composite?
extra symmetries?

Mass

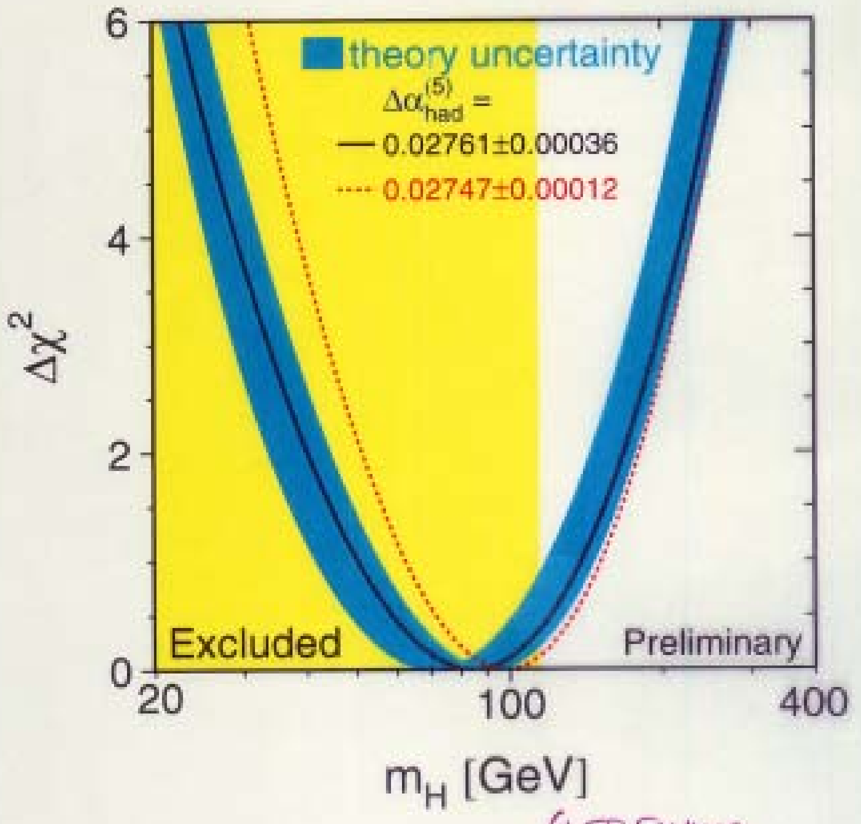
origin of particle masses?
Higgs boson?
why are masses so small?
supersymmetry?

Theory of Everything

include gravity
reconcile it with quantum mechanics
origin of space-time
why 4 dimensions?
⋮
superstring?
M theory?

Precision Electroweak Data

favour a light Higgs boson
$m_H < 199$ GeV @ 99% c.l.
~ 115 GeV 'most likely'



(LEP EWWG

-Why Supersymmetry?

Hierarchy Problem:

energy: gravity ~ other forces: $m_P \sim 10^{19}$ GeV

why is $m_W \ll m_P$?

alternatively

why is $G_F \gg G_N$? $\frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_P^2}$

or

why is $V_{Coulomb} \gg V_{Newton}$? $e^2 \gg G_N m^2 \sim m^2/m_P^2$

Set by hand?

what about quantum corrections?

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)\Lambda^2 \gg m_W^2$$

cut off $\Lambda \sim m_P$?

made naturally small by supersymmetry:

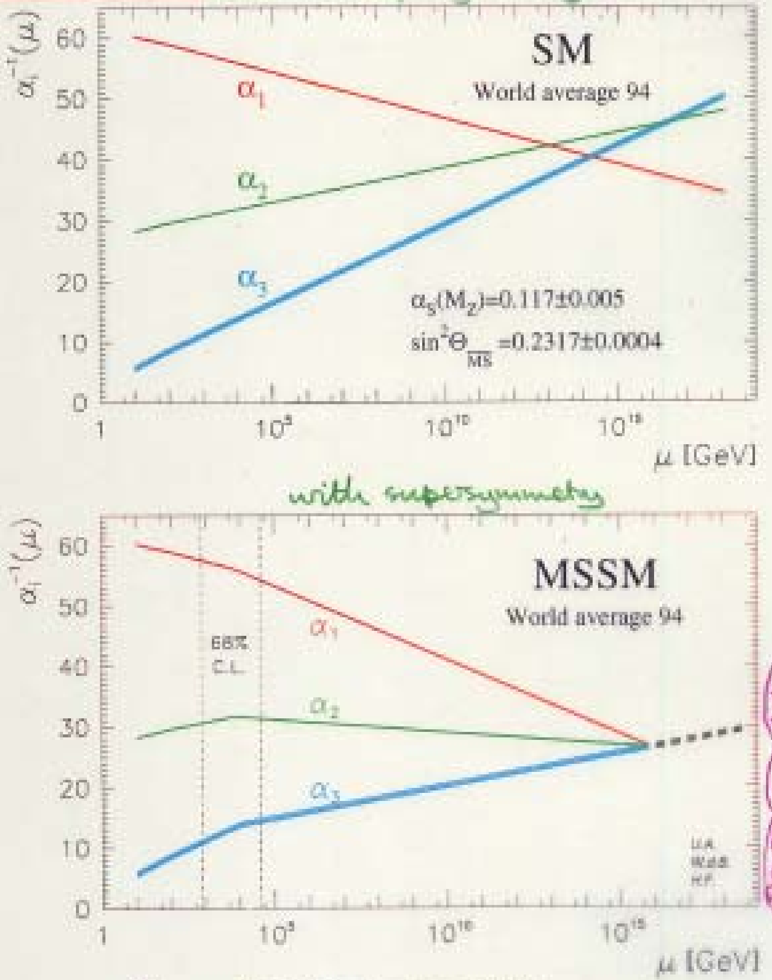
$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)\left(m_B^2 - m_F^2\right)$$

$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1\ \text{TeV}^2$$

Low-energy supersymmetry

Unification!

without supersymmetry



with supersymmetry

1990
(S.E. + Kelley + Nanopoulos
(Langacker + Luo
(Amaldi de Boer Fürstenau
1991

Glasgow HEP Conference 1994 :

$M_S=10^{3.7\pm0.8\pm1.4}$ GeV $M_U=10^{15.9\pm0.2\pm0.1}$ GeV

return to this later!

Minimal Supersymmetric Model

postulate doubling of particle spectrum

$\gamma \quad W \quad Z \quad g \quad l \quad q \quad H$

photino gluino slepton squark Higgs (x2)

$\tilde{\gamma} \quad \tilde{W} \quad \tilde{Z} \quad \tilde{g} \quad \tilde{l} \quad \tilde{q} \quad \tilde{H}$

supersymmetry guarantees equal couplings

sparticle masses unknown: expect $\lesssim 1$ TeV

$\boxed{\text{postulate}}$ universal masses = CMSSM

before renormalization m_0 $\tilde{l}, \tilde{q}, H$

$m_{1/2}$ $\tilde{\gamma}, \tilde{W}, \tilde{Z}, \tilde{g}$

other basic parameters

$\tan\beta$ ratio of Higgs vacuum expectn values

μ mixing between Higgs fields

Assume conservation of $R = (-1)^{3B+L+2S}$

⇒ lightest sparticle stable $\chi = \tilde{\gamma}/\tilde{Z}/\tilde{H}^0$

relic from Big Bang

Supersymmetric Relic Density

controlled by annihilation rate

$$\rho_\chi = m_\chi n_\chi \; : \; n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \dots)}$$

typical annihilation rate $\sigma_{ann} \sim \frac{1}{m^2}$

⇒ relic density increases with mass

$$m_\chi \lesssim O(1)\ \text{TeV}$$

BUT sometimes density reduced by coannihilation: $\sigma_{coann}(\chi\tilde{X} \to \text{ordinary})$

important if $\frac{\Delta m}{m} \sim 0{\cdot}1$

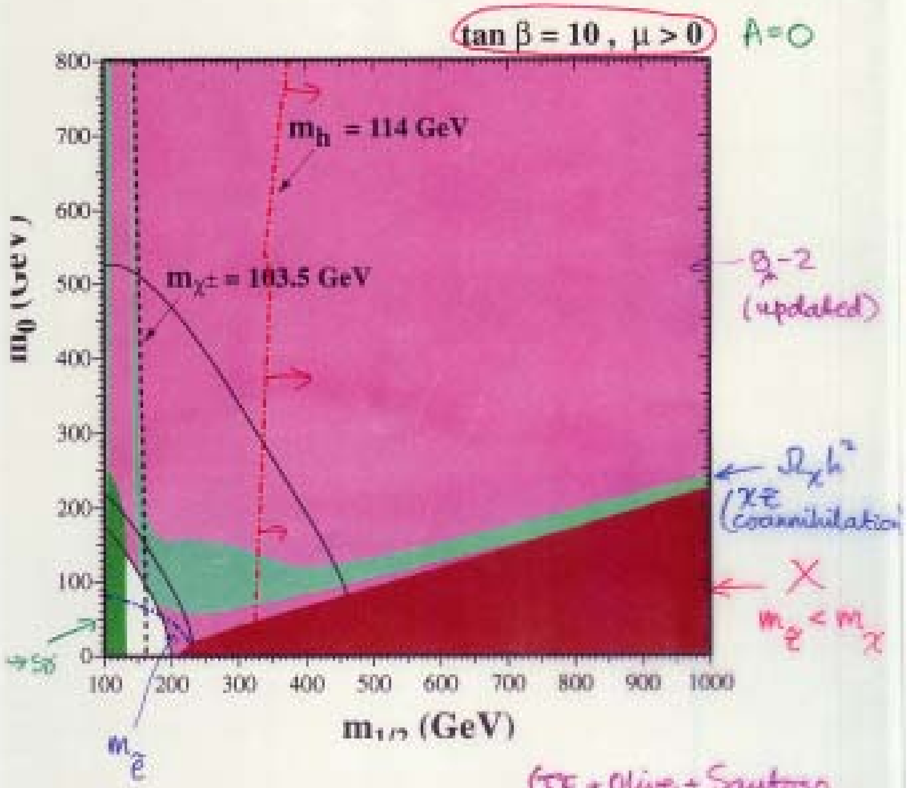
⇒ possible 'tail' out to large m_χ

AND sometimes rapid annihilation via direct-channel pole: $m_\chi \sim \frac{1}{2} M_{Higgs, Z, \dots}$

⇒ possible 'funnel' out to large m_χ

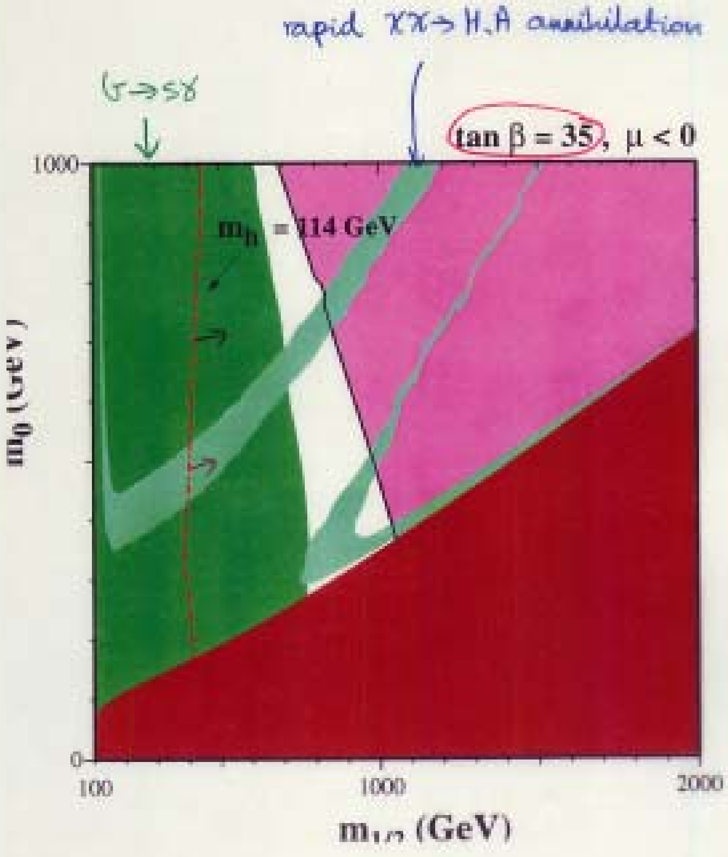
can be important @ large $\tan\beta$

Constraints on CMSSM



(J.E. + Olive + Santoso

Constraints on CMSSM



(J.E. + Olive + Santoso

Proposed Supersymmetric Benchmarks

(Battaglia + De Roeck + J.E. + Gianotti + Matchev + Olive + Pape + Wilson hep-ph/0106204

- post - LEP
  - sparticle, Higgs ← theoretical uncertainties
- $b \to s\gamma$
- cosmological relic density
  - $0.1 \leq \Omega_\chi h^2 \leq 0.3$ ← hard upper limit
- $g_\mu - 2$
  - favour $\Delta(g_\mu - 2) \leq 2\sigma$: not required ⊛

Choose points that illustrate possibilities

not 'fair' sampling of parameter space

5 in 'bulk' of cosmological region

4 spread along coannihilation 'tail'

2 in 'focus-point' region

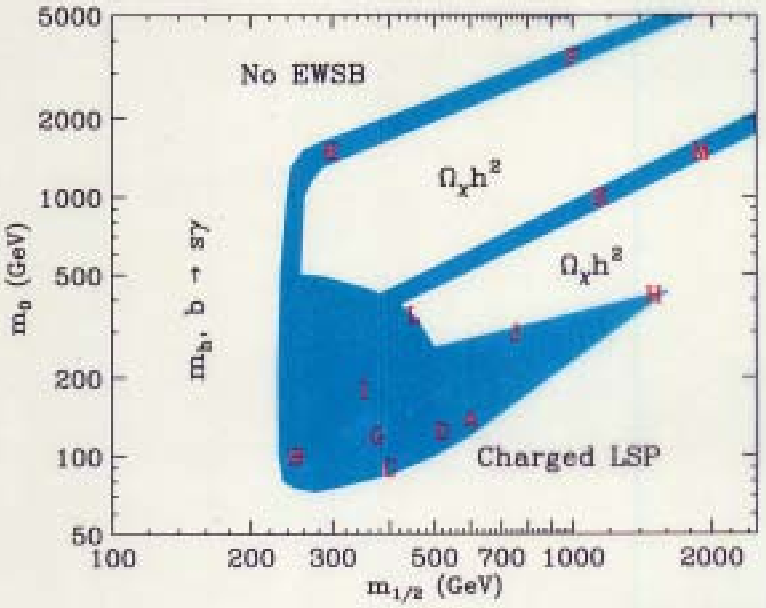
2 in rapid-annihilation 'funnels'

$\tan\beta = 5, 10, 20, 35, 50$

two points with $\mu < 0$ ⊛

Benchmark Supersymmetric Scenarios

illustrated range of allowed possibilities



(Battaglia + De Roeck + J.E. + Gianotti + Matchev + Olive + Pape + Wilson

Characteristic Spectra & Decay Patterns

in a few selected benchmarks

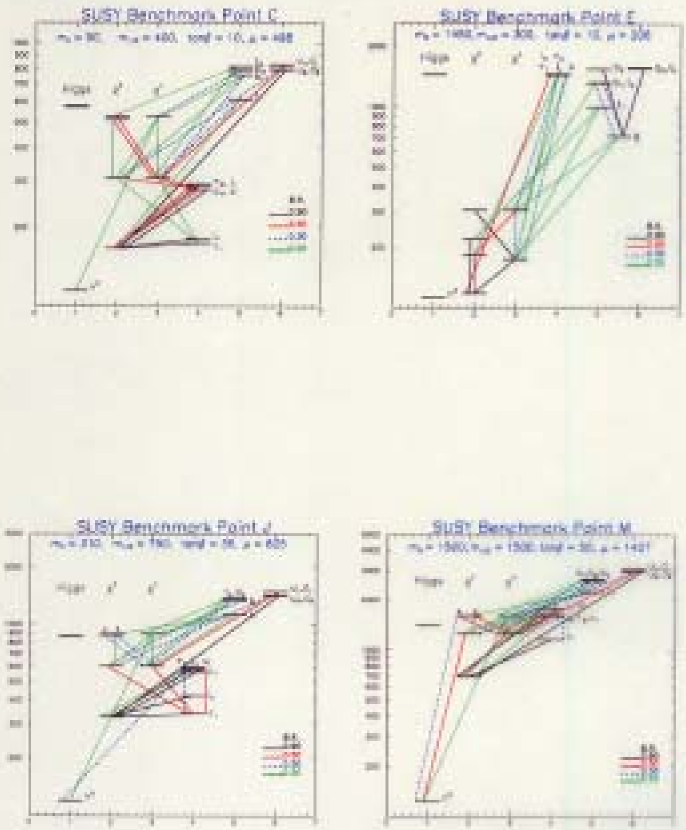


Figure 4: The supersymmetric spectra and principal decay modes for benchmark points [C,E,J,M]

(Battaglia + De Roeck + JE + Gianotti + Matchev + Olive + Pape + Wilson : hep-ph/0106204

- Neutrino Masses & Oscillations

Why not? there is no good reason why $m_\nu = 0$

vanishing masses ⇔ exact symmetries

e.g.: photon

e.g.: gauge invariance, Q_{e}

There is no massless gauge boson coupling to lepton number

⇒ do not expect lepton number conserved $\overset{\equiv}{L}$ cf string theory

⇒ ν mass possible

e.g. $m_\nu \, \nu \cdot \nu$ $\Delta L = 2$

- generic feature of Grand Unified Theories

- even possible in the Standard Model (Barbieri + JE + Gaillard

$$\underset{\substack{\uparrow \\ \text{some heavy} \\ \text{mass scale} \\ \gg m_W}}{\frac{1}{M}} \nu H \cdot \nu \underset{\substack{\uparrow \\ \text{Higgs} \\ \text{field}}}{H} \Rightarrow m_\nu = \frac{\langle 0|H|0\rangle^2}{M}$$

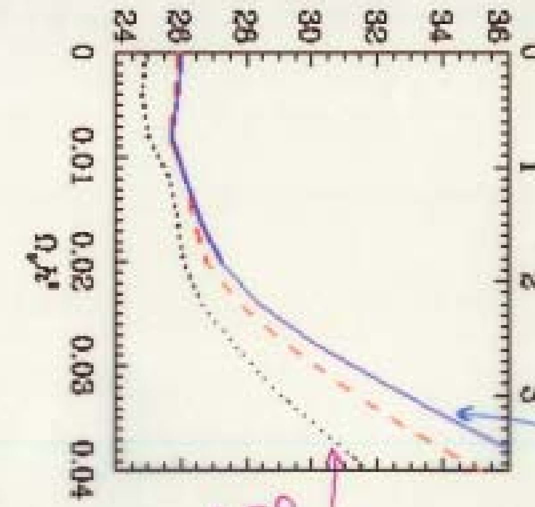
very small ?

not so small in M theory

$M \ll m_P$

2- Present upper limit on $\sum_\nu m_\nu$

from cosmology + astrophysics



<2.5eV : all data

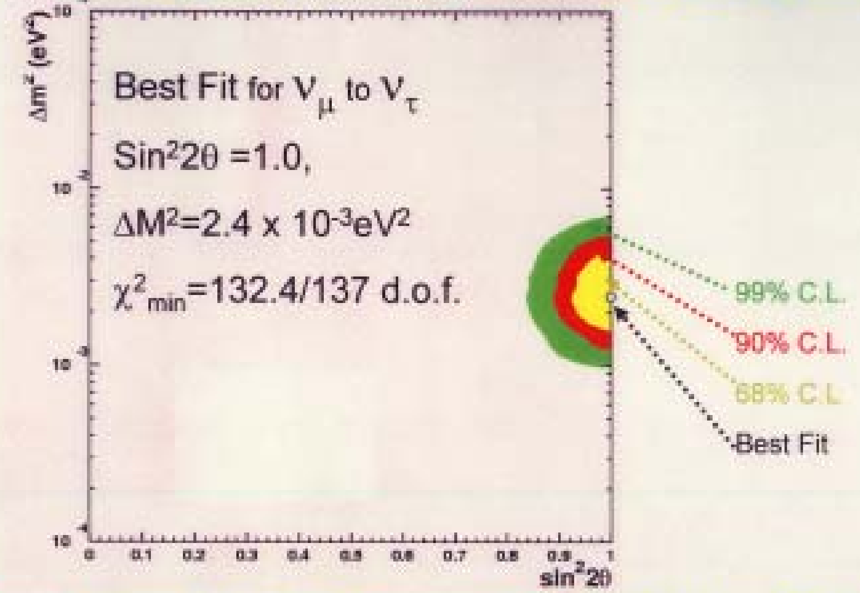
< 3eV CMB + large-scale structure

FIG. 2: χ^2 as a function of $\Omega_\nu h^2$, plotted for the three different priors. The dotted curve is for CMB+LSS, the dashed for CMB+LSS+BBN+H_0, and the full curve for CMB+LSS+BBN+H_0+SNIa.

equal masses would ⇒ $m_\nu \leq 1$ eV

(Hannestad

Summary of Atmospheric Results



Best Fit for V_μ to V_τ

$\sin^2 2\theta = 1.0$,

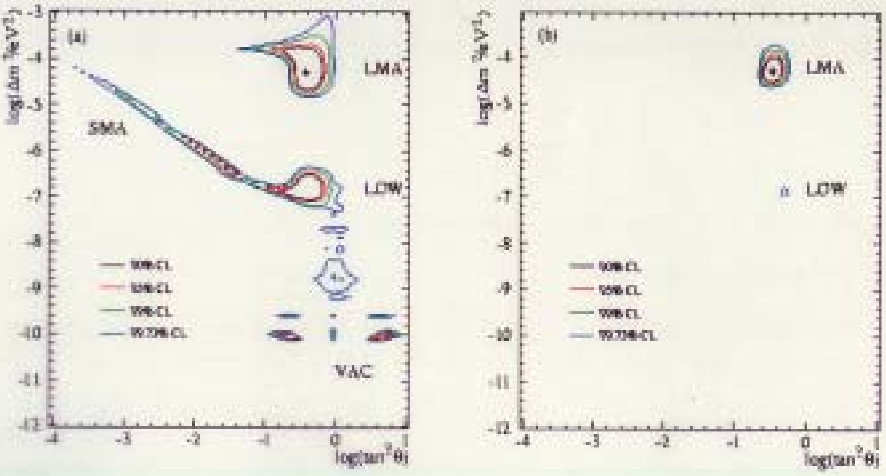
$\Delta M^2 = 2.4 \times 10^{-3}$ eV^2

$\chi^2_{min} = 132.4/137$ d.o.f.

J. Goodman – LP01

Effect of the Neutral-Current SNOfall

before after



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the waters part...

The Emerging Default Option

- 3 light ν
- hierarchical masses
- ~bimaximal mixing

$$\begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

- masses mainly Majorana
- small dipole moments
- $\tau_\nu \gg$ age of Universe

Prima facie evidence for new physics
@ GUT scale

→ The BIG ISSUES

Can we exclude ν_s?

{degenerate?
{which order?

are SMA, VO allowed?

how to discriminate LMA/

size of Θ_{13}? CP?

fixed by $\beta\beta_{0\nu}$?

measure?

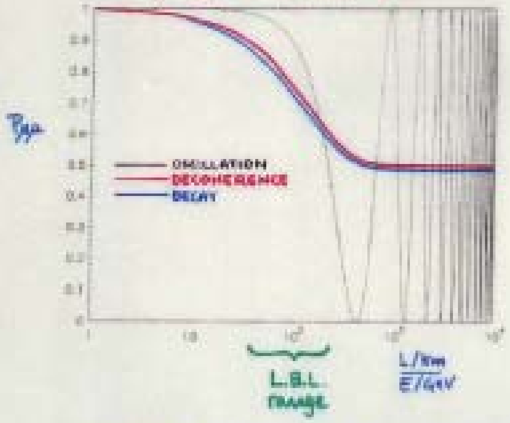
see oscillation pattern?

How do we prove $m_\nu \neq 0$?

plenty of work for the ν factory!

So, the lack of periodicity in SK μ data can be interpreted in two ways:

- smearing of oscillation pattern
- signal of non-oscillatory new physics (decay, decoherence, ...)*



→ Important to see at least one oscillation cycle (or the lack of it) in the energy and/or pathlength domain (LBL?)

Lisi

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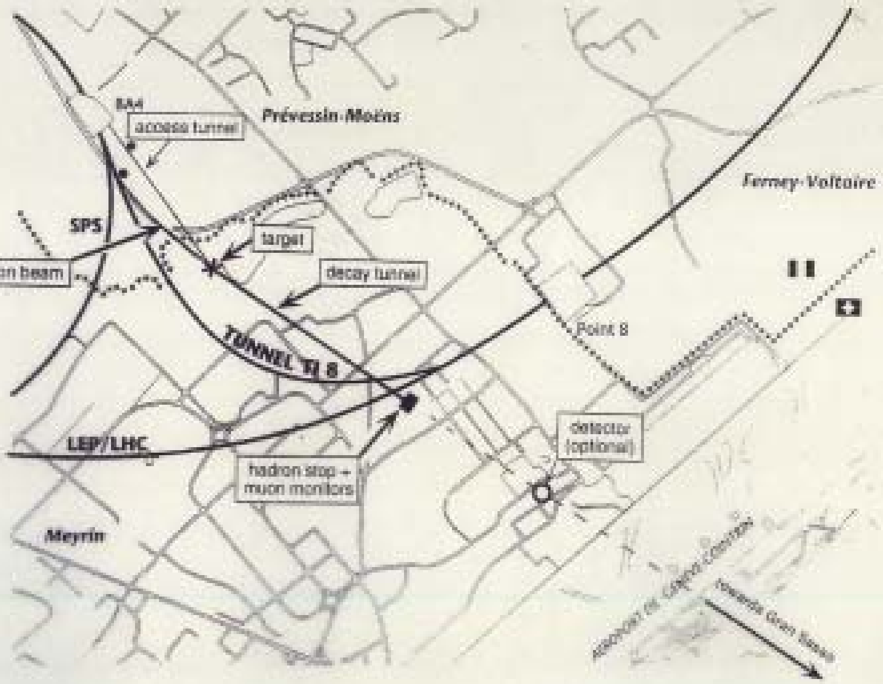
* Another example: Barbieri et al., $\nu_\mu \to \nu_{bu}$ in extra-dim. models

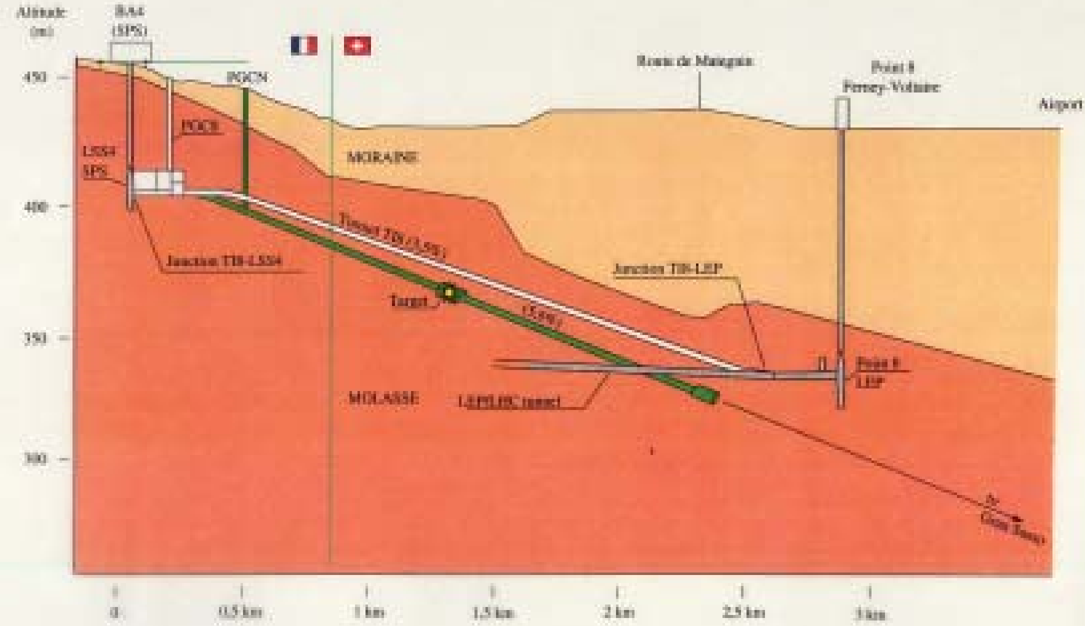
Ongoing Experiments

COMPASS	gluon contribution to proton spin
NA48...	K_s, $K^\pm$, Λ decays
NA60	charm production in Pb-Pb collisions
DIRAC	$\pi^+\pi^-$ atoms
HARP	hadron production for ν factory
AD	antiproton decelerator ATHENA, ATRAP, ASACUSA
nTOF	neutron time-of-flight facility
ISOLDE	isotope separator

recognized experiments
(not CERN accelerators, 'no' resources)
AMS, Auger, L3+C, Explorer, Antares, CAST, LISA, NESTOR, CAPRICE, PAMELA

CERN → Gran Sasso ν Beamline





Layout of Gran Sasso Laboratory

oriented towards CERN

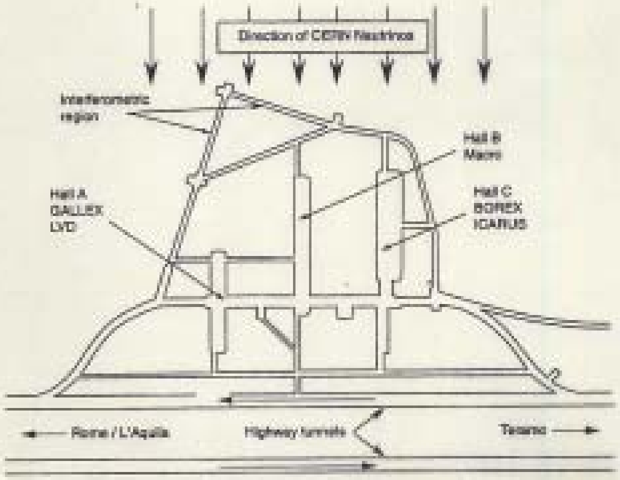
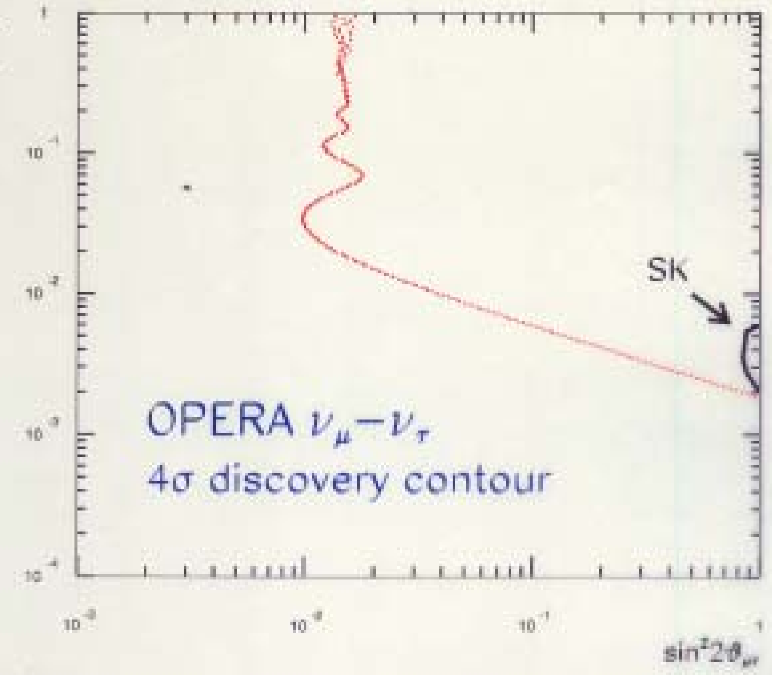


Figure 4: *Overview of the Gran Sasso underground laboratory, showing experiments which are presently running or approved for construction.*

CERN's primary objective in ν oscillations

$\nu_\mu \rightarrow$ Gran Sasso

Discover τ Production in a ν_μ Beam



Future Sensitivity to $\nu_\mu \to \nu_e$

combination of MINOS, ICARUS, OPERA

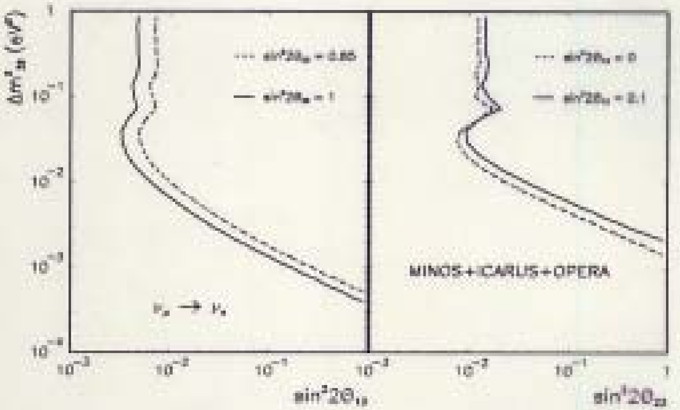
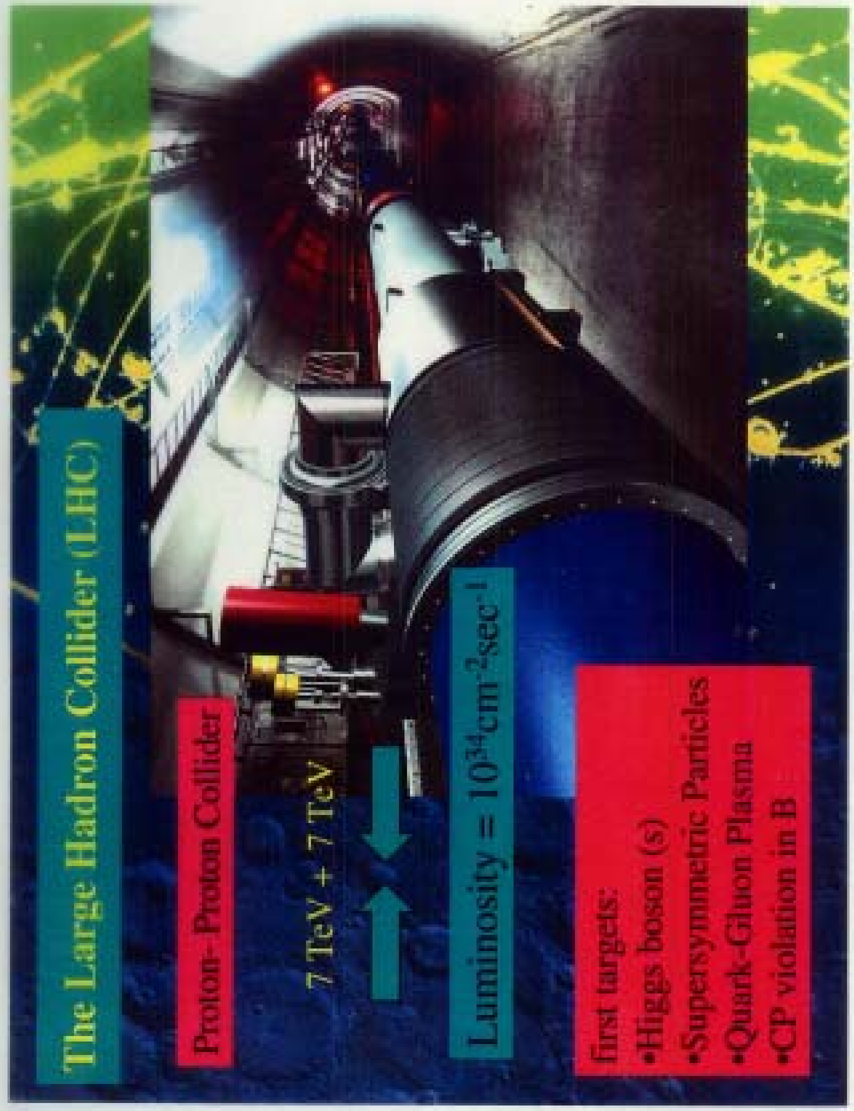


FIG. 7. The global sensitivity of the $\nu_\mu \to \nu_e$ mode at 90% C.L. is shown on the left. The sensitivity to $\sin^2 2\theta_{23}$ and Δm^2_{32} by combining the MINOS sensitivity in the disappearance channel and the ICARUS and OPERA sensitivities in the $\nu_\mu \to \nu_\tau$ channels at the 90% C.L. is on the right.

(Barger + Gago + Marfatia + Teves + Wood + Zukanovich Funchal:
hep-ph/0110393



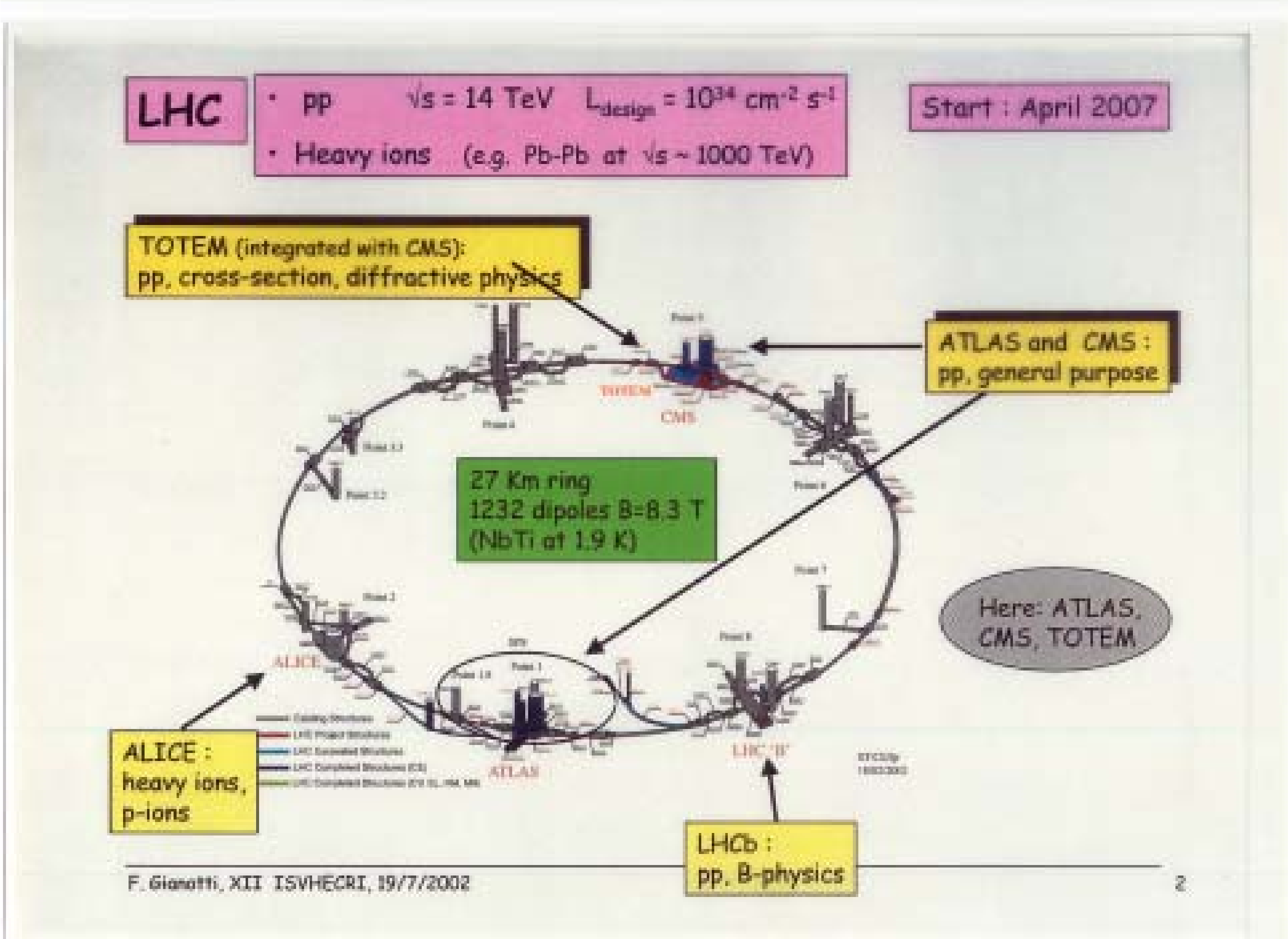
The Large Hadron Collider (LHC)

Proton- Proton Collider

7 TeV + 7 TeV

Luminosity = 10^{34}cm^{-2}sec^{-1}

first targets:
- Higgs boson (s)
- Supersymmetric Particles
- Quark-Gluon Plasma
- CP violation in B



LHC

- pp $\sqrt{s}$ = 14 TeV $L_{design} = 10^{34}$ cm^{-2} s^{-1}
- Heavy ions (e.g. Pb-Pb at $\sqrt{s}$ ~ 1000 TeV)

Start : April 2007

TOTEM (integrated with CMS): pp, cross-section, diffractive physics

ATLAS and CMS : pp, general purpose

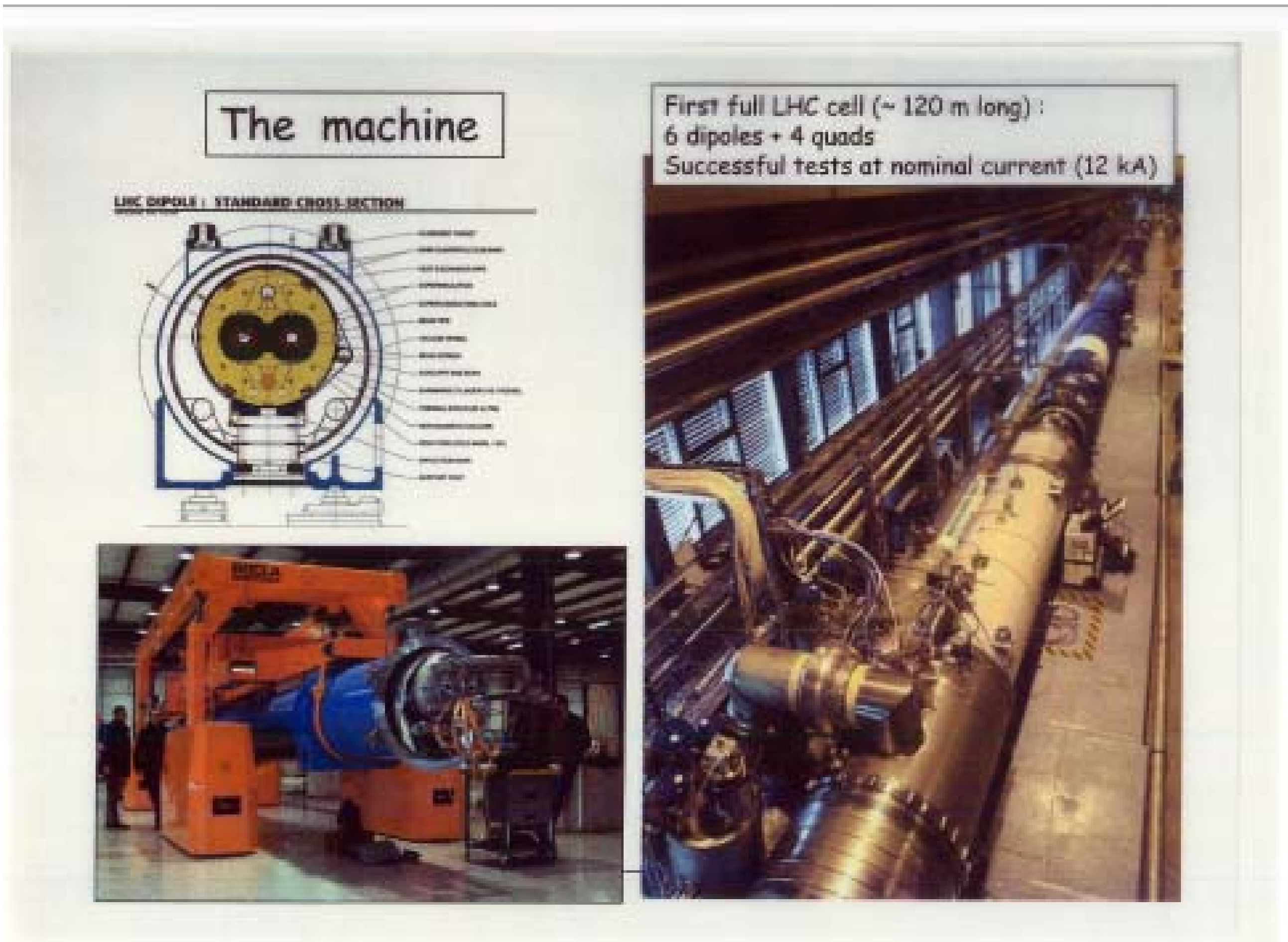
27 Km ring
1232 dipoles B=8.3 T
(NbTi at 1.9 K)

Here: ATLAS, CMS, TOTEM

ALICE : heavy ions, p-ions

LHCb : pp, B-physics

F. Gianotti, XII ISVHECRI, 19/7/2002



The machine

LHC DIPOLE : STANDARD CROSS-SECTION

First full LHC cell (~ 120 m long) :
6 dipoles + 4 quads
Successful tests at nominal current (12 kA)

Civil engineering

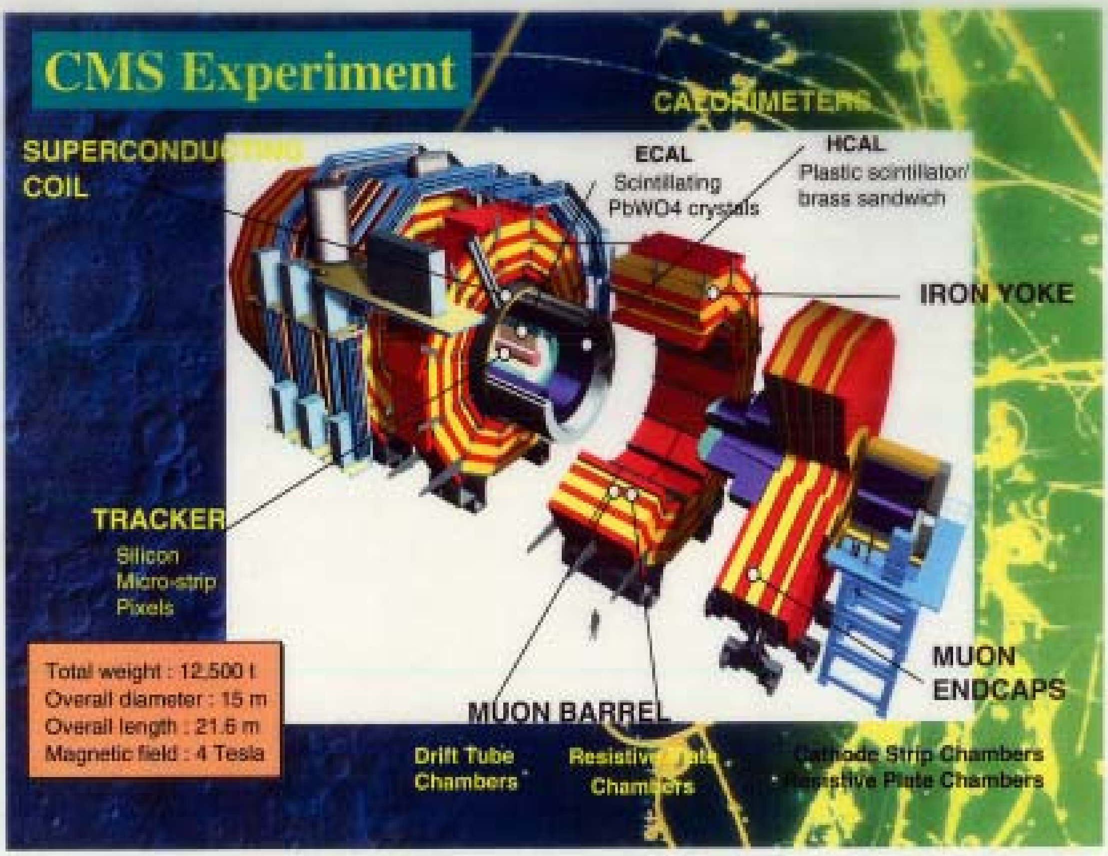
Cavern for CMS experiment

Main asset : the huge event statistics thanks to high √s and L

Expected event rates in ATLAS or CMS for representative (known and new) physics processes at low luminosity ($L=10^{33}$ cm^{-2} s^{-1})

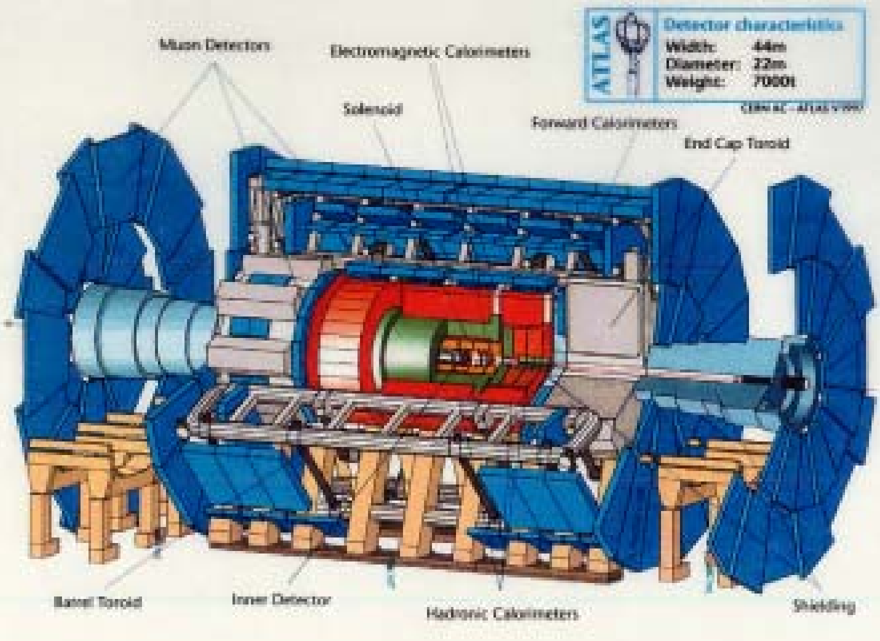
Process	Events/s	Events/year	Total statistics at previous machines
$W \to e\nu$	15	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	1.5	10^7	10^7 LEP
$t\bar{t}$	0.8	10^7	10^4 Tevatron
$b\bar{b}$	10^5	10^{12}	10^8 Belle/BaBar
$\tilde{g}\tilde{g}$ (m=1 TeV)	0.001	10^4	—
H (m=0.8 TeV)	0.001	10^4	—

→ LHC is a B-factory, top factory, W/Z factory, Higgs factory, SUSY factory, etc.



CMS Experiment

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla



Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t

CERN AC - ATLAS V1997

Detector construction and performance : a few examples .....

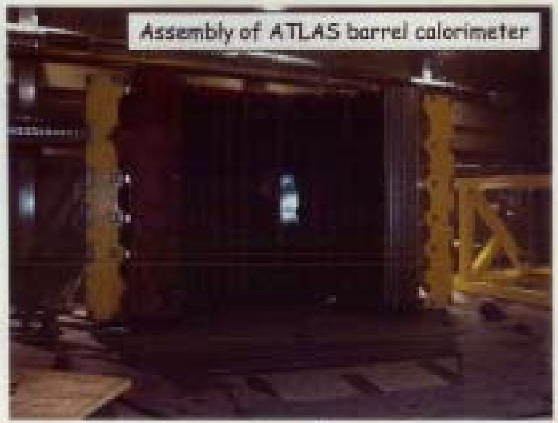
MAGNETS

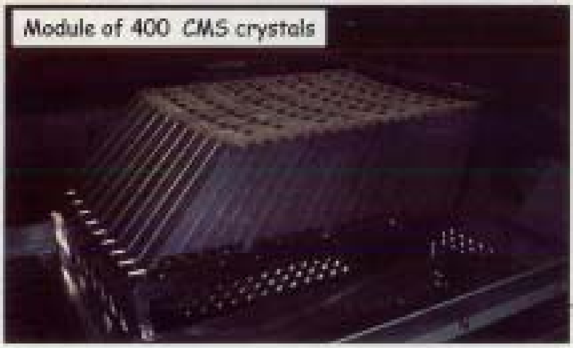

ATLAS solenoid


CMS magnet yoke

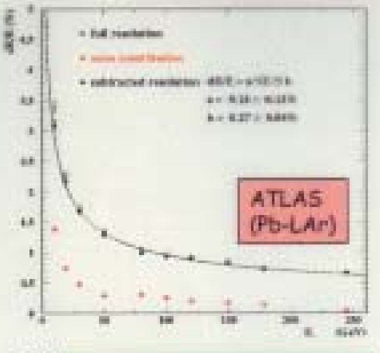

First ATLAS coil cryostat

Electromagnetic calorimeters

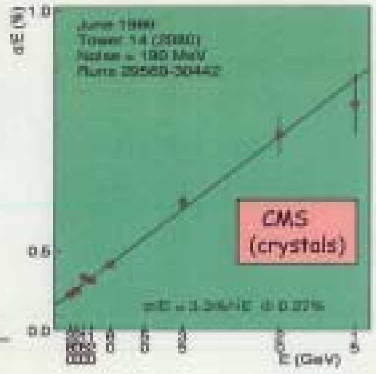

Assembly of ATLAS barrel calorimeter


Module of 400 CMS crystals

electron E-resolution
from test beam



ATLAS
(Pb-LAr)



CMS
(crystals)

3 - Where do we go from here?

Prospects for Higgs Discovery

Tevatron — will have chance if $m_H = 115\,\mathrm{GeV}$

if heavier?

not before 2007?

LHC — will discover it @ any mass

will observe 2 or 3 decay modes

measure mass to ~ 1%

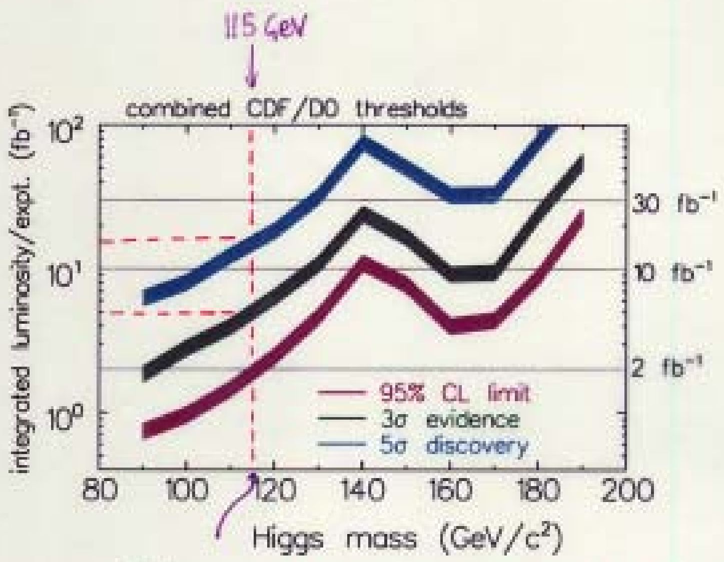
cover MSSM parameter space

→ several times?

new analysis including LEP, universality, cosmology

measure MSSM parameters?

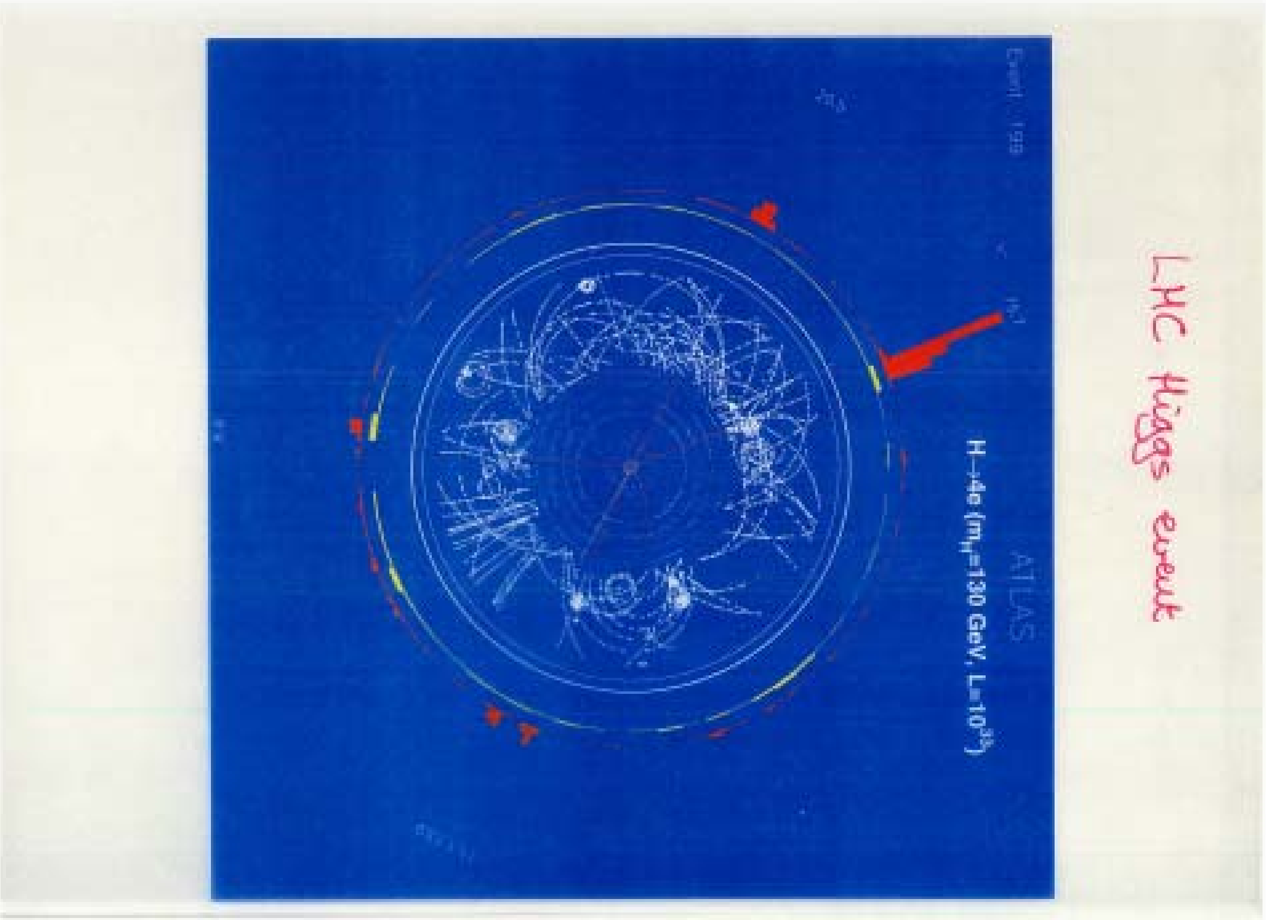
Prospects for the Tevatron Collider



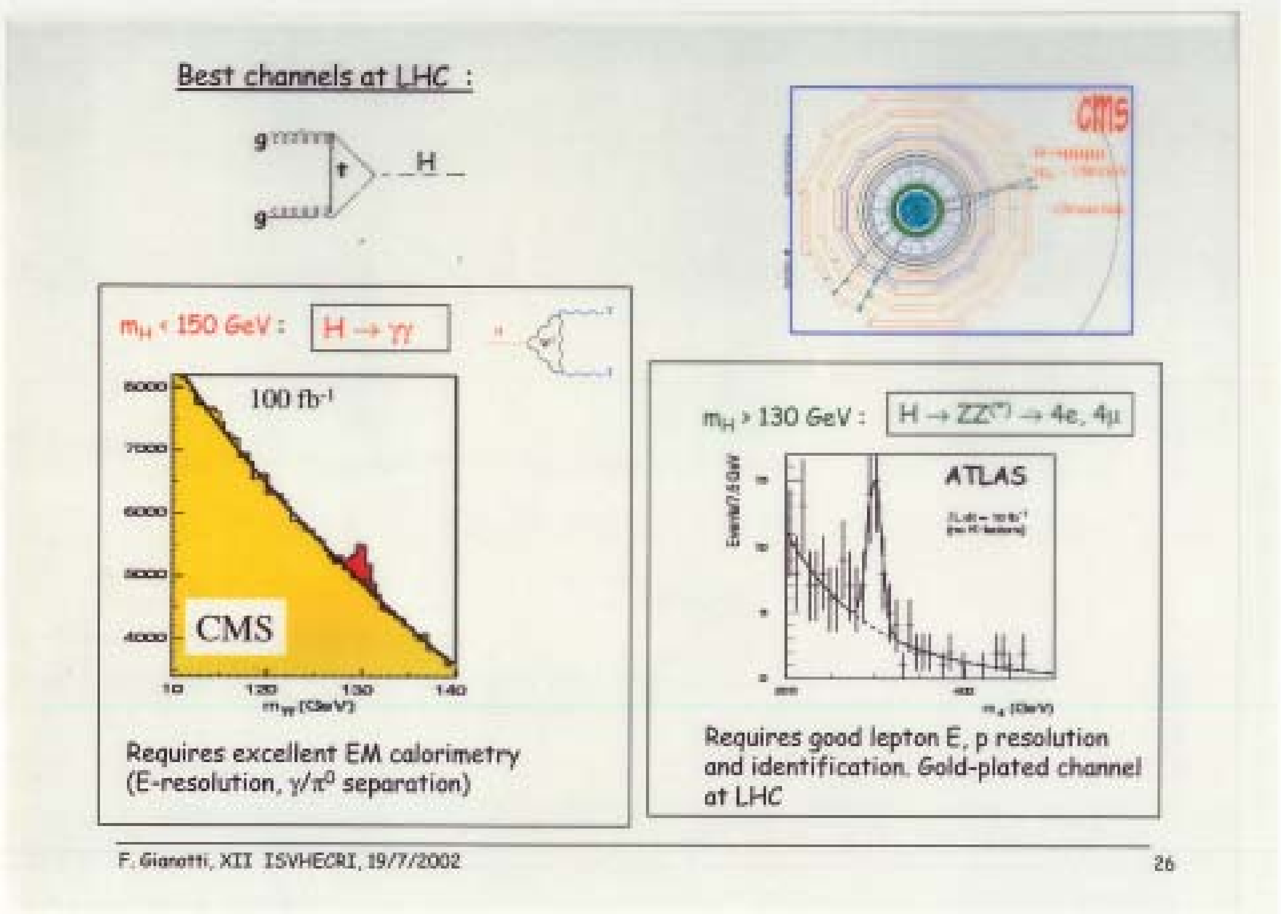
5 fb^{-1} needed to duplicate LEP 'signal'

15 fb^{-1} needed for 5σ discovery

(Tevatron Higgs Working Group



LHC Higgs event



Best channels at LHC :

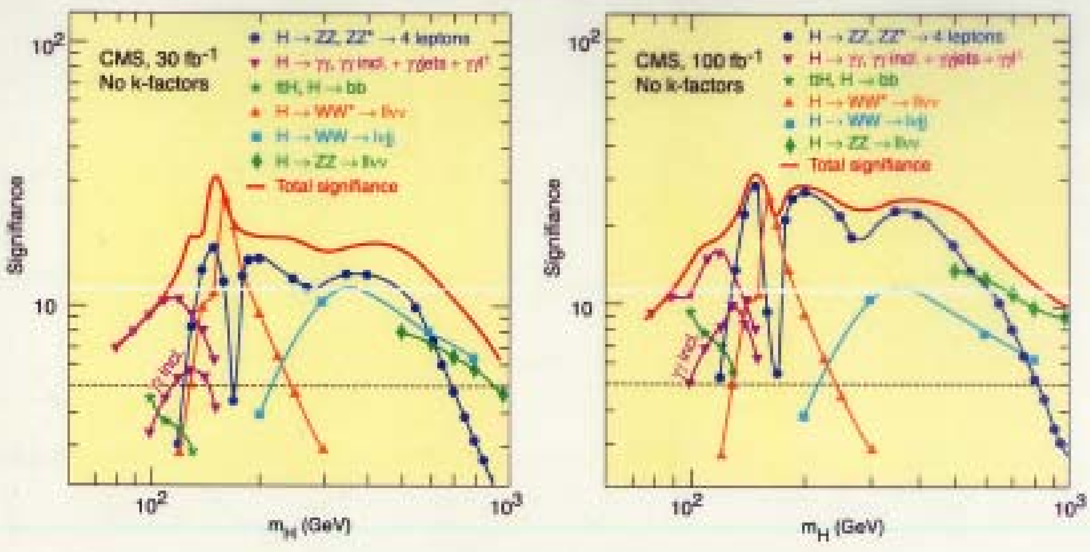
m_H < 150 GeV : $H \to \gamma\gamma$

Requires excellent EM calorimetry (E-resolution, γ/π^0 separation)

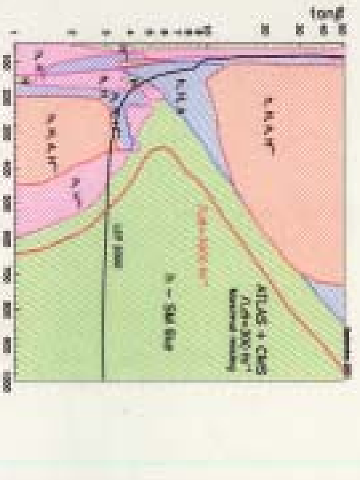
m_H > 130 GeV : $H \to ZZ^{(*)} \to 4e, 4\mu$

Requires good lepton E, p resolution and identification. Gold-plated channel at LHC

CMS discovery potential for SM Higgs



Will the LHC see the other Higgses?



5-Prospects for Supersymmetry Discovery

Tevatron most of parameter space $\subset$ LEP disfavoured by Higgs 'limit'

little chance?

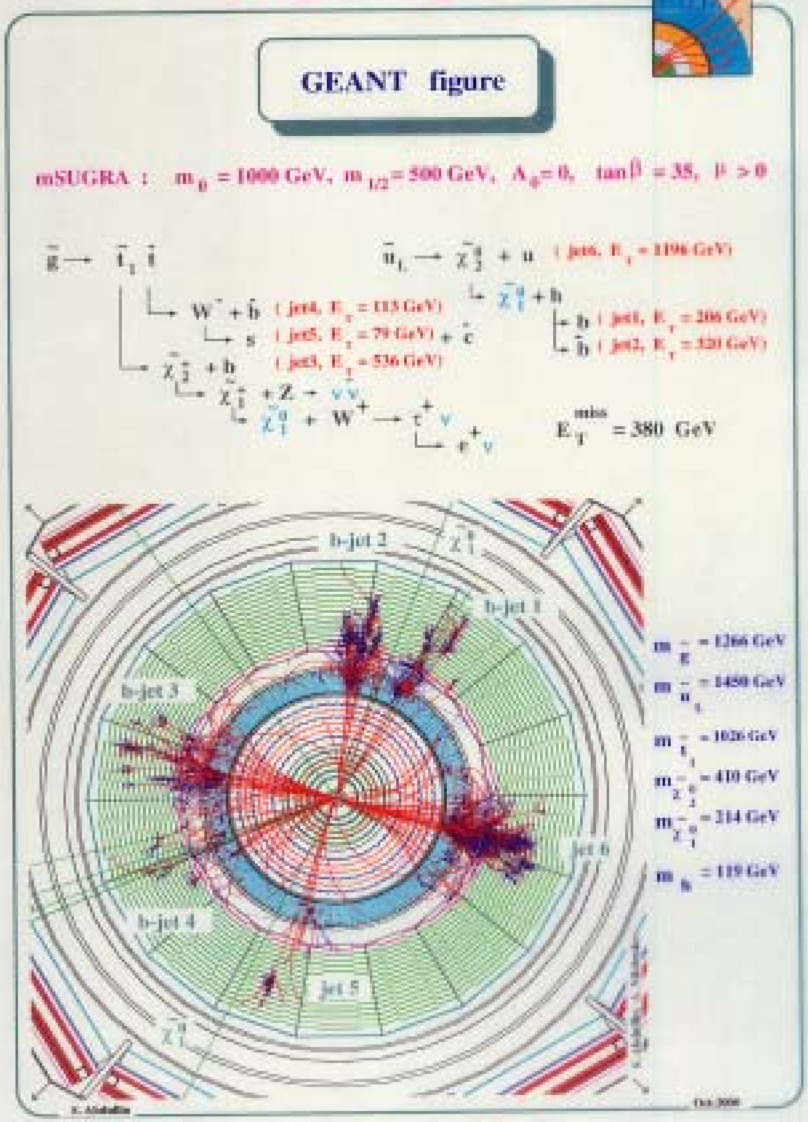
LHC 'guaranteed' discovery

can 'cover' cosmological region

rich opportunities in cascades

some sensitivity to sleptons, $\chi^{\pm}$, ...

Supersymmetry @ LHC



GEANT figure

mSUGRA : $m_0 = 1000$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$, $\tan\beta = 35$, $\mu > 0$

$\tilde{g} \rightarrow \tilde{t}_1\, \bar{t}$

$\quad \bar{t} \rightarrow W^- + \bar{b}$ (jet4, E_T = 113 GeV)

$\quad\quad W^- \rightarrow s$ (jet5, E_T = 79 GeV) + $\bar{c}$

$\quad \tilde{t}_1 \rightarrow \tilde{\chi}_2^+ + b$ (jet3, E_T = 536 GeV)

$\quad\quad \tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^+ + Z \rightarrow \nu\nu$

$\quad\quad\quad \tilde{\chi}_1^+ \rightarrow \tilde{\chi}_1^0 + W^+ \rightarrow \tau^+ \nu$

$\quad\quad\quad\quad \tau^+ \rightarrow e^+ \nu$

$\tilde{u}_L \rightarrow \tilde{\chi}_2^0 + u$ (jet6, E_T = 1196 GeV)

$\quad \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 + h$

$\quad\quad h \rightarrow b$ (jet1, E_T = 206 GeV)

$\quad\quad h \rightarrow \bar{b}$ (jet2, E_T = 320 GeV)

$E_T^{miss} = 380$ GeV

$m_{\tilde{g}} = 1266$ GeV

$m_{\tilde{u}_L} = 1450$ GeV

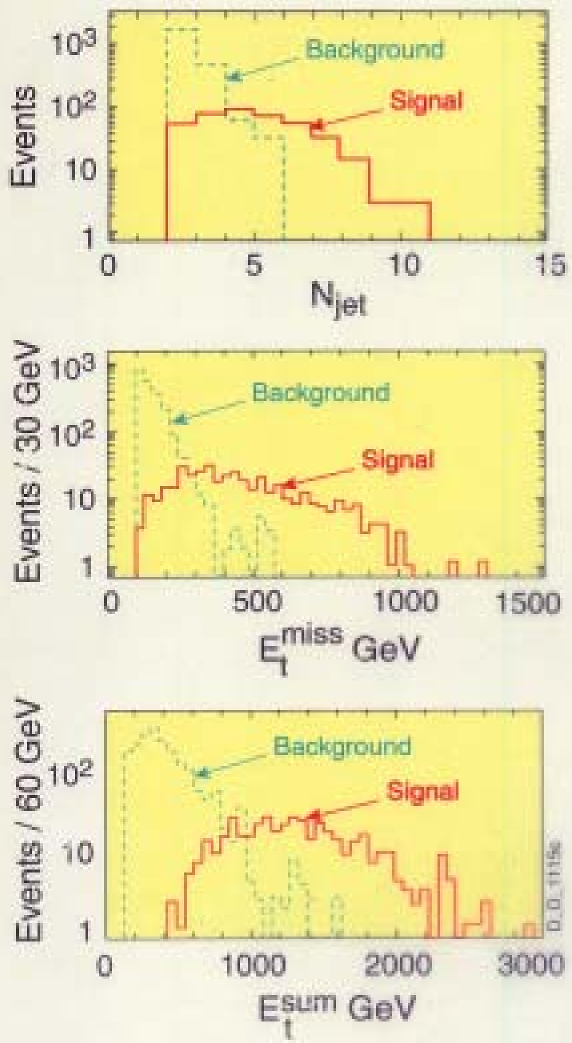
$m_{\tilde{t}_1} = 1026$ GeV

$m_{\tilde{\chi}_2^0} = 410$ GeV

$m_{\tilde{\chi}_1^0} = 214$ GeV

$m_h = 119$ GeV

Easy to see Supersymmetry @ LHC



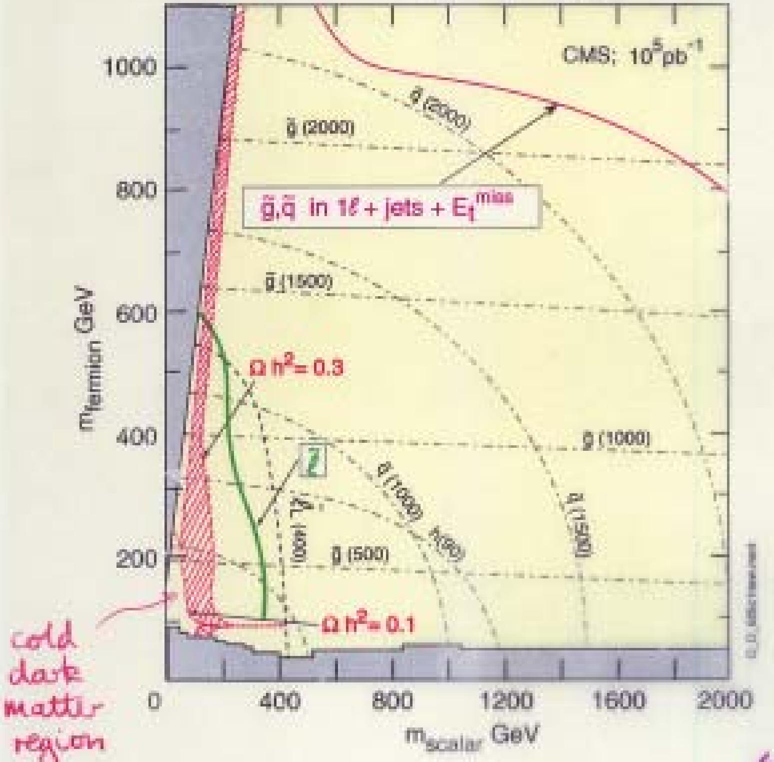
(CMS)

F

Expected reach in various channels

m SUGRA; tgβ = 2 (~ same up to tgβ ~ 5), $A_0 = 0$, $\mu < 0$

5 σ contours ($N_\sigma = N_{sig}/\sqrt{N_{sig}+N_{bkgd}}$) for $10^5 pb^{-1}$



(CMS

Precision Mass Measurements

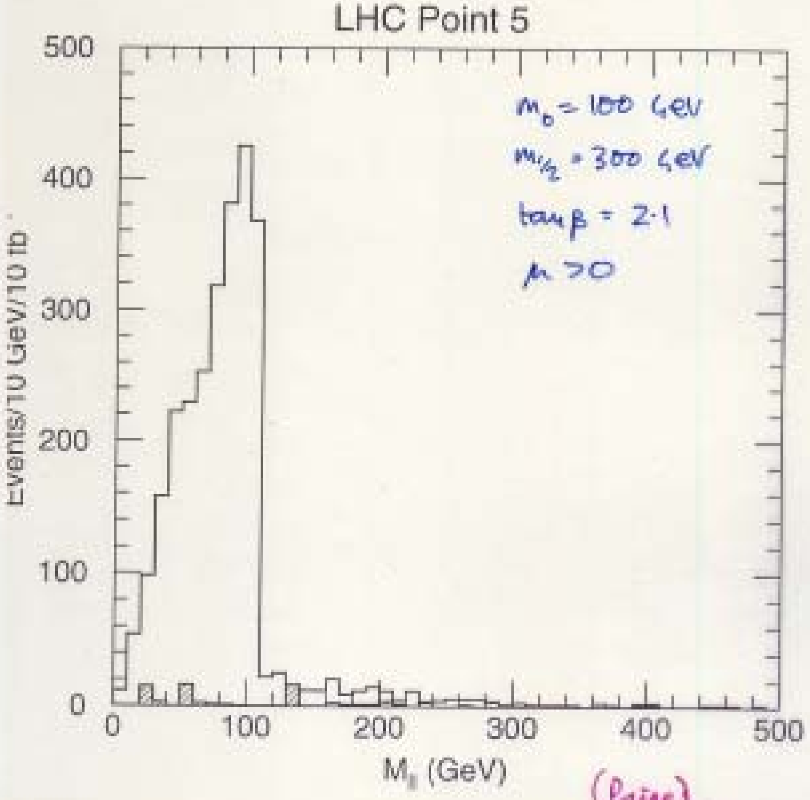
$\chi_2 \to \chi\,(l^+l^-)$

mass difference from end point

$\Delta(\delta m)_{syst} \leq 50$ MeV

⊕ measurements of other sparticle masses

eg. $\tilde{g} \to \tilde{b}b$, $\tilde{b} \to \chi_2 b$, $\chi_2 \to \chi l^+ l^-$

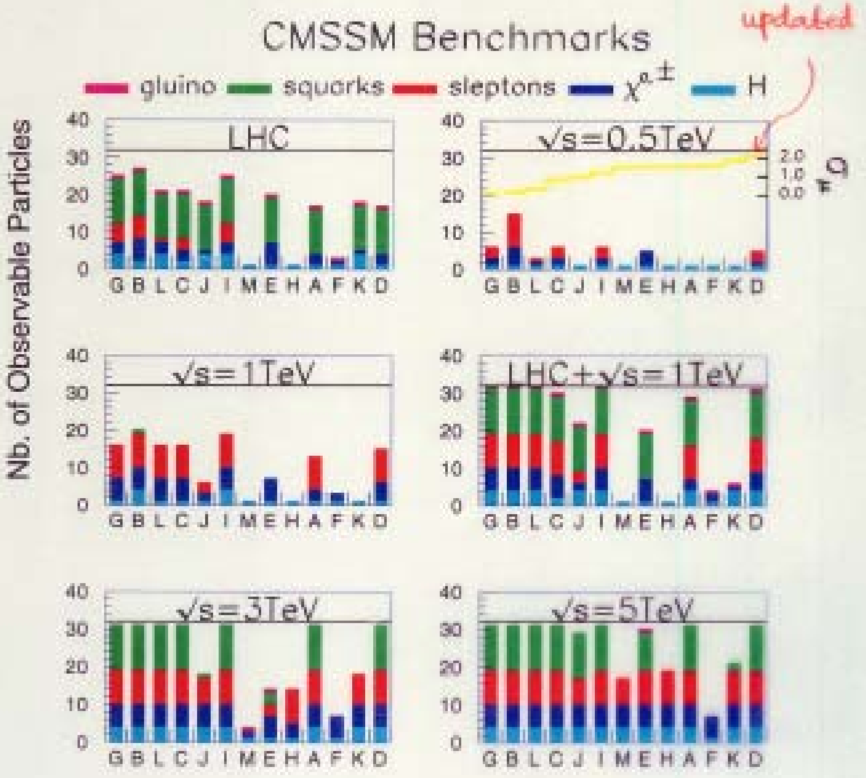


(Paige)

Observability of Supersymmetry

(Battaglia et al.: hep-ph/0106204

with future accelerators

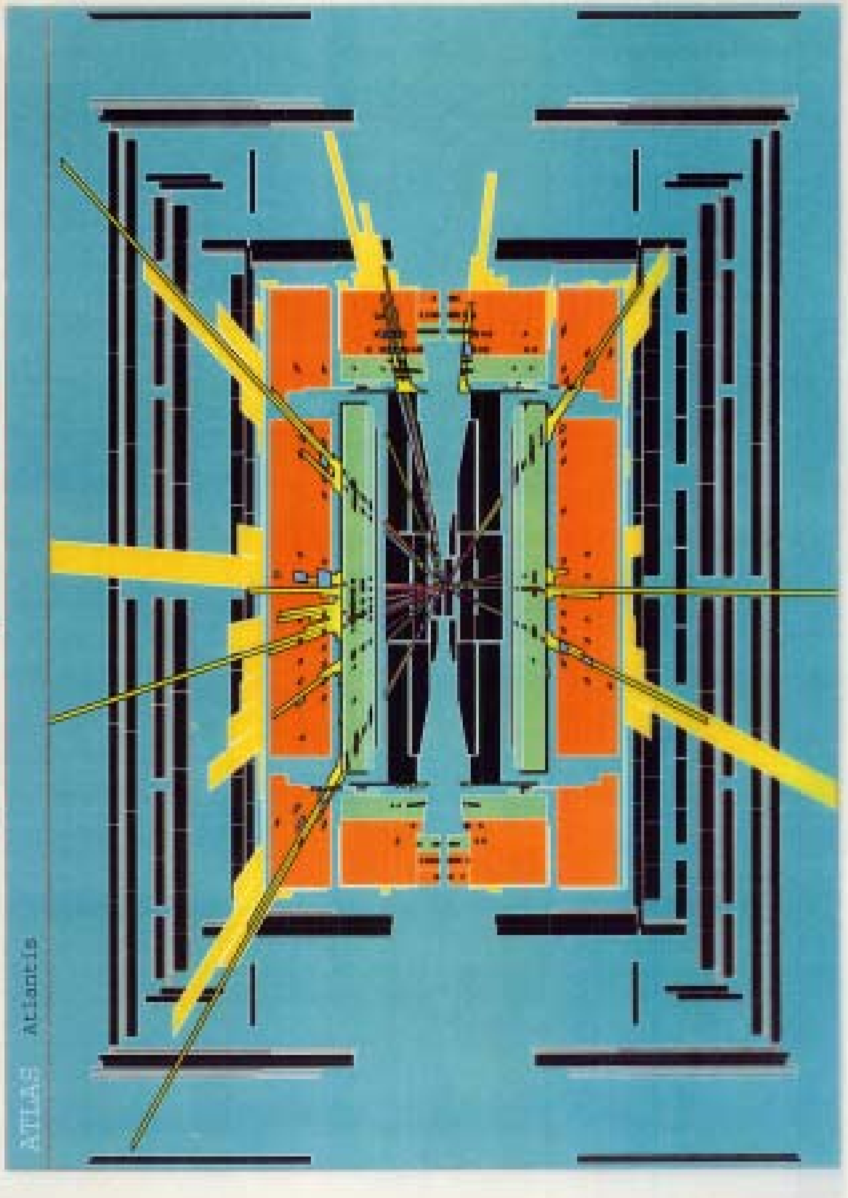


Post-LHC Physics Scenario

Higgs: discovered
$\Delta m/m \sim 10^{-2}$ to 10^{-3}
one or two decays observed

MSSM: found several sparticles
not heavier higgses, charginos, sleptons
some precision measurements

Black hole production at LHC!



3 - Possible Projects beyond the LHC

(J.E.+Keil+Roland: CERN-TH-98-5
(J.E.+Gianotti+de Roeck: hep-ex/0112004

- upgrade of the LHC?

  'possible' to increase $\mathcal{L} \to 10^{35} cm^{-2} s^{-1}$

  (Gianotti et al.: hep-ph/0204087

  'very difficult' to increase E substantially

  magnets, synchrotron radiation, ...

- CLIC — R&D funded by CERN

  linear e^+e^- collider @ $E_{cm} \leq 3$ to 5 TeV

  (http: clicphysics.web.cern.ch/CLICphysics/

- neutrinos — seek R&D funding

  intense proton source (SPL)

  β-beams — based on heavy-ion decays

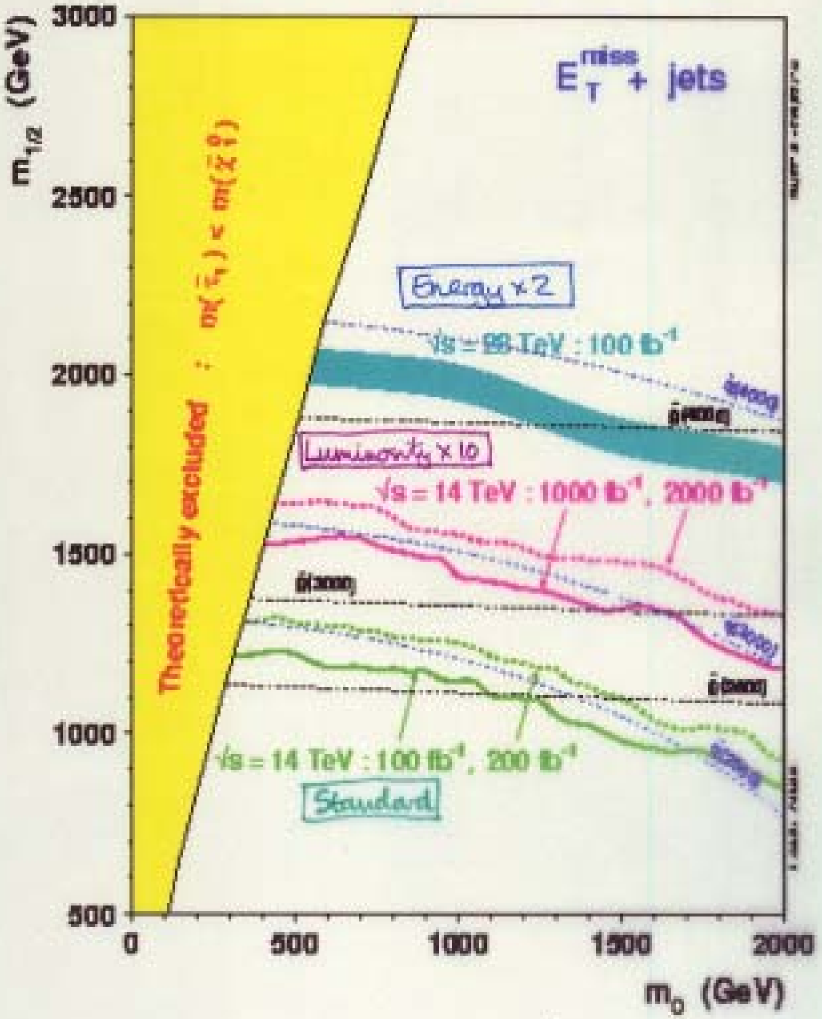
  ν factory — based on μ decays

  ($\mu^+\mu^-$ collider)

Aim for options to be available when LHC starts up in 2007

LHC Machine Upgrade?

2500GeV → 3000GeV → 4000GeV



(Mangano et al.

e^+e^- Linear Collider Physics

- very clean experimental environment
- egalitarian production of new weakly-interacting particles
- polarization
- $e\gamma$, $\gamma\gamma$, e^-e^- colliders "for free"
- complementary to LHC

what energy scale?

$2m_t$? $m_Z + m_H$? $2\tilde{m}$?

$\uparrow$ estimated $\uparrow$ unknown

how/when to fix energy scale?

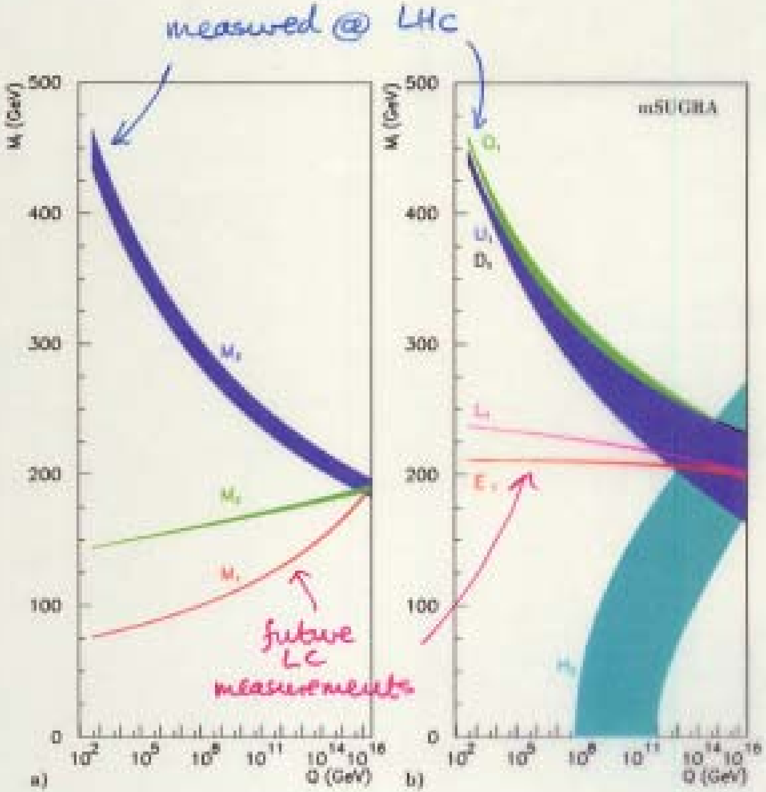
- flexibility essential

$m_Z, 2m_W \leftarrow ?$ → 2 TeV

$\uparrow$ 10^9 polarized Z? $\uparrow$ δm_W ↑ for reach comparable to LHC

Will Sparticle Masses Unify?

mSUGRA vs GMSB vs ...



measured @ LHC

future LC measurements

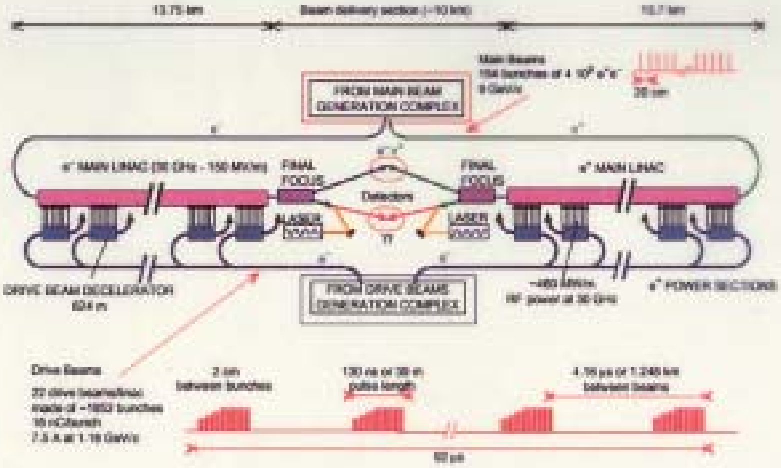
Figure 1: **mSUGRA:** *Evolution of (a) gaugino and (b) sfermion mass parameters in the bottom-up approach. The mSUGRA point probed is characterized by the parameters M_0 = 200 GeV, $M_{1/2}$ = 190 GeV, A_0 = 550 GeV, $\tan\beta$ = 30, and sign(μ) = (−). [The widths of the bands indicate the 95% CL.]*

(Blair + Porod + Zerwas

- We will need a LC
- Complementary to LHC
  - exploration ⊕ precision
- Need widest possible energy range
  - initial ⊕ extensions ⊕ back to Z/WW
- Should converge on single project

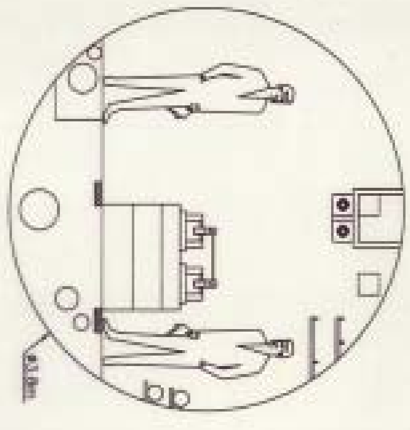
presume a LC in the ~ TeV Ecm
range will be built

CLIC Layout



Tunnel Layout

Surprisingly Simple!



- No active RF components
(No klystrons or modulators)
- Single small-diameter tunnel
(3.8m - same as LEP)

CLIC Parameters

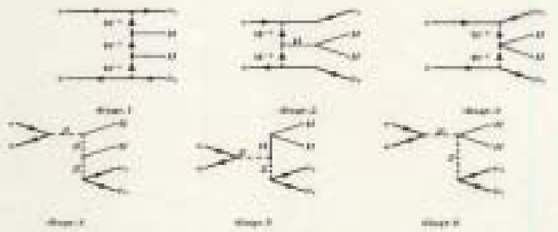
Beam param. at I.P. E_{CM} =	0.5 TeV	1 TeV	3 TeV	5 TeV
Luminosity ($10^{34}cm^{-1}s^{-1}$)	0.5	1.1	10.6	14.9
Mean energy loss (%)	3.6	9.2	32	40
Photons /electrons	0.8	1.1	2.2	2.6
Rep. Rate (Hz)	200	150	75	50
10^9 $e^{\pm}$ / bunch	4	4	4	4
Bunches / pulse	150	150	150	150
Bunch spacing (cm)	20	20	20	20
H/V ε_n (10^{-8} rad.m)	188/10	148/7	60/1	58/1
Beam size (H/V) (nm)	196/4.5	123/2.7	40/0.6	27/0.45
Bunch length (μm)	50	50	30	25
Accel.gradient (MV/m)	100	100	150	200
Two linac length (km)	7	14	27.5	35
Power / section (MW)	116	116	231	386
RF to beam effic. (%)	35.5	35.5	26.6	19.4
AC to beam effic. (%)	14.2	14.2	10.6	7.8
AC power (MW)	68	102	206	310

Light Higgs

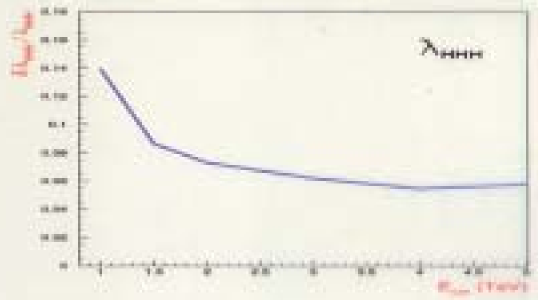
Study of Triple Higgs Coupling at CLIC

M. Battaglia

- ◆ Extract λ_{HHH} from $\sigma(e^+e^- \to \nu\nu HH)$ for $M_H = 120$ GeV$/c^2$ ($\sim 20 - 25\%$ atTESLA)
- ◆ $\sigma(e^+e^- \to \nu\nu HH) \simeq \sigma(e^+e^- \to \nu\nu ZZ \to b\bar{b})$

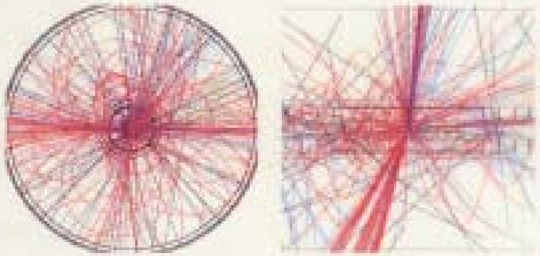


Precision on λ_{HHH} (5000 fb^{-1})

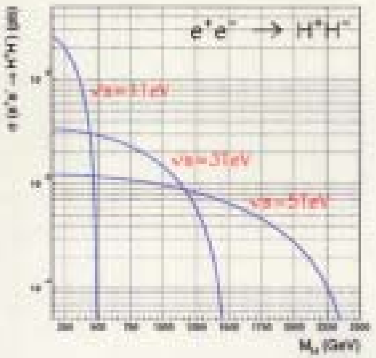


Heavy Higgs

$e^+e^- \rightarrow H^+H^-$ $M_H = 900$ GeV



Cross section as function of mass



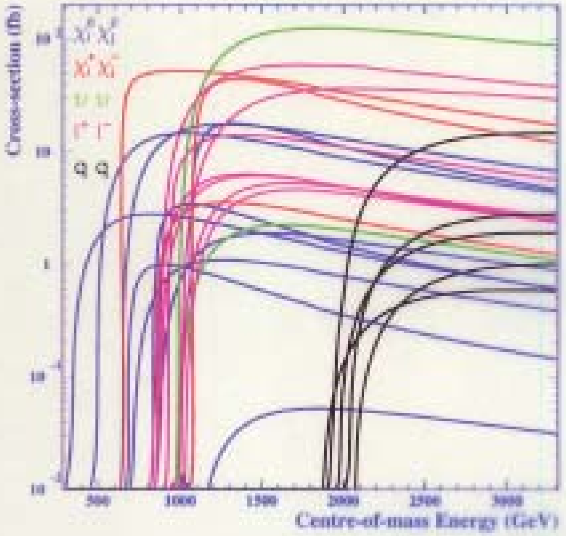
- Note: to make full use of available kinematic range for searches, high luminosity will be needed

---

SUSY

Particle pair thresholds

$m_{1/2} = 400$ GeV, $m_0 = 400$ GeV, $\tan\beta = 35$,
$A = -400$ GeV, $sign(\mu) < 0$ (mSUGRA)



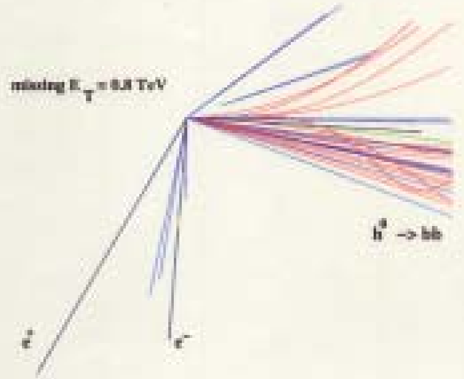
Many new particles with nearly degenerate masses

SUSY

Completing the Sparticle Spectrum at a multi-TeV Collider

CLIC 3 TeV

$e^+e^- \to e_L e_R$



$m_{\tilde{e}} = 1050$ GeV $\quad m_{H^0} = 115$ GeV

$\tilde{e}_L \to e\tilde{\chi}_2^0 \quad \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h \quad h \to b\bar{b}$

$\tilde{e}_R \to e\tilde{\chi}_1^0$

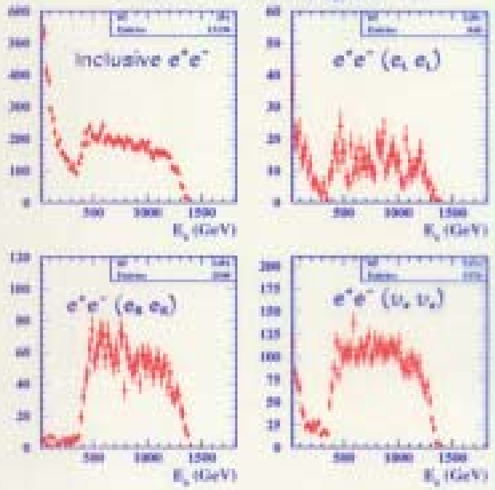
SUSY

Case Study: sneutrino pair production

sneutrino mass determination

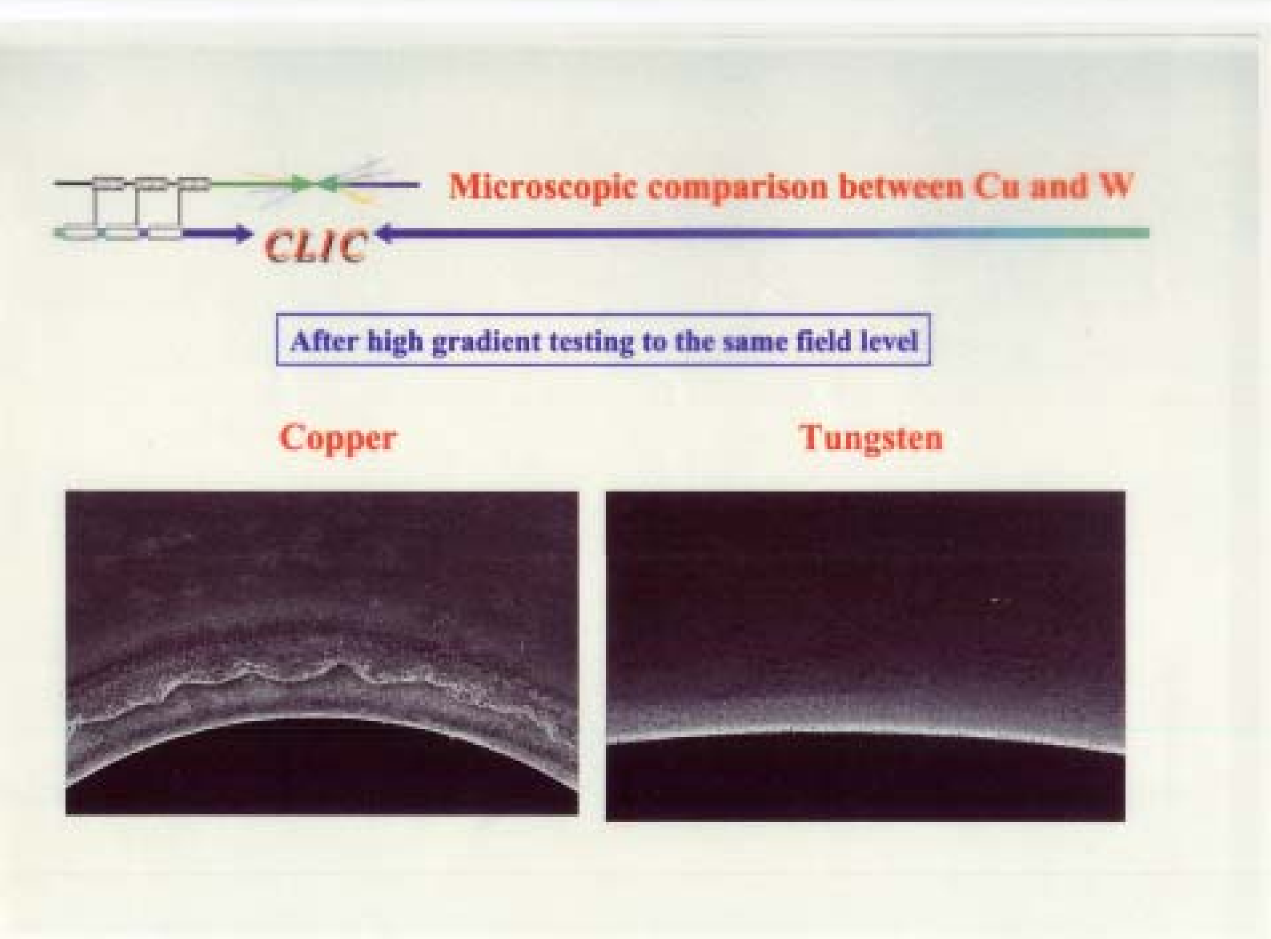
E.G. $m_{1/2} = 300$ GeV, $m_0 = 1450$ GeV, $\tan\beta = 10$, $A = 0$ GeV, $sign(\mu) > 0$ (mSUGRA) (KM1)

CLIC beamstrahlung (10^{35})



Signal $\tilde{\nu}_e\tilde{\nu}_e \to e^+\tilde{\chi}_1^- e^-\tilde{\chi}_1^+ (180)$

Typical 'box' shape of the signal preserved in CLIC environement

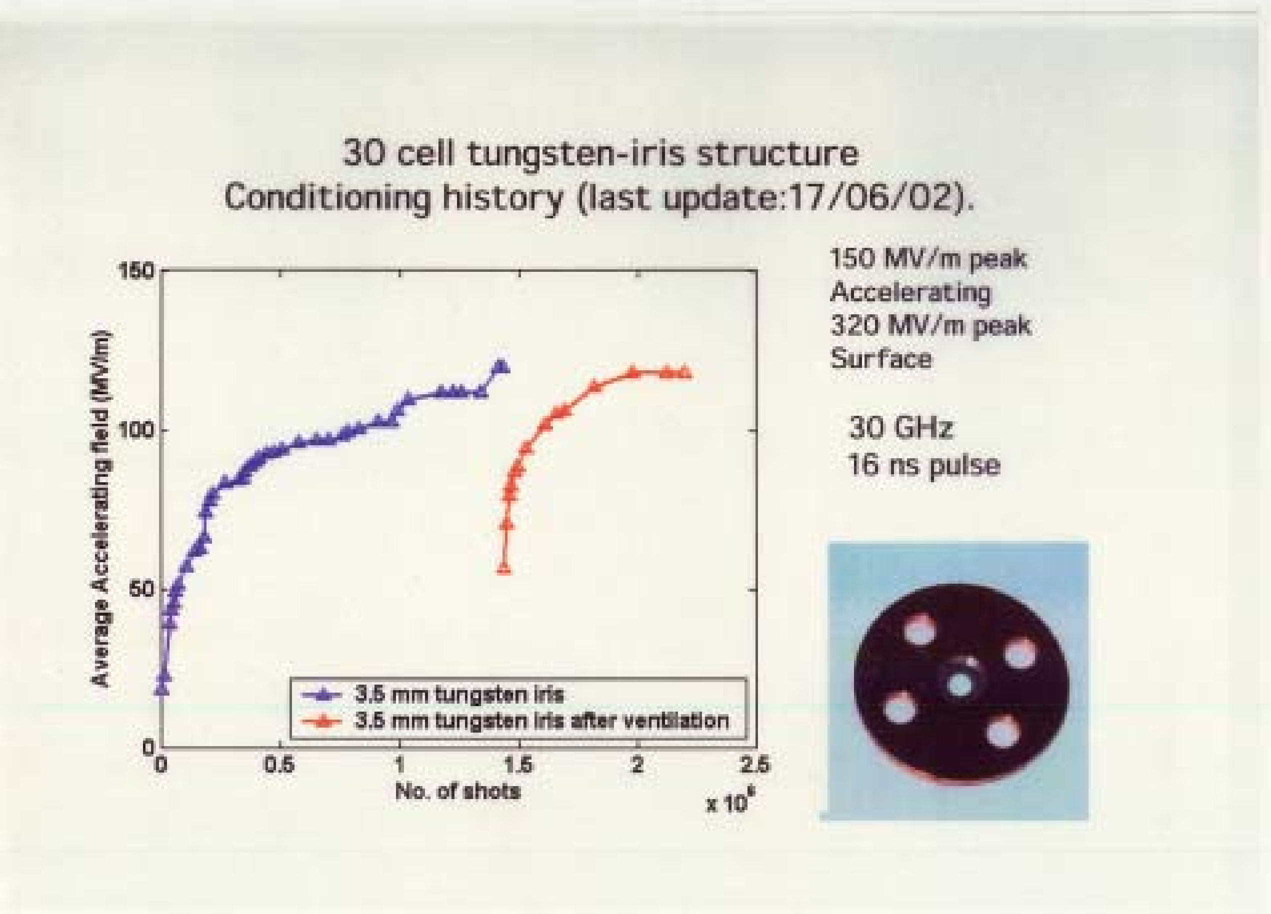


Microscopic comparison between Cu and W

After high gradient testing to the same field level

Copper

Tungsten



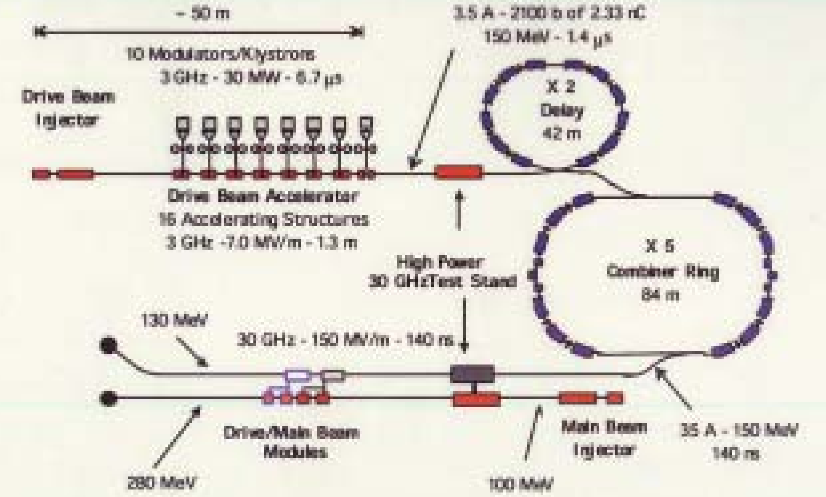
30 cell tungsten-iris structure
Conditioning history (last update:17/06/02).

150 MV/m peak
Accelerating
320 MV/m peak
Surface

30 GHz
16 ns pulse

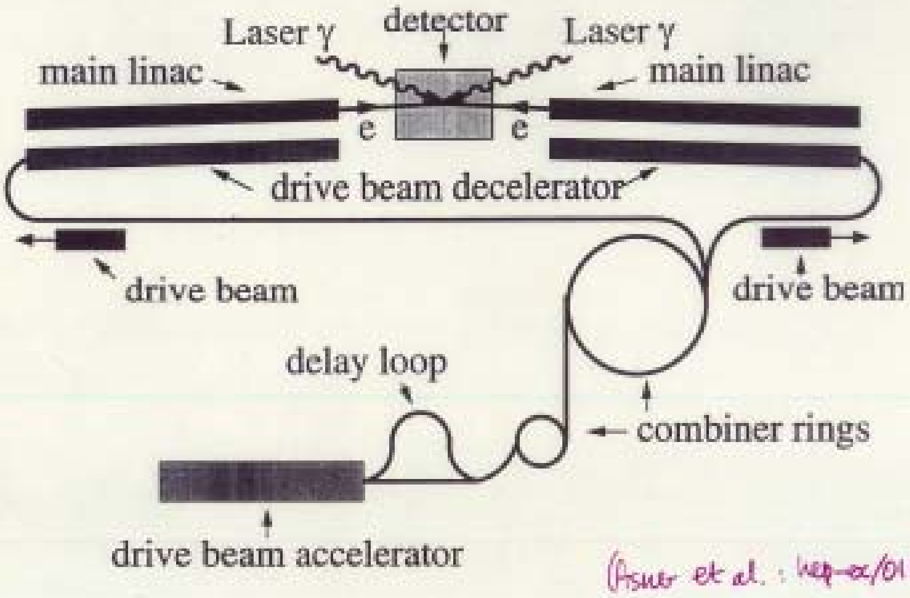
Generic layout of CTF3

CTF3 - Test of Drive Beam Generation, Acceleration & RF Multiplication by a factor 10



CLICHE : $\gamma\gamma$ Higgs factory @ CLIC 1

$E_{cm}^{e^+e^-} \sim 150\,\text{GeV} \Rightarrow E_{cm}^{\gamma\gamma} \sim 120\,\text{GeV}$



(Asner et al. : hep-ex/0111056

Higgs signal @ CLICHE

$H \to \bar{b}b$

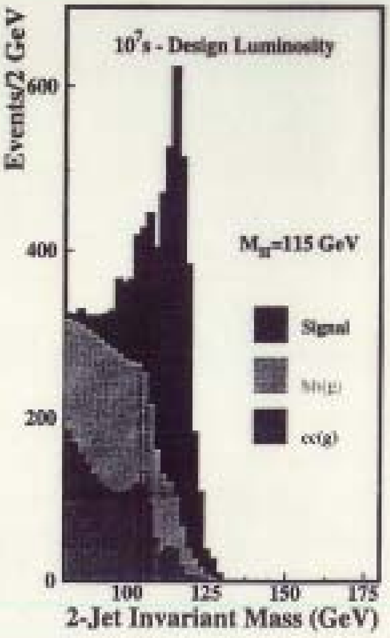


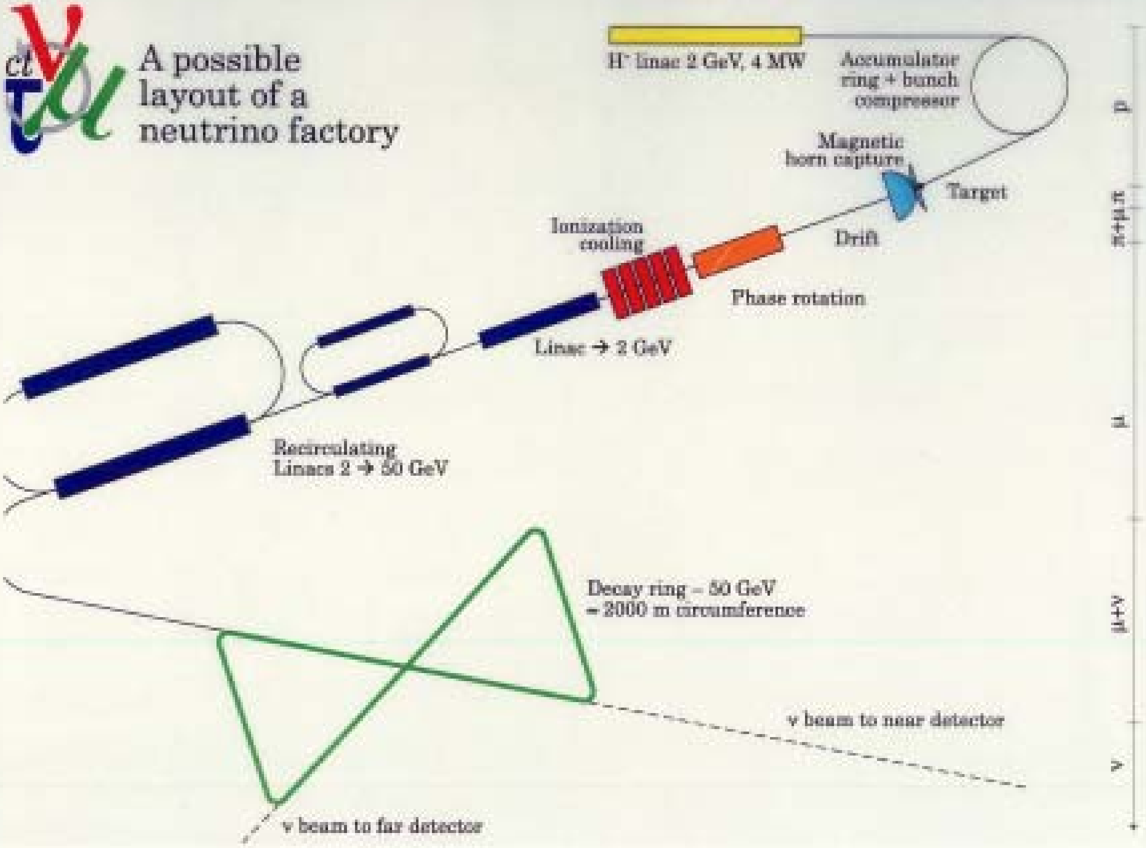
Figure 7: *Observability of the* $H \to \bar{b}b$ *decay mode for* $m_H = 115$ *GeV, with CLICHE running so that the peak* $E_{CM}(\gamma\gamma) = 115$ *GeV.*

(Asner et al.: hep-ex/0111056

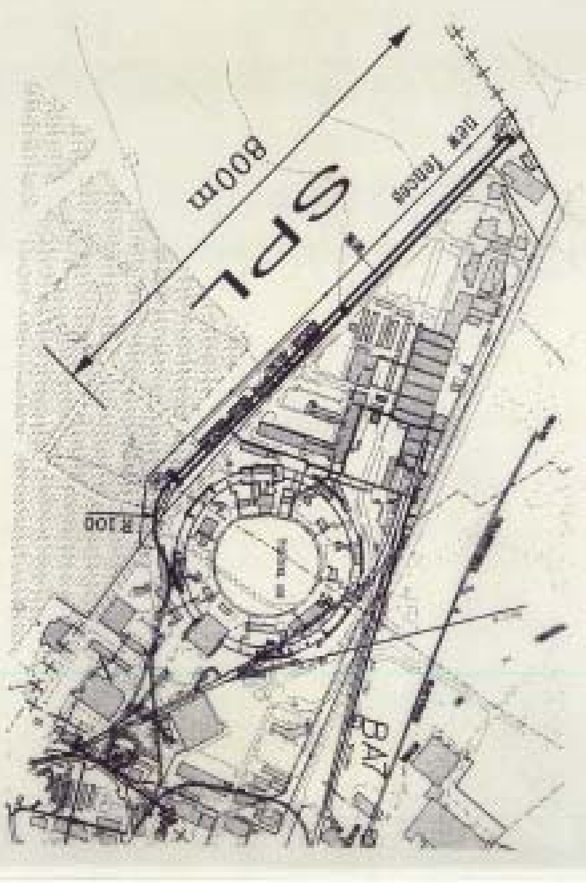
Concept for a ν Factory

- intense proton source
  - linac @ 2GeV → rapid-cycling synchrotron
- accumulator/compressor ring
  - modify time structure
- target + horn system
  - $p \to \pi \to \mu$
- cooling and phase rotation
  - 'tame' μ beam
- recirculating linacs
  - accelerate $\mu \to$ 20 to 50 GeV
- store and allow to decay
  - SBL + LBL + VLBL ?
- (more cooling for muon collider?
  - Higgs factory: CP violation?
  - high-energy frontier?)

A possible layout of a neutrino factory



Possible Layout of Proton Driver @ CERN



- better PS beams
- ISOLDE current × 5, new radioactive beam facility?
- better SPS beams: CNGS, ...
- better beams for LHC, shorter filling time

(B. Autin et al.)

Programme of Work for a ν Factory

ν oscillation studies

magnitude of θ_{13}

CP violation

MSW effects

sign of Δm^2_{23}

⋮

other physics

slow (stopped) μ physics

deep-inelastic ν (μ?) scattering

neutron physics

kaon physics

⋮

Neutrino factory activities @ CERN

European muon working groups

(http://muonstoragerings.web.cern.ch/
muonstoragerings/Welcome.html

ECFA physics studies:

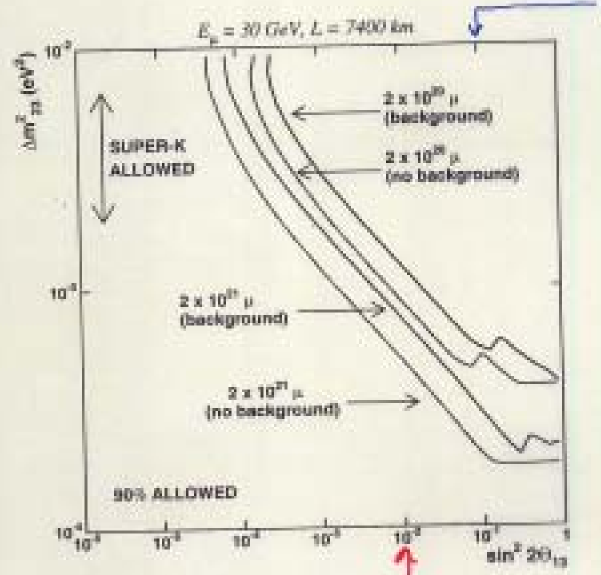
short-baseline	(Mangano et al.: hep-ph/0105155
kaon physics	(Belyaev et al.: hep-ph/0107046
low-E muons	(Äystö et al.: hep-ph/0109217
$\mu^+\mu^-$ collider	(Blochinger et al.: hep-ph/0202199
ν oscillations	(http://campanel.home.cern.ch/ campanel/oscillations.html

European muon concetation and oversight group

representatives of major interested laboratories

Sensitivity to $\nu_\mu \to \nu_e$ oscillations

@ 7400km



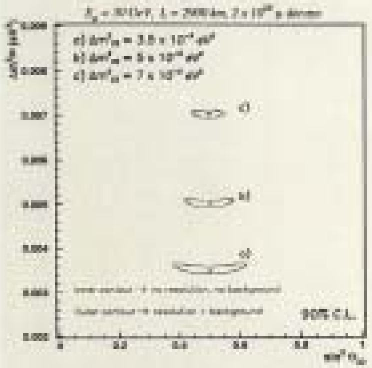
limit from Chooz

sensitivity of MINOS

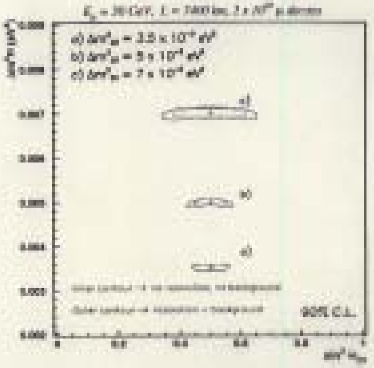
(Bueno + Campanelli + Rubbia'
hep-ph/0005007

Prospective Accuracy of $\nu_\mu \to \nu_e$ Measurements

@ 2900km



@ 7400 km



(Bueno + Campanelli + Rubbia'
hep-ph/0005007

CP-Violating Observable

$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)$

$= 16\, s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta$

$\times \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$

possible only if

Δm_{12}^2, s_{12} large enough: LMA

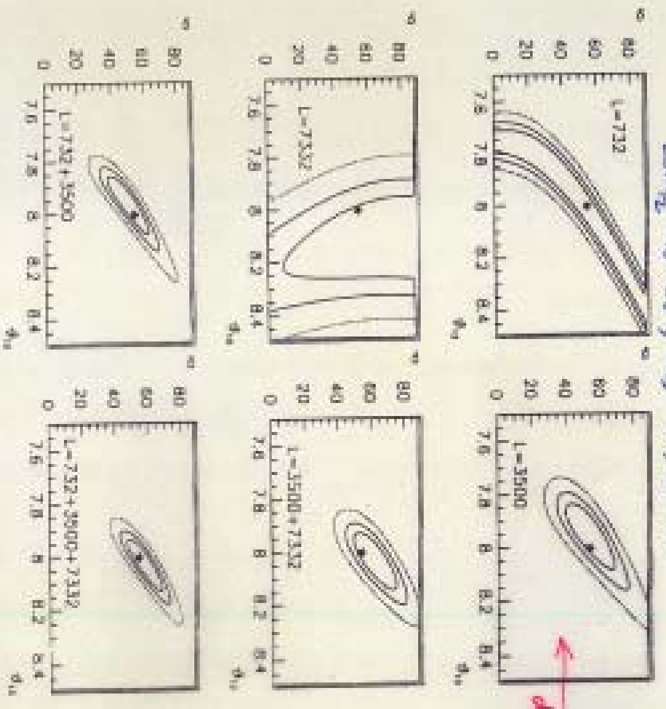
θ_{13} large enough

we need to know!

CP-Violating Phase Measurements

@ ν factory

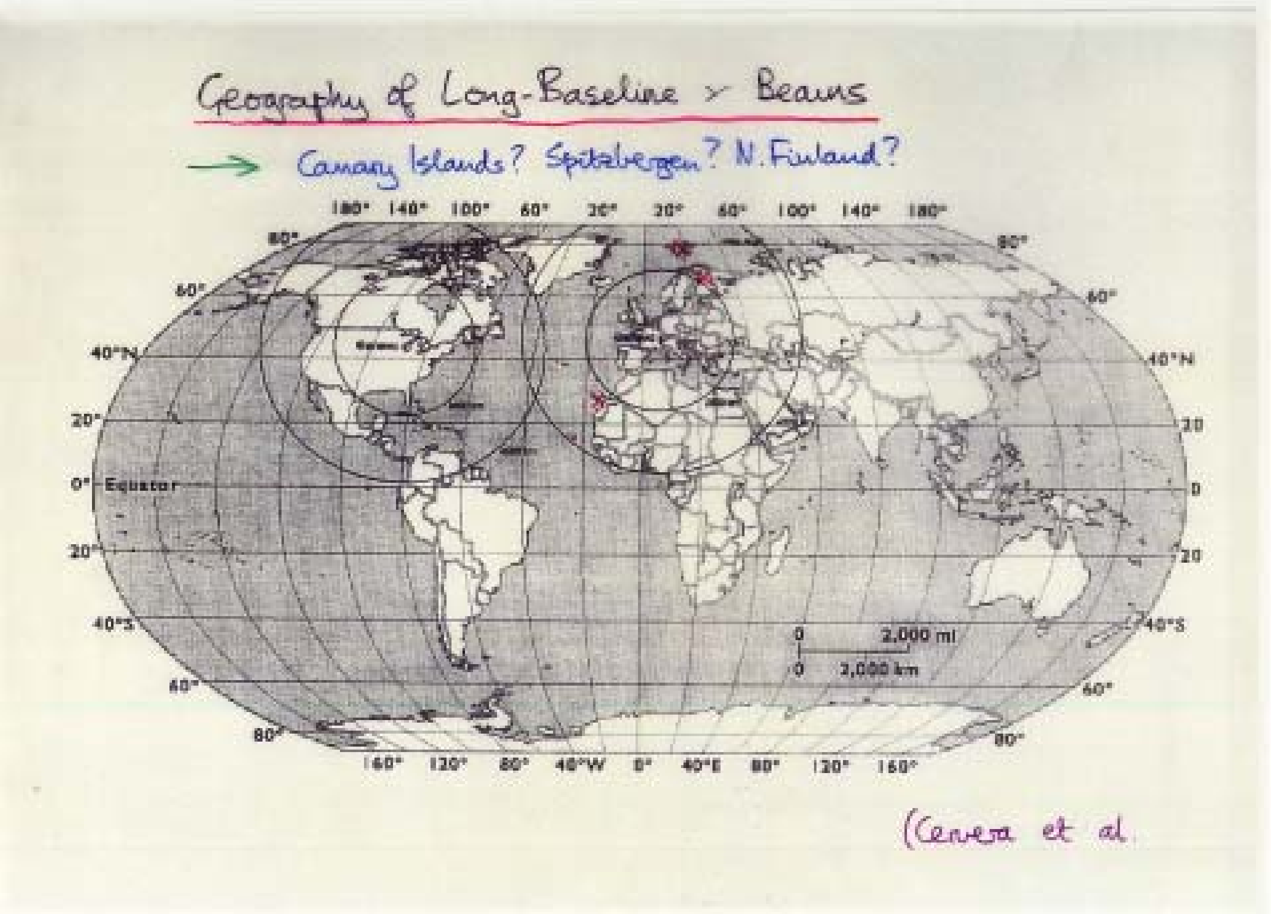
$\Delta m_{12}^2 = 10^{-4}\,\mathrm{eV}^2$, $\theta_{13} = 8°$, $\delta = 54°$



← good distance

including backgrounds, efficiencies

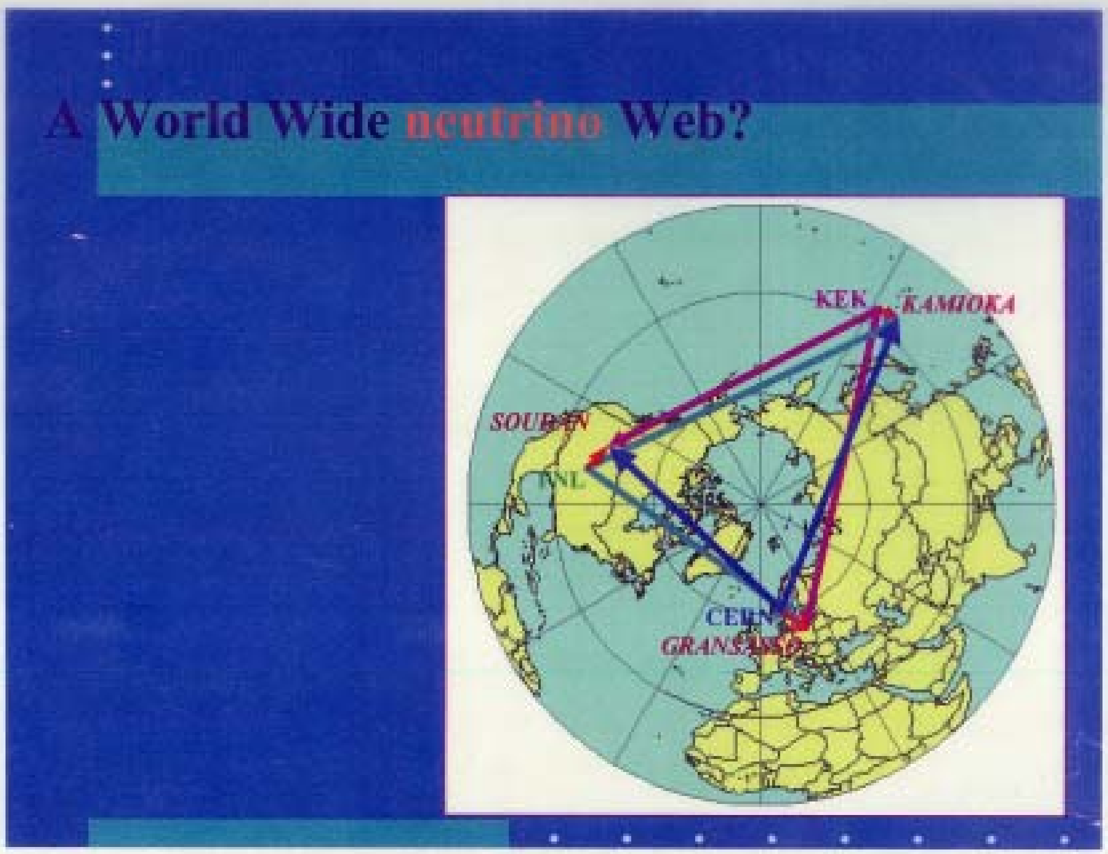
(Cervera et al.



Geography of Long-Baseline ν Beams

→ Canary Islands? Spitsbergen? N. Finland?

(Cervera et al.



A World Wide neutrino Web?

Beam Requirements for Low-Energy μ Experiments

possible at front end of ν factory

$\mu \to e$ conv^n (

$\mu \to e\gamma$

$\mu \to 3e$

$g_\mu - 2$

d^e_μ

μSR

Experiment	q_μ	$\int I_\mu dt$	I_0/I_μ	δT [ns]	ΔT [ns]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{19}	$< 10^{-9}$	≤ 100	≥ 1000	< 20	1...5
$\mu^- N \to e^- N^\dagger$	$-$	10^{19}	n/a	continuous	continuous	< 20	1...5
$\mu \to e\gamma$	$+$	10^{17}	n/a	continuous	continuous	1...4	1...5
$\mu \to eee$	$+$	10^{17}	n/a	continuous	continuous	1...4	1...5
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000s	≥ 20000	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20000	4	1...10
transvers.polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 20	430-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^6$	3100	10^{-4}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^6$	≤ 1000	$\leq 10^{-5}$
M_{HFS}	$+$	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20000	4	1...3
M_{1s2s}	$+$	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^6$	1...4	1...2
μ^-*atoms*	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20000	1...4	1...5
condensed matter (incl.bio sciences)	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20000	1...4	1...5

pulse length

pulse separation

(Giudice et al.

Parameter Counting in Seesaw Model

$$\mathcal{L}_\nu = (Y_\nu)_{ij} H \overline{N}_i \binom{\nu}{L}_j + \frac{1}{2} \overline{N}_i \mathcal{M}_{ij} \overline{N}_j$$

physical parameters = 18

$$\underbrace{3m_\nu + \underbrace{(\delta, \phi_1, \phi_2)}_{CP\times} + \theta_{12,23,13}}_{9 \text{ 'observable' @ low energies}} + \underbrace{3M_\nu + \overbrace{3\alpha_H + \underbrace{3\beta_H}_{CP\times}}^{\text{matrix } R}}_{9 \text{ heavy sector}}$$

4 'known'

+ renormalization

Total of 6 CP-violating parameters

MNS phase + 2 Majorana phases $\leftarrow \beta\beta_{0\nu}$

3 extra phases control leptogenesis

Origin of baryon asymmetry?

$\Gamma(N \to L + H) \neq \Gamma(N \to \bar{L} + H)$?

possible via 1-loop CPx diagrams

Lepton asymmetry → baryon asymmetry

via non-perturbative electroweak interactions

(S.E.+Hisano+Ueda+Raidal hep-ph/0109125)

Slepton Mass Renormalization

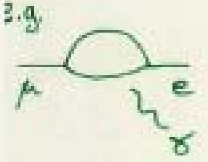
assume degenerate universal $m^2_{\tilde{\ell}}$ @ M_{GUT}

renormalization: $\delta m^2_{\tilde{\ell}} = -\frac{1}{8\pi^2}(3m_0^2+A_0^2)(Y_\nu^\dagger Y_\nu)_{ij}\ln\left(\frac{M_{GUT}}{M_{N}}\right)$

$\delta A_e = -\frac{3}{8\pi^2}A_0 Y_{e_i}(Y_\nu^\dagger Y_\nu)_{ij}\ln\left(\frac{M_{GUT}}{M_N}\right)$

non-universal ⇒ lepton flavour violation

e.g.



$\propto (Y_\nu^\dagger Y_\nu)_{ij}$

$= (U\sqrt{m^d}R^\dagger M^d R\sqrt{m^d}U^\dagger)_{ij}$

depends on 6 phases: $\beta_i, \delta, \phi_{1,2}$

+ 6 real angles: α_i, Θ_{MNS}

many low-energy observables:

$\mu\to e\gamma$, $\tau\to\mu\gamma$, $\tau\to e\gamma$; $\mu N\to eN$,

$\mu\to 3e$, $\tau\to 3e$, $e2\mu$, $2e\mu$, 3μ

many CP-violating observables:

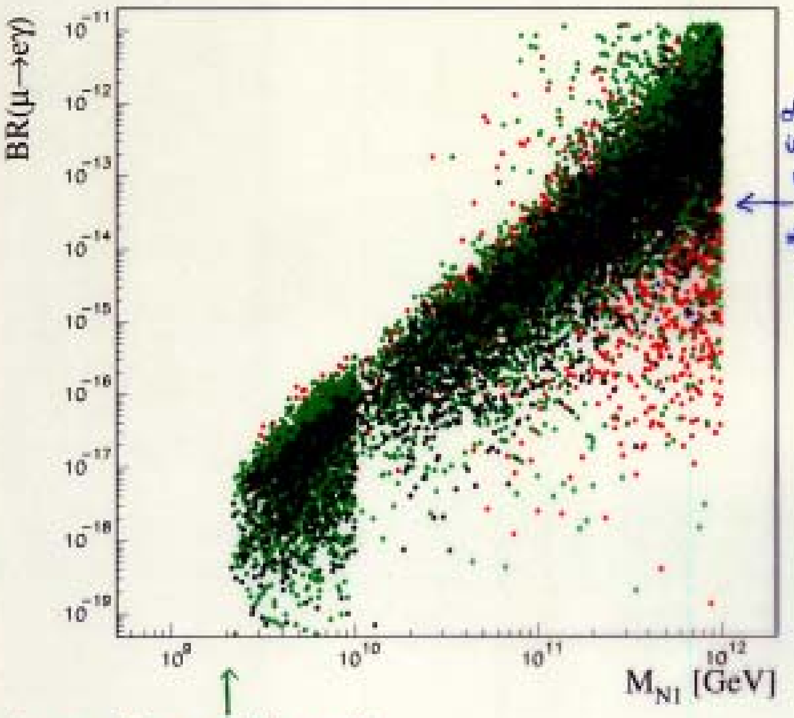
EDM_e, EDM_μ,

$A_T(\mu\to 3e)$, ...

$\mu\to e\gamma$ vs lightest heavy ν

in texture H'

for $10^{-11} \le Y_B \le 3\times10^{-10}$



observable in many models: would ⇒ large M_{N_1}

Lower limit: problematic for gravitinos if leptogenesis from thermalized N_1

(EHRS'

Concluding Remarks

- LBL ν oscillation experiments are the 'core business' of a ν factory

  bears on fundamental theoretical issues

  possibilities for exciting experiments

- Many other exciting prospects

  (muon colliders Higgs factories, H.E. frontier)

- Low-energy μ physics @ front end

  $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion,

  $g_\mu - 2$, d^e_μ, ...

- Short-baseline neutrino physics

  DIS, ν-e ; deep-inelastic μ-N?

A ν factory is a complex (& expensive) project

ν physicists likely to need support of others

We must work with other communities

Table 4: Example parameters for feasibility studies of $\mu^+\mu^-$ colliders of 4 TeV and 100 GeV CoM energy

CoM Energy (GeV)	4000	100	
Proton energy (GeV)	16	16	
Proton bunch population (10^{13})	2.5	5	
Proton beam power (MW)	4	4	
Repetition rate (Hz)	15	15	
No. of $\mu^\pm$ bunches/sign	2	1	
$\mu^\pm$ bunch population (10^{12})	2	4	
Collider circum. (m)	8000	260	
Free space ℓ^* at IP (m)	6.5	5	
RMS momentum spread $\Delta p/p$	0.12%	0.12%	0.003%
Normalized emittance ϵ_n (π mm mrad)	50	85	280
β^* at IP (cm)	0.3	4	13
Bunch lengthσ_z (cm)	0.3	4	13
RMS beam radius at IPσ_r (μm)	2.8	82	270
Beam-beam tune shift ξ	0.04	0.05	0.015
Luminosity (nbs)$^{-1}$	100	0.12	0.01

problem of ν radiation?

"Higgs factory" demonstrator project?

The H,A Peaks in the MSSM

relatively large widths

⇒ no need for fine energy resolution