Physics at the Large Hadron Collider

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Taller de Altas Energías

Jaca, 16-18 May 2007

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Reports & talks: K. Desch, R.D. Heuyer, M. Mangano, D. Wood, D. Fournier, K. Jakobs

Layout of lectures:

1.- General overview of collider particle physics
(where do we stay & where do we go)

2.- The accelerator and its physical implications

3.- The detectors, performance and operation

4.- Physics channels: Top quark, W, Higgs,
SUSY and beyond

Large Hadron Collider

Lecture 1

General overview of collider particle physics (where do we stay & where do we go)

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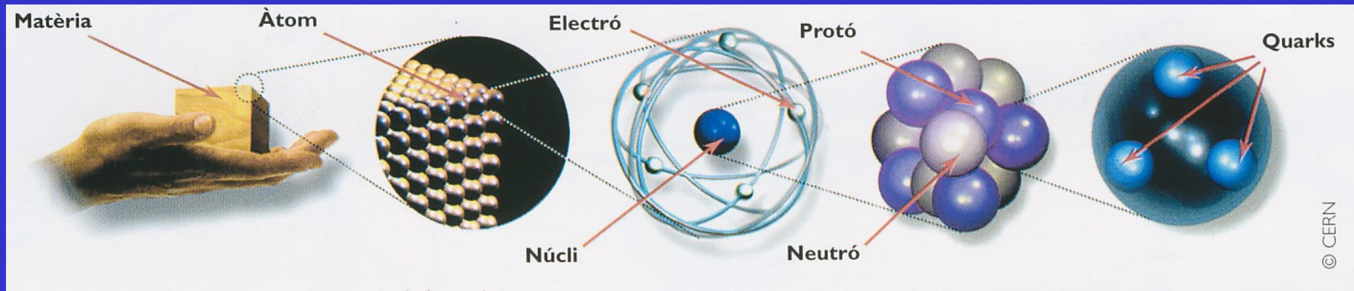
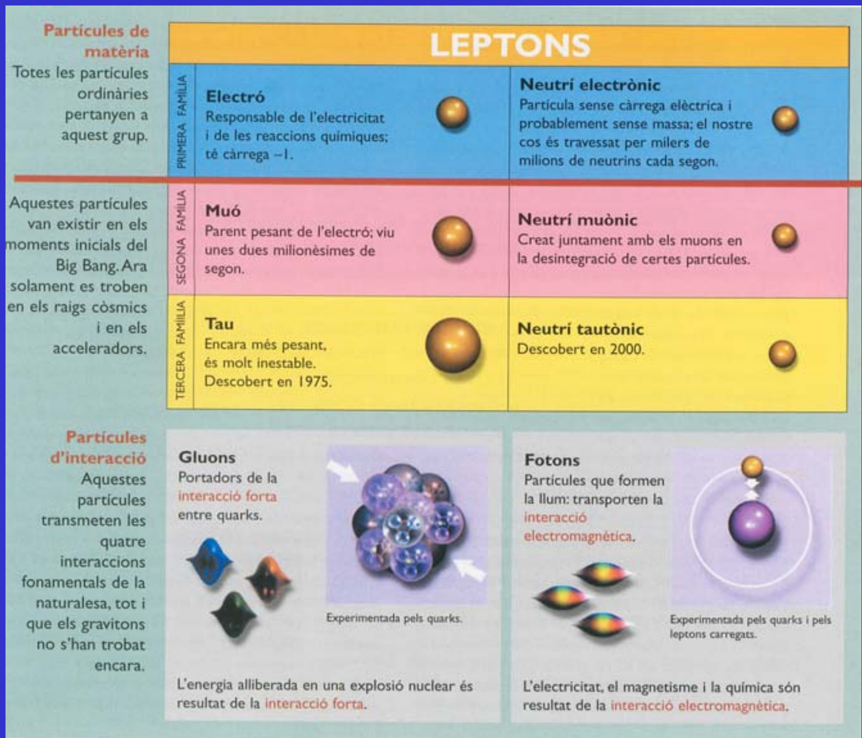
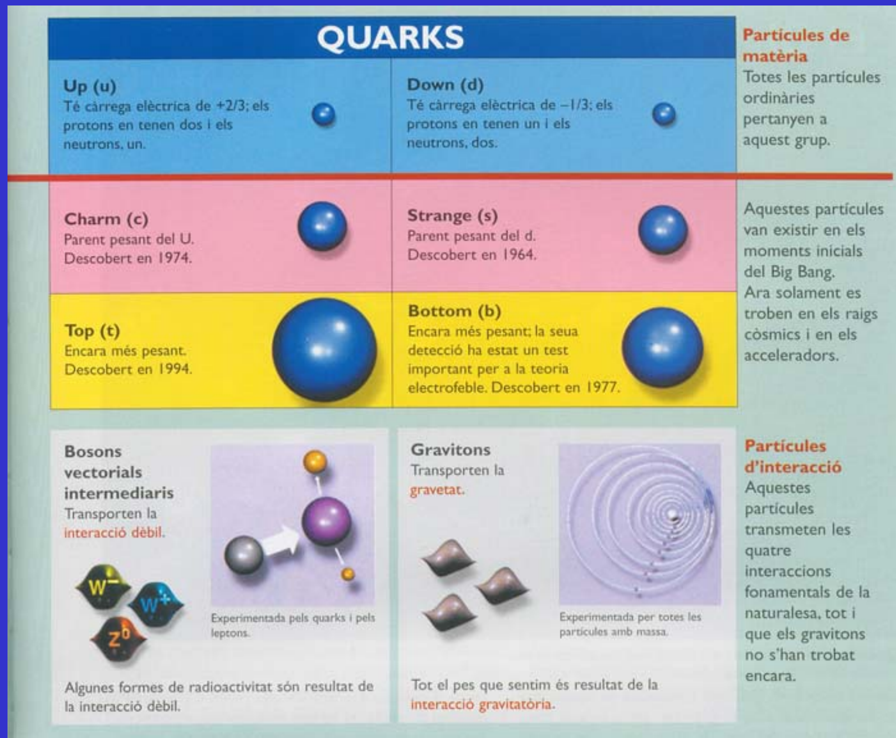
The elements of the Standard Model (SM)

The Table of elementary particles



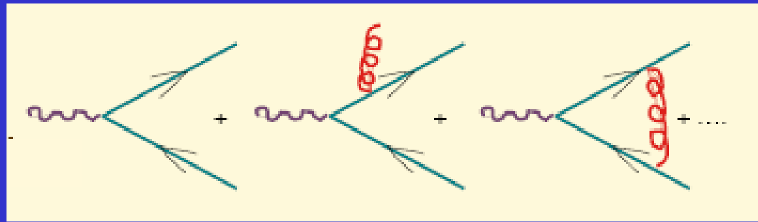




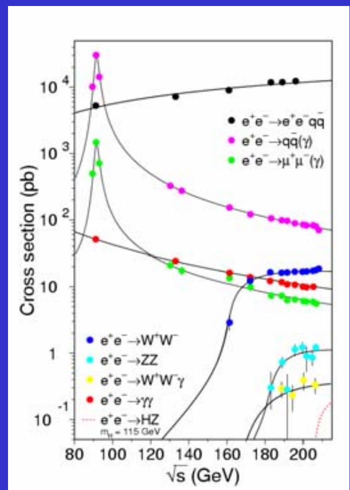
The Dynamics of the Standard Model (SM)

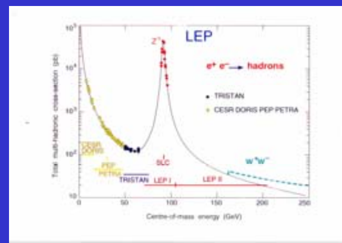
- Renormalizable Quantum Field Theory
- Gauge symmetry principle, with group structure SU(3)xSU(2)xU(1), confirmed by experimental evidence
- Reliable perturbation theory:

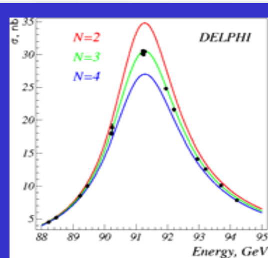
(Z ⟶ hadrons)



- Well tested:
  - U(1) sector to $1/10^8$
  - SU(2) sector to $1/10^3$
  - SU(3) sector to 1/10







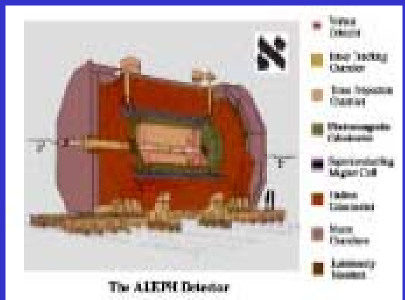
LEP & SLC Experiments

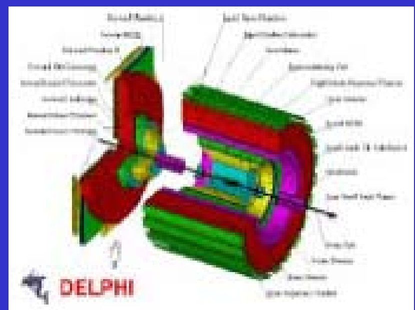
LEP1: (Aleph, Delphi, L3,Opal) 1989-1995, e+e- collisions Z pole ($1,7 \times 10^7$ Z events recorded)

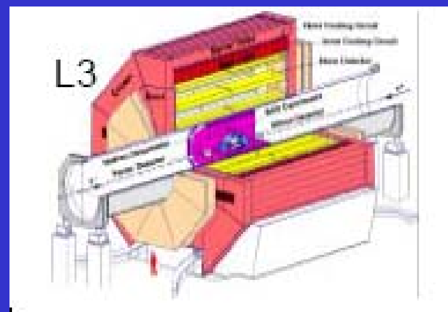
SLC: (SLD) 1992-1998, e+e- collisions on Z pole using polarized beam (6×10^5 Z events recorded)

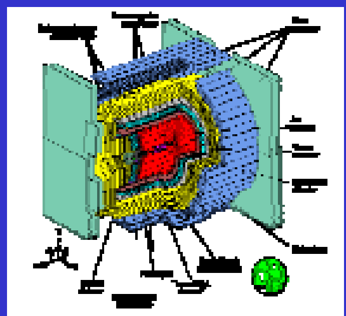
Final combined Z-pole results released September 2005

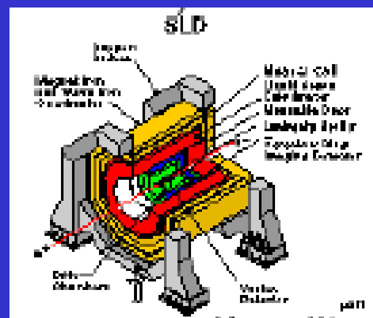
LEP2: (Aleph, Delphi, L3,Opal) 1996-2000, e+e- collisions at E_{cm}= 130 GeV – 209 GeV (4×10^4 WW events recorded)









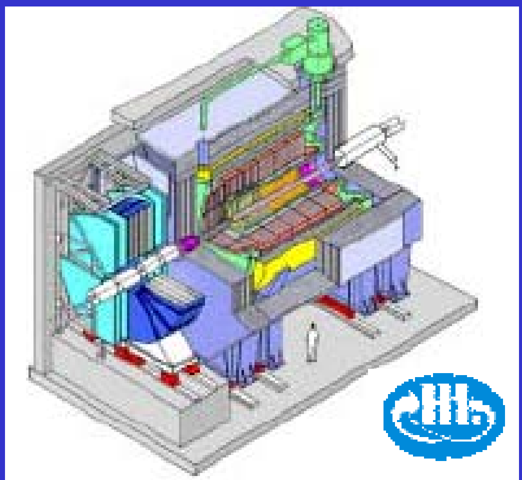


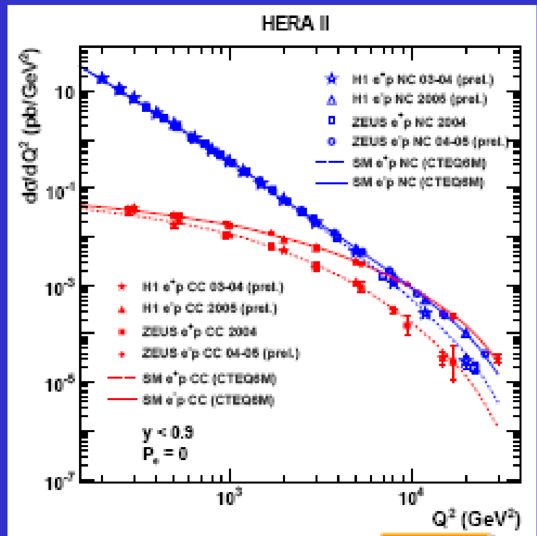
HERA Experiments

e±p collisions at Ecm= 318 GeV

HERA-I 1994-2000 (~100 pb^{-1})
HERA-II 2003-present

Polarized e± beams (left and right) ~10 pb^{-1} to ~80 pb^{-1} in each of the four configurations (taking polarized e^+ until mid 2007)



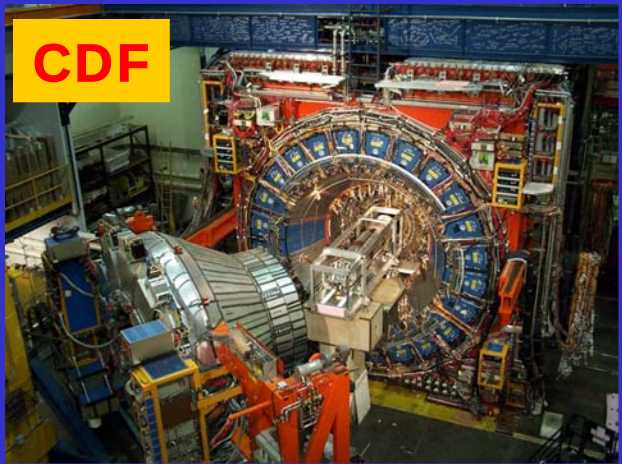


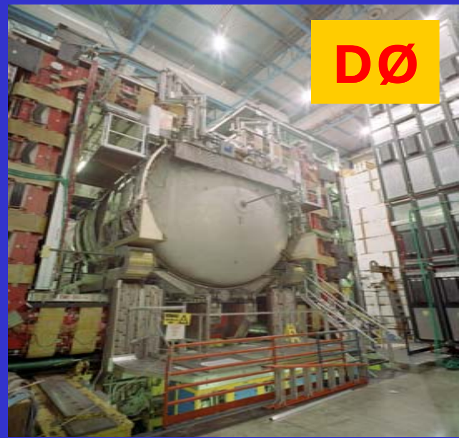
Tevatron Experiments

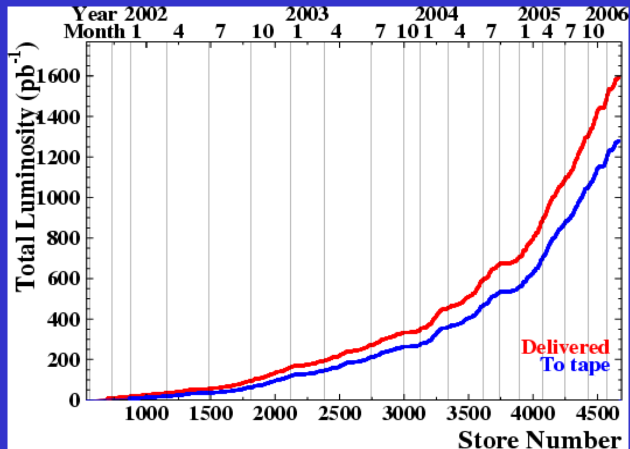
Proton-antiproton ⟶ W+X, Z+X, $t\bar{t}$+X (CDF,D0) (discovery of top)

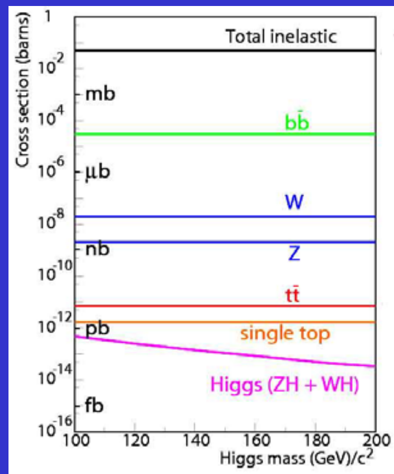
Run 1: 1992-1996, E_{cm}= 1,6 TeV, ~100 pb^{-1}/experiment

Run 2: 2003-present, E_{cm}= 1,96 TeV, >1 pb^{-1}/experiment so far







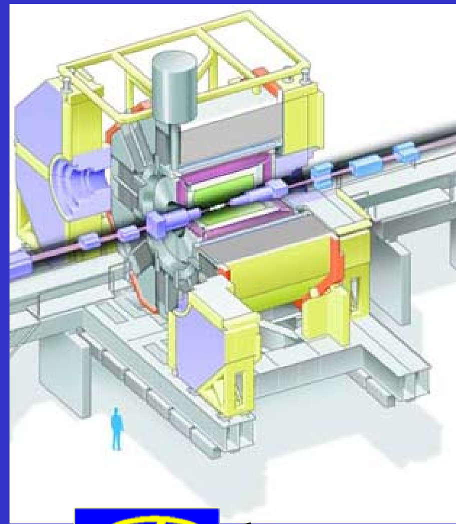


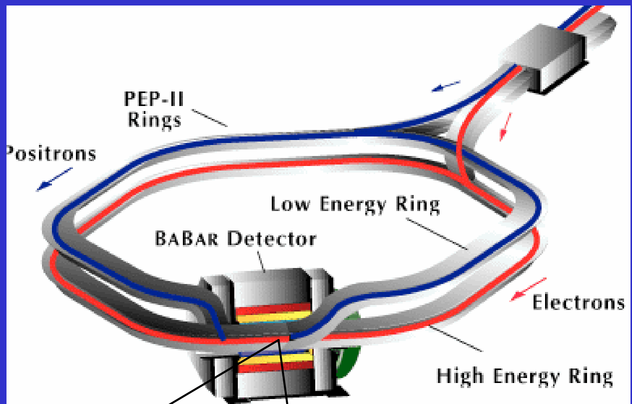
Two Asymmetric-energy *B* Factories

PEP-II at SLAC

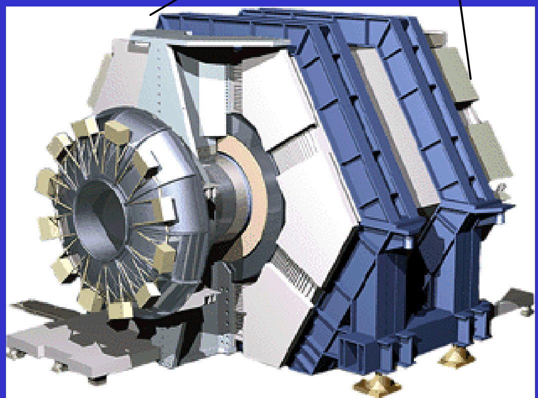
9GeV (e^-) $\times$ 3.1GeV (e^+)
peak luminosity:
$1.12 \times 10^{34} cm^{-2} s^{-1}$

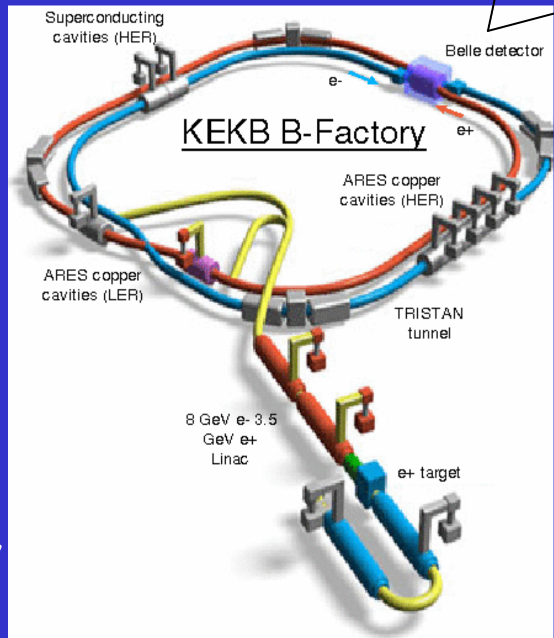
13 countries,
57 institutes,
~400 collaborators





BaBar





11 nations,
80 institutes,
623 persons

KEKB at KEK

8GeV (e^-) $\times$ 3.5GeV (e^+)
peak luminosity:
$1.65 \times 10^{34} cm^{-2} s^{-1}$

world record

High Energy and High Precision !!

Unique role of high energy hadron and lepton colliders:

They are two distinct and complementary strategies for gaining understanding of matter, space and time at colliders

High Energy (usualy hadron colliders)

- direct discovery of new phenomena

High Precision (usually lepton colliders)

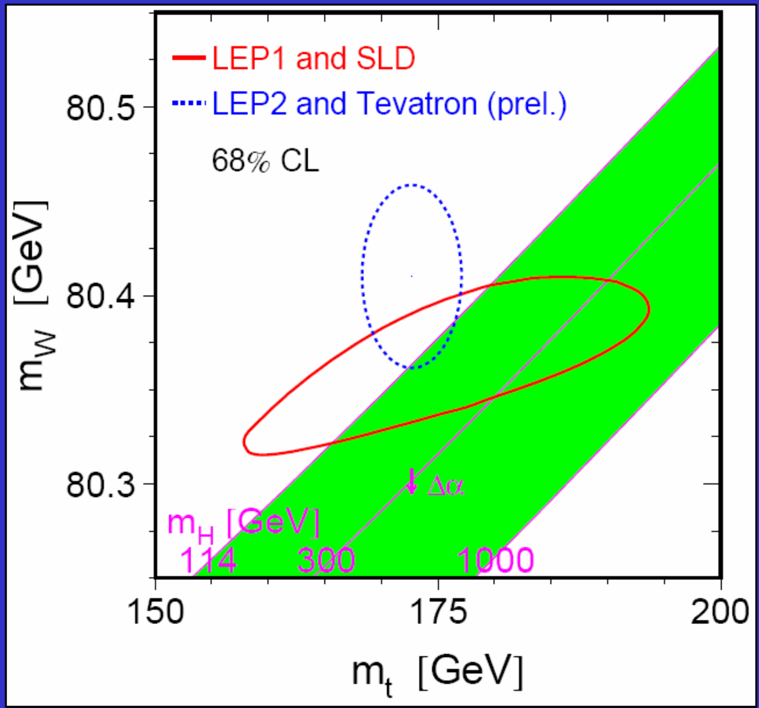
- quantum effects of new physics at high energies through
- precise measurements of phenomena at lower scales

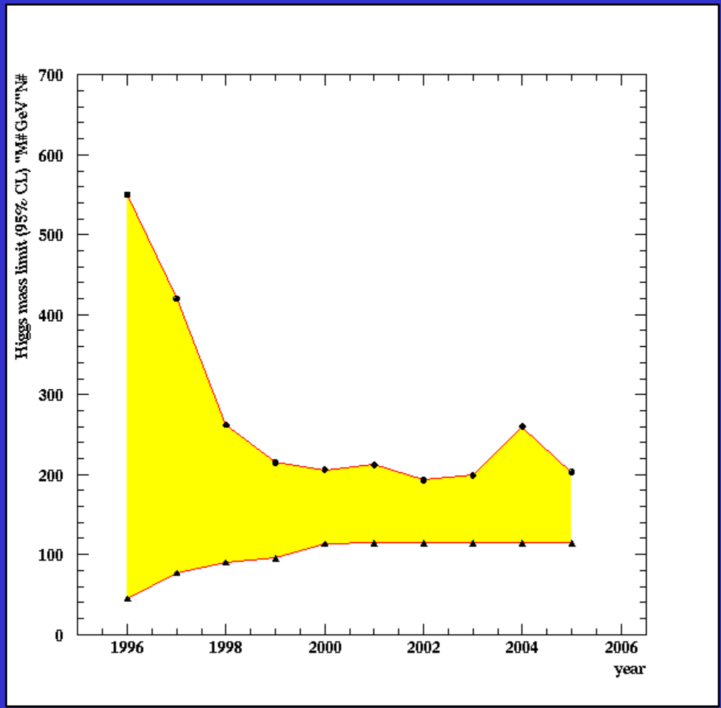
Both strategies have worked well together

"much more complete understanding than from either one alone"

Successful example: LEP+SLC / Tevatron

LEP/SLC-Tevatron, example of success





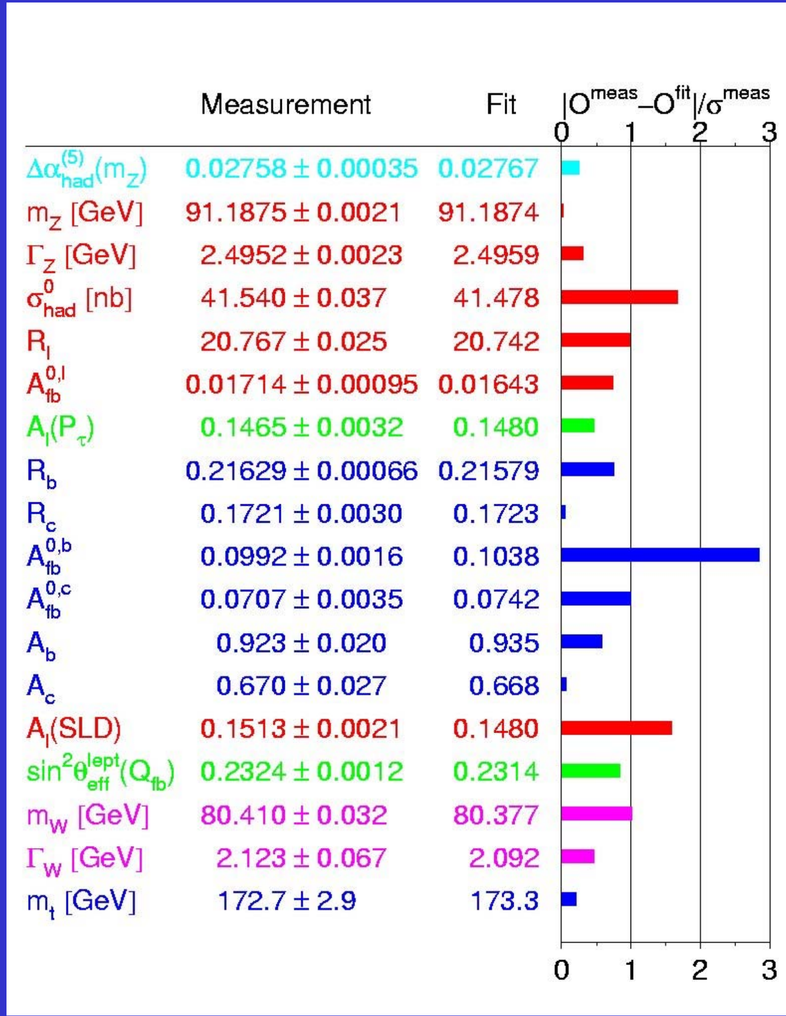
- Led to understanding the SM at the quantum level
- Possibility to predict phenomena at the TeV scale and beyond

Where do we stand today with SM ?

e^+e^- colliders LEP at CERN and SLC at SLAC and many other experiments (Tevatron, fixed target…….) have explored the energy range up to **~100 GeV** with high precision

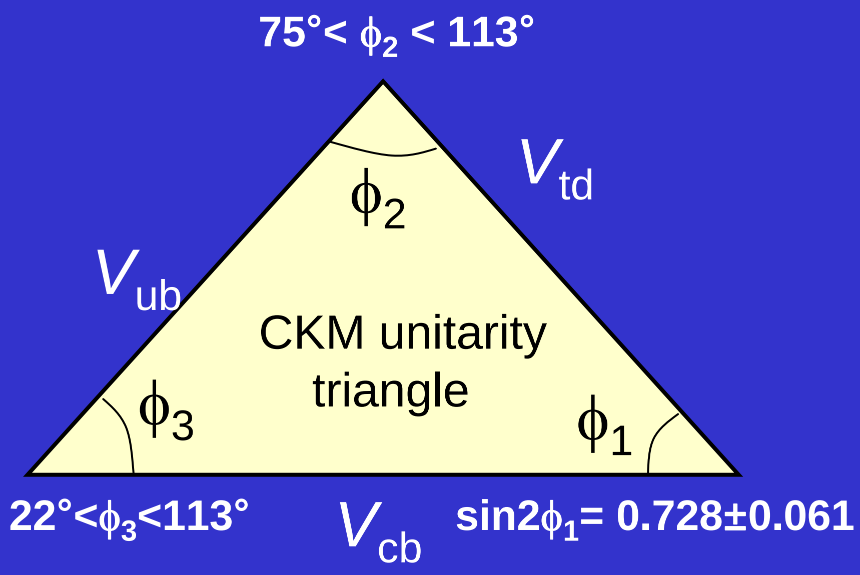
<u>Result:</u>

The Standard Model is consistent with all experimental data !
A Light Higgs boson is favoured
But no evidence for phenomena beyond the SM



Achievements of the *B* Factories

Quantitative confirmation of the CKM theory

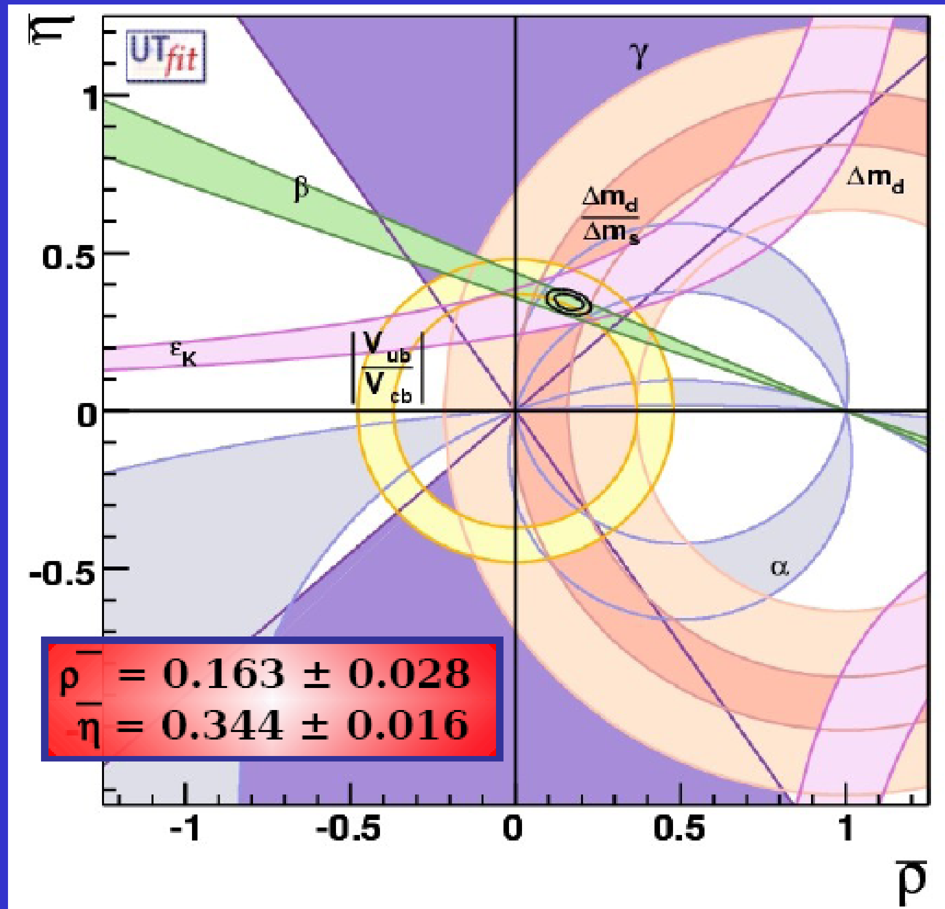


$|V_{cb}|=(4.08\pm0.27)\times10^{-2}$

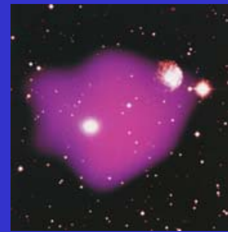
$|V_{td}/V_{ts}|= 0.200\pm0.046$

$|V_{ub}|=(4.35\pm0.52)\times10^{-3}$

$\Delta m_d=0.511 ps^{-1}$



What we don't understand yet, open questions



- Formal questions:
  - Why gauge theory ?
  - Are particles really pointlike ? strings ? membranes ?
- Phenomenological questions:

  1 - Why three families ? (flavour)

  2 - Why some particles have mass ? (EW-Symmetry Breaking)

  3 - Why m(neutrino) ~ 10^{-7} m(e) ? (flavour)

  4 - Why there is "such" asymmetry matter-antimatter in the Universe ?

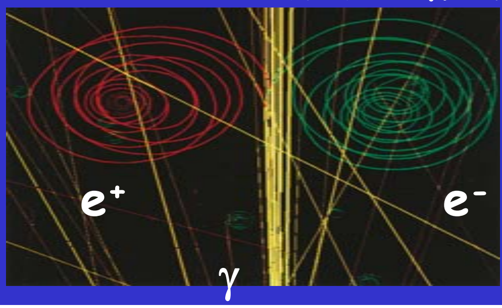
  (sources of CP violation)

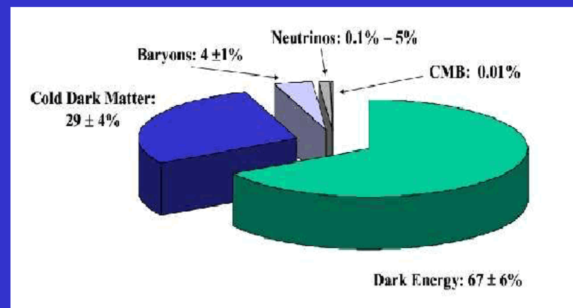
  5 - Origin and nature of dark matter (EW-Symmetry Breaking)

  6 - Why f(gravity) ~ 10^{-40} f(electric), are forces unified ? (EW-SB)

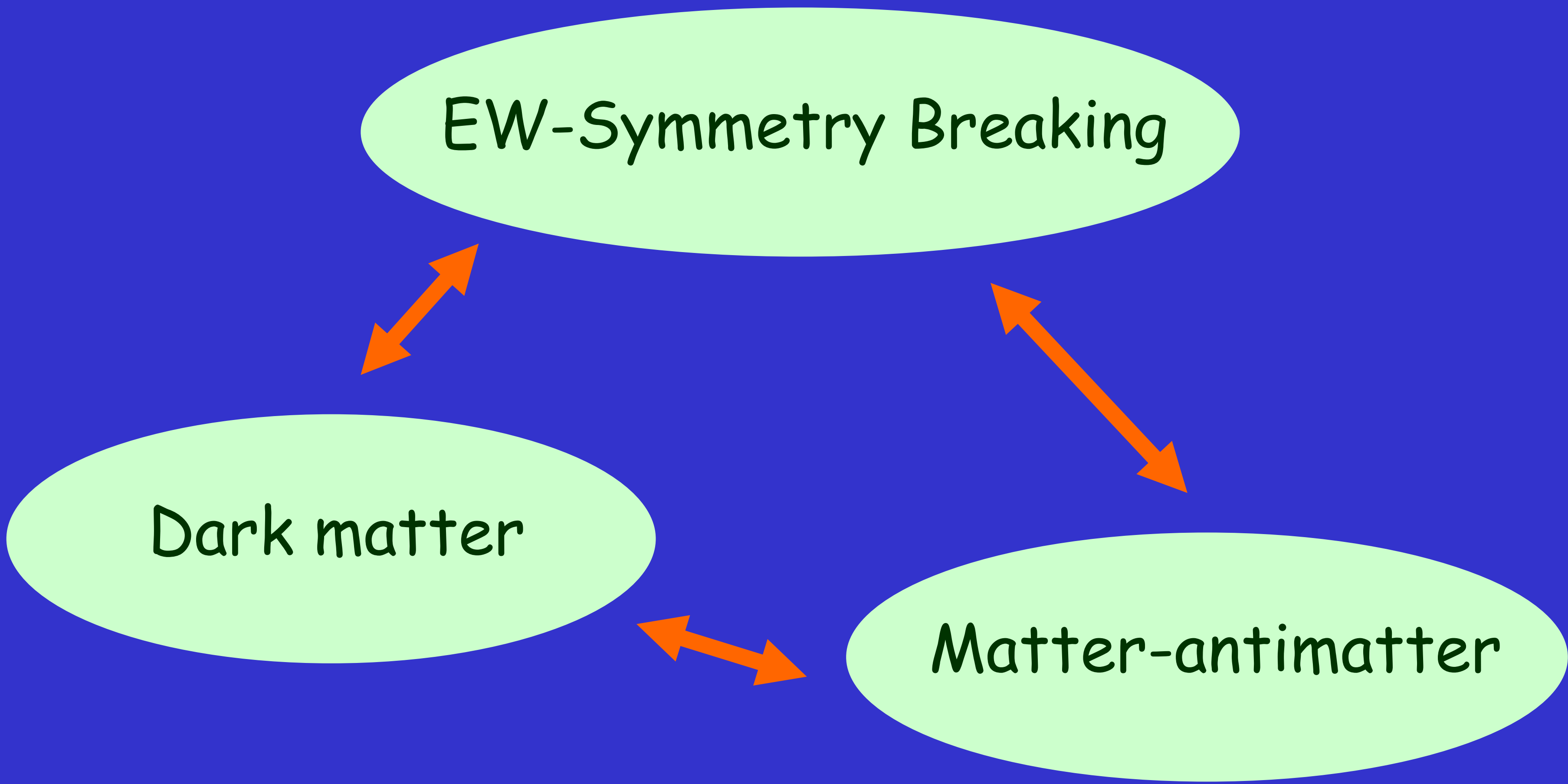
  7 - Why number ofdimension are D=3+1 ? (Quantum gravity,

  extra-dimensions)



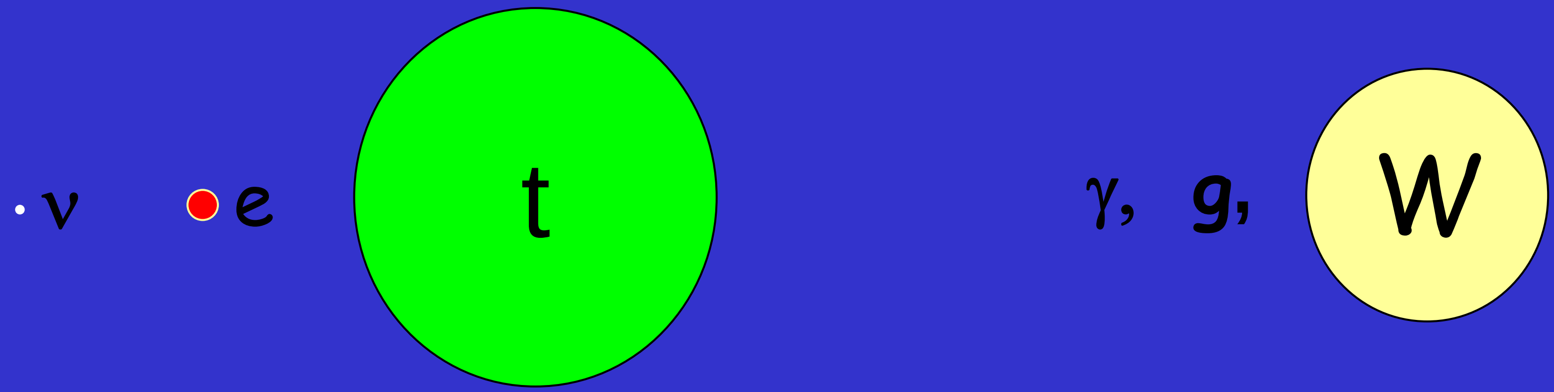


Three main topics, three main challenges to understand



EW-SB

What is the origin of mass ?



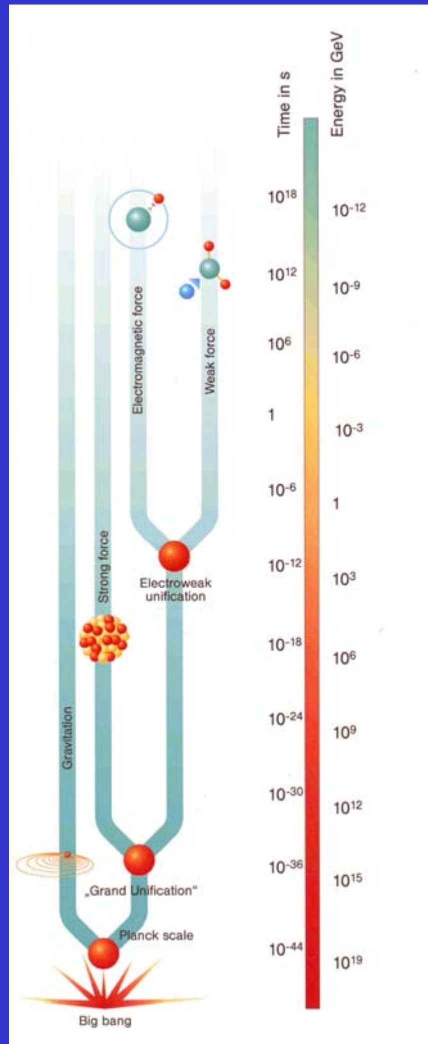
Does the Higgs particle exist as proposed by P. Higgs (1964) ?

All properties of the Higgs particle are known, once its mass is fixed.
Its mass is a free parameter in the Standard Model (though can be constraint by experiment and theory considerations)

EW-SB

Is there a universal force, a common origin of the different interactions ?

Impact in our current understanding of the origin of the Universe, the Big-bang?



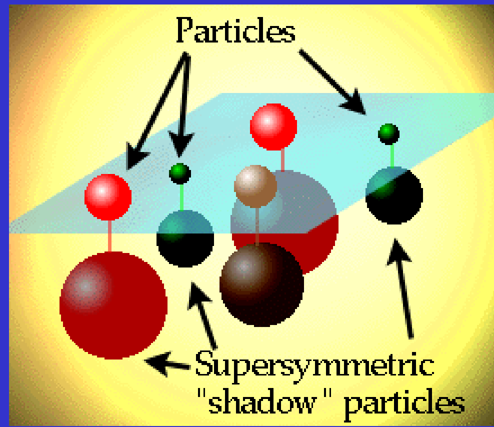
1962-1973: Glashow, Salam and Weinberg

Unification of the electromagnetic and weak interactions

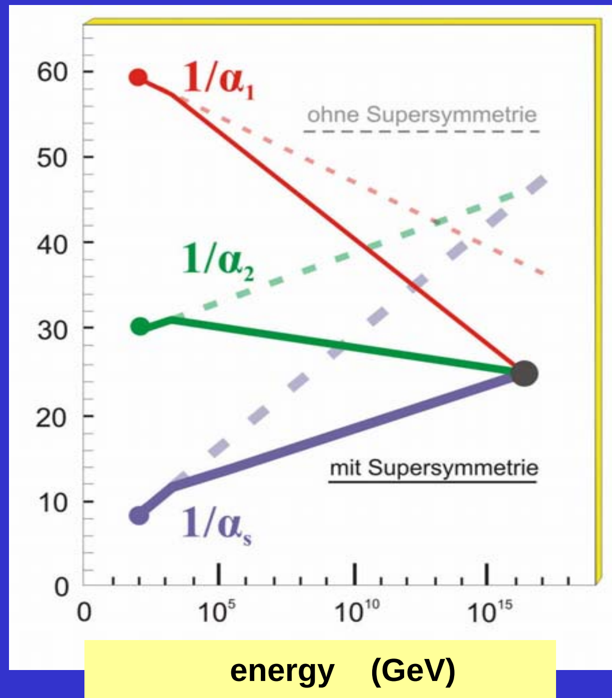
Higgs mechanism is a cornerstone of the model

EW-SB, dark matter, matter-antimatter

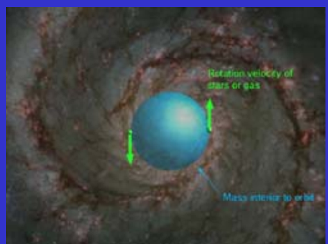
Are there new, yet unknown types of matter ?
Will we meet supersymmetry (SUSY) on the way towards unification ?

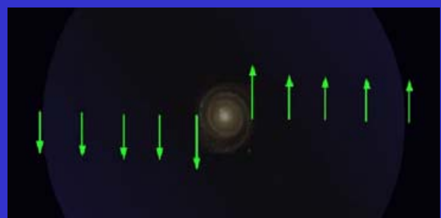


Quark	**Squark**
Top	**Stop**
Electron	**Selectron**
Wino	**W**
Higgsino	**H**



Motivation for SUSY:
(i) Unification of forces seems possible
(ii) Supersymmetry provides a candidate for dark matter in the universe





SUSY

?

Role of future accelerators and experiments

EW-SB

- Test of the Standard Model
- Search for the Higgs boson

EW-SB+Dark Matter

- Test of the Standard Model
- Search for other Physics Beyond the SM

Matter-antimmater

- B hadron masses and lifetimes
- Mixing of neutral B mesons
- CP violation

Two main actors in the coming years picture:

Search of Higgs and Top Physics

Why do we need the Higgs mechanism

1- To preserve renormalizability in the Standard Model (SM) while giving mass to the Z, W^+,W^- and their interactions.

2- Goldstone bosons appearing in the mechanism are eliminated (massless spin 0 bosons)

"From today's perspective, it may seem odd that so much attention was focused on the issue of renormalizability. Like general relativity, the old theory of weak interactions based on four fermion interactions could have been regarded as an effective quantum field theory which works perfectly well at sufficiently low energy and with the introduction of a few additional free parameters even allows the calculation of quantum corrections."

S. Weinberg, The making of Standard model
(CERN, 16 – Sept – 2003)

Is "renormalizability" just to please theory ?

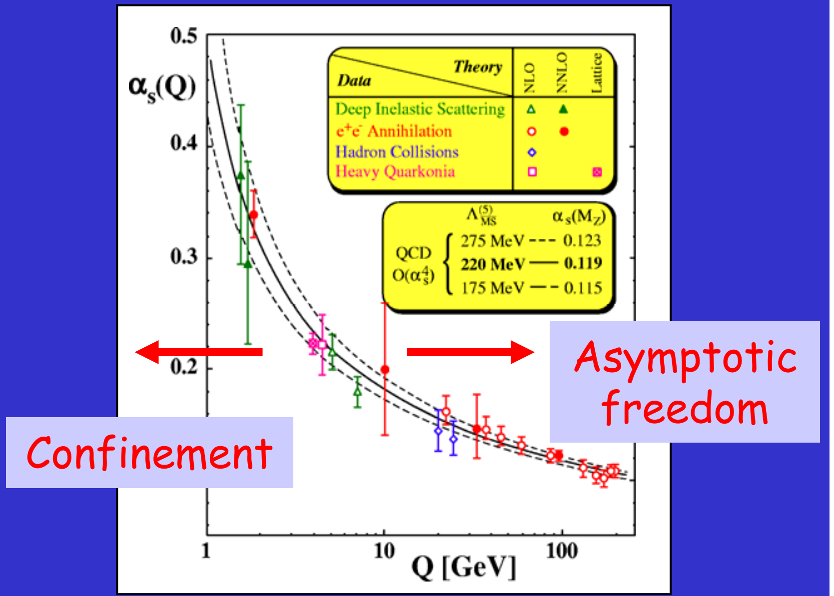
Strong coupling constant

$$\alpha_s(Q) = \frac{\alpha_s(\mu)}{1 + \alpha_s(\mu)\beta_0 \log(Q^2/\mu^2)}$$

$$\alpha_s(Q) = \frac{1}{\beta_0 \log \frac{Q^2}{\Lambda^2}}$$

$\beta_0 > 0 \Leftrightarrow n_f \leq 16$

It has been observed experimentally!

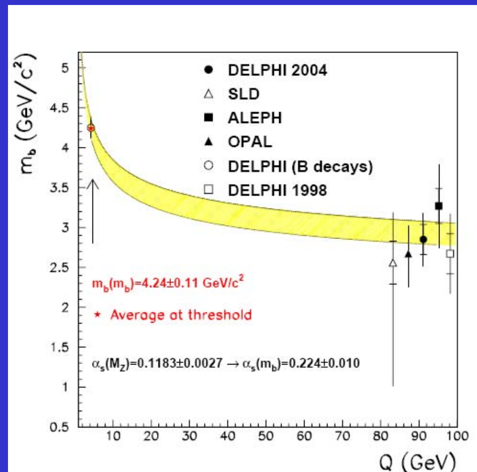


Quark masses

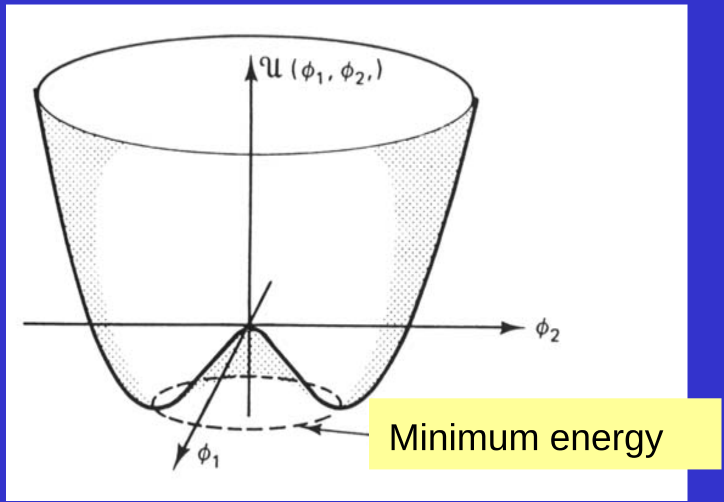
$$m_q(Q) = m_q(\mu)\left[1 + \alpha_s(\mu)\beta_0 \log(Q^2/\mu^2)\right]^{-\gamma_0/\beta_0}$$

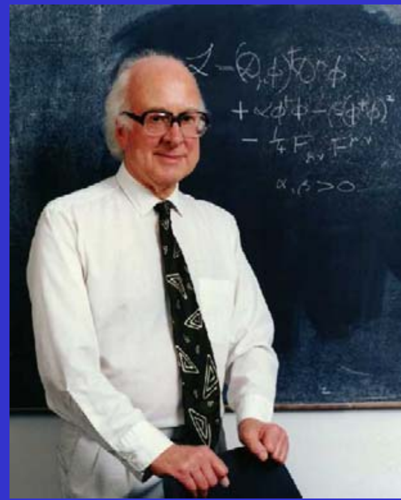
$\gamma(\alpha_s)/\beta(\alpha_s) > 0 \Rightarrow m_q\,(Q)$ decreases at higher energies.

It has also been observed experimentally!



Search for the Higgs boson

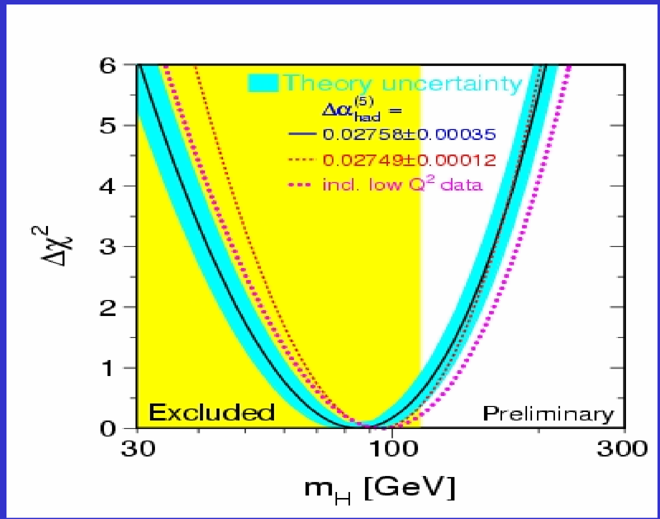




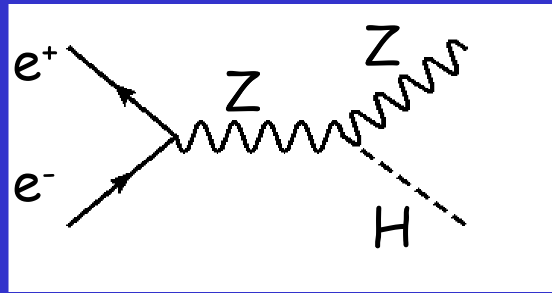
- Revealing the physical mechanism that is responsible for the breaking of electroweak symmetry is one of the key problems in particle physics

- The LHC & ILC must have the potential to detect this particle, if it exists

What have we learned of the SM Higgs ?

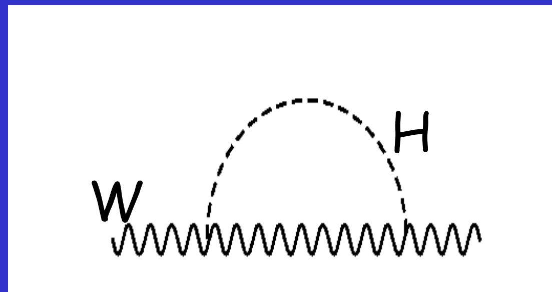


M_H = 85 (+39) (-28) GeV/c^2



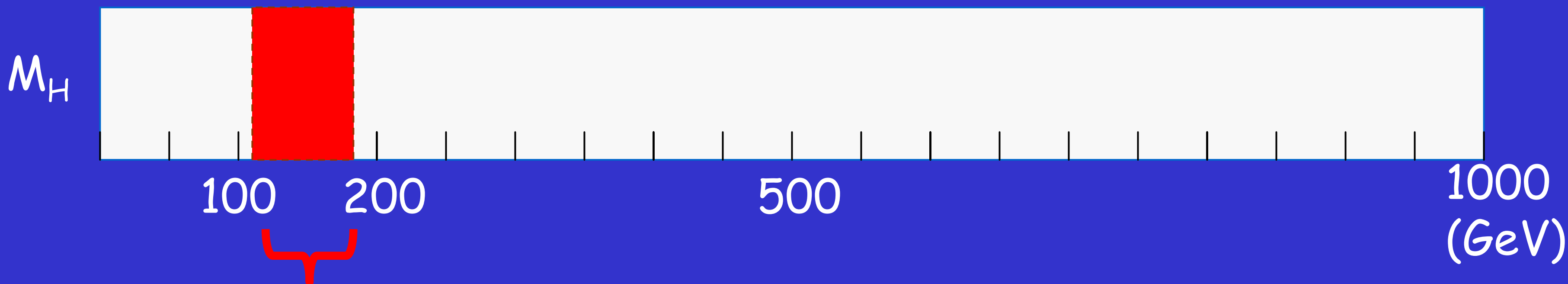
Direct Search

$M_H > 114$ GeV/c^2



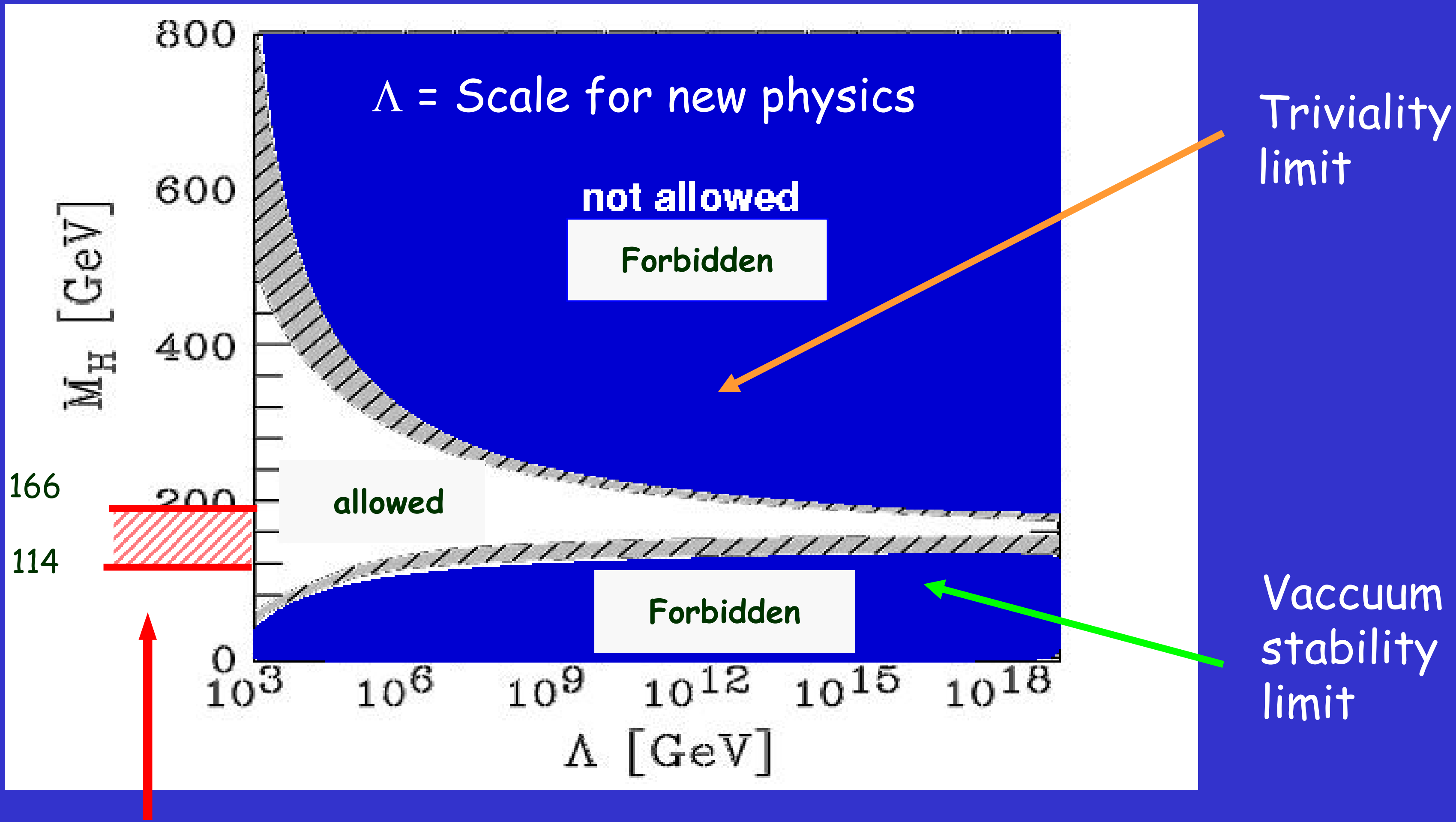
Higher order corrections

$M_H < 166$ GeV/c^2
(95% CL)



The only open window for the SM Higgs

Estimating the scale of new physics using radiative corrections in the SM

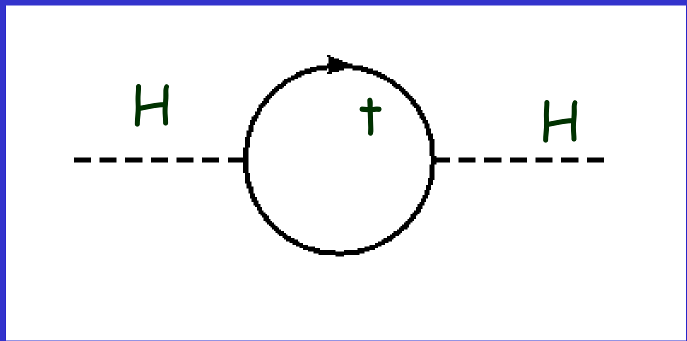


Allowed region from data

Λ can be almost any value !! in particular very large

However...Λ.. is either small or "fine tunning"

One "loop" corrections to the Higgs mass



$$m_H^2 = \underbrace{m_H^2(0)}_{\text{Bare mass}} + \underbrace{\delta m_H^2}_{\text{One loop correction}}$$

Λ = Scale for new physics beyond the SM

$$\delta m_H^2 = \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim (115\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$

m_H is small therefore $m_H(0)$ and δm_H have to be of the same order or "fine tunning" is needed

No "fine tunning" → $\Lambda \approx$ 400 GeV

No real contradiction but..

SuperSymmetric Higgs: Light Higgs prediction

- MSSM = Minimal SuperSimmetictric Model
- Higgs Sector = H A h (neutral) H^+ H^- (charged)

  h, H = scalar
  A = pseudoscalar

- Mass relation : $m_H < m_A < m_h$
- Tree level: $m_H^2 < M_Z^2 \cos 2\beta < M_Z^2$

  Free parameters = m_A, $\tan \beta$

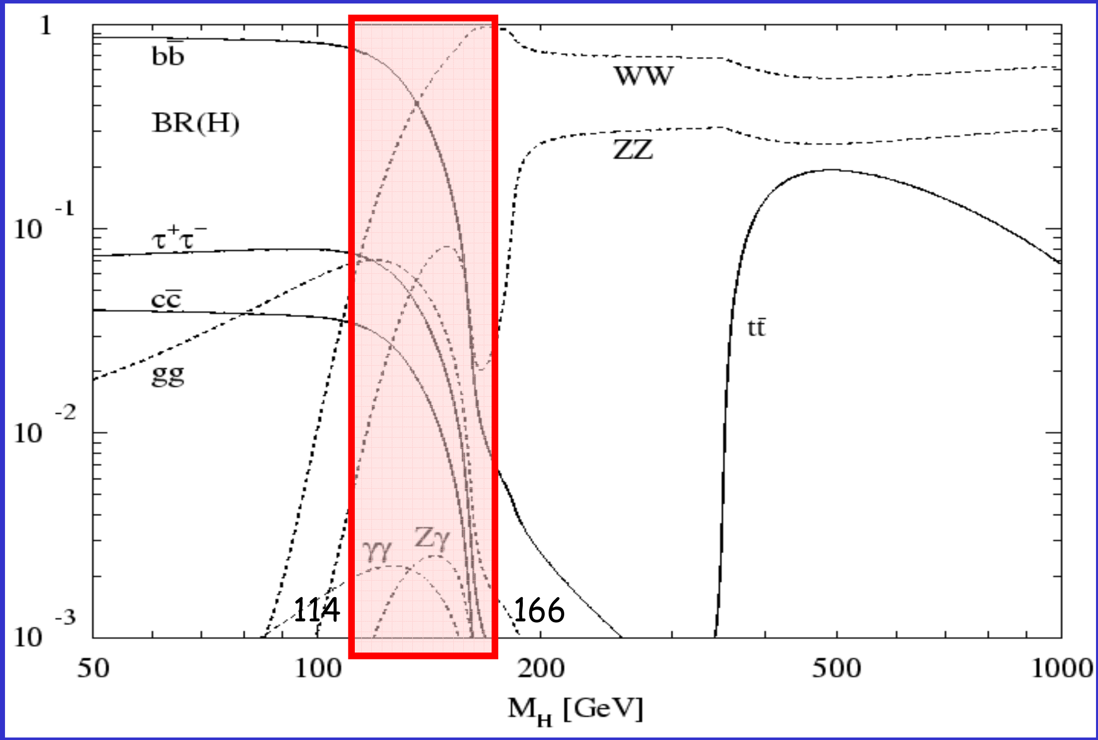
In "natural" SUSY
no fine tunning problem
But at least one Higgs
needs to be light

- Higher order: $m_h^2 < M_Z^2 \cos 2\beta + \varepsilon(M_s, M_2, \mu, X_t, m_g)$

  New free parameters $\rightarrow$ many different scenarios

LEP limit: $m_H > 91$ GeV/c^2

SM Higgs decay



Example
m_h = 140 GeV

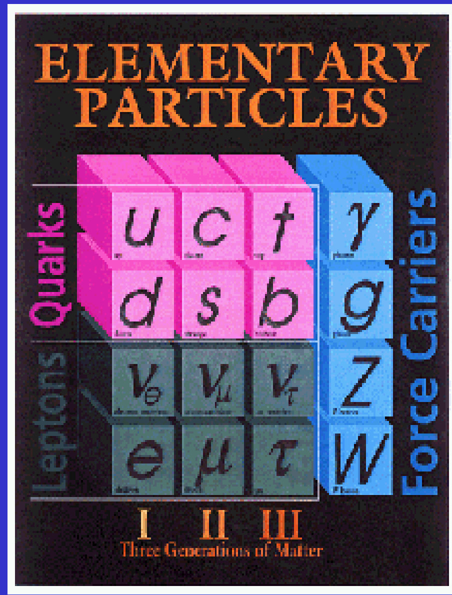
decay	BR(%)
W W*	50
b b	33
Z Z*	6
g g	6
τ τ	4
c c	1
γ γ	0.2

Very unlucky, the SM Higgs seems to be in the most difficult place,

- complicated final state topologies !!!
- is there any reason behind ?

The other actor: the top

- ✓ The top quark completes the three family structure of the SM
- ✓ It´s massive, "very heavy" — Δm_t ~ 2,1 GeV (CDF+D0)
- ✓ Spin=1/2 — Not directly
- ✓ Charge=+2/3 — -4/3 excluded @ 94% C.L.(D0)
- ✓ Isospin=+1/2 — Not directly
- ✓ $t \rightarrow bW$ — ~100%
- ✓ Large Γ=1.42 GeV (m_b,M_W,a_s,EW corr.)
- ✓ Short lifetime — $c\tau$<53μm @ 95%C.L.(CDF)
- ✓ Couplings: a_t,v_t V_{td} ,V_{ts},V_{tb}, g_{ttH} — not yet measured, ΔV_{tb} ~ 11%



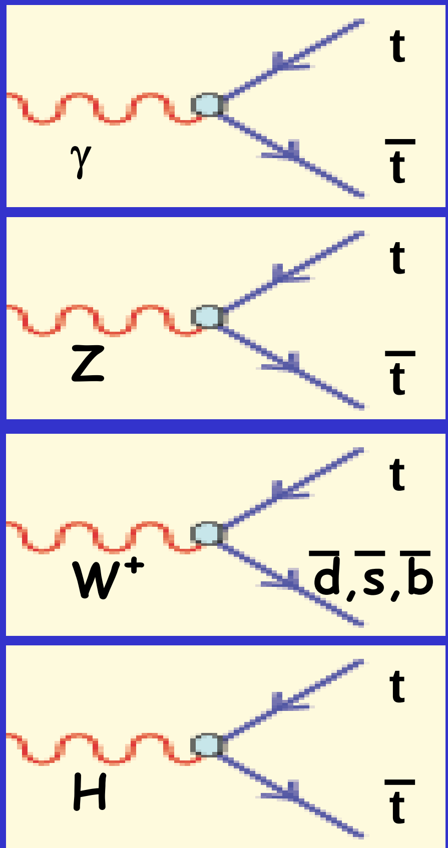
$$\tau_{had} = L_{QCD}^{-1} > \tau_{decay}$$

→ "t-quarks are produced and decay as free particles"

NO top hadrons

Accurate measurements of SM-top parameters:

Top couplings



q_t = +2/3 |e|

Natural in e+e-

a_t , v_t

V_{td} , V_{ts} , V_{tb}

g_{ttH} ,

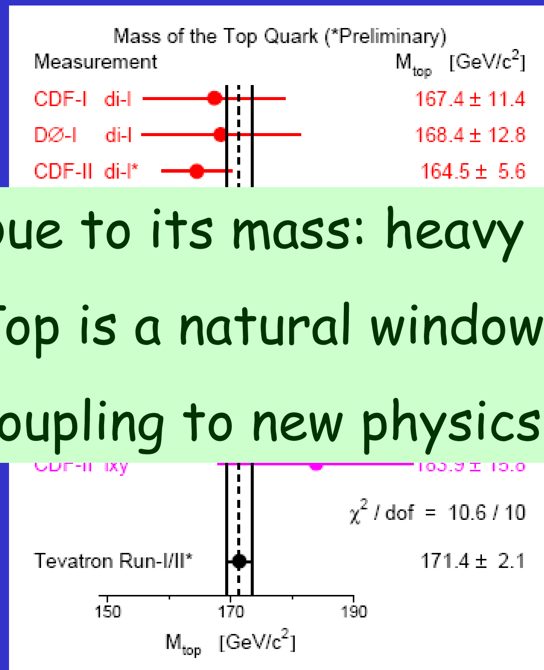
top Yukawa Coupling

σ_{tt} ($e^+e^- \longrightarrow tt$)

Γ_{tt}

m_t (1‰) at ILC

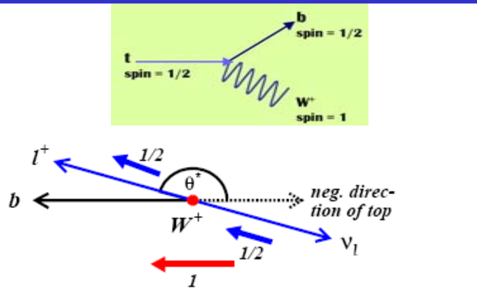
(at threshold and above)



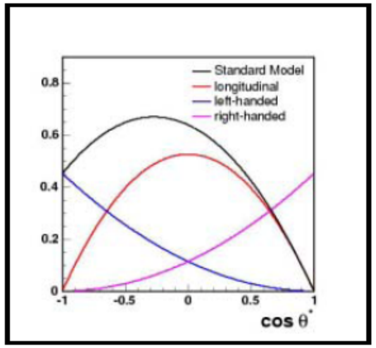
Due to its mass: heavy Top is a natural window coupling to new physics

Accurate measurements of SM-top parameters:

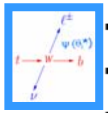
Polarizations and Asymmetries



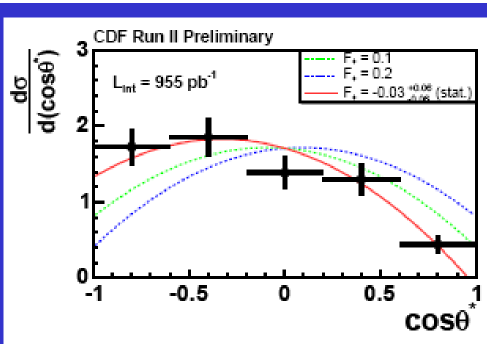
$$\frac{1}{N}\frac{dN}{d\cos\Psi} = \frac{3}{2}\left[F_0\left(\frac{\sin\Psi}{\sqrt{2}}\right)^2 + F_L\left(\frac{1-\cos\Psi}{2}\right)^2 + F_R\left(\frac{1+\cos\Psi}{2}\right)^2\right]$$

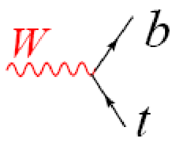


SM prediction of helicity fractions (assuming M_t=175GeV):



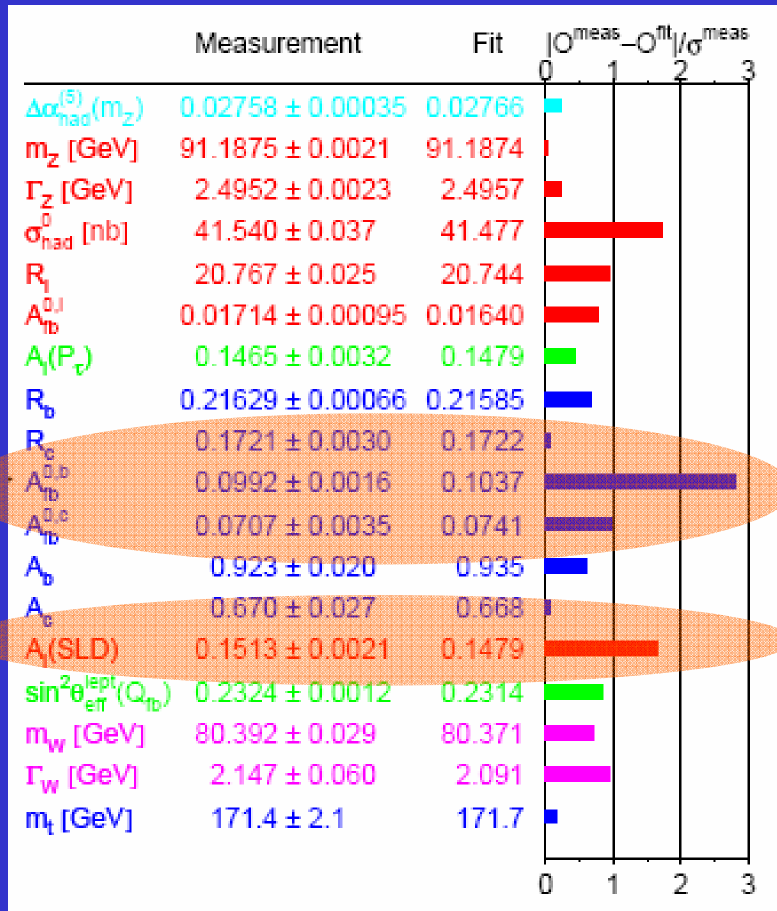
- SM(LO): F_0=0.703 , F_L=0.297 , F_R=3.6x10^{-4}
- (NLO): F_0=0.695 , F_L=0.304 , F_R=0.001





	F_0	F_R
CDF (~700 pb^{-1}) [prelim]		-0.02±0.07
CDF (955 pb^{-1}) [prelim]	0.61±0.12(stat)±0.04(syst)	-0.06±0.06(stat)±0.03(syst)
CDF (955 pb^{-1}) [prelim]	0.59±0.12(stat)$^{+0.07}_{-0.06}$(syst)	-0.03±0.06(stat)$^{+0.04}_{-0.03}$(syst)
DØ (370 pb^{-1}) [prelim]		0.08±0.08(stat)±0.05(syst)

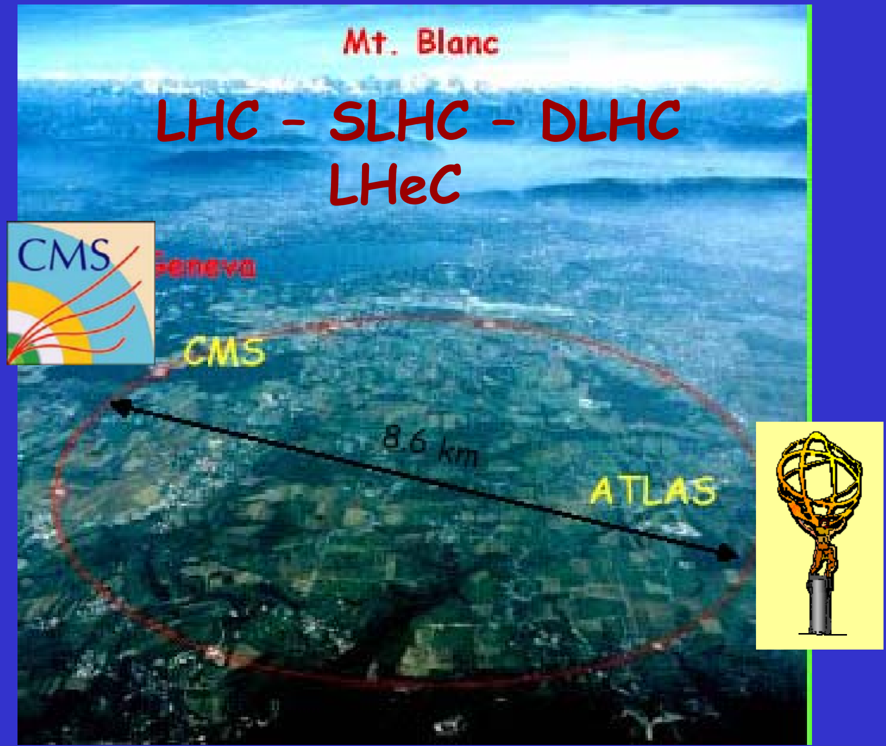
Darien Wood, ICHEP'06, "Electroweak Physics"

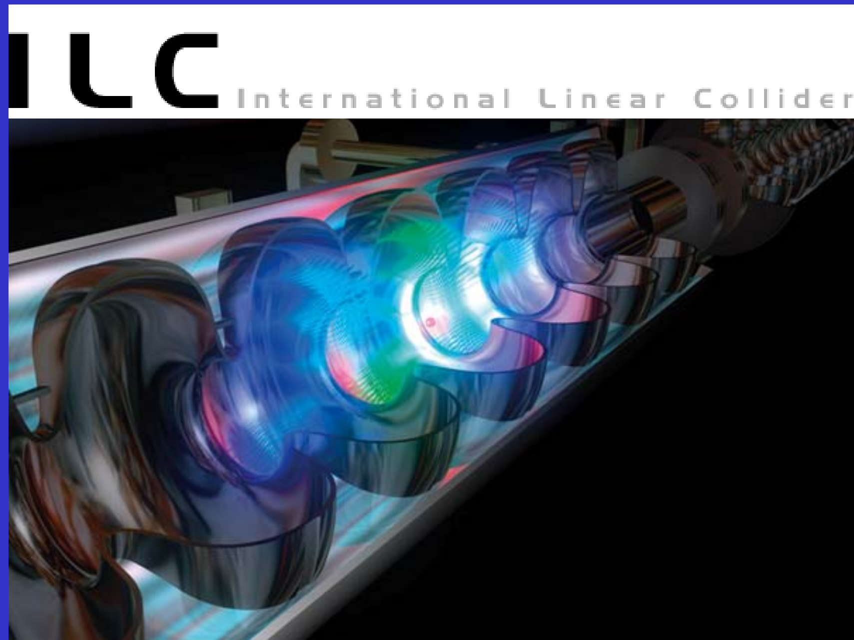


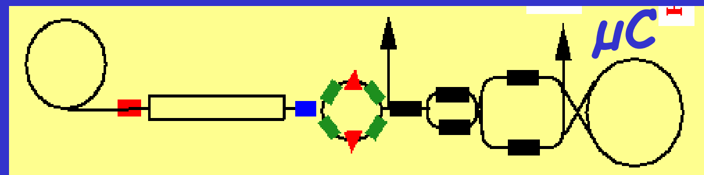
Asymmetries of heavy fermions are the most problematic

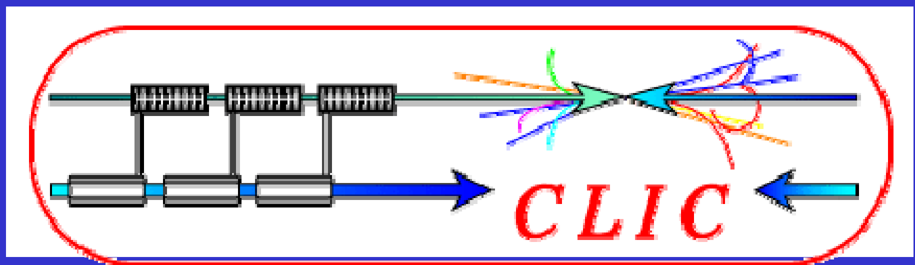
What will happen with top ?

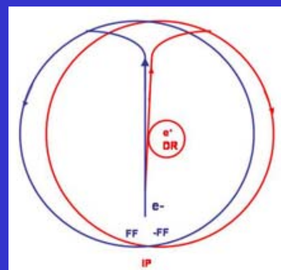
Which will be the tools ? The accelerators











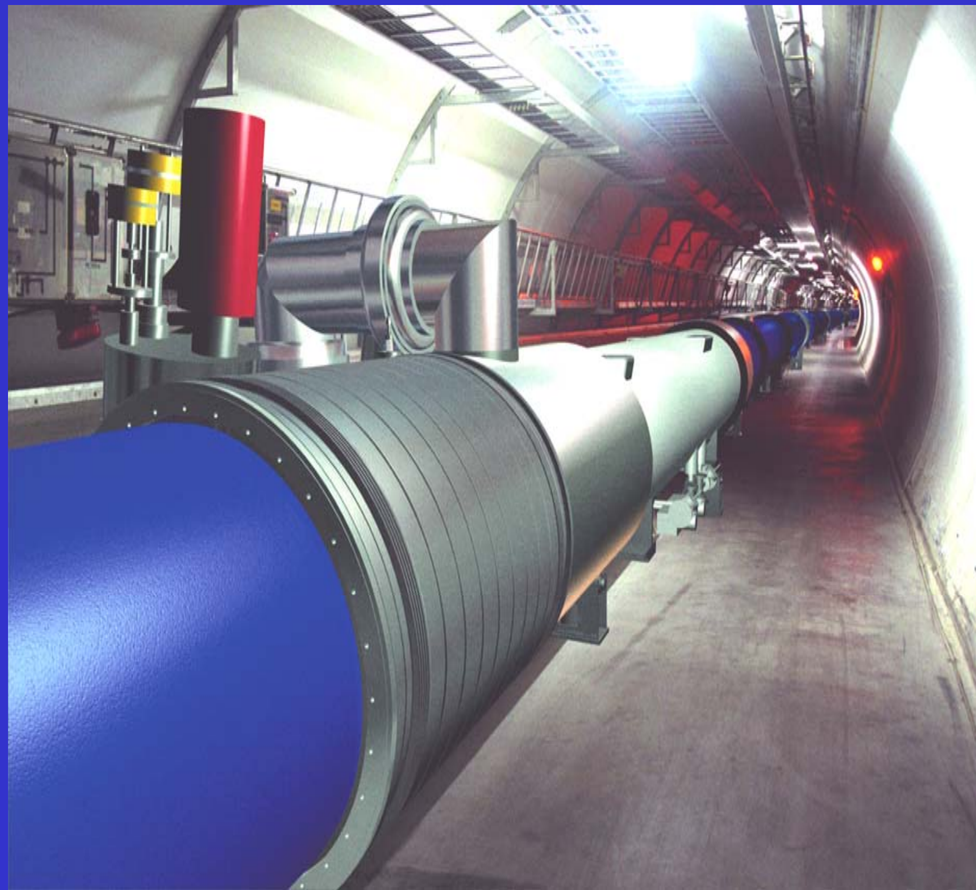
SuperB

The Large Hadron Collider

Protón-Protón Collider

7 TeV + 7 TeV

Luminosity = $10^{34} cm^{-2} s^{-1}$



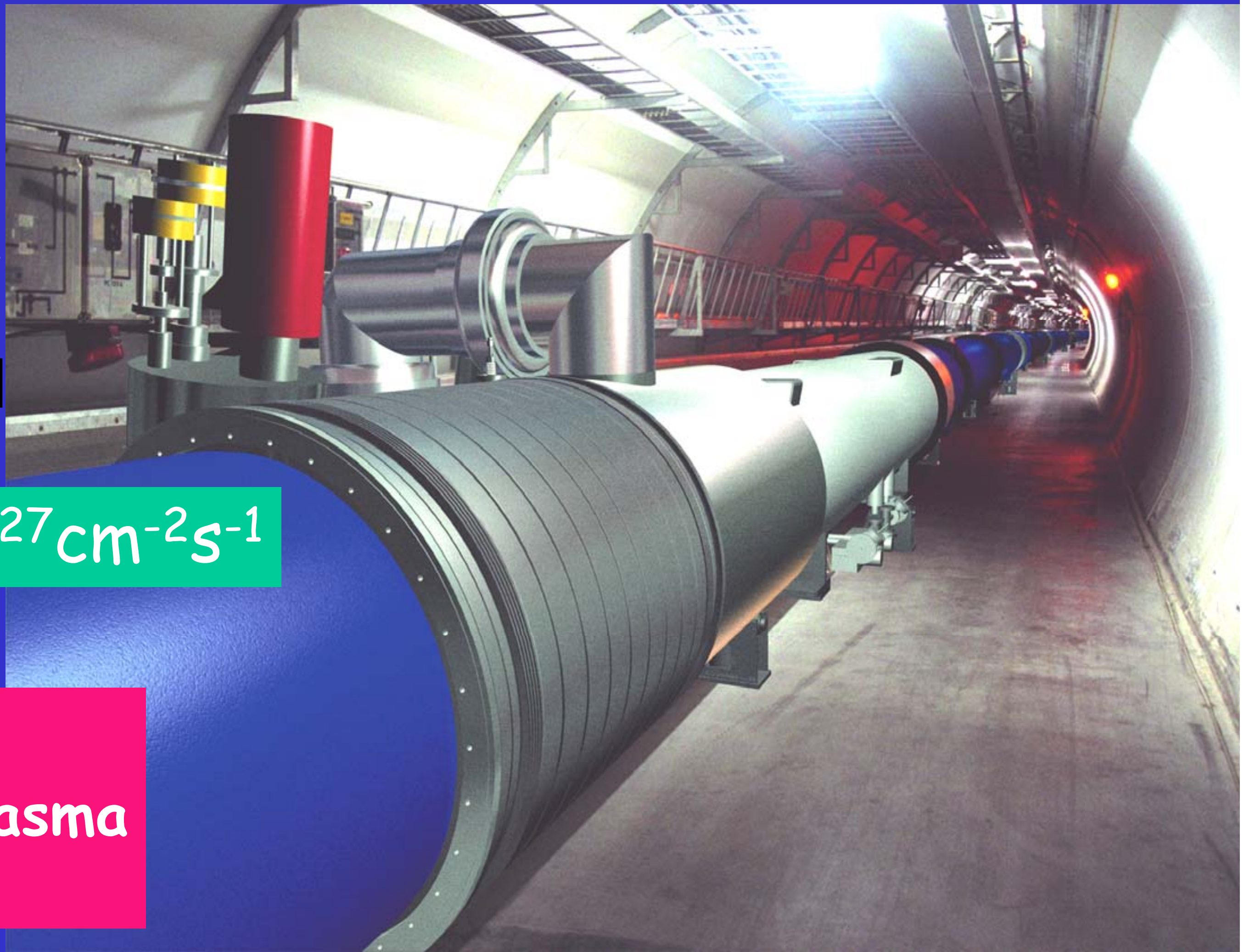
Physics Goals:

- Origin of mass
- Dark matter
- Matter vs Antimatter

(ATLAS, CMS, LHC-B)

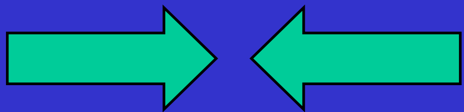
1 TeV = 1000 GeV
~ 1000 times the proton mass

The Large Hadron Collider



Pb-Pb collisions

7 TeV +7 TeV

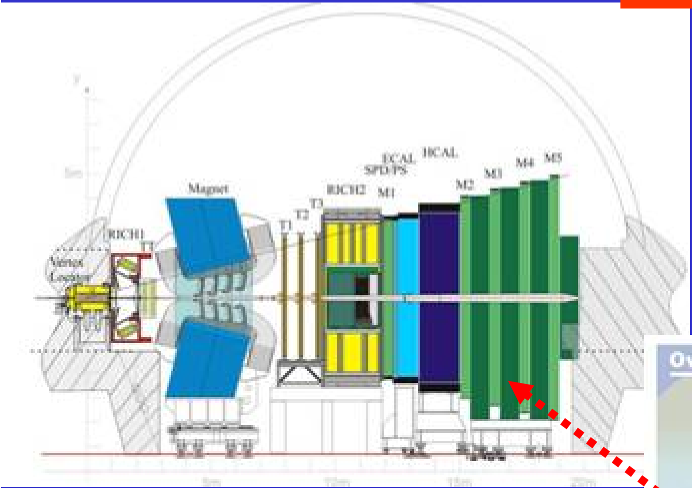


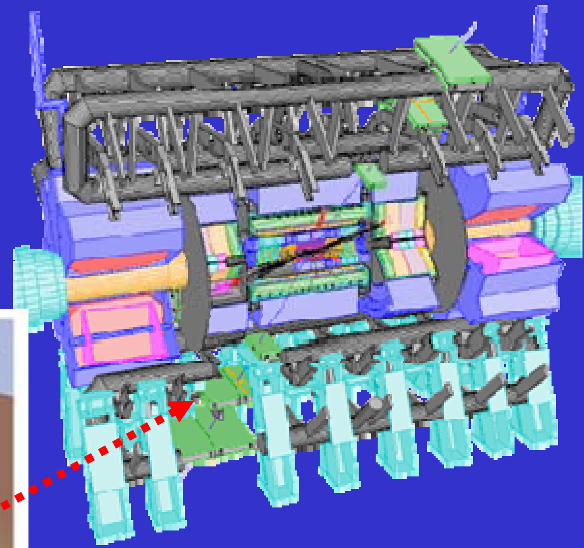
Luminosity = $10^{27} cm^{-2} s^{-1}$

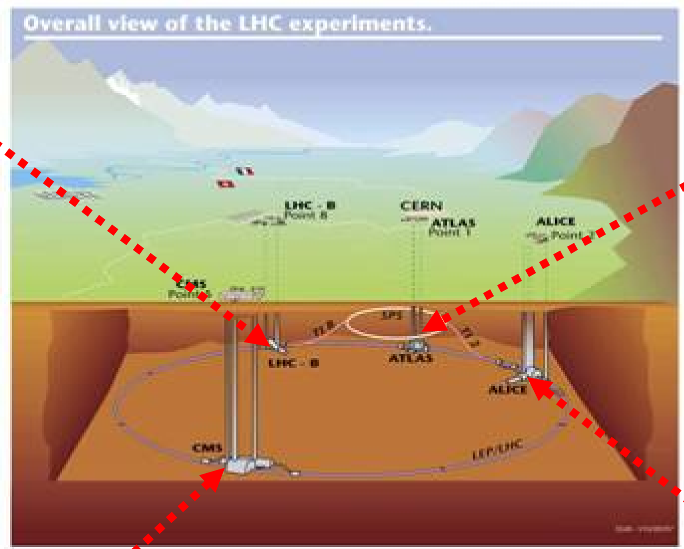
Physics goal:

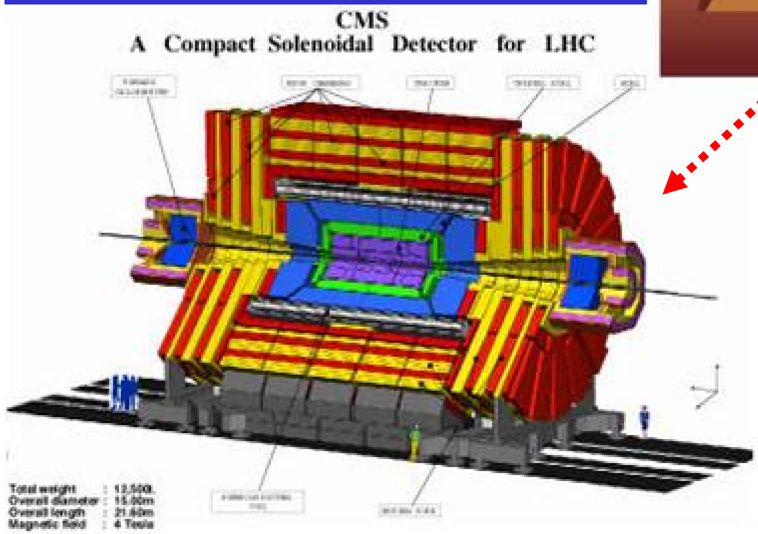
- Quark-gluon plasma (ALICE)

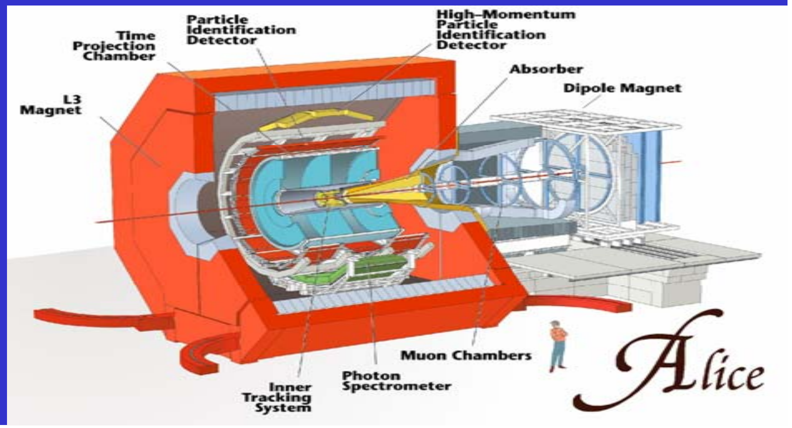
The LHC experiments











J. Fuster

The LHC computing

40 MHz (1000 TB/sec)

Level 1 - Special Hardware

75 KHz (75 GB/sec)

Level 2 - Embedded Processors

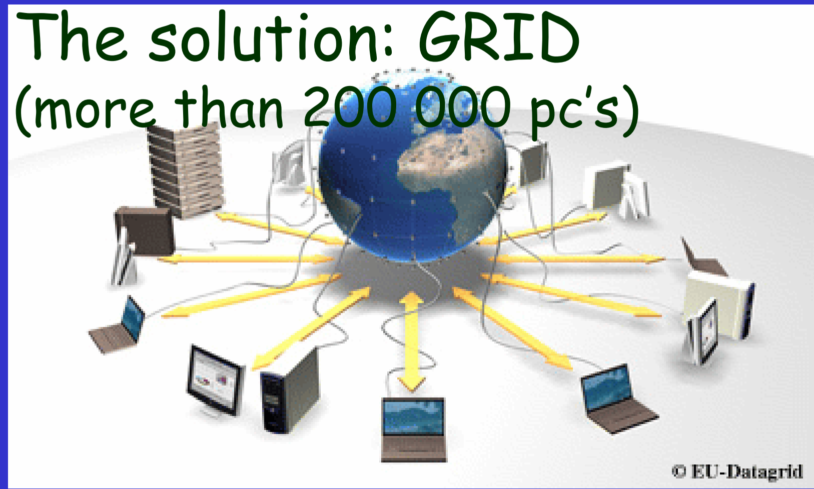
5 KHz (5 GB/sec)

Level 3 - Farm of CPUs

100 Hz (100 MB/sec)

100 MB/sec ~ 2 Petabytes/year

(1 PB = 10^3 TB = 10^6 GB)



Data Recording, Reconstruction, & Offline Analysis

Spanish participation in LHC experimetns

ATLAS

IFAE (Barcelona)
CNM (Barcelona)
IFIC (Valencia)
UAM (Madrid)

CMS

CIEMAT (Madrid)
IFCA (Santander)
UAM (Madrid)

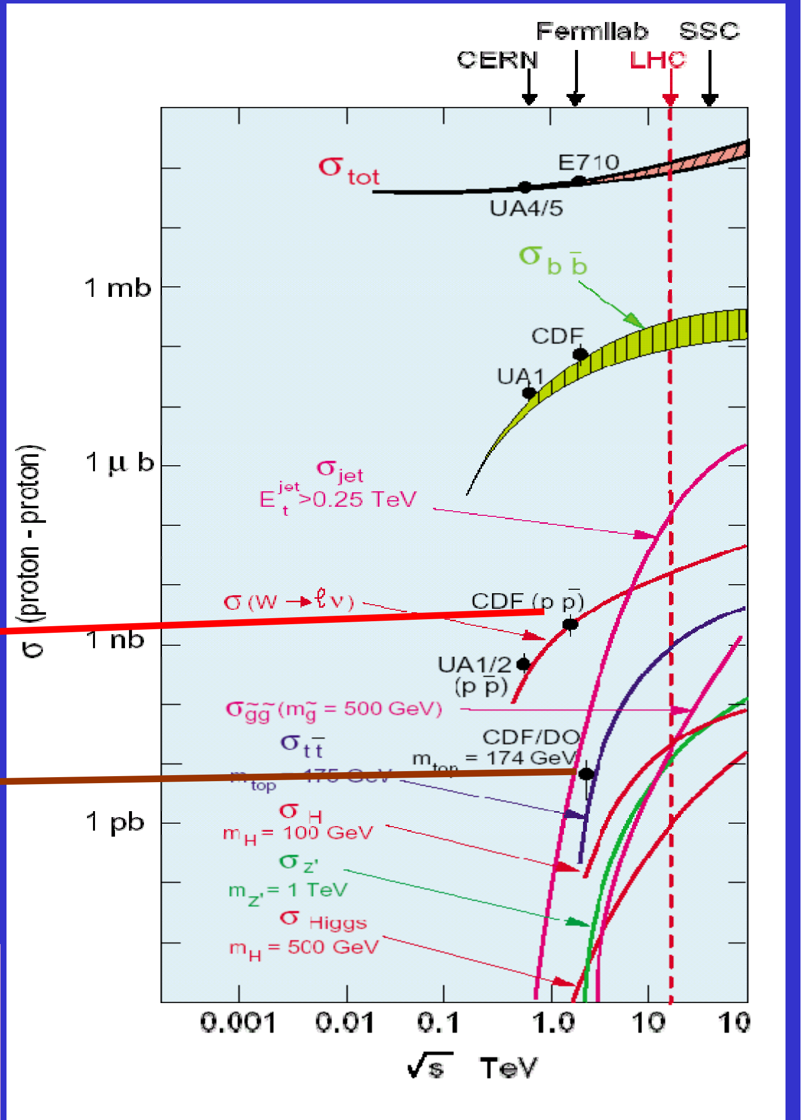
LHCb

UB (Barcelona)
USC (Santiago)

Cross sections and processes at LHC

	E_{CM} TeV	Lumi $cm^{-2}s^{-1}$	Lumi/year fb^{-1}
TeVatron	2	$<10^{32}$	0.3
LHC (Low Lum)	14	$2x10^{33}$	10
LHC (High Lum)	14	10^{34}	100

Process	σ(pb)	Events/s	Events/year
bb	5×10^{8}	10^{6}	10^{12}
Z→ee	1.5×10^{3}	~3	10^{7}
W→eν	1.5×10^{4}	~30	10^{8}
WW→eνX	6	10^{-2}	6×10^{3}
tt	830	~2	10^{7}
H (500 GeV)	1	2×10^{-3}	10^{4}



1- High backgrounds to the physics interesting processes

2.- Many other processes than Higgs search will be studied

Luminosity upgrade of LHC: SLHC

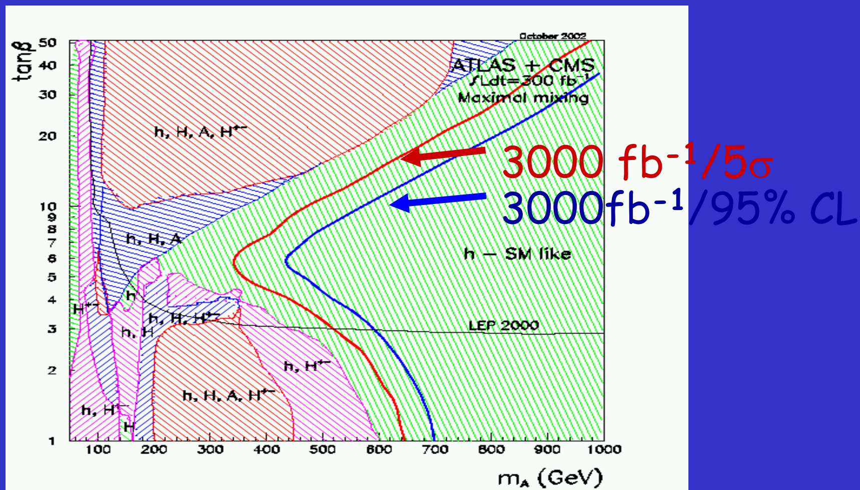
Plans to increase luminosity to 10^{35} $cm^{-2}s^{-1}$
with moderate effort (injection system, collimation,…)
natural evolution after LHC-running for several years at design-L

Consequences for detectors:
shorter bunch spacing, larger pile-up
needs improved detectors + trigger/DAQ → R&D needed now
expect some degradation of detector resolutions
(b-tagging, track finding, forward jet tagging, …)

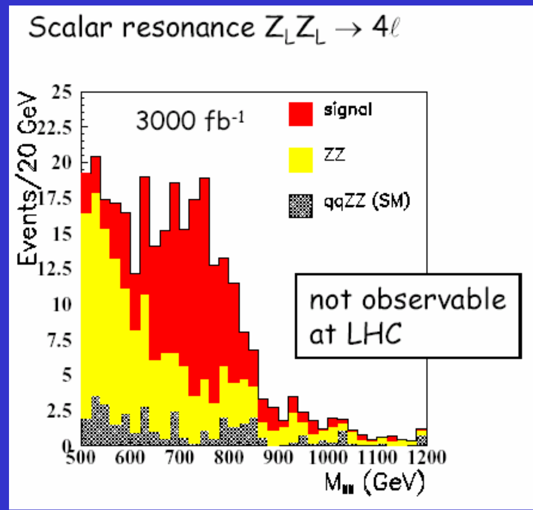
Physics potential:
- 20-30% increase in discovery potential e.g. SUSY 2.5→3 TeV
- improve on precision of statistically limited measurements
- some sensitivity to triple Higgs coupling for m_H~160 GeV

Examples of improvements at SLHC

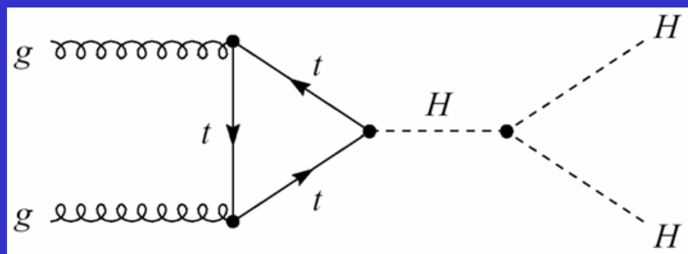
Heavy SUSY Higgs:
observable region increased by ~100 GeV.



Broad resonances in no-Higgs scenarios:



Higgs self coupling: potential for first observation if m_H~160 GeV with 3000 fb^{-1}



Energy upgrade of LHC (DLHC)

double beam energy to 14 TeV
needs new magnets = new machine = major effort

in general larger discovery potential than SLHC
(but also less well studied)

needs very good physics justification from future data

Electron-Proton collider (LHeC)

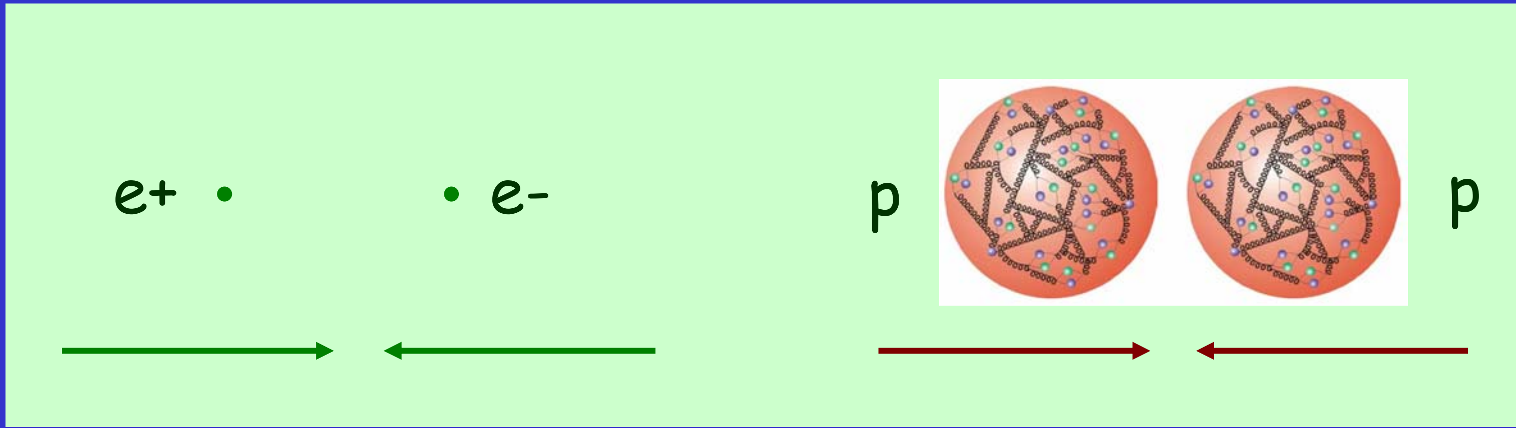
supplement LHC by 70 GeV e^-/e^+ storage ring

structure functions, low-x physics, QCD

potential for new physics:
unique for eq-resonances, e.g. Leptoquarks, Squarks in RPV-SUSY,...

$\sqrt{s}$ = 1.4 TeV
(=4.5xHERA)
L = 10^{33} $cm^{-2}s^{-1}$
(=20xHERA)

Electron-Positron collisions



Electron positron collisions at high energy provide a powerful tool to explore TeV-scale physics complementary to the LHC

Due to their point-like structure and absence of strong interactions there are clear advantages of e^+e^- collisions:

- known and tunable centre-of-mass energy
- clean, fully reconstructable events
- polarized beams
- moderate backgrounds
  → no trigger

broad consensus for a Linear Collider with up to at least ~500 GeV

The International Linear Collider

Huge world-wide effort to be ready for construction in >2010 ??
(Global Design Effort GDE)
Result of an intense R&D process since 1992

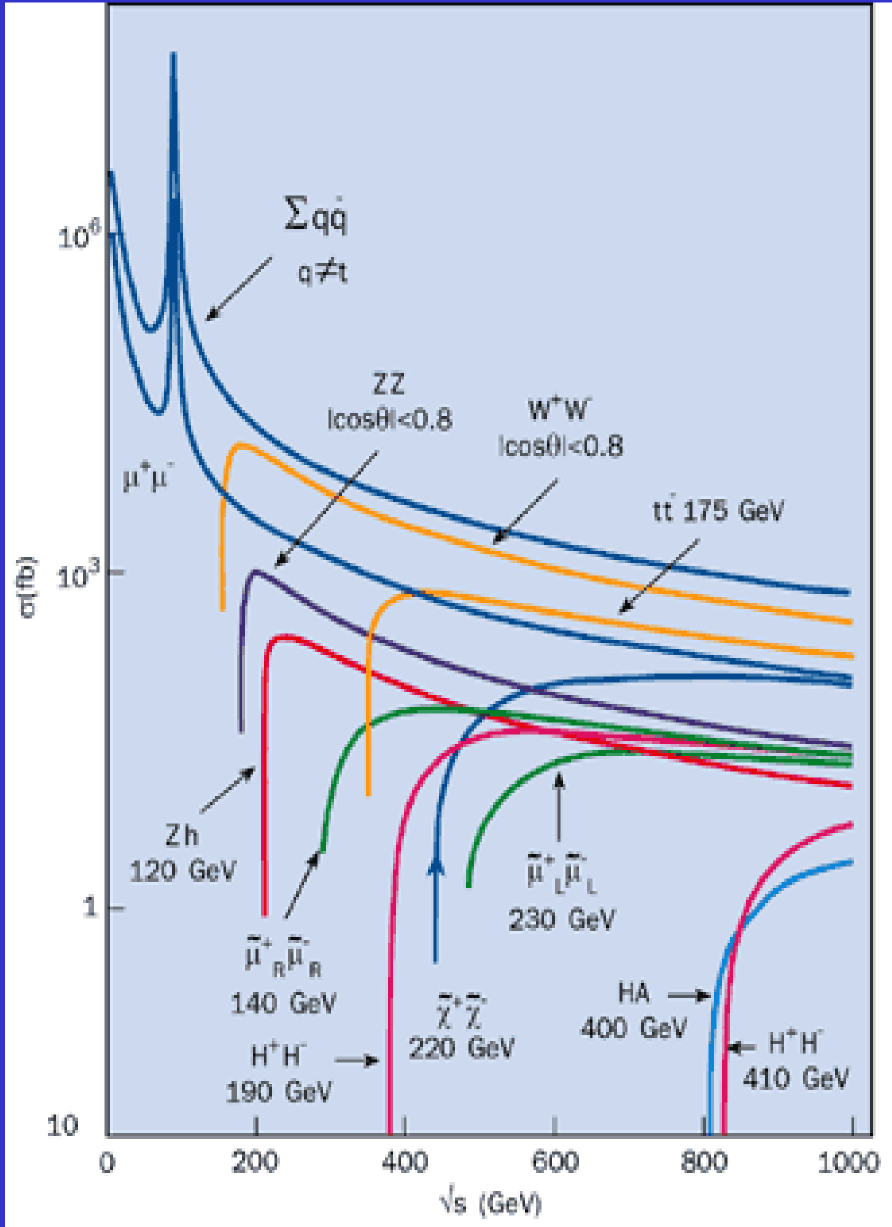
Parameters (ICFA parameter document/ILC baseline)

The baseline:
e^+e^- LC operating from M_Z to 500 GeV, tunable energy
e^- /e^+ polarization
at least 500 fb^{-1} in the first 4 years

Upgrade: to ~ 1 TeV 500 fb^{-1} /year

Options :
- GigaZ (high luminosity running at M_Z)
- $\gamma\gamma$, $e\gamma$, e^-e^- collisions

Choice of options and energy “should” depend on LHC results (2010)



Standard Production of top in e+e-:

$\mathscr{L}$ ~ 500 fb^{-1}

Events ~ 5x10^5

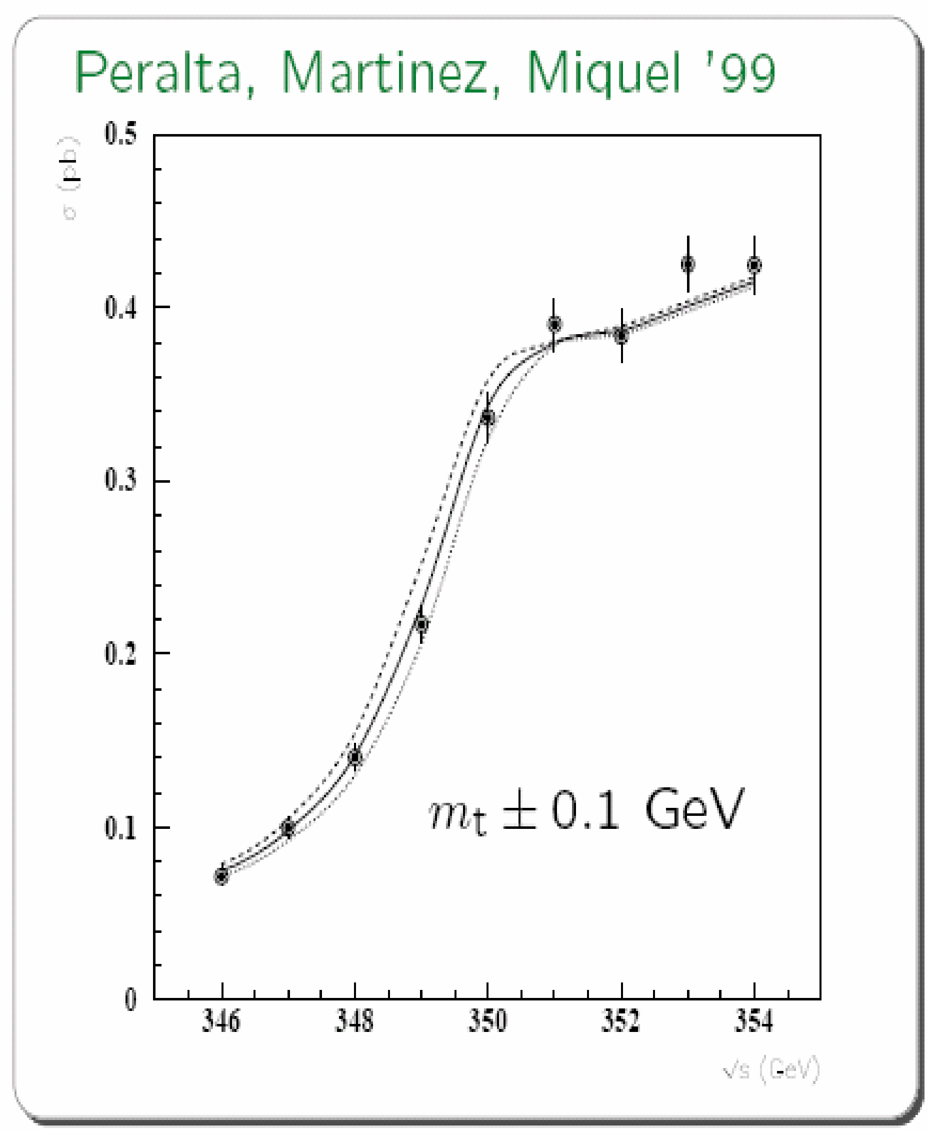
Statistics Low (compared to LHC)

Excellent signal/background ratio

(accurate measurements possible)

ILC: Top cross section:

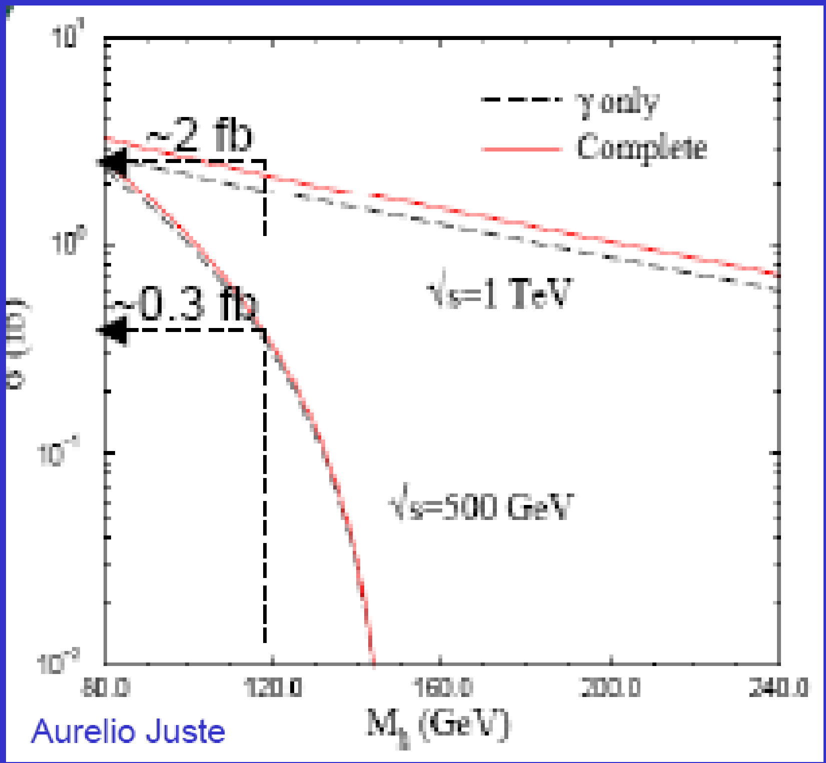
- ✓ Measurement of tt cross section at various points around the production threshold. Fit top mass (and width).
- ✓ Total error top mass expected < 100 MeV or better.
- ✓ Complementary kinematic reconstruction of top anti-top events above threshold expected to yield good statistical uncertainty

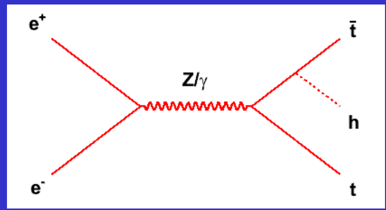


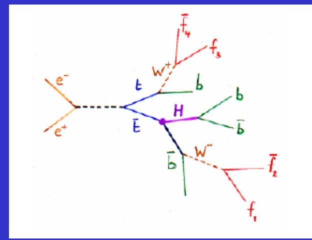
ILC top Yukawa coupling to Higgs

tt production cross-section at threshold is sensitive to **tt**h Yukawa coupling.

For m_h = 115 GeV, a variation of 14% in SM Yukawa coupling leads to a 2% change in normalization of the cross section near the 1S peak.







Very complicated topology

6jets +2bjets+leptons+missing energy

4jets +2bjets

2jets + 4bjets ... neutrinos

$\frac{\Delta g_{ttH}}{g_{ttH}}$ ~ 15% ... GeV

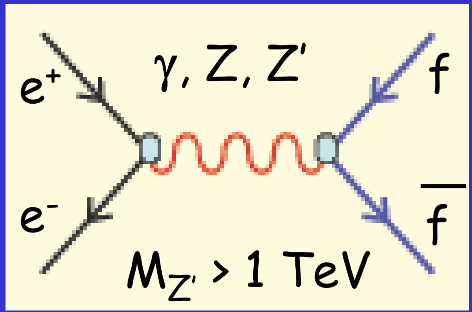
(E_{beam} ~ ... V, $\mathscr{L}$ ~1000 fb^{-1})

(with polariztion 60%e+,-80%e-)

Energy operation is crucial (LHC input is needed)

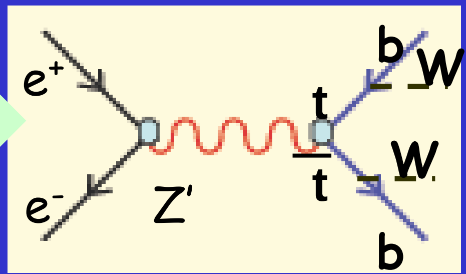
LHC+ILC: t and exotic physics, Z' resonances

Even, if Z' discovered at LHC in leptonic decays



$\rightarrow \quad \bar{f}\gamma^{\mu}(v_f' - a_f'\,\gamma^5)f$

$\downarrow$ f=t



Very important to make accurate measurements of the couplings to discrimante between Z' models (very difficult at LHC):

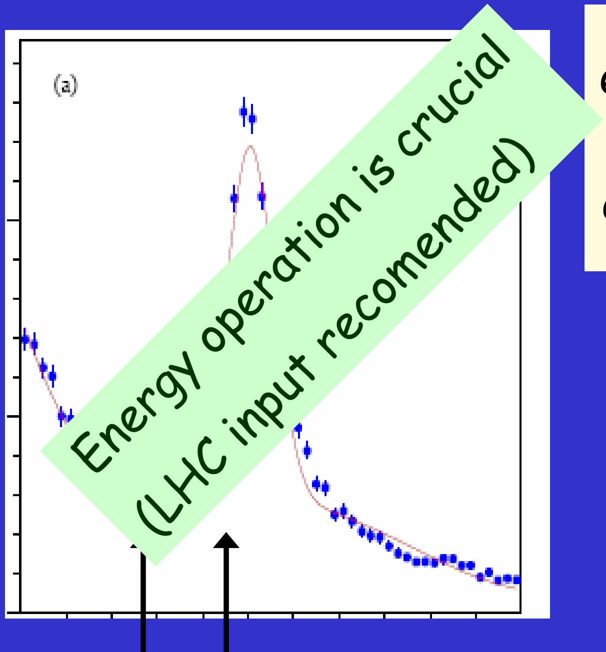
SM Z'

LR symmetric models

Little Higgs

Extra dimensions

Effective symmetries



Depending on the beam energy it will be more or less difficult to extract couplings ! Energy crucial !!

Key Observables

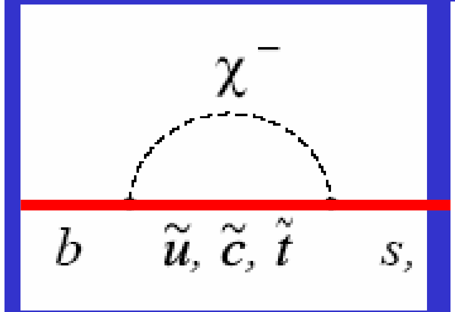
$\sigma_t \sim (v_t')^2 + (a_t')^2 \qquad A_f^{FB} \sim \dfrac{2v_f'\,a_f'}{(v_t')^2 + (a_t')^2}$

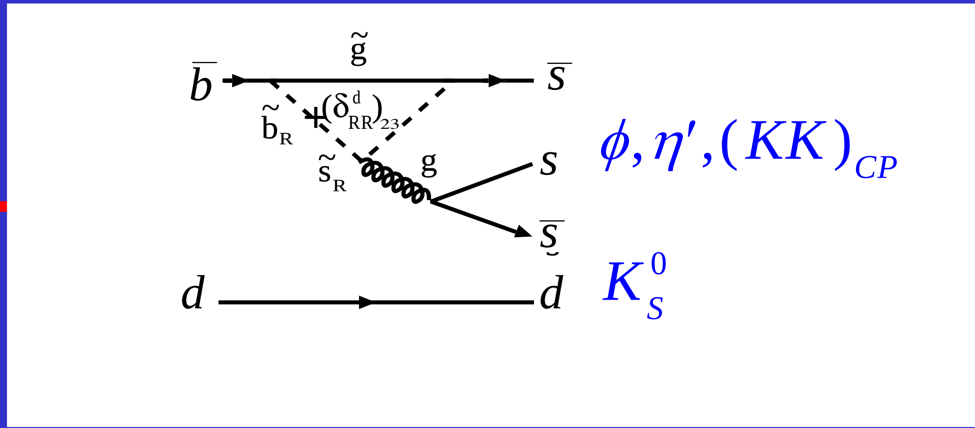
Polarization studies also possible (like τ at LEP)

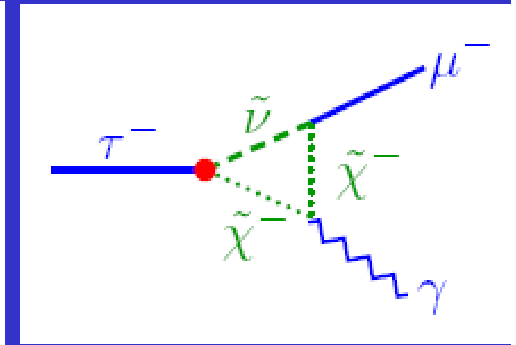
(if all decay productis recosntructed)

Polarized beams very beneficial !

The case for a high luminosity flavour factory



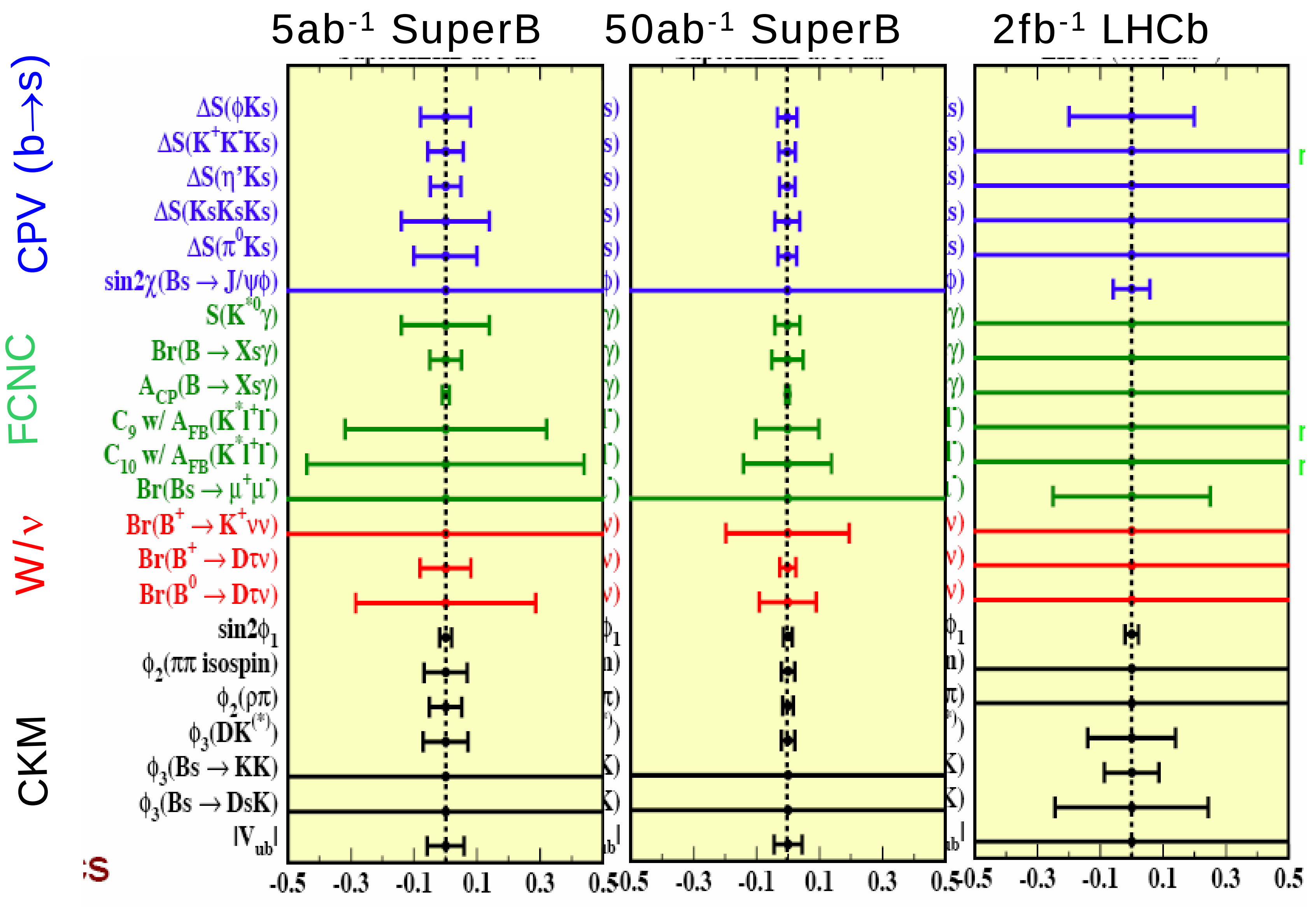




- Prejudice: if there is New Physics at the TeV scale it must have a flavor/CP structure
- New heavy quanta can be detected through precision measurement of processes involving loop diagrams
- Statistics of O(50 ab^{-1}) is necessary to reduce the experimental error below the theoretical uncertainty for the most sensitive analyses
- Physics reach is complementary to LHC-LHCb:
  - many rare decays are not accessible at LHC;
  - sensitivity to off-diagonal term of squark mixing matrix,
  - test of LFV in t decays

Physics reach at SuperB

From '05 T.Iijima talk



Summary

After many years of construction and building of the Standard Model and Experiments (LHC)

Exciting moments are coming, just in the corner

Summary

The Standard Model has been tested with high precision. Still many questions remain to be answered, in particular, EW Symmetry Breaking still needs to be understood

Hadron colliders play an important role in particle physics and complement with Linear colliders. High energy versus high precision. A complete future program is developing (ILC, SLHC, SuperB..). LHC is crucial to understand EW-SB but not only (important implications in dark matter, CP-Violation).

Search for the Higgs particle and study of top physics will concentrate main efforts of data analyses. New scenarios and physics models will also emerge (SUSY, Extra-dimensions. etc..).

LHC interesting processes have large cross sections but also large backgrounds: intelligent and sophisticated analyses using full detector capabilities will be needed.