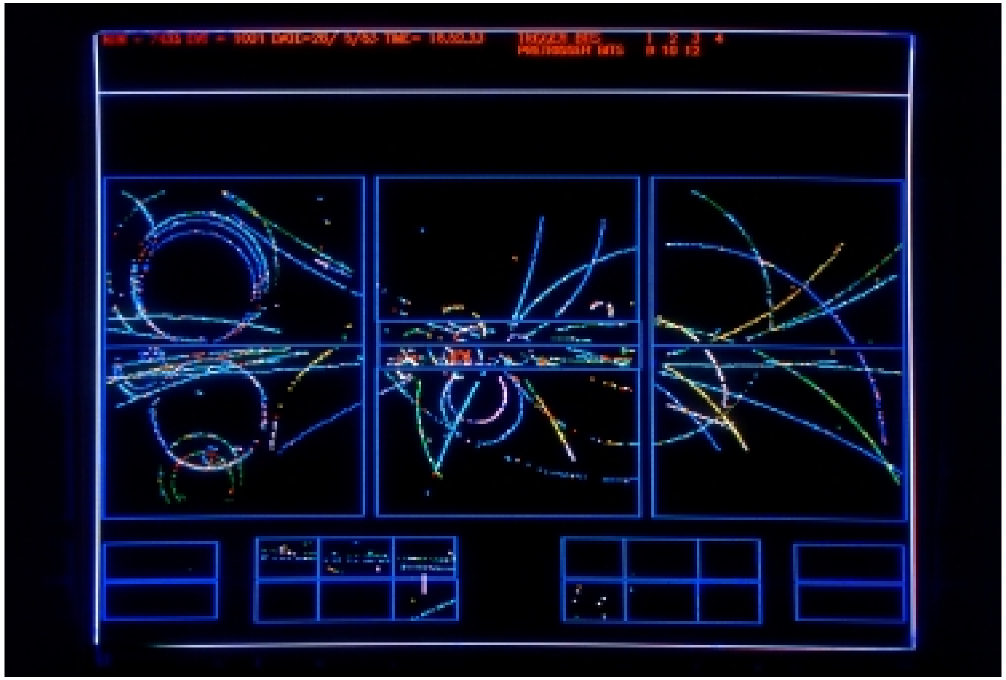
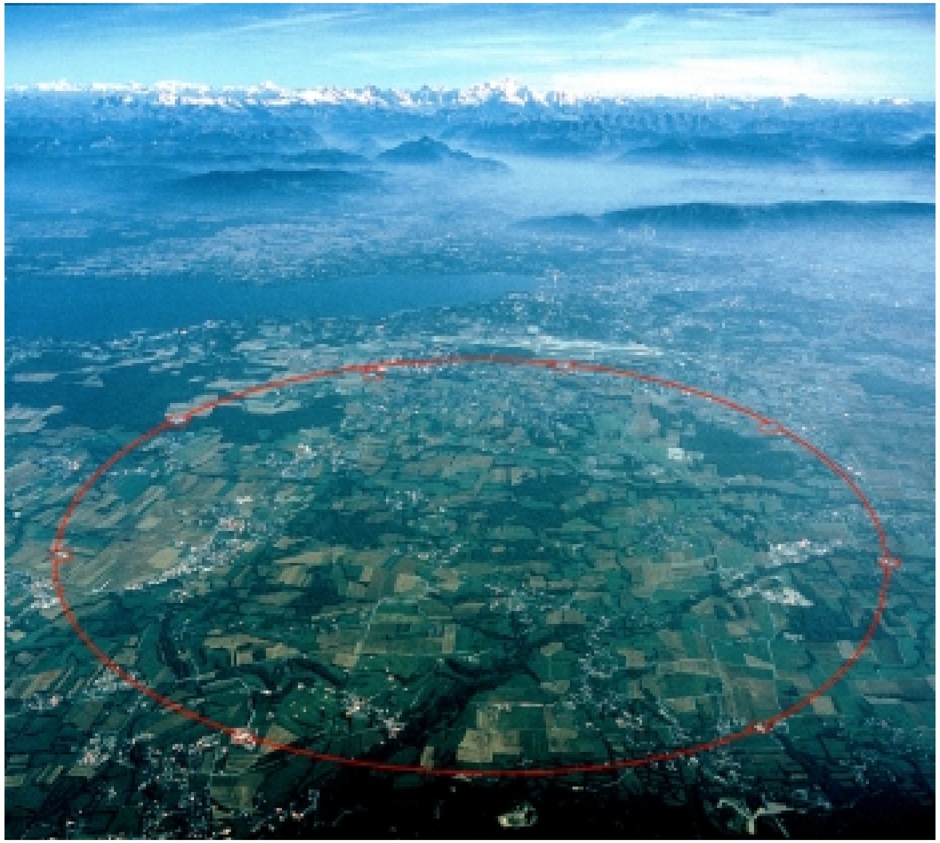


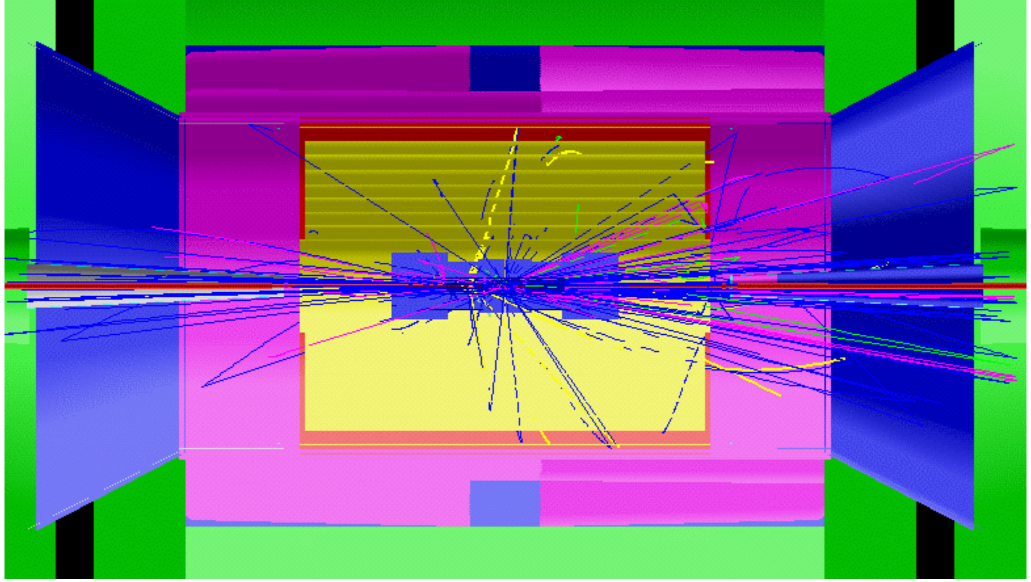
What have Experiments Taught us ? ……..

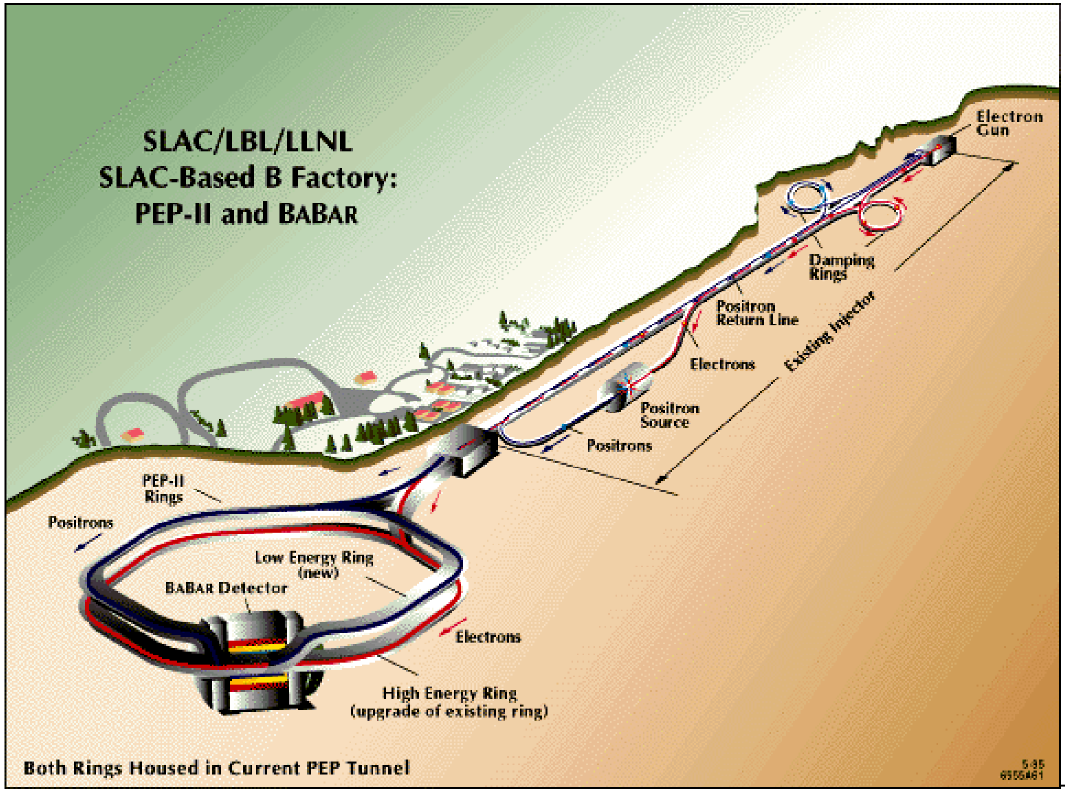


EPS-12: *General Conference*
TRENDS IN PHYSICS
Budapest, 29/8/2002

Gigi Rolandi (CERN)

That the Standard Model gives a very accurate description...





...of the constituents of matter and of their interactions

Outline

- Standard Model and its open questions
- Few examples of SM tests:
  - --- Structure Functions at Hera (Desy/Hamburg)
  - --- Sin (2β) at PepII (Slac/Stanford) and Kekb (Kek/Tsukuba)
  - --- Z lineshape at LEP (Cern/Geneva)
  - --- Mtop at Tevatron (Fermilab/ Chicago)
  - --- Mw at Lep and Tevatron
  - --- Global fit of SM Data
  - --- Direct Higgs search
- Conclusions

Fundamental particles and interactions

Matter particles : fermions, spin =1/2

e	μ	τ	q= -1
ν_e	ν_μ	ν_τ	q= 0

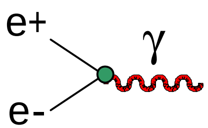
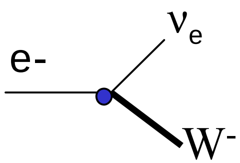
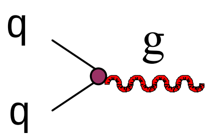
u	c	t	q= +2/3
d	s	b	q= -1/3

+ anti-particles

Why 3 families ?
Why fermion masses ?
Why boson masses ?
Are quarks elementary ?
Why gauge symmetries ?
etc ...

Interactions specified by symmetry : $U(1)_Y \times SU(2)_W \times SU(3)_C$

Force carriers : bosons, spin=1

Particle	Force	Coupling (E~100 GeV)	Mass	Intensity
γ	EM (charged particles) 	$\alpha_{EM} = \frac{e^2}{4\pi} \approx 0.008$	0	~ 10^{-1}
$W^\pm$, Z	weak (q, ℓ, $W^\pm$, Z) 	$\alpha_W = \frac{g^2}{4\pi} \approx 0.03$	~ 100 GeV	~ 10^{-5}
8 g	strong (q, g) 	$\alpha_s = \frac{g_s^2}{4\pi} \approx 0.12$	0	1

Intensity: relative to strong

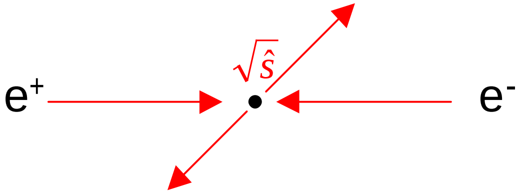
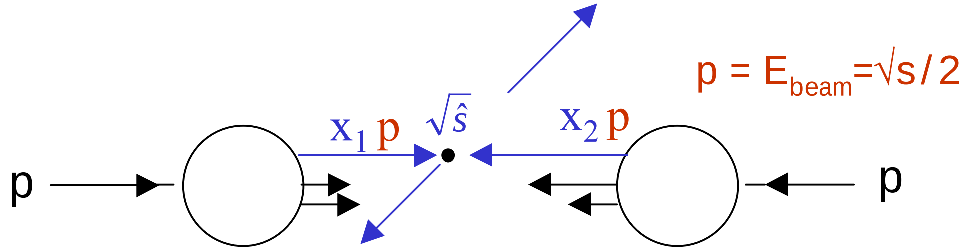
Mass "generator " : Higgs scalar, spin=0 ?

(EWSB)

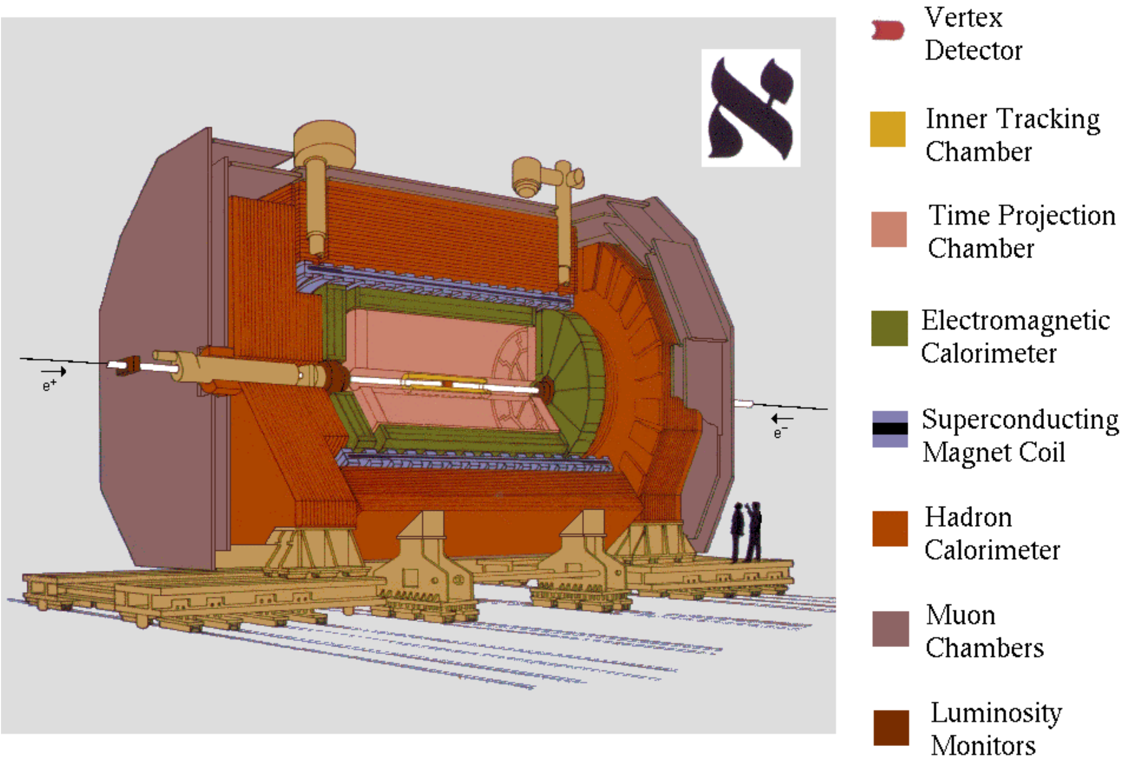
predicted by SM but not yet observed

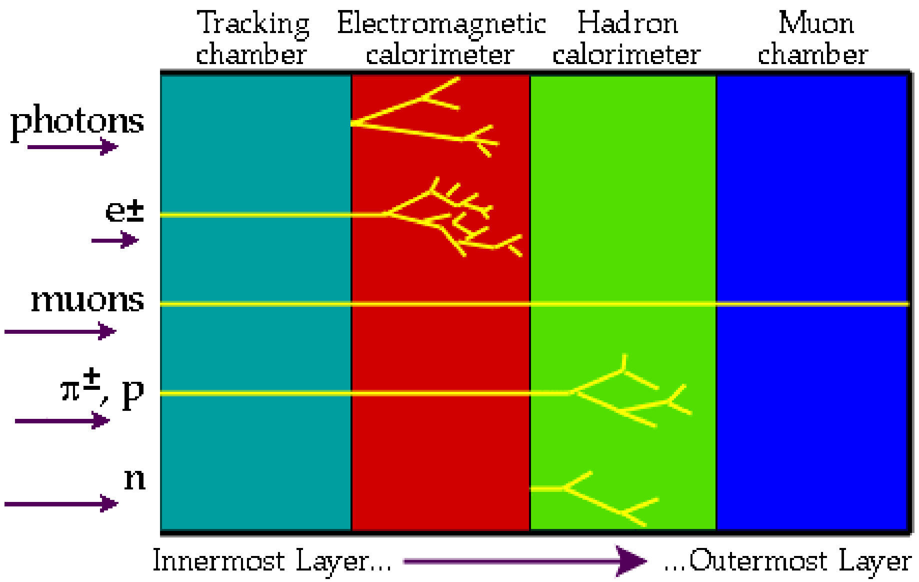
The precision tests of the Standard Model are mainly carried out with large high energy colliders and complex particle detectors in few international laboratories

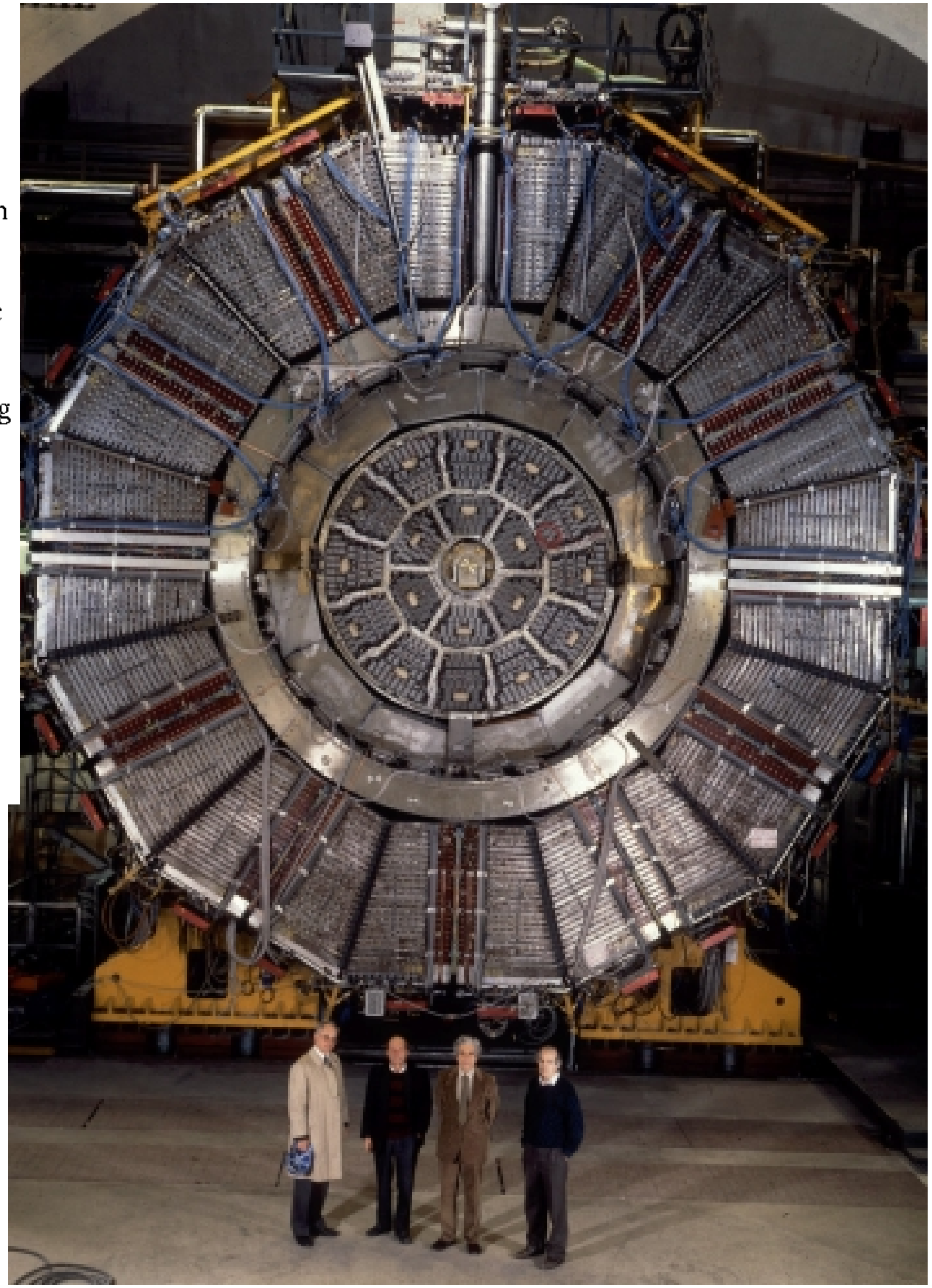
e^+e^- Colliders vs $pp/p\bar{p}$ Colliders

e^+e^- Colliders	$pp/p\bar{p}$ Colliders
 $E_{beam}=\sqrt{s}/2$	
• Energy of elementary interaction known $\sqrt{\hat{s}} = E(e^-) + E(e^+) = \sqrt{s}$	• Energy of elementary interaction not known $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$
• Only two elementary particles collide → clean final states	• Elementary interaction (hard) + interaction of "spectator" q,g (soft) overlapped in detector
• Mainly EW processes	• EW processes suffer from huge backgrounds from strong processes
• $\sqrt{s}$ limited by $e^{\pm}$ synchrotron radiation: $E_{loss} \sim \frac{E^4_{beam}}{R}\frac{1}{m_e^4}$ $E_{loss} \sim 2.5$ GeV/turn LEP2 ($E_{beam} \sim 100$ GeV)	• Synchrotron radiation is ~ $(m_p/m_e)^4 \sim 10^{13}$ smaller
⬇ -- high energy more difficult → next machine : Linear Collider (TESLA, NLC, JLC, $\sqrt{s}$ =500-800 GeV ?) -- clean environment → precision measurements machines	⬇ -- high energy easier → discovery machines next machine : LHC, pp, $\sqrt{s}$ = 14 TeV in the LEP ring -- " dirty" environment

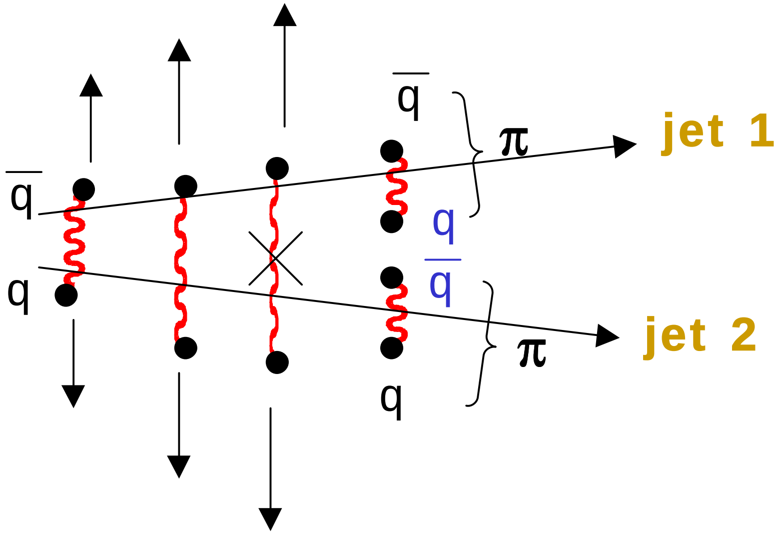
Example of detector : ALEPH

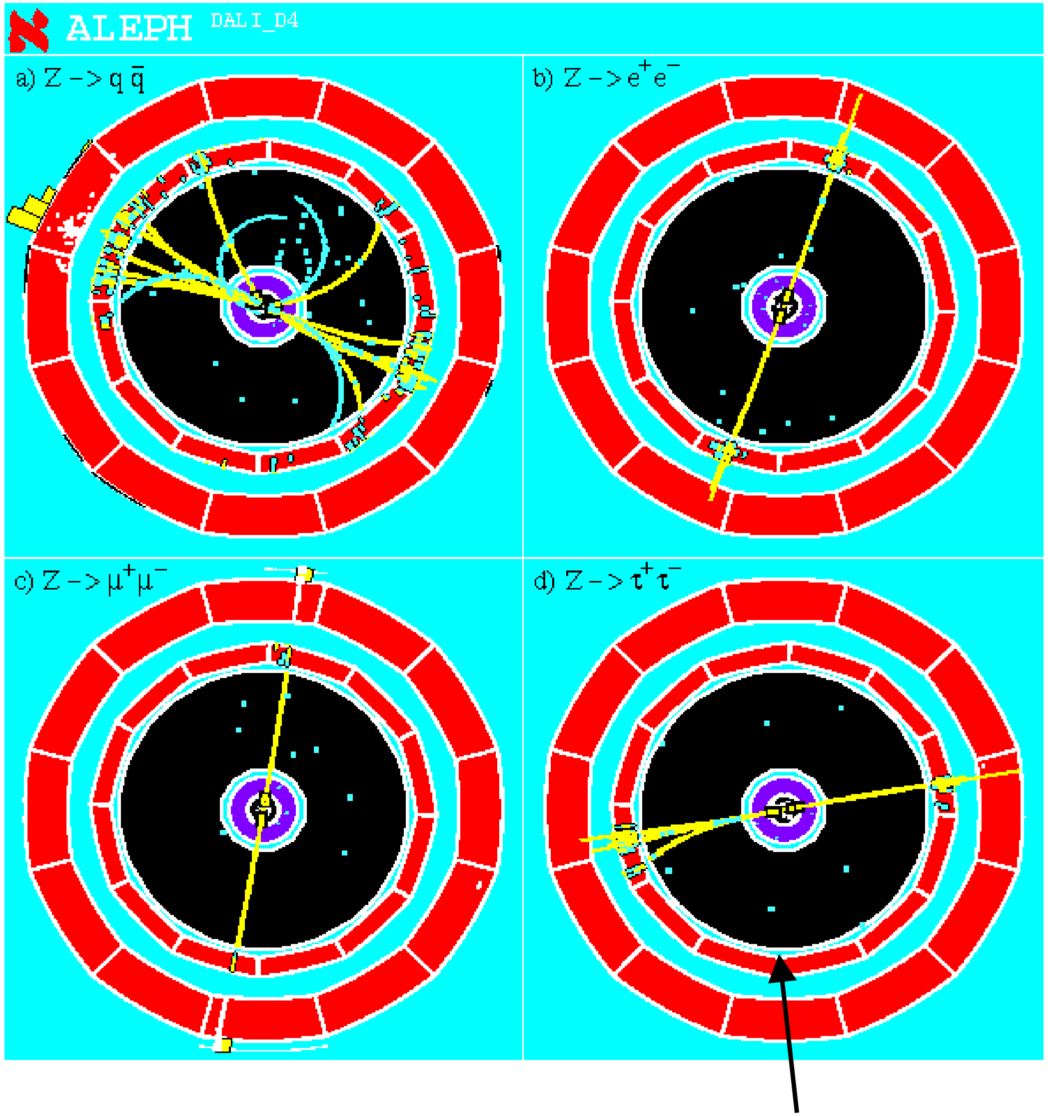


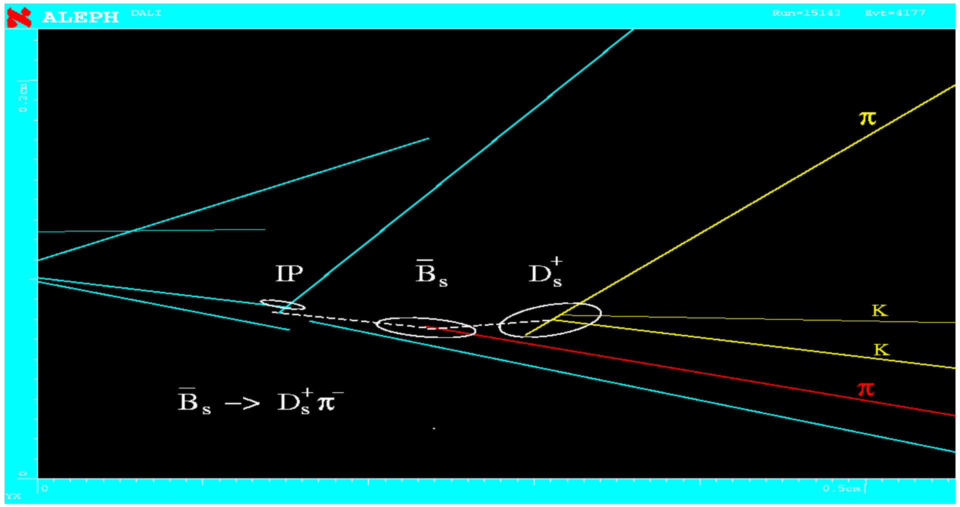




Example of detector





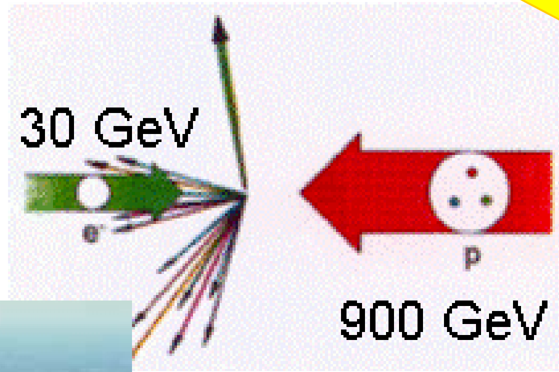


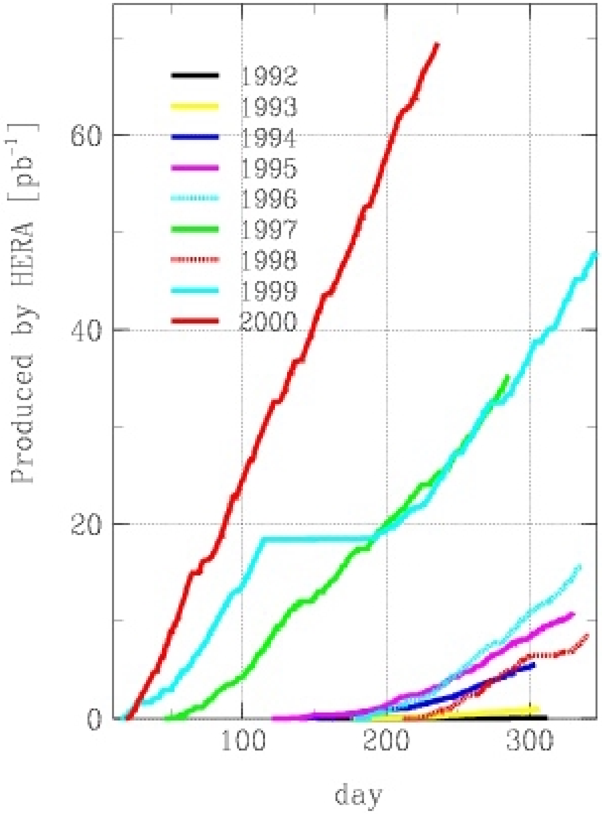
2 jets of hadrons
with low multiplicity
+ missing E carried
by neutrinos

The Hera ep collider at Desy

Are quarks elementary ?

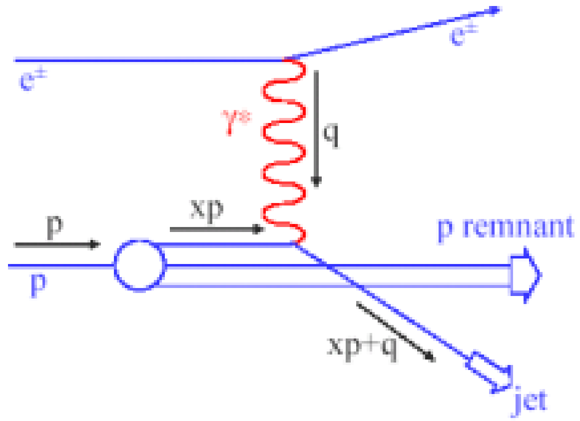
ep collisions allow to probe efficiently the structure of the quarks





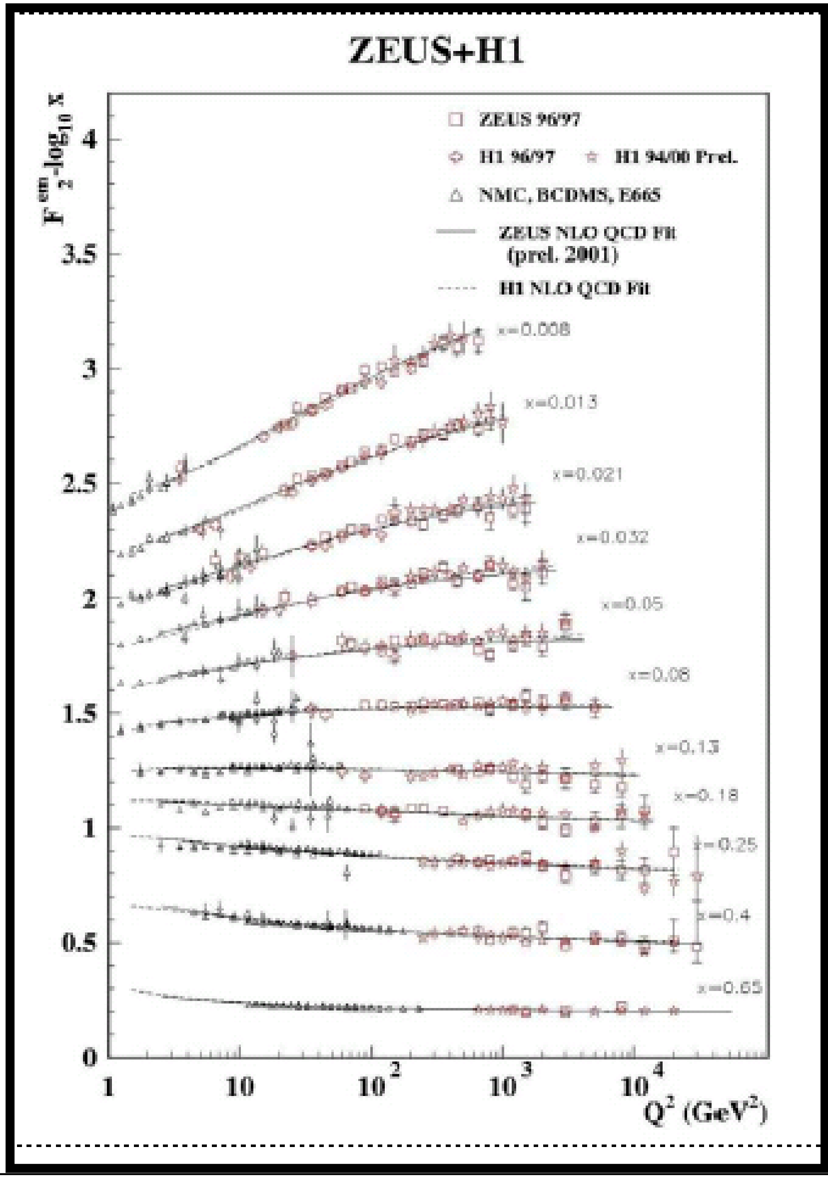
'94-'00 ~ 0.1 fb^{-1} per experiment

'02-'06 ~ 1 fb^{-1} per experiment



Describe the scattering in term of

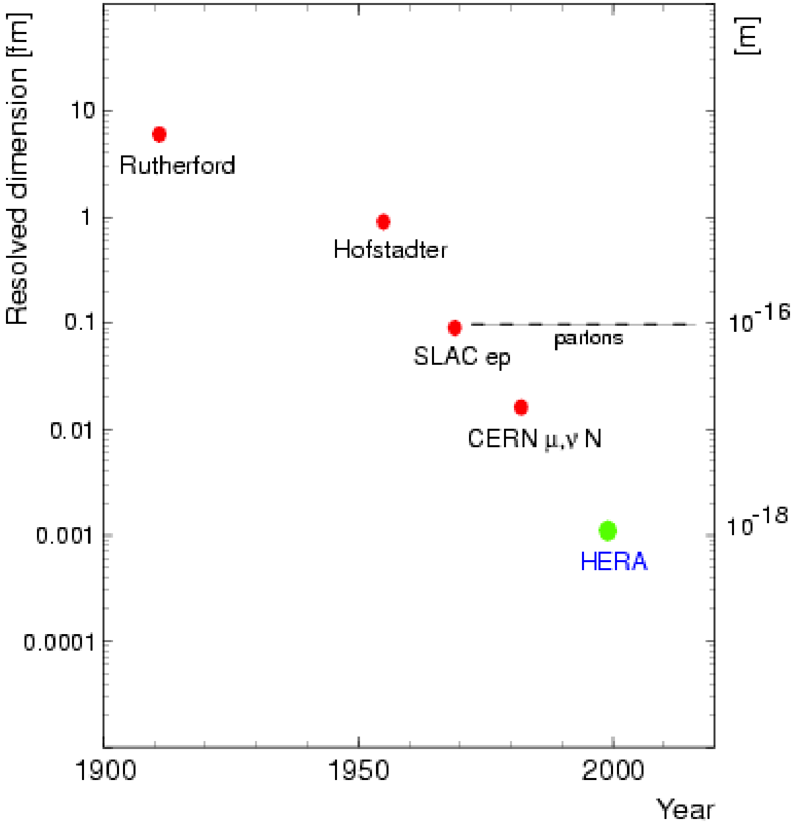
$$Q^2 = -q^2 \text{ and } x = \frac{Q^2}{2p \cdot q}$$

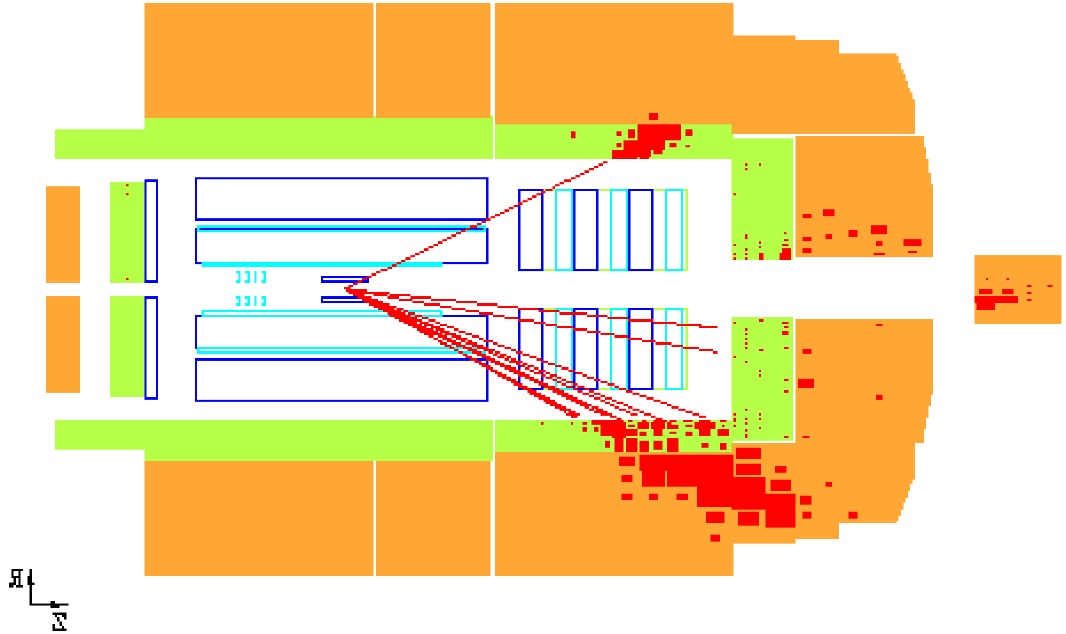


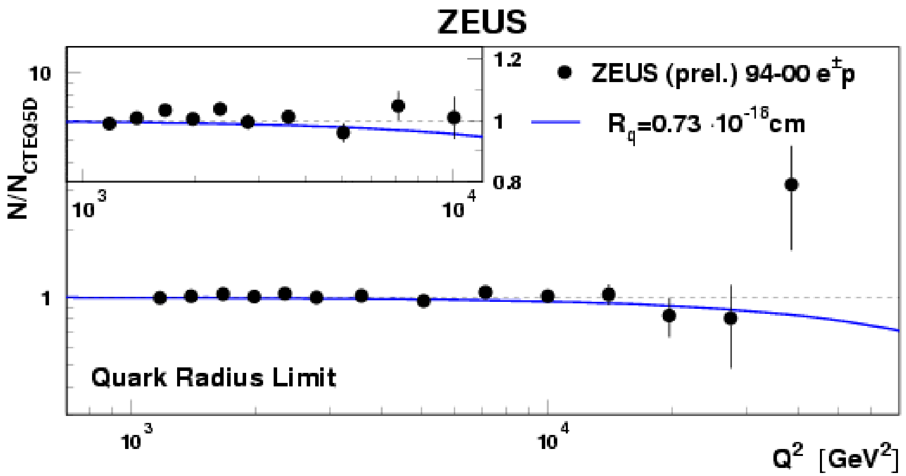
The cross section is expressed in term of the quark densities

$$\frac{d^2\sigma_{ep \to eX}}{dx\, dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4} F_2(x, Q^2)$$

The accuracy of the measurement of angles and energies of leptons and jets is the challenge of the measurement to the cross section at high Q2



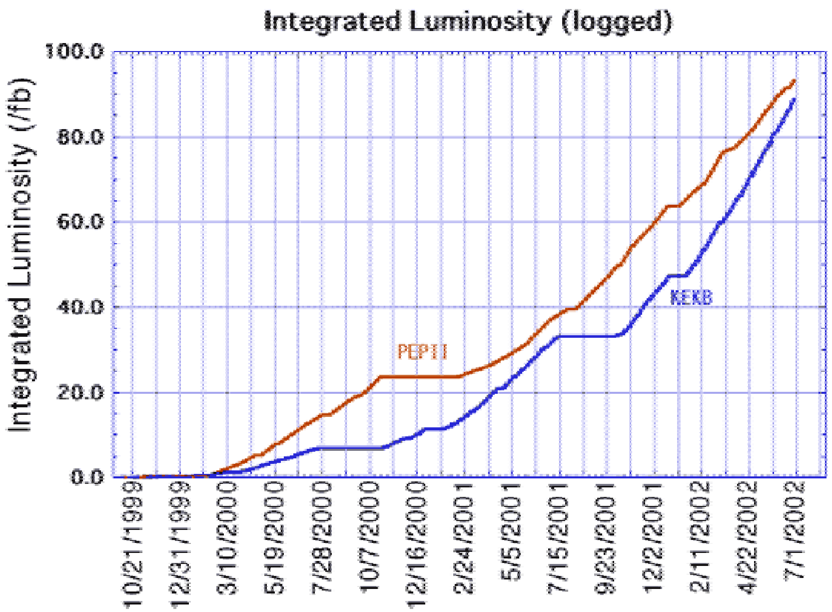




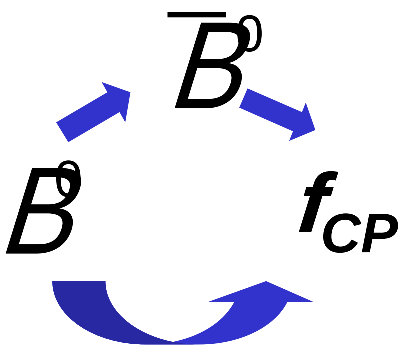
QCD with elementary quarks describes the scattering up to the highest accessible Q^2

The asymmetric B factories at Kek and Slac

Why three families ?
Why matter ?



~100.000.000 B B_{bar} Events Collected



In the weak interaction u-type quarks couple to d-type quarks via the CKM matrix

CKM Matrix

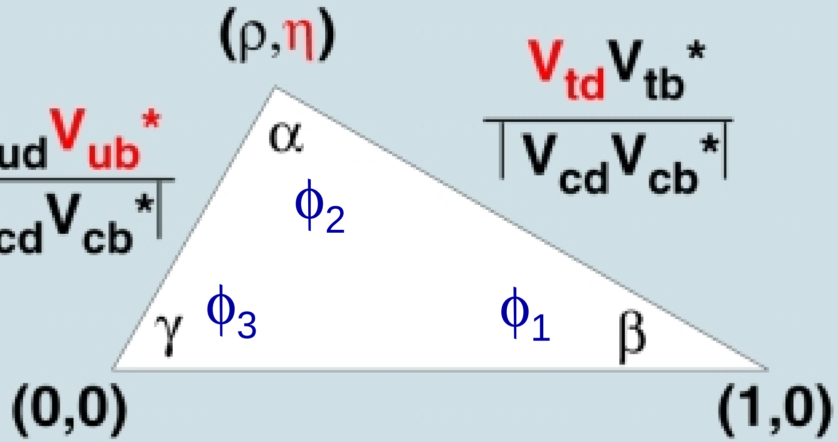
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

$V^{\dagger}V = I$, and quark phases
$\Rightarrow$ 4 parameters

$$\begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

Unitarity Triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



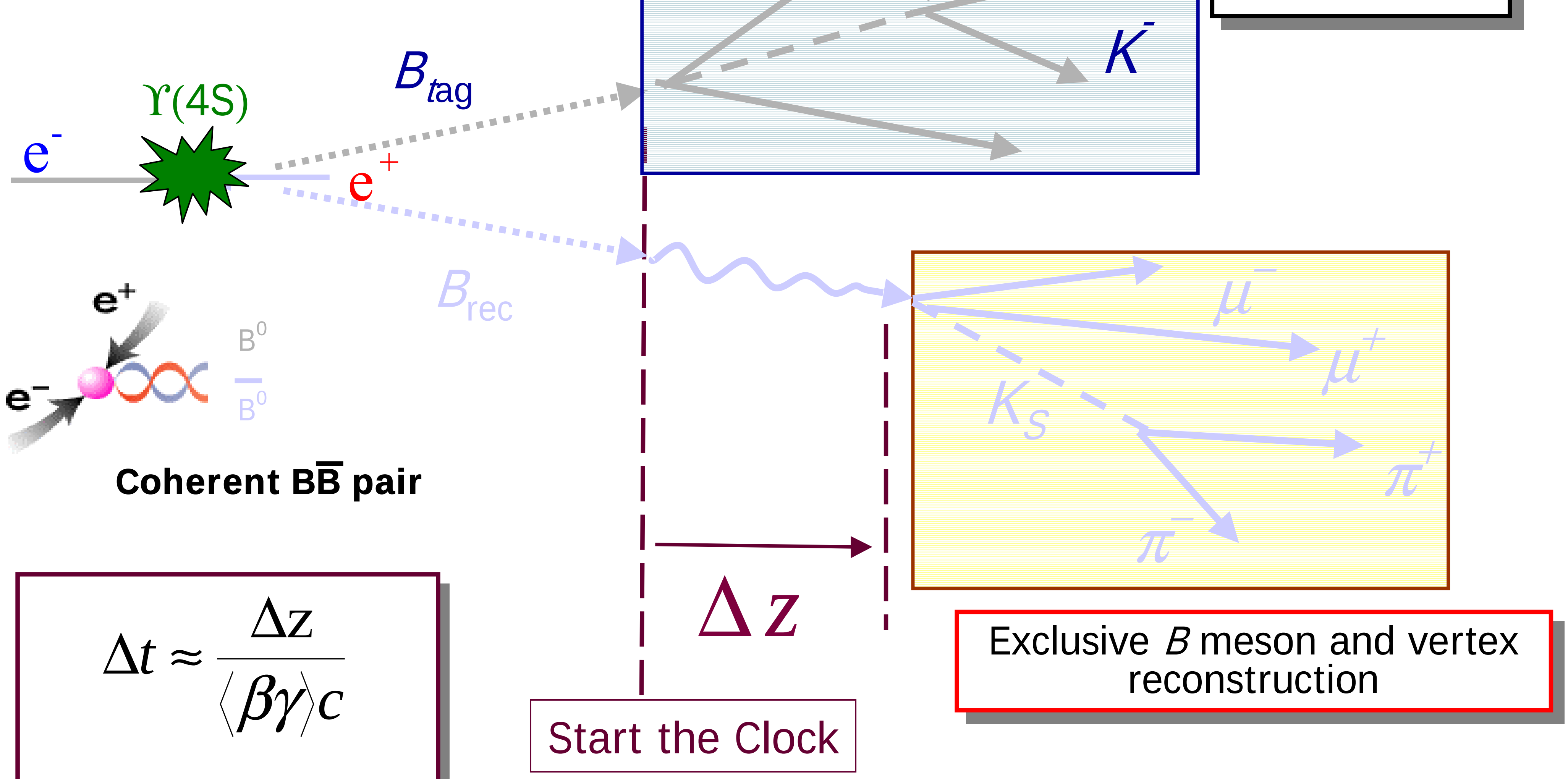
$$\frac{V_{ud}V_{ub}^*}{|V_{cd}V_{cb}^*|} \qquad \frac{V_{td}V_{tb}^*}{|V_{cd}V_{cb}^*|}$$

CP violation will arise from complex component of V_{ub}, V_{td}

Experimental technique at the ϒ(4S) resonance

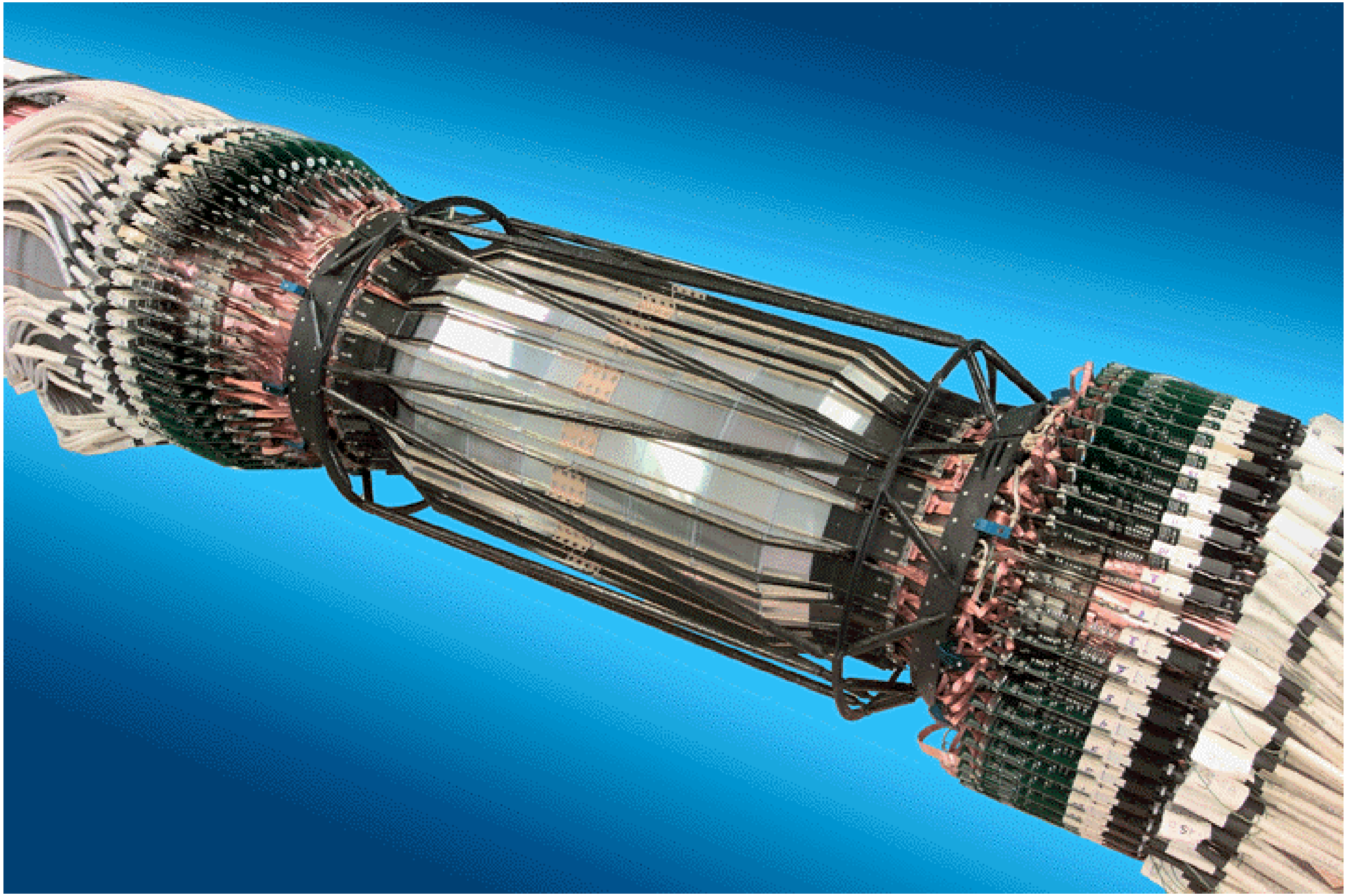
$e^+e^- \to \Upsilon(4S) \to B\,\bar{B}$

Boost: $\beta\gamma = 0.55$

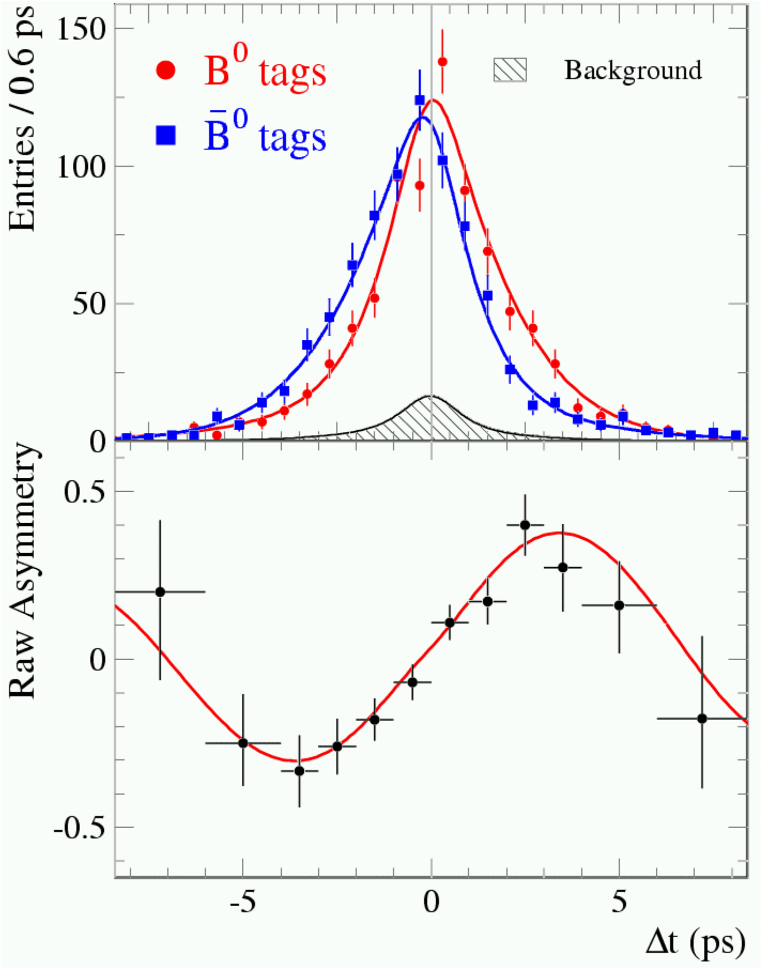


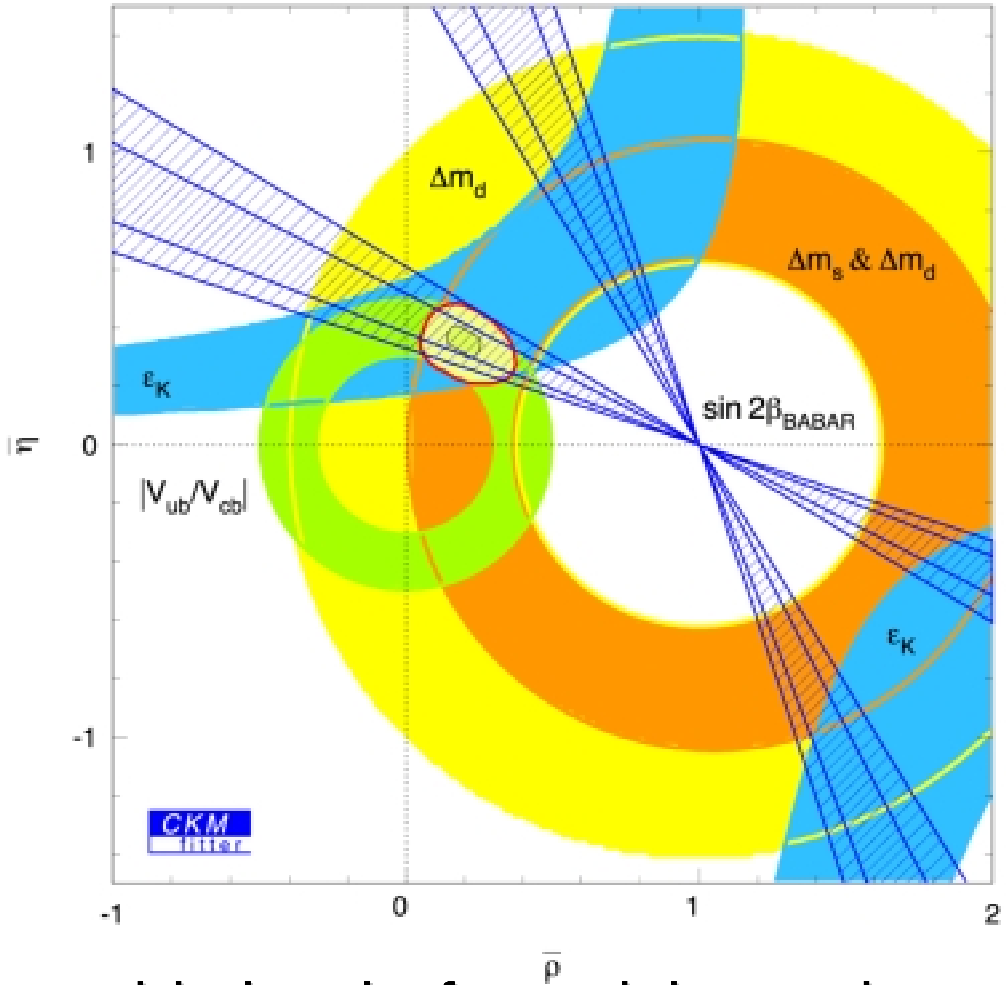
$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

Sophisticated silicon detectors and fast electronics allow to track the decay point of the B mesons with the precision of few dozens microns



The measurement of the beta angle agrees at few percent level to its SM prediction based on other measured quantities



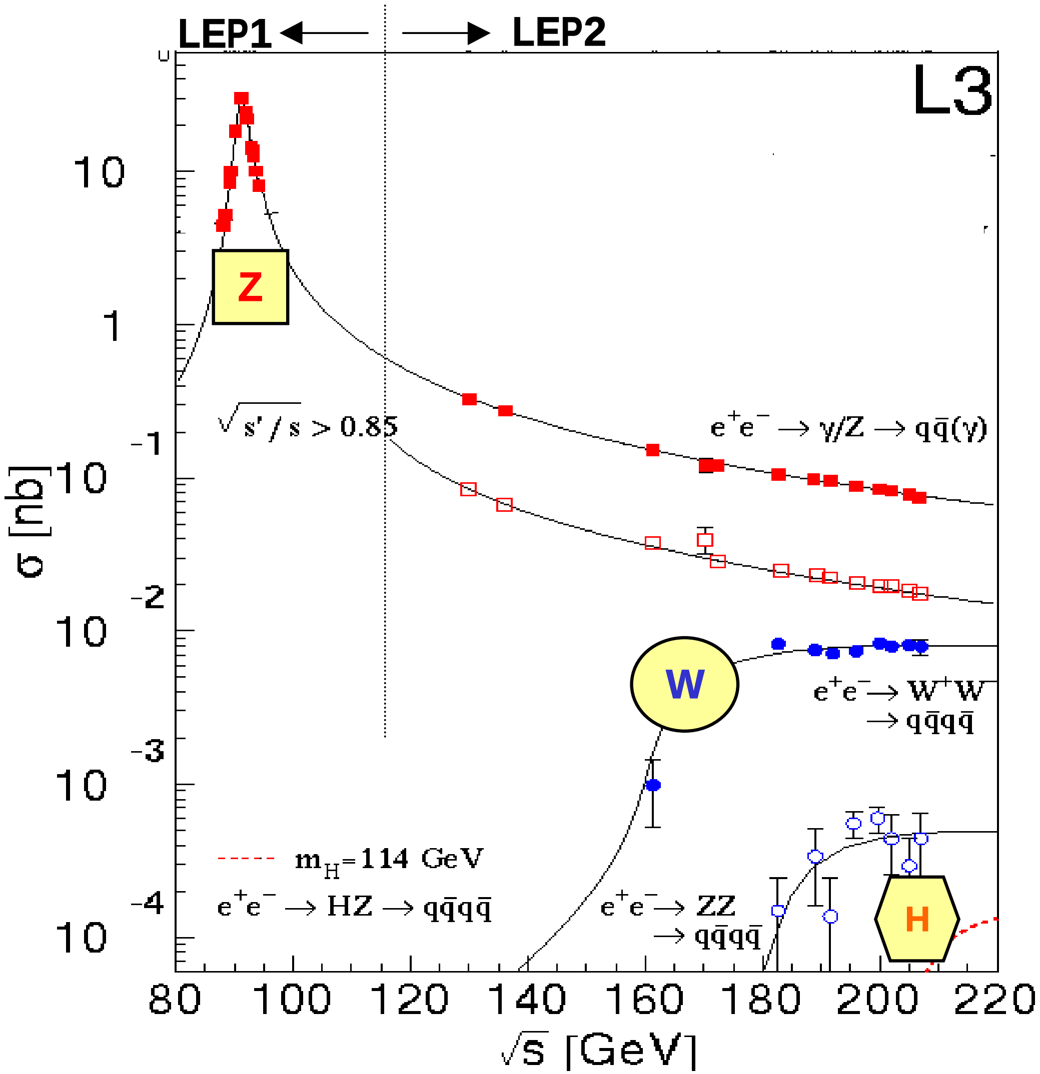


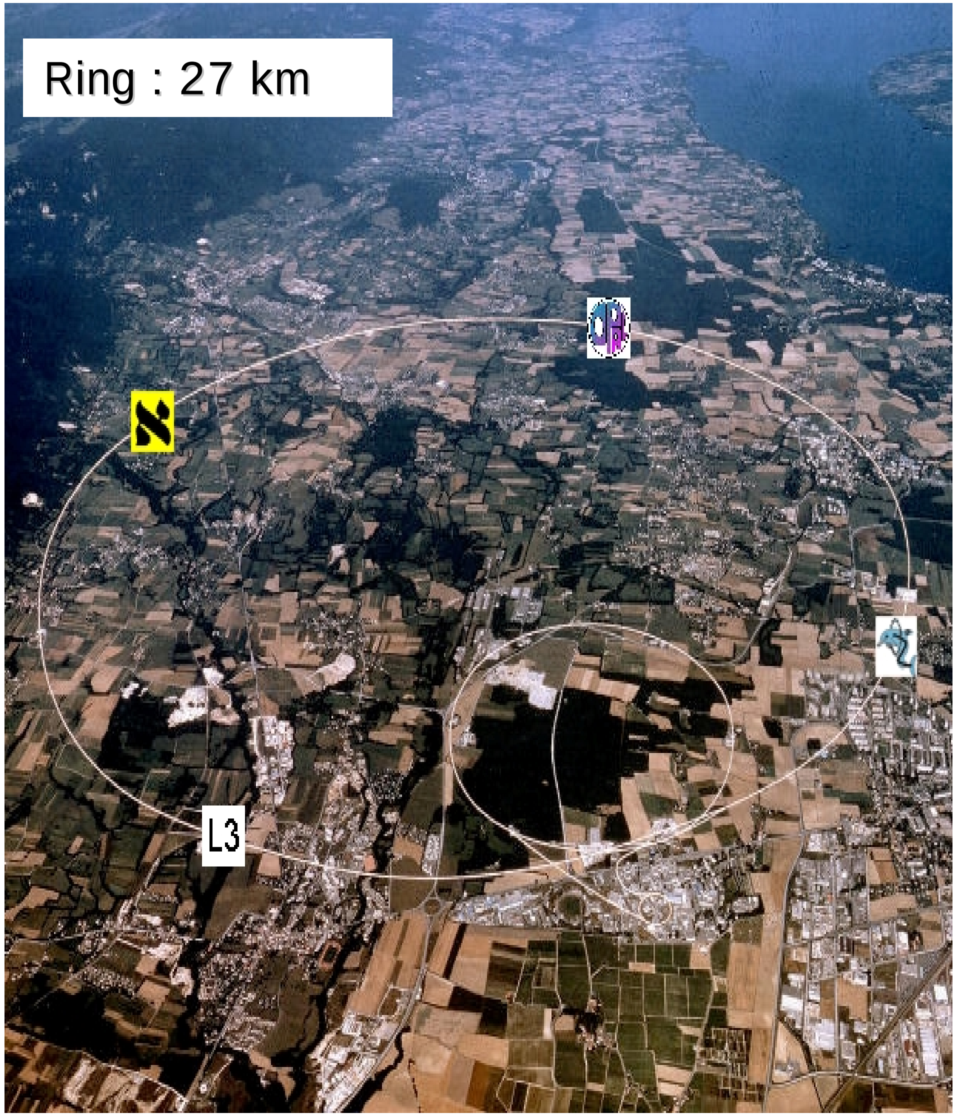
CKM matrix is unitary to this level of precision and incorporates CP violation with thee generations

The LEP e+e- Collider at CERN

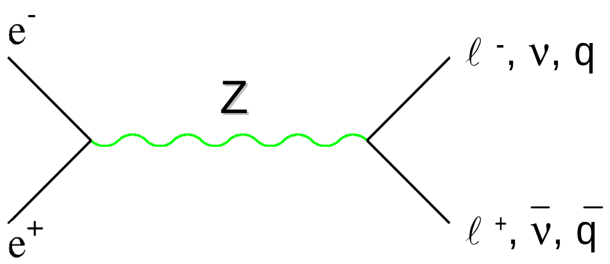
LEP1 ('89-'95) : $\sqrt{s} \approx m_Z \rightarrow 2\ 10^7$ Z recorded → precise Z measurements

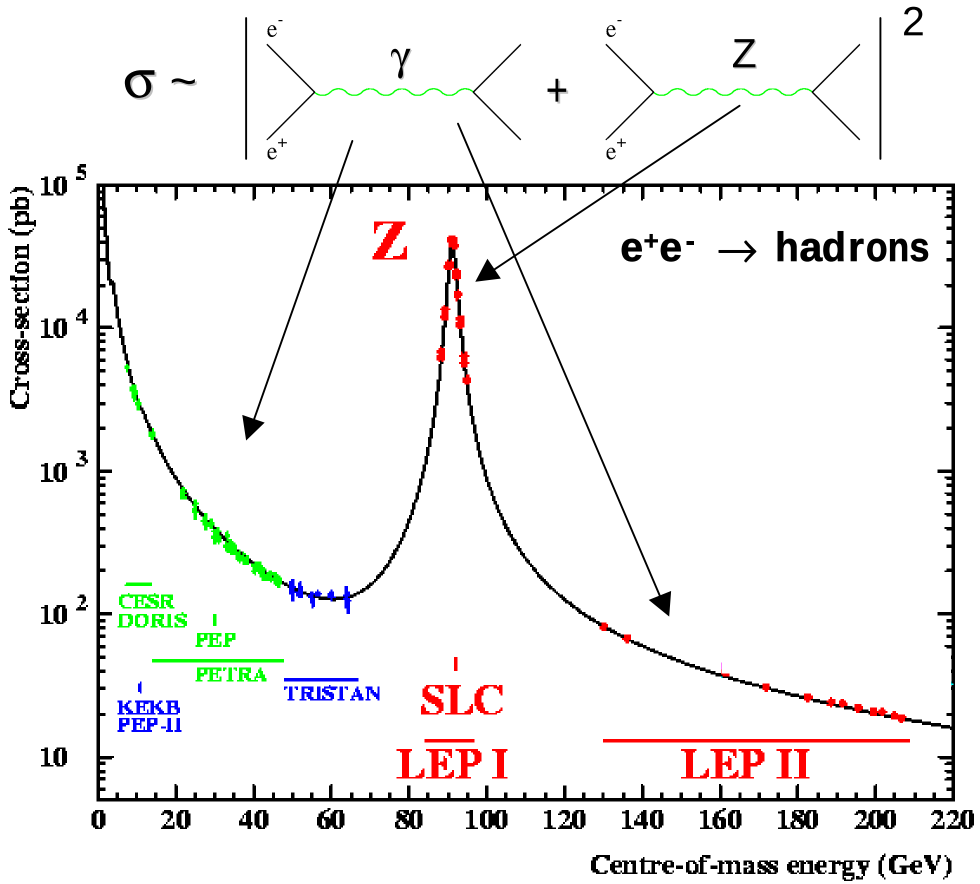
LEP2 ('96-2000) : $\sqrt{s} \rightarrow 209$ GeV → WW production, m_W, search for Higgs and new particles





LEP1 (CERN) and SLC (Stanford) e^+e^- Colliders start precision tests of SM at high energy $\sqrt{s} = E(e^-) + E(e^+) \approx m_Z \approx 90$ GeV





Achieved precision: better than 10^{-3}

Measured observables:

-- m_Z, Γ_Z

-- Z production cross-section

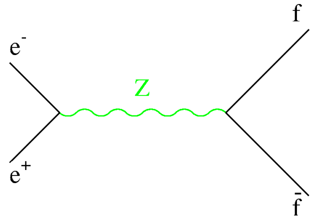
-- all properties of Z couplings to fermions:
e.g. decay modes, angular distributions

-- etc..

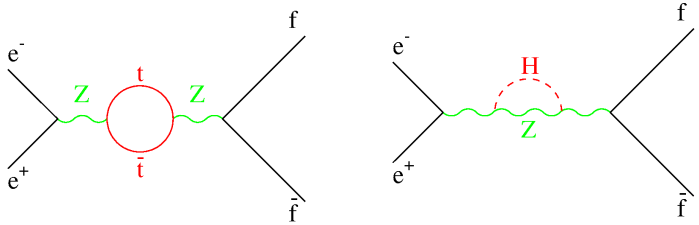
WHY precision tests of the SM at high energy ?

Test radiative quantum corrections (sensitive to heavy physics) :

Lowest order



Examples of radiative corrections



$\sim m_{top}^2$ $\sim \log m_H$

$\rightarrow$ $O_i \sim f_i\,(\alpha_{EM}, G_F, m_Z, m^2_{top}, \log m_H, \ldots)$

$\rightarrow$ deduce masses of particles not directly produced

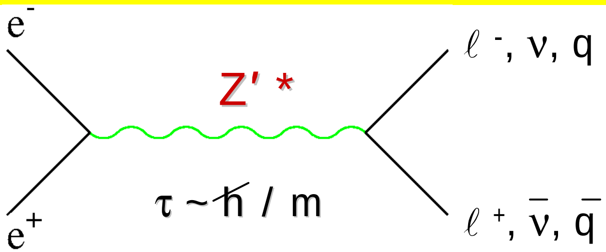
R.C. modify observables by $\approx$ % :
experimental precision of $\approx$‰ and improved theoretical needed

$m_{top} \sim 175$ GeV predicted by LEP/SLC in '94 before direct discovery at Tevatron $p\bar{p}$ Collider in '94-'95

New Physics can also contribute to loops (e.g. SUSY particles if light)

Beyond Z peak, search indirectly for New Physics by looking for deviations from SM

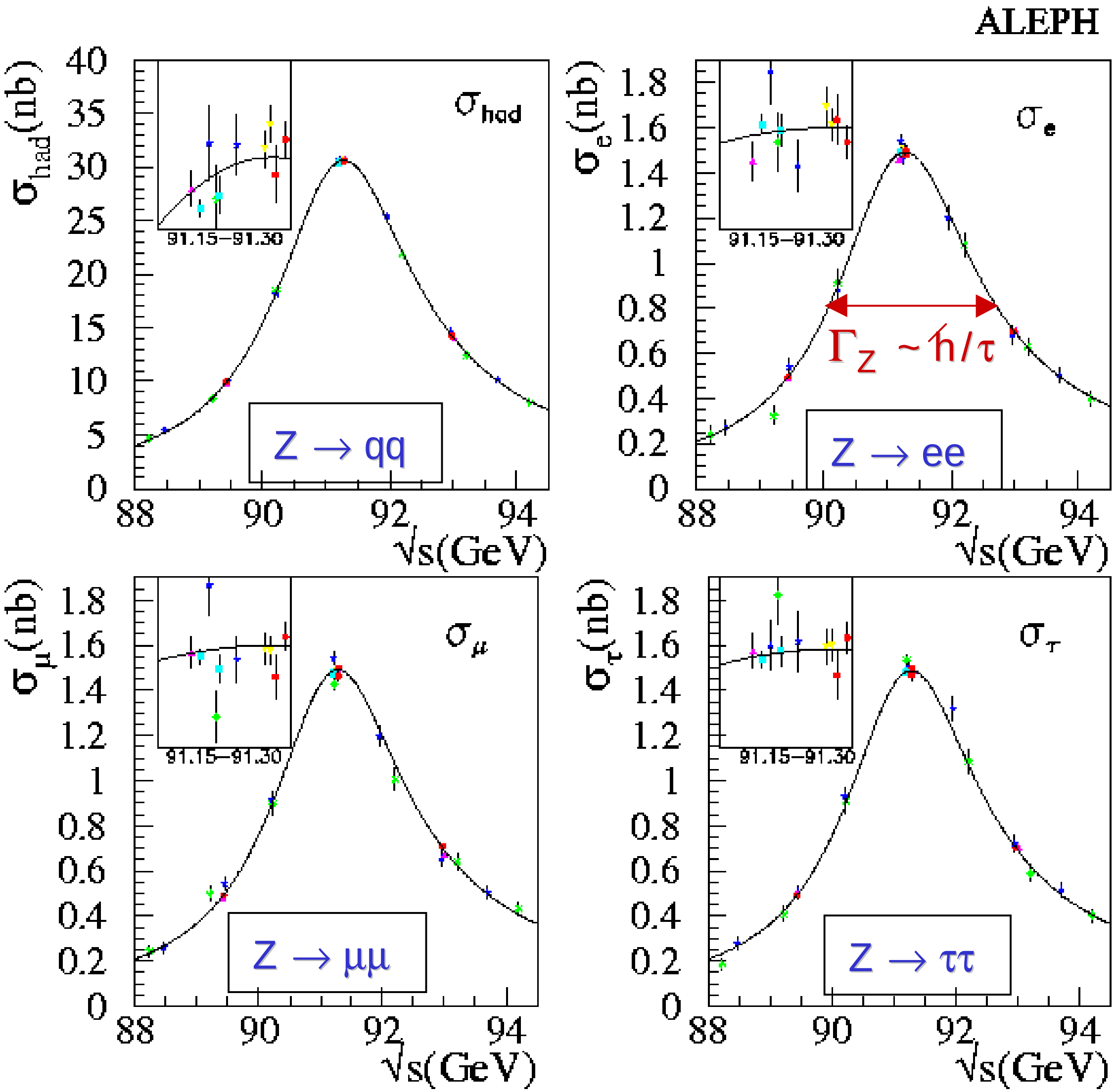
e.g. additional weak bosons



interferes with SM processes
$\rightarrow$ deviations from SM expectations

Measurement of the Z lineshape

- $\sqrt{s}$ varied from 88 to 94 GeV
- measure cross-section vs $\sqrt{s}$
- lines are fits to Z lineshape

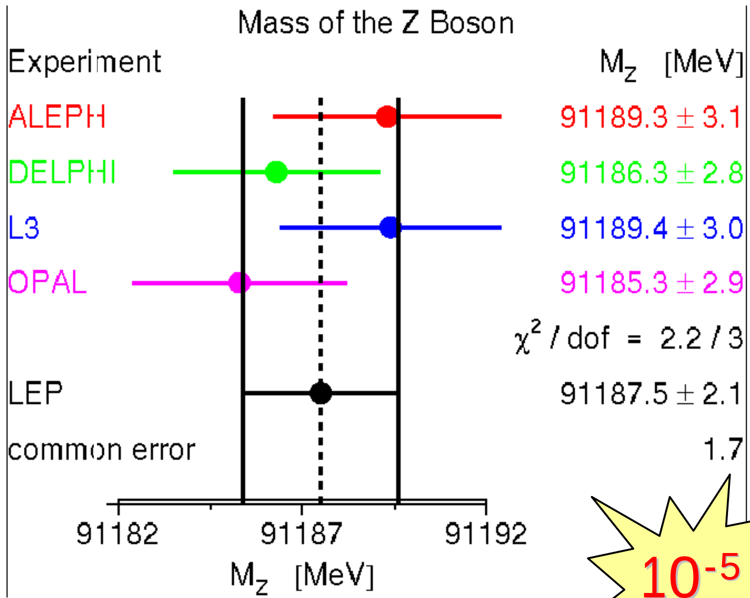


measure

measure

$\downarrow$

m_Z, Γ_Z, σ^{peak}



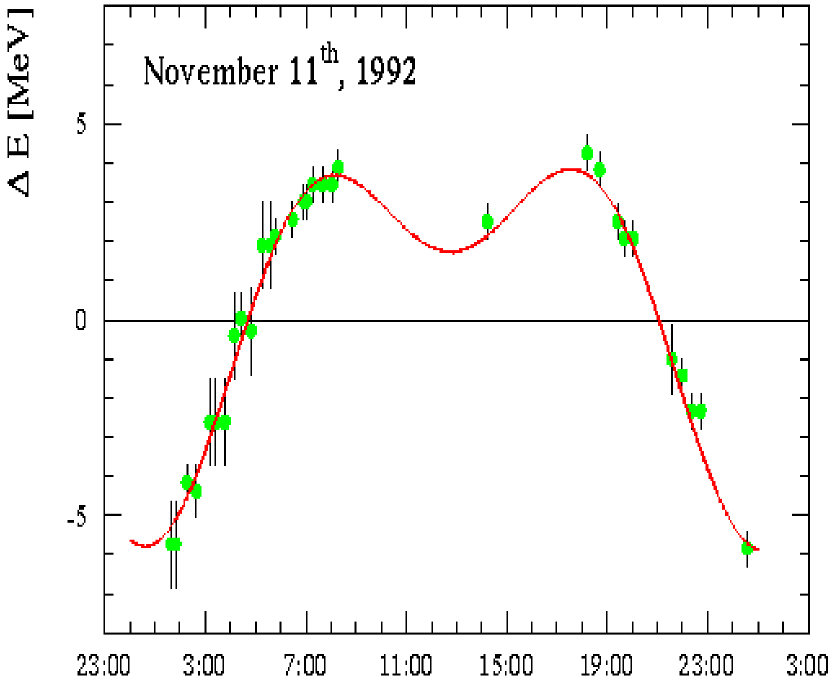
10^{-5}

Dominant error: knowledge of LEP beam energy ($\Delta E_{beam} \approx 1.7$ MeV)

Measurement of the LEP beam energy : two subtle effects ...

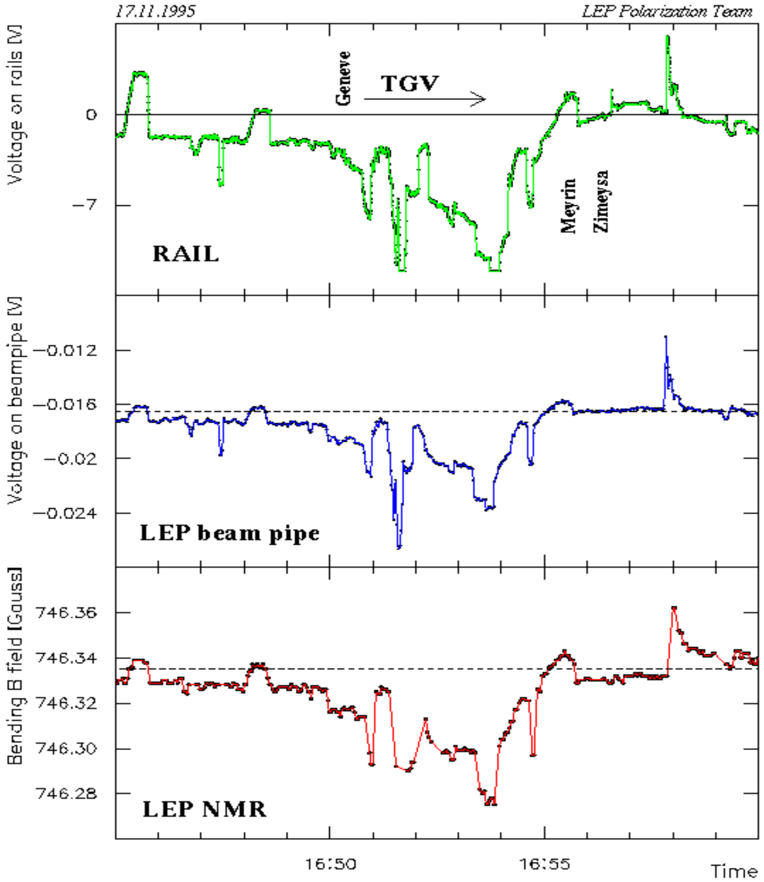
The effect of the moon:

LEP at midnight is ~300 μm longer than at noon → $e^{\pm}$ see less B-field → E is smaller



The effect of the TGV:

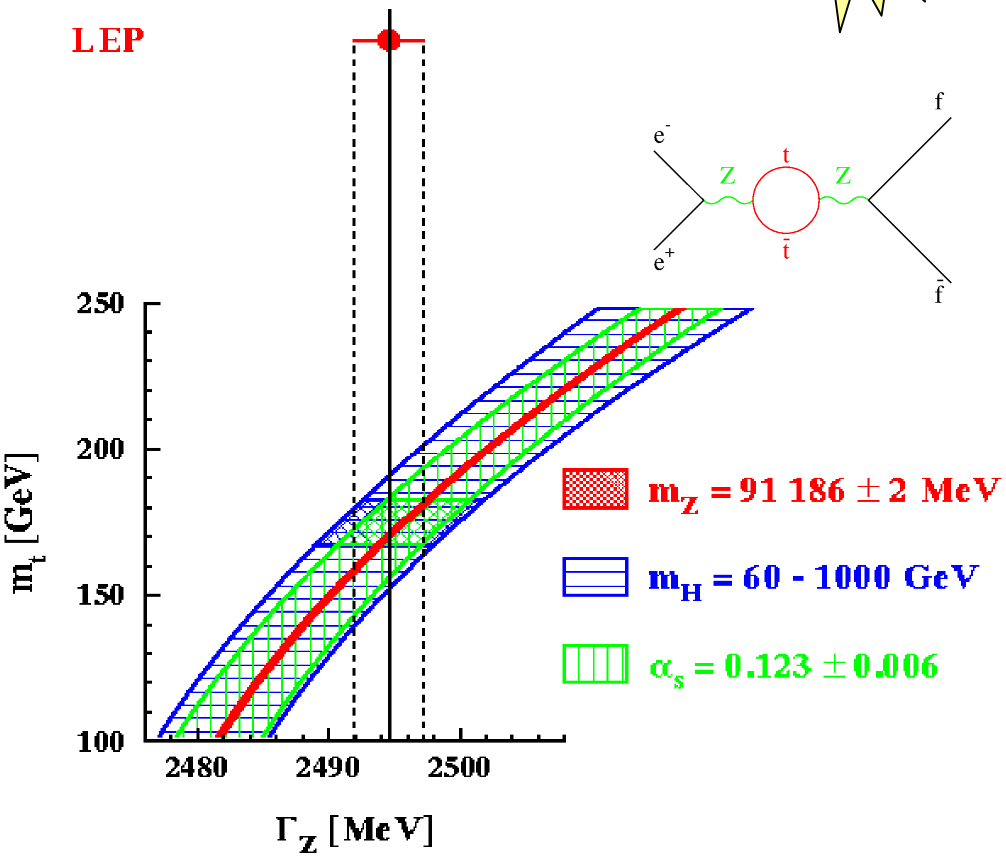
Currents induced on LEP beam pipe change B-field



Up to ~ 20 MeV variations but effects well understood → corrected

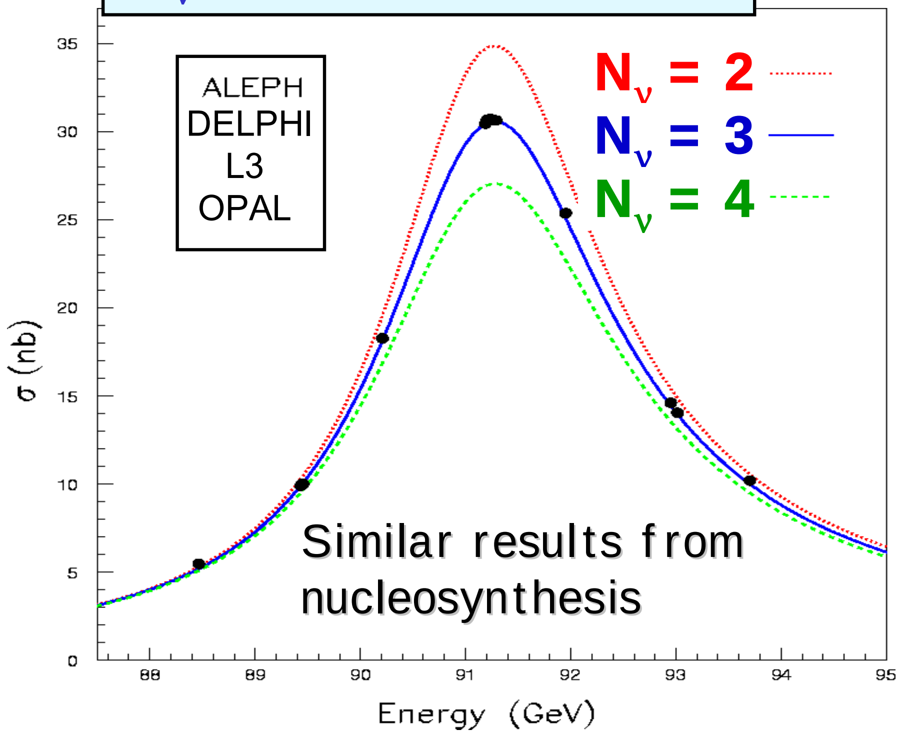
Z width and the number of neutrinos

Γ_Z = 2495.2 ± 2.3 MeV 10^{-3}



N. of light neutrinos ($m_\nu \ll m_Z/2$):

N_ν = 2.984 ± 0.008



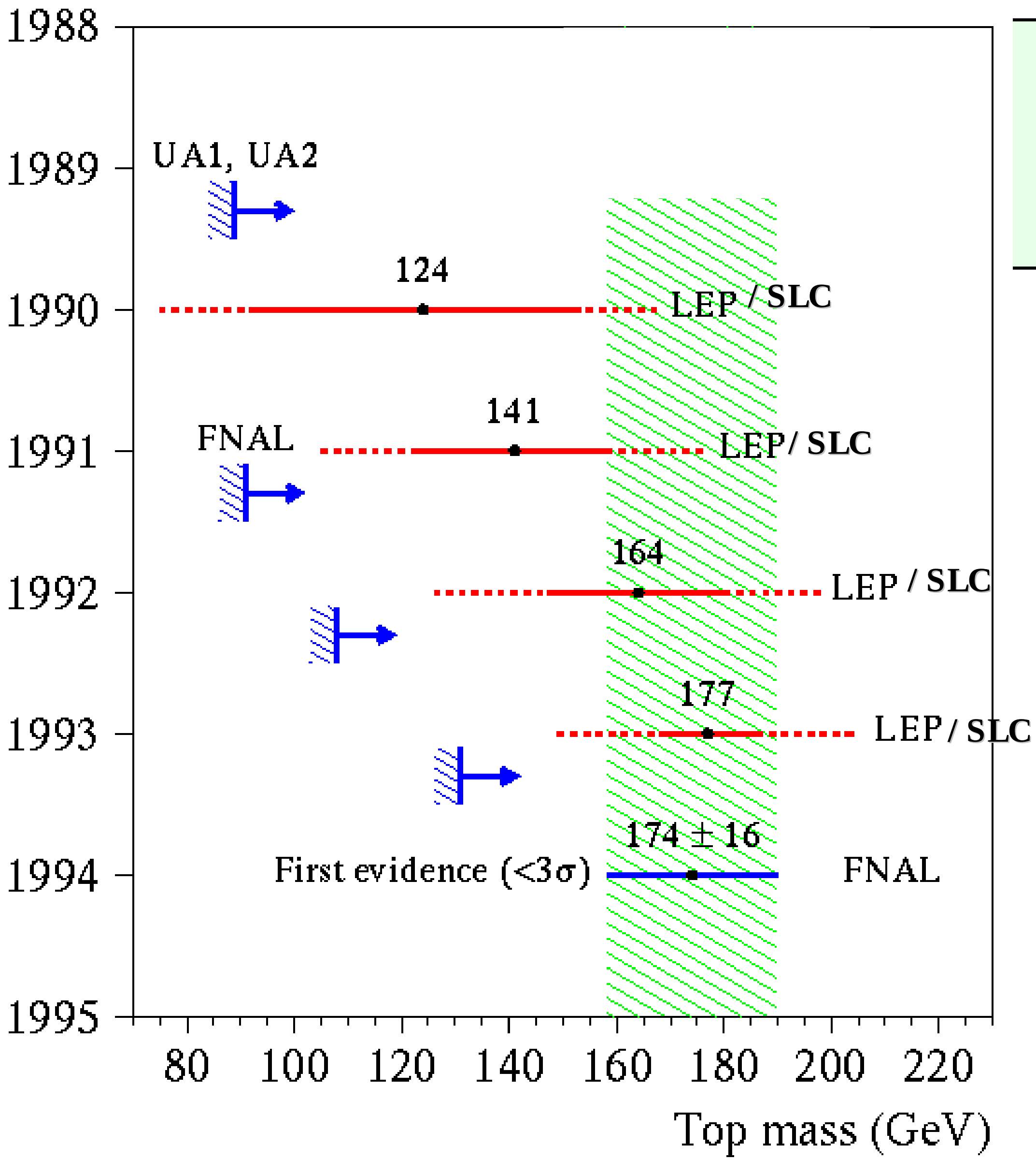
Similar results from nucleosynthesis

m_{top}^{EW} = 180.8 ± 9.7 GeV from EW measurements

m_{top}^{direct} = 174.3 ± 5.1 GeV from Tevatron

Radiative corrections exist as predicted by SM

Prediction of m_{top} from EW measurements



<u>March 1994</u>:
m_{top}^{EW} = 177 ± 10 GeV
predicted by LEP & SLC

<u>April 1994</u>:
first direct evidence at
Fermilab pp Collider

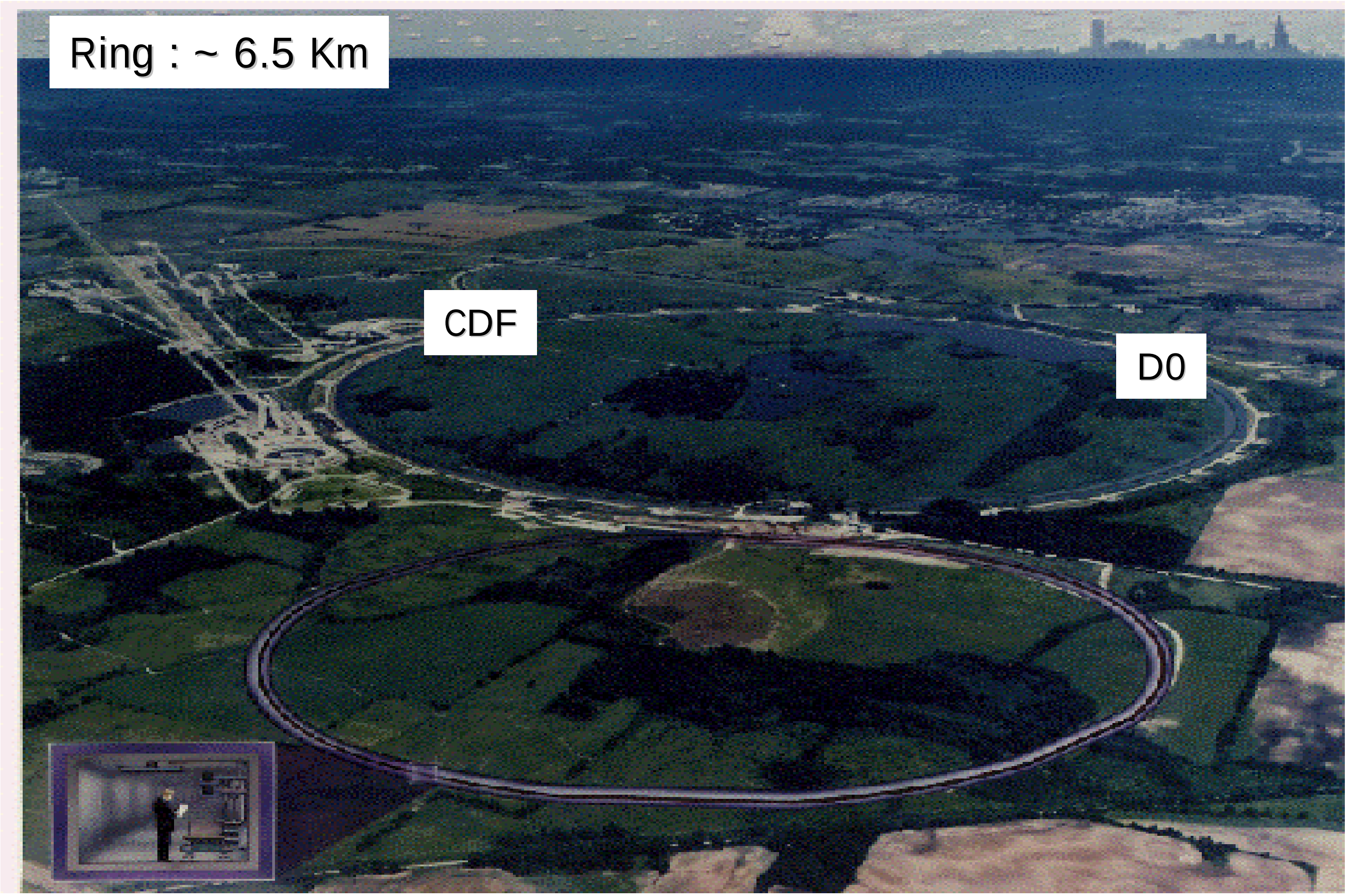
In 2002:

m_{top}^{EW} = 180.8 ± 9.7 GeV
m_{top}^{direct} = 174.3 ± 5.1 GeV

Radiative corrections
exist as predicted by SM

The Tevatron $\bar{p}p$ Collider at Fermilab

$\sqrt{s} \approx 2$ TeV



Run 1 ('89-'96) : ≈ 200 top events → discovery of top

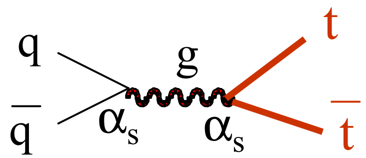
≈ 80 000 W events measurement of m_W and m_{top}

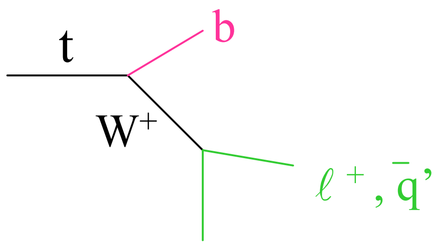
Run 2 ('01-'07?) ≥ 100 times more data →

better measurements of m_W and m_{top},

searches for Higgs and new particles

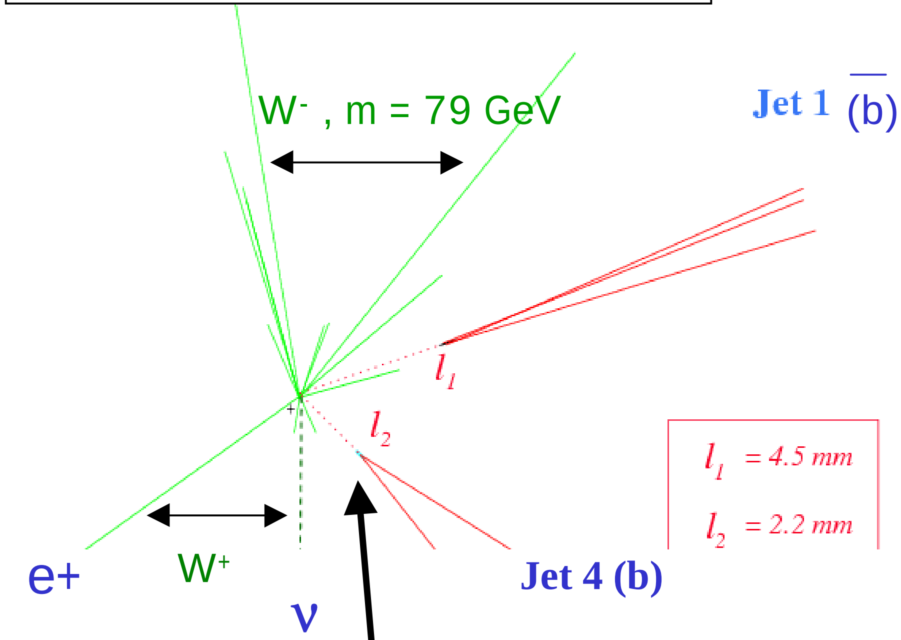
The top quark at the Tevatron



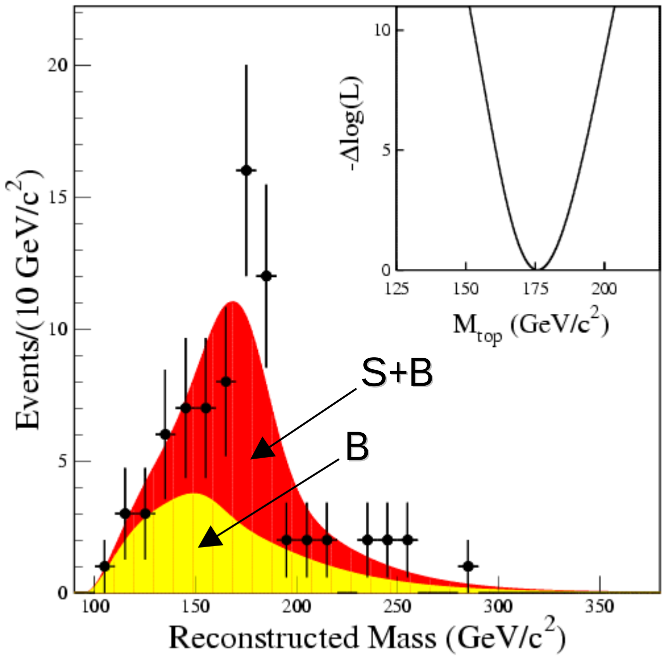


Heaviest particle observed so far (and m_{top}-m_b ~ 170 GeV) → clues about origin of masses ?

$t\bar{t} \to bW\bar{b}W \to b\ell\nu\bar{b}jj$ event from CDF data



CDF : $t\bar{t} \to b\ell\nu\, bjj$ events



<u>Secondary vertices</u>

τ (b-hadrons) ~ 1.5 ps → decay at few mm from primary vertex detected with high-granularity Si detector (b-tagging)

m_{top} (CDF + D0) = 174.3 ± 5.1 GeV

3%

↑ statistics, calorimeter calibration

Measurement of the W mass

from data
+ theory

$$m_W^{\,2} = \left(\frac{\pi\,\alpha_{EM}\,(m_Z)}{\sqrt{2}\,G_F} \right) \frac{1}{\sin^2\theta_W\,(1-\Delta r)}$$

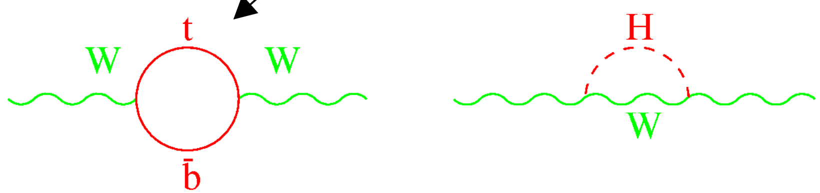
from μ decay

Weinberg angle,
from LEP

$$\cos^2\theta_W = \frac{m_W^{\,2}}{m_Z^{\,2}\,\rho}$$

ρ = 1 from
SM Higgs
mechanism

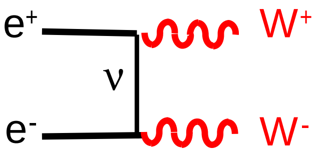
radiative corrections
$\Delta r = f\,(m^2_{top},\ \log m_H) \approx 3\%$

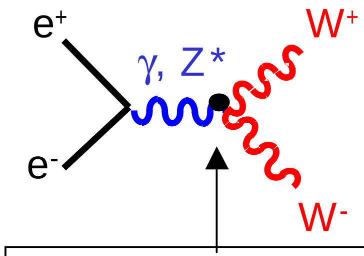


➡ measurements of m_{top} and m_W constrain m_H

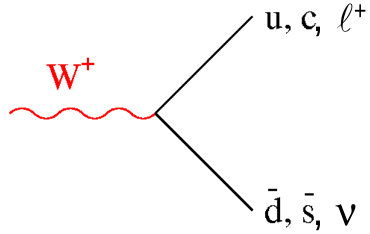
W mass measured at LEP2 and Tevatron

LEP2 : $\sqrt{s} > 2\,m_W$ since '96





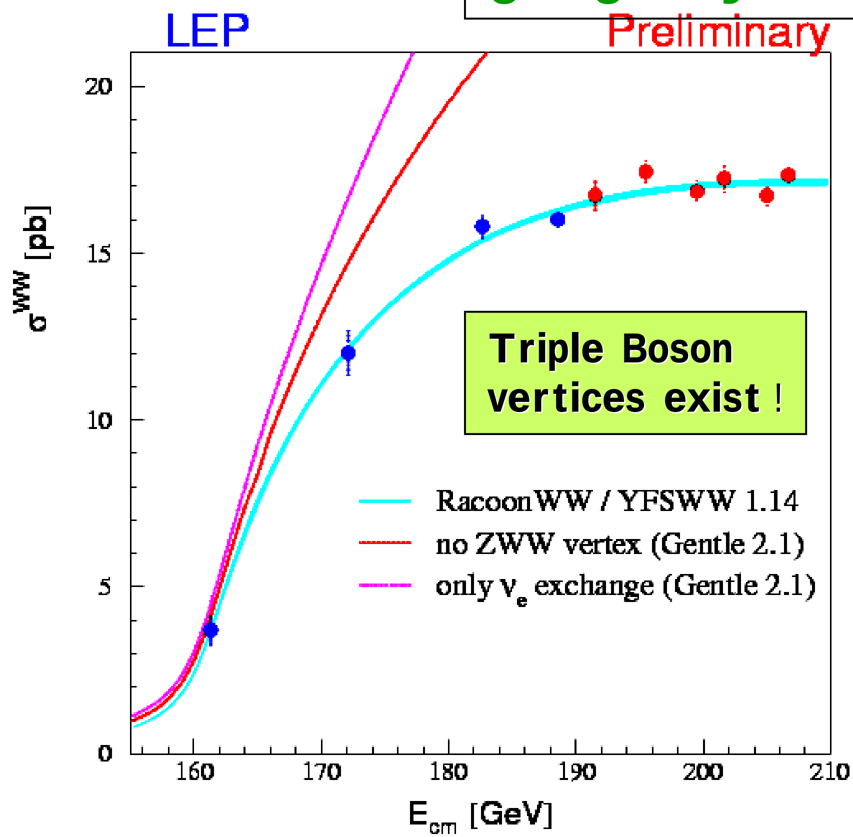
Triple boson vertices related to SM SU(2) gauge symmetry



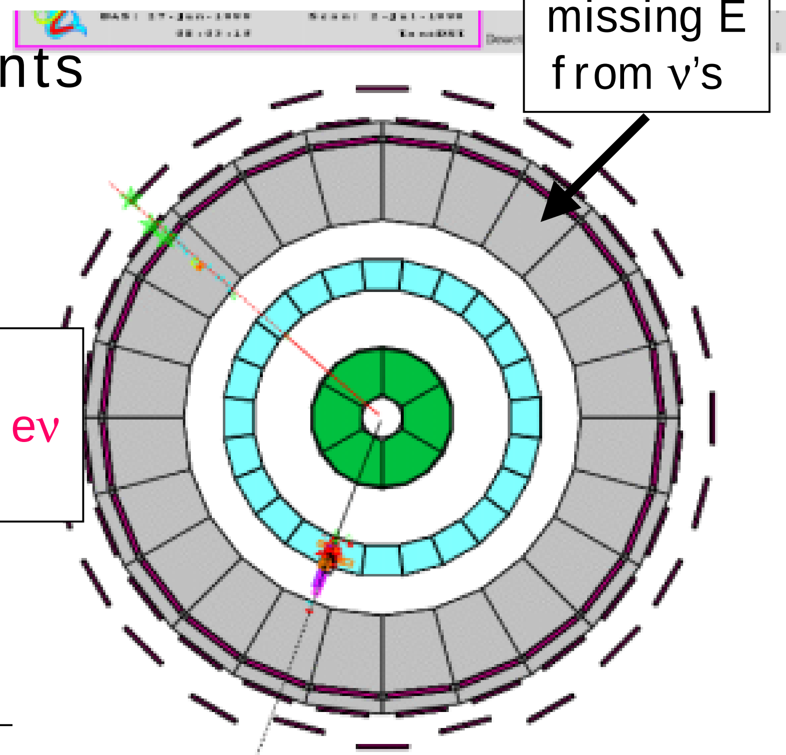
$W \to e\nu$	$\approx 10\%$
$W \to \mu\nu$	$\approx 10\%$
$W \to \tau\nu$	$\approx 10\%$
$W \to qq'$	$\approx 70\%$

measured to 10^{-3}-10^{-2}

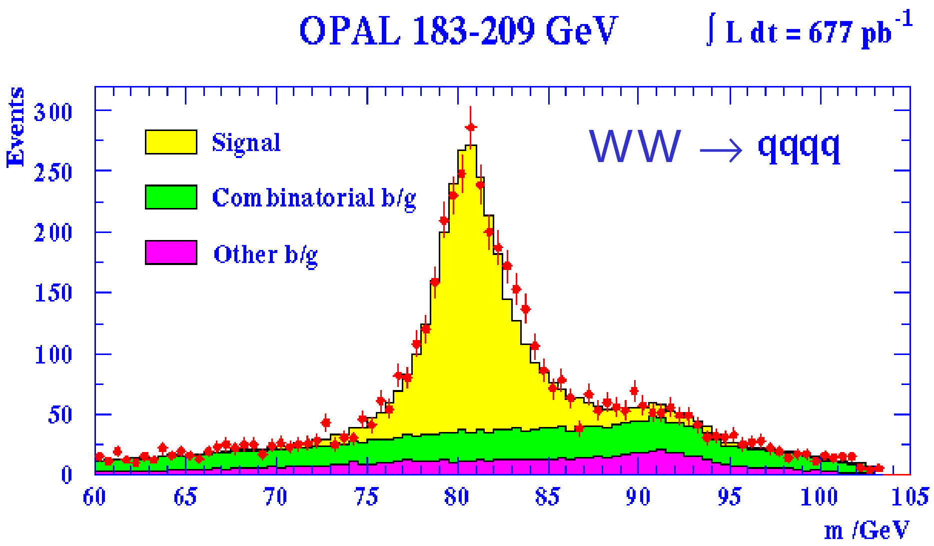
3 colours per quark

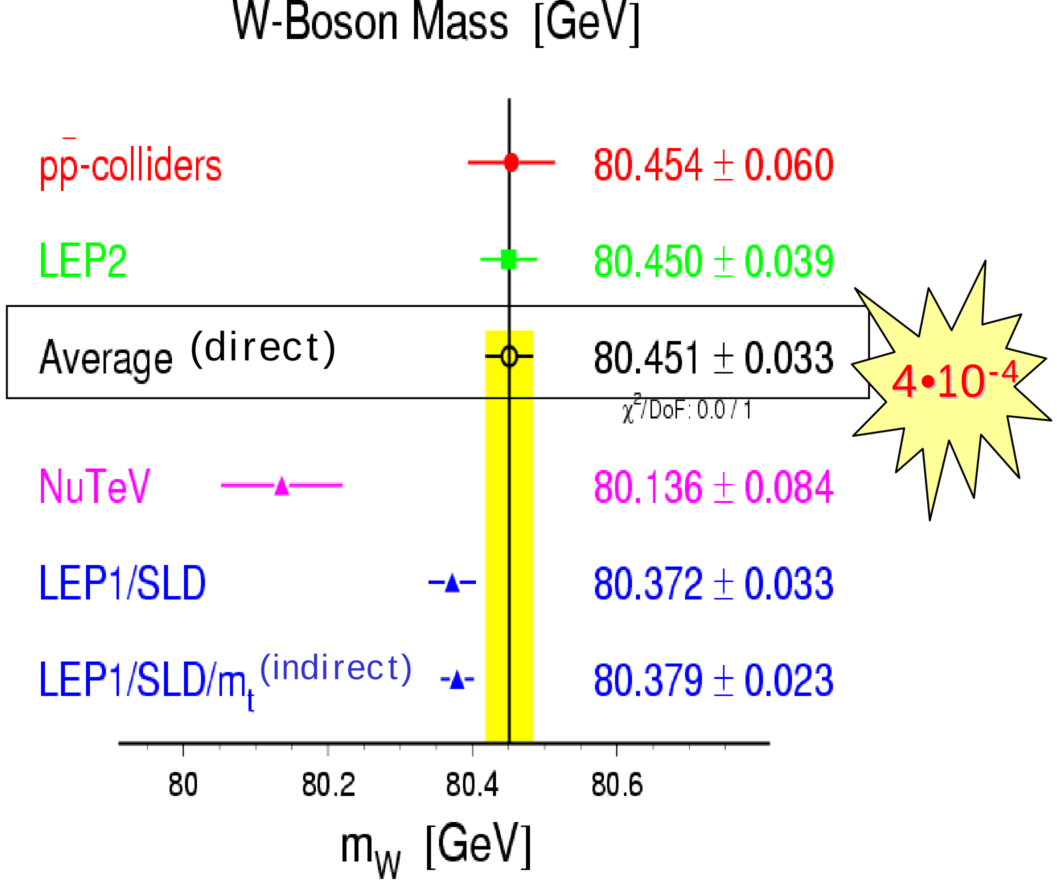


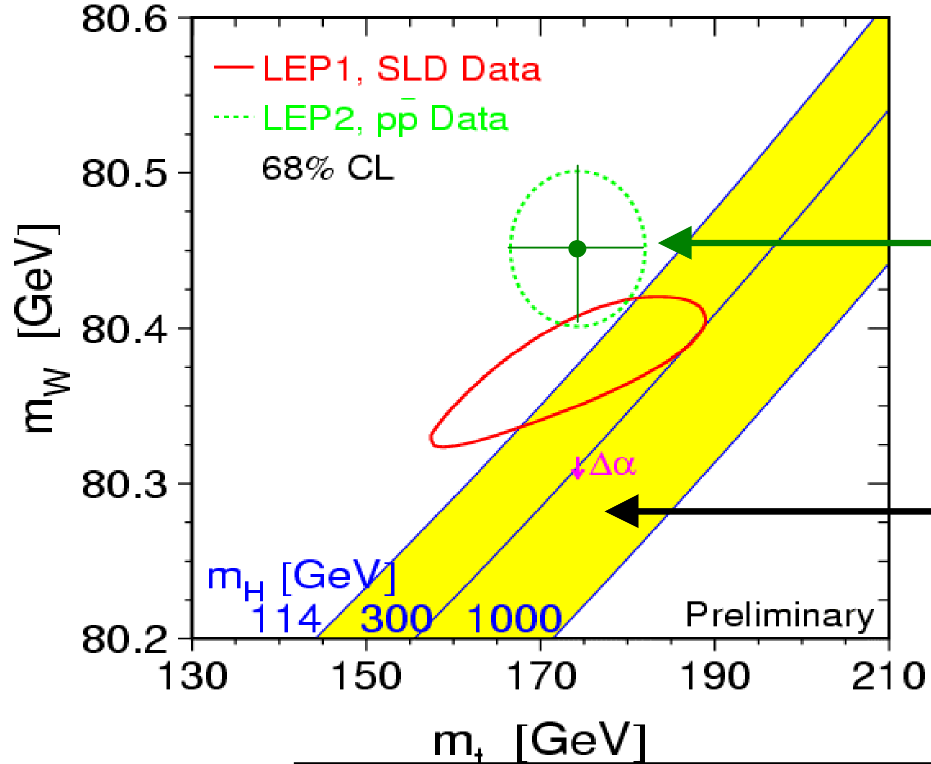
10000 WW events collected per experiment



DELPHI: $WW \to \mu\nu\ e\nu$ event







Direct measurements

m_H dependence in SM through radiative corrections

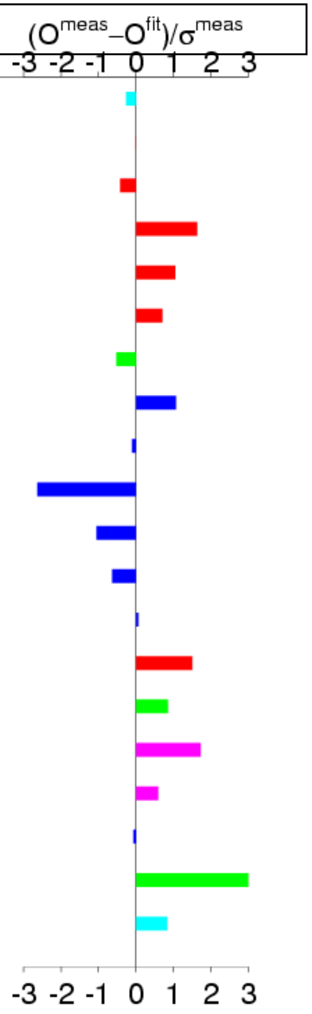
Δr (measured) = 0.0311 ± 0.0020 (~ 15σ from 0)

→ light Higgs is favored

Global fit of the SM to data

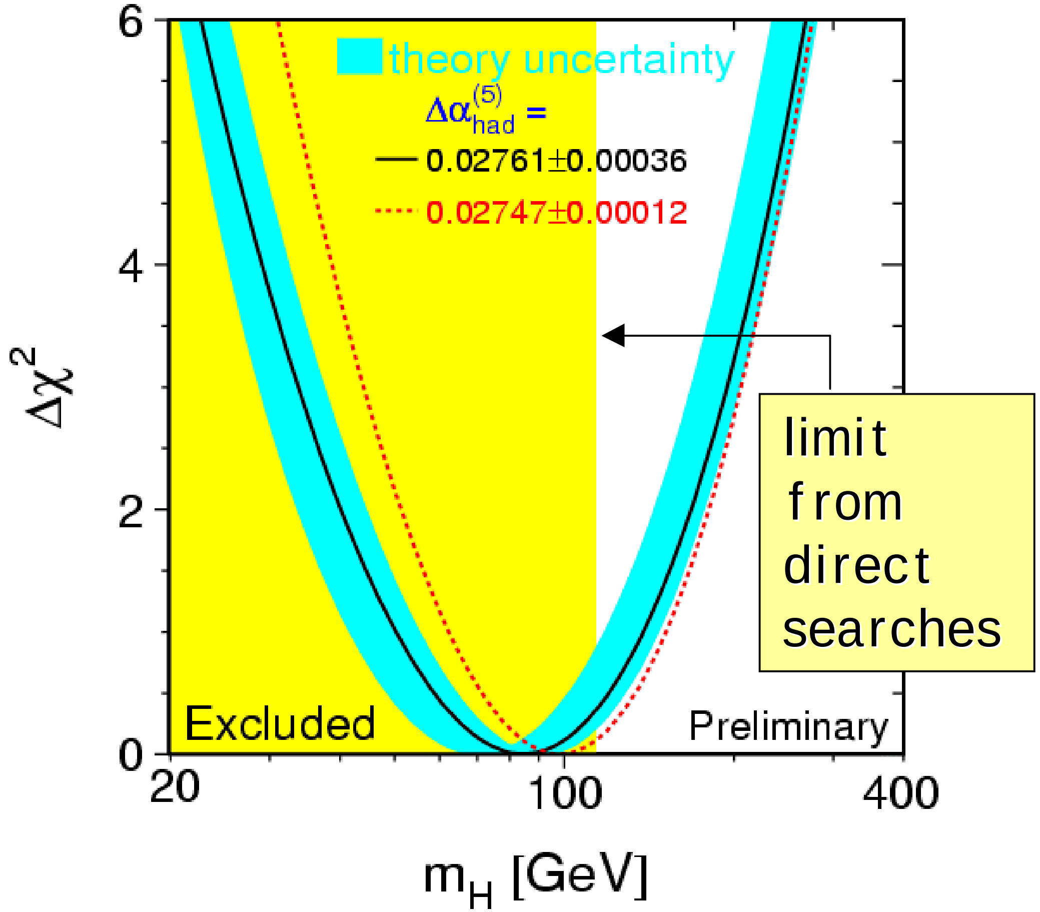
Winter 2002 preliminary

	Measurement		Pull
→	$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.27
→	m_Z [GeV]	91.1875 ± 0.0021	.01
→	Γ_Z [GeV]	2.4952 ± 0.0023	-.42
→	σ^0_{had} [nb]	41.540 ± 0.037	1.63
	R_l	20.767 ± 0.025	1.05
	$A^{0,l}_{fb}$	0.01714 ± 0.00095	.70
	$A_l(P_\tau)$	0.1465 ± 0.0033	-.53
	R_b	0.21646 ± 0.00065	1.06
	R_c	0.1719 ± 0.0031	-.11
	$A^{0,b}_{fb}$	0.0994 ± 0.0017	-2.64
	$A^{0,c}_{fb}$	0.0707 ± 0.0034	-1.05
	A_b	0.922 ± 0.020	-.64
	A_c	0.670 ± 0.026	.06
	A_l(SLD)	0.1513 ± 0.0021	1.50
	$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
→	m_W [GeV]	80.451 ± 0.033	1.73
	Γ_W [GeV]	2.134 ± 0.069	.59
→	m_t [GeV]	174.3 ± 5.1	-.08
→	$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
	Q_W(Cs)	-72.39 ± 0.59	.84



from NuTeV (νN scattering)

→ deduce m_H which gives best χ^2



Largest discrepancies (two observables): ≤ 3σ

P (χ^2) ~ 2% all

P (χ^2) ~ 14% without NuTeV

(affected by some theoretical uncertainties)

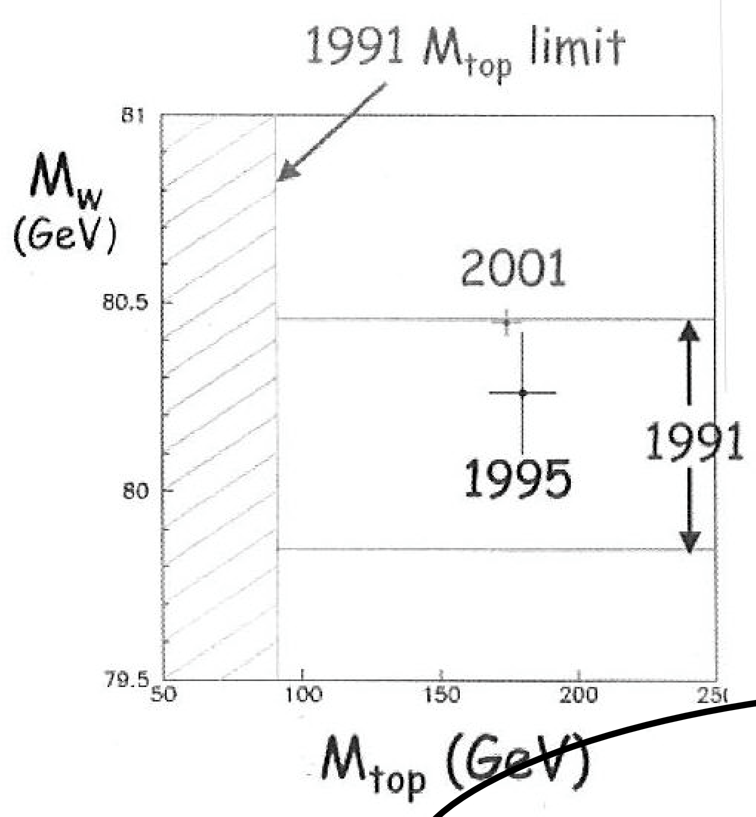
$m_H^{EW} = 85^{+54}_{-34}$ GeV

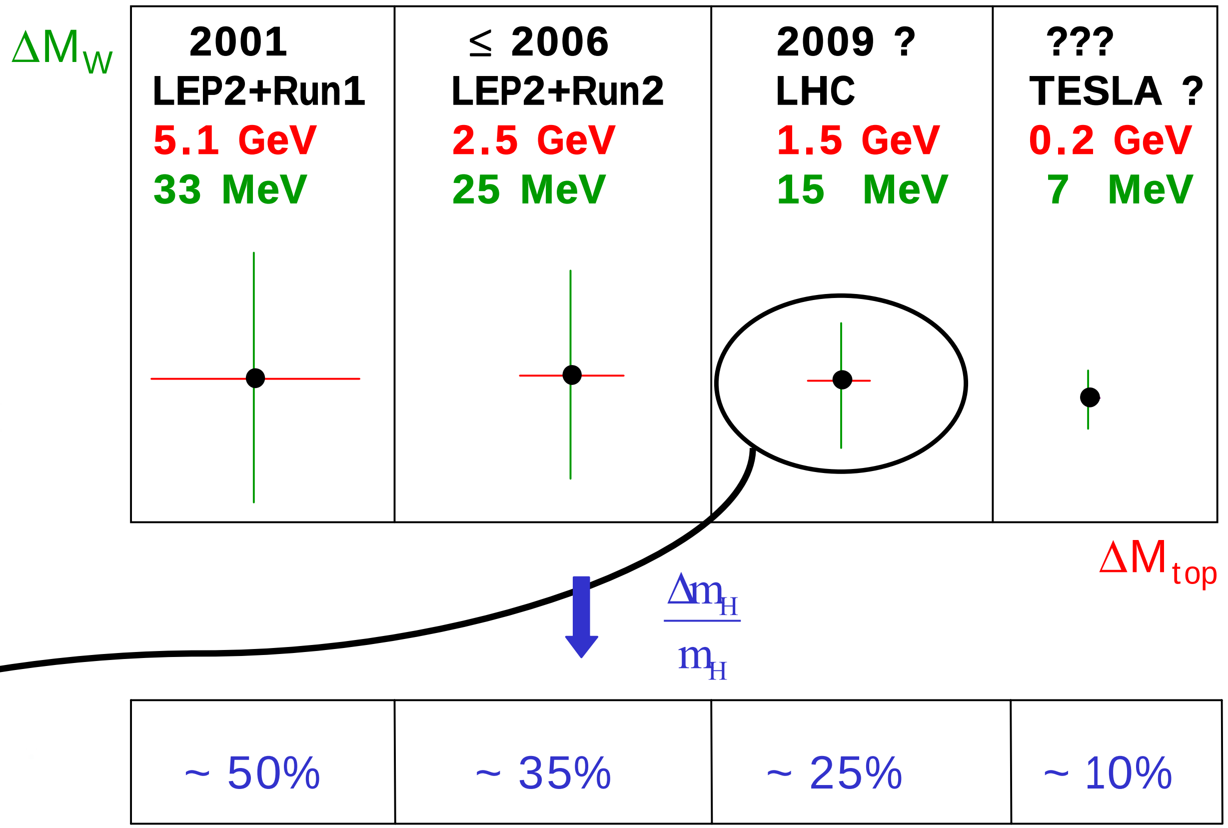
$m_H^{EW} < 196$ GeV 95% C.L.

radiative corrections ~ log m_H

The last ~ 10 years …

… and the future



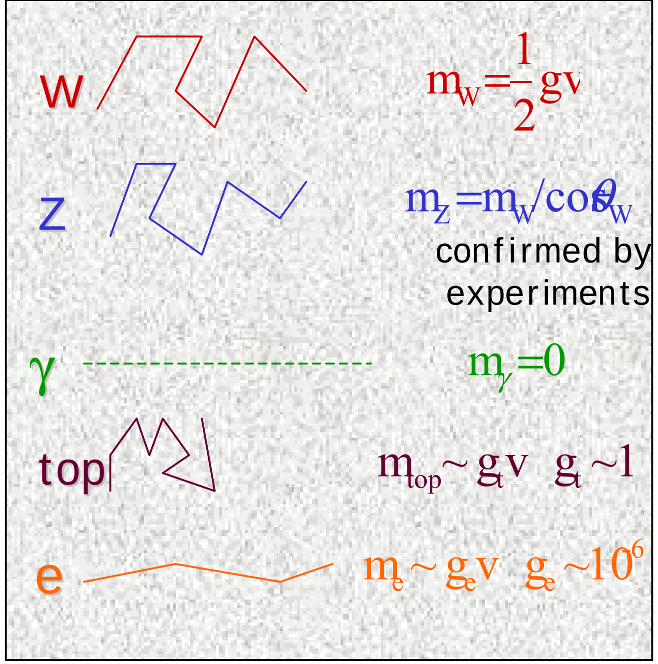


LHC, pp, $\sqrt{s}$= 14 TeV , L= 10^{34} cm^{-2} s^{-1}

	LHC events in 1 yr	Previous machines total statistics
Z	10^8	LEP: 10^7 in ~ 10 yrs
W	10^9	FNAL: 10^7 in ~7 yrs
top	10^8	FNAL: 10^5 in ~7 yrs

If Higgs discovered →
comparison of measured m_H
with indirect measurement
→ important consistency
checks of EWSB

Where is the Higgs ?



- Needed in SM to generate particle masses

-- Higgs field fills vacuum

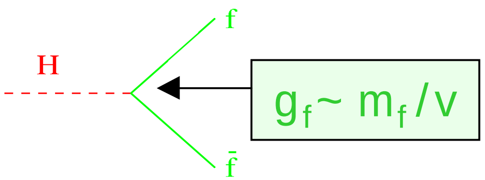
-- vacuum ground state : $v \approx 250$ GeV $\neq 0$

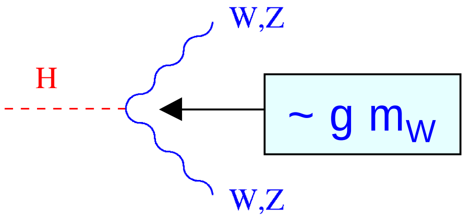
-- particles interact with non-empty vacuum

$\rightarrow$ get mass

- Higgs couples to fermions and bosons

the stronger the interaction the larger the mass :





- Higgs mass not predicted. Today we know:

-- 114 GeV (from LEP) < m_H < 1000 GeV (from theory)

-- EW data prefer light Higgs (≤ 200 GeV)

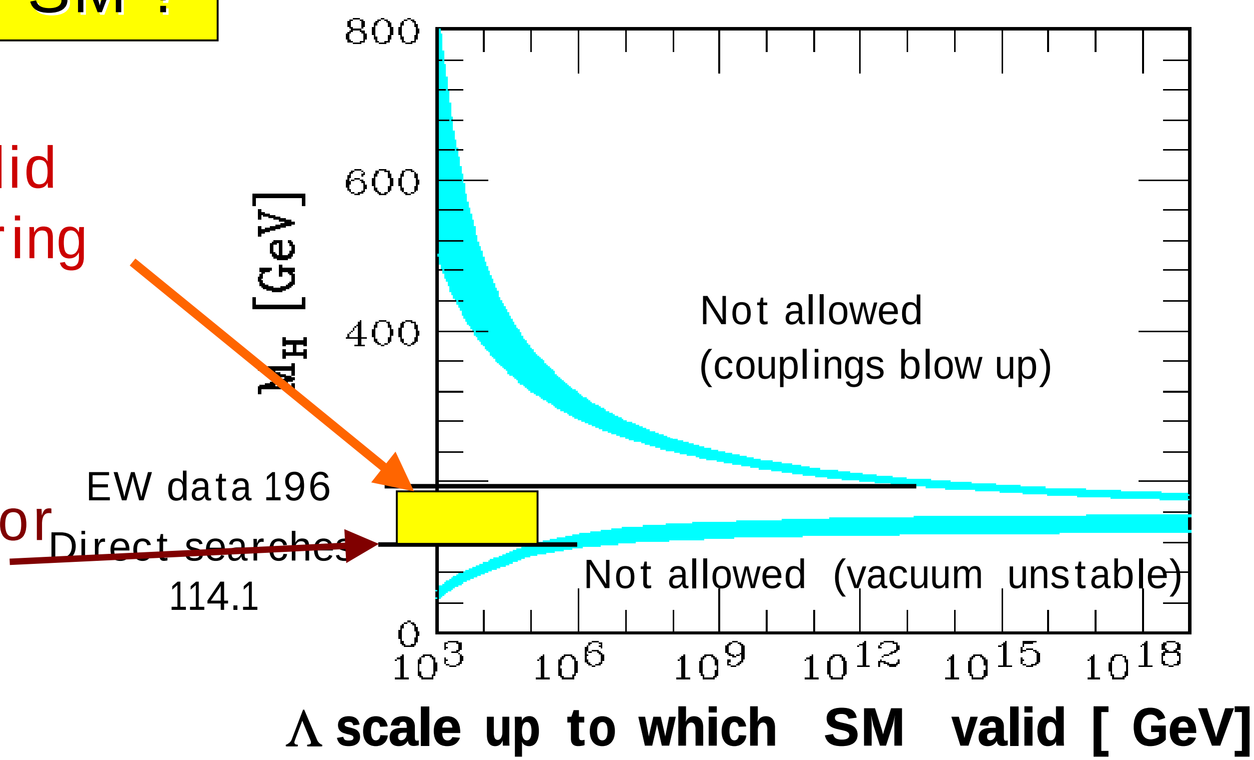
-- LEP " hint " for $m_H \sim 115$ GeV ?

Note : contribution of EW vacuum to cosmological constant ($\sim v^4$) is ~ 55 orders of magnitudes too large

What is wrong with the SM ?

130 < mH < 180 GeV : SM valid up to Λ ~ Mplanck (VERY boring ...)

$m_H \approx$ 115 GeV : New Physics for $\Lambda < 10^6$ GeV

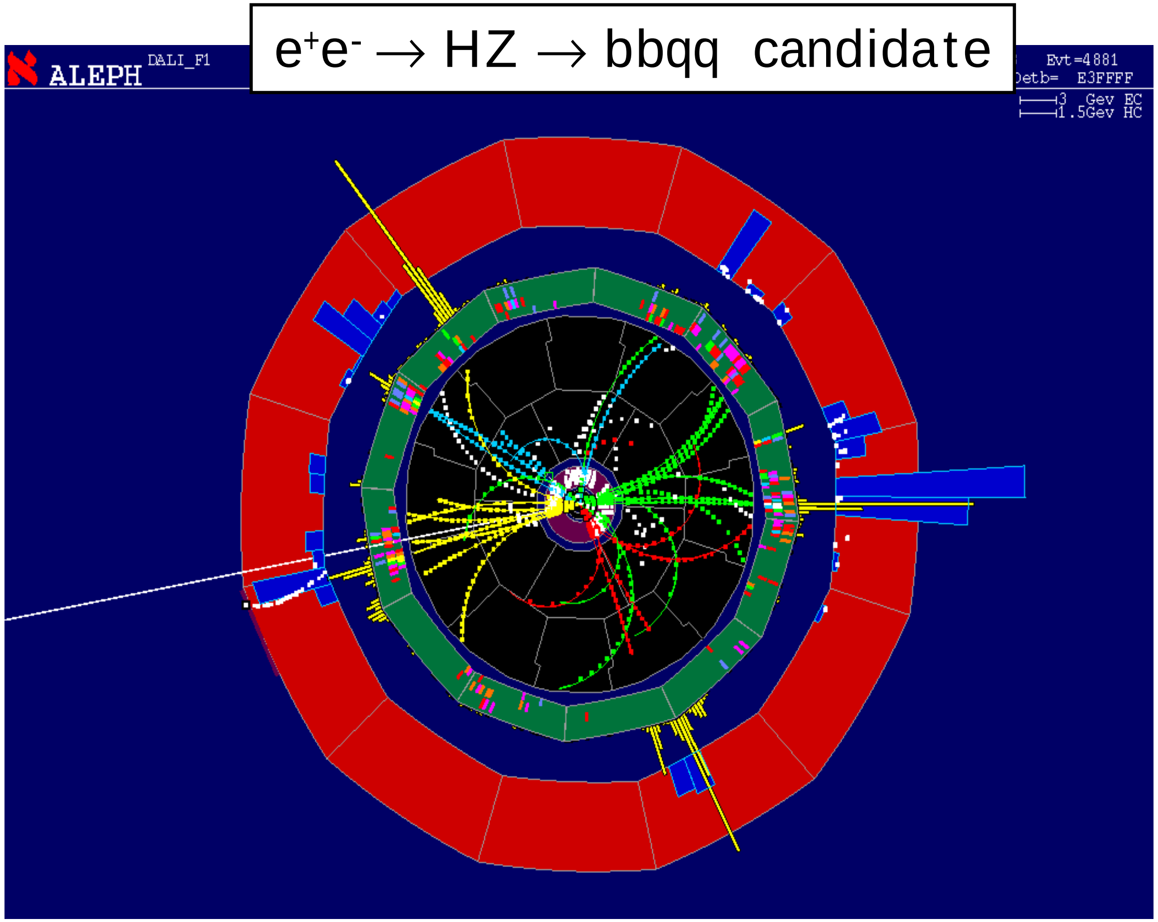


- "Hierarchy" : Why $M_{EW} / M_{Planck} \sim 10^{-17}$?
- "Naturalness" : If Λ >> works only with very accurate fine tuning in radiative corrections
- "Vacuum expectation value" contribution to the cosmological constant too large by 10^{55}

Where is the Higgs ?

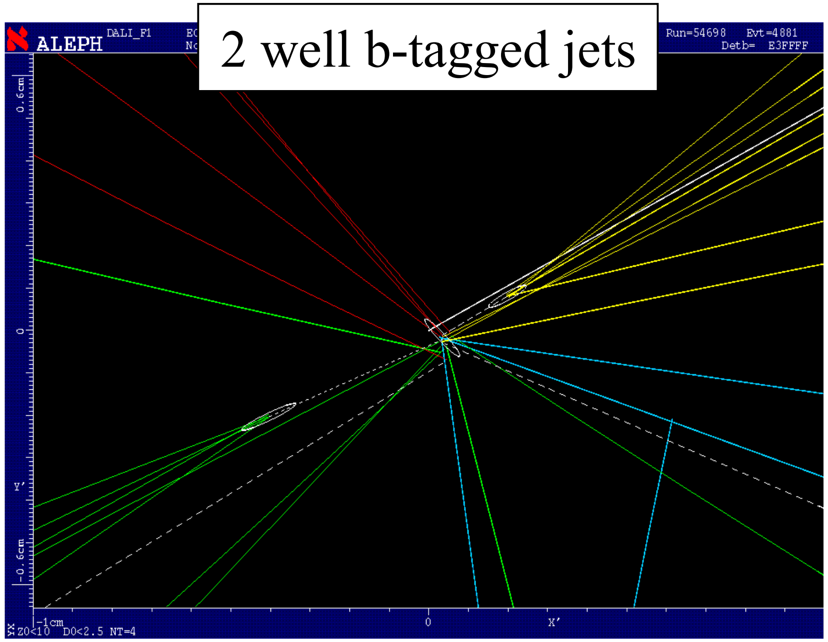
In year 2000 (last year of LEP) few events observed (2 σ effect)

Best candidate : collected by ALEPH on 14/6/2000 at $\sqrt{s}$ = 206.7 GeV

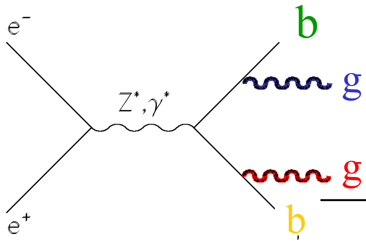


$m(j_1, j_2) = 92.1$ GeV

$m_H(j_3\, j_4) = 114.3 \pm 3$ GeV

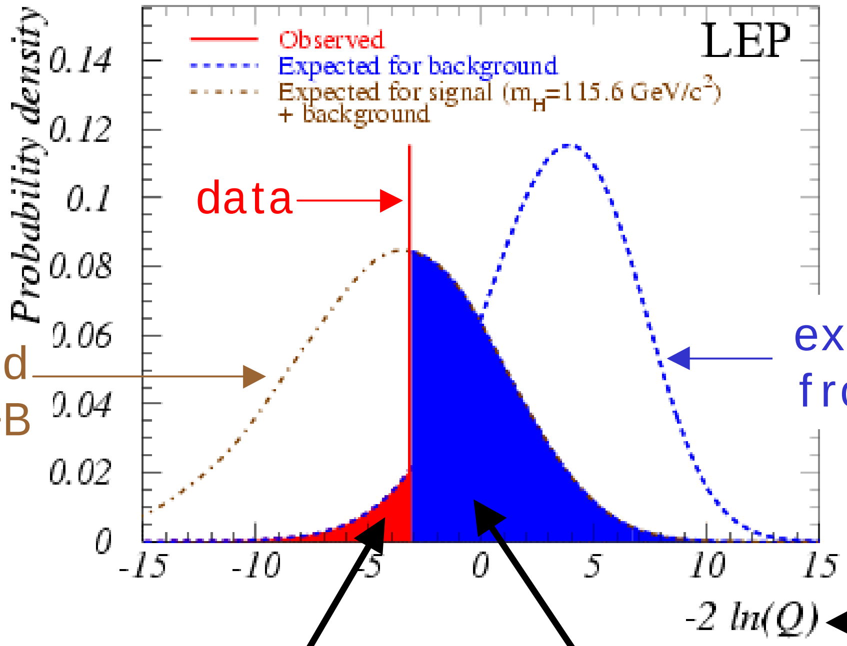


Background interpretation: bbgg



P ~ 1%

A ≈ 2σ excess ....



variable related to event features (e.g. b-tagging)

probability of B fluctuation : 3.5%
→ ~ 2σ excess

probability of S+B : 43%
Note : consistent with expectation for signal with m_H~ 115 GeV

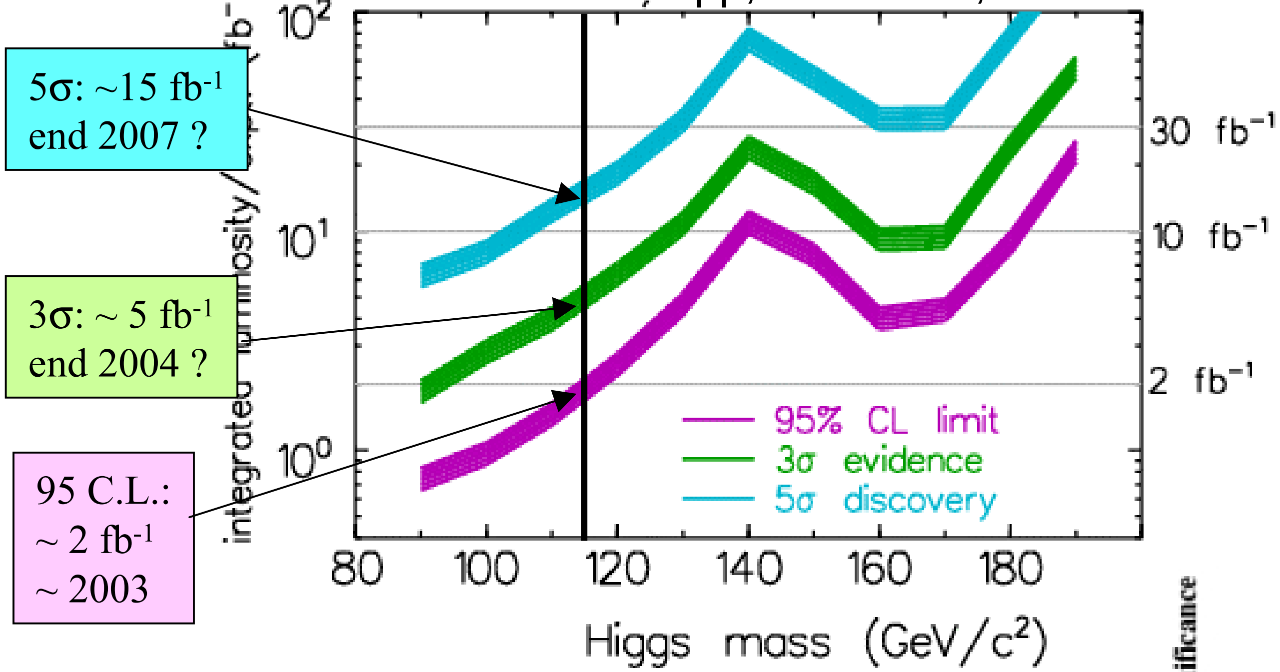
not enough to claim discovery
need 5σ, i.e. P (B fluctuation) ~ 10^{-7}

Mass lower limit :
m_H > 114.1 GeV 95% C.L.

The future

More difficult than at LEP
if Higgs light (small S/B)

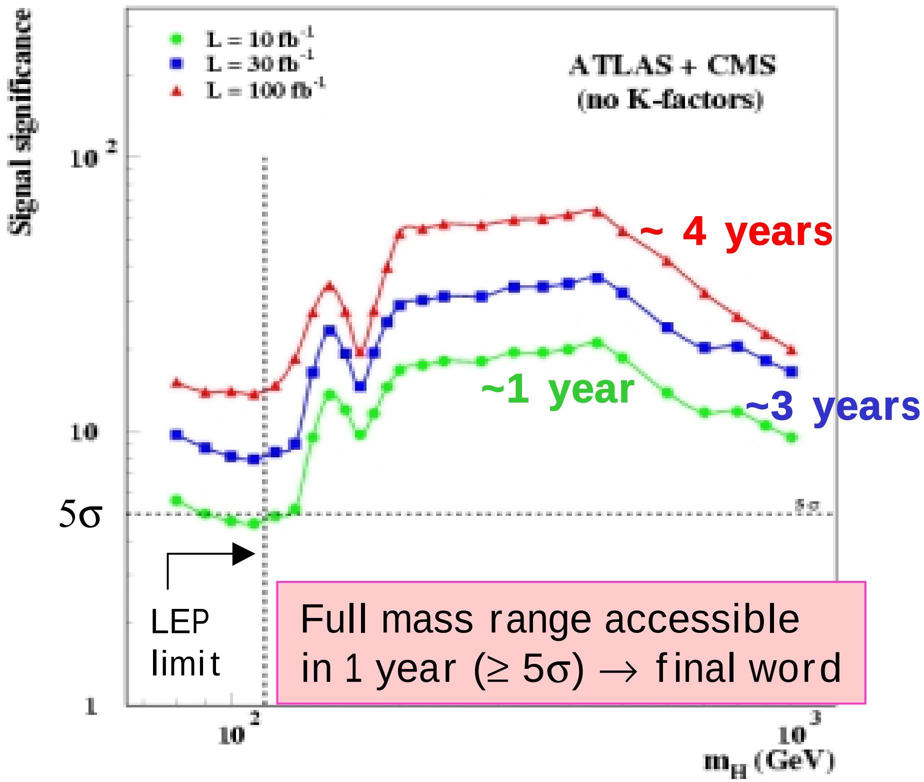
Tevatron Run 2 $p\bar{p}$, $\sqrt{s}$=2 TeV, started



By end 2007 (?) :
- -- 5σ discovery if $m_H \leq 120$ GeV
- -- 95% C.L. exclusion up to $m_H \sim 185$ GeV

2007-2008 : Tevatron-LHC competition
for Higgs discovery if $m_H \leq 120$ GeV

LHC pp, $\sqrt{s}$=14 TeV, start 2007 ?



All this calls for

A more fundamental theory
of which SM is low-E approximation ⇒ **New Physics**

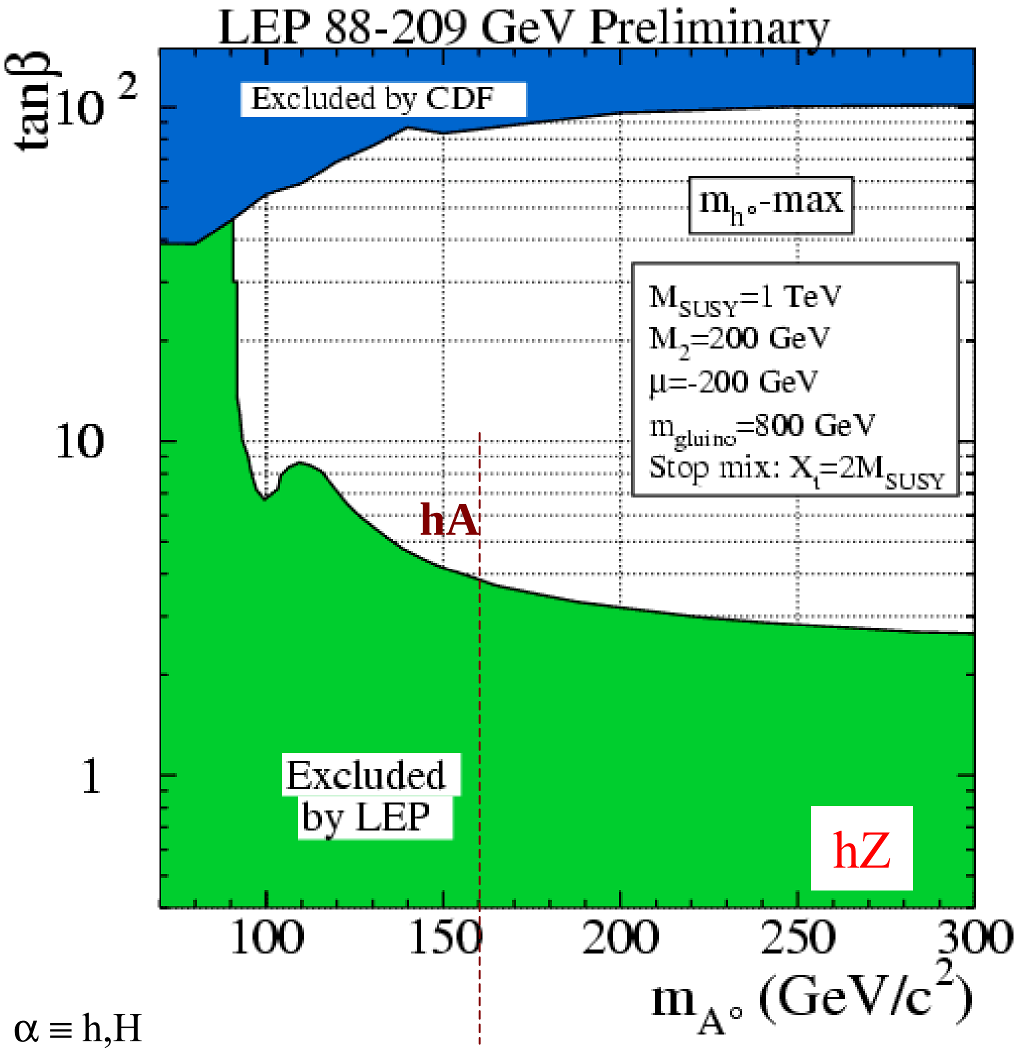
Difficult task : solve SM problems without contradicting EW data

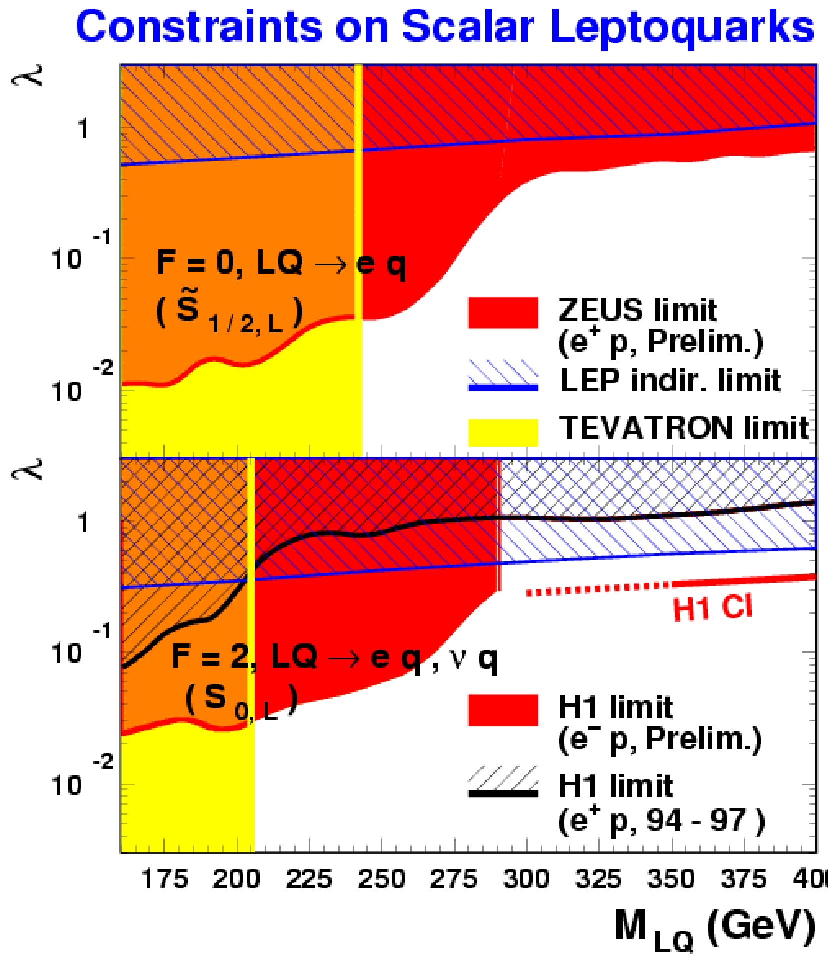
Best candidates :	Supersymmetry Extra-dimensions Technicolour

← all predict New Physics at **≈ TeV scale**

➡ strong motivation for LHC : discovery reach up to m ≈ 5 TeV

Signal of new physics directly searched at all high energy colliders





$\alpha \equiv h,H$ mixing

$m_{h,A} > 91, 92$ GeV

Exclusion of a fraction of the Susy parameter space

In spite of all its success Standard Model is likely not the ultimate theory

The open questions call for New Physics and motivate future machines (LHC, LC, ...)

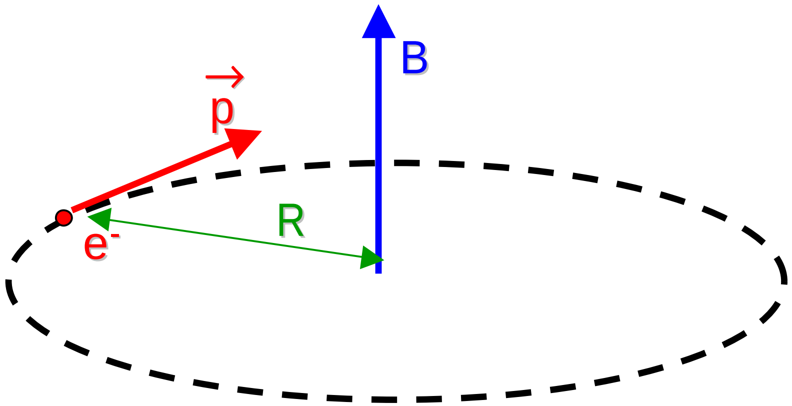
In a decade or two, we can hope to . . .

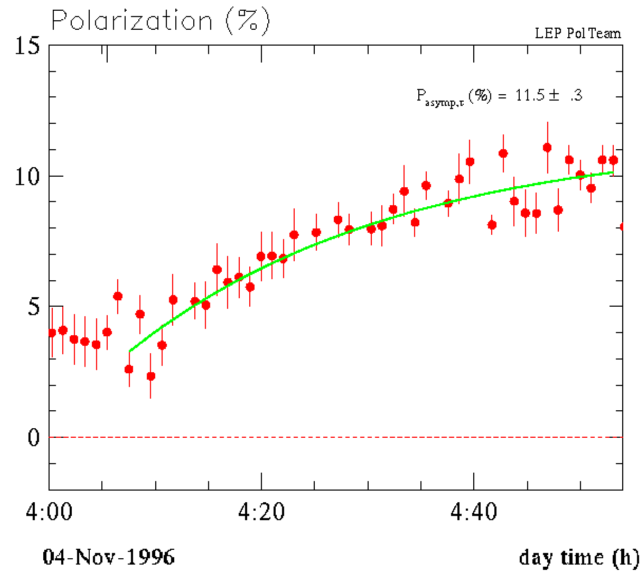
WE ≡ astro/cosmo/particle physicists

- Understand electroweak symmetry breaking
- Observe the Higgs boson
- Measure neutrino masses and mixings
- Establish Majorana neutrinos ($\beta\beta_{0\nu}$)
- Thoroughly explore CP violation in B decays
- Exploit rare decays (K, D, . . .)
- Observe neutron EDM, pursue electron EDM
- Use top as a tool
- Observe new phases of matter
- Understand hadron structure quantitatively
- Uncover the full implications of QCD
- Observe proton decay
- Understand the baryon excess
- Catalogue matter and energy of the universe
- Measure dark energy equation of state
- Search for new macroscopic forces
- Determine GUT symmetry
- Detect neutrinos from the universe
- Learn how to quantize gravity
- Learn why empty space is nearly weightless
- Test the inflation hypothesis
- Understand discrete symmetry violation
- Resolve the hierarchy problem
- Discover new gauge forces
- Directly detect dark-matter particles
- Explore extra spatial dimensions
- Understand the origin of large-scale structure
- Observe gravitational radiation
- Solve the strong CP problem
- Learn whether supersymmetry is TeV-scale
- Seek TeV-scale dynamical symmetry breaking
- Search for new strong dynamics
- Explain the highest-energy cosmic rays
- Formulate the problem of identity

C.Quigg

Measurement of the LEP beam energy : resonant depolarization

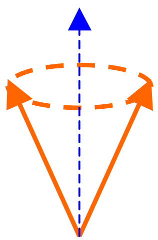




$E_{beam} \sim p = e\, B\, R$

- $e^{\pm}$ get polarized, i.e. their spins tend to align with B. Spins precess around B with

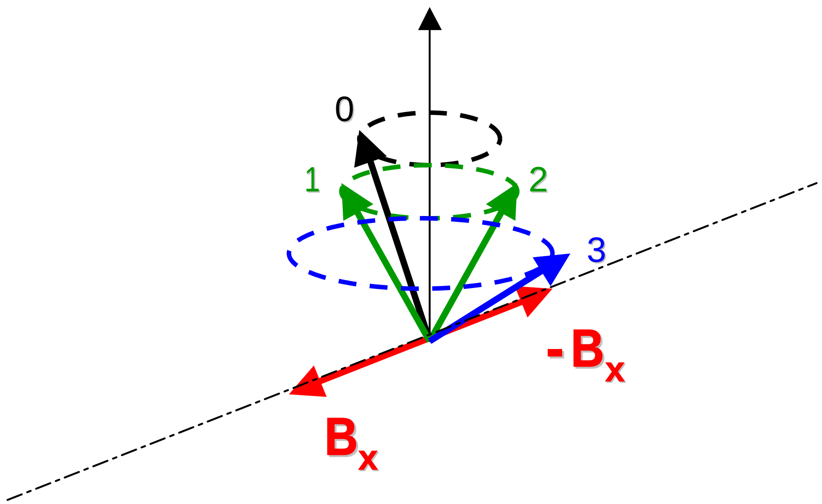
$\nu_L \sim \mu B \sim E_{beam}$



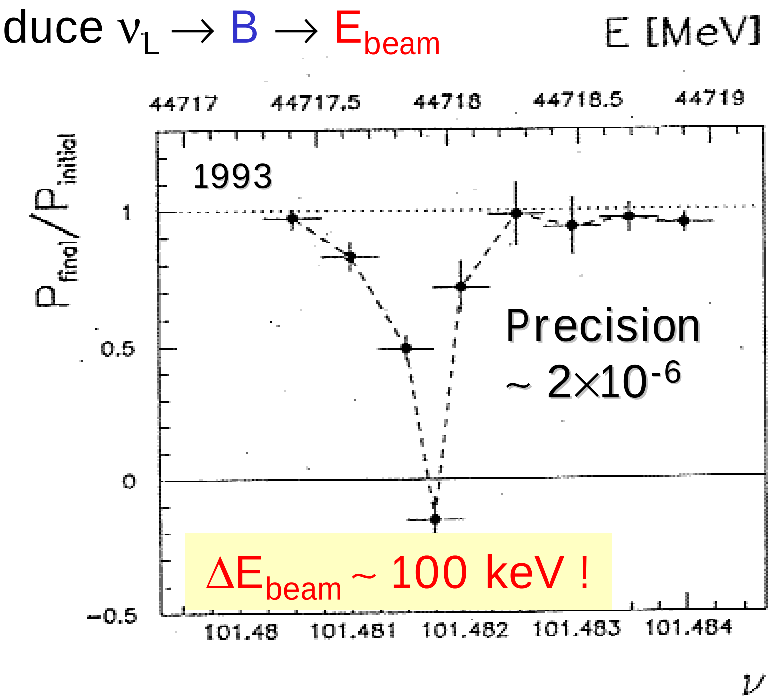
- process sensitive to imperfections
  → slow, limited to ~10% polarization

- polarization measured with Compton back scattering of laser light

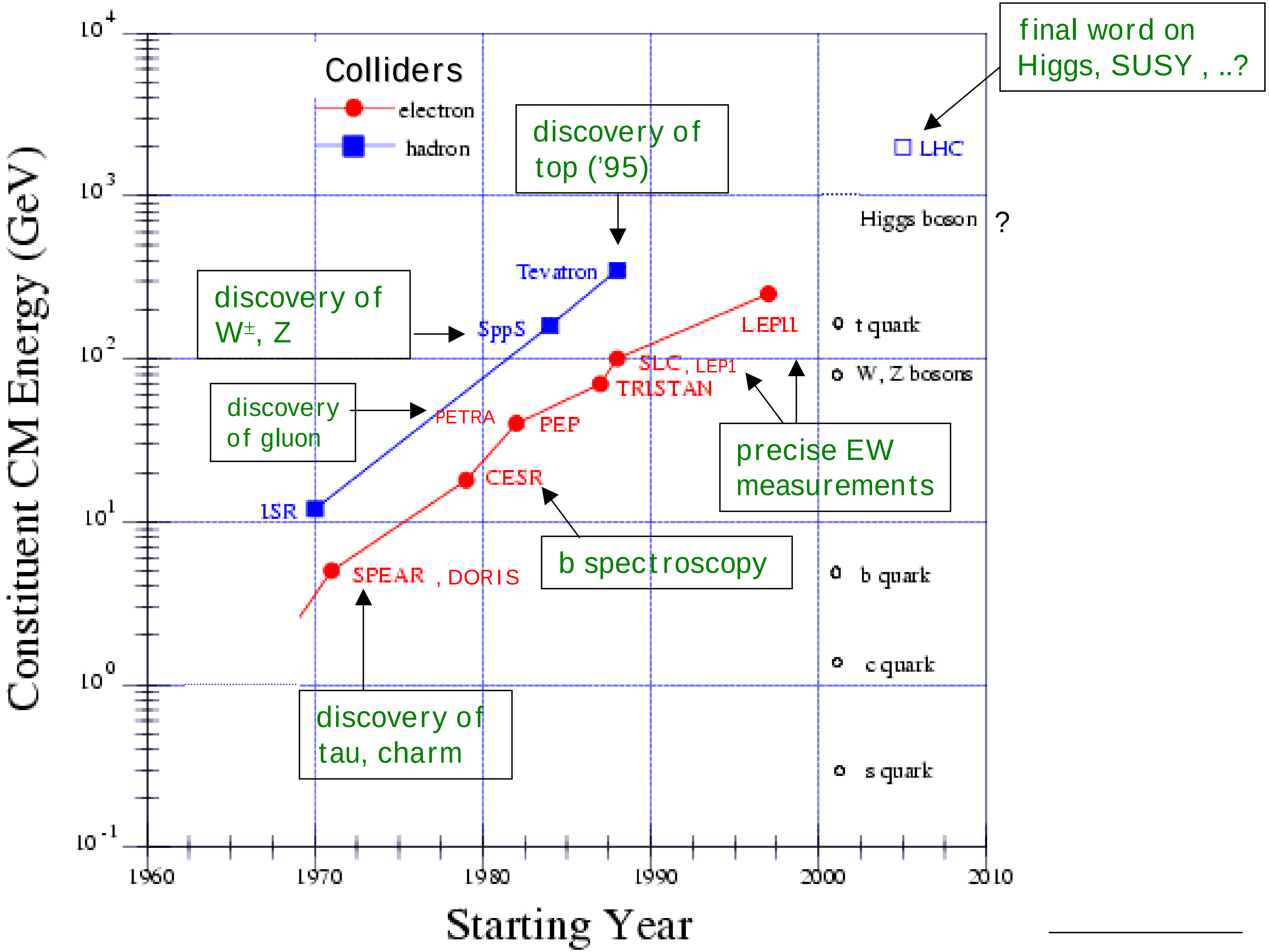
Measurement of the LEP beam energy : resonant depolarization



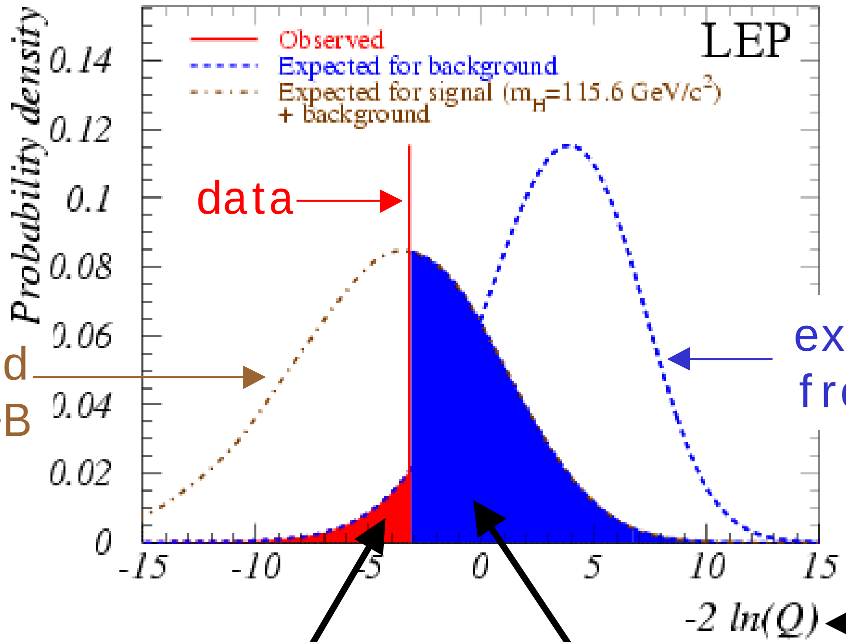
- apply field B_x oscillating with frequency ν and vary ν. When $\nu = \nu_L$ polarisation = 0 $\rightarrow$ deduce $\nu_L \rightarrow$ B $\rightarrow E_{beam}$



Simplified and non-exhaustive summary of SM tests at Colliders



A $\approx$ 2σ excess ....

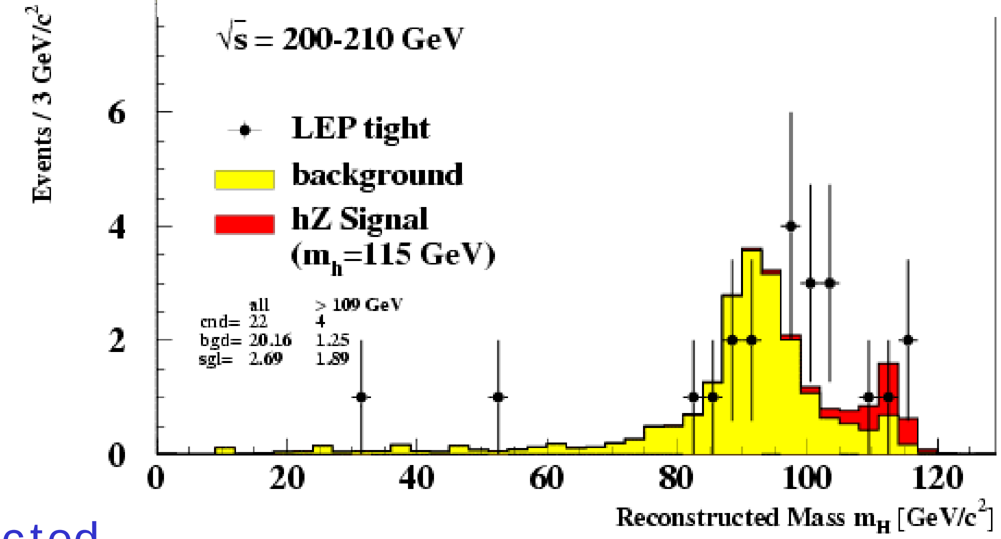


data

expected from S+B

expected from B only

variable related to event features (e.g. b-tagging)



probability of
B fluctuation : 3.5%
$\rightarrow$ ~ 2σ excess

probability of S+B : 43%
Note : consistent with
expectation for signal
with m_H~ 115 GeV

not enough to claim discovery
need 5σ, i.e. P (B fluctuation) ~ 10^{-7}

Mass lower limit :
m_H > 114.1 GeV 95% C.L.

Fundamental particles and interactions

Matter particles : fermions, spin =1/2

e	μ	τ	q= -1
ν_e	ν_μ	ν_τ	q= 0

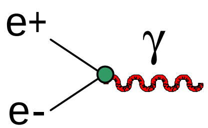
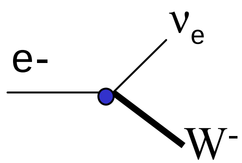
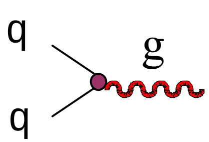
u	c	t	q= +2/3
d	s	b	q= -1/3

+ anti-particles

Why 3 families ?
Why 1^{st} family privileged ?
Why fermion masses ?
Why boson masses ?
Are quarks elementary ?
Why gauge symmetries ?
etc ...

Interactions specified by symmetry : $U(1)_Y \times SU(2)_W \times SU(3)_C$

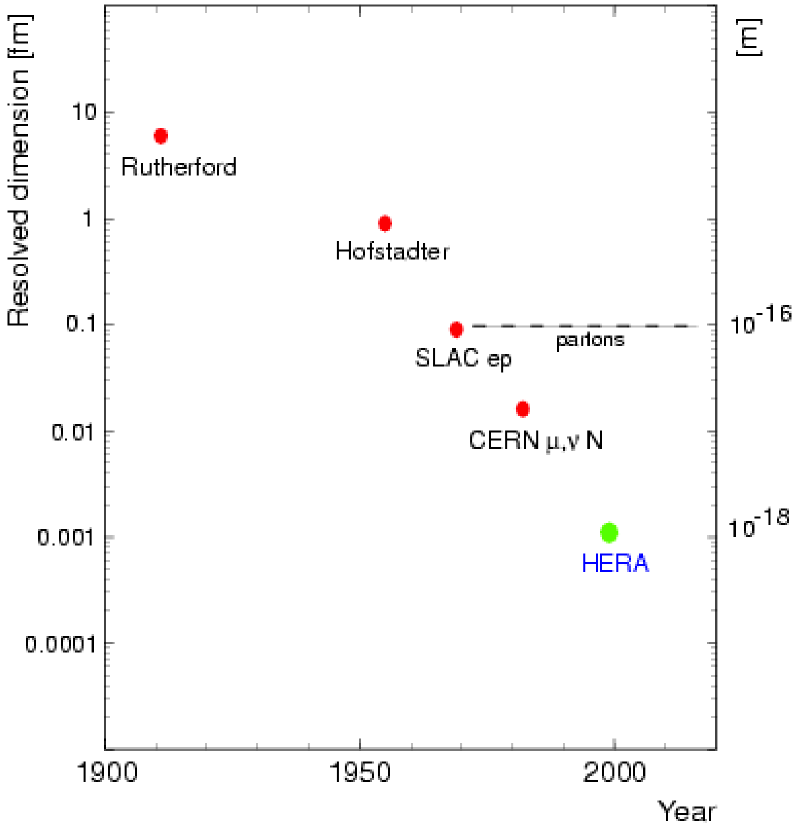
Force carriers : bosons, spin=1

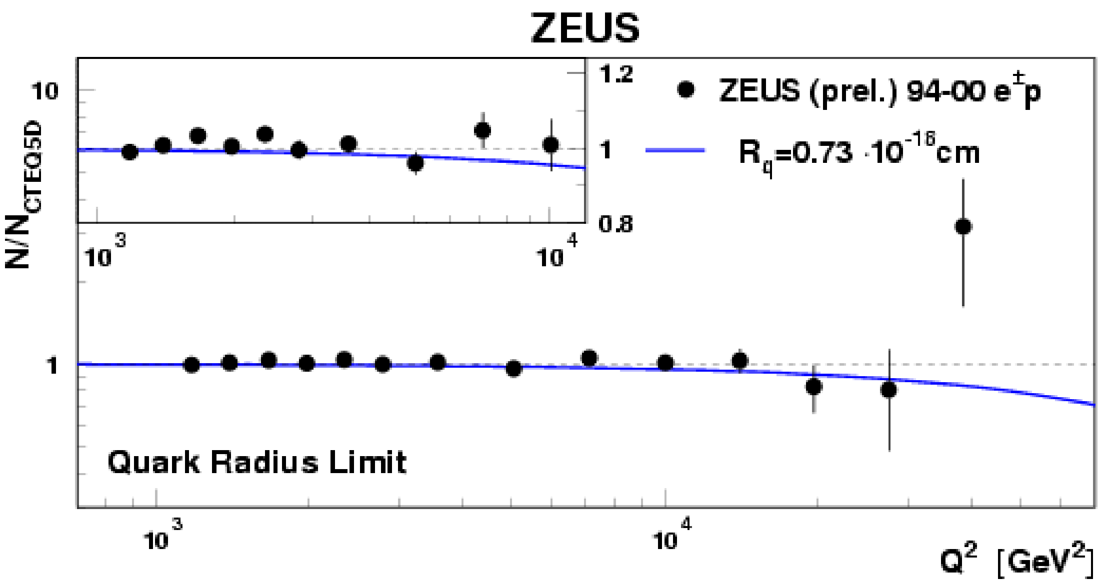
Particle	Force	Coupling (E~100 GeV)	Mass	Intensity
γ	EM (charged particles) 	$\alpha_{EM} = \frac{e^2}{4\pi} \approx 0.008$	0	~ 10^{-1}
$W^\pm$, Z	weak (q, ℓ, $W^\pm$, Z) 	$\alpha_W = \frac{g^2}{4\pi} \approx 0.03$	~ 100 GeV	~ 10^{-5}
8 g	strong (q, g) 	$\alpha_s = \frac{g_s^2}{4\pi} \approx 0.12$	0	1

Intensity: relative to strong

Mass "generator " : Higgs scalar, spin=0 ?
(EWSB)

predicted by SM but not yet observed


Resolved dimension [fm]
[m]
10
1
0.1
0.01
0.001
0.0001
10^{-16}
10^{-18}
Rutherford
Hofstadter
SLAC ep
partons
CERN μ,ν N
HERA
1900
1950
2000
Year


ZEUS
ZEUS (prel.) 94-00 $e^{\pm}p$
R_q=0.73 $\cdot 10^{-16}$cm
N/N_{CTEQ5D}
Quark Radius Limit
Q^2 [GeV^2]

SM : a bit of history ....

1967

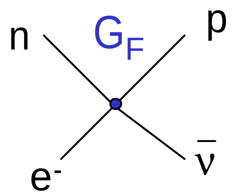
Standard Model of ElectroWeak interactions (Glashow, Salam, Weinberg) :

- as EM force mediates by γ, weak force mediated by $W^{\pm}$, Z
- unification of EM and weak forces : $g \approx e$
- $W^{\pm}$, Z mass ≈ 100 GeV → weak force is weak and short range
- masses from Higgs mechanism (EW Symmetry Breaking)

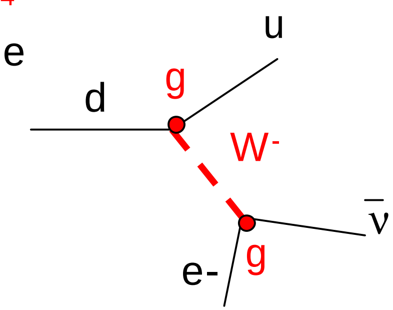
no experimental evidence at that time

β decay : $n \rightarrow p\, e^- \bar{\nu}_e$

Fermi theory ('34):
contact interaction (short range)
→ decay rate ~ G_F^2
Cross-sections diverge at high E

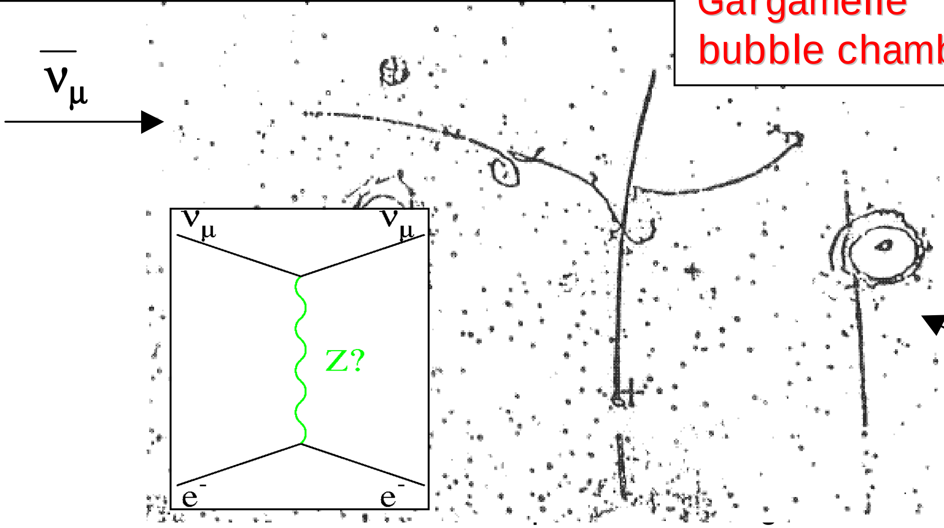


Standard Model ('67):
W^- exchange → rate ~ g^4/m_W^4
If g ~ e, from measured rate
get m_W ~ 100 GeV
Cross-sections are finite



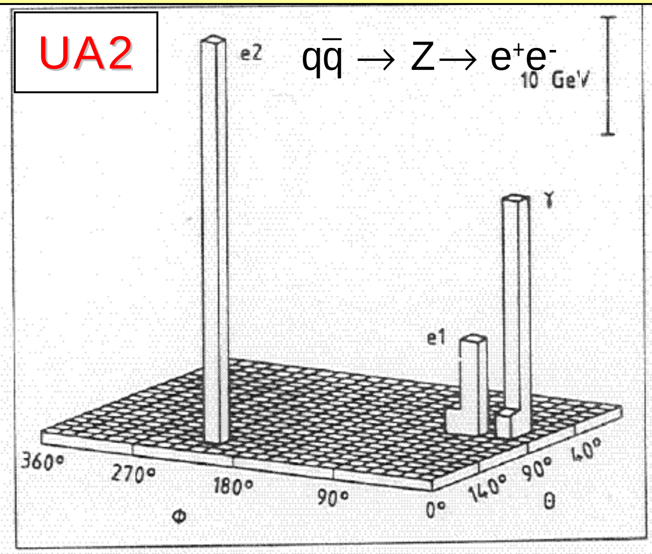
1973 : Discovery of weak neutral currents at CERN in $\bar{\nu}_\mu e^-$ interactions

Gargamelle bubble chamber



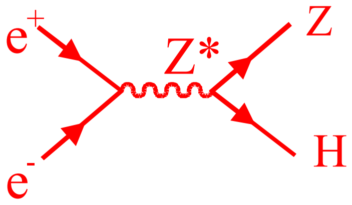
first two events

1983 : Discovery of W,Z at CERN $p\bar{p}$ Collider, m ~ 100 GeV

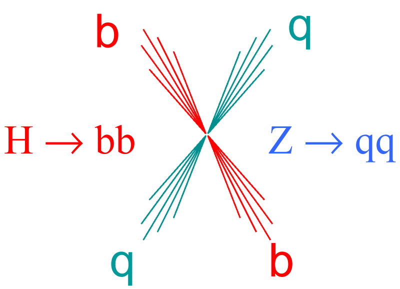
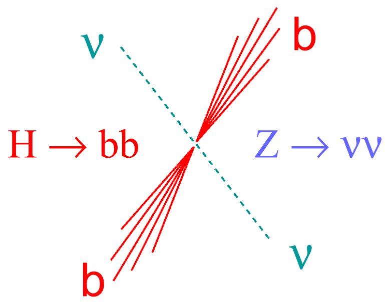
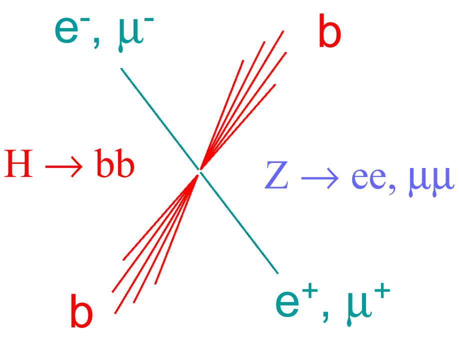
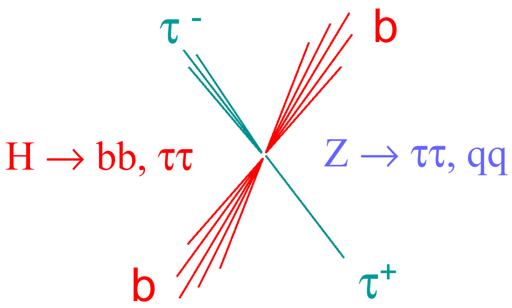


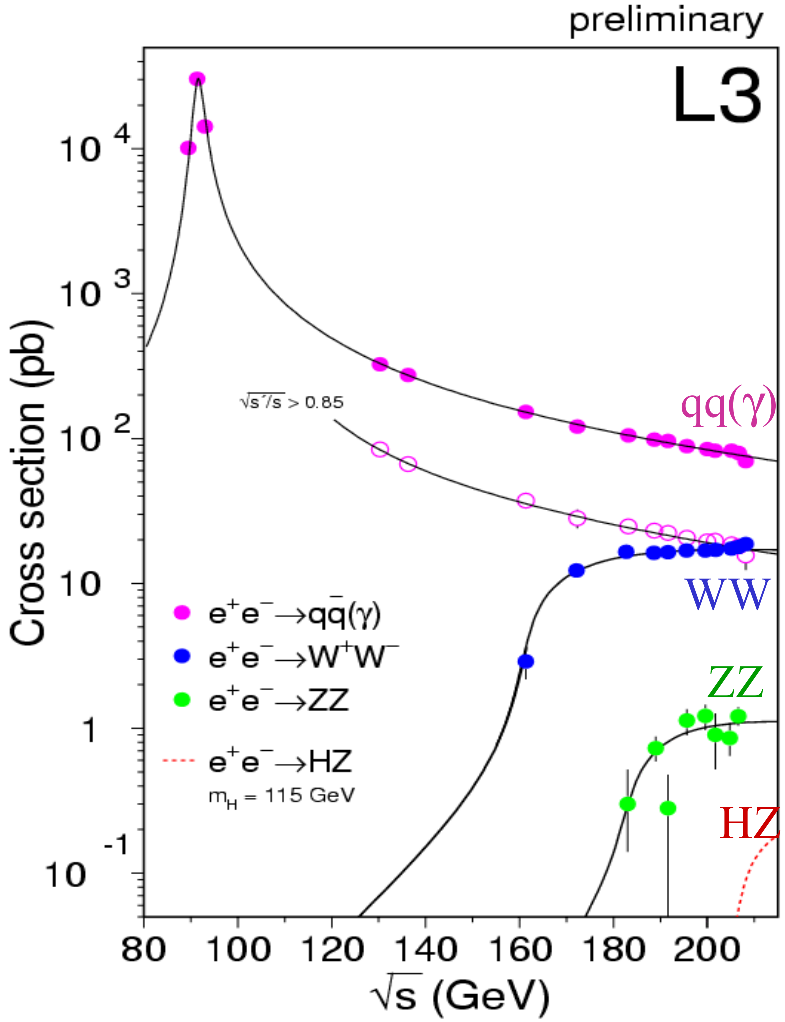
Direct Higgs searches at LEP2

$\sqrt{s} \to 209$ GeV



$m_H + m_Z < \sqrt{s} \to$ LEP sensitive up to $m_H \approx 116$ GeV

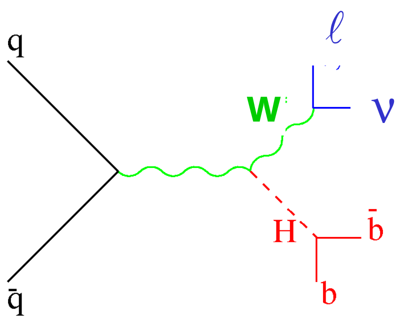
4 jets (BR ~ 52%) 	**2 jets + missing E (BR~ 14%)** 
2 jets + 2ℓ (BR ~ 5%) 	**2 jets + 2τ (BR ~ 7%)** 

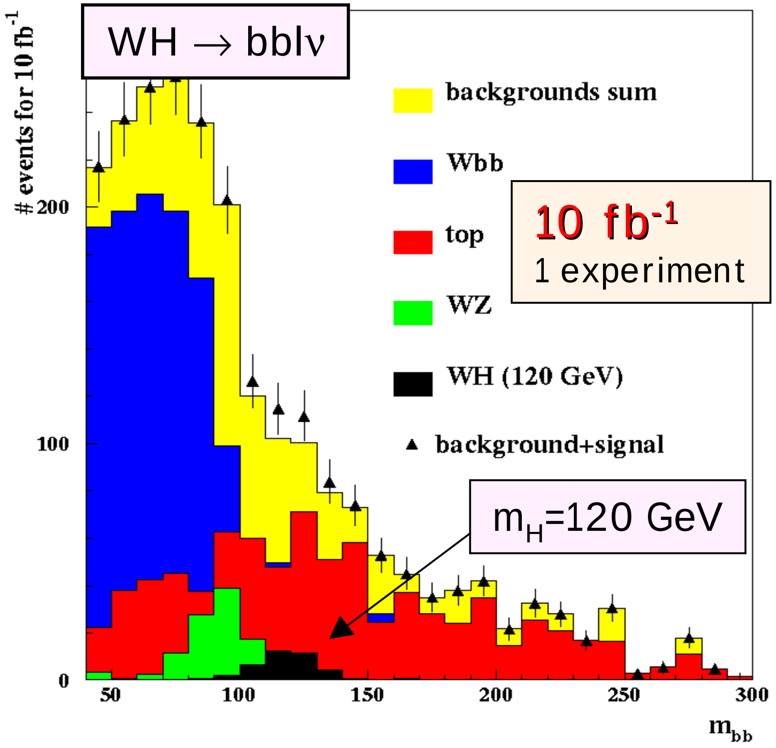


Main handles to reject background : b-tagging , presence of Z, m_H is large, etc...

Best channel at the Tevatron :

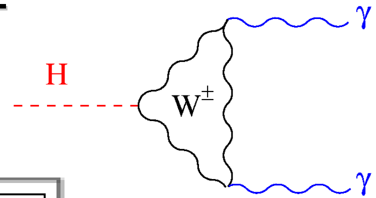
$WH \to \ell\nu\, bb$



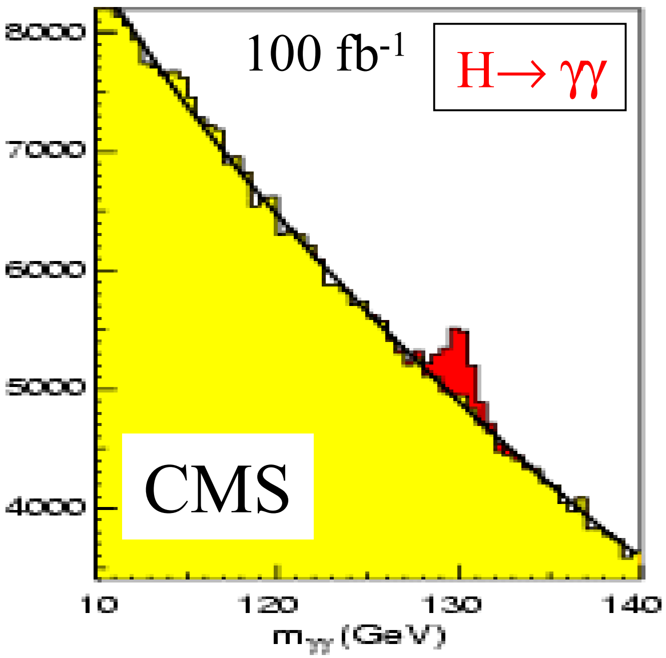


Best channels at LHC :

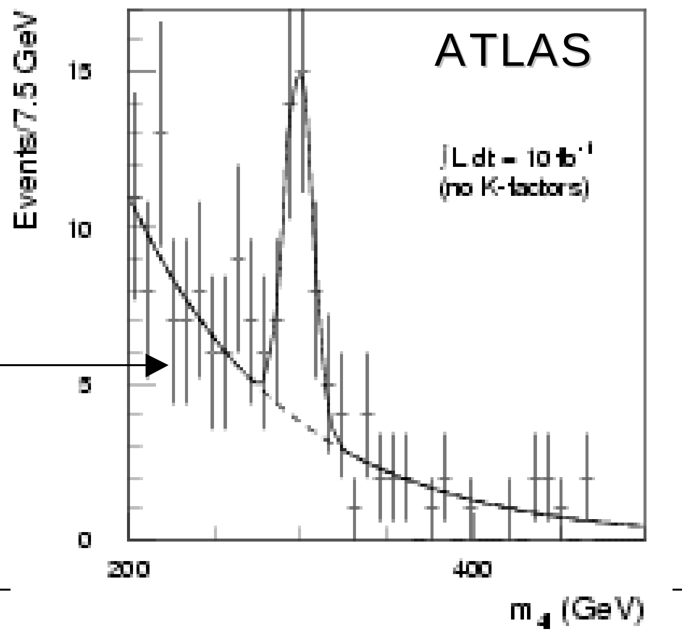
$m_H < 150$ GeV : $H \to \gamma\gamma$



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



gold-plated
channel
at LHC



SUPERSYMMETRY (SUSY) ≡ symmetry between fermions (matter) and bosons (forces)

- All SM particles p have SUSY partner $\tilde{p}$ with same couplings and quantum numbers except $\text{spin}(\tilde{p}) = \text{spin}(p) - 1/2$

SM particle	SUSY partner	spin
ℓ	sleptons $\tilde{\ell}$	0
q	squarks $\tilde{q}$	0
g	gluino $\tilde{g}$	1/2
$W^{\pm}$ (+Higgs)	charginos $\chi^{\pm}_{1,2}$	1/2
γ, Z (+Higgs)	neutralinos $\chi^{0}_{1,2,3,4}$	1/2

Particle spectrum in minimal models (MSSM)

+ 5 Higgs : h, H, A, $H^{\pm}$

$m_h < 130$ GeV

- No experimental evidence for SUSY → sparticles are heavy

However : to solve SM naturalness problem need : $m(\tilde{p}) <\sim 1$ TeV

- R-Parity (multiplicative quantum number) = + 1 (-1) SM (SUSY) particles

If conserved : -- SUSY particles produced in pairs

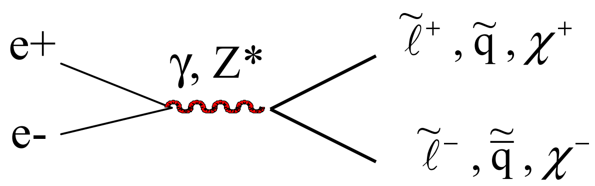
-- Lighest Supersymmetric Particle (LSP) is stable

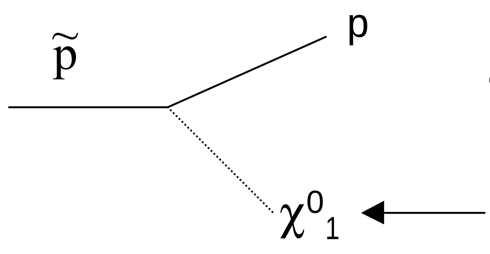
LSP ≡ χ^{0}_{1} weakly interacting ⟷ dark matter candidate

-- all SUSY particles decay to LSP

SUSY searches at LEP2

$\sqrt{s} \leq 209$ GeV

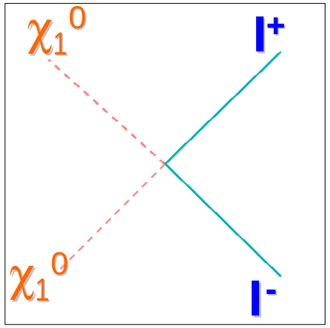




in most cases at LEP2 energies

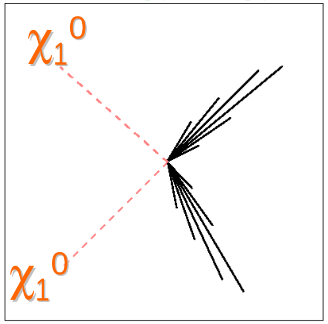
missing energy

$\tilde{\ell}\tilde{\ell} \to \ell\,\chi^0{}_1\,\ell\chi^0{}_1$



Acoplanar leptons

$\tilde{q}\tilde{q} \to q\,\chi^0{}_1\,q\chi^0{}_1$



Acoplanar jets

- democratic production
- simple final states
- SM backgrounds rejected by asking large missing E and missing mass (LSP is heavy)

$$m(\tilde{\ell}, \tilde{q}, \chi^{\pm}{}_1) > 80 - 100\ \text{GeV}$$

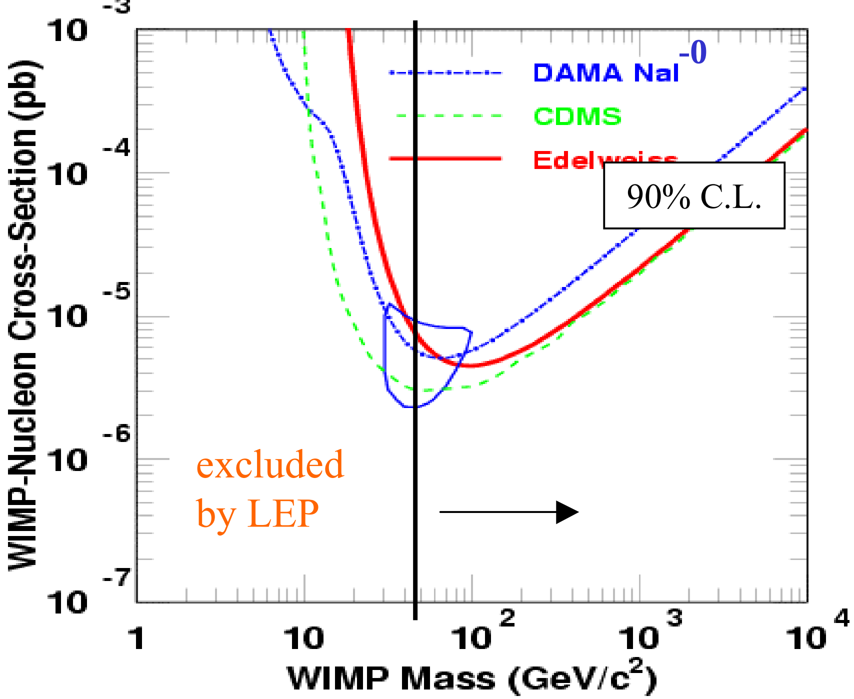
$\chi^0{}_1\,\chi^0{}_1$ production not observable

→ indirect limit on m ($\chi^0{}_1$) from other searches + theory relations

(e.g. LSP and chargino masses are related)

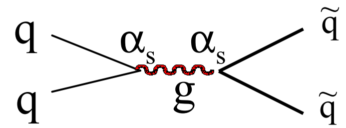
From LEP2 data : m ($\chi^0{}_1$) > 45.6 GeV 95% C.L.

Direct searches for dark matter



SUSY searches at Tevatron (and LHC)

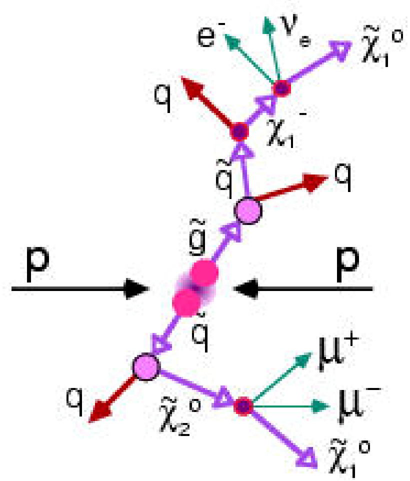
Mainly sensitive to $\tilde{q}, \tilde{g}$ ⟶ e.g.



- Strong production → large cross-section
- $\tilde{q}, \tilde{g}$ heavy → cascade decays

  → complicate/spectacular signatures with many jets, leptons + missing E

  → rejection of large SM backgrounds



Tevatron better than LEP2 for $\tilde{q}, \tilde{g}$ (strong production, high $\sqrt{s}$).
Worse for charginos, sleptons, neutralinos (large backgrounds)
→ complementary machines

Limits/reach on squark and gluino masses

Lower limits from Tevatron Run 1	200-300 GeV
Discovery reach of Tevatron Run 2	up to ~ 450 GeV
Discovery reach of LHC	up to ~ 2.5 TeV

→ either SUSY found before/at LHC or dead

Conclusions

Over last decade, high-E physics experiments (e.g. at LEP, SLC, Tevatron)
have performed precise measurements with accuracy $\leq 10^{-3}$
and looked for new particles/physics in large variety of topologies

⬇

- Wealth of outstanding physics results, very challenging for any theory
- Spectacular experimental achievements
  (accelerators, detectors, data analysis techniques, ideas ...)
- Huge amount of theoretical work to match experimental accuracy

- Triumph for the **Standard Model**

⬇

-- predicted particles discovered (except the Higgs .....)
-- theory structure, predicted interactions and predicted
phenomenological consequences confirmed to better than 10^{-3}
(i.e. at level of radiative corrections)
up to few hundreds GeV (i.e. ~ 10^{-10} s after Big Bang)