3rd WORKSHOP ON PARTICLE PHYSICS

NATIONAL CENTRE FOR PHYSICS
(QUAID-I-AZAM UNIVERSITY)

Detectors for High Energy Physics

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Literature on particle detectors (1)

ext books

- C. Grupen, Particle Detectors, Cambridge University Press, 1996
- G. Knoll, Radiation Detection and Measurement, 3rd Edition, 2000
- W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd edition, Springer, 1994
- R.S. Gilmore, Single particle detection and measurement, Taylor&Francis, 1992
- W. Blum, G. Rolandi, Particle Detection with Drift Chambers, Springer, 1994
- K. Kleinknecht, Detektoren für Teilchenstrahlung, 3rd edition, Teubner, 1992

Literature on particle detectors (2)

eview articles

- Experimental techniques in high energy physics, T. Ferbel (editor), World Scientific, 1991.
- Instrumentation in High Energy Physics, F. Sauli (editor), Worl Scientific, 1992.
- Many excellent articles can be found in Ann. Rev. Nucl. Part. Sci.

ther sources

- Particle Data Book (Phys. Rev. D, Vol. 54, 1996)
- R. Bock, A. Vasilescu, Particle Data Briefbook
  http://www.cern.ch/Physics/ParticleDetector/BriefBook/
- Proceedings of detector conferences (Vienna VCI, Elba, IEEE)

High Energy Physics Experiments

High Energy Physics studies the interactions between elementary particles:

QUARKS AND LEPTONS

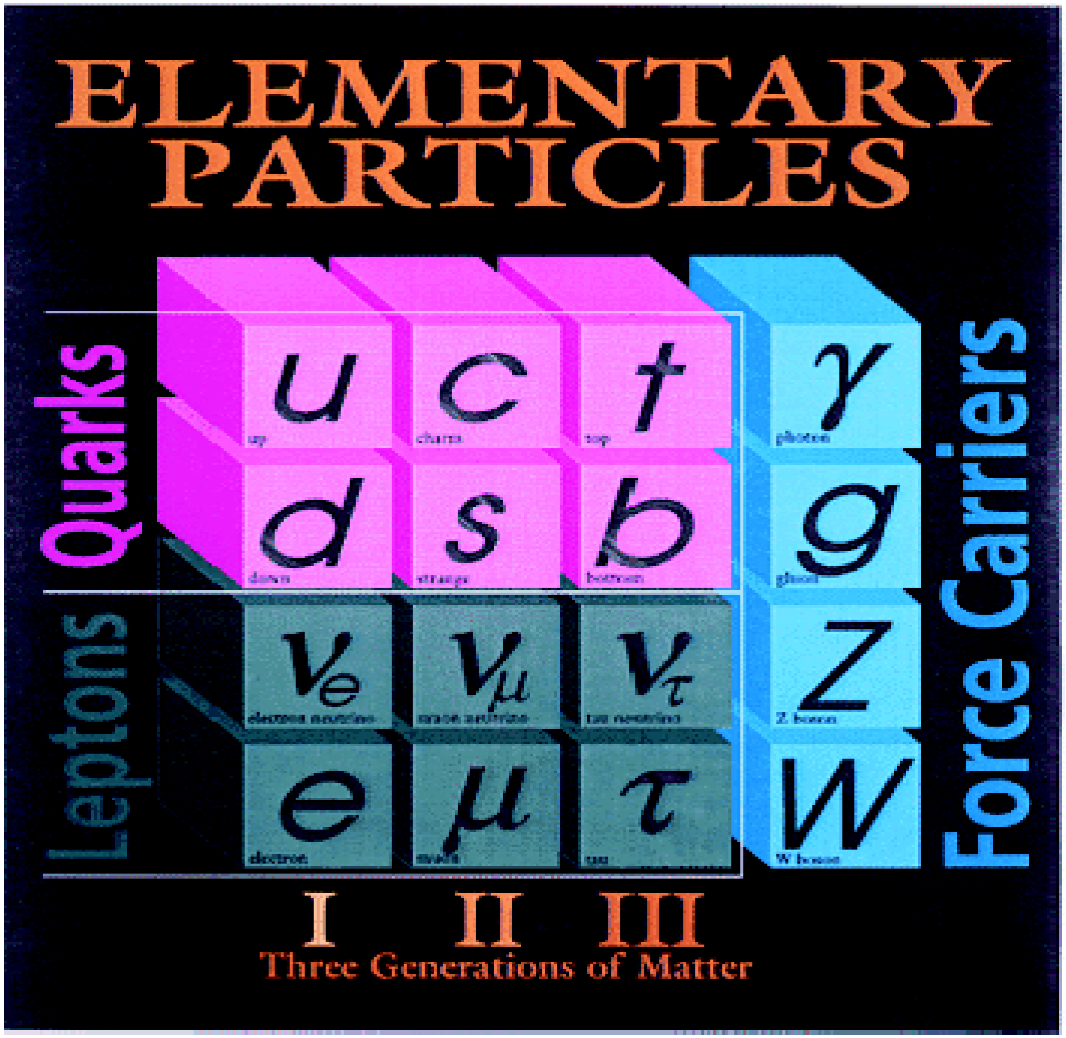
These interactions are mediated by

FORCE CARRIERS

Elementary particles

Jets of particles

Electrons, Muons, Missing E_T



photons

Fundamental particles and interactions

Matter particles : fermions, spin =1/2

e	μ	τ	q= -1
ν_e	ν_μ	ν_τ	q= 0

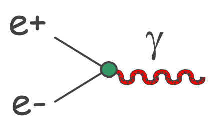
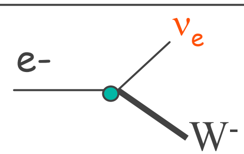
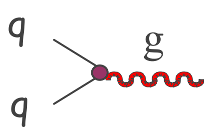
u	c	t	q= +2/3
d	s	b	q= -1/3

+ 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	$\sim 10^{-1}$
$W^\pm$, Z	weak $(q, \lambda, W^\pm, Z)$ 	$\alpha_W = \frac{g^2}{4\pi} \approx 0.03$	~ 100 GeV	$\sim 10^{-5}$
8 g	strong (q, g) 	$\alpha_s = \frac{g_s^2}{4\pi} \approx 0.12$	0	1

relati
to str

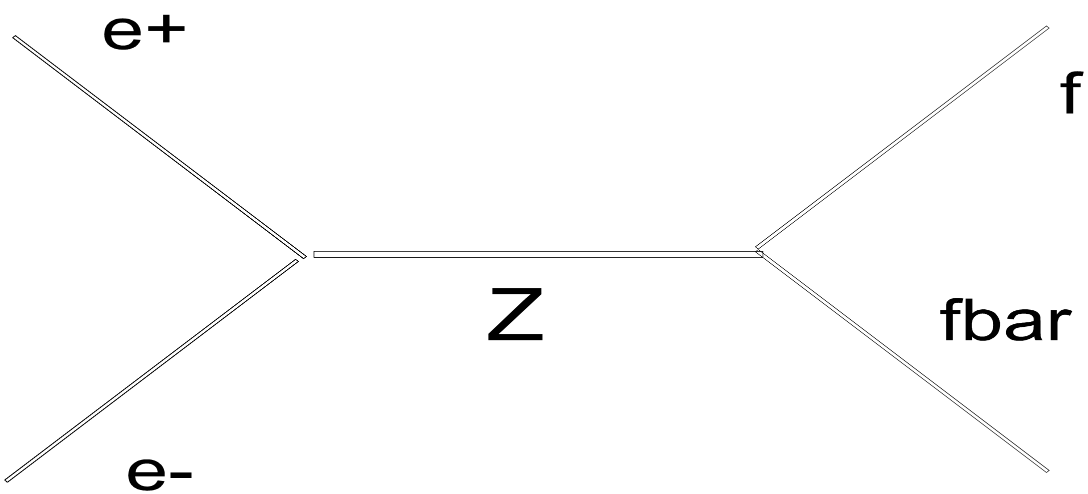
Mass "generator " : Higgs scalar, spin=0 ?
(EWSB)

predicted by SM but not yet observed

High Q2 Reactions

High Q2 reactions involve partons (quarks and leptons)

Measure the properties (parameters) of the partons in the initial and final state

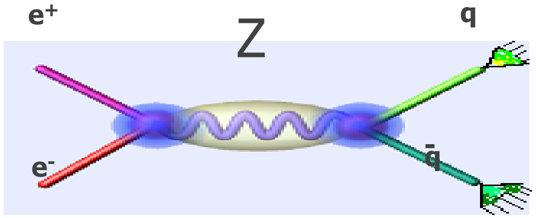


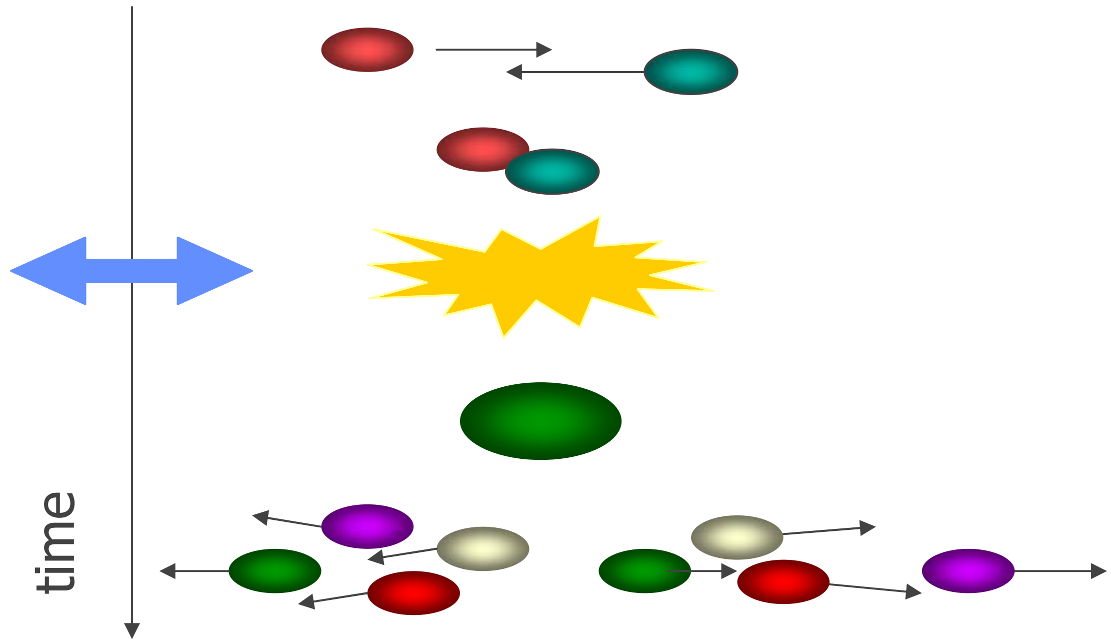
- Charge
- Direction
- Flavor
- Energy
- Spin

dealistic views of an elementary particle reactio

$$e^{+} + e^{-} \rightarrow Z^{0} \rightarrow q\,\overline{q}$$

Quarks hadronize in jets





Usually we can only ‘see’ the end products of the reaction, but not the reaction itself.

In order to reconstruct the reaction mechanism and the properties of the involved particles, we want the maximum information about the initial state and the end products !

Colliding beams

Colliding beams are the most efficient way to maximize the center of mass energy of the collision between the partons

In order to store and collide efficiently the beams, only charged and stable particle can be used:

Electrons and positrons

Protons and anti-protons

Nuclei

(muon colliders are also under study)

Luminosity

articles are grouped in
packets called bunches

erminology:

- N_p = # protons in bunch
- $N_{\bar{p}}$ = # p-bar in bunch
- B = # bunches
- f = revolution freq.
-

^{2} scales with E_{beam}

- Smaller beams at higher energies

Protons in Bunch

Total Antiproto

Revolution Frequency

$$L = \frac{f N_p (B N_{\bar{p}})}{2\pi(\sigma_p^2 + \sigma_{\bar{p}}^2)} F(\sigma_z / \beta^*)$$

Beam Sizes

Beam Shape Form factor at Intersection

Luminosity

Luminosity, *L*, is a measurement of the brightness of the interaction region

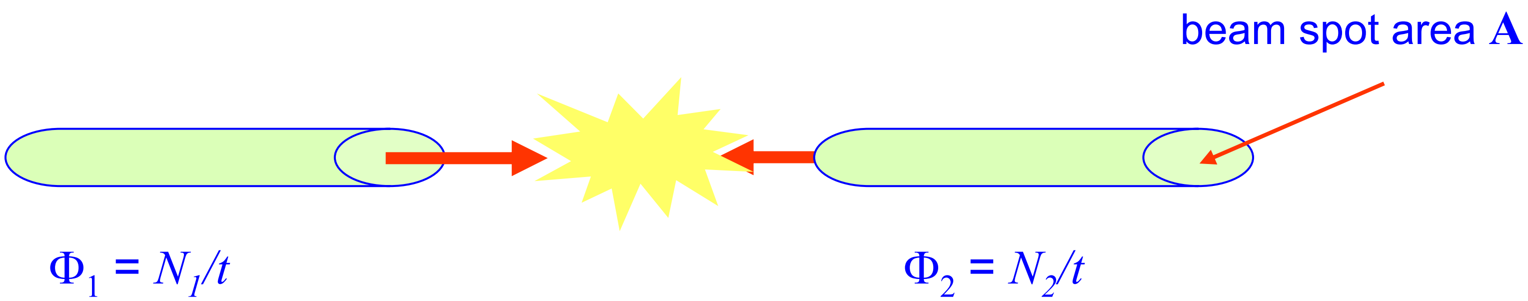
The luminosity is a major machine parameter

– High luminosity → sensitivity to rare events

The concept of cross sections

Cross sections σ or differential cross sections $d\sigma/d\Omega$ are used to express the probability of interactions between elementary particles.

<u>Example:</u> 2 colliding particle beams



What is the interaction rate *Rint.* ?

$$R_{int} \propto N_1 N_2 / (A \cdot t) = \sigma \cdot L$$

Luminosity L [$cm^{-2}\ s^{-1}$]

σ has dimension area !

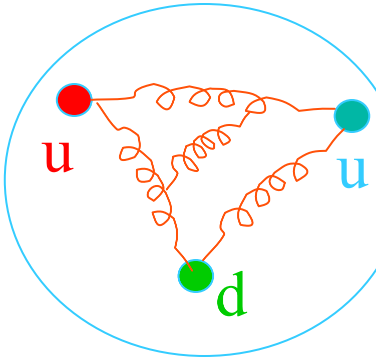
Practical unit:

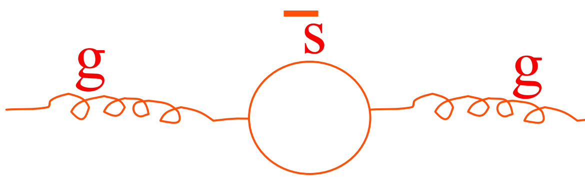
1 barn (b) = $10^{-24}\ cm^2$

ifferent beams properties

- lectrons are point-like

- rotons are a quark-gluon soup
  – 3 valence quarks bound by exchange of gluons
    - Gluons are colored and interact with other gluons
    - Virtual quark pair loops can pop-up generating additional quark content (sea-quarks)
  – Proton momentum is shared among all constituent partons (quarks& gluons)





- ffective parton collision energy is lower than available CM energy and depends on the proton structure described by pdf

Proton structure

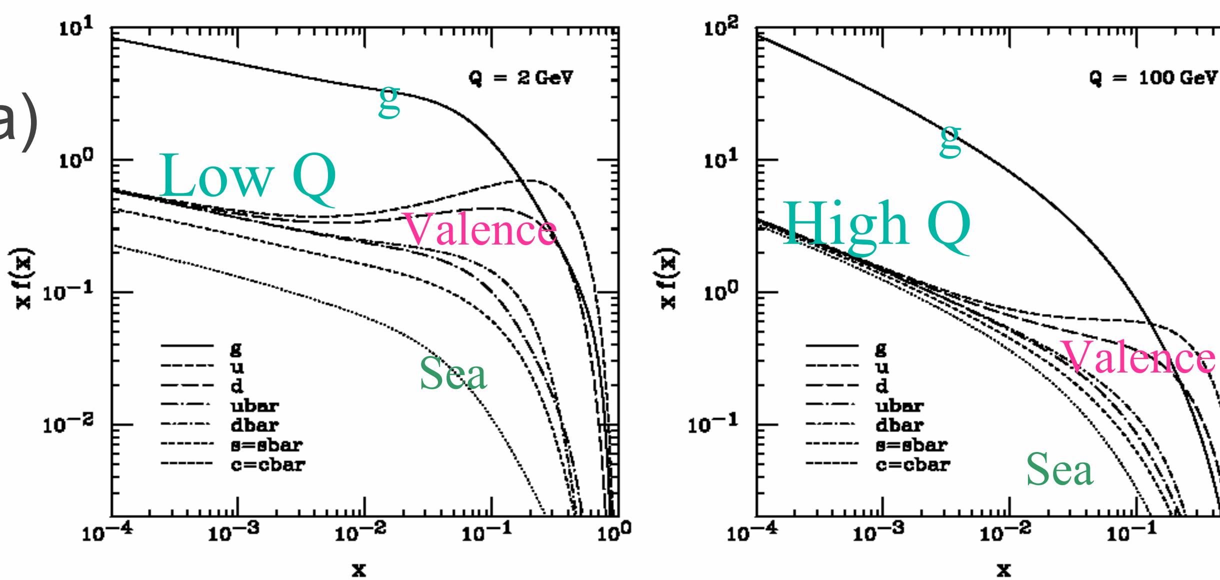
arton distribution functions (pdf) describe the momentum distribution of each parton species in the proton

- When protons collide their structure is affected
  - Pdf's depend on Q of interaction
- **$F_i(x, Q)$**
  - $x = p_{parton}/p_{proton}$ = fractional momentum carried by parton
  - Q = momentum transfer of interaction
  - i = parton species

fective coll. Energy (Teva)

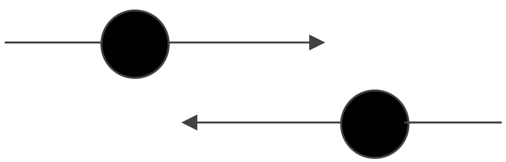
- $E^{CM}_{parton} = \sqrt{x_1 x_2}\, E^{CM}$
- $<x> \sim 0.1$)
- $< E^{CM}_{parton} > \sim 200$ GeV
  - **Max E^{CM}_{parton}**

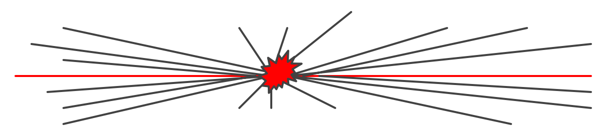
Observed 1364 GeV



Phenomenology of pp collisions

Most interactions due to collisions at large distance between incoming protons where protons interact as " a whole " → small momentum transfer ($\Delta p \approx \eta / \Delta x$) → particles in final state have large longitudinal momentum but small transverse momentum (scattering at large angle is small)



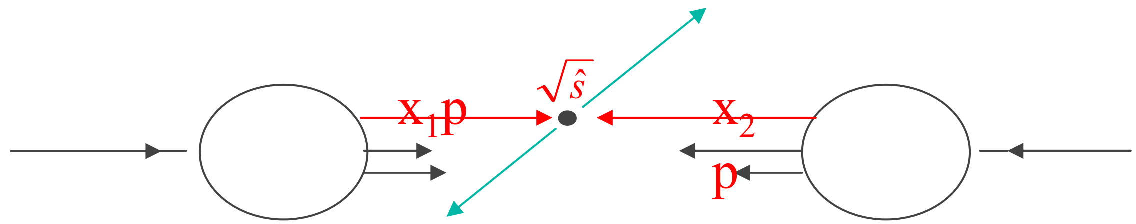


charged particles uniformly distributed in ϕ Most energy escapes down the beam pipe

These are called minimum-bias events (" soft " events).
They are the large majority but are not very interesting

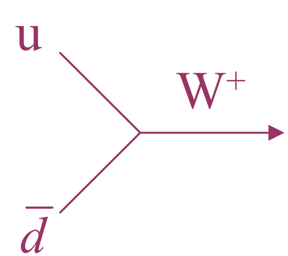
Phenomenology of pp collisions

Monochromatic proton beam can be seen as beam of quarks and gluons with a wide band of energy. Occasionally hard scattering ("head on") between constituents of incoming protons occurs.



teractions at small distance → large momentum transfer → massive rticles and/or particles at large angle are produced. These are teresting physics events but they are rare.

Ex. $u + \bar{d} \rightarrow W^+$



σ(pp → W) ≈ 150 nb ≈ 10-6 σtot (pp) @LHC

Hadron Colliders vs. e+e-

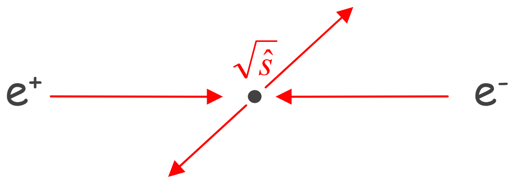
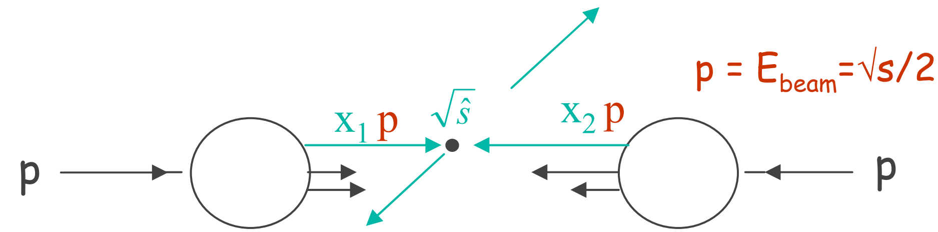
e^+e^- storage rings: best for precision measurements

- Very clean and well defined final state…. However
  - Max energy limited by electron radiation:
    - Energy loss: $8.85 \times 10^{-5}\ E^4/\rho$ MeV/turn (E is in GeV, ρ in km)
      - » Scales with 4th power of particle mass
    - Max LEP CM energy ~200 GeV
- Only final states which couple to photon or Z boson at precise CM energy

adron colliders: best as discovery machines

- Final state is more complex….. However
  - Much higher energy available
    - Energy loss: $7.8 \times 10^{-18}\ E^4/\rho$ MeV/turn (E is in GeV, ρ in km)
    - Max Tevatron CM energy ~2,000 GeV (14,000 GeV at LHC !)
- Broad band collisions of many different initial partons

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

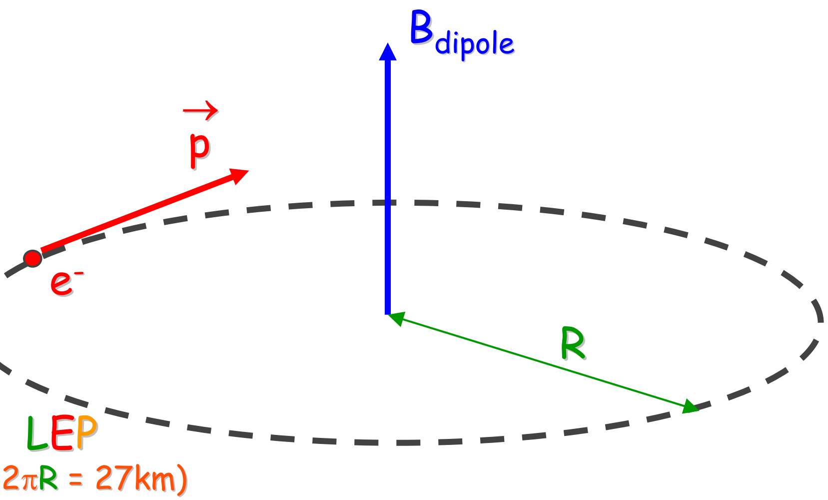
e^+e^- Colliders	$pp/p\bar{p}$ Colliders
 $E_{beam}=\sqrt{s}/2$	
Energy of elementary interaction known $\sqrt{\hat{s}} = E(e^-) + E(e^+) = \sqrt{s}$	• Energy of elementary interaction not known $\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} < \sqrt{s}$
Only two elementary particles collide $\rightarrow$ clean final 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} ~ 2.5 GeV/turn LEP2 (E_{beam}~ 100 GeV)	• Synchrotron radiation is ~ $(m_p/m_e)^4$ ~ 10^{13} smaller
⬇ high energy more difficult $\rightarrow$ next machine : Linear Collider (TESLA, NLC, JLC, $\sqrt{s}$ =500-800 GeV ?) clean environment $\rightarrow$ precision measurements machines	⬇ -- high energy easier $\rightarrow$ discovery machines next machine : LHC, pp, $\sqrt{s}$ = 14 TeV in the LEP ring -- " dirty" environment

Parameters of some colliders

	PEP II	LEP	Hera	Tevatron	LHC
	e+e-	e+e-	e p	p pbar	p p
Circumference (km)	2.2	26.6	6.3	6.3	26.6
Peak magnetic field (T)	0.18 and 0.75	0.135	0.27 and 4.6	4.4	8.3
Number of Dipoles	192	3280	396 and 413	774	1232
Maximum beam energy (GeV)	4 and 12	100	30 and 920	1000	7000
Luminosity (10^{30} $cm^{-2}s^{-1}$)	4600	24	75	210	10000
Time between collisions (μs)	0.0042	22	0.096	0.396	0.025
Energy spread (units 10^{-3})	0.7	1	1 and 0.2	0.09	0.1
Bunch length (cm)	1.1	1	1 and 8.5	38	7.5
Beam Radius (μm)	460 x 4	250 x 4	270 x 50	34 and 29	16
Particles per bunch (units 10^{10})	2.1 and 5.9	45	3 and 7	27 and 7.5	11
Average current (μAmp)	800 and 1100	5	40 and 90	81 and 22	536
Beam Polarization (%)	none	55	50	none	none

Measurement of the LEP Beam Energy (I)

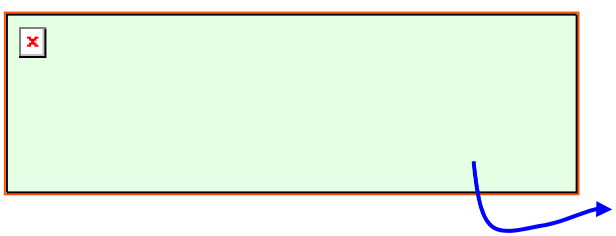
Approximation: LEP is a circular ring immersed in a uniform magnetic field:



$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$

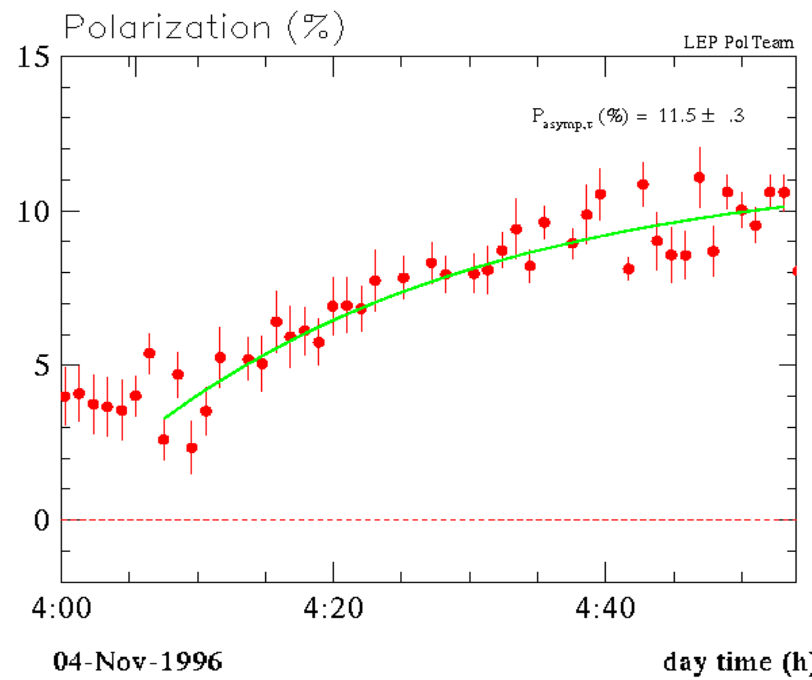
In real life:

B non-uniform, ring not circular



1) The electrons get transversally polarized (i.e., their spin tends to align with B), but

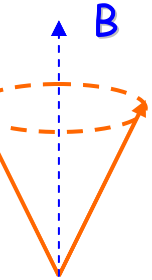
- Process very sensitive to imperfections ($\rightarrow$ slow, typically hours, and limited to o(10%) polarization)



- Process very sensitive to beam-beam interactions ($\rightarrow$ one beam, no polarization in collisions)

Measurement of the LEP Beam Energy (II)

) The spin precesses around B with a frequency proportional to B.



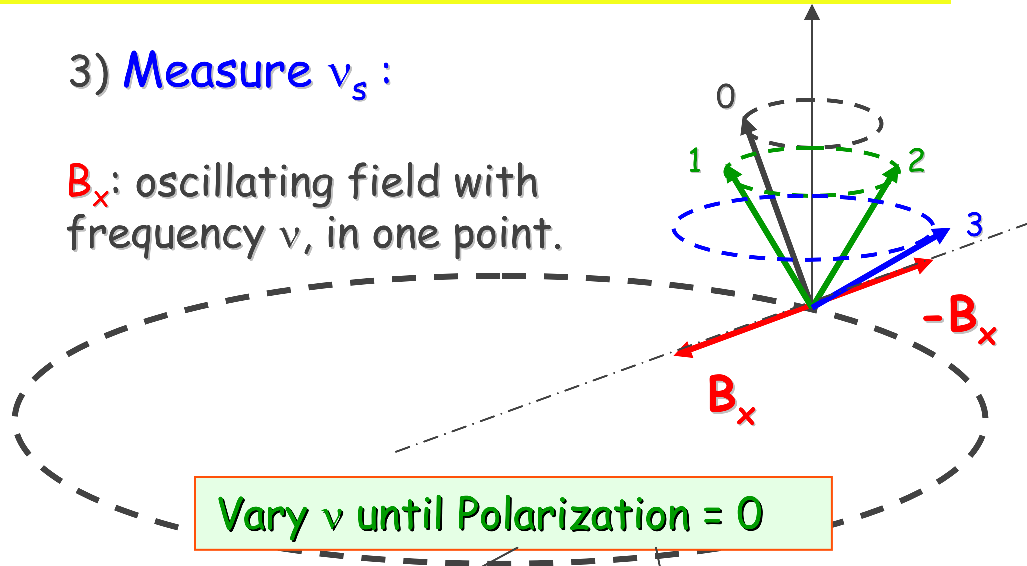
The number of revolutions for each LEP turn is thus proportional to B L (in fact, to ∫ B dl, and then to E_{beam})

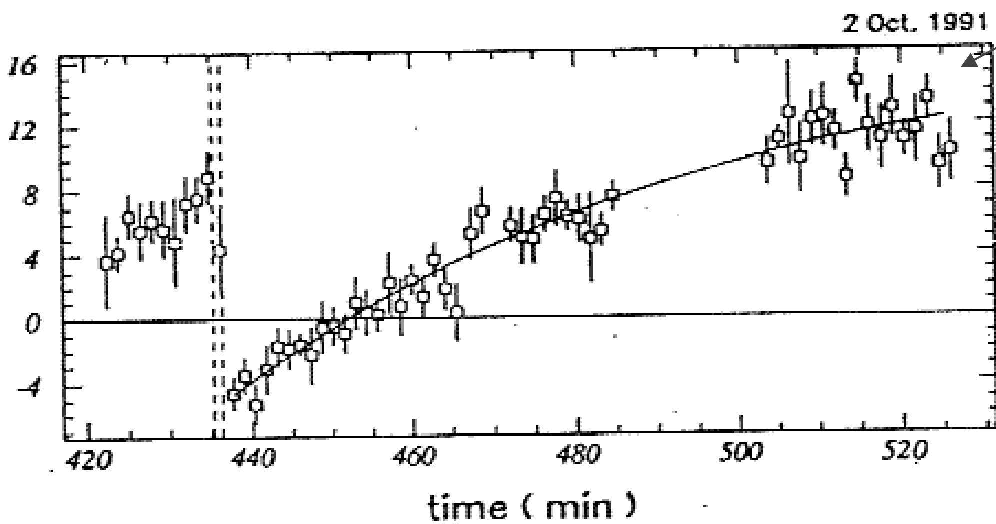
$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{\text{beam}}$$

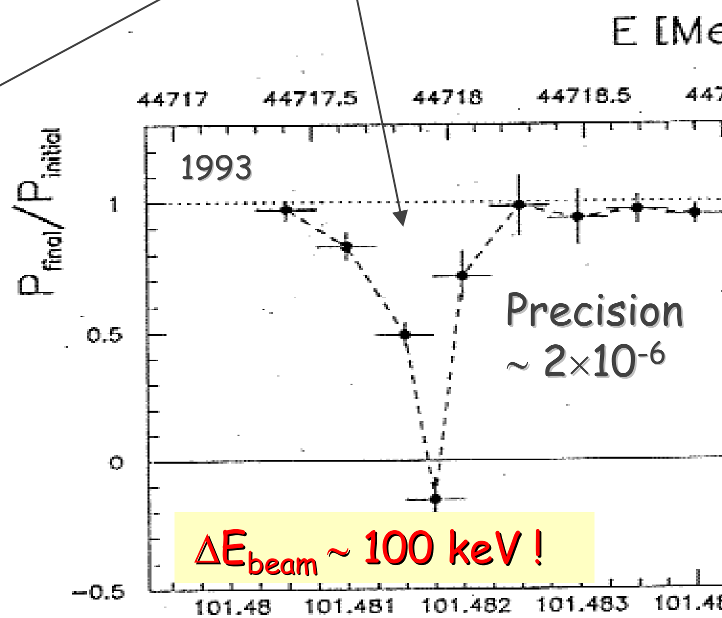
101.5 Peak-2
103.5 Peak
105.5 Peak+2

3) Measure ν_s :

B_x: oscillating field with frequency ν, in one point.

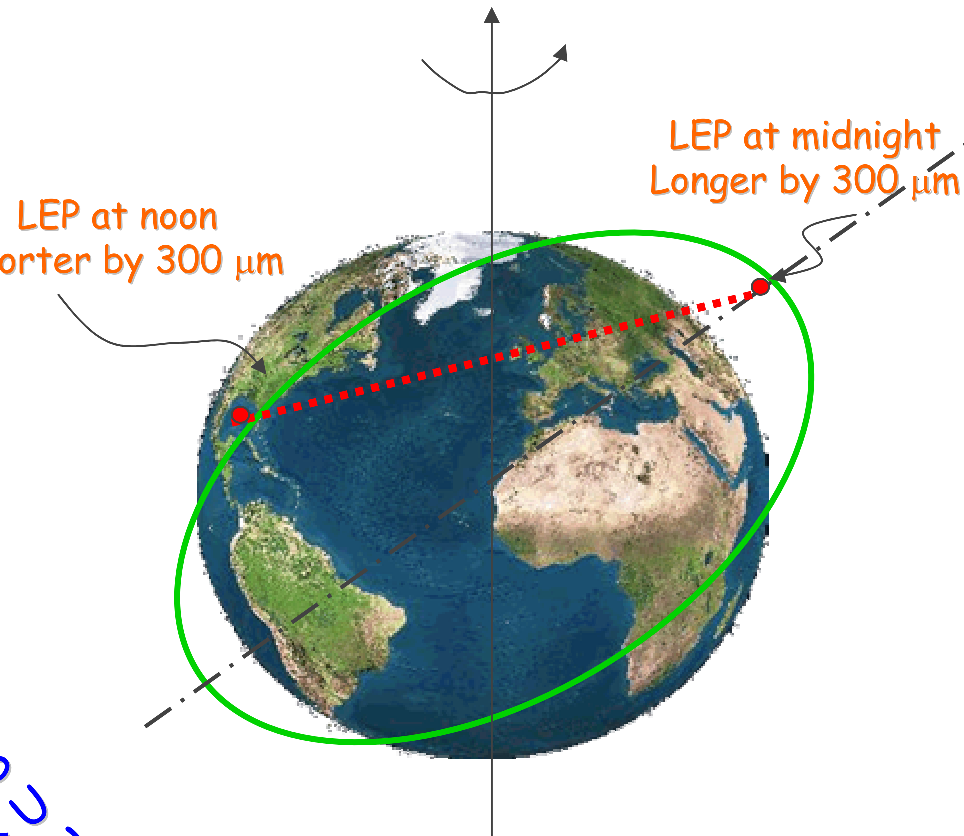




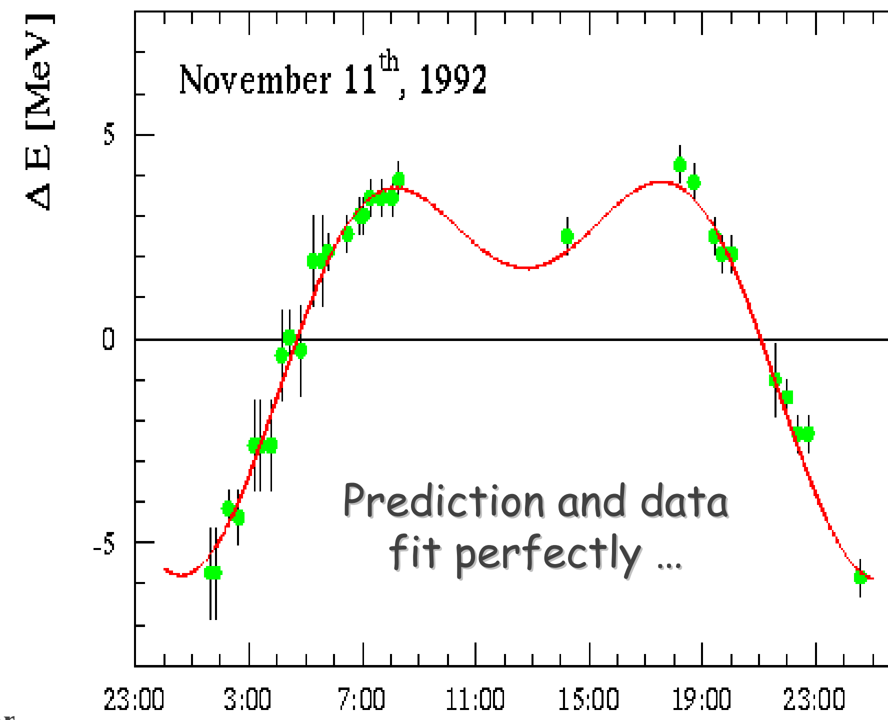


Measurement of the LEP Beam Energy (III)

… dispersion of 10 MeV is observed (>> 100 keV) … the same machine conditions. Correlation with … the moon found on 1992, Nov 11th:



- At midnight, the electrons see less magnetic field, E is smaller;
- At noon, they see more magnetic field, and E is larger.



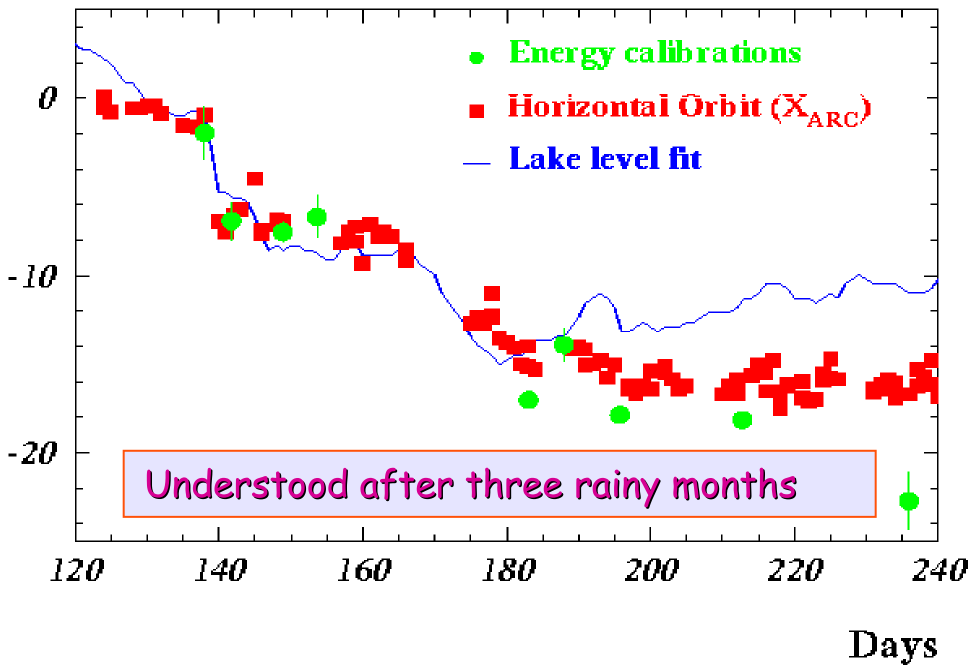
However, the electron orbit length is fixed by the RF frequency:

$$L = c \times \Delta t$$

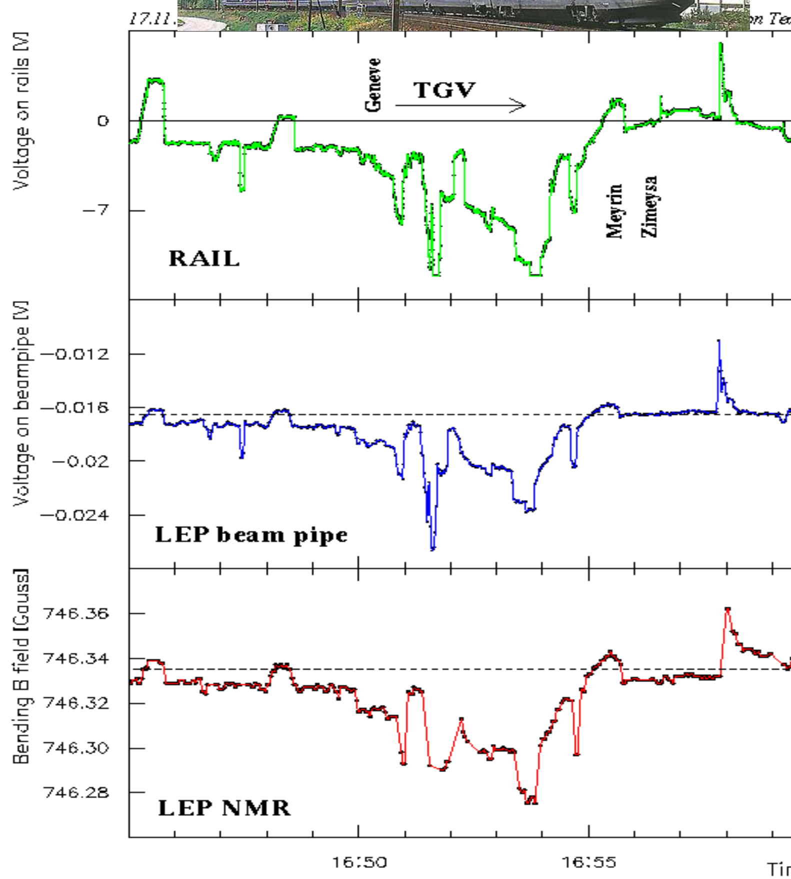
Measurement of the LEP Beam Energy (IV)

ther 10 MeV-ish effects understood even later:

Geological deformation due to the level of the lake
rain change LEP circumference;
(controlled with the BOM's)



Understood after one-day strike



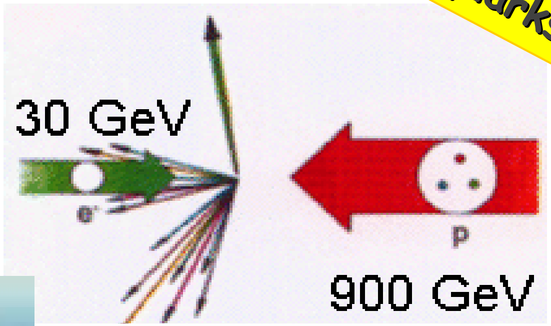
Effect of the TGV: currents induced on the
P beam pipe induce changes in the magnetic field
ontrolled by 16 NMR probes)

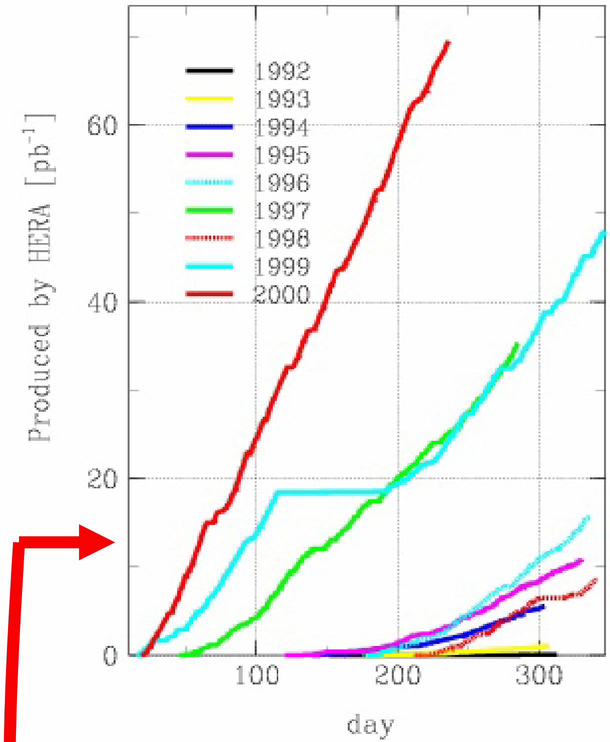
Now: $\Delta E_{beam} < 2$ MeV

The Hera ep collider at Desy

Are quarks elementary ?

ep collisions allow to probe efficiently the structure of the quarks

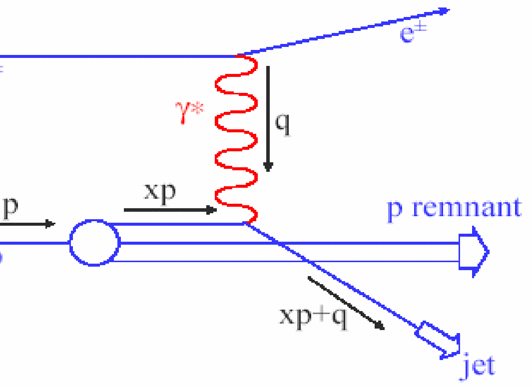




20 Feb 2004

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

-'06 ~ 1 fb^{-1} per experiment (?)

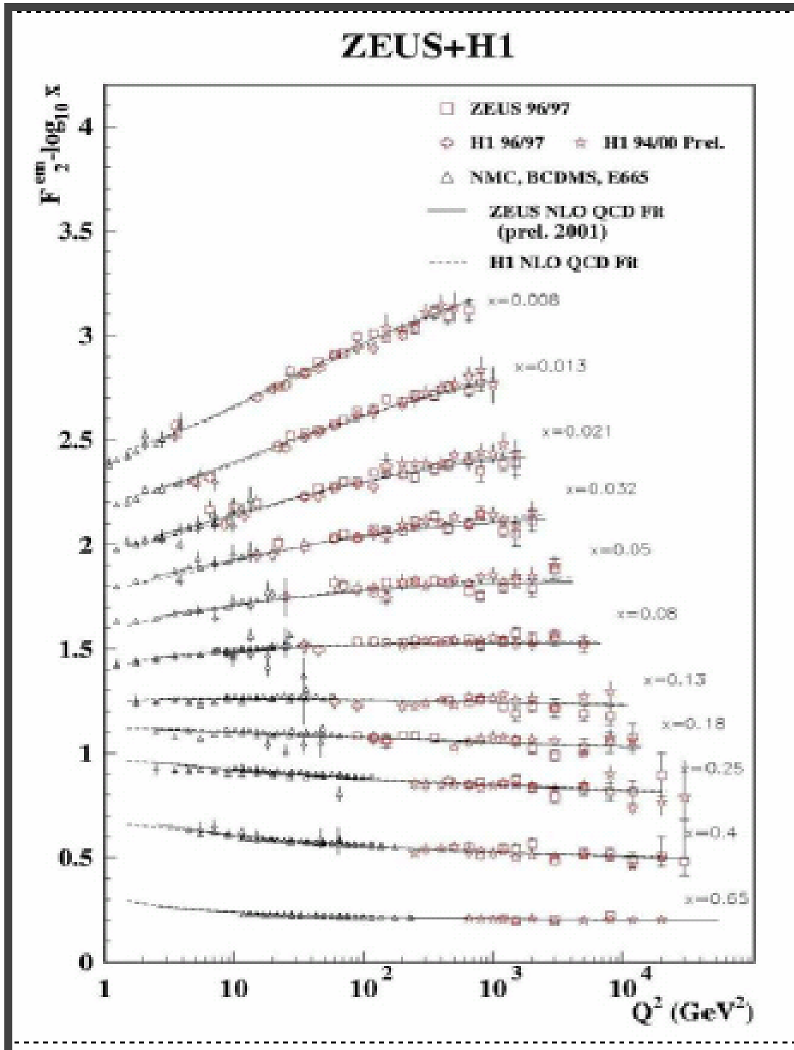


Describe the scattering in term of

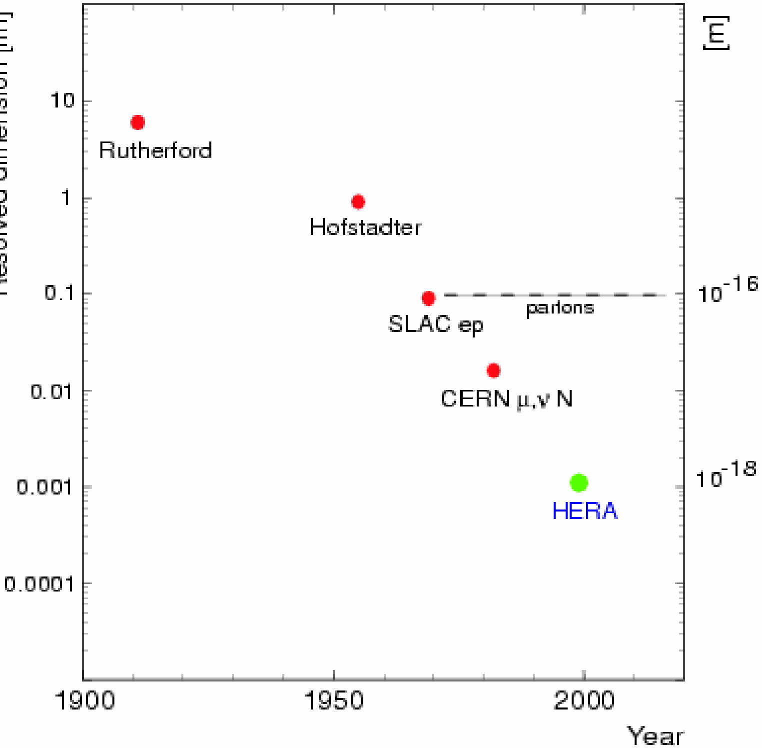
$$Q^2 = -q^2 \text{ and } x = \frac{Q^2}{2p \cdot q}$$

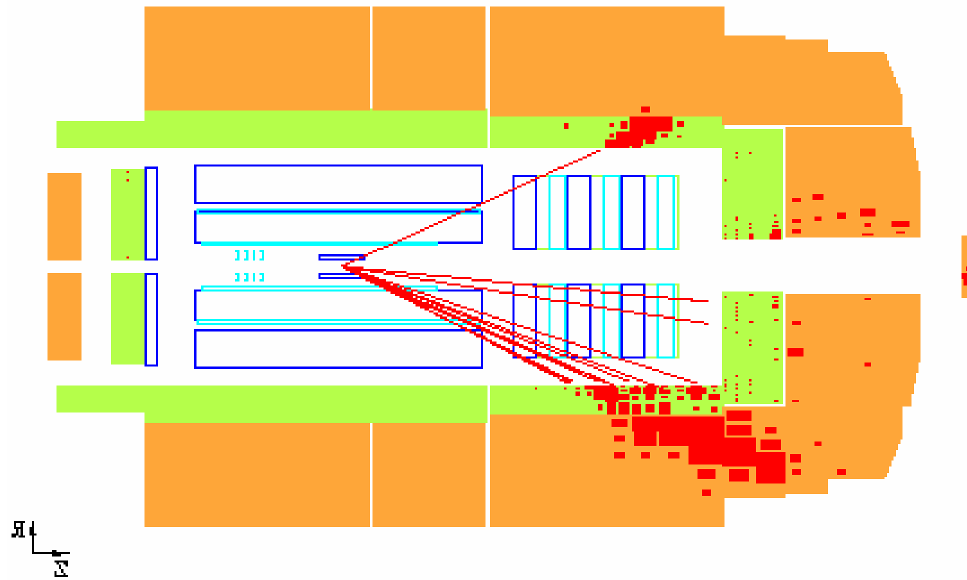
ne cross section is expressed in
rm of the quark densities

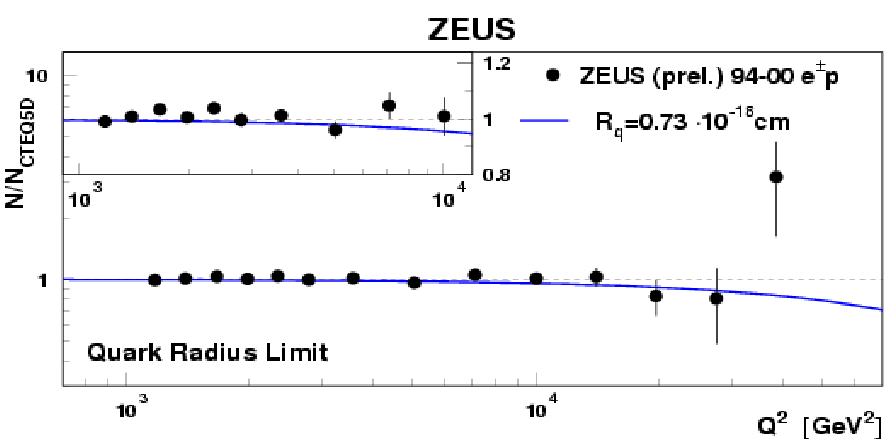
$$\frac{d^2\sigma_{ep\to eX}}{dx\,dQ^2} \approx \frac{2\pi\alpha^2}{xQ^4} F_2(x, Q^2)$$



ne accuracy of the measurement of
gles and energies of leptons and
ts is the challenge of the
easurement to the cross section at
gh Q2



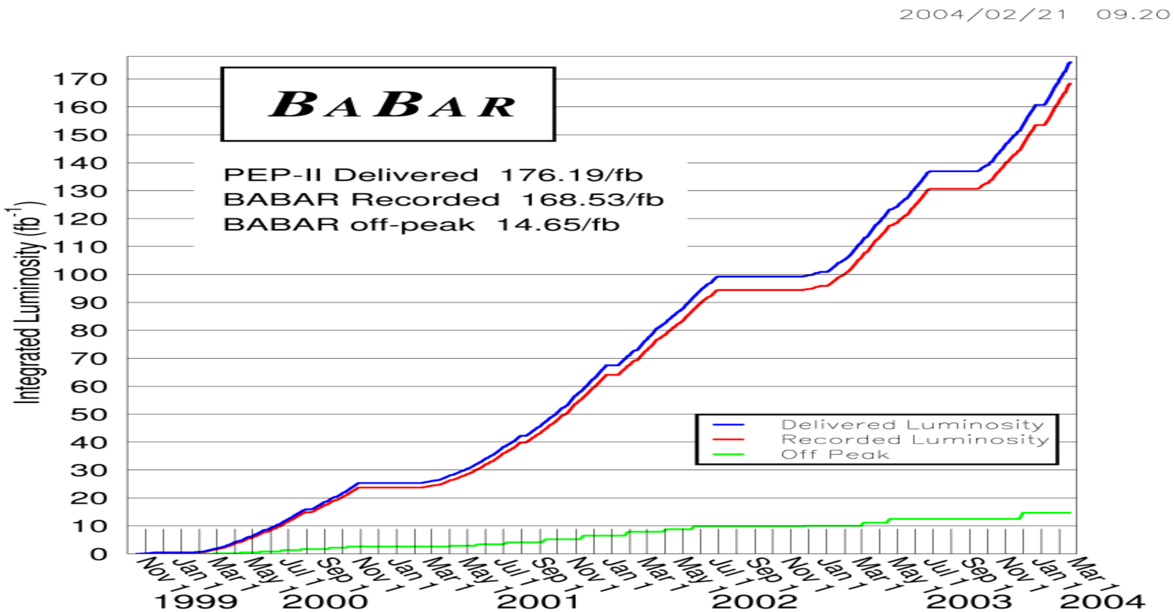




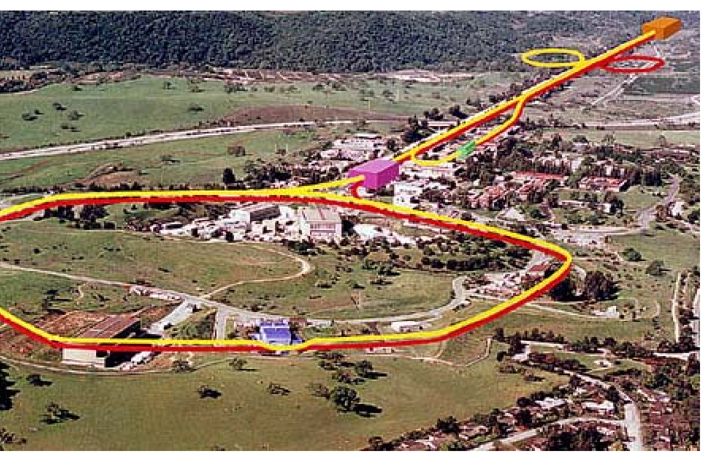
QCD with elementary quarks describes the scattering up to the highest accessible Q^2

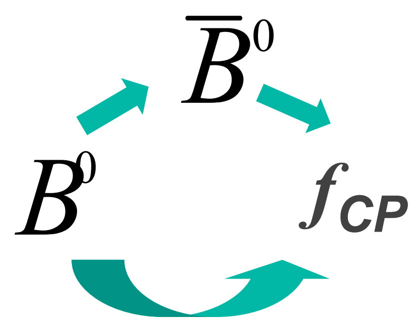
he asymmetric B factories at Kek and Slac

Why three familie
Why matter ?



~200.000.000 B B_{bar} Events Collected





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

CKM Matrix

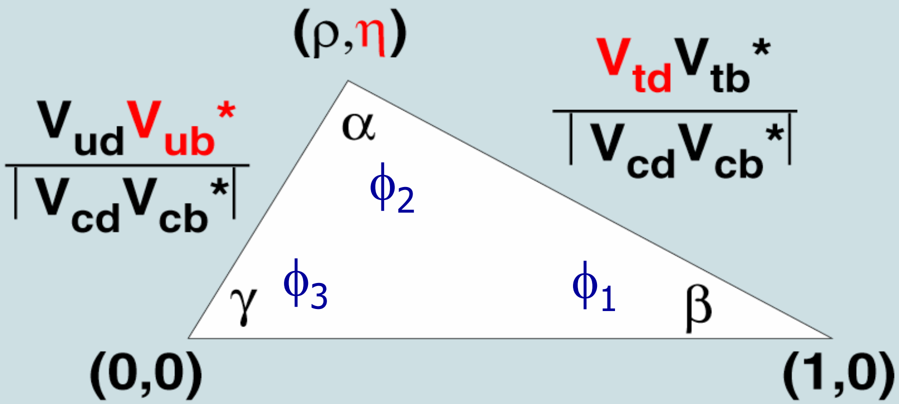
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

$V^\dagger V = I$, 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

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

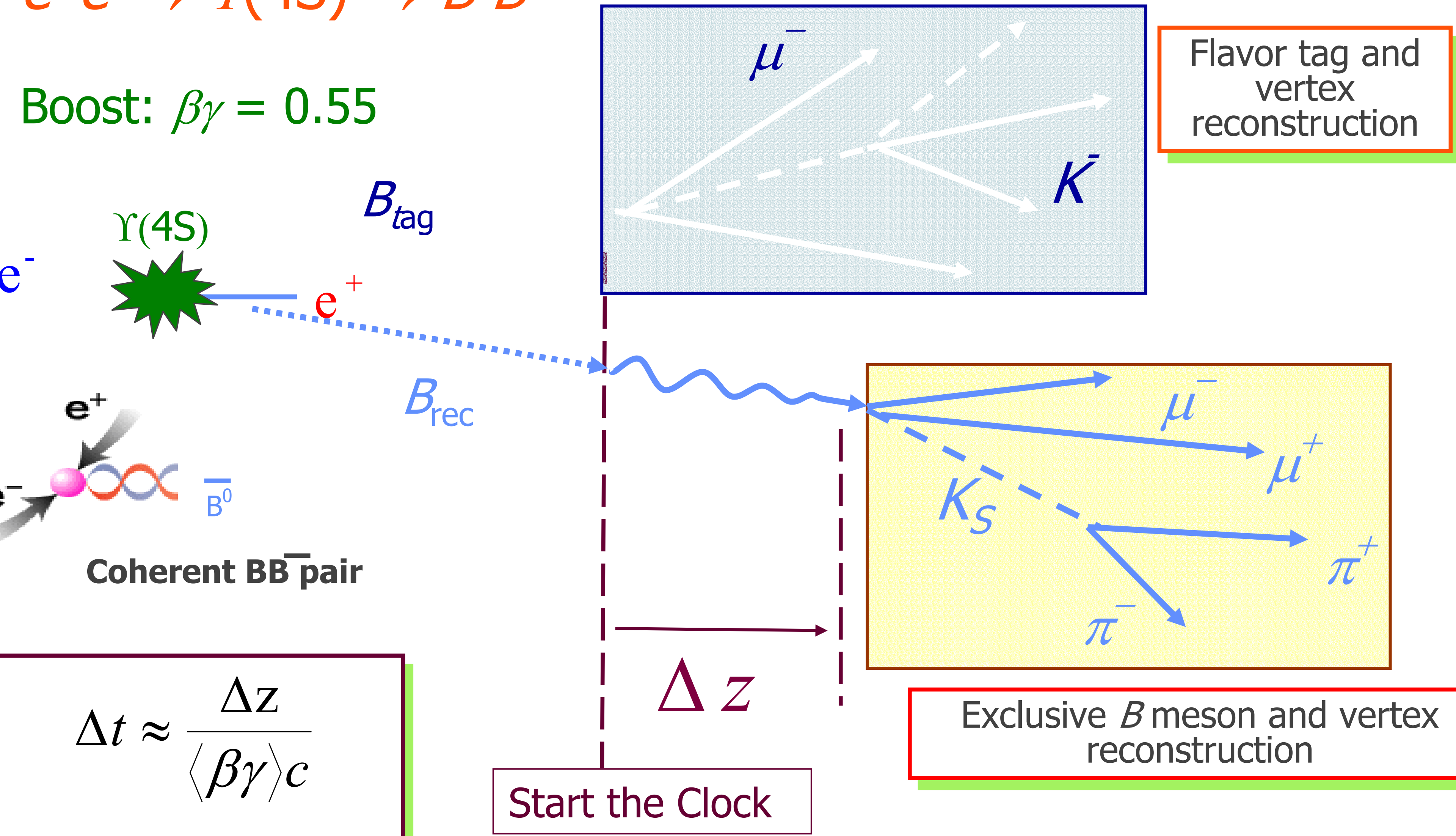


CP violation will arise from complex component of V_{ub}, V_{td}

xperimental technique at the $\Upsilon(4S)$ resonance

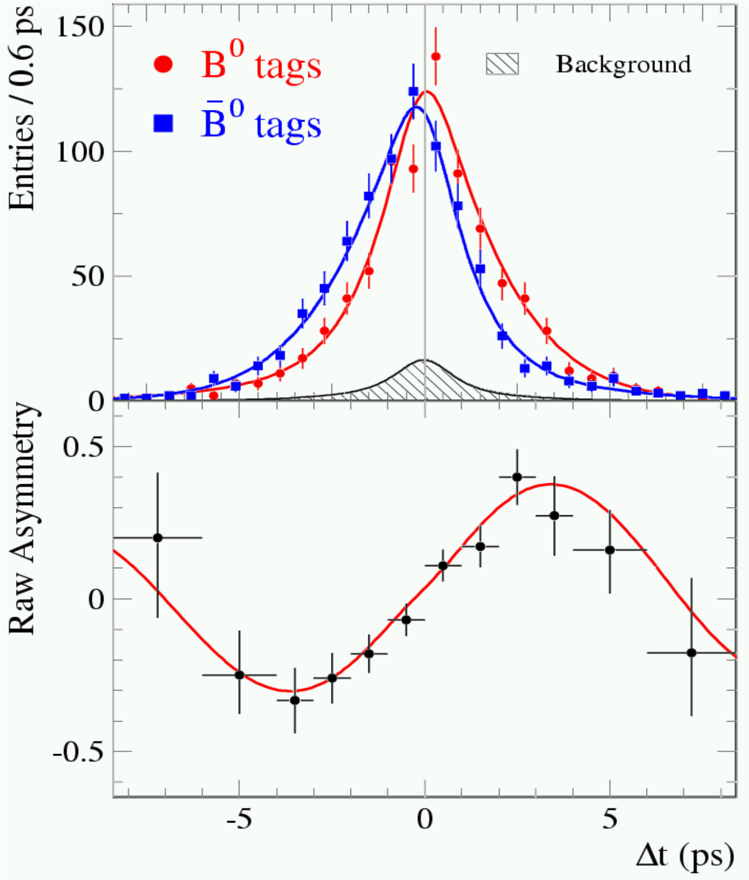
$$e^+e^- \rightarrow \Upsilon(4S) \rightarrow B\bar{B}$$

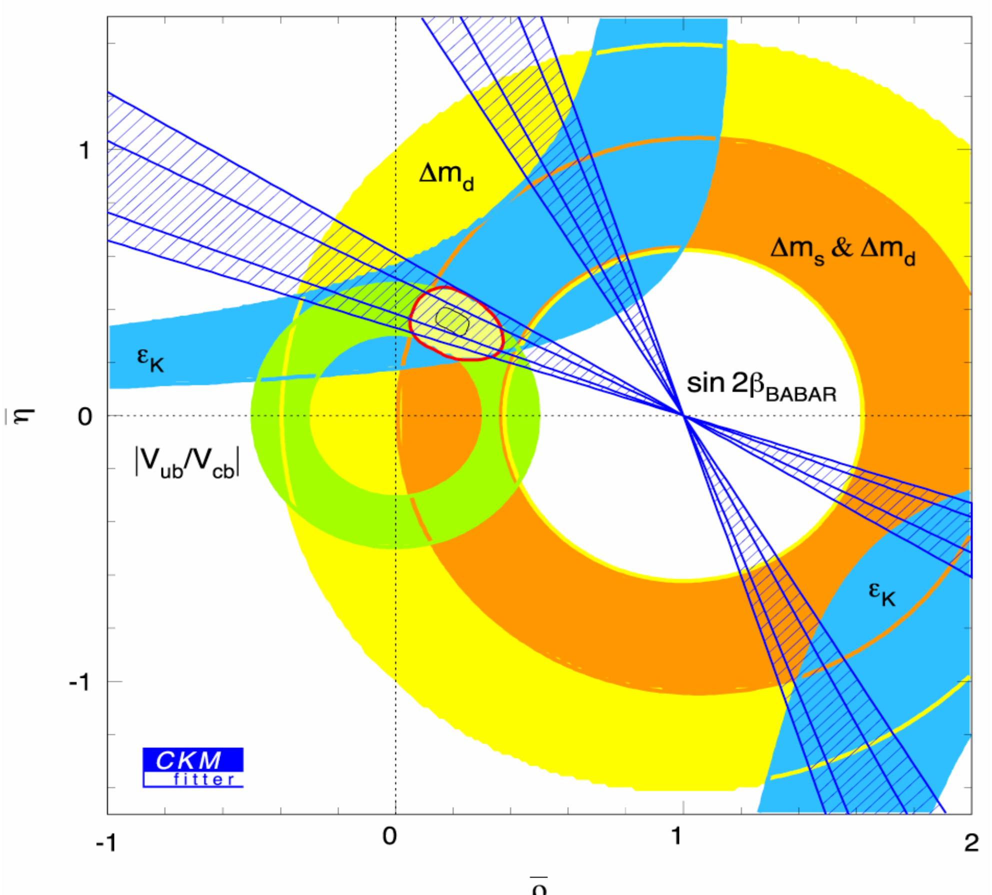
Boost: $\beta\gamma = 0.55$



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

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

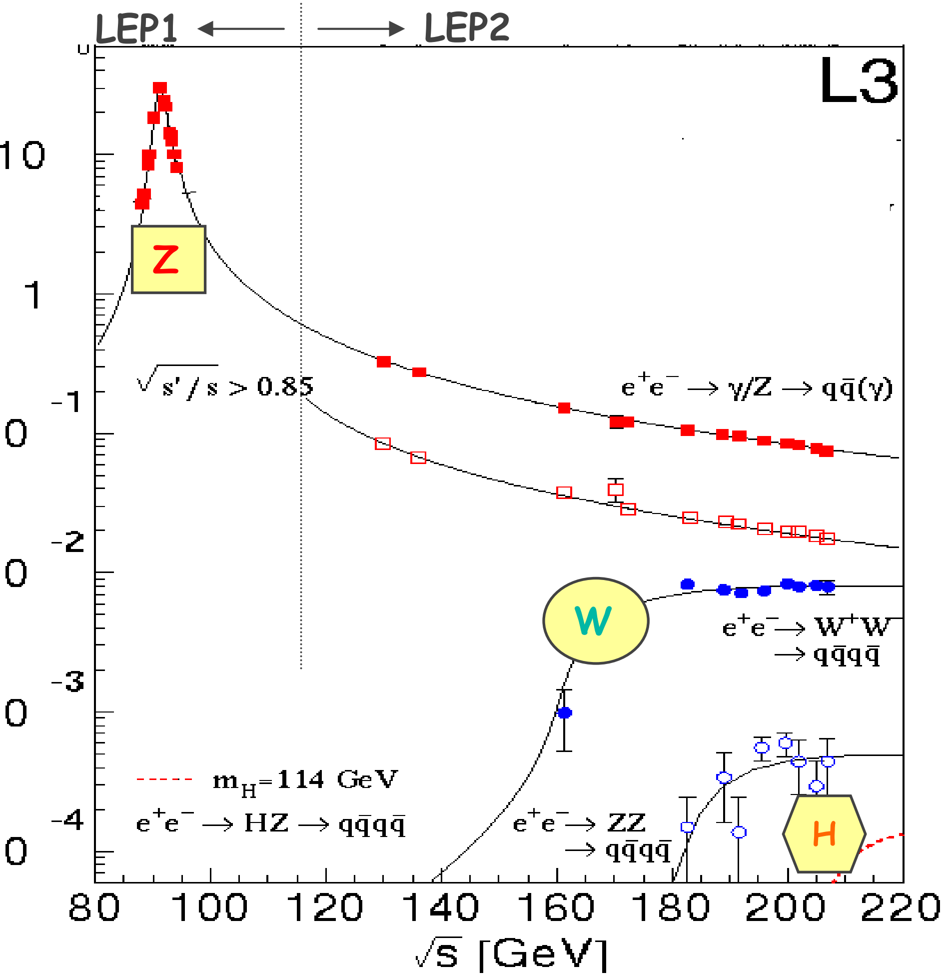




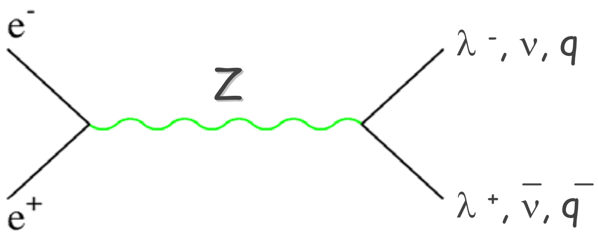
CKM matrix is unitary to this level of precision and incorporates CP violation with thee generations

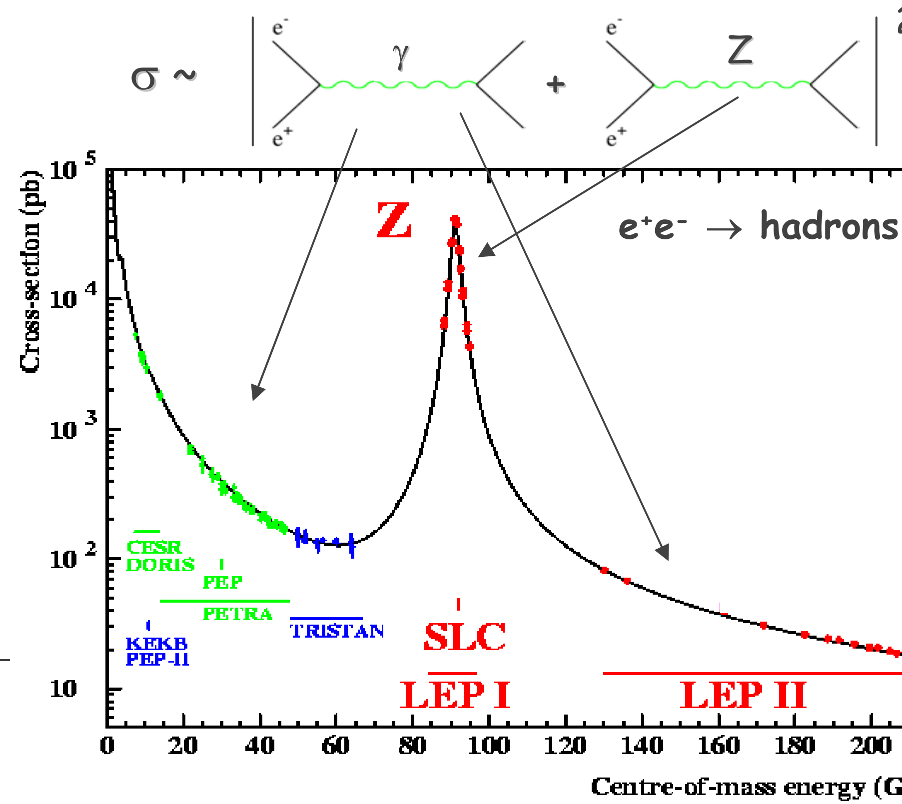
...he LEP e+e- Collider at CERN

...EP1 ('89-'95) : $\sqrt{s} \approx m_Z \rightarrow 2\ 10^7$ Z recorded → precise Z measurements
...EP2 ('96-2000) : $\sqrt{s} \rightarrow 209$ GeV → WW production, m_W, search for Higgs
...nd new particles



EP1 (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





chieved precision: better than 10^{-3}

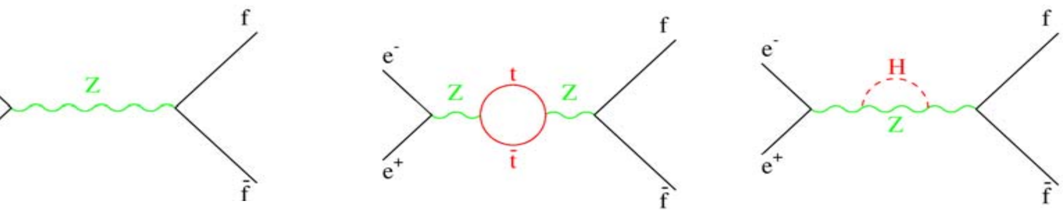
easured observables:

- 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 ?

est radiative quantum corrections (sensitive to heavy physics) :

west order — Examples of radiative corrections



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

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

→ deduce masses of particles not directly produced

C. modify observables by $\approx$ % :

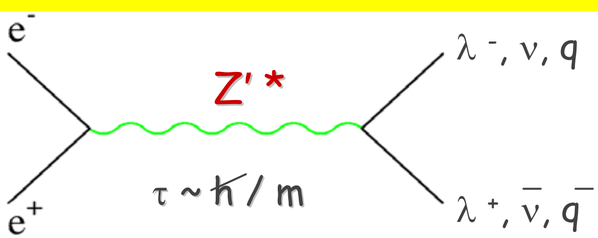
perimental precision of $\approx$‰ and improved theoretical needed

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

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

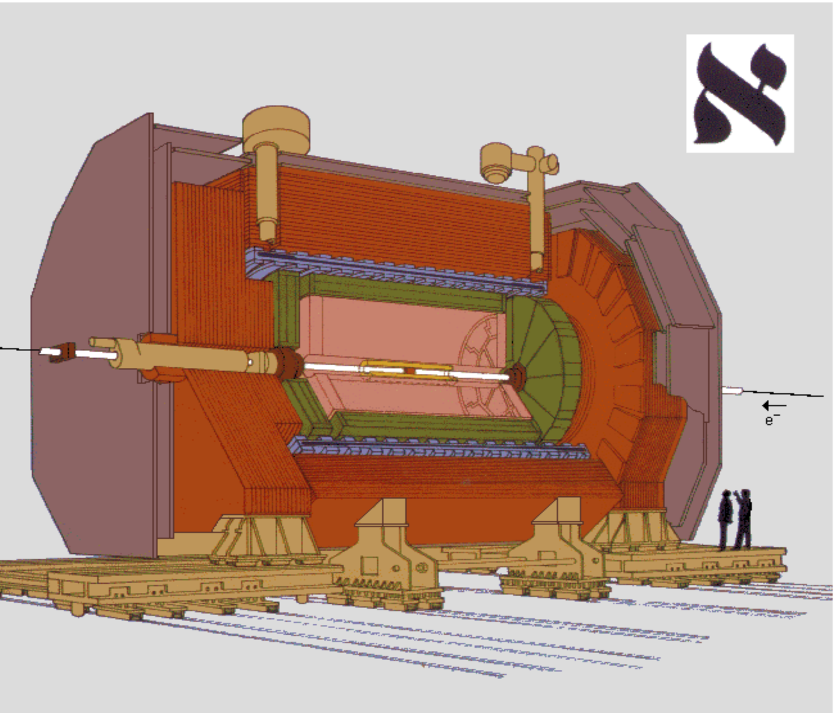
Beyond Z peak, search indirectly for New Physics by looking for deviations from SM

e.g. additional weak bosons



interferes with SM processes
→ deviations from SM expectations

Z Lineshape: Final State Identification (I)



Vertex Detector

Inner Tracking Chamber

Time Projection Chamber

Electromagnetic Calorimeter

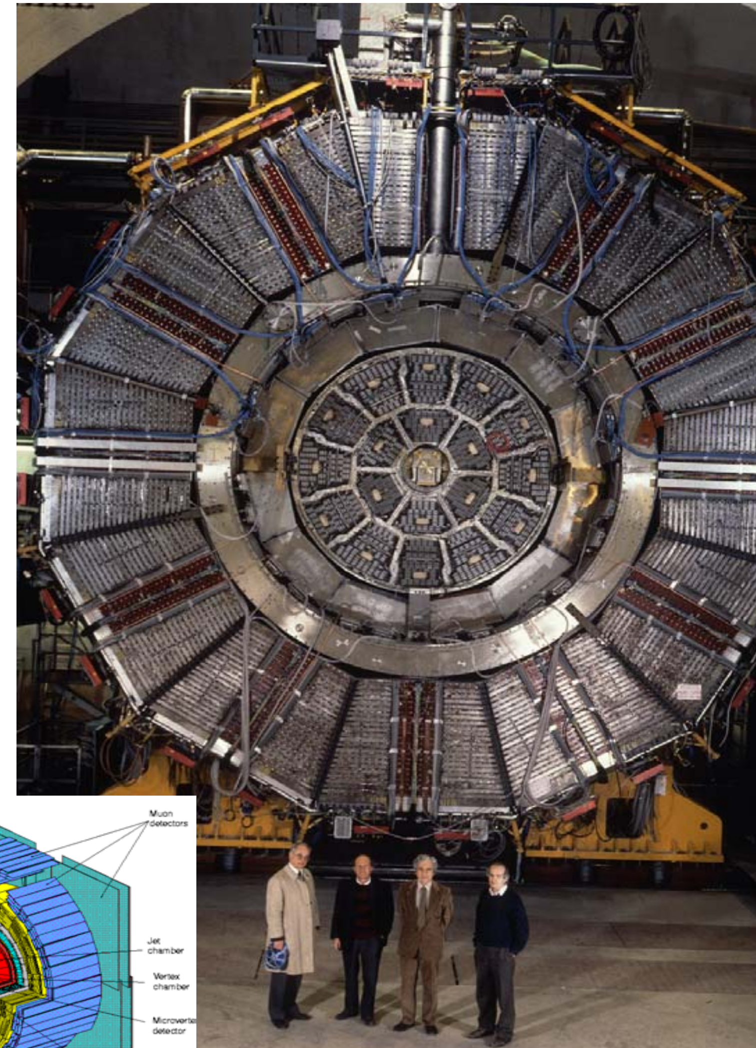
Superconducting Magnet Coil

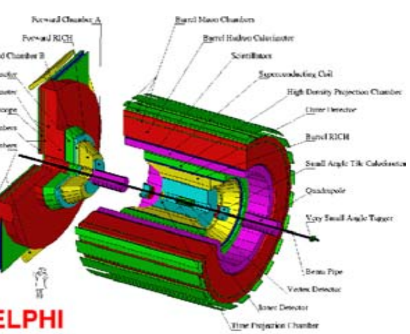
Hadron Calorimeter

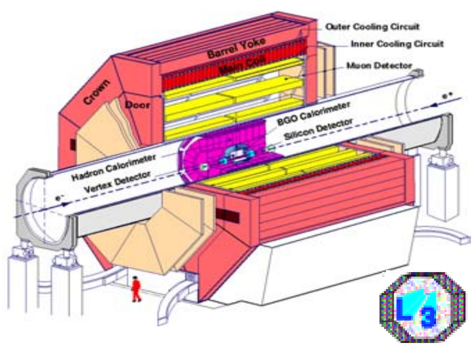
Muon Chambers

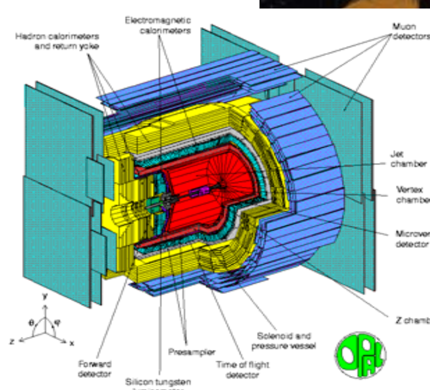
Luminosity Monitors

The ALEPH Detector

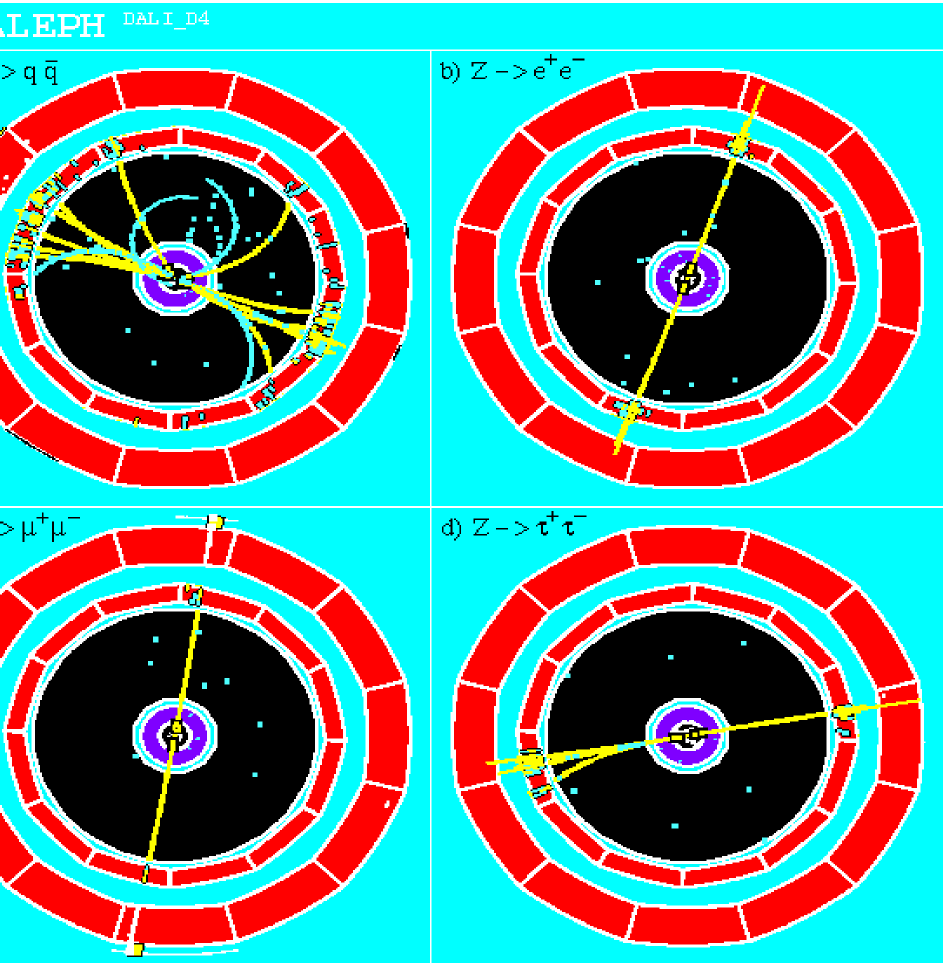


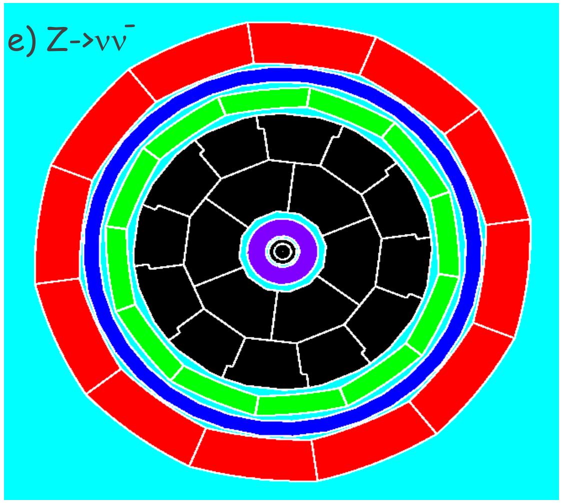






Z Lineshape: Final State Identification (II)





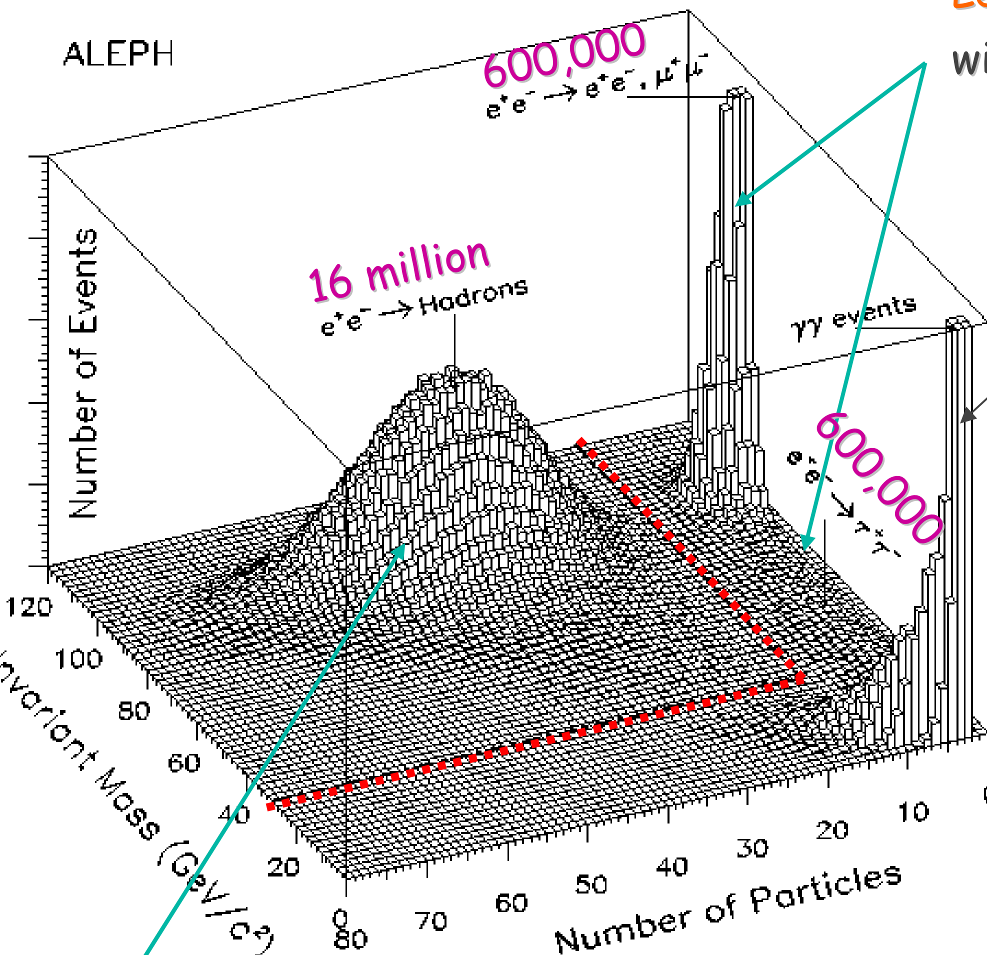
- $Z \to \nu\bar{\nu}$: Not detectable.
- $Z \to \tau^+\tau^-$: Two low multiplicity jets + missing energy carried by the decay neutrinos

Channel	Partial Width	Branching Ratio
Hadrons	1.739 GeV	70%
Neutrinos	0.497 GeV	20%
Leptons	0.250 GeV	10%

$Z \to q\bar{q}$: Two jets, large particle multiplicity.

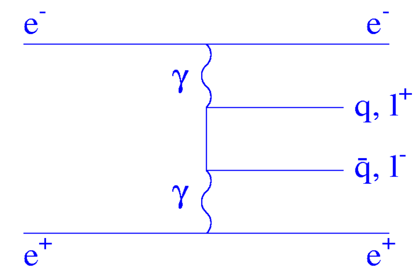
$Z \to e^+e^-, \mu^+\mu^-$: Two charged particles (e or μ.)

Z Lineshape: Final State Identification (III)



Leptonic decays: Low multiplicity, with (τ) or without (e, μ) missing energy

γγ Collisions: Low multiplicity, Low mass



Selections with

- ❑ High Efficiency;
- ❑ High Purity;

Count events : Easy?

FLORIDA VOTE COUNT TOTALS Nov. 26, 20

PRESIDENT	Nov. 7	First Recount	Certified
R Bush	2,909,176	2,911,872	2,912,790
D Gore	2,907,451	2,910,942	2,912,253
Bush Lead	1725	930	537

Source: State of Florida Systematic Uncertainty ~ 0.1%

25 electoral votes at sta

adronic decays:
gh multiplicity
gh mass

Note: Also need precise Luminosity determination

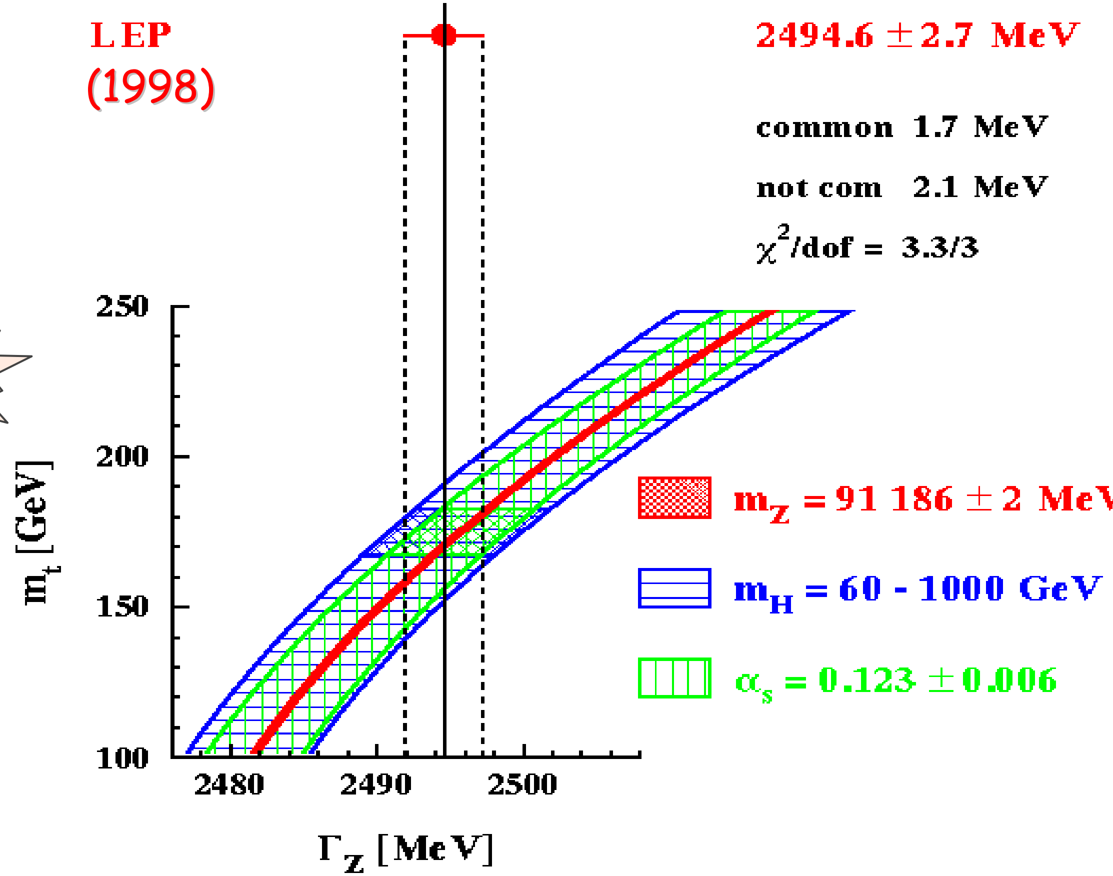
Z Lineshape: Results (III)

Obs.	Value	Error
m_Z	91187.5	2.1 MeV
Γ_Z	2495.2	2.3 MeV
σ^0	41.540	0.037 nb
R_l	20.767	0.025

10^{-3}

$\sigma^0_{had}/\sigma^0_l$

500 MeV in 1989



$$\Gamma_Z \propto (1 + \Delta\rho)^2$$

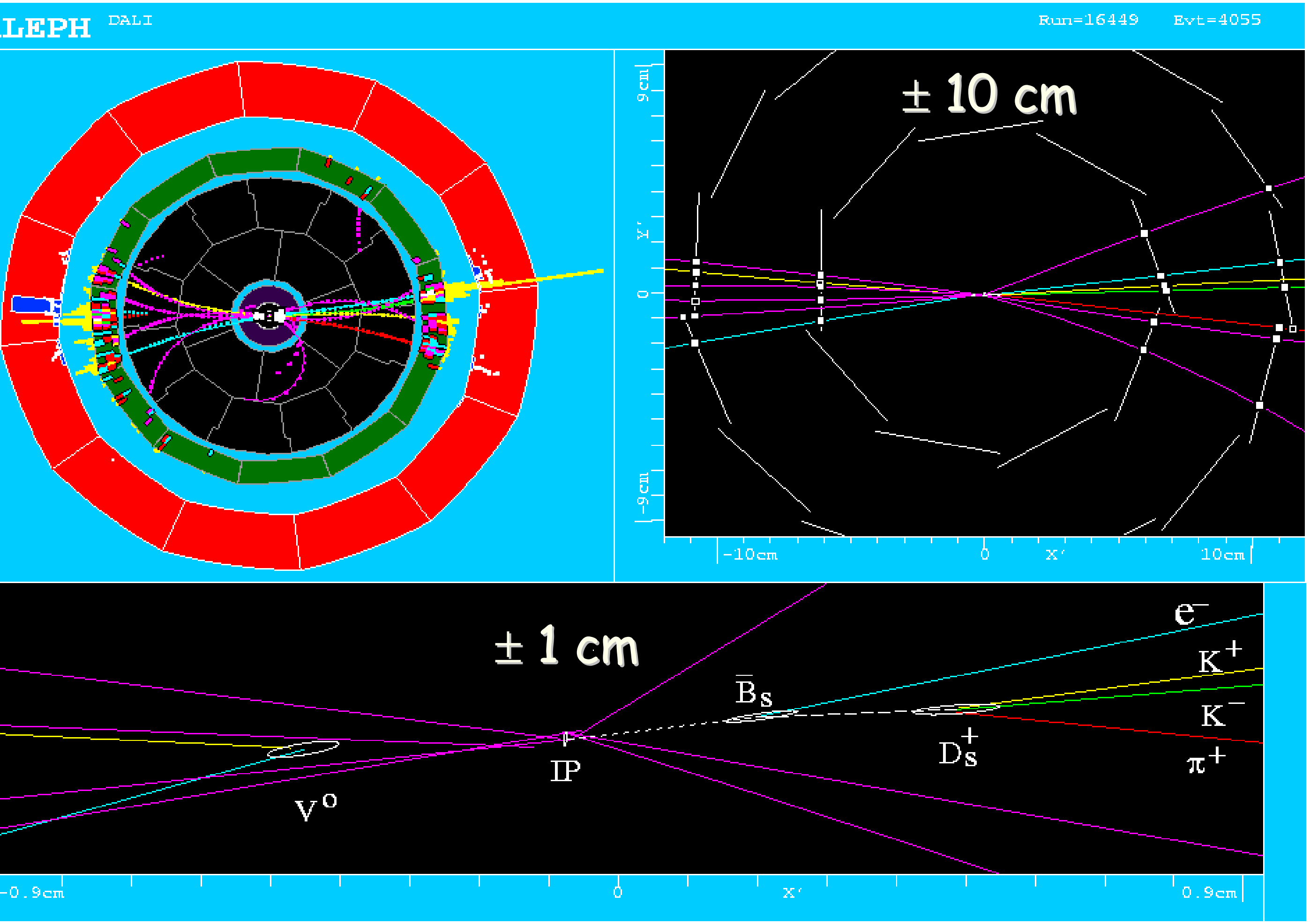
With this measurement alone:

$m_{top} \sim 165 \pm 25\ GeV/c^2$

(+small sensitivity to m_H)

Heavy Flavour Rates: Identification (I)

b- and c-hadrons decay weakly towards c- and s-hadrons, with a macroscopic lifetime (1.6 ps for b's), corresponding to few mm's at LEP



3d-vertexing determines secondary and tertiary vertices.

High resolution is crucial

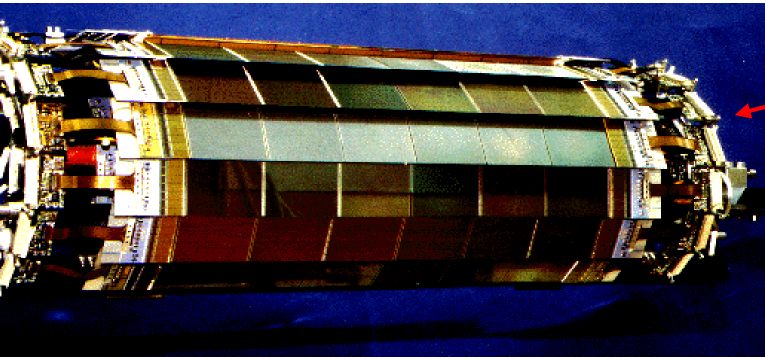
Impact parameters of reconstructed tracks allow b quarks to be tagged with very good purity.

Mass of secondary vertex tracks is a very powerful discriminator of flavour (b, c, and light quarks):

$m_b \sim 5$ GeV/c^2, and

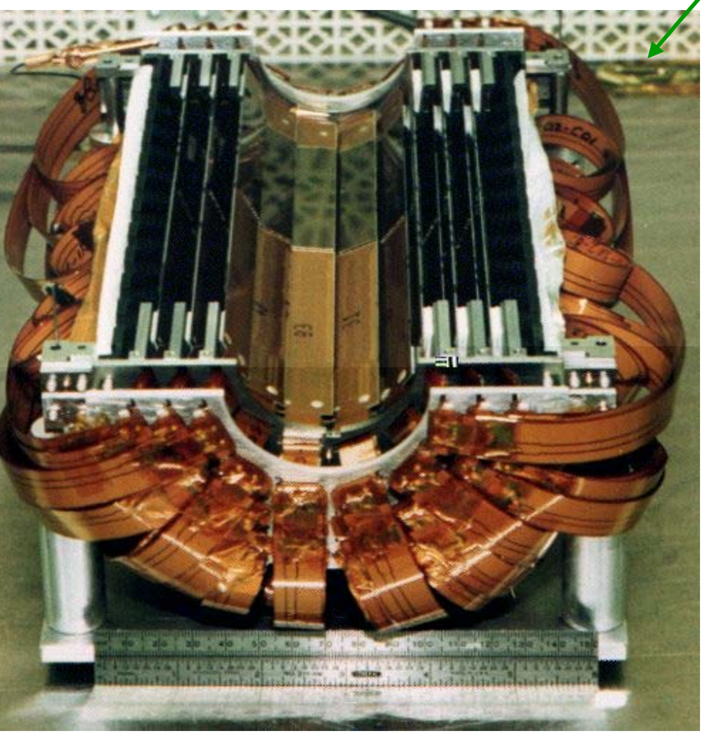
$m_c \sim 1.5$ GeV/c^2.

Heavy Flavour Rates: Identification (II)

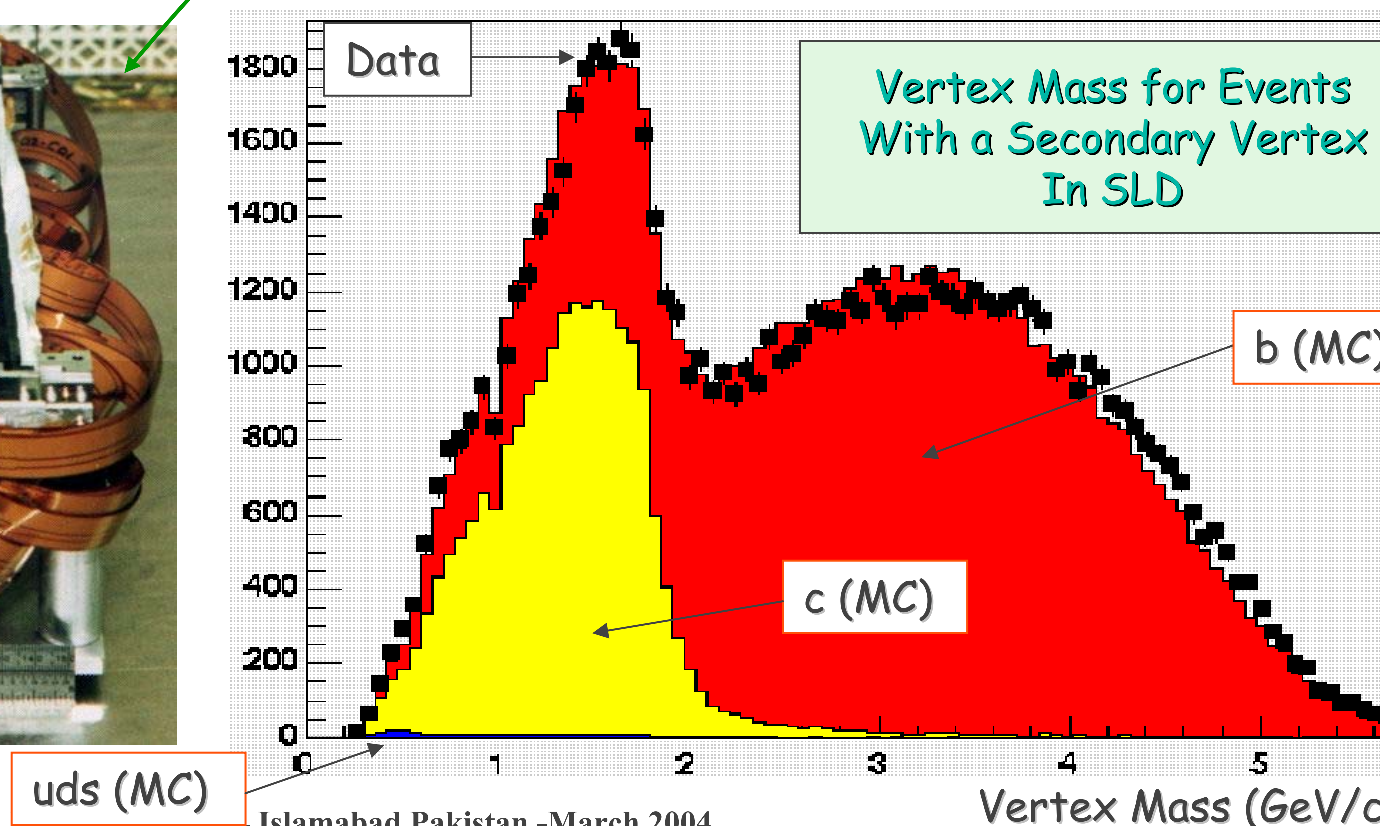


Vertex detectors (Si μ-strips, CCD's, pixels):

- At LEP: inner radius 6 cm, good resolution;
- At SLC: inner radius 2.3 cm, superior resolution.

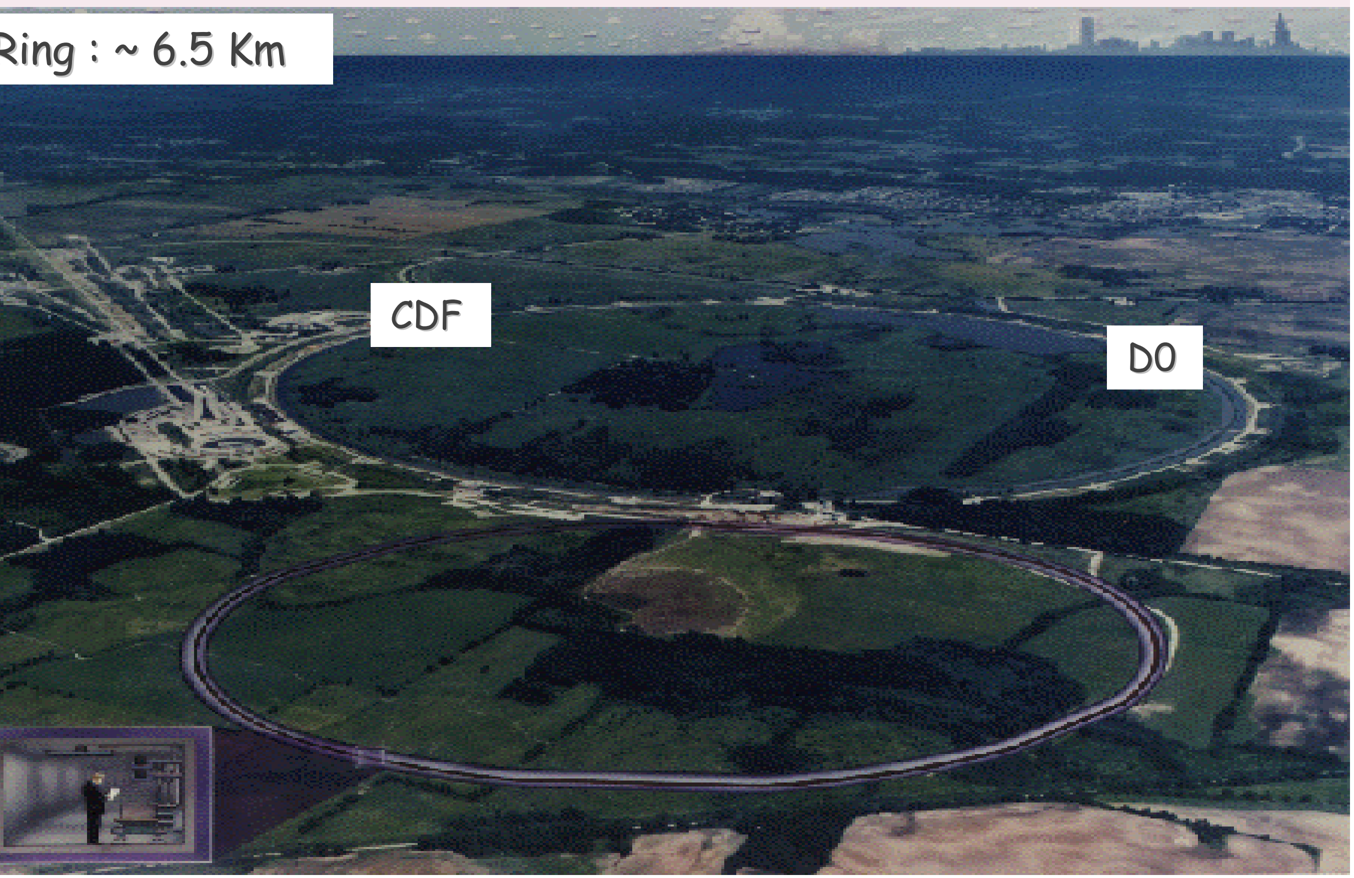


SLD can do both b- and c-tagging with good purity.



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

$\sqrt{s} \approx 2$ TeV



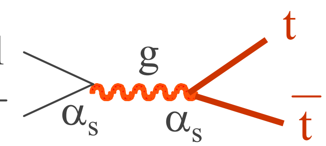
un 1 ('89-'96) : ≈ 200 top events → <u>discovery of top</u>

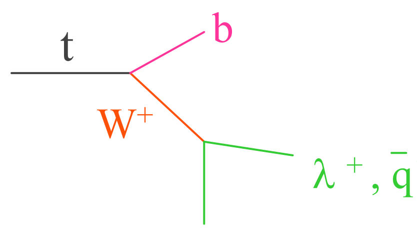
≈ 80 000 W events measurement of m_W and m_{top}

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

better measurements of m_W and m_{top},
searches for Higgs and new particles

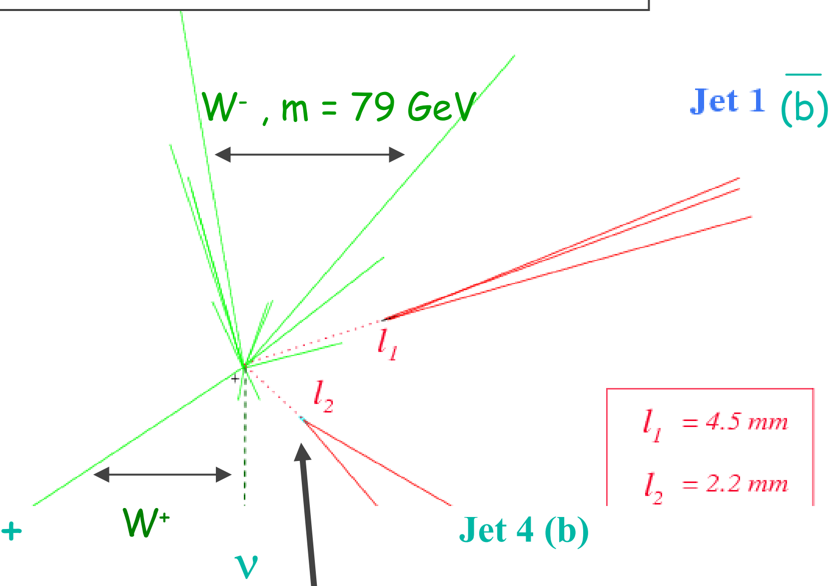
he top quark at the Tevatron



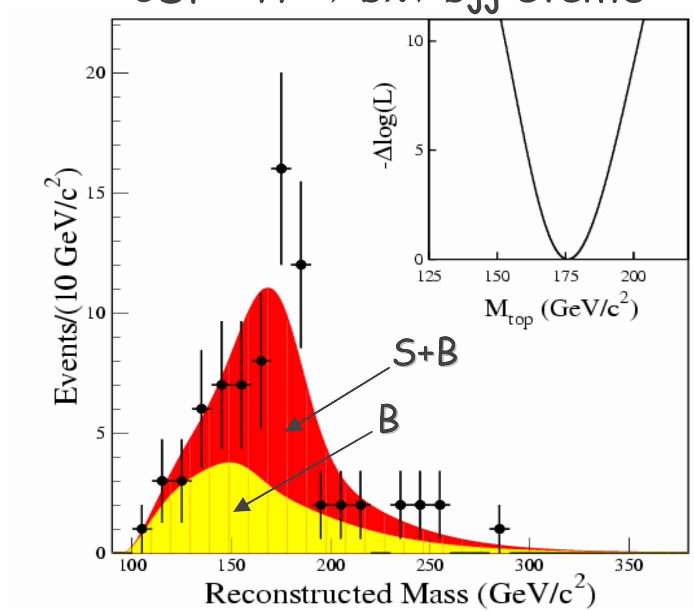


Heaviest particle observed so far (and $m_{top}-m_b \sim 170$ GeV) → clues about origin of masses ?

$\bar{t} \to bW\bar{b}W \to b\lambda\nu\, \bar{b}jj$ event
rom CDF data



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



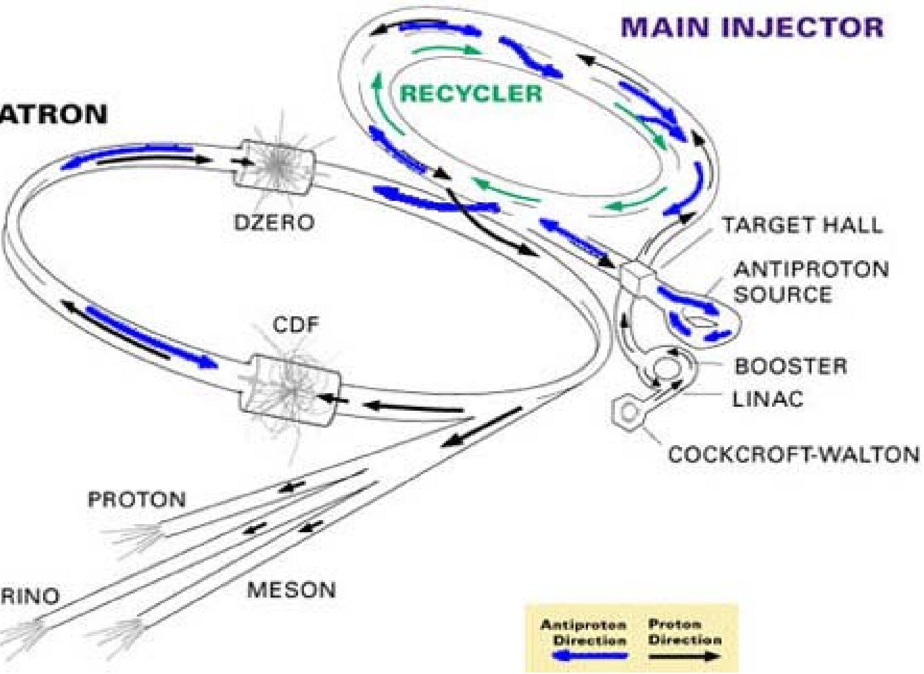
m_{top} (CDF + D0) = 174.3 ± 5.1 GeV

3%

statistics, calorimeter calibration

Secondary vertices
(b-hadrons) ~ 1.5 ps → decay at
w mm from primary vertex
tected with high-granularity
Si detector (b-tagging)

Upgraded Tevatron



New Main Injector:

- Improve p-bar production

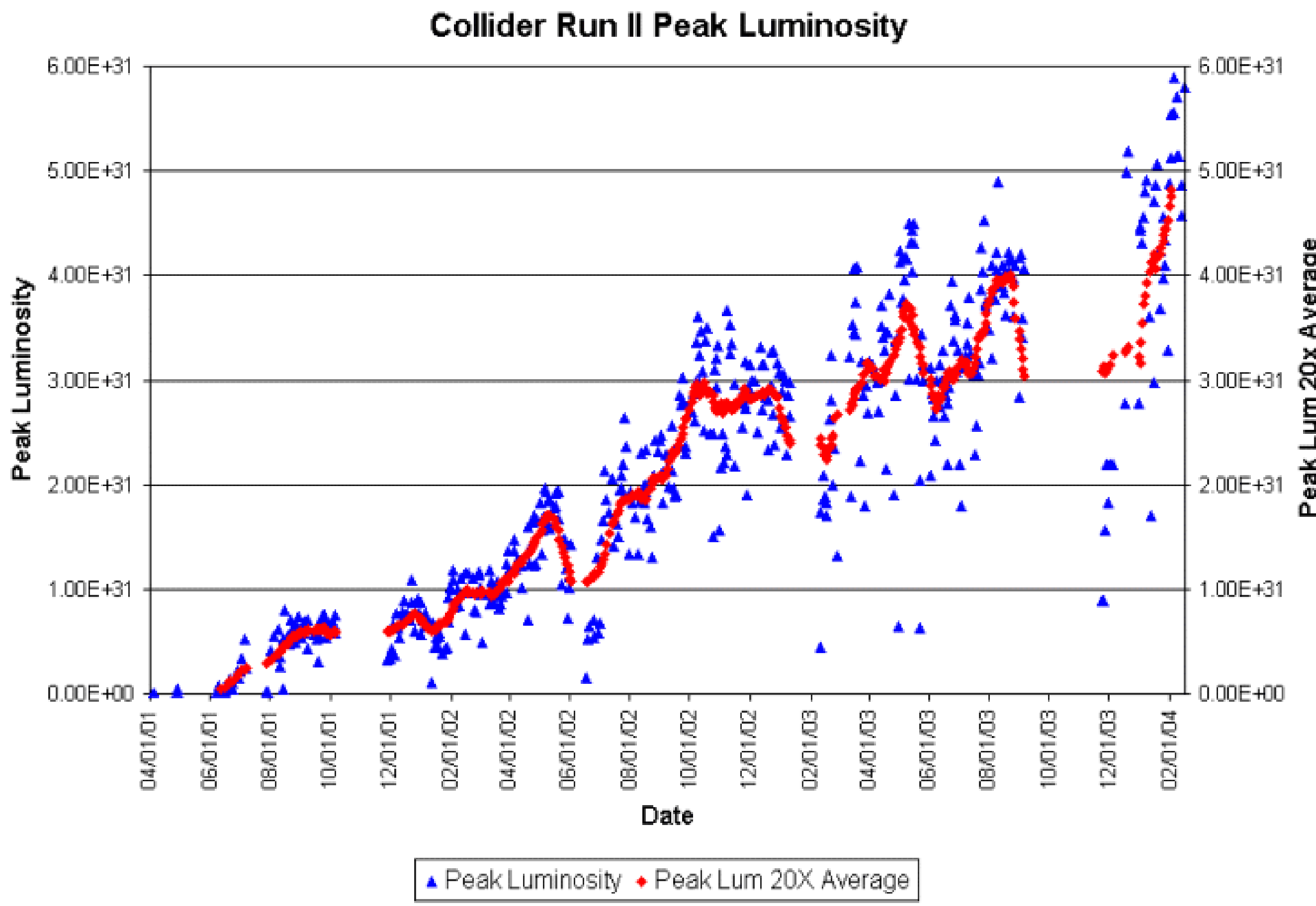
Recycler ring:

- Reuse p-bars! (current crisis)

TeV Luminosity (current situation)

eak luminosity still low but improving

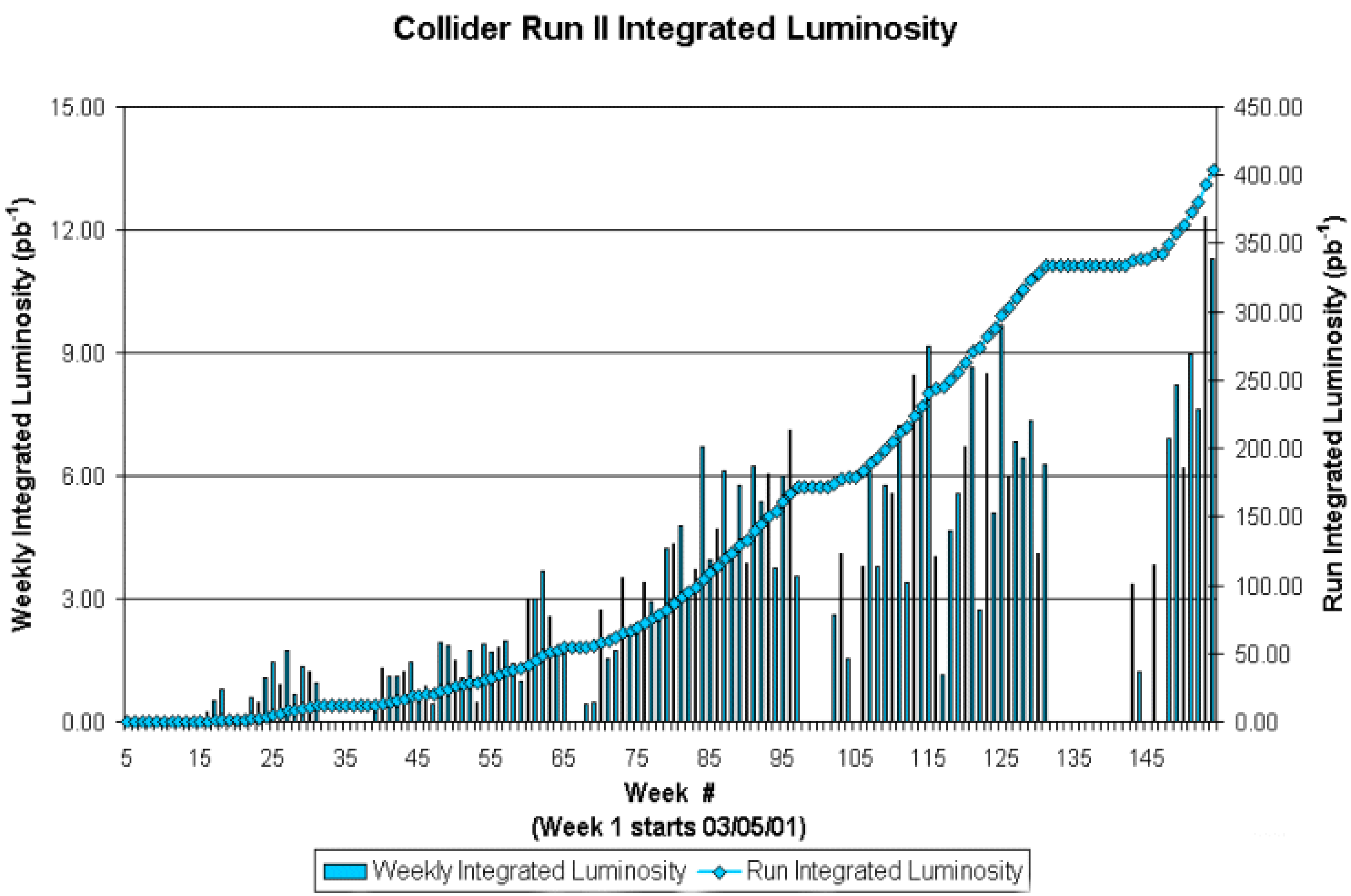
– Best $6x10^{31}$



Tev luminosity

6 pb^{-1} /wk typical

– Peak 12 pb^{-1} /wk



Trigger

- ome basic numbers at Tevatron
  - Bunch crossing frequency = 2.5 MHz
  - > 1 interaction/crossing
  - Max data logging frequency ~ 100 Hz
- eed ~ 10^4 rejection factor
- rovided by trigger system
  - Custom electronics on detector (L1)
  - ~1 room full of custom electronics (L1/2)
  - ~1 room full of dedicated PC's (L3)
- gnificant fraction of analysis done at trigger level