Adriatic School on Particle Physics and Physics Informatics, Split '01

Electroweak physics at LEP

19.-21.9.2001

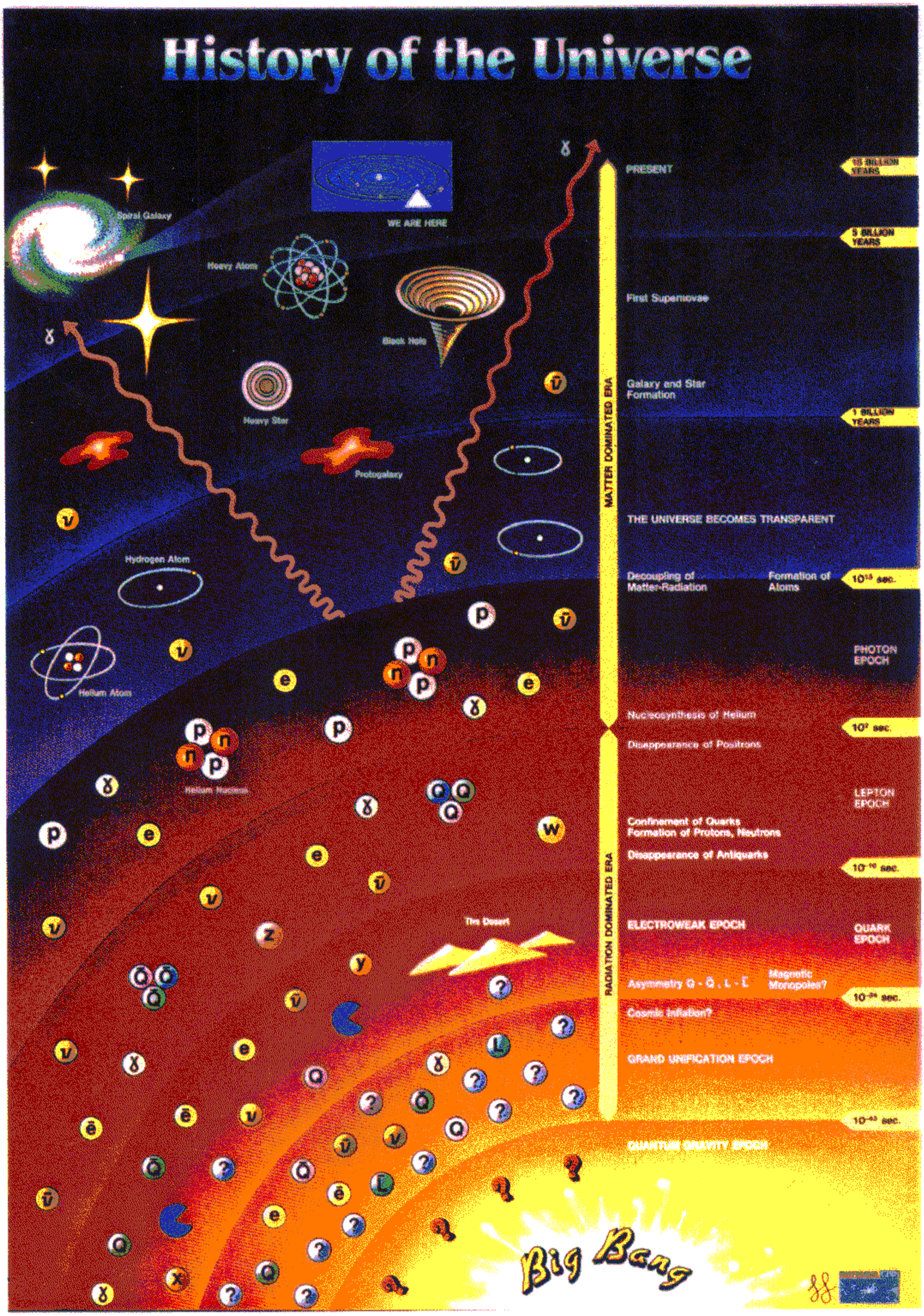
Otmar Biebel
(MPI Munich)

Content:

- Introduction and motivation
- Z boson physics
- W boson physics
- Search for the Higgs boson
- Summary and outlook

(Transparencies on the Web: www.mppmu.mpg.de/~biebel)

History of the Universe



MATTER DOMINATED ERA

PRESENT — 15 BILLION YEARS

5 BILLION YEARS

First Supernovae

Galaxy and Star Formation

1 BILLION YEARS

THE UNIVERSE BECOMES TRANSPARENT

Decoupling of Matter-Radiation — Formation of Atoms — 10^{13} sec.

PHOTON EPOCH

Nucleosynthesis of Helium

10^{2} sec.

RADIATION DOMINATED ERA

Disappearance of Positrons

LEPTON EPOCH

Confinement of Quarks
Formation of Protons, Neutrons

Disappearance of Antiquarks

10^{-10} sec.

ELECTROWEAK EPOCH

QUARK EPOCH

Asymmetry $Q - \bar{Q}$, $L - \bar{L}$ — Magnetic Monopoles?

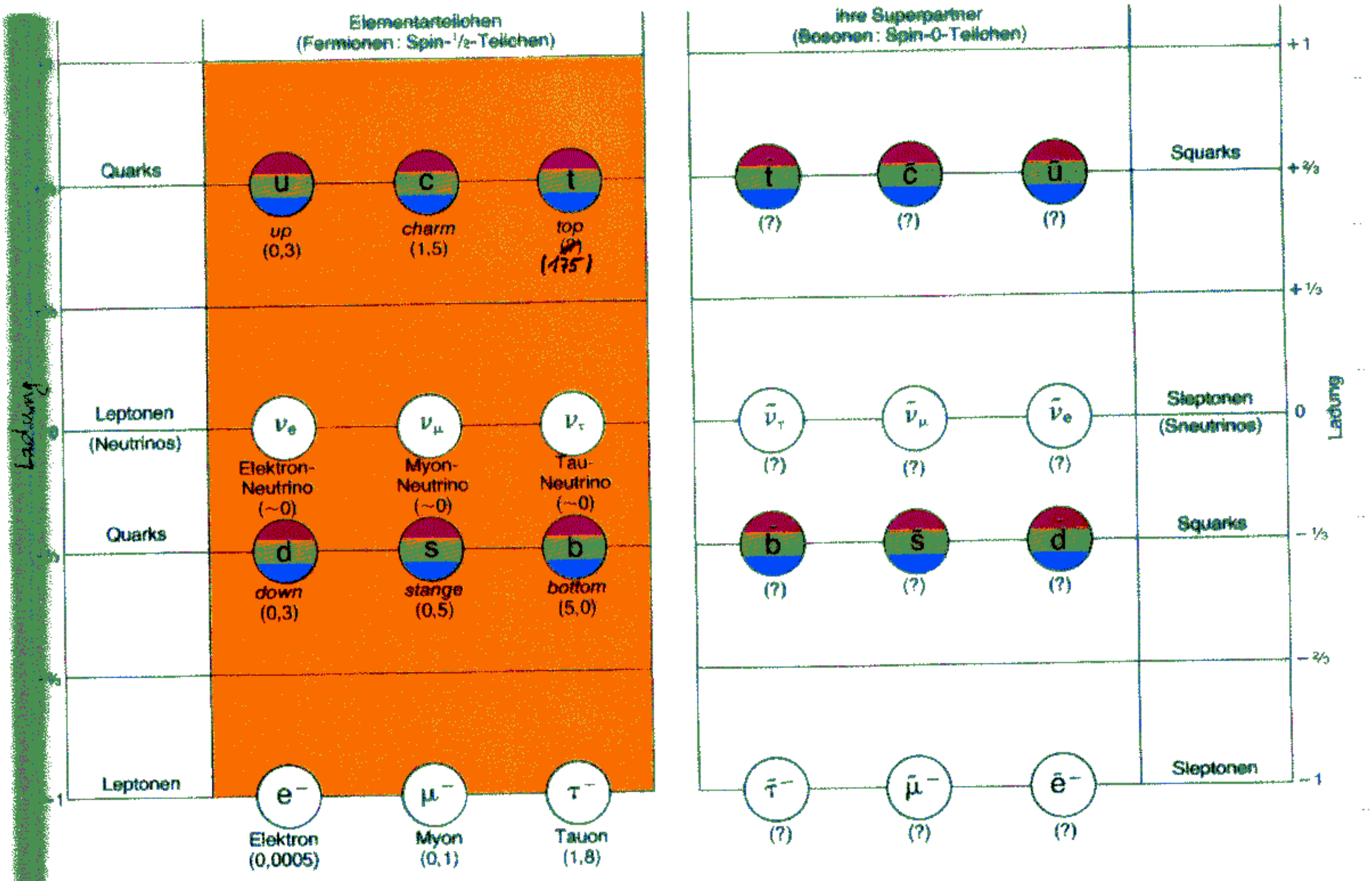
10^{-34} sec.

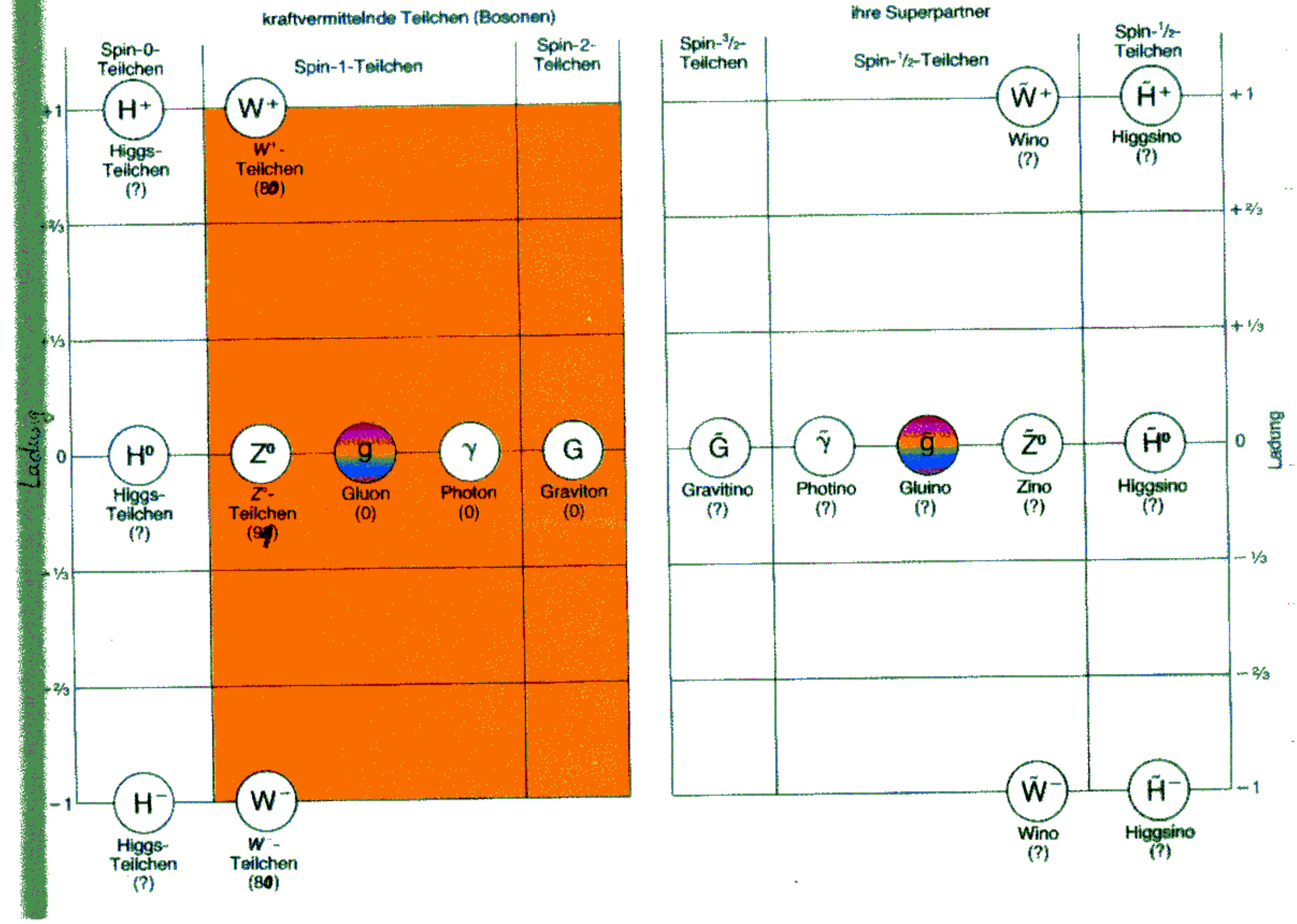
Cosmic Inflation?

GRAND UNIFICATION EPOCH

10^{-43} sec.

QUANTUM GRAVITY EPOCH


Elementarteilchen
(Fermionen: Spin-½-Teilchen)
ihre Superpartner
(Bosonen: Spin-0-Teilchen)
Ladung
+1
+⅔
+⅓
0
−⅓
−⅔
−1
Quarks
u
up
(0,3)
c
charm
(1,5)
t
top
~~(?)~~
(175)
t̃
(?)
c̃
(?)
ũ
(?)
Squarks
Leptonen
(Neutrinos)
ν_e
Elektron-
Neutrino
(~0)
ν_μ
Myon-
Neutrino
(~0)
ν_τ
Tau-
Neutrino
(~0)
$\tilde{\nu}_\tau$
(?)
$\tilde{\nu}_\mu$
(?)
$\tilde{\nu}_e$
(?)
Sleptonen
(Sneutrinos)
Quarks
d
down
(0,3)
s
stange
(0,5)
b
bottom
(5,0)
b̃
(?)
s̃
(?)
d̃
(?)
Squarks
Leptonen
e⁻
Elektron
(0,0005)
μ⁻
Myon
(0,1)
τ⁻
Tauon
(1,8)
τ̃⁻
(?)
μ̃⁻
(?)
ẽ⁻
(?)
Sleptonen
Ladung


kraftvermittelnde Teilchen (Bosonen)
ihre Superpartner
Ladung
+1
+⅔
+⅓
0
−⅓
−⅔
−1
Spin-0-
Teilchen
Spin-1-Teilchen
Spin-2-
Teilchen
Spin-3/2-
Teilchen
Spin-½-Teilchen
Spin-½-
Teilchen
H⁺
Higgs-
Teilchen
(?)
W⁺
W⁺-
Teilchen
(80)
W̃⁺
Wino
(?)
H̃⁺
Higgsino
(?)
H⁰
Higgs-
Teilchen
(?)
Z⁰
Z⁰-
Teilchen
(91)
g
Gluon
(0)
γ
Photon
(0)
G
Graviton
(0)
G̃
Gravitino
(?)
γ̃
Photino
(?)
g̃
Gluino
(?)
Z̃⁰
Zino
(?)
H̃⁰
Higgsino
(?)
H⁻
Higgs-
Teilchen
(?)
W⁻
W⁻-
Teilchen
(80)
W̃⁻
Wino
(?)
H̃⁻
Higgsino
(?)
Ladung

Aims of LEP

- Precision test of Standard model (SM) of electroweak ($SU(2) \times U(1)$) and strong ($SU(3)$) interactions, eg. for the electroweak part:

▷ Measure properties of Z and $W^{\pm}$-bosons

▷ Search for Higgs boson

▷ Probe for physics beyond the Standard model

- LEP's design parameters and running strategy:

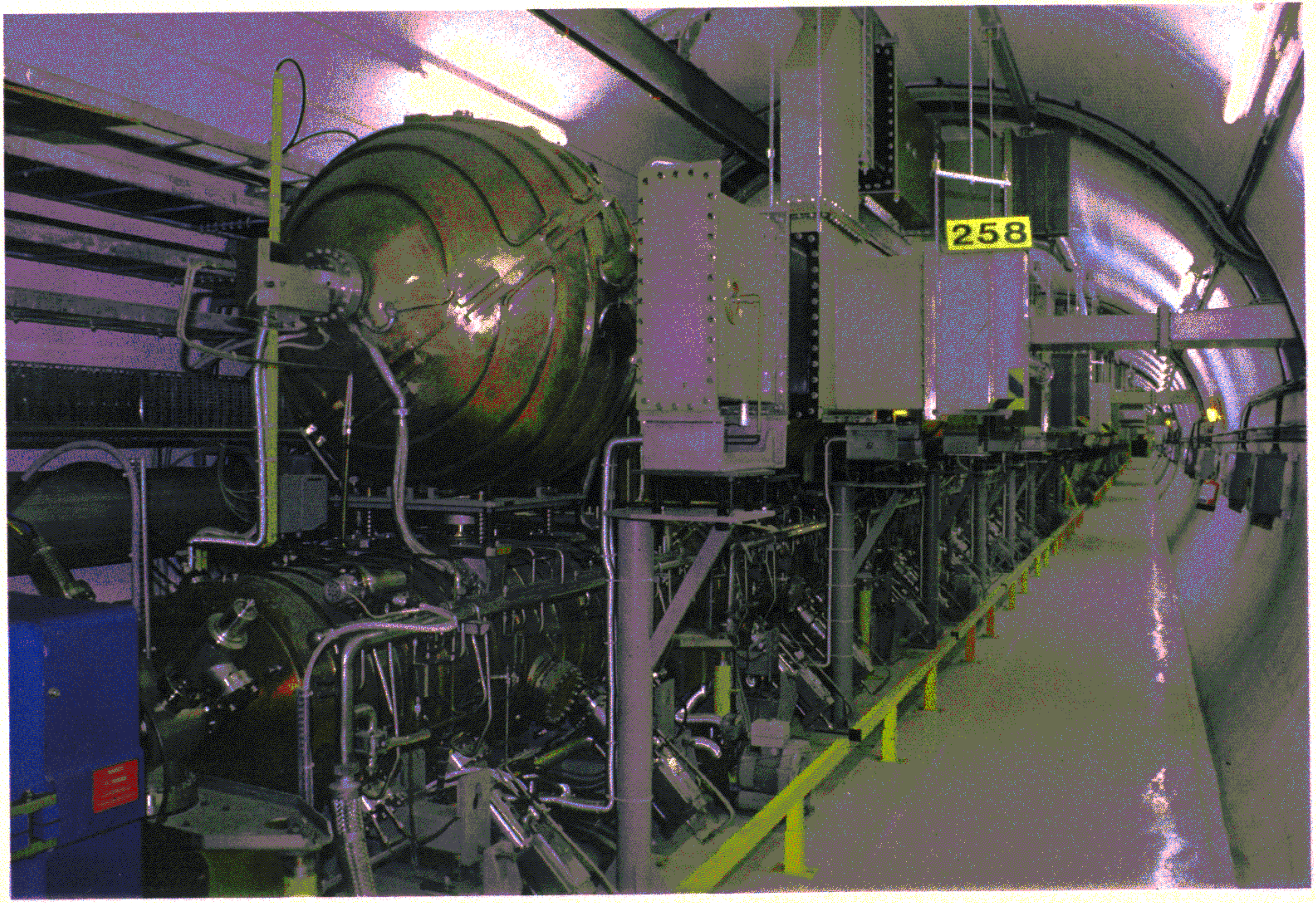
LEPI: centre-of-mass energy $\sqrt{s} = (91 \pm 3)$ GeV
to study Z bosons (1989 – 1995)

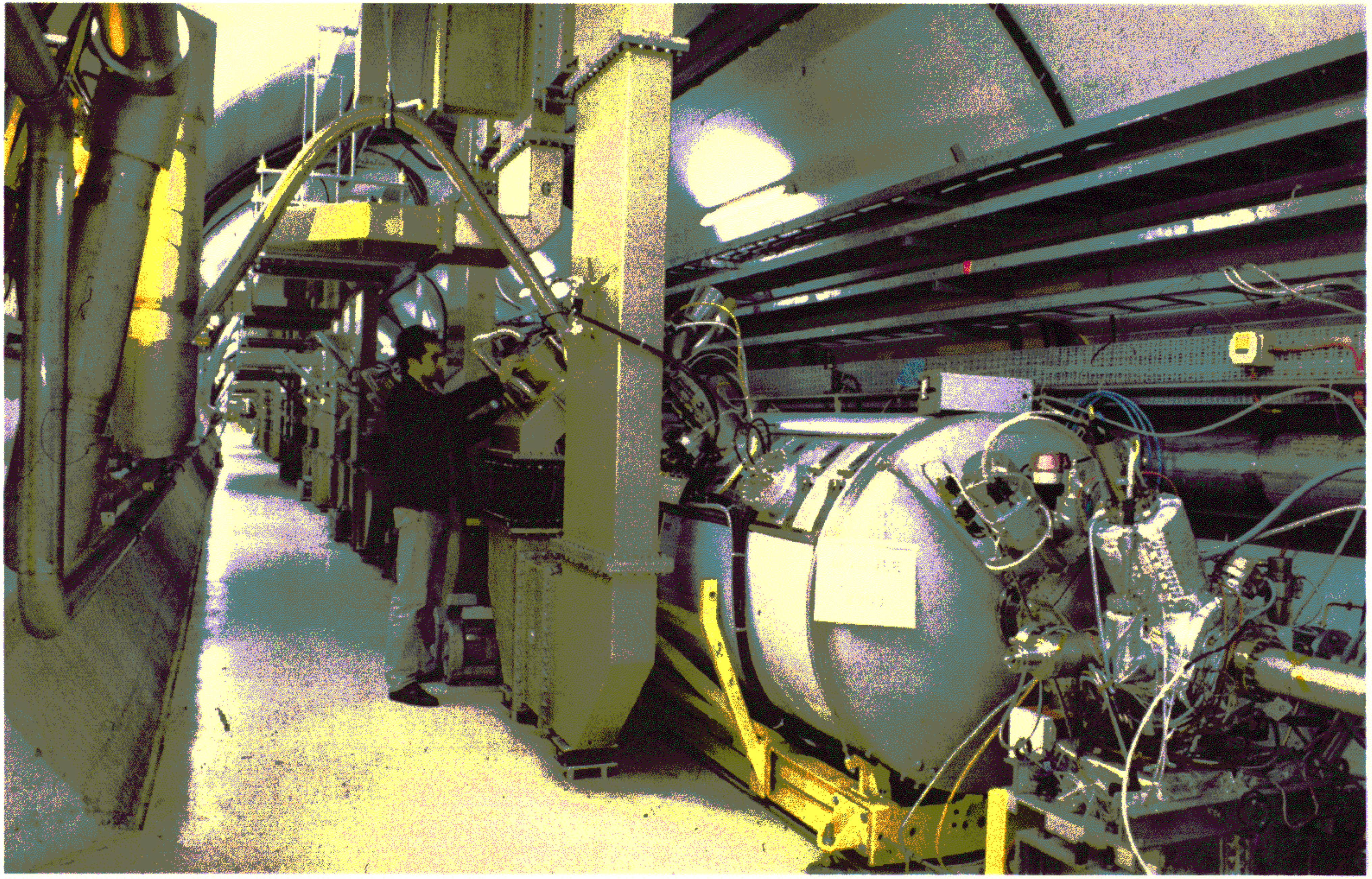
LEPII: centre-of-mass energy $\sqrt{s} = 130 \ldots 208$ GeV
to study W bosons (1995 – 2000)
to search for Higgs boson

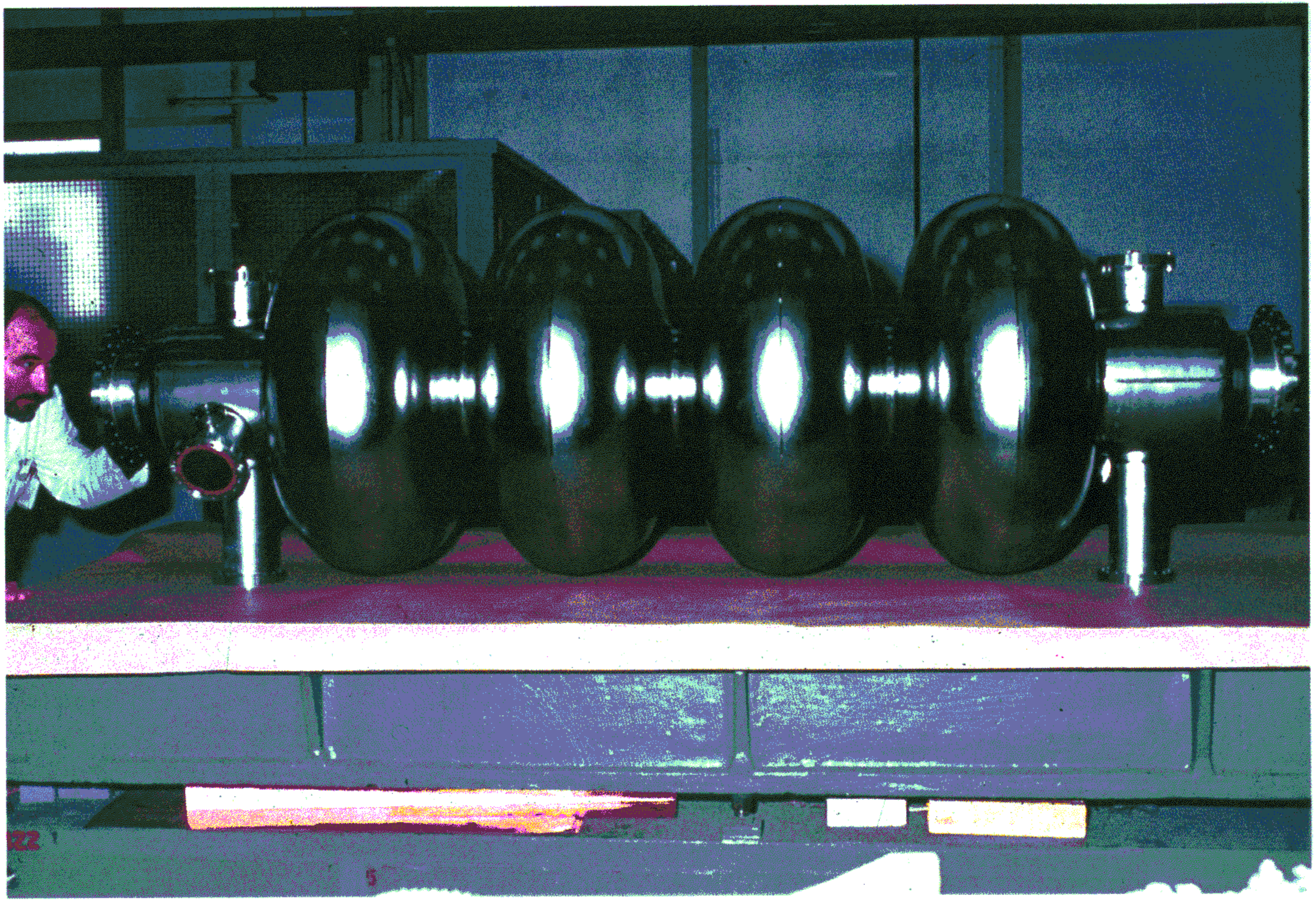
A few data on LEP

• circumference	26 658.90 m
• bending radius	3 026.42 m
• beam energy	44 – 104 GeV
⇒ bending field	upto 0.12 T
• cavities	≈ 350 MHz
# warm Cu cavities	48
# superconducting Nb- and CuNb-cav.	16 + 272 = 288
⇒ max. acceleration	≈ 3700 MV
• max. beam current	5...6 mA
• no. of e^+e^- bunches	4 × 4 à 2 bundl
• max. luminosity	$\approx 5 \cdot 10^{31}\ cm^{-2} s^{-1}$
• energy spread of beam	ca. 280 MeV
• syst. uncertainty of beam energy	ca. 20 - 30 MeV
• beam lifetime	ca. 4-10 hours
• energy loss by synchrotron radiation	ca. 16 MW @ 100 Ge

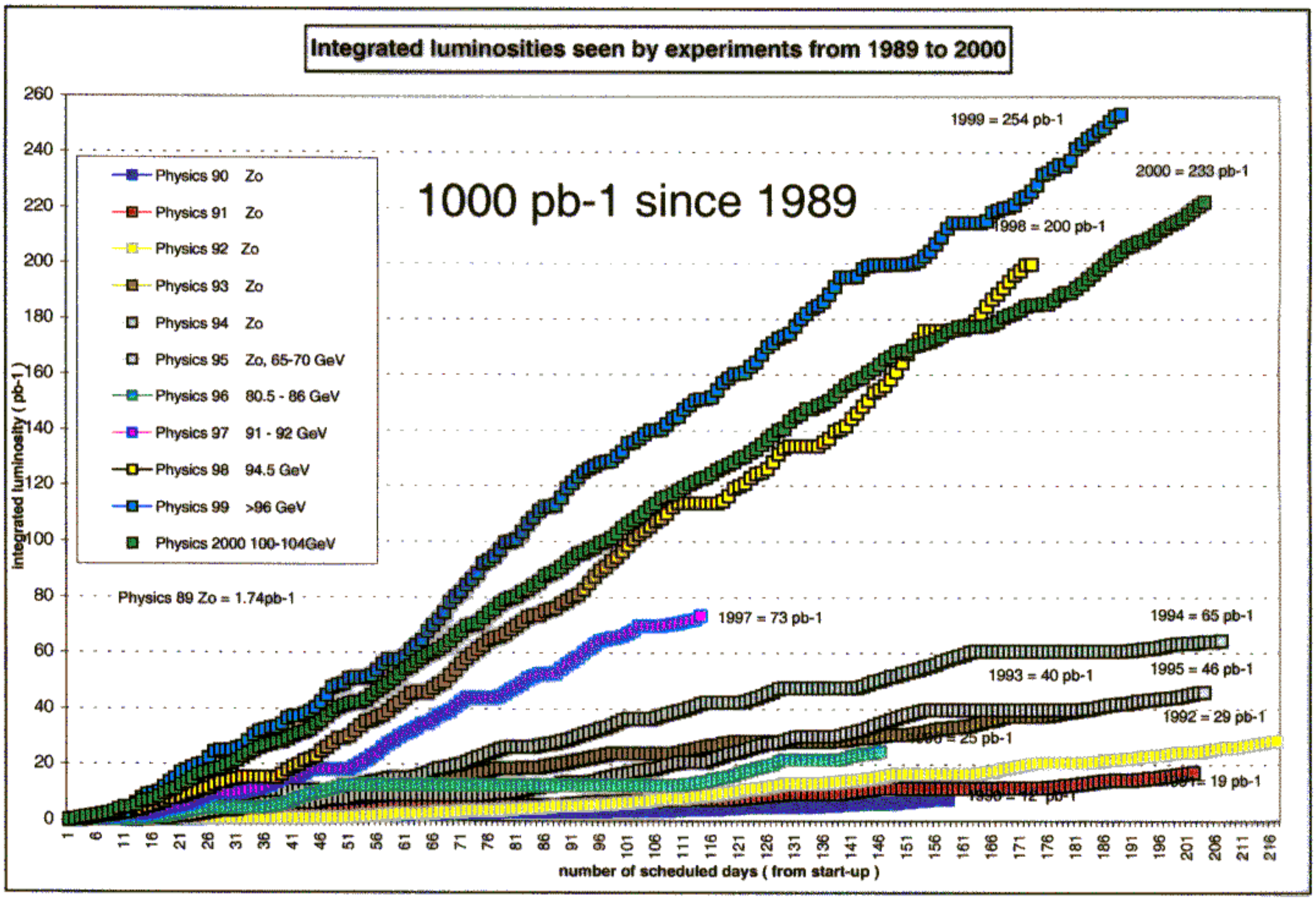
$$P_{sync} \sim \frac{1}{R} \left(\frac{E}{m_e} \right)^4$$

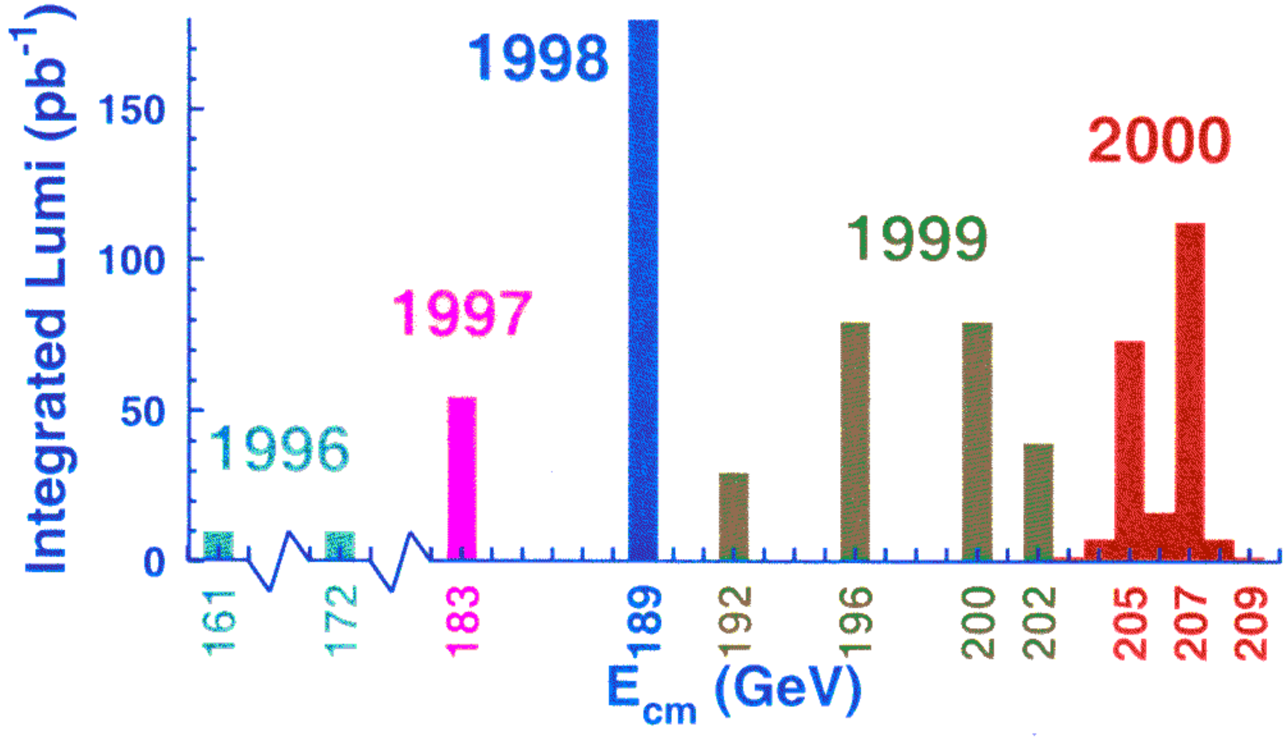

258



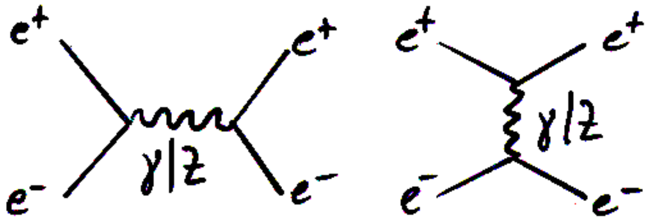


LEP luminosity performance

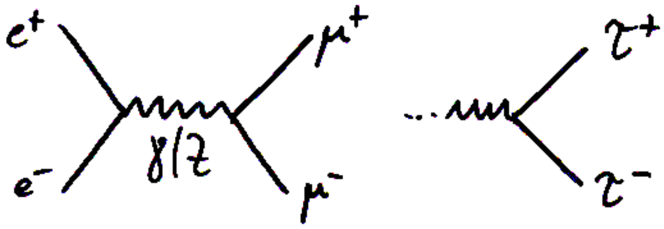




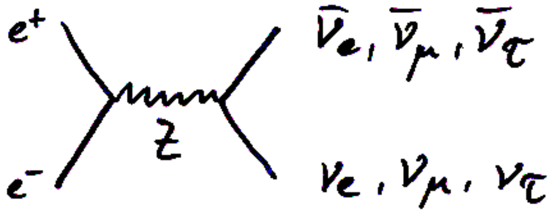
Detectors at LEP — what's to measure?



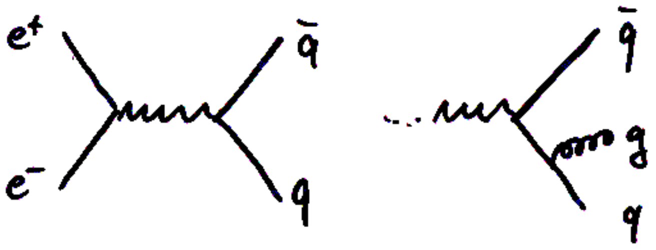
Bhabha scattering



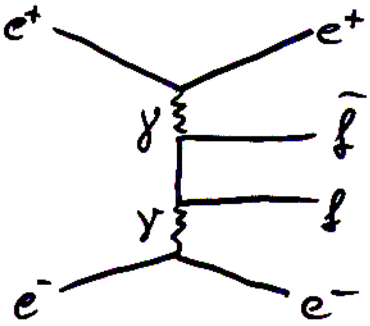
μ, τ pair production



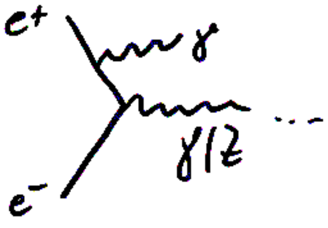
ν pair production
(unmeasurable)



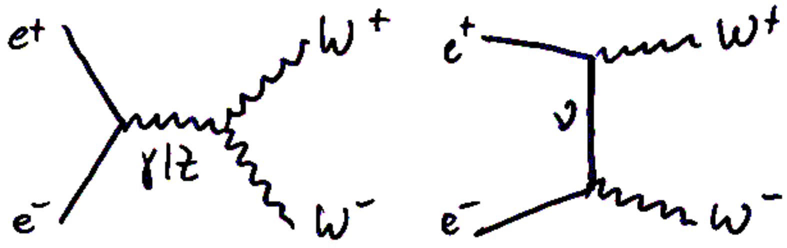
quark anti-quark pairs
+ gluons
→ hadronic events



2 photon processes

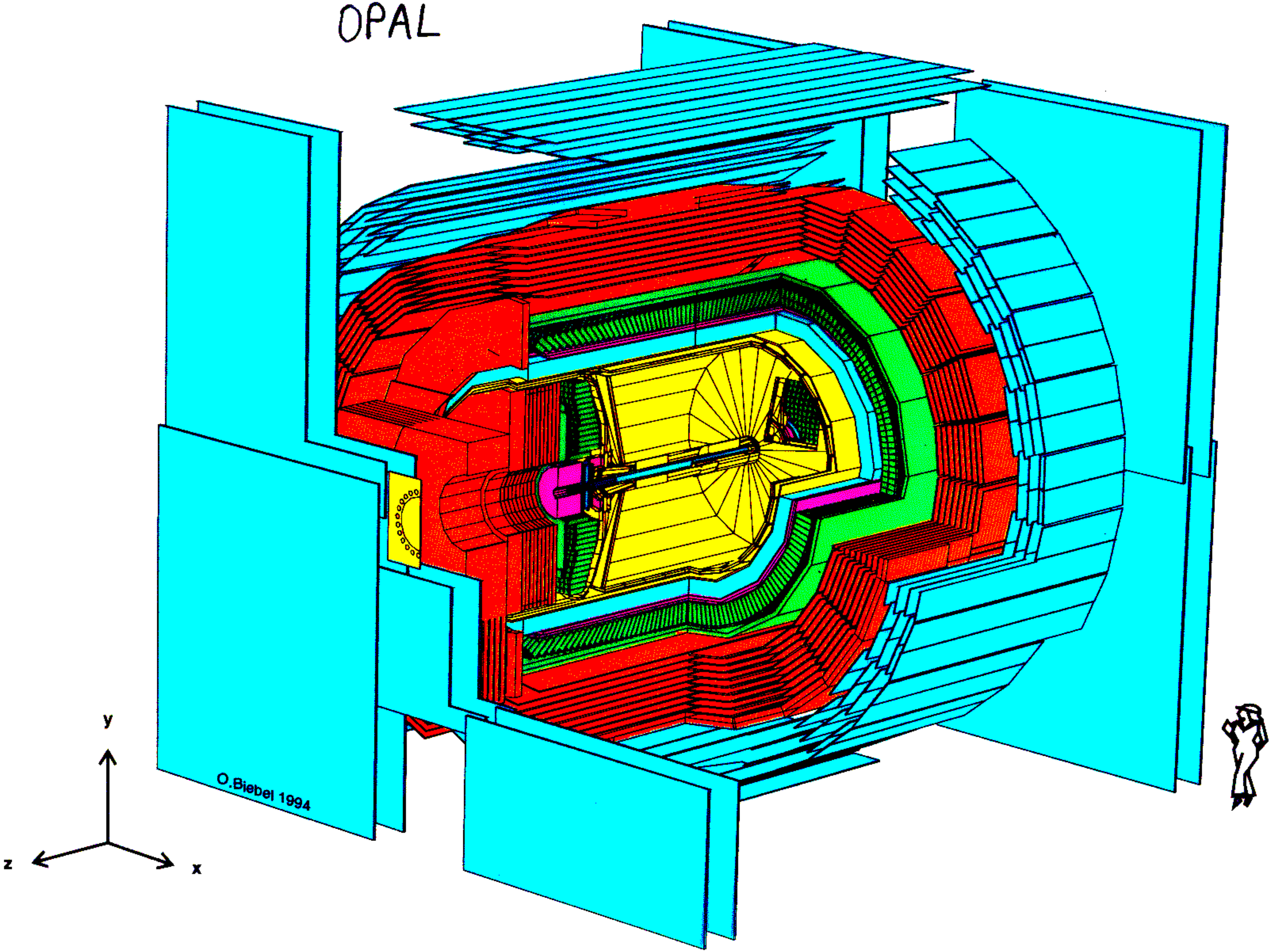


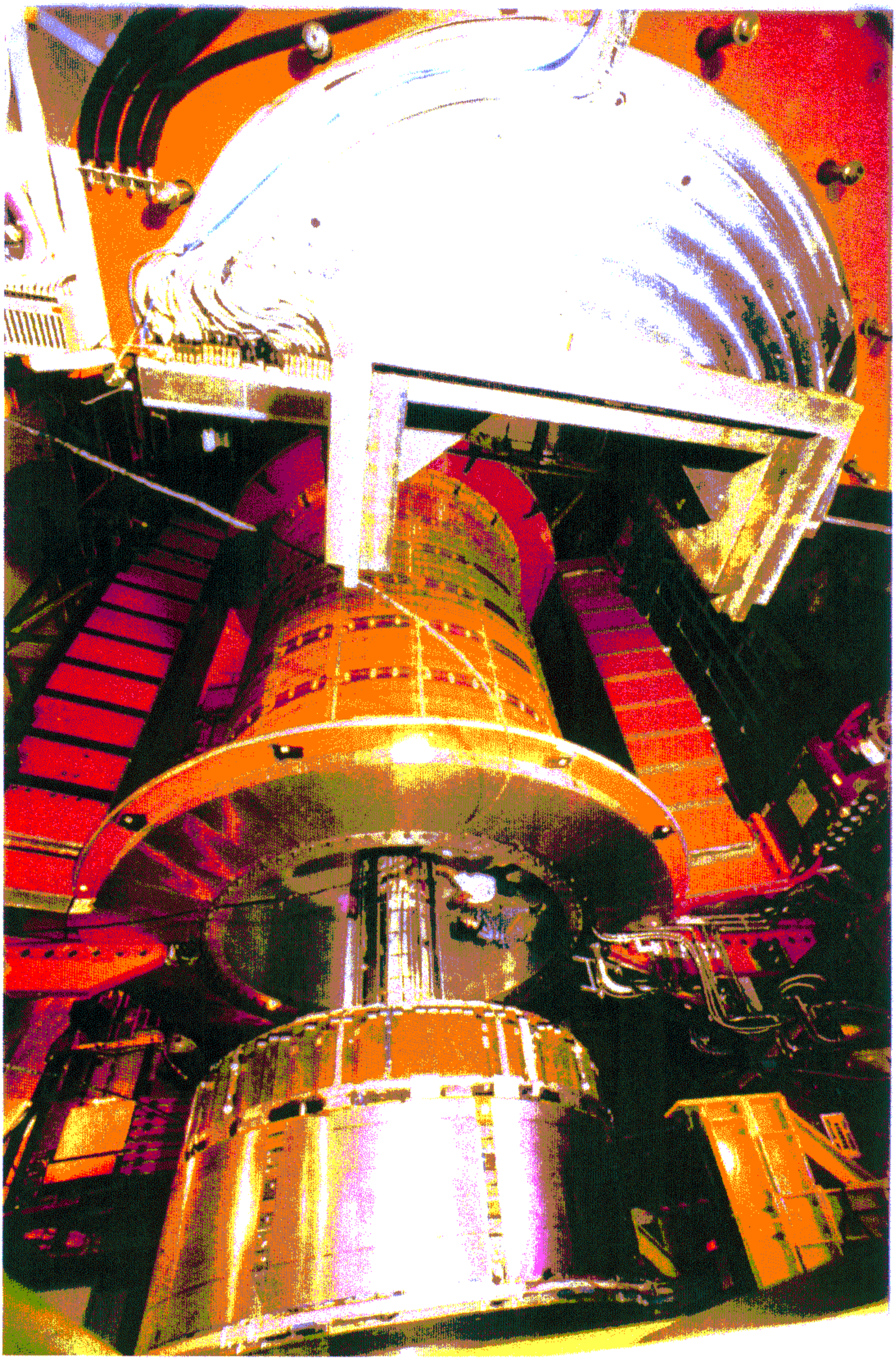
initial state photon bremsstrahlung (ISR)

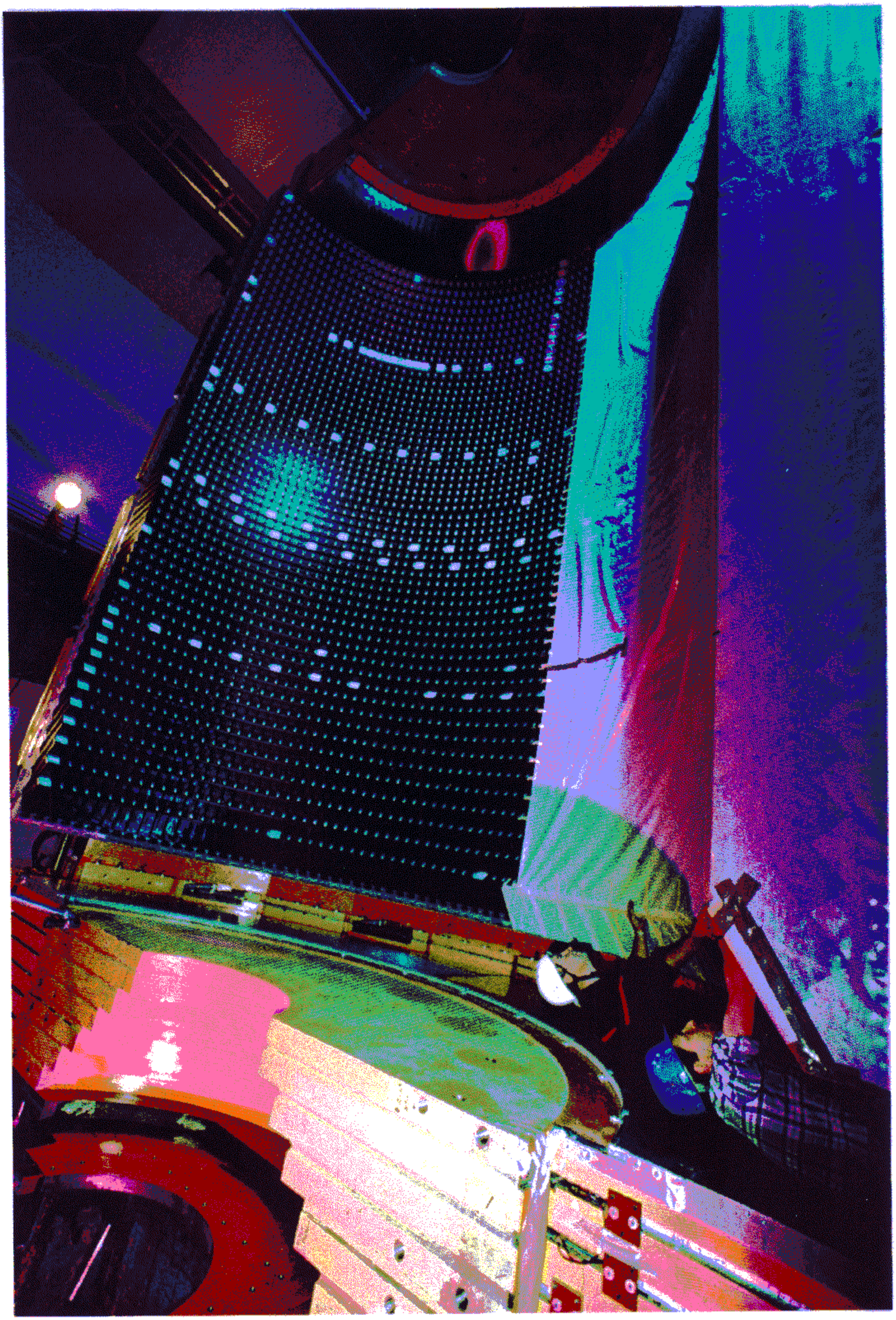


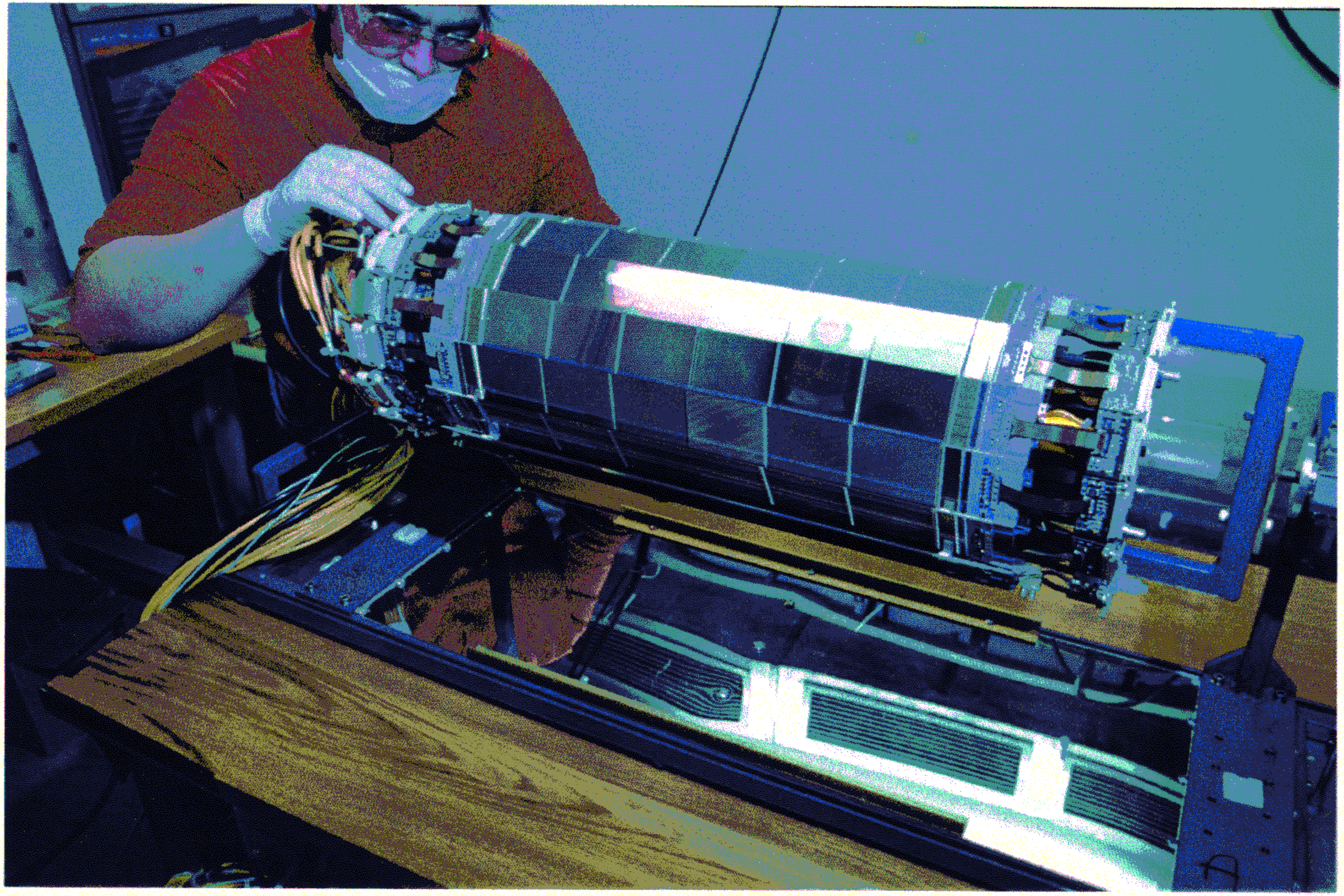
W pair production
above W threshold

. . .

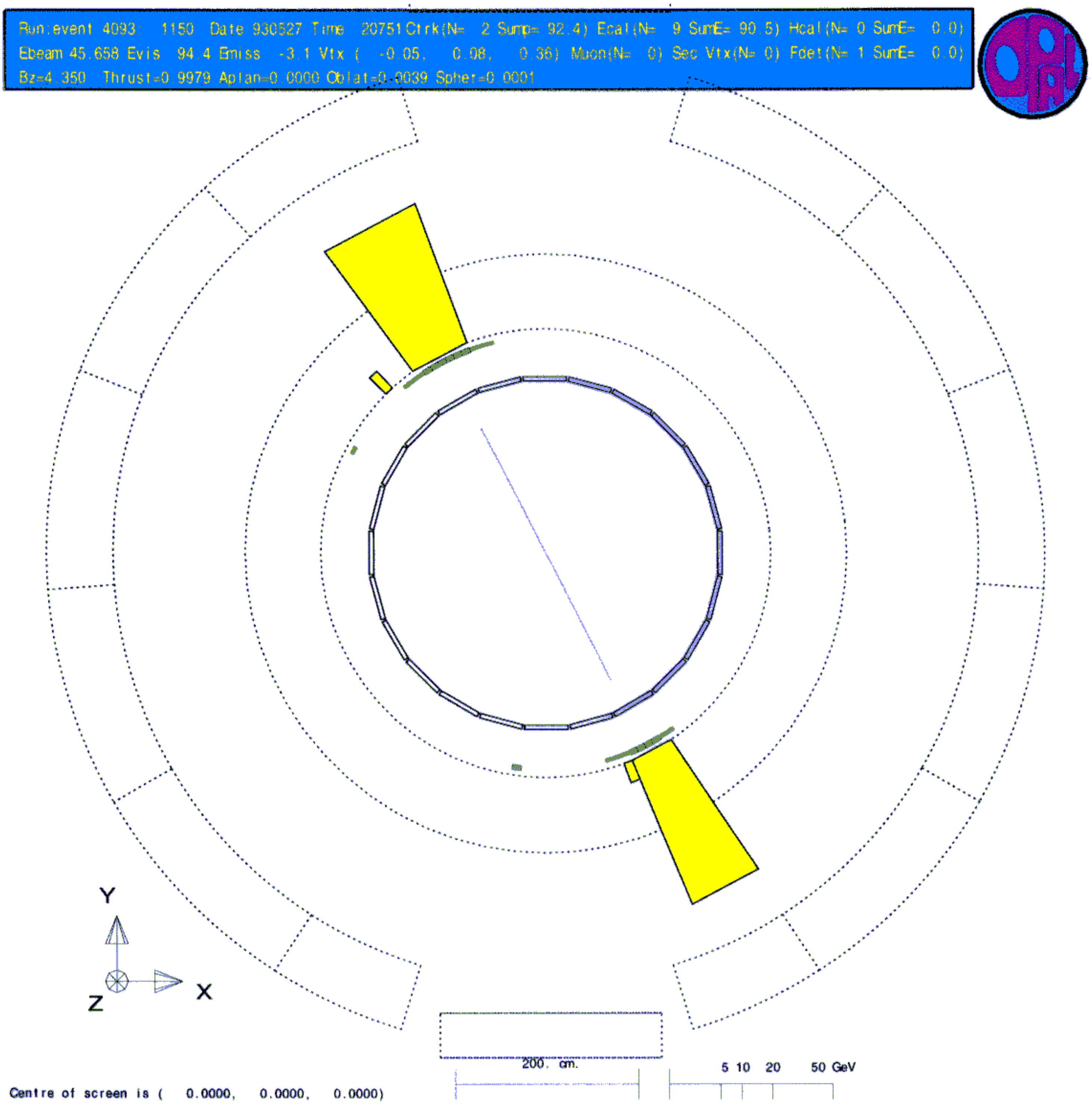

OPAL
y
z
x
O.Biebel 1994







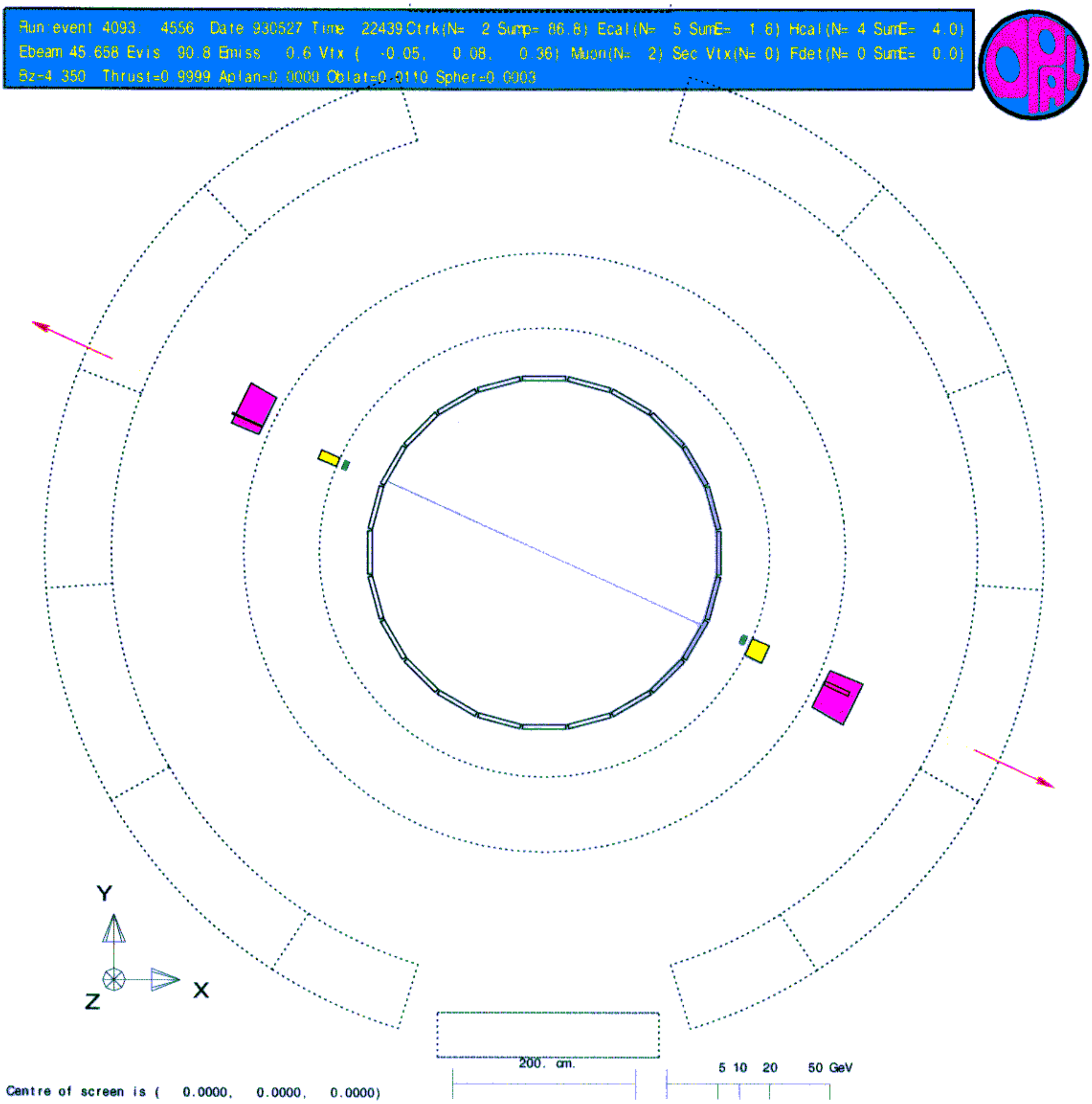
$e^+e^- \longrightarrow Z \longrightarrow e^+e^-$



```
Run:event 4093:  1150  Date 930527 Time  20751 Ctrk(N=  2 Sump= 92.4) Ecal(N=  9 SumE= 90.5) Hcal(N= 0 SumE=  0.0)
Ebeam 45.658 Evis  94.4 Emiss  -3.1 Vtx (  -0.05,   0.08,   0.36) Muon(N=  0) Sec Vtx(N= 0) Fdet(N= 1 SumE=  0.0)
Bz=4.350  Thrust=0.9979 Aplan=0.0000 Oblat=0.0039 Spher=0.0001
```

```
Centre of screen is (   0.0000,   0.0000,   0.0000)
```

$e^+e^- \rightarrow Z \rightarrow \mu^+\mu^-$



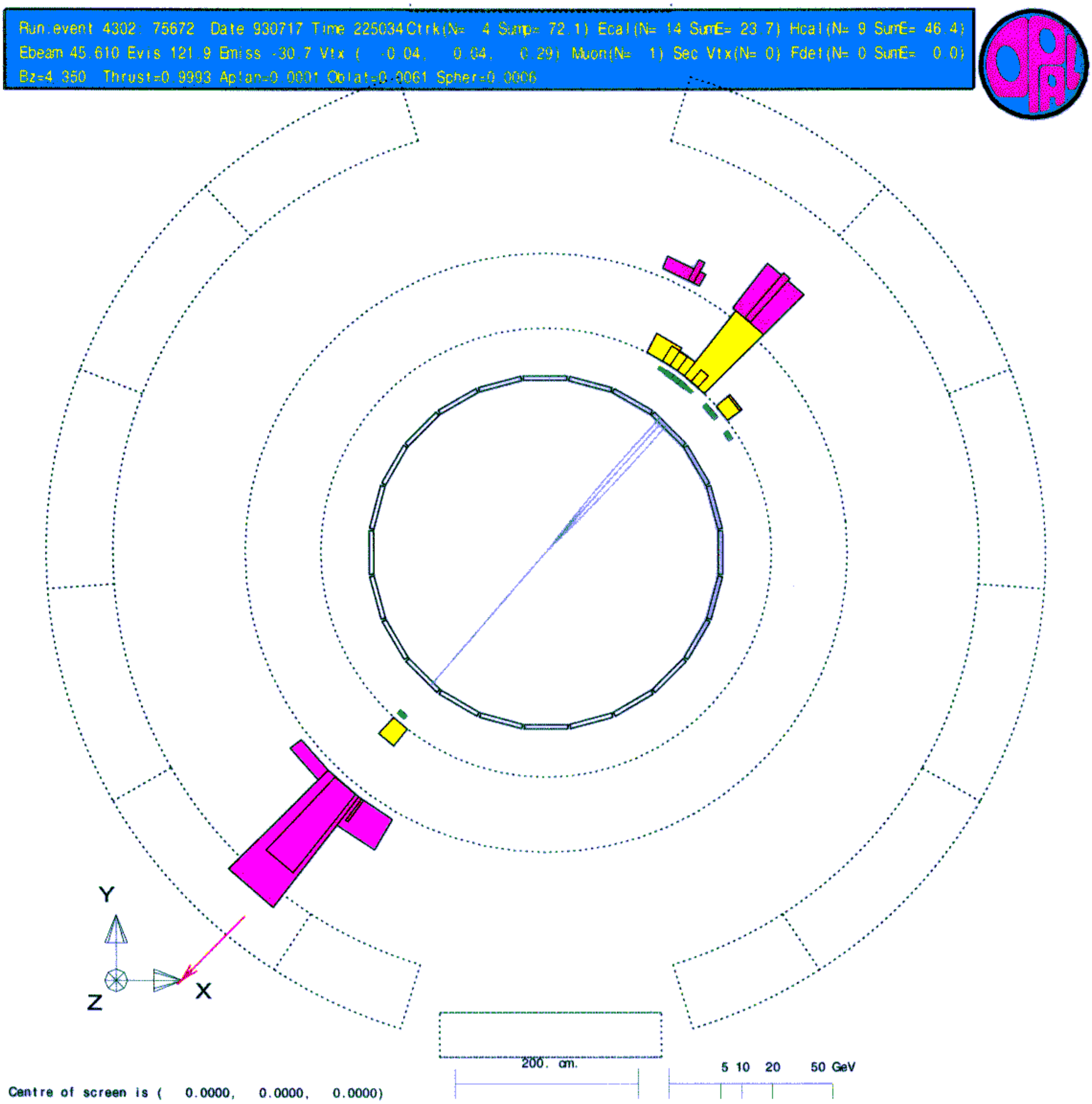
```
Run:event 4093.  4556  Date 930527 Time  22439 Ctrk(N=  2 Sump= 86.8) Ecal(N=  5 SumE=  1.6) Hcal(N= 4 SumE=  4.0)
Ebeam 45.658 Evis  90.8 Emiss  0.6 Vtx (  -0.05,   0.08,   0.36) Muon(N=  2) Sec Vtx(N= 0) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9999 Aplan=0.0000 Oblat=0.0110 Spher=0.0003
```

```
Centre of screen is (   0.0000,    0.0000,    0.0000)
```

$e^+e^- \rightarrow Z \rightarrow \tau^+\tau^-$

$\tau^- \rightarrow 3\pi^\pm \nu_\tau$

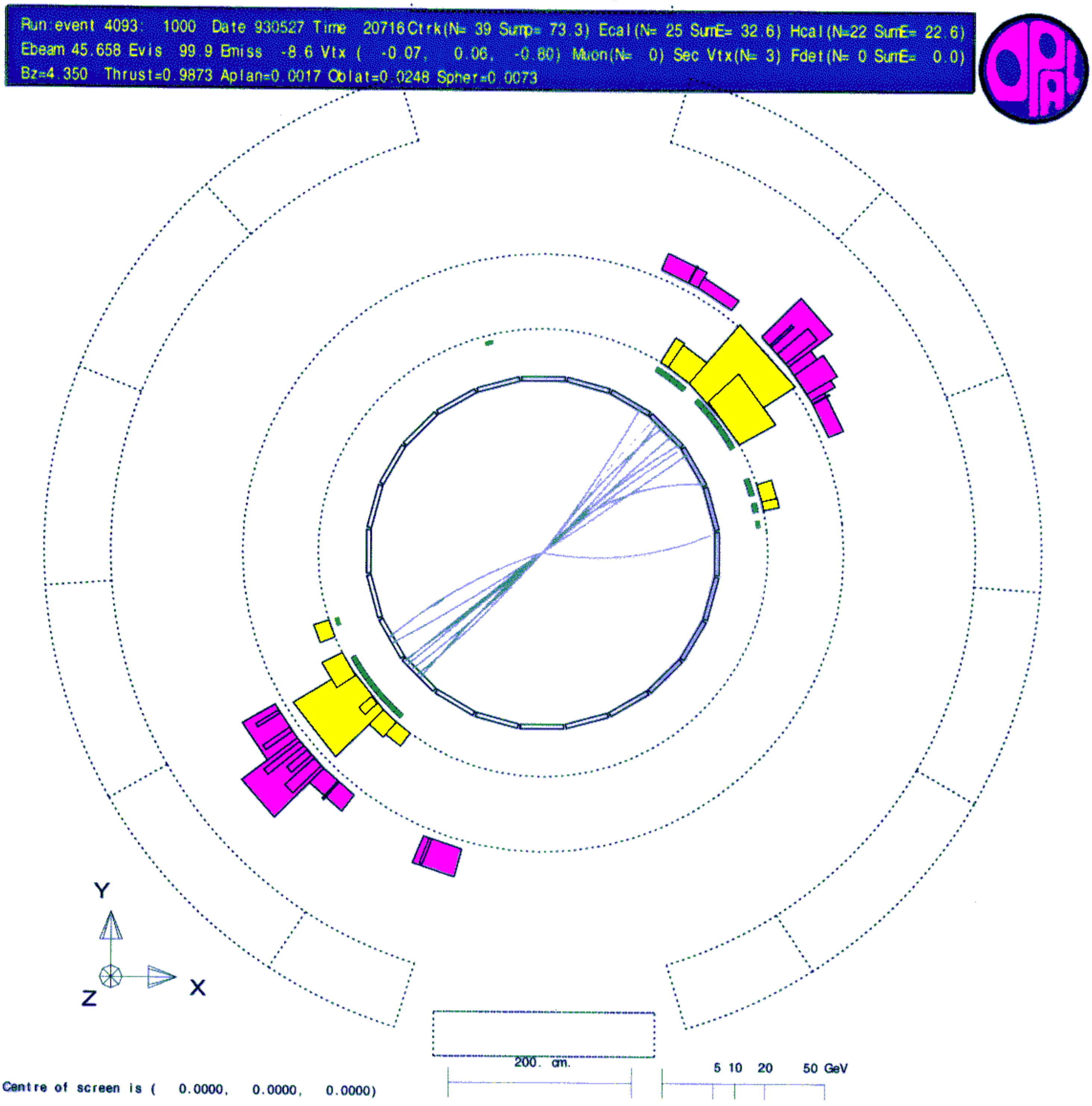
$\tau^+ \rightarrow 1\pi^+ \overline{\nu_\tau}$



```
Run:event 4302: 75672  Date 930717 Time 225034 Ctrk(N=  4 Sump= 72.1) Ecal(N= 14 SumE= 23.7) Hcal(N= 9 SumE= 46.4)
Ebeam 45.610 Evis 121.9 Emiss -30.7 Vtx (  -0.04,   0.04,   0.29) Muon(N=  1) Sec Vtx(N= 0) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9993 Aplan=0.0001 Oblat=0.0061 Spher=0.0006
```

```
Centre of screen is (   0.0000,    0.0000,    0.0000)
```

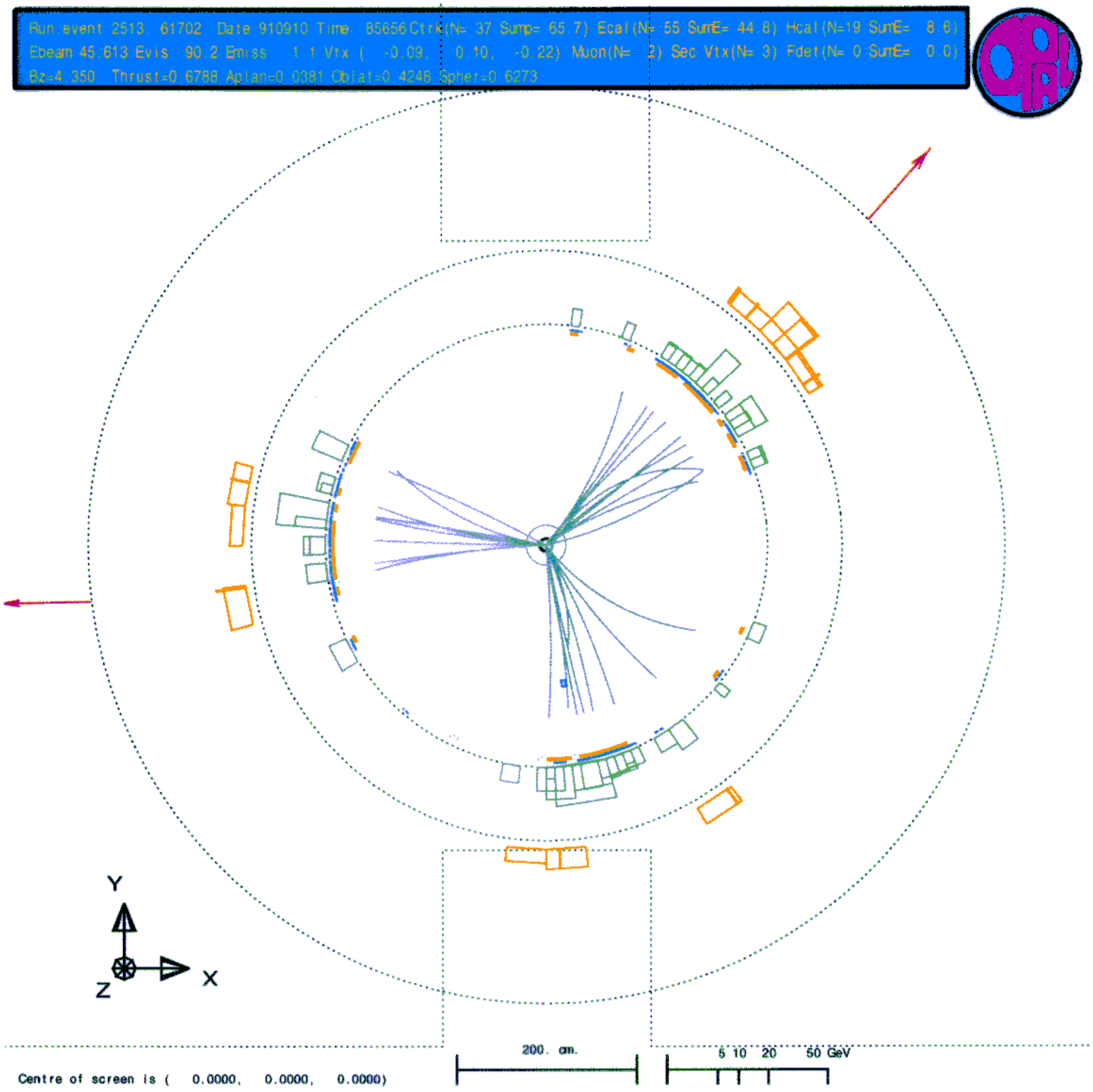
$$e^+e^- \to Z \to \underbrace{q\bar{q}}_{\text{2 jets}}$$



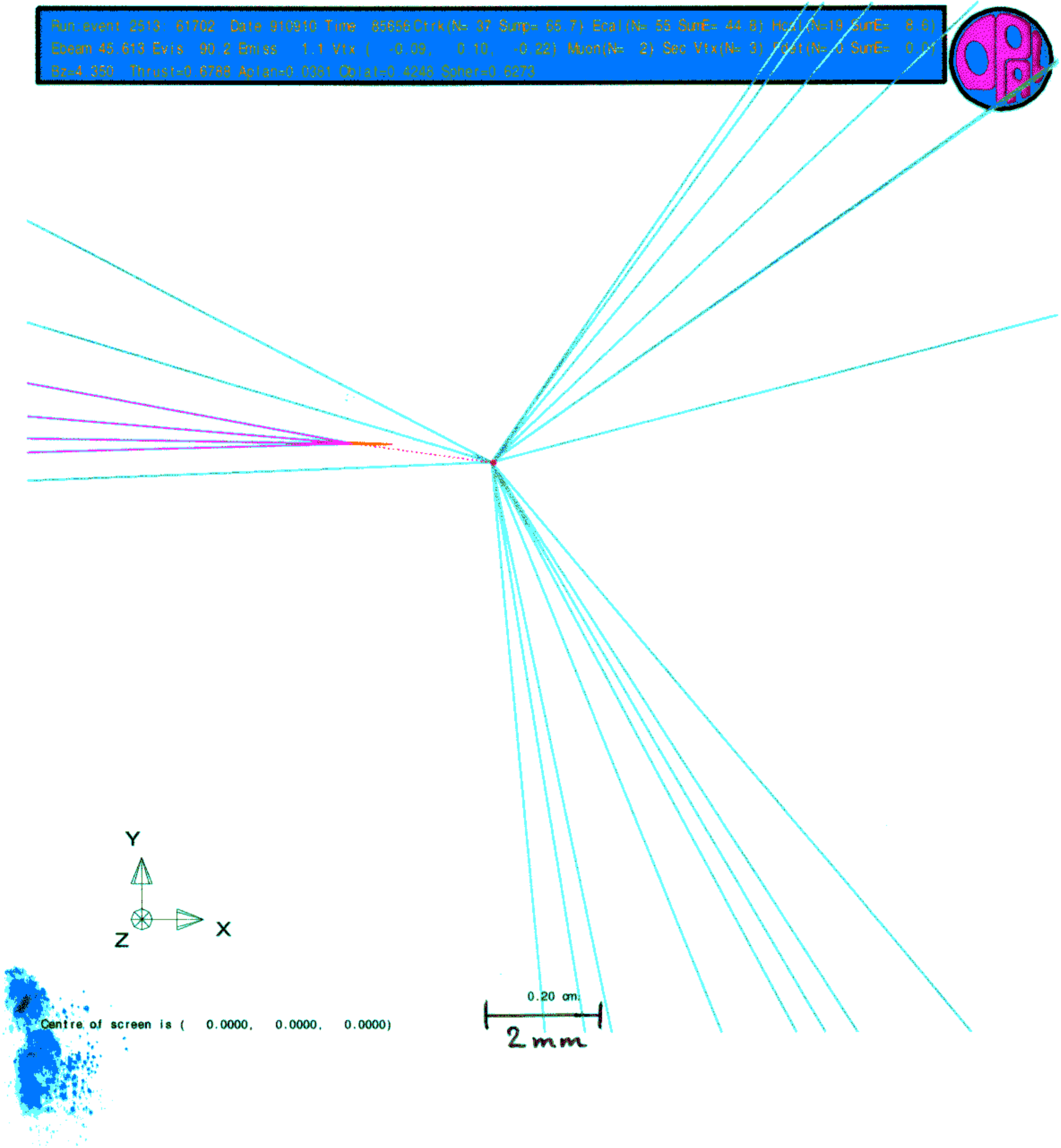
```
Run:event 4093:  1000  Date 930527 Time  20716Ctrk(N= 39 Sump= 73.3) Ecal(N= 25 SumE= 32.6) Hcal(N=22 SumE= 22.6)
Ebeam 45.658 Evis  99.9 Emiss  -8.6 Vtx (  -0.07,   0.06,  -0.80) Muon(N=  0) Sec Vtx(N= 3) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9873 Aplan=0.0017 Oblat=0.0248 Spher=0.0073
```

```
Centre of screen is (   0.0000,   0.0000,   0.0000)
```

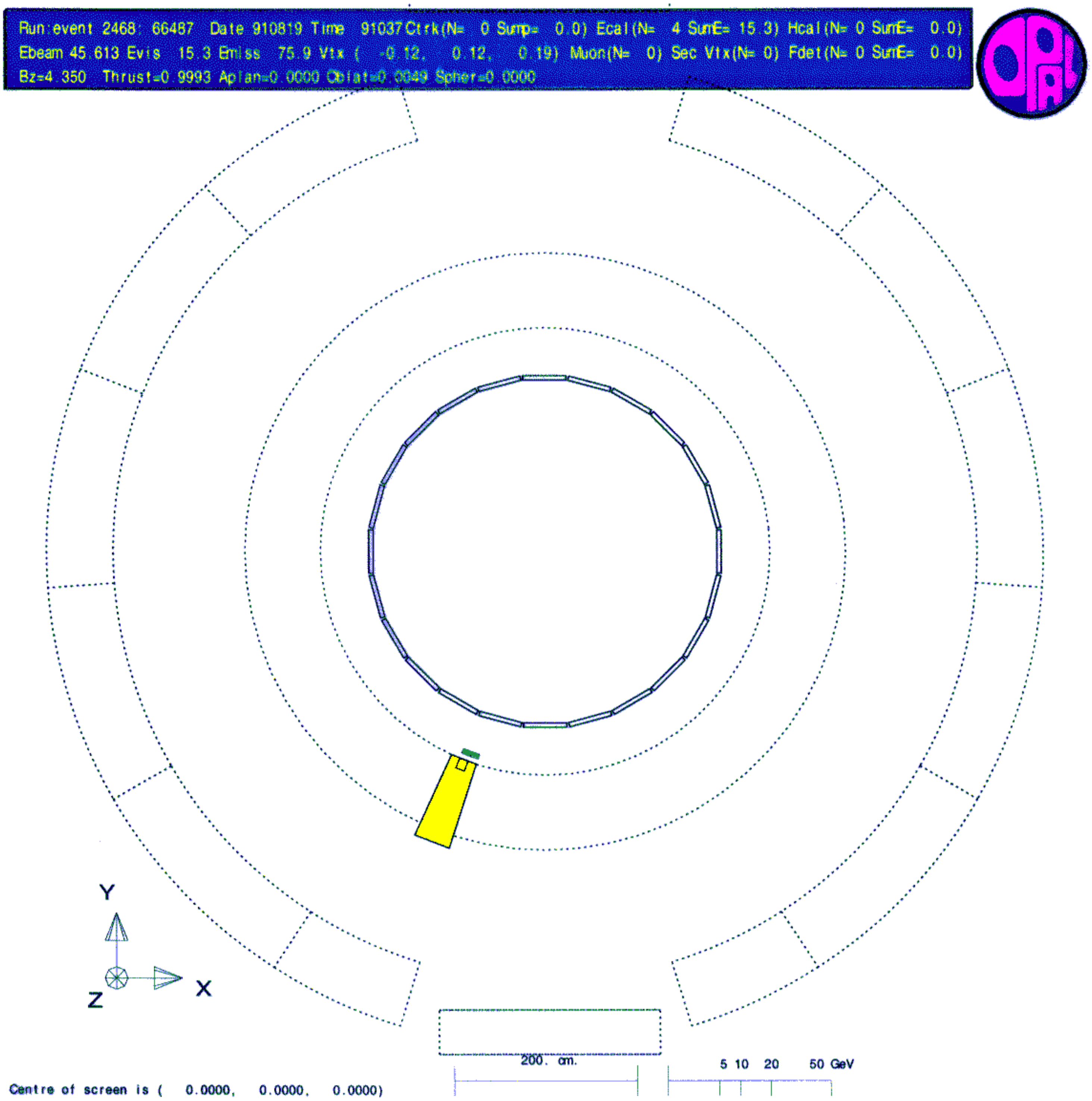
$Z \to q\bar{q}g \to 3$ Jets



sekundärer Zerfallsvertex eines b-Hadrons



$e^+e^- \longrightarrow Z \longrightarrow \nu\bar{\nu}$ + ISR photon



```
Run:event 2468: 66487  Date 910819 Time  91037 Ctrk(N=  0 Sump=  0.0) Ecal(N=  4 SumE= 15.3) Hcal(N= 0 SumE=  0.0)
Ebeam 45.613 Evis  15.3 Emiss  75.9 Vtx (  -0.12,   0.12,   0.19) Muon(N=  0) Sec Vtx(N= 0) Fdet(N= 0 SumE=  0.0)
Bz=4.350  Thrust=0.9993 Aplan=0.0000 Oblat=0.0049 Spher=0.0000
```

```
Centre of screen is (   0.0000,   0.0000,   0.0000)
```

Advantages of e^+e^- physics (at LEP)

- well-defined initial state (momentum, energy, quantum numbers)
- no "multiple interaction"
- in general complete measurement of final state in particular no hadronic contribution along beampipe
- in general max. available energy in interaction
- fairly small no. of particles in final state
- low event rate but high purity simple and unbiased trigger conditions

⇒ cross-section measurement with small corrections

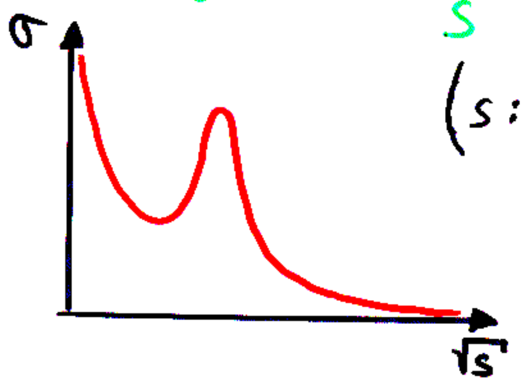
$$\underbrace{N}_{\text{no. of events}} = \underbrace{\sigma}_{\text{cross-section}} \cdot \underbrace{\int \mathcal{L}\, dt}_{\text{integrated luminosity}}$$

(from acceleration params. or reference process with well-known cross-section)

cross-section in e^+e^- collisions (annihilation)

$$\sigma \propto \frac{1}{s} + Z \text{ resonance}$$

(s: centre-of-mass energy^2)



Z boson

Standard model in a nut shell

Electroweak interaction described by gauge group

$$U(1) \times SU(2)$$

contains massless gauge bosons

$$B \text{ and } W^1, W^2, W^3$$

with couplings g' and g_W

Creation of mass by Higgs field $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$, a complex doublett with vacuum expectation value

$$H_{vac} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \text{ and } v = \frac{1}{\sqrt{\sqrt{2}\, G_F}} \simeq 246\,\text{GeV}$$

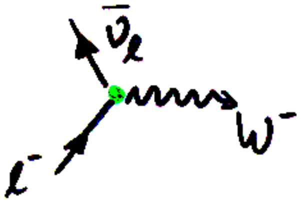
observable particles	mass	and their coupling:
$W^{\pm} = \frac{1}{\sqrt{2}}(W^1 \mp i W^2)$	; $m_W = g_W \cdot \frac{v}{2}$	; $g_W = e / \sin\Theta_W$
$Z = W^3 \cos\Theta_W - B \sin\Theta_W$	; $m_Z = m_W / \cos\Theta_W$	; $g_Z = e / \sin\Theta_W \cdot \cos\Theta_W$
$\gamma = W^3 \sin\Theta_W + B \cos\Theta_W$	; $m_\gamma = 0$	; $g_e = e = \sqrt{4\pi\alpha_{em}}$
H^0	; $m_{H^0} = ?$	; $g_H = m_f = f_f \cdot v$ for fermion f

NB: parameters G_F, m_Z, α_{em} are sufficient to describe the Standard model (without the Higgs)

Standard model — couplings

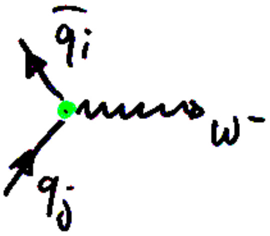
Coupling of fermions to

- **W boson**



vertex factor $\frac{-ig_w}{2\sqrt{2}} \underbrace{\gamma^\mu (1-\gamma_5)}_{V-A}$

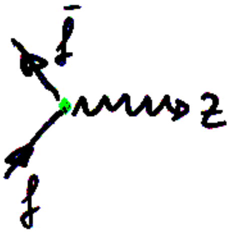
vector – axialvector



$$\frac{-ig_w}{2\sqrt{2}} \gamma^\mu (1-\gamma_5) \underbrace{V_{ij}}_{\text{CKM mixing matrix}}$$

- **γ boson (photon)** $\quad i g_e \gamma^\mu$

- **Z boson**



$$\frac{-ig_Z}{2} \gamma^\mu (g_{Vf} - g_{Af}\gamma_5)$$

fermion f	charge Q	vector coupling $g_{Vf} = T_f^3 - 2Q\sin^2\theta_w$		axialvector ~ $g_{Af} = T_f^3$
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$= +0.50$	$+\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2} + 2\sin^2\theta_w$	≈ -0.05	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2} - \frac{4}{3}\sin^2\theta_w$	$\approx +0.20$	$+\frac{1}{2}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2} + \frac{2}{3}\sin^2\theta_w$	≈ -0.35	$-\frac{1}{2}$

with $\sin^2\theta_w \approx 0.223$

Weak-isospin structure of fermions

family			T_f	T_f^3	Q_f	electroweak coupling
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$1/2$	$+1/2$ $-1/2$	0 -1	$g_L = T_f^3 - Q_f\sin^2\theta$
e_R	μ_R	τ_R	0	0	-1	$g_R = -Q_f\sin^2\theta$
$\begin{pmatrix}u\\ d\end{pmatrix}_L$	$\begin{pmatrix}c\\ s\end{pmatrix}_L$	$\begin{pmatrix}t\\ b\end{pmatrix}_L$	$1/2$	$+1/2$ $-1/2$	$+2/3$ $-1/3$	$g_L = T_f^3 - Q_f\sin^2\theta$
u_R	c_R	t_R	0	0	$+2/3$	$g_R = -Q_f\sin^2\theta$
d_R	s_R	b_R	0	0	$-1/3$	

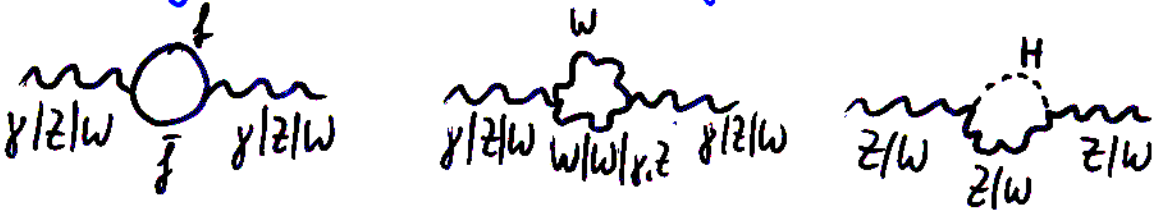
$\Rightarrow$ vector and axial-vector couplings:

$$\left[\begin{array}{l} g_{Vf} = g_{Lf} + g_{Rf} = T_f^3 - 2Q_f\sin^2\theta_W \\ g_{Af} = g_{Lf} - g_{Rf} = T_f^3 \end{array}\right.$$

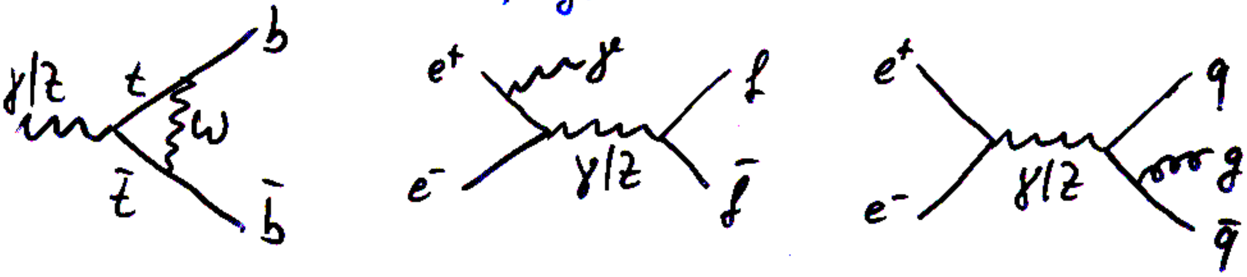
These tree-level (ie. lowest order) relations are modified by radiative corrections when real electroweak processes are considered.

Radiative corrections

- Propagator corrections, e.g.



- Vertex corrections, e.g.



- Bulk of electro-weak corrections absorbed by defining effective couplings

▷ $g_V \equiv g_V^{eff} = \sqrt{1+\Delta\rho} \cdot \left(T^3 - 2Q\sin^2\theta_W\right)$

▷ $g_A \equiv g_A^{eff} = \sqrt{1+\Delta\rho} \cdot \left(T^3\right)$

▷ $\sin^2\theta_{eff} = \left(1 + \frac{\cos^2\theta_W}{\sin^2\theta_W} \cdot \Delta\rho + \dots\right) \cdot \sin^2\theta_W$

where (note that $\Delta\rho$ is flavour dependent in general)

▷ $\Delta\rho = \frac{3 G_F m_W^2}{8\pi^2\sqrt{2}} \cdot \left(\frac{m_{top}^2}{m_W^2} - \frac{11}{9} \cdot \tan^2\theta_W \left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \dots\right)$

⇒ quadratic m_{top}, logarithmic m_H dependence! of radiative corrections

Radiative corrections

- The G_F relation is also modified:

$$\underbrace{G_F = \frac{\pi \alpha_{em}}{\sqrt{2}\, m_W^2 \sin^2\theta_W}}_{\text{The } G_F \text{ relation}} \cdot \underbrace{\frac{1}{1-\Delta r}}_{\text{modified}}$$

where

$$\Delta r = \Delta\alpha_{em} - \frac{\cos^2\theta_W}{\sin^2\theta_W} \cdot \Delta_S + \ldots$$

- The $\Delta\alpha_{em}$ term accounts for the running of the fine structure constant α_{em} due to fermion loops in the photon propagator

$$\alpha_{em}(s) = \frac{\alpha_{em}(0)}{1-\Delta\alpha}$$

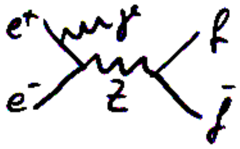
- $\alpha_{em}(0) = 1/137.03599976$ ± 0.0036 pp

$\Delta\alpha \Rightarrow \alpha_{em}(m_Z^2) = 1/128.936$ ± 0.36%

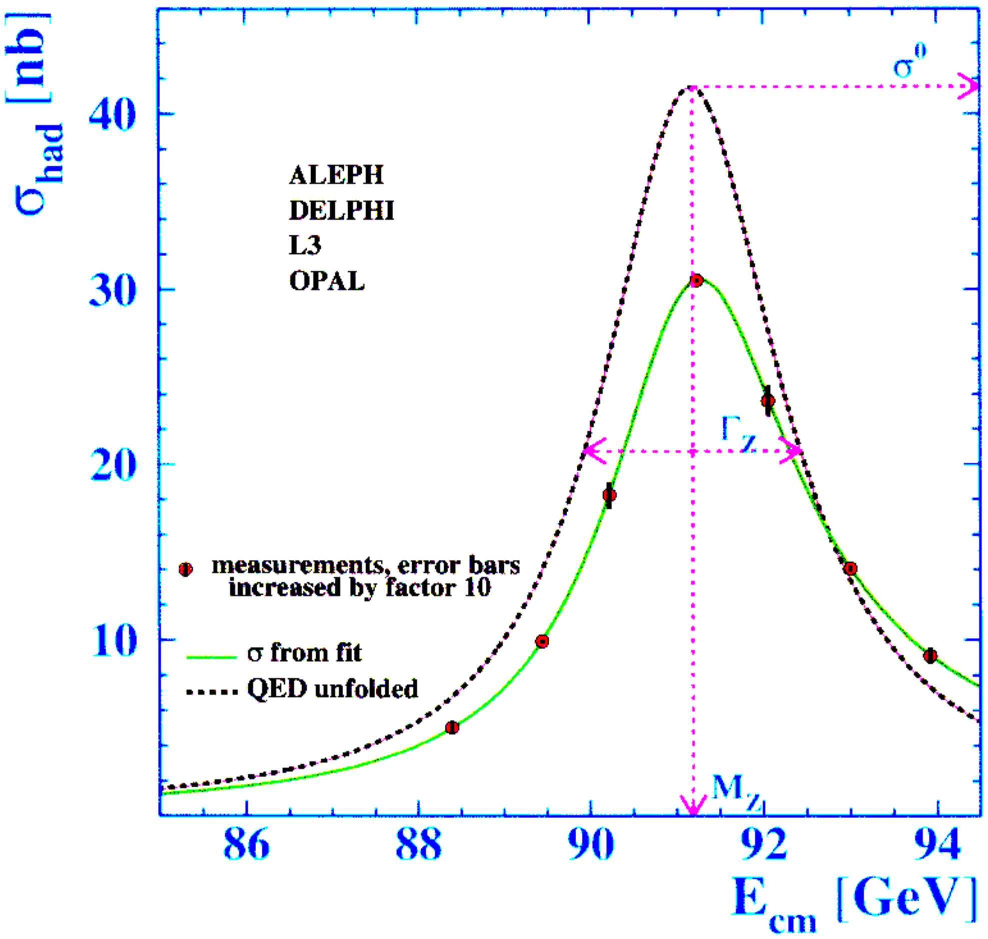
$G_F(0) = 1.16639 \cdot 10^{-5}/\text{GeV}^2$ ± 9 pp

Z cross-section and partial widths

- measured cross-section : convolution with



$$\sigma(s) = \text{QEDradiation}(s) \otimes \sigma_Z(s)$$



- "Z lineshape" : $\sigma_{Z\to f\bar f}(s) = \sigma^0_{f\bar f}\cdot\frac{s\Gamma_Z^2}{(s-m_Z^2)^2 + s^2\Gamma_Z^2/m_Z^2}$

- pole cross-section : $\sigma^0_{f\bar f} = \frac{12\pi}{m_Z^2}\,\frac{\Gamma_{ee}\cdot\Gamma_{f\bar f}}{\Gamma_Z^2}$

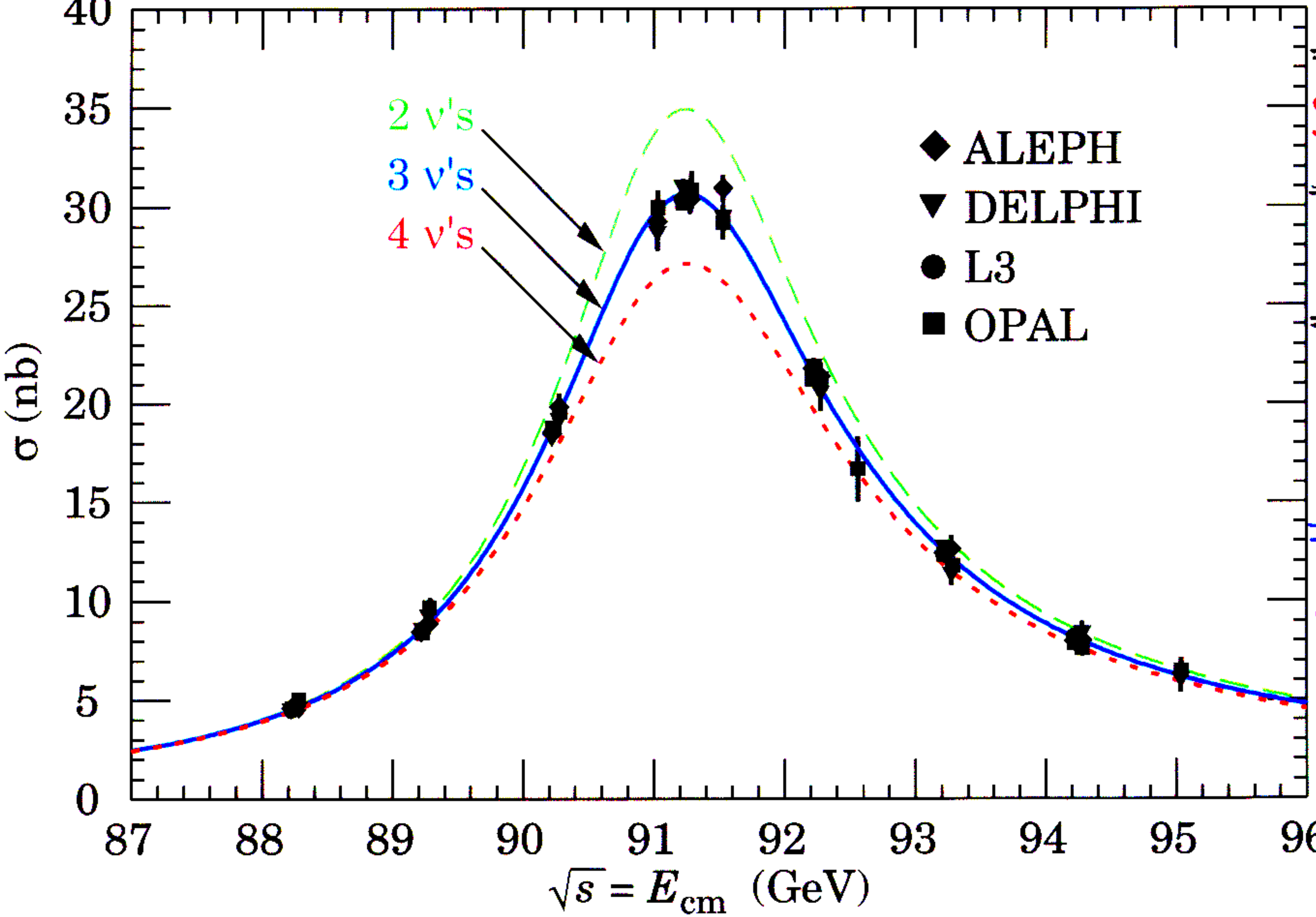
- partial width : $\Gamma_{f\bar f} = \frac{G_F\, m_Z^3}{6\pi\sqrt{2}}\left(g_{Af}^2 + g_{Vf}^2\right)\cdot\underbrace{N_c}_{\text{colour factor}}$

  (× QED/QCD corrections)

- total width : $\Gamma_Z = \Gamma_{had} + 3\cdot\Gamma_{\ell\bar\ell} + N_\nu\Gamma_{\nu\bar\nu}$

Z lineshape

$Z \to q\bar{q} \to \text{hadrons}$



$\Rightarrow m_Z = 91.1875$ GeV

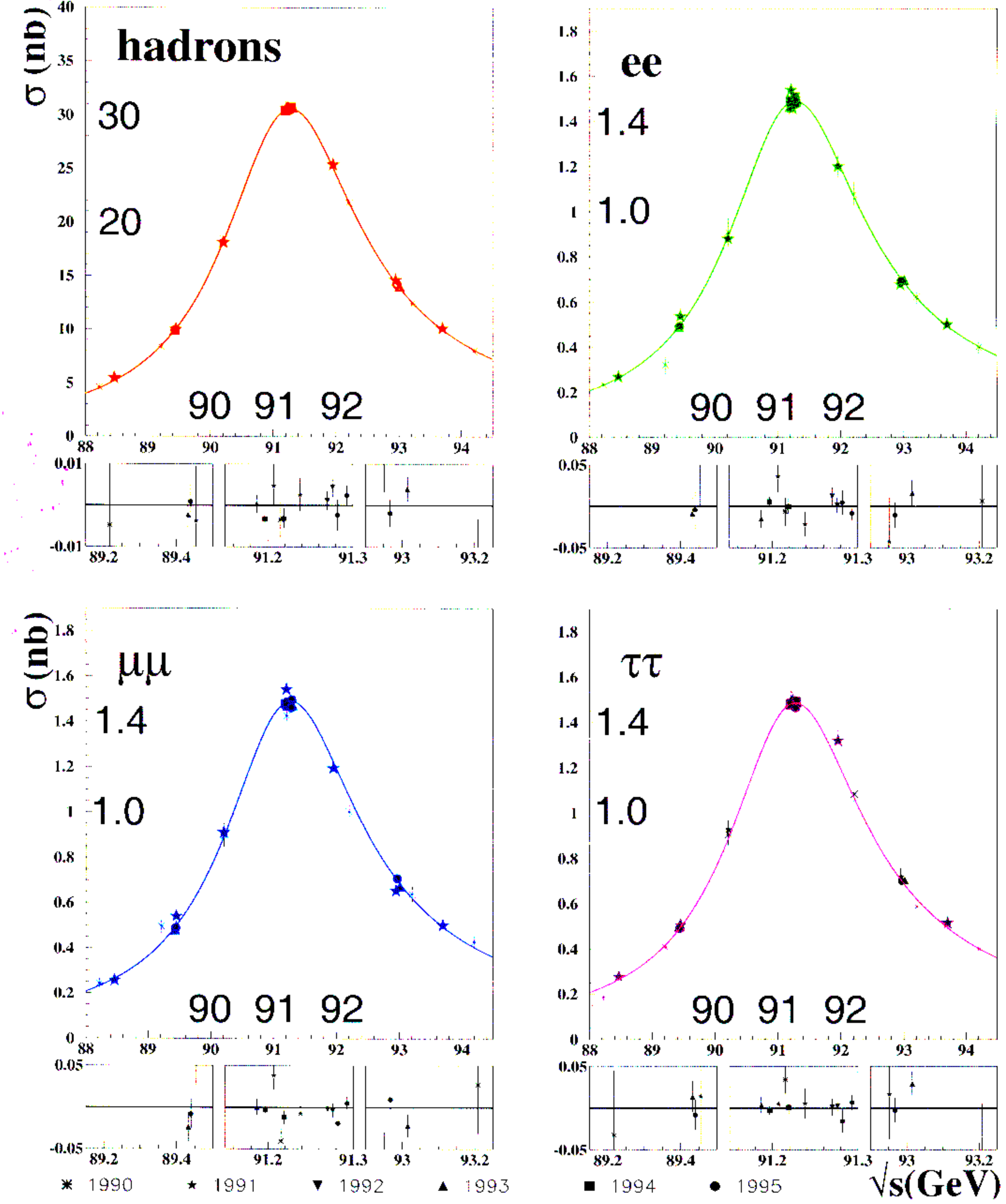
$\Rightarrow \Gamma_Z = 2.4952$ GeV

$\Rightarrow \sigma^0_{\rm had} = 40.540$ nb

$\Rightarrow N_\nu = 2.984 \pm 0.008$

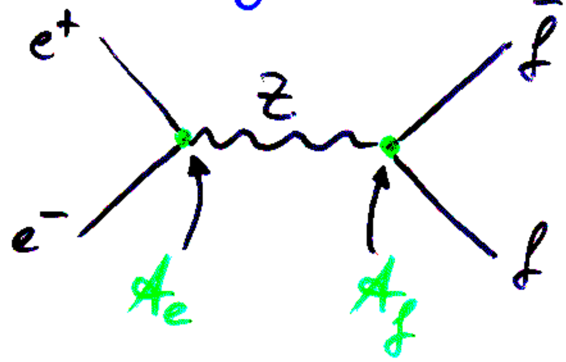
Cross-sections vs $\sqrt{s}$

ALEPH



Asymmetries and couplings

- Z-$f\bar{f}$ couplings:

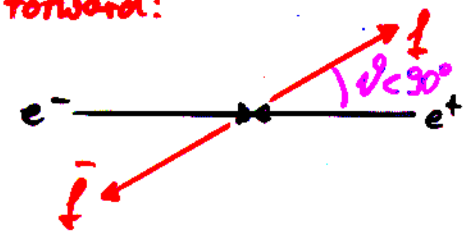


▷ $\mathcal{A}_f = 2\cdot\left(g_{Vf}\cdot g_{Af}\right)/\left(g_{Af}^2+g_{Vf}^2\right)$

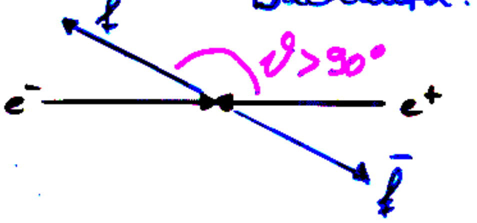
- Measurement by forward-backward asymmetries:

$$A_{FB}^{0,f} \equiv \frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

Forward:



Backward:



- or by polarized e^- beam as in SLC (SLAC):

$$A_{LR}^{0} \equiv \frac{\sigma_{Left}-\sigma_{Right}}{\sigma_{Left}+\sigma_{Right}} = \mathcal{A}_e$$

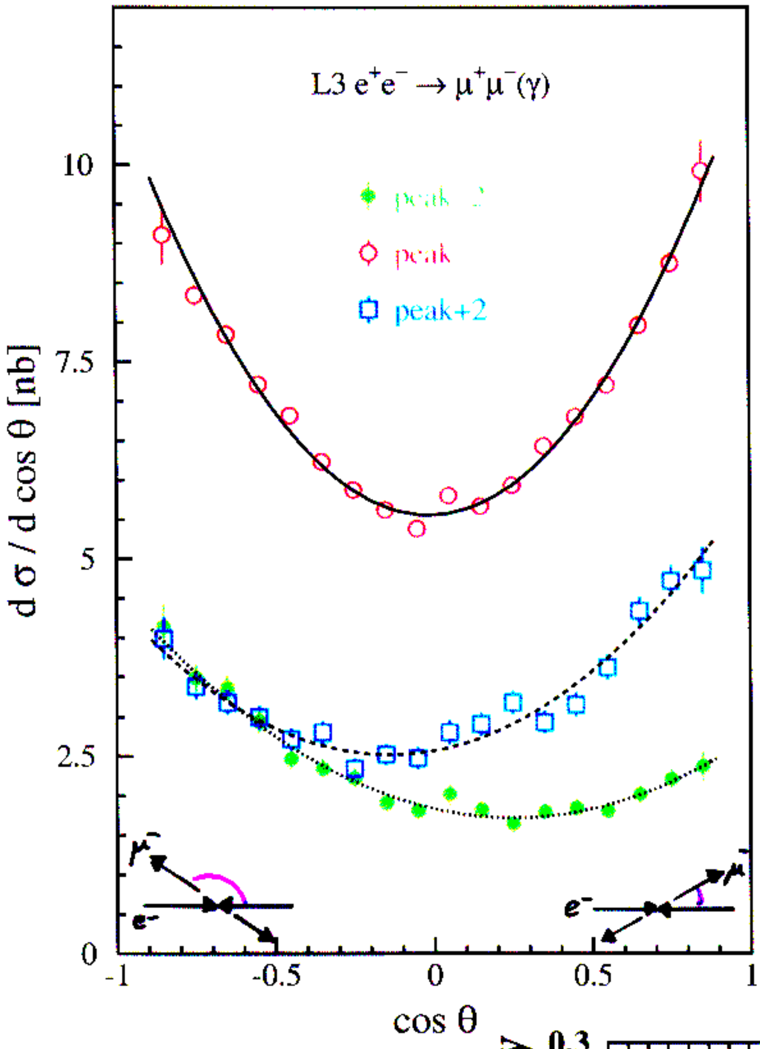
← handedness of e^- polarization
Left: $\Leftarrow e^-$, Right: $\Rightarrow e^-$

$$A_{LR|FB}^{0,f} = \frac{3}{4}\mathcal{A}_f$$

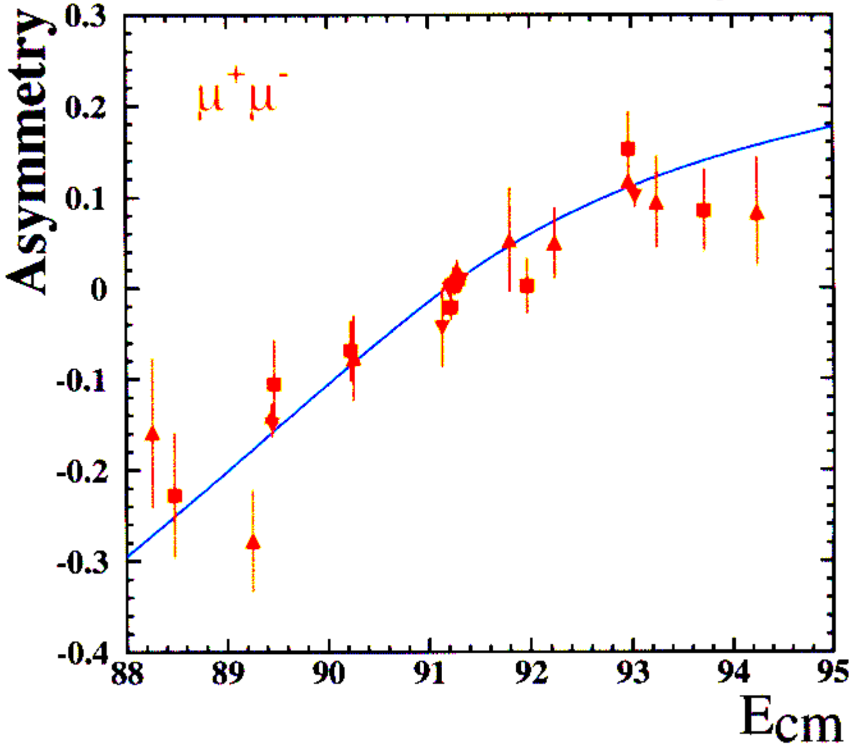
- from polarization of τ lepton in $e^+e^-\to\tau^+\tau^-$

$$\mathcal{P}_\tau\left(\cos\vartheta_{\tau^-e^-}\right) \longrightarrow \mathcal{A}_\tau, \mathcal{A}_e\ ; \quad \langle\mathcal{P}_\tau\rangle = -\mathcal{A}_\tau$$

Lepton forward-backward asymmetries



Forward-backward asymmetry for lepton pairs is straightforward to measure. Charge of lepton from tracking.

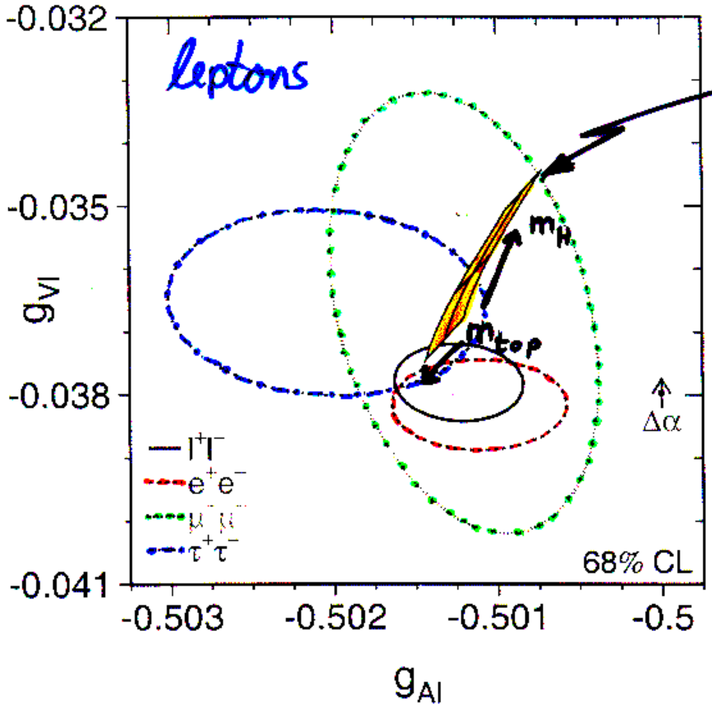


Asymmetry varies with centre-of-mass energy.

effective coupling constants g_V, g_A

$\Gamma_{ff} \sim (g_{Af}^2 + g_{Vf}^2)$

$A_{FB}^{0,f} \sim \frac{g_{Af}\, g_{Vf}}{(g_{Af}^2 + g_{Vf}^2)}$



Standard model
notice: light Higgs
preferred

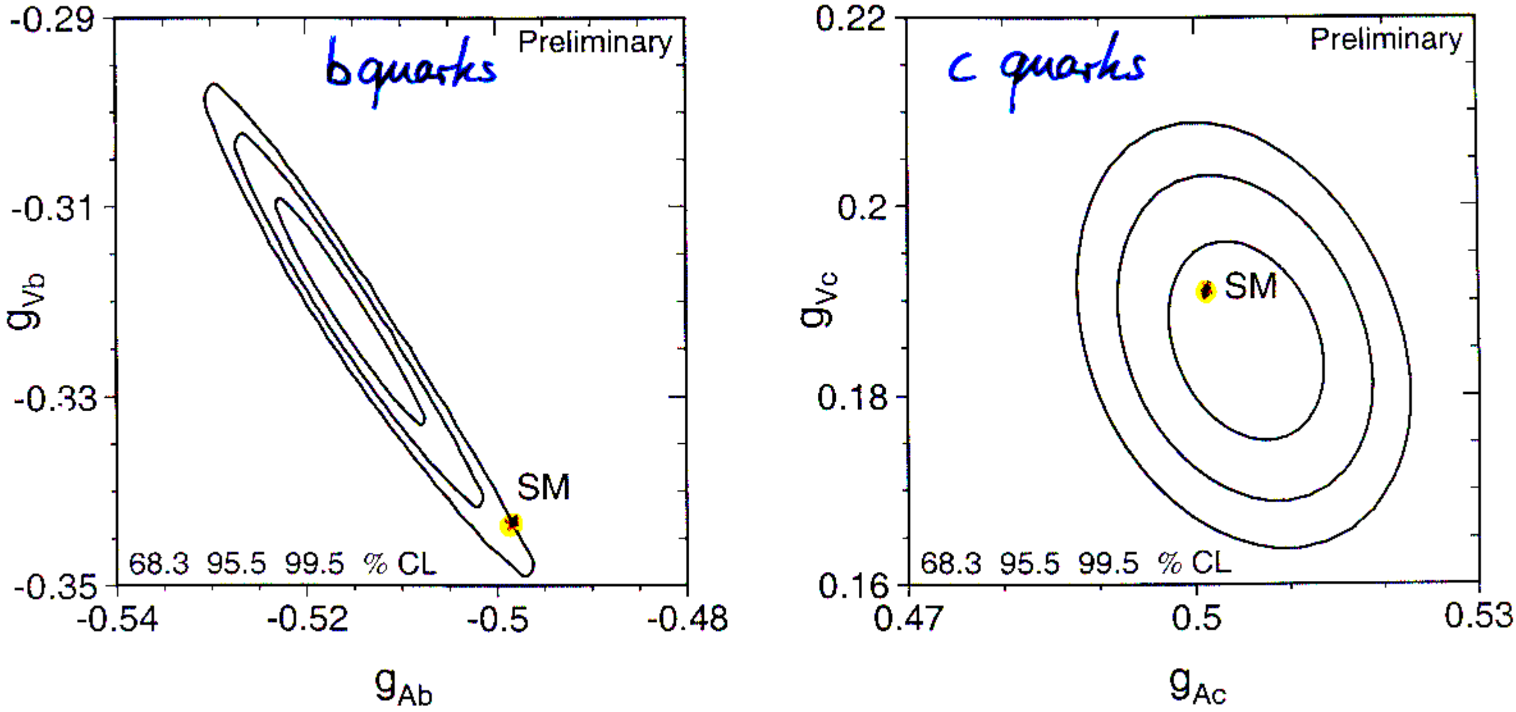
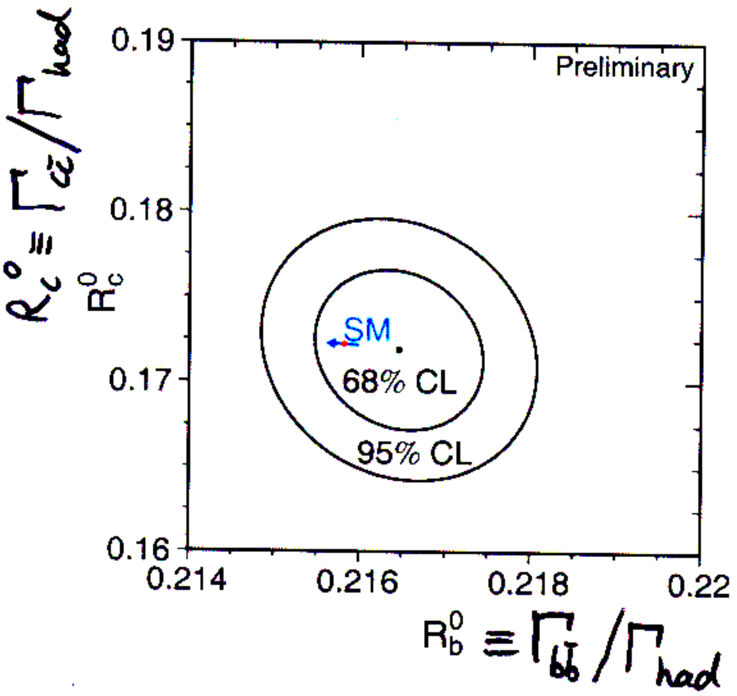
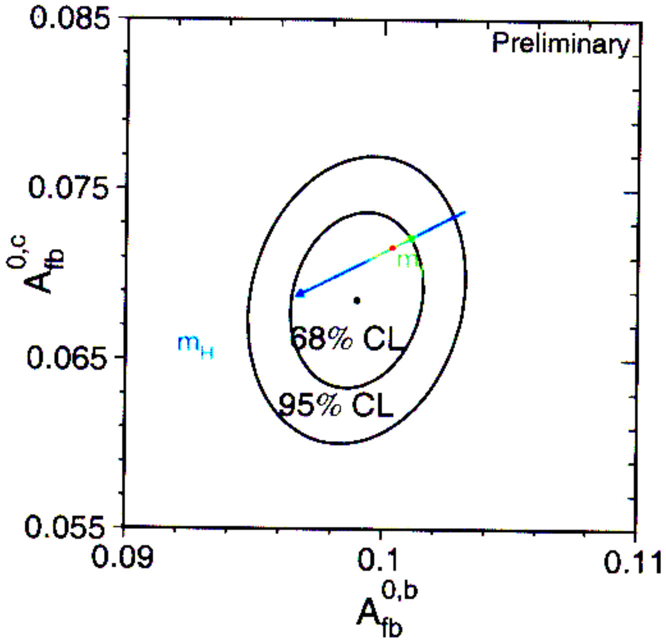


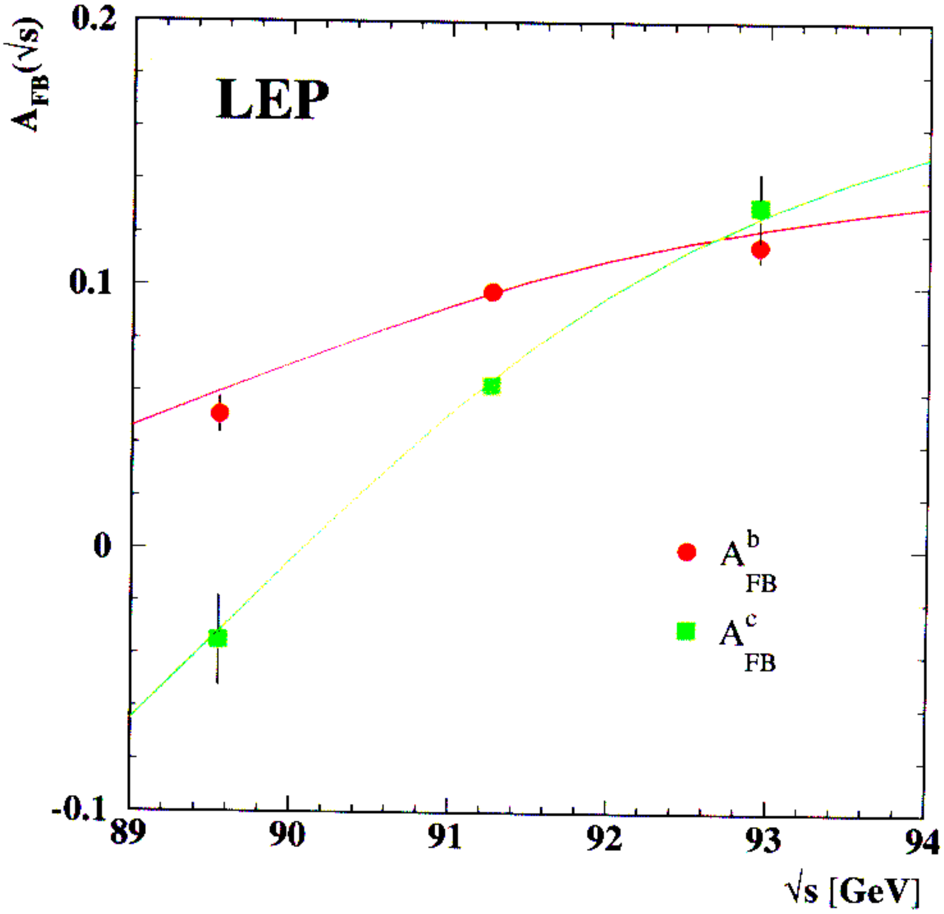
Figure 8.2: Comparison of the effective vector and axial-vector coupling constants for fermions: (a) charged leptons; (b) b quarks; (c) b quarks; (d) s quarks?. The shaded region in (a) shows the predictions within the Standard Model for $m_t = 174.3 \pm 5.1$ GeV and $m_H = 300^{+700}_{-187}$ GeV; varying the hadronic vacuum polarisation by $\Delta\alpha^{(5)}_{\rm had}(m_Z^2) = 0.02761 \pm 0.00036$ yields an additional uncertainty on the Standard-Model prediction shown by the arrow labelled Δα. Compared to the experimental uncertainties, the Standard Model predictions in (b) and (c) are nearly constant for the quark coupling constants.

Heavy Flavour Electroweak Results



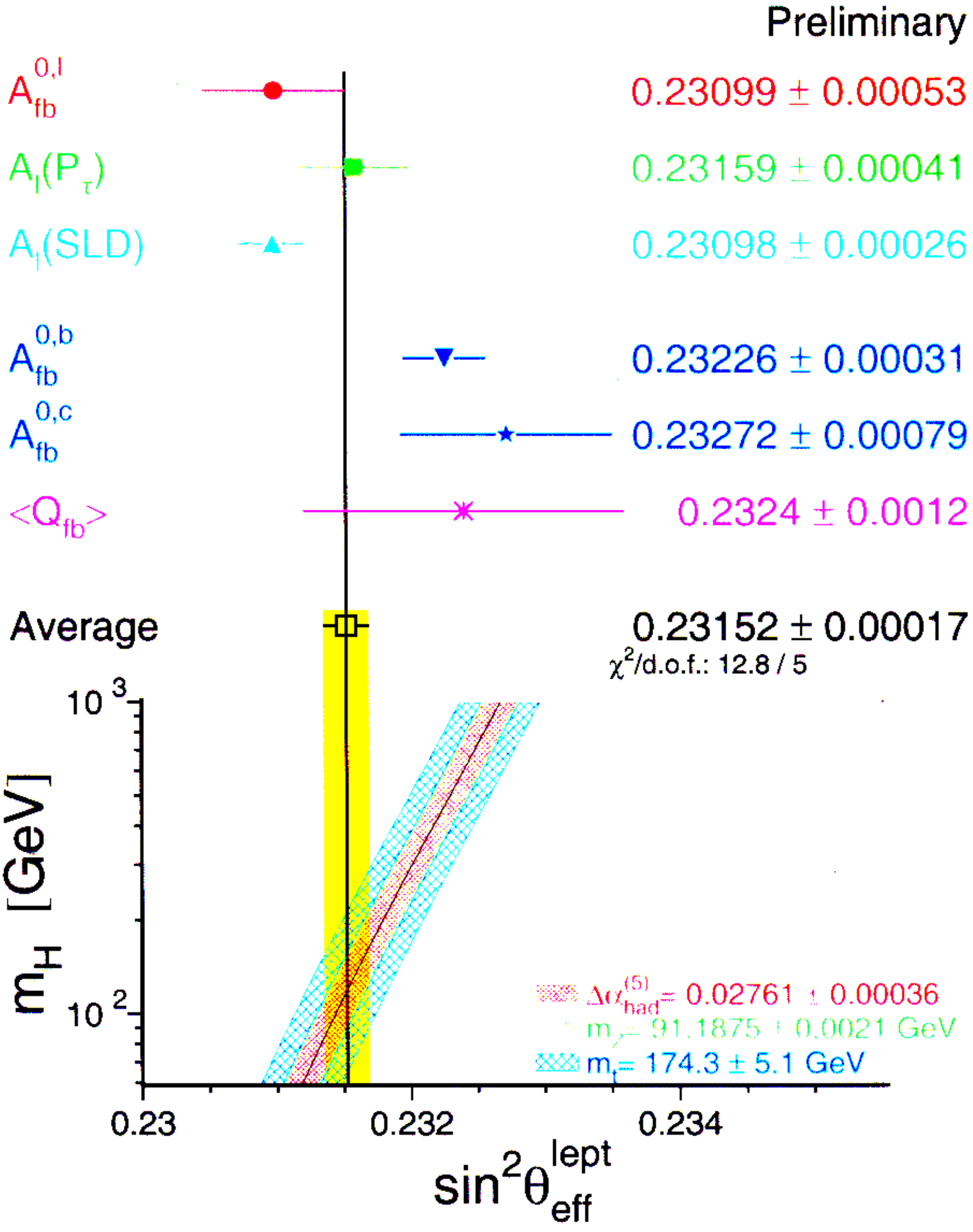


Notice discrepancy with SM for $A_{\rm FB}^{0,b}$ and light Higgs



Effective Leptonic Electroweak Mixing Angle

$\sin^2\theta_{\rm eff}^{\rm lept} = (1 - g_{V\ell}/g_{A\ell})/4$ ← eliminates flavour dependences



Leptons	0.23113 ± 0.00021	χ^2/d.o.f. : 1.6/2
Hadrons	0.23230 ± 0.00029	χ^2/d.o.f. : 0.3/2
Difference	3.3 sigma	

(No theory beyond SM can accomodate this difference)

Standard model — properties of the Z boson

- partial decay width (massless fermions, w/o correction term

$$\Gamma_f = \underbrace{\frac{G_F\, m_Z^3}{6\pi\sqrt{2}}}_{\approx 332\,\mathrm{MeV}} \left(g_{Vf}^2 + g_{Af}^2\right) \cdot \underbrace{N_c}_{\substack{\text{colour}\\ \text{factor}}} \quad \begin{cases} = 1 & \text{leptons} \\ = 3 & \text{quarks} \end{cases}$$

$\Rightarrow$ branching ratios

$Z \to \nu\bar{\nu} : \ell^+\ell^- : q\bar{q} \approx 20\% : 10\% : 70\%$

with $Z \to q\bar{q}$

$Z \to d\bar{d} : u\bar{u} : s\bar{s} : c\bar{c} : b\bar{b} \approx 22\% : 17\% : 22\% : 17\% : 22\%$

and lepton universality in $Z \to \nu\bar{\nu}, \ell^+\ell^-$

$Z \to \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau = \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$

$Z \to e^+e^-, \mu^+\mu^-, \underset{\uparrow}{\tau^+\tau^-} = \frac{1}{3} : \frac{1}{3} : \underset{\uparrow}{\frac{1}{3}}$

$m_\tau = 1.77\,\mathrm{GeV}$ yields corrections

- total width*

$\Gamma_Z = (2495.2 \pm 2.3)\,\mathrm{MeV} \mathrel{\widehat{=}} \pm 1‰$

SM:

- mass*

$m_Z = (91187.5 \pm 2.1)\,\mathrm{MeV} \mathrel{\widehat{=}} \pm 23\,\mathrm{ppm}$

* = from precision measurements at LEP I

Origin of high precision

- incredible effort of electroweak precision calculatio

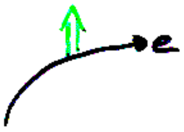
implemented in programs: ZFITTER (D.Bardin et al.), TOPAZ0 (G.Montagn
et al.
and precision calculation working groups: CERN 95-03 and
hep-ph/990245

- exceptional performance of detectors: eg. calibration, alignment, ...

- fantastic precision of LEP's beam energy determinatio

▷ $E_{beam} = \frac{e}{2\pi} \oint \vec{B} \cdot d\vec{\ell}$

▷ measure $\oint \vec{B}\, d\vec{\ell}$ by resonant depolarization:



☐ transverse polarization of e^- & e^+ due to synchrotron radiation (Sokulov-Ternov effect)

☐ electron spin precession in B field; no. of precessions per turn of LEP

$$\nu_s = \frac{g_e - 2}{2} \frac{e}{2\pi m_e} \oint \vec{B}\, d\vec{\ell} = \frac{g_e - 2}{2} \cdot \frac{E_{beam}}{m_e}$$

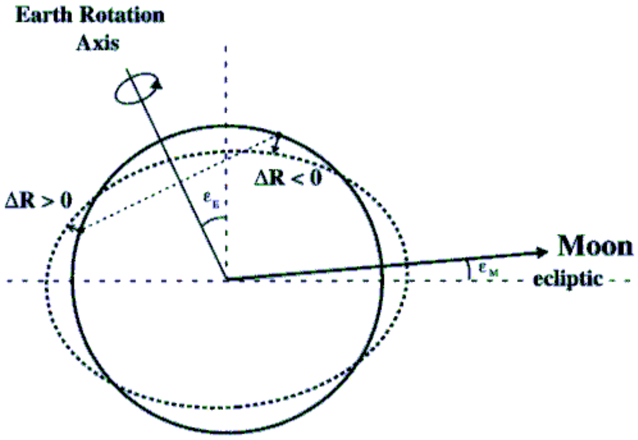
☐ kick electrons by oscillating horizontal B field at one place.
If $\nu_{Bfield} = \nu_s$, polarization is destroyed

⇒ instantaneous precision: ≈ 100 keV

⤳ stability of LEP and everything else?

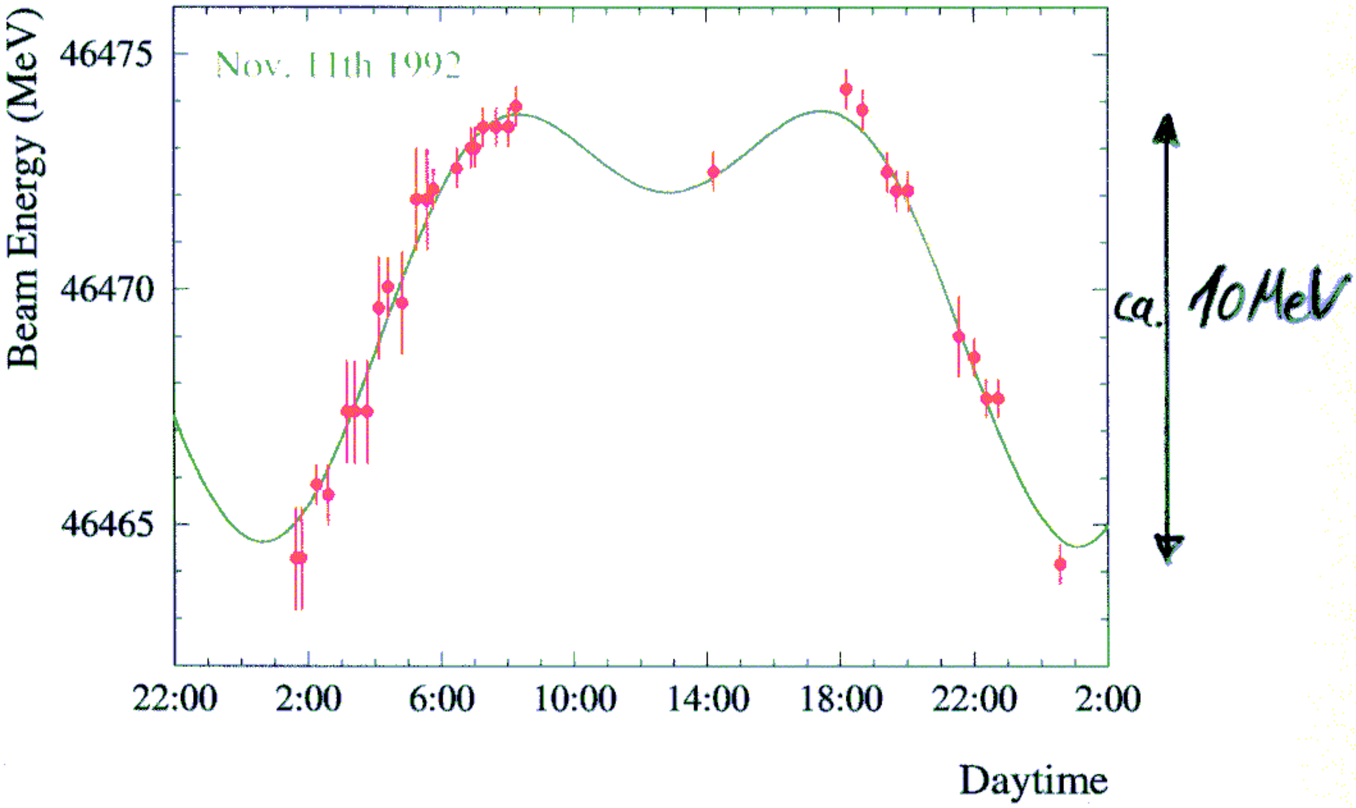
Stability? Quadrupole movements...

1991 - first calibrations saw fluctuations of order 10 MeV. Earth tides driven by moon and sun.



Length of orbit fixed by RF system, but magnets move with ground. Beam no longer goes through centre of quadrupoles. Sensitive to 1mm change in 27 km, typical 10 MeV peak-to-peak.

$$\frac{\Delta E}{E} = -\frac{1}{\alpha}\frac{\Delta C}{C}$$



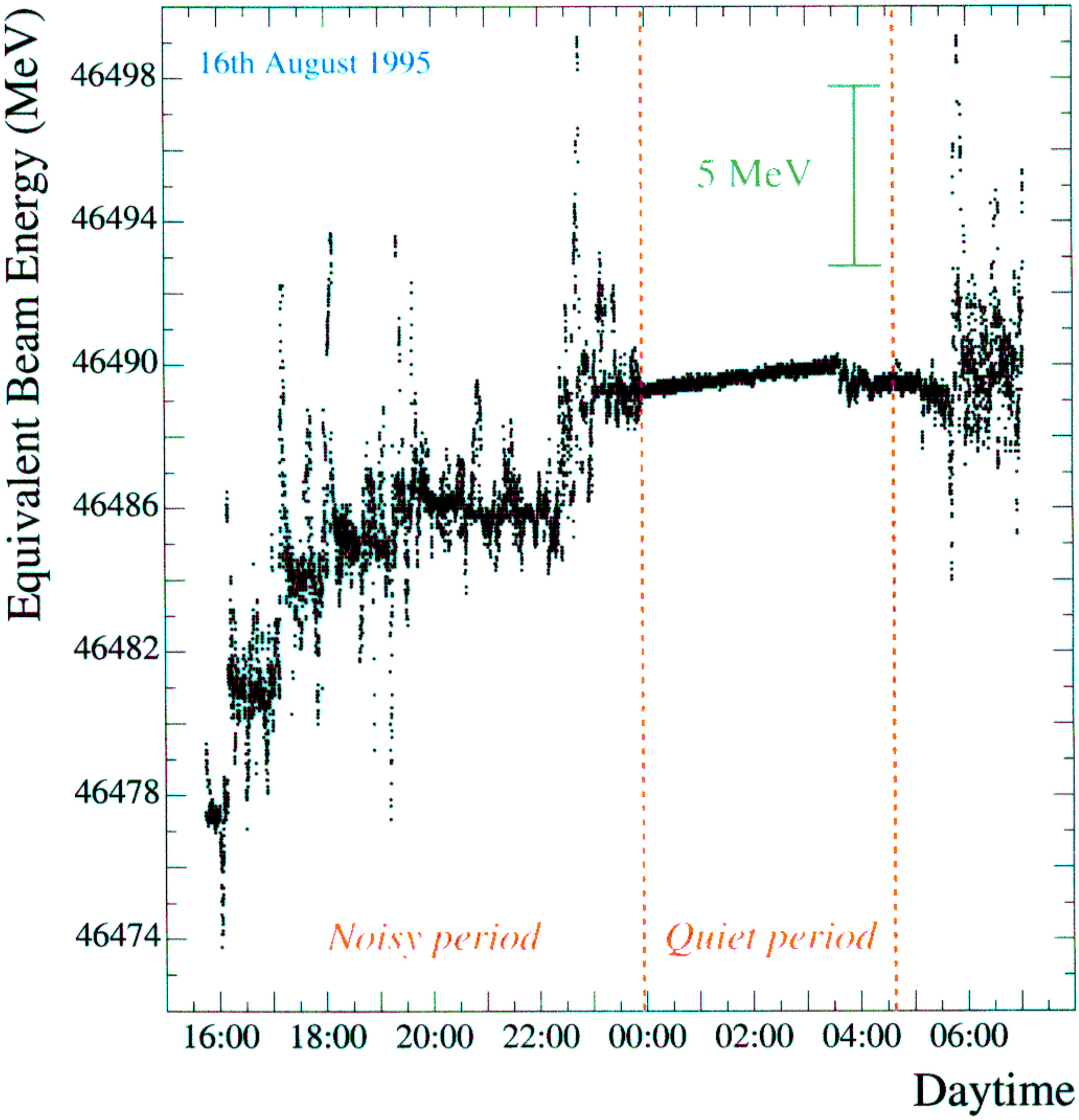
Also see ground distortion due to lake level, heavy rain...

(© P. Wells 2001)

Stability? Dipole fields...

1993: Tide model and resonant depolarisation measurements made at the ends of many fills: M_Z systematic of 1.4 MeV .

Summer 1995 - first measurements of B field in tunnel dipoles

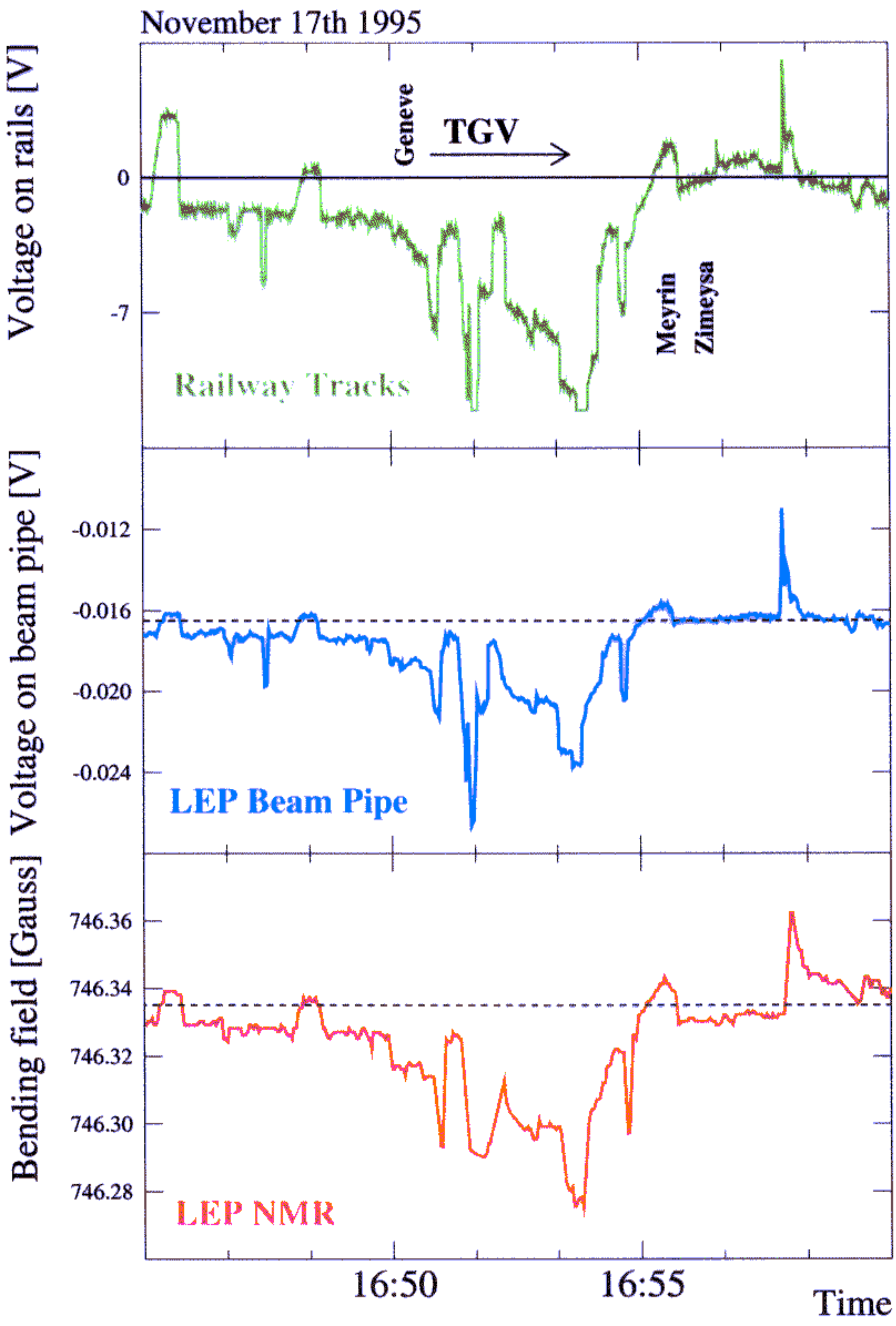


Some human activity is driving the dipole fields up during the fill:

BIAS of order 5 MeV

(©P.Wells, 2001)

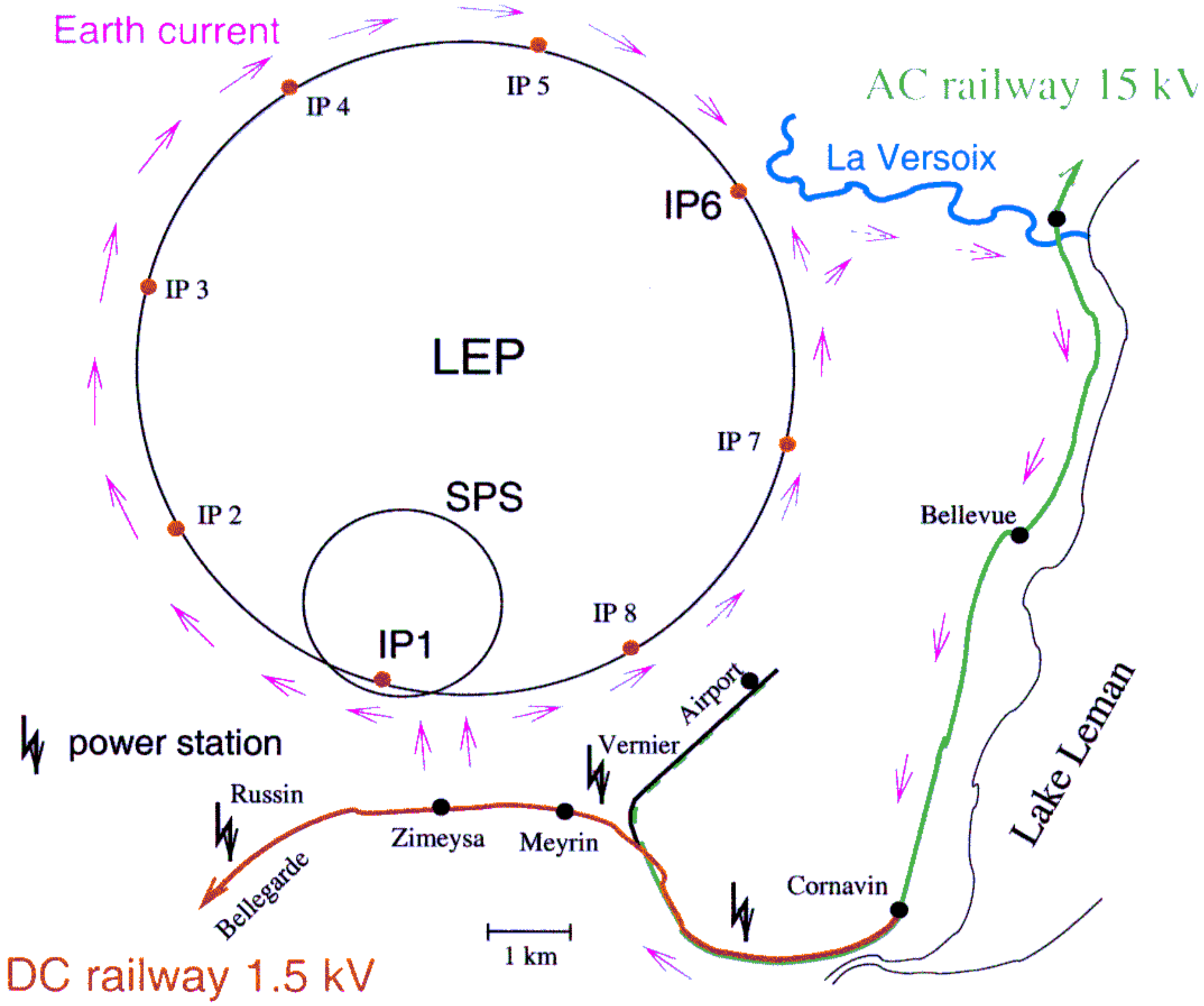
Vagabond currents from trains



Model using average train behaviour used to correct earlier years' data: M_Z systematic of 1.7 MeV

(© P.Wells, 2001)

The current flow...



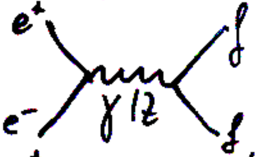
(©P.Wells, 2001)

From the Z pole towards higher energies

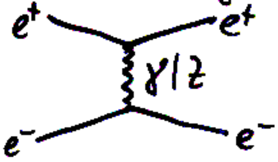
Reactions which contribute also at higher energies:

eg. 2 fermion final states

s-channel

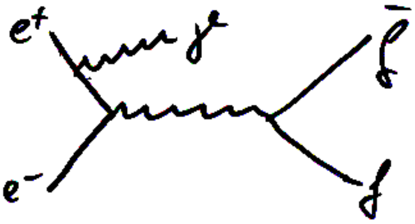


t-channel

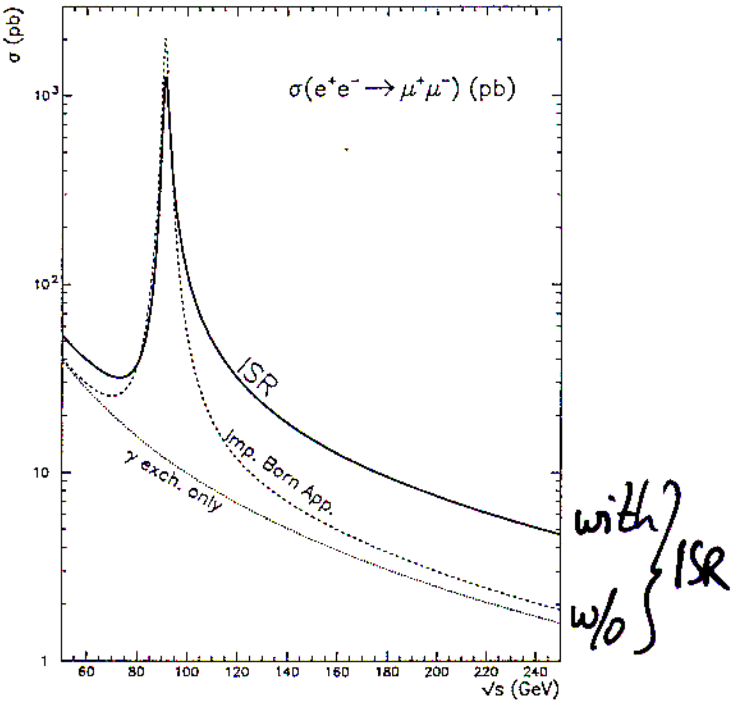


(Bhabha scattering = reference process for the determination of the integrated luminosity)

Contrary to the Z pole bremsstrahlung "before" the annihilation (ISR) becomes important:



reason: radiative return to the Z peak due to bremsstrahlung

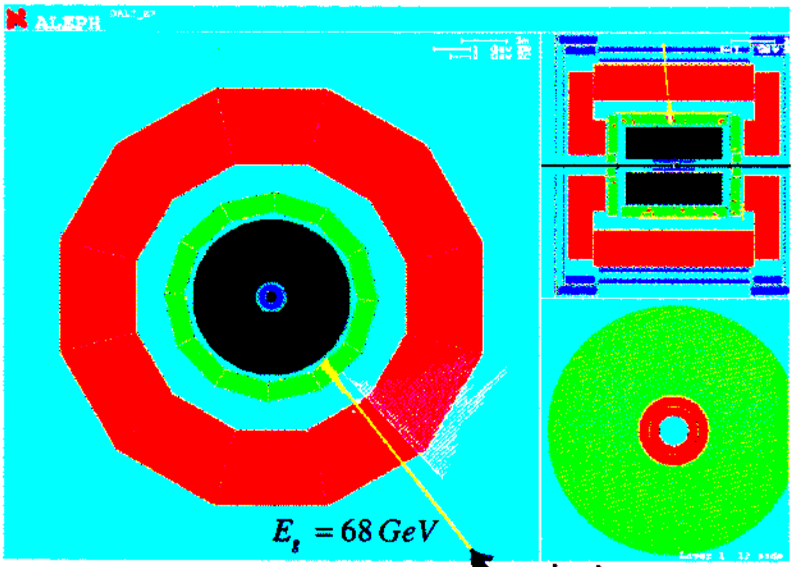


⇒ reduced effective centre-of-mass energy (≙ recoil mass to the photon)

$$s' = s - 2E_\gamma\sqrt{s} \underset{\uparrow}{\simeq} m_Z^2$$

in case of radiative return to the Z peak

Final states with a single photon



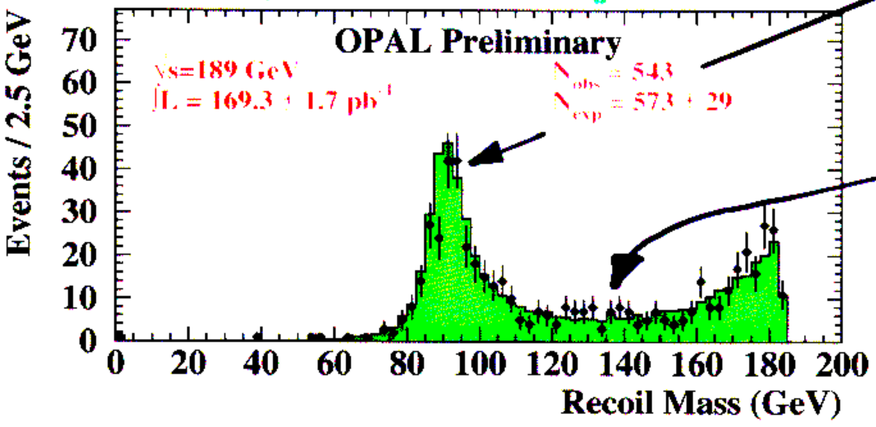
photon signal

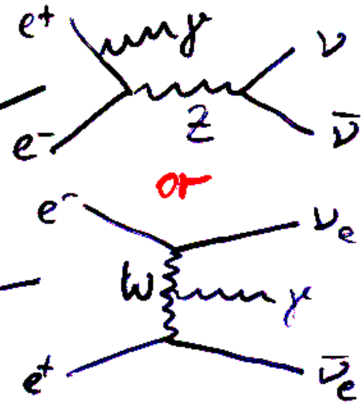
single, highly energetic photon

no other energy deposits in detector

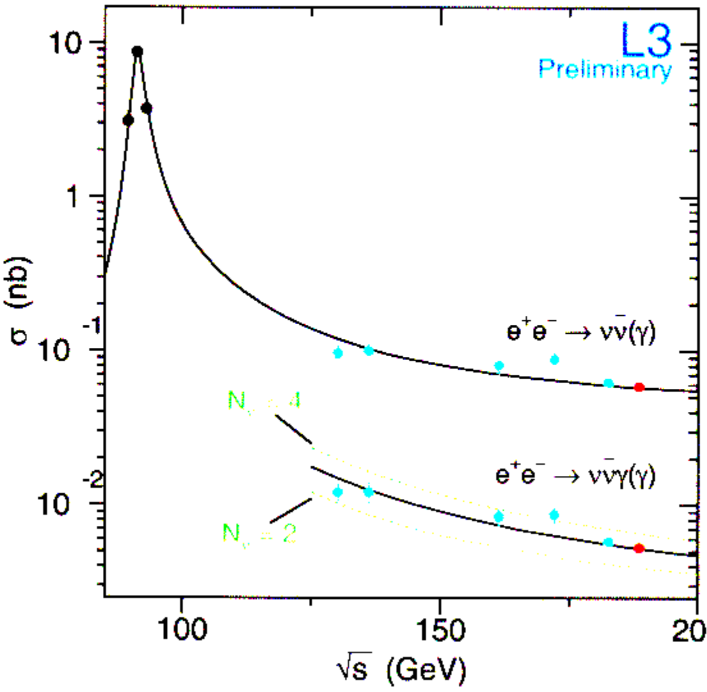
Standard model interpretation

$$m_r^2 = s' = s - 2E_\gamma\sqrt{s}$$





cross section:



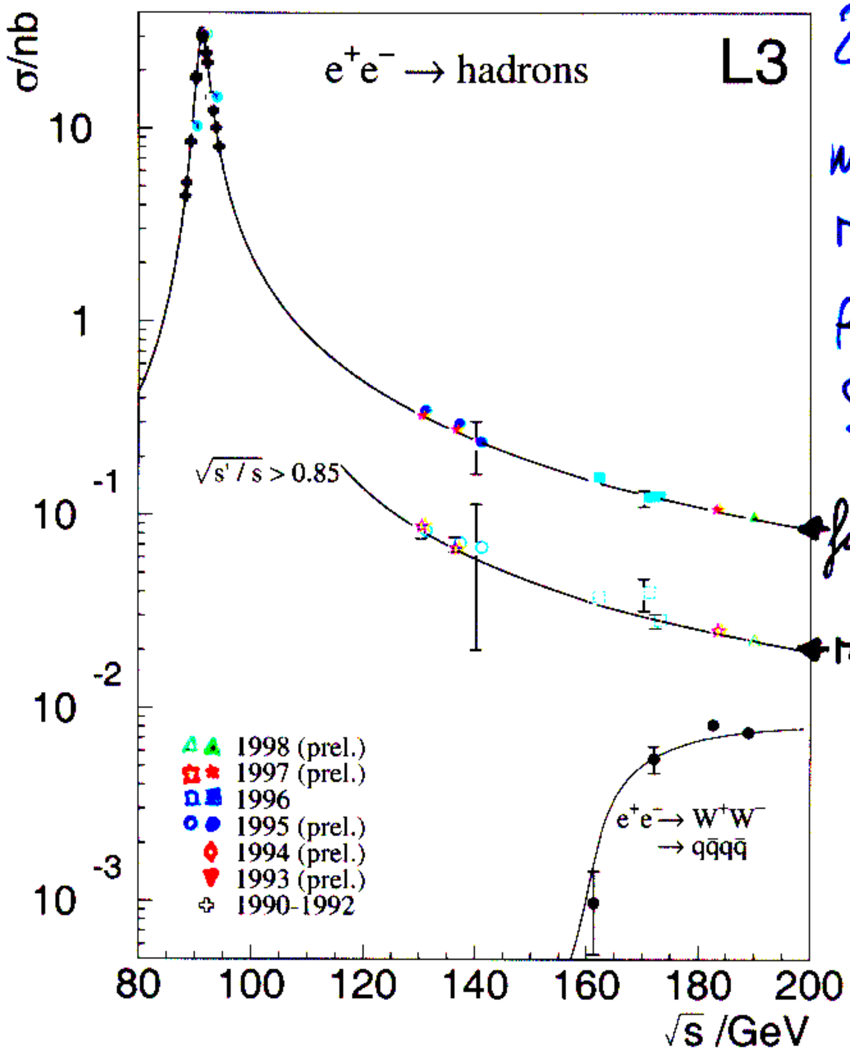
total

with 1 observed γ

Number of ν-species:

⇒ LEP II: $N_\nu = 2.99 \pm 0.1$

Energy dependence of the 2 fermion cross-section



2 fermion production measured over vast energy range : perfect agreement with Standard model

← full radiative contribution

← radiative contrib. suppressed

S-matrix ansatz:

$$\sigma\left(e^+e^- \to f\bar{f}(\gamma)\right) = \frac{3\pi\alpha^2}{4}\left[\frac{g_f}{s} + \frac{j_f\left(s-\bar{m}_Z^2\right) + r_f s}{\left(s-\bar{m}_Z^2\right)^2 + \bar{\Gamma}_Z^2\bar{m}_Z^2}\right] \otimes \text{photon radiation}$$

$$g_f \propto Q_e^2 Q_f^2 \; ; \quad j_f \propto g_{Ve}\, g_{Vf} \; ; \quad r_f \propto \left(g_{Ve}^2 + g_{Ae}^2\right)\cdot\left(g_{Vf}^2 + g_{Af}^2\right)$$

$$m_Z^2 = \bar{m}_Z^2 + \bar{\Gamma}_Z^2 \; ; \quad \bar{\Gamma}_Z = \Gamma_Z \cdot \frac{\bar{m}_Z}{m_Z} \quad \left(\begin{aligned} m_Z &\simeq \bar{m}_Z + 34.1\text{ MeV} \\ \Gamma_Z &\simeq \bar{\Gamma}_Z + 0.9\text{ MeV}\end{aligned}\right)$$

- New job for LEP experiments:

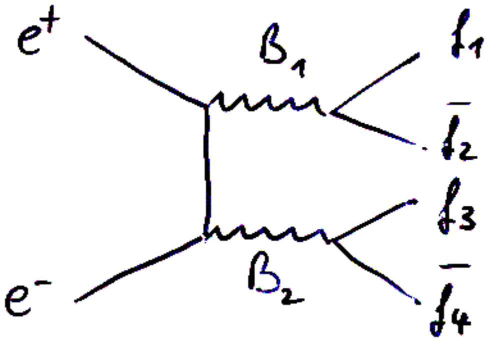
LEP I : "Z factory" ⟶ LEP II : "WW factory"

↓ σ_Z, m_Z, Γ_Z ↓ $\sigma_{WW}, m_W, \Gamma_W$

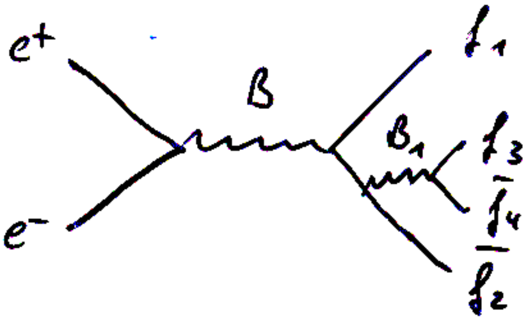
W boson

4 fermion physics at LEP II

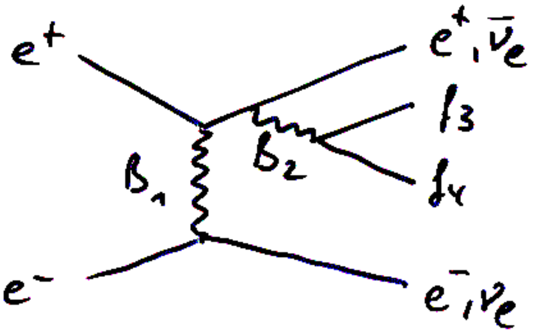
At energies above the Z peak: 4 fermion final states have substantial production cross-sections:



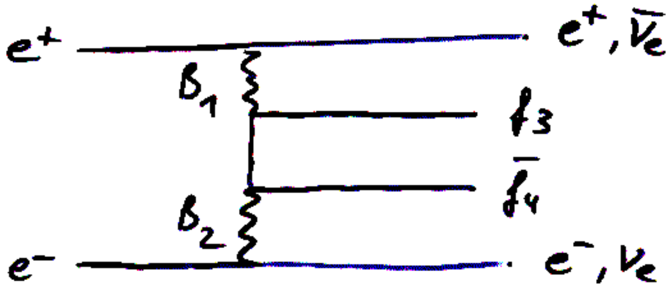
conversion



annihilation

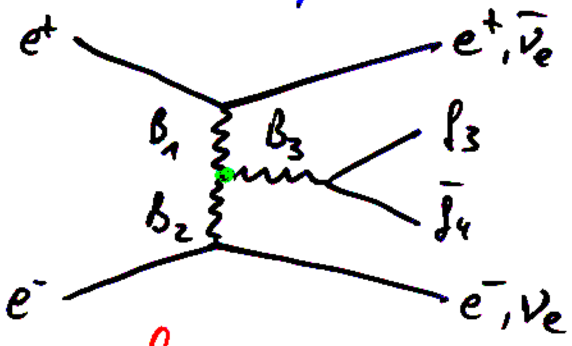


bremsstrahlung

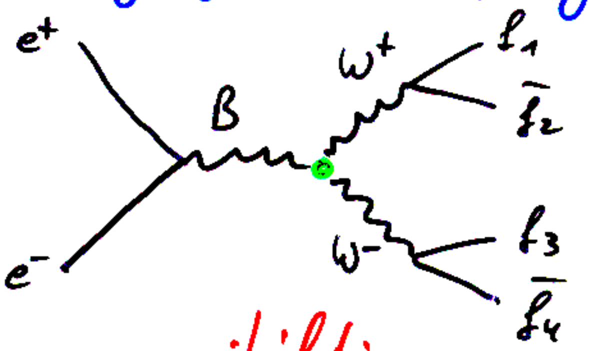


multiperipheral (includes 2γ-processes)

additionally classes of triple gauge boson coupling (non-abelia



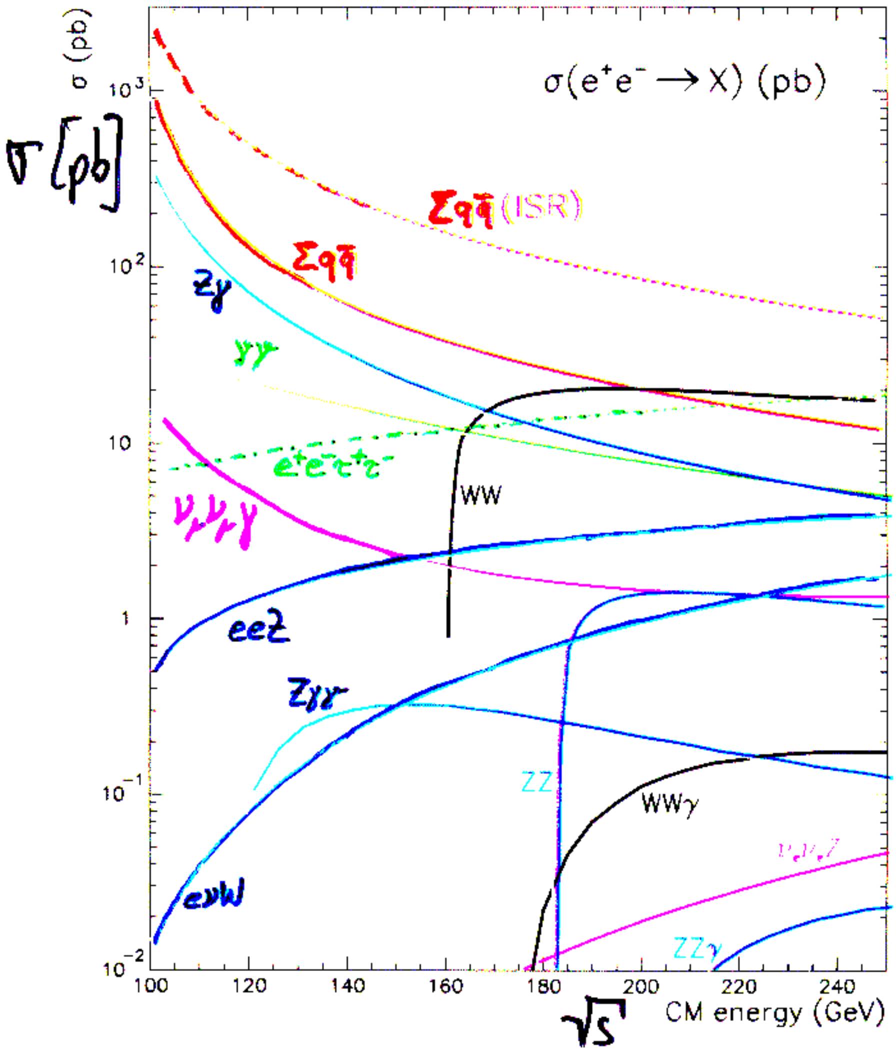
fusion



annihilation

$B = \gamma, Z$; $B_1, B_2, B_3 = \gamma, Z, W^\pm$; + Higgs graphs

cross-sections of typical Standard model processes

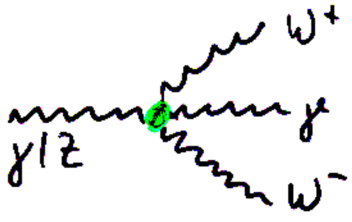


Only dominating t-channel contribution for

$e^+e^- \to e^+e^- Z\,,\; e\nu_e W,\; \nu_e\bar{\nu}_e Z$

shown.

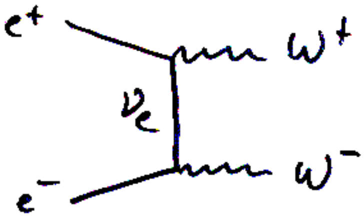
WWγ contains contrib. from quartic gauge boson coupling

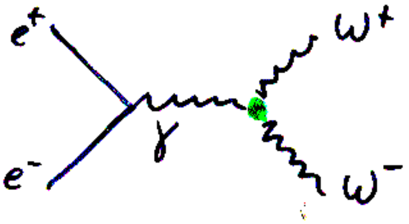


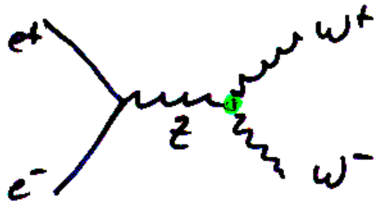
Zγγ, ZZγ in Standard model only via conversion + Bremsstrahlung

W pair production at LEP II

At c.m. energies $\sqrt{s}$ above $\simeq 2 \cdot m_W$ W^+W^- can be produced in e^+e^- annihilation







conversion (t-channel) annihilation (s-channel)

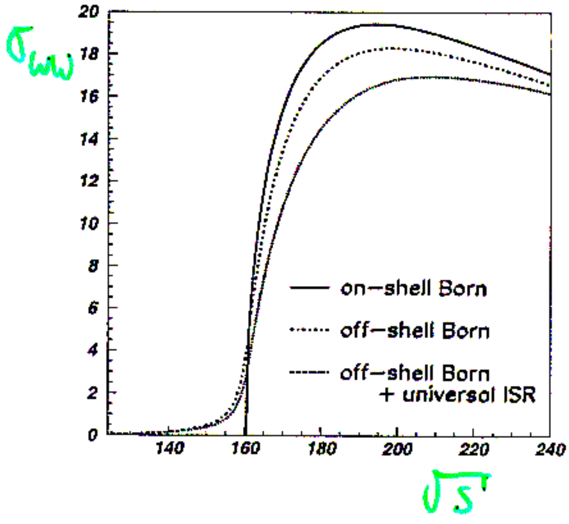
(so called CC3 graphs: "charged current", 3 graphs)

At threshold W pair production is dominated by t-channel ($\sim\beta$) exchange; s-channel is $\sim\beta^3$.

Lowest order cross-section (Born term) for on-shell W bosons:

$$\sigma_{WW}^{\text{Born}} \approx \frac{\pi \alpha_{em}^2}{s} \frac{1}{(1 - m_W^2/m_Z^2)} \cdot \beta$$

where $\beta = \frac{v}{c} = \sqrt{1 - 4m_W^2/s}$



finite width Γ_W (→ off-shell production) and initial state radiation (ISR) wash out the production threshold

Properties of W bosons

- partial decay width (massless fermions, w/o correction terms)

$$\Gamma_{f_i \bar{f}_j} = \underbrace{\frac{G_F m_W^3}{6\pi\sqrt{2}}}_{\approx 227\,\text{MeV}} \cdot \underbrace{|V_{ij}|^2}_{\substack{\text{CKM} \\ \text{matrix for quarks}}} \cdot \underbrace{N_c}_{\text{colour factor} \begin{cases} =1 & \text{leptons} \\ =3 & \text{quarks} \end{cases}}$$

⇒ branching ratios:

$W \to \ell\bar{\nu} : q\bar{q}' \simeq 32\% : 68\%$

(or from simple counting: $\underbrace{e^-\bar{\nu}_e, \mu^-\bar{\nu}_\mu, \tau^-\bar{\nu}_\tau,}_{3} : \underbrace{3\cdot d\bar{u}, 3\cdot s\bar{c}}_{6}$ rest suppressed by CKM matrix)

where $W \to q\bar{q}'$ $\left(\sum_{i,j=u,d,s,c,b} |V_{ij}|^2 \simeq 2 \right)$

$W^+ \to u\bar{d} : c\bar{s} : u\bar{s} : c\bar{d} : c\bar{b} : u\bar{b} \simeq 47.5\% : 47.5\% : 2.4\% : 2.4\% : 0.3\% : 10^{-}$

and lepton universality in $W \to \ell\nu$

$W^+ \to e^+\nu_e, \mu^+\nu_\mu, \tau^+\nu_\tau = \frac{1}{3} : \frac{1}{3} : \frac{1}{3}$

$m_\tau \simeq 1.776\,\text{GeV}$ yields corrections

- total width $\Gamma_W \simeq 2093$ MeV in the Standard model

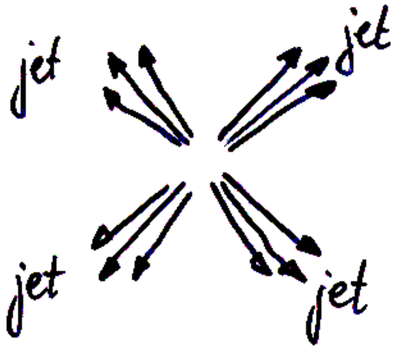
- mass $m_W \simeq 80.4$ GeV

- branching ratios for W pairs:

$W^+W^- \to q\bar{q}q\bar{q} : q\bar{q}\ell\nu : \ell\nu\ell\nu \simeq 45\% : 44\% : 11\%$

W physics: topologies of W pair production

- $WW \to q\bar{q}q\bar{q}$ ca. 45% of all WW final states

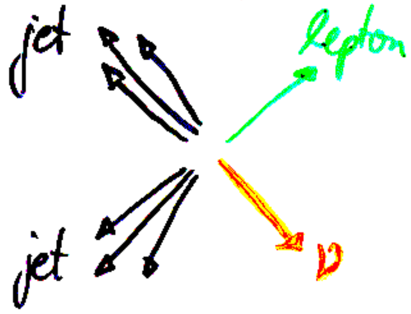


4 jets

total momentum balanced

energy sum $\sum E \approx \sqrt{s}$

- $WW \to q\bar{q}\,\ell\nu$ ca. 44% of all WW final states

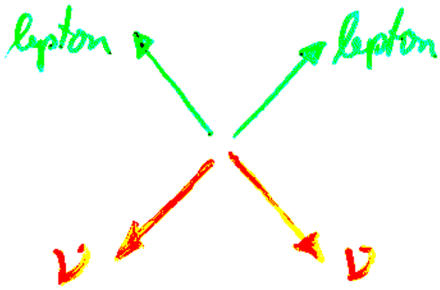


2 jets

1 energetic lepton (well-separated from jets)

missing transverse momentum & energy

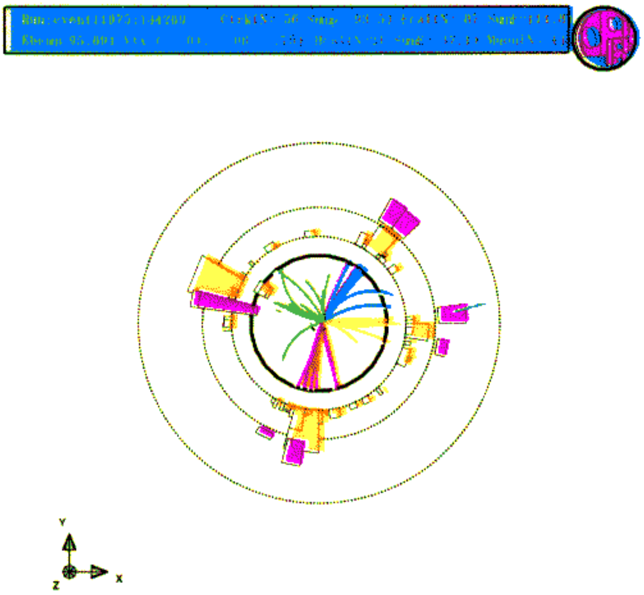
- $WW \to \ell\nu\,\ell\nu$ about 11% of all WW final states



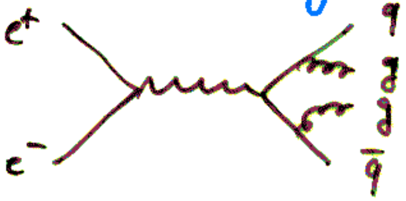
2 energetic leptons (in general acoplanar)

missing transverse momentum & energy

WW → $q\bar{q}q\bar{q}$ selection



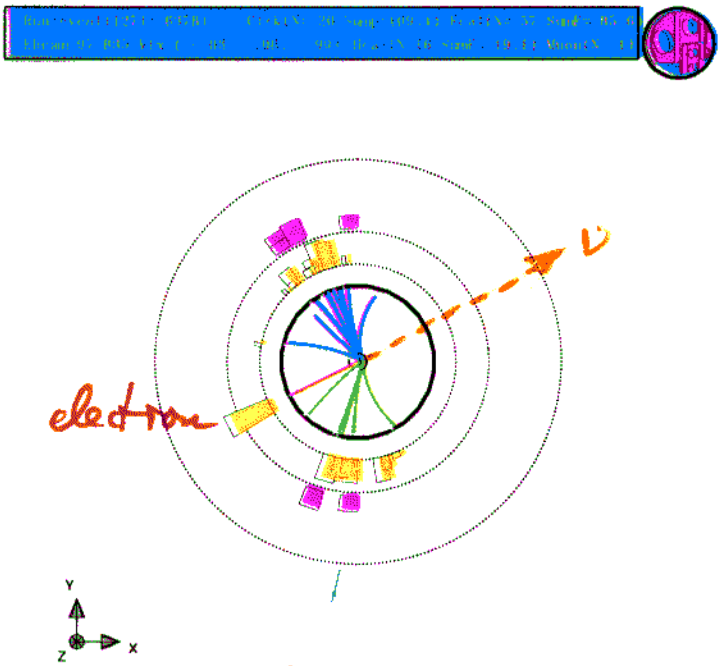
- characteristics:
  - 4 jets
  - no missing energy nor momentum
- main background



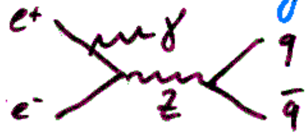
QCD jets

- selection relies on
  - probability selections (likelihood functions)
  - neural networks

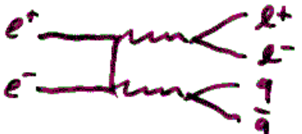
$WW \to q\bar{q}\ell\nu$ selection



- two event classes : $q\bar{q}e\nu$, $q\bar{q}\mu\nu$
- common properties :
  - two jets
  - isolated lepton (e,μ)
  - missing transverse momentum
- main background sources:



radiative quark pairs

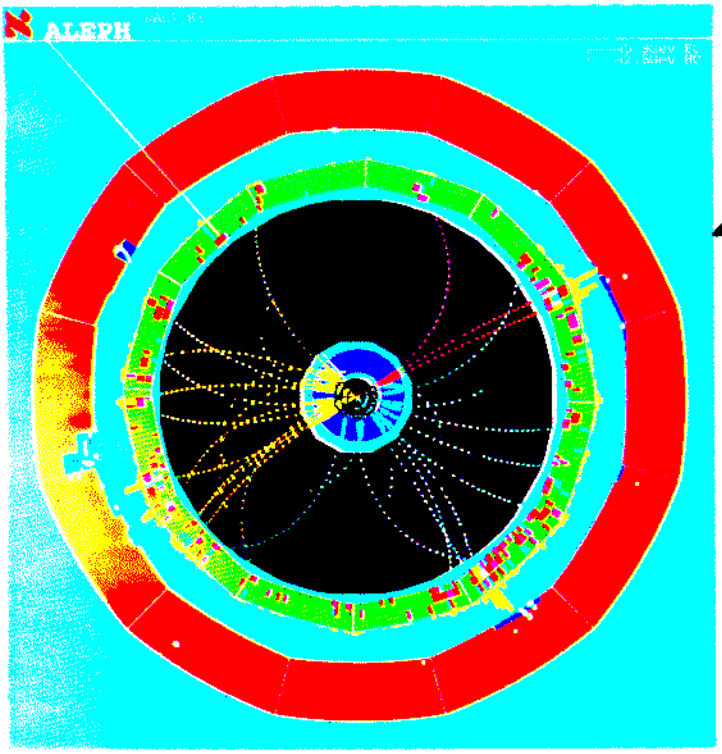


neutral current events

single Ws

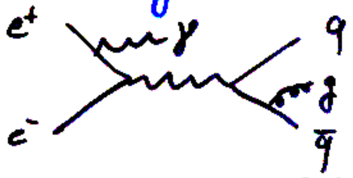
- selection: lepton identification and momentum
  - missing momentum not along beam axis

$WW \rightarrow q\bar{q}\tau\nu$ selection

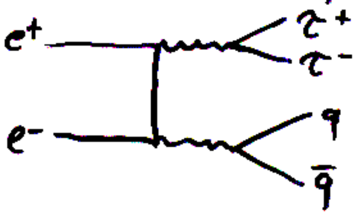


$\tau \rightarrow 3\pi\,\nu_\tau$

- characteristics:
  - 3 jets (including τ-jet)
  - missing mass ($\nu_\tau, \bar{\nu}_\tau$), missing transverse momentum
- background from:



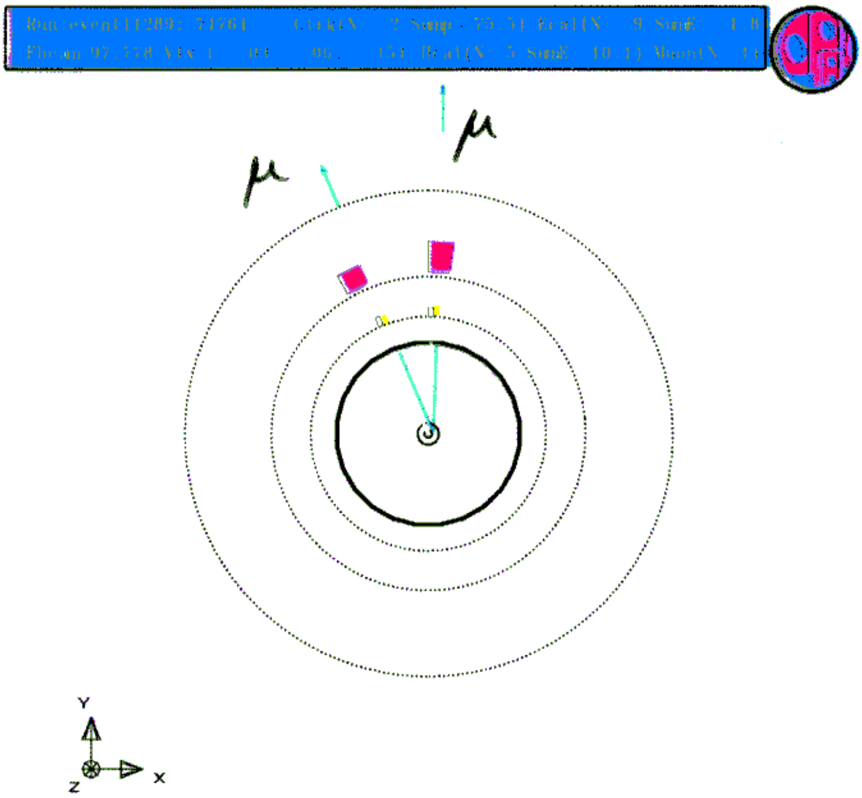
radiative quark pairs



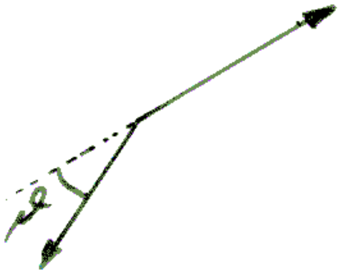
neutral current events

- selection employs:
  - probability selections (likelihood functions)
  - neural networks

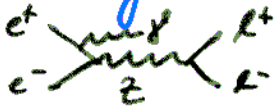
$WW \to \ell\nu\ell\nu$ selection



- six event classes: $ee, \mu\mu, \tau\tau, e\mu, e\tau, \mu\tau$
- common properties:
  - acoplanarity of leptons (ϑ)
  - high lepton momentum
  - high visible mass
  - identification of e and μ



- background mainly from



radiative lepton pairs

neutral current events

2-photon physics

- selection: lepton momentum (and identification), acoplanarity

WW selection: efficiency and purity

typical efficiencies ε and purities π

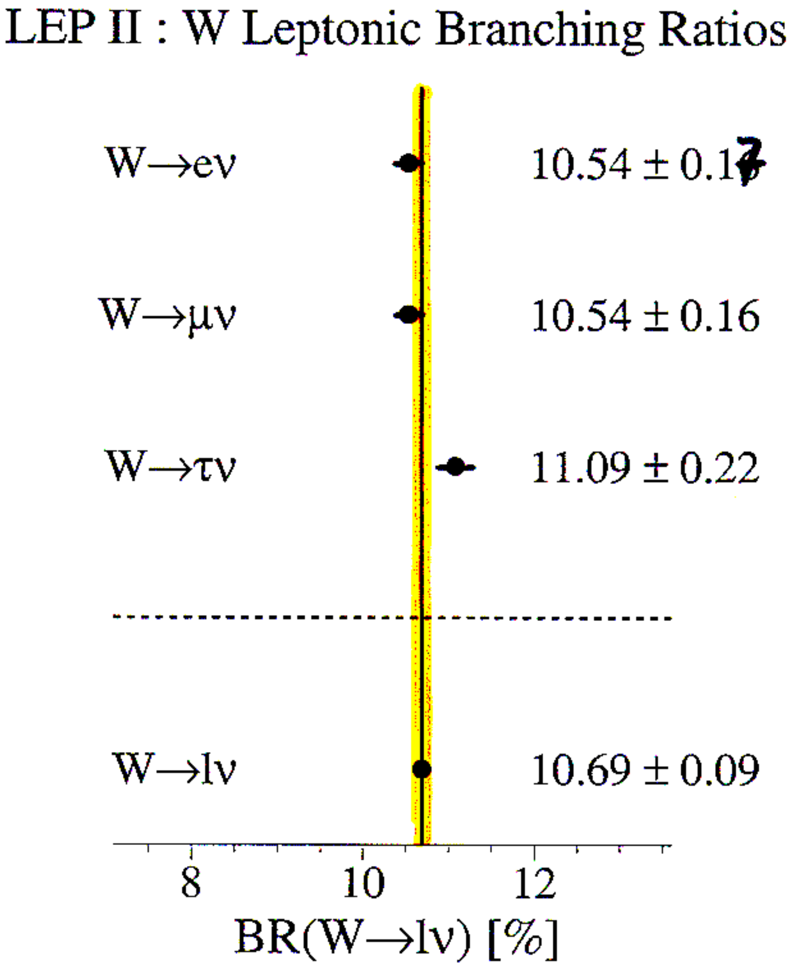
	ε	π	BR
$l\nu l\nu$	30 – 70% ↑ if τ lepton involved	80%	11%
$q\bar{q}l\nu$	50 – 80% ↑ τ lepton	80 - 90%	44%
$q\bar{q}q\bar{q}$	80%	80%	45%

needed for X-section and BR measurements:

eg.: $$\sigma_{WW} = \frac{N_{cand}^{WW\to q\bar{q}q\bar{q}}\cdot\pi}{\varepsilon}\cdot\frac{1}{\int\mathcal{L}dt}\cdot\frac{1}{B(WW\to q\bar{q}q\bar{q})}$$

$$B(W\to l\nu) = \frac{1}{N^W}\cdot\frac{N_{cand}^{W\to l\nu}\cdot\pi}{\varepsilon}$$

$W \to \ell\nu$ branching ratios



$(\chi^2/d.o.f = 4.96/2)$

$\Rightarrow$ universality of W-lepton coupling tested

[In principle lepton universality already tested in τ-lepton decays at very high accuracy.]

$W \to q\bar{q}'$ branching ratio

LEP II : $B(W \to q\bar{q}') = (67.92 \pm 0.27)\%$

SM 67.51%

depends on CKM matrix elements!

Of the involved CKM matrix elements

$$V_{ud},\ V_{cs},\ V_{us},\ V_{cd},\ \underbrace{V_{cb},\ V_{ub}}_{\text{negligibly small}}$$

V_{cs} is the least known

- indirect determination from hadr. branching ratio

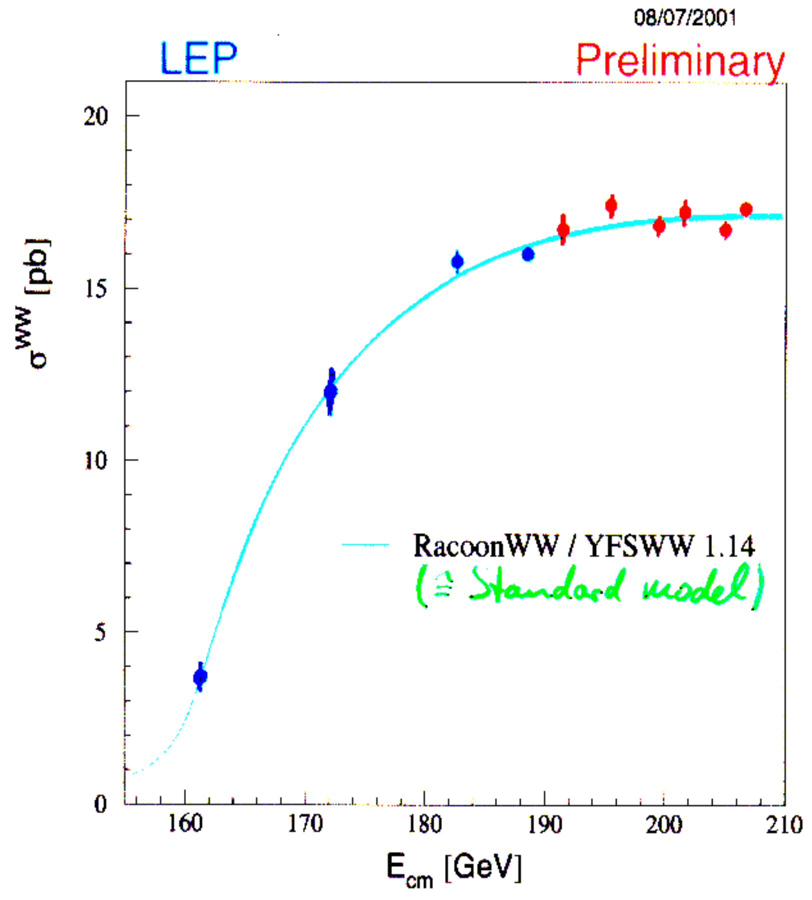
$$\frac{B(W \to q\bar{q}')}{3 \cdot B(W \to \ell\nu)} = \sum_{\substack{i=u,c \\ j=d,s,b}} |V_{ij}|^2 \cdot \underbrace{\left(1 + \frac{\alpha_s}{\pi}\right)}_{\text{QCD correction}}$$

$$\Rightarrow |V_{cs}| = 0.989 \pm 0.016$$

- direct measurement by identifying c quarks in W decays at $\sqrt{s} = 189$ GeV

	$\Gamma(W \to cX)/\Gamma(W \to \text{had})$	$\lvert V_{cs} \rvert$
LEP	0.49 ± 0.05	0.97 ± 0.06

W pair production cross-section



- Standard model in agreement with measurements

small < 1% theoretical uncertainty on standard model prediction

- Cross-section depends on W mass ($\sigma \sim \sqrt{1-\frac{4m_W^2}{s}}$ @ threshold)

Highest sensitivity on m_W at threshold of pair prod.; optimal sensitivity at $\sqrt{s} \approx 2 \cdot m_W + 0.5\,\text{GeV} \simeq 161\,\text{GeV}$ (compromise between statistical uncertainty $\underset{\sqrt{s}}{\searrow}$ and systematic errors $\underset{\sqrt{s}}{\nearrow}$)

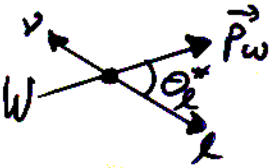
$\Rightarrow$ from σ_{WW}(threshold): $m_W = 80.40 \pm 0.21\,\text{GeV}$

W boson mass from lepton spectrum

endpoints of lepton momentum spectrum depend on m_W

$$E_\ell = \frac{\sqrt{s}}{4} + \cos\theta_\ell^* \underbrace{\sqrt{\frac{s}{16} - \frac{m_W^2}{4}}} = \frac{\sqrt{s}}{4} \cdot \beta$$

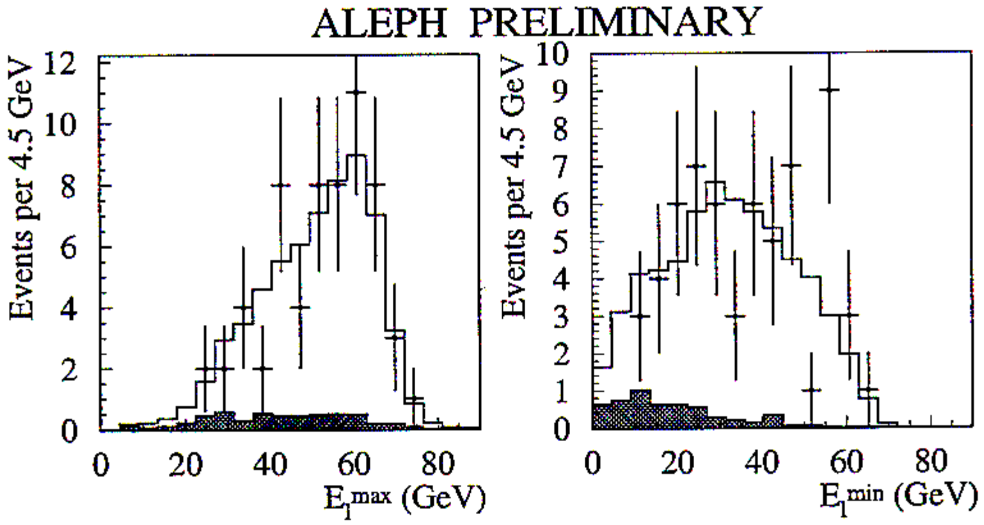
where $\cos\theta_\ell^*$ = lepton angle in W rest frame



endpoint of spectrum at $\cos\theta_\ell^* = \pm 1$

eg. for $m_W = 80.5$ GeV at $\sqrt{s} = 189$ GeV

$\Rightarrow$ $E_{\ell,max} = 72.0$ GeV, $E_{\ell,min} = 22.5$ GeV



need to consider finite W width

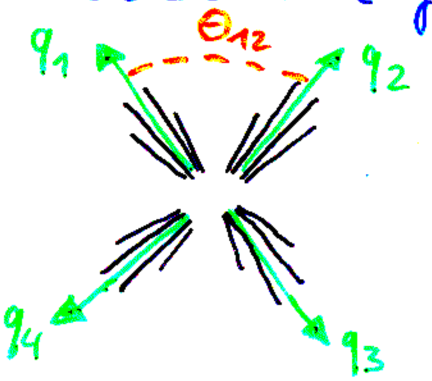
→ m_W from fit of lepton momentum spectrum

principle disadvantage: small $WW \to \ell\nu\ell\nu$ branching ratio

→ small statistics

W mass from direct reconstruction

Reconstruction of W decay products → m_W determination



$$\Rightarrow m_{12} = \sqrt{2E_1E_2\left(1-\cos\Theta_{12}\right)}$$

dito m_{34}

Problem: detector resolution typ. 5-10%

⇒ exploit advantageous properties of e^+e^- annihilation

initial state : $(\vec{p}, E) = (\vec{0}, \sqrt{s})$

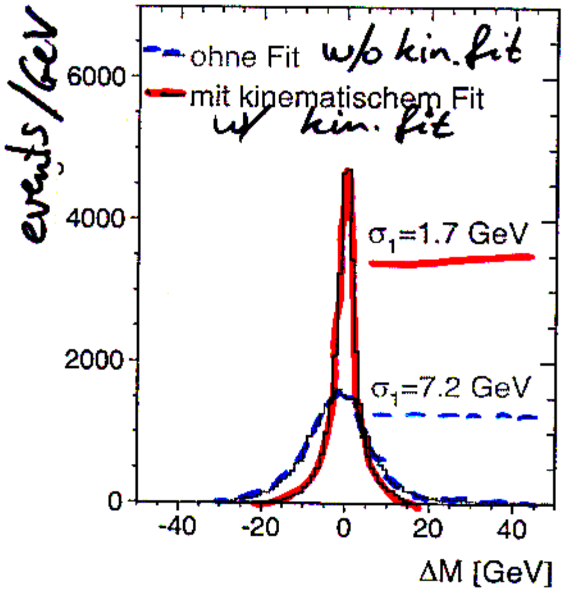
and event fully contained in detector

⇒ energy & momentum conservation

⇒ kinematic fits: (using Lagrange multipliers)

- input values: measured energies and angles of leptons and jets
- constraints: (4C) 4-momentum conservation
  $\Sigma(\vec{p}, E) = (\vec{0}, \sqrt{s})$
  $\Rightarrow 2$ fitted masses m_1^{rec}, m_2^{rec}

  (5C) as (4C) plus $m_1^{rec} = m_2^{rec}$
  $\Rightarrow 1$ fitted mass m^{rec}



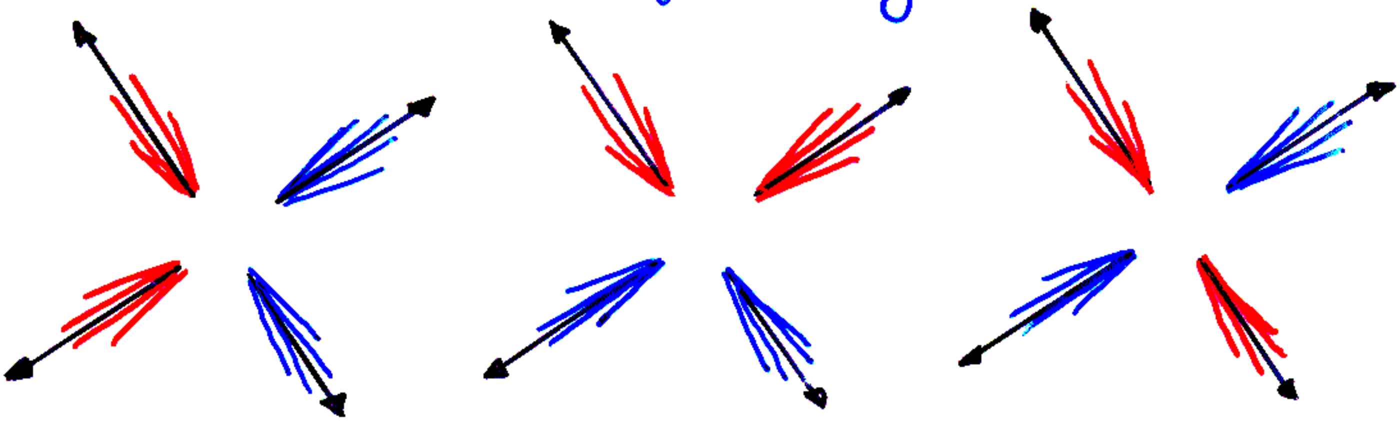
If ν involved:

$\vec{p}_\nu = -\Sigma\vec{p}$ ⇒ 3 constraints less

in the case of τ leptons

E_τ undetermined ⇒ 1 constraint less

The problem of jet pairing in $WW \to q\bar{q}q\bar{q}$



In 4-jet final states there are 3 combinations for (m_1^{rec}, m_2^{rec}) (5 jets ⇝ 10 combinations)

Only one combination has m_W information

Several approaches to find this combination

- fit probability of 5C fit

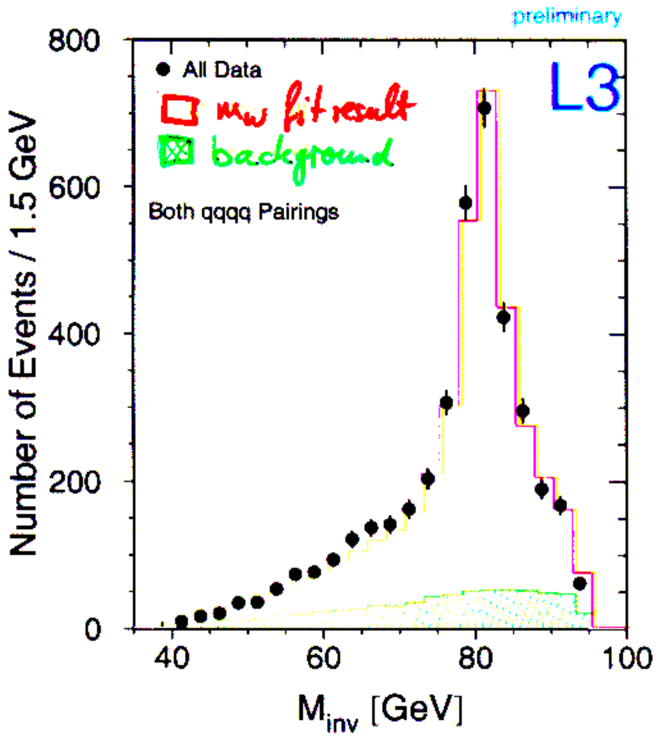
  $\mathcal{P}_1 > \mathcal{P}_2 > \mathcal{P}_3$, $\mathcal{P}_1$ in 65% of the cases correct comb.
  $\mathcal{P}_2$ in ≈ 25%
  additional combinatorics if $\mathcal{P}_1$ and $\mathcal{P}_2$ chose

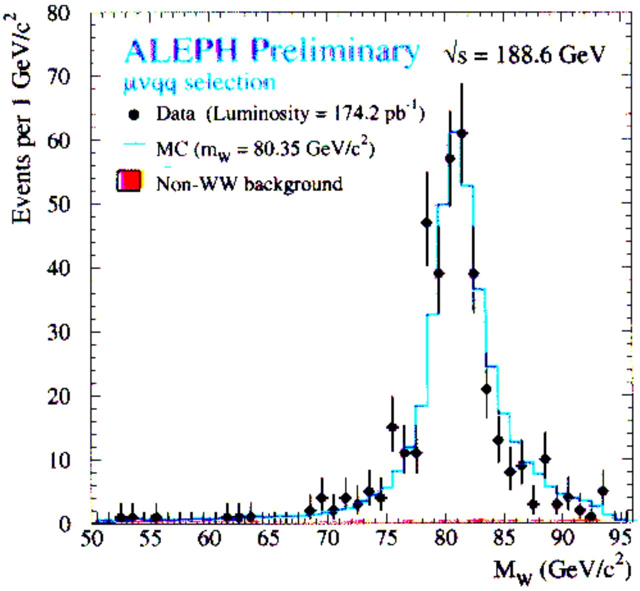
- use 4C fit result $\Delta m^{rec} = m_1^{rec} - m_2^{rec}$

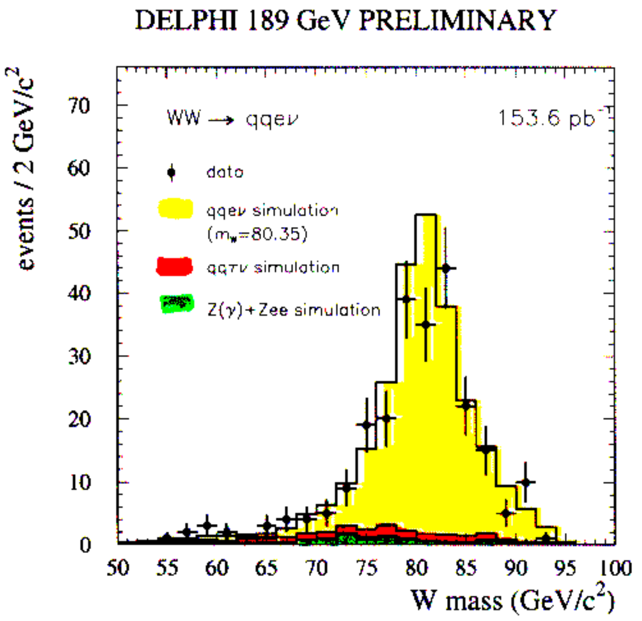
  and sum of jet-jet angle

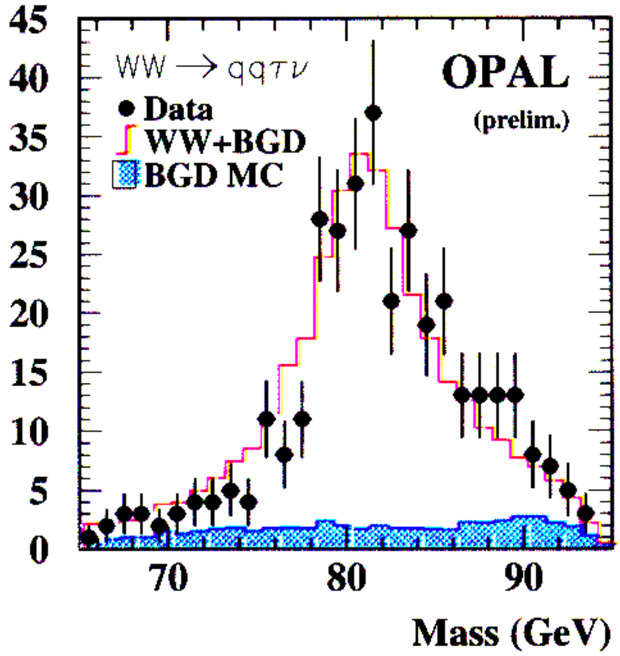
  If one combination per event chosen then it is in about 85% of the cases the correct one
  but: background distribution distorted, ≈ peaked @ m_W

W mass distributions









m_W determination:

- analytic: Breit-Wigner $BW(m_{rec}) \sim \frac{m_{rec}^2}{(m_{rec}^2 - m_W^2)^2 + (m_{rec}^4 \Gamma_W^2/m_W^2}$

  + background (eg. polynomial in m_{rec})
- comparison of data and reweighted MC-distributions
- convolution techniques, eg. $\int BW(m_{rec}) \otimes$ resolution + background

m_W from comparing data & reweighted MC

- begin with: measured mass spectrum $\frac{d\sigma}{dm}$
- generate MC simulated data sets for various m_W
- reweighting of MC data sets gives $\frac{d\sigma}{dm}$ also for inbetween m_W values

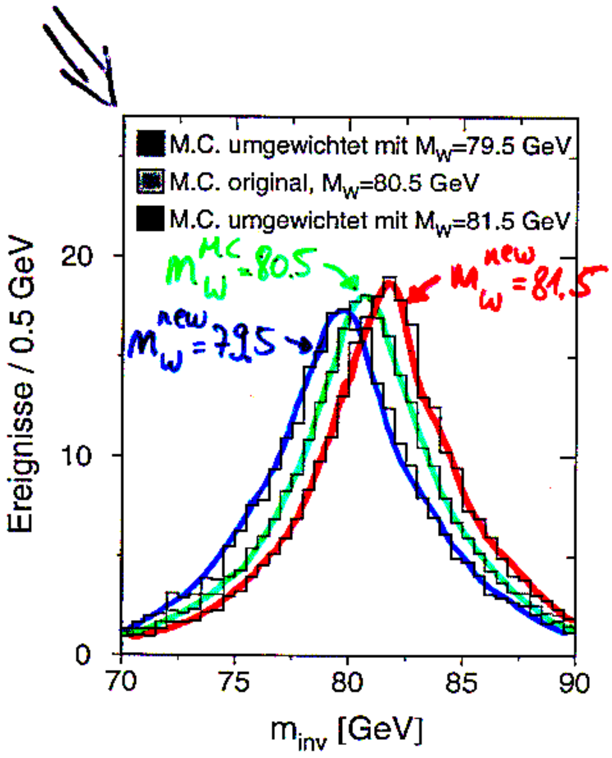
⇒ per MC event a weighting factor:

$$w_i = \frac{\sigma_{Born}(m_1, m_2, s) \cdot BW(m_W^{new}, \Gamma_W^{new}, m_1) \cdot BW(m_W^{new}, \Gamma_W^{new}, m_2)}{\sigma_{Born}(m_1, m_2, s) \cdot BW(m_W^{MC}, \Gamma_W^{MC}, m_1) \cdot BW(m_W^{MC}, \Gamma_W^{MC}, m_2)}$$

or alternatively a ratio of matrix elements

$$w_i = \frac{|\mathcal{M}(m_W^{new})|^2}{|\mathcal{M}(m_W^{MC})|^2}$$

where m_W^{new} is the new mass value the MC distribution is reweighted to



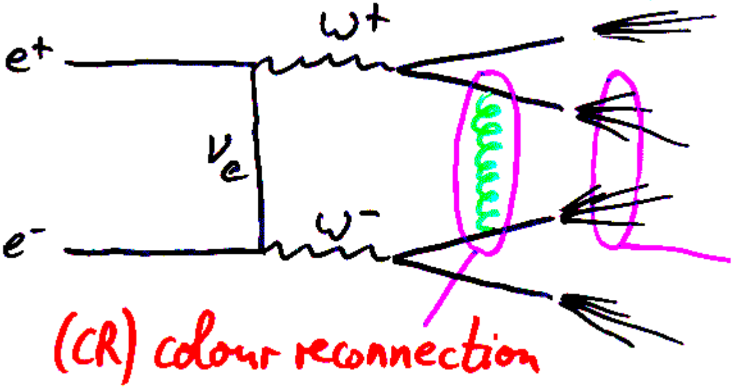
fit of reweighted $\frac{d\sigma}{dm}(m_{rec})$ to data

m_W (and Γ_W)

Interactions in the $qq\bar{q}q$ final state

- Decays of the two W's are not independent:

  decay length $\tau = \frac{1}{\Gamma_W} \approx 0.1\,\mathrm{fm} \ll$ hadronization $\approx 1\,\mathrm{fm}$



- MC models usually consider independent W decays

- CR causes energy & momentum exchange between quarks (and gluons) of different W's

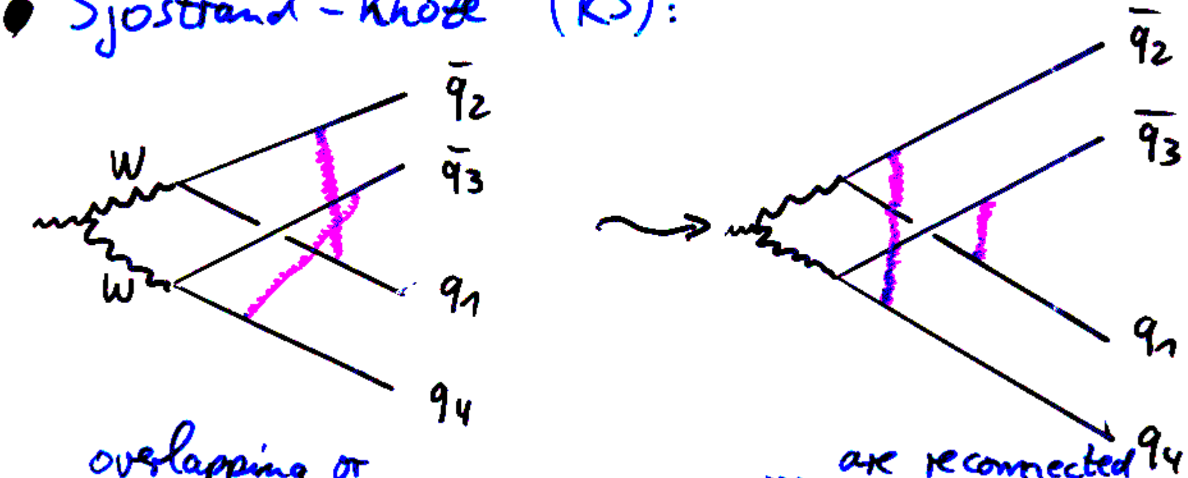
- BEC concerns charged and neutral mesons and affects their energy and momentum

$\Rightarrow$ CR and BEC act on jet energies and might bias m_W measurements

Colour reconnection

Three main philosophies (very simplified):

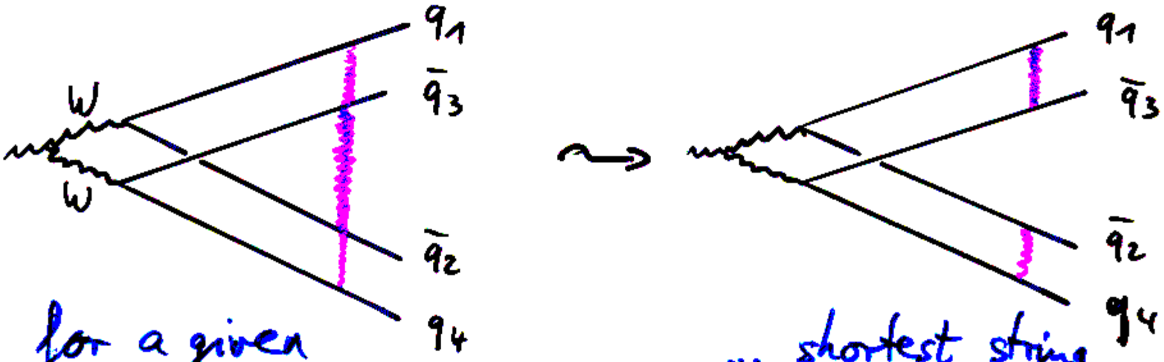
- Sjöstrand-Khoze (KS):



overlapping or crossing colour strings ...

... are reconnected with given probability

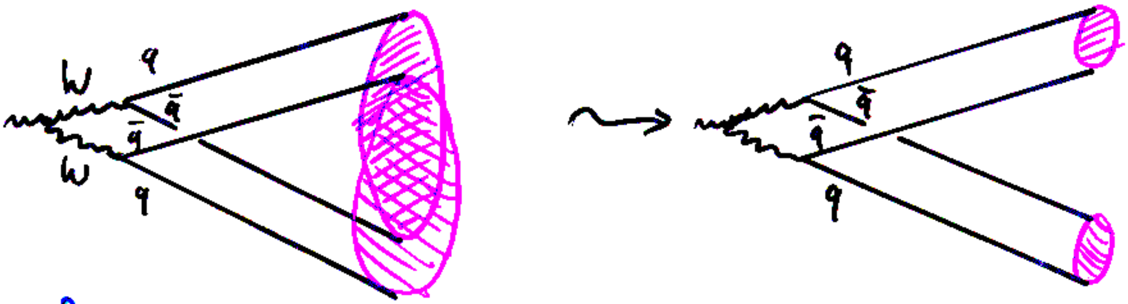
- Ariadne (AR):



for a given colour configuration ...

... shortest string lengths are chosen (string tension ~ 1 GeV/fm)

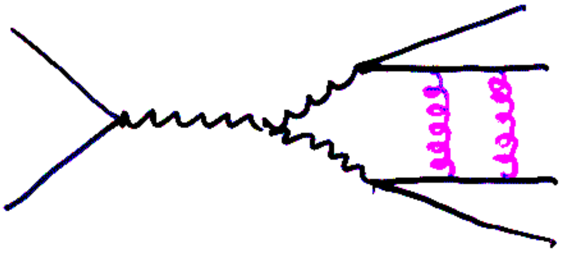
- Herwig (HR):



for a given cluster configuration ...

... a new configuration with reduced cluster size might be chosen

colour reconnection



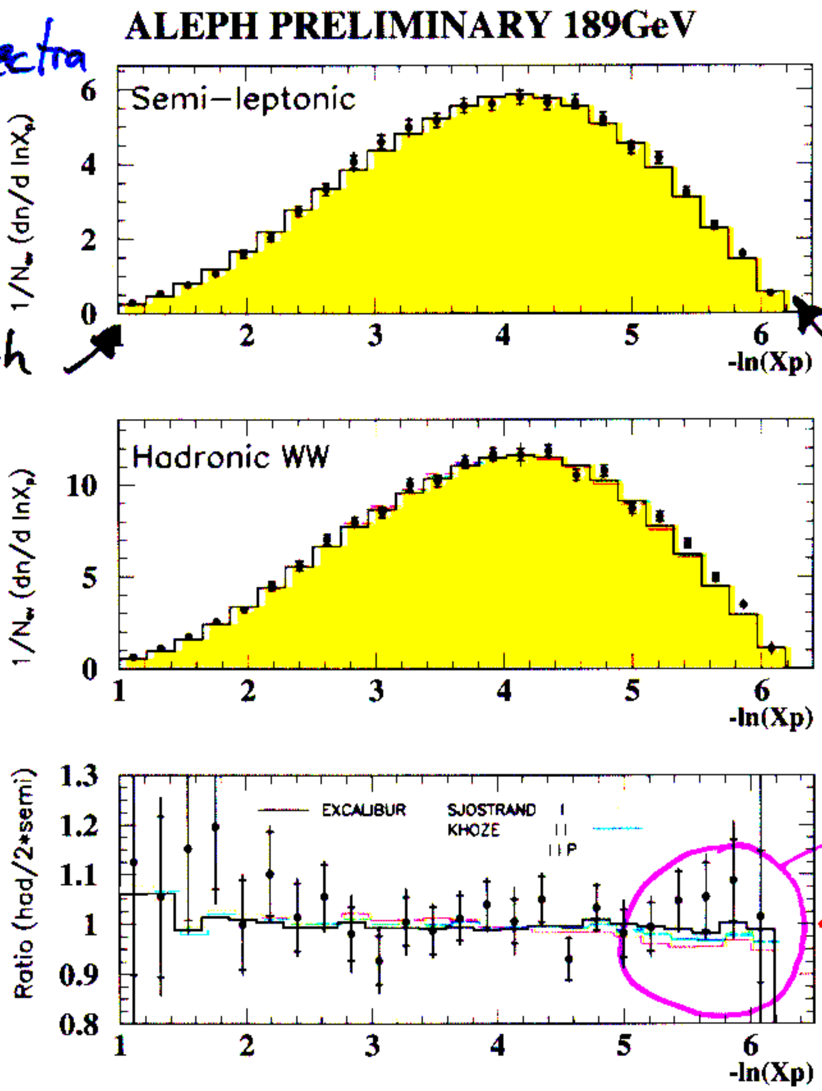
← effect on number of low-momentum hadrons

momentum spectra

$WW \to q\bar{q}\ell\nu$

$WW \to q\bar{q}q\bar{q}$

ratio



high

low momenta $(-\ln x_p = +\ln\frac{s}{2p})$

no reduction

quantitatively : $\Delta\langle n_{ch}\rangle = \langle n_{ch}^{q\bar{q}q\bar{q}}\rangle - 2\cdot\langle n_{ch}^{q\bar{q}\ell\nu}\rangle$

LEP : $\Delta\langle n_{ch}\rangle = +0.30 \pm 0.52$

models: $\Delta\langle n_{ch}\rangle = -0.2 \ldots -0.3$

⇒ no evidence for CR

Bose-Einstein correlations

Hadronization regions of both W's overlap

⇒ effects due to coherence between identical bosons from different W's are possible

In the case of Bose-Einstein correlations: identical bosons are created closer together in phase space

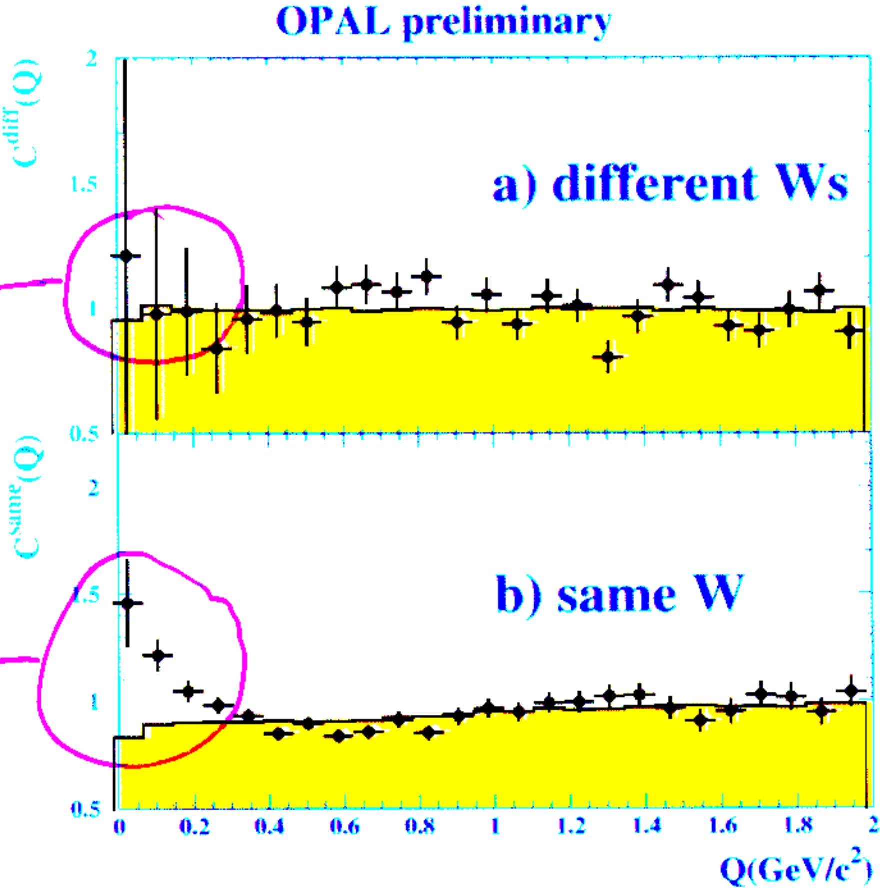
⇒ 4-momentum difference $Q^2 = -(p_1 - p_2)^2 \simeq 0$

correlation described by two-particle correlation fct.:

$$\frac{C_{BE}(Q^2)}{C_{noBE}(Q^2)} = 1 + \underset{\uparrow}{\lambda} \cdot \exp(-Q^2 \cdot \underset{\uparrow}{R}^2)$$

correlation strength
($\lambda = 0$ → no BEC)

size of source



particles from different W's

no correlation

... same W

correlation

LEP: $\lambda^{diff.W} =$

-0.15 ± 0.21

⇓

no evidence for BEC between different W's

final state interaction (FSI) in $q\bar{q}q\bar{q}$

- effects from CR and BEC on m_W determination

model	effect	Δm_W [MeV]
SK I	CR	$+10 \pm 25$
SK II	CR	-25 ± 25
SK II'	CR	-20 ± 25
HW	CR	-30 ± 25
AR2	CR	$+50 \pm 15$
Pythia	BEC	~20..50
KoralW	BEC	~20..50

⇒ uncertainty on m_W from $q\bar{q}q\bar{q}$ due to FSI $\simeq 50$ MeV

- investigate effect from data directly:

compare:

LEP II

$m_W(q\bar{q}q\bar{q}) = 80.457 \pm 0.062$ GeV (FSI: 47 MeV, LEP: 17 MeV)

$m_W(q\bar{q}\ell\nu) = 80.448 \pm 0.043$ GeV (LEP: 17 MeV)

$\Rightarrow \quad \Delta(m_W) = 0.009 \pm 0.044$ GeV (w/o FSI & LEP)

⇒ effect insignificant

W mass : Summary

direct determinations:

LEP II

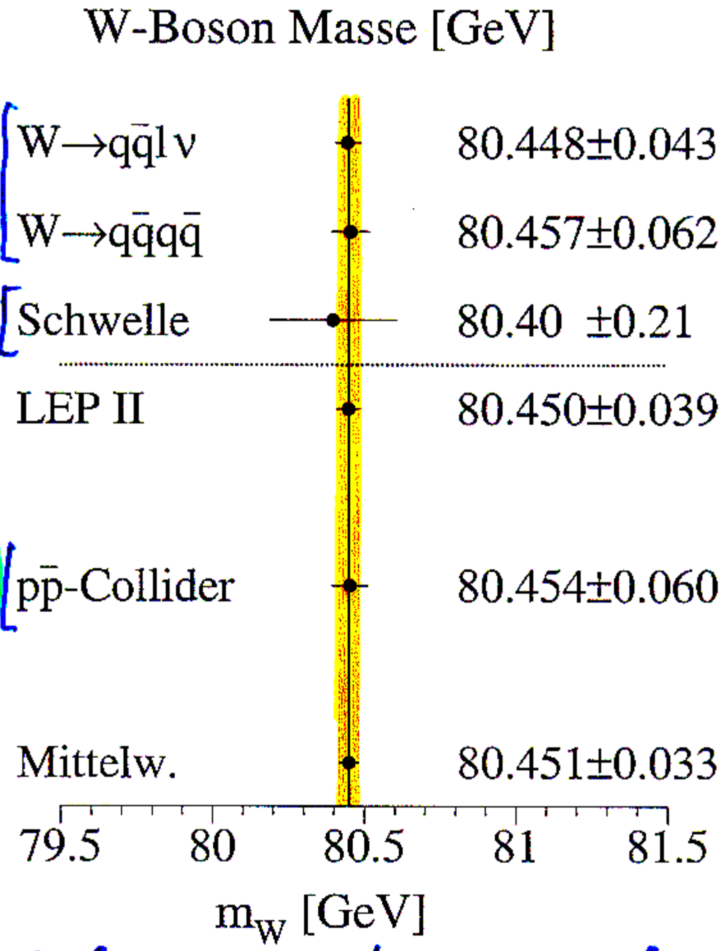
data 172...206 GeV

threshold: 161 GeV

from transv. mass

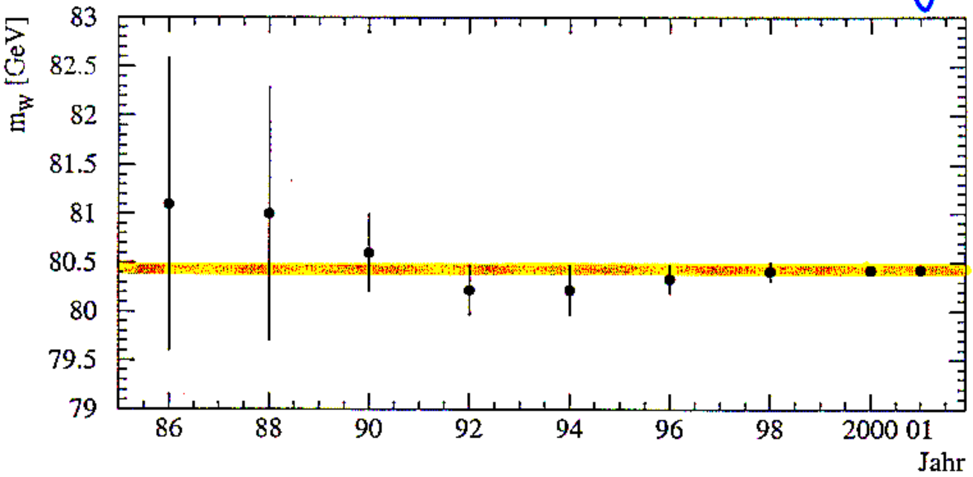
$m_T^2 = 2E_T^e E_T^\nu (1-\cos\vartheta_{e\nu})$

in $W\to e\nu$



total error about 30 MeV!

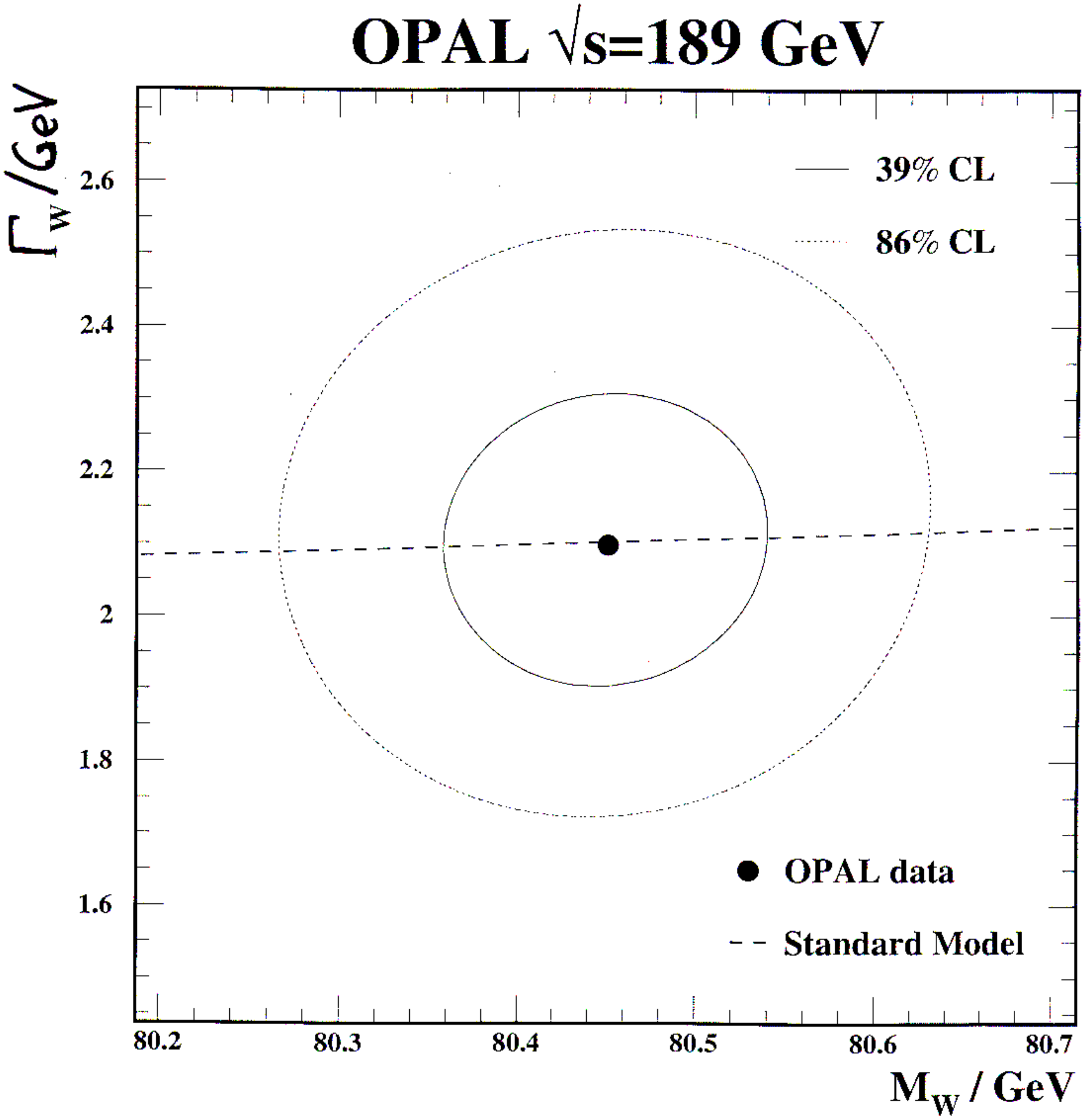
historical development of knowledge of m_W



meanwhile m_W known at level of ≈ ±400 ppm

W width : Γ_W

from simultaneous fit of m_W and Γ_W to mass distributions

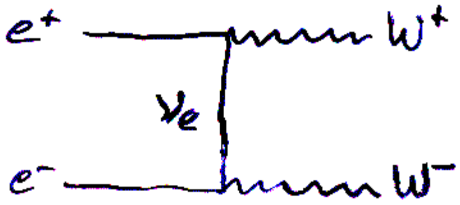


LEP II : $\Gamma_W = 2.15 \pm 0.09$ GeV
(172 - 202 GeV)

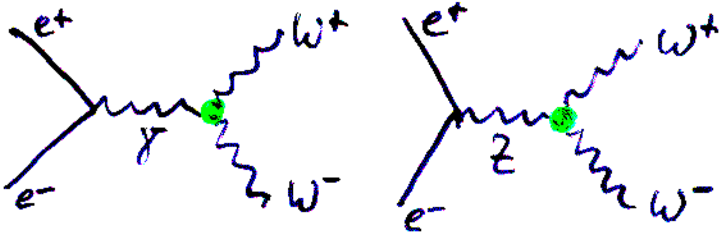
SM : $\Gamma_W = 2.09$ GeV

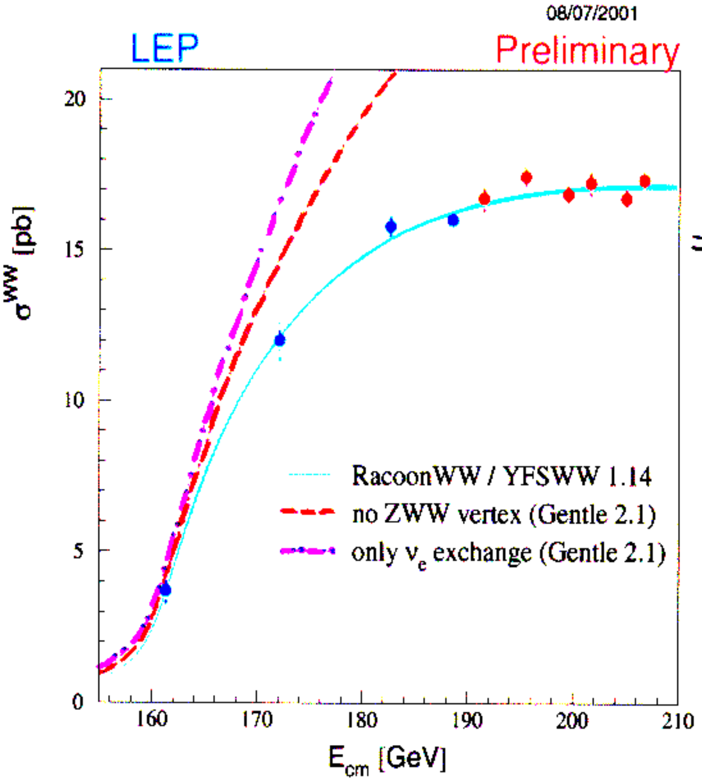
Triple gauge boson coupling

Standard model:



non-abelian gauge theory





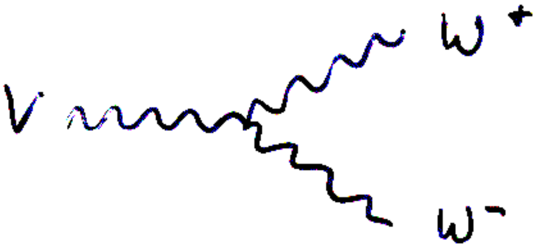
⇒ indirect evidence for ZWW coupling

note: theories without ZWW or with ν_e-exchange only violate unitarity since cross-section diverges with increasing $\sqrt{s}$

► test of the non-abelian structure in ZWW and γWW coupling

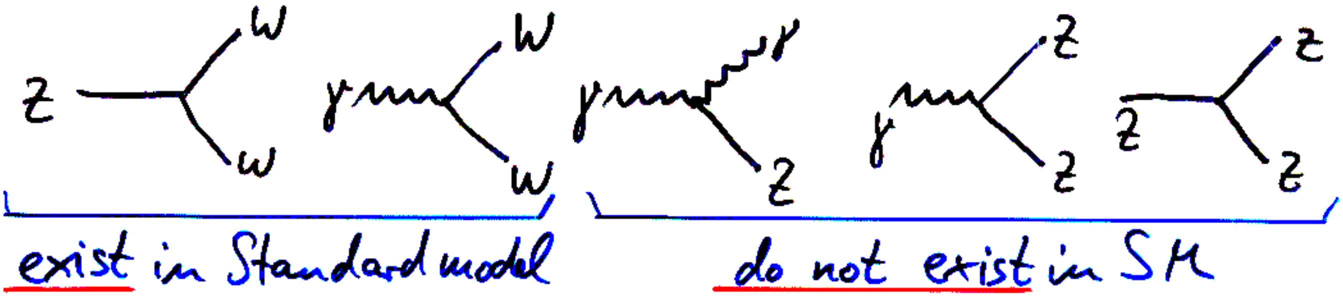
VWW couplings

The most general form of the VWW coupling, where $V = \gamma, Z$, contains 7 form factors to describe



7 are sufficient because 2 of the 9 possible W^+W^- spin combinations have a total $J \neq 1$ for the boson $V = \gamma, Z$.

This structure can be generalised to further triple gauge boson vertices:



⇓

- 2×7 coupling factors needed for complete description
- too many to be measured simultaneously

⇒ assume : C, P, CP invariance and el. charge of $W = \pm 1e$

⇒ 5 parameters : $\Delta g_1^Z, \Delta \kappa_\gamma, \Delta \kappa_Z, \lambda_\gamma, \lambda_Z$ (all $\overset{SM}{=} 0$)

Meaning of the (remaing) couplings

- Consider electromagnetic static properties of W:

E1 W charge $Q_W = e \cdot (1 + \Delta g_1^\gamma)$

M2 magn. dipolemoment $\mu_W = \frac{e}{2m_W}(2 + \Delta\kappa_\gamma + \Delta g_1^\gamma + \lambda_\gamma$

E4 electr. quadrupolemom. $q_W = -\frac{e}{m_W^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma)$

free parameters:
$$\left.\begin{array}{ccc} \underline{\Delta g_1^Z} & \longleftrightarrow & \Delta g_1^\gamma \\ \underline{\Delta \kappa_Z} & \longleftrightarrow & \Delta \kappa_\gamma \\ \underline{\lambda_Z} & \longleftrightarrow & \lambda_\gamma \end{array}\right\} \overset{SM}{=} 0$$

Replacement $\gamma \to Z$ in electromagn. moments

⟶ "weak moments"

Recall: anomalous magn. dipole moment of proton

⟶ (quark-) substructure of proton

- Further reduction of parameter by requiring SU(2) × U(1) gauge invariance:

$$\Delta\kappa_Z = \underline{\Delta g_1^Z} - \underline{\Delta\kappa_\gamma} \cdot \tan^2\Theta_W$$

$$\lambda_Z = \lambda_\gamma = \underline{\lambda}$$

$\Rightarrow$ 3 free parameters

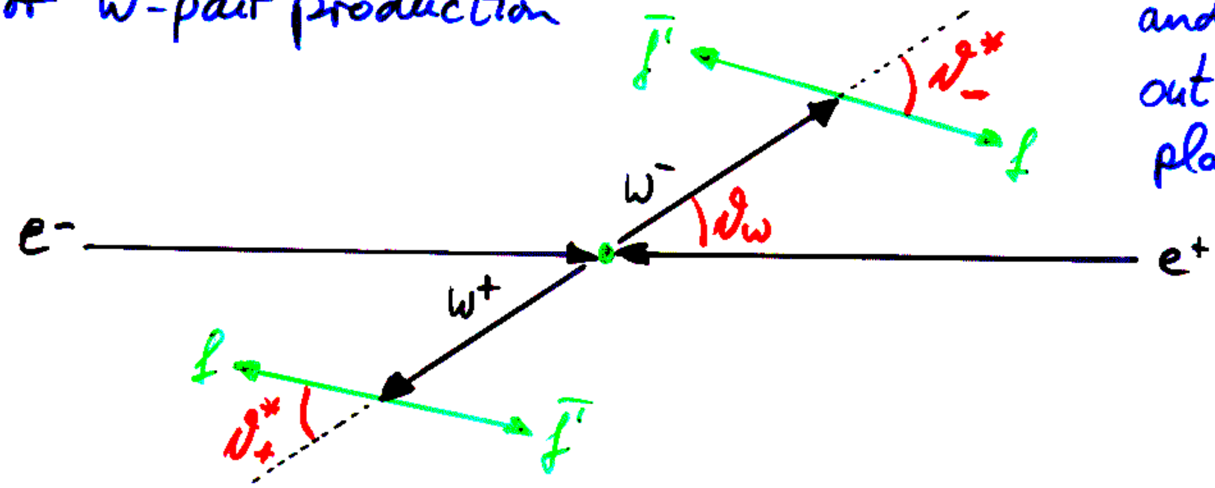
Observables for anomalous couplings

... for all $W \to f\bar{f}'$ channel

- cross-sections: quadratic dependence on coupling params.

... and in particular

- for W-pair production

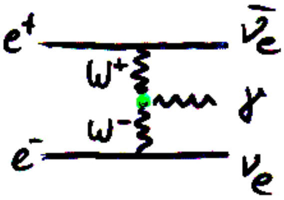


and $\phi^*_\pm$ out of plane

- ▷ polar angle ϑ_W of W^-
- ▷ polar and azimuthal angles of leptons in W rest frame $(\vartheta^*_\pm, \varphi^*_\pm)$
  → measure W polarization

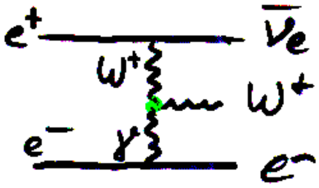
5 angles

- for single-γ production
  - ▷ energy spectrum and polar angle



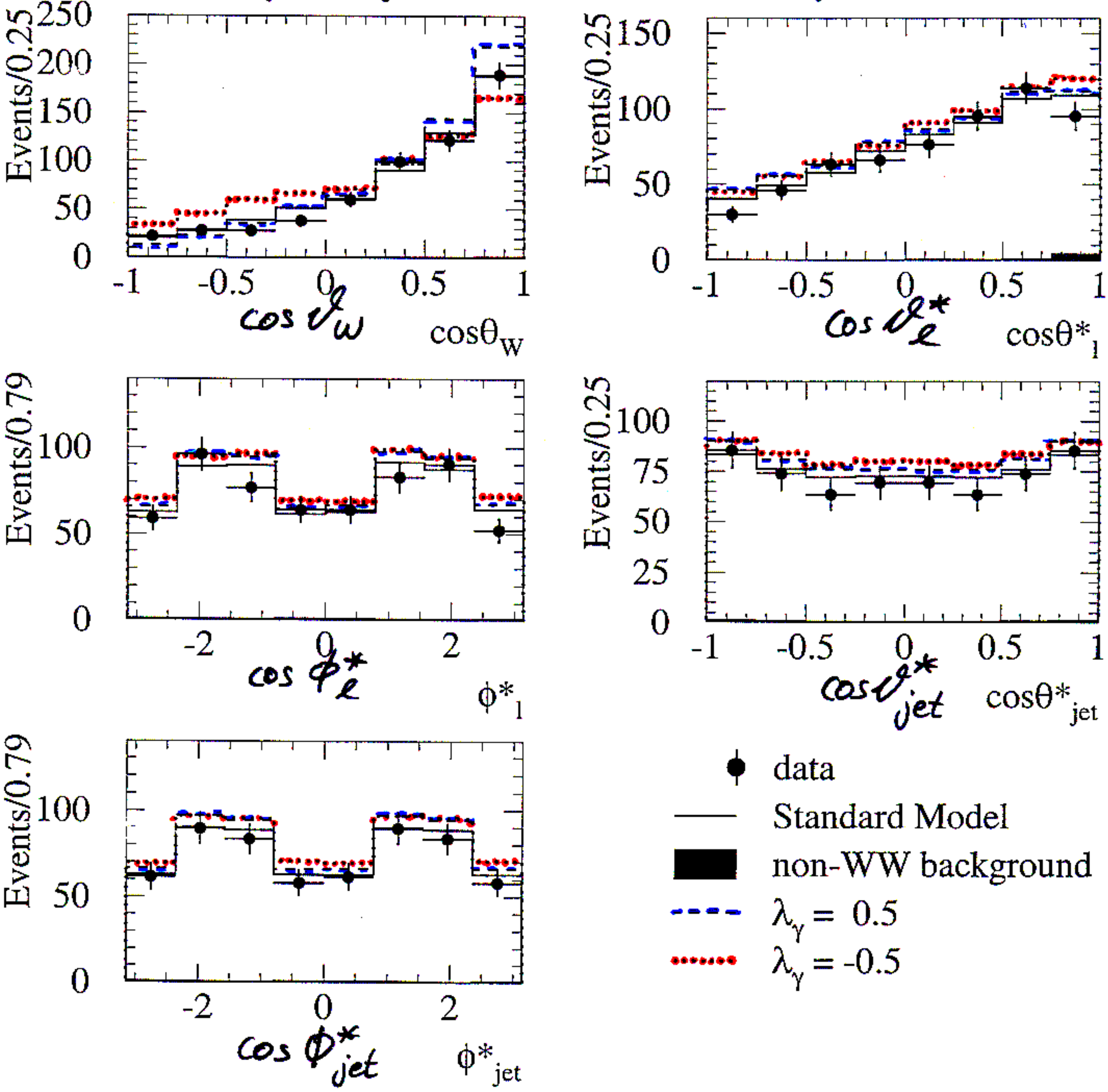
WW fusion

- for single-W production
  - ▷ lepton energy spectrum in $W \to \ell\nu$



Triple gauge coupling (TGC) in $W^+W^- \to q\bar{q}\ell\nu$

- all angles measurable in $W \to \ell\nu$ part
  W charge given by lepton charge
- hadronic side ($W \to q\bar{q}$) has ambiguity since quark q and its charge cannot be determined
  $$(\cos\vartheta^*_{jet}, \phi^*_{jet}) \leftrightarrow (-\cos\vartheta^*_{jet}, \phi^*_{jet} + \pi)$$



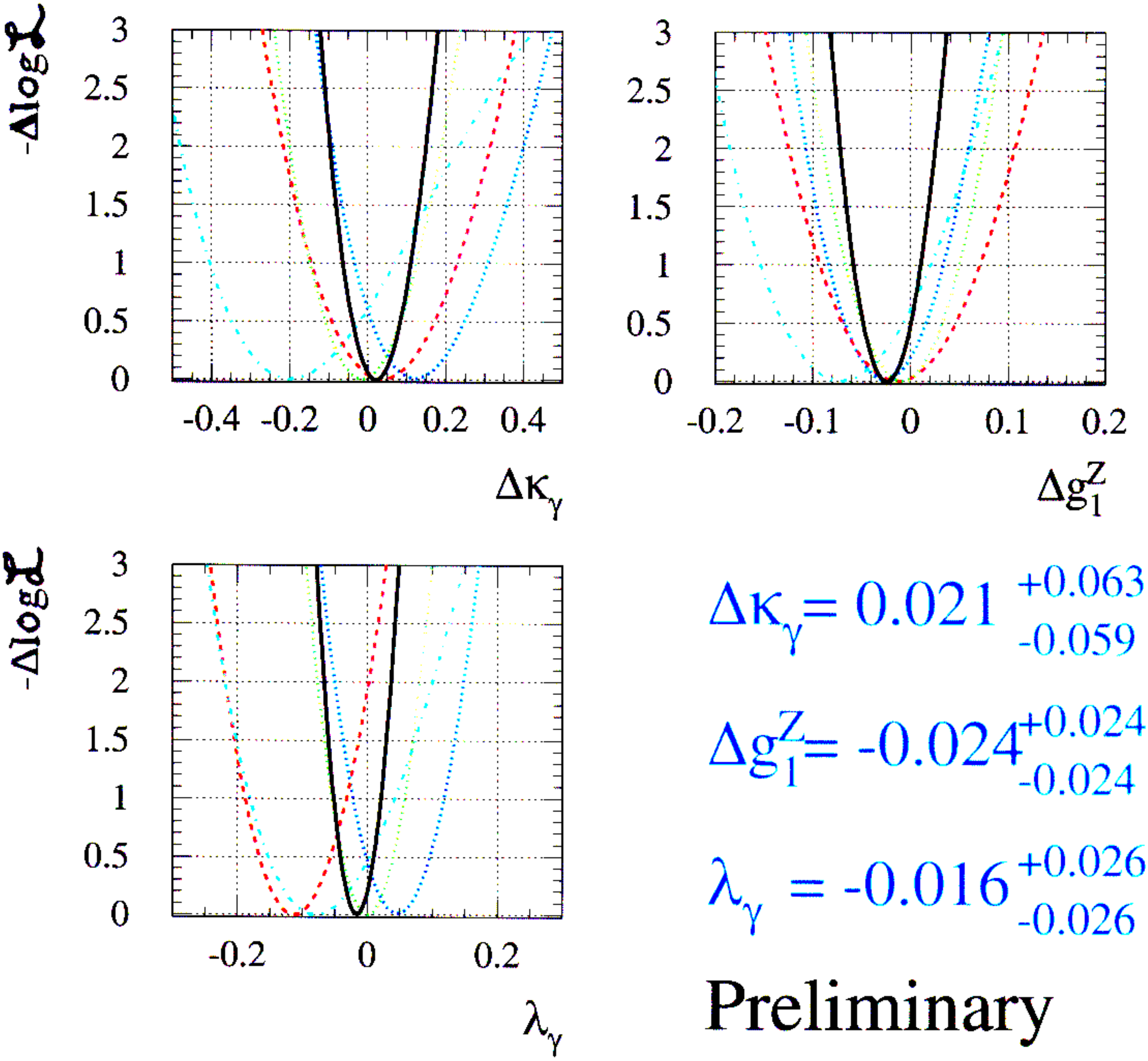
⇒ $WW \to q\bar{q}\ell\nu$ provides most information about final state

- $WW \to q\bar{q}q\bar{q}$: only $\cos\vartheta_W$ measurable
- $WW \to \ell\nu\ell\nu$: $\cos\vartheta_W$, ϑ^*_+, and ϑ^*_- accessible but ambiguities

anomalous couplings

- 1 dimensional fit : two anomalous couplings = SM, fit third o
  - ▷ combination of LEP results in principle by adding log-likelihood curves since statistical uncertainties dominate and correlated systematic errors are small

ALEPH + DELPHI + L3 + OPAL



$$\Delta\kappa_\gamma = 0.021 \,^{+0.063}_{-0.059}$$

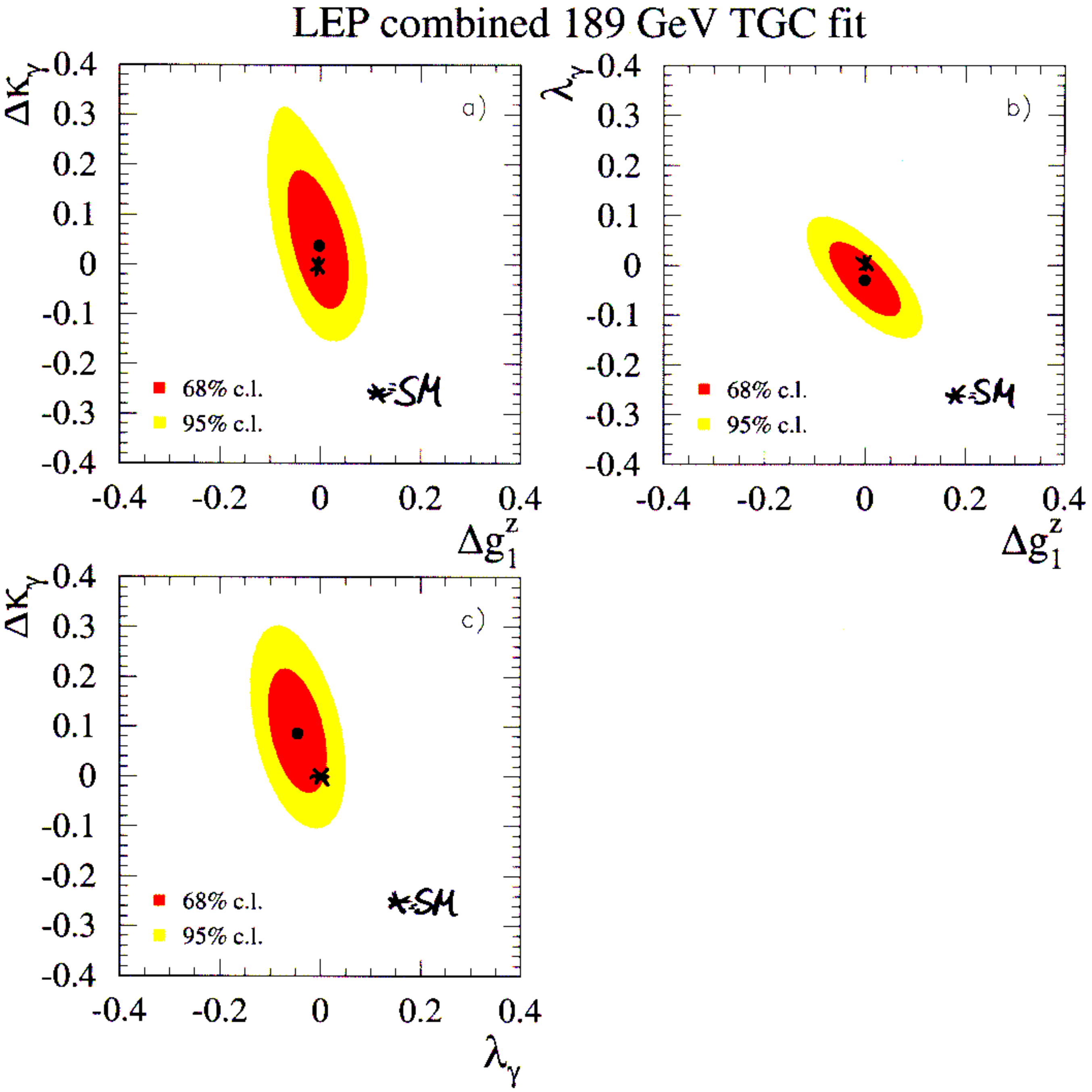
$$\Delta g_1^Z = -0.024 \,^{+0.024}_{-0.024}$$

$$\lambda_\gamma = -0.016 \,^{+0.026}_{-0.026}$$

Preliminary

anomalous couplings

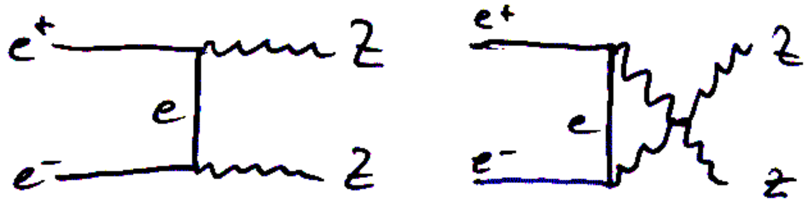
2 dimensional fit: one anomalous coupling = SM, fit others



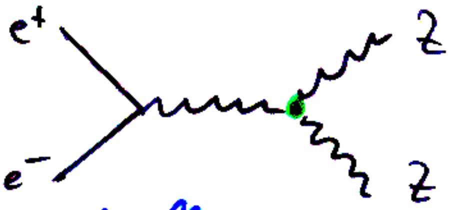
⇒ no evidence for anomalous ZWW/γWW coupling!

ZZ production

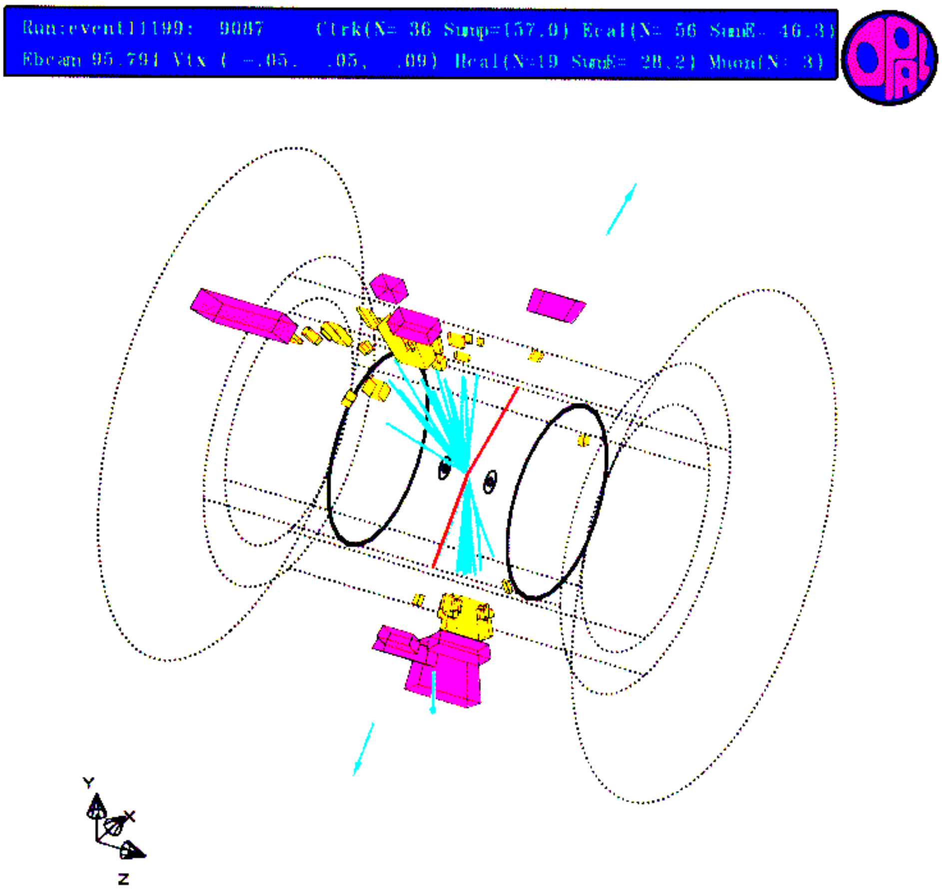
at $\sqrt{s}$ above $2 \cdot m_Z$ Z-pair production starts to contrib.



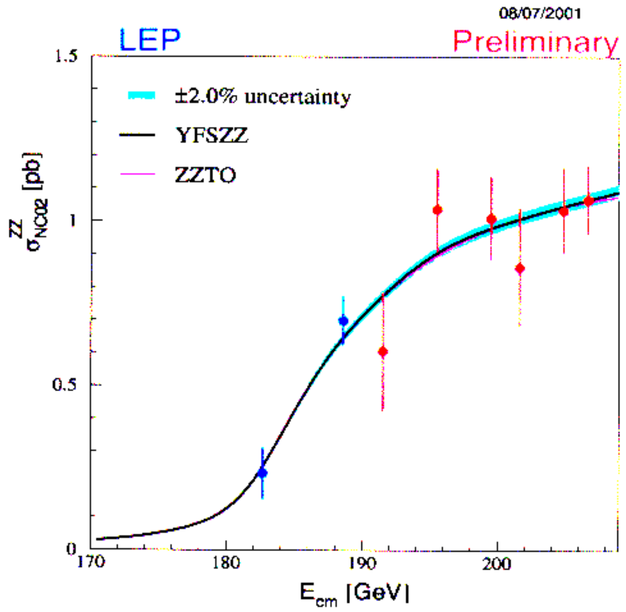
NC02 graphs



not allowed in SM
(→ anomalous coupling)



$$e^+e^- \to ZZ \quad \begin{array}{l} \to \mu^+\mu^- \\ \to q\bar{q} \end{array}$$



- production cross-section in agreement with Standard model
- no evidence for anomalous coupling

Standard model in Σ

Bulletin of the Standard model

- status: all results in good agreement with SM

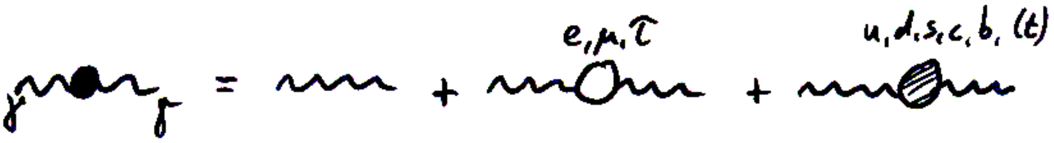
- $\propto$ consitency of directly and indirectly measured m_W

  ▷ indirectly from G_F relation

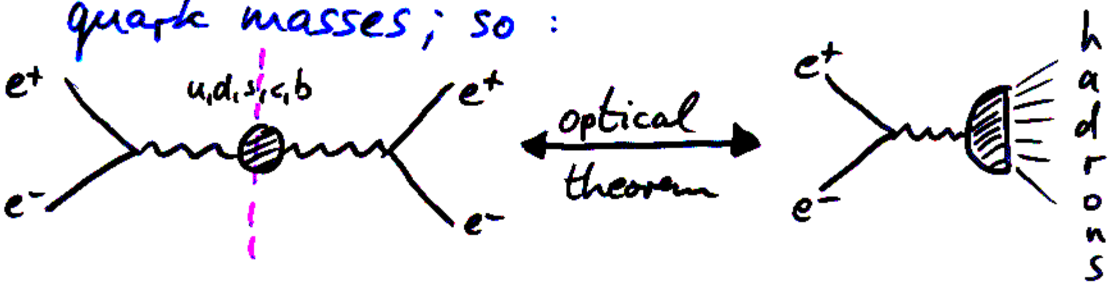
$$m_W^2 = \underbrace{\frac{\pi \alpha_{em}}{\sqrt{2}\, G_F \sin^2\theta_W}}_{\text{Born term}} \cdot \underbrace{\frac{1}{1-\Delta r}}_{\text{loop corrections}} \quad \text{where} \quad \sin^2\theta_W = 1-\frac{m_W^2}{m_Z^2}$$

  ▷ loop corrections

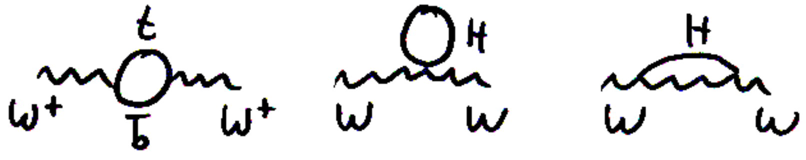
  □ QED :



hadronic contribution depends on barely known quark masses; so :



  □ electroweak :



significant contributions due to top-quark mass and Higgs-boson mass

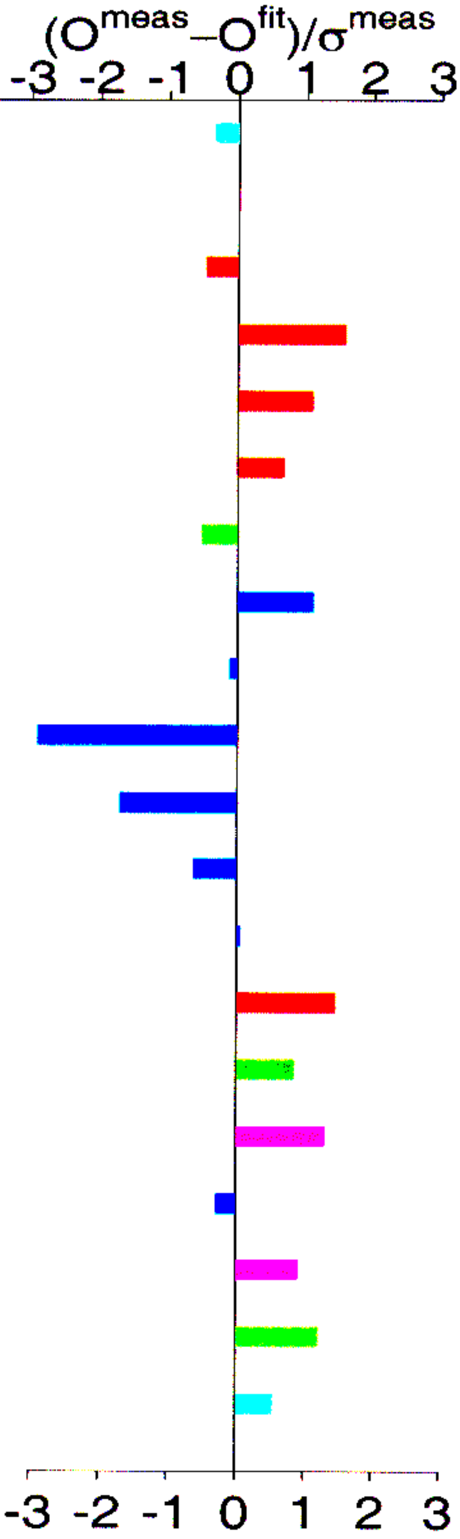
⟹ Comparison: $m_W^{\text{direct}} \leftrightarrow m_W^{\text{indirect}}$ tests loop corrections

and : provides information on Higgs mass

results of Standard model fit

Summer 2001

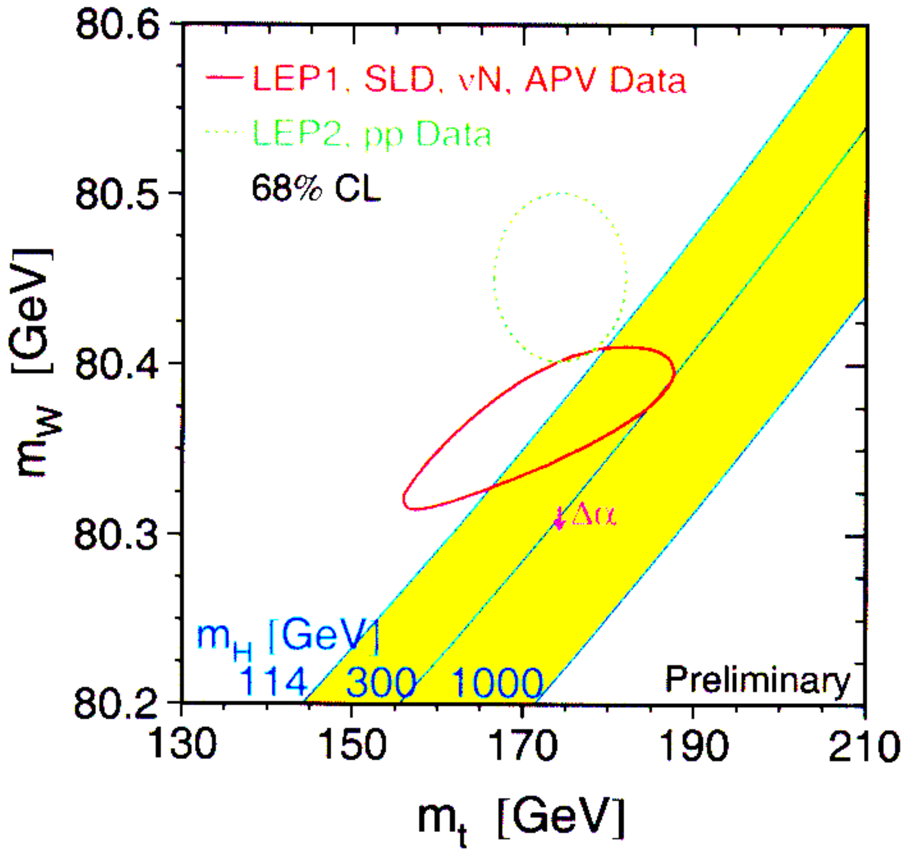
	Measurement	Pull
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	-.35
m_Z [GeV]	91.1875 ± 0.0021	.03
Γ_Z [GeV]	2.4952 ± 0.0023	-.48
σ^0_{had} [nb]	41.540 ± 0.037	1.60
R_l	20.767 ± 0.025	1.11
$A^{0,l}_{fb}$	0.01714 ± 0.00095	.69
$A_l(P_\tau)$	0.1465 ± 0.0033	-.54
R_b	0.21646 ± 0.00065	1.12
R_c	0.1719 ± 0.0031	-.12
$A^{0,b}_{fb}$	0.0990 ± 0.0017	-2.90
$A^{0,c}_{fb}$	0.0685 ± 0.0034	-1.71
A_b	0.922 ± 0.020	-.64
A_c	0.670 ± 0.026	.06
A_l(SLD)	0.1513 ± 0.0021	1.47
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	.86
$m_W^{(LEP)}$ [GeV]	80.450 ± 0.039	1.32
m_t [GeV]	174.3 ± 5.1	-.30
$m_W^{(TEV)}$ [GeV]	80.454 ± 0.060	.93
$\sin^2\theta_W(\nu N)$	0.2255 ± 0.0021	1.22
$Q_W(Cs)$	-72.50 ± 0.70	.56



comparison: indirect ↔ direct m_W, m_{top}

▷ $m_W^{indirect}$ from G_F relation of Standard model

▷ $m_{top}^{indirect}$ from radiative corrections

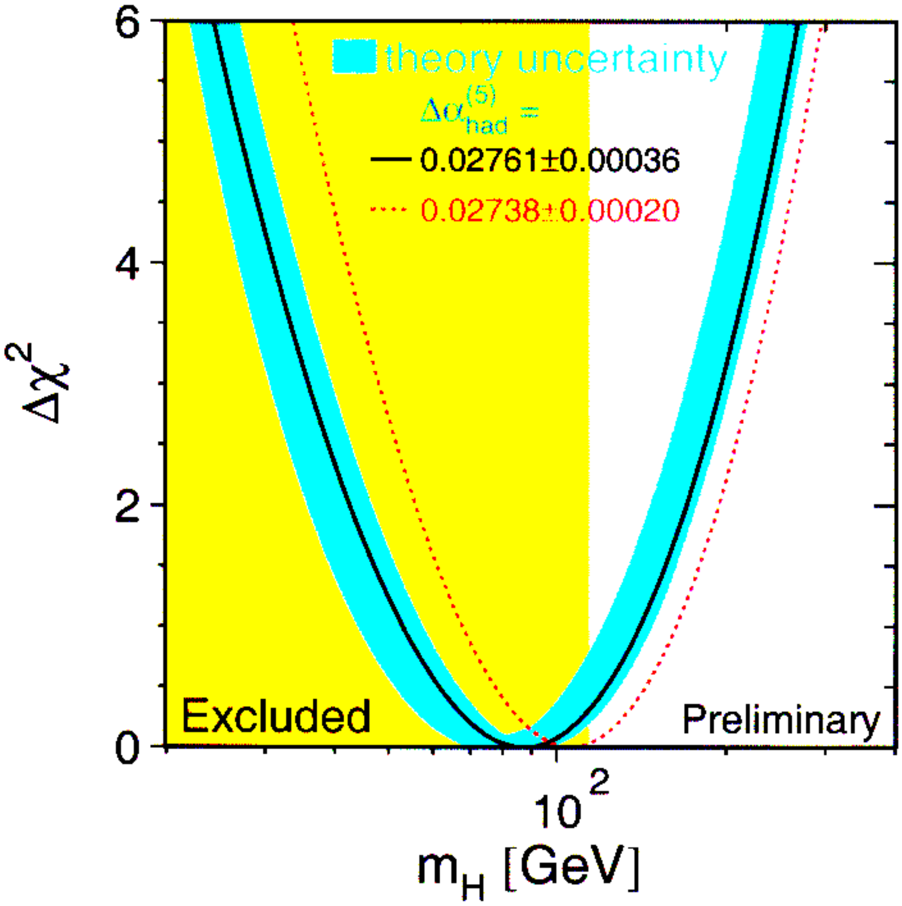


⇒ ≈ consistency!

	indirect	direct
m_W	80.363 ± 0.032 GeV	80.451 ± 0.033 GeV
m_{top}	169.0 ± 10.0 GeV	174.3 ± 5.1 GeV

Higgs-boson mass from indirect + direct m_W, m_{top} measurements

in particular m_W and $\sin^2\Theta_W$ depend on m_H



- fit yields (i.e. full Standard model + all electroweak measurements

$$m_H = 88 \begin{smallmatrix} +53 \\ -35 \end{smallmatrix}\ \text{GeV}$$

⇒ $m_H < 196$ GeV at 95% confidence level

($\Delta\alpha^{(5)}_{had} = 0.02738 \rightarrow m_H < 222$ GeV@95%CL)

- direct Higgs search:

$m_H > 114.1$ GeV at 95% confidence level

⇒ If Standard model OKAY then Higgs must be light!
... has LEP seen it already ... ?

Higgs boson

Higgs boson in the Standard model

$W^\pm$ and Z-gauge bosons get massive by the "Higgs mechanism" (Higgs; Weinberg & Salam 1960-67)

i.e. spontaneous breaking of $U(1) \times SU(2)$ symmetry due to a new scalar background field (Higgs) which is non-zero in its ground state and which fills the whole cosmos at all times with a vacuum field $v = \text{const} \neq 0$

Spontaneous sym. breaking (SSB): fundamental laws (Lagrange densities, field eq.) are symmetric, their special solution are not symmetric

The Higgs field couples to leptons, quarks, and the gauge fields $\vec{W}_\mu, B_\mu$. Leptons and quarks acquire their mass due to their potential energy in the vacuum Higgs field, eg. for the electron

$$f_e \frac{v}{\sqrt{2}} \bar{\Psi}_e \Psi_e = m_e \bar{\Psi}_e \Psi_e \Rightarrow m_e = f_e \frac{v}{\sqrt{2}}$$

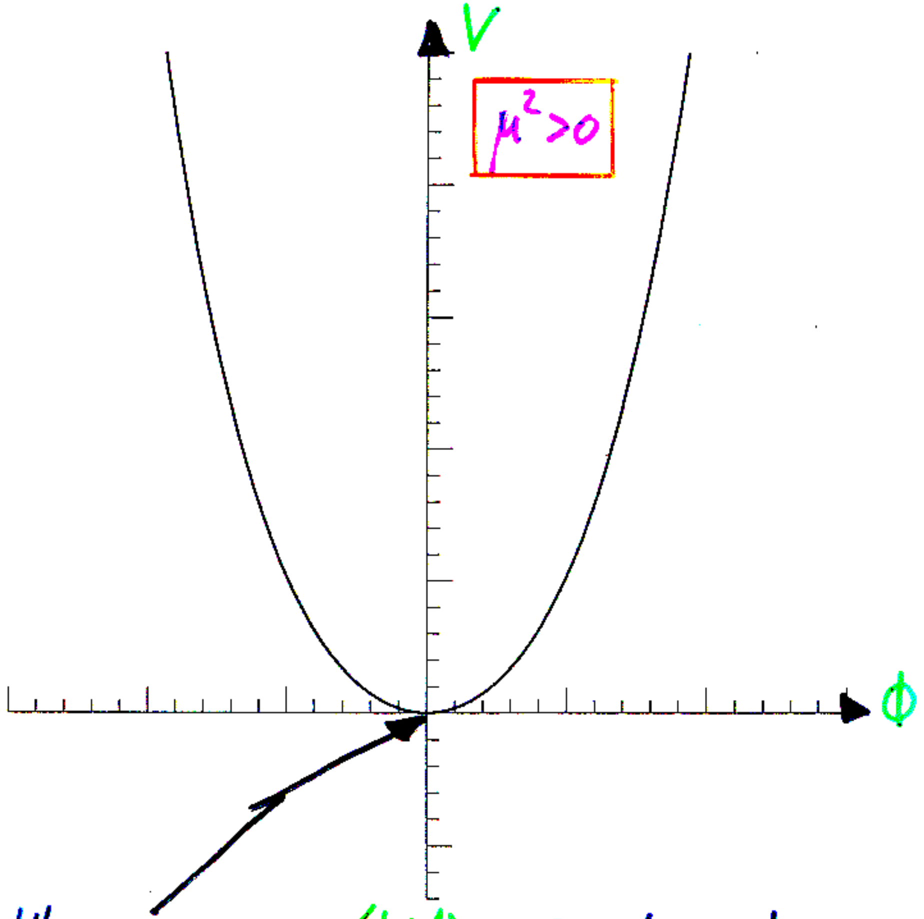
The Yukawa coupling f_e and the vac. expectation value v cannot be calculated.

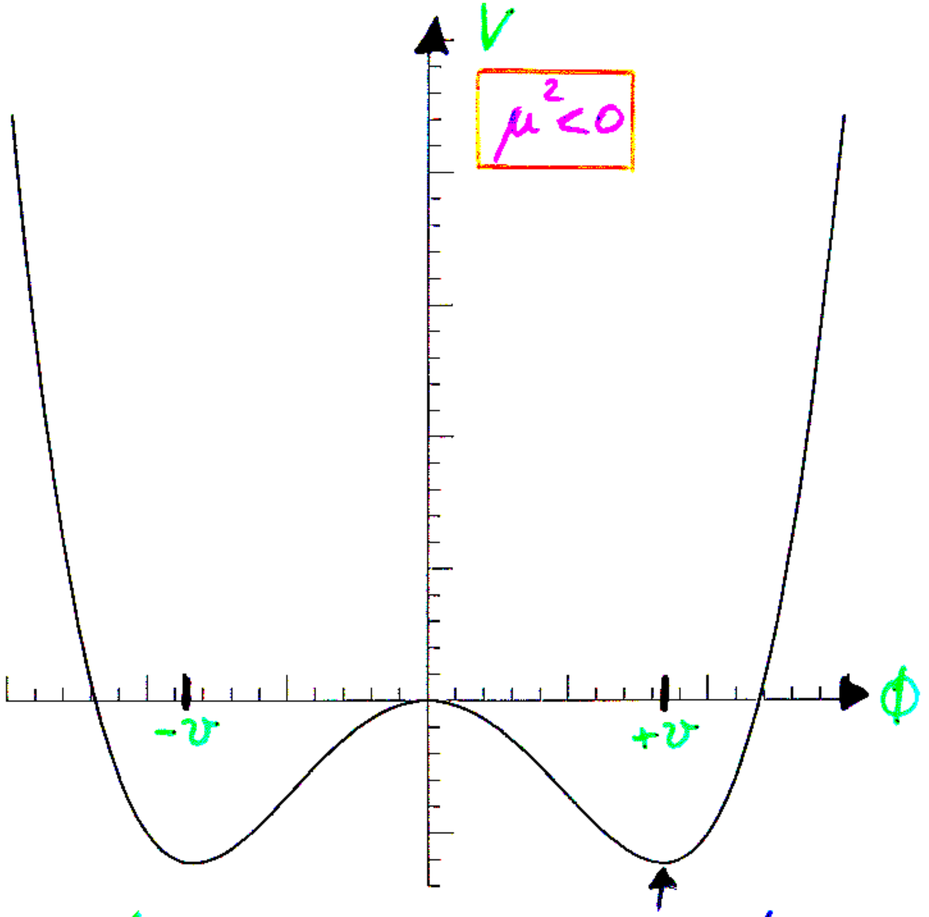
The gauge boson masses are determined by the coupling constants g_W and g_Z:

$$m_W = g_W \cdot \frac{v}{2} \quad ; \quad m_Z = g_Z \cdot \frac{v}{2}$$

Spontaneous symmetry breaking

- Lagrangian of background field: $\mathcal{L} = T - V = \frac{1}{2}(\partial_\mu \phi)^2 - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda^2\phi^4\right)$





at the minimum: $\langle|\phi|\rangle = 0$, $\phi \mapsto -\phi$ symmetry

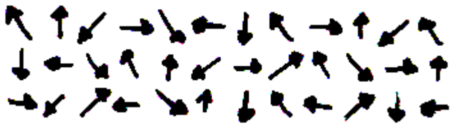
$\langle|\phi|\rangle = \pm v$, no symmetry

- analogy: e.g. ferromagnetism above/below Curie temperature

Spontaneous symmetry breaking

- example: ferromagnetism

$\boxed{T > T_{curie}}$



$\langle B \text{ field} \rangle = 0$

rotational symmetry

$\boxed{T < T_{curie}}$

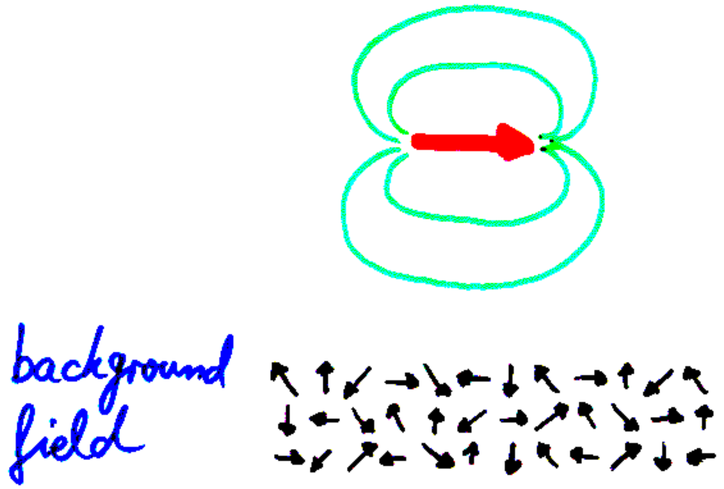
$\langle B \text{ field} \rangle \neq 0$

no rotational symmetry

Spontaneous symmetry breaking

- example: ferromagnetism

$T > T_{curie}$



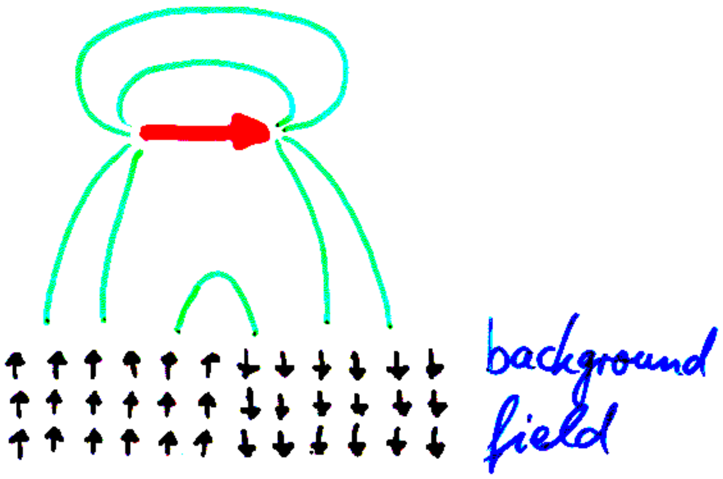
$\langle B \text{ field} \rangle = 0$

rotational symmetry

no interaction
with background field

→ pot. energy = 0

$T < T_{curie}$



$\langle B \text{ field} \rangle \neq 0$

no rotational symmetry

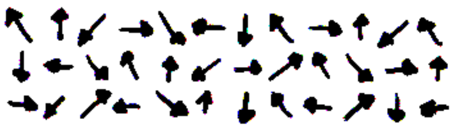
interaction
with background field

→ pot. energy ≠ 0

Spontaneous symmetry breaking

- example: ferromagnetism

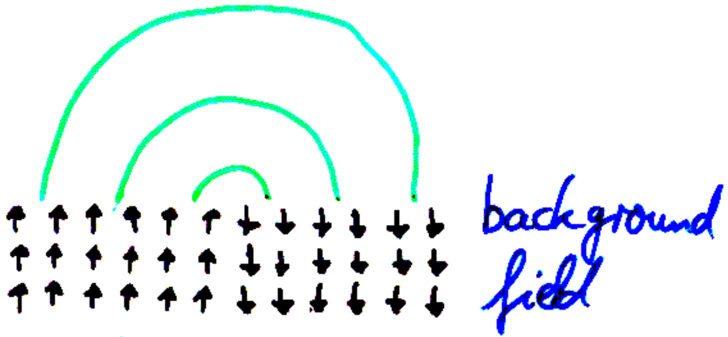
$\boxed{T > T_{\text{curie}}}$



$\langle B \text{ field} \rangle = 0$

rotational symmetry

$\boxed{T < T_{\text{curie}}}$



$\langle B \text{ field} \rangle \neq 0$

no rotational symmetry

self interaction of background field

→ pot. energy $\neq 0$

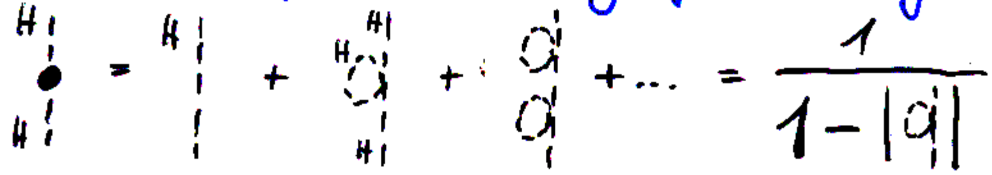
theoretical mass limits on the Higgs boson

Higgs mass : $m_H = v \cdot \sqrt{2\lambda}$

where the quartic coupling λ is a free parameter

- upper limit on m_H from running of coupling λ

consider:

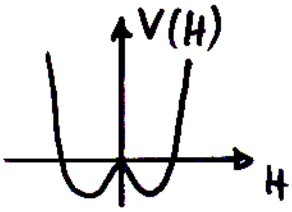


$$\Rightarrow \quad \lambda(\mu^2) = \frac{\lambda(v^2)}{1 - \frac{3}{4\pi^2}\lambda(v^2)\ln(2\mu^2/v^2)}$$

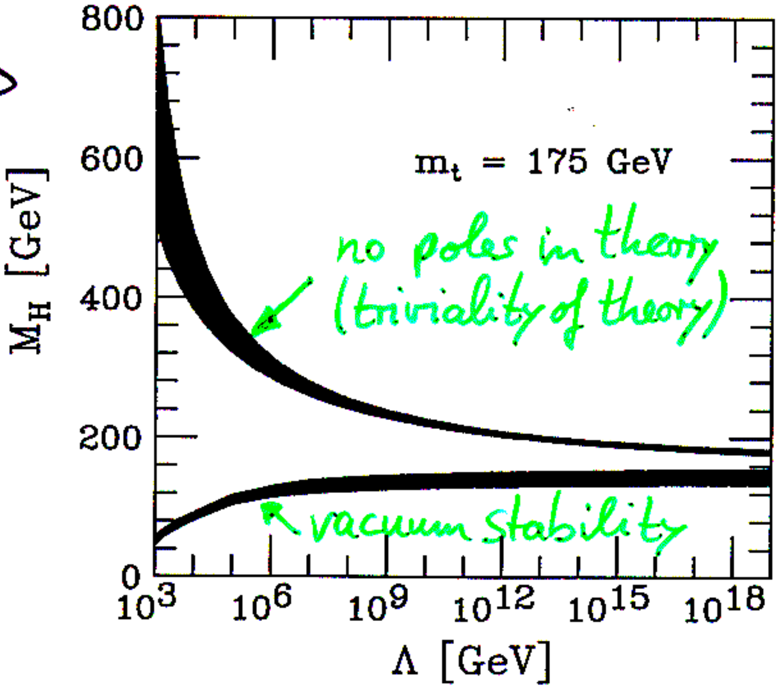
has a Landau pole at $\mu \equiv \Lambda = \frac{v}{\sqrt{2}} \exp\left(\frac{4\pi^2}{3\lambda}\right)$
(analogous to the Landau pole in QED & QCD)

$\Rightarrow \quad m_H < \Lambda$

- lower limit from vacuum stability
ie. there is no other minimum in the Higgs potential lying lower than the electroweak minimum



$\Rightarrow$

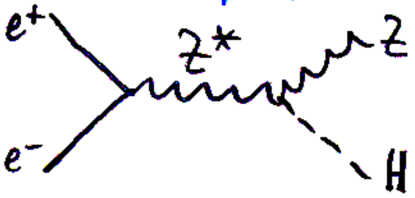


$\Rightarrow$ if $m_H \simeq 160 \dots 180$ GeV
the Standard model
could be valid up to
the scale of gravity,
$\Lambda_{Planck} \simeq 10^{19}$ GeV.

Higgs production in e^+e^- annihilation

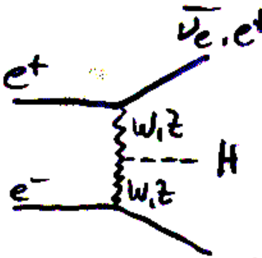
Standard model Higgs:

- dominantly produced at LEP by Higgs-strahlung

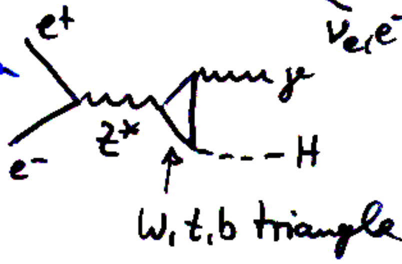


kinematical limit at $m_H \simeq \sqrt{s} - m_Z$

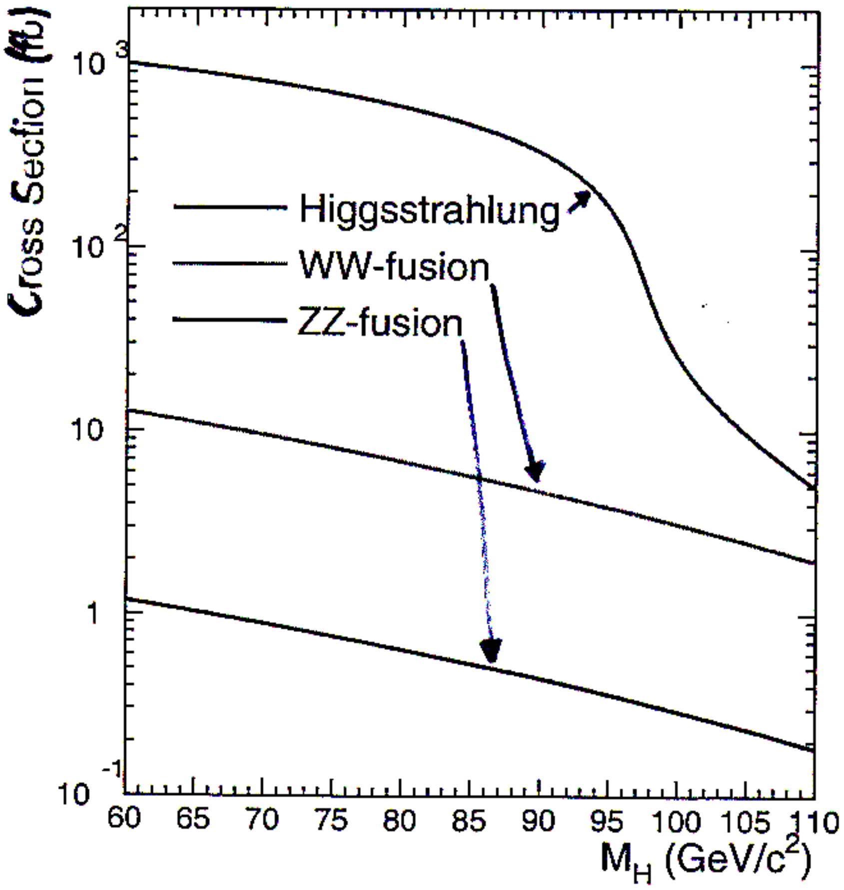
- smaller contributions from WW and ZZ fusion
no kinemat. limit



- small contributions from $H\gamma$ production



$\Rightarrow$ eg. $m_H = 95\,\text{GeV}$ @ $\sqrt{s} = 200\,\text{GeV}$



Properties of the Higgs boson

- SM Higgs: partial decay width

$$\Gamma(H\to f\bar{f}) = \frac{G_F}{4\pi\sqrt{2}}\cdot m_f^2(m_H)\cdot m_H\cdot \underset{\uparrow}{N_c}\cdot(1+\delta_{QCD})$$

colour factor = 1 (leptons), 3 (quarks

$m_f(m_H)$ is fermion mass at m_H energy scale

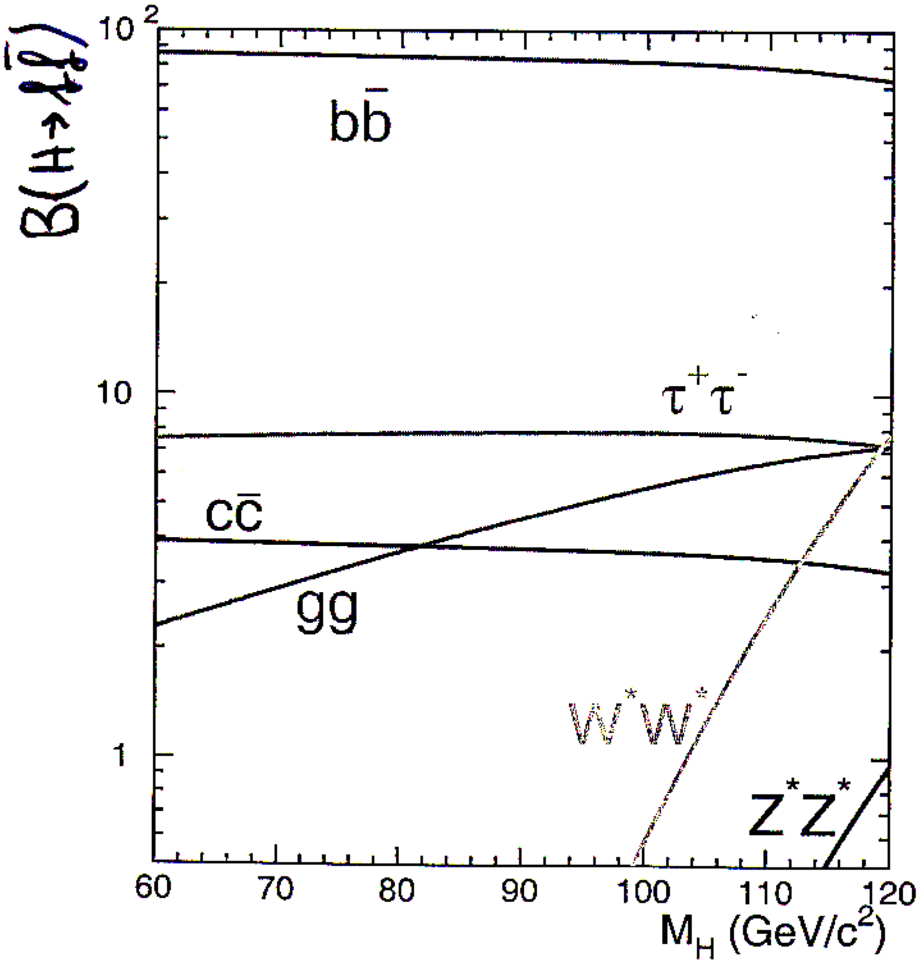
eg: $m_\tau \simeq 1.77$ GeV

$$\left.\begin{array}{l} m_c(m_H) \simeq 0.6\ \text{GeV} \\ m_b(m_H) \simeq 2.9\ \text{GeV} \end{array}\right\}\ \text{"running" quark masses}$$

$\Rightarrow$ branching ratios:

dominating decays: $B(H\to b\bar{b}) \simeq 85\%$

$B(H\to\tau^+\tau^-) = 8\%$



- total width

$\Gamma_H \simeq \mathcal{O}(10\ \text{MeV})$

if $m_H \simeq 100$ GeV

Higgs searches: topologies at LEP

$HZ \to b\bar{b}q\bar{q}$, $b\bar{b}\ell^+\ell^-$ $(\ell = e, \mu)$, $b\bar{b}\nu\bar{\nu}$ and $b\bar{b}\tau^+\tau^- \mid \tau^+\tau^- q\bar{q}$

$BR = 61\%$, 6%, 17% and 8%

- $Z \to q\bar{q}$

$H \to b\bar{b}$

  - ▷ 4 jets
  - ▷ energy & momentum conservation
  - ▷ 2 b quark jets, 2 jet system with Z mass (→ kin. fits)
  - ▷ efficiency 30-40%

- $Z \to \nu\bar{\nu}$

$H \to b\bar{b}$

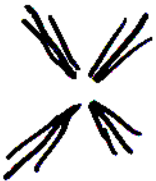
  - ▷ missing energy
  - ▷ 2 b quark jets, recoil mass m_Z
  - ▷ efficiency 30-40%

- $Z \to \ell^+\ell^-$, $\ell = e, \mu$

$H \to b\bar{b}$

  - ▷ 2 energetic leptons with pair mass: m_Z
  - ▷ clean channel, efficiency 50-60%, $BR \approx 6\%$

- $Z \to \tau^+\tau^- \mid q\bar{q}$



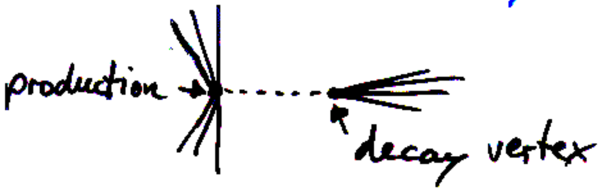
$H \to b\bar{b} \mid \tau^+\tau^-$

  - ▷ 2 τ jets + 2 jets
  - ▷ one pair of jets has m_Z
  - ▷ efficiency ≃ 30%

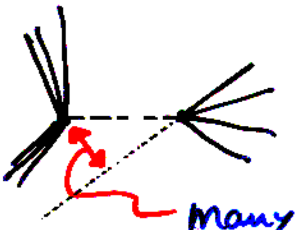
b-quark jet identification

... indispensable to identify the Higgs boson at LEP
enormous effort on b quark identification:

- **secondary vertices:** b-hadron lifetime ≃ 1.5 ps
  → detached decay vertices

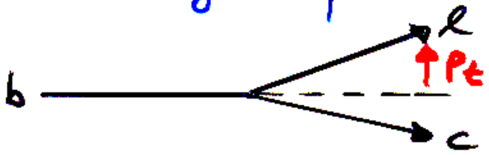


- **impact parameter:**



many particles with large impact parameter in b eve

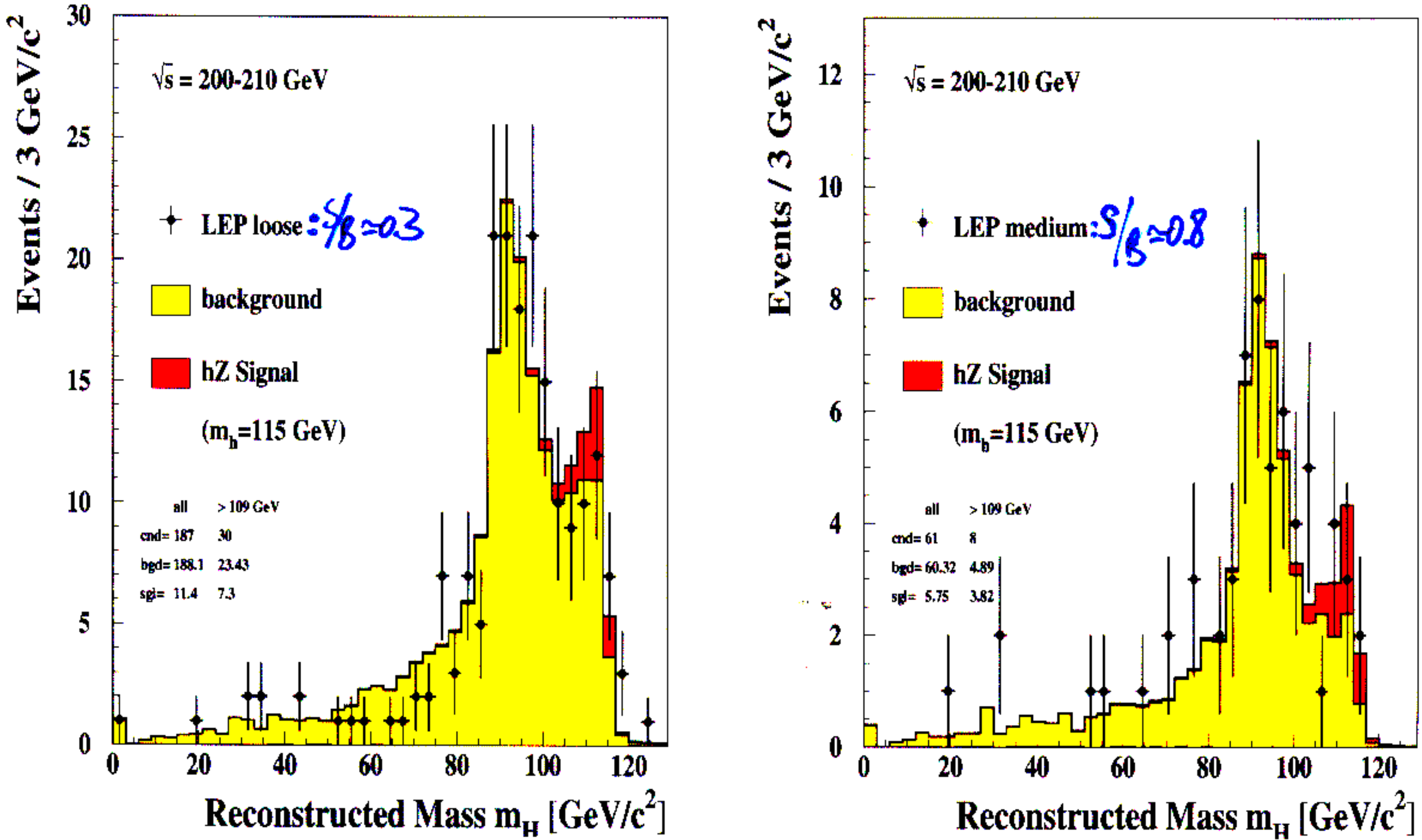
- **leptonic decay:** large momentum of lepton ⊥ jet axis of b-quark decay due to mass diff. between b and c quar

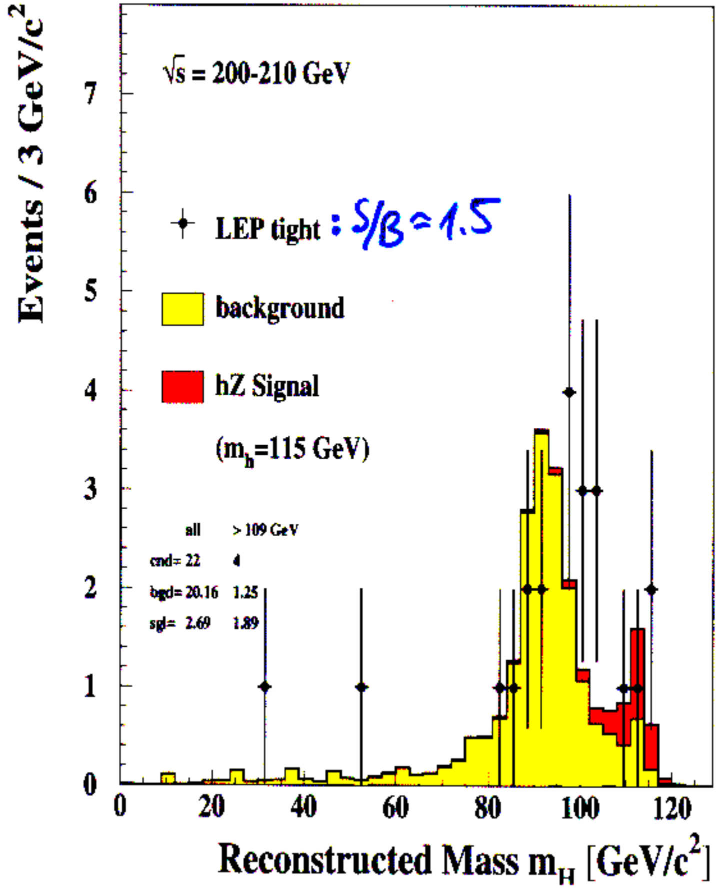


- **fragmentation:** kinematical observables, eg. momentum spectrum of b-decay products softer due to b→c→s Casca

All information fed into neural networks & likelihoo fits ⇒ ≃50% efficiency at ≲8% impurity

Mass distribution of Higgs candidates





background from

$q\bar{q}(\gamma)$, ZZ, W^+W^-, $W^\pm e^\mp \nu_e$, $Z e^+ e^-$, ..

irreducible:

$B(ZZ \to b\bar{b} f\bar{f}) \simeq 22\%$

$\sigma(e^+e^- \to ZZ) \simeq 0.8\,\mathrm{pb}$

$\approx$

while

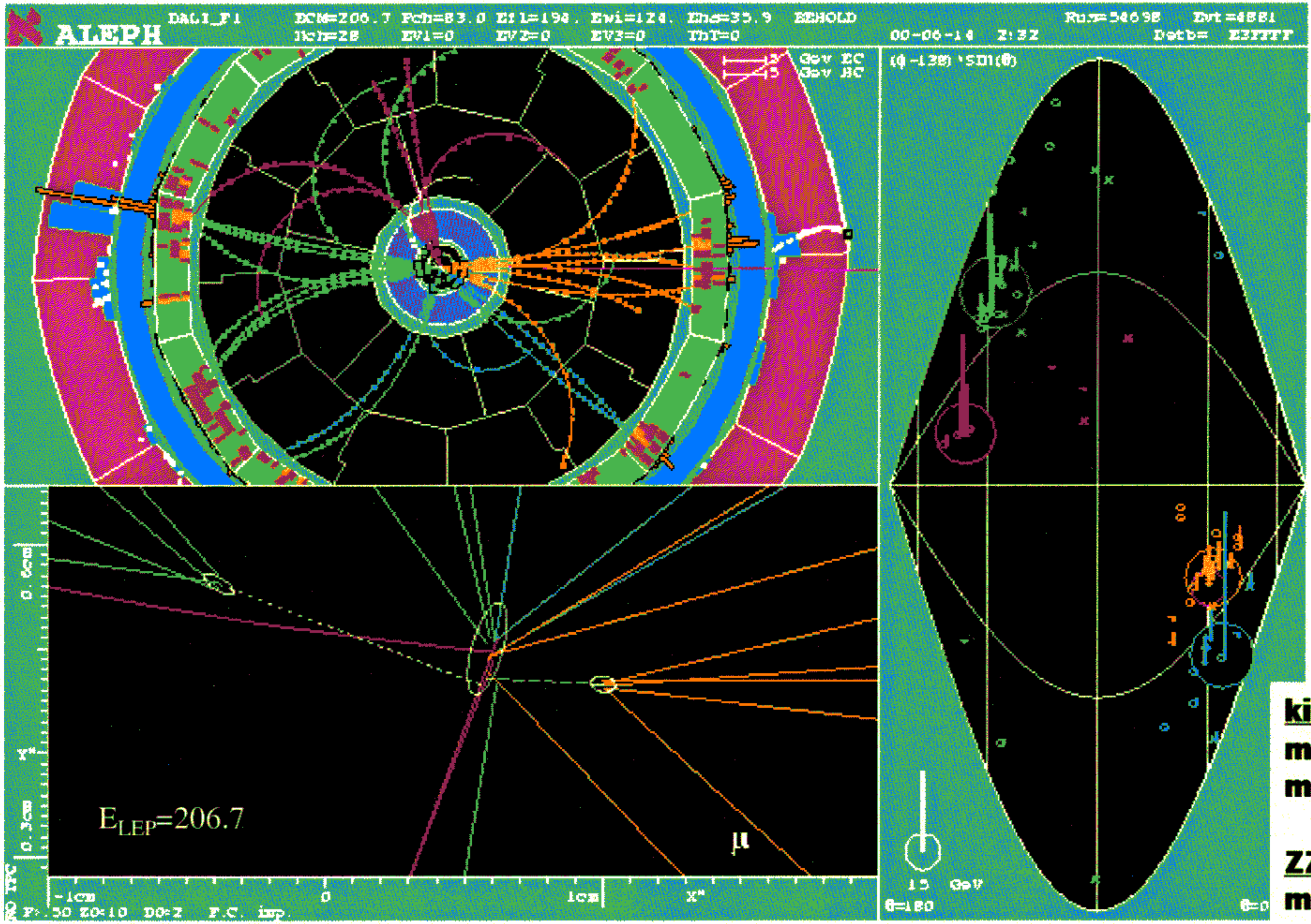
$B(HZ \to b\bar{b} f\bar{f}) \simeq 85\%$

$\sigma(e^+e^- \to HZ) \simeq 0.3\,\mathrm{pb}$

(if $m_H = 95$ GeV & $\sqrt{s} = 196$ GeV)

Figure 6: Distributions of the reconstructed Higgs mass, m_H^{rec}, from three special, non-biasing, selections with increasing purity of a signal from a 115 GeV Higgs boson.

LEP II: SM-Higgs



2 b cand.

HZ hyp.
m_H=114 GeV
±3 GeV

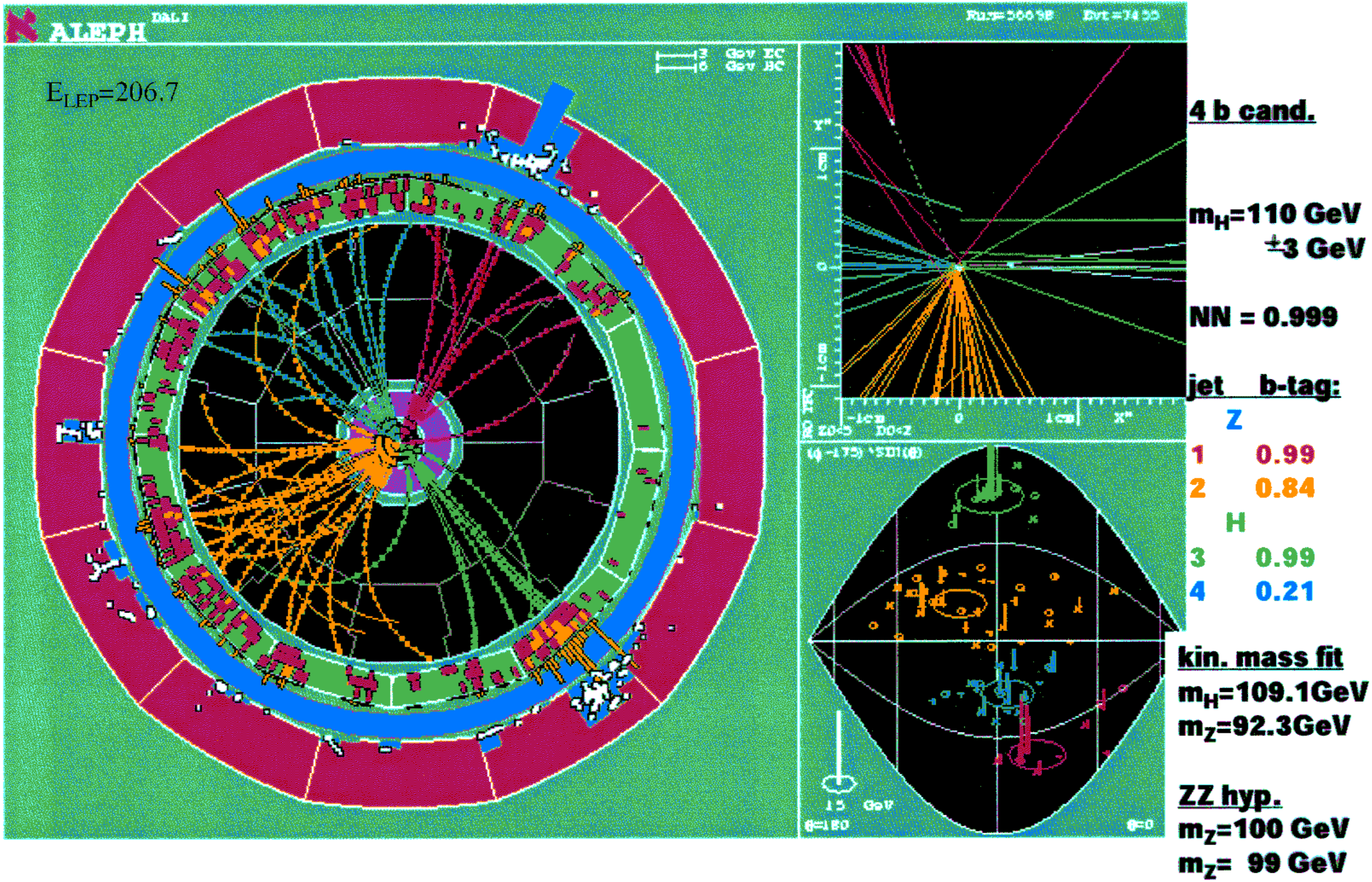
NN = 0.996

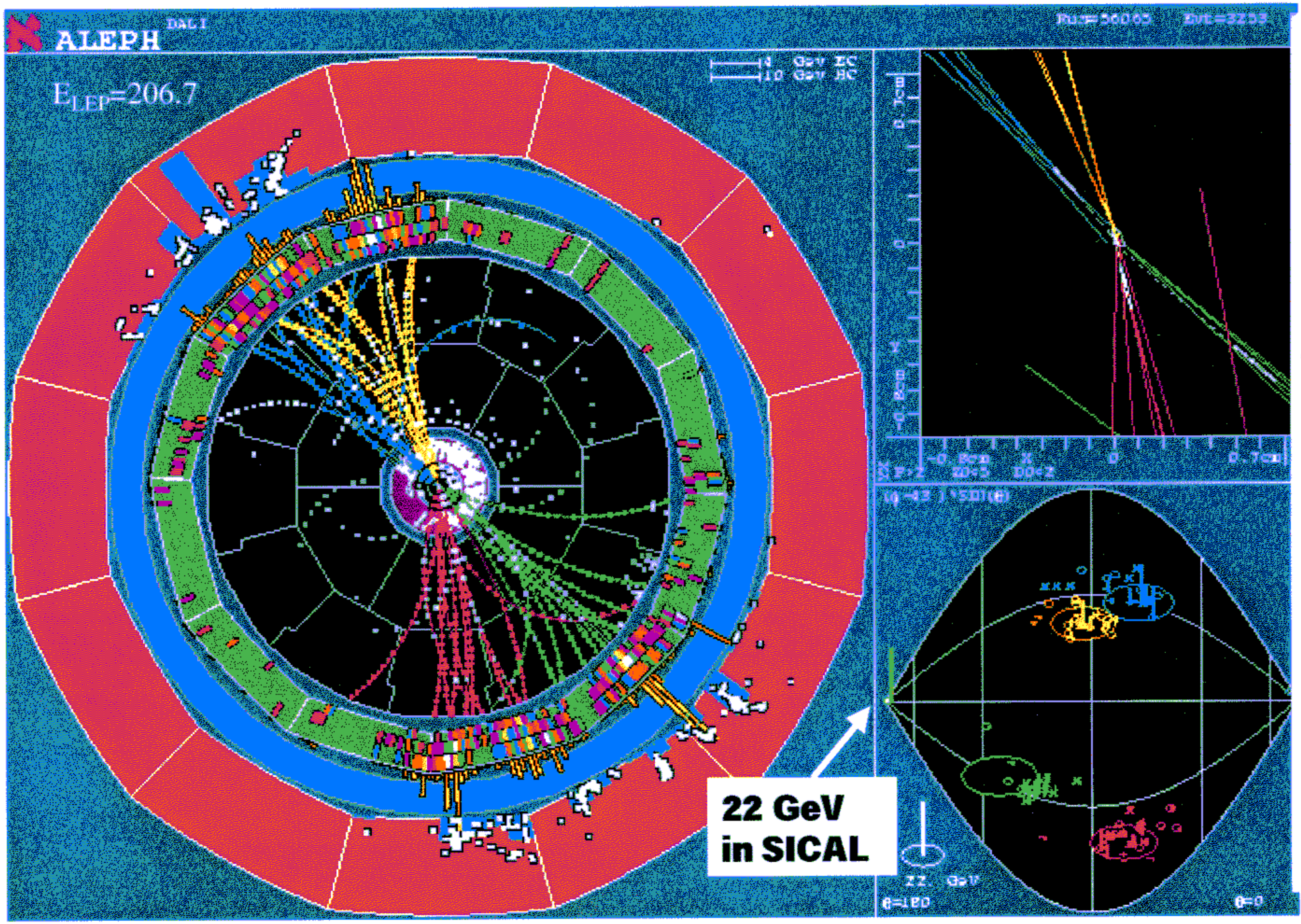
jet	**b-tag:**
Z	
1	0.14
2	0.01
H	
3	0.99
4	0.99

kin. mass fit
m_H=112.4GeV
m_Z=93.3GeV

ZZ hyp.
m_Z=102 GeV
m_Z=91.7GeV

⇒ 2 b-tags, $m_H = 114$ GeV


ALEPH
DALI
Run=56698
Evt=7455
3 GeV EC
6 GeV HC
E_LEP=206.7
Y"
1cm
0
-1cm
X"
RO TPC
ZO<5 DO<2
15 GeV
θ=180
θ=0
4 b cand.
m_H=110 GeV
±3 GeV
NN = 0.999
jet b-tag:
Z
1 0.99
2 0.84
H
3 0.99
4 0.21
kin. mass fit
m_H=109.1GeV
m_Z=92.3GeV
ZZ hyp.
m_Z=100 GeV
m_Z= 99 GeV



22 GeV in SICAL

4 b cand.

HZ hyp.

m_H= 112.8 GeV

NN = 0.997

jet	**b-tag:**
Z	
1	**0.994**
2	**0.78**
H	
3	**0.993**
4	**0.999**

Evis= 252 GeV !

very bad kin. fit!

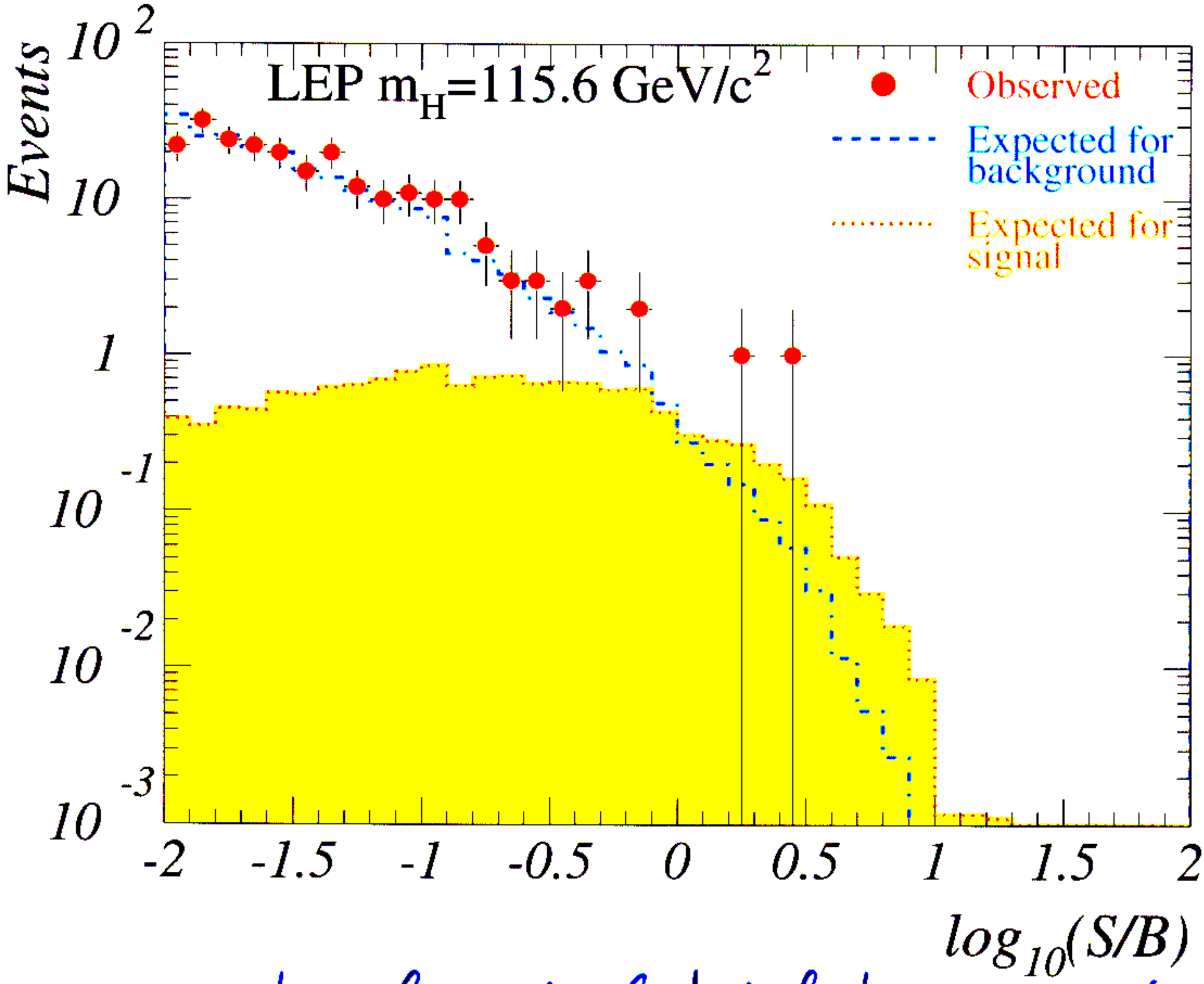
⇒

assumption: 22 GeV in SICAL is beam related

Higgs candidates at 115 GeV?

- no. of observed events versus signal/background

⇒ more events than expected at large S/B ($\log_{10} S/B > 0$) ?



⇒ not a clear signal but lost many events due to tight S/B cuts. Try to consider every event by calculating Poissonian probabilities..

Counting candidates

▷ b_i expected no. of background evts. in channel i

▷ $s_i(m_H)$ expected no. of signal (Higgs) evts in channel i
(depends on Higgs mass)

▷ n_i no. of observed events in channel i

→ define ratio of likelihoods for
Poissonian probabilities (for small no. of observed evts.

$$Q(m_H) := \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = \prod_i \frac{(s_i+b_i)^{n_i}\, e^{-(s_i+b_i)} \big/ \cancel{n_i!}}{(b_i)^{n_i}\, e^{-(b_i)} \big/ \cancel{n_i!}}$$

$$\Rightarrow -2\ln Q = 2\cdot\Big(\sum_i s_i\Big) - 2\sum_i n_i \ln\left(1 + \frac{s_i}{b_i}\right)$$

↑ total no. of expected signal evts.

↑ no. of observed events

↑ expected S/B ratio

- if measurement "signal-like": $-2\ln Q < 0$
- " " "background-like": $-2\ln Q > 0$

Notice: value of $-2\ln Q$ depends on assumed Higgs mass m_H

LEP's result on Higgs search

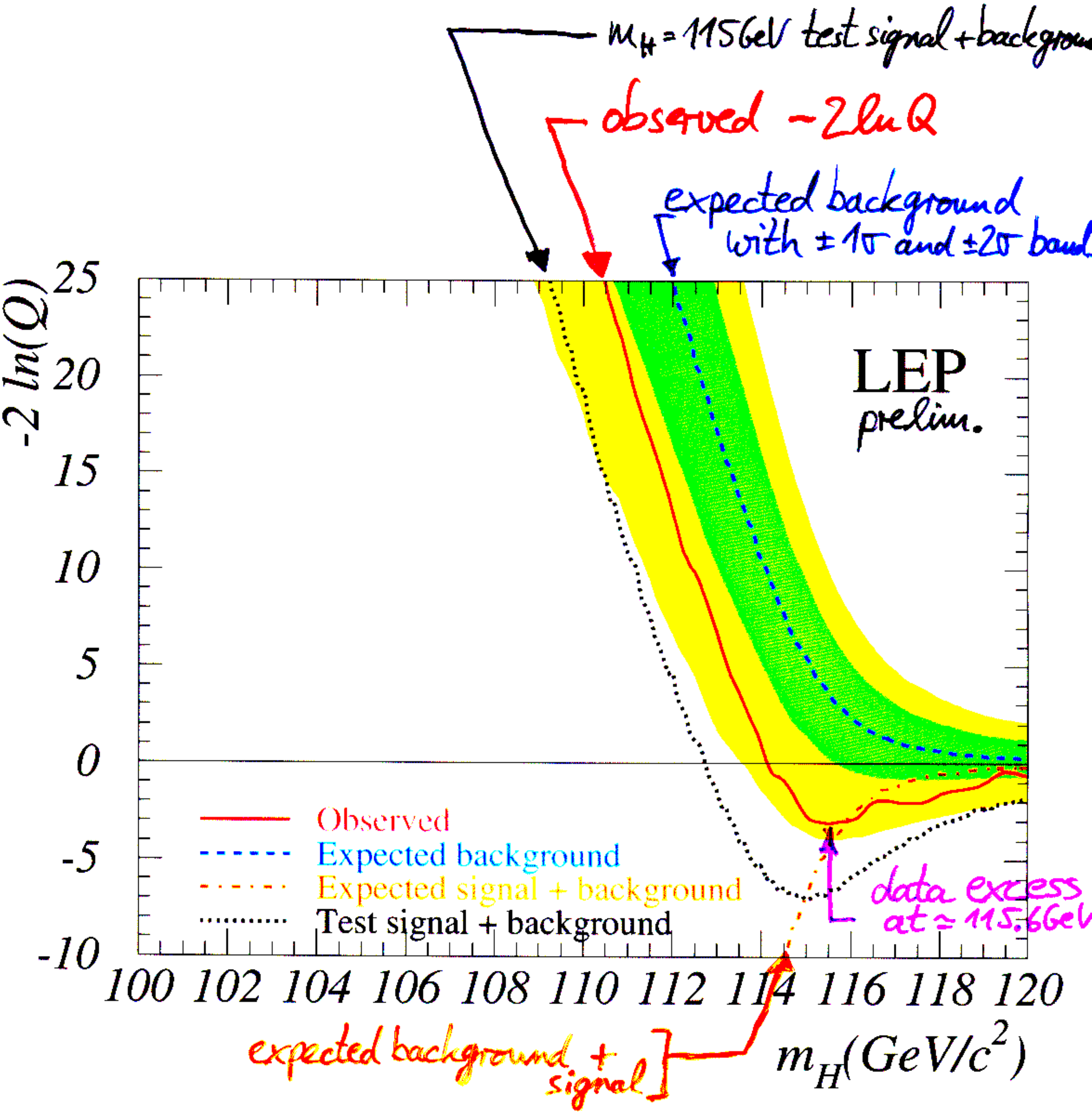


Figure 1: Observed and expected behaviour of the likelihood ratio $-2\ln Q$ as a function of the test-mass m_{H}, obtained by combining the data of all four experiments. The solid line represents the observation; the dashed/dash-dotted lines show the median background/signal+background expectations. The dark/light shaded bands around the background expectation represent the ±1/±2 standard deviation spread of the background expectation obtained from a large number of background experiments. The dotted line is the result of a test where the signal from a 115 GeV Higgs boson has been added to the background and propagated through the likelihood ratio calculation.

⇒ LEP observes a ≈2.1σ excess over background

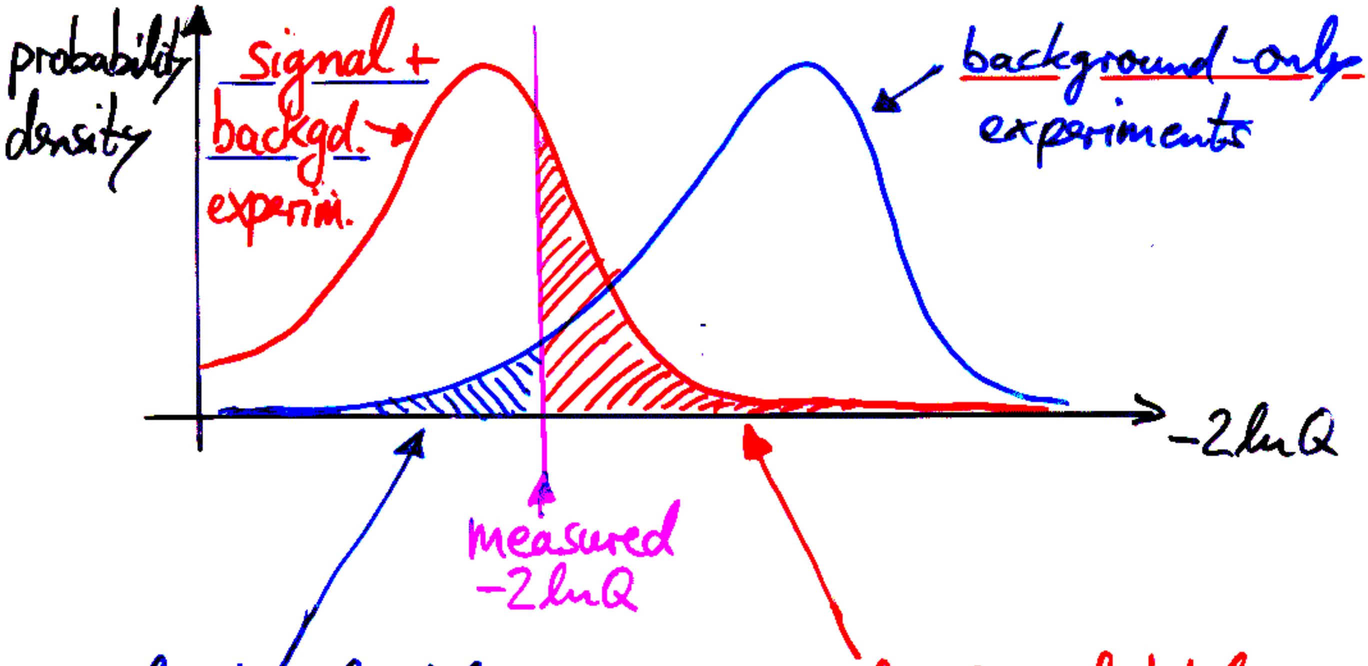
Higgs mass limit

- For a given m_H

▷ simulate many background-only experiments

▷ " " signal+background experiments

$\Rightarrow$ $-2\ln Q$ distributions (with unit area)



fraction of total area under backgr.-only curve : $1-CL_b$

fraction of total area under signal+backgd. curve : CL_{s+b}

▷ $CL_s := \frac{CL_{s+b}}{CL_b} = 0.05$ $(\hat{=} 5\%)$

defines 95% CL on mass m_H

i.e. the probability to get a $-2\ln Q$ smaller than actually observed is 5% only for that m_H

Higgs mass limit

- from $-2\ln Q$ one obtains:

  $1-CL_b$: measure of inconsistency with background

  CL_{s+b} : measure of inconsistency with signal+backg.

$\Rightarrow$ $CL_s := CL_{s+b}/CL_b$ to set lower bound on Higgs mas

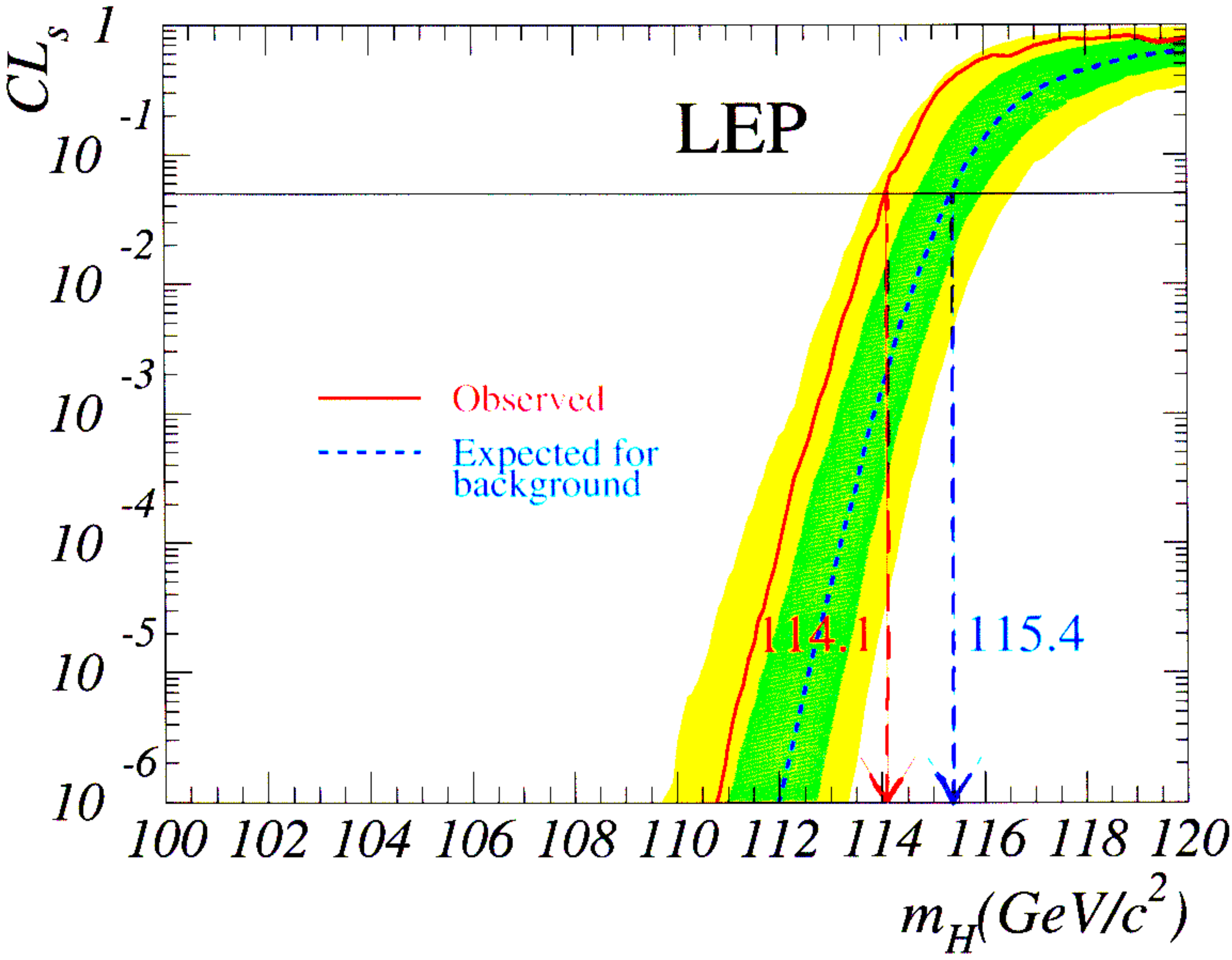


Figure 9: Confidence level CL_s for the signal+background hypothesis. Solid line: observation; dashed line: median background expectation. The dark/light shaded bands around the median expected line correspond to the ±1/±2 standard deviation spreads from a large number of background experiments.

$\Rightarrow$ $m_H > 114.1$ @ 95% confidence level

Summary and outlook

- LEP's measurement programme finished
  (see current status on next slide
- LEP's major achievements
  - ▷ test of the Standard model at ‰ level
  - ▷ Z-boson parameters: mass $\Delta m_Z \simeq 2.1\,\mathrm{MeV}$
    width, branching ratios, couplings, ...
  - ▷ W-boson parameters: mass $\Delta m_W \simeq 30\,\mathrm{MeV}$,
    width, branching ratios, triple gauge
    boson coupling, ...
  - ▷ Higgs-boson search: evidence for $m_H = 115.6\,\mathrm{GeV}$
    Higgs mass range stringently constrained:
    $114\,\mathrm{GeV} < m_H < 196\,\mathrm{GeV}$
    (TeVatron, LHC, or NLC should find it if it's there!
  - ▷ established Standard model as a very
    serious and successful theory of
    electroweak interactions (+ strong interactions,
- LEP's analysis programme still ongoing

OPAL after end of LEP

left out this time ...

... a lot !

- QCD and strong interaction, eg. α_s, ...
- Heavy flavour (b-) physics, eg. lifetime, spectroscopy, oscillation, $\not{CP}$, ...
- τ-lepton physics, eg. V-A structure of electroweak decays, ν_τ mass limit, ...
- 2-photon physics, eg. photon structure function F_2, charm content of γ, ...
- searches for physics beyond the Standard model, eg. SUSY, contact interactions, Z', compositeness, extra dimensions, ...
- ...

⇒ LEP has still a rich analysis programme for the next few years !
(before LHC starts in ~2006)