e+e- Physics
at the Energy Frontier

Felix Sefkow

DESY

3. The LEP / SLC legacy

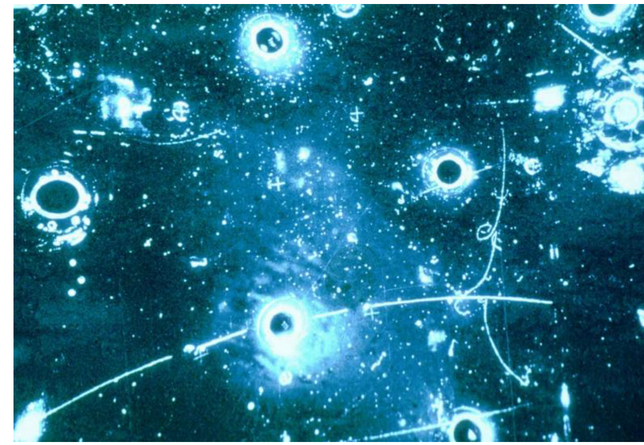
Machines and detectors

Physics highlights

LEP

- Conceived 1976: Burt Richter suggest a 200 GeV machine for electroweak physics
  - until then only studied with neutrinos and E_{cm} = 10-20 GeV
- Planned 1979: John Adams at Les Houches
- Approved 1982
- First physics 1989
- In the meantime:
  - 1978 approve SppS
  - 1981 have it built and commissioned
  - 1982 discover W and Z (1983)
  - but no new quarks and leptons
  - 1987 Tevatron started, 92 HERA

Gargamelle



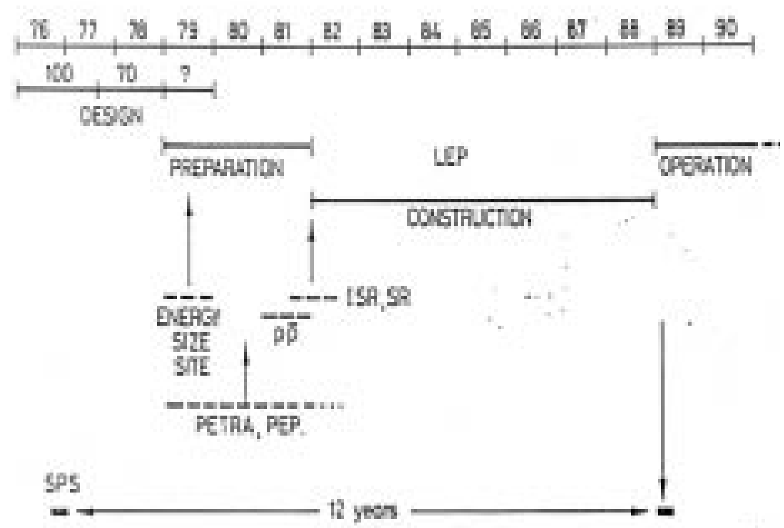
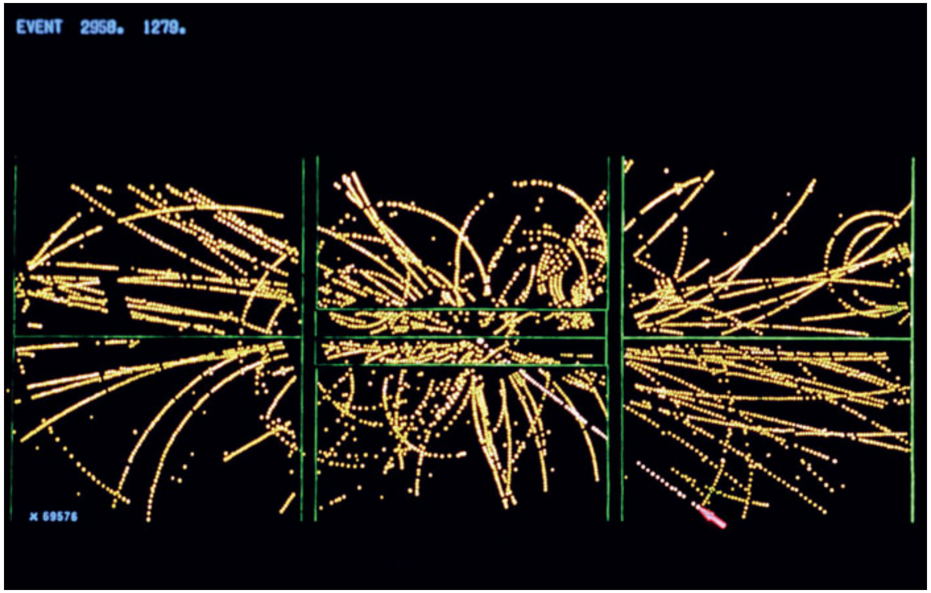
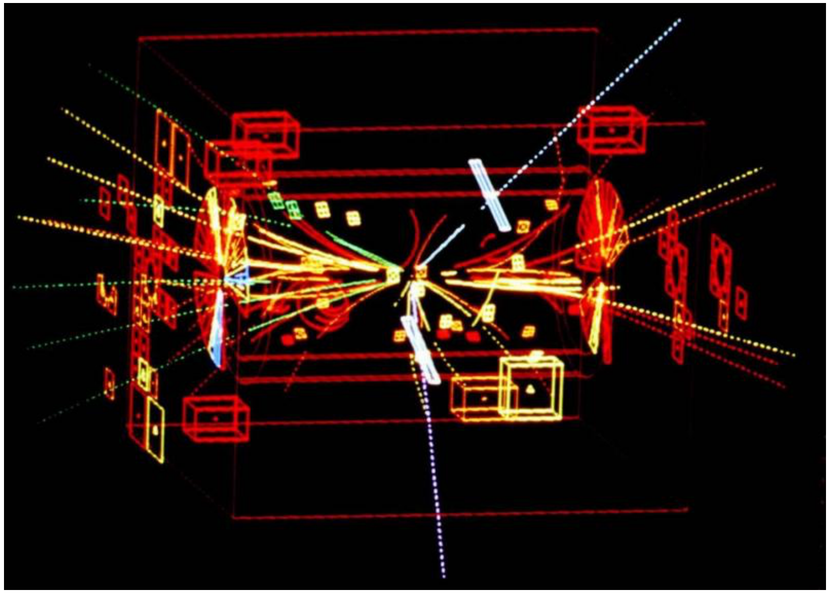
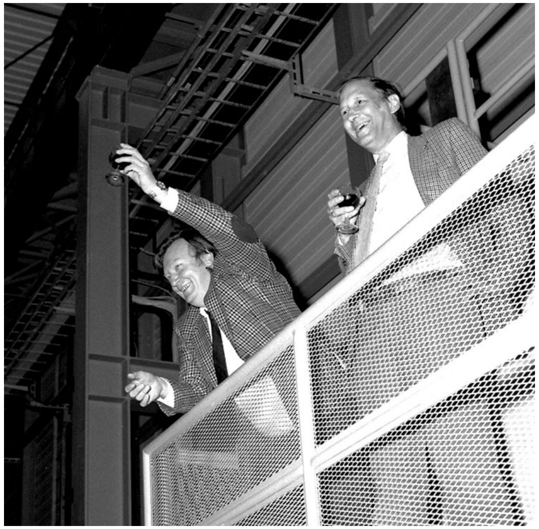


Figure 2: John Adams' first LEP construction plan

Discovery of W and Z

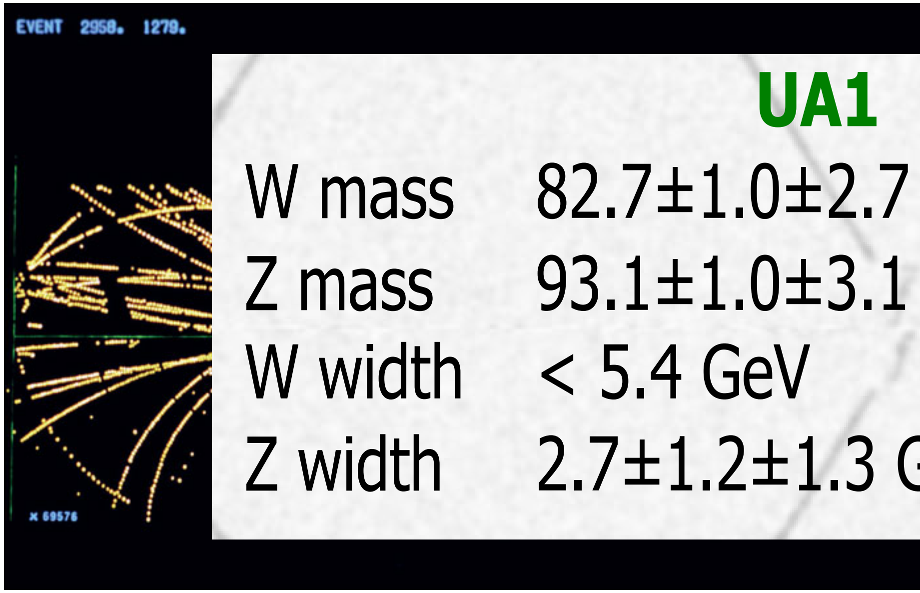


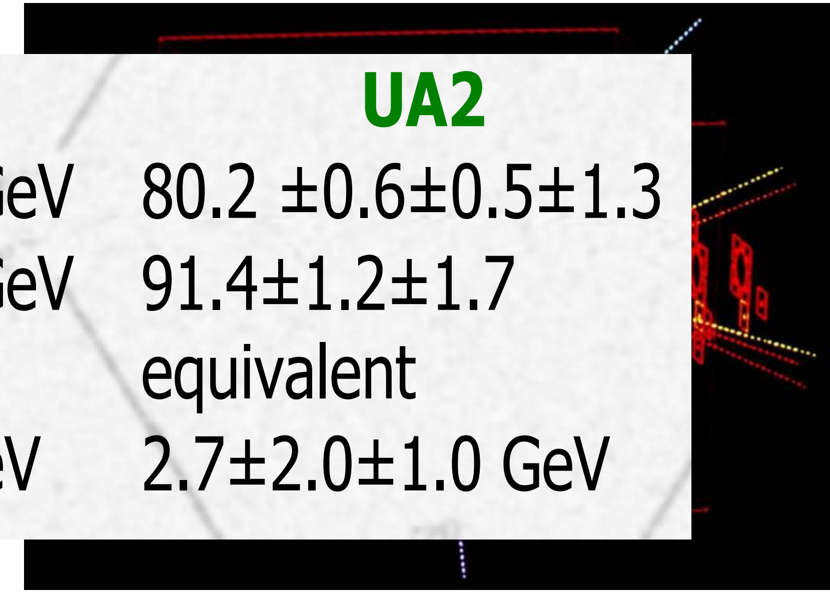




- UA1 and UA2 experiments
- Masses of 80 and 90 GeV
  - as predicted
- Nobel Prize 1984

Discovery of W and Z





	UA1	UA2
W mass	82.7±1.0±2.7 GeV	80.2 ±0.6±0.5±1.3
Z mass	93.1±1.0±3.1 GeV	91.4±1.2±1.7
W width	< 5.4 GeV	equivalent
Z width	2.7±1.2±1.3 GeV	2.7±2.0±1.0 GeV

- UA1 and UA2 experiments
- Masses of 80 and 90 GeV
  - as predicted
- Nobel Prize 1984

LARGE Electron Positron Ring

LARGE Electron Positron Ring

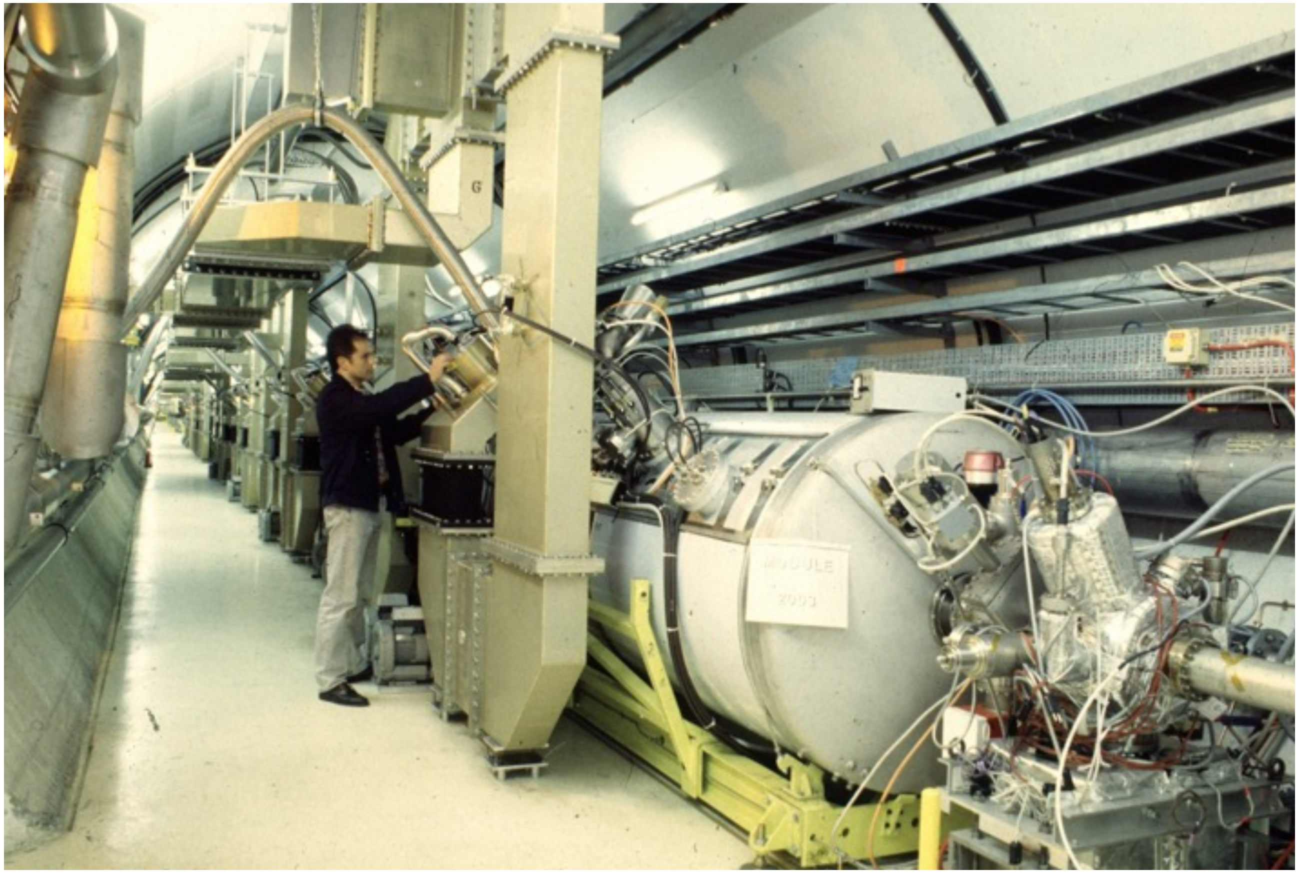
- Accelerator physics very similar to PEP / PETRA / TRISTAN
- The challenge was in civil engineering and logistics
  - 26,7 7km, 3368 dipoles, 816 quadrupoles, 500 sextuples and 700 correction magnets, P = 1/4 Geneva

Optimising the circumference

- Energy loss due to synchrotron radiation
  - $U = 4\pi r_e m_e c^2 \gamma^4 / 3R$, $R = 3096$ m
  - Per turn:
    - 140 MeV at 47 GeV
    - 2.33 GeV at 95 GeV
- Cost:
  - Tunnel, magnets, vacuum $\sim L \sim R$
  - RF system $\sim U \sim \gamma^4 / R$
- $C \sim a \cdot R + b \cdot \gamma^4 / R$
- $dC / dR = a - b\, \gamma^4 / R^2$
- $\Rightarrow R \sim \gamma^2 \sim E^2$, $U \sim E^2$, Cost $\sim E^2$
- Magnets: $B \sim 1 / E$
  - at LEP: 0.05 - 0.1 T
  - widely spaced iron lamination and concrete

Super-conducting cavities

- RF cavity has a shunt impedance
- Power = $P_{beam} + P_{cavity} = N\cdot e\cdot U / \Delta t + U^2 / R_{shunt}$, $eU = \Delta E_{sync.rad}$
- At high E cavity losses dominate

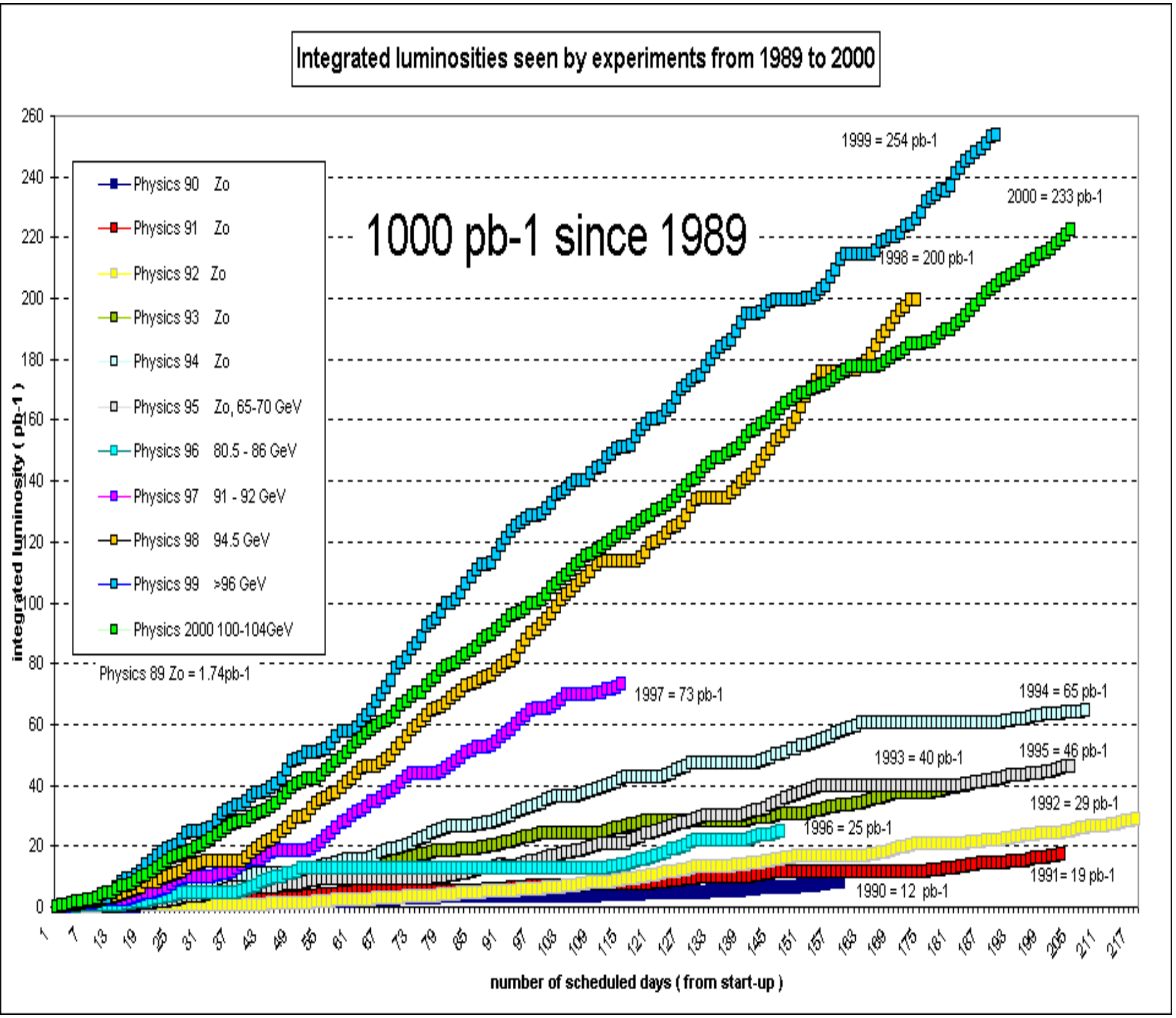


LEP parameters

Circumference	~27 km
Centre-of-mass energy	92.1 GeV(LEP1) to 209 GeV(LEP 2)
Accelerating gradient	Up to 7 MV/m (SC cavities)
Number of bunches	4 x 4
Current per bunch	~ 750 μA
Luminosity (at Z0)	~ $24 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (~1 Z0/sec)
Luminosity (at LEP2)	~ $50 \times 10^{30}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ (3 WW/hour)
Interaction regions	4 (ALEPH,DELPHI,L3,OPAL)
Energy calibration	< 1 MeV (at Z0)

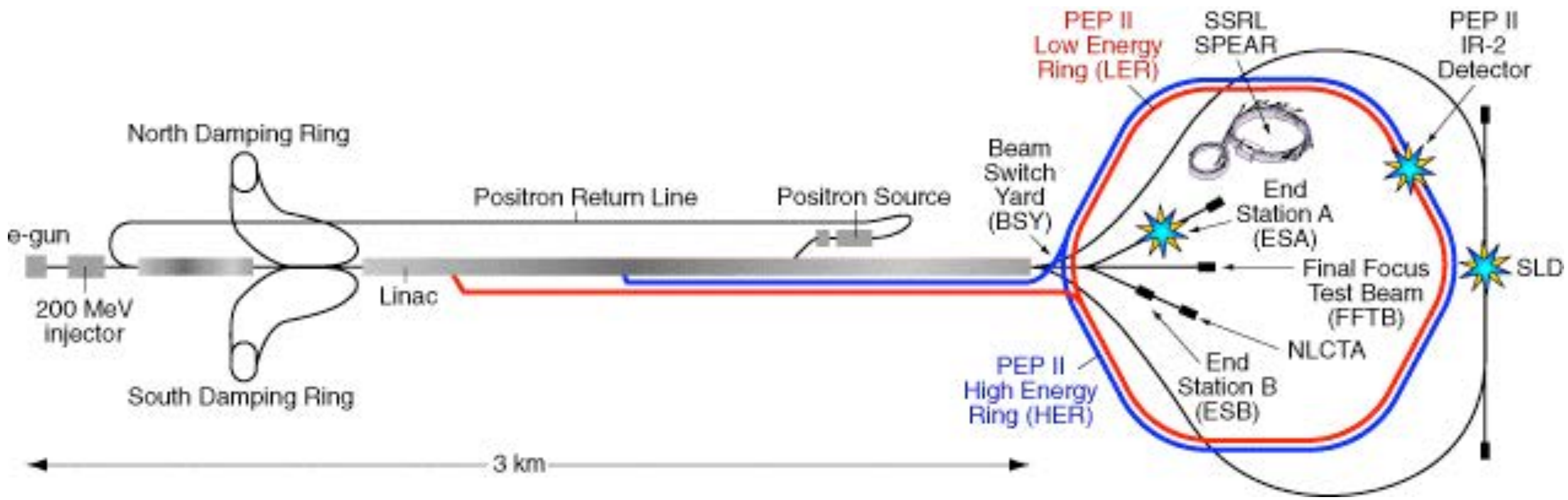
- Collisions every … ?

LEP running



1990-1995	~91 GeV 4 Million Z0's
1995	Test phase for LEP2: 130 GeV
1996	161-172 GeV: WW-threshold
1997	183 GeV 1000 W-pairs
1998	189 GeV 2500 W-pairs
1999	192-200 GeV 3000 W-pairs
2000	200-209 GeV 3000 W-pairs

Stanford Linear Collider SLC



- e^- up to 50 GeV; fixed-target program (until 1980's)
- e^- and e^+ for PEP-I storage rings (E_{cm} = 29 GeV; early 1980's)
- e^- and e^+ for SLC collider ($E_{cm} = M_Z \sim 91$ GeV; 1989 - 1999)
- e^- and e^+ for PEP-II storage rings (E_{cm} ~10 GeV; 1999 - 2008)

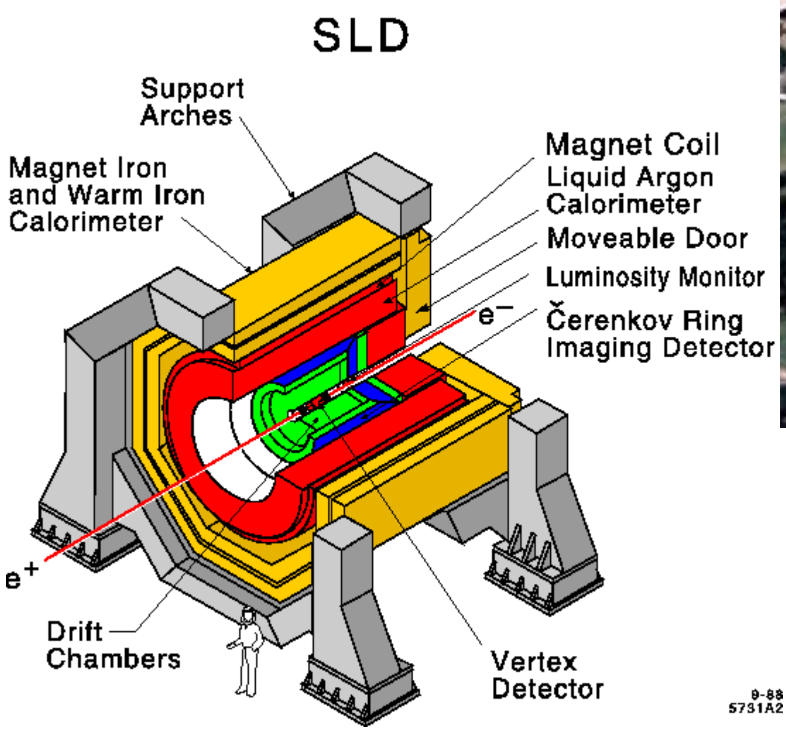
SLC:

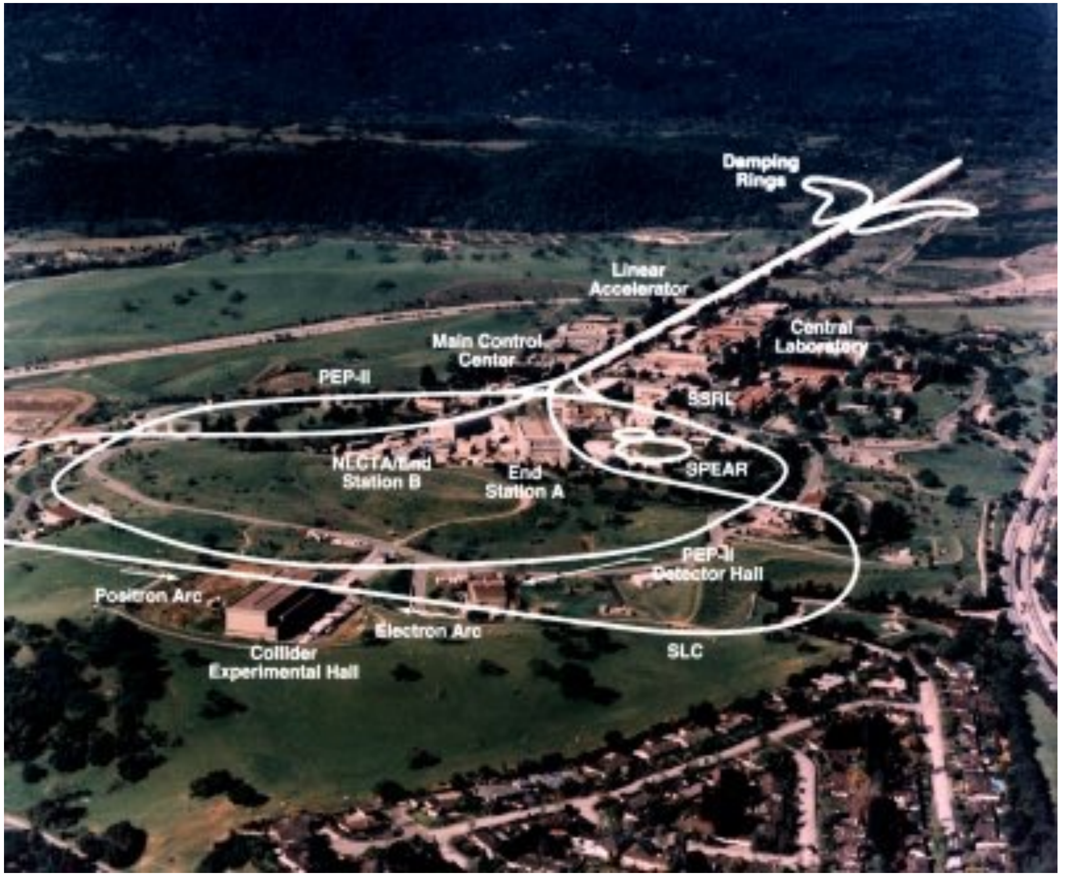
– substantially smaller luminosities and data statistics than LEP (e-, e+ are not recycled but are dumped after each collision)

+ polarisation of e^- beam up to 80% (polarised e- -source; conservation of polarisation due to ~absence of synchrotron radiation)

SLD at SLC

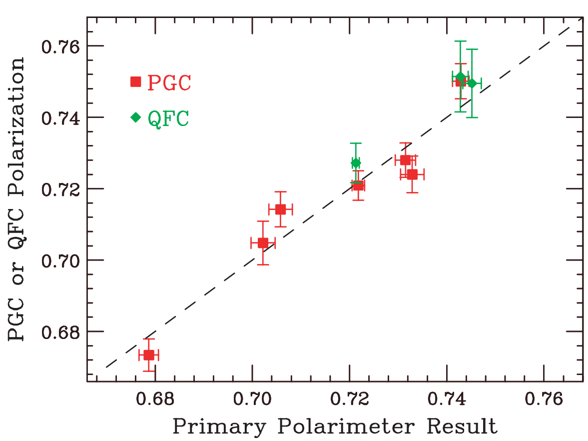
- SLC physics tarted with MARK-II in 1988
- Replaced by SLD in 1991

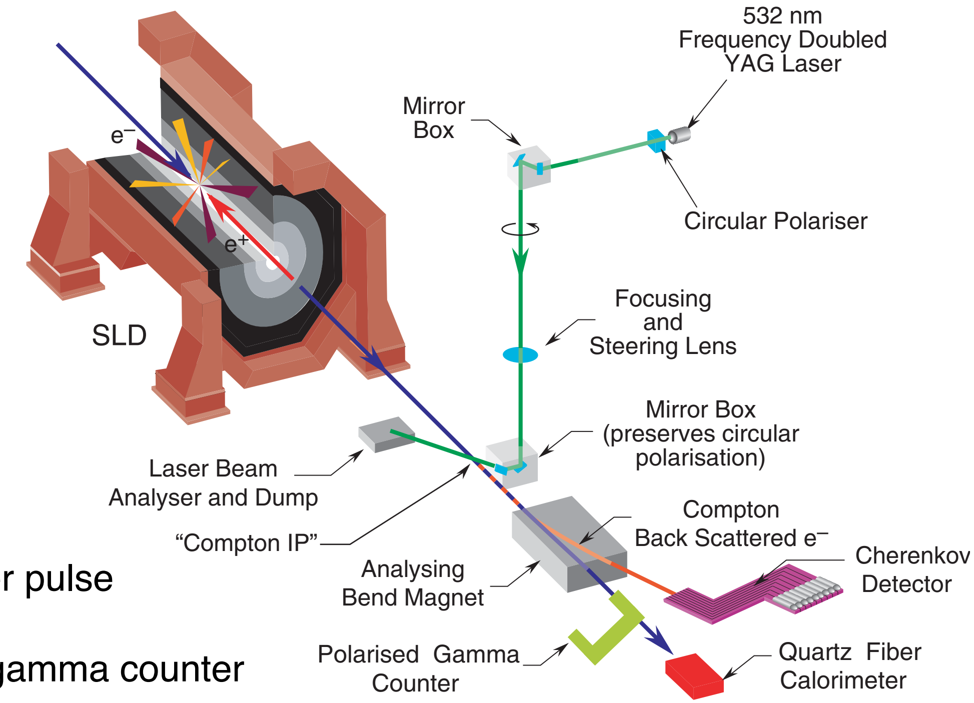




Polarimetry at SLC

- At SLC, can chose electron polarisation
- Polarised source, spin transport and rotation
- Polarimeter: Compton scattering of circular polarised photons on longitudinally polarised electrons
  - cross section dependence on scattered photon energy depends on parallel or anti-parallel spin alignment
  - detect momentum-analysed lector s in multi-channel Cherenkov detector

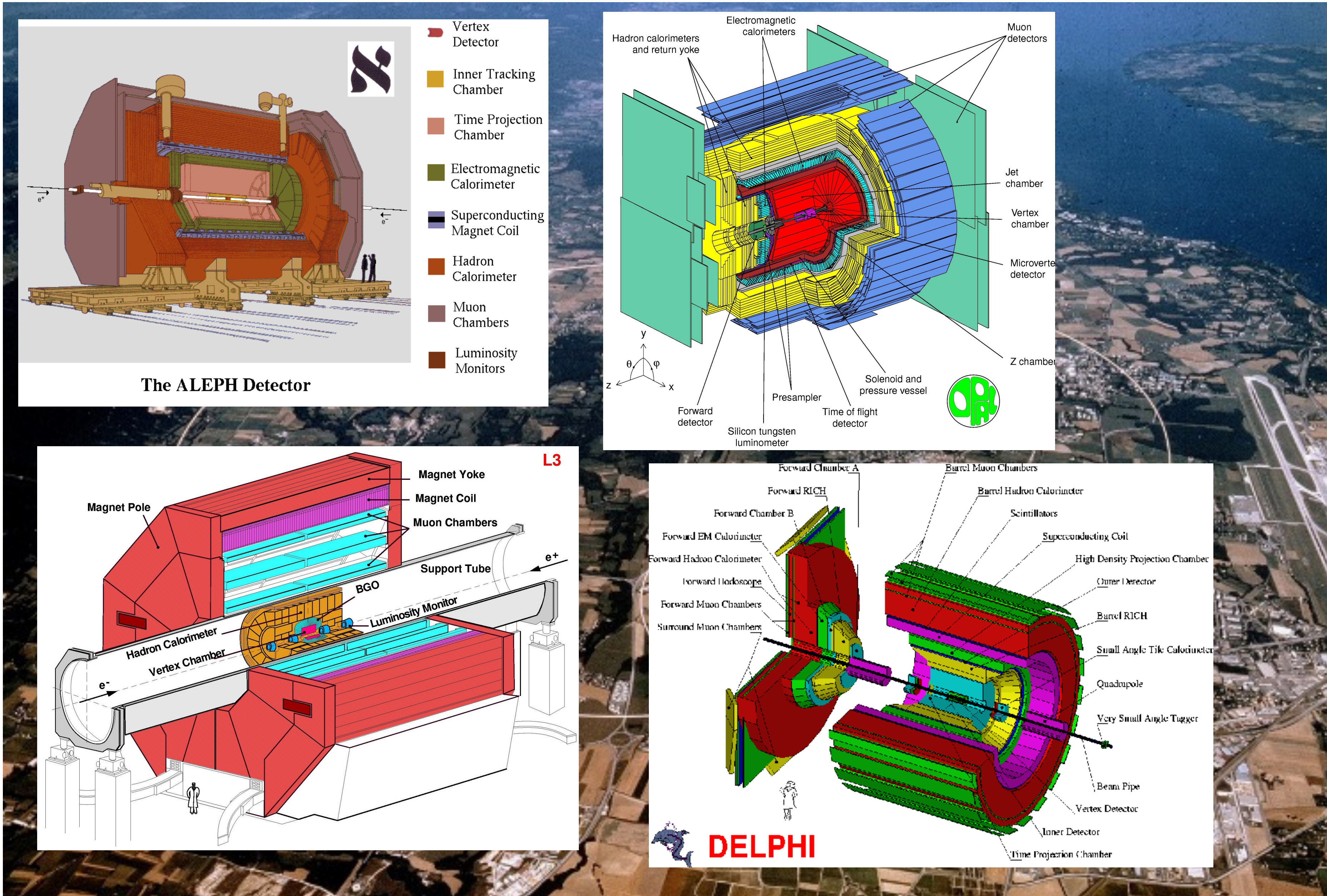




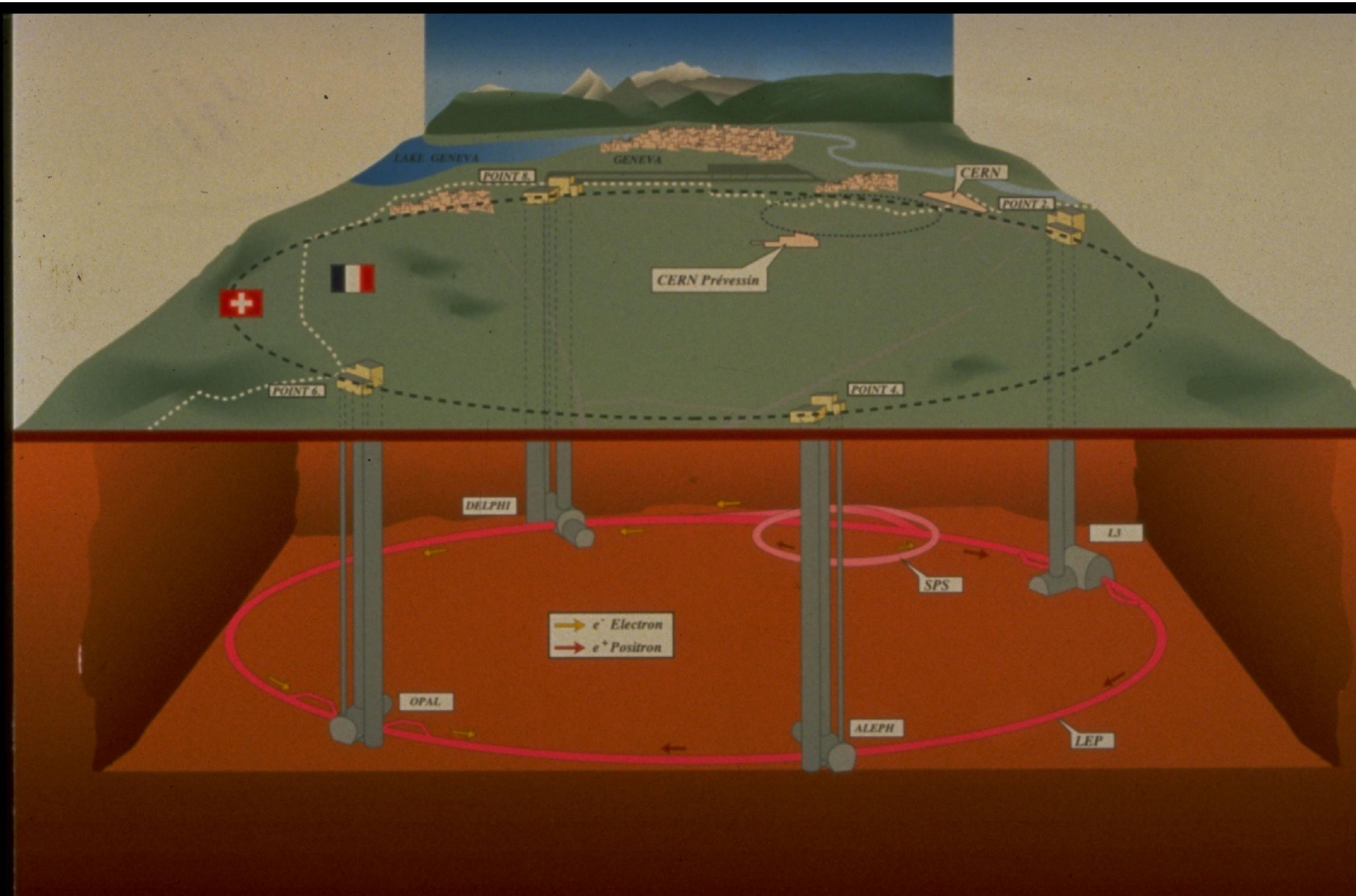
Integrate over 1000 scatters per laser pulse
Require highly linear detector
Cross-checks with calorimeter and gamma counter

LEP experiments

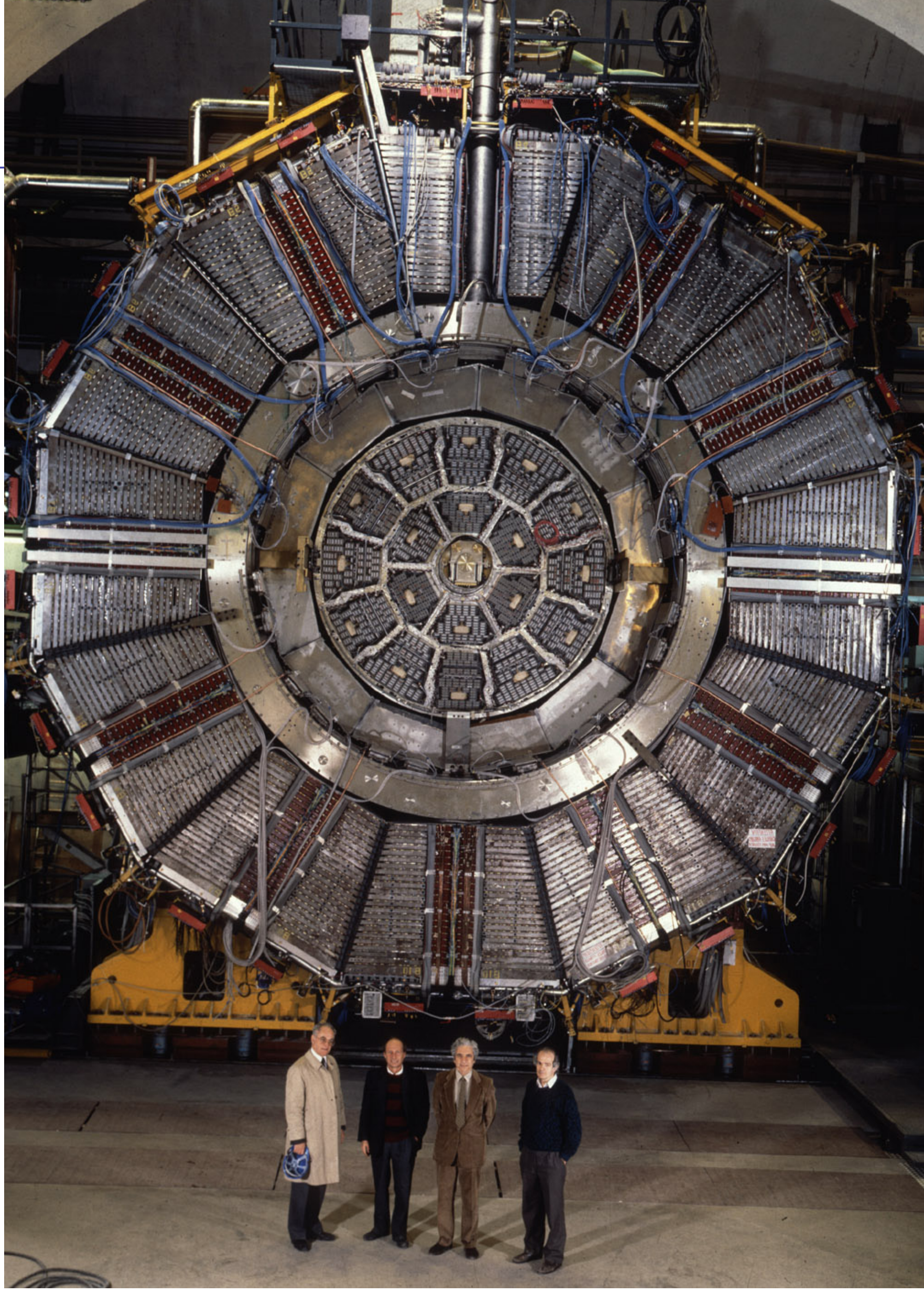
LEP experiments



LEP experiments

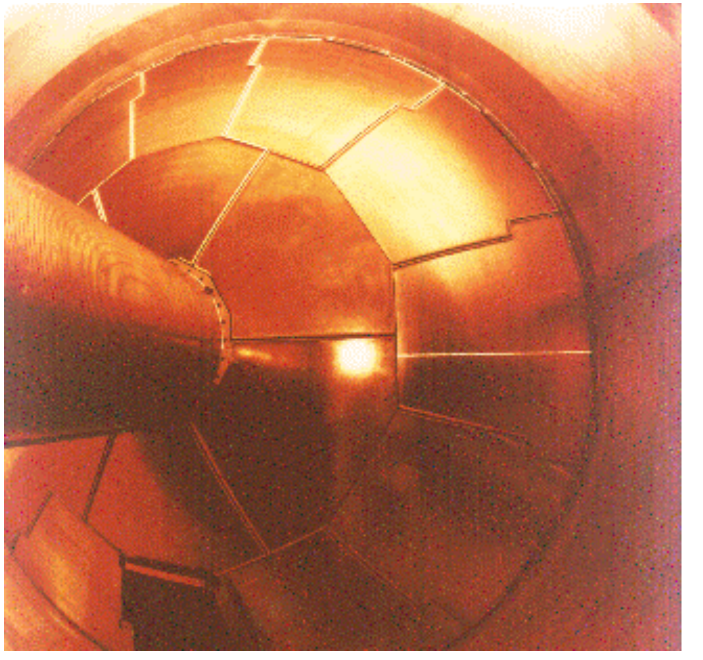


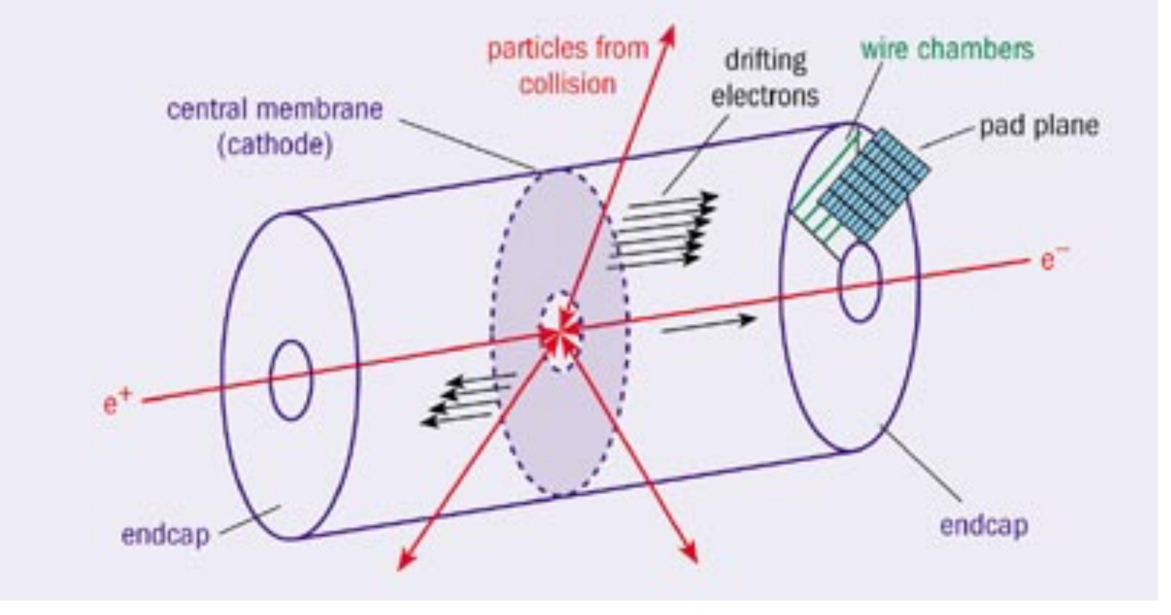
ALEPH



ALEPH TPC

- TPC: time projection chamber
  - “no" material
  - r = 1.8m, L = 4.4 m
  - 41’000 pads
  - up to 480 dE/dx measurements / track





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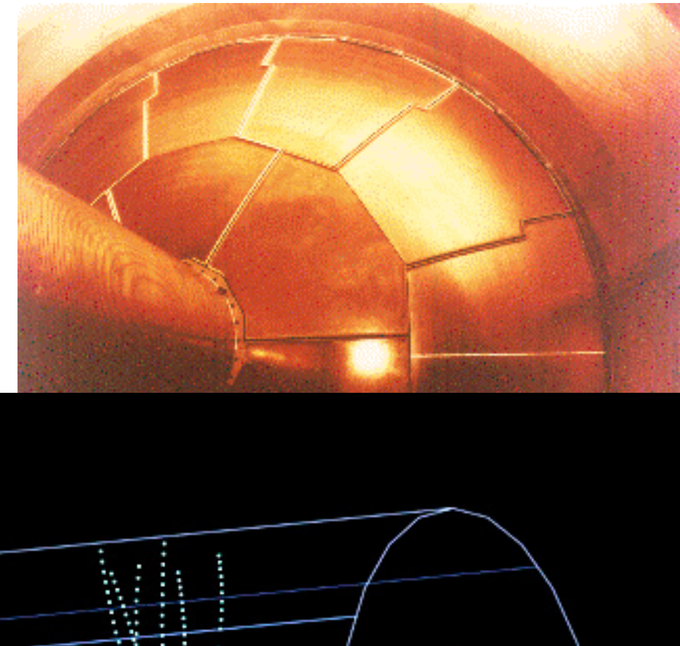
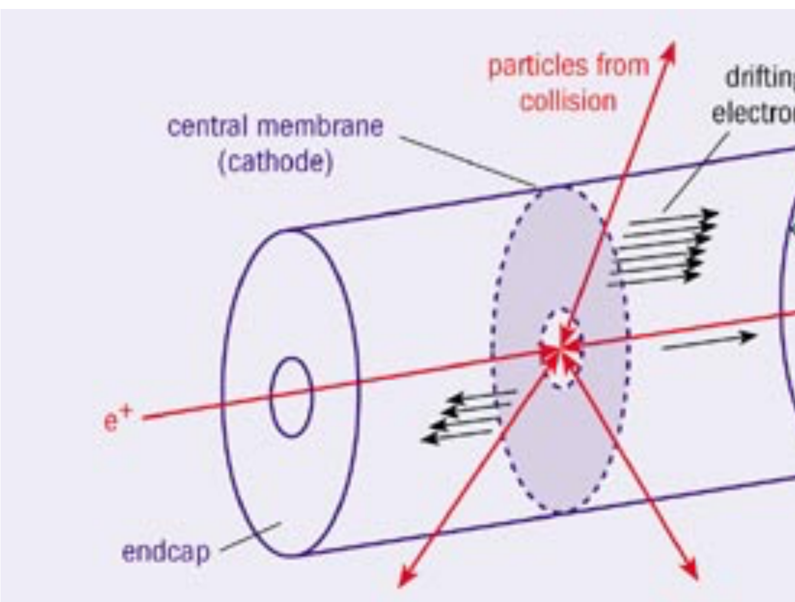
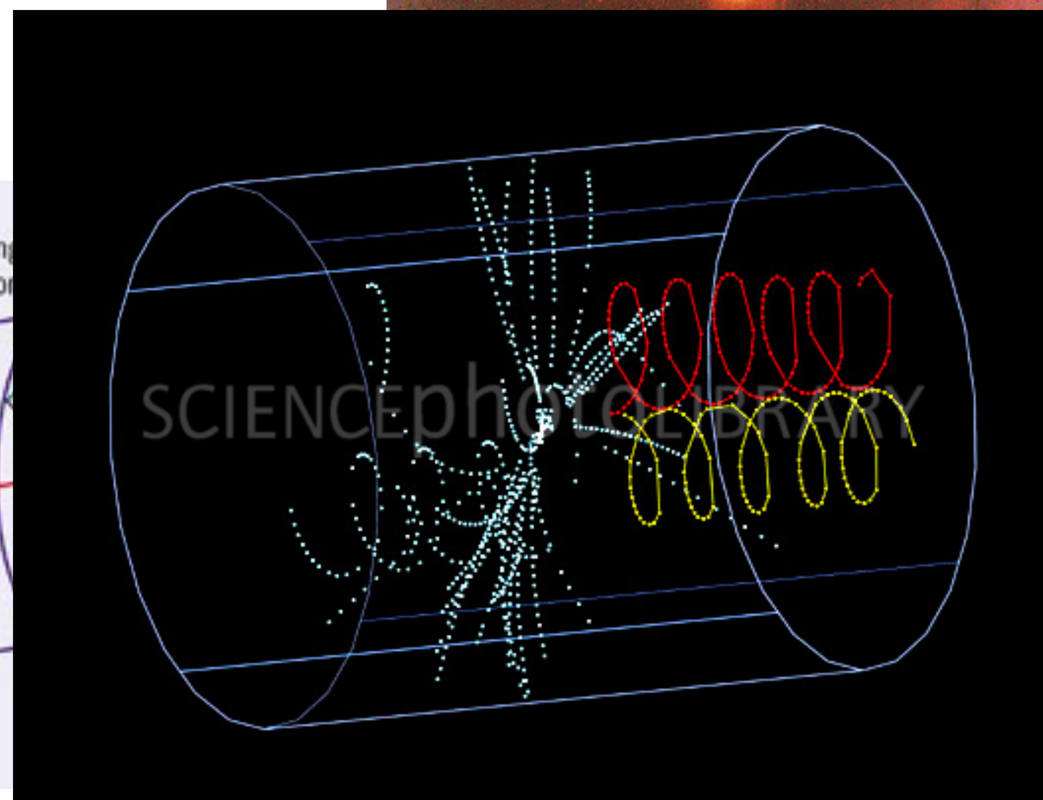




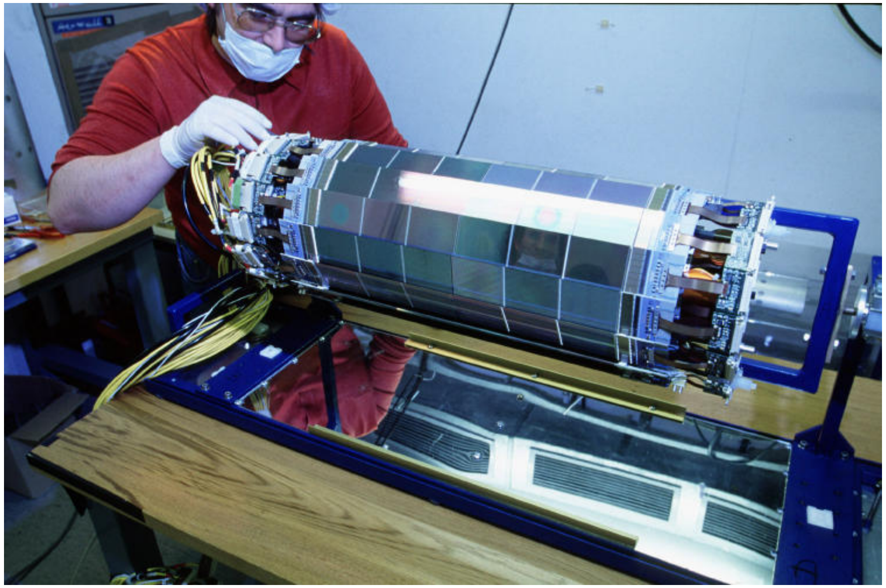


Silicon vertex detector

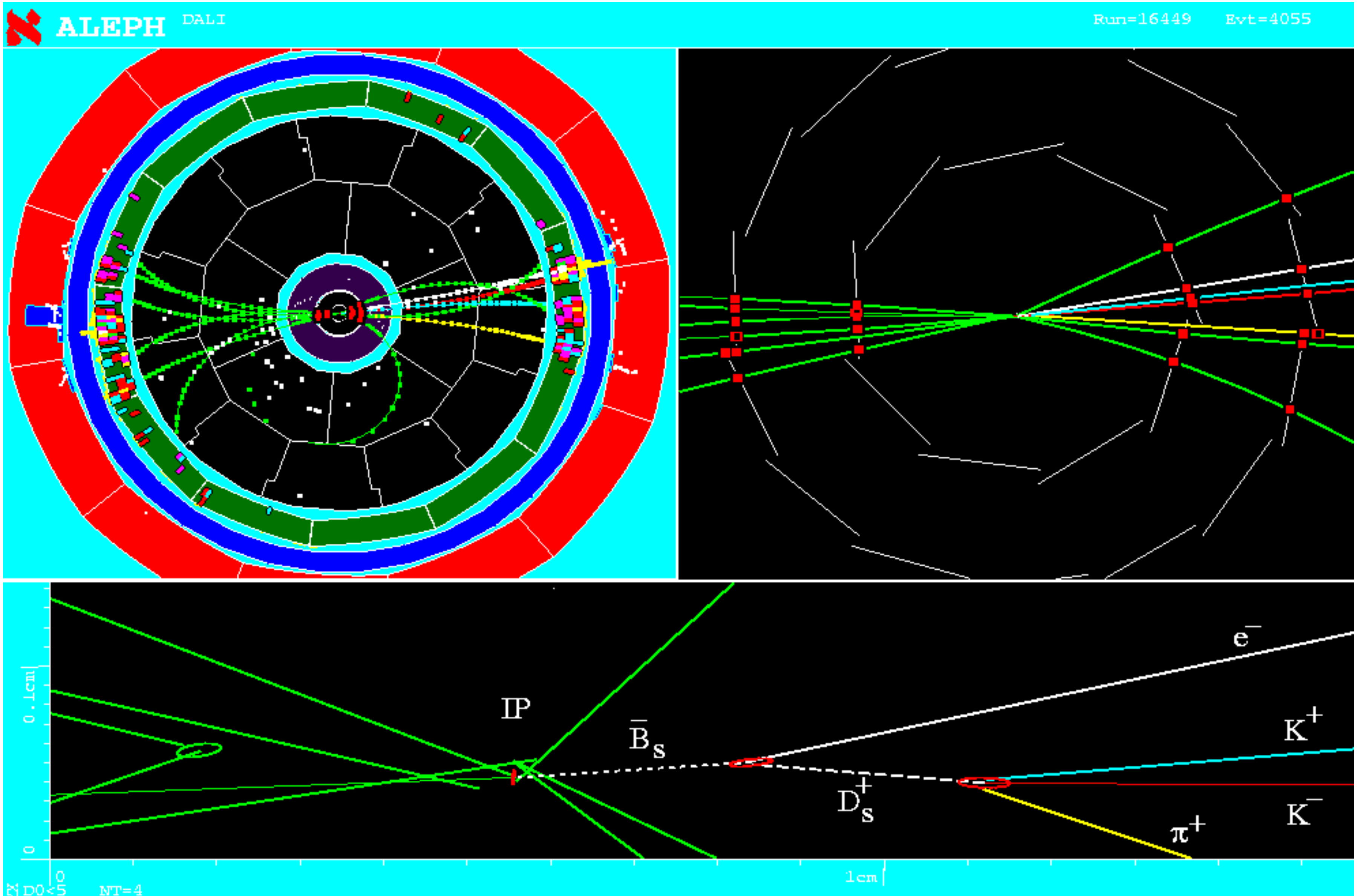
- Then brand-new technology
- Added after first years of running to all the LEP detectors

- ALEPH:
  - 100 µm strips
  - 12 µm resolution

- Break-through in heavy-flavour physics
  - lifetimes, oscillations, inclusive secondary vertex tags



Silicon vertex detector



2. The LEP legacy

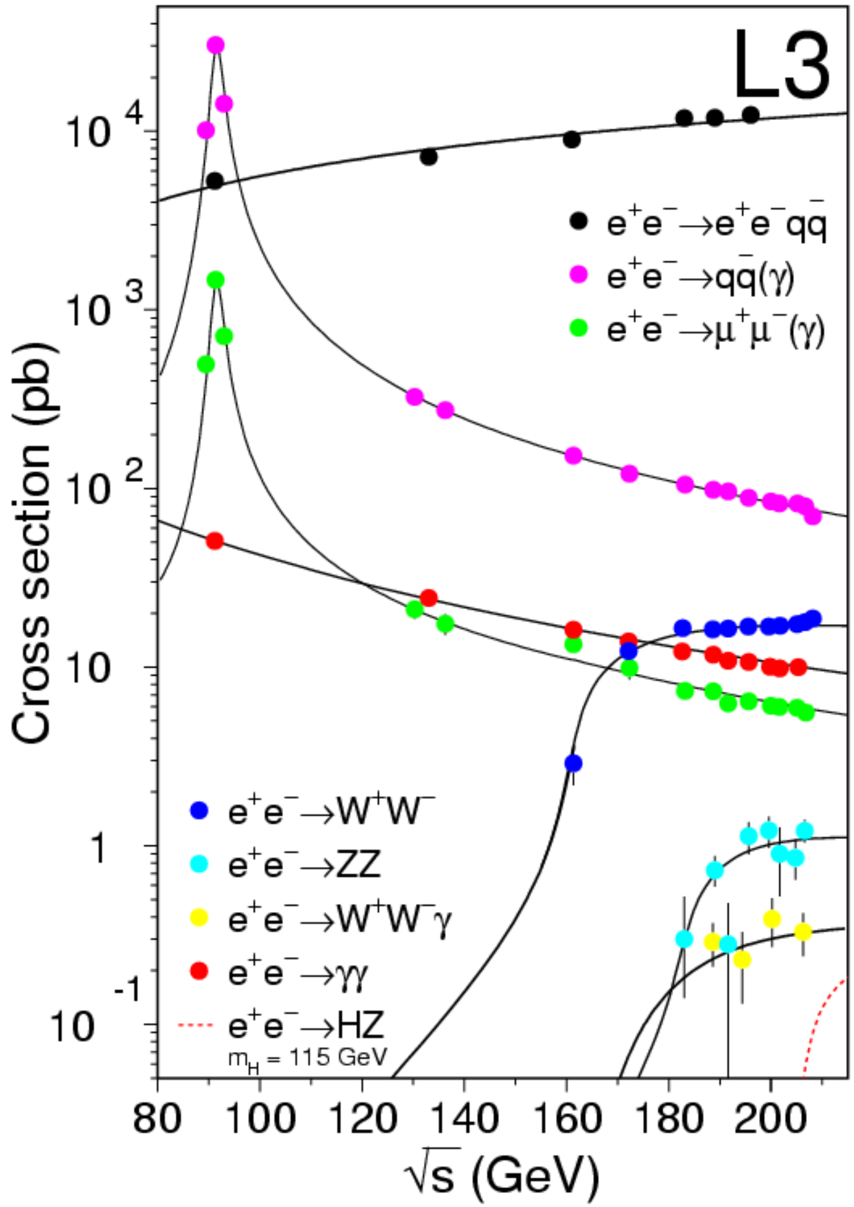
Machines and detectors

Physics highlights

Physics Highlights

- Electro-weak precision studies at the Z
- W boson physics
- QCD and heavy flavours

Cross sections at LEP



Electro-weak physics at the Z resonance

Electro-weak interactions

- Weak interaction couples to LH doublets of weak isospin I

$$(\nu_e)_R,\ (e^-)_R, \ldots (u)_R,\ (d)_R, \ldots$$ I = 0

$$\begin{pmatrix}\nu_e\\ e^-\end{pmatrix}_L, \begin{pmatrix}\nu_\mu\\ \mu^-\end{pmatrix}_L, \begin{pmatrix}\nu_\tau\\ \tau^-\end{pmatrix}_L \quad \begin{pmatrix}u\\ d'\end{pmatrix}_L, \begin{pmatrix}c\\ s'\end{pmatrix}_L, \begin{pmatrix}t\\ b'\end{pmatrix}_L$$

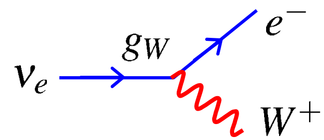
$I_3 = +1/2$

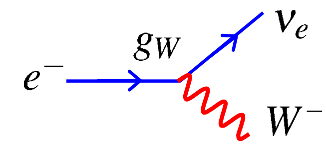
$I_3 = -1/2$

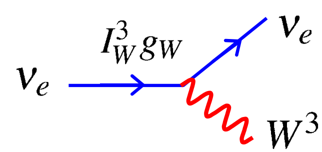
- Local SU(2) gauge invariance: 3 gauge bosons
  - charged and neutral currents

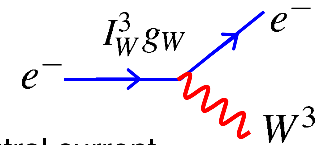
$$W_1^\mu,\ W_2^\mu,\ W_3^\mu$$

$W^\pm = 1/\sqrt{2}\,(W_1 \pm W_2)$



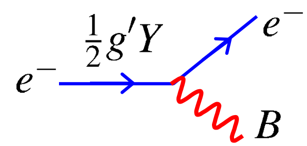






neutral current

- Add neutral spin 1 field B
- Coupling to hypercharge Y



Hypercharge $Y = 2Q - 2I_3$

- γ and Z super-positions of W_3 and B
- Weak mixing angle θ_W

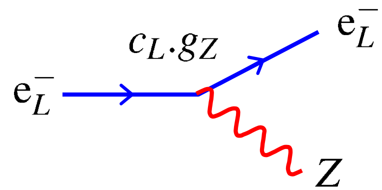
$$A_\mu = B_\mu \cos\theta_W + W_\mu^3 \sin\theta_W$$
$$Z_\mu = -B_\mu \sin\theta_W + W_\mu^3 \cos\theta_W$$

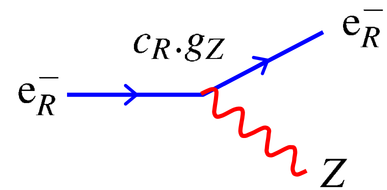
- Couplings related

$$e = g_W \sin\theta_W = g' \cos\theta_W = g_Z \cos\theta_W \sin\theta_W$$

Z boson couplings

- $W^{\pm}$ couples to LH only
- Z couples to both LH and RH, but differently





$$\boxed{c_L = I^3_W - Q\sin^2\theta_W}$$

$$\boxed{c_R = -Q\sin^2\theta_W}$$

W^3 part of Z couples only to LH components (like $W^{\pm}$)

B_μ part of Z couples equally to LH and RH components

- In terms of vector and axial vector
- Width $\Gamma(Z \to f\bar{f}) = \dfrac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2)$

$$\boxed{c_V = c_L + c_R = I_3 - 2\,Q\,\sin^2\theta_W}$$

$$\boxed{c_A = c_L - c_R = I_3}$$

Z boson couplings

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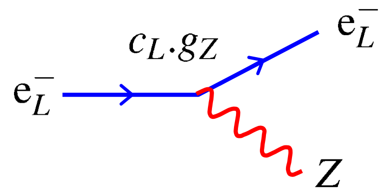
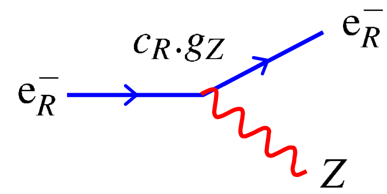




$$\boxed{c_L = I_W^3 - Q\sin^2\theta_W}$$

$$\boxed{c_R = -Q\sin^2\theta_W}$$

W^3 part of Z couples only to LH components (like $W^\pm$)

B_μ part of Z couples equally to LH and RH components

- In terms of vector and axial vector

$$\boxed{c_V = c_L + c_R = I_3 - 2\,Q\sin^2\theta_W}$$

$$\boxed{c_A = c_L - c_R = I_3}$$

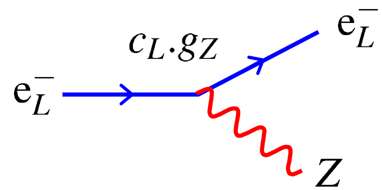
- Width $\Gamma(Z \to f\bar{f}) = \dfrac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2)$

using $\sin^2\theta_W = 0.23$

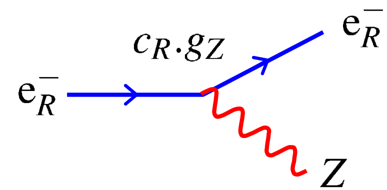
Fermion	Q	I_W^3	c_L	c_R	c_V	c_A
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$+\frac{1}{2}$
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$

Z boson couplings

- $W^{\pm}$ couples to LH only
- Z couples to both LH and RH, but differently



$$\boxed{c_L = I_W^3 - Q\sin^2\theta_W}$$



$$\boxed{c_R = -Q\sin^2\theta_W}$$

W^3 part of Z couples only to LH components (like $W^{\pm}$)

B_μ part of Z couples equally to LH and RH components

- In terms of vector and axial vector

$$c_V = c_L + c_R = I_3 - 2\,Q\,\sin^2\theta_W$$

$$c_A = c_L - c_R = I_3$$

- Width $\Gamma(Z \to f\bar{f}) = \frac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2)$

using $\sin^2\theta_W = 0.23$

Fermion	Q	I_W^3	c_L	c_R	c_V	c_A	$c_V^2 + c_A^2$
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0.50
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$	0.25
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$+\frac{1}{2}$	0.29
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$	0.37

Z boson couplings

- $W^{\pm}$ couples to LH only
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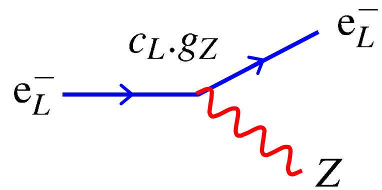

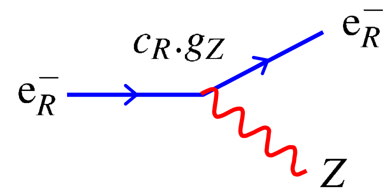

$\boxed{c_L = I_W^3 - Q\sin^2\theta_W}$ $\boxed{c_R = -Q\sin^2\theta_W}$

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B_μ part of Z couples equally to LH and RH components

- In terms of vector and axial vector

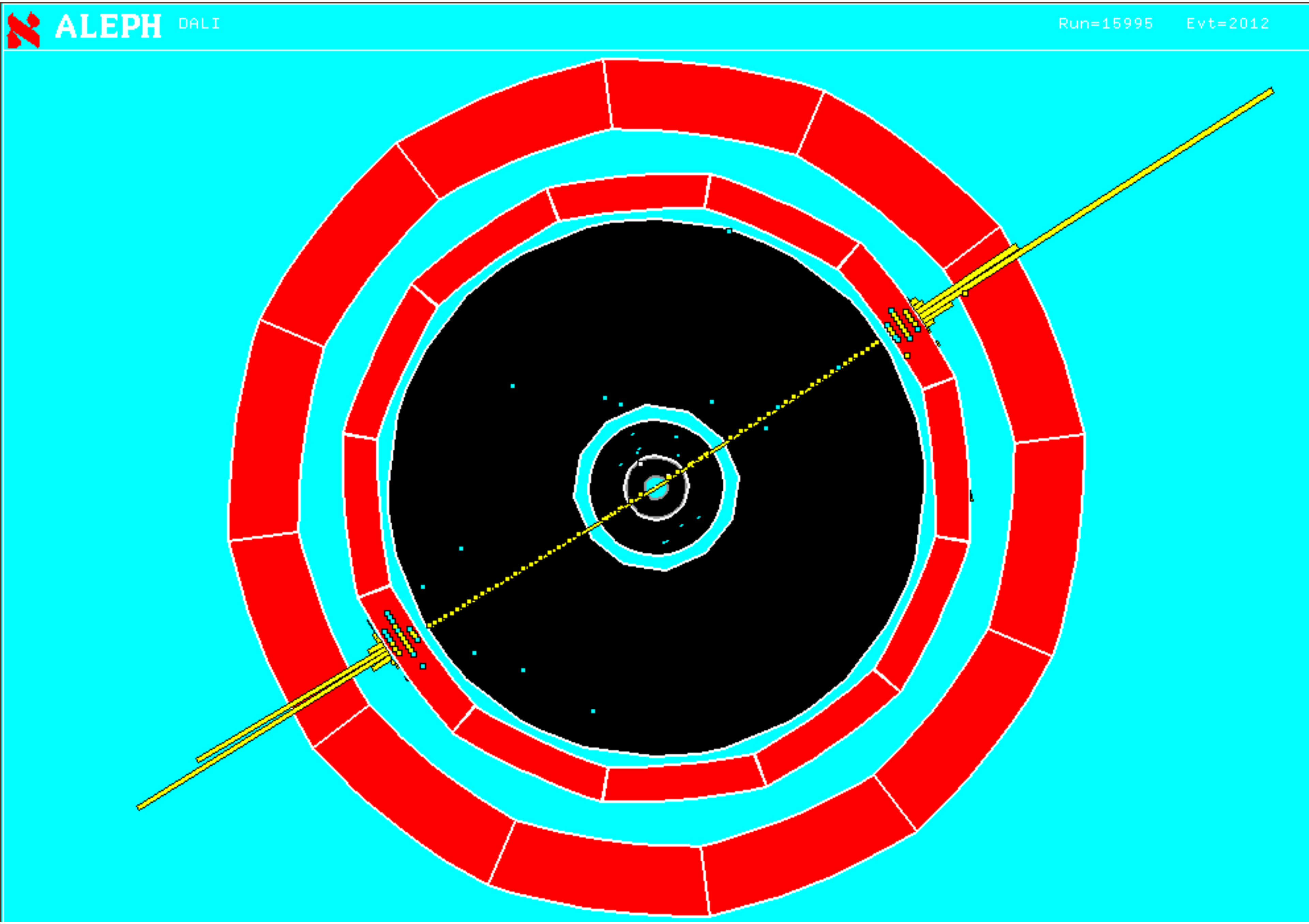
$\boxed{c_V = c_L + c_R = I_3 - 2\,Q\sin^2\theta_W}$

$\boxed{c_A = c_L - c_R = I_3}$

- Width $\Gamma(Z \to f\bar{f}) = \dfrac{g_Z^2 m_Z}{48\pi}(c_V^2 + c_A^2)$

using $\sin^2\theta_W = 0.23$

Fermion	Q	I_W^3	c_L	c_R	c_V	c_A	$c_V^2 + c_A^2$	BR
ν_e, ν_μ, ν_τ	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{1}{2}$	$+\frac{1}{2}$	0.50	6.9%
e^-, μ^-, τ^-	-1	$-\frac{1}{2}$	-0.27	0.23	-0.04	$-\frac{1}{2}$	0.25	3.5%
u, c, t	$+\frac{2}{3}$	$+\frac{1}{2}$	0.35	-0.15	$+0.19$	$+\frac{1}{2}$	0.29	12%
d, s, b	$-\frac{1}{3}$	$-\frac{1}{2}$	-0.42	0.08	-0.35	$-\frac{1}{2}$	0.37	15%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DALI
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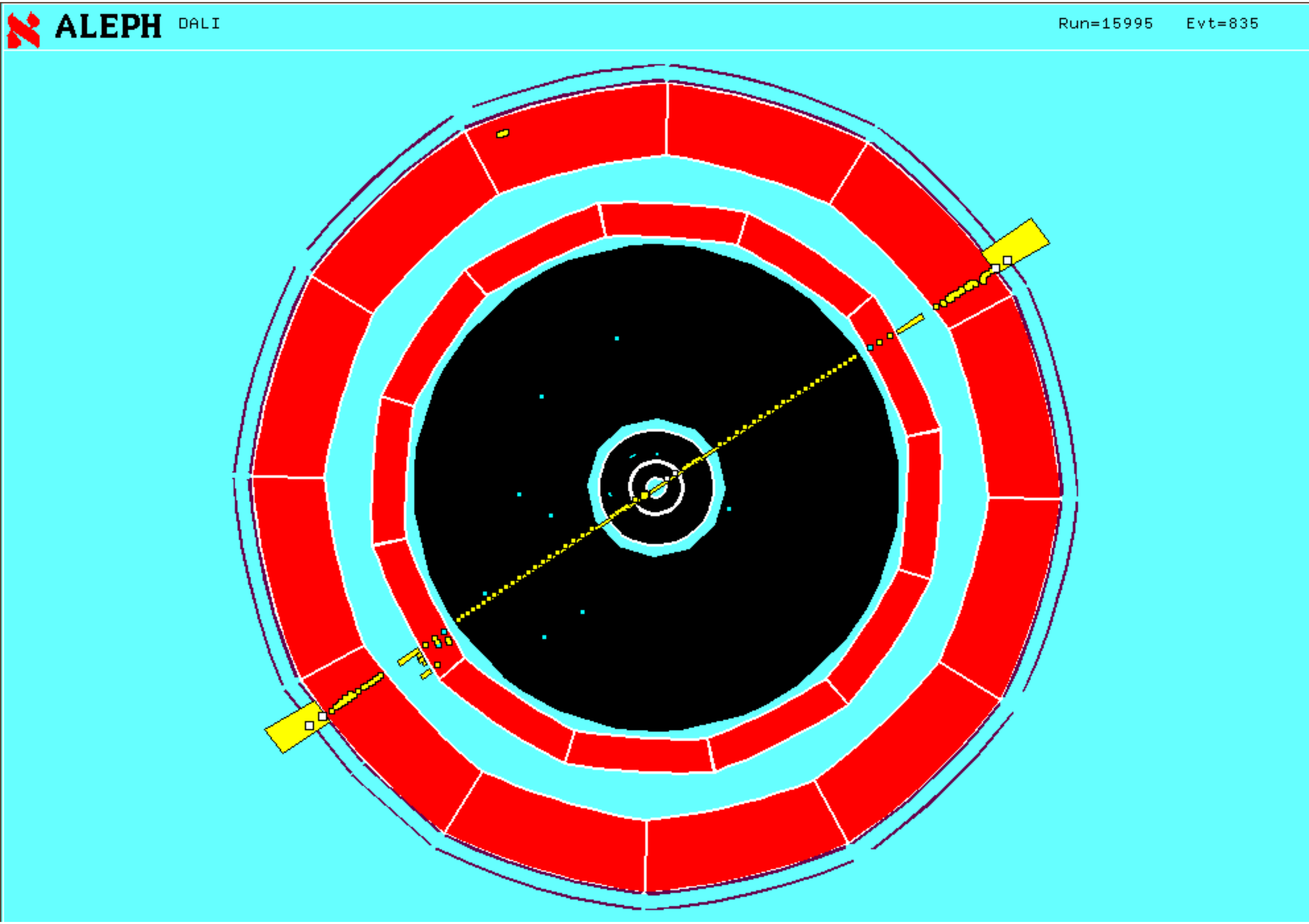
Evt=2012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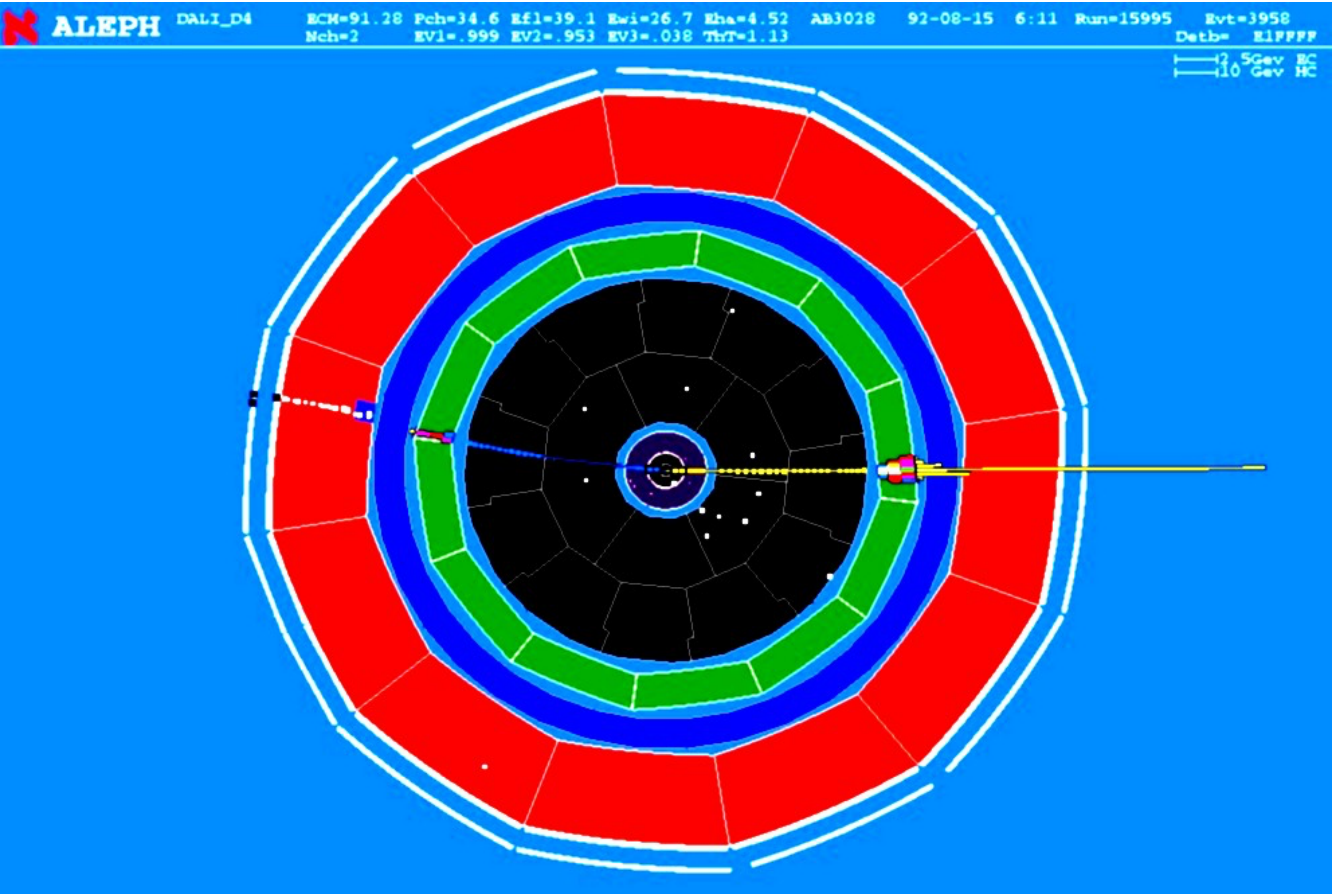
DALI
Run=15995
Evt=835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DALI_D4
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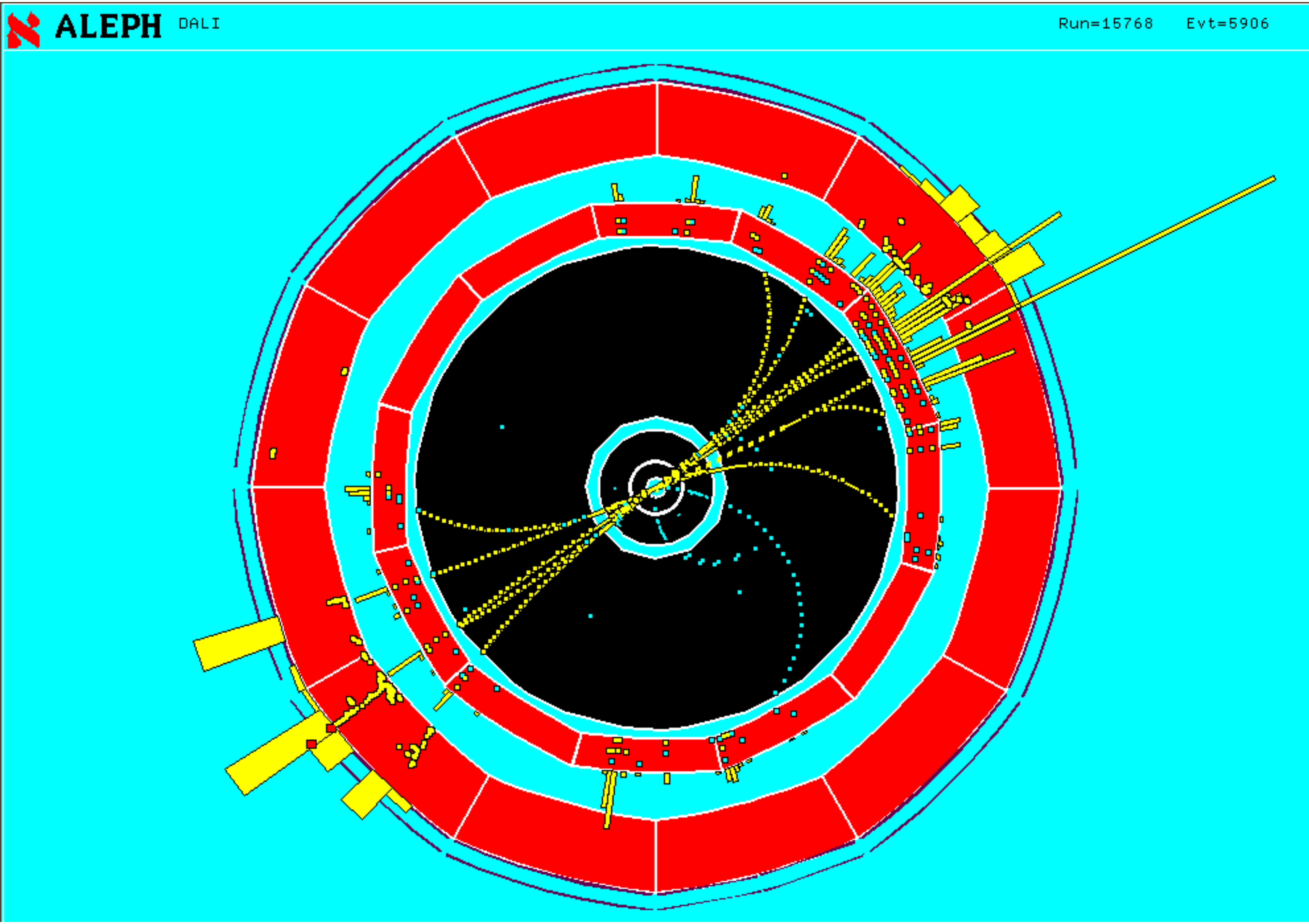
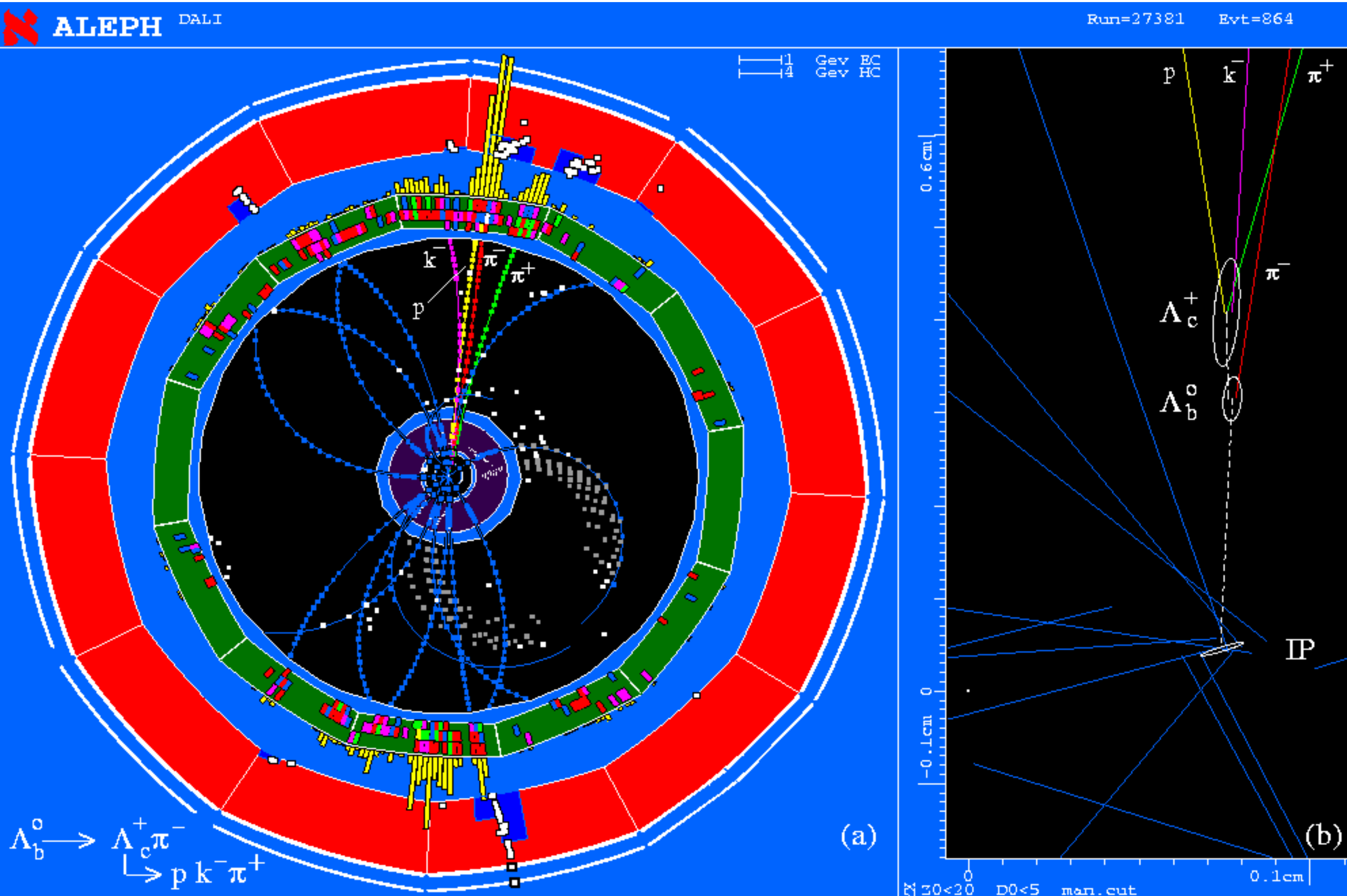
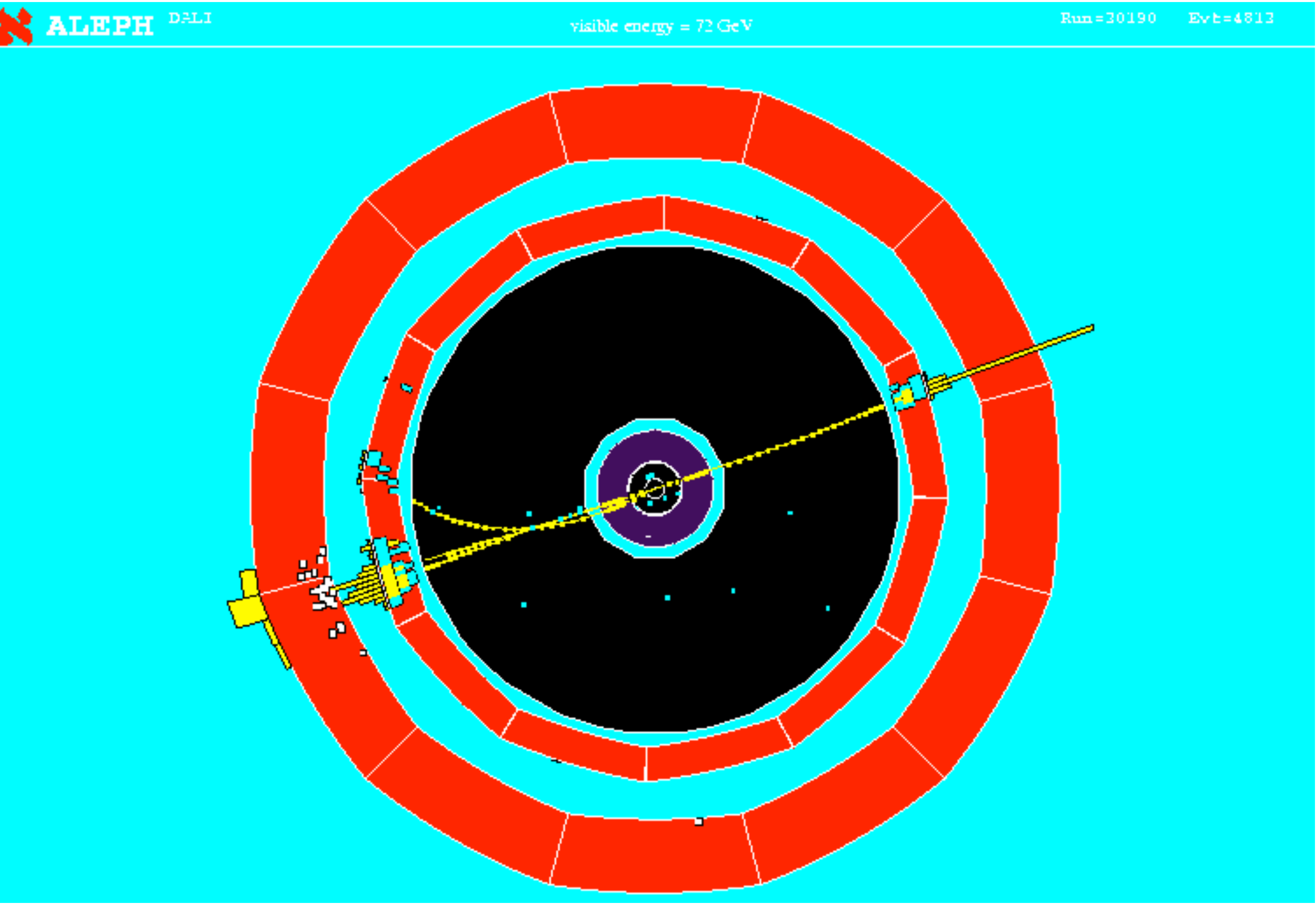
Nch=2 EV1=.999 EV2=.953 EV3=.038 ThT=1.13
AB3028
92-08-15 6:11 Run=15995 Evt=3958
Detb= E1FFFF
2.5Gev EC
10 Gev HC

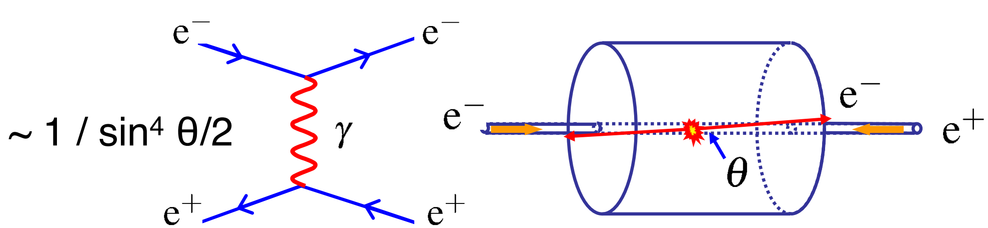

ALEPH
DALI
Run=15768
Evt=5906

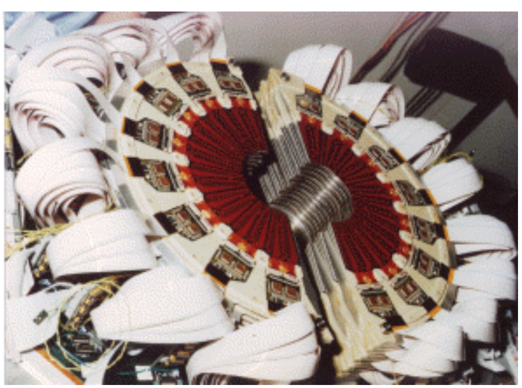

ALEPH DALI
Run=27381 Evt=864
1 Gev EC
4 Gev HC
k⁻
π⁻
π⁺
p
(a)
$\Lambda_b^o \longrightarrow \Lambda_c^+ \pi^-$
$\hookrightarrow p\, k^- \pi^+$
p
k⁻
π⁺
π⁻
Λ_c^+
Λ_b^o
IP
0.6cm
0
-0.1cm
0.1cm
(b)
YX 30<20 D0<5 man.cut


ALEPH
DALI
visible energy = 72 GeV
Run=30190
Evt=4813

Z branching ratios

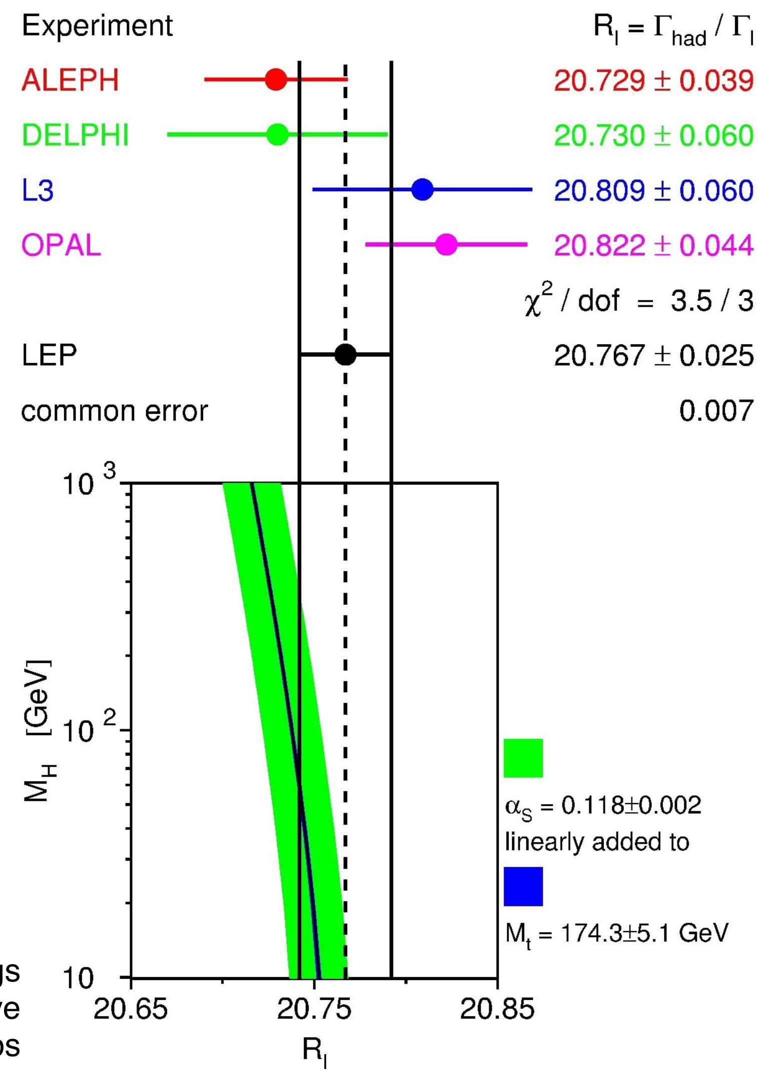
- Classify events and count them
- Normalise to luminosity
  - Bhabha events
  - only QED, exact
  - but experimentally non-trivial ?
- Or to each other
  - cancel systematics



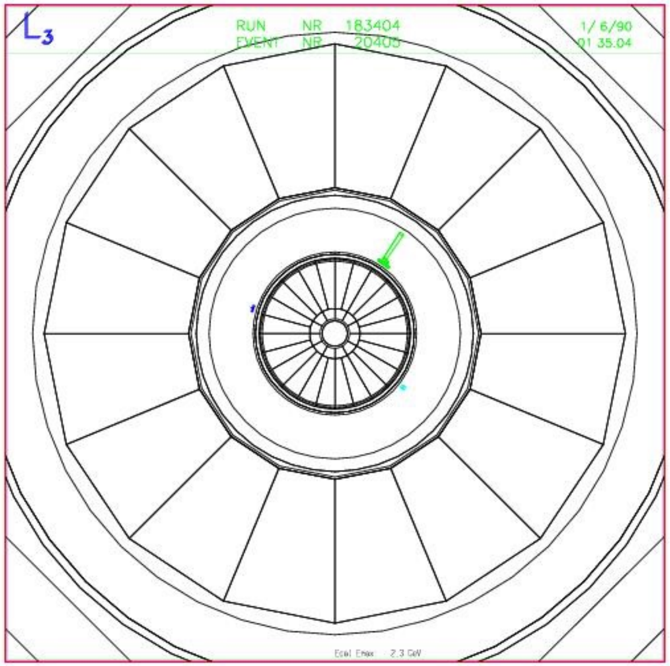


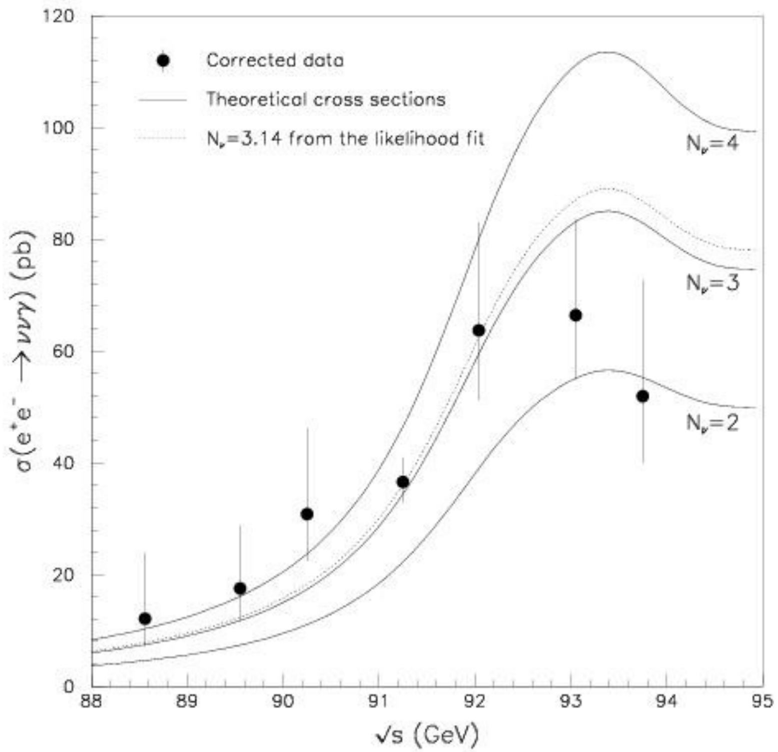
ALEPH
SiW calo

Masses of top and Higgs enter through radiative corrections, e.g. virtual loops

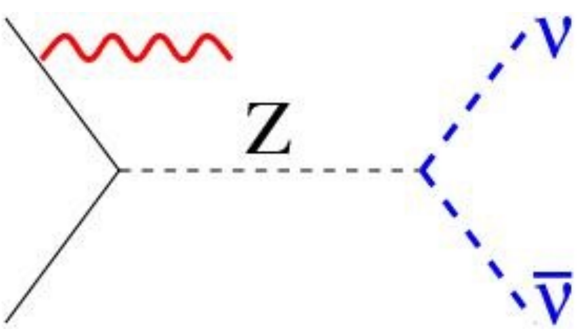


Counting neutrinos



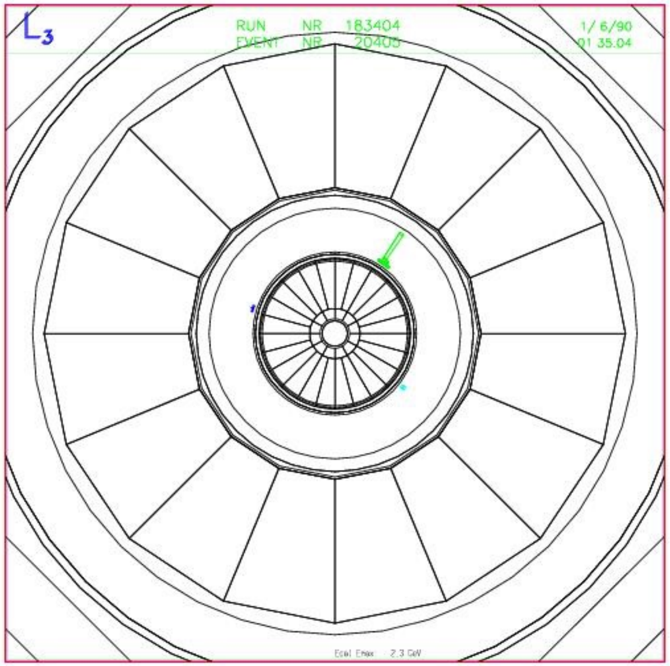


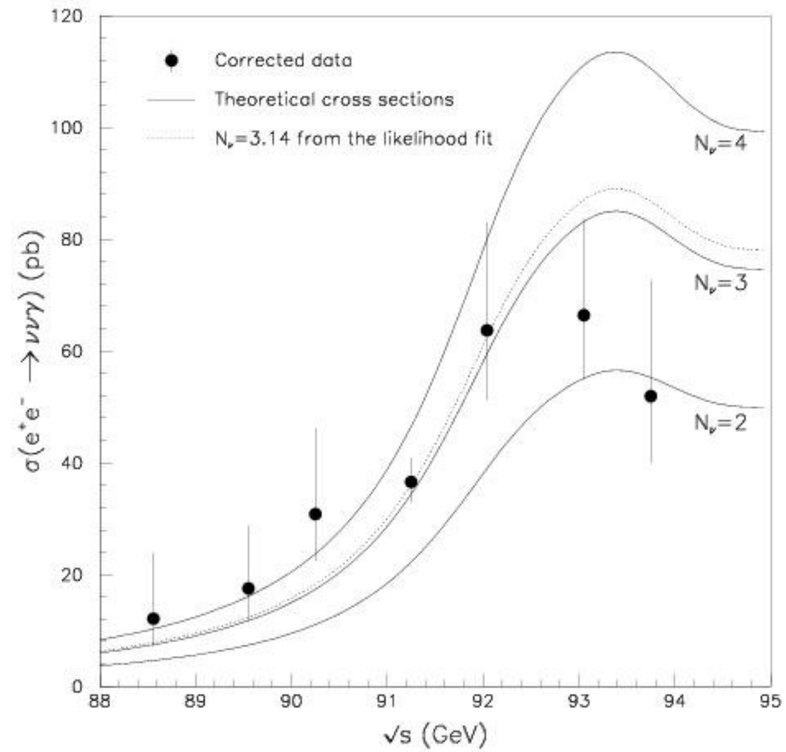
$\sqrt{s} = 2\, E_{beam} - E_\gamma$



- prefers N = 3, but…
- smarter way:

Counting neutrinos





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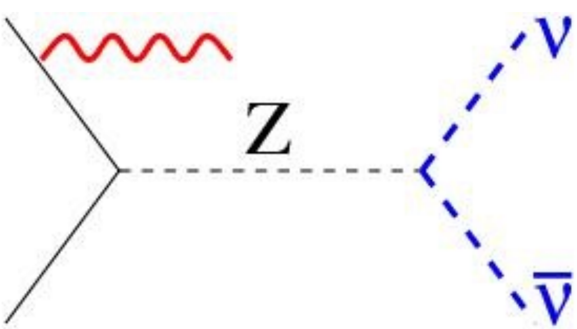
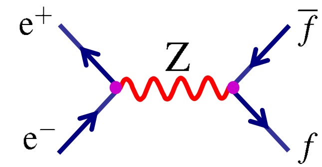


- prefers N = 3, but…
- smarter way:

$$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{qq} + N_{families}\Gamma_{\nu\nu}$$

The Z resonance



$$\psi \sim e^{-imt} e^{-\Gamma t/2}$$

- Z cross-section:

$$\sigma_{e^+e^- \to Z \to \mu^+\mu^-} = \frac{1}{192\pi} \frac{g_Z^4 s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \left[(c_V^e)^2 + (c_A^e)^2 \right] \left[(c_V^\mu)^2 + (c_A^\mu)^2 \right]$$

- Recall:

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s} \frac{|\vec{p}_f|}{|\vec{p}_i|} |M_{fi}|^2 \qquad \Gamma = \frac{p^*}{32\pi^2 m_a^2} \int |M_{fi}|^2 d\Omega$$

- Partial width:

$$\Gamma(Z \to \mu^+\mu^-) = \frac{g_Z^2 m_Z}{48\pi} \left[(c_V^\mu)^2 + (c_A^\mu)^2 \right]$$

- Relation:

$$\sigma = \frac{12\pi}{m_Z^2} \frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma(Z \to e^+e^-) \Gamma(Z \to \mu^+\mu^-)$$

- For any fermion pair:

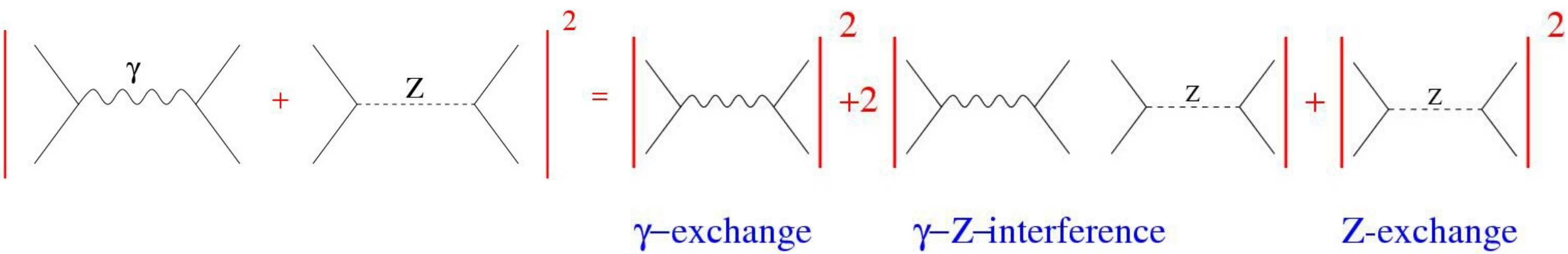
$$\sigma(e^+e^- \to Z \to f\bar{f}) = \frac{12\pi}{m_Z^2} \frac{s}{(s-m_Z^2)^2 + m_Z^2\Gamma_Z^2} \Gamma_{ee}\Gamma_{ff}$$

- At the peak:

$$\sigma^0_{f\bar{f}} = \frac{12\pi}{m_Z^2} \frac{\Gamma_{ee}\Gamma_{ff}}{\Gamma_Z^2}$$

- Full width half maximum FWHM: $\Gamma_Z = 1 / \tau_Z$

Total cross section

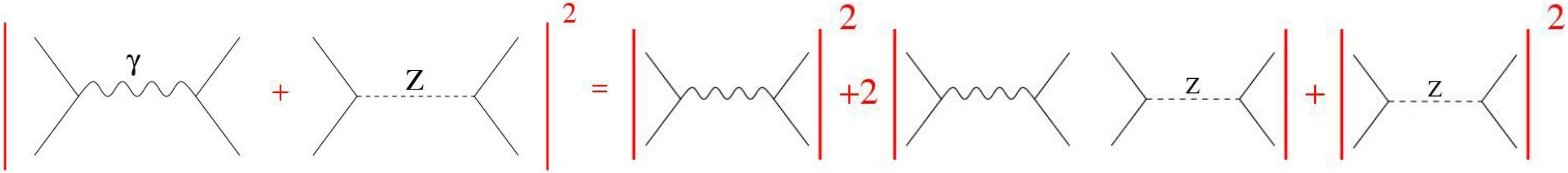


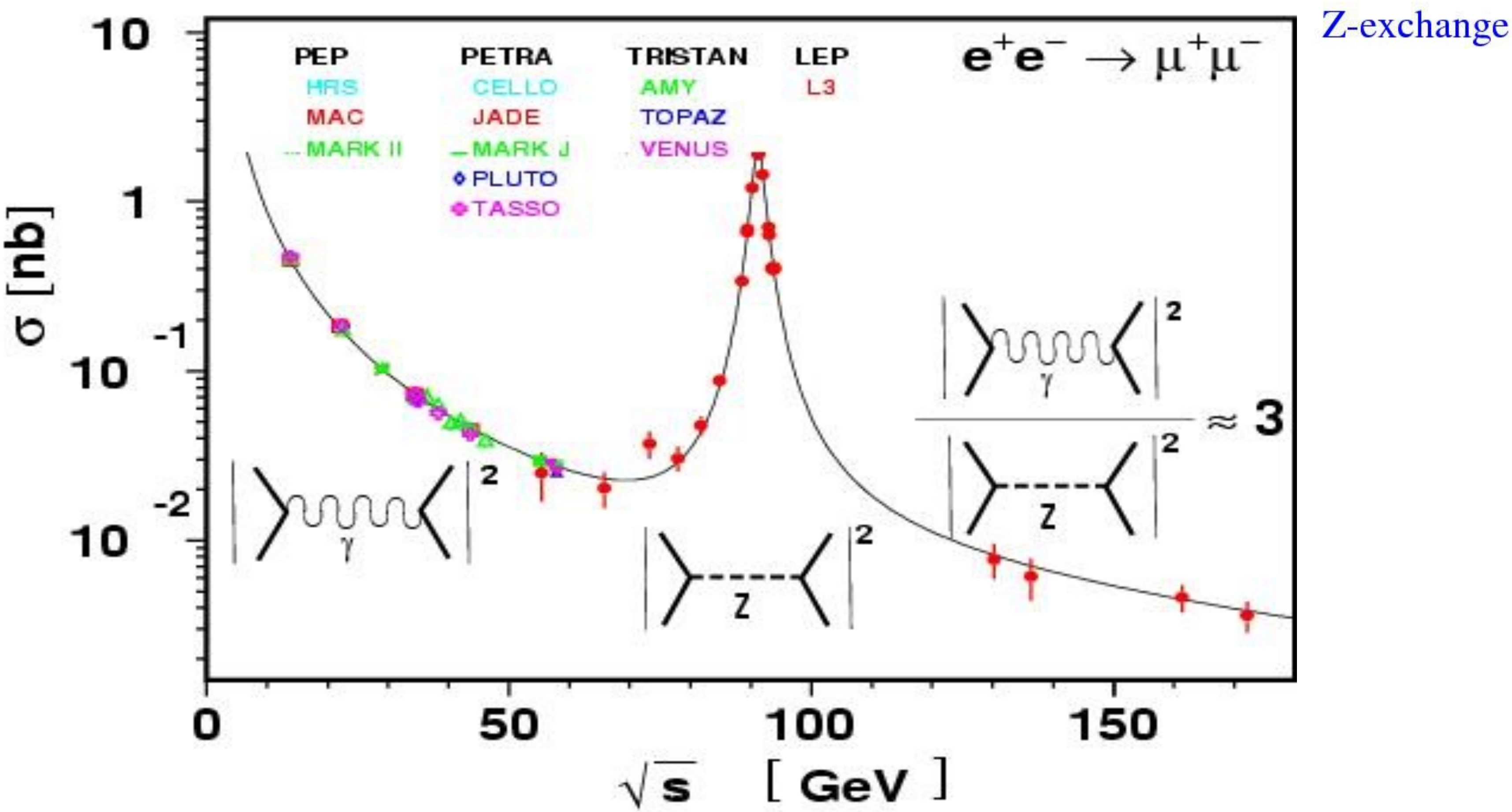
$$\frac{d\sigma}{d\Omega} = N_c \frac{\alpha^2}{4s} \quad \{(1+\cos^2\theta)\left[Q_f^2 - 2\chi_1 v_e v_f Q_f - \chi_2 \left(a_e^2+v_e^2\right)\left(a_f^2+v_f^2\right)\right]$$

$$+2\cos\theta\left[-2\chi_1 a_e a_f Q_f + 4\chi_2 a_e a_f v_e v_f\right]\}$$

$$\begin{aligned}
\chi_1 &= \frac{1}{16\sin^2\theta_W\cos^2\theta_W}\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\\
\chi_2 &= \frac{1}{256\sin^4\theta_W\cos^4\theta_W}\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}\\
a_e &= -1\\
v_e &= -1+4\sin^2\theta_W\\
a_f &= 2T_{3f}\\
v_f &= 2T_{3f}-4Q_f\sin^2\theta_W
\end{aligned}$$

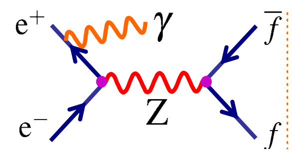
Total cross section

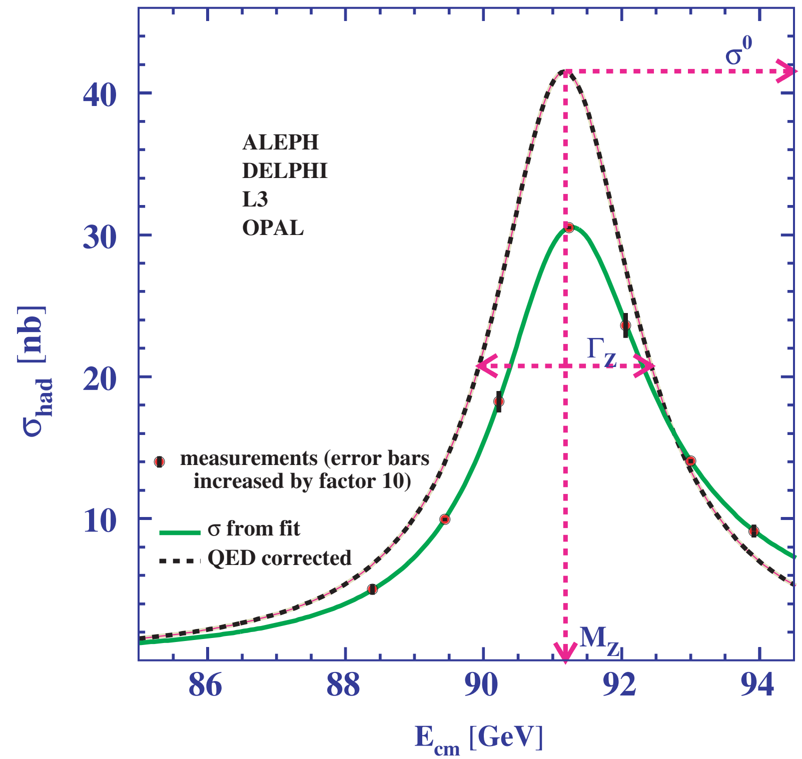


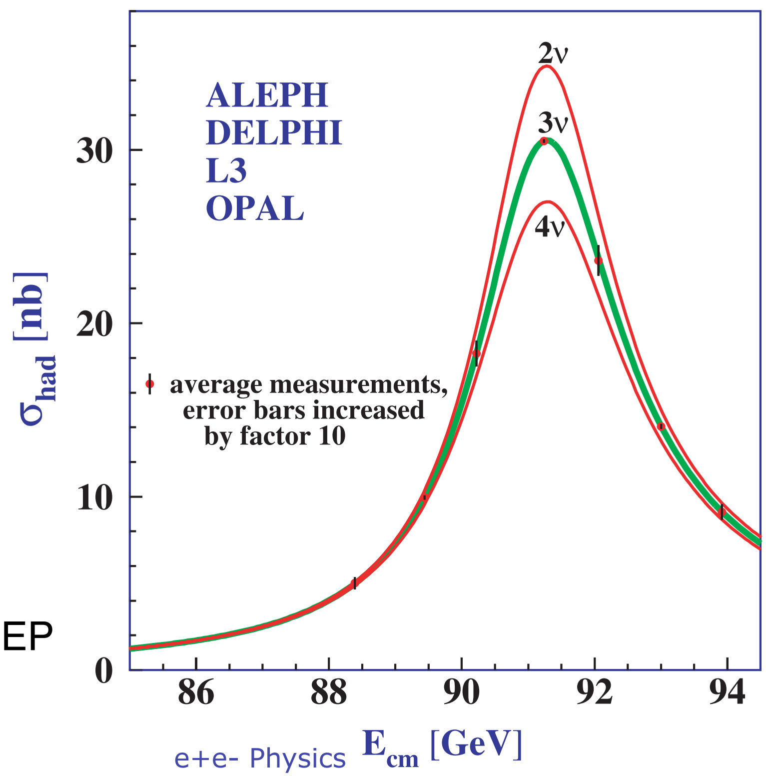


Z line shape analysis

- In practice, radiative corrections are important
  - and for electrons: t channel
- Assuming lepton universality:
- $\Gamma_Z = 3\ \Gamma_{lepton} + \Gamma_{hadrons} + \mathbf{N_\nu}\ \Gamma_{\nu\nu}$
  - Γ_{lepton}, $\Gamma_{hadrons}$ from σ_0, $\Gamma_{\nu\nu}$ calc.
- $N_\nu = 2.9840 \pm 0.0082$







N < 5.9
before LEP

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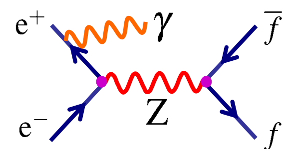
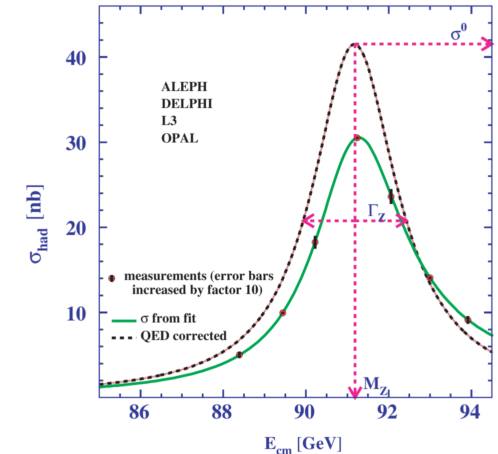
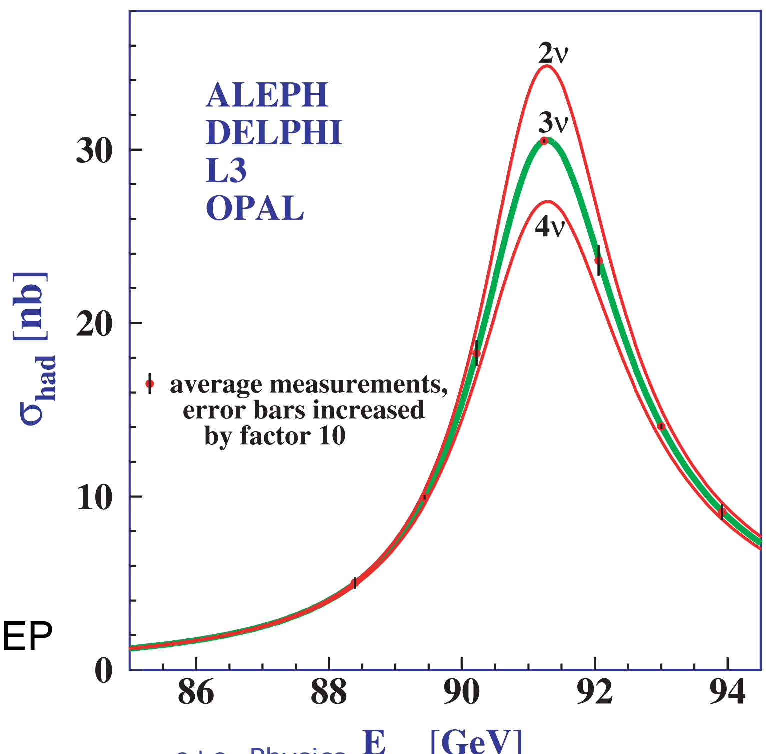
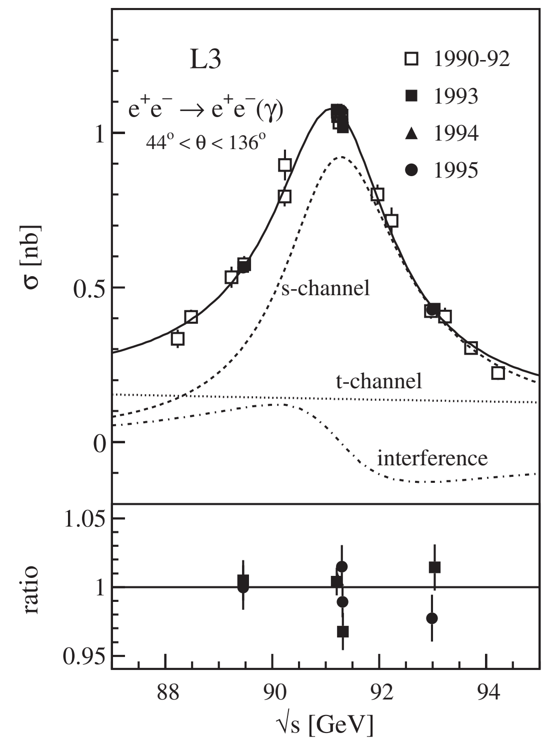




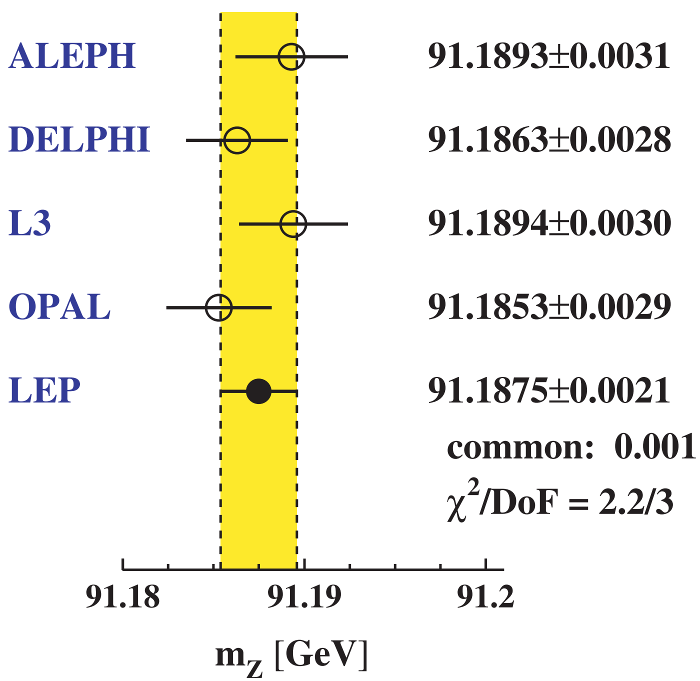


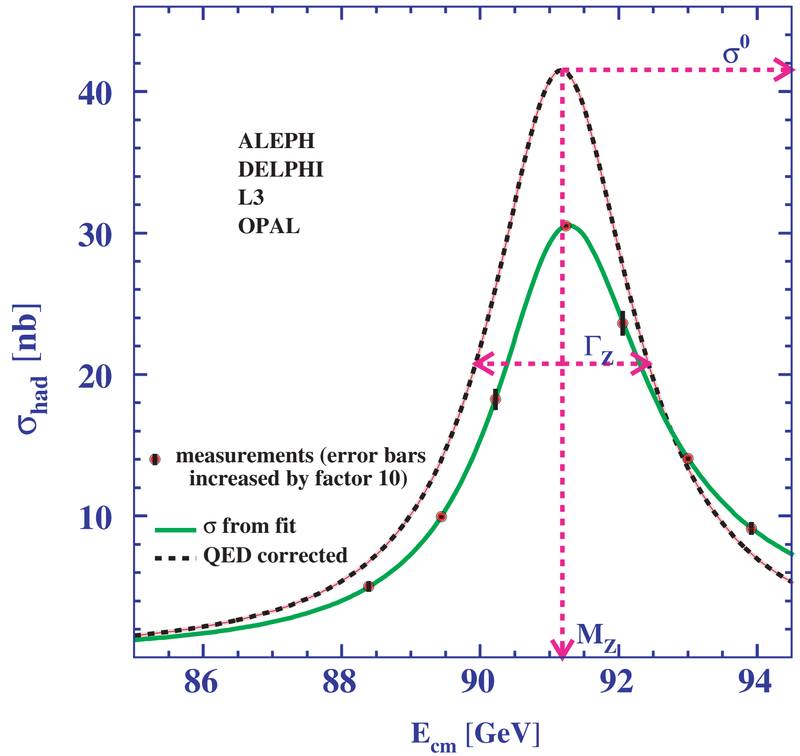
N < 5.9
before LEP



The Z mass

- From the line shape
- Precision 2 x 10^{-5}
- Need to understand many tiny effects
- Crucial: beam energy calibration
- NB: Z width much less affected





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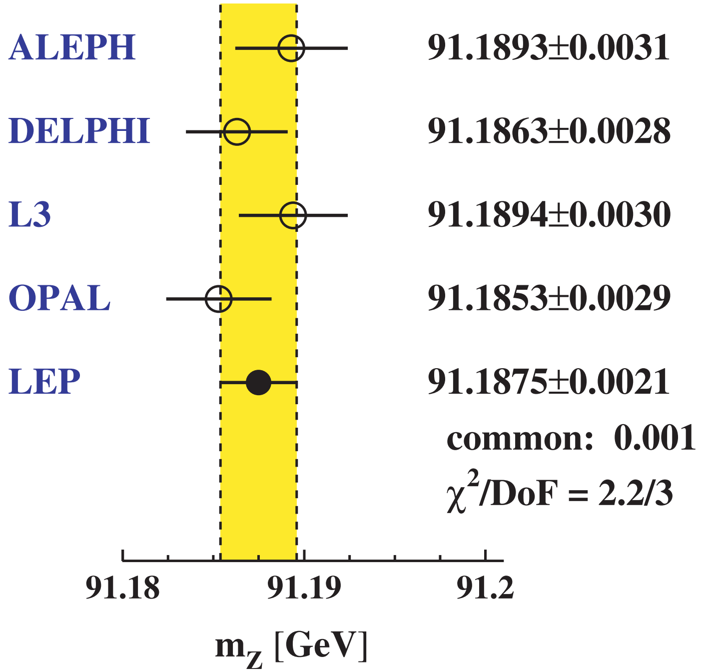
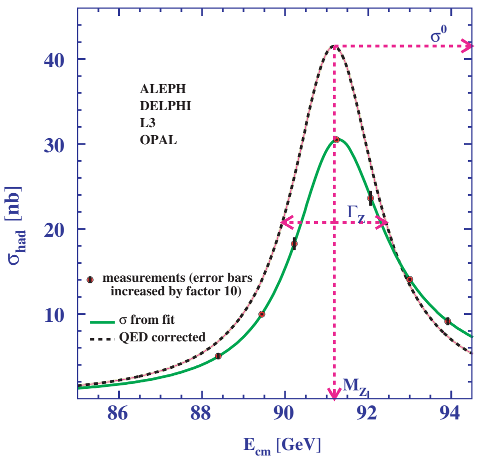
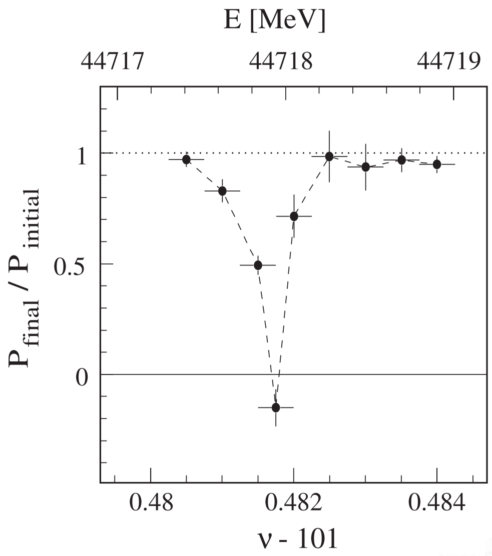
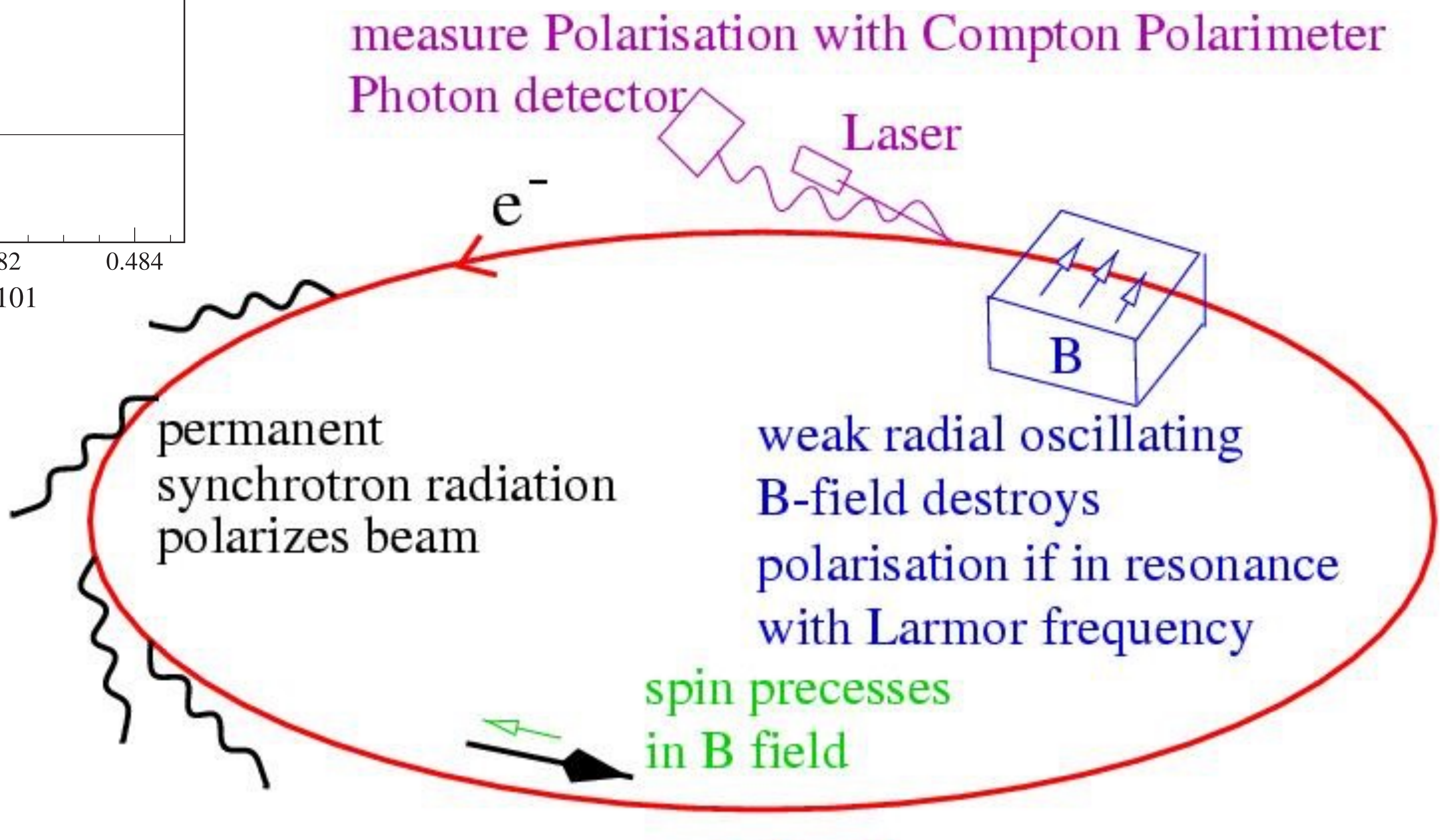




LEP beam energy calibration

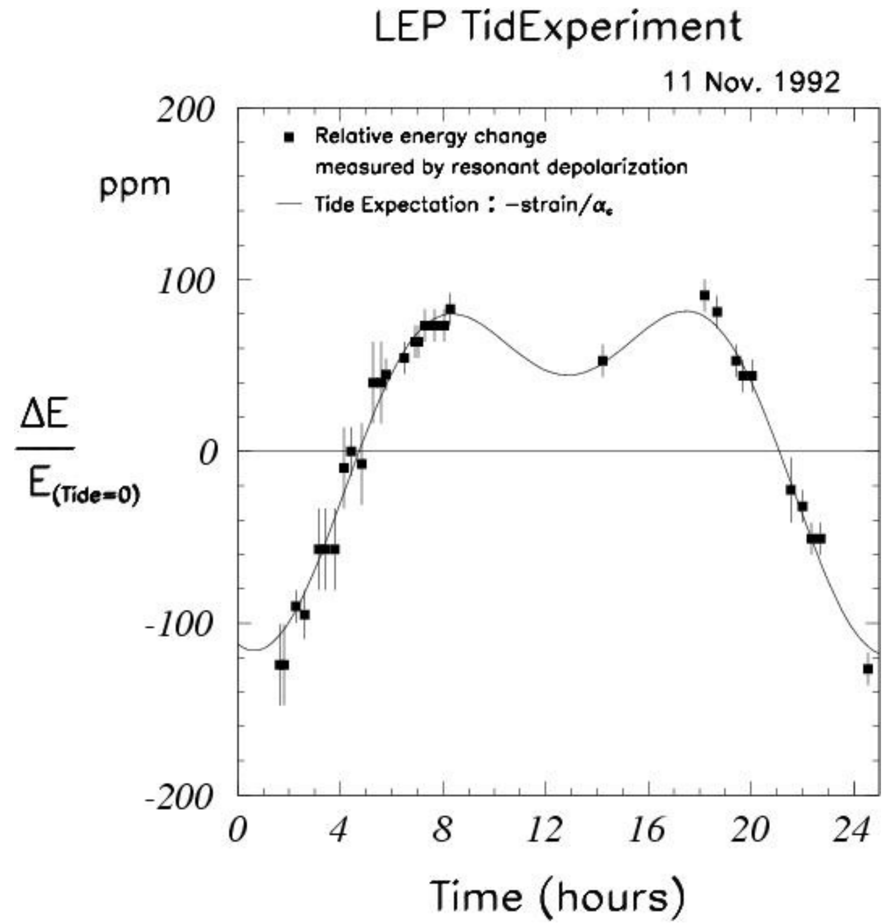


- Resonant depolarisation

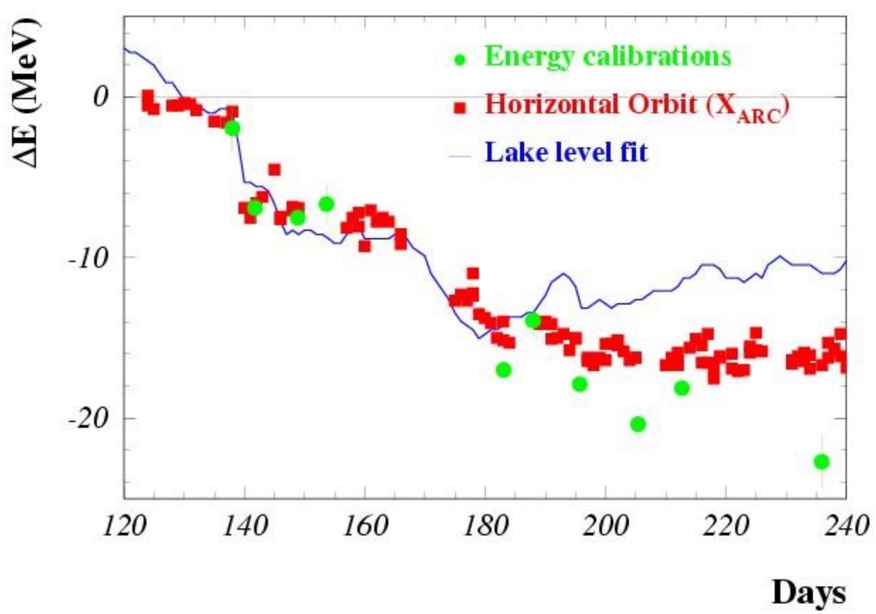


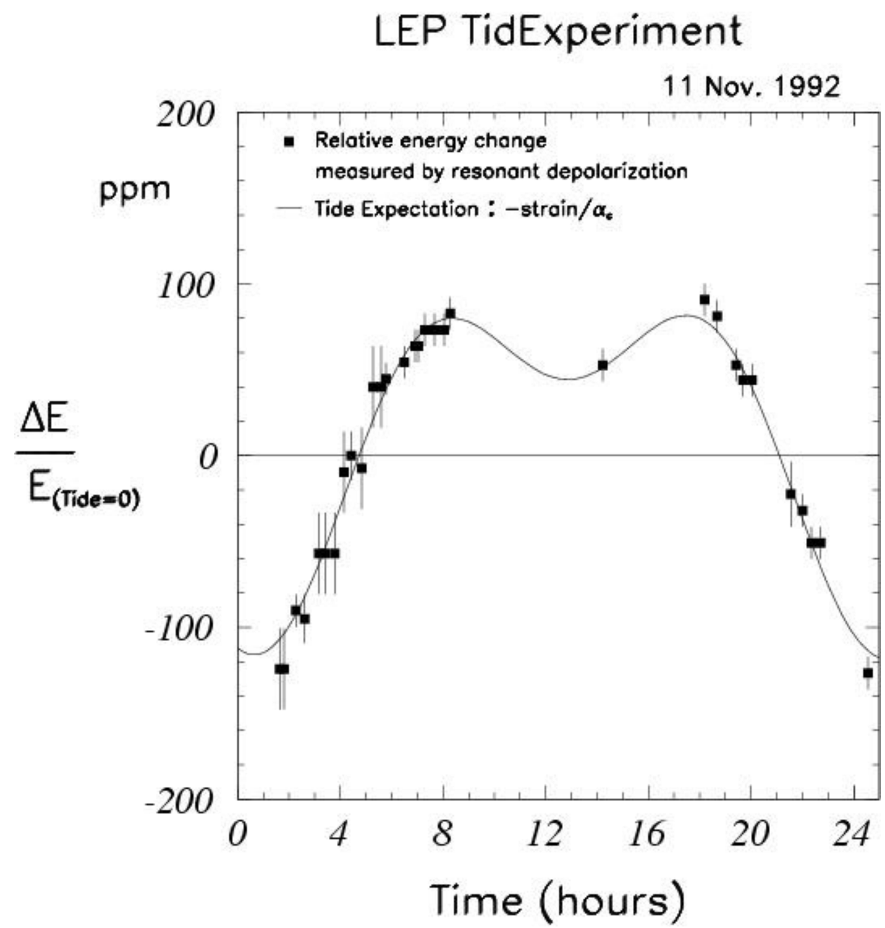
$$\nu = \frac{g-2}{2} \frac{E}{mc^2}$$ (Larmor frequency)

Beam energy variations



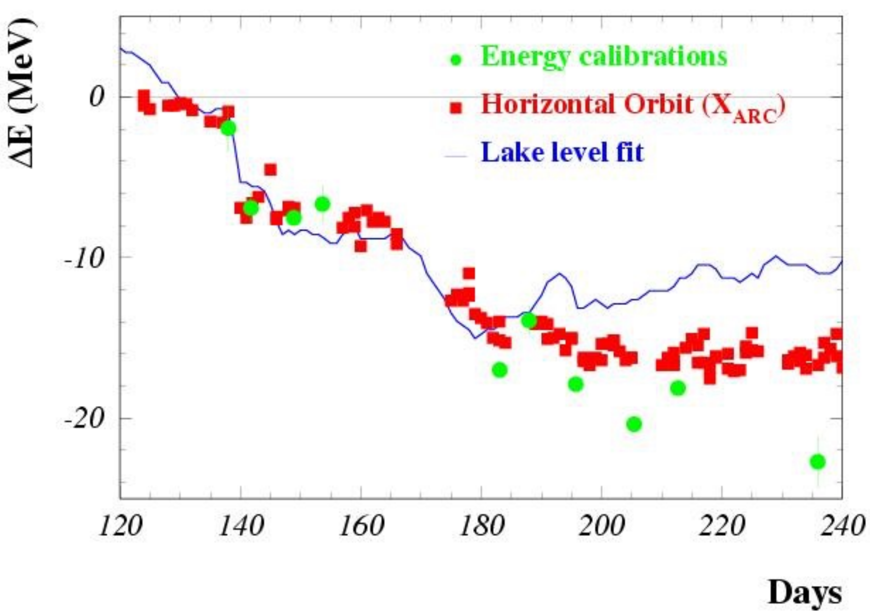
Beam energy variations

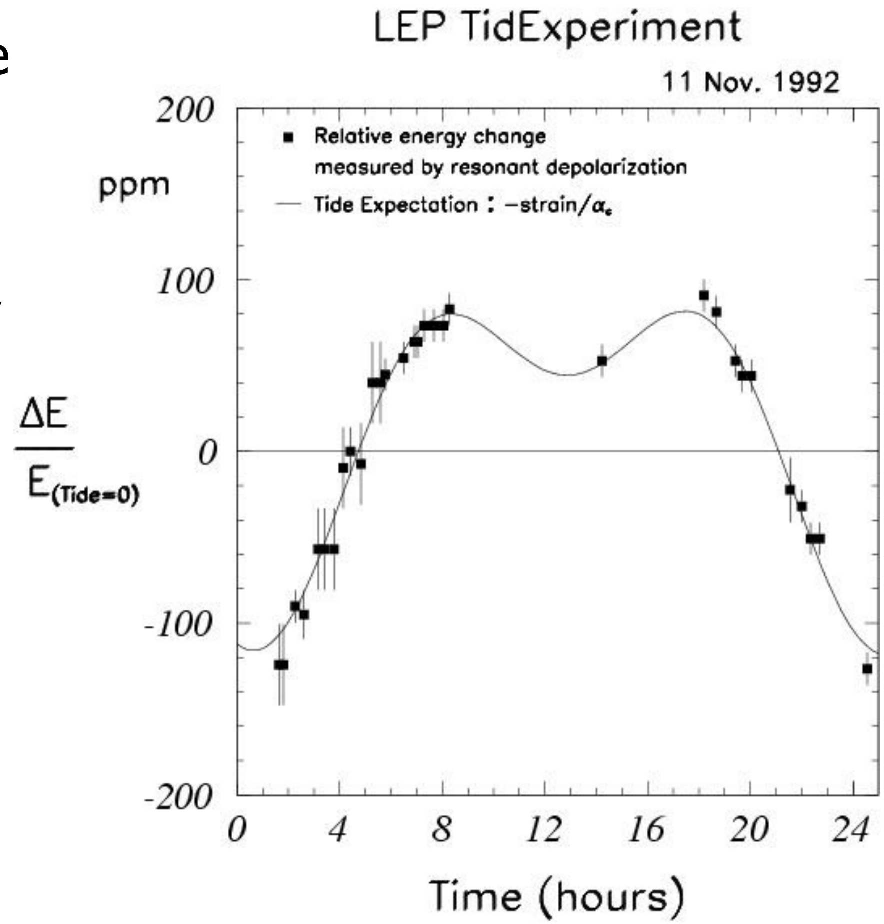




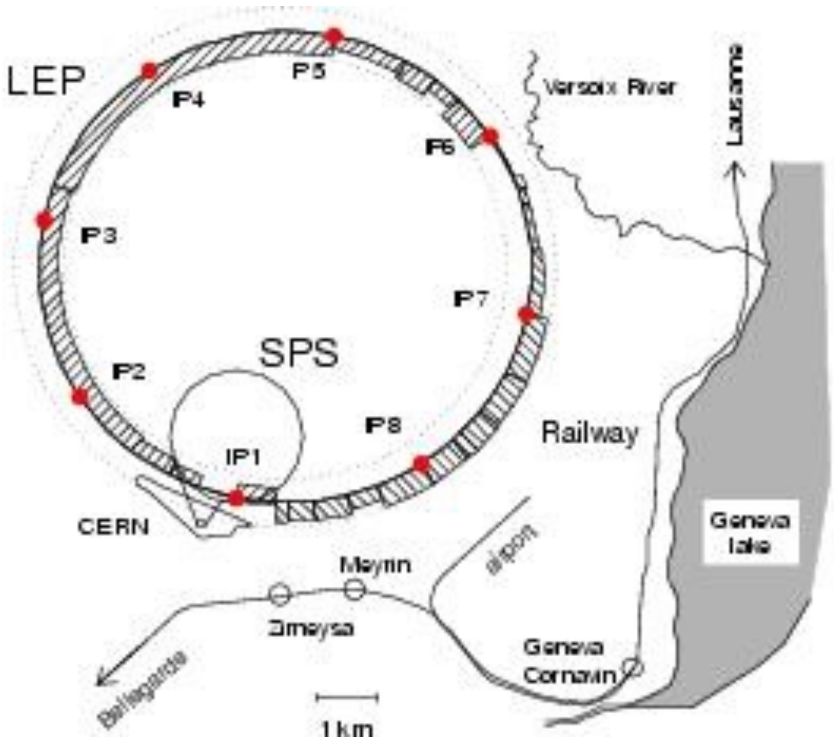
Beam energy variations

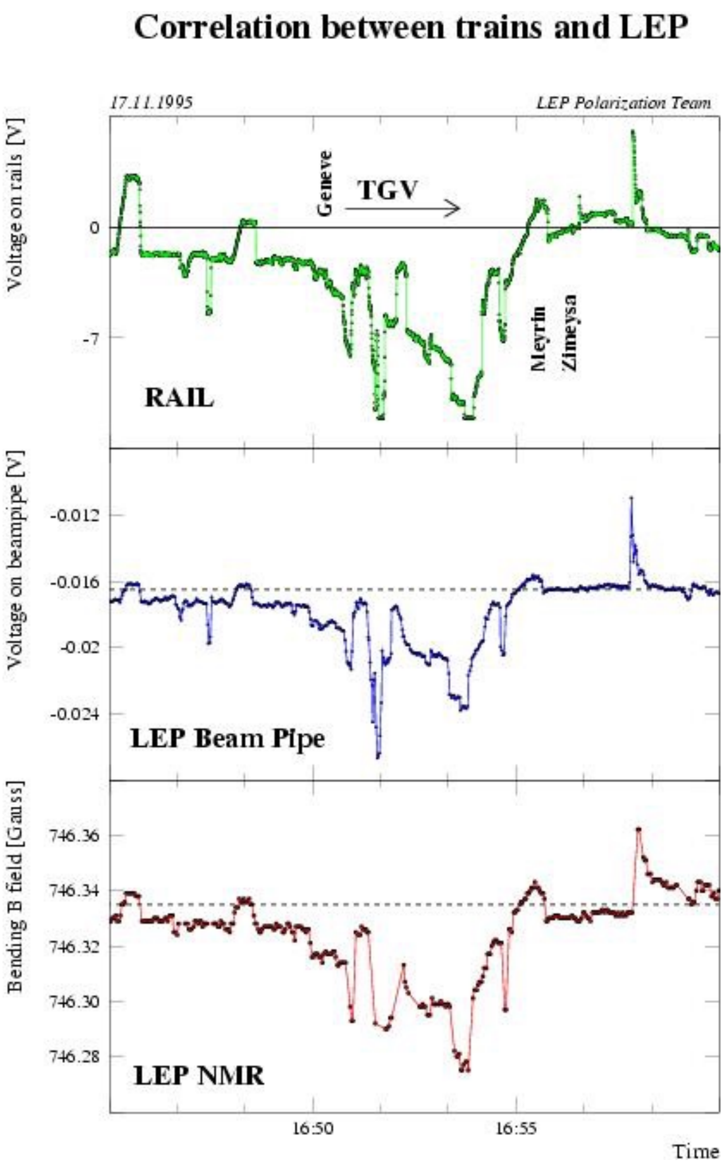
- Tidal effects in the rock move the magnets and change the orbit, thus RF phase and energy
- 1mm larger radius → 10 MeV more energy
- Similar effect by Lake Geneva water level





More energy variations





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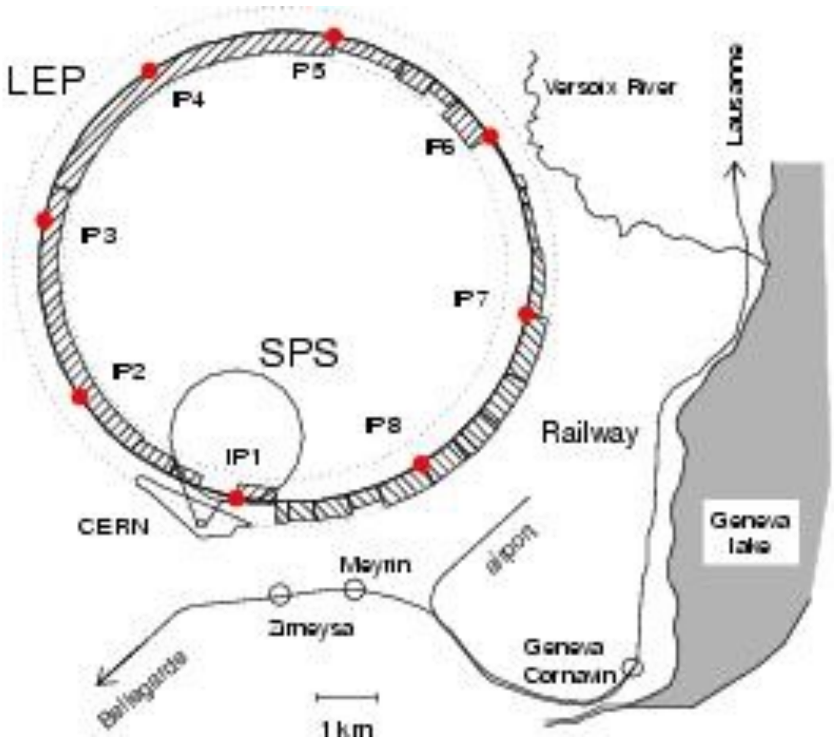

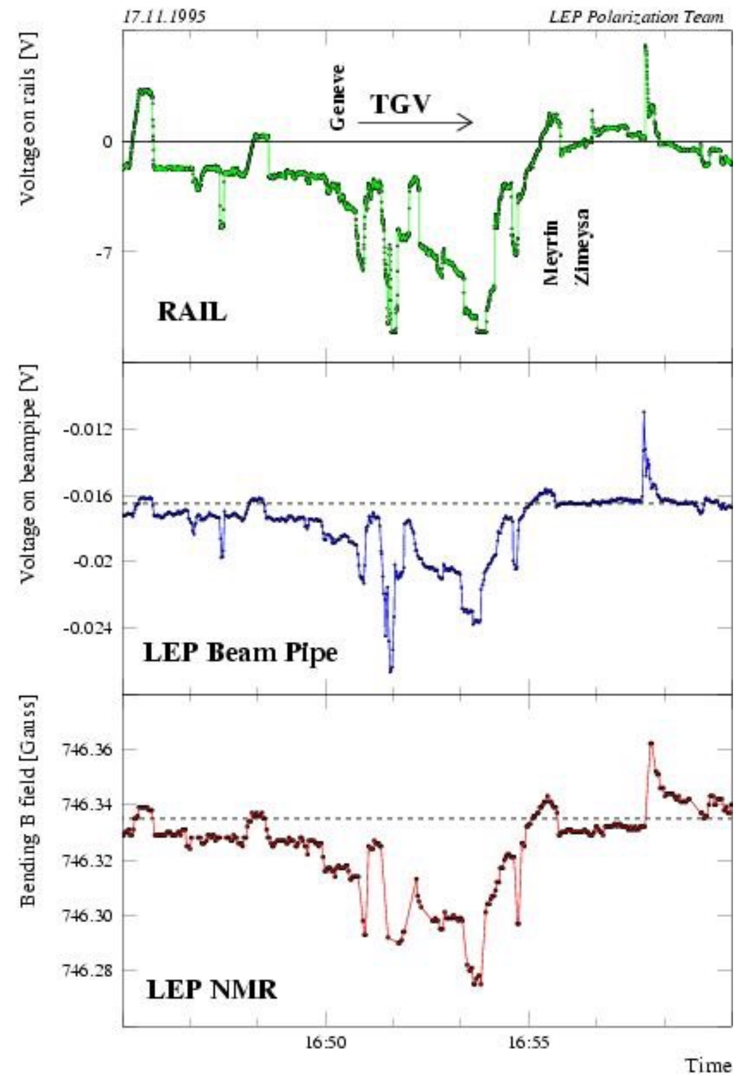

- Electrical ground loops

Differential cross section

$$\frac{d\sigma}{d\Omega} = \frac{1}{4} \times \frac{1}{64\pi^2 s}(|M_{RR}|^2 + |M_{RL}|^2 + |M_{LR}|^2 + |M_{LL}^2|)$$
$$= \frac{(4\pi\alpha)^2}{256\pi^2 s}(2(1+\cos\theta)^2 + 2(1-\cos\theta)^2)$$

- Recall QED case
- Now replace e with c and introduce propagator
- Since RH and LH couplings are different, the cos θ term does not drop out anymore

- Asymmetry

- A_{FB} = 3/8 *B/A* = 3/4 $A_e A_\mu$
- c_V / c_A = 1 - 4 |Q| $\sin^2 \theta_W$

- Asymmetries measure weak couplings and Weinberg angle

- All depend on A_e
- Use A^e_{FB} = 3/4 A^2_e or A_{LR}

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$$\begin{aligned}\frac{d\sigma}{d\Omega} &= \frac{1}{4}\times\frac{1}{64\pi^2 s}\left(|M_{RR}|^2+|M_{RL}|^2+|M_{LR}|^2+|M_{LL}^2|\right)\\ &= \frac{(4\pi\alpha)^2}{256\pi^2 s}\left(2(1+\cos\theta)^2+2(1-\cos\theta)^2\right)\end{aligned}$$

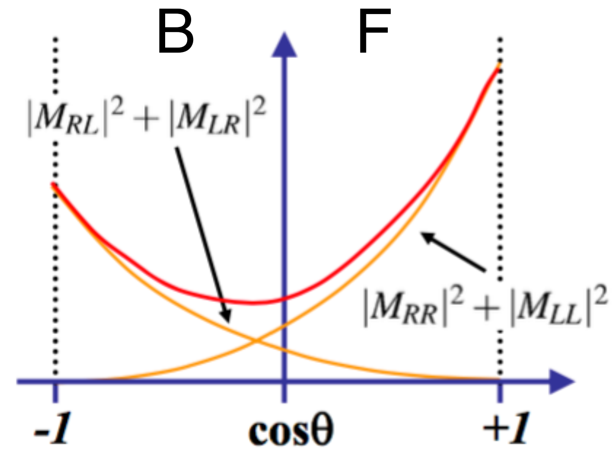
$$\frac{d\sigma_{RR}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_R^e)^2(c_R^\mu)^2(1+\cos\theta)^2$$

$$\frac{d\sigma_{LL}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_L^\mu)^2(1+\cos\theta)^2$$

$$\frac{d\sigma_{LR}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$

$$\frac{d\sigma_{RL}}{d\Omega} = \frac{1}{64\pi^2}\frac{g_Z^4 s}{(s-m_Z^2)^2+m_Z^2\Gamma_Z^2}(c_L^e)^2(c_R^\mu)^2(1-\cos\theta)^2$$

Differential cross section



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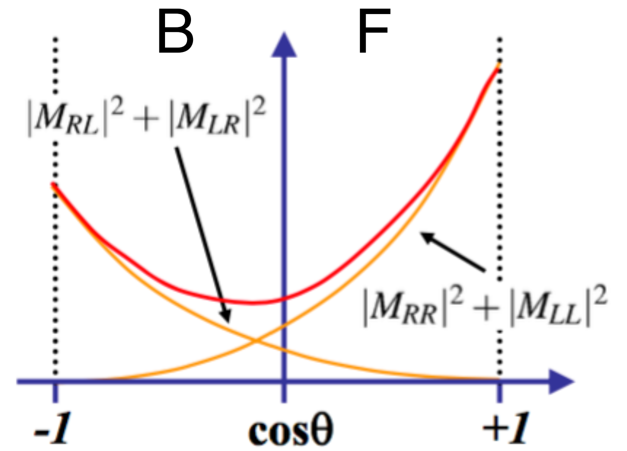

- Asymmetry

$$\frac{d\sigma}{d\Omega} = \kappa \times [A(1+\cos^2\theta) + B\cos\theta]$$

$$A = [(c_L^e)^2 + (c_R^e)^2][(c_L^\mu)^2 + (c_R^\mu)^2]$$

$$B = [(c_L^e)^2 - (c_R^e)^2][(c_L^\mu)^2 - (c_R^\mu)^2]$$

- A_{FB} = 3/8 B/A = 3/4 $A_e A_\mu$
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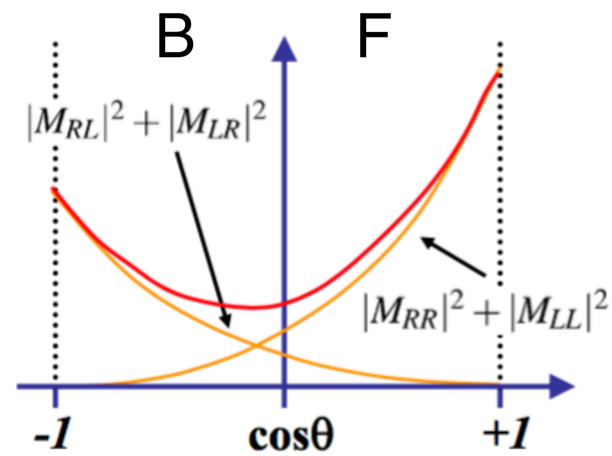

- Asymmetry $$A_{\text{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\frac{d\sigma}{d\Omega} = \kappa \times [A(1+\cos^2\theta) + B\cos\theta]$$

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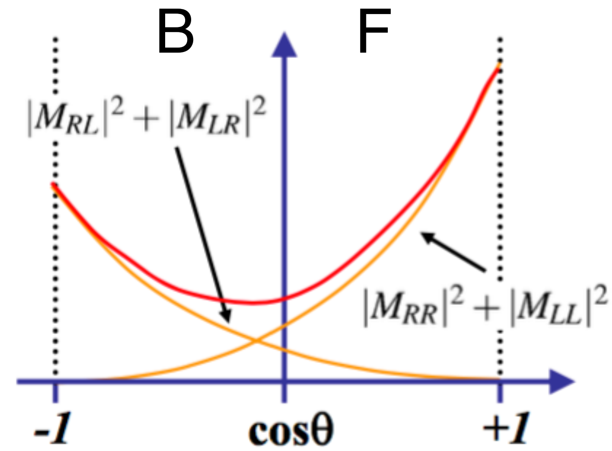

- Asymmetry $$A_{\mathrm{FB}} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \kappa \times [A(1+\cos^2\theta) + B\cos\theta]$$

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- c_V / c_A = 1 - 4 |Q| $\sin^2 \theta_W$

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$$B = [(c_L^e)^2 - (c_R^e)^2][(c_L^\mu)^2 - (c_R^\mu)^2]$$

- Asymmetries measure weak couplings and Weinberg angle

$$A_f \equiv \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = \frac{2c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2}$$

- All depend on A_e
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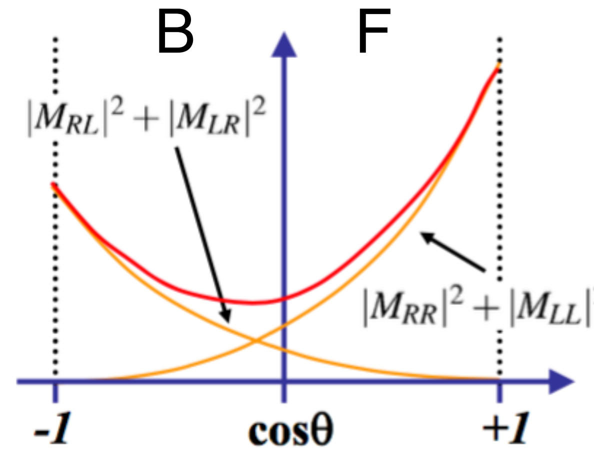
- Recall QED case
- Now replace e with c and introduce propagator
- Since RH and LH couplings are different, the cos θ term does not drop out anymore



- Asymmetry $$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\frac{d\sigma}{d\Omega} = \kappa \times [A(1+\cos^2\theta) + B\cos\theta]$$

- $A_{FB} = 3/8\ B/A = 3/4\ A_e A_\mu$
- $c_V / c_A = 1 - 4\,|Q|\,\sin^2\theta_W$

$$A = [(c_L^e)^2 + (c_R^e)^2][(c_L^\mu)^2 + (c_R^\mu)^2]$$

$$B = [(c_L^e)^2 - (c_R^e)^2][(c_L^\mu)^2 - (c_R^\mu)^2]$$

- Asymmetries measure weak couplings and Weinberg angle

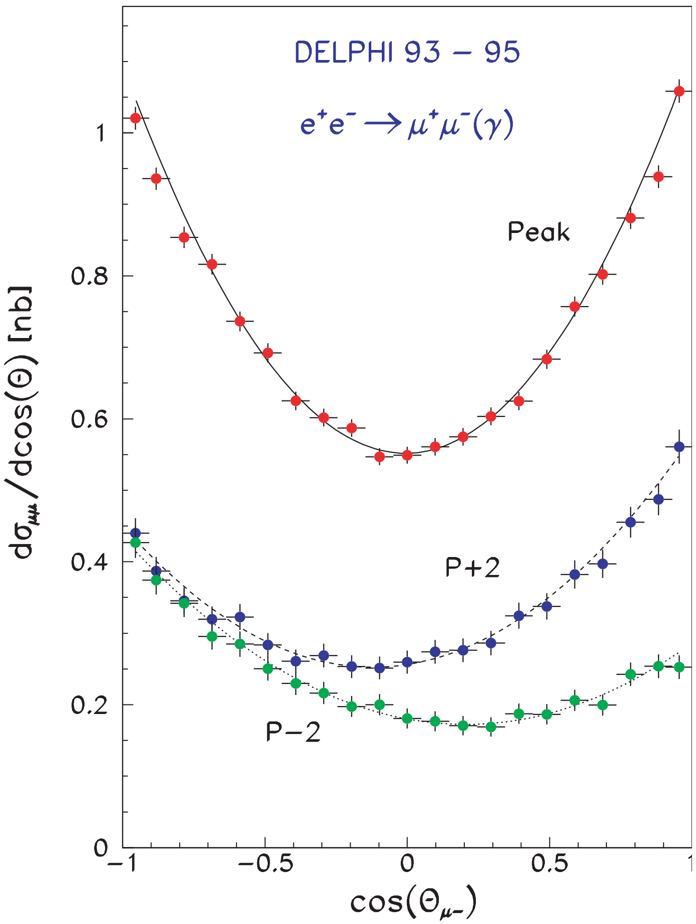
$$A_f \equiv \frac{(c_L^e)^2 - (c_R^e)^2}{(c_L^e)^2 + (c_R^e)^2} = \frac{2c_V^f c_A^f}{(c_V^f)^2 + (c_A^f)^2}$$

$$= 2\frac{c_V/c_A}{1+(c_V/c_A)^2}$$

- All depend on A_e
- Use $A^e_{FB} = 3/4\ A^2_e$ or A_{LR}

Forward backward asymmetries

- For data above and below Z peak interference with γ change enhances A_{FB}
- Need to account for QED here, too
  - and t channel interference for ee
- Off-peak runs enhance EW sensitivity, but less statistics or everyone else
- Running strategy not trivial



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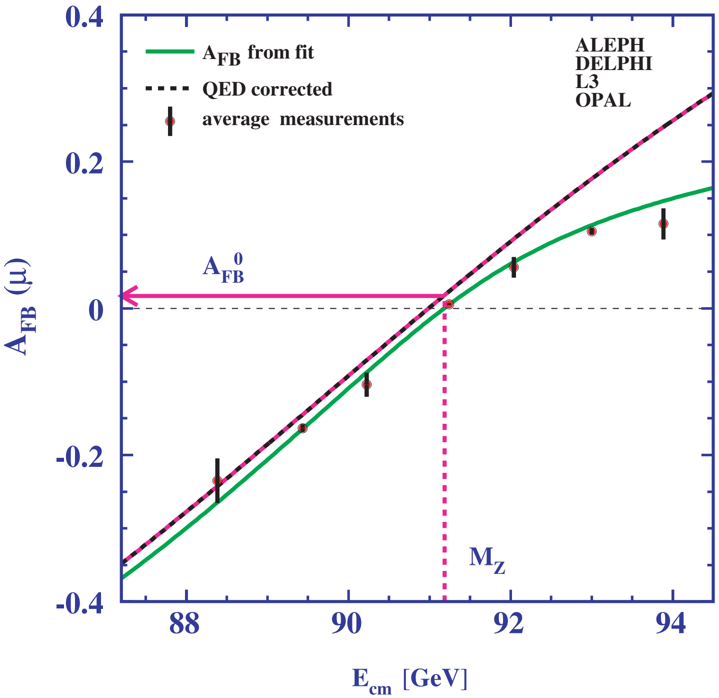

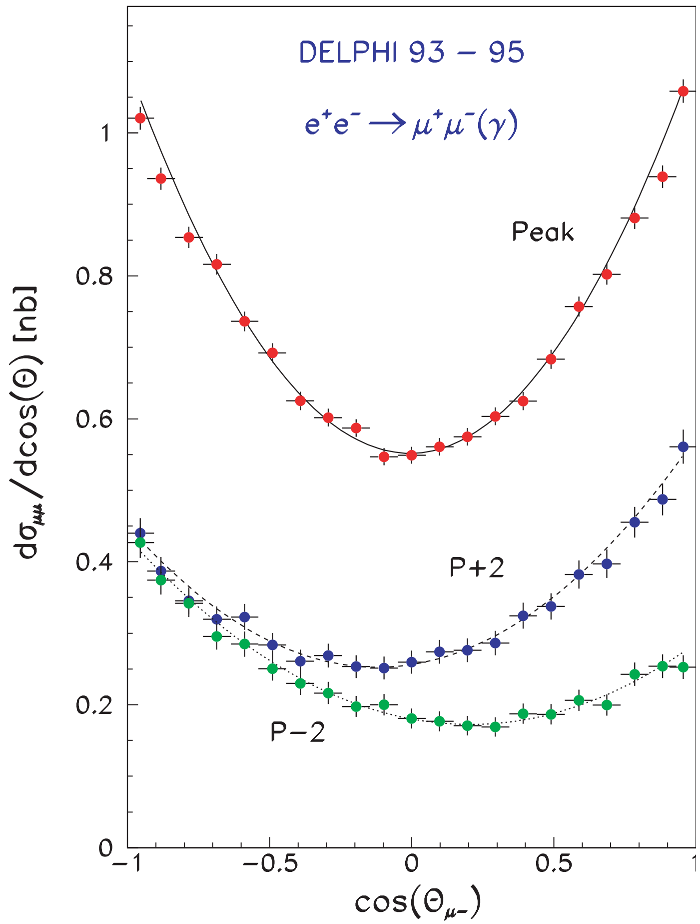

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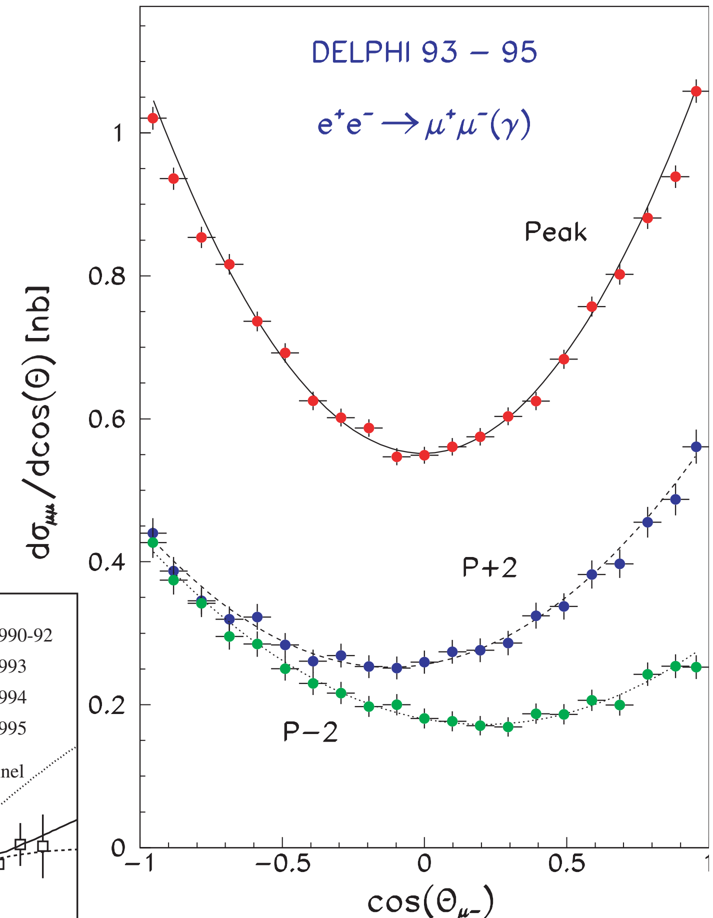
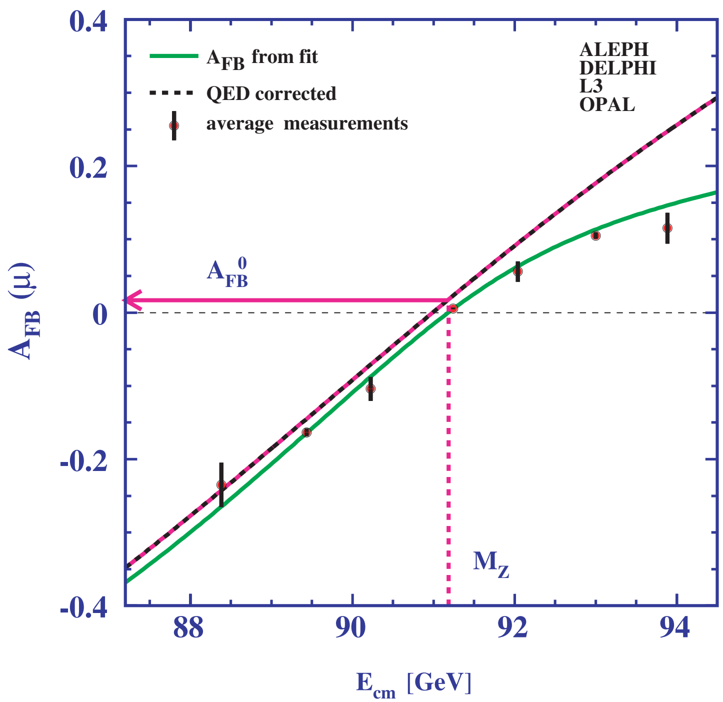
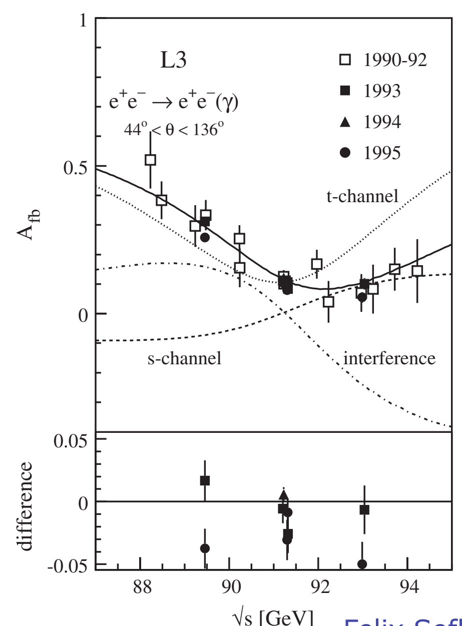
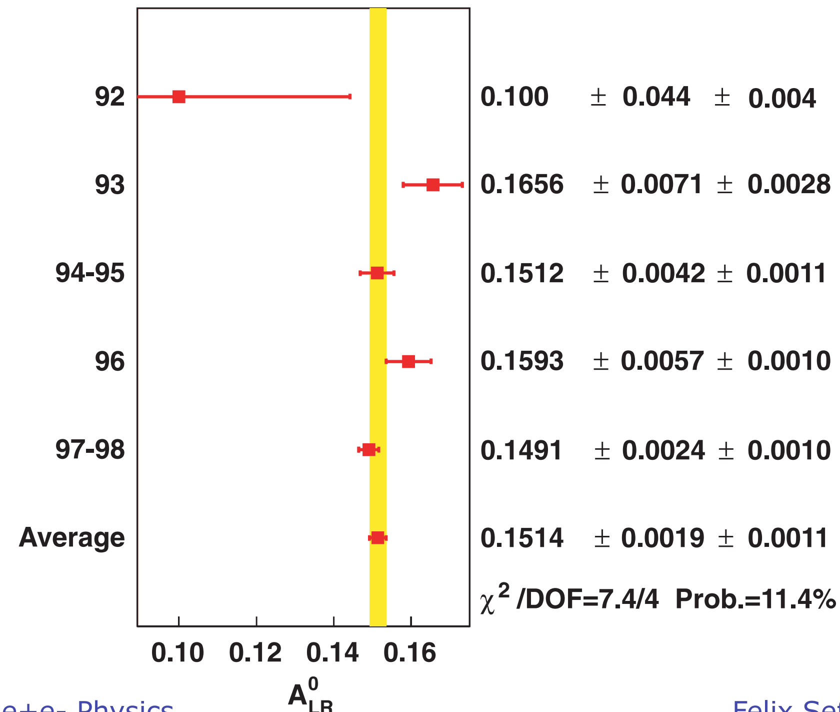


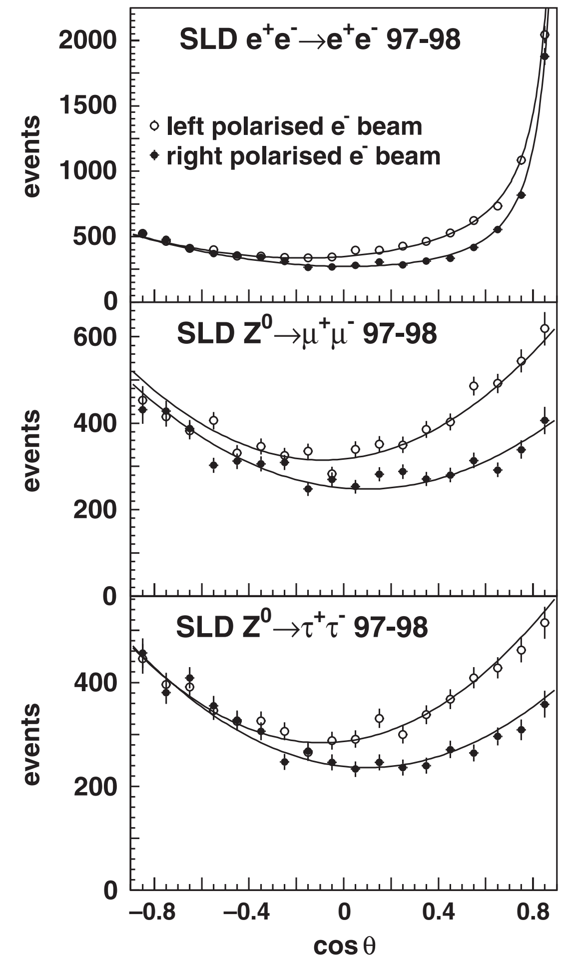




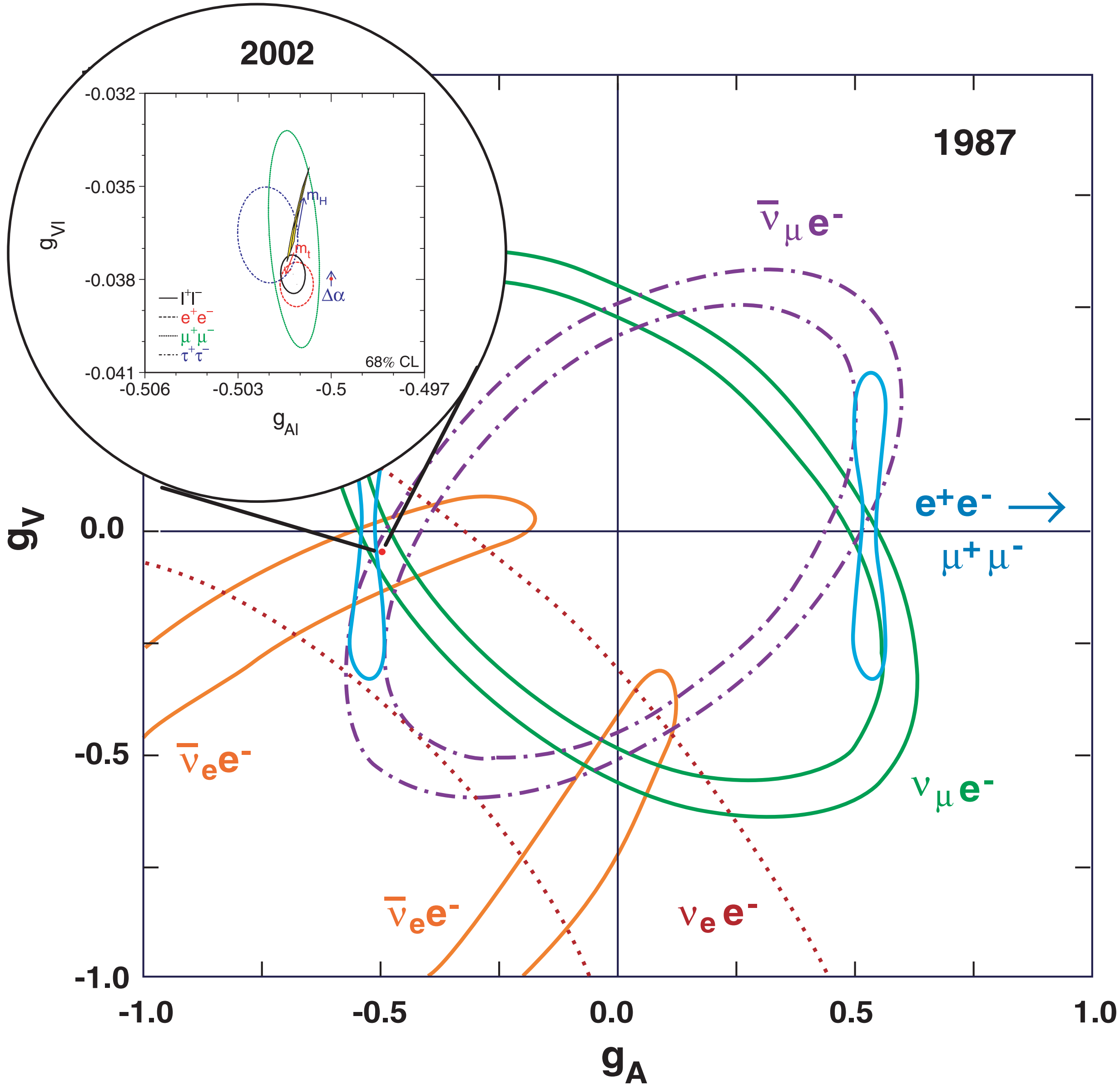
Left Right Asymmetry

- At SLC, can chose electron polarisation
- Average over positron polarisation states
- $\sigma_L = 1/2\ (\sigma_{LR} + \sigma_{LL}) \sim (c^e{}_L)^2\ [(c^\mu{}_L)^2 + (c^\mu{}_L)^2]$
- A_{LR} depends on c^e only: $A_{LR} = A_e$
- Additional observables: polarised forward backward asymmetries



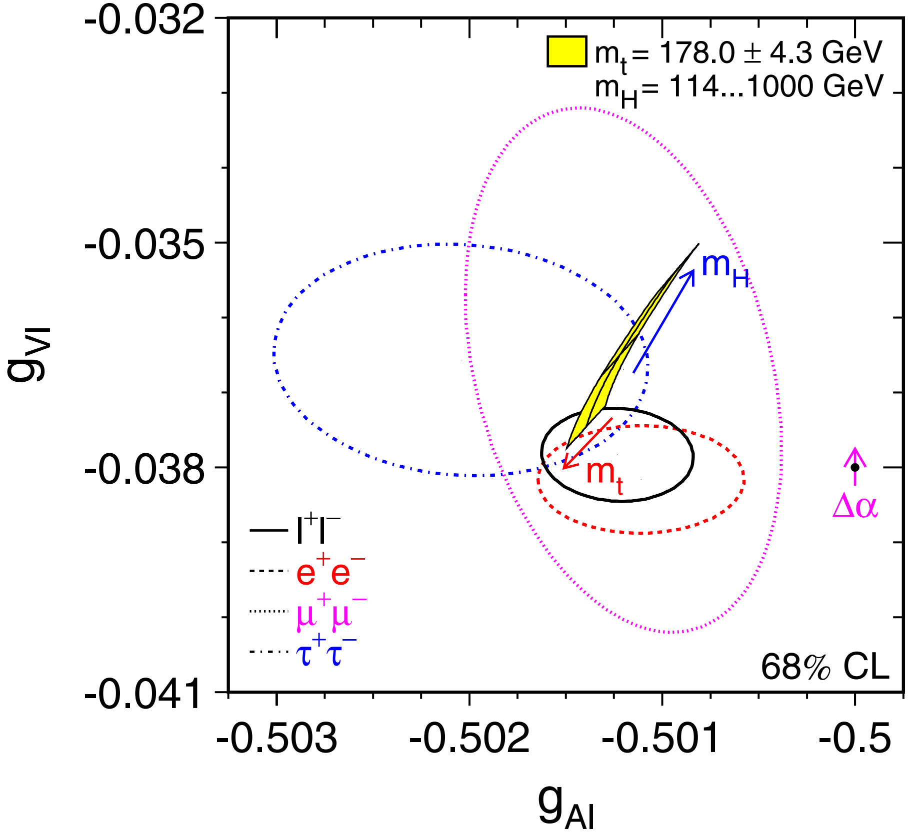


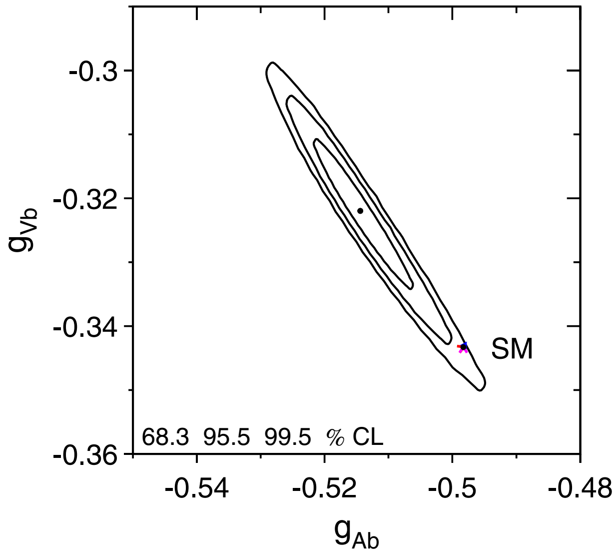
Before - after

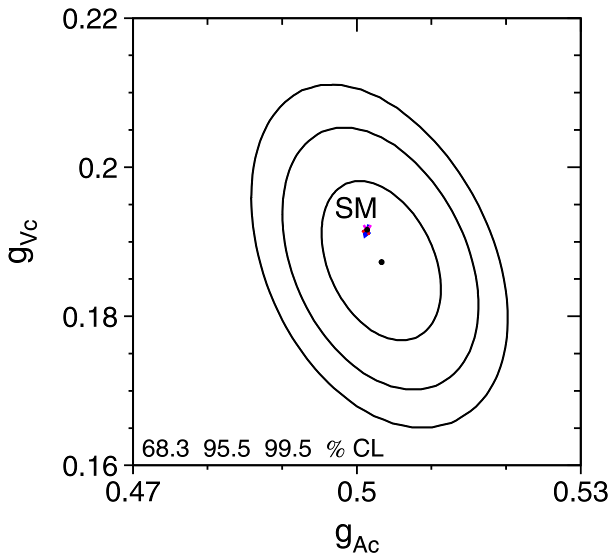


Measurements of Z couplings

- Extracted from FB asymmetries
- Lepton universality confirmed with per-mil precision

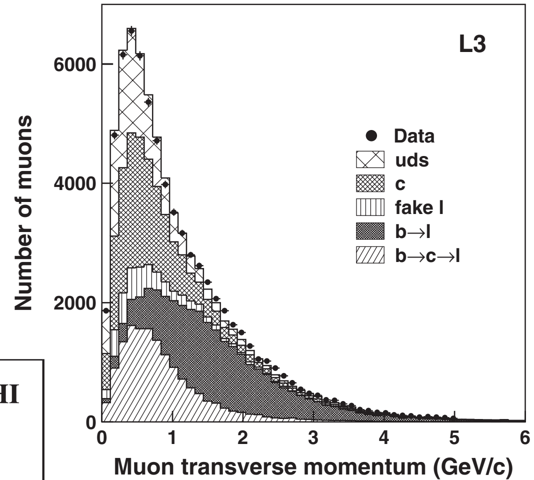


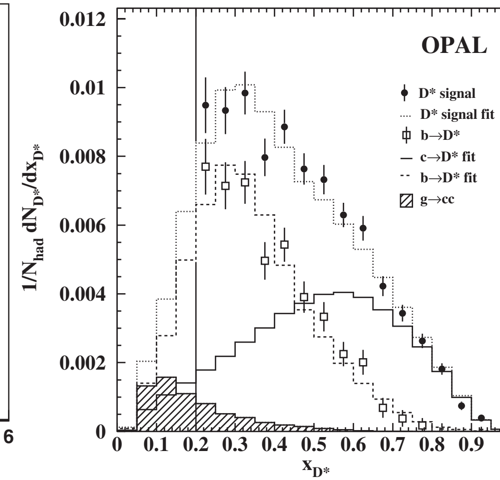


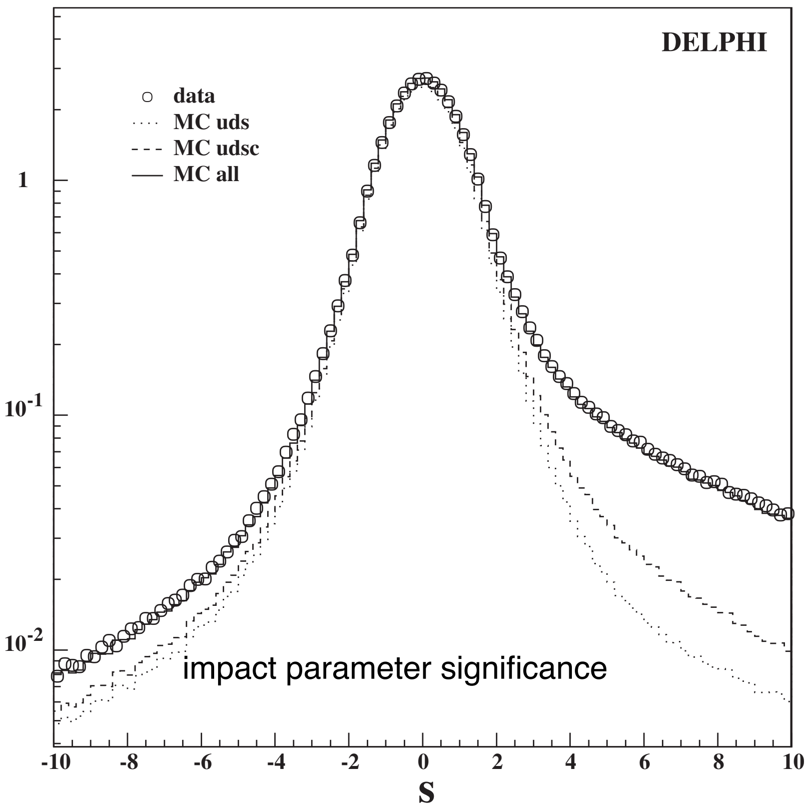


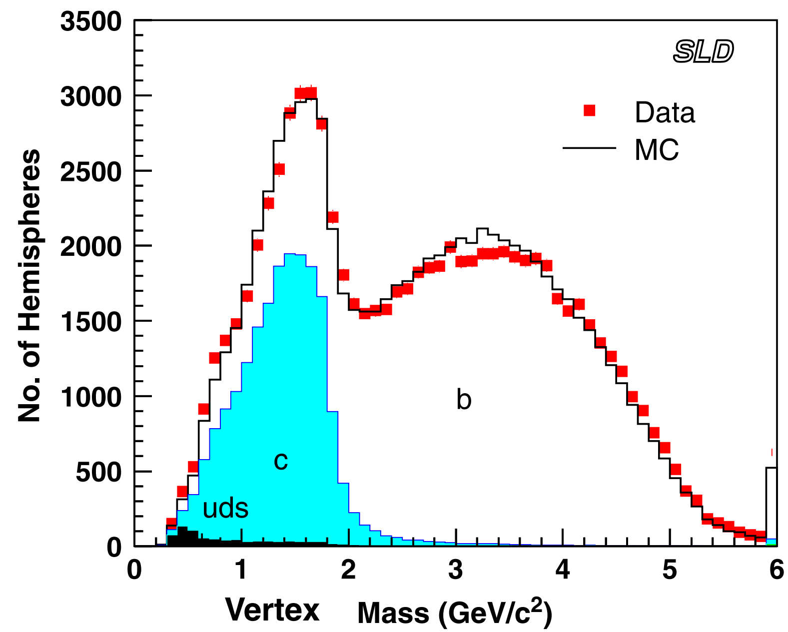
Heavy flavour tags

- Initially: leptons, D*
- Si vertex detectors: statistically much more powerful tags

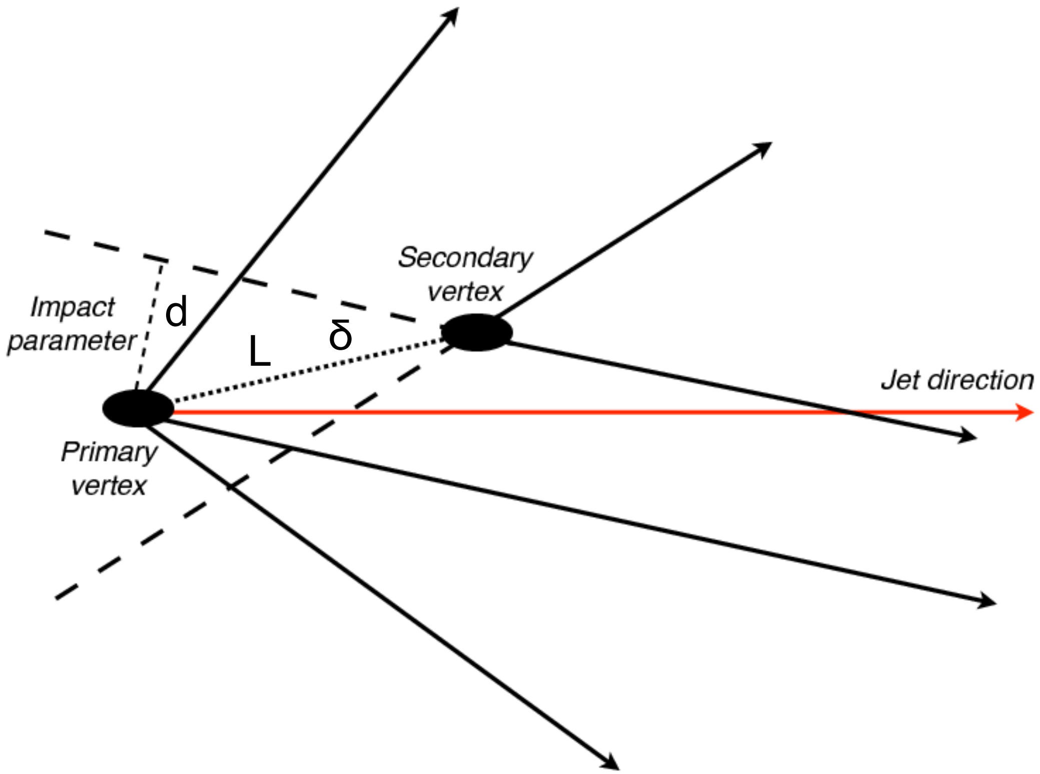








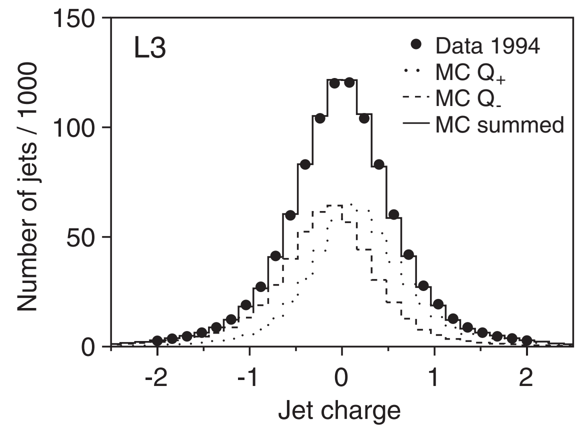
Impact parameter

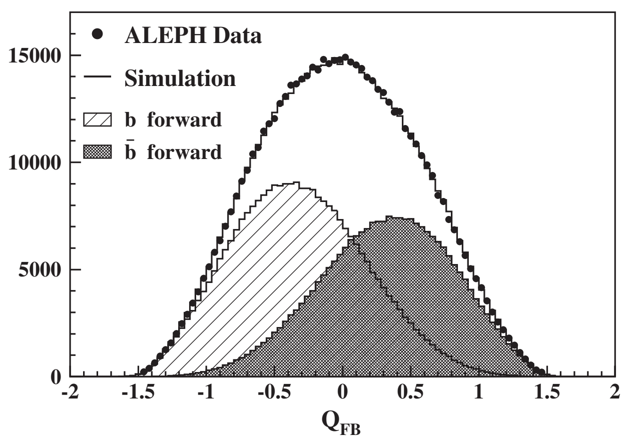


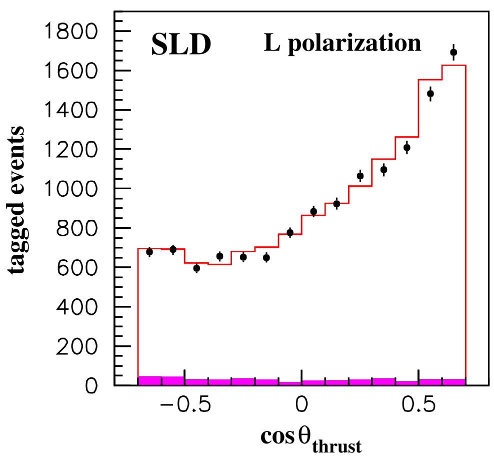
- Almost a Lorentz invariant
- $d = L \sin \delta$, $L = \beta\gamma\, \tau$
- $\sin \delta = p_T / p$, $p = \beta\gamma\, m$, $p_T = p^*_T$
- $\Rightarrow d = \tau \cdot\ p^*_T/m$ - but of course p_T still varies from event to event

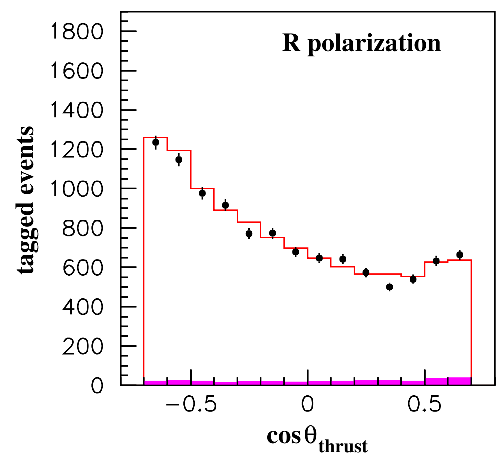
Inclusive charge tags

- Inclusive: jet charge
- b quarks: vertex charge



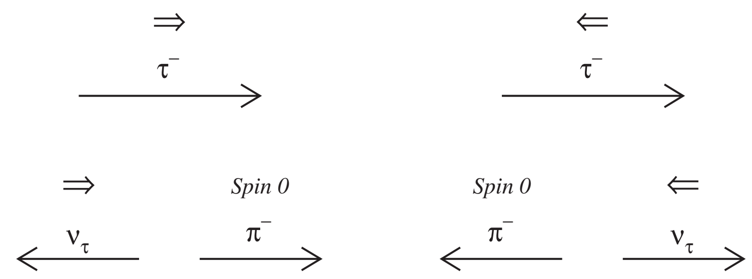






tau polarisation

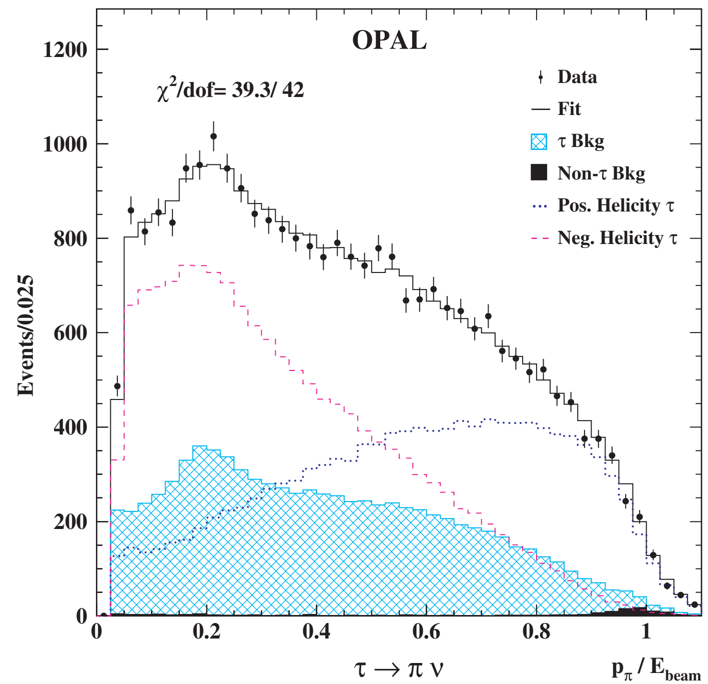
- All fermions are produced in polarised state
- But observable only for tau via decay distributions



$$\mathscr{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathscr{A}_\tau(1+\cos^2\theta_{\tau^-}) + 2\mathscr{A}_e\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A^\tau_{FB}\cos\theta_{\tau^-}}.$$

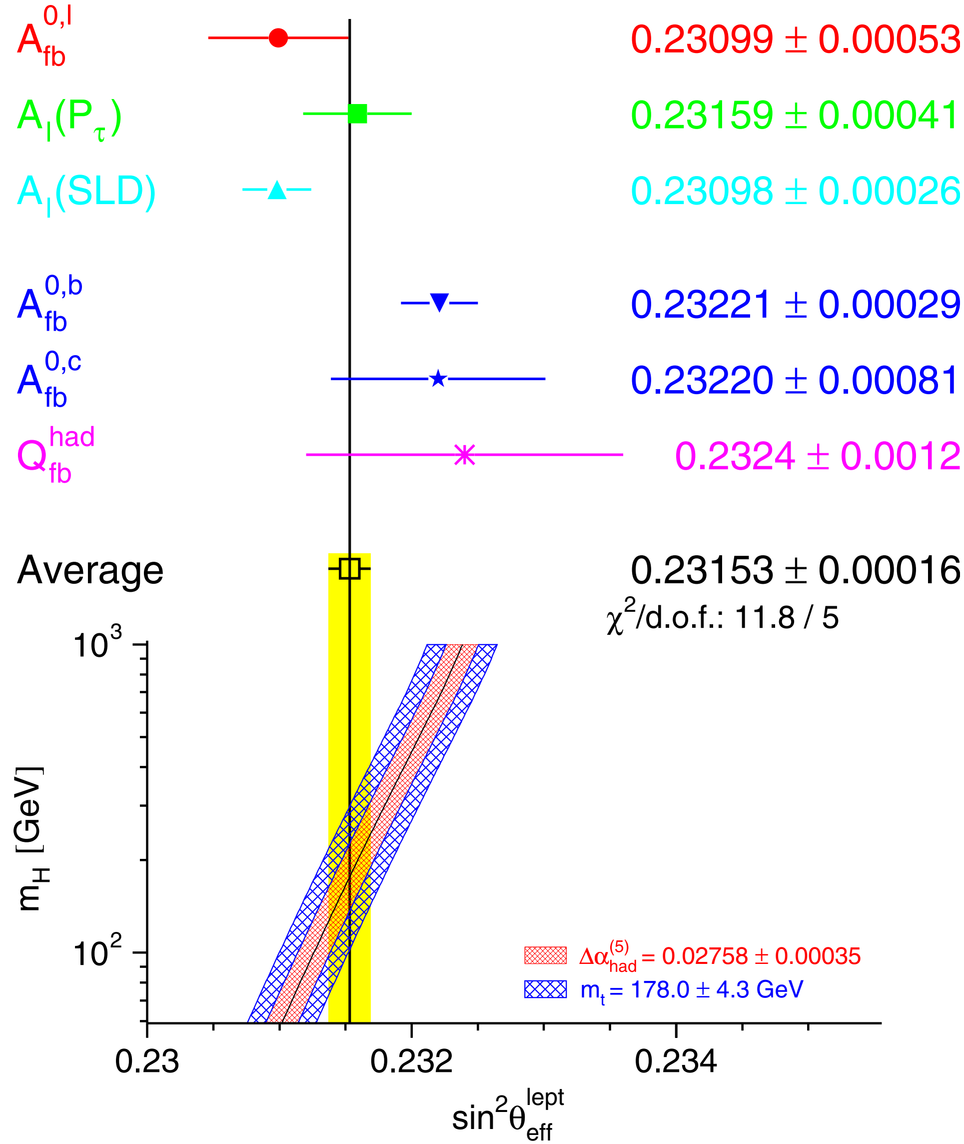
- Can extract A_τ and A_e

more complex observable for ρ and a_1
muons less sensitive



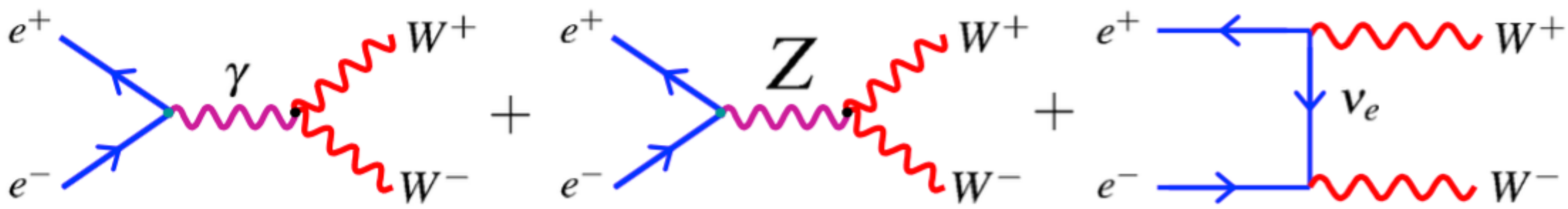
Weak mixing angle

- 0.7 per-mil accuracy
- The A_l A_b tension is still there…

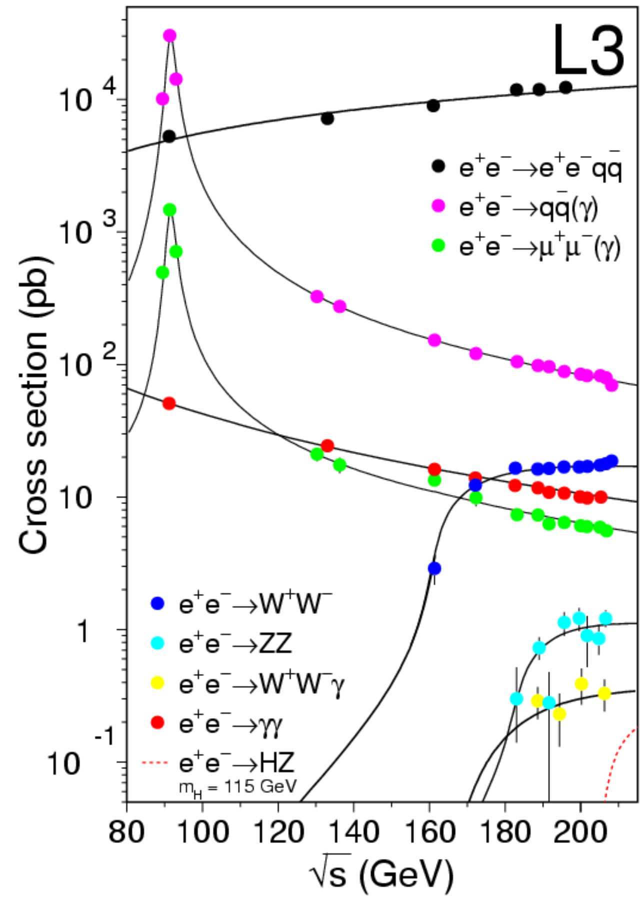


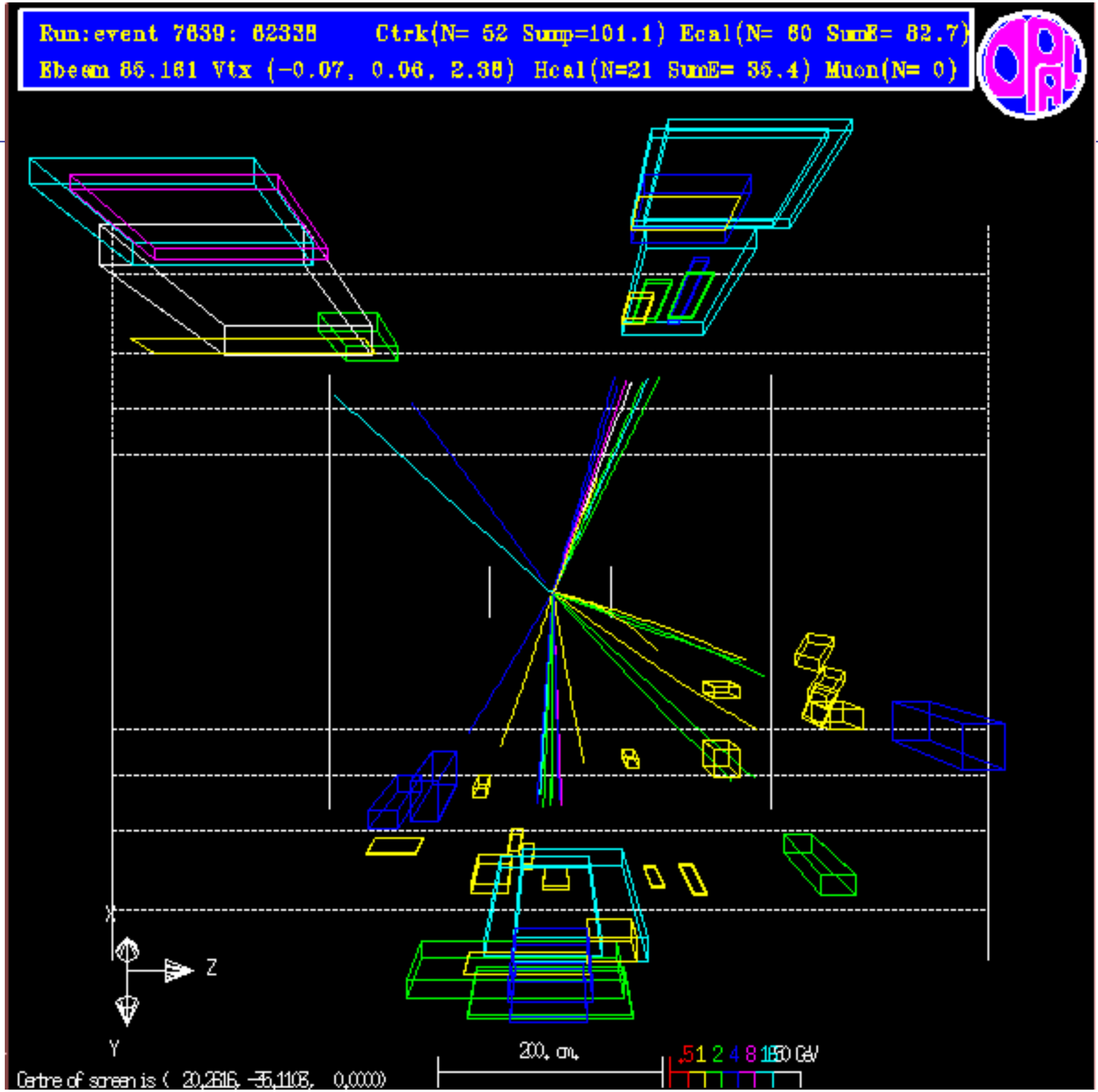
Electro-weak physics at LEP2

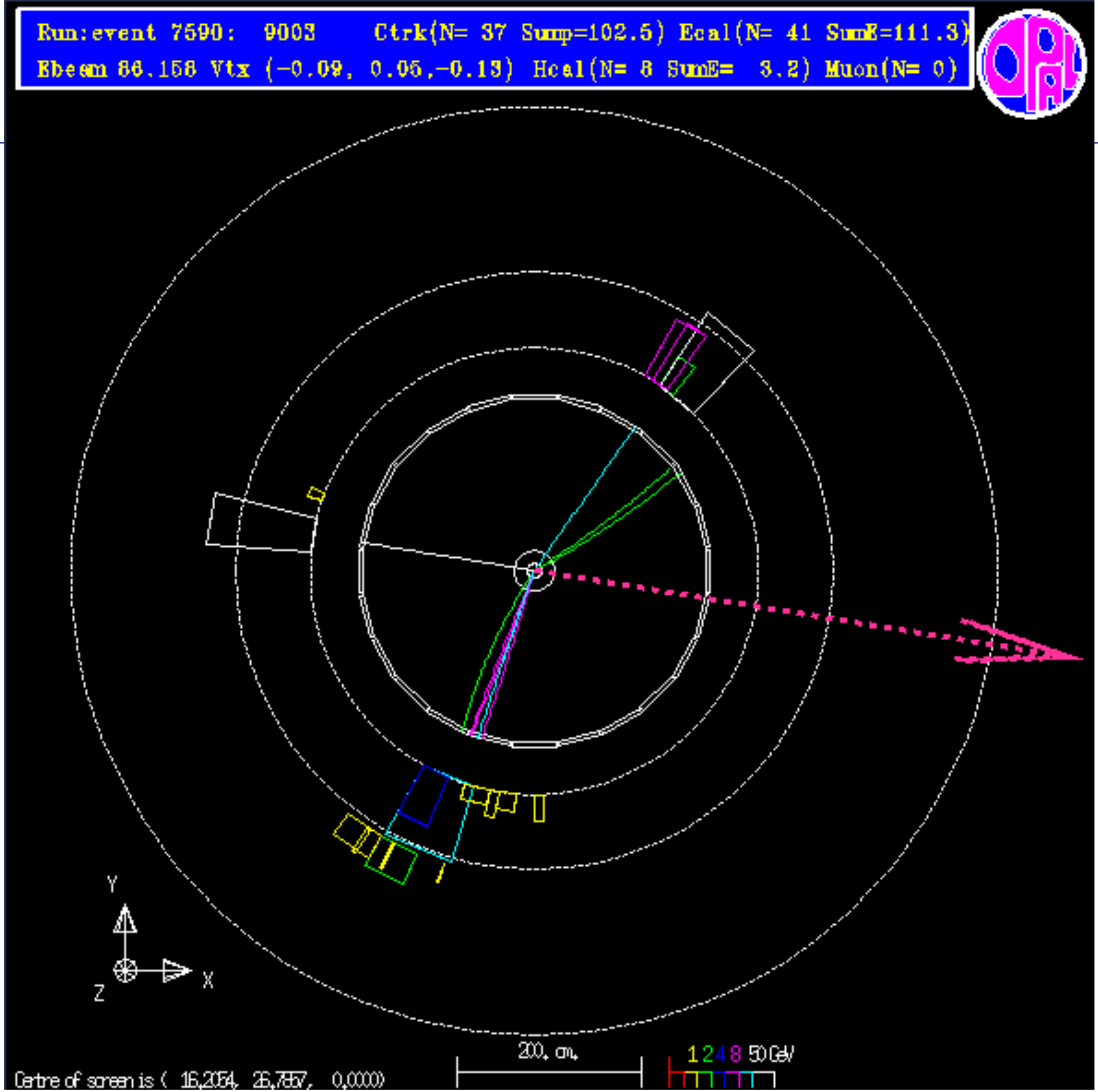
LEP2: W boson pair production

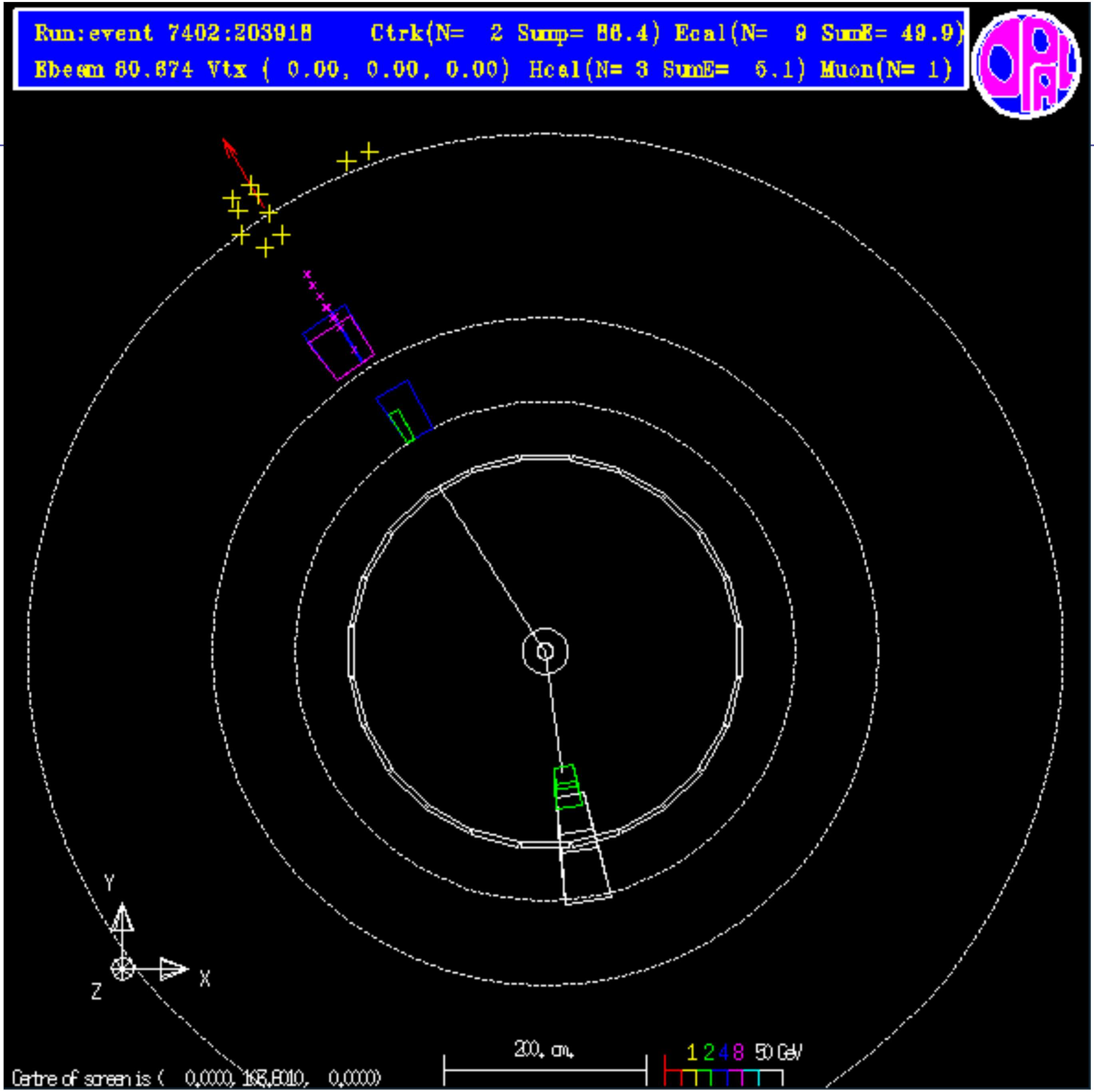


- No resonance: much smaller cross section than at LEP1
  - only few 1000 events / year
- Precise standard model predictions
  - mass
  - fermion couplings
  - gauge (self) couplings

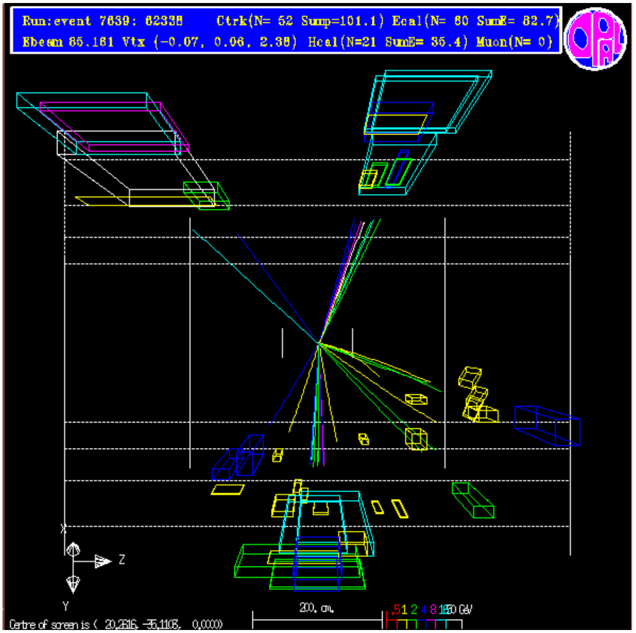


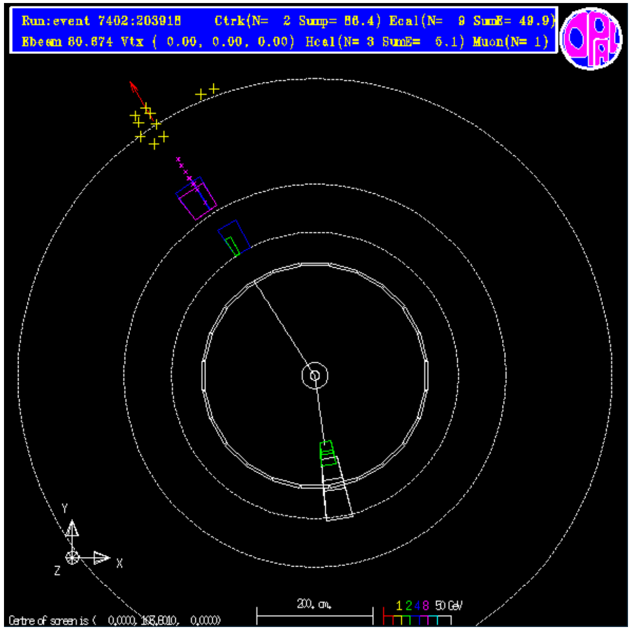

Run:event 7639: 62338 Ctrk(N= 52 Sump=101.1) Ecal(N= 60 SumE= 82.7)
Ebeam 85.161 Vtx (-0.07, 0.06, 2.38) Hcal(N=21 SumE= 35.4) Muon(N= 0)
X
Z
Y
200. cm.
Centre of screen is (20.2816, -35.1103, 0.0000)

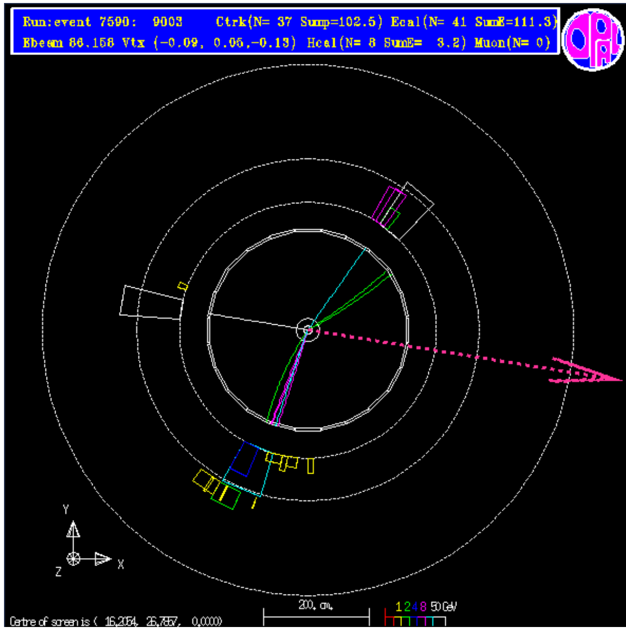

Run:event 7590: 9003 Ctrk(N= 37 Sump=102.5) Ecal(N= 41 SumE=111.3)
Ebeam 86.158 Vtx (-0.09, 0.05,-0.13) Hcal(N= 8 SumE= 3.2) Muon(N= 0)
Y
Z
X
200. cm.
1 2 4 8 50 GeV
Centre of screen is (16.2054, 26.7857, 0.0000)


Run:event 7402:203918 Ctrk(N= 2 Sump= 88.4) Ecal(N= 9 SumE= 49.9)
Ebeam 80.874 Vtx (0.00, 0.00, 0.00) Hcal(N= 3 SumE= 5.1) Muon(N= 1)
Y
X
Z
200. cm.
1 2 4 8 50 GeV
Centre of screen is (0.0000, 165.8010, 0.0000)

W decay modes







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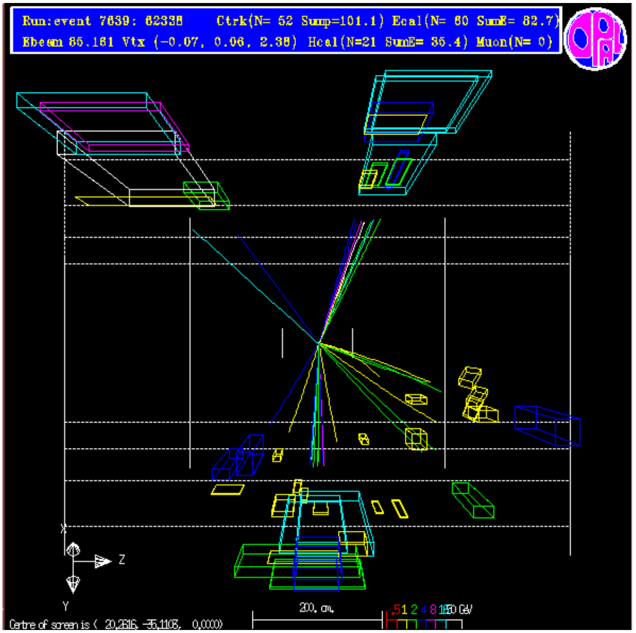
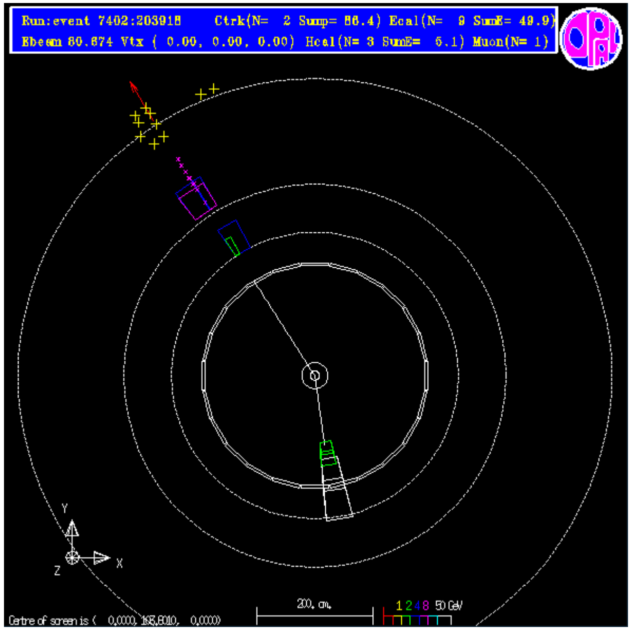
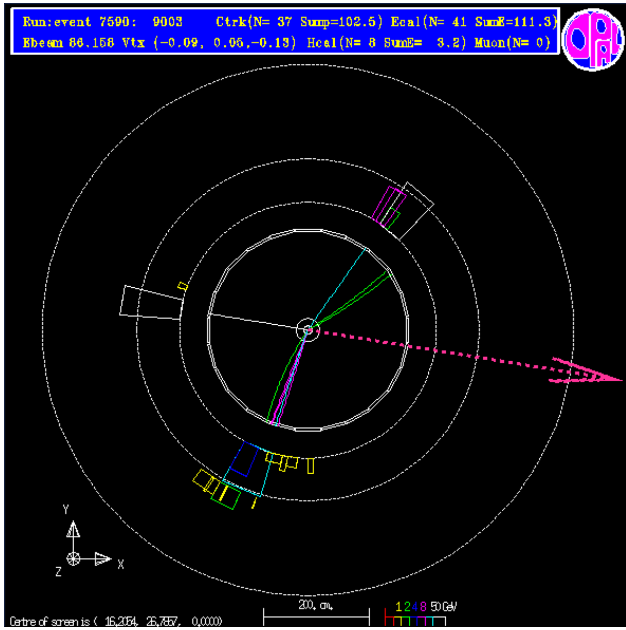
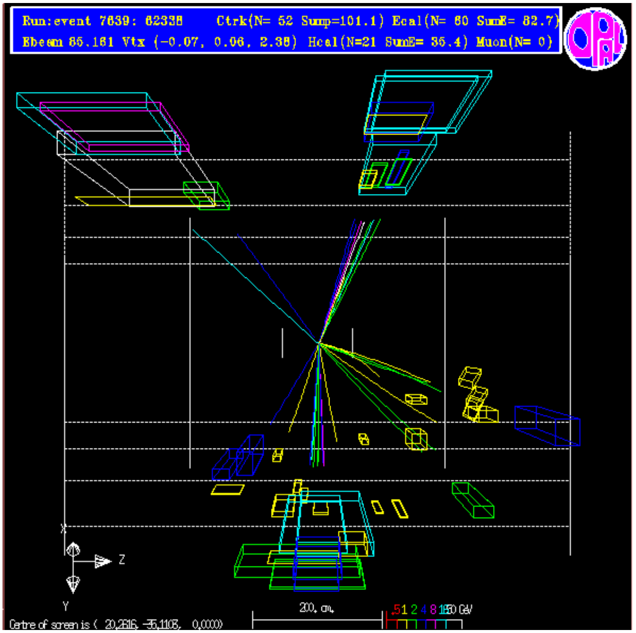


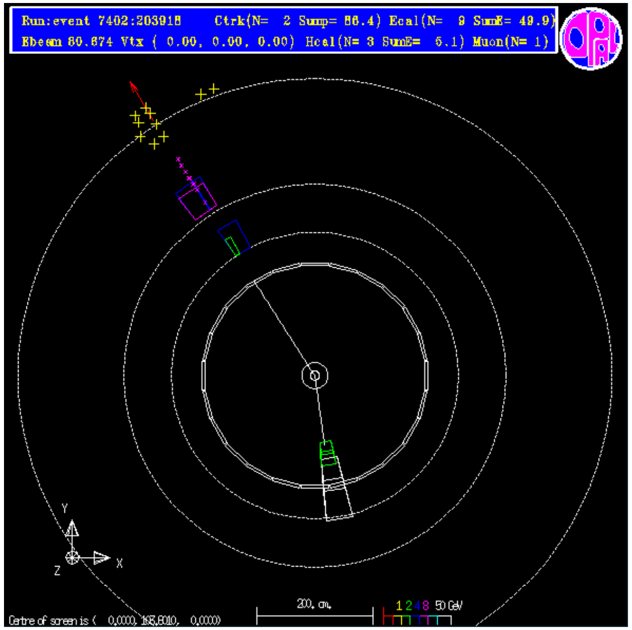


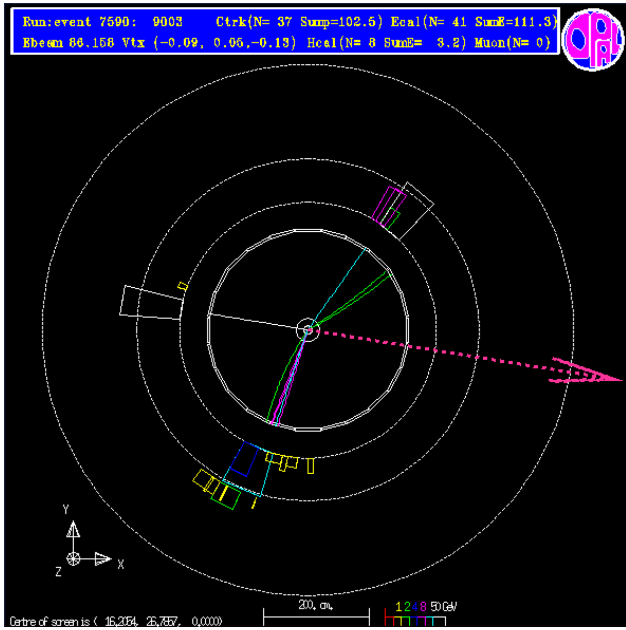


- eν, μν, τν: 1/9 each
- u d-bar, c s-bar: 3/9 each

W decay modes





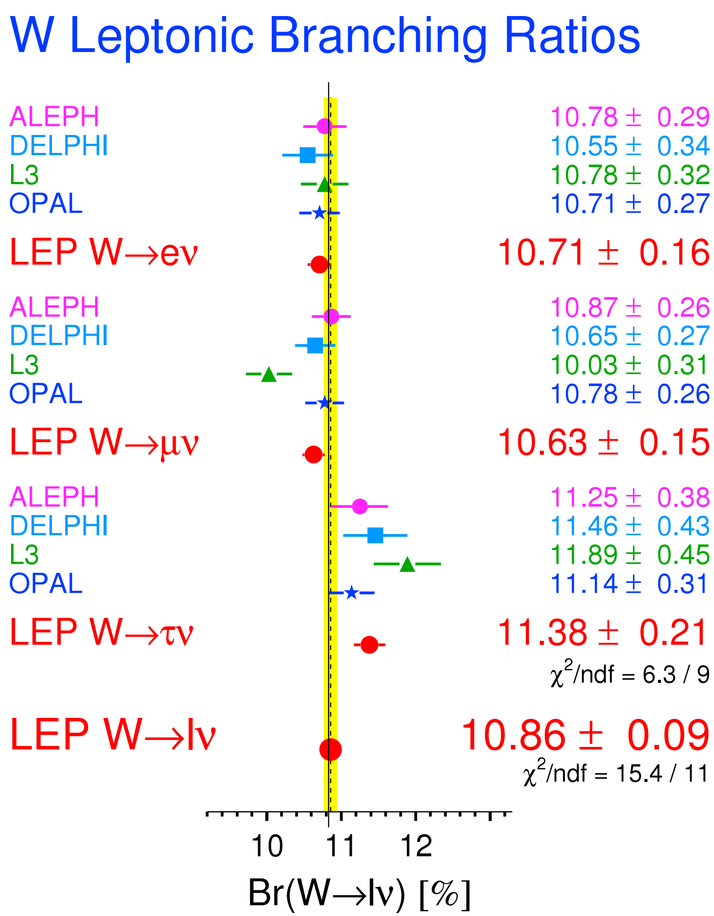


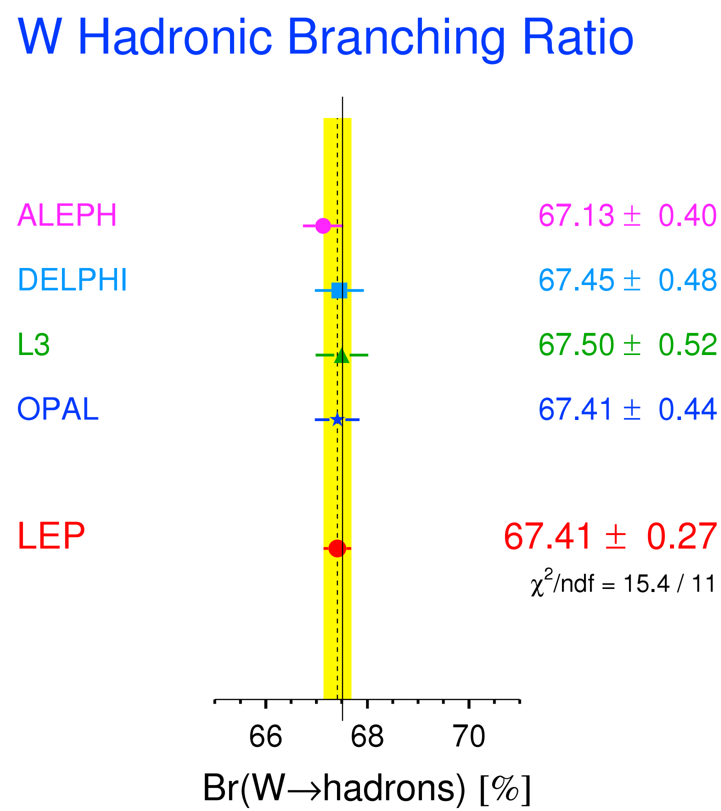
- eν, μν, τν: 1/9 each
- u d-bar, c s-bar: 3/9 each

- hadron hadron: 45%
- lepton-hadron: 44%
- lepton lepton: 11%
- e, μ only: 5%

W branching ratios

- Again: count and normalise to luminosity





V_{cs} ?

τ agreement with e, μ average only 2.6 σ

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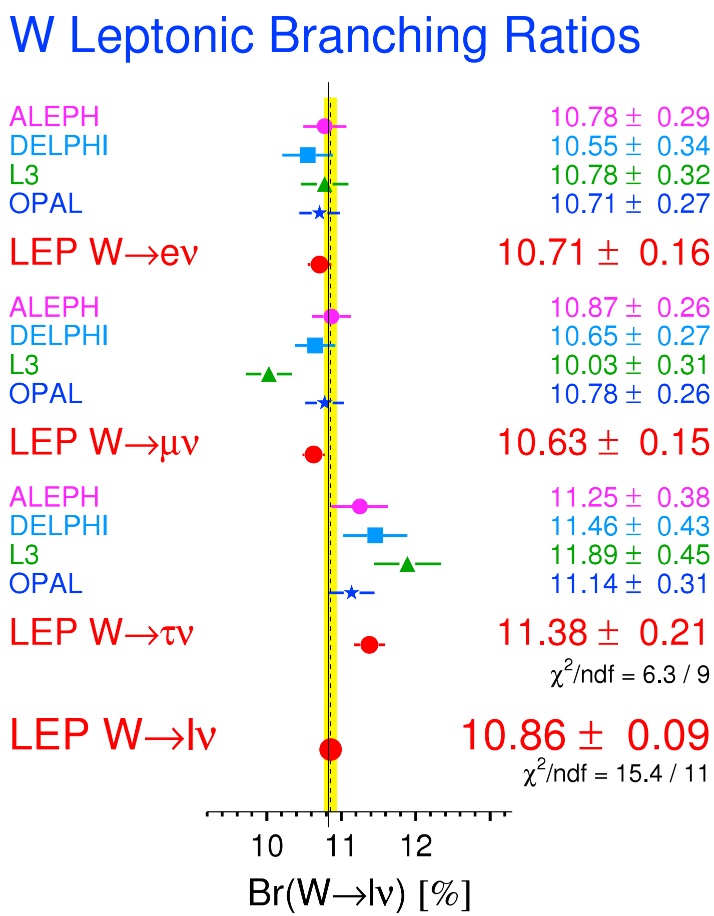
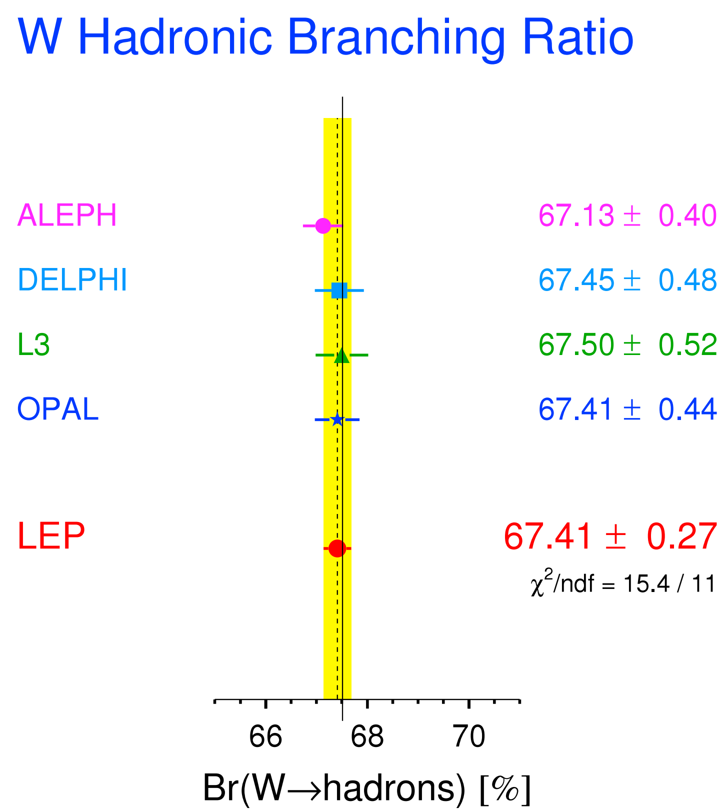




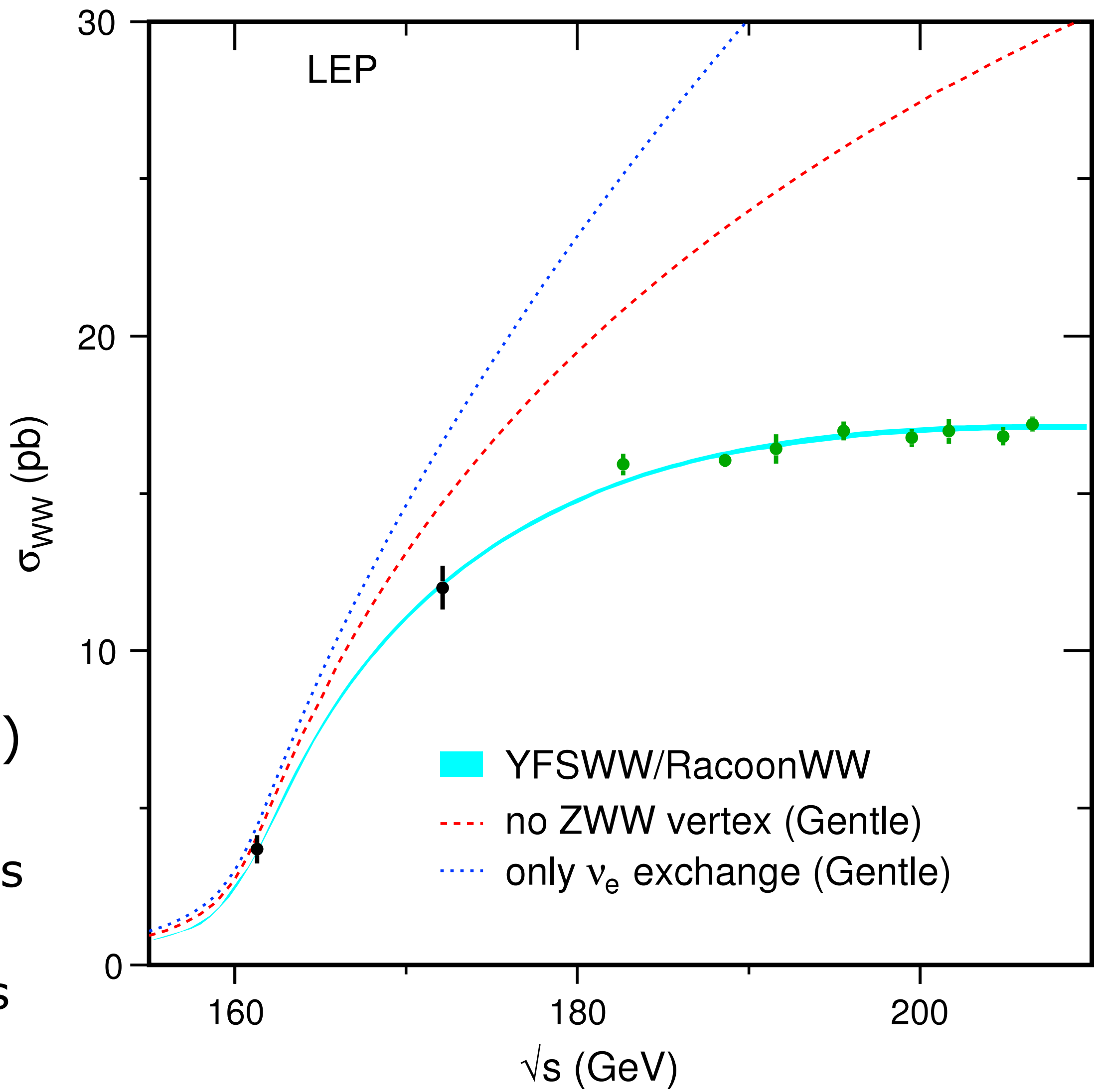
V_{cs} ?

$$\frac{1}{\mathcal{B}(W \to \ell\overline{\nu}_\ell)} = 3\left\{1 + \left[1 + \frac{\alpha_s(M_W^2)}{\pi}\right] \sum_{\substack{i=(u,c),\\ j=(d,s,b)}} |V_{ij}|^2\right\}$$

τ agreement with e, μ average only 2.6 σ

W pair cross section

- Dramatic evidence for non-Abelian nature of electro-weak interaction
  - without Z exchange cross section would violate unitarity
- Rise ~ $\beta = \sqrt{(1 - 4m^2_W/s)}$
  - mass measurement
  - intrinsically as precise as direct reconstruction
  - but only 3% of statistics near threshold



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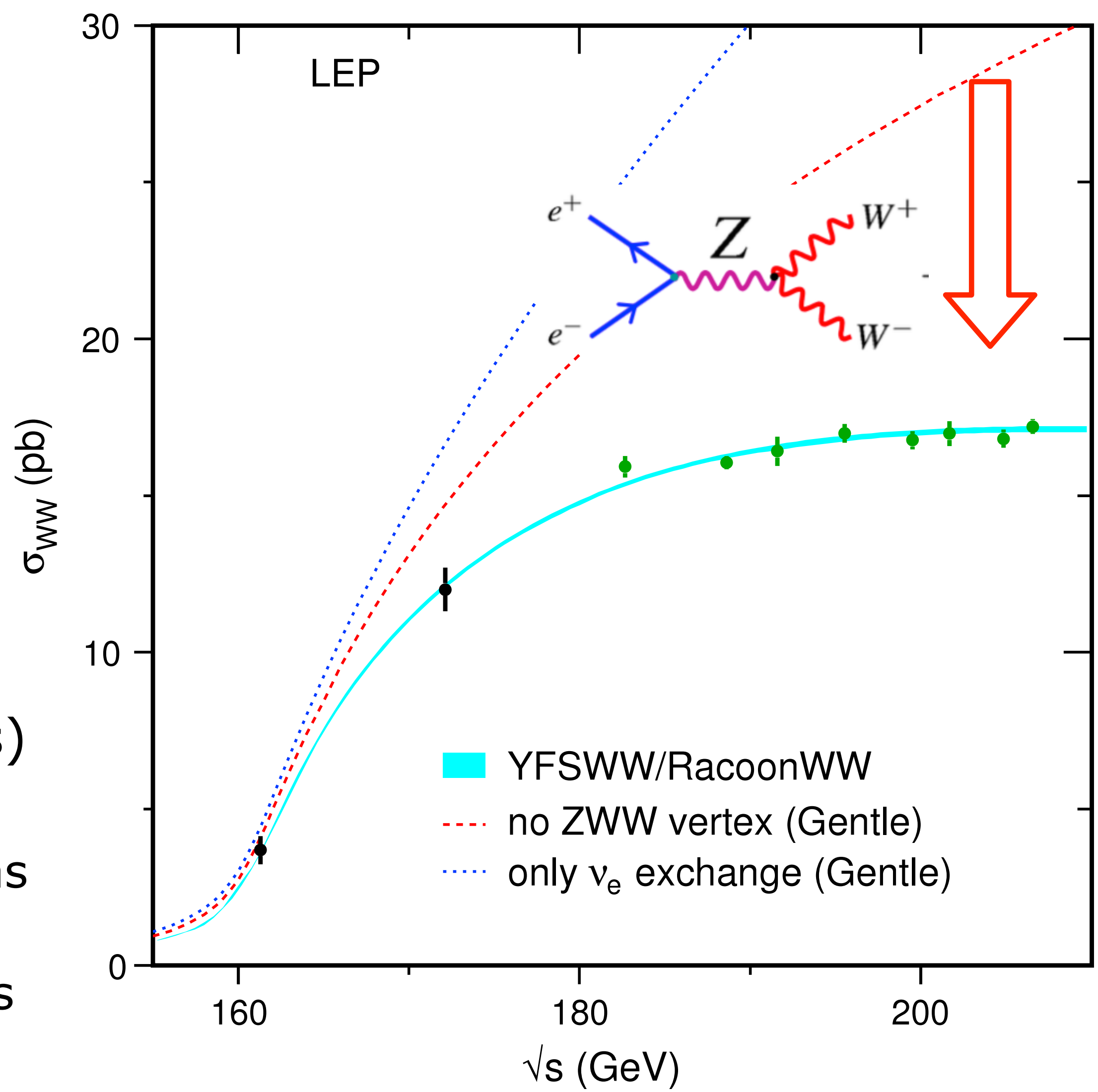
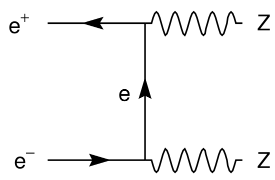
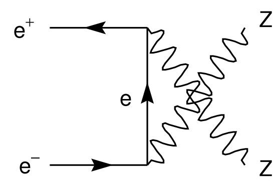
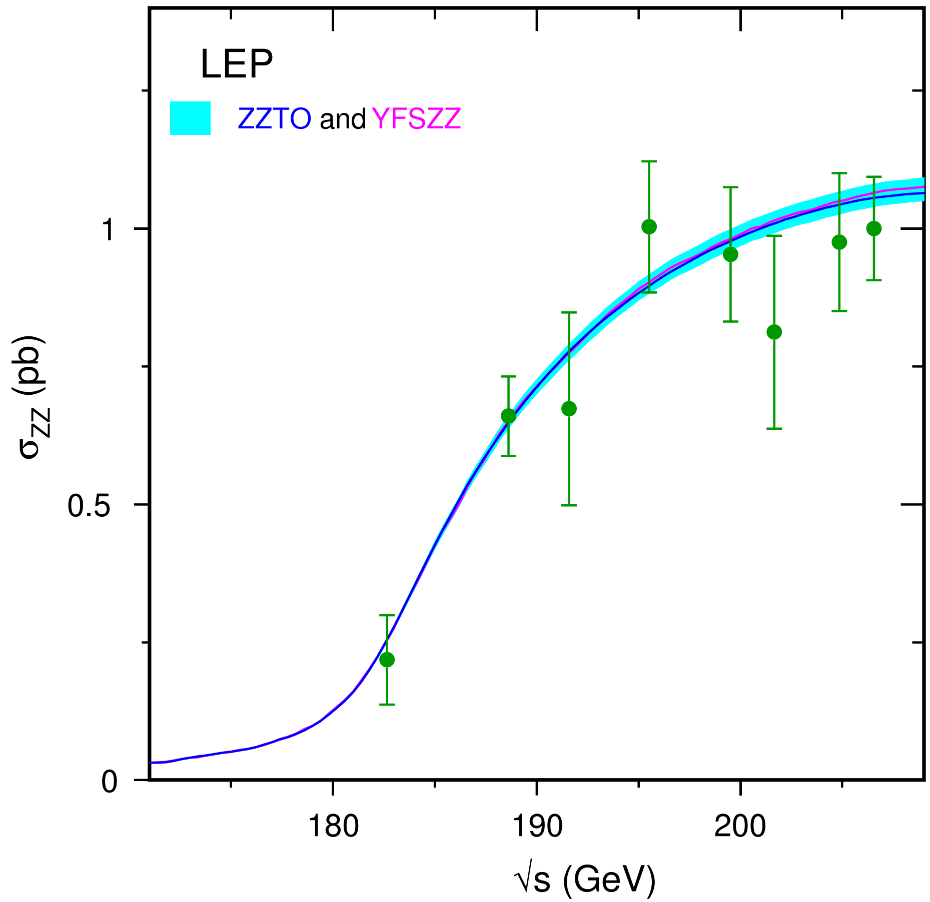


Z pair production

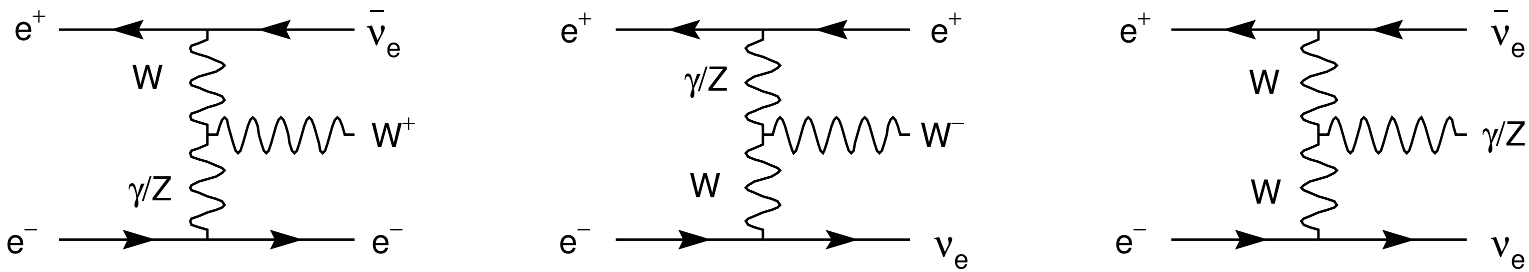




- No ZZZ or γZZ vertex



Single W, single Z production

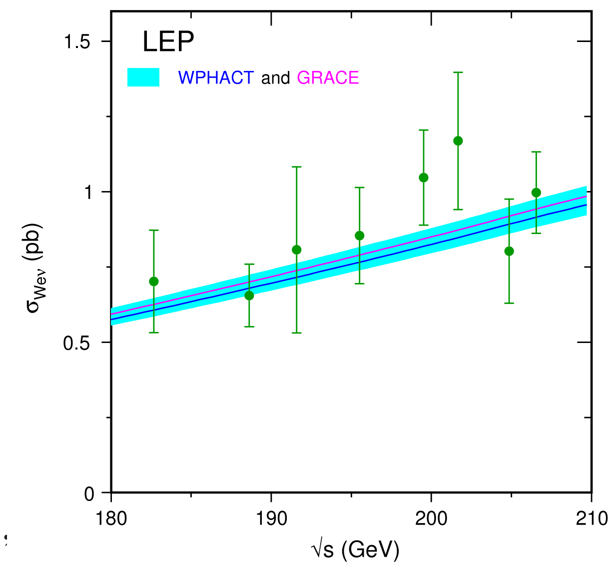


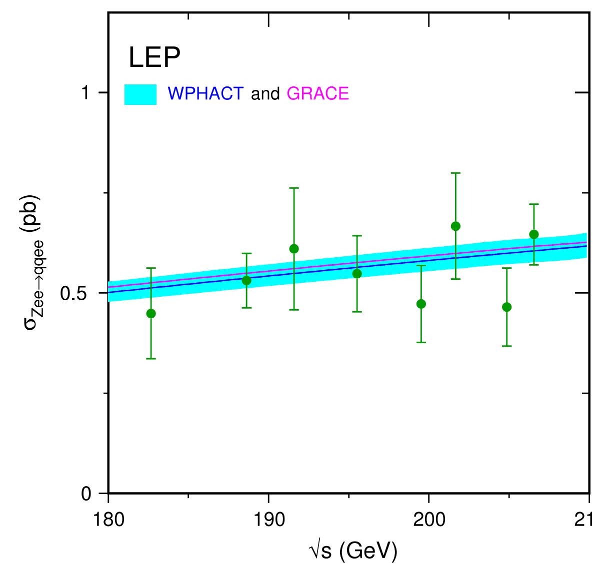
Striking signature,
found in SUSY search

Sensitive to electromagnetic properties of W
(el. dipole, magn. quadrupole moments)

$$q_{\mathrm{W}} = -\frac{e}{m_{\mathrm{W}}^2}(\kappa_\gamma - \lambda_\gamma)$$

$$\mu_{\mathrm{W}} = \frac{e}{2m_{\mathrm{W}}}(1 + \kappa_\gamma + \lambda_\gamma),$$





- Powerful constraints also from WW angular distributions and correlations
- Putting everything together, constrain anomalous triple gauge couplings

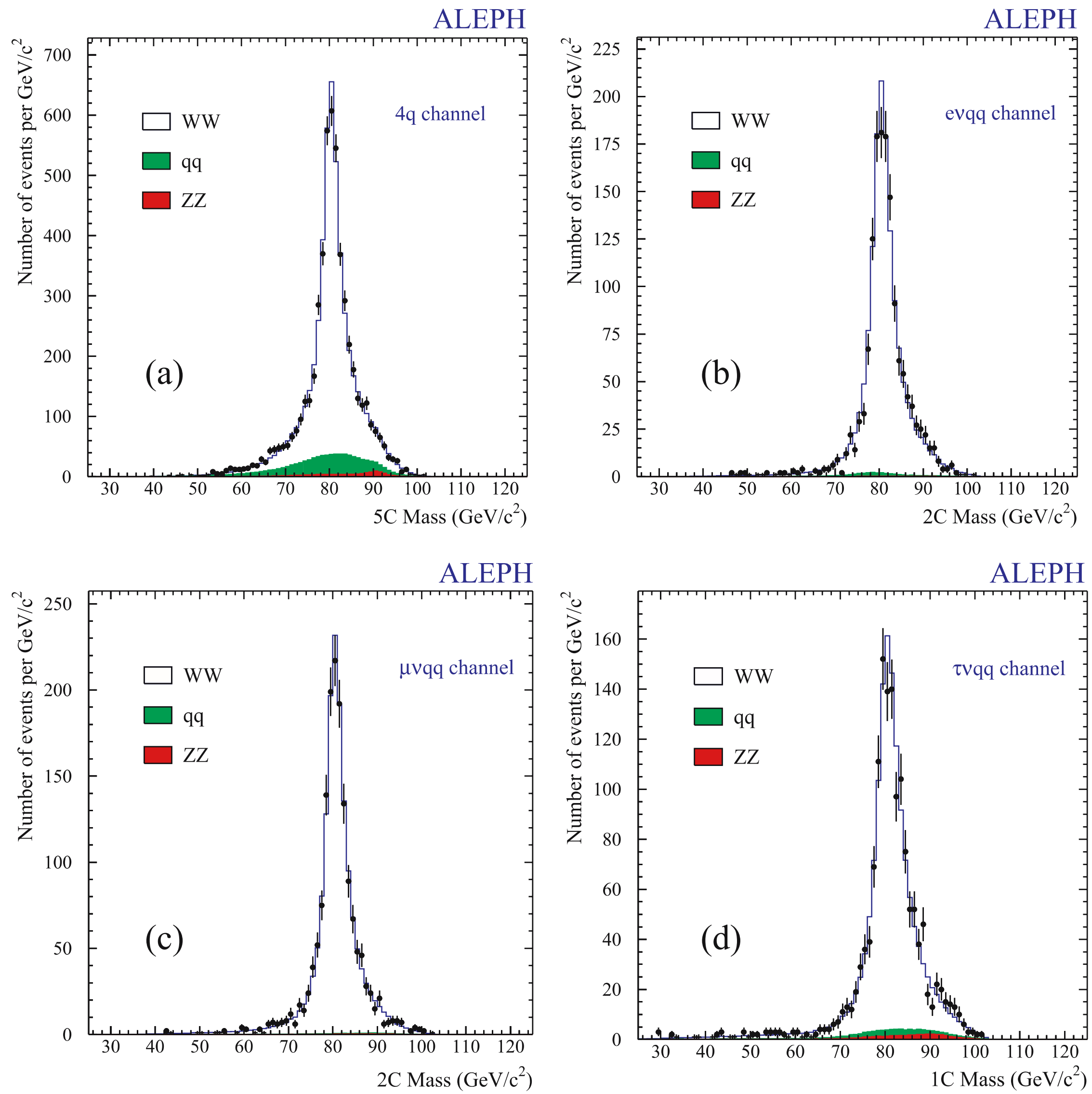
$\kappa_\gamma = 0.982^{+0.042}_{-0.042}$

$\lambda_\gamma = -0.022^{+0.019}_{-0.019}$

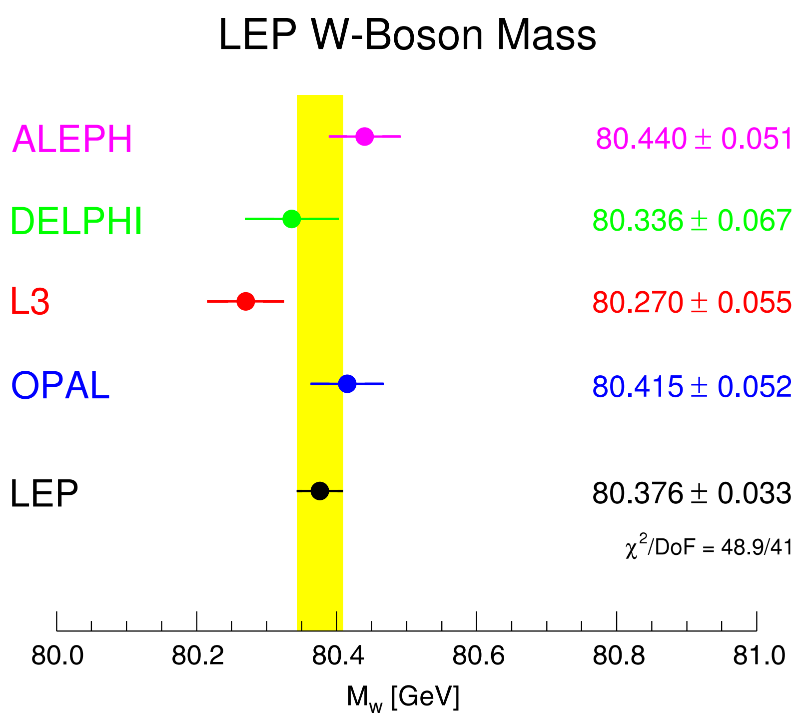
$g_1^Z = 0.984^{+0.018}_{-0.020}$

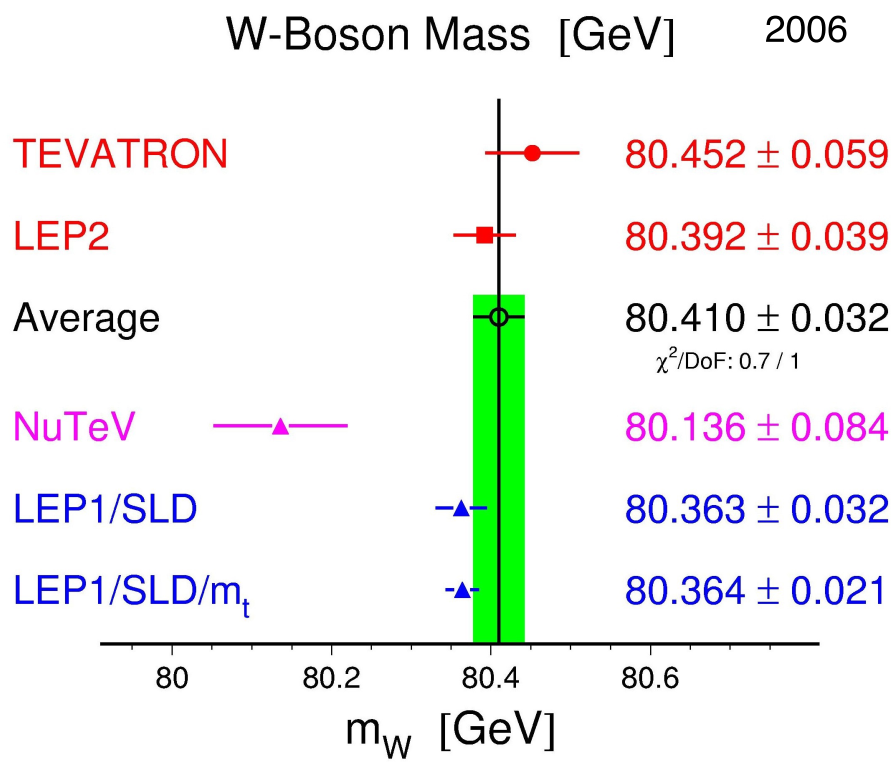
W boson mass

- Cross section threshold
- Direct reconstruction
  - hadronic or semi-leptonic
- Limited by jet energy resolution
- Use kinematic constraints:
  - energy, momentum: 4C
  - 2 masses in 1 event equal: 5C
  - in s.l. case: reconstruct neutrino momentum and perform 2C fit
    - 1C in the case of τ



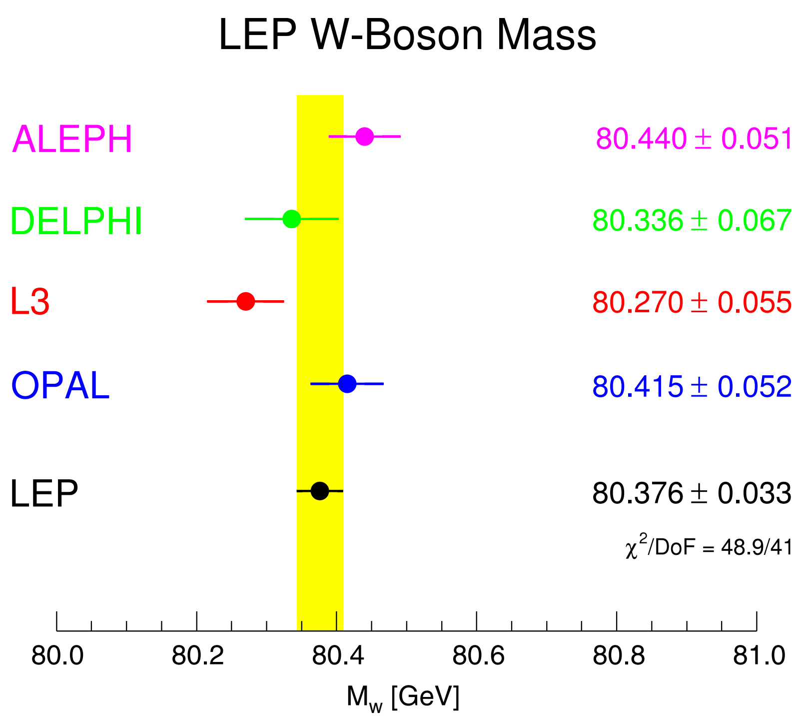
W mass results

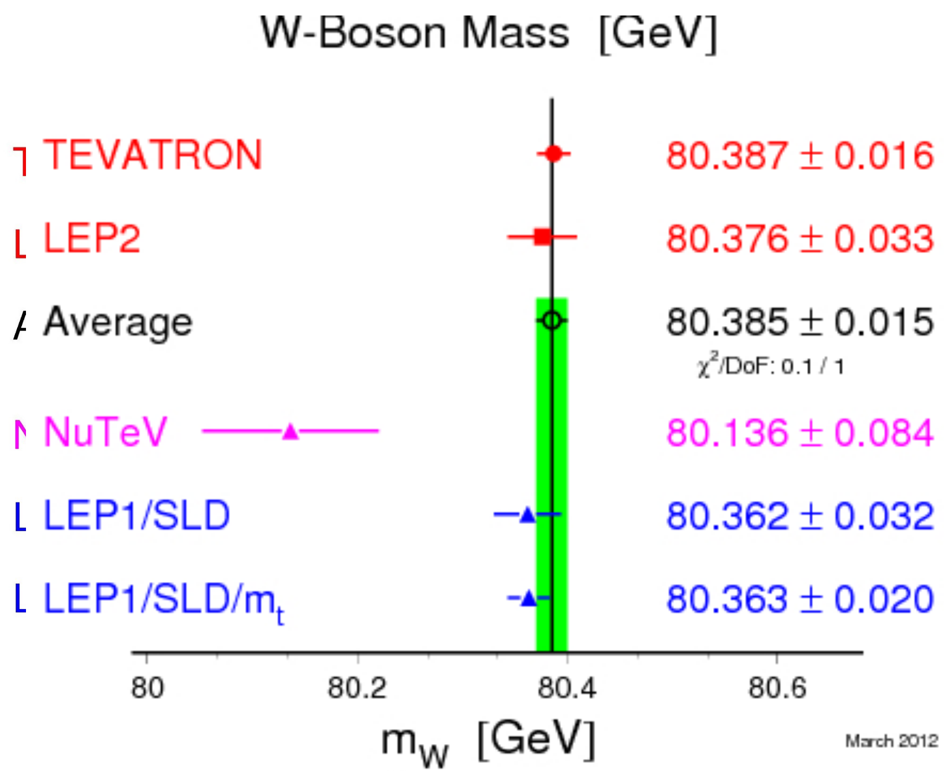




- indirect: $\cos\theta_W = m_W / m_Z$

W mass results

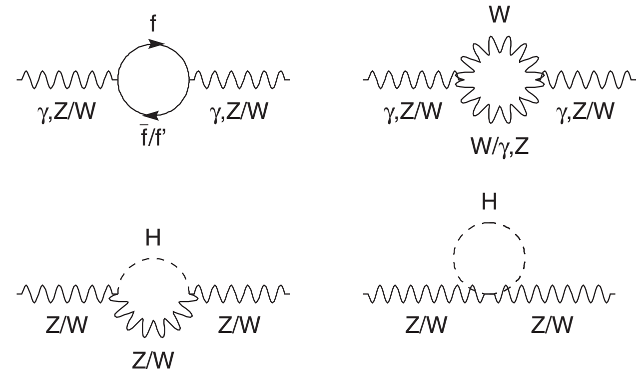


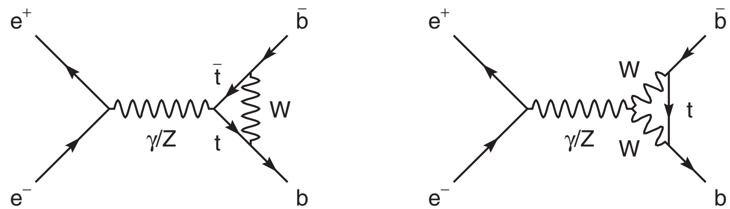


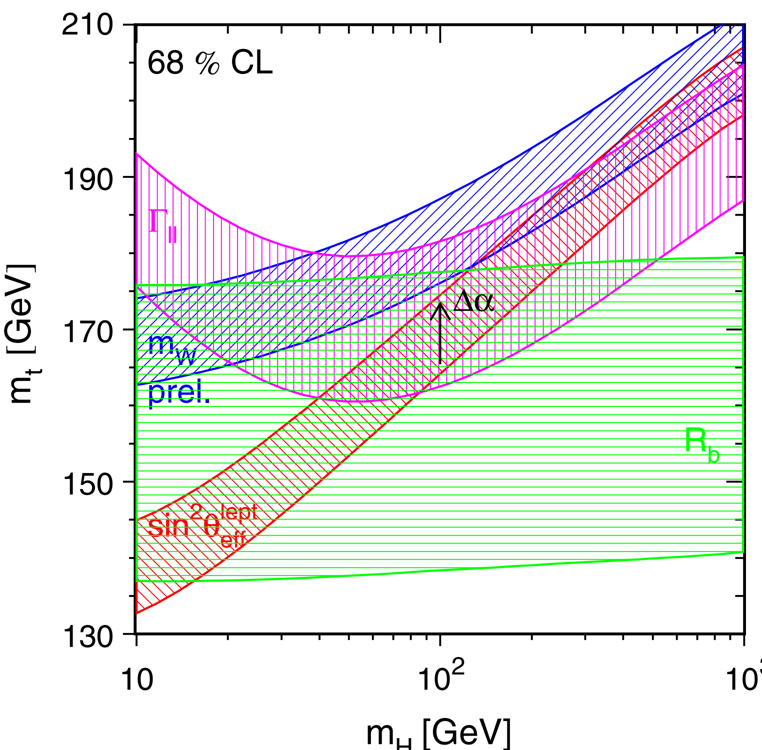
- indirect: $\cos\theta_W = m_W / m_Z$

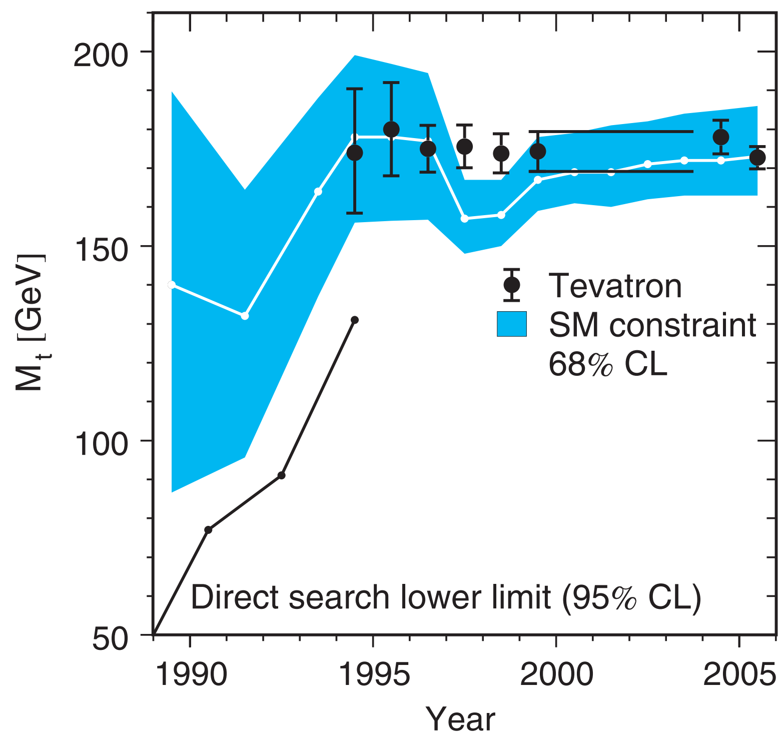
Constraints on the standard model

- Heavy particles enter via loops into radiative corrections
  - top: quadratic, Higgs: logarithmic

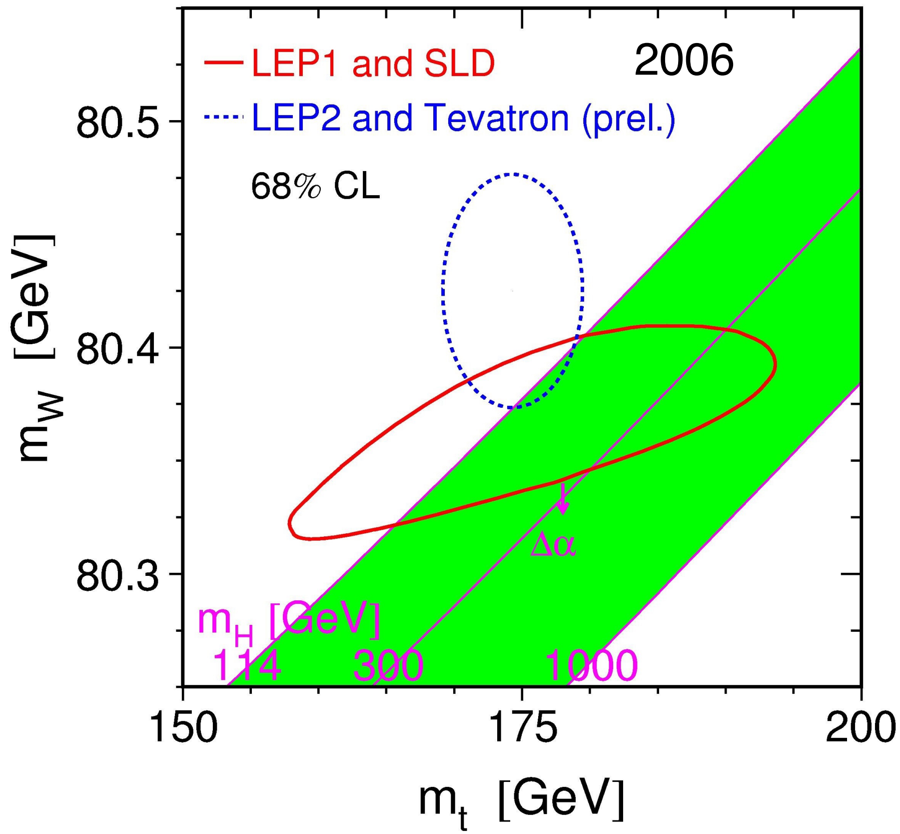


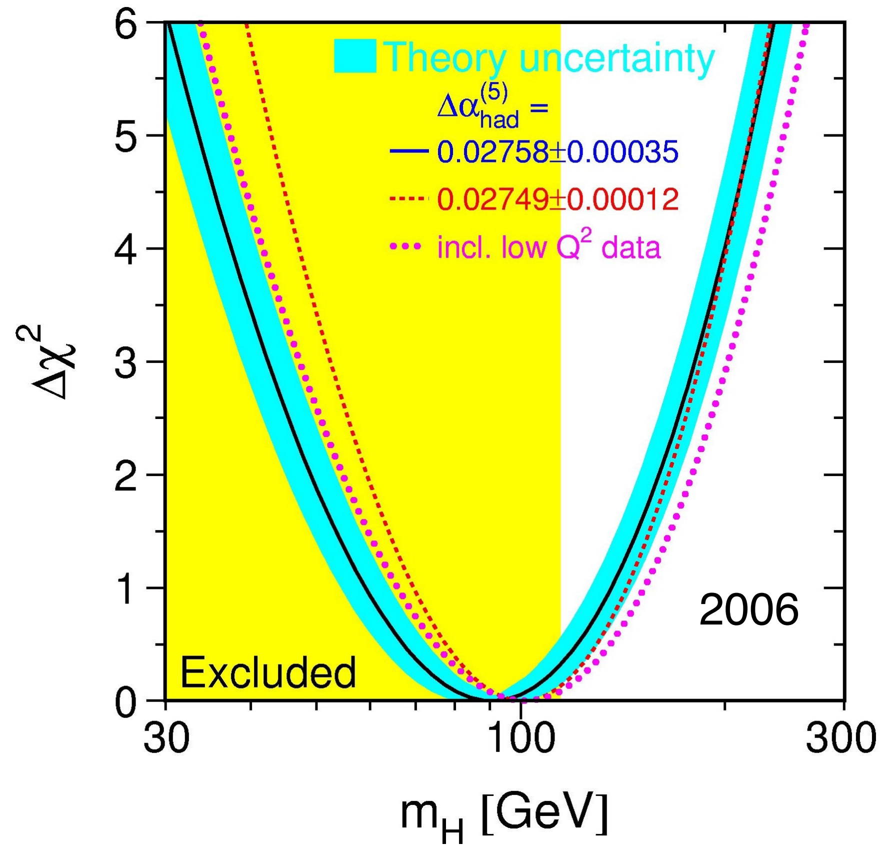






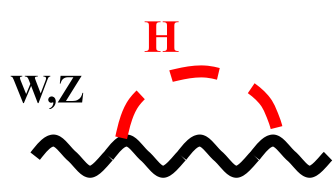
Testing the Standard Model





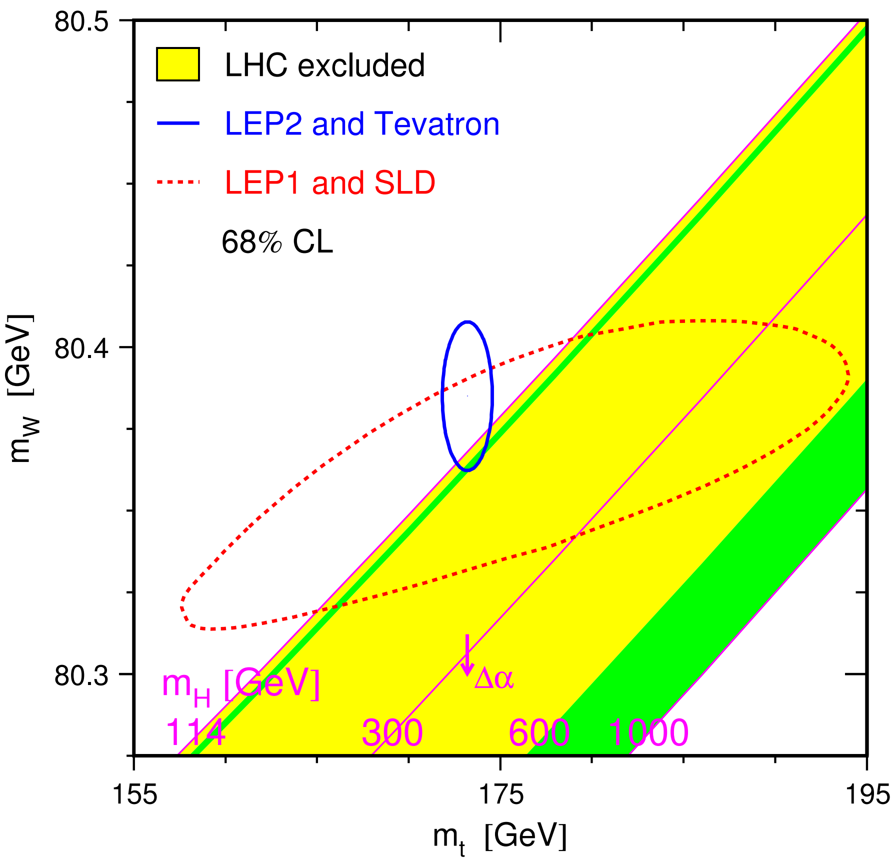
$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2}\frac{1}{m_W^2 \sin^2\upsilon_W}\frac{1}{1-\Delta r}$$

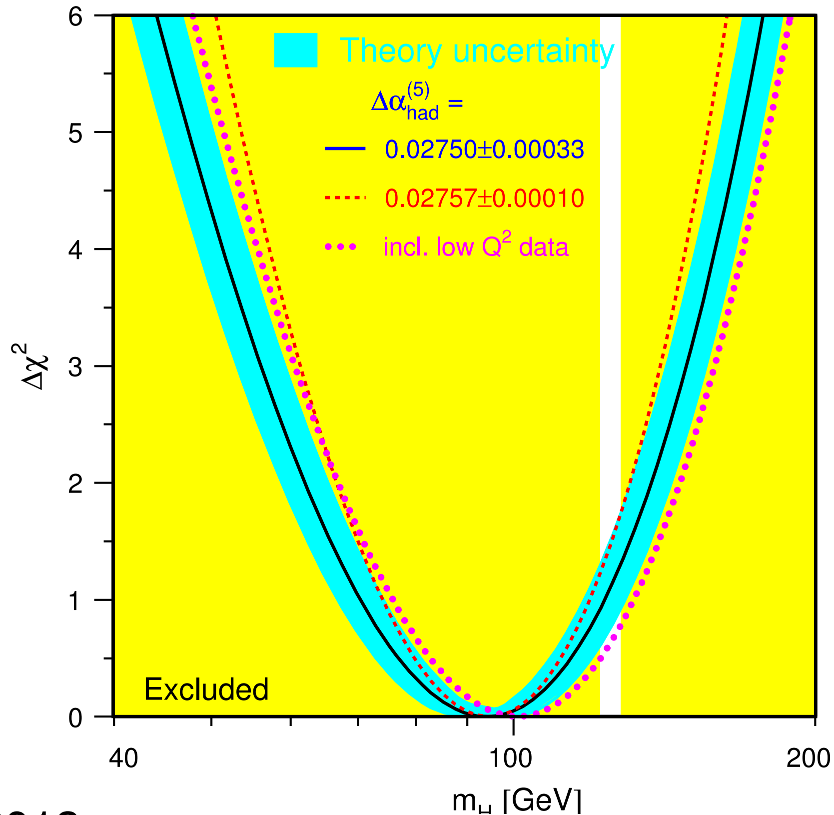
$$1-\Delta r \approx (1-\Delta\alpha)(1-\Delta r_W)$$



contribution to Δr, ~log m_H

Testing the Standard Model





2012

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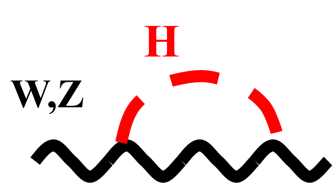
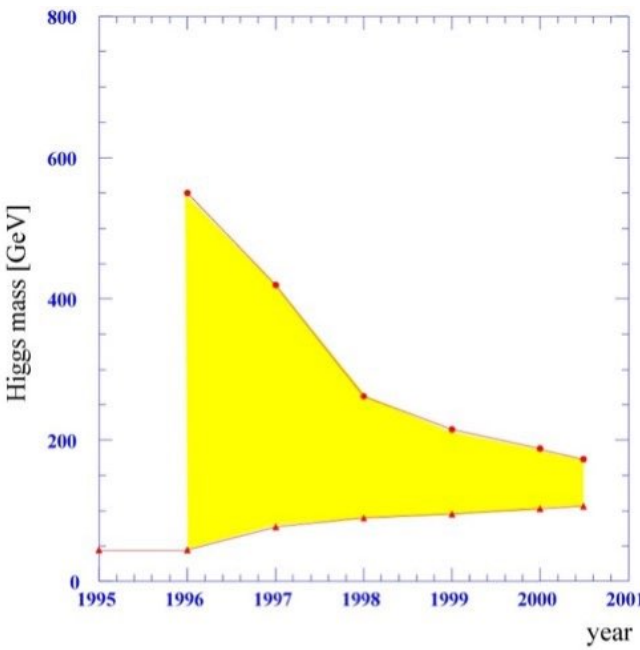
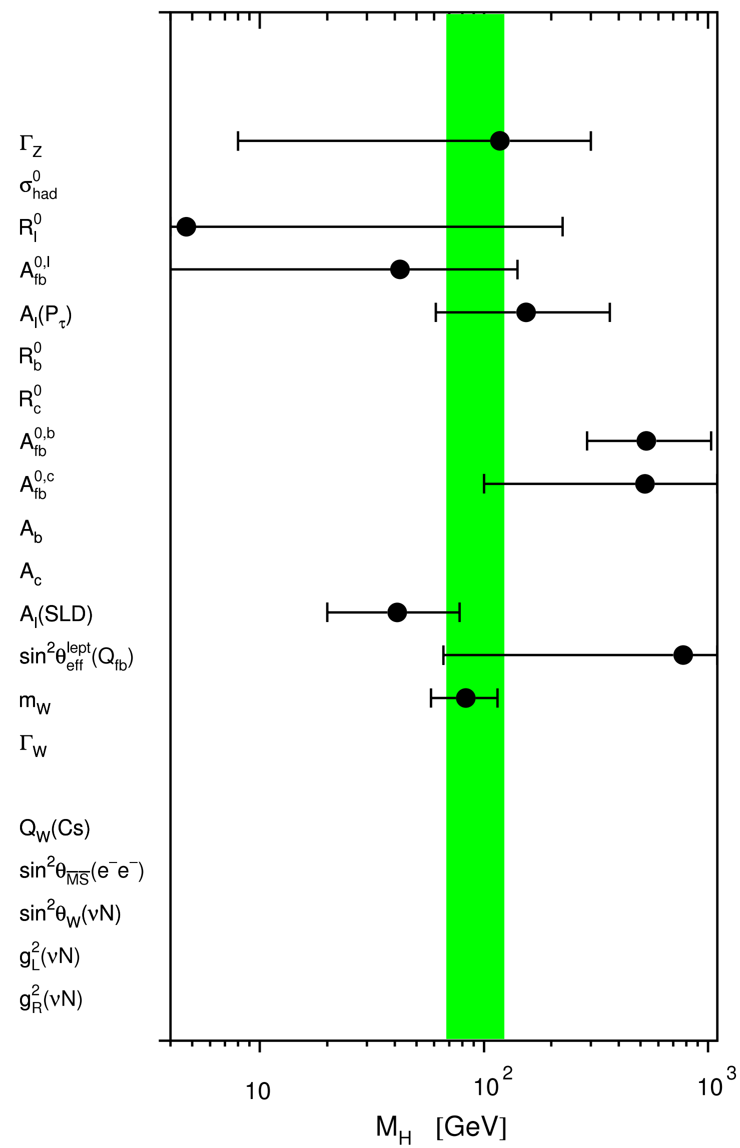


contribution to Δr, ~log m_H

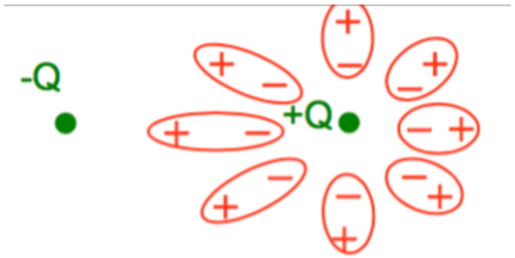
Sensitivity to M_H

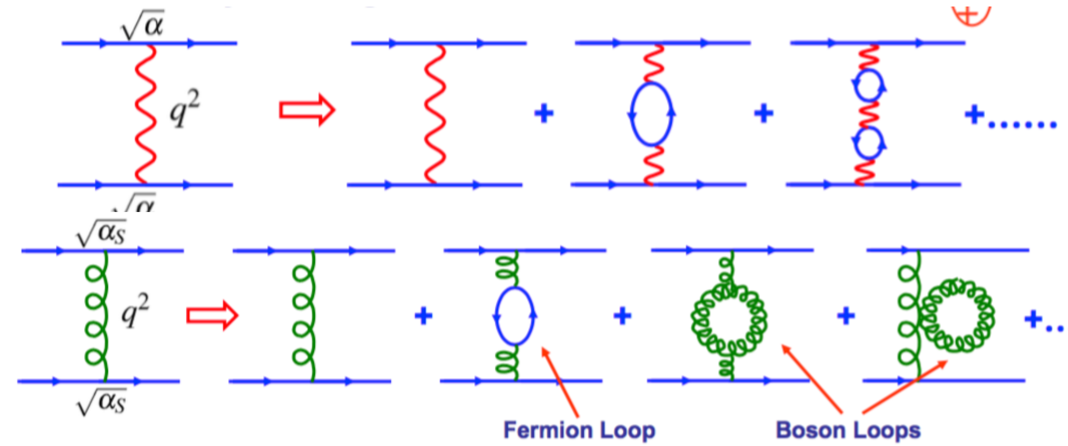




QCD and Heavy Quarks

Running coupling constants





- Screening by vacuum polarisation in Feynman diagram language:
- Summing the series: effective “running” coupling
- QED: alpha increases with energy
- QCD: self-interaction, boson and fermion loops: alpha-s decreases with energy

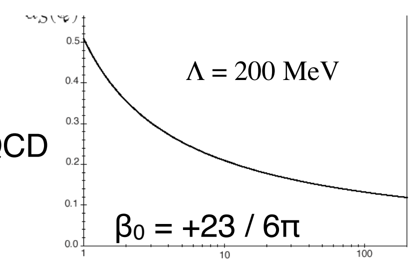
Renormalisation group equation

$$\mu \frac{\mathrm{d}}{\mathrm{d}\mu}\alpha_i(\mu) = -\beta_0\, \alpha_i^2$$

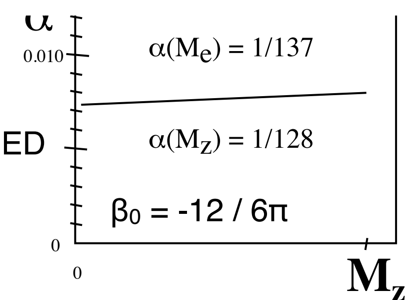
$$\alpha_i\left(q^2\right) = \frac{\alpha_i\left(\mu^2\right)}{1+\frac{\beta_0}{2}\alpha_i\left(\mu^2\right)\ln\frac{q^2}{\mu^2}}$$

$$\beta_0 = \frac{1}{2\pi}\left[\frac{11}{3}\begin{pmatrix} N_c \equiv 0 \\ N_c \equiv 2 \\ N_c \equiv 3 \end{pmatrix} - \frac{4}{3}\begin{pmatrix} N_{fam} \\ N_{fam} \\ N_f/2 \end{pmatrix} - N_{Higgs}\begin{pmatrix} \frac{1}{10} \\ \frac{1}{6} \\ 0 \end{pmatrix}\right] \begin{array}{l} \longleftarrow \text{QED} \\ \longleftarrow \text{weak} \\ \longleftarrow \text{QCD} \end{array}$$

QCD

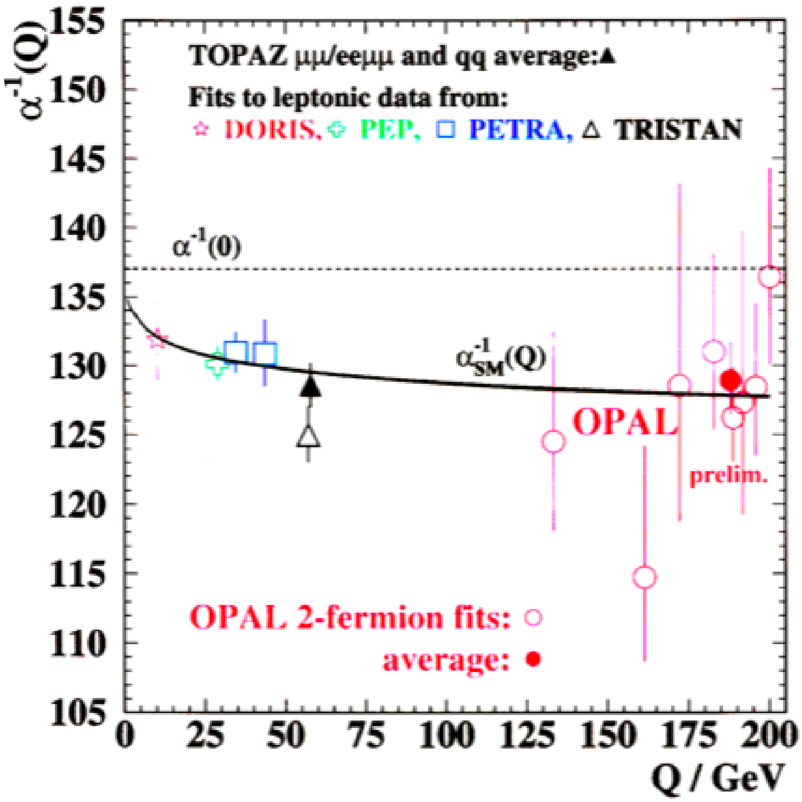


QED

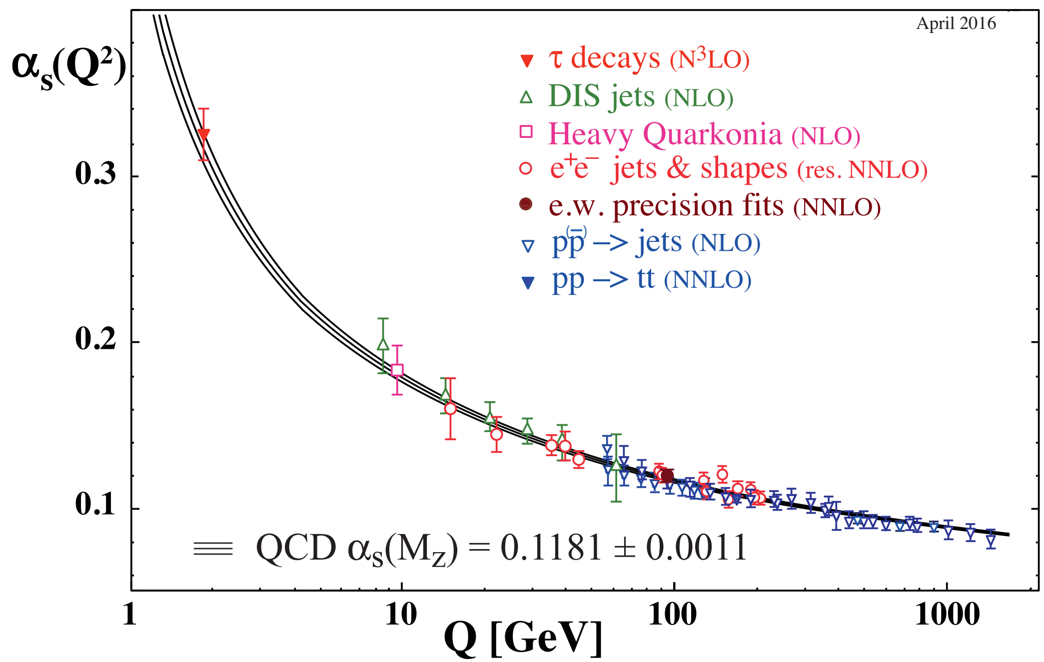


Measurements of running couplings

QED



QCD

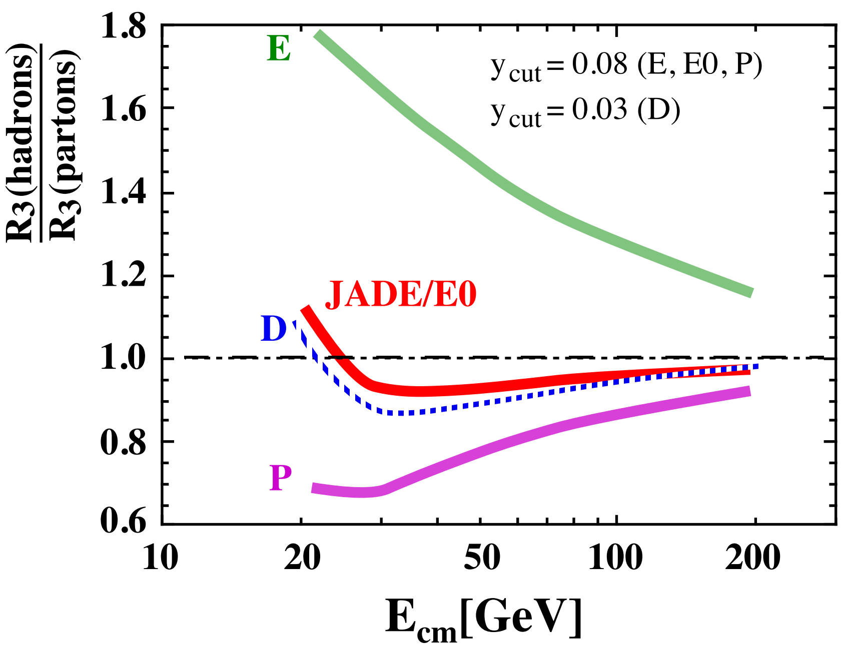


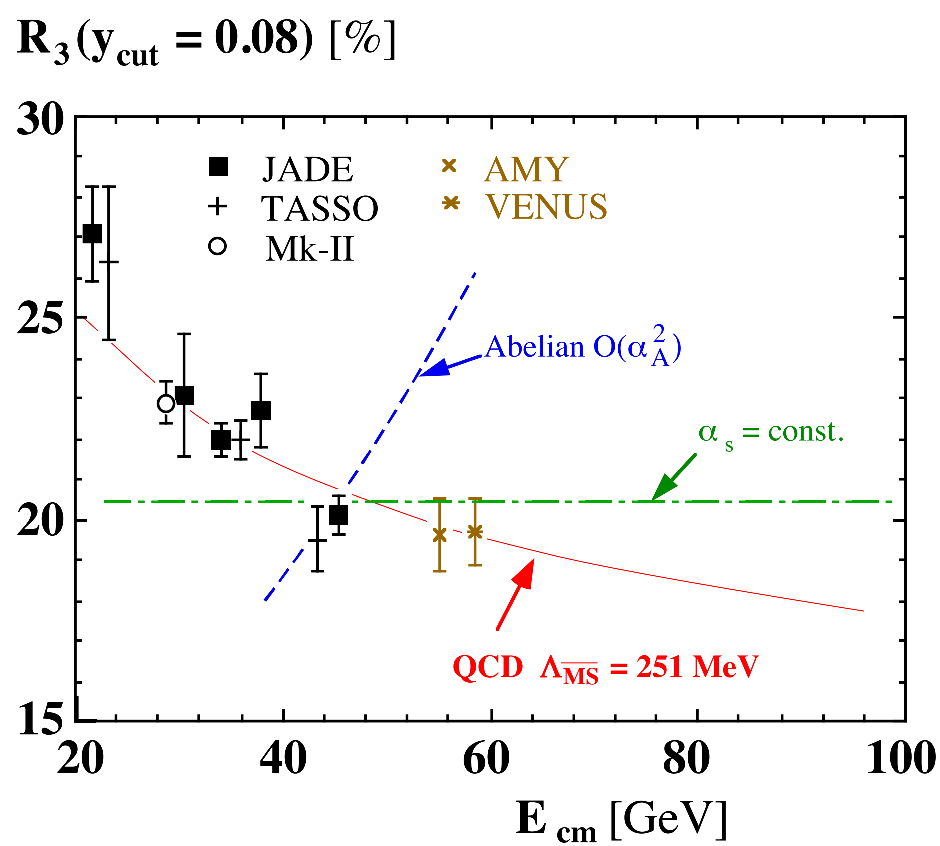
- Confirmed with precision over wide energy range
- alpha-s at LEP:
  - jet rates: common analysis with JADE data
  - event shapes, Z hadronic width, tau decay rates and spectra

3-jet rates

- Historically, already seen at PETRA
- Jet algorithm must reflect parton configuration
  - "hadronisation correction"

JADE Jet finder:
small and (almost) energy independent
hadronisation corrections:





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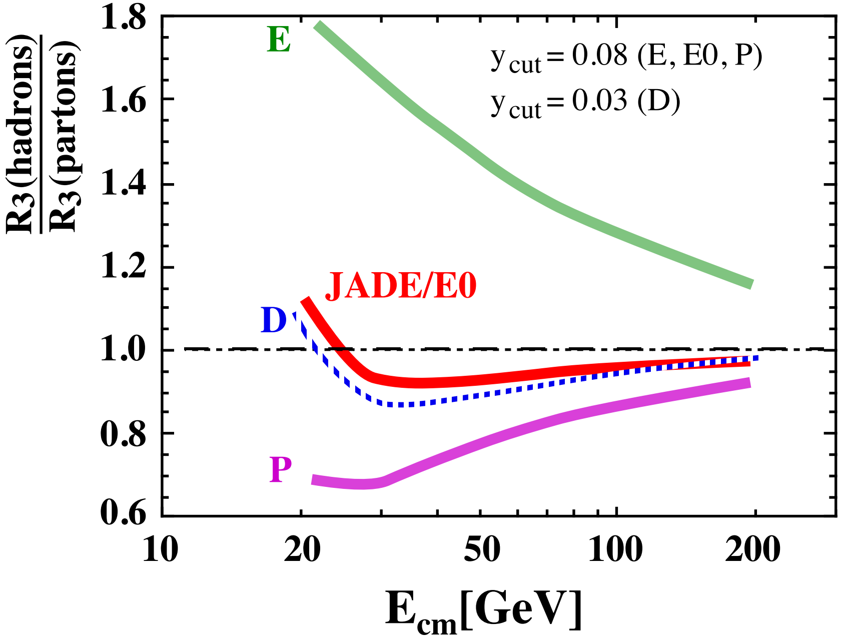
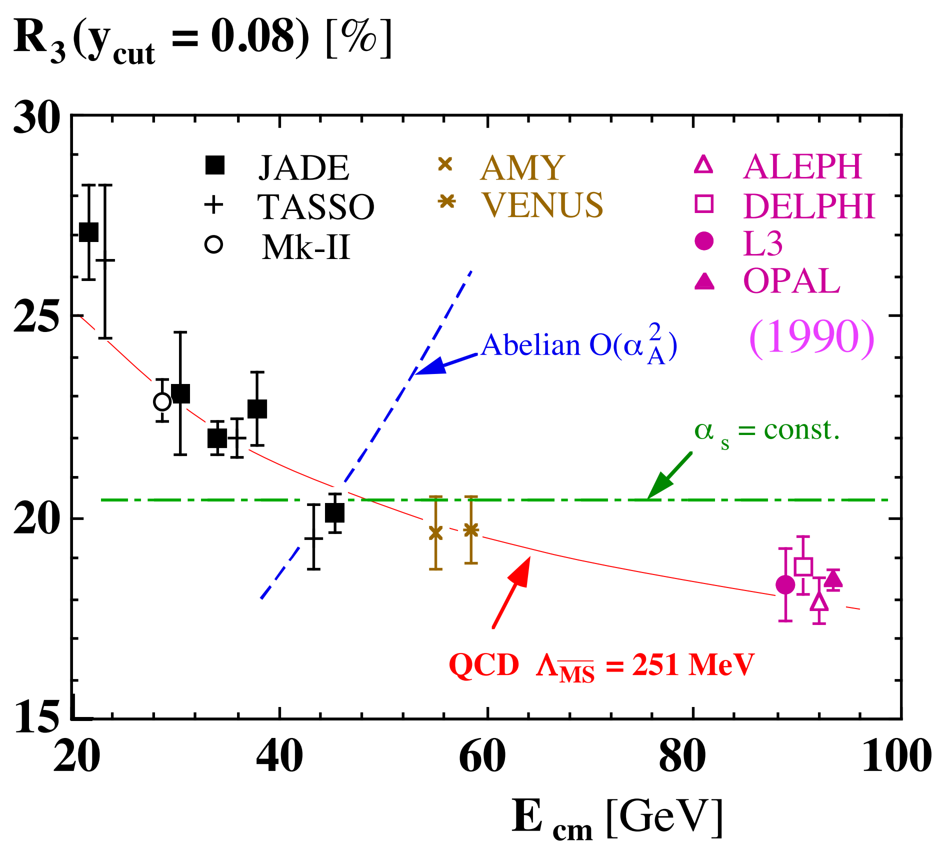
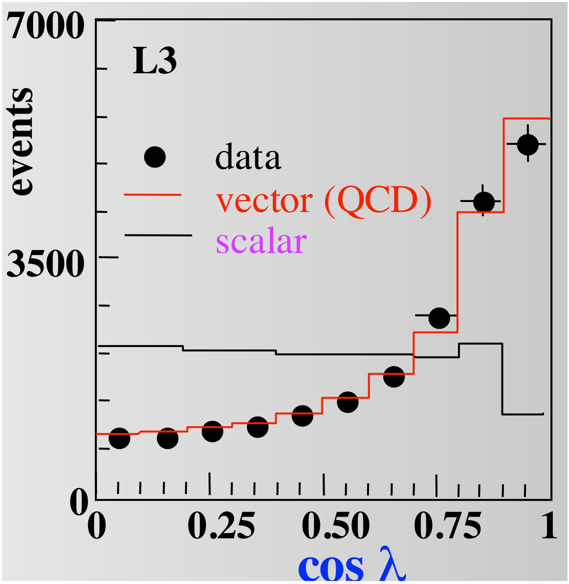
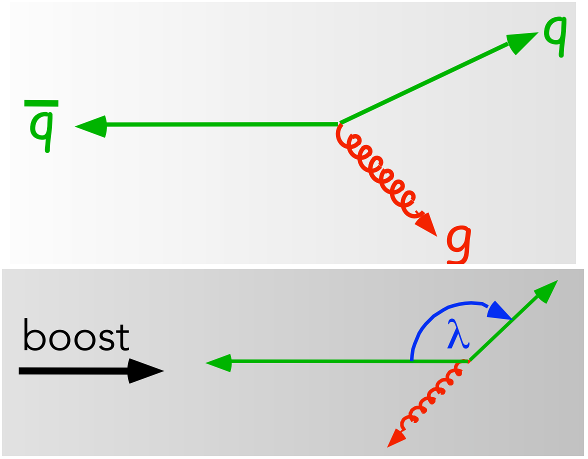




Structure of QCD interaction

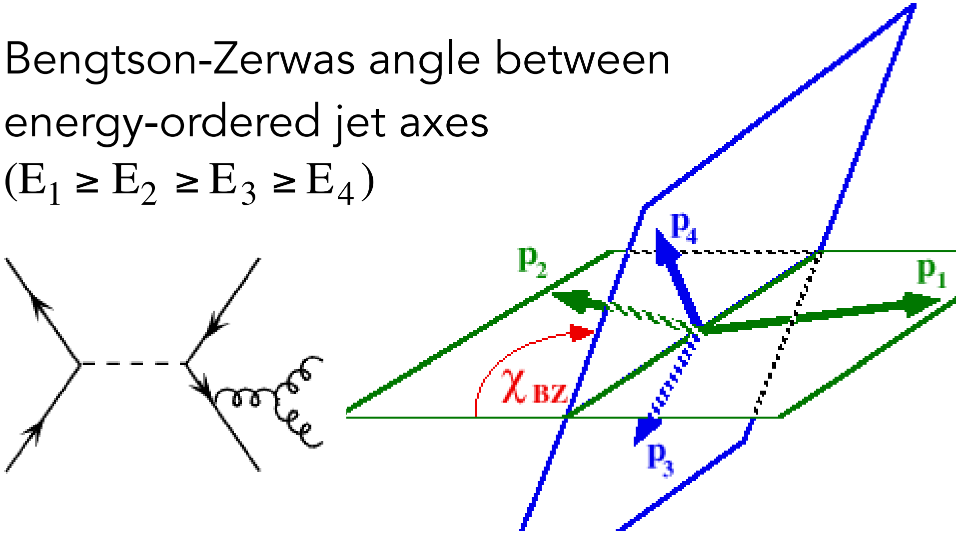
- Spin of the gluon
  - Ellis Karliner angle

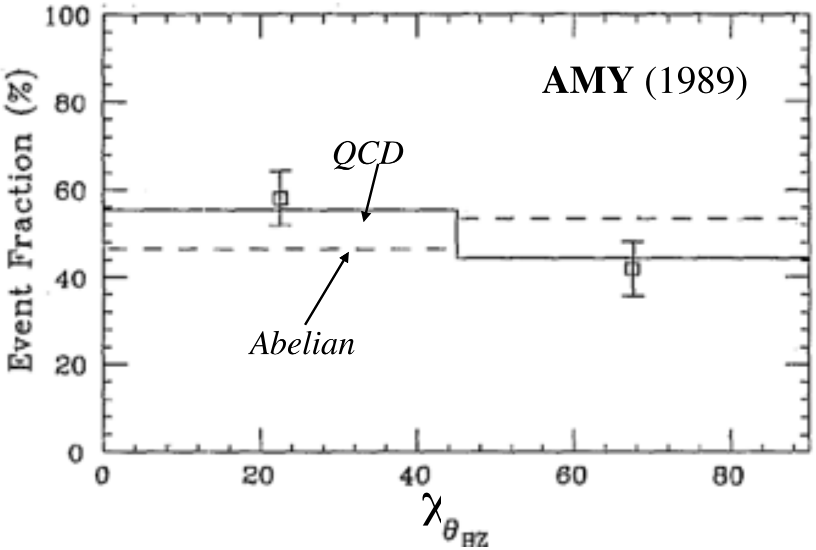




- Non-Abelian nature of QCD

Bengtson-Zerwas angle between energy-ordered jet axes
$(E_1 \geq E_2 \geq E_3 \geq E_4)$





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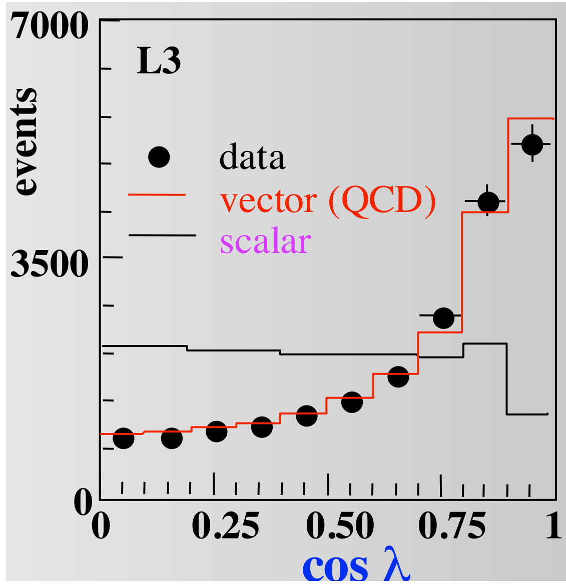

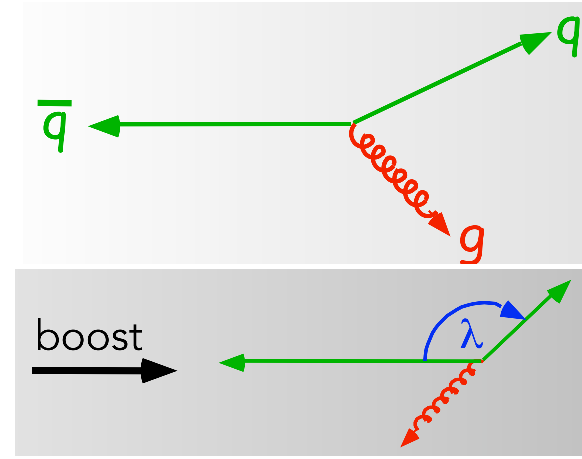

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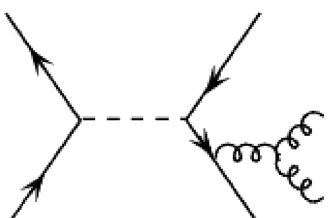
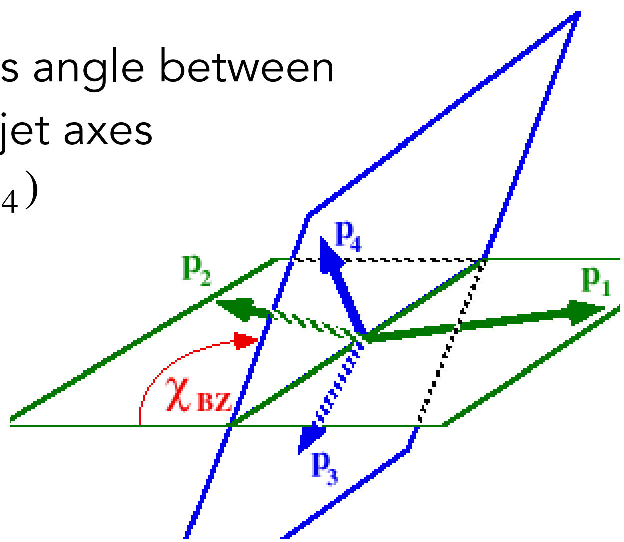
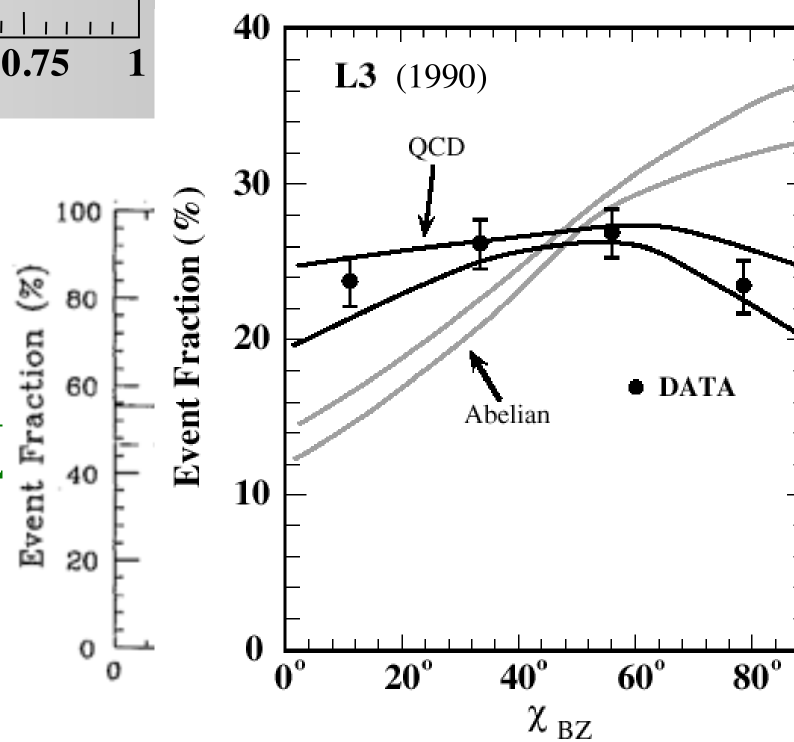
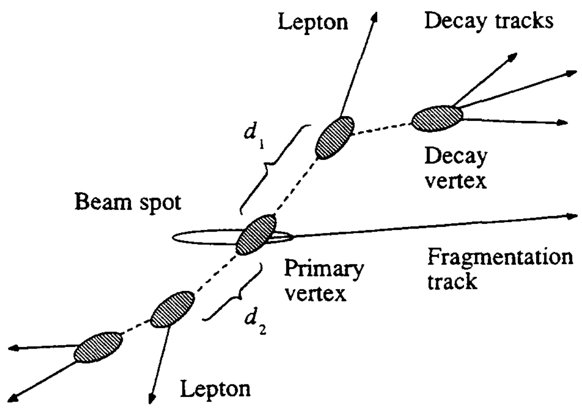


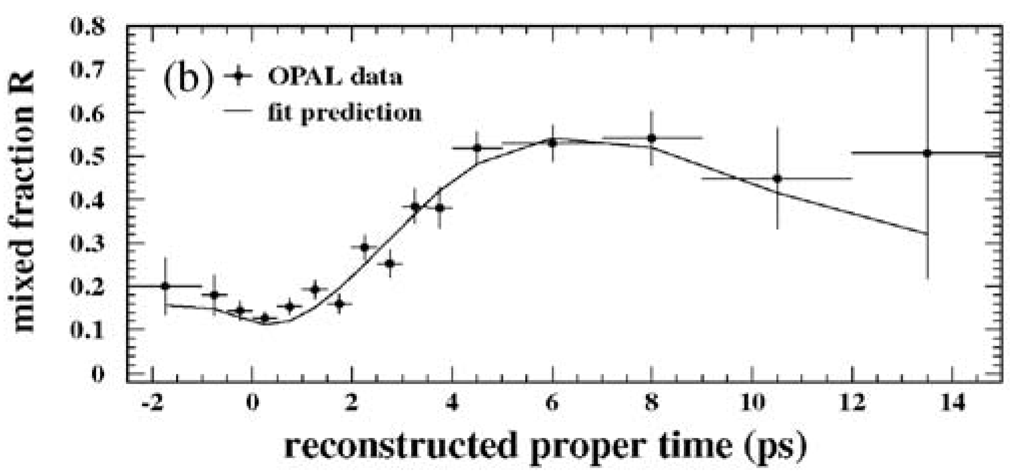


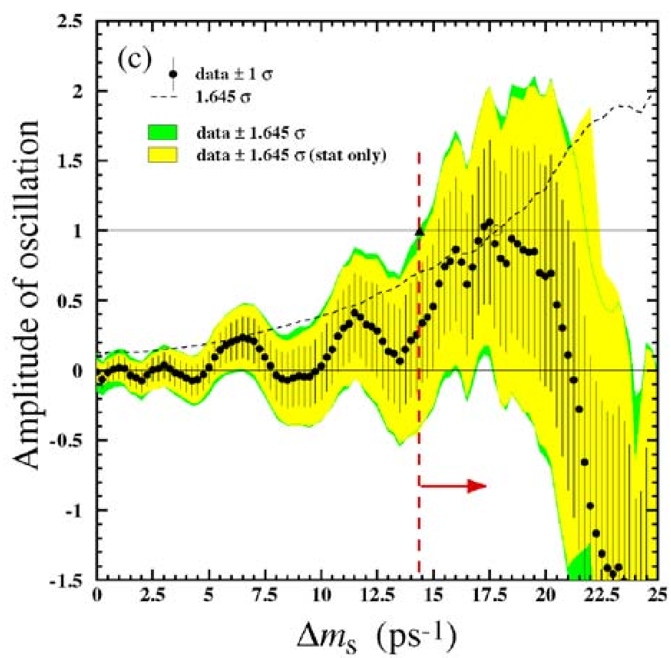


B mixing again: time dependence

- Boost allows observation of decay length
- Need to convert to proper time: reconstruct momentum event by event
  - use tracks from secondary vertex, missing energy techniques for the neutrino plus an estimator for the neutral energy of B decay products
- Observe B_d oscillations vs time
- Set stringent limits on B_s oscillations







- CDF (2006): $\Delta m_s = 18\ \mathrm{ps}^{-1}$

Wrap-up LEP:

- LEP and SLC were a triumph for the Standard Model.
- Tests with per-mil precision prove that it is correct at the one-loop quantum level.
- This IS a discovery.
- The precision resulted in quantitative predictions for the discovery of new particles, which were confirmed.
- Many text book experiments made - electro-weak and QCD.
- Clean environment, well defined initial state, polarisation, kinematic fits made that possible.
- New experimental techniques - vertex detectors - unfolded the potential of heavy flavour observables.
- In the end, the redundancy of using many observables and the possibility to perform internal cross-checks were crucial for the success.