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ELECTROWEAK PHYSICS

Overview

- Theory Introduction
- Physics at the Z-pole: LEP and SLC
- W-physics: LEP-II & Tevatron
- Top physics: Tevatron & LHC
- Higgs Physics
- Fitting the Standard Model

The Electroweak Lagrangian

$$\mathcal{L}_{\rm MSM} = \mathcal{L}_{\rm QED} + \mathcal{L}_{\rm free\ V} + \mathcal{L}_{\rm ffW} + \mathcal{L}_{\rm ffZ} + \mathcal{L}_{\rm 3V} + \mathcal{L}_{\rm 4V} + \mathcal{L}_{\rm free\ H} + \mathcal{L}_{\rm ffH} + \mathcal{L}_{\rm VVH} + \mathcal{L}_{\rm VVHH} + \mathcal{L}_{\rm 3,4H}$$

$$\mathcal{L}_{\rm QED} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \sum_j \left\{ \bar{f}_j (i\partial^\mu \gamma_\mu - m_j) f_j - iQ_j \bar{f}_j \gamma^\mu A_\mu f_j \right\}$$

$$\mathcal{L}_{\rm free\ V} = -\frac{1}{2}W^*_{\mu\nu}W^{\mu\nu} - m_W^2 W^*_\mu W^\mu - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} - \frac{1}{2}m_Z^2 Z_\mu Z^\mu$$

$$\mathcal{L}_{\rm ffW} = i\frac{e}{s_w\sqrt{8}} \sum_{j=u,k=d} \left\{ \bar{f}_j (1+\gamma^5)\gamma_\mu W^{*\mu} f_k V_{jk} + \text{h.c.} \right\}$$

$$\mathcal{L}_{\rm ffZ} = i\frac{e}{4 s_w c_w} \sum_j \bar{f}_j (v_j + a_j \gamma^5)\gamma_\mu Z^\mu f_j$$

$$\mathcal{L}_{\rm 3V} = ie\left(\frac{c_w}{s_w}Z_\nu - A_\nu\right)\left[W_\mu W^{*}{}_{\mu\nu} - W^*{}_\mu W_{\mu\nu} + \partial_\mu \left(W^\mu W^{*\nu} - W^{*\mu}W^\nu\right)\right]$$

$$\mathcal{L}_{\rm 4V} = e^2 (g^{\mu\rho}g^{\nu\sigma} - g^{\mu\nu}g^{\rho\sigma}) \left[\frac{1}{2s_w^2} W^*{}_\mu W_\nu W^*{}_\rho W_\sigma + \left(\frac{c_w}{s_w}Z_\mu - A_\mu\right)\left(\frac{c_w}{s_w}Z_\nu - A_\nu\right) W^*{}_\rho W_\sigma \right]$$

$$\mathcal{L}_{\rm free\ H} = -\frac{1}{2}(\partial_\mu H)(\partial^\mu H) - \frac{1}{2}m_H^2 H^2$$

$$\mathcal{L}_{\rm ffH} = -\frac{e}{2s_w}\sum_j \frac{m_j}{m_W}\bar{f}_j f_j H$$

$$\mathcal{L}_{\rm VVH} = -e\frac{m_W}{s_w}W^\mu W^*{}_\mu H - e\frac{m_Z}{2s_w c_w}Z^\mu Z_\mu H$$

$$\mathcal{L}_{\rm VVHH} = -\frac{e^2}{4s_w^2}W^\mu W^*{}_\mu H^2 - \frac{e^2}{8s_w^2 c_w^2}Z^\mu Z_\mu H^2$$

$$\mathcal{L}_{\rm 3,4H} = -e^2\frac{m_H^2}{4m_w s_w}H^3 - e^2\frac{m_H^2}{32 m_W^2 s_w^2}H^4$$

Q: How do we relate this to observables that we can measure in experiments?

A: Take one piece at a time!

Often need to consider corrections from other terms

LEP1 + SLC: Z0 physics

LEP2 (+Tevatron): W, TGC

Parameters of the Electroweak Sector

- Three key parameters:
  - The two gauge coupling constants: ***g_W*** and ***g'_W***
  - The vacuum expectation value of the Higgs field: ***v***
- These can be obtained through 3 measurements.
- Choose the 3 most precise:
  - The electric charge, ***e-***
    - measured by the electric dipole moment
  - The Fermi Constant, ***G_F*** (precision: 0.9×10^{-5})
    - measured by the muon lifetime
  - The mass of the Z boson, ***M_Z*** (precision: 2.3×10^{-5})

$$e = \frac{g_W g'_W}{\sqrt{g_W^2 + g'^2_W}}$$

$$M_Z = \tfrac{1}{2} v \sqrt{g_w^2 + g'^2_w}$$

$$G_F = \frac{1}{\sqrt{2}v^2}$$

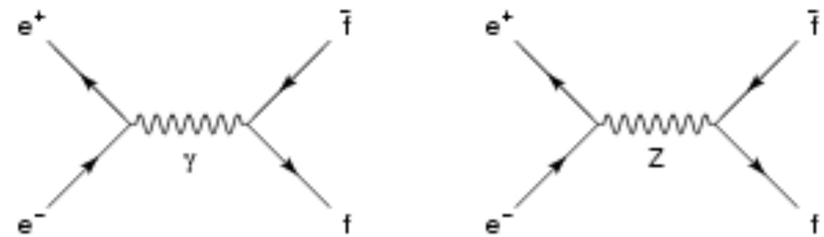
Other Useful Combinations

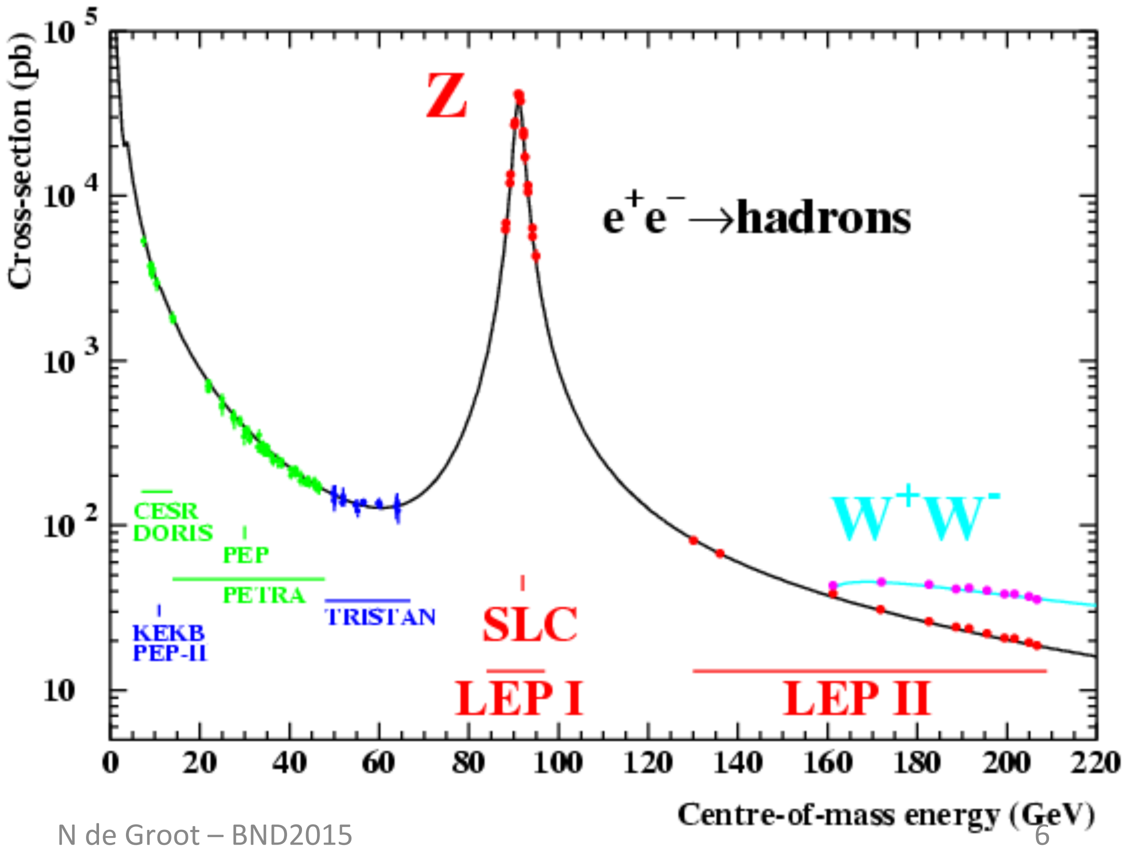
- Mass of the W boson: $$M_W = \frac{v g_W}{2}$$ $$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8 M_W^2} = \frac{1}{2v^2}$$
- Weak mixing angle: $$\sin^2\theta_W = \frac{g'^2_W}{g'^2_W + g_W^2} \approx 0.23$$
- Relationship between W and Z mass: $$M_Z = \frac{M_W}{\cos\theta_W}$$

Physics at the Z0-Pole: LEP I & SLD

- What EWK theory tells us about Z
- How to make and detect Zs

- Physics Topics:
  – Z mass
  – Partial and Total Widths
  – Z couplings to fermion pairs
  – Asymmetries





Z^0-fermion coupling

A look at the theory – tree level relations

Vector and axial-vector couplings for $Z \rightarrow ff$ in SM:

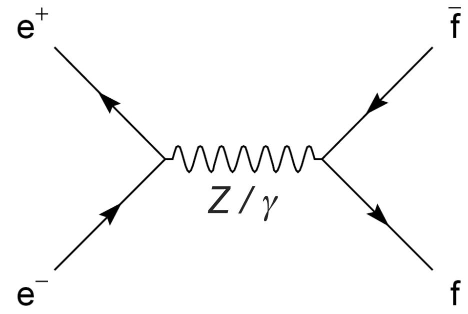
$$g_{V,f}^{(0)} \equiv g_{L,f}^{(0)} + g_{R,f}^{(0)} = I_3^f - 2Q^f \sin^2\theta_W \qquad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

$$g_{A,f}^{(0)} \equiv g_{L,f}^{(0)} - g_{R,f}^{(0)} = I_3^f$$

Electroweak unification: relation between weak and electromagnetic couplings:

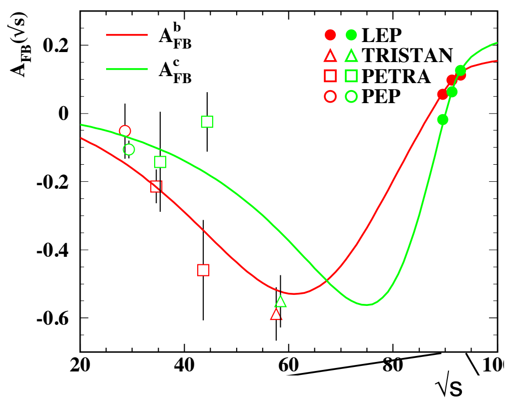
$$G_F = \frac{\pi\alpha(0)}{\sqrt{2}M_W^2\left(1 - M_W^2/M_Z^2\right)} \quad , \quad M_W^2 = \frac{M_Z^2}{2}\cdot\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Gauge sector of SM on tree level is given by 3 free parameters, *e.g.*: α, M_Z, G_F (best known!)



Z–lepton coupling almost pure axial-vector

(γ pure vector → large off-peak interference → could establish Z-fermion coupling at PETRA, interesting for Z' searches via interference)



Radiative Corrections

Radiative corrections –
modifying propagators and vertices

Significance of radiative corrections can be illustrated by verifying tree level relation:

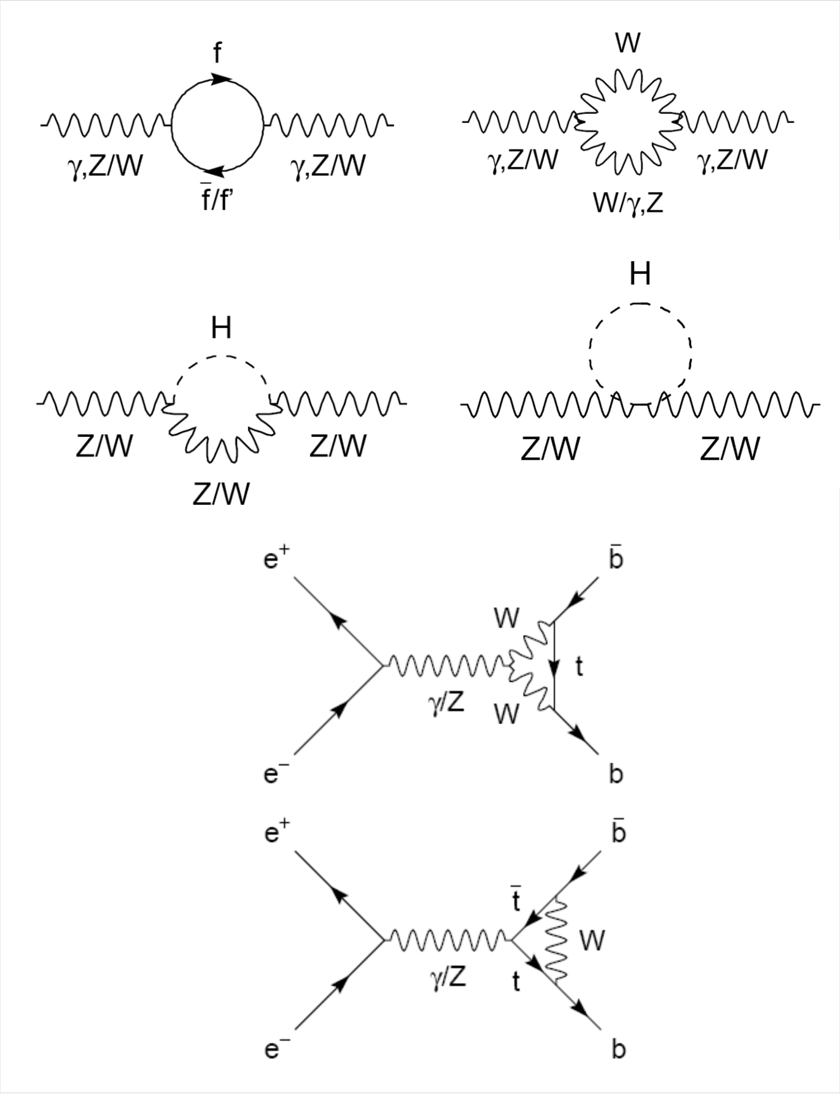
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- Using the measurements:

$$M_W = (80.399 \pm 0.023)\ \text{GeV}$$
$$M_Z = (91.1875 \pm 0.0021)\ \text{GeV}$$

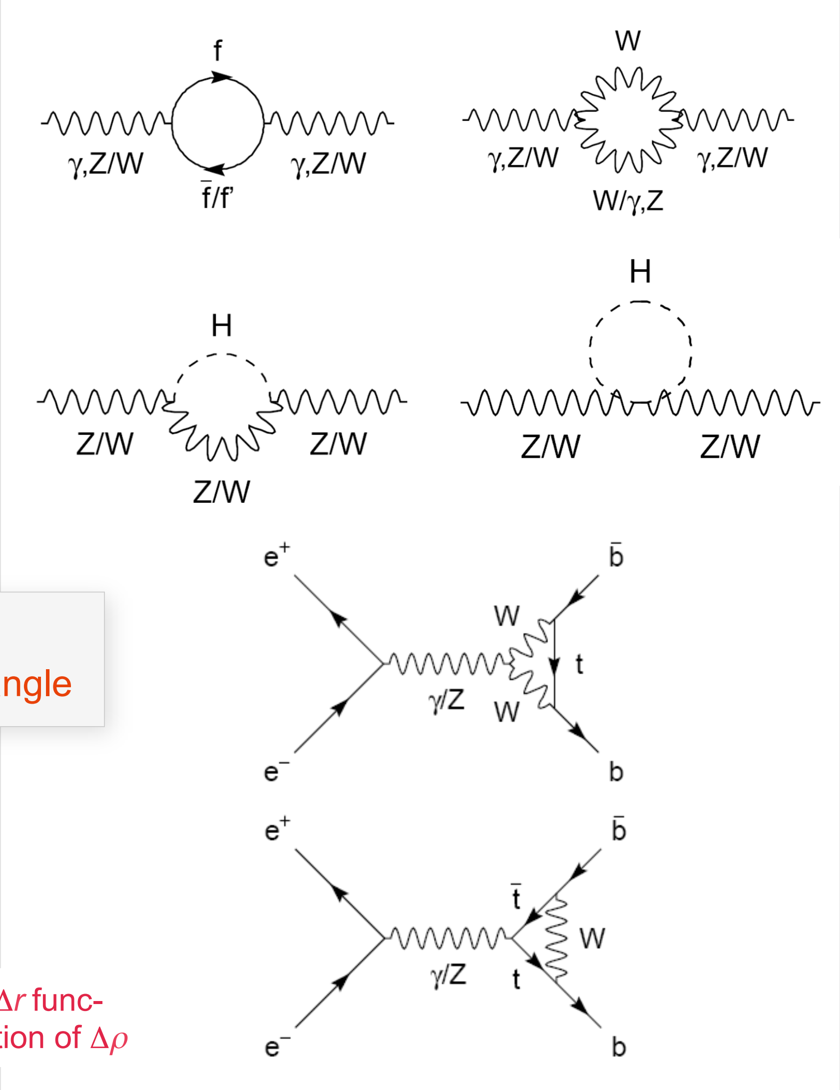
one predicts: $\sin^2\theta_W = 0.22284 \pm 0.00045$

which is 18 σ away from the experimental value obtained by combining all asymmetry measurements: $\sin^2\theta_W = 0.23153 \pm 0.00016$



Radiative Corrections

Radiative corrections – modifying propagators and vertices



Parametrisation of radiative corrections:
"electroweak form-factors": ρ, κ, Δr

- Modified ("effective") couplings at the Z pole:

$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\rm eff}^f\right)$$

$$g_{A,f} = \sqrt{\rho_Z^f}\, I_3^f$$

$$\sin^2\theta_{\rm eff}^f = \kappa_Z^f \sin^2\theta_W$$

ρ : overall scale
κ : on-shell mixing angle

- Modified W mass:

$$M_W^2 = \frac{M_Z^2}{2}\cdot\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha}{G_F M_Z^2\cdot\left(1-\Delta r\right)}}\right)$$

Δr function of $\Delta\rho$

Radiative Corrections

Radiative corrections – modifying propagators and vertices

Leading order terms ($M_W \ll M_H$)

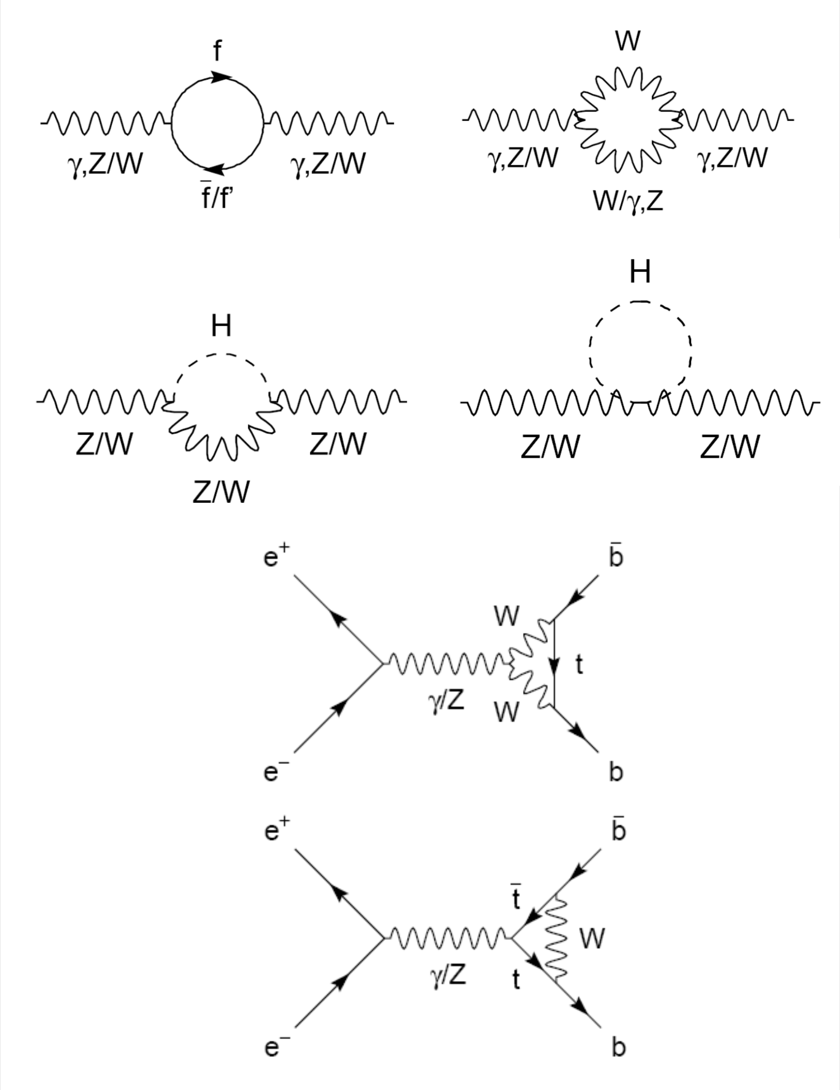
- ρ_Z and κ_Z can be split into sum of universal contributions from propagator self-energies:

$$\Delta\rho_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{M_W^2} - \tan^2\theta_W\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots\right]$$

$$\Delta\kappa_Z = \frac{3G_F M_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{M_W^2}\cot^2\theta_W - \frac{10}{9}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right) + \ldots\right]$$

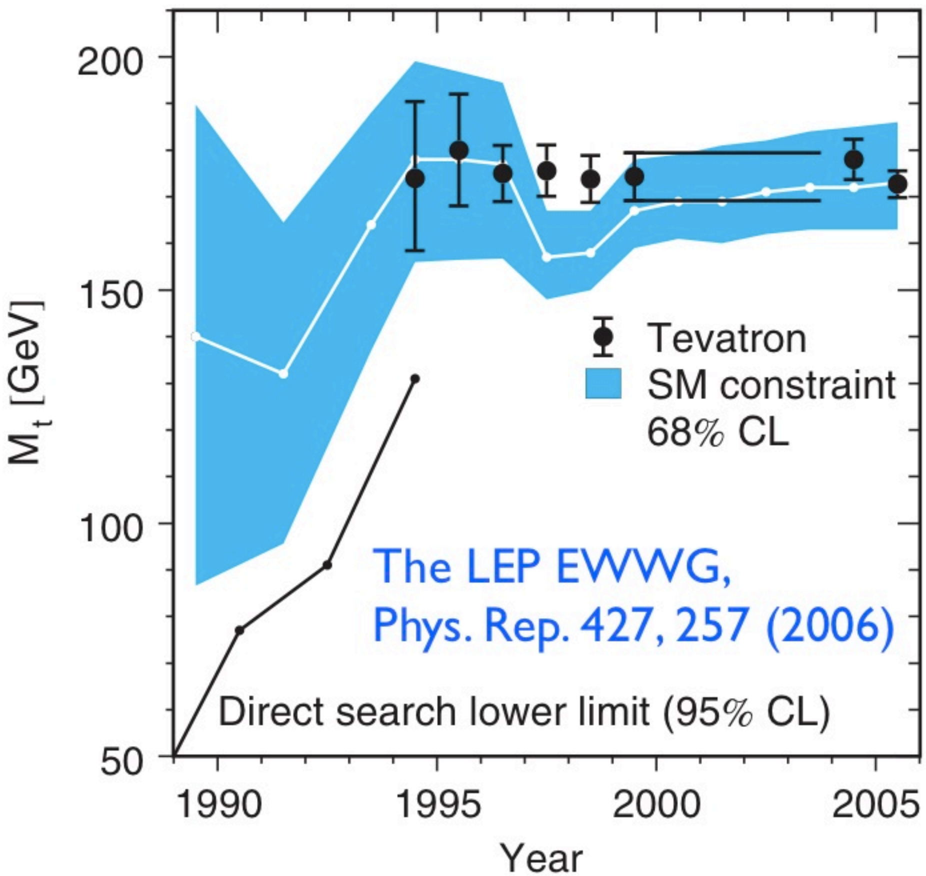
- and flavour-specific vertex corrections, which are very small, except for top quarks, owing to large mass and $|V_{tb}|$ CKM element

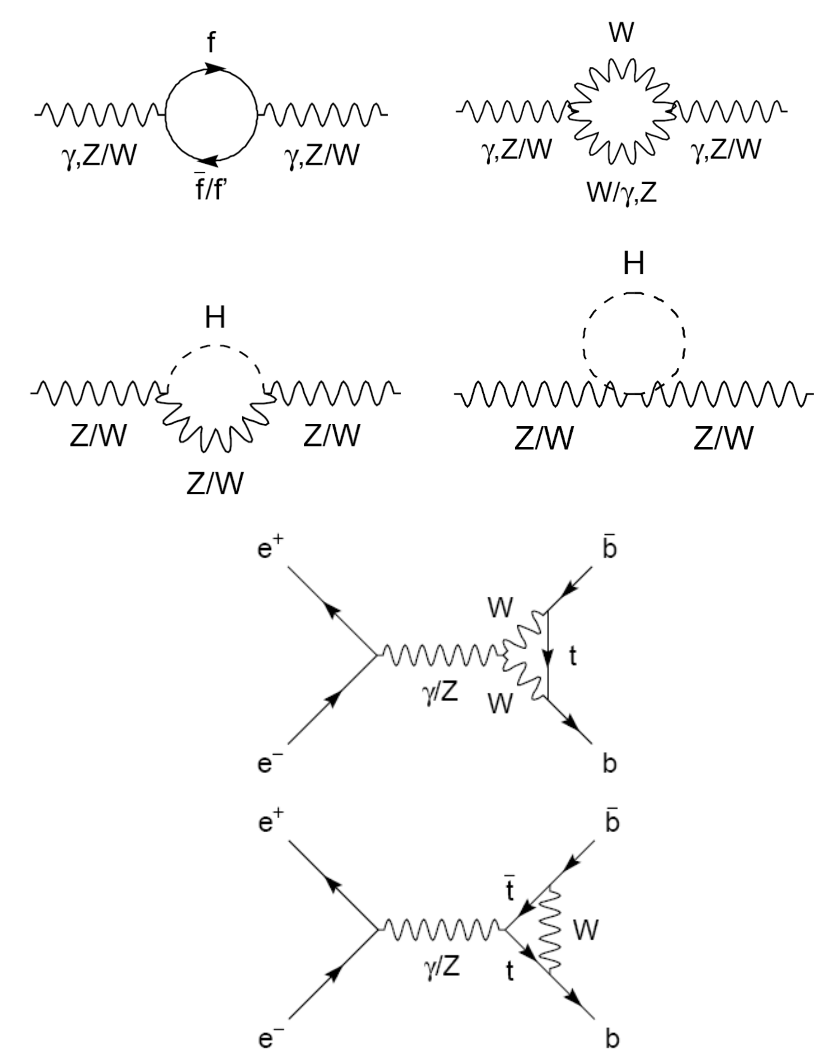
$$\Delta\rho^f = -2\Delta\kappa^f = -\frac{G_F m_t^2}{2\sqrt{2}\pi^2} + \ldots$$



Radiative Corrections

Radiative corrections –
modifying propagators and vertices

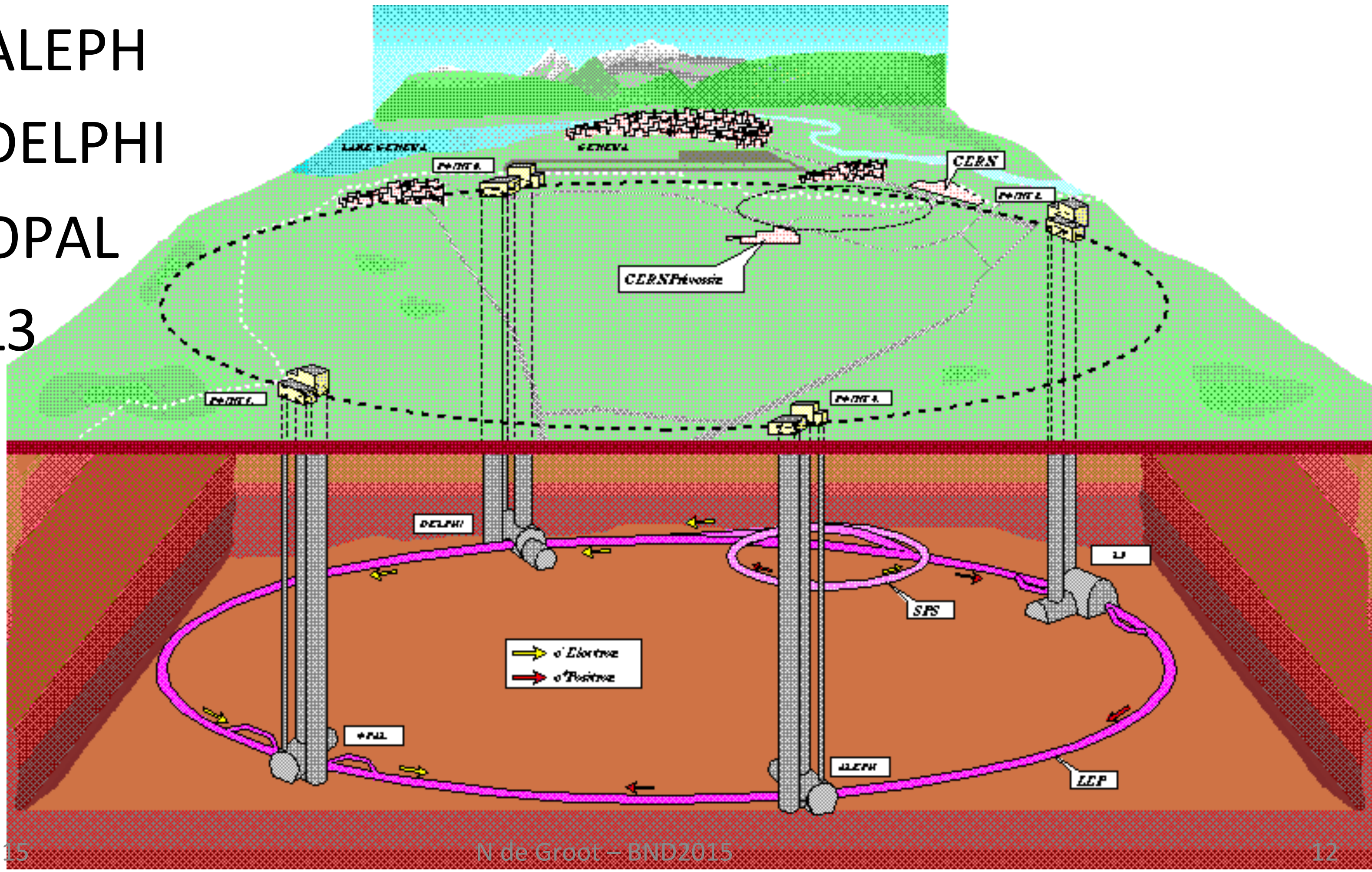




Great success Standard Model (Nobel prize for 't Hooft and Veltman)

LEP Experiments

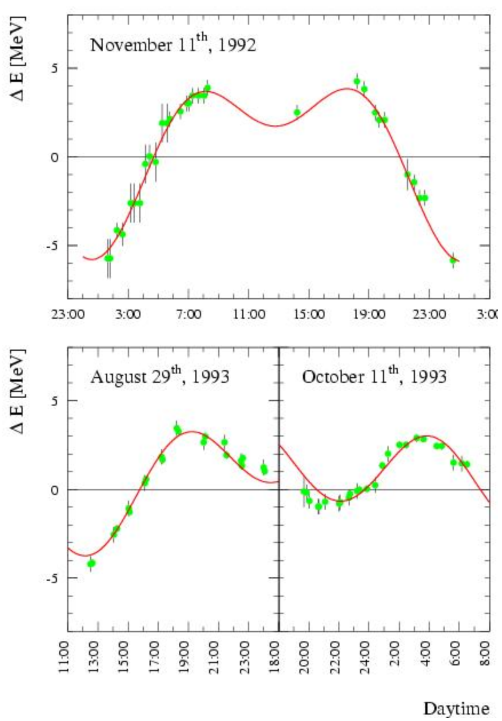
- 4 experiments:
  - ALEPH
  - DELPHI
  - OPAL
  - L3

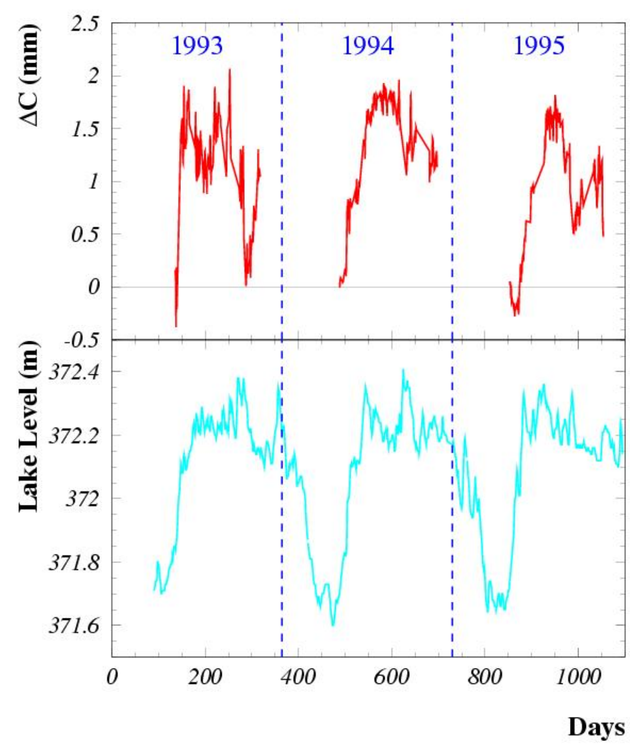


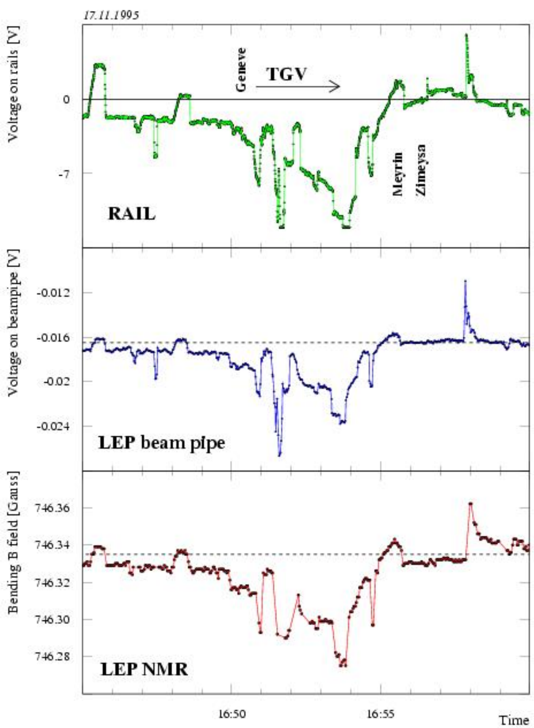
Beam energy precision ±0.2 MeV from resonant depolarisation

But corrections needed due to:

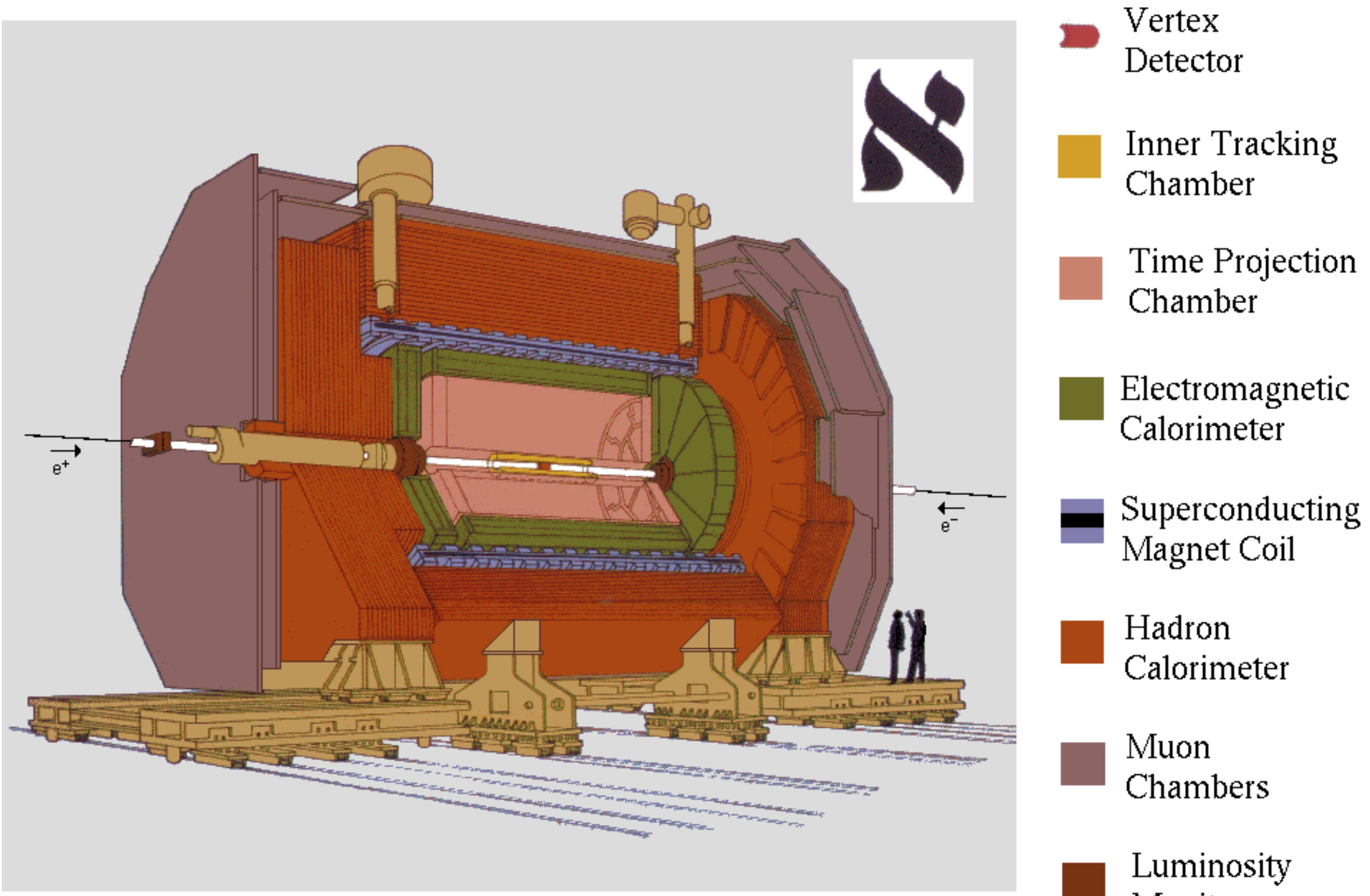
TIDES	LEVEL LAKE	TGV





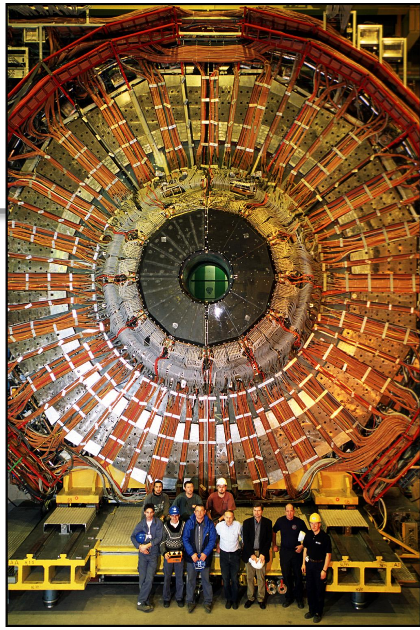


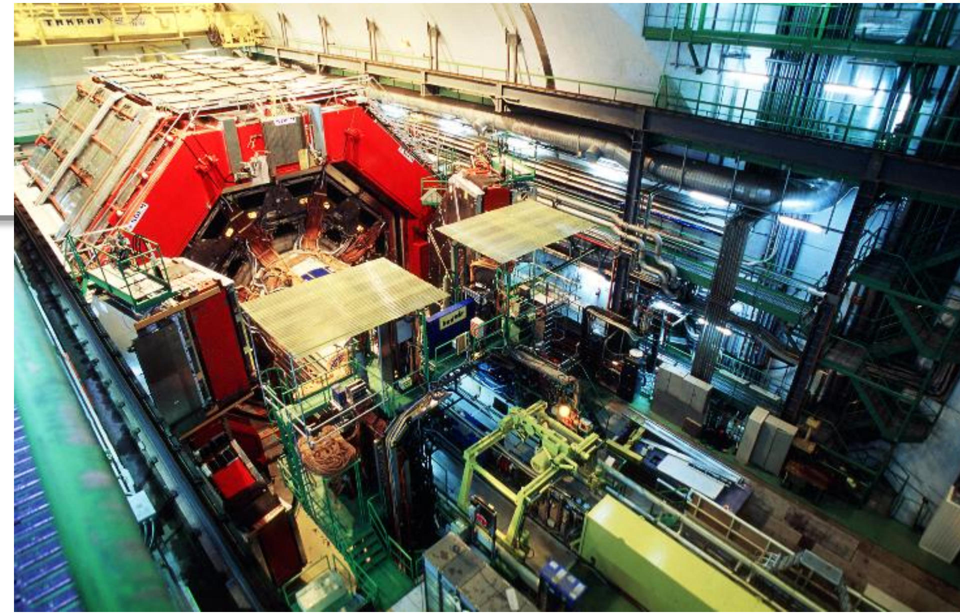
The Aleph Experiment

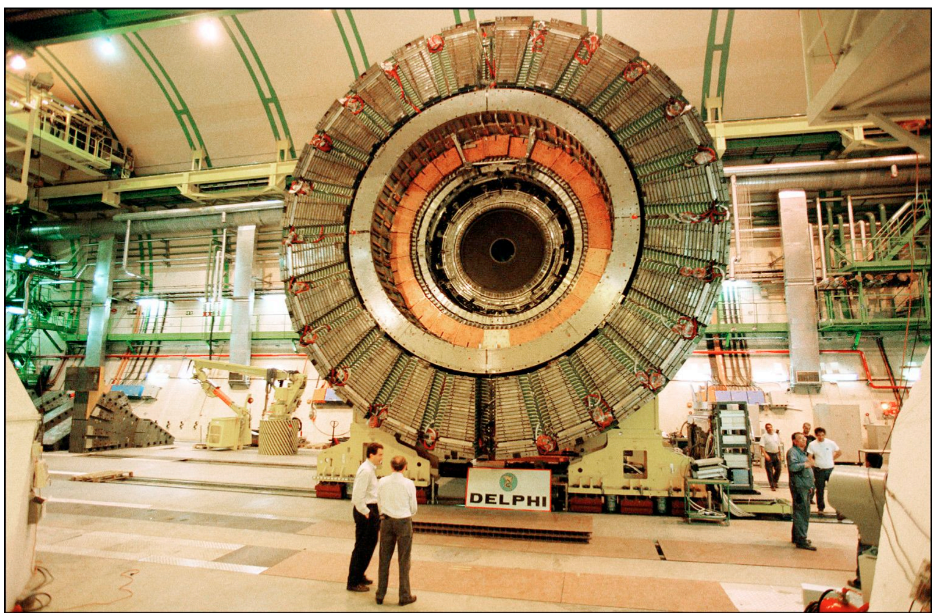


The ALEPH Detector

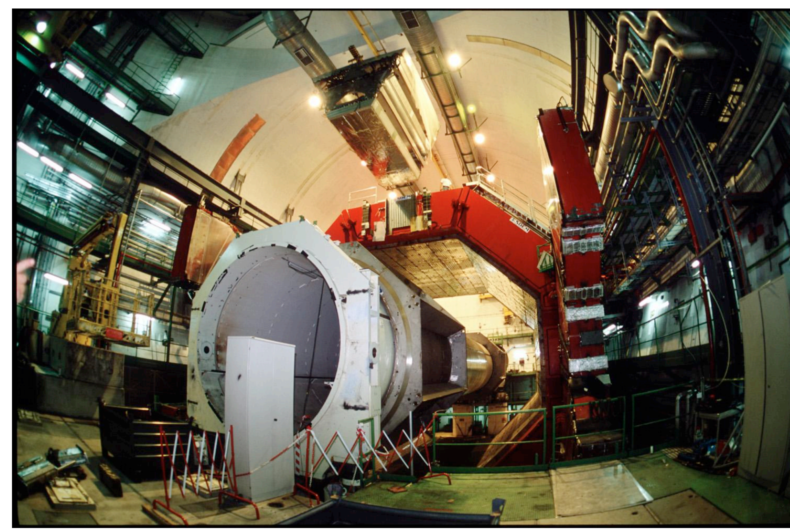
D
E
L
P
H
I



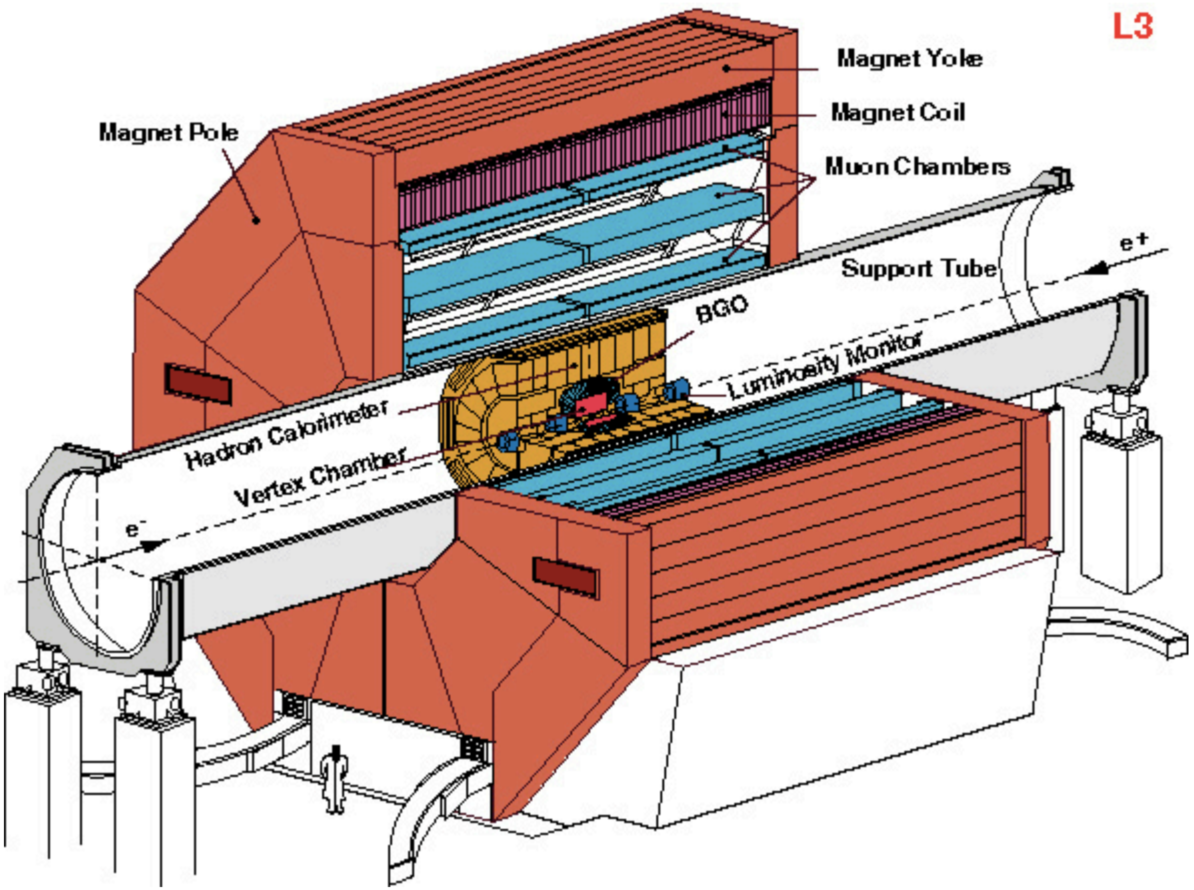




L3



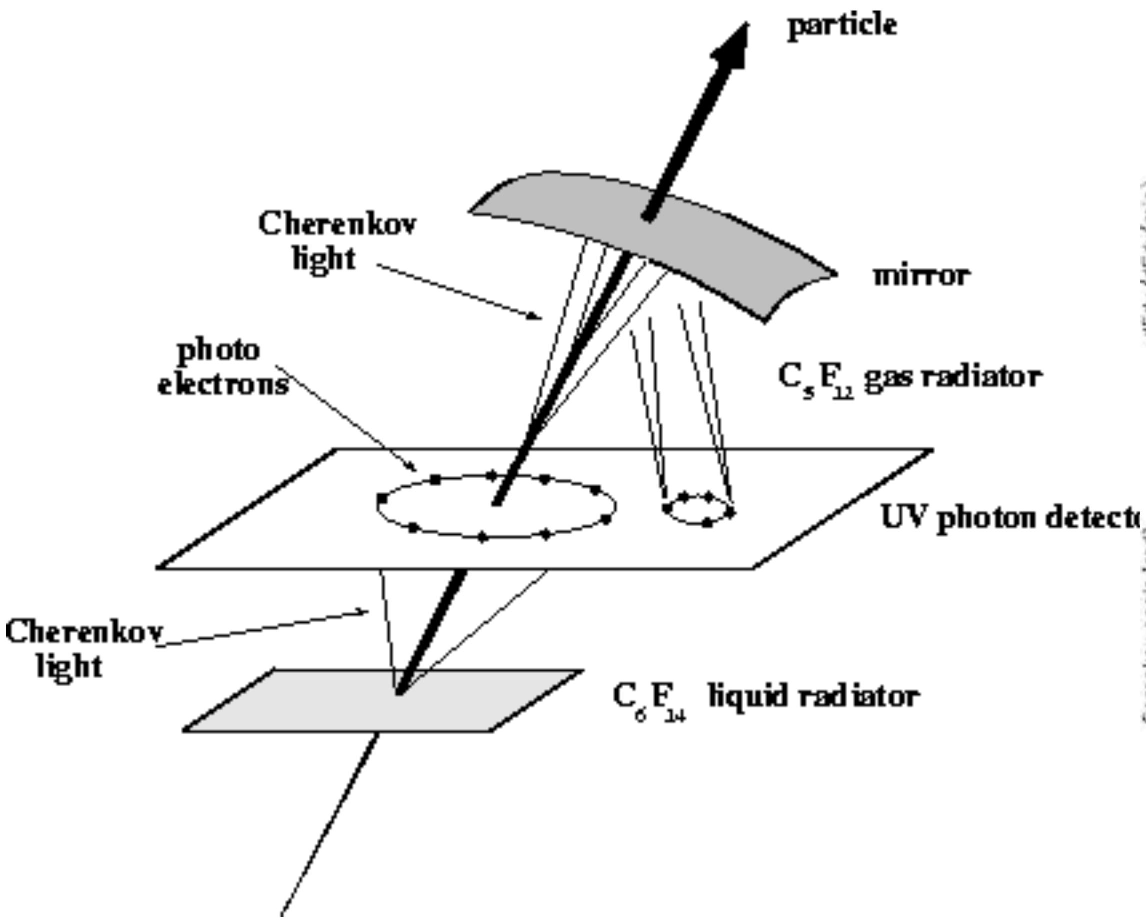
L3

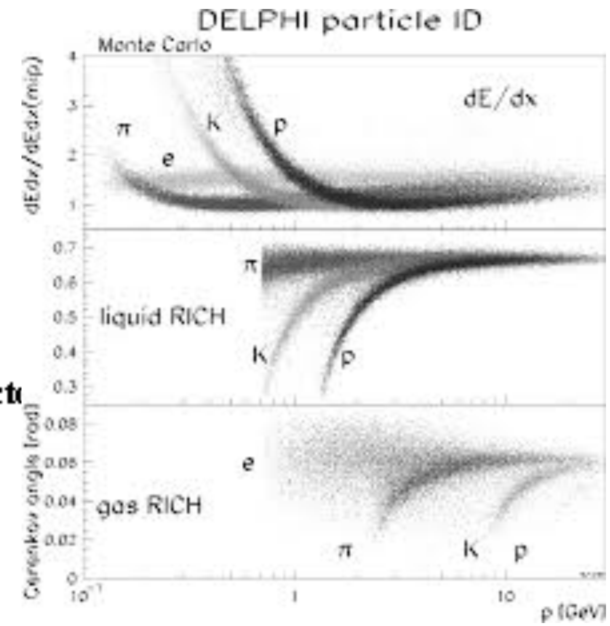


- Large muon system
- BGG crystal calorimeter

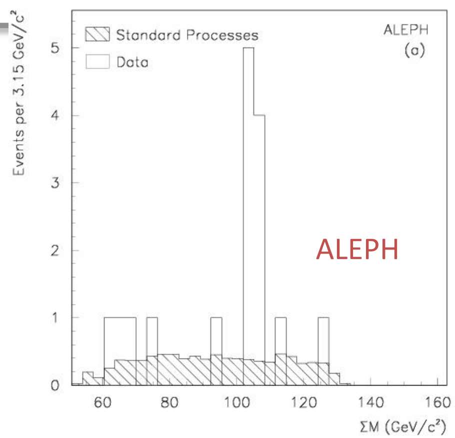
- Excellent for μ, e, γ
- Weaker for jets

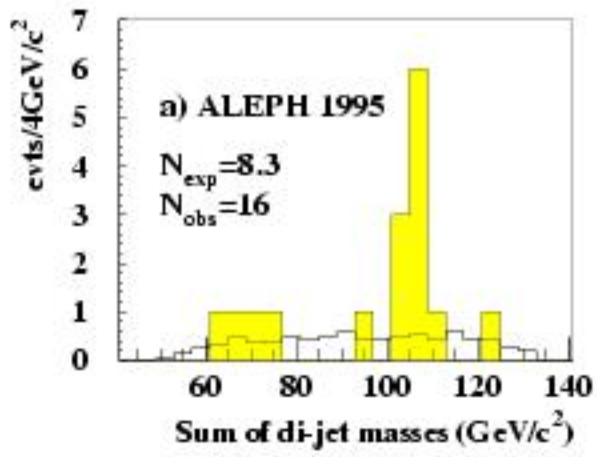
Delphi RICH: Kaon ID

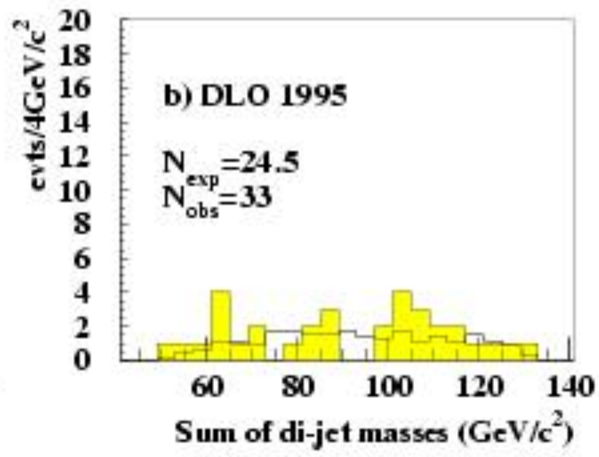




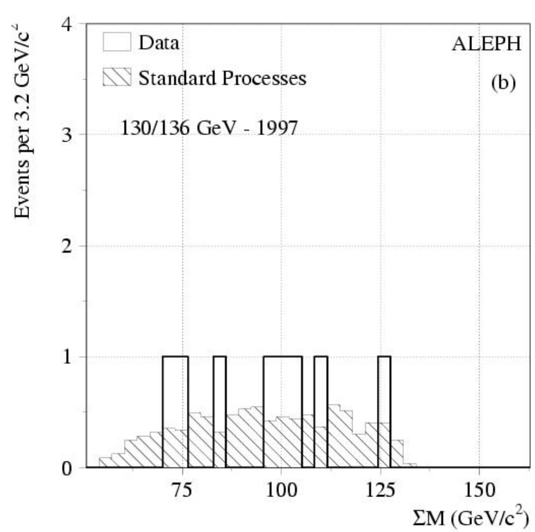
Why it is good to have more than one experiment

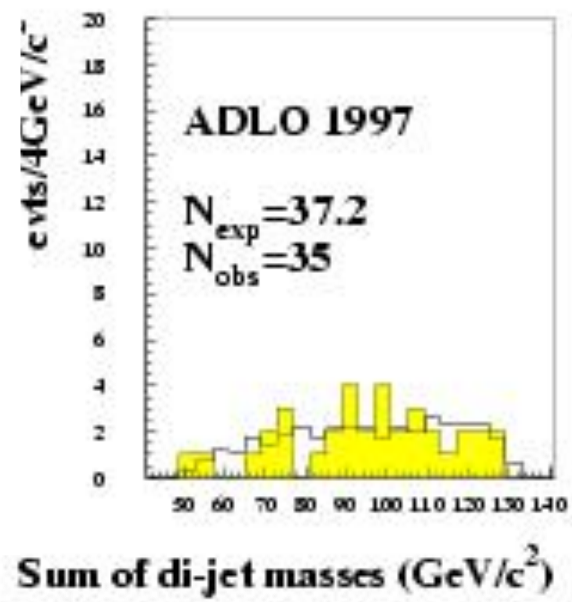






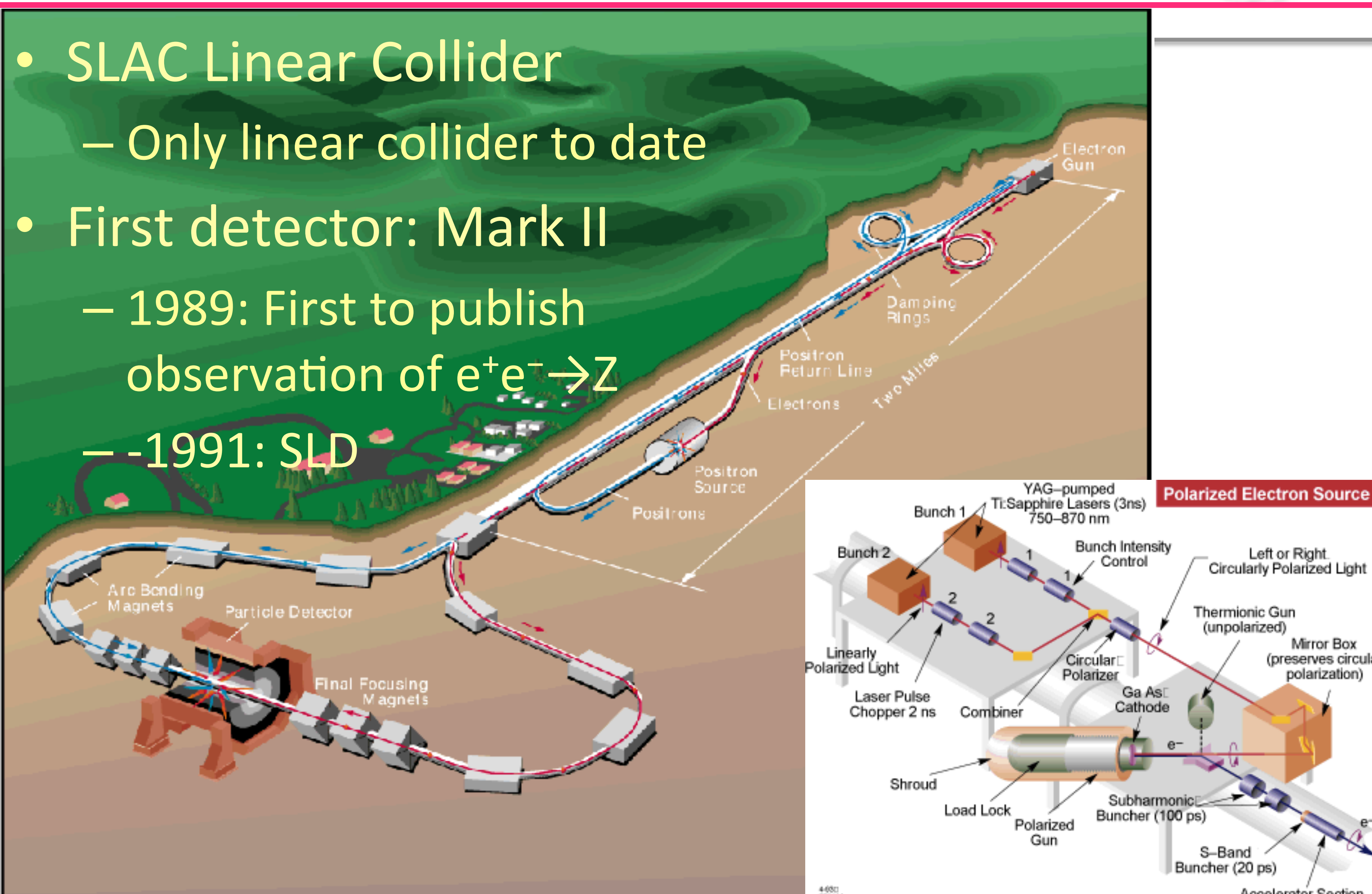
- 1995: 130-136 GeV
- 4-jet events
- Sum of di-jet masses with smallest ΔM
- 16 events (8.3 exptd)
- Prob. accumulation in 6.3 GeV bin: 0.01%





SLC & SLD

- SLAC Linear Collider
  - Only linear collider to date
- First detector: Mark II
  - 1989: First to publish observation of $e^+e^- \rightarrow Z$
  - -1991: SLD

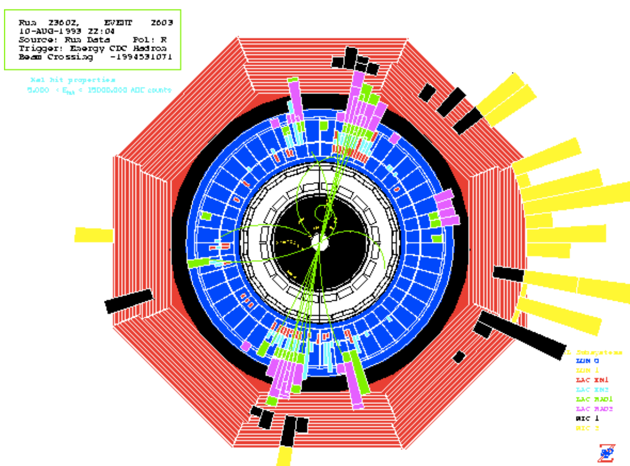


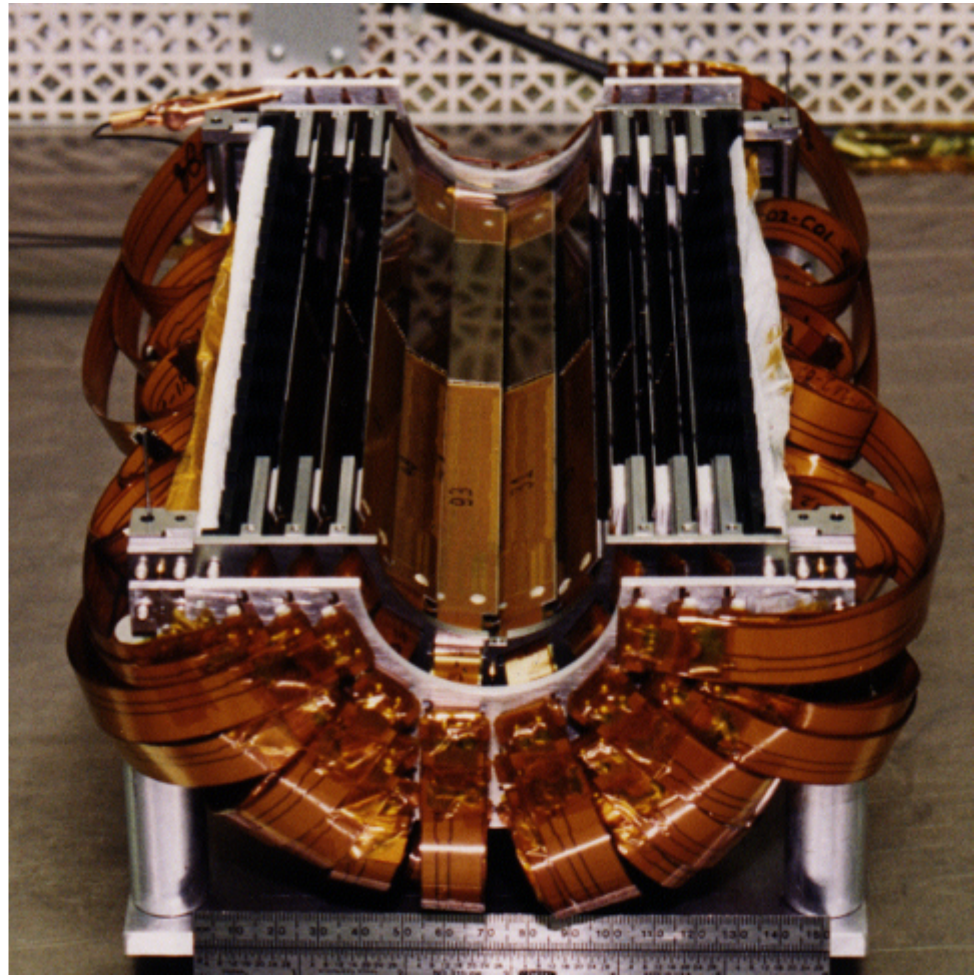
SLD Vertex detector VXD3

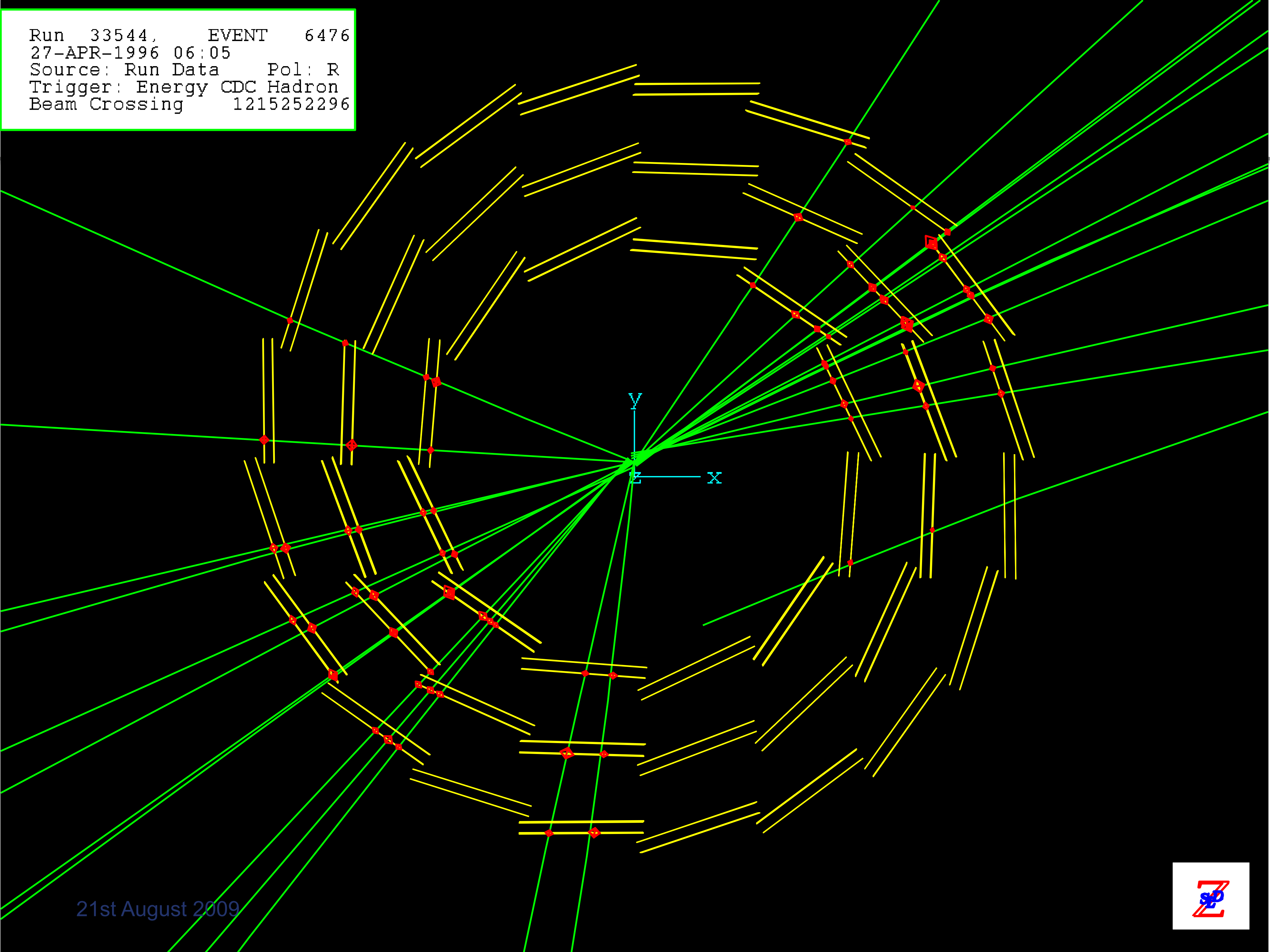
SLD:

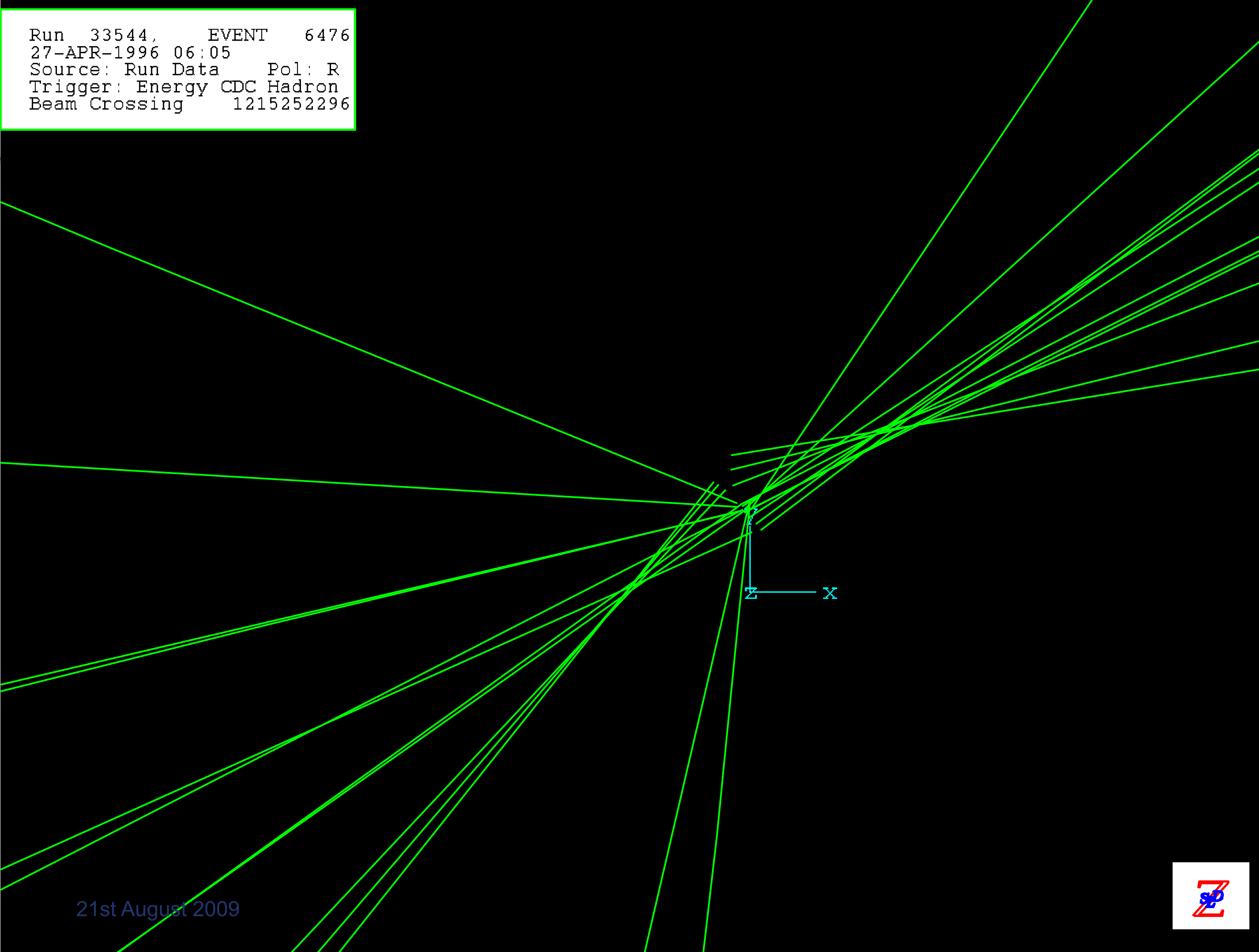
- **Polarized beams P_e = 80%**
- **Particle ID (like Delphi)**
- **Small beam spot**
- **Best vertex detector in the world:**
  - **Installed 1995**
  - **307 Mpixels**
  - **Layer thickness 0.4% X_0**
  - **R_{bp} = 25 mm**
  - **Resolution: 4μ**

But 600k Events only

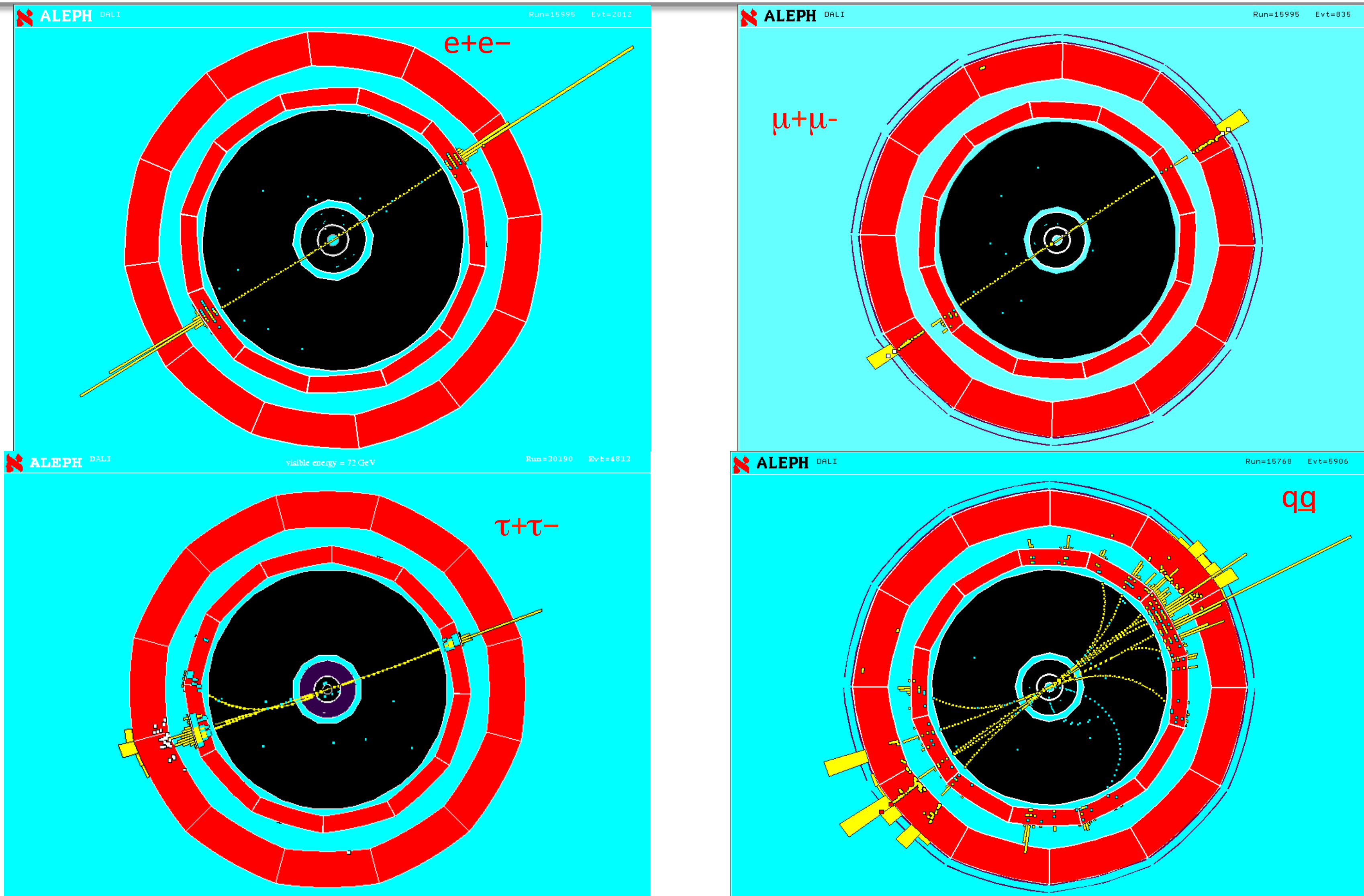





Run 33544, EVENT 6476
27-APR-1996 06:05
Source: Run Data Pol: R
Trigger: Energy CDC Hadron
Beam Crossing 1215252296
Y
X
Z


Run 33544, EVENT 6476
27-APR-1996 06:05
Source: Run Data Pol: R
Trigger: Energy CDC Hadron
Beam Crossing 1215252296
Y
Z
X

Z^0 events



ALEPH DALI
e+e−
ALEPH DALI
μ+μ-
ALEPH DALI
visible energy = 72 GeV
τ+τ−
ALEPH DALI
qq

Measurements at the Z^0-pole

Example – electroweak cross-section formula for unpolarised beams (LEP)

$$\frac{2s}{\pi}\frac{1}{N_c^f}\frac{d\sigma_{ew}(e^+e^- \to f\bar{f})}{d\cos\theta} = \left|\alpha(s)\cdot Q_f\right|^2\left(1+\cos^2\theta\right)$$
$$-8\,\mathrm{Re}\left\{\alpha^*(s)Q_f\chi_{BW}(s)\left[g_{V,e}g_{V,f}\left(1+\cos^2\theta\right)+2g_{A,e}g_{A,f}\cos\theta\right]\right\}$$
$$+16\left|\chi_{BW}(s)\right|^2\left[\left(\left|g_{V,e}\right|^2+\left|g_{A,e}\right|^2\right)\left(\left|g_{V,f}\right|^2+\left|g_{A,f}\right|^2\right)\left(1+\cos^2\theta\right)+8\,\mathrm{Re}\left\{g_{V,e}g_{A,e}^*\right\}\mathrm{Re}\left\{g_{V,f}g_{A,f}^*\right\}\cos\theta\right]$$

- Pure γ exchange
- γ–Z interference
- Pure Z exchange

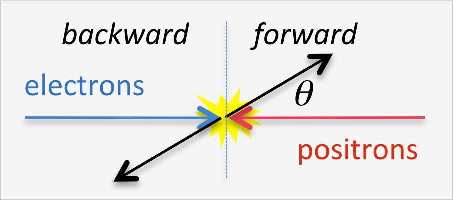
Neglects photon ISR & FSR, gluon FSR, fermion masses

The $\propto$ $(1 + \cos^2\theta)$ terms contribute to total **cross-sections**

- Measure cross-sections around M_Z via corrected event counts: $\sigma = \left(N_{sel} - N_{bg}\right)/\varepsilon_{sel}L$

The $\propto$ $\cos\theta$ terms contribute only to **asymmetries**

- Measure *Forward–Backward asymmetries* in angular distributions final-state fermions: $A_{FB} = \left(N_F - N_B\right)/\left(N_F + N_B\right)$

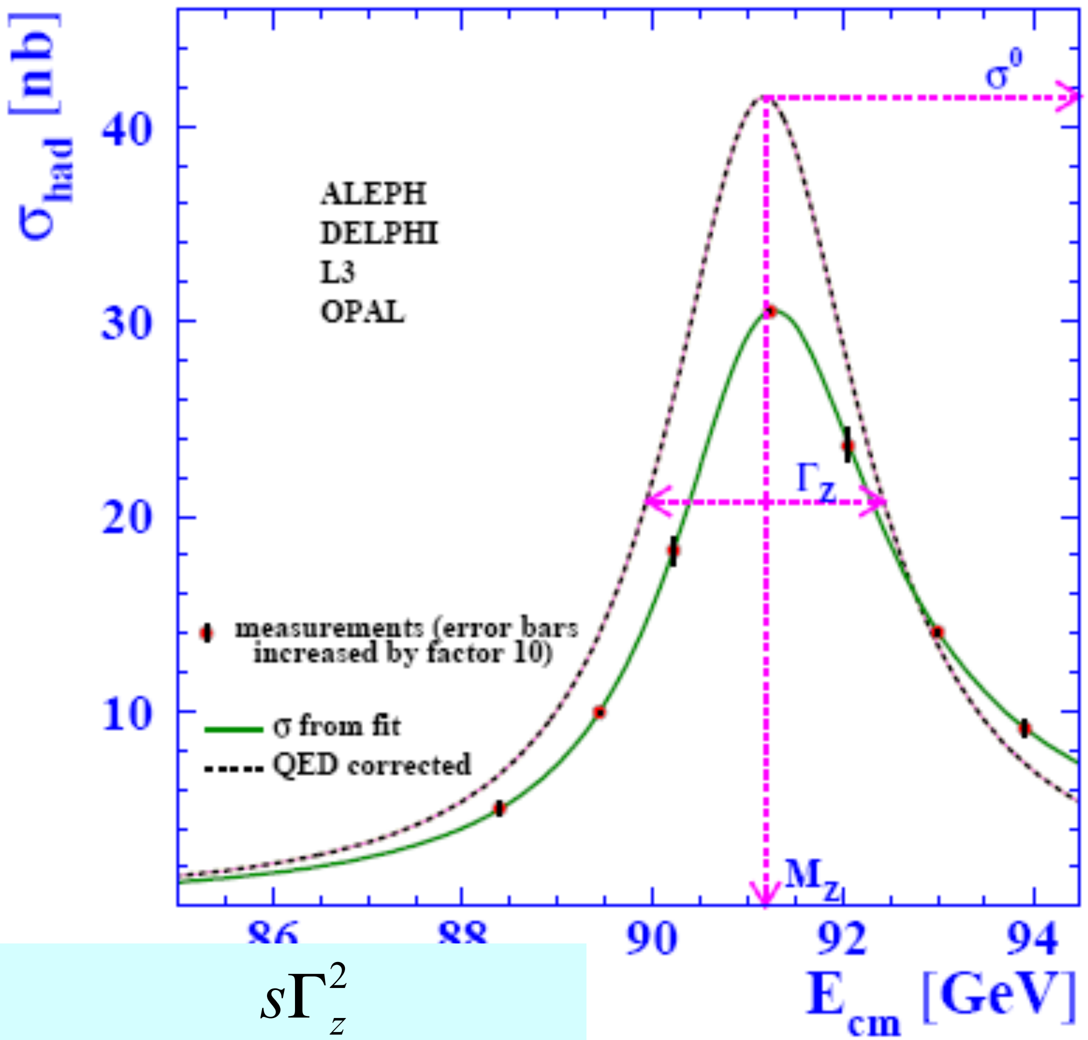


Other asymmetries (not in above cross section formula)

- Dependence of Z^0 production on helicities of initial state fermions (SLC) → *Left–Right asymmetries*
- Polarisation of final state fermions (can be measured in tau decays)

Use Fit to Extract Parameters

- Fit σ(e+e −→hadrons) as function of ***s*** with to find best value for parameters:
  - m_Z
  - Γ_Z
  - σ^0_{had}



$$\sigma\left(Z \to \text{hadrons}\right) = \sigma^0_{had} \frac{1}{R_{QED}} \frac{s\Gamma_z^2}{(s - m_z^2)^2 + s^2\Gamma_z^2 / m_z^2}$$

Number of light neutrino species

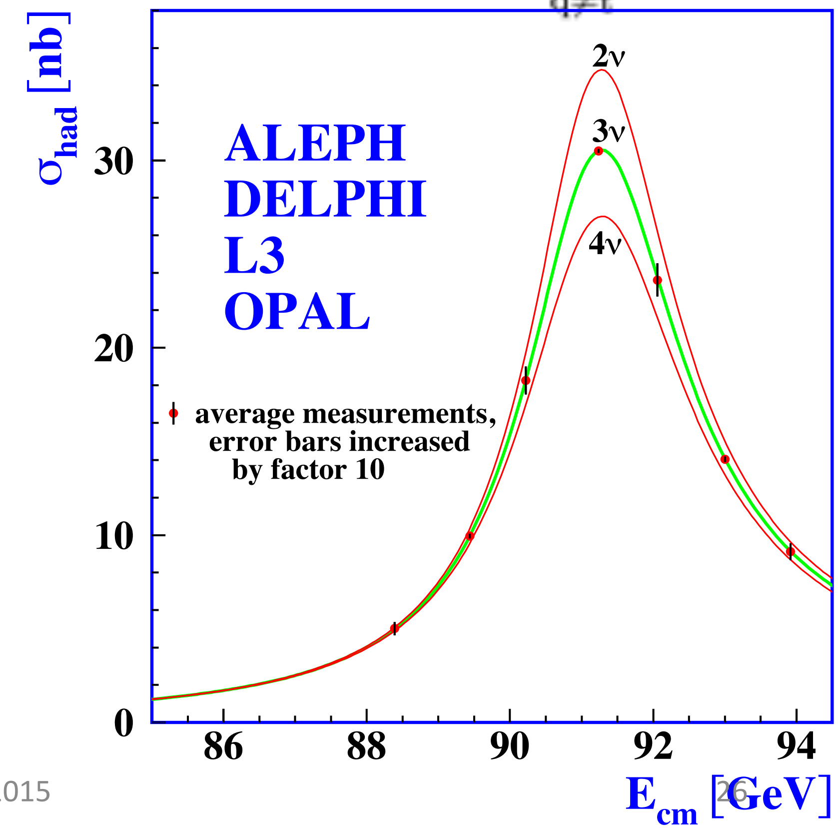
Total width of the Z^0 is sum of widths of all decay modes:

$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$$

- Hadronic modes due to quarks: $\Gamma_{had} = \sum_{q \neq t} \Gamma_{q\bar{q}}.$
  - (top is too heavy)
- Invisible width from ν's

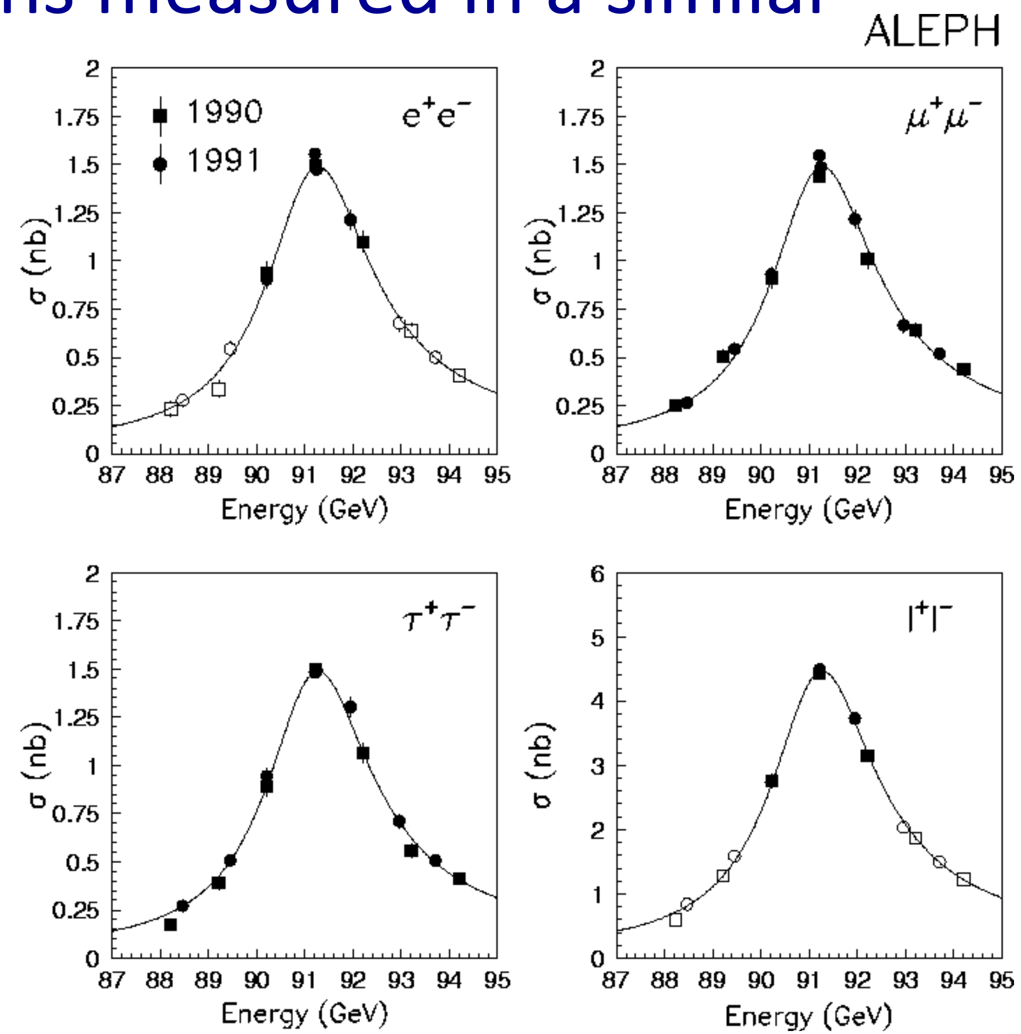
$$\Gamma_{inv} = N_\nu \Gamma_{\nu\bar{\nu}};$$

- M_Z = 91187.5 ± 2.1 MeV
- Γ_Z = 2495.2 ± 2.3 MeV
- N_ν = 2.9841 ± 0.0083



Leptonic Cross Sections

- Leptonic cross sections measured in a similar way:
  - σ(e+e−→e+e−)
  - σ(e+e−→μ+μ−)
  - σ(e+e−→τ+τ−)



- Use to extract values for

$$R_e^0 = \frac{\Gamma_{had}}{\Gamma_{ee}} \approx \frac{\sigma_{had}^0}{\sigma_{ee}^0}$$

Equal up to QED, QCD corrections

$$R_\mu^0 = \frac{\Gamma_{had}}{\Gamma_{\mu\mu}}$$

$$R_\tau^0 = \frac{\Gamma_{had}}{\Gamma_{\tau\tau}}$$

R_b & R_c : hadronic partial widths

$R_b = \Gamma_{bb}/\Gamma_{had}$

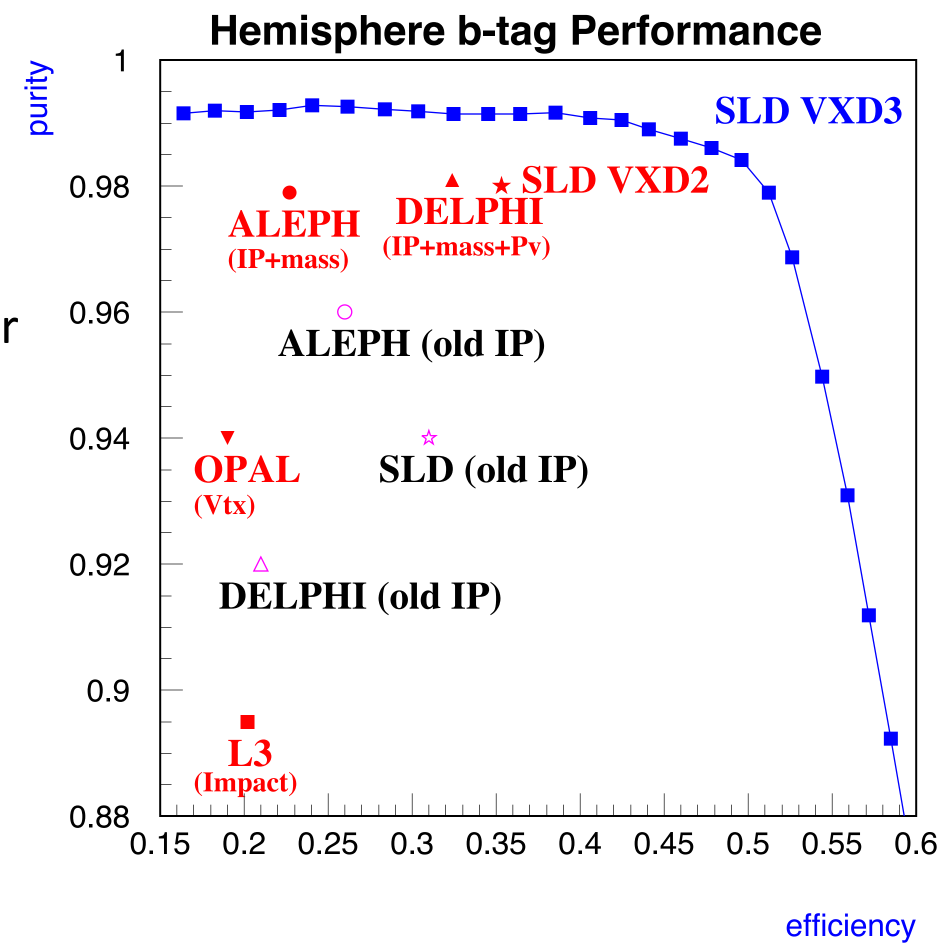
$R_c = \Gamma_{cc}/\Gamma_{had}$

- Identification of b and c jets
- Lifetime tag ➔vertex detector
- Lepton tags
- D* (charm)

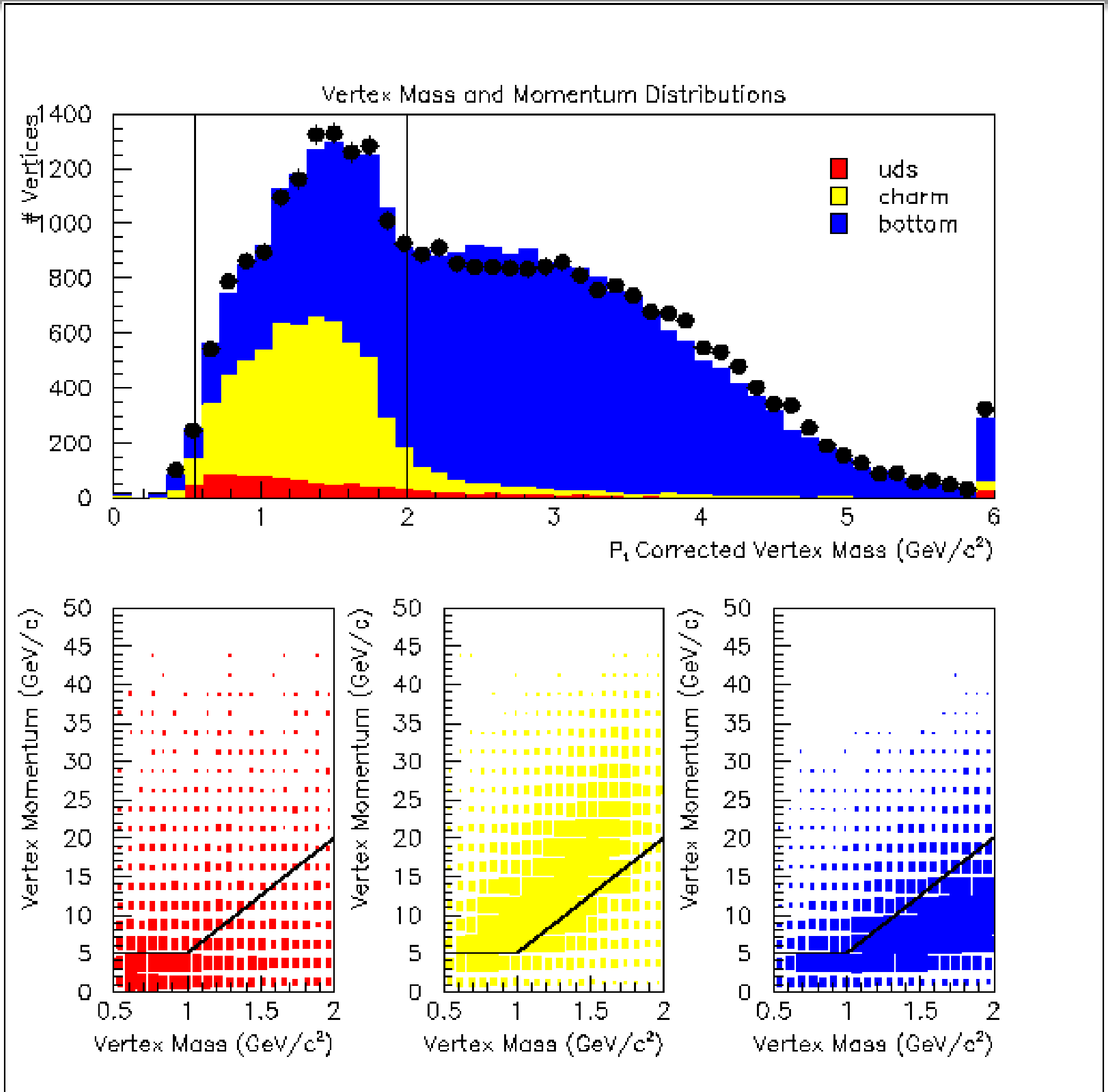
SLD

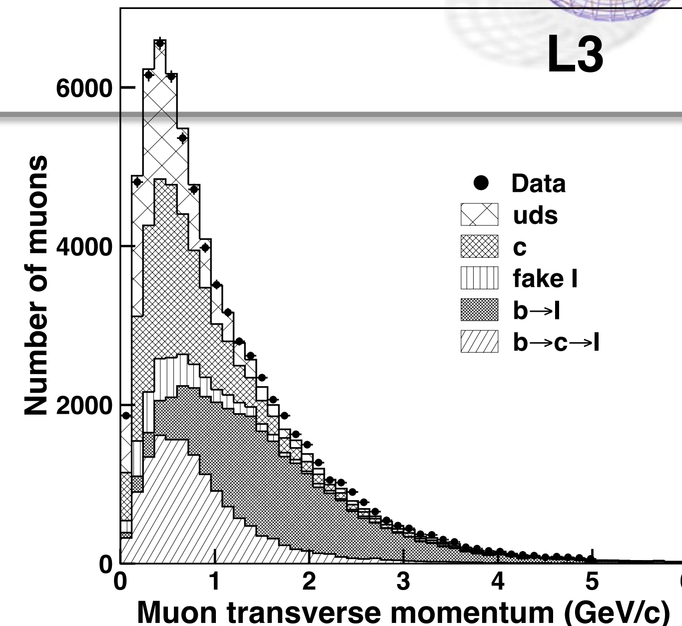
B-tag: 62% eff, 98% pure

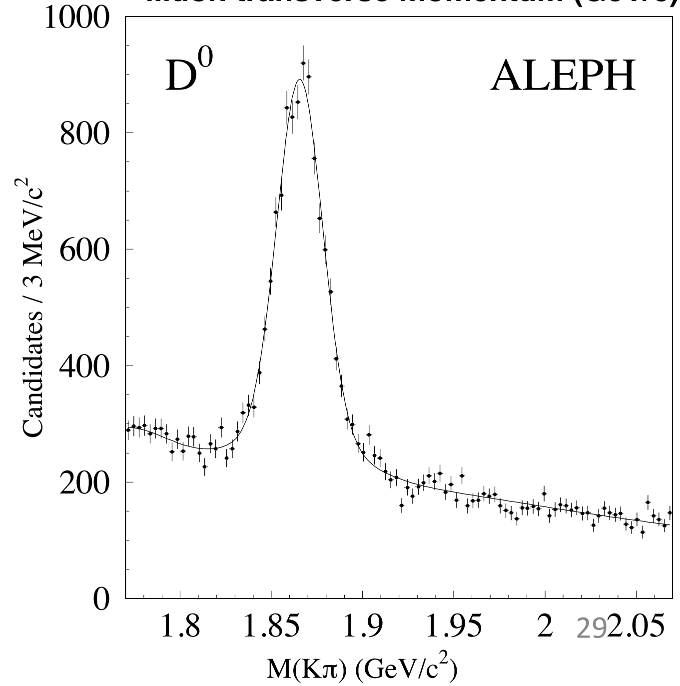
C-tag: 18% eff, 85% pure



Tagging methods







Double tag method (R_c only SLD)

$F_s = \varepsilon_B\, Rb + \varepsilon_C\, Rc + \varepsilon_{uds}\, (1 - Rc - Rb)$

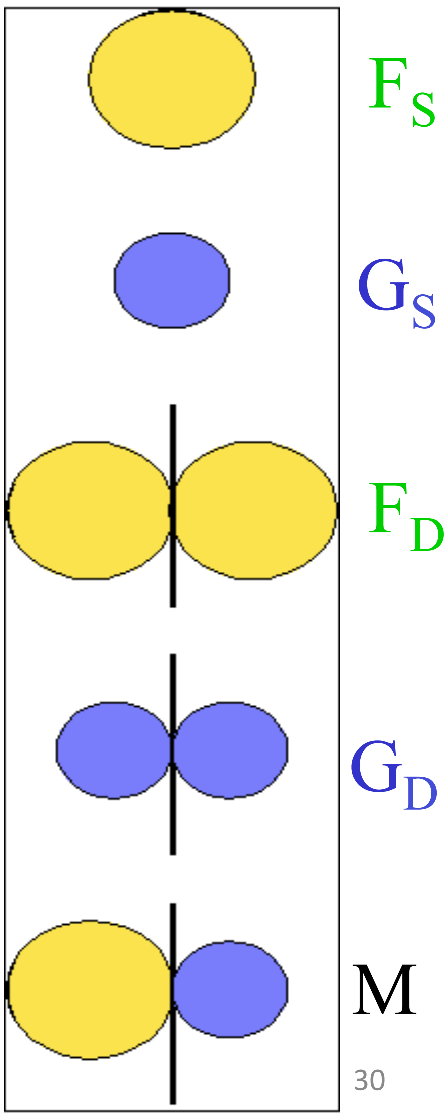
$F_d = \varepsilon_B^{\,d}\, Rb + \varepsilon_C^{\,d}\, Rc + \varepsilon_{uds}^{\,d}\, (1 - Rb - Rc)$

$G_s = \eta_B Rb + \eta_C\, Rc + \eta_{uds}\, (1 - Rb - Rc)$

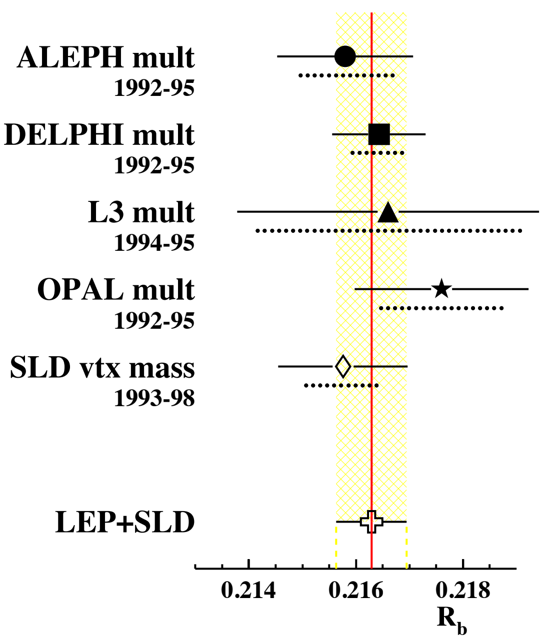
$G_d = \eta_B^{\,d} Rb + \eta_C^{\,d}\, Rc + \eta_{uds}^{\,d}\, (1 - Rb - Rc)$

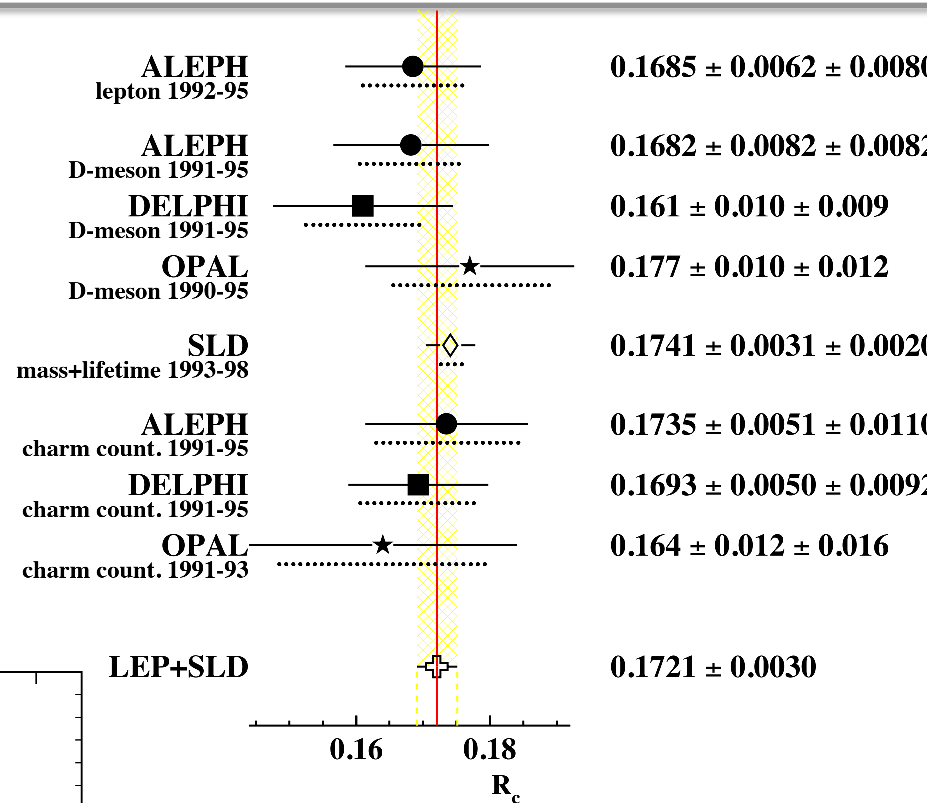
$M = 2\, (\varepsilon_B \eta_B Rb + \varepsilon_C\, \eta_C Rc + \varepsilon_{uds} \eta_{uds}\, (1 - Rb - Rc))$

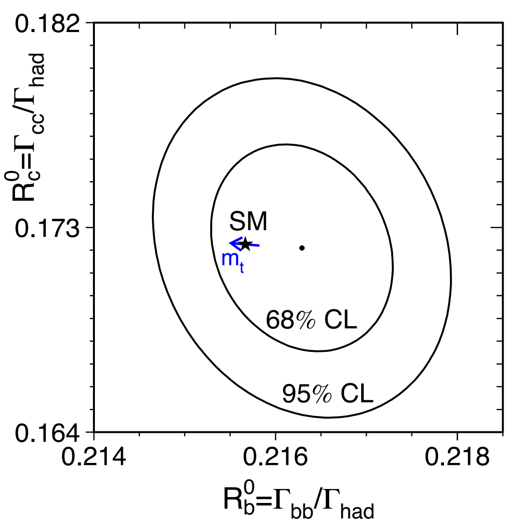
- Correlations: $\varepsilon^d = \varepsilon^2 + \lambda\, (\varepsilon - \varepsilon^2)$
- R_b: take R_c from SM, $\varepsilon_C, \varepsilon_{uds}, \lambda_B$ from Monte Carlo => R_b, ε_B from data, F_s and F_d only
- R_c: take η_{uds}, λ'_B, λ'_C from MC solve 5 equations



R_b and R_c results







Asymmetries

The polarized differential cross section (Z^0 exchange only) :

$$\frac{d\sigma}{d\cos\theta} \propto (1 - P_e A_e)(1+\cos^2\theta) + 2A_f(A_e - P_e)\cos\theta \qquad A_f = \frac{2v_f a_f}{v_f^2 + a_f^2}$$

A_{LR} : The left-right asymmetry

$$A_{LR}^0 \equiv \frac{1}{|P_e|}\frac{\sigma(e^+e_L^- \to Z^0) - \sigma(e^+e_R^- \to Z^0)}{\sigma(e^+e_L^- \to Z^0) + \sigma(e^+e_R^- \to Z^0)} = A_e$$

$$\cong \frac{1}{P_e}\frac{N_L - N_R}{N_L + N_R}$$

A_{LRFB} : forward-backward asymmetry

$$\tilde{A}_{FB}^f \equiv \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} = \frac{3}{4}A_e A_f$$

A_{LRFB} : left-right-forward-backward asymmetry

$$\tilde{A}_{LRFB}^f \equiv \frac{(\sigma_{LF} - \sigma_{LB}) - (\sigma_{RF} - \sigma_{RB})}{(\sigma_{LF} + \sigma_{LB}) + (\sigma_{RF} + \sigma_{RB})} = \frac{3}{4}|P_e|A_f$$

Tau polarization

$$< P_\tau^0 >= -A_\tau$$

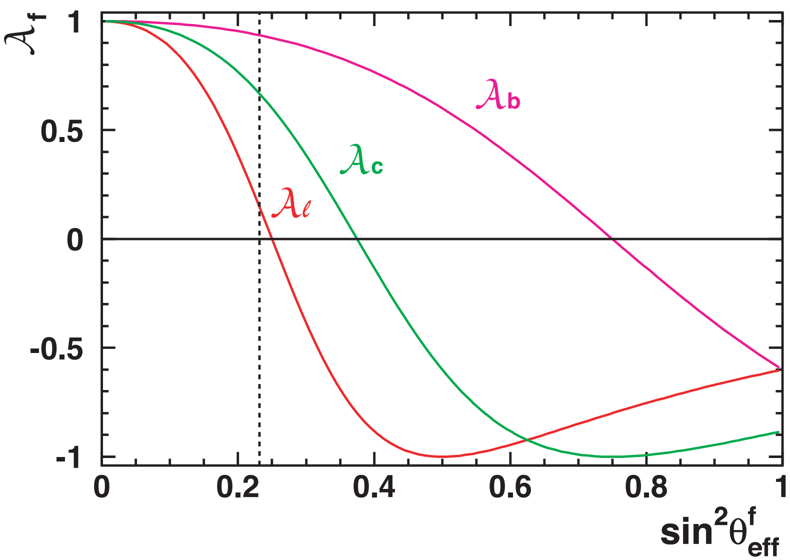
Asymmetries: what do we measure

- *b* and *c* quarks can be identified efficiently by LEP / SLD → R_b, R_c
- Especially R_b is sensitive to new physics connected to *tb* couplings

  [With the m_t from the Tevatron the interest from SM is minor]

- SLC measures in addition the asymmetry parameters A_b, A_c
- These parameters are only sensitive to new physics at Born level

➠ Hence, these and the LEP $A^{b/c}_{FB}$ measurements cleanly determine $\sin^2\theta_{eff}$



A_{LR} (SLD)

- This is a *counting experiment* - **no** complicated final state identification is required, **no** efficiency or acceptance effects. This contrasts with *all* other E/W measurements.
- The polarization measurement is *precise* (→ 0.5%)
- E/W radiative correction is *small* (<2%) - all other corrections (experimental) are *smaller* (<0.2% total).
- The measurement is *statistically* dominated.

- e.g., for 1998 (N=224,962; N_L=124,404; N_R=100,558)

$$A_m = \frac{N_L - N_R}{N_L + N_R} = 0.1060 \pm 0.0021$$

- With polarization (P_e = 73.1%) :

$$A_{LR}^{meas} = \frac{A_m}{P_e} = 0.1450 \pm 0.0030$$

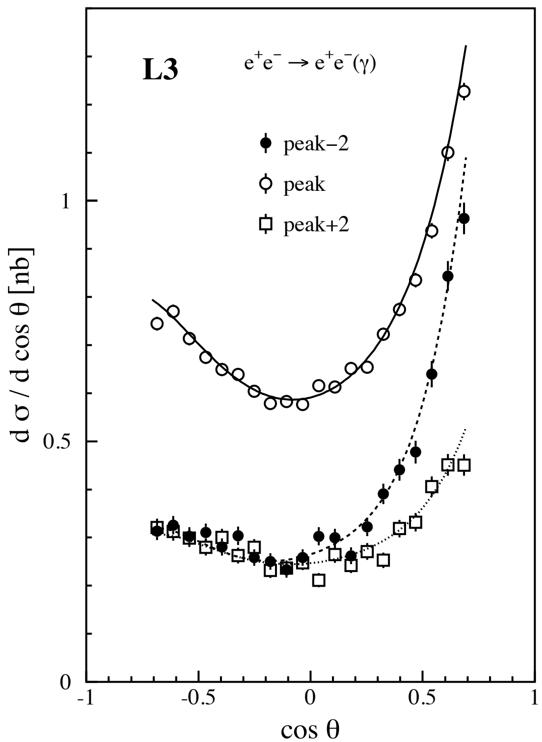
- An additional EW correction of ~2% is applied to get from A_{LR}^{meas} to A_{LR}^0 (the Z^0 pole)

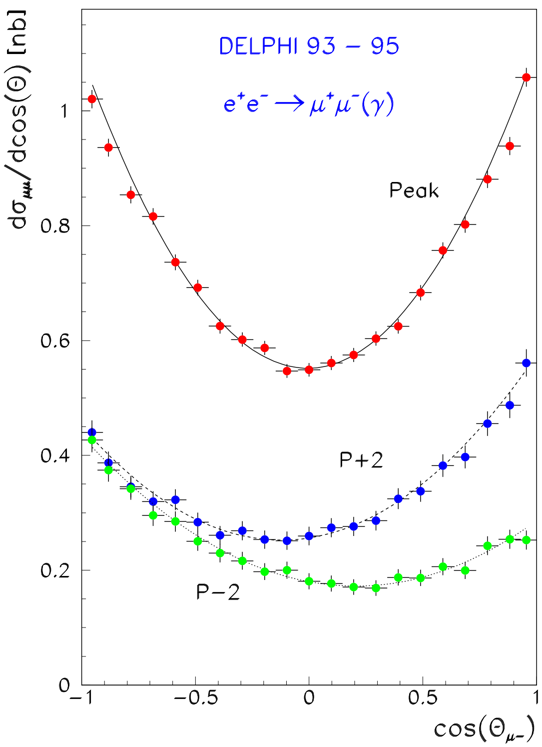
$$A_{LR}^0 = 0.1487 \pm 0.0031 \pm 0.0017$$

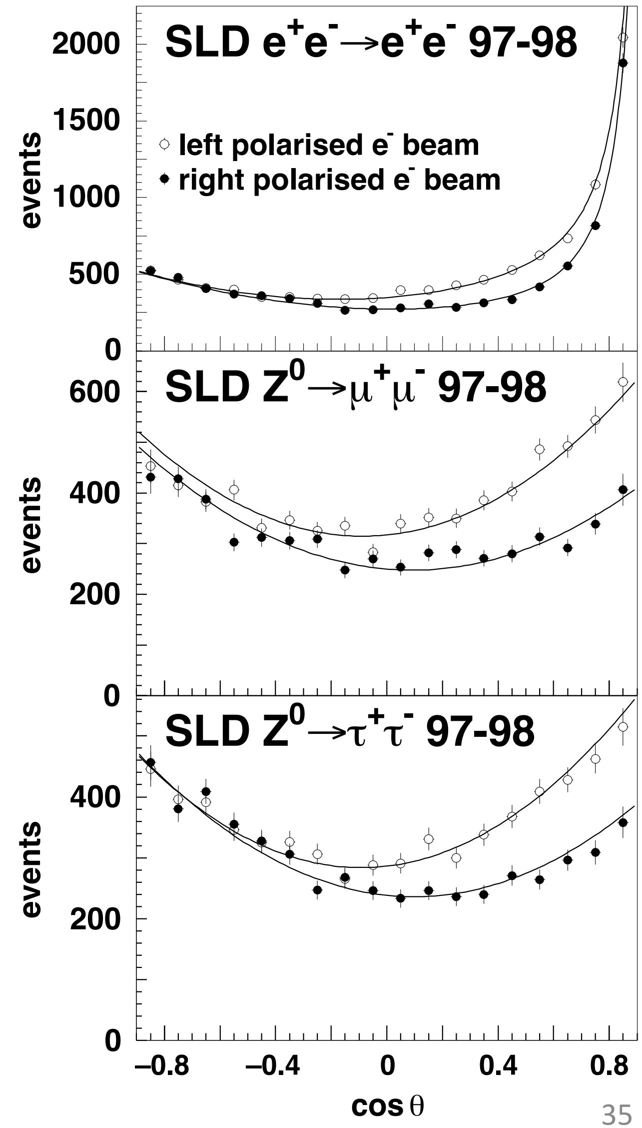
- This corresponds to the 1998 effective weakmixing angle of

$$\sin^2\theta_W^{eff} = 0.23130 \pm 0.00039 \pm 0.00022$$

Lepton asymmetries



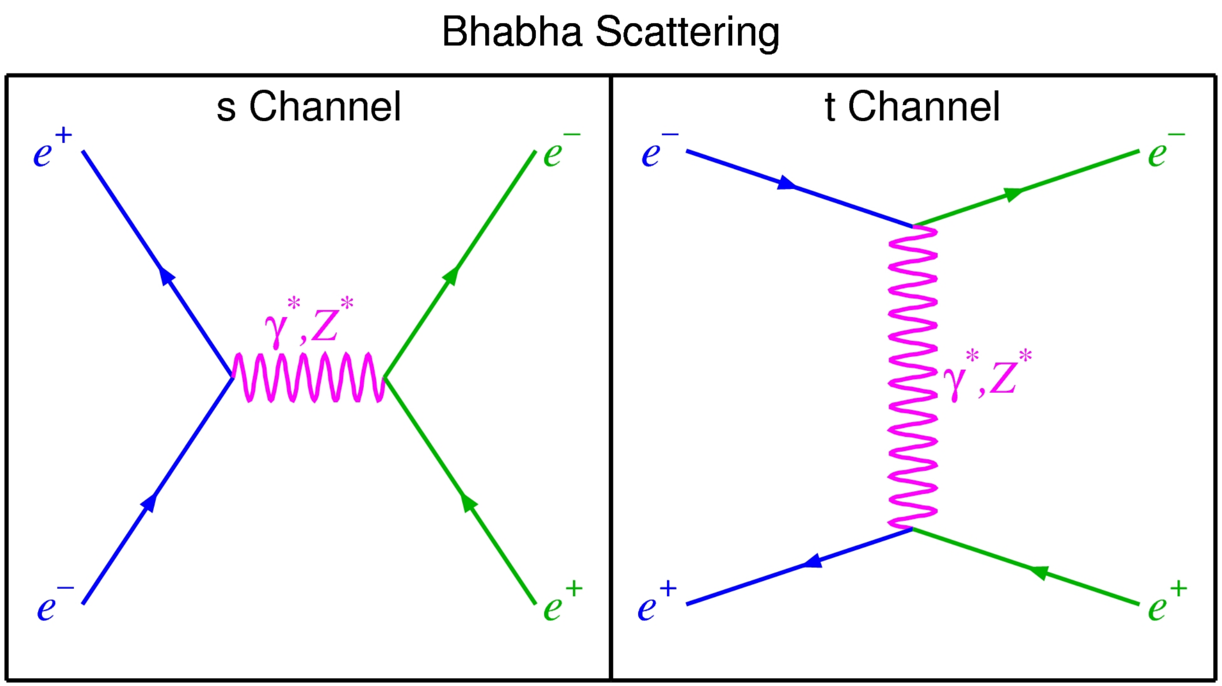




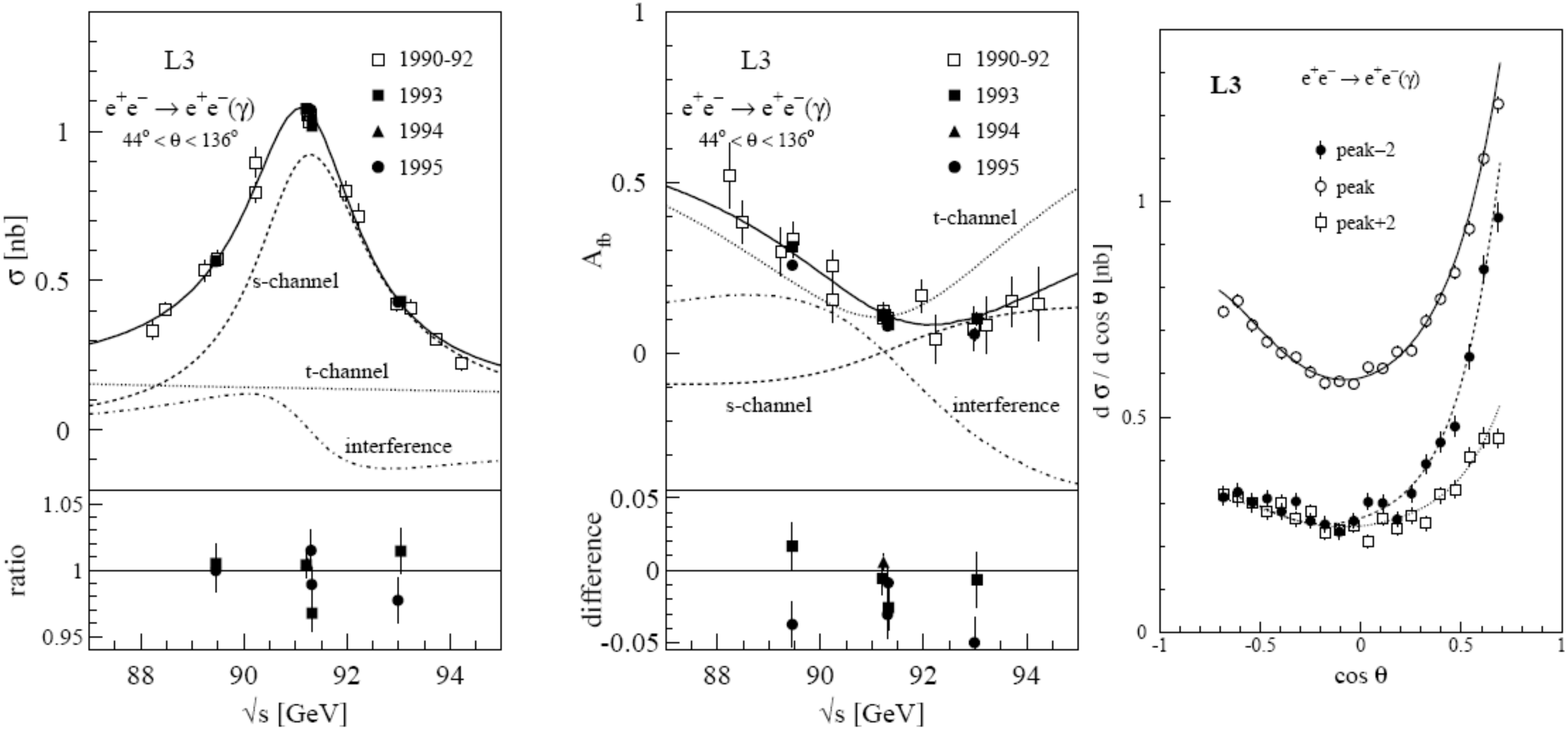
Note: away from Z^0 peak interference with γ changes asymmetry

An aside: $e^+e^-\rightarrow e^+e^-$

- Complication for e+e−→e+e− channel…
  – Initial and final state are the same
  – Two contributions: s-channel, t-channel
  –



Angular Measurements of $e^+e^- \rightarrow e^+e^-$



Direction of quarks: thrust

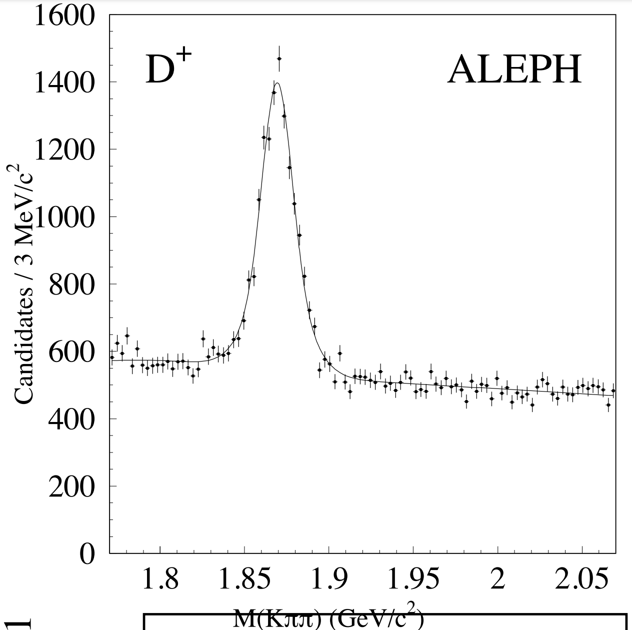
- *Thrust* measures the distribution of jets in a event.

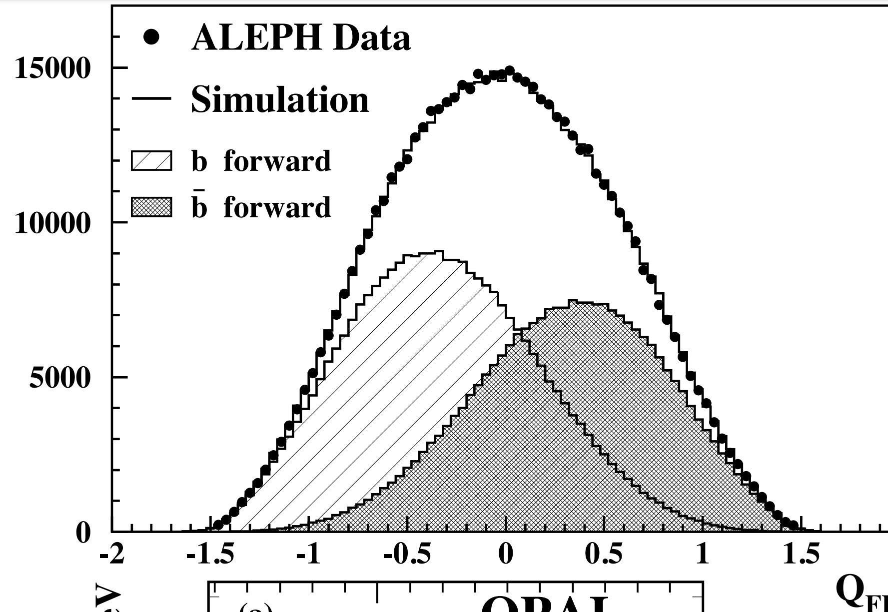
$$T = \max\left(\frac{\sum_{i=1,N} \vec{p}_i \cdot \hat{n}_T}{\sum_{i=1,N} |\vec{p}_i|}\right)$$

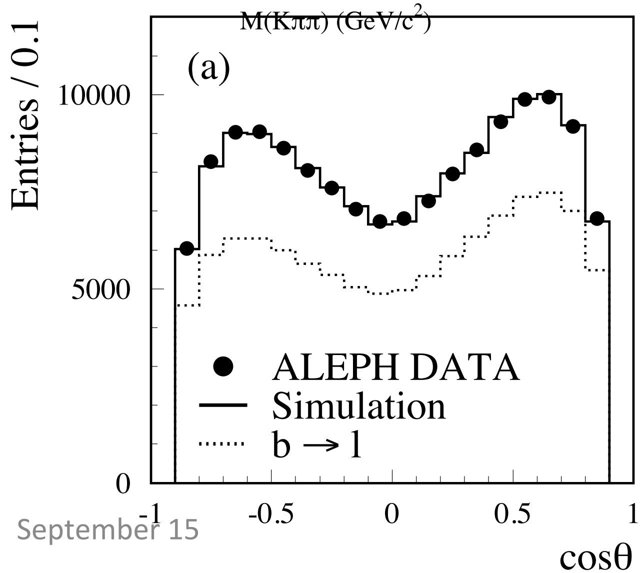
- The unit vector $\hat{n}$ is where T is maximized is known at the *thrust axis*

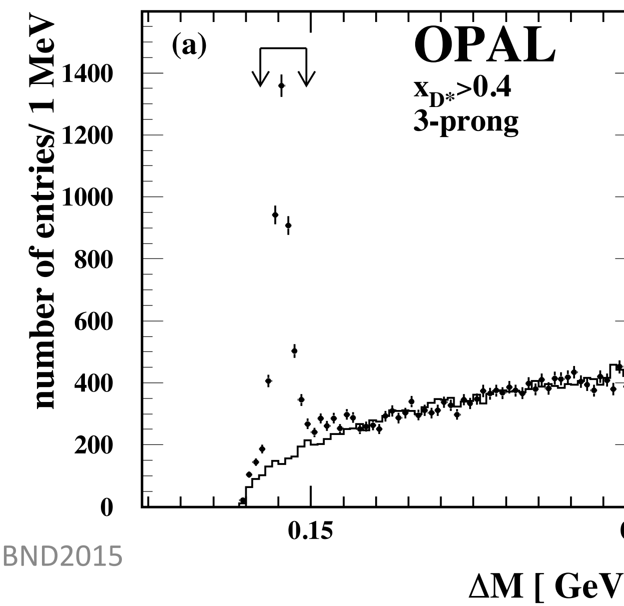
- The range of T is: $½<T<1$
  - $T≈½$ for an isotropic event
  - $T=1$ for an event with 2 back-to-back jets

Charge identification

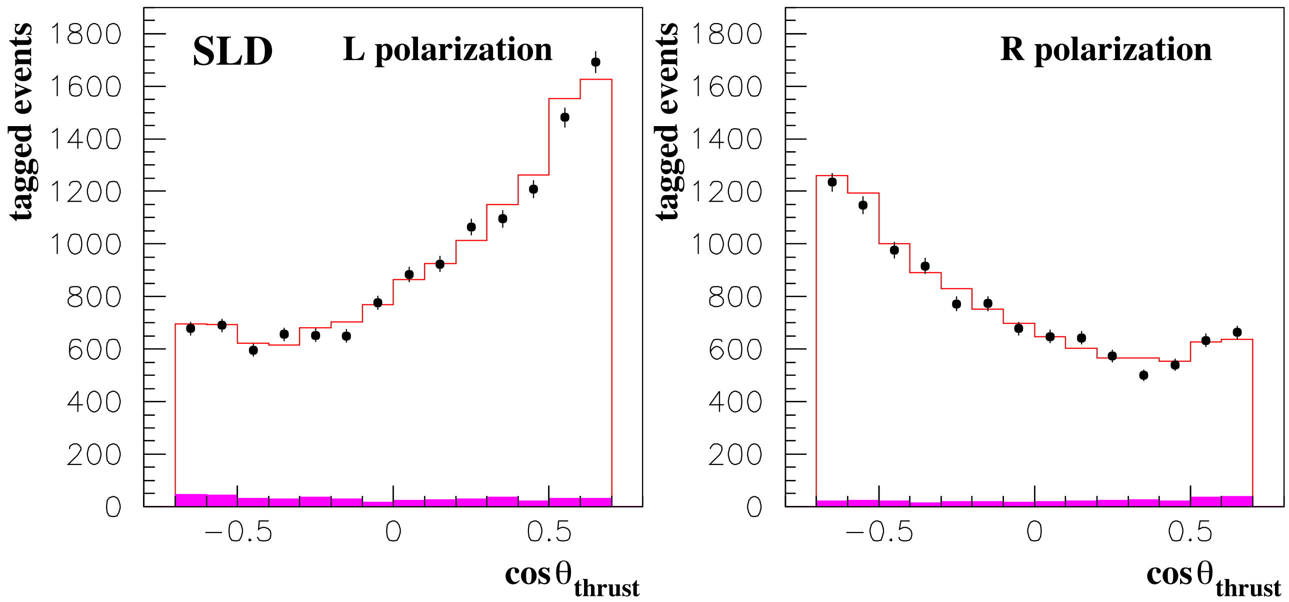






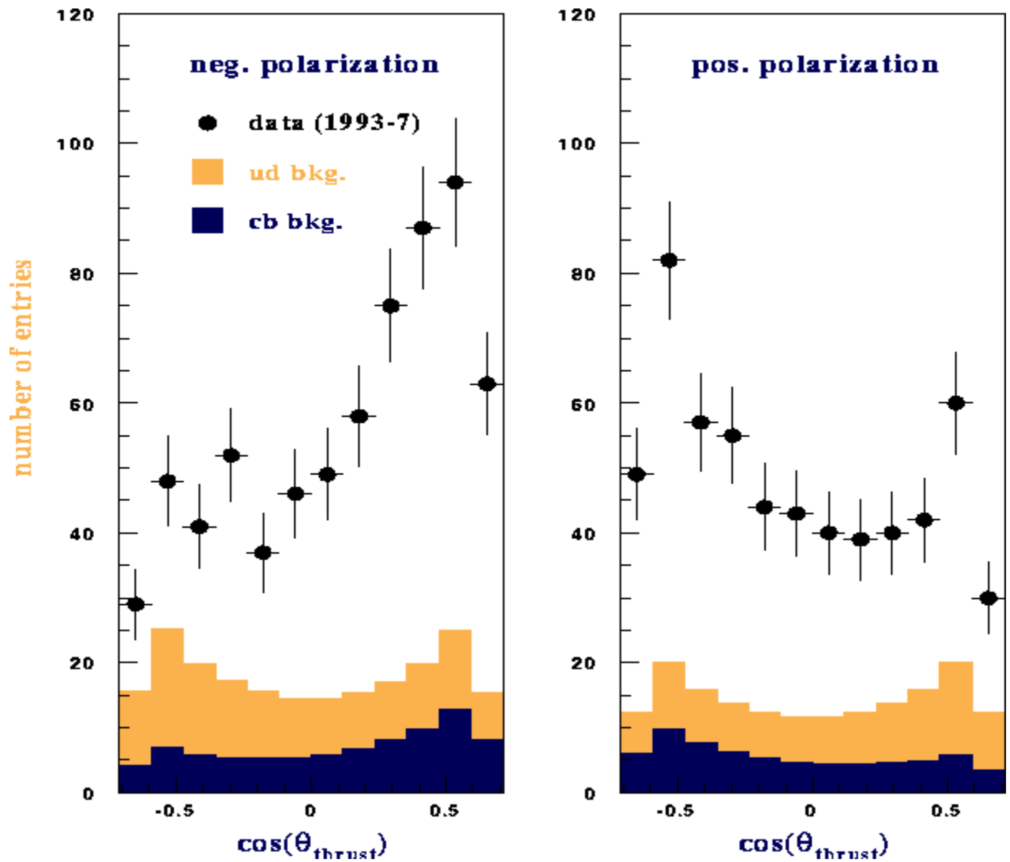


Vertex charge and Kaon



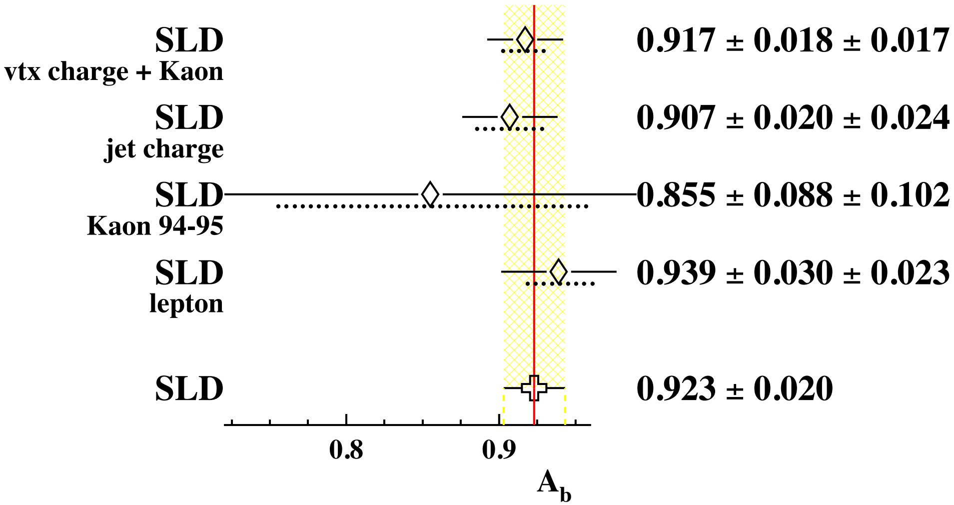
A_s

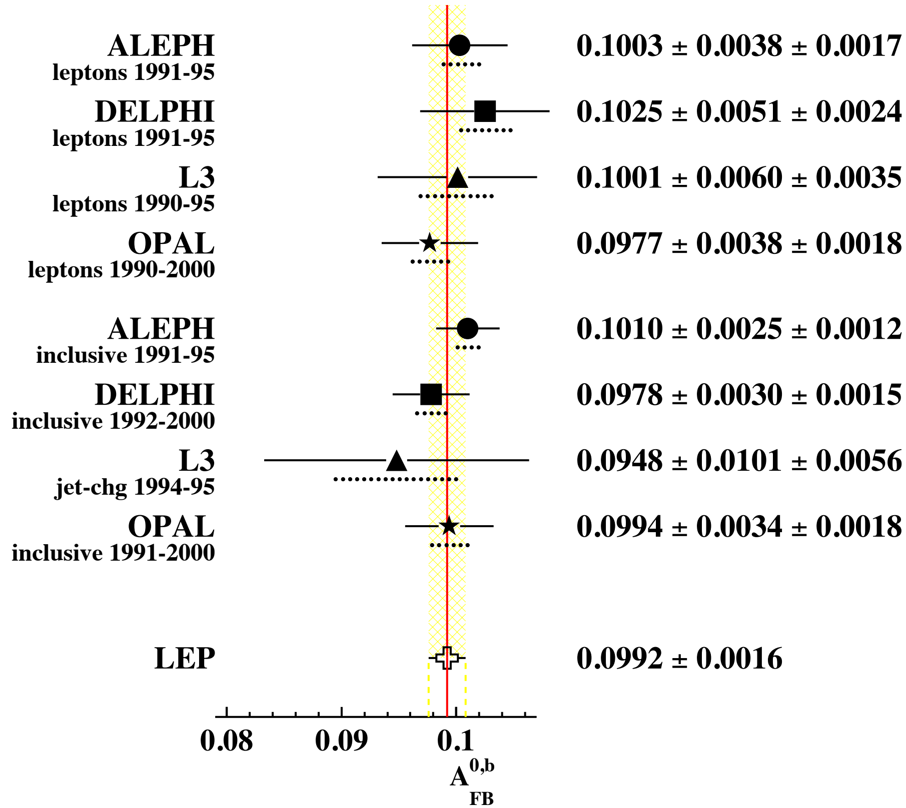
- Use fast charged kaons and no secondary vtx
- Not very precise, but valuable check of b-type quark



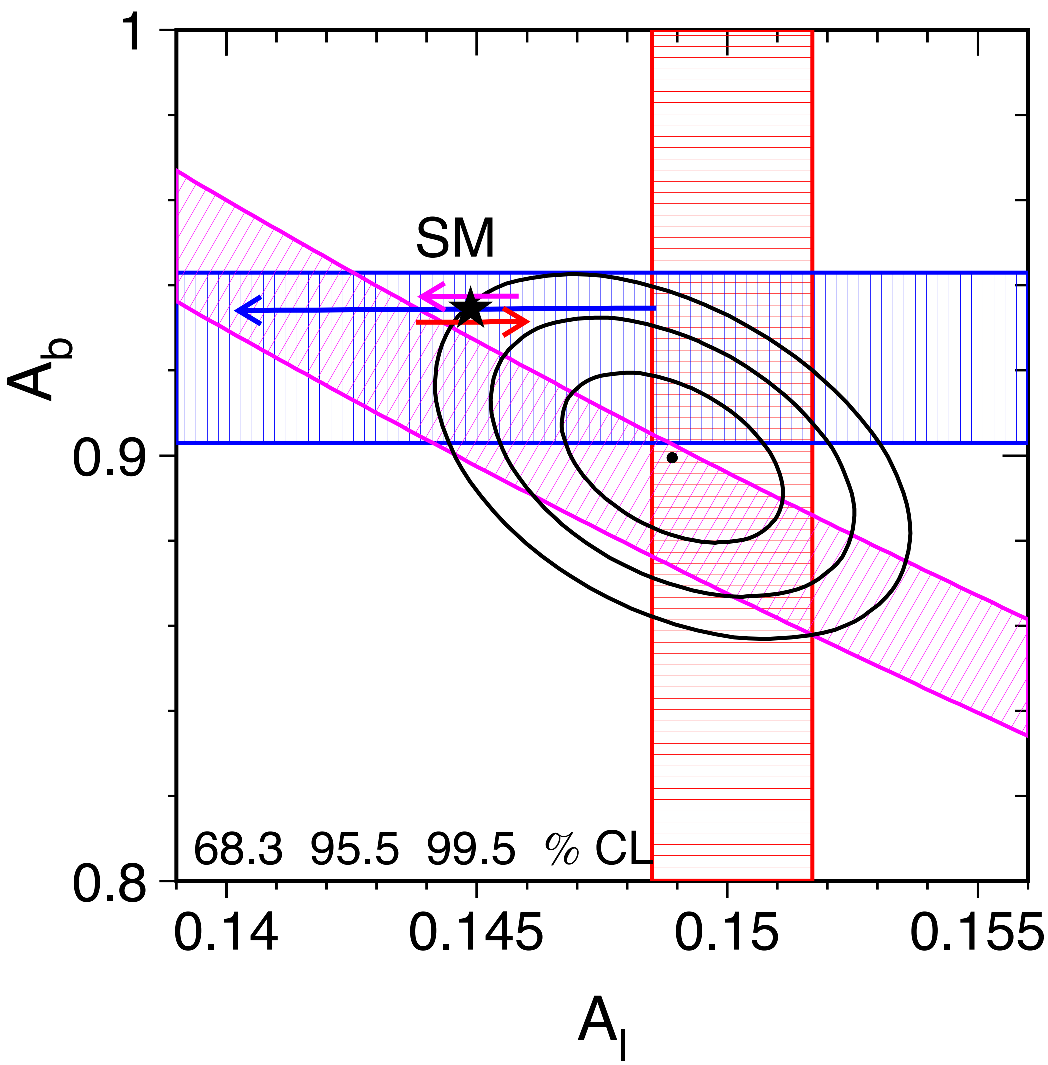
Other measurements
From Delphi (kaons)
And Opal (Λ)

Overview results A_b, A_b^{FB}

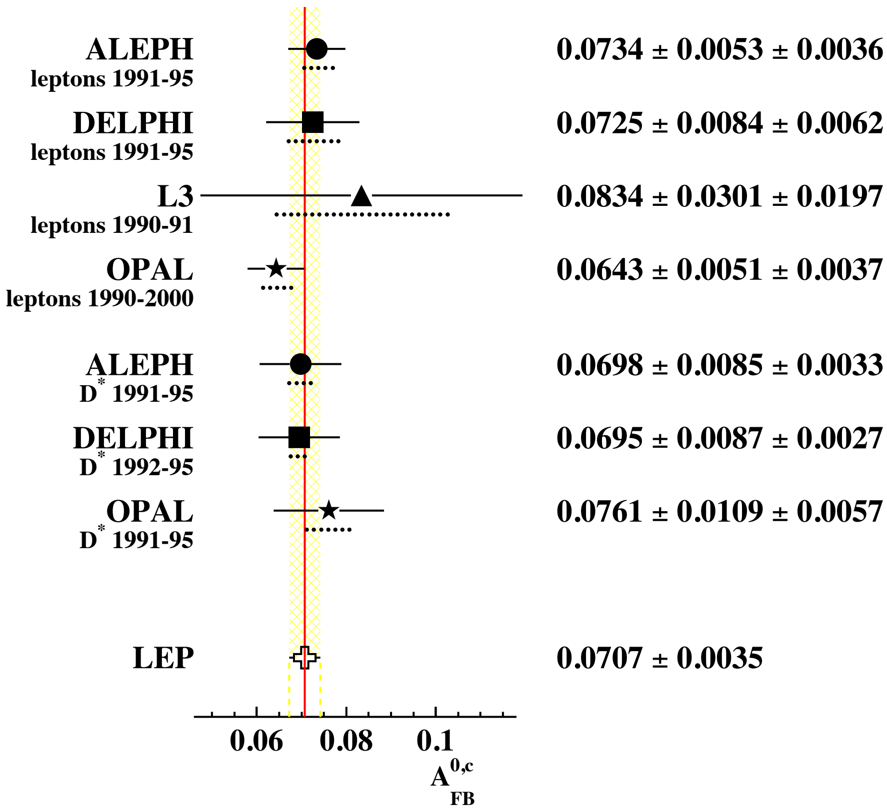


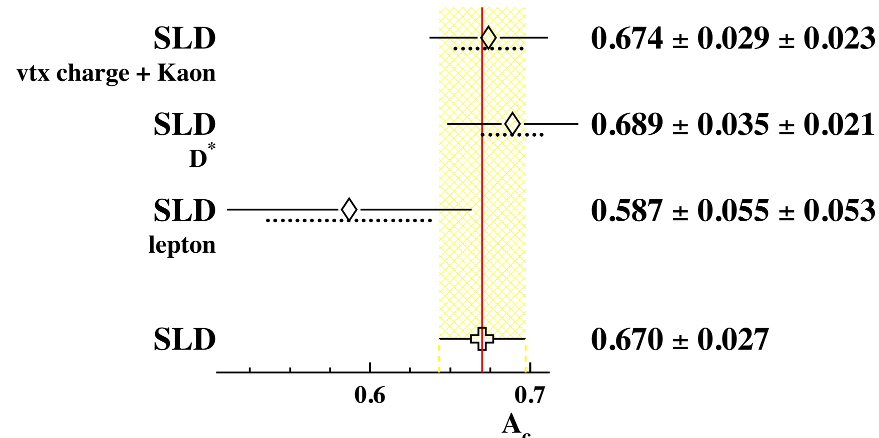


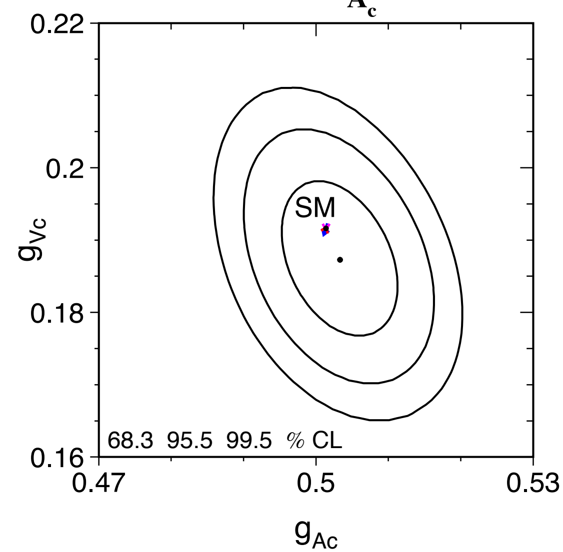
Problem or not ?



Overview results A_c, A_c^{FB}







τ-polarisation measurement

- Parity-violation (V–A) results in longitudinal polarised fermions in $e^+e^- \rightarrow Z \rightarrow f\!f$

- At LEP τ is the only fermion whose polarisation can be measured
  - That's because τaus can decay in the detector
  - We can look at the decay modes to determine the polarisation

Polarisation, Helicity & Chirality

- Polarisation measures *helicity* states.

- Theory tells us about the *chirality* states
  - Chirality: $\psi_L = ½(1-\gamma^5)\psi$ $\psi_R = ½(1+\gamma^5)\psi$
  - Helicity: projection of spin on momentum: *s·p*

- In the relativistic limit: $\mathcal{P}_\tau \equiv (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$
  - left-handed chirality is same as −ve helicity
  - right-handed chirality is same as +ve helicity

σ−: −ve helicity of τ− (+ve for τ+)

σ+: +ve helicity of τ− (−ve for τ+)

Polarisation Distribution

- Couplings of Z to chirality states:

$$g_L = (V_f + A_f)/2 \quad g_R = (V_f - A_f)/2$$

$$g_L = T_3 - Q\sin^2\theta_W \quad g_R = -Q\sin^2\theta_W$$

- The polarisation of a τ− produced in e+e−⟶Z⟶τ+τ- depends on cosθ:

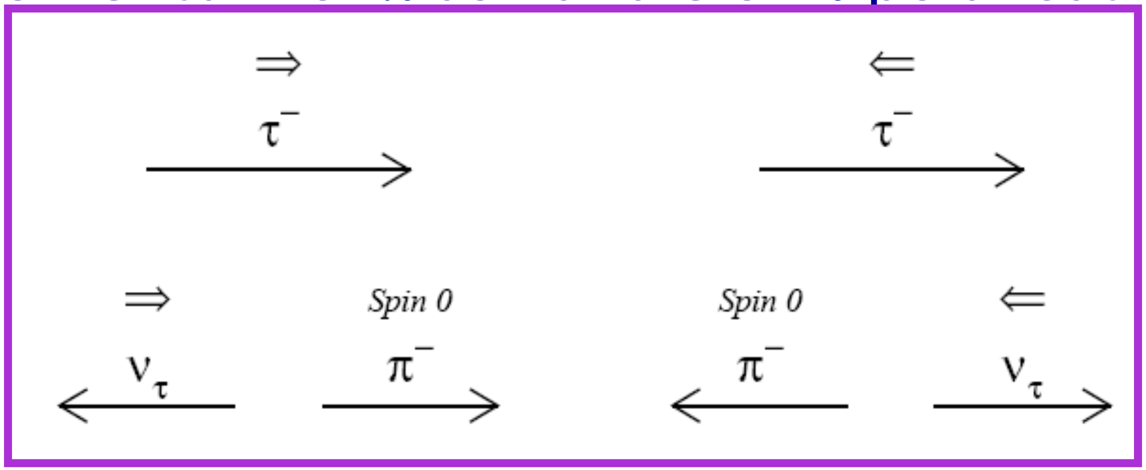
$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A_{FB}^{\tau}\cos\theta_{\tau^-}}.$$

- A_e A_τ are nearly uncorrelated. Insensitive to A^τ_{fb}.

- Another measure of V–A structure, $\sin^2\theta_W$

$\tau \rightarrow \pi \nu_\tau$ Decays

- Use momentum of π as handle on τ polarisation



- Helicity of ν is in same direction as τ-helicity
  – (True in limit of massless particles)
- $\rightarrow$ Effects resulting momentum distribution of π

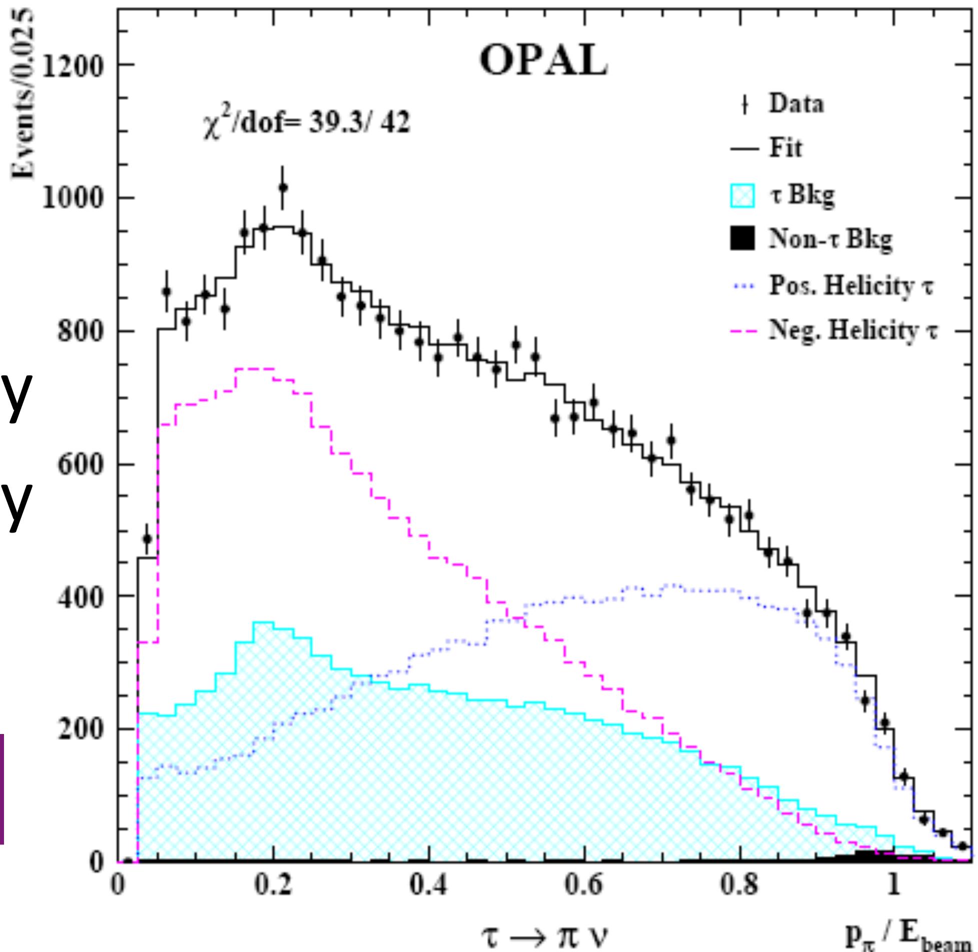
- In $\tau^- \rightarrow \pi^- \nu$ decay:
  – If $P(\tau-)=+1$ momentum of $\pi-$ is higher than for $P(\tau+)=-1$

Fit to Obtain Helicity

- Event-by-event measurement of polarisation not possible.
- Use statistical fit
- Sum of:
  - τ with +ve helicity
  - τ with −ve helicity

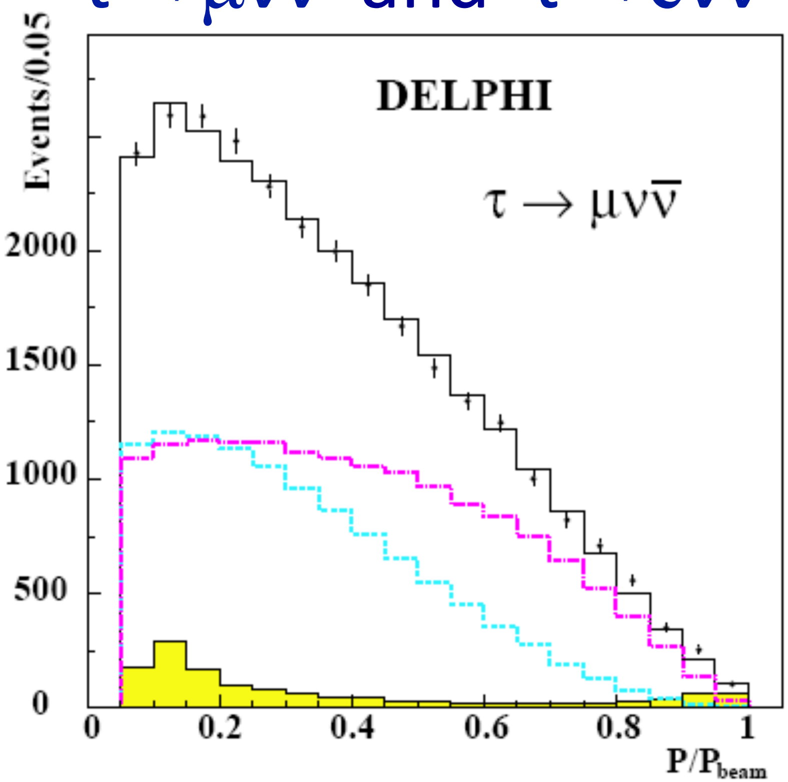
$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1 + \mathcal{P}_\tau(2x_\pi - 1)$$

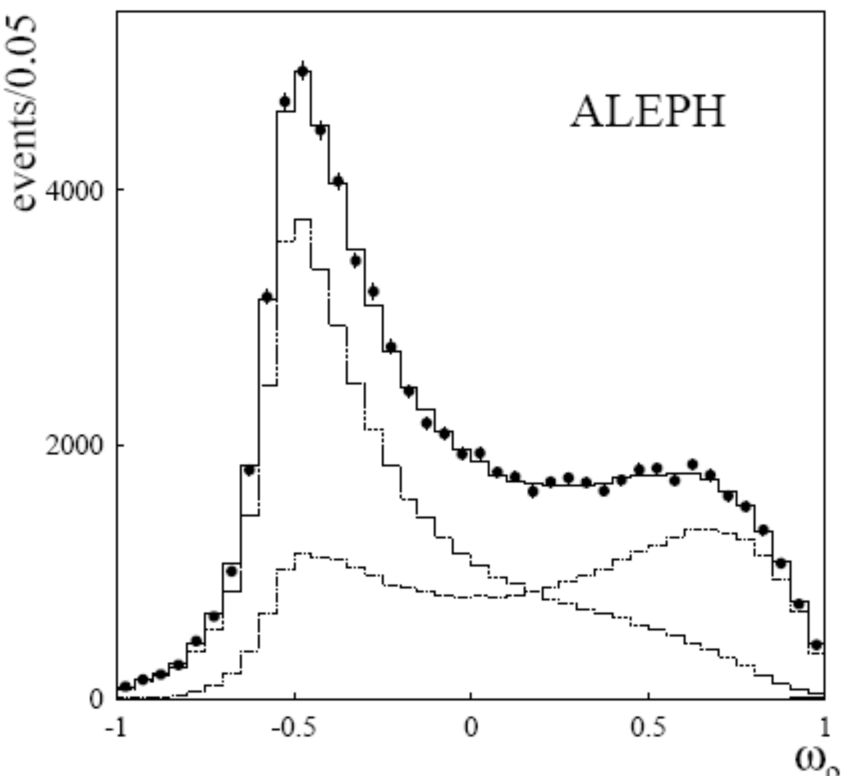
$$x_\pi = E_\pi / E_\tau$$



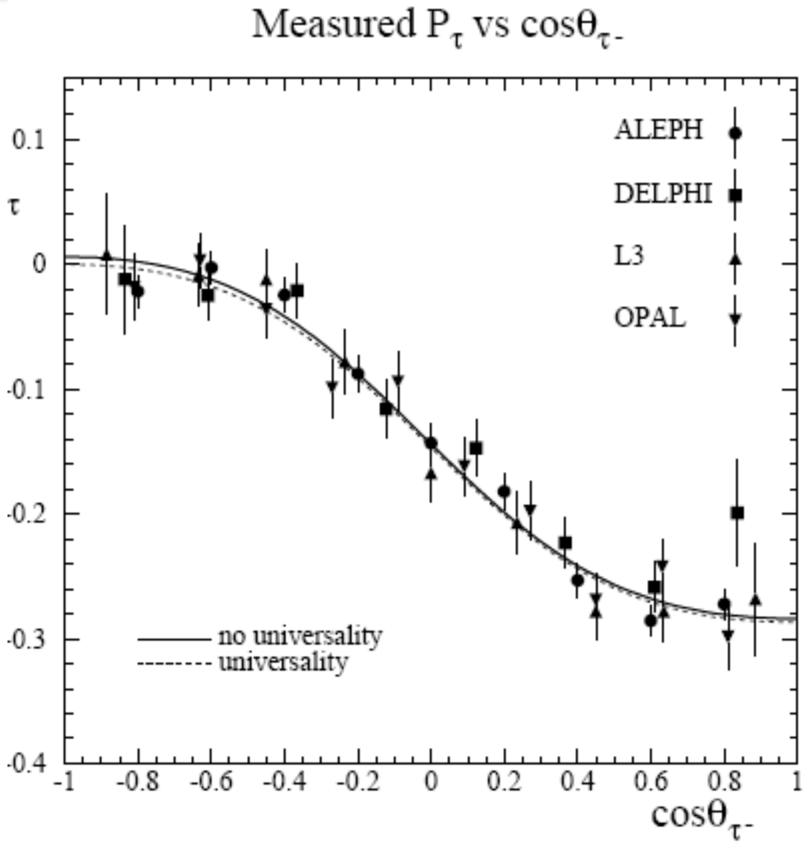
Other Modes

- $\tau \to \rho \nu$ followed by $\rho \to \pi\pi$
- $\tau \to a_1 \nu$ followed by $a_1 \to \pi\pi\pi$
- $\tau \to \mu\nu\nu$ and $\tau \to e\nu\nu$



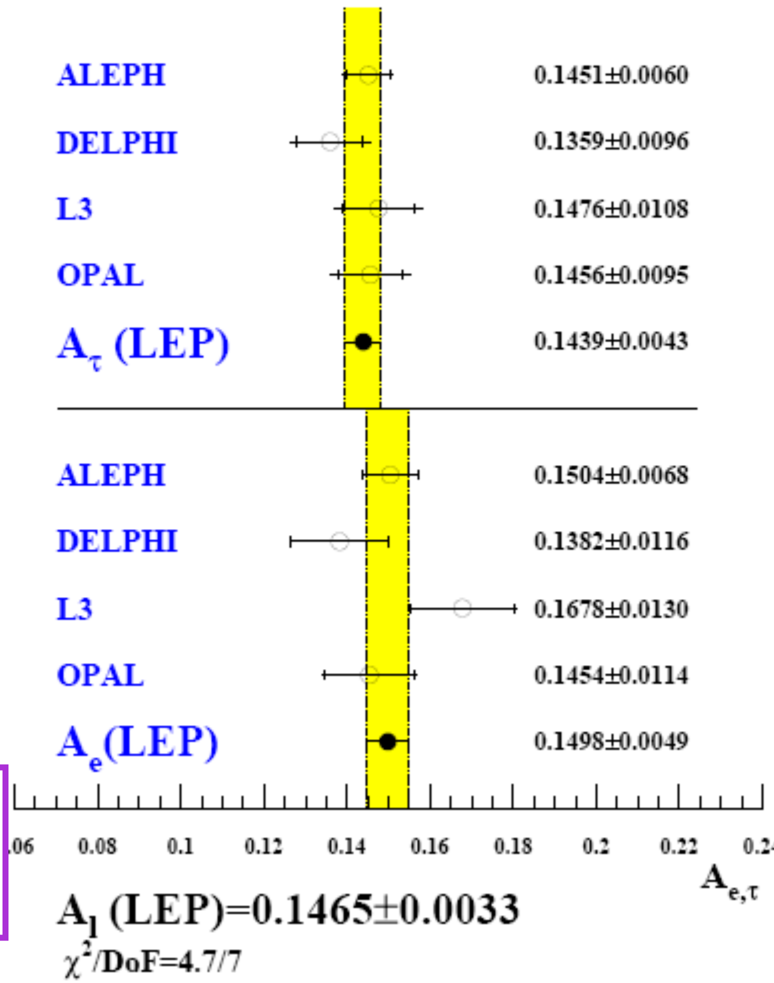


Final τ-polarisation Results



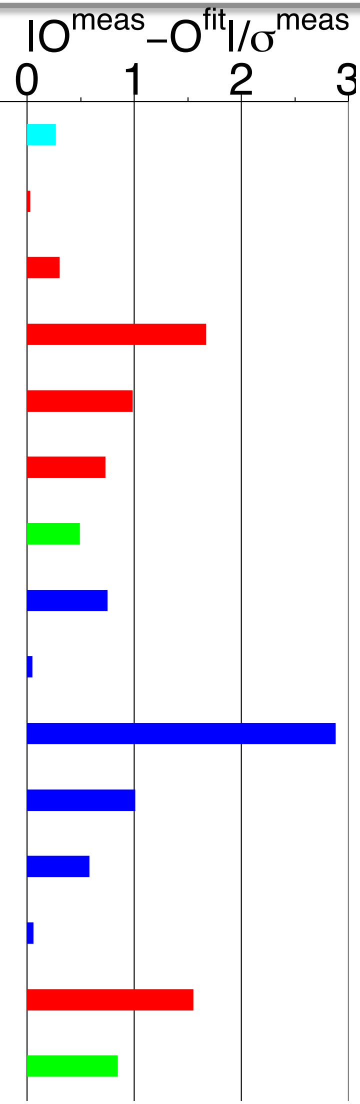
$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A_{FB}^\tau\cos\theta_{\tau^-}}.$$

- Extracted values for A_e A_τ



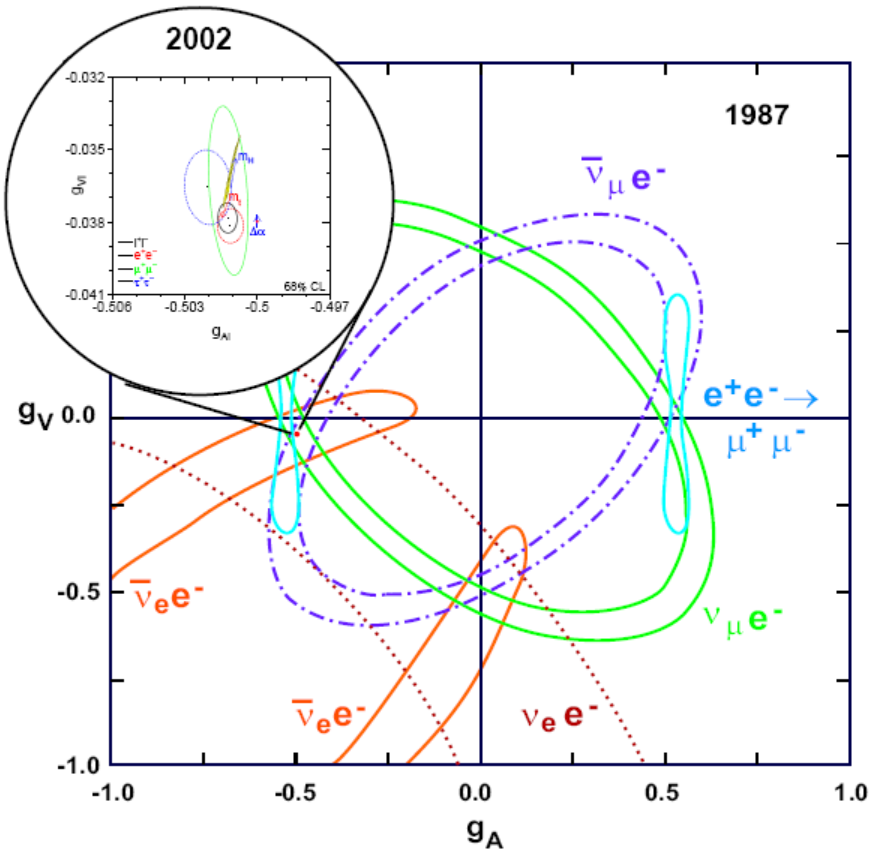
Putting it all together: Z0-pole

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314



LEP & SLD: Before and After

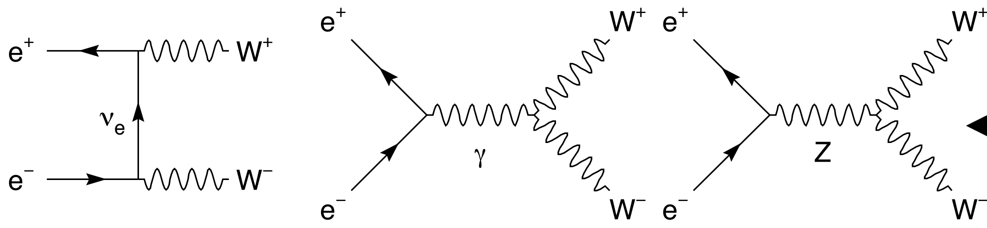
- Truly established the EWK theory as the correct description of fermion interactions at $\sqrt{s}$ < 100 GeV



W measurements: LEP II & Tevatron

- W- mass
- W-width
- TGB couplings

Di-boson production at LEP II



Triple Gauge Coupling

Figure 1.4: Feynman diagrams (CC03) for the process $e^+e^- \rightarrow W^+W^-$ at the Born level.

Figure 1.5: Feynman diagrams (NC02) for the process $e^+e^- \rightarrow ZZ$ at the Born level.

Theory predictions include full $O(\alpha_{em})$ corrections;

theory error ~ 0.5%

WW cross section & BR

$$R(D^*) = 0.336 \pm 0.027(stat) \pm 0.030(syst)$$

LHCb-PAPER-2015-02
arXiv:1506.08614

- In agreement with previous measurements.
- 2.1 σ higher than SM
  $R(D^*)^{SM} = 0.252 \pm 0.003$

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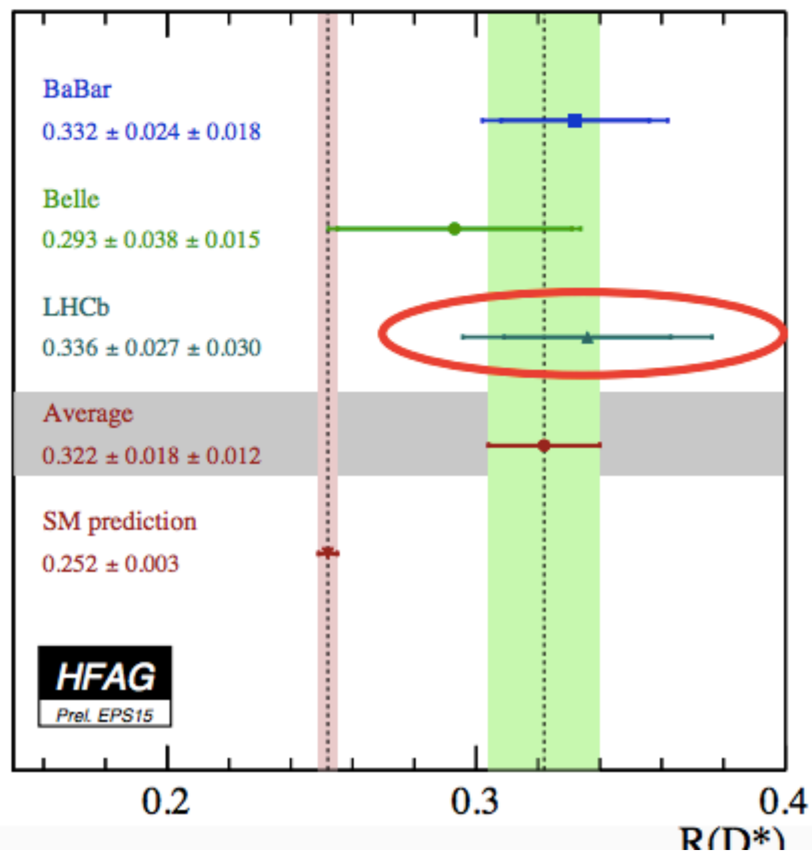
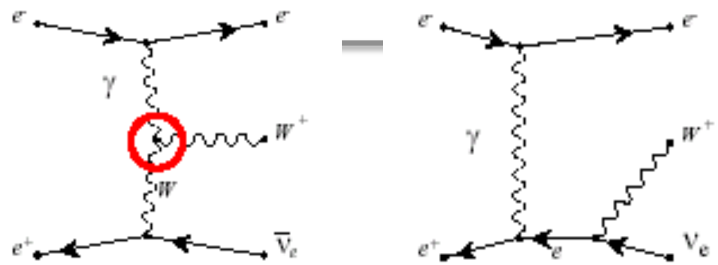
New HFAG average

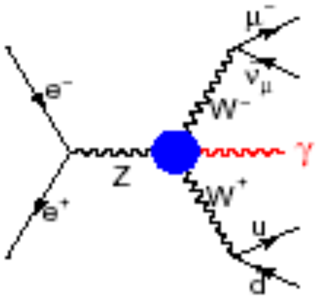
http://www.slac.stanford.edu/xorg/hfag/semi/eps15/eps15_dtaunu.html



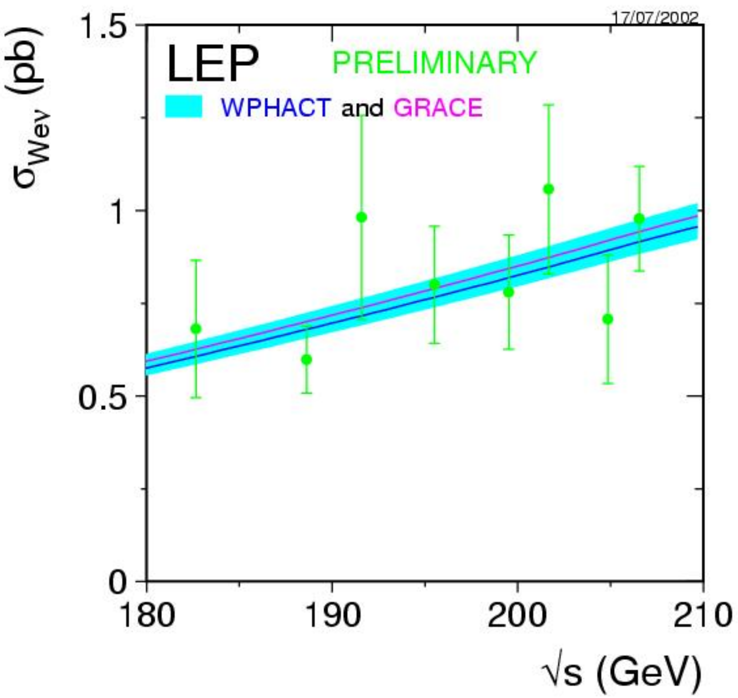
Single W

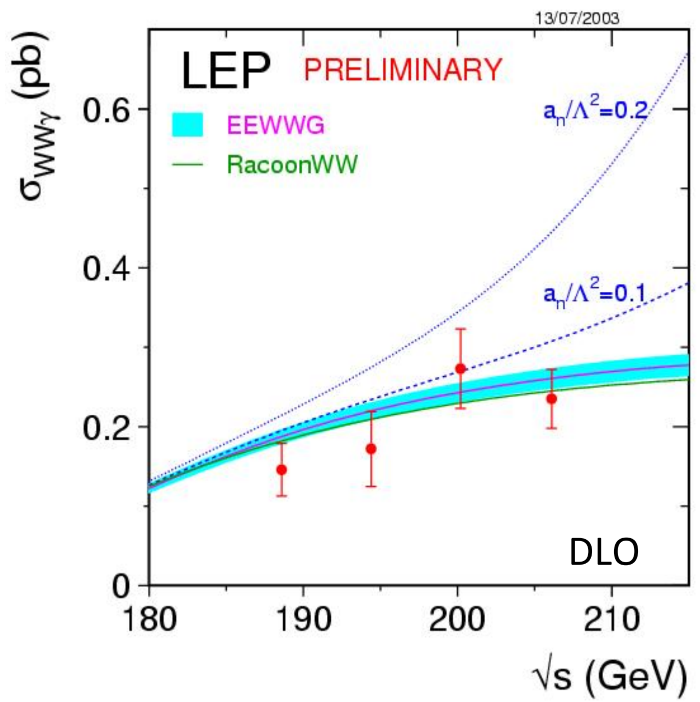


WWγ



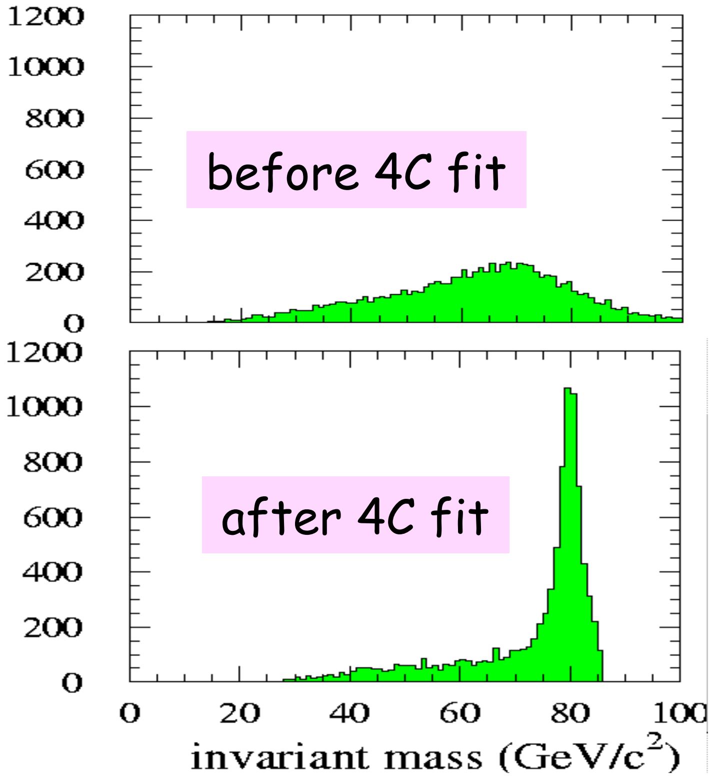
Quartic Gauge Couplings

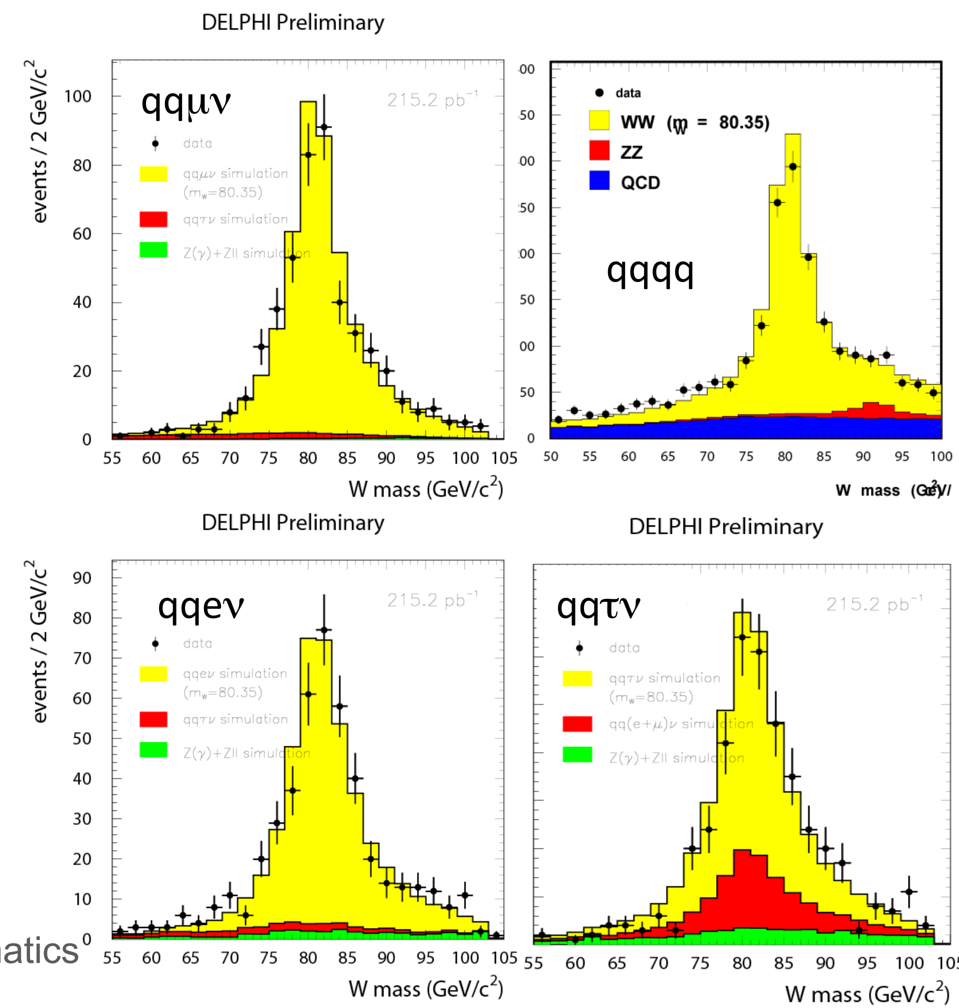




W mass reconstruction

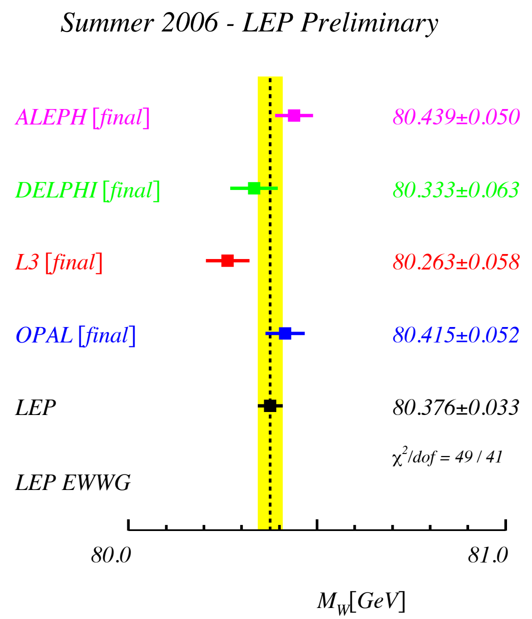
- Reconstructed directly from the decay products
- Constrained fits improve mass resolution from ~8 GeV to ~3 GeV

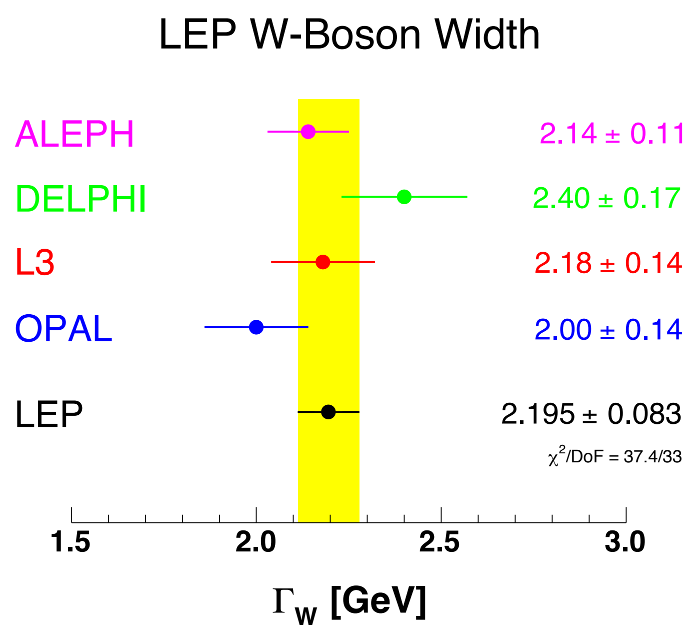




- Large FSI ("colour reconnection") systematics in hadronic channel (35 MeV)

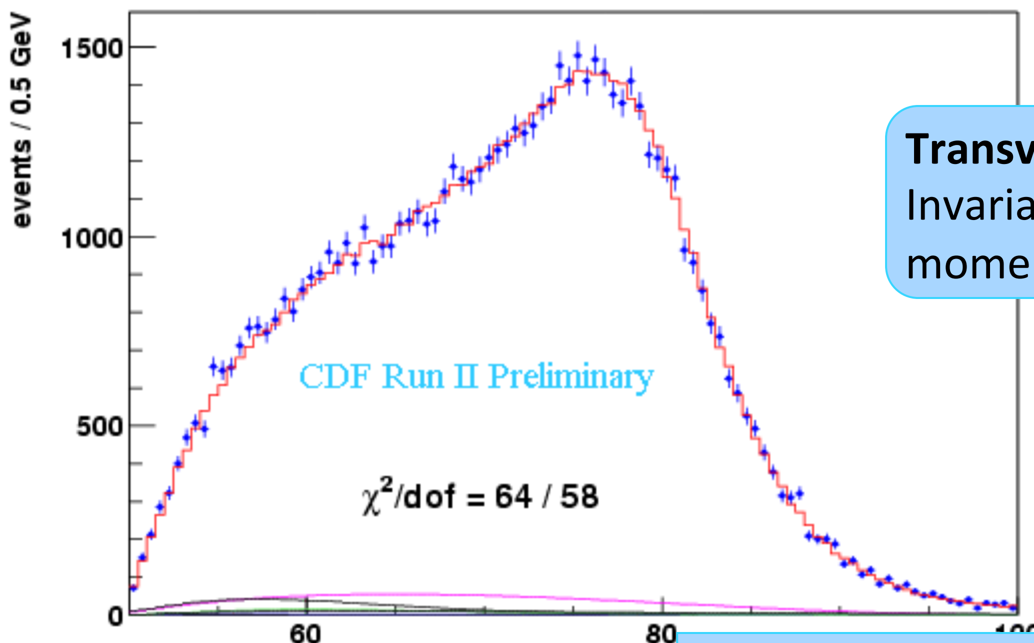
W mass: LEP combined results (2006)





Extracting W Mass at Tevatron

- Value of M_W is sensitive to P_T of lepton and Missing-E_T
- The combination of both quantities in the Transverse Mass (M_T) has best sensitivity to M_W
- Generate lots of MC samples with different M_W
- Fit each one to date to find test M_W value

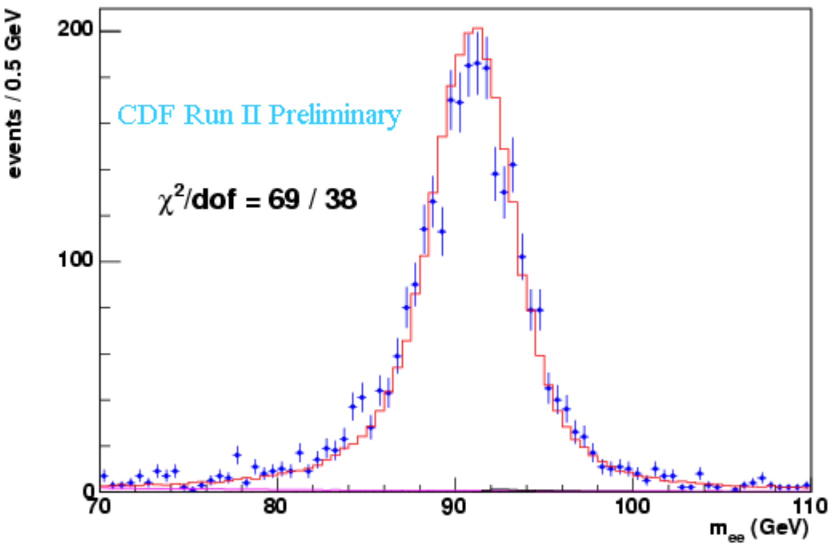


Transverse Mass of muon and neutrino.
Invariant mass only using components of the momentum transverse to the beam

$$M_T(\mu\nu) = \sqrt{E(\mu)\cdot E(\nu) - p_x(\mu)\cdot p_x(\nu) - p_y(\mu)\cdot p_y(\nu)}$$

Largest W Mass Systematics

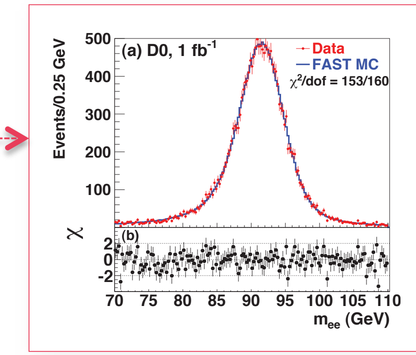
- How well do we understand energy scale of calorimeter?
  - Use Z→e+e− to calibrate detector
- How well do we understand hadronic recoil
  - Effects resolution of missing E_T

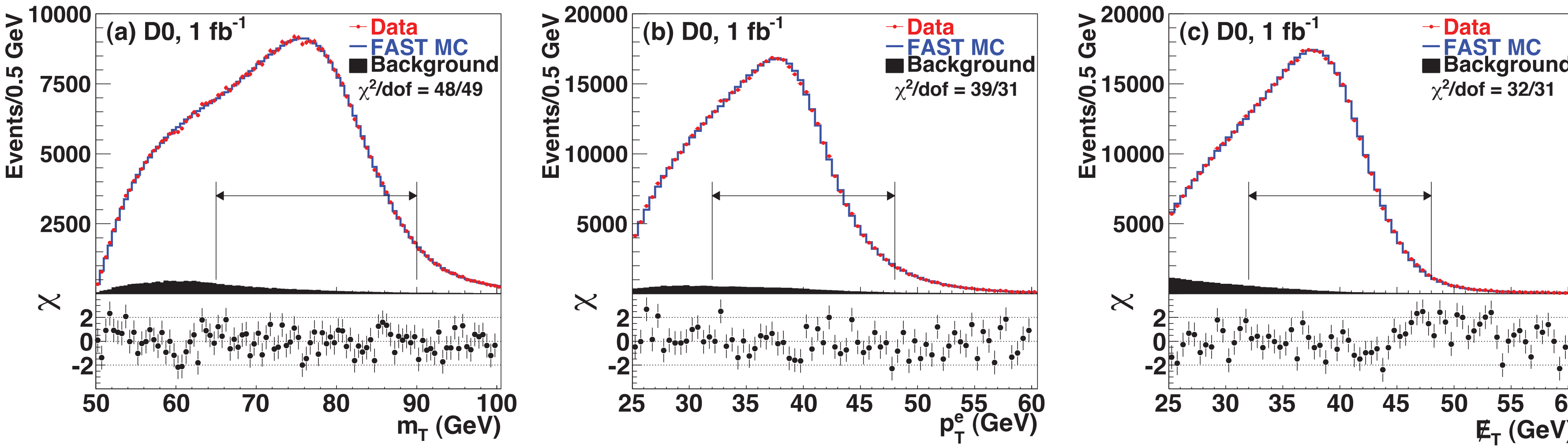


Precision Measurement of the W mass

D0 measurement of M_W in $W \to e\nu$

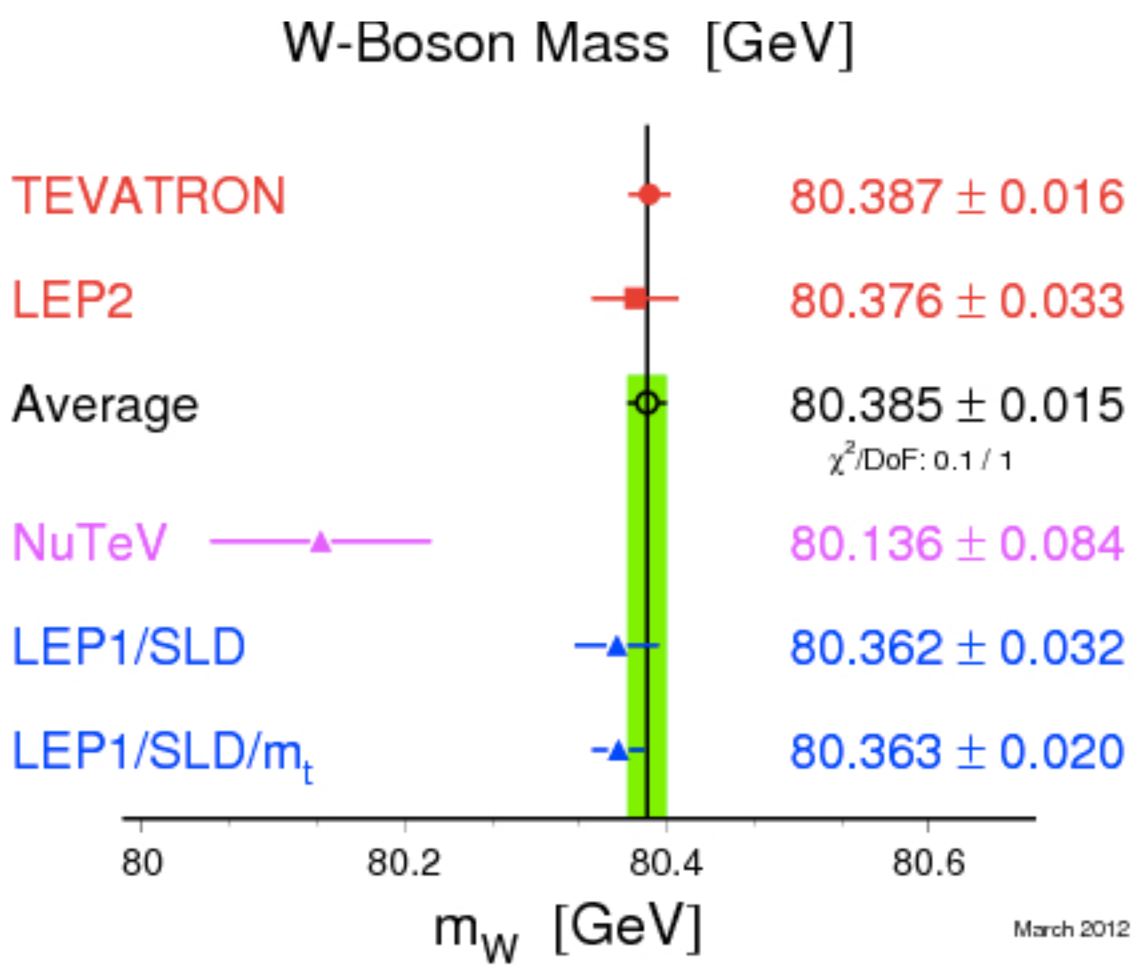
- Analysis relies on energy calibration with $Z \to ee$
- Result: M_W = (80.401 ± 0.021 ± 0.038) GeV
- Greatly deserves the label *"precision measurement"*





The (a) m_T , (b) $p^e{}_T$, and (c) $E_{T,\mathrm{miss}}$ distributions for data and fastmc simulation with backgrounds. The χ values are shown below each distribution where $\chi_i = [N_i - (\mathrm{fastmc}_i)]/\sigma_i$ for each point in the distribution, N_i is the data yield in bin i and only the statistical uncertainty is used. The fit ranges are indicated by the double-ended horizontal arrows.

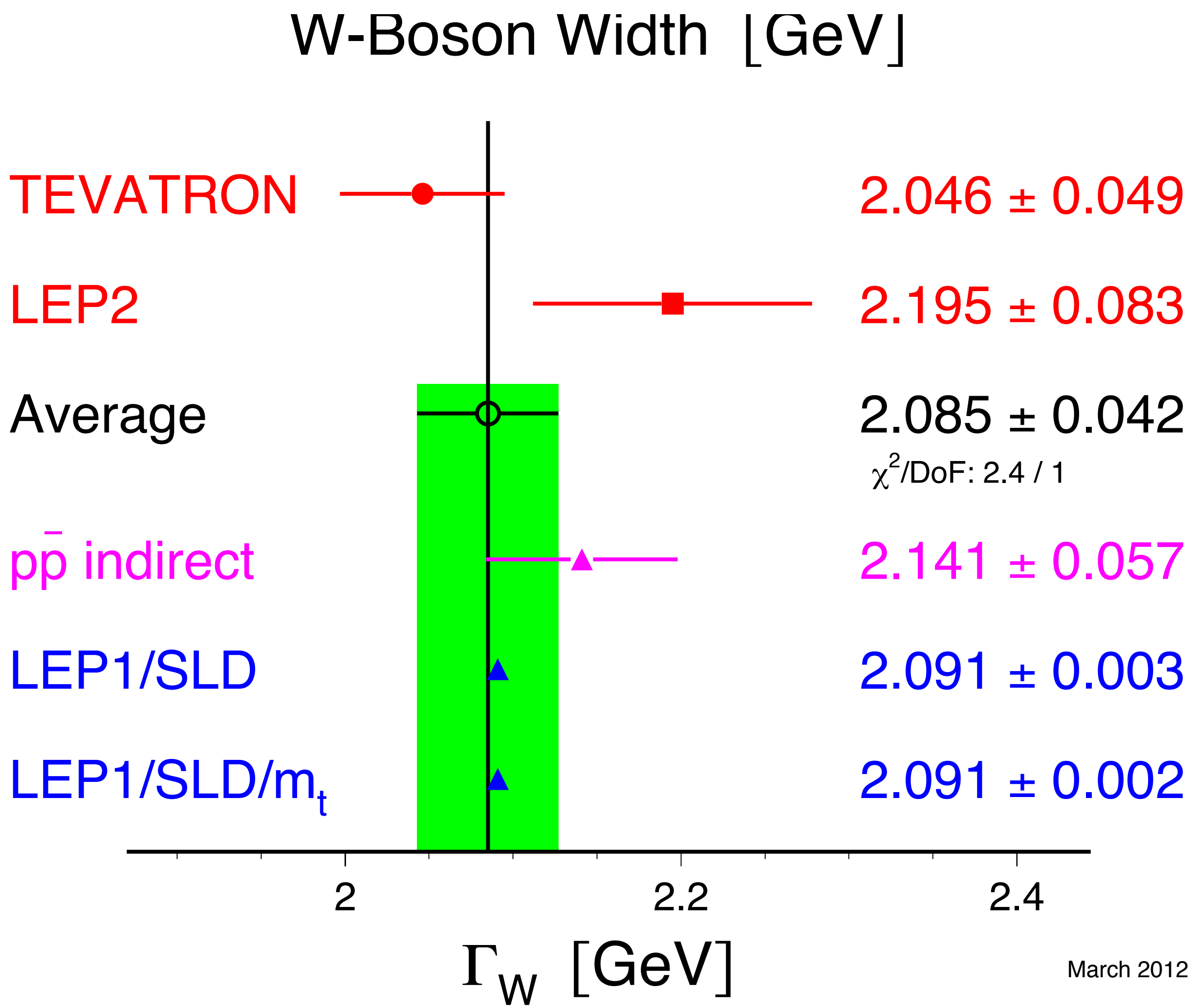
W-mass summary



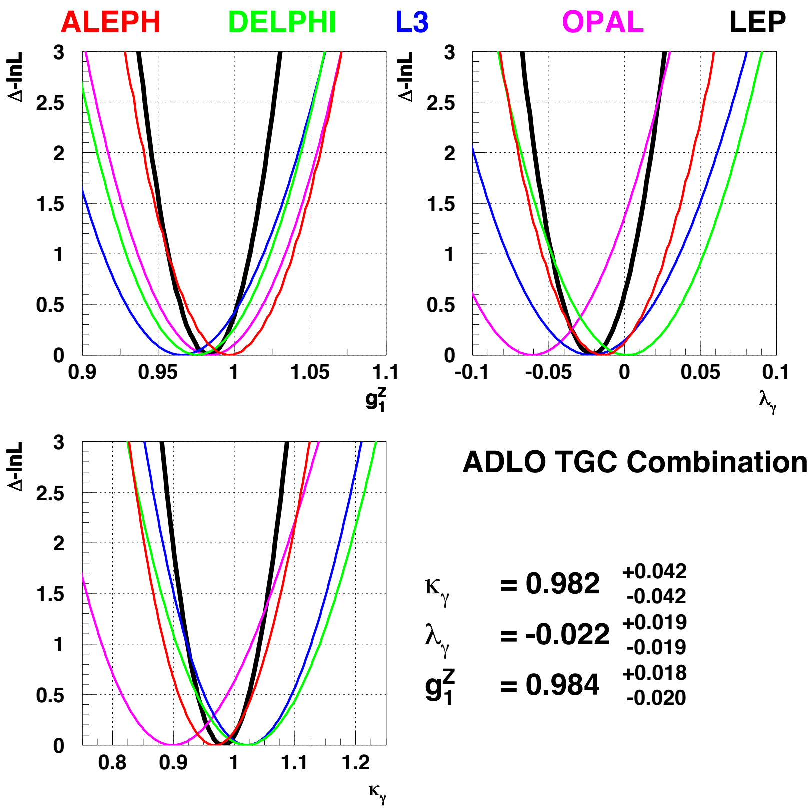
Apart from NuTeV result (ν scattering)

Very good agreement between direct and indirect measurements

W-width summary

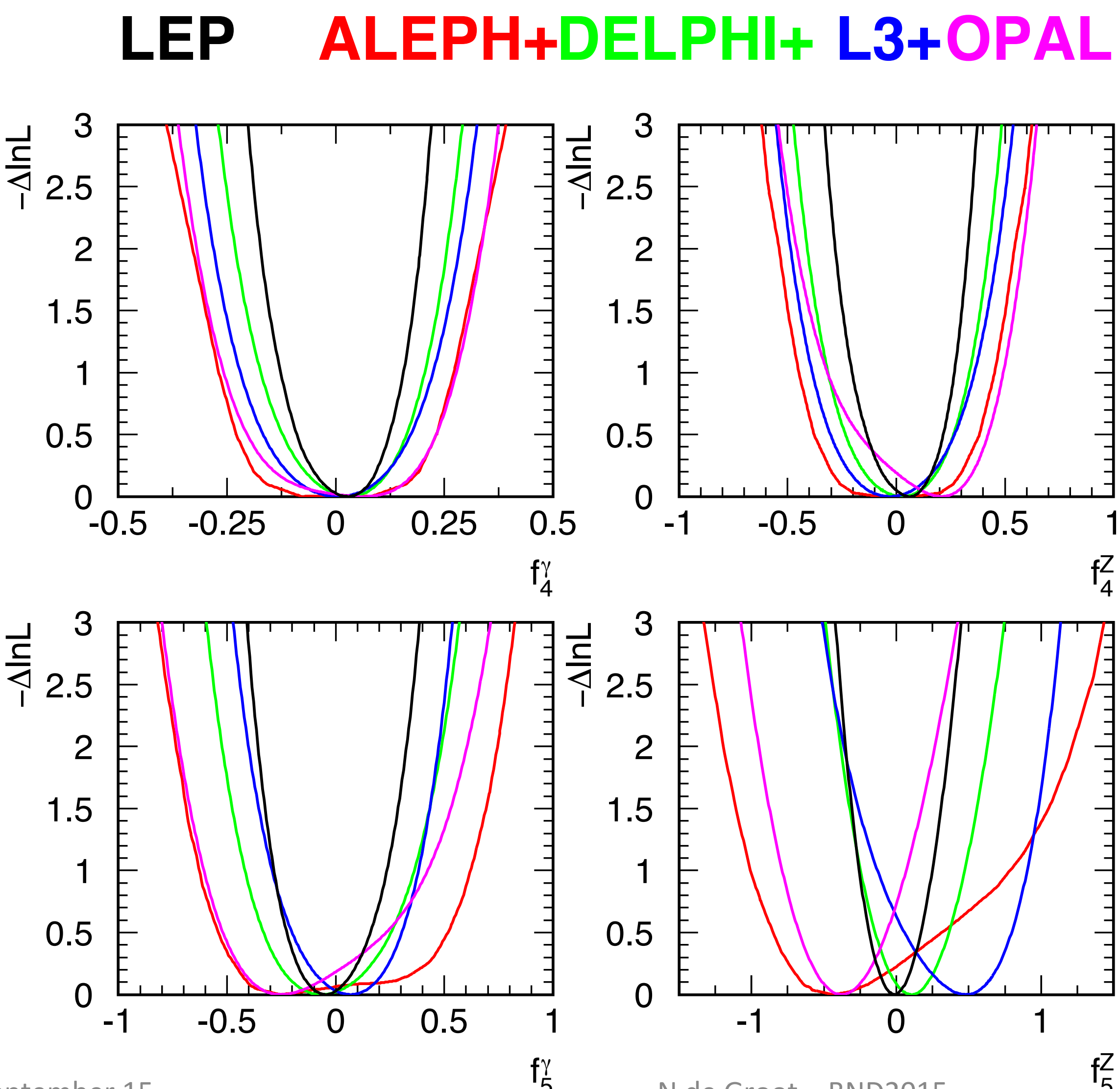


Charged triple gauge bosons



Parameter	ALEPH	DELPHI	L3	OPAL	SM
g_1^Z	$0.996^{+0.030}_{-0.028}$	$0.975^{+0.035}_{-0.032}$	$0.965^{+0.038}_{-0.037}$	$0.985^{+0.035}_{-0.034}$	1
κ_γ	$0.983^{+0.060}_{-0.060}$	$1.022^{+0.082}_{-0.084}$	$1.020^{+0.075}_{-0.069}$	$0.899^{+0.090}_{-0.084}$	1
λ_γ	$-0.014^{+0.029}_{-0.029}$	$0.001^{+0.036}_{-0.035}$	$-0.023^{+0.042}_{-0.039}$	$-0.061^{+0.037}_{-0.036}$	0

Neutral TGC

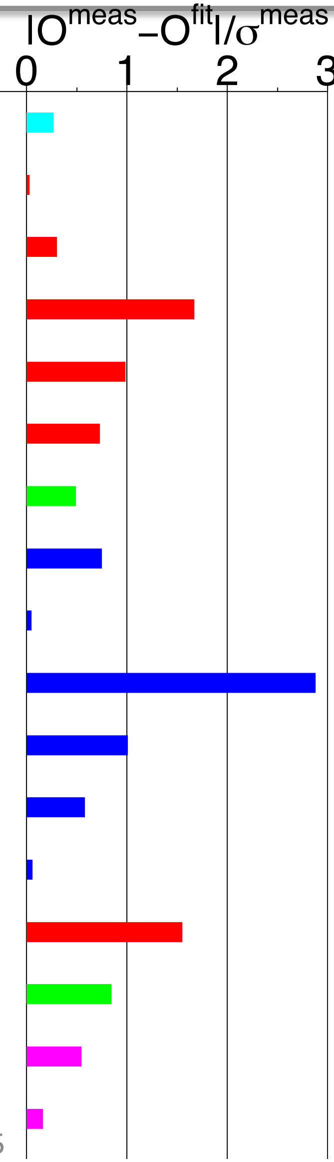


In SM they
Should be 0.

There is no ZZγ
or Zγγ vertex.

All together now

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092

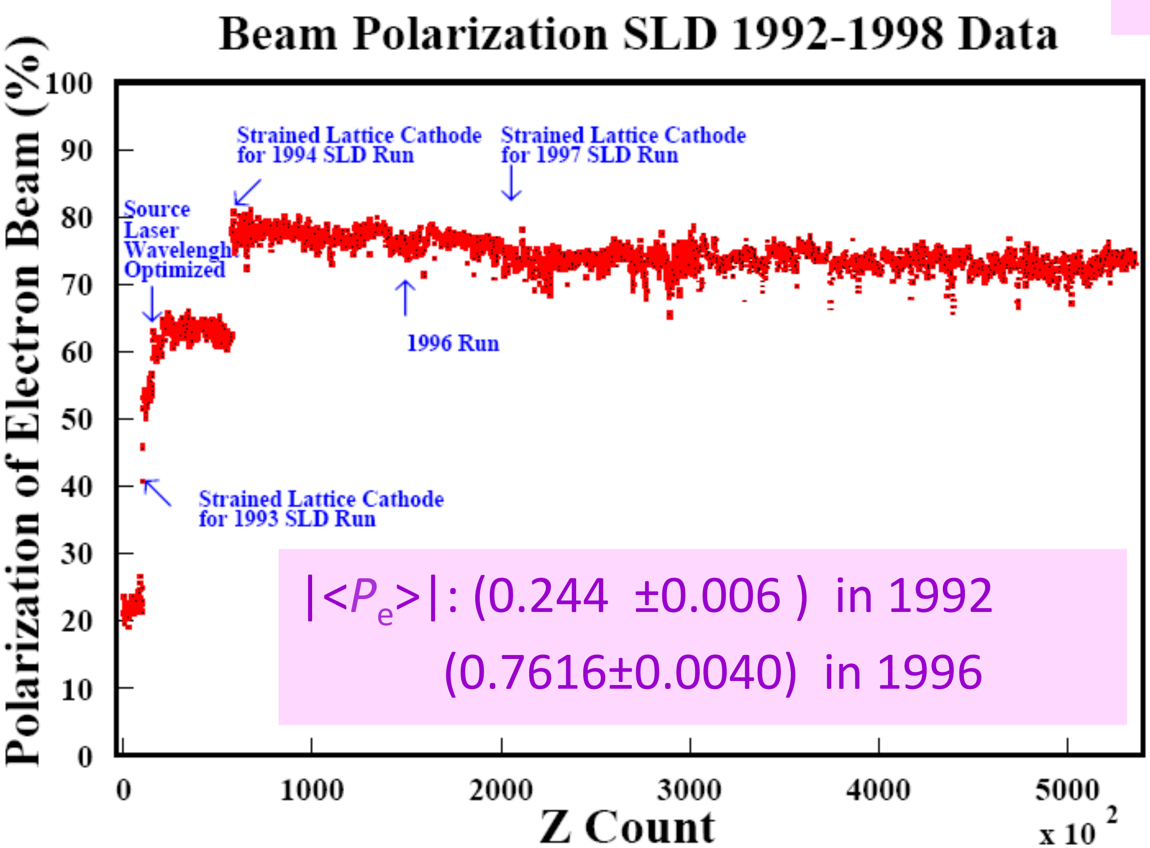


BACK UP

Beam Polarisation at SLC

- Polarised beams means that the beam are composed of more e_L than e_R, or vice versa

$$\langle P \rangle_e = \frac{N(e_R) - N(e_L)}{N(e_R) + N(e_L)}$$



$|\langle P_e \rangle|$: (0.244 ±0.006) in 1992

(0.7616±0.0040) in 1996

- $|\langle P_e \rangle|$ = 100% for fully polarised beams

Cross-section

$$N_{obs} = \int L dt \cdot \varepsilon \cdot \sigma$$

$$L = \frac{f_{rev}\, n_{bunch}\, N_p^2}{4\pi\sigma_x\sigma_y}$$

revolving frequency: f_{rev}=11245.5/s
#bunches: n_{bunch}=2808
#protons / bunch: N_p= 1.15 x 10^{11}
Area of beams: $4\pi\sigma_x\sigma_y$~40 μm

number of observed events

background contamination in the sample

cross section: $\sigma = \dfrac{N_{obs} - N_{bkg}}{\varepsilon \cdot \int \mathcal{L} dt}$

analysis efficiency

$\varepsilon = \varepsilon_{tr} \cdot \varepsilon_{reco} \cdot \varepsilon_{ID} \cdot \varepsilon_{sel}$

luminosity delivered by LHC

Number of observed events proportional to luminosity and analysis efficiency.

$1 \text{ barn} = 10^{-28}\text{ m}^2 = 10^{-24}\text{ cm}^2$