Lecture:

Standard Model of Particle Physics

Heidelberg SS 2016

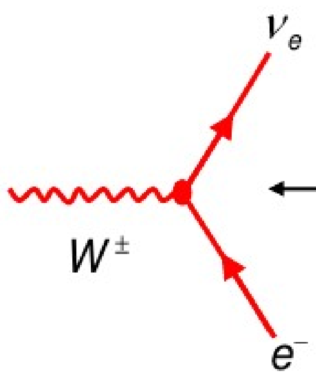
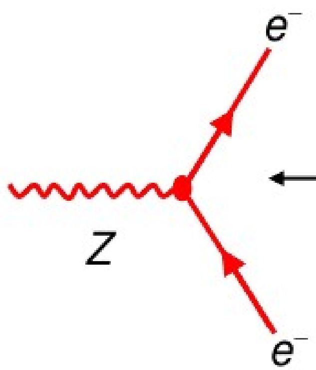
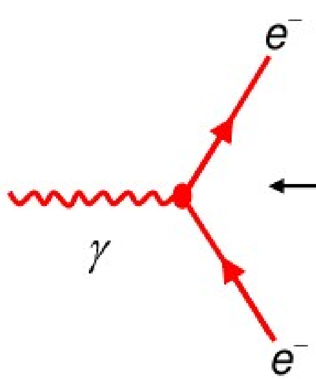
Tests of the Standard Model at LEP

Contents

- Introduction
- Z-Lineshape*
- Fermion couplings and Forward-Backward Asymmetries
- Top-Mass Prediction and Discovery
- Triple Gauge Boson couplings

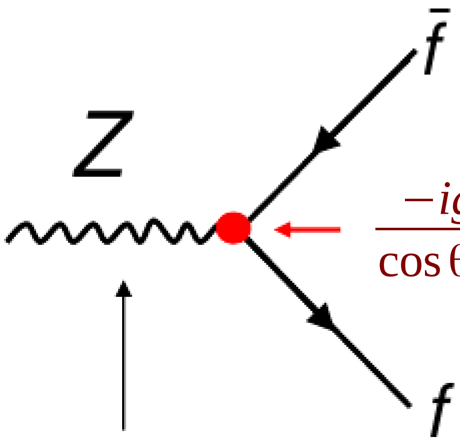
* *Precision electroweak measurement on the Z resonance, Phys. Rept. 427 (2006), hep-ex/0509008.*
http://lepewwg.web.cern.ch/LEPEWWG/1/physrep.pdf

Feynman Rules Electroweak Theory

	Vertex factors	Propagator (unitary gauge)
	$-i\frac{g}{\sqrt{2}}\gamma_\mu\frac{1}{2}(1-\gamma^5)$	$\frac{g_{\mu\nu}-q_\mu q_\nu/M_W^2}{q^2-M_W^2}$
	$-i\frac{g}{\cos\theta_W}\gamma_\mu\frac{1}{2}(g_V-g_A\gamma^5)$	$\frac{g_{\mu\nu}-q_\mu q_\nu/M_Z^2}{q^2-M_Z^2}$
	$-ie\gamma_\mu$	$\frac{1}{q^2}$

slide from U.Uwer

SM Precision Tests



$$\frac{-ig}{\cos\theta_W}\gamma^\mu\frac{1}{2}\left(g_V^f - g_A^f\gamma^5\right)$$

$$g = \frac{e}{\sin\theta_w}$$

$$\frac{-i\left(g_{\mu\nu} - q_\mu q_\nu / M^2\right)}{q^2 - M^2}$$

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

Standard Model

$$g_V = T_3 - 2Q\sin^2\theta_W \quad \text{and} \quad g_A = T_3$$

$$g_L = \frac{1}{2}(g_V + g_A) \qquad g_R = \frac{1}{2}(g_V - g_A)$$

$$\frac{g_V}{g_A} = 1 - 2\frac{Q}{T_3}\sin^2\theta_W = 1 - 4|Q|\sin^2\theta_W$$

	g_V	g_A
ν	$1/2$	$1/2$
ℓ^-	$-1/2 + 2\sin^2\theta_W$	$-1/2$
$u-quark$	$+1/2 - 4/3\sin^2\theta_W$	$1/2$
$d-quark$	$-1/2 + 2/3\sin^2\theta_W$	$-1/2$

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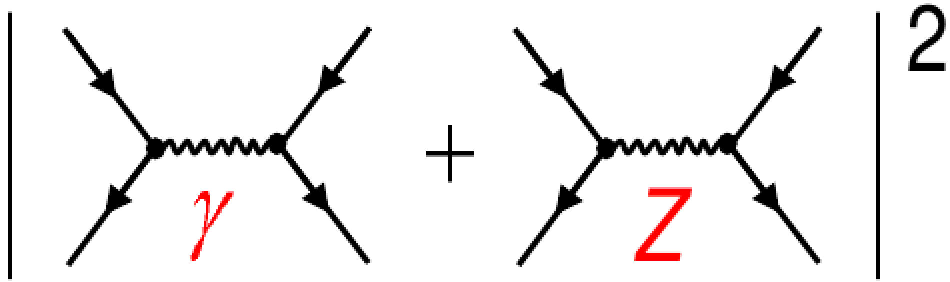
LEP1 + SLC Cross Section

$|A|^2 =$ 

for $e^+ e^- \to \mu^+ \mu^-$

Matrix elements:

$$A_\gamma = -ie^2 (\bar{u}_\mu \gamma^\nu v_\mu) \frac{g_{\rho\nu}}{q^2} (\bar{v}_e \gamma^\rho u_e)$$

$$A_Z = -i \frac{g^2}{\cos^2\theta_W} \left[\bar{u}_\mu \gamma^\nu \frac{1}{2}(g_V^\mu - g_A^\mu \gamma^5) v_\mu \right] \underbrace{\frac{g_{\rho\nu} - q_\rho q_\nu / M_Z^2}{(q^2 - M_Z^2) + iM_Z\Gamma_Z}} \left[\bar{v}_e \gamma^\rho \frac{1}{2}(g_V^e - g_A^e \gamma^5) u_e \right]$$

Z propagator considering a finite Z width (real particle)

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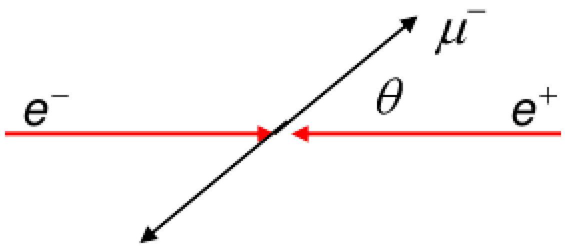
LEP1 + SLC Cross Section

One finds for the differential cross section:

$$\frac{d\sigma}{d\cos\theta} = \underbrace{\frac{\pi\alpha^2}{2s}}_{\text{known}}\left[\underbrace{F_\gamma(\cos\theta)}_{\gamma} + \underbrace{F_{\gamma Z}(\cos\theta)\frac{s(s-M_Z^2)}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}_{\gamma/Z\text{ interference}} + \underbrace{F_Z(\cos\theta)\frac{s^2}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}}_{Z}\right]$$

Vanishes at $\sqrt{s} \approx M_Z$



$$F_\gamma(\cos\theta) = Q_e^2 Q_\mu^2\,(1+\cos^2\theta) = (1+\cos^2\theta)$$

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W\cos^2\theta_W}\,[2 g_V^e g_V^\mu (1+\cos^2\theta) + 4 g_A^e g_A^\mu \cos\theta]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W\cos^4\theta_W}\,[(g_V^{e\,2}+g_A^{e\,2})(g_V^{\mu\,2}+g_A^{\mu\,2})(1+\cos^2\theta) + 8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta]$$

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Total Cross Section

$$\sigma_Z = \frac{4\pi\alpha^2}{3s}\frac{1}{16\sin^4\theta_W\cos^4\theta_W}\left[\left(g_V^{e\,2}+g_A^{e\,2}\right)\left(g_V^{\mu\,2}+g_A^{\mu\,2}\right)\right]\frac{s^2}{\left(s-M_Z^2\right)^2+\left(M_Z\Gamma\right)^2}$$

Breit-Wigner Resonance:
BW description is very general

$$\sigma(s) = 12\pi\frac{\Gamma_e\Gamma_\mu}{M_Z^2}\cdot\frac{s}{(s-M_Z^2)^2+M_Z^2\Gamma_Z^2}$$

$$\sigma_Z(\sqrt{s}=M_Z) = \frac{12\pi}{M_Z^2}\frac{\Gamma_e\Gamma_\mu}{\Gamma_Z^2}$$

With partial and total widths:

$$\Gamma_f = \frac{\alpha M_Z}{12\sin^2\theta_W\cos^2\theta_W}\left(g_V^{f\,2}+g_A^{f\,2}\right)$$

$$\Gamma_Z = \sum_i \Gamma_i \qquad BR(Z\to ii) = \frac{\Gamma_i}{\Gamma_Z}$$

Cross sections and widths can be calculated within the Standard Model if all parameters are known

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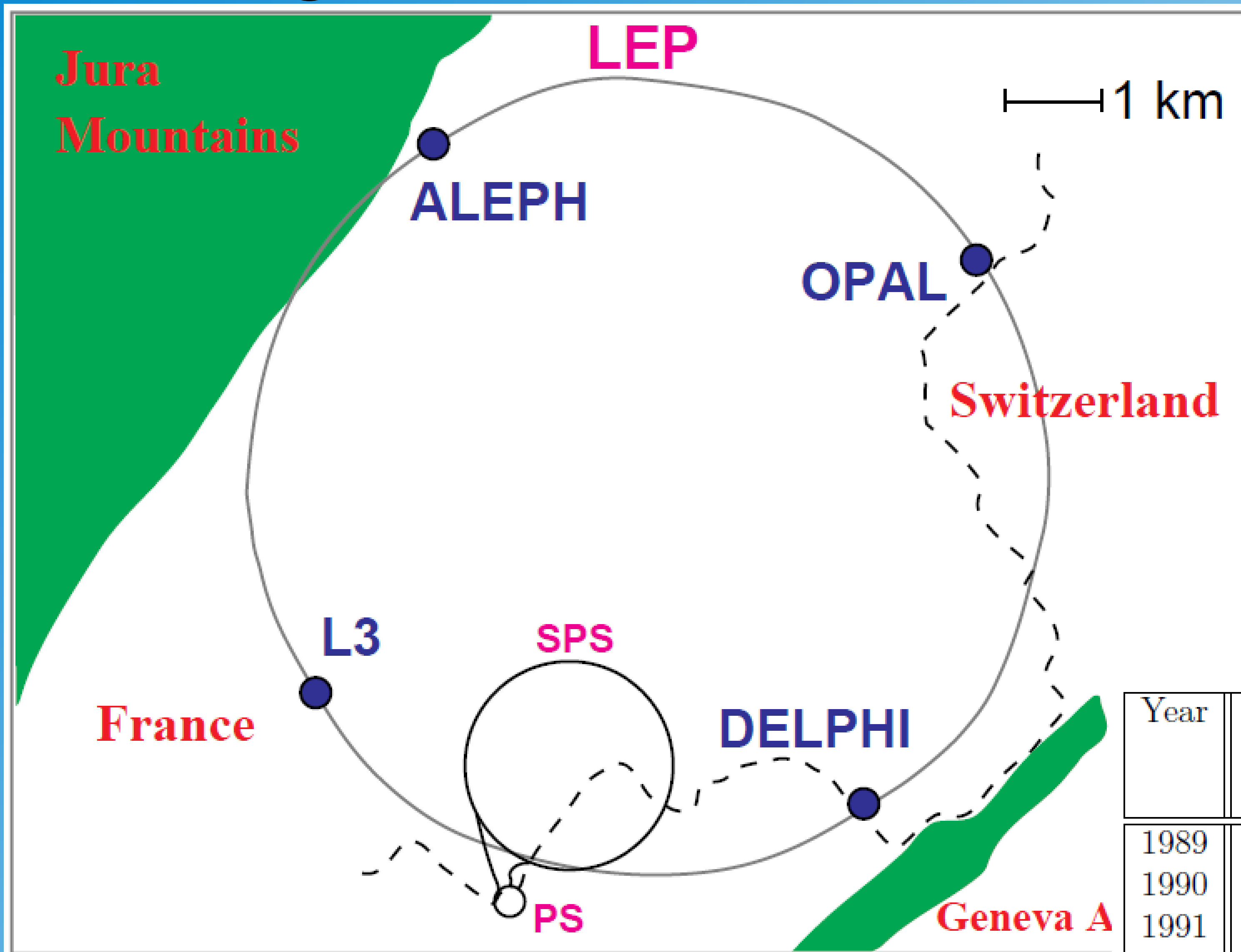
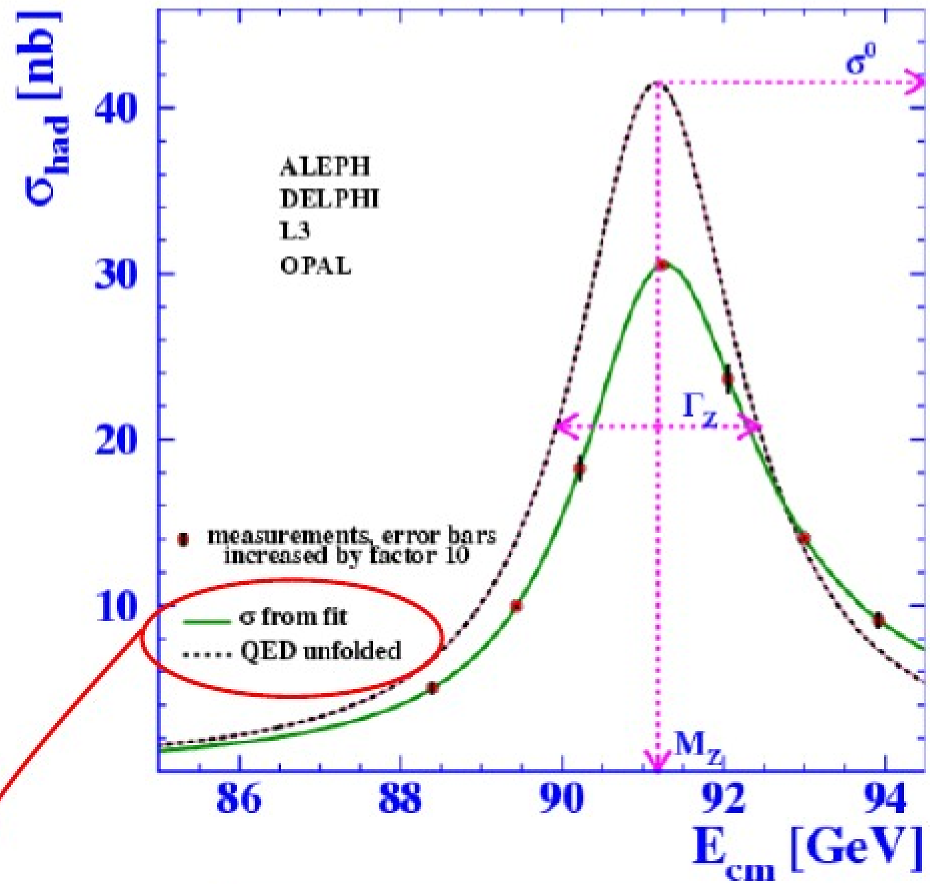
Large Electron Positron Collider



Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

Measurement of the Z-lineshape



Z Resonance curve:

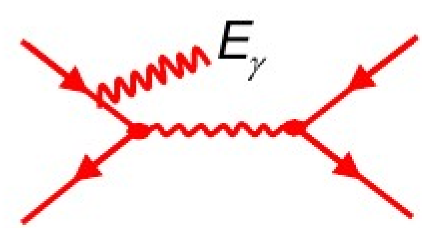
$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak: $\sigma_0 = \frac{12\pi}{M_Z^2} \frac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

- Resonance position $\rightarrow M_Z$
- Height $\rightarrow \Gamma_e \Gamma_\mu$
- Width $\rightarrow \Gamma_Z$

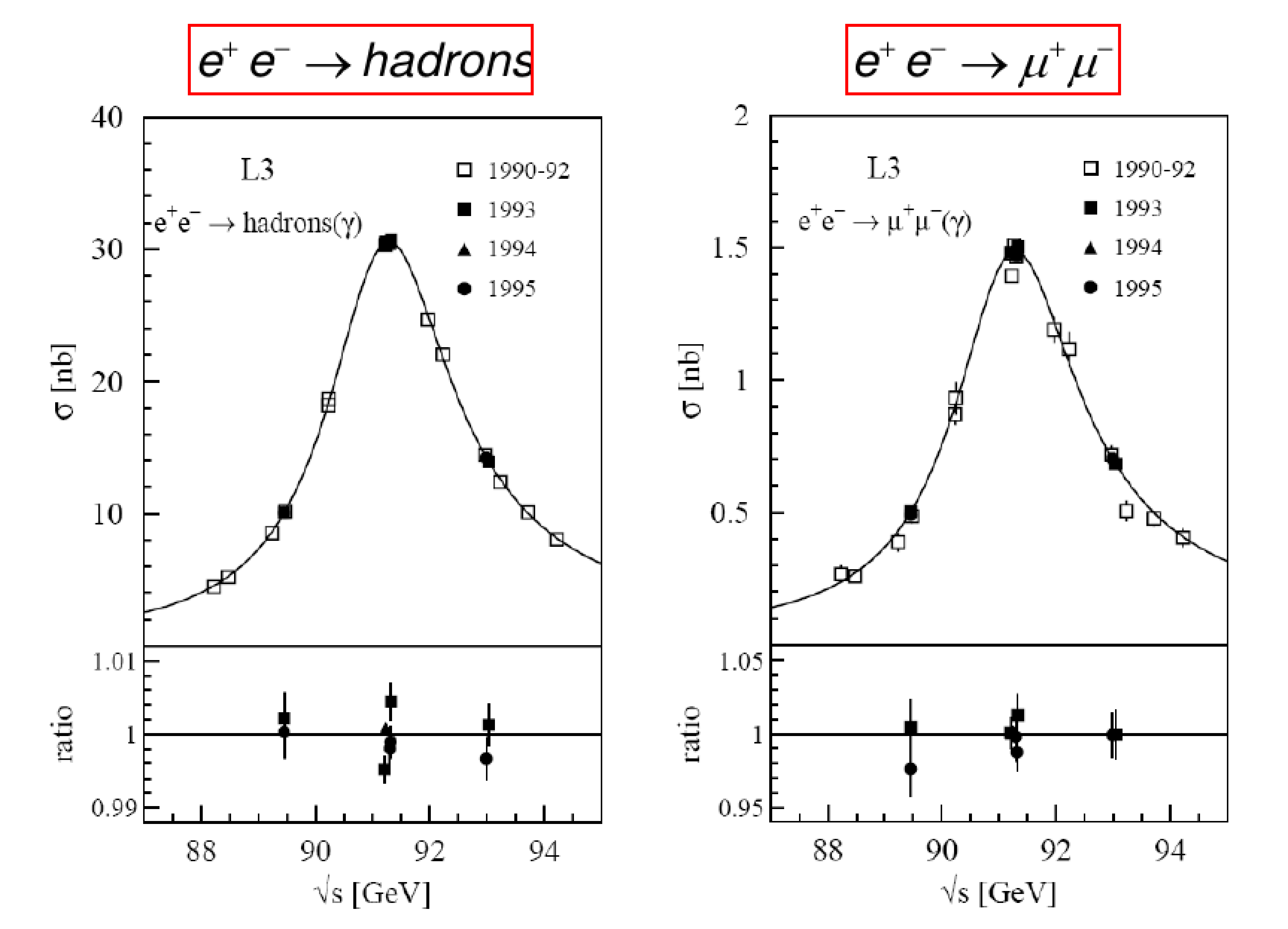
Initial state Bremsstrahlung corrections

$$\sigma_{ff(\gamma)} = \int_{4m_f^2/s}^{1} G(z) \sigma_{ff}^0(zs)\, dz \qquad z = 1 - \frac{2E_\gamma}{\sqrt{s}}$$



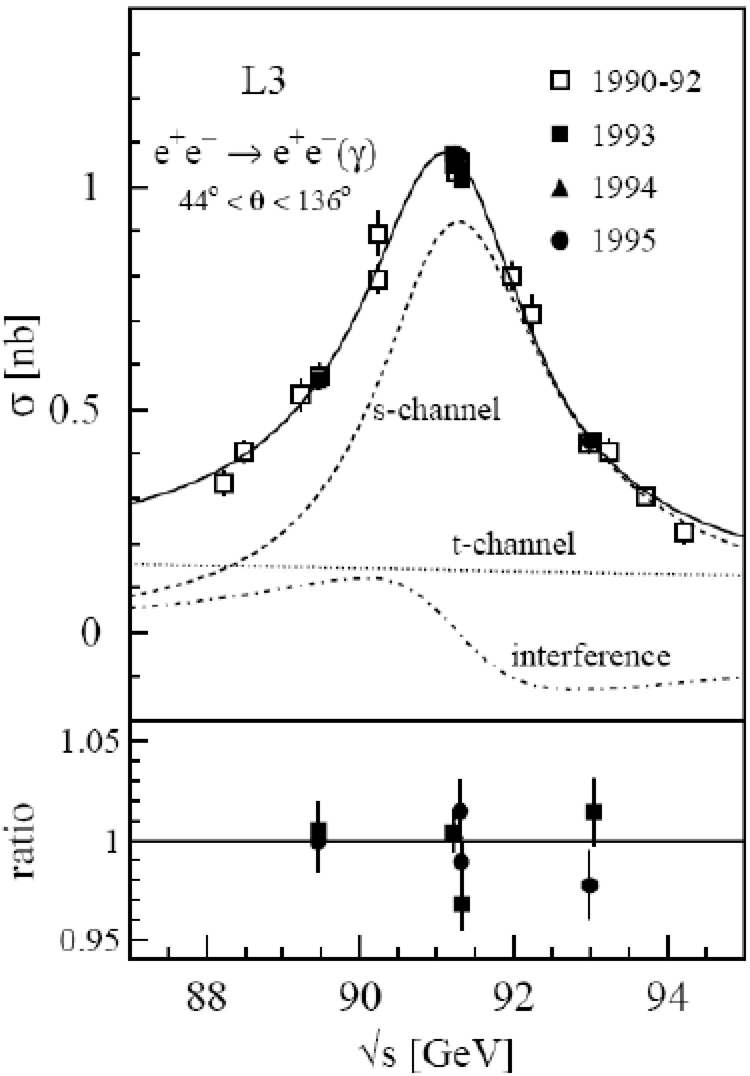
Leads to a deformation of the resonance: large (30%) effect !

Final State Comparisons

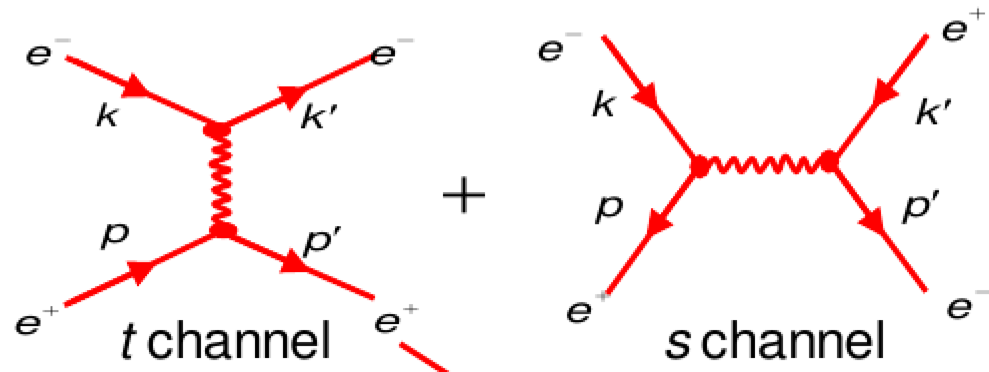


Same resonance shape!

$e^+ e^- \to e^+ e^-$

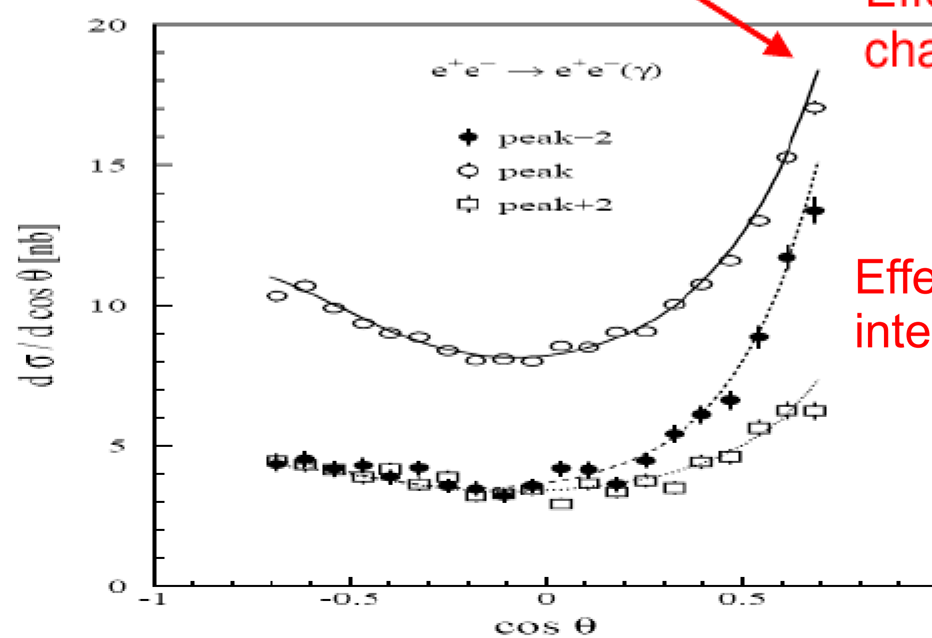


t channel contribution → forward peak



Effect of t channel

Effect of interference



s-channel contribution ~ $(\Gamma_e)^2$

Z Lineshape Parameters LEP (Average)

$M_Z = 91.1876 \pm 0.0021$ GeV ± 23 ppm (*)

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV
$\Gamma_{had} = 1.7458 \pm 0.0027$ GeV
$\Gamma_e = 0.08392 \pm 0.00012$ GeV
$\Gamma_\mu = 0.08399 \pm 0.00018$ GeV
$\Gamma_\tau = 0.08408 \pm 0.00022$ GeV

± 0.09 %

3 leptons are treated independently

test of lepton universality

$\Gamma_Z = 2.4952 \pm 0.0023$ GeV
$\Gamma_{had} = 1.7444 \pm 0.0022$ GeV
$\Gamma_e = 0.083985 \pm 0.000086$ GeV

Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
(predicted by SM: g_A and g_V are the same)

*) error of the LEP energy determination: ± 1.7 MeV (19 ppm)

http://lepewwg.web.cern.ch/   (Summer 2005)

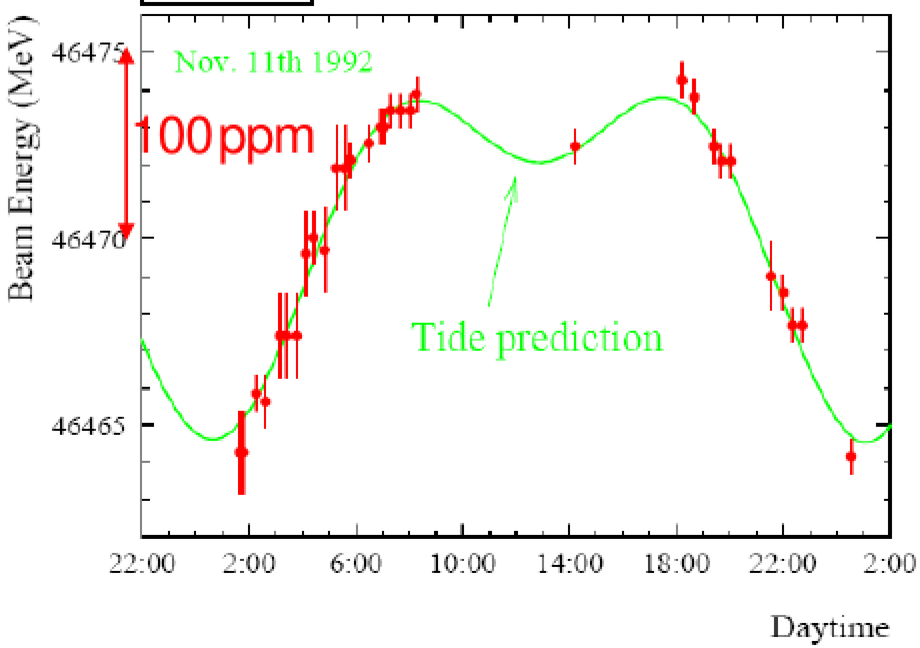
LEP Energy Calibration

Changes of the circumference of the LEP ring changes the energy of the electrons and thus the CM energy (shifts M_Z) :

- tide effects
- water level in lake Geneva

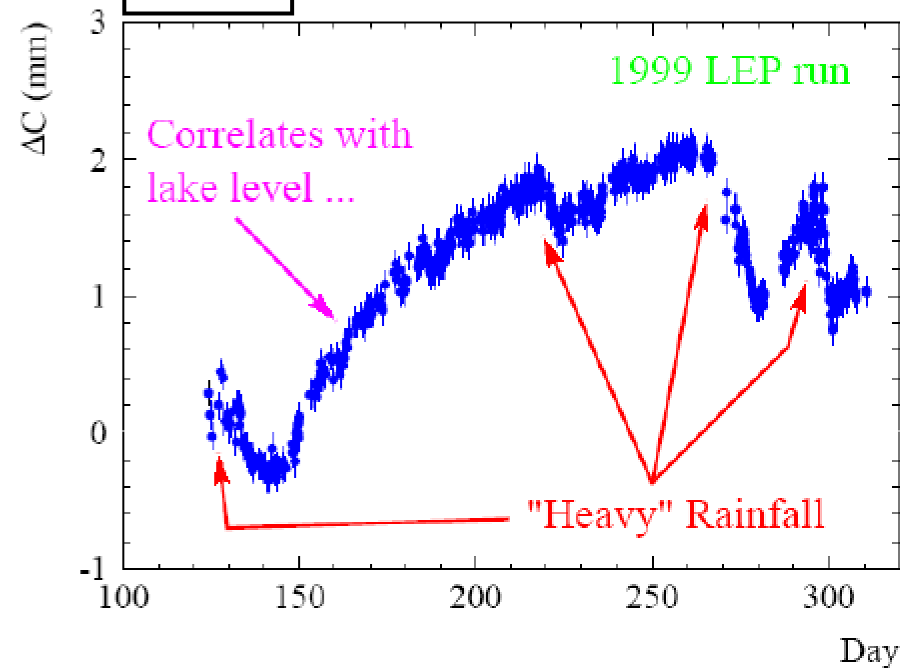
Changes of LEP circumference ΔC=1…2 mm/27km (4…8x10^{-8})

1992 Effect of moon

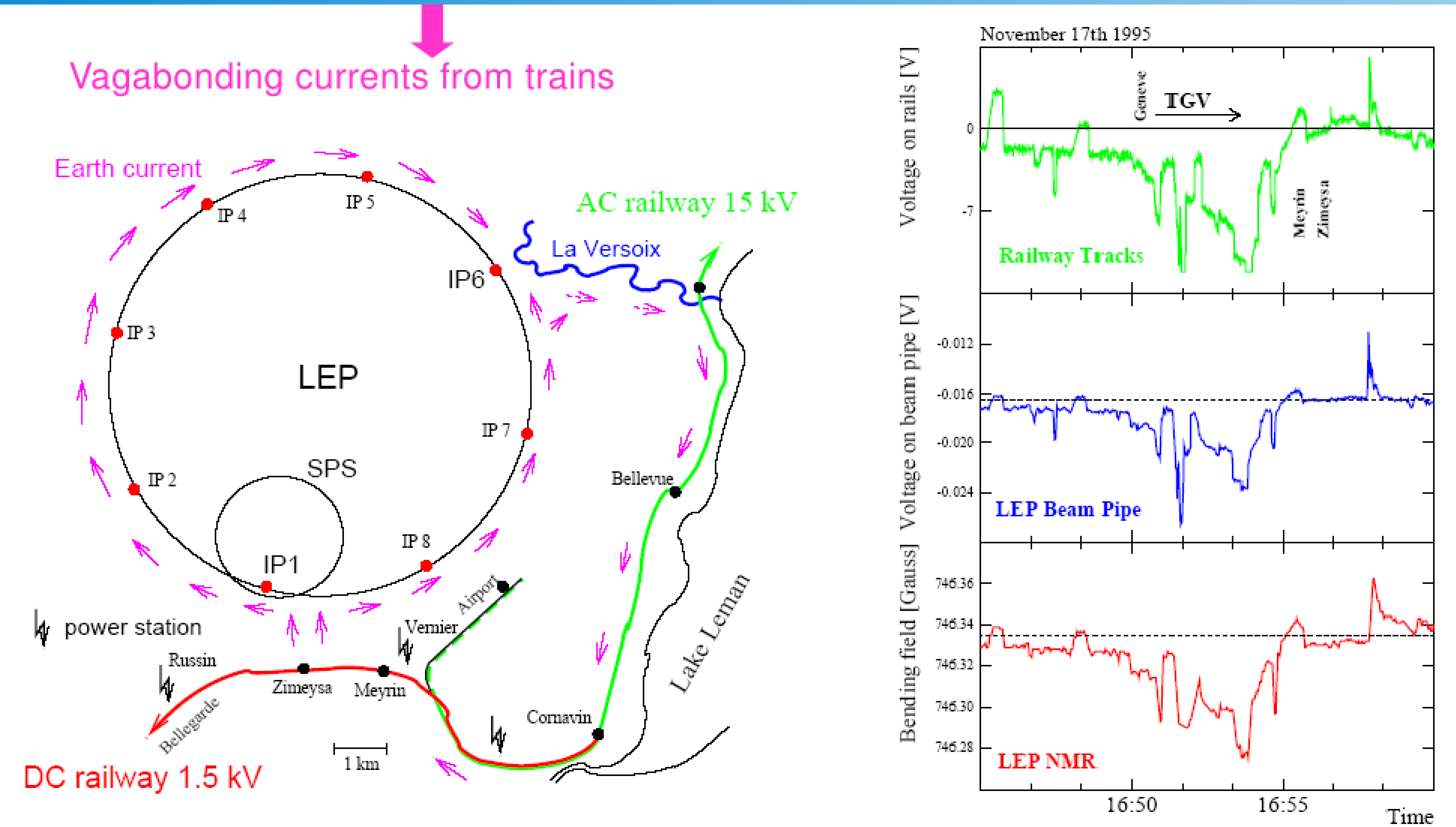


The total strain is 4 x 10^{-8} (ΔC = 1 mm)

1993 Effect of lake



TGV (Trains Grand Vitesse) Effect



In conclusion: Measurements at the ppm level are difficult to perform. Many effects must be considered!

Number Light Neutrino Generations

In the Standard Model:

$$\Gamma_Z = \Gamma_{had} + 3\cdot\Gamma_\ell + \underbrace{N_\nu \cdot \Gamma_\nu}_{\text{invisible } :\Gamma_{inv}} \rightarrow \begin{cases} e^+e^- \to Z \to \nu_e\bar{\nu}_e \\ e^+e^- \to Z \to \nu_\mu\bar{\nu}_\mu \\ e^+e^- \to Z \to \nu_\tau\bar{\nu}_\tau \end{cases}$$

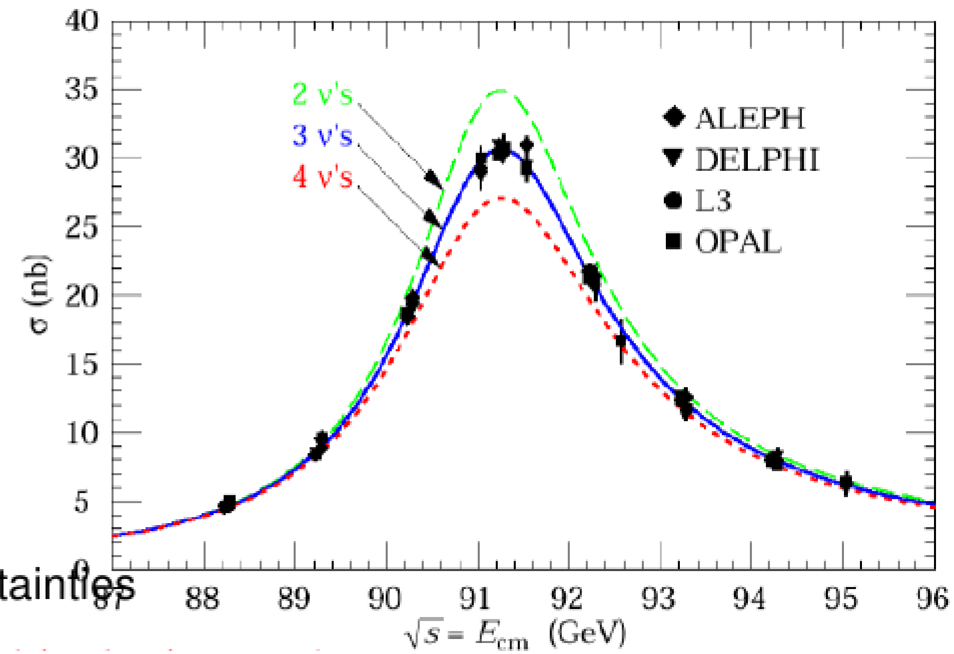
$$\Gamma_{inv} = 0.4990 \pm 0.0015 \text{ GeV}$$

To determine the number of light neutrino generations:

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\nu,SM}} = \underbrace{\left(\frac{\Gamma_{inv}}{\Gamma_\ell}\right)_{exp}}_{5.9431\pm0.0163} \cdot \underbrace{\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}}_{=1/1.991\pm0.001}$$

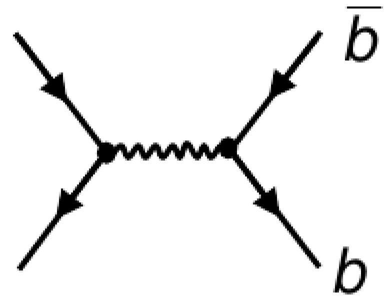
(small theo. uncertainties from m_{top} M_H)

$N_\nu = 2.9840 \pm 0.0082$



No room for new physics: Z→new

Heavy Quark production

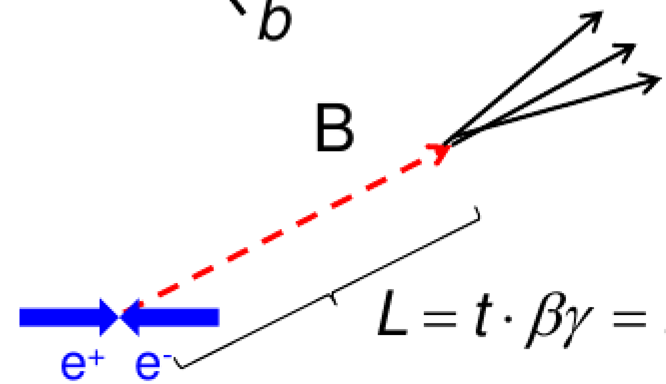


$$R_b = \frac{\Gamma_b}{\Gamma_{had}}$$

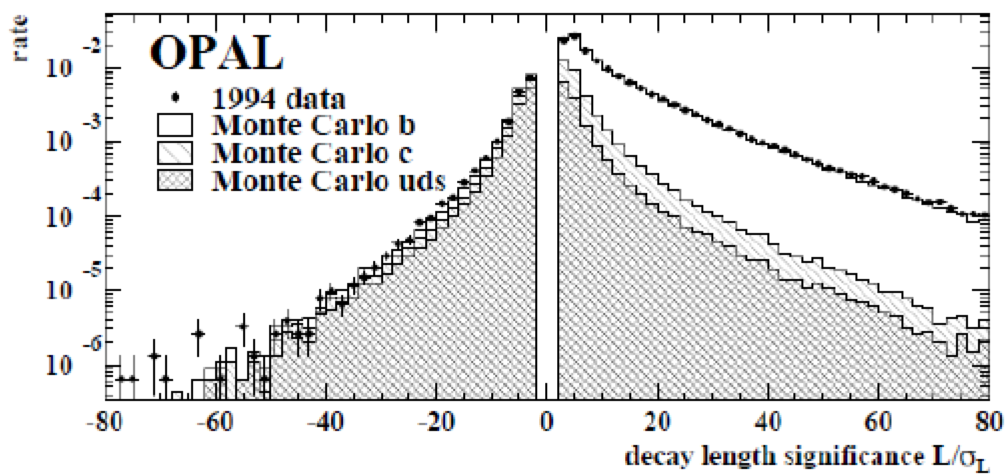
Identification of b-Quark events:

b-quarks hadronize to b-hadrons (B's, Λ_b) with typical lifetime of ~ 1 ps $\rightarrow$ decay length

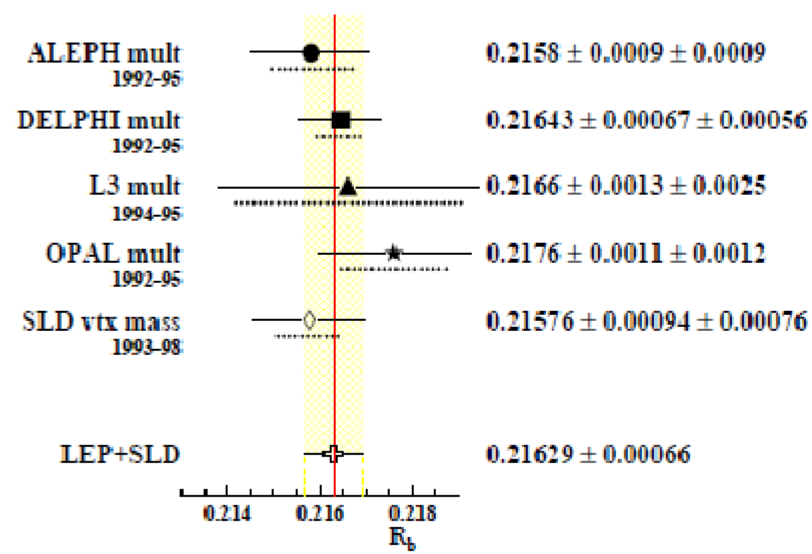
Use displaced "2nd" B decay vertex as signature.



$$L = t \cdot \beta\gamma = t \cdot \frac{p_B}{m_B}$$

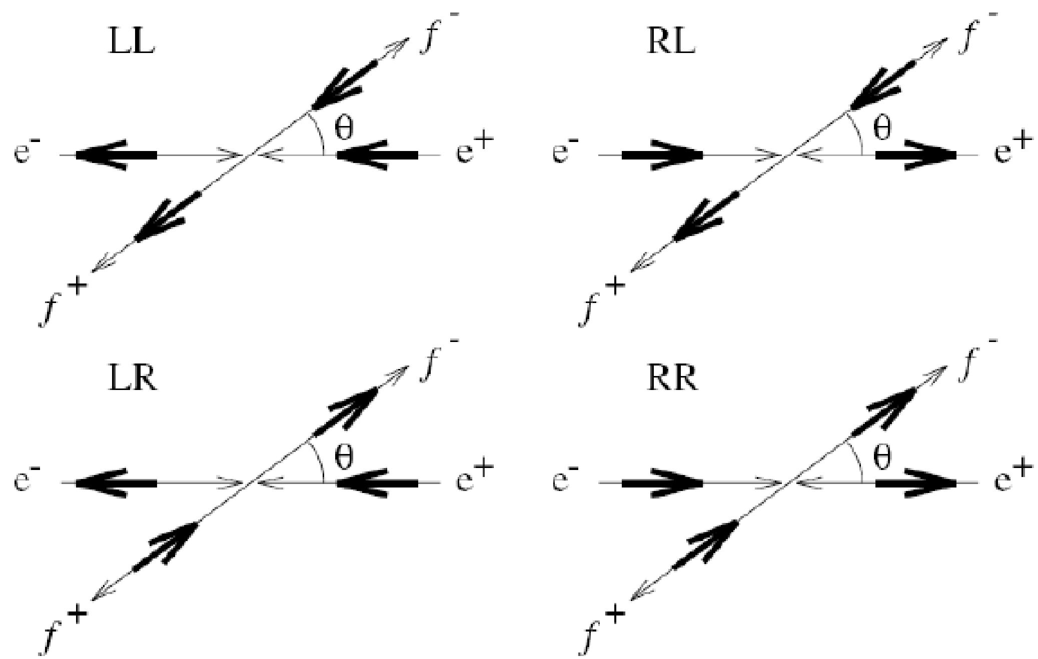


Significance = L / error



$Z \rightarrow b\bar{b}$ decay ratio

Helicity Amplitudes and Asymmetries



J=1

Observables:

$\sigma_F = \sigma_{LL} + \sigma_{RR}$ $\quad$ $\sigma_B = \sigma_{RL} + \sigma_{LR}$

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

Forward-backward asym. (final)

$\sigma_L = \sigma_{LL} + \sigma_{LR}$ $\quad$ $\sigma_R = \sigma_{RL} + \sigma_{RR}$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Left right asym. (initial)

$\sigma_- = \sigma_{LL} + \sigma_{RL}$ $\quad$ $\sigma_+ = \sigma_{RR} + \sigma_{LR}$

$$\mathcal{P}_f = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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fermion polarization (final)

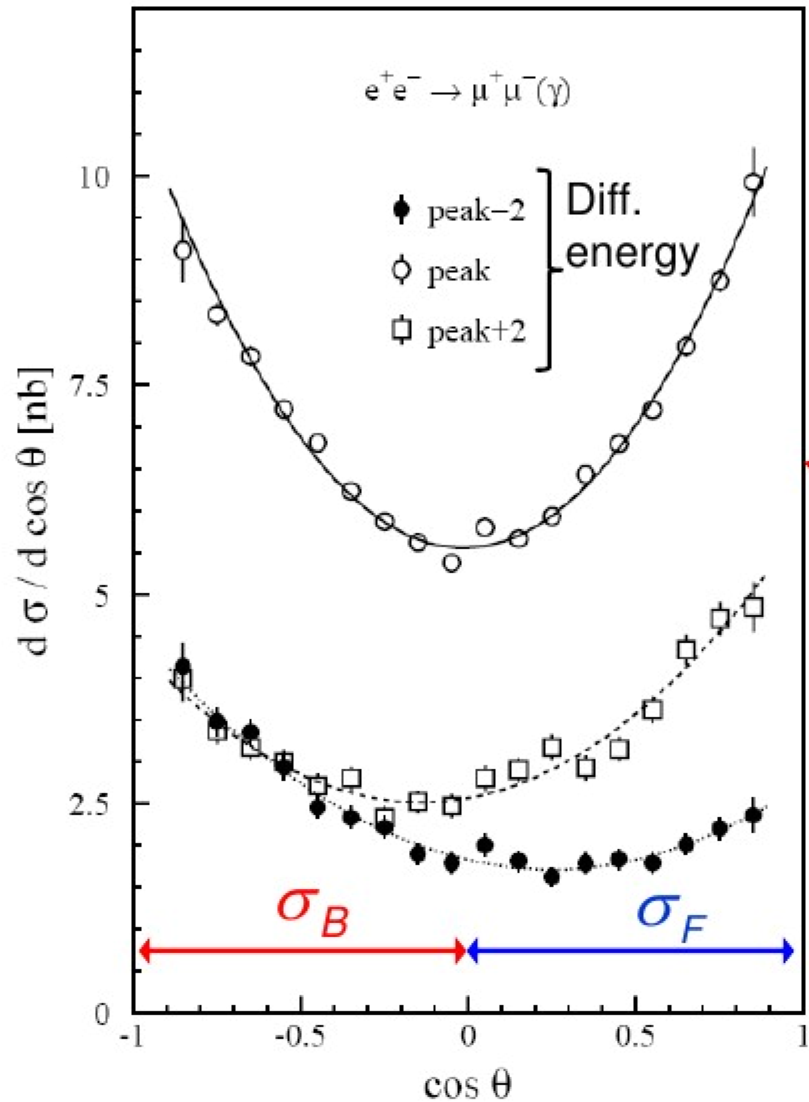
Forward-Backward Asymmetry

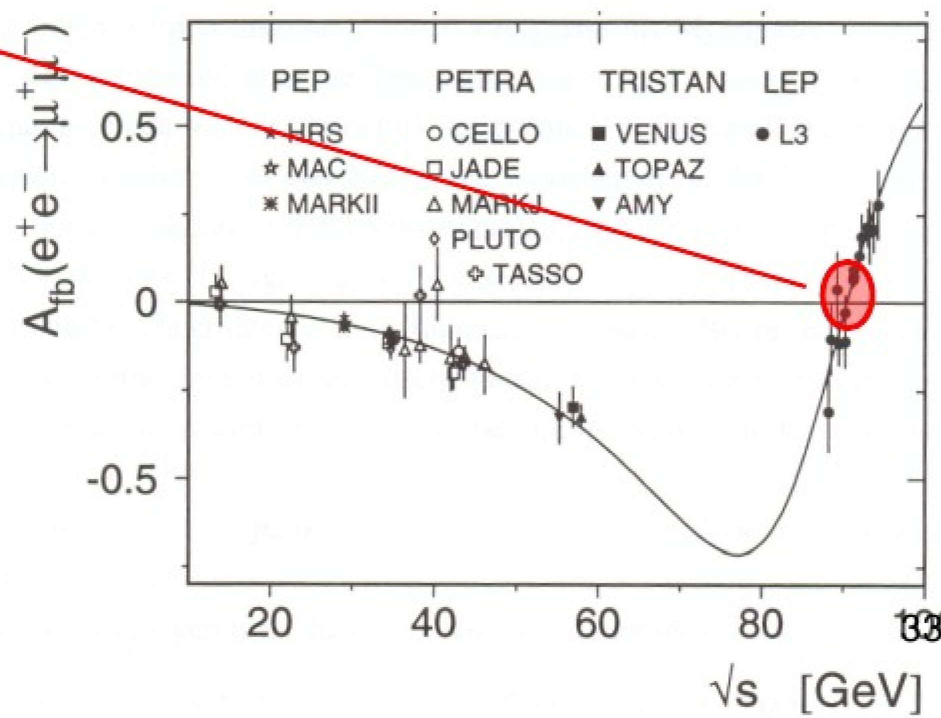
$$e^+ e^- \to Z \to \mu^+ \mu^-$$

$$\frac{d\sigma}{d\cos\theta} \sim (1+\cos^2\theta) + \frac{8}{3} A_{FB} \cos\theta$$

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

$$\sigma_{F(B)} = \int_{0\,(-1)}^{1\,(0)} \frac{d\sigma}{d\cos\theta} d\cos\theta$$





Forward-Backward Asymmetry

Angular distribution: (see above)

$$F_{\gamma Z}(\cos\theta) = \frac{Q_e Q_\mu}{4\sin^2\theta_W \cos^2\theta_W}\left[2 g_V^e g_V^\mu (1+\cos^2\theta) + 4 g_A^e g_A^\mu \cos\theta\right]$$

$$F_Z(\cos\theta) = \frac{1}{16\sin^4\theta_W \cos^4\theta_W}\left[({g_V^e}^2 + {g_A^e}^2)({g_V^\mu}^2 + {g_A^\mu}^2)(1+\cos^2\theta) + 8 g_V^e g_A^e g_V^\mu g_A^\mu \cos\theta\right]$$

Forward-backward asymmetry A_{FB}

- Away from the resonance large → interference term dominates

$$A_{FB} \sim g_A^e g_A^f \cdot \frac{s(s-M_Z^2)}{(s-M_Z^2)^2 + M_Z^2\Gamma_Z^2} \qquad \rightarrow \text{large}$$

- At the Z pole: Interference = 0 (see energy dependence of interference term)

$$A_{FB} = 3 \cdot \frac{g_V^e g_A^e}{(g_V^e)^2 + (g_A^e)^2} \cdot \frac{g_V^\mu g_A^\mu}{(g_V^\mu)^2 + (g_A^\mu)^2} \qquad = \tfrac{3}{4} A_e A_\mu$$

→ very small because g_V^l small in SM

Forward-Backward Asymmetry

Asymmetrie at the Z pole

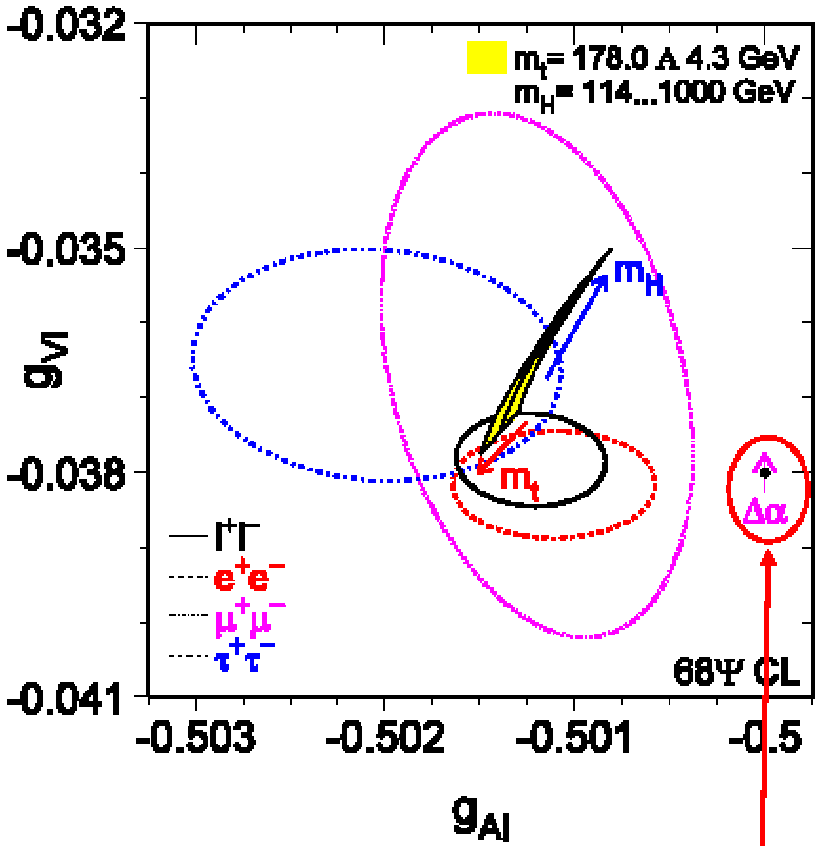
$$A_{FB} \sim g_A^e g_V^e g_A^f g_V^f$$

Cross section at the Z pole

$$\sigma_Z \sim \left[(g_V^e)^2 + (g_A^e)^2\right]\left[(g_V^\mu)^2 + (g_A^\mu)^2\right]$$

Lepton asymmetries together with lepton pair cross sections allow the determination of the lepton couplings g_A and g_V.

Good agreement between the 3 lepton species confirms “lepton universality”

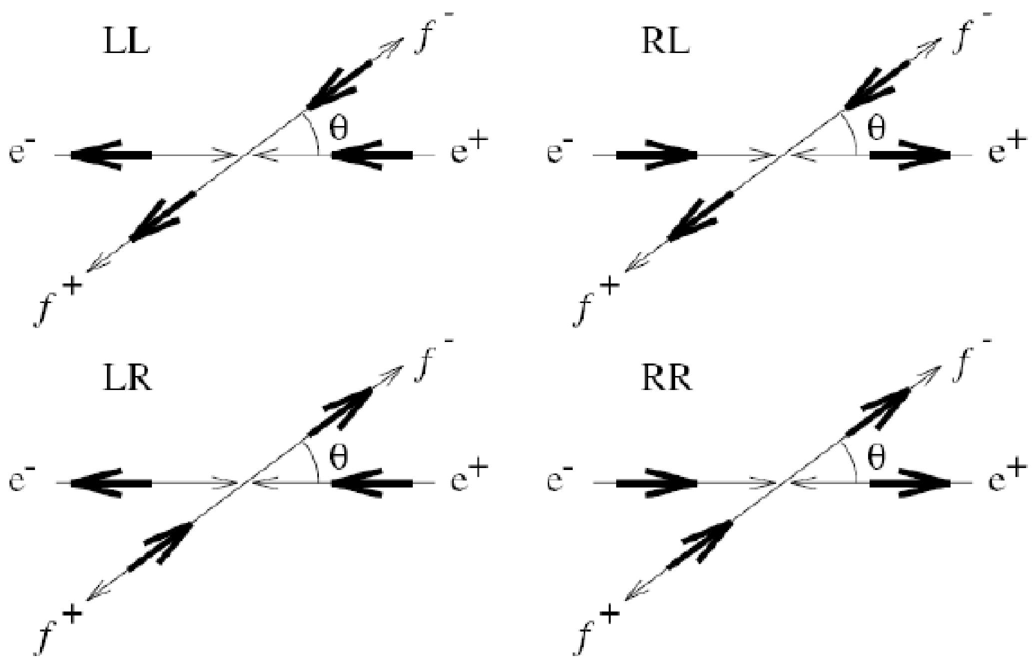


Lowest order SM prediction:

$$g_V = T_3 - 2q\sin^2\theta_W \quad g_A = T_3$$

Deviation from lowest order SM prediction is an effect of higher-order electroweak corrections. 35

Helicity Amplitudes and Asymmetries



J=1

Observables:

$\sigma_F = \sigma_{LL} + \sigma_{RR}$ $\quad$ $\sigma_B = \sigma_{RL} + \sigma_{LR}$

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

Forward-backward asym. (final)

$\sigma_L = \sigma_{LL} + \sigma_{LR}$ $\quad$ $\sigma_R = \sigma_{RL} + \sigma_{RR}$

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Left right asym. (initial)

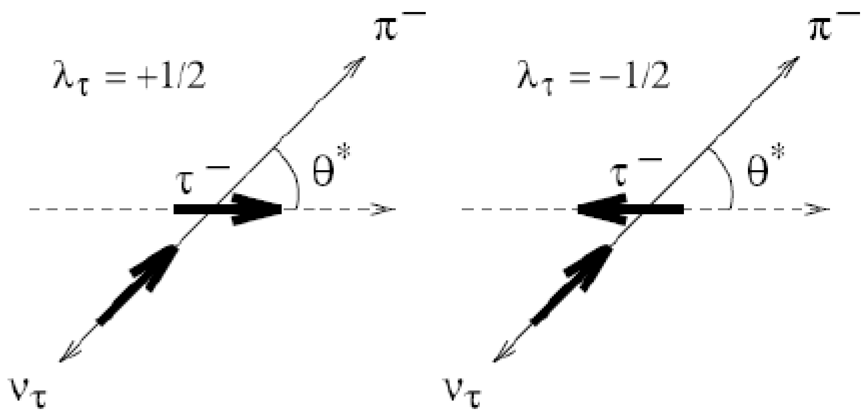
$\sigma_- = \sigma_{LL} + \sigma_{RL}$ $\quad$ $\sigma_+ = \sigma_{RR} + \sigma_{LR}$

$$\mathcal{P}_f = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

fermion polarization (final)

Experimental Method to measure tau polarization:

$\tau^- \rightarrow \pi^- \nu_\tau$ Spin ½ → Spin 0 + Spin ½

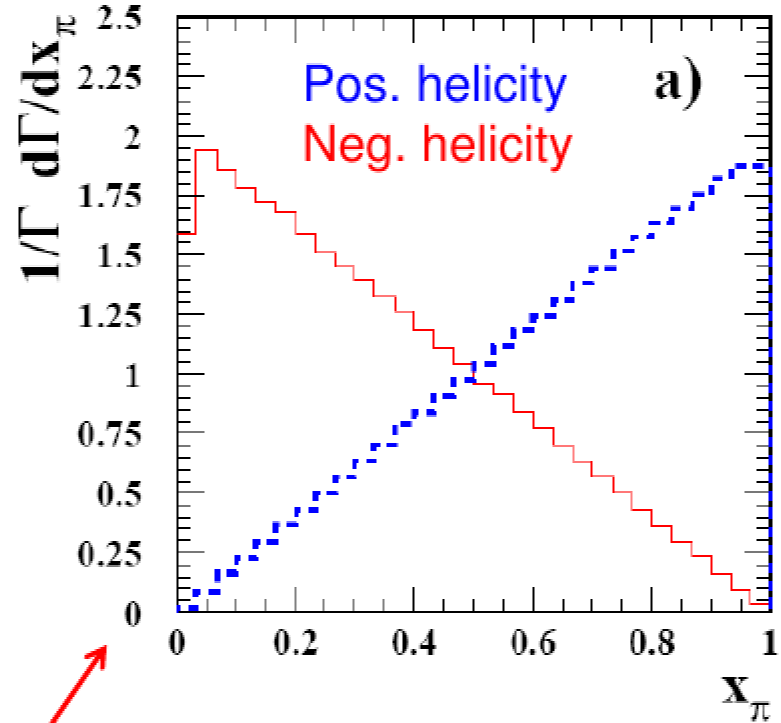


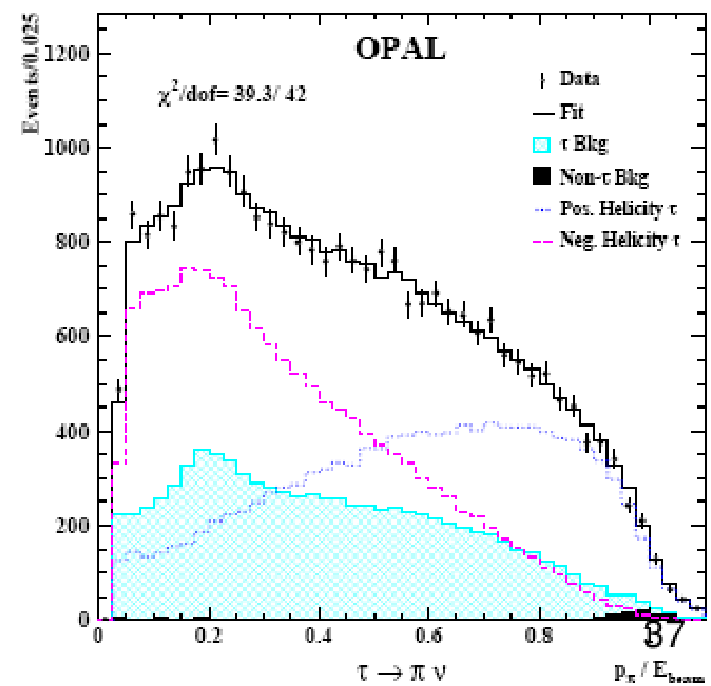
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{1}{2}(1+\mathcal{P}_\tau\cos\theta^*)$$

Boost into lab frame

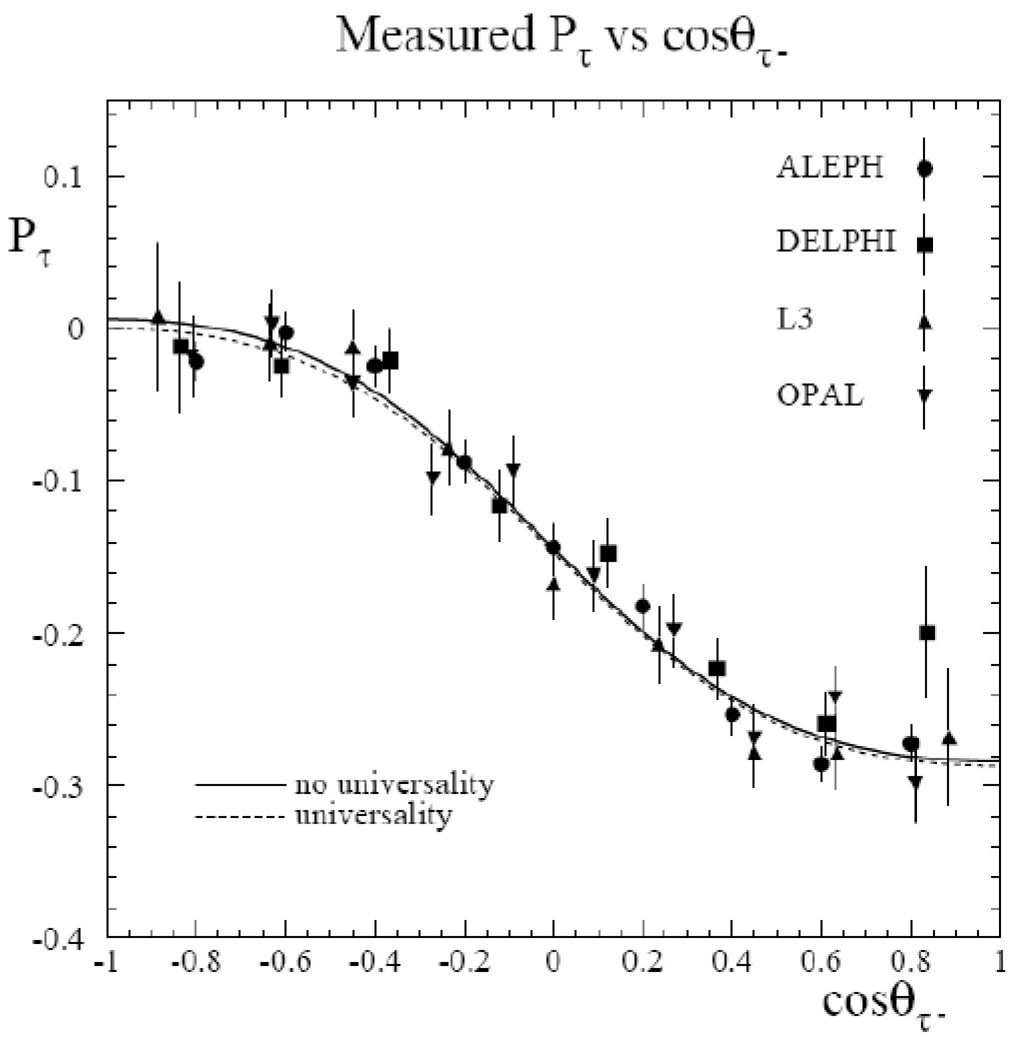
$$\frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1+\mathcal{P}_\tau(2x_\pi-1) \qquad x_\pi = E_\pi/E_\tau$$

Fit of the two theoretical distribution to data yields the polarization: ~ 0.15





Result Tau Polarisation



$$\mathcal{P}_f(\cos\theta) = -\frac{\mathcal{A}_f(1+\cos^2\theta)+2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta)+2\mathcal{A}_f\mathcal{A}_e\cos\theta}$$

$$\mathcal{A}_\tau = 0.1439 \pm 0.0043$$

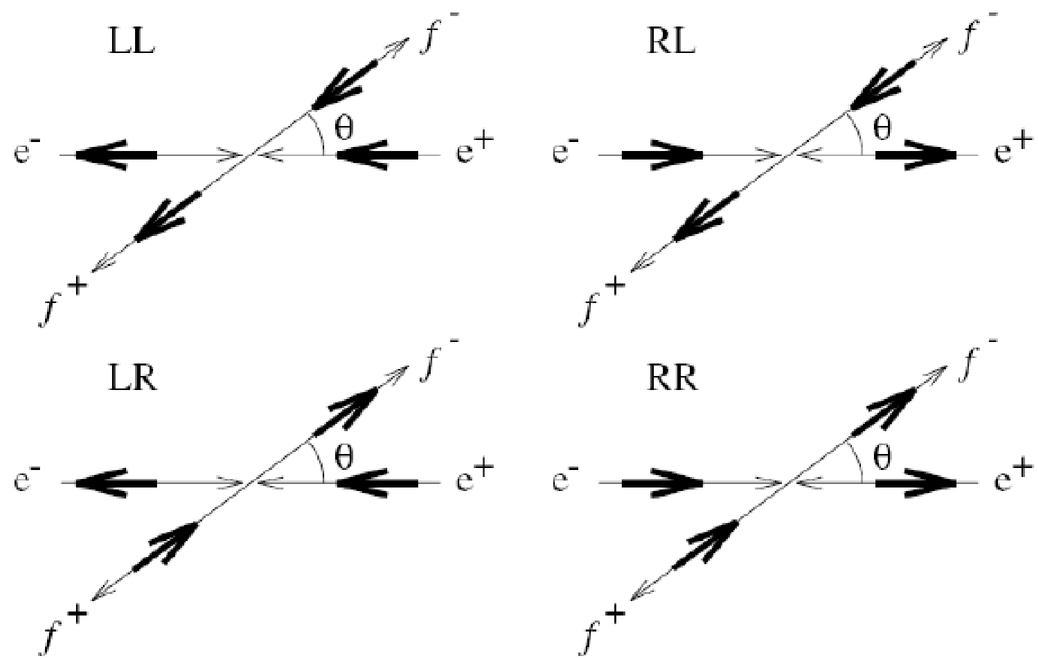
$$\mathcal{A}_e = 0.1498 \pm 0.0049$$

$$\mathcal{A}_\ell = 0.1465 \pm 0.0033$$

$$\sin^2\theta_w^{eff} = 0.23159 \pm 0.00041$$

hep-ex/0509008

Helicity Amplitudes and Asymmetries



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Forward-backward asym. (final)

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$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Left right asym. (initial)

$\sigma_- = \sigma_{LL} + \sigma_{RL}$ $\quad$ $\sigma_+ = \sigma_{RR} + \sigma_{LR}$

$$\mathcal{P}_f = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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fermion polarization (final)

Left Right Asymmetry at SLD

Measure cross section σ_L (σ_R) for LH (RH) initial state electrons:

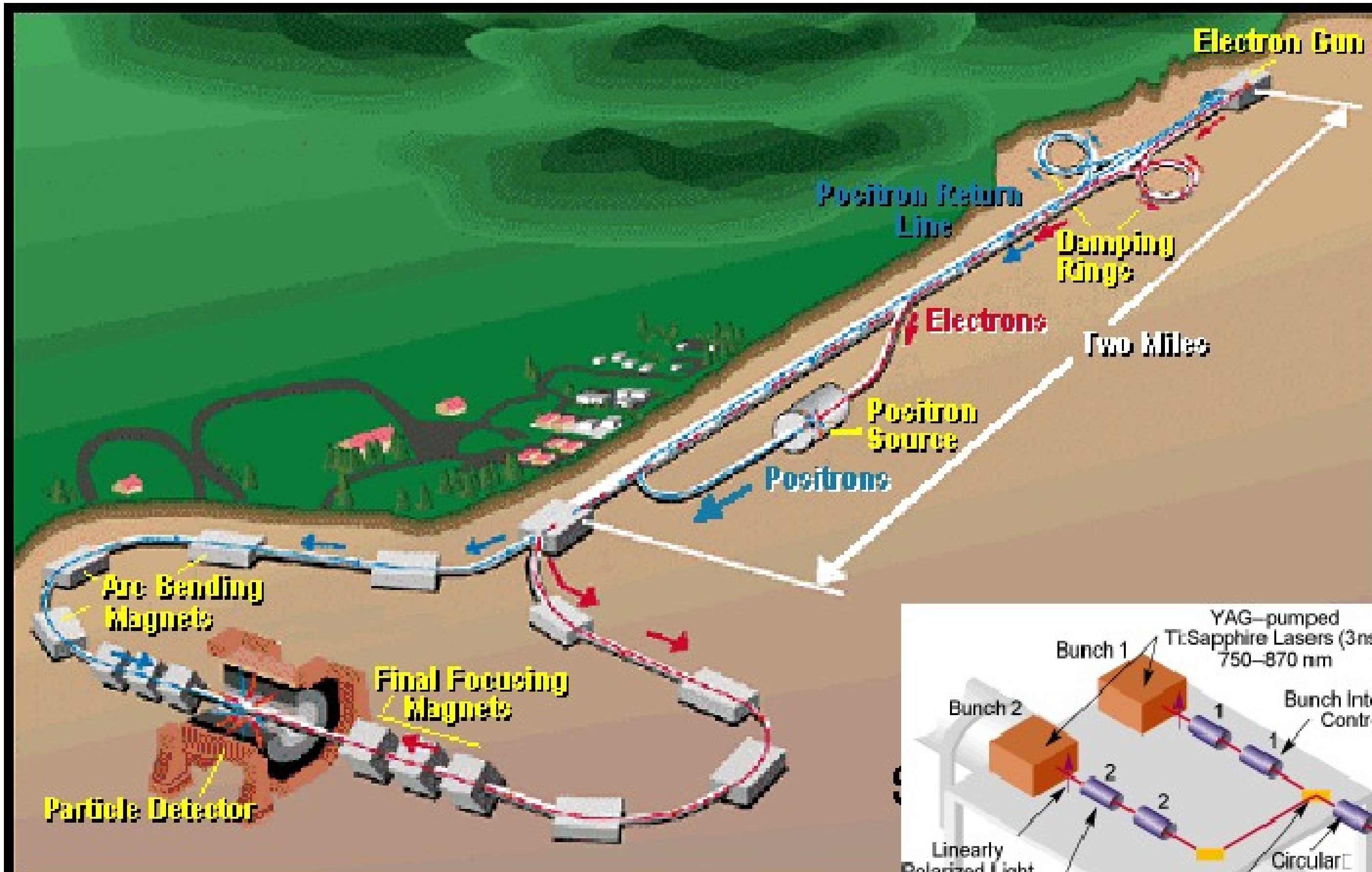
Polarization of electron beam: P~70 – 80%

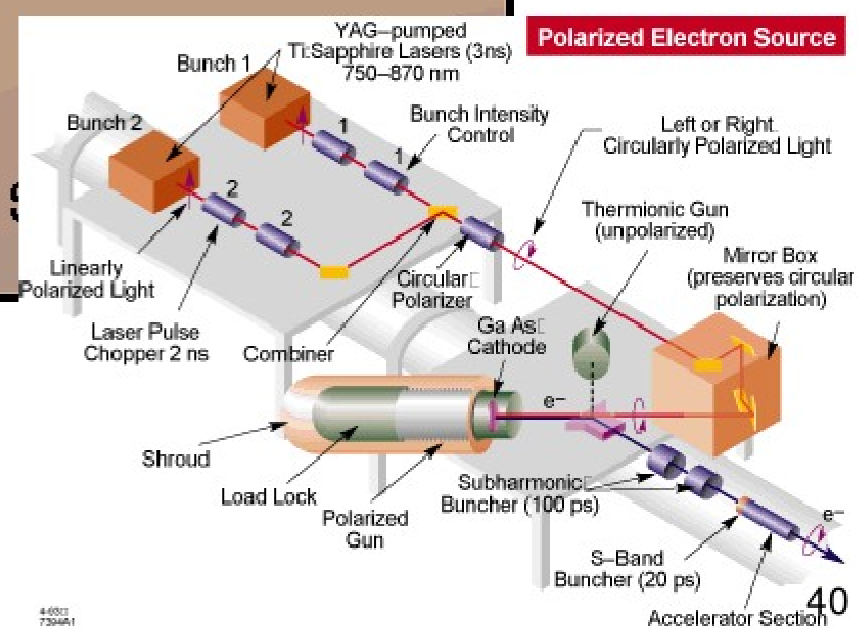
$$A_{LR} = \frac{1}{\mathcal{P}_e} \frac{\sigma_L^f - \sigma_R^f}{\sigma_L^f + \sigma_R^f}$$

$$A_{LR} = \frac{2 g_V^e g_A^e}{\left(g_V^e\right)^2 + \left(g_A^e\right)^2} = \frac{2(1-4\sin^2\theta_w)}{1+(1-4\sin^2\theta_w)^2} = A_e$$

Powerful determination of $\sin^2\theta_w$.
Requires longitudinal polarization of colliding beams

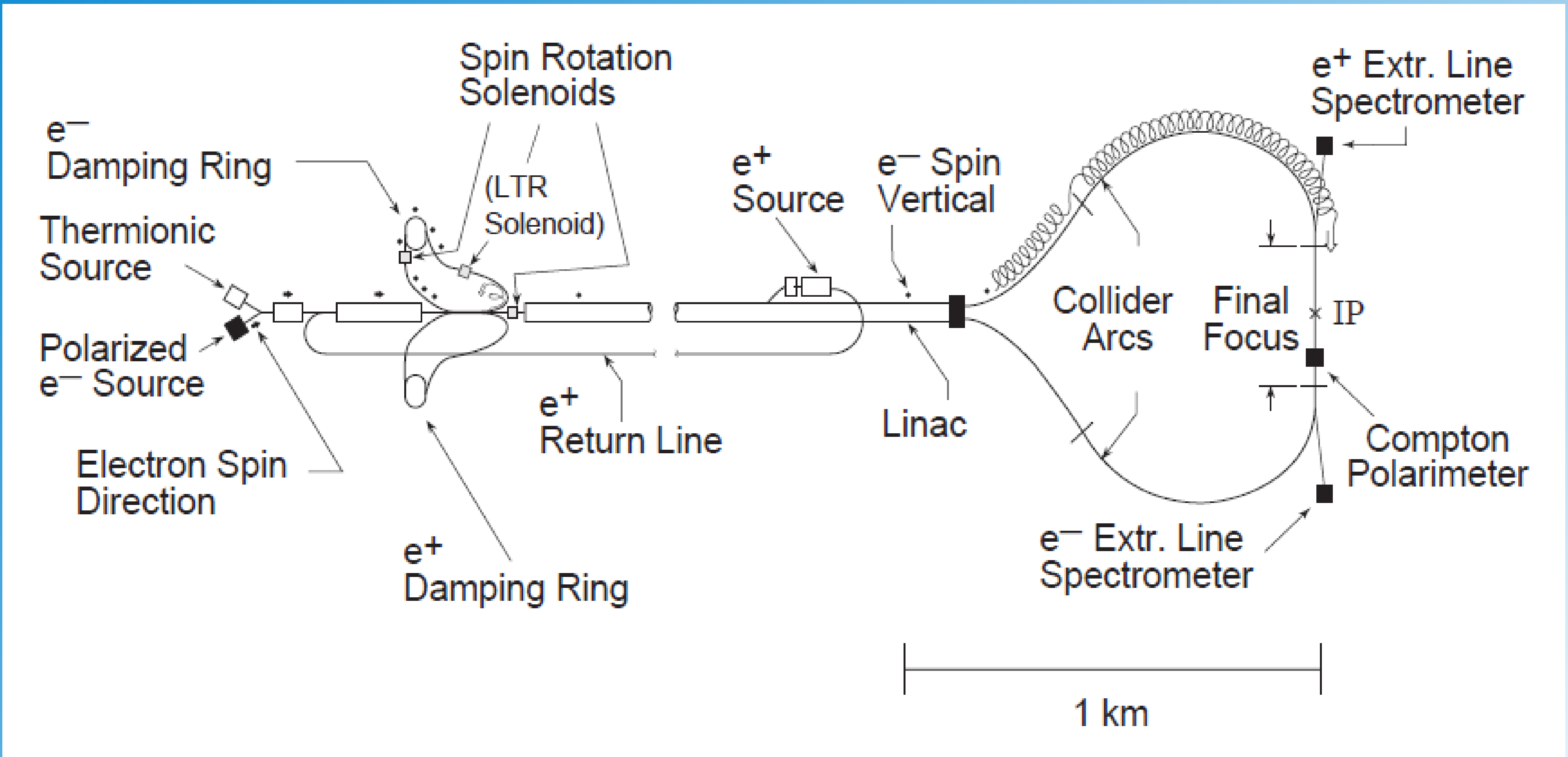
SLAC Linear Accelerator





Typical beam polarization of 70%.

SLAC Linear Accelerator



Compton Polarimeter

$e^- \gamma \rightarrow e^- \gamma$

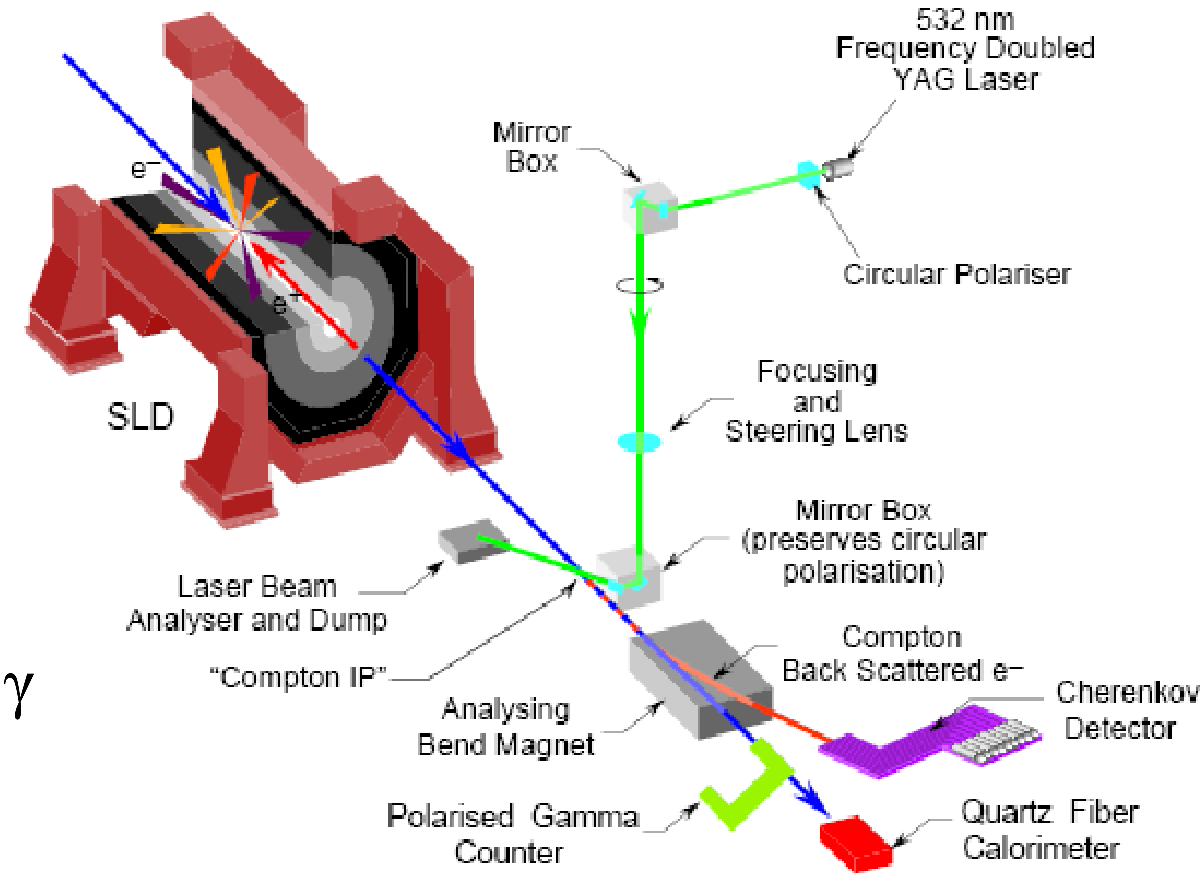
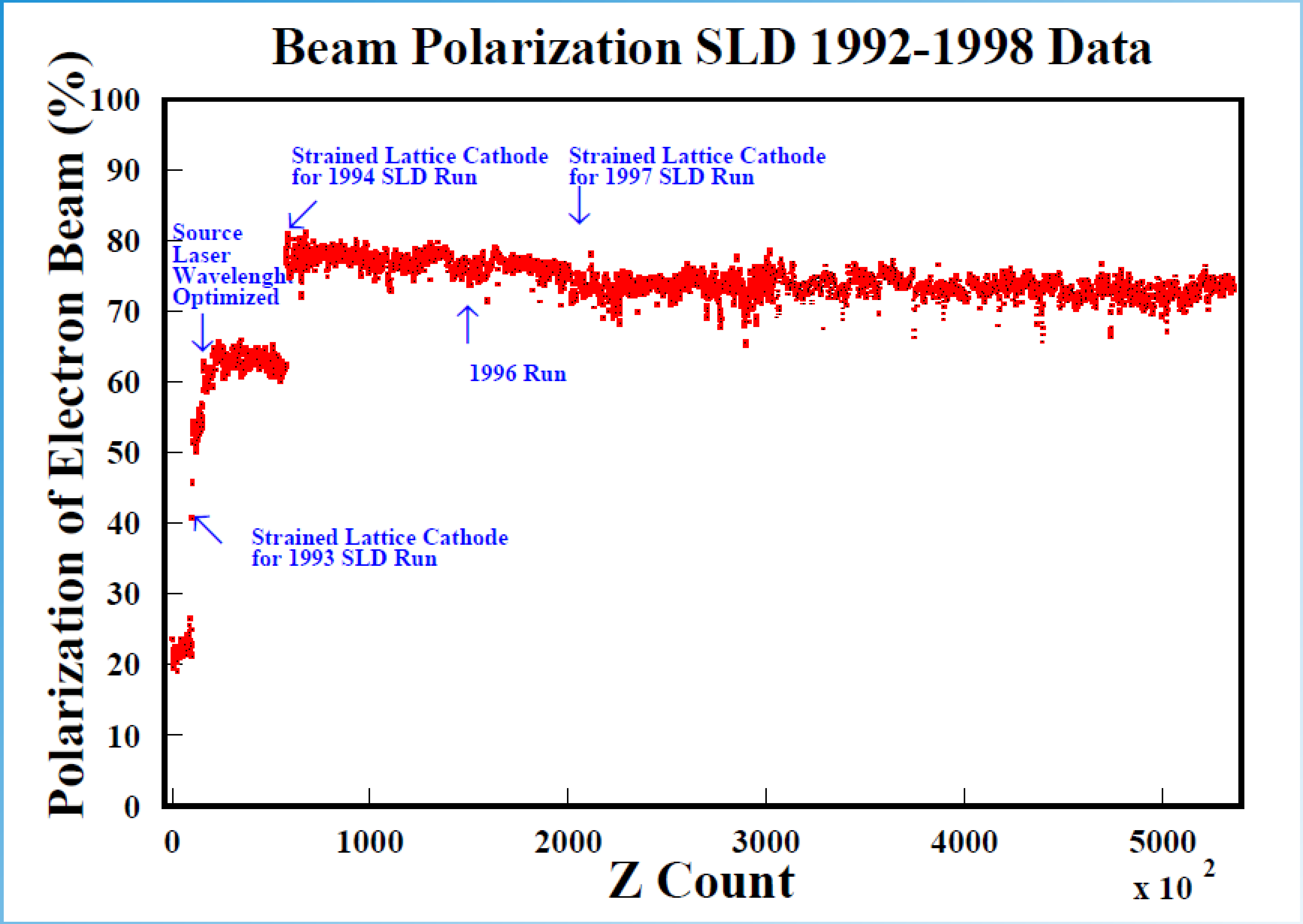
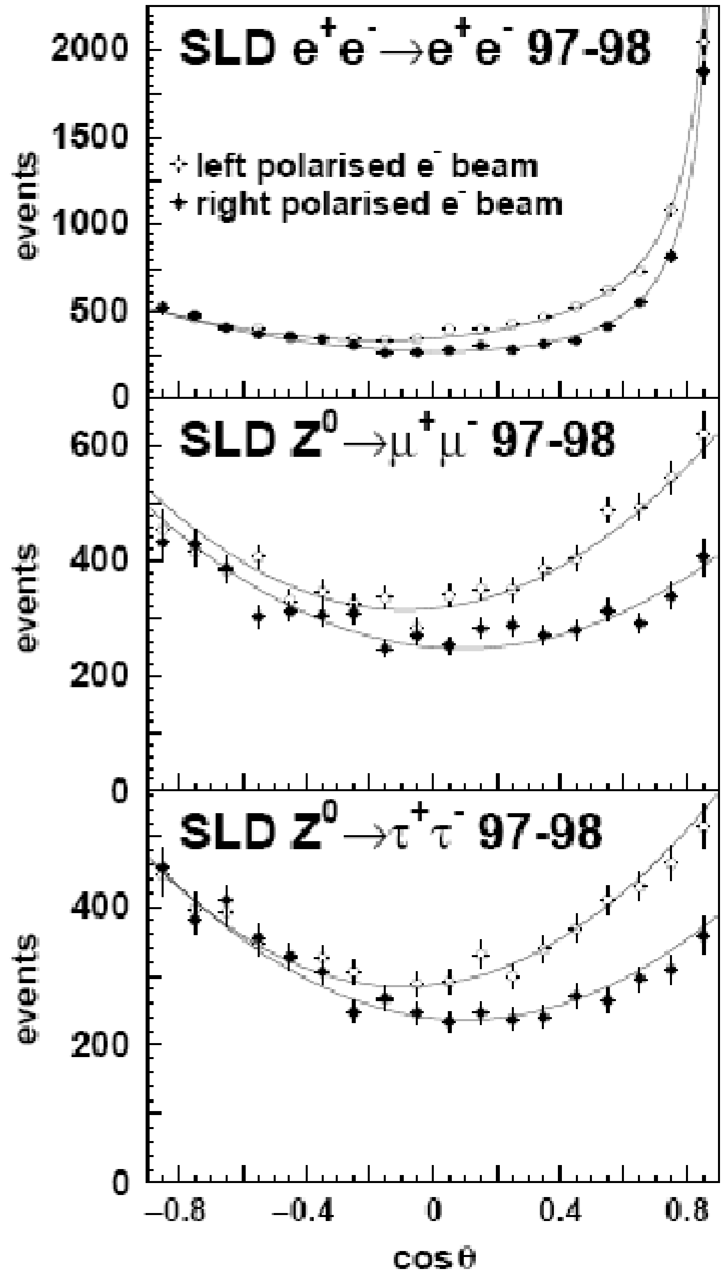


Figure 3.1: A conceptual diagram of the SLD Compton Polarimeter. The laser beam, consisting of 532 nm wavelength 8 ns pulses produced at 17 Hz and a peak power of typically 25 MW, were circularly polarised and transported into collision with the electron beam at a crossing angle of 10 mrad approximately 30 meters from the IP. Following the laser/electron-beam collision, the electrons and Compton-scattered photons, which are strongly boosted along the electron beam direction, continue downstream until analysing bend magnets deflect the Compton-scattered electrons into a transversely-segmented Cherenkov detector. The photons continue undeflected and are detected by a gamma counter (PGC) and a calorimeter (QFC) which are used to cross-check the polarimeter calibration.

SLAC Electron Polarisation



Results Polarisation Asymmetry



Leptonic Final States

SLD

Asymmetry clearly seen for LH and RH cross section.

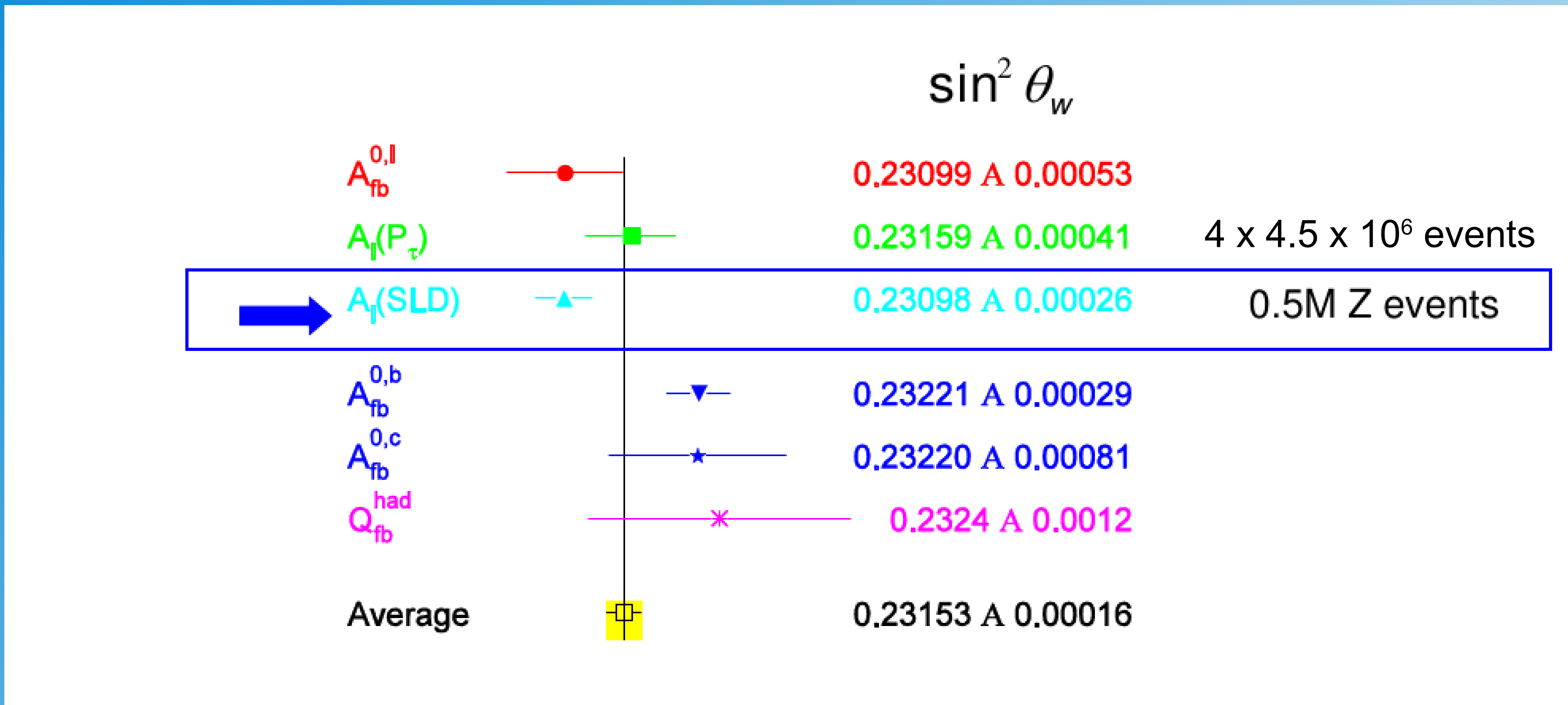
SLD All data:

$$A_{LR} = 0.1513 \pm 0.0021$$

$$\sin^2 \theta_w = 0.23098 \pm 0.00026$$

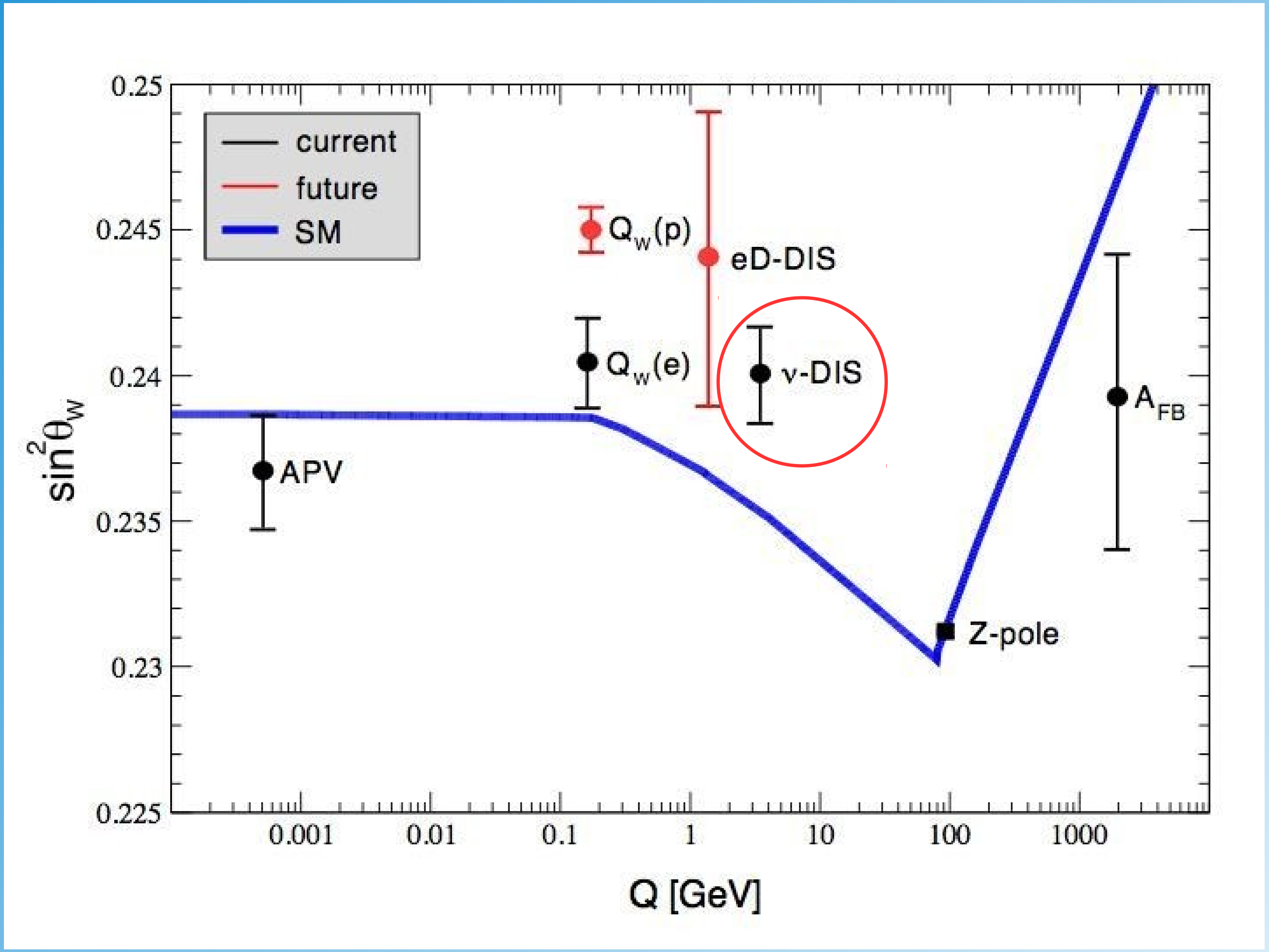
With 0.5×10^6 Z-decays

Results Weinberg Angle



Despite the smaller statistics – SLD beats LEP in precision!

“Running” of Weinberg Angle



→ note: here $\sin^2 \Theta_W$ defined in the $\overline{\text{MS}}$ scheme

Discrepancies in the SM

A Precise Determination of Electroweak Parameters in Neutrino-Nucleon Scattering

G. P. Zeller[5], K. S. McFarland[8,3], T. Adams[4], A. Alton[4], S. Avvakumov[8], L. de Barbaro[5], P. de Barbaro[8], R. H. Bernstein[3], A. Bodek[8], T. Bolton[4], J. Brau[6], D. Buchholz[5], H. Budd[8], L. Bugel[3], J. Conrad[2], R. B. Drucker[6], B. T. Fleming[2], R. Frey[6], J.A. Formaggio[2], J. Goldman[4], M. Goncharov[4], D. A. Harris[8], R. A. Johnson[1], J. H. Kim[2], S. Koutsoliotas[2], M. J. Lamm[3], W. Marsh[3], D. Mason[6], J. McDonald[7], C. McNulty[2], D. Naples[7], P. Nienaber[3], A. Romosan[2], W. K. Sakumoto[8], H. Schellman[5], M. H. Shaevitz[2], P. Spentzouris[2], E. G. Stern[2], N. Suwonjandee[1], M. Tzanov[7], M. Vakili[1], A. Vaitaitis[2], U. K. Yang[8], J. Yu[3], and E. D. Zimmerman[2]

[1] *University of Cincinnati, Cincinnati, OH 45221*
[2] *Columbia University, New York, NY 10027*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[4] *Kansas State University, Manhattan, KS 66506*
[5] *Northwestern University, Evanston, IL 60208*
[6] *University of Oregon, Eugene, OR 97403*
[7] *University of Pittsburgh, Pittsburgh, PA 15260*
[8] *University of Rochester, Rochester, NY 14627*

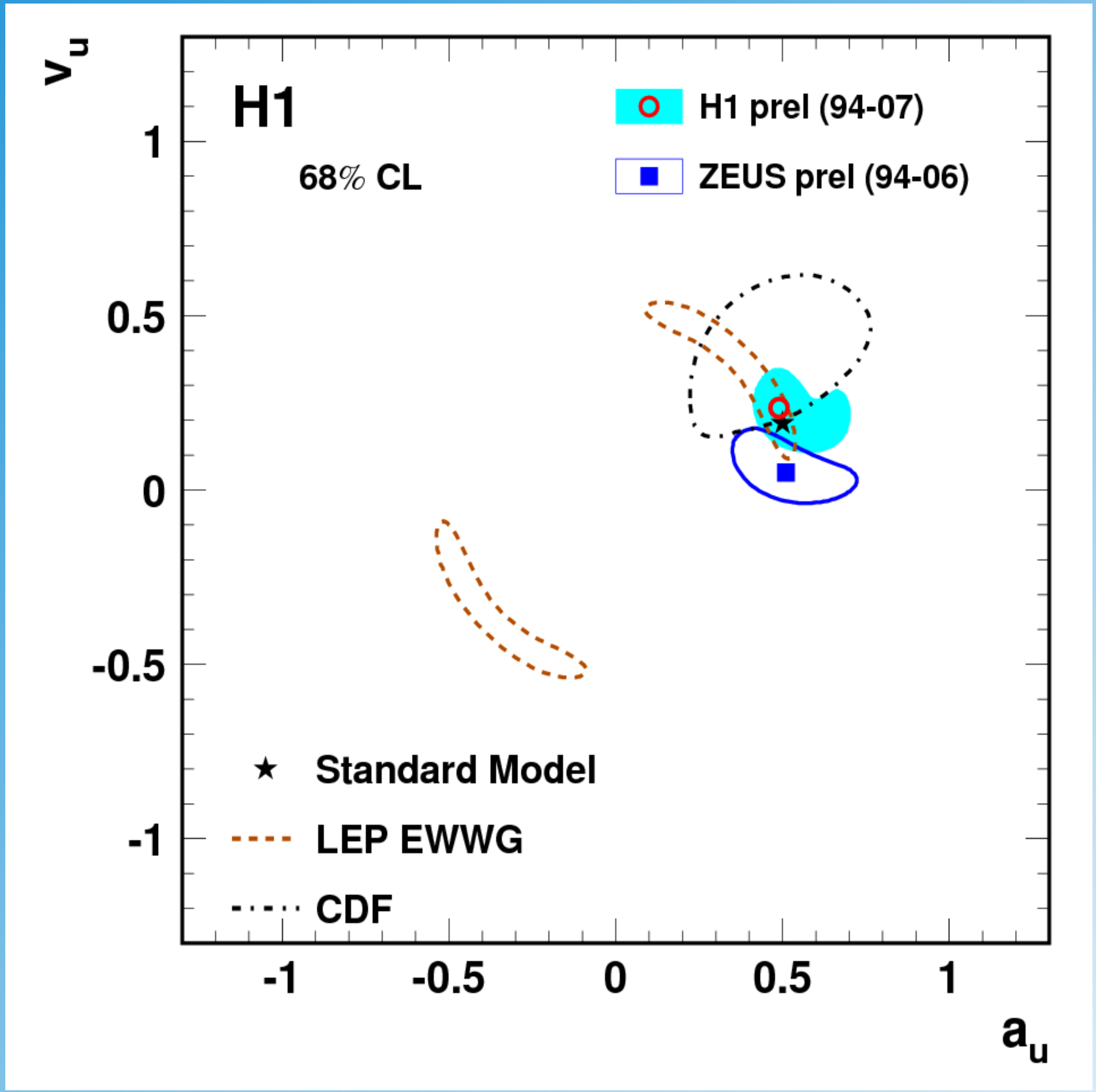
(February 4, 2008)

The NuTeV collaboration has extracted the electroweak parameter $\sin^2\theta_W$ from the measurement of the ratios of neutral current to charged current ν and $\overline{\nu}$ cross-sections. Our value, $\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, is 3 standard deviations above the standard model prediction. We also present a model independent analysis of the same data in terms of neutral-current quark couplings.

NuTev: $\sin^2\theta_W = 0.2277 \pm 0.0015$ (2003)

SM prediction: $\sin^2\theta_W = 0.22280 \pm 0.00035$ (2004)

NC Quark Couplings: HERA + Tevatron

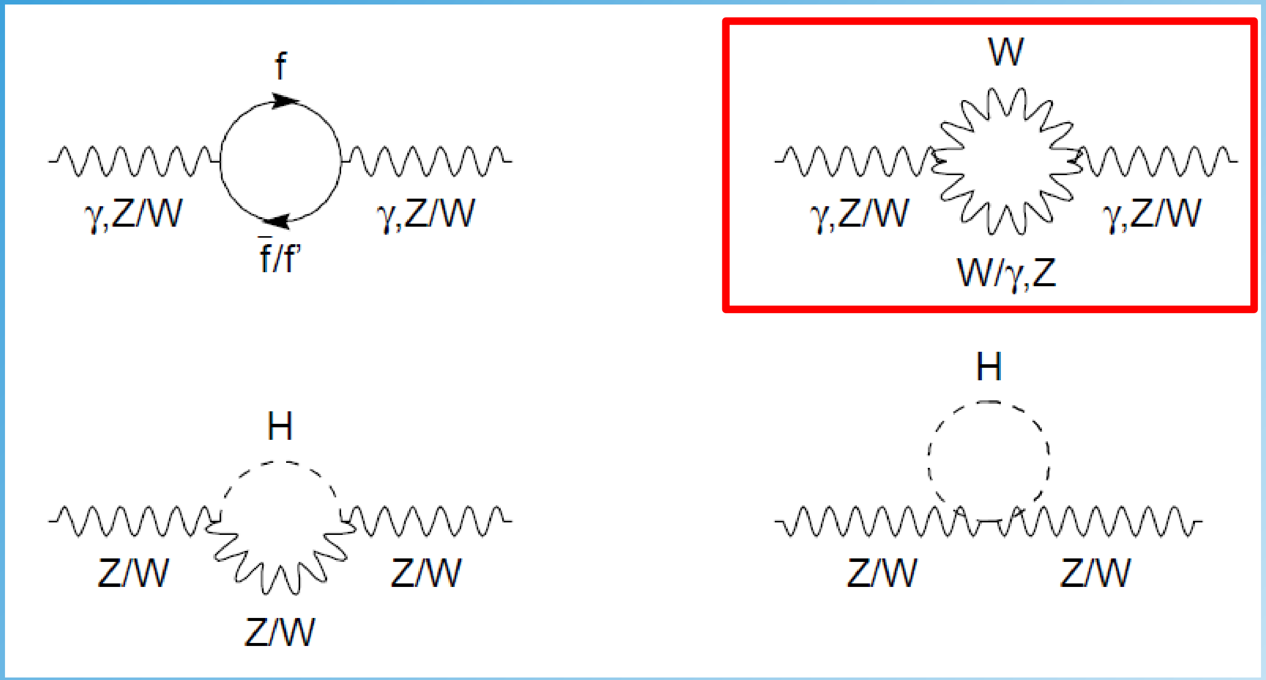


comparison LEP, Tevatron, HERA

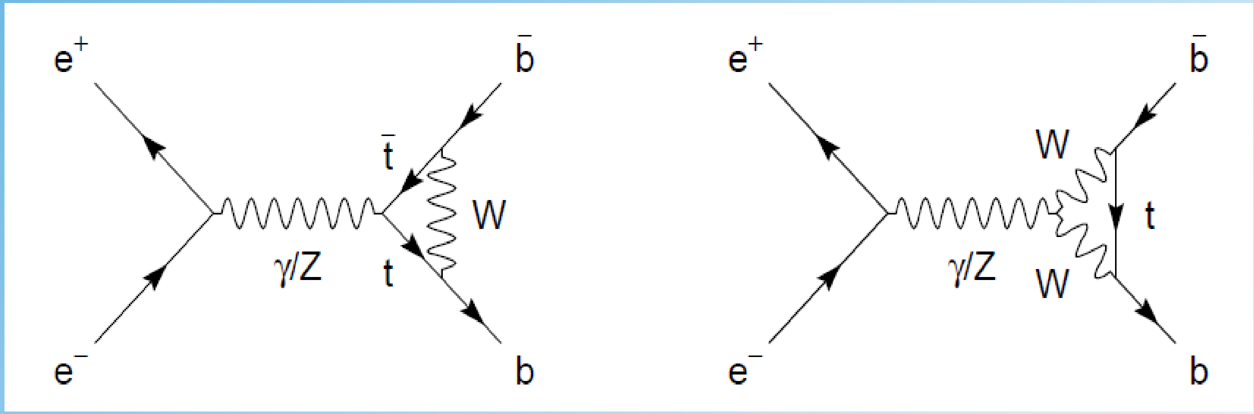
Indirect W-Mass Constraints from LEP1

W-mass also enters in virtual radiative corrections:

self-energy

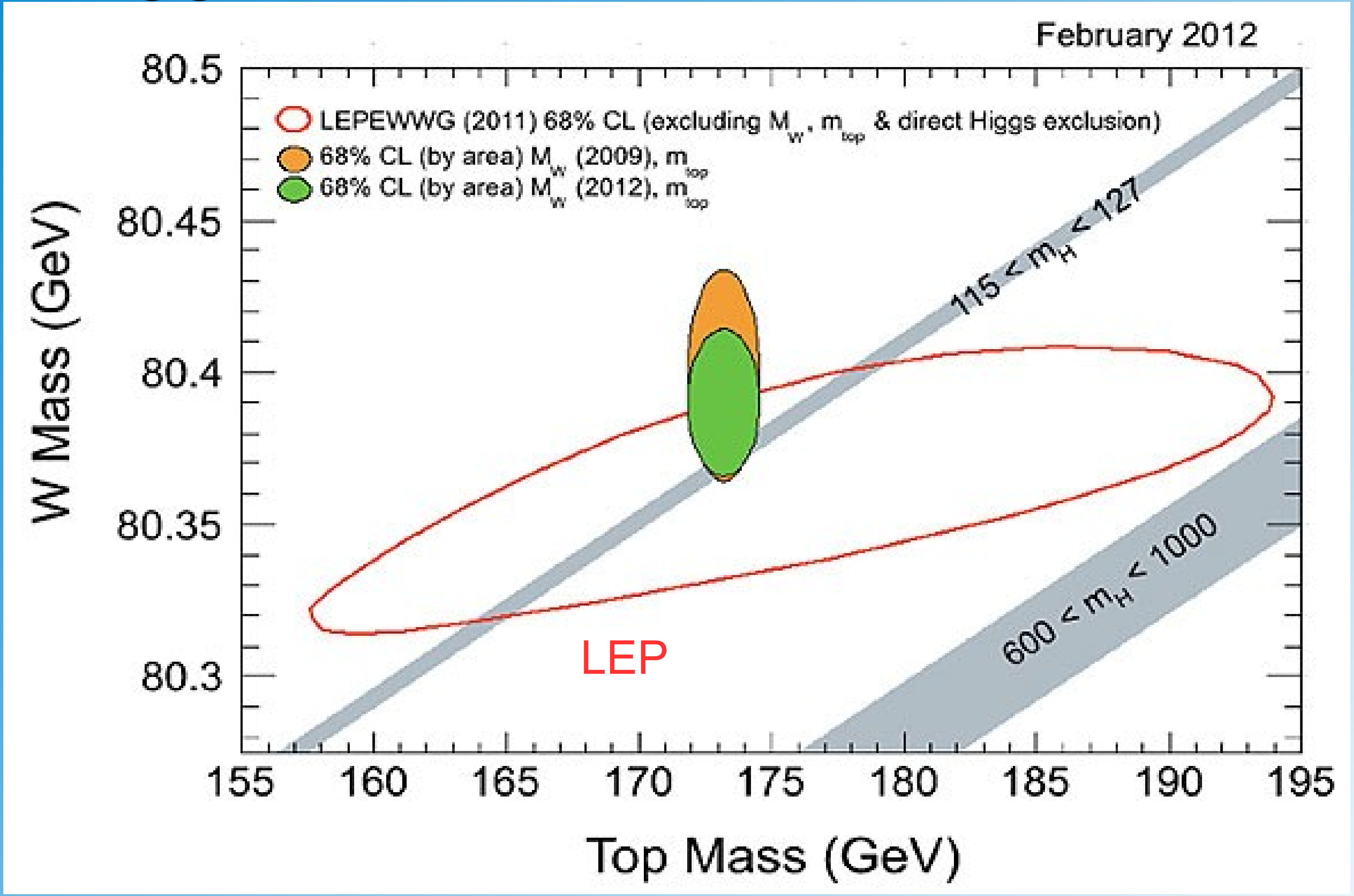


vertex correction



+ box diagrams

Higgs Mass Constraint from LEP

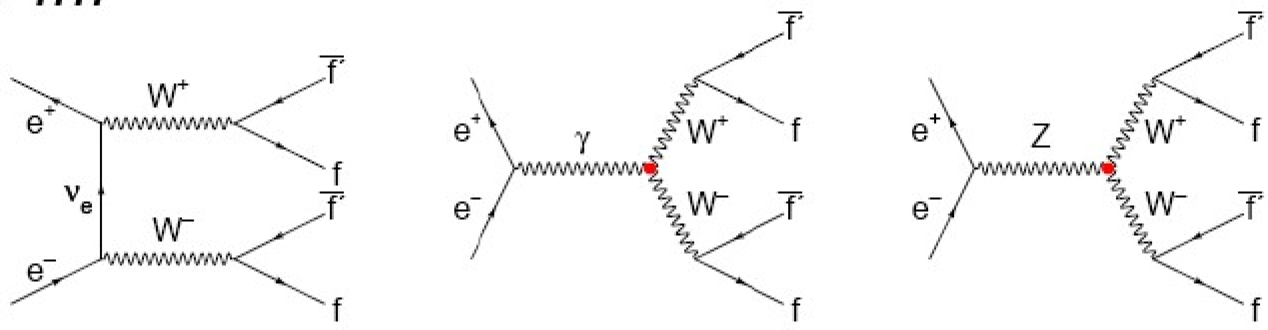


LEP 2

after 1996 the LEP energy was steadily increased up to more than E_{cms} = 200 GeV

$W^+ W^-$ Pair Production

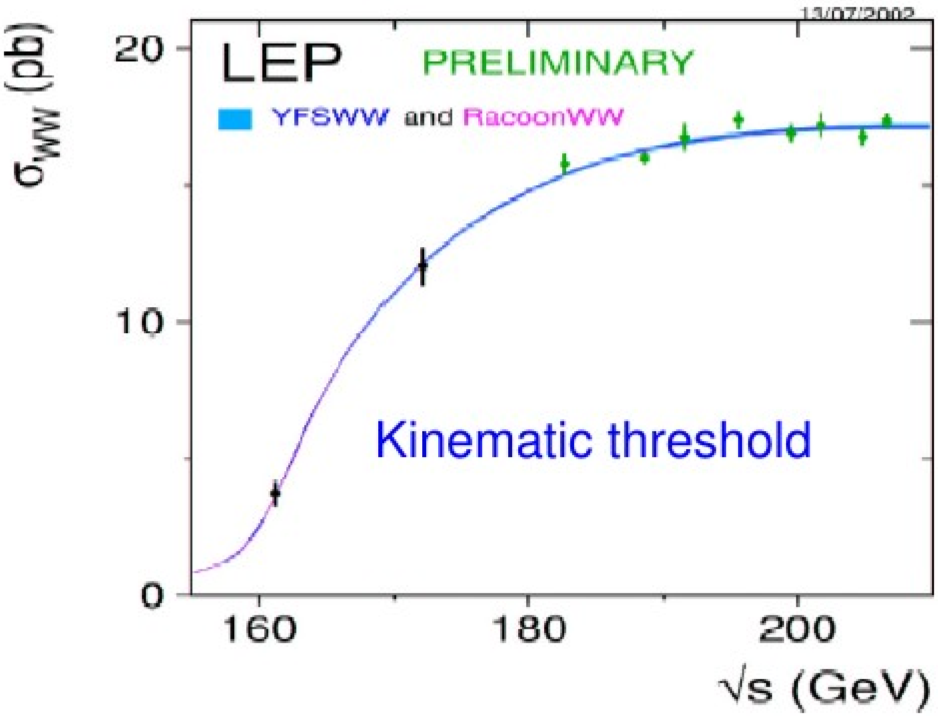
$$e^+e^- \to WW \to f\bar{f}f\bar{f}$$



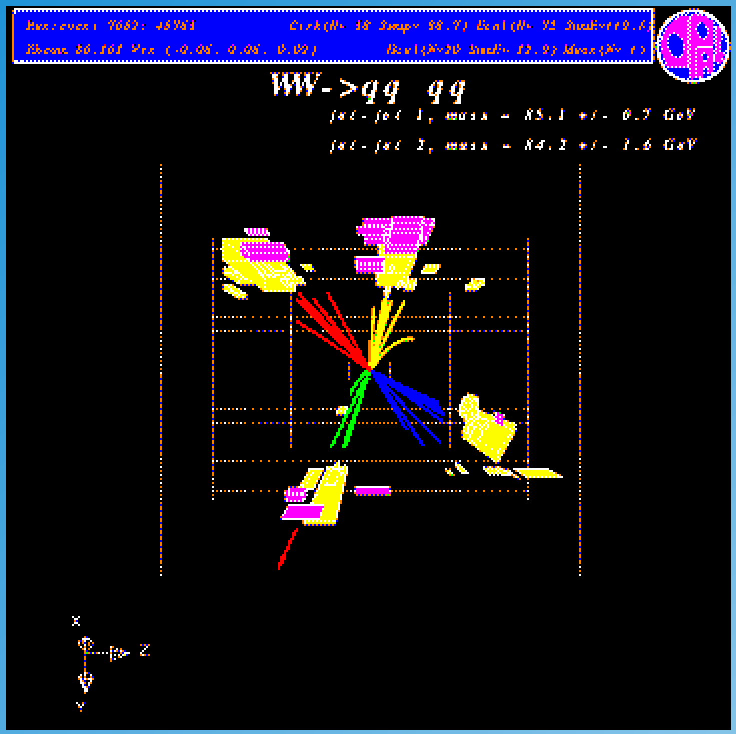
Threshold behavior of the cross section (kinematics, phase space) for ee→WW production:

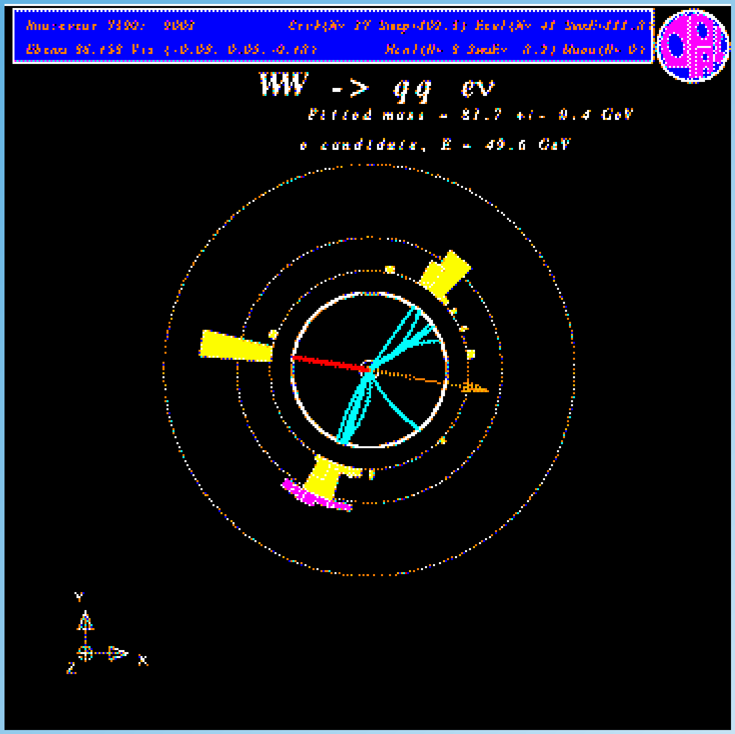
Phase space factor = f(M_W, √s):

→ Allows determination of M_W



WW Candidates

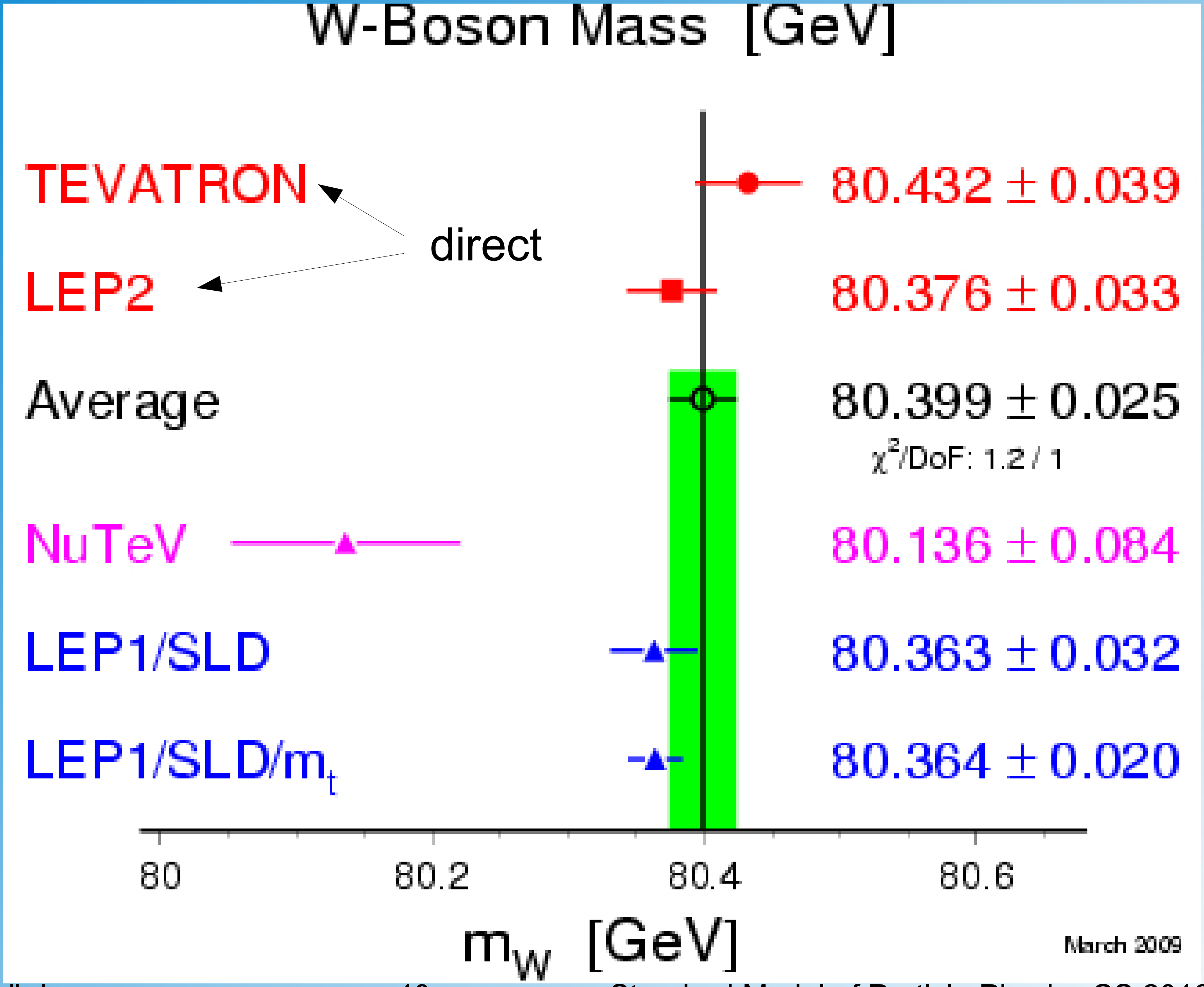




kinematics of WW → qqqq (46%) and WW → qqlν (44%) used to reconstruct W-mass

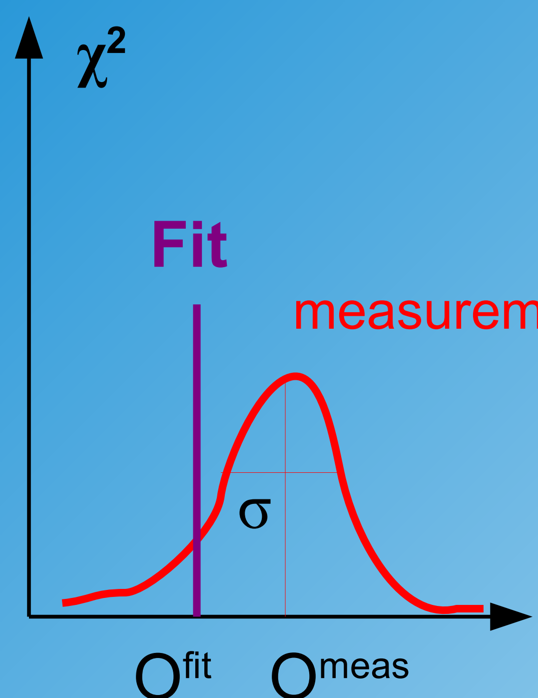
problems: color reconnection + missing neutrino!

Electroweak Fit of the W-Boson Mass

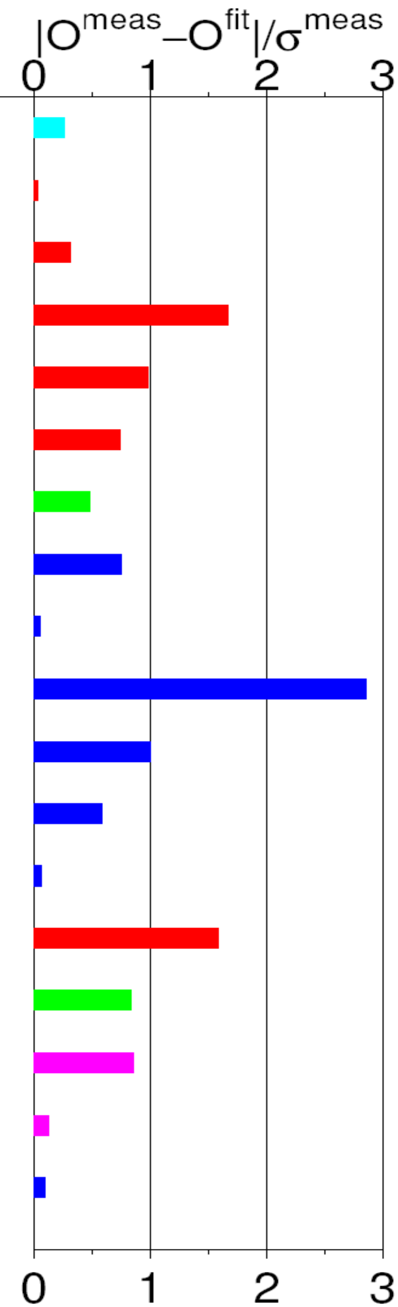


The SM pull plot

Z-pole parameters



	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
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	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
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	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.025	80.378
Γ_W [GeV]	2.098 ± 0.048	2.092
m_t [GeV]	173.1 ± 1.3	173.2

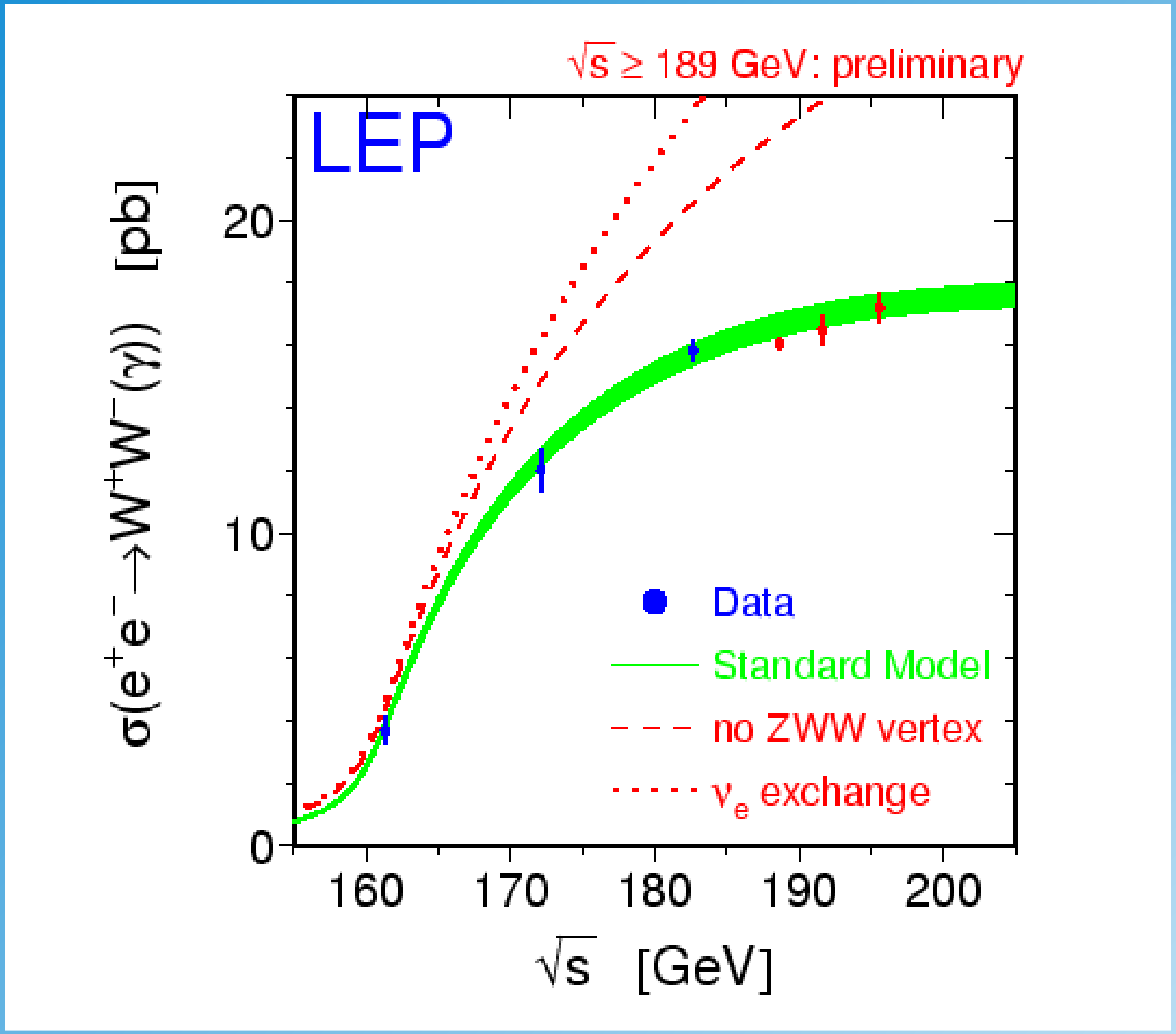


March 2009

=> consistent with SM

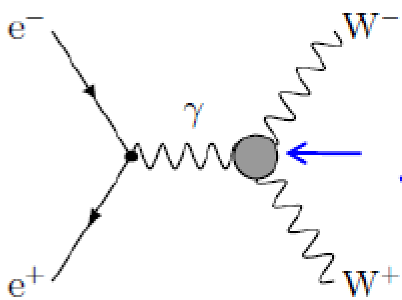
Triple Gauge Couplings

WW Production Cross Section



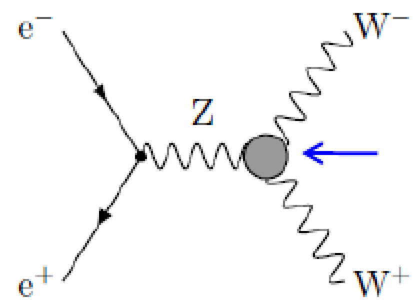
LEP 2 has proven existence of triple gauge couplings

Test of trilinear gauge boson coupling in WW production



SM

$g_{\gamma WW} = e$



$g_{ZWW} = e\,\dfrac{\cos\theta_w}{\sin\theta_w}$

Triple gauge coupling an important result of the non-abelian gauge structure.

Most general Lagrangian for VWW:

$$
\begin{aligned}
i\mathcal{L}_{\rm eff}^{\rm VWW}/g_{\rm VWW} = \;& \boxed{g_1^{\rm V}} V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) \\
&+ \boxed{\kappa_{\rm V}} W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_{\rm V}}{m_W^2} V^{\mu\nu} W^{+\rho}_\nu W^-_{\rho\mu} \\
&+ i g_5^{\rm V} \varepsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right) V^\sigma \\
&+ i g_4^{\rm V} W^+_\mu W^-_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\
&- \frac{\tilde{\kappa}_{\rm V}}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_{\rm V}}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}.
\end{aligned}
$$

$\Box$ =1,
all others 0

$\Delta\kappa, \Delta g_1 \neq 0$
Deviation from SM

Interpretation for γWW

$q_W = \pm g_V^\gamma$ charge

$\mu_W = \dfrac{e}{2M_W}(1 + \kappa_\gamma + \lambda_\gamma)$

Dipol moment

Triple Gauge couplings:

Assuming electromagnetic gauge invariance as well as C and P conservation, the number of independent TGCs reduces to five. Common set: $\{ g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z, \lambda_\gamma \}$

Parameters used by the LEP experiments are: g_1^Z, κ_γ, λ_γ

With additional gauge constraints

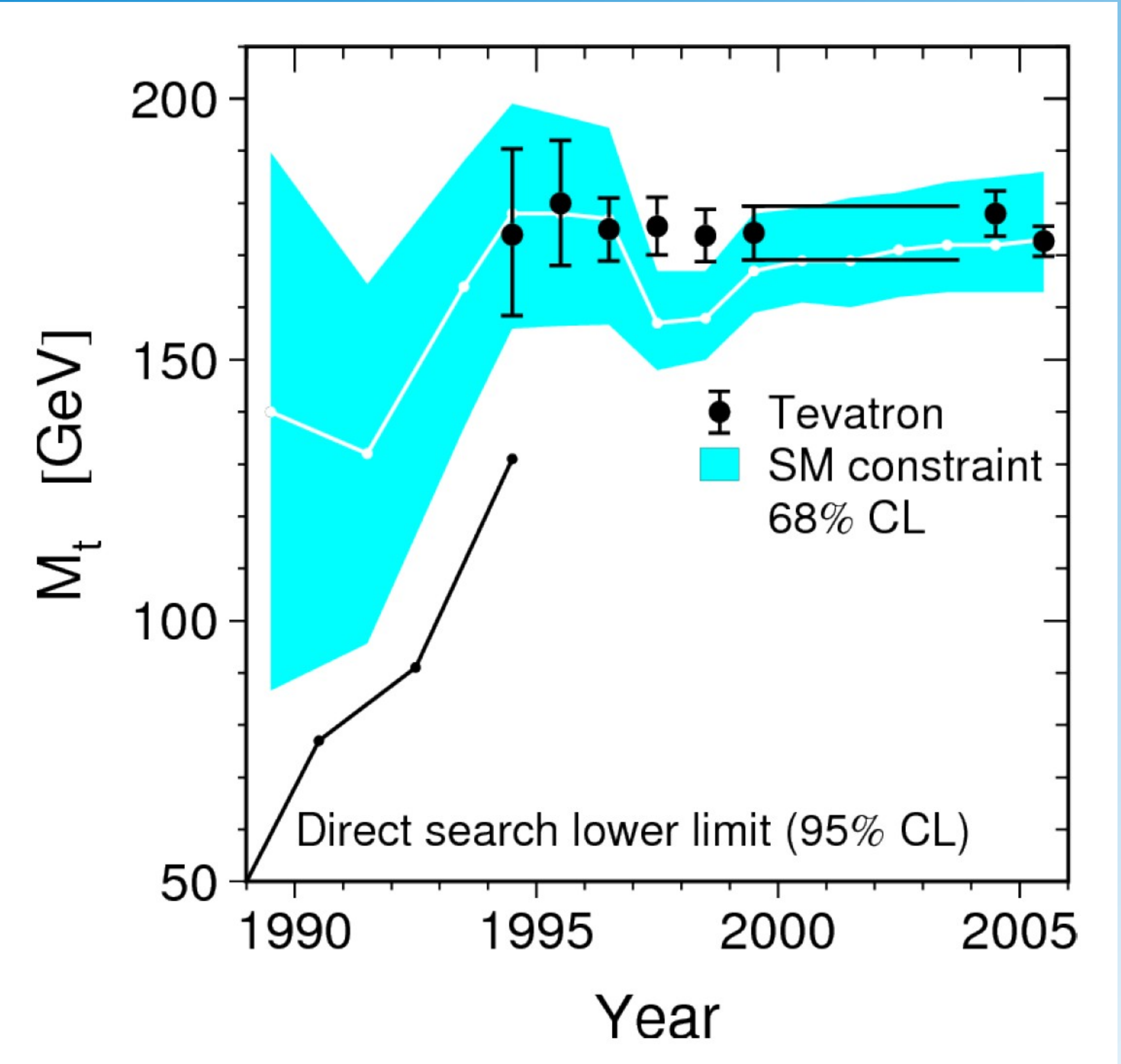
$$\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$$
$$\lambda_Z = \lambda_\gamma \,,$$

From a fit to the angular distribution of the WW:

Parameter	68% C.L.	
g_1^Z	$0.984^{+0.022}_{-0.019}$	=1 in SM
κ_γ	$0.973^{+0.044}_{-0.045}$	=1 in SM
λ_γ	$-0.028^{+0.020}_{-0.021}$	=0 in SM

Standard Model structure of VWW triple boson coupling confirmed.

Top Mass Prediction



Top Mass Prediction from Radiative Corrections

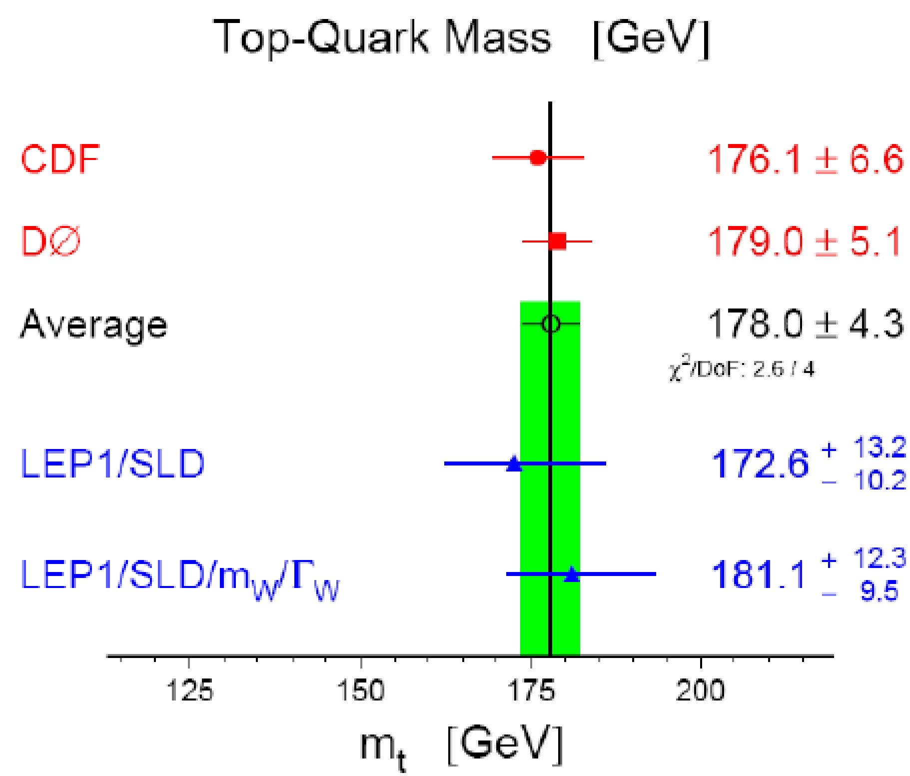
e.g.: $$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \ldots$$

The measurement of the radiative corrections:

$$\sin^2\theta_{eff} \equiv \frac{1}{4}(1 - \bar{g}_V/\bar{g}_A)$$

$$\sin^2\theta_{eff} = (1+\Delta\kappa)\sin^2\theta_w$$

Allows the indirect determination of the unknown parameters m_t and M_H.



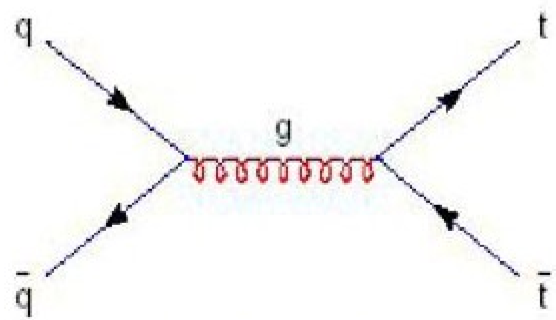
Direct measurement of m_t

Good agreement between the indirect prediction of m_t and the value obtained in direct measurements confirm the radiative corrections of the SM

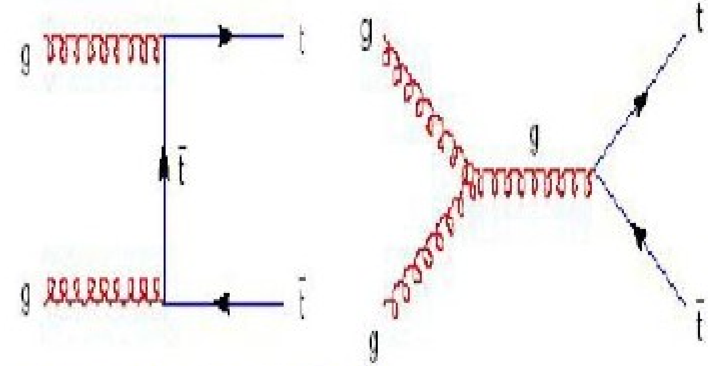
Prediction of m_t by LEP before the discovery of the top at TEVATRON.

Top Discovery at Tevatron in 1995

$p\bar{p}$ @ 2 TeV

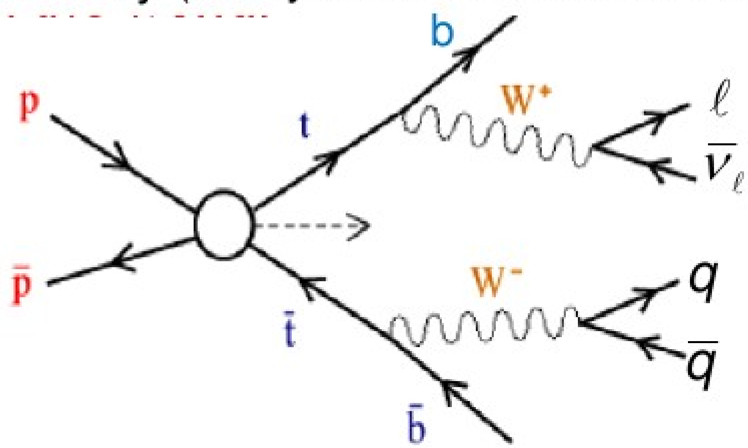


$q\bar{q}$ annihilation (85%)



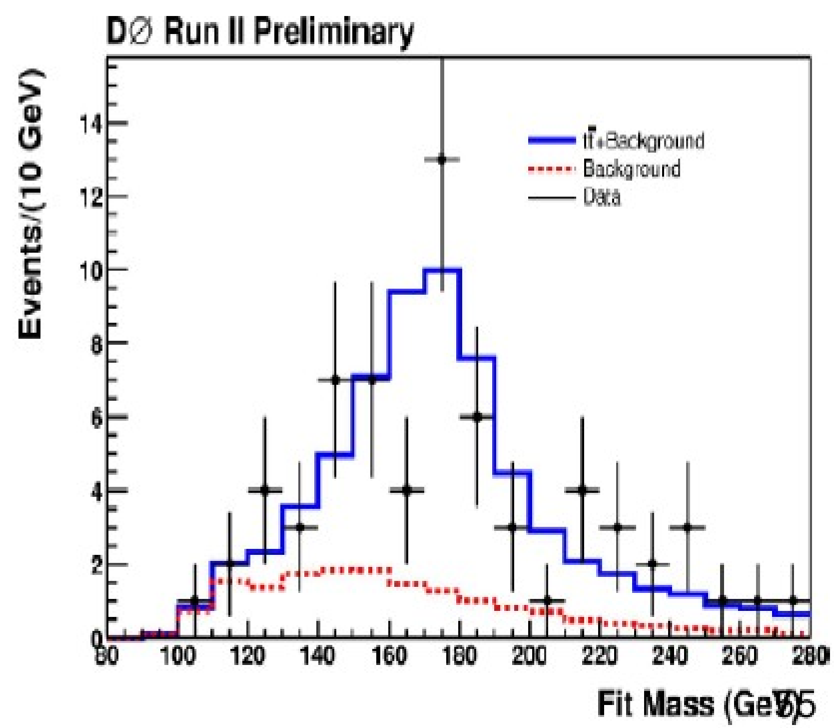
gluon fusion (15%)

Top decay (decays before hadronization)

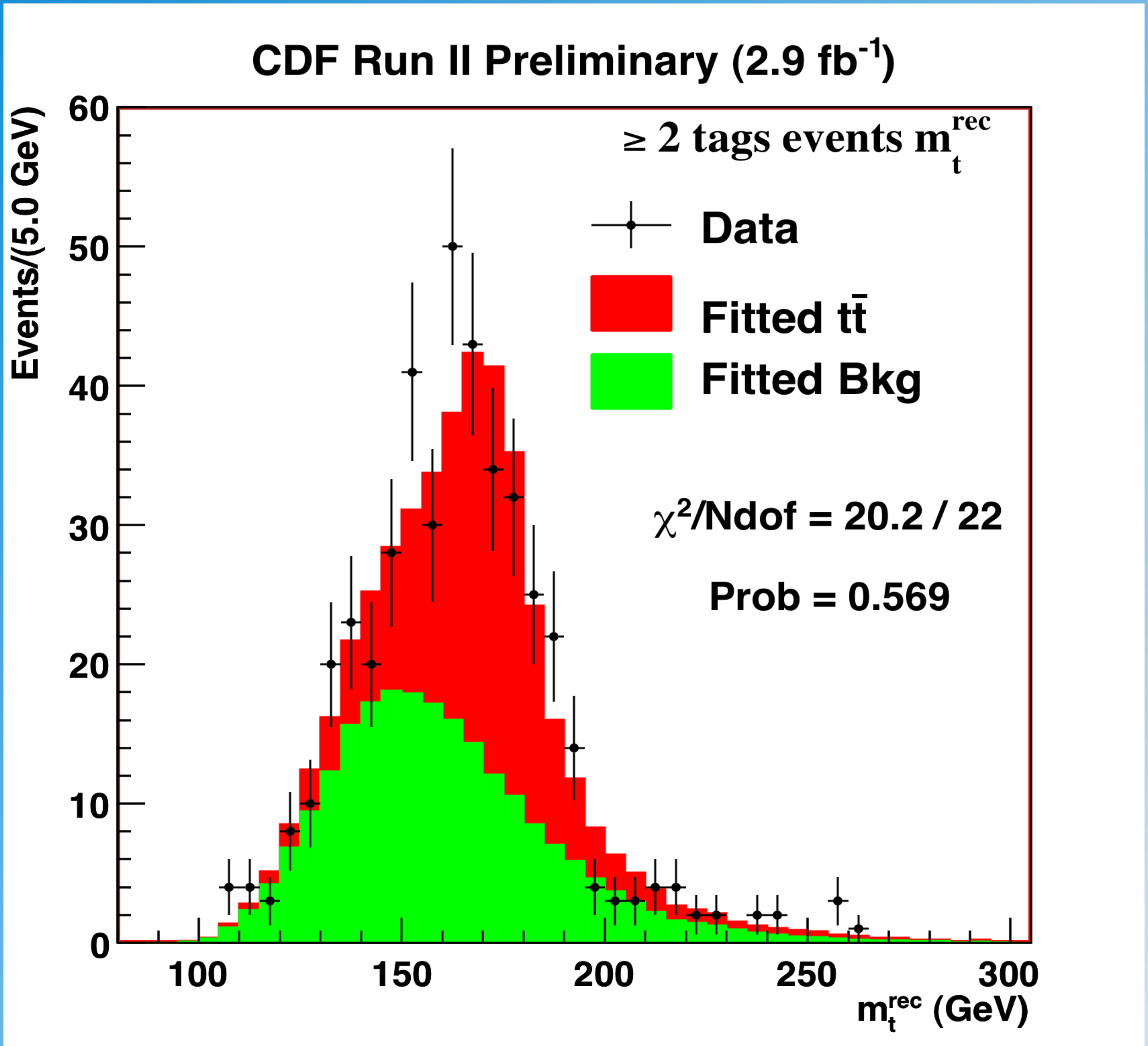


Channel used for mass reconstruction:

$$m_t = m_{inv}(b - jet, W \rightarrow jet + jet)$$



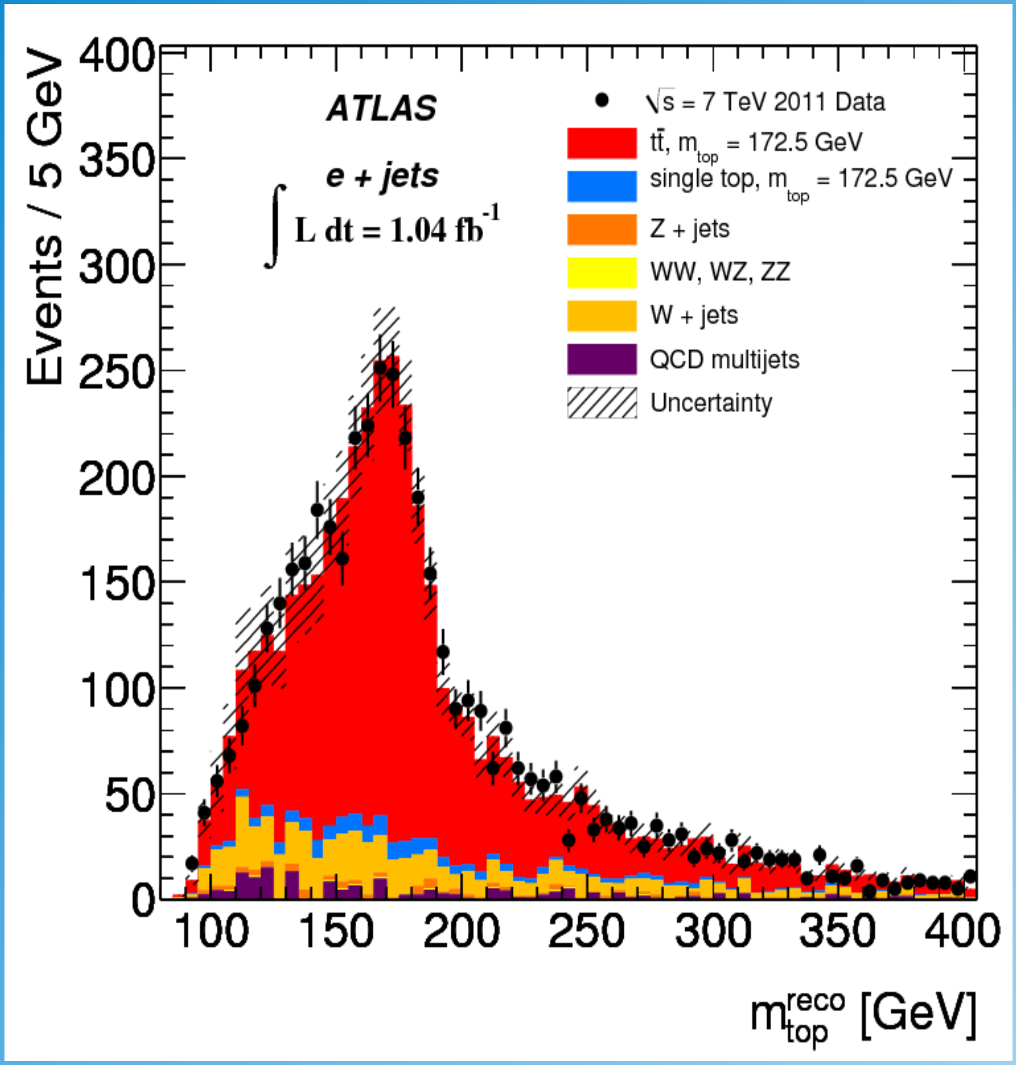
Top Mass Reconstruction

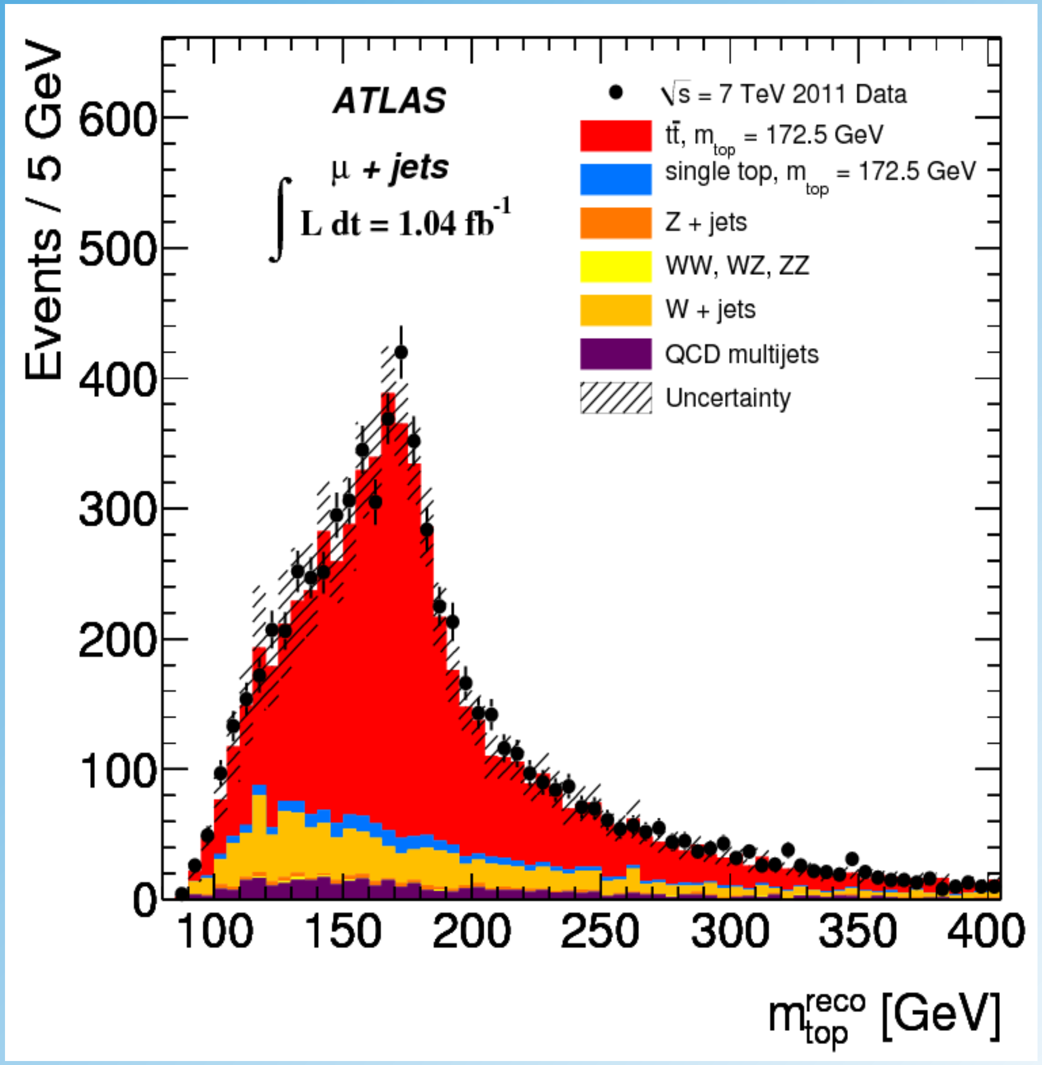


multi-channel analysis

$m_t \sim 172$ (1) GeV

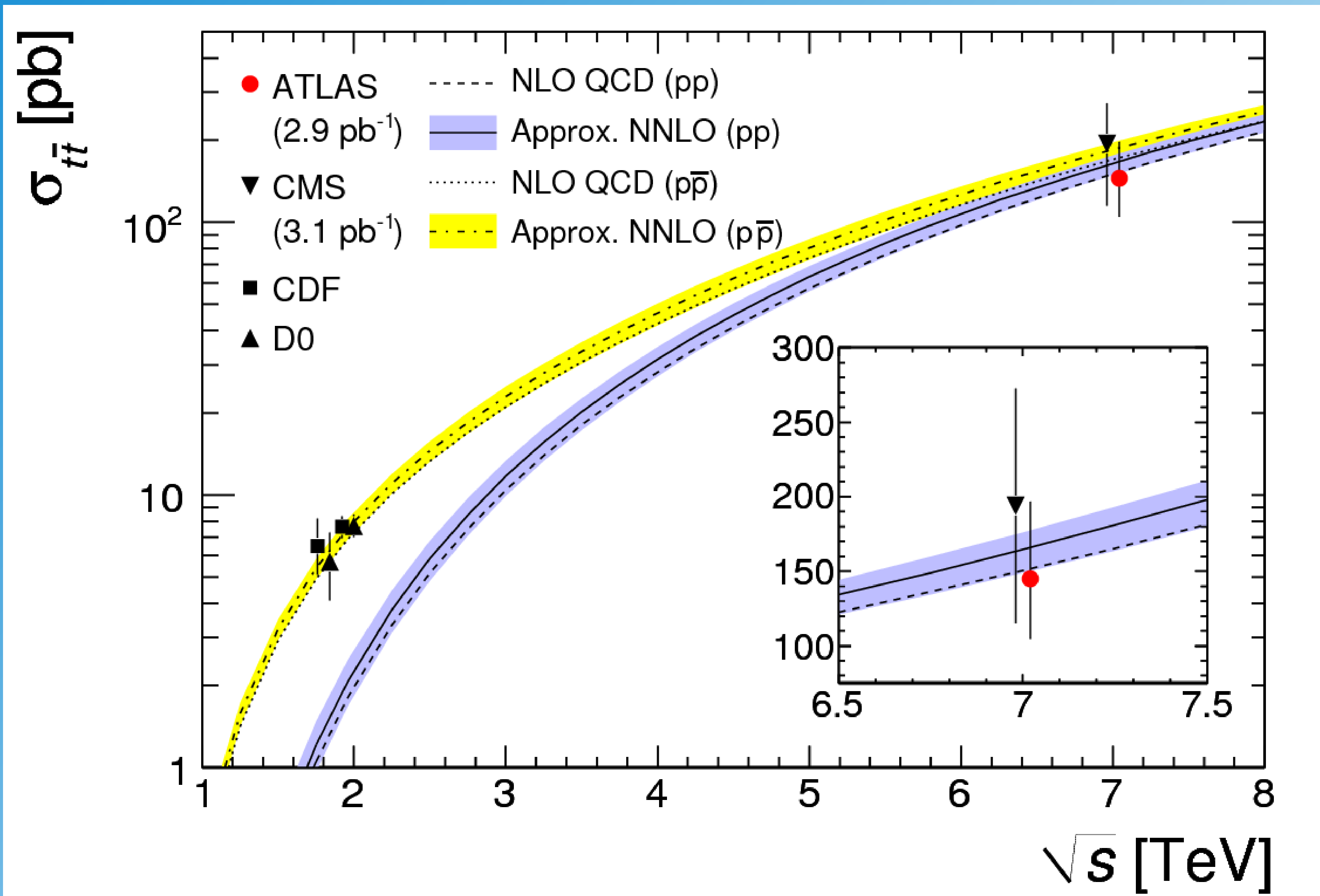
First Results from ATLAS (LHC)





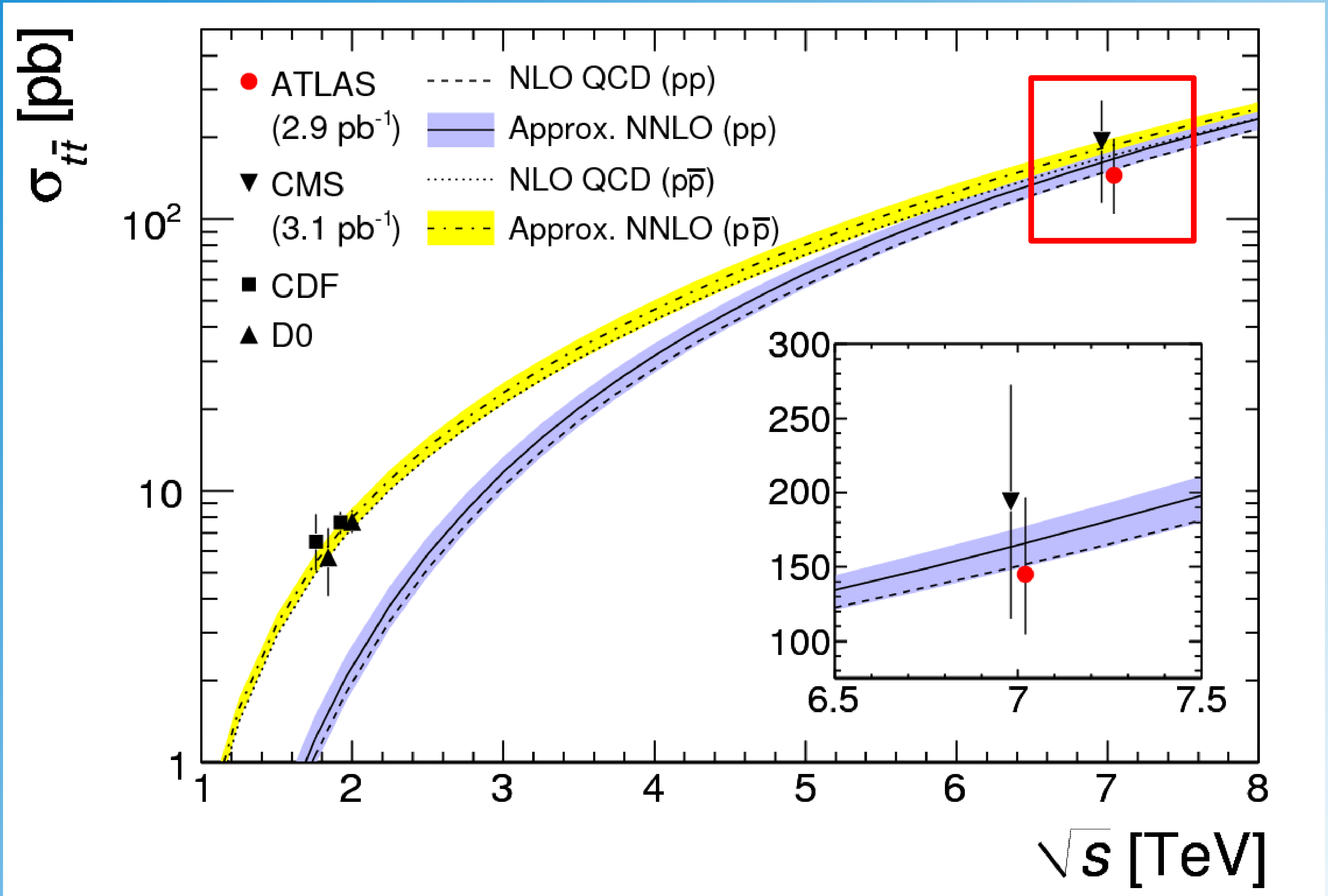
in the mean time millions of tops recorded!

First Results from ATLAS (LHC)

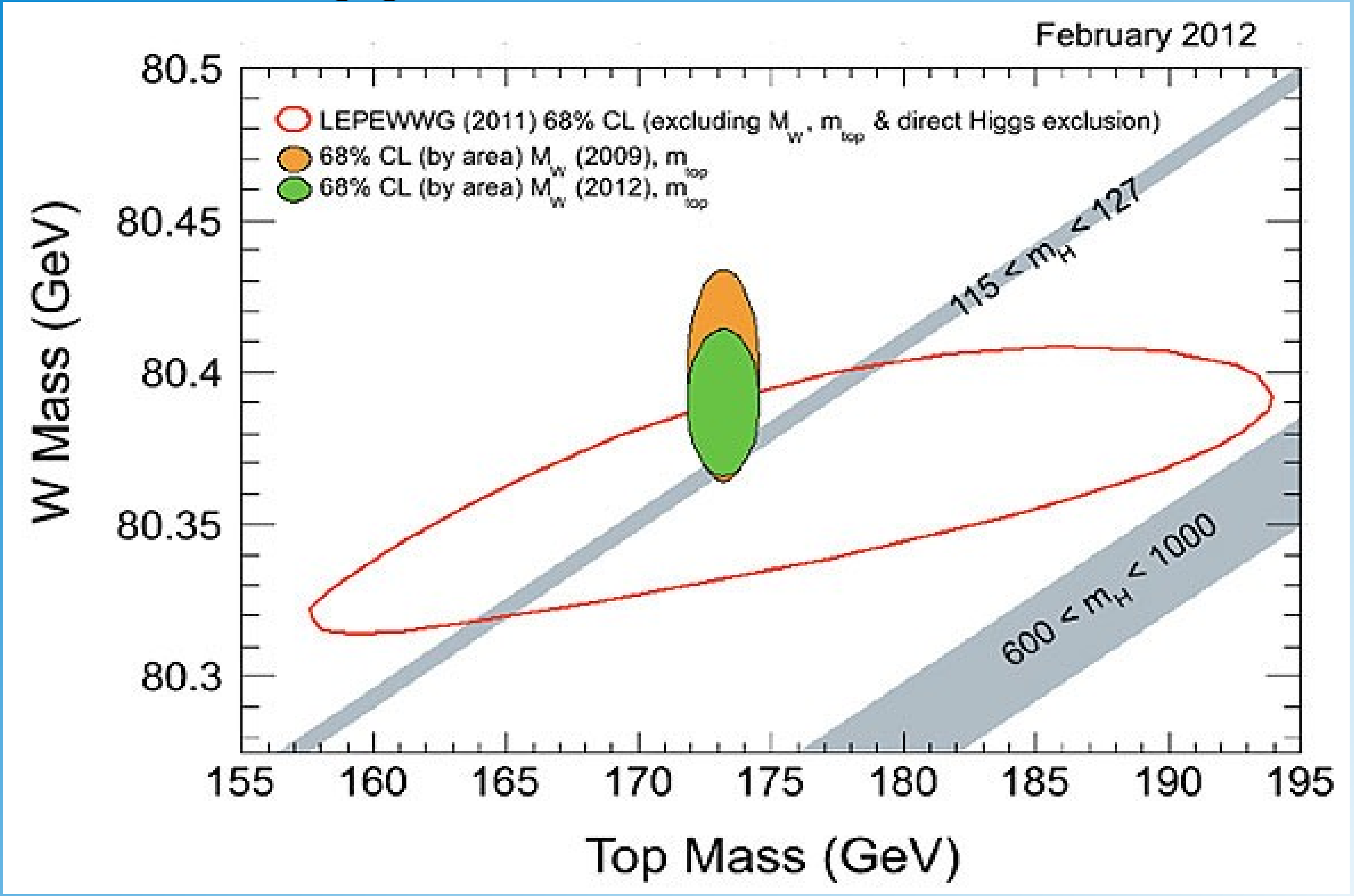


First Results from ATLAS (LHC)

mainly gluon fusion



Higgs Mass Constraint



Higgs mass should be light!