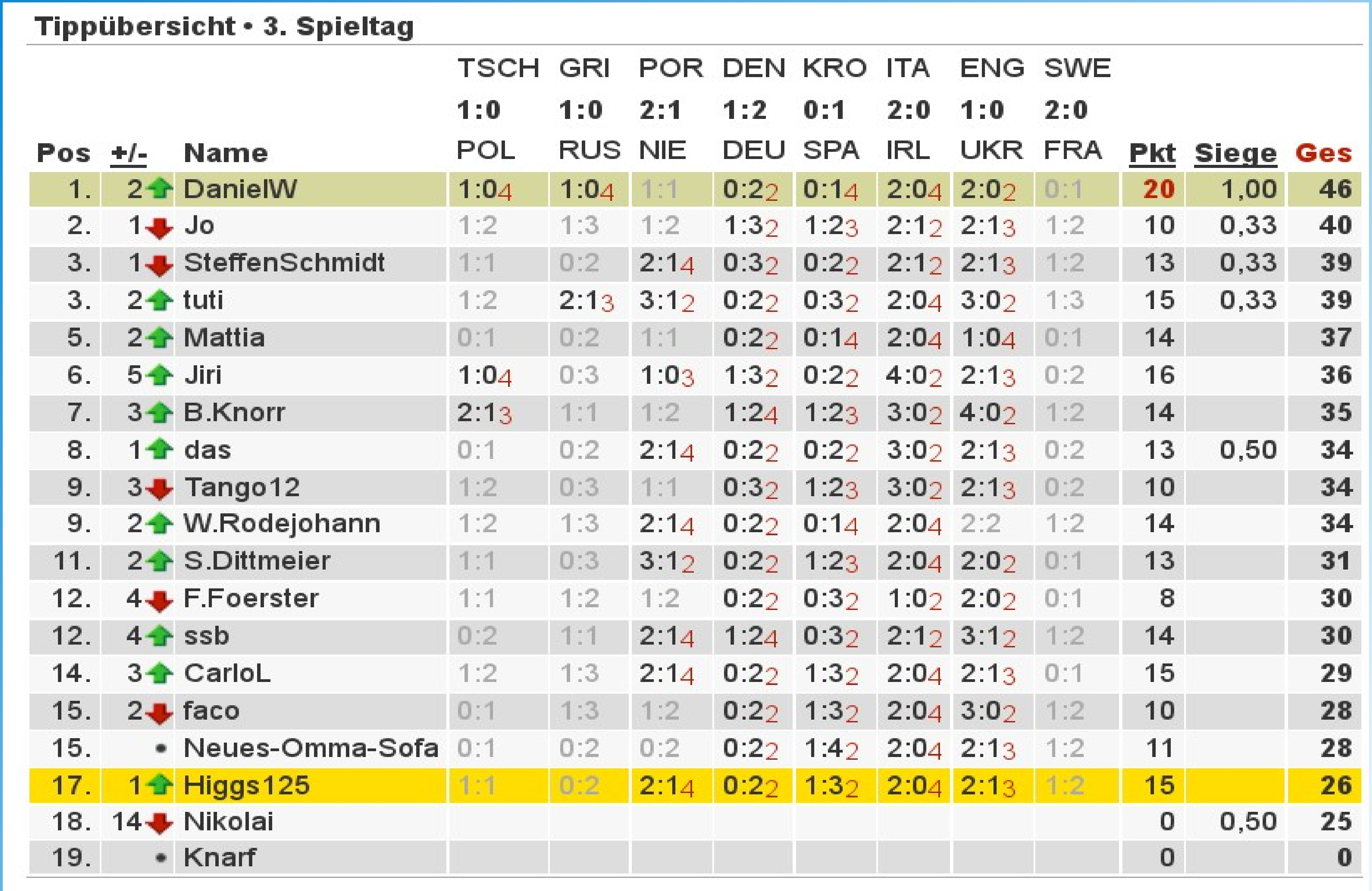
Lecture:

Standard Model of Particle Physics

Heidelberg SS 2012

Tests of the Standard Model I



Tippübersicht • 3. Spieltag

Pos	+/-	Name	TSCH 1:0 POL	GRI 1:0 RUS	POR 2:1 NIE	DEN 1:2 DEU	KRO 0:1 SPA	ITA 2:0 IRL	ENG 1:0 UKR	SWE 2:0 FRA	Pkt	Siege	Ges
1.	2↑	DanielW	1:04	1:04	1:1	0:22	0:14	2:04	2:02	0:1	20	1,00	46
2.	1↓	Jo	1:2	1:3	1:2	1:32	1:23	2:12	2:13	1:2	10	0,33	40
3.	1↓	SteffenSchmidt	1:1	0:2	2:14	0:32	0:22	2:12	2:13	1:2	13	0,33	39
3.	2↑	tuti	1:2	2:13	3:12	0:22	0:32	2:04	3:02	1:3	15	0,33	39
5.	2↑	Mattia	0:1	0:2	1:1	0:22	0:14	2:04	1:04	0:1	14		37
6.	5↑	Jiri	1:04	0:3	1:03	1:32	0:22	4:02	2:13	0:2	16		36
7.	3↑	B.Knorr	2:13	1:1	1:2	1:24	1:23	3:02	4:02	1:2	14		35
8.	1↑	das	0:1	0:2	2:14	0:22	0:22	3:02	2:13	0:2	13	0,50	34
9.	3↓	Tango12	1:2	0:3	1:1	0:32	1:23	3:02	2:13	0:2	10		34
9.	2↑	W.Rodejohann	1:2	1:3	2:14	0:22	0:14	2:04	2:2	1:2	14		34
11.	2↑	S.Dittmeier	1:1	0:3	3:12	0:22	1:23	2:04	2:02	0:1	13		31
12.	4↓	F.Foerster	1:1	1:2	1:2	0:22	0:32	1:02	2:02	0:1	8		30
12.	4↑	ssb	0:2	1:1	2:14	1:24	0:32	2:12	3:12	1:2	14		30
14.	3↑	CarloL	1:2	1:3	2:14	0:22	1:32	2:04	2:13	0:1	15		29
15.	2↓	faco	0:1	1:3	1:2	0:22	1:32	2:04	3:02	1:2	10		28
15.	•	Neues-Omma-Sofa	0:1	0:2	0:2	0:22	1:42	2:04	2:13	1:2	11		28
17.	1↑	Higgs125	1:1	0:2	2:14	0:22	1:32	2:04	2:13	1:2	15		26
18.	14↓	Nikolai									0	0,50	25
19.	•	Knarf									0		0

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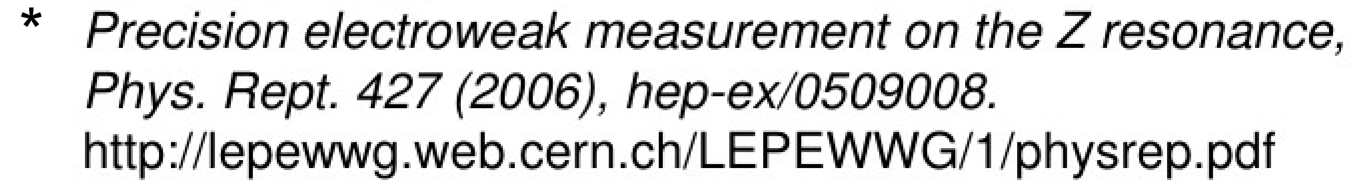
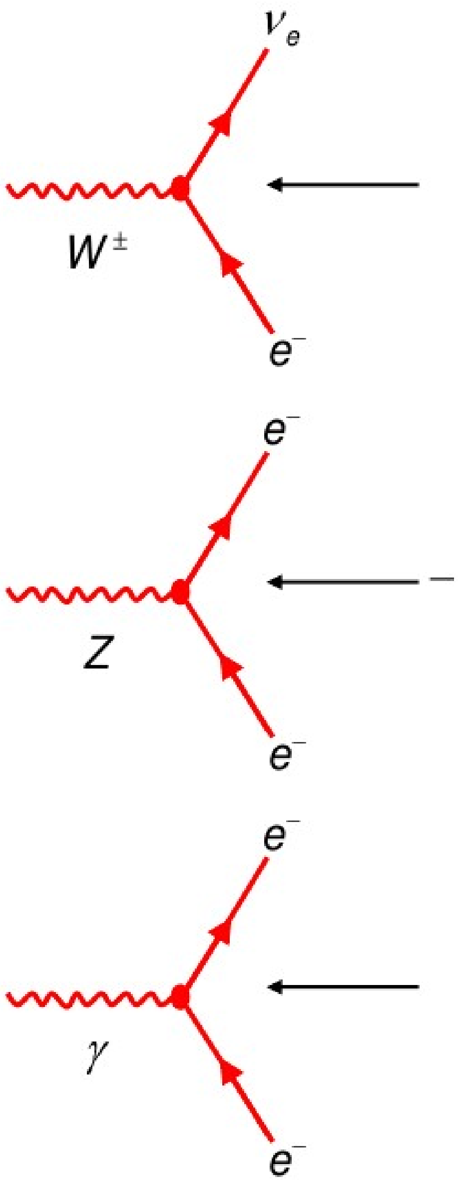
- Top-Mass Prediction and Discovery
- Triple Gauge Boson couplings



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

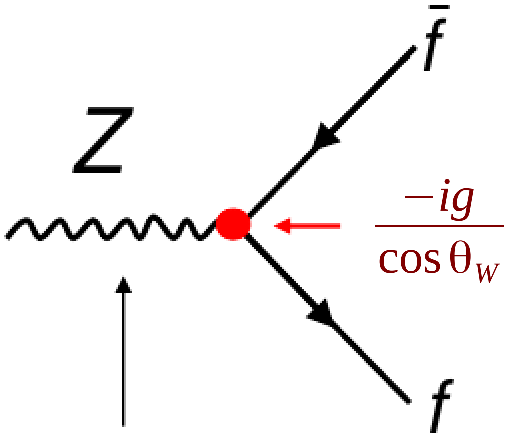
Feynman Rules Electroweak Theory



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

U.Uwer

SM Precision Tests



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

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

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

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

Standard Model

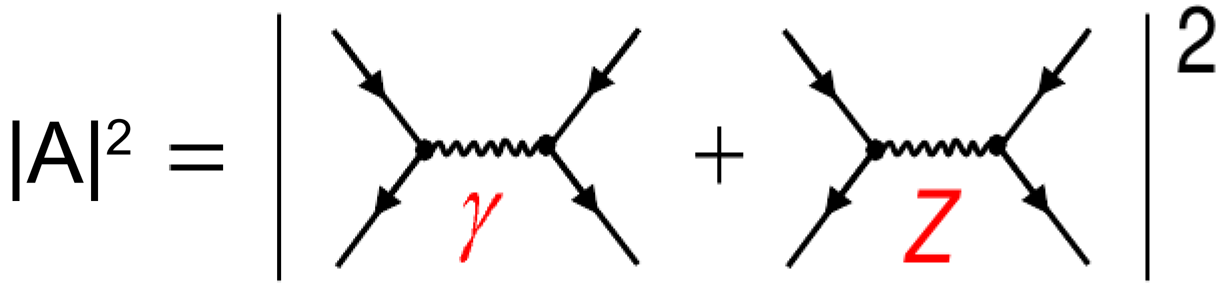
$$g_V = T_3 - 2Q\sin^2\theta_W \quad \text{and} \quad g_A = T_3$$

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

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

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

LEP1 + SLC Cross Section



$\boxed{\text{for}\quad e^+ e^- \to \mu^+ \mu^-}$

Matrix elements:

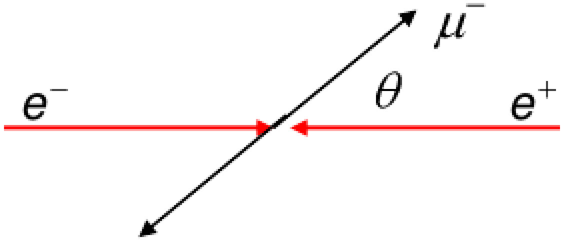
$$A_\gamma = -ie^2 (\bar{u}_\mu \gamma^\nu v_\mu) \frac{g_{\rho\nu}}{q^2} (\bar{v}_e \gamma^\rho u_e)$$

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

LEP1 + SLC Cross Section

One finds for the differential cross section:

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



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

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

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

Total Cross Section

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

Breit-Wigner Resonance:
BW description is very general

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

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

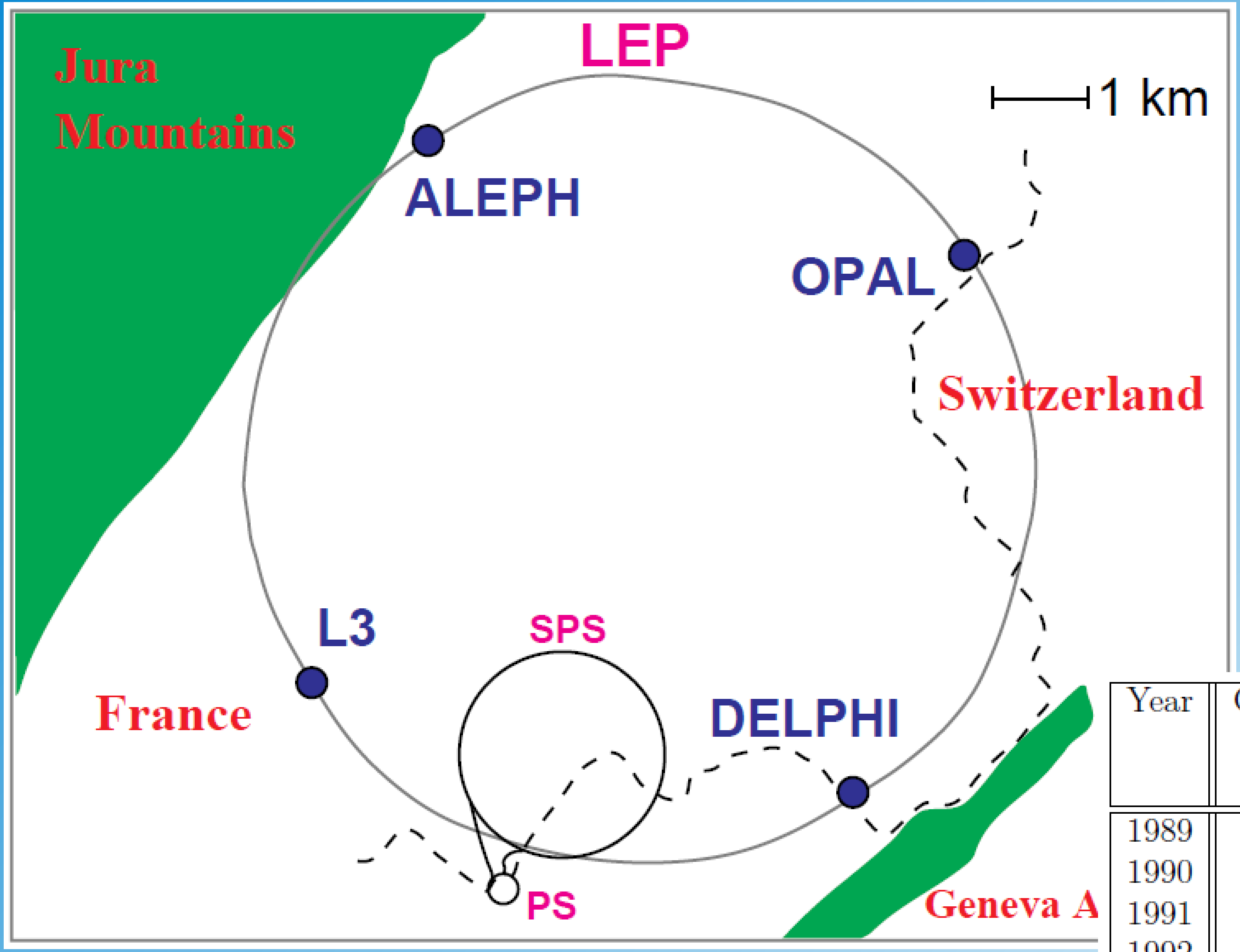
With partial and total widths:

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

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

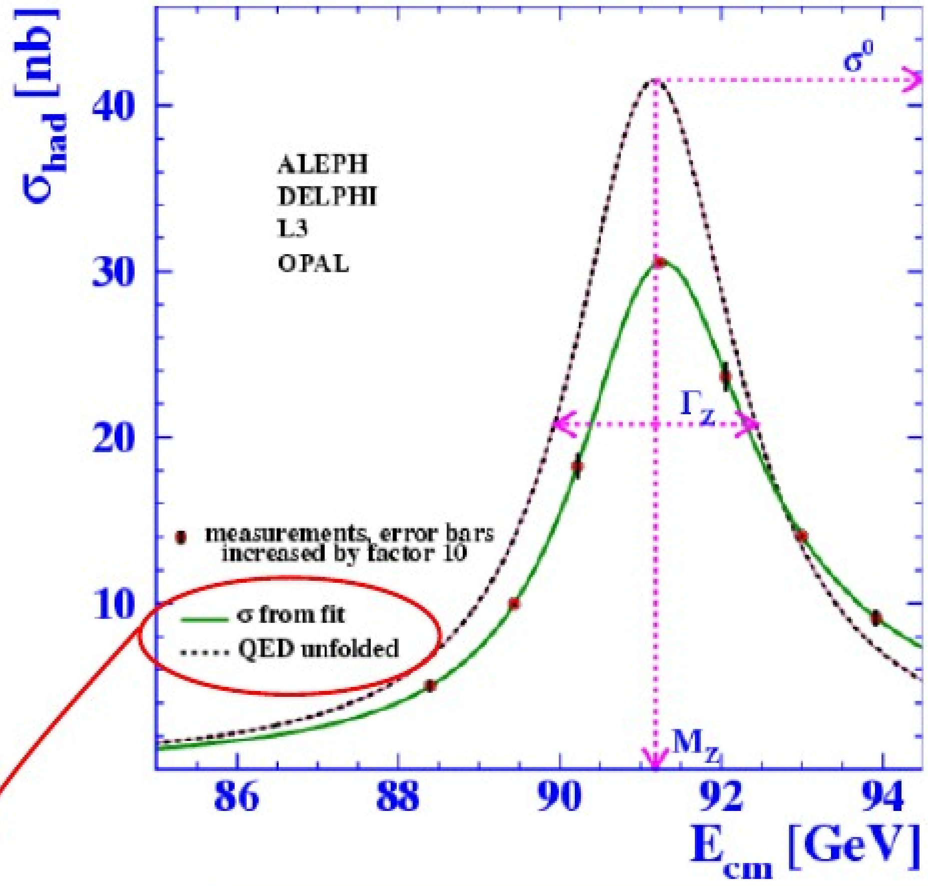
Cross sections and widths can be calculated within the Standard Model if all parameters are known

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:

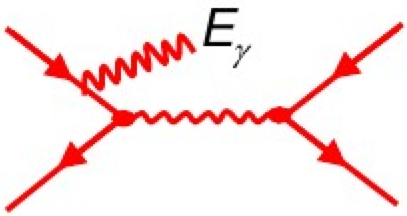
$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

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

- Resonance position → M_Z
- Height → $\Gamma_e \Gamma_\mu$
- Width → Γ_Z

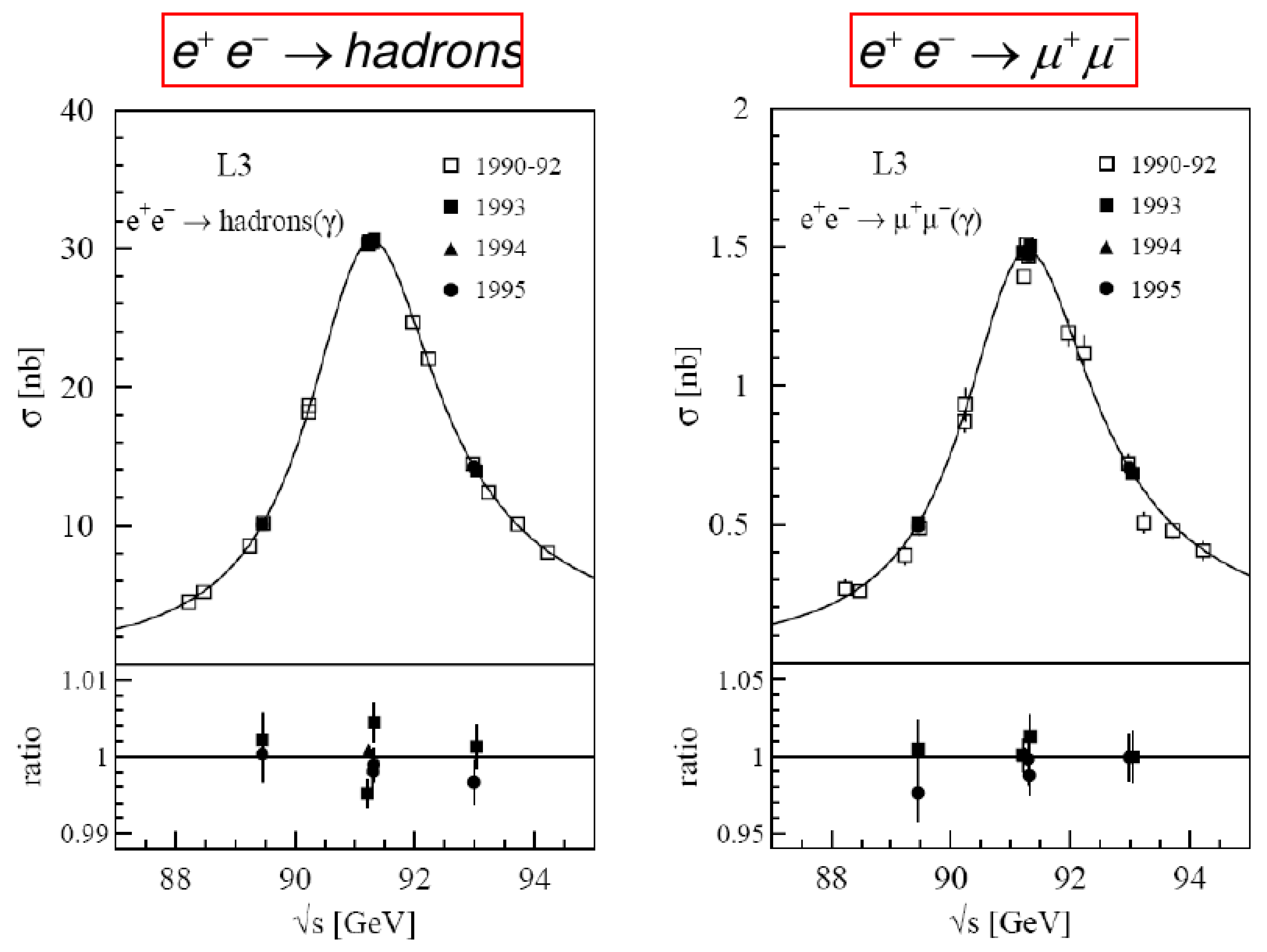
Initial state Bremsstrahlung corrections

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



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

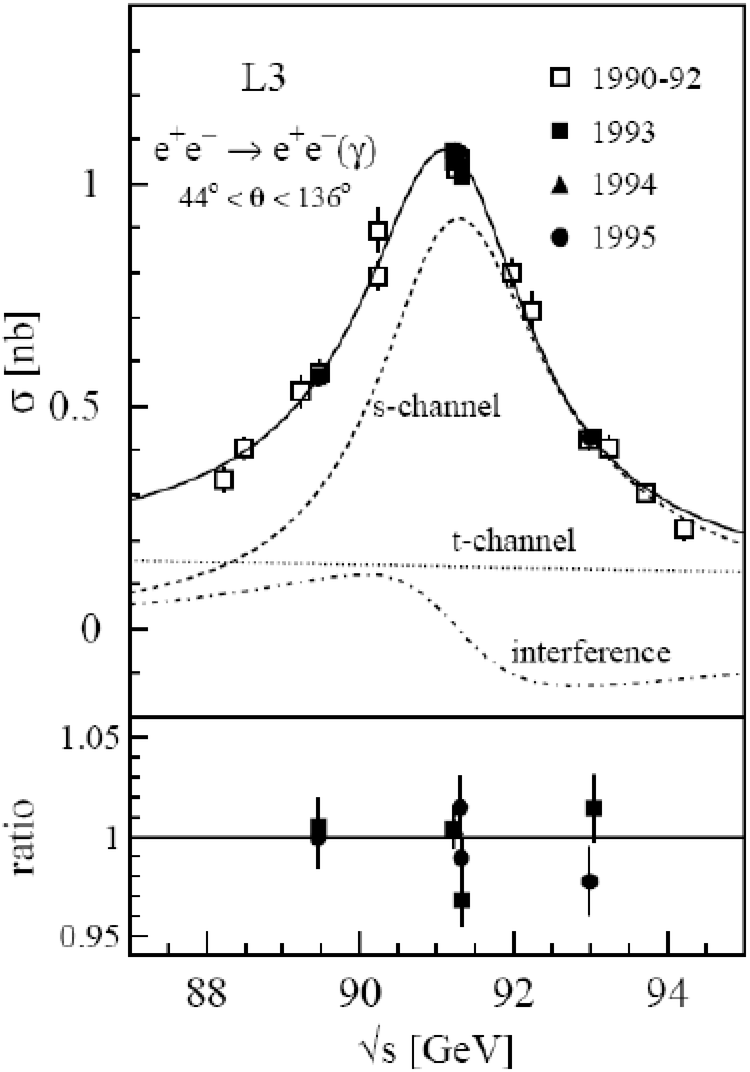
Final State Comparisons

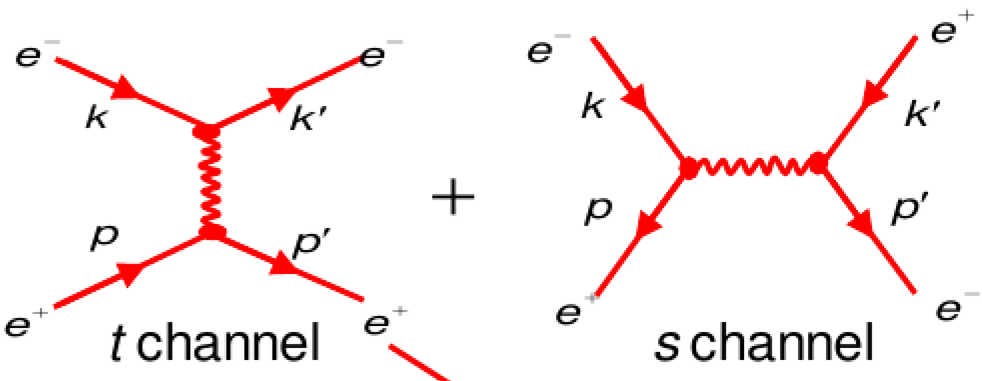


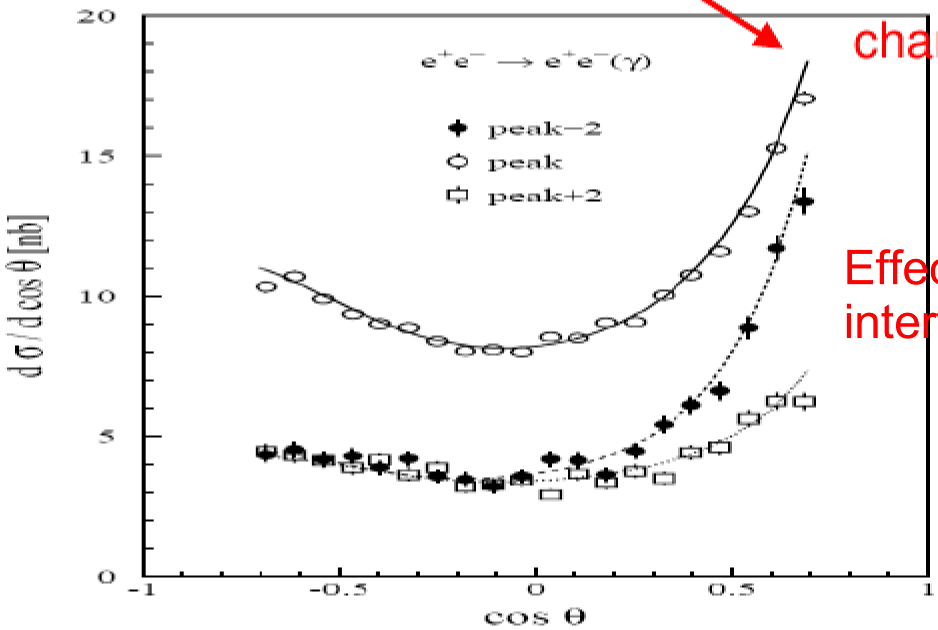
Same resonance shape!

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

t channel contribution → forward peak





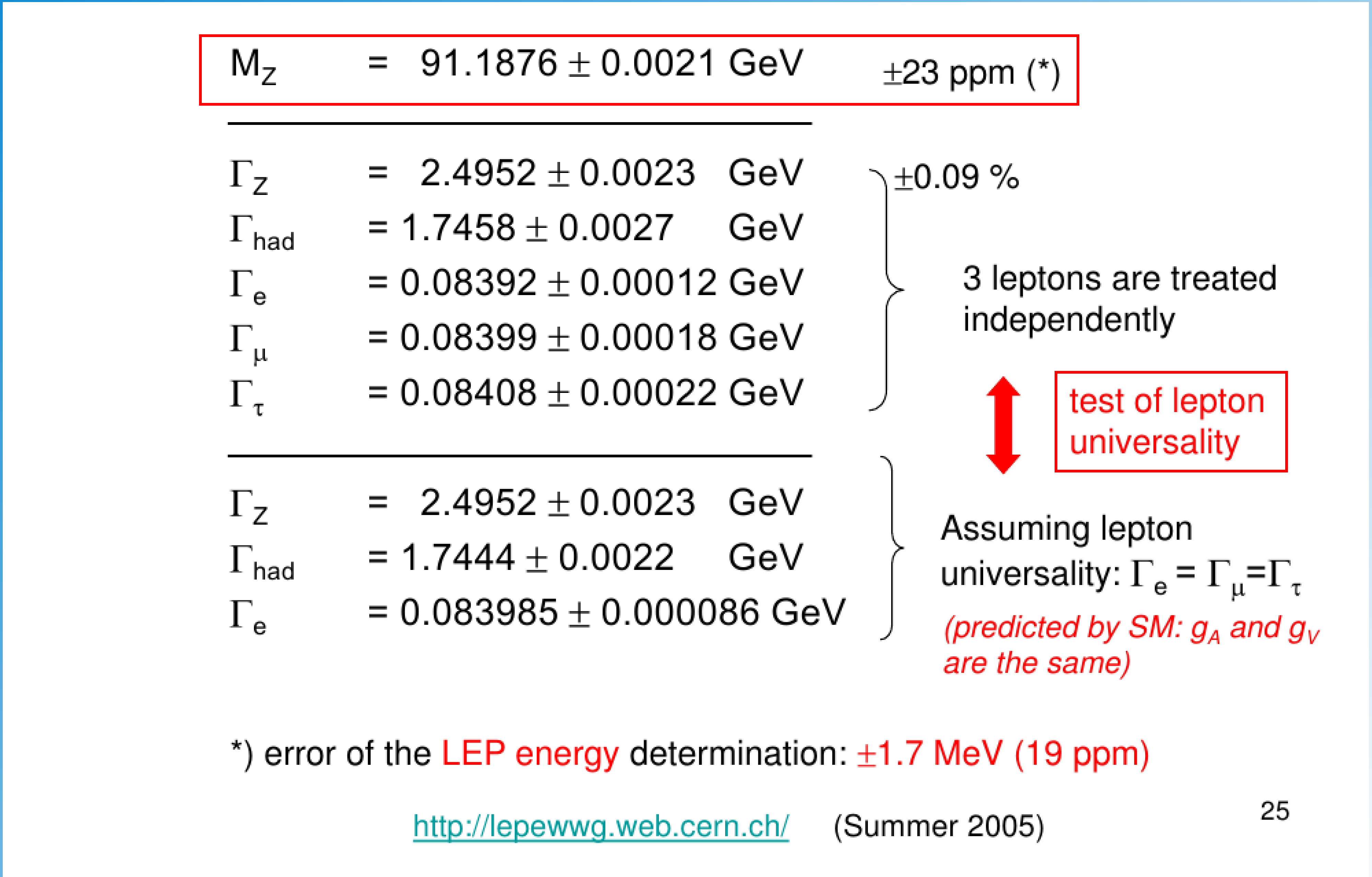


Effect of t channel

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 ±0.09 %

$\Gamma_{had} = 1.7458 \pm 0.0027$ 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

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)

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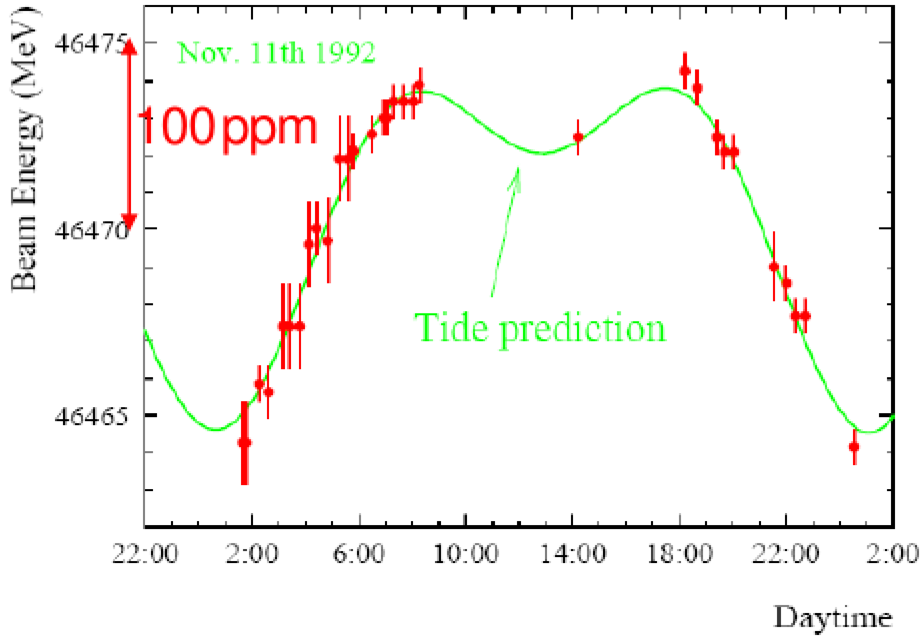
LEP Energy Calibration

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

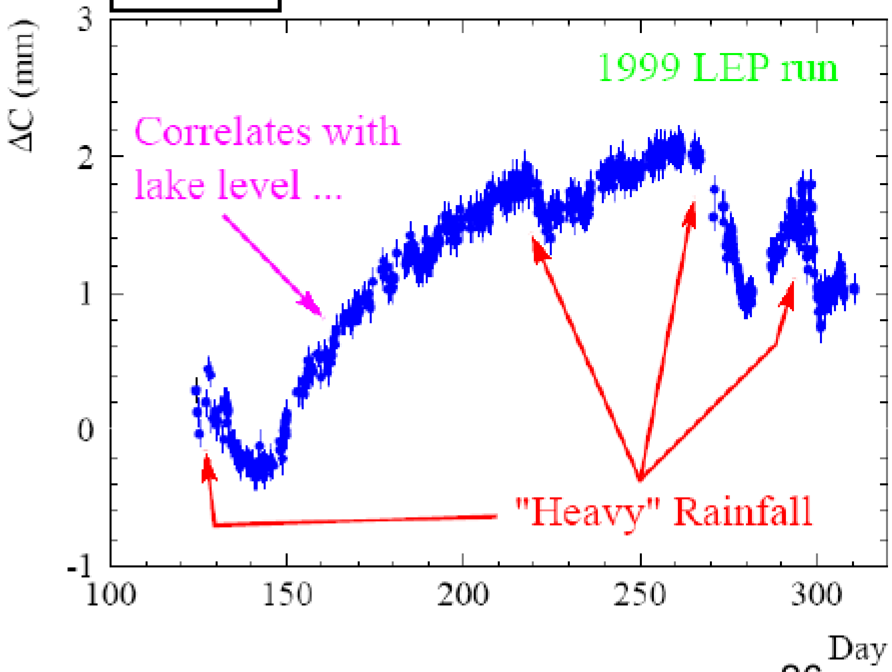
Changes of LEP circumference $\Delta C = 1\ldots2$ mm/27km ($4\ldots8 \times 10^{-8}$)

1992 Effect of moon



The total strain is 4×10^{-8} ($\Delta C =$ 1 mm)

1993 Effect of lake



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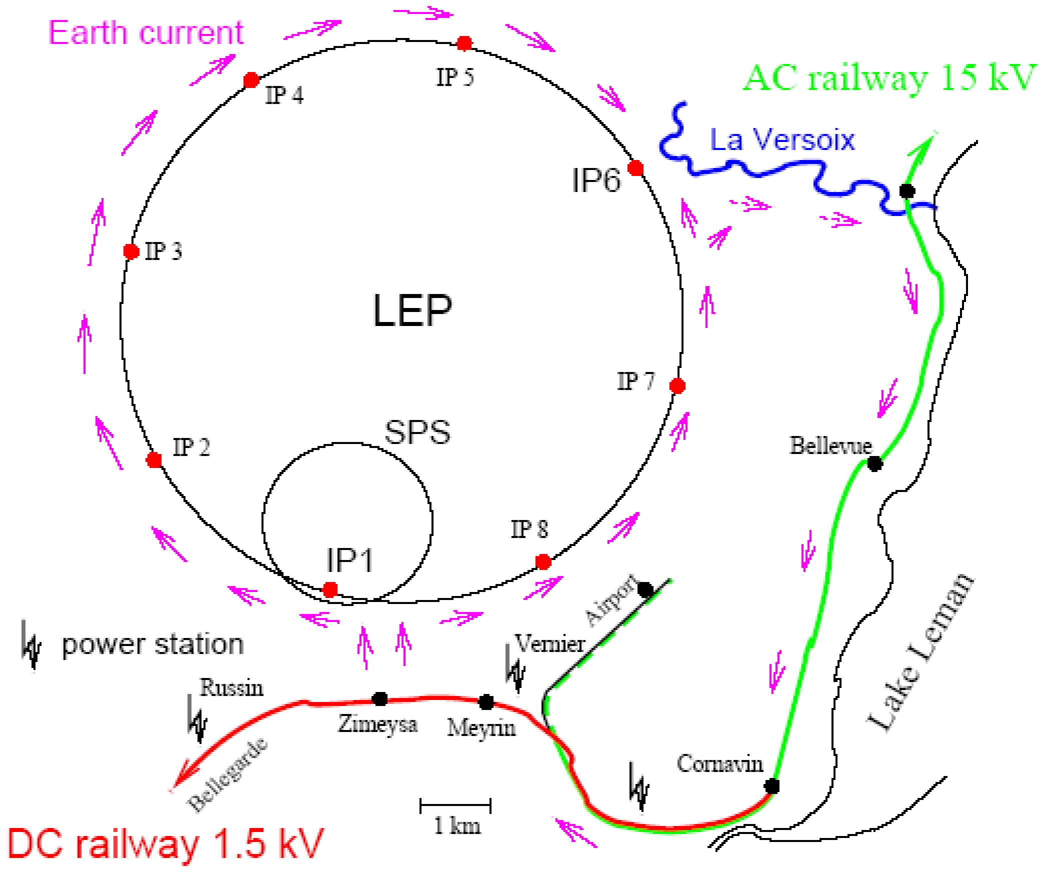
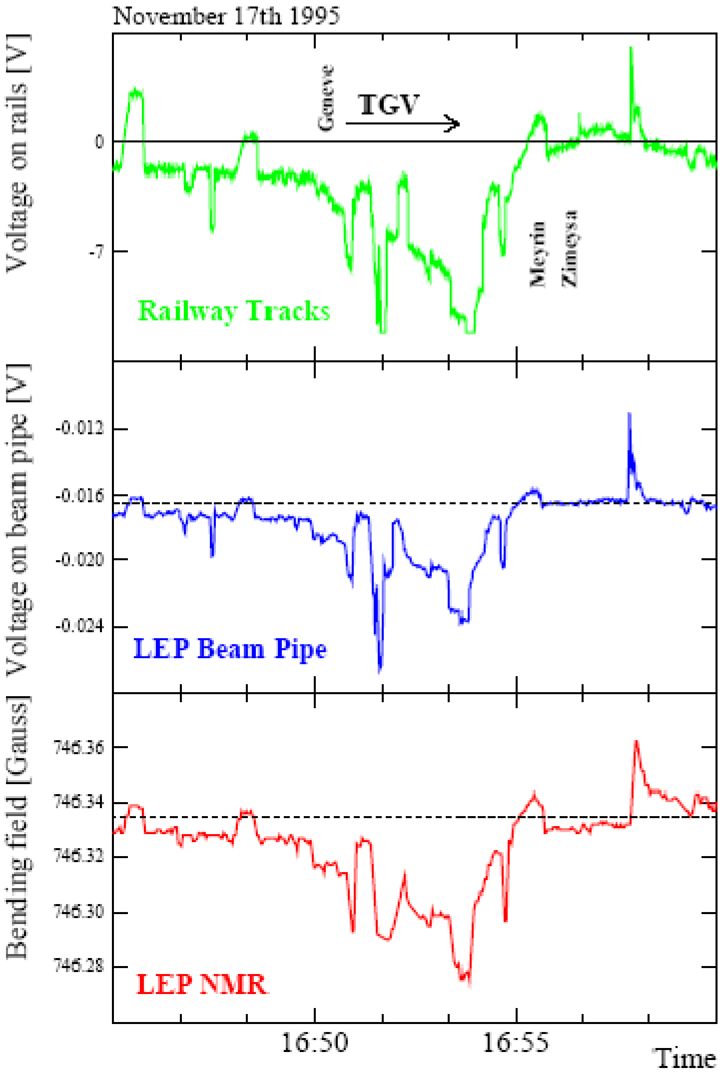
TGV (Trains Grand Vitesse) Effect

Vagabonding currents from trains





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

Number Light Neutrino Generations

In the Standard Model:

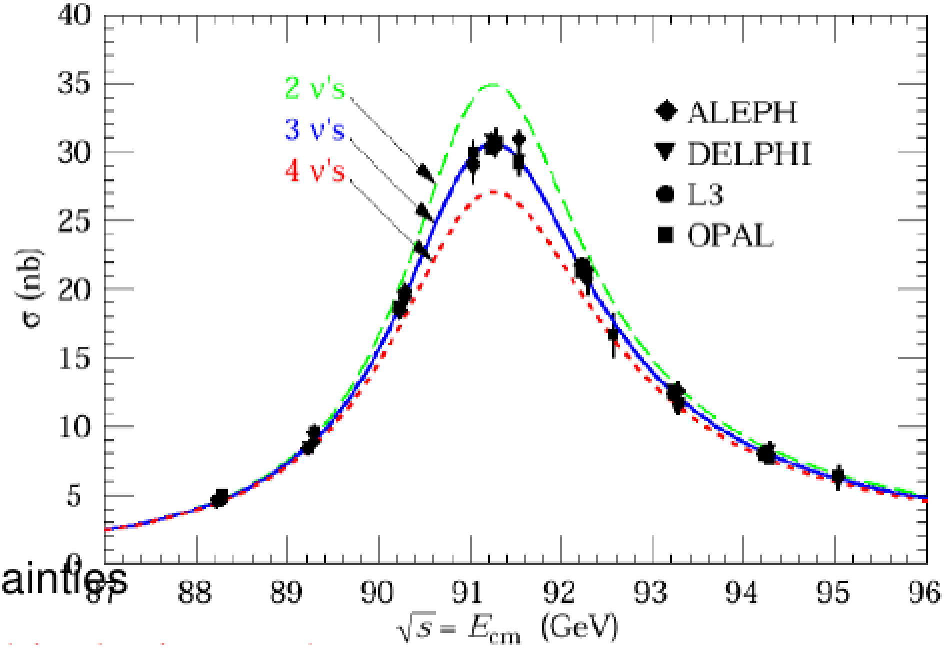
$$\Gamma_Z = \Gamma_{had} + 3 \cdot \Gamma_\ell + \underbrace{N_\nu \cdot \Gamma_\nu}_{\text{invisible } : \Gamma_{inv}} \rightarrow \left\{ \begin{array}{l} e^+ e^- \rightarrow Z \rightarrow \nu_e \bar{\nu}_e \\ e^+ e^- \rightarrow Z \rightarrow \nu_\mu \bar{\nu}_\mu \\ e^+ e^- \rightarrow Z \rightarrow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

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

To determine the number of light neutrino generations:

$$\boxed{N_\nu = \frac{\Gamma_{inv}}{\Gamma_{\nu,SM}}} = \underbrace{\left(\frac{\Gamma_{inv}}{\Gamma_\ell}\right)_{exp}}_{5.9431 \pm 0.0163} \cdot \underbrace{\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{SM}}_{=1/1.991 \pm 0.001}$$

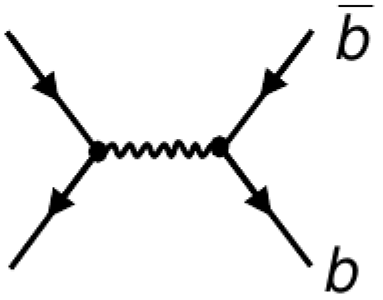
(small theo. uncertainties from m_{top} M_H)



$$\boxed{N_\nu = 2.9840 \pm 0.0082}$$

No room for new physics: Z→new

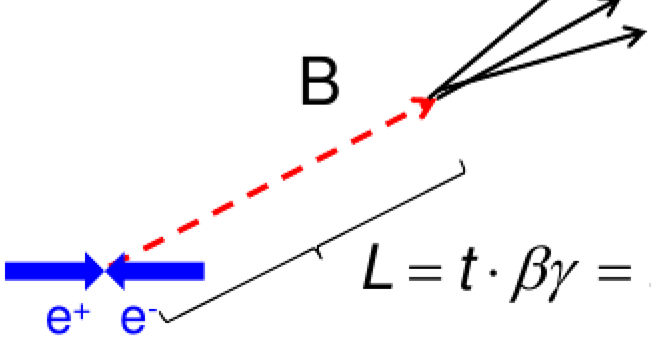
Heavy Quark production



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

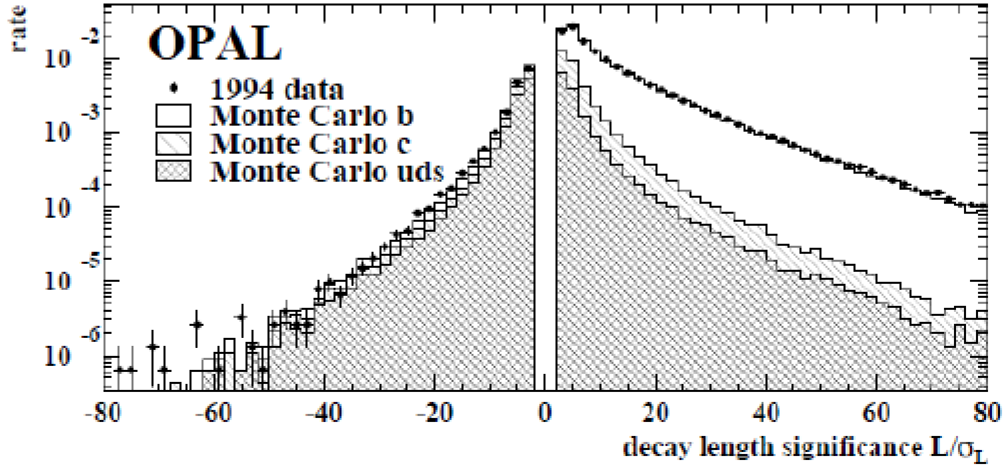
Identification of b-Quark events:

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

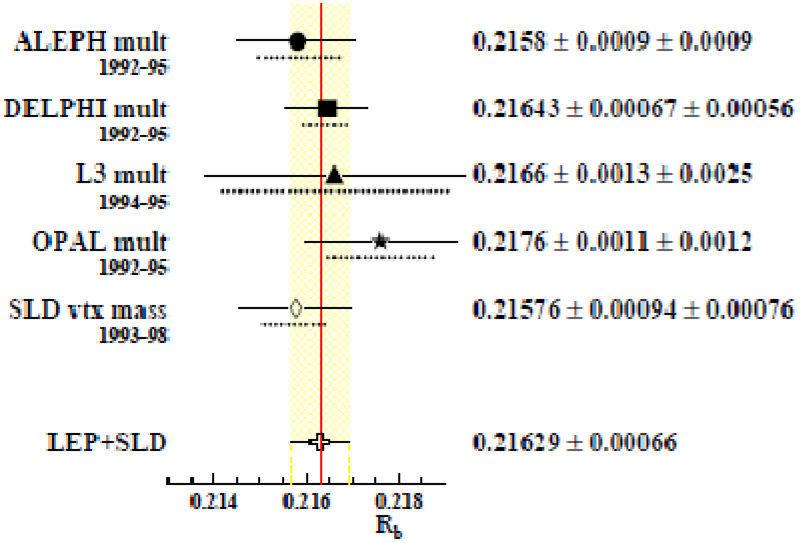


$$L = t \cdot \beta\gamma = t \cdot \frac{p_B}{m_B}$$

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

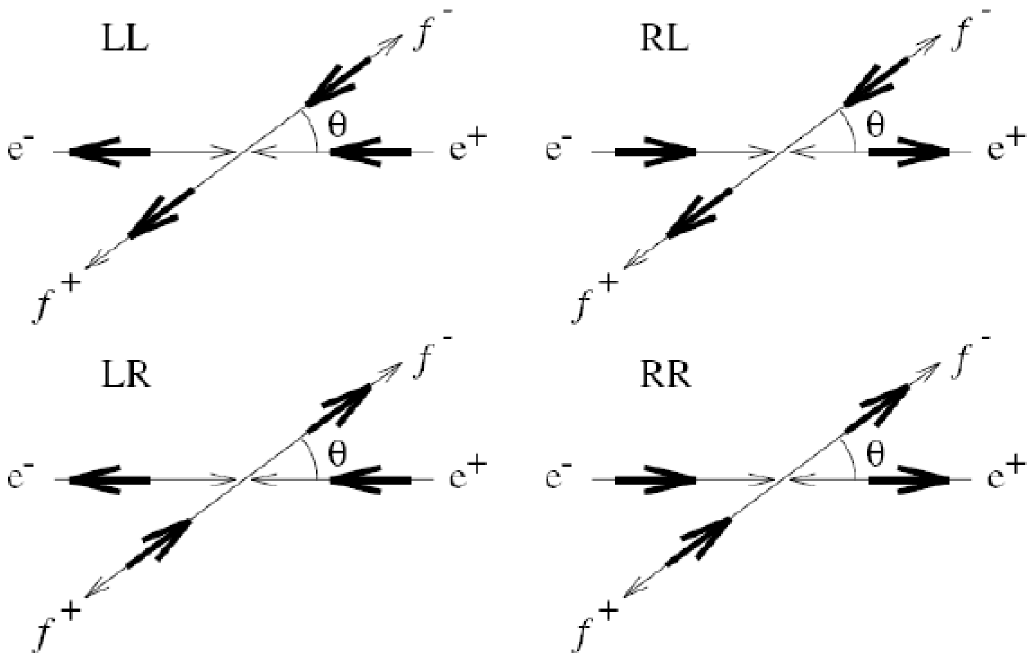


Significance = L / error



ratio of Z decays to b

Helicity Amplitudes and Asymmetries



J=1

Observables:

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

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

Forward-backward asym. (final)

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

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

Left right asym. (initial)

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

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

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fermion polarization (final)

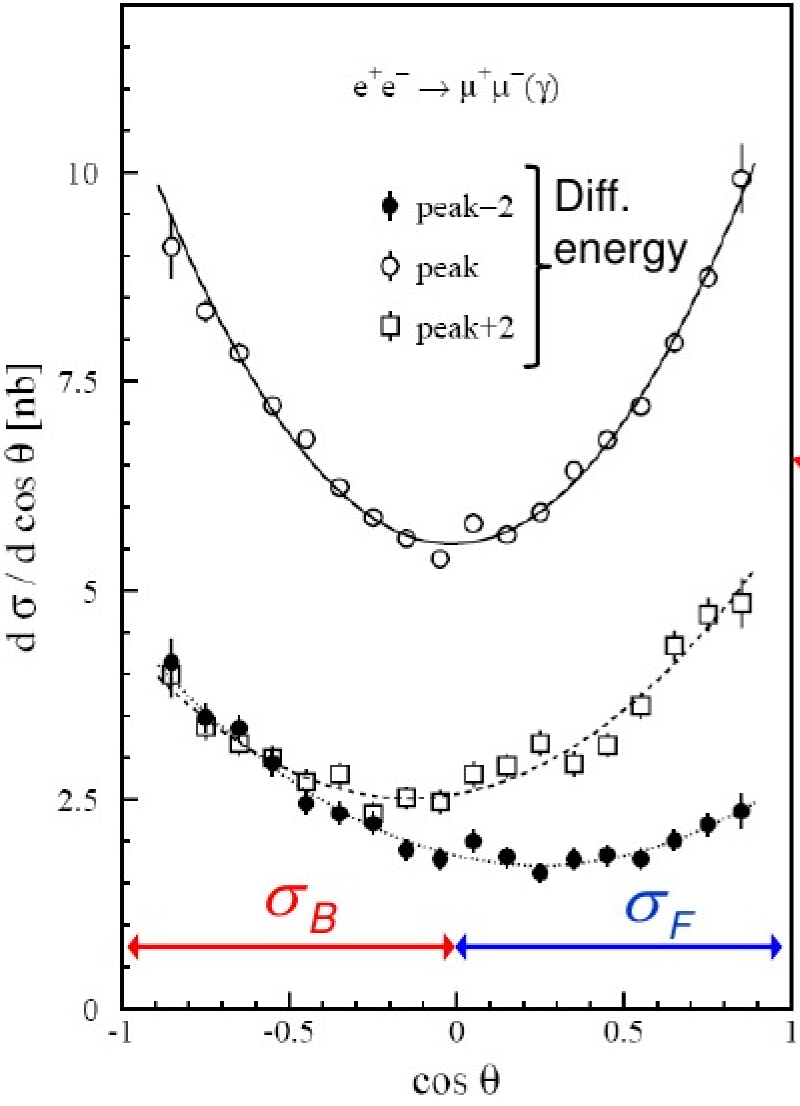
Forward-Backward Asymmetry

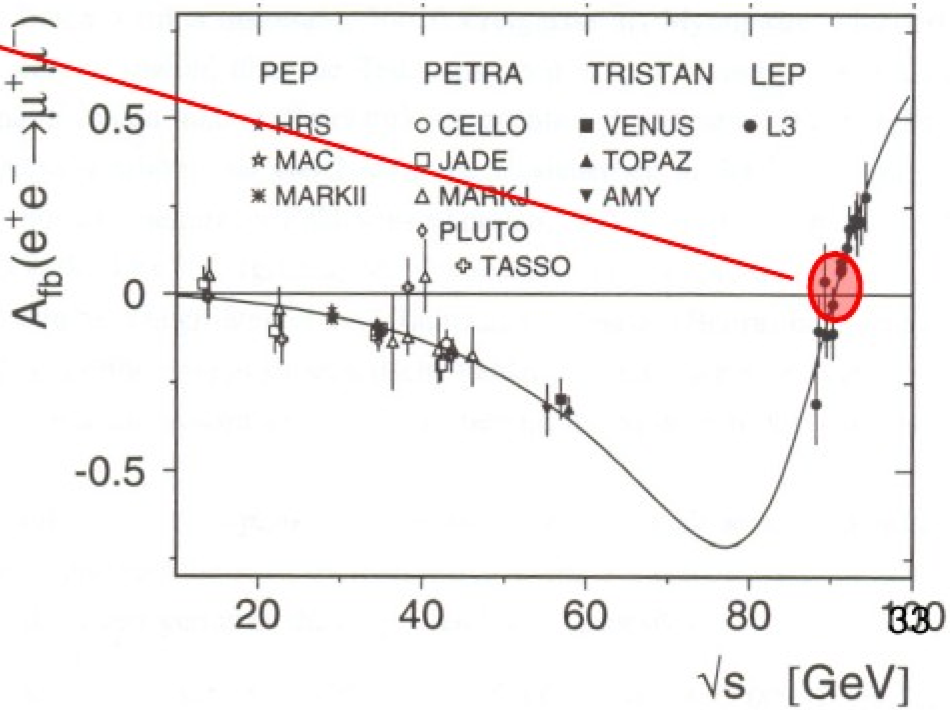
$$\boxed{e^+ e^- \rightarrow Z \rightarrow \mu^+ \mu^-}$$

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

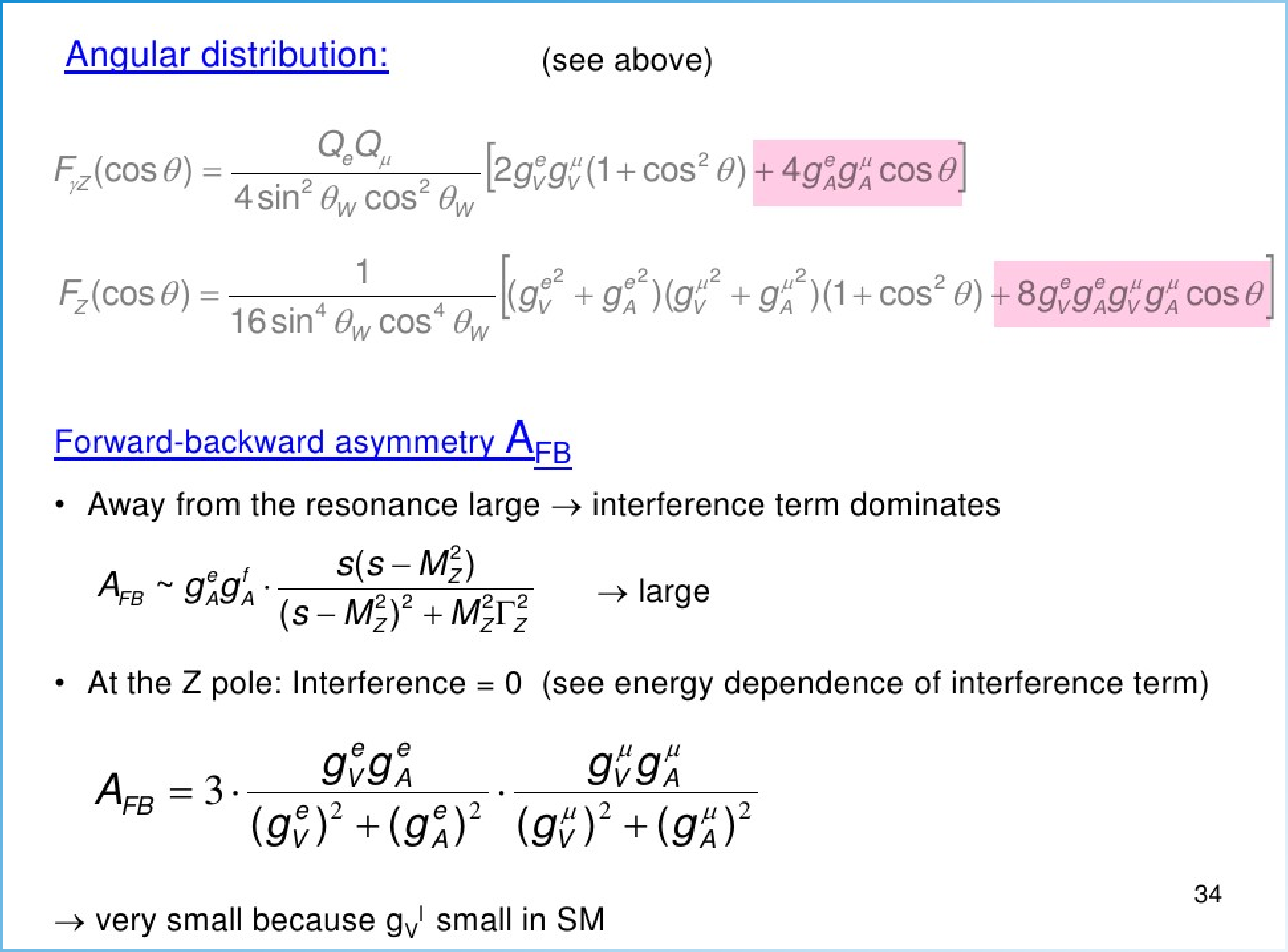
with $$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

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





Forward-Backward Asymmetry



Angular distribution:

(see above)

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

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

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)

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

→ very small because g_V^l small in SM

Forward-Backward Asymmetry

Asymmetrie at the Z pole

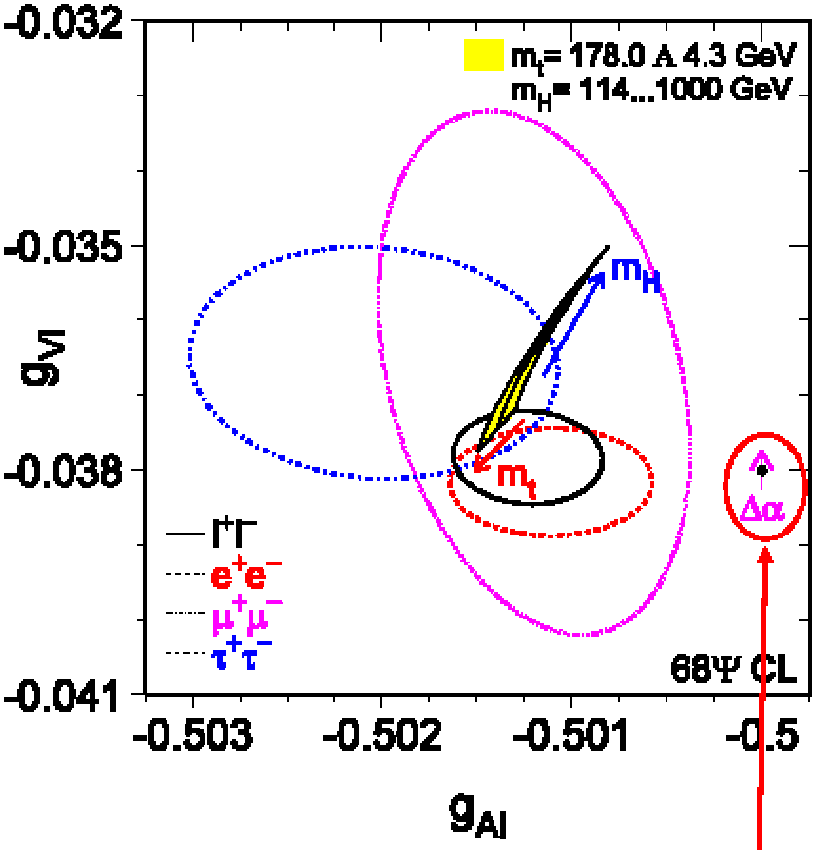
$$A_{FB} \sim g_A^e g_V^e g_A^f g_V^f$$

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”

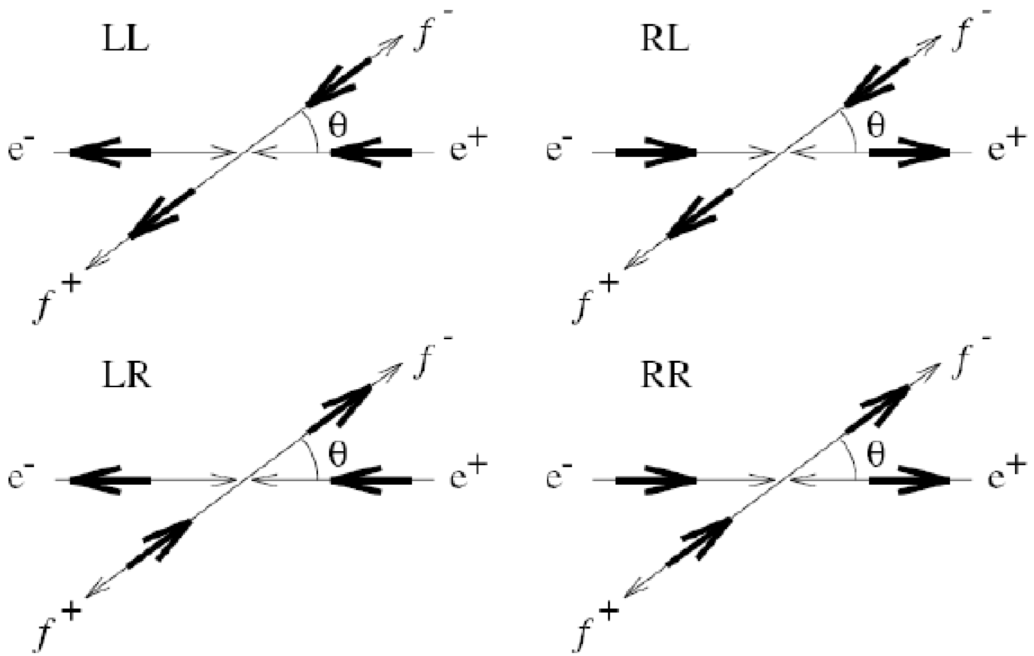


Lowest order SM prediction:

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

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

Helicity Amplitudes and Asymmetries



J=1

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$\sigma_F = \sigma_{LL} + \sigma_{RR}$ $\quad$ $\sigma_B = \sigma_{RL} + \sigma_{LR}$ $\quad$ $A_{FB} = \dfrac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$

Forward-backward asym. (final)

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

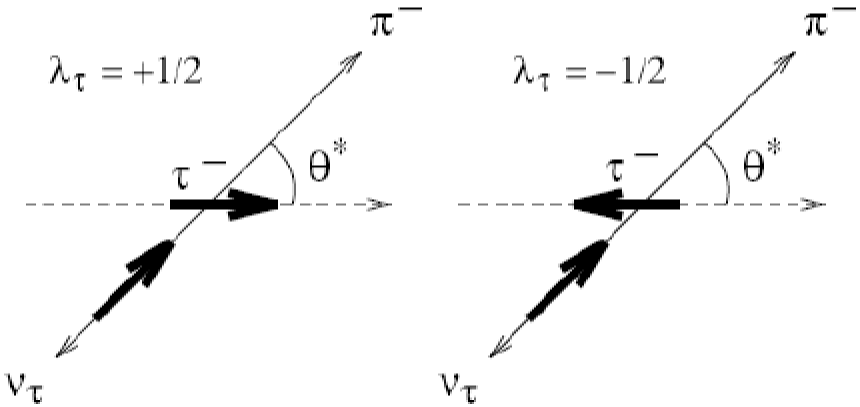
Left right asym. (initial)

$\sigma_- = \sigma_{LL} + \sigma_{RL}$ $\quad$ $\sigma_+ = \sigma_{RR} + \sigma_{LR}$ $\quad$ $\mathcal{P}_f = \dfrac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$

fermion polarization (final)

Experimental Method to measure tau polarization:

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

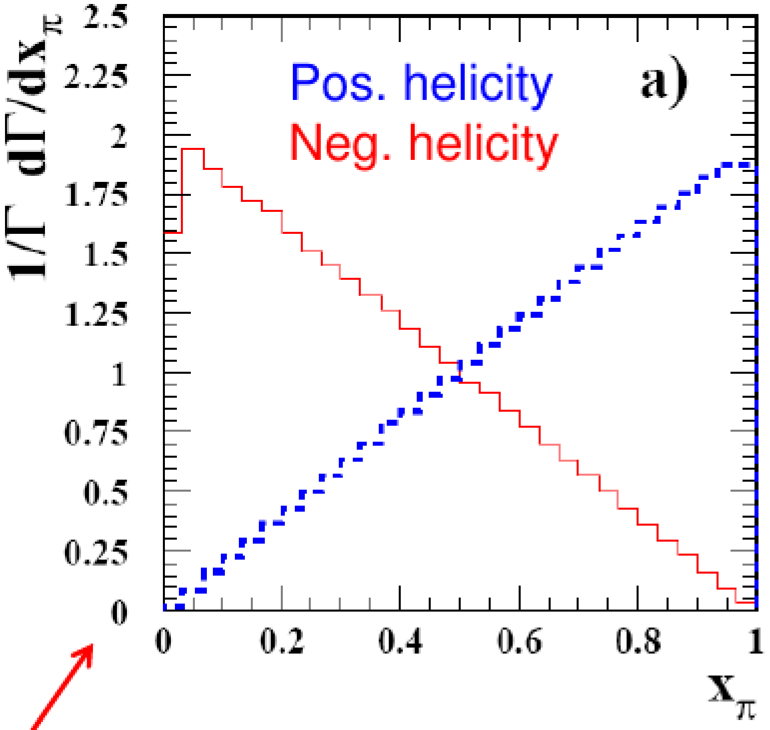


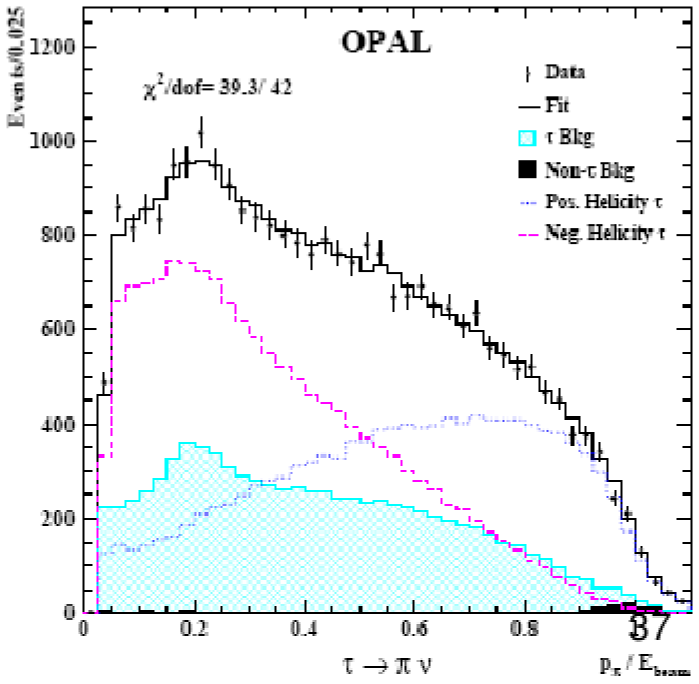
$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{1}{2}\left(1+\mathcal{P}_\tau\cos\theta^*\right)$$

Boost into lab frame

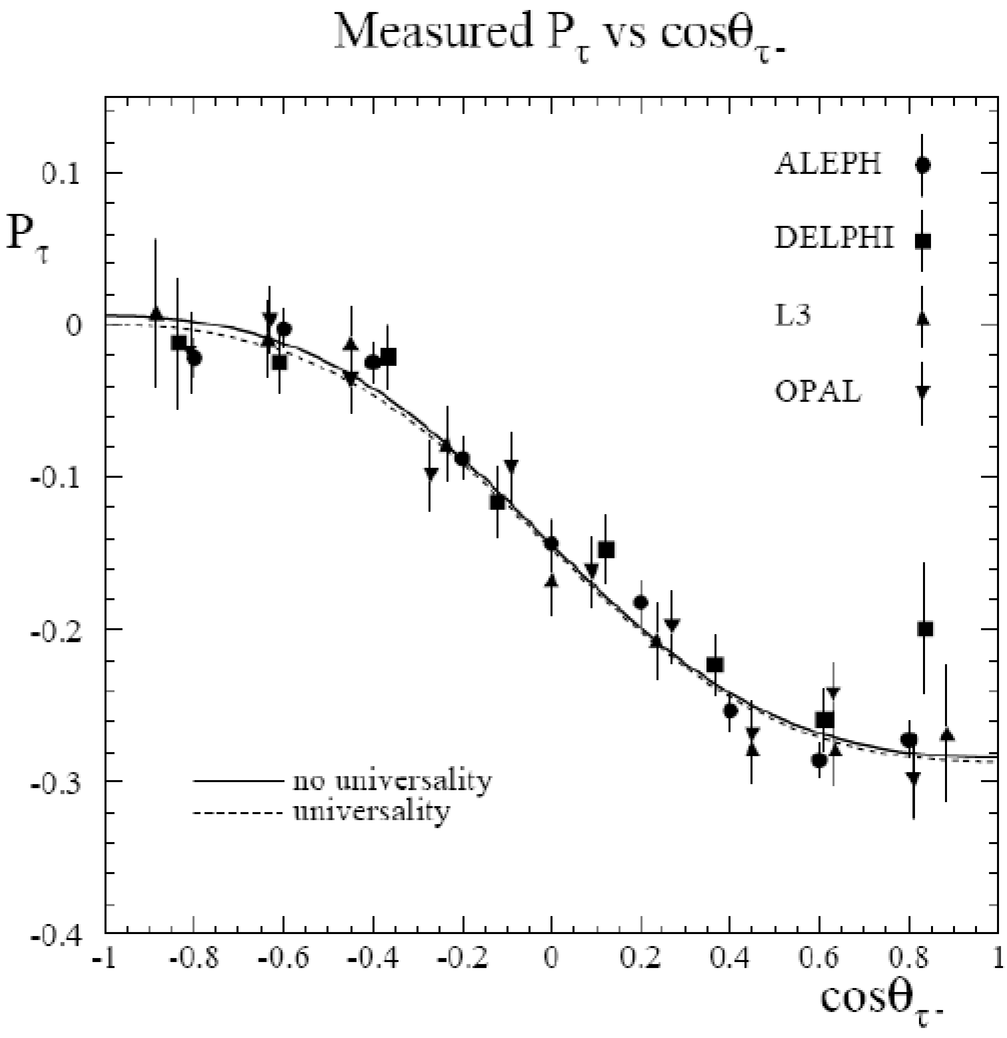
$$\boxed{\frac{1}{\Gamma}\frac{d\Gamma}{dx_\pi} = 1+\mathcal{P}_\tau(2x_\pi - 1) \qquad x_\pi = E_\pi / E_\tau}$$

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





Result Tau Polarisation

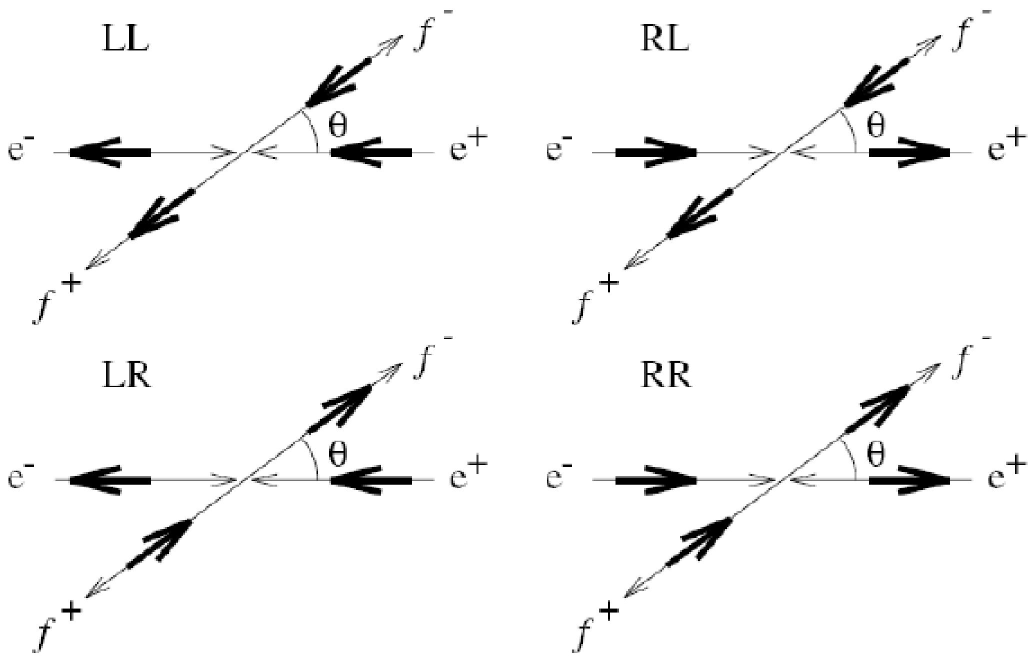


$$\mathcal{A}_\tau = 0.1439 \pm 0.0043$$
$$\mathcal{A}_e = 0.1498 \pm 0.0049$$
$$\mathcal{A}_\ell = 0.1465 \pm 0.0033$$

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

hep-ex/0509008

Helicity Amplitudes and Asymmetries



J=1

Observables:

$\sigma_F = \sigma_{LL} + \sigma_{RR}$ $\sigma_B = \sigma_{RL} + \sigma_{LR}$ $$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

Forward-backward asym. (final)

$\sigma_L = \sigma_{LL} + \sigma_{LR}$ $\sigma_R = \sigma_{RL} + \sigma_{RR}$ $$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Left right asym. (initial)

$\sigma_- = \sigma_{LL} + \sigma_{RL}$ $\sigma_+ = \sigma_{RR} + \sigma_{LR}$ $$\mathcal{P}_f = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

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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:

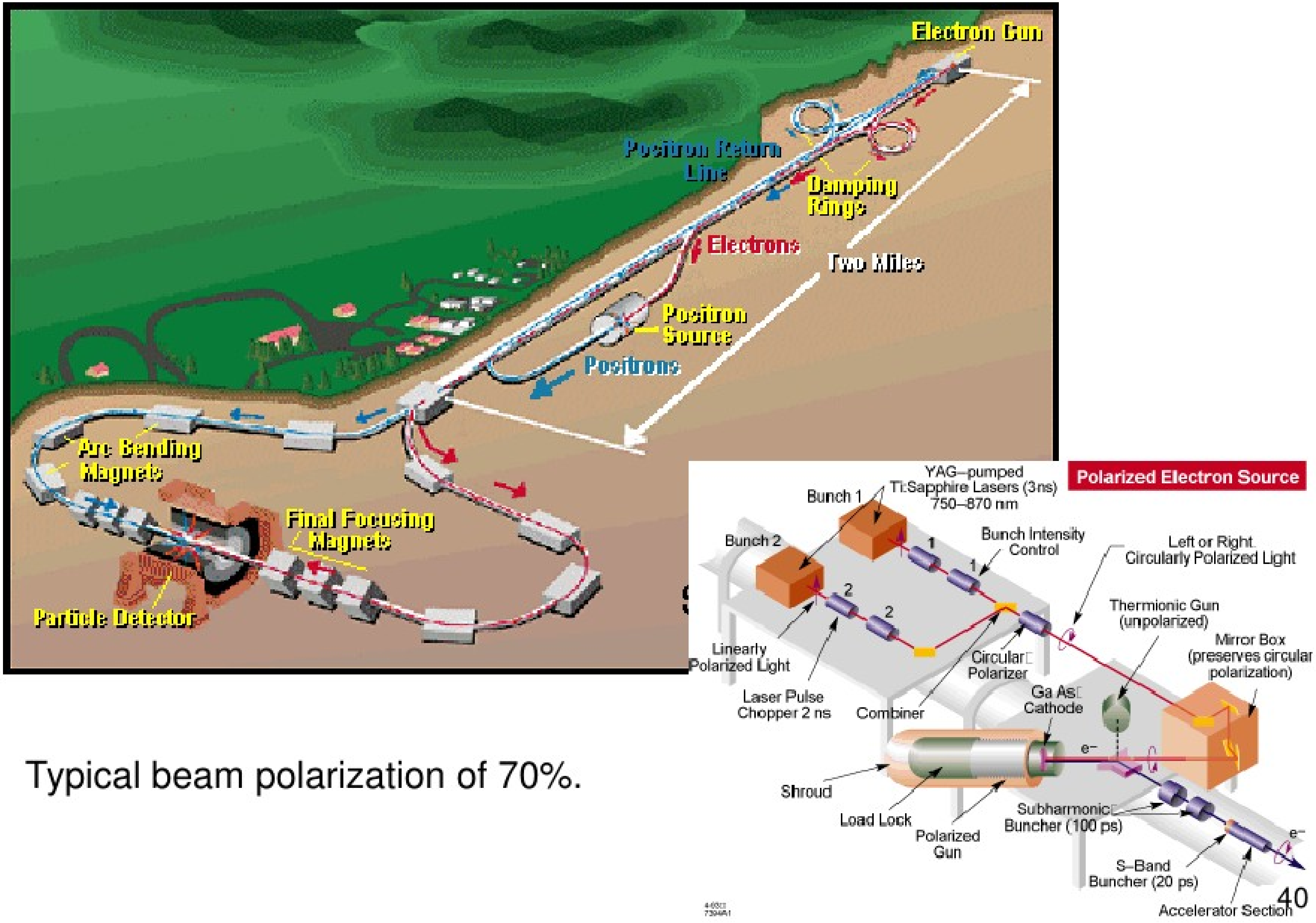
Polarization of
electron beam:
P~70 – 80%

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

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

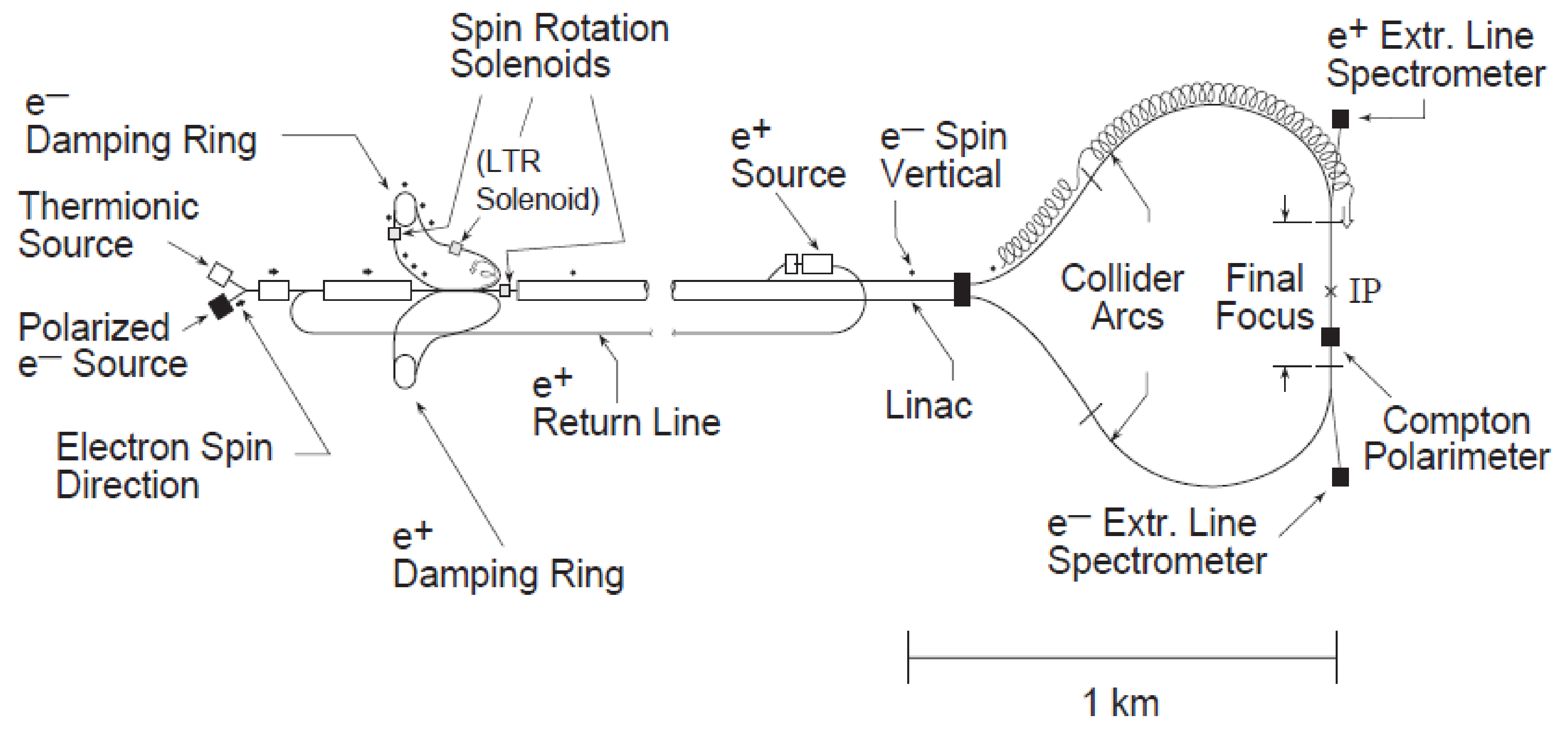
Powerful determination of $\sin^2\theta_w$.
Requires longitudinal polarization of colliding beams

SLAC Linear Accelerator

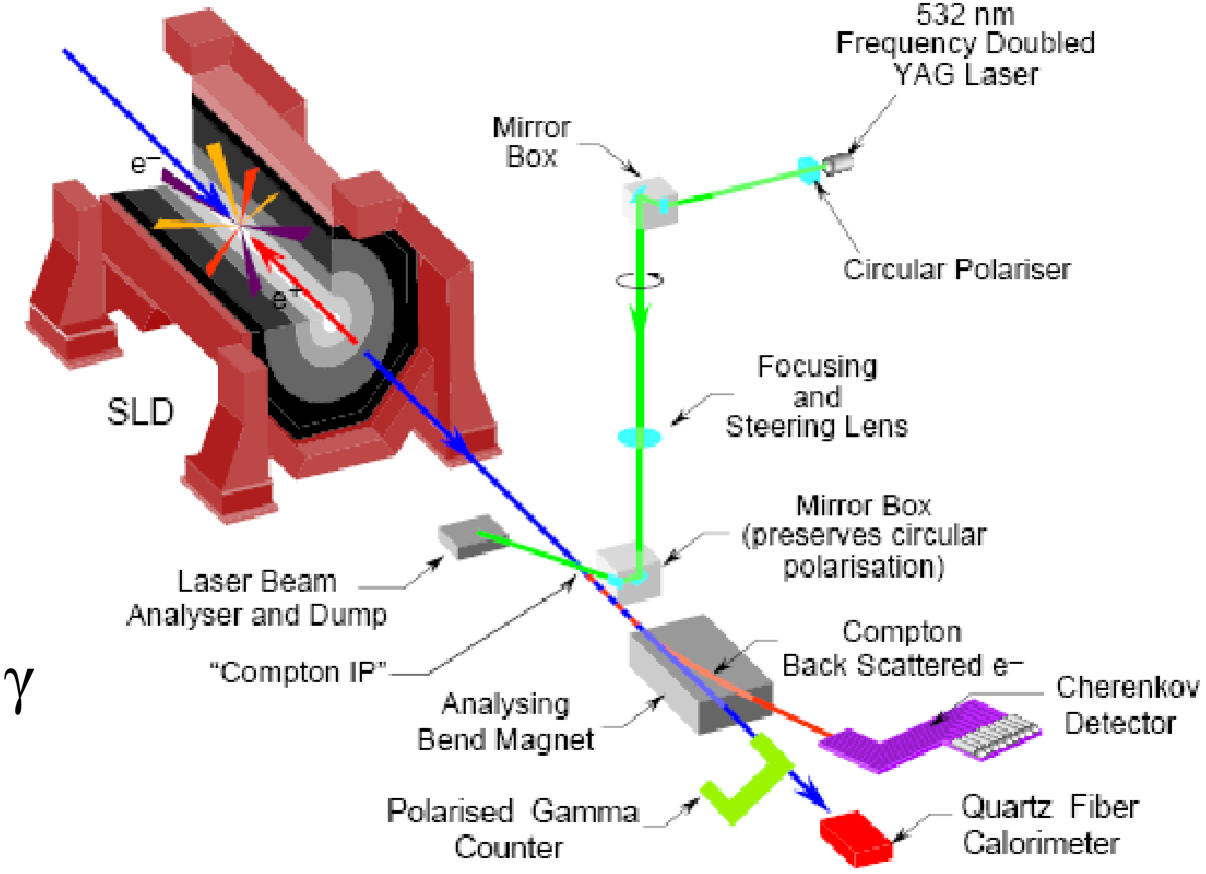


Typical beam polarization of 70%.

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.

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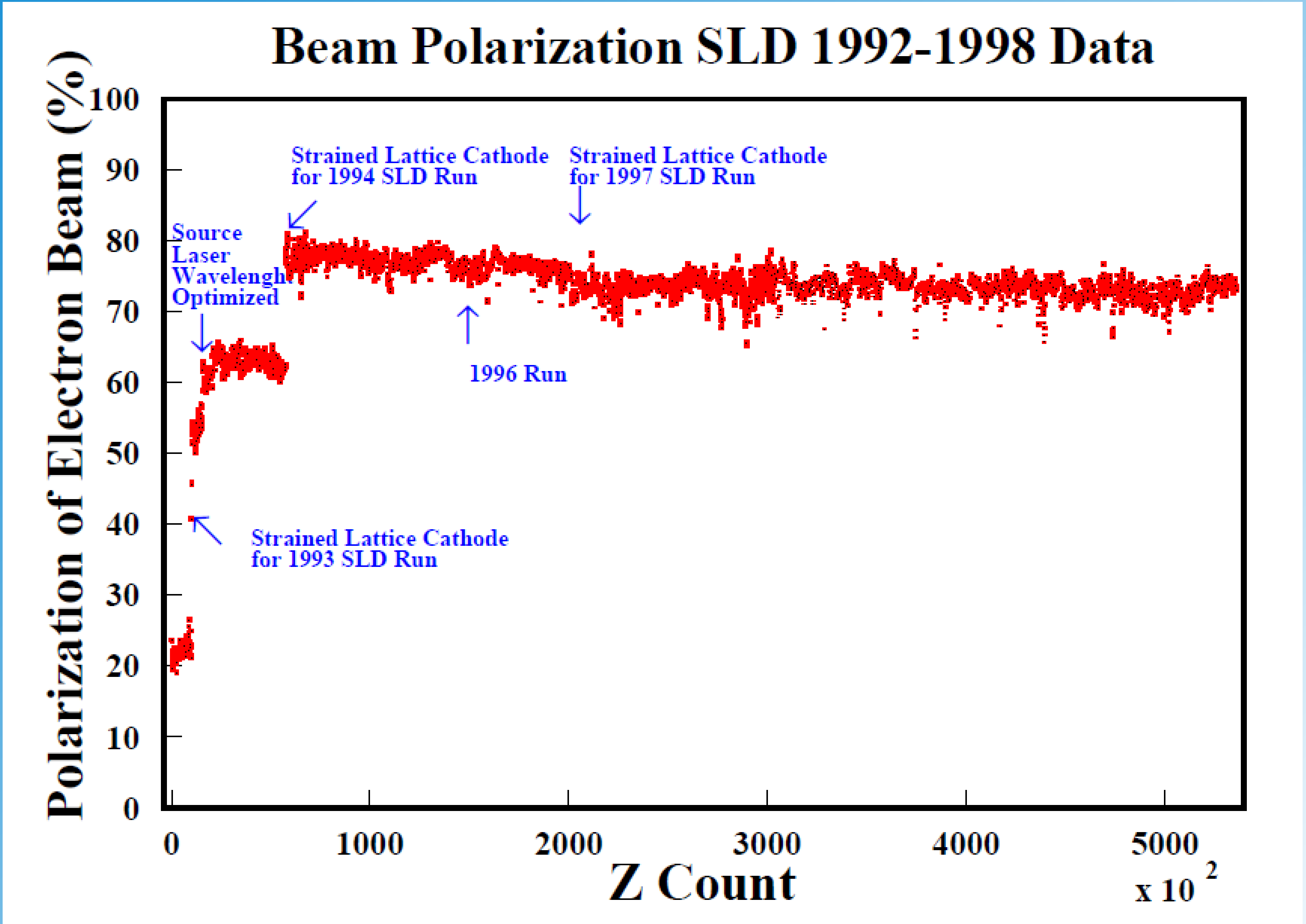
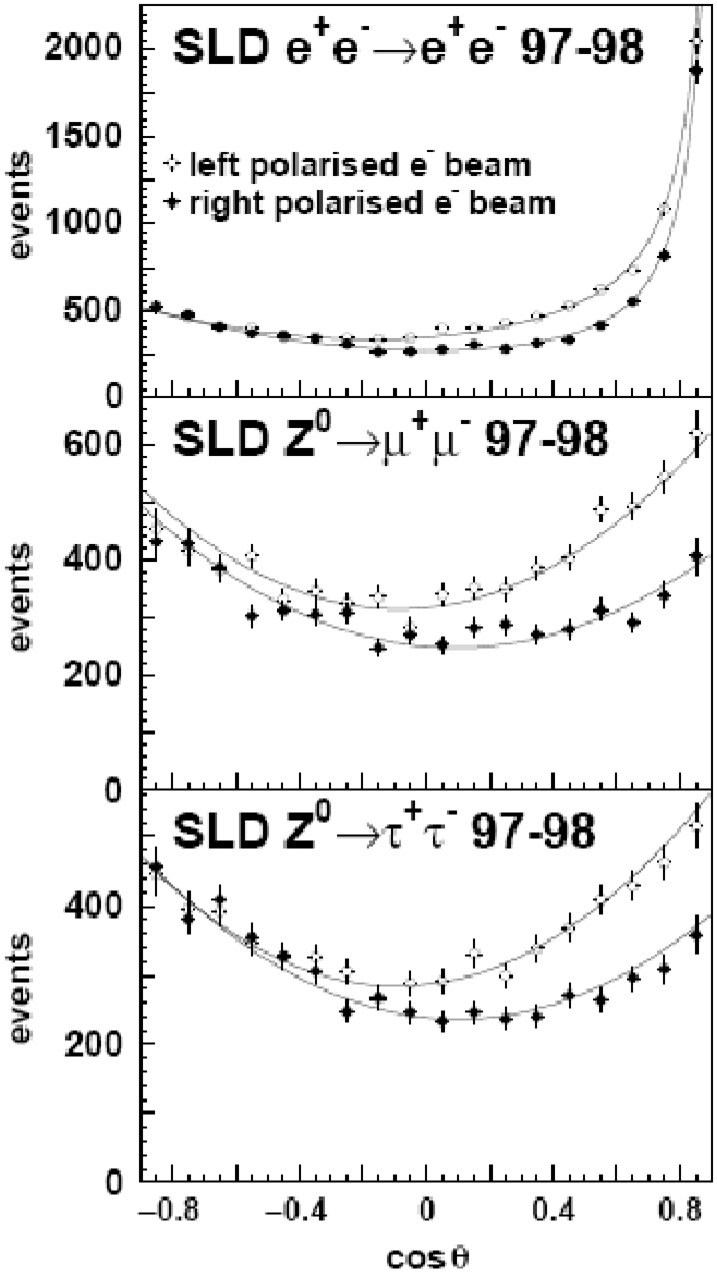
SLAC Electron Polarisation



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

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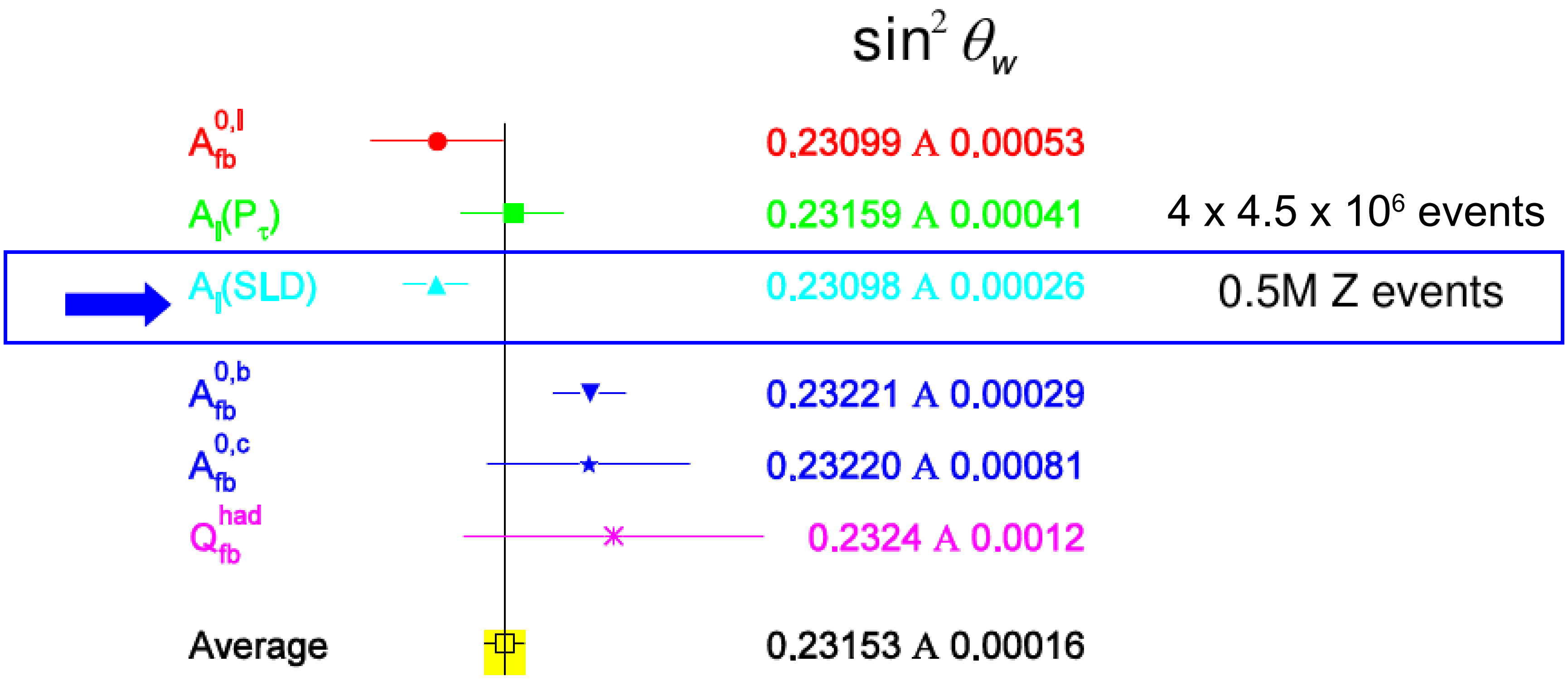
Results Weinberg Angle

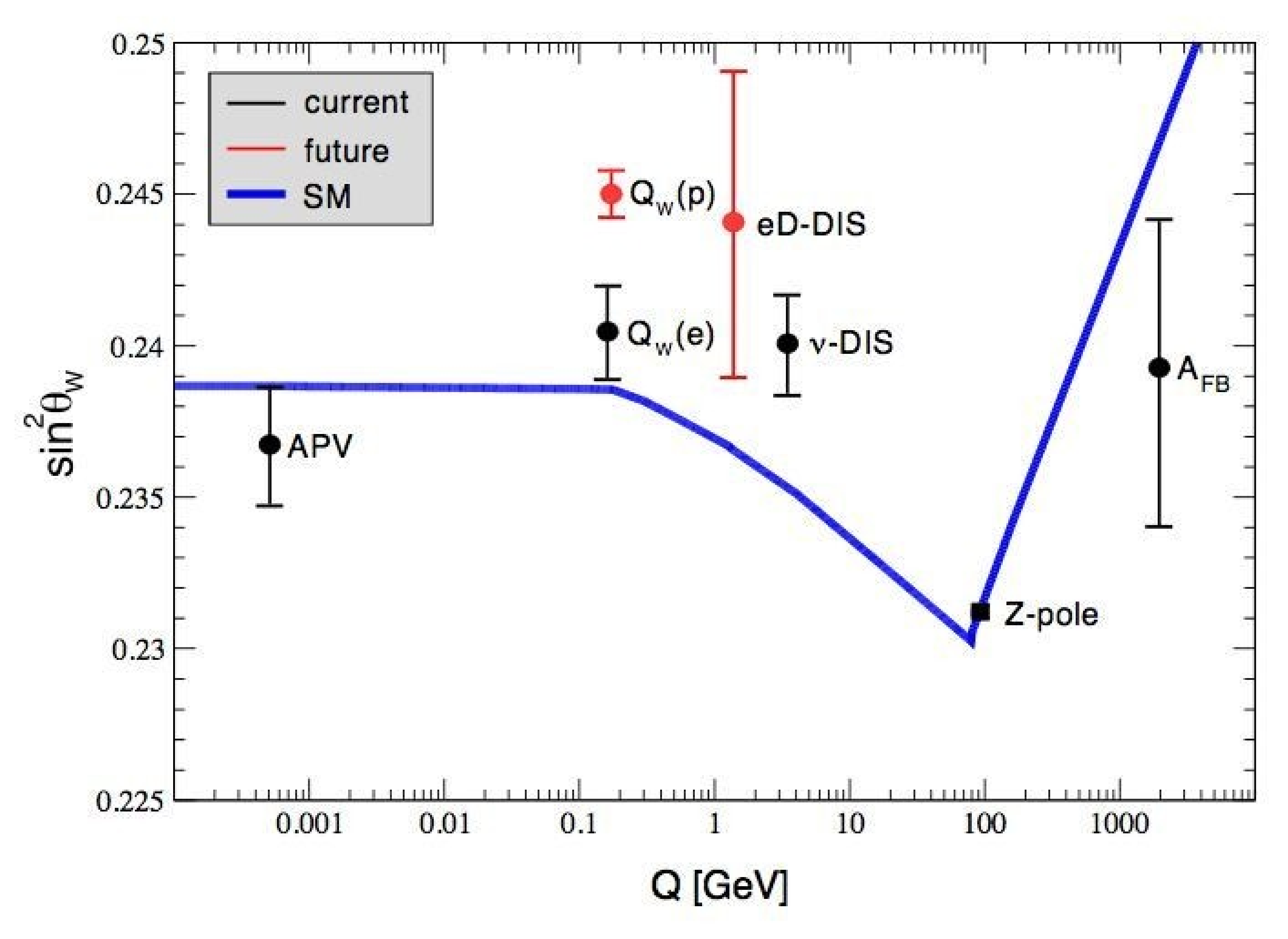


4 x 4.5 x 10^6 events

0.5M Z events

Despite the smaller statistics – SLD beats LEP in precision!

“Running” of Weinberg Angle



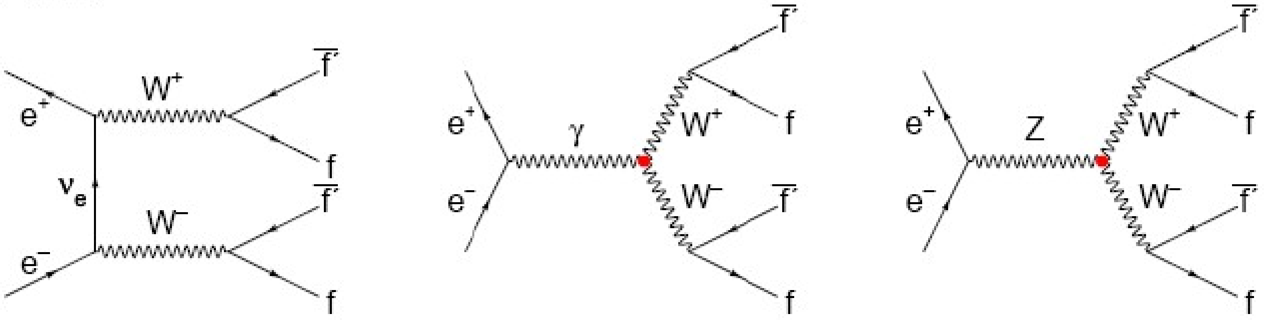
→ discussion later

LEP 2

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

$W^+ W^-$ Pair Production

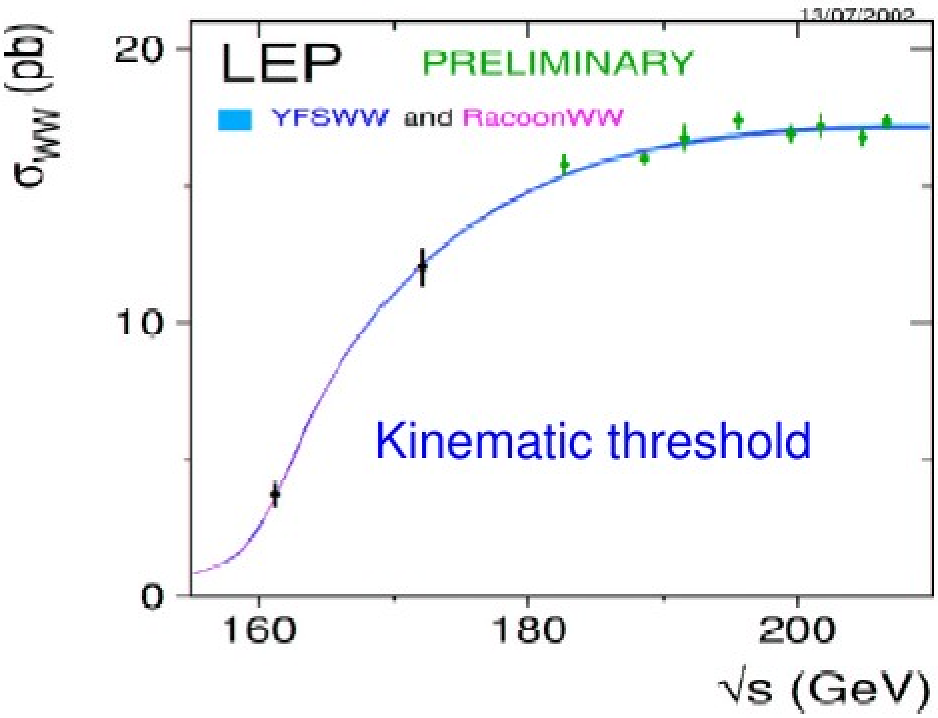
$$e^+e^- \rightarrow WW \rightarrow f\bar{f}f\bar{f}$$



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



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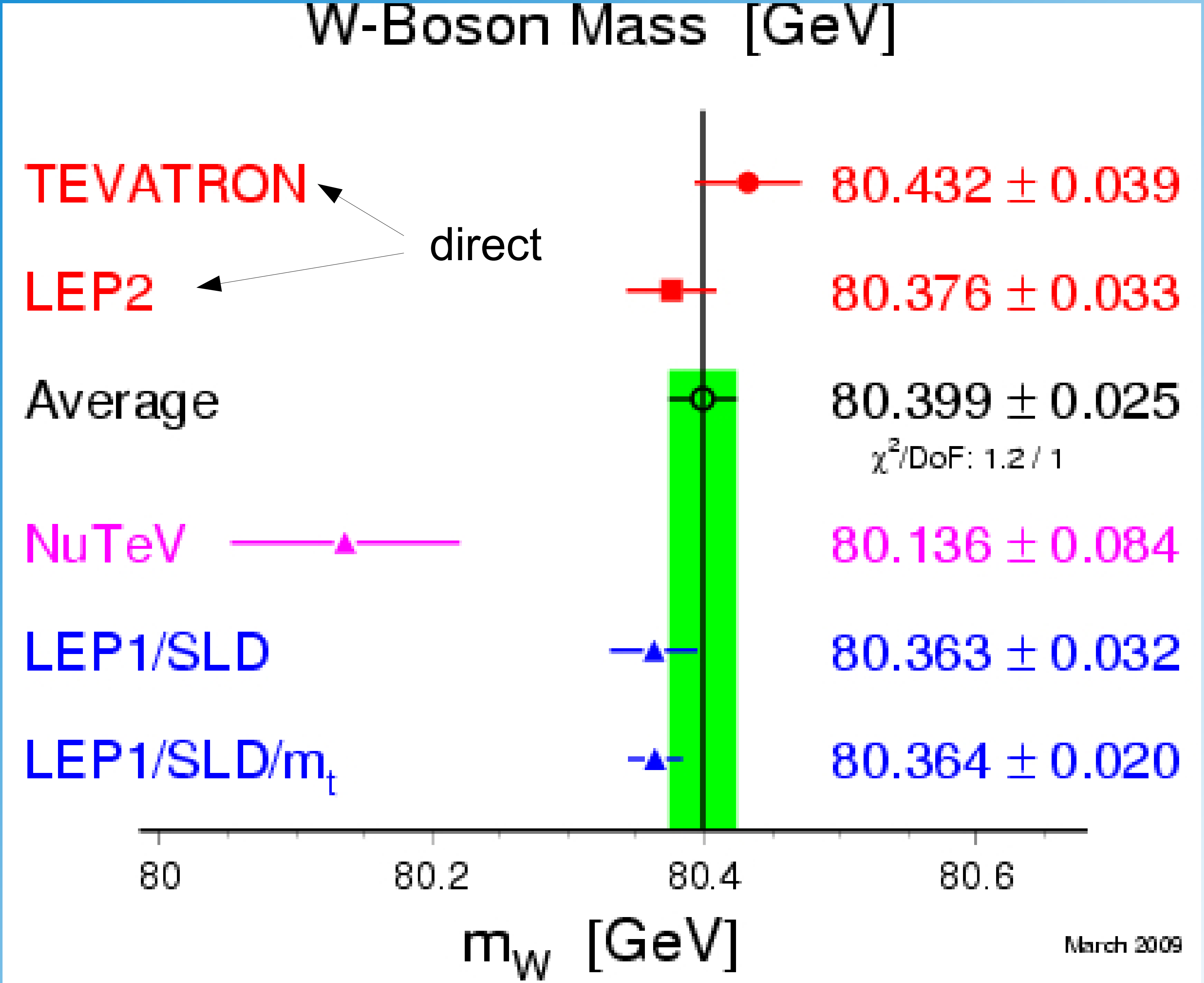
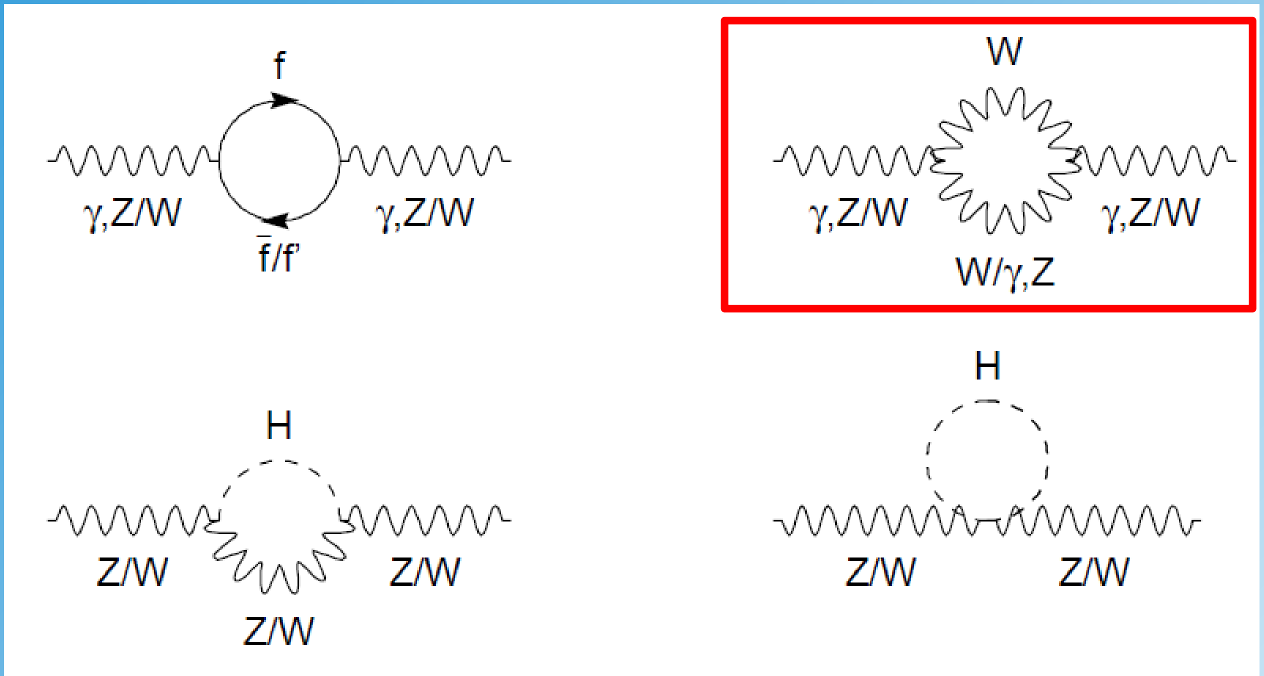
Electroweak Fit of the W-Boson Mass



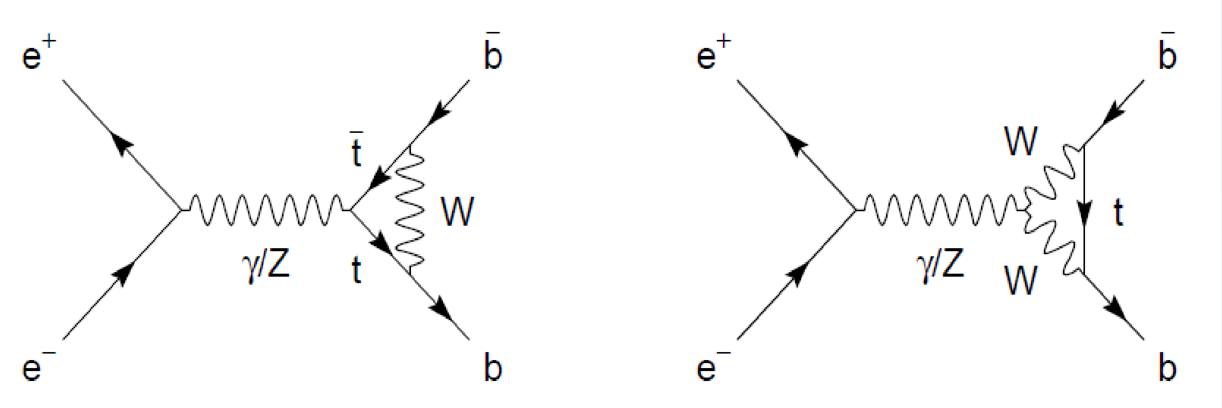
Indirect W-Mass Constraints from LEP1

W-mass also enters in virtual radiative corrections:

self-energy

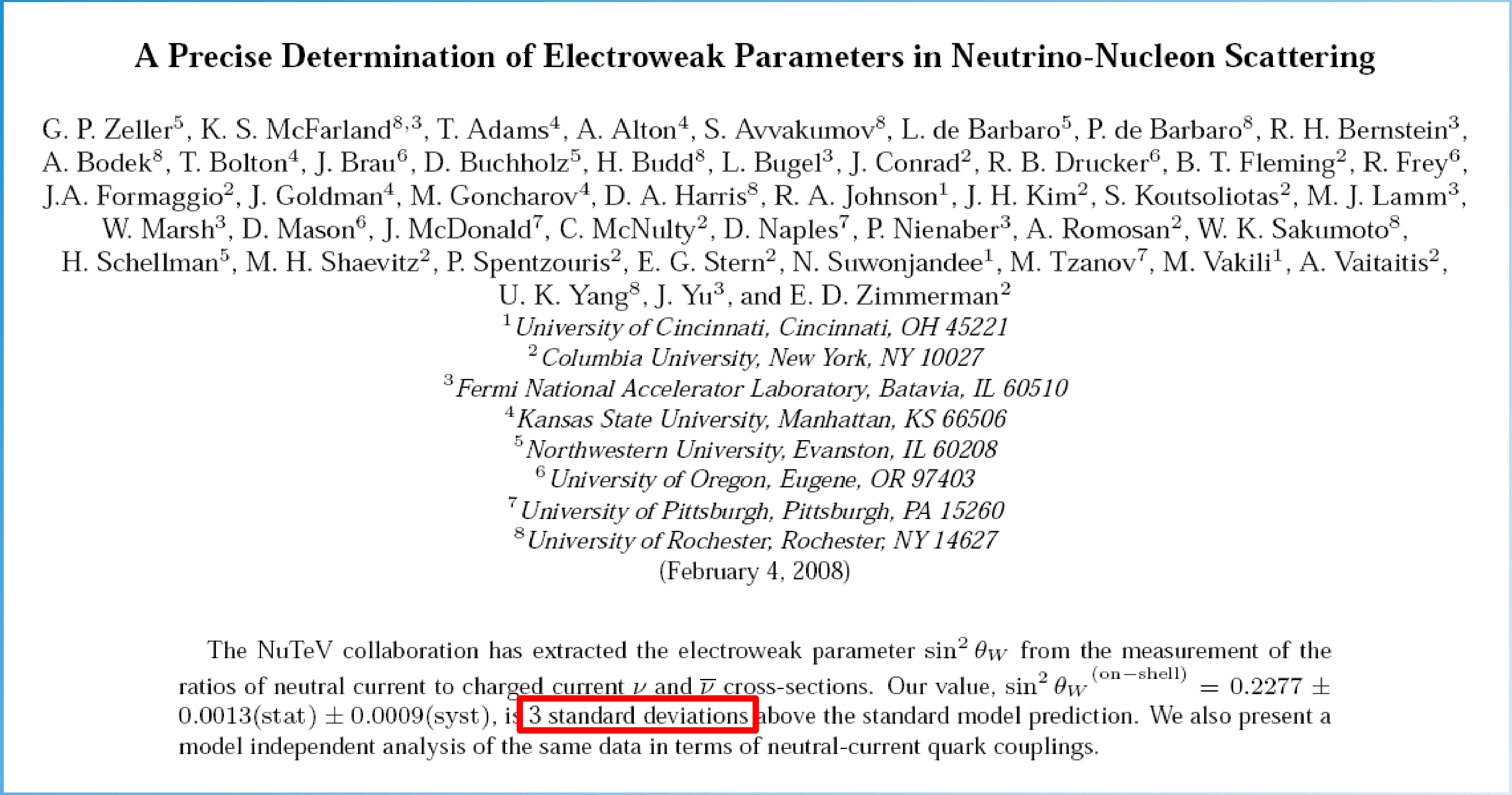


vertex correction



+ box diagrams

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)

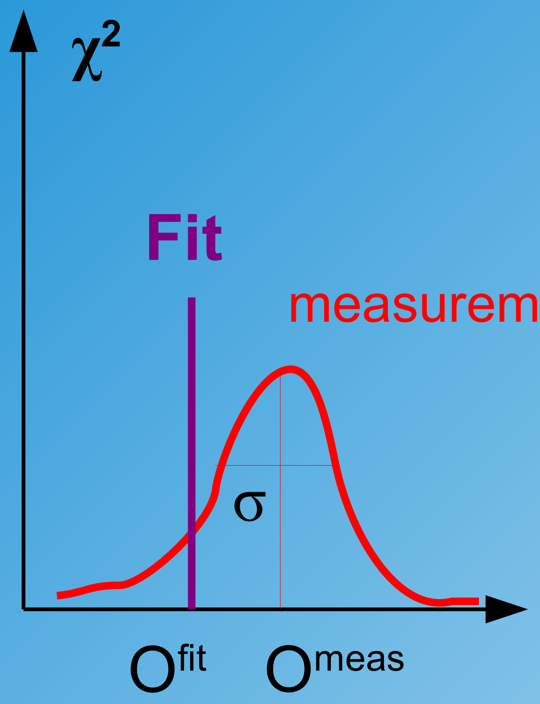
The NuTeV collaboration has extracted the electroweak parameter $\sin^2\theta_W$ from the measurement of the ratios of neutral current to charged current ν and $\overline{\nu}$ cross-sections. Our value, $\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, is 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.

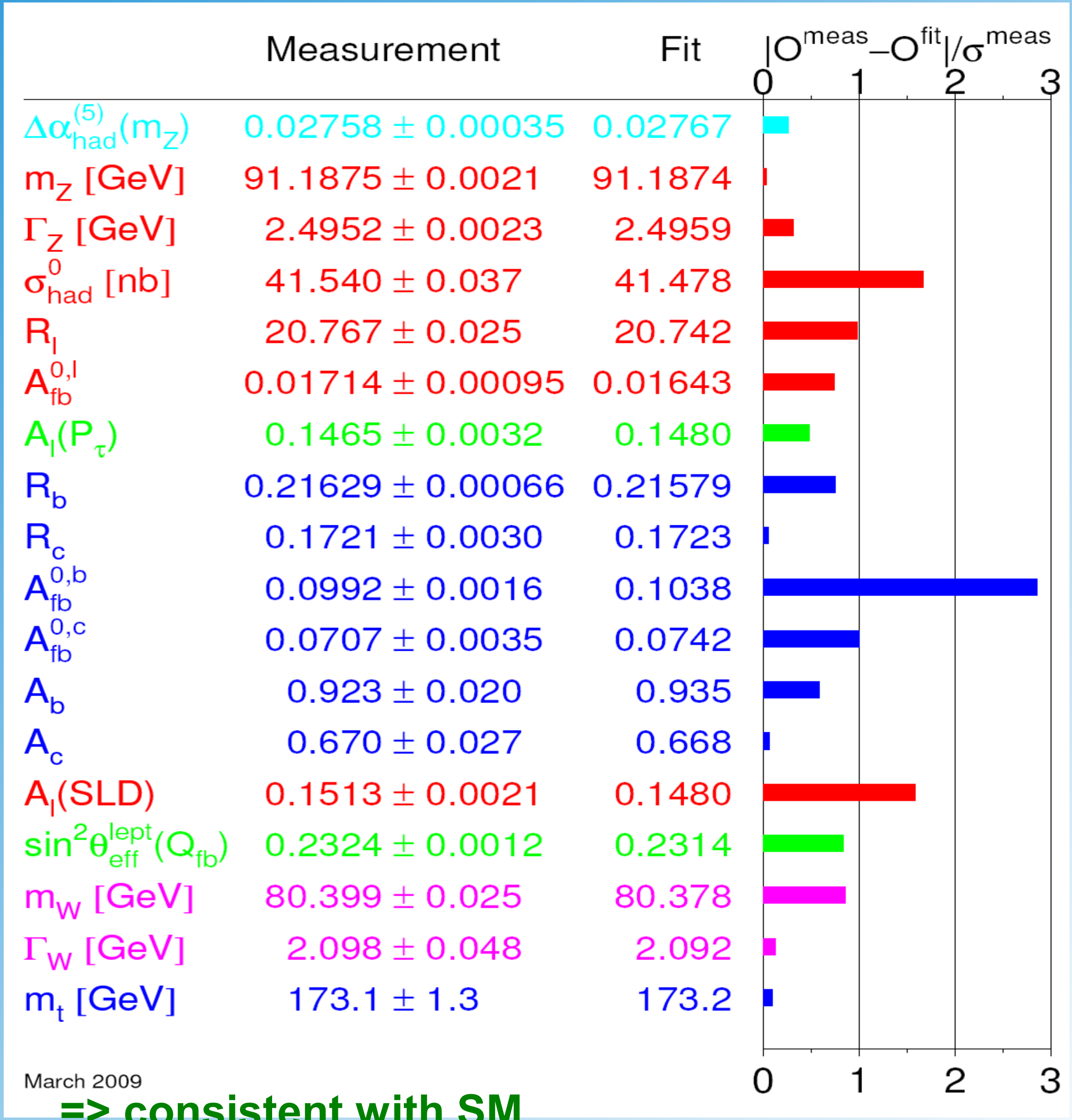
NuTev: $\sin^2\theta_W = 0.2277 \pm 0.0015$ (2003)

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

The SM pull plot

Z-pole parameters



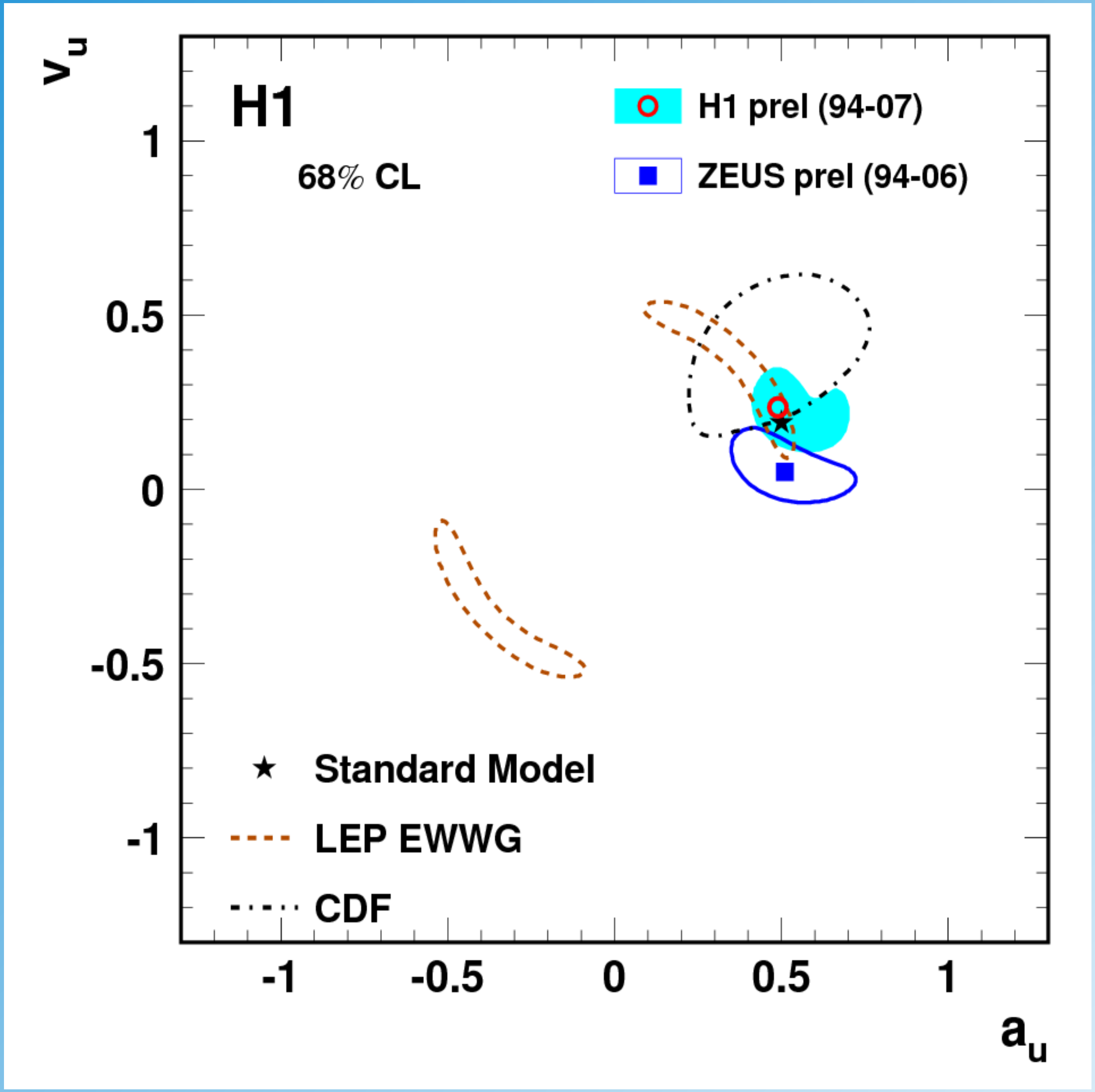


	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	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

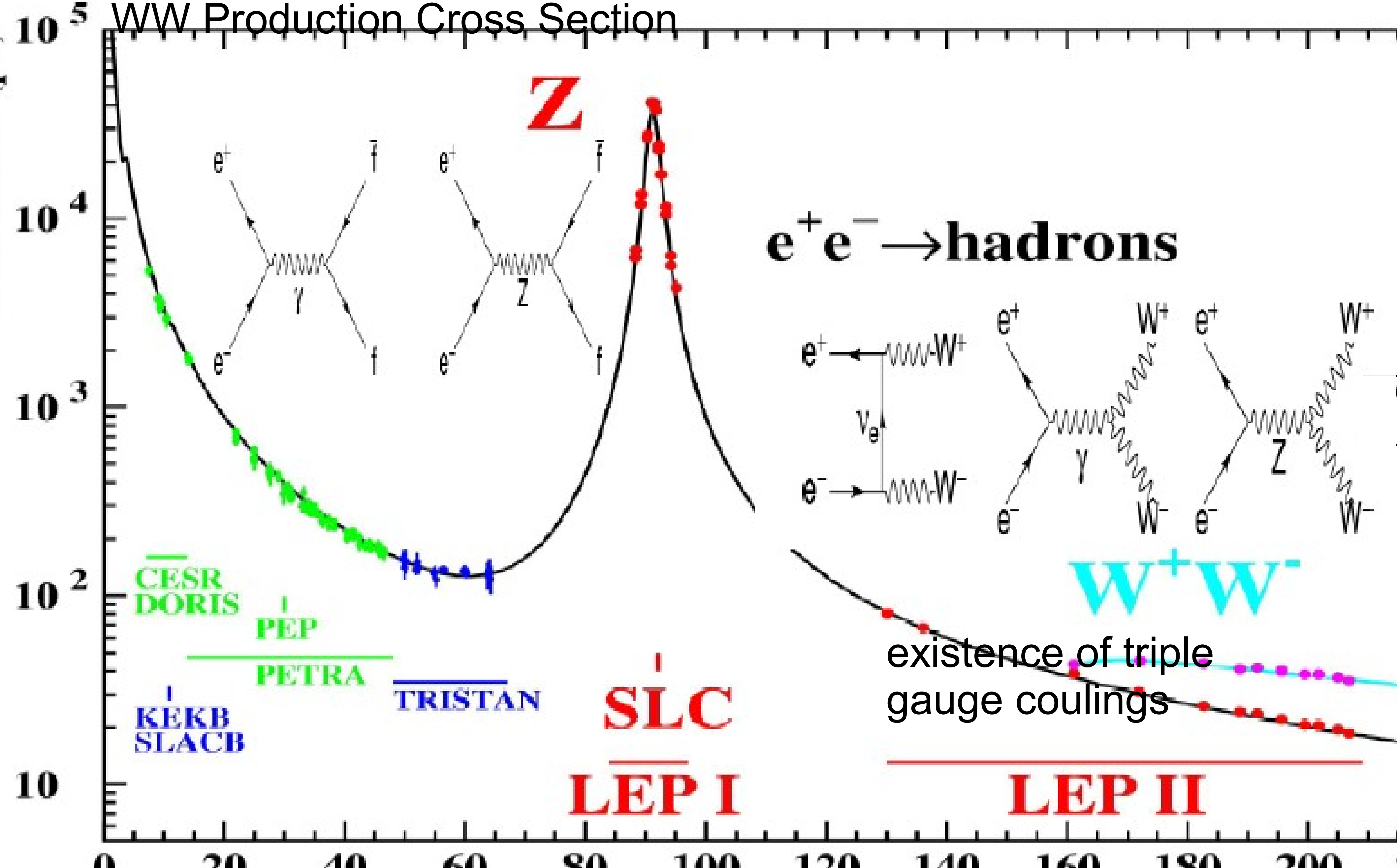
=> consistent with SM

NC Quark Couplings HERA + Tevatron



comparison LEP, Tevatron, HERA

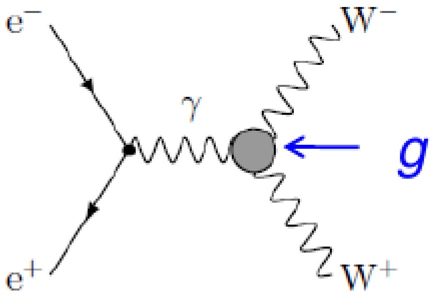
Triple Gauge Couplings



WW Production Cross Section

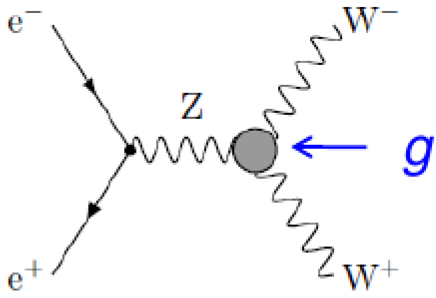
existence of triple gauge coulings

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:

$$
\begin{aligned}
i\mathcal{L}_{\mathrm{eff}}^{\mathrm{VWW}}/g_{\mathrm{VWW}} = {} & \boxed{\mathrm{g}_1^{\mathrm{V}}} V^\mu \left(W^-_{\mu\nu}W^{+\nu} - W^+_{\mu\nu}W^{-\nu}\right) \\
& + \boxed{\kappa_{\mathrm{V}}} W^+_\mu W^-_\nu V^{\mu\nu} + \frac{\lambda_{\mathrm{V}}}{m_W^2} V^{\mu\nu} W_\nu^{+\rho} W^-_{\rho\mu} \\
& + i\mathrm{g}_5^{\mathrm{V}} \varepsilon_{\mu\nu\rho\sigma} \left((\partial^\rho W^{-\mu})W^{+\nu} - W^{-\mu}(\partial^\rho W^{+\nu})\right) V^\sigma \\
& + i\mathrm{g}_4^{\mathrm{V}} W^+_\mu W^-_\nu \left(\partial^\mu V^\nu + \partial^\nu V^\mu\right) \\
& - \frac{\tilde{\kappa}_{\mathrm{V}}}{2} W^-_\mu W^+_\nu \varepsilon^{\mu\nu\rho\sigma} V_{\rho\sigma} - \frac{\tilde{\lambda}_{\mathrm{V}}}{2m_W^2} W^-_{\rho\mu} W^{+\mu}_\nu \varepsilon^{\nu\rho\alpha\beta} V_{\alpha\beta}.
\end{aligned}
$$

☐ =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

LEPEWWG/TGC/2005-01

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, κ_Z, κ_γ, λ_Z, λ_γ }

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

With additional gauge constraints

$$\begin{aligned} \kappa_Z &= g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W \\ \lambda_Z &= \lambda_\gamma \,, \end{aligned}$$

From a fit to the angular distribution of the WW:

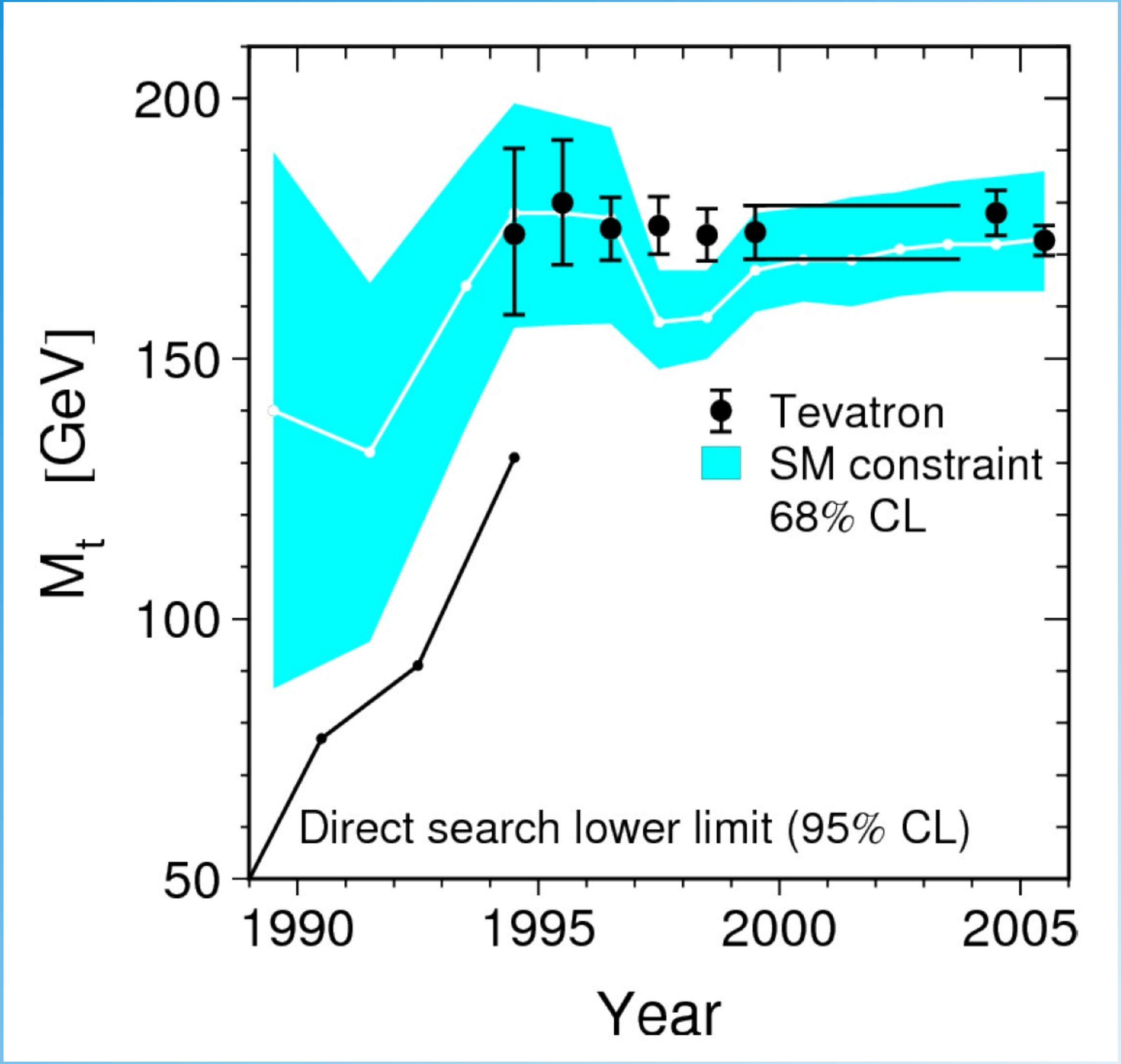
Parameter	68% C.L.
g_1^Z	$0.984^{+0.022}_{-0.019}$
κ_γ	$0.973^{+0.044}_{-0.045}$
λ_γ	$-0.028^{+0.020}_{-0.021}$

} =1 in SM

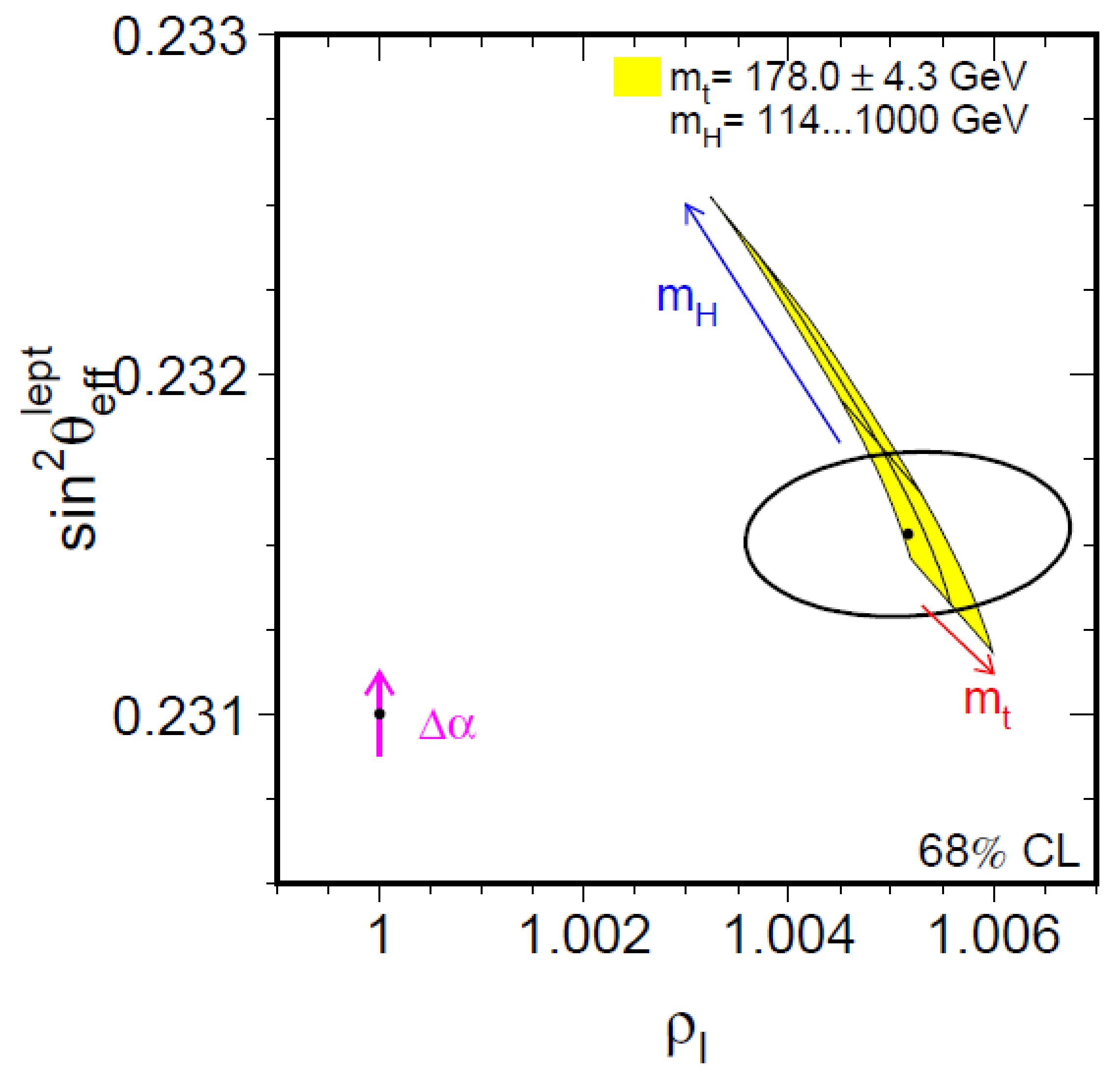
=0 in SM

Standard Model structure of VWW triple boson coupling confirmed.

Top Mass Prediction



Prediction Top and Higgs Mass



Top Mass Prediction from Radiative Corrections

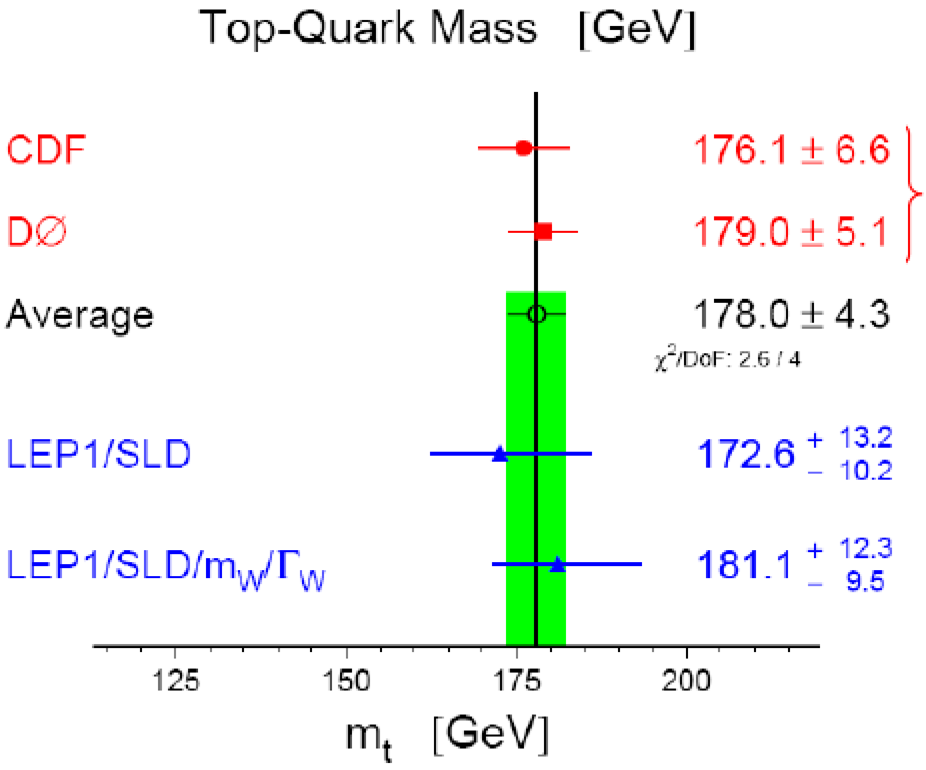
e.g.: $$\Delta r(m_t, M_H) = -\frac{3\alpha\cos^2\theta_w}{16\pi\sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi\sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \dots$$

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.



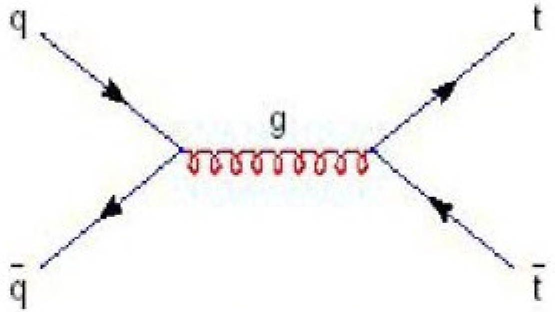
Direct measurement of m_t

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

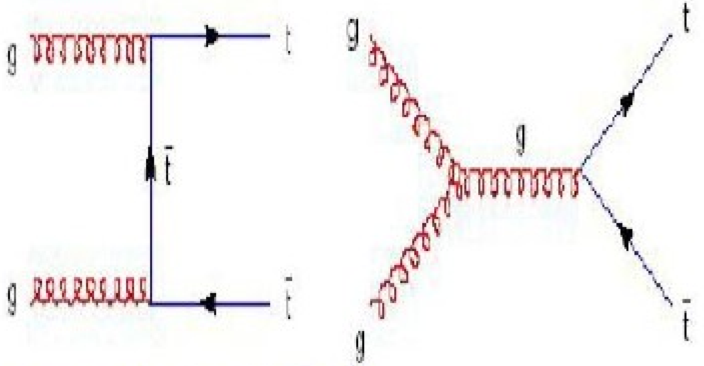
Prediction of m_t by LEP before the discovery of the top at TEVATRON.

Top Discovery at Tevatron in 1995

$p\bar{p}$ @ 2 TeV

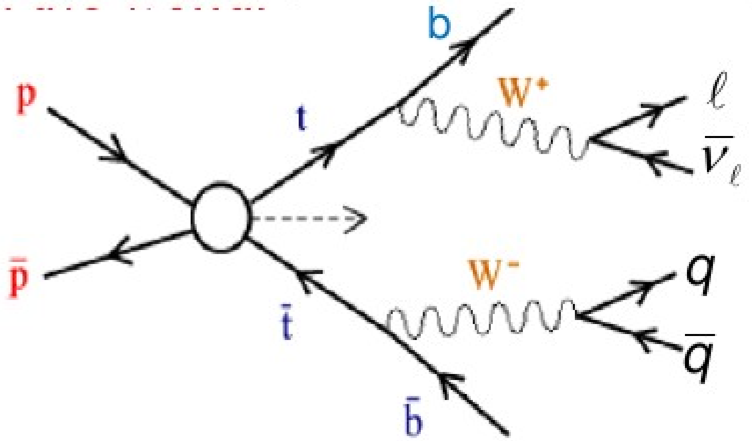


$q\bar{q}$ annihilation (85%)



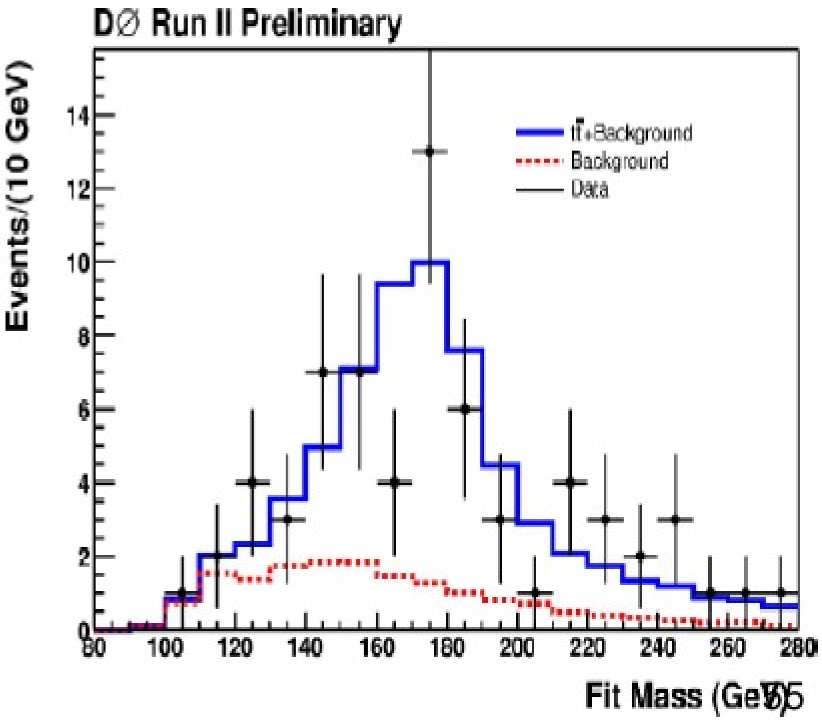
gluon fusion (15%)

Top decay (decays before hadronization)

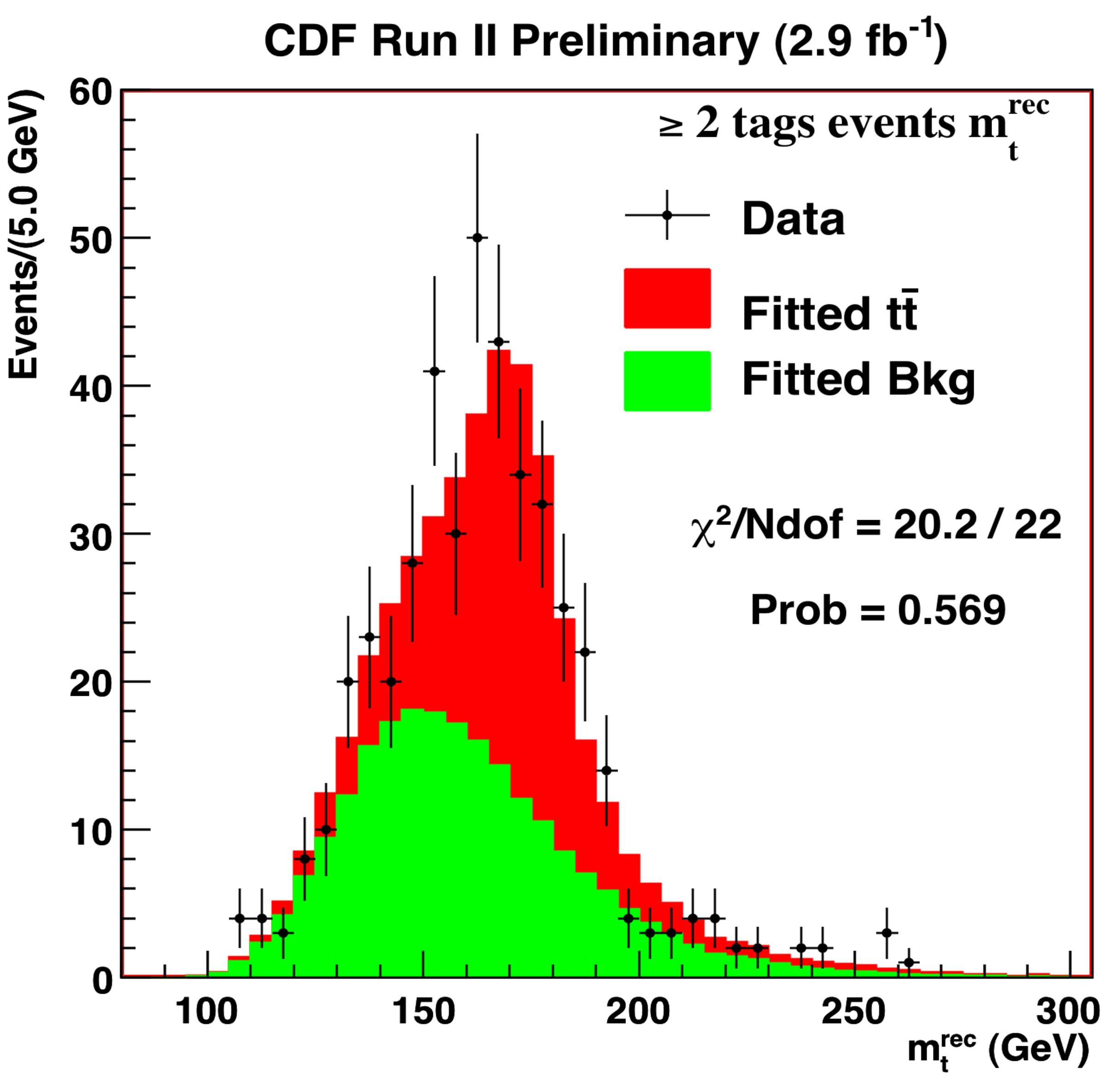


Channel used for mass reconstruction:

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



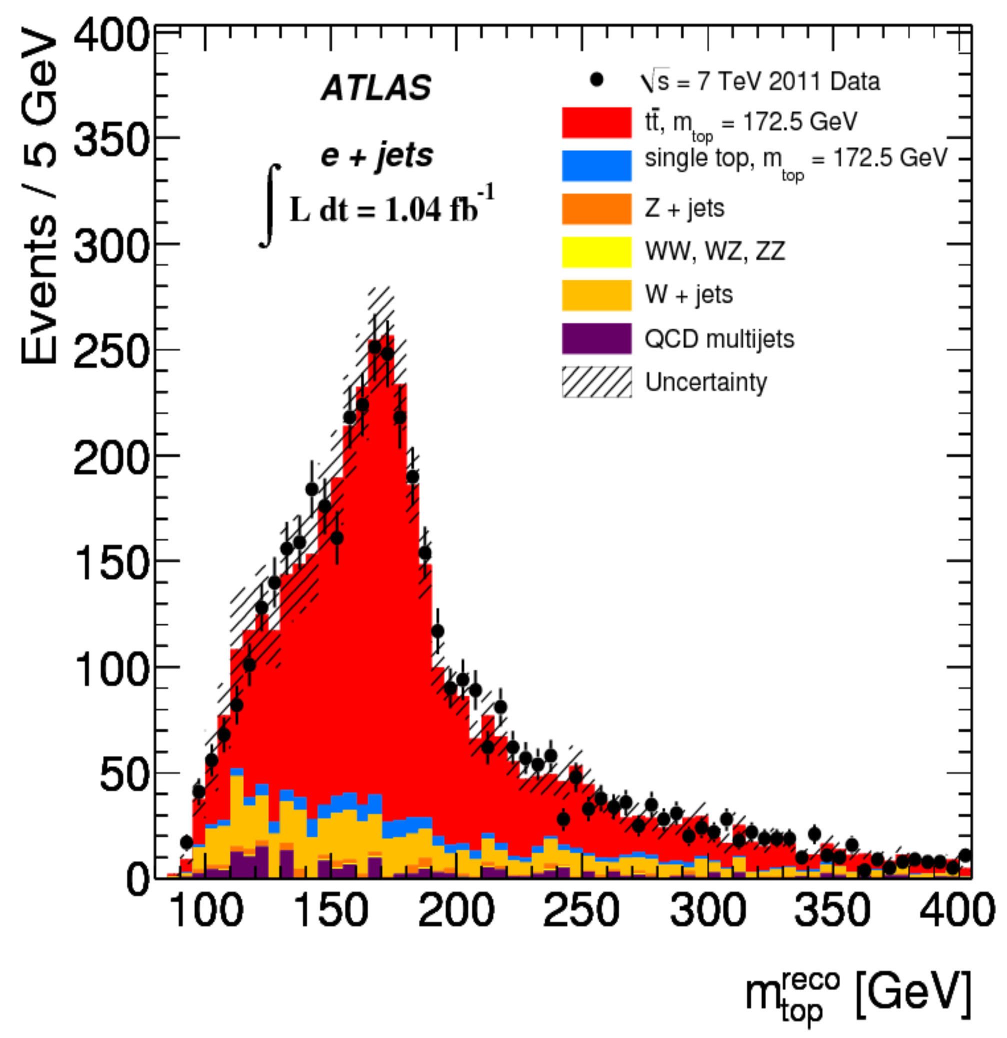
Top Mass Reconstruction

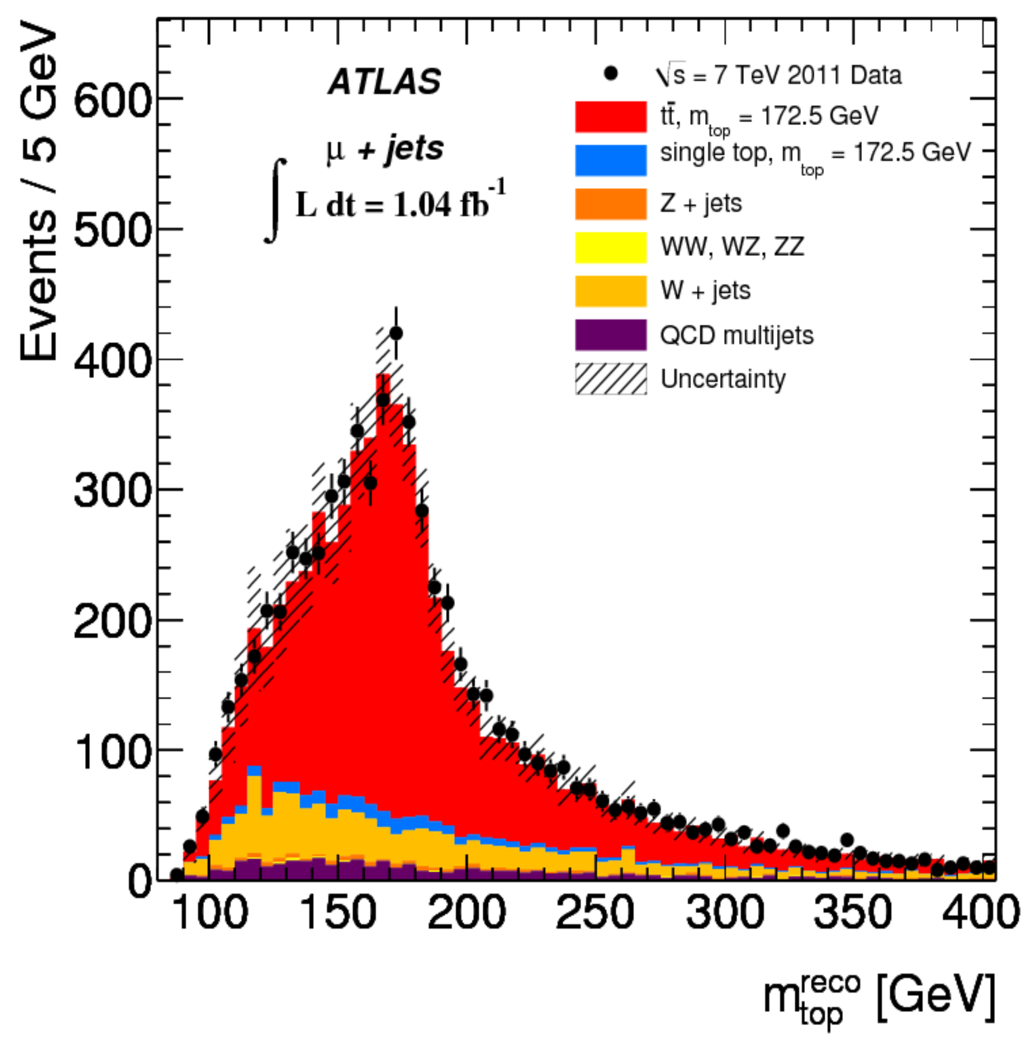


multi-channel analysis

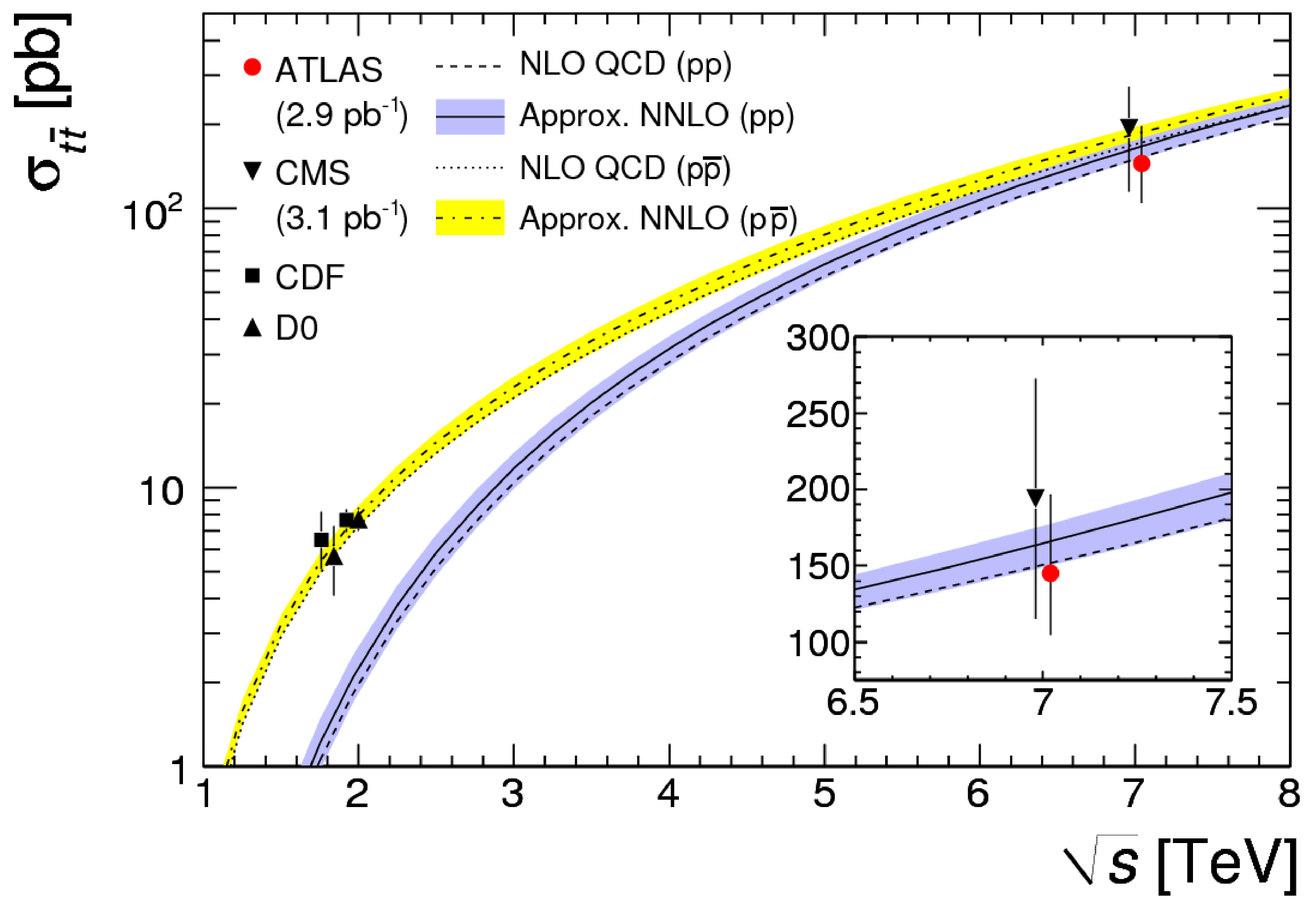
$m_t \sim 172$ (1) GeV

First Results from ATLAS (LHC)



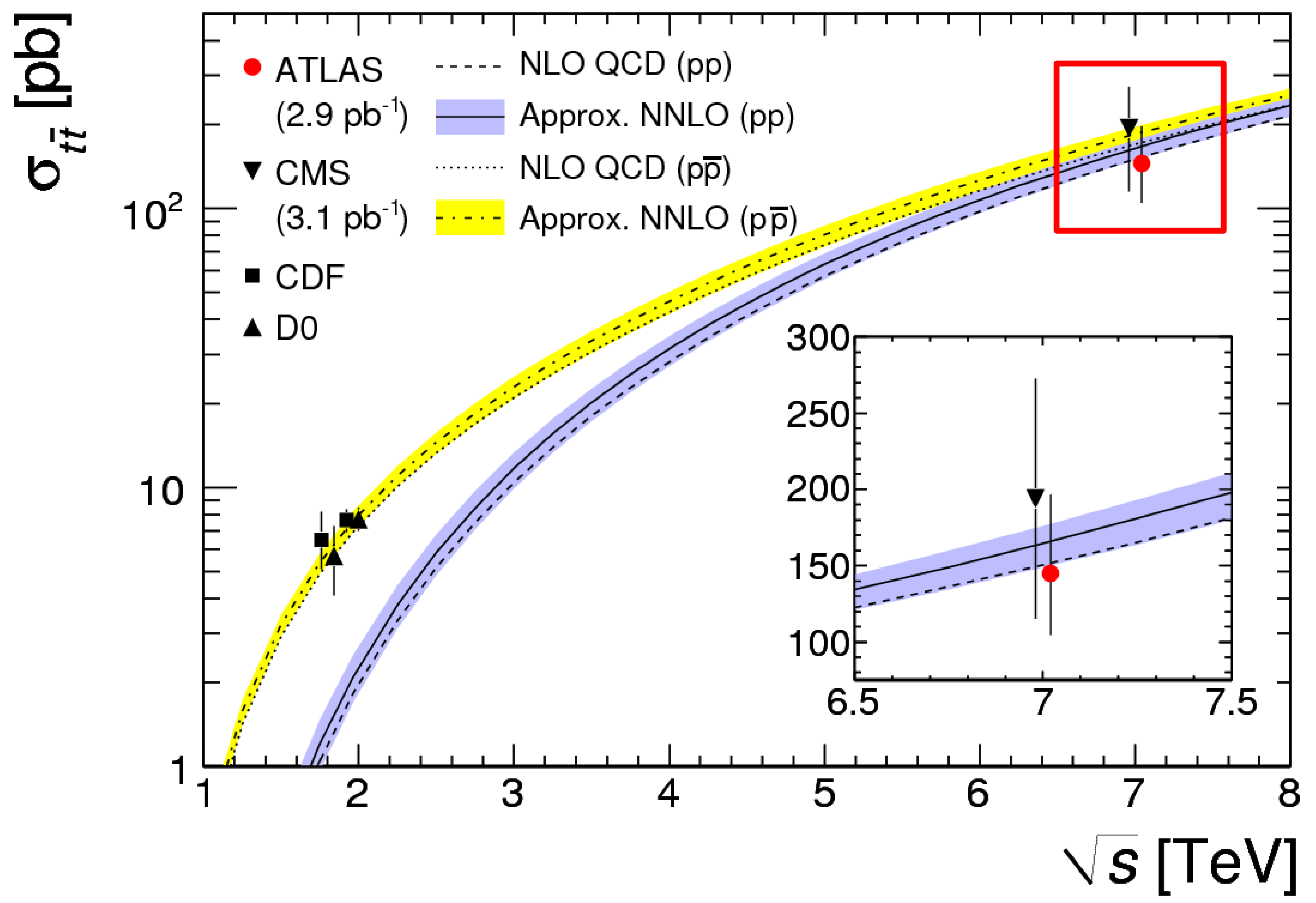


First Results from ATLAS (LHC)

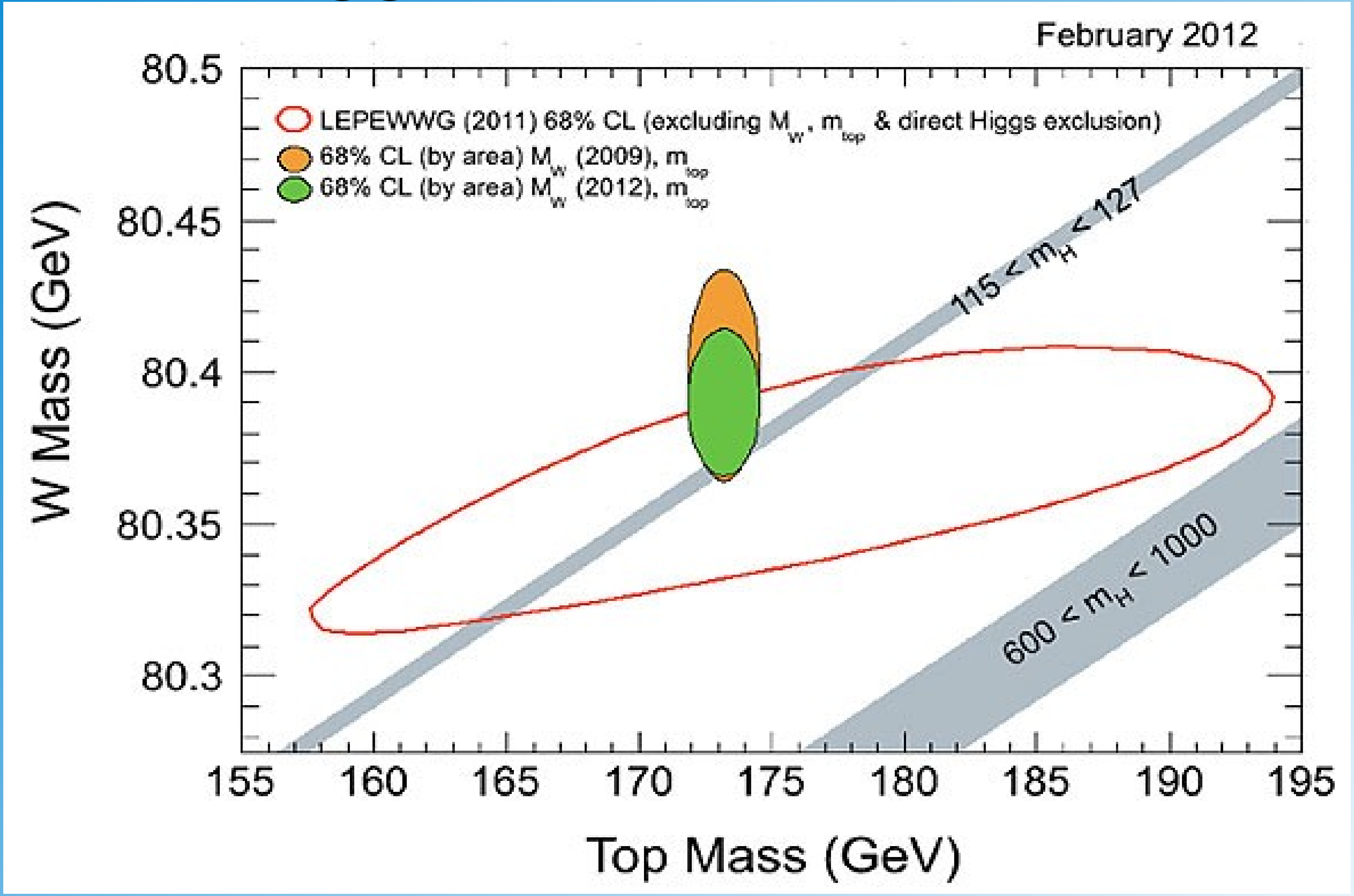


First Results from ATLAS (LHC)

mainly gluon fusion



Higgs Mass Constraint



Higgs mass should be light!