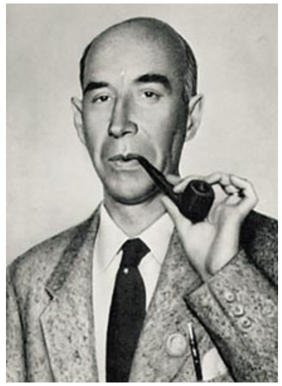
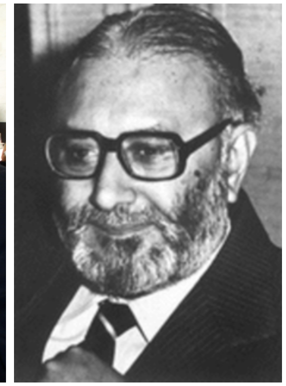
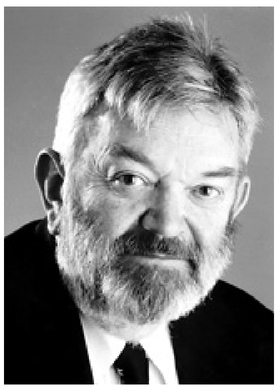
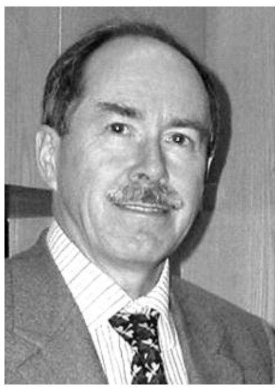
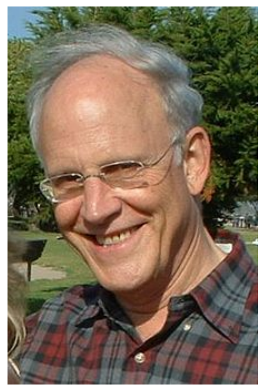
Experimental Foundations of the Standard Model III



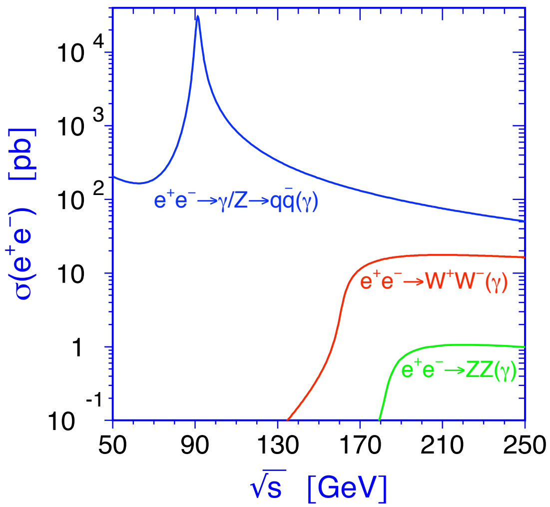
Postgraduate Course, UC Louvain, 2009

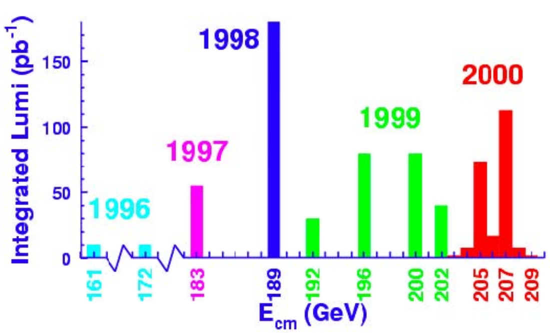
UNIVERSITÉ DE GENÈVE

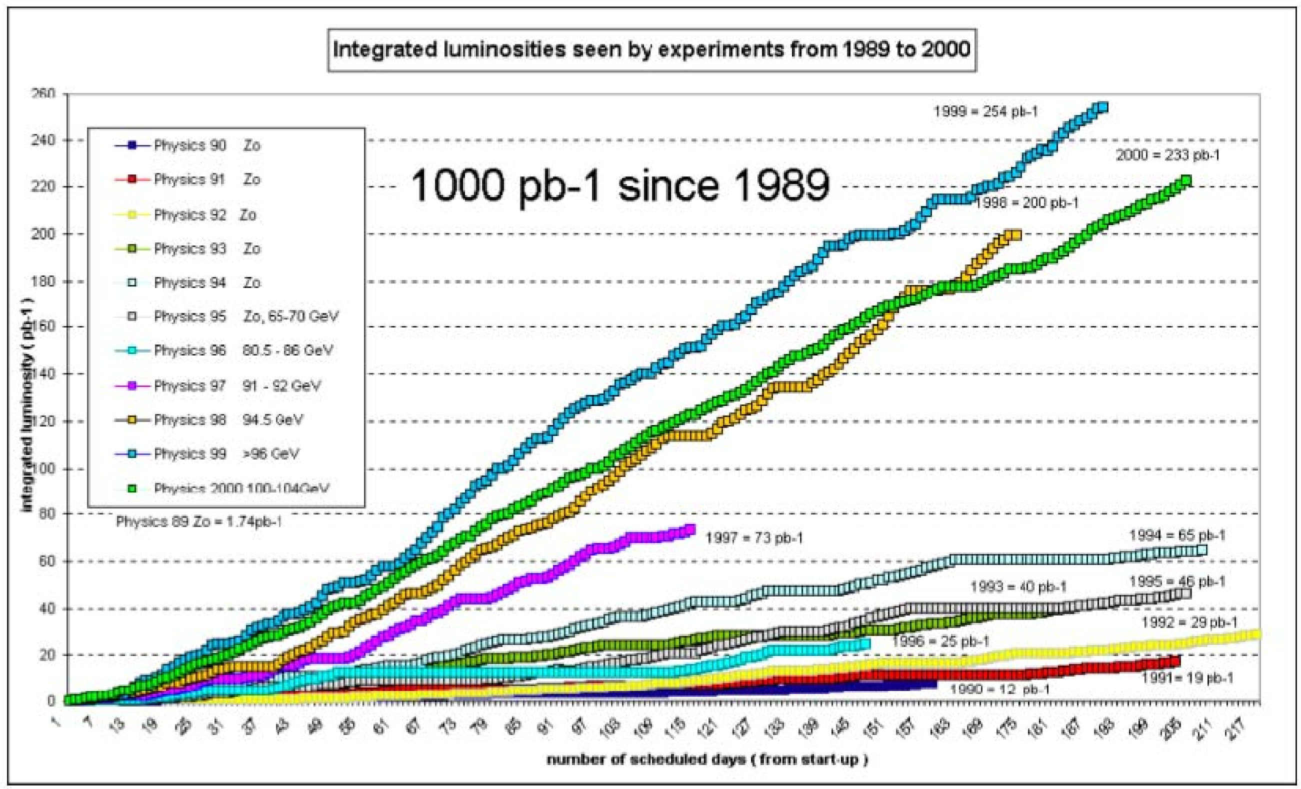
Martin Pohl

LEP II

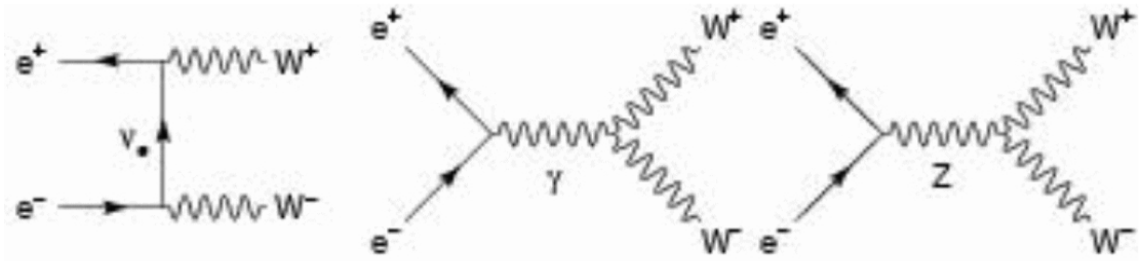
- LEP Energy upgrade, high energy running from 1995 to 2000
- Measurements at and above the threshold for $e^+e^- \rightarrow W^+W^-$
- W physics, triple gauge couplings, search for new particles

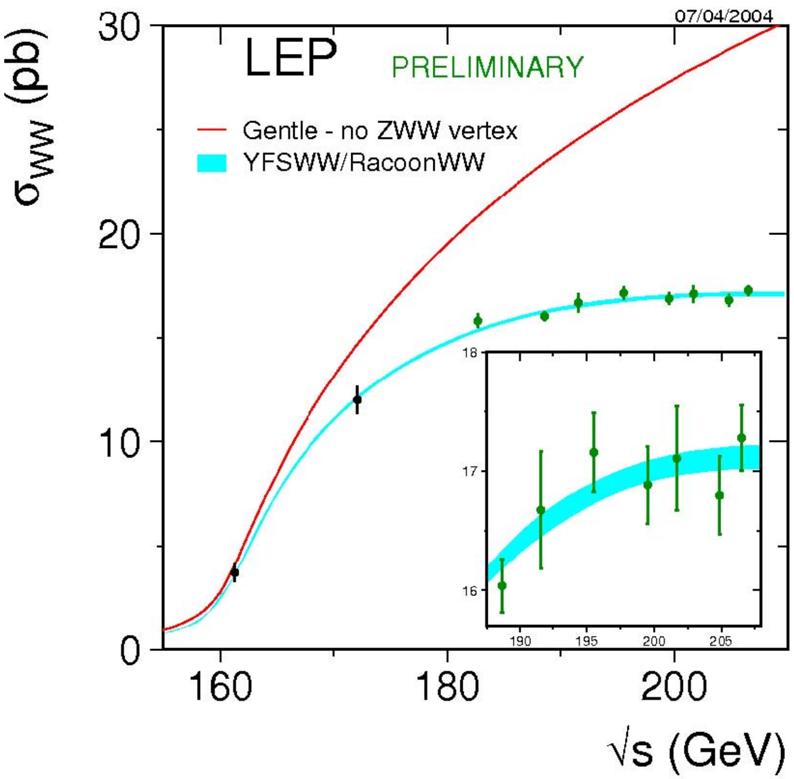






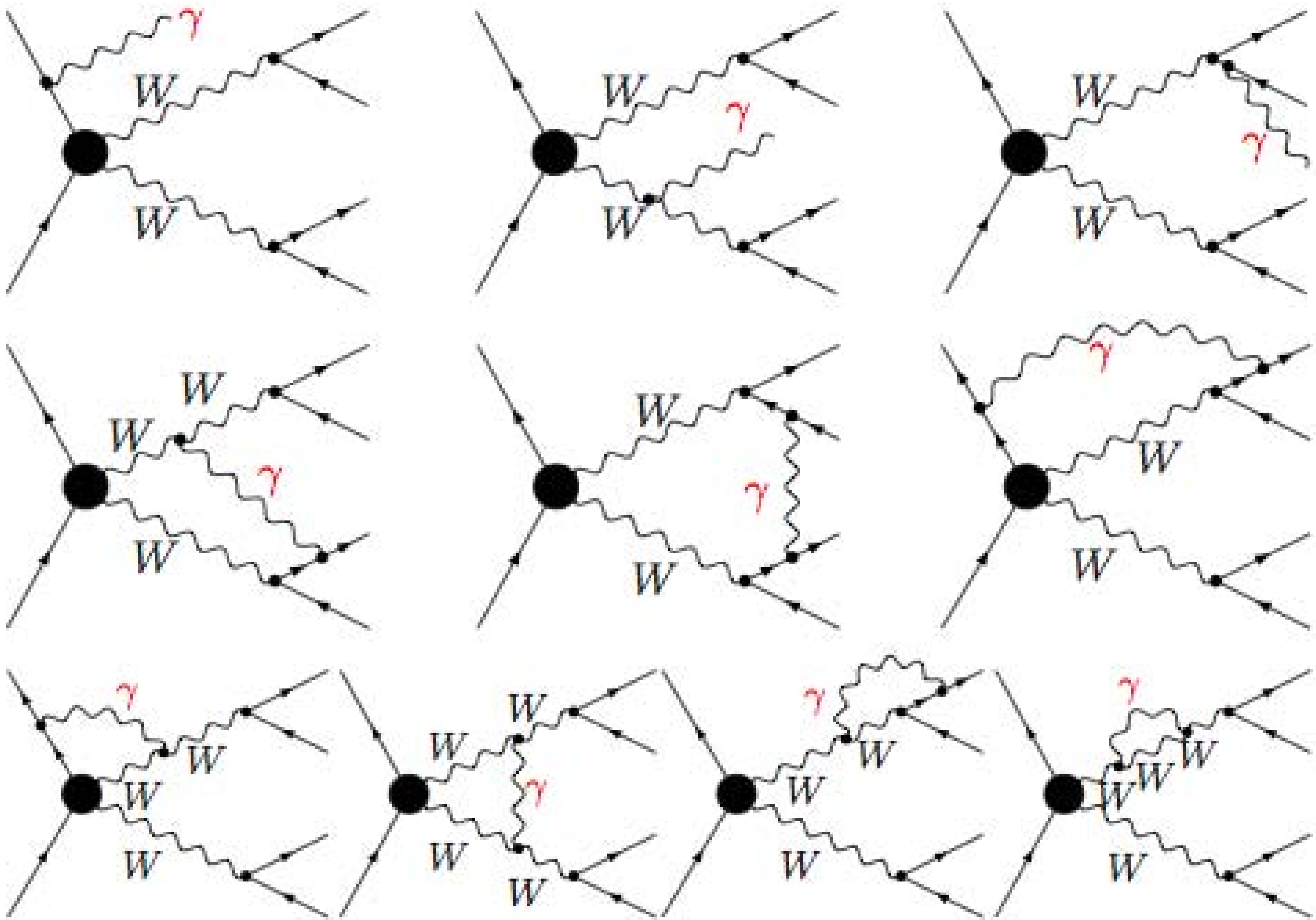
The Mass of the W Boson



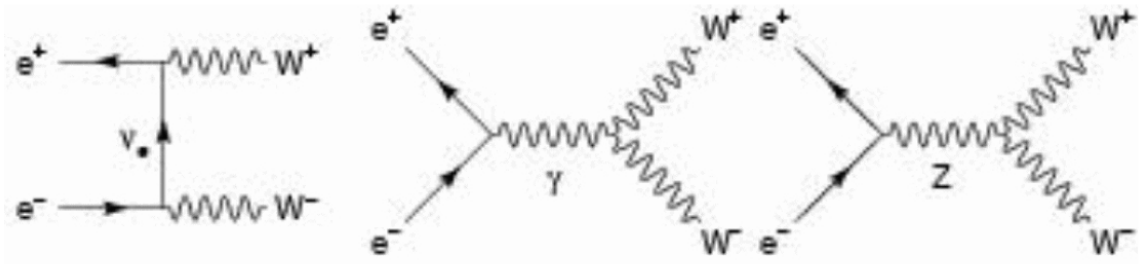


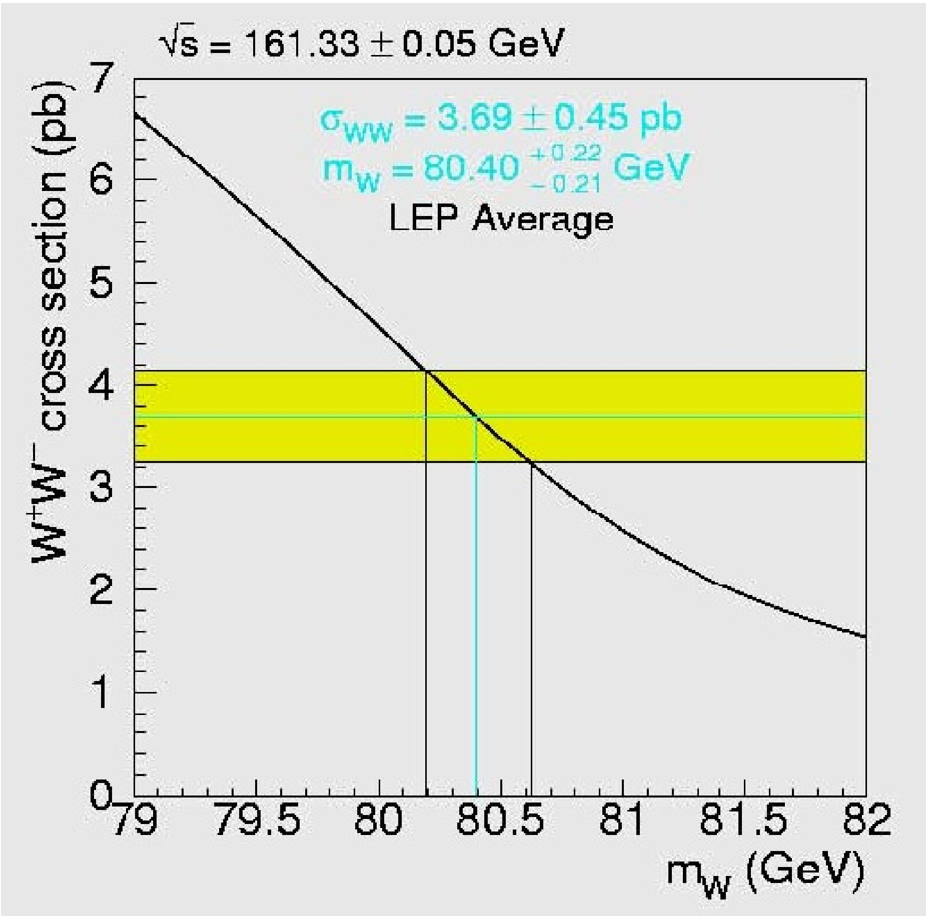
- Expect about 10000 W-pairs/experiment
- Br(W $\rightarrow l\nu$) = 32.5%, Br(W $\rightarrow qq$) = 67.5%
- $qqqq : qql\nu : l\nu l\nu = 4/9 : 4/9 : 1/9$
- Boson self-couping required by data, regularizes WW production process

QED Radiative Corrections for WW Final State



W Mass from Threshold Scan





- Cross section at threshold sensitive to W mass
- Result:

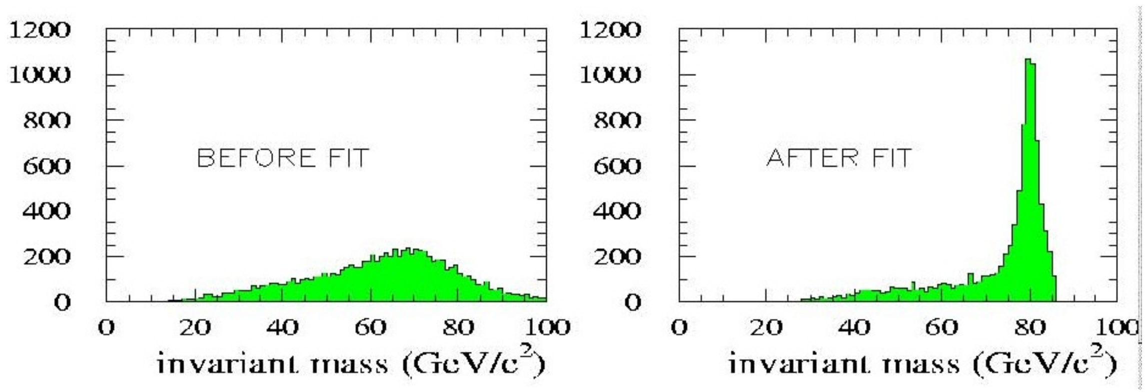
$$\sigma_{\mathrm{WW}} = 3.69 \pm 0.45\mathrm{pb}$$

$$M_{\mathrm{W}} = 80.40 \pm 0.22\mathrm{GeV}$$

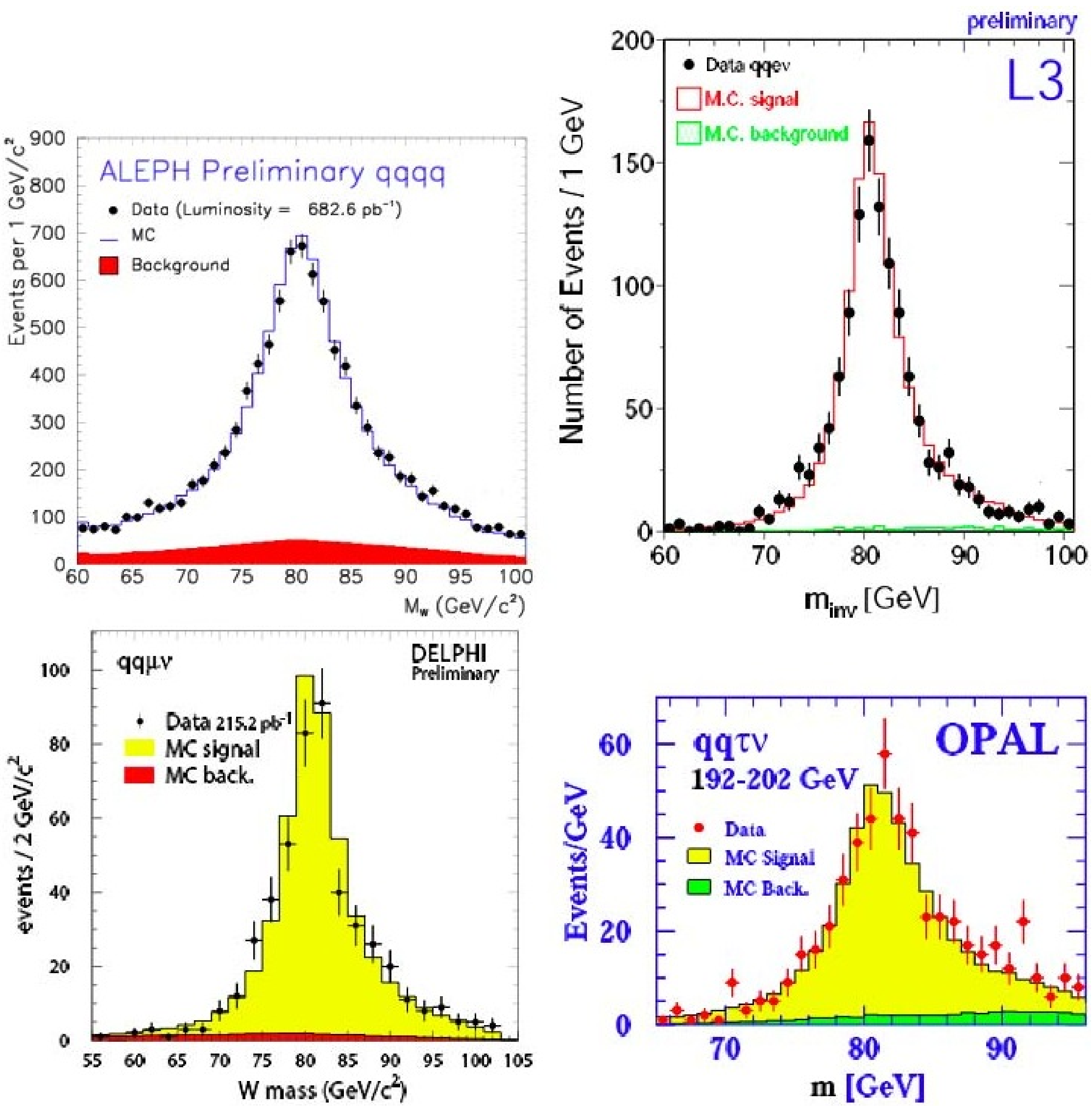
- Small rate, low sensitivity, little other physics, frustrating...

W Mass from Decay Products

- Limited by experimental resolution on variant mass, M(jet,jet), $M(l,\vec{E}_{miss})$
- Can be improved by kinematic fit, finding measured angles and energies best compatible with measured values and energy-momentum conservation.
- Effectively transfers good angular resolution towards less good energy resolution.
- Simultaneously determines unknow neutrino momentum vector.
- 4 constraints for $qqqq$, 5 if one imposes $M_{\mathrm{W}^+} = M_{\mathrm{W}^-}$
- 1 constraints for $ql\nu$, 2 for equal masses



W Mass from Decay Products



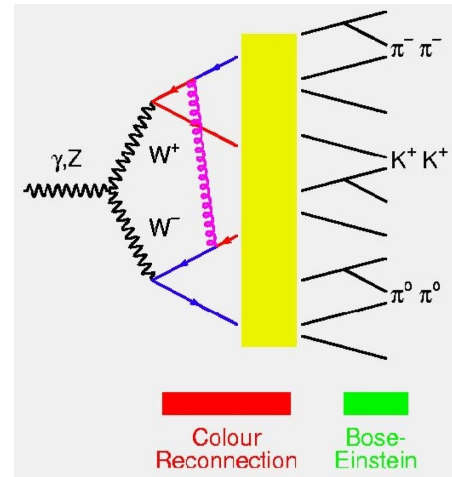
- Prepare Monte Carlo simulation of all small detector imperfections
- Generate Monte Carlo events for a given M_W
- Reweight these events to emulate any possible value of M'_W:

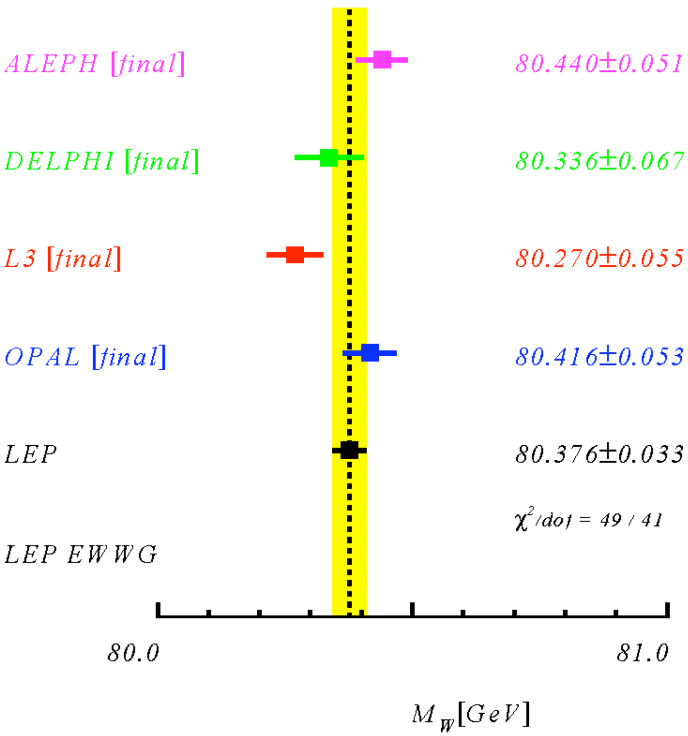
$$w_i(M'_W) = \frac{|\mathcal{M}(M'_W)|^2}{|\mathcal{M}(M_W)|^2}$$

- Compare data and Monte Carlo to find the best-fitting value of M_W
- Tedious but straight forward

Hadronization Corrections

- Main systematics from hadronization corrections
- Bose-Einstein correlations: identical bosons influence each other's phase-space
- Color reconnection: gluons can transfer energy-momentum between quarks from different W's

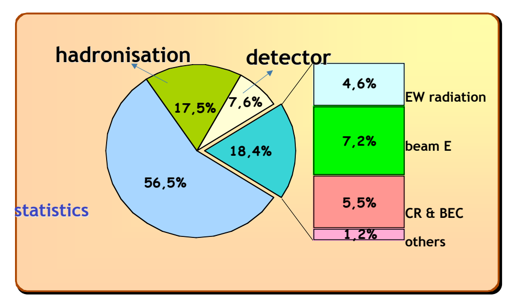




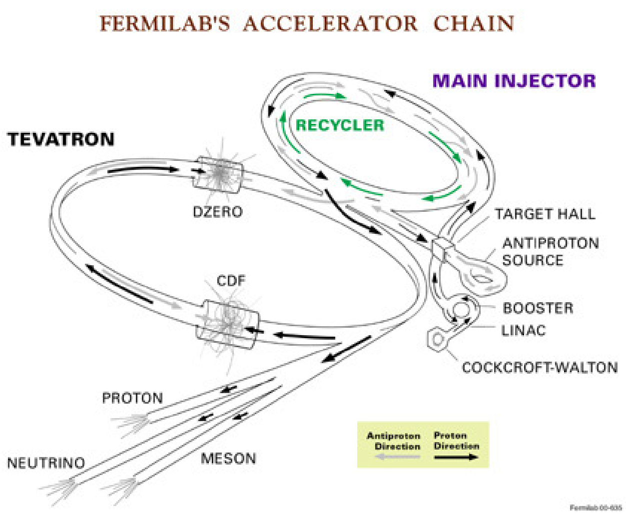
m_W (LEP) = 80.376 ± 0.033 GeV/c²

weights : qqqq=22% , qqlv=76% , σ=2%
(prob. fit. : 11.1%)

Difference between channels:
m_W(4q-2q) = -11.7 ± 44.6 MeV/c²

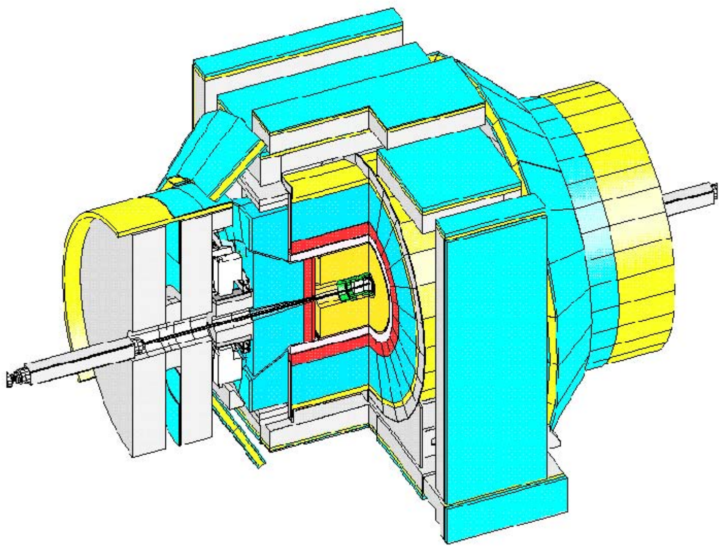


Fermilab Tevatron



- Proton-antiproton collider
- $\sqrt{s} = 1.96$TeV
- 1 fb^{-1} of data per experiment, ~ 500k W events, ~ 19k Z events

Fermilab Tevatron Detectors

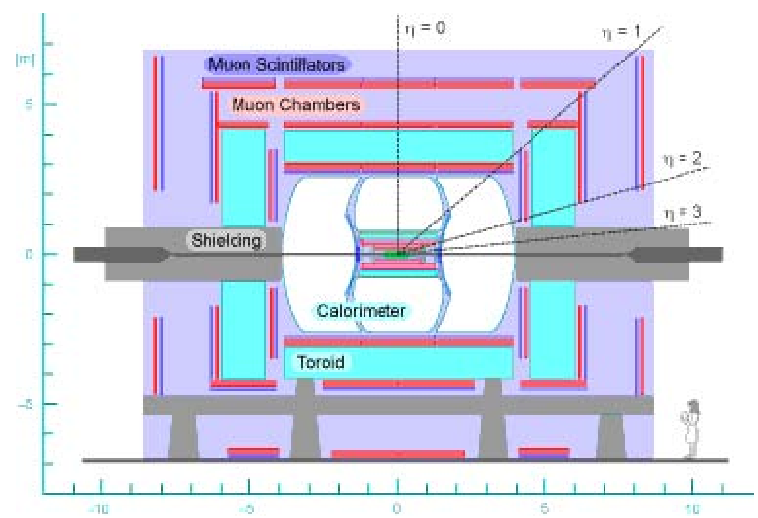


CDF:

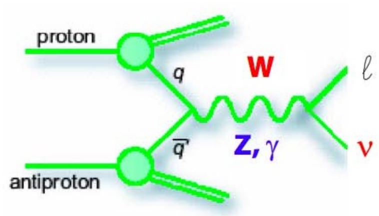
- Precision silicon vertexing
- Large radius drift chamber ($r = 1.4$m)
- 1.4 T solenoid
- EM+HAD Calorimetry
- Muon chambers $|\eta| < 1.1$
- Particle Identification

D0:

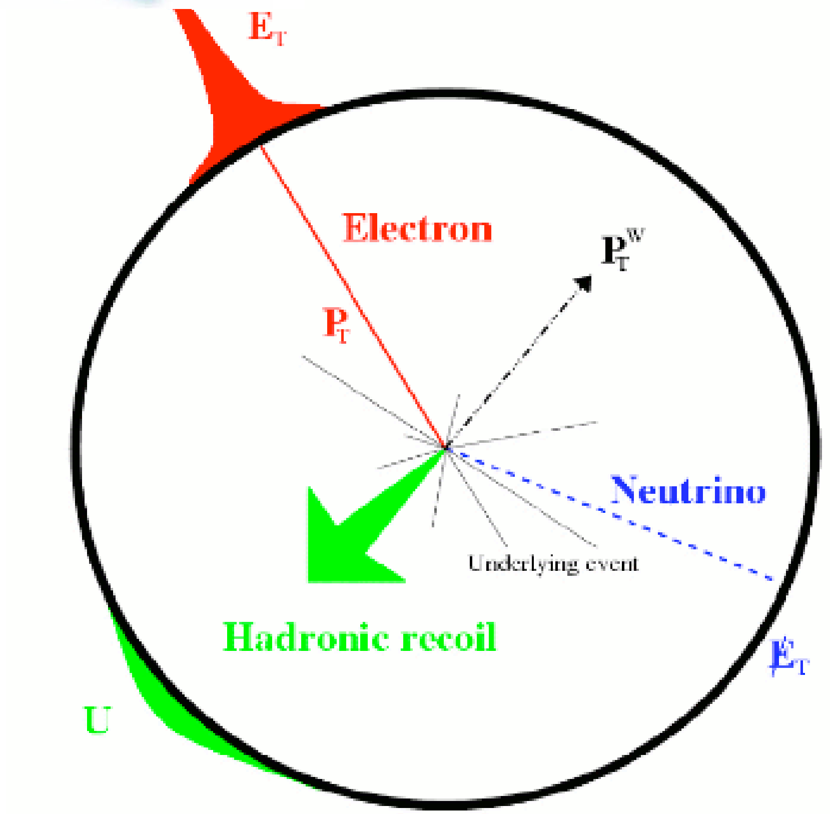
- Precision silicon vertexing
- Outer Fiber Tracker ($r = 0.5$m)
- 2.0 T solenoid
- EM+HAD Calorimetry
- Muon chambers $|\eta| < 2.0$



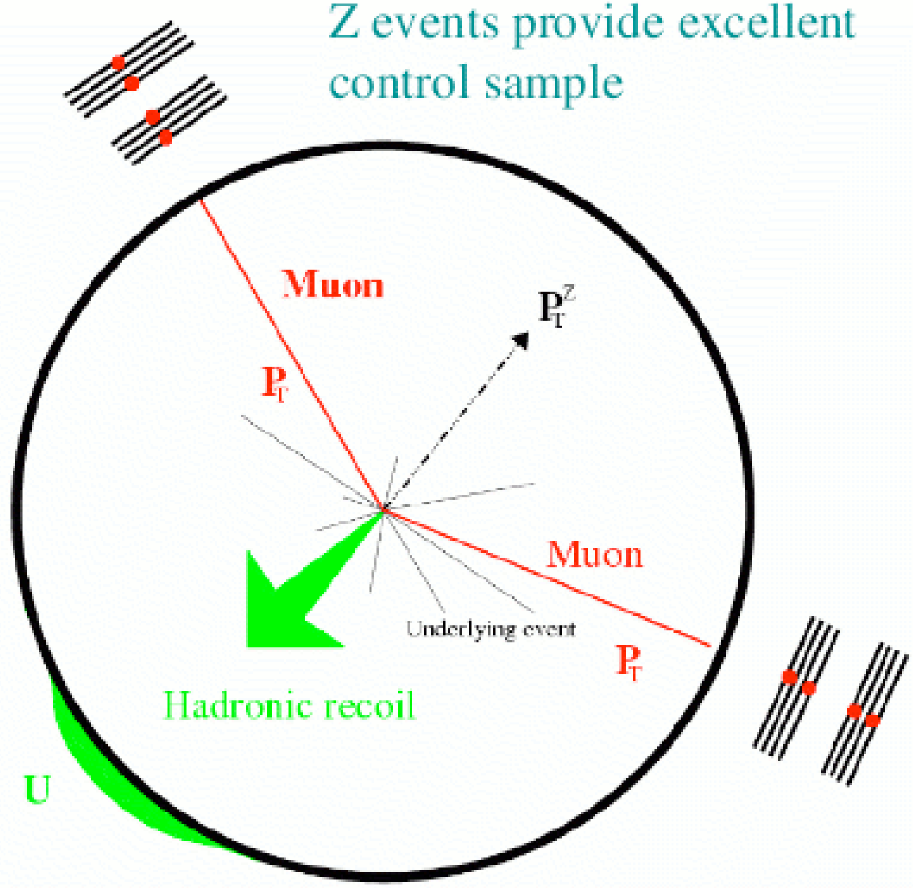
W Signature at Hadron Colliders



Isolated, high p_T leptons,
missing transverse momentum in W's

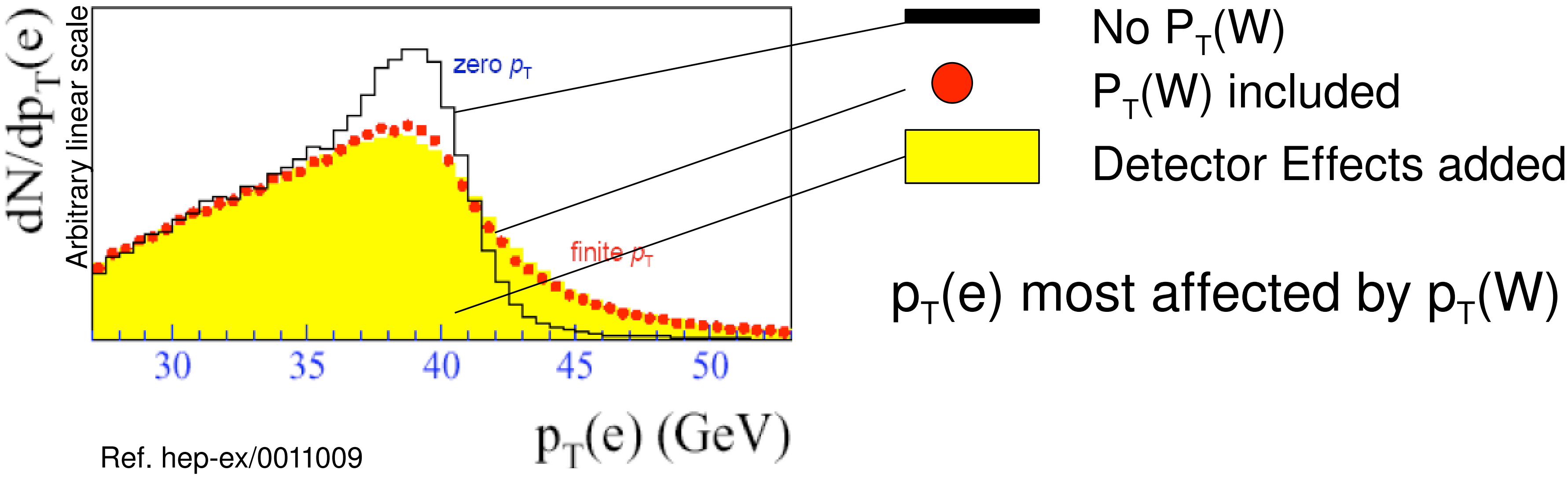


Z events provide excellent control sample



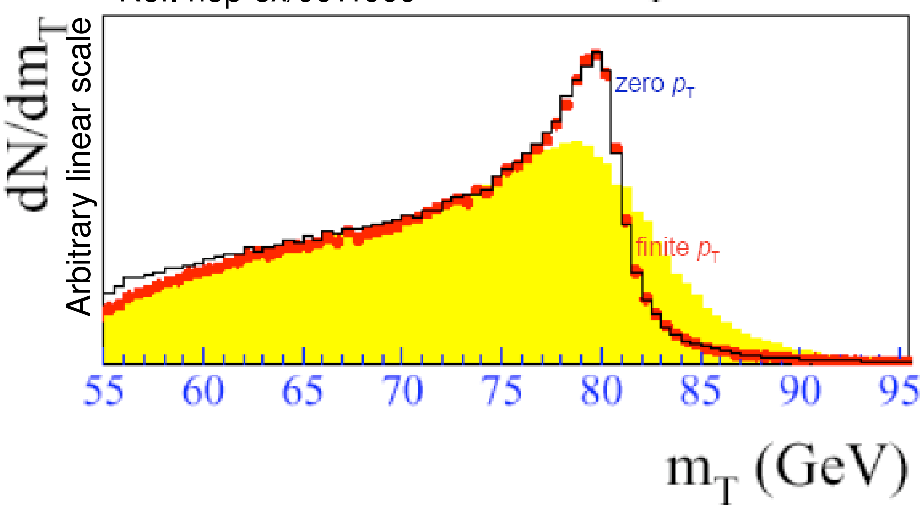
In a nutshell, measure two objects in the detector:
- Lepton (e or μ), need energy measurement with 0.2 per-mil precision (!!)
- Hadronic recoil, need ~ 1% precision

Transverse Variables



$p_T(e)$ most affected by $p_T(W)$

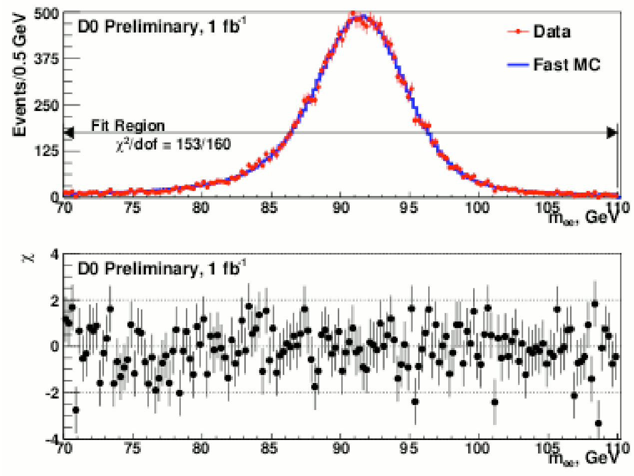
Ref. hep-ex/0011009

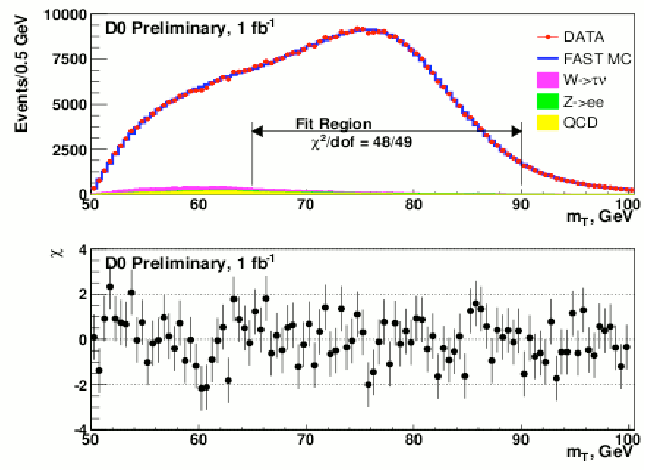


$$M_T = \sqrt{2 E_T^l \not{E}_T (1 - \cos \Delta\phi)}$$

M_T most affected by measurement of missing transverse momentum

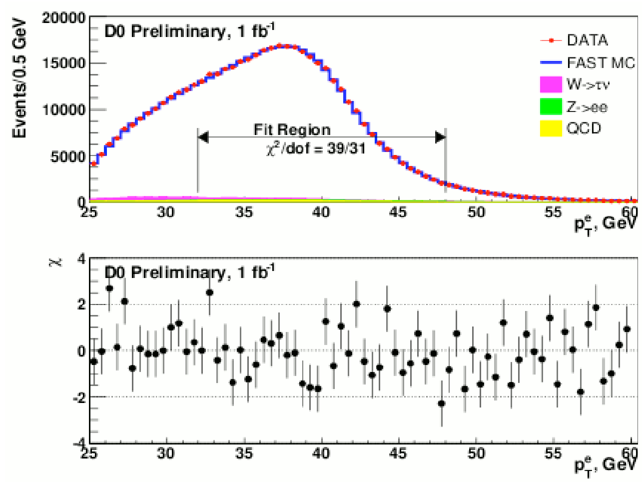
D0 Mass Fits (Preliminary

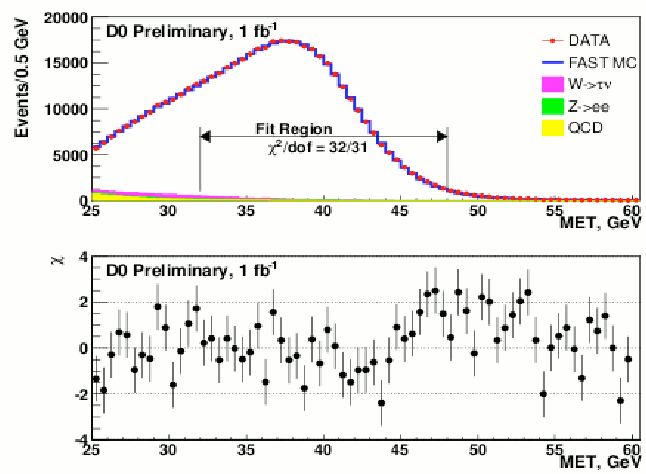




$M_Z = 91.185 \pm 0.033$ GeV (stat)

$M_W = 80.401 \pm 0.023$ GeV (stat)





$M_W = 80.400 \pm 0.027$ GeV (stat)

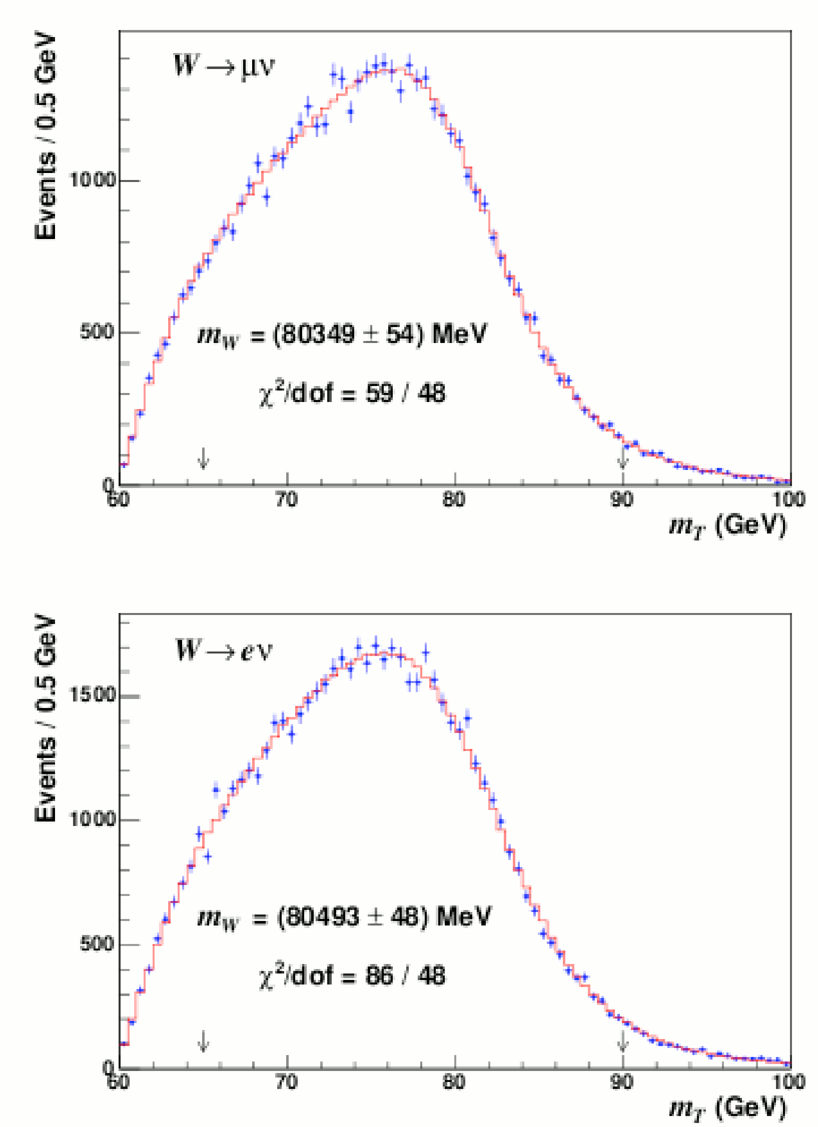
$M_W = 80.402 \pm 0.023$ GeV (stat)

D0 Mass Uncertainties (Preliminary)

systematic uncertainties

Source	$\sigma(m_W)$ MeV m_T	$\sigma(m_W)$ MeV p_T^e	$\sigma(m_W)$ MeV $\not{E}_T$
Experimental			
Electron Energy Scale	34	34	34
Electron Energy Resolution Model	2	2	3
Electron Energy Nonlinearity	4	6	7
W and Z Electron energy loss differences (material)	4	4	4
Recoil Model	6	12	20
Electron Efficiencies	5	6	5
Backgrounds	2	5	4
Experimental Total	35	37	41
W production and decay model			
PDF	9	11	14
QED	7	7	9
Boson p_T	2	5	2
W model Total	12	14	17
Total	37	40	44
statistical	23	27	23
total	44	48	50

CDF Mass Fits and Uncertainties



m_T Fit Uncertainties

Source	$W \to \mu\nu$	$W \to e\nu$	Correlation
Tracker Momentum Scale	17	17	100%
Calorimeter Energy Scale	0	25	0%
Lepton Resolution	3	9	0%
Lepton Efficiency	1	3	0%
Lepton Tower Removal	5	8	100%
Recoil Scale	9	9	100%
Recoil Resolution	7	7	100%
Backgrounds	9	8	0%
PDFs	11	11	100%
W Boson p_T	3	3	100%
Photon Radiation	12	11	100%
Statistical	54	48	0%
Total	60	62	-

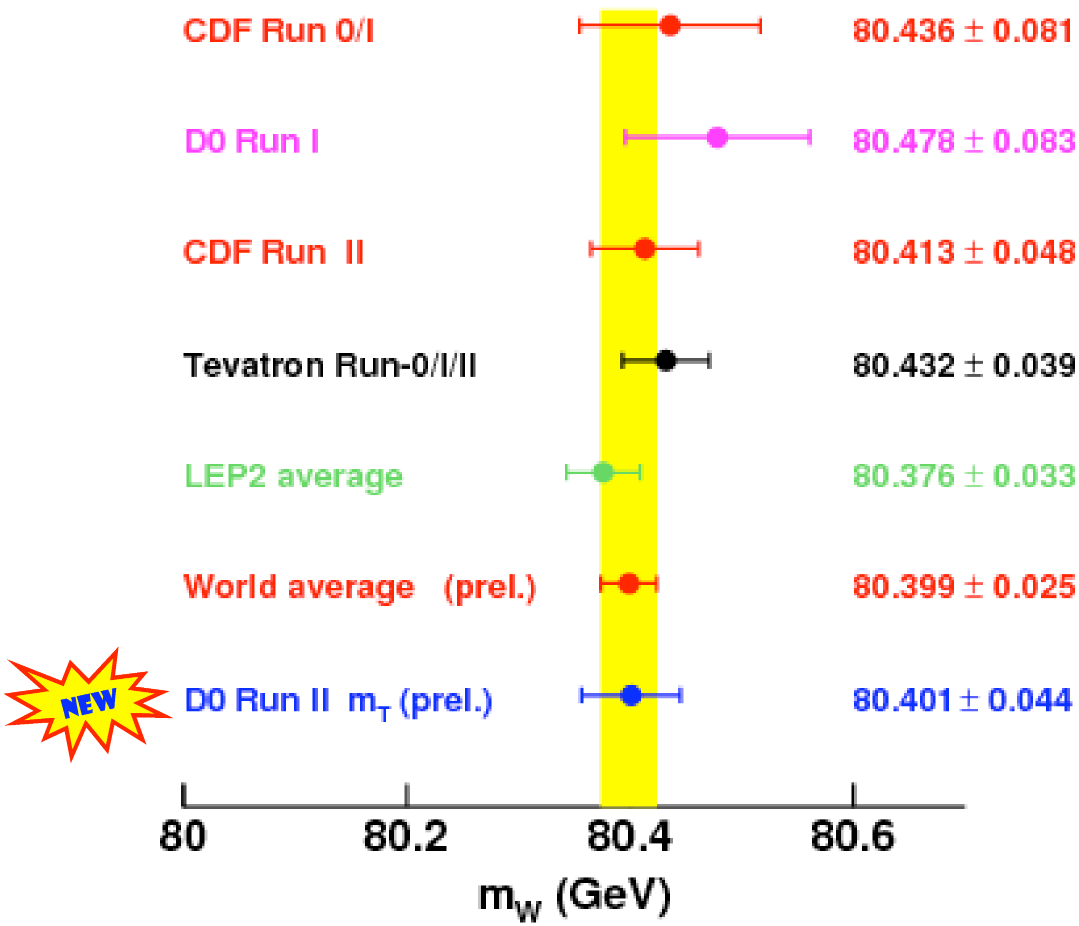
Combined result (electrons, muons; three observables):

m(W) = 80.413 ± 0.048 GeV

Phys.Rev.Lett.99:151801 (2007)
Phys.Rev.D77:112001 (2008)

Summary of Results on W Mass

J. Stark, Moriond 2009



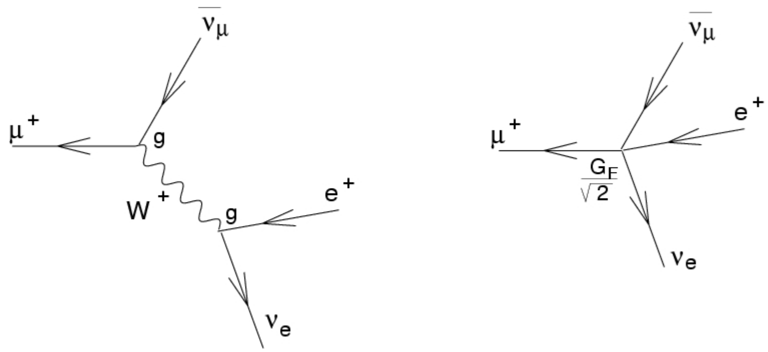
The new result from DØ is the single most precise measurement of the W boson mass to date.

So far, we quote our m_T result as the main result. Will combine results from the three observables; expect ~ 10 % improvement in total error over m_T alone.

The new result is in good agreement with previous measurements.

Attention: New D0 result not yet used in electroweak fits.

W Couplings to Matter



- At $q^2 \ll M_W^2$, contract charged current coupling and W propagator:

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

- Electron spectrum and total width given by V-A structure:

$$\frac{d\Gamma}{dE'} = \frac{G_F^2}{12\pi^3} m_\mu^2 E'^2 (3 - \frac{4E'}{m_\mu}) \quad ; \quad \Gamma = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3}$$

- Radiative corrections and W propagator effects:

$$\Gamma = \frac{1}{\tau_\mu} = \frac{G_F^2 m_\mu^5}{192\pi^3} (1 + \Delta q)$$

known to second order, Ritbergen and Stuart Phys.Rev.Lett. 82, 488 (1999), estimated precision 0.03ppm.

FAST Collaboration

A.Barczyk[1], G. Barone[3], J.Berdugo[2], J.Casaus[2], C.Casella[3], K.Deiters[4], S.de Laere[3], J.Kirkby[1], L.Malgeri[1], C.Mana[2], J.Marin[2], G.Martinez[2], C.Petitjean[4], M.Pohl[3], E.Sanchez[2], C.Willmott[2]

CERN [1] CIEMAT [2] UNIGE [3] PSI [4]

Ciemat

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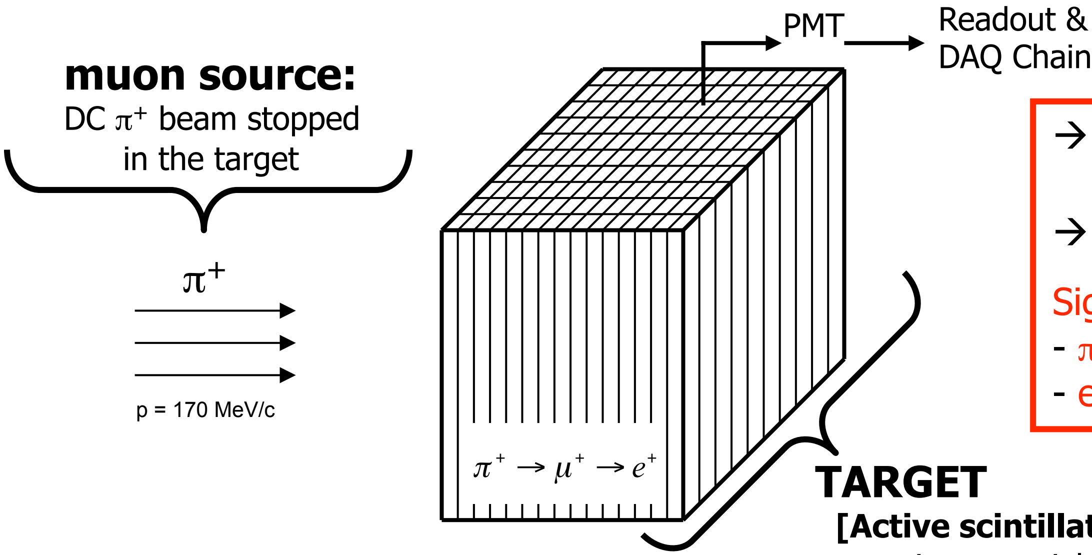
FAST Design Requirements



TARGET

[Active scintillator target]:

- stopping material for π^+ and μ^+
- detector for e^+

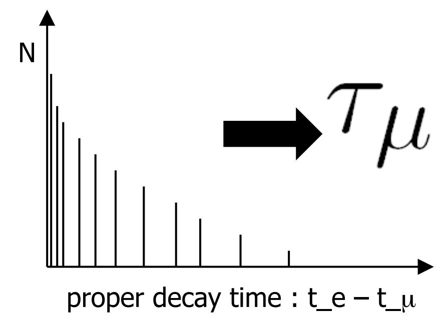
SIGNATURE FOR AN EVENT:

→ $\pi^+ \rightarrow \mu^+ \, \nu_\mu \; (\tau_\pi \sim 26ns)$ $\quad E_\mu^{cin} \sim 4 \; MeV$, $\rho_\mu \sim 1.5 \; mm$

→ $\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \; (\tau_\mu \sim 2.2\mu s)$

Signature:

- π^+ & μ^+ close in time & space [high pulses]
- e^+ track [mip's]



Size of the statistical sample =>
achievable precision in the measurement

$$\frac{(\delta\tau)_{stat}}{\tau} = \frac{1}{\sqrt{N_{events}}}$$

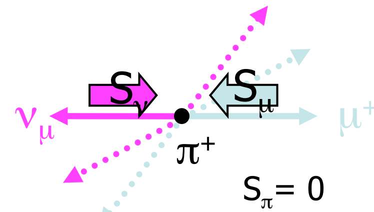
New generation muon lifetime experiments ($\delta\tau_\mu/\tau_\mu$ ~ ppm) → 2 main requirements:

1. Achieve a large statistical sample (N_events ~ 10^{11} - 10^{12})
2. Control the systematic effects

PSI Beam

μ source = π decay at rest in the target

➔ isotropic & unpolarized μ source

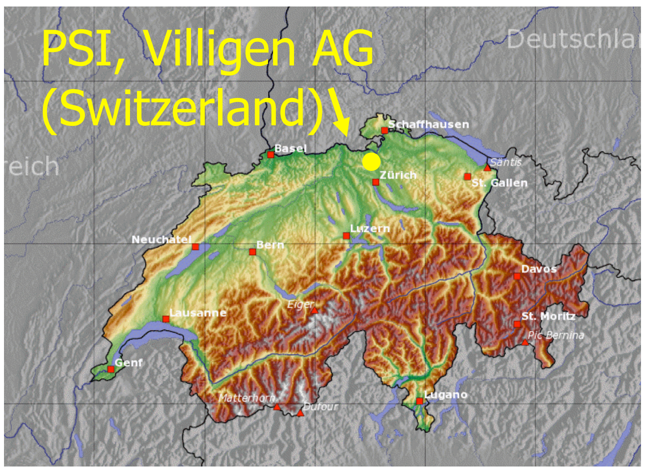


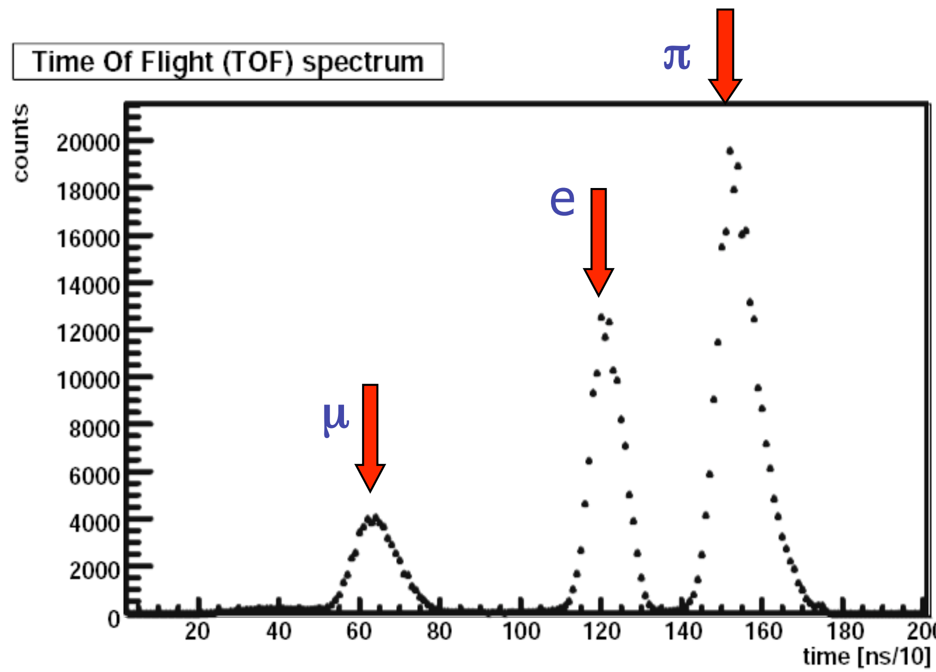
DC π^+ BEAM @ Paul Scherrer Institute (PSI)

PSI :

proton cyclotron (590 MeV) 2mA p curr)

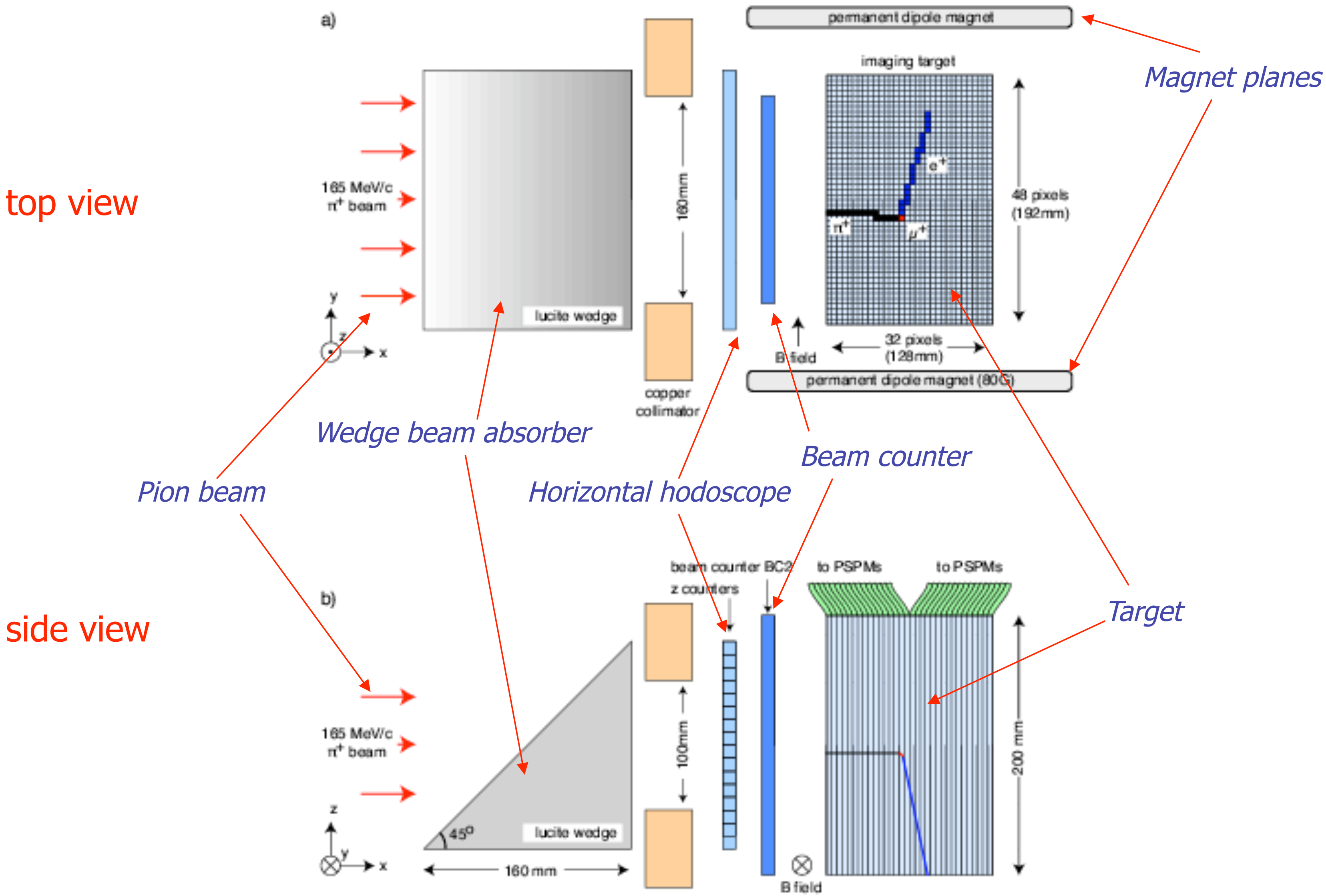
several secondary beamlines





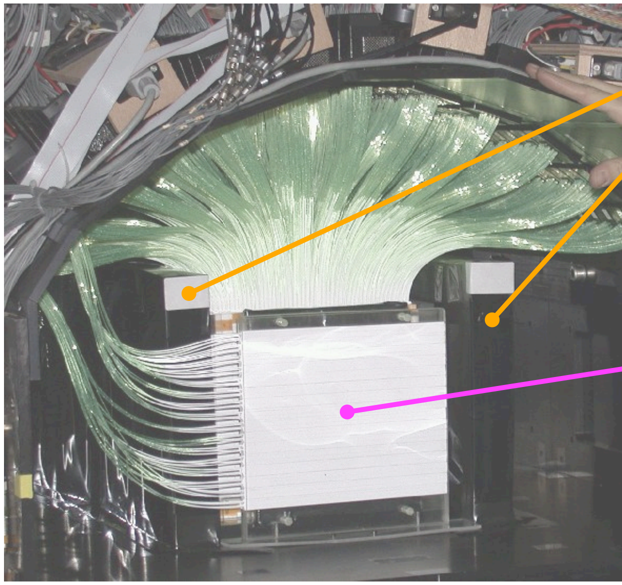
- **πM1 area** : **π^+ DC beam**
- momentum : **170 MeV/c** (±3%)
- RF frequency : 50.633 MHz (T=19.75 ns)
- size : variable **(~ 10 x 10 cm^2)**
- intensity : variable **(~ 500 kHz)**
- purity : ~ 50%

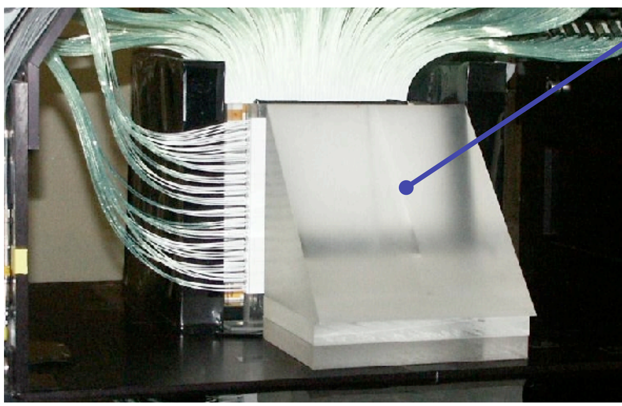
FAST Setup



top view
side view
a)
b)
165 MeV/c
π^+ beam
lucite wedge
copper
collimator
160mm
permanent dipole magnet
imaging target
48 pixels
(192mm)
32 pixels
(128mm)
B field
permanent dipole magnet (80G)
e^+
π^+
μ^+
Magnet planes
Wedge beam absorber
Pion beam
Horizontal hodoscope
Beam counter
Target
beam counter BC2
z counters
to PSPMs
to PSPMs
100mm
200 mm
45^o
160 mm

FAST Setup





dipolar magnetic field:

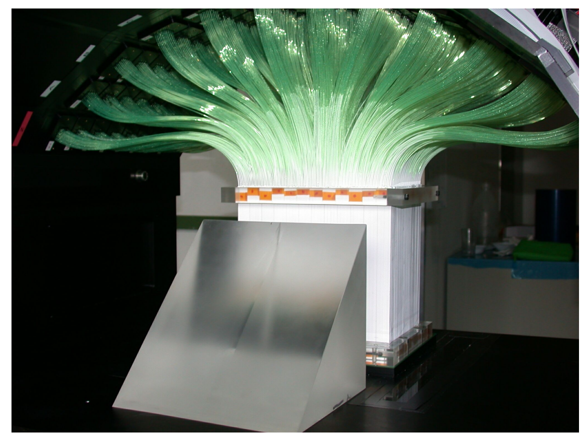
- permanent magnet
  (2 planes of magnetized ferrite blocks)
- B = 80 G
- homogeneous & transverse magnetic field
- assess systematics related to μSR effects

z-counter hodoscope:

- 16 horizontal counters (10x10x200mm3)
- register vertical entry position of the beam pcls
- range requirements on beam pions

wedge shaped beam degrader

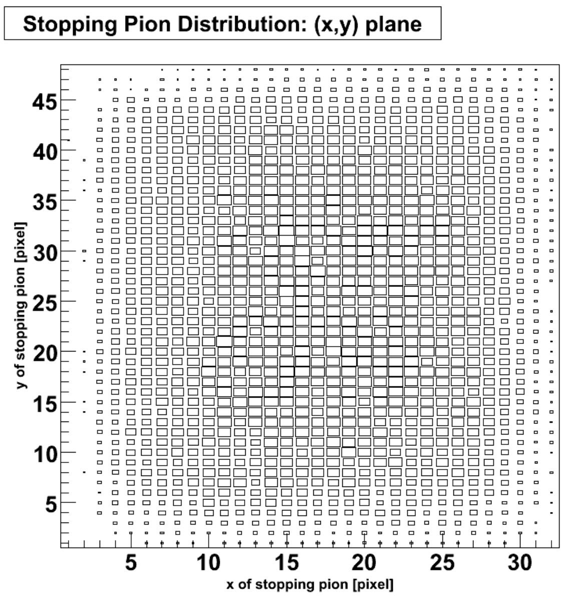
- vertical gradient in the thickness of the absorber
- achieve a uniform distribution of the pion stopping points
  (combined with large beam profiles)



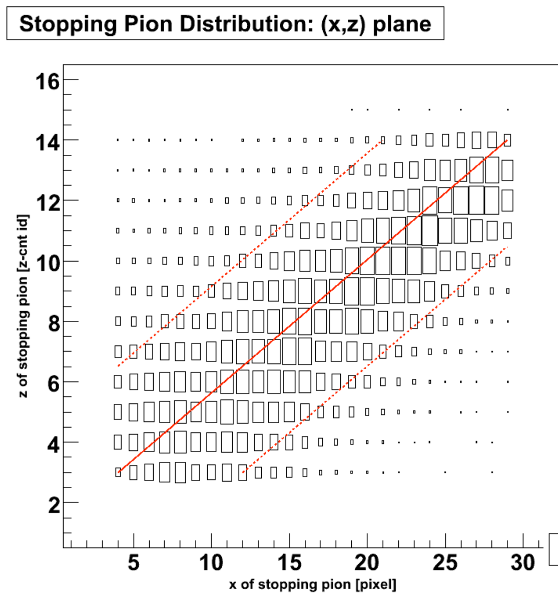
FAST Occupancy and Range Requirements

PION BEAM (nominal running conditions)

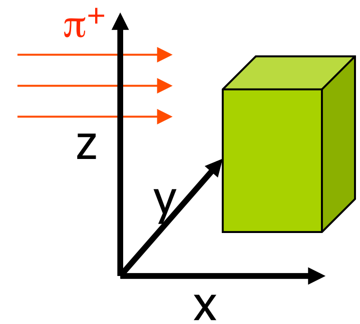
achieved uniform occupancy of pion stopping point



transverse plane (x,y)

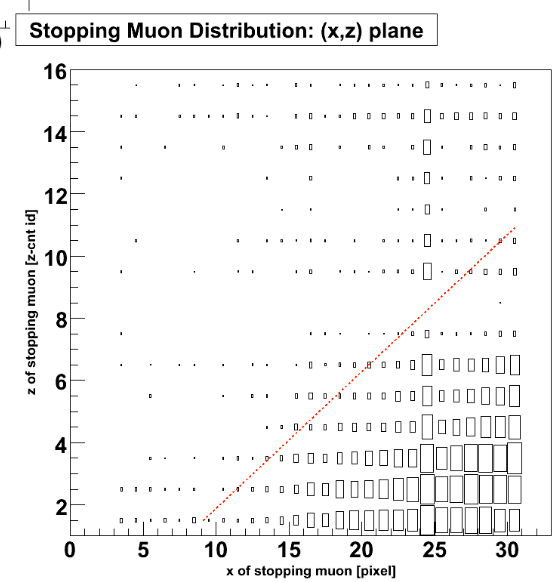


vertical plane (x,z)



MUON BEAM

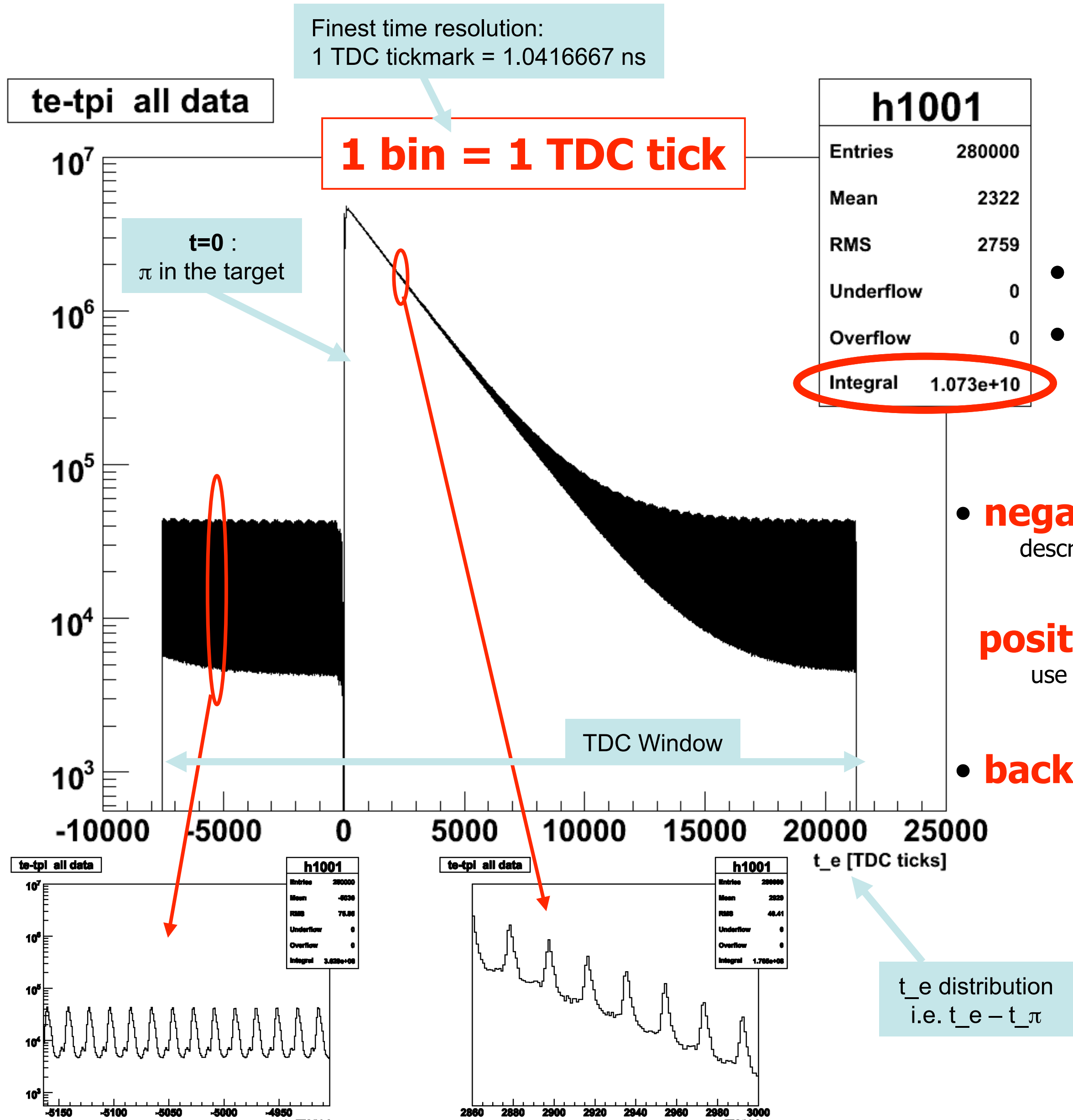
vertical plane (x,z)



Strong range separation (20 pixel ~ 8 cm)
between beam π's and μ's :

Wedge + hodoscope z-cnt tags
efficient suppression of residual beam muons

FAST Raw Muon Decay Time Distribution



"THE" PLOT

- t_e distribution i.e. t_e-t_π
- total stat : 10^{10} μ decay events

- **negative times** (pure bkg events) &
  description of the background (totally decoupled from the signal) from the negative times region

  positive times (signal+bkg)
  use the background description also for the positive times region

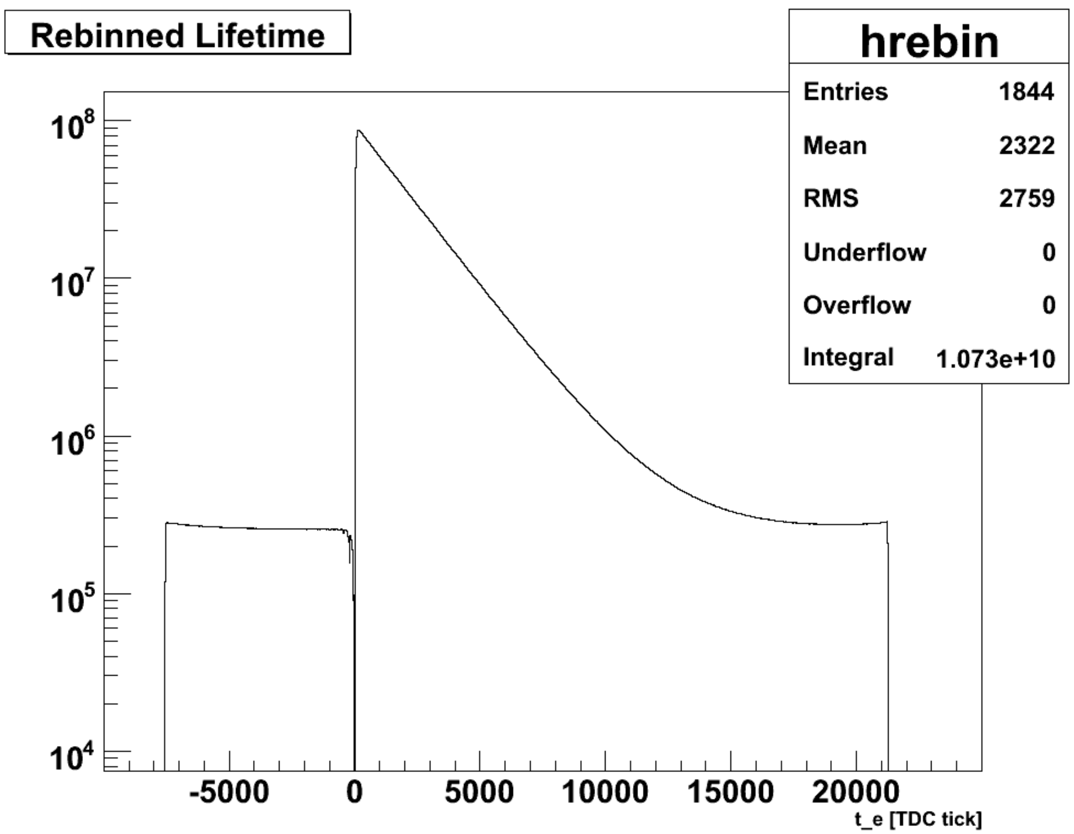
- **background**: flat component
  no time dependent

  \+ RF periodicity structure (T_{RF})
  beam induced background

FAST Smart Rebin Method

Rebin the histogram using the measured beam period T_{RF}

- to minimize the influence of the periodic background on τ_μ measurement
- information loss – but only on the details of the background, not the lifetime

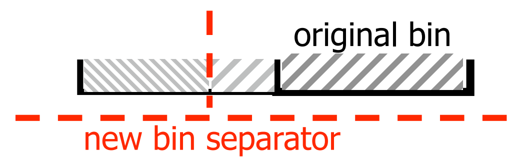


T_{RF}

1 new bin = 18.960051 original bins

"SMART REBIN"

i. e. rebin + bin sharing procedure :

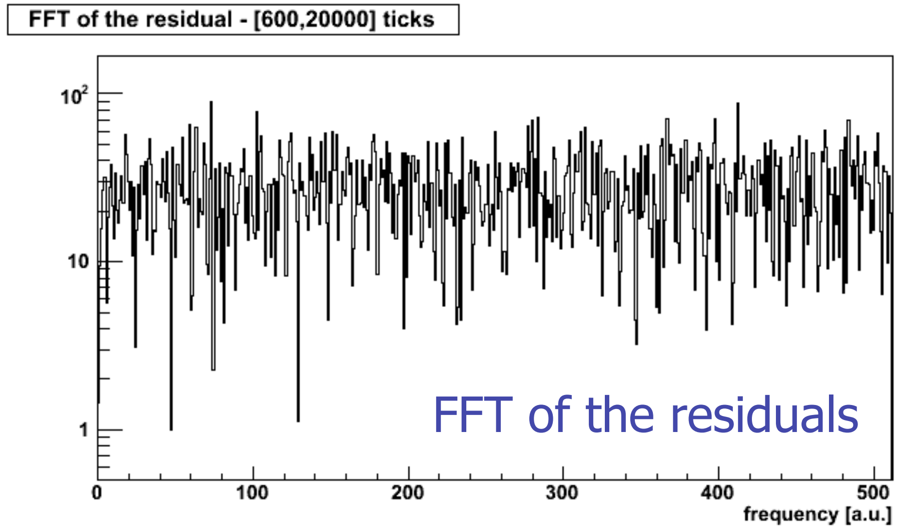


→ different algorithms tried (uniform, linear, quadratic, exp) for the sharing of evts inside the original bin
→ no appreciable differences found (see systematics)
→ default: uniform distribution inside the bin

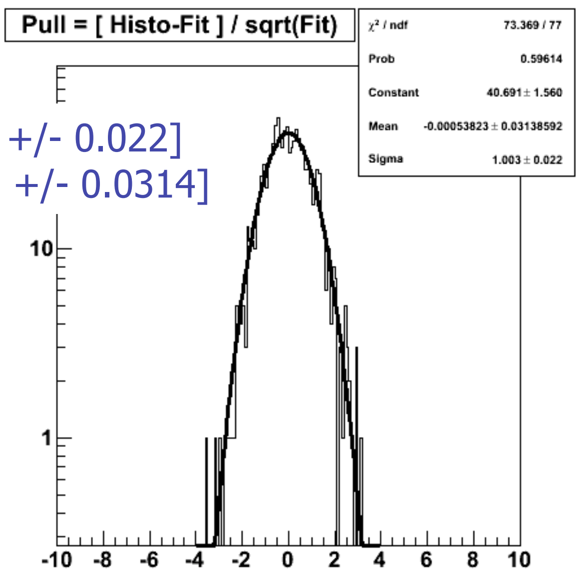
FAST Fit Quality

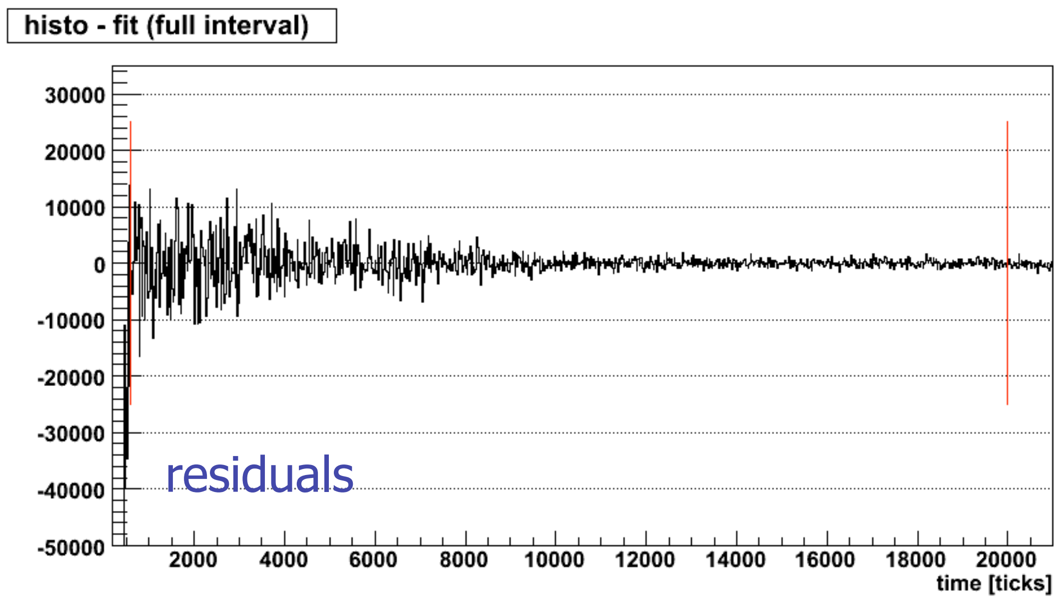
Full Statistics Sample (Run2006) *Smart Rebin Method*		*Fit:* [600, 20000] *ticks*
χ^2/ndf		1030.65/1020 = 1.0104
Prob(χ^2,ndf)		0.4014
Fitted Parameters		
Offset	P_0	253135 ± 39
Exp. Tail Norm.	P_2	$(1.180 \pm 0.008) \times 10^{-8}$
Normalization	N_0	$(2.00104 \pm 0.00002) \times 10^{11}$
Lifetime [ticks]	τ	2109.200 ± 0.031

	P_0	P_2	N_0	τ
P_0	1.000	-0.714	-0.104	-0.498
P_2	-0.714	1.000	0.084	0.335
N_0	-0.104	0.084	1.000	-0.157
τ	-0.498	0.335	-0.157	1.000



σ=[1.003 +/- 0.022]
X=[-0.0005 +/- 0.0314]





FAST Systematics

- Different classes of systematic errors identified:
  - DETECTOR UNIFORMITY ($\tau\mu$ VS: x_π; y_π; position inside PSPM; PSPM; chip; TDC)
  - FIT METHOD
  - τ_μ ESTIMATOR ($t_e - t_\pi$ VS $t_e - t_\mu$)
  - μSR EFFECTS
  - STABILITY OF THE MEASUREMENT (time stability, clock, rate dependence)

- Evaluated using several dedicated histograms (produced online)
- General recipe (when several lifetime measurements are available)

  - Any deviation inconsistent with the statistical fluctuations is considered to be of systematic origin
  - **A PRIORI consistency criteria = 3 sigma's**

  1. Fit histograms corresponding to the subsamples & compute the average
  2. Look if there are statistically incompatible points (i.e. deviation from the average $\Delta\tau_\mu > 3\sigma$)
  3. How much the average changes when those points are excluded
  4. Quote this variation as (signed) systematic shift

FAST Current Result on Muon LIfetime

- first precise measurement of the positive muon lifetime with the FAST experiment:

$$\tau_\mu = [2197.083 \pm 0.032\ (\mathrm{stat}) \pm 0.015\ (\mathrm{syst})]\ \mathrm{ns}$$

$$\frac{\delta\tau_\mu}{\tau_\mu} = 16\ \ \mathrm{ppm}$$

  - run 2006 [3 weeks data taking, Nov-Dec06]
  - data sample : 1.073 10^{10} μ^+ decay events
  - precision comparable to PDG, value compatible with PDG
  - uncertainty dominated by the statistics

- FAST measurement of the Fermi coupling constant G_F

$$G_F = [1.166353 \pm 0.000009] \times 10^{-5}\ \mathrm{GeV}^{-2}$$

$$\frac{\delta G_F}{G_F} = 8\ \ \mathrm{ppm}$$

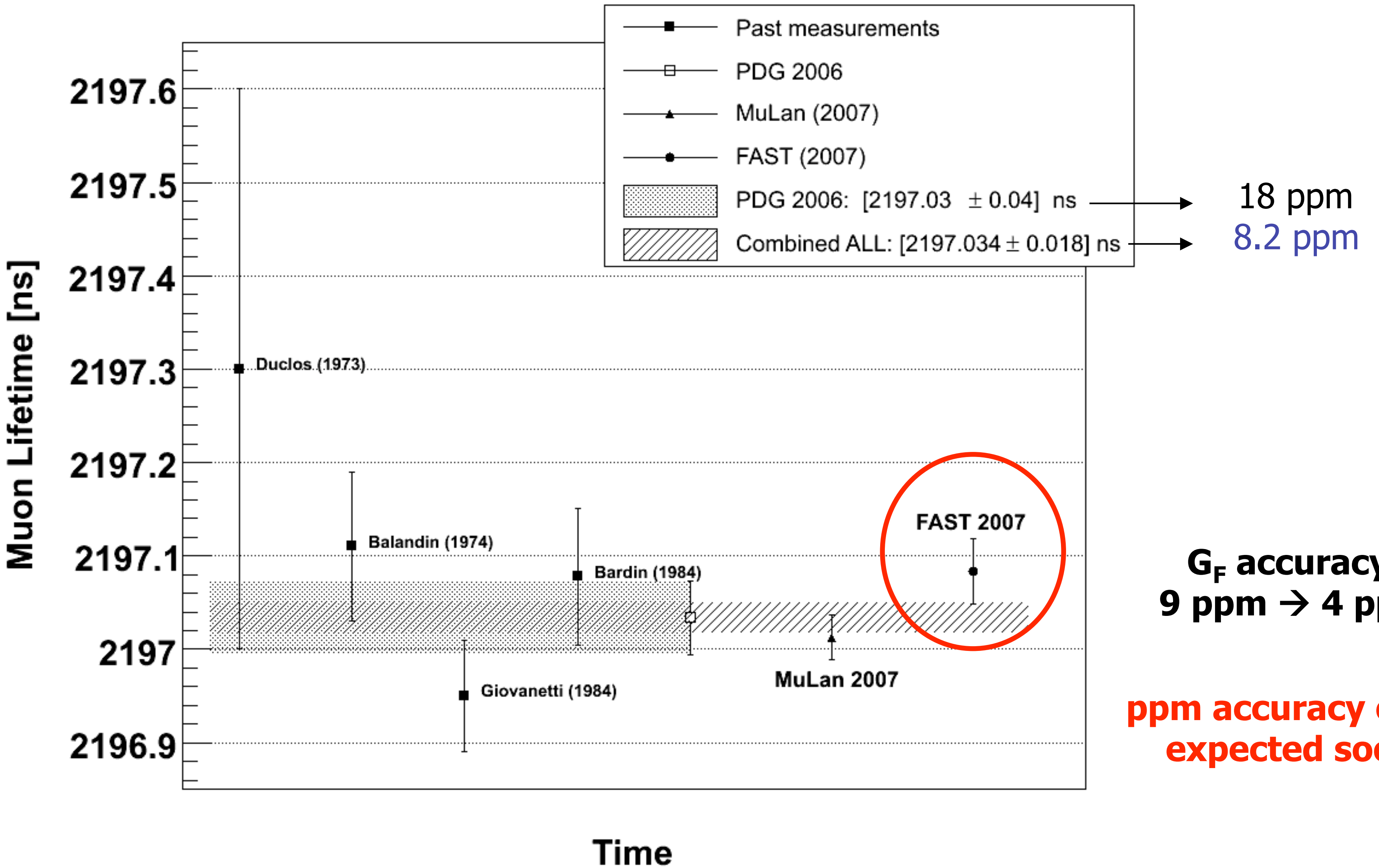
arXiv: 0707.3904 [hep-ex]

FAST Collaboration (A. Barczyk et al.), Phys.Lett. **B663** 172-180, 2008

Current Muon LIfetime Results

OUR MEASUREMENT IN THE WORLD SCENARIO OF MUON LIFETIME EXPERIMENTS

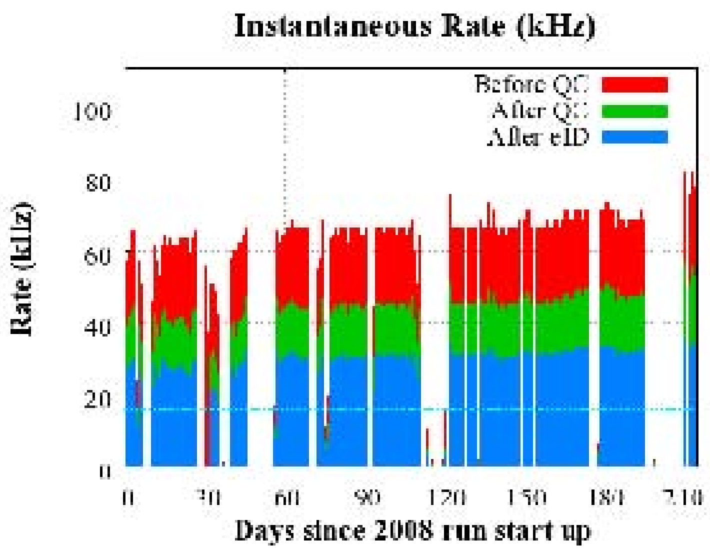
→ after more than 20 years two new experiments (MuLan & FAST) are taking the lead

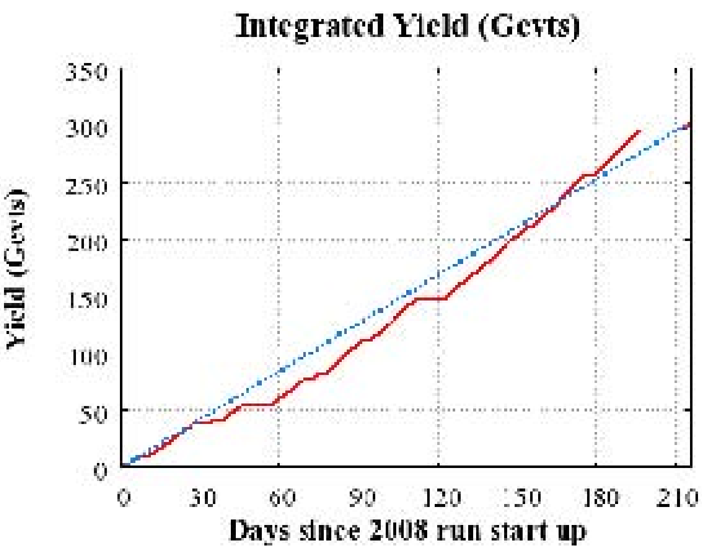


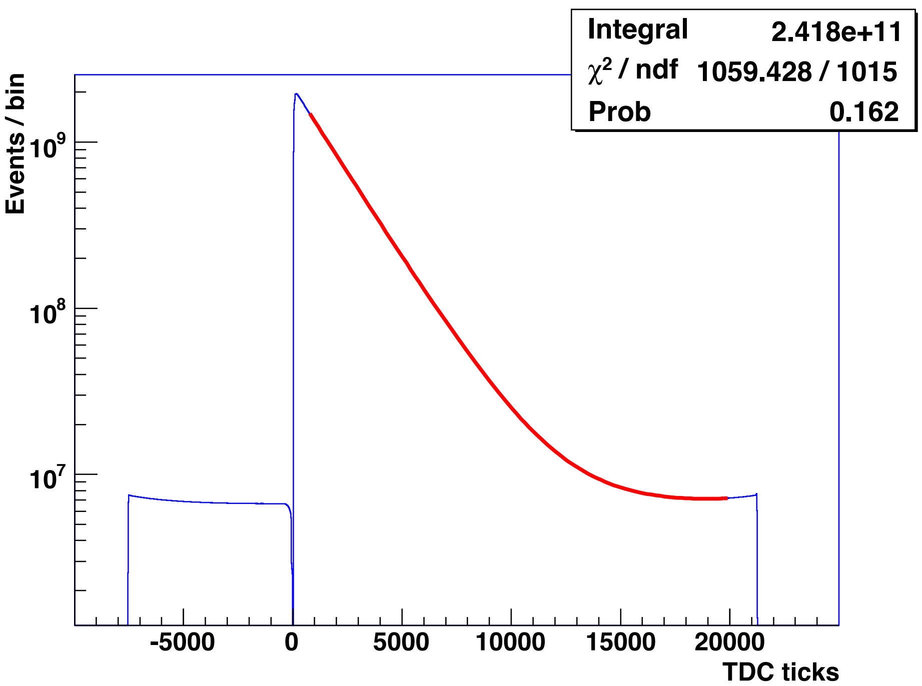
G_F accuracy:
9 ppm → 4 ppm

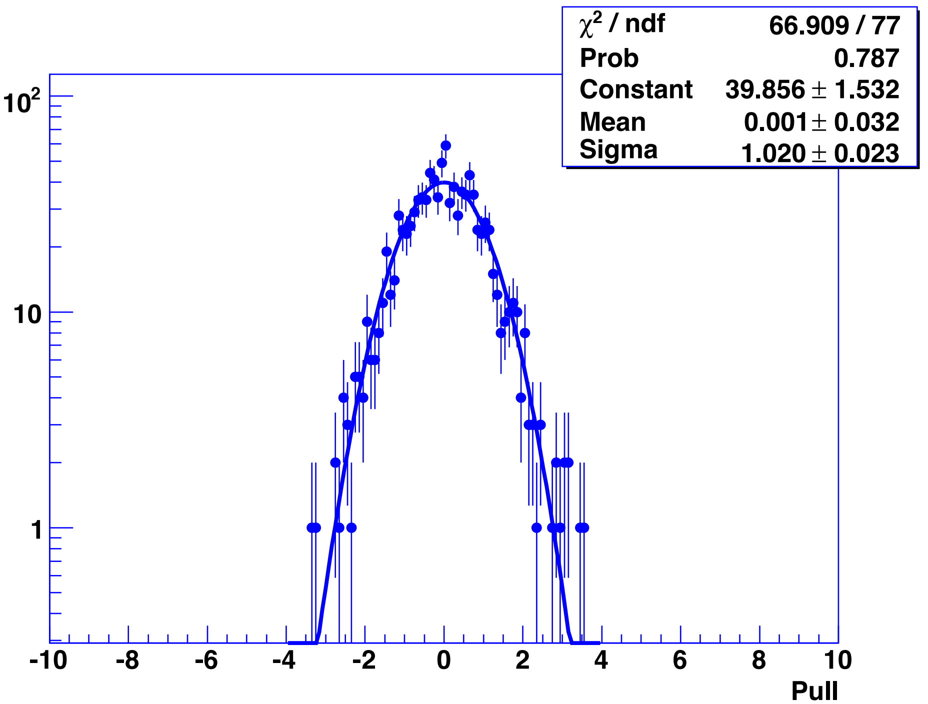
ppm accuracy on G_F expected soon!

FAST Progress in 2008



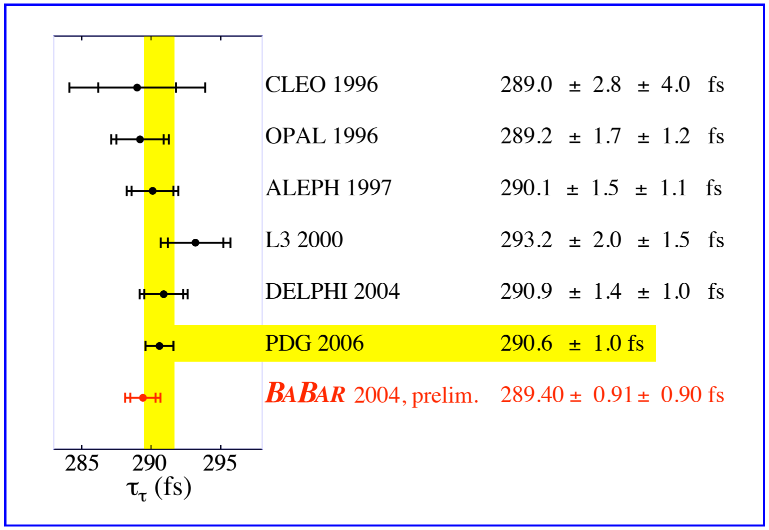


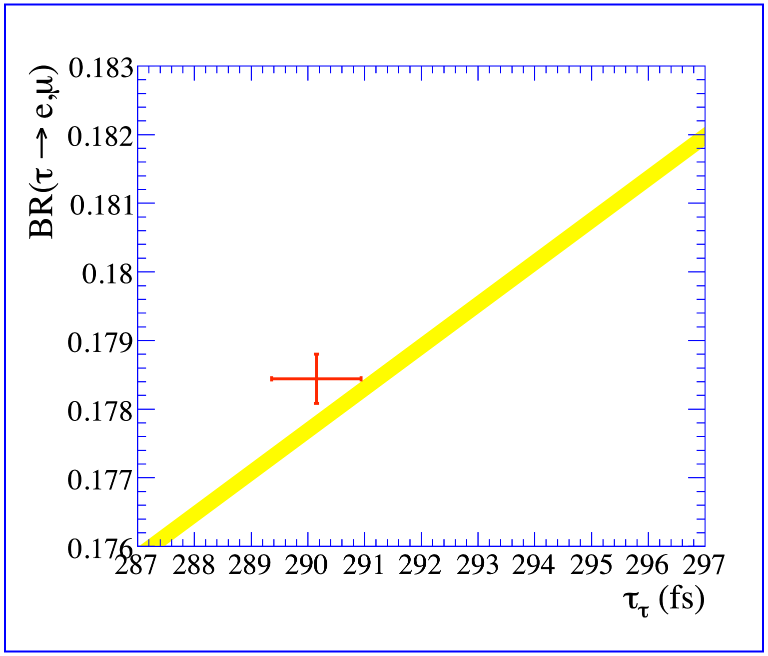




Current Tau Lifetime Results

A.Lusiani arXiv:0709.1599 [hep-ex]





Lifetime of μ and τ equal up to phase space:

$$\Gamma(\tau \to e\nu\nu) = \frac{\text{BR}(\tau \to e\nu\nu)}{\tau_\tau} = \frac{Q_{PS}(m_\tau^5)}{\tau_\mu}$$

Coupling strengths of weak charged current:

$$\frac{g_\mu}{g_\tau} = 0.9982 \pm 0.0020 \quad ; \quad \frac{g_e}{g_\tau} = 0.9980 \pm 0.0020 \quad ; \quad \frac{g_{e,\mu}}{g_\tau} = 0.9981 \pm 0.0017$$

Universality of weak charged current confirmed at the permille level.

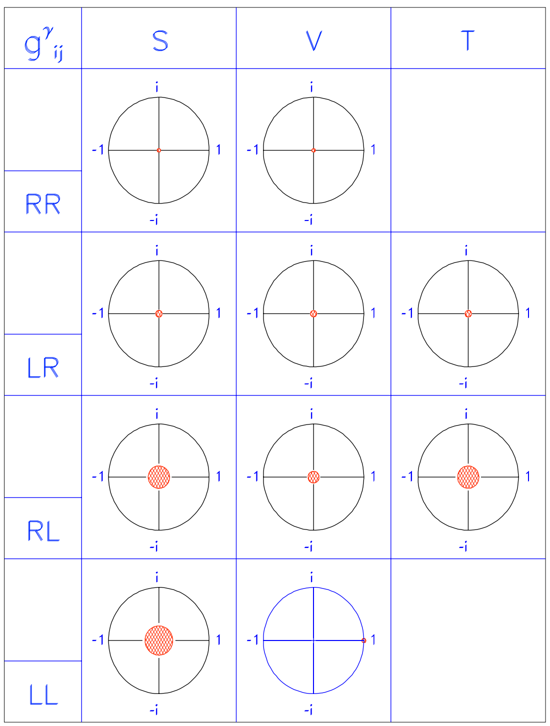
Transformation Properties of W Couplings

General amplitude: Michel (50), Fetscher, Gerber, Johnson (86)

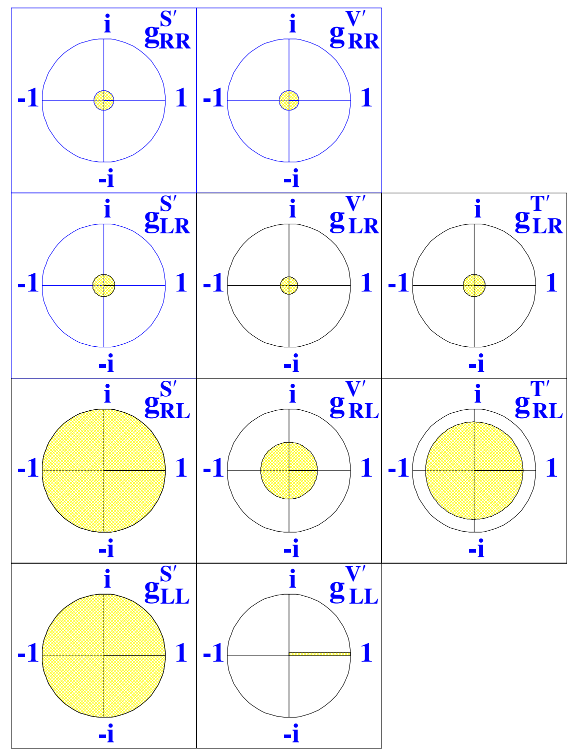
$$\mathcal{M} = 4\frac{G_F}{\sqrt{2}} \sum g^{\gamma}{}_{\epsilon\xi} < \bar{e}_{\epsilon}|\Gamma^{\gamma}|\nu_e >< \bar{\nu}_{\mu}|\Gamma_{\gamma}|\mu_{\xi} >$$

Operators: $\gamma = S, V, T$, Chirality: $\epsilon, \xi = L, R$, SM: $g^V_{LL} = 1$, all others 0.

Muon: PDG



Tau: CLEO 98



Precision today: pure $V - A$ within few % for μ, some 10% for τ

W Does Not Couple to Ordinary Quarks

The W does not interact with the eigenvalues of the mass operator (real particles):

$$\begin{pmatrix} u \\ d \end{pmatrix}_L ; \begin{pmatrix} c \\ s \end{pmatrix}_L ; \begin{pmatrix} t \\ b \end{pmatrix}_L$$

but with the rotated flavor eigenstates:

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L ; \begin{pmatrix} c \\ s' \end{pmatrix}_L ; \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

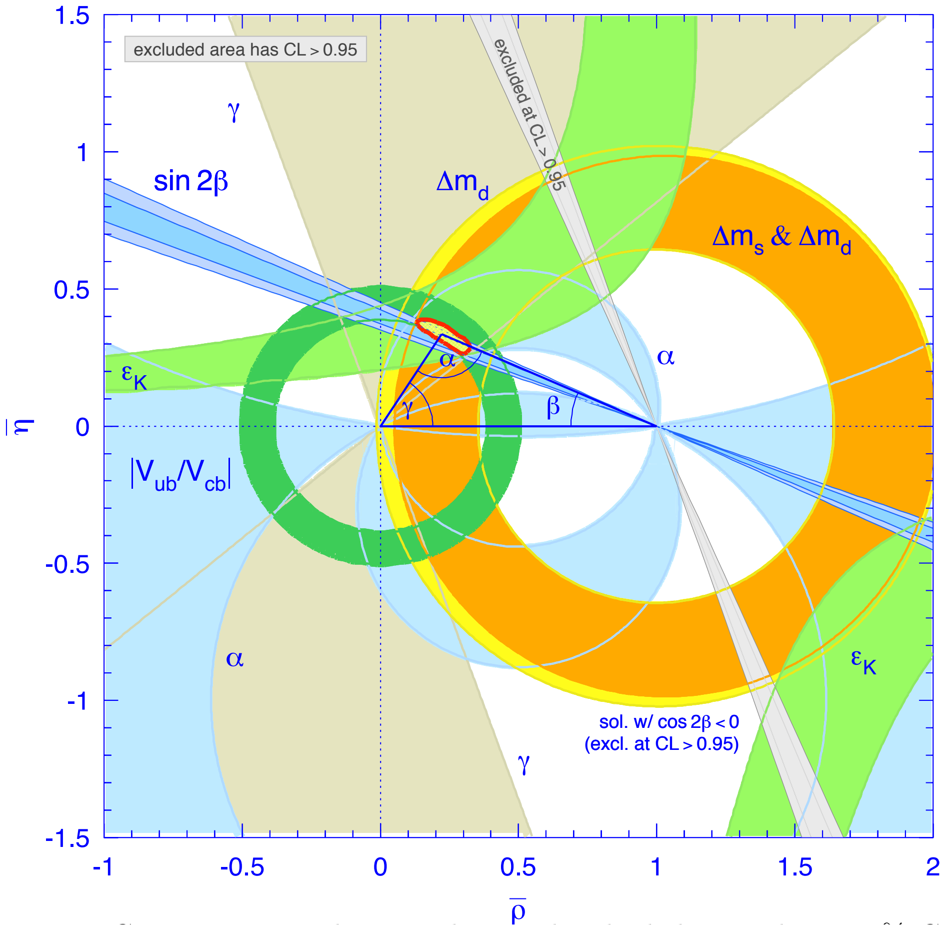
This changes the invariant amplitude for a generic quark decay into:

$$\mathcal{M} = \frac{4G_F}{\sqrt{2}} J_q^\nu J_{\mu\nu}^\dagger$$

$$J_q^\mu = (\bar{u}\ \bar{c}\ \bar{t})\, \gamma_\mu \frac{1}{2}(1-\gamma^5) V \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

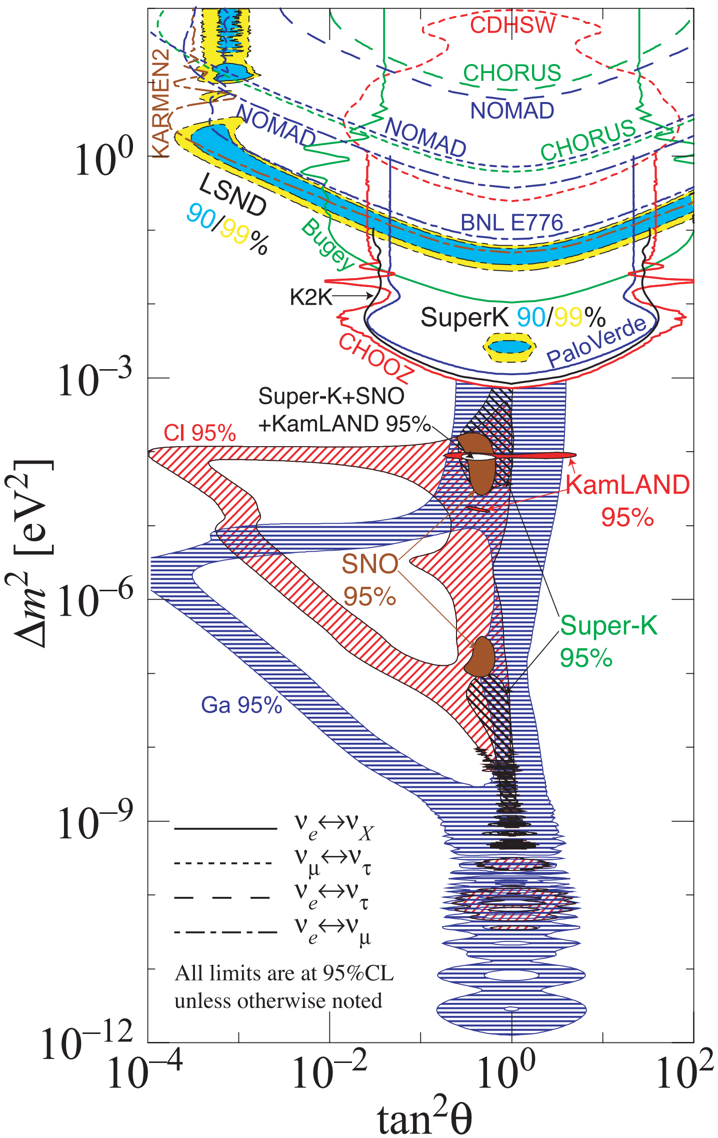
with the Cabibbo-Kobayashi-Maskawa matrix V.

Cabibbo-Kobayashi-Maskawa Matrix



$$V = \begin{pmatrix} 0.97383^{+0.00024}_{-0.00023} & 0.2272^{+0.0010}_{-0.0010} & (3.96^{+0.09}_{-0.09}) \times 10^{-3} \\ 0.2271^{+0.0010}_{-0.0010} & 0.97296^{+0.00024}_{-0.00024} & (42.21^{+0.10}_{-0.80}) \times 10^{-3} \\ (8.14^{+0.32}_{-0.64}) \times 10^{-3} & (41.61^{+0.12}_{-0.78}) \times 10^{-3} & 0.999100^{+0.000034}_{-0.000004} \end{pmatrix}$$

Maki-Nakagawa-Sakata Matrix



Relates mass eigenstate $\nu_i, i = 1, 2, 3$ with flavor eigenstate $\nu_\alpha, \alpha = e, \mu, \tau$:

$$\nu_i = \sum_\alpha U_{\alpha i} \nu_\alpha$$

$$U = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

$$= \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$= \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Weak decay produces flavor eigenstate, mass eigenstates travel at different speed depending on their mass. $\rightarrow$ Neutrino flavor oscillations

W Couplings to Gauge Bosons

General Lagrangian for VWW-coupling ($V = \gamma, Z$, with C- and P-invariance):

$$\frac{i\mathcal{L}_{eff}}{g_{VWW}} = g_1^V V^\mu (W_{\mu\nu}^- W^{+\nu} - W_{\mu\nu}^+ W^{-\nu})$$

$$\kappa_V W_\mu^+ W_\nu^- V^{\mu\nu} + \frac{\lambda_V}{M_W^2} V^{\mu\nu} W_\nu^{+\rho} W_{\rho\mu}^-$$

Normalization: $g_{\gamma WW} = -e \quad ; \quad g_{ZWW} = -e \cot\theta_W$

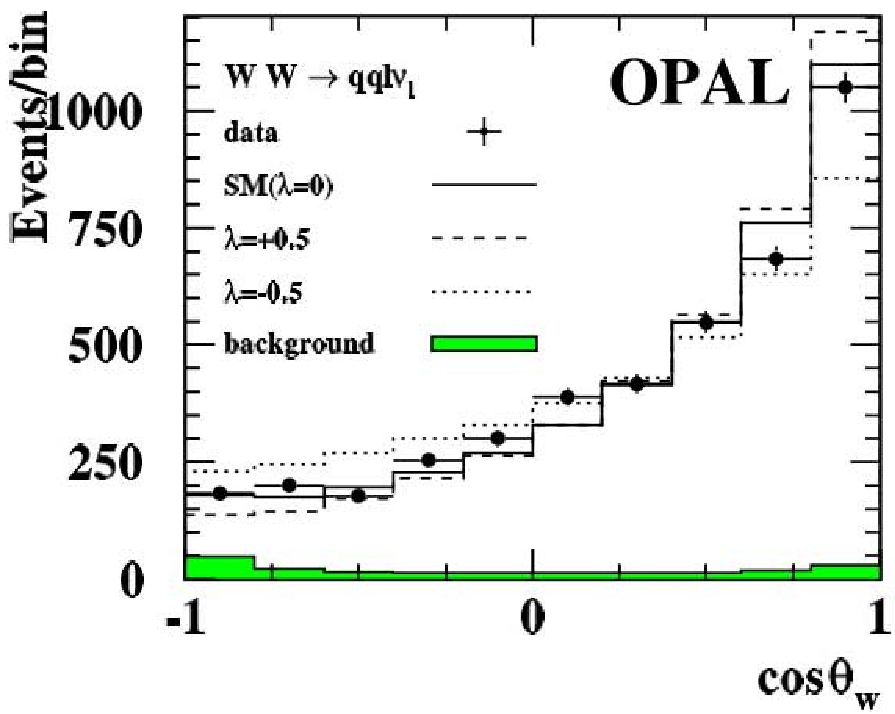
Multipole expansion of γW term $\longrightarrow$ static properties of W:

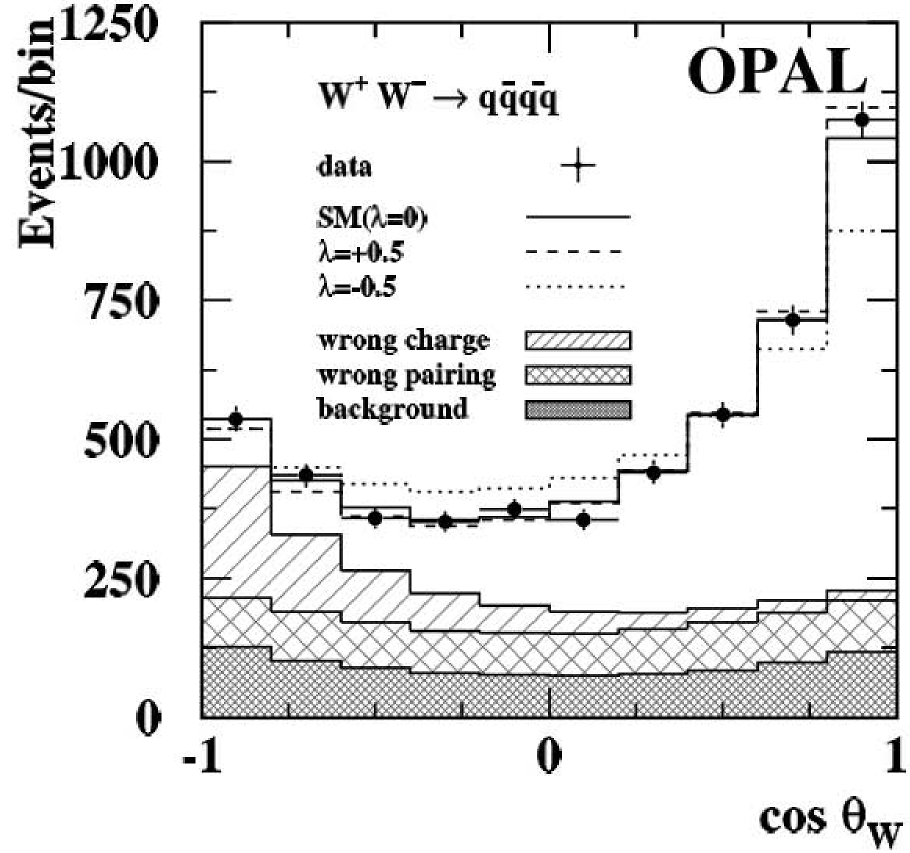
- Electric charge: $q_W = e g_1^\gamma$
- Magnetic dipole moment: $\mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$
- Electric quadrupole moment: $\mathcal{Q}_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$

E.m. gauge invariance:	$SU(2) \otimes U(1)$ gauge invariance:
$g_1^\gamma = 1$	$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$
	$\lambda_Z = \lambda_\gamma$

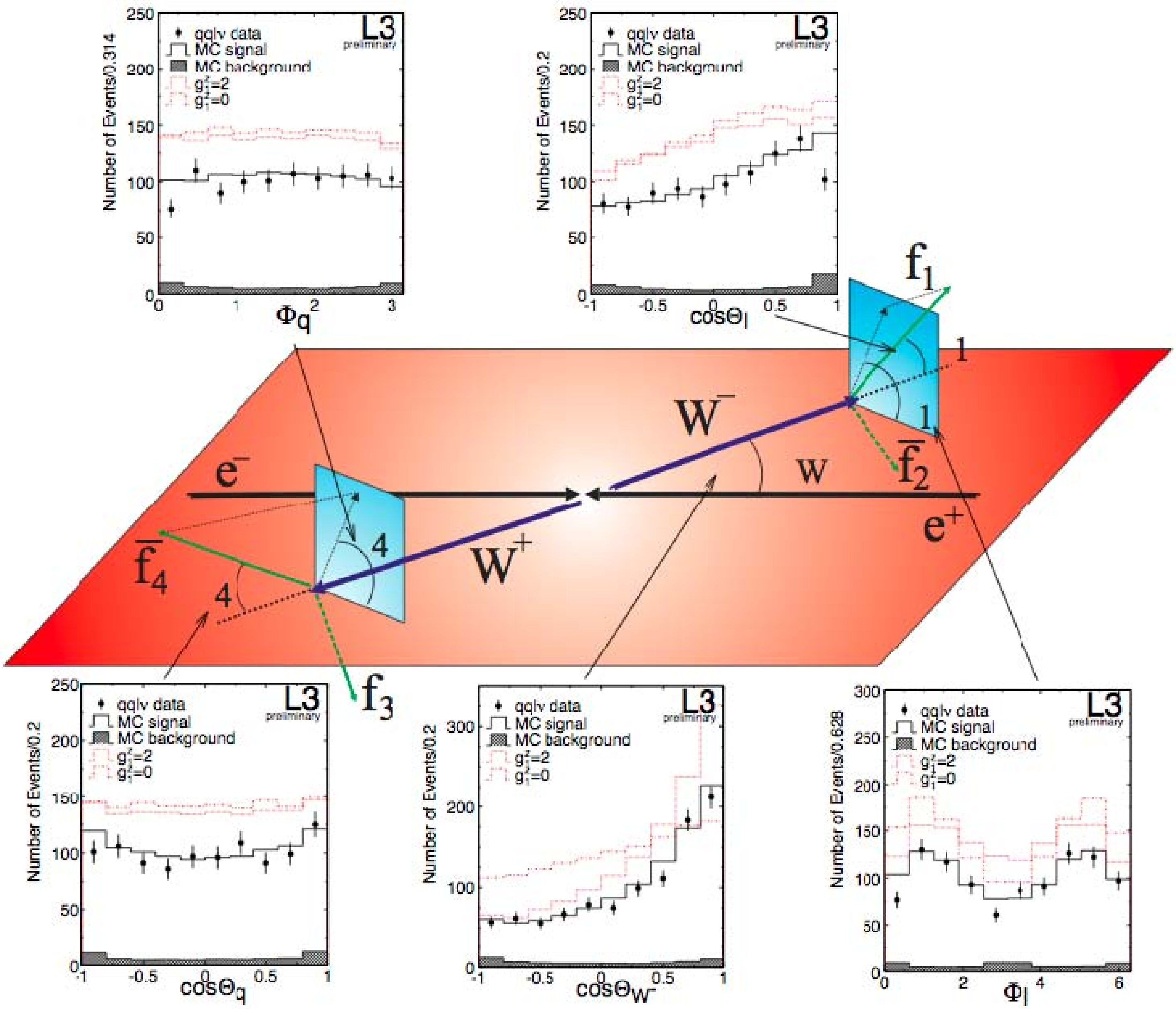
W Pair Production Angle

Distribution of W-pair production angle carries information about coupling structure:

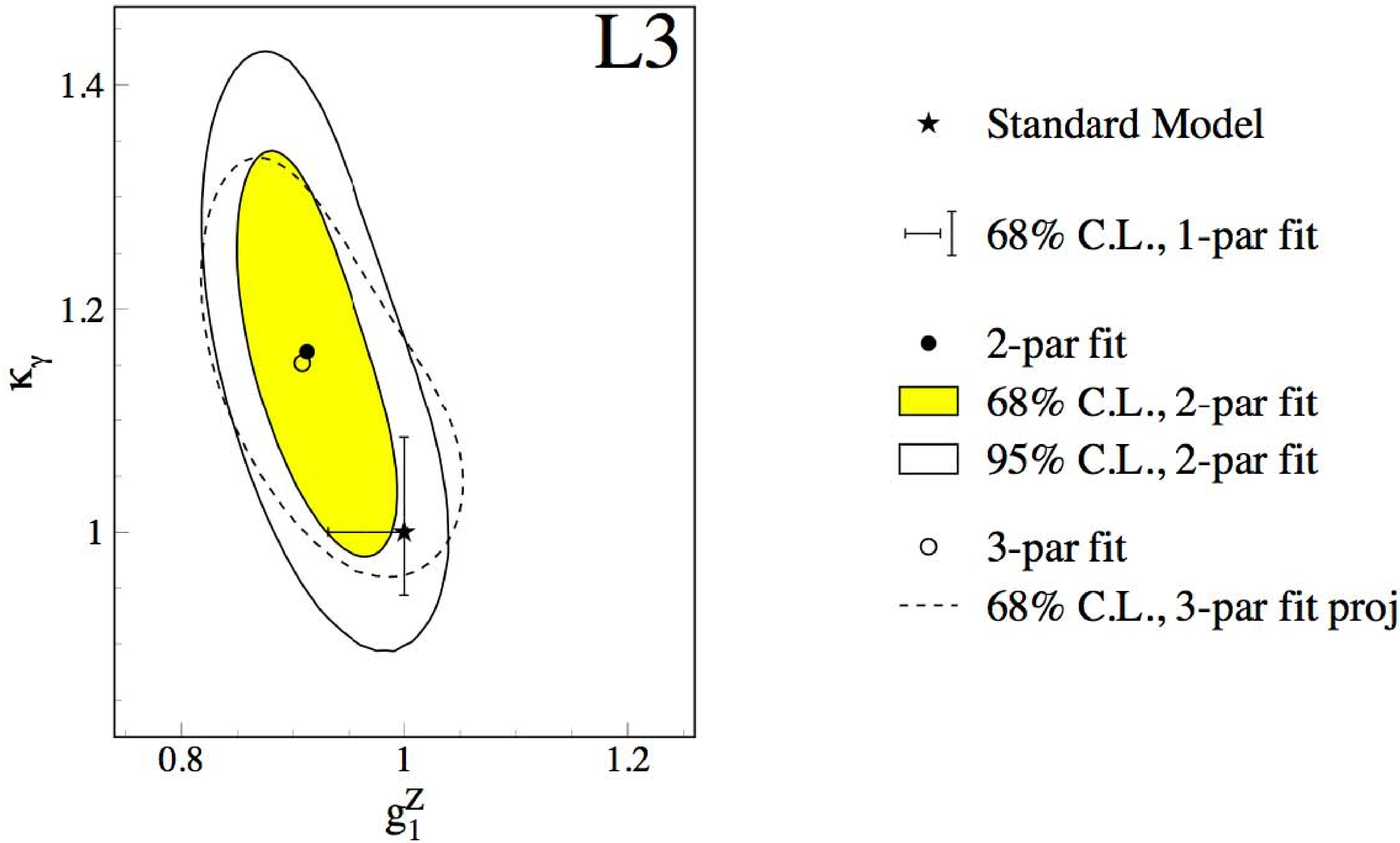




W Pair Decay Angles



W Couplings to Gauge Bosons



Compared to other couplings: qualitative result, accuracy $\mathcal{O}(10\%)$.

Precision Tests of the Standard Model

- At tree level, three gauge couplings, but only two independent ones:

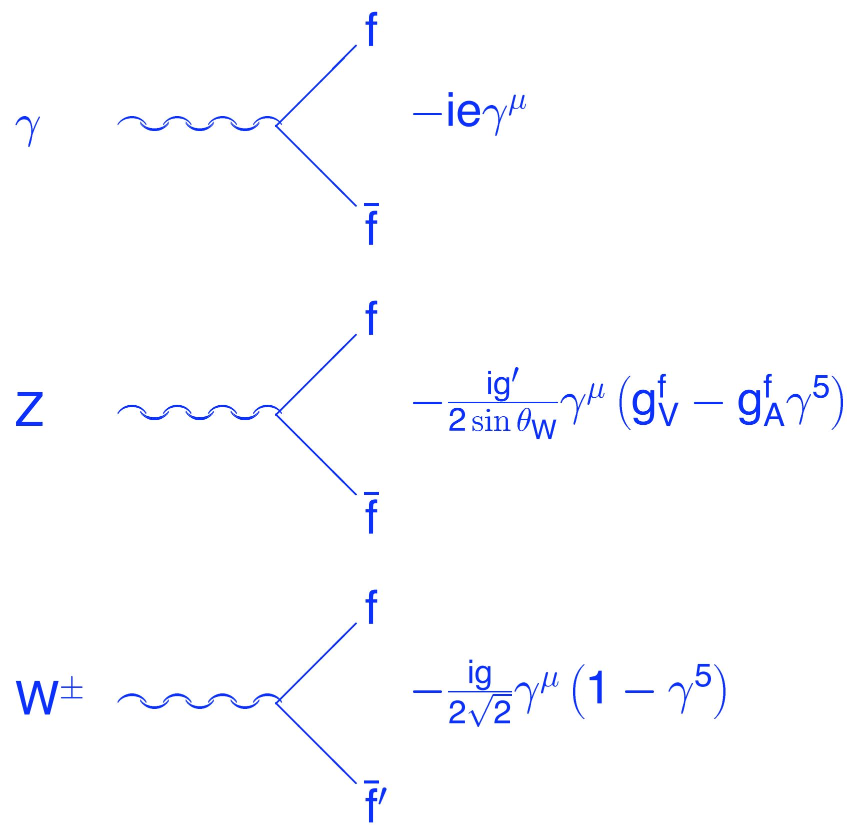
$$e = g \sin\theta_W = g' \cos\theta_W$$

Partial unification of electroweak forces.

- Higgs mechanism with doublets only:

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

Relation between couplings and gauge boson masses.

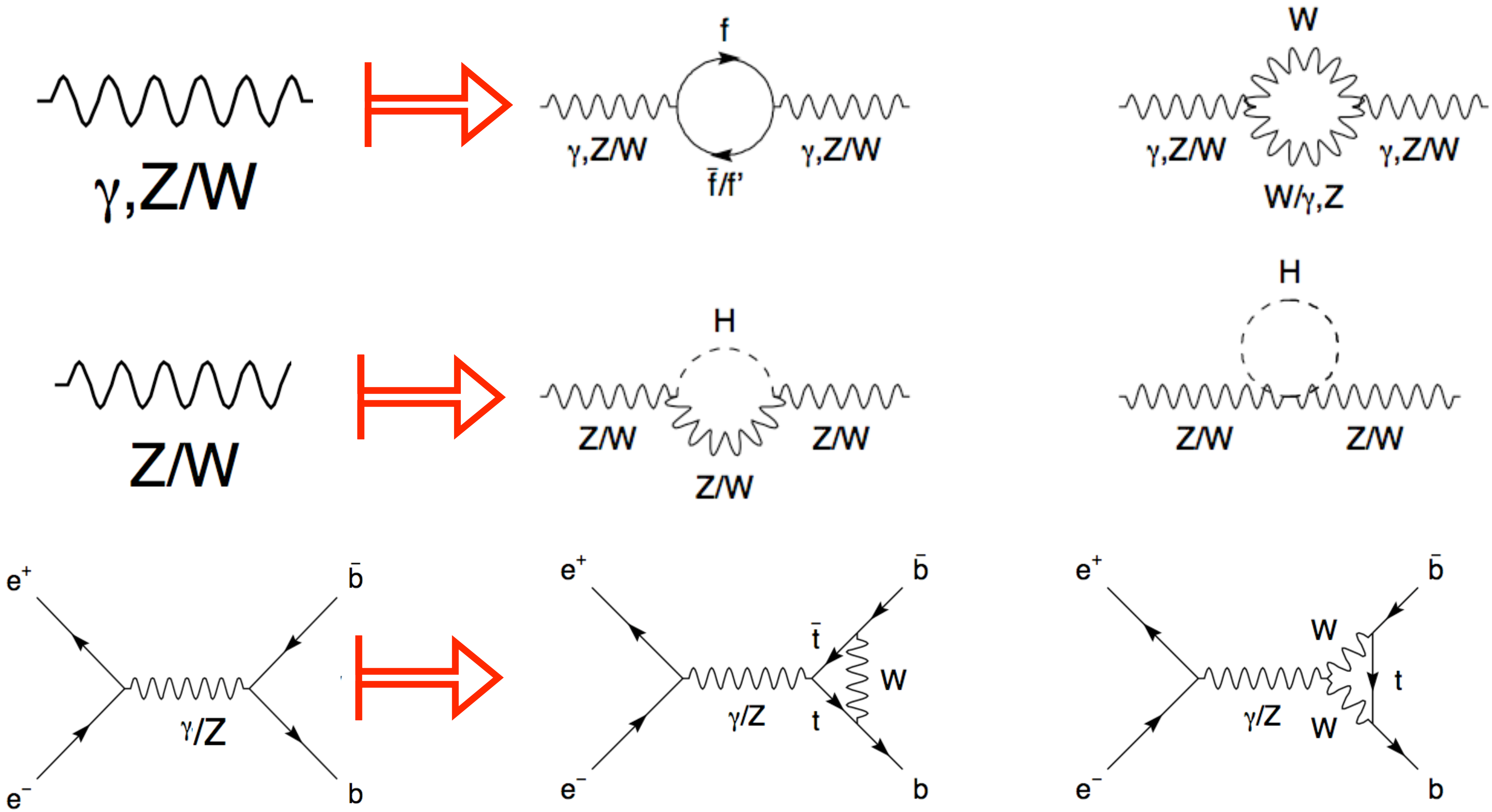


- Space-time structure of vertices given by electroweak multiplets:

$$g_V^f = \sqrt{\rho_0}\left(T_3^f - 2Q_f \sin^2\theta_W\right) \quad ; \quad g_A^f = \sqrt{\rho_0}\,T_3^f$$

For Higgs doublets, $\rho_0 = M_W^2/(M_Z^2\cos^2\theta_W) = 1$.

Electroweak Propagator and Vertex Corrections



Radiative Corrections Formalism

Define weak mixing angle to all orders by:

$$\rho_0 = \frac{M_W^2}{M_Z^2 \cos^2\theta_W} = 1 \quad ; \quad \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

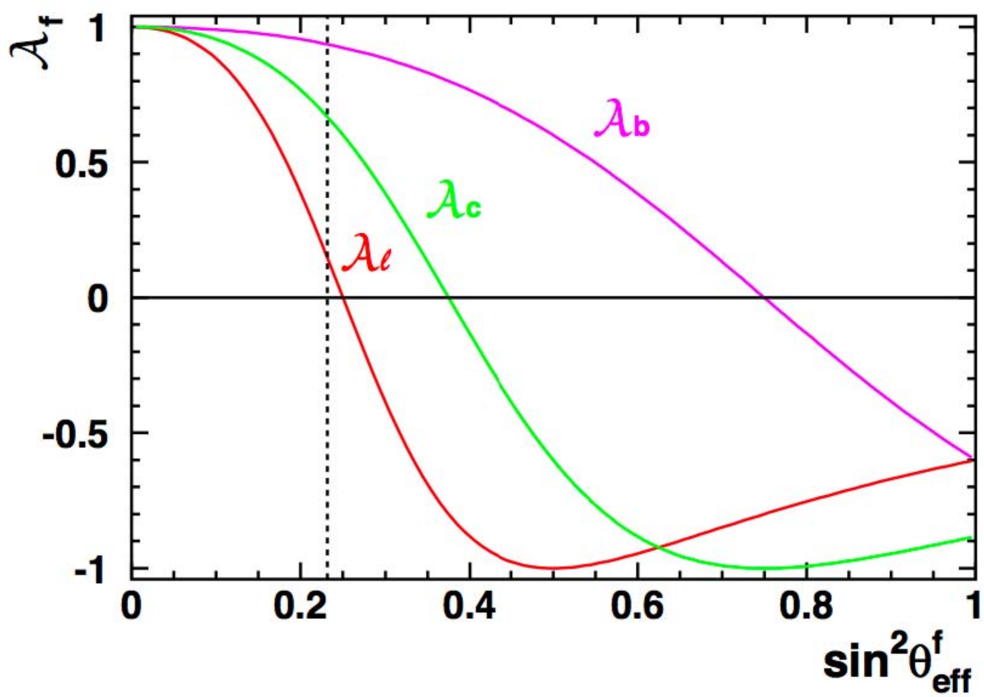
Absorb all radiative corrections into two form factors, which depend on the fermion species f:

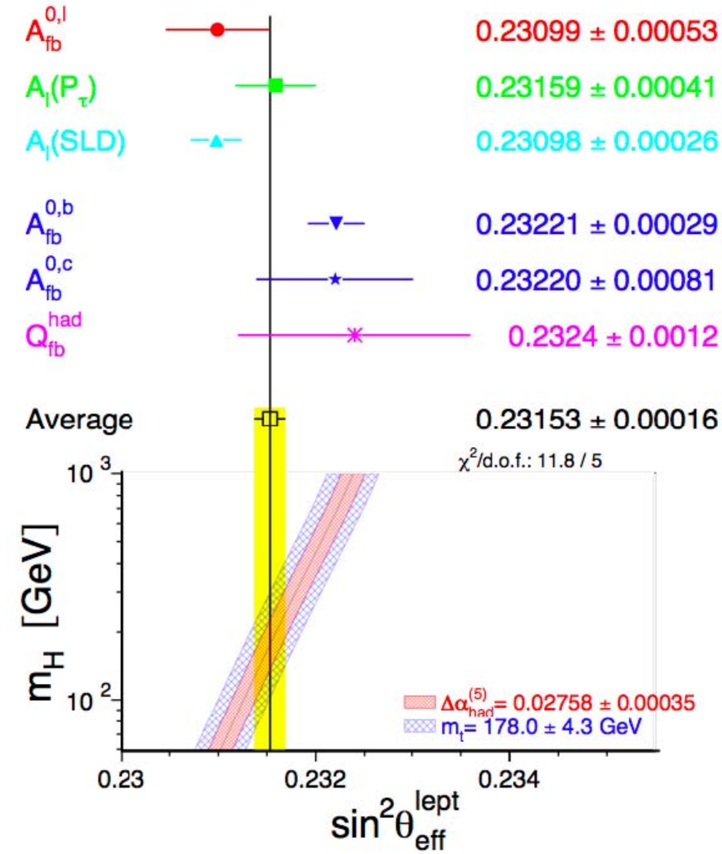
$$\begin{aligned} \sin^2\theta_{eff}^f &\equiv \kappa_f \sin^2\theta_W \\ g_V^f &\equiv \sqrt{\rho_f}\left(T_3^f - 2Q_f \sin^2\theta_{eff}^f\right) \\ g_A^f &\equiv \sqrt{\rho_f}T_3^f \end{aligned}$$

These definitions preserve the basic structure of electroweak coupling relations:

$$\frac{g_V^f}{g_A^f} = 1 - \frac{2Q_f}{T_3^f}\sin^2\theta_{eff}^f = 1 - 4|Q_f|\sin^2\theta_{eff}^f$$

Asymmetry Parameters and Weak Mixing Angle





Attention: The values extracted from A_{LR} and A^b_{FB} are the most precise and differ by 3.2σ. The reason is not know:

Thus the shift is either a sign for new physics which invalidates the simple relations between the effective parameters assumed in this chapter, or a fluctuation in one or more of the input measurements. In the following we assume that measurement fluctuations are responsible.

Standard Model Parameters

- Couplings for all forces (except gravity):
  - Electromagnetic α, weak G_F, strong α_s
  - Relation $G_F = \pi\alpha/(\sqrt{2}M_W^2 \sin^2\theta_W)$ reduces couplings to two: α and α_s
- Fermion masses:
  - Lepton masses precise, light quark masses irrelevant at $E \simeq M_Z$: m_t
- Boson masses:
  - $M_\gamma = M_g = 0$
  - Replace M_W by using $G_F = \pi\alpha/(\sqrt{2}M_W^2 \sin^2\theta_W)$: leaves M_Z
- And the Higgs boson mass M_H...

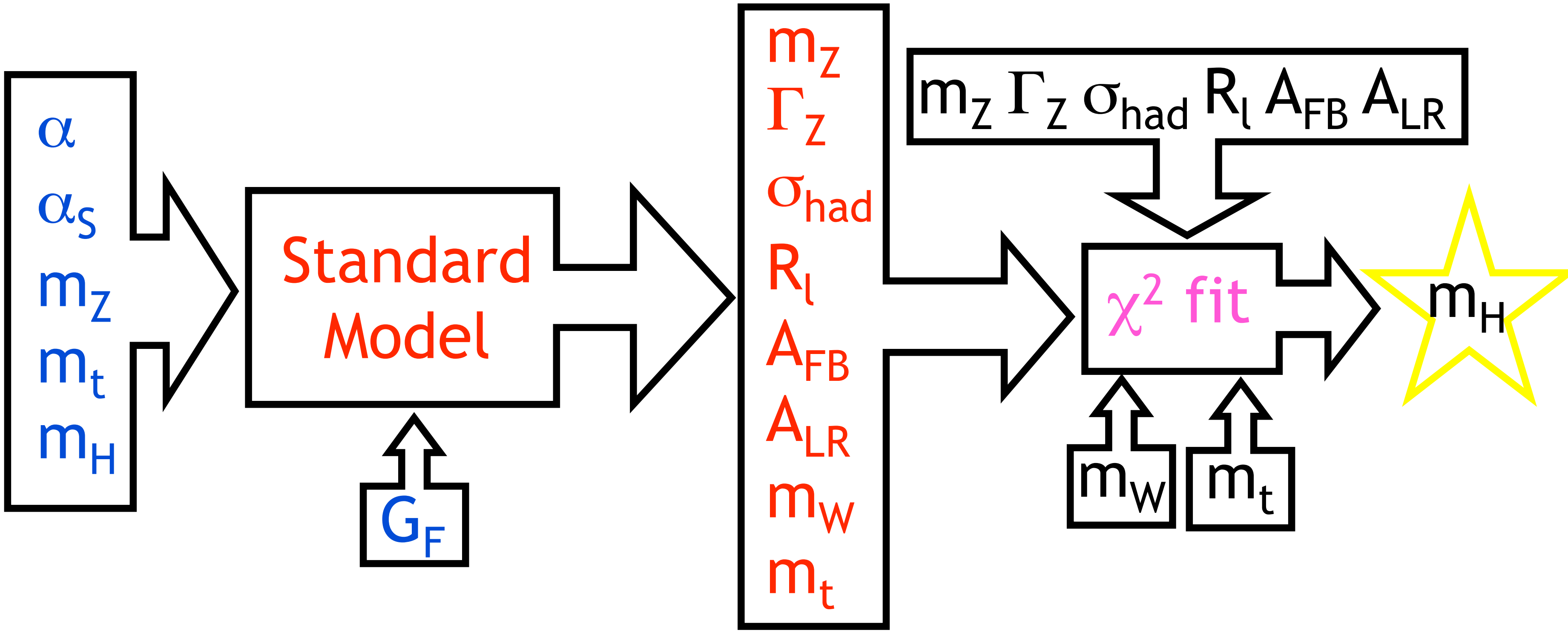
Given this input, the Standard Model become highly predictive!

The Standard Model Black Box (courtesy S. Mele)

Use input parameters...

to predict values...

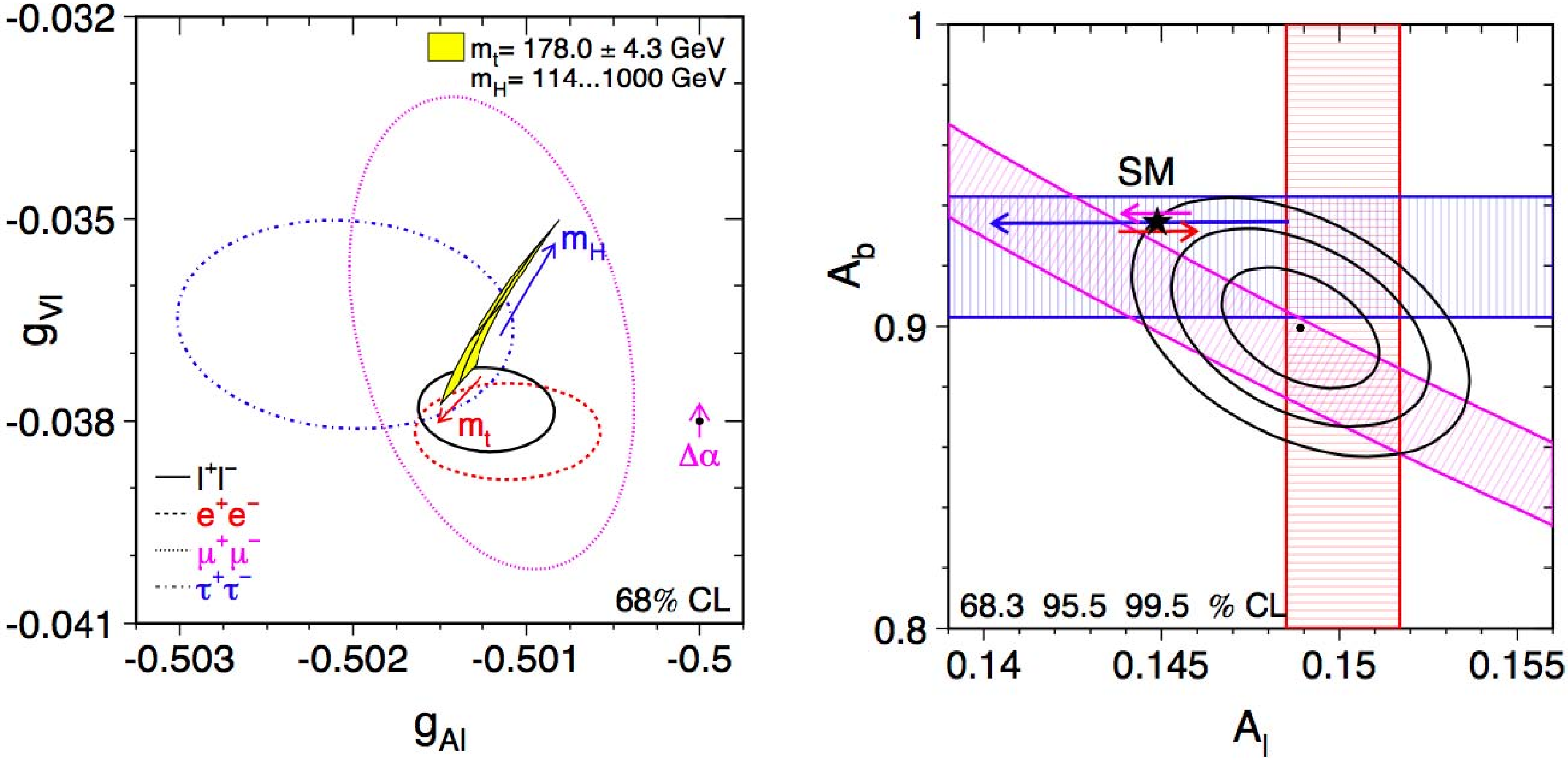
to compare to measurements...



...to check the Standard Model

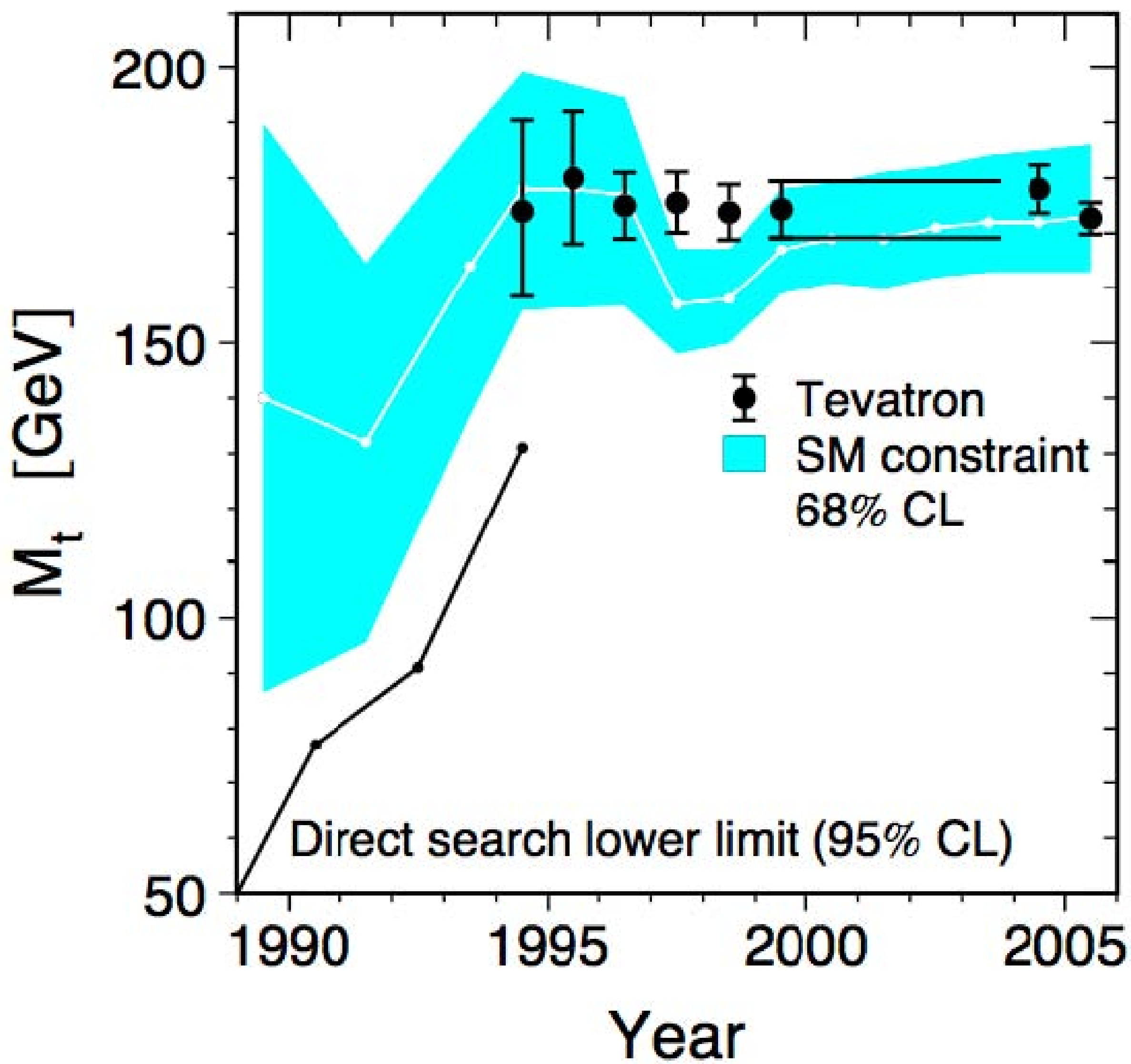
...to predict m_H

Test Coupling Predictions



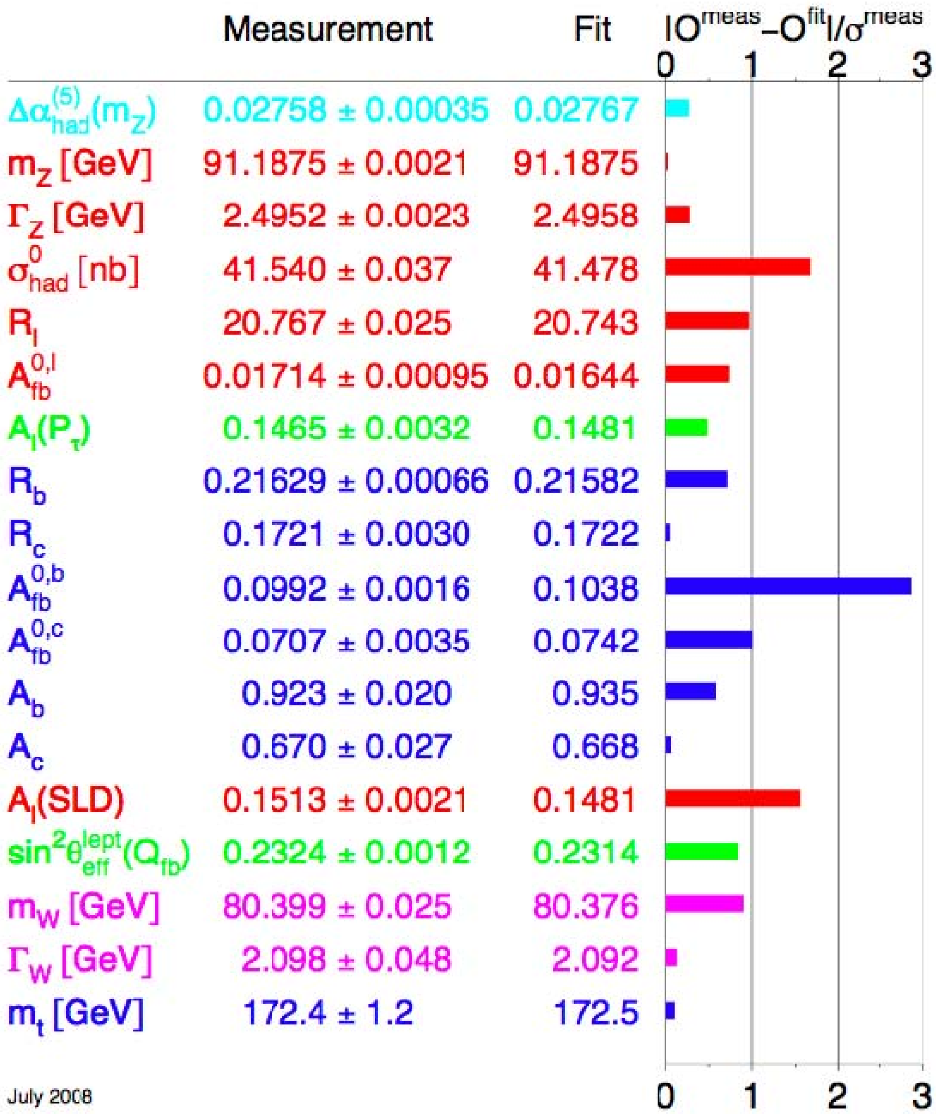
Attention: effective couplings $\rightarrow g_A \neq 1/2$

Top Mass from Radiative Correction



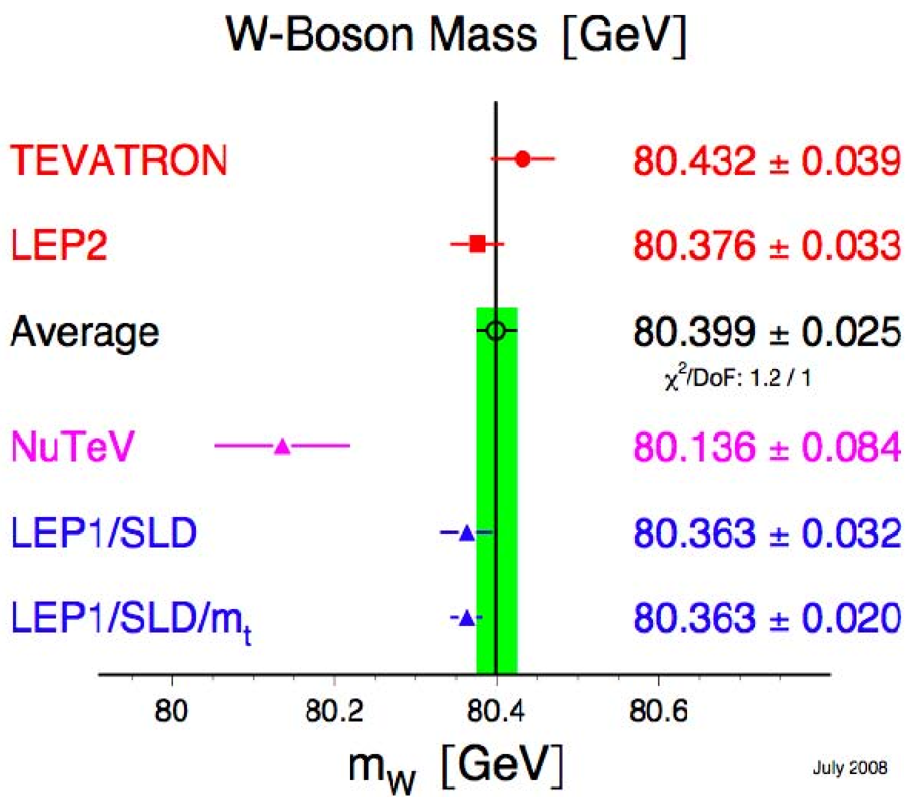
- Vertex corrections $\propto m_t^2$
- Propagator corrections $\propto \log_{10} M_H$

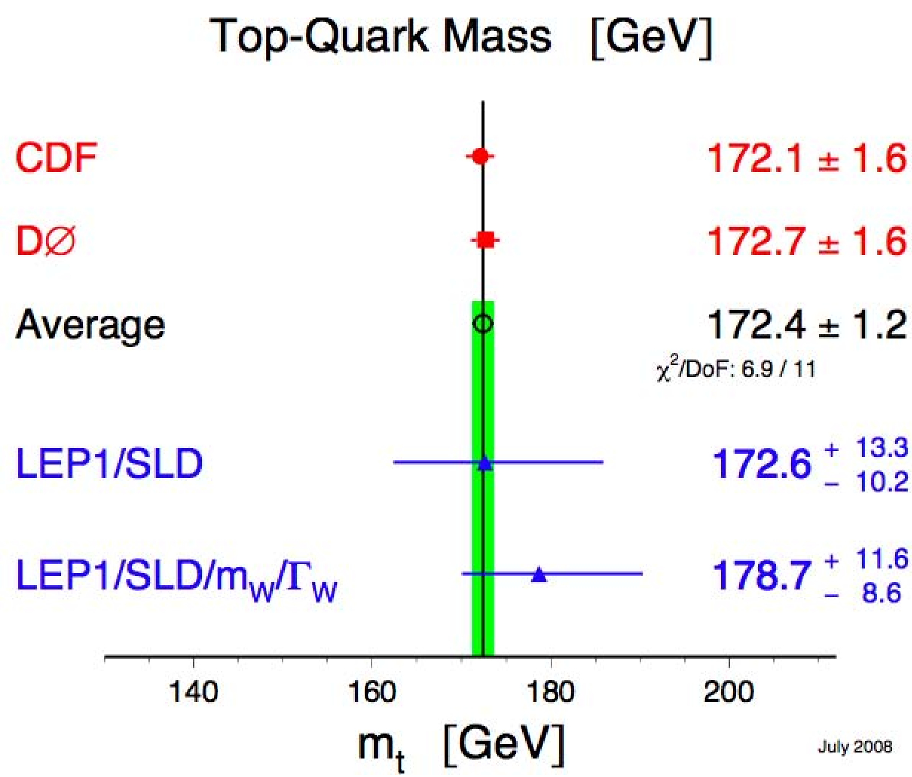
Fever Curve of the Standard Model



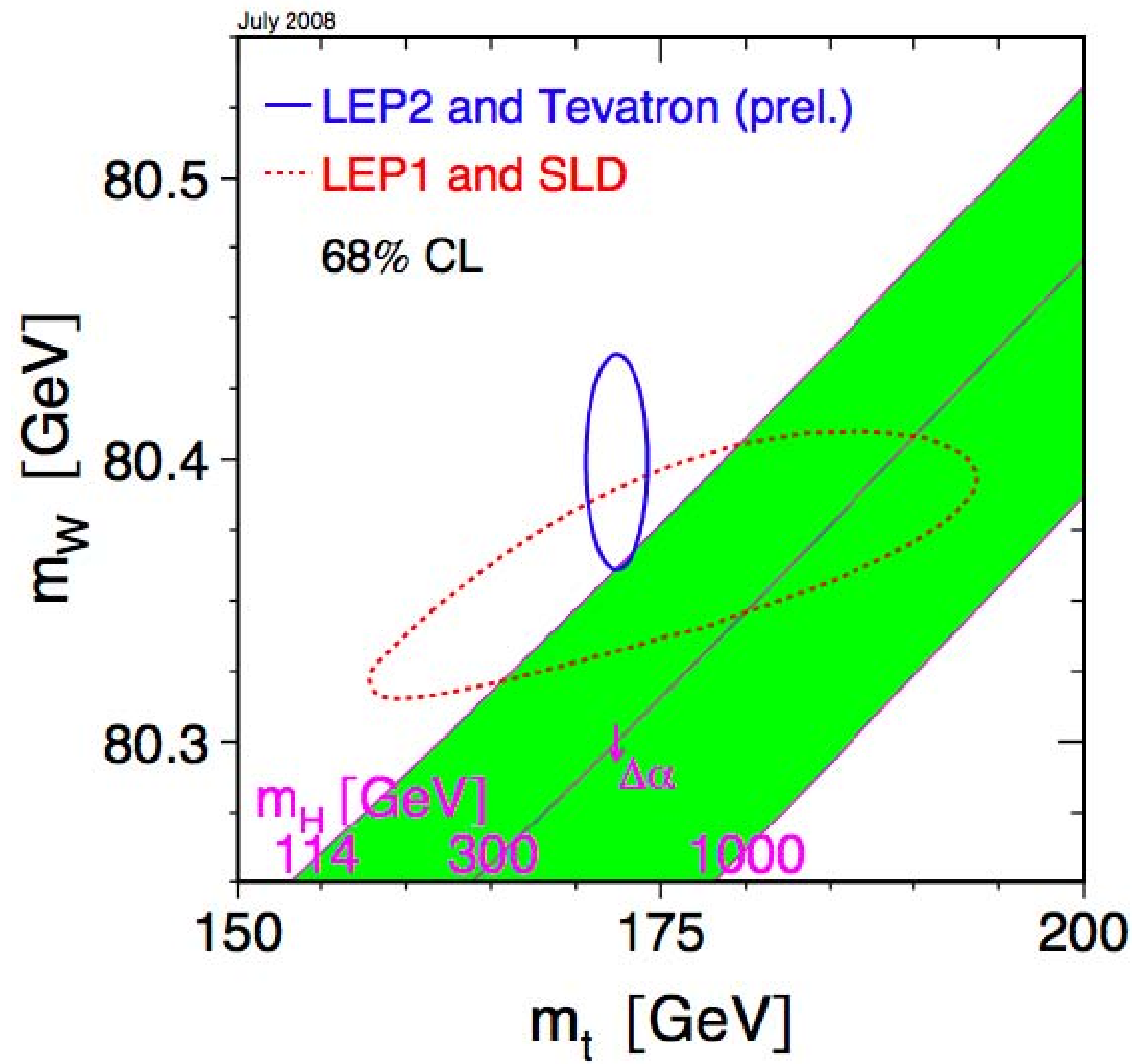
- Choose one parameter, remove it from the fit
- Predict its value from all other inputs and the SM black box
- Compare to measured values

W Boson Mass and Top Mass

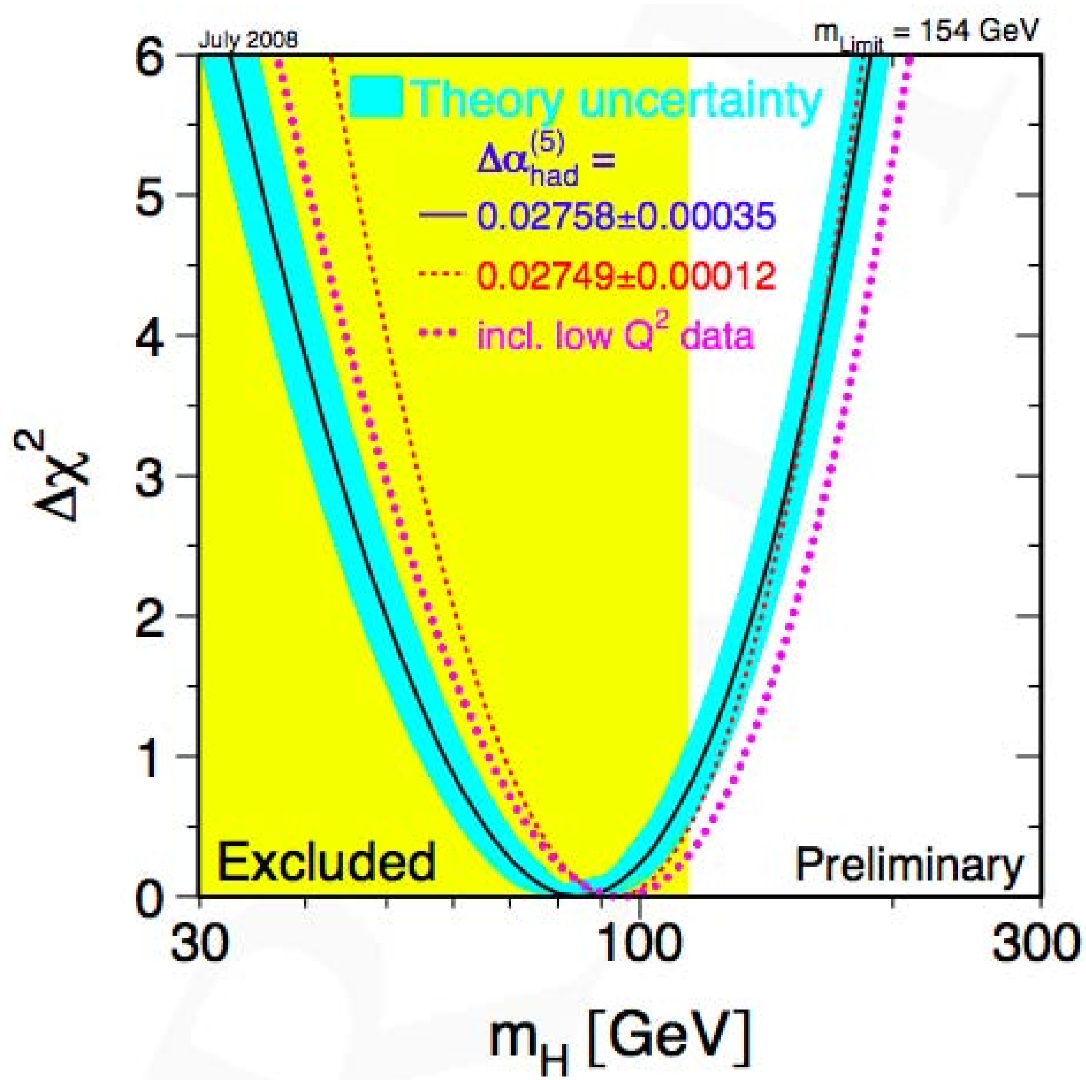




W Boson Mass and Top Mass vs Standard Model

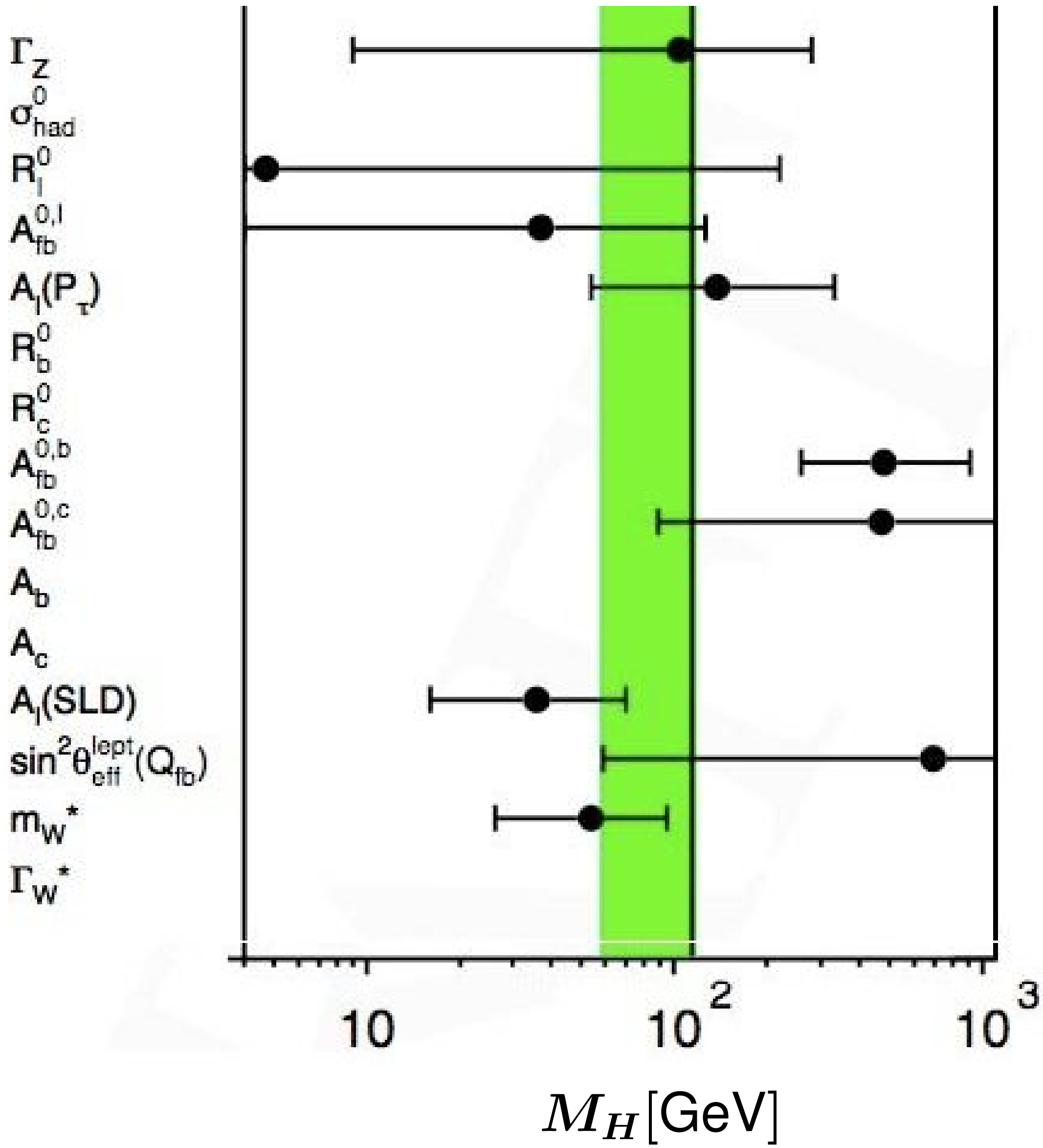


Higgs Mass Limits from LEP/SLD



- $M_H < 154$GeV @ 95% CL with blue band included
- $M_H > 114.4$GeV @ 95% CL from LEP direct search
- $M_H < 185$GeV @ 95% CL combination of all data

Higgs Mass Limit Sensitivity to Input



- $A_{LR} - A^b_{FB}$ discrepancy is important
- W mass measurement has high sensitivity

Standard Model Health Bulletin

	- 1 - all Z-pole data	- 2 - all Z-pole data plus m_t	- 3 - all Z-pole data plus m_W, Γ_W	- 4 - all Z-pole data plus m_t, m_W, Γ_W
m_t [GeV]	173^{+13}_{-10}	$172.4^{+1.2}_{-1.2}$	179^{+12}_{-9}	$172.5^{+1.2}_{-1.2}$
m_H [GeV]	111^{+190}_{-60}	110^{+55}_{-38}	144^{+240}_{-81}	84^{+34}_{-26}
$\log_{10}(m_H/\text{GeV})$	$2.05^{+0.43}_{-0.34}$	$2.04^{+0.18}_{-0.19}$	$2.16^{+0.42}_{-0.35}$	$1.93^{+0.15}_{-0.16}$
$\alpha_S(m_Z^2)$	0.1190 ± 0.0027	0.1190 ± 0.0027	0.1190 ± 0.0028	0.1185 ± 0.0026
χ^2/d.o.f. (P)	16.0/10 (9.9%)	16.0/11 (14%)	16.8/12 (16%)	17.3/13 (18%)
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	0.23149 $\pm$0.00016	0.23149 $\pm$0.00016	0.23143 $\pm$0.00014	0.23139 $\pm$0.00013
$\sin^2\theta_W$	0.22331 $\pm$0.00062	0.22332 $\pm$0.00039	0.22289 $\pm$0.00038	0.22306 $\pm$0.00029
m_W [GeV]	80.363 ± 0.032	80.363 ± 0.020	80.385 ± 0.020	80.376 ± 0.015

All in all, the patient survived the operation...