Electroweak precision physics from low to high energy

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Marie Curie Fellowships

Many thanks to

Gino Isidori, Wu-Ki Tung, Stefano Forte, Martin Grunewald, Thomas Teubner, Bolek Pietrzyk, German Rodrigo, Antonello Polosa, Kevin McFarland, Alessandro Strumia, Andrea Ferroglia, Stefan Kretzer, Uli Haisch

From low to high energy

Three orders of magnitude at high speed:

Neutral currents Parity Violating asym in Møller scattering

Charged currents Test of universality

Neutral/Charged currents NuTeV

The muon anomalous magnetic moment

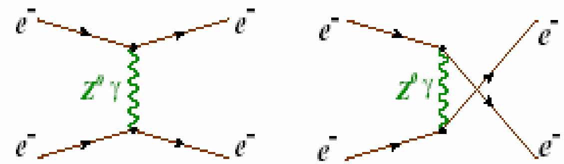
Collider data M_W, asymmetries...

Global fits and the mass of the Higgs

PV in Møller scattering

- Scatter polarized 50 GeV electrons off *unpolarized* atomic electrons
- Measure $A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -A_{LR}$
- Small tree-level asymmetry

$$A_{PV} = -mE\frac{G_F}{\sqrt{2\pi\alpha}}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}\left(\frac{1}{4} - \sin^2\theta_W\right)$$



E158 at SLAC
first measurement of PV in Møller sc.

huge luminosity
high polarization (~80%)

At tree level, $A_{PV} \approx 280\ 10^{-9}$

Suppressed ⇒ very sensitive to $\sin^2\theta_w$

Large radiative corrections, ≈-40%

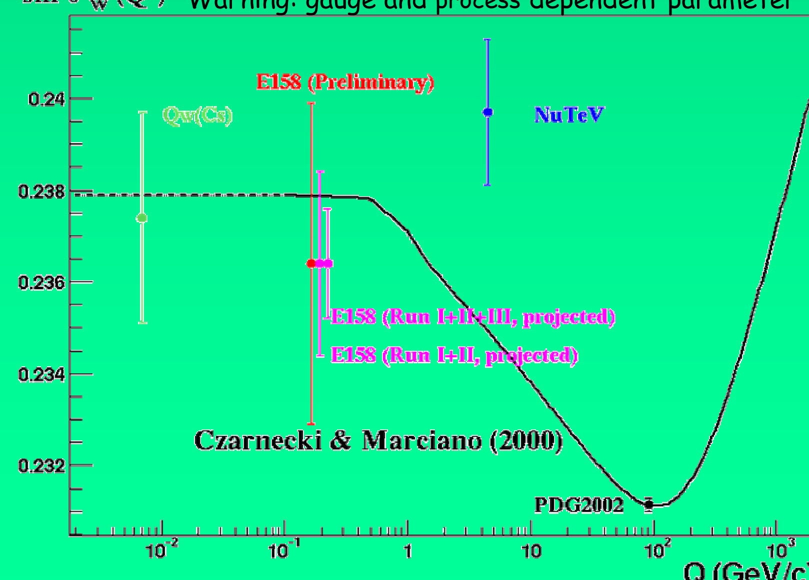
Czarnecki-Marciano, Denner-Pozzorini, Petriello, Ferroglia et al

Large theory uncertainty from γZ VP ≈5%

can and should be reduced

Sensitive to new physics orthogonal or complementary to collider physics (PV contact interations, loops…)

$\sin^2\theta_W^{eff}(Q^2)$ Warning: gauge and process dependent parameter



Preliminary results from E158

$A_{PV}(Q^2=0.027\ GeV^2)=-151.9\pm29.0(stat)\pm32.5(syst)$
parts per billion (*preliminary, Run I only*)

GOAL: 8% precision in A_{PV}, $\delta\sin^2\theta_w \approx 10^{-3}$

$\sin^2\theta_{eff}(Q^2=0.027\ GeV^2)=0.2371\pm0.0025(stat)\pm0.0027(syst)$
preliminary

$\sin^2\theta_W^{\overline{MS}}(M_Z)$ =0.2296±0.0038

In agreement with SM
$\sin^2\theta_W^{\overline{MS}}(M_Z)$=(0.2312±0.0003)

Soon results from Run II

Last run (III) is going very well

Final results next year

Universality of charged currents

CC involve CKM…

consistency of Cabibbo angle
& Fermi const measurmnts

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

$|V_{ub}|^2$: O(10^{-5})

Superallowed Fermi transitions ($0^+ \to 0^+$ β decay)
extremely precise, 9 expts, δV_{ud}~0.0005

neutron β decay δV_{ud}~0.0015, will be improved at PERKEO, Heidelberg

π decay th cleanest, promising in long term
PIBETA at PSI already at δV_{ud}~0.005(new)

Semileptonic K_{l3} (K->πlν)
E865 K^+ disagrees 2.3σ from older exp
while KLOE K^0 prelimin agrees, K^+ from KLOE & NA48 should settle. th error?
E865 is higher -> unitarity OK

τ decay promising, may become competitive with B factories, δV_{us}~0.0045

Hyperon decays δV_{us}~0.0027 new (Cabibbo et al) but th error?lattice?

$|V_{us}|$(from unit)=0.2269±0.0021
$|V_{us}|_{Kl3}$=0.2201 ±0.0016(exp) ±0.0018(th)

→ **2.2σ puzzle persists at least K_{l3} soon clear**

See CKM Yellow Book, Isidori talk at Durham CKM & K. Schubert talk here

The NuTeV EW result

NuTeV measures ratios of NC/CC cross-sections in ν DIS

$$R_\nu \equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)}{\sigma(\nu\mathcal{N}\to\mu X)} = g_L^2 + r g_R^2$$

$$R_{\bar\nu} \equiv \frac{\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\bar\nu\mathcal{N}\to\bar\mu X)} = g_L^2 + \frac{1}{r} g_R^2,$$

$$r \equiv \frac{\sigma(\bar\nu\mathcal{N}\to\bar\mu X)}{\sigma(\nu\mathcal{N}\to\mu X)}$$

R^{exp} differ from these because of ν_e contamination, cuts,NC/CC misID, 2[nd] generation, non isoscalar target, QCD-EW corr.: need detailed MC

NuTeV main new feature is having both ν and $\bar\nu$ beams. R_ν most sensitive to $\sin^2\theta_{w,}$ $R_{\bar\nu}$ control sample $\rightarrow m_{c.}$

Most uncertainties and $O(\alpha_s)$ corrections cancel in the PASCHOS-WOLFENSTEIN ratio

$$R_{\rm PW} \equiv \frac{R_\nu - r R_{\bar\nu}}{1-r} = \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)} = g_L^2 - g_R^2 = \frac{1}{2} - \sin^2\theta_{\rm W}$$

NuTeV do not measure R_{PW} directly, they fit for m_c^{eff} and $\sin^2\theta_w$. Exactly to what extent this corresponds to R_{PW} remains unclear

NuTeV EW result (II)

NuTeV work at LO in QCD (with improvements) and find

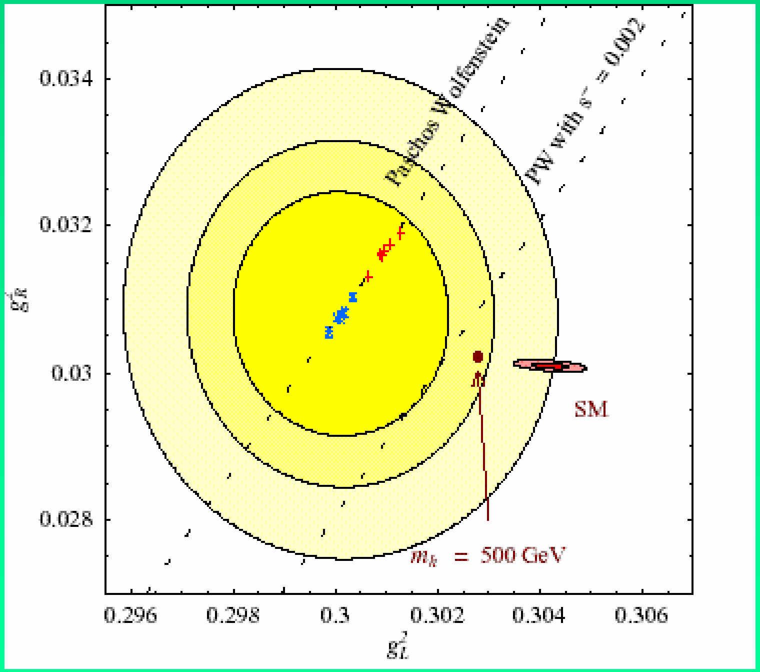
$$s^2_w(\text{NuTeV})=0.2276\pm0.0013_{stat}\pm0.0006_{syst}\pm0.0006_{th}$$
$$-0.00003(M_t/\text{GeV}-175)+0.00032\ \ln M_H/100\text{GeV}$$

where $s^2_w=1-M^2_w/M^2_z$ (on-shell)

Global fit: $s^2_w= 0.2229\pm0.0004$

a ~2.8σ discrepancy

Nuclear effects and ν oscillations explanations very unlikely



The usual suspects

- PDFs uncertainties — Small for standard PDFs
  Davidson et al.

- NLO corrections — Small $\delta s_w^2 \approx -0.0003$
  Moch & McFarland, Kretzer & Reno

- EW(photonic) corrections — Under control? old Bardin code,
  ongoing work Diener,Dittmaier,Hollik
  ready for comparisons. error underestimated?

All this holds for the idealized observable R_{PW} with asymmetric cuts, non-isoscalar target, and different nu,nubar spectra.
Only complete NLO analysis can ensure this applies to NuTeV fit as well

NuTeV is investigating a NLO analysis. Meanwhile

Small → Likely small

Asymmetric sea

Without assumptions on the parton content of target

$$R_{PW} = \frac{1}{2} - s_W^2 + \frac{\tilde{g}^2}{Q^-}\left[u^- - d^- + c^- - s^-\right]\{1 + O(\alpha_s)\}$$

Davidson et al, '01

$\tilde{g}^2 \approx 0.23$ $Q^- \approx 0.18$ $q^- = \int dx\, x(q(x)-\bar{q}(x))$

Isospin violation

Non-isoscalar target: accounted by NuTeV. Uncertainty originally underestimated Kulagin '03

Isospin violation in the pdfs

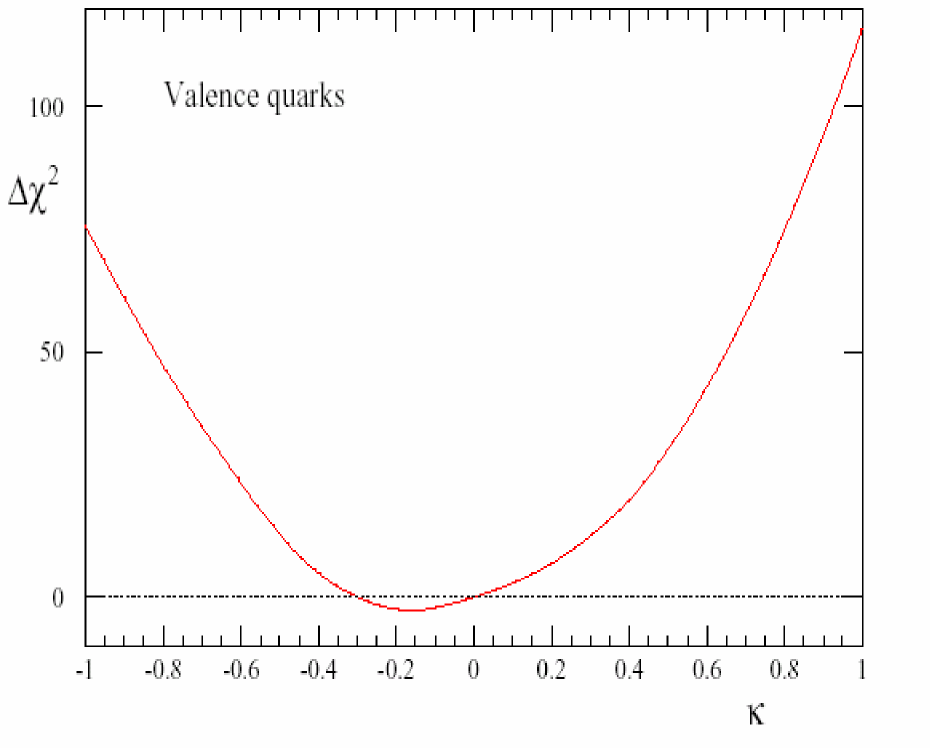
$$u_p(x) \neq d_n(x)$$

Naturally of O(1%), $\delta s^2_W \approx 0.002$
exp constraints: see next

Different models give this order of magnitude $\delta s^2_W < 0$,
Sather, Rodionov et al, Londergan&Thomas
(NuTeV finds much smaller)

We cannot rely on models!

New MRST isospin violation fit



MRST 03, see R. Thorne talk

$$u_V^n(x) = d_V^p(x) + \kappa f(x)$$

$$d_V^n(x) = u_V^p(x) - \kappa f(x)$$

$f(x)$ has zero first moment

Mild indication for κ<0, O(1%) effect
VERY LARGE UNCERTAINTY

Estimated impact on NuTeV
for central value $\delta\ s^2_W$=0.0015

remakable (accidental) agreement w Londergan&Thomas

Such a strange asymmetry…(I)

$$R_{PW} = \frac{1}{2} - s_W^2 + \frac{\tilde{g}^2}{Q^-}\left[u^- - d^- + c^- - s^-\right]\{1 + O(\alpha_s)\}$$

Strange quark asymmetry
Non-perturbatively induced by p <-> KΛ
A positive s^- reduces the anomaly

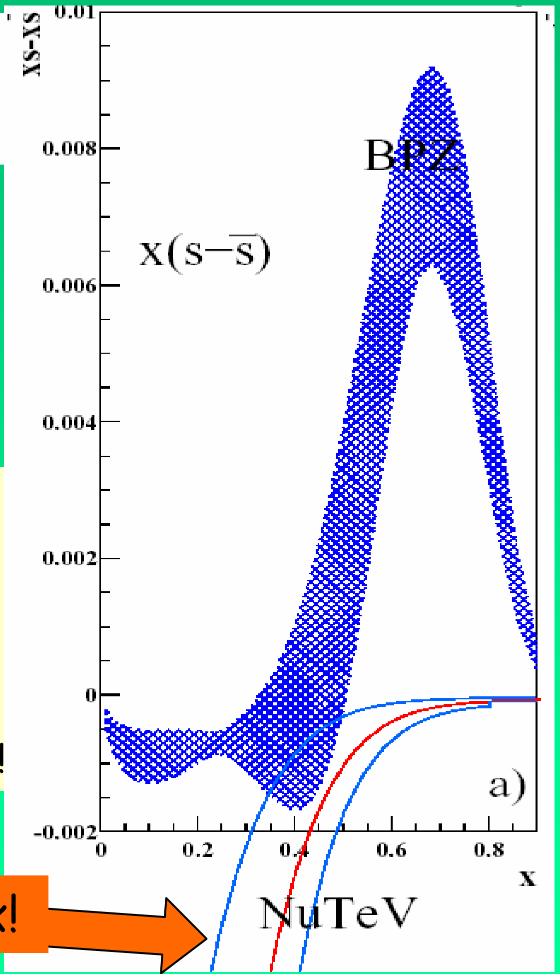
Only ν-induced processes are sensitive to $s^-(x)$

<u>Inclusive ν-DIS</u>
Barone et al (BPZ99) found s^-=0.002
Recently updated (Portheault et al)
couldn't access dimuon data!

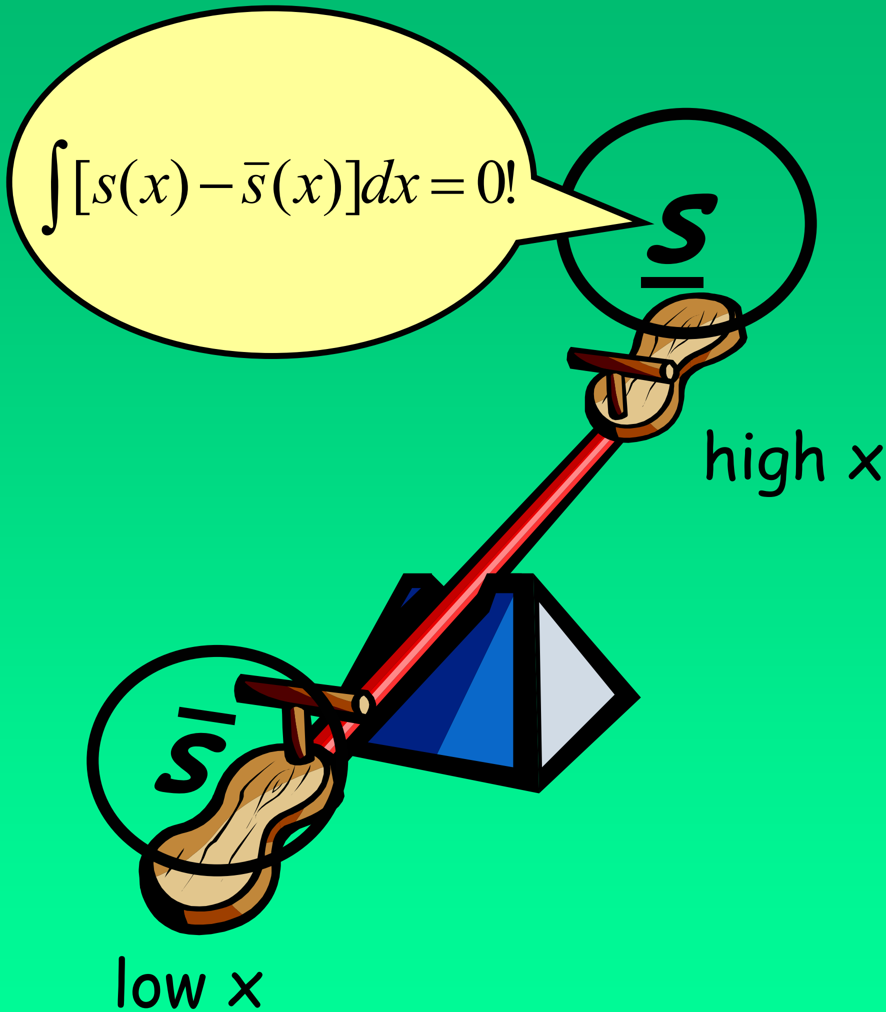
<u>Dimuons (charm production)</u>

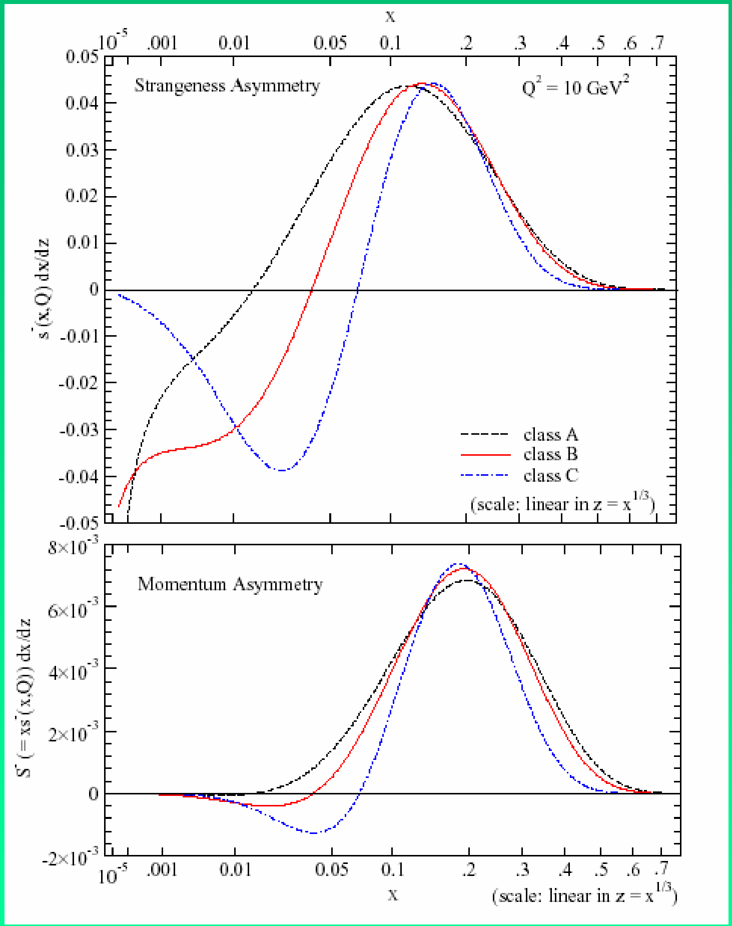
NuTeV has found (low x)
s^-=-0.0027±0.0013

negative s^- at small x!



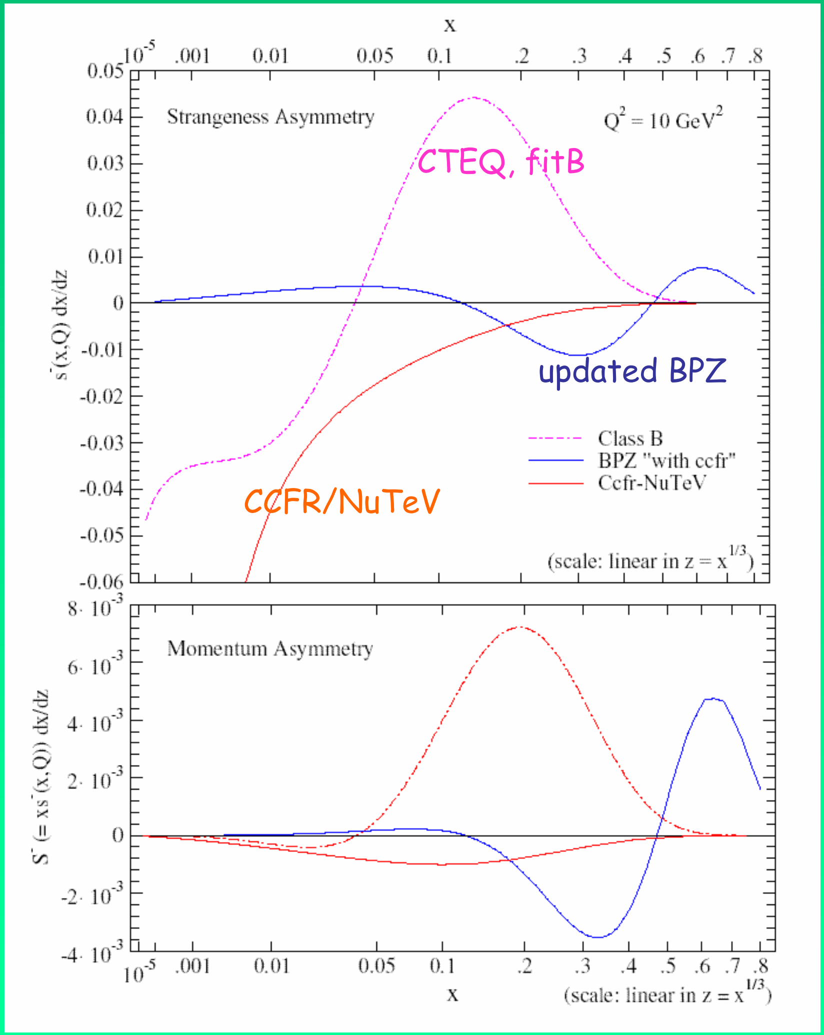
BUT NuTeV fit to s^-
a) relies on inconsistent parameterization (strangess not conserved)
b) does not fit s^- in the context of global fit



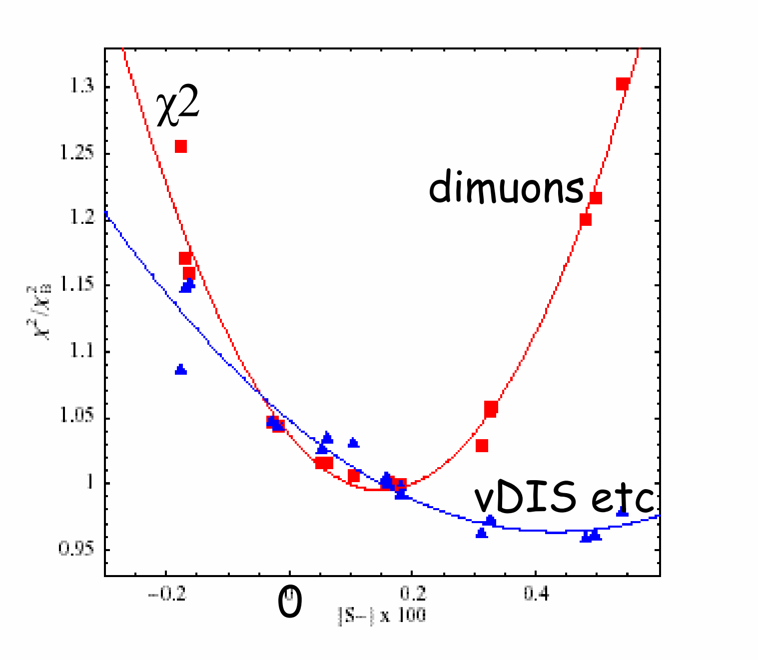


Kretzer, Olness, Pumplin, Stump,Tung et al.

The new CTEQ fit



- includes all available data
- explores full range of parametrns withS_N=0
- fits s,sbar together with other pdfs



Most reasonable range 0.001< s- <0.003

Kretzer, Olness, Pumplin, Stump,Tung et al.

A strange end?

- Negative s^- strongly disfavoured, acceptable fits have $0.001 < s^- < 0.0031$, depending on low-x behavior

  Possible new info from W+charmed jet, lattice

fit	$[S^-] \times 100$	$\chi^2_{\rm dimuon}$	$\chi^2_{\rm inclusiveI}$	δR^-
B^+	0.540	**1.30**	0.98	-0.0065
A	0.312	1.02	0.97	-0.0037
B	0.160	*1.00*	*1.00*	-0.0019
C	0.103	1.01	1.03	-0.0012
B^-	-0.177	**1.26**	**1.09**	0.0023

Kretzer et al

- Impact on R_{PW} in NuTeV setup estimated wrt to CTEQ s=sbar fit: $0.0012 < \delta s^2_W < 0.0037$
  very likely to carry on to NuTeV analysis

- NuTeV : a few minor issues open. In my opinion, large sea uncertainties and shift from s^- reduce discrepancy below 2σ

Given present understanding of hadron structure, R_{PW} is no good place for high precision physics

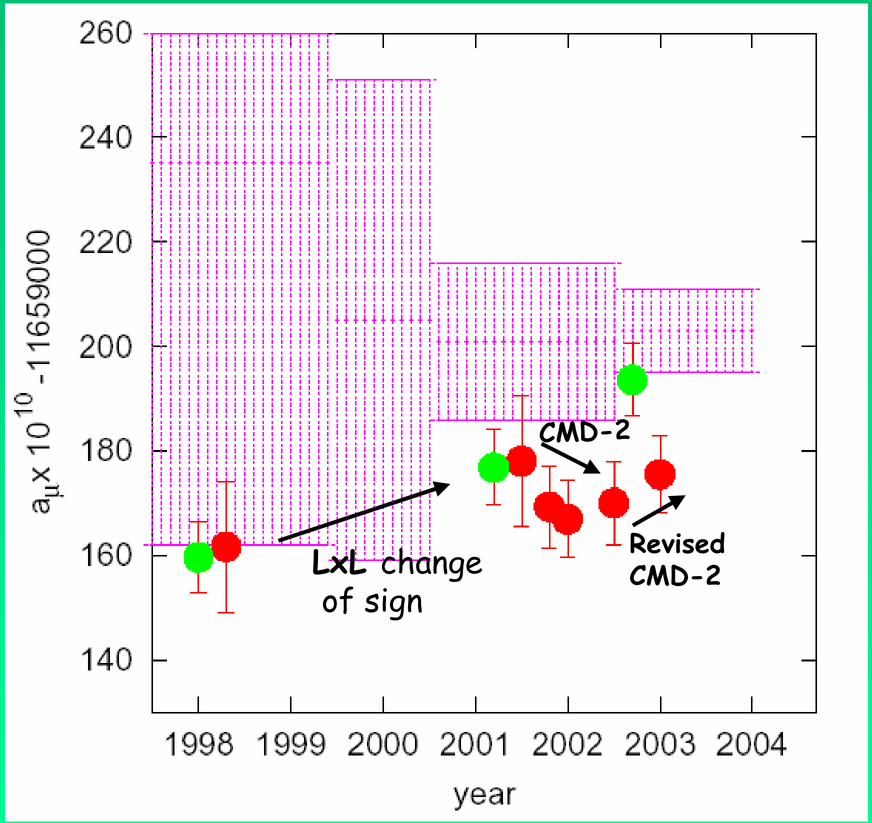
NuTeV vs. New Physics

NuTeV anomaly would require ~1% effect

Very difficult to build realistic models that satisfy all exp constraints and account for whole discrepancy Davidson et al

- NO supersymmetry, with or without R parity Davidson et al, Kurylov et al
- NO models with only oblique corrections
- YES contact interactions of the form $\overline{L}_2 \gamma_\mu L_2 \overline{Q}_1 \gamma_\mu Q_1$
- MAYBE… Vector/scalar leptoquarks ONLY with split SU(2) triplet
- MAYBE… unmixed Z', can account only for a fraction of anomaly
- MAYBE… mixing with heavy ν, but only with sizeable oblique corrections (T,U) that cannot be given by heavy SM Higgs Loinaz et al

The (g-2)$_\mu$ ups and downs



Incomplete compilation of theory predictions
Eidelman-Jegerlehner, Davier et al, Hagiwara etal

BNL *g*-2 experiment latest result from 2000 μ^+ data released 2002

it dominates present w.a.

$$a_\mu = 11659203(8)\ \mathrm{x}10^{-10}$$

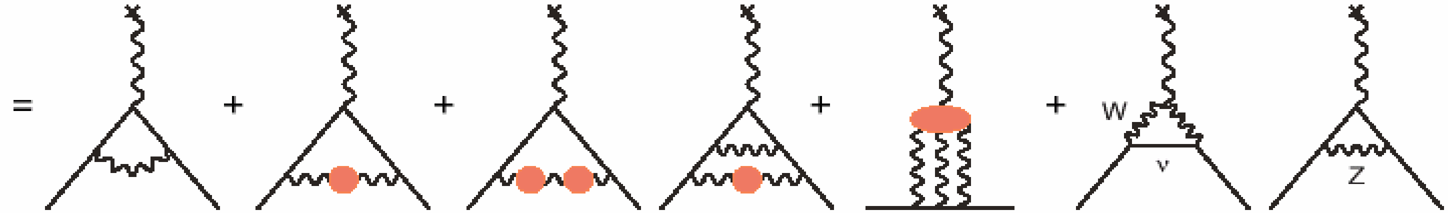
soon result of 2001 μ^-data
expected 30% error reduction

Excellent place for new physics
unexplored loop effects ~ m^2_μ/Λ^2
but needs chiral enhancement

Supersymmetry is natural
candidate at moderate/large tanβ

How to compute $(g\text{-}2)_\mu$

$$a_\mu^{SM} = a_\mu^{QED} + a_\mu^{had,LO} + a_\mu^{had,HO} + a_\mu^{had,LBL} + a_\mu^{weak}$$



= (QED) $(11\,658\,470.35 \pm 0.28)10^{-10}$ 4loop big, never checked!

+ (had,LO) $(684.7 \text{ to } 709.0 \pm 6)10^{-10}$ (Big spread, largest error)

+ (had,HO) $(-10.0 \pm 0.6)10^{-10}$

+ (had,LBL) $(8.0 \pm 4.0)10^{-10}$ (sign change since 1998)

+ (weak) $(15.4 \pm 0.2)10^{-10}$ (2-loop)

$a_\mu^{had,LO}$ from data via dispersion integral

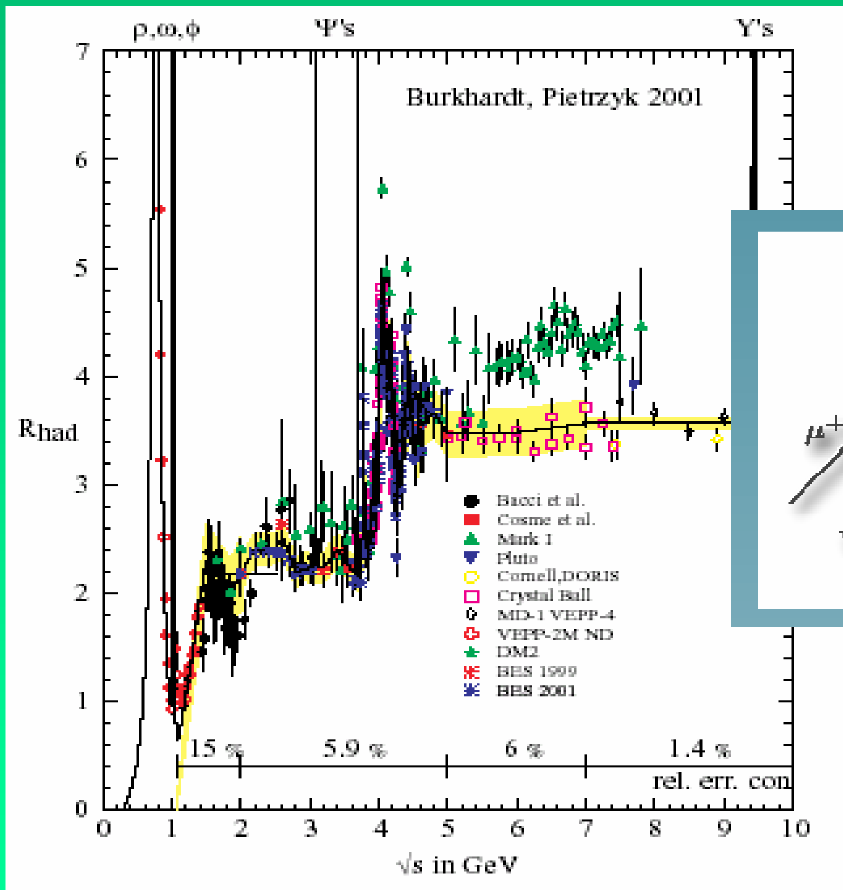
$$a_\mu^{had,LO} = \frac{1}{4\pi^3} \int_{4m_\pi^2}^{\infty} \sigma^0_{had}(s) K(s) ds$$

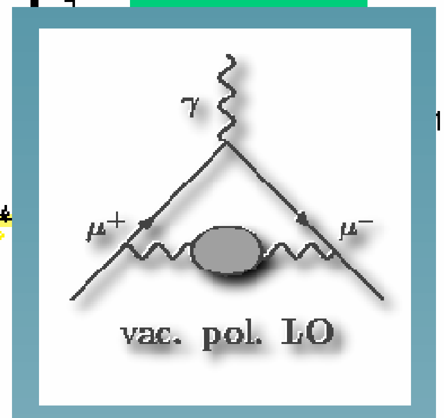
Recent data included CMD-2, SND, BES 2-5 GeV, ALEPH τ.
NEW: CMD-2 prelim update

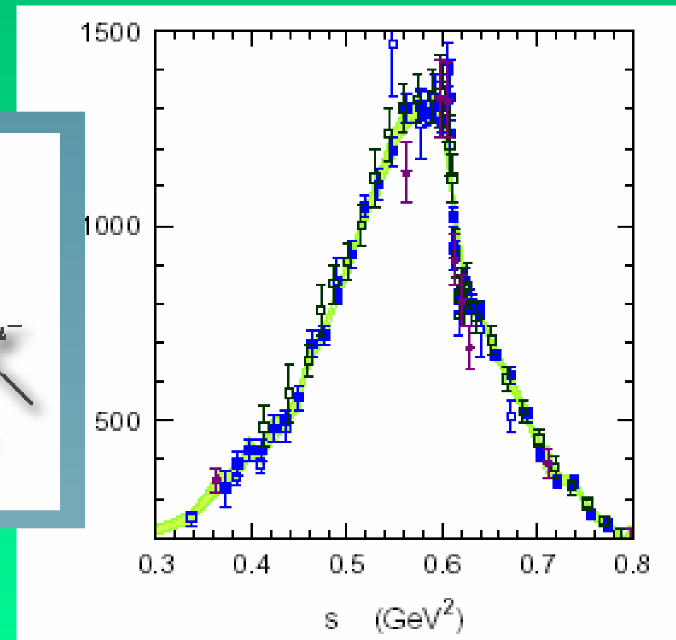
Dominated by low energy region, ρ resonance

from Pippa Wells

The spectral function







The pion form factor

> 70% of $a_\mu^{had,LO}$

The spectral function from e^+e^-

Tau data below 1.8GeV

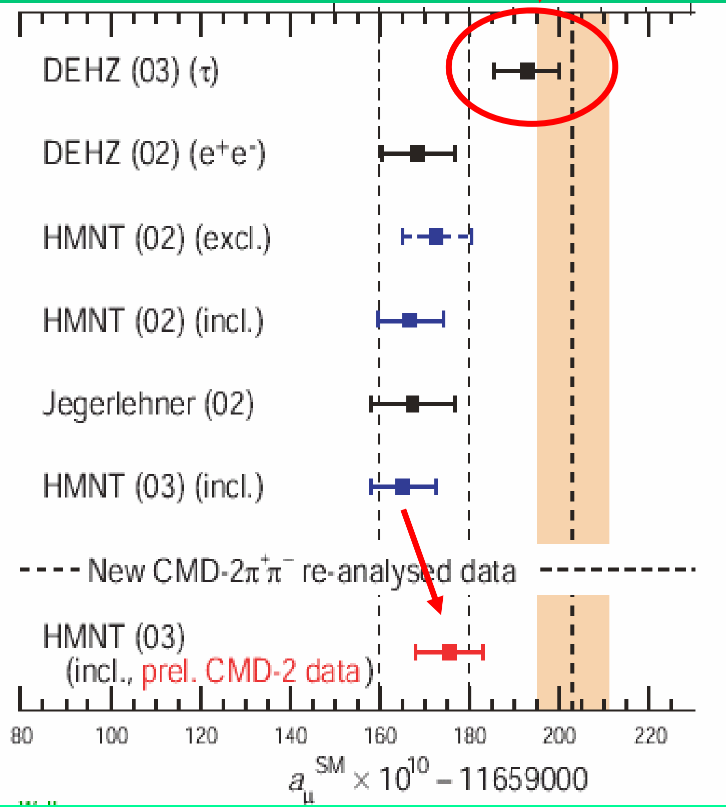
Final CMD-2 $\pi\pi$ data (2002) 0.6% syst error!
CMD-2 have recently reanalyzed their data

Hagiwara et al (HMNT) NEW result:
$a_\mu^{had,LO}=691.7\pm5.8_{exp}\pm2.0_{r.c.}$

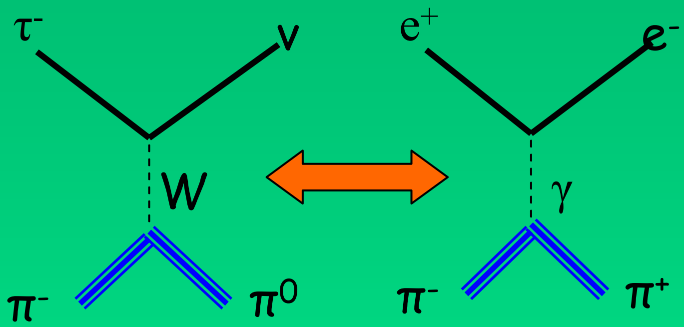
This translates in a ~2-2.5σ discrepancy depending on which e^+e^- analysis

Using τ data below 1.8 GeV Davier at al (DEHZ)
$a_\mu^{had,LO}=709.0\pm5.1_{exp}\pm1.2_{r.c}\pm2.8_{SU(2)}$

Good agreement between Aleph, CLEO, Opal τ data

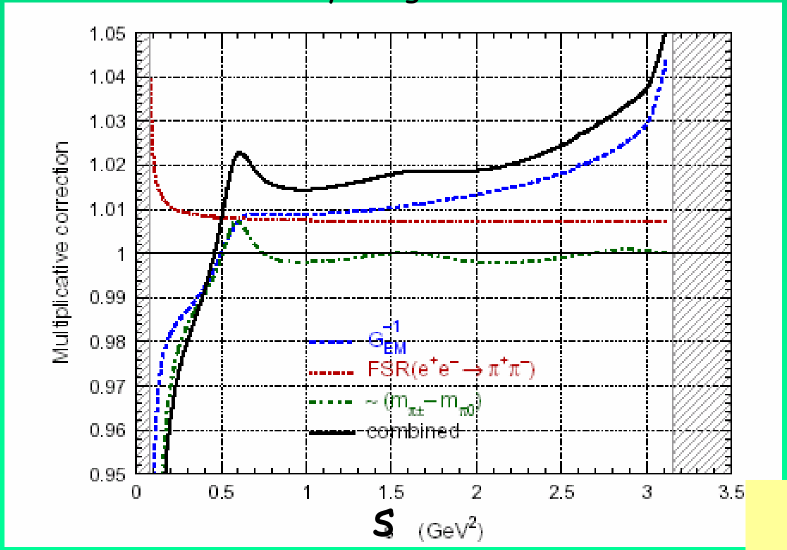


The spectral function from τ decays



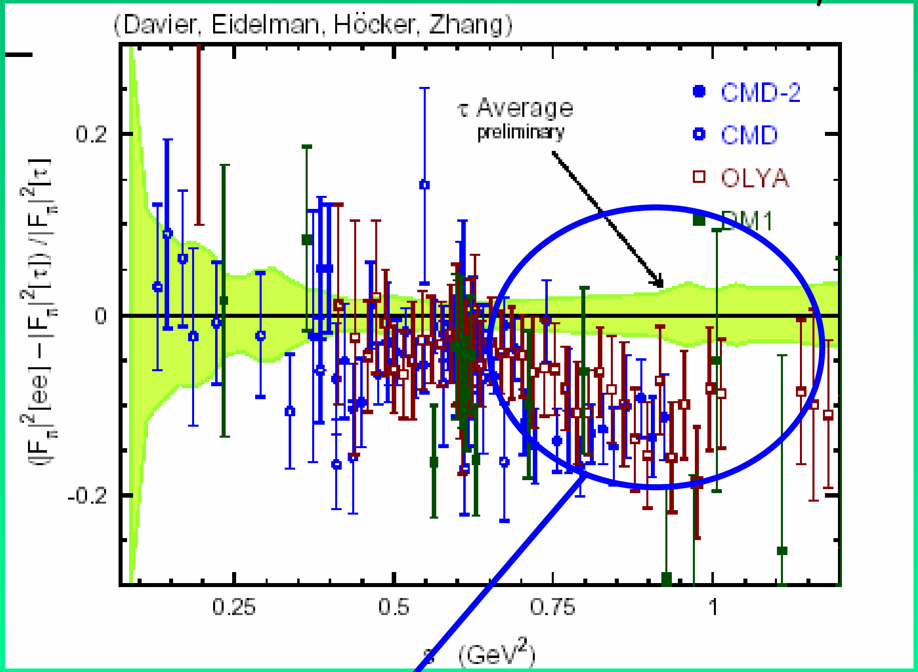
CVC + isospin symmetry

Corrections by Cirigliano et al 02



Corrections applied to τ data

NB CMD-2 before reanalysis

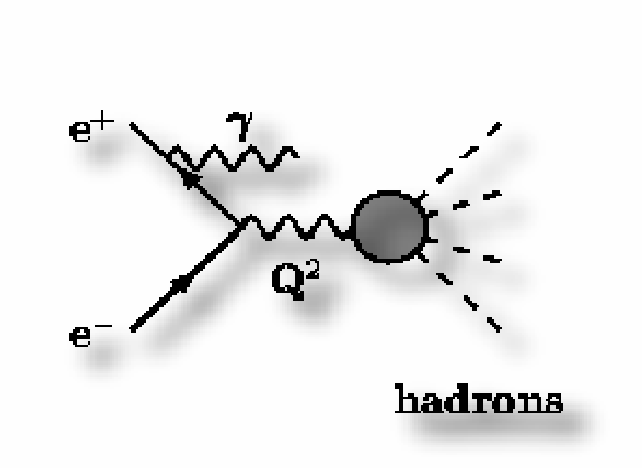


Relative difference between π form f. from τ and e^+e^-

>5% difference! cannot be isospin breaking. Needs further study. Data?

After new CMD-2 for $\Delta_{\pi\pi}$=(11-13±7) 10^{-10}(was 21)

Radiative return, first results



Photon radiated off initial e^+e^- (ISR) reduces the effective energy of the collision: even colliders at fixed energy can investigate range of Q^2

Large luminosity at DAΦNE, B-factories, Cleo-c largely compensates factor α/π

Radiative corrections essential
At low-energy (KLOE) kinematic cuts (small angle) can stronly suppress FSR

Monte Carlo Phokara 2.0 Czyz et al

First KLOE results NEW: (in 10^{-10})

$\delta a_\mu(\text{had})=374.1\pm1.1_{stat}\pm5.2_{syst}\pm2.6_{th}+7.5-0.0$

FSR, it will almost disappear

to be compared with the NEW CMD-2

$\delta a_\mu(\text{had})=378.6\pm2.6_{stat}\pm2.2_{syst\&th}$

it was 368.1

in the region $0.37 < s_\pi < 0.93$ GeV

DISCREPANCY with tau data CONFIRMED, wait for smaller error

Perspectives for R(s)

- KLOE will soon improve the RR analysis
- Babar is finalizing RR analysis, Belle?
- CMD-2, SND (Novosibirsk), BES (Beijing), CLEO-c(Cornell)
- Possible improvements in the very low-energy tail using analyticity, unitarity, and chiral symm Colangelo et al

Impact on $\alpha(M_Z)$

$\alpha(M_Z)$ appropriate parameter for EW

Spectral function enters its calculation similarly, but higher energy data have more weight. Results are converging

$\delta\alpha(M_Z)$ is no more the main bottleneck for precision EW

Further improvements expected
Conservative estimate
(upper bound of uncertainty)

$\Delta\alpha_{had}=0.02768\pm0.00036$

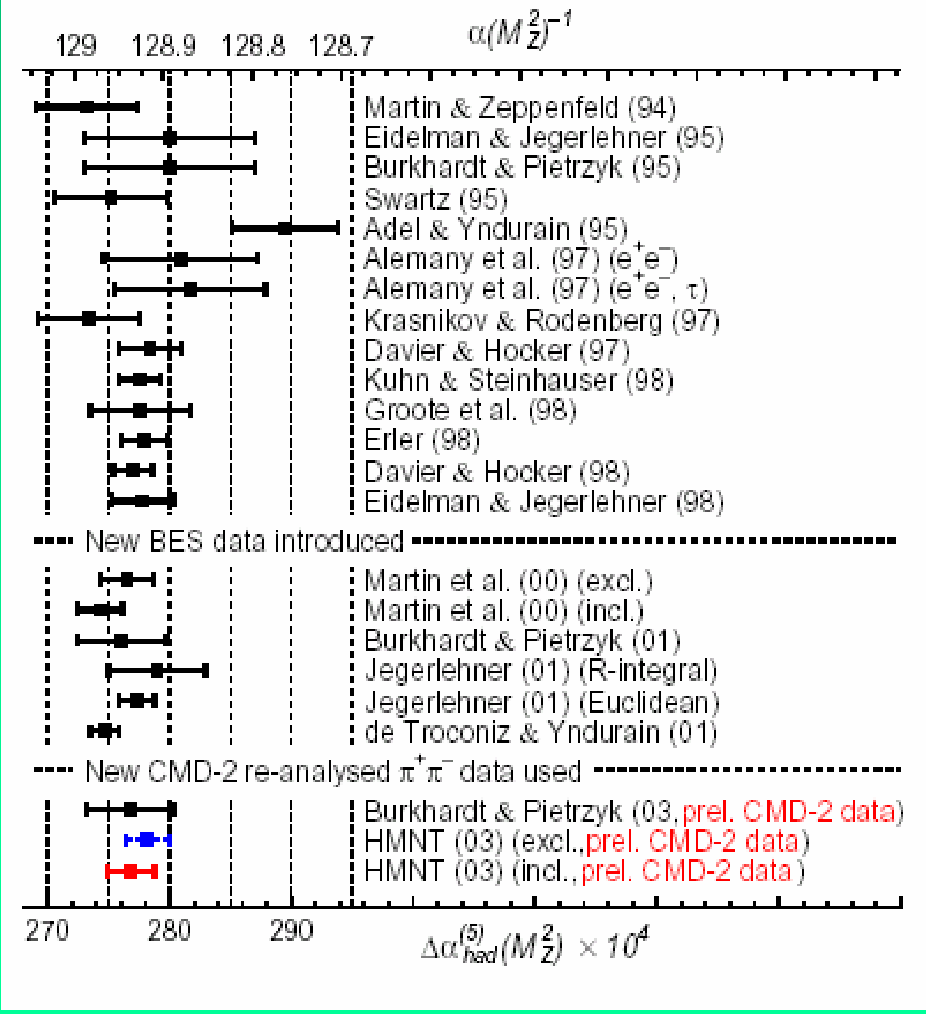
Burkhardt & Pietrzyk 2003

With more efficient use of exp data

$\Delta\alpha_{had}=0.02769\pm0.00018$

Hagiwara et al 2003

Use of τ data + ~0.002



The global EWWG fit

NEW: M_W(Aleph) lower, small shifts in heavy flavors, atomic PV close to SM

new M_t D0 Run I and CDF Run II not included

M_H^{fit}=96 GeV, M_H<219 GeV at 95%CL
χ^2/dof=25.4/15 4.5% prob

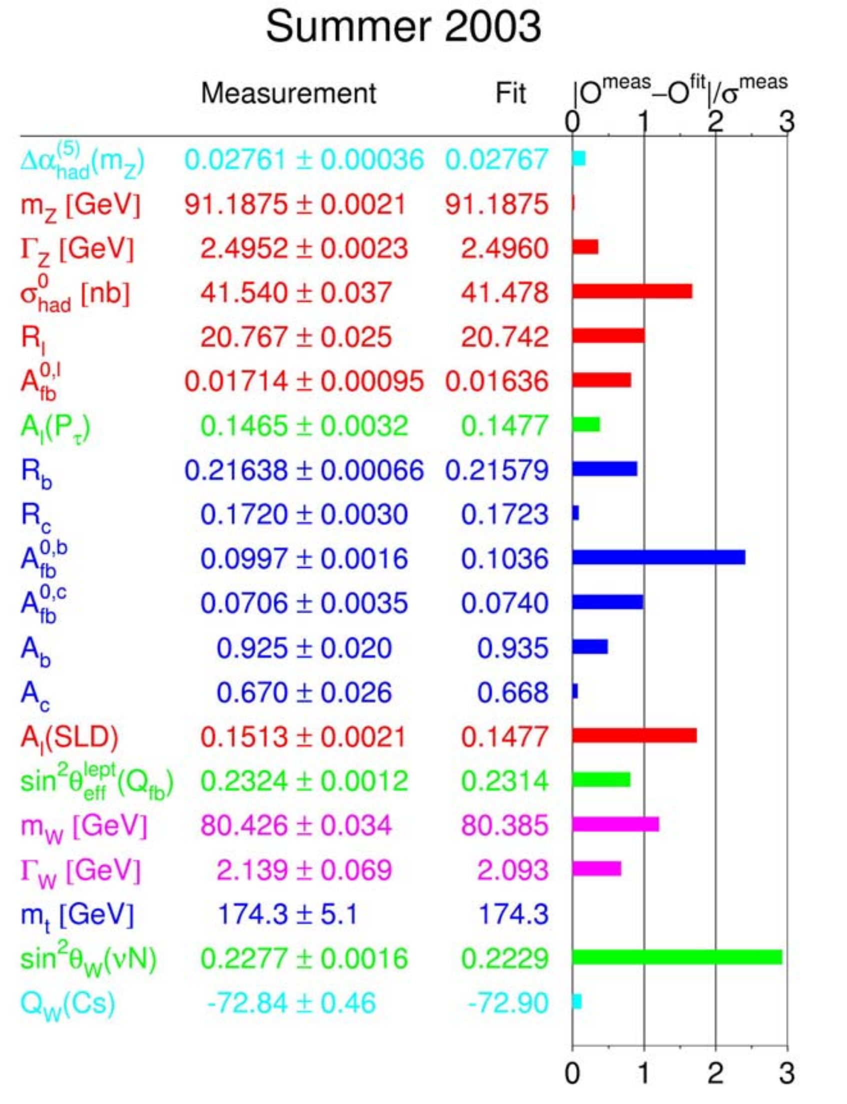
without NuTeV

M_H^{fit}=91 GeV, M_H<202 GeV at 95%CL
χ^2/dof=16.8/14 26.5% prob

M_H fit independent of NuTeV

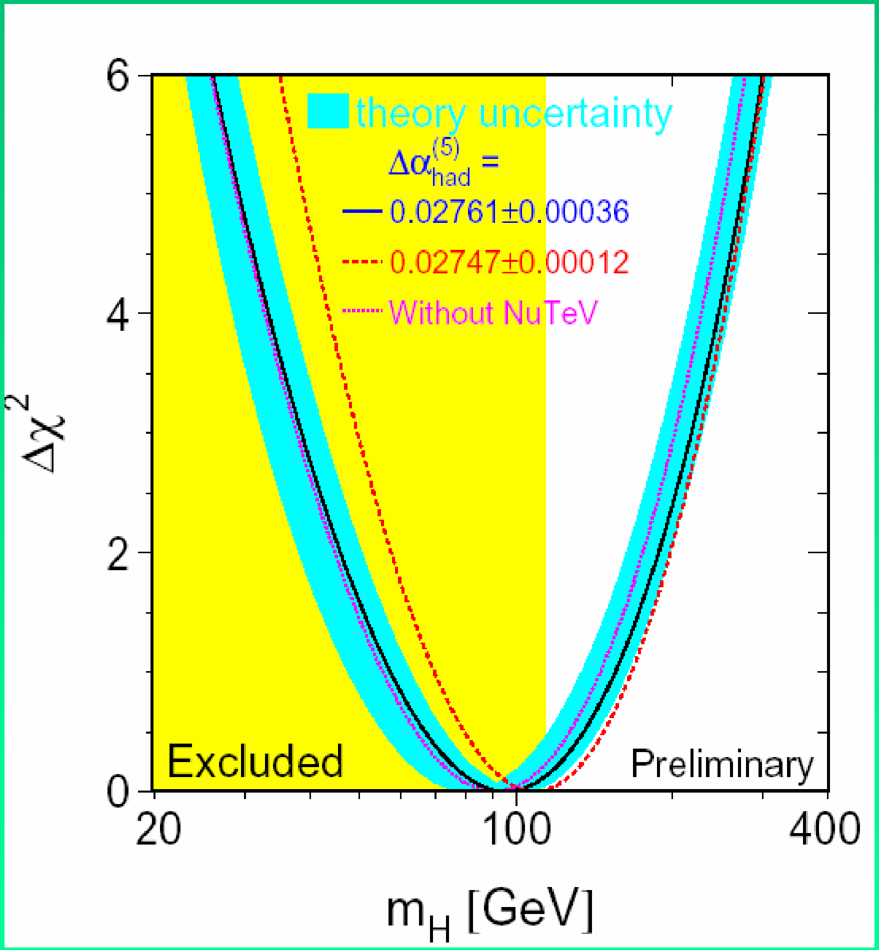
OVERALL, SM fares well

except for NuTeV



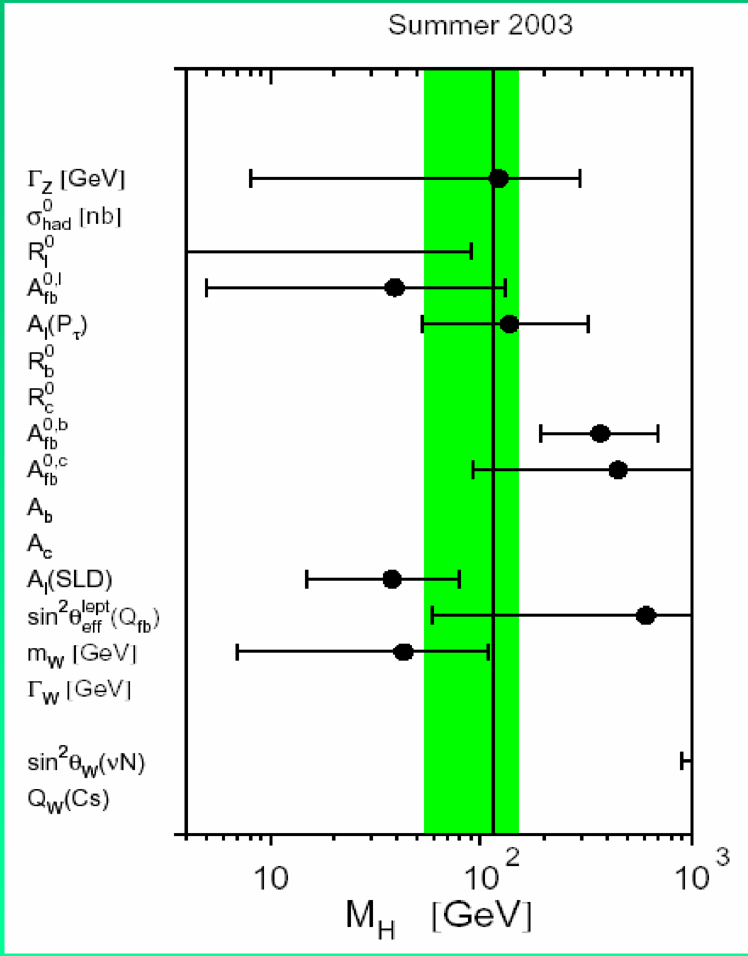
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90

The blue band



LEP-SLD EW Working Group `http://lepewwg.web.cern.ch/LEPEWWG`

The M_H fit



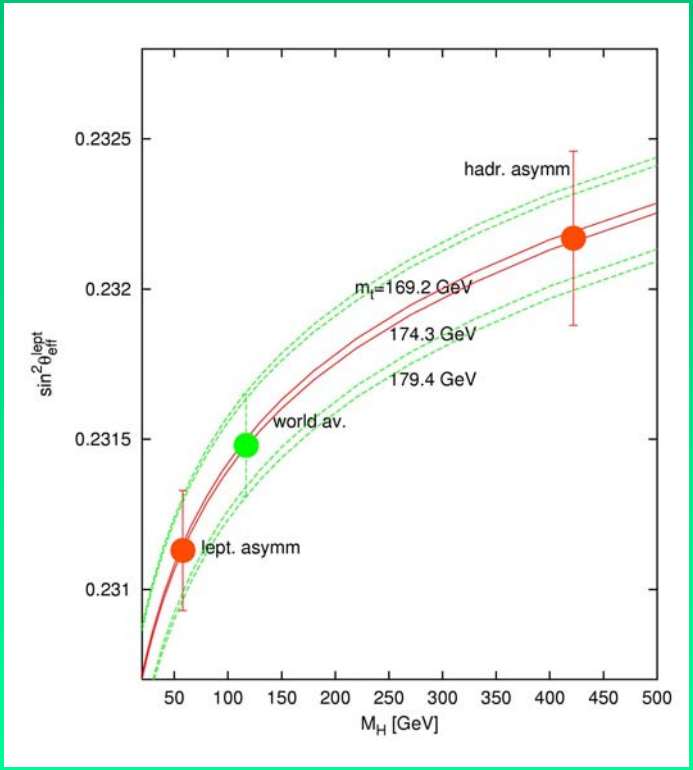
EWWG fits an arbitrary set
no $(g-2)_\mu$, no universality, no $b \to s\gamma$

Only a subset of observables
is sensitive to M_H (no NuTeV)

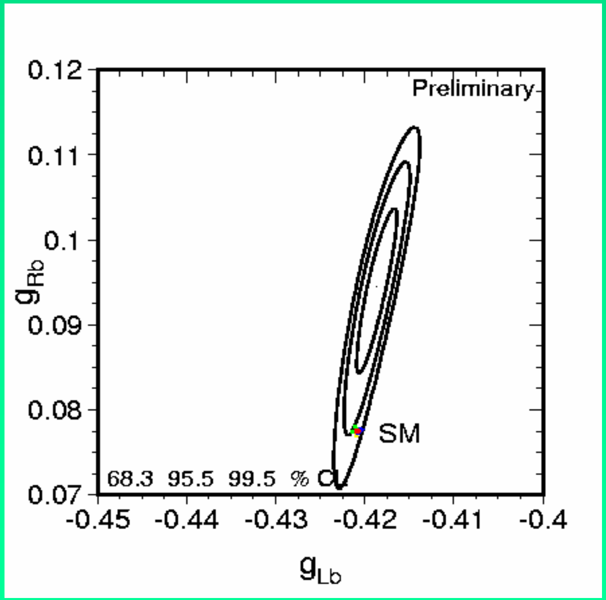
M_H^{fit}=98 GeV, $M_H<210$ GeV at 95%CL
χ^2/dof=11/4 2.6% prob

LOWER probability

New physics in the b couplings?

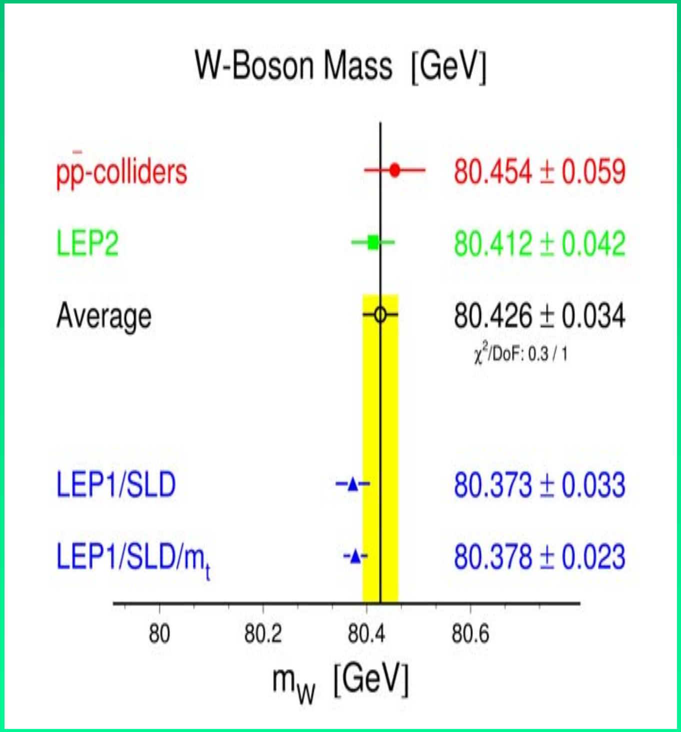


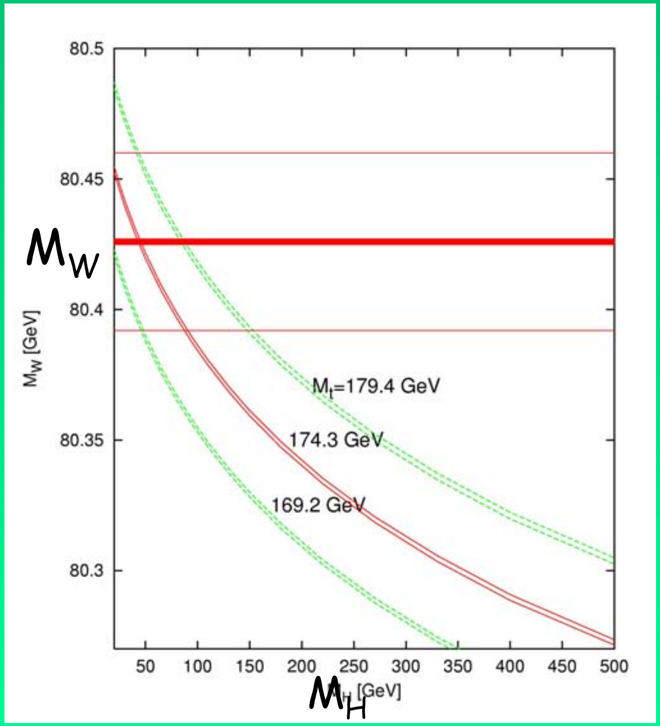
Root of the problem: old ~3σ discrepancy between LR asymmetry of SLD and FB b asymmetry of LEP: in SM they measure the same quantity, $\sin^2\theta^{eff}$



New physics such that $|\delta g_R{}^b| \gg |\delta g_L{}^b|$?
Problematic and ad-hoc Choudhury et al, He-Valencia

The W mass





The W mass likes it light too

The Chanowitz argument

2 possibilities, both involving new physics:

a) $A_{FB}(b)$ points to new physics

b) it's a fluctuation or is due to unknown systematics

without $A_{FB}(b)$, the M_H fit is very good, but in conflict with direct lower bound M_H>114.4 GeV

M_H^{fit}=42 GeV, M_H<120 GeV at 95%CL

Even worse if $\alpha(M_Z)$ from HMNT or especially from tau is used

If true, not difficult to find NP that mimics a light Higgs.

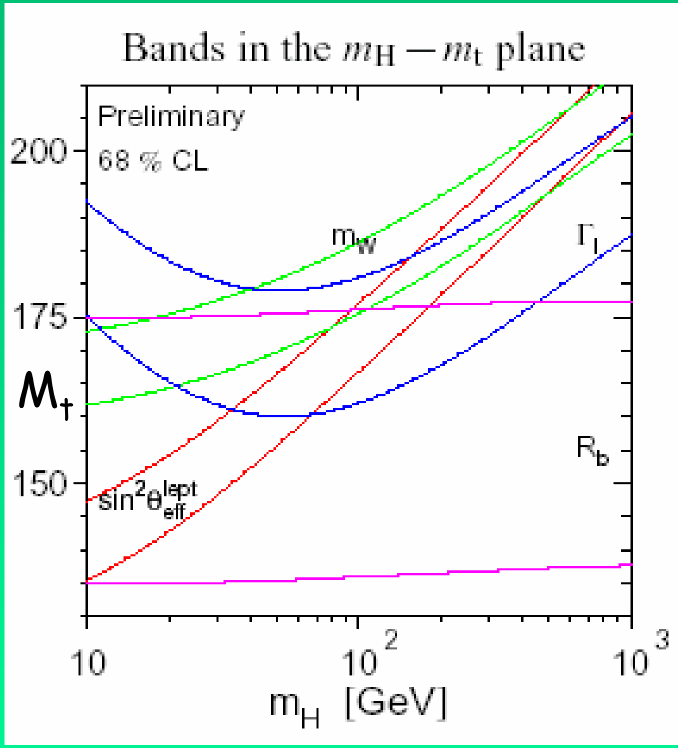
Non-trivially, SUSY can do that with light sleptons, tanβ>4

Altarelli et al

Statistically weak at the moment is 5% small enough?

Very sensitive to M_t

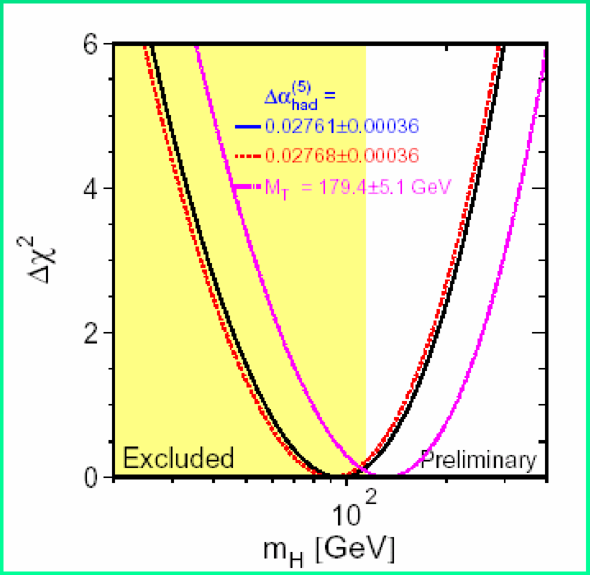
the TOP priority



a factor 2 improvement in $\Delta\alpha_{had}$ would lower the upper bound on M_H by ~5 GeV

a factor 2 improvement in δM_t would lower the upper bound on M_H by ~35 GeV

a shift of +5 GeV in M_t would imply M_H<280 GeV



Experimental perspectives

- New (last?) $(g\text{-}2)_\mu$ result soon
- CMD-II,Cleo-c,BES & KLOE, B-factories for RR
- Many developments for universality test
- E158(Møller scatt) & QWeak
- Tevatron Run IIa: $\delta M_t \approx 3$ GeV & $\delta M_w \approx 30$ MeV
- LHC: $\delta M_t \approx 2$ GeV & $\delta M_w \approx 25$ MeV
- Linear collider at Z^0 peak:

  $\delta M_w \approx 6$MeV, $\delta M_t \approx 200$MeV, $\delta s^2_{eff} \approx 1\times10^{-5}$

The primary goal of colliders is the direct observation of new particles, but precision tests will be crucial if they are found

Will we be able to exploit this precision?

Major theoretical effort needed.

- automatic 2loop EW calculation nowhere in sight, despite progress (eg Turin & Dubna groups)
  We don't even have complete 2loop EW to $\sin^2 \vartheta_W^{eff,l}$
- first complete 2loop EW calculation of Δr (ie M_W)
  Awramik & Czakon, Freitas et al. (shits M_w by ≈2-4MeV)
- 3loop contributions to $\Delta\rho$ enhanced by m_t
  tiny if MS definition of m_t is used Faisst et al
- EW corrections to W,Z production at Tevatron
  Baur et al, Dittmaier et al, Carloni et al

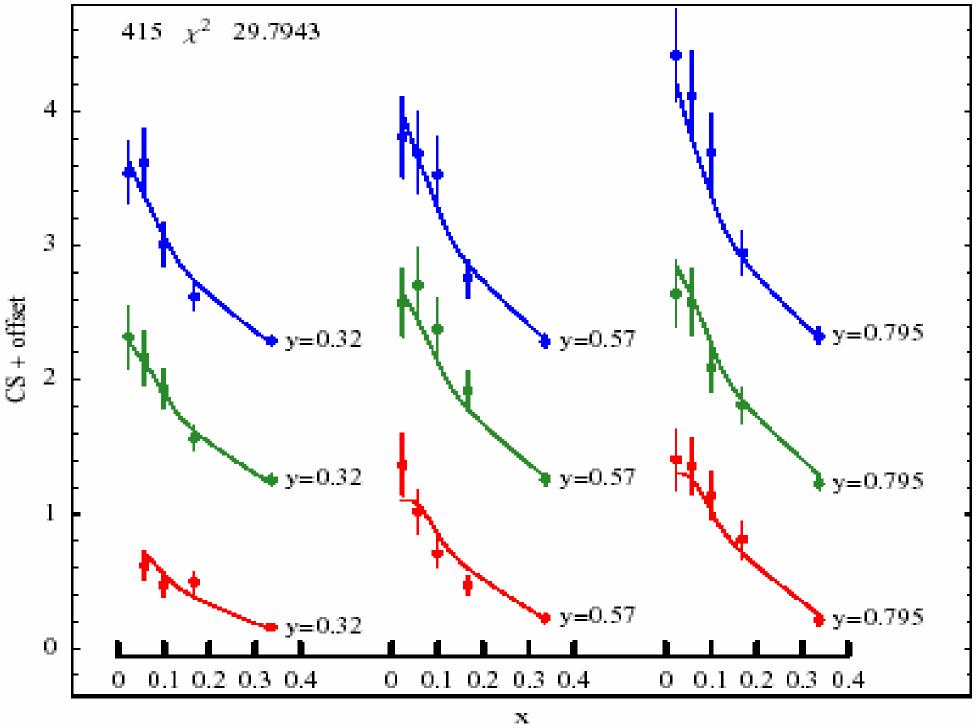
Summary

- CC universality puzzle persists, at ~2.2σ. New data expected soon
- New CTEQ fit establishes a strange asymmetry, reducing the NuTeV anomaly. MRST attempts at constraining isospin violation in pdfs. NuTeV can probably be explained by standard physics, R_{PW} is not the right place for high precision physics.
- Revised CMD-2 data reduce discrepancy between $(g-2)_\mu$ and its SM prediction, to ~2σ. First RR KLOE analysis agrees with CMD-2. Tau data still conflict with e^+e^-: exp or th problem?
- Clear evidence for a light Higgs. Details depend strongly on conflicting data. Top priority is the top mass
- The SM works fine, but there are several points of tension in the data. None is convincing yet. Despite recent progress, more work and patience needed to see if these cracks will doom the building.

Backup-slides: CTEQ new analysis

Comparison of data and theory

(Olness et al)



- Data points: CCFR $\nu + N \rightarrow \mu\overline{\mu} + X$
- Theory curves: Class B PDF's with $s \neq \overline{s}$
- The graphs show $d^3\sigma / dx\,dy\,dE_h$ versus x for fixed y and E_h.

  (Data points are offset horizontally and vertically to fit on one graph.)

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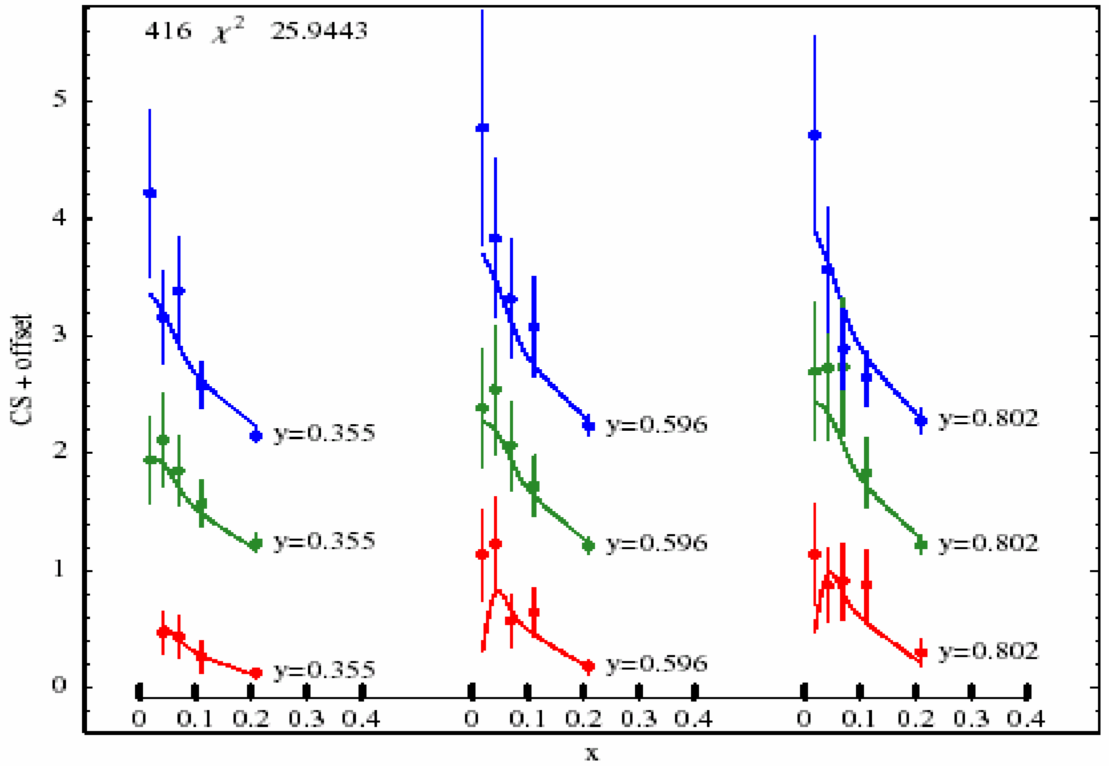

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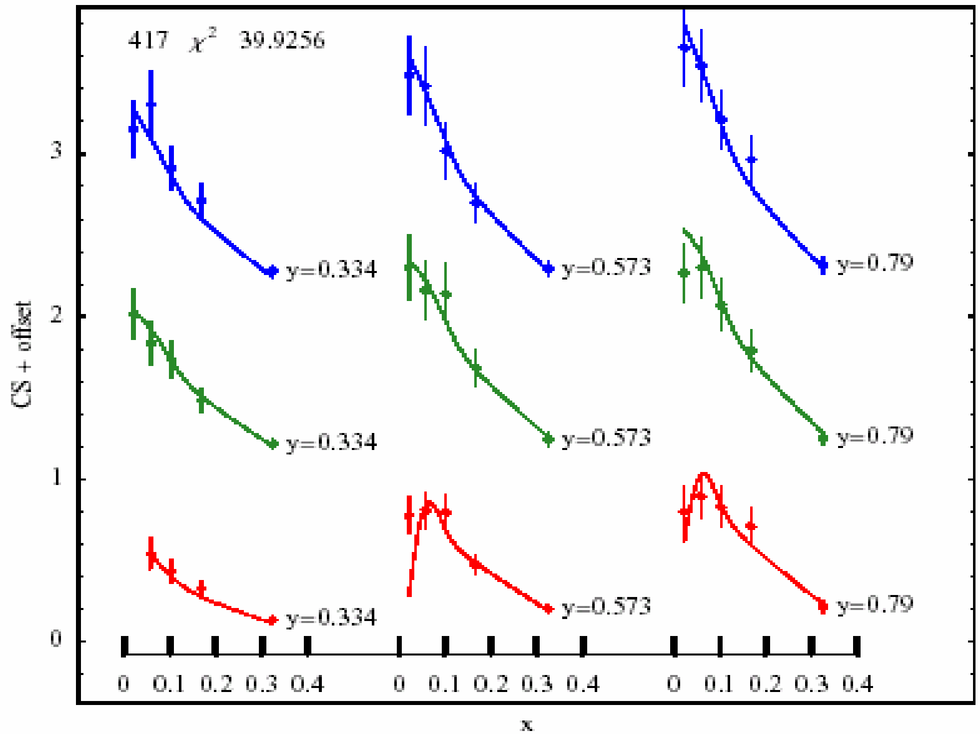
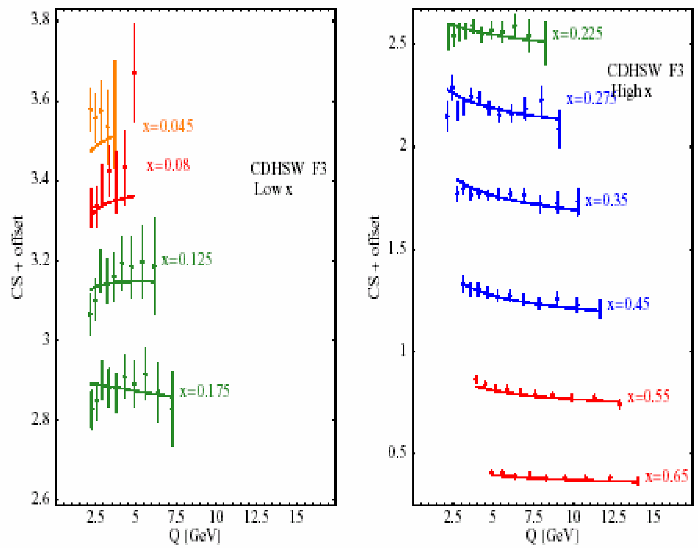


- Data points: NuTeV $\nu + N \to \mu\bar{\mu} + X$
- Theory curves: Class B PDF's with $s \neq \bar{s}$
- The graphs show $d^3\sigma / dx\, dy\, dE_h$ versus x for fixed y and E_h.
  (Data points are offset horizontally and vertically to fit on one graph.)

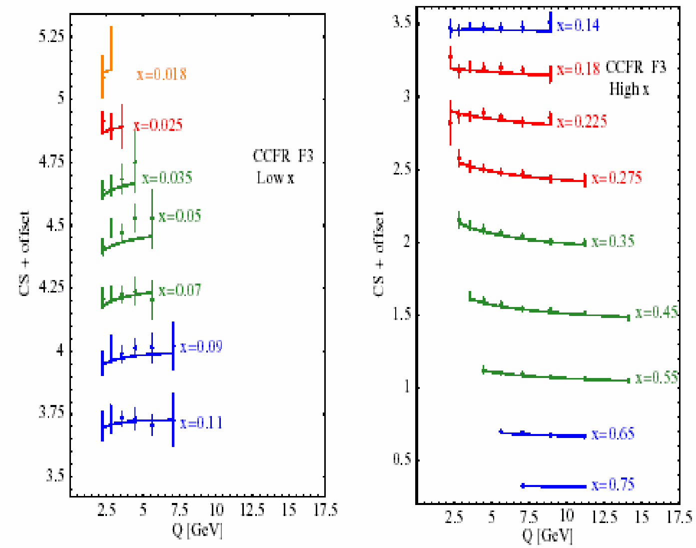
Backup-slides: CTEQ new analysis

Comparison of data and theory – CDHSW F_3
(Olness et al)



- Data points: CDHSW $F_3(x,Q)$ structure function from inclusive neutrino scattering
- Theory Curves: Class B PDF's with $s \neq \bar{s}$
- The graphs show $xF_3(x,Q)$ versus Q for fixed x.
  (Data points and curves are offset vertically to fit on one graph.)

Comparison of data and theory – CCFR F_3
(Olness et al)



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