The SM fit and all its troubles: New Physics around the corner?

Roma Tre, December 5, 2002

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- NuTeV: a catalogue of possible old and new physics explanations
- The hadronic FB asymmetries and the SM fit
- New physics explanations for the muon $g-2$
- Summary/Outlook

The global SM fit

$M_H^{fit} = 81$ GeV

$M_H < 193$ GeV at 95% CL

χ^2/d.o.f.=29.7/15

probability=1.3%.

Two $\sim 3\sigma$ *anomalies*

Without NuTeV:

$M_H^{fit} = 78$ GeV

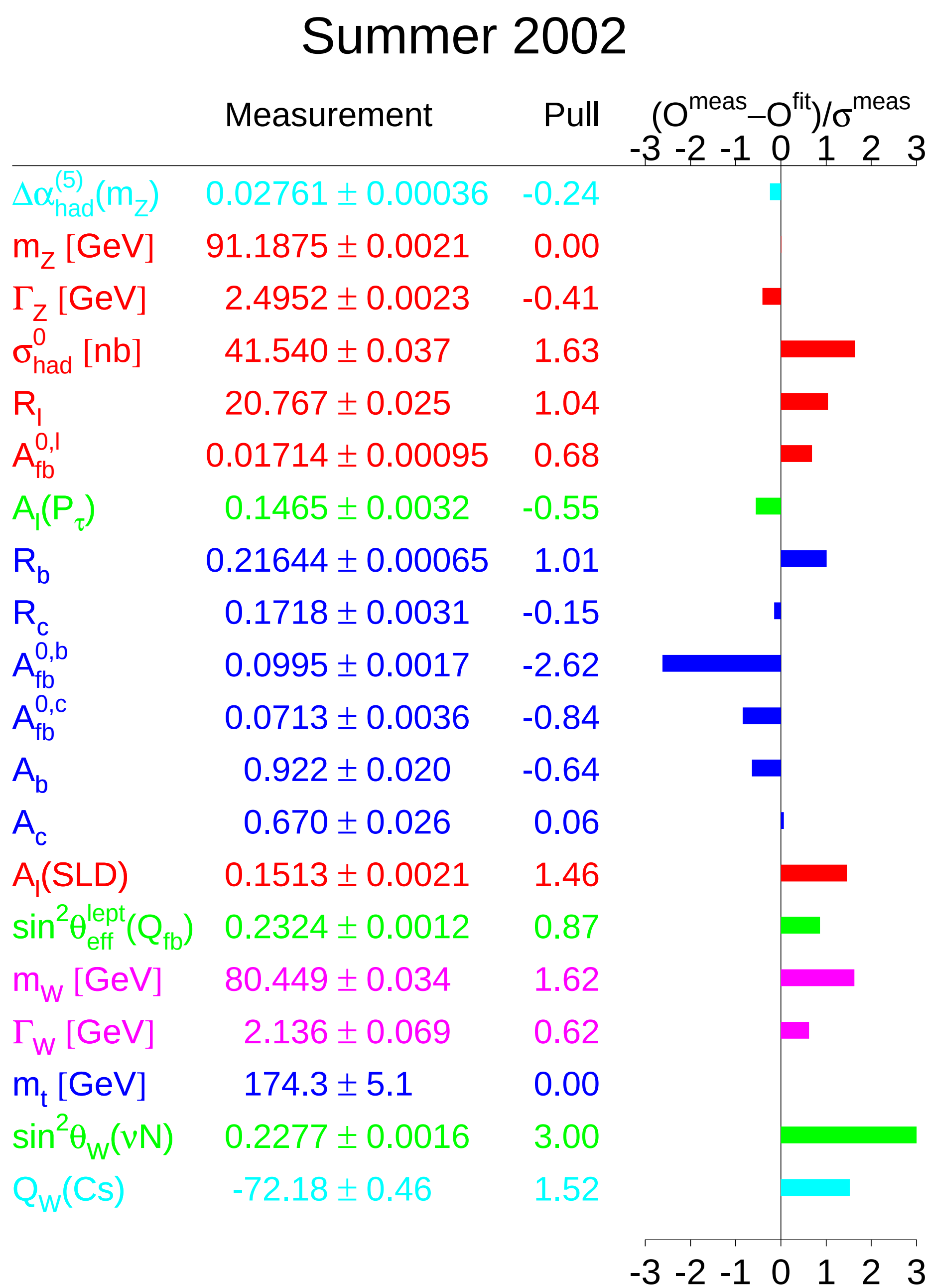
$M_H \lesssim 190$ GeV at 95% CL

χ^2/d.o.f.=20.5/14

probability=11.4%.

M_H fit independent of NuTeV

$(g-2)_\mu$ is traditionally a test of QED



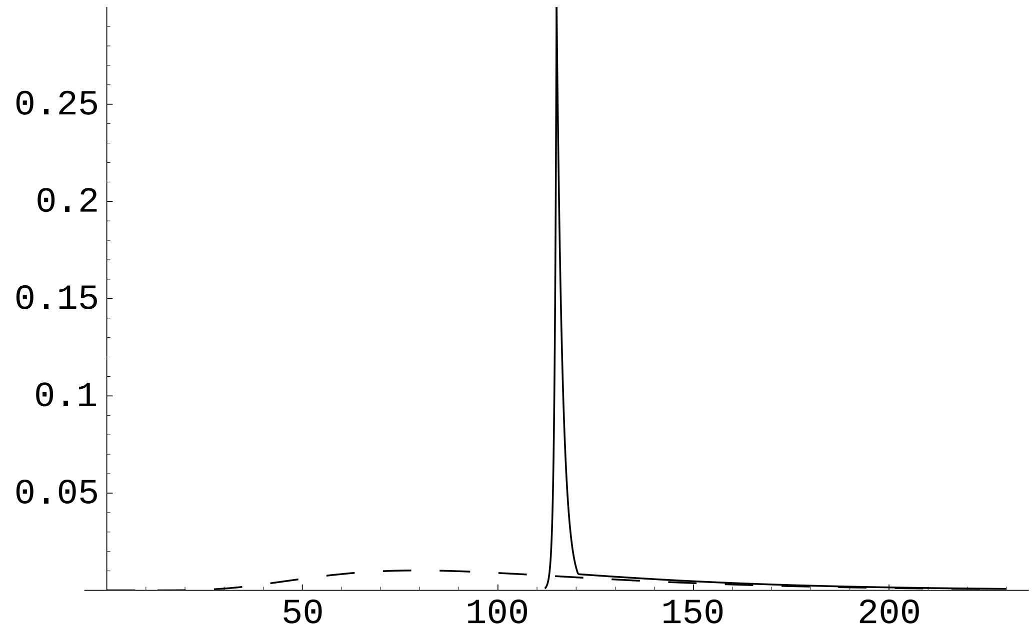
Combining direct and indirect bounds on M_H

Degrassi and D'Agostini have consistently combined $M_H > 114$ GeV from LEP and precision measurements

pdf peaks close to $M_H = 115$ GeV

95% CL bounds slightly higher

$P(M_H \leq 130\,\mathrm{GeV})$ =68%



THE NUTEV ELECTROWEAK RESULT

NuTeV measures ratios of NC/CC cross sections in νN DIS. Ideally

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

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

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

$R^{exp}_{\nu,\bar\nu}$ differ from above because of ν_e contamination, cuts, NC/CC misID, 2nd gen quarks, non isoscalar target, QCD-EW corrections... MonteCarlo relates $R^{exp}_{\nu,\bar\nu}$ to $R_{\nu,\bar\nu}$.

Most uncertainties and $O(\alpha_s)$ effects drop from Paschos-Wolfenstein relation

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

Since $\frac{\partial R_\nu}{\partial s_W^2} \gg \frac{\partial R_{\bar\nu}}{\partial s_W^2}$, NuTeV fit $R^{exp}_{\nu,\bar\nu}$ for $\sin^2\theta_{\rm W}, m_c$ or $g^2_{L,R}$ at LO in QCD (with some improvements)

NuTeV relies heavily on MC. In first approx corresponds to a measurement of R_{PW}

NuTeV result is expressed as a test on s_W^2

$$s_W^2\,(\mathrm{NuTeV}) = 0.2276 \pm 0.0013\ (\mathrm{stat}) \pm 0.0006\ (\mathrm{syst}) \pm 0.0006\ (\mathrm{th})$$
$$-0.00003(M_t/\,\mathrm{GeV} - 175) + 0.00032\ln(m_h/100\,\mathrm{GeV}).$$

$s_W^2 \equiv 1 - M_W^2/M_Z^2$ (on-shell) $\Rightarrow M_W = 80.14 \pm 0.09\mathrm{GeV}$
$M_W^{exp} = 80.449 \pm 0.034$

Global fit $s_W^2 = 0.2226 \pm 0.0004 \Rightarrow 3\sigma$!

Is NuTeV theoretical error realistic?

QED corrections important, but unlikely explanation

EW corrections small and under control

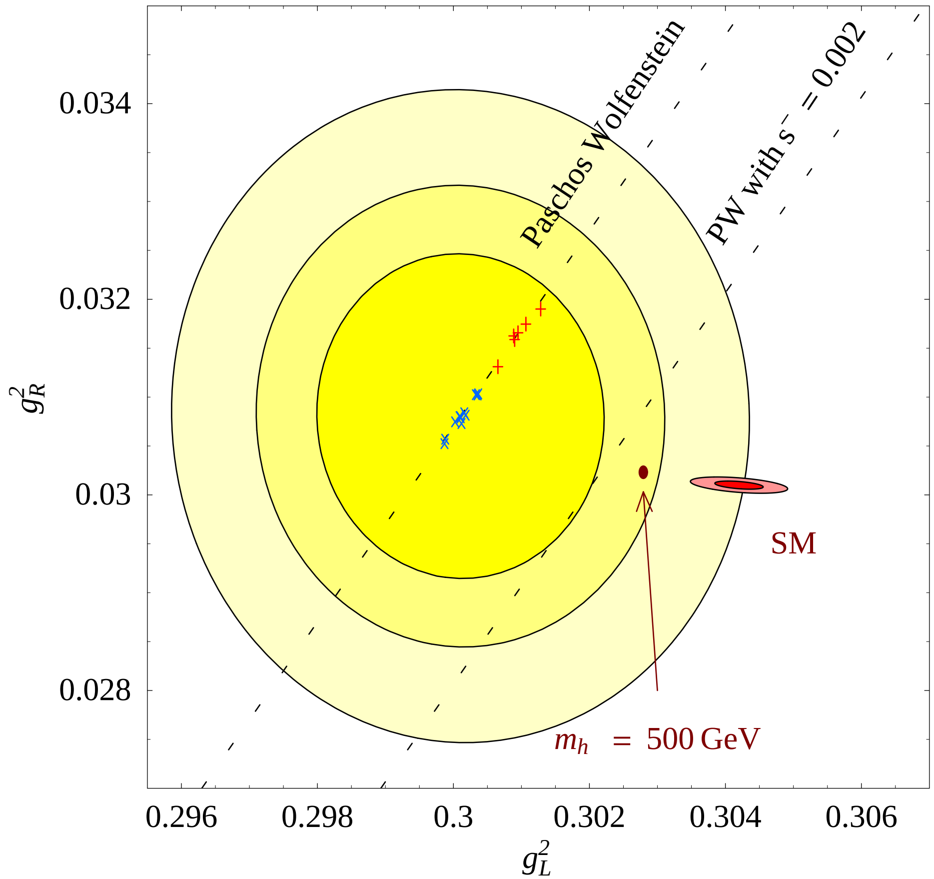
Is NuTeV theoretical error realistic?

• Could PDFs be responsible for the discrepancy?

Not in R_{PW}, with *standard* PDFs.

• Are Next-to-Leading QCD corrections necessary?

Not in R_{PW}, but any CC/NC or $\nu/\bar{\nu}$ asymmetry (cuts, spectra, sensitivity) spoils delicate cancellations. NuTeV differs from R_{PW}. NLO analysis would simplify other issues



≫≫ NuTeV ANALYSIS NEEDS TO BE UPGRADED TO NLO ≪≪

Asymmetric Sea

if no assumptions is made on the parton content of (isoscalar) targets Davidson,Forte,PG,Rius,Strumia

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

with quark/antiquark mom fractions $q^- = \int_0^1 x\,[q(x) - \bar{q}(x)]\,dx \quad Q^- = (u^- + d^-)/2$

R_{PW} is very stable. Violations only occur with $small$ isospin violation or $s - \bar{s}$ asymmetry

ISOSPIN VIOLATION

A small violation of charge symmetry

$$u_p(x) \neq d_n(x), \qquad \frac{u_p - d_n}{u_p + d_n} \approx \frac{m_u - m_d}{\Lambda_{QCD}} \approx 1\%$$

would NOT give visible effects elsewhere. In R_{PW} would lead to $\delta s_W^2 \sim 0.002$

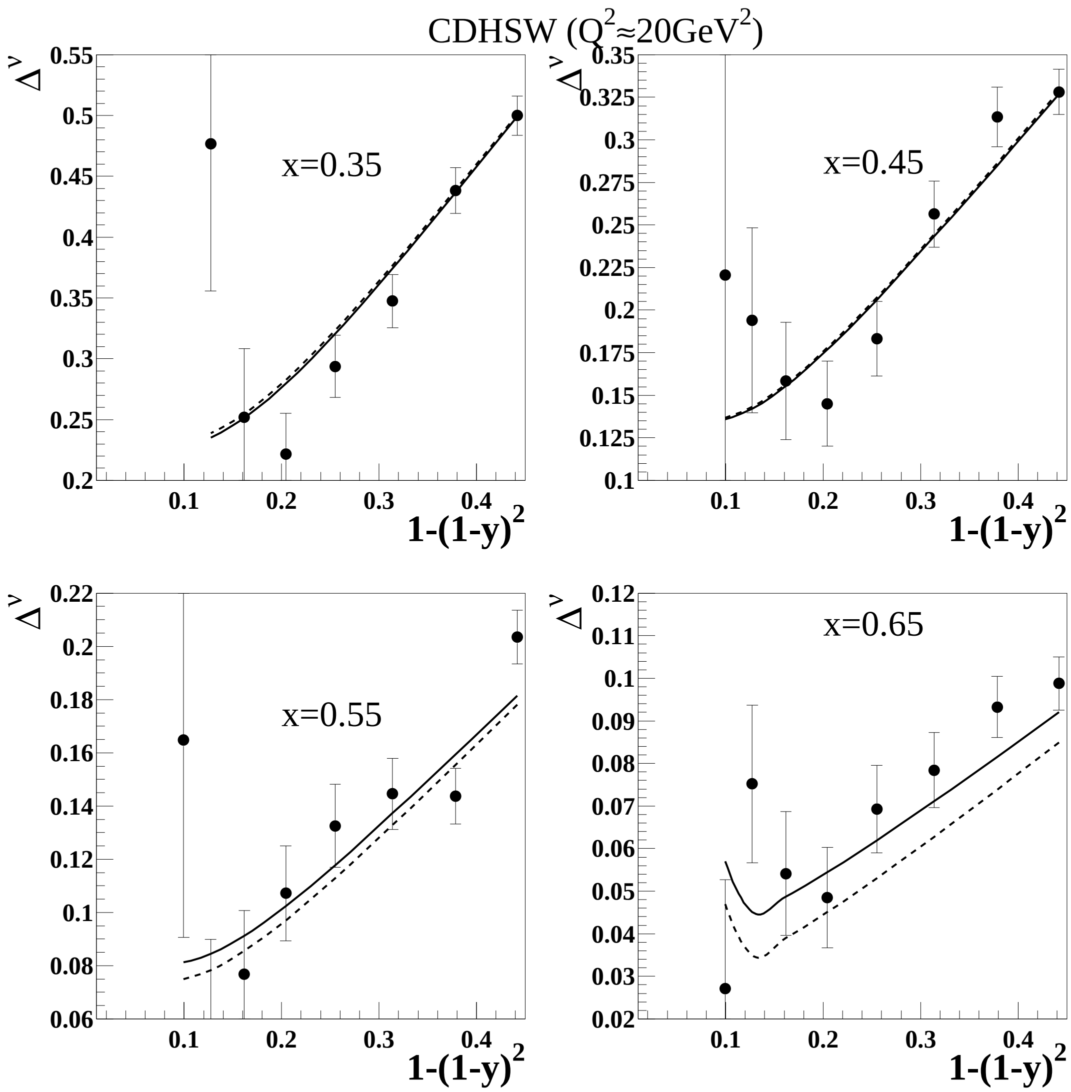
This agrees with a bag model estimate ($\delta s_W^2 < 0$) Sather

other models predict 10 times smaller effects but with subtle cancellations Rodionov et al, Signal Cao

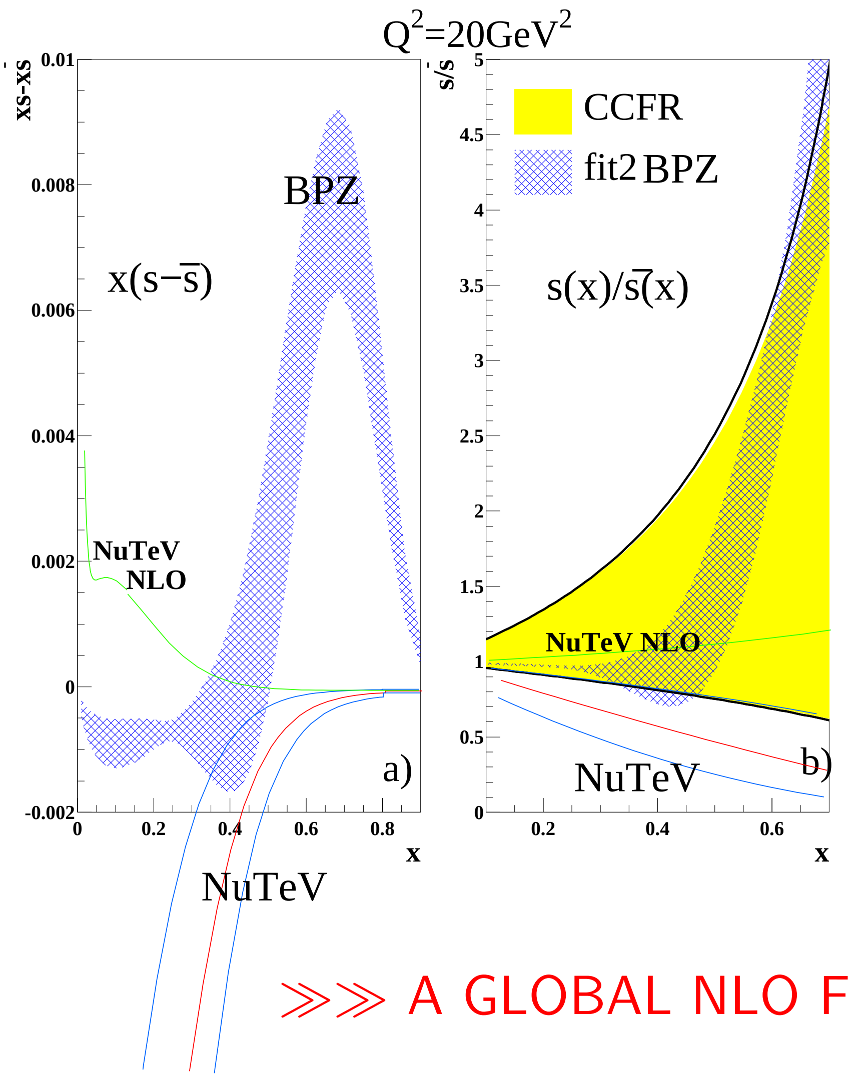
What do we know about the strange sea asymmetry?

- $s \neq \bar{s}$ of sign needed to explain NuTeV can be induced non-perturbatively (*intrinsic strange*) by higher Fock states: $p \leftrightarrow \Lambda K^+$ fluctuations $\Rightarrow$ $\bar{s}$ has smaller x Brodsky et al., Signal, Thomas
- $s(x)$ is mainly constrained by νN DIS. (MRST, CTEQ) use $s = \bar{s} = \frac{\bar{u}+\bar{d}}{4}$
- Barone et al. (BPZ, 1999) reanalysed at NLO all νN DIS together with ℓN and Drell-Yan data. EW and bin center corrections need to be applied $\Rightarrow$ Higher sensitivity to strange sea than standard fits
- BPZ $s(x)$ is larger than usual at high-x, due to CDHSW/BCDMS data. This is in contrast to NuTeV dimuon results, not included in BPZ, but agrees well with positivity constraints from polarized DIS
- Allowing $s \neq \bar{s}$ leads to $\Delta\chi^2 = -25$ with 2 more parmts. Best fit $\boxed{s^- \approx 0.002}$ could explain a fraction of discrepancy and agrees with th estimates.
- NO other exp is sensitive to effects of this kind!

BPZ strange sea fit



The strange sea asymmetry (II)



NuTeV fits from dimuons $s^- = -0.0027 \pm 0.0013$ (hep-ex/0102049,hep-ex/0203004) which would increase the anomaly to 3.7σ.

This estimate cannot be interpreted as a measurement of s^-, should *not* be compared to BPZ and employed in s_W^2 extraction

bad parametrization, LO fit depending on underlying PDF and not global, NLO important for dimuons, theory error much larger than statistical...

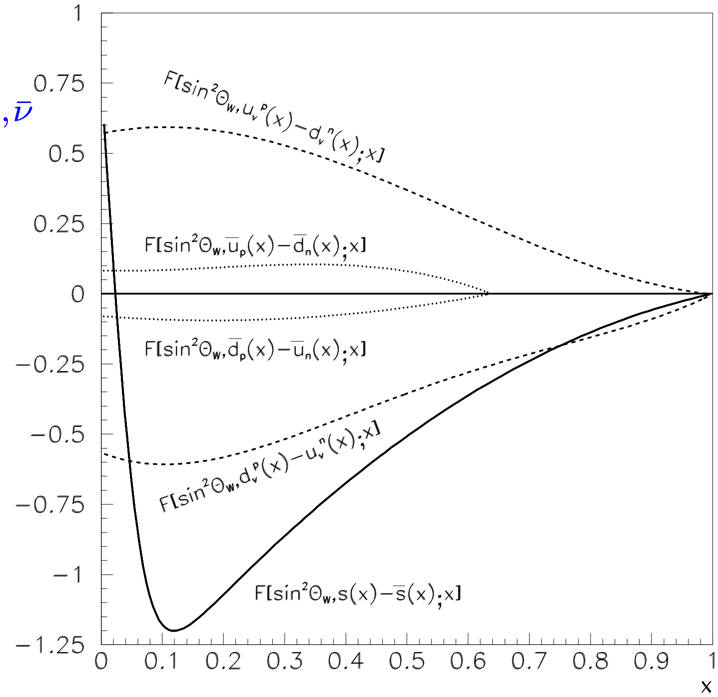
Preliminary NuTeV NLO dimuons analysis finds result closer to BPZ...

Bottom line: we know very little on the strange sea.

≫≫ A GLOBAL NLO FIT INCLUDING ALL DATA IS NEEDED ≪≪

NuTeV also pointed out (`hep-ex/0203004`) that cuts, charm threshold effects, and different sensitivity to $R_{\nu,\bar{\nu}}$ dilute the effect of $s/\bar{s}$ and isospin asymmetry by a factor 0.5 or less

we include cuts on R_{PW} and find less dilution



Quark sea asymmetries contribute significant uncertainty!

Other effects proposed to explain NuTeV

- Nuclear Shadowing:
  Miller and Thomas (VMD model, wrong sign), Kovalenko *et al.* (nuclear rescaling model that explains EMC, but NuTeV fits self-consistently its PDFs)

- Neutrino oscillations
  NO, they could explain result only with large $\nu_e - \nu_s$ but NuTeV measures ν_e spectrum to a few percent

New Physics vs NuTeV

NuTeV requires a $\sim 1\%$ (tree level) effect. Very difficult to build realistic models that satisfy all exp constraints and account for whole discrepancy

Davidson, Forte, PG, Rius, Strumia, JHEP

⋆ NO Supersymmetry, with or without R parity

⋆ NO Models inducing only oblique corrections

⋆ YES Contact interactions $(-0.024 \pm 0.009)\, 2\sqrt{2} G_F\, [\bar{L_2}\gamma_\mu L_2][\bar{Q_1}\gamma_\mu Q_1]$

⋆ Maybe... Vector/scalar Leptoquarks but only with split SU(2) triplet: $\pi \to \mu \bar{\nu}_\mu$

⋆ Maybe... unmixed Z' light or heavy, for ex. narrow superweak abelian $B - 3L_\mu$ Z', $2 \lesssim M_{Z'} \lesssim 10$GeV, Davidson *et al.* Z'/Z mixing should be tiny because of bounds on ϵ_i and anomalous Z couplings ($L_\mu - L_\tau$, Ma & Roy, Langacker, technicolor)

New Physics: Anomalous Z^0 Couplings

NuTeV can be explained by lower ($\sim -0.6\%$) $Z\nu\bar{\nu}$ coupling, also favored by $-(0.53 \pm 0.28)\%$ deviation in Γ_Z^{inv}. However, realistic models alter either

- other Z couplings

  e.g.: extra U(1) Z' mixing with Z. Model indep fit to SU(2) invariant and gen. universal Z couplings shows only marginal improvement. Dropping SU(2) requirement improves fit. Non universal couplings less constrained

- the charged current couplings of ν

  e.g.: SM neutrinos mix with heavy ν_R (extra dim or not – Babu & Pati, Davidson *et al.*)

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \epsilon_{ij}\; 2\sqrt{2} G_F (H^\dagger \bar{L}_i) i\partial\!\!\!/ (H L_j),$$

NuTeV needs $\epsilon_{\mu\mu}$ ∼1.2%, excluded by EW precision obs.
Possible in conjunction with large O(1%) oblique corrections — Loinaz *et al.*

Heavy SM-like Higgs *cannot* do that! At least not without disposing of M_W...

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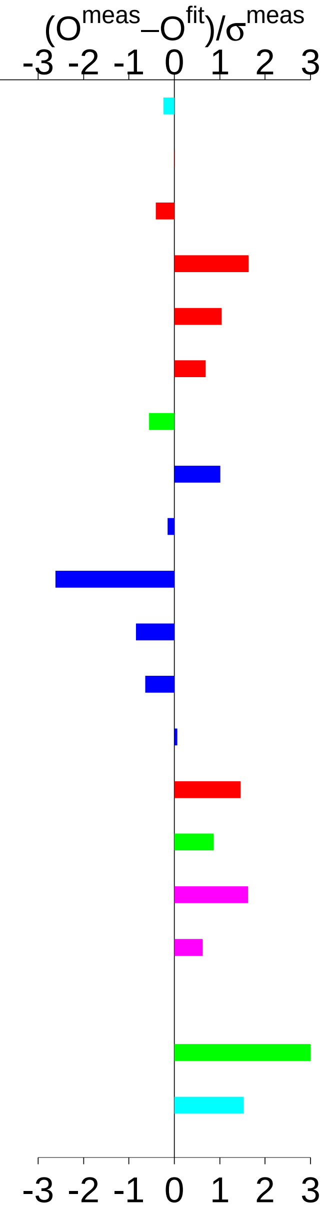
Summer 2002

	Measurement	Pull
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02761 ± 0.00036	-0.24
m_Z [GeV]	91.1875 ± 0.0021	0.00
Γ_Z [GeV]	2.4952 ± 0.0023	-0.41
σ_{had}^0 [nb]	41.540 ± 0.037	1.63
R_l	20.767 ± 0.025	1.04
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.68
$A_l(P_\tau)$	0.1465 ± 0.0032	-0.55
R_b	0.21644 ± 0.00065	1.01
R_c	0.1718 ± 0.0031	-0.15
$A_{fb}^{0,b}$	0.0995 ± 0.0017	-2.62
$A_{fb}^{0,c}$	0.0713 ± 0.0036	-0.84
A_b	0.922 ± 0.020	-0.64
A_c	0.670 ± 0.026	0.06
A_l(SLD)	0.1513 ± 0.0021	1.46
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.87
m_W [GeV]	80.449 ± 0.034	1.62
Γ_W [GeV]	2.136 ± 0.069	0.62
m_t [GeV]	174.3 ± 5.1	0.00
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	3.00
$Q_W(Cs)$	-72.18 ± 0.46	1.52



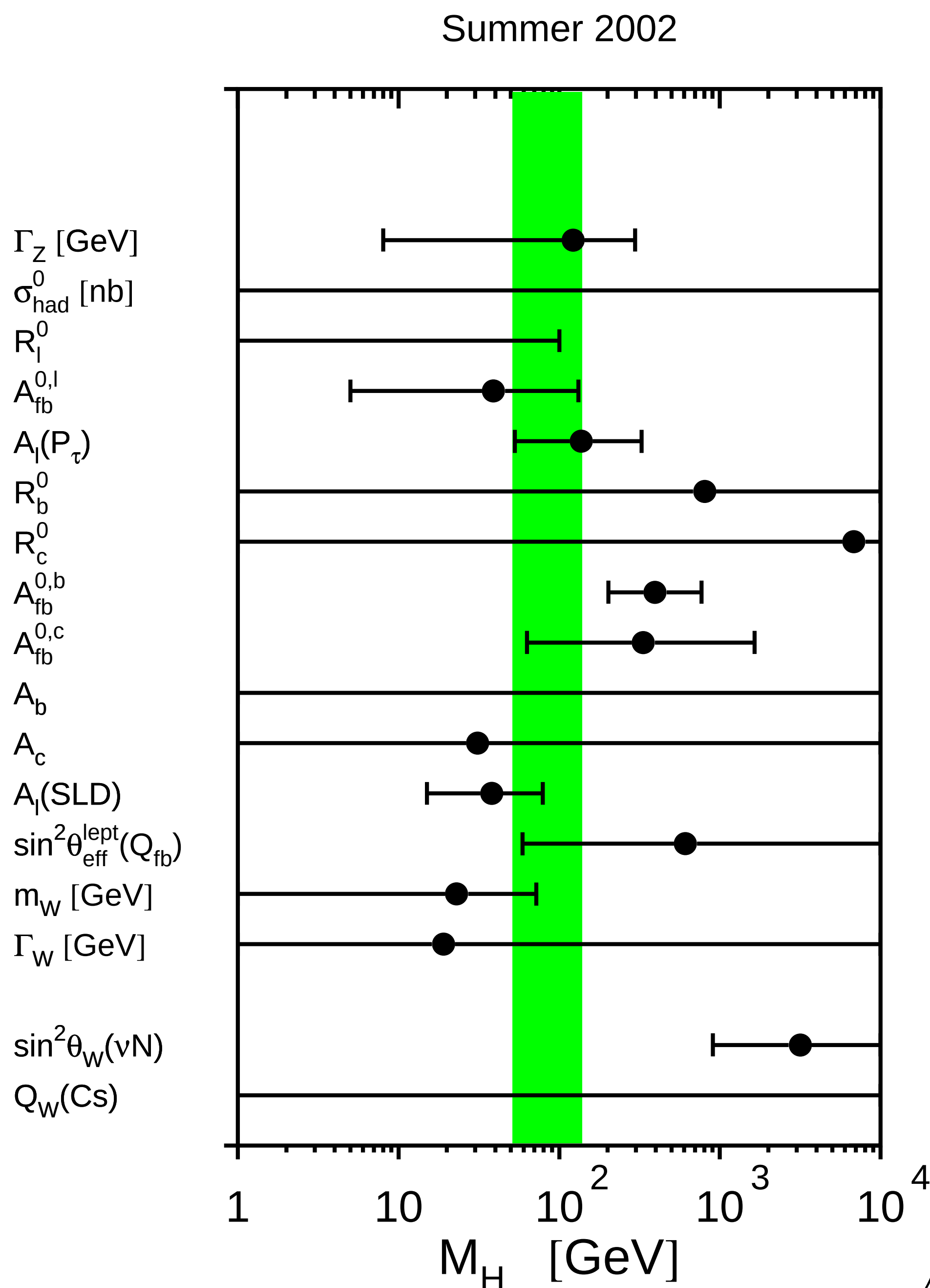
The SM fit to M_H is not satisfactory

Only a subset of observables are really SENSITIVE to M_H (and M_t)

Using only M_W,M_t,Γ_ℓ, the asymmetries, R_b (NOT NuTeV):

$M_H^{fit} = 90$ GeV, $M_H^{95\%} < 195$ GeV

χ^2/dof=13/4, prob=0.9%



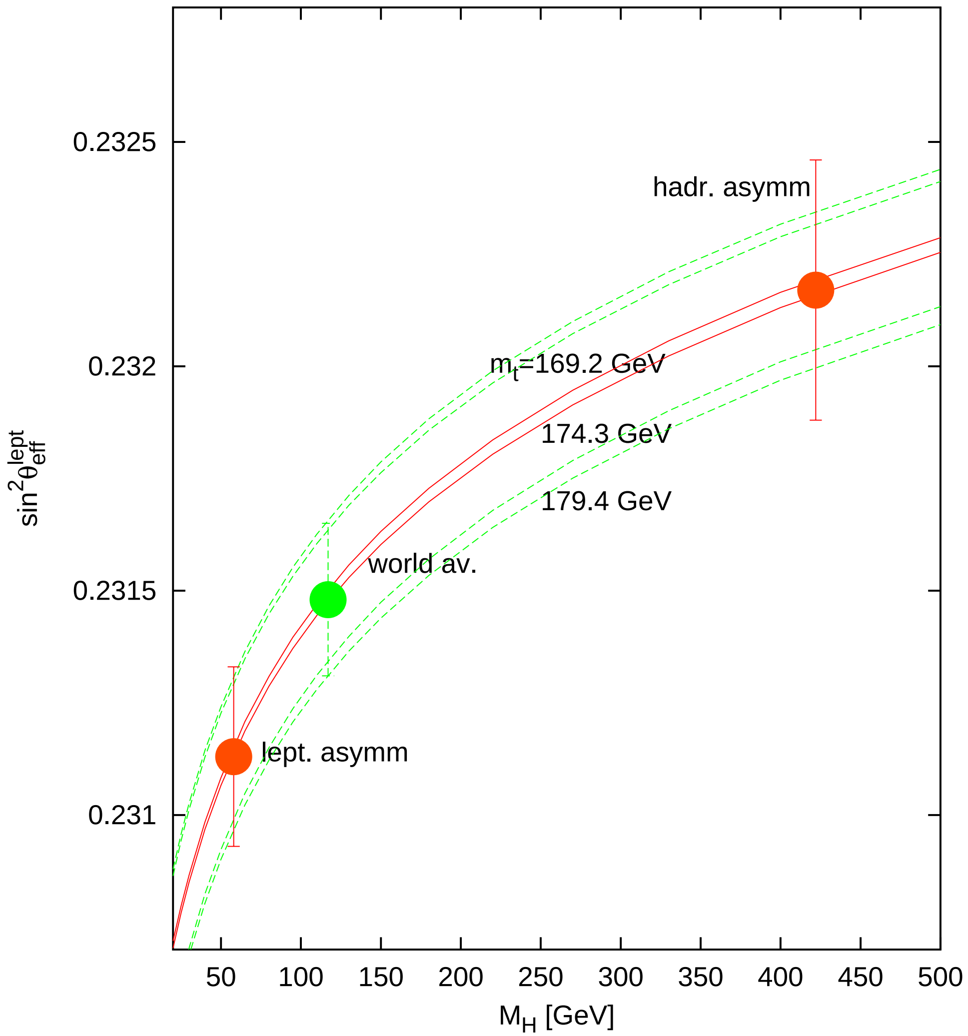
Another unwelcome anomaly

Root of the problem is the 3σ discrepancy between the L-R asymmetries of SLD (*very light Higgs*, like M_W) and the FB b asymmetries of LEP (*heavy Higgs*)

In the SM leptonic and hadronic asymmetries measure the SAME quantity, $\sin^2\theta_{eff}^{lept}$

leptonic asymmetries are mutually consistent and M_W pushes for a light Higgs too. Hadronic ones dominated by b:
NEW PHYSICS in the b couplings?

QCD systematics in A_{FB}^b are well studied

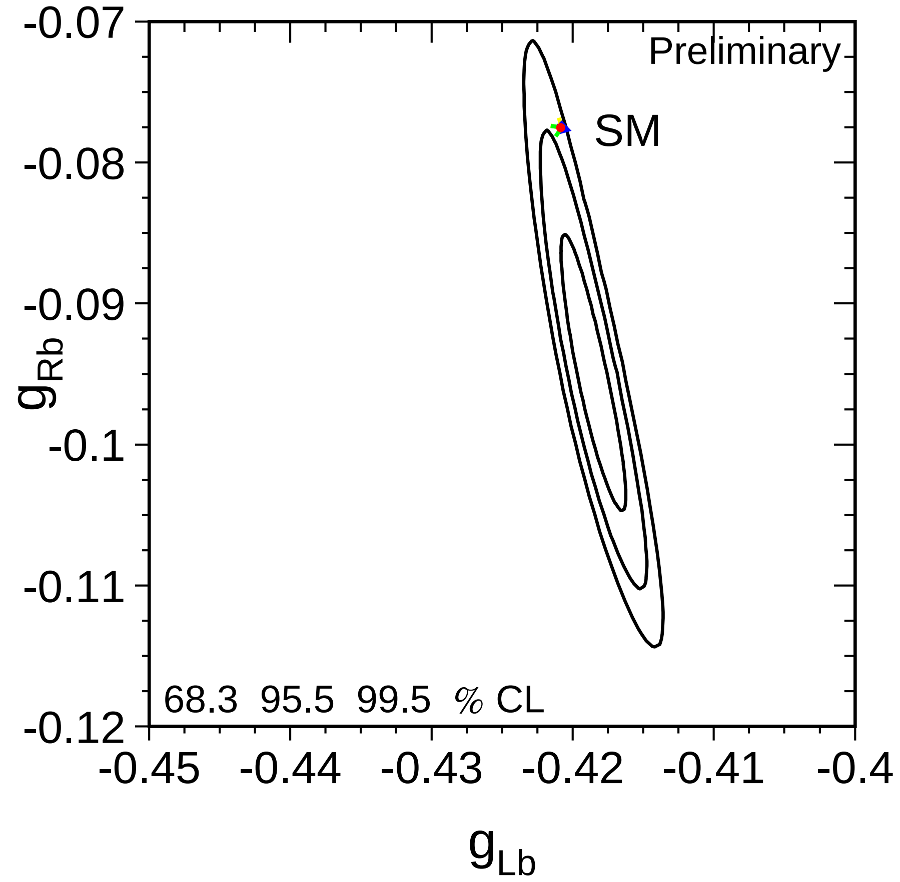


New Physics in the b couplings?

⋆ A_{LR}^{FB} of SLD agree with SM

⋆ fixing lept coupling, A_{FB}^{b} implies 30% correction to b vertex $\Rightarrow$ needs tree level physics

⋆ R_b agrees with SM, $|\delta g_R^b| \gg |\delta g_L^b|$



EXOTIC SCENARIOS that shift b_R coupling:

- Mirror Vector-like fermions mixing with b quark   Choudhury *et al.* hep-ph/0109097
- L-R models that single out the third generation   He, Valencia hep-ph/0203036
  both problematic

both problematic

Too light a Higgs

Dilute all asymmetries according to PDG, preferred M_H slightly lighter

Ferroglia *et al.*

Diluting only the hadronic asymmetries, a consistent picture emerges

$M_H^{fit} = 40$ GeV prob=75%, $M_H^{95\%} < 109$ GeV but LEP: $M_H > 114$ GeV

Why hasn't the Higgs been found?

Chanowitz hep-ph/0207123; Altarelli *et al.* hep-ph/0106029

NB: small sensitivity to $\alpha(M_Z)$: most unfavorable $M_H^{95\%} \sim 120$ GeV. Theoretical error cannot shift up $M_H^{95\%}$ more than 20 GeV

The problem is alleviated if $M_t \gtrsim 180$ GeV, but the fit does not suggest it

Combined probability of global fit and of $M_H > 114$GeV is the same with/without $A_{FB}^b \sim 0.003/0.025$ (with/without NuTeV)

Chanowitz, hep-ph/0207123

New physics simulating a light Higgs

Excluding A^b_{FB} and NuTeV from global fit the quality of the fit improves considerably, but M_H^{fit} becomes very small

Finding New Physics that simulates a very light Higgs is much easier than explaining NuTeV or the FB b asymmetries!

- oblique corrections: in general requires $S < 0 (T > 0)$ or $\epsilon_{2,3} < 0$
- A non-degenerate unmixed 4th generation with $m_N \approx 50$ GeV
  Novikov et al. hep-ph/0205321, 0111028
- More interestingly, the MSSM offers:
  - rapid decoupling (strongly constrained by direct searches)
  - M_W always higher than in SM, $\sin^2\theta^{lept}_{eff}$ lower than in SM

  A plausible MSSM scenario involves light $\tilde{\nu}, \tilde{\ell}$ and possibly charginos, heavy squarks, at $\tan\beta \gtrsim 5$, and is testable at Tevatron Altarelli *et al.* hep-ph/0106029

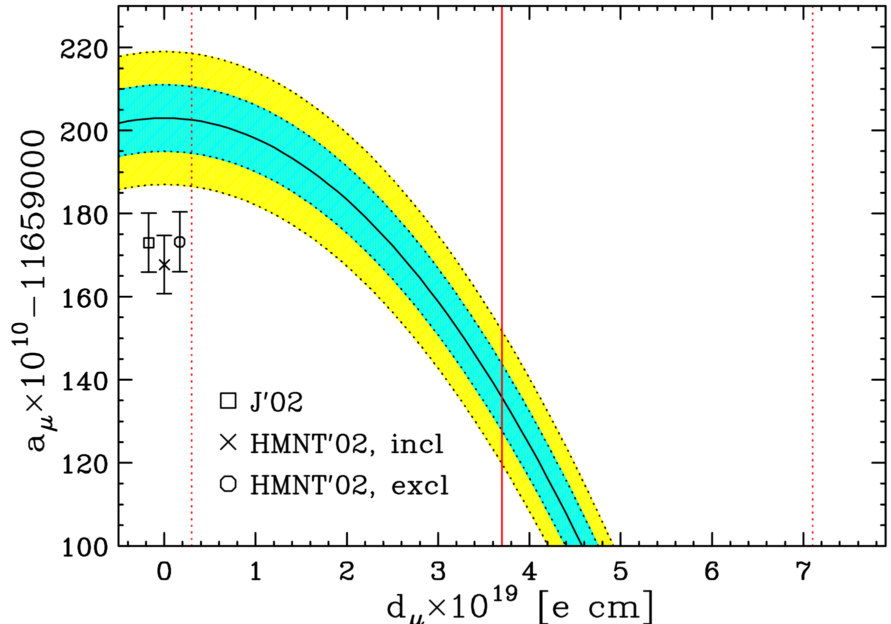
  Other susy scenario: EMSSM, Babu & Pati, hep-ph/0203029

The measurement of the muon's anomalous magnetic moment isn't

Matchev, Feng, Shadmi noticed that the anomalous spin precession frequency is

$$|\omega_a| \approx |B| \left[\left(\frac{e}{m_\mu} \right)^2 a_\mu^2 + \left(\frac{2c}{\hbar} \right)^2 d_\mu^2 \right]^{1/2} ,$$

and it constrains only a *combination* of the muon's magnetic and electric dipole moments.



Electron EDM has very strong bound, $d_e \lesssim 10^{-26}$. In most models, like MSSM with univ soft terms, $d_\mu / d_e \propto m_\mu / m_e \Rightarrow d_\mu \lesssim 0.3 \times 10^{-22}$

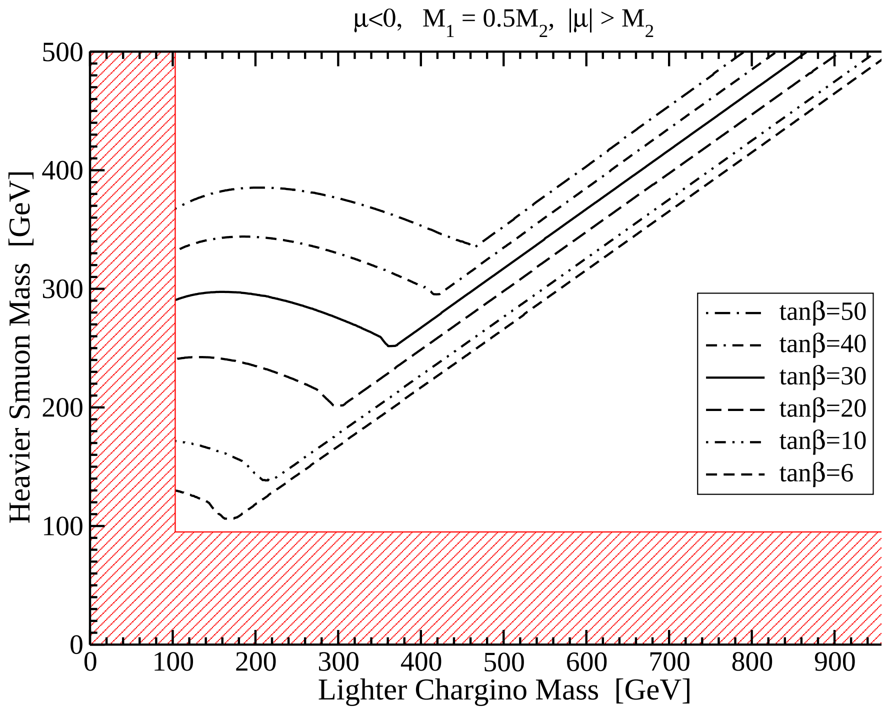
In MSSM, $d_\mu / m_\mu \gg d_e / m_e$ possible but not appealing. Some flavor symmetries lead "naturally" to $d_\mu \approx 10^{-22}$, much too small... Romanino, Strumia, NPB 2002

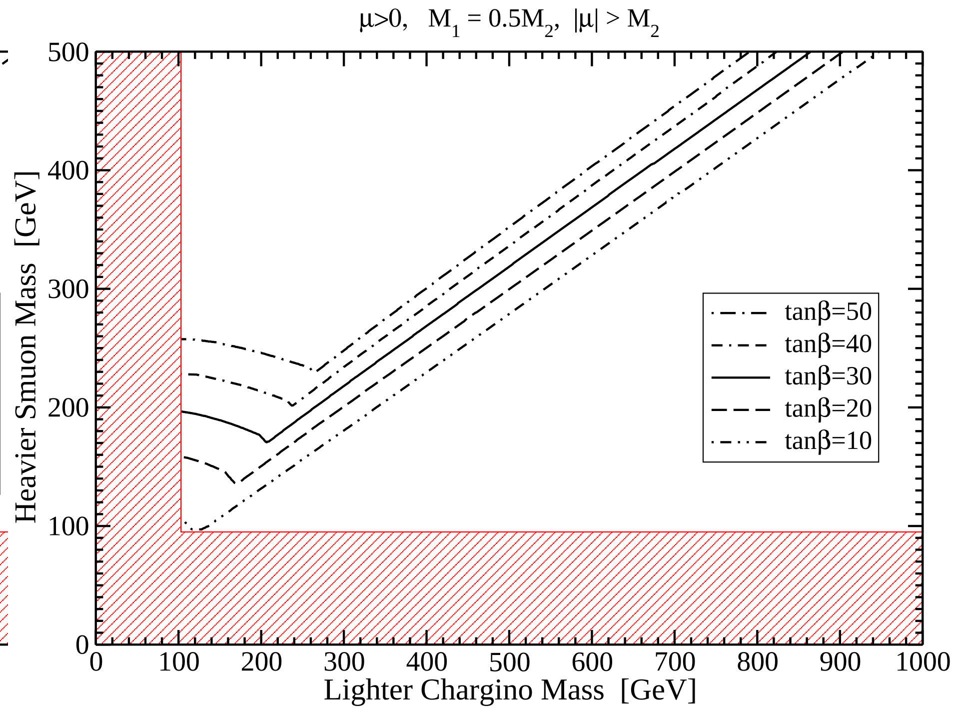
a_μ vs New physics

a_μ is the ideal place for NP to show up: unexplored loop effects $\propto \frac{m_\mu^2}{M^2}$ but pure EW contributions ($M \approx M_W$) contribute $a_\mu^{EW} \approx 15 \times 10^{-10}$, hence to fit the BNL result with $M > M_W$ one needs an enhancement factor

- MSSM $|a_\mu^{SUSY}| \simeq 130 \times 10^{-11} \left(\frac{100\,\mathrm{GeV}}{\tilde{m}}\right)^2 \tan\beta$
- Z', of course, but no specific model can give large contributions without problems elsewhere
- Leptoquarks (but not those fitting NuTeV)
- VERY light 2HDM Higgses (Dedes, Haber)?? very small window...
- compositeness
- ....

The superconservative approach Martin & Wells, 2002





SUMMARY

- NuTeV aims at precision measurements in a complex hadronic environment. Theoretical systematics not fully under control or untested include a small strange/antistrange asymmetry and isospin violation. The analysis should be upgraded to NLO.
- Even without NuTeV, the SM fit to M_H is not good. What we know on M_H depends $heavily$ on the measurement of the b FB asymmetries, which represents another (even more) puzzling anomaly.
- Both anomalies require new tree level effects. No susy. Proposed new physics explanations for both NuTeV and A_{FB}^b, when viable, are ad-hoc and exotic.
- removing the anomalies from the SM fit leads to inconsistency with the direct lower bound on M_H (do M_W and A_{LR} show a hint of New Physics?). Some solution of this problem will be tested at Tevatron
- a_μ is an ideal place for new physics / a serial killer of new physics models

- the new physics preferred by the three anomalies is orthogonal. Susy with large $\tan\beta$ and light sleptons could only explain high M_W and A_{LR}, and a_μ.
- upcoming experiments will help a bit to resolve some of the anomalies: Tevatron M_W and M_t, BNL... Do we want to think about GigaZ??
- the SM looks extremely resistant and resilient One thing is clear: if we are not able to reliably predict (and extract) observables in the SM, it will be a terrible waste...