Electroweak precision physics before (and after) LHC

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UNIVERSITÀ DEGLI STUDI ROMA TRE

INFN Sezione di Roma III

DIPARTIMENTO DI FISICA EDOARDO AMALDI

Outline

- $(g-2)_\mu$ first indication for NP?
- Precision physics era has not ended with LEP: improvements in $M_t,\ M_W$ $\Longrightarrow$ improvement in the SM Higgs determination from the EW fit
- Old problem with the SM fit: “weak” indication for NP?
- Electroweak physics at LHeC from the experience of HERA

Experimental Status of $a_i \equiv (g-2)_i/2$

- Electron: $a_e = 1159652180.73(28) \times 10^{-12}$
  0.24 parts per billion. Hanneke, Fogwell, Gabrielse (08)

- Muon: $a_\mu = 116592080(63) \times 10^{-11}$
  0.5 parts per million. Muon g-2 Coll. (06)

- Tau: $a_\tau = -0.018(17)$
  DELPHI Coll. (04)

a_e insensitive to hadronic, weak and NP contributions $(\lesssim 1 \times 10^{-12})$
best determination of α

sensitivity to hadronic, weak and NP contributions increased in a_μ
by a factor $(m_\mu/m_e)^2 \sim 4 \cdot 10^4$ with respect to a_e

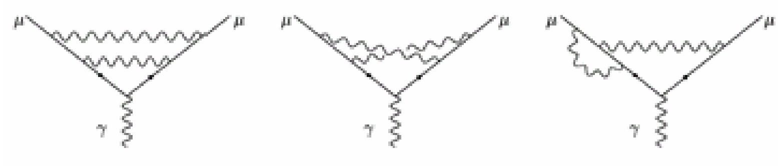
Theoretical Status of a_μ

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm EW} + a_\mu^{\rm HLO} + a_\mu^{\rm HHO}$$

Perturbative Contributions:

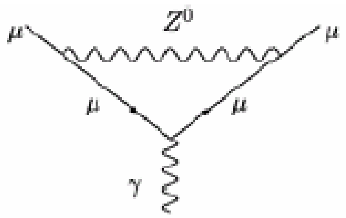
$$\begin{aligned} a_\mu^{\rm QED} &= c_1\left(\frac{\alpha}{\pi}\right) + \ldots + c_5\left(\frac{\alpha}{\pi}\right)^5 \\ &= 116584718.09(14)(04)\times 10^{-11} \end{aligned}$$

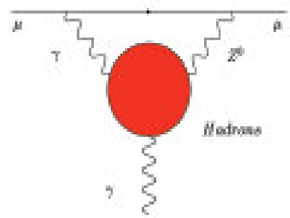
c_5 unc. ↑ ↑ err. on α



$$\begin{aligned} a_\mu^{\rm EW} &= \frac{5\,G_\mu m_\mu^2}{24\sqrt{2}\pi^2}\left({\rm c}_1 + {\rm c}_2\left(\frac{\alpha}{\pi}\right)\right) \\ &= 154(2)(1)\times 10^{-11} \end{aligned}$$

M_H, M_t, h.o err. ↑ ↑ hadronic loop unc.

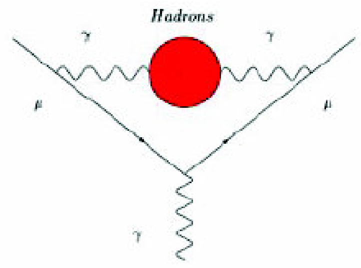




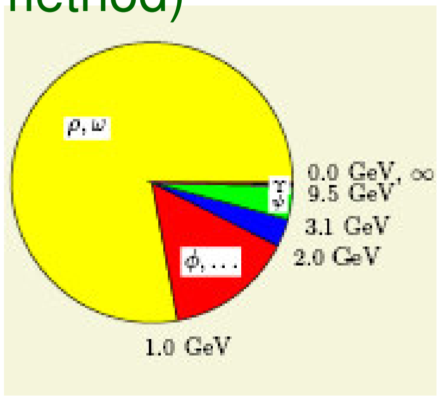
Non-Perturbative Contributions: hadronic leading order

$$a_\mu^{\rm HLO} = \frac{\alpha^2}{3\,\pi^2}\int_{4\,m_\pi^2}^{\infty}\frac{ds}{s}K(s)R(s)$$

$$R(s) = \frac{\sigma^{(0)}(e^+e^- \to \gamma^* \to {\rm hadrons})}{(4\pi\alpha^2)/(3s)}$$



e^+e^- data, including KLOE & BABAR (radiative return method)



$$a_\mu^{\rm HLO} = 6909(39)_{exp}(20)_{rad}\times 10^{-11}$$ Eidelman (07)

$$= 6894(42)_{exp}(18)_{rad}\times 10^{-11}$$ Hagiwara et al. (07)

$$= 6923(60)_{tot}\times 10^{-11}$$ Jegerlehner (08)

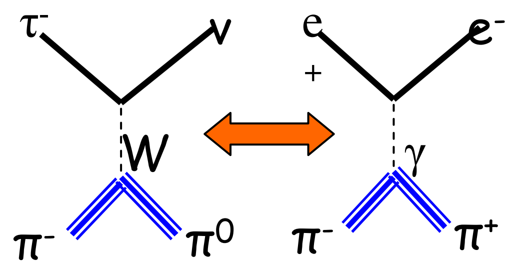
$$= 6941(50)_{exp}(10)_{rad}\times 10^{-11}$$ de Troconiz, Yndurain (05)

90% of $a_\mu^{\rm HLO}$ is accumulated for $\sqrt{s} \leq 1.8\ {\rm GeV}$

including τ data

$$a_\mu^{\rm HLO} = 7110(58)\times 10^{-11}$$ Davier et al. (03)

$$= 7024(50)\times 10^{-11}$$ de Troconiz, Yndurain (05)



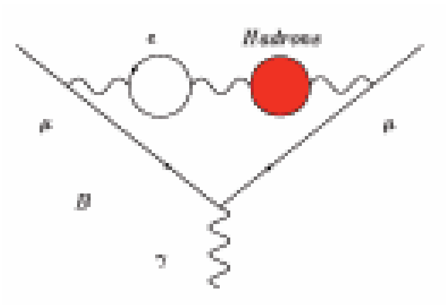
CVC + isospin symmetry
isospin breaking under control?

Non-Perturbative Contributions: hadronic higher-order

$$a_\mu^{\rm HHO} = a_\mu^{\rm HHO}({\rm vp}) + a_\mu^{\rm HHO}({\rm lbl})$$

vacuum polarization

$$a_\mu^{\rm HHO}({\rm vp}) = -98(1) \times 10^{-11}$$

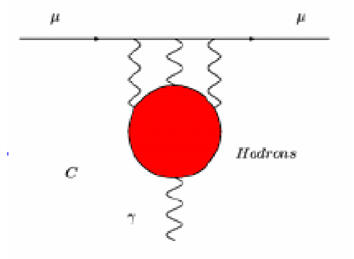


Light-by-Light

$$a_\mu^{\rm HHO}({\rm lbl}) = +80(40) \times 10^{-11}$$ Knecht, Nyffeler (02)

$$= +136(25) \times 10^{-11}$$ Melnikov, Vainshtein (03)

$$= +110(40) \times 10^{-11}$$ Bijnens, Prades (07)



evaluation relies on models of low-energy hadronic interactions with electromagnetic currents.

a_μ: SM vs. Experiment

Using $a_\mu^{\rm HHO}({\rm lbl}) = +110(40) \times 10^{-11}$

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM}$$

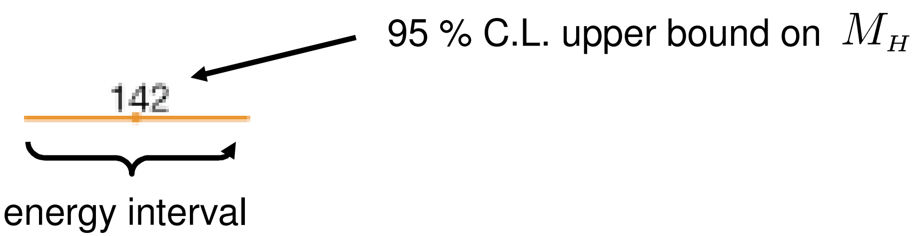
$a_\mu^{\rm SM} \times 10^{11}$	$\Delta a_\mu \times 10^{11}$	σ	
116 591 793 (60)	287 (87)	3.3	
116 591 778 (61)	302 (88)	3.4	e^+e^- data
116 591 807 (72)	273 (96)	2.8	
116 591 824 (65)	256 (88)	2.9	
116 591 991 (70)	89 (95)	0.9	τ data
116 591 907 (64)	173 (87)	2.0	

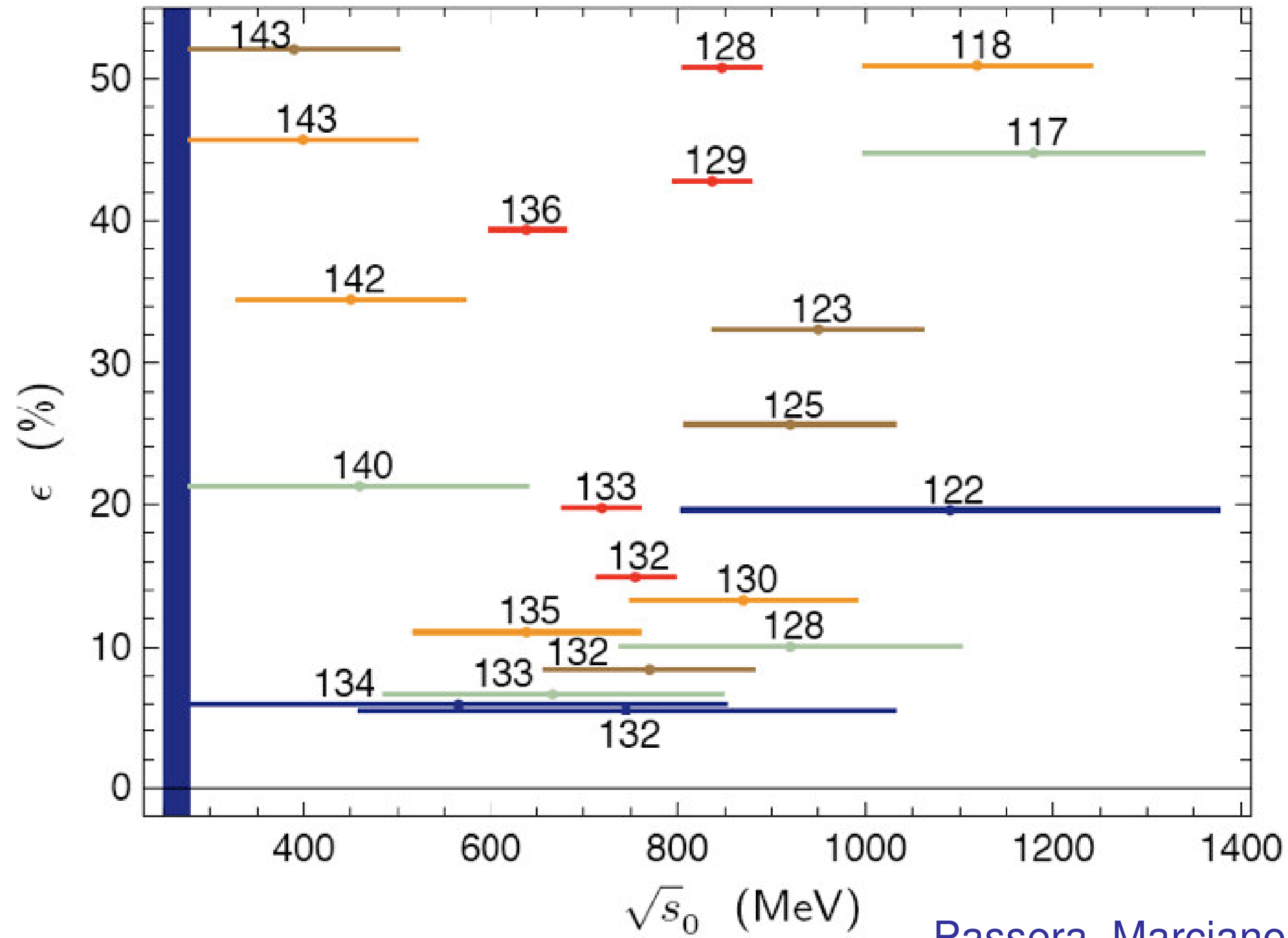
$$\Delta a_\mu \sim 0 : \quad \sim 4 \times a_\mu^{\rm HHO}({\rm lbl})$$
$$\sim 1.04 \times a_\mu^{\rm HLO}$$

A change in $R(s)$ affects also $(\Delta\alpha)_h = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} ds \frac{M_Z^2}{s(s-M_Z^2)} R(s)$

⟹ Higgs mass bound

$$\epsilon = \frac{\Delta\sigma^{(0)}}{\sigma^{(0)}}$$ in





Passera, Marciano, Sirlin (08)

Δa_μ: New Physics Explanations

Δa_μ is in the right ballpark for many NP explanations.

- Extra Z

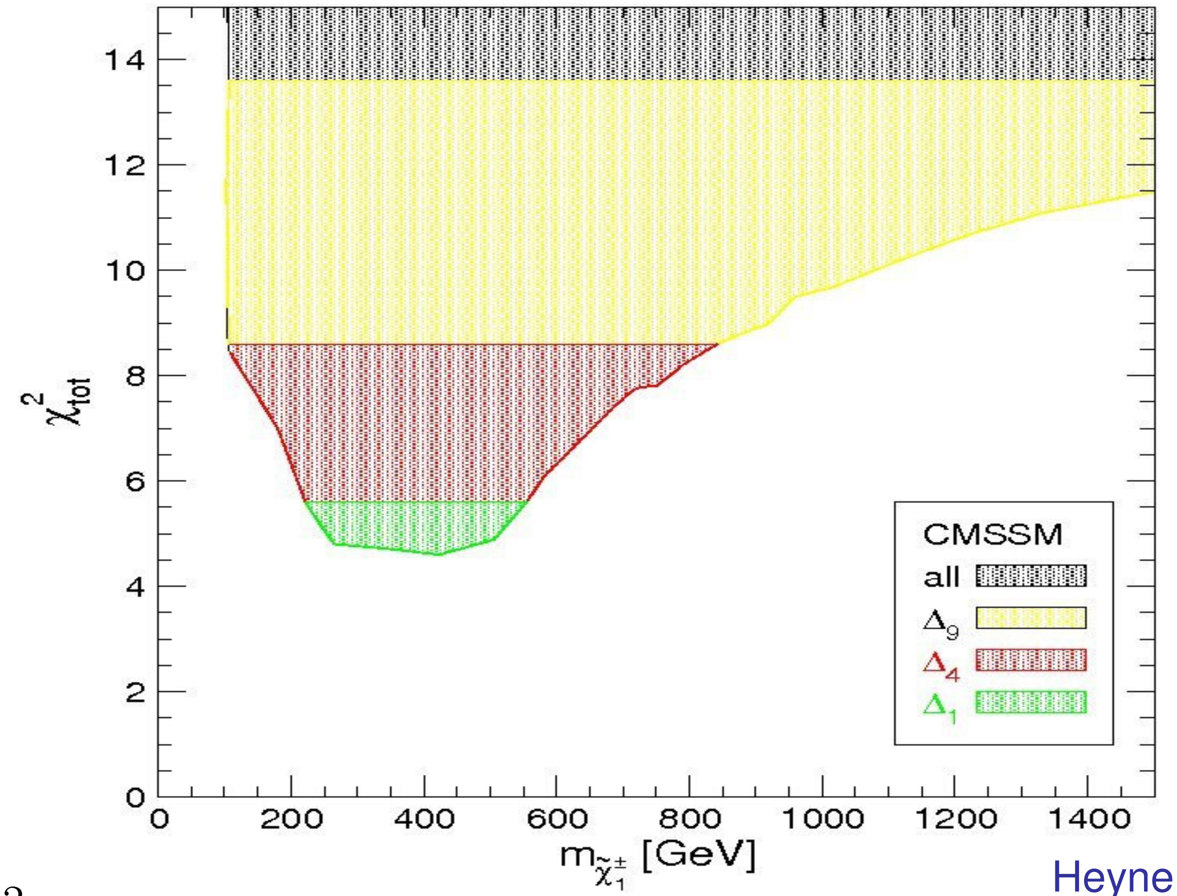
$$a_\mu(\hat{Z}) = (480 \times 10^{-11}) \frac{\hat{g}^2}{g^2} \frac{M_Z^2}{M_{\hat{Z}}^2} \left(3\hat{Q}_L\hat{Q}_R - \hat{Q}_L^2 - \hat{Q}_R^2 \right)$$

- Supersymmetry

$$a_\mu^{\mathrm{SUSY}} \simeq (\mathrm{sgn}\,\mu) \times (130 \times 10^{-11}) \left(\frac{100\,\mathrm{GeV}}{M_{\mathrm{SUSY}}} \right)^2 \tan\beta$$

$\mu > 0,$ indication for light sleptons and gauginos

CMMS Fit including a_μ

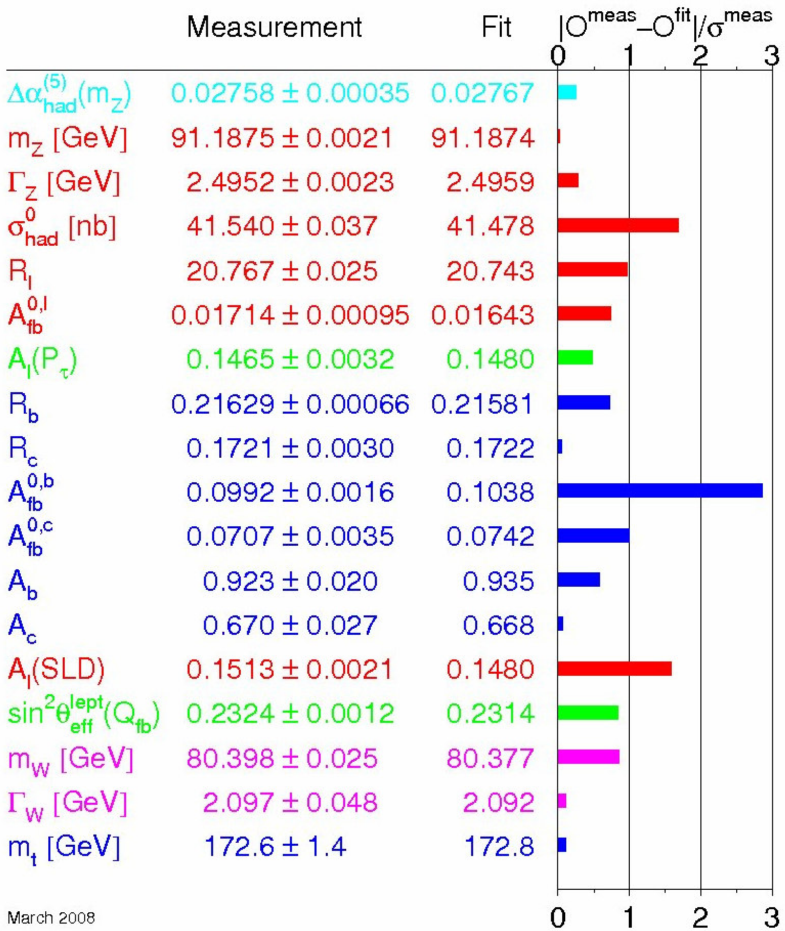


Heynemeyer et al (08)

$$\Delta_n = \Delta\chi^2 = n$$

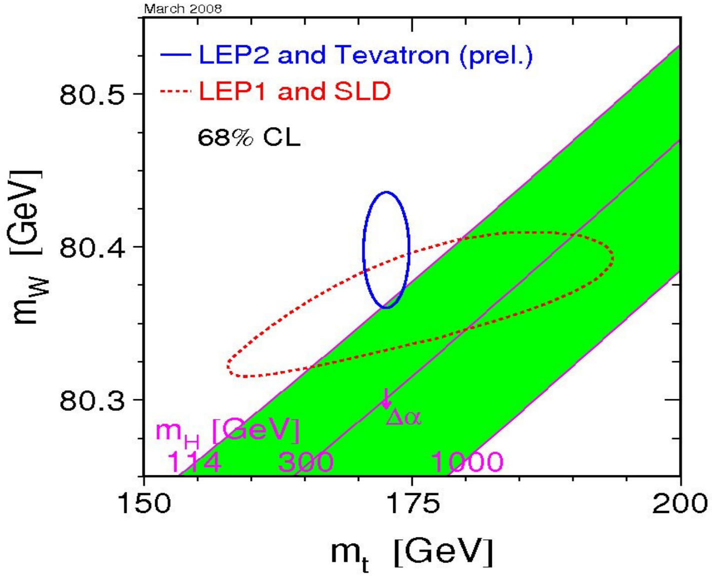
low chargino mass is favored by a_μ

The LEP/SLC Era

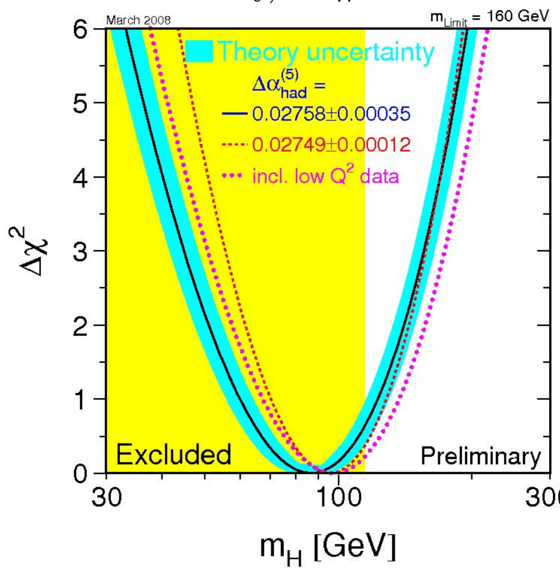


	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	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
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.377
Γ_W [GeV]	2.097 ± 0.048	2.092
m_t [GeV]	172.6 ± 1.4	172.8

without direct M_t, M_W determination



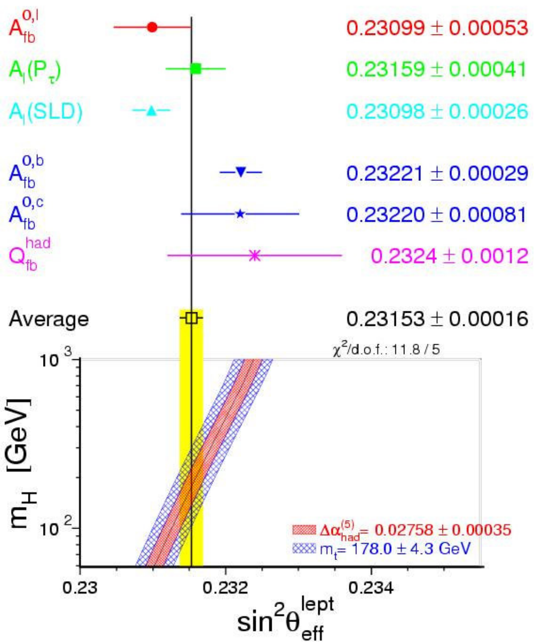
with direct M_t, M_W determination

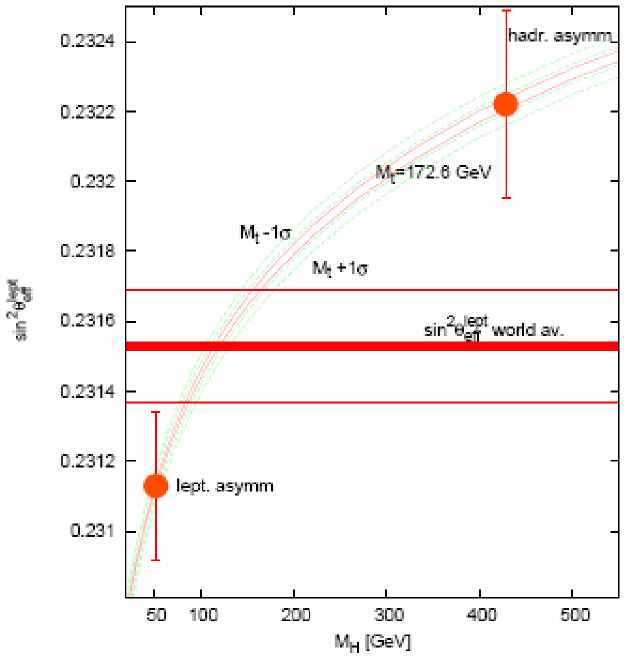


Strong indication for a light Higgs

Any indication of NP?

Indication of NP (I)?





$A_l(\mathrm{SLD}) - A_{\mathrm{FB}}^{0,\mathrm{b}} \sim 3\sigma; \quad A_{\mathrm{FB}}^{0,\mathrm{b}} = (3/4) A_e A_b$ ⟶ δA_b large, tree-level effect

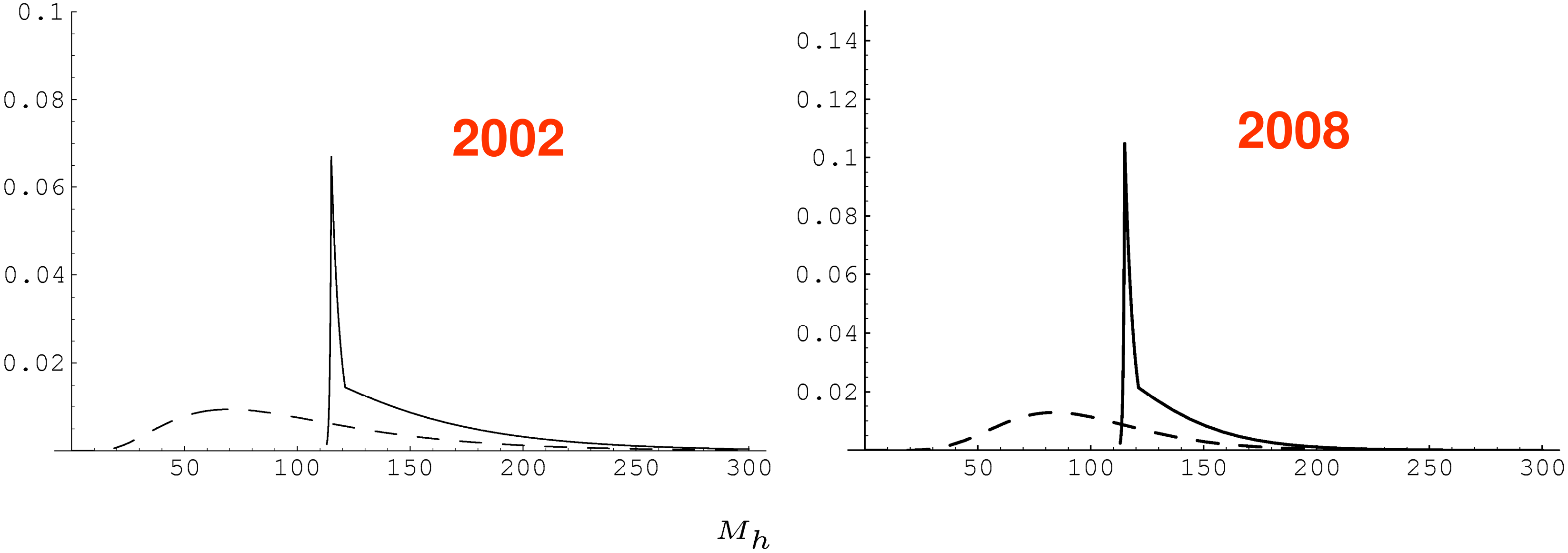
but direct A_b measure (from SLAC) is OK with SM
R_b (from LEP) is OK with SM

⟹

Need a mixing giving $\delta g_R^b \sim 30\%$:
- b-heavy vectorlike quark
  Choudhury et al. (02)
- Z-heavy Z'
  Djouadi et al. (07)

Status of the SM Higgs

$$f(M_h) \propto \frac{\mathcal{R}(M_h)\, e^{-(\chi^2/2)}}{M_h}$$



M_t=174.3±5.1 GeV,

M_W=80.449±0.034 GeV

M_t=172.6±1.4 GeV,

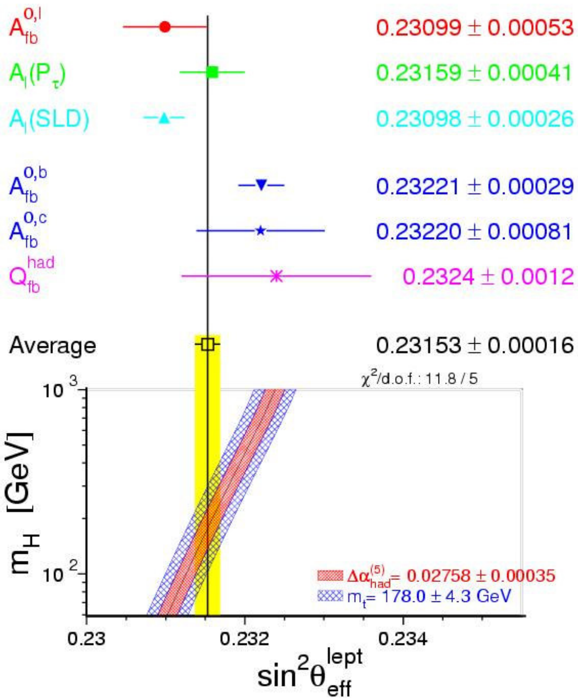
M_W=80.398±0.025 GeV

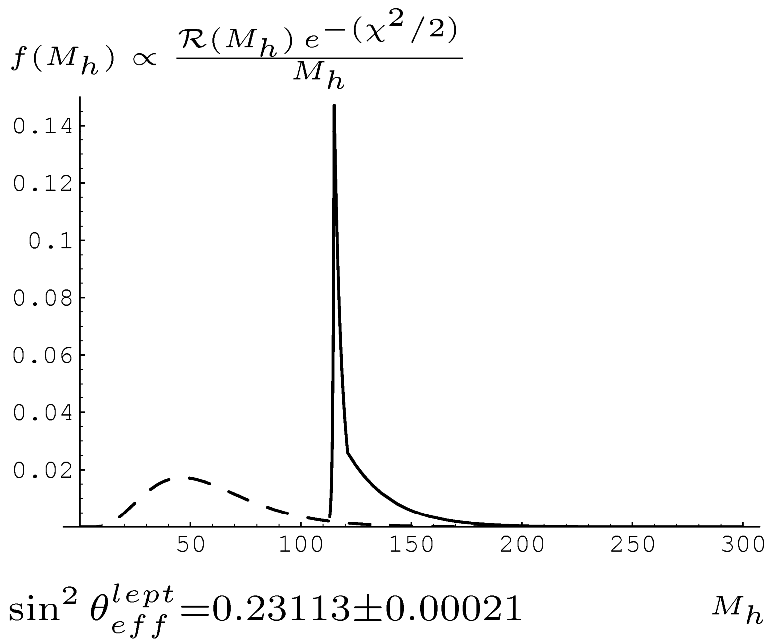
New values of $M_t,\ M_W$ have significantly reduced the tail

key ingredients: SM couplings HVV, no additional non SM $(\epsilon_1,\ T),(\epsilon_3,\ S)$

A Higgs boson ligther than 220 GeV has no problem with the EW fit.
A Higgs boson heavier than 220 GeV requires NP of non decoupling type

Indication of NP (II)?



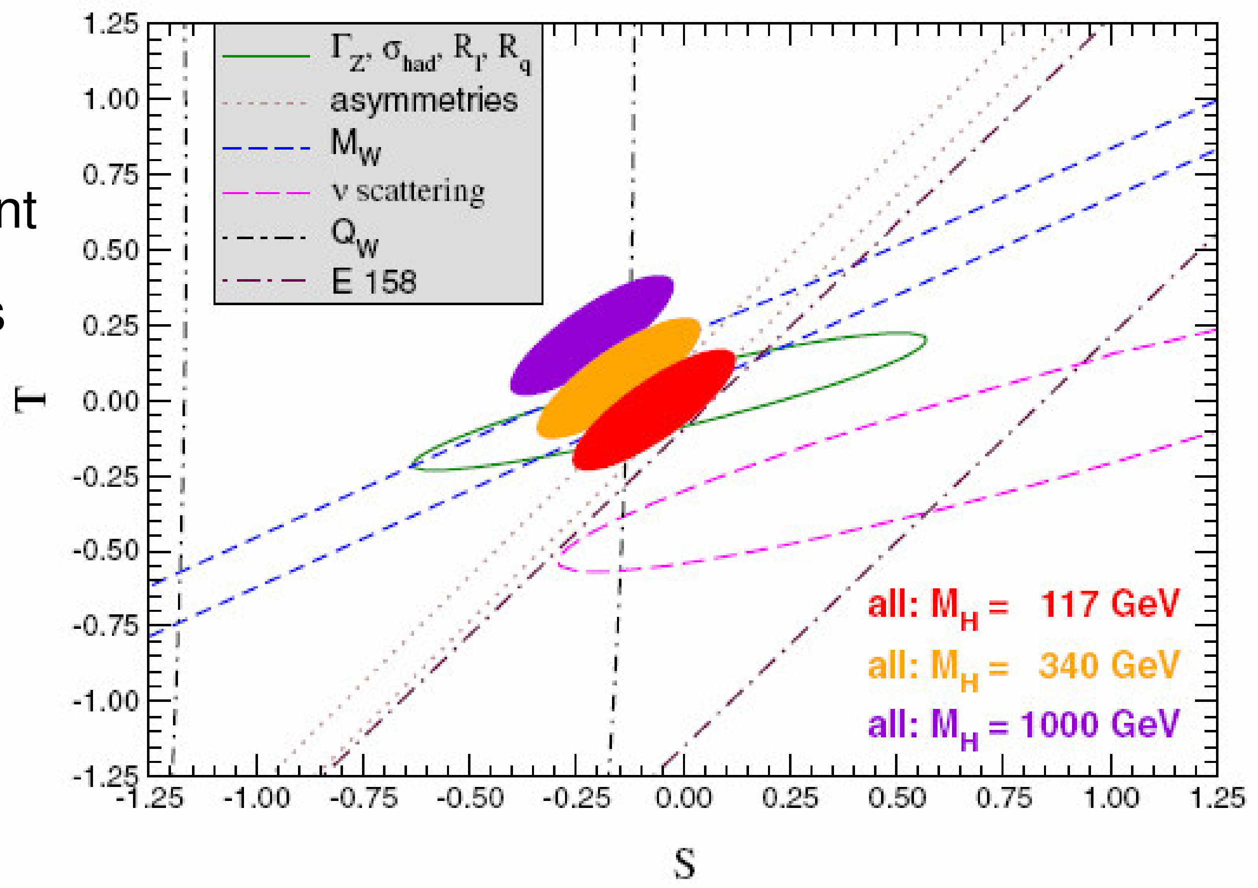


If the hadronic asymmetries are not taken into account the probability become quite small: $P(M_h > 120\,\mathrm{GeV}) \leq 3\%$.

In this scenario SM is NOT ruled out, but NP of non decoupling type would be welcome!

Beyond the SM Fit

1σ constraint on NP S, T contributions

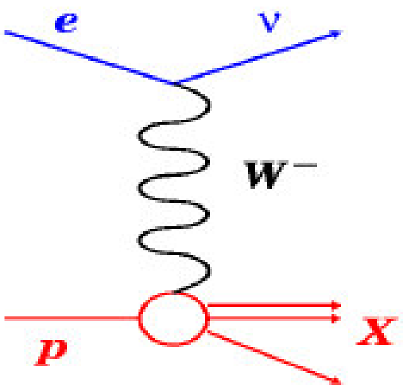


Erler, Langacker (08)

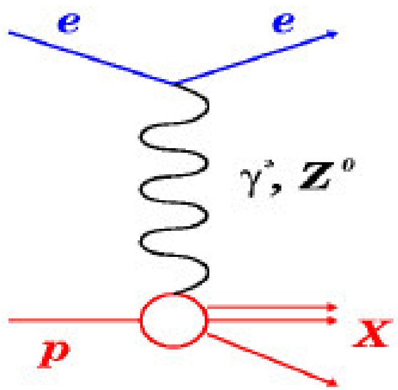
APV is very efficient in constraining S > 0

heavier Higgs: T > 0, Extra Z (tree-level), Isosplitted particles (loops)
S <0, light sleptons

Electroweak Physics @ LHeC after HERA



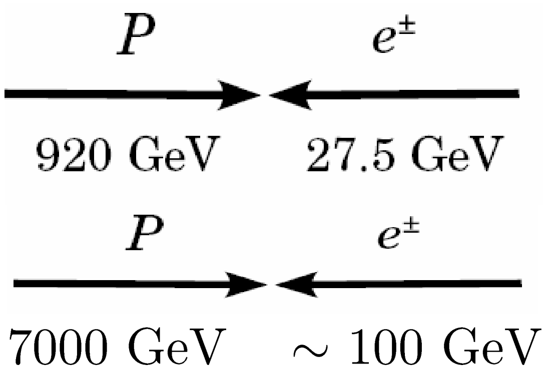
CC



NC

HERA:

LHeC:



$\sqrt{s} = 318\ \mathrm{GeV},\ Q^2_{max} \sim 10^5\,\mathrm{GeV}^2$

$\sqrt{s} \sim 1.5\ \mathrm{TeV},\ Q^2_{max} \sim 1\,\mathrm{TeV}^2$

Polarized CC cross section

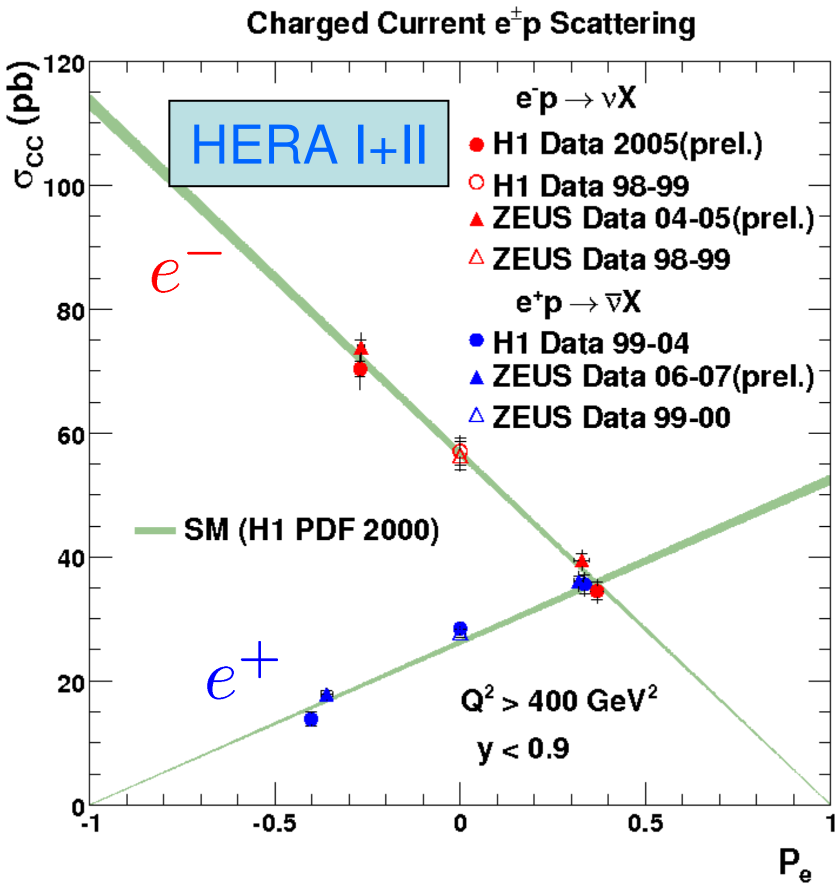
In the SM the charged current is purely LH

$$P_e = \frac{N_R - N_L}{N_R + N_L} \qquad \sigma^{\pm}_{CC}(P_e) = (1 \pm P_e)\sigma^{\pm}_{CC}(P_e = 0)$$

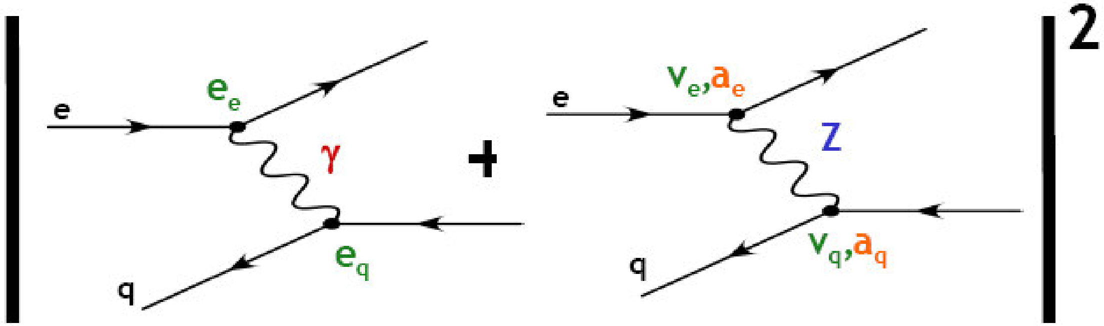
linear dependence on P_e

Limits on W_R

$$M_{W_R} > 208 \text{ @ } 95\ \%\ \text{C.L.}$$



NC cross section



$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2^{NC} \mp Y_-\, xF_3^{NC}\right]$$

$$F_2^{NC}(P_e) = F_2^{\gamma} - k_Z(v_e \pm P_e a_e)F_2^{\gamma Z} + k_Z^2(v_e^2 + a_e^2 \pm P_e(2v_e a_e))F_2^Z$$

$$xF_3^{NC}(P_e) = -k_Z(a_e \pm P_e v_e)xF_3^{\gamma Z} + k_Z^2(2v_e a_e \pm P_e(v_e^2 + a_e^2))xF_3^Z$$

$$k_Z = \frac{1}{\sin^2 2\theta_W}\frac{Q^2}{Q^2+M_Z^2},$$

$$\left(F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z\right) = \sum_q \left(e_q^2, 2e_q v_q, v_q^2 + a_q^2\right) x(q+\bar{q})$$

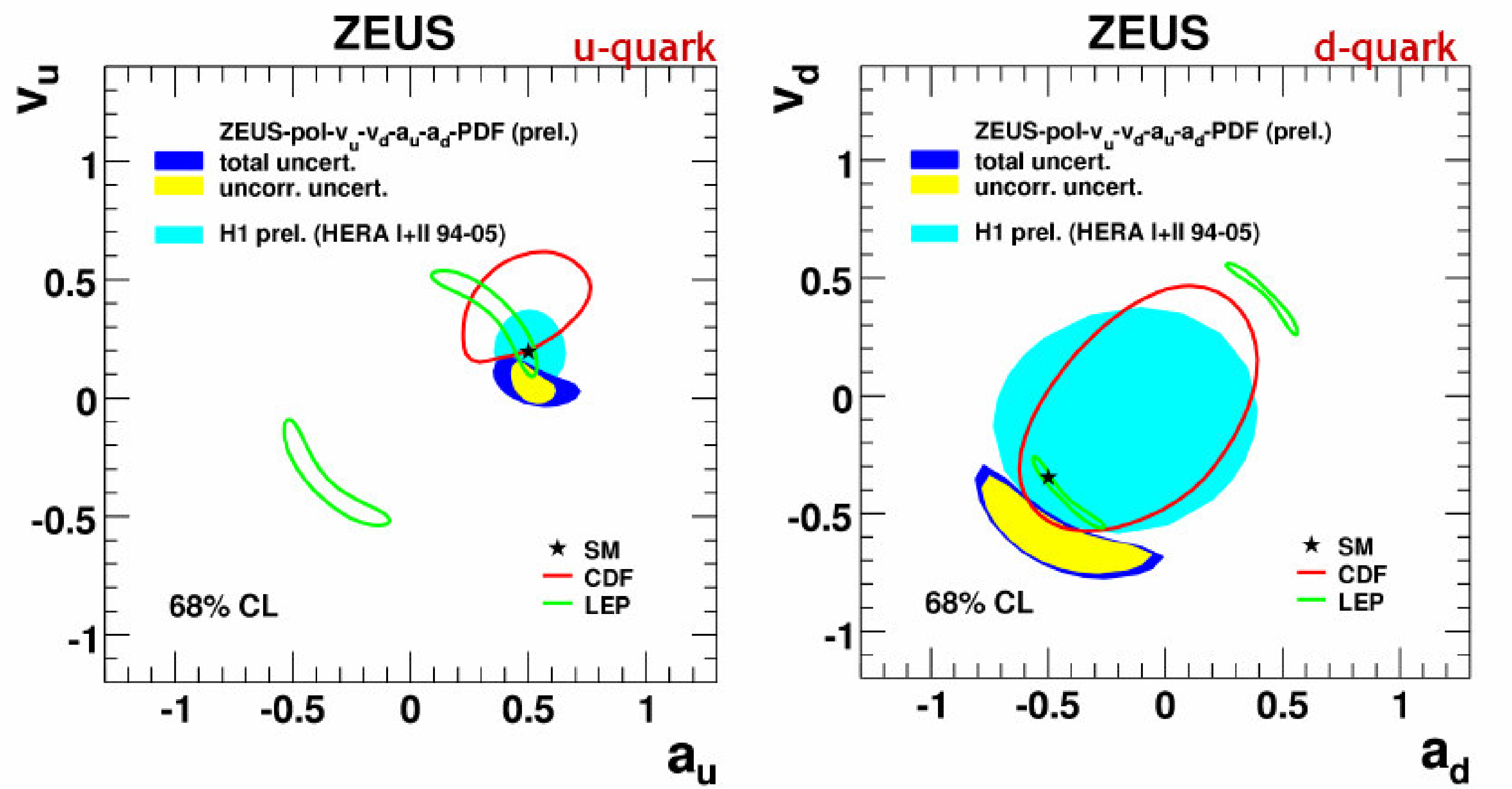
$$\left(xF_3^{\gamma Z}, xF_3^Z\right) = \sum_q \left(2e_q a_q, 2v_q a_q\right) x(q-\bar{q})$$

Parity violating effects in γZ, Z terms. Pure Z term also penalized by $v_e \simeq 0.04$

NC couplings to light quarks

unpol: $\sigma(e^+) - \sigma(e^-) \quad \rightarrow \quad a_e\, k_Z\, xF_3^{\gamma Z} \propto e_q a_q$

pol: $\sigma(P_R) - \sigma(P_L) \quad \rightarrow \quad a_e\, k_Z\, F_2^{\gamma Z} \propto e_q v_q$

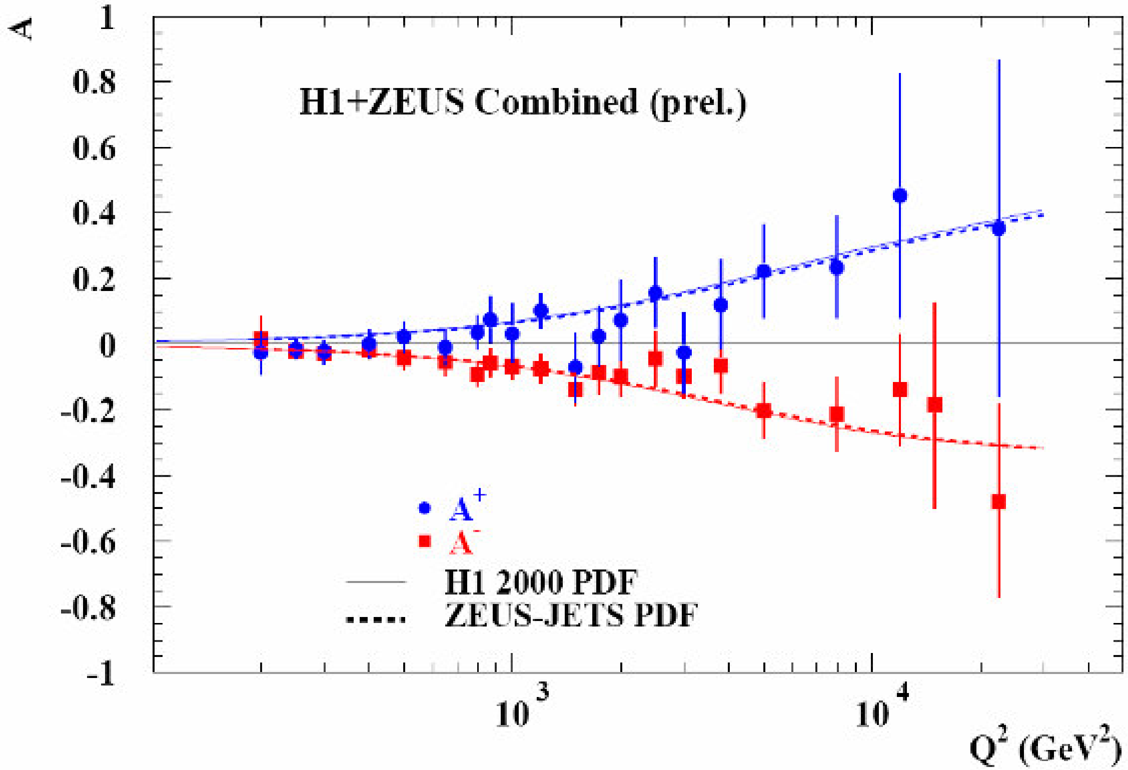


Improvements: $v_q \rightarrow$ polarization
$a_q \rightarrow$ luminosity

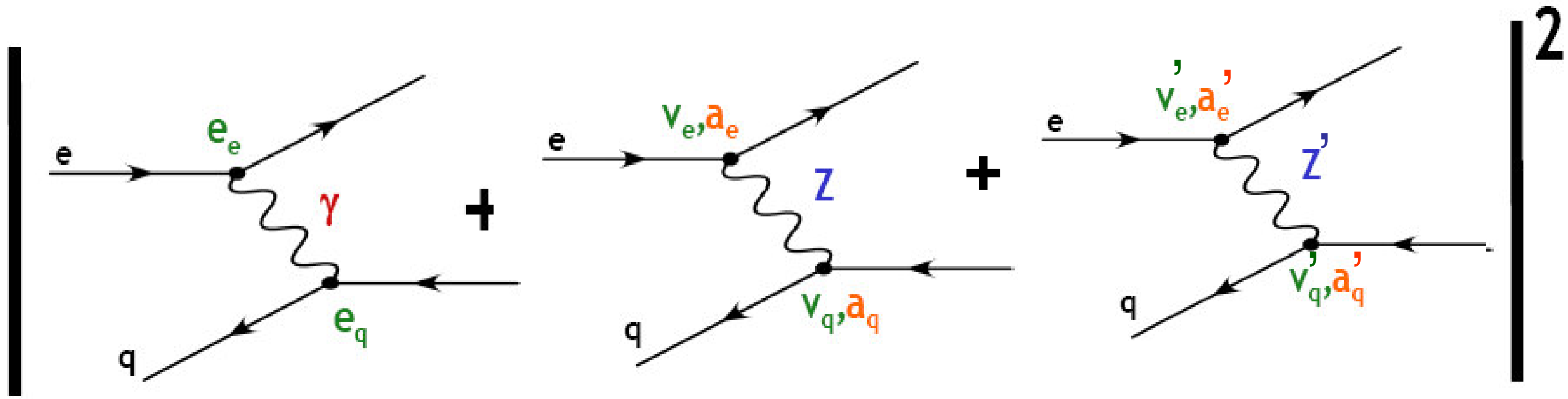
NC high Q^2 Asymmetries

$$A^{\pm} = \frac{2}{P_R - P_L}\frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)}$$
$$\simeq \mp k_Z a_e \frac{F_2^{\gamma Z}}{F_2^{\gamma}} \propto a_e v_q$$

In the SM $A^+ \simeq -A^-$



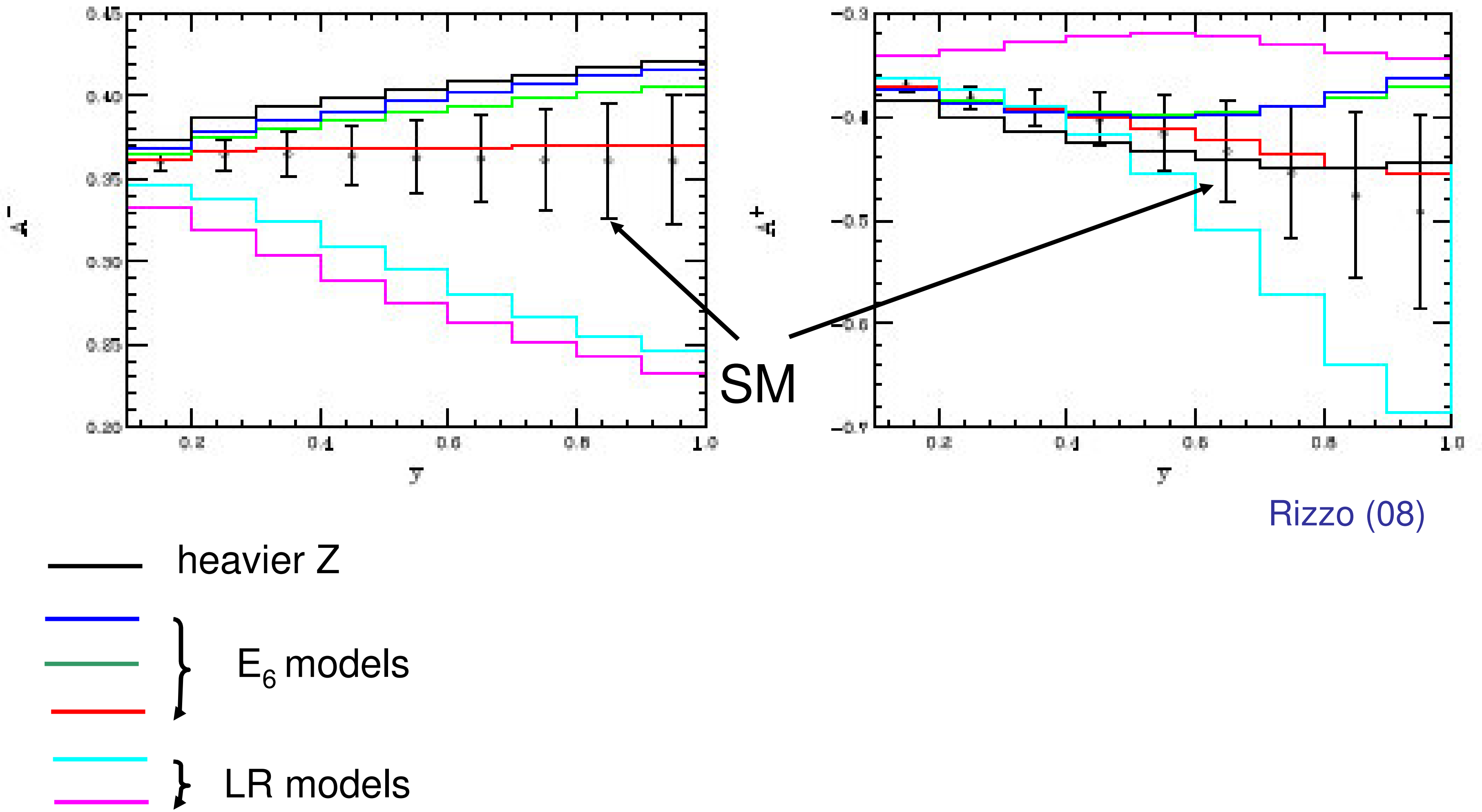
Z' physics@ LHeC

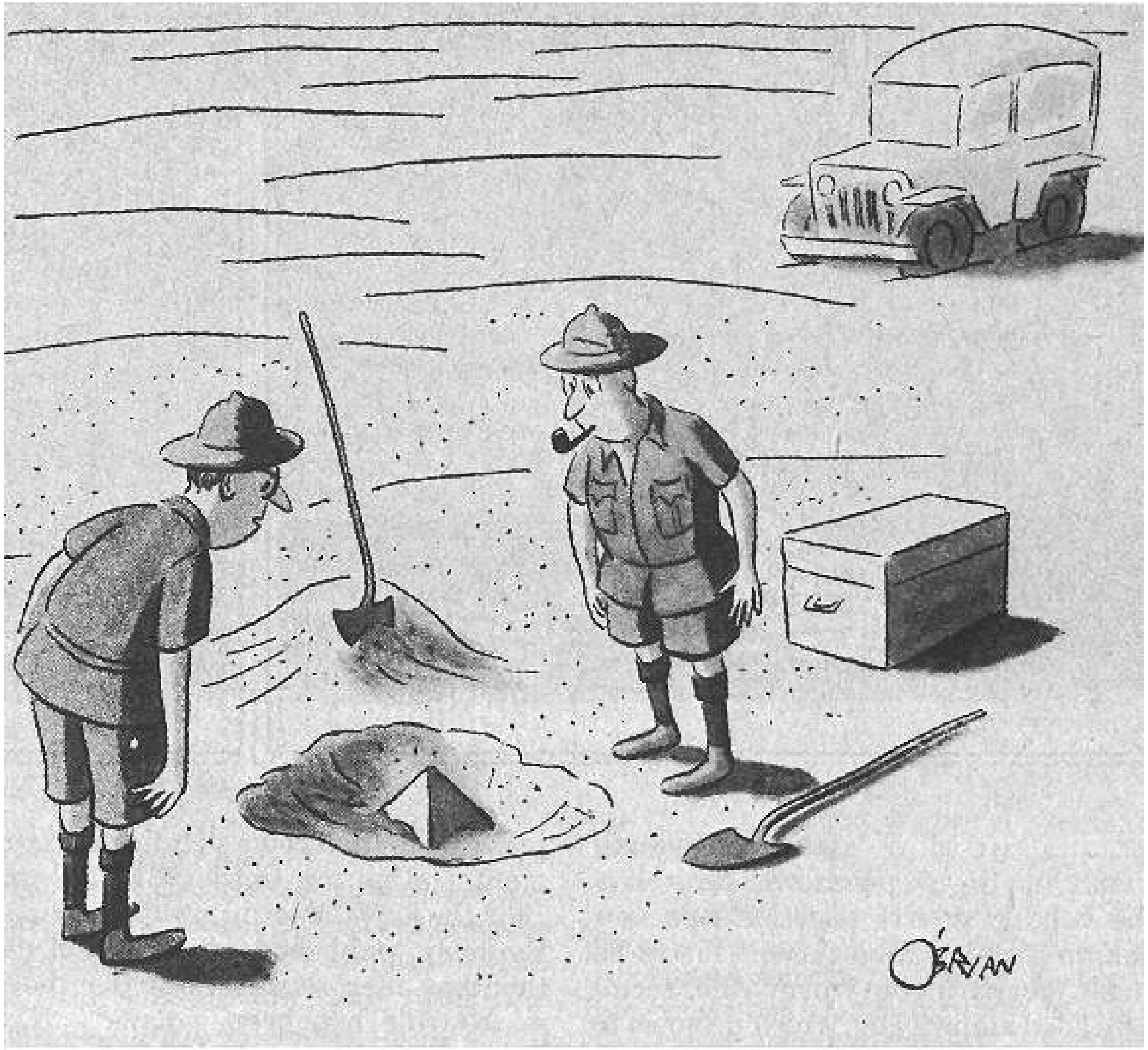


Z' effects can show up in NC asymmetries from the interference with SM contributions

$$A^{\pm} = \frac{2}{P_R - P_L} \frac{\sigma^{\pm}(P_R) - \sigma^{\pm}(P_L)}{\sigma^{\pm}(P_R) + \sigma^{\pm}(P_L)} \approx k_Z \frac{F_2^{\gamma Z}}{F_2^{\gamma}} + k_{Z'} \frac{F_2^{\gamma Z'}}{F_2^{\gamma}} \propto k_Z v_q + k_{Z'} v'_q$$

$$\sqrt{s} = 1.5\,\text{TeV},\ M_{Z'} = 1.2\,\text{TeV},\ x \geq 0.25,\ y \geq 0.1$$





"This could be the discovery of the century. Depending, of course, on how far down it goes."

THE END

Comparison of measurements of $\sin^2 \hat{\theta}_W(M_z)$

Expressing the various experimental results in terms of the same quantity requires a careful application of EW radiative corrections

APV: atomic parity violation

A_{PV}: $e^- e^-$ polarization asymmetry

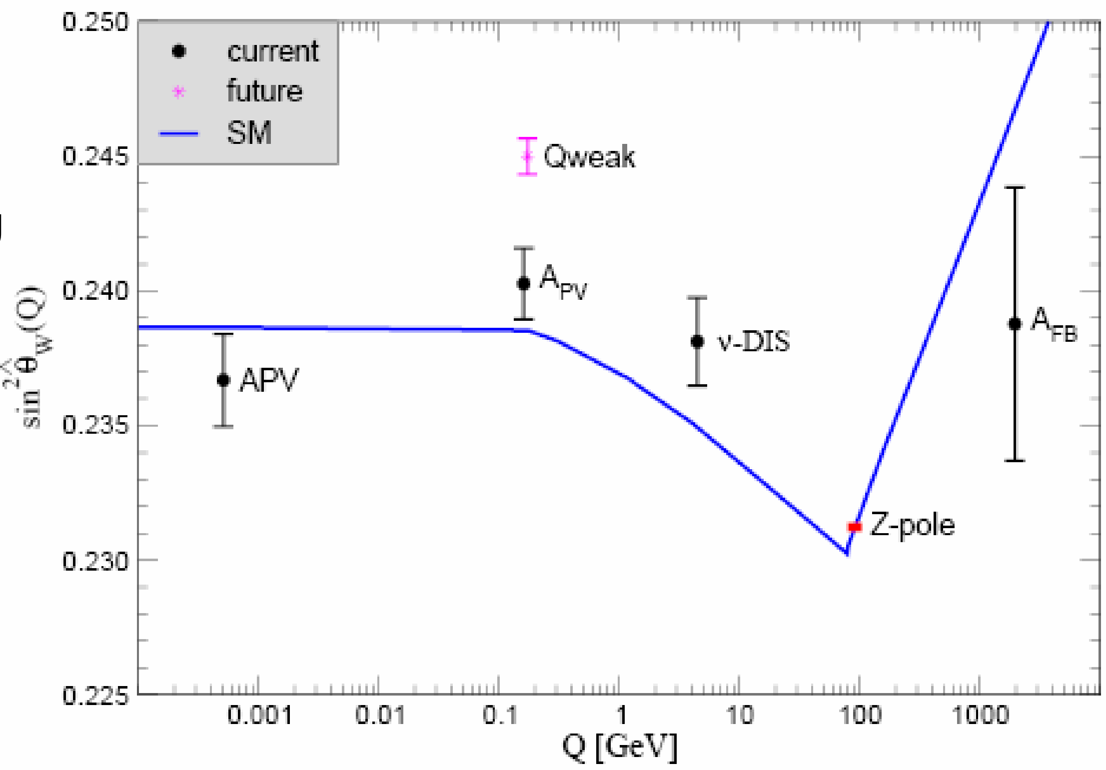
Q_{weak}: e^--hadron polarized scattering

ν-DIS: NuTeV

A_{FB}: charge asymmetry at Tevatron

NuTeV is $\sim 2\sigma$ away.

Difference in $s, \bar{s}$ momentum distribution is taken into account, but there probably also other effects



Erler, Langacker (08)