Electroweak Measurements

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- **Experimental framework (LEP,Tevatron,HERA)**
- **Precision tests**
- **Confrontation with lower energy data**
- **Weak boson production and properties**
- **Electroweak measurements in DIS at HERA**
- **Future**
- **Conclusions**

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Max Klein, Martin Grunewald, Pippa Wells, Dmitri Denisov, Jan Timmermans, Bolek Pietrzyk, Emmanuelle Perez, Matthew Wing, Richard Hawkings, David Waters, Chris Hays

Colliders at Fermi Scale

LEP

e　　　　$\bar{p}$

e　　　　p

TEVATRON

HERA

-> e+e- collider(2000)
E_{cm}=90-209 GeV
Lumi=900 pb-1/exp.(phys)
ALEPH,DELPHI
L3,OPAL

SLC: polarized e^+e^-
at Z peak

-> $e^{\pm}p$ collider
E_{cm}=320 GeV
H1, ZEUS
HERA I 120 pb-1/expt(phys.)
HERA II 2007 ->700 pb-1(delivered,$e^{\pm}$,$\pm P_e$)

-> $p\bar{p}$ collider: CDF, D0

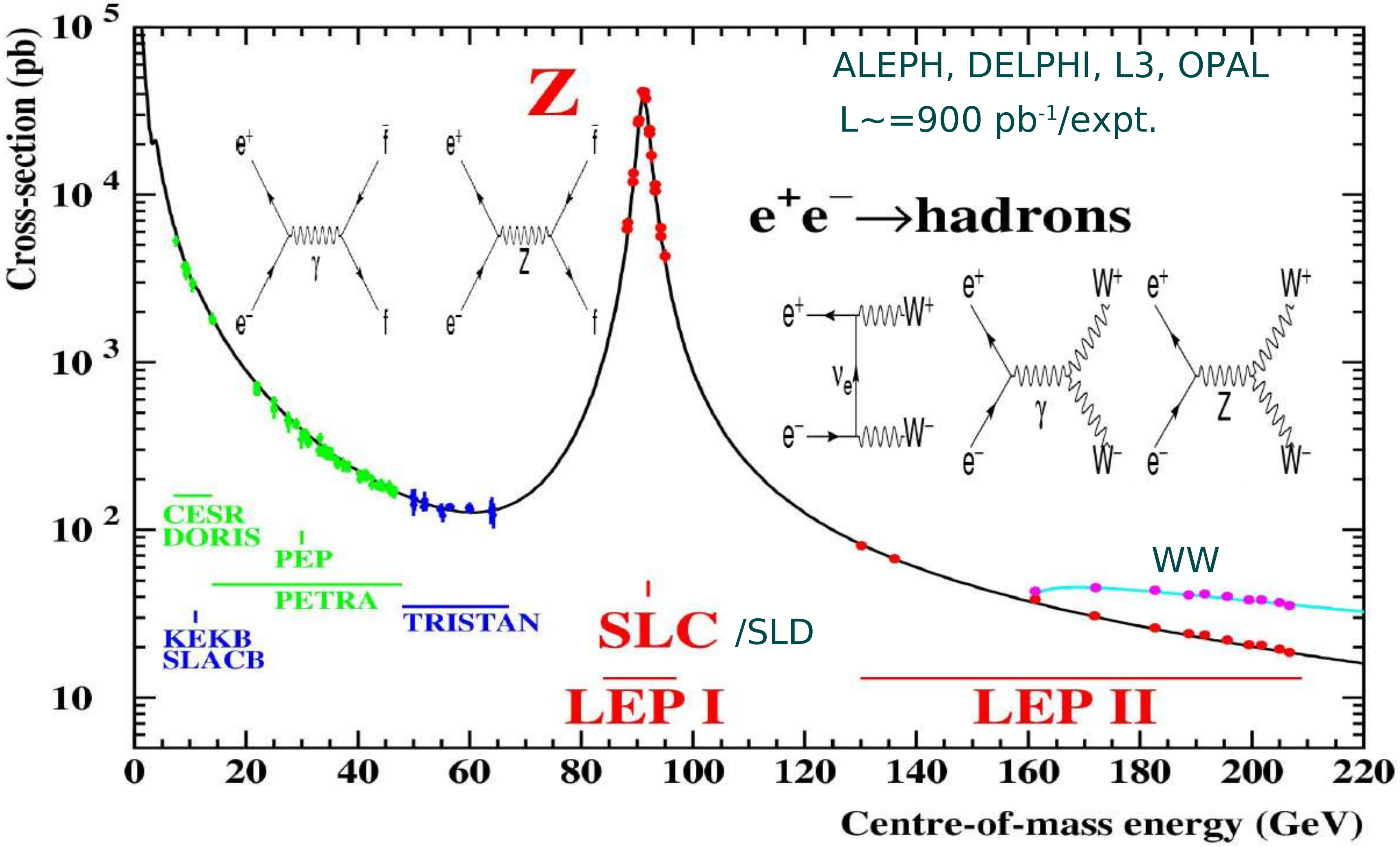
Run I E_{cm}=1.8 TeV
130 pb^{-1}/exp.(phys.)

Run II E_{cm}=1.96 TeV
1fb^{-1} delivered
2009 -> 4-8 fb^{-1}

Many other interesting results from lower energy facilities

LEP/SLC

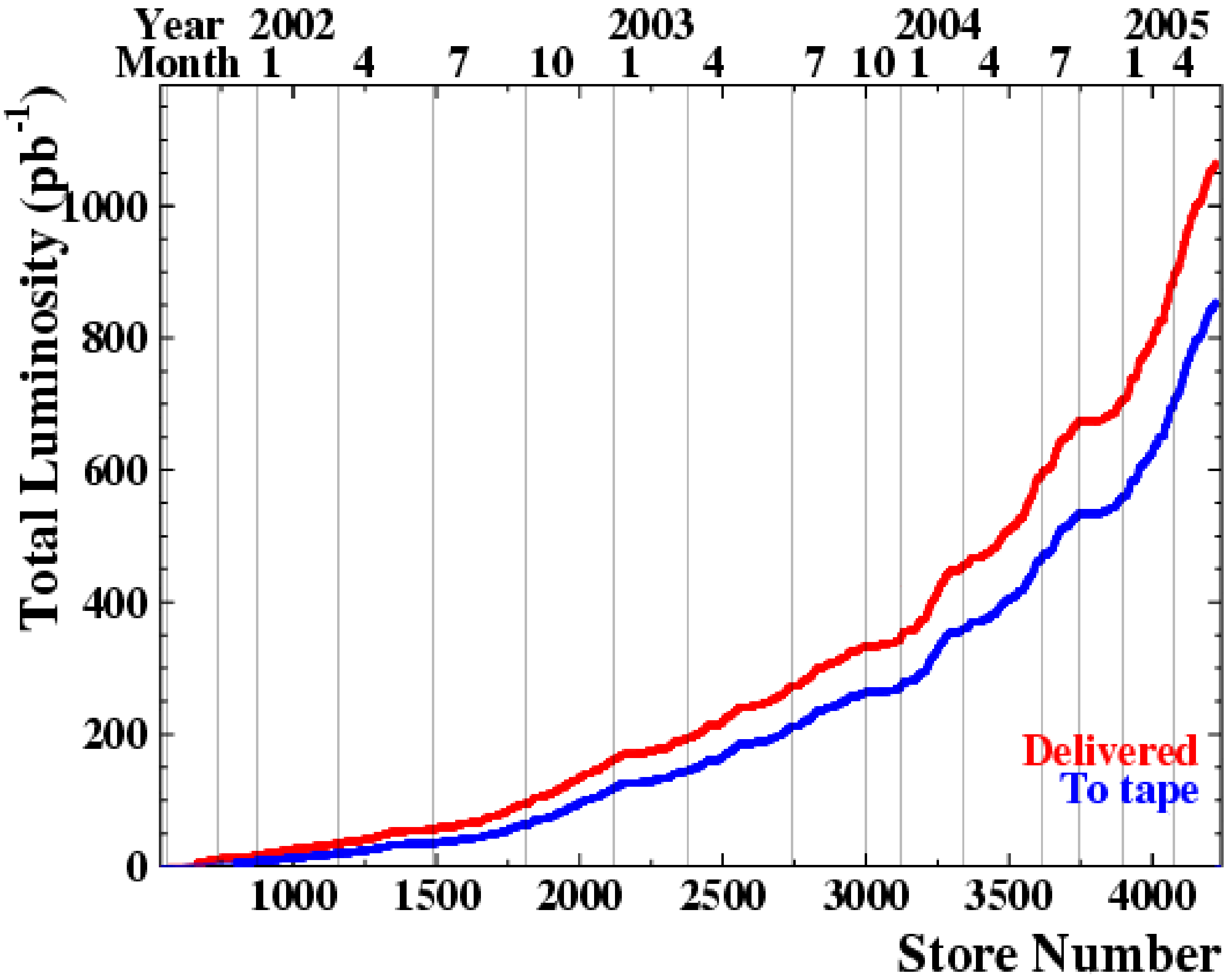
The masters of the EW sector: Z pole, W-pairs, final refined analysis still improve



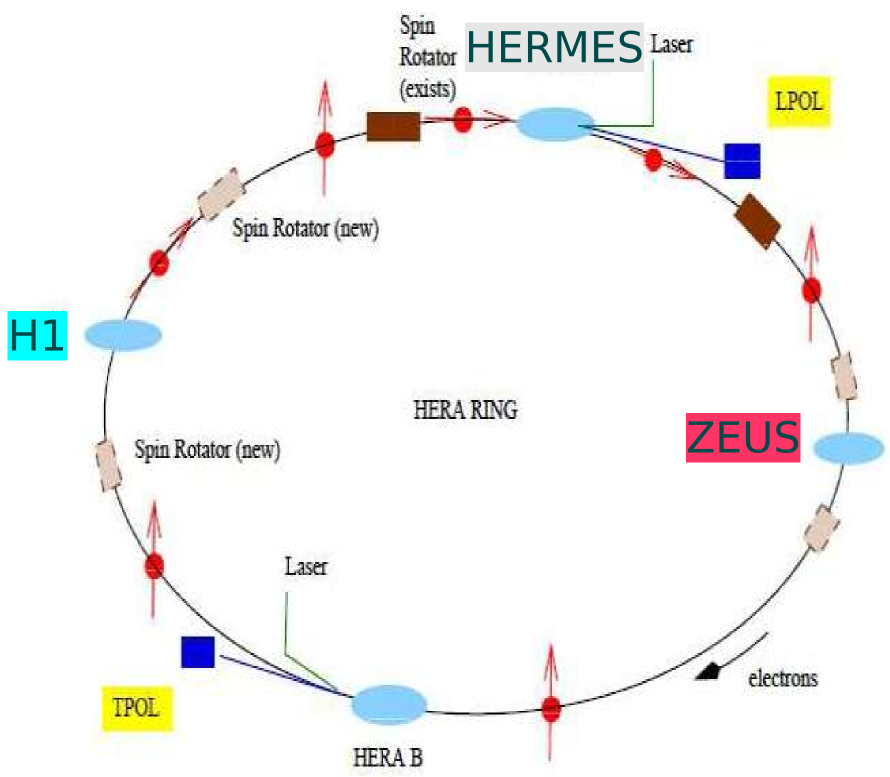
Tevatron

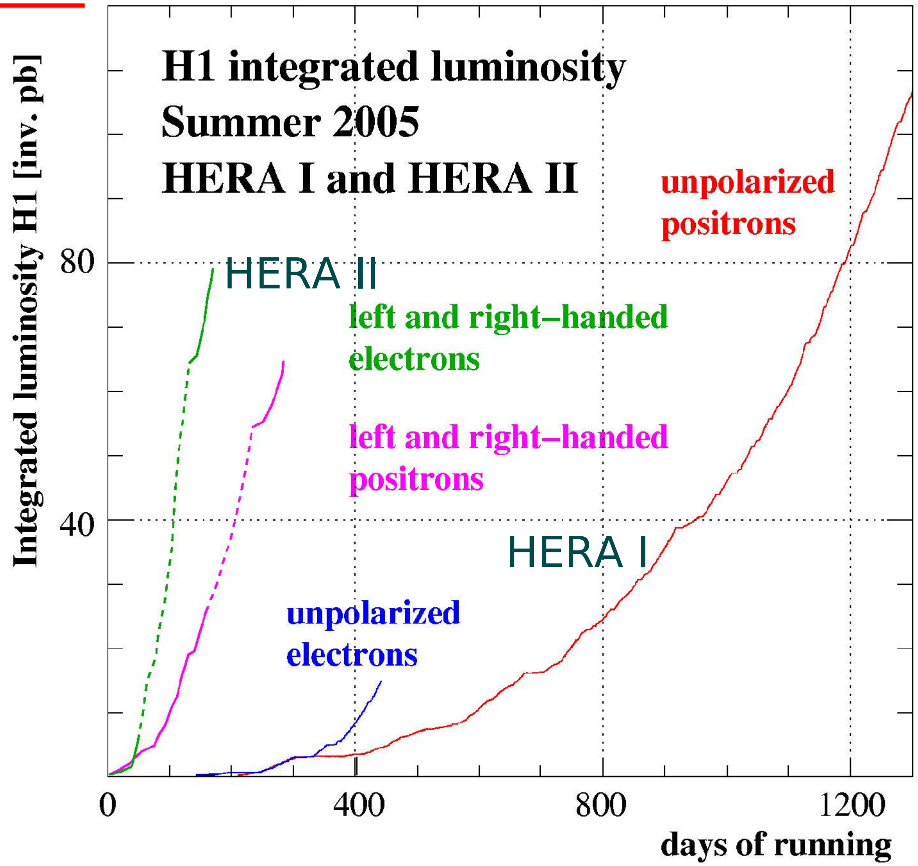
L(deliv 06/2005) ~= 1 fb^{-1}

L(2009) = 4-8 fb-1



HERA





Unique e(27 GeV) p(920 GeV) collider, E_{cm}=320 GeV

2 collider experiments **H1 and ZEUS**, HERMES(fixed target)

HERA I (1994-2000): for physics ~120 pb^{-1} /experiment

HERA II (since 2003): polarized e-beam in collision

L(HERA II): $e^{\pm}p$ (phys.): 100 pb^{-1}

$e^{\pm}$ polarization: 25-40%

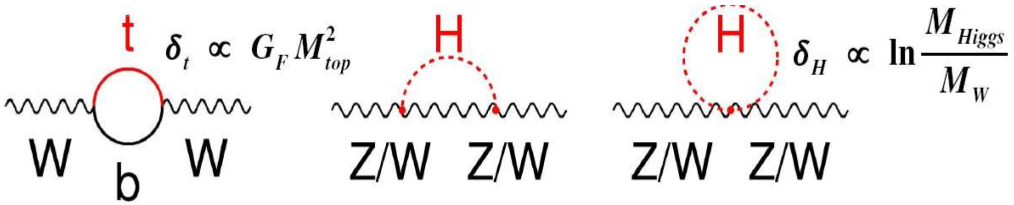
2007: 700 pb^{-1} delivered

Status of the SM

http://lepewwg.web.cern.ch/LEPEWWG/

last update June 2005

- Consistency check of the SM based on high precision measurements
- More than 1000 data points combined in 17 observables calculated in the SM from:
  - α_{em} (precision $3 \cdot 10^{-9}$) the critical part $\Delta\alpha_{had}$ (from e+e-->hadrons)
  - G_F (precision 9.10^{-6}) (->MW)
  - M_Z (precision 2.10^{-5}) from lineshape (LEP-1)
  - $\alpha_s(M_Z)$ (precision 2.10^{-2}) hadronic observables
  - M_{top} and M_{Higgs}



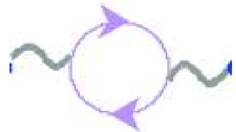
- Zfitter 6.42, precision at 2 loop (M_W , $\sin^2\theta_W$) 3-loop for ρ

D.Bardin et al., Comput.Phys.Commun.133(229)2001

Improved precision in final results from LEP collaborations

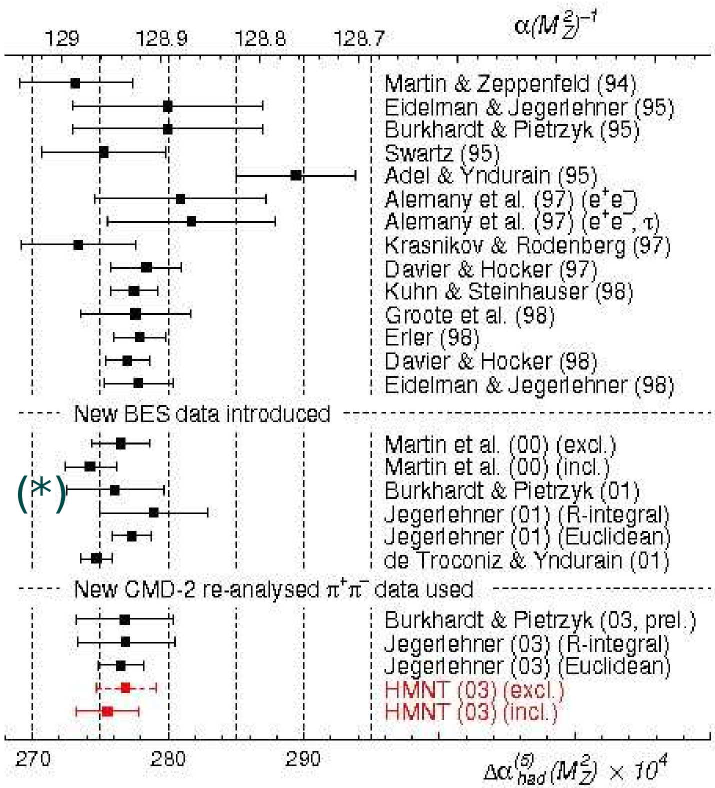
New input from low Q2 experiments very valuable

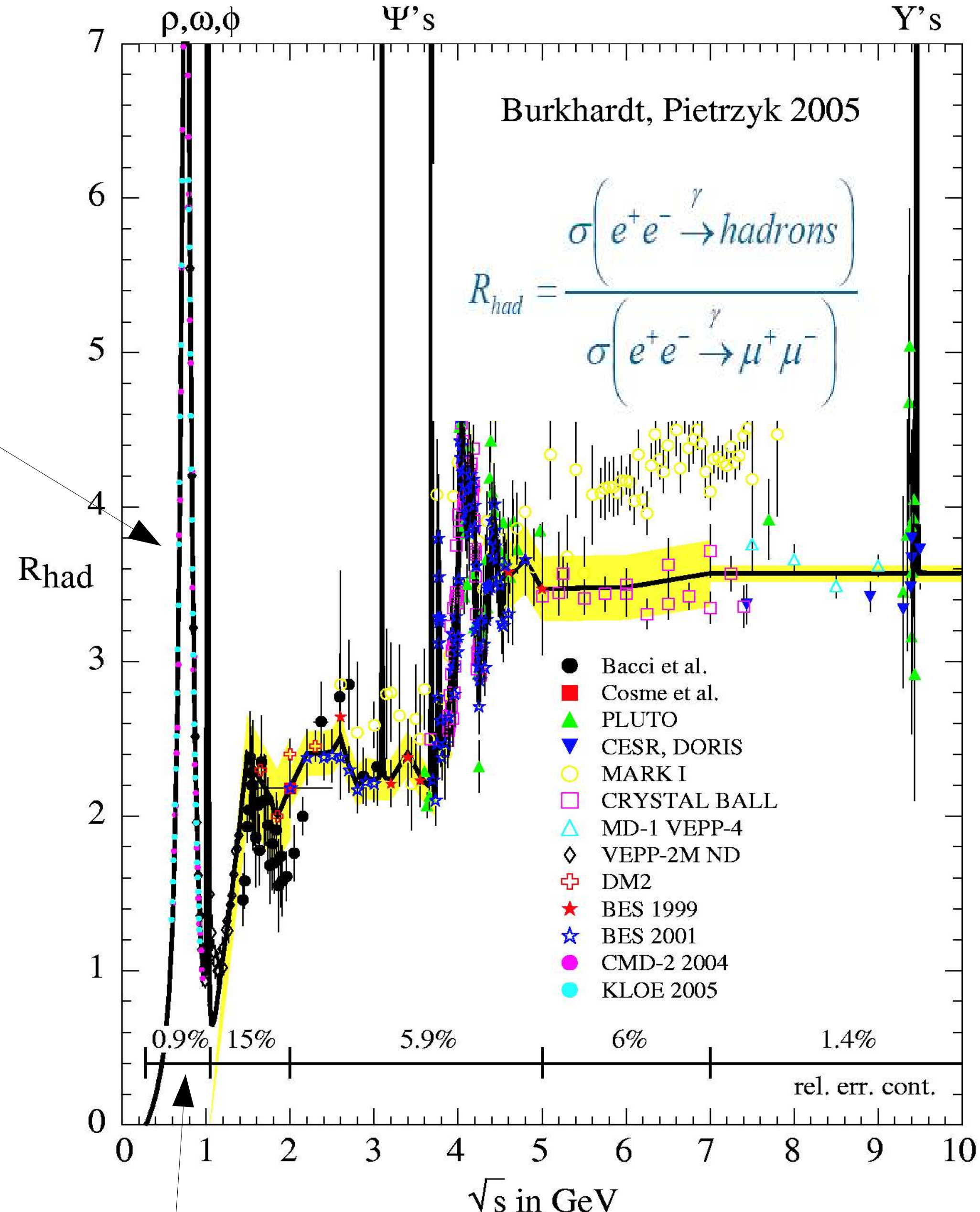
$\Delta\alpha^5_{had}$



$$\Delta\alpha^{(5)}_{had}\left(q^2\right) = -\frac{\alpha q^2}{3\pi}\mathrm{Re}\int_{4m_\pi^2}^{\infty} ds\, \frac{R_{had}(s)}{s\left(s-q^2-i\varepsilon\right)}$$

New data from KLOE/CMD-2 (ρ)





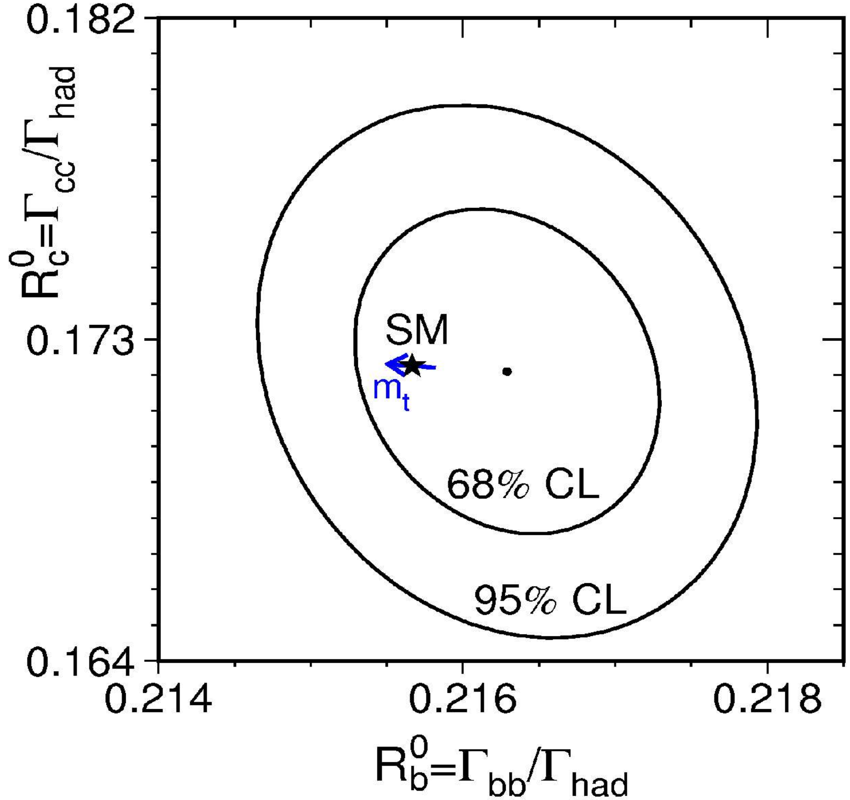
(*) **old value 0.02761 ± 0.00036**

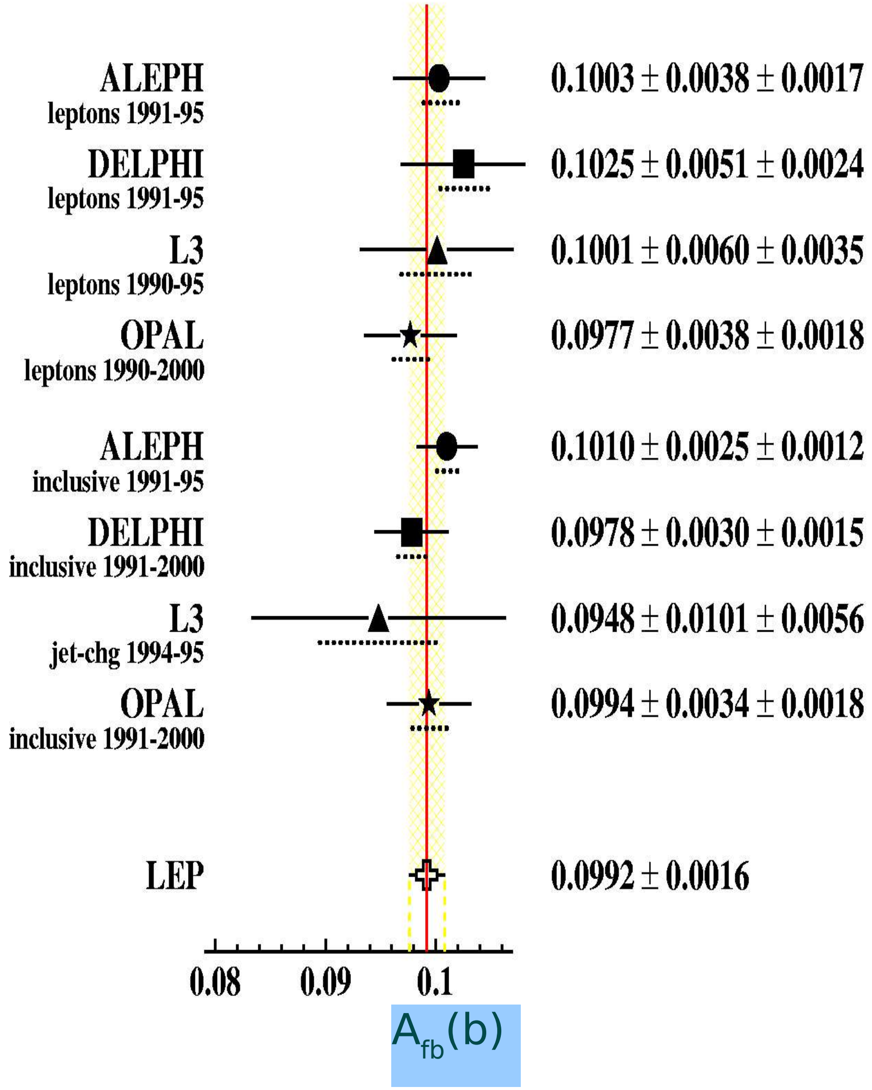
error 0.9%(was 2.3%)

New value of $\Delta\alpha^5_{had}$: 0.02758±0.00035
used in the EW fit (small change)

Heavy Flavours: Final Results

- $R_b=\Gamma_b/\Gamma_{had}$ $R_c=\Gamma_c/\Gamma_{had}$
- $A_{fb}(b)=¾A_eA_b$ $A_{fb}(c)=¾A_eA_c$
- A_b A_c
- χ^2/Ndof = 53/(105-14)



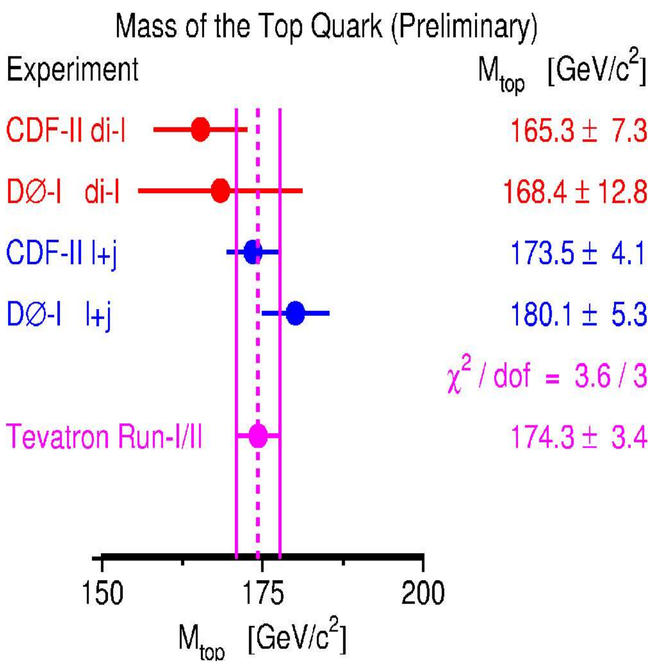


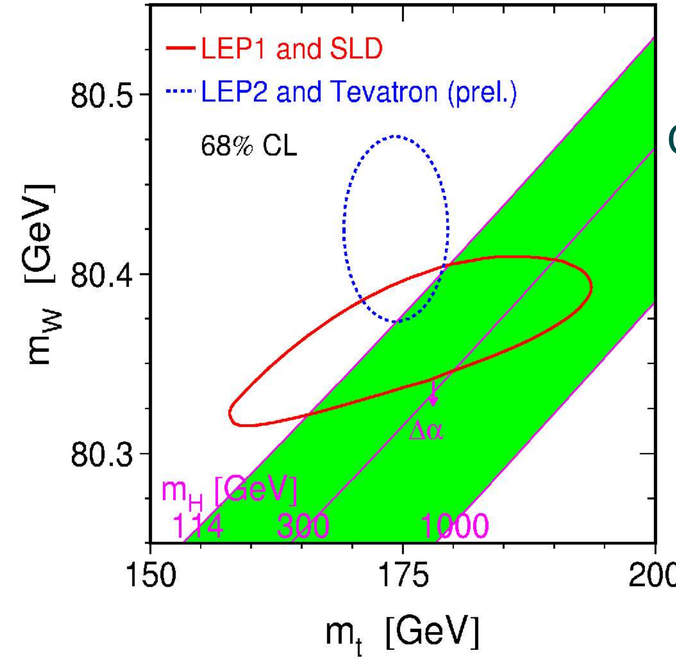
Central values very consistent
Asym. are statistics dominated

New top mass measurement

M_{top} (GeV):
old (2004): 178.0 ± 4.2
new(2005): 174.3 ± 3.4

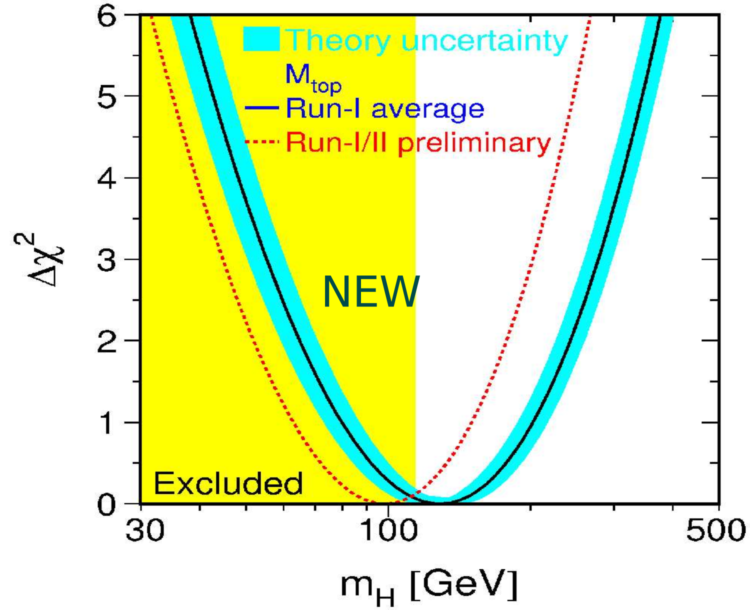
(D0 run II in progress)





G_F

M_{top} error crucial for indirect M_{higgs} determination



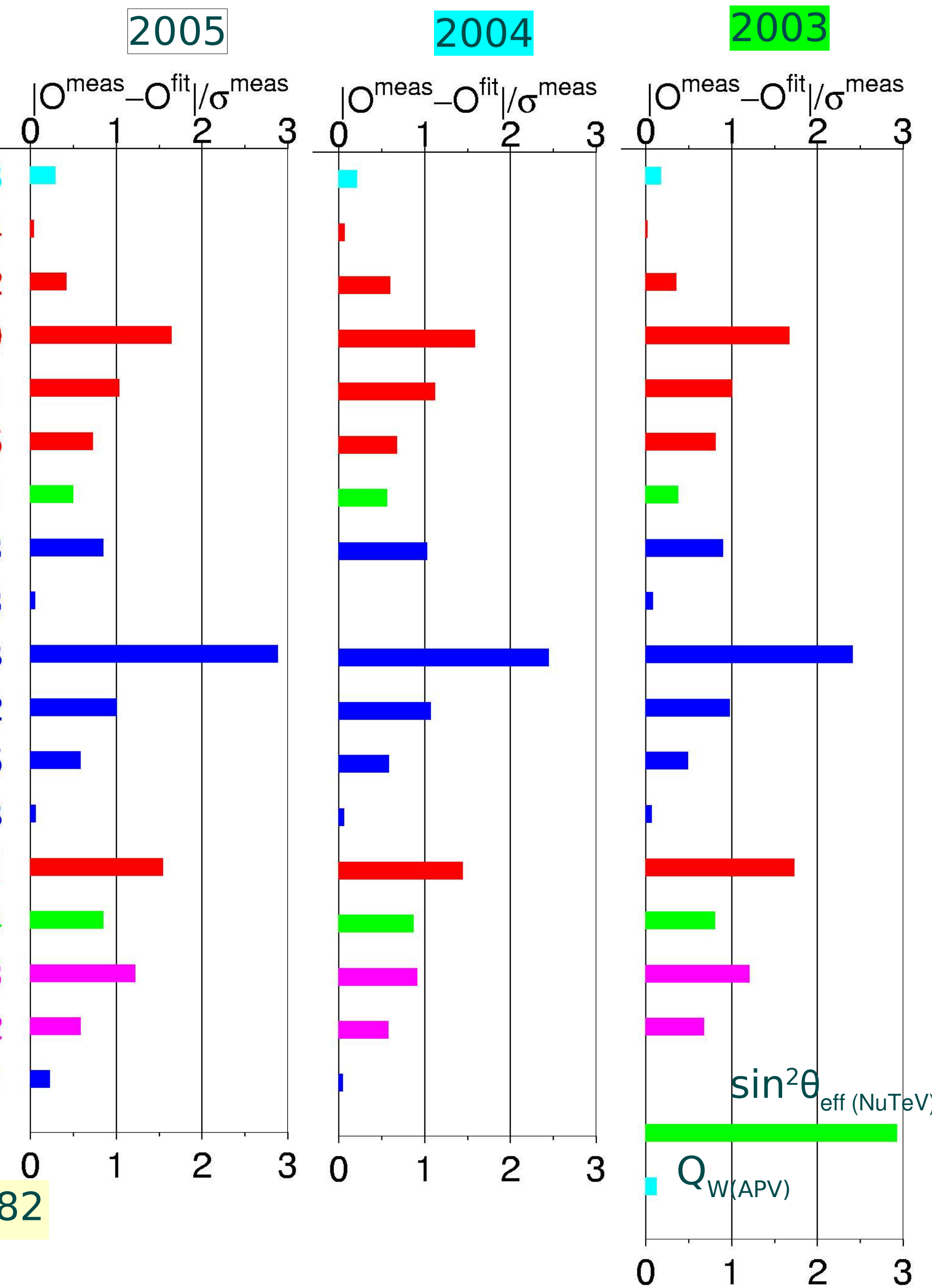
$M_{Higgs}=98^{+52}_{-26}$ GeV

M_{higgs} <208 GeV @95% C.L.

The EW fit: picture confirmed

Preliminary

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4962
σ_{had}^0 [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.741
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21573
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016 *	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(SLD)$	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.383
Γ_W [GeV]	2.133 ± 0.069	2.092
m_t [GeV]	174.3 ± 3.4	175.1



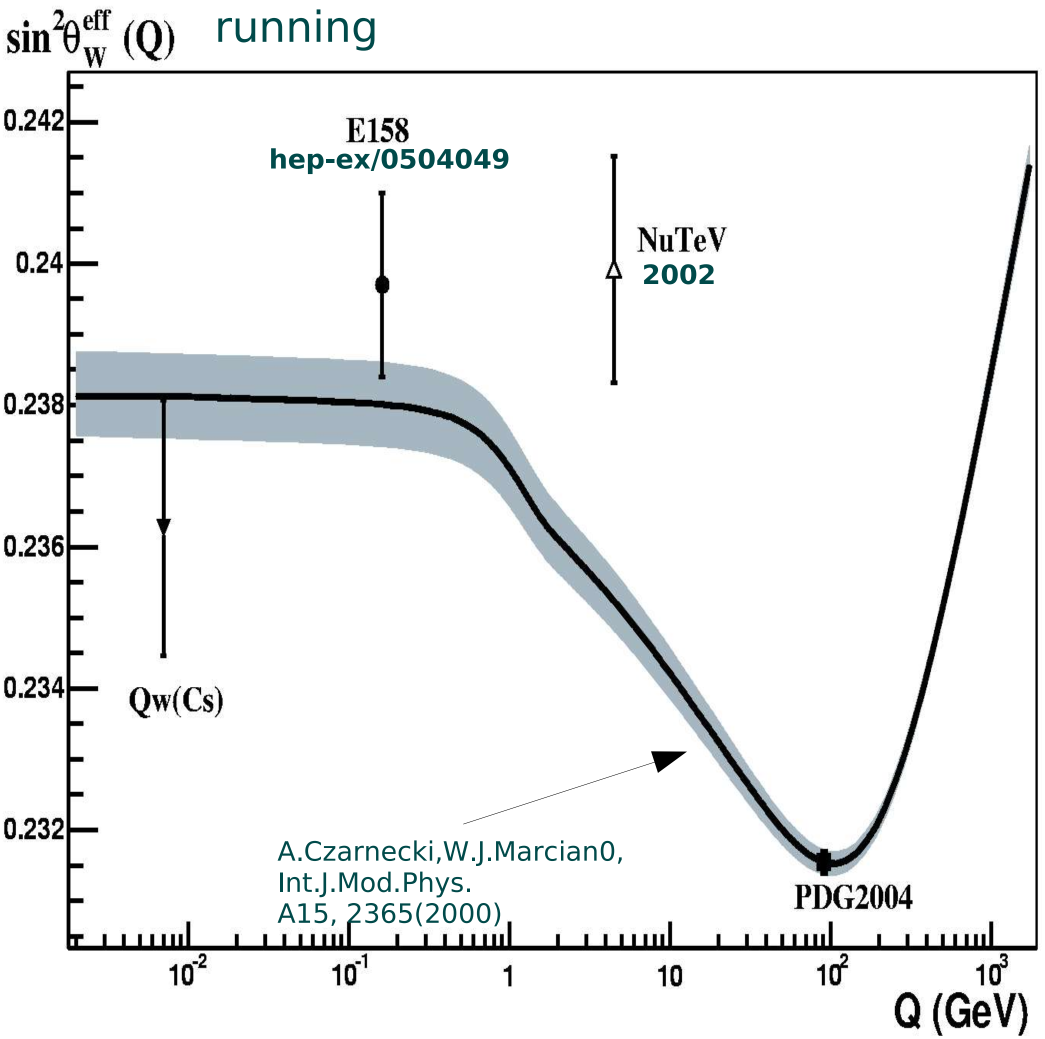
$\alpha_s(M_Z) = 0.1188 \pm 0.0027$

(PDG 2004: 0.1187 ± 0.0020)

N_ν 2.9840 ± 0.0082

Confrontation with low Q2

- APV Cs 0.4% (Q^2=0 GeV^2)
    - Q_W=-72.60±0.48 (PDG2004)
    - Q_W^{SM}=-72.94±0.04
    - $Q_w^{Z,N} \simeq Z(1-4\sin^2\theta_w)-N$
- E158 (Q^2=0.036 GeV^2)
    - polarized e- e- scattering
    - measure A_{LR} deduce $\sin\theta^{eff}$
    - $\sin^2\theta_w^{eff}$(Q=0.6)=0.2397±0.0013
- NuTeV (Q^2=~25GeV^2):CC/NC in ν–N
    - $\sin^2\theta_w$ 3.0σ from the SM
- a_μ: BNL($\mu^\pm$) @ 2.7σ

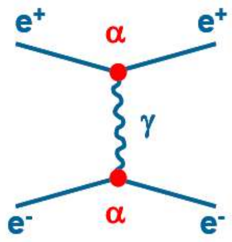


(a_μ - 11659000)exp x 10^{-10} = 208 ± (5 stat. ⊕ 4 syst.)

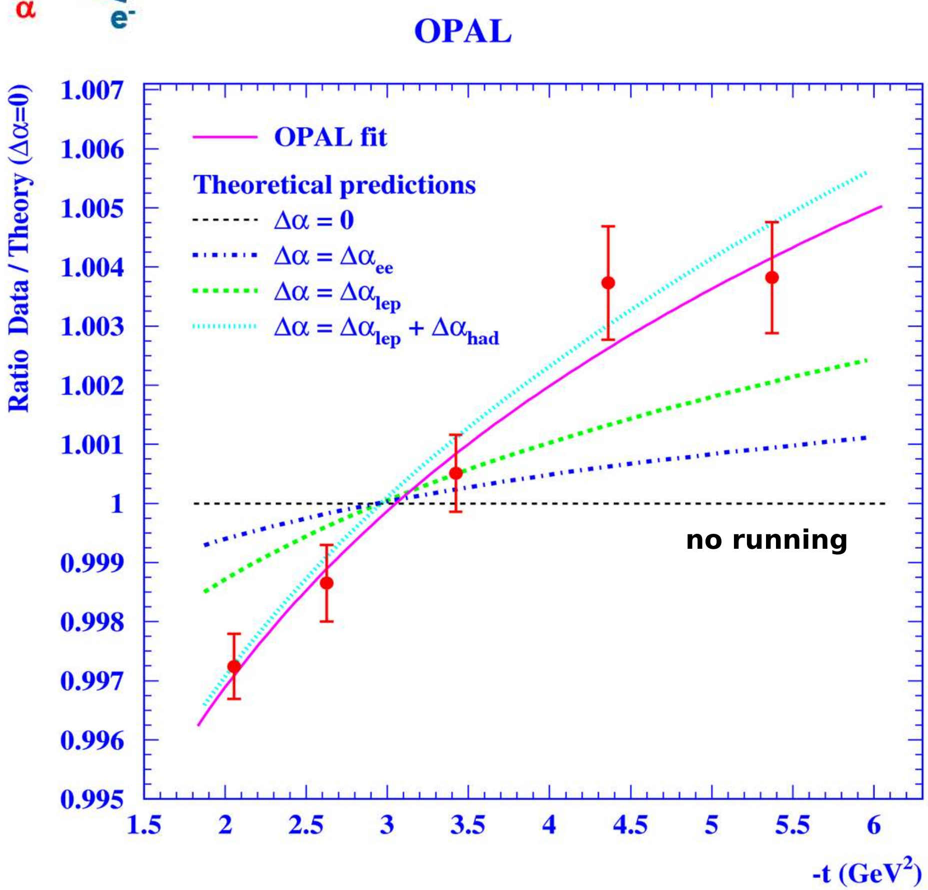
(a_μ - 11659000)th x 10^{-10} = 183 ± 7 [e+e-] DEHZ04

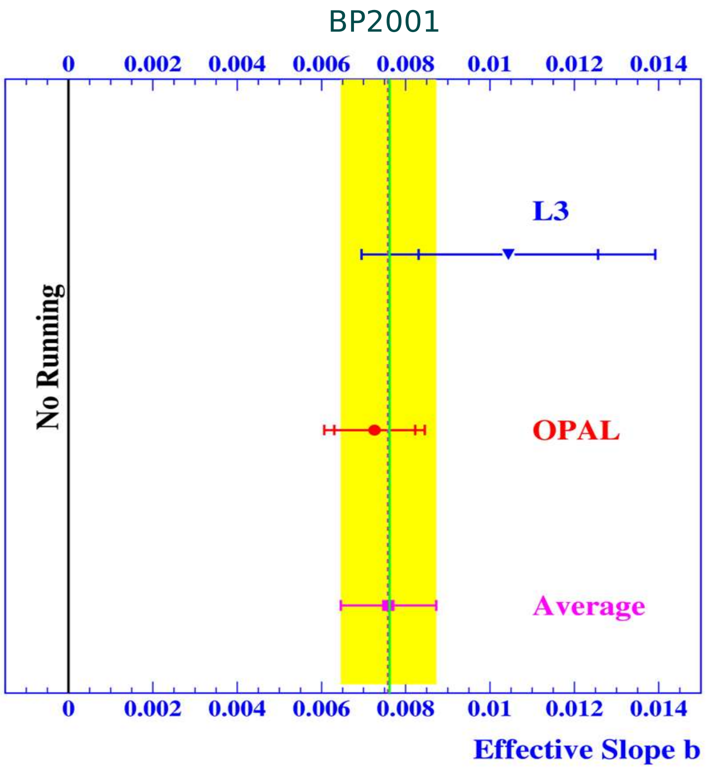
Running of α^{em} at low energy

OPAL, CERN-PH-EP-2005-014



Measure the dependence σ(t) using the luminometers
(only scaling, not the absolute value)





$$\Delta\alpha(t_2) - \Delta\alpha(t_1) \simeq \frac{b}{2} \ln\left(\frac{t_2}{t_1}\right)$$

$$\Delta\alpha(-6.07\,\mathrm{GeV}^2) - \Delta\alpha(-1.81\,\mathrm{GeV}^2) = (440 \pm 58 \pm 43 \pm 30) \times 10^{-5}$$

$$\Delta\alpha_{\mathrm{had}}(-6.07\,\mathrm{GeV}^2) - \Delta\alpha_{\mathrm{had}}(-1.81\,\mathrm{GeV}^2) = (237 \pm 58 \pm 43 \pm 30) \times 10^{-5}$$

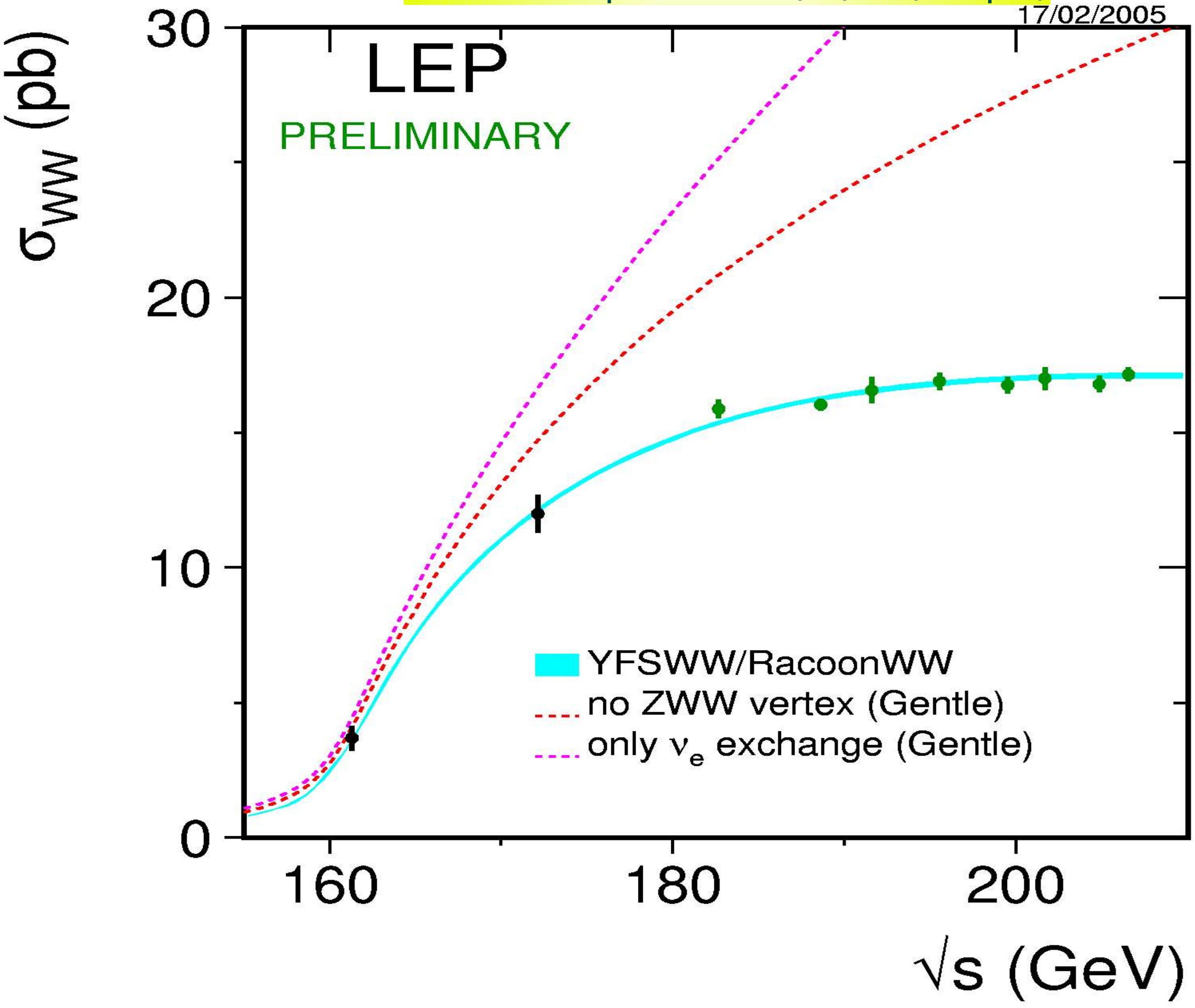
(stat/exp/model)

Direct evidence for α running (>5 σ) ; hadronic contribution to running (3σ)

W pair production: the LEP harvest

Gauge structure of the SM

A rich sample of W's($O(10^4)$/expt.)

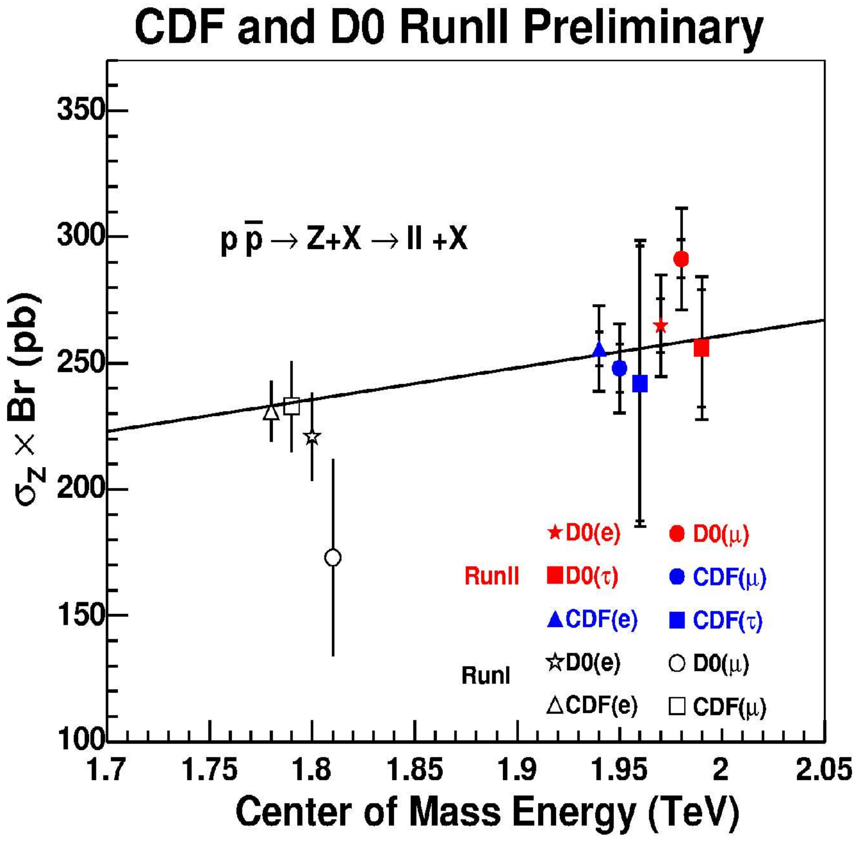


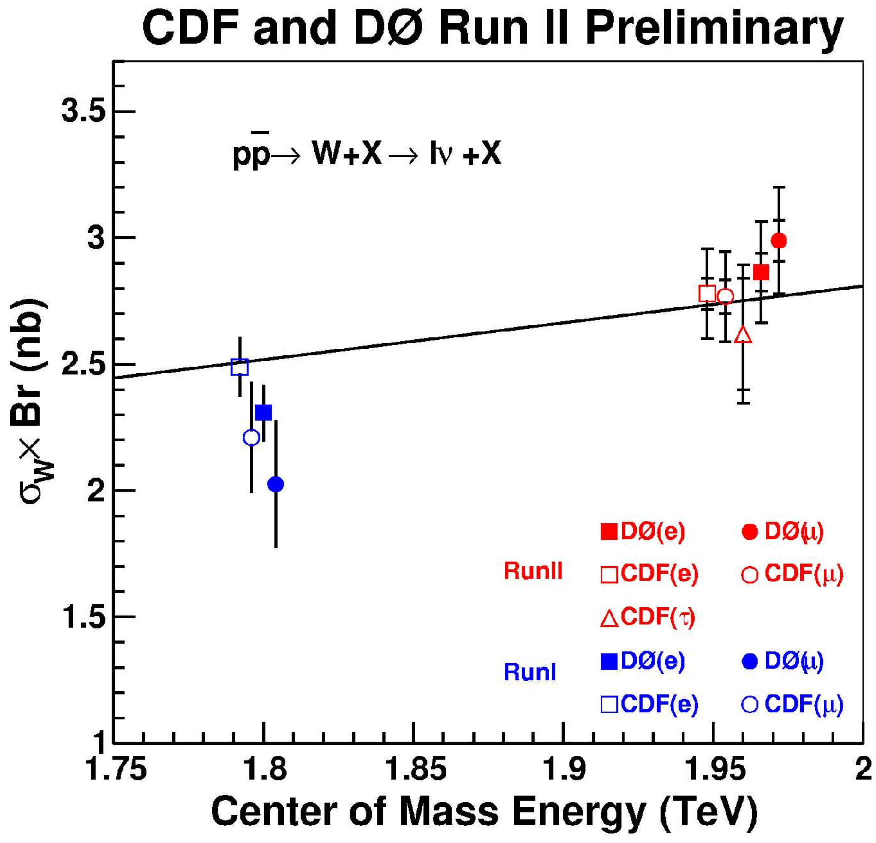
W/Z boson production at Tevatron

Leptonic decay modes of W and Z (e,μ,τ)

4,000-14,000 Z's

40,000-120,000 W



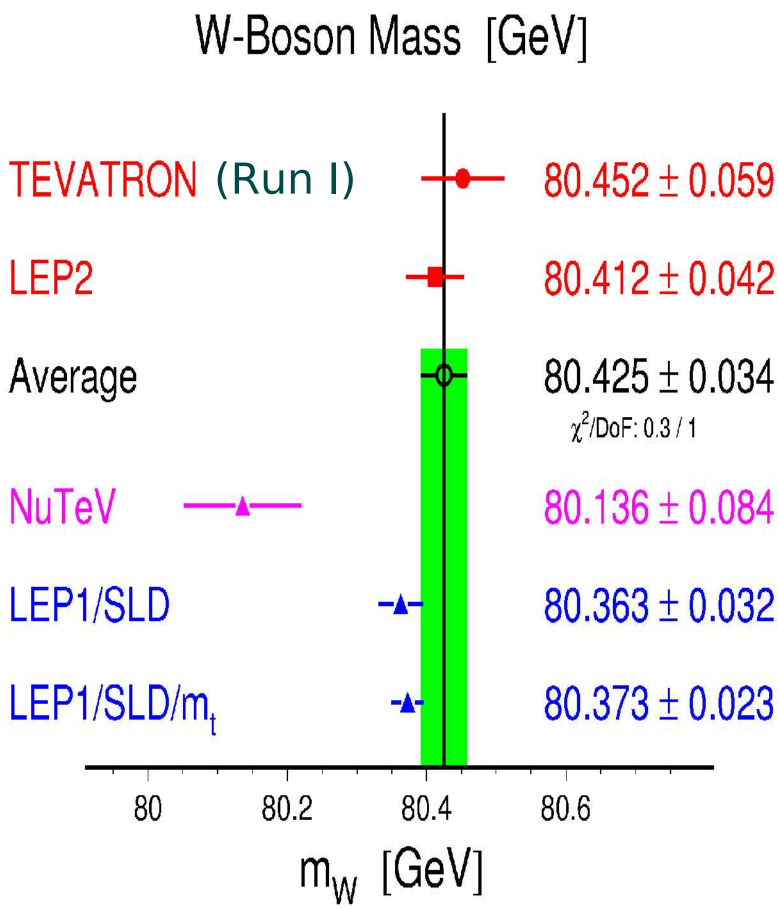


$\sigma(E)$ consistent with the theoretical prediction (NNLO)

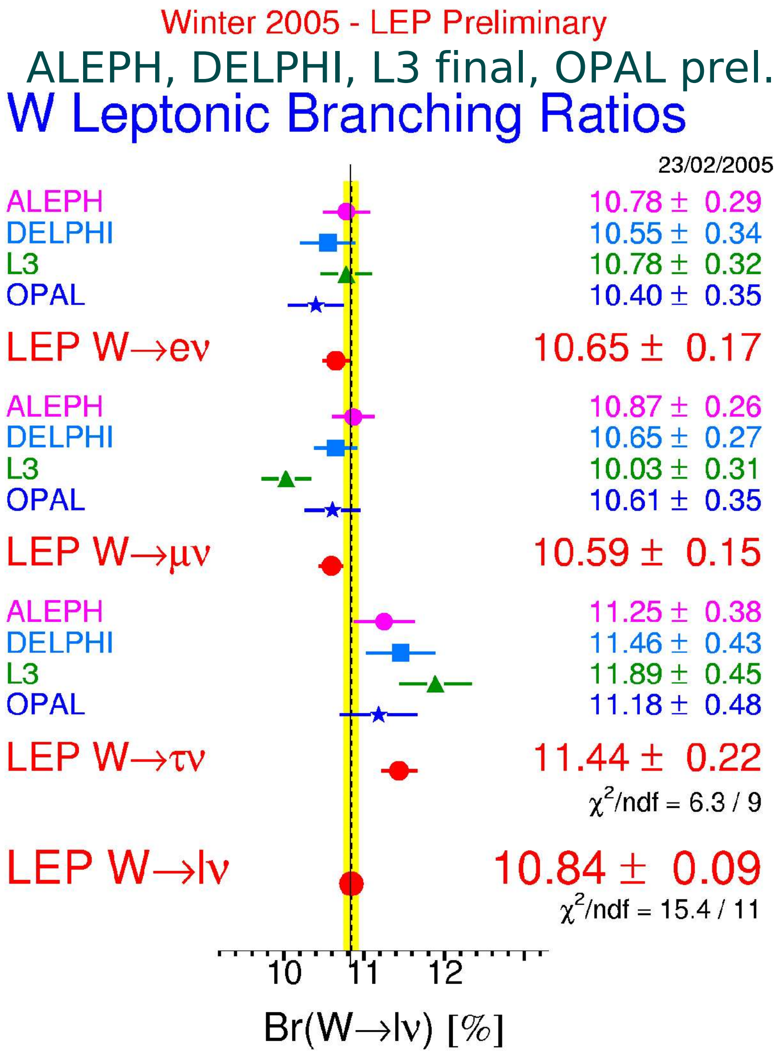
C.R. Hamberg, W.L. van Neerven and T. Matsuura, Nucl. Phys. **B359**, 343 (1991)

Large sample available for the study of W properties

W Mass and branching ratios



2.9σ



New published OPAL: M_W=80.415±0.052
(preliminary error was 67 MeV)

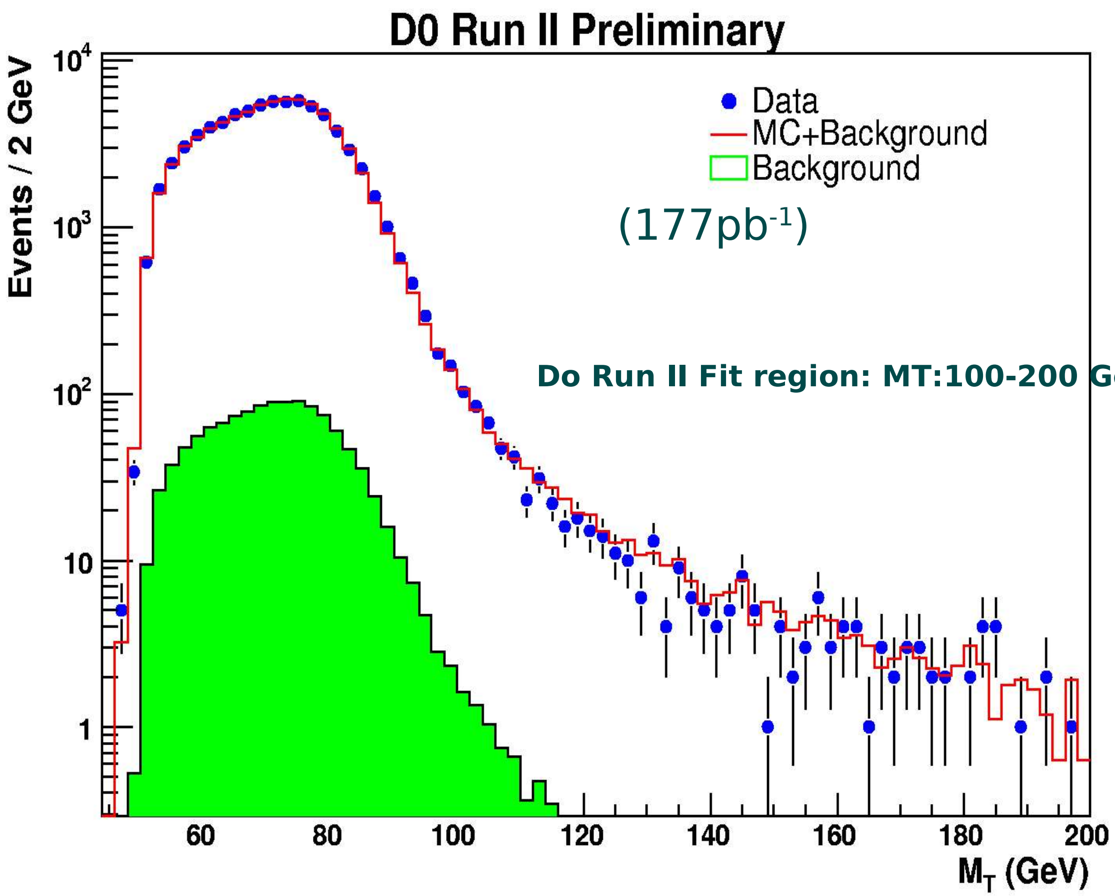
Analysis in progress at Tevatron Run II:
$M_{W,}$ Br(W→τ)

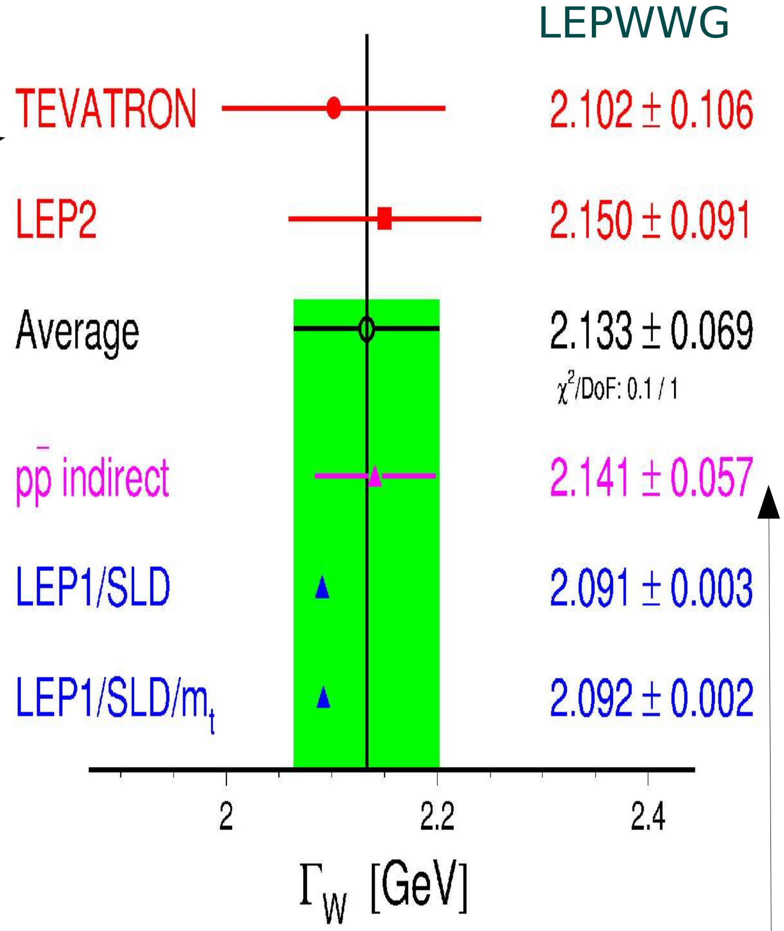
BR(W->qq)=67.48±0.28

W boson width

Direct measurement from M_T fit

New preliminary result D0 RunII 177 pb^{-1}:
$2.011 \pm 0.093_{(stat)} \pm 0.099_{(syst)}$





Indirect determination at Tevatron from W/Z cross section ratio

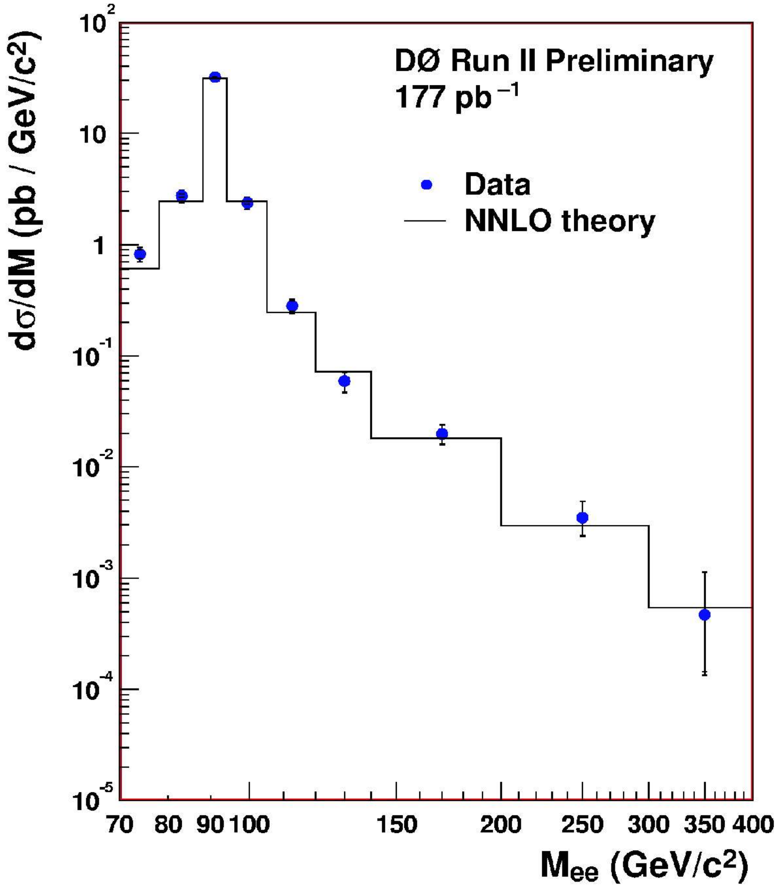
CDF RunII (72 pb^{-1}) 2.079 ± 0.041

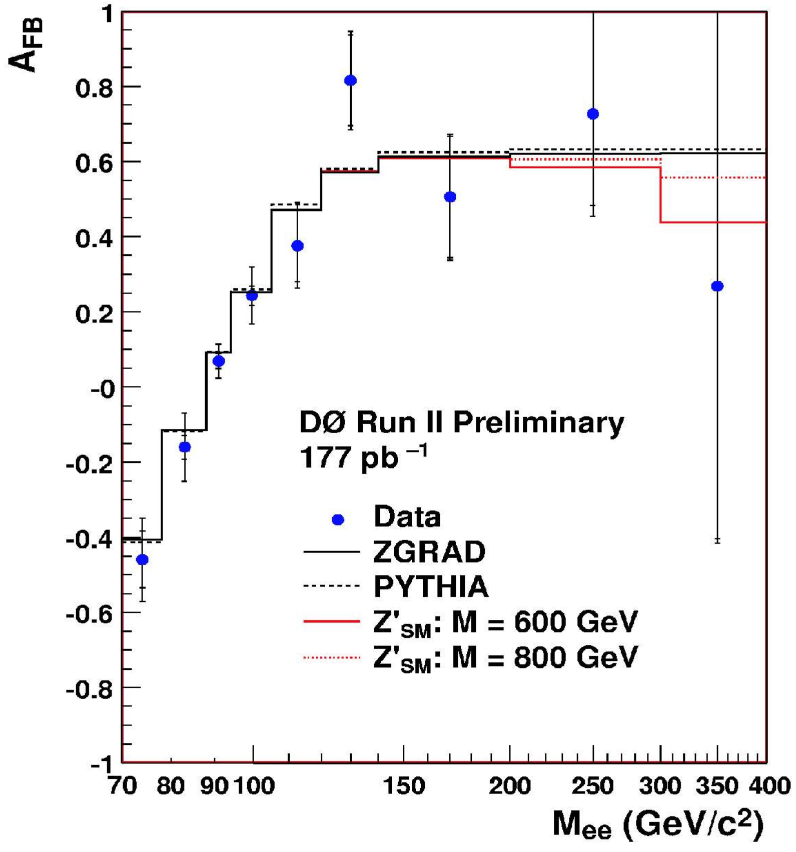
Phys. Rev. Lett. 94, 091803 (2005)

e^+e^- events at Tevatron

Drell-Yan: qq->e^+e^-, measures γZ interference, $A_{FB}=f(M_{ee})$

sensitive to $\sin^2\theta_W^{eff}$, quark couplings and new physics



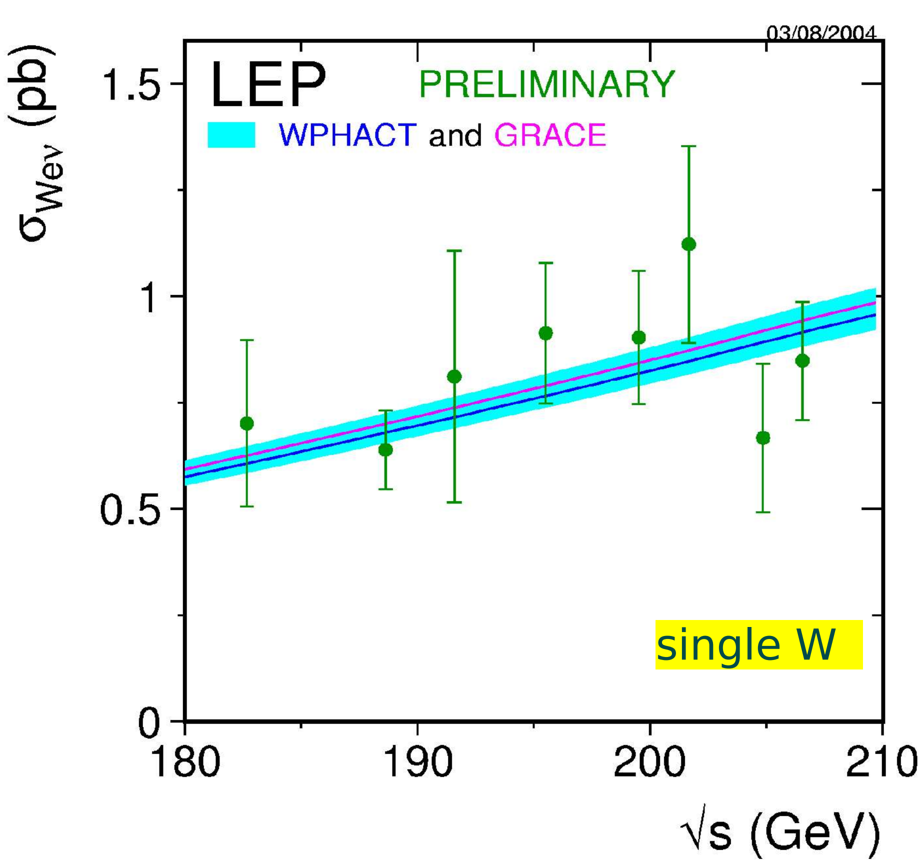


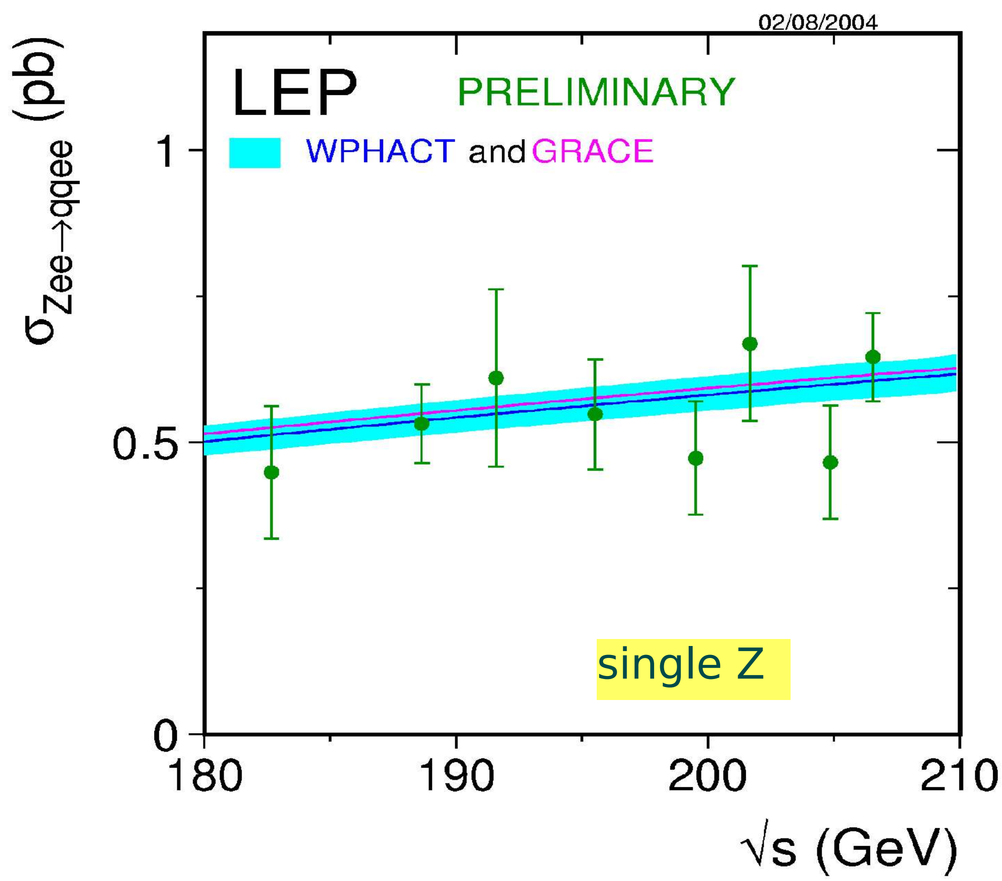
CDF $\sin^2\theta_W^{eff} = 0.2238 \pm 0.0040(stat) \pm 0.0030(syst)$ (EW Fit: 0.2314)

Rev. D 71, 052002 (2005)

Single boson production at LEP

Rare processes: Cross section<1 pb
statistically limited,
in agreement with the SM

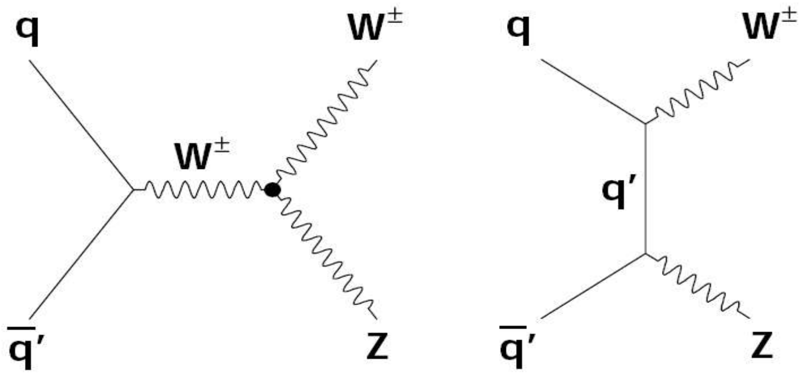




Di-boson production at Tevatron

EW processes are “weak” but rich topologies

Irreducible background for searches:
→ anomalous couplings or higgs

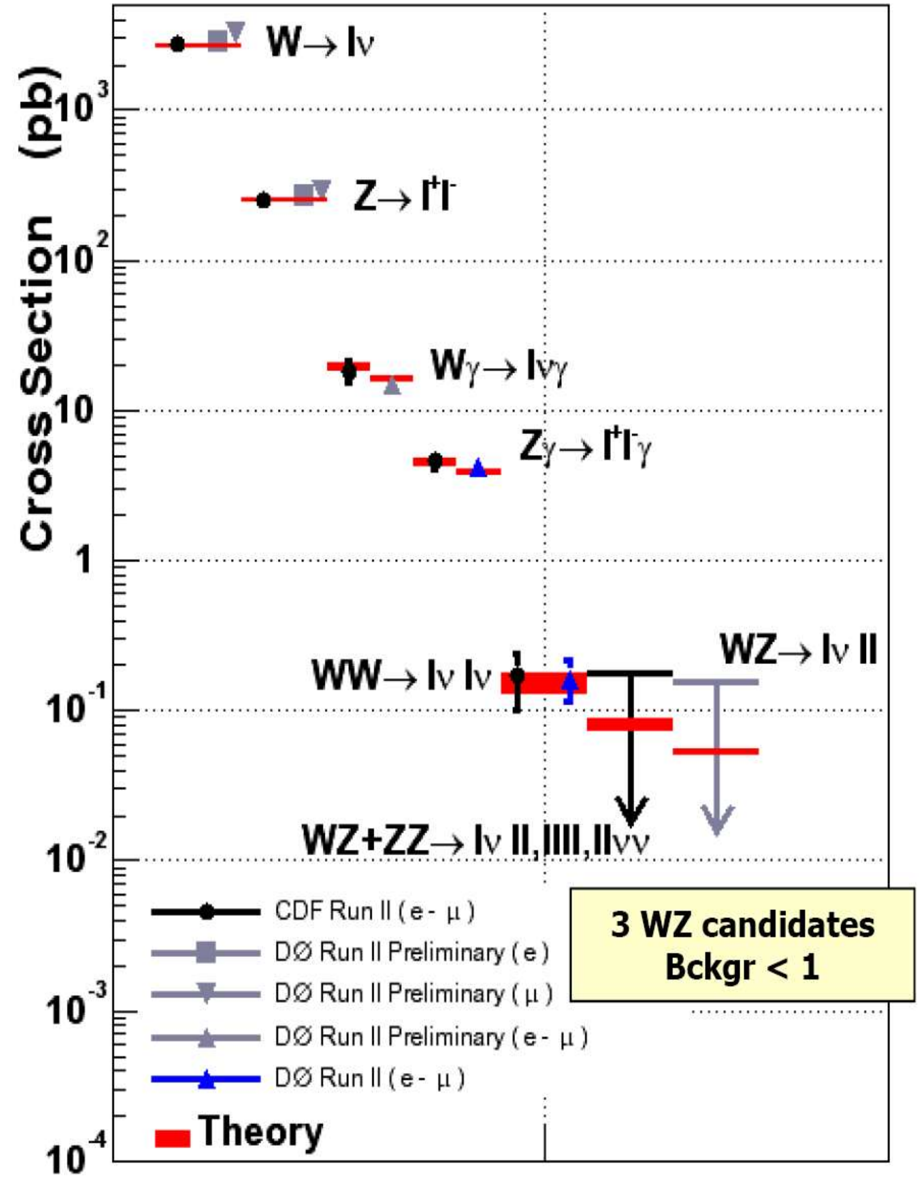


WZ+ZZ production:

D0:0.3 fb^{-1} (run II)
3 events obs. / 0.7±0.1 (exp.)
σ <13.3 pb @ 95% CL

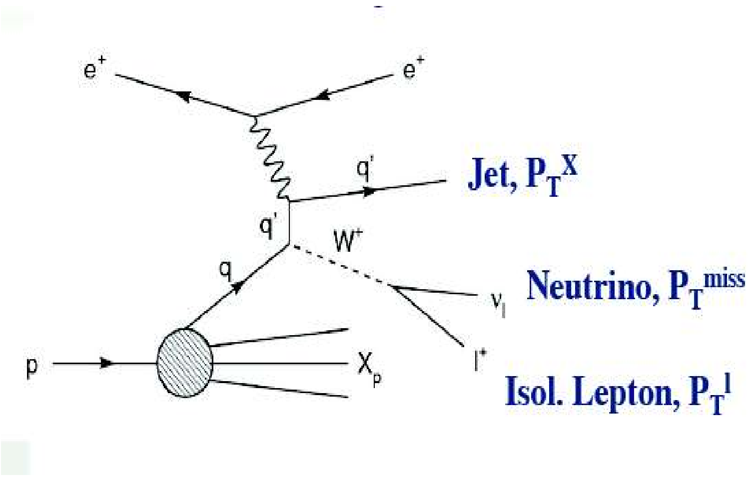
CDF 0.2 fb^{-1} (run II) Phys. Rev. D 71, 091105 (2005)
3 events obs. / 1.0±0.2 (exp.)
σ <15.2 pb @ 95% CL

σ_{SM}=5.0±0.4



Single W production at HERA

- Events with isolated leptons and P_T^{miss}
- X section $\simeq$ 1 pb => $O(10^2)$ events/expt. at HERA I+II
- Events with large hadronic momentum observed by H1



PTX>25 GeV

•H1(update) (211 pb^{-1}) 17 / 6.4±1.1 (e,μ)

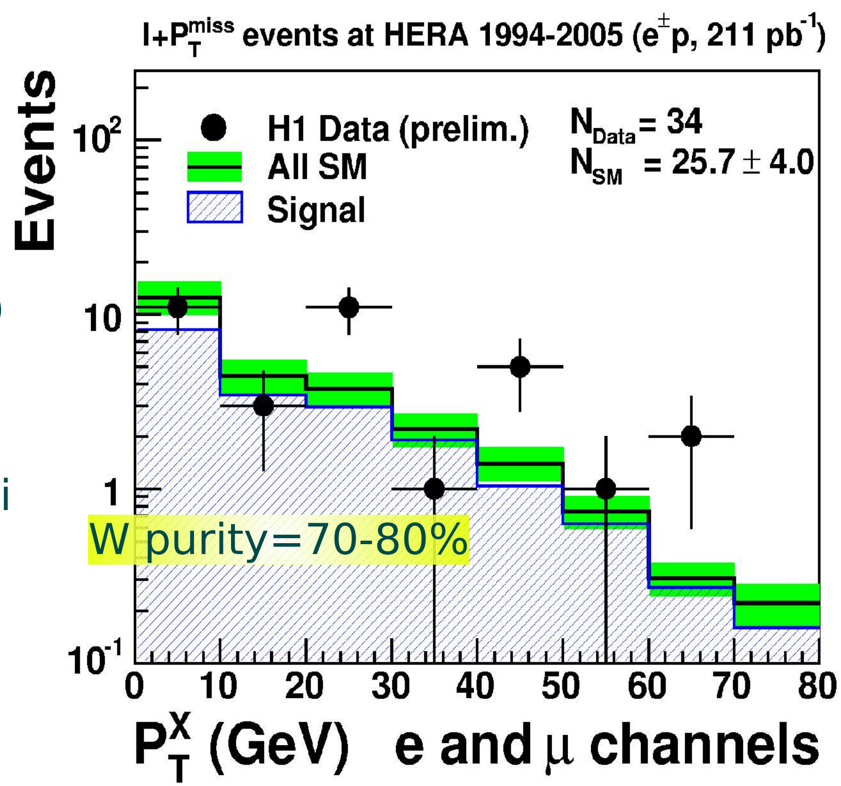
HERA I and II data

•ZEUS(new analysis) (106 pb^{-1}) 1/ 1.5±0.2 (e only)

previous search (130pb^{-1},HERA I) 7/5.7 (e,μ) (W:45%)

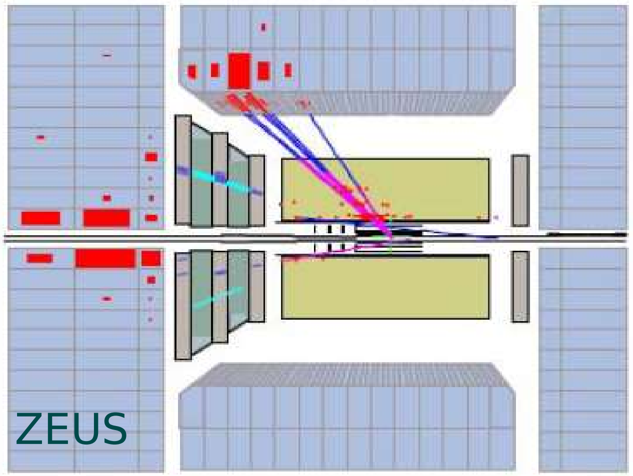
No deviation observed by ZEUS with present lumi

More $\int\mathscr{L}$ necessary

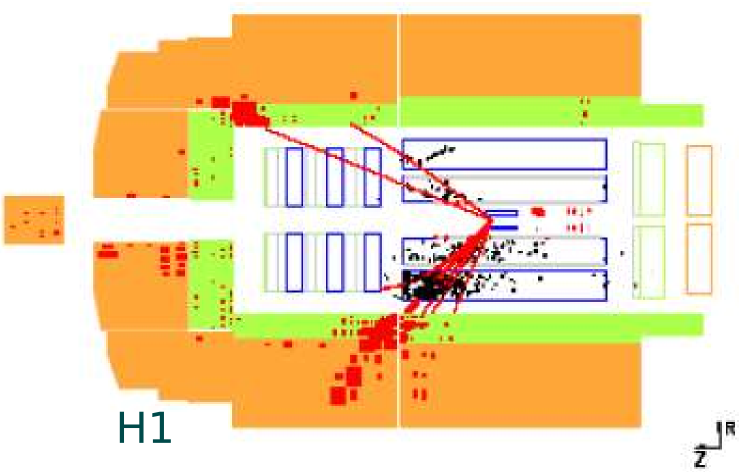


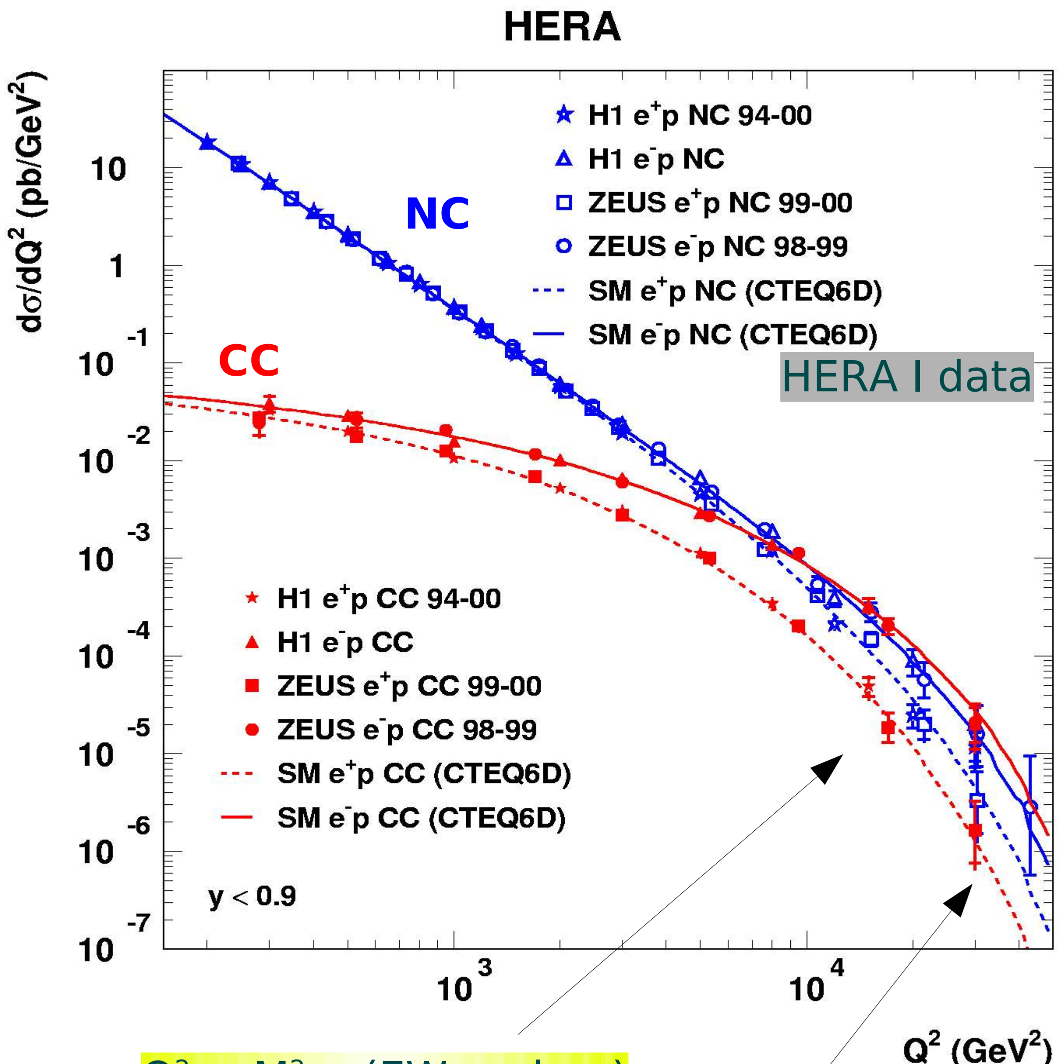
DIS at HERA

Charged Current (CC)



Neutral Current (NC)

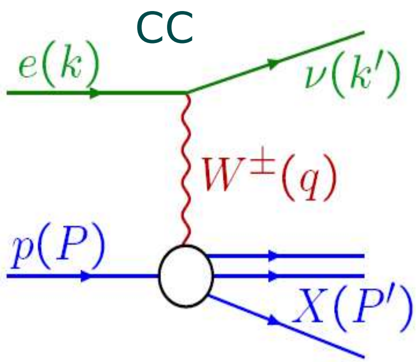




$Q^2 \sim M^2_{W,Z}$ (EW regime)

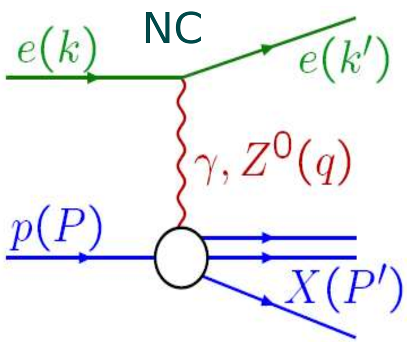
$r_{quark} < 10^{-18}$m
"p"/1000

Proton structure and EW effects from DIS



- $\mathbf{Q^2 = -(k-k')^2 = -q^2}$ boson virtuality
- $\mathbf{x = \frac{Q^2}{2P \cdot q}}$ quark p momentum fraction
- $\mathbf{y = \frac{P \cdot q}{P \cdot k}}$ inelasticity

Only 2 independent $Q^2 = sxy$



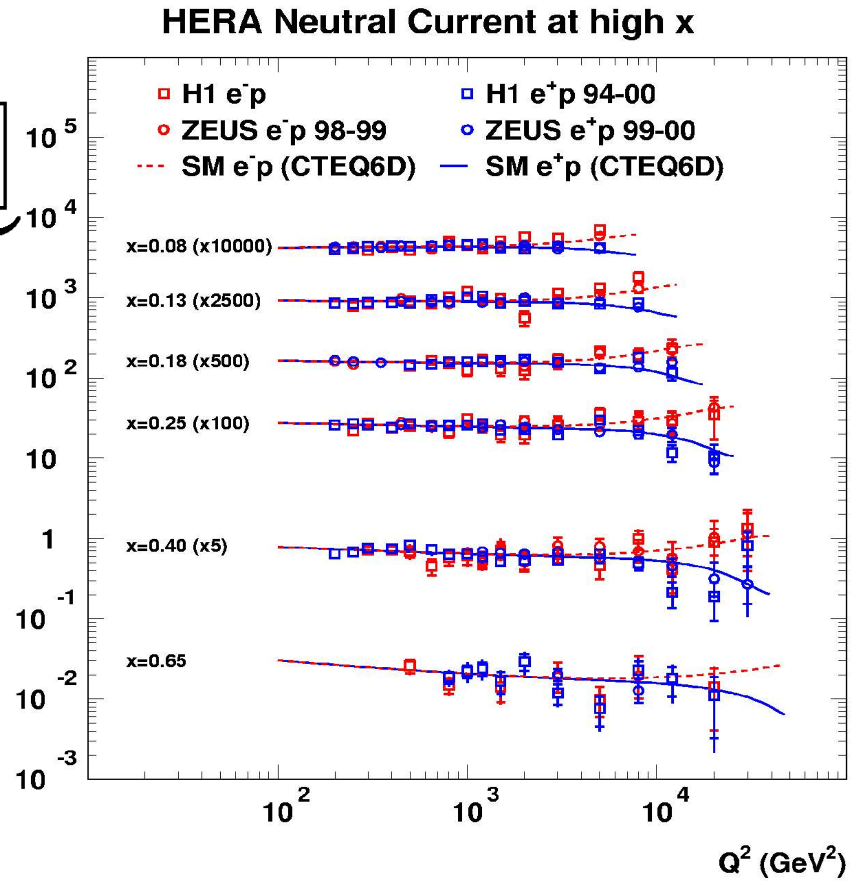
$$\frac{d^2\sigma_{\rm NC}^{e^\pm p}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left[Y_+\tilde{F}_2(x,Q^2) \mp Y_- x\tilde{F}_3(x,Q^2)\right]}_{\Phi_{\rm NC}}$$

$$Y_\pm \equiv 1 \pm (1-y)^2$$

[example of decomposition]

$$x\tilde{F}_3 \equiv -\, a_e \,\frac{\kappa Q^2}{(Q^2+M_Z^2)} xF_3^{\gamma Z} + \,(2v_e a_e)\,\left(\frac{\kappa Q^2}{Q^2+M_Z^2}\right)^2 xF_3^Z$$

$$[xF_3^{\gamma Z}, xF_3^Z] = 2x\sum_q [e_q a_q, v_q a_q]\{q - \bar{q}\}$$



HERA experiments constrain parton distributions
CC [pure weak process] => resolve quark flavours
NC also sensitive to electroweak effects at high Q2

Combined EW-QCD fits

New approach (H1): common fit EW+QCD;

- use CC/NC HERA I data (>600 measurements)
- Fit: Structure Functions ⊕ $EW_{parameters}$

First example: CC Propagator Mass measurement

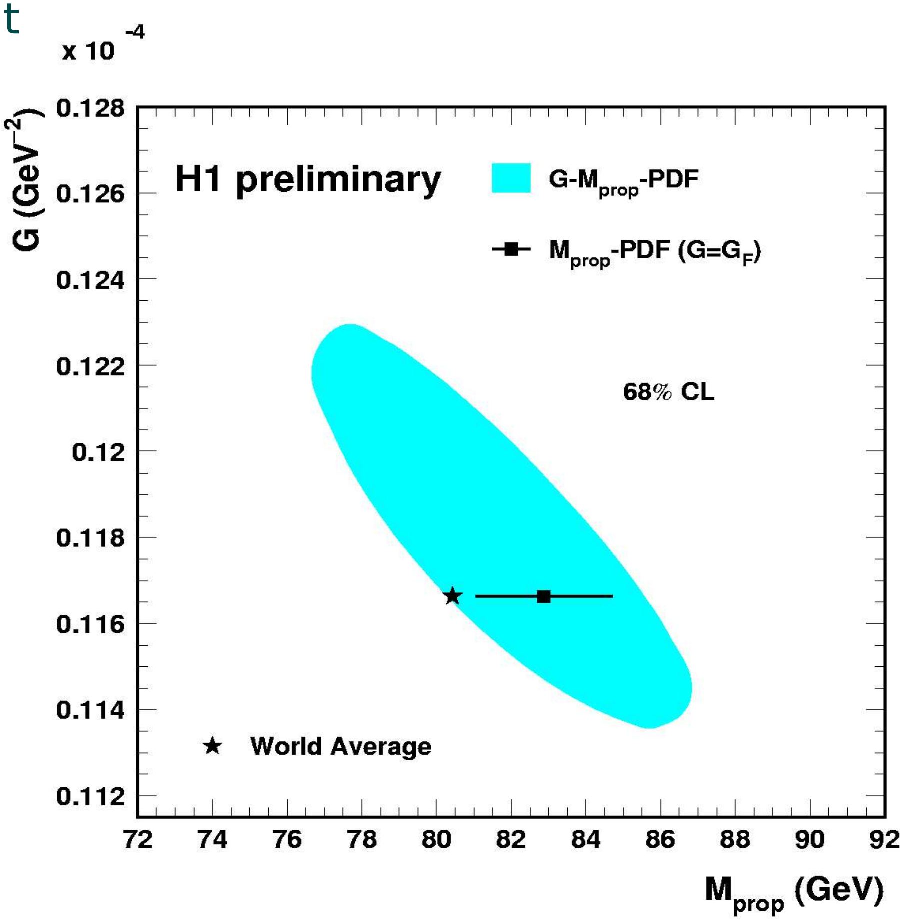
$$\frac{d^2\sigma^{\pm}_{CC}}{dxdQ^2} = \frac{G_F^2}{2\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \tilde{\Phi}_{CC}$$

Normalisation (includes rad.corr.)

Propagator Mass

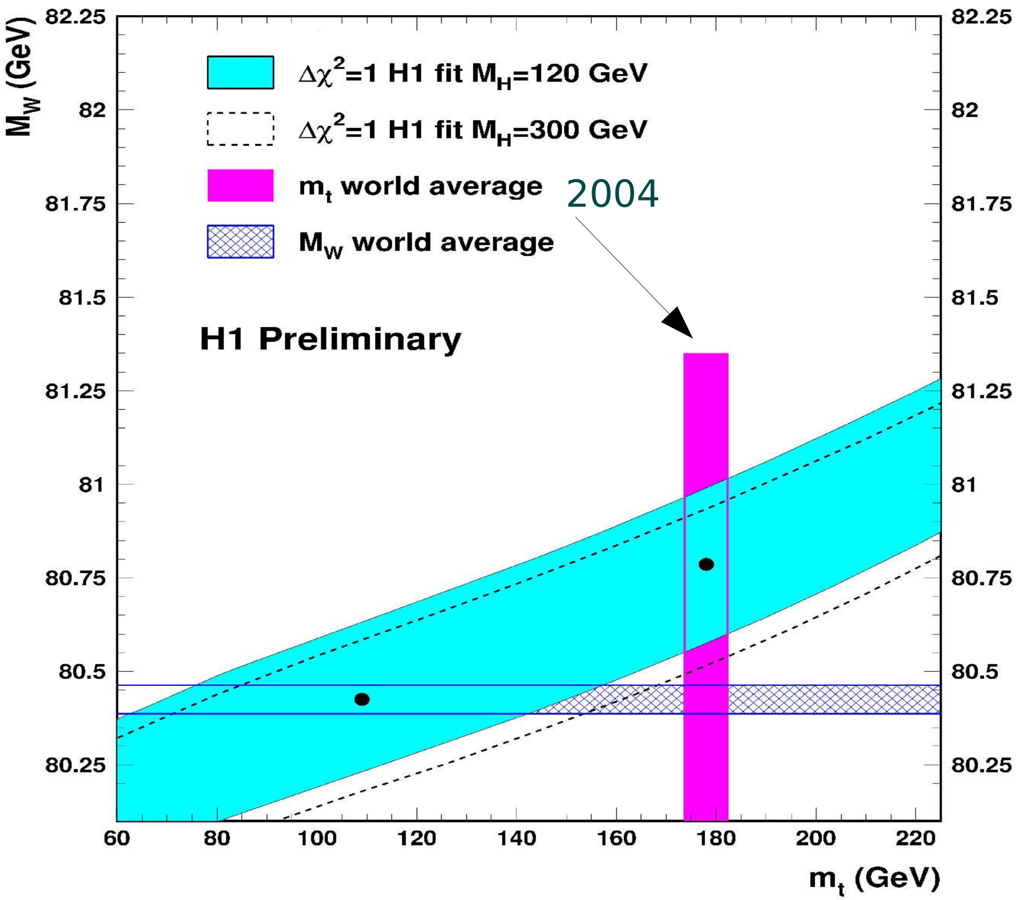
$$M_W^{prop} = 82.87 \pm 1.82(\exp)^{+0.30}_{-0.16}(\mathrm{mod})\ \mathrm{GeV}$$

- model independent $M_{boson(W)}$ measurement
- unique using HERA t-channel exchange



On Mass Shell scheme

- α, M_W , M_Z => $G_F(M_W)$
- Radiative corrections computed in SM
- M_W is a parameter, dependent on $M_{H,top}$



$$M_W = 80,709 \pm 0,205(\text{exp})^{+0,048}_{-0,029}(\text{mod}) \pm 0,025(\text{top}) \pm 0,033(\text{th}) - 0,084(\text{Higgs})\ \text{GeV}$$

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

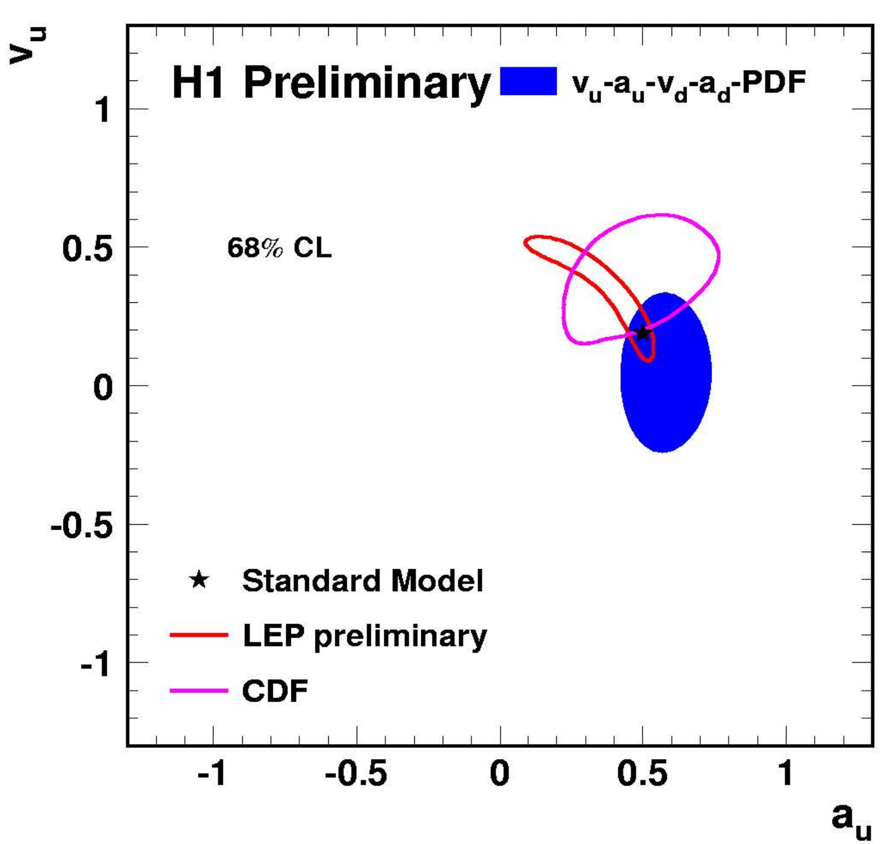
$$\sin^2\theta_W = 0.2151 \pm 0.0040_{exp.}{}^{+0.0019}_{-0.0011}|_{th}$$

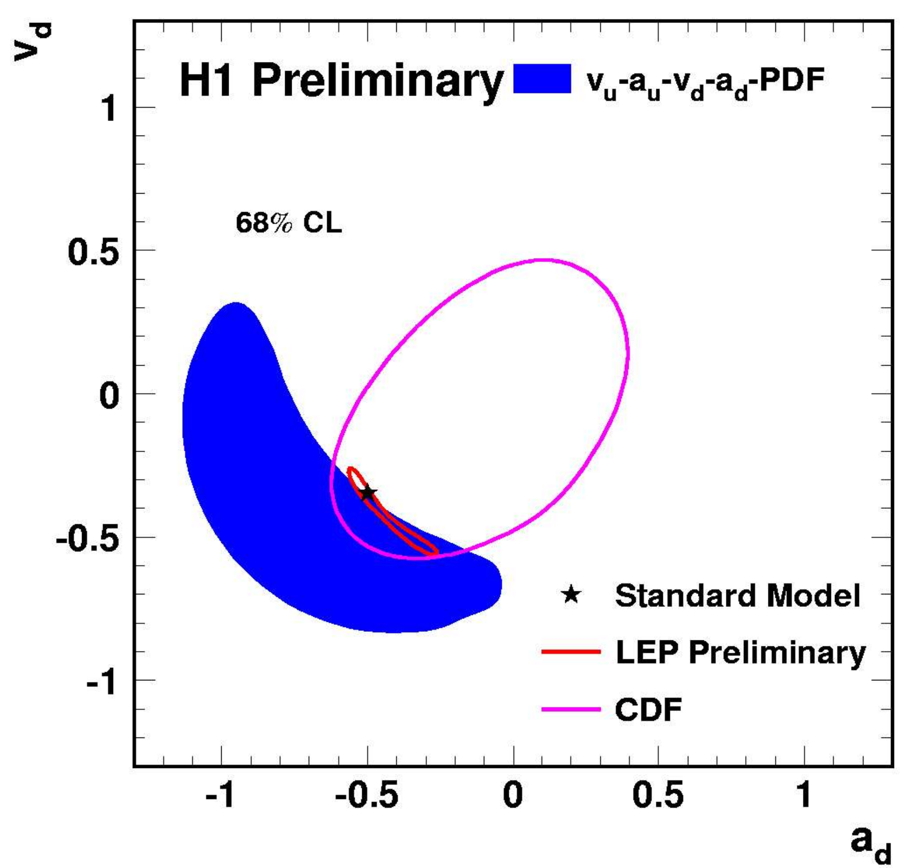
First determination in DIS @ EW scale

EW fit : 0.2228±0.0003

Light quarks couplings to the Z

- b,c couplings very well known (few % LEP from $A_{FB}(c,b)$)
- Light quarks (u,d) couplings determination
  - HERA: eq->eq Combined fit Z couplings + PDF
  - LEP : ee-->qq at Z peak (a^2v^2, a^2+v^2)
  - TEVATRON: qq->ee from Drell-Yan (electrons) A_{FB}





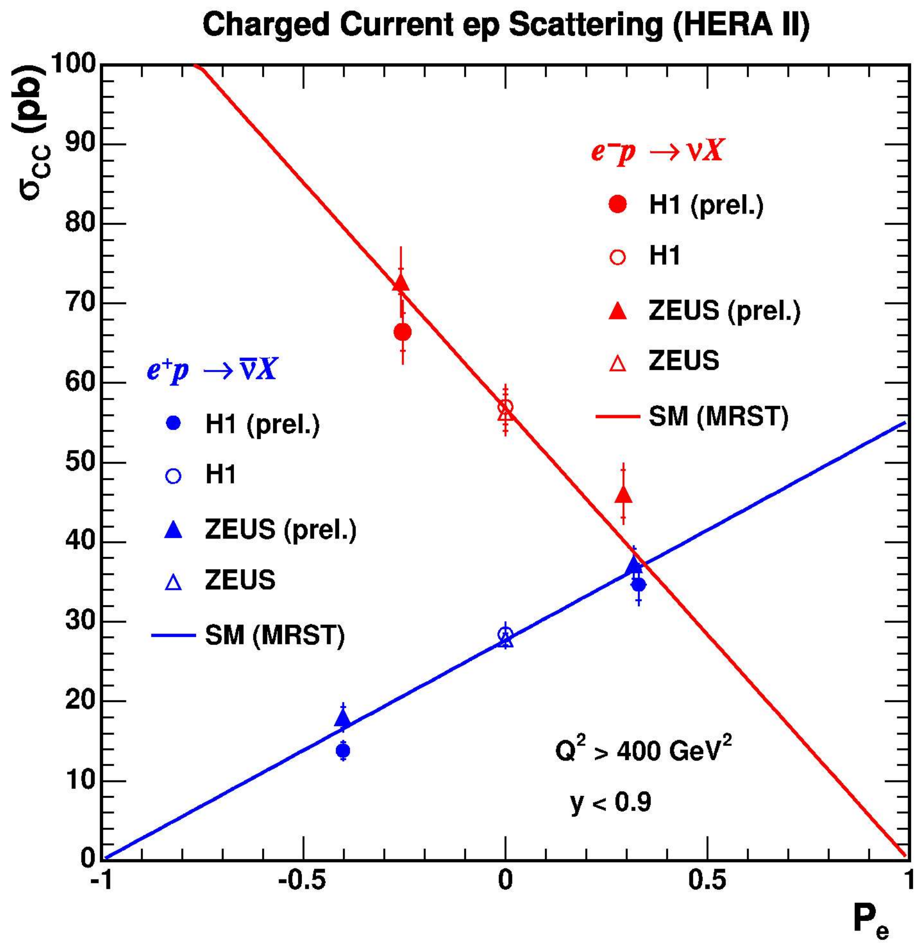
HERA II results with polarized beams

HERA can run with $e^{\pm}$
and both e-beam polarisations (P=0.25-0.4)

$$\sigma^{e^{\pm}p}(P) = (1 \pm P)\sigma^{e^{\pm}p}_{P=0}$$

CC: linear dependence established
in DIS at HERA

Compatible with V-A structure
(no RH currents)

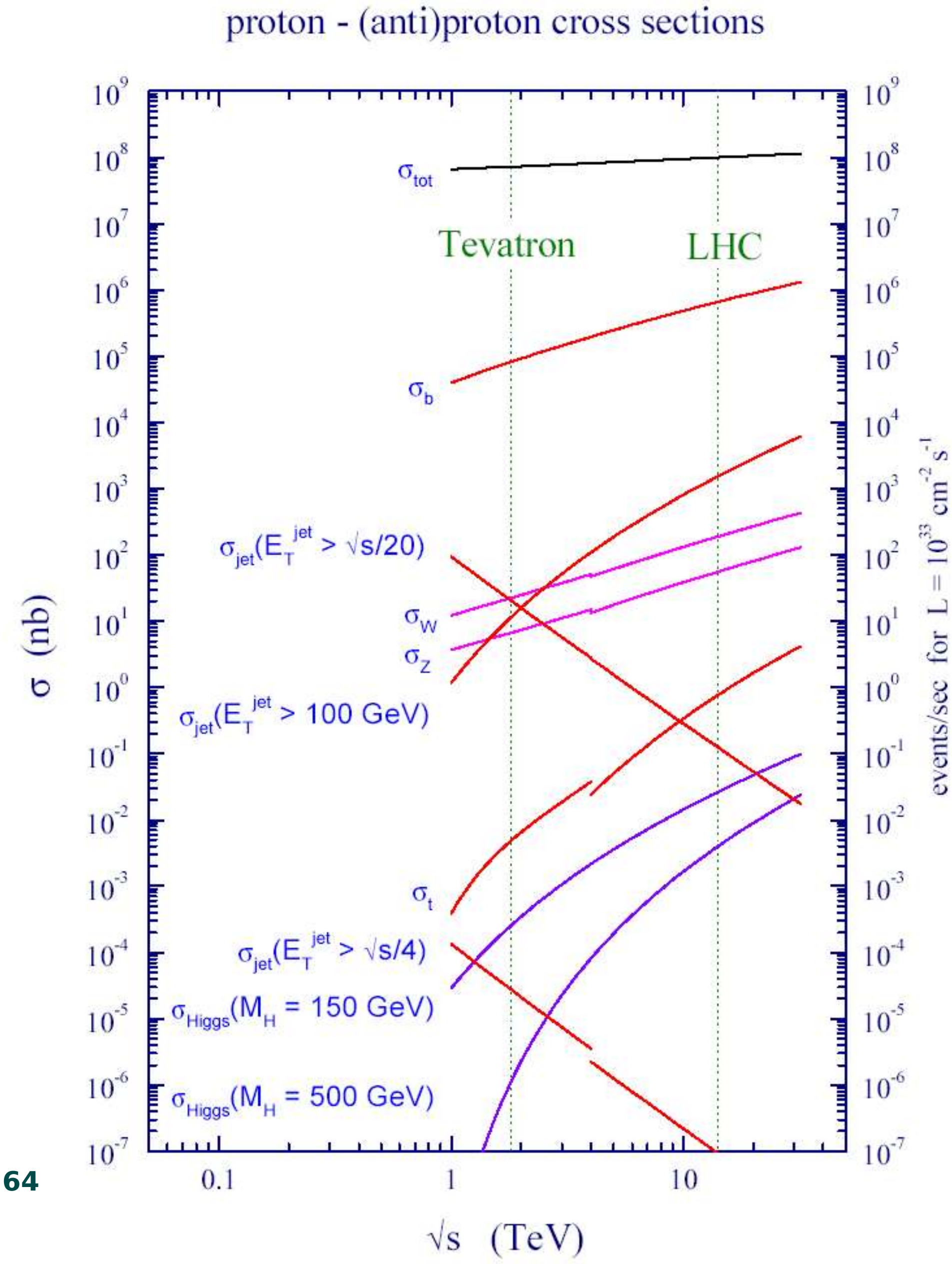


CHARM (1979):
$\nu_{\mu} N \rightarrow \mu X$

It may be concluded that positive muons produced by interactions of high-energy antineutrinos with nuclei have a longitudinal polarization oriented along their momentum direction. Within the experimental errors the helicity is found to be +1, consistent with a purely V-A form of the interaction. An upper limit

The future of precision EW measurements at high energy

- **LHC (E_{cm}=14TeV) large statistics:**
  - **generous cross sections W,Z,top**
  - **2.10^6 W's for 0.1 fb^{-1}**
  - **top, triple/quartic gauge couplings,...**
- **LC (GigaZ or E_{cm}=1 TeV) interplay:**



	now	Tev. Run II	LHC	LC	GigaZ
$\delta \sin^2\theta_{\rm eff}(\times 10^5)$	17	78	14–20	(6)	1.3
δM_W [MeV]	34	27	15	10	7
δm_t [GeV]	5.1	2.7	1.0	0.2–0.1	0.1
δm_h [MeV]	—	—	200	50	50

hep-ph/0410364

Conclusions

- SM is in good shape
  - new physics is not (yet) on the SM territory
  - a few peculiarities 2.5-3σ (A_{fb}(b), N_ν, NuTeV, Br(W->τ), a_μ)
- LEP is finalizing results:
  - improving in precision amazing and worth the effort
- Tevatron is refining the analysis of Run II data
  - increase in the luminosity will improve the precision.
- HERA : a first coherent QCD+EW analysis of DIS data
  - increase luminosity, $e^{\pm}$-beam polarization
- Precision measurement will continue soon at LHC and (latter) at the LC

Polarisation effects in NC-DIS

- NC(P_e) via parity violating couplings of the Z in the t-channel
- The effect is not yet established experimentally
- Improvement in L/P will improve the outcome for NC's
  - (q densities, couplings)