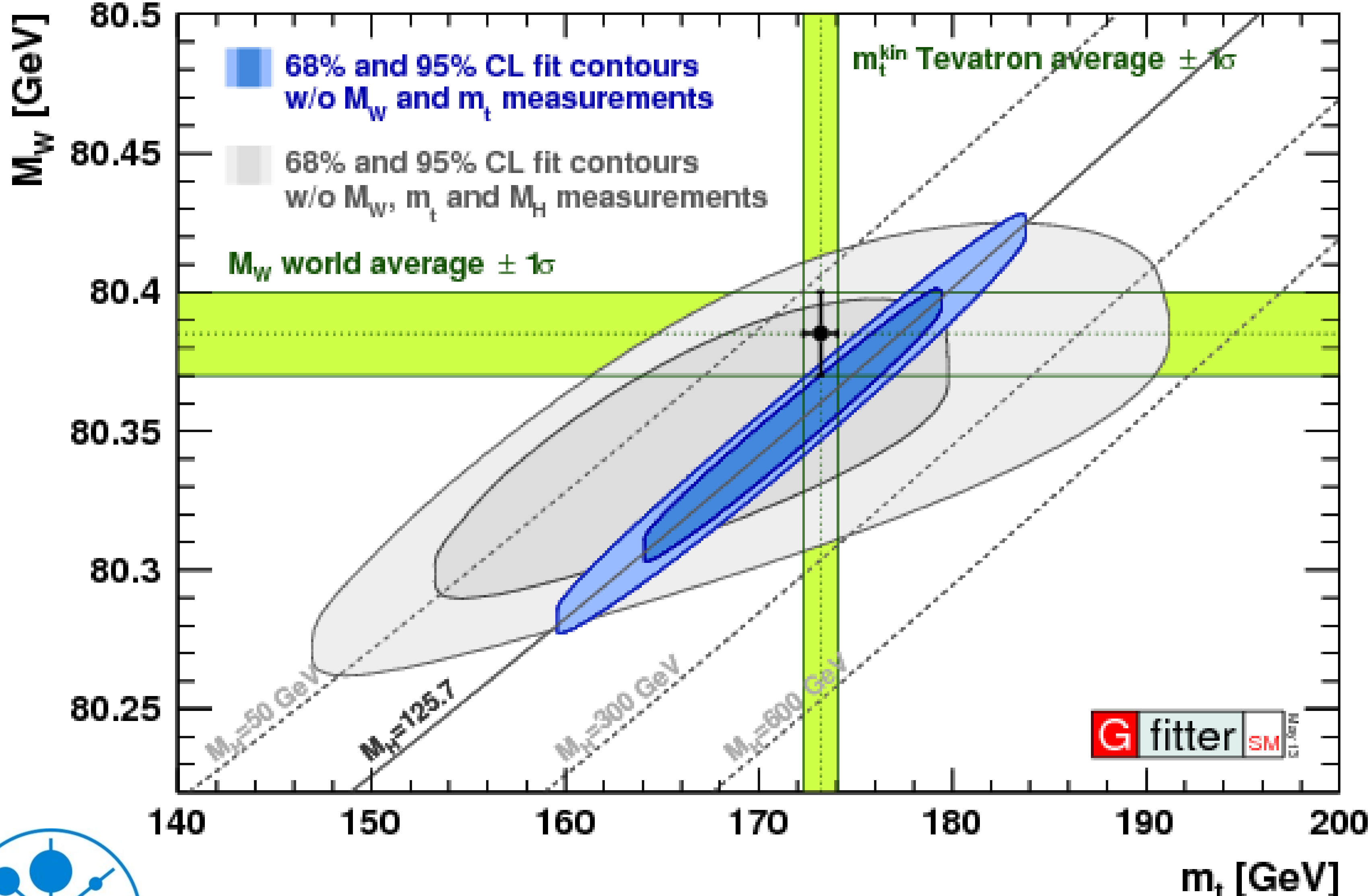
Electroweak Measurements



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Outline

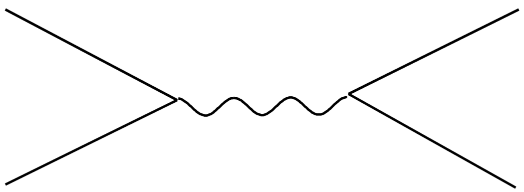
- Introduction
- Accelerators for electroweak physics
- Electroweak measurements at LEP and SLD
- Electroweak measurements at hadron colliders
- Electroweak measurements at HERA
- Electroweak fits
- Higgs boson production
- Gauge boson production and couplings

Introduction

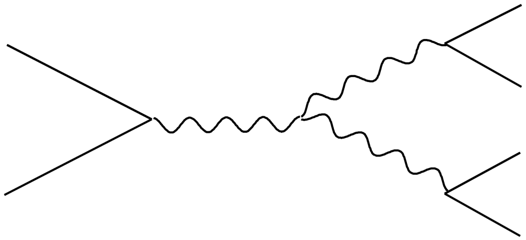
- Electroweak physics is the physics of the W- Z- and Higgs bosons
- All bosons have masses in the 100 GeV range, this sets the scale for the energy of the accelerators
- The Standard Model predicts the masses, couplings to fermions and couplings among the bosons, so want to test all these parameters

Relevant Feynman graphs for gauge boson production

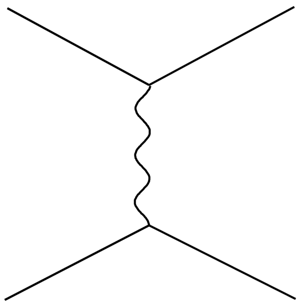
- s-channel production
  - Large cross section
  - Useful for mass and fermion couplings



- s-channel pair production
  - Useful for gauge boson couplings



- t-channel production
  - Can be used for cross section measurements



Accelerators for electroweak physics

Accelerator types

- e^+e^-:
  - Elementary particle → initial state fully known
  - Polarisation possible → double number of measurements in a parity violating model like SM
  - Full energy in detector → can use 4-momentum conservation in reconstruction
  - No strong interaction → low background
  - However synchrotron radiation goes with $(E/m)^4$ → difficult to reach high energy

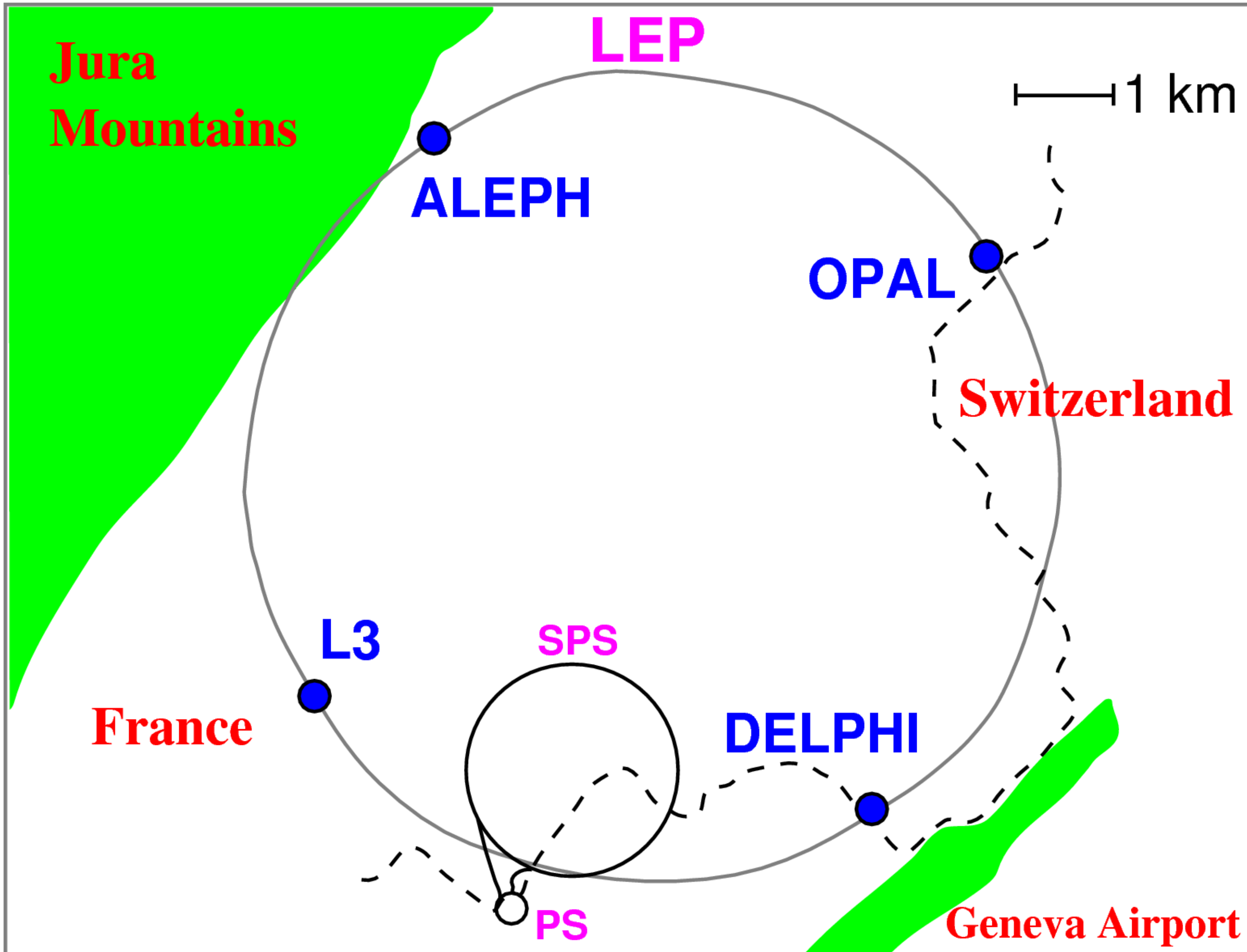
Accelerator types (ii)

- pp,$p\bar{p}$:
  - Easier to reach high energy, limited by B-field
  - However soup of quarks and gluons → initial state not known on event-by-event basis and parton cms energy much smaller than beam energy
  - Proton remnants disappear in beam-pipe → only transverse momentum conservation usable
  - Strong interactions → large backgrounds
- ep:
  - Mainly for measurement of proton structure
  - Sensitive to electroweak couplings from W, Z t-channel exchange

LEP

- e^+e^- collider at CERN (1989-2000)
- Circumference 27 km (tunnel now hosts LHC)
- 4 experiments: ALEPH, DELPHI, L3 and OPAL
- 1989-1995:
  - running at or near the Z-pole ($\sqrt{s}\approx 91$ GeV)
  - $4\cdot 10^6$ Zs/experiment for Z properties
- 1996-2000:
  - Running at 161 GeV$<\sqrt{s}<$208 GeV
  - 750 pb^{-1}/experiment (10000 W-pairs)
  - W properties and Higgs searches

LEP (ii)

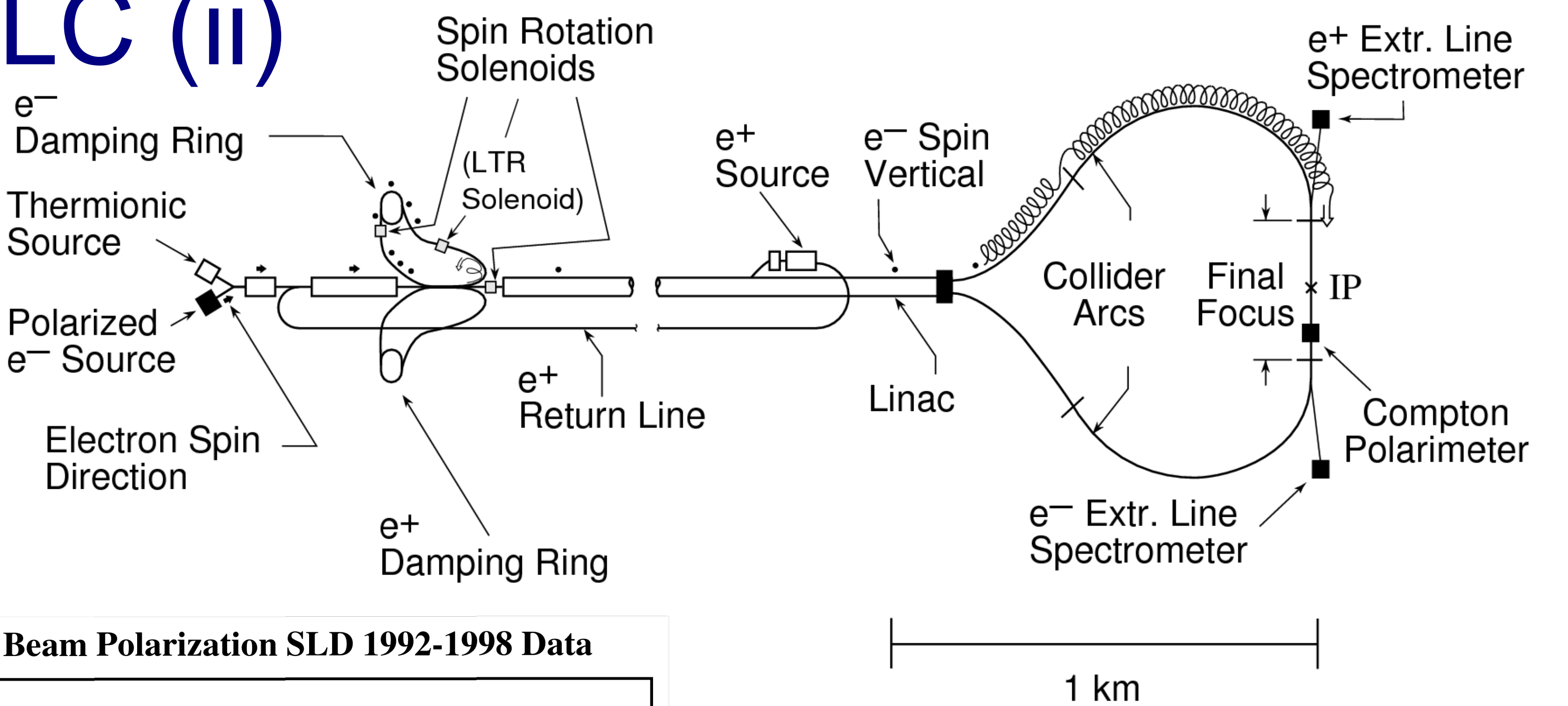


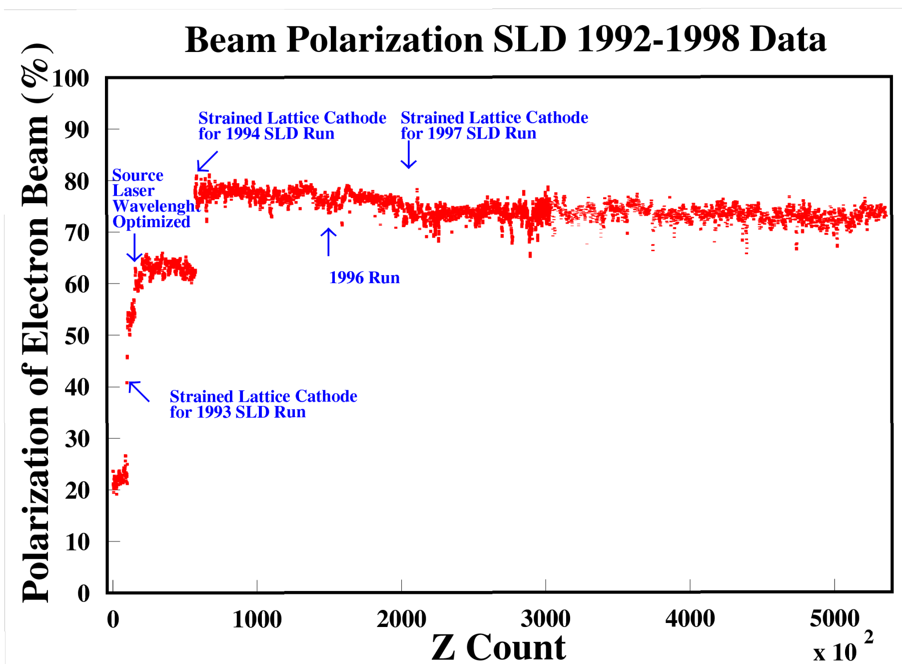
LEP
Jura
Mountains
1 km
ALEPH
OPAL
Switzerland
L3
SPS
France
DELPHI
PS
Geneva Airport

SLC

- Linear e^+e^- collider at SLAC
- Running 1992-1998 at the Z-pole
- One experiment: SLD
- Low luminosity (≈500000Zs)
- However beam polarisation <80%
- Competitive measurement of $\sin^2\theta$

SLC (ii)


Spin Rotation
Solenoids
e−
Damping Ring
(LTR
Solenoid)
Thermionic
Source
Polarized
e− Source
Electron Spin
Direction
e+
Return Line
e+
Damping Ring
e+
Source
e− Spin
Vertical
Linac
e+ Extr. Line
Spectrometer
Collider
Arcs
Final
Focus
IP
Compton
Polarimeter
e− Extr. Line
Spectrometer
1 km


Beam Polarization SLD 1992-1998 Data
Polarization of Electron Beam (%)
100
90
80
70
60
50
40
30
20
10
0
Strained Lattice Cathode
for 1994 SLD Run
Strained Lattice Cathode
for 1997 SLD Run
Source
Laser
Wavelenght
Optimized
1996 Run
Strained Lattice Cathode
for 1993 SLD Run
0
1000
2000
3000
4000
5000
Z Count
x 10 2

Tevatron

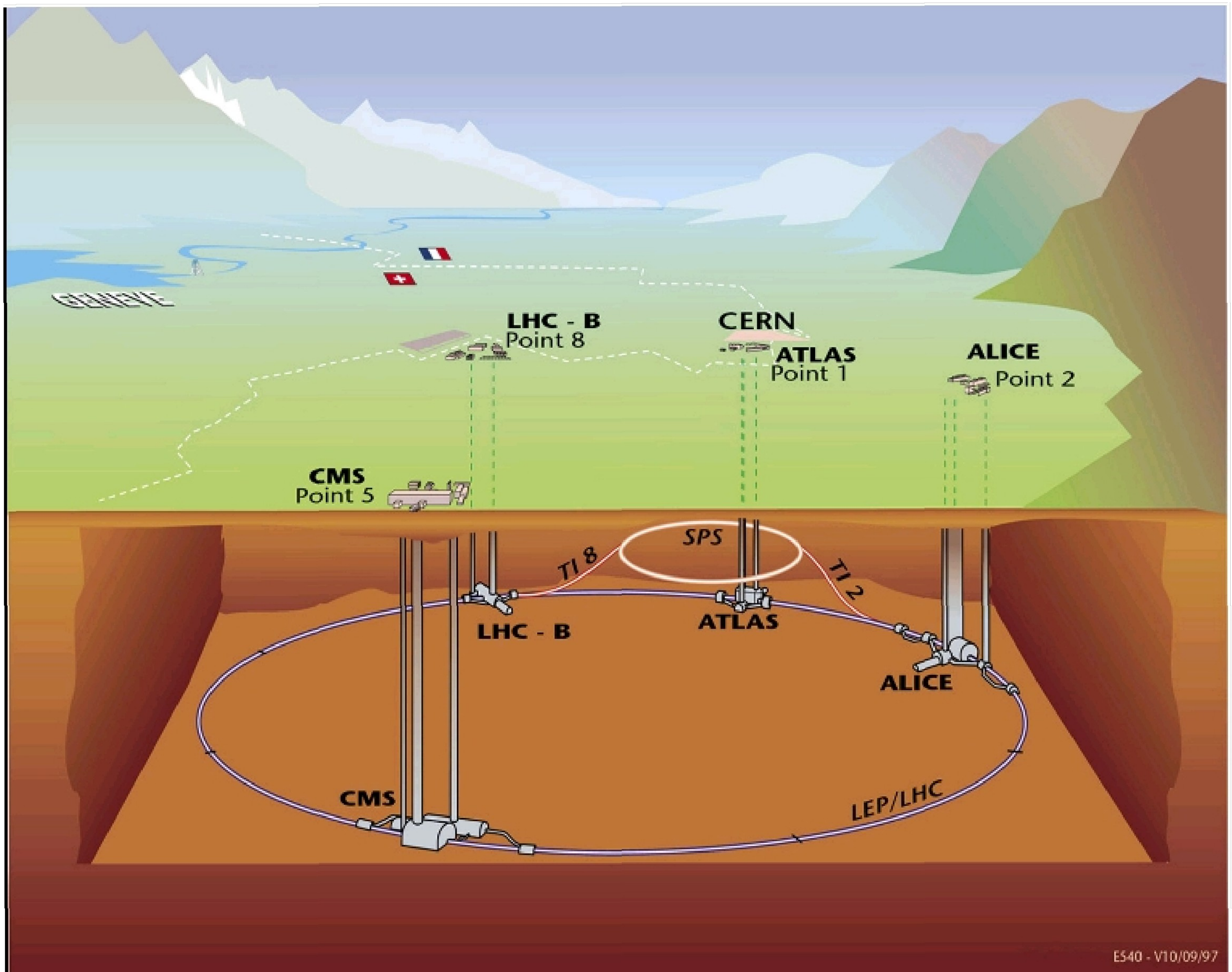
- $p\bar{p}$ collider at Fermilab/Illinois, 1985 – 2011
- Running at 1.8 TeV<$\sqrt{s}$<1.96 TeV
- Two experiments: CDF, D0
- Total luminosity 10 fb^{-1}/experiment
- Discovery of top-quark (1995)
- Precise measurement of W-mass
- Triple gauge couplings
- Higgs searches

Tevatron (ii)

LHC

- pp collider at CERN (in LEP tunnel)
- Two experiments: ATLAS, CMS (+specialised ones: ALICE, LHCb, Totem)
- Running 2010-2012 with 7 TeV<$\sqrt{s}$<8 TeV
- Luminosity up to now 25 fb^{-1}/experiment
- From 2015 onwards running with $\sqrt{s} \leq 14$ TeV
- Higgs discovery and properties
- First TGC results
- Potential for accurate W mass

LHC (ii)



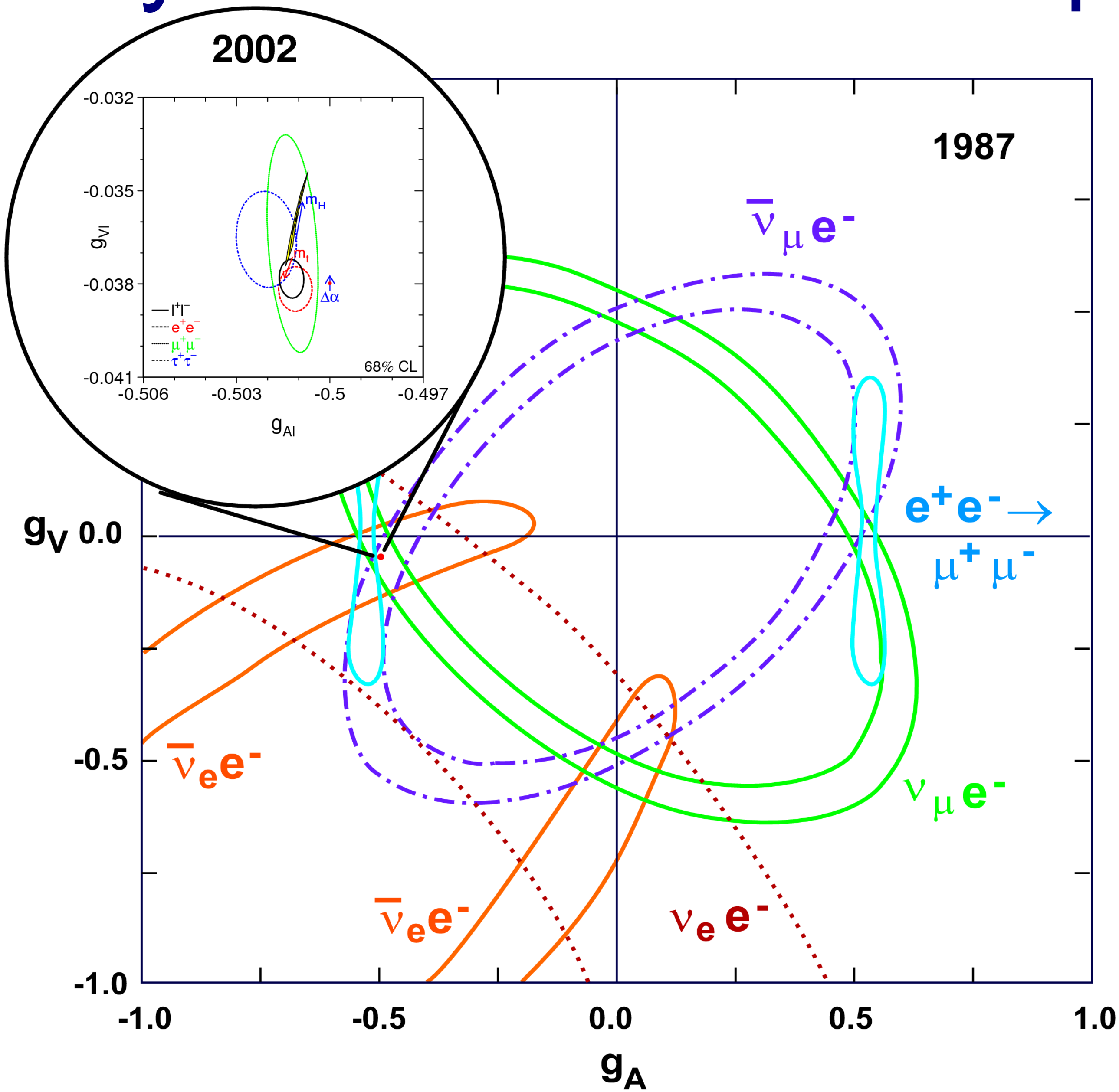
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

Electroweak measurements at LEP and SLD

Situation before LEP

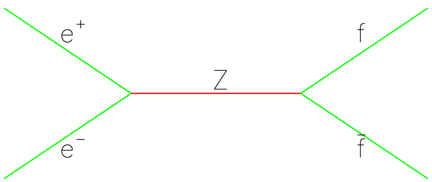
- All particles except top and Higgs were discovered
- The Standard Model was established as an effective theory
- The precision was not good enough to establish quantum effects
- Aim at LEP/SLC:
  - Improve precision by at least one order of magnitude
  - Establish the Standard Model as a quantum theory

History of electroweak couplings

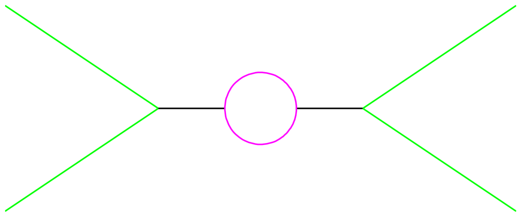


LEP/SLC goals

- Dominant process:



- Important loop corrections:



- Observables get dependent on invisible particles
- Can constrain new physics with precision measurements

Electroweak couplings

- On tree level need three parameters to define electroweak coupling sector

  → use the most precise: α ($\Delta\alpha/\alpha = 3\cdot10^{-9}$), G_F ($\Delta G_F/G_F = 5\cdot10^{-7}$), m_Z ($\Delta m_Z/m_Z = 2\cdot10^{-5}$)
- Z-fermion couplings:
  - axial-vector coupling: $g_{Af} = I_3^f$
  - vector coupling: $g_{Vf} = g_{Af}\left(1 - 4|Q_f|\sin^2\theta_W\right)$
- W-Z mass relation: $$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2}$$
- Loop corrections introduce differences between $\sin^2\theta$ definitions

Loop corrections

- On the Z-pole resonant diagrams dominate → loop corrections can be parametrised by 2 form-factors
- $g_(A,f) = \sqrt{1+\Delta\rho_f} I_3$
- $\sin^2\theta^f_{\text{eff}} = (1+\Delta\kappa_f)\sin^2\theta$ (g_V/g_A)
- $m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$
- e.g. Δρ:

$$\Delta\rho = \frac{3G_F}{4\pi^2\sqrt{2}}\left(\frac{m_t^2}{2} - m_W^2\frac{s^2}{c^2}\ln\frac{m_H}{m_Z}\right) + \dots$$

Z-observables

- Two types of observables:
  - Partial widths:

$$\Gamma_f \propto |g_{Af}|^2 + |g_{Vf}|^2 \rightarrow \Delta\rho_f$$

$$\Gamma_q = \Gamma_q^0 \left(1 + \frac{\alpha_s}{\pi} + \ldots\right)$$

  - Asymmetries:

$$\mathcal{A}_f = \frac{2 g_{Vf} g_{Af}}{g_{Vf}^2 + g_{Af}^2} \rightarrow \sin^2\theta_{\text{eff}}$$

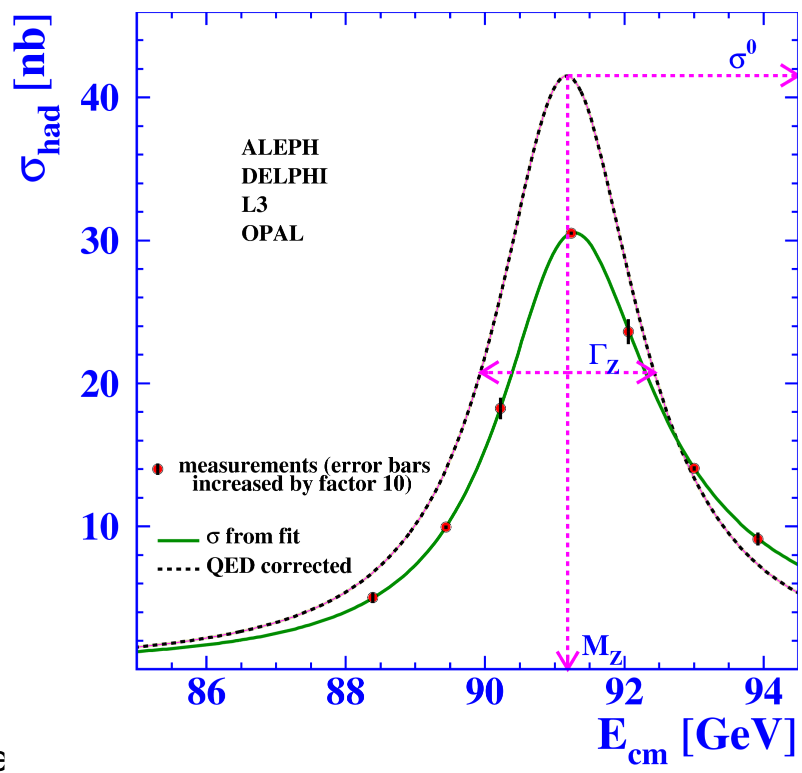
- Can be measured for leptons, b-quarks, c-quarks and Σ(quarks)

The Z lineshape

- Scan few GeV around Z-resonance
- Measure cross section for leptons and hadrons

$$\sigma_f(s) = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_f s}{(s - m_Z^2)^2 + \left(\frac{s}{m_Z}\right)^2 \Gamma_Z^2} + \sigma_{\text{int}} + \sigma_\gamma$$

- Express results in terms of minimal correlated variables:
  - m_Z
  - Γ_Z
  - $\sigma_0^{\text{had}} = \frac{12\pi}{m_Z} \frac{\Gamma_e \Gamma_{\text{had}}}{\Gamma_Z^2}$
  - $R_l = \frac{\Gamma_{\text{had}}}{\Gamma_l}$



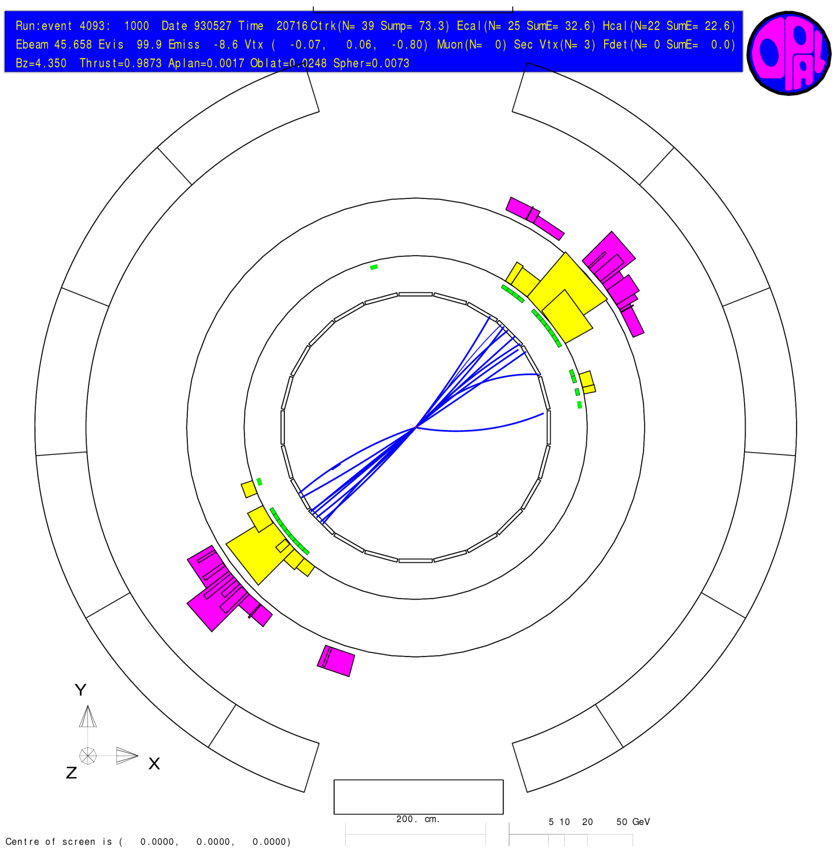
The Z lineshape (ii)

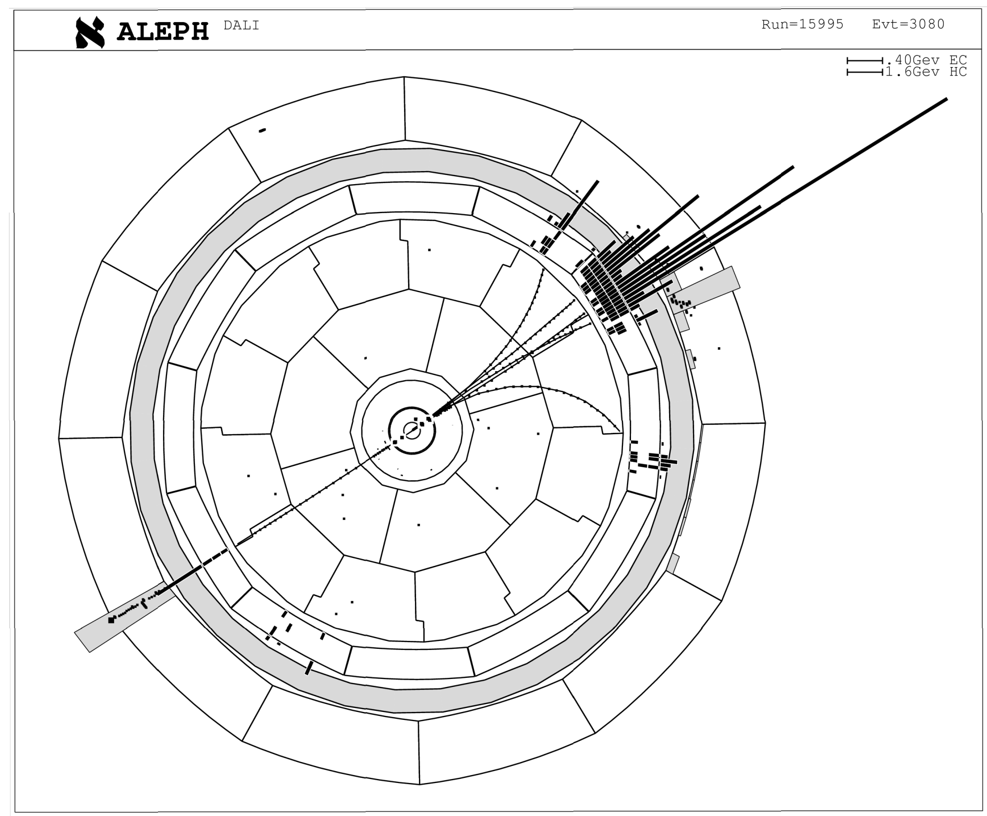
$$\sigma(s) = \frac{N - N_{\rm bg}}{\epsilon\mathcal{L}}$$

- Need to measure
  - Number of events, efficiency background
  - Luminosity
  - Centre of mass energy

Event counting

- Event counting, efficiency, background is easy at LEP



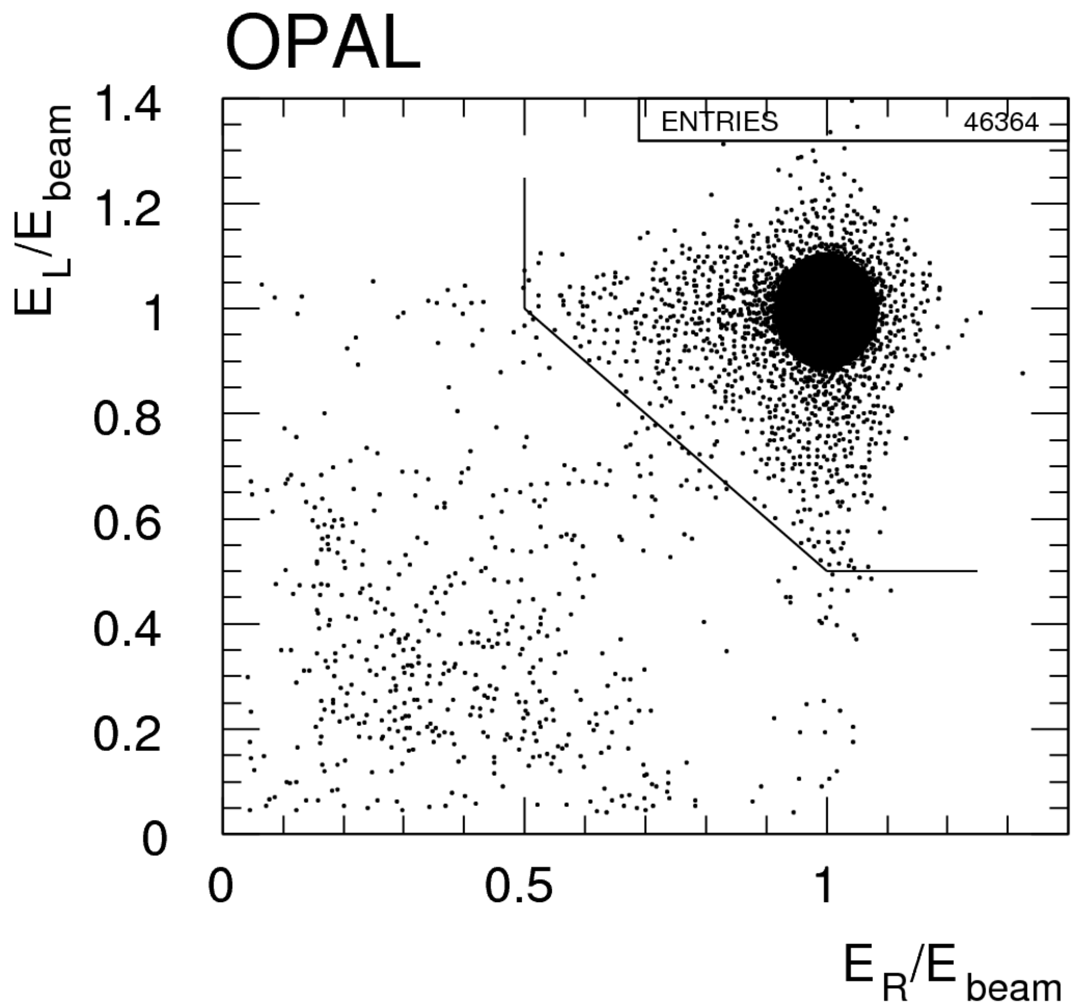


Luminosity measurement

- In principle luminosity can be calculated from machine parameters
- However, if a gauge reaction is available with known cross section,luminosity can be obtained much more precise from this
- Bhabha scattering ($e^+e^- \rightarrow e^+e^-$) at low angles is, apart from small corrections, a pure QED process with a large cross section
- Typical LEP acceptance 30mrad < θ < 180mrad
- Total cross section above $\theta_{min} \sim 1/\theta^3$
- Need to know very precisely the lower acceptance cut (20 μm is needed for <0.1% error)

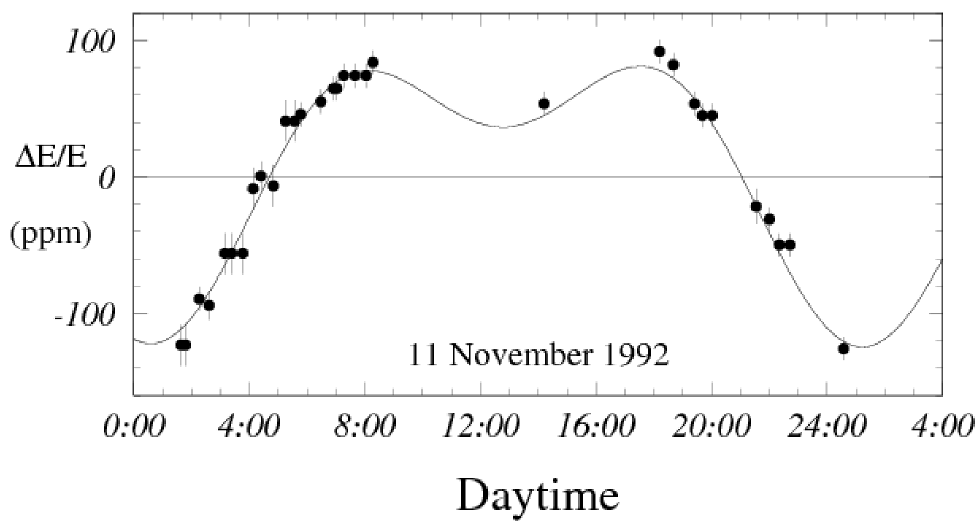
Luminosity measurement (ii)

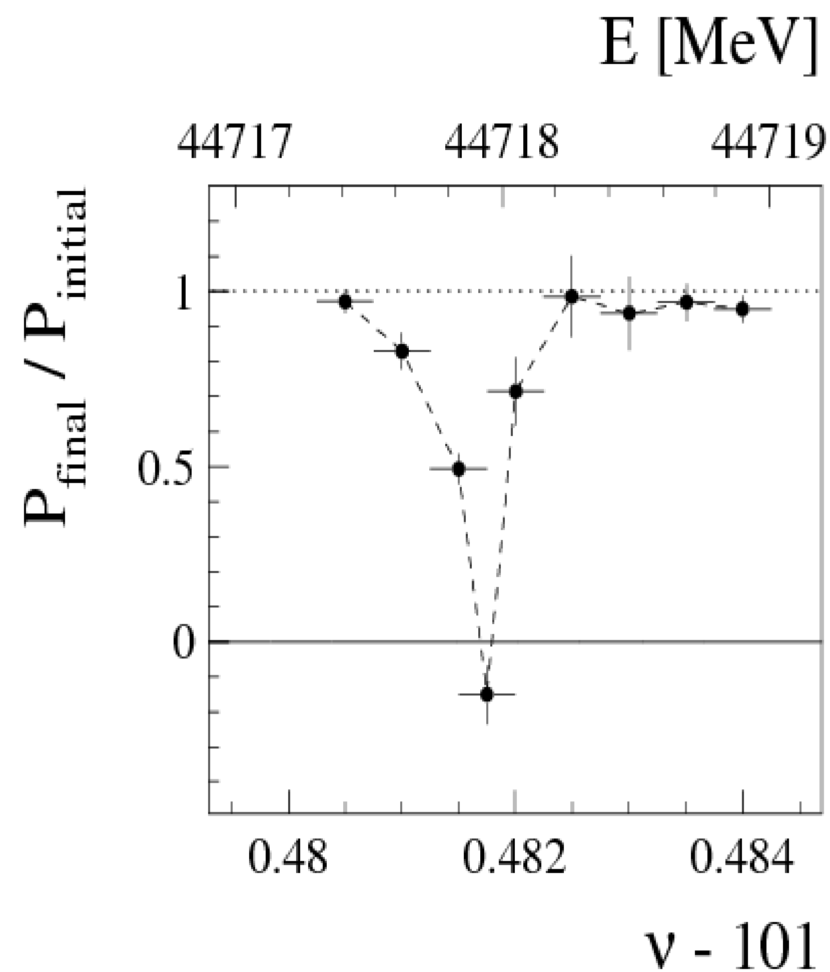
- Experimental accuracy:
  ≈0.05%
- Theoretical accuracy:
  ≈0.05%
- Limiting error for σ_0



Beam energy Measurement

- The beam energy was measured at the end of a fill using resonant depolarisation with 0.2MeV precision
- However several corrections for time drifts have to be applied: e.g.
  - Earth tides: <15MeV

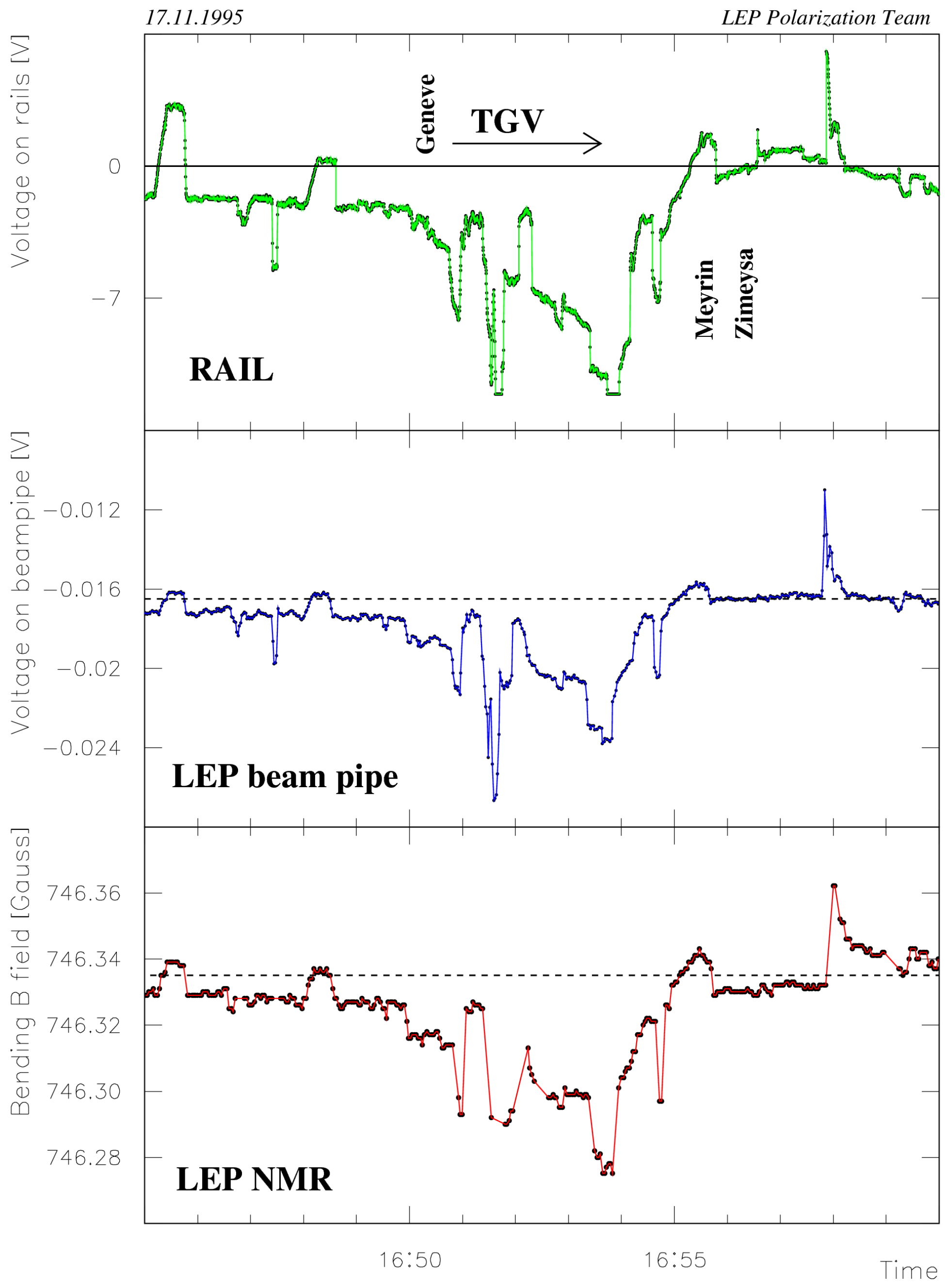




Beam energy Measurement

- Hysteresis effect from TGV Geneva-Bellegarde

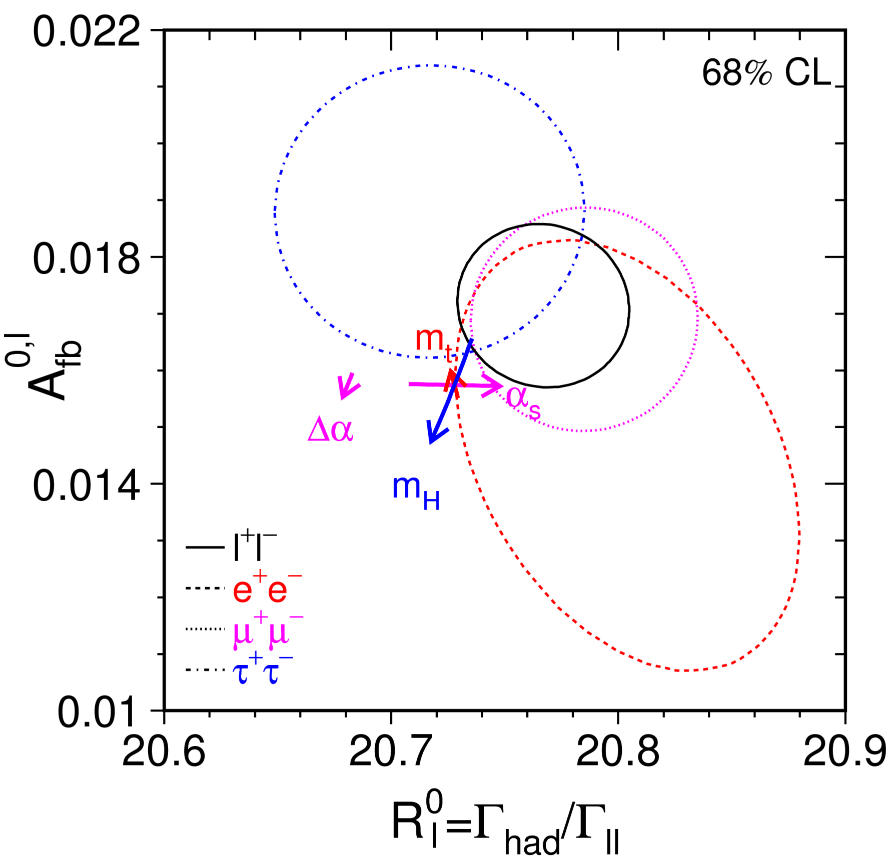
- Total error from beam energy:
  - Δm_Z = 1.7MeV
  - $\Delta \Gamma_Z$ = 1.2 MeV

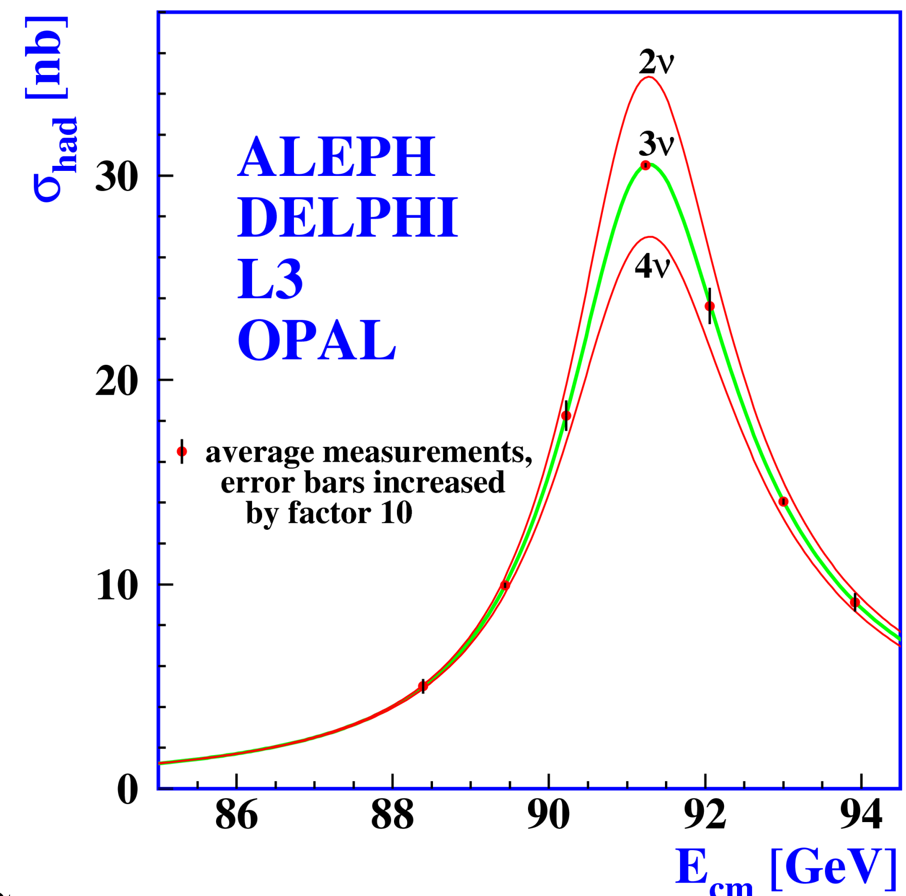


Z-scan results

- Results agree well with lepton universality
- The results establish clearly 3 light neutrino species

- $M_Z = 91.1875 \pm 0.0021$ GeV
- $\Gamma_Z = 2.4952 \pm 0.0023$ GeV
- $\sigma_0^{had} = 41.540 \pm 0.037$ nb
- $R_l = 20.767 \pm 0.025$





Measurements of the weak mixing angle

- $\sin^2\theta_{eff}$ is sensitive to g_V/g_A and measured from asymmetries
- Available asymmetries:
  - Forward-backward asymmetry

$$A^f_{\mathrm{FB}} = \frac{N_{\mathrm{F}} - N_{\mathrm{B}}}{N_{\mathrm{F}} + N_{\mathrm{B}}} = \frac{3}{4}\mathcal{A}_e\mathcal{A}_f$$

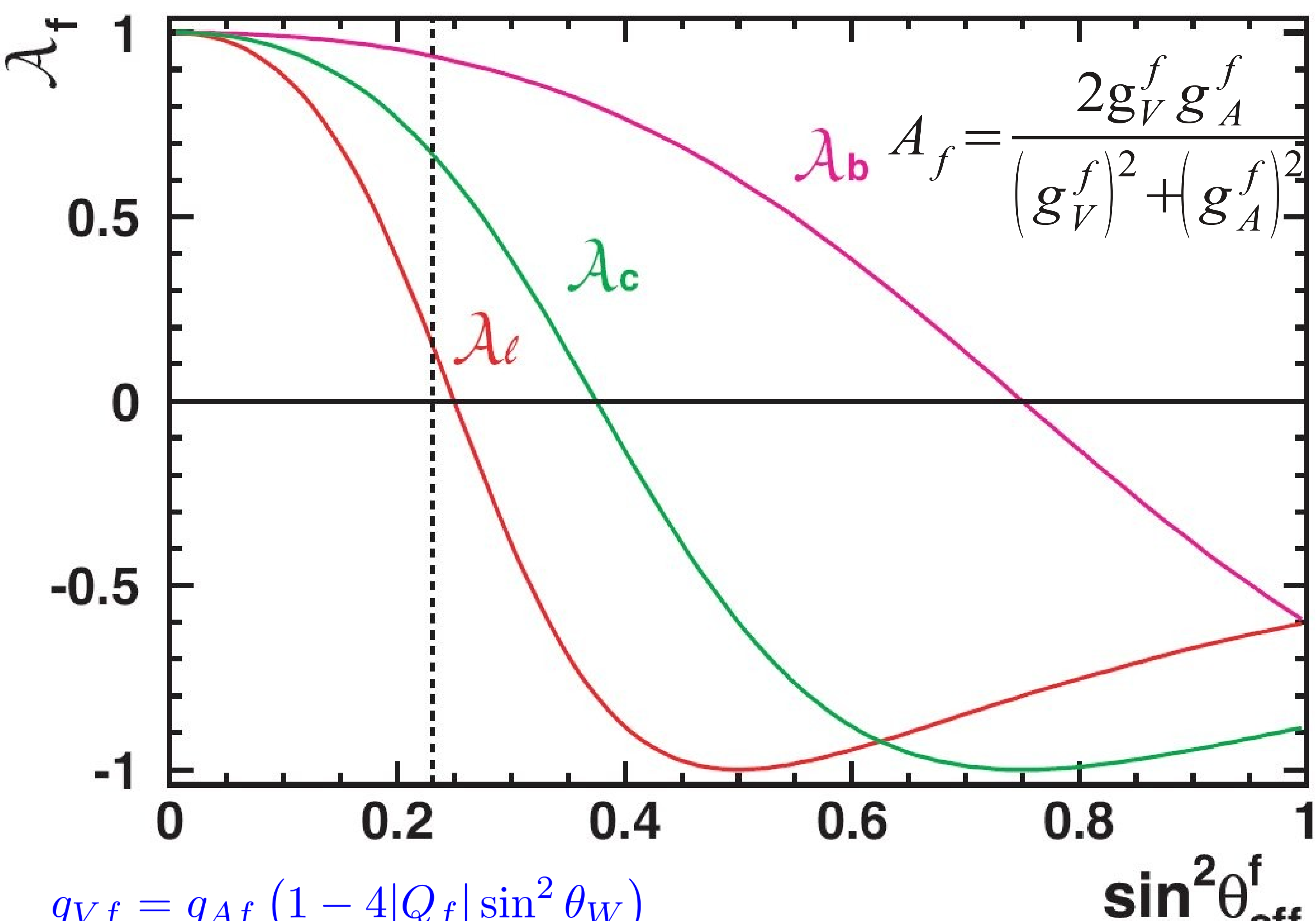
  - Left right asymmetry with polarised beams

$$A_{\mathrm{LR}} = \frac{1}{\mathcal{P}}\frac{N_{\mathrm{L}} - N_{\mathrm{R}}}{N_{\mathrm{L}} + N_{\mathrm{R}}} = \mathcal{A}_e$$

  - τ-polarisation

$$\mathcal{P}_\tau(\cos\theta) = \frac{\mathcal{A}_\tau(1+\cos^2\theta) + 2\mathcal{A}_e\cos\theta}{(1+\cos^2\theta) + 2\mathcal{A}_\tau\mathcal{A}_e\cos\theta}$$

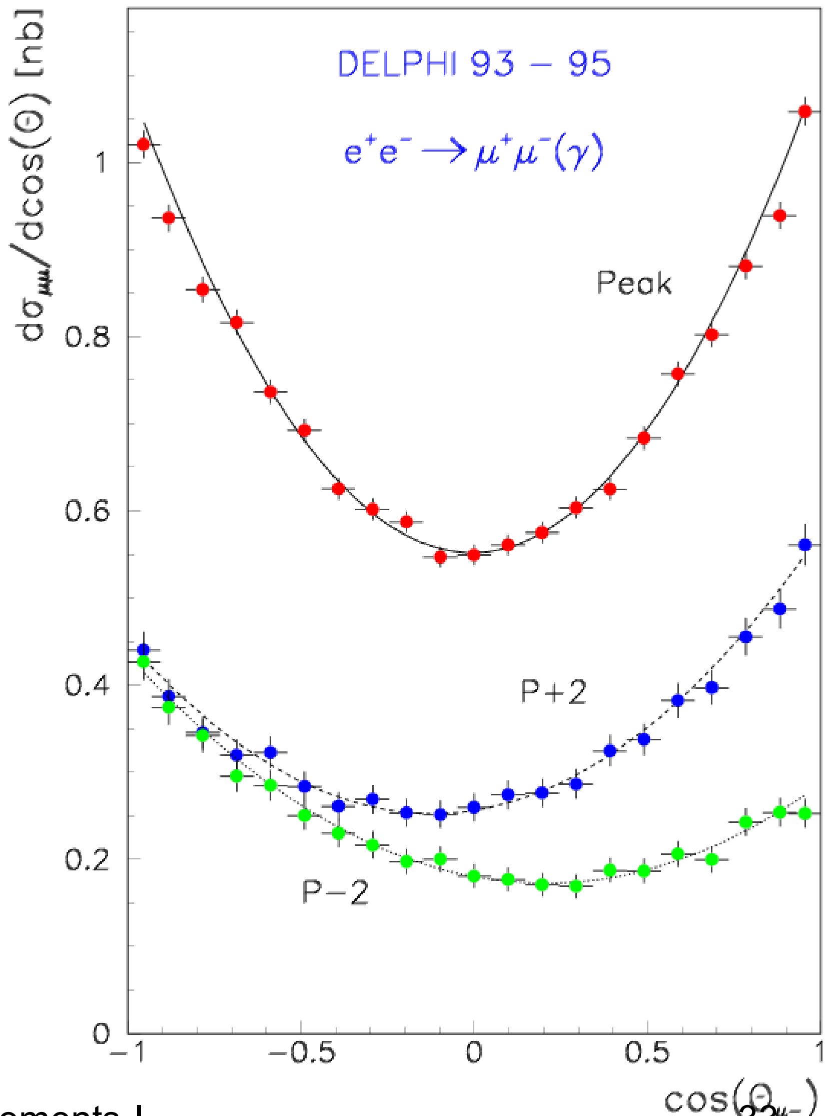
Sensitivity of the As on $\sin^2\theta_{eff}$



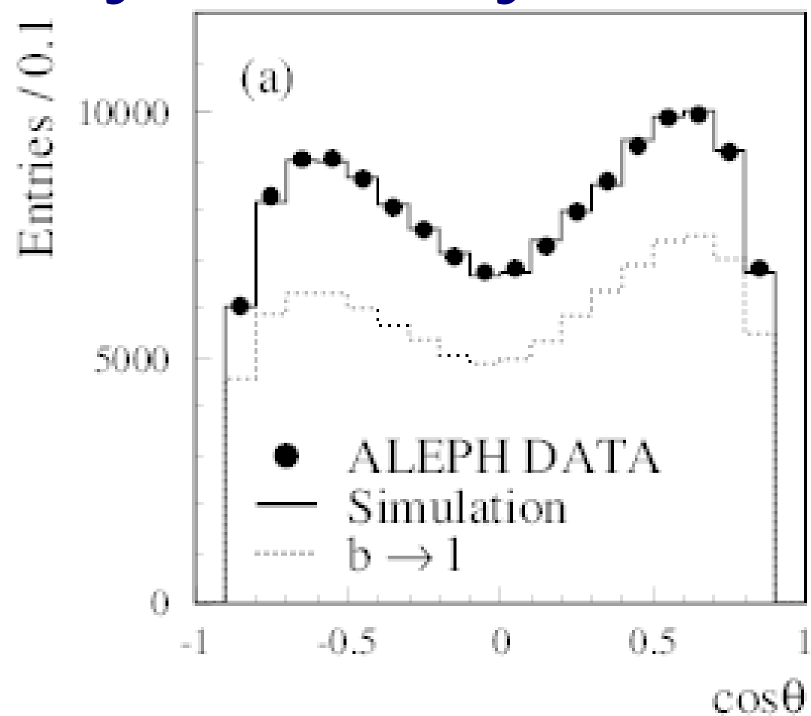
$$g_{Vf} = g_{Af}\left(1 - 4|Q_f|\sin^2\theta_W\right)$$

Forward-backward asymmetry for leptons

- Relatively easy and clean measurement
- However because of quadratic dependence on $\mathcal{A}_l$ and $\mathcal{A}_l$≈0.15 sensitivity to $\sin^2\theta$ low
- Because of large √s dependence technically included in scan



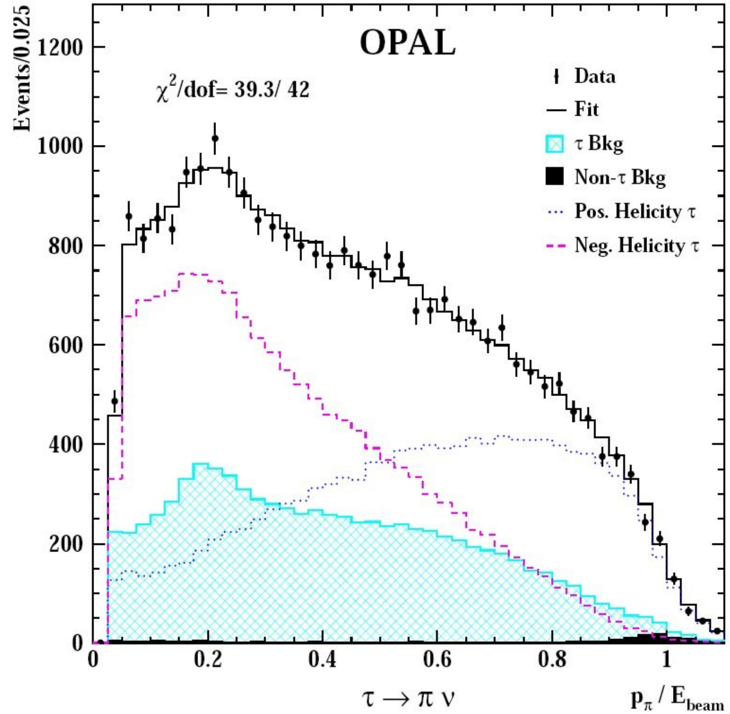
Forward-back asymmetry for quarks

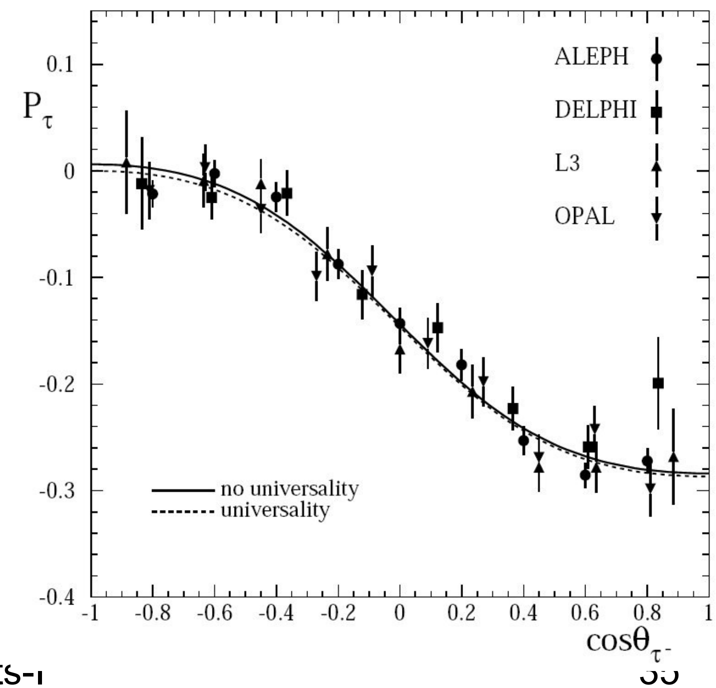


- A_{FB} can be measured for b- and c-quarks
- Because $\mathcal{A}_b$ is large ($\mathcal{A}_b$≈0.94) A_{FB}^b is a clean measurement of $\sin^2\theta^l_{eff}$
- The branching ratio $Z \rightarrow b\bar{b}$ is large,however one looses due to the b tagging and charge identification
- This is done with leptons or b-tagging+jet-charge
- A_{FB}^b gives the 2nd most precise $\sin^2\theta^l_{eff}$ measurement
- A_{FB}^c is less interesting because of the smaller sensitivity and efficiency

τ-polarisation

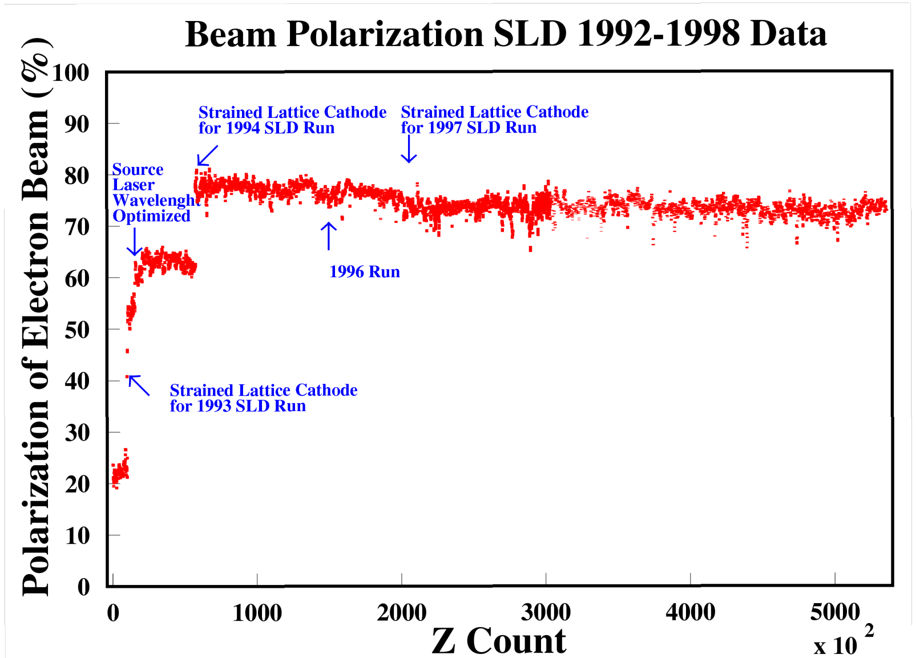
- The τ-polarisation is measured from the energy spectrum of the τ-decay products
- Especially sensitive are the τ→πν and τ→ρν decays
- Using the angular dependence $\mathcal{A}_e$ and $\mathcal{A}_\tau$ can be measured independently





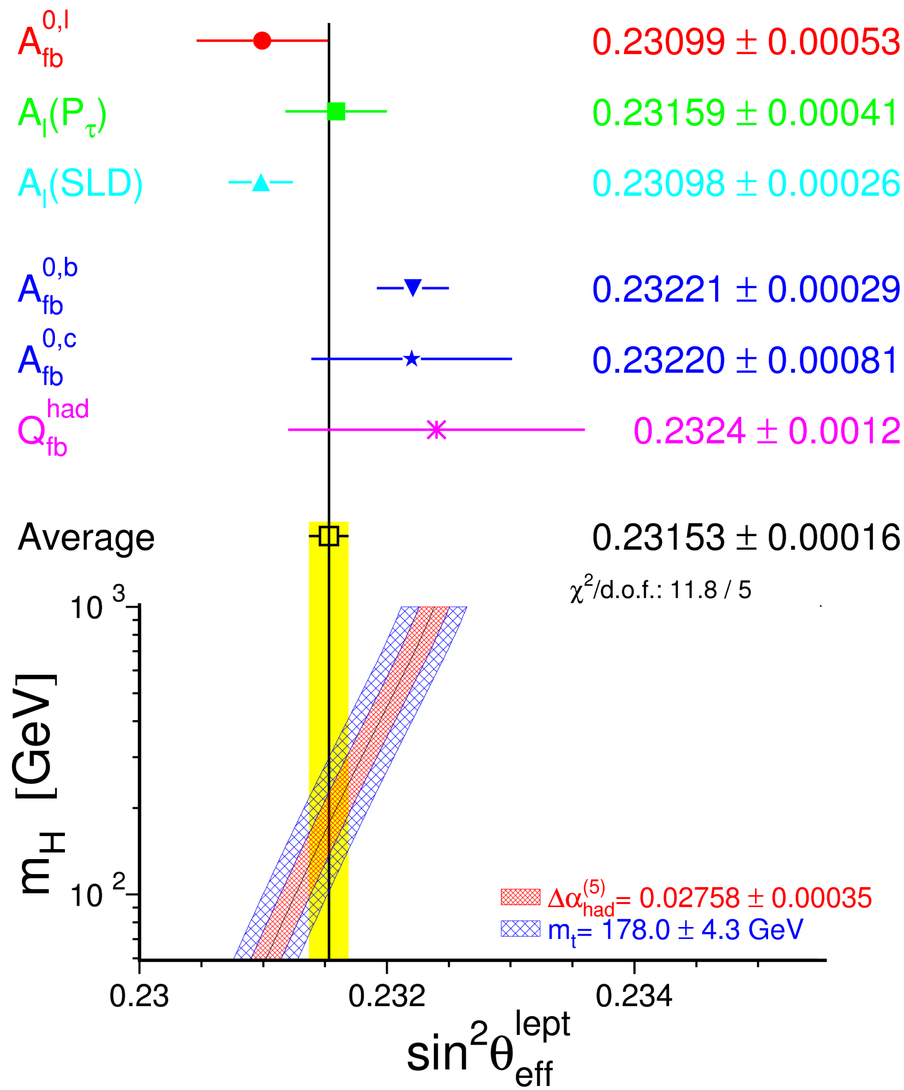
Left-right asymmetry

- ALR measures $\mathcal{A}_e$ independent of the final state → all final states can be used without flavour tagging
- The statistical error gets small quickly if polarisation is high
- The challenge of the experiment is an accurate polarisation measurement



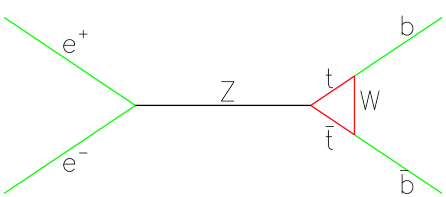
$\sin^2\theta_{eff}$ results

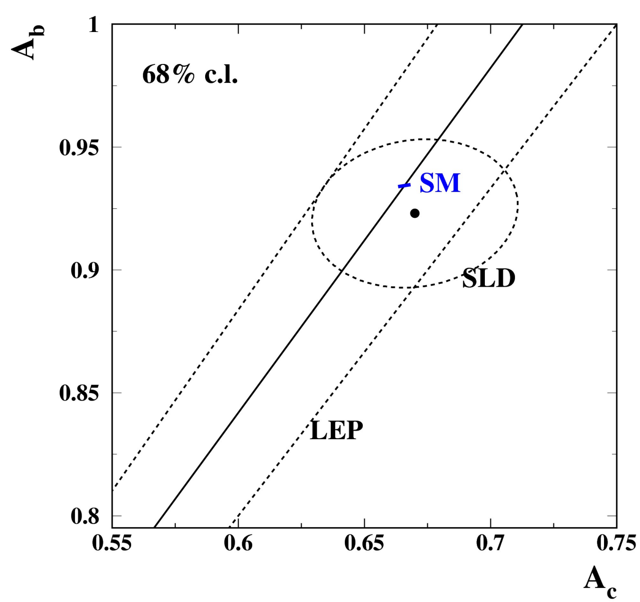
- Slight tension (3.2σ) between most precise measurements
- Both measurements are statistics limited
- No sign for a problem, so probably statistical fluctuation
- Total precision $1.6\cdot10^{-4}$
- Restricts Higgs-mass on its own

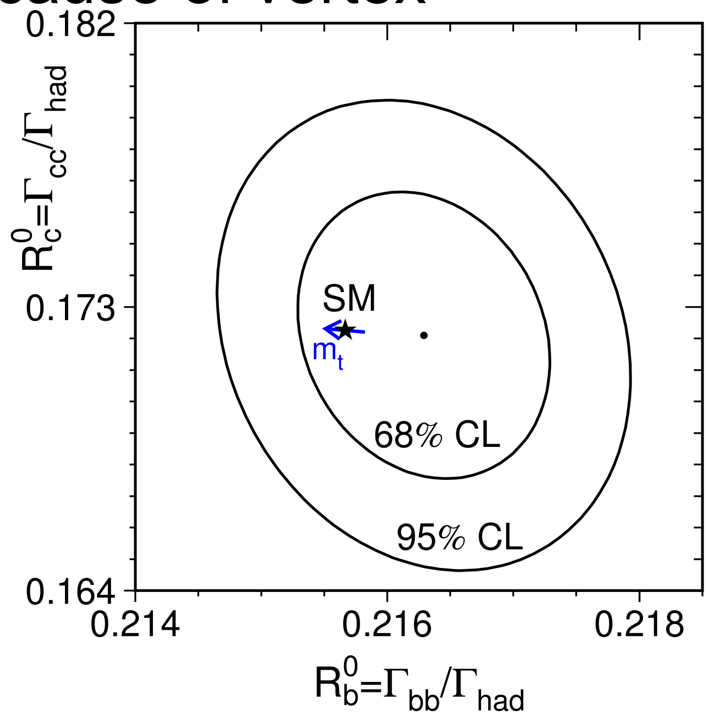


Heavy flavour results

- The partial width ratios R_b, R_c ($R_q = \Gamma_q \Gamma_{had}$) can be measured at LEP/SLC using b/c-tagging
- The coupling parameters $\mathcal{A}_{b/c}$ can be measured with the left-right-forward-backward asymmetry and the ratio $A_{FB}{}^{b}/A_{LR}$
- For b-quarks this is interesting because of vertex corrections with top quarks







The W-mass at LEP

- W-bosons at LEP are produced in pairs
- The branching ratio $W \to l\nu$ is 1/9 per lepton
  - $WW \to l\nu l\nu$ ($l=e,\mu$): 5%
  - $WW \to l\nu qq$ ($l=e,\mu$): 30%
  - $WW \to qqqq$: 44%
  - Rest involving τs
- The W mass must be reconstructed from the final state
- To improve the energy resolution of jets the 4-momentum constraint is needed

Constraint fits

- 4-momentum conservation gives 4 constraints
- For a WW→qqqq event this is sufficient to get the 4 jet energies assuming the jet directions are well measured
- For WW→lνqq (l=e,μ) events 3 constraints are used to "measure" the neutrino
- One can also assume that both Ws have the same mass to fix the jet energies also in this case
- In WW→lνlν events and in events with τs due to additional neutrinos there are not enough constraints so that the resolution is worse
- In all cases due the constraints the measurements are sensitive to the beam energy

WW→lνqq

- Cleanest mode with good resolution
- Very little background
- Result statistics dominated

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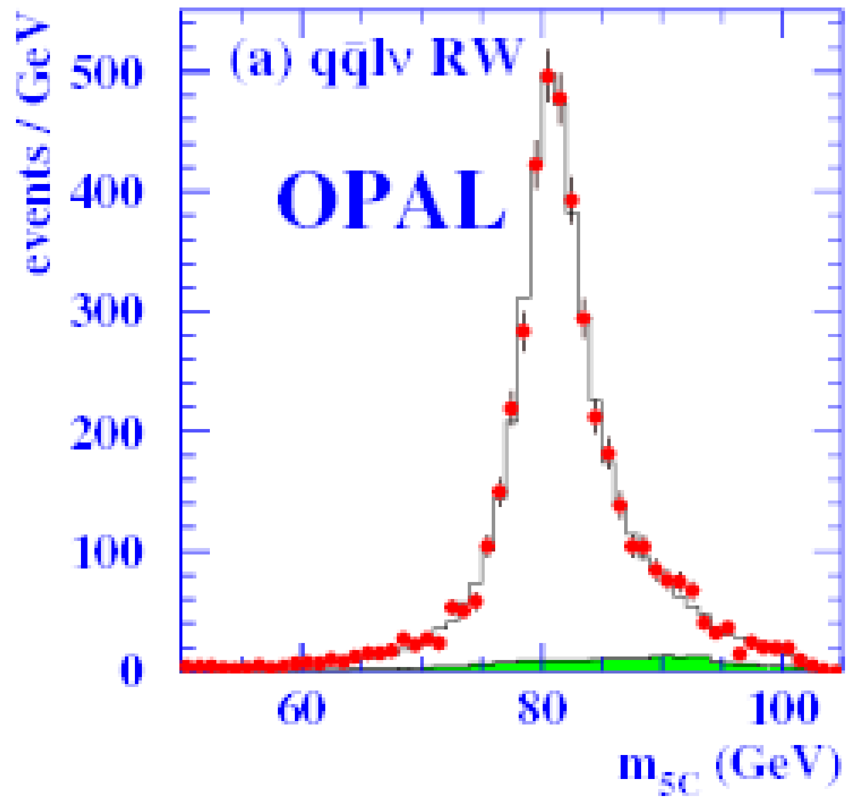

$m_W(l\nu qq) = 80.372 \pm 0.030(stat) \pm 0.021(syst)$ GeV

WW→qqqq

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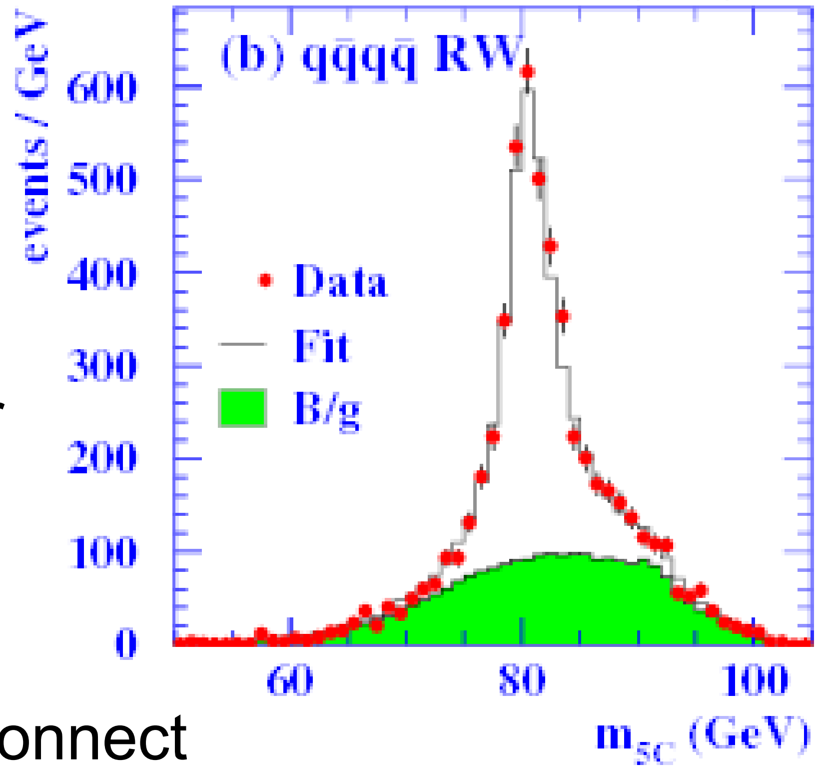


- Largest dataset with no missing information
- In principle very good resolution
- However serious problem: colour reconnection
  - W-lifetime shorter than fragmentation time
  - Colour stings of two Ws can connect
  - Mass of jet-jet system gets distorted
  - Can be partially solved by restriction to high momentum hadrons

    →larger statistical and still substantial systematic error

m_W(qqqq) = 80.387 ±0.040(stat) ±0.044(syst) GeV

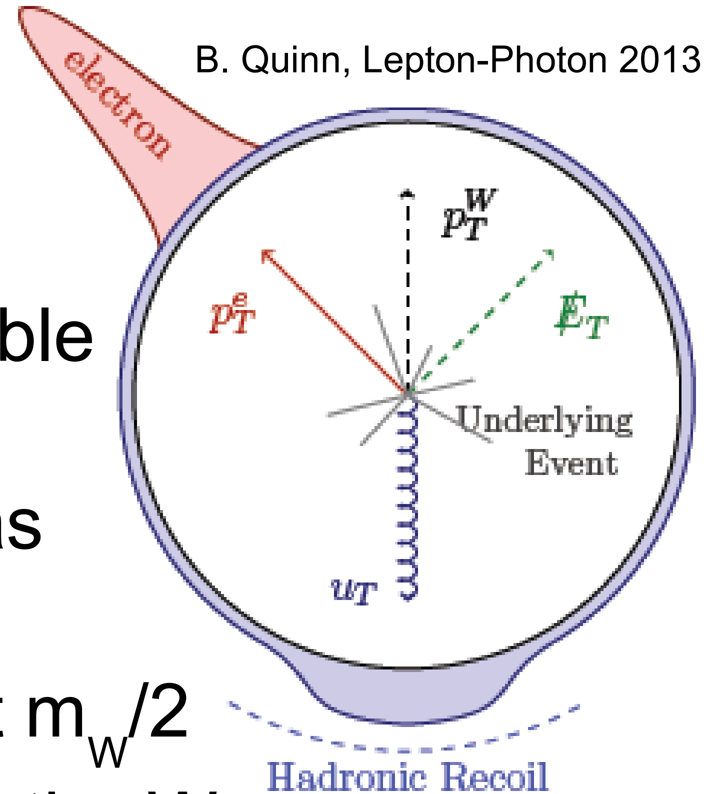
Electroweak measurements at hadron colliders

Generalities

- Hadron colliders have a large cross section for W- and Z-production
- Only the leptonic decays are usable, for the hadronic decays the QCD background is too large
- Since only one parton out of each (anti)proton interacts and the rest disappears in the beampipe the beam energy cannot be used in the analysis
- Transverse momentum conservation can still be used
- Hadron colliders are the only place where top-quarks can be produced up to now

The W-mass at the Tevatron

B. Quinn, Lepton-Photon 2013



- W-bosons are produced in $q\bar{q}'$-annihilation
- Only W→eν,μν decays are usable for analysis
- To first approximation the W has no transverse momentum
- The lepton p_T spectrum ends at $m_W/2$
- From ISR and underlying event the W gets a small p_T, transferring to the lepton
- This can be cured using the transverse mass instead

W-mass observables

- p_t^l: experimentally clean, smeared by p_T^W
- m_T: p_T^W safe, dependent on hadronic resolution

$$m_T = \sqrt{p_T^l E_T^{\text{miss}}(-1 \cos \Delta\Phi)}$$

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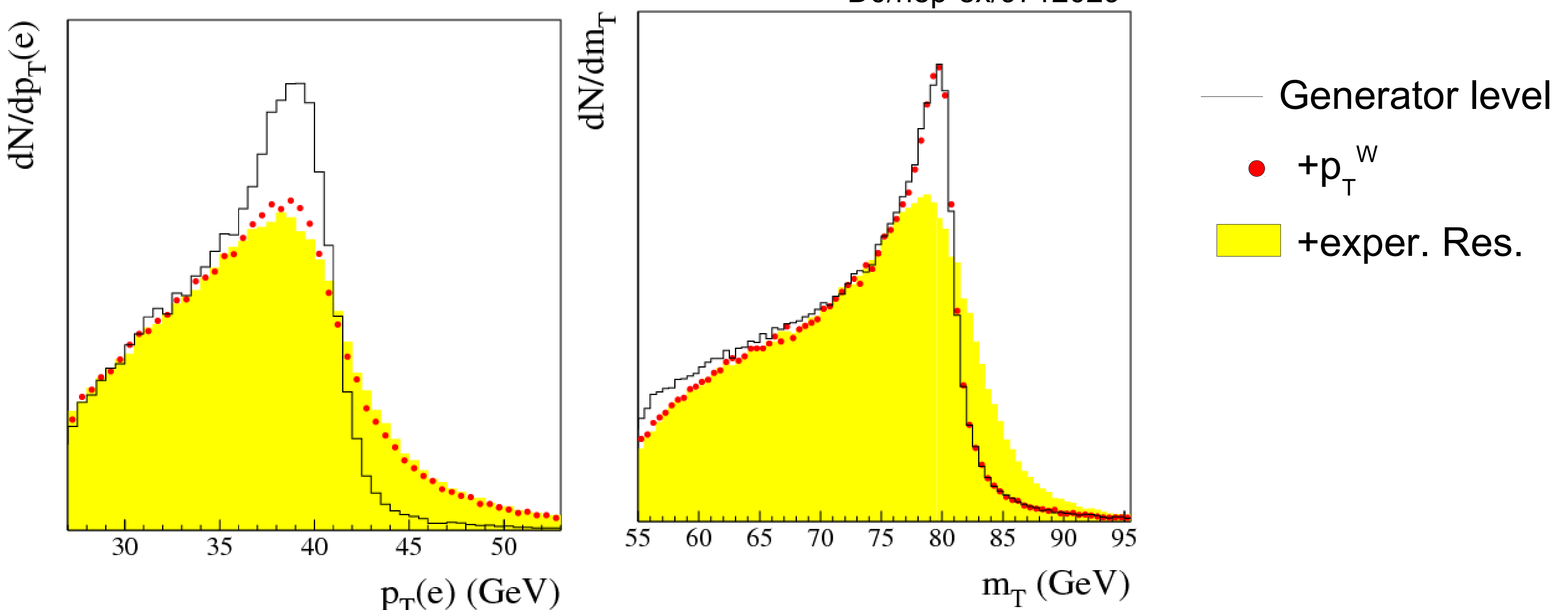
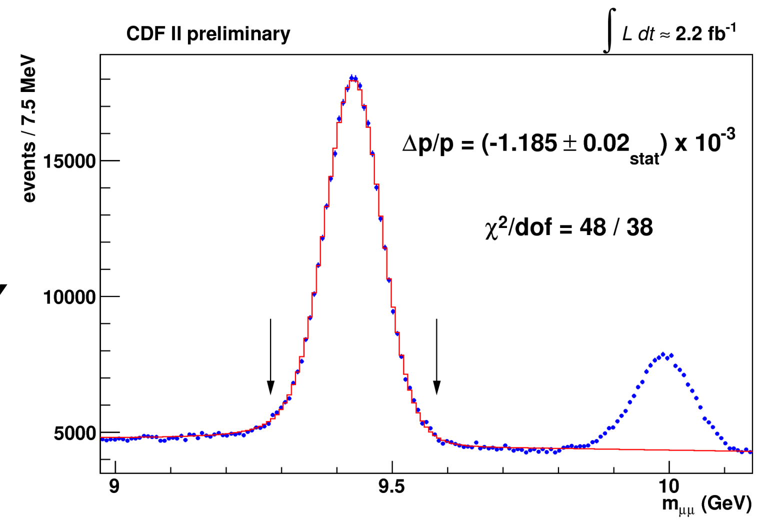
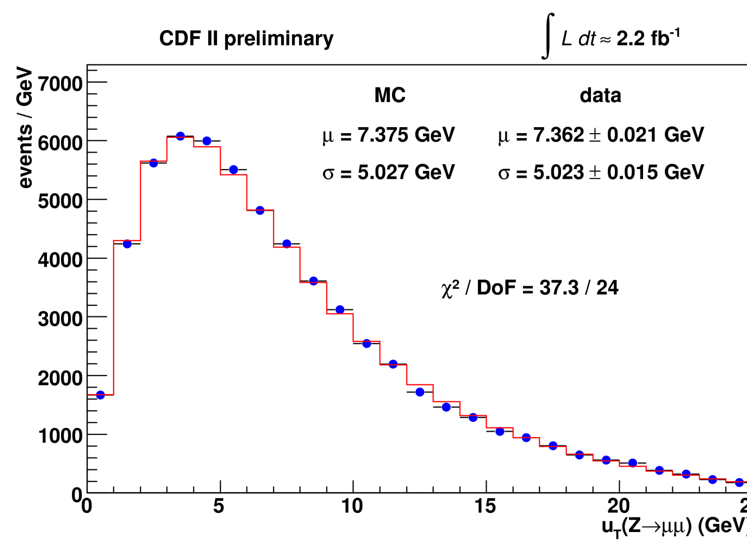


W-mass observables (ii)

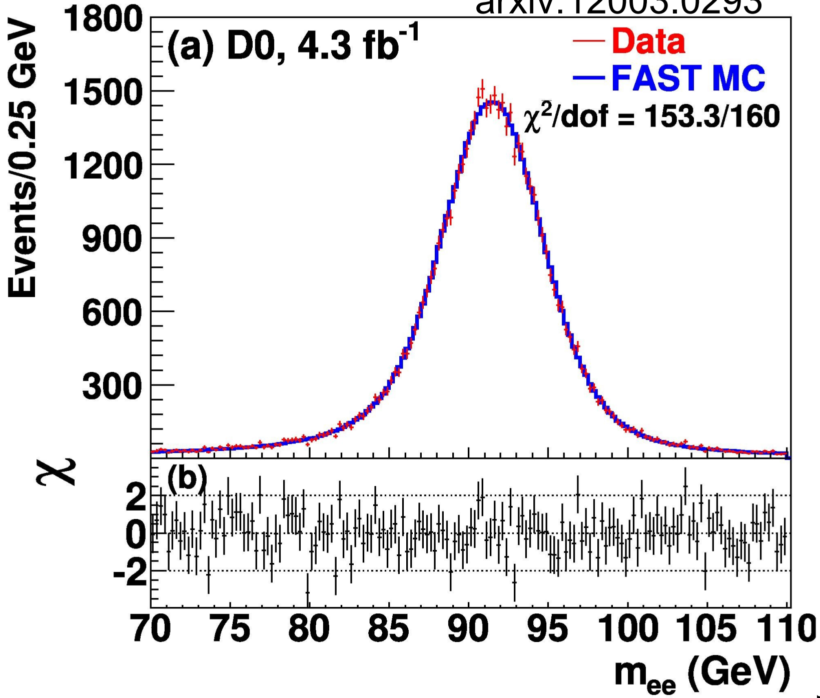
- For Δm_W~10MeV need to know
  - Lepton momentum: 0.01% precision
  - Hadronic recoil: 1% precision
- Must be calibrated using Z, J/Ψ, Υ

arxiv:12003.0275





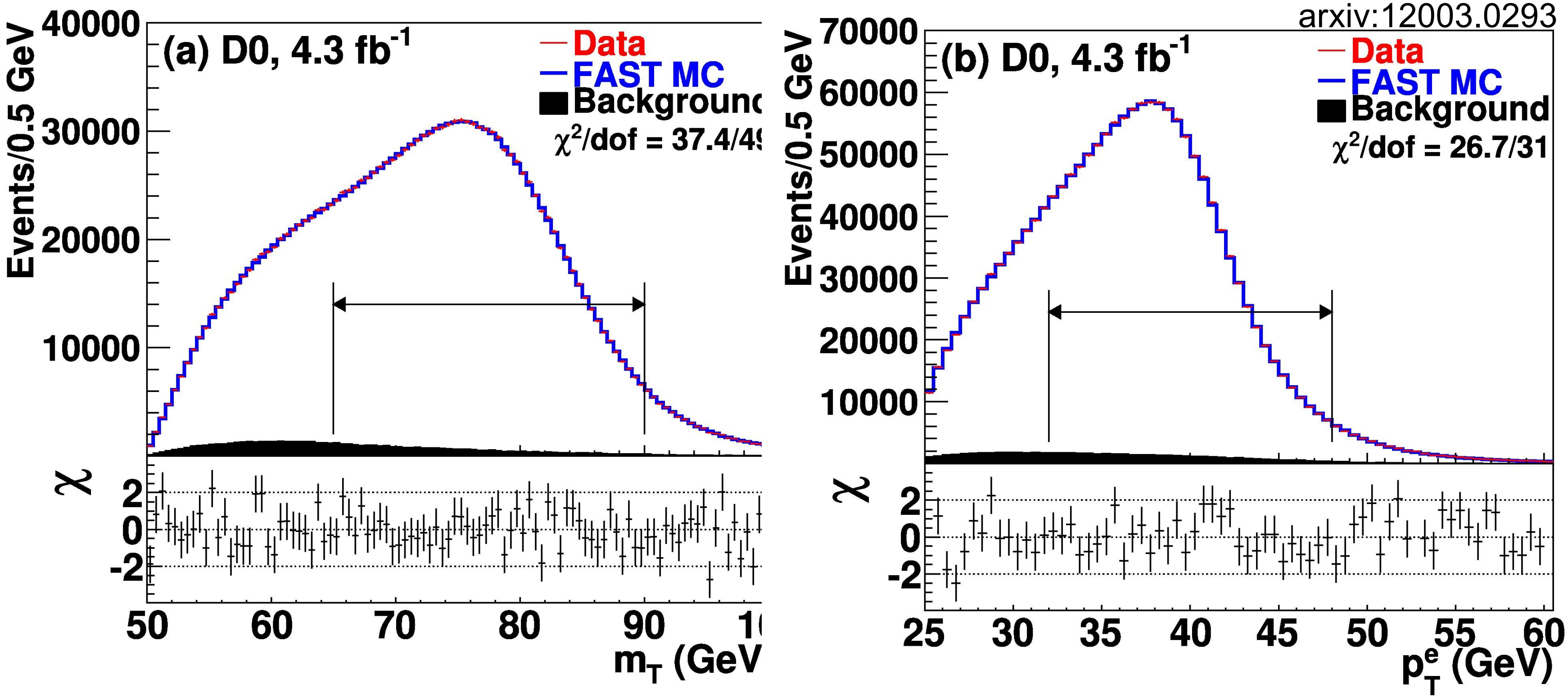
arxiv:12003.0293



W-mass extraction

- The W-mass is obtained from p_T^l and m_T and the results are combined
- m_T has a slightly smaller error but due to the large correlation it carries most of the weight

arxiv:12003.0293



Results

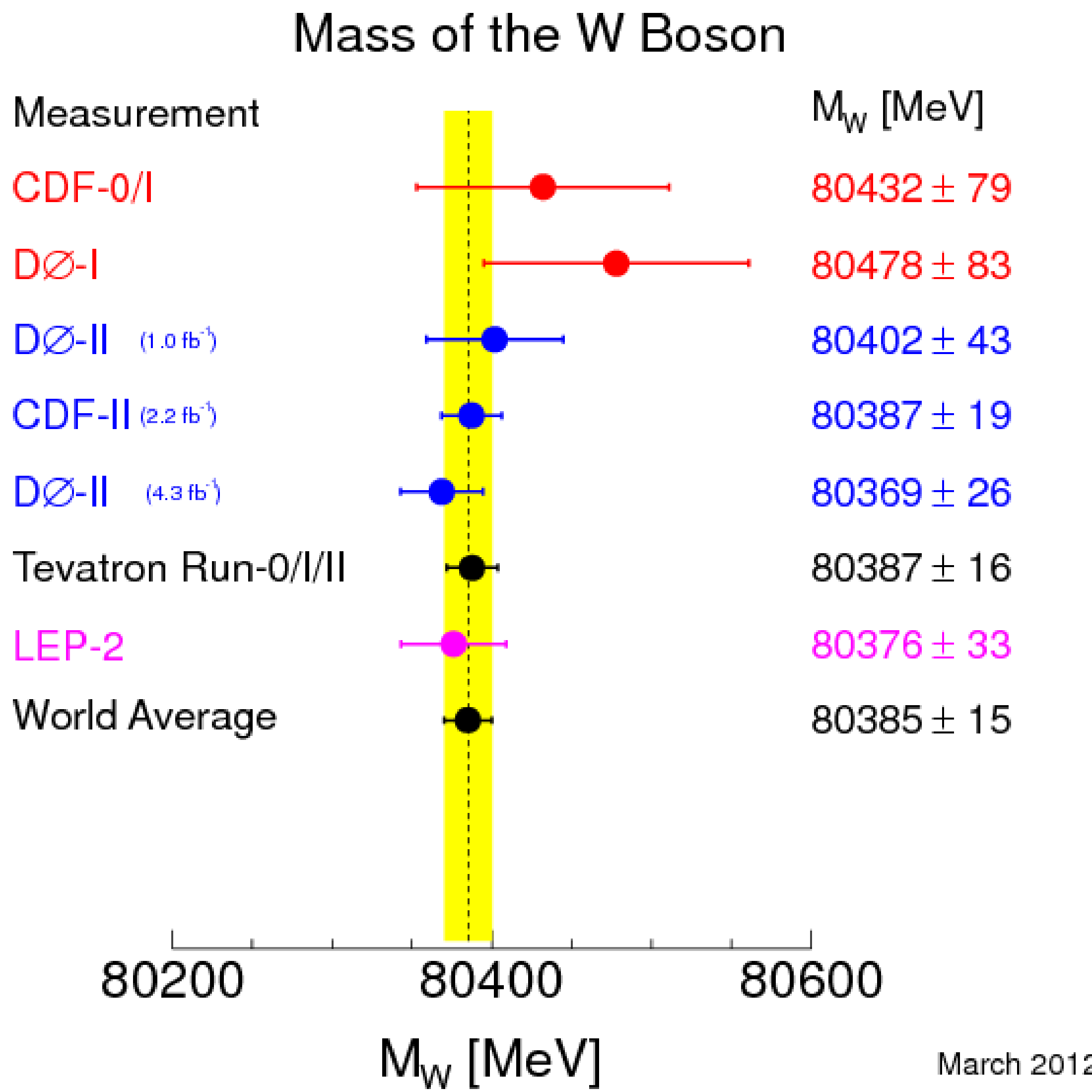
- CDF(2.2 fb^{-1}) m_W=80.387±0.012±0.015 GeV
- D0 (4.3+1.0 fb^{-1}) m_W=80.375±0.011±0.020 GeV

B. Quinn, Lepton-Photon 2013

Source	CDF $m_T(\mu,\nu)$	CDF $m_T(e,\nu)$	DØ $m_T(e,\nu)$
Experimental – Statistical power of the calibration sample.			
Lepton Energy Scale	7	10	16
Lepton Energy Resolution	1	4	2
Lepton Energy Non-Linearity			4
Lepton Energy Loss			4
Recoil Energy Scale	5	5	
Recoil Energy Resolution	7	7	
Lepton Removal	2	3	
Recoil Model			5
Efficiency Model			1
Background	3	4	2
W production and decay model – Not statistically driven.			
PDF	10	10	11
QED	4	4	7
Boson p_T	3	3	2

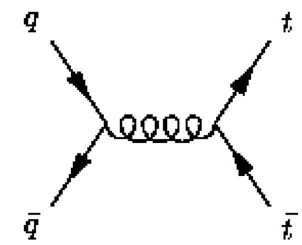
World m_W combination

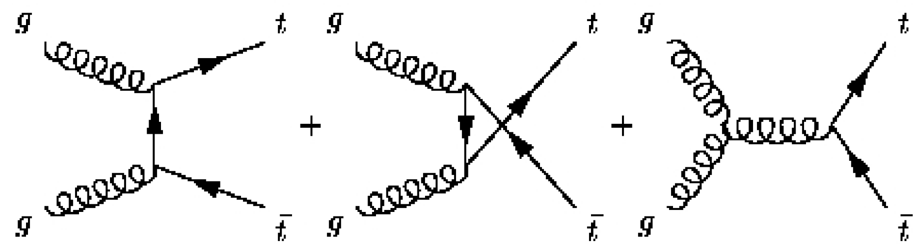
- Current error of combination: 15MeV
- Dominated by Tevatron
- LHC had potential to go to 5 MeV
- However no results yet



Top-quark production

- Top-quarks are produced in pairs
- At the Tevatron they are mainly produced from $q\bar{q}$, at the LHC from gg



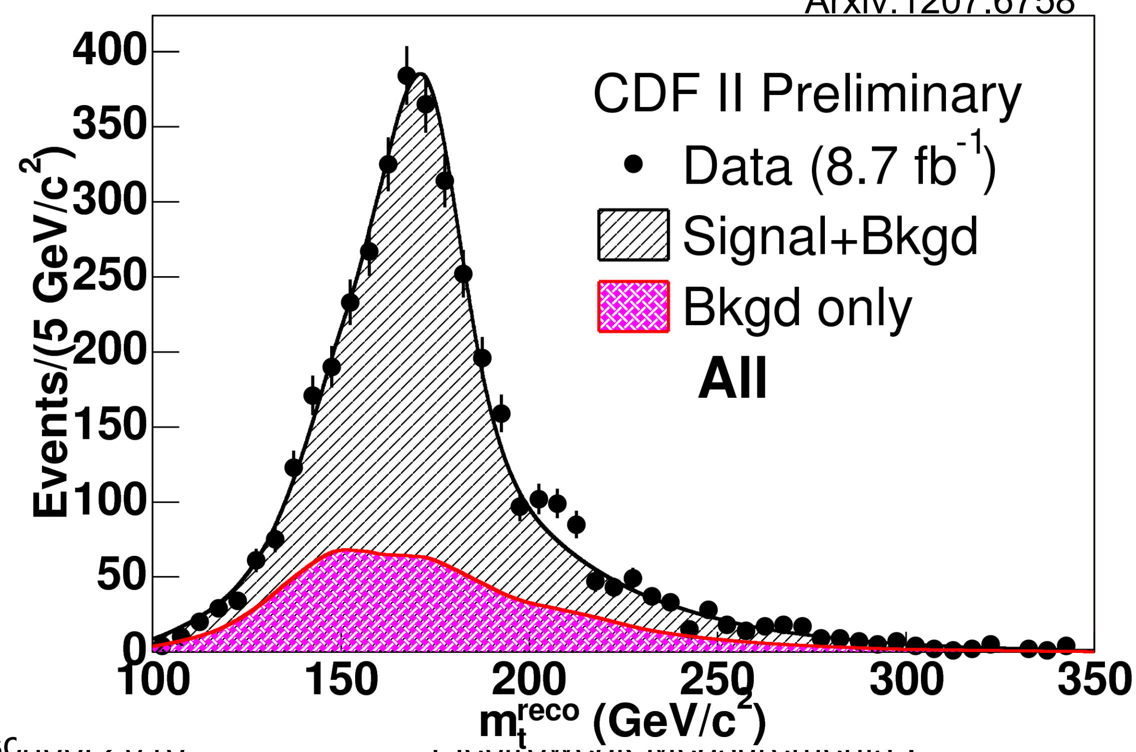


- The top quark decays almost always in Wb with subsequent $W \to l\nu, q\bar{q}'$
- The top mass can be reconstructed from the decay products of the top quark
- The most precise channel it $tt \to WWbb \to l\nu qqbb$ $(l=e,\mu)$

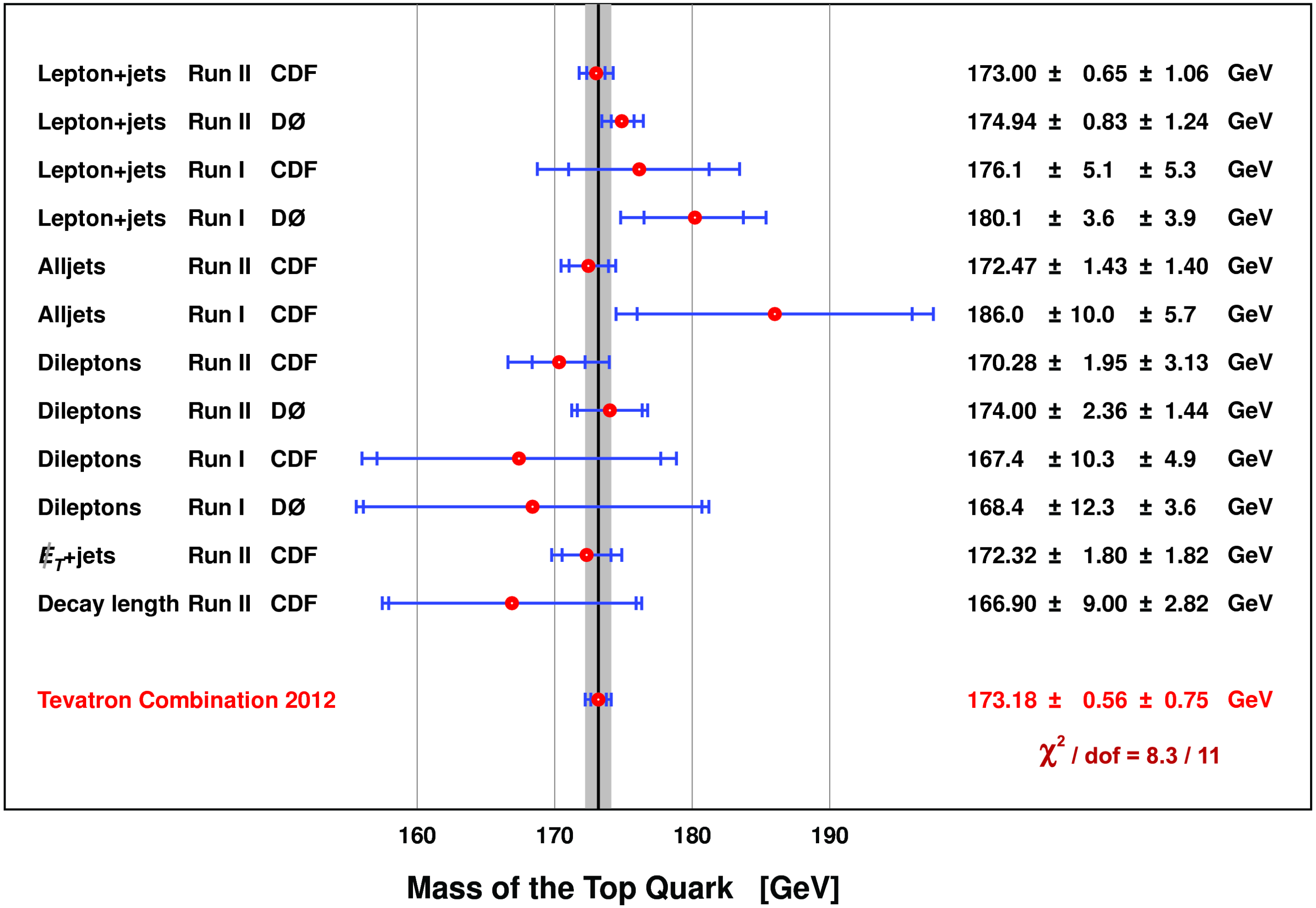
Top-mass measurement

- In tt→lνqqbb events the neutrino can be reconstructed from E_t^{miss} and the W-mass constraint and the jet energy scale can be improved using the W-mass constraint
- This allows to get the JES error to the 0.5GeV and the total error to the 1 GeV level

Arxiv:1207.6758



Top-mass results



- LHC is getting close
- No recent combination exists

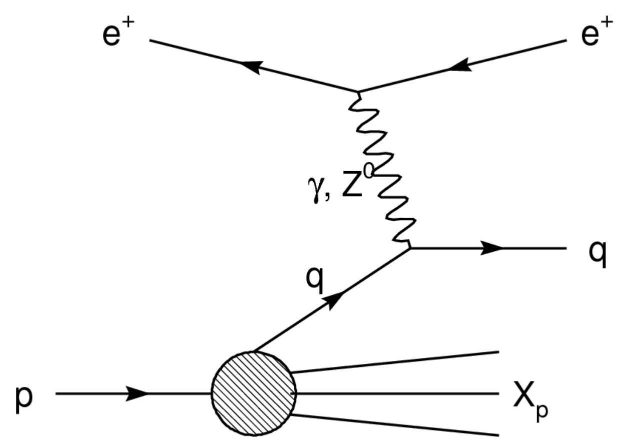
What is the top-mass

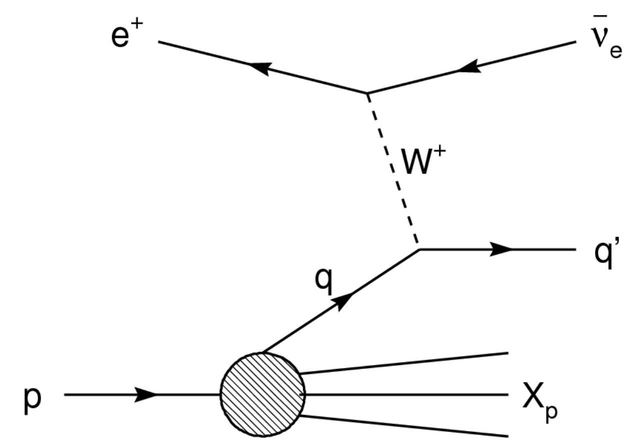
- The top is not a stable particle → the top-mass is not a well defined quantity
- The top is a colour triplet → one can never measure the top-mass from its decay products
- In reality the experiments measure a parameter called top-mass in their Monte Carlo
- This is believed to be close to the pole-mass
- The pole-mass has to be transferred to the running mass for the loop calculations
- In the whole procedure there is room for another error which may be about 1 GeV

Electroweak measurements at HERA

- HERA measured neutral currents and charged currents in polarised e^-p and e^+p scattering
- The data are mainly used for Parton Distribution Functions (PDF)
- However they allow also to measure couplings of quarks to gauge bosons

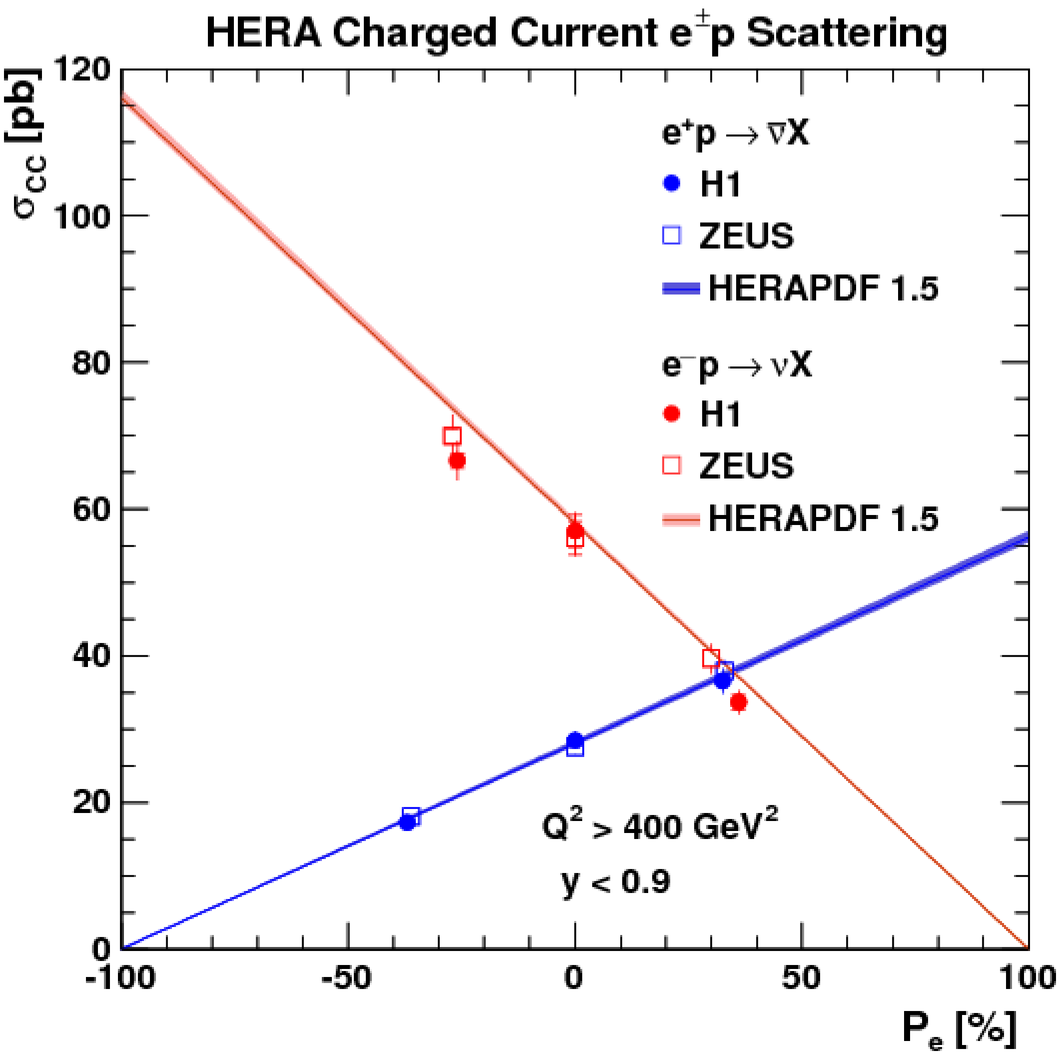
G. Brandt http://www.desy.de/~gbrandt/feyn/





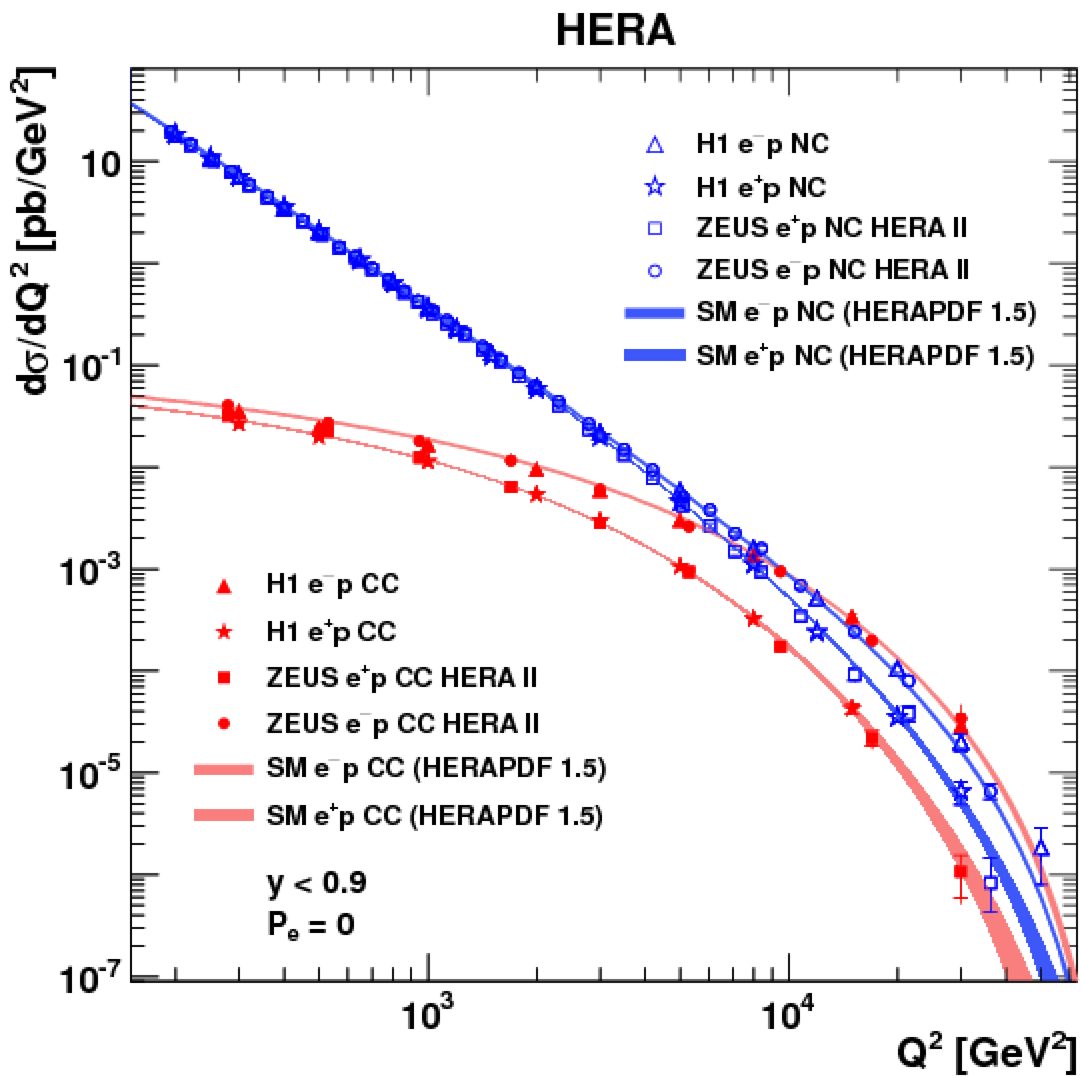
Charged currents at HERA

- Running with different beam polarisations HERA shows clearly that the W couples to left-handed electrons and right-handed positrons



Electroweak unification

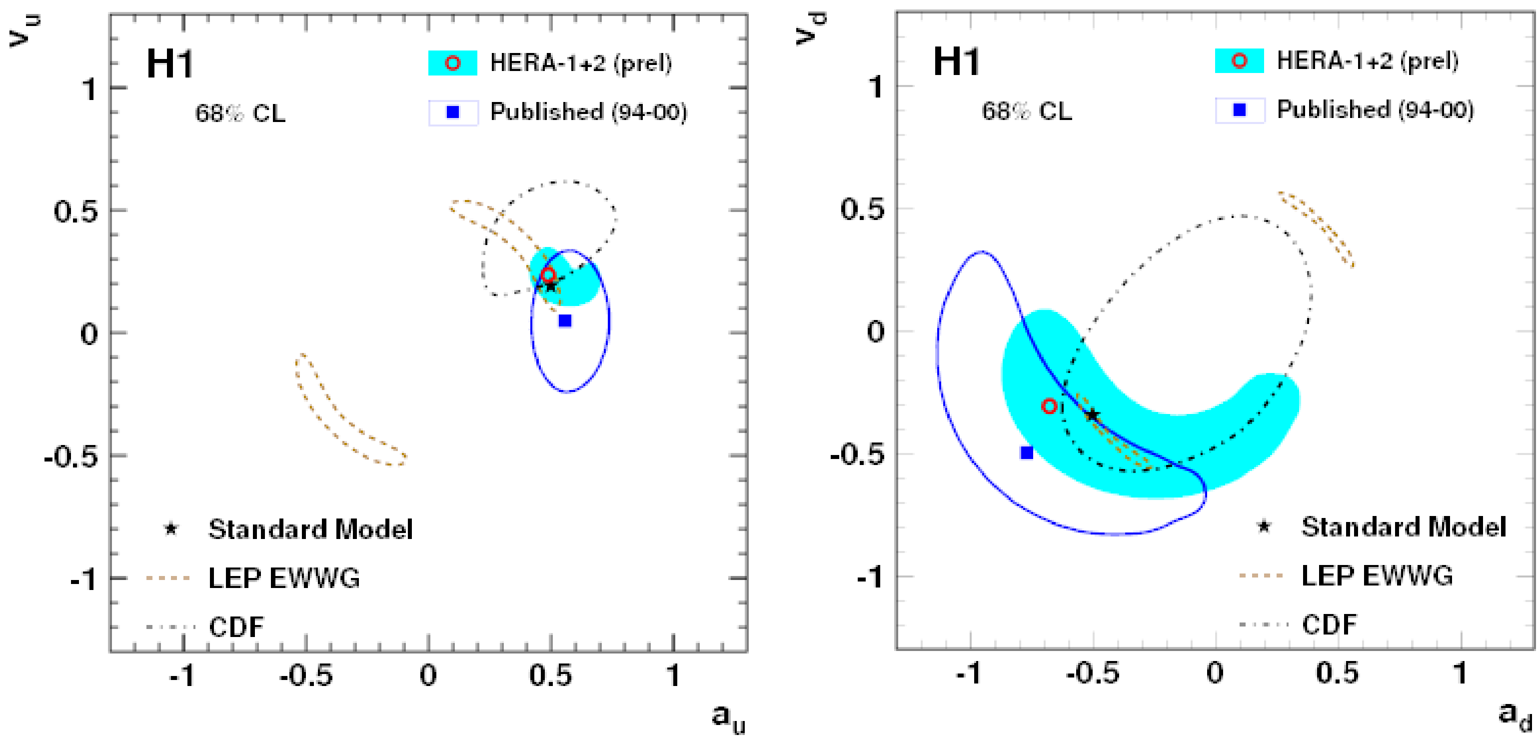
- The cross section of charged and neutral current processes also shows that the electromagnetic and weak forces unify at high energy



Quark couplings

- HERA measures also couplings of the Z to light quarks
- They are however not (yet) interesting for the electroweak fits

Vector and axial-vector couplings of u and d quarks to the Z



Electroweak fits

Idea of electroweak fits

- Observables receive loop corrections from unseen effects
- If the system is overconstrained one can fit for unknown parameters or test the model for consistency
- If precision is better than typical loop factor ($\alpha \approx 1/137$) one can test the model or try to obtain information on new physics in loops

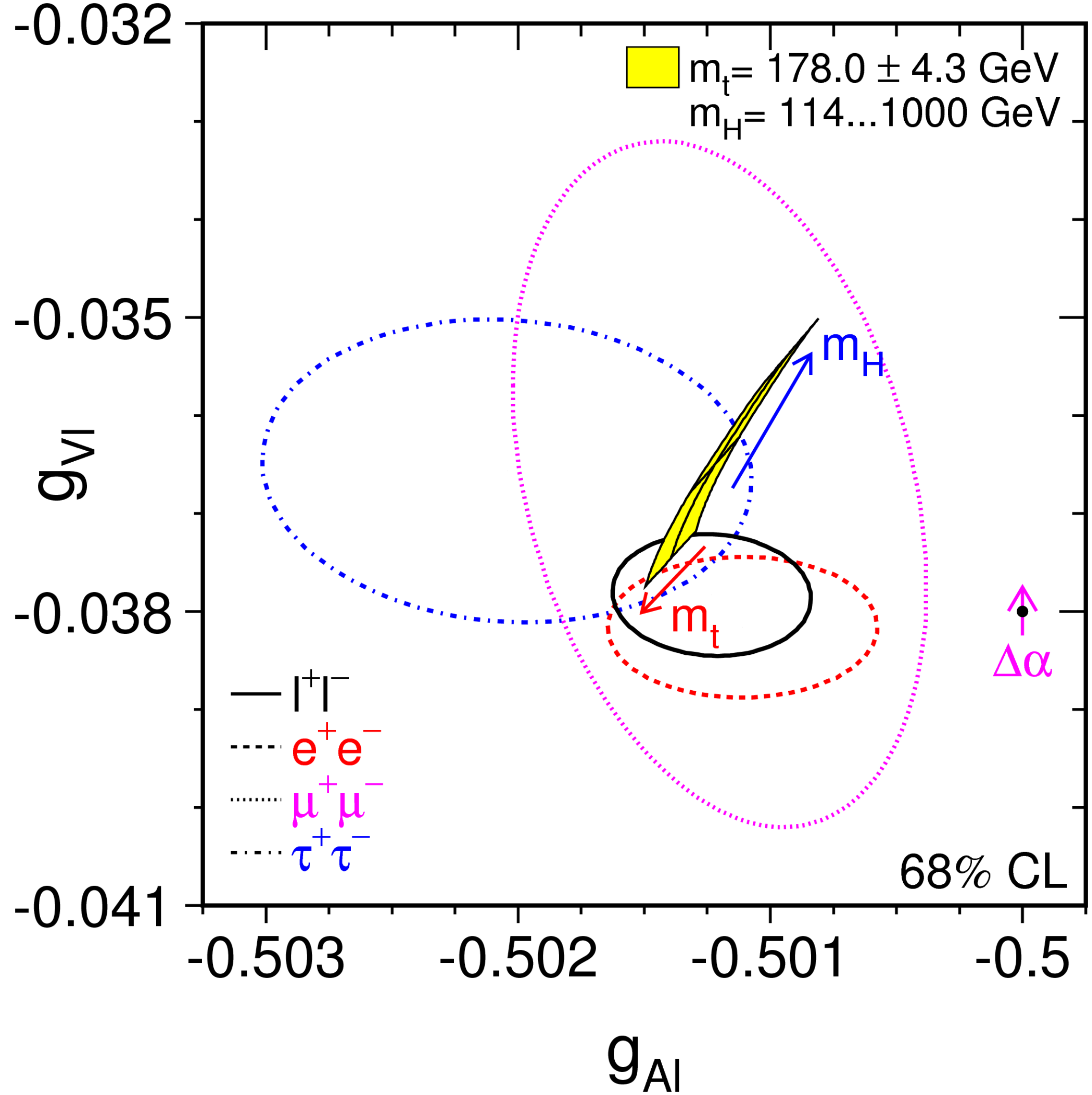
Fixing the Standard Model

- On tree level need three parameters to define electroweak coupling sector (g, g', v)

  → use the most precise: $\alpha(\Delta\alpha/\alpha=3\cdot10^{-9})$, $G_F(\Delta G_F/G_F=5\cdot10^{-7})$, $m_Z(\Delta m_Z/m_Z=2\cdot10^{-5})$
- Fixing the loops: m_t from Tevatron, m_H from LHC
- Running of α:
  - α runs with energy (~+10% up to m_Z)
  - Can be obtained from low energy e^+e^--data and theory
- Other low energy data play only a minor role

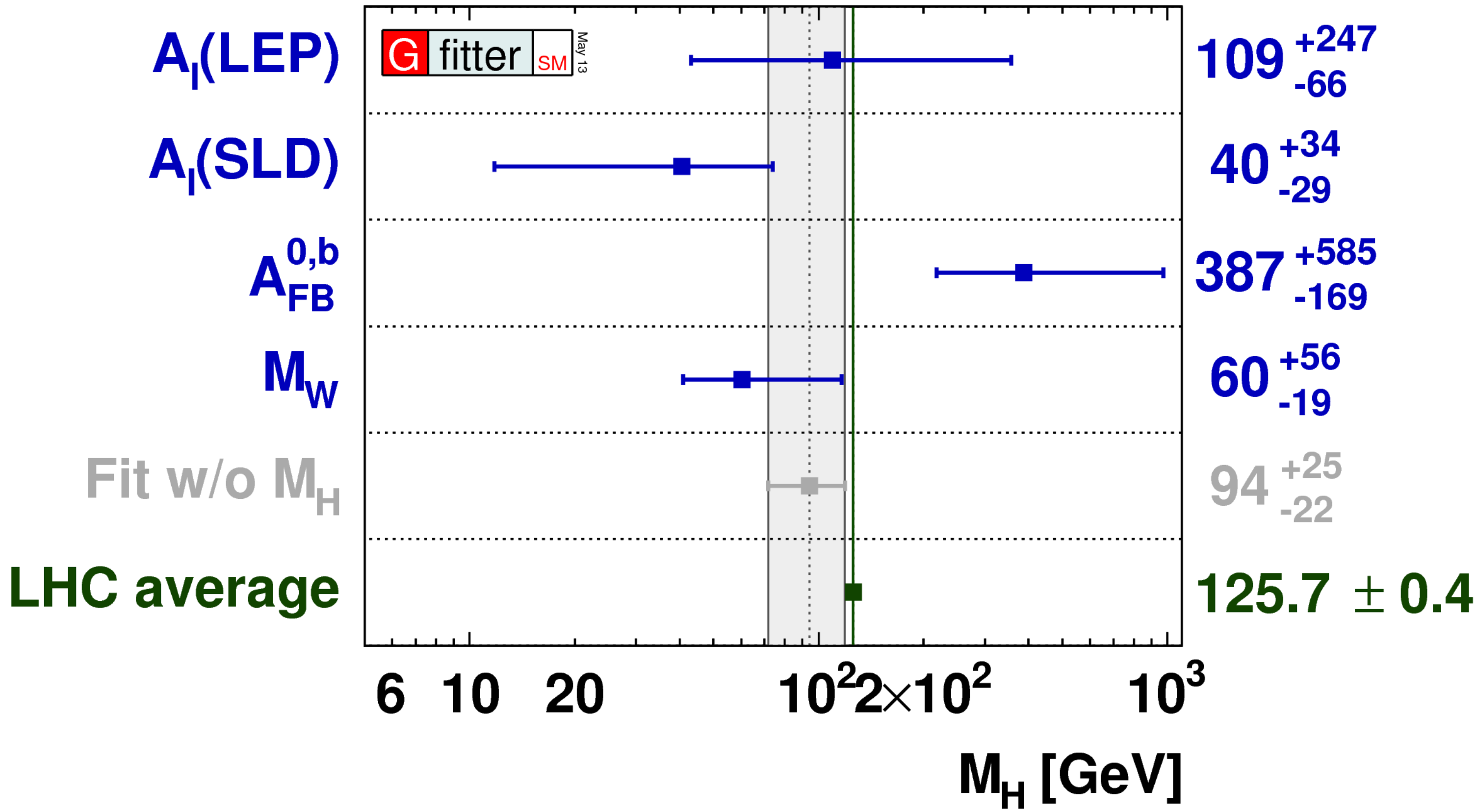
Extraction of weak couplings (ii)

- With the $\sin^2\theta$ and partial width measurements the vector and axial-vector coupling of the Z can be extracted
- The couplings confirm lepton universality to better than a percent and are sensitive to loop-corrections



Individual sensitivity to m_H

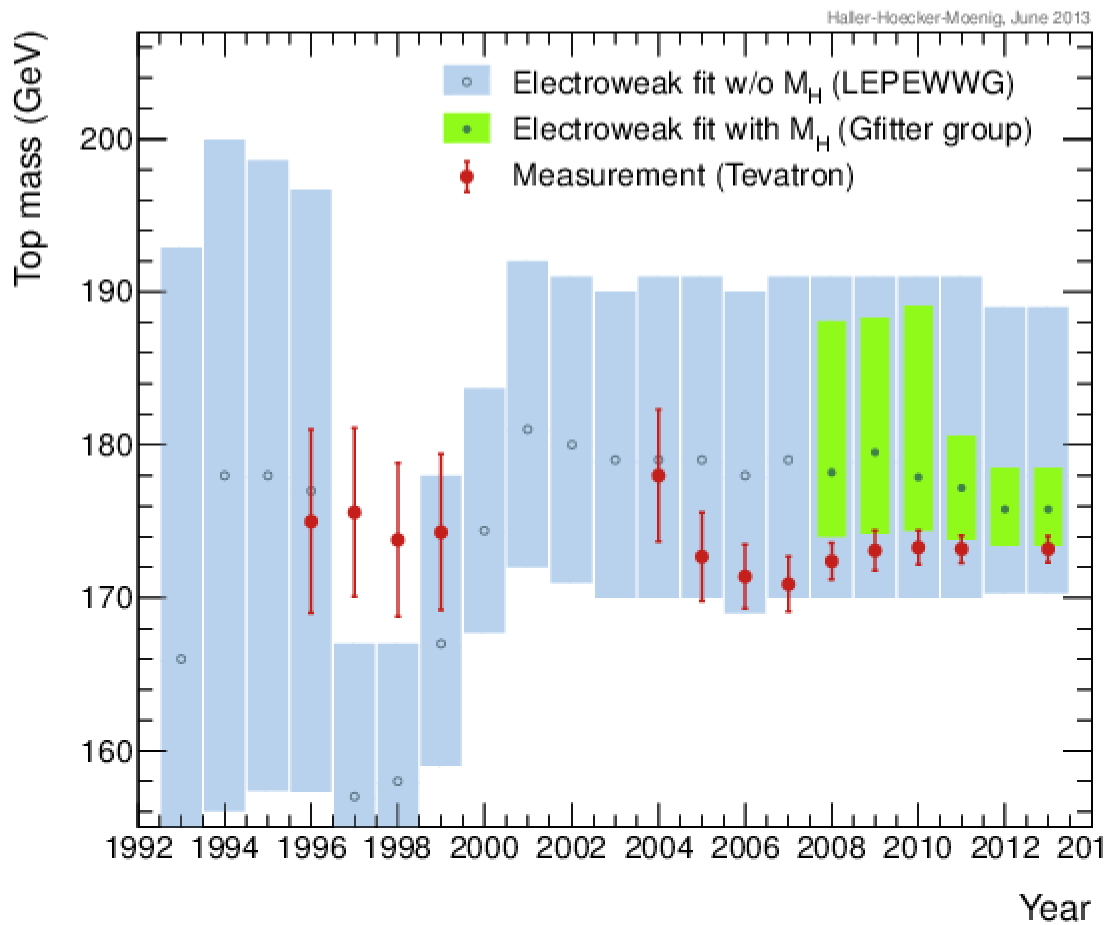
- Fixing the SM parameters each observable can be used to "measure" the Higgs-mass



Fit history

- The precision data have been used since ~1990 to predict the top-mass
- The Higgs-mass has been varied from the minimum allowed value to 1TeV

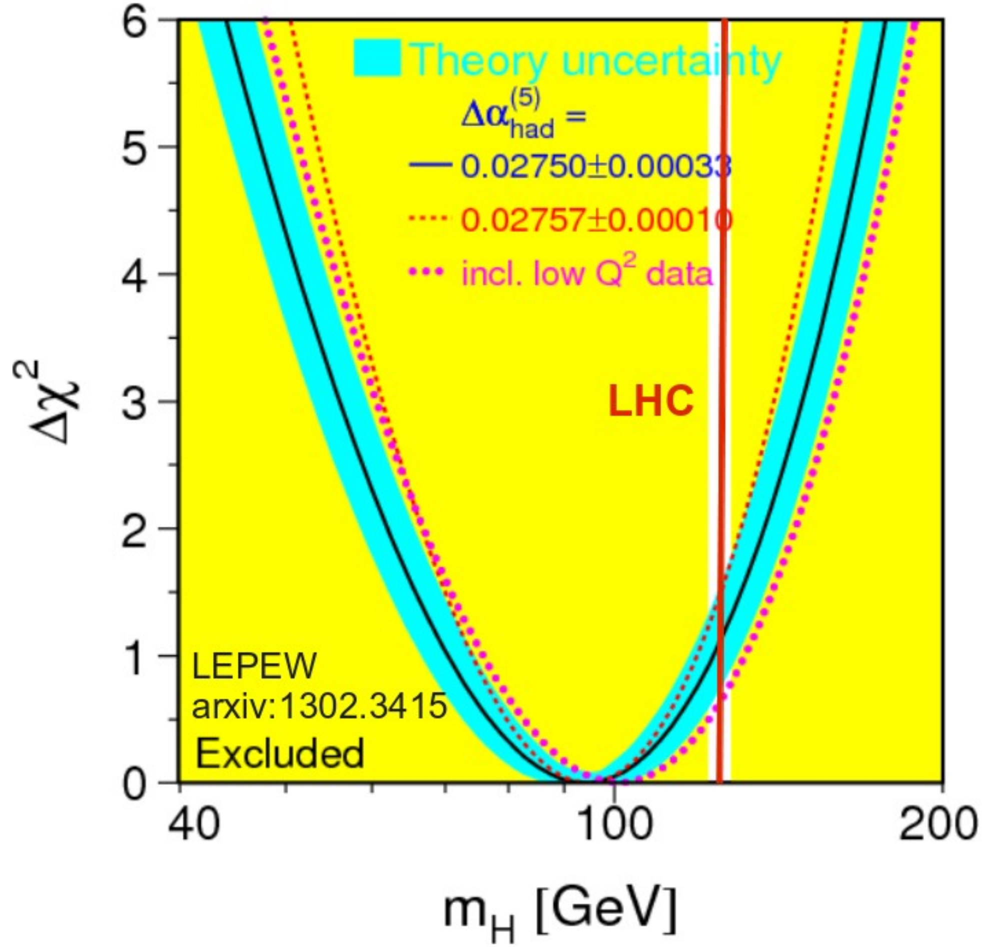
History of top-mass predictions

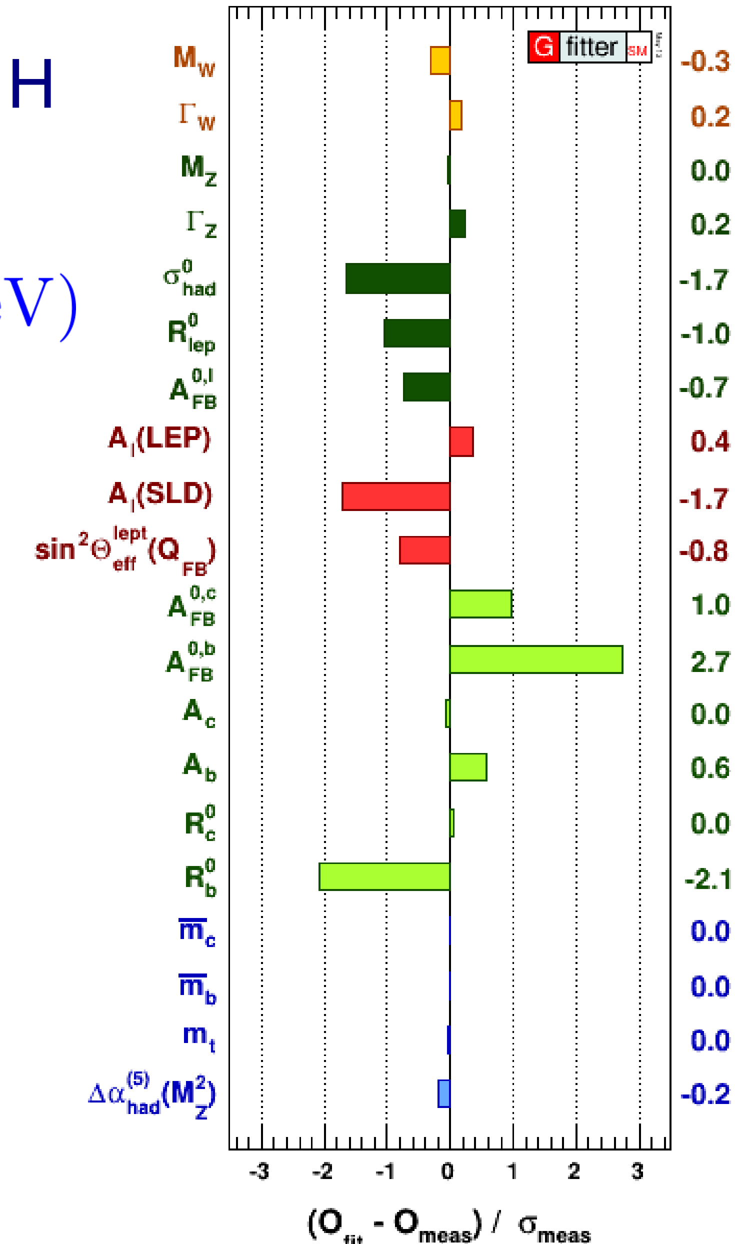


Global fit without m_H

Fit quality good

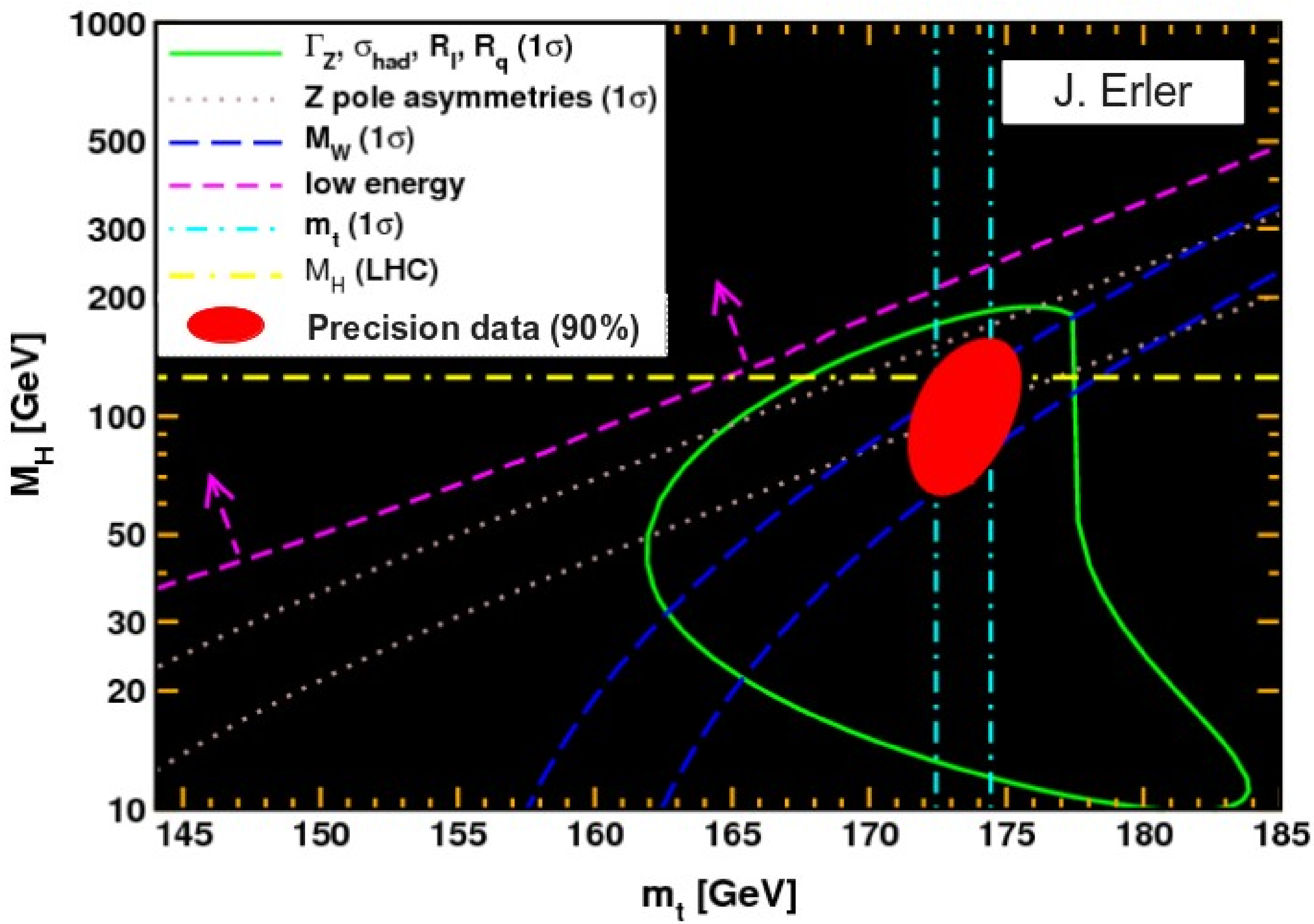
Predicted Higgs mass well compatible with LHC measurement $(m_H = 94^{+29}_{-24}\,\mathrm{GeV})$





http://cern.ch/gfitter/Standard_Model/

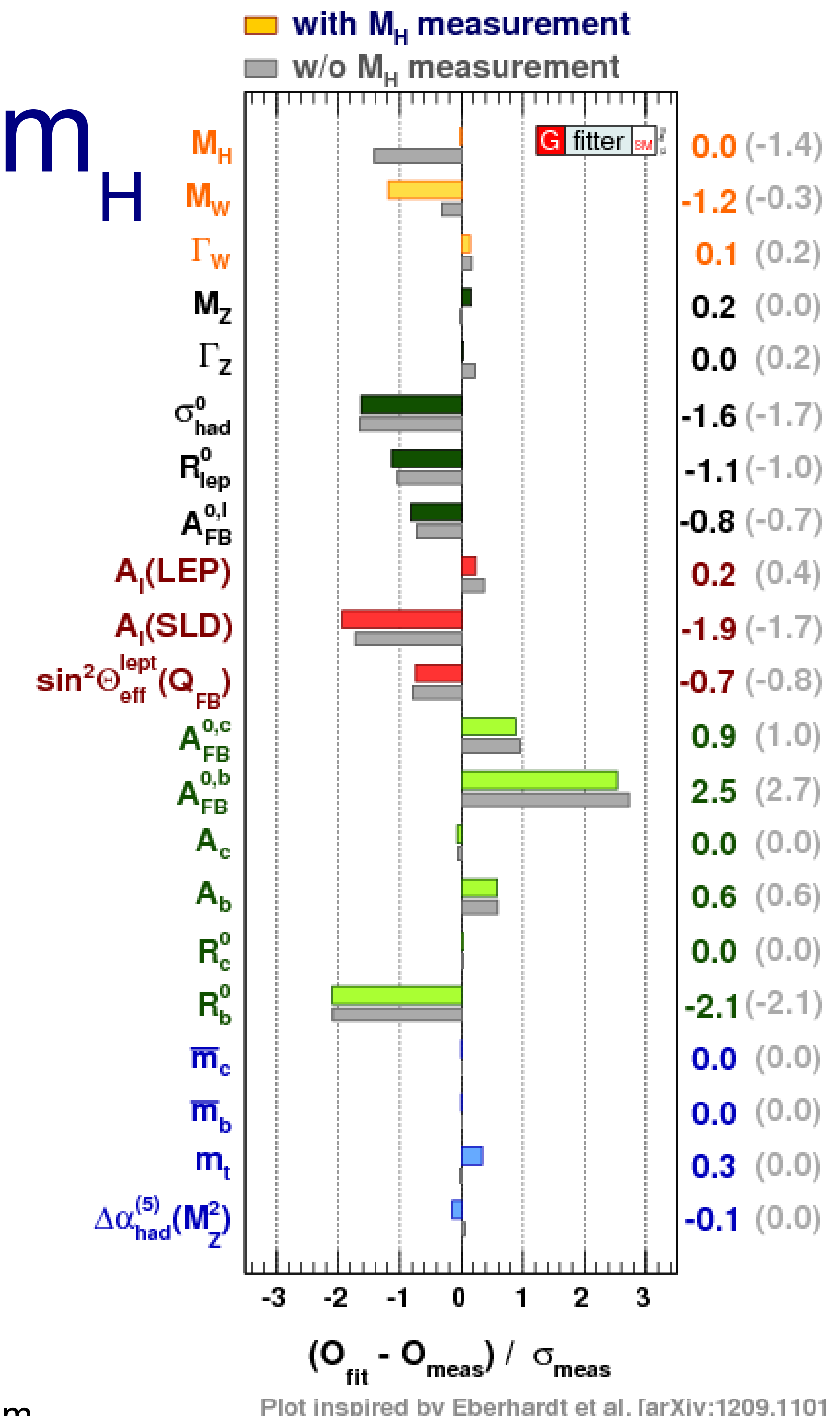
Prediction of m_t and m_H



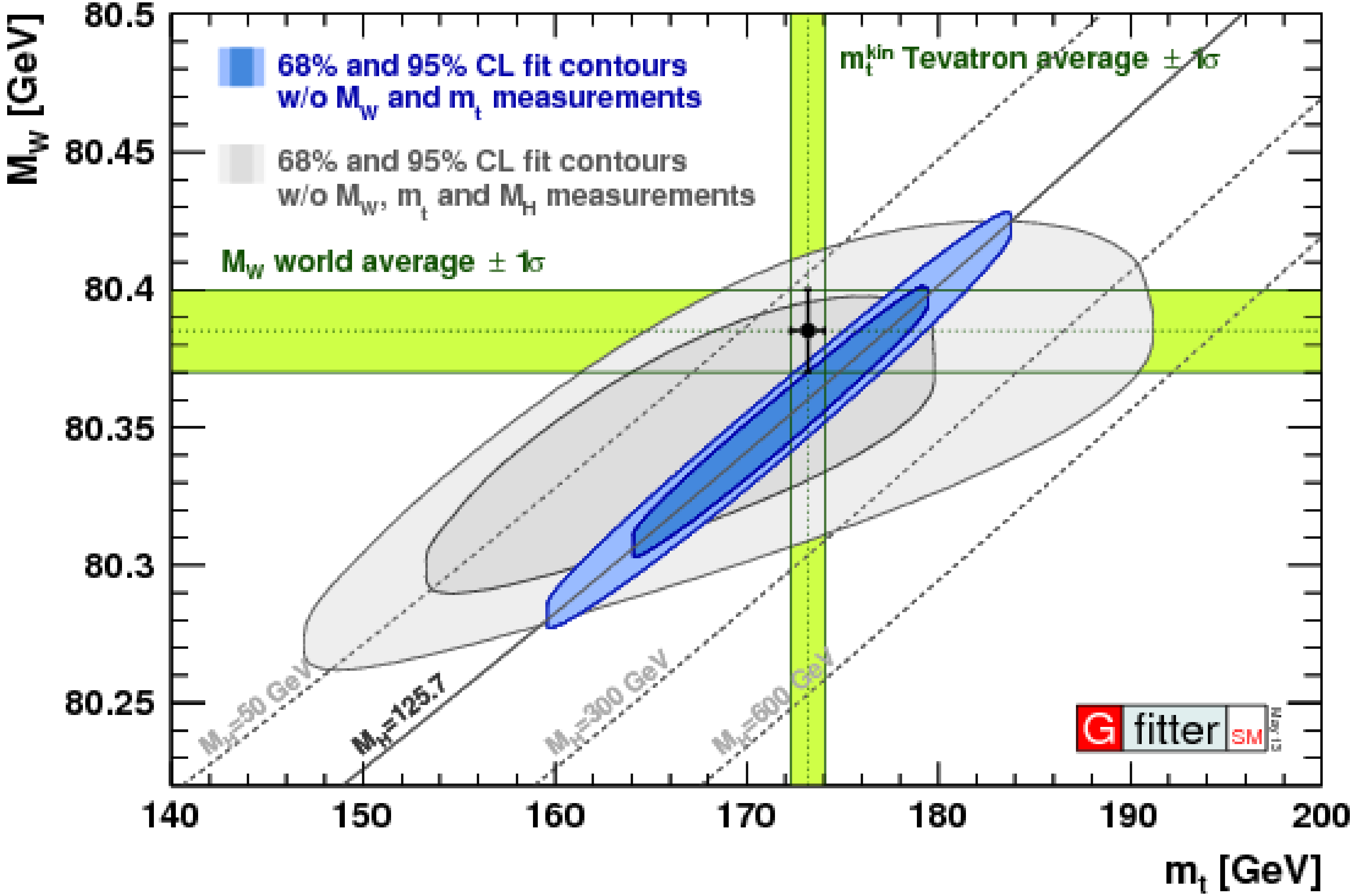
- Precision mainly from m_W, $\sin^2\theta_{eff}$
- Partial widths play only minor role

Fit results including m_H

- Again good agreement of data with fit
- Modifications due to m_H inclusion modest
- $X^2/ndf=20.7/14$, p-value from a toy MC study: 11%
- $\alpha_s=0.1188\pm0.0027$ (4th order) in good agreement with world average ($\alpha_s=0.1184\pm0.0007$)



Prediction of W- and top mass



Numerical results

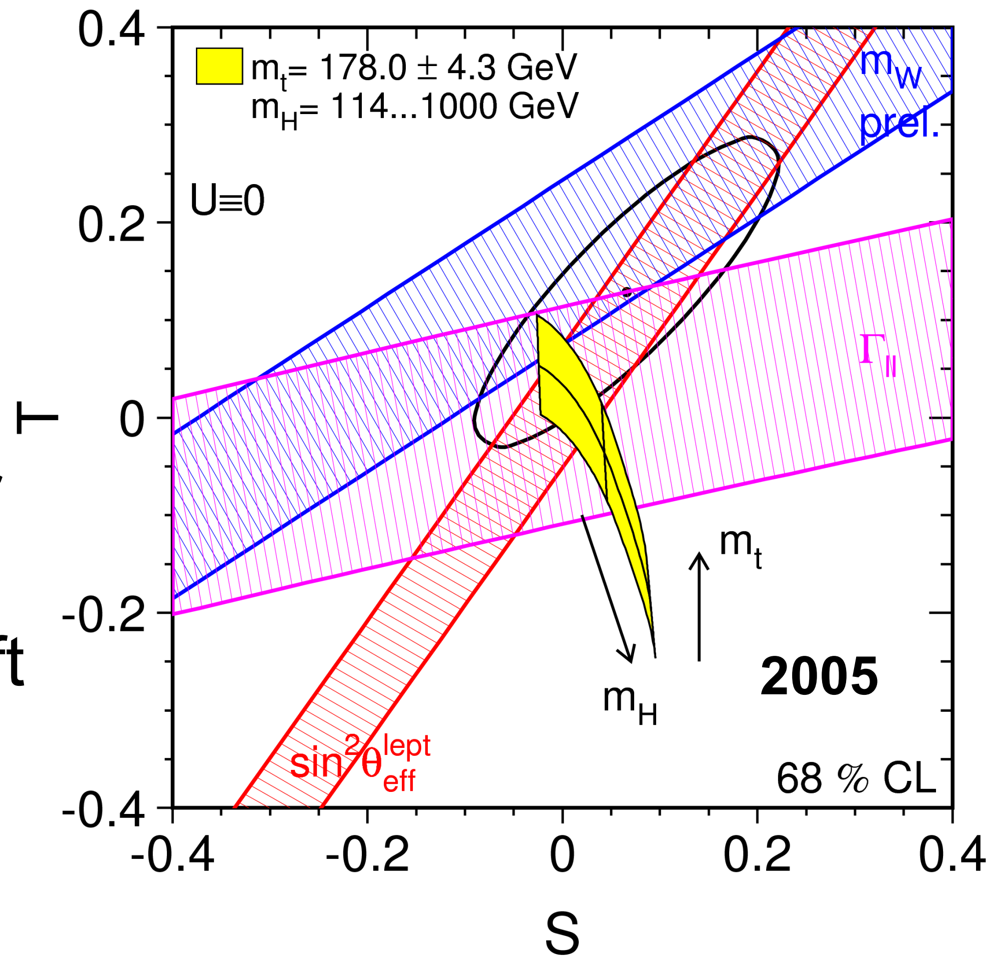
Parameter	Input value	Free in fit	Fit result incl. M_H	Fit result not incl. M_H	Fit result incl. M_H but not exp. input in row
M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	yes	125.7 ± 0.4	$94\,^{+25}_{-22}$	$94\,^{+25}_{-22}$
M_W [GeV]	80.385 ± 0.015	–	80.367 ± 0.007	80.380 ± 0.012	80.359 ± 0.011
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1878 ± 0.0021	91.1874 ± 0.0021	91.1983 ± 0.0116
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4954 ± 0.0014	2.4958 ± 0.0015	2.4951 ± 0.0017
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.479 ± 0.014	41.478 ± 0.014	41.470 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.740 ± 0.017	20.743 ± 0.018	20.716 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01627 ± 0.0002	0.01637 ± 0.0002	0.01624 ± 0.0002
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	$0.1473\,^{+0.0006}_{-0.0008}$	0.1477 ± 0.0009	$0.1468 \pm 0.0005^{(\dagger)}$
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	$0.23148\,^{+0.00011}_{-0.00007}$	$0.23143\,^{+0.00010}_{-0.00012}$	0.23150 ± 0.00009
A_c	0.670 ± 0.027	–	$0.6680\,^{+0.00025}_{-0.00038}$	$0.6682\,^{+0.00042}_{-0.00035}$	0.6680 ± 0.00031
A_b	0.923 ± 0.020	–	$0.93464\,^{+0.00004}_{-0.00007}$	0.93468 ± 0.00008	0.93463 ± 0.00006
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	$0.0739\,^{+0.0003}_{-0.0005}$	0.0740 ± 0.0005	0.0738 ± 0.0004
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	$0.1032\,^{+0.0004}_{-0.0006}$	0.1036 ± 0.0007	0.1034 ± 0.0004
R^0_c	0.1721 ± 0.0030	–	0.17223 ± 0.00006	0.17223 ± 0.00006	0.17223 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21474 ± 0.00003	0.21475 ± 0.00003	0.21473 ± 0.00003
$\overline{m}_c$ [GeV]	$1.27\,^{+0.07}_{-0.11}$	yes	$1.27\,^{+0.07}_{-0.11}$	$1.27\,^{+0.07}_{-0.11}$	–
$\overline{m}_b$ [GeV]	$4.20\,^{+0.17}_{-0.07}$	yes	$4.20\,^{+0.17}_{-0.07}$	$4.20\,^{+0.17}_{-0.07}$	–
m_t [GeV]	173.18 ± 0.94	yes	173.52 ± 0.88	173.14 ± 0.93	$175.8\,^{+2.7}_{-2.4}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\triangledown)}$	2757 ± 10	yes	2755 ± 11	2757 ± 11	$2716\,^{+49}_{-43}$
$\alpha_s(M_Z^2)$	–	yes	0.1191 ± 0.0028	0.1192 ± 0.0028	0.1191 ± 0.0028
$\delta_{\rm th} M_W$ [MeV]	$[-4, 4]_{\rm theo}$	yes	4	4	–
$\delta_{\rm th}\sin^2\theta^\ell_{\rm eff}$ $^{(\triangle)}$	$[-4.7, 4.7]_{\rm theo}$	yes	-1.4	4.7	–

$^{(\circ)}$Average of ATLAS ($M_H = 126.0 \pm 0.4$ (stat) ± 0.4 (sys)) and CMS ($M_H = 125.3 \pm 0.4$ (stat) ± 0.5 (sys)) measurements assuming no correlation of the systematic uncertainties. $^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. $^{(\dagger)}$The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1474\,^{+0.0005}_{-0.0009}$ ($A_\ell = 0.1467\,^{+0.0006}_{-0.0004}$). $^{(\triangle)}$In units of 10^{-5}. $^{(\triangledown)}$Rescaled due to α_s dependency.

http://cern.ch/gfitter/Standard_Model/

STU-parameters

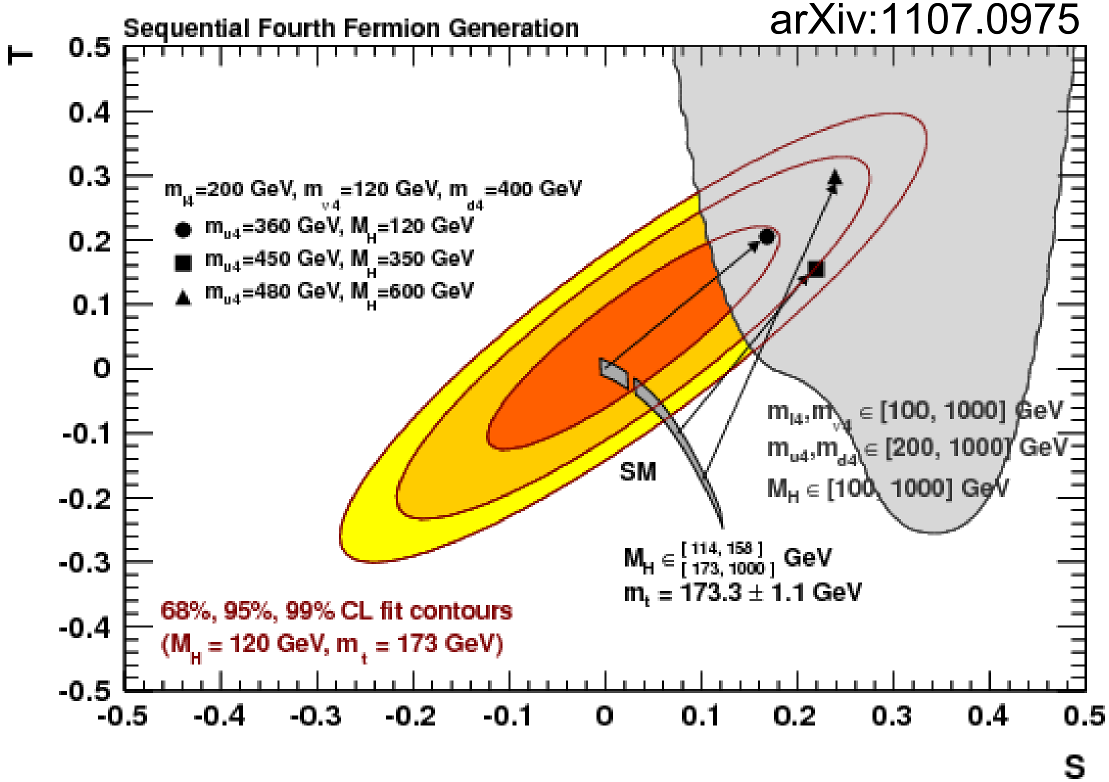
- The STU parameters were designed to ease BSM analyses:
  - T absorbs the isospin breaking contributions (Δρ)
  - S takes the remainder in Δκ
  - U takes what is still left in Δr (U=0 in many models)



STU-parameters (ii)

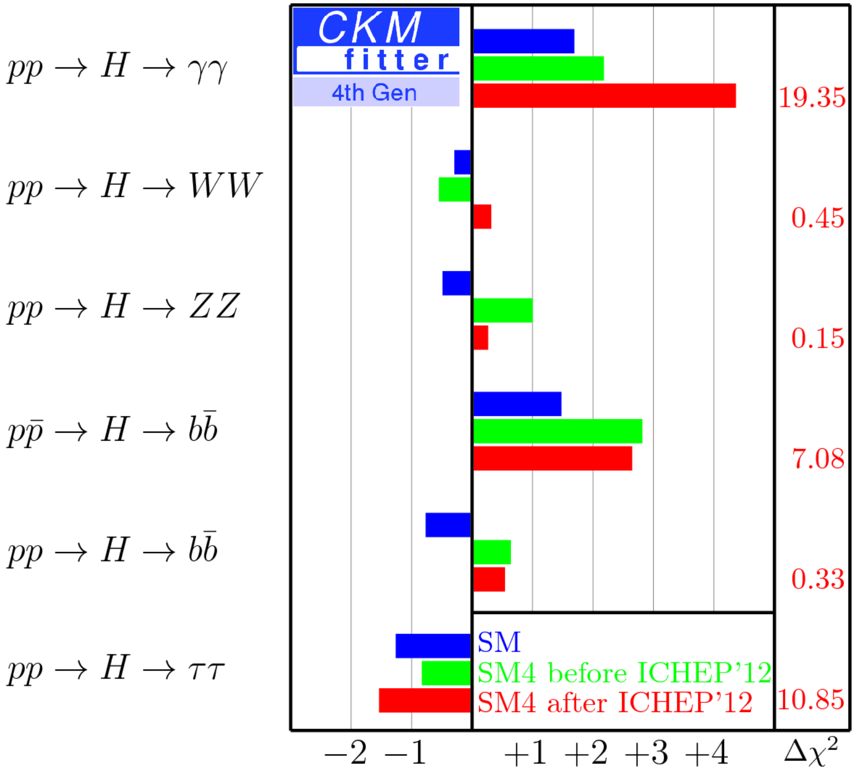
- STU parameters can be calculated by theorists for BSM models without calculating the whole SM
- Example: 4th fermion generation before Higgs discovery

arXiv:1107.0975



4th generation

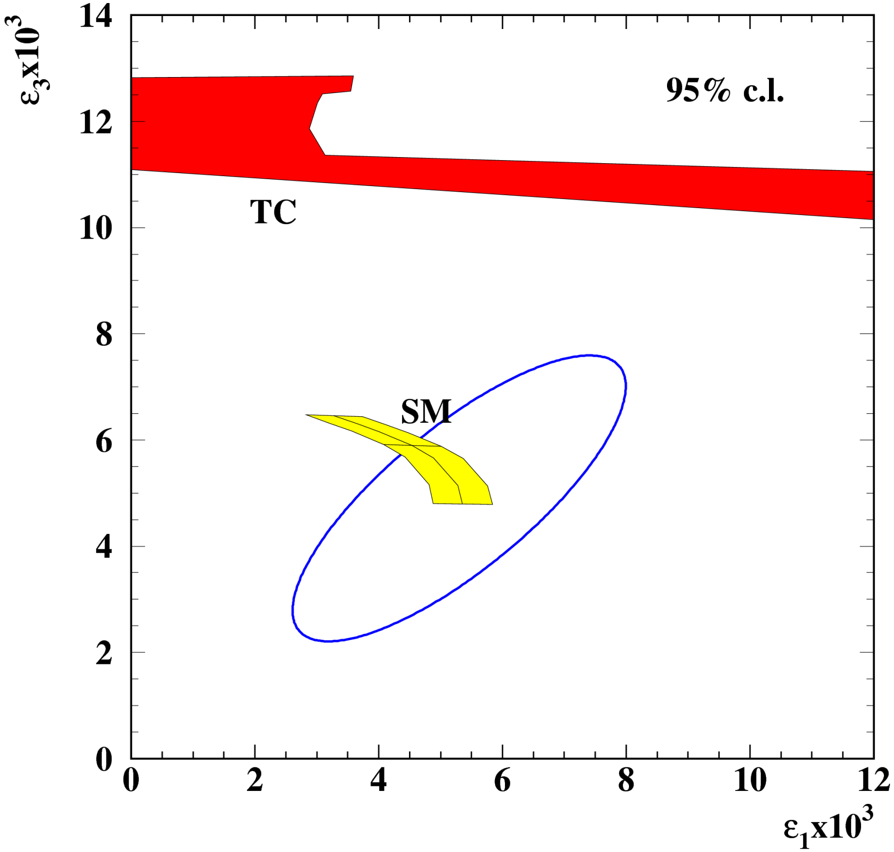
- A sequential 4th generation has been reanalysed using STU parameters and Higgs couplings
- A 4th generation is excluded independent of its mass assuming a SM Higgs sector

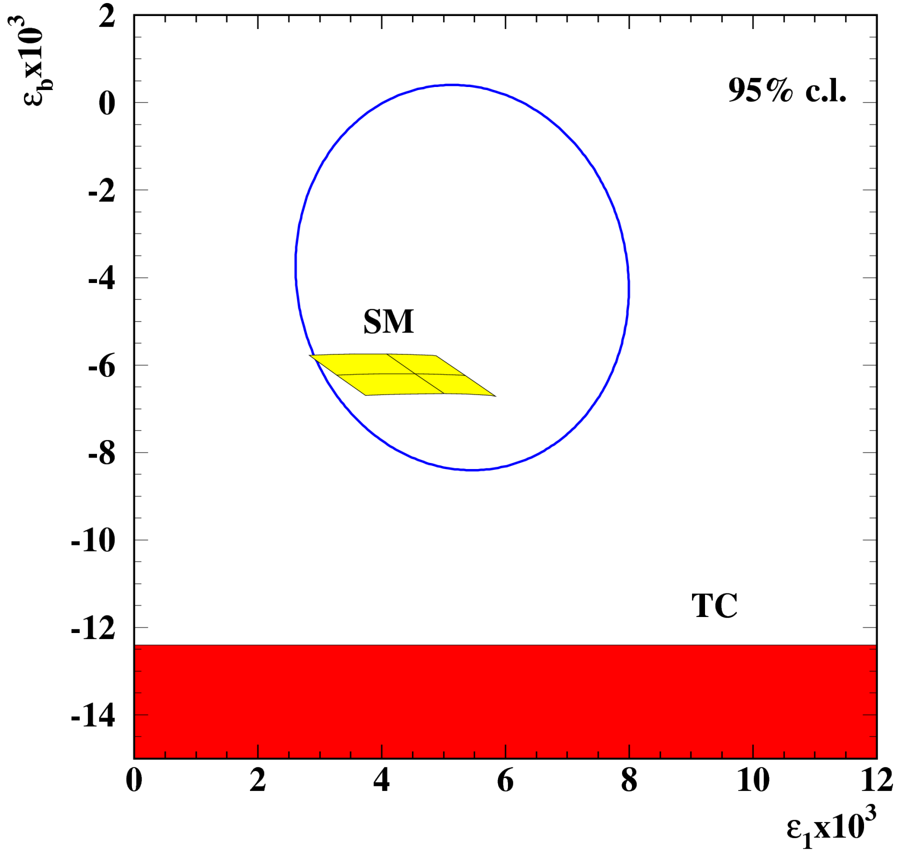


Eberhardt et al.
arXiv:1209.1101

Techincolour

- In the same way technicolour could be excluded long before the Higgs discovery (ε_1~T, ε_3~S,ε_b~R_b)





Conclusions electroweak precision measurements

- Masses and couplings of electroweak gauge bosons have been measured at the per mille level
- They agree perfectly with 2-loop electroweak calculations
- This constraints many models beyond the Standard Model
- There are only few and moderate improvements possible at the LHC, major progress can only be achieved at an e^+e^- linear collider

Literature

- LEP1/SLD electroweak report: hep-ex/0509008
- LEP2 electroweak report: arxiv:1302.3415
- Tevatron W-mass: arxiv:1204:0042
- Tevatron top-mass: arxiv:1305.3929
- Latest electroweak fits (Gfitter): arxiv:1209.2716