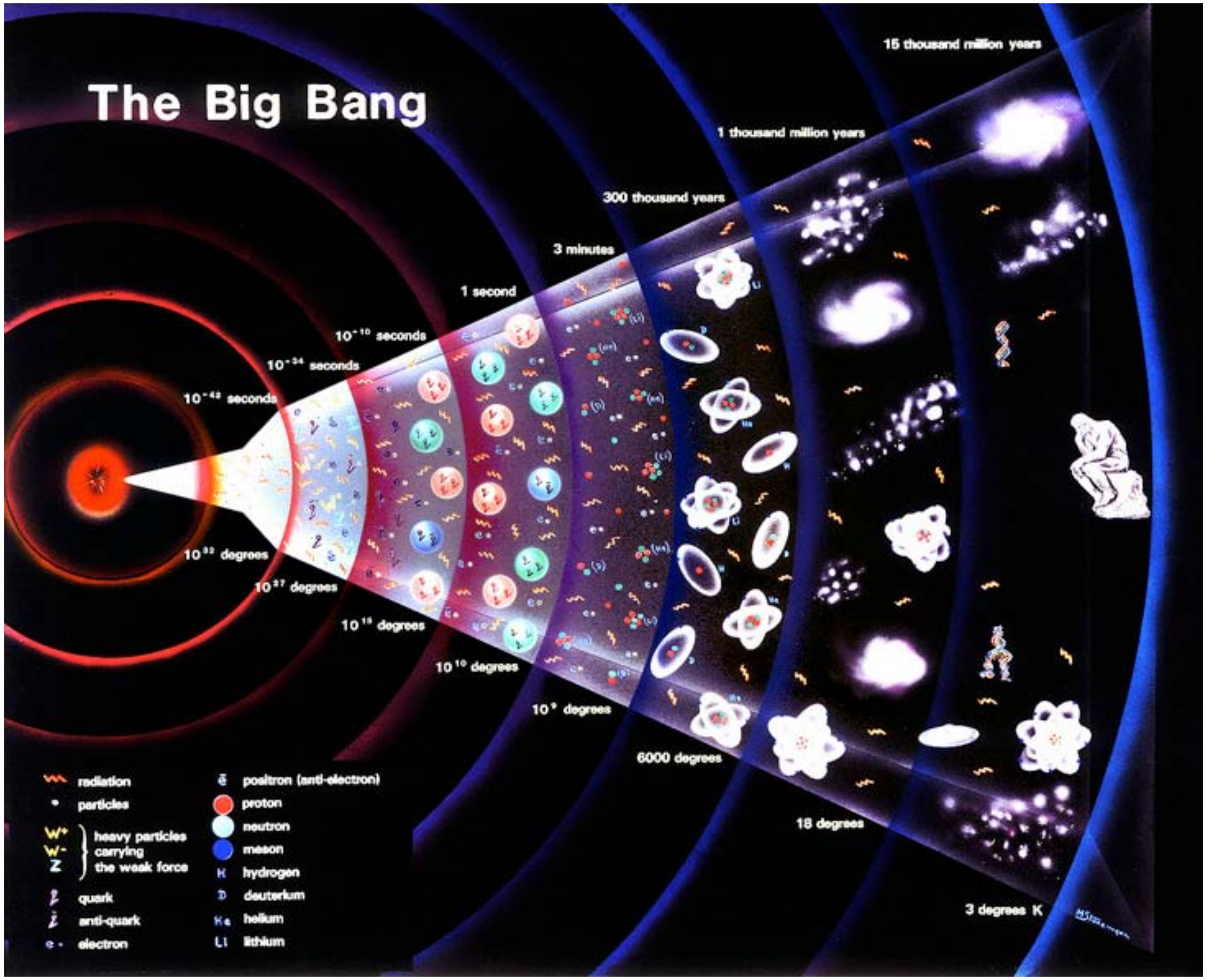
Precision Tests of the Standard Model

Ashutosh Kotwal
Duke University



22nd Rencontres de Blois
July17, 2010

Spontaneous Symmetry Breaking

- 2008 Nobel Prize in Physics

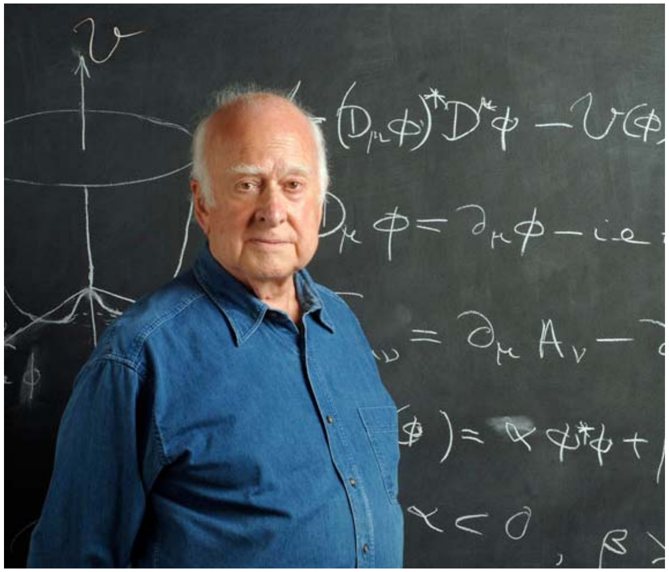
  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

Yoichiro Nambu

- Experimentally, jury is still out on Higgs mechanism of Electroweak Symmetry Breaking in the Standard Model of Particle Physics

Outline

- Importance of precision electroweak observables in the gauge and Higgs sectors of the Standard Model
- Current and future measurements of the top quark mass and W boson mass at the Tevatron
- Top quark and W boson mass measurements at the LHC
  - potential for high precision
  - issues to address
- Summary

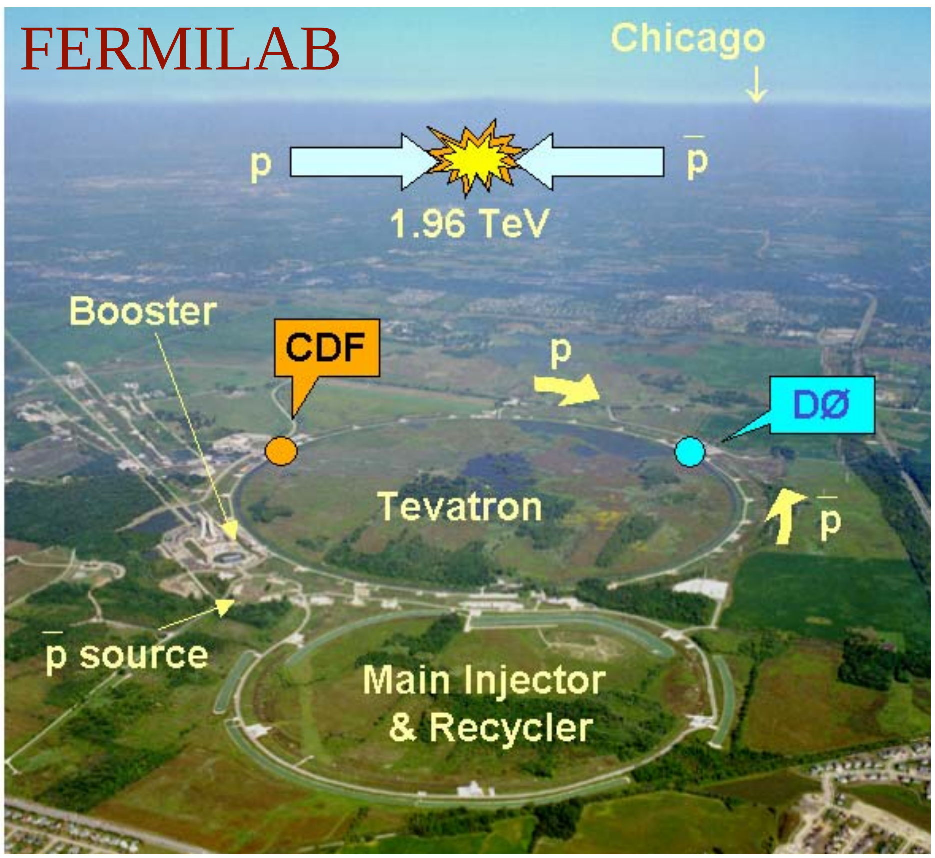


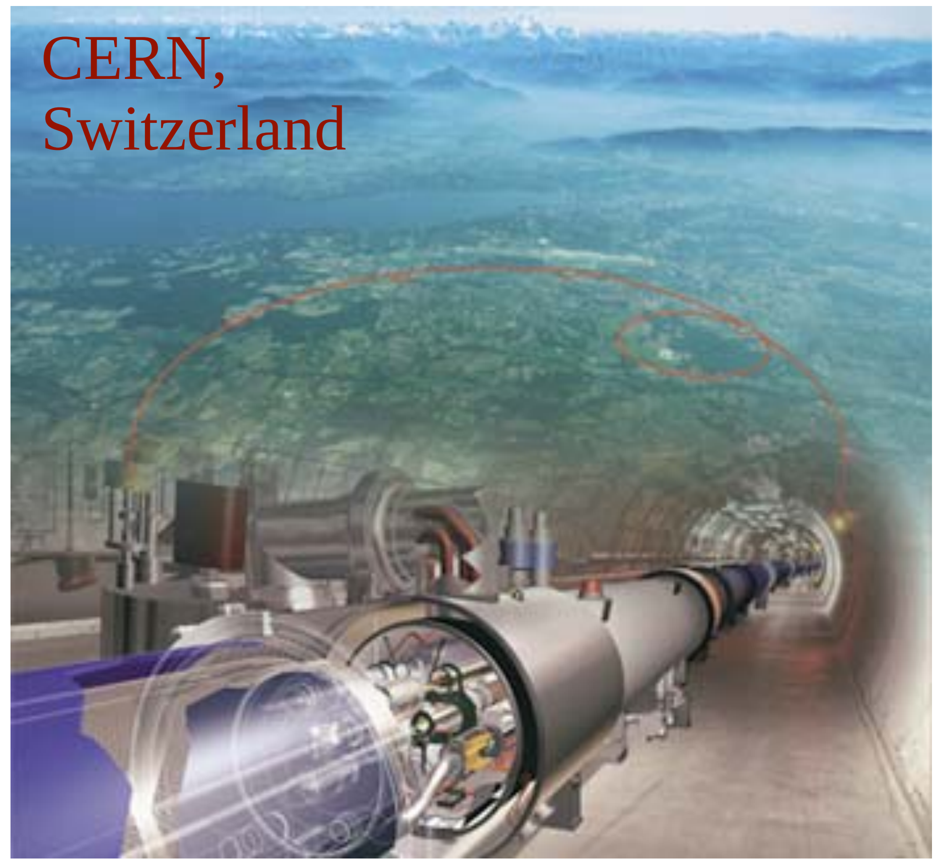
Peter Higgs

Electroweak Symmetry Breaking

Searches for standard model Higgs at the Tevatron and LHC

Precision measurements and Electroweak Fits





Motivation for Precision Measurements

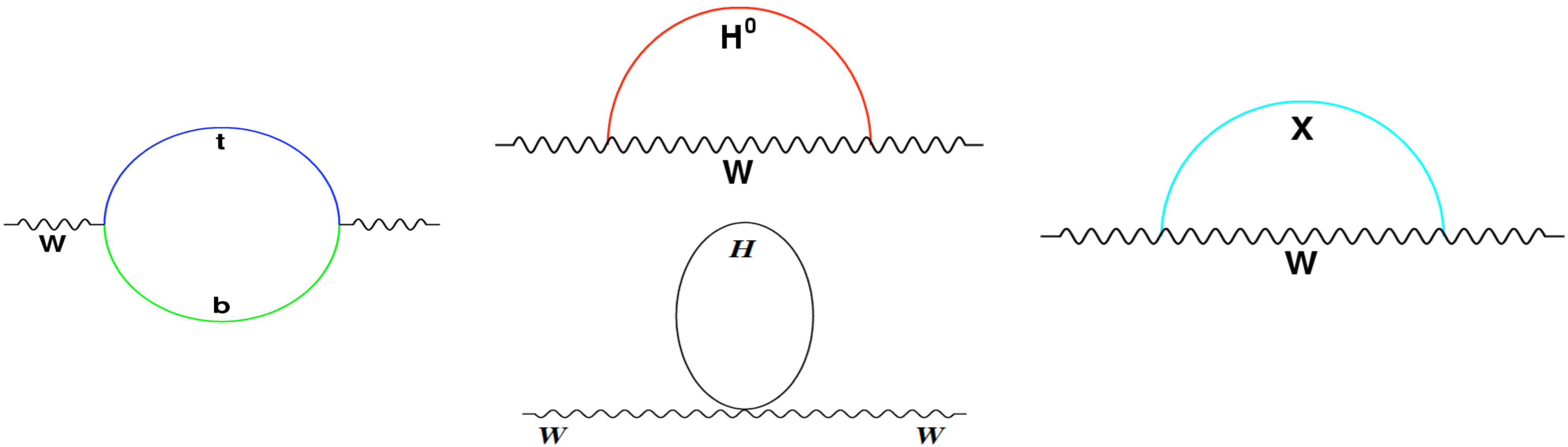
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$

    $M_Z = 91.1876\ (21)\ \mathrm{GeV}$
- At tree-level, these parameters are related to other electroweak observables, *e.g.* M_W
  - $M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where ϑ_W is the weak mixing angle, defined by (in the on-shell scheme)

      $$\cos\vartheta_W = M_W/M_Z$$

Motivation for Precision Measurements

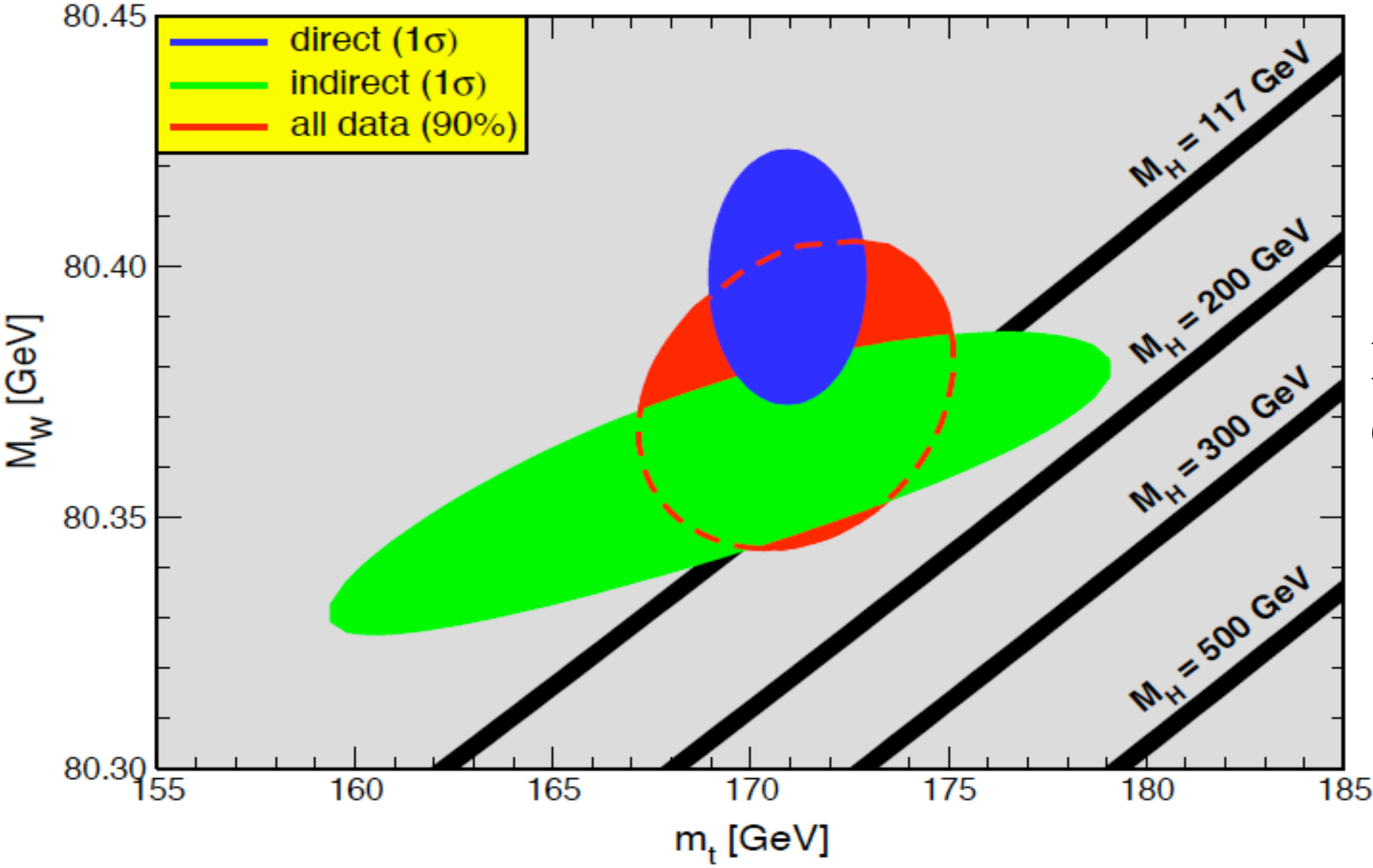
- Radiative corrections due to heavy quark and Higgs loops and exotica



Motivate the introduction of the ρ parameter: $M_W^2 = \rho\, [M_W(\text{tree})]^2$
with the predictions $(\rho\text{-}1) \sim M_{top}^2$ and $(\rho\text{-}1) \sim \ln M_H$

- In conjunction with M_{top}, the W boson mass constrains the mass of the Higgs boson, and possibly new particles beyond the standard model

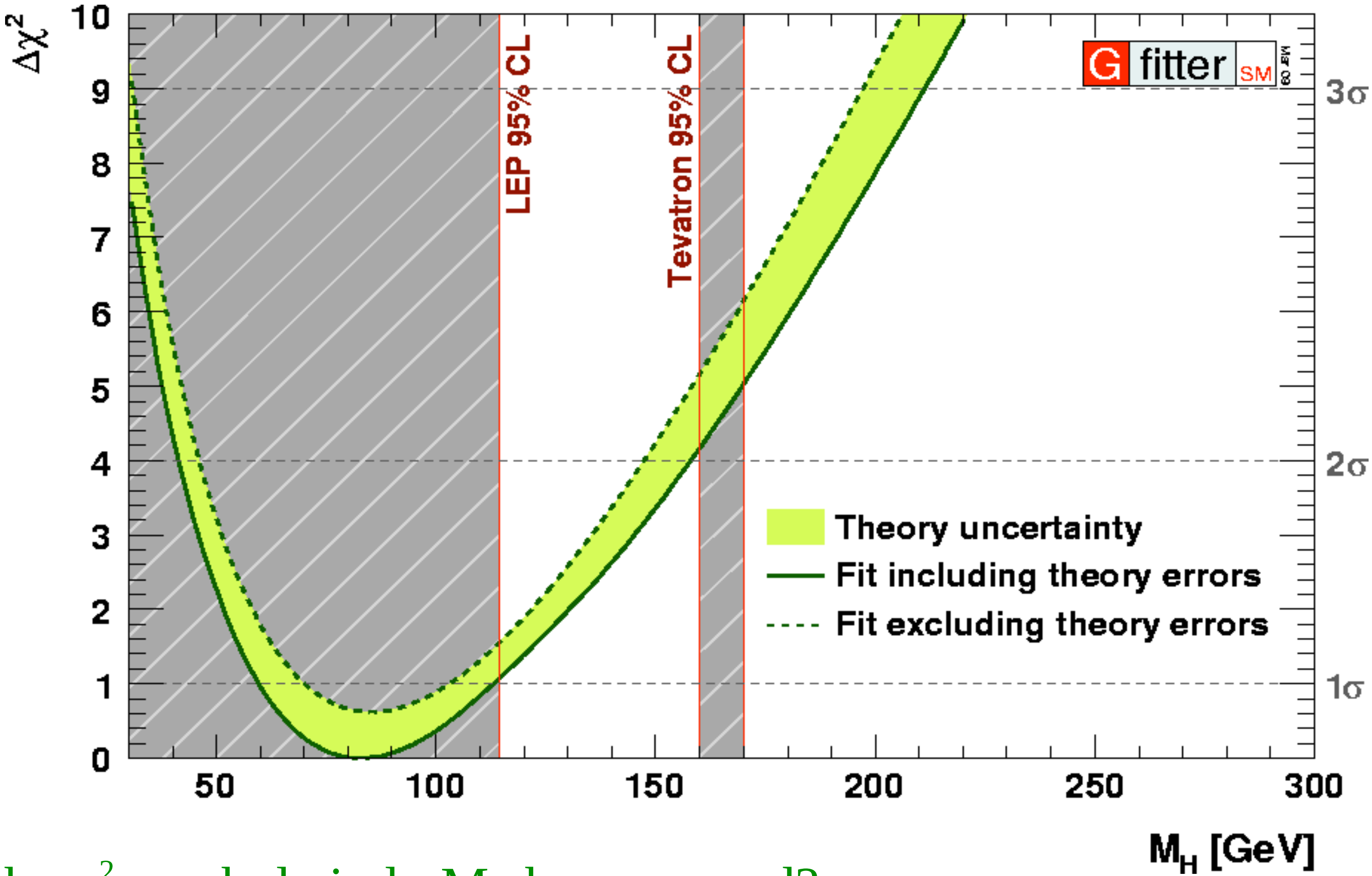
Uncertainty from $\alpha_{EM}(M_Z)$



Line thickness due to $\delta\alpha_{EM}$

- $\delta\alpha_{EM}$ dominated by uncertainty from non-perturbative contributions: hadronic loops in photon propagator at low Q^2
- equivalent $\delta M_W \approx 4$ MeV for the same Higgs mass constraint
  - Was equivalent $\delta M_W \approx 15$ MeV a decade ago !

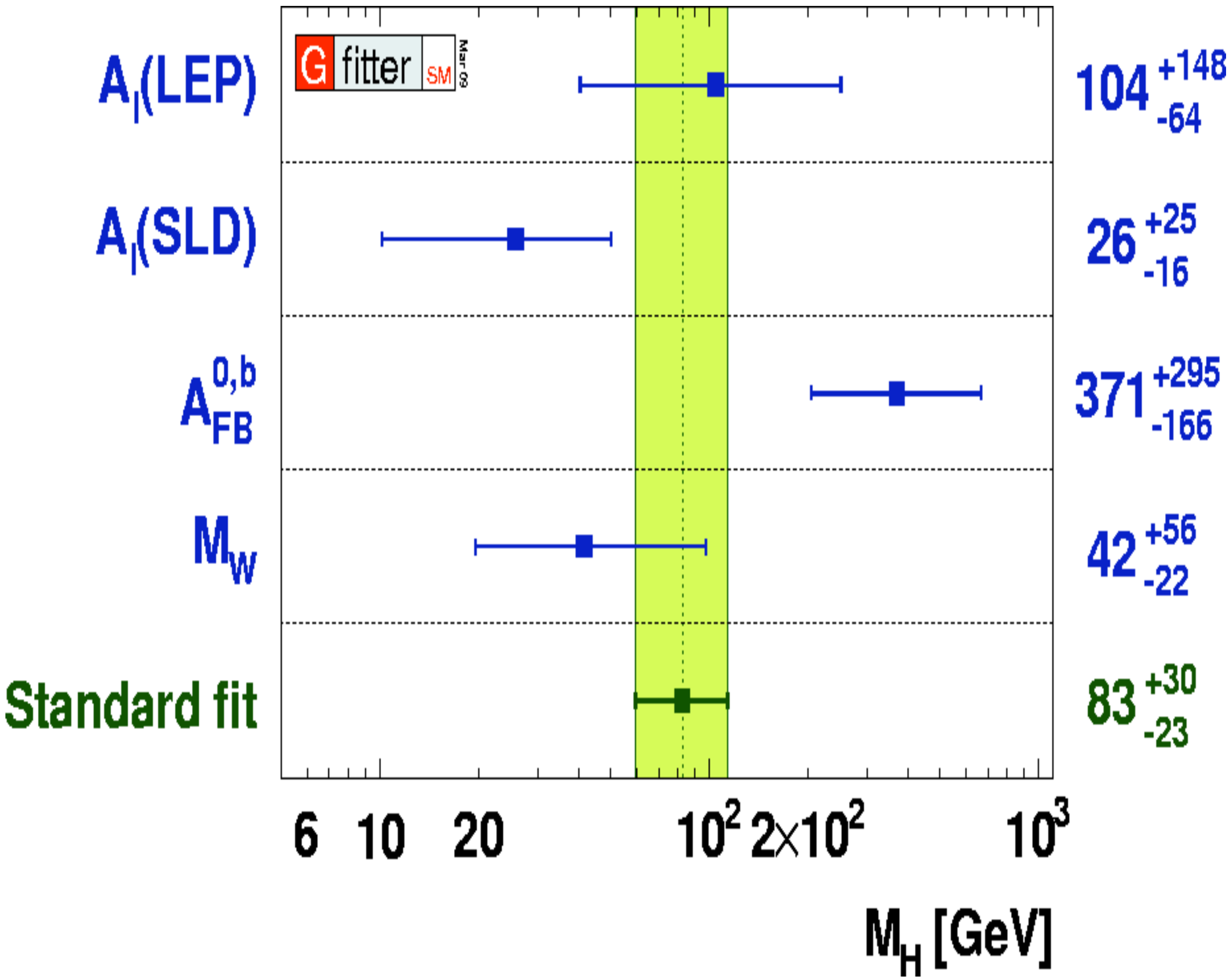
Current Higgs Constraint from SM Electroweak Fit



- Can the χ^2 parabola in ln M_H be narrowed?
- Where will it minimize in the future?
- Can Tevatron exclude the Higgs in the preferred (M_H<200 GeV) range?
- Will LHC see the (SM or non-SM) Higgs inside or outside the preferred mass range?

Motivation II

- SM Higgs fit: $M_H = 83^{+30}_{-23}$ GeV (gfitter.desy.de)
- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs, is there another missing piece in this puzzle?

(A_{FB}^b *vs* A_{LR}: 3.2σ)

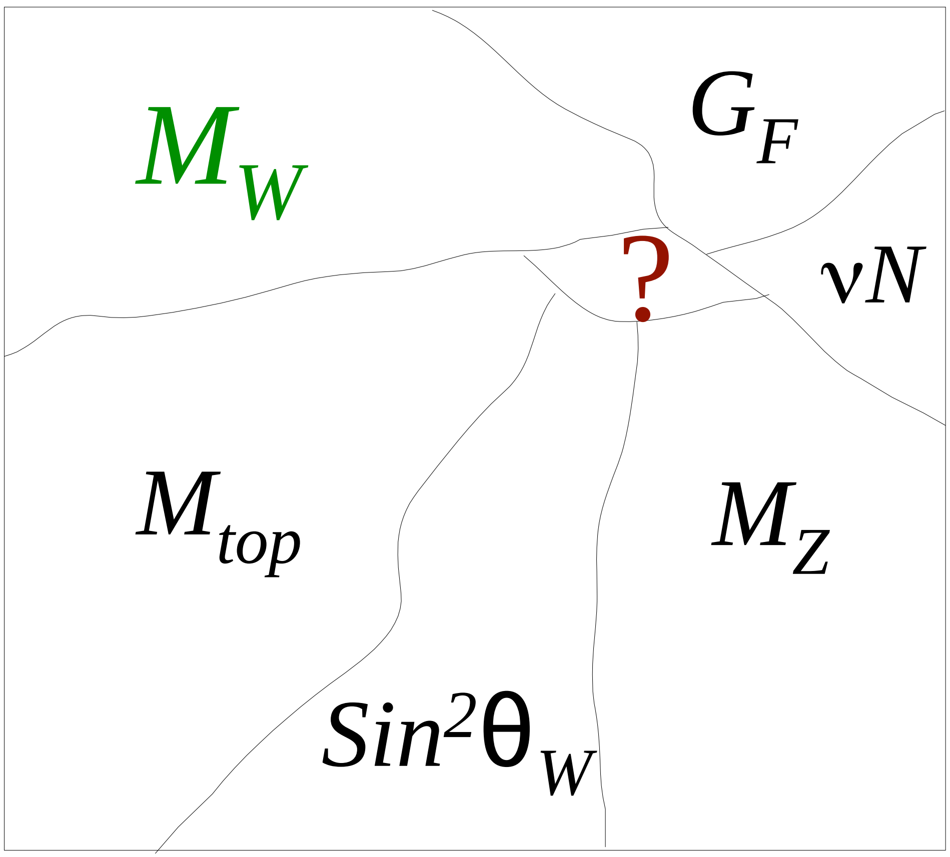
Must continue improving precision of M_W, M_{top} ...

other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 15$ MeV

Motivate direct measurement of M_W at the 15 MeV level and better

Motivation II

- SM Higgs fit: $M_H = 83^{+30}_{-23}$ GeV (gfitter.desy.de)
- LEPII direct searches: $M_H > 114.4$ GeV @ 95% CL (PLB 565, 61)



In addition to the Higgs, is there another missing piece in this puzzle?

(A_{FB}^{b} *vs* A_{LR}: 3.2σ)

Must continue improving precision of M_W, M_{top} ...

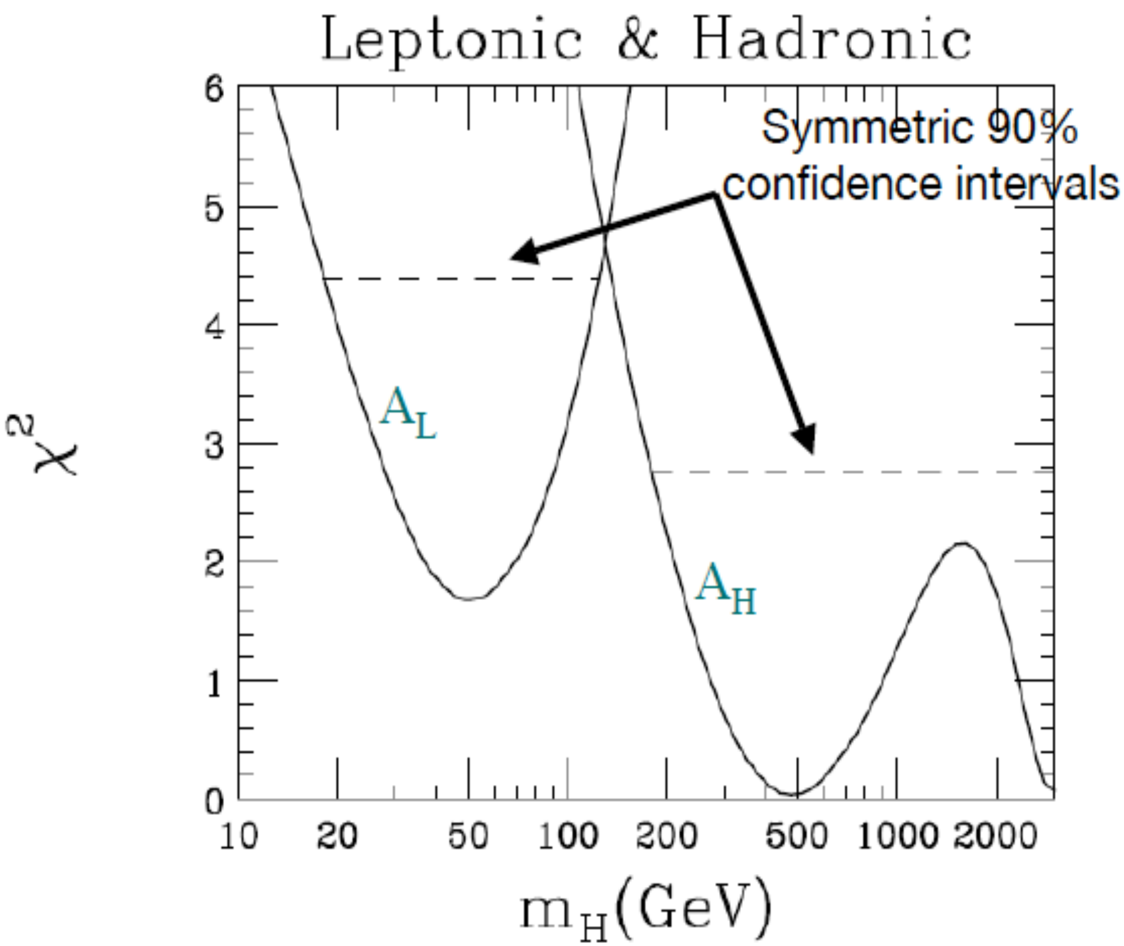
other precision measurements constrain Higgs, equivalent to $\delta M_W \sim 15$ MeV

Motivate direct measurement of M_W at the 15 MeV level and better

Motivation II

- Separate fits for M_H using only leptonic and only hadronic measurements of asymmetries: marginal difference in preferred Higgs mass (from M. Chanowitz, February 2007 Seminar, Fermilab)

χ^2 Distributions: Leptonic vs. Hadronic



Possible explanations:

Statistical fluctuation

Systematic experimental bias

New physics contributions:

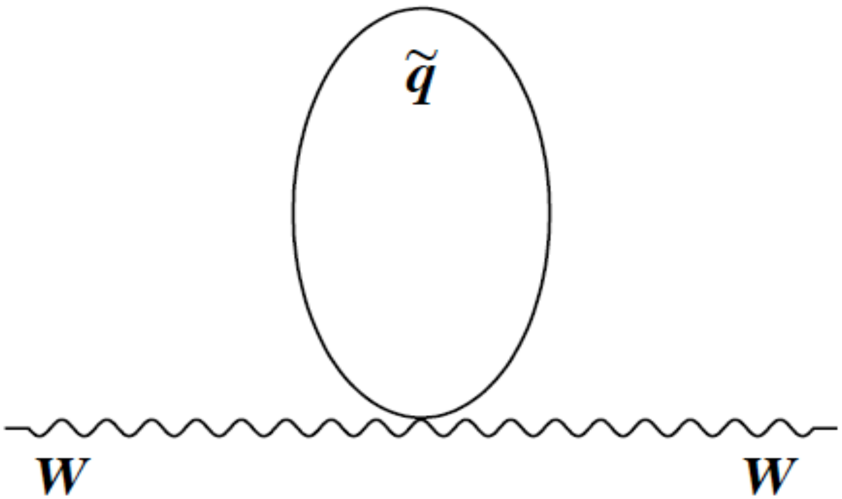
MSSM	Altarelli *et. al.*
4th family	Okun *et. al.*
Opaque branes	Carena *et. al.*

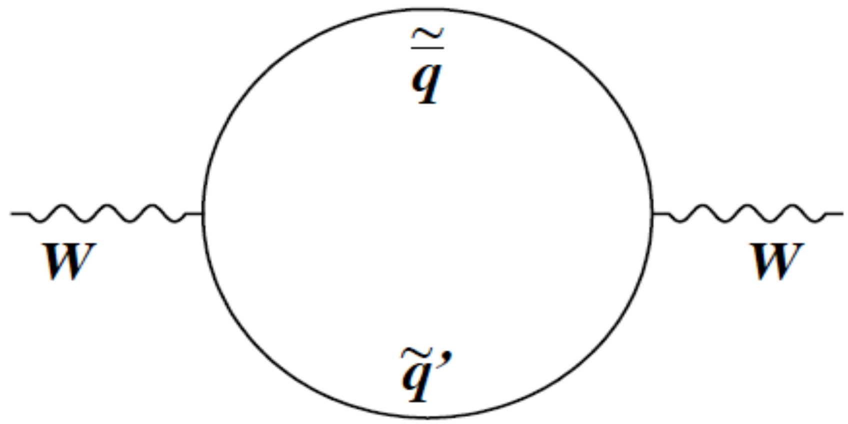
To raise M_H prediction of leptonic asymmetries

New physics in b-quark asymmetry requires large modification to Zbb vertex

Contributions from Supersymmetric Particles

(or any other model of new physics with calculable radiative corrections)

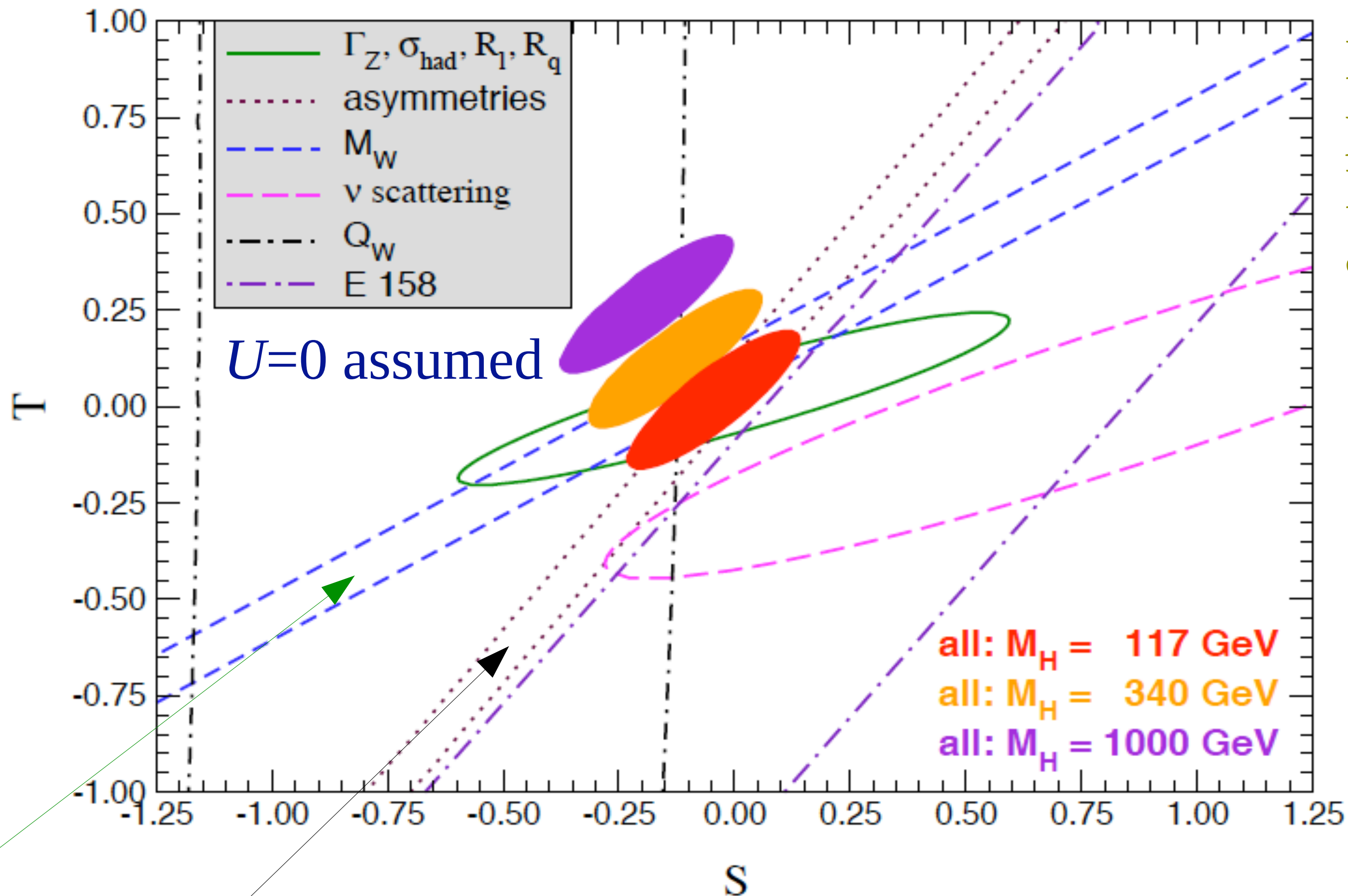




- Radiative correction depends on mass splitting (Δm^2) between squarks in SU(2) doublet
- After folding in limits on SUSY particles from direct searches, SUSY loops can contribute 100-200 MeV to M_W
- Ratio of squark masses > 2.5 already disfavored by precision electroweak measurements

Motivation III

- Generic parameterization of new physics contributing to W and Z boson self-energies: *S, T, U* parameters
  - Does not parameterize new physics in boson-fermion vertices



New Moller Scattering proposal at Jefferson Lab to measure leptonic asymmetry

(From PDG 2009)

M_W and Asymmetries are the most powerful observables in this parameterization

NuTeV Measurement of $\sin^2\Theta_W$

Using neutrino and anti-neutrino beams at Fermilab, NuTeV measured

$$\sin^2\theta_W^{(on\text{-}shell)} = 0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})$$

With a standard model prediction of 0.2227 ± 0.0003, ~3σ deviation

Paschos - Wolfenstein Relation

$$R^- = \frac{\sigma_{NC}^{\nu} - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^{\nu} - \sigma_{CC}^{\bar{\nu}}} = \rho^2 \left(\tfrac{1}{2} - \sin^2\theta_W\right) = g_L^2 - g_R^2$$

$$g_{L,R}^2 = u_{L,R}^2 + d_{L,R}^2$$

Minimizes sensitivity to charm quark production and sea quarks

no obvious experimental problem in the measurement

NuTeV Measurement of $\sin^2\Theta_W$

Using neutrino and anti-neutrino beams at Fermilab, NuTeV measured

$$\sin^2\theta_W^{(on\text{-}shell)} = 0.2277 \pm 0.0013(\text{stat.}) \pm 0.0009(\text{syst.})$$

With a standard model prediction of 0.2227 ± 0.0003, ~3σ deviation

Beyond SM Physics explanations are not easy to construct

QCD effects are a possibility: large isospin violation, nuclear effects, NLO effects...QED radiative corrections also large

Large amount of literature generated, studying various hypotheses!

NuSonG: Neutrino Scattering on Glass (experiment proposed at Fermilab)

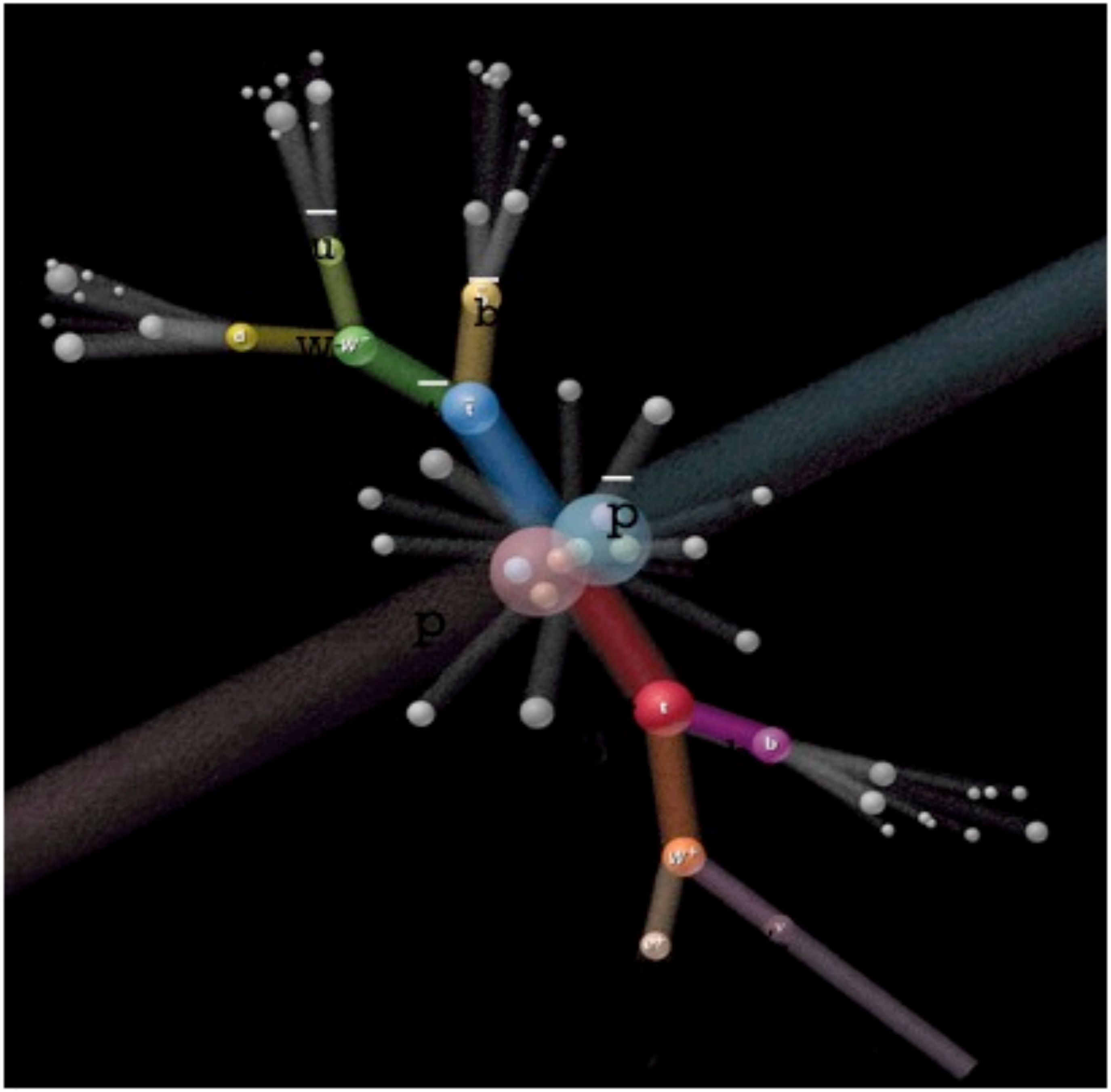
Global Electroweak fit for SM Higgs not changed much by inclusion of NuTeV and other low Q^2 measurements of $\sin^2\Theta_W$

Motivational Summary

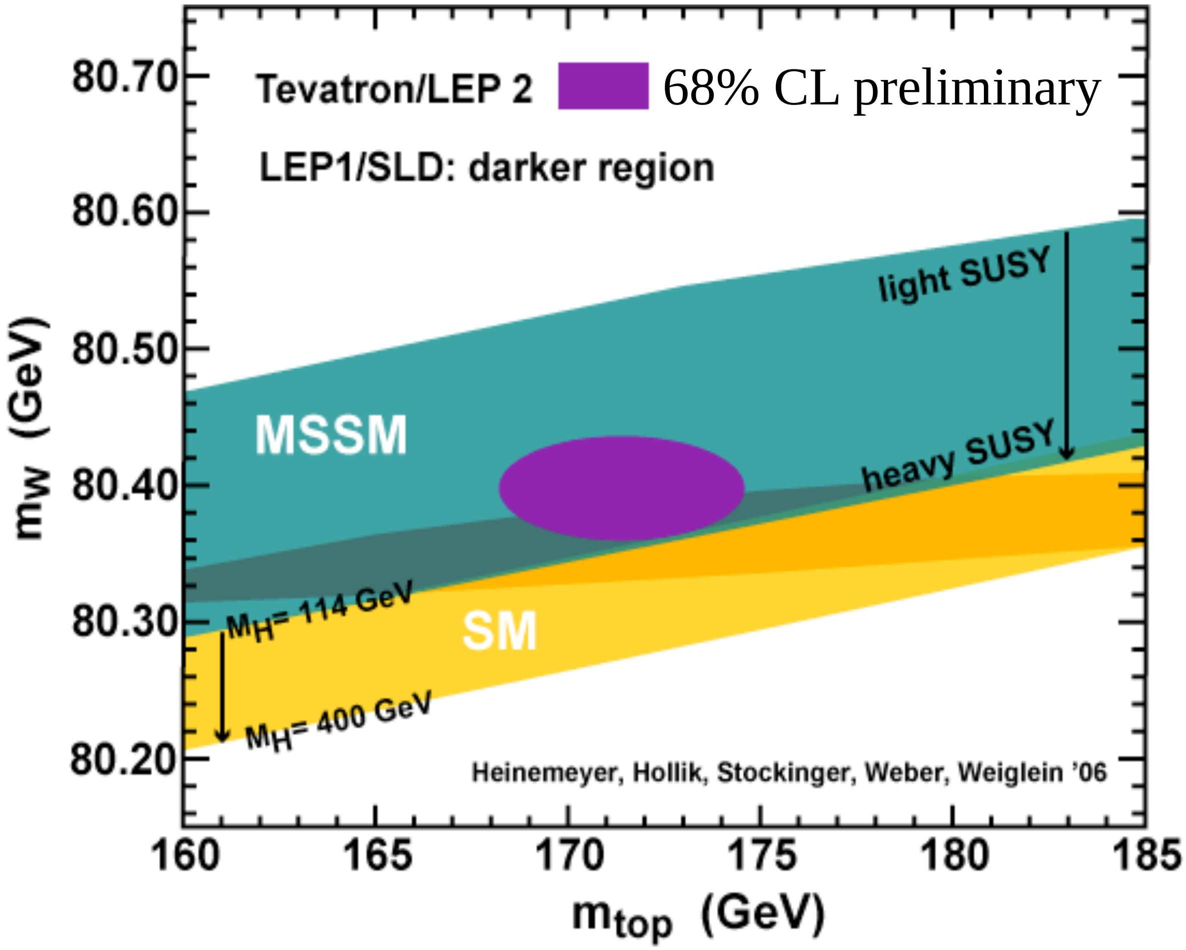
- At the dawn of the LHC era, we don't know
  - Mechanism of electroweak symmetry breaking
  - Solution to electroweak scale *vs* Planck scale hierarchy
  - …
- If there is new physics, there is a large range of models
- Precision electroweak measurements have provided much guidance
  - But some intriguing tension in electroweak fits already
- Will LHC discoveries decrease or increase this tension?
- Higher precision on electroweak observables makes LHC discoveries *even* more interesting:
  - Guide interpretation of what we see
  - Triangulate for what is not yet seen, e.g. Higgs, SUSY
  - M_W and m_{top} have become major players, and become more powerful as precision keeps improving

Top Quark Mass Measurement

Top Mass Measurement at the Tevatron



Progress on M_{top} at the Tevatron



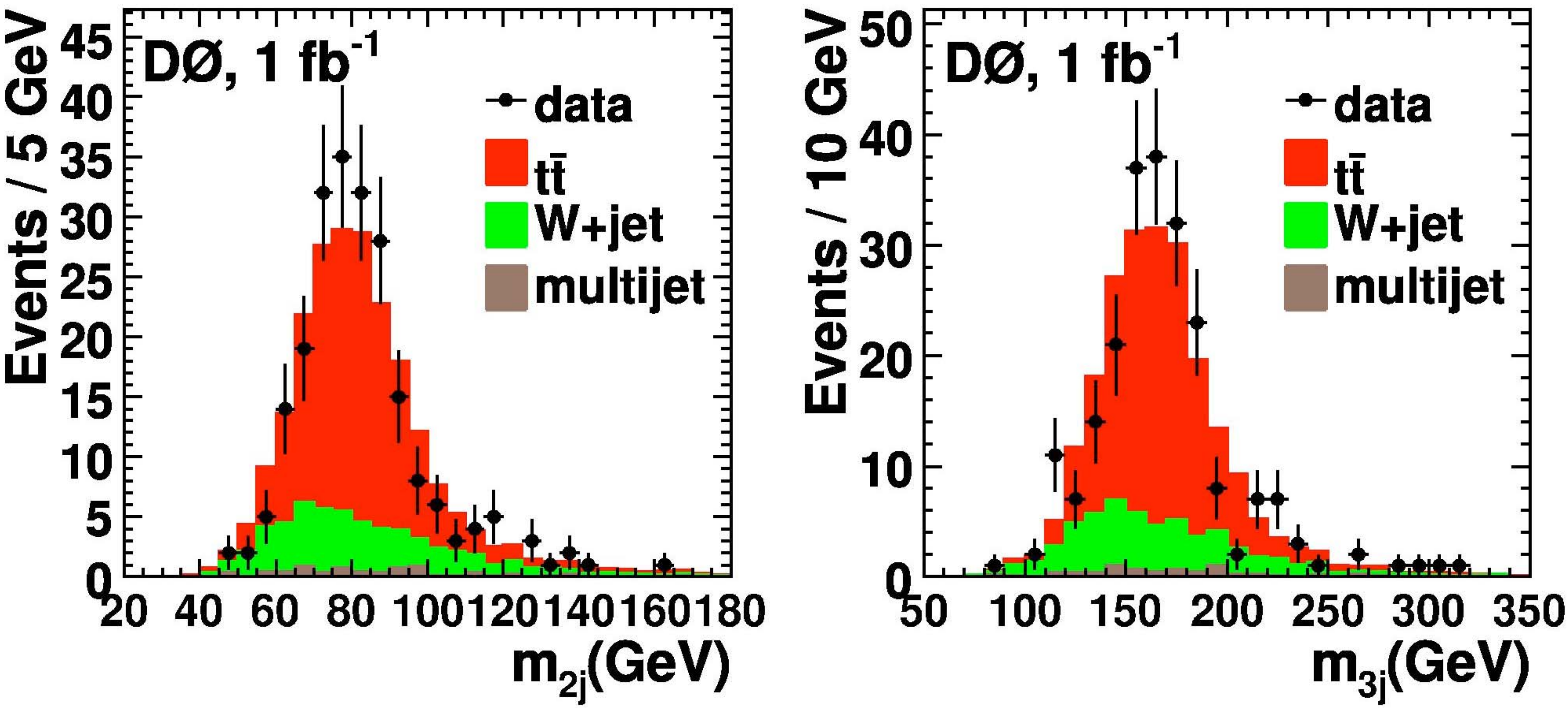
- From the Tevatron, δM_{top} = 1.1 GeV => $\delta M_H / M_H$ = 9%
- equivalent δM_W = 7 MeV for the same Higgs mass constraint
- Current world average δM_W = 25 MeV
  - δM_{top} is ahead of the game!

Progress on M_{top} at the Tevatron

- Exploiting all top quark decay channels
  - Lepton + jets + missing E_T (one W decays hadronically, one leptonically, most sensitive channel)
  - Dilepton + 2 b-quark jets (largest signal/background ratio)
  - All-jets (both W's decay hadronically, largest signal)
- ...and different techniques, e.g.
  - Fitting reconstructed top mass with simulated templates
  - Maximizing dynamical likelihood computed using SM matrix elements
  - Neutrino-weighting
  - Ideogram method
  - Lepton transverse momentum and boost of *b* quarks

Progress on M_{top} at the Tevatron

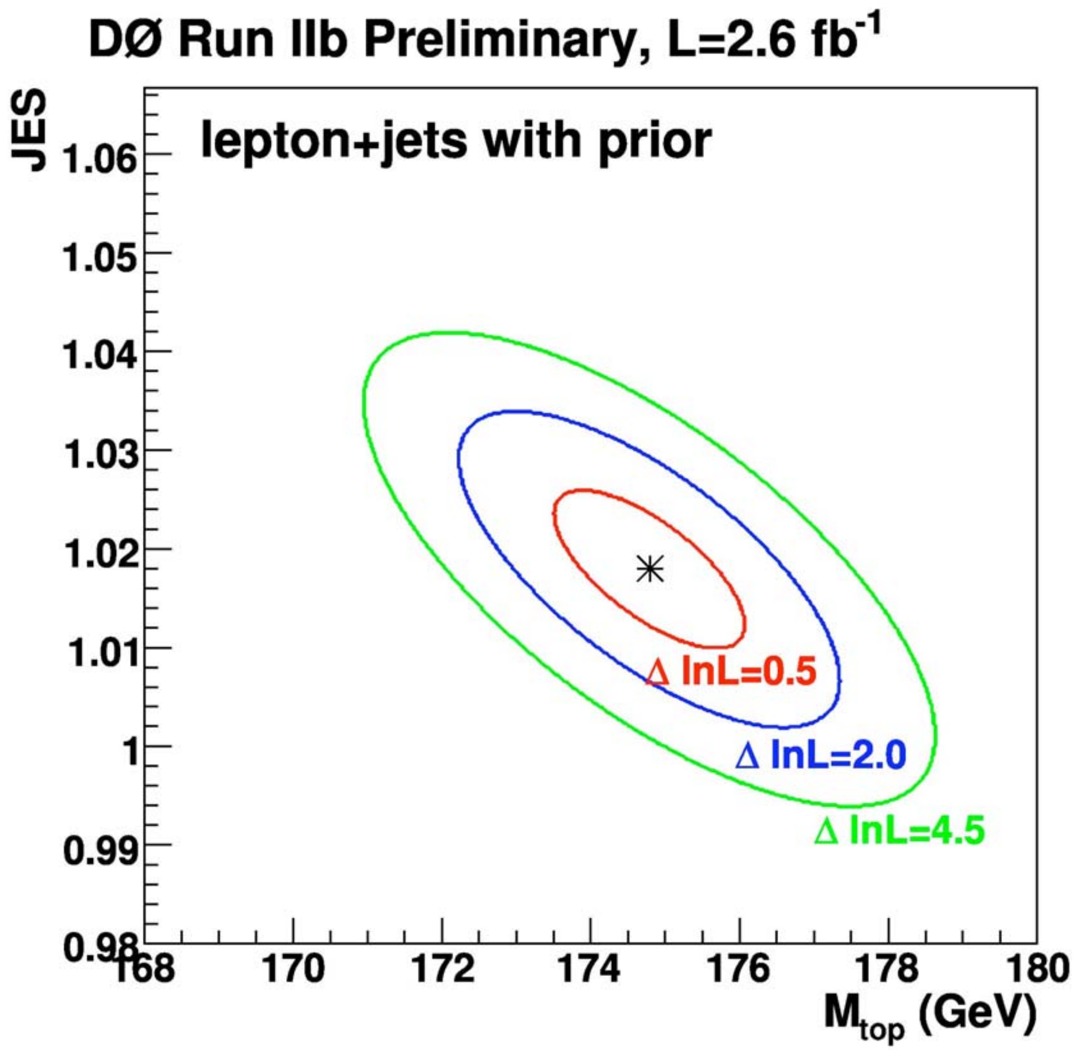
Improved top mass precision due to *in-situ* calibration of jet energy using W->jj decays in the same events



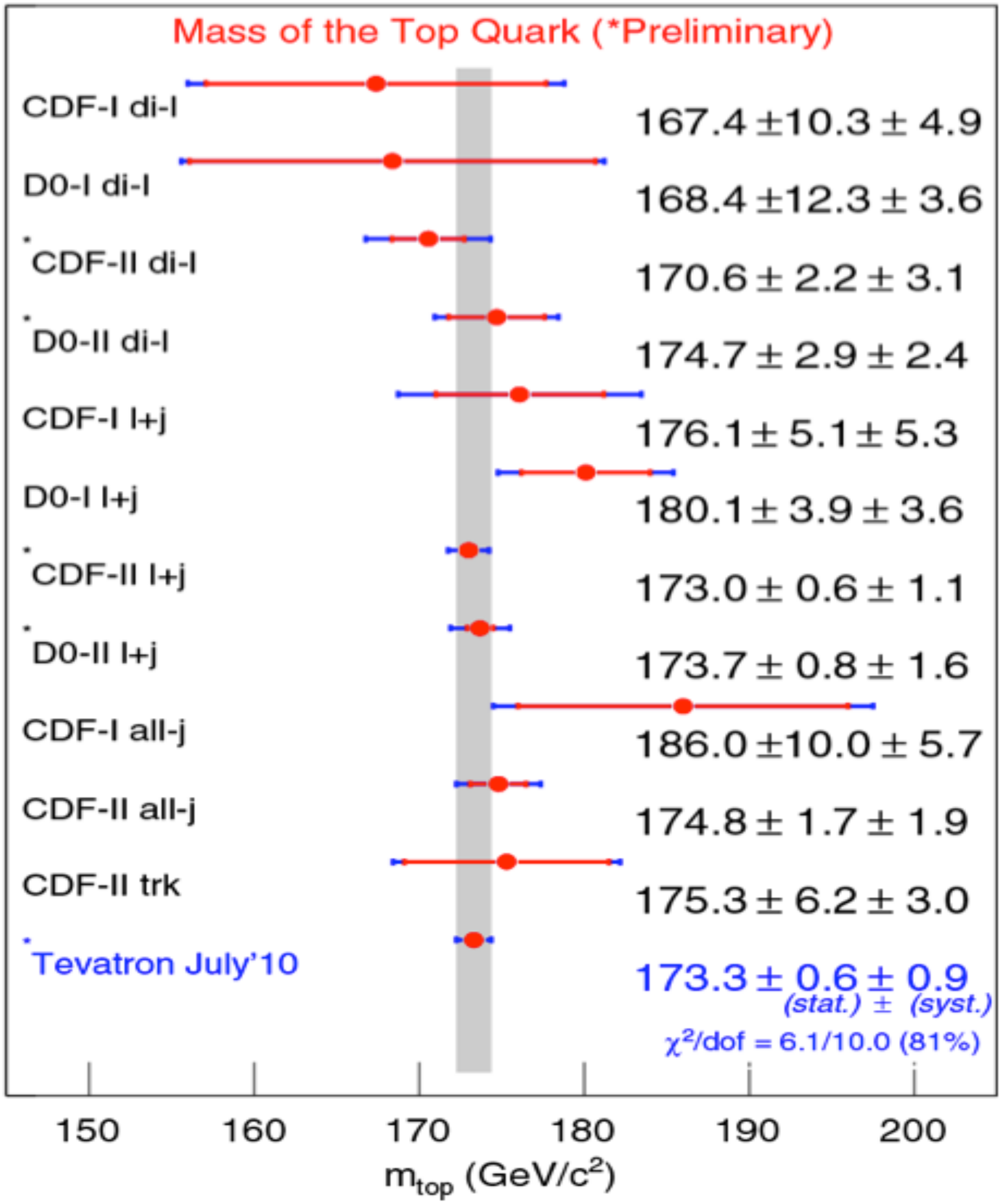
Progress on M_{top} at the Tevatron

Use the W boson mass as a constraint on the hadronic jets

2D fit for W->jj mass (to obtain jet energy scale JES) and top quark mass



Progress on M_{top} at the Tevatron



M_{top} measurement is now in systematics-dominated regime

Progress on M_{top} at the Tevatron

Uncertainty GeV/c2	Tevatron
Stat.	0.56
iJES	0.46
aJES	0.21
bJES	0.2
cJES	0.13
dJES	0.19
rJES	0.15
Lepton Pt	0.09
Signal	0.19
Generator	0.4
UM	0.02
Background	0.23
Method	0.11
CR	0.39
MHI	0.08

Jet Energy Scale uncertainty: 0.61 GeV

← Statistical component from *in-situ* W->jj calibration: 0.46 GeV

Non-statistical JES component: 0.4 GeV
Rapidity & p_T dependence,
Fragmentation & out-of-cone showering

← QCD radiation and parton distributions

← Differences in *tt* generators

← Color reconnection

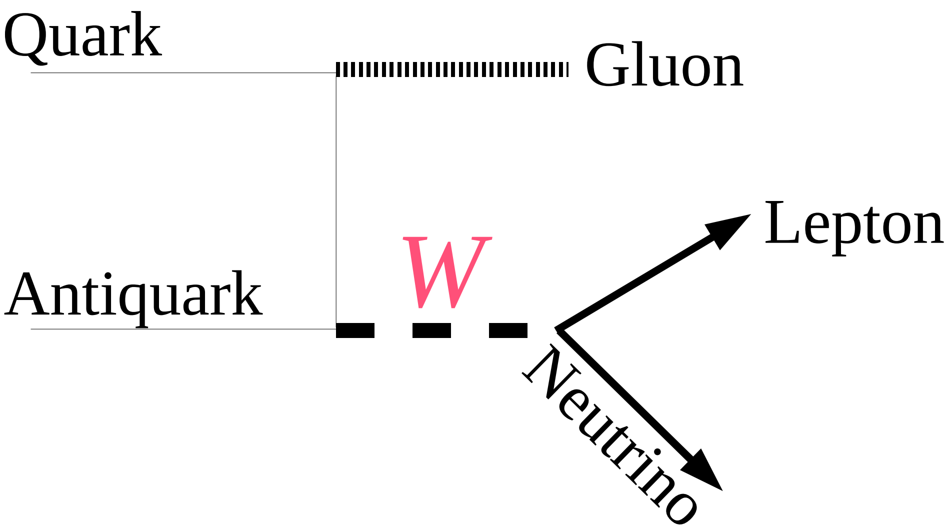
Summary of M_{top} Uncertainties

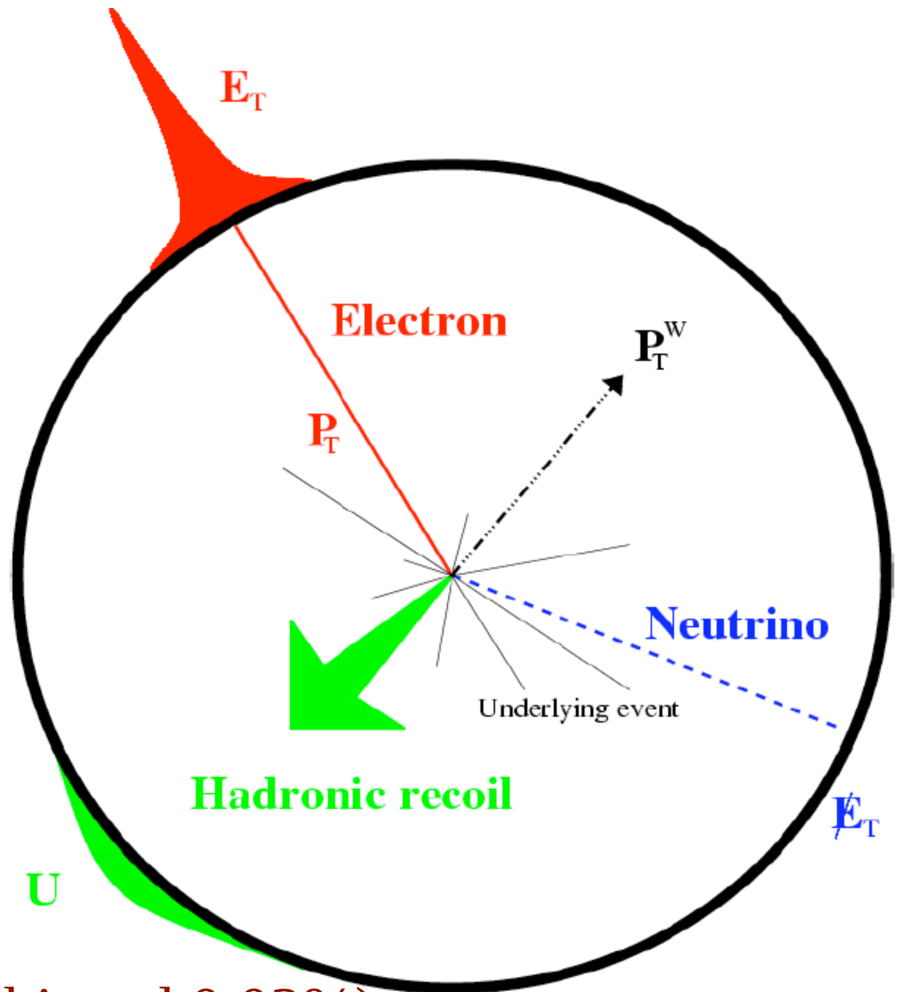
- $M_{top} = 173.3 \pm 1.1$ GeV
  - Statistical uncertainty 0.56 GeV
  - Statistical uncertainty of JES from *in-situ* W->jj : 0.46 GeV
  - Other JES systematics: 0.4 GeV
  - Generator physics: 0.4 GeV
  - Color reconnection: 0.39 GeV
  - Other systematics: 0.36 GeV
- Total uncertainty of statistical origin: 0.73 GeV
- Total uncertainty of non-statistical origin: 0.77 GeV

$\delta M_{top} < 1$ GeV may be possible at the Tevatron

W Boson Mass Measurement

W Boson Production at the Tevatron





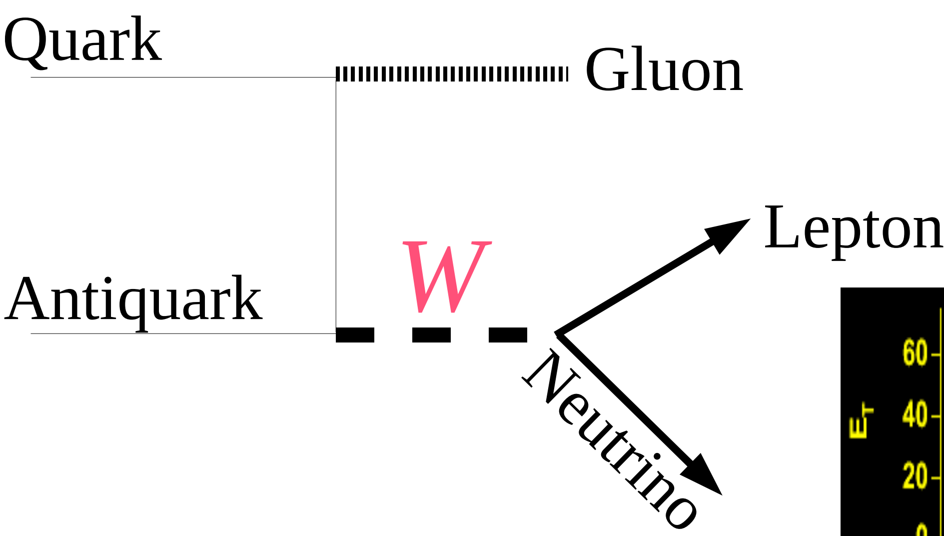
Quark-antiquark annihilation dominates (80%)

Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.03%)

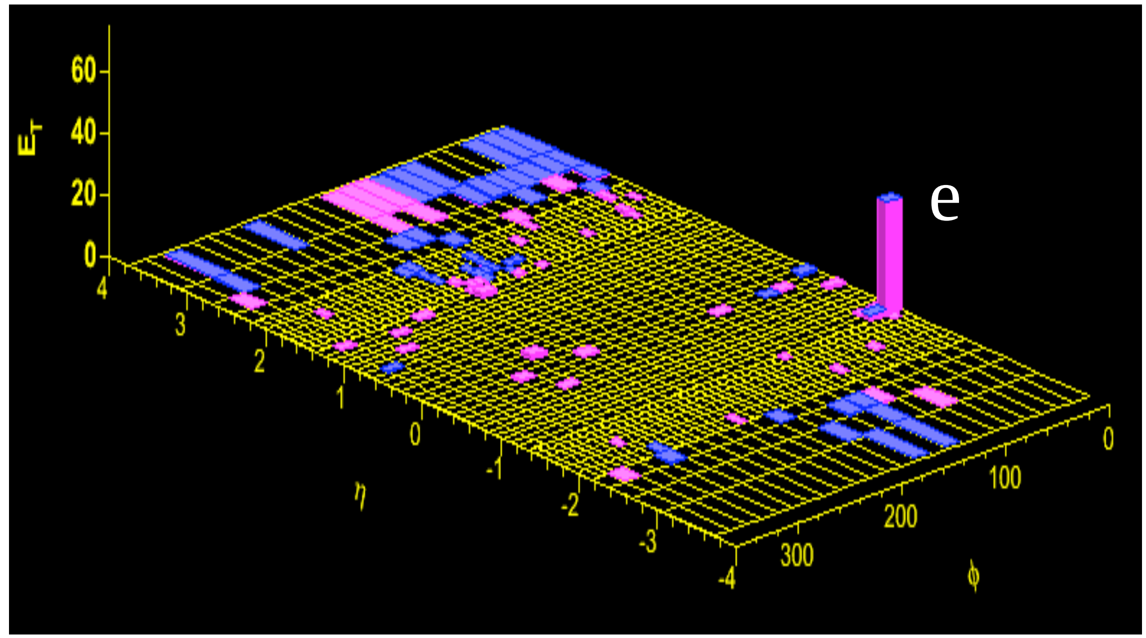
Initial state QCD radiation is *O*(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)

Pollutes *W* mass information, fortunately $p_T(W) \ll M_W$

W Boson Production at the Tevatron



Quark-antiquark annihilation dominates (80%)

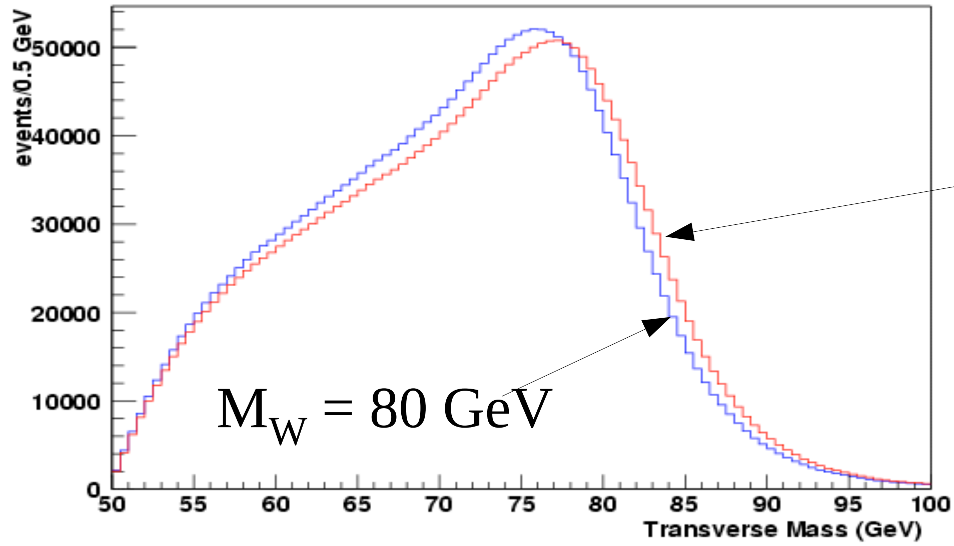


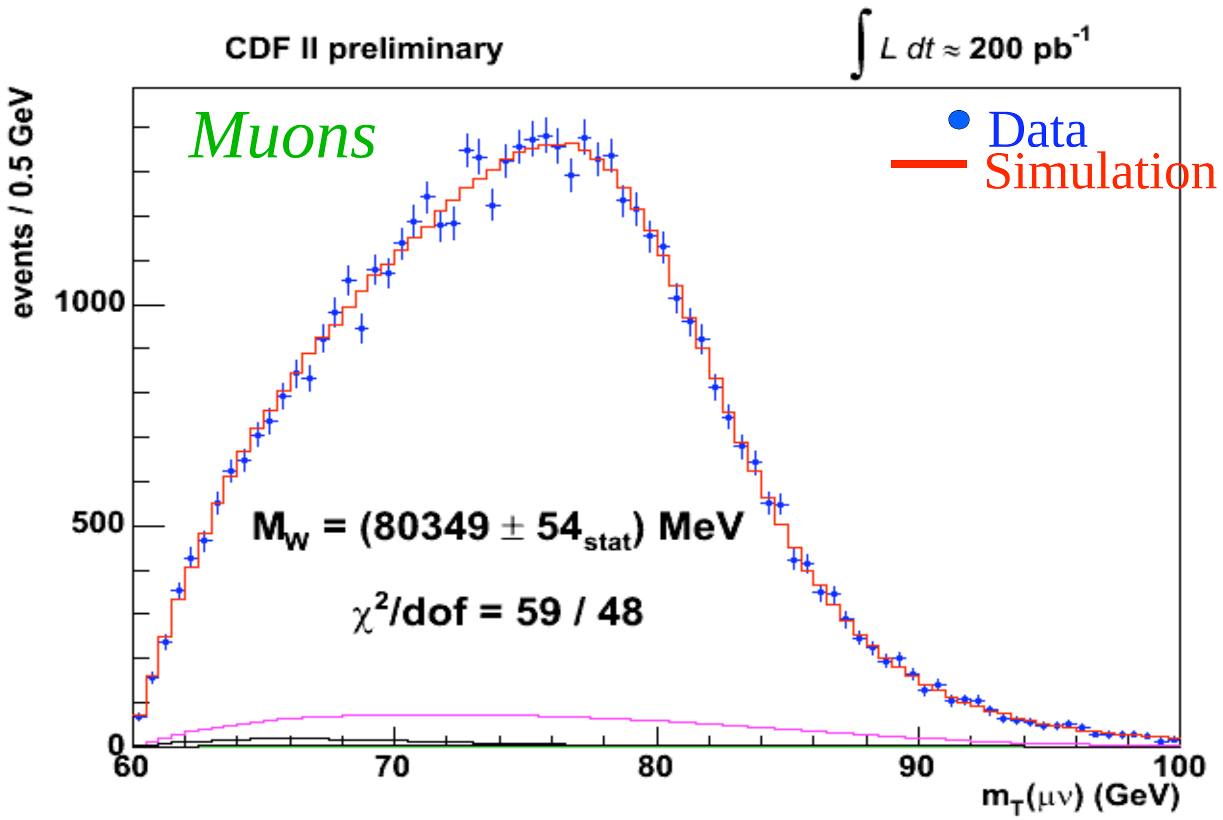
Lepton p_T carries most of W mass information, can be measured precisely (achieved 0.03%)

Initial state QCD radiation is O(10 GeV), measure as soft 'hadronic recoil' in calorimeter (calibrated to ~1%)

Pollutes W mass information, fortunately $p_T(W) << M_W$

Fitting for the *W* Boson Mass





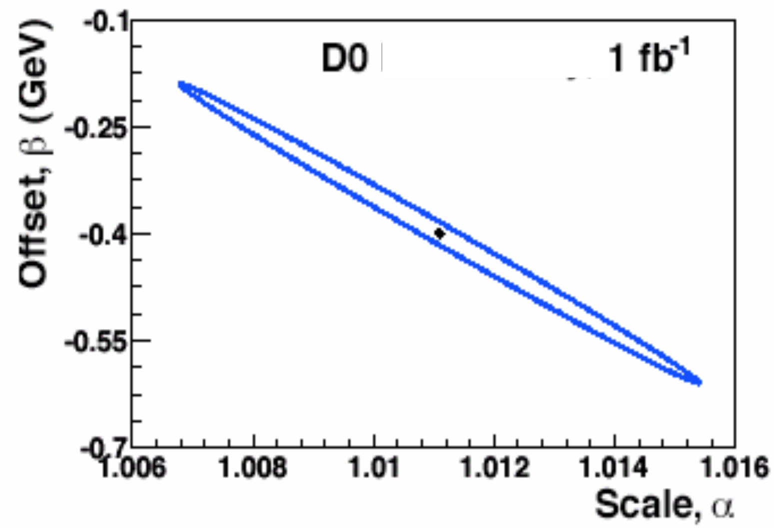
Perform fits to kinematic distributions sensitive to the W boson mass

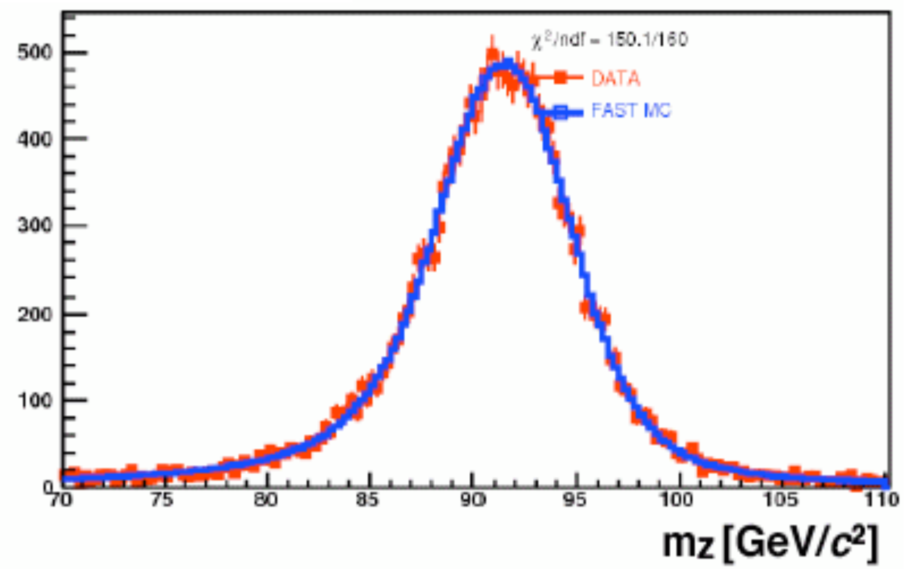
Energy scale and resolution at DØ

- Calibrate EM energy scale using $Z \rightarrow ee$ decays and LEP value for m_Z

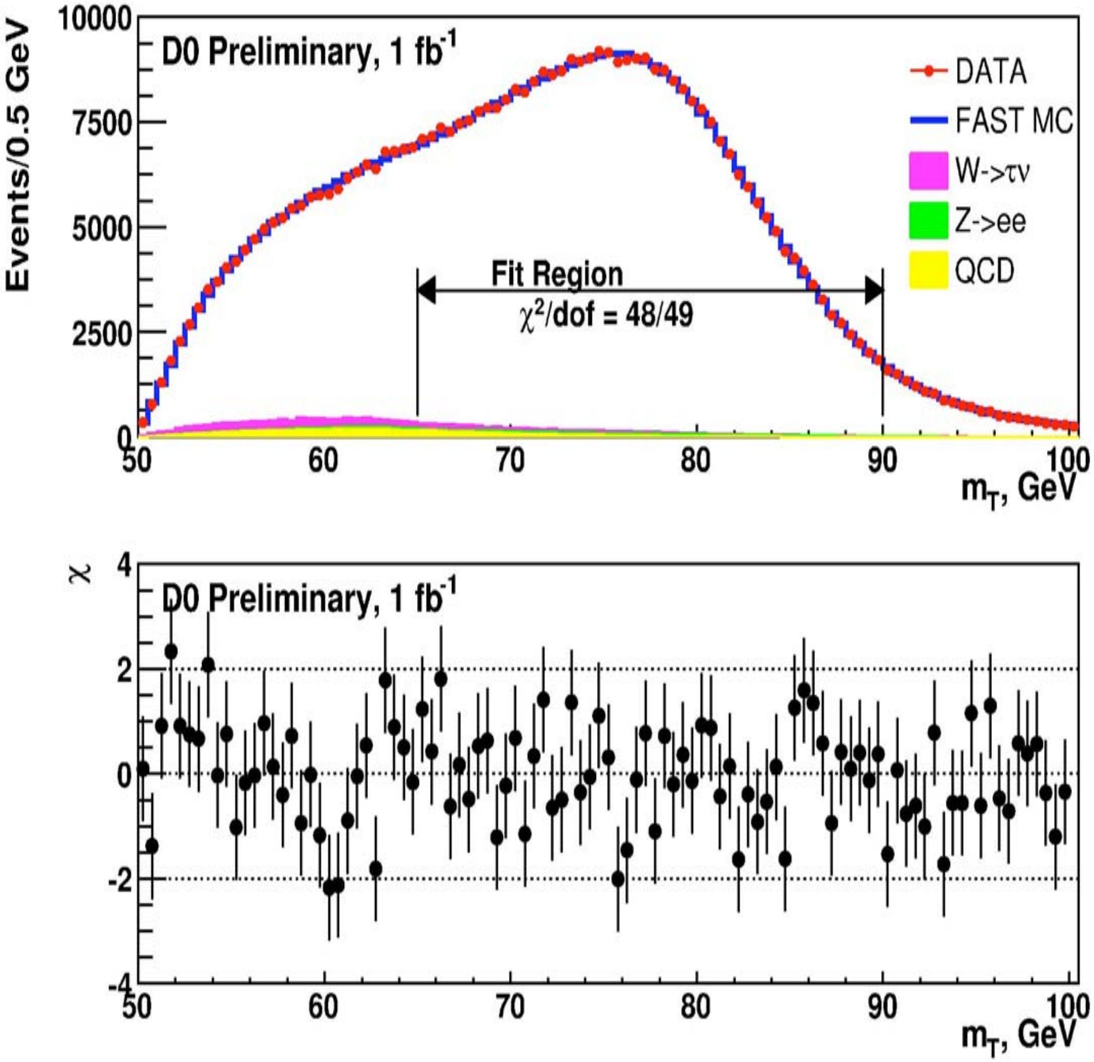
$$R_{EM}(R_0) = \alpha \times E_0 + \beta$$

  - Δm_W=34 MeV
    - Dominant systematic, limited by Z statistics
- Parameterize energy resolution as constant term and sampling term
  - Sampling term driven by knowledge of amount of material in CAL
  - Constant term from Z peak
    - Obtain C=(2.05±0.1)%
  - Δm_W=2 MeV





New Measurement of the W Boson Mass by D0



uncertainties

Source	$\sigma(m_W)$ MeV m_T
Experimental	
Electron Energy Scale	34
Electron Energy Resolution Model	2
Electron Energy Nonlinearity	4
W and Z Electron energy loss differences	4
Recoil Model	6
Electron Efficiencies	5
Backgrounds	2
Experimental Total	35
W production and decay model	
PDF	9
QED	7
Boson p_T	2
W model Total	12
Total	37

Best single measurement of M_W!

Consistent results from lepton and neutrino p_T fits

Outline of CDF Analysis

Energy scale measurements drive the W mass measurement

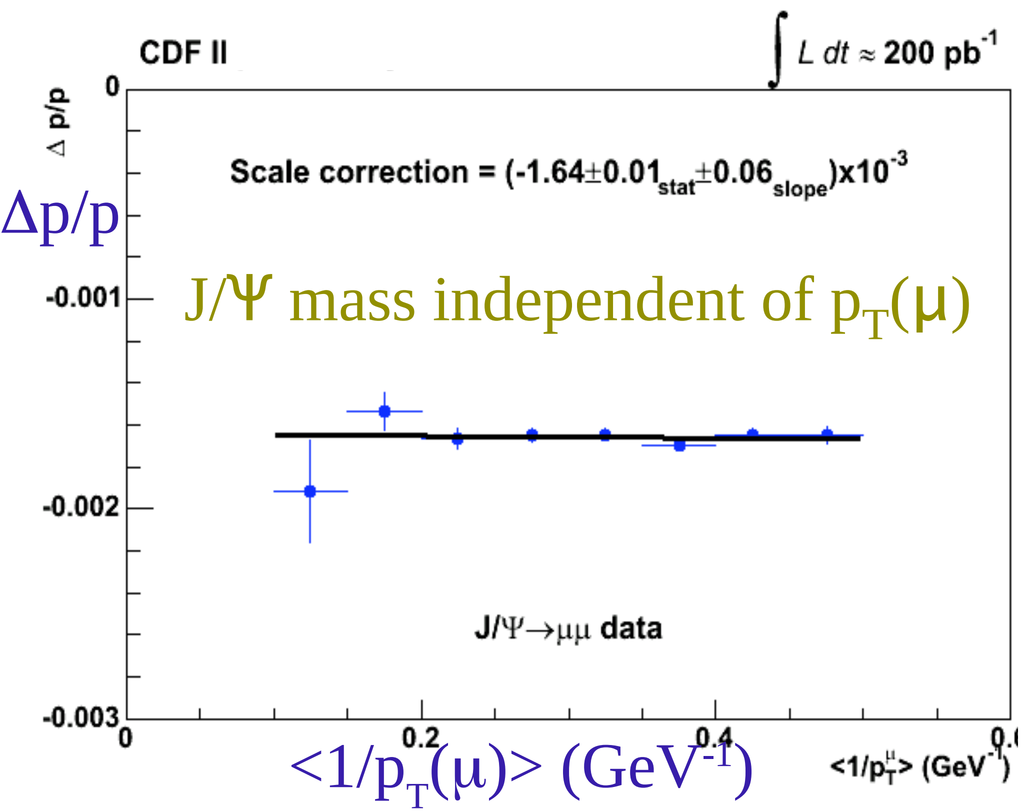
- Tracker Calibration
  - alignment of the central drift chamber (COT with ~2400 cells) using cosmic rays
  - COT momentum scale and tracker non-linearity constrained using $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ mass fits
    - Confirmed using $Z \rightarrow \mu\mu$ mass fit
- EM Calorimeter Calibration
  - COT momentum scale transferred to EM calorimeter using a fit to the peak of the E/p spectrum, around E/p ~ 1
  - Calorimeter energy scale confirmed using $Z \rightarrow ee$ mass fit
- Tracker and EM Calorimeter resolutions
- Hadronic recoil modelling
  - Characterized using p_T-balance in $Z \rightarrow ll$ events

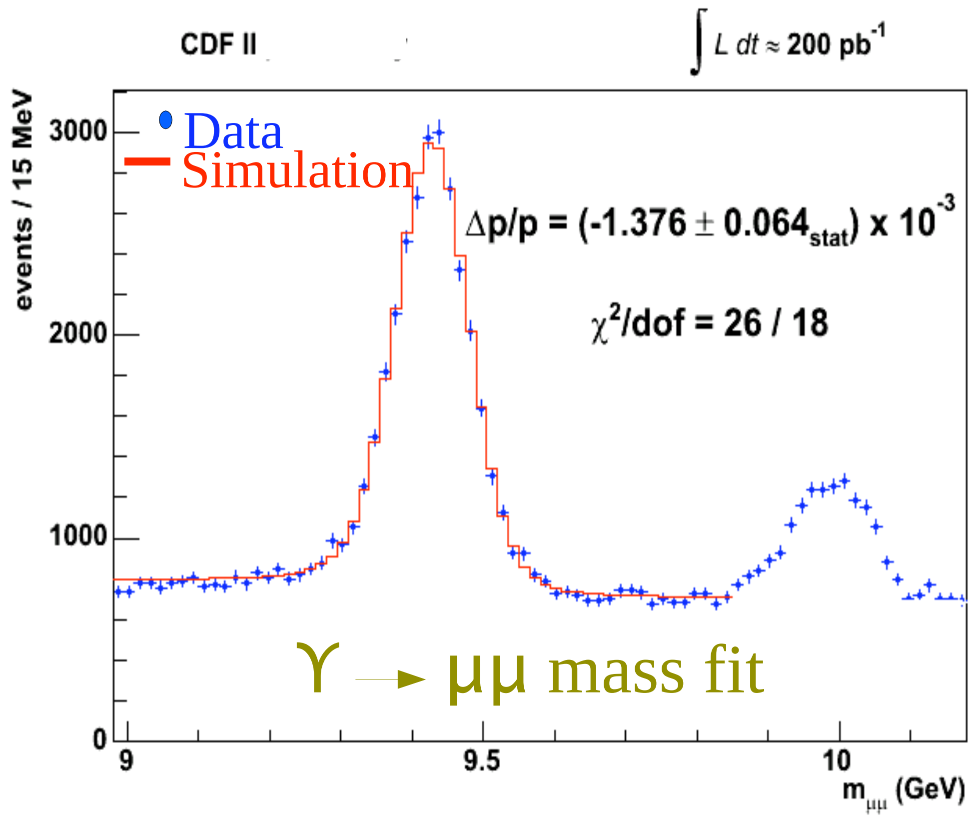
Tracking Momentum Calibration

- Set using $J/\Psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ resonances
  - Consistent within total uncertainties

- Use J/Ψ to study and calibrate non-linear response of tracker

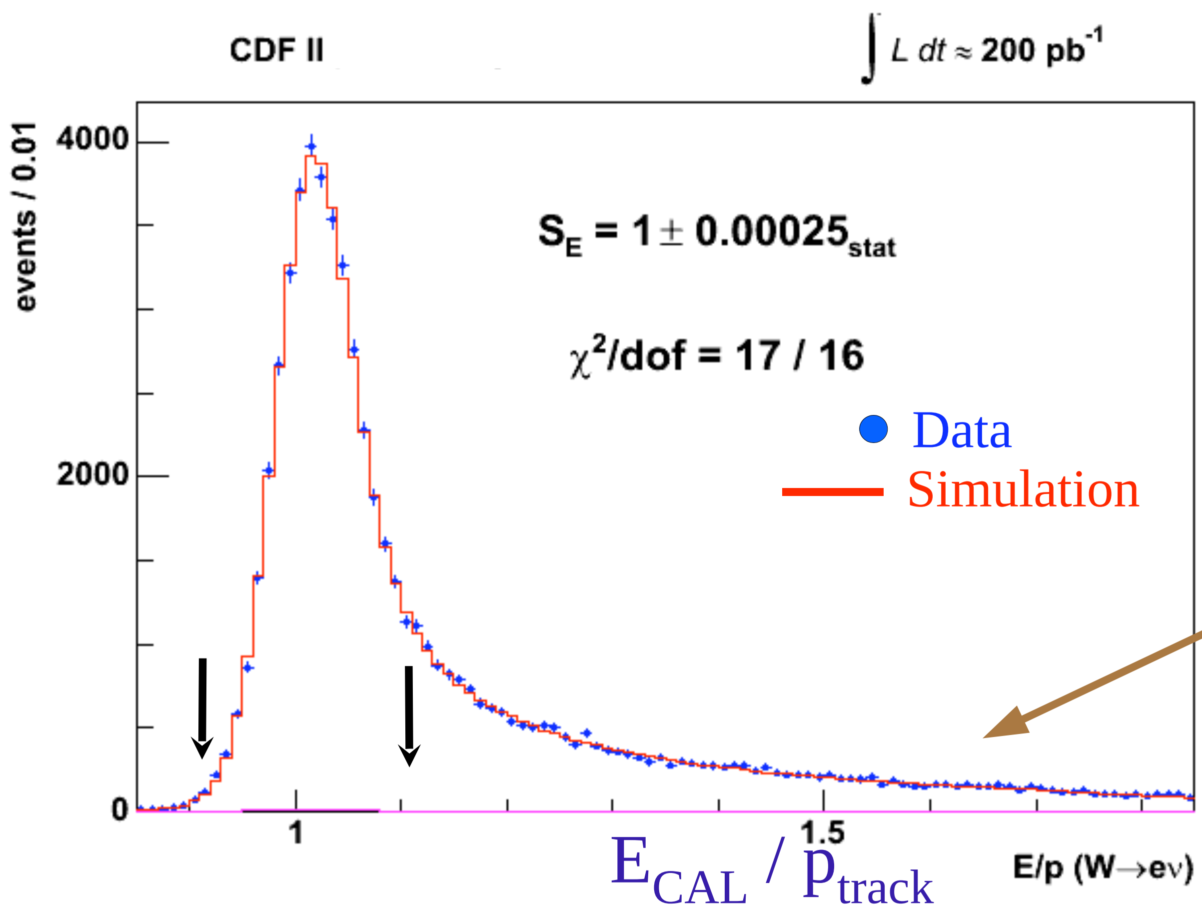
- Systematics-dominated, improved detector modelling required





Electromagnetic Calorimeter Calibration

- E/p peak from $W \rightarrow e\nu$ decays provides EM calorimeter calibration relative to the tracker
  - Calibration performed in bins of electron energy

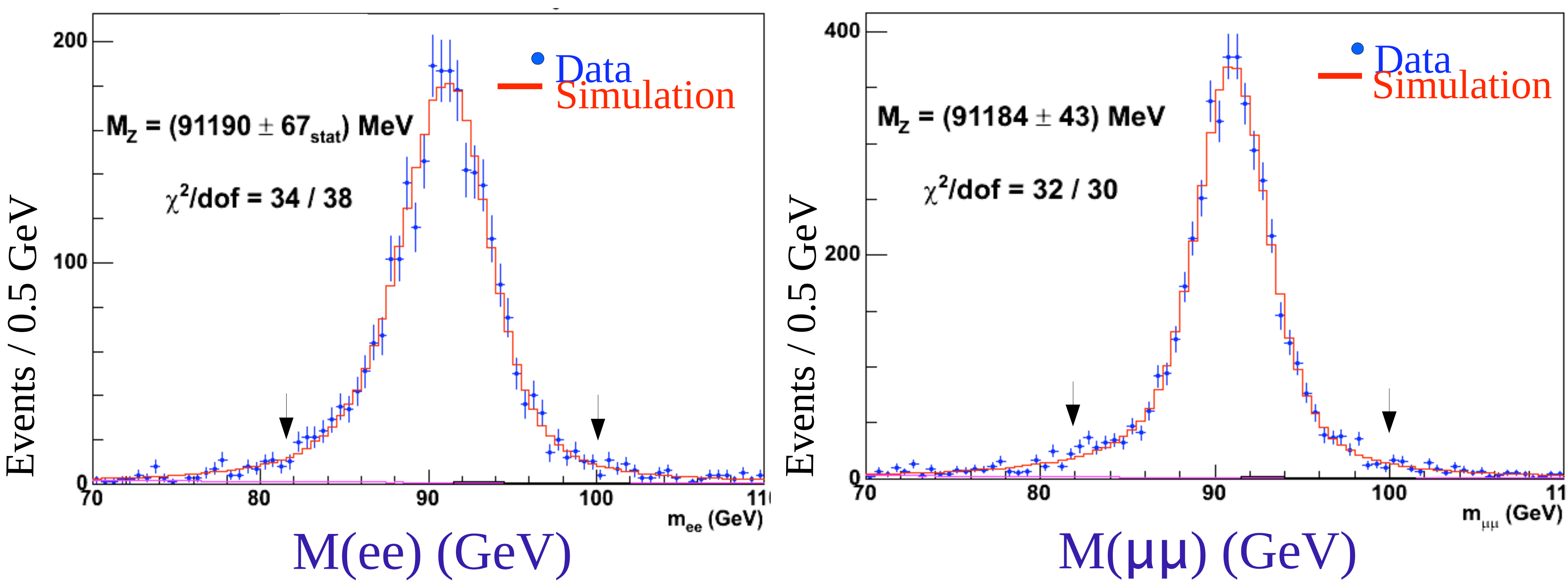


Tail region of E/p spectrum used for tuning model of radiative material

$Z \rightarrow ll$ Mass Cross-checks

- Z boson mass fits consistent with tracking and E/p-based calibrations

CDF II $L \sim 200$/pb



Transverse Mass Fit Uncertainties (MeV)

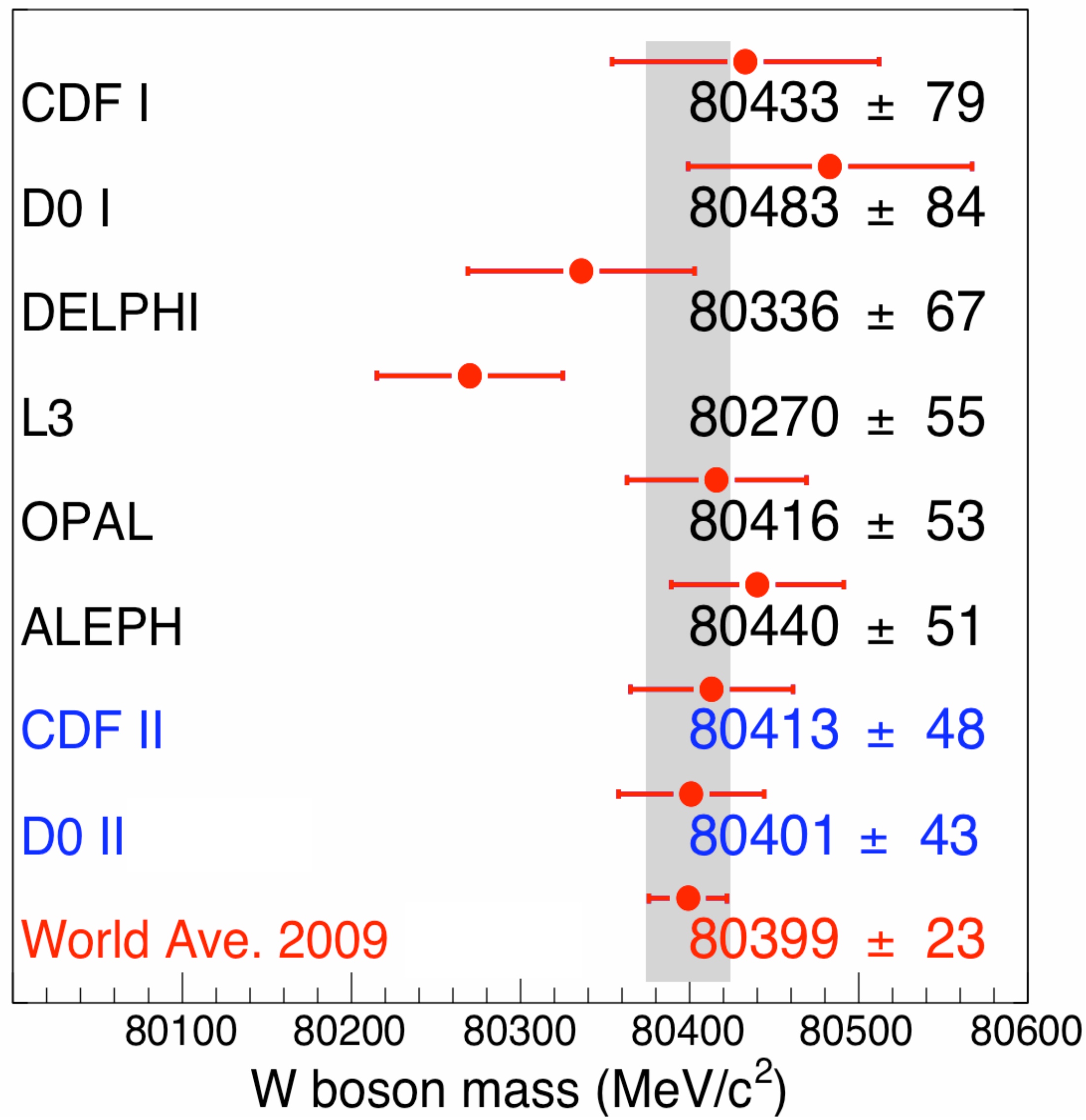
(CDF, PRL 99:151801, 2007; Phys. Rev. D 77:112001, 2008)

	electrons	*muons*	*common*
W statistics	48	54	0
Lepton energy scale	30	17	17
Lepton resolution	9	3	-3
Recoil energy scale	9	9	9
Recoil energy resolution	7	7	7
Selection bias	3	1	0
Lepton removal	8	5	5
Backgrounds	8	9	0
production dynamics	3	3	3
Parton dist. Functions	11	11	11
QED rad. Corrections	11	12	11
Total systematic	39	27	26
Total	62	60	

W charge asymmetry from Tevatron helps with PDFs → Parton dist. Functions

Systematic uncertainties shown in green: statistics-limited by control data samples

W Boson Mass Measurements

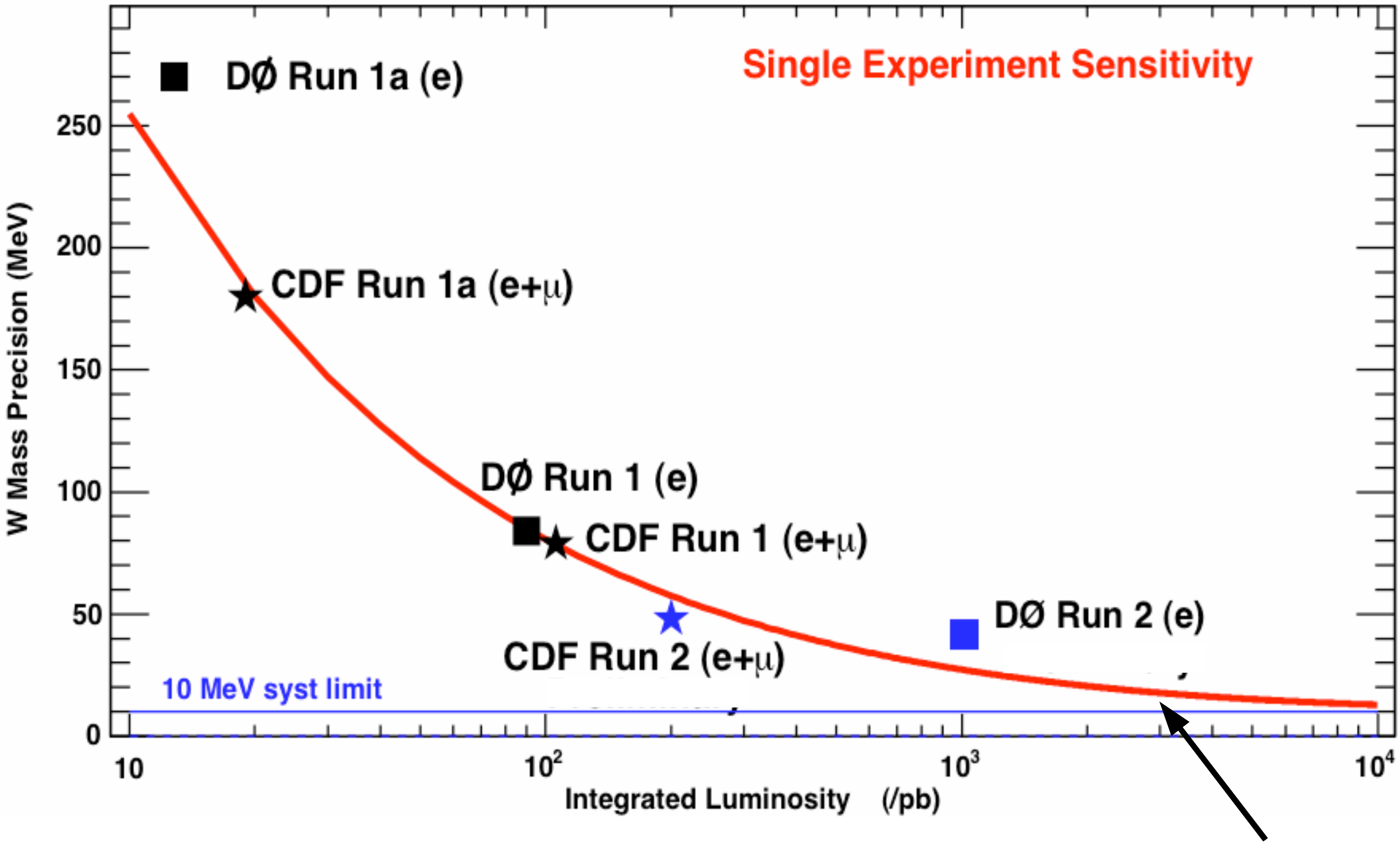


CDF: 200 pb^{-1}, electron and muon channels

D0: 1 fb^{-1}, electron channel

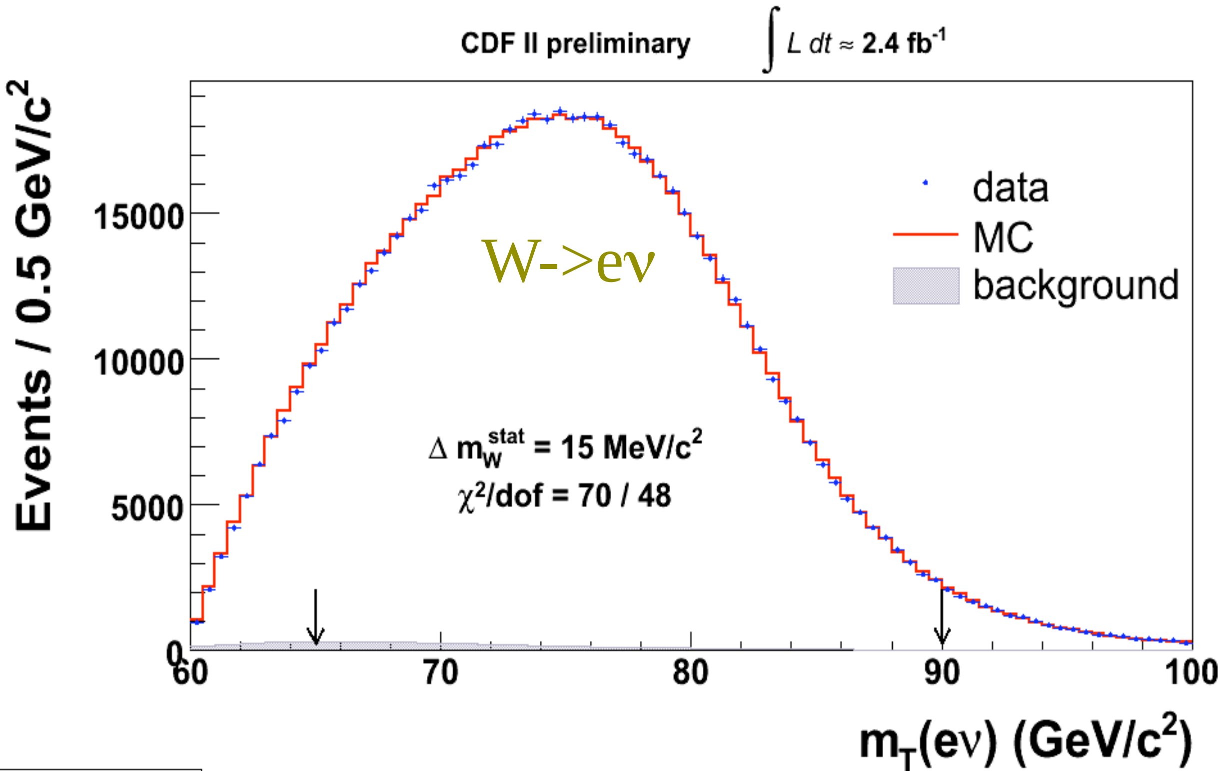
(D0 Run II: PRL 103:141801, 2009)
(CDF Run II: PRL 99:151801, 2007; PRD 77:112001, 2008)

Improvement of M_W Uncertainty with Sample Statistics



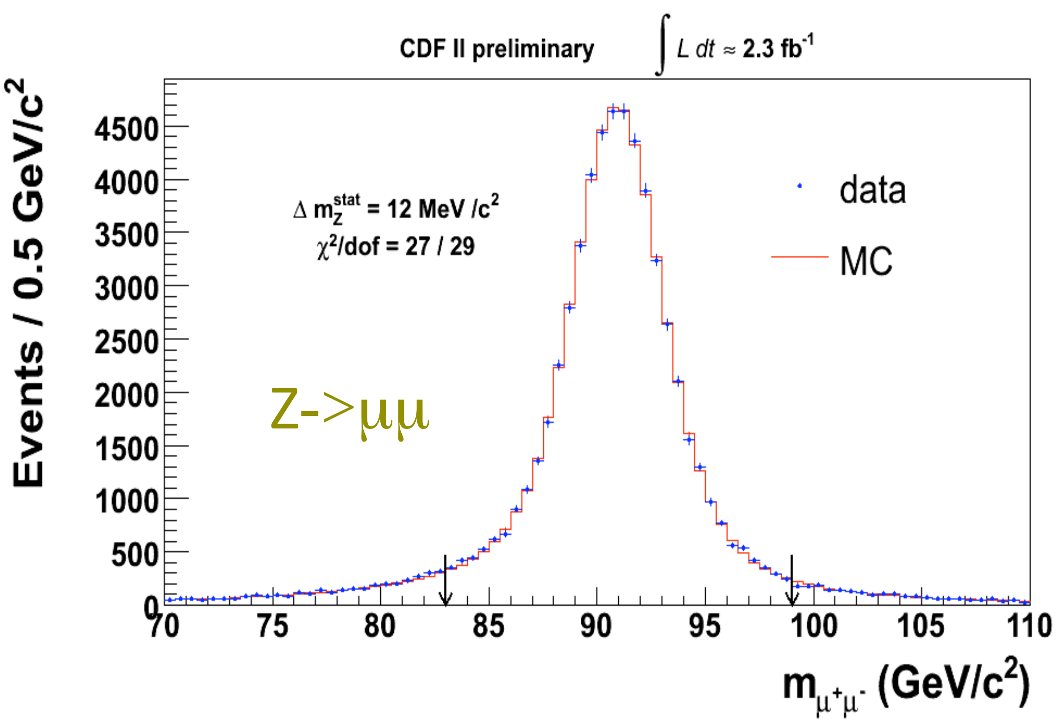
Next target: 15-20 MeV measurement of M_W from the Tevatron

Preliminary Studies of 2-4 fb^{-1} Data at CDF/D0



Detectors performing well

Efficiencies are resolutions are stable over time



statistical errors on W and Z boson mass fits and calibrations are scaling with statistics

Large Hadron Collider Prospects

- prospects for W boson mass measurement:
  - Consider statistical and systematic uncertainties that can be calibrated with Z boson data
  - W mass uncertainty of 7 MeV assuming all Z-based calibrations
  - Key issues: backgrounds, production and decay model uncertainties, cross-checks on calibrations
- prospects for top mass measurement: 800,000 tt pairs / fb^{-1} per leptonic decay channel
  - Suggested top mass precision ~ 1 GeV
- References: SN-ATLAS-2008-070; Eur. Phys. J. C 41 (2005), s19-s33; CMS-NOTE-2006-061; CMS-NOTE-2006-066; arXiv:0812.0470

M_W Measurement at LHC

- Very high statistics samples of W and Z bosons
  - 10 fb^{-1} at 14 TeV: 40 million W boson and 4 million Z boson candidates per decay channel per experiment

- Statistical uncertainty on W mass fit ~ 2 MeV

- Calibrating lepton energy response using the Z → *ll* mass resonance, best-case scenario of statistical limit ~ 5 MeV precision on calibrations

- Calibration of the hadronic calorimeter based on transverse momentum balance in Z → *ll* events also ~ 2 MeV statistical limit

- Total uncertainty on M_W ~ 5 MeV if Z → *ll* data can measure all the W boson systematics

M_W Measurement at LHC

- Can the $Z \rightarrow ll$ data constrain all the relevant W boson systematics?
- Production and decay dynamics are slightly different
  - Different quark parton distribution functions
  - Non-perturbative (e.g. charm mass effects in $cs \rightarrow W$) effects
  - QCD effects on polarization of W *vs* Z affects decay kinematics
- Lepton energies different by ~10% in W *vs* Z events
- Presence of second lepton influences the Z boson event relative to W
- Reconstructed kinematic quantity different (invariant vs transverse mass)
- Subtle differences in QED radiative corrections
- ....
- .... (A.V. Kotwal and J. Stark, Ann. Rev. Nucl. Part. Sci., vol. 58, Nov 2008)

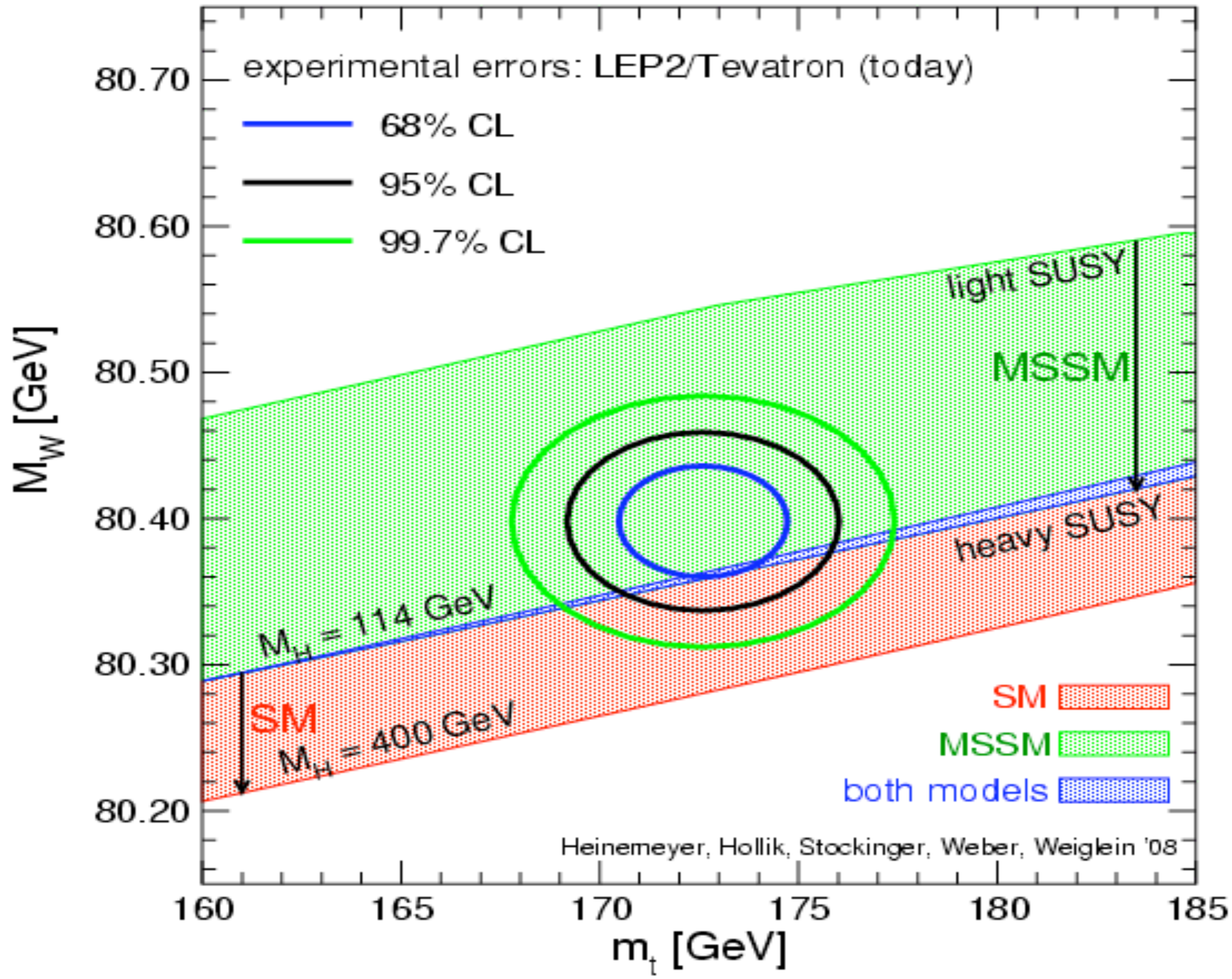
M_W Measurement at LHC

- Can the Z → *ll* data constrain all the relevant W boson systematics?
- Can we add other constraints from other mass resonances and tracking detectors ?
- With every increase in statistics of the data samples, we climb a new learning curve on the systematic effects
  - Improved calculations of QED radiative corrections available
  - Better understanding of parton distributions from global fitting groups (CTEQ, MSTW, Giele *et al*)
- large sample statistics at the LHC imply the potential is there for 5-10 MeV precision on M_W

Summary

- The *W* boson mass and top quark mass are very interesting parameters to measure with increasing precision
- W boson mass measurement from the Fermilab Tevatron and LEP data:
  - $M_W = 80399 \pm 23$ MeV
- Top quark mass measurement from the Tevatron data:
  - $M_{top} = 173.1 \pm 1.3$ GeV
- Tevatron pushing towards $\delta M_W < 25$ MeV and $\delta M_{top} < 1$ GeV
- SM Higgs excluding direct searches yields $m_H < 155$ GeV @ 95% CL
- Learning as we go: Tevatron $\rightarrow$ LHC may produce $\delta M_W \sim 5$-10 MeV and $\delta m_{top} \sim 0.5$ GeV

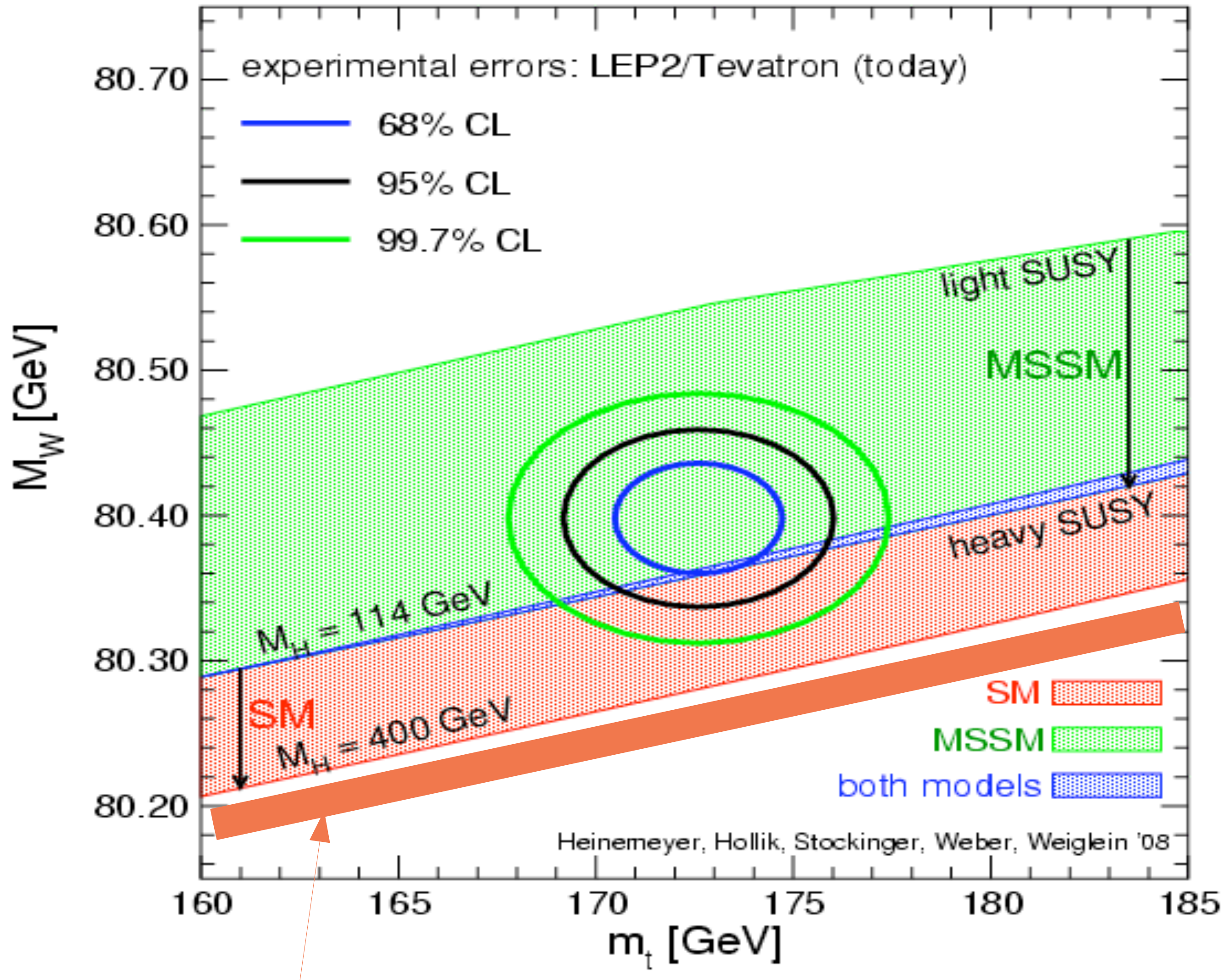
M_W *vs* M_{top}



How will this plot change after (if) LHC observes

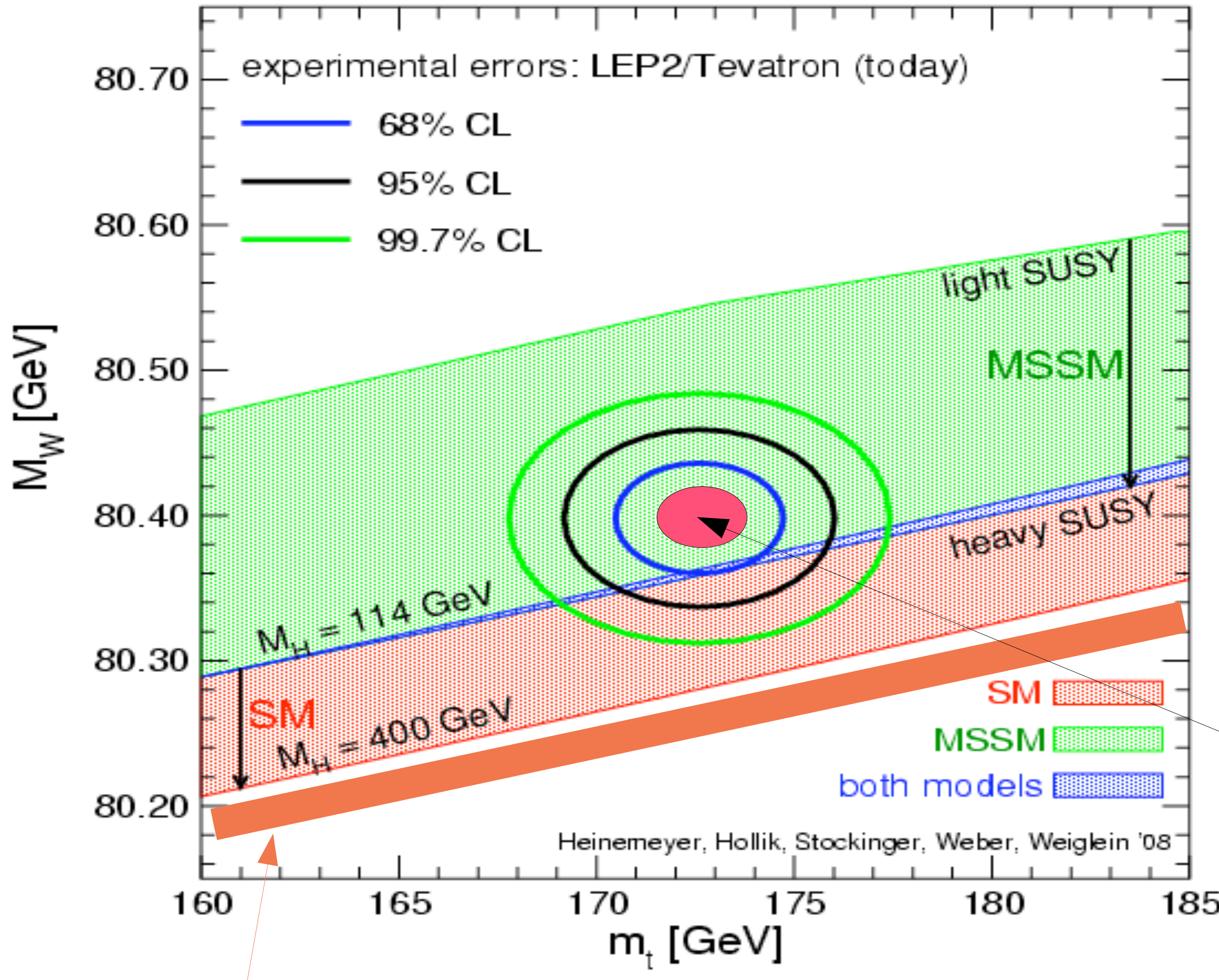
(I) the Higgs (ii) one or more SUSY particles (iii) something else ?

M_W *vs* M_{top}



Higgs discovery with a large Higgs mass (measured with say 25% precision) would create an interesting landscape

A possible future scenario



$\delta M_W = 10$ MeV

$\delta m_{top} = 0.5$ GeV

Higgs discovery with a large Higgs mass