Testing Particle Physics through Precision Measurements

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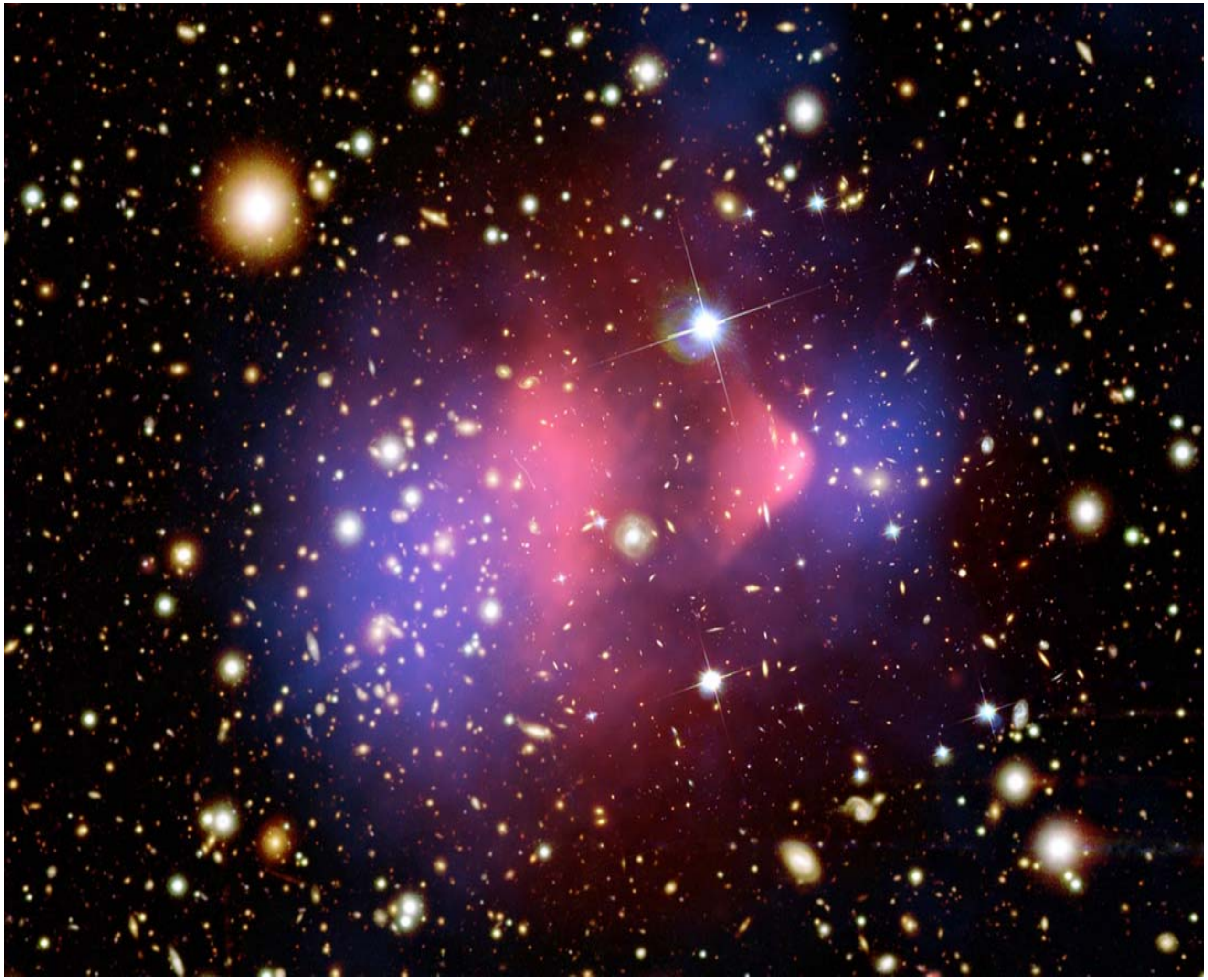

Inter-University Center for Astronomy and Astrophysics
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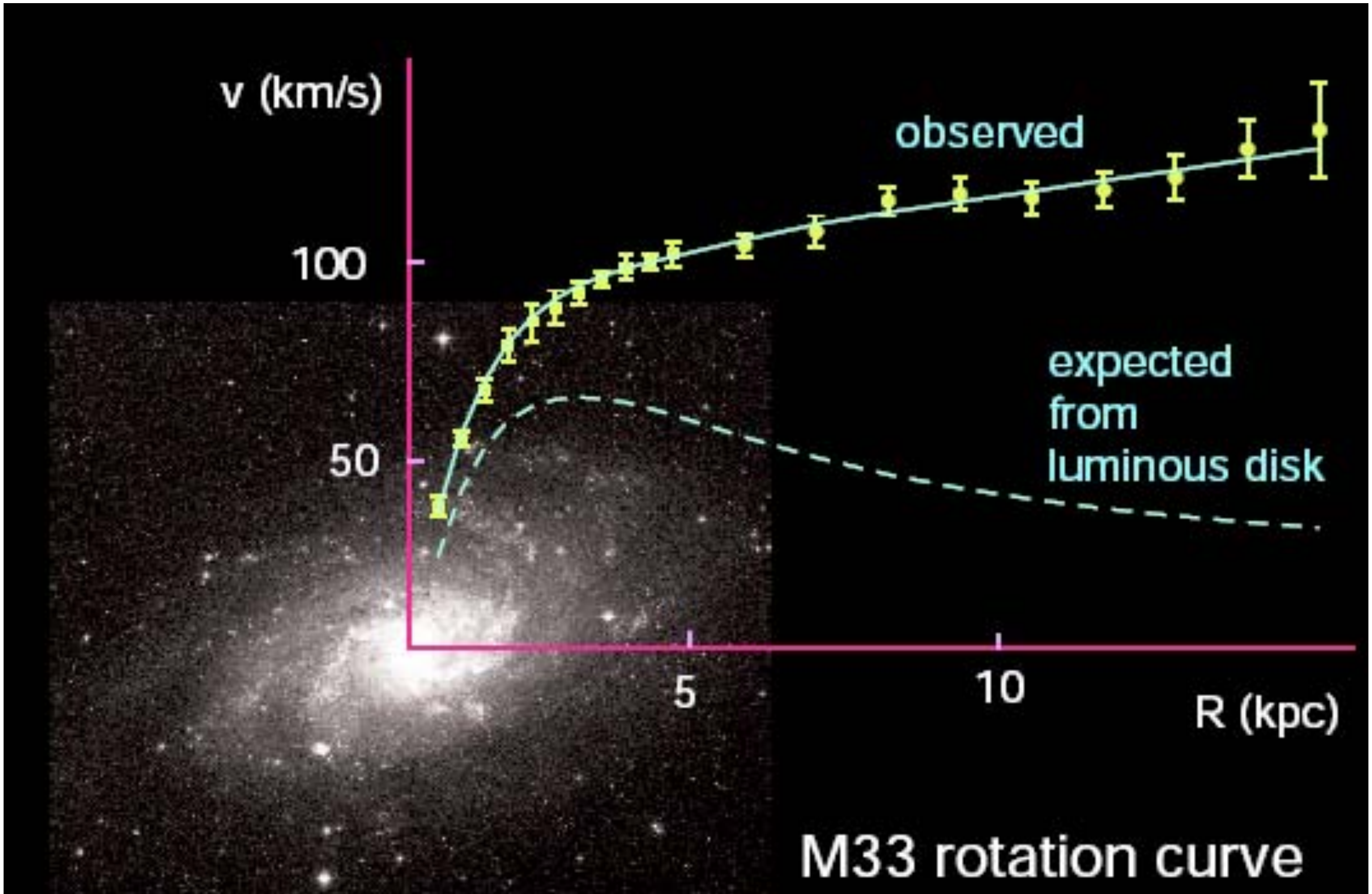
Evidence for Dark Matter



(fig. 1)

Evidence for Dark Matter

- Studies of collision of two clusters of galaxies - “Bullet Cluster” studied in 2006
  - Luminous baryonic matter detected by X-ray emission, separated from distribution of total mass as deduced from gravitational lensing
  - Supports the hypothesis of dark matter whose dominant effect is gravitational
  - One of the favored hypotheses for dark matter is a galactic cloud of “weakly interacting massive particles”
  - With this hypothesis, dark matter bridges astrophysics/cosmology and particle physics
  - What new particles could constitute dark matter?

SuperSymmetry

- SuperSymmetry is a space-time symmetry introduced in particle physics in the 1970's

  A SuperSymmetry (SUSY) operator Q is defined by

  $$Q \,| j > \; = \; | j \pm ½ >$$

  ie. angular momentum of a quantum state is changed by ½ unit

  $$Q^{\dagger} \,| \text{fermion} > \, = \, |\text{boson} >$$
  $$Q \,| \text{boson} > \, = \, |\text{fermion} >$$

- What is the current theory of particle physics ?
- How can SUSY be incorporated into this theory ?
- Could SUSY particles constitute the dark matter ?
- What can we learn about SUSY particles from precision measurements ?

Standard Model of Particle Physics

- A Lorentz-invariant quantum field theory
- Success # 1: theory of matter: discovery of 6 quarks and 6 leptons
- 12 fundamental fermions

Quarks

$$\begin{array}{lll} \mathrm{u} < 1\ \mathrm{GeV} & \mathrm{c} \sim 1.5\ \mathrm{GeV} & \mathrm{t} \sim 175\ \mathrm{GeV} \\ \mathrm{d} < 1\ \mathrm{GeV} & \mathrm{s} < 1\ \mathrm{GeV} & \mathrm{b} \sim 4.5\ \mathrm{GeV} \end{array}$$

Leptons

$$\begin{array}{lll} \nu_e < 1\ \mathrm{eV} & \nu_\mu < 0.17\ \mathrm{MeV} & \nu_\tau < 24\ \mathrm{MeV} \\ \mathrm{e}\ 0.5\ \mathrm{MeV} & \mu\ 106\ \mathrm{MeV} & \tau\ 1.8\ \mathrm{GeV} \end{array}$$

Standard Model of Particle Physics

- Success # 2: *predictive* theory of fundamental forces
  - matter particles (quarks and leptons) transform in *curved* internal spaces
  - Lagrangian required to be invariant under above “gauge” or coordinate transformations of fermions in internal spaces
  - Invariance *predicts* bosonic vector fields → gauge fields
  - Gauge field coupling to fermion field is prescribed by symmetry
  - Gauge field → gauge invariant force fields

- Analogous to the Coriolis and Centrifugal forces generated in rotating frames of reference

A Century of Particle Physics: Standard Model

- Idea of symmetry under "gauge transformations" not just a theoretical success: beautifully confirmed by large amount of experimental particle physics measurements, for

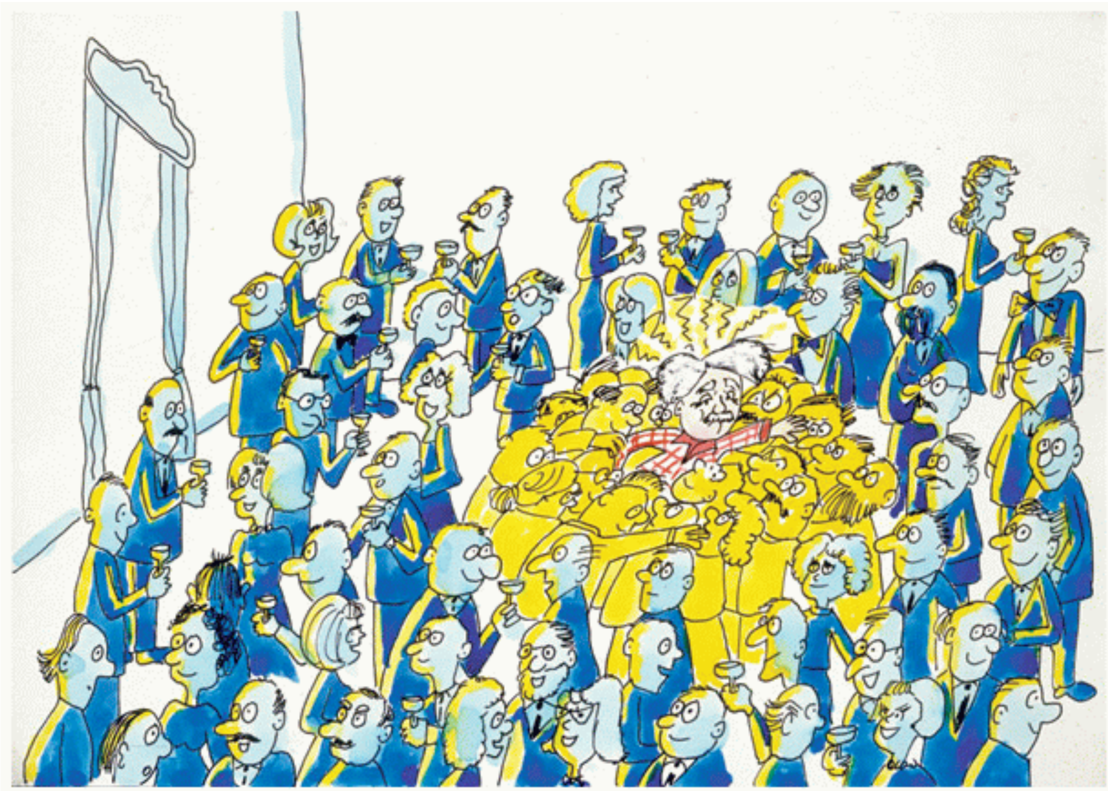
  - Electromagnetic force $\Psi(x) \longrightarrow e^{i\varphi(x)}\,\Psi(x)$

    Gauge group is U(1)

  - Weak force (radioactivity): gauge group is SU(2)
  - Strong (nuclear) force: gauge group is SU(3)

The “Problem” of Particle Physics

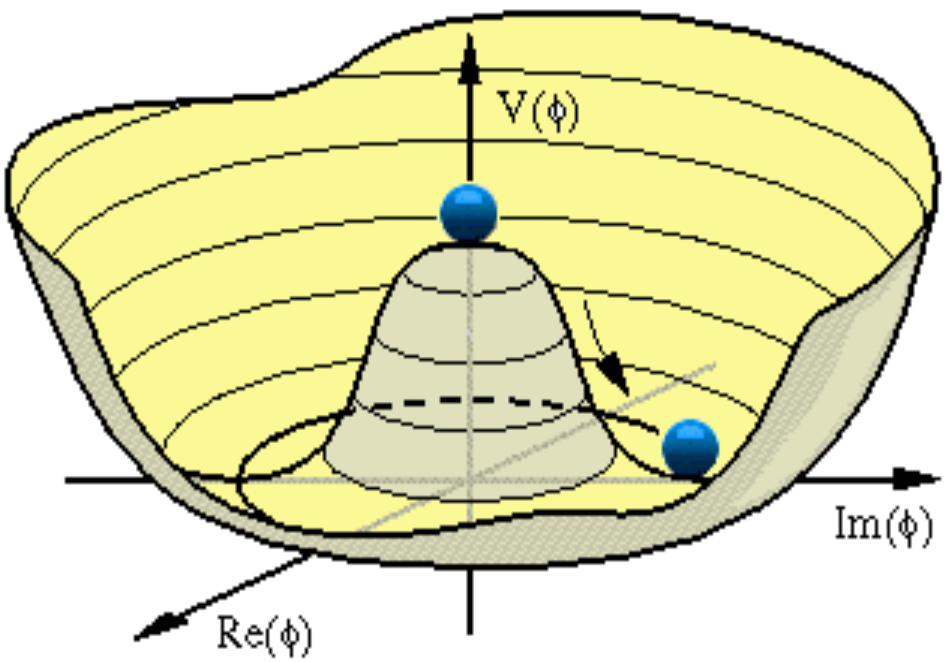
- This highly successful theory predicts that particles should be massless!
  - not true in nature
  - Not only “Dark Matter”, we do not even know the origin of “Visible Matter”
- Theory rescued by postulating a new “Higgs” field, which permeates all space
  - A sticky field, particles moving through space scatter off the Higgs field, thereby *appearing* to be massive

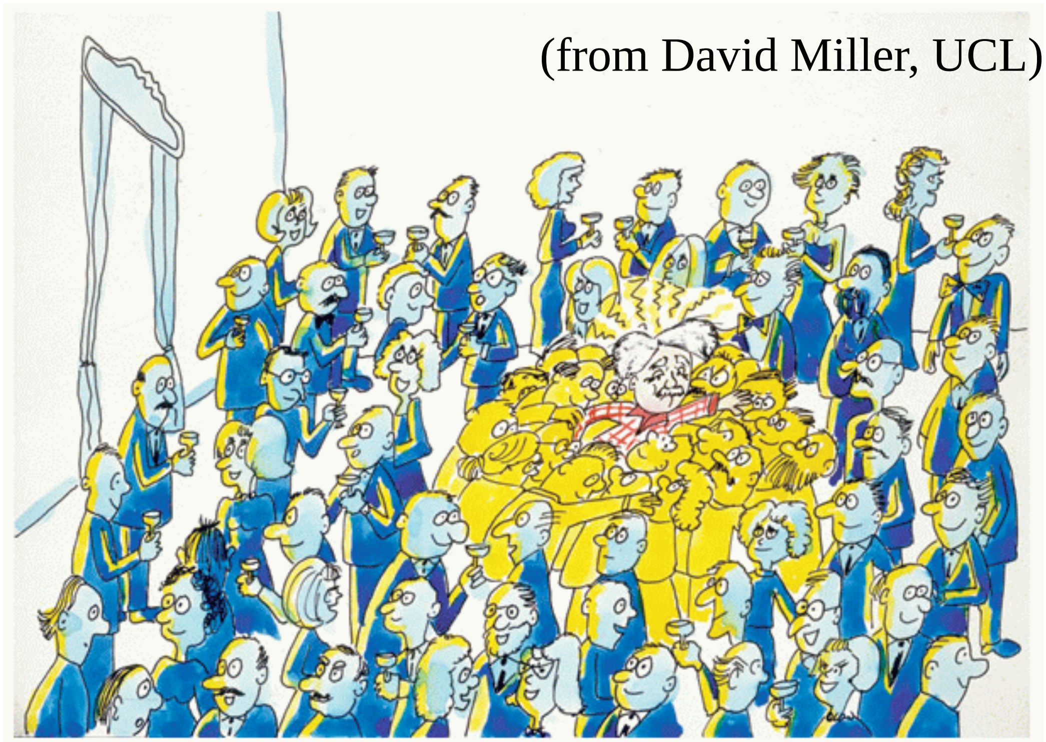


[Image proposed by David Miller, University College London]

The "Problem" of Particle Physics

- As generators of gauge transformations, gauge bosons should be massless
  - Not true in nature for weak interaction: SU(2) generators are $W^{\pm}$, Z bosons
  - W and Z gauge bosons are very massive (W ~ 80 GeV, Z ~ 91 GeV)
- Unconfirmed postulate of scalar Higgs field which develops a vacuum expectation value via spontaneous symmetry breaking





Spontaneous Symmetry Breaking

- 2008 Nobel Prize in Physics

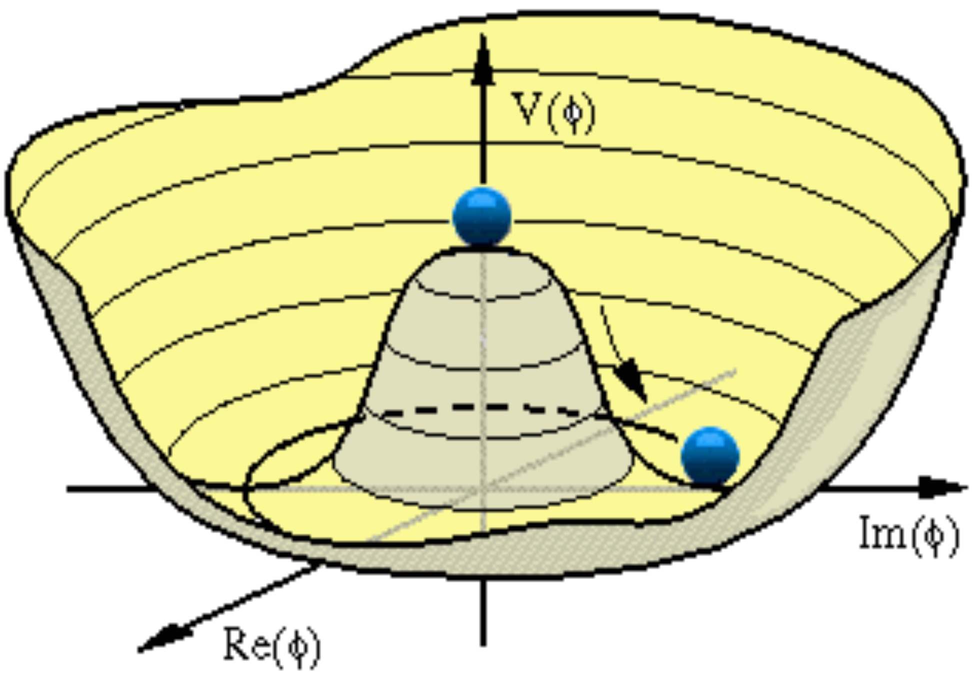
  "for the discovery of the mechanism of spontaneously broken symmetry in subatomic physics"

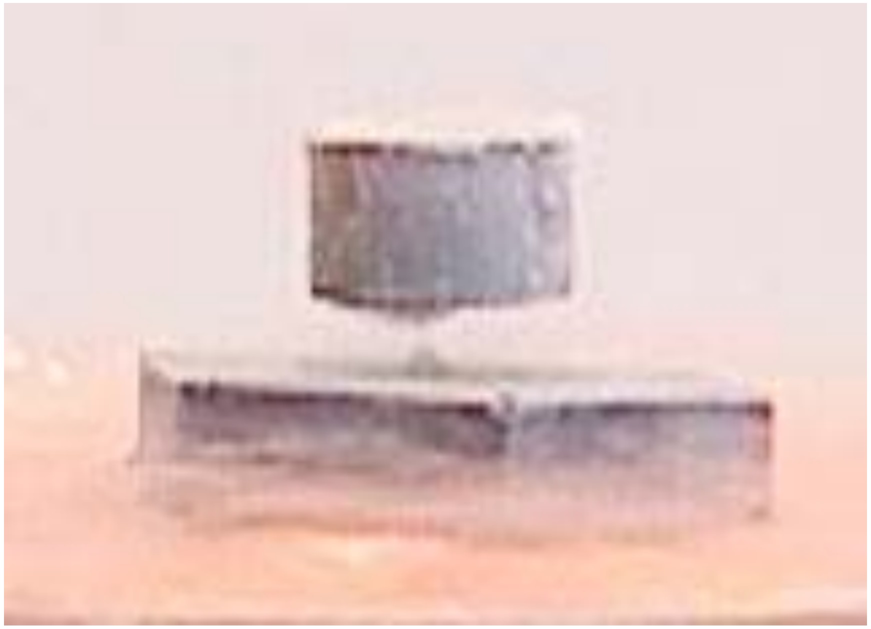
Yoichiro Nambu

- A prime motivation of Large Hadron Collider: expose the mechanism of Electroweak Symmetry Breaking
  - Is it the Higgs mechanism?

The "Problem" of Particle Physics

- Proof of the concept: superconductivity
  - Normally massless photon (quantum of electromagnetic force) becomes massive in a superconductor
- Conclusion: our vacuum is not a true vacuum
  - Its a "false vacuum", behaving like a superconductor

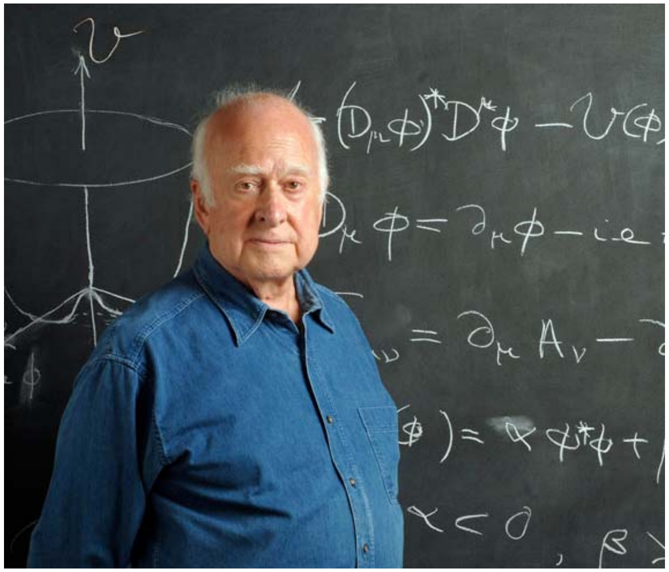




Particle Physics after Higgs Boson

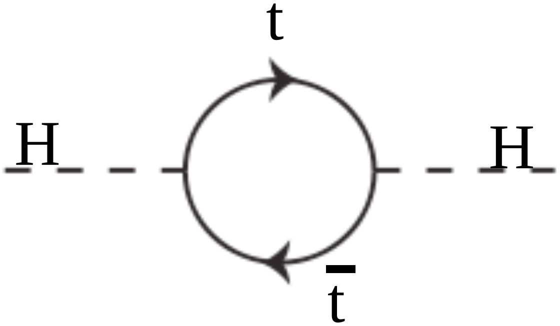
- Would the discovery of the Higgs boson conclude the development of particle physics?

- Higgs mechanism solves the problem of electroweak symmetry breaking in a self-consistent manner.....



Peter Higgs

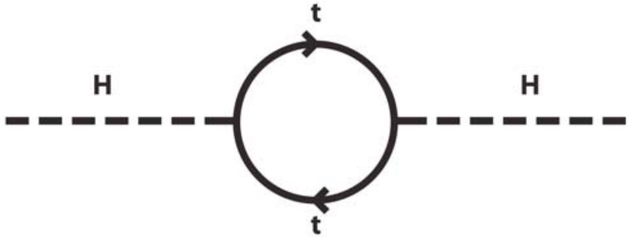
- But it creates a new problem
  - Quantum radiative corrections to the Higgs boson mass are very large and uncontrolled....
  - a worrisome side-effect that cannot be resolved within the quantum field theory containing only the Higgs field



SUSY to the Rescue

- The divergent integral in this quantum loop must be regulated by a high-momentum cutoff, Λ, which could be the gravitational Planck energy scale $M_{planck} \sim 10^{19}$ GeV
  - Loop calculation gives Higgs boson mass correction $\sim M^2_{planck}$

Top quark loop

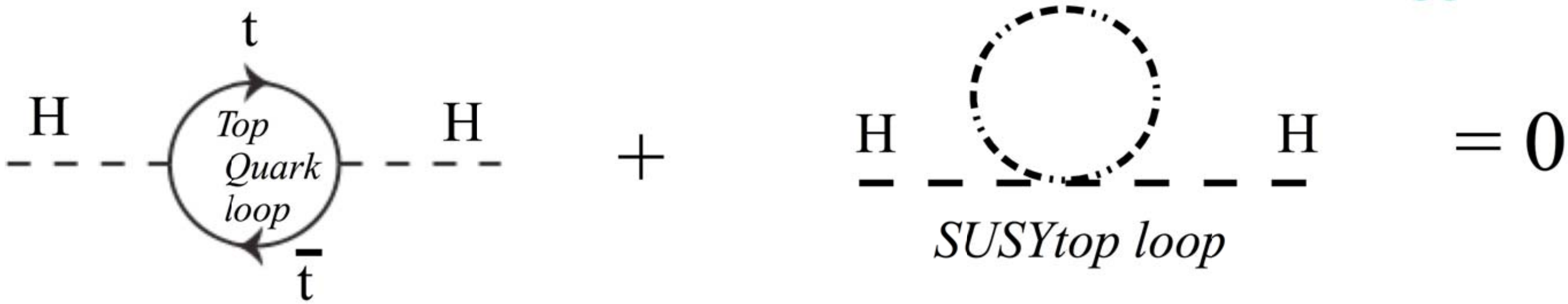


SUSY top loop

- physical Higgs boson mass ~ 1000 GeV
- Therefore need extreme "fine-tuning" through renormalization
- SUSY vastly reduces fine-tuning requirement by introducing additional amplitudes containing fermion → boson loops and boson → fermion loops

SUSY to the Rescue

- SUSY adds bosonic (scalar) partners to fermions and fermionic partners to scalar and vector bosons
  - Higgs bosons ↔ Higgsino fermions
  - Top quark fermions ↔ supersymmetric top bosons
- By construction, all properties other than spin identical between super-partners
- Fermion loop with negative sign relative to boson loop, cancels exactly if SUSY was a exact symmetry
  - Eliminates uncontrolled radiative corrections in the Higgs sector

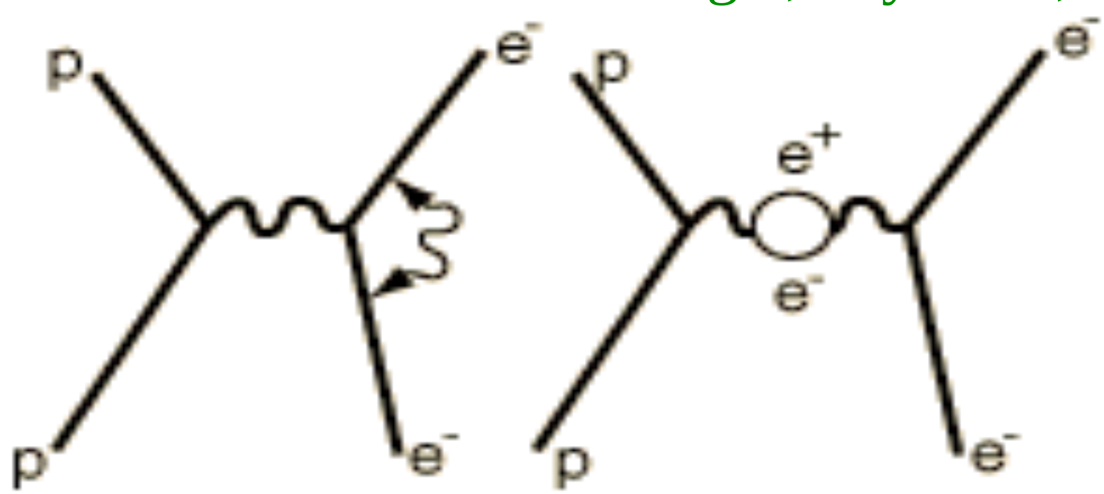


SUSY Particles as Dark Matter

- By definition, all SUSY particles would participate in the same interactions as the Standard Model particles
  - SUSY particles would be produced in the Universe
  - Should also be produced in high energy particle colliders
- As with their Standard Model partners, certain SUSY particles are electrically neutral and interact only by the weak interaction
  - Eg, SUSY partner of the Z boson, the "Zino"
  - Zino is a good candidate for the "weakly interacting massive particle" (WIMP) interpretation of dark matter
- Conserved multiplicative quantum number, "R parity" is natural in SuperSymmetric theories
  - R = +1 for Standard Model particles
  - R = -1 for SUSY particles
- Implies pair-production of SUSY particles and antiparticles
- Also implies lightest SUSY particle, eg, Zino is stable → WIMP

Detecting New Physics through Precision Measurements

- Willis Lamb (Nobel Prize 1955) measured the difference between energies of $^2S_{1/2}$ and $^2P_{1/2}$ states of hydrogen atom
  - 4 micro electron volts difference compared to few electron volts binding energy
  - States should be degenerate in energy according to tree-level calculation
- Harbinger of vacuum fluctuations to be calculated by Feynman diagrams containing quantum loops
  - Modern quantum field theory of electrodynamics followed (Nobel Prize 1965 for Schwinger, Feynman, Tomonaga)



Parameters of Electro-Weak Interactions

- Gauge symmetries related to the electromagnetic and weak forces in the standard model, extension of QED
  - U(1) gauge group with gauge coupling g
  - SU(2) gauge group with gauge coupling g'

- And gauge symmetry-breaking via vacuum expectation value of Higgs field $v \neq 0$

- Another interesting phenomenon in nature: the U(1) generator and the neutral generator of SU(2) get mixed (linear combination) to yield the observed gauge bosons
  - Photon for electromagnetism
  - Z boson as one of the three gauge bosons of weak interaction

- Linear combination is given by Weinberg mixing angle ϑ_W

Parameters of Electro-Weak Interactions

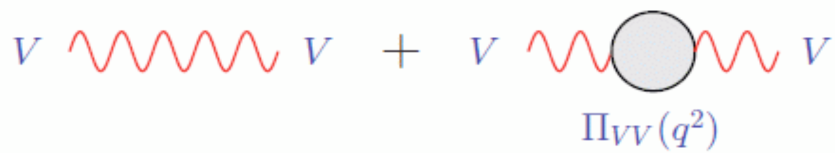
At tree level, all of the observables can be expressed in terms of *three* parameters of the SM Lagrangian: $v,\ g,\ g'$ or, equivalently, $v,\ e,\ s \equiv \sin\theta_W$ (also $c \equiv \cos\theta_W$)

$$\alpha = \frac{e^2}{4\pi}, \qquad G_F = \frac{1}{2\sqrt{2}v^2}, \qquad m_Z = \frac{e\,v}{\sqrt{2}sc}, \qquad m_W = \frac{e\,v}{\sqrt{2}s}, \qquad s^2_{\rm eff} = s^2,$$

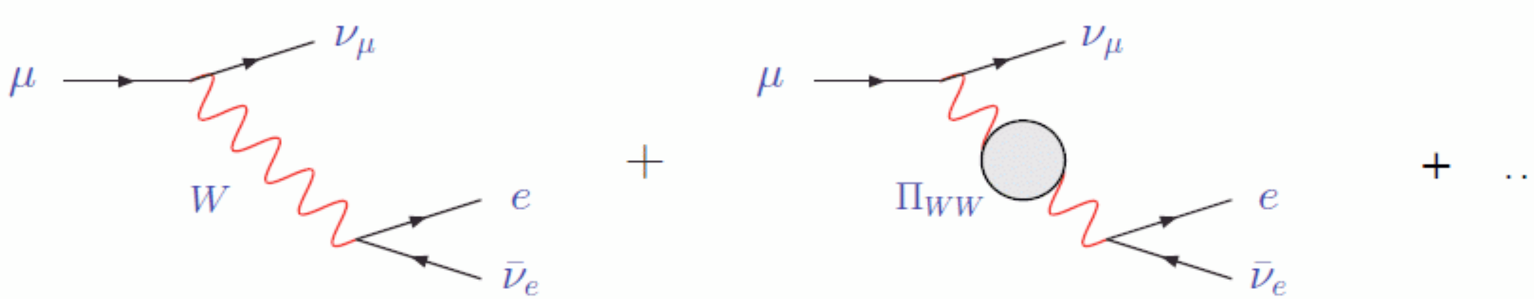
Radiative corrections to the relations between physical observables and Lagrangian params:

$$m_Z^2 \;=\; \frac{e^2 v^2}{2\,s^2 c^2} + \Pi_{ZZ}(m_Z^2)$$

$$m_W^2 \;=\; \frac{e^2 v^2}{2\,s^2} + \Pi_{WW}(m_W^2)$$

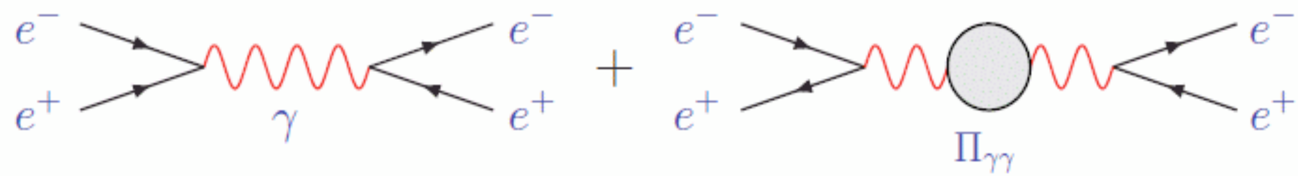


$$G_F = \frac{1}{2\sqrt{2}v^2}\left[1 - \frac{\Pi_{WW}(0)}{m_W^2} + \delta_{\rm VB}\right]$$



Radiative Corrections to Electromagnetic Coupling

$$\alpha = \frac{e^2}{4\pi}\left[1 + \lim_{q^2->0}\frac{\Pi_{\gamma\gamma}(q^2)}{q^2}\right]$$



this one is tricky: the hadronic contribution to $\Pi'_{\gamma\gamma}(0)$ cannot be computed perturbatively

We can however trade it for another experimental observable: $R_{\text{had}}(q^2) = \dfrac{\sigma_{\text{had}}(q^2)}{\sigma_{\ell^+\ell^-}(q^2)}$

$$\alpha(m_Z) = \frac{e^2}{4\pi}\left[1 + \frac{\Pi_{\gamma\gamma}(m_Z)}{m_Z}\right] = \frac{\alpha}{1-\Delta\alpha(m_Z)}$$

$$\Delta\alpha(m_Z) = \underbrace{\Delta\alpha_\ell(m_Z) + \Delta\alpha_{\text{top}}(m_Z)}_{\text{calculable}} + \Delta\alpha^{(5)}_{\text{had}}(m_Z)$$

$$\Delta\alpha^{(5)}_{\text{had}}(m_Z) = -\frac{m_Z^2}{3\pi}\int_{4m_\pi^2}^{\infty}\frac{R_{\text{had}}(q^2)\mathrm{d}q^2}{q^2\,(q^2-m_Z^2)} \;=\; 0.02758 \pm 0.00035$$

(This hadronic contribution is one of the biggest sources of uncertainty in EW studies)

Radiative Corrections to W Boson Mass

All these corrections can be combined into relations among physical observables, e.g.:

$$m_W^2 = m_Z^2 \left[\frac{1}{2} + \frac{1}{2} \sqrt{1 - \frac{2\sqrt{2}\,\pi\alpha}{G_F\, m_Z^2}\,(1+\Delta r)} \right]$$

Δr can be parametrized in terms of two universal corrections and a remainder:

$$\Delta r \;=\; \Delta\alpha(m_Z) \;-\; \frac{c^2}{s^2}\,\Delta\rho \;+\; \Delta r_{\mathrm{rem}}$$

The leading corrections depend quadratically on m_t but only logarithmically on m_H :

$$\Delta\rho \;=\; \frac{\Pi_{ZZ}(0)}{m_Z^2} - \frac{\Pi_{WW}(0)}{m_W^2} \;\approx\; \frac{3\,\alpha}{16\pi c^2} \left(\frac{m_t^2}{s^2 m_Z^2} \;+\; \log \frac{m_H^2}{m_W^2} \;+\; \ldots \right)$$

$$\frac{\delta m_W^2}{m_W^2} \;\approx\; \frac{c^2}{c^2 - s^2}\,\Delta\rho\,, \qquad \delta\,\sin^2\theta_{\mathrm{eff}} \;\approx\; -\,\frac{c^2\,s^2}{c^2 - s^2}\,\Delta\,\rho$$

Motivation for Precision Measurements

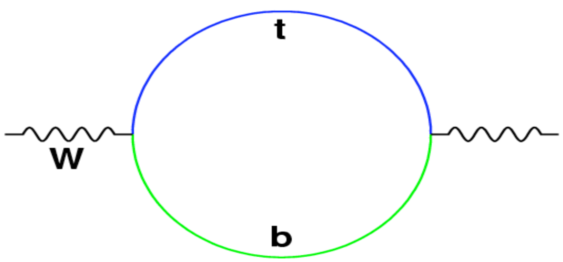
- The electroweak gauge sector of the standard model is constrained by three precisely known parameters
  - $\alpha_{EM}(M_Z) = 1 / 127.918(18)$
  - $G_F = 1.16637\ (1) \times 10^{-5}\ \mathrm{GeV}^{-2}$

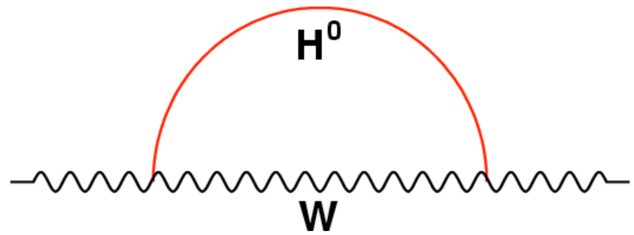
    $M_Z = 91.1876\ (21)\ \mathrm{GeV}$
- At tree-level, these parameters are related to other electroweak observables, *e.g.* M_W
  - $M_W^2 = \pi\alpha_{EM} / \sqrt{2}G_F \sin^2\vartheta_W$
    - Where ϑ_W is the Weinberg mixing angle, defined by

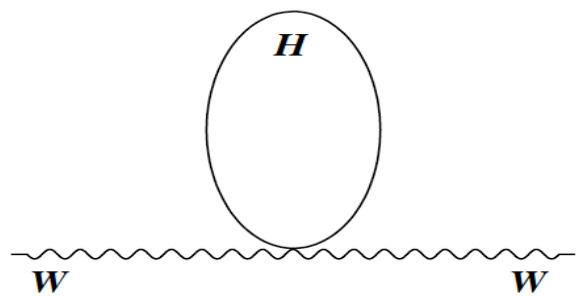
      $$\cos\vartheta_W = M_W/M_Z$$

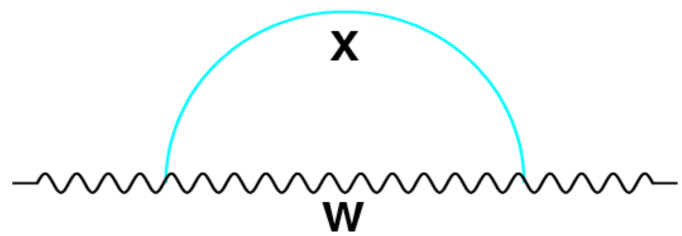
Motivation for Precision Measurements

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





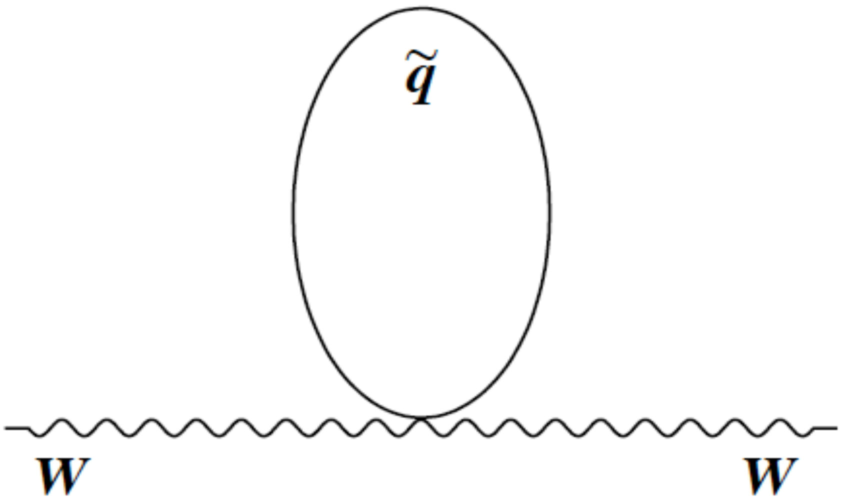


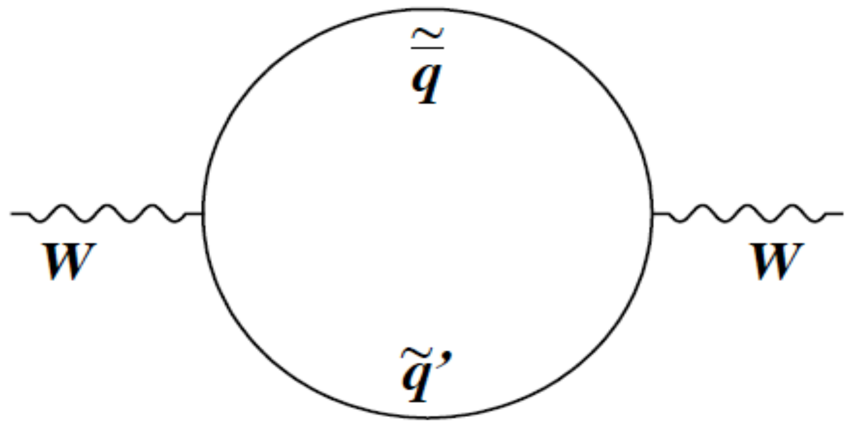


Motivate the introduction of the ρ parameter: $M_W^2 = \rho\,[M_W(\text{tree})]^2$
with the predictions $\Delta\rho = (\rho-1) \sim M_{top}^2$ and $\Delta\rho \sim \ln M_H$

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

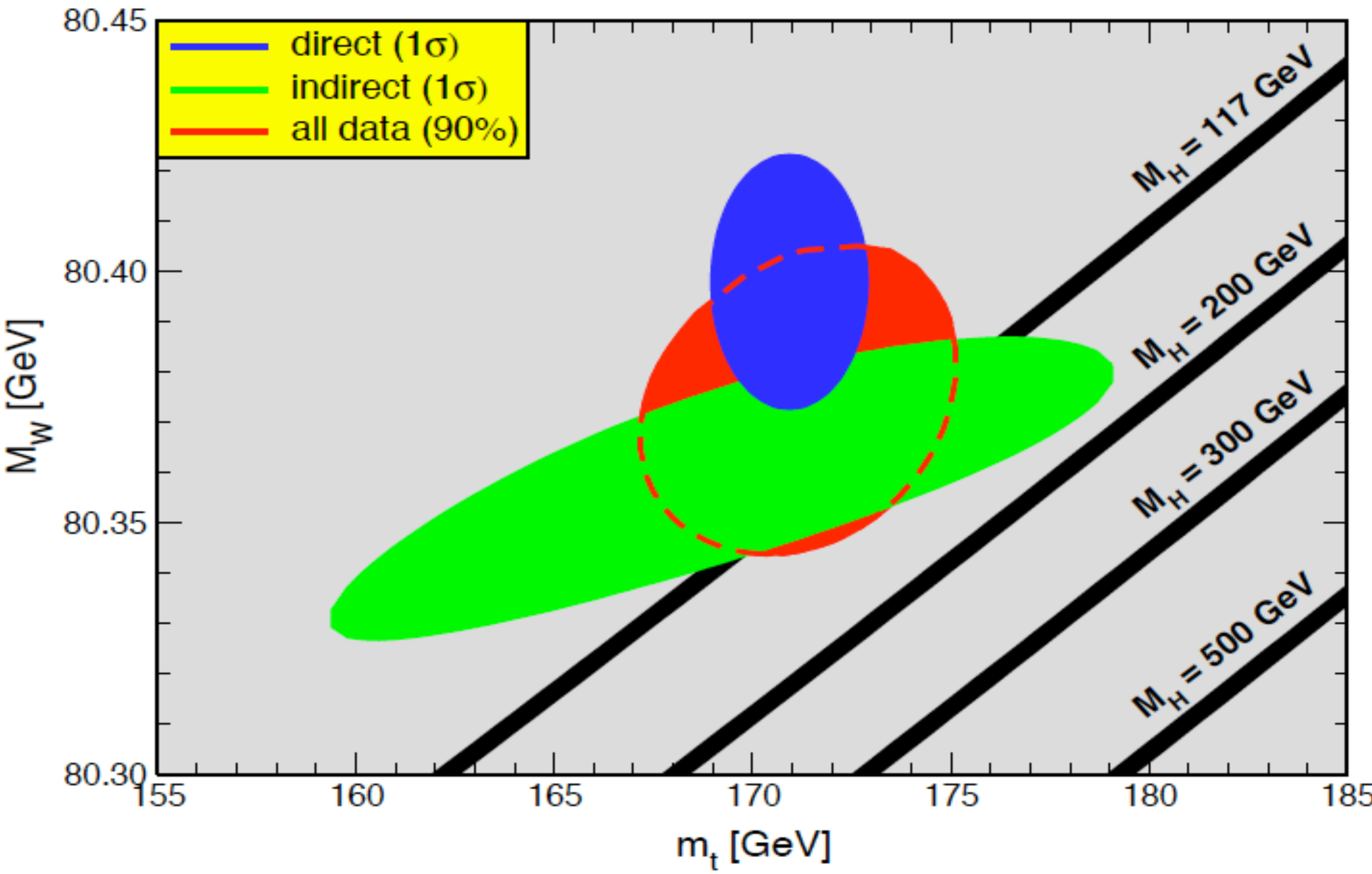
Contributions from Supersymmetric Particles





- 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

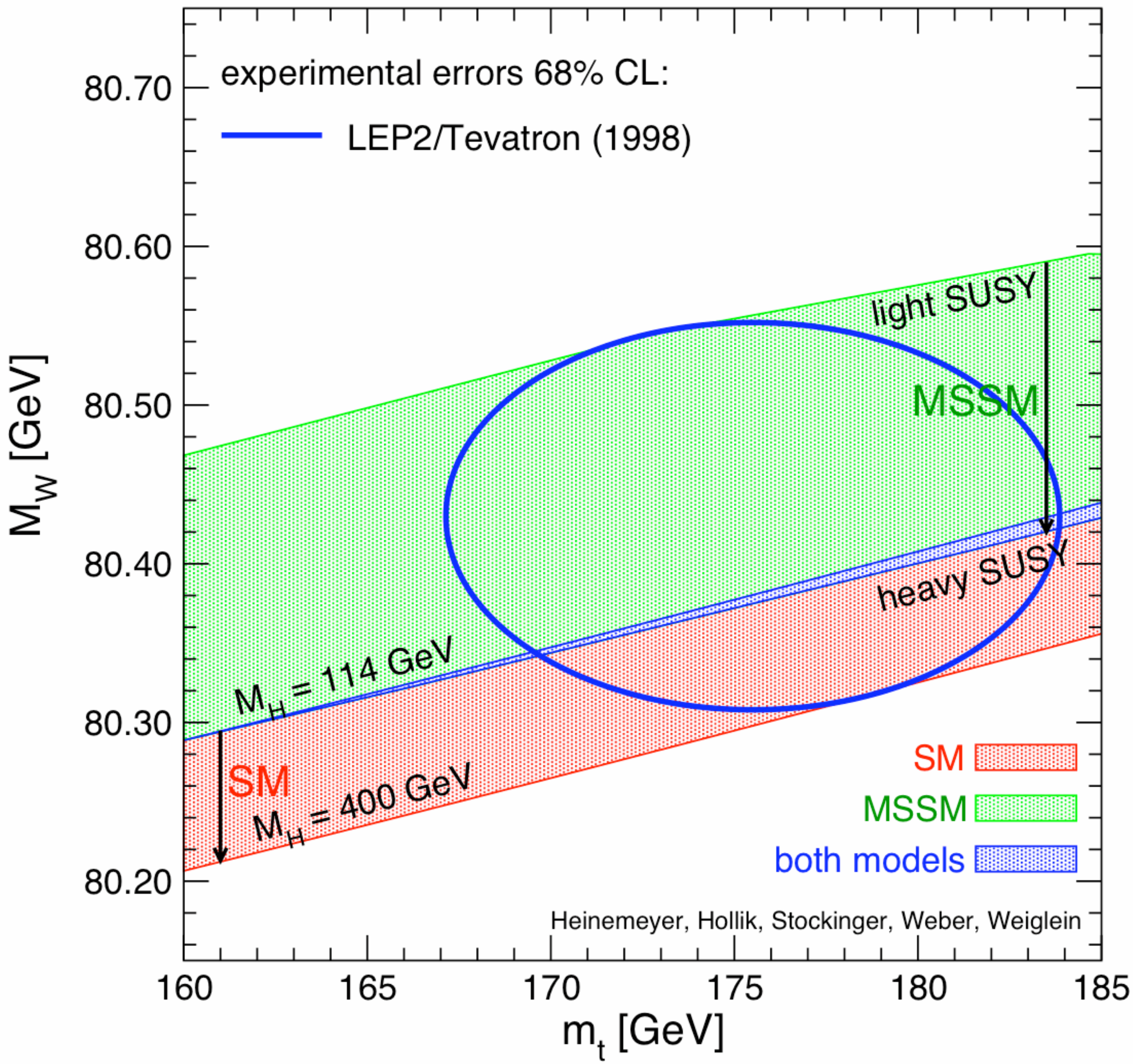
Uncertainty from $\alpha_{EM}(M_Z)$



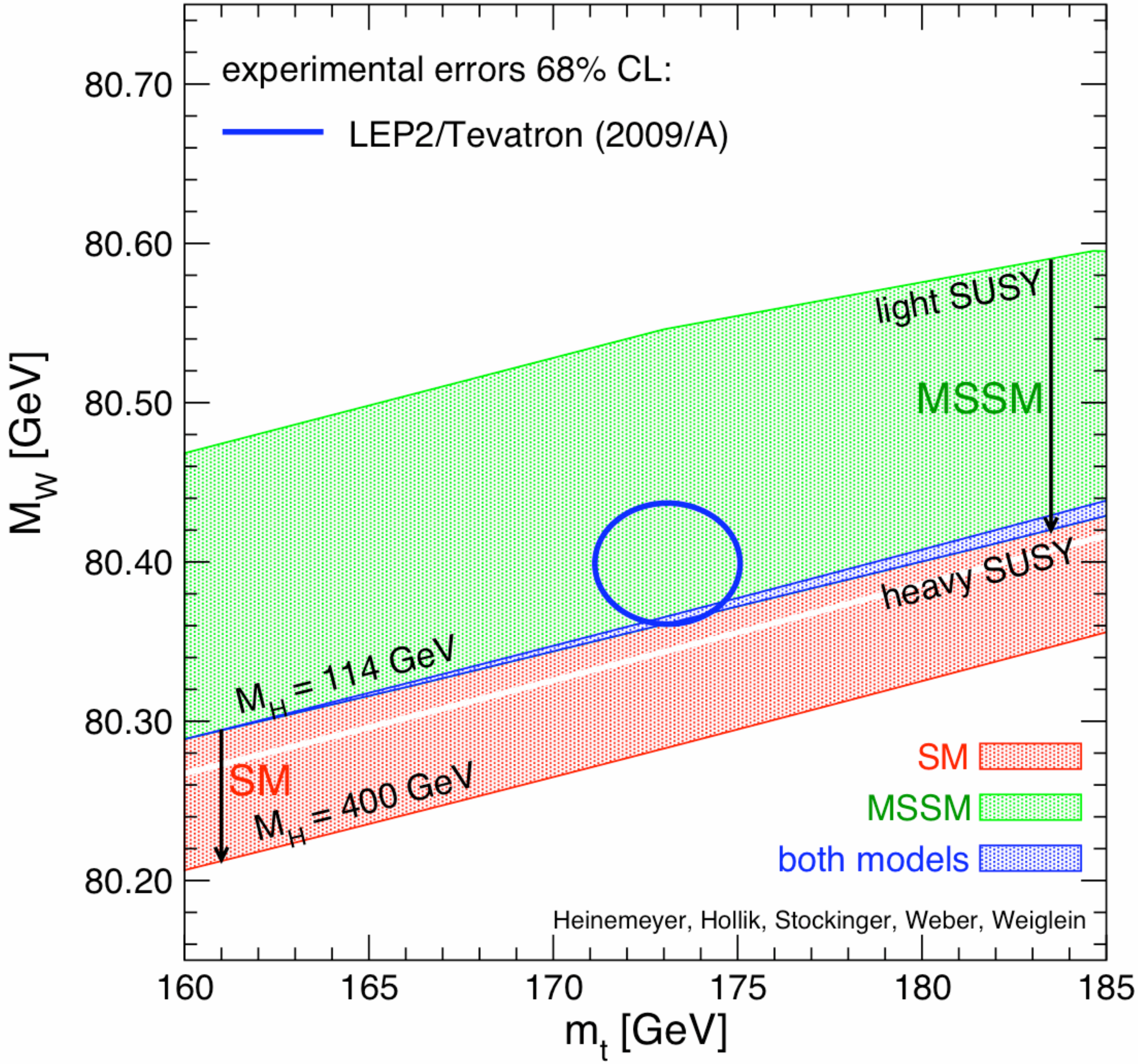
Line thickness due to $\delta\alpha_{EM}$

- $\delta\alpha_{EM}$ 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 !

1998 Status of M_W *vs* M_{top}

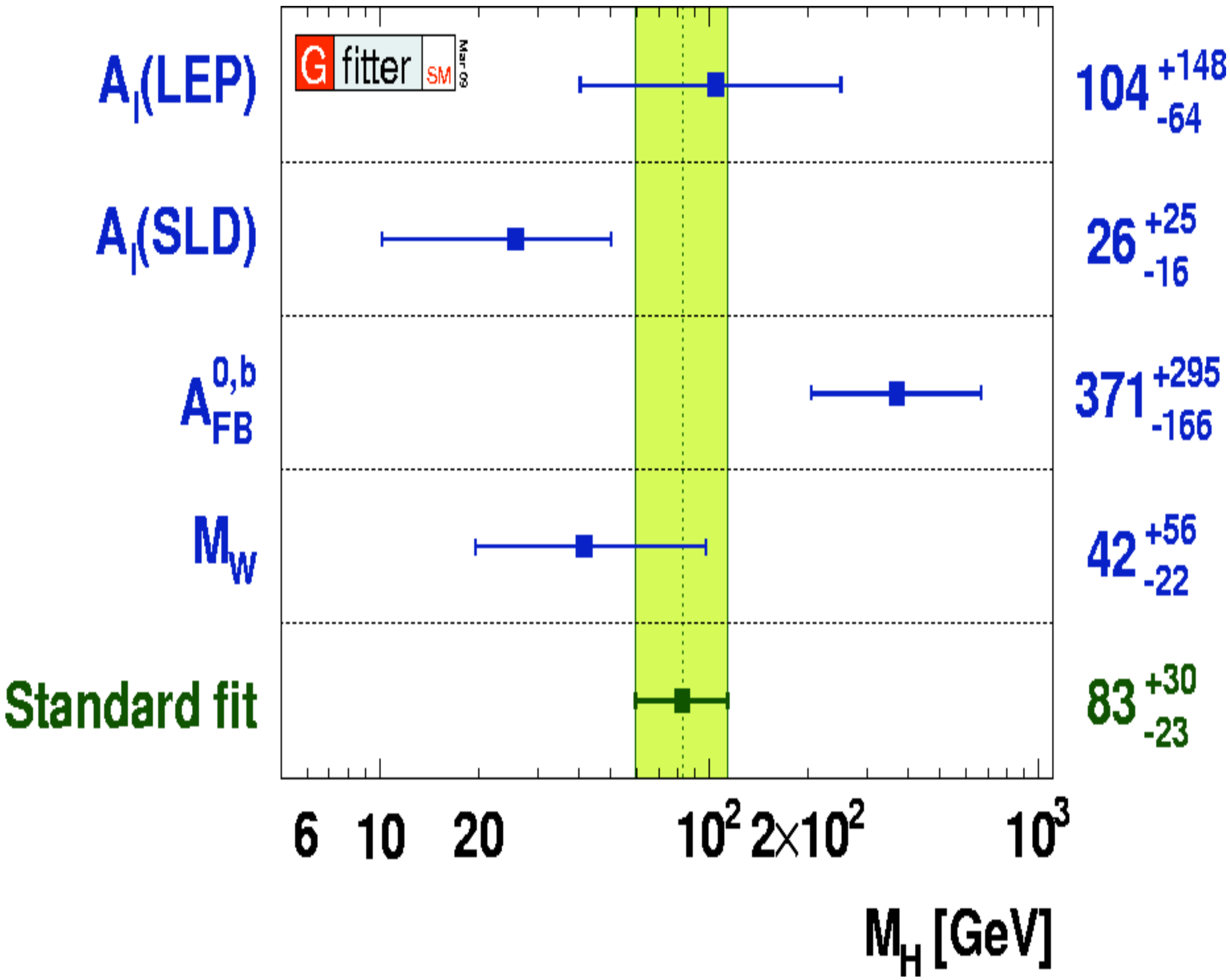


Current Status of M_W *vs* M_{top}



Motivation II

- SM Higgs fit: $M_H = 83^{+30}_{-23}$ GeV (gfitter.desy.de)
- Direct searches: $M_H > 114.4$ GeV (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

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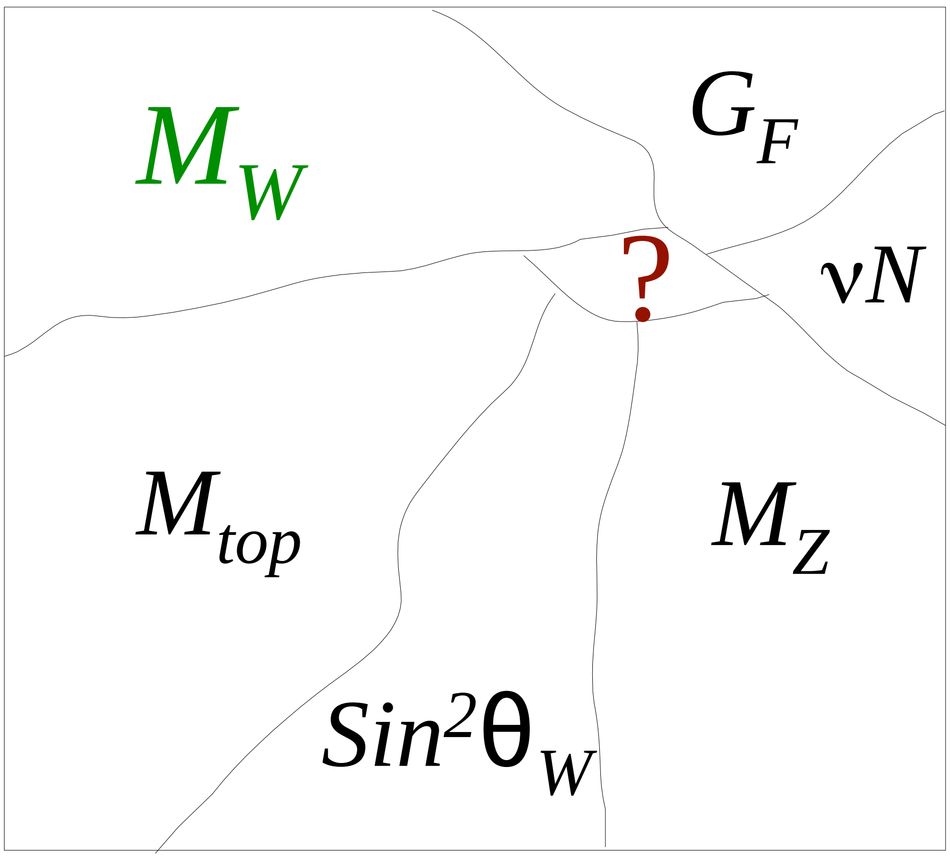

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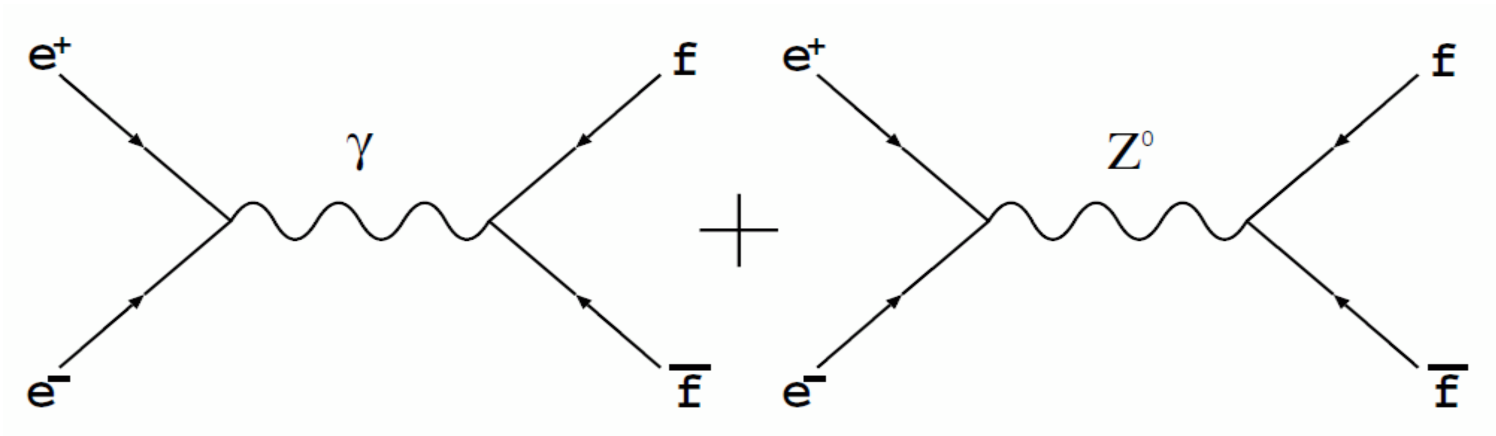
Motivate direct measurement of M_W at the 15 MeV level and better

A_{FB} and A_{LR} Observables

- Asymmetries definable in electron-positron scattering sensitive to Weinberg mixing angle ϑ_W



- Higgs and Supersymmetry also contribute radiative corrections to ϑ_W via quantum loops

- A_{FB} is the angular (forward – backward) asymmetry of the final state

- A_{LR} is the asymmetry in the total scattering probability for different polarizations of the initial state

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)

Possible explanations:

Statistical fluctuation

Systematic experimental bias

New physics contributions:

To raise M_H prediction of leptonic asymmetries:

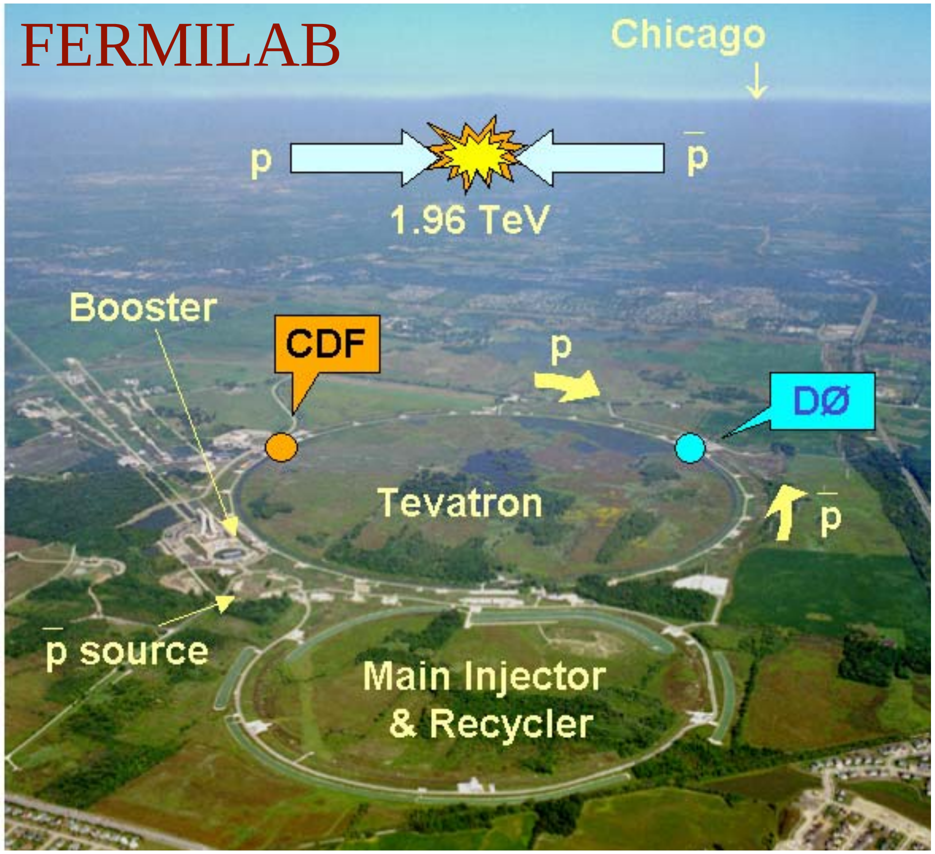
Minimal SuperSymmetric Standard Model	Altarelli *et. al.*
4^{th} family of fermions	Okun *et. al.*
Opaque branes	Carena *et. al.*

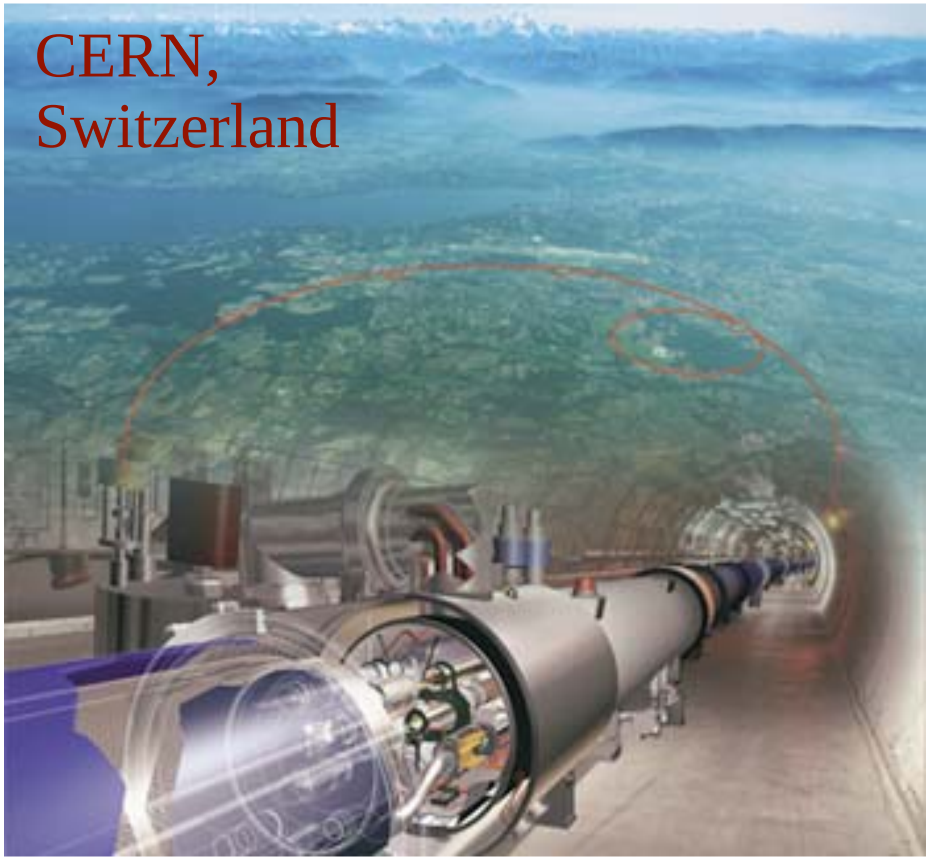
New physics in b-quark asymmetry requires large modification to Zbb vertex

Electroweak Symmetry Breaking

Searches for Higgs and SUSY particles at the LHC

Precision measurements and Electroweak Fits





Motivational Summary

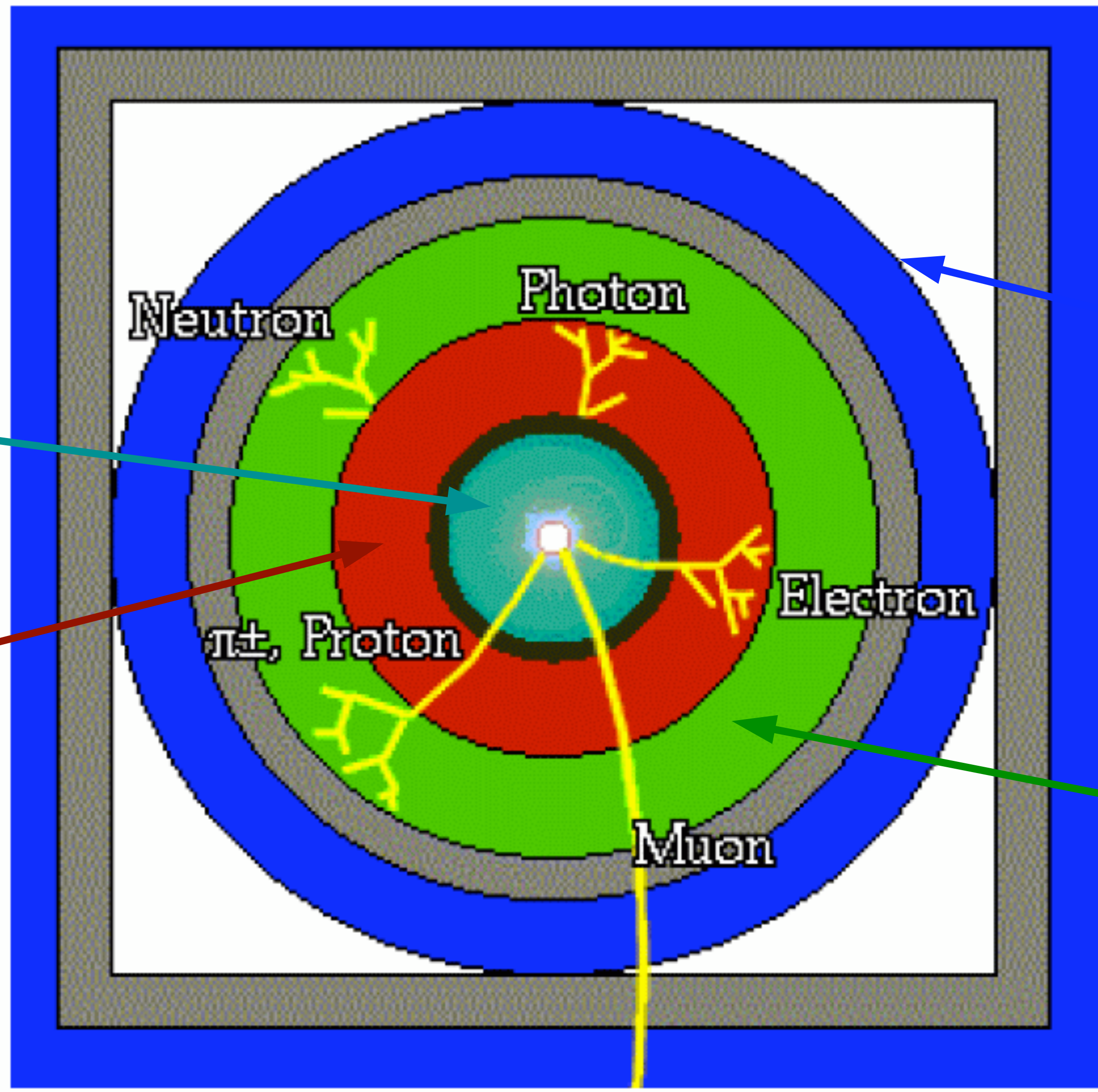
- At the dawn of the LHC era, we don't know
  - Mechanism of electroweak symmetry breaking
  - Solution to electroweak scale *vs* Planck scale hierarchy
  - …
- If there is new physics, there is a large range of models
- Precision electroweak measurements have provided much guidance
  - But some intriguing 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

Precise W Boson Mass Measurement

Particle Detection

Drift chamber: reconstuct particle trajectory by sensing ionization in gas on high voltage wires

Electromagnetic (EM) calorimeter: lead sheets cause *e*/γ shower, sense light in alternating scintillator sheets



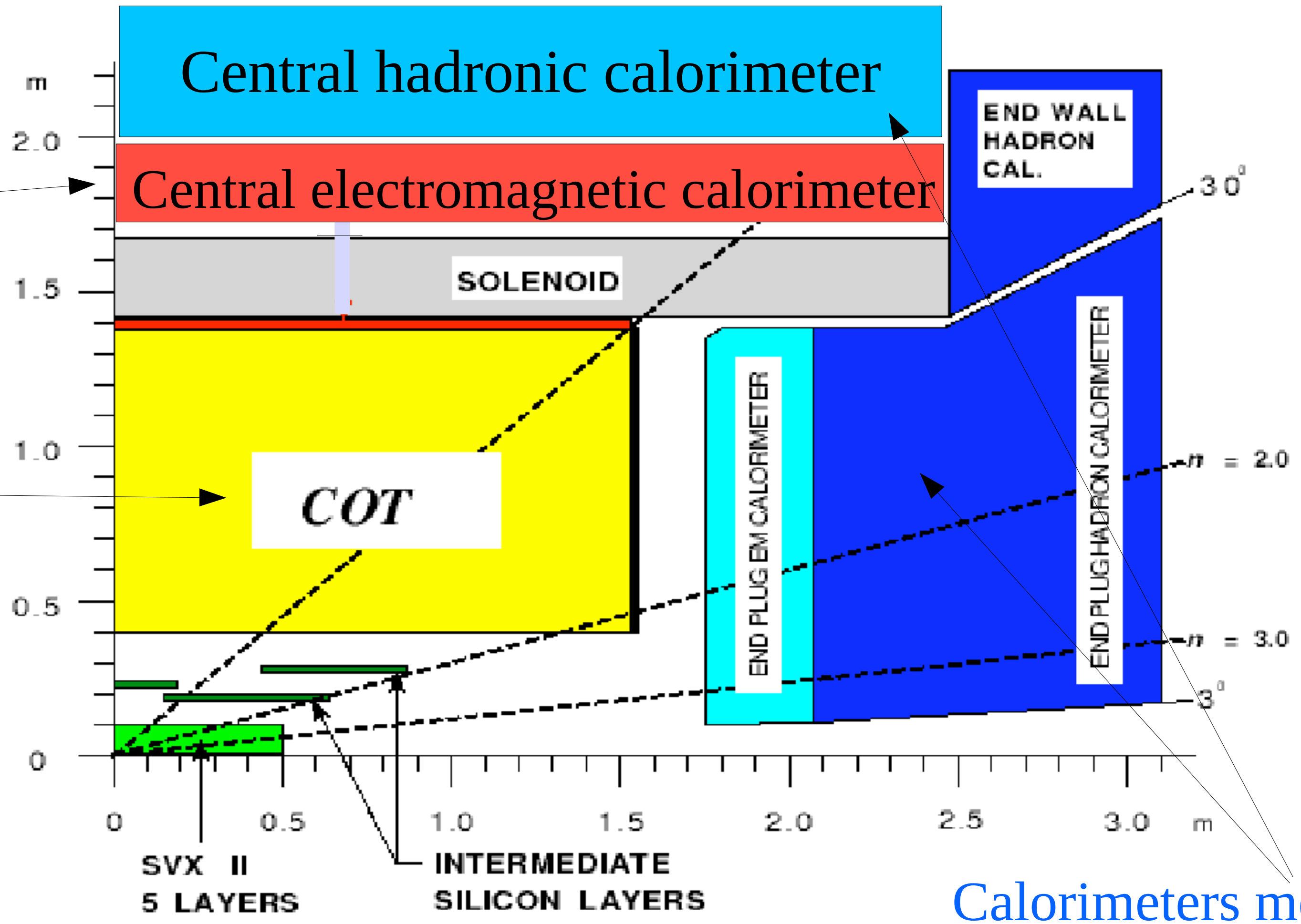
Muon chambers: detect penetrating particles behind shielding

Hadronic calorimeter: steel sheets cause hadronic showers, sense scintillator light

Quadrant of Collider Detector at Fermilab (CDF)

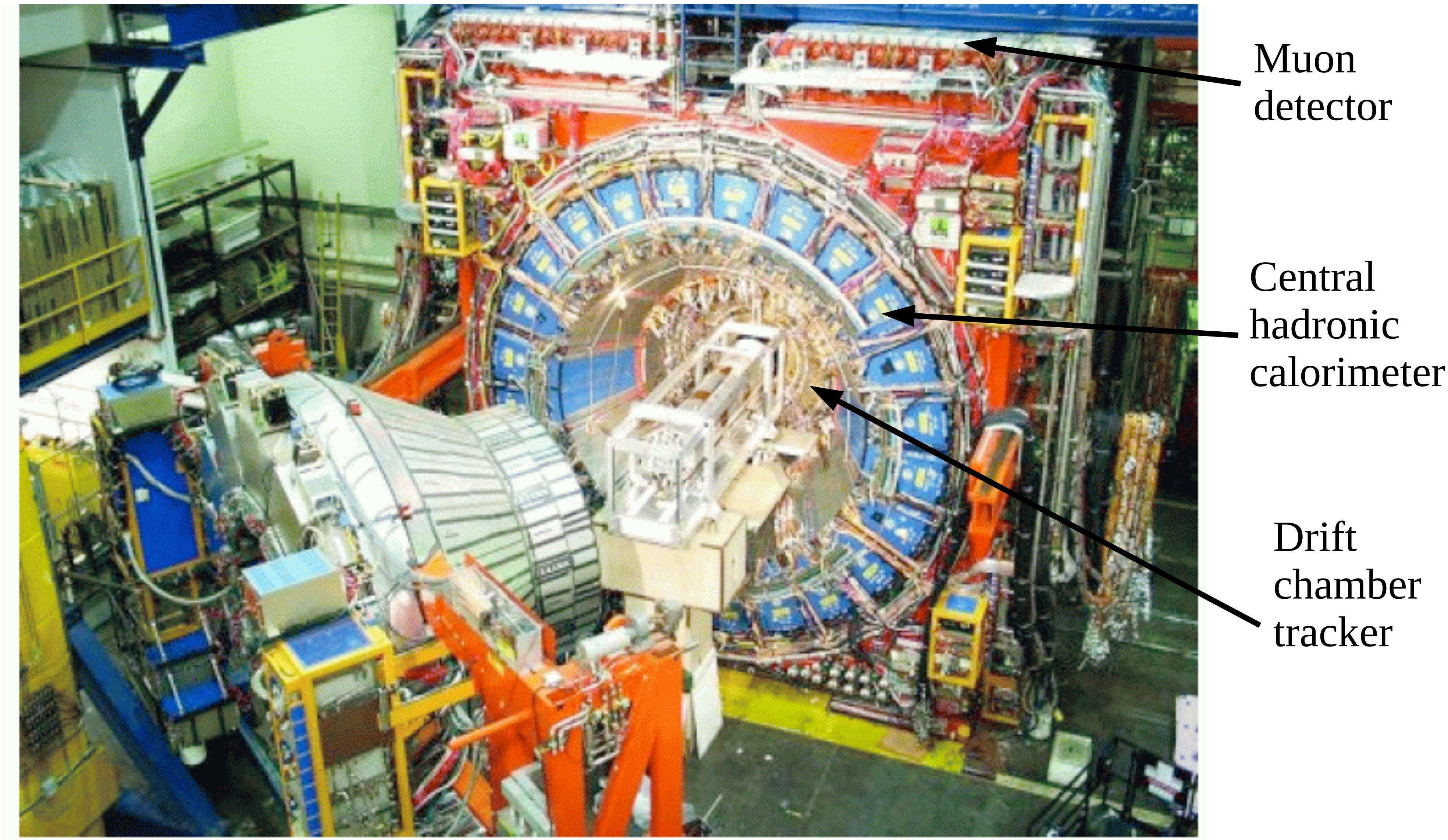
Electromagnetic calorimeter provides precise electron energy measurement

Drift chamber tracker provides precise lepton track momentum measurement

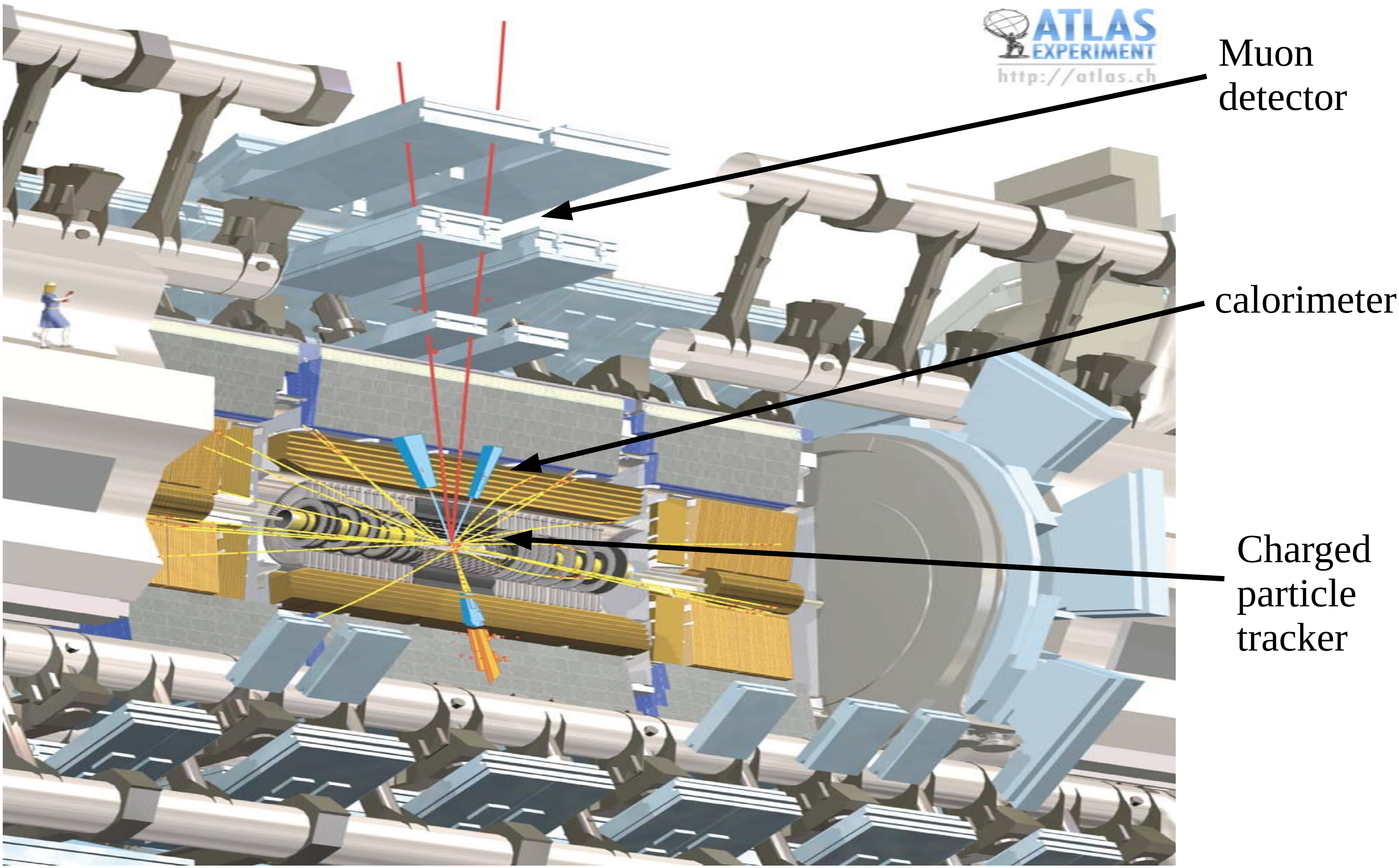


Calorimeters measure hadronic recoil particles

Collider Detector at Fermilab (CDF)



ATLAS Detector at LHC



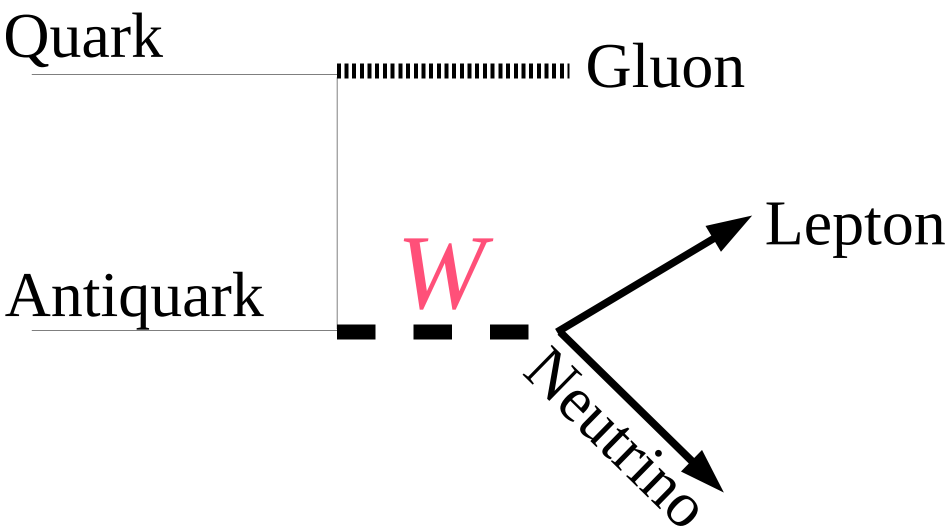
Particle Tracking Chamber

Reconstruction of particle trajectories, calibration to ~2 μm accuracy:

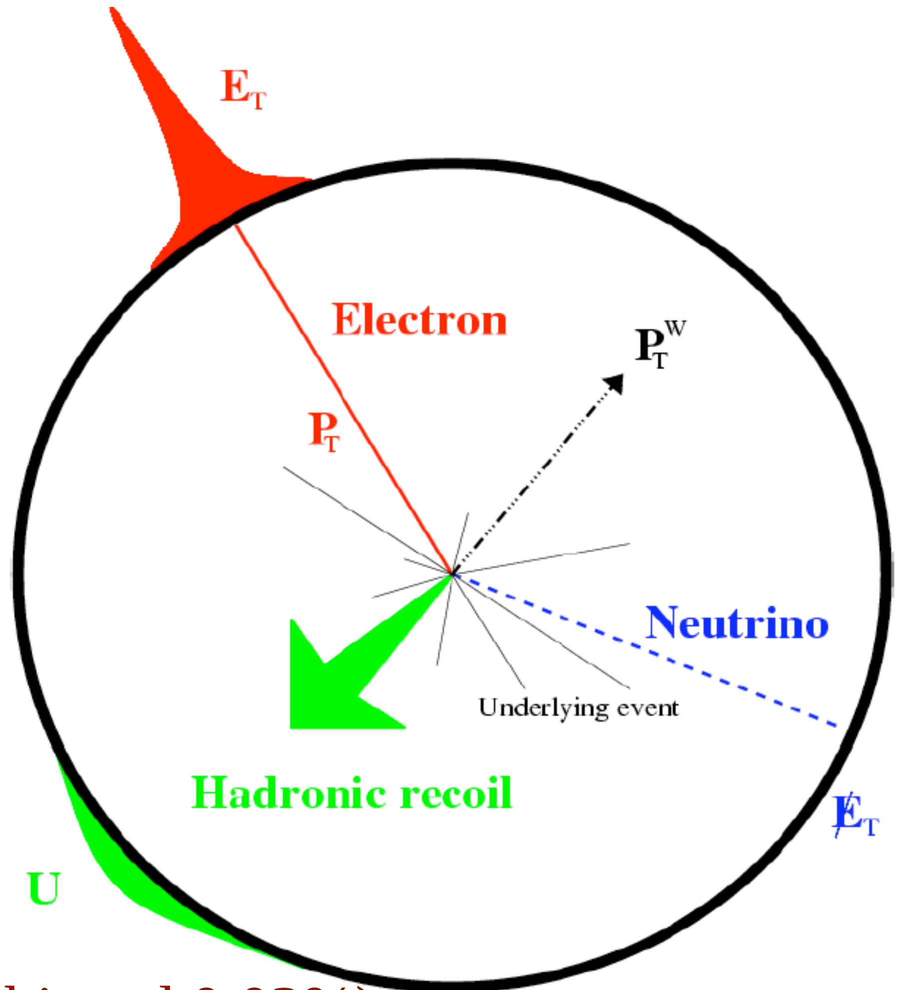
A. Kotwal, H. Gerberich and C. Hays, NIM A506, 110 (2003)

C. Hays et al, NIM A538, 249 (2005)

W Boson Production at the Tevatron



Quark-antiquark annihilation dominates (80%)

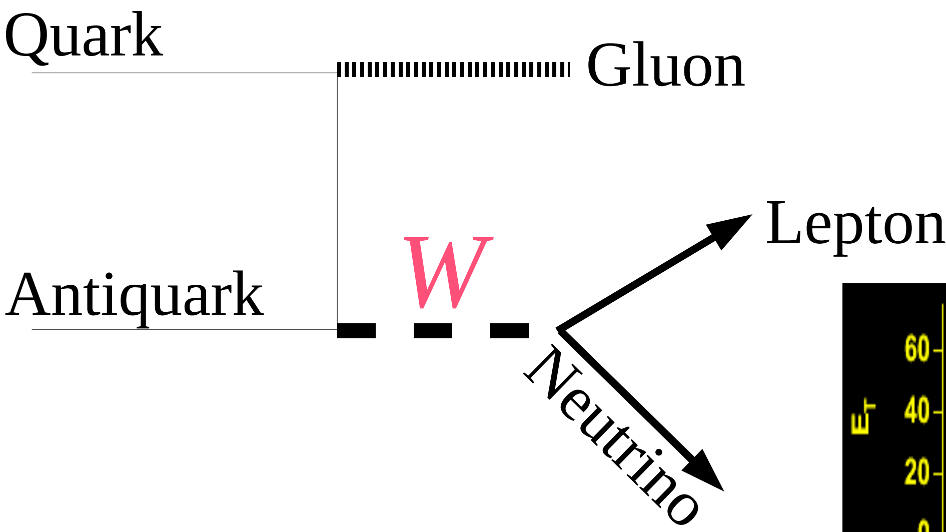


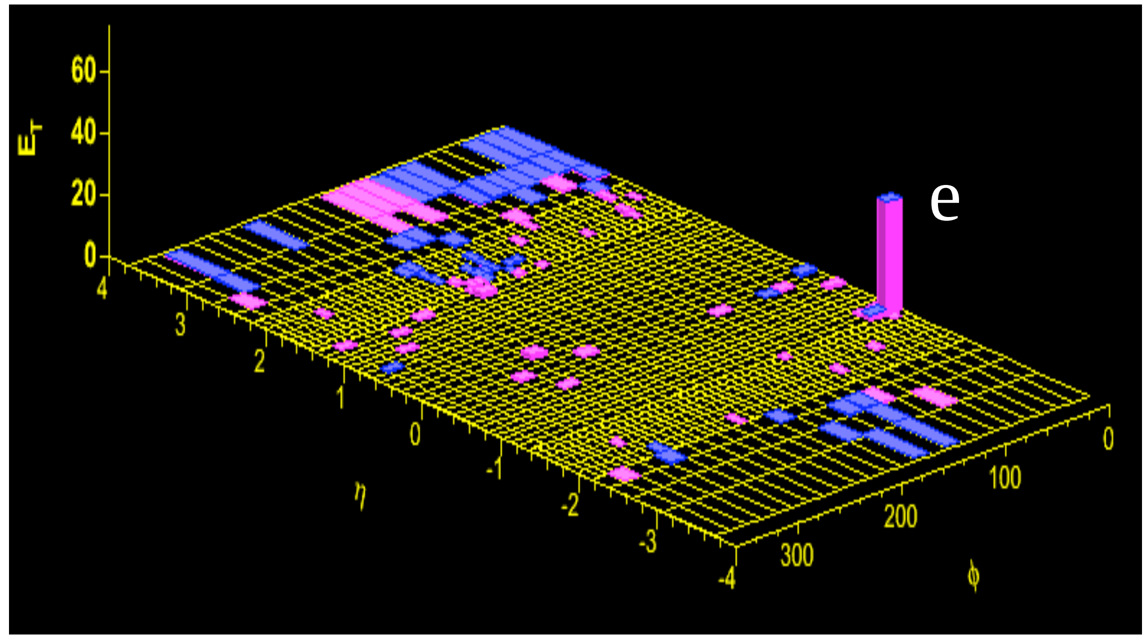
Lepton p_T carries most of *W* mass information, can be measured precisely (achieved 0.03%)

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

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

W Boson Production at the Tevatron





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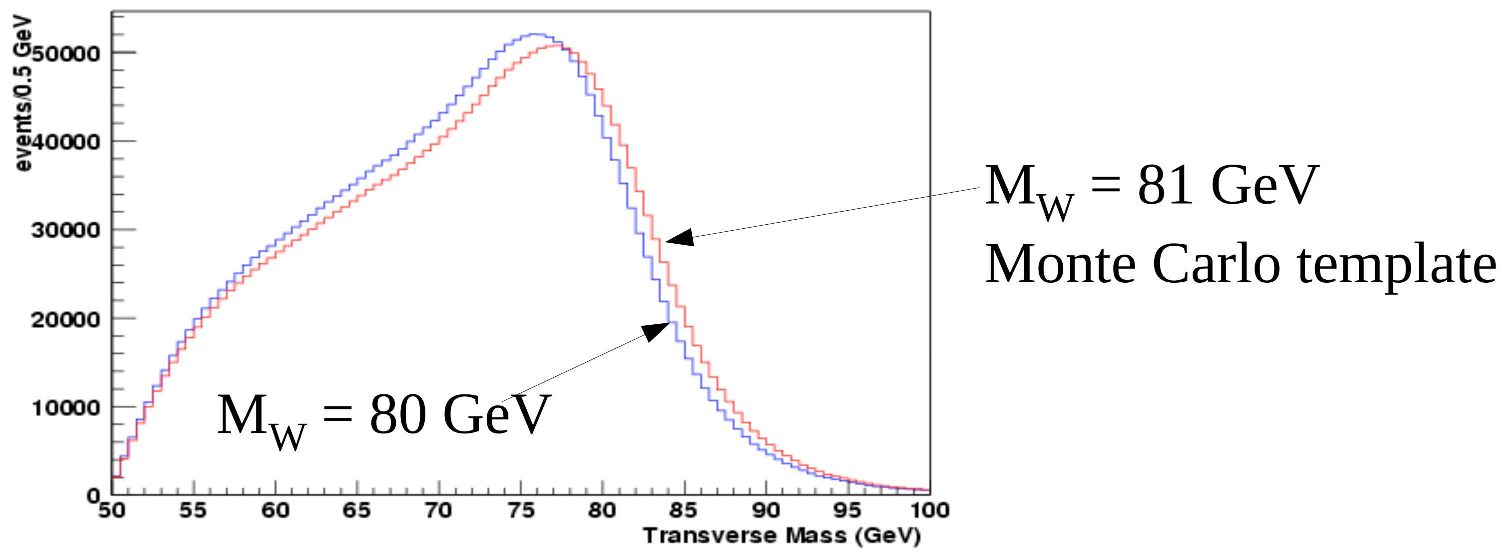
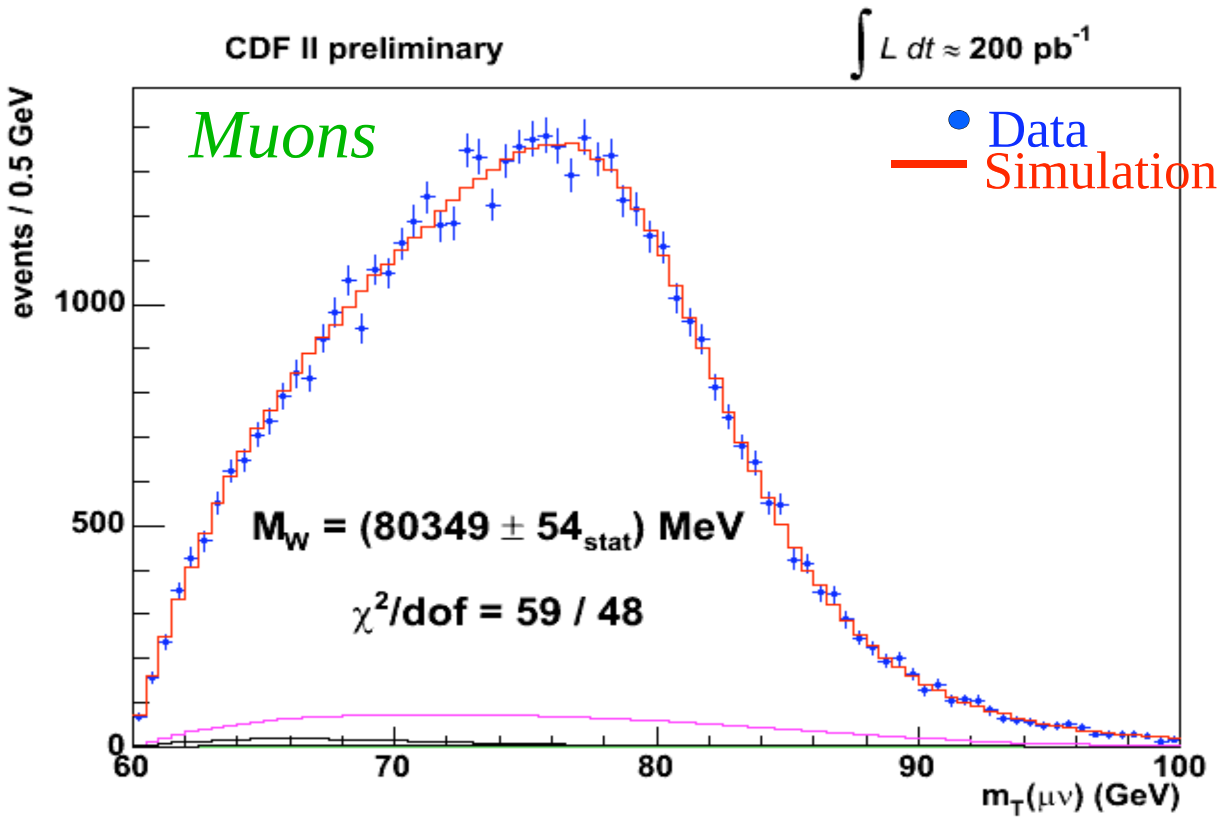
Fitting for the *W* Boson Mass

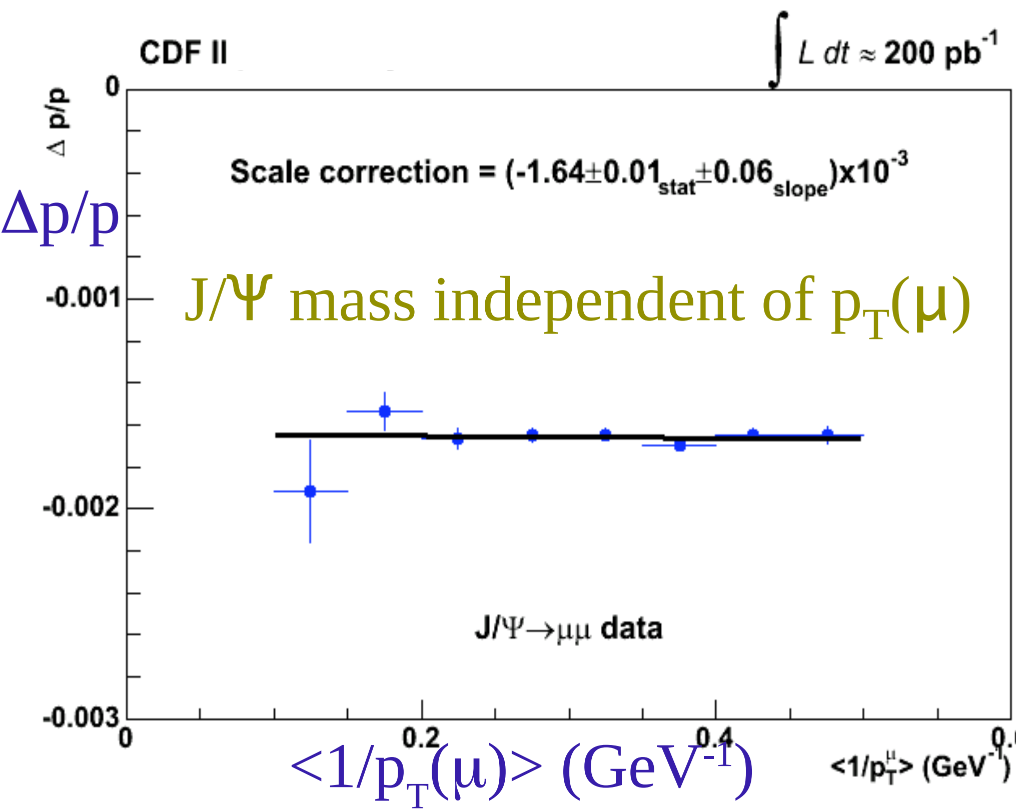


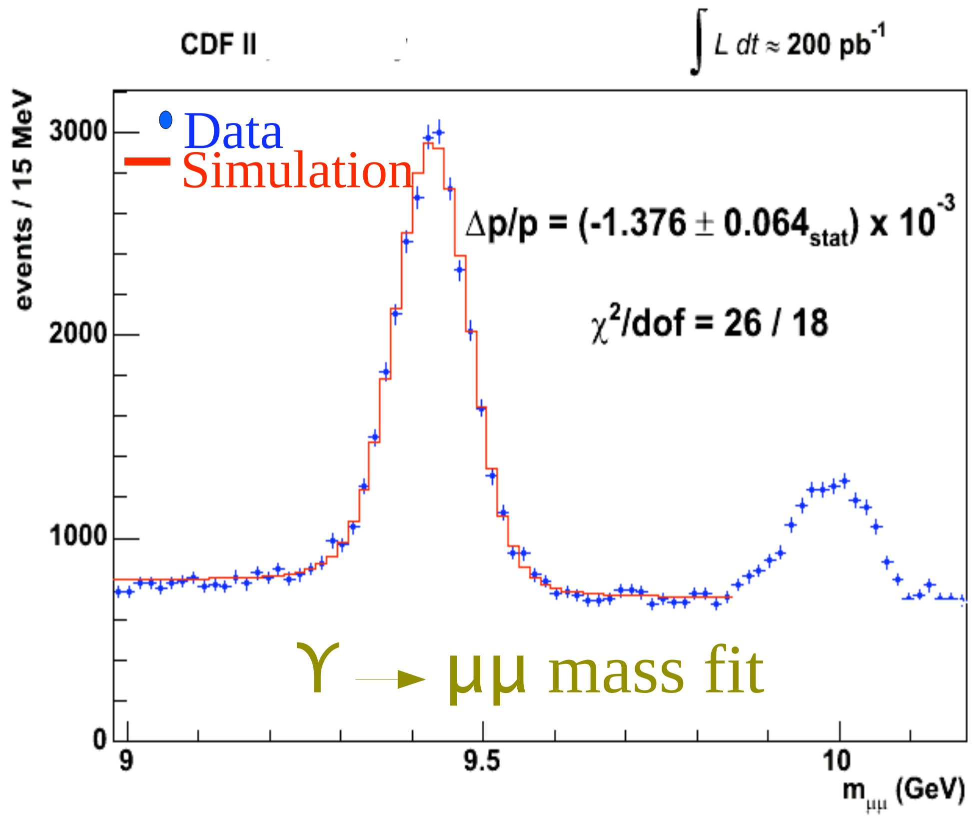


Perform fits to kinematic distributions sensitive to the W boson mass

Tracking Momentum Calibration

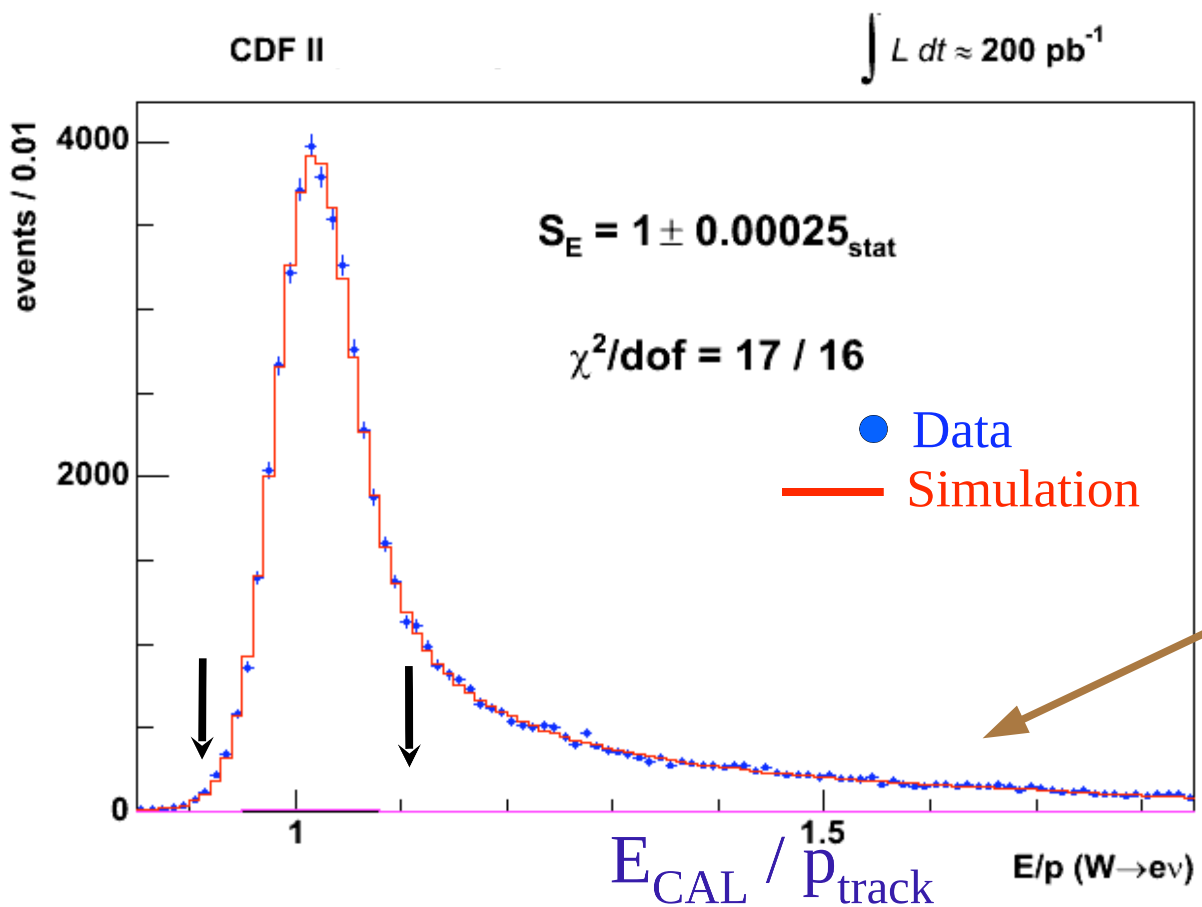
- Set using $J/\Psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ resonances
  - Prior measurements of their mass with high precision provide calibration source





Electromagnetic Calorimeter Calibration

- E/p peak from $W \rightarrow e\nu$ decays provides EM calorimeter calibration relative to the tracker

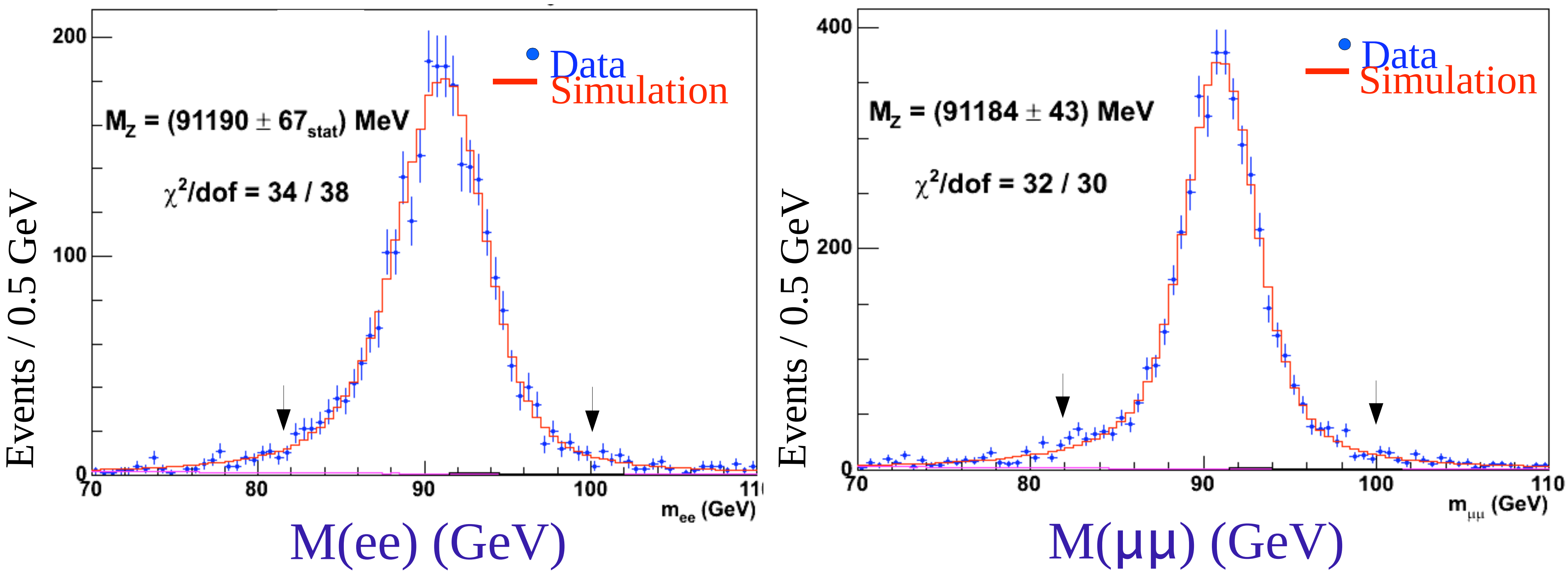


Tail region of E/p spectrum used for tuning model of radiative material

$Z \rightarrow ll$ Mass Cross-checks

- Z boson mass measurements using tracking and E/p-based calibrations, consistent with other precise measurements of Z boson mass = 91187 MeV

CDF II $\quad\quad$ L ~ 200/pb



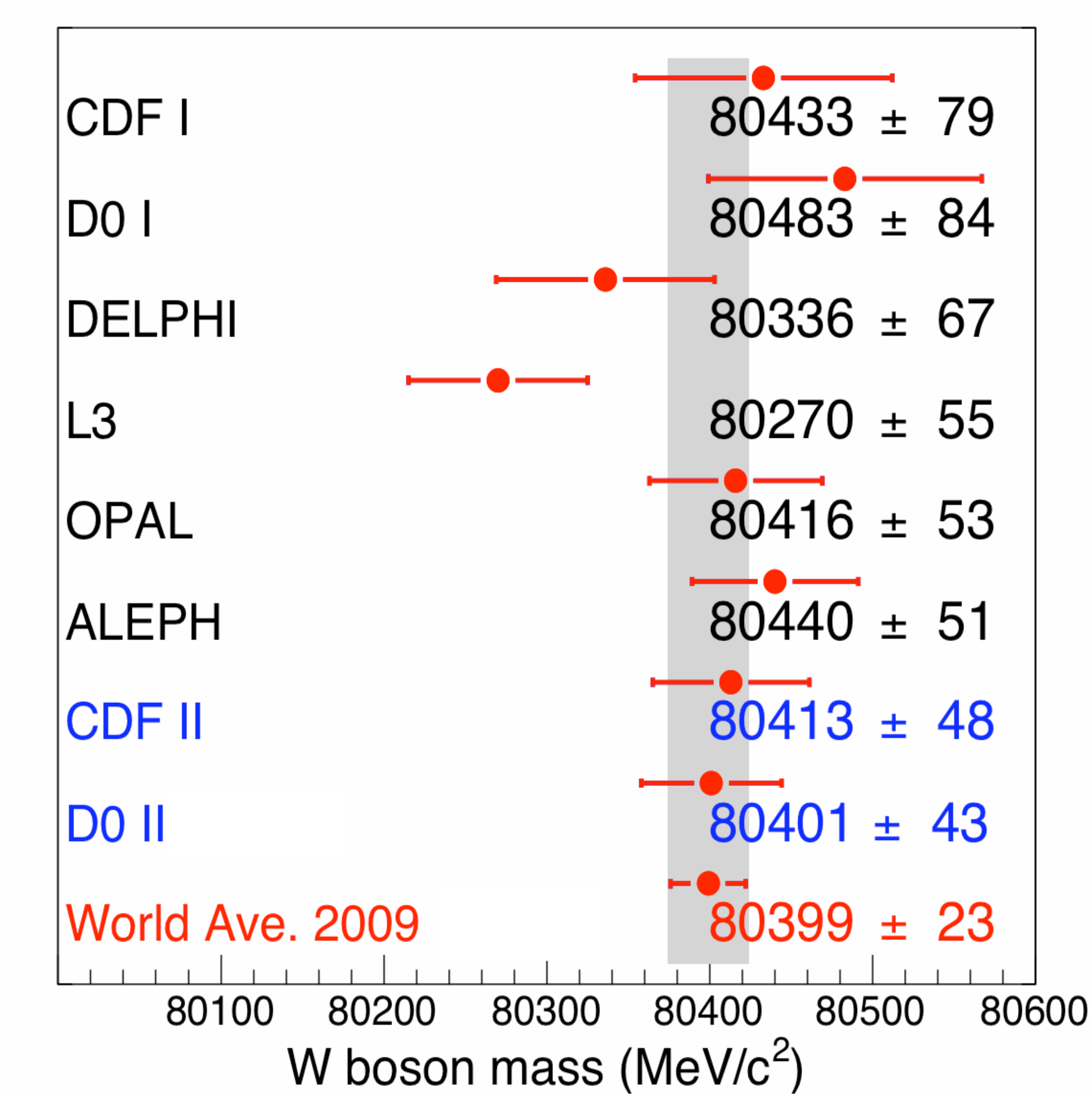
Transverse Mass Fit Uncertainties (MeV)

(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	

Many sources of uncertainty are fractionally smaller than 10^{-3}, approaching 10^{-4}

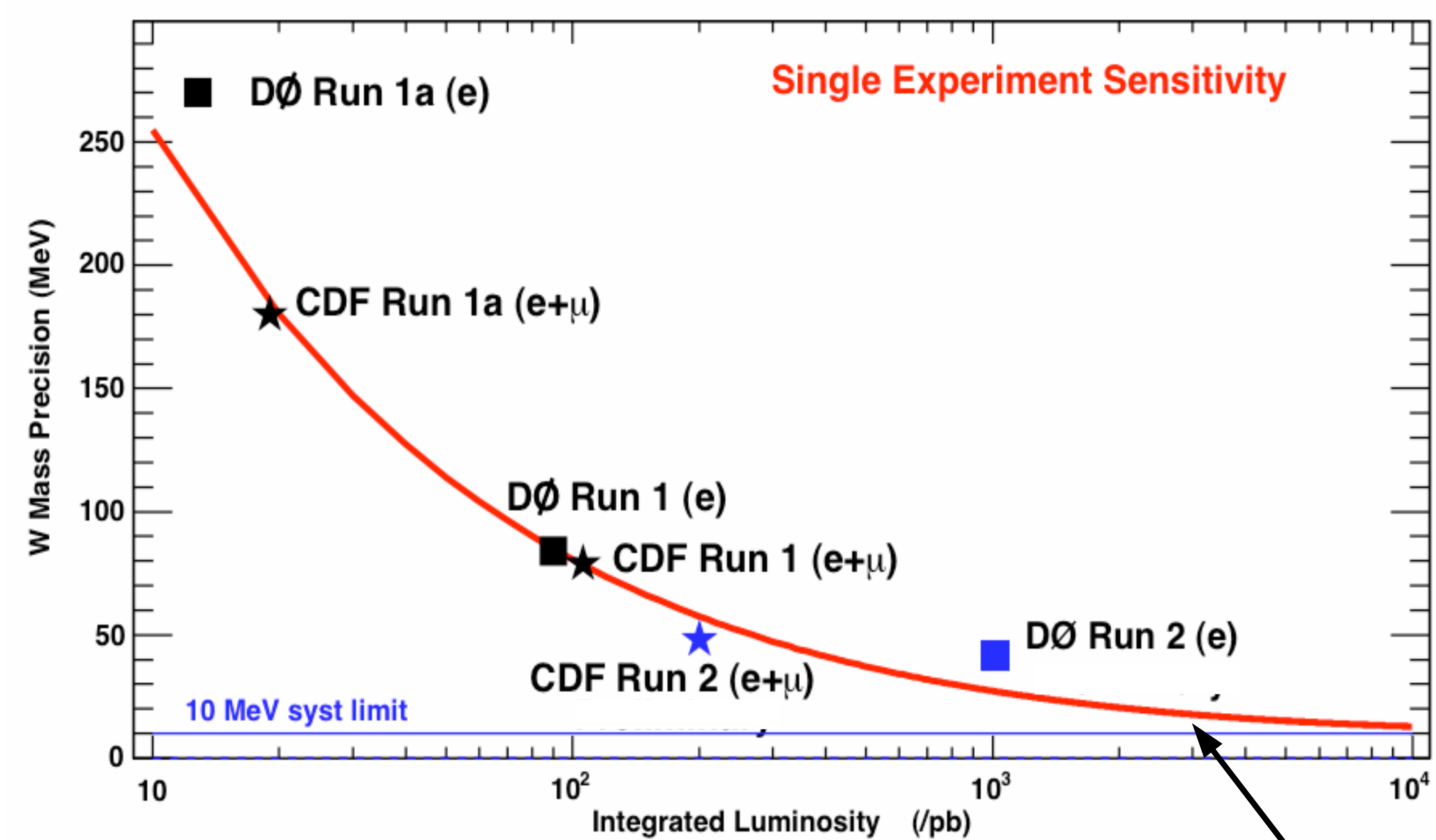
W Boson Mass Measurements from Different Experiments



(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

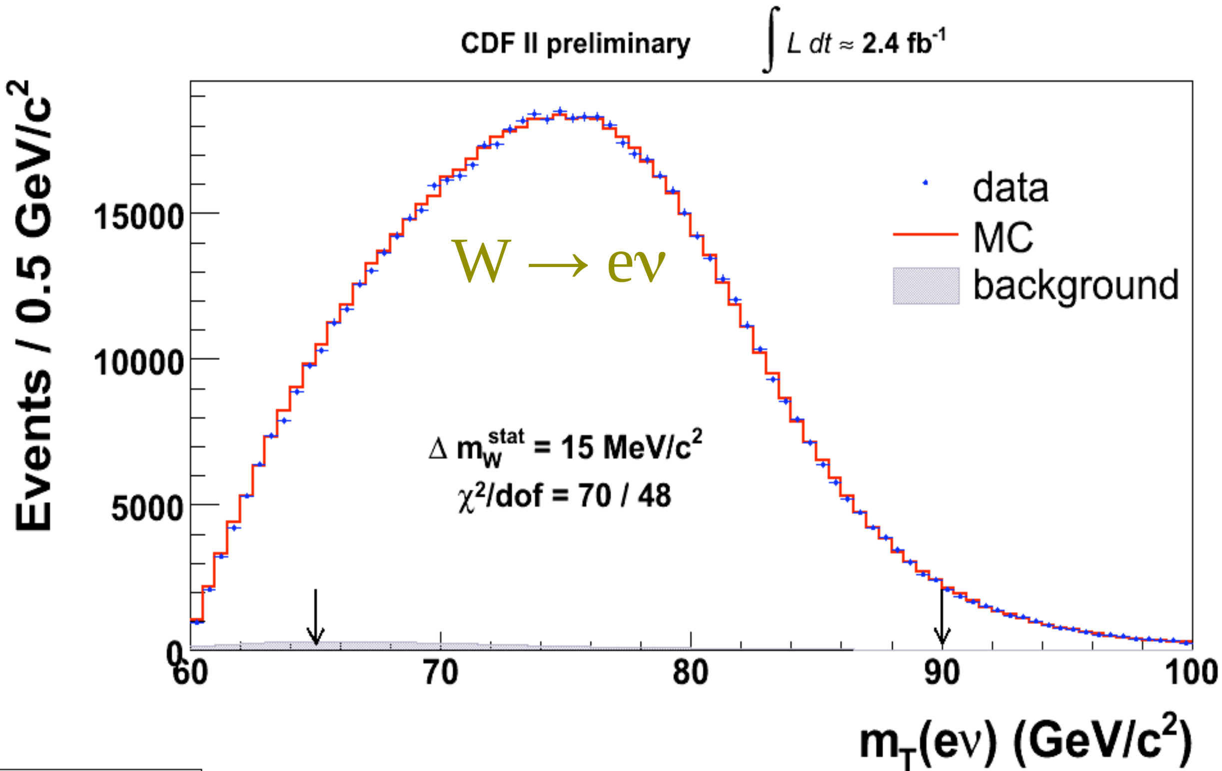


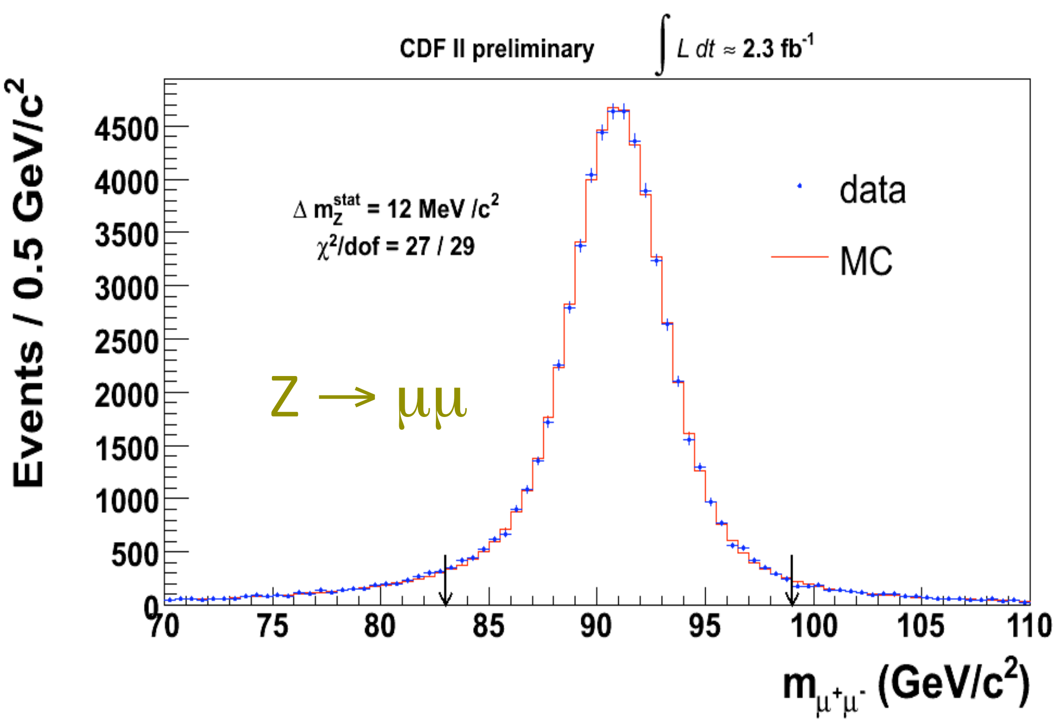
Next target: 15 MeV measurement of M_W from the Fermilab

Preliminary Studies of New Data at Fermilab

Detectors performing well

apparatus stable over time





uncertainties on W and Z boson mass fits and calibrations are reducing as data quantity increases

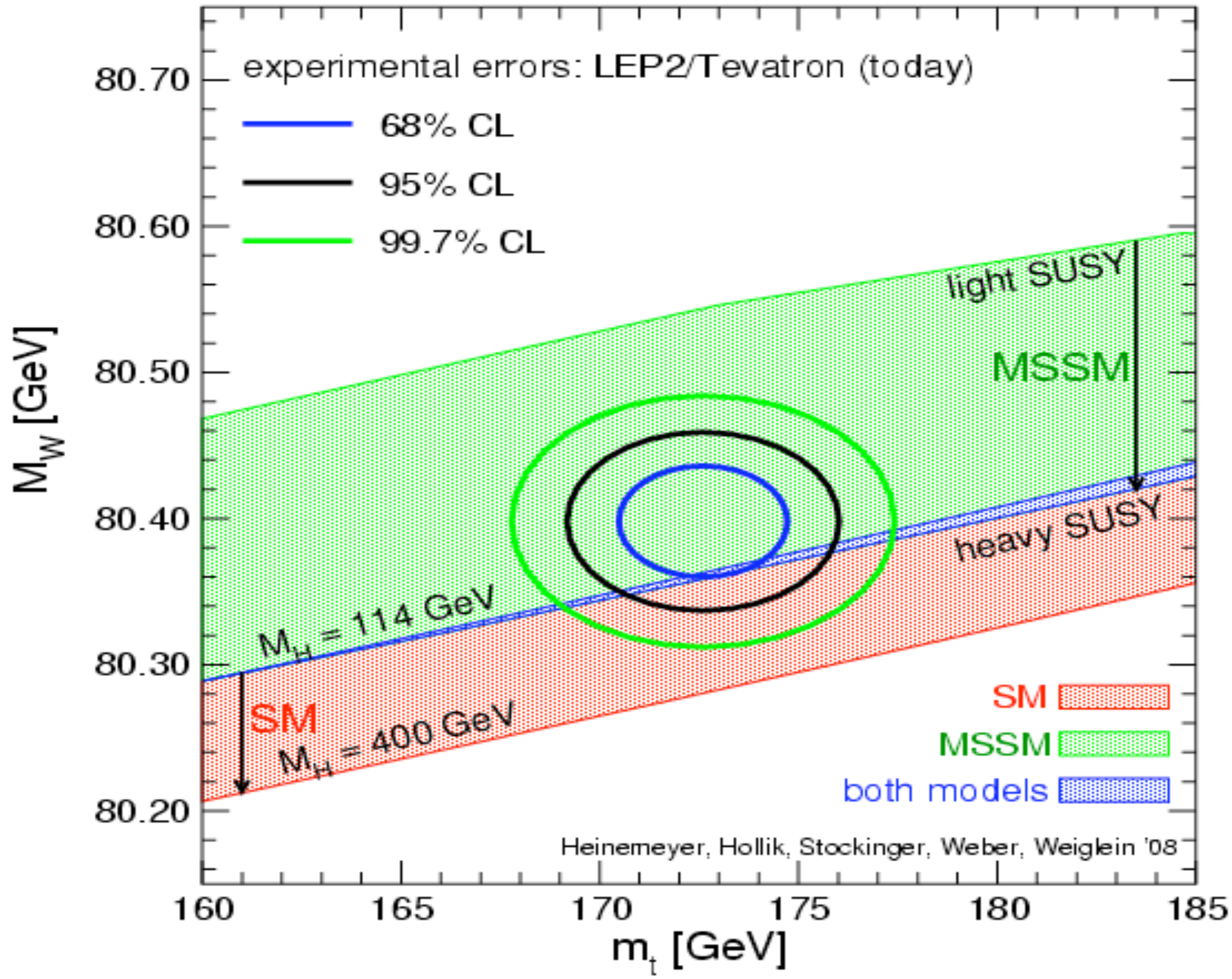
M_W Measurement at LHC

- 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 $Z \rightarrow ll$ mass resonance, best-case scenario of statistical limit ~ 5 MeV precision on calibrations
- Calibration of the hadronic calorimeter based on transverse momentum balance in $Z \rightarrow ll$ events also ~ 2 MeV statistical limit
- Total uncertainty on M_W ~ 5 MeV may be possible
- (A.V. Kotwal and J. Stark, Ann. Rev. Nucl. Part. Sci., vol. 58, Nov 2008)

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 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
- Fermilab pushing towards $\delta M_W \sim 15$ MeV and $\delta M_{top} < 1$ GeV
- Will provide strong constraints on Higgs boson mass and SUSY theories
- Learning as we go: Fermilab → LHC may produce $\delta M_W \sim 5$ MeV and $\delta m_{top} \sim 0.5$ GeV

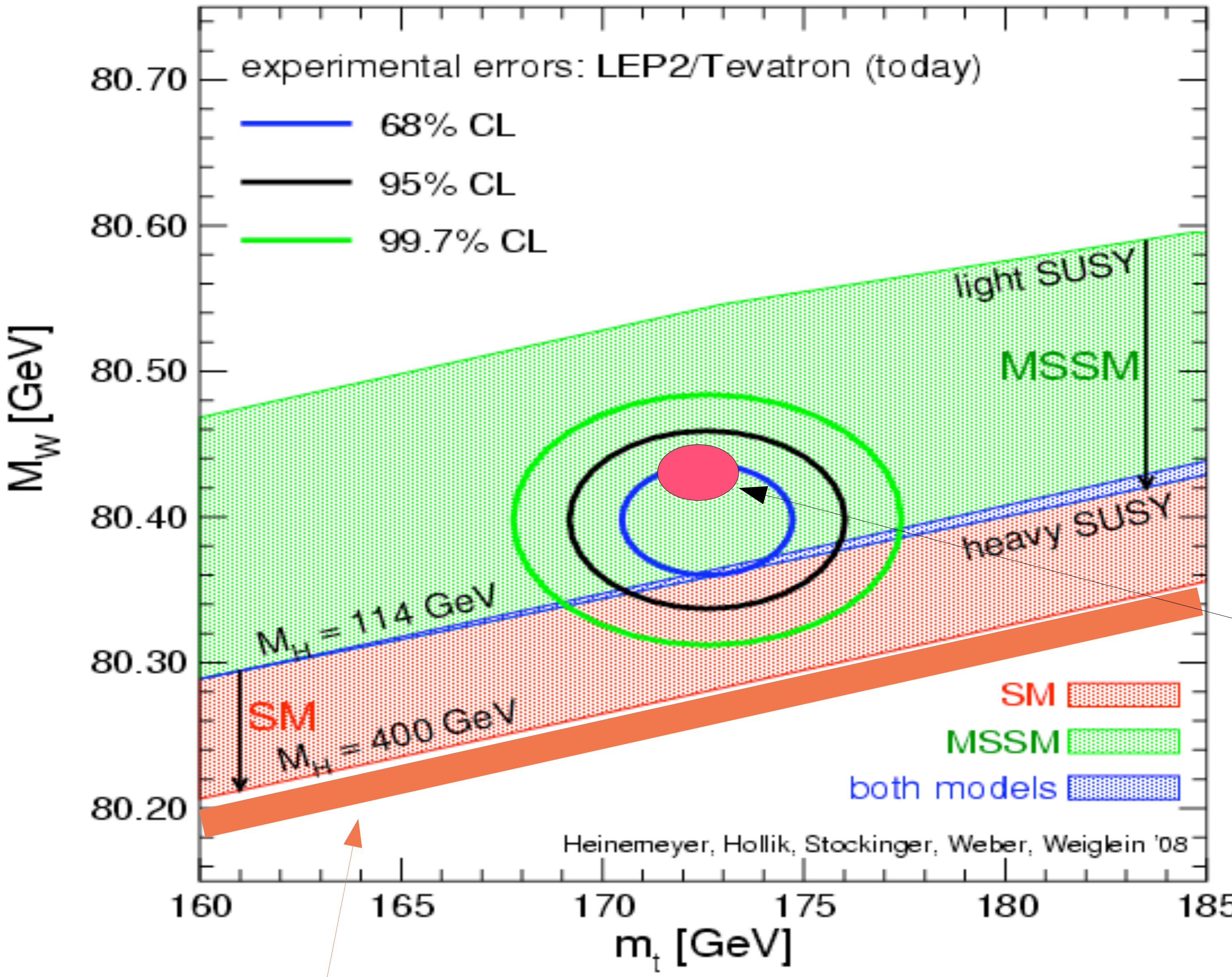
M_W *vs* M_{top}



How will this plot change after (if) LHC observes

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

A possible Future Scenario



δM_W = 10 MeV

δm_{top} = 0.5 GeV

If Higgs is discovered with a large Higgs mass → inconsistency with W mass → additional new physics such as SUSY