8.882 LHC Physics

Experimental Methods and Measurements

High Energy Physics Overview

[Lecture 16, April 6, 2009]

Organization

Next lecture: Michael Betancourt

- Baysians versus Frequentists: lesson on statistics
- I will be on a plane at that time: so be nice to Michael

Project 2

- due April 9 (Wednesday)
- check web page for instructions, in particular triggers

Project 3

- *B* lifetime is coming up....

Final Conference Project

- planning for ? May 20 at 13:00am in the Kolker Room ?
- program should be fixed pretty quickly

Lecture Outline

High Energy Physics overview

- overview of the program
- *B* physics, LHCb experiment
  - cross sections, production fractions, branching ratios
  - lifetimes and lifetime ratios
  - *CP* asymmetries, mixing and lifetime differences
- QCD and Electroweak
- top physics
- Standard Model Higgs
- SUSY
- extra dimensions

HEP Program Overview

Precursor: Planck mass, m_P

- Schwarzschild radius: r_S ; characteristic radius for which a particle would just turn into a black whole if all its mass was inside that radius
- Compton length: λ ; intrinsic position uncertainty for the position measurement of a particle due to its wave character as defined by QM
- Planck mass: particle has $r_S = \lambda/\pi$

$$m_P = \sqrt{\frac{\hbar c}{G}} = 1.2209 \times 10^{19}\,\mathrm{GeV}$$

Mass of a flea is about 5000 x m_P

HEP Program Overview

Precursor: Charge Conjugation, *C*

- replacing a particle with its own antiparticle is called charge conjugation: operator in QM

Precursor: Parity Inversion, *P*

- inverting the spacial coordinates is called the parity operation and is a QM operator

Precursor: *CP*

- combining charge conjugation and parity inversion is called the *CP* operation

E&M and QED completely symmetric under *C* and *P*

Weak force

- violates *C* and *P* maximally
- *CP* also violated, less obvious (1964, K^0, Cronin, Fitch)

HEP Program Overview

Big questions in High Energy Physics

- the matter problem
  - where does matter originate from? which mechanism?
  - what is the large amount of dark matter in the universe?
  - (what is the even larger amount of dark energy?)

- matter anti-matter asymmetry and *CP* violation
  - why is there so much matter and so little anti-matter?
  - big bang should have produced them in equal amounts
  - *CP* operation has to be asymmetric (violates symmetry)
  - Standard Model *CP* violation cannot explain observed asymmetry
    - could explain existence of just one galaxy but not the universe
    - there must be something else, *CP* violating, generating the rest

HEP Program Overview

Big questions in High Energy Physics, *continued*

- Hierarchy problem(s)
  - general idea: fundamental parameters are much smaller/bigger than parameters measured in the experiment
  - why is the weak force 10^{32} times stronger than gravity?
  - or otherwise put: why is the Higgs mass that much smaller then the Planck mass? to explain this in a natural fashion new physics should appear in vicinity of the Higgs boson (what ever that means)

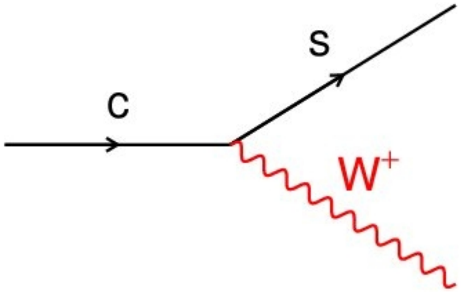
LHCb Experiment and B Physics

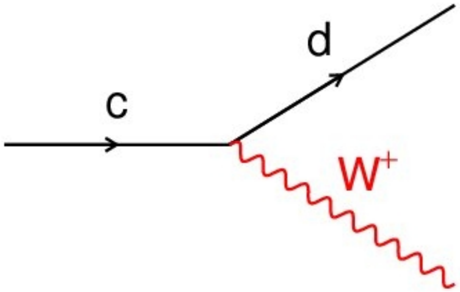
Matter build of families of fermion doublets

$$\text{Leptons} \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$$

$$\text{Quarks} \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L$$

Weak interaction through $W^\pm$ bosons





In general: weak eigenstates ≠ strong eigenstates

- ▶ mixing between families possible
- ▶ lower quark doublet components absorb difference
- ▶ neutrinos also mix

LHCb Experiment and B Physics

Example: two families of quark pairs → one mixing angle

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix} \quad \text{rotation matrix}$$

Matrix has to be unitary: $V^\dagger V = 1$

Describe mixing between three quark-pair families

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V \times \begin{pmatrix} d \\ s \\ b \end{pmatrix} \quad \text{with} \quad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

V is Cabbibo–Kobayashi–Maskawa matrix

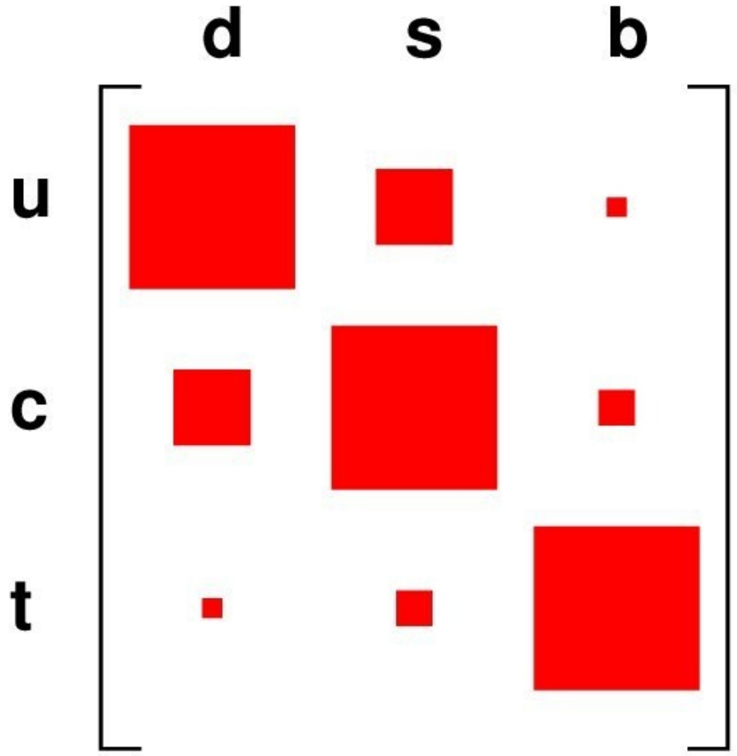
Three families → 4 degrees of freedom

- 3 angles
- 1 complex phase → *CP* violation

LHCb Experiment and B Physics

Matrix structure

- mostly diagonal
- crossing of families suppressed
- the further the less probable
- values not predicted



Particles are conserved:

$$V^\dagger V = 1$$

→ unitarity condition

Wolfenstein parametrization ($\lambda = 0.2272 \pm 0.0010$):

$$V = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

Least known parameters: ρ and η

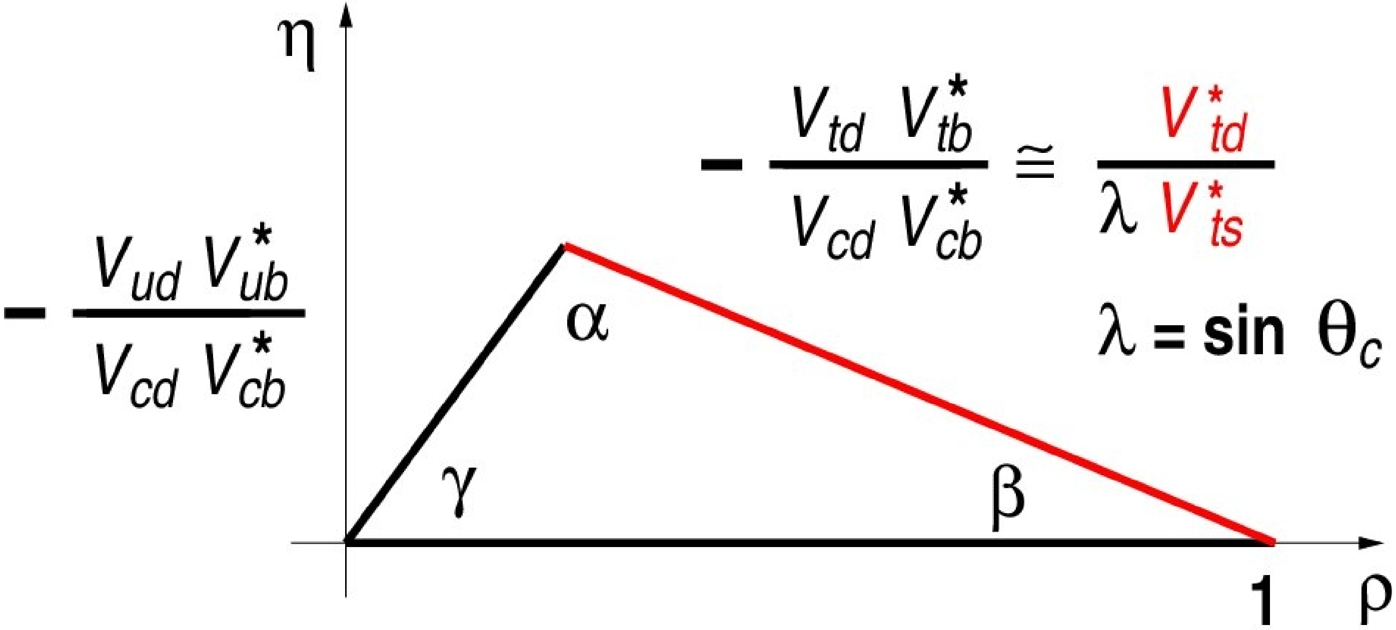
LHCb Experiment and B Physics

Unitarity condition: $V^\dagger V = 1$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\rightarrow V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

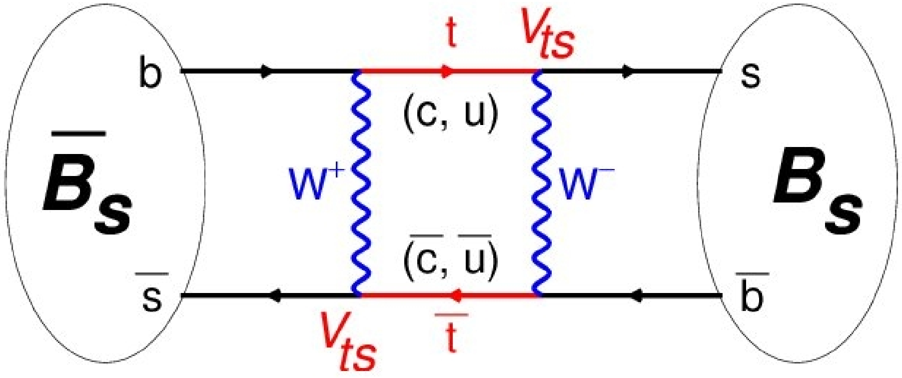
$$\rightarrow 1 + V_{ud}V_{ub}^*/V_{cd}V_{cb}^* + V_{td}V_{tb}^*/V_{cd}V_{cb}^* = 0$$

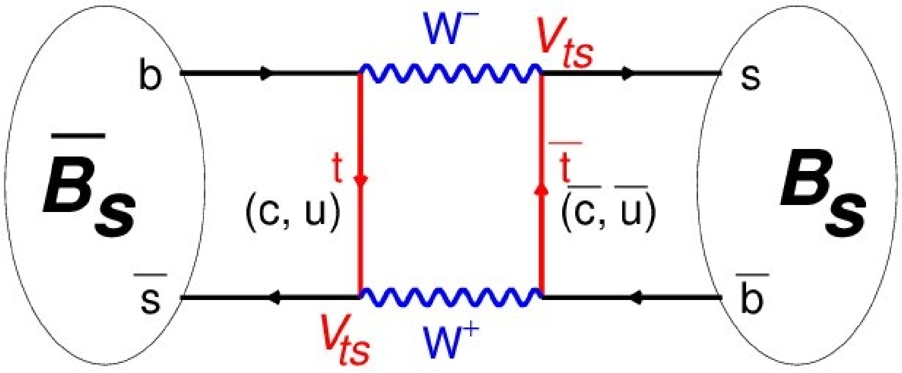


Measure triangle in all possible independent ways and confirm its closure

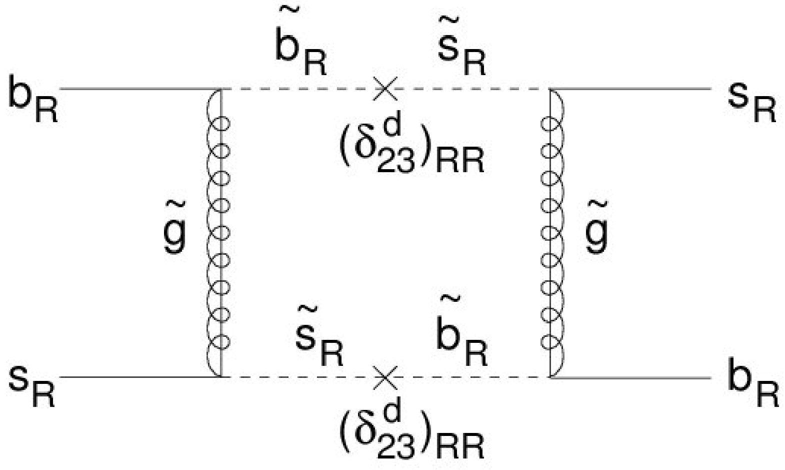
LHCb Experiment and B Physics

In the Standard Model we expect:

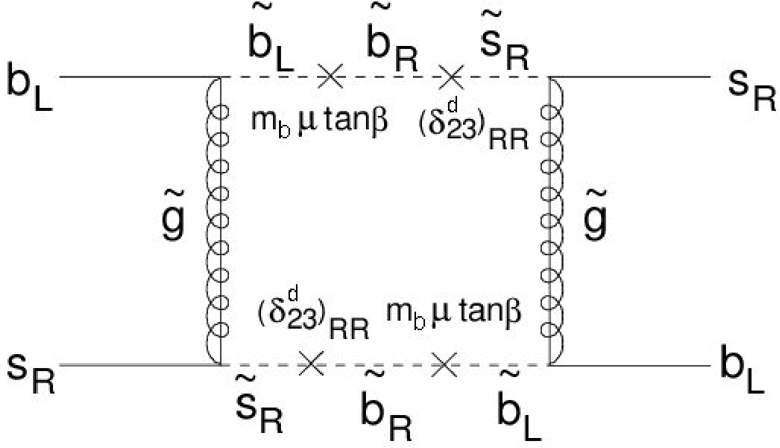




Beyond the Standard Model there could be:



from Murayama et al. hep-ph/0212180



Mixing frequency different: unitarity triangle not closed!

Atlas&CMS: High p_T Physics

Standard Model: Electroweak - Parameters

- masses: fermion masses (12), boson masses (4)
- couplings(4): α_{QED}, α_{QCD}, g_W, v_0
- 4 quark and 4 leptonic mixing parameters

Standard Model

- Classical Mechanics is ultimately described by a Lagrangian and the Hamilton Principle
- Classical Field theory adds the field to CM and the Lagrangian density
- Quantum Mechanics adds uncertainty principles and Operators
- SM is a Quantum Field Theory (quantize classical field)
- in particular needed to explain particle reactions

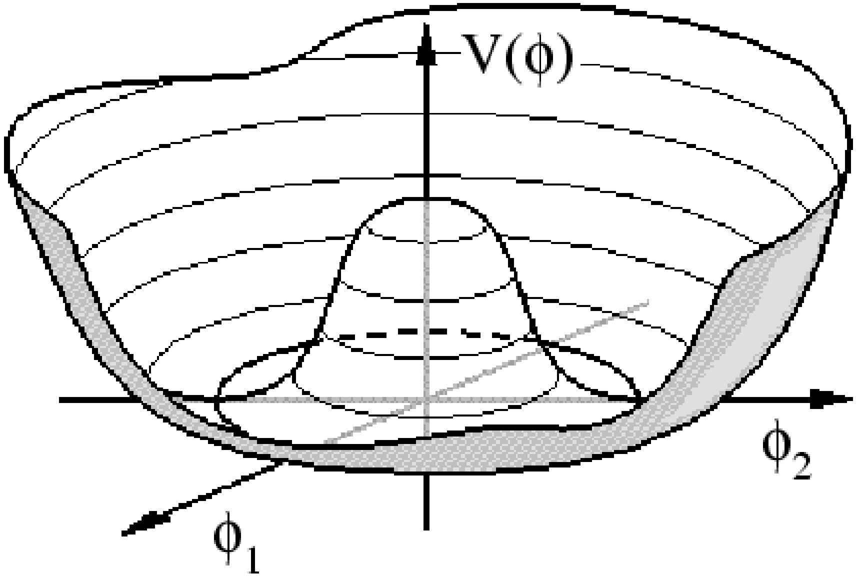
Generation of Mass with Higgs Boson

A gauge invariant Lagrangian cannot support simple by hand introduced mass terms because they destroy the gauge invariance

Introducing an additional scalar field modifies the derivative and thus the gauge transformation

Additional terms appear now in the Lagrangian which have the form of mass terms

Vacuum expectation value non zero, particle move through a field which gives them mass



A Popular Explanation [CERN]

Empty space is like a room full of chattering scientists

A highly regarded scientist arrives.... (she represents a particle)

While moving through the room people gather around her producing resistance against her motion here interpreted as mass

A Popular Explanation [CERN]

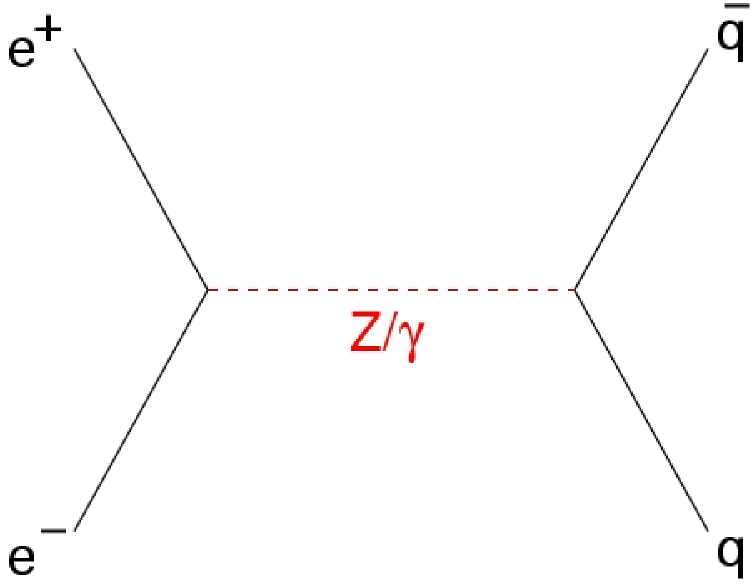
A rumor is created and crosses the room.

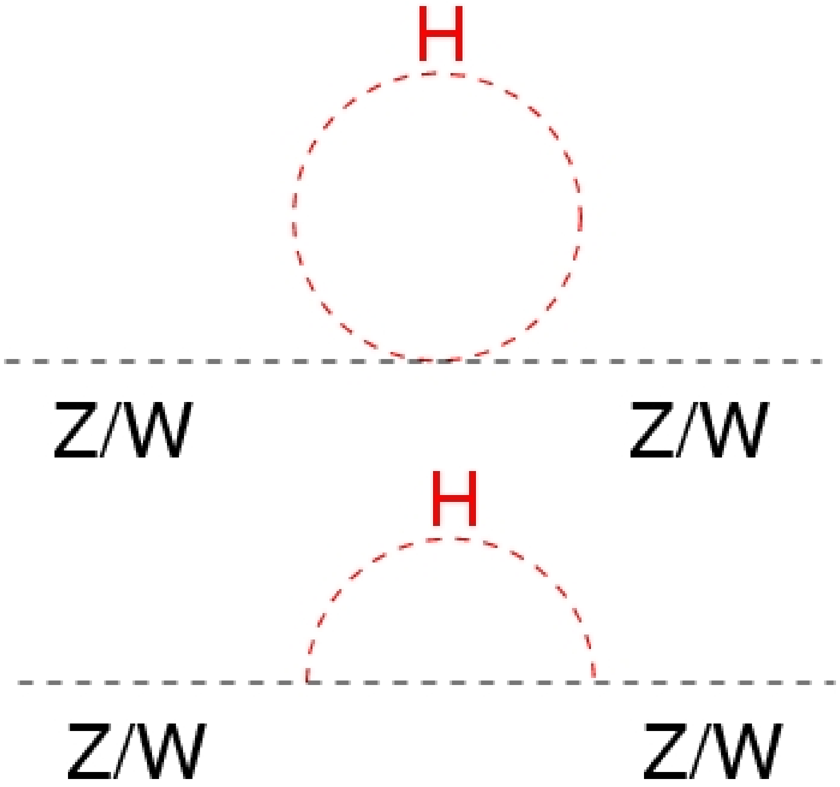
The people in the room create a clustering just by themselves which is interpreted as the Higgs boson.

Goal of Electroweak Physics

Measure electroweak reactions to constrain Standard Model

- direct measure of SM parameters m_t, m_W, ...
- measurements: $O_i(m_W, m_Z, m_t, m_H, ...)$
- example: cross section, asymmetries, polarizations





Interpreting Electroweak Results in SM

All essential world EW measurements compared to the predicted value

Some of the measurements are very high level, combining very many individual measurements

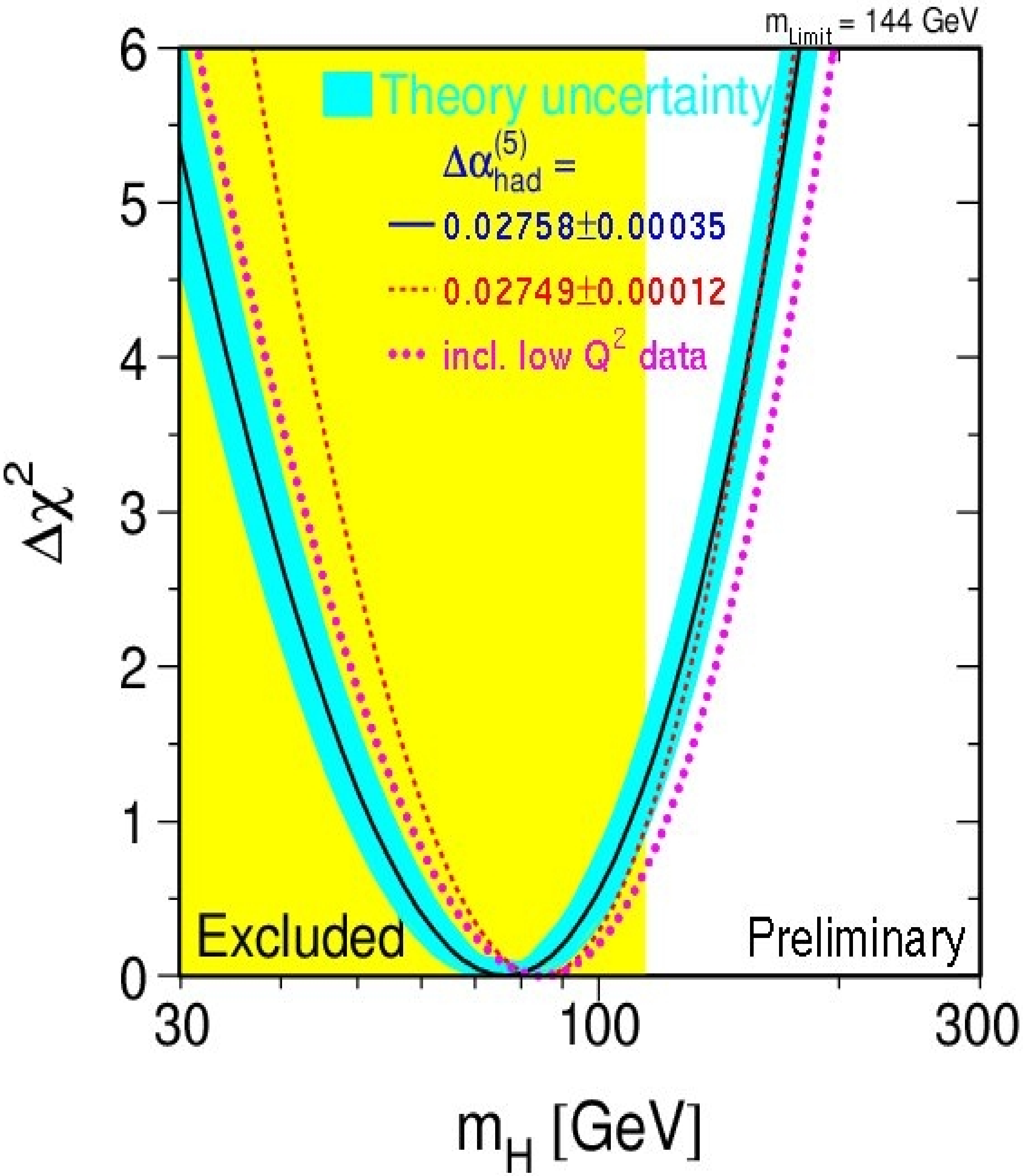
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

Interpreting Electroweak Results in SM

The one free unknown is obviously the most important goal

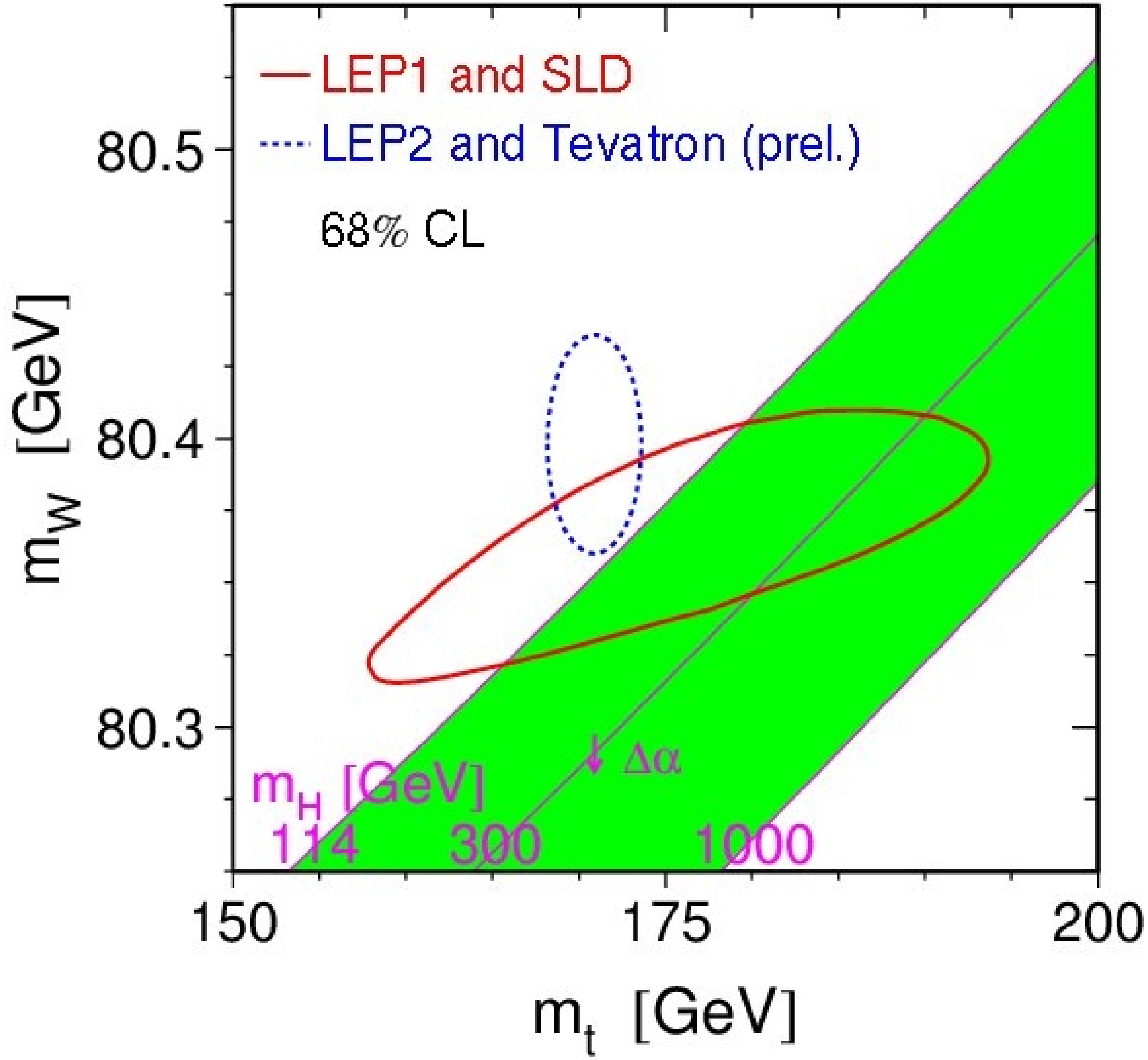
Higgs mass enters as a logarithm into the electroweak corrections

Either Higgs is found or SM is shown to be wrong



Interpreting Electroweak Results in SM

Indirect information of the top and W masses versus direct measurement



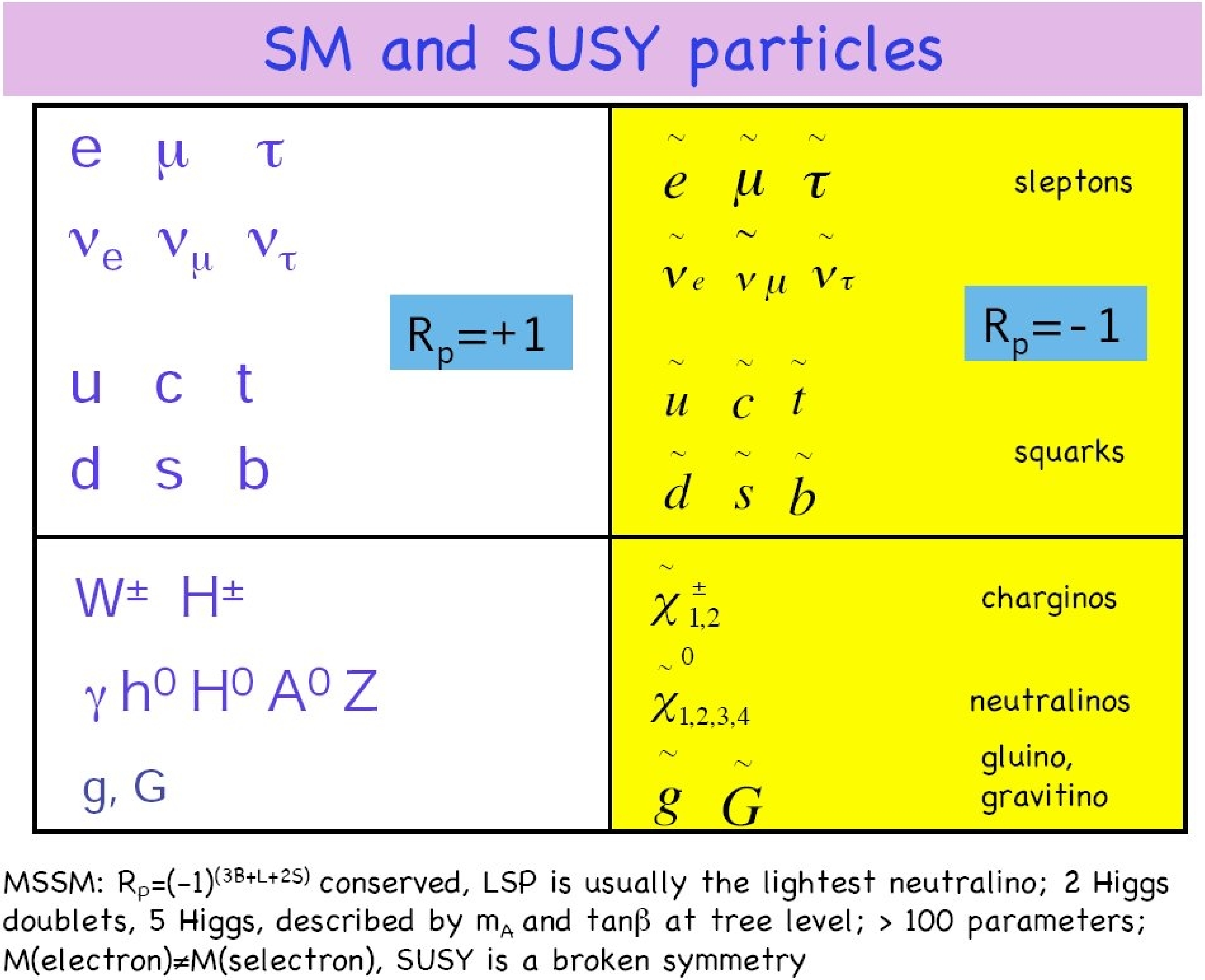
SuperSymmetry

Why do the theorists like it?

- it solves the hierarchy problem!
- coupling constants unify at the Grand Unified Theory, GUT, scale
- it may provide a dark matter candidate
- well.... it is very nice and symmetric (super symmetric)
- why some experimentalists do not like it:
  - much more new parameters
  - many new CP violating phases, we did not see any
  - why does it have to be around the corner?

SuperSymmetry

What is SUSY?

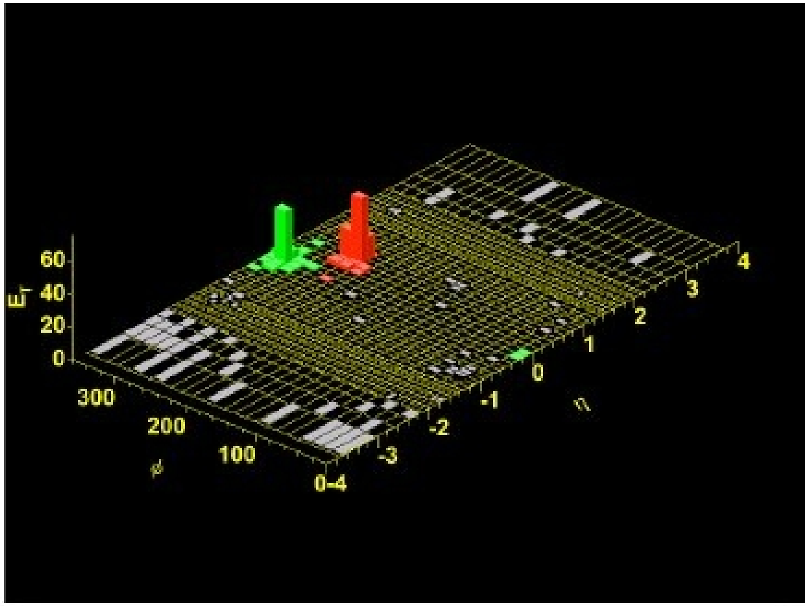


SM and SUSY particles

e μ τ	$\tilde{e}$ $\tilde{\mu}$ $\tilde{\tau}$	sleptons
ν_e ν_μ ν_τ	$\tilde{\nu}_e$ $\tilde{\nu}_\mu$ $\tilde{\nu}_\tau$	
$R_p=+1$		$R_p=-1$
u c t	$\tilde{u}$ $\tilde{c}$ $\tilde{t}$	
d s b	$\tilde{d}$ $\tilde{s}$ $\tilde{b}$	squarks
$W^\pm$ $H^\pm$	$\tilde{\chi}^\pm_{1,2}$	charginos
γ h^0 H^0 A^0 Z	$\tilde{\chi}^0_{1,2,3,4}$	neutralinos
g, G	$\tilde{g}$ $\tilde{G}$	gluino, gravitino

MSSM: $R_p=(-1)^{(3B+L+2S)}$ conserved, LSP is usually the lightest neutralino; 2 Higgs doublets, 5 Higgs, described by m_A and tanβ at tree level; > 100 parameters; M(electron)≠M(selectron), SUSY is a broken symmetry

Searches for Signatures



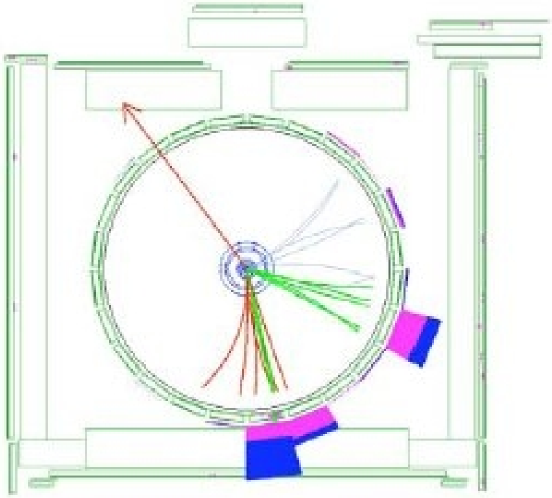
- For 3rd gen squarks, large mixing in the L- and R-handed weak eigenstates could lead to light stop or sbottom quark.

- Produced in pairs at Tevatron for Rp conserving (RPC), cross section could be high.

- Assume they decay in q+LSP

$$p\bar{p} \rightarrow \tilde{t}_1 \bar{\tilde{t}}_1 \rightarrow c\tilde{\chi}_1^0 \bar{c}\tilde{\chi}_1^0$$

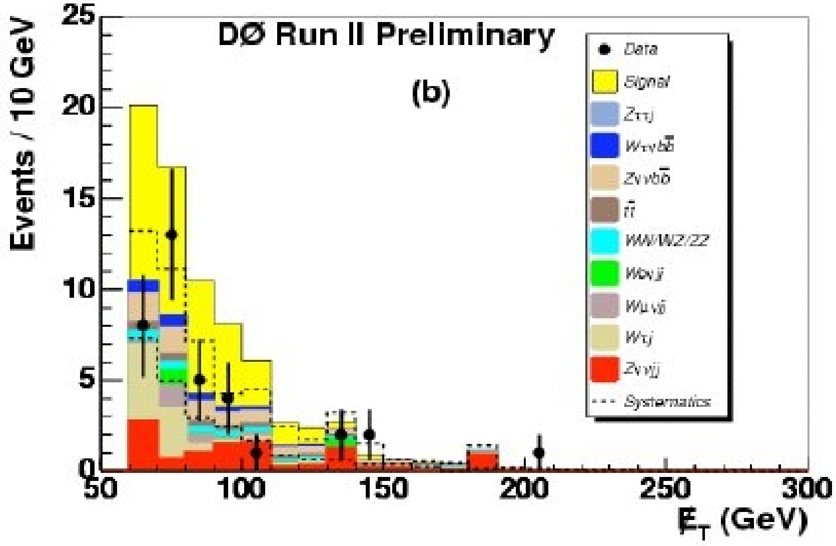
$$p\bar{p} \rightarrow \tilde{b}_1 \bar{\tilde{b}}_1 \rightarrow b\tilde{\chi}_1^0 \bar{b}\tilde{\chi}_1^0$$



i.e. two acoplanar b-jets and MET

Search for sbottom at Tevatron

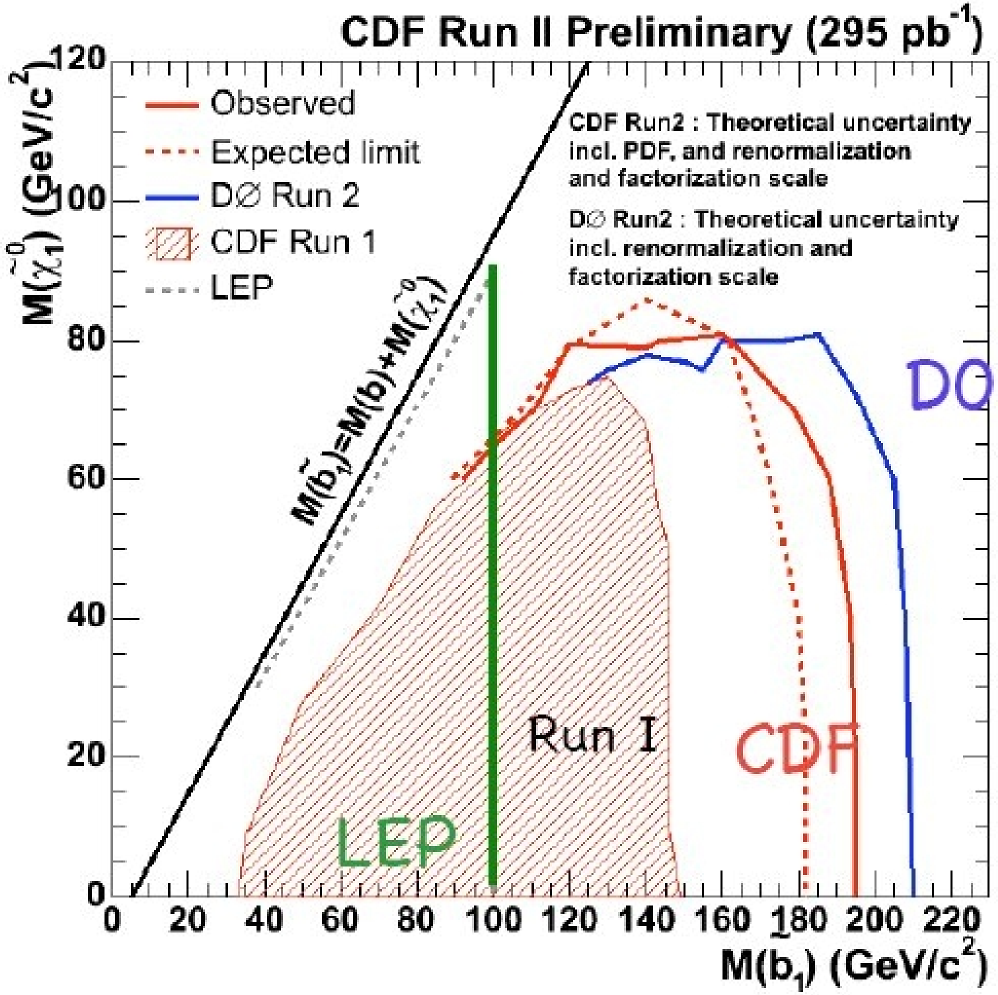
$$p\bar{p} \rightarrow \tilde{b}_1\bar{\tilde{b}}_1 \rightarrow b\tilde{\chi}_1^0\bar{b}\tilde{\chi}_1^0$$



After b-tagging

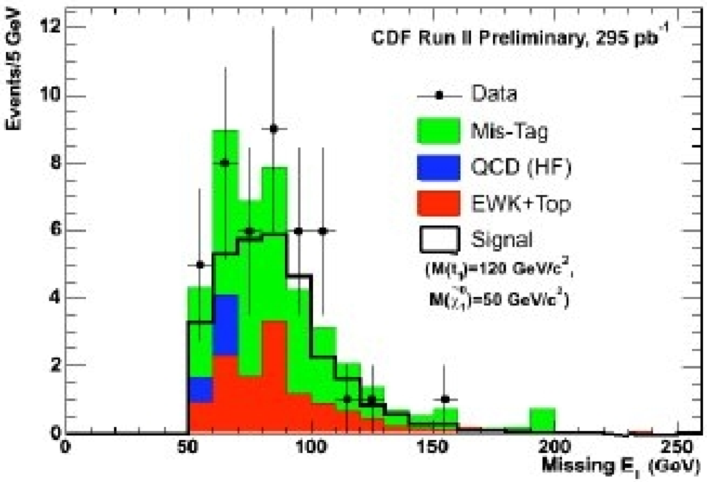
Dominant backg is W/Z+jets

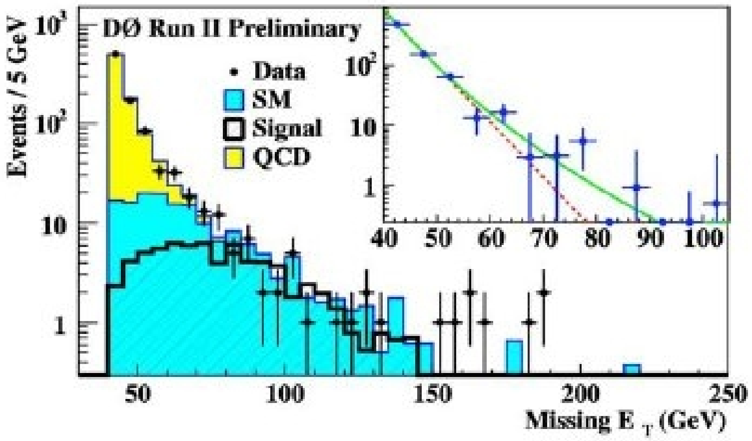
No excess observed, previous limits are improved

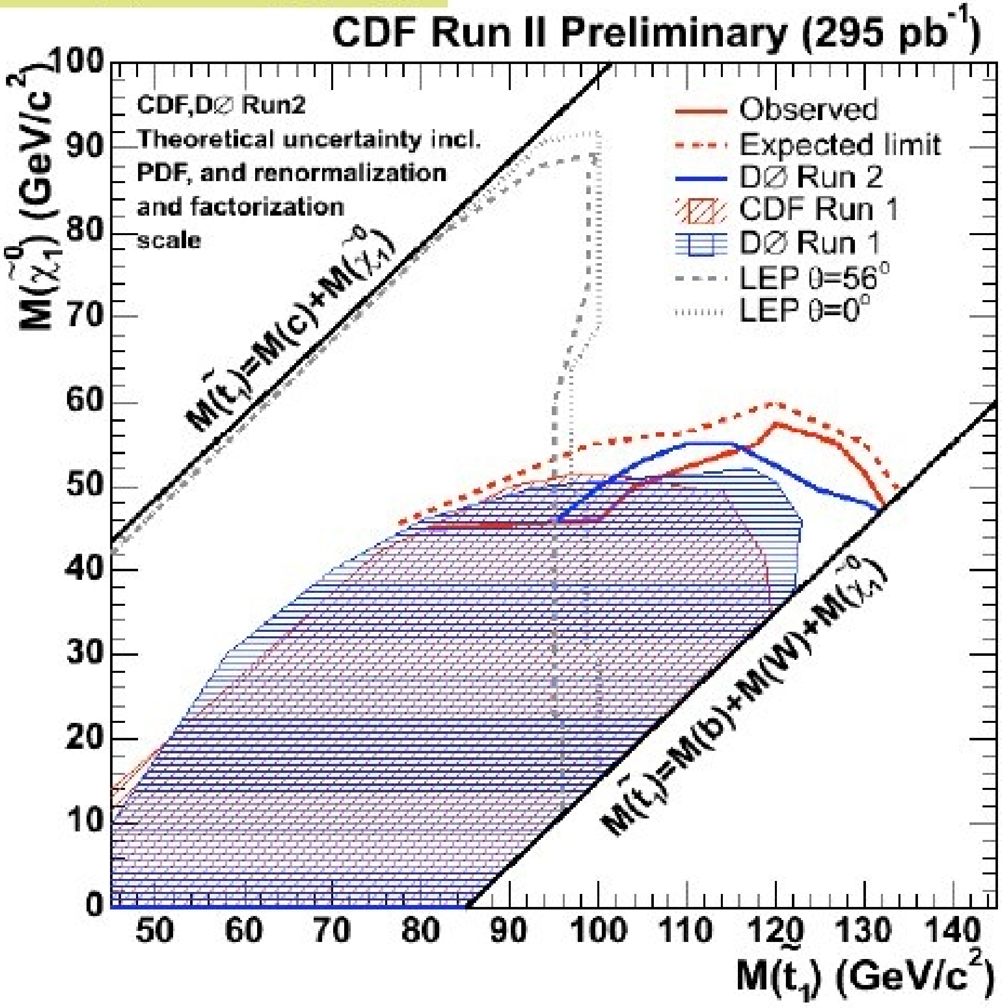


Search for stop at Tevatron

$$p\bar{p} \rightarrow \tilde{t}_1\bar{\tilde{t}}_1 \rightarrow c\tilde{\chi}_1^0\bar{c}\tilde{\chi}_1^0$$







Main SM backg is W/Z+jets

D0: 8 obs./3 exp. At MET>150 GeV

But not in the stop signal region

Largest stop mass excluded is

>131 GeV for M(neutralino)=46 GeV

Conclusion

High Energy Physics at LHC

- a huge amount of physics can be done
- most exciting is the new energy and instantaneous luminosity regime one enters: huge discovery potential: beyond the Standard Model is the biggest price
- the guaranteed result is the Higgs question
  - either we find it
  - or it is not there and the radiative corrections kill the Standard Model
- tons of bread and butter physics
  - B, top, electroweak physics
  - QCD

Next Lecture

b Hadron Lifetimes and Other Essentials

- why measure lifetimes and lifetime ratios?
- Heavy Quark Effective Theory, HQET
- proper time reconstruction and detector resolution
- systematic uncertainties
  - detector alignment
  - fitting model
  - event selection