Searches for New Physics at Hadron Colliders

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Mass Shapes the Universe

- Gravitation is the only force that is important over astronomical distances
- Despite the successes of general relativity, we still do not understand gravity in a quantum framework
- But we believe we are getting closer to understanding the origin of mass

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Mass in the Cosmos

- **Masses of Atoms**
  - rest masses of the fermions
  - plus binding energies of quarks in nucleons, nucleons in nucleus, electrons in electromagnetic field.
- **Dark Matter**
  - mass implied by dynamics (rotational velocities) is much greater than visible luminous material
  - primordial nucleosynthesis predicts D/He abundance as a function of nucleon density
  - all this mass cannot be “baryonic” (protons and neutrons) and suggests the presence of unobserved or “new” particles?

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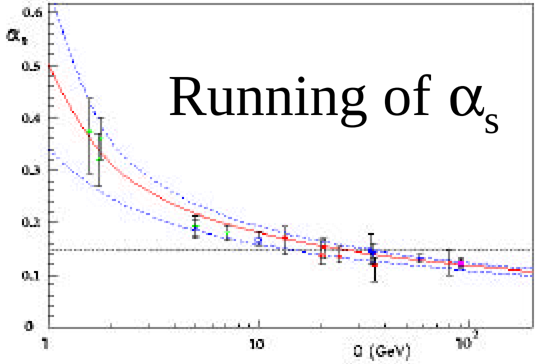
Mass of Hadrons

- **Mass of a proton = 938 MeV but mass of two u quarks and a d quark ~ 10 MeV**
  - **99% of the mass of a proton (and therefore of the mass of a hydrogen atom) is due to the binding energy**
- **Which is described with Quantum Chromodynamics (QCD)**
  - **the strong force that acts on quarks**
  - **a gauge theory (like electromagnetism)**
  - **unlike electromagnetism, the vector bosons of the theory (gluons) themselves carry the charge ("color")**
    - **gluons are self-interacting**
    - **coupling constant runs rapidly — force becomes strong for small momentum transfers**
    - **confinement**



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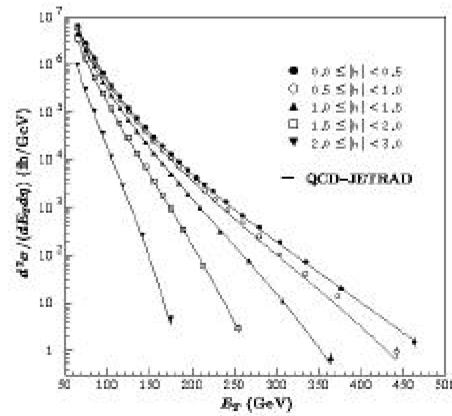
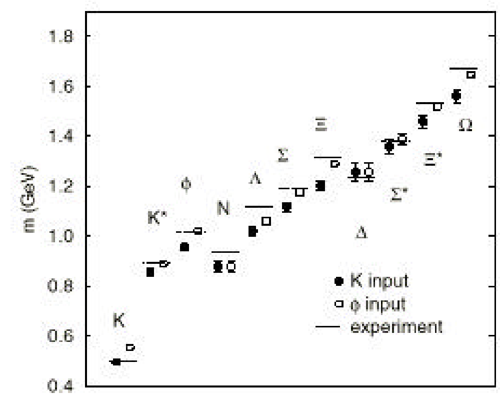
Understanding QCD

- **As we saw in Lecture 3, precisely testable QCD calculations are available for high momentum transfer processes at particle accelerators**
  - **In particular the production of jets of high momentum hadrons through quark-antiquark scattering in`pp collisions**



- **Soft QCD is calculable only numerically — lattice gauge theory**
  - **initially somewhat disappointing**
  - **recent advances in computing, and in the techniques used, lead to very credible results**
  - **predicted and measured hadron masses**



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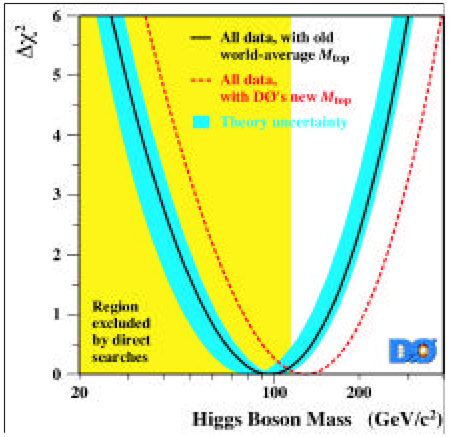
Does this mean we understand mass?

- **There is not much doubt that QCD is the theory of the strong interaction, and we are making progress in understanding how to calculate reliably in this framework**
- **But:**
  - **We still need to understand fermion masses**
    - **Second and third generations of quarks and leptons are much more massive**
    - **The masses exhibit patterns**
  - **We still need to understand vector boson masses**
    - **masses of the W and Z bosons are what makes the weak force weak**

The Higgs Mechanism

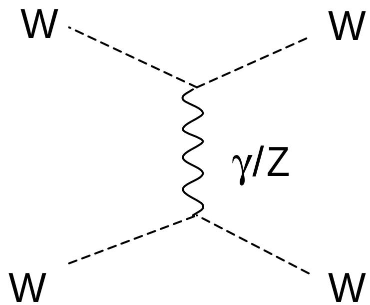
- **In the Standard Model (Glashow, Weinberg, Salam, ‘t Hooft, Veltmann)**
  - **Higgs field, f, permeates space with a finite vacuum expectation value - cosmological implications!**
  - **“Electroweak symmetry breaking” through introduction of a scalar field f ® masses of W and Z**
  - **If f also couples to fermions ® generates fermion masses**
- **An appealing picture: is it correct?**
  - **One clear and testable prediction: there exists a neutral scalar particle which is an excitation of the Higgs field.**
  - **All its properties (production and decay rates, couplings) are fixed except its mass.**
- **A very high priority of worldwide high energy physics program: find it!**
- **Since it’s massive and unknown the hadron collider may be the best opportunity**

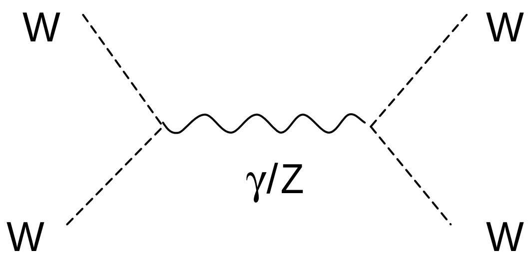
Searching for the Higgs

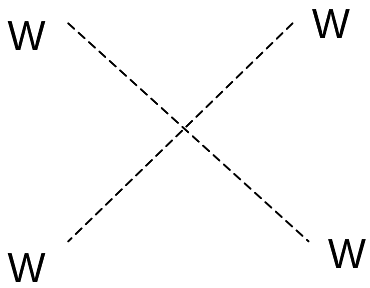


- **Over the last decade, the focus has been on experiments at the LEP e^+e^- collider at CERN (European Laboratory for Particle Physics)**
  - **Precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of m_H of 251 GeV**
  - **direct searches for Higgs production exclude $m_H < 114.4$ GeV**
- **Summer and Autumn 2000: Hints of a Higgs**
  - **the LEP data may have indicated a Higgs with mass 115 GeV (right at the limit of sensitivity)**
  - **LEP ceased operation in order to start construction on a future machine (the Large Hadron Collider or LHC)**
- **Eyes are on Fermilab until the LHC data are available in about 2008**

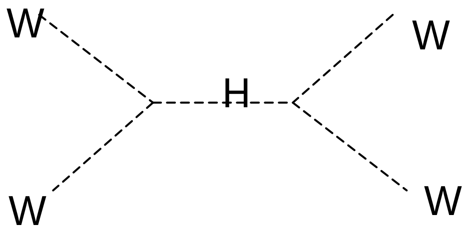
WW Scattering







- **Direct computation reveals that the individual WW scattering diagrams diverge as** s^2/M_W^4**, the divergence of the sum is more gentle**: s/M_W^2 **.**
- **The only solution is to introduce a scalar particle which cancels these residual divergences:**



- **A detailed investigation would reveal that the Higgs couplings are proportional to masses.**
- **As the Higgs mass increases, the amplitude for WW scattering via Higgs exchange becomes large, and lowest-order diagrams exceeds the unitarity limit unless the mass of the Higgs is less than 1 TeV**
- **Again hadron colliders are good tools for this energy regime now bounded between 114 and 1000 GeV.**

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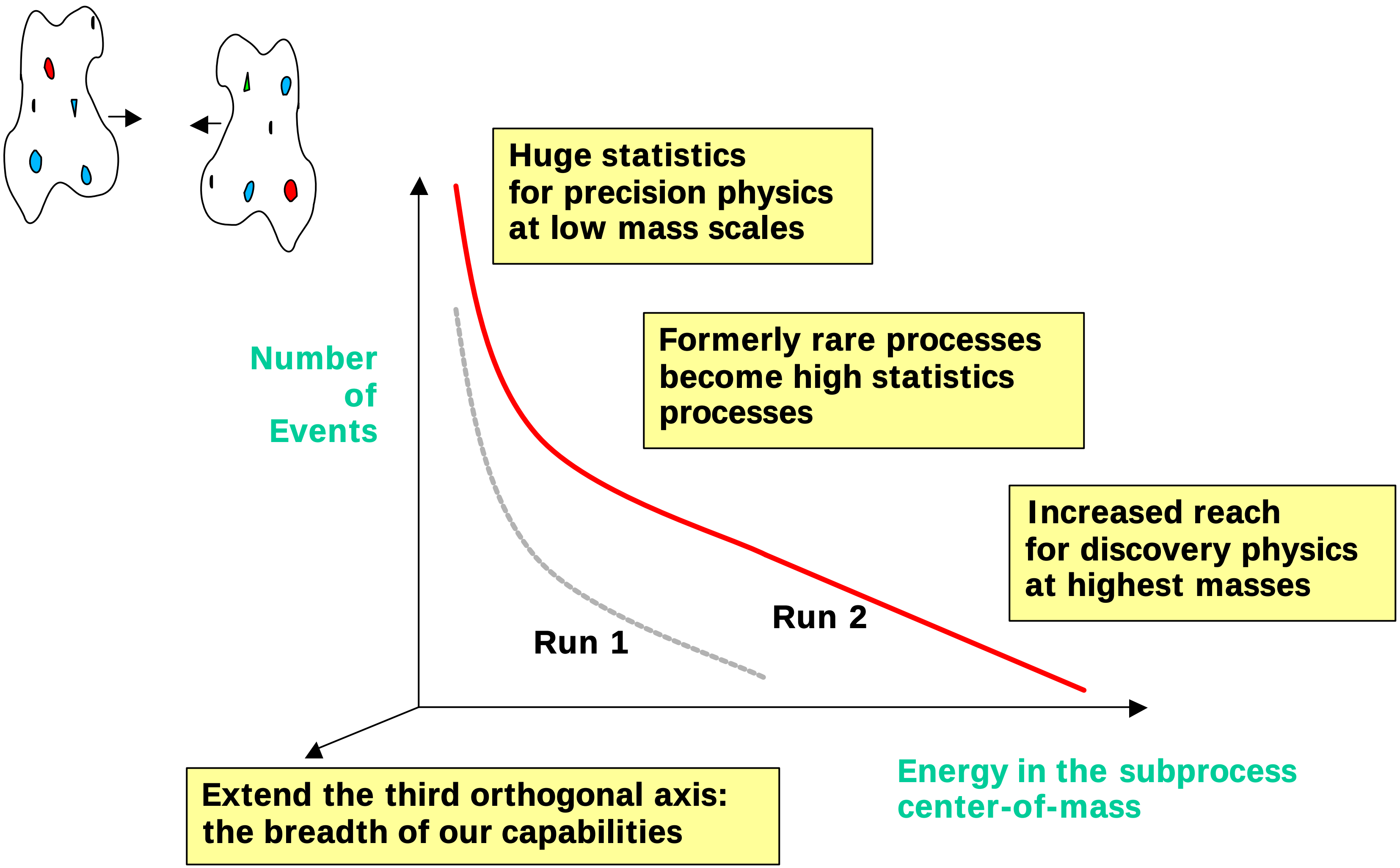
Hadron Collider Advantage



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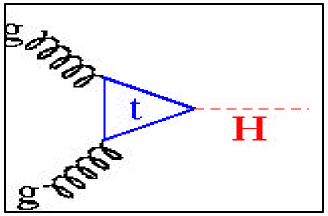
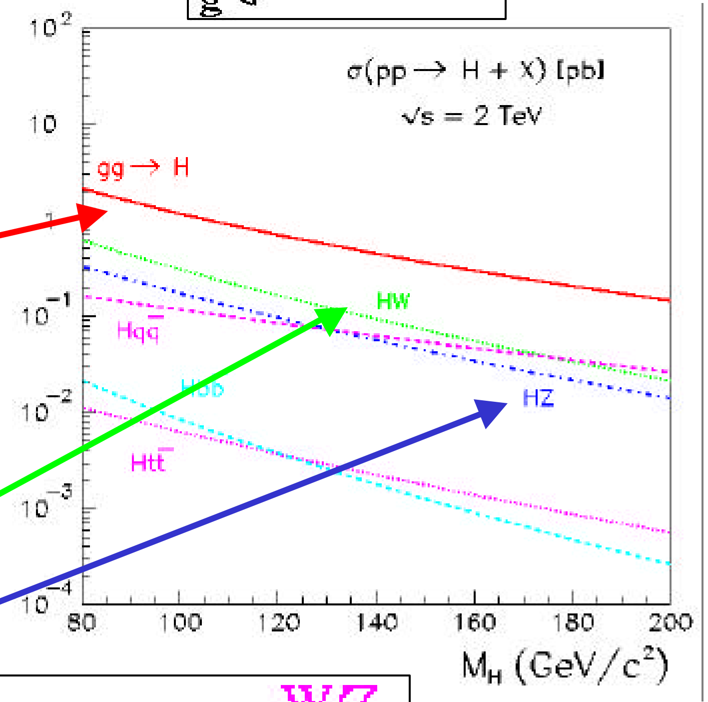
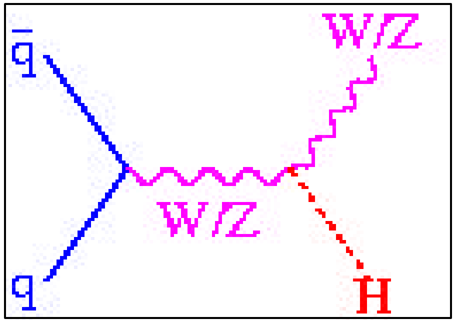
Higgs Hunting at the Tevatron



- If you know the Higgs mass, then the production cross section and decays are all calculable within the Standard Model
- inclusive Higgs cross section is quite high:
  ~ 1pb → 500 events/year
- but the dominant decay H ® bb is swamped by background
- Best bet
  - appears to be associated production of H plus a W or Z
  - Leptonic decays of W/Z help give the needed background rejection
  - ~ 0.2 pb → 100 events/year





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Higgs Discovery Channels

m_H < 140 GeV

- **WH ® qq b$\bar{b}$ is the dominant decay mode but is overwhelmed by QCD background**
- **WH ® ln bb   backgrounds Wbb, WZ, tt, single top**
- **ZH ® l l bb   backgrounds Zbb, ZZ, tt**
- **ZH ® nn bb   backgrounds QCD, Zbb, ZZ, tt**
- **Powerful mode but requires relatively soft missing E_T trigger (35 GeV?)**

m_H > 140 GeV

- **gg ® H ® WW*   backgrounds Drell-Yan, WW, WZ, ZZ, tt, tW, t t**
  initial signal:background ratio ~ 0.007!
- **Angular cuts to separate signal from “irreducible” WW background**

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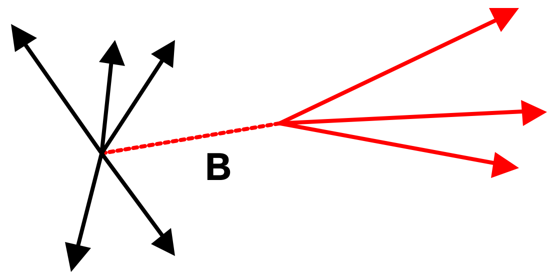
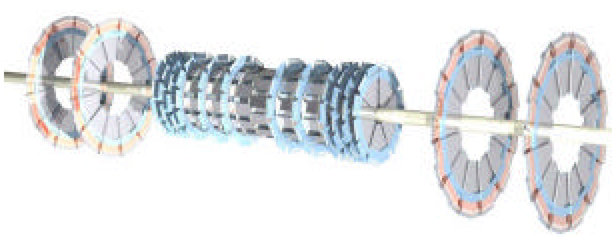
Displaced Vertex Tagging

- **The ability to identify b-quarks is very important in Higgs searches (also top, supersymmetry)**

- **b quark forms a B-meson, travels ~ 1-2mm before decaying**



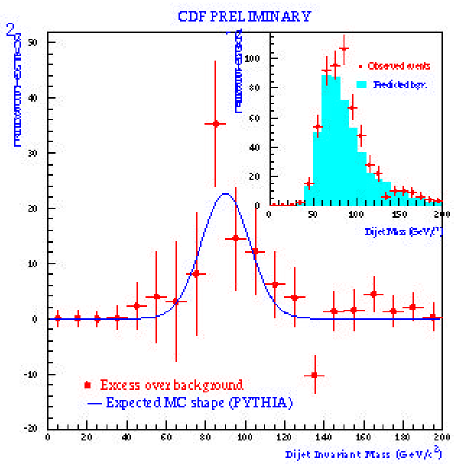
- **To reconstruct this decay, need to measure tracks with a precision at the 10μm level, silicon vertex trackers!**



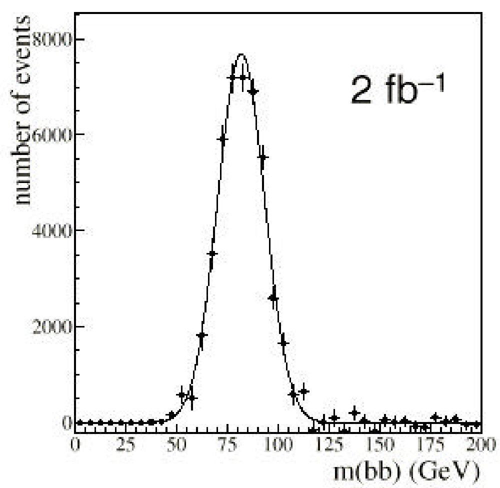
`bb Mass Resolution

- Directly influences ability to pull signal from background (See Homework 9, Slide 21, Lecture 3) and associated signal significance
- Requires corrections for missing E_T and muon
- Z ® `bb will be a calibration signal: silicon trigger

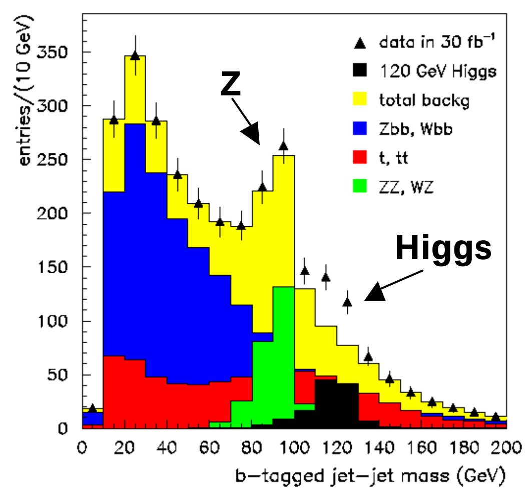
CDF observation in Run I



DØ simulation for $2fb^{-1}$



Higgs simulation for $30fb^{-1}$



m_H = 120 GeV

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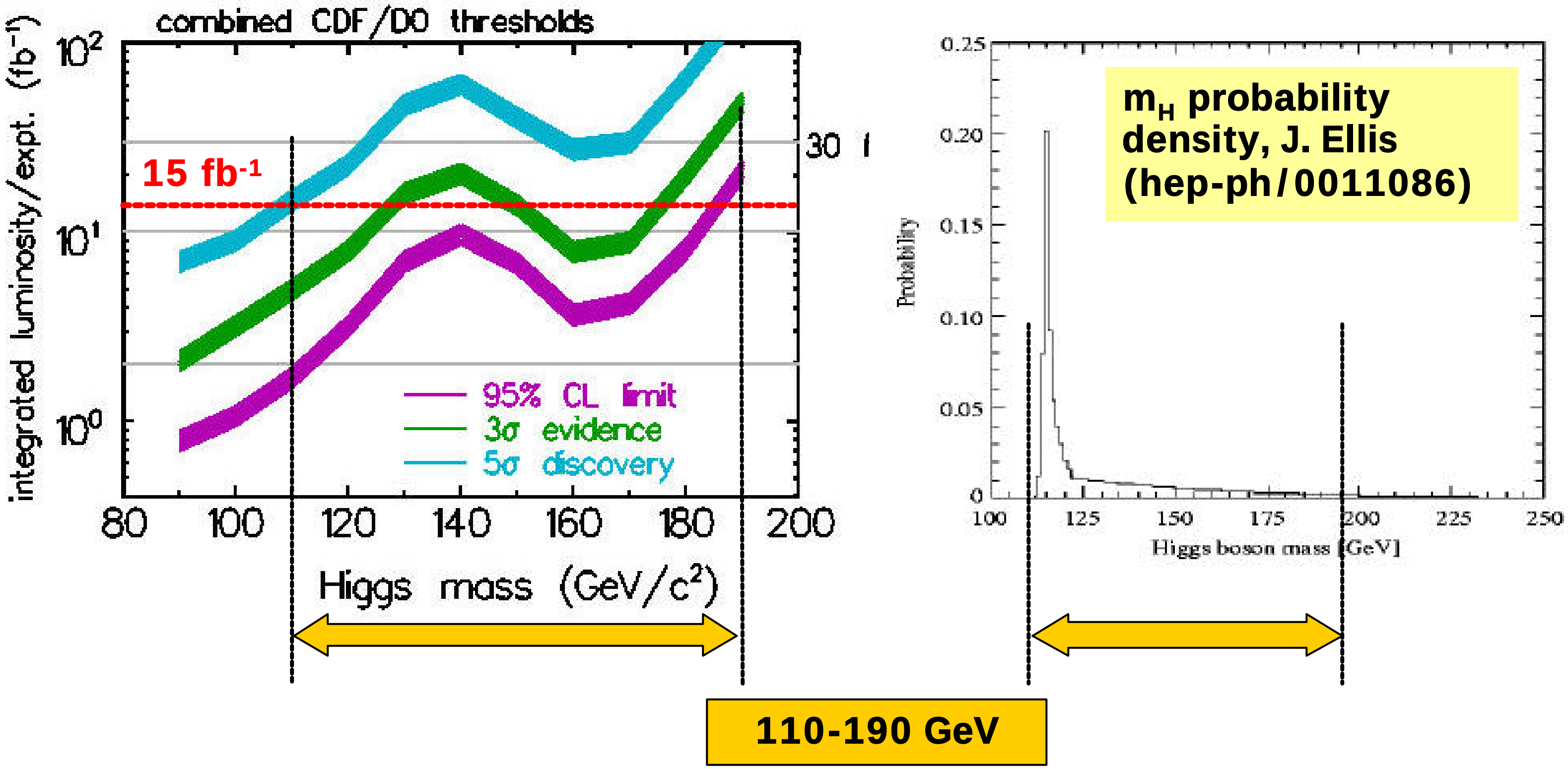
Higgs Mass Reach



The limits have been somewhat improved w/ recent working group studies.

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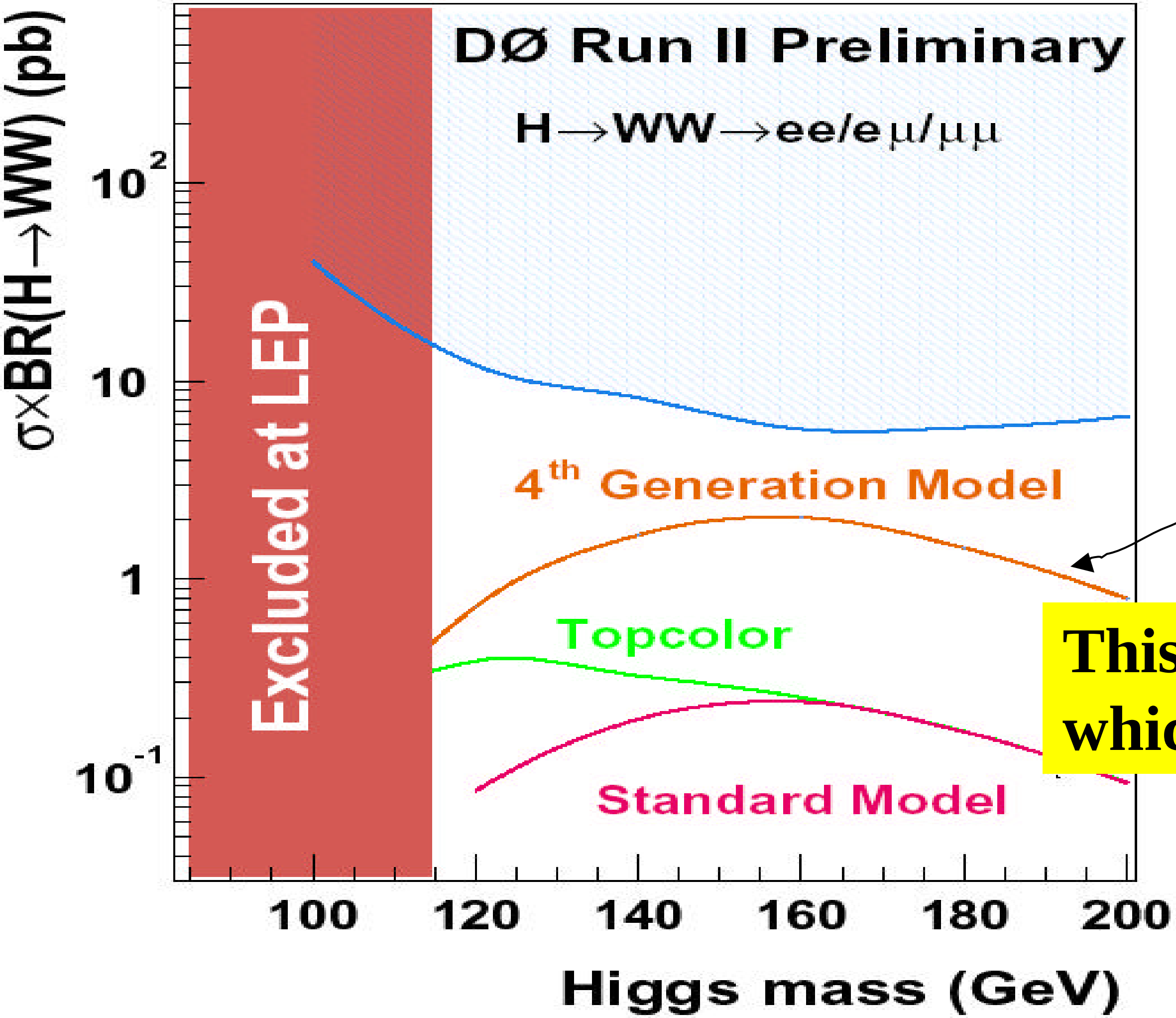
What about m_H = 115 GeV?

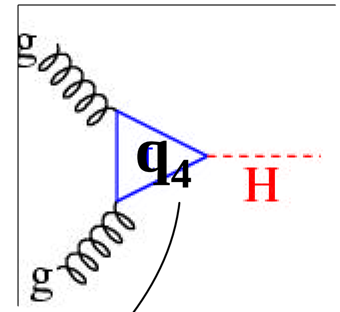
- If the LEP hints are false, we can exclude at 95% with ~2fb^{-1} of data if no evidence is seen
- Evidence at 3 standard deviation level with ~5 fb^{-1}
- If we do see something, we will want to test whether it is really a Higgs by measuring:
  - mass
  - production cross section
  - Can we see H ® WW? (Branching Ratio ~ 9%)
  - Can we see H ® tt? (Branching Ratio ~ 8%)
  - Most likely this is the realm of the LHC at CERN

Searches at the Tevatron

- **In Lecture 1 we introduced and discussed a low mass H→bb search. Searches for high mass H→WW* underway as well**
- **An interesting channel since di-leptons from the decay of W and virtual W are easily distinguished from backgrounds.**
  - **H→WW* → $e^{+}ne^{-}n$, $e^{+}nm^{-}n$, $m^{+}ne^{-}n$, $m^{+}nm^{-}n$**
- **Procedure:**
  - **Select high pt electrons and muons, > 10-20 GeV**
  - **Calculate backgrounds: Z, WW, tt, WZ, W all decaying into leptons**
  - **Calculate efficiency (~5-15%) for observing H→WW* as a function of H mass.**
  - **Calculate cross section in the usual way:**

    [N(candidates)-N(background)]/[Efficiency*Luminosity]
  - **If no events seen set an upper limit on possible cross-section.**





This is an exciting story which awaits more data!

Homework 11: For 2, 4 and 8fb^{-1} what are the ranges and likely search channels in each range for evidence of the Higgs at the Tevatron?

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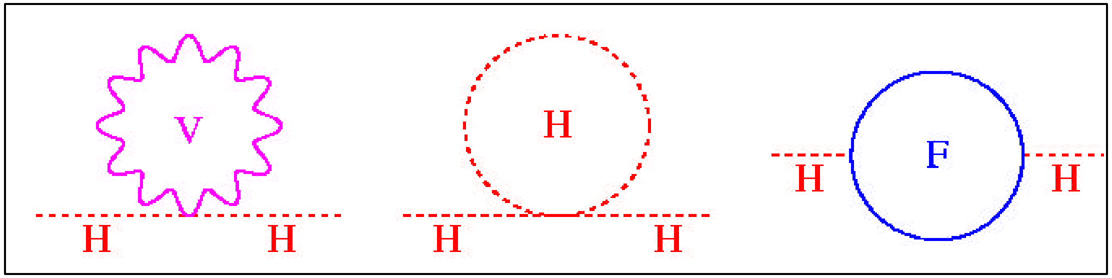
Beyond the Higgs…SUSY & Exotica

- **The standard model works at the 10^{-3} level and would be completed by the discovery of the Higgs. But there are good reasons to believe that the Higgs is in fact the first window on to a new domain of physics at the electroweak scale**
- **Strong suggestions that there is something beyond the Higgs:**
  - **There are no other elementary scalars particles**
  - **The patterns of the fundamental particles suggest a deeper structure**
  - **A fundamental Higgs would have a mass unstable to radiative corrections (quantum effects: $m_H \sim 10^{15}$ GeV, unless parameters fine tuned at the level of 1 part in 10^{26})**
- **Perhaps the SM is a low energy approximation to something larger. Theoretically the most attractive option is supersymmetry**

Theoretical Problems of the Standard Model

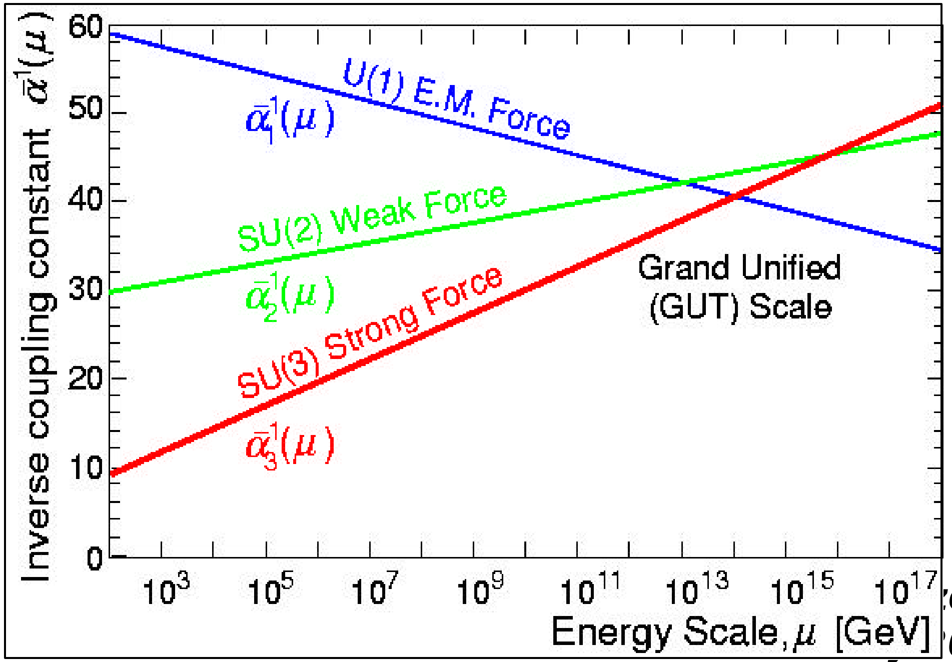
As much as we love the Standard Model,
it is unlikely to be a complete theory

Higgs boson mass receives radiative corrections which are quadratically divergent



Standard Model does not incorporate gravity

Strong, electromagnetic and weak interactions do not unify at high energies without new physics



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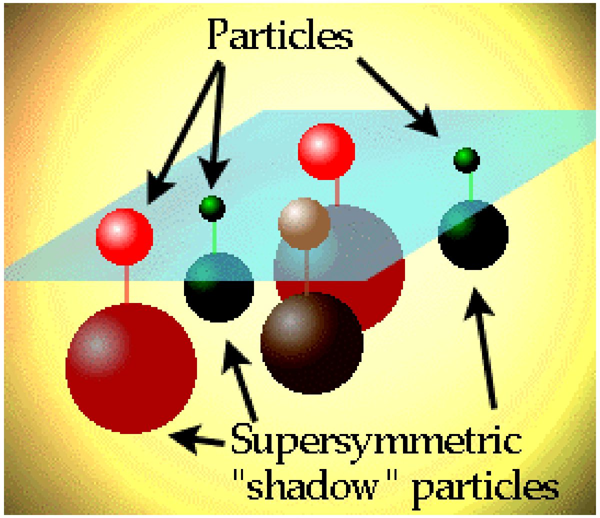
Supersymmetry Solution

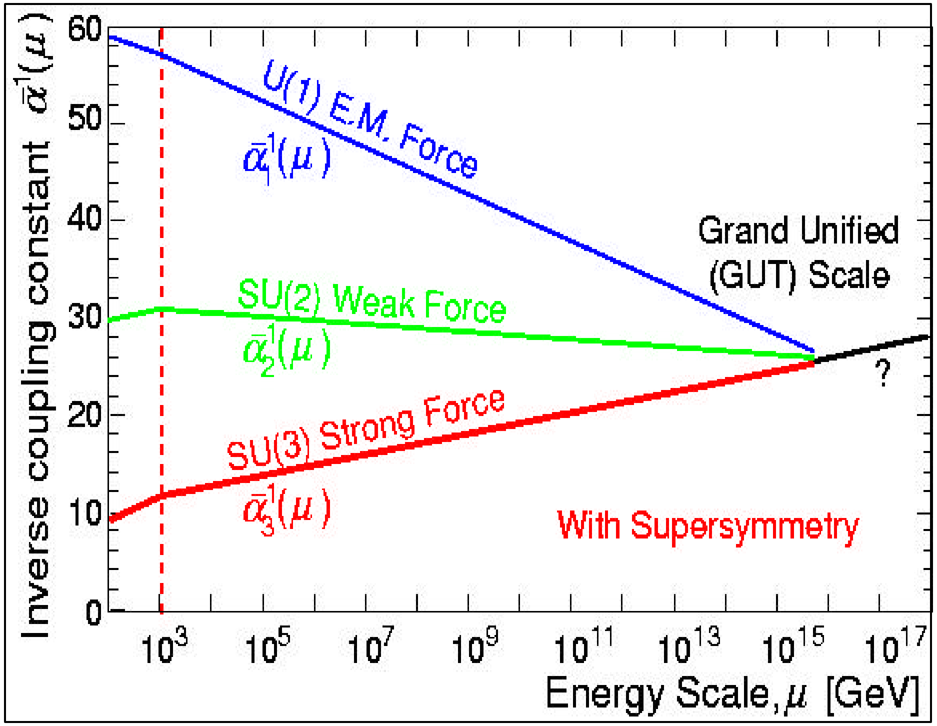


It is a theory
popular theoretically but
unobserved experimentally

Provides a solution to Higgs mass problem

Offers a path to the incorporation of gravity

Unifies strong, electromagnetic and weak forces at high energies



Predicts the radiative breaking of EW symmetry

Supersymmetry Particles

The simplest supersymmetric model
is the minimal supersymmetric standard model (MSSM)

(1) An extra Higgs doublet of opposite hypercharge
(2) Supersymmetrizing the gauge field

Standard Model Particles

$W^{\pm} H^{\pm}$ $\quad \gamma \; Z \; h \; H \; A$ $\quad u \; d \; e \; \nu$ $\quad \ldots\ldots$

$\Downarrow \qquad \Downarrow \qquad \Downarrow$

$\tilde{\chi}_2^{\pm} \; \tilde{\chi}_1^{\pm}$ $\quad \tilde{\chi}_4^0 \; \tilde{\chi}_3^0 \; \tilde{\chi}_2^0 \; \tilde{\chi}_1^0$ $\quad \tilde{u}_L \; \tilde{d}_L \; \tilde{e}_L \; \tilde{\nu}_L$, $\tilde{u}_R \; \tilde{d}_R \; \tilde{e}_R \; \tilde{\nu}_R$ $\quad \tilde{\ldots}\tilde{\ldots}$

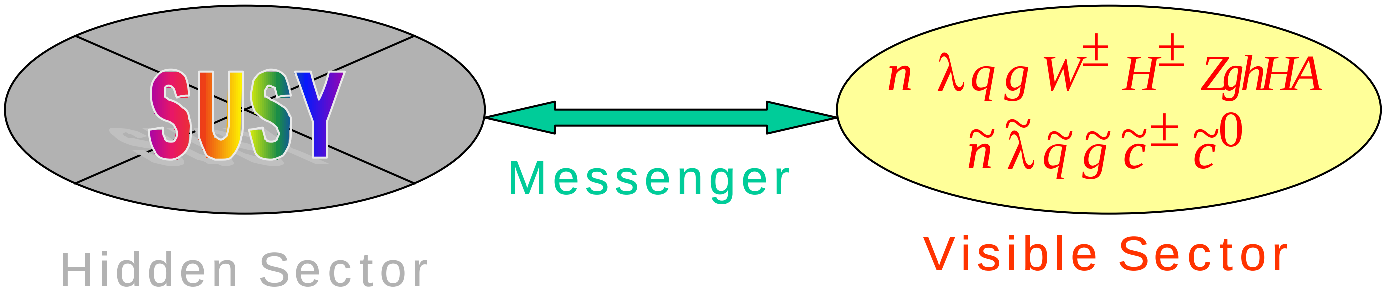
Supersymmetric Particles

For every spin degree of freedom in SM,
there is a supersymmetric spin degree of freedom

Lots of new particles and lots of free parameters
$\Rightarrow$ lots of opportunity

Broken Symmetry

Supersymmetry must be broken



The symmetry is assumed to be broken
in a hidden sector, a messenger sector mediates
the breaking to the visible sector

Different mediation leads to different classes of models

Gravity inspired models

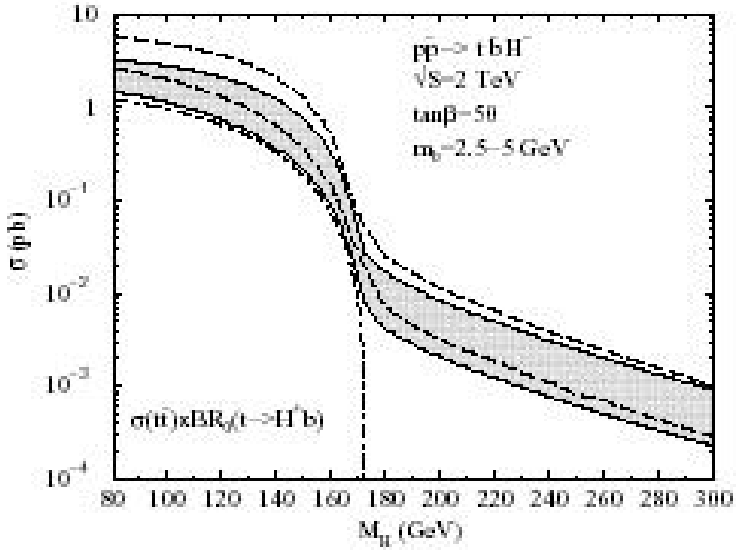
The messenger interaction is of gravitational strength

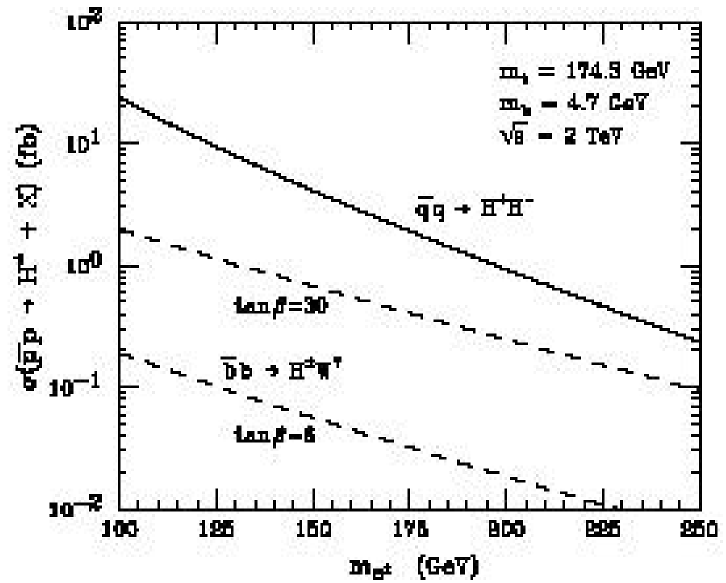
Gauge mediated models

SM gauge interactions play the role of messenger force

Anomaly mediations, Gaugino mass dominance

MSSM Higgs Production at Tevatron





Note: tan b is a reflection of the strength of the supersymmetric Higgses and is related to the coupling with other particles.

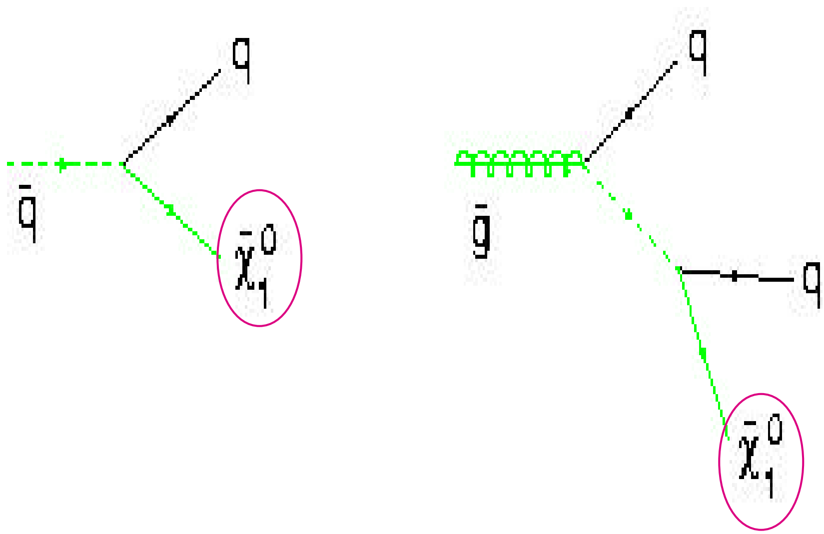
Supersymmetry Searches at Hadron Colliders

- Supersymmetry predicts
  - Partners to the quarks and gluons: strongly interacting squarks and gluinos
  - Partners to the leptons, W, Z: electroweakly interacting sleptons, charginos, and neutralinos
  - Multiple partners to the Higgs bosons: Higgsinos
  - Masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV
- Direct searches all negative so far. From LEP
  - squarks (stop, sbottom) > 80-90 GeV
  - sleptons (selectron, smuon, stau) > 70-90 GeV
  - charginos > 70-90 GeV
  - lightest neutralino > 36 GeV
- Many searches are possible at a hadron collider with high mass reach and varied initial states.

Supersymmetric Signatures

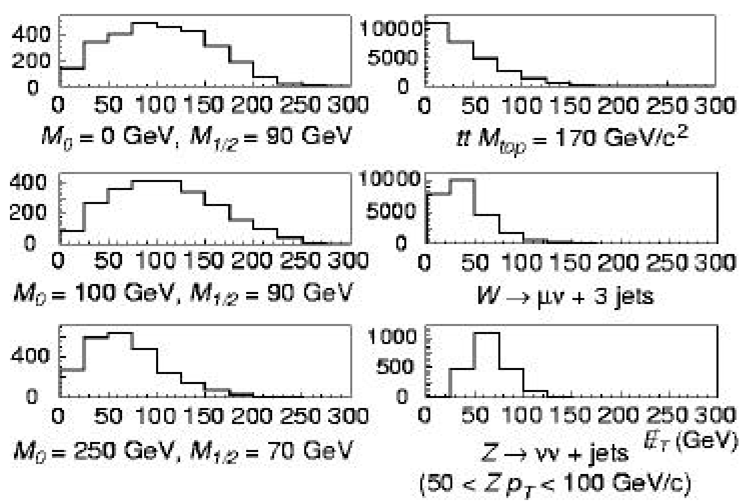
- Squarks and gluinos most copiously produced SUSY particles
- If R-parity (a new quantum number associated with many SUSY theories) is conserved, cannot decay to normal particles
- Missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)

Possible decay chains always end in the LSP:



SUSY

Missing E_T backgrounds



Search region typically > 75 GeV

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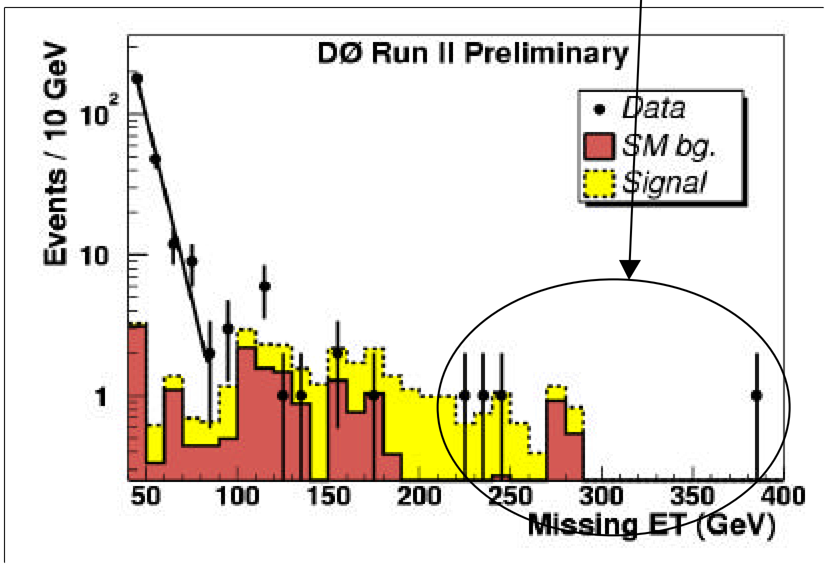
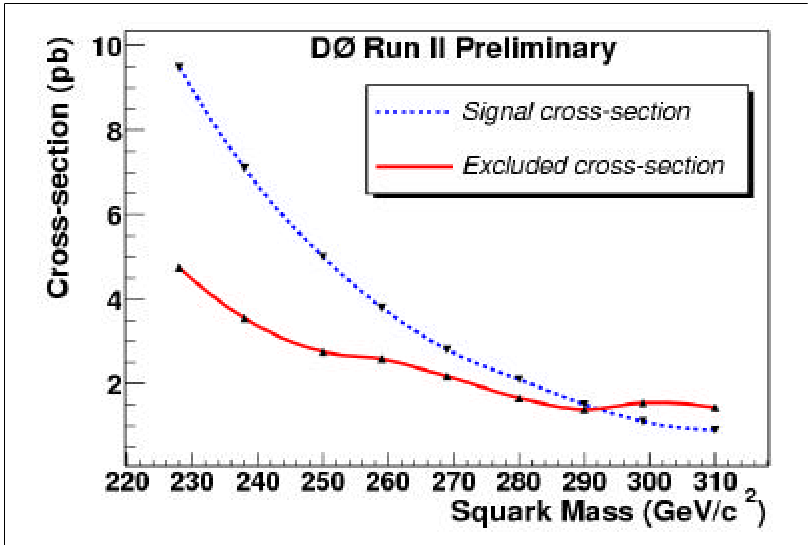
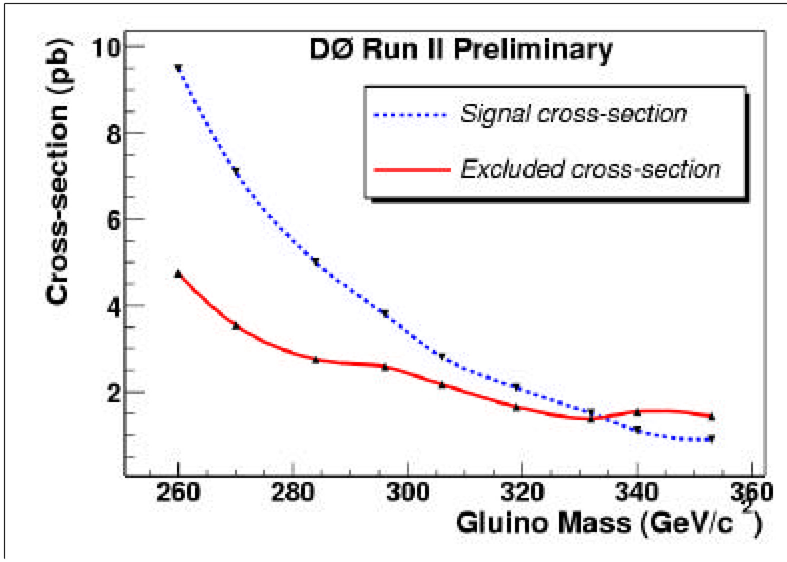
Squarks & Gluinos

- Produced in pairs
- Each would decay to normal particle and LSP
- Event would have two jets + missing transverse energy
- Four events with expected
- Background of three.







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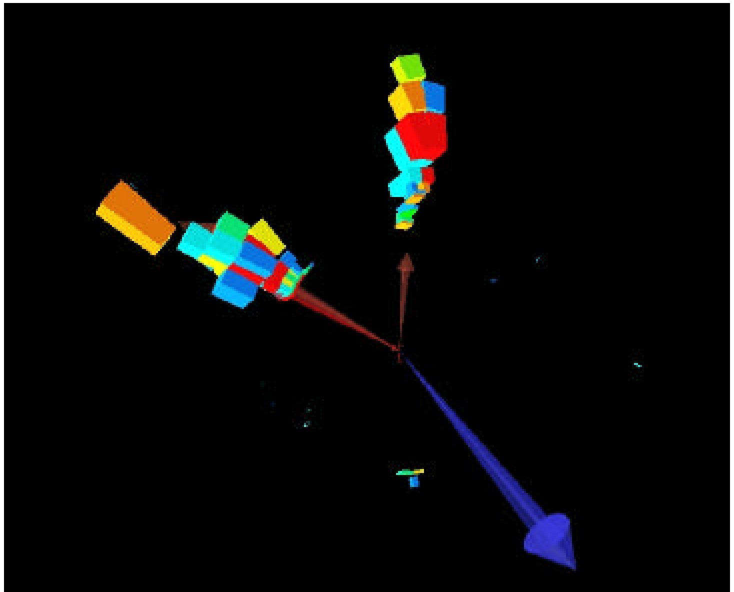
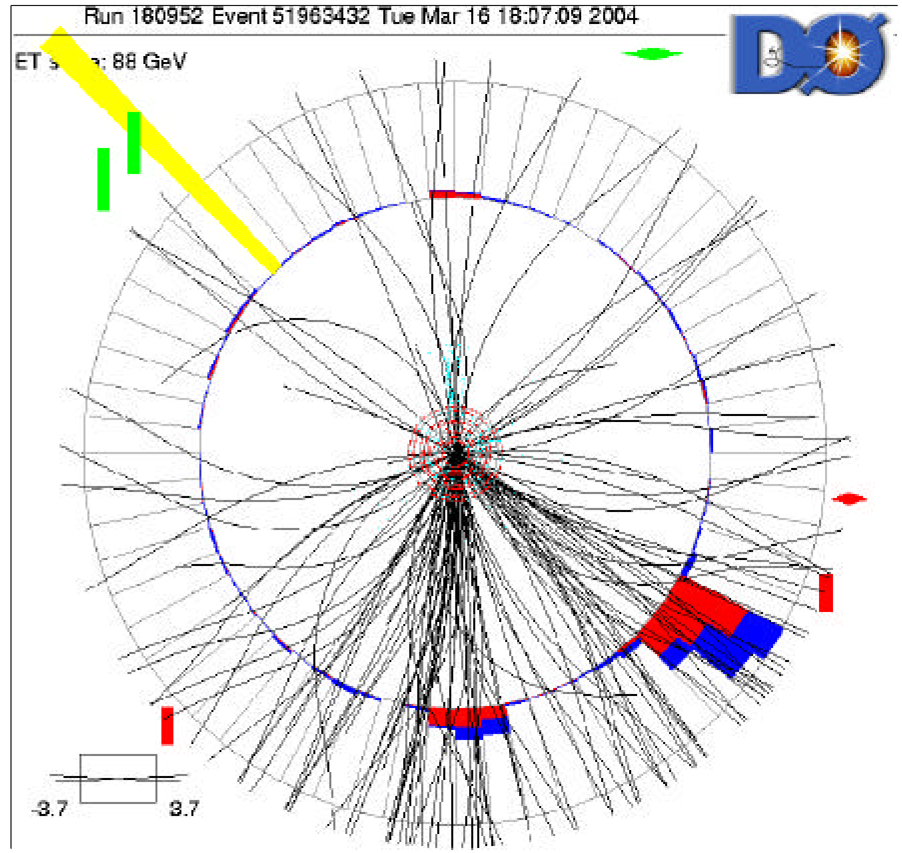


Highest missing E_T candidate



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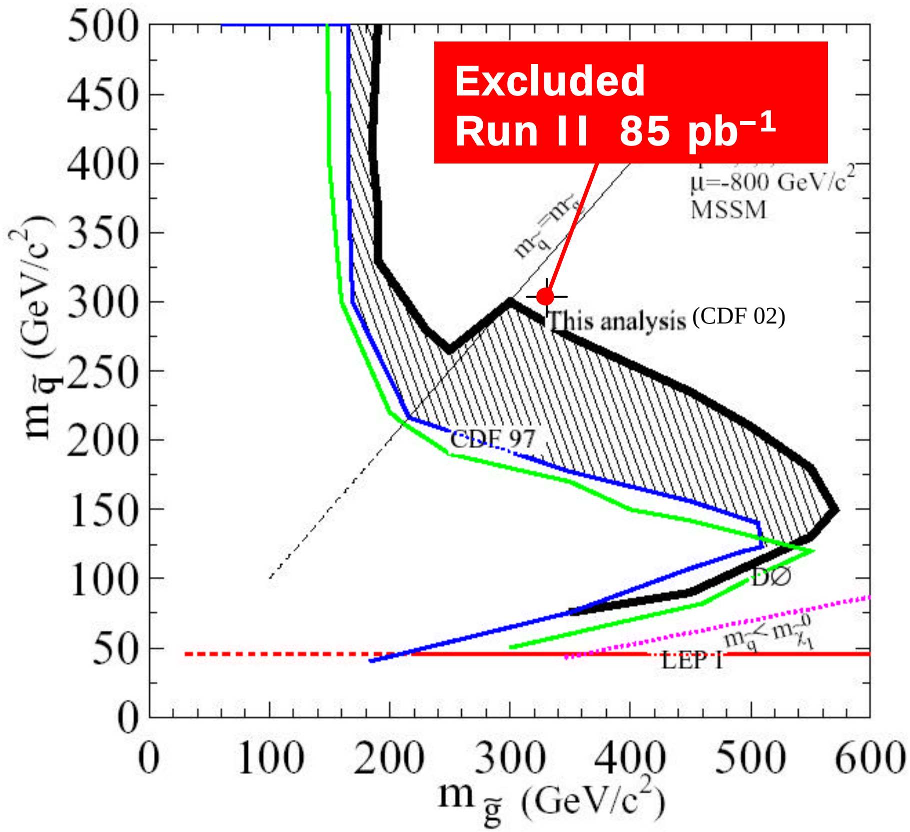
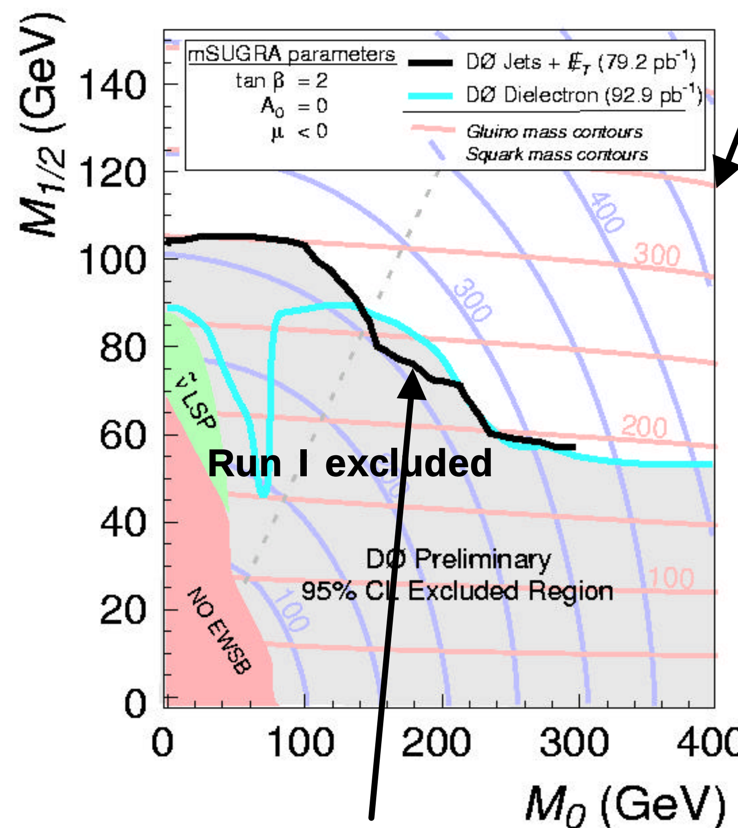
Squarks & Gluinos: Limits & Expectations



$\tilde{m}_g$ **> 333 GeV** for M_0 =25 GeV

Reach with 2 fb^{-1}:
gluino mass ~ 400 GeV



Run I reach
gluino ~ 200 GeV
squark ~ 250 GeV

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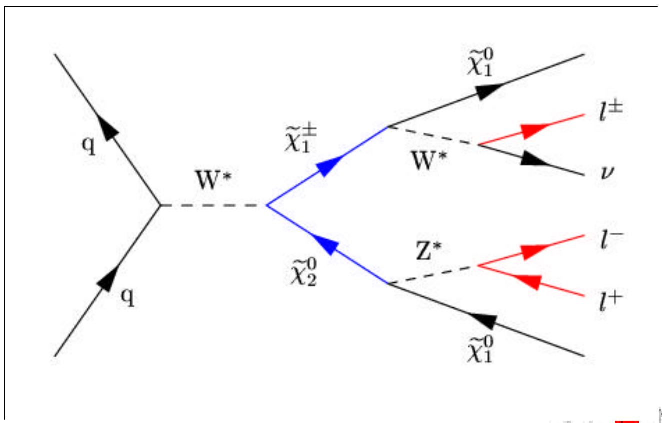
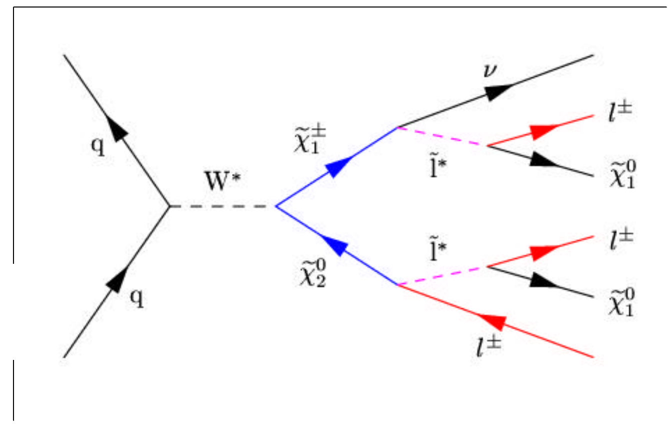
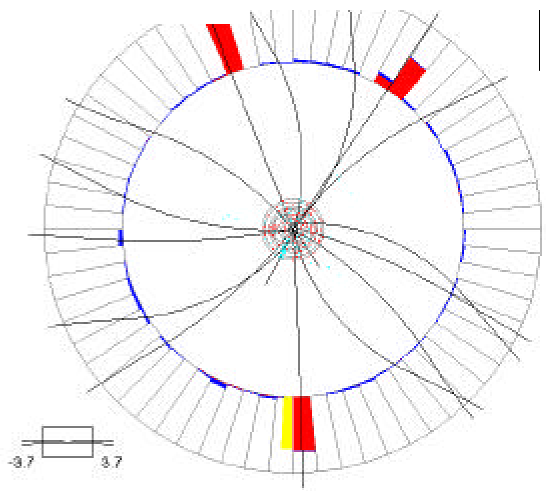
Charginos & Neutralinos: Tri-leptons

“Golden” channel with low backgrounds

Coupling strength, undetermined, denoted tanb







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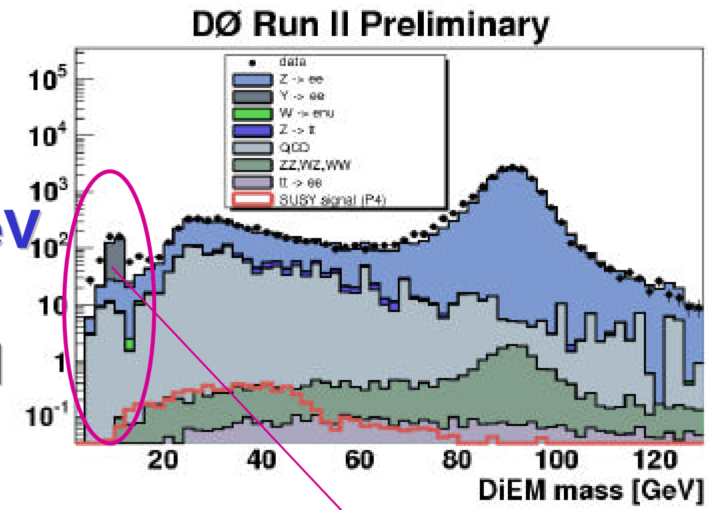
Experimental Challenge

- **Leptons are "soft" or have low momentum:**
  - at tanβ > 8 most of the leptons are τ's
  - e and μ from cascade decays are even softer
- **Many Backgrounds to soft leptons**
  - electrons - asymmetric photon conversions from pion in flight decays (remember problem 3?)
  - Muons - from b and c quark jets
  - Hadronic taus – QCD jets
- **Preparatory work and calibration:**
  - Study $\Upsilon \rightarrow ee, \mu\mu$ production
  - Study $Z \rightarrow \tau\tau$ production

Soft Leptons

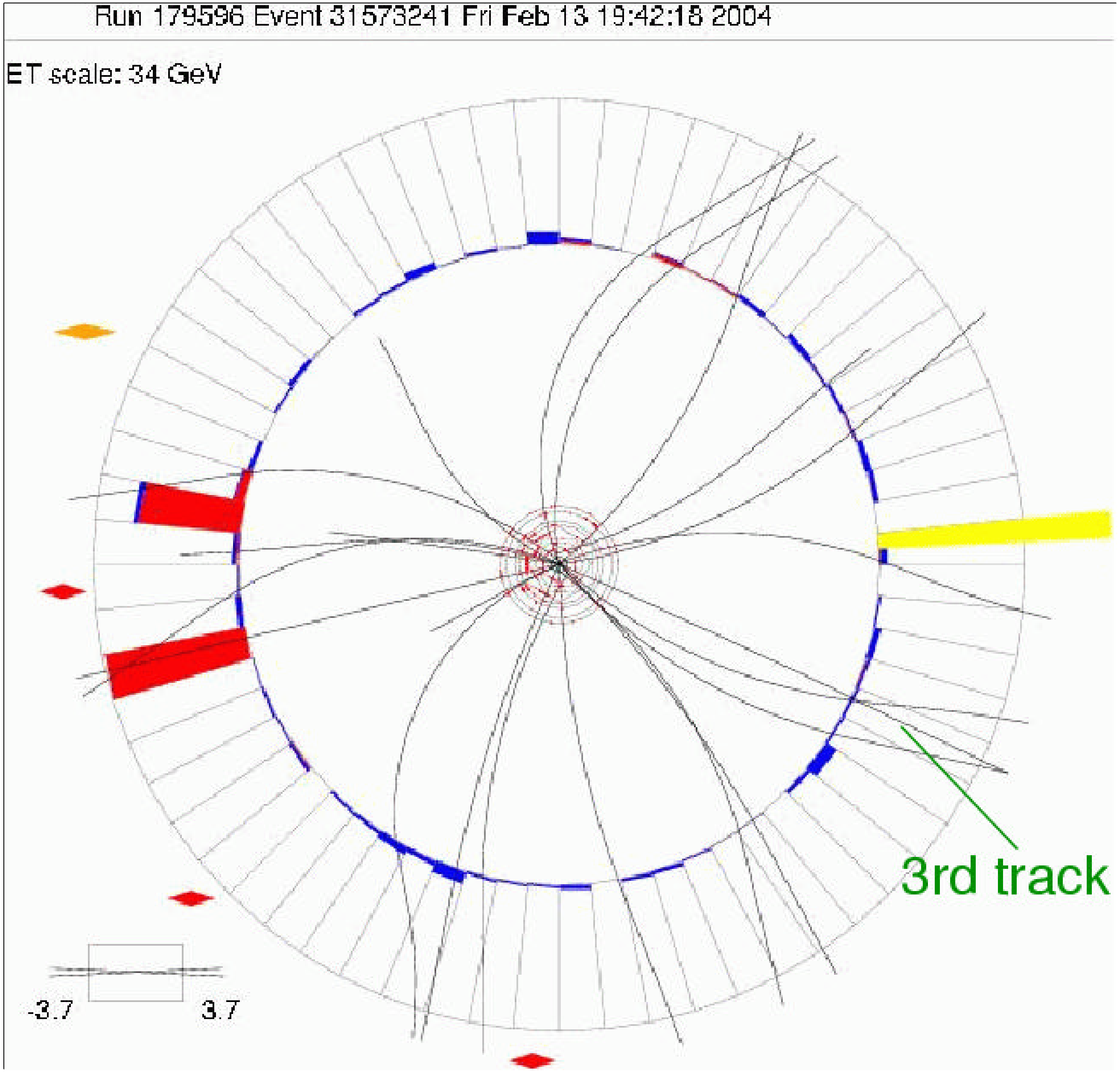
- Selecting soft electrons
  - Two electrons $p_T > 10$ GeV
  - At least one electron $p_T < 20$ GeV
- Good agreement with MC
- Implies mis-identification is small



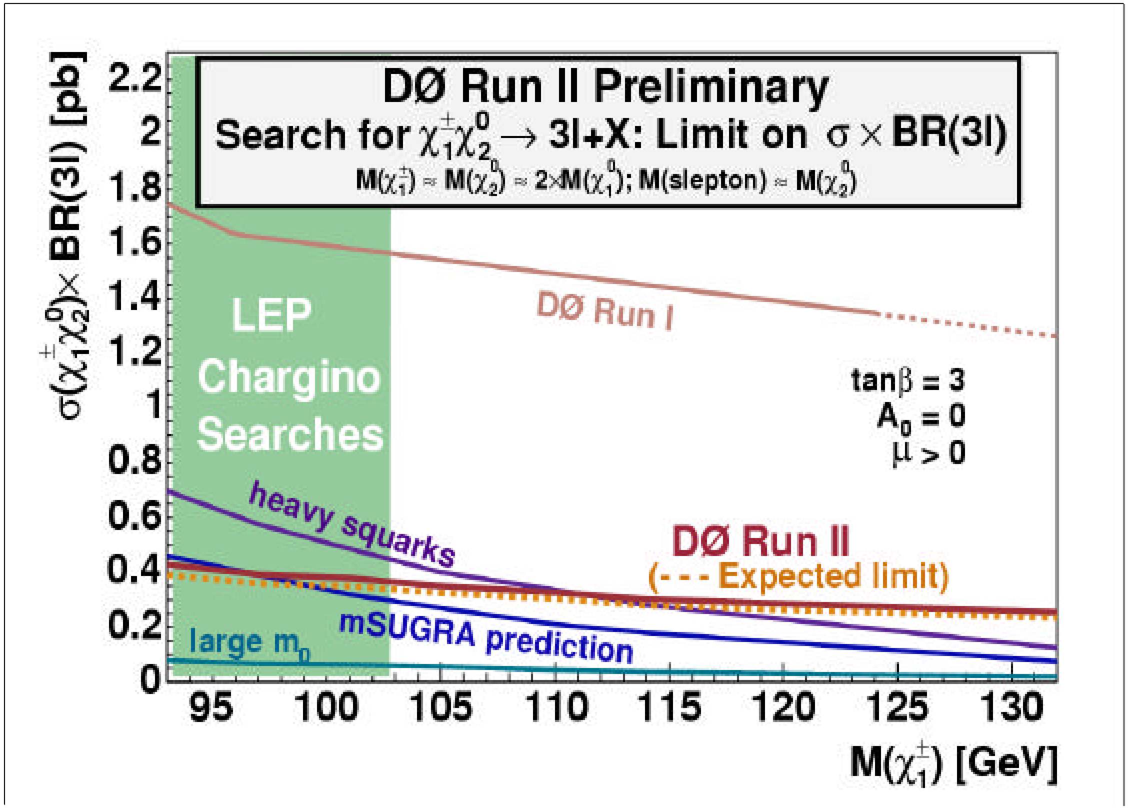
ϒ→ee

<u>A specific channel: e+e+l</u>

	"Cuts"	Backgrounds	Observed
1.	$p_T^{e1} > 8$ GeV, $p_T^{e2} > 12$ GeV	21540 ±520	23035
2.	15 < m(ee) < 60 GeV	2149 ± 60	2182
3.	Remove Jet, Drell-Yan	21 ± 7	33
4.	Track $p_T > 3$ GeV	2.5 ± 1.6	7
5.	Tr x missing E_T > 250 GeV	0.7 ± 0.5	1


Run 179596 Event 31573241 Fri Feb 13 19:42:18 2004
ET scale: 34 GeV
3rd track
-3.7
3.7

- **Adding four channels**
  - **e+e+l, e+m+l, m+m+l, two like-sign m+m**
  - **3 events observed and 3 expected.**
- **Can calculate cross sections and set limits**

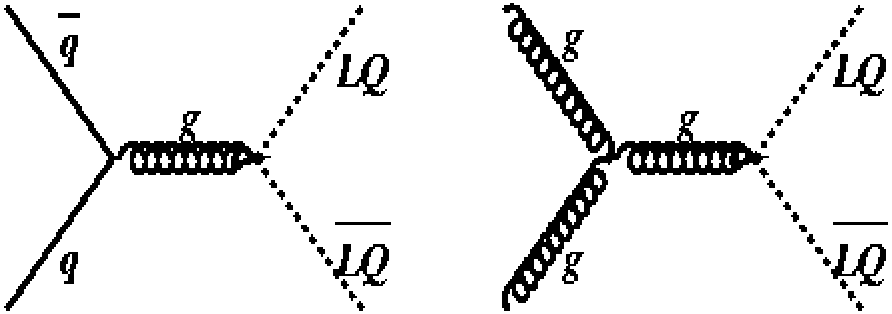


The Future: SUSY is an exciting topic experimentally and theoretically, It may well dominate particle physics in the coming decades!

Jerry Blazey
January 2005
Vietnam

One Example of Exotica: Leptoquarks

- **Lepton and quarks appear in three very similar generations**
- **Theories suggestion a symmetry between the leptons and quarks give rise to a particle that couples to both:**
  leptoquarks
- **Couples to strong and weak forces.**
- **Produced in pairs: scalar or vector**
- **Three generations: LQ1, LQ2, LQ3**
  - **Each one decays to same generation of quarks and leptons**
  - **Prevents flavor changing neutral currents such as e → m and u → c.**



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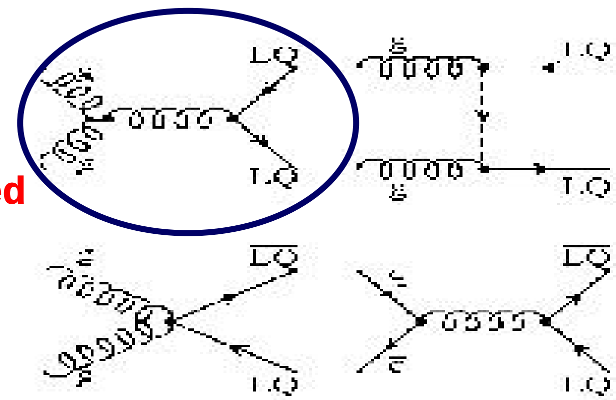
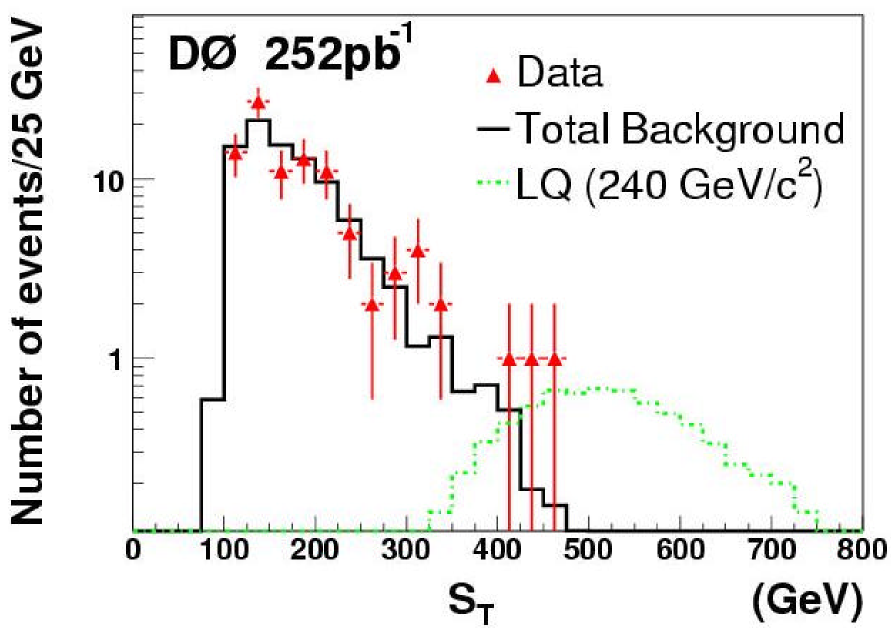
1st Generation Leptoquarks

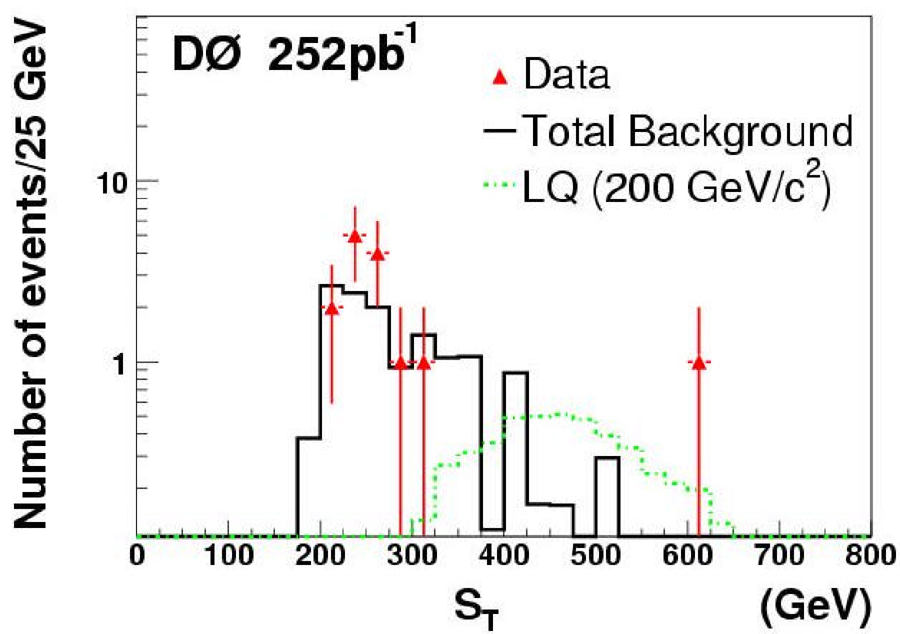
- LQ1LQ1 → e^+e^-qq
  - 2 high Et electrons
  - 2 jets
  - Sum of Et > 450 GeV
- Background, 1.1 expected
  - Z/DY
  - Multijet
  - top antitop
- One Event Observed

Dominant

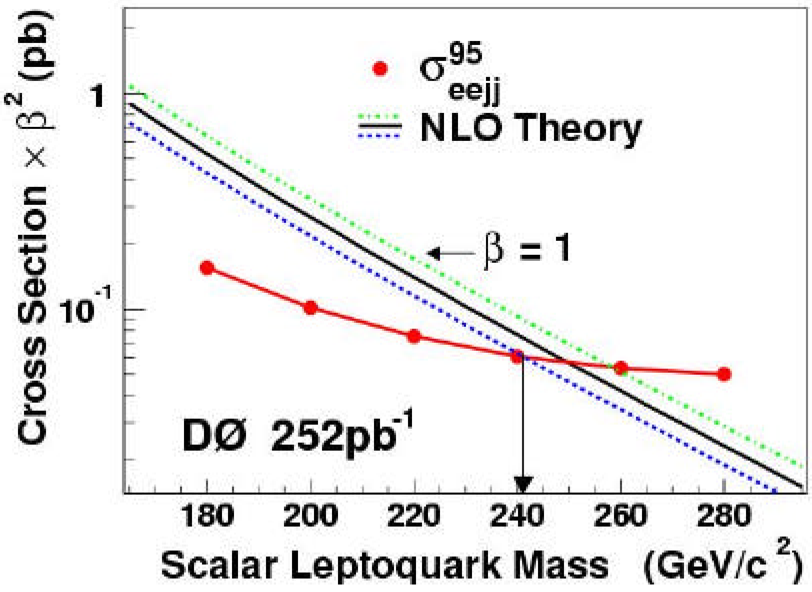


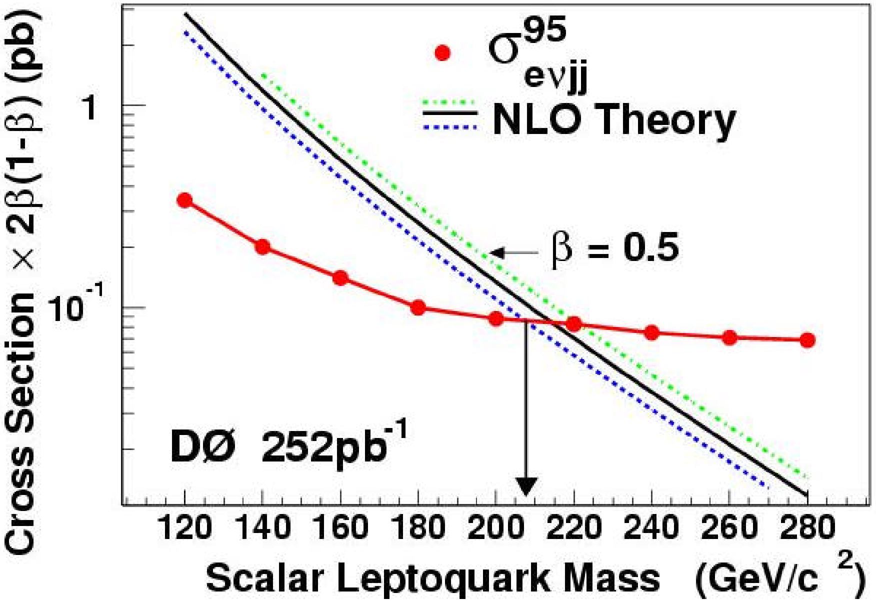
- LQ1LQ1→ e?qq
  - 1 high Et electron
  - 2 high Et jets
  - Sum of Et > 330 GeV
- Background, 3.6 expected:
  - W + jet
  - Multijet
  - top antitop
- One Event Observed

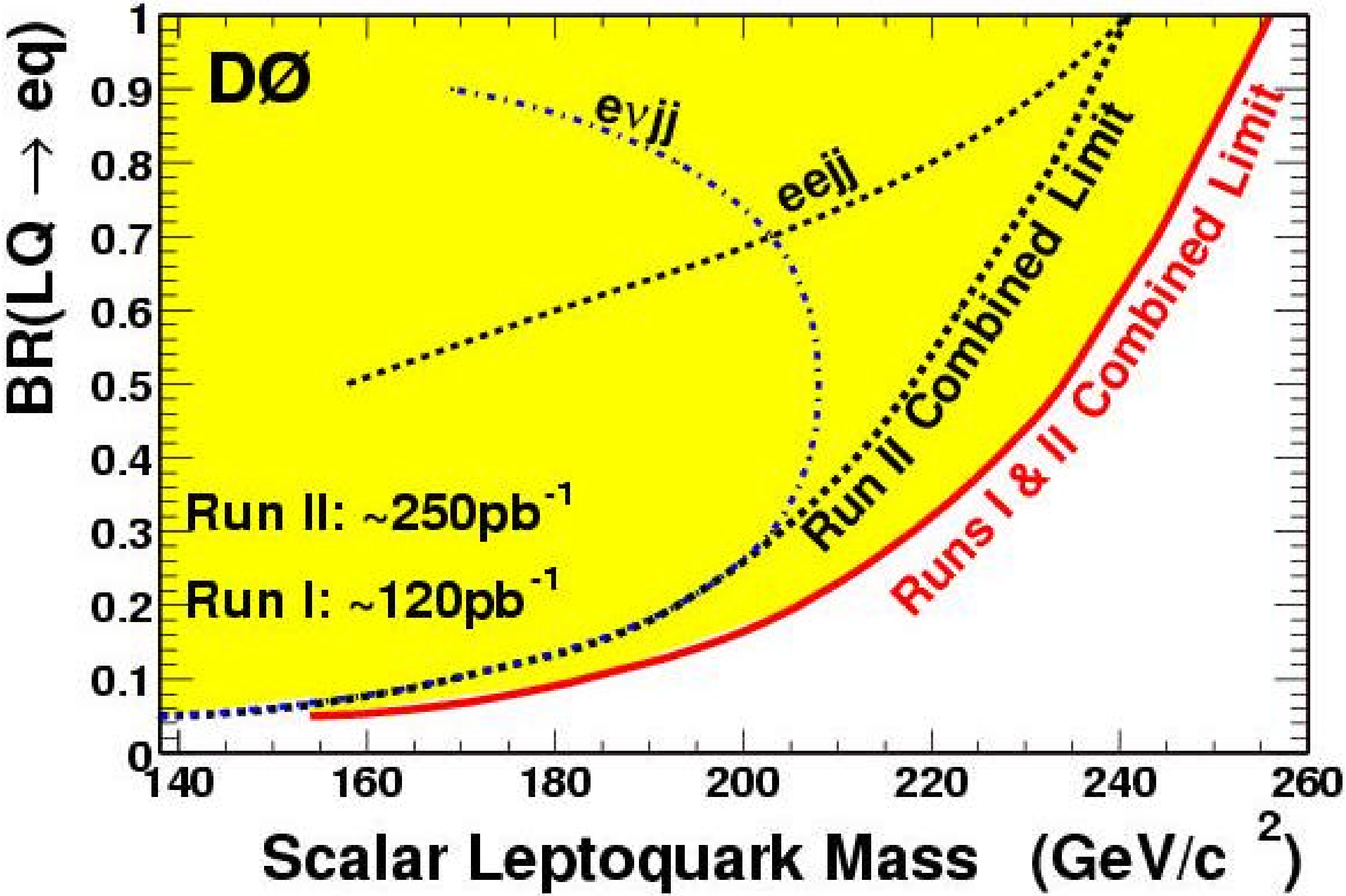




Setting Leptoquark Limits







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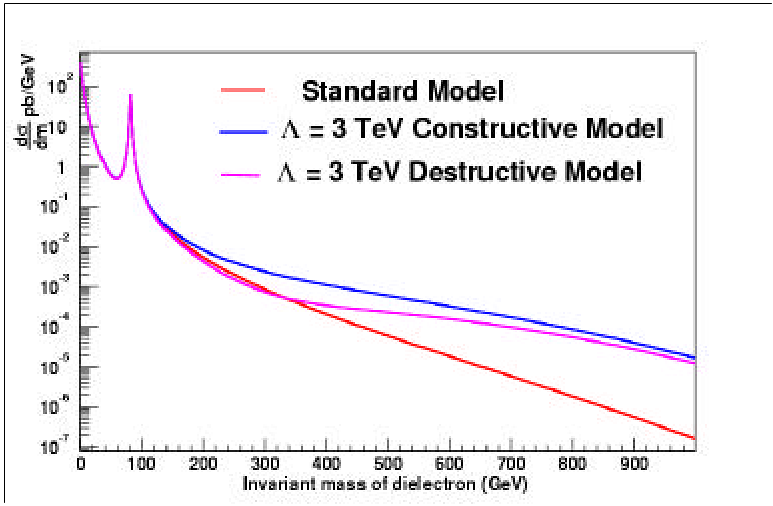
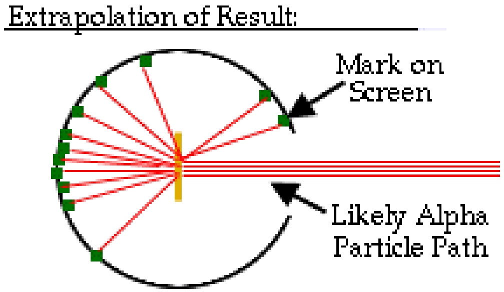
A Second Example: Quark Compositeness

- An excess of very high mass dielectron pairs (which are preferentially produced at 90 degrees relative to the proton-antiproton beams) would signal scattering between sub-constituents of the quarks.



- This is completely analogous to Rutherford scattering (Lecture 2).
- Look for two electrons with pT > 25 GeV
- Calculate efficiency for high mass pair detection, ~55%.
- Estimate background, dominated by jets faking electrons.



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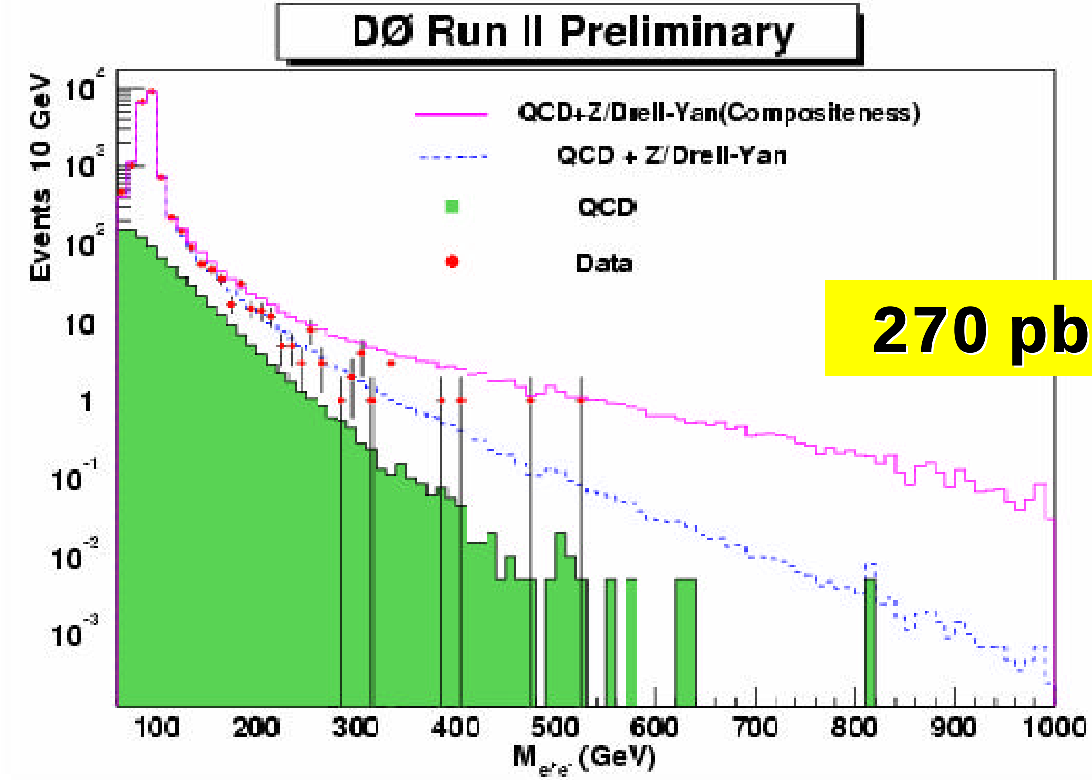
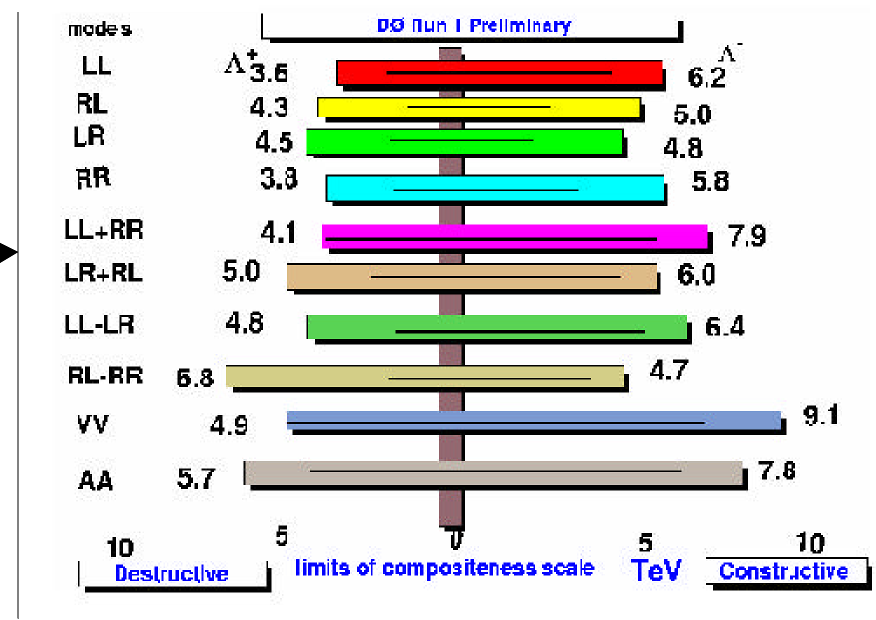


270 pb^{-1}

Mass scale Eliminated



Coupling of constituents

The Future

- Until the end of the decade the Tevatron proton-antiproton collider offers a real opportunity to discover new physics.
- The Large Hadron Collider with a 2007 start, will almost certainly discover the Higgs and/or new phenomena.

2007: The next "discovery machine"
pp collisions @ 14 TeV!

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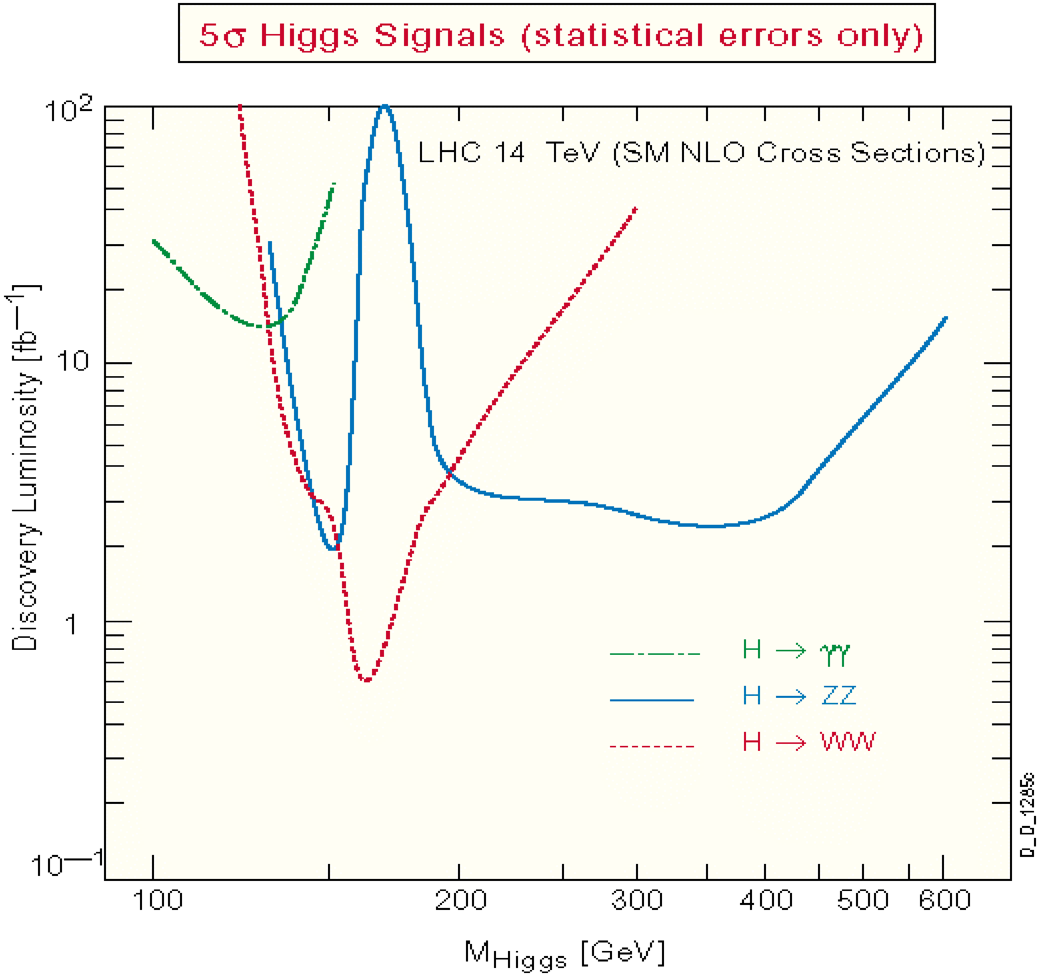

1 year ~ 10 fb^{-1}

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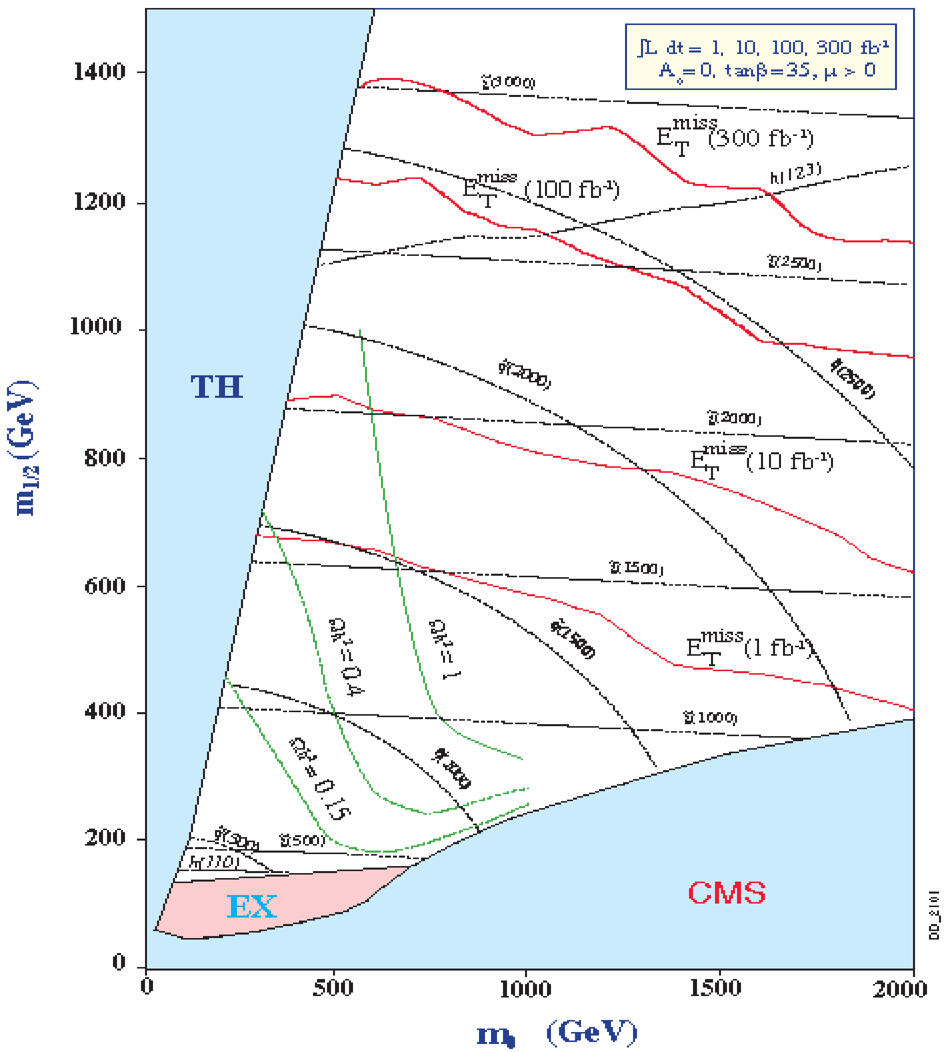
The CMS $\tilde{q},\tilde{g}$ mass reach in E_T^{miss} + jets inclusive channel for various integrated luminosities



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In Conclusion

- ✓ We've explored particle from one hadron collider experimentalists (biased) view.
- ✓ Most notable omissions would be a quantitative description of kinematics, the Standard Model, and Standard Model extensions; and heavy flavor physics.
- ✓ Lectures by P. Darriulat are an excellent companion!
- ✓ Two good links to start broader reading:
  - The Particle Adventure: http://particleadventure.org/particleadventure/
  - The Particle Data Group: http://pdg.lbl.gov/
- ✓ Thank You & Happy New Year!