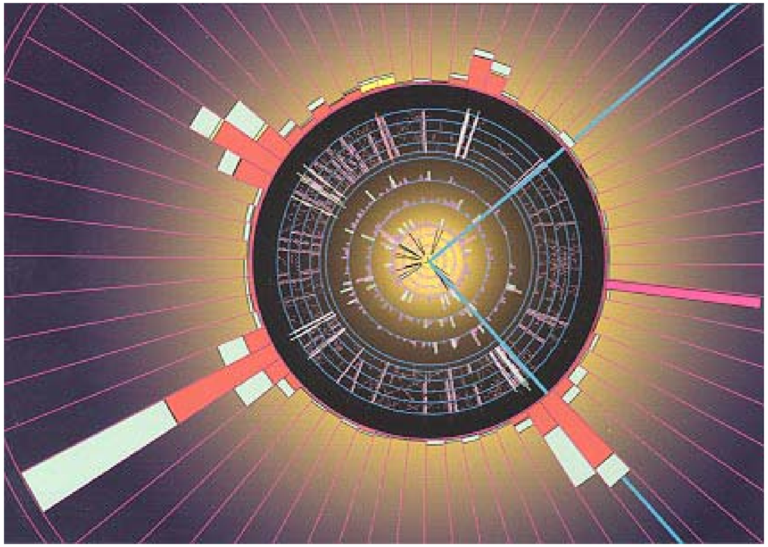
Physics at Hadron Colliders
Selected Topics: Lecture 4



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Hue, Vietnam

http://d0server1.fnal.gov/users/klima/Vietnam/Hue/Lecture_4.pdf

Mass shapes the Universe

…through gravitation, the only force that is important over astronomical distances

- **Despite the successes of general relativity, we still do not understand <u>gravity</u> in a quantum framework**
- **but we believe we are getting closer to understanding the origin of <u>mass</u>**

Mass in the cosmos

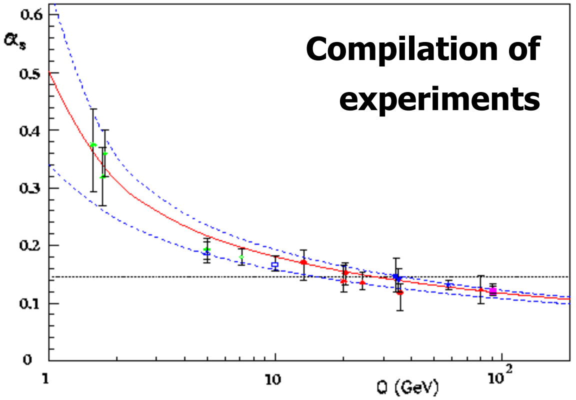
- **Masses of Atoms**
  - are made up from
    - rest masses of the fermions
    - plus binding energies

- **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
    $\rightarrow$ all this mass cannot be "baryonic" (protons and neutrons)
    - new particles?

Mass of Hadrons

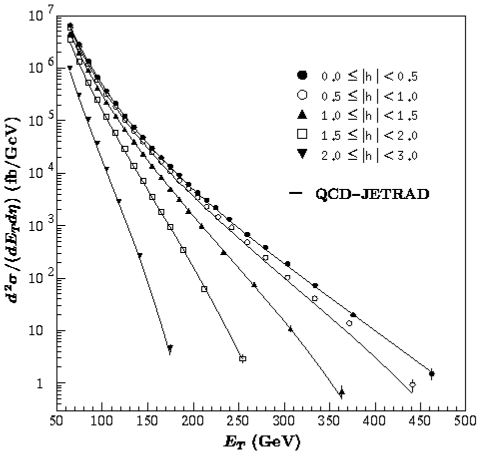
- Mass of a proton = 938 MeV
  Mass of two u quarks plus a d quark = 10 ± 5 MeV
  - 99% of the mass of a proton (and therefore of the mass of a hydrogen atom) is due to the binding energy

- 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

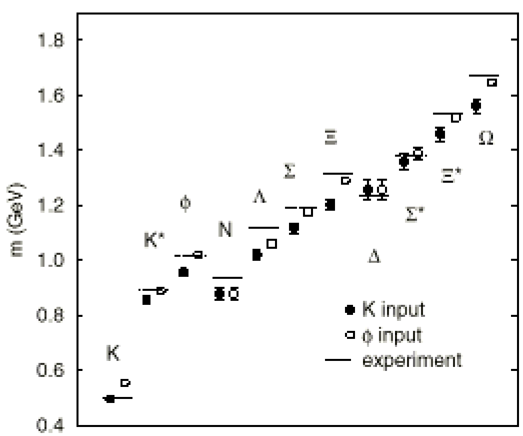


Understanding QCD

- **As we have seen, precisely testable QCD calculations are available for high momentum transfer processes at particle accelerators**
  - **e.g. production of jets of high momentum hadrons through quark-antiquark scattering in $\bar{p}p$ collisions**



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



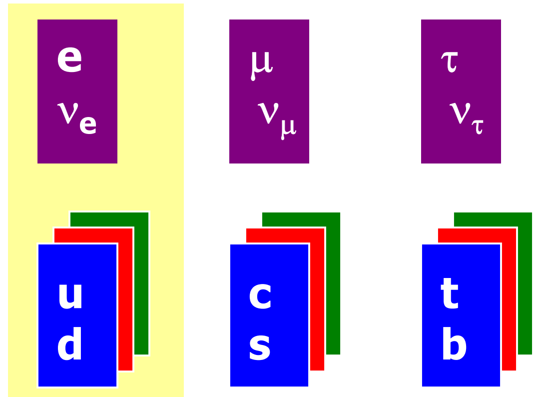
Does this mean we understand mass?

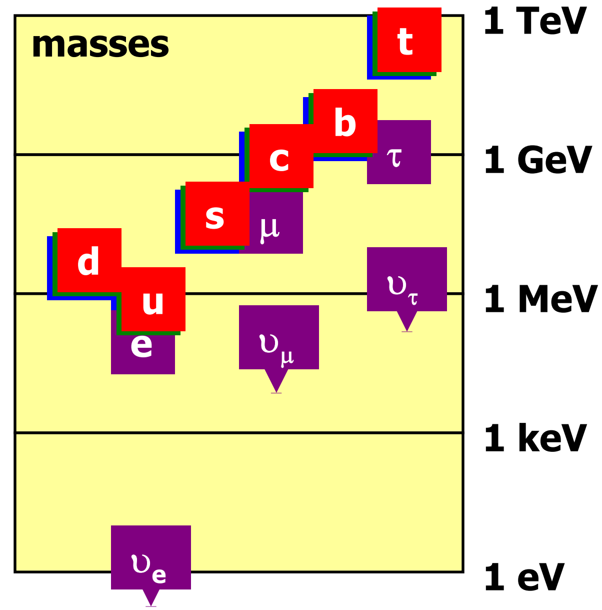
- There is not much doubt that QCD is the theory of the strong interaction, and we are making progress in understanding how to calculate reliably in this framework
  - and recall that 99% of the mass of the (visible) universe is QCD

- 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
    - mass of the W and Z bosons is what makes the weak force weak

Fundamental particles and forces

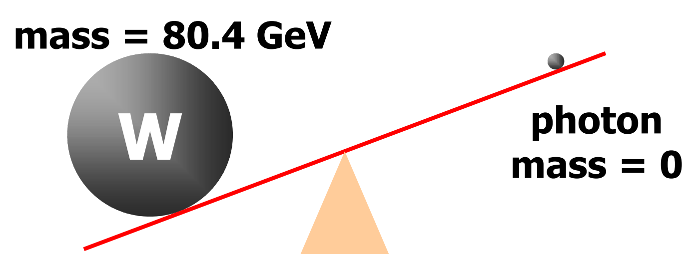
- leptons q = 1
  q = 0
- quarks q = $^{2}/_{3}$
  q = $-^{1}/_{3}$





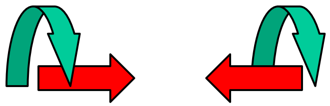
<u>**Forces**</u>

- QCD
- Electroweak force
  - interaction between quarks and leptons, mediated by photons (electromagnetism) and W and Z bosons (weak force)
    - same couplings to matter (except angles)
    - very different masses



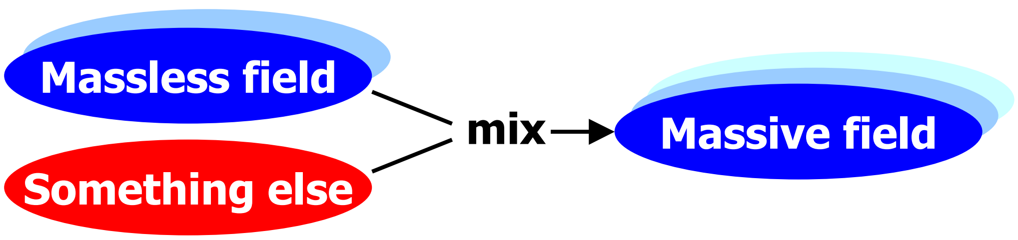
What does mass mean?

- For an elementary pointlike particle
  - propagates through the vacuum at $v < c$
  - Lorentz transform mixes LH and RH helicity states: symmetry is broken



    - mass is equivalent to an <u>interaction</u> with the (Quantum Mechanical) vacuum
    - coupling strength = mass

- For a spin-1 state like a photon, there is an extra effect
  - massless → two polarization states
  - massive → three polarization states
    - where does this additional degree of freedom come from?



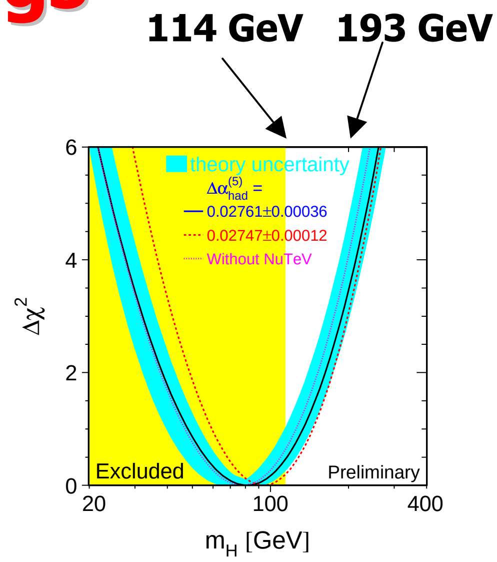
The Higgs Mechanism

- **Hence, in the Standard Model**
  (Glashow, Weinberg, Salam, 't Hooft, Veltmann)
  - **"electroweak symmetry breaking" through introduction of a scalar field $\phi \rightarrow$ masses of W and Z**
  - **Higgs field permeates space with a finite vacuum expectation value**
    - **cosmological implications! (inflation)**
  - **If ϕ also couples to fermions $\rightarrow$ 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 own mass**

Highest priority of worldwide high energy physics program: find it!

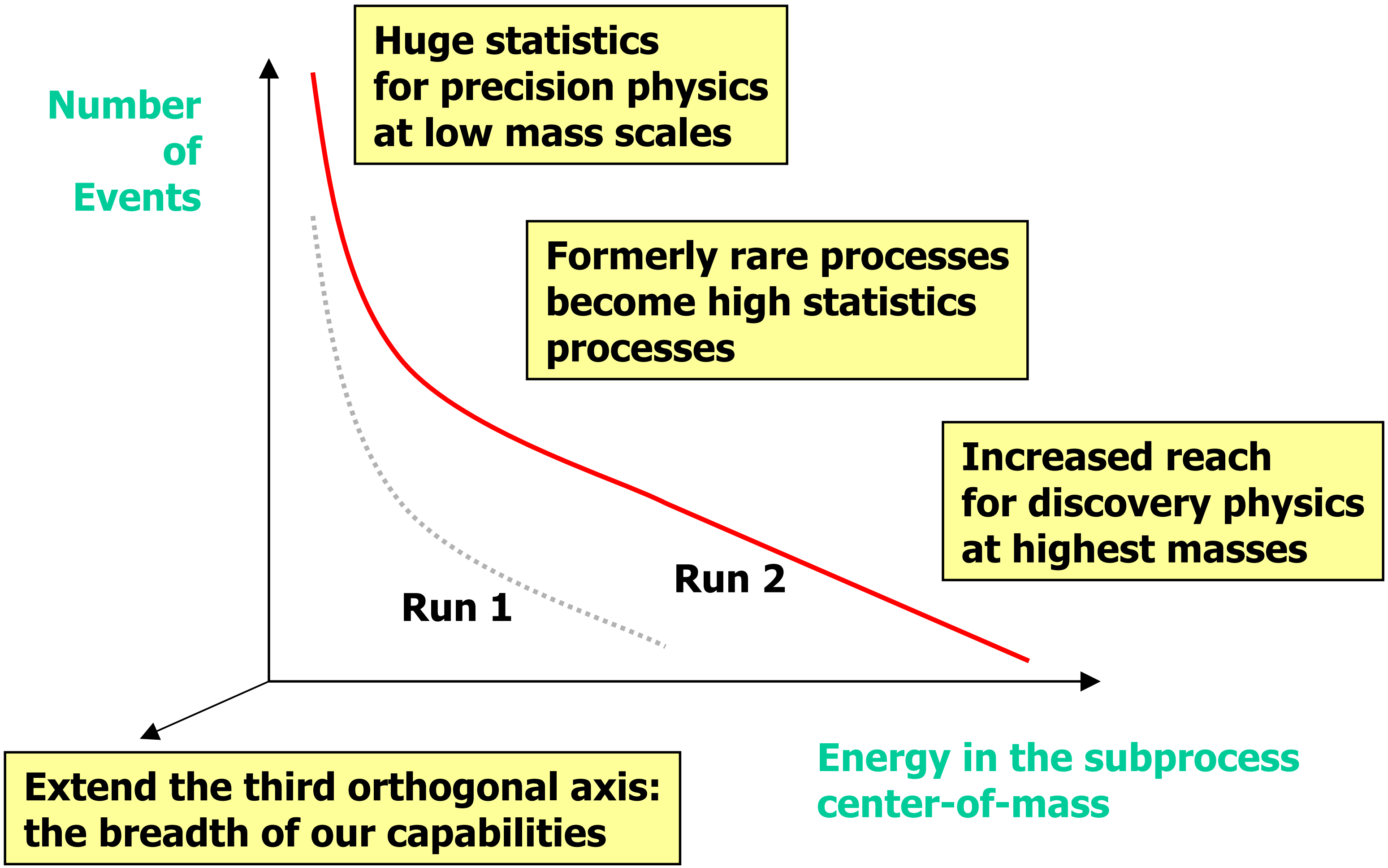
Searching for the Higgs



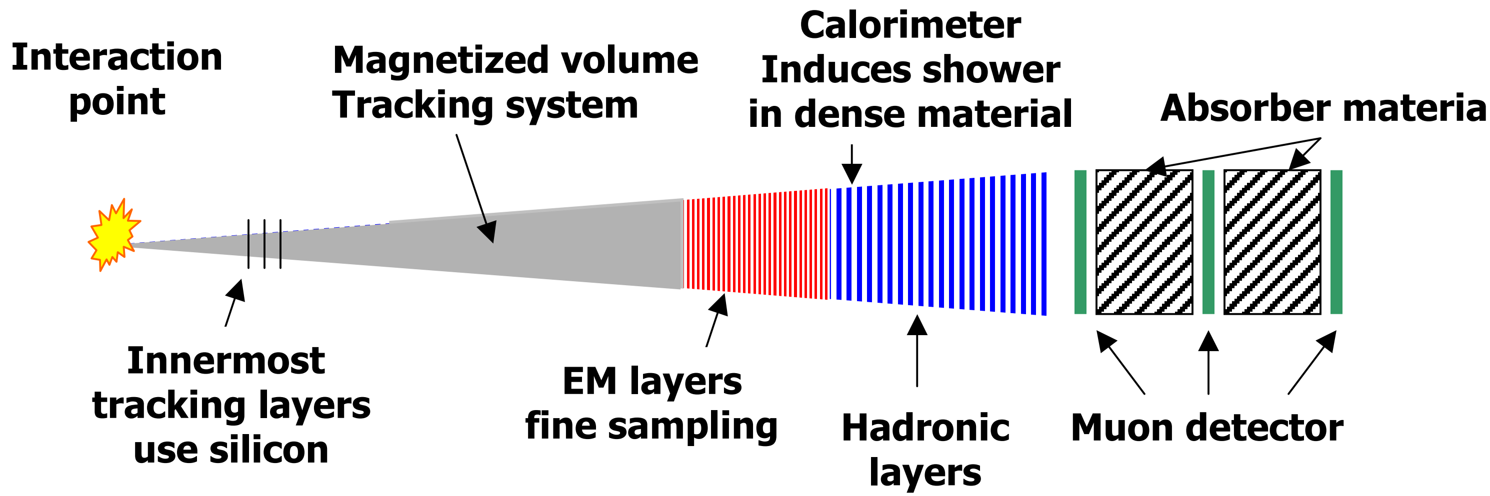
- **Over the last decade, the focus has been on experiments at the LEP e^+e^- collider at CERN (European Laboratory for Particle Physics)**
  - **precision measurements of parameters of the W and Z bosons, combined with Fermilab's top quark mass measurements, set an upper limit of m_H of 193 GeV**
  - **direct searches for Higgs production exclude m_H < 114.4 GeV**
- **Summer and Autumn 2000: Hints of a Higgs**
  - **the LEP data may be giving some indication of a Higgs with mass 115 GeV (right at the limit of sensitivity)**
  - **despite these hints, CERN management decided to shut off LEP operations in order to start construction on a future machine (the Large Hadron Collider or LHC)**
- **All eyes on Fermilab:**
  - **until about 2008, we have the playing field to ourselves**

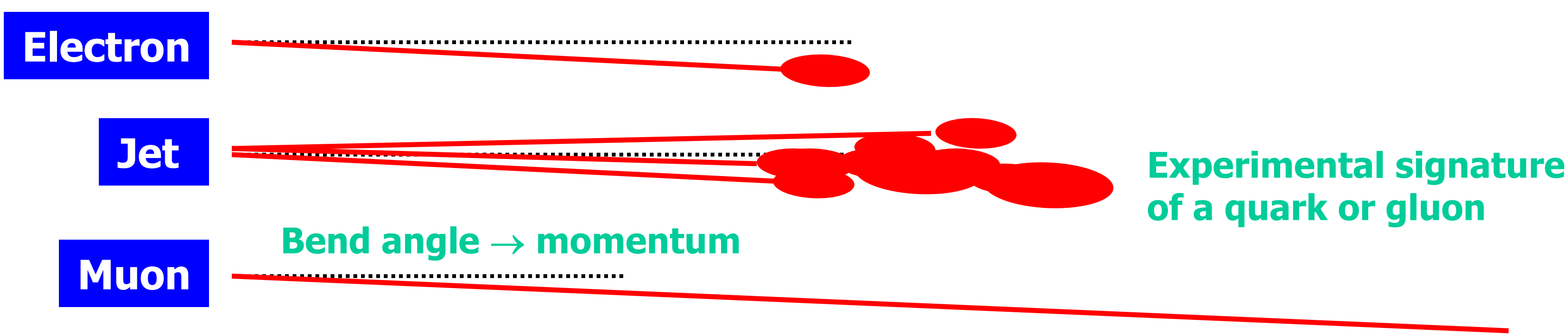
Run 1 → Run 2

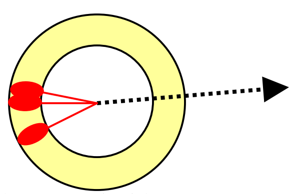
- The Tevatron is a broad-band quark and gluon collider



Typical detector

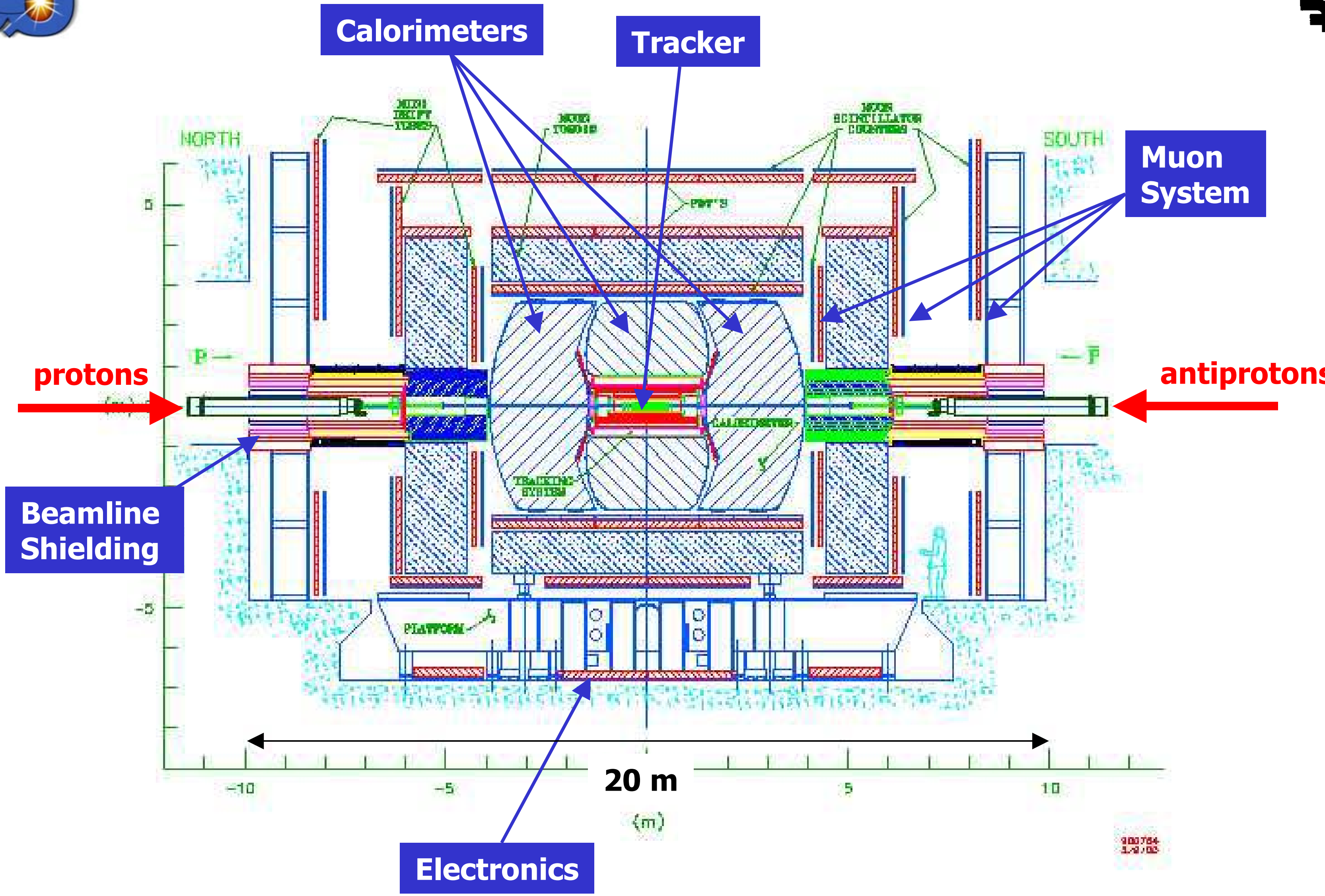






"Missing transverse energy"

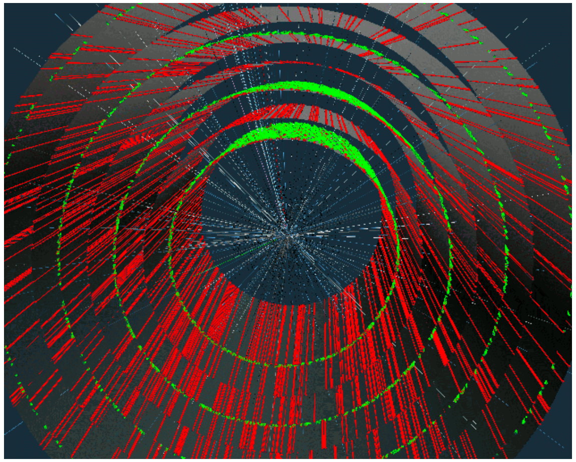
Signature of a non-interacting (or weakly interacting) particle like a neutrino



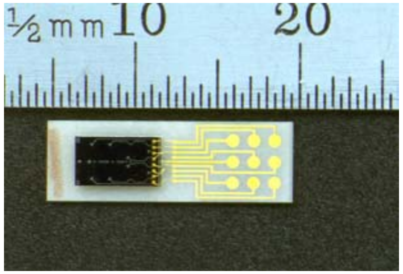
Calorimeters
Tracker
Muon System
NORTH
SOUTH
protons
antiprotons
Beamline Shielding
Electronics
20 m
5
-5
-10
-5
5
10
(m)

Scintillating Fiber Tracker

Tracker geometry and simulation of particle tracks



Ribbon manufacture



VLPC chip (photon detector)

Cylinder nesting

Fiber Tracker Installation

Muon Detectors

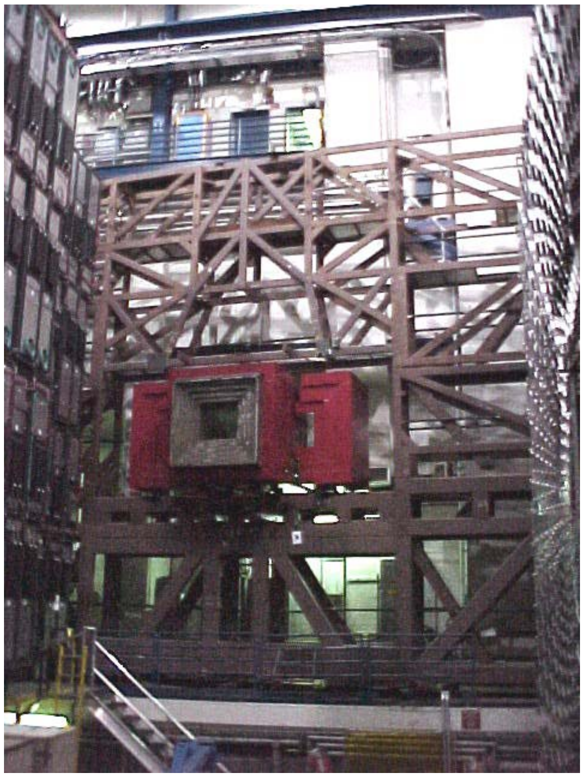
Forward muon truss (supports C layer detectors and shielding)

Forward mini drift tube detectors (from JINR, Dubna, Russia)

Forward muon trigger scintillators (From Protvino, Russia)

Muon Detector Installation

Shielding mounted on support truss

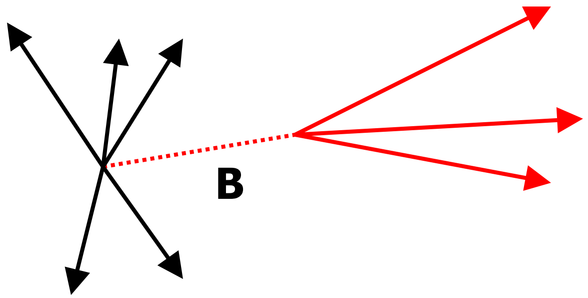


Trigger scintillator Plane complete (10m × 10m)

Mini drift tube plane complete (10m × 10m)

Displaced vertex tagging

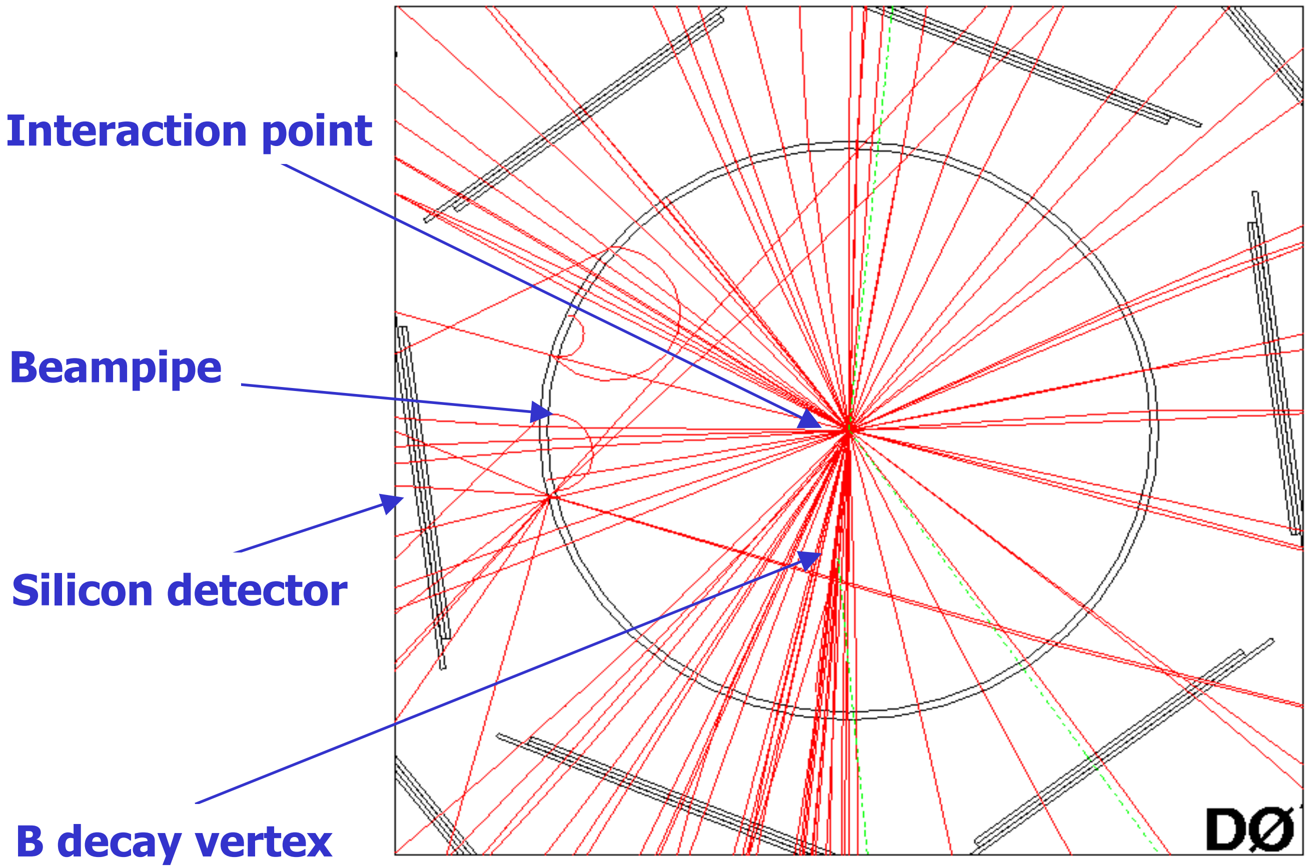
- The ability to identify b-quarks is very important in Higgs searches (also top, supersymmetry)
- b quark forms a B-meson, travels ~ 1mm before decaying



- to reconstruct this decay, need to measure tracks with a precision at the 10μm level

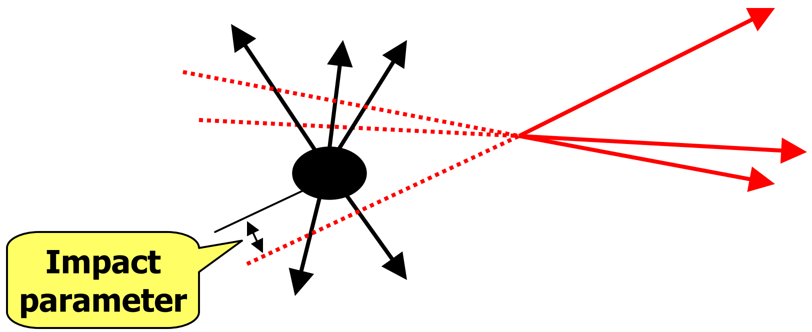
Displaced vertex tagging

The ability to identify b quark jets is very important in Higgs searches

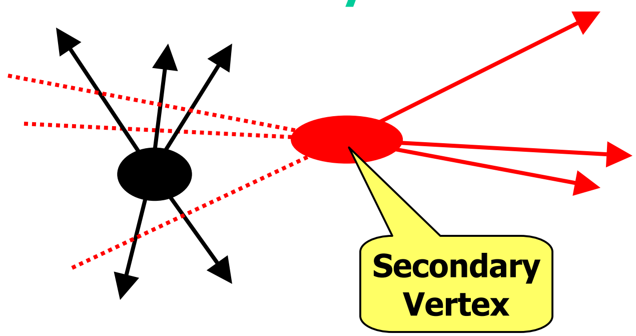


B-tagging

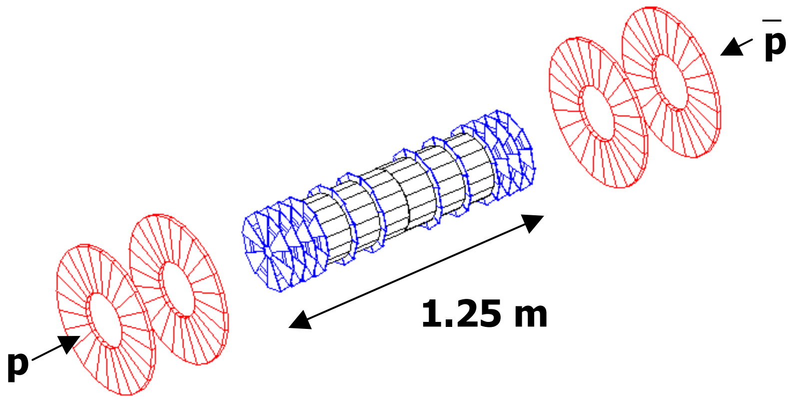
- **Typical algorithms**
  - **require 2 or 3 tracks with significant impact parameter (distance of closest approach to the fitted primary vertex)**

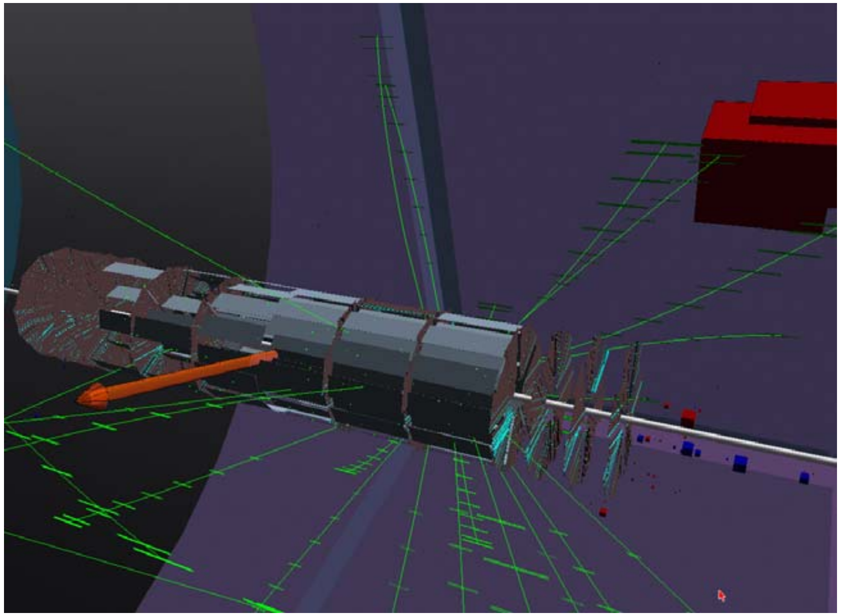


  - **reconstruct a secondary vertex**

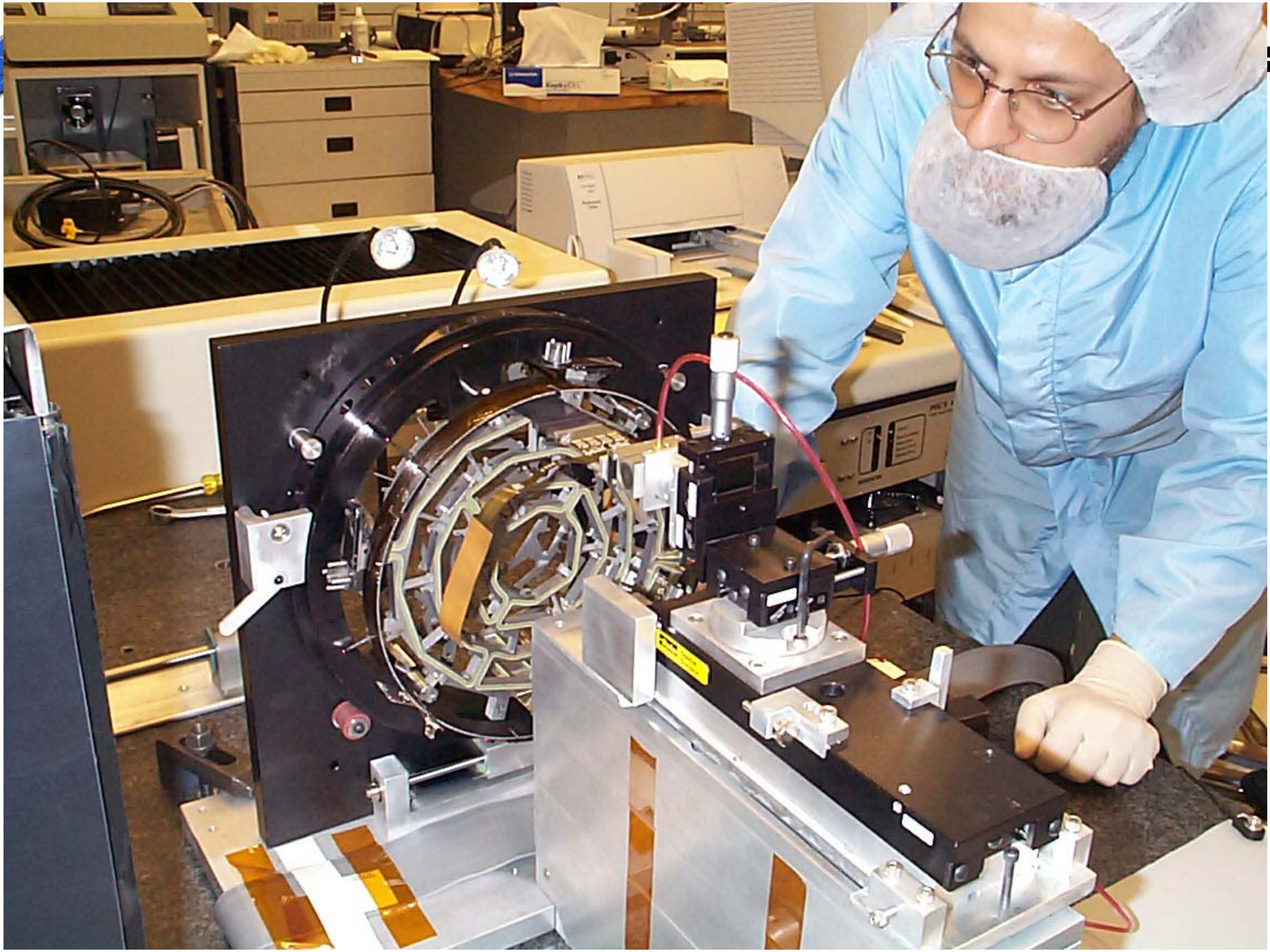


DØ Silicon Detector



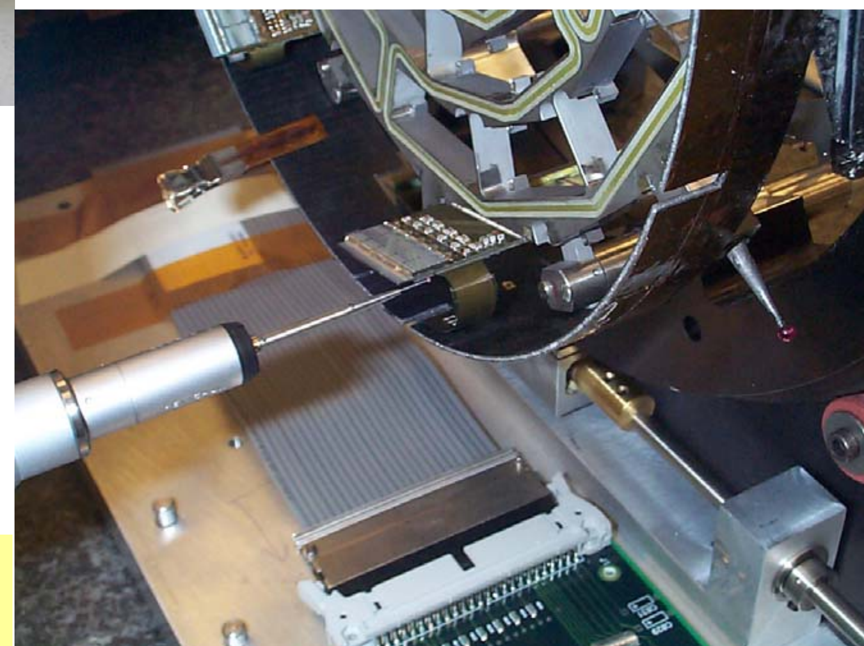


- The silicon detector is the closest detector element to the collision point; ~800,000 channels of electronics
- tagging efficiency at p_T = 50 GeV/c
  - ~ 50% for b-quark jets, ~ 10 % for c-quark jets
  - ~ 0.5% fake tag rate for u,d,s quark jets
  - efficiency rises as a function of p_T

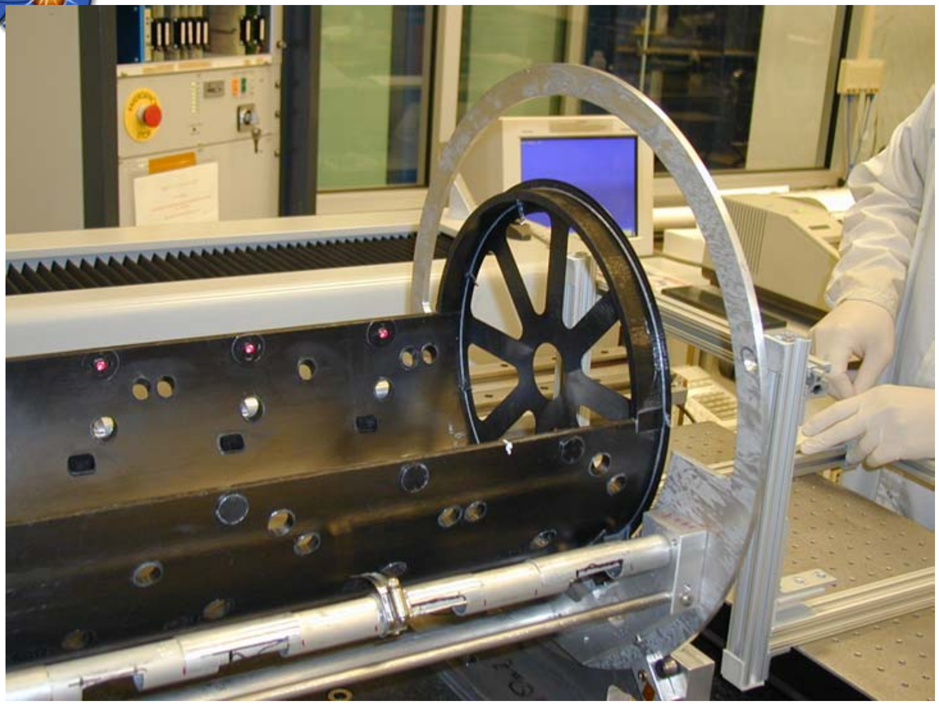


Ladder insertion

Zeiss coordinate measuring machine at Fermilab's Silicon Detector Facility

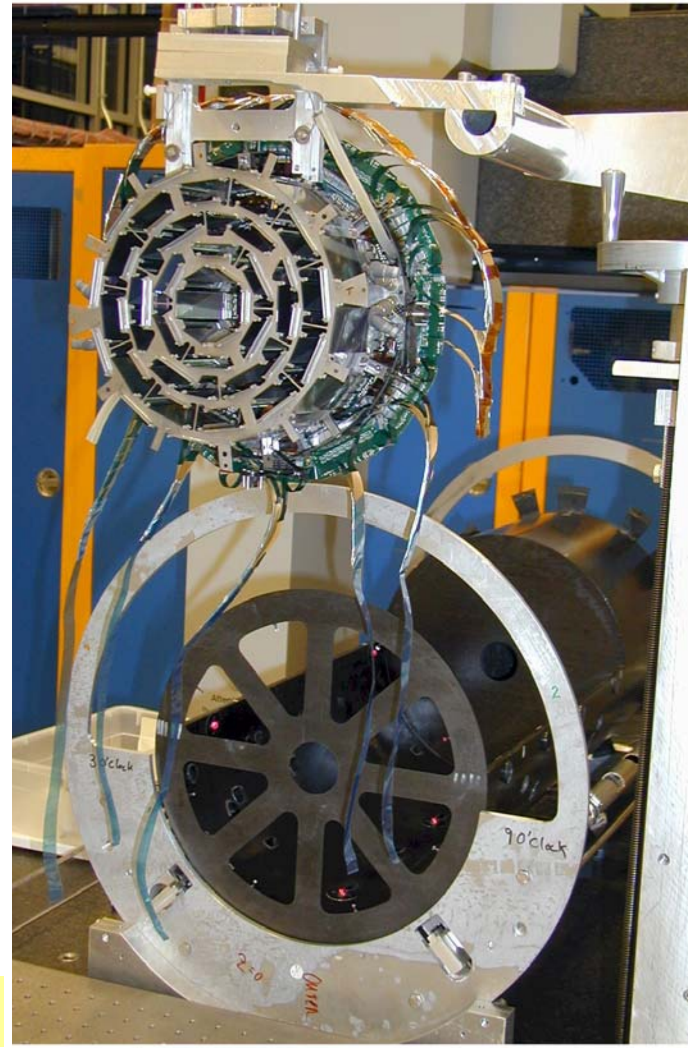


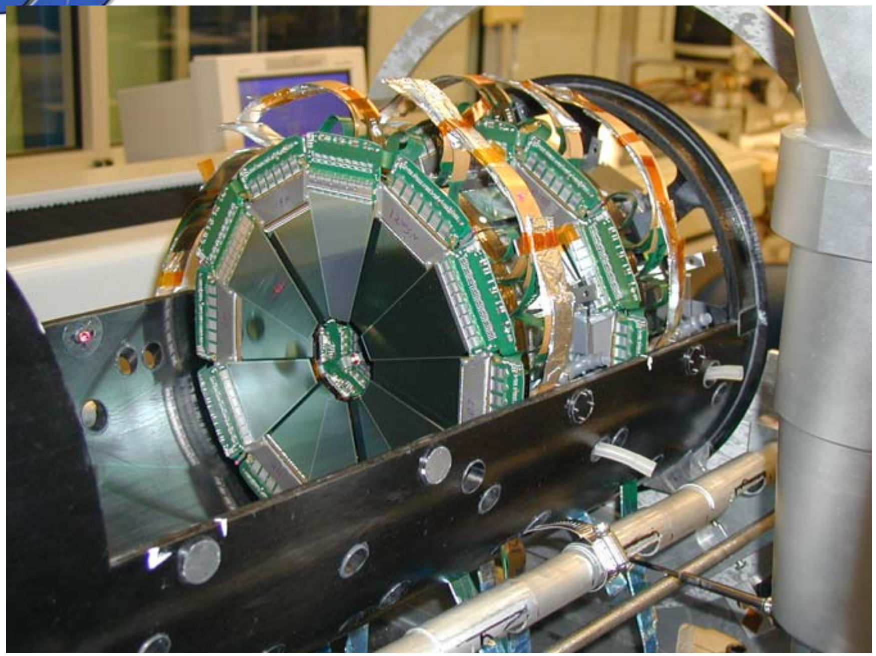
Measuring ladder position after insertion



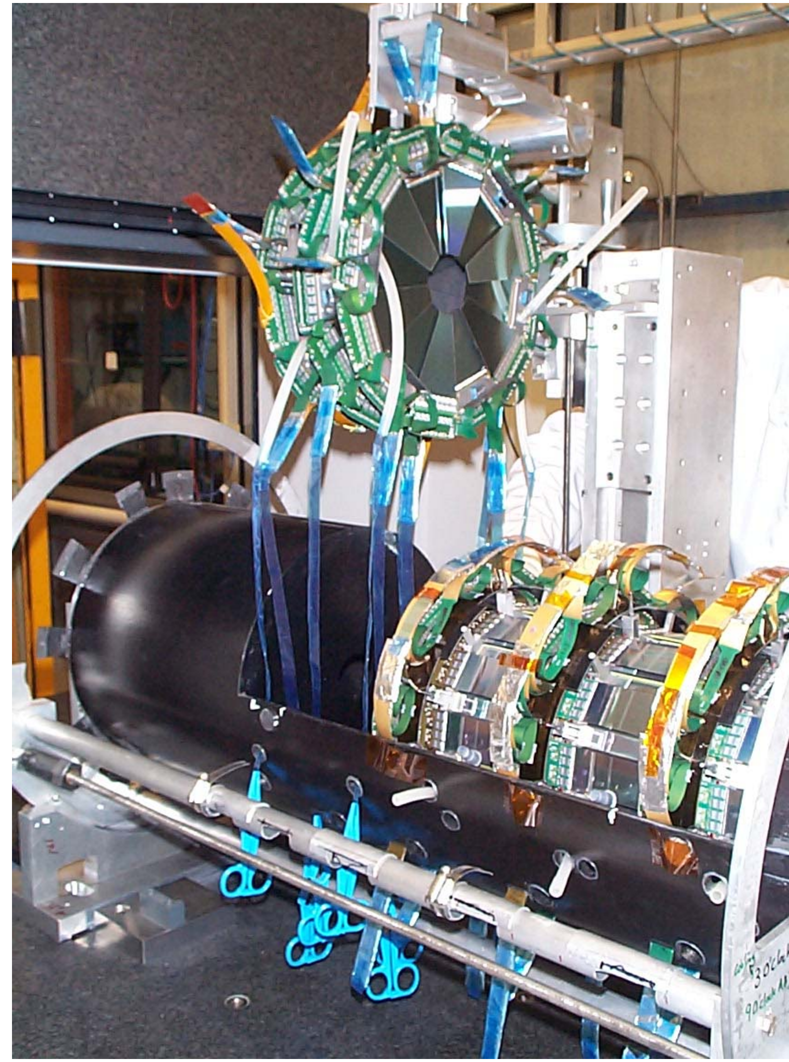
Empty carbon fiber support cylinder

Insert first barrel/disk





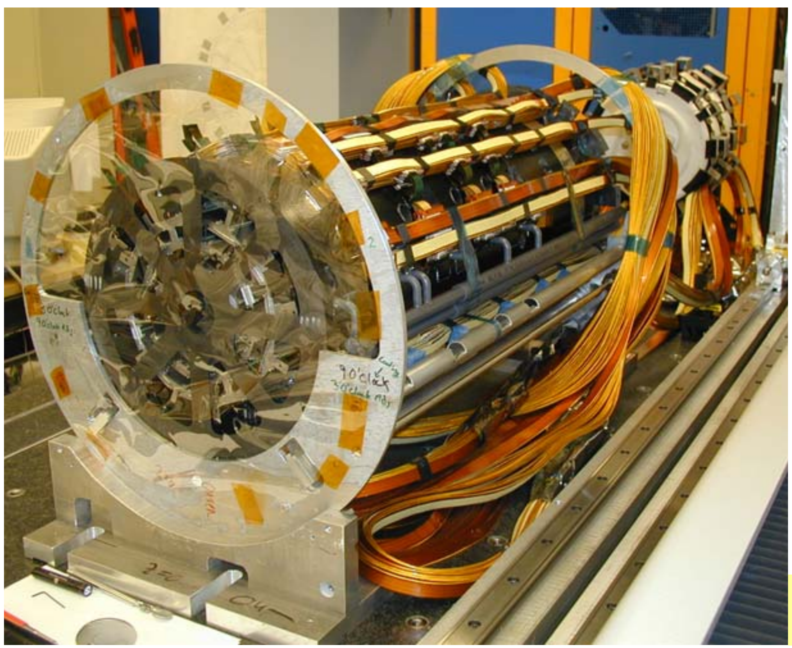
Two barrel/disk assemblies in place



Insert forward disks

All barrels & disks installed

Putting cover on

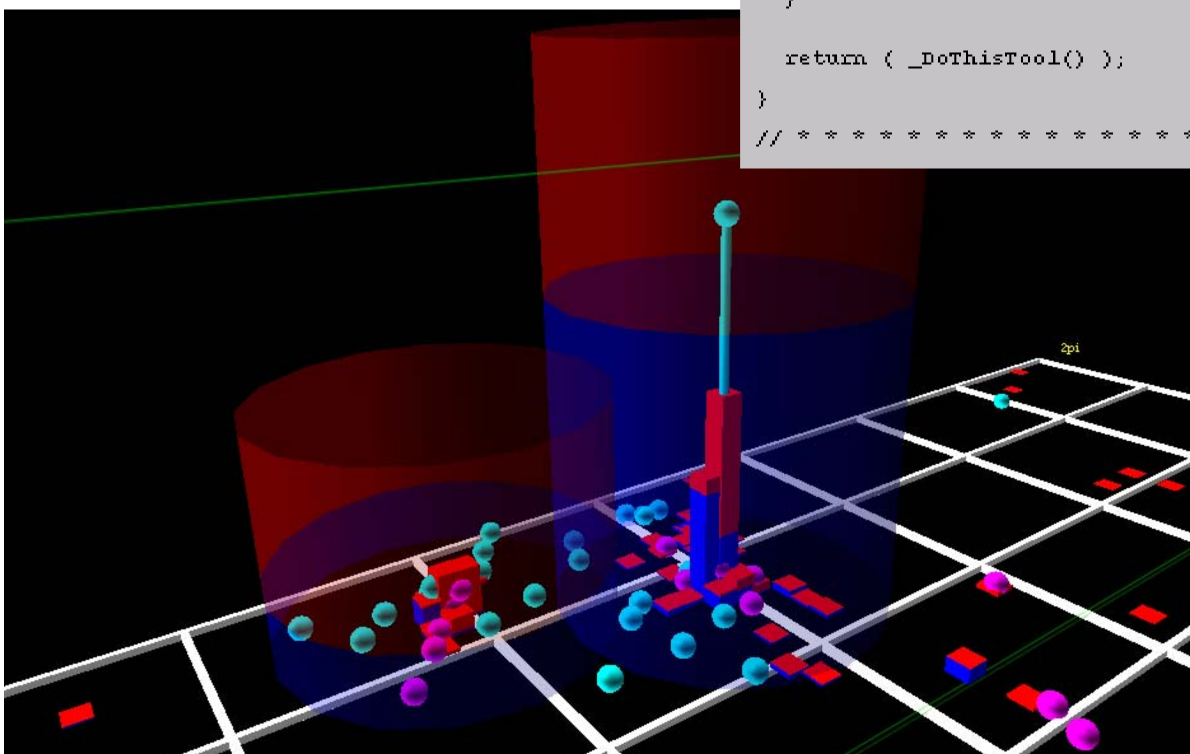


Cabled up and ready for DØ

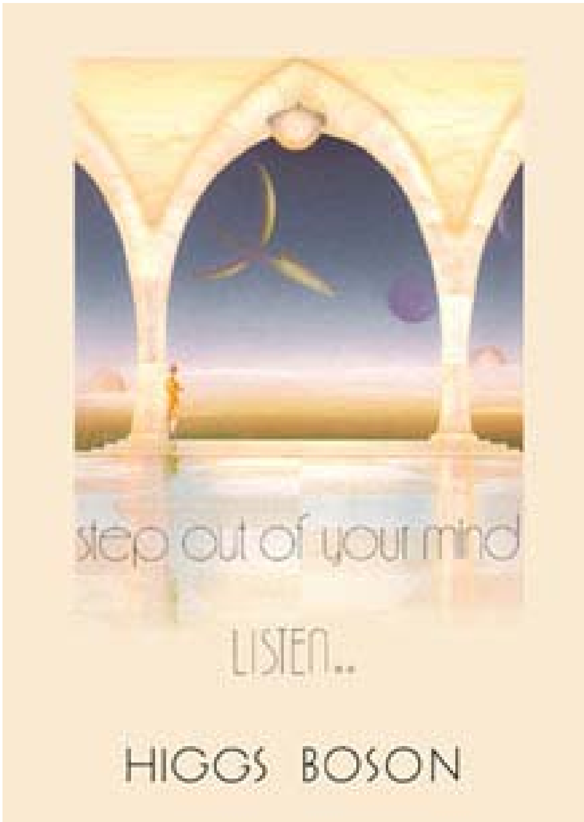
New tools: all new software

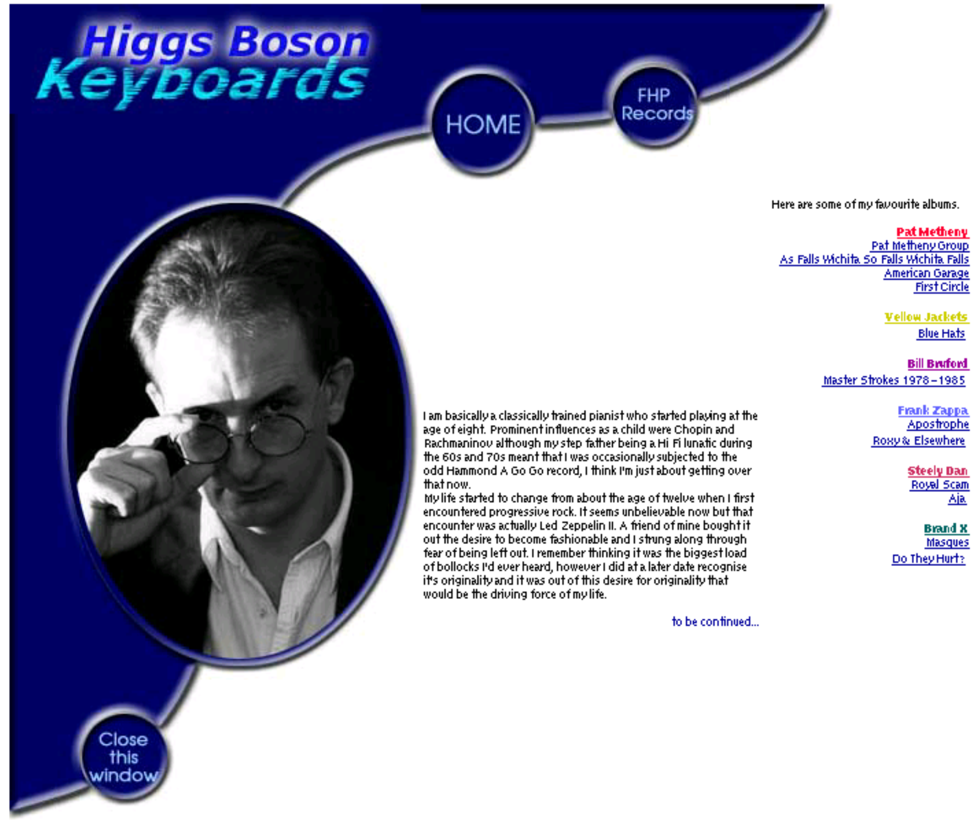
- **Full rewrite of online code, level 3 trigger and offline reconstruction in C++**

```
// * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
bool L3TCalUnpTool::DoThisTool() {

  MakeRawDataChunk();

  if ( unpack_all == 0 ) {
    SeedTowers = GetTrigSeedTowers();
//      cout << "\nGetting trigger seed towers" << endl;
//    } else {
//      cout << "\nUnpacking Entire Detector" << endl;
  }

  return ( _DoThisTool() );

}

// * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
```



www.higgsboson.com

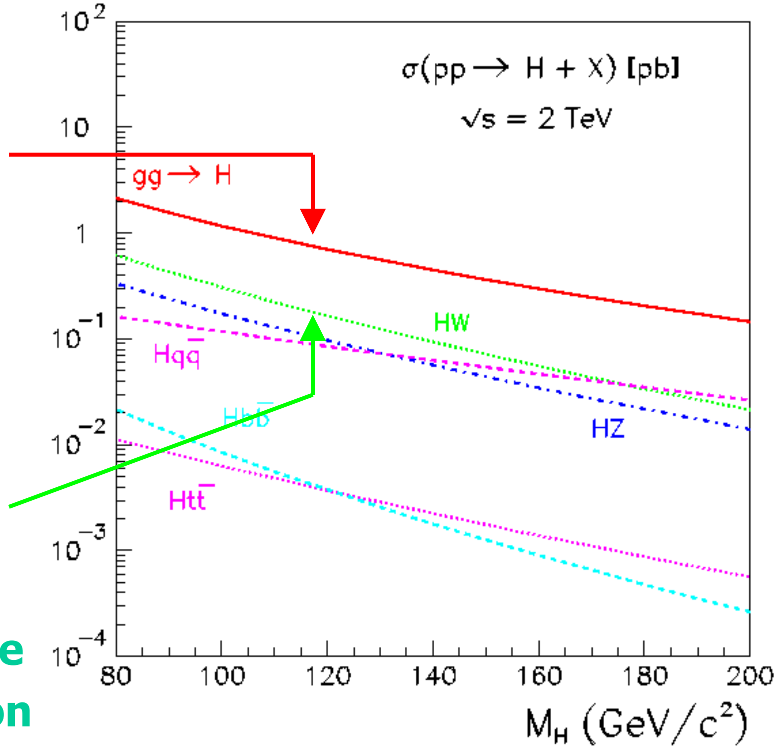




- **Higgs Boson is the name of a British musician**

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 = 1000 events/year**
  - **but the dominant decay H → bb is swamped by background**
  - **thus the 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 = 200 events/year**



Higgs Discovery Channels

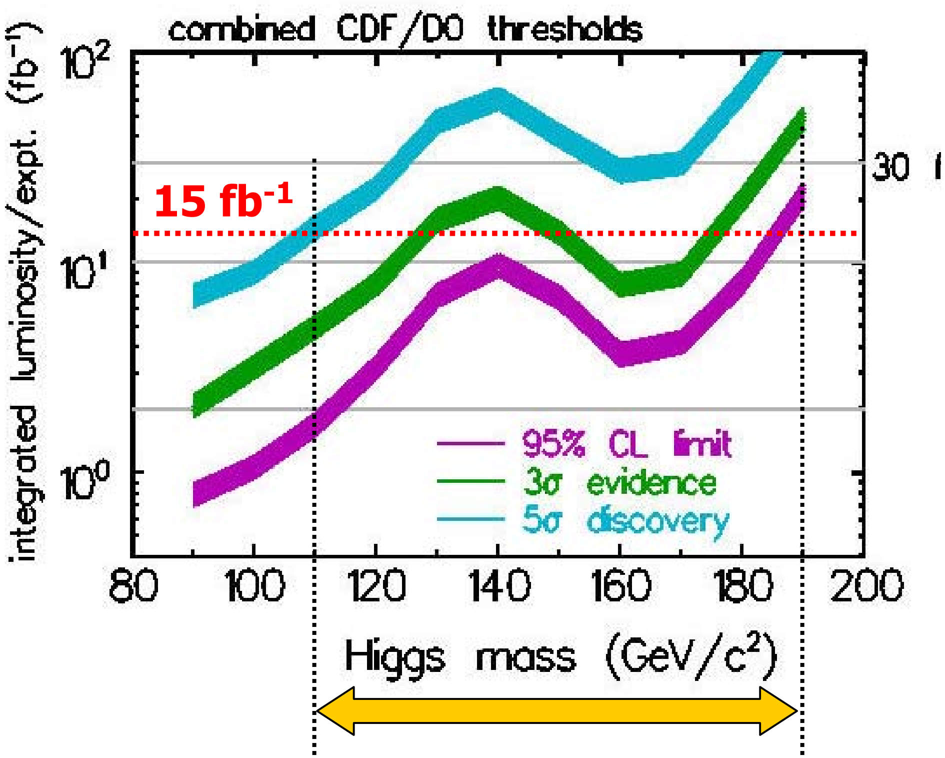
m_H < 130-140 GeV

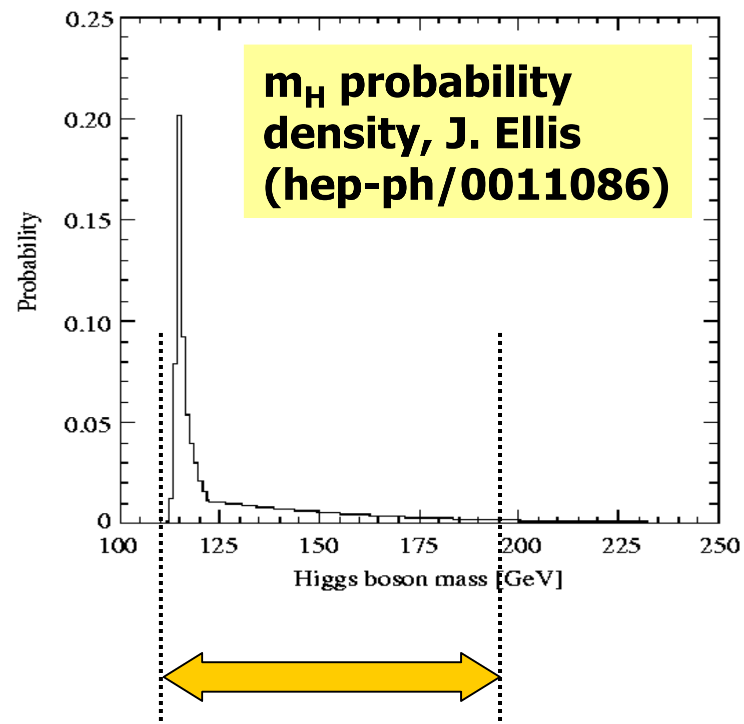
- WH → qq bb is the dominant decay mode but is overwhelmed by QCD background
- WH → lν bb   backgrounds Wbb, WZ, tt, single top
- ZH → l l bb   backgrounds Zbb, ZZ, tt
- ZH → νν bb   backgrounds QCD, Zbb, ZZ, tt
  - powerful mode but requires relatively soft missing E_T trigger (35 GeV?)

m_H > 130-140 GeV

- gg → H → WW*   backgrounds Drell-Yan, WW, WZ, ZZ, tt, tW, ττ
  initial signal:background ratio ~ 7×10^{-3} !
  - Angular cuts to separate signal from "irreducible" WW background

Higgs mass reach





110-190 GeV

"that's where the money is"

What about m_H = 115 GeV?

- If the LEP hints are incorrect, we can exclude at 95% with 2fb^{-1} of data (2003) if no evidence is seen
- Evidence at 3 standard deviation level with ~ 5 fb^{-1} (2004-5)
- With ~ 15 fb^{-1} (2008?) we expect a 5 standard deviation signal
  - expected events in one experiment:

Mode	*Signal*	*Background*	*S/√B*
lνbb	92	450	4.3
ννbb	90	880	3.0
llbb	10	44	1.5

- 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 → ττ? (Branching Ratio ~ 8%)

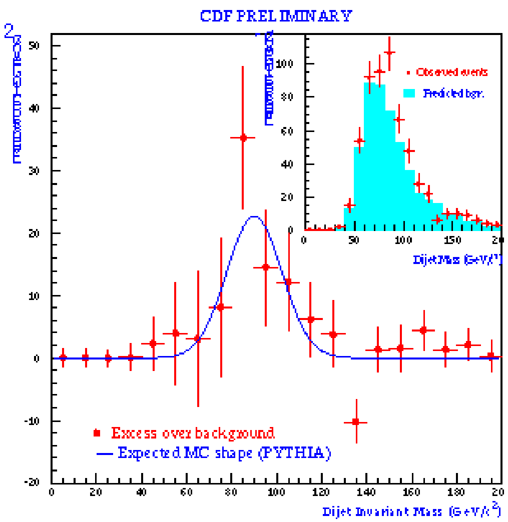
Challenges

- **Is the Tevatron Higgs search credible?**
  - It is an exercise similar in scale to the top discovery, with a similar number of backgrounds and requiring similar level of detector understanding, though it will be harder: the irreducible signal:background is worse
- **some serious challenges:**
  - maintaining detector performance at high luminosities
  - mass resolution on $\bar{b}b$ system is critical
- **it has already caught the imagination of experimenters**
  - factor ~ 1.3 improvement in S/B demonstrated with neural network
  - possibility to exploit angular distributions (WH vs. Wbb)
- **never underestimate the ingenuity of physicists confronted with real data!**
  - similar simulation studies before run I indicated that the maximum reachable top quark mass would be ~ 140 GeV
  - in 1995 we discovered it at 175 GeV

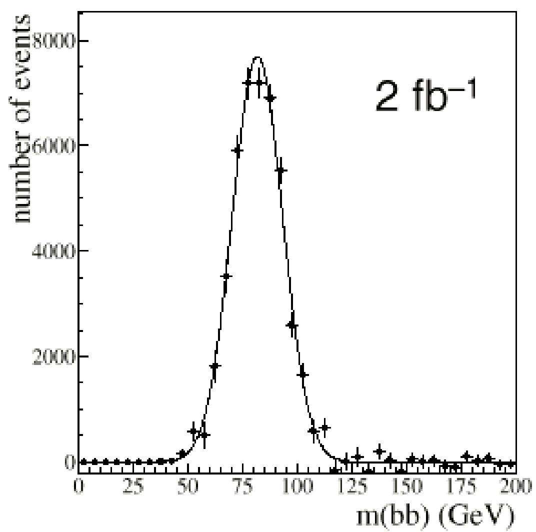
$\bar{b}b$ mass resolution

- **Directly influences signal significance**
- **Requires corrections for missing E_T and muon**
- **$Z \rightarrow \bar{b}b$ will be a calibration signal: silicon trigger**

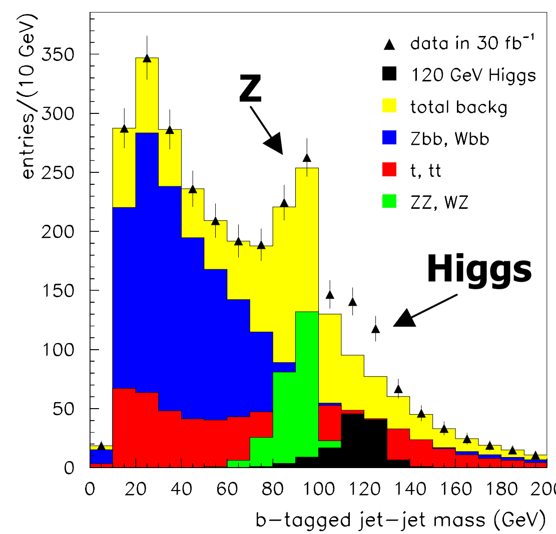
CDF observation in Run I



DØ simulation for 2fb^{-1}



Higgs simulation for 30fb^{-1}



m_H = 120 GeV

Beyond the Higgs

- **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 the Higgs is not all we are missing**
  - **This Higgs boson is unlike any other particle in the SM (no other elementary scalars)**
  - **a fundamental Higgs would have a mass unstable to radiative corrections (quantum effects): m_H would become very large**
    - **$m_H \sim 10^{15}$ GeV, unless parameters fine tuned at the level of 1 part in 10^{26}**
  - **the patterns of the fundamental particles suggest a deeper structure**
  - **the SM is a low energy approximation to something larger**
- **Theoretically the most attractive option is supersymmetry**

Supersymmetry

- **Introduce a symmetry between bosons and fermions:**
  - all the presently observed particles have new, more massive superpartners
  - SUSY is a broken symmetry
  - Allows a fundamental scalar (the Higgs) at low mass:
    - additional bosons cancel the divergences in m_H
    - m_H can naturally be of order the SUSY scale (SUSY partner masses ≈ electroweak scale, 250 GeV?)
  - closely approximates the standard model at low energies
  - allows unification of forces with common couplings at much higher energies
  - provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity

- **lightest neutral superpartner (neutralino) is massive, weakly interacting and stable**
  - cosmic dark matter candidate!

Supersymmetry searches

- Supersymmetry predicts multiple Higgs bosons, strongly interacting squarks and gluinos, and electroweakly interacting sleptons, charginos and neutralinos
  - masses depend on unknown parameters, but expected to be 100 GeV - 1 TeV

Direct searches all negative so far

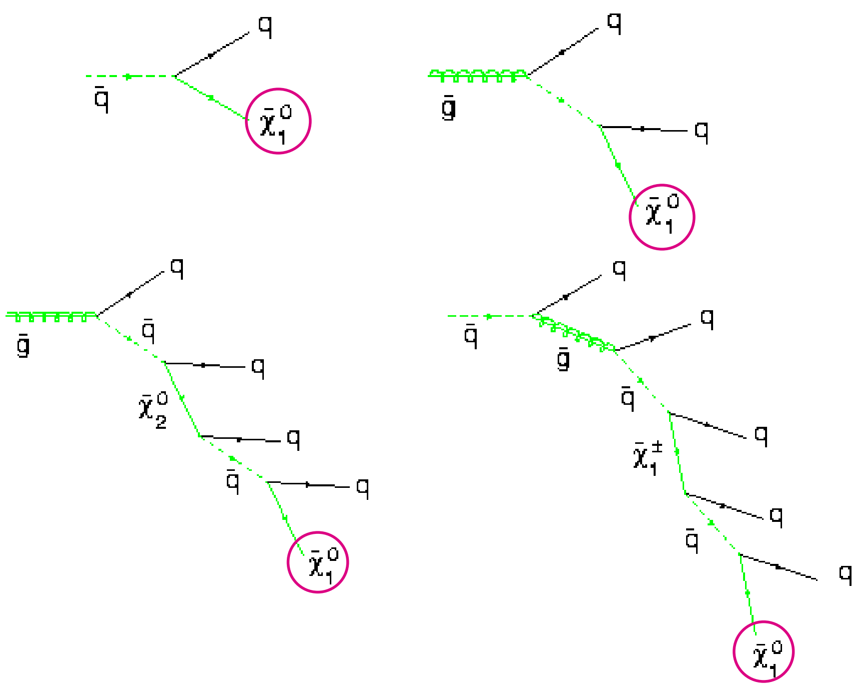
- LEP
  - squarks (stop, sbottom) > 80-90 GeV
  - sleptons (selectron, smuon, stau) > 70-90 GeV
  - charginos > 70-90 GeV
  - lightest neutralino > 36 GeV

- Tevatron Run I
  - squarks and gluinos
  - stop, sbottom
  - charginos and neutralinos

Supersymmetry signatures

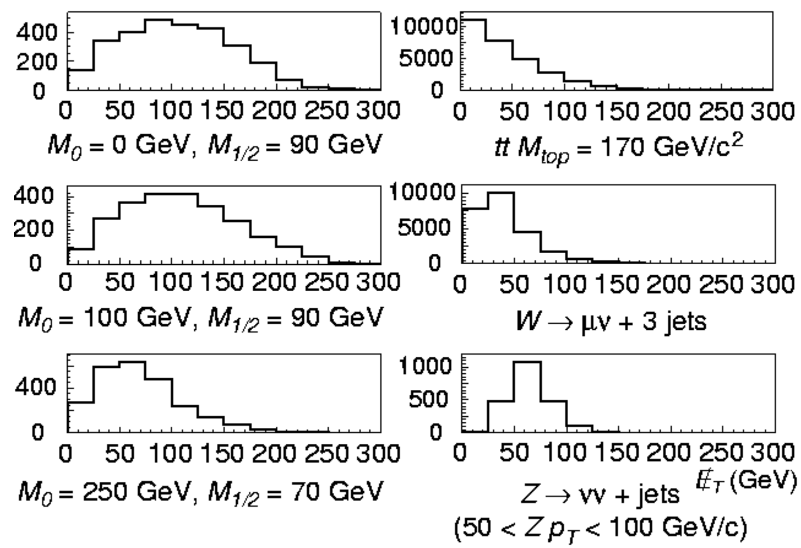
- **Squarks and gluinos are the most copiously produced SUSY particles**
- **As long as R-parity is conserved, cannot decay to normal particles**
  - **missing transverse energy from escaping neutralinos (lightest supersymmetric particle or LSP)**

Possible decay chains always end in the LSP:



Missing E_T

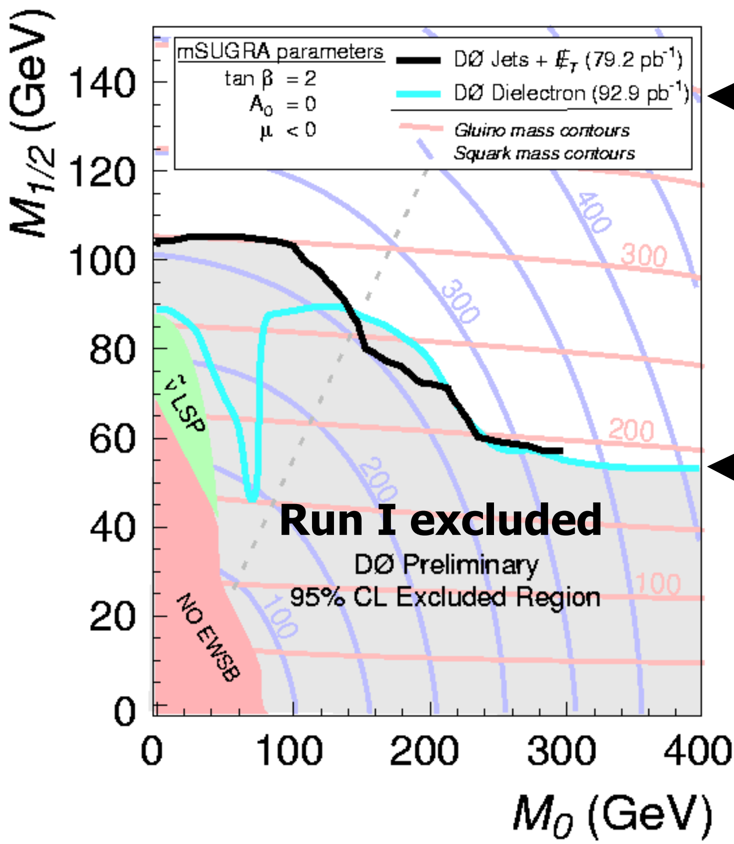
SUSY **backgrounds**



Search region typically > 75 GeV

Run I search for squarks and gluinos

- **Two complementary searches**
  - jets plus missing E_T and no electrons/muons
  - 2 electrons, 2 jets + Missing E_T

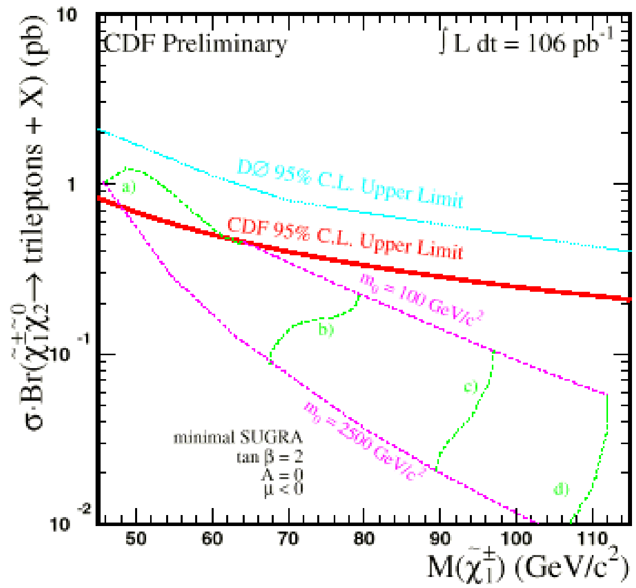


Reach with 2 fb^{-1}: gluino mass ~ 400 GeV

Run I reach gluino ~ 200 GeV squark ~ 250 GeV

Chargino/neutralino production

- "Golden" signature: three leptons
  - very low standard model backgrounds
- This channel was searched in Run 1, but limits not competitive with LEP
  - however, becomes increasingly important as squark/gluino production reaches its kinematic limits (masses 400-500 GeV)

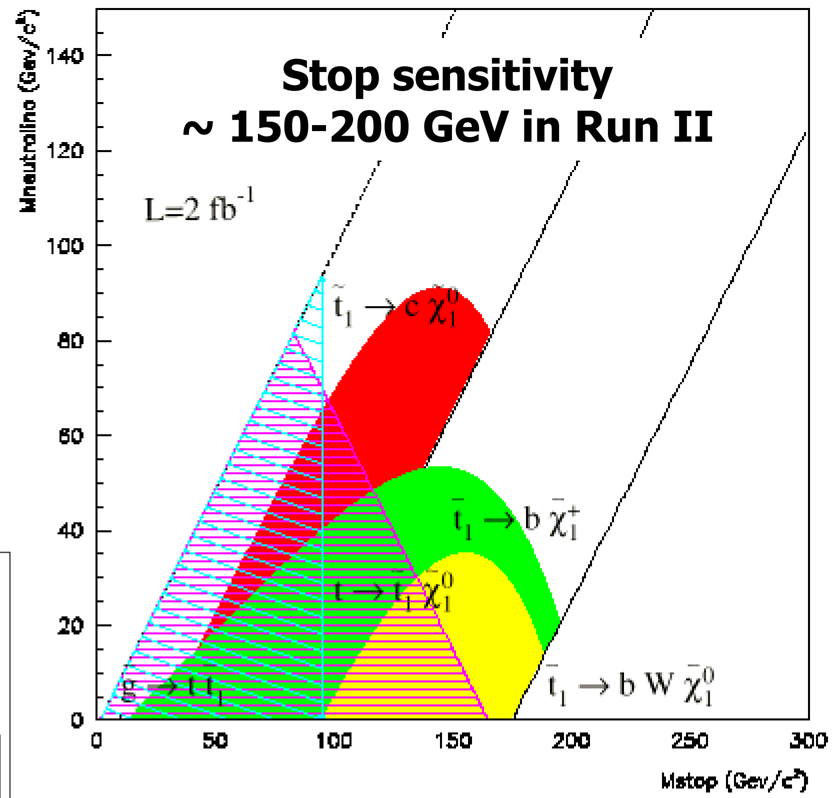


- Run II reach on $\chi^{\pm}$ mass ~ 180 GeV (tan β = 2, μ< 0)
  ~ 150 GeV (large tan β)
- Challenges
  - triggering on low momentum leptons
  - how to include tau leptons?

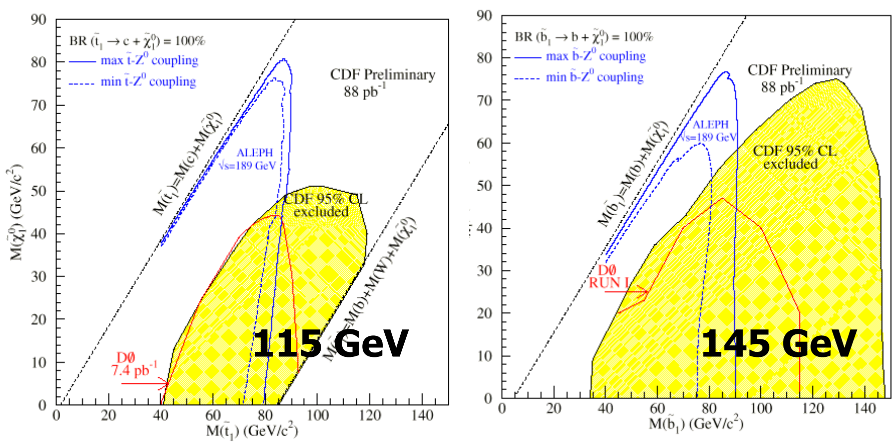
It is quite conceivable that we discover SUSY in this mode before we find the Higgs!

Stop and Sbottom

- Often the SUSY partners of b and t are the lightest squarks
- Stop
  - stop $\rightarrow$ b + chargino or W (top like signatures)
  - stop $\rightarrow$ c + neutralino
  - top $\rightarrow$ stop and gluino $\rightarrow$ stop
- Sbottom
  - 2 acollinear b-jets + E_T^{miss}



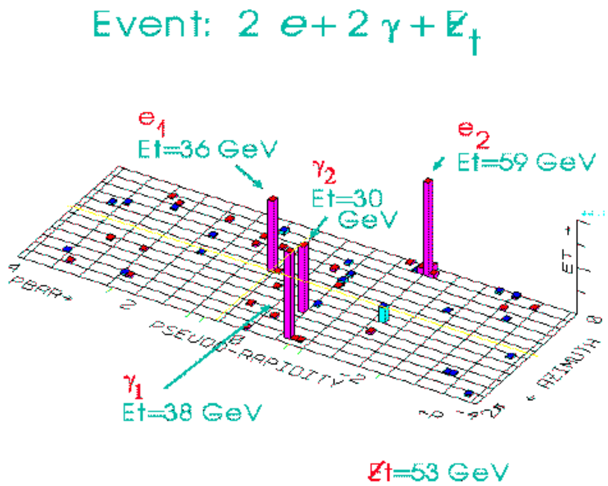
CDF Run I stop and sbottom limits

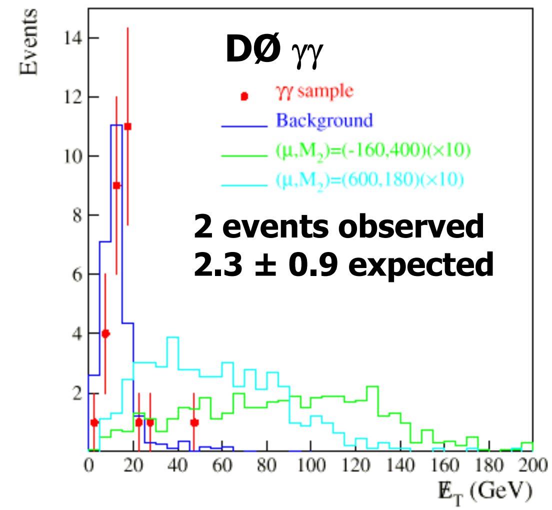


Sbottom sensitivity
~ 200 GeV in Run II

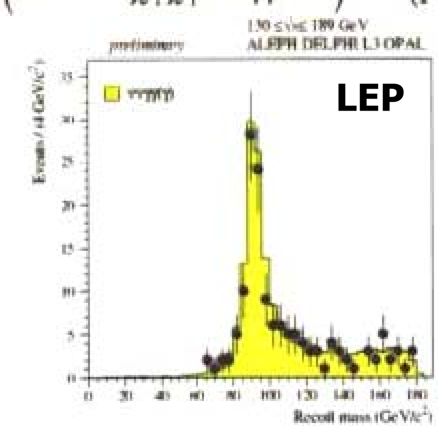
Has SUSY been discovered?

- **Is this selectron pair production?**





$$\sigma\left(e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \gamma\gamma\tilde{G}\tilde{G}\right) \sim O(pb)$$

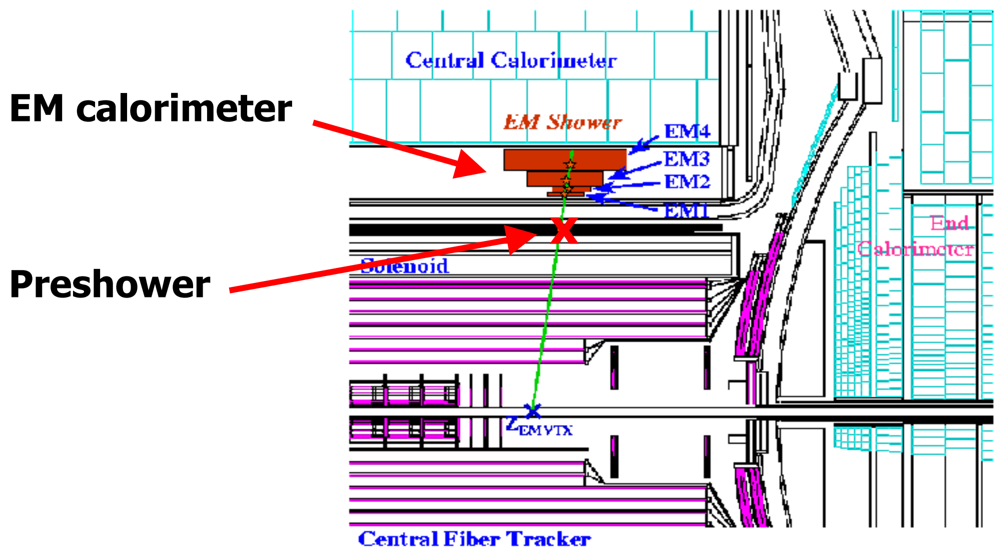


- **No! Already been ruled out by LEP**
- **All we can say is that searches for related signatures have all been negative**
  - **CDF and DØ γγ + missing E_T**
  - **DØ γ + jets + missing E_T**
  - **LEP**

NOT YET !?

Gauge mediated SUSY

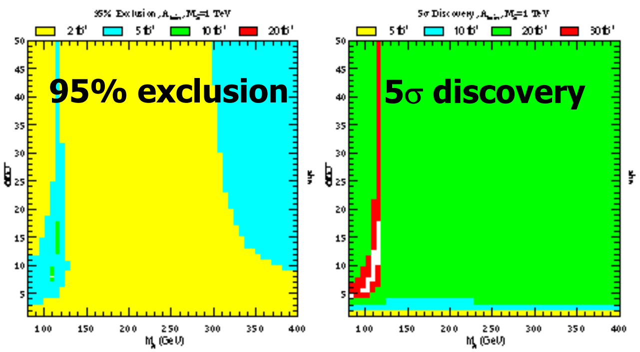
- **Standard benchmark is so-called "minimal supergravity inspired" (mSUGRA) models — but other scenarios for SUSY breaking give other signatures**
- **e.g. Gauge mediated SUSY:**
  - **lightest neutralino decays to a photon plus a gravitino, maybe with a finite path length**
- **Run II DØ direct reconstruction with σ_z = 2.2 cm, σ_r = 1.4 cm**



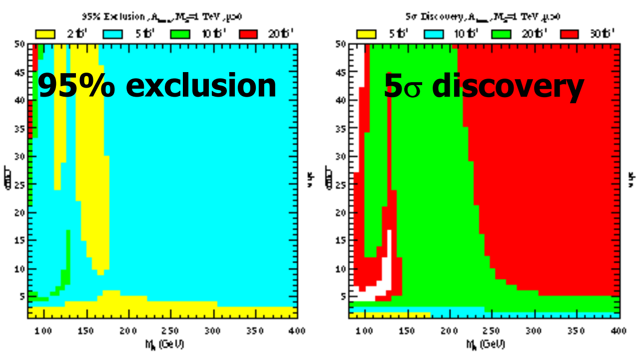
SUSY Higgs sector at the Tevatron

Assuming 1 TeV sparticle masses, $\mu < 0$

minimal stop mixing

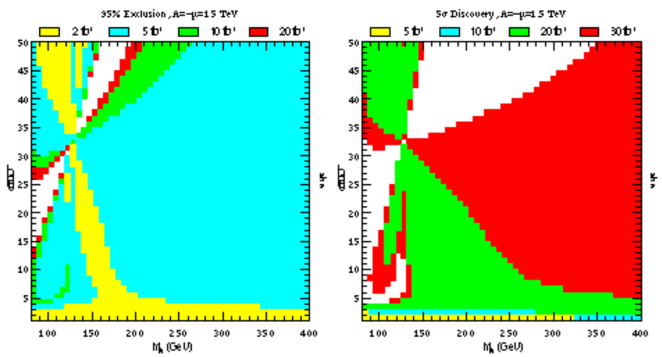


maximal stop mixing (heaviest h)



But not always so straightforward:

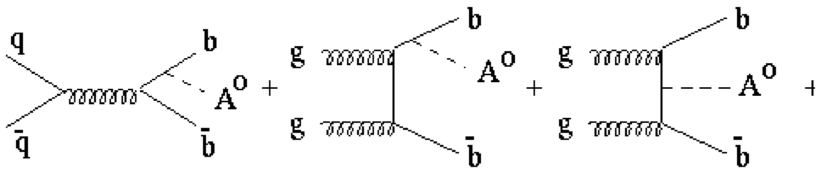
Fixed A (= $-\mu$ = 1.5 TeV here) suppresses hbb, $h\tau\tau$ couplings for certain (m_A, $\tan\beta$)



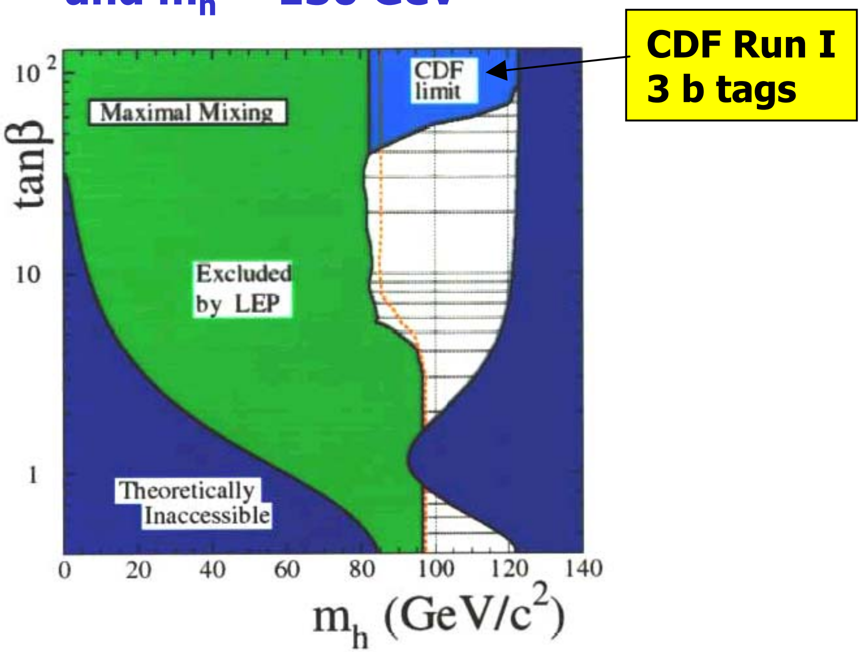
Enhances $h \to \gamma\gamma$ (branching ratio as high as 10%?)

Strong SUSY Higgs Production

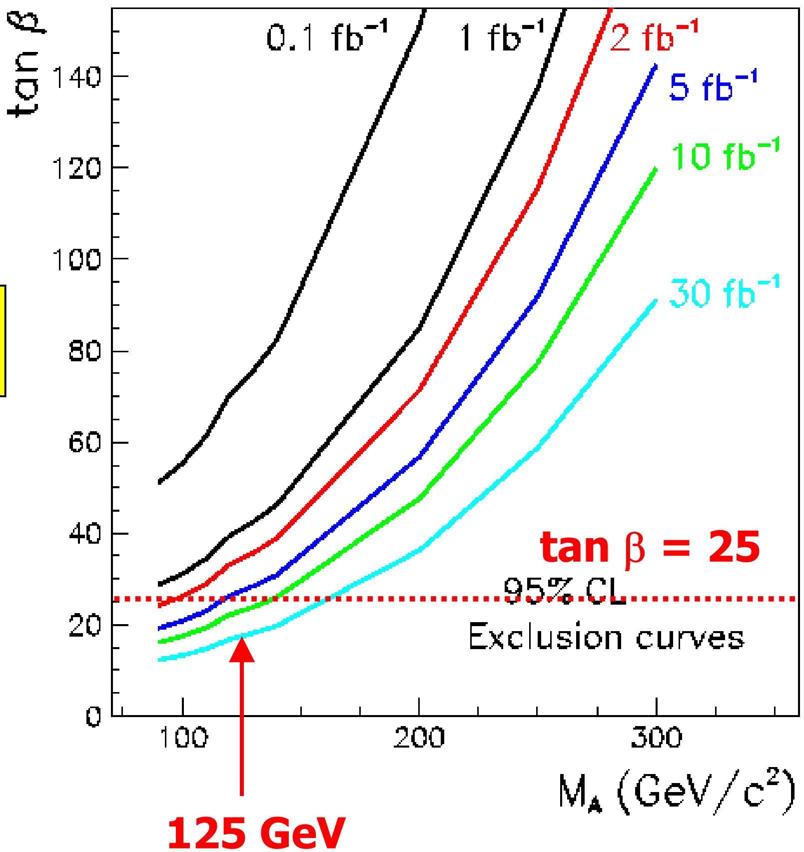
- **bb(h/H/A) enhanced at large tan β:**



- **σ ~ 1 pb for tanβ = 30 and m_h = 130 GeV**

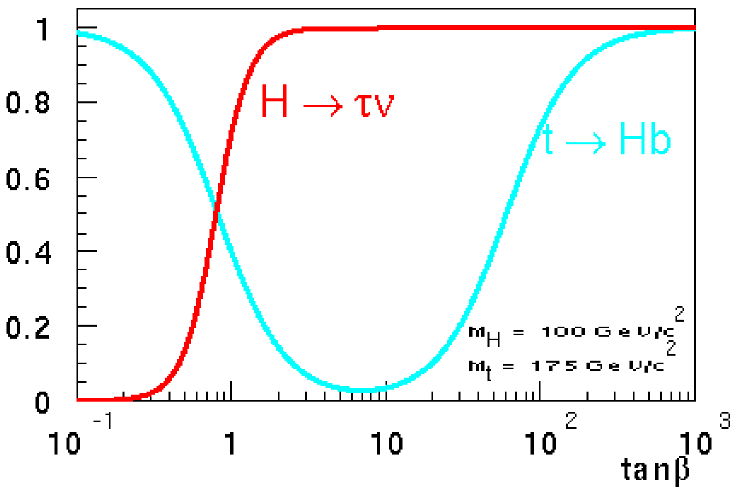


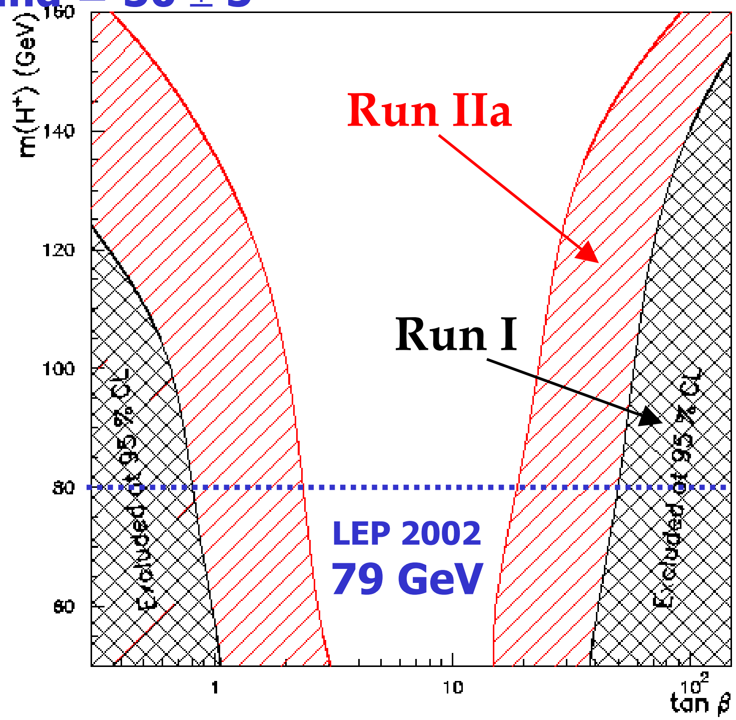
bb(h/A) → 4b



Charged Higgs

- Tevatron search in top decays
- Standard $t\bar{t}$ analysis, rule out competing decay mode $t \rightarrow H^{\pm}b$
- Assumes 2 fb^{-1}, n_{obs} = 600, background = 50 ± 5

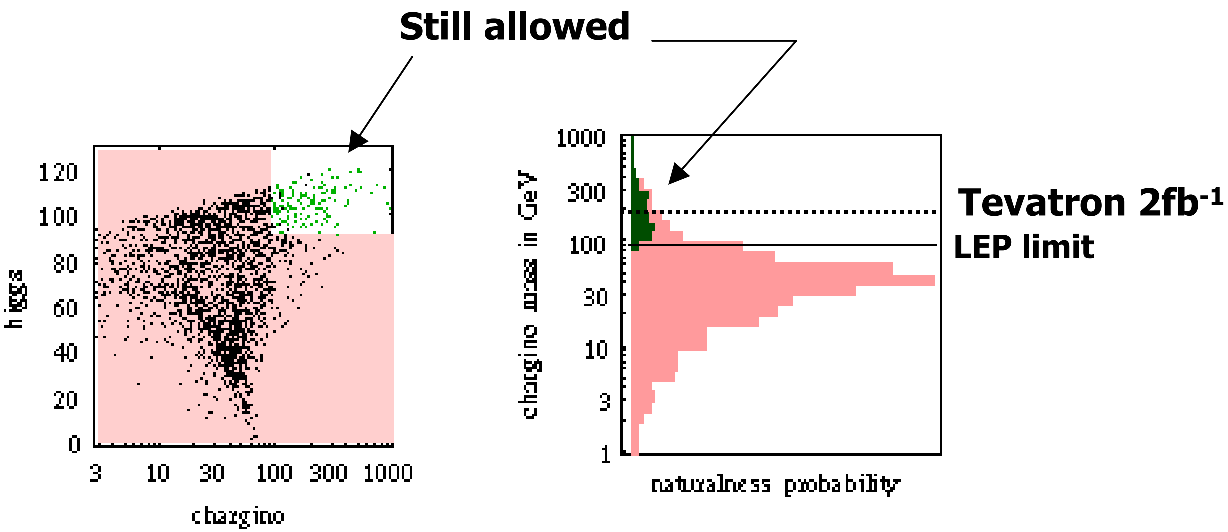




- LEP not really sensitive to MSSM region (expect $m_H > m_W$)

Excluding SUSY

- It is amusing to note that typical minimal supergravity-inspired SUSY models are already excluded at the 95% level
(e.g. Strumia, hep-ph/9904247)

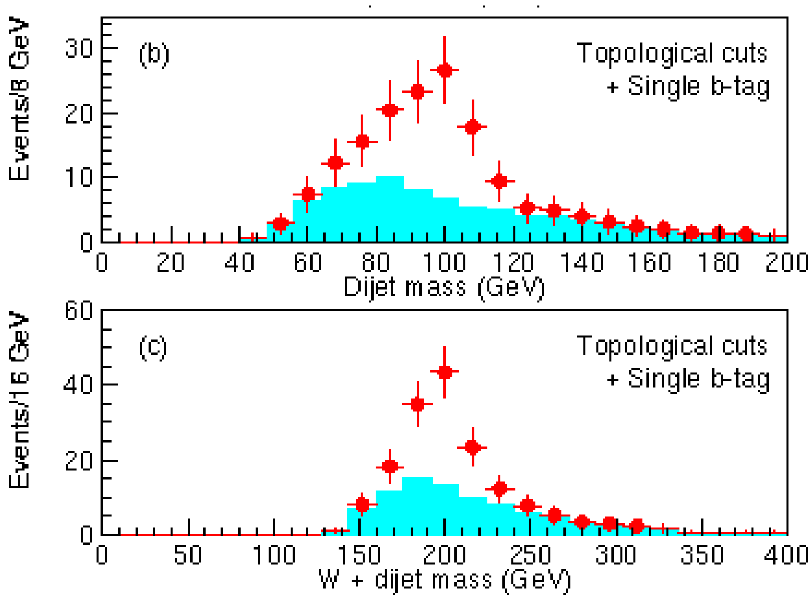


- Either we should expect to see something soon, or we are on the wrong track . . .

Technicolor

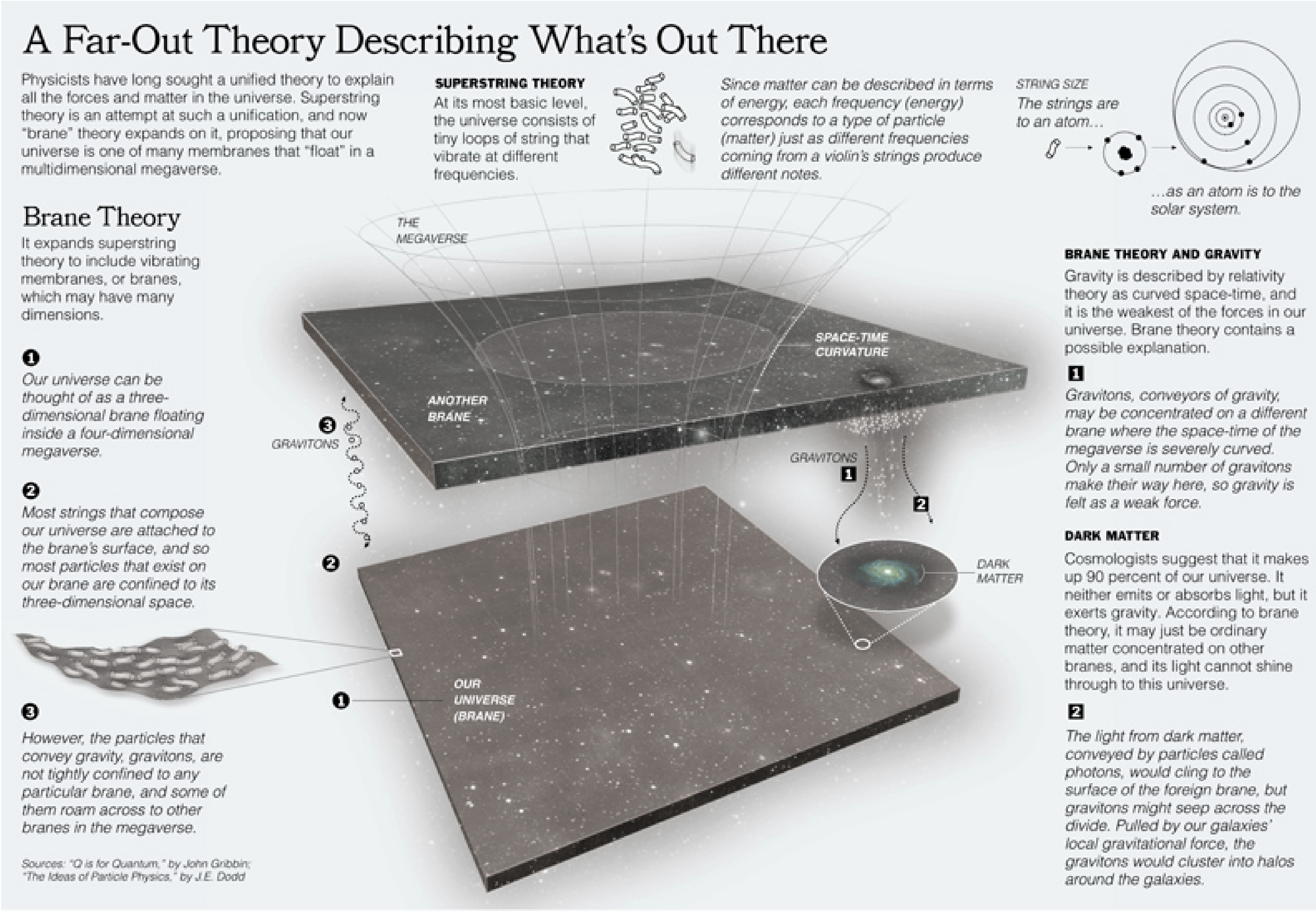
- **Alternatives to SUSY: dynamical models like technicolor and topcolor**
  - **the Higgs is a composite particle: no elementary scalars**
  - **many other new particles in the mass range 100 GeV - 1 TeV**
  - **with strong couplings and large cross sections**
  - **decaying to vector bosons and (third generation?) fermions**

Technicolor $\rho_T \rightarrow W\pi_T \rightarrow l\nu bb$
Tevatron, $1fb^{-1}$



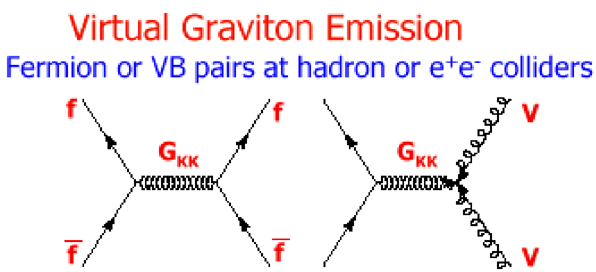
Connections with Gravity

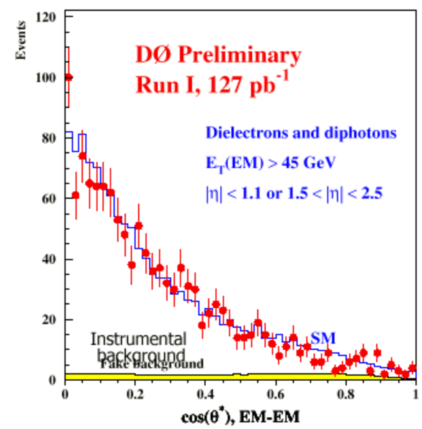
- While supersymmetry is required for supergravity, it was normally assumed that any unification of forces would occur at the Planck scale ~ 10^{19} GeV
  - very large hierarchy between the electroweak scale and gravitational scales
- Powerful new idea:
  Gravity may propagate in extra dimensions, while the gauge particles and fermions (i.e. us) remain trapped in 3+1 dimensional spacetime
  - extra dimensions not necessarily small in size (millimeters!)
  - true Planck scale may be as low as the electroweak scale
  - Gravity could start to play a role in experiments at ~ TeV


A Far-Out Theory Describing What's Out There
Physicists have long sought a unified theory to explain all the forces and matter in the universe. Superstring theory is an attempt at such a unification, and now "brane" theory expands on it, proposing that our universe is one of many membranes that "float" in a multidimensional megaverse.
SUPERSTRING THEORY
At its most basic level, the universe consists of tiny loops of string that vibrate at different frequencies.
Since matter can be described in terms of energy, each frequency (energy) corresponds to a type of particle (matter) just as different frequencies coming from a violin's strings produce different notes.
STRING SIZE
The strings are to an atom…
…as an atom is to the solar system.
Brane Theory
It expands superstring theory to include vibrating membranes, or branes, which may have many dimensions.
1
Our universe can be thought of as a three-dimensional brane floating inside a four-dimensional megaverse.
2
Most strings that compose our universe are attached to the brane's surface, and so most particles that exist on our brane are confined to its three-dimensional space.
3
However, the particles that convey gravity, gravitons, are not tightly confined to any particular brane, and some of them roam across to other branes in the megaverse.
Sources: "Q is for Quantum," by John Gribbin; "The Ideas of Particle Physics," by J.E. Dodd
THE MEGAVERSE
ANOTHER BRANE
SPACE-TIME CURVATURE
GRAVITONS
GRAVITONS
DARK MATTER
OUR UNIVERSE (BRANE)
BRANE THEORY AND GRAVITY
Gravity is described by relativity theory as curved space-time, and it is the weakest of the forces in our universe. Brane theory contains a possible explanation.
1
Gravitons, conveyors of gravity, may be concentrated on a different brane where the space-time of the megaverse is severely curved. Only a small number of gravitons make their way here, so gravity is felt as a weak force.
DARK MATTER
Cosmologists suggest that it makes up 90 percent of our universe. It neither emits or absorbs light, but it exerts gravity. According to brane theory, it may just be ordinary matter concentrated on other branes, and its light cannot shine through to this universe.
2
The light from dark matter, conveyed by particles called photons, would cling to the surface of the foreign brane, but gravitons might seep across the divide. Pulled by our galaxies' local gravitational force, the gravitons would cluster into halos around the galaxies.
Steve Duenes/The New York Times

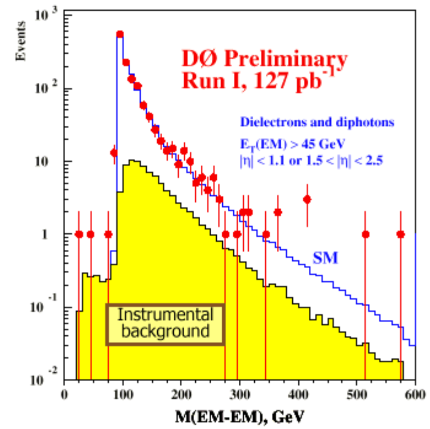
Large extra dimensions

- **New DØ Run I limits on scale of extra dimensions: virtual graviton effects on e^+e^- and $\gamma\gamma$ production**





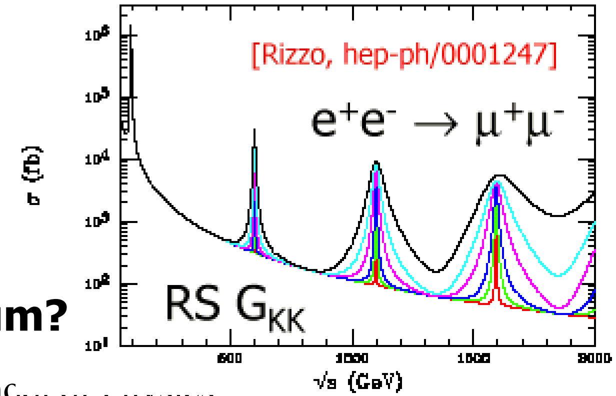
Data agree well with the SM



Note zero-events bins at high masses!

- **Limits: 1.0 - 1.3 TeV for 2-7 extra dimensions**
- **Prospects for Run II:**
  1.5 - 2.5 TeV ($2fb^{-1}$)
  2.1 - 3.5 TeV ($20fb^{-1}$)

Effects could be spectacular:
KK Resonances in Drell-Yan spectrum?

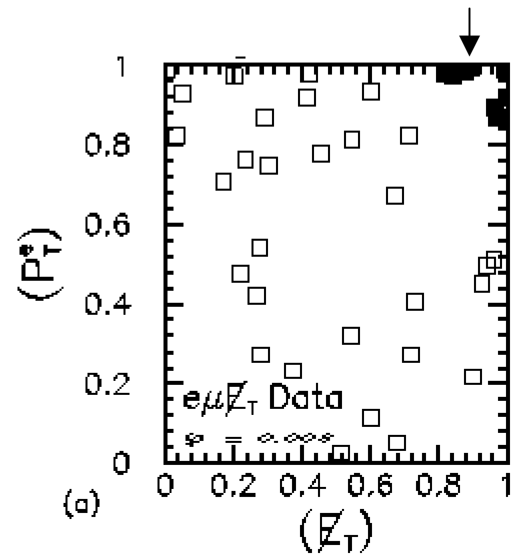


Sleuth

- **A new approach: attempt at a truly model-independent analysis framework to search for new physics**
  - **will never be as sensitive to a particular model as a targeted search, but open to anything**

- **Proof of principle using DØ Run 1 data (Phys. Rev. D 2000)**
  - **$e\mu jj+X$ sample, using p_T^e and Missing E_T as a measure of rarity**
    - **if background = WW, fakes and $\tau\tau$, the top signal is seen at the 2σ level (Standard Model Probability = 3%)**
    - **if top is then included in the background, no excess is seen (Standard Model Probability = 31%)**

Most interesting events



Are there any hints in Run I data?

- Systematic Sleuth study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the Run 1 data

- The only channels with some hint of disagreement were
  - 2 electrons + 4 jets
    - observe 3, expect 0.6± 0.2, CL = 0.04
  - 2 electrons + 4 jets + Missing E_T
    - observe 1, expect 0.06±0.03, CL = 0.06

- While interesting, these events are not an indication of a deviation from the standard model, given the number of channels searched
  - 89% probability of agreement with the Standard Model, alas!

This approach will be extremely powerful in Run 2

What are we doing now?

- Run II started
- Both experiments are up and running, accumulating data fast
- Detectors, trigger systems, and software are all operational
- First results were presented at Moriond 2002
- First physicsresults were presented at ICHEP and HCP 2002

Come to the seminar on “Status of the Tevatron Collider Program”

- Planning has already started on the additional detector enhancements that will be needed to meet the goal of accumulating ~15 fb^{-1}
- Detector upgrade has been approved by DOE and is underway

Very exciting future ahead of us !!

The work of many people…

Institutions:

33 US, 40 non US

Collaborators:

334 from US
312 from non US institutions

Conclusions

- The Tevatron collider program in the next 8 years offers a real opportunity to significantly advance our understanding of the fundamental properties of matter
- It is an exciting, challenging program that goes straight to the highest priority of high energy physics worldwide
- We want to find the Higgs! And more!!