Run 2 at the Tevatron Collider

John Womersley

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http://www-d0.fnal.gov/~womersle/womersle.html

Particle Physics

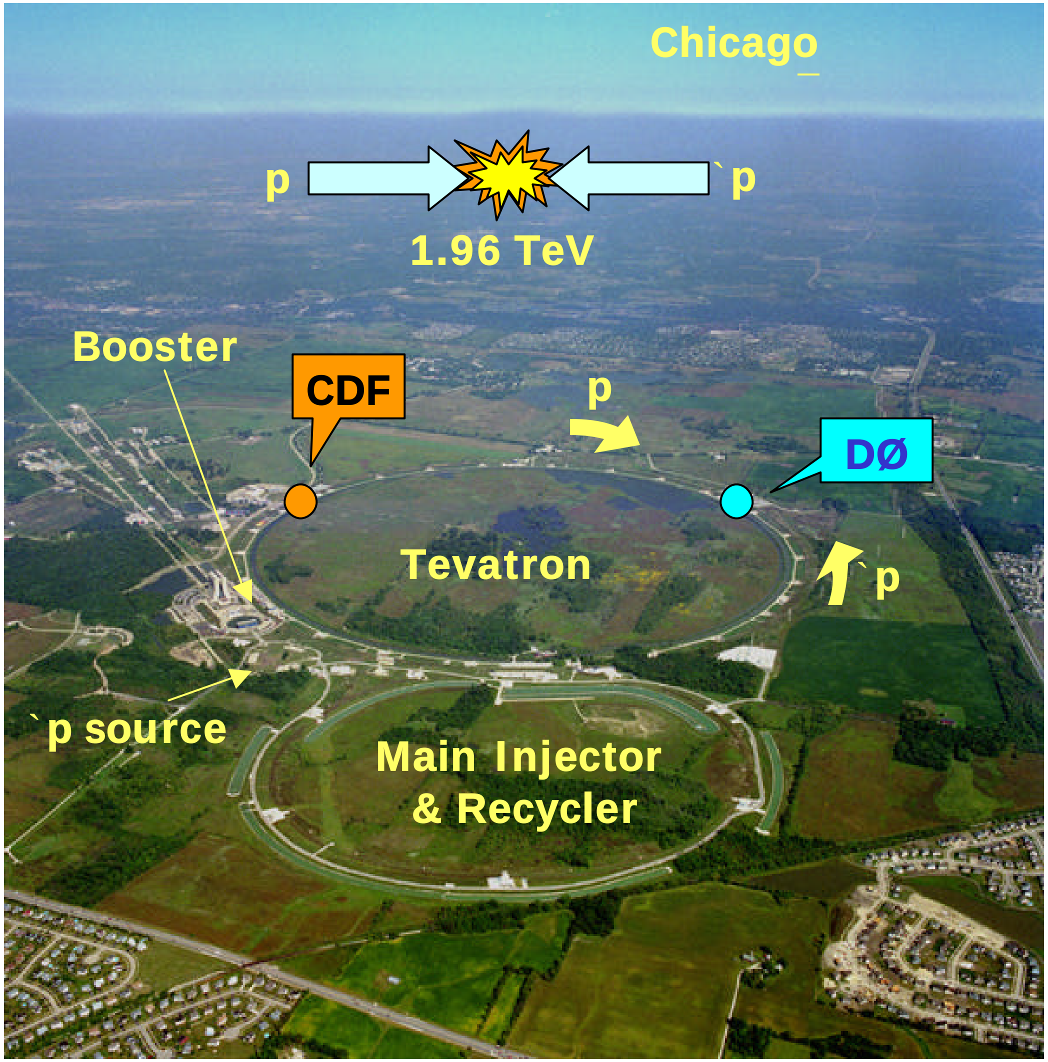
"Everything in the universe seems to be made of simple, small objects which like to stick together"

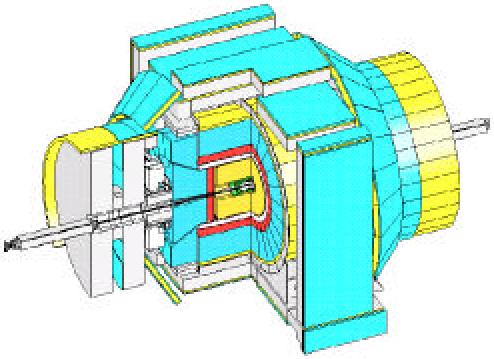
- Modern realisation of this: <u>The Standard Model</u>
  - A quantum field theory in which point-like, spin-1/2 fermions interact through the exchange of spin-1 vector bosons
  - Electroweak interaction
    - photons, W and Z bosons
  - Strong interaction (QCD)
    - gluons
  - Three generations of leptons (electron, muon, tau, 3 neutrinos)
    - electroweak interaction only
  - Three generations of quarks (u,d,s,c,t,b)
    - electroweak and strong interactions
- Standard Model predictions have been verified at the 10^{-3} level up to energies of a few hundred GeV
- Point-like nature of quarks and leptons tested up to TeV scales

Isn't this good enough?

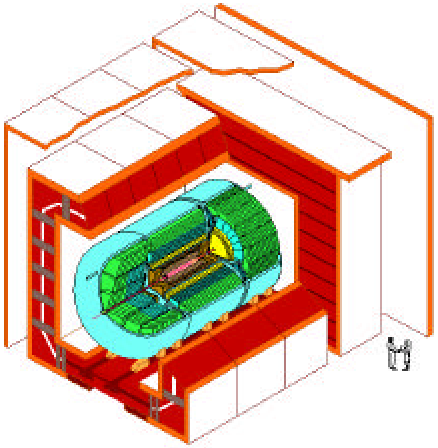
- No: at least one extra field is needed — the Higgs field
  - without it, the WW scattering amplitude becomes infinite at energies of ~ 1 TeV
    - real experiments in the next decade would see this!
  - with it, "electroweak symmetry breaking" explained
  - the Higgs field is a property of spacetime, but at least one real particle will result
- Even with the Higgs, the Standard Model requires unreasonable fine tuning of parameters to avoid ~ infinite Higgs masses from quantum corrections
  - leads to strong belief that it is merely an effective (low energy) theory valid up to some scale, where additional physics appears
    - mass scale of Higgs ® that scale is close (few hundred GeV)
    - also, the Higgs boson is unlike any other particle in the SM (no other elementary scalars)
    - the patterns of fermion masses hint at deeper structures
  - most popular theoretical option: supersymmetry
- Current accelerators can access these energy scales
  - make discoveries!

The Fermilab Tevatron Collider





CDF



DØ

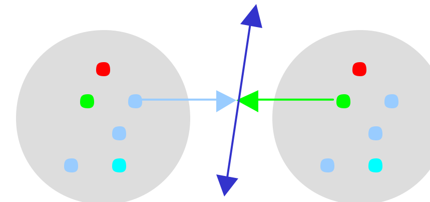
Tevatron timeline

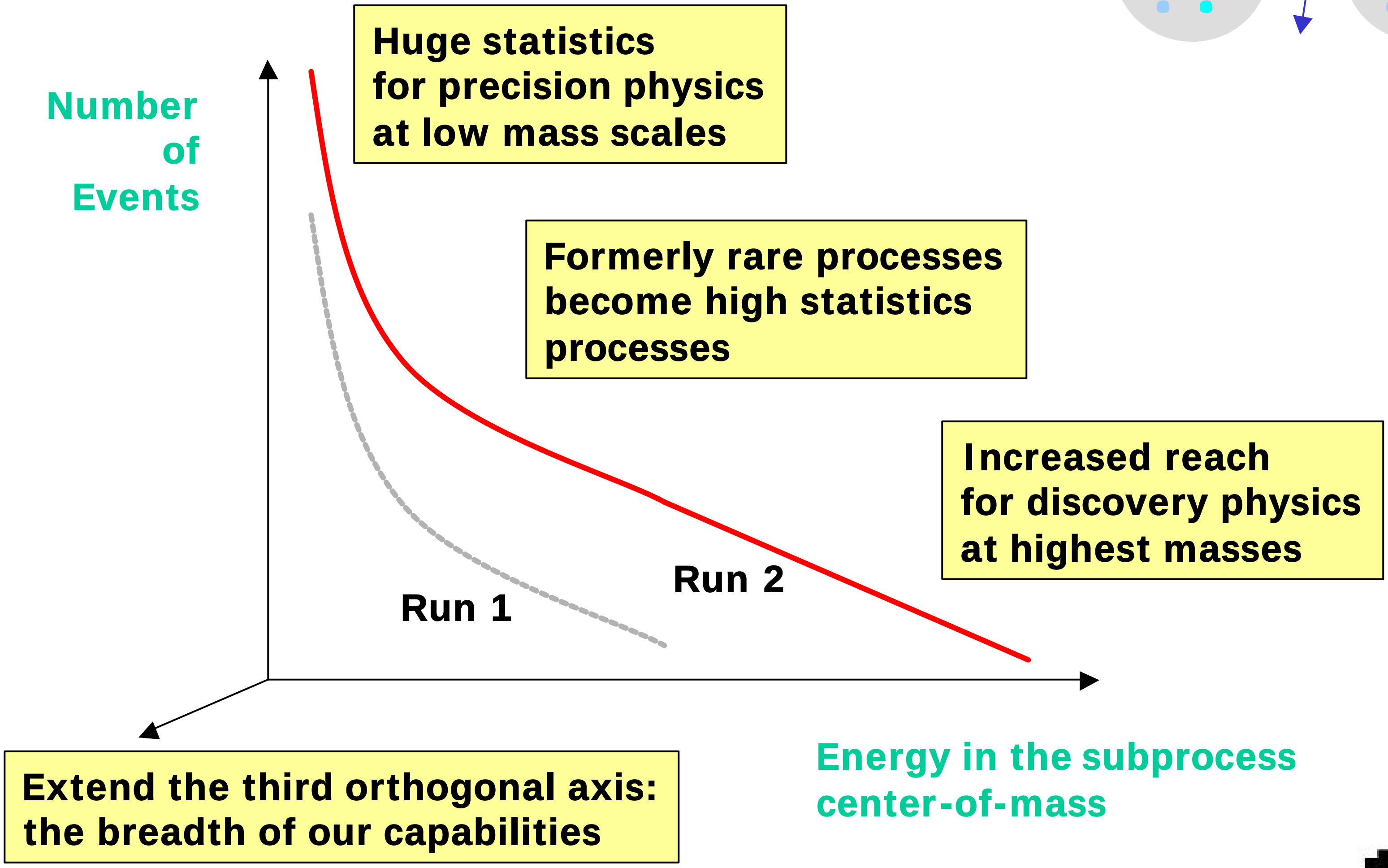
1985	first proton-antiproton collisions
1988-89	first physics run, CDF
1992-96	Run 1: 120 pb^{-1}, 1.8TeV, CDF and DØ
1996-2001	Major detector upgrades
2001-04	Run 2a: 2 fb^{-1}, 1.96 TeV
2004	Short shutdown to install new silicon detectors
2004-07	Run 2b: ~ 15 fb^{-1}
2007?	LHC operation starts at CERN

- 1pb^{-1} is a measure of the integrated luminosity:
  - 1pb^{-1} = 1 event produced for a process with a cross section of 1 pb
  - 1000 pb^{-1} = 1 fb^{-1}
  - Top quark production cross section ~ 5 pb
  - Higgs and supersymmetry ~ few ´ 100 fb

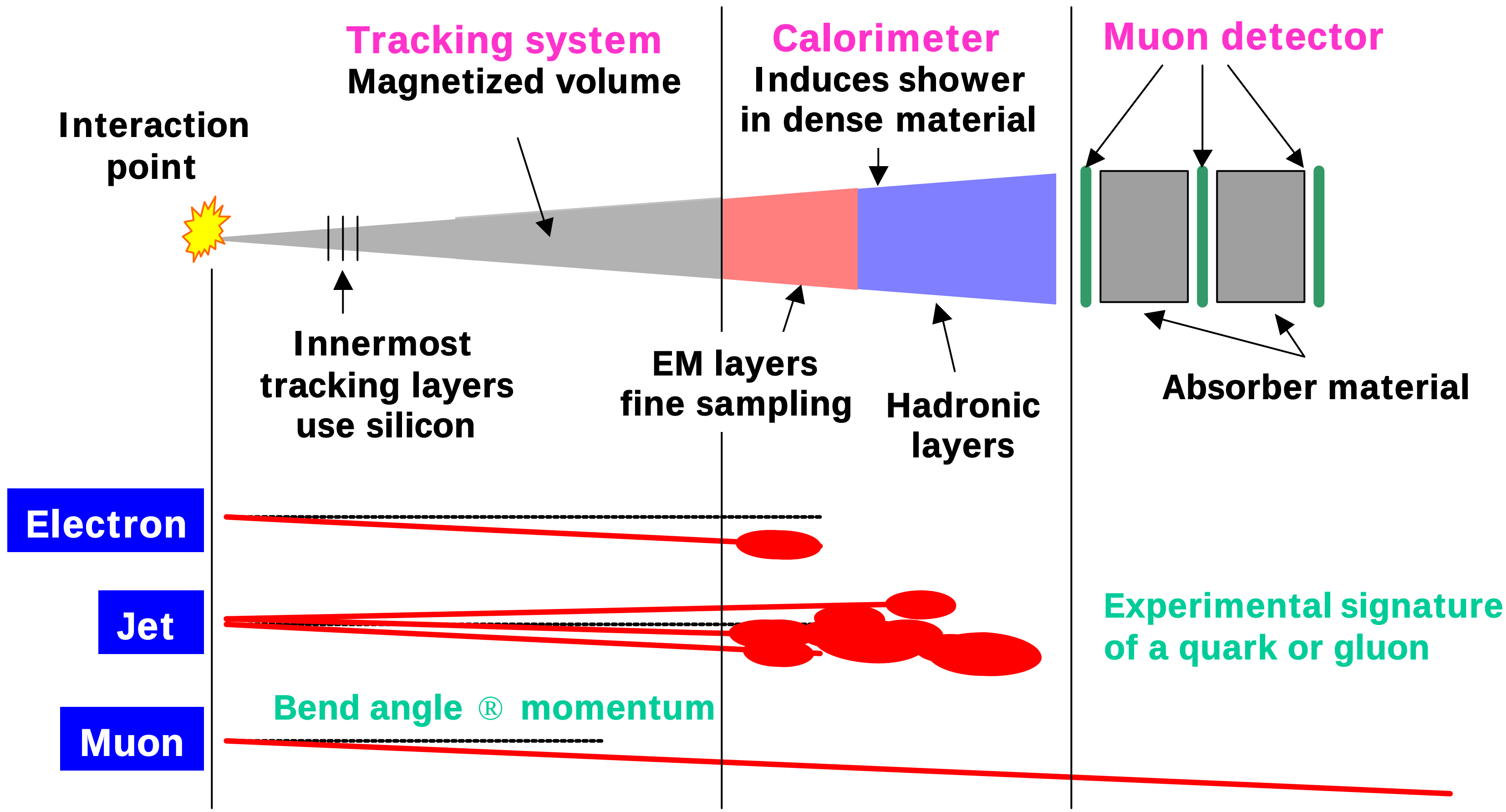
Run 1 ® Run 2

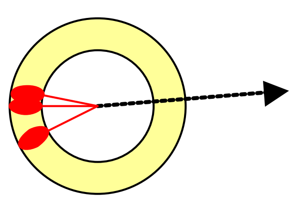
- The Tevatron is a broad-band quark and gluon collider





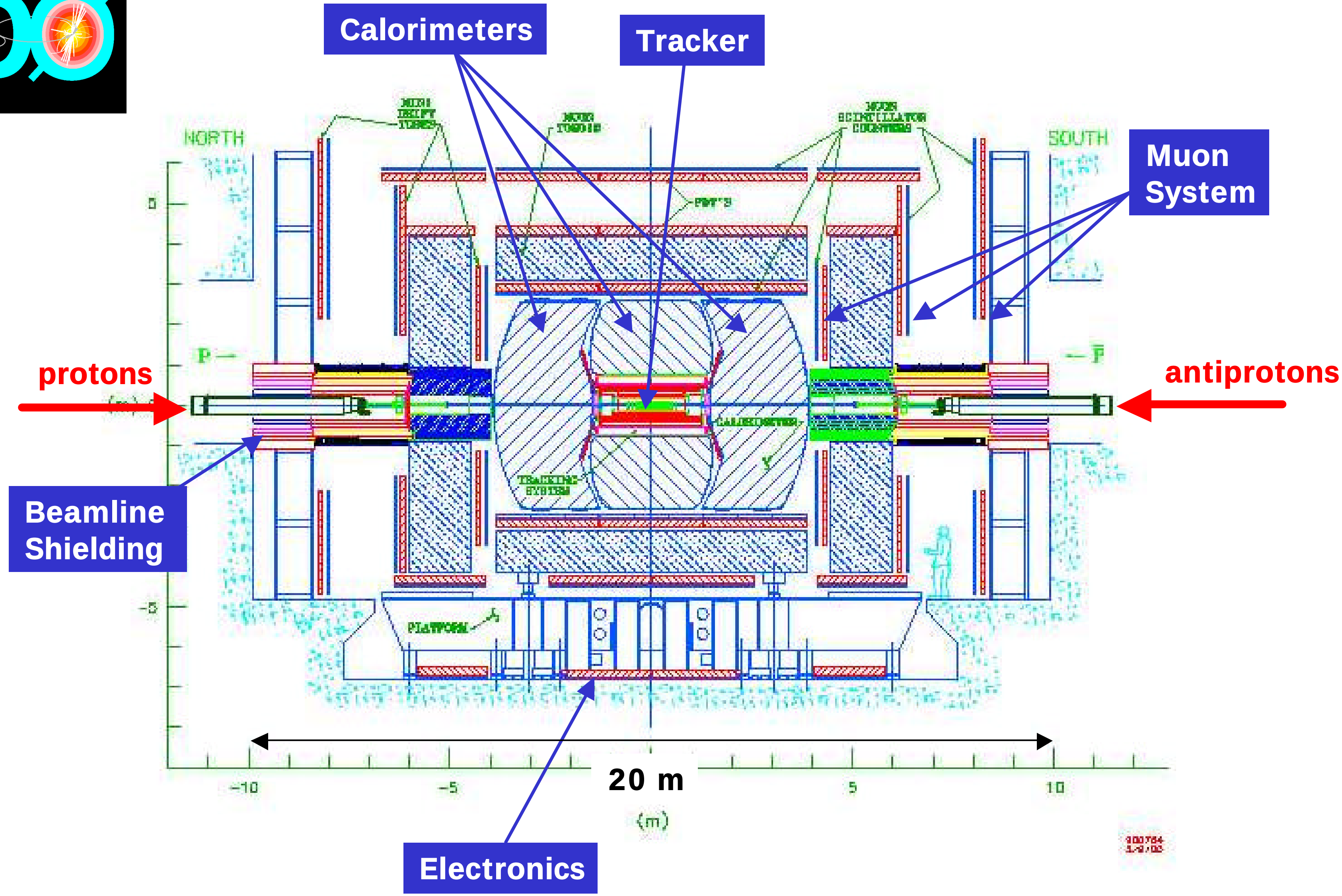
Typical detector

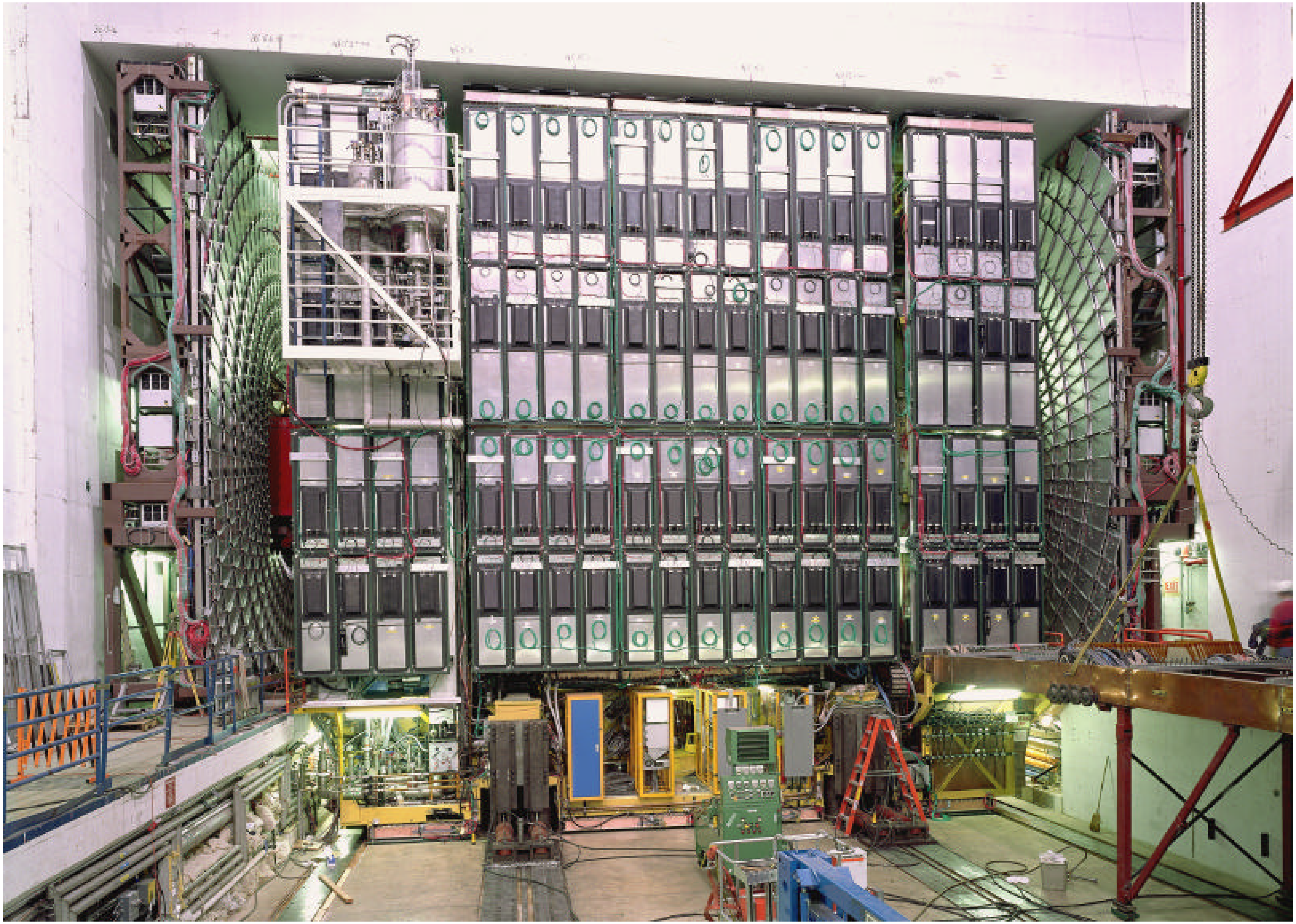




"Missing transverse energy"

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


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



DØ detector installed in the Collision Hall, January 2001

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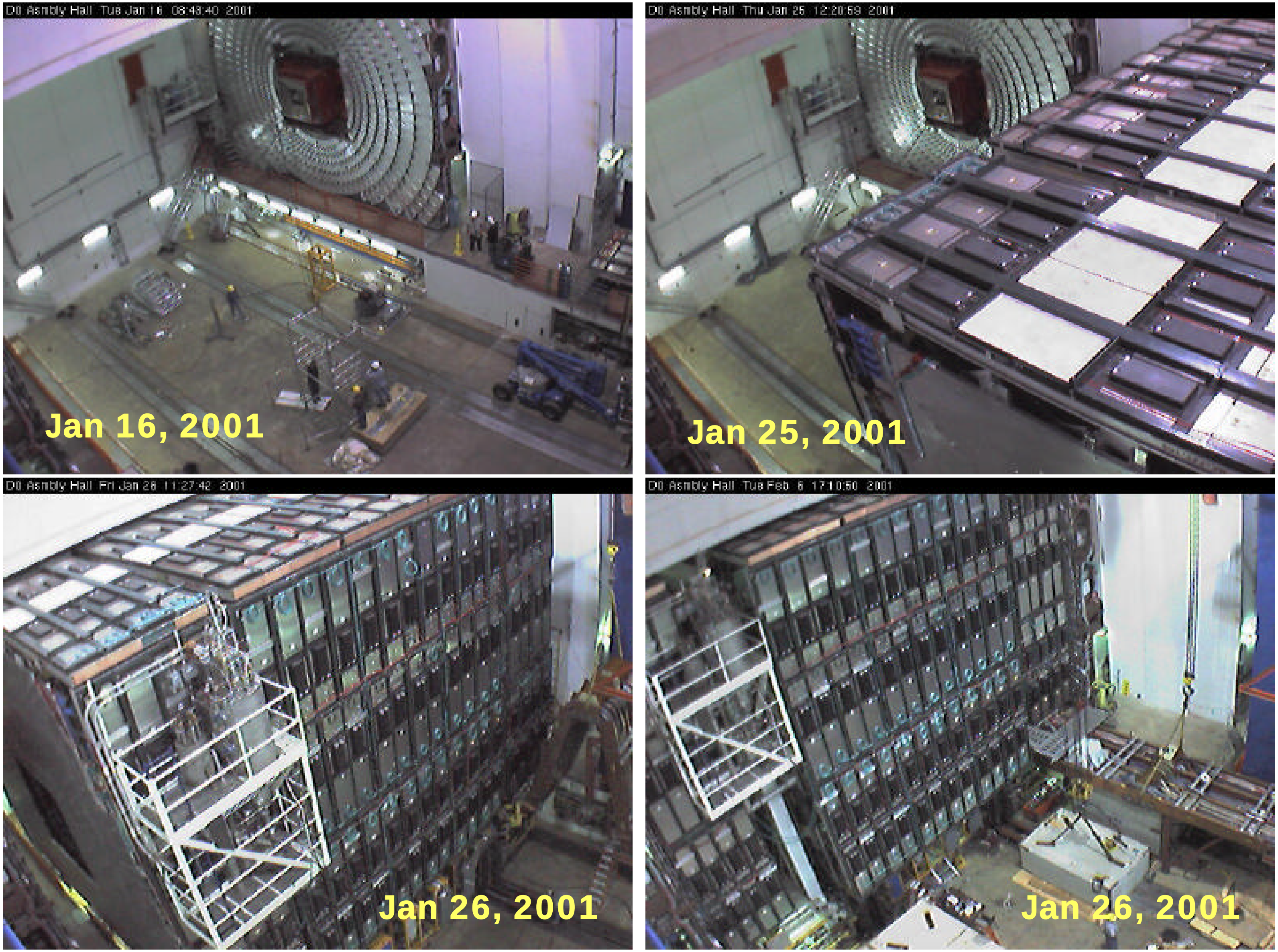
The work of many people...

The DØ detector was built and is operated by an international collaboration of ~ 550 physicists from 18 nations

> 50% non-USA
~ 120 graduate students


D0 Asmbly Hall Tue Jan 16 08:48:40 2001
Jan 16, 2001
D0 Asmbly Hall Thu Jan 25 12:20:59 2001
Jan 25, 2001
D0 Asmbly Hall Fri Jan 26 11:27:42 2001
Jan 26, 2001
D0 Asmbly Hall Tue Feb 6 17:10:50 2001
Jan 26, 2001

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Muon Detectors

Forward muon truss (supports C-layer detectors and shielding)

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

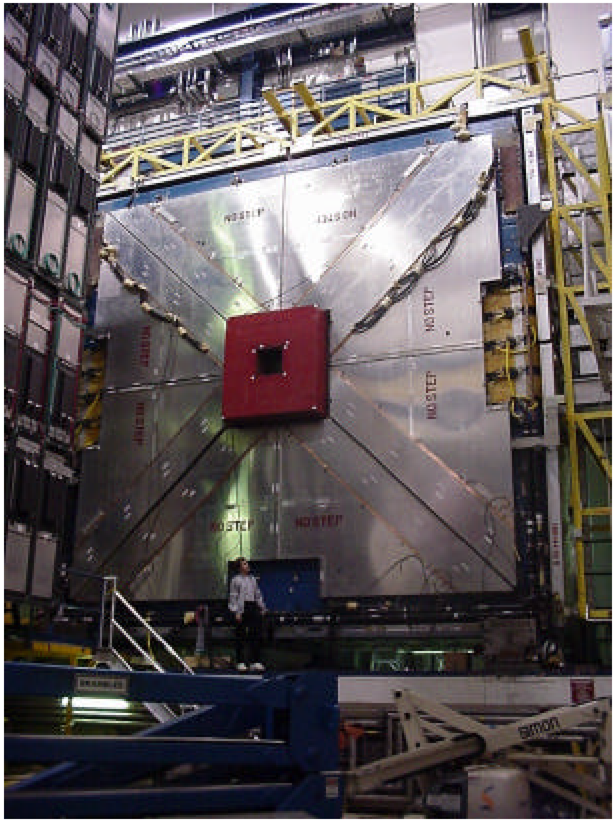
Forward muon trigger scintillators (From Protvino, Russia)

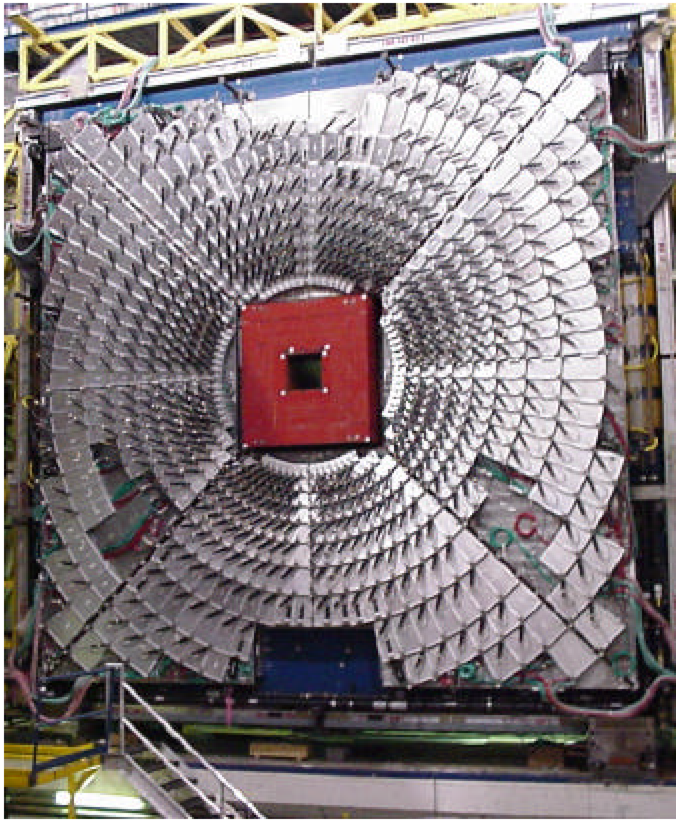
Muon Detector Installation

Shielding mounted on support truss

Mini drift tube plane (10m ´ 10m)

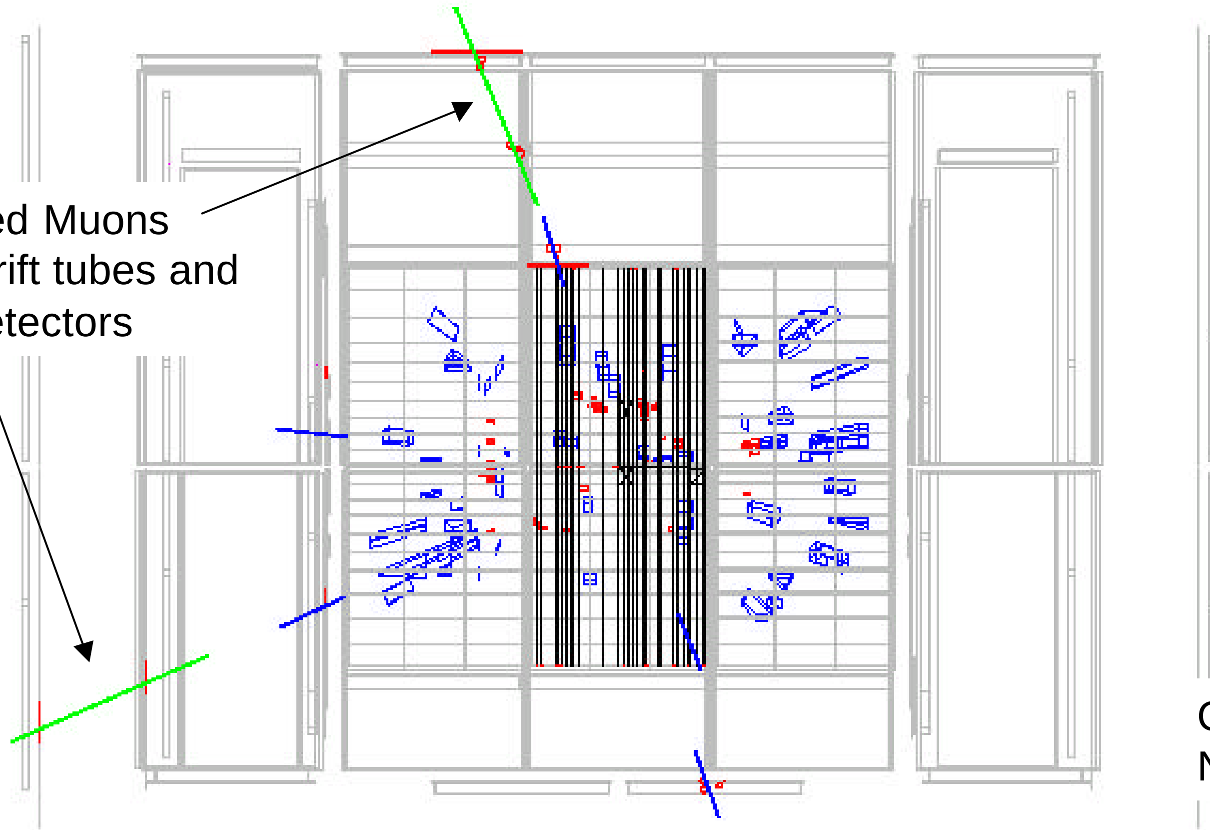
Trigger scintillator Plane (10m ´ 10m)





Dimuon Z candidate

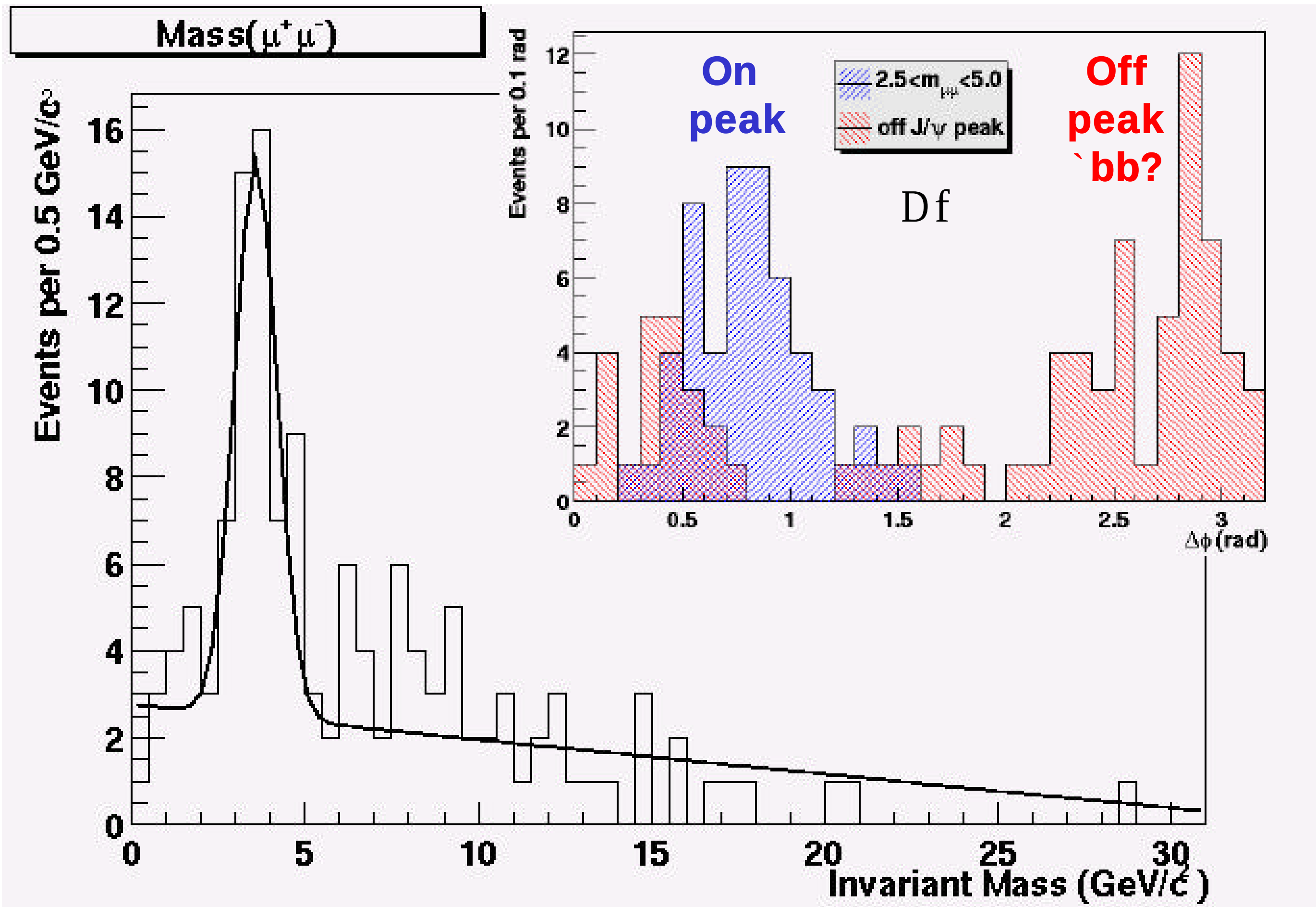
- **Two muons recoiling against a jet**
- **Dimuon invariant mass = 55 GeV**



Onne Peters
NIKHEF

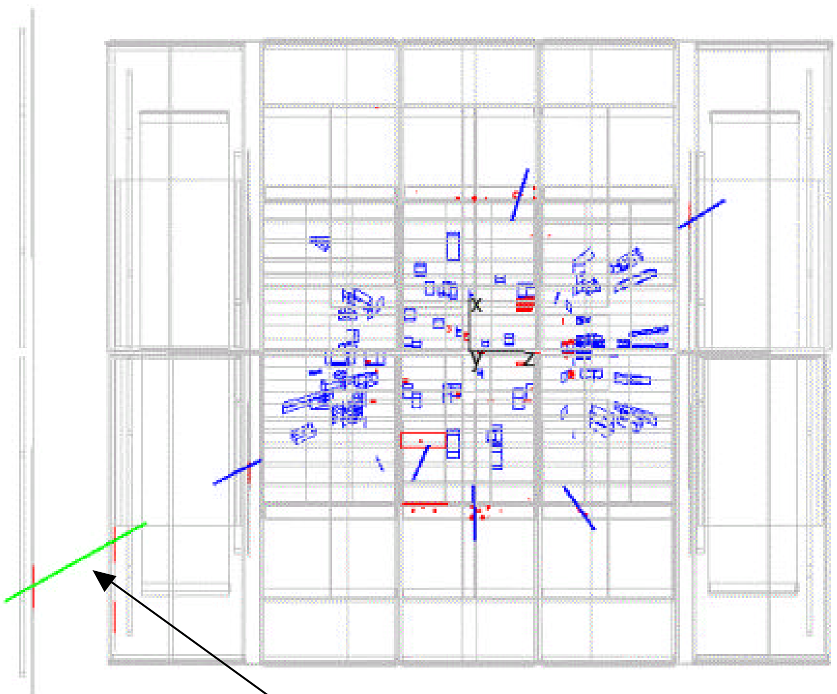
J/y ®m$^+$m$^-$ candidates

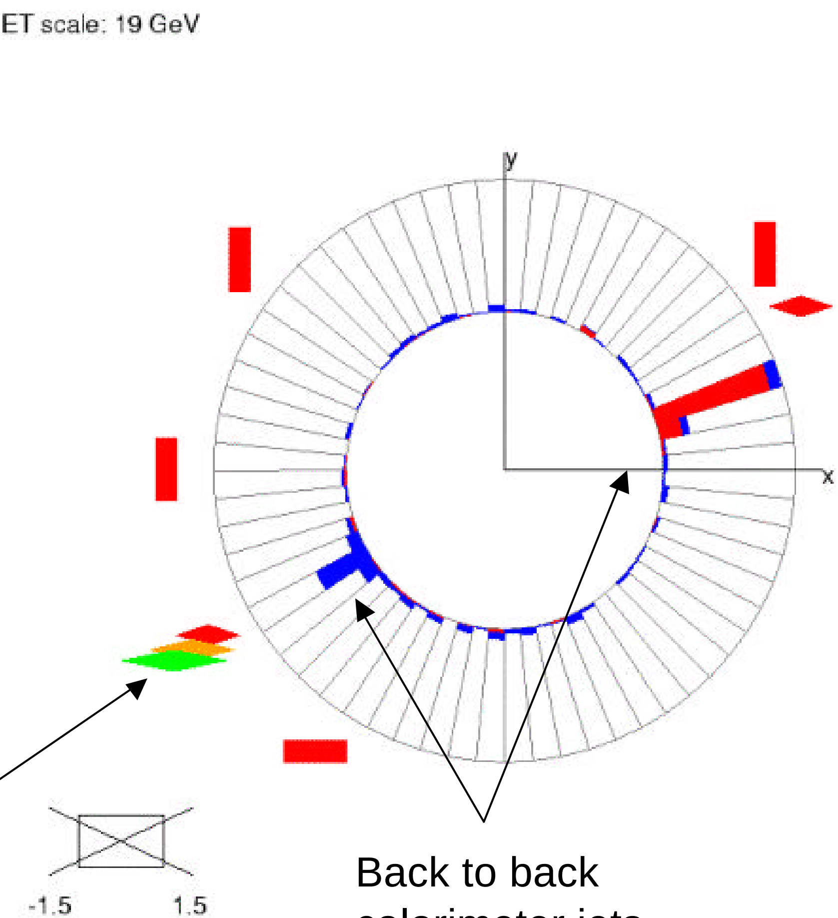
DØ: dimuons reconstructed in the forward region



Muons in jets

Onne Peters, NIKHEF

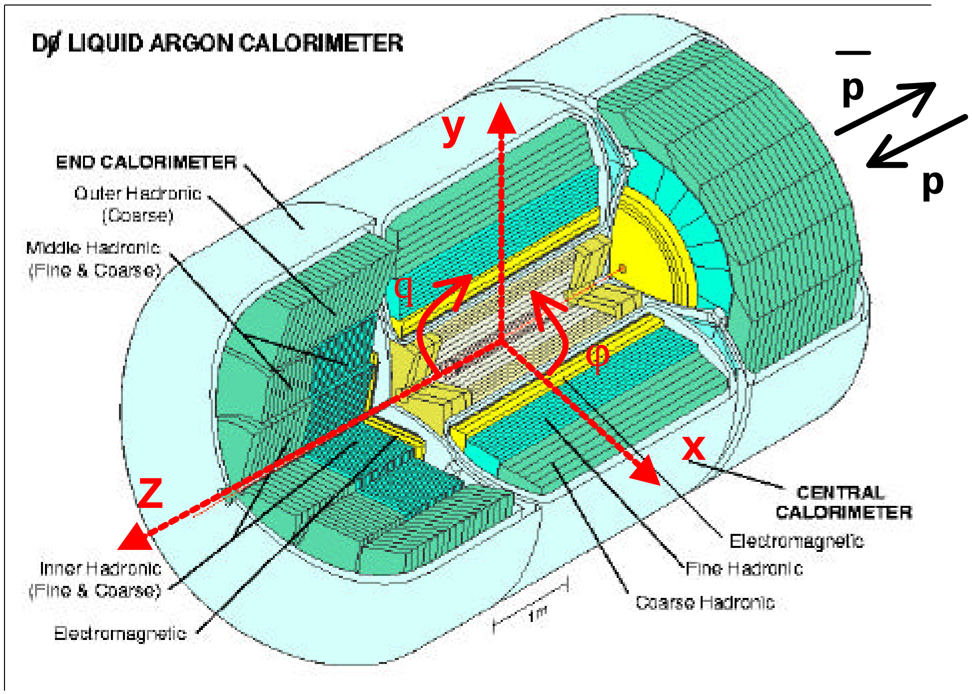


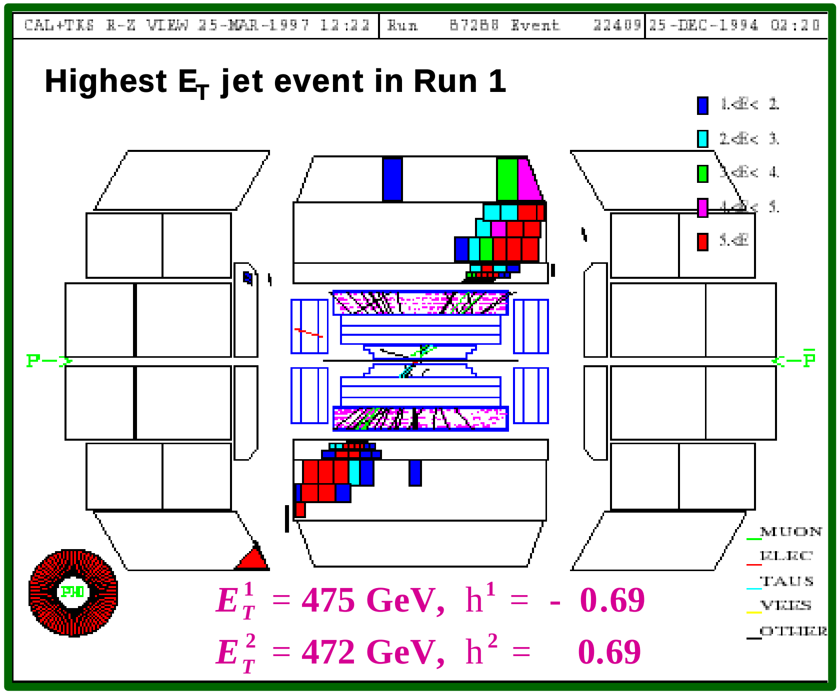


Muon in jet (b candidate)
Hits in A,B,C layers

Back to back
calorimeter jets

Liquid Argon Calorimeter





- **Liquid argon sampling with uranium absorber**
- **Transverse segmentation $\Delta\eta \times \Delta\phi$ = 0.1 × 0.1 (0.05 × 0.05 in EM3)**
- **Hermetic with full coverage: $|\eta| < 4.2$, $\lambda_{int} > 7.2$ (total)**

Electrons:	$\sigma_E / E = 15\% / \sqrt{E\,(GeV)} \oplus 0.3\%$
Jets:	$\sigma_E / E \sim 80\% / \sqrt{E\,(GeV)}$

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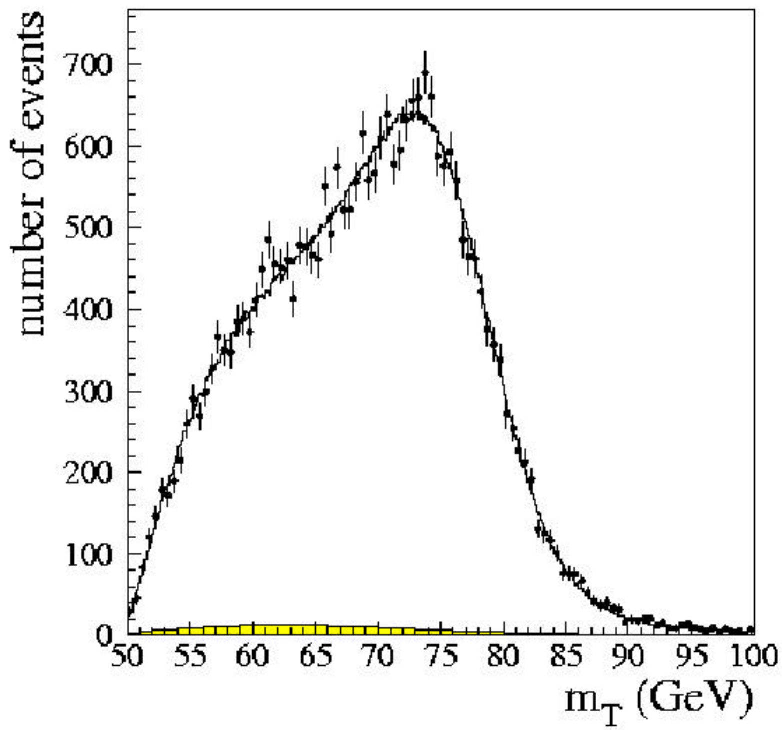
Run 1 Calorimeter Performance

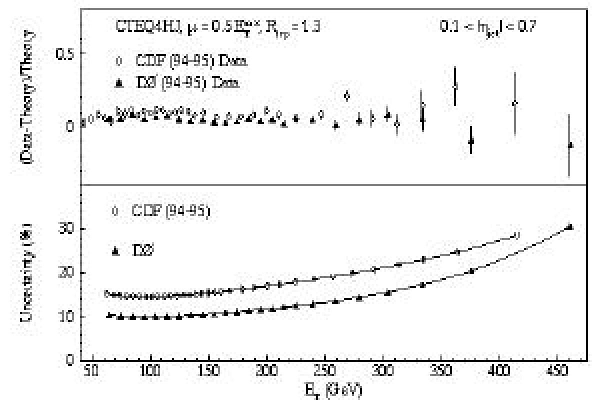
Electrons



m_W = 80.483 ± 0.084 GeV
DØ electrons

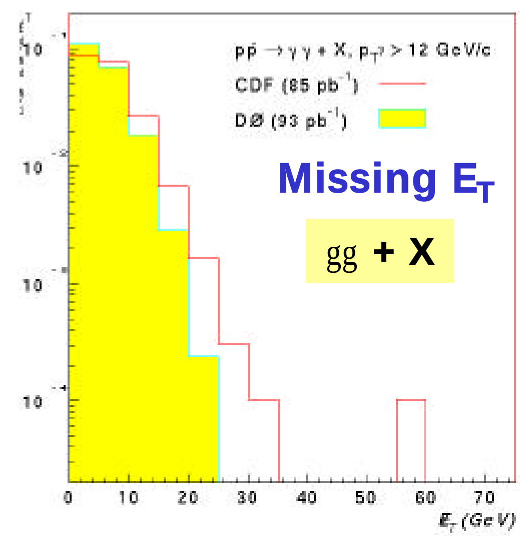
For Run 2, new calorimeter electronics (faster shaping, switched capacitor arrays)

Jets | **Inclusive jet cross section**



<u>Data-QCD</u>
QCD

% error



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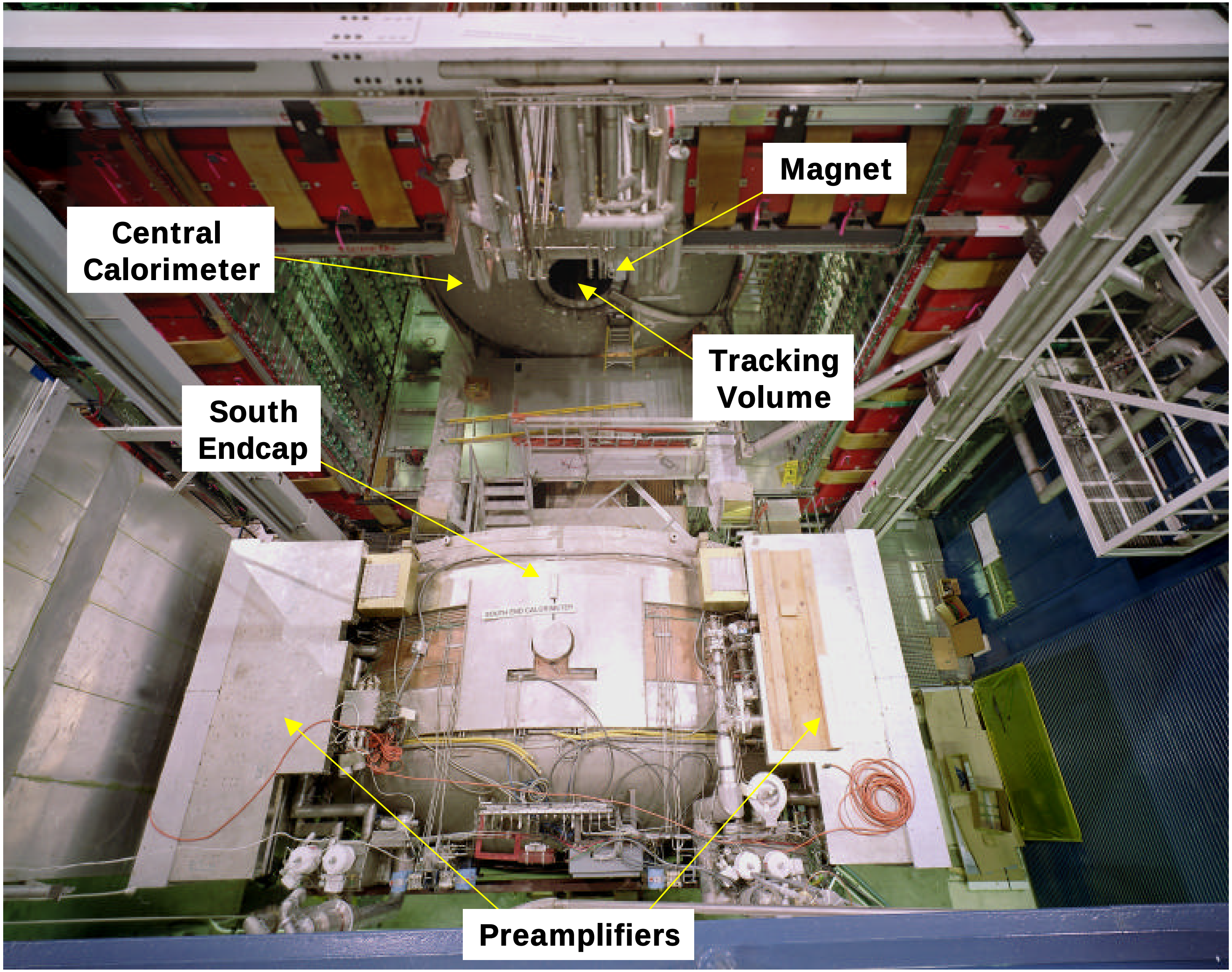
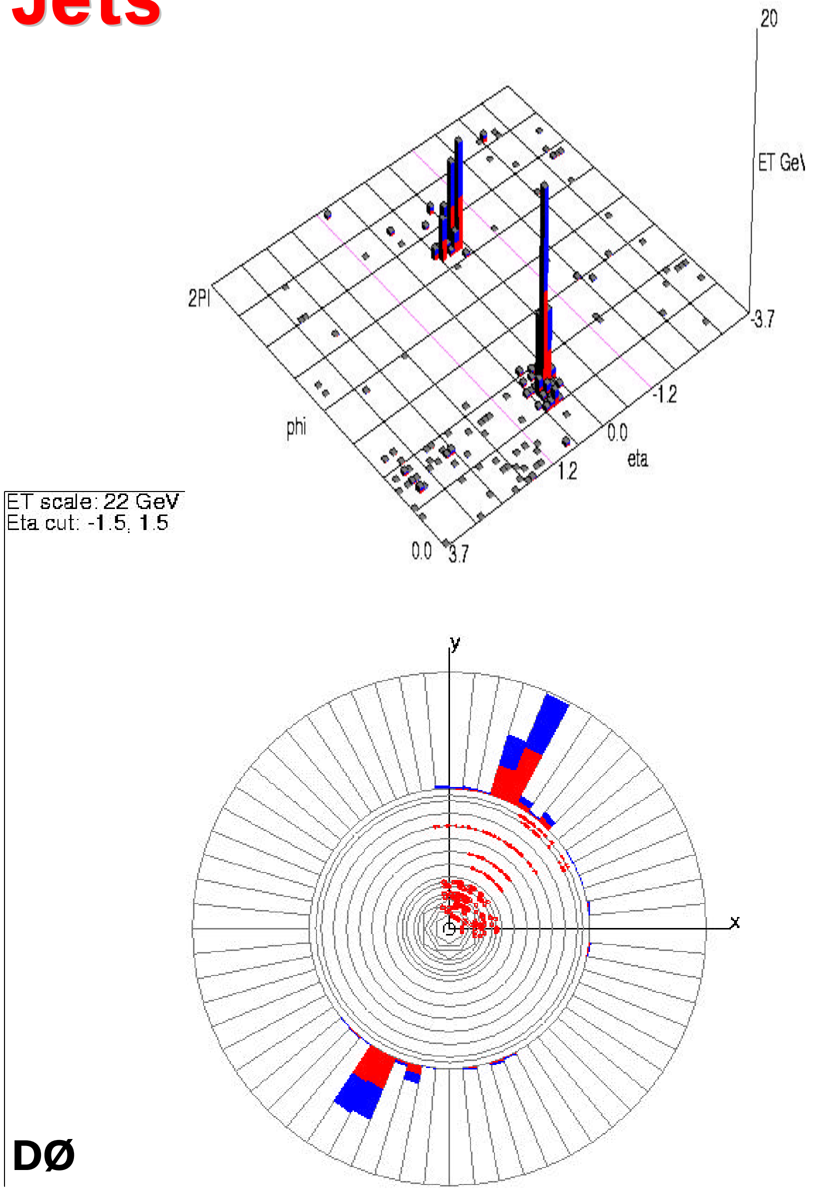

Magnet
Central Calorimeter
Tracking Volume
South Endcap
Preamplifiers

Jets



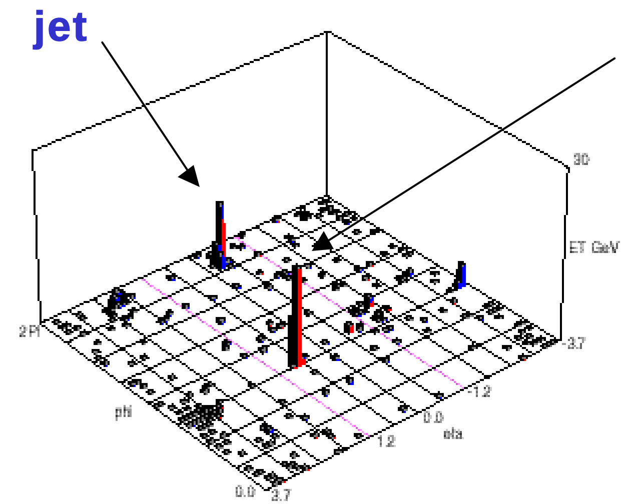
DØ

Gamma + Jet Candidate

Run 128309 Event 256324

jet

g



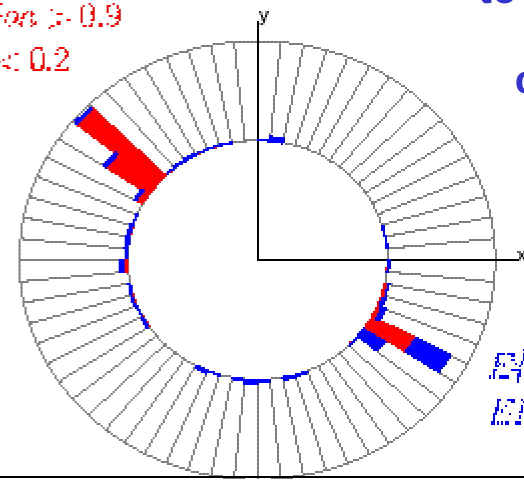
g candidate

E_T^{γ}=27 GeV,

EM fraction > 0.9

Isolation < 0.2

This type of event is used to derive the jet energy calibration



jet

E_T^{jet}=24 GeV

EM fraction = 0.48

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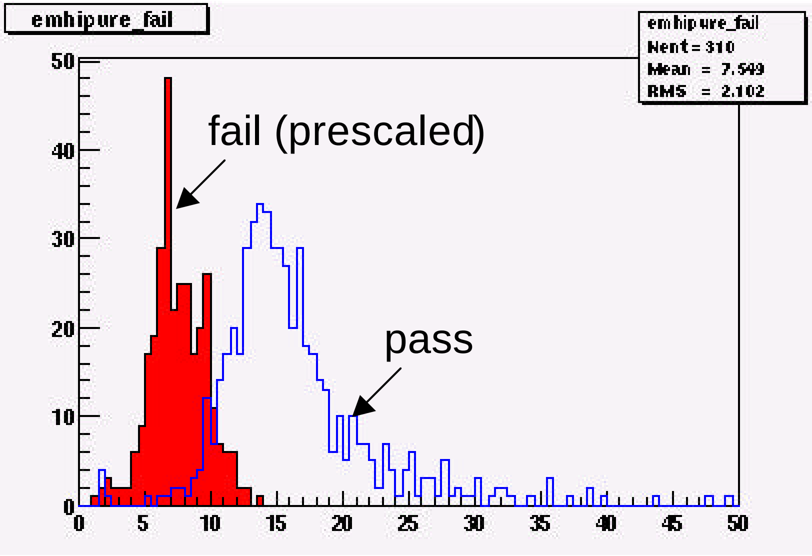
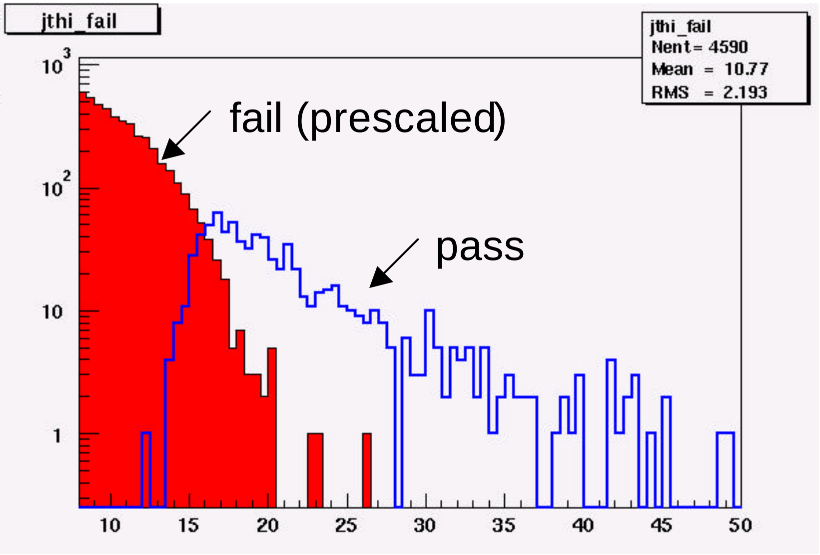
Level 3 calorimeter trigger

EM clusters, p_T > 10 GeV
Isolated, EM fraction > 0.9
|h| < 1.1

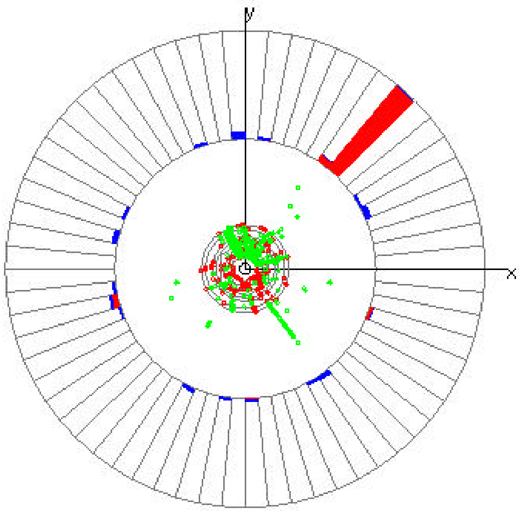


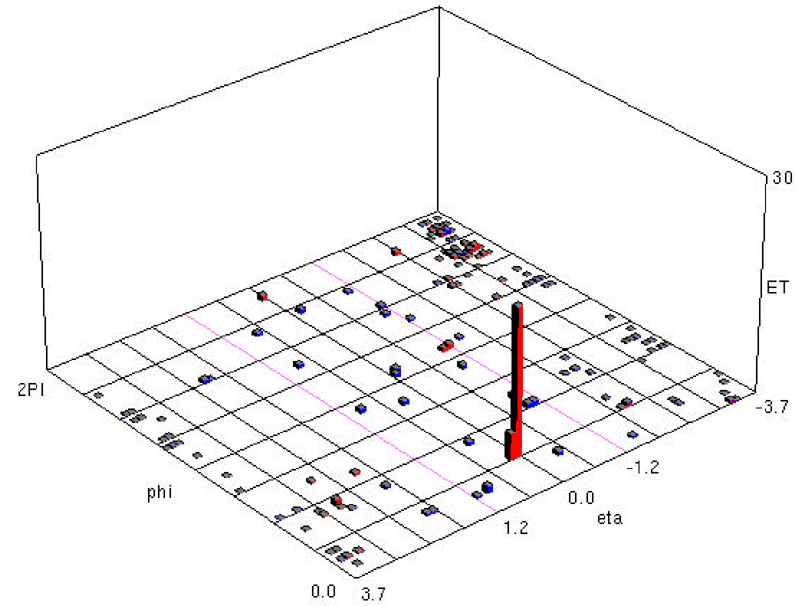
Jets, p_T > 15 GeV
R = 0.7 cone
|h| < 1.1

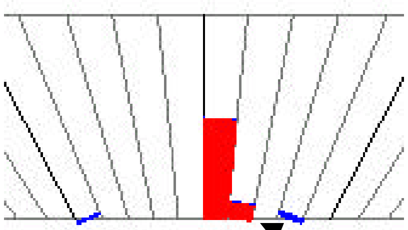


Volker Buescher
Mainz

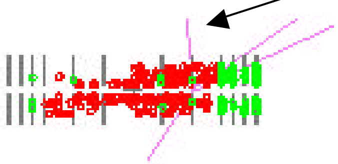
W ® en candidates

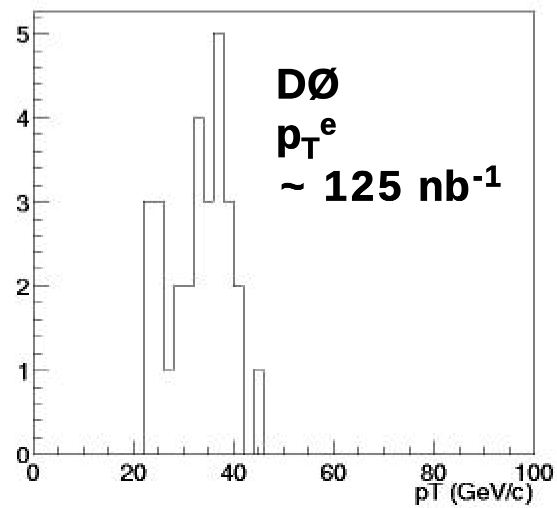






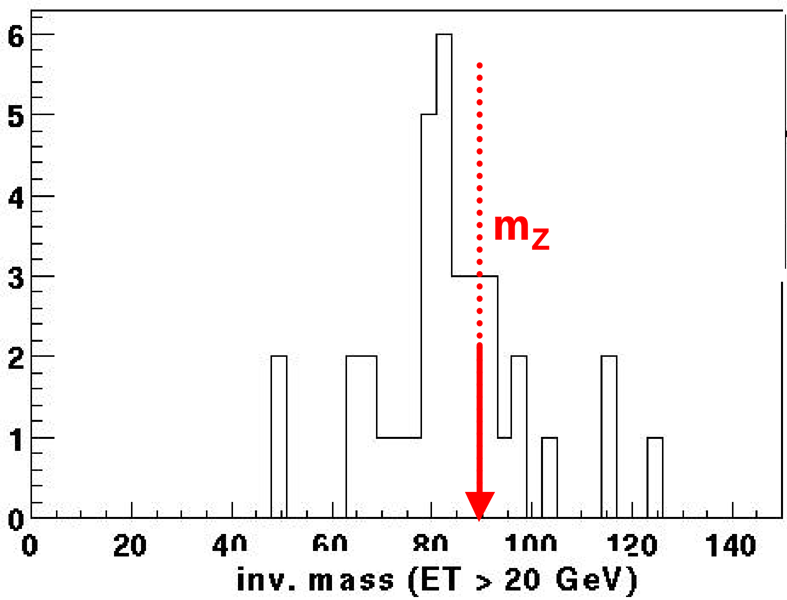
EM cluster with track



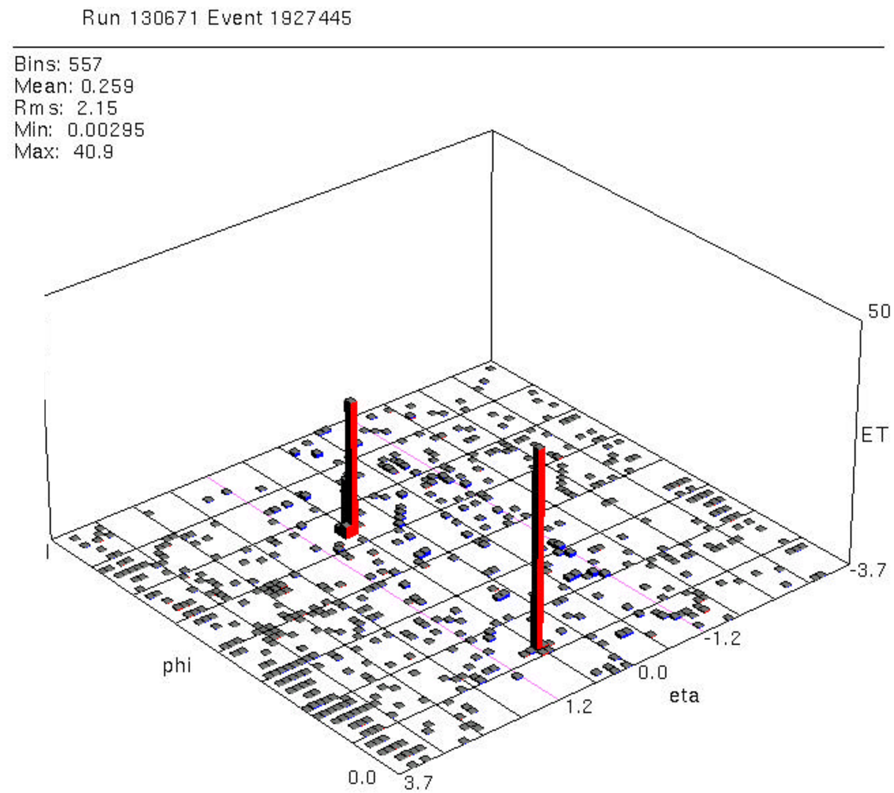


Z ® ee candidates

2 EM objects, $E_T > 20$ GeV,
isolation and shower shape cuts



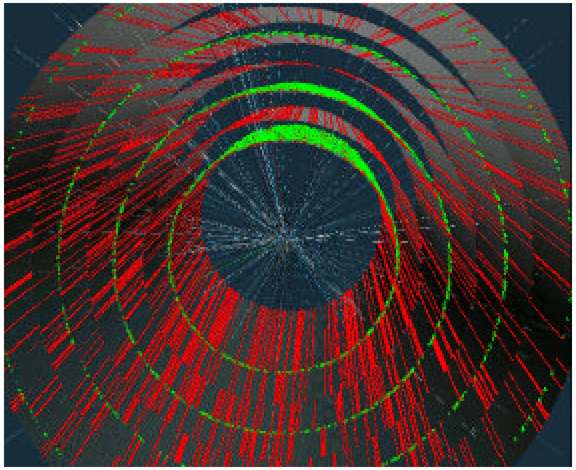
(uncalibrated energy scale)

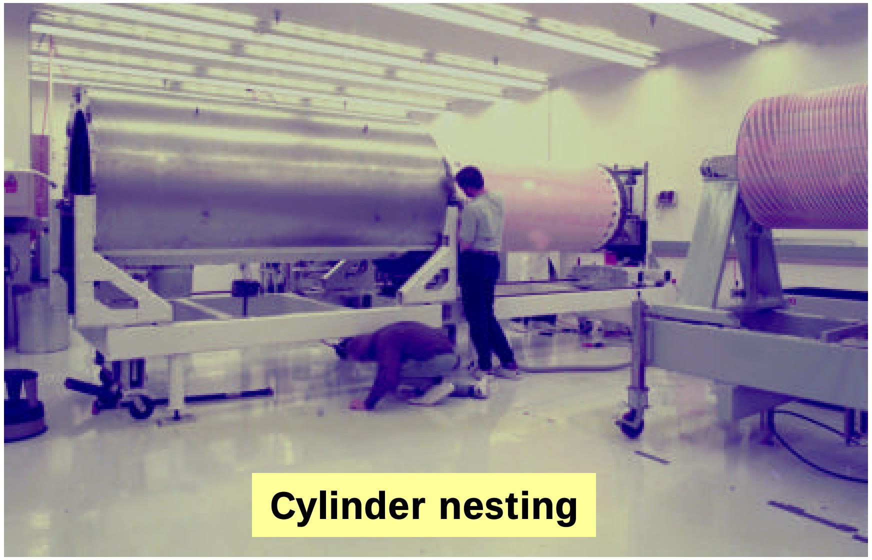


Leo Chan, Rochester

Scintillating Fiber Tracker

Tracker geometry and simulation of particle tracks



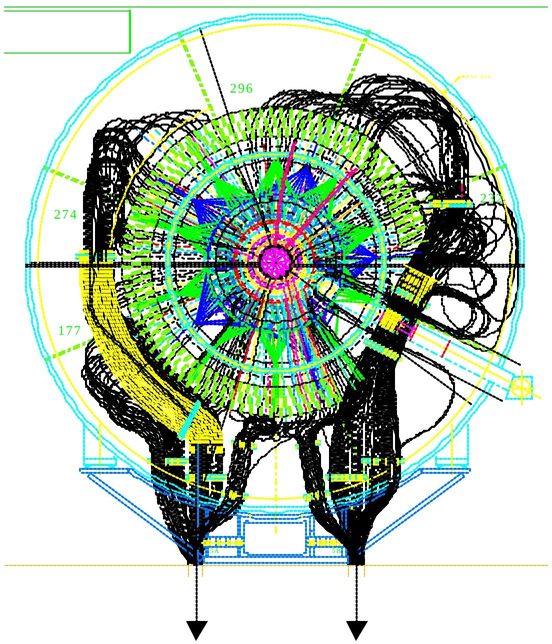


Cylinder nesting

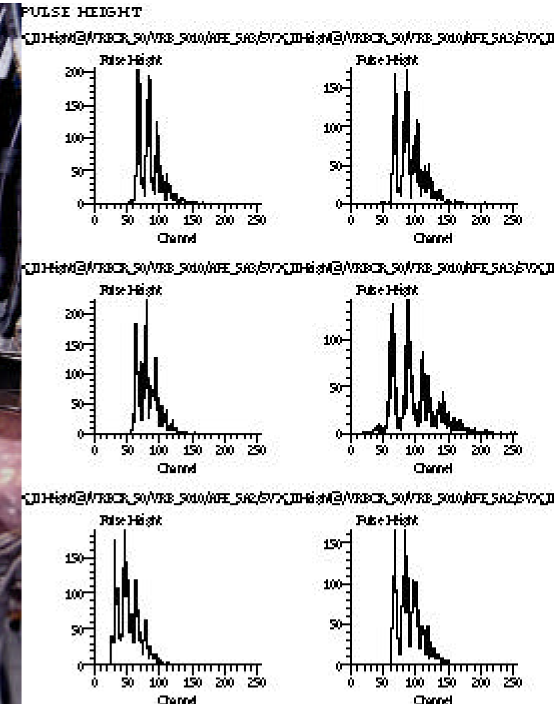
Ribbon manufacture

Tracker Installation

Fiber tracker readout



Readout under detector

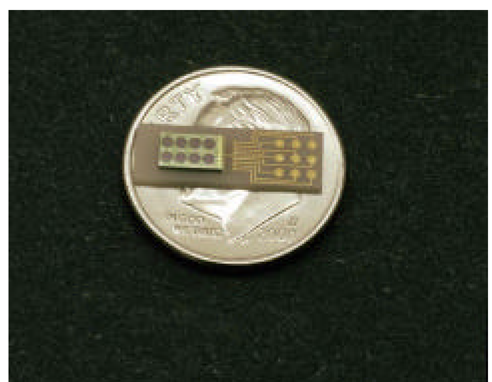


Photoelectron peaks in final electronics in DØ

1 pe ~ 7 fC

Clear Fiber Waveguides carry the signals to VLPC's

Solid state photon counters Operate at LHe temperature



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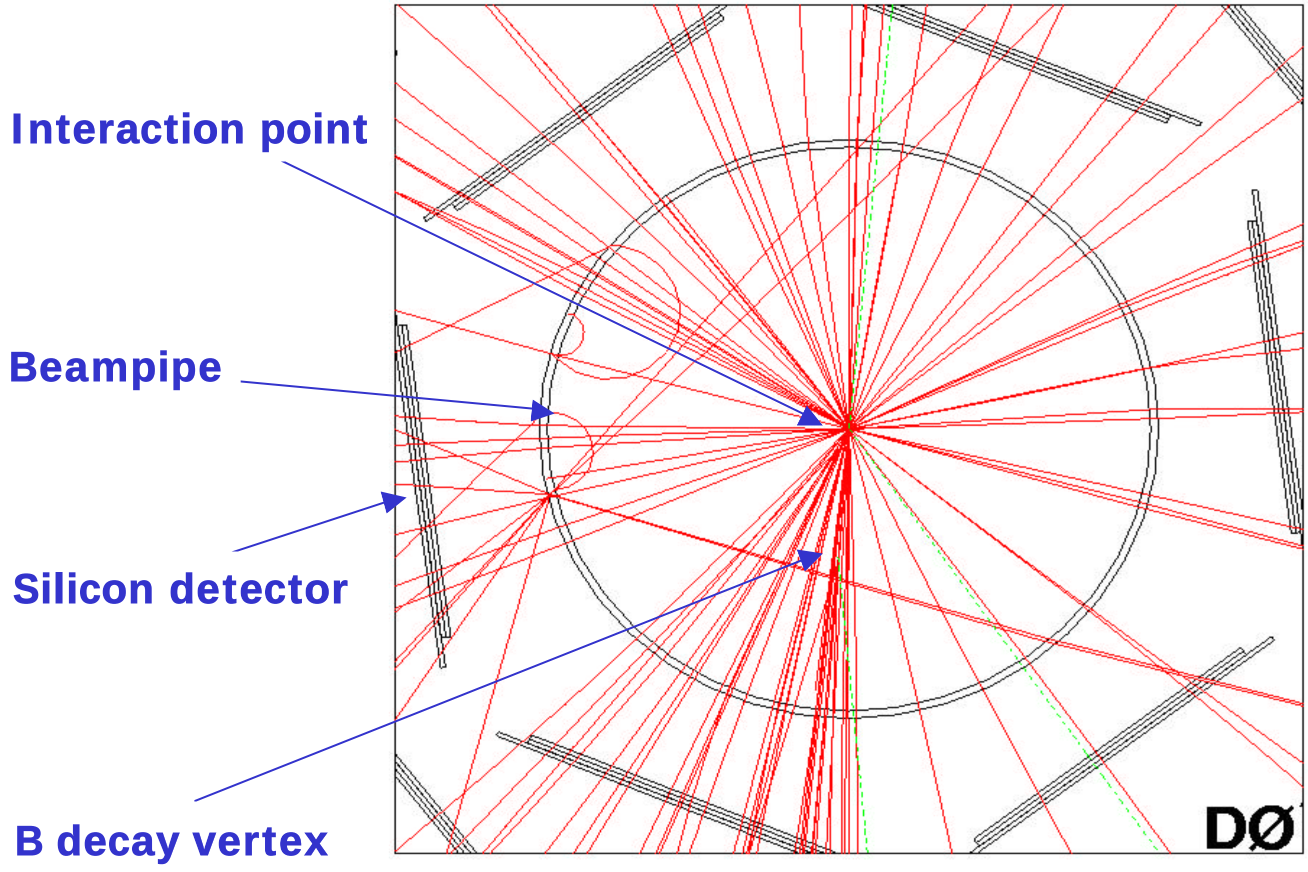
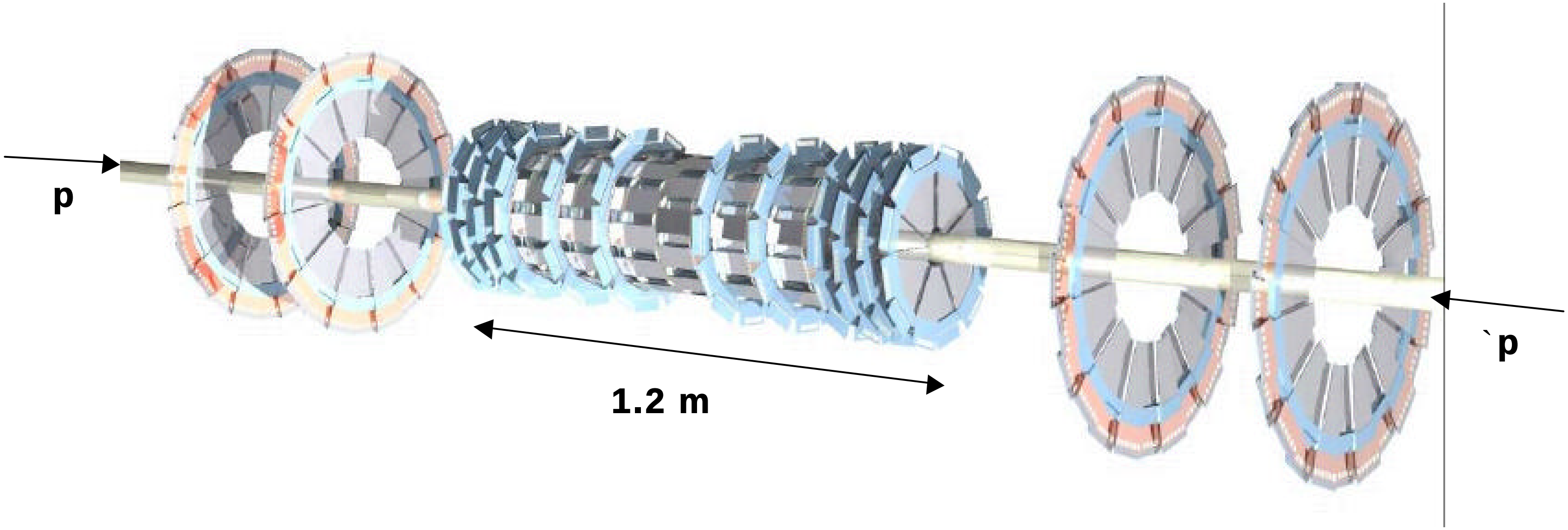
Displaced vertex tagging

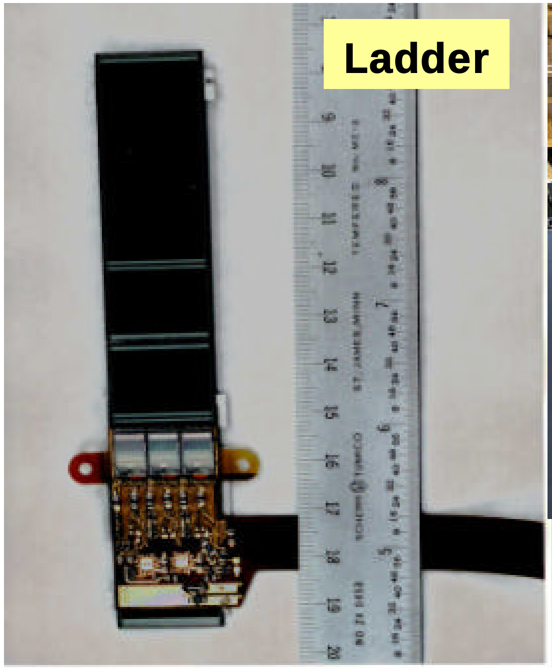
The ability to identify b quark jets is very important both for standard model physics (top . . .) and searches (Higgs, supersymmetry . . .)



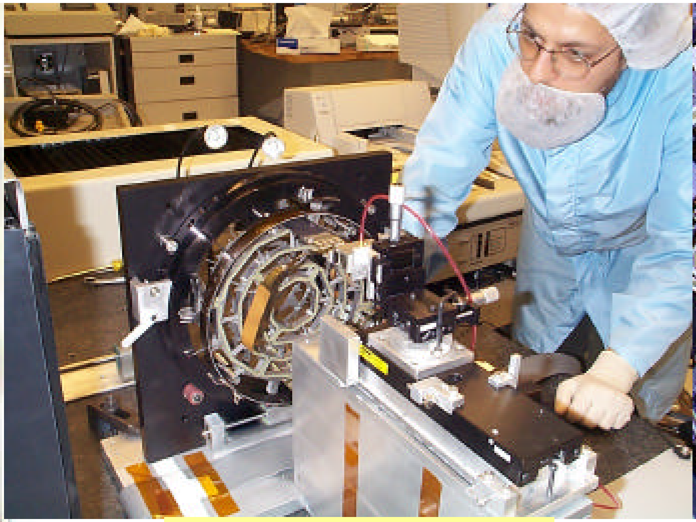
DØ Silicon Detector



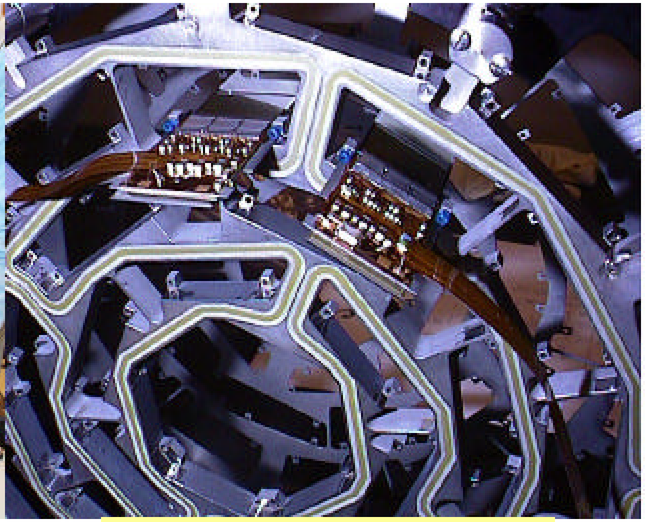
- The silicon detector is the closest detector element to the collision point
- ~ 800,000 channels of electronics (multiplexed readout on detector)
- Tagging efficiency at p_T = 50 GeV/c
  - ~ 50% for b-quark jets, ~ 10 % for c-quark jets
  - ~ 0.5% fake tag rate for u,d,s quark jets



Ladder

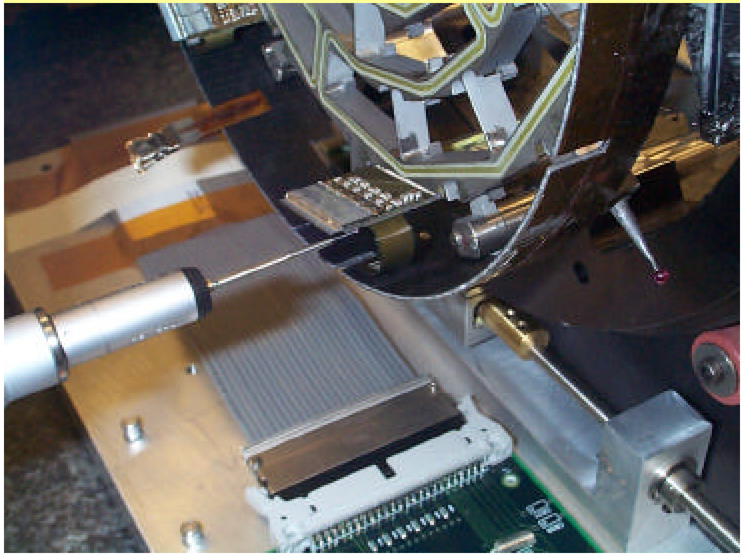


Ladder insertion



Beryllium bulkhead

Measuring ladder position after insertion



Coordinate measuring machine

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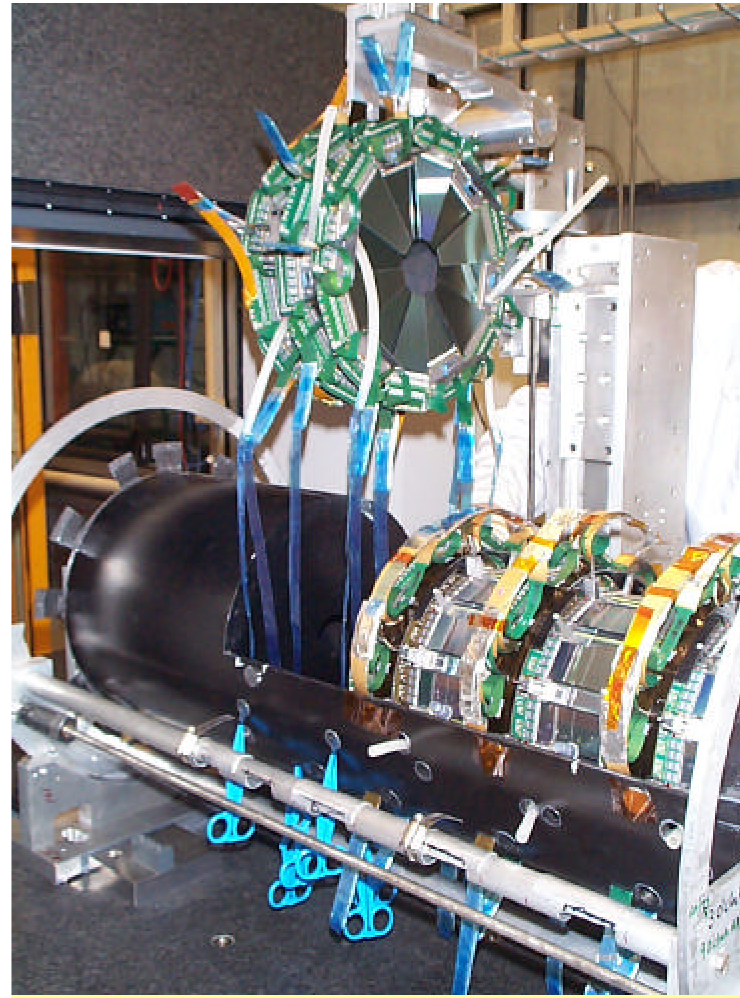
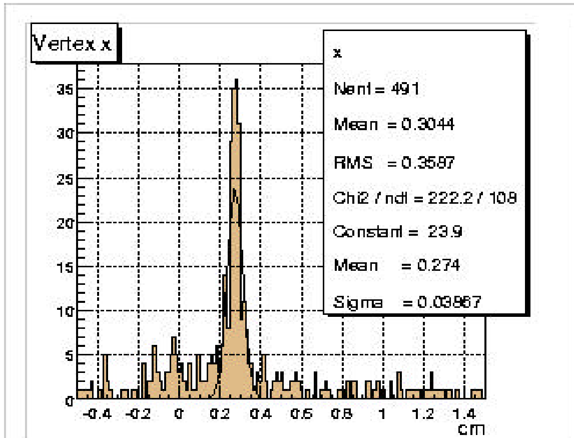
DØ south half detector



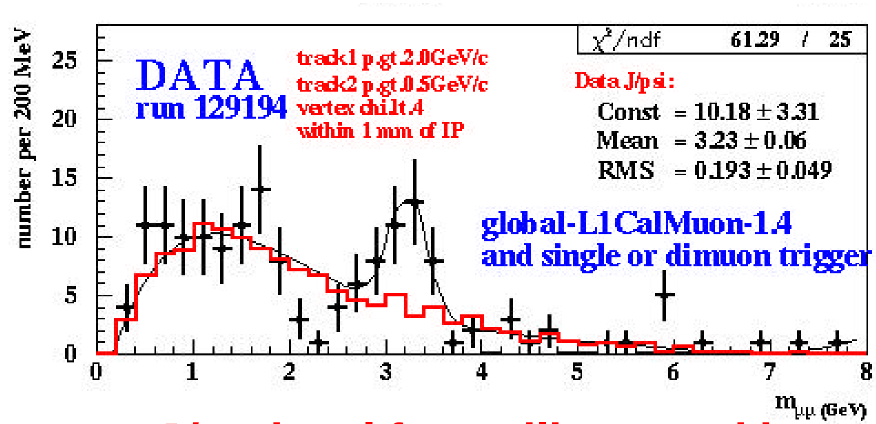
Inserting the forward disks

Silicon being inserted into centre of fiber tracker at DØ

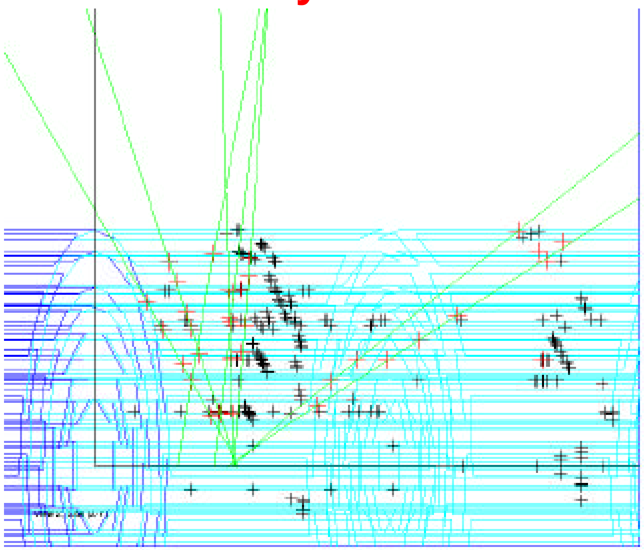
DØ silicon performance



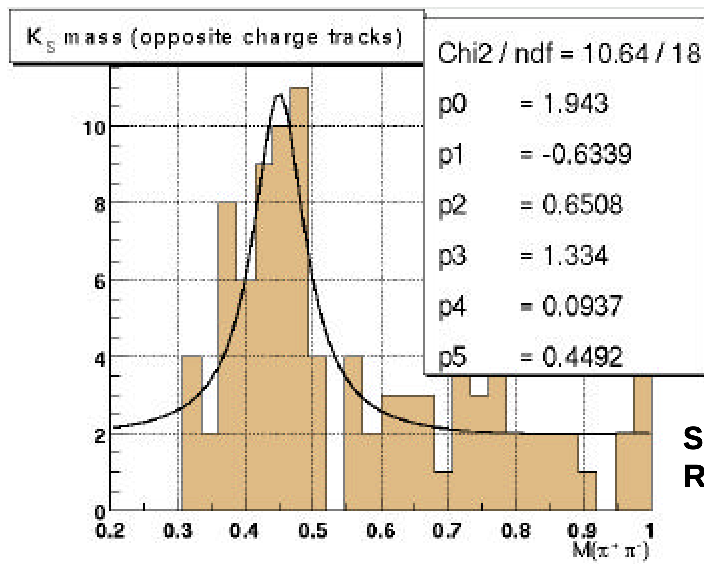
Primary vertex



J/y signal from silicon tracking



First reconstructed tracks
April 2001



Single Run

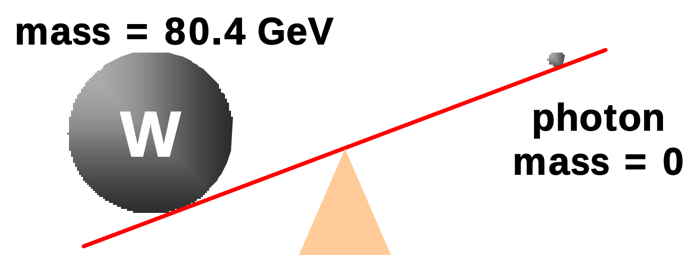
K^0 signal from silicon tracking

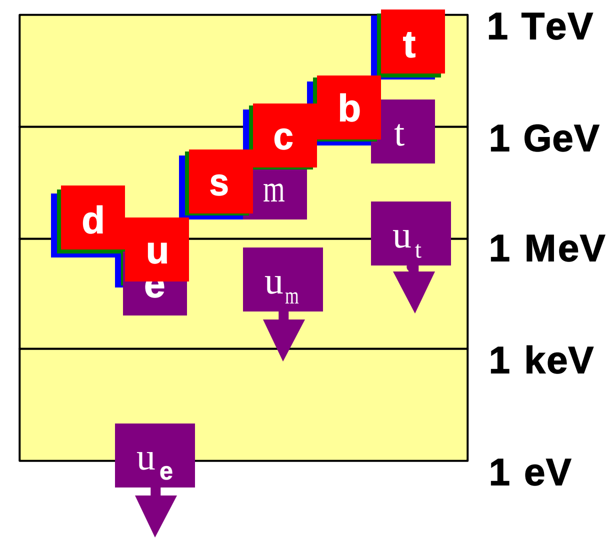
The Tevatron Physics Program

1. Direct searches for new physics
   - i.e. beyond the known Standard Model particles and forces
2. Precise measurements of the known quanta of the Standard Model
   - indirect hints (or constraints) on new particles and forces

The Higgs Mechanism

- **In the Standard Model**
  - **Electroweak symmetry breaking occurs through introduction of a scalar field f ® masses of W and Z**
  - **Higgs field permeates space with a finite vacuum expectation value = 246 GeV**
  - **If f also couples to fermions ® generates fermion masses**

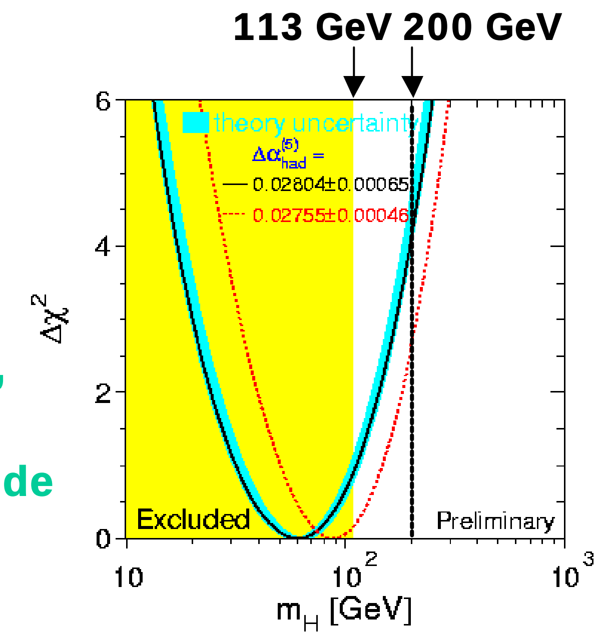




- **An appealing picture: is it correct?**
  - **One clear and testable prediction: there exists a neutral scalar particle which is an excitation of the Higgs field**
  - **All its properties (production and decay rates, couplings) are fixed except its own mass**

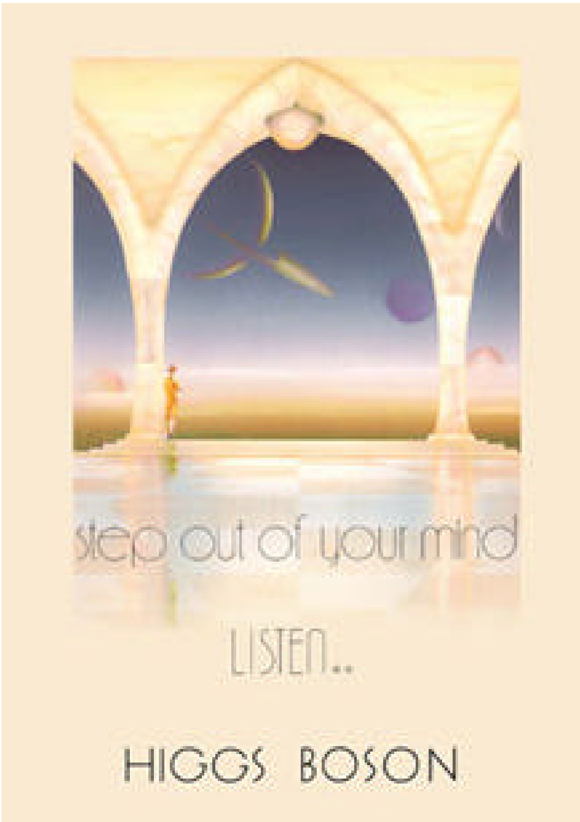
Highest priority of worldwide high energy physics program: find it!

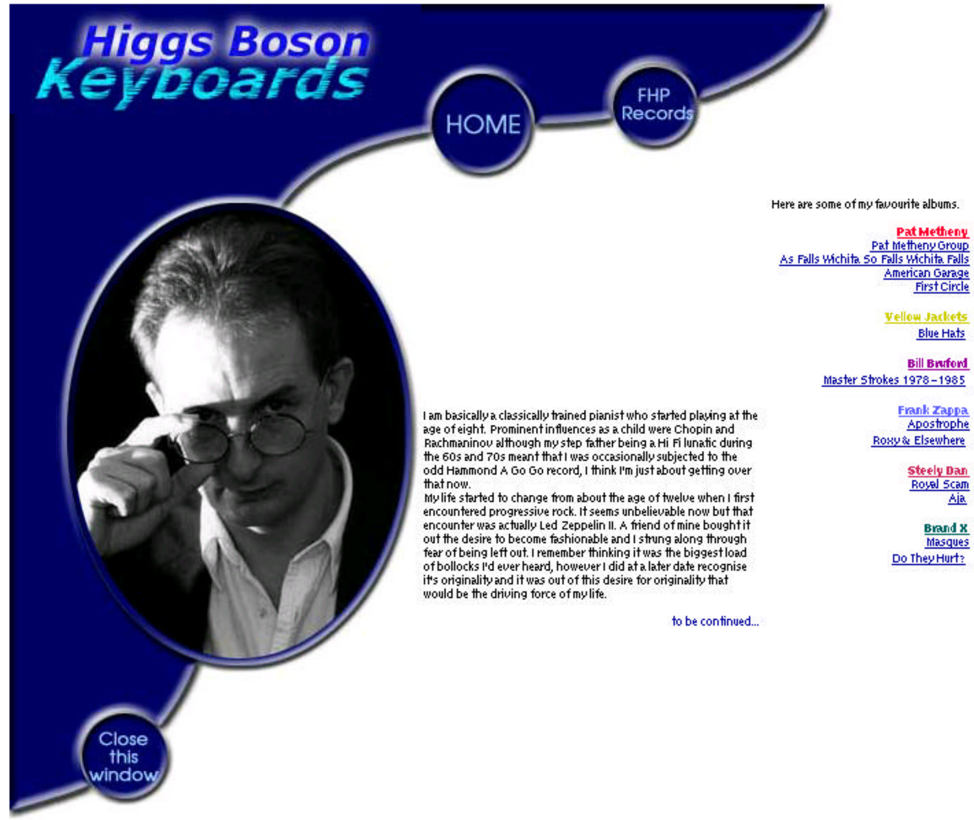
Searching for the Higgs



- 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 $m_H \sim 200$ GeV
  - direct searches for Higgs production exclude $m_H < 113$ 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 the Large Hadron Collider
- All eyes on Fermilab:
  - until about 2007, we have the playing field to ourselves

www.higgsboson.com

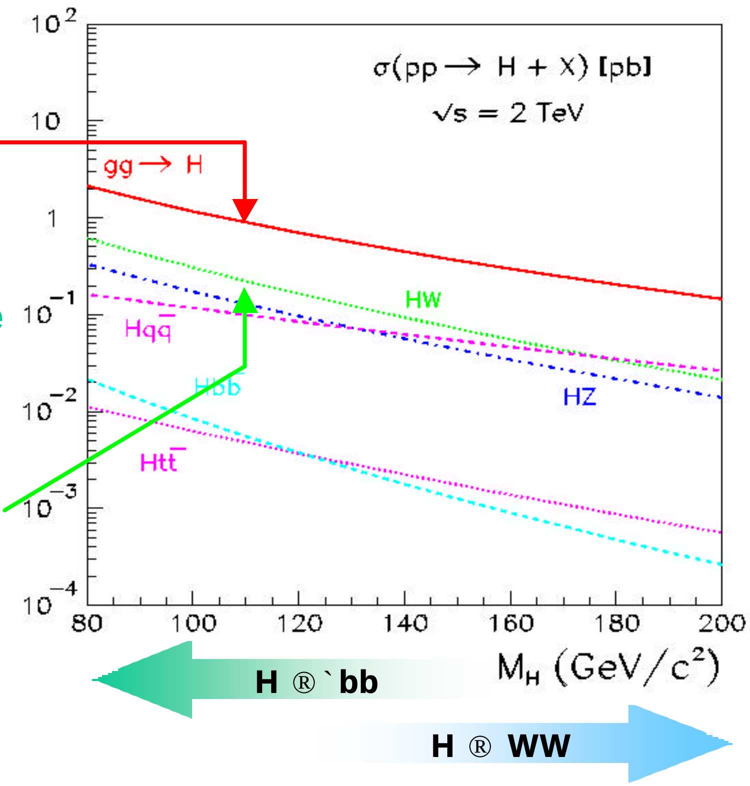




- Higgs Boson is the name of a British musician

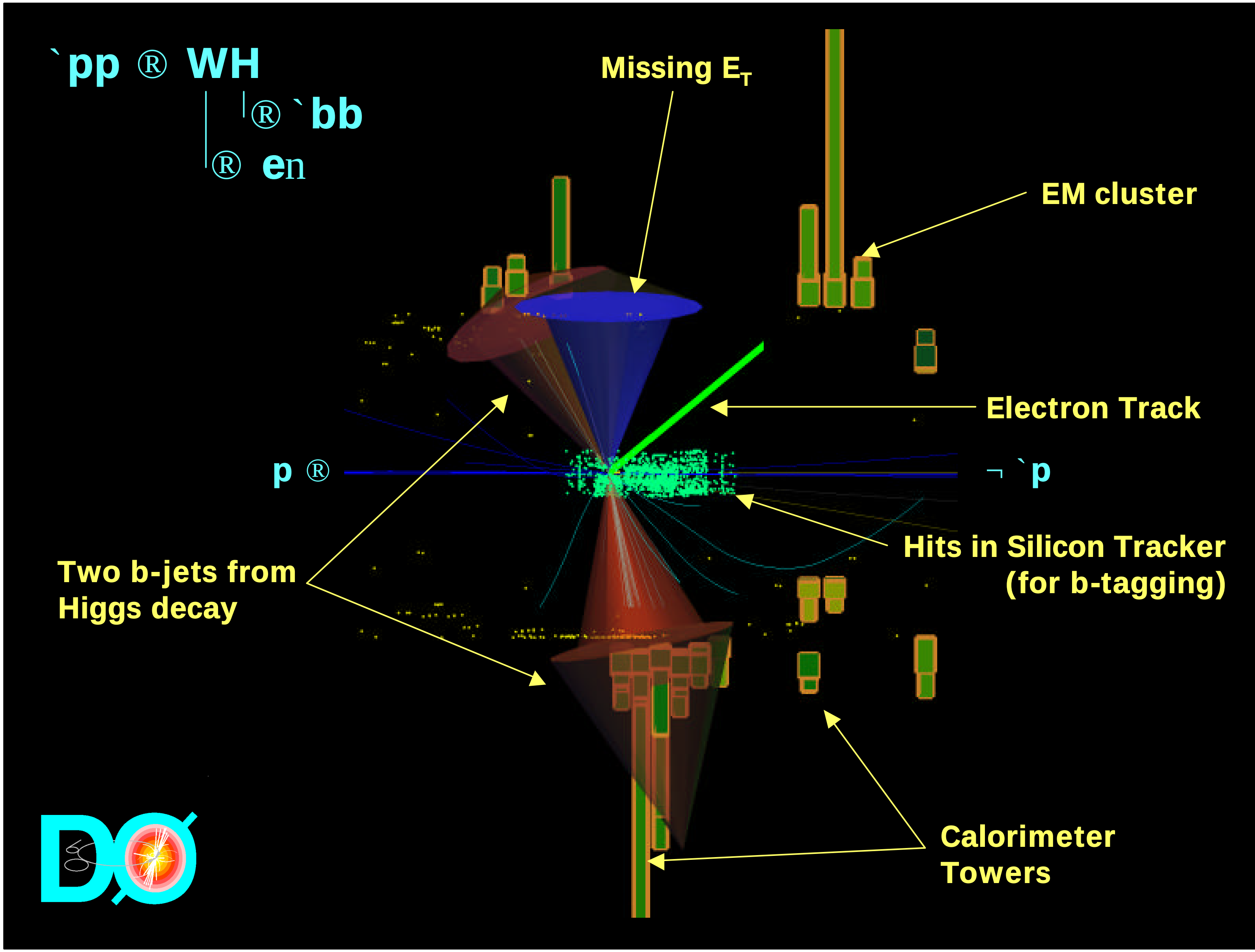
Higgs Hunting at the Tevatron

- **For any given Higgs mass, the production cross section and decays are all calculable within the Standard Model**
- **Inclusive Higgs cross section is quite high: ~ 1pb**
  - **for masses below ~ 140 GeV, the dominant decay is H ® bb which is swamped by background**
  - **at higher masses, can use inclusive production plus WW decays**



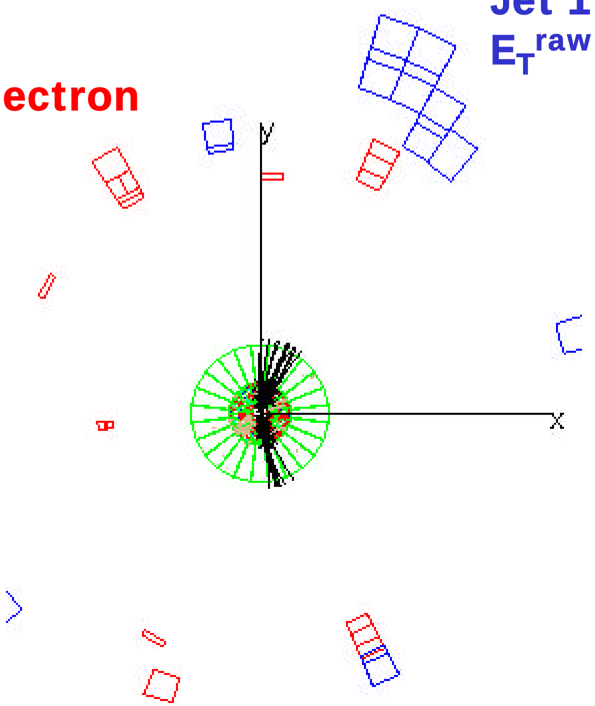
Dominant decay mode

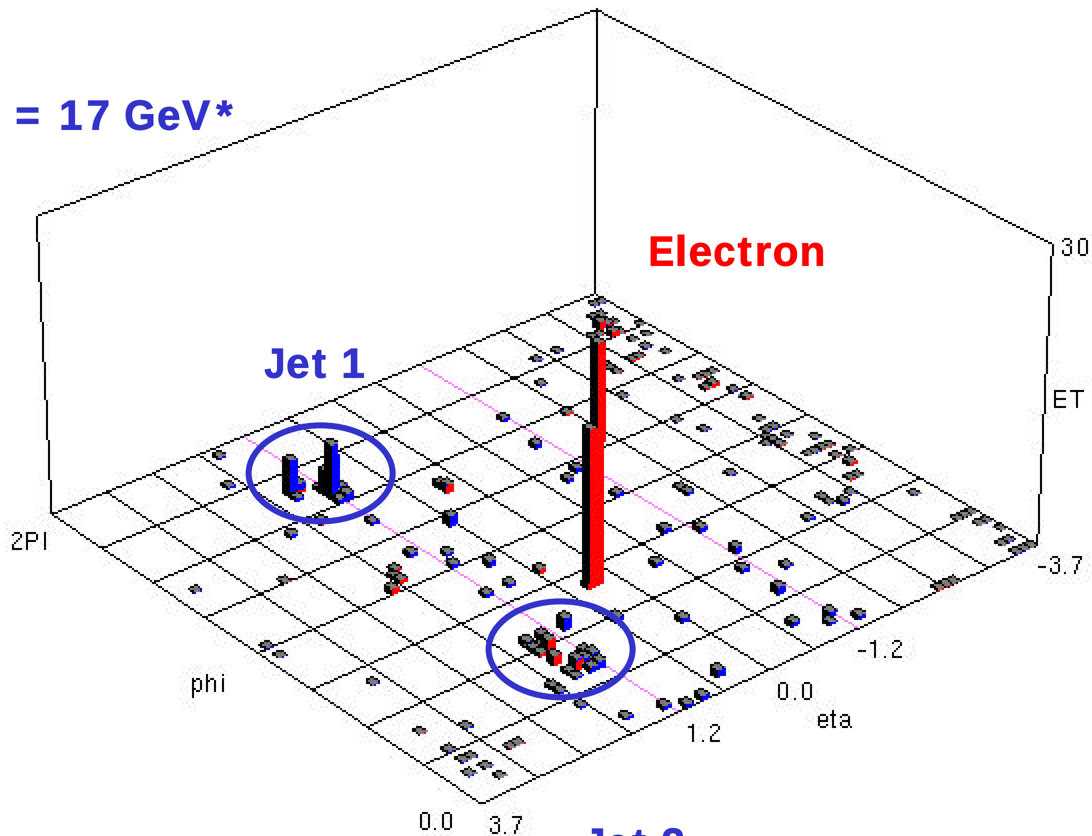
- **The best bet below ~ 140 GeV appears to be associated production of H plus a W or Z**
  - **leptonic decays of W/Z help give the needed background rejection**
  - **cross section ~ 0.2 pb**


`pp ® WH
® `bb
® en
Missing E_T
EM cluster
Electron Track
p ®
¬ `p
Hits in Silicon Tracker
(for b-tagging)
Two b-jets from
Higgs decay
Calorimeter
Towers

Just for fun . . .

DØ W + 2 jet (Higgs!) candidate, October 2001





*** Jet E_T corrections will be large**

Example: m_H = 115 GeV

- ~ 2 fb^{-1}/expt (2003): exclude at 95% CL
- ~ 5 fb^{-1}/expt (2004-5): evidence at 3s level
- ~ 15 fb^{-1}/expt (2007): expect a 5s signal

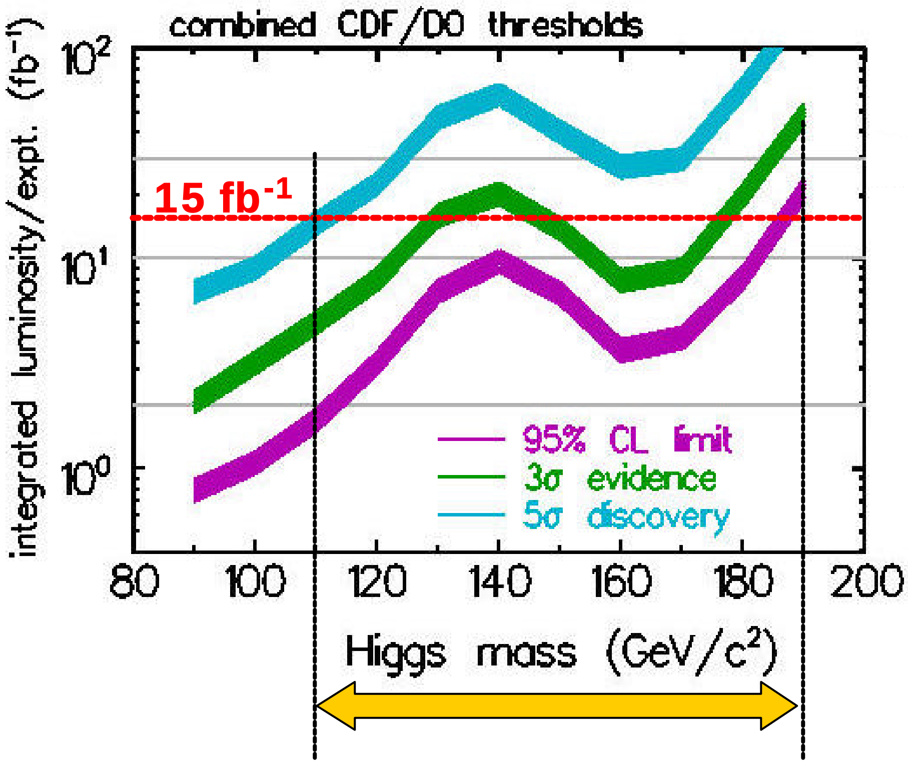
Every factor of two in luminosity yields a lot more physics

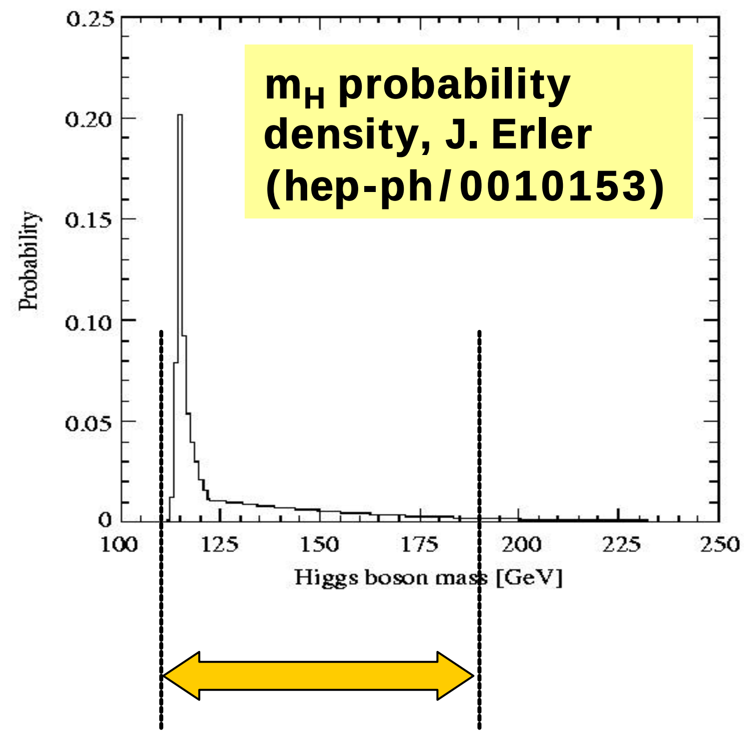
- Events in one experiment with 15 fb^{-1}:

Mode	Signal	Background	S/ÖB
l νbb	92	450	4.3
ννbb	90	880	3.0
l l bb	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 ® tt? (Branching Ratio ~ 8%)

Combined Higgs mass reach





110-190 GeV

"that's where the money is"

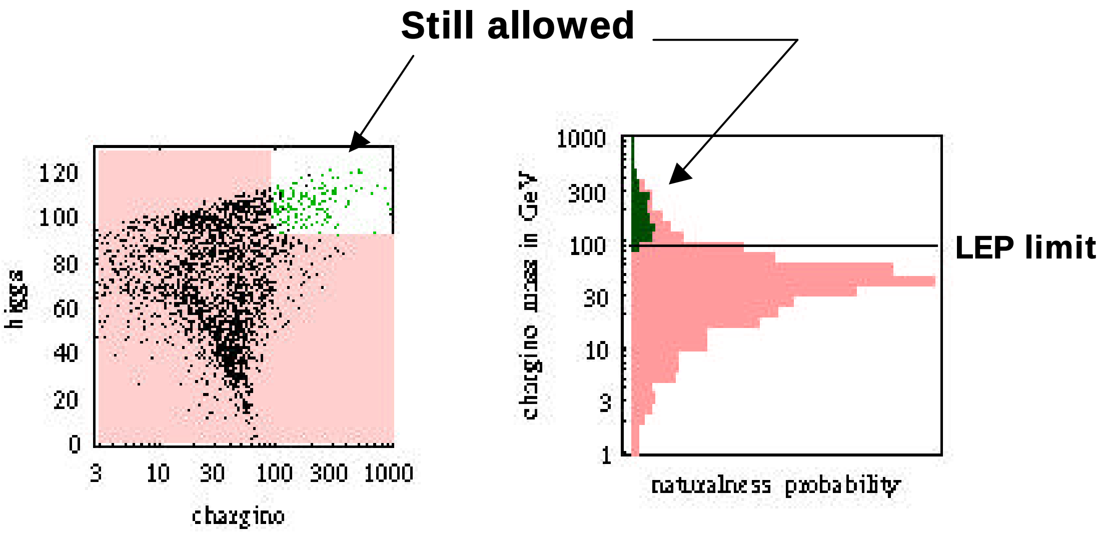
Supersymmetry

- Postulate a symmetry between bosons and fermions:
  - all the presently observed particles have new, more massive superpartners (SUSY is a broken symmetry)
- Theoretically nice:
  - additional particles cancel divergences in m_H
    - can naturally be of order the EW scale, ~ 250 GeV
  - SUSY closely approximates the standard model at low energies
  - allows unification of forces at much higher energies
  - provides a path to the incorporation of gravity and string theory: Local Supersymmetry = Supergravity
  - lightest neutralino is a cosmic dark matter candidate
- 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

Where is SUSY?

Direct searches at LEP and the Tevatron all negative so far

- Typical minimal supergravity-inspired SUSY models are already excluded at the 95% level
  (e.g. Strumia, hep-ph/9904247)

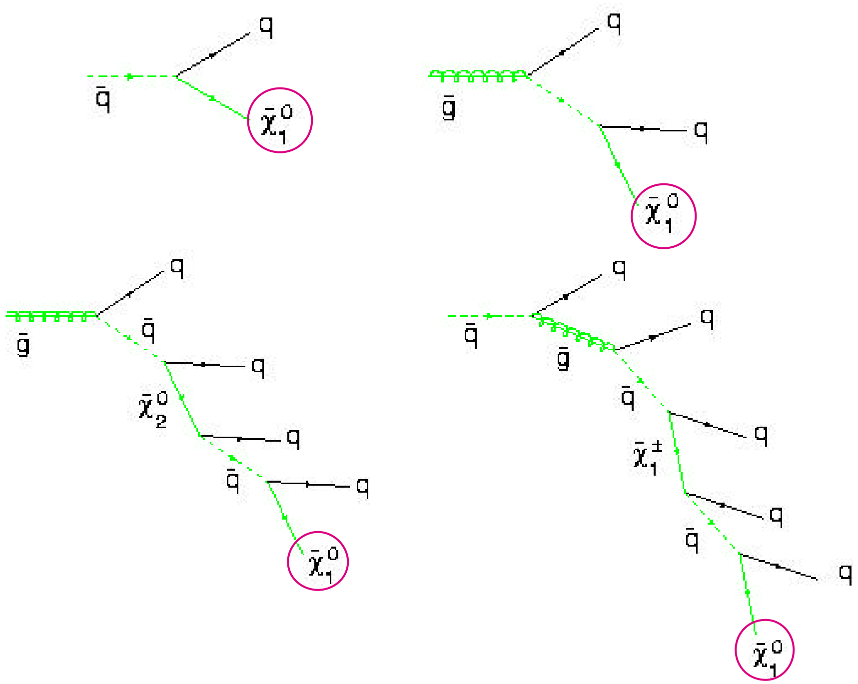


- Either we should expect to see something soon, or we are on the wrong track . . .

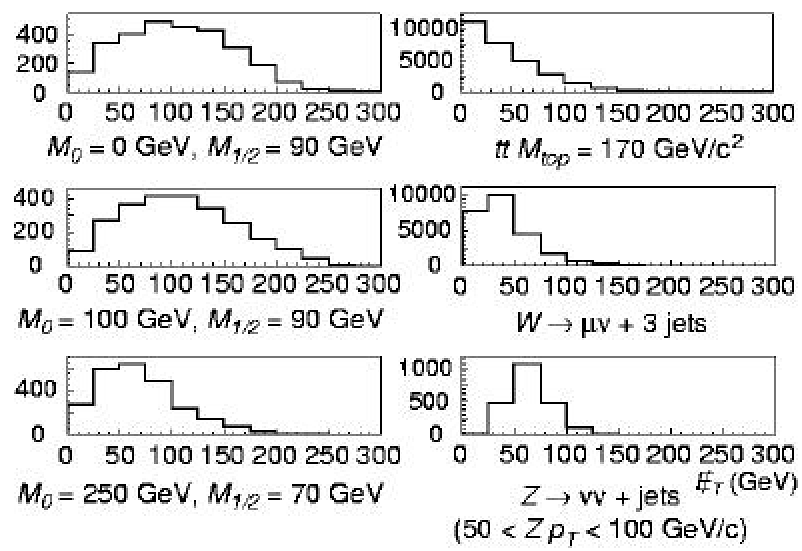
Supersymmetry signatures

- **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:



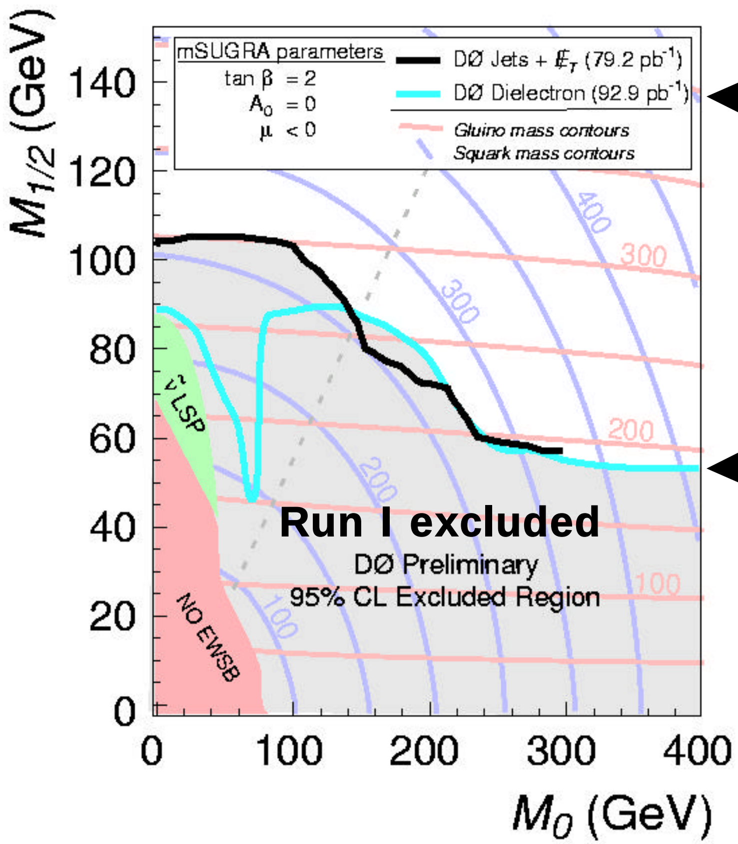
SUSY **Missing E_T backgrounds**



Search region typically > 75 GeV

Run 1 search for squarks and gluinos

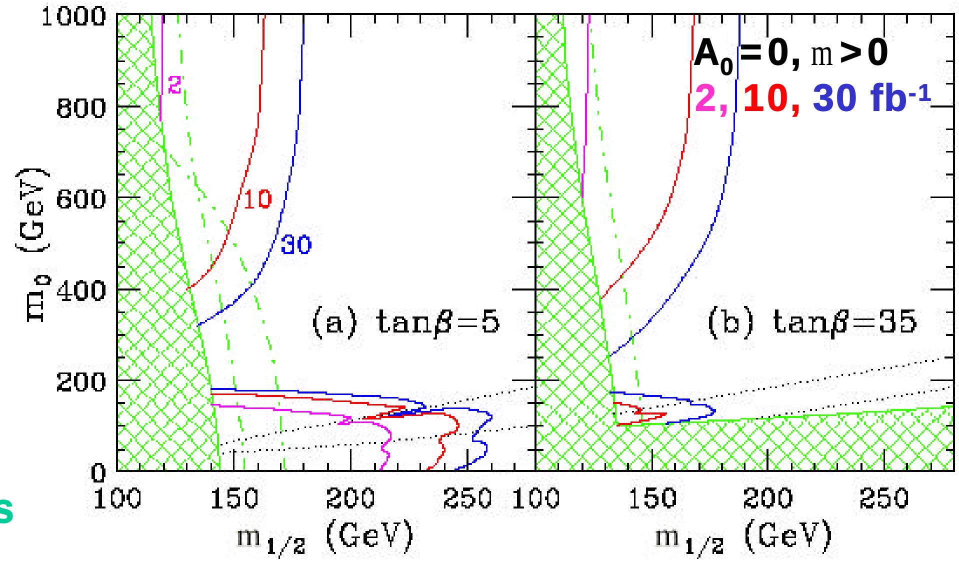
- **Two complementary searches**
  - jets plus missing E_T and no electrons/muons
  - 2 electrons, 2 jets + Missing E_T



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

Run I reach
gluino ~ 200 GeV
squark ~ 250 GeV

Chargino / neutralino production

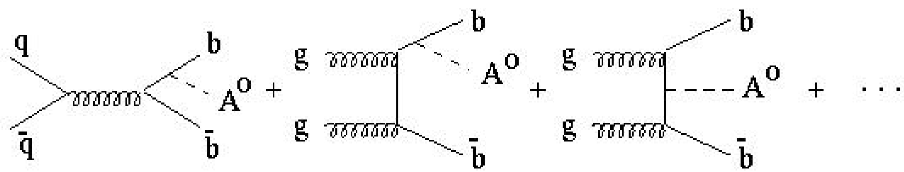


- **“Golden” signature**
  - **Three leptons**
    - **very low standard model backgrounds**
- **In Run 1 this channel was not competitive with LEP**
  - **but becomes increasingly important as squark / gluino production reaches its kinematic limits (masses ~ 400-500 GeV)**
- **Run 2 reach on $c^{\pm}$ mass ~ 180 GeV (tan b = 2, μ < 0)**
  ~ 150 GeV (large tan b)
- **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!

SUSY Higgs sector

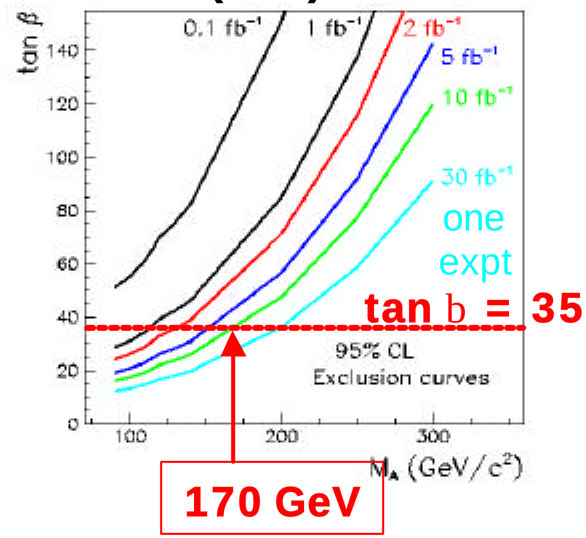
- Associated production bb(h/H/A) enhanced at large tan b:



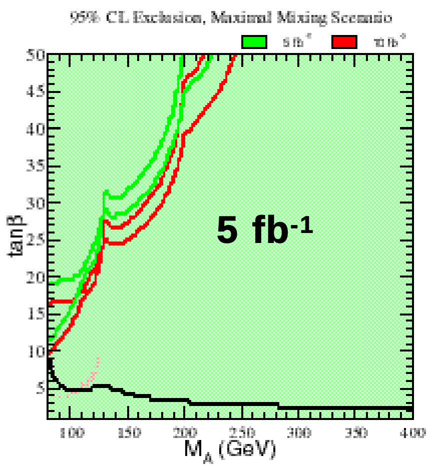
- s ~ 1 pb for tanb = 30 and m_h = 130 GeV

- Combined limits:

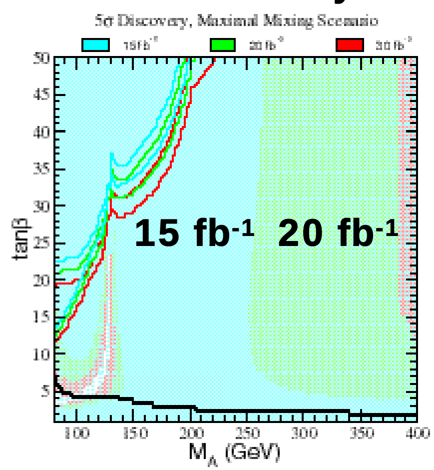
bb(h/A) ® 4b



95% exclusion



5s discovery



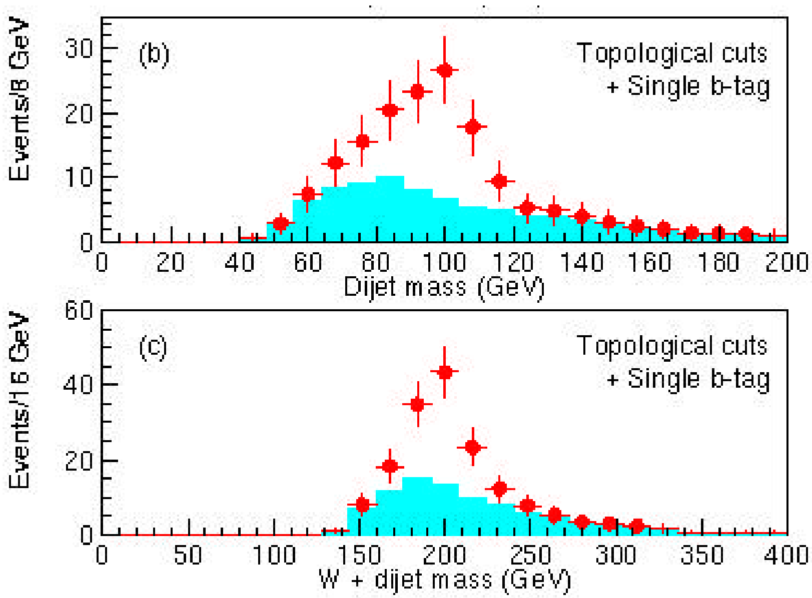
Exclusion and discovery for maximal stop mixing, sparticle masses = 1 TeV

Luminosity per experiment, CDF + DØ combined

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 r_T ® Wp_T ® lnbb
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

- Many different theoretical ideas, with different topologies possible
  - large extra dimensions (ADD)
  - TeV scale extra dimensions
  - warped extra dimension (RS)

New York Times

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.

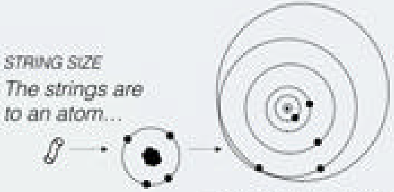
SUPERSTRING THEORY

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

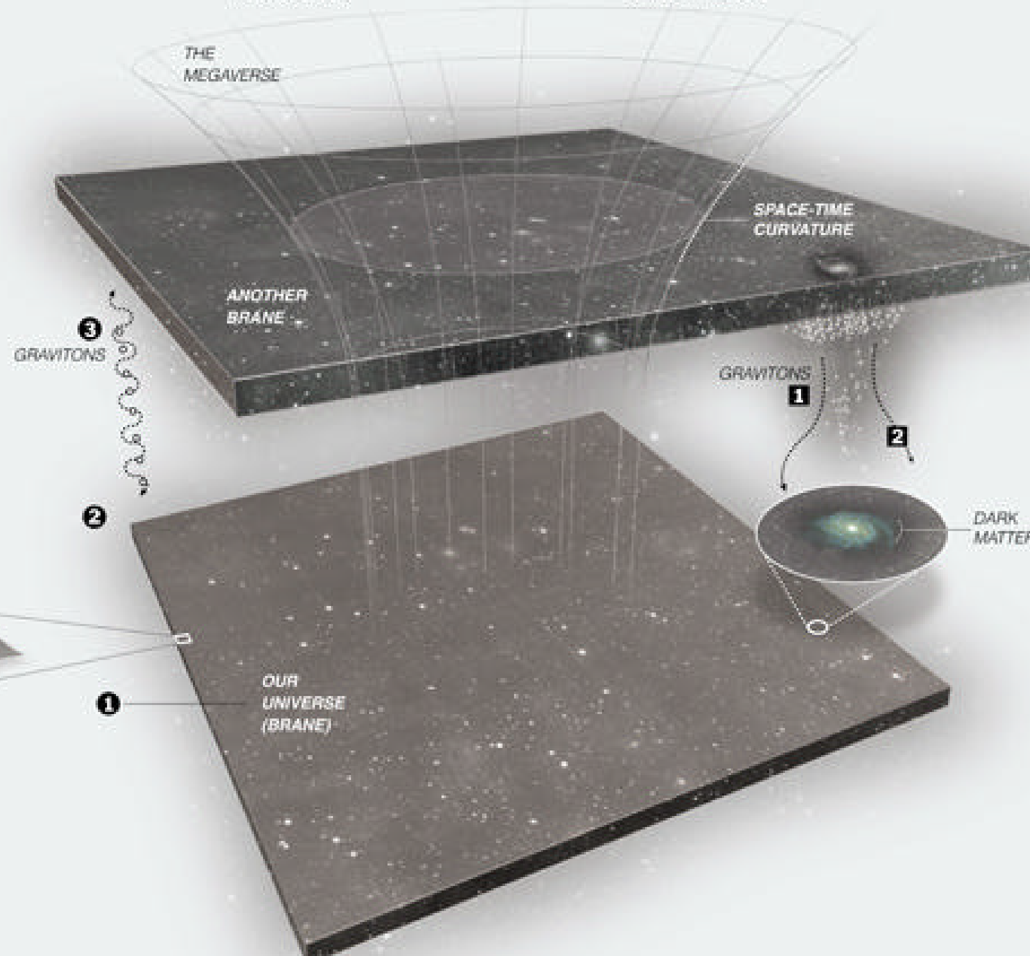
It expands superstring theory to include vibrating membranes, or branes, which may have many dimensions.

❶ *Our universe can be thought of as a three-dimensional brane floating inside a four-dimensional megaverse.*

❷ *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.*

❸ *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



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.

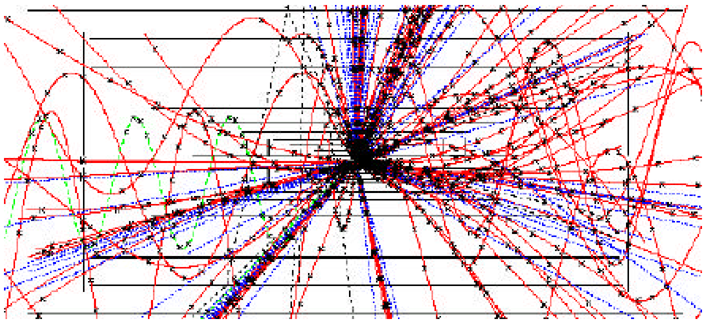
2 *The light from dark matter, conveyed by particles called photons, would cling to the surface of the foreign brane, but gravitons might seep across the divide. Pulled by our galaxies' local gravitational force, the gravitons would cluster into halos around the galaxies.*

Steve Duenes/The New York Times

John Womersley

TeV-scale gravity

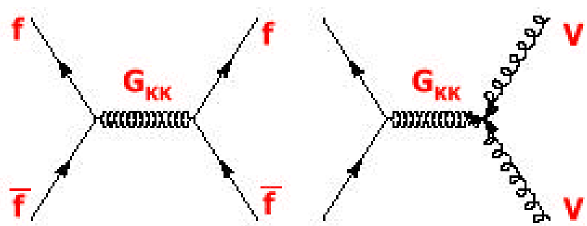
- **Observable effects can be direct and spectacular . . .**

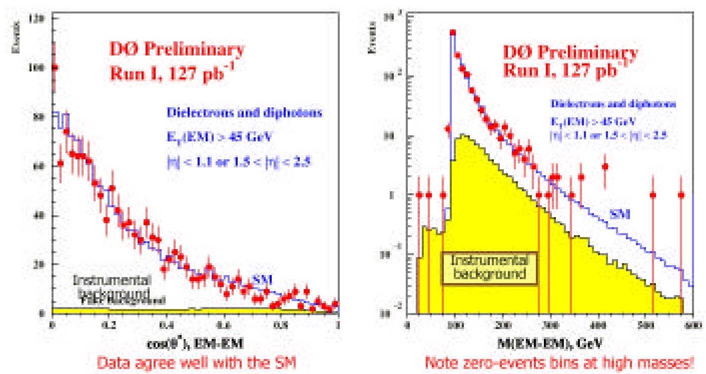


Production of Black Holes may even occur

Decay extremely rapidly (Hawking radiation) with spectacular signatures

- **Or indirect . . .**
  - **DØ Run 1 limits from virtual graviton effects on e^+e^- and gg production (1.0 - 1.3 TeV for 2-7 extra dimensions, ADD)**





  - **Prospects for Run 2: 1.5 - 2.5 TeV ($2fb^{-1}$) 2.1 - 3.5 TeV ($20fb^{-1}$)**

Sleuth

- A new approach from DØ: attempt at a 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
  - searches for deviations from standard model predictions
- Systematic study of 32 final states involving electrons, muons, photons, W's, Z's, jets and missing E_T in the DØ Run 1 data
- Only two channels with some hint of disagreement
  - 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 new physics, given the large number of channels searched
  - 89% probability of agreement with the Standard Model (alas!)

This approach will be extremely powerful in Run 2

Quaero

- DØ has now largely completed the analysis of Run 1 data
- We have therefore decided to make a number of well-understood Run 1 data sets publicly available through a web interface

http://quaero.fnal.gov

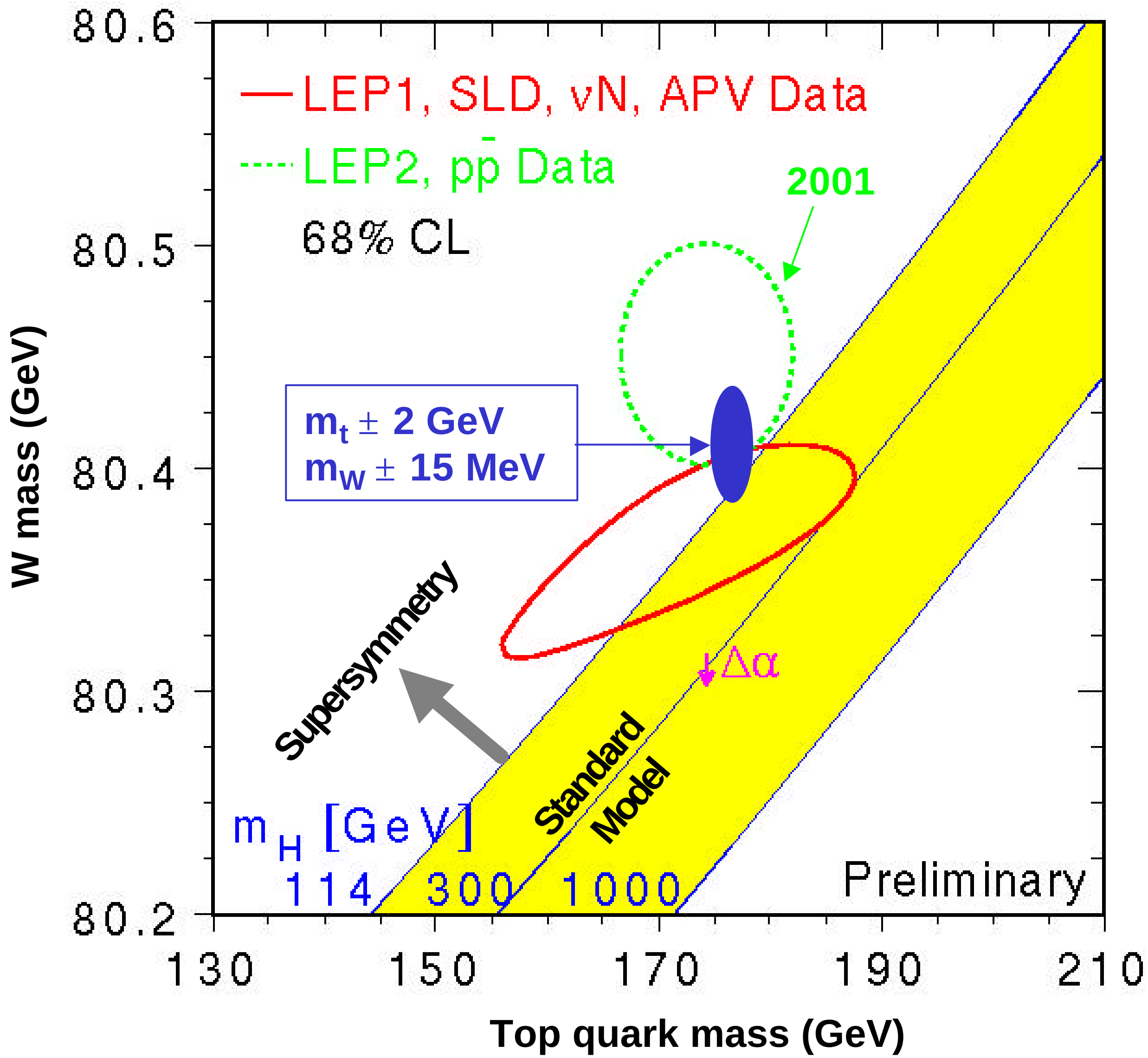
- This is a new direction for high energy physics
- Please try it!
  - For details see hep-ex/0106039

Standard Model Physics in Run 2

Some highlights:

- A targeted program of B-physics measurements
  - CP violation in $B \rightarrow \psi K_S$
  - $B \rightarrow X\mu\mu$
- QCD
  - jets at high E_T
  - photon and b cross sections
  - parton distributions
  - diffraction
- Top physics
  - observe single top production
  - precise measurement of m_t (Δm_t = 2-3 GeV/expt with 2 fb^{-1})
- Electroweak
  - precise measurement of m_W (Δm_W = 40 MeV/expt with 2 fb^{-1})

Indirect constraints on new physics



What are we doing now?

- **Run 1 officially started on March 1, 2001**
  - first collisions April 3
  - consistent running with 36 ´ 36 proton and antiproton bunches started early June
  - < 10 pb^{-1} delivered so far, still commissioning both the detectors and the accelerator
  - currently in a six-week shutdown (Oct-Nov 2001)
  - DØ is completing installation of the fiber tracker electronics, and the trigger is being phased in (bandwidth limited at start)

- **Planning has started on the additional detector enhancements that will be needed to meet the goal of accumulating 15 fb^{-1} by end 2007**
  - major component is a new silicon detector to replace the present device which can not survive the radiation dose
  - Technical design reports submitted to the laboratory Oct 2001
  - goal: installed and running by early 2005

Complementarity with LHC

- **The Physics goals of the Tevatron and the LHC are not very different, but the discovery reach of the LHC is hugely greater**
  - **SM Higgs:**
    - **Tevatron < 180 GeV** — **LHC < 1 TeV**
  - **SUSY (squark / gluino masses)**
    - **Tevatron < 400-500 GeV** — **LHC < 2 TeV**

Despite its limited reach, the Tevatron is interesting because both Higgs and SUSY "ought to be" light and within reach — and because of the timing

- **For Standard Model physics systematics may dominate:**
  - **Top mass precision**
    - **Tevatron ~ 2 GeV** — **LHC ~ 1 GeV?**
  - **m_W precision**
    - **Tevatron ~ 20 MeV?** — **LHC ~ 20 MeV?**

Conclusions

- The Tevatron collider program in the next five years offers a real opportunity to significantly advance our understanding of the fundamental properties of the universe
- It is an exciting, challenging program that goes straight to the highest priorities of high energy physics worldwide

"To the Higgs —
and beyond!"

We anticipate first physics results in spring/summer 2002