Tevatron Collider Physics

Annual Theory Meeting, Durham
December 16, 2002

John Womersley

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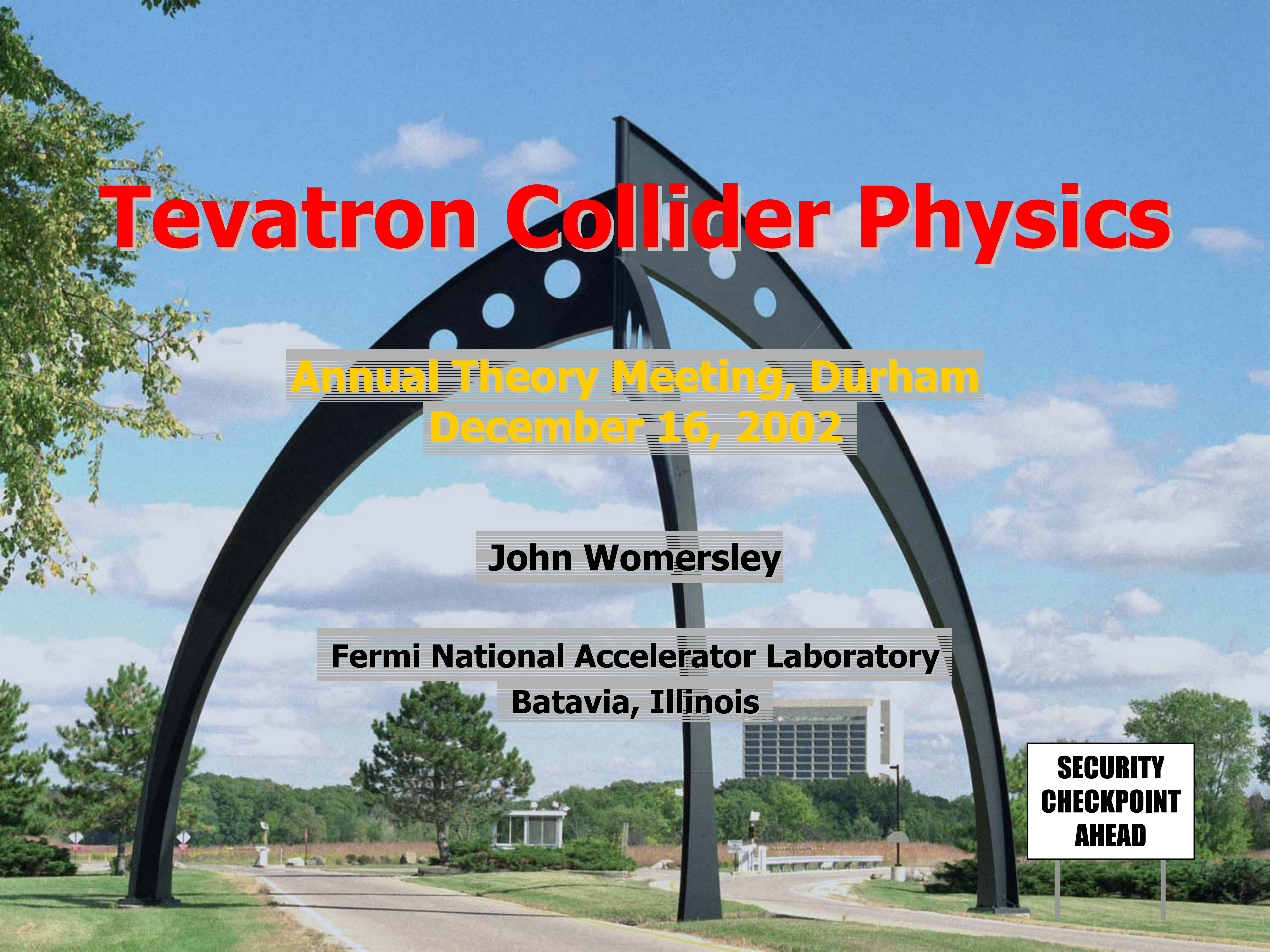
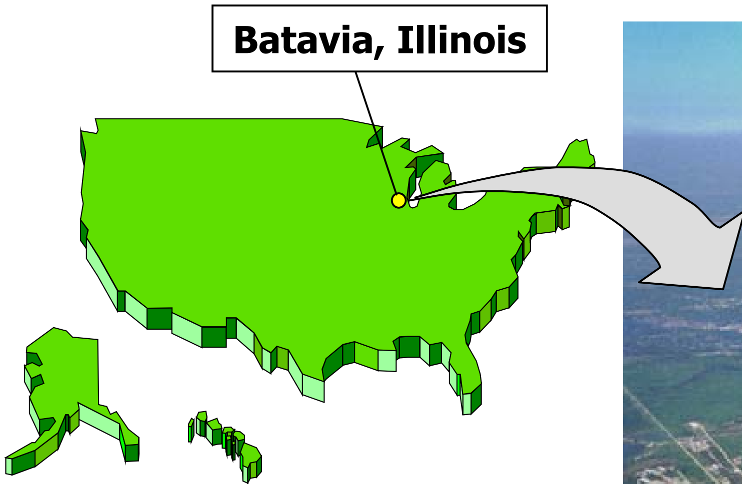
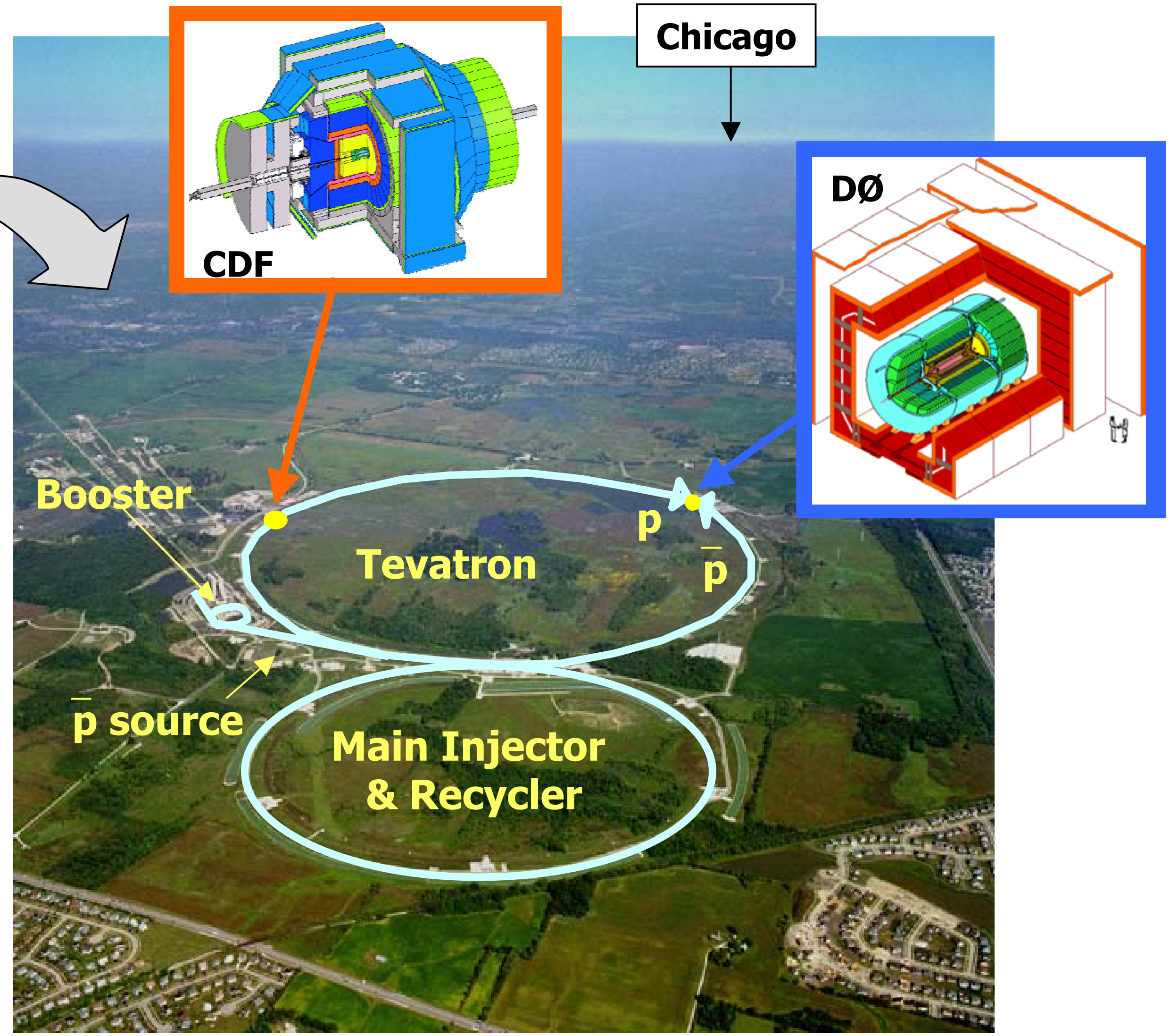
Batavia, Illinois



Fermilab





p → ← $\bar{p}$

$\sqrt{s}$ =1.96 TeV

Δt = 396 ns

Luminosity goals

4×10^{31} cm^{-2}s^{-1} (FY02)

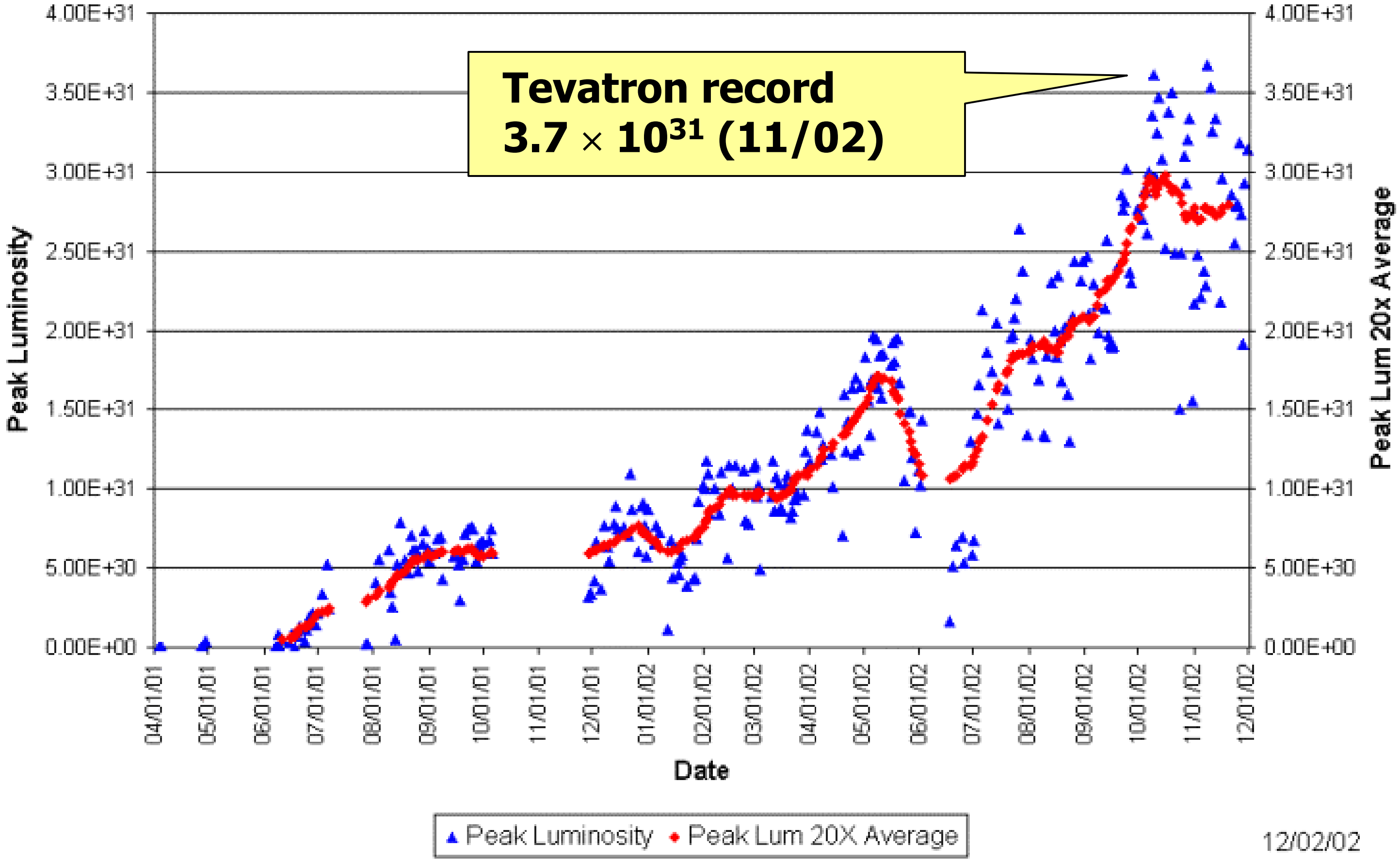
8×10^{31} cm^{-2}s^{-1} (Run IIa)

Big Questions

- The physics goals of Run II at the Tevatron are broad and fundamental
- The Tevatron is the only facility in operation that can help to answer all these really big questions:
  - What is the structure and what are the symmetries of space-time?
  - Why is the weak force weak?
  - What is cosmic dark matter made of?
  - Why is matter-antimatter symmetry not exact?
- To do this
  - Confront the standard model through precise measurements
    - the strong interaction, the quark mixing matrix, the electroweak force and the top quark
  - Directly search for particles and forces not yet known,
    - Those predicted and those that would come as a surprise

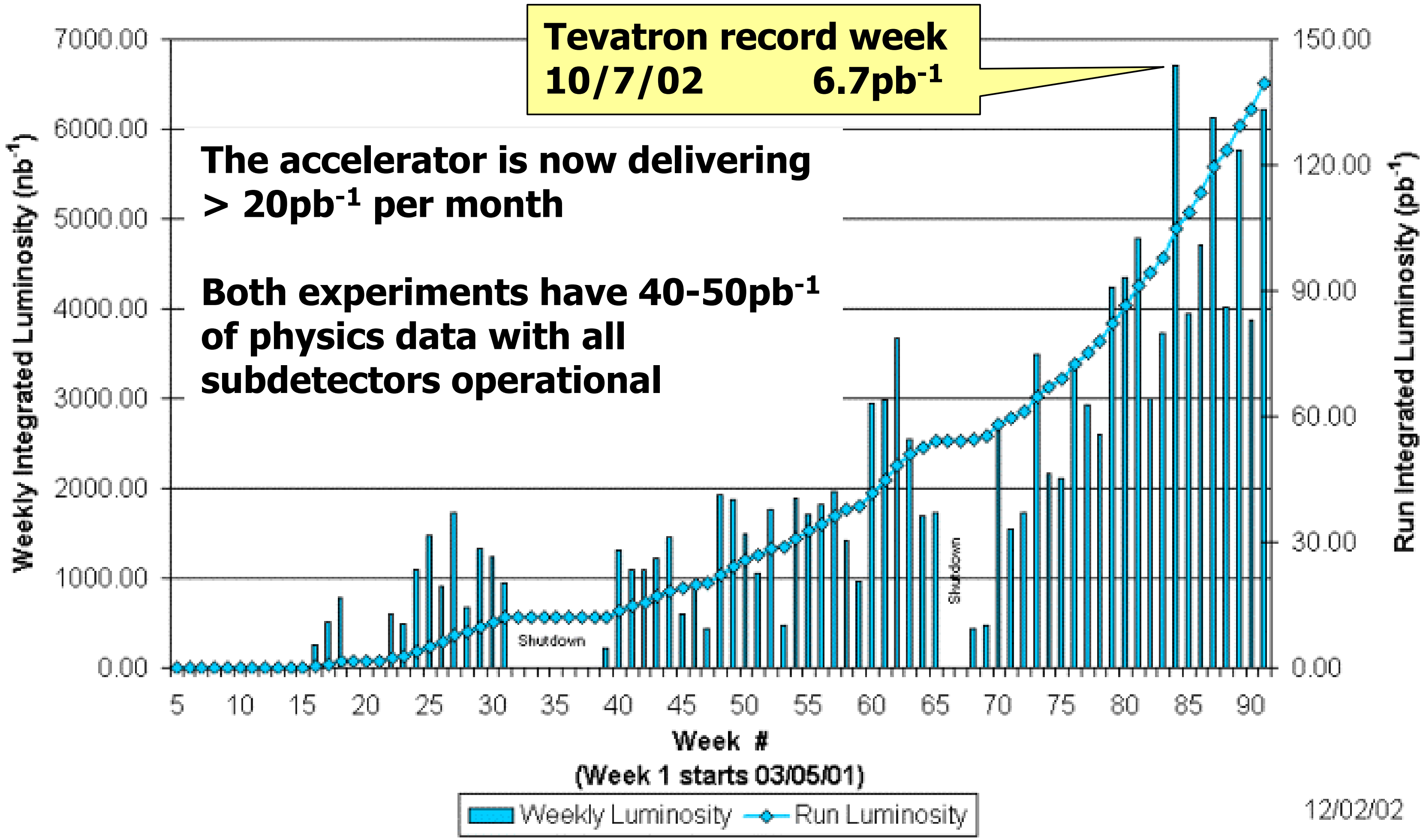
Tevatron Performance

- Not out of the woods yet, but gratifying progress recently
- Tevatron peak luminosity:



Average CDF + DØ luminosity

- **Luminosity per week and total Run II integrated luminosity**



12/02/02

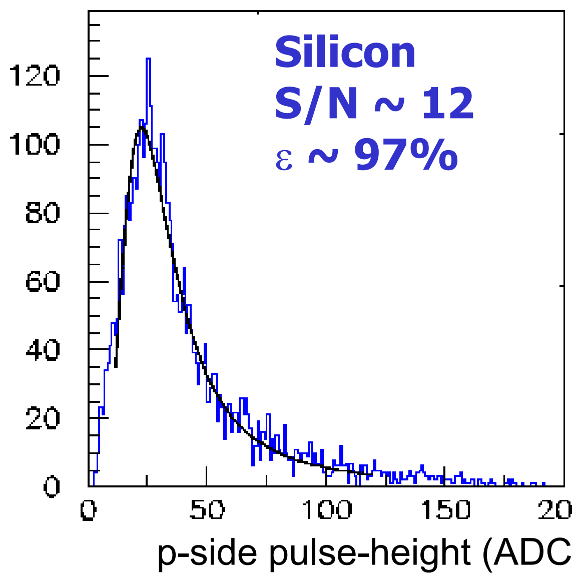
Tevatron prospects

- Now exceeding Run I performance
- Improvements have come from specific modifications to the complex
- Resource loaded schedule and plan in place for FY03
- Major issues are:
  - Tevatron transfer and acceleration efficiencies
  - Emittance dilution
  - Beam lifetime at 150 GeV
  - Role of long range beam-beam effects
- No silver bullets
    - $(1.15)^{10} = 4.0$

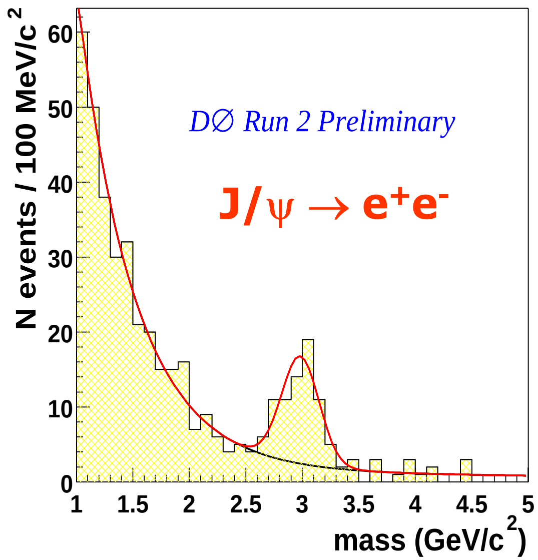
Status of DØ

- The detector is working well and recording physics data:

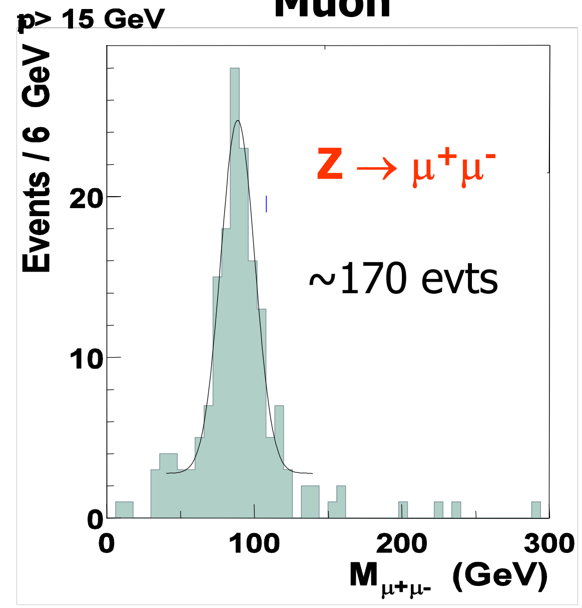
Tracking



Calorimeter



Muon



- Currently emphasizing operational efficiency
- Improvements still in store
  - Trigger capabilities and L1 rate
  - Silicon vertex trigger under construction

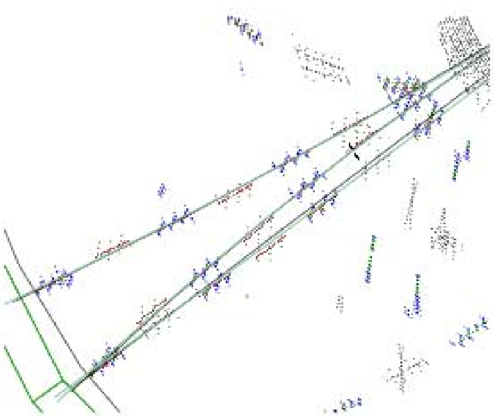
Status of CDF and Prospects for Run II

Run II upgrades build on the experience from Run I

→ Improved acceptance
→ New trigger capabilities
→ Better detectors

Detector and Trigger are commissioned and working well, taking Physics Quality data since Jan 2002

Currently running with $\sim$ 40/80/140 triggers at L1/L2/L3

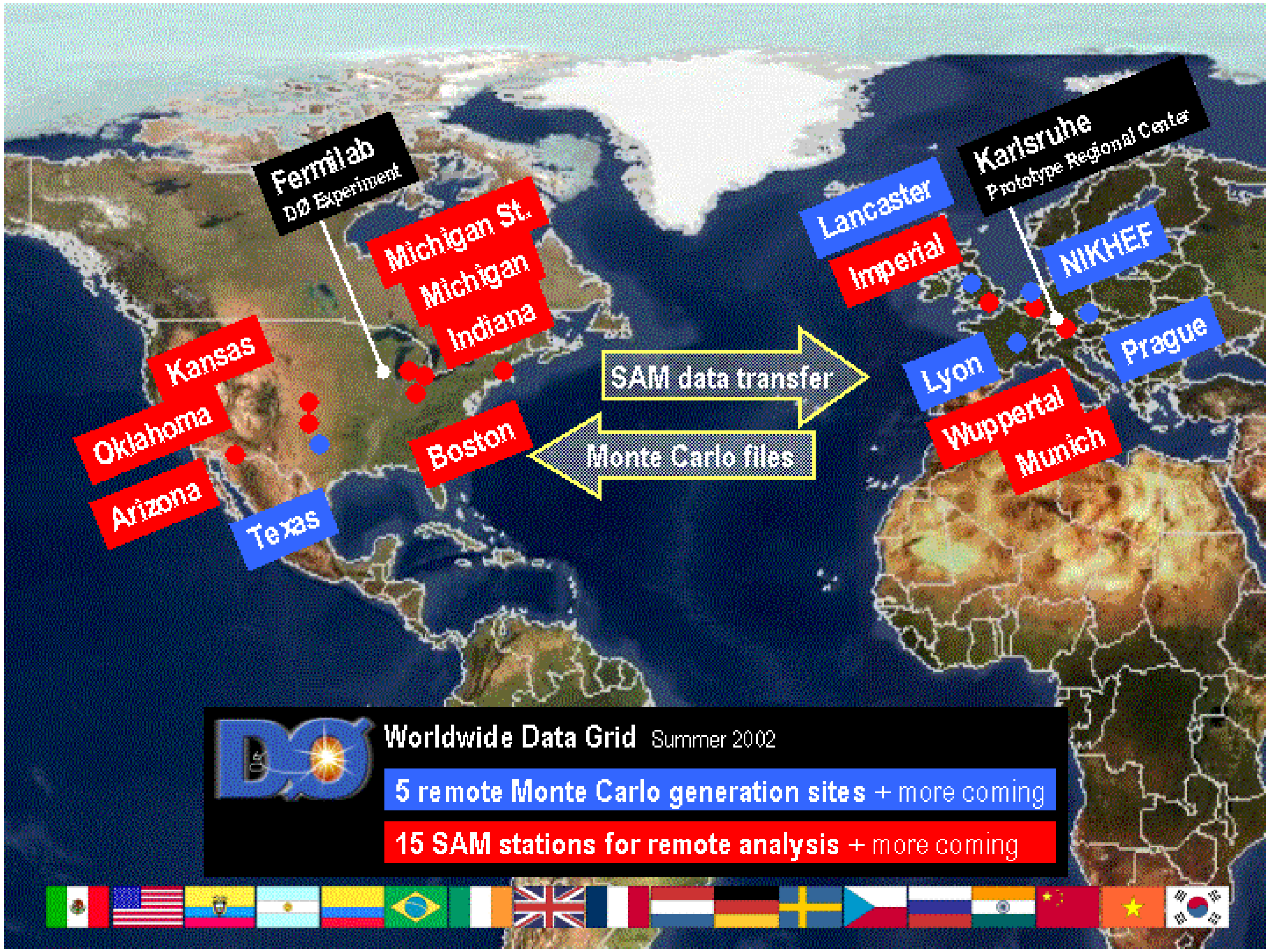


The Extremely Fast Tracking trigger (XFT) able to select tracks with p_T as low as 1.5 GeV at *L1!*

Silicon Vertex Tracker (SVT) working well, selects events with displaced tracks at *L2!*

Computing Infrastructure

- "Something like" the Grid is becoming real:
  - SAM data access and distribution now being used by CDF and DØ
  - Major push towards offsite analysis of Run II data



Remote International Monitoring for the DØ Experiment

Detector Monitoring data sent in real time over the internet

2 am

Fermilab

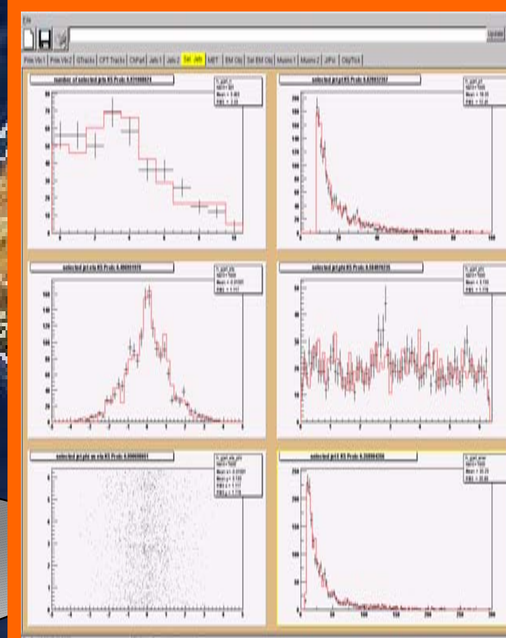
9 am

NIKHEF Amsterdam

DØ physicists in Europe use the internet and monitoring programs to examine collider data in real time and to evaluate detector performance and data quality.

They use web tools to report this information back to their colleagues at Fermilab.

DØ detector



The online monitoring project has been developed by DØ physicists and is coordinated by Dr. Pushpa Bhat from Fermilab. Jason Webb, a DeVry University, Chicago, undergraduate student is helping develop and maintain the interactive tools for the remote physicists.

Our theoretical toolkit

- **Parton distributions**
  - Largely determined by DIS data (esp. HERA)
  - Much recent effort to understand uncertainties
    - How to handle systematic errors?
  - Uncertainties on PDF's are 1-5 % except in certain regions
    - g(x), d(x) at high x
  - Find variation from changing assumptions, α_S, cuts, etc. is much greater than experimental errors
    - Points to inadequacy of theoretical predictions?
- **QCD calculations**
  - NNLO is needed – and coming
  - Also: LO parton-level simulations for up to 8 partons in the final state now available
    - e.g. QCD backgrounds to ttH
- **Event generators**
  - Work underway to improve showering Monte Carlo programs, merge with higher order calculations without double-counting
  - Can we improve modelling of soft underlying event?

QCD

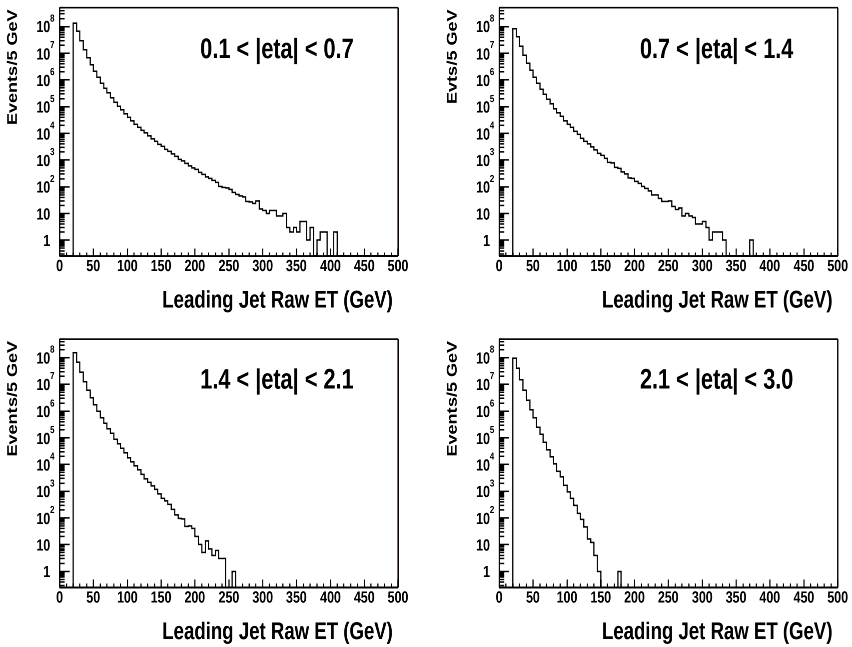
- No one doubts that QCD describes the strong interaction between quarks and gluons
  - Its effects are all around us:
    - masses of hadrons (stars and planets)
  - But it is not an easy theory to work with

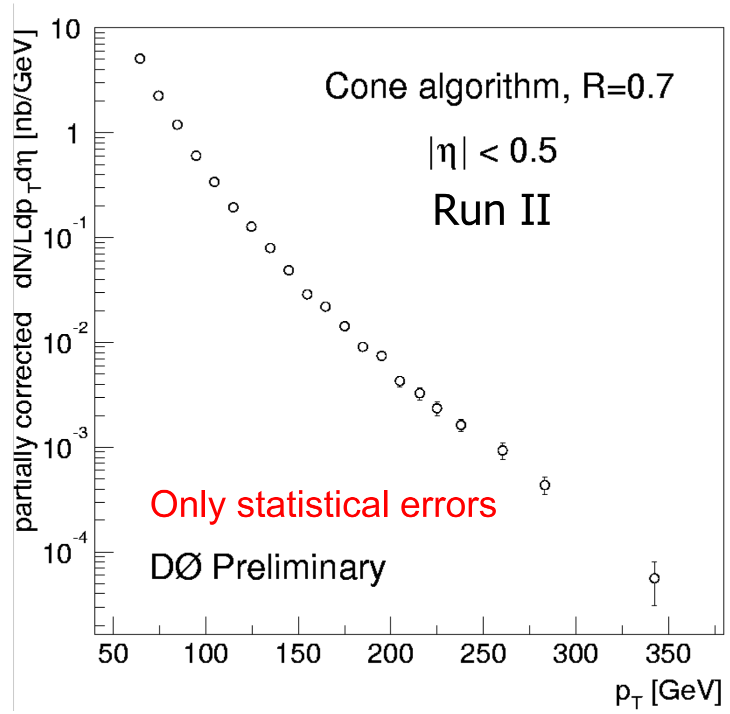
- Use the Tevatron to
  - Test QCD itself
  - Understand some outstanding puzzles from Run I
  - Develop the expertise to calculate, and confidence in, the backgrounds to new physics

Jets in Run II

Leading Jet Raw ET in CDF Jet Events

CDF Run 2 Preliminary (12/14/2001 - 9/13/2002) 45.3 pb-1

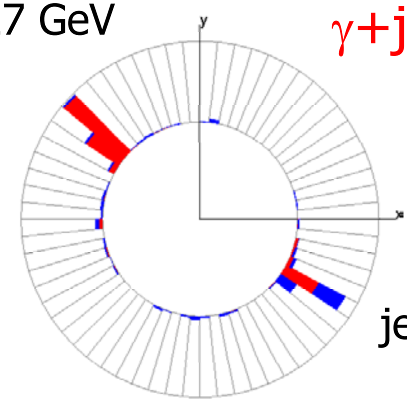




CDF using new forward calorimeters to cover the whole range of jet rapidity

γ E_T=27 GeV

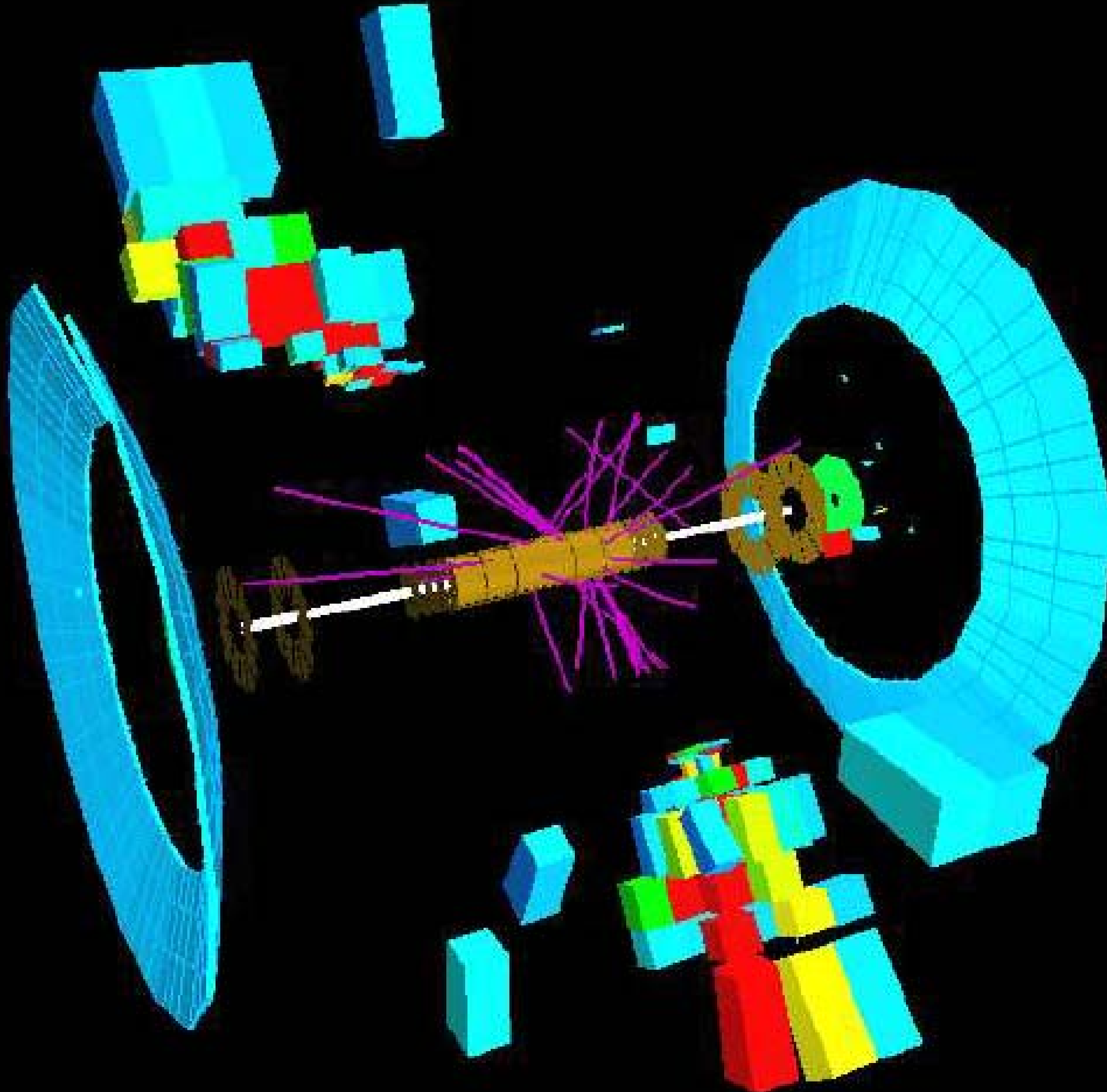
γ+jet Event



jet E_T=24 GeV

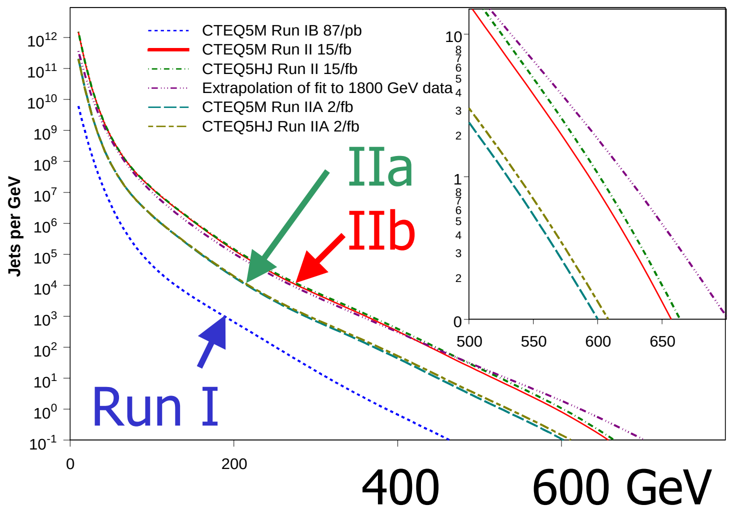
- **DØ have applied a preliminary correction for jet energy scale derived from p_T balance in photon + jet events**

EM scale set by Z → ee events:



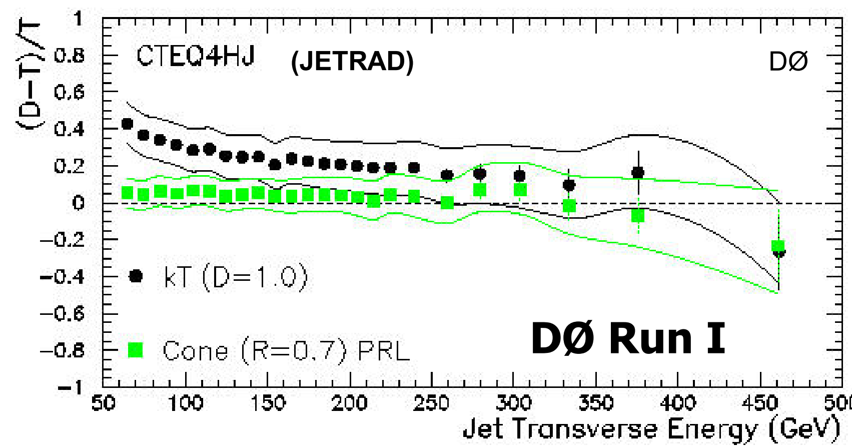
Physics goals for jets

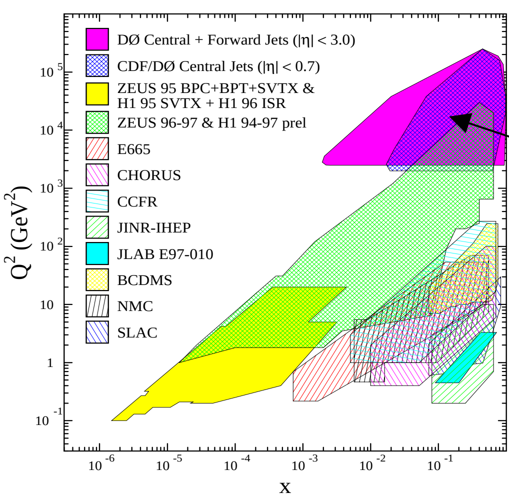
High p_T jets constrain the gluon content of the proton



Much theoretical discussion:

choice of Jet Algorithm for Run II and why $k_T \neq$ cone





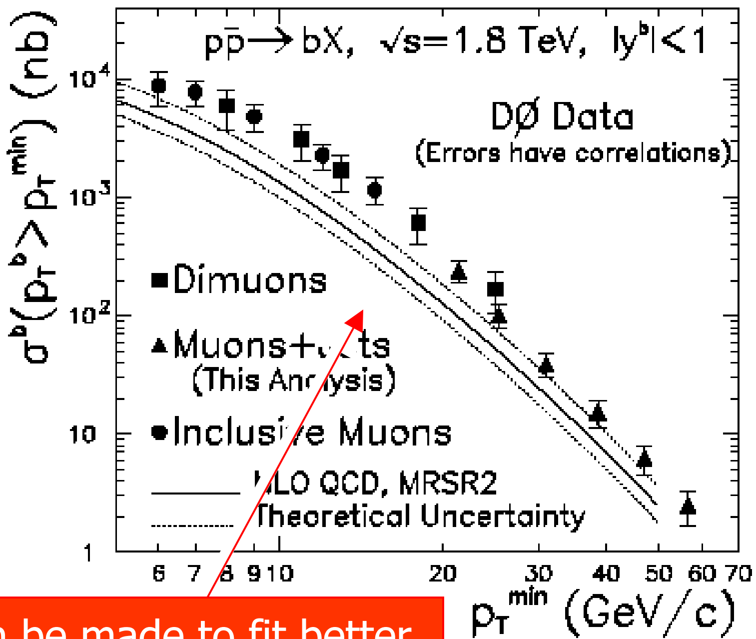
DØ Run I jet data already used in CTEQ6 and MRST2001 parton distribution fits
Complement HERA's kinematic range

John Womersley

Heavy flavour production

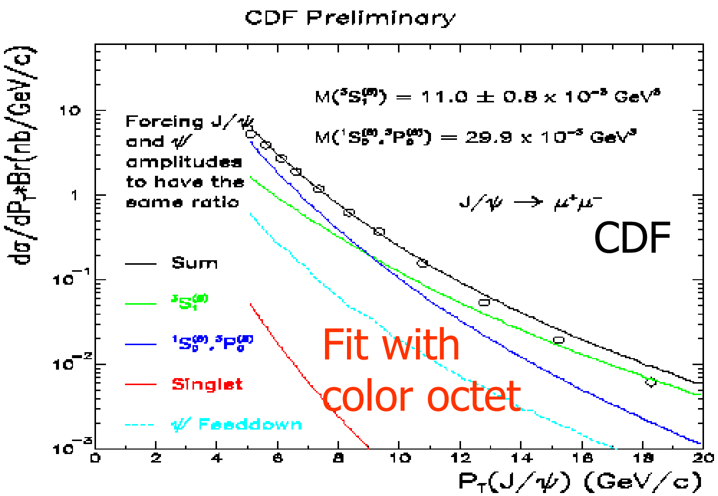
Important background to new physics!

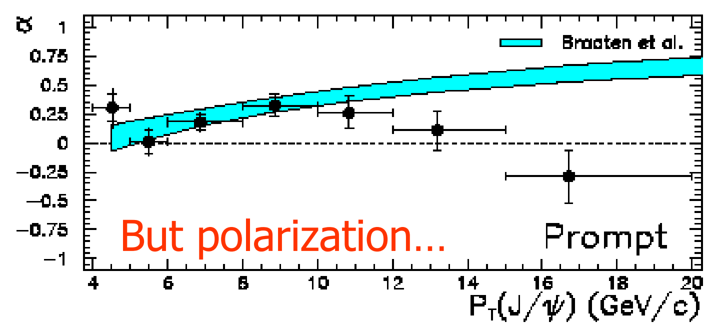
- **Lots of unanswered questions from Run I**
  - **B production cross section**



Can be made to fit better using resummation and retuned fragmentation

Charmonium cross section

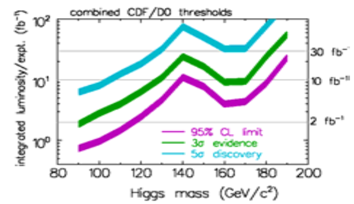
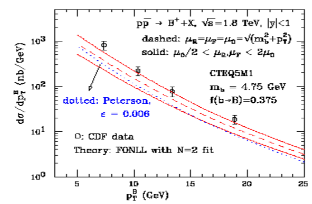
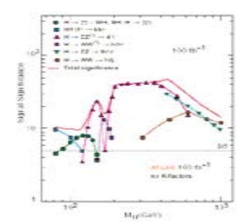
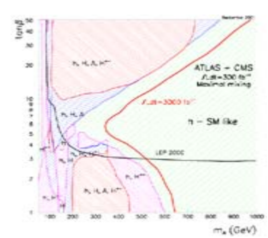




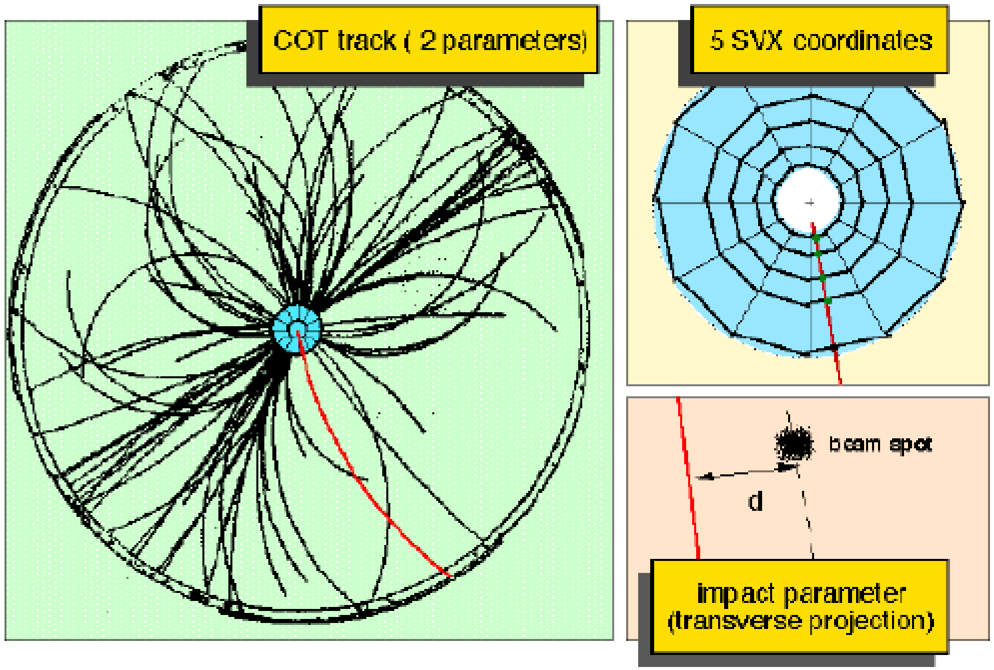
How to connect to HERA and LEP?
Do we need higher order QCD calculations?

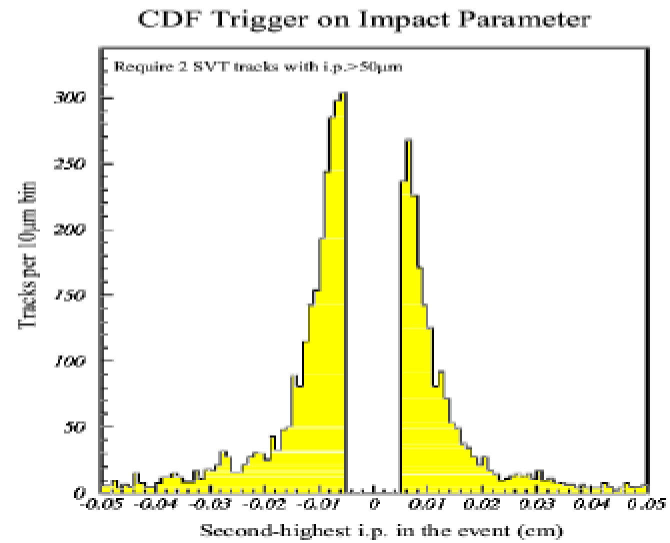
Polarization is determined from angle of μ^+ emitted in J/ψ rest frame

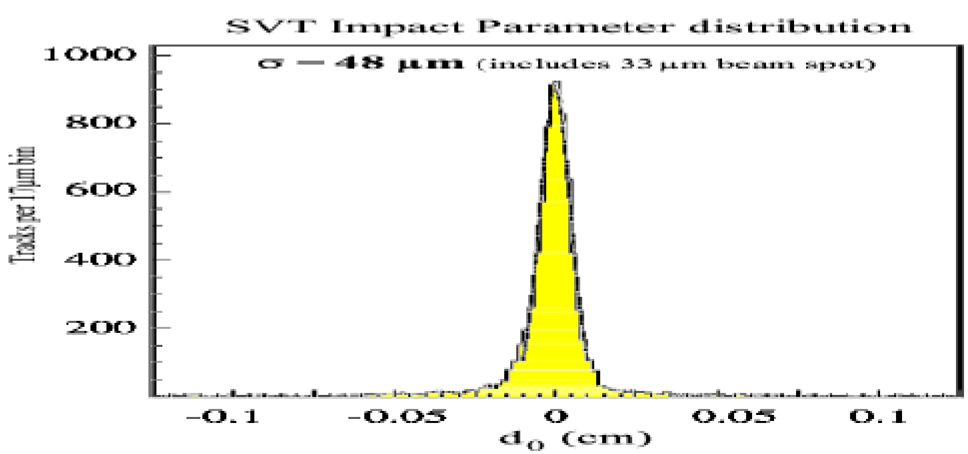
Just for fun: most-shown plots at HCP2002

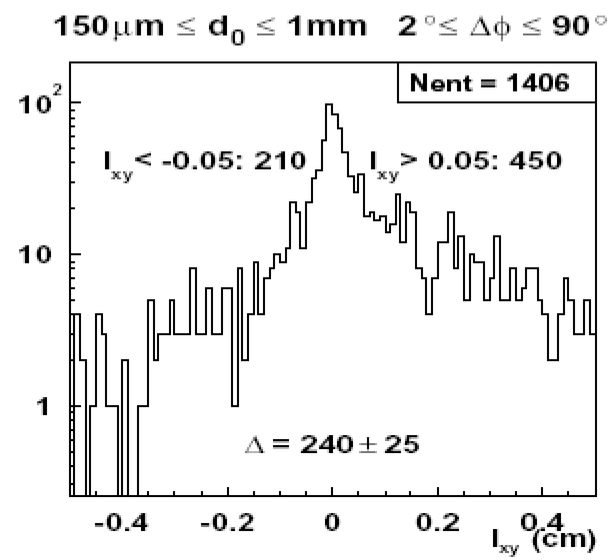
	Plot	Number of showings
Tevatron Higgs reach		**8**
Tevatron B-cross section		**6**
LHC Higgs sensitivity		**5**
LHC SUSY Higgs m_A, tan β		**3**

Run II Secondary Vertex Trigger





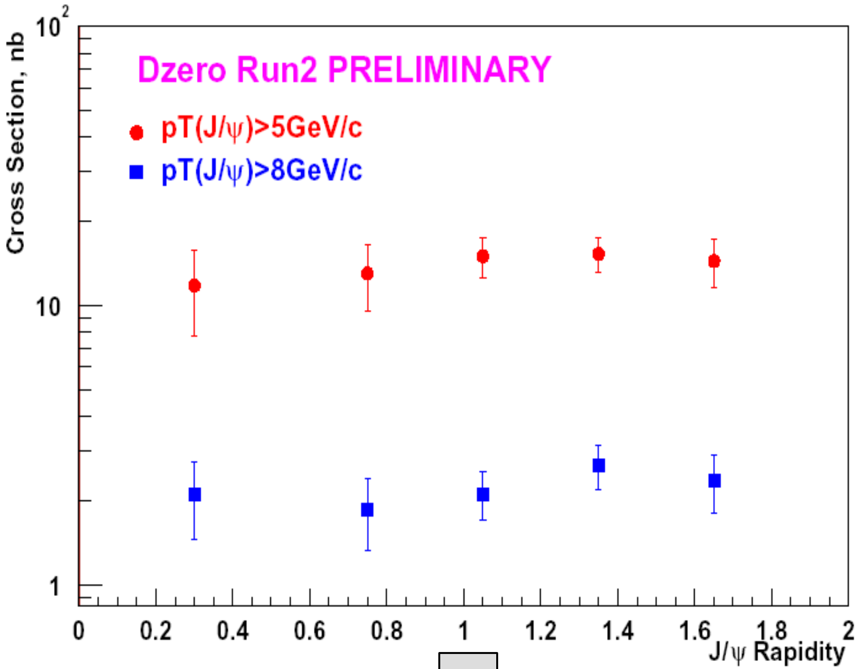




Heavy Flavour Production in Run II

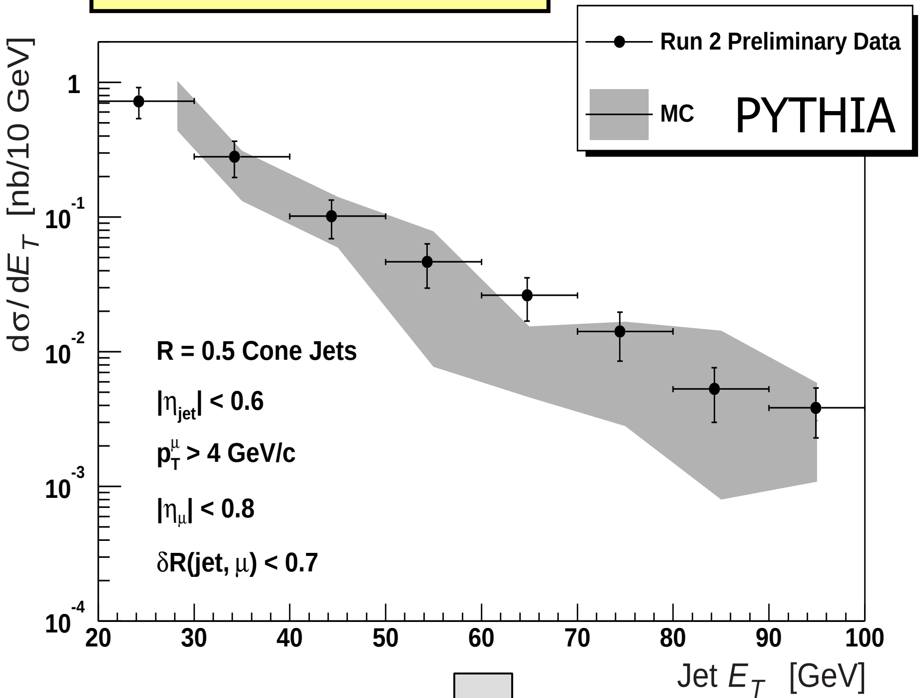
results from ICHEP

J/ψ cross section as a function of η



measure polarization
test production mechanism

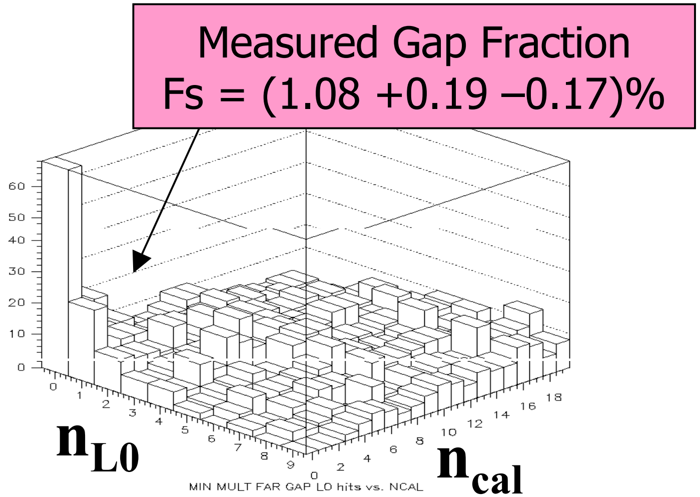
μ+jet cross-section

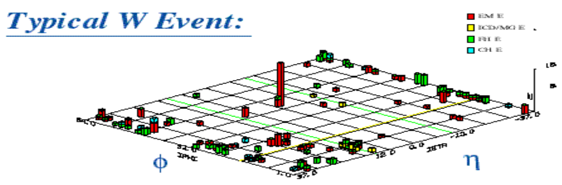


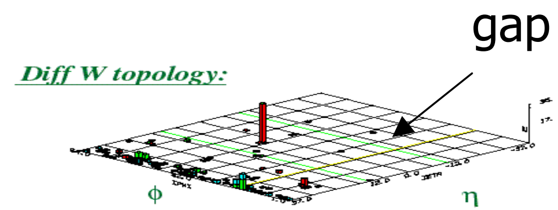
Determine b-jet cross-section
including high p_T behavior

Hard Diffraction

- **Run I signal for diffractive W production tagged with a rapidity gap**





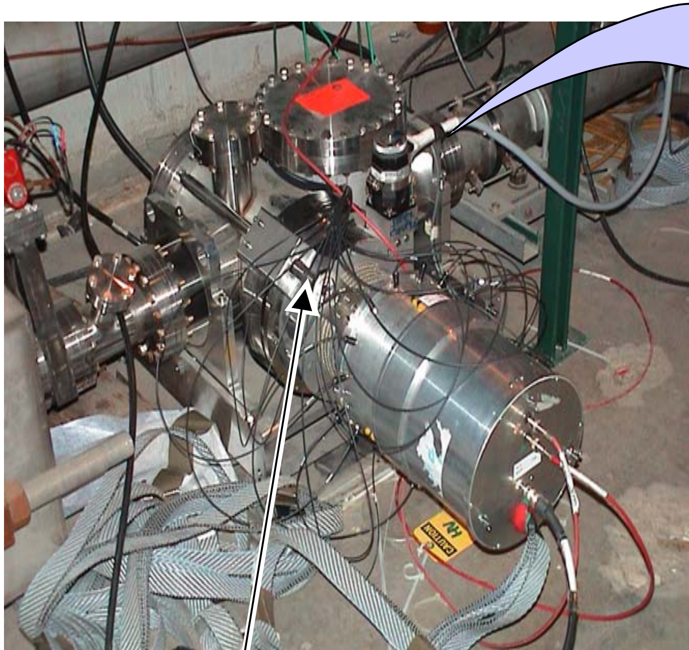


- **How can it be that we can kick a parton out of a proton with $Q^2 = m_W^2$ and not destroy the proton in the process?**
  - **And how can we do this 10% of the time?**
    - *1% rate, 10% gap survival probability*
  - **What does this tell us about the structure of the proton?**
- **In Run II, we are installing new detectors to test whether diffraction always accompanies a rapidity gap and to measure the "gap survival probability"**

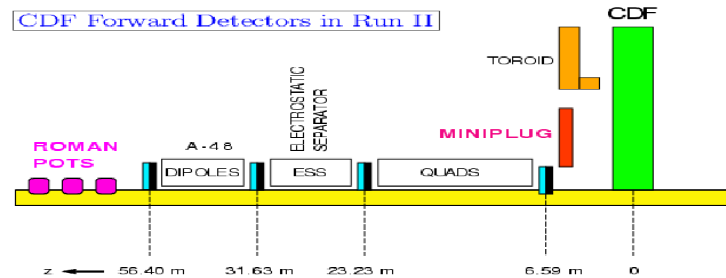
Forward Proton Detectors

Both CDF and DØ are improving their diffractive instrumentation for Run II

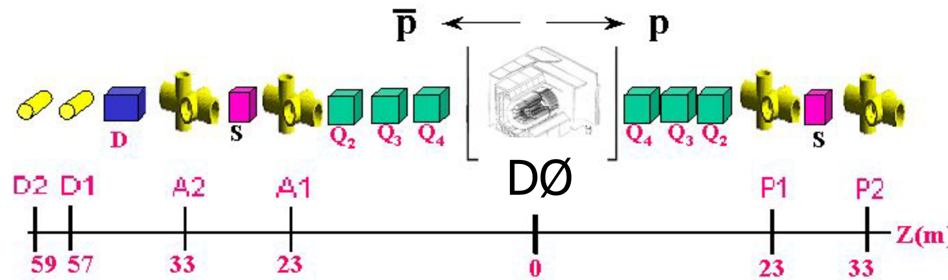
- Shower and veto counters to cover roughly $3 < \eta < 6$
- Roman pots 20-50m downstream of the detector



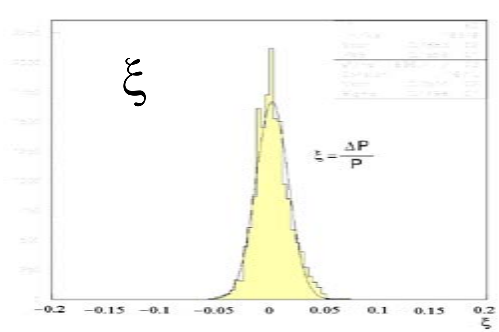
Scintillating fiber detector inside

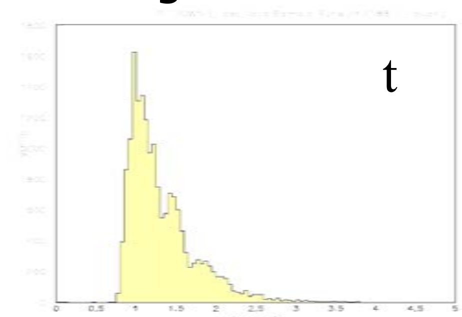


CDF



DØ Elastic scattering data

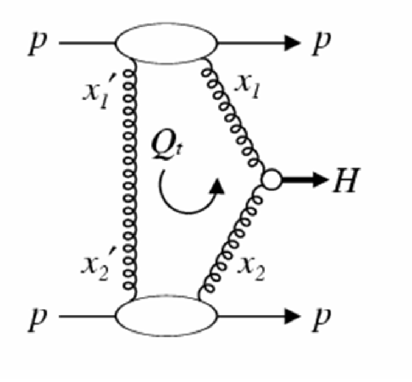




Diffraction in Run II

Some physics goals *for the "Pomeron skeptical"*

- **Measure the gap survival probability: relate rapidity gaps to diffractive (anti-)protons seen in Roman Pots**
- **Measure $\bar{p}p \rightarrow \bar{p}$ (gap) jj (gap) p**
  - **Will provide a sanity check for "loose talk of Higgs production" at the LHC**



Khoze, Martin & Ryskin predict S/B > 1 for m_H = 115 GeV includes gap survival factor 1/50

BUT other authors say it's impossible (e.g. Schlein)

Published cross section estimates cover 3 orders of magnitude

B-Physics and the Quark Mixing Matrix

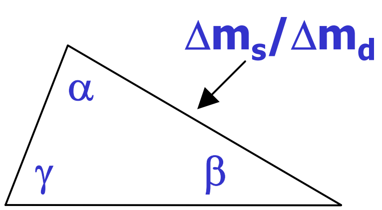
- Three generations of quarks plus mixing between them results in a subtle violation of matter-antimatter asymmetry (CP)
  - Why is the universe filled with matter and not antimatter?
    - If, as the SM predicts, CP violation in the CKM matrix is governed by a single parameter, then it is too small
    - Is this the only thing going on?

- In the decays of B-mesons, the symmetry violations can be large
  - B-hadrons have become an important laboratory to explore CP violation and the quark mixing matrix (CKM matrix)
  - In Run II, we want to confront the CKM matrix in ways that are complementary to the electron-positron B-factories.

- We now know that there is an analogous mixing matrix in the lepton sector, but that its structure is very different
  - Why?

B-physics at Hadron Colliders

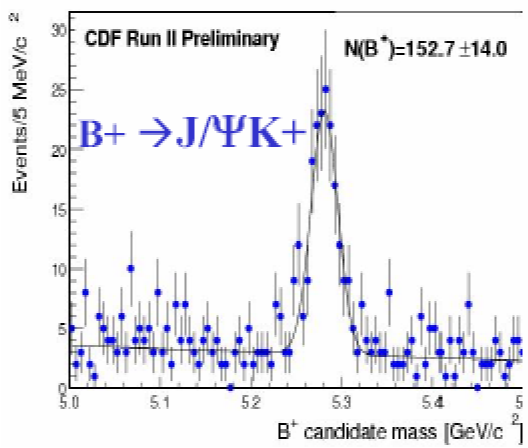
- CP violation established in the B system through $B_d \to J/\psi\ K_S$
  - $\sin\phi_d = 0.734 \pm 0.054$
    - Either $\phi_d = 47^\circ$ (2β in SM) or 133° (new physics)
- BaBar and BELLE will do much more with their data e.g.
  - Is $B \to \pi K$ consistent with SM $\gamma < 90°$?
  - Same mixing asymmetry in $B_d \to J/\psi\ K_S$ and $B_d \to \phi\ K_S$?
  - $B_d \to \pi\ \pi$ will be an important piece of the puzzle
- For hadron colliders (first CDF and DØ, then BTeV and LHCb) the B_S system is the "El Dorado"
  - Mixing parameters Δm_s, $\Delta\Gamma_s$
    - $x_s = \Delta m_s / \Gamma_s > 20$ (LEP)
  - $B_S \to D_S K$: extract $\phi_S + \gamma \to \gamma$
  - Sizeable CP violation in $B_S \to J/\psi\ \phi$?
  - $B_S \to KK$ complements $B_d \to \pi\ \pi$; $\to$ extract γ

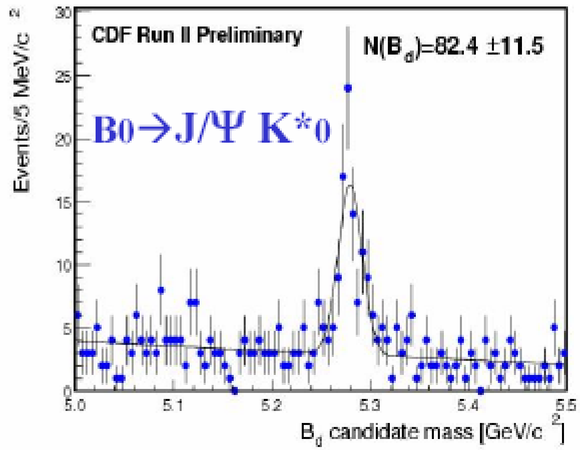


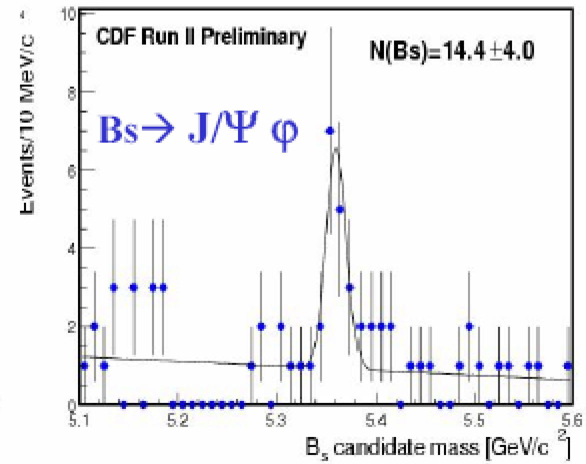
- Many other interesting topics e.g.
  - Rare decays e.g. $B \to K^*\mu^+\mu^-$, $B_{s,d} \to \mu^+\mu^-$

B-physics at CDF in Run II

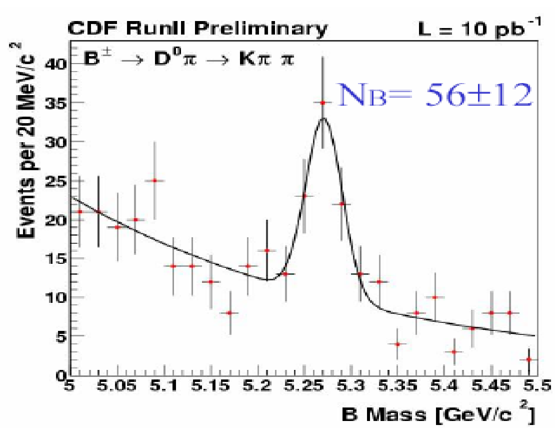
- **Build on Run I experience + new capabilities (SVT, TOF)**
  - **Leptonic signals**

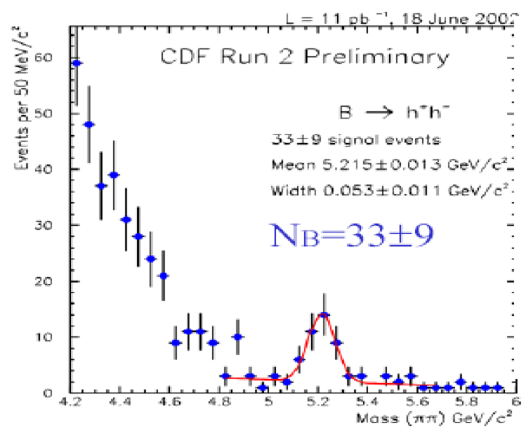






  - **First purely hadronic signals (using SVT)**





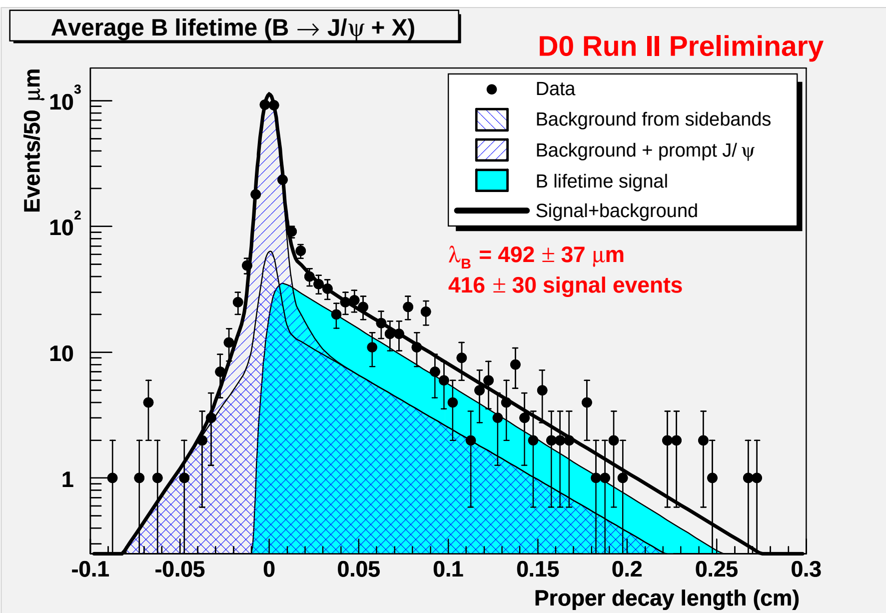
Hugely impressive results; impossible for me to do justice to them here!

John Womersley

B Physics at DØ in Run II

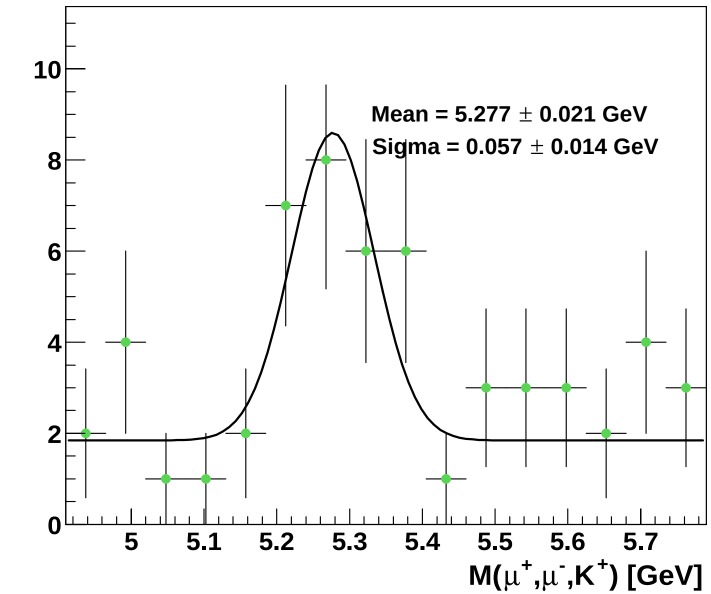
Putting the tools in place:

- $J/\psi \rightarrow \mu^+\mu^-$
- $J/\psi \rightarrow e^+e^-$
- $K_S \rightarrow \pi^+\pi^-$
- B tagging
    - muons
    - electrons (working on it!)
    - displaced vertices



$\tau(B) = 492 \pm 37\ \mu m$

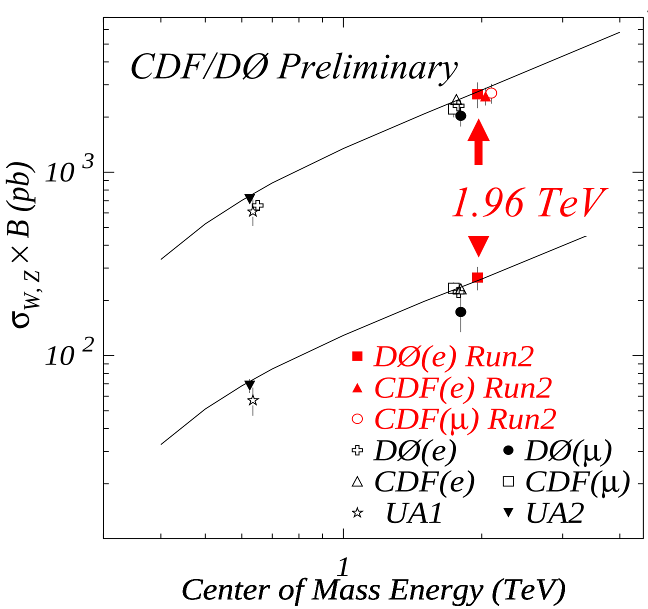
DØ's First B mesons:
$B \rightarrow J/\psi\ K^{\pm}$

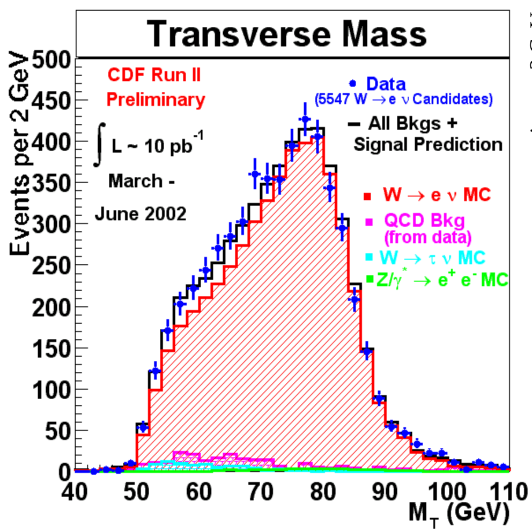


DØ cannot exploit purely hadronic triggers, but benefits from large muon acceptance, forward tracking coverage, and ability to make use of $J/\psi \rightarrow e^+e^-$

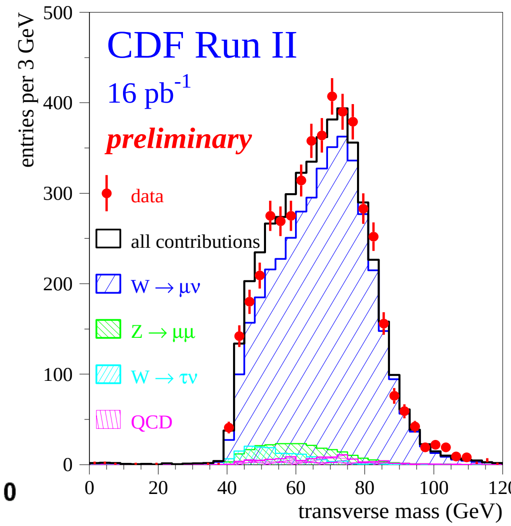
Electroweak Physics

- **In Run II we will complement direct searches for new phenomena with indirect probes**
  - **New particles and forces can be seen indirectly through their effects on electroweak observables.**
  - **Tightest constraints come from improved determination of the masses of the W and the top quark.**
- **Both experiments have preliminary results from Run II samples of W and Z candidates:**





$W \rightarrow e\nu$

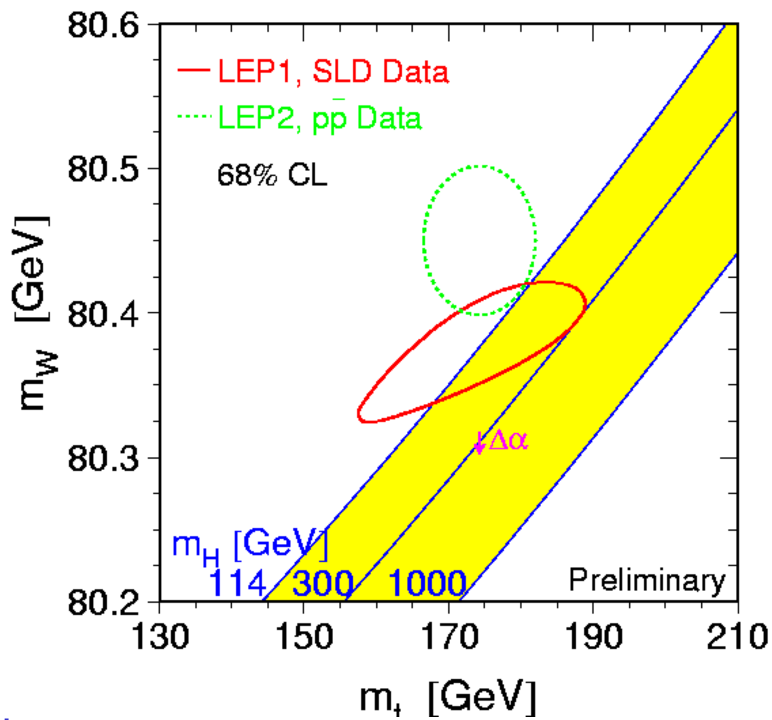


$W \rightarrow \mu\nu$

Prospects for electroweak measurements

Current knowledge of m_W

- **DØ:**
  - **80 483 ± 84 MeV**
- **hadron colliders:**
  - **80 454 ± 59 MeV**
- **world:**
  - **80 451 ± 33 MeV**



Run II prospects (per experiment)

	Δm_W
2 fb^{-1}	**±27 MeV**
15 fb^{-1}	**±15 MeV**

To improve on LEP wil require ~ fb^{-1} datasets
Clearly not a short term goal

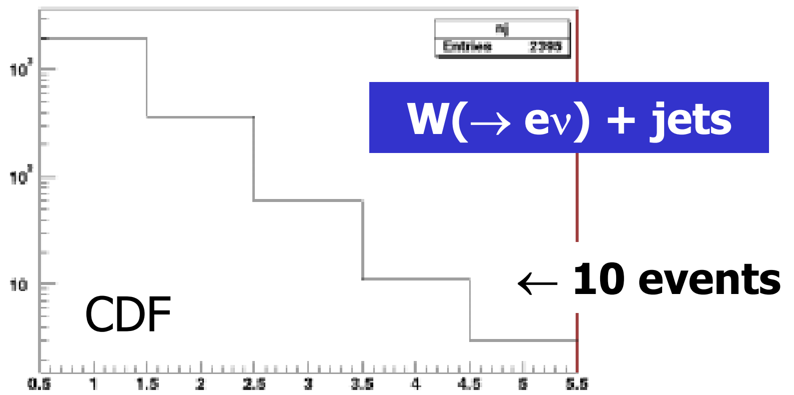
- **We will also measure forward-backward asymmetry in Z production, multiboson production, boson + jets, …**

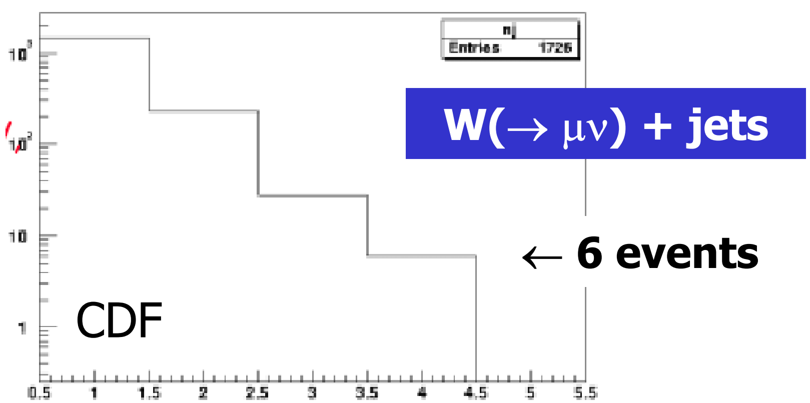
The Top Quark

- Why, alone among the elementary fermions, does the top quark couple strongly to the Higgs field?
  - Is nature giving us a hint here?
    - Is the mechanism of fermion mass generation indeed the same as that of EW symmetry breaking?
  - The top is a window to the origin of fermion masses

- The Tevatron Collider is the world's only source of top quarks
- Measure its
  - Mass
  - Production cross section
  - Spin
    - Through top-antitop spin correlations
  - Electroweak properties
    - Through single top production

The Top Quark in Run II





- **W+jets scaling in CDF Run II data**
  ~ 44 pb^{-1}, E_T^{jet} > 20 GeV, $|\eta^{jet}|$ < 2

Improved top mass measurements will help to constrain the Higgs mass:

	Δm_t
2 fb^{-1}	**± 2.7 GeV**
15 fb^{-1}	**± 1.3 GeV**

In contrast to the W, we can look forward to improved precision on m_t in the near future

- More data (few hundred pb^{-1})

- Improved techniques

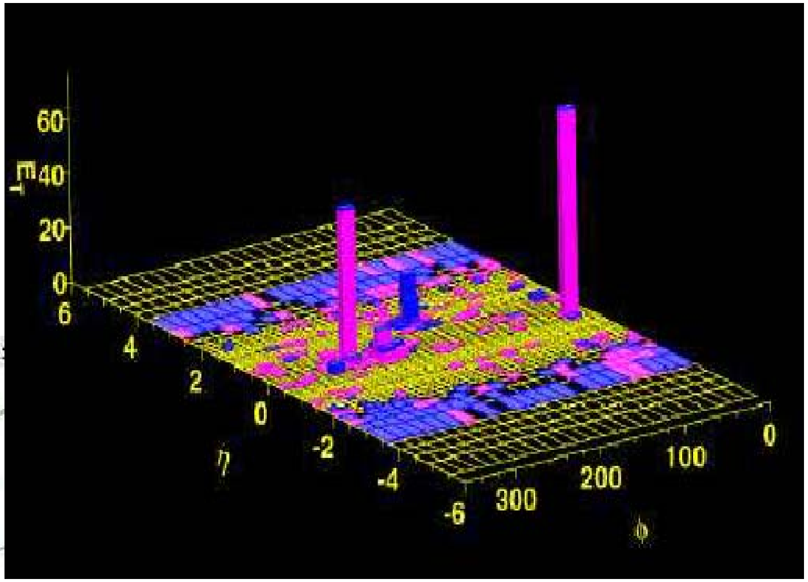
Expect ~ 500 b-tagged lepton+jets events per experiment per fb^{-1}

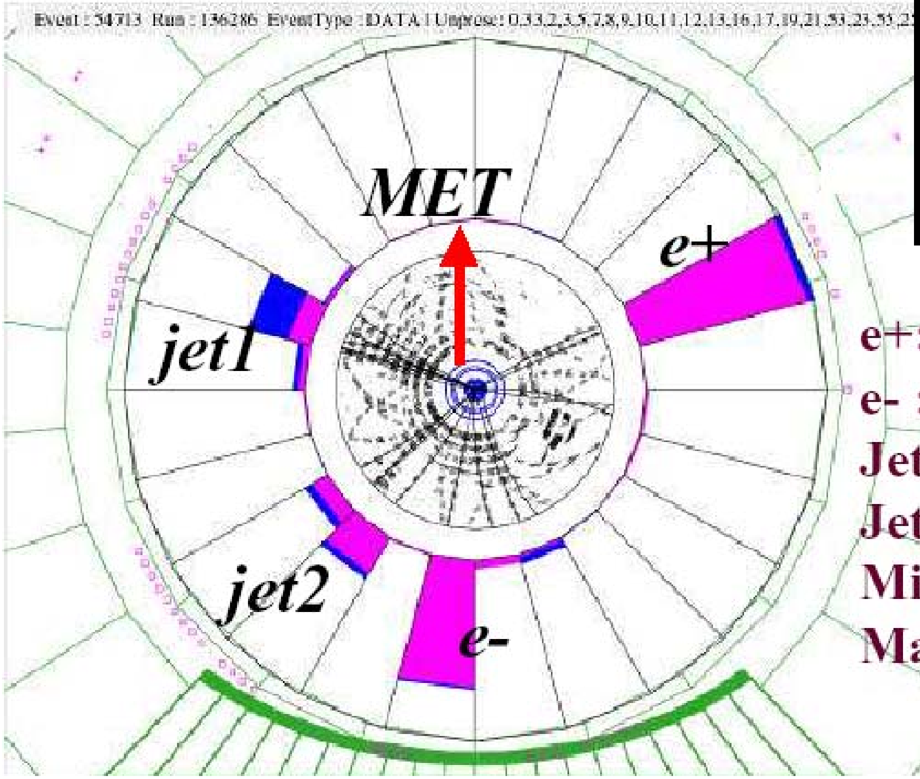
World total at end of Run I ~ 50

CDF top dielectron candidate

e^+e^- not consistent with a Z
two jets
large missing E_T

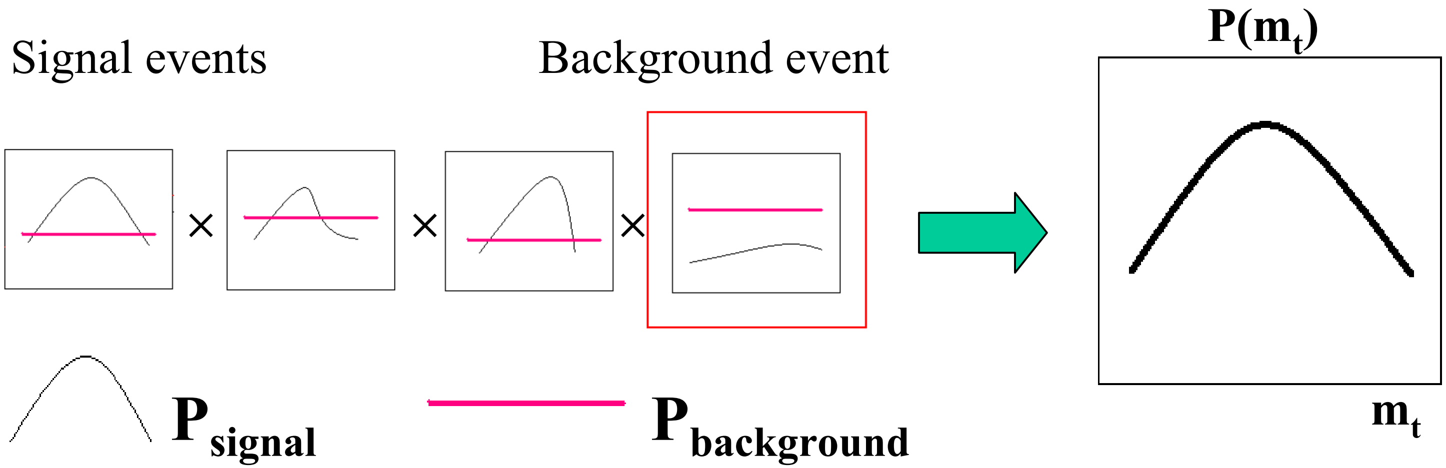
Run 136286, event 54713





e+: Et=73 GeV
e- : Et=56 GeV
Jet1: Et= 35 GeV
Jet2: Et = 34 GeV
Missing Et = 43 GeV
Mass (e-e+)=118 GeV

A new measurement of the top mass

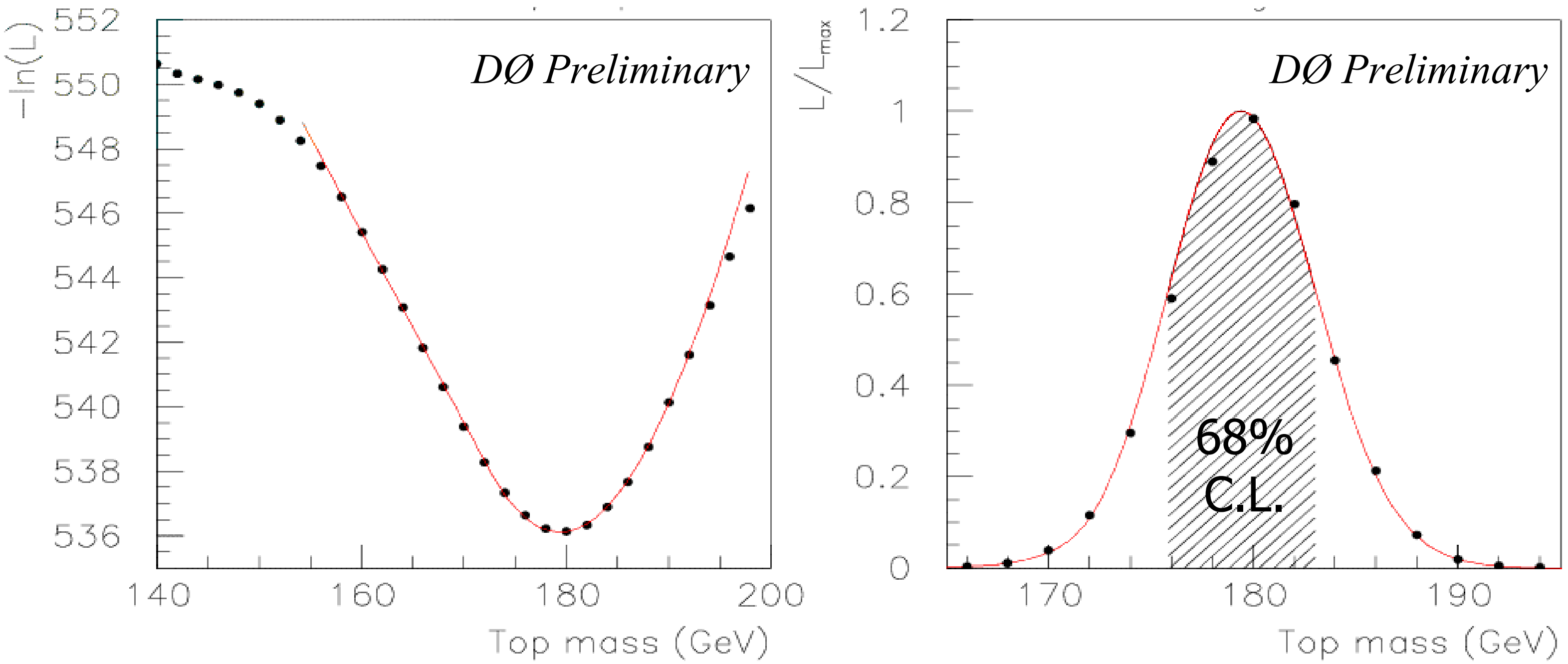


For each event, signal and background probabilities are added. The probabilities for individual events are then multiplied together.

- **Uses all measured quantities per event and their errors**
  - **consider all 12 jet combinations, all neutrino momenta**
    - **Analogous to Kondo, Dalitz, Goldstein technique as used for the top dilepton sample**
- **Run I dataset**

For more details: see J. Estrada, in Proceedings of HCP 2002 (in preparation)

New Preliminary Top Mass

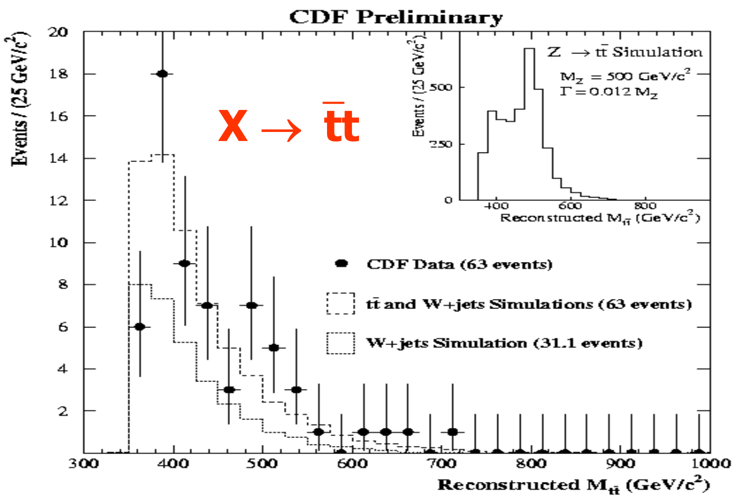


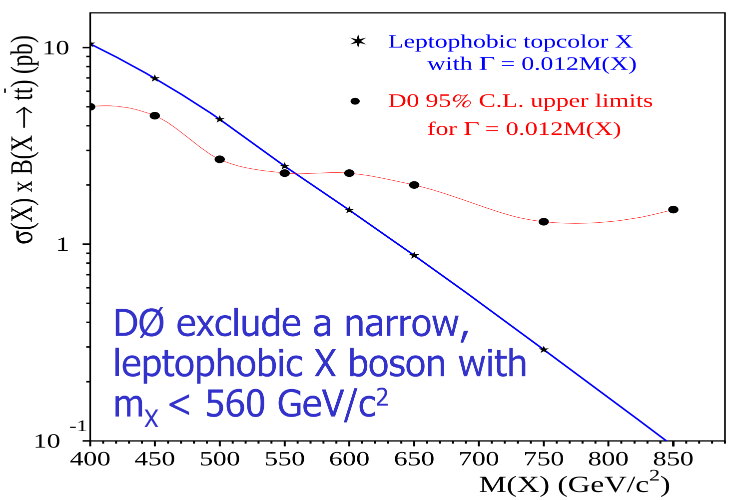
m_t = 179.9 ± 3.6 (stat) ± 6.0 (sys) GeV *preliminary*

- **Improves statistical error from 5.6 GeV [PRD 58 52001, (1998)] to 3.6 GeV: equivalent to a factor of 2.4 in the number of events**
- **22 events pass final cuts (from fit: 12 S + 10 B)**

Top as a window on new physics

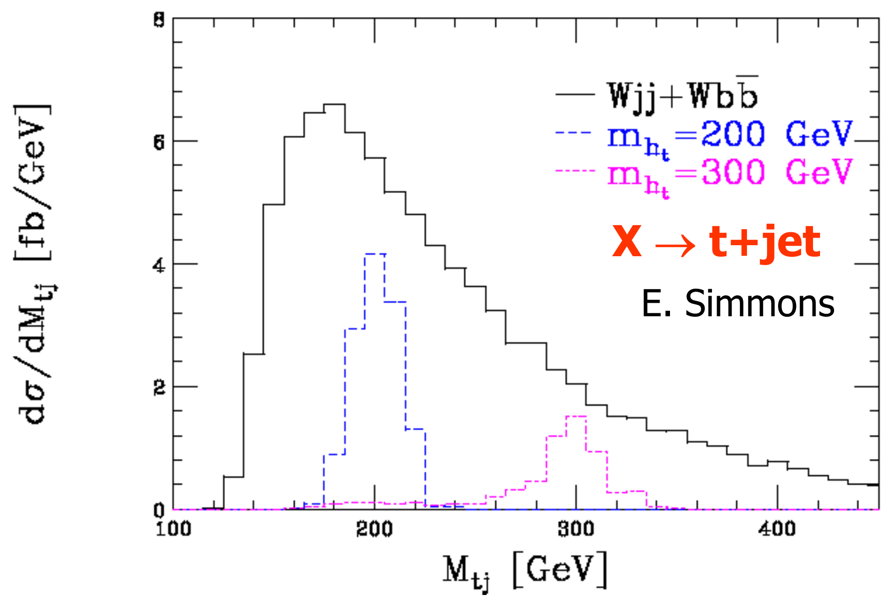
Can top provide insight into electroweak symmetry breaking?





BSM theories predict unusual top properties and states visible in Run II

- **Z′ (analyses of Run I data at left)**
- **top-higgs with FC decays (simulation below)**

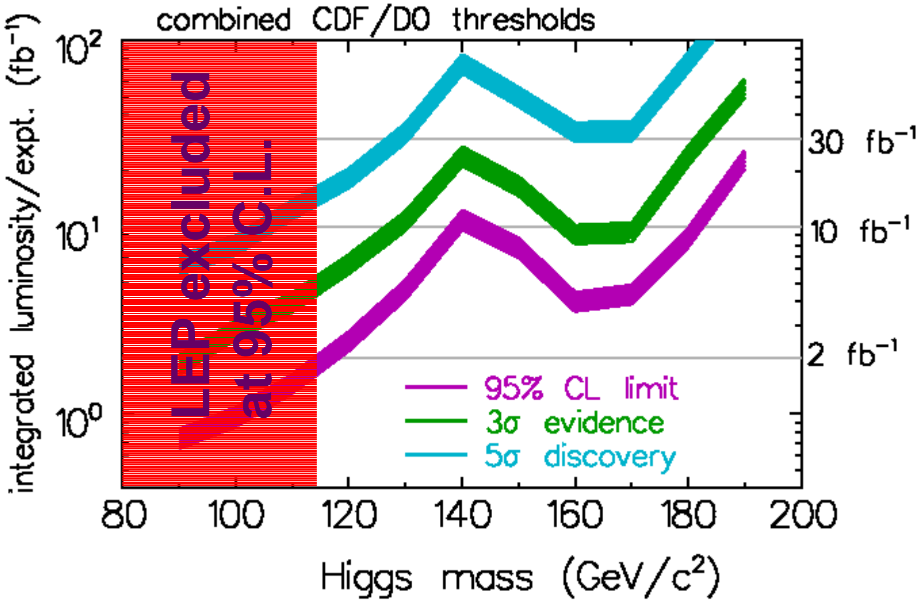


The Higgs Boson

- In the Standard model, the weak force is weak because the W and Z gain mass from a scalar field that fills the universe
- The same field is responsible for the mass of the fundamental fermions
- If it exists, we can excite the field and observe its quanta in the lab
  - The Higgs boson
    - Last piece of the SM
    - Key to understanding beyond-the-SM physics like supersymmetry: a light Higgs is a basic prediction of SUSY
- All the properties of the Higgs are fixed in the SM with the exception of its own mass: simulations have no free parameters


University of Durham
THE HIGGS BOSON
1964
Peter Higgs suggested introducing
widely accepted scenario.
The Higgs boson is the only missing ingredient of the Standard Model
2008
Ogden Centre for Fundamental Physics

The Higgs boson at the Tevatron



- **To make this a reality, we need**
  - **Resolutions at least as good as Run I**
  - **Good b-jet and lepton identification**
  - **Triggers efficient at high luminosities**
  - **Good understanding of all the backgrounds**

What we are focused on at the moment

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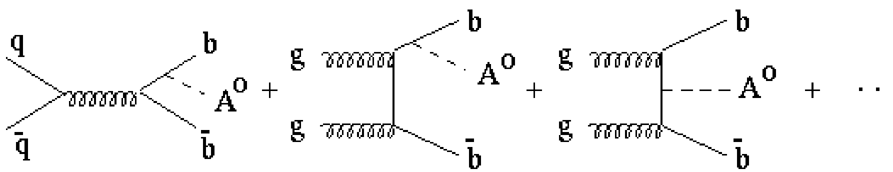
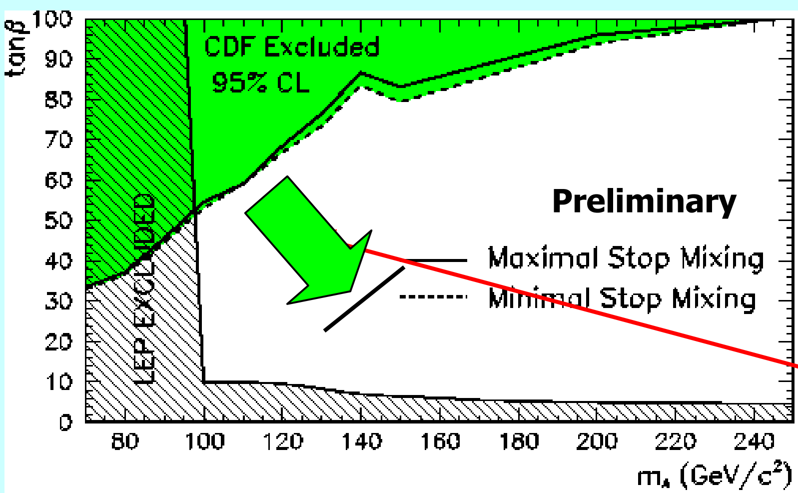
SUSY Higgs Production at the Tevatron

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

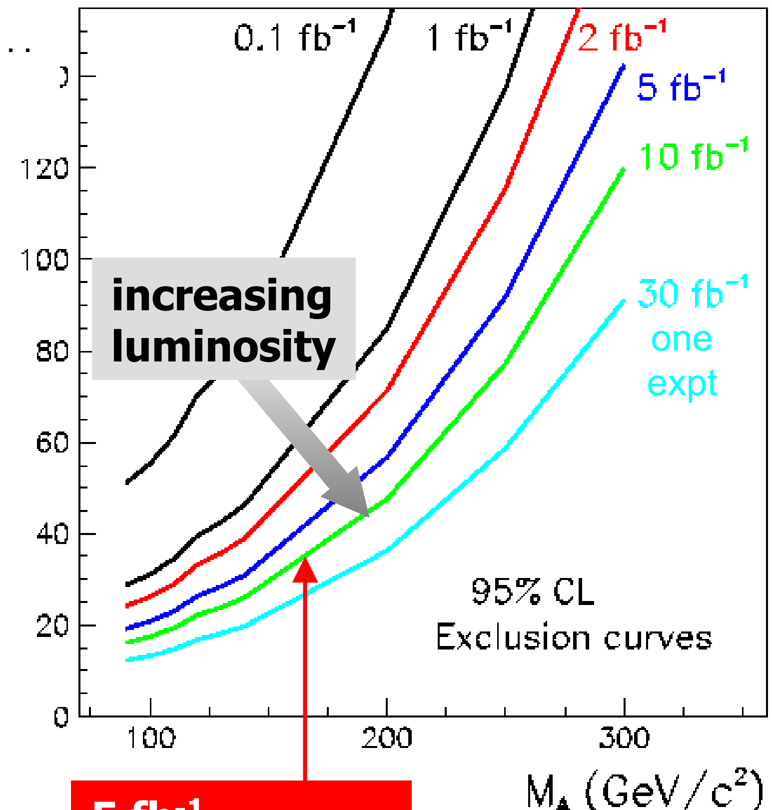


- **σ ~ 1 pb for tanβ = 30 and m_h = 130 GeV**

CDF Run 1 analysis (4 jets, 3 b tags) sensitive to tan β > 60



bb(h/A) → 4b



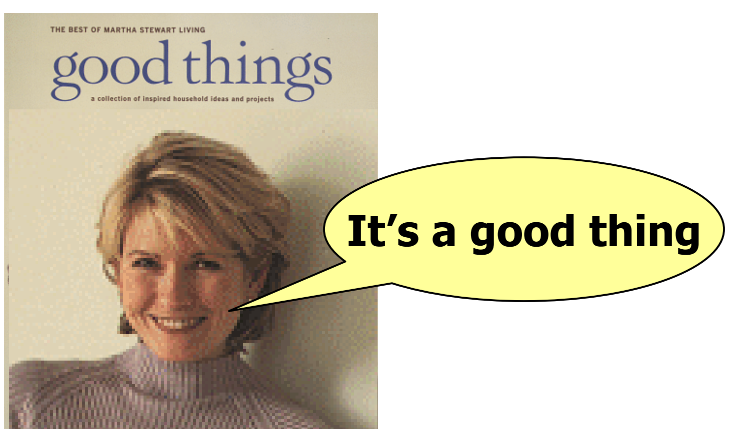
5 fb^{-1}
m_A =140 GeV,
tan β = 30

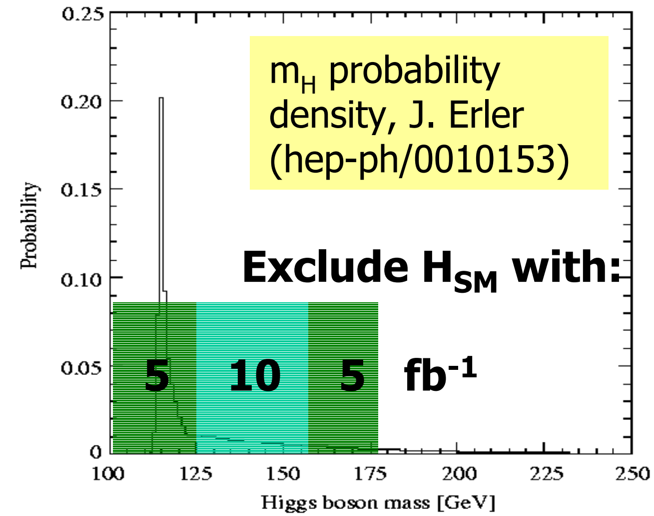
John Womersley

What if we see nothing?

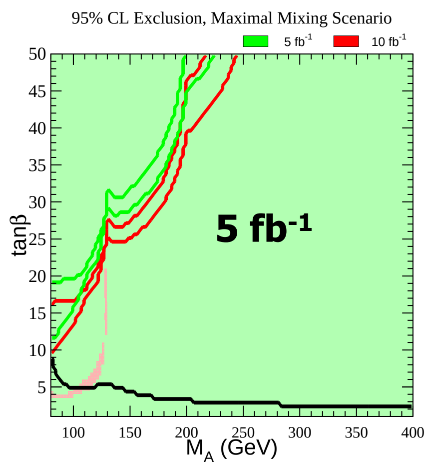
As long as we have adequate sensitivity, exclusion of a Higgs would itself be a very important discovery for the Tevatron

- In the SM, can exclude most of the allowed mass range with 10 fb^{-1}
- In the MSSM, can potentially exclude <u>all</u> the remaining parameter space with 5 fb^{-1}
- Would certainly make life “interesting” for SUSY at the TeV scale

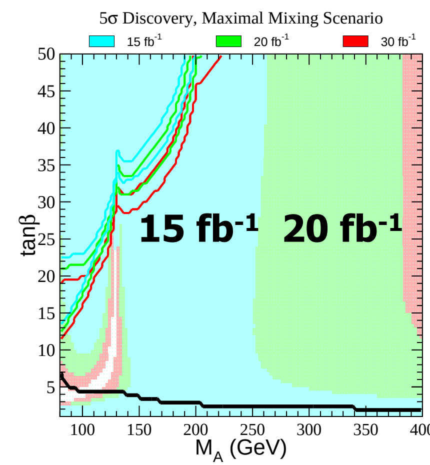




95% exclusion



5σ discovery



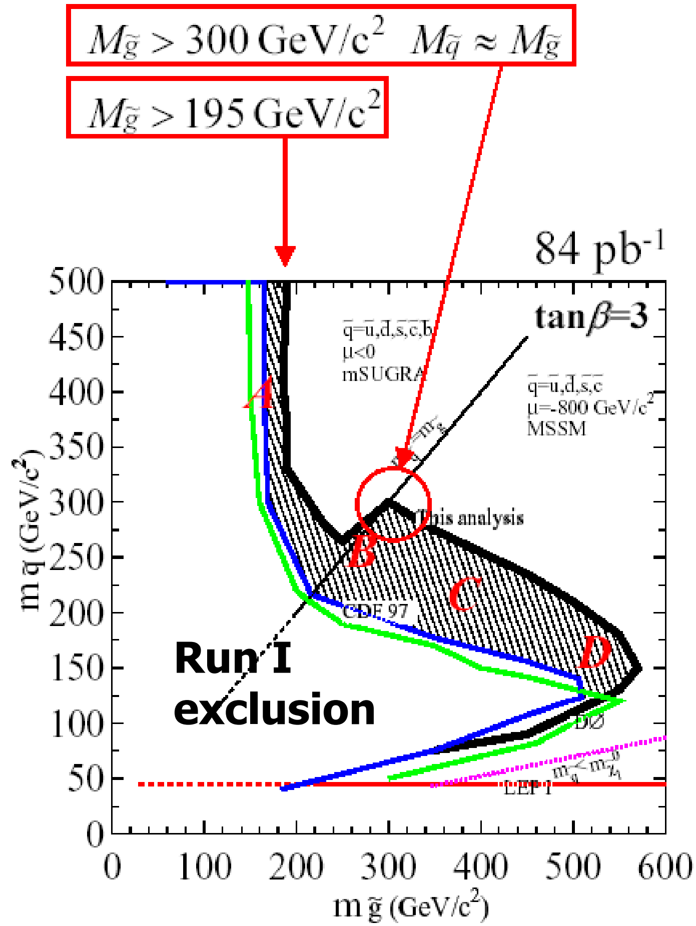
Exclusion and discovery for SUSY Higgs sector, maximal stop mixing, sparticle masses = 1 TeV

Searches for New Physics

- The Tevatron is the world's highest energy collider
- The most likely place to directly discover a new particle or force
- We know the SM is incomplete
- Most popular extension: supersymmetry
  - Predicts a large number of new particles with masses in the range 100 GeV – 1 TeV
  - Lightest neutralino could explain cold dark matter in the cosmos
  - Run II could discover supersymmetry over a wide range of parameter space
- Run II will also test the new and exciting idea of extra dimensions
  - Can gravity propagate in more than four dimensions of space-time?
  - If these dimensions are not open to the other SM particles and forces, we would not perceive them
  - Particle physics experiments at the TeV scale could see effects (direct and indirect)
    - Measure the structure of space-time!

Searches at the Tevatron

- **Tevatron search channels for SUSY**
  - Squarks/gluinos → Missing E_T + jets (+ lepton(s))
  - Charginos/neutralinos → multileptons
  - GMSB → Missing E_T + photon(s)
  - Stop, sbottom
  - RPV signatures
- **Searches for other new phenomena**
  - leptoquarks, dijet resonances, W′,Z′, massive stable particles, extra dimensions . . .



- **No significant indication of new physics was found in Run I**

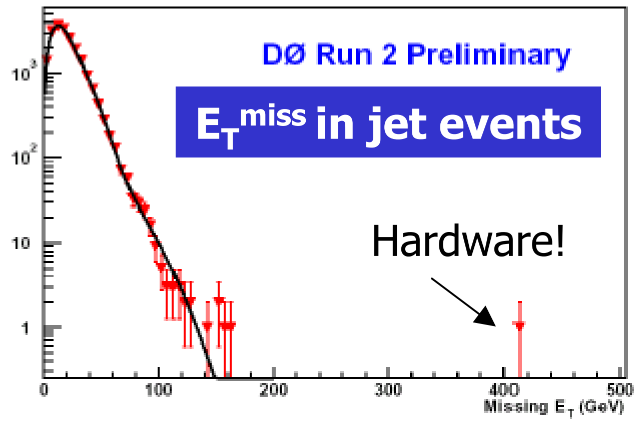
  Different psychologies:

  DØ quote an 89% CL for agreement with the Standard Model

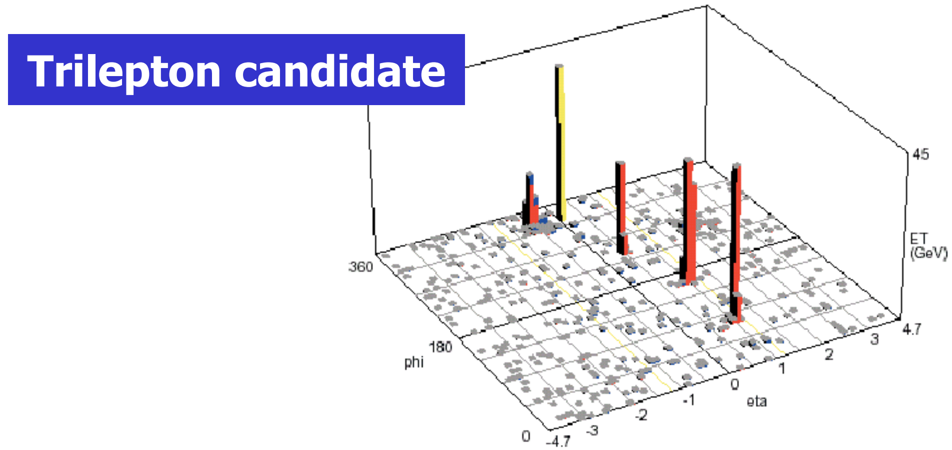
  CDF prefer to point out some anomalies worth pursuing early in Run II

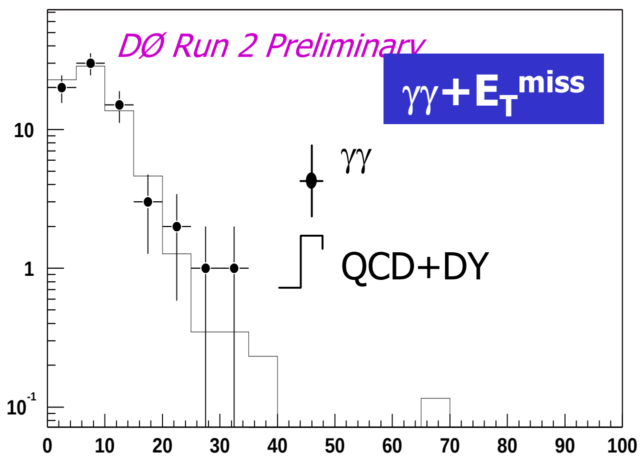
Run II mass reach
q̃, g̃ ~ 500 GeV
$\chi^{\pm}$ ~ 180 GeV

SUSY searches in Run II



Missing Transverse Energy





Missing Transverse Energy

First Run II SUSY limit

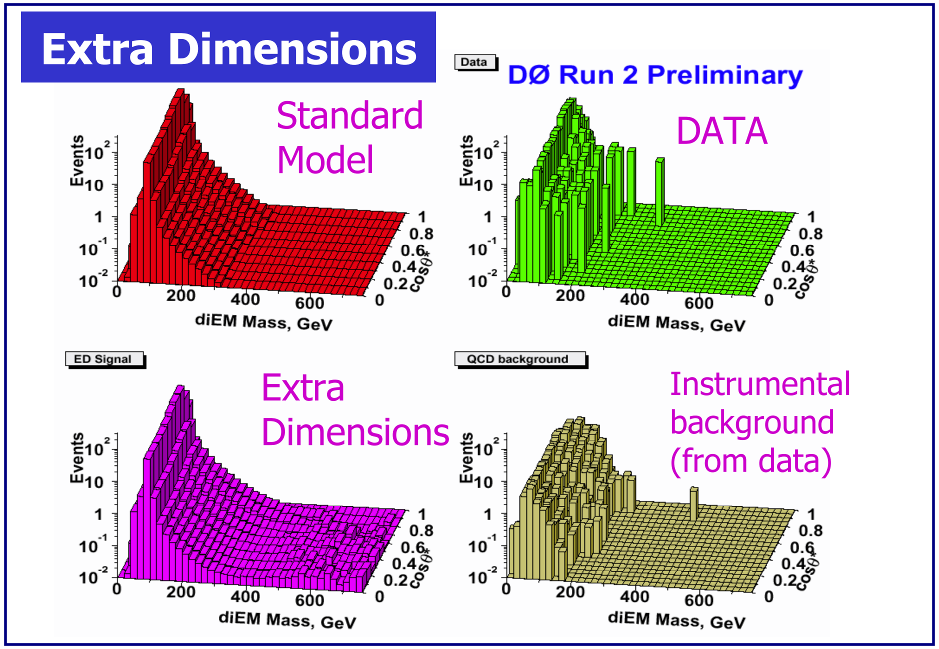
Gauge mediated SUSY $\bar{p}p \rightarrow \gamma\gamma + E_T^{miss}$

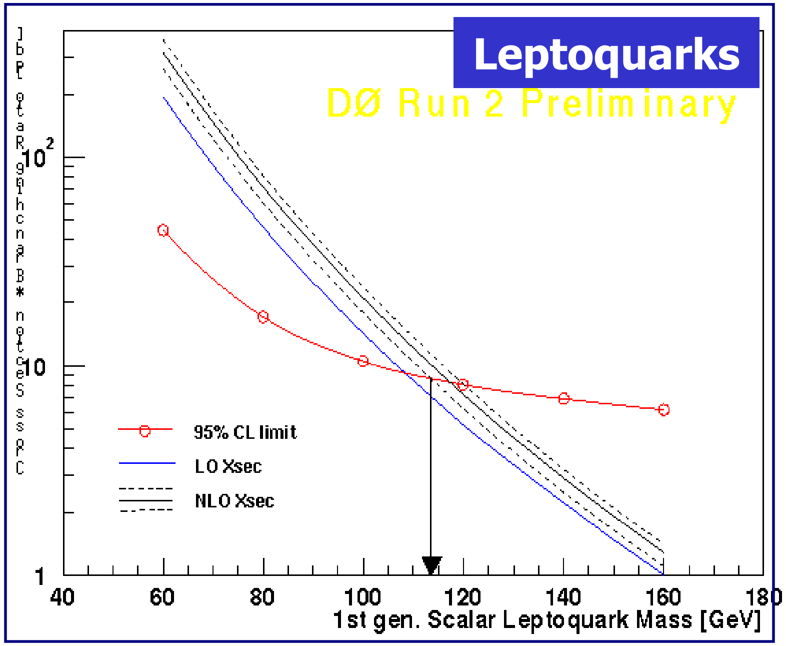
Cross section for $\gamma\gamma + E_T^{miss}$ > 0.9pb

Run II limits are not yet competitive, but show we are ready for this physics

Run II students are graduating

Other new phenomena in Run II





Run II limits from $p\bar{p} \rightarrow ee, \mu\mu, \gamma\gamma$

M_S(GRW) > 0.92 TeV ($ee/\gamma\gamma$)

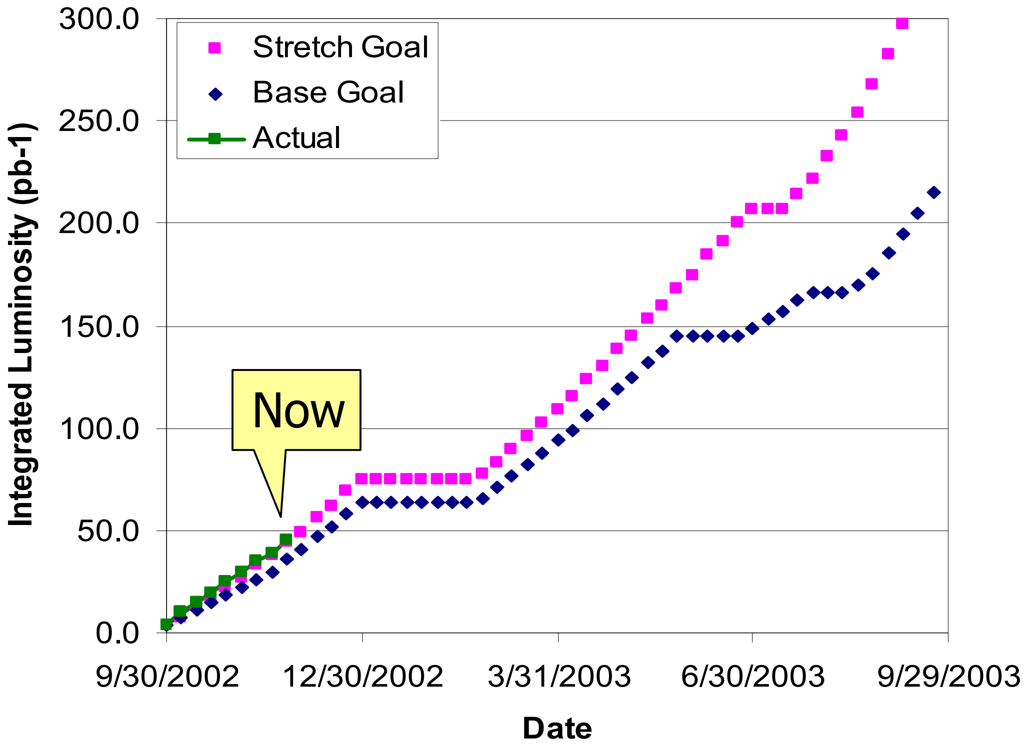
M_S(GRW) > 0.50 TeV ($\mu\mu$)

(first limit from a hadron collider in this channel)

First generation leptoquark Run II mass limit

M_{LQ} > 113 GeV for B(LQ $\rightarrow$ ej) = 1

Prospects for 2003

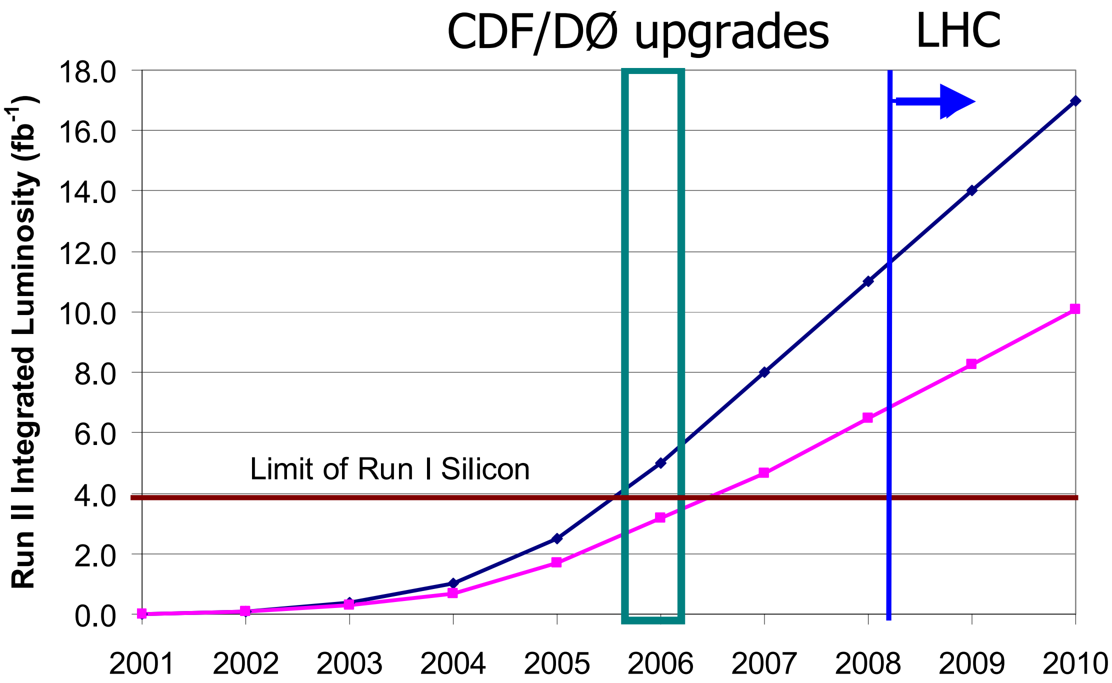


- **Department of Energy Review Committee, October 2002:**
  - **… Fermilab has embraced the challenge of meeting the luminosity goals for the Tevatron complex…**
  - **… there is a good likelihood that the "base" luminosity goal set for FY03 will be met or even exceeded.**

Short term prospects

- For the spring conferences, we plan to "rediscover" the top quark, and present other improved results with ~ 50pb^{-1}
- By next summer (LP2003 at Fermilab), we expect physics results from Run II with ~ 200 pb^{-1}
  - significantly increased sample over Run I with improved detectors and a higher center of mass energy
    - Top quark measurements with increased statistics and purity
      - Cross section is 35% higher
      - Silicon b-tagging capability
    - Increased statistics W and Z samples, multiboson samples
    - Start to explore the B sector
    - Jet cross section at high E_T
      - constrain the gluon PDF
    - New limits on physics beyond the SM
      - e.g. MSSM A/H at large tan β
    - . . .

The longer term future



- **To realize the full potential of Run II we must upgrade the detectors, starting now, and also invest in the accelerator**
- **We will run CDF and DØ until the LHC experiments start to produce competitive physics results**
  - **The experiments, and the laboratory director, believe we should be prepared to run until the end of the decade**

Run II Physics Program

15 fb^{-1}

- 5σ Higgs signal @ m_H = 115 GeV
- 3σ Higgs signal @ m_H = 115-135, 150-175 GeV
- Reach ultimate precision for top, W, B physics

10 fb^{-1}

- 3σ Higgs signal @ m_H = 115-125, 155-170 GeV
- Exclude Higgs over whole range of 115-180 GeV
- Possible discovery of supersymmetry in a larger fraction of parameter space

5 fb^{-1}

- 3σ Higgs signal @ m_H = 115 GeV
- Exclude SM Higgs 115-130, 155-170 GeV
- Exclude much of SUSY Higgs parameter space
- Possible discovery of supersymmetry in a significant fraction of minimal SUSY parameter space (the source of cosmic dark matter?)

2 fb^{-1}

- Measure top mass ± 3 GeV and W mass ± 25 MeV
- Directly exclude m_H = 115 GeV
- Significant SUSY and SUSY Higgs searches
- Probe extra dimensions at the 2 TeV (10^{-19} m) scale
- B physics: constrain the CKM matrix

300 pb^{-1}

- Improved top mass measurement
- High p_T jets constrain proton structure
- Start to explore B_s mixing and B physics
- SUSY Higgs search @ large tan β
- Searches beyond Run I sensitivity

Each gain in luminosity yields a significant increase in reach and lays the foundation for the next steps

Conclusions

- The world's highest energy accelerator is back online:
  - The Run II physics program has begun
- The combination of high accelerator energy, excellent detectors, enthusiastic collaborations, and data samples that double every year guarantees interesting new physics results at every step.
- Each step answers important questions
- Each step leads on to the next
- This is how we will lay the foundations for a successful LHC program, and hopefully a linear collider to follow