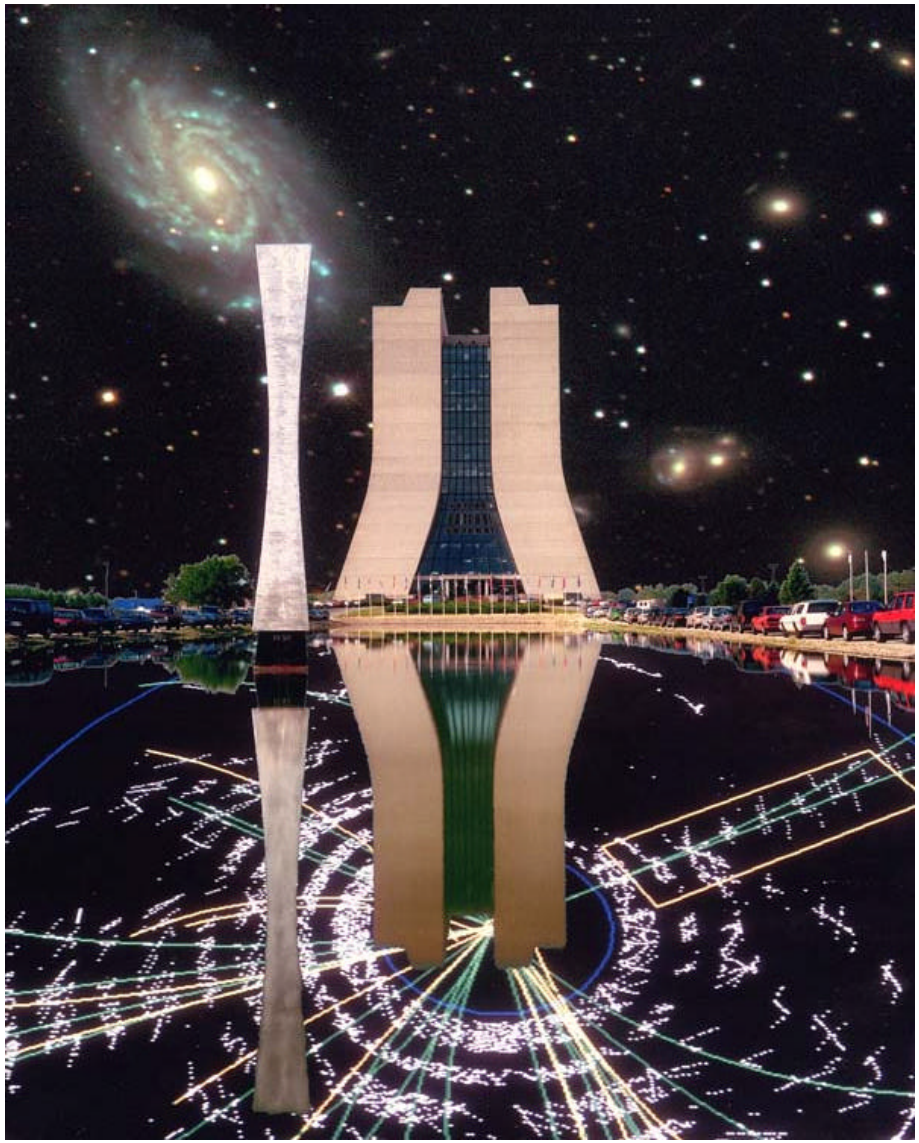

HIGHLIGHTS from FERMILAB

Stephen Parke
Fermilab

Erice Summer School
September 1, 2003

Contributions from…

- Lepton-Photon Speakers:
  - Patrizia Azzi (Padova), Terry Wyatt (Manchester)
  - Michael Schmitt (NorthWestern), Robert Hirosky (Virginia)
  - Koichiro Nishikawa (Kyoto)
- Fermilab JET Seminar Speakers:
  - Aaron Dominguez (LBNL), Robert Kehoe (MSU).
- Many Fermilab Colleagues including
  - Peter Cooper, Stephen Kent, John Beacom, Adam Para,
  - Heidi Schellman, Rajendran Raja, ……

Outline:

- **Vernon Hughes:**
  - E061 and E665
- **Tevatron Collider:**
  - Machine, Detectors and Physics
- **Hadronic Fixed Target:**
- **Theory:**
- **Astrophysics:**
- **Neutrinos:**
- **Summary:**

Vernon Hughes at Fermilab

- E61 Proposed March 1977
  - Proposal to Measure Polarization in P P, PI- P and PI+ P Elastic Scattering at 50, 100 and 150 GeV/c at FNAL.
- First pub May 1977
- Completed Oct 1977
- 3 papers: 2 in PRL, 1 PRD

VOLUME 39, NUMBER 6 PHYSICAL REVIEW LETTERS 8 AUGUST 1977

Measurement of the π^+p and π^-p Polarization Parameters at 100 GeV/c

I. P. Auer, D. Hill, B. Sandler,[a] and A. Yokosawa
Argonne National Laboratory, Argonne, Illinois 60439

and

W. Brückner, O. Chamberlain, H. Steiner, and G. Shapiro
Lawrence Berkeley Laboratory, Berkeley, California 94720

and

A. Jonckheere and P. F. M. Koehler
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

R. V. Kline, M. E. Law, and F. M. Pipkin
Harvard University, Cambridge, Massachusetts 02138

and

W. Johnson
Suffolk University, Boston, Massachusetts 02114

and

J. Snyder and M. E. Zeller
Yale University, New Haven, Connecticut 06520
(Received 24 May 1977)

We report measurements of the polarization parameters in π^+p and π^-p elastic scattering at an incident momentum of 100 GeV/c. The results cover the range $0.18 \leq -t \leq 1.4$ GeV^2 and are in agreement with current Regge-model predictions.

In the first experiment of its kind at Fermilab we have measured the polarization parameter $P(t)$ in the elastic scattering of mesons and protons from polarized protons. We present here the results for π^+p and π^-p scattering which were obtained at a beam momentum of 100 GeV/c over the range of the square of the four-momentum transfer $0.18 \leq -t \leq 1.4$ GeV^2.

While recent measurements of elastic differential cross sections in this kinematic region[1,2] have confirmed phenomenological predictions of the s and t dependence of the dominant Pomeron amplitude,[3,4] polarization measurements provide more stringent tests of present models because they are sensitive to interference between amplitudes. For example, a model in which Pomeron- and ρ-exchange contributions dominate predicts that $P(t)$ in πp scattering should be proportional to s^x with $x = \alpha_\rho(t) - \alpha_P(t)$, where s is the square of the total energy of the system, and $\alpha_\rho(t)$ and $\alpha_P(t)$ are the effective trajectories for the ρ- and Pomeron-exchange contributions, respectively. This s dependence is approximately $s^{-1/2}$ at small $|t|$. This model also predicts that the mirror symmetry $P_{\pi^+p} \cong -P_{\pi^-p}$ persists at high energies.[5] In the region $0.6 \leq -t \leq 1.5$ GeV^2 the dominant amplitudes are strongly affected by shrinkage and absorption, resulting in small polarization values at high energies.[5]

The experiment was performed in the 3.5-mrad beam (M1) in the Meson Laboratory which had a size of 2×2 cm^2 and a divergence of ± 0.2 mrad at the target while transporting a momentum bite of $\pm 1\%$. The small divergence was necessary for kinematic separation of elastic from quasielastic events. In order to determine polarizations of $\lesssim 0.05$ with high precision, we placed no components in the beam, enabling the apparatus to handle incident fluxes as large as 10^6/sec.

The layout of the apparatus is shown schematically in Fig. 1. It consisted of a double-arm spectrometer capable of detecting both final-state particles with uniform acceptance over the range $0.25 \leq -t \leq 1.5$ GeV^2. The final-state trajectories were measured with eight planes of multiwire proportional chambers (PWC's) in

Vernon Hughes (conti)

- E665
  - Proposed Oct 1980,
  - Began 1987
- VH also on CERN's EMC
- Muon Scattering with Hadron Detection at the Tevatron.
- First Results Pub. Aug 1991
- Completed Jan 1992
- 26 papers: 6 in PRL

VOLUME 68, NUMBER 22 PHYSICAL REVIEW LETTERS 1 JUNE 1992

Saturation of Shadowing at Very Low Bjorken x

M. R. Adams,[6] S. Aïd,[9] P. L. Anthony,[10] M. D. Baker,[10] J. Bartlett,[4] A. A. Bhatti,[13] H. M. Braun,[14] W. Busza,[10] T. J. Carroll,[6] J. M. Conrad,[5] G. Coutrakon,[4] R. Davisson,[13] I. Derado,[11] S. K. Dhawan,[15] W. Dougherty,[13] T. Dreyer,[1] K. Dziunikowska,[8] V. Eckardt,[11] U. Ecker,[14] M. Erdmann,[1] A. Eskreys,[7] J. Figiel,[7] H. J. Gebauer,[11] D. F. Geesaman,[2] R. Gilman,[2] M. C. Green,[2] J. Haas,[1] C. Halliwell,[6] J. Hanlon,[4] D. Hantke,[11] V. W. Hughes,[15] H. E. Jackson,[2] D. E. Jaffe,[6],[a] G. Jancso,[11] D. M. Jansen,[13] S. Kaufman,[2] R. D. Kennedy,[3] T. Kirk,[4] H. G. E. Kobrak,[3] S. Krzywdzinski,[4] S. Kunori,[9] J. J. Lord,[13] H. J. Lubatti,[13] D. McLeod,[6] S. Magill,[6] P. Malecki,[7] A. Manz,[11] H. Melanson,[4] D. G. Michael,[5] W. Mohr,[1] H. E. Montgomery,[4] J. G. Morfin,[4] R. B. Nickerson,[5] S. O'Day,[9] K. Olkiewicz,[7] L. Osborne,[10] V. Papavassiliou,[15] B. Pawlik,[7] F. M. Pipkin,[5] E. J. Ramberg,[9] A. Röser,[14] J. J. Ryan,[10] A. Salvarani,[3] H. Schellman,[12] M. Schmitt,[5] N. Schmitz,[11] K. P. Schüler,[15] H. J. Seyerlein,[11] A. Skuja,[9] G. A. Snow,[9] S. Söldner-Rembold,[11] P. H. Steinberg,[9] H. E. Stier,[1] P. Stopa,[7] R. A. Swanson,[3] R. Talaga,[9] S. Tentindo-Repond,[2] H.-J. Trost,[2] H. Venkataramania,[15] M. Vidal,[11] M. Wilhelm,[1] J. Wilkes,[13] Richard Wilson,[5] W. Wittek,[11] S. A. Wolbers,[4] and T. Zhao[13]

(Fermilab E665 Collaboration)

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(Received 2 March 1992)

The ratio of cross sections for inelastic muon scattering on xenon and deuterium nuclei was measured at very low Bjorken x ($0.00002 < x_{Bj} < 0.25$). The data were taken at Fermilab experiment E665 with a 490 GeV/c muon beam incident on liquid deuterium and gaseous xenon targets. Two largely independent analysis techniques gave statistically consistent results. The xenon-to-deuterium per-nucleon cross-section ratio is constant at approximately 0.7 for x_{Bj} below 0.003.

PACS numbers: 13.60.Hb, 25.30.Mr

Shadowing, a depletion of the cross section per nucleon in heavy nuclei as compared to deuterium, has been observed in collisions of real and virtual photons with nuclei in several experiments [1–5]. These experiments showed that the ratio of the inelastic per-nucleon cross sections of heavy nuclei to deuterium decreases from unity as Bjorken x decreases from 0.1 to 0.002 ($x_{Bj} = Q^2/2M\nu$, where Q^2 is the four-momentum squared, ν is the energy transferred in the laboratory from the muon to the target, and M is the proton mass) [2–5]. Within the quark-parton model, the observation of shadowing at high Q^2 implies that the quark and gluon distributions of the nucleus differ from those of the free proton [6]. A complementary viewpoint usually employed in photon-nucleus interactions attributes shadowing to quark-antiquark fluctuations of the photon in the laboratory frame [7]. The data at the lowest measured x_{Bj} tend toward the photoproduction data [1] on heavy nuclei, although no evidence for saturation has been observed in previous inelastic-scattering experiments. It was the aim of this experiment to investigate the behavior of the ratio of the xenon and deuterium per-nucleon cross sections down to x_{Bj} of 0.00002, 2 orders of magnitude lower than any previous experiment.

Fermilab experiment 665 has been described in detail elsewhere [8]; only relevant features will be mentioned here. A 490-GeV/c positive muon beam impinged upon either a liquid deuterium (15.5 g/cm^2, length = 115 cm)

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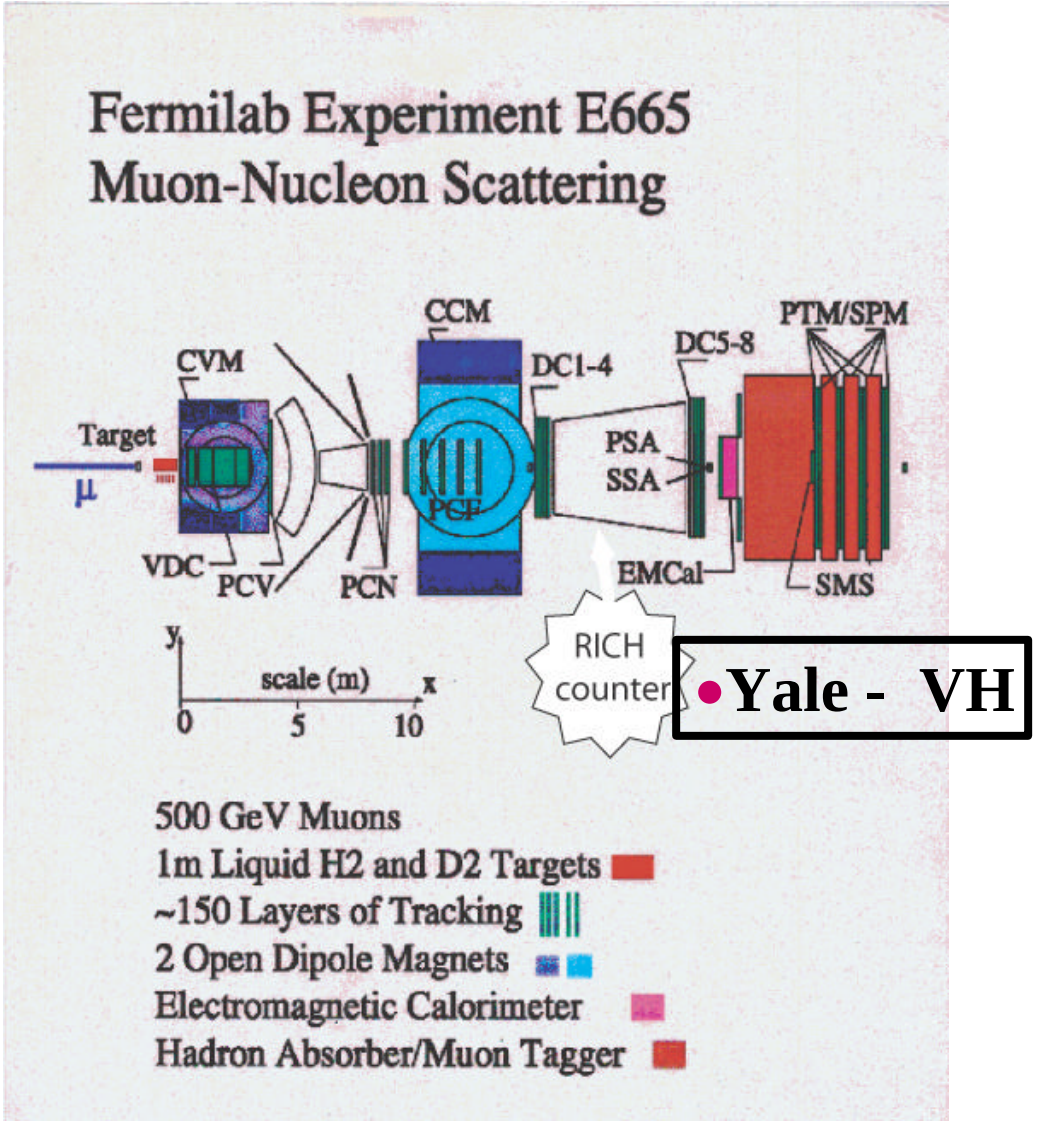
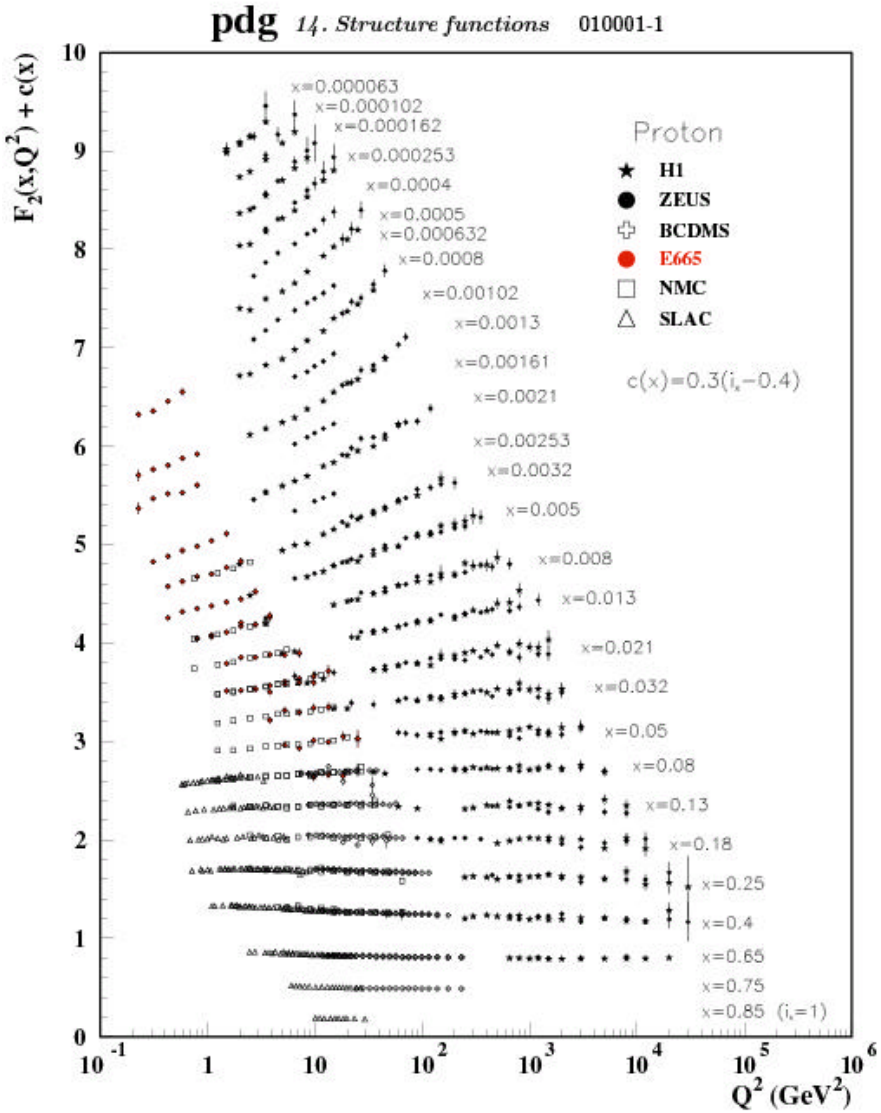
E665 unpolarized muon scattering at 500 GeV



• **Yale - VH**

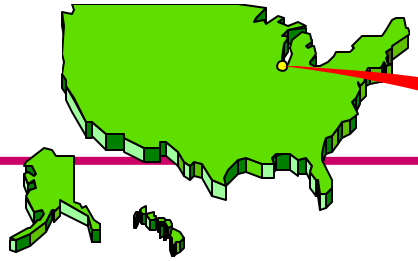
E665 Fame

Structure Functions at Low x and Q squared

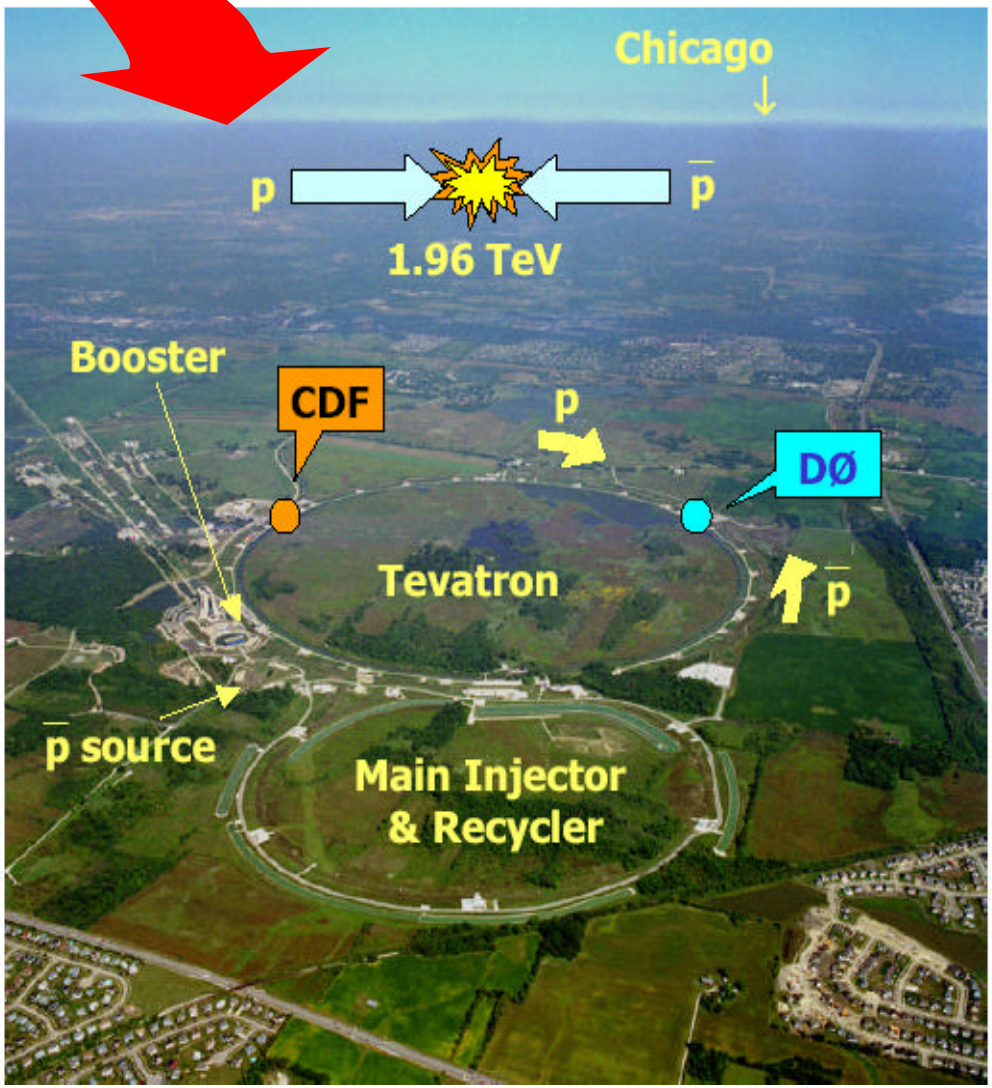


Structure functions at low X and Q^2

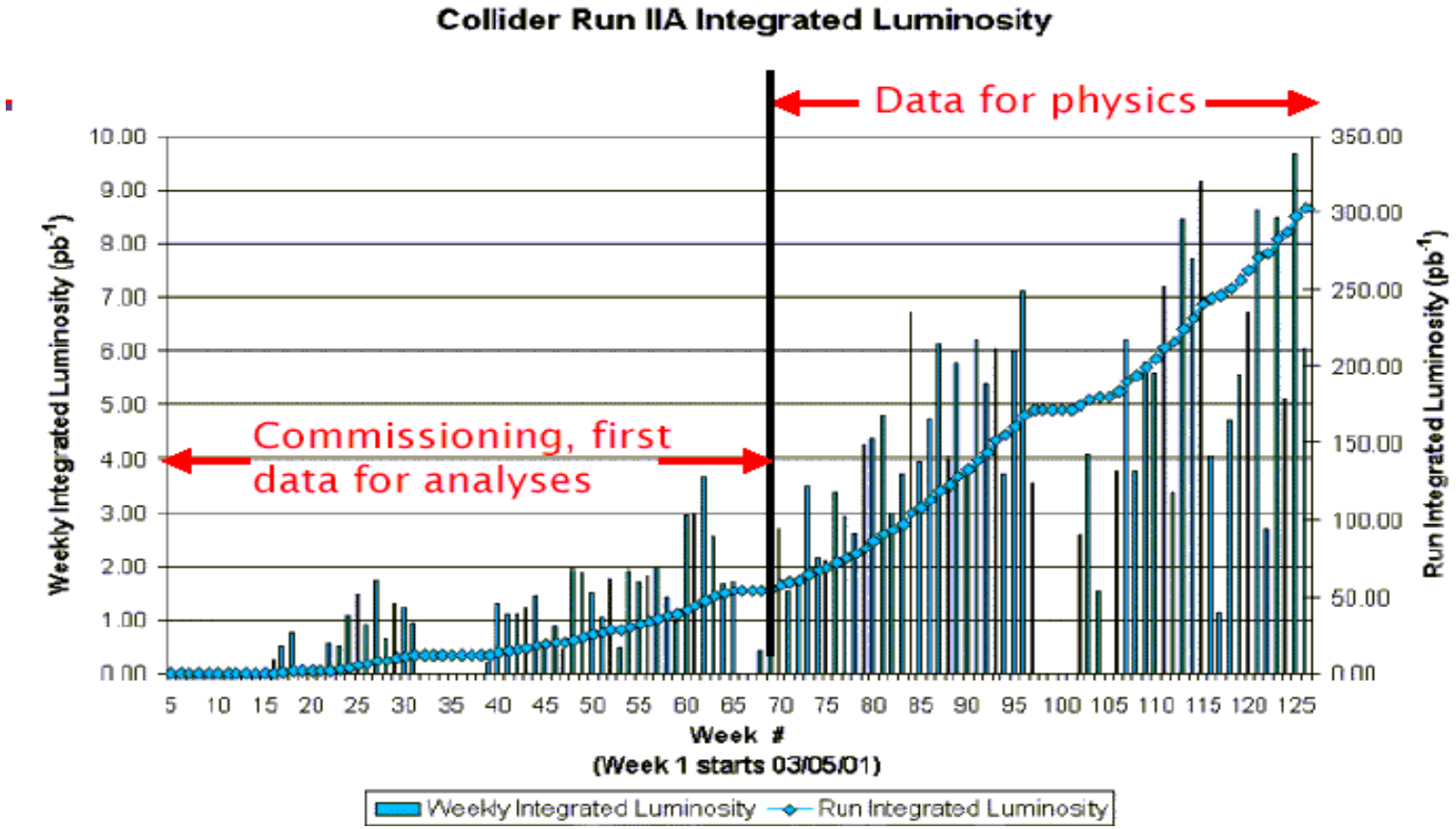
Tevatron Collider in Run II



- The Tevatron is a proton-antiproton collider with 980 GeV/beam. 10% increase over Run I
- Main Ring → Main Injector
- 36 p and pbar bunches →396 ns between bunch crossing
  - Increased from 6x6 bunches with 3.5μs in Run I
- Increased instantaneous luminosity:
  - Run II goal 30 x 10^{31} cm^{-2} s^{-1}
  - Current: 3 to 5 x 10^{31} cm^{-2} s^{-1}



Run II Data Taking Status



- L_{int}~300 pb^{-1} delivered
- Good quality data since Spring 2002
- Data collection efficiency 85÷90%

- **Best L_{peak}~ 5 x 10^{31} cm^{-2} s^{-1}**
- **Best Week ~10 pb^{-1}**
- Steady Improvement.

Integrated Luminosity Projections

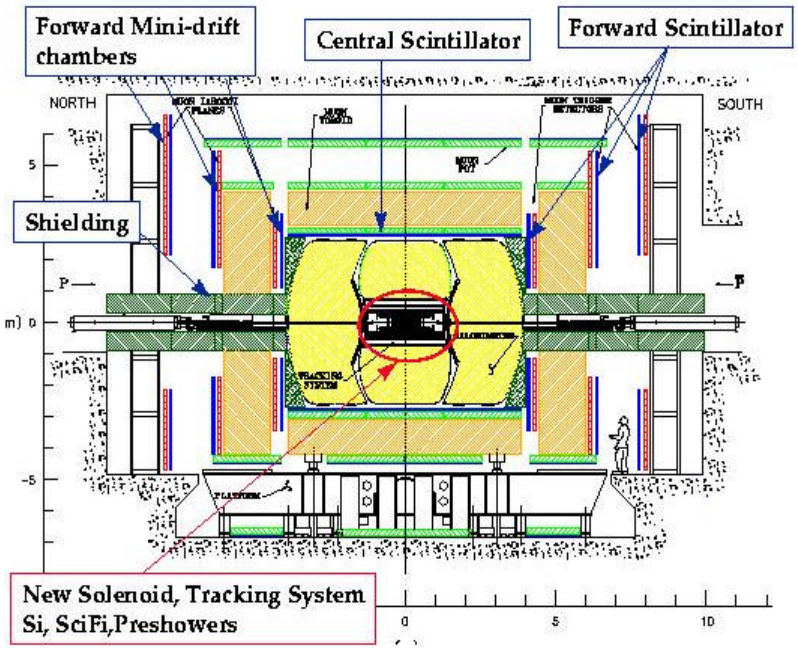
- **Original Goals:**
  - Run II-a 2 fb^{-1}
  - Run II-b 15 fb^{-1}
- **Current Goals:**
  - FY 2003 ~225 pb^{-1} ***<u>**ACHIEVED**</u>
  - FY 2004 200 - 300 pb^{-1} ***Recycler Studies will limit this number
  - FY 2005 390 - 670 pb^{-1}
  - Giving a Total of **1 fb^{-1}** sometime in 2005
- **By End of FY 2009:**

  "Base" 4.4 fb^{-1} "Design" 8.6 fb^{-1}

- **Lab is revisiting the questions?**
  - Detector upgrades - silicon
  - Roll of Recycler
  - Electron cooling of anti-protons

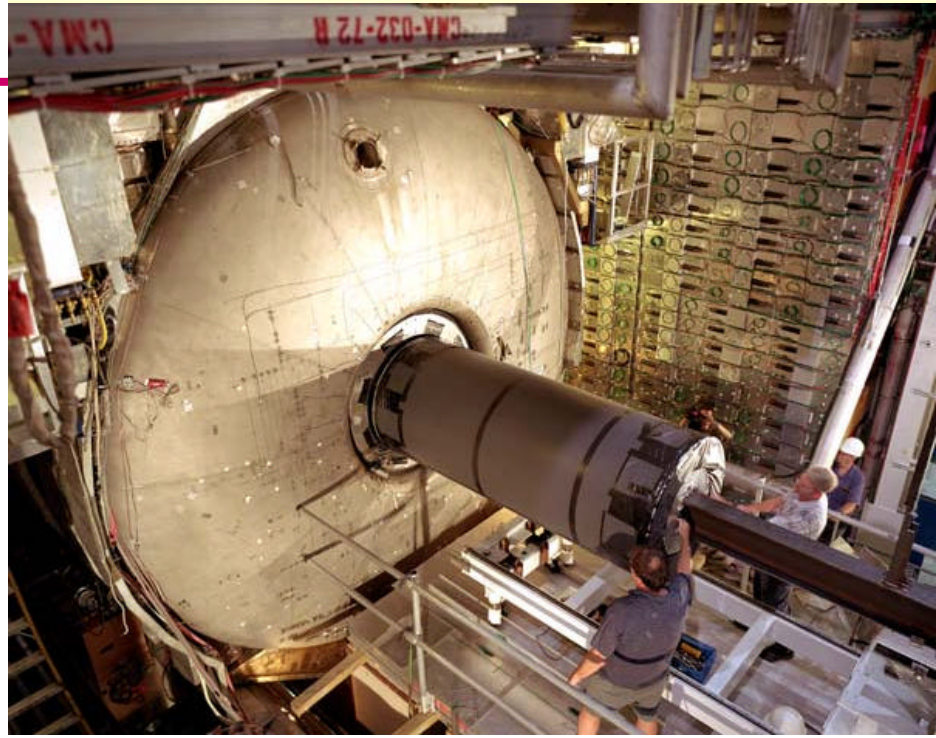
D0 Detector

D0



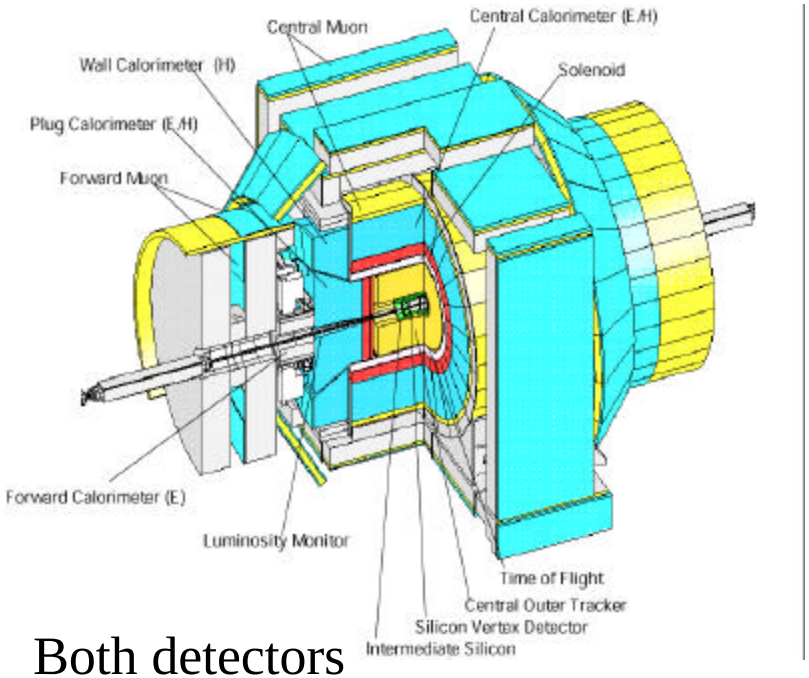
- Both detectors
  - silicon microvertex detectors
  - axial solenoid
  - central tracking
  - high rate trigger/DAQ system
  - calorimeter & muon systems

DØ fiber tracker installation



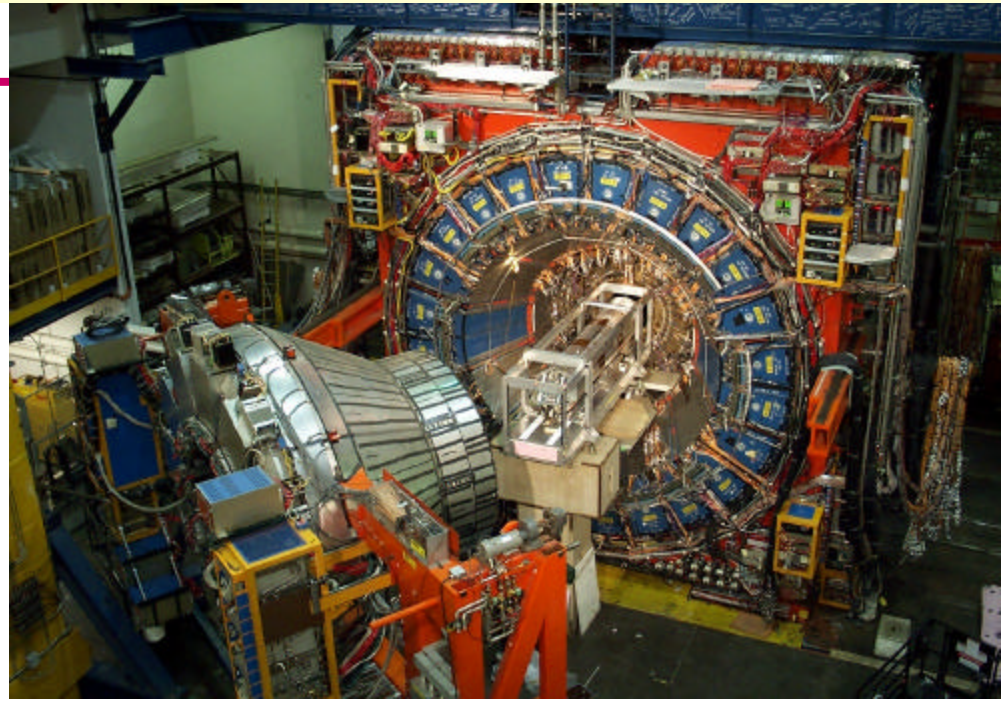
- New tracking: silicon and fibers in magnetic field
- Upgraded muon system
- Upgraded DAQ/trigger (displaced track soon)
  - **Excellent tracking acceptance**
  - **Excellent electron & muon ID**

CDF Detector



- Both detectors
  - silicon microvertex detectors
  - axial solenoid
  - central tracking
  - high rate trigger/DAQ system
  - calorimeter & muon systems

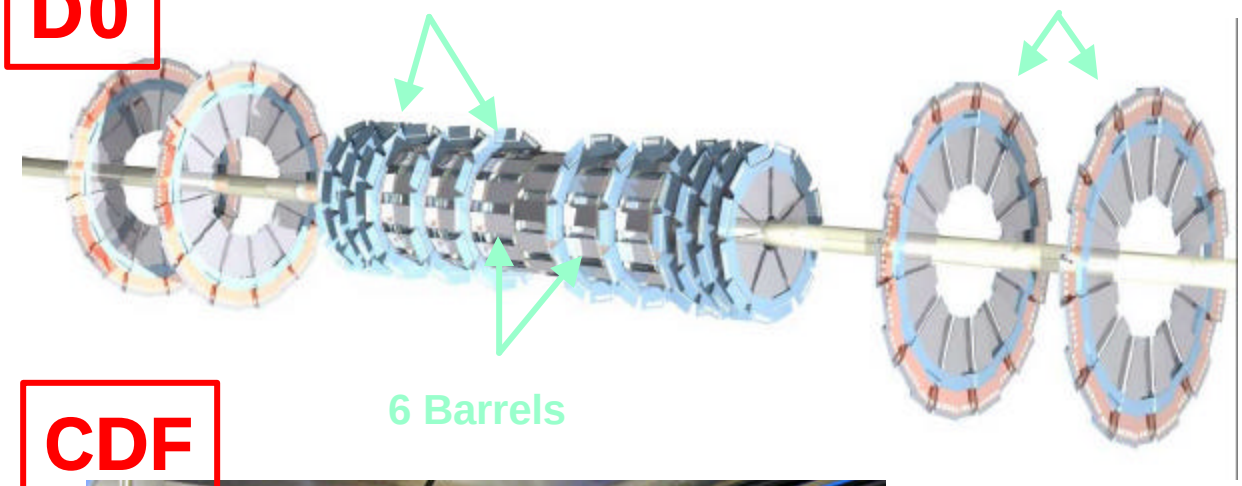
CDF silicon detector installation



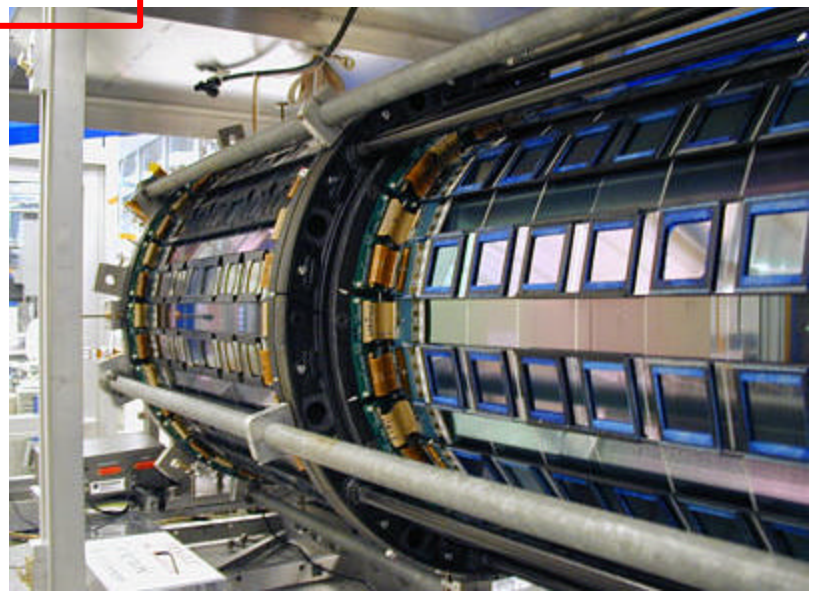
- New bigger silicon, new drift chamber
- Upgraded calorimeter, μ
- Upgraded DAQ/trigger, esp. displaced-track trigger
- Particle ID (TOF and dE/dx)
- Excellent mass resolution

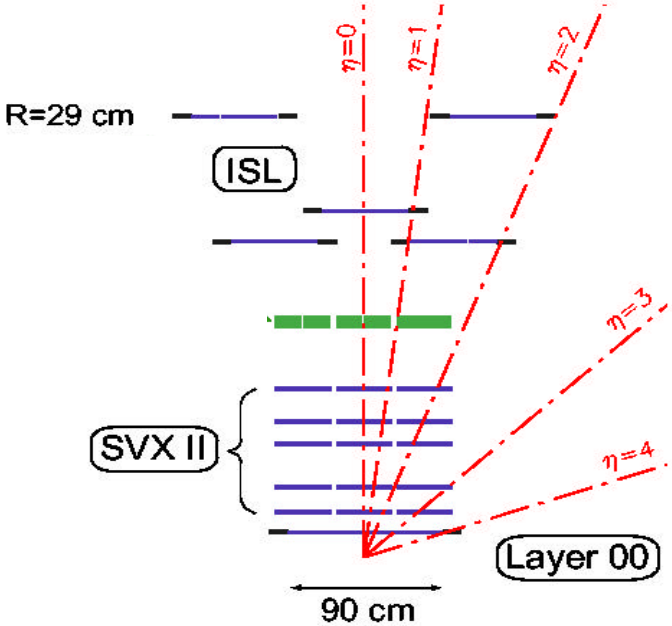
New Silicon Detectors:

D0



CDF





Common features:

- Coverage of the luminous regions
- Extended acceptance at large pseudo-rapidity
- 3D Tracking capability
- Excellent I.P. resolution

The Tevatron Collider Program

- The **Accelerator complex** and the **CDF** and **D0** experiments have been rebuilt for Run-II, to initially collect 2000 pb^{-1} per experiment..

Physics of the Weak Energy Scale

- Supersymmetry
- Precise *t*, *W* mass measurements
- Low mass Higgs with more luminosity
- Search for effects of large hidden dimensions or other new physics.

CP Violation

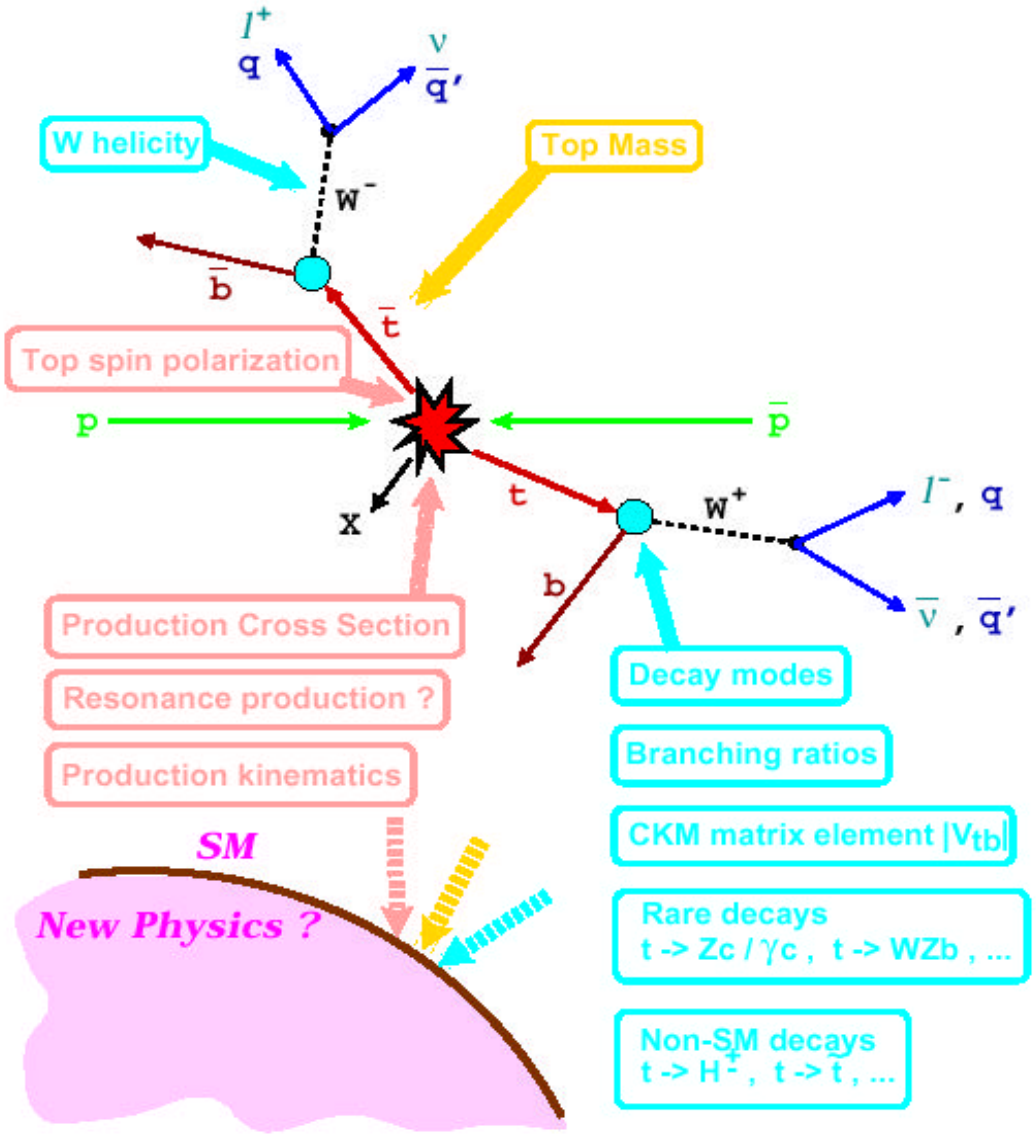
- Use B_s mixing to determine V_{ts}.
- Measure CP-violating asymmetries

Today's Physics Topics:

- Top Quark
- QCD Jets
- Electro-Weak
- Heavy (b,c) Flavors

TOP

TOP QUARK PHYSICS:

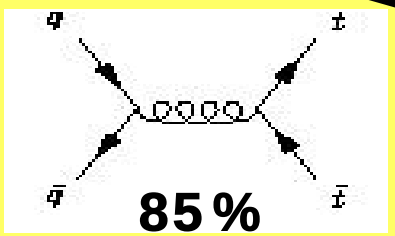


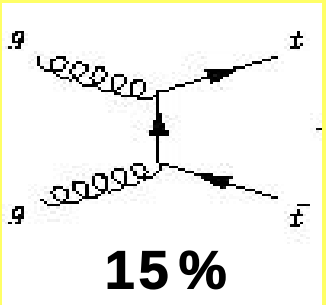
Program

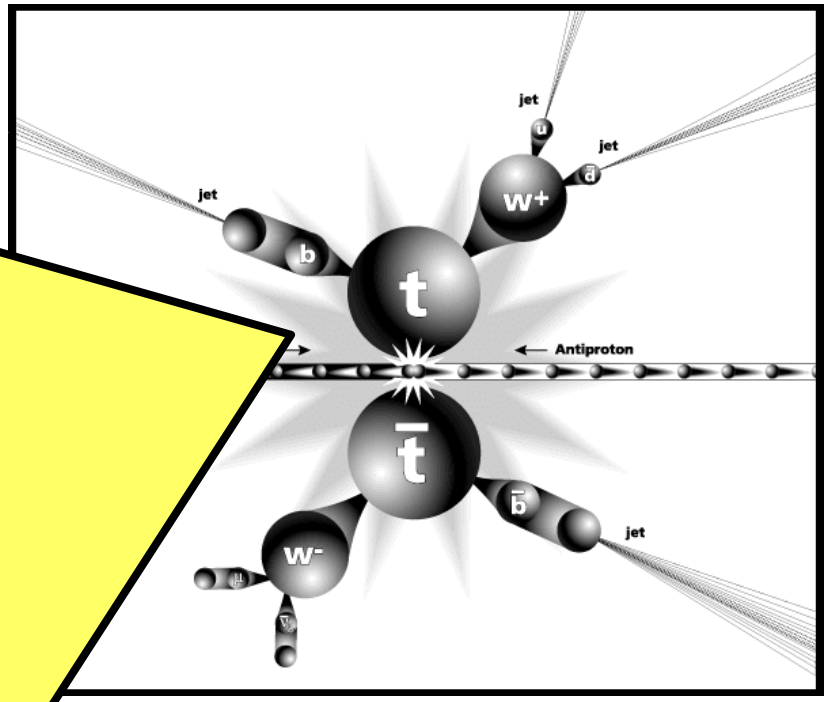
- Top production & decay
- Tools
- Cross section
- Single top
- W helicity
- Mass

•Top Quarks at the Tevatron

Pair production





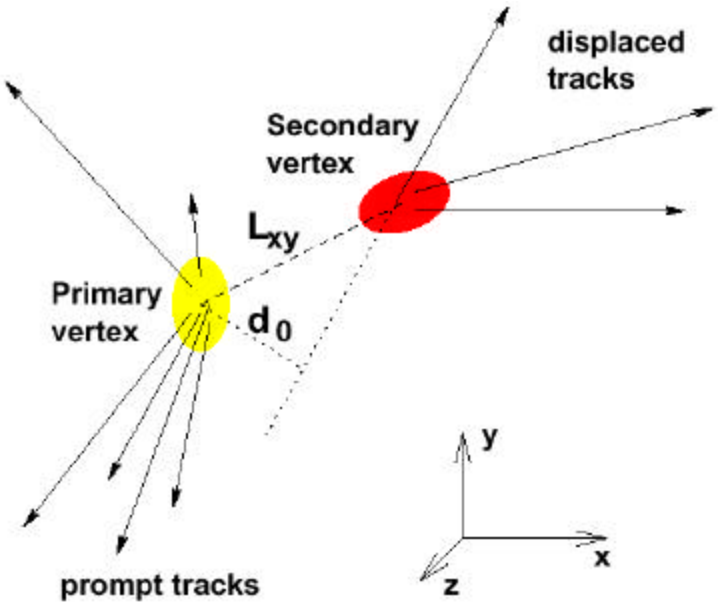


B(t? Wb) = 100%

W's decay modes used to classify the final states

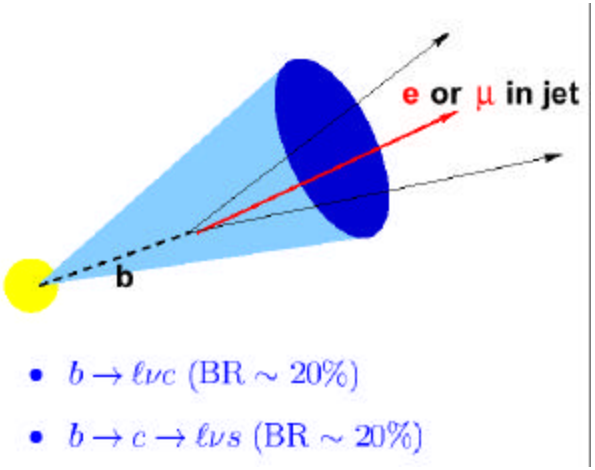
- Dilepton (e,μ) BR=5%
- Lepton (e,μ) +jets BR=30%
- All jets BR=44%
- τ_{had}+X BR=21%

How to tag a high p_T B-jet



Silicon Vertex Tag

- Signature of a b decay is a displaced vertex:
  - Long lifetime of b hadrons ($c\tau$ ~ 450 μm)+ boost
  - B hadrons travel L_{xy}~3mm before decay with large charged track multiplicity

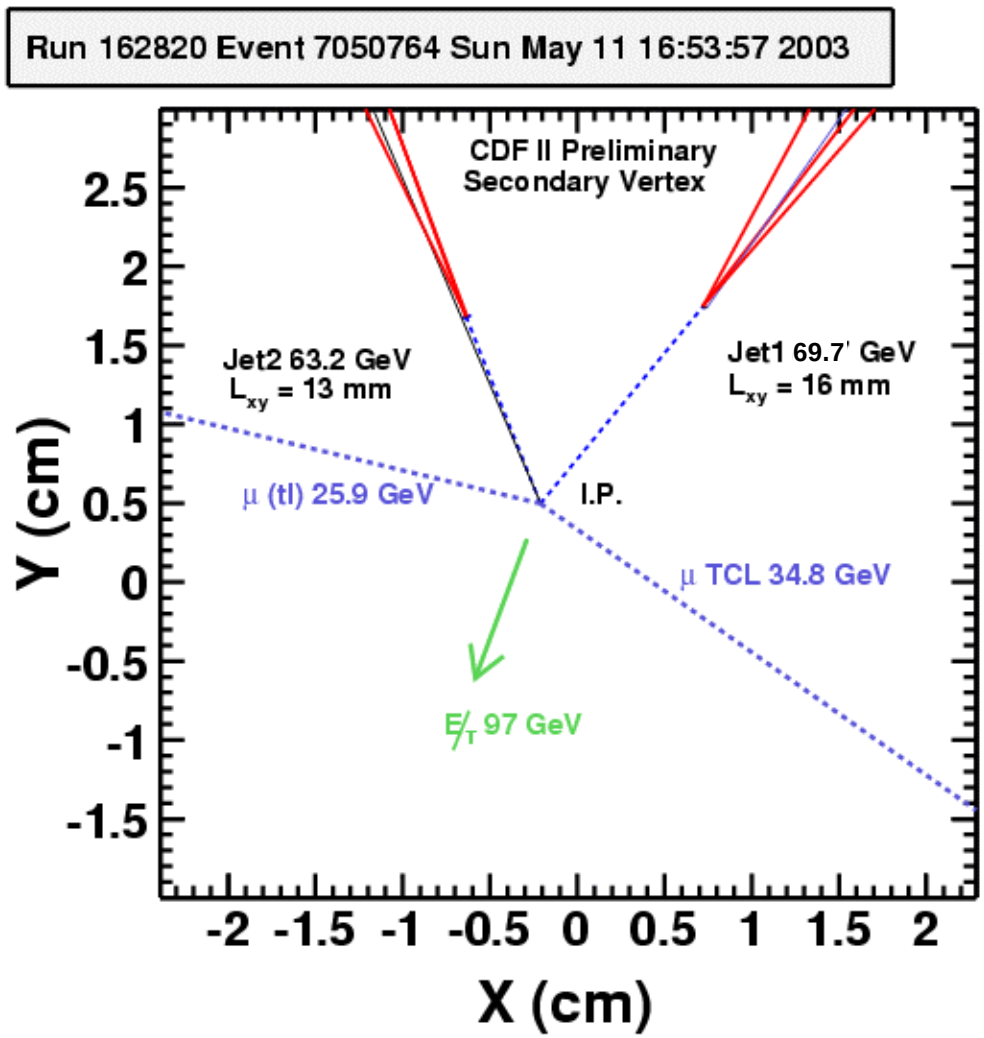


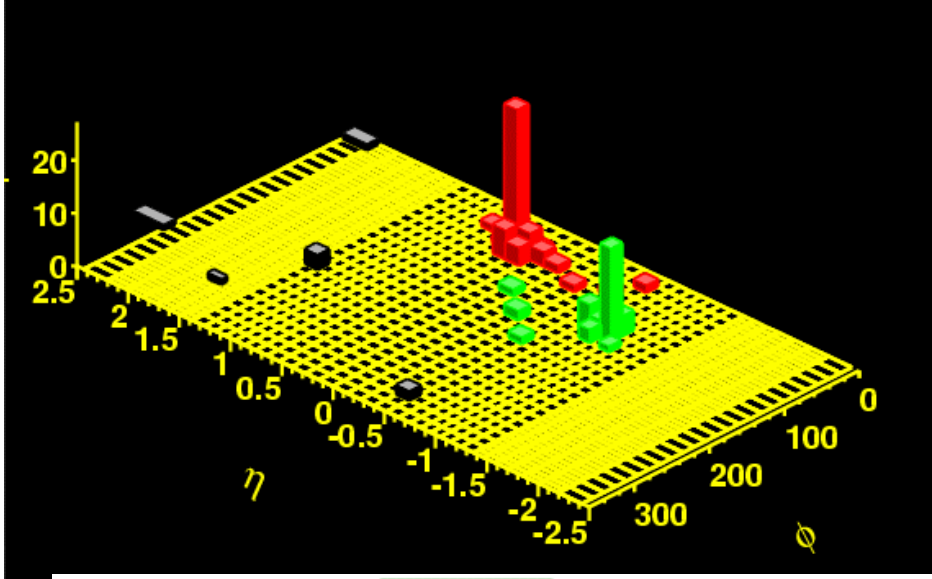
Soft Lepton Tag

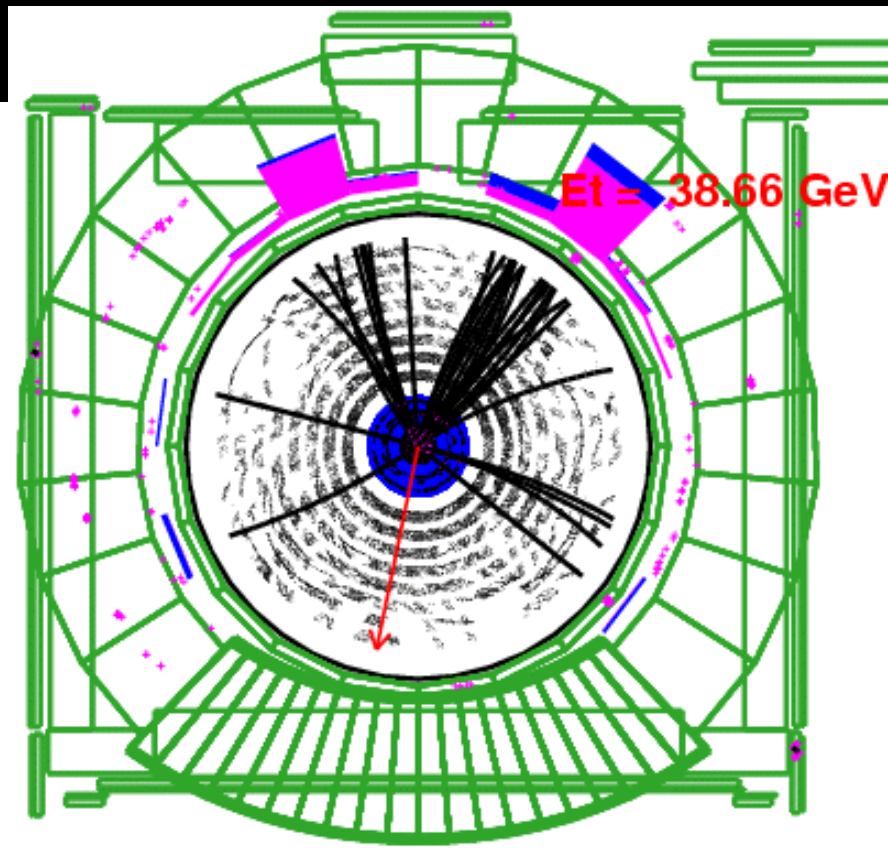
- Exploits the b quarks semi-leptonic decays
  - ⇒ These leptons have a softer p_T spectrum than W/Z leptons
  - ⇒ They are less isolated

B-tagging at hadron machines established:
- crucial for top discovery in RunI
- essential for RunII physics program

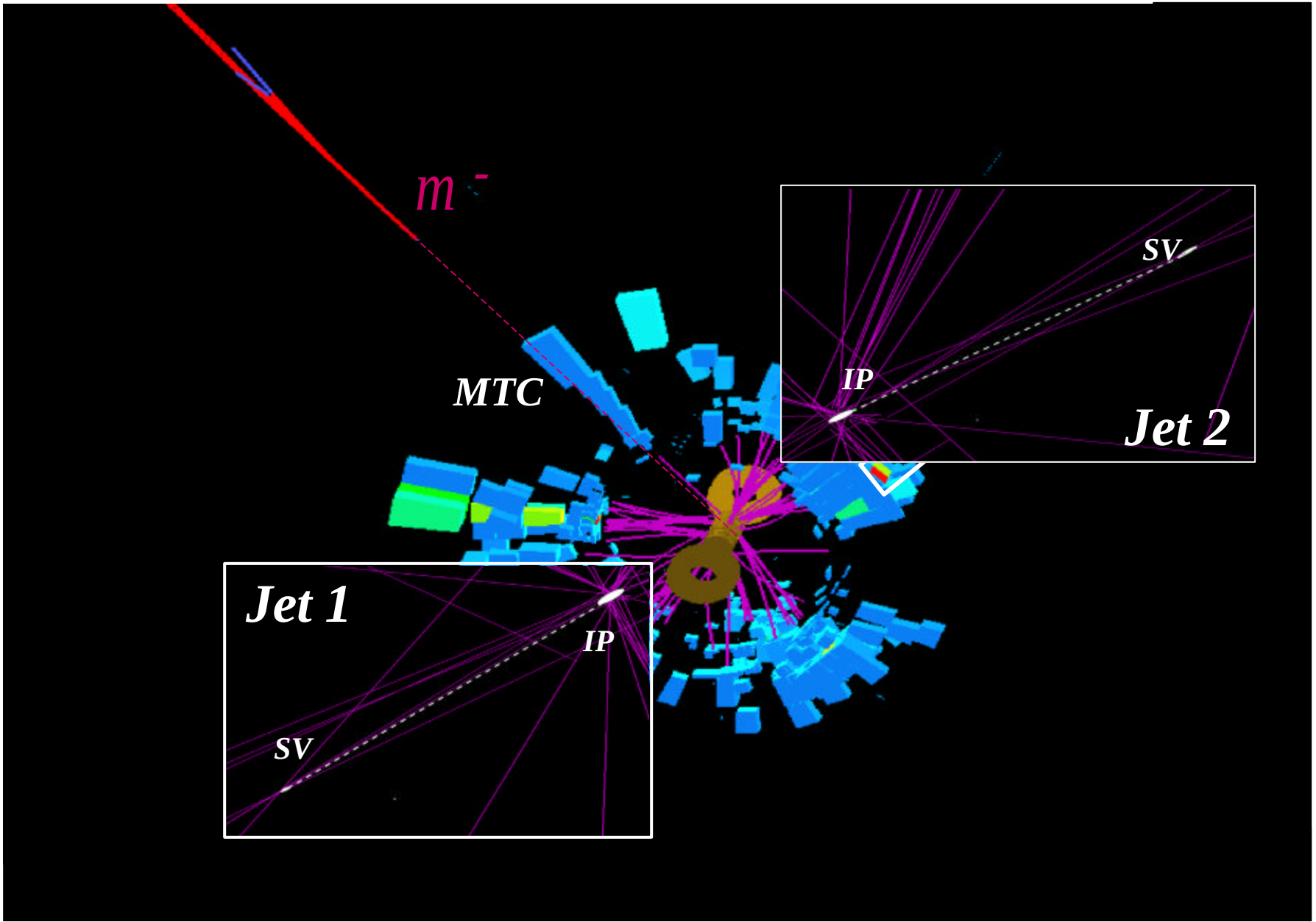
Double b-tagged dilepton event @ CDF



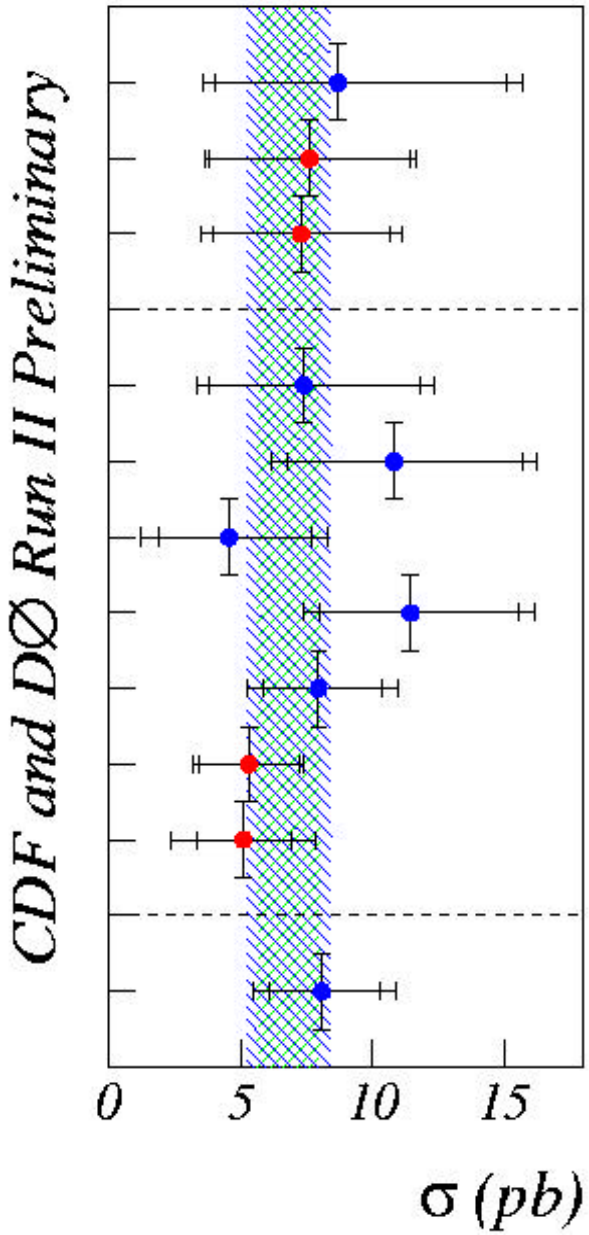




m+jets double tagged event @D0

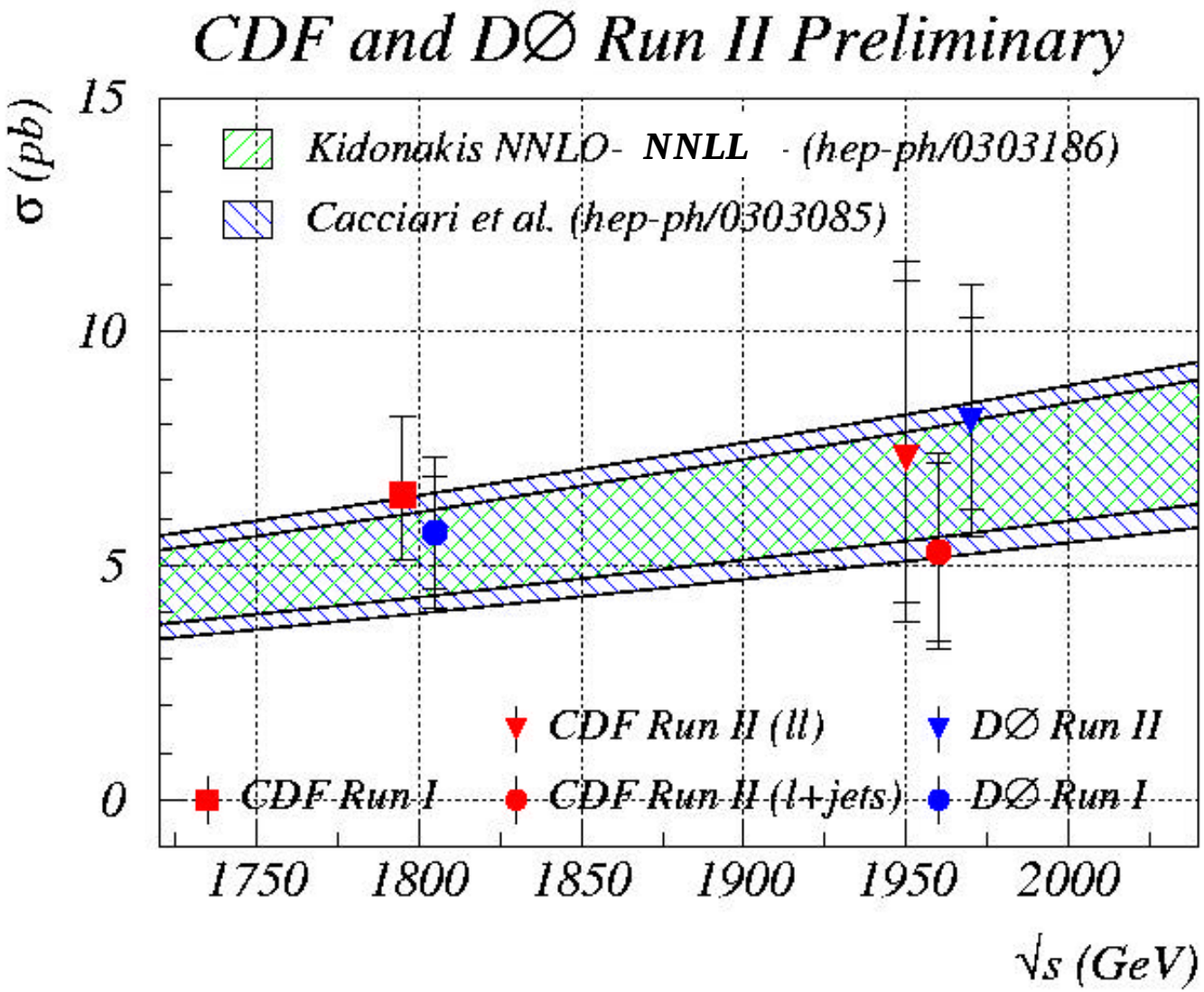


Run II cross section summary

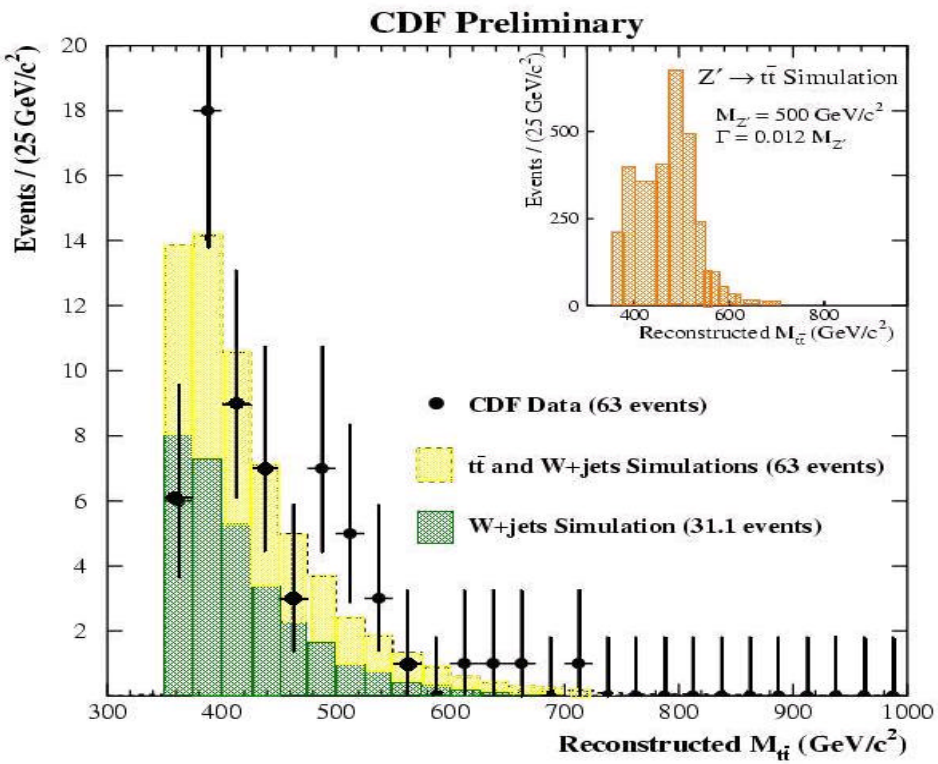


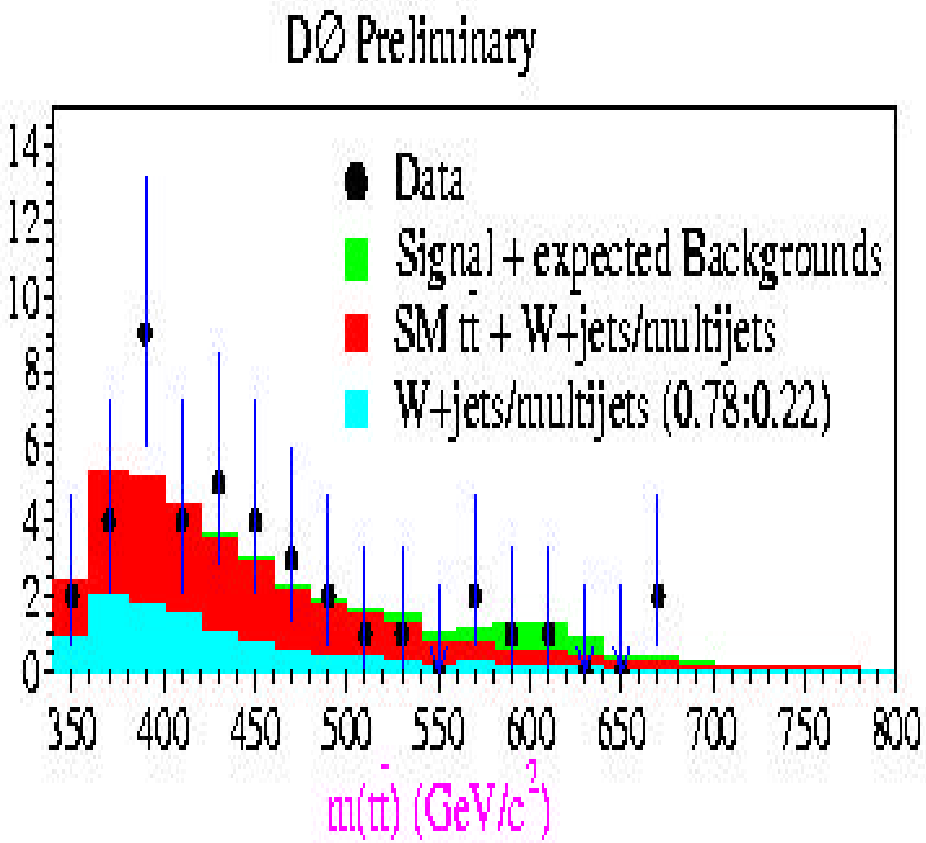
DØ Dileptons 90-107 pb^{-1}	$8.7^{+6.4}_{-4.7}(\text{stat})^{+2.7}_{-2.0}(\text{syst}) \pm 0.9(\text{lum})$
CDF Dileptons 126 pb^{-1}	$7.6^{+3.8}_{-3.1}(\text{stat})^{+1.5}_{-1.9}(\text{syst})$
CDF L+Track 126 pb^{-1}	$7.3 \pm 3.4(\text{stat}) \pm 1.7(\text{syst})$
DØ L+jets/CSIP 45 pb^{-1}	$7.4^{+4.4}_{-3.6}(\text{stat})^{+2.1}_{-1.8}(\text{syst}) \pm 0.7(\text{lum})$
DØ L+jets/SVT 45 pb^{-1}	$10.8^{+4.9}_{-4.0}(\text{stat})^{+2.1}_{-2.0}(\text{syst}) \pm 1.1(\text{lum})$
DØ L+jets/topo 92 pb^{-1}	$4.6^{+3.1}_{-2.7}(\text{stat})^{+2.1}_{-2.0}(\text{syst}) \pm 0.5(\text{lum})$
DØ L+jets/soft muon 92 pb^{-1}	$11.4^{+4.1}_{-3.5}(\text{stat})^{+2.0}_{-1.8}(\text{syst}) \pm 1.1(\text{lum})$
DØ L+jets combined 92 pb^{-1}	$8.0^{+2.4}_{-2.1}(\text{stat})^{+1.7}_{-1.5}(\text{syst}) \pm 0.8(\text{lum})$
CDF L+jets/SVX 57 pb^{-1}	$5.3 \pm 1.9(\text{stat}) \pm 0.9(\text{syst})$
CDF L+jets/HT 126 pb^{-1}	$5.1 \pm 1.8(\text{stat}) \pm 2.1(\text{syst})$
DØ Combined 90-107 pb^{-1}	$8.1^{+2.2}_{-2.0}(\text{stat})^{+1.6}_{-1.4}(\text{syst}) \pm 0.8(\text{lum})$

Cross section Ös dependence



Test for new physics in ttbar production

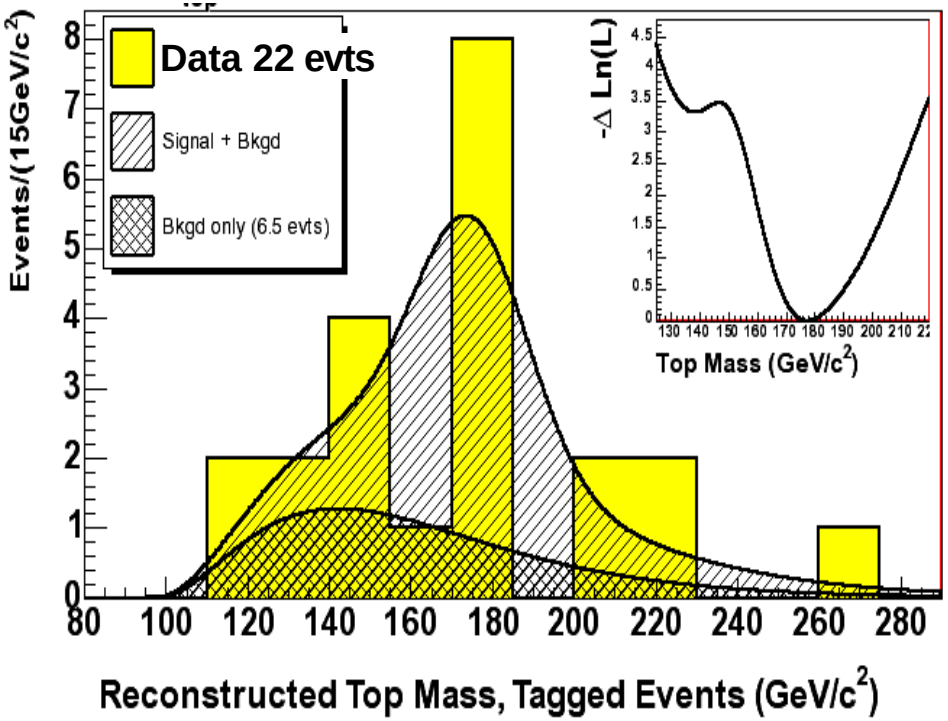




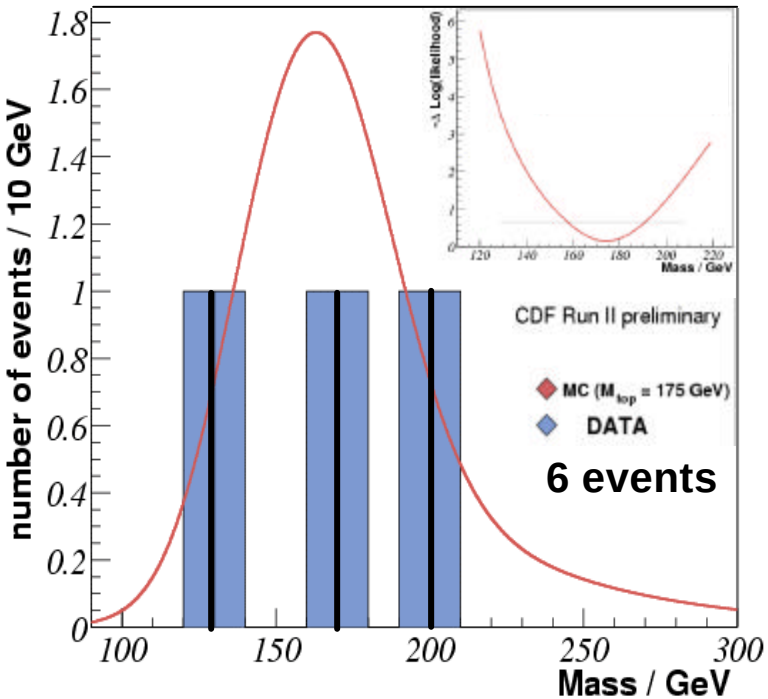
Model independent search for a narrow resonance X→tt exclude a narrow, leptophobic X boson with m_X < 560 GeV/c^2 (CDF) and m_X < 585 GeV/c^2 (D0)

First look at top mass in Run II

CDF RunII preliminary, 108 pb^{-1}



CDF RunII preliminary, 126 pb^{-1}



Mass in lepton+jets channel with a b-tagged jet

$$177.5^{+12.7}_{-9.4}\,(\text{stat}) \pm 7.1(\text{syst}) \quad \text{GeV/c}^2$$

Mass in dilepton channel

$$175.0^{+17.4}_{-16.9}(\text{stat}) \pm 7.9(\text{syst})\,\text{GeV/c}^2$$

Top Conclusions

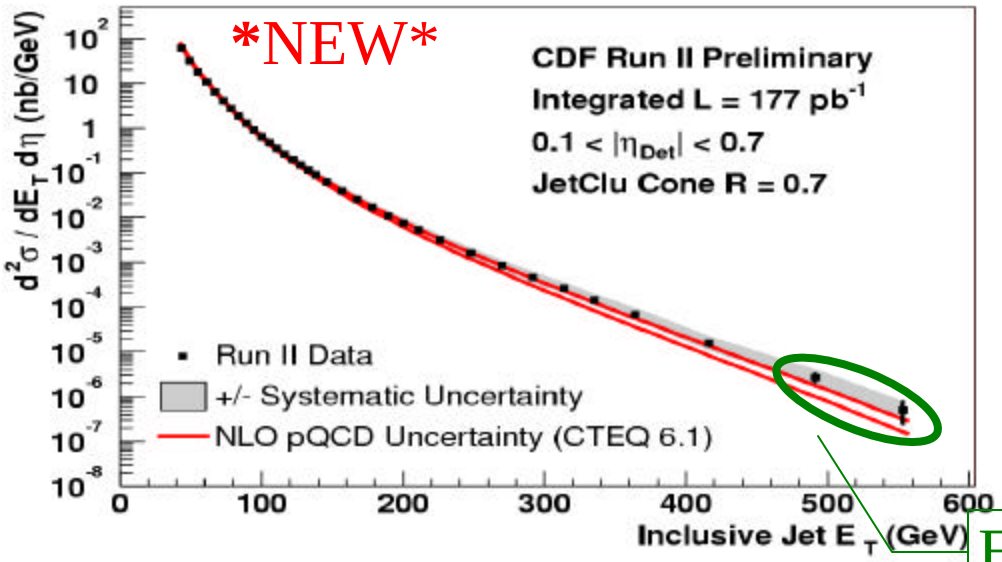
- Top quark existence established at the Tevatron in 1995
- Several top properties studied using Run I data
  - limited statistic
- The Tevatron is the top quark factory until LHC:
  - Run II ~50 times Run I statistics → precision measurements
  - Constraints on the SM Higgs boson mass and SM consistency
  - …or surprises?
  - First Run II results cover a variety of channels and topics
  - CDF and D0 are exploiting their upgraded detector features

A very rich top physics program is underway:

let's see what the top quark can do for us!

JETS - QCD

Inclusive Jets



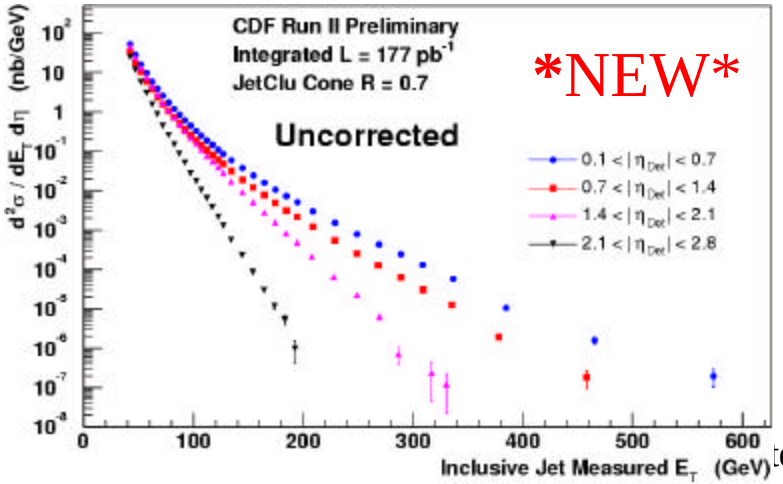
Central 0.1<|h|<0.7 inclusive jets
R=0.7 Run I cone algorithm
L= 177 pb-1

Overall Escale normalized to Run 1 (w/ 5 ± 3% [*NEW*] correction factor)
Reapply PT-dependent systematics from Run I

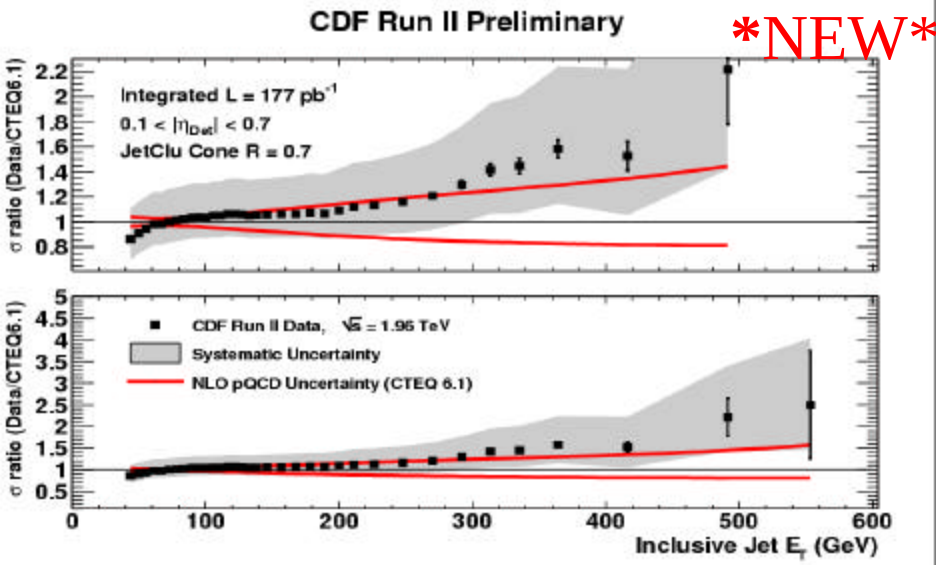
Extended wrt Run I by 150 GeV!

Scale dominates systematics
±~6% normalization

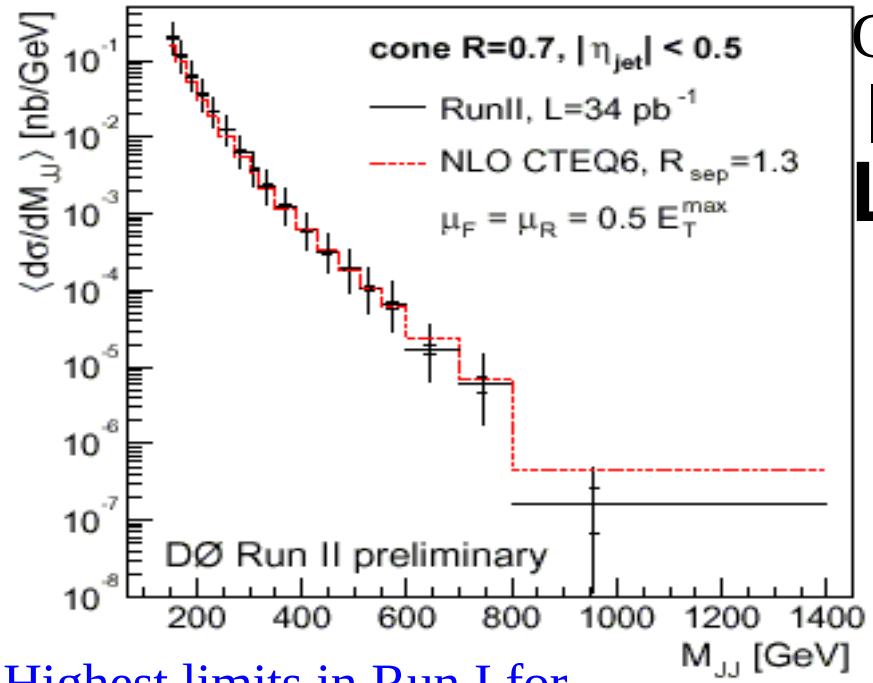
Preliminary distributions for |η| < 2.8



uncorrected

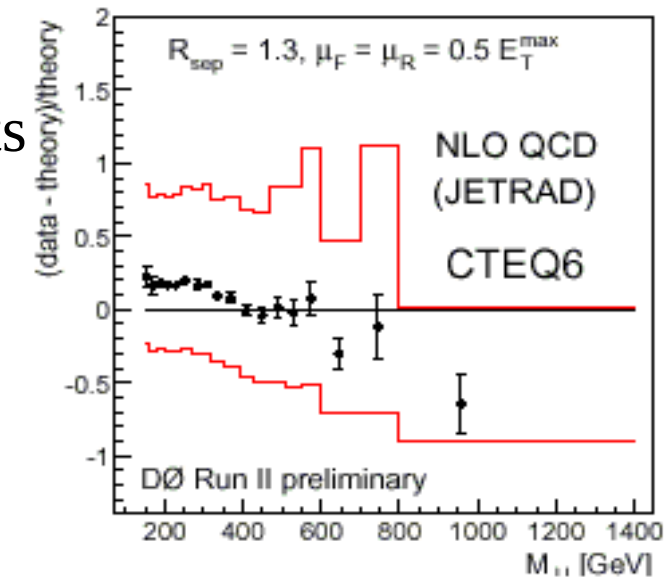


Dijet mass spectrum $\frac{d^2\sigma}{dM_{jj}\,d\eta}$

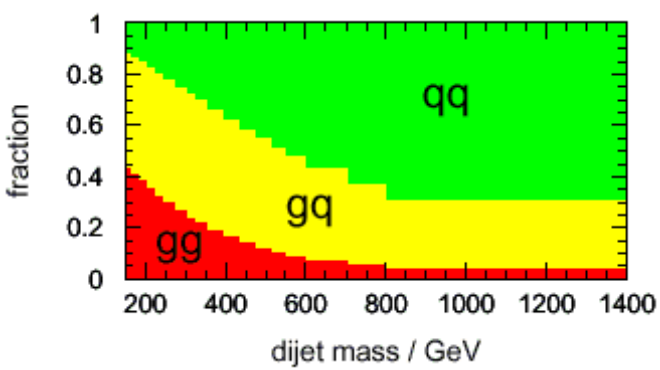


Central $|\eta| < 0.5$ jets

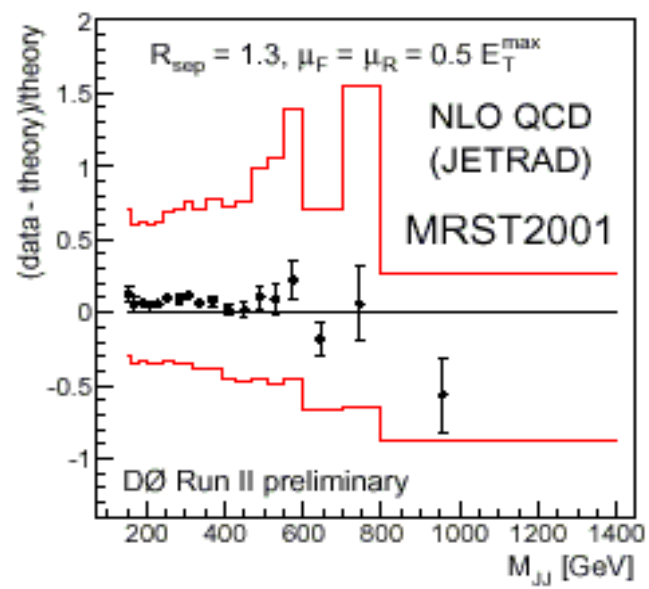
$\mathcal{L} = 34\ \mathrm{pb}^{-1}$



Highest limits in Run I for Compositeness from this analysis

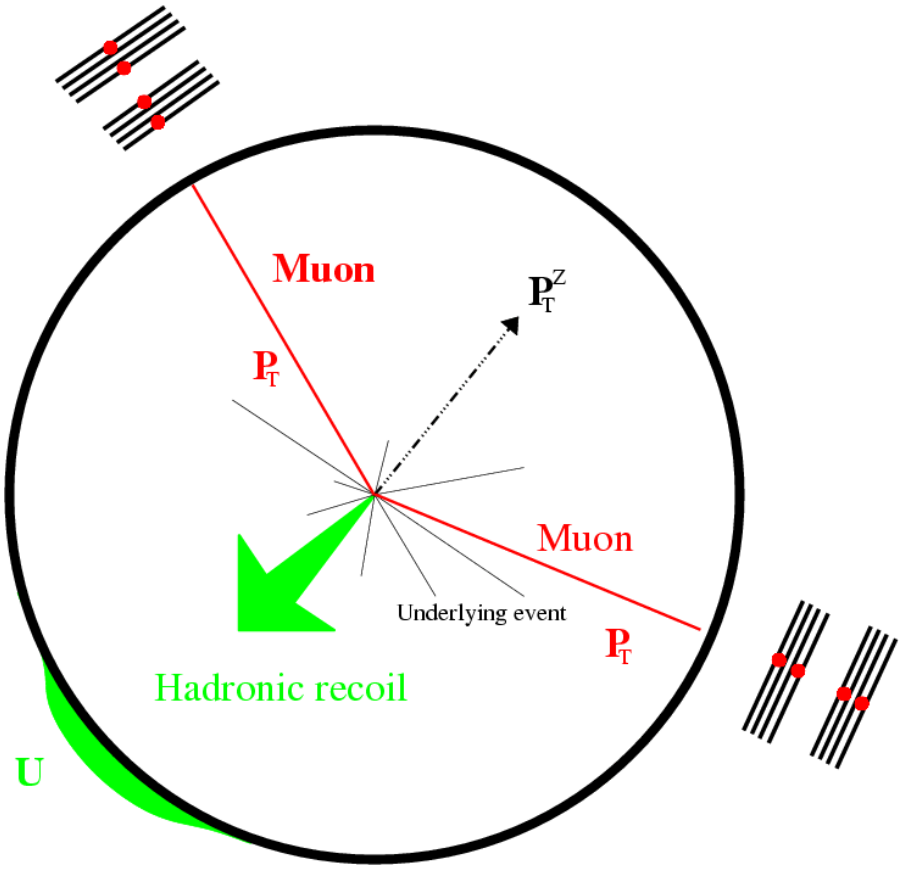


Also good sensitivity to gluons at large-x



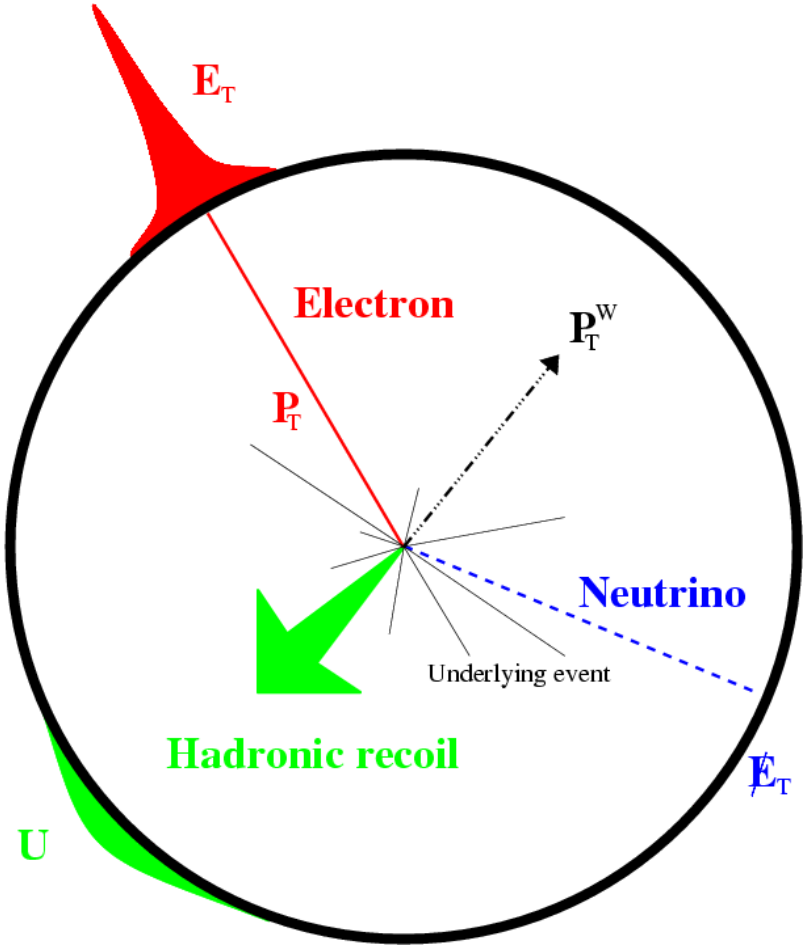
W and Z

Experimental Signature: Z? l^+l^-



- pair of charged leptons:
  - high p_T
  - isolated
  - opposite-charge
- redundancy in trigger and offline selection
- low backgrounds
- control of systematics

Experimental Signature: W? lν

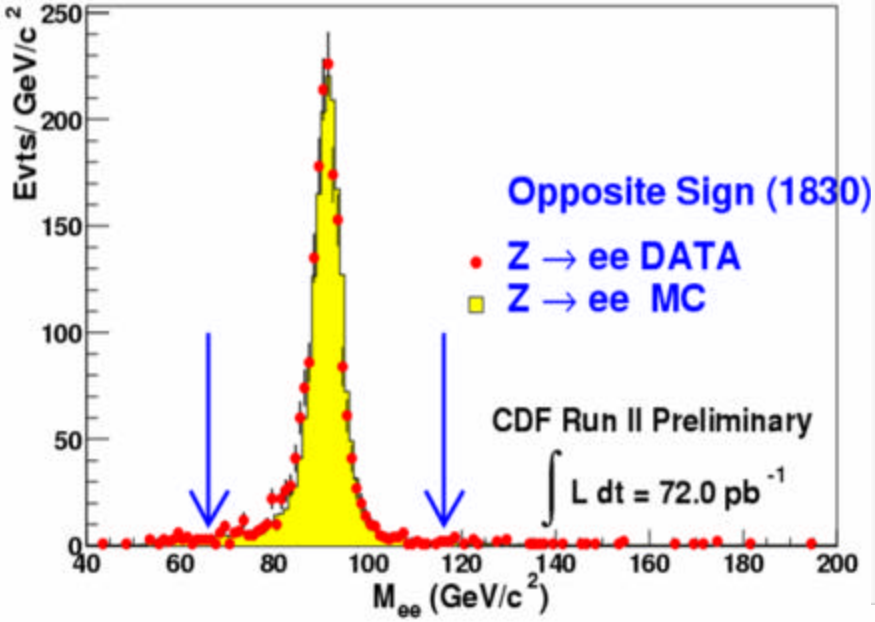


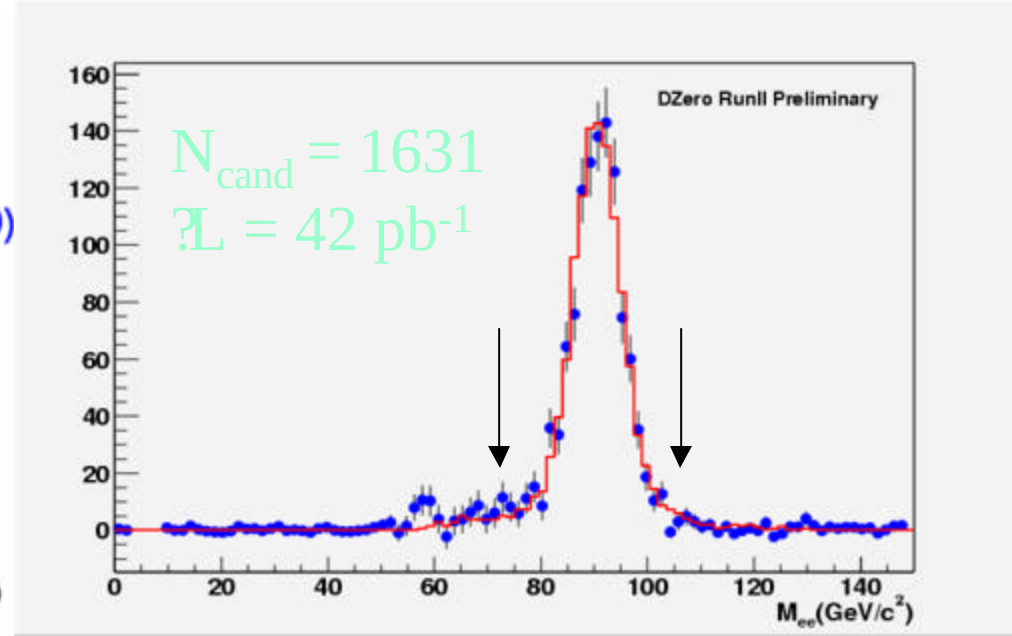
- single charged lepton:
  - high p_T
  - isolated
- E_T^{miss} (from neutrino)

- less redundancy in trigger and offline selection
- more difficult to control backgrounds and systematics
- need to understand hadronic recoil
- but more 'interesting' than Z! (post-LEP)
- s•Br 10 times larger than Z

CDF and DØ Z? e^+e^-

Two isolated electrons, $E_T > 25$ GeV, $|?| < 1.1$





CDF: $s_Z \bullet Br(Z? \ e^+e^-) = 267.0 \pm 6.3 \pm 15.2 \pm 16.0$ pb

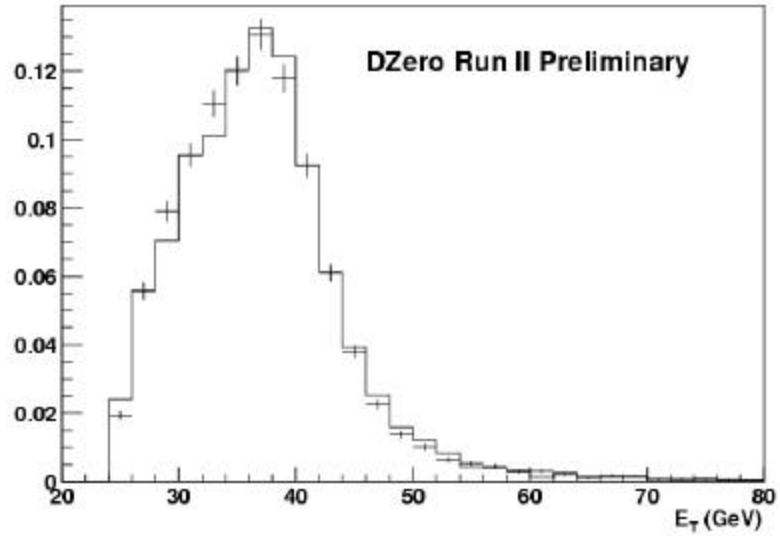
DØ: $s_Z \bullet Br(Z? \ e^+e^-) = 275 \pm 9 \pm 9 \pm 28$ pb

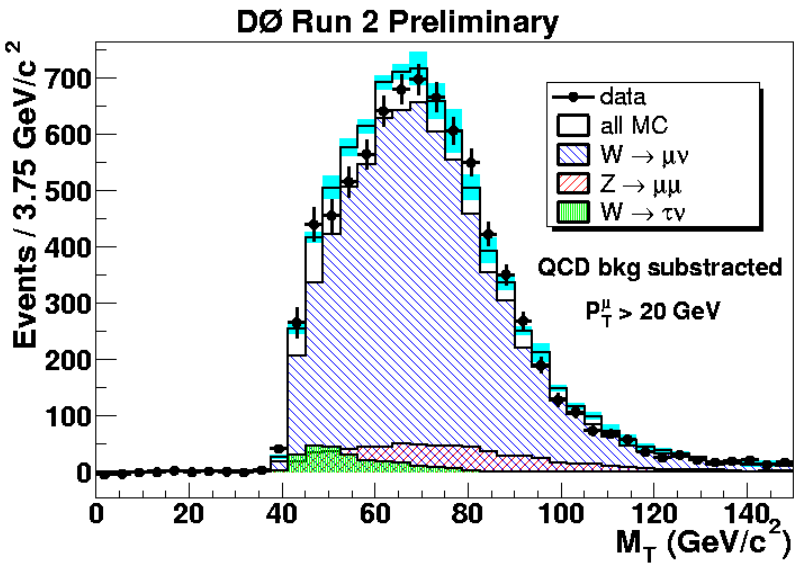
stat. syst. lumi.

DØ: W? eν and W? μν

- $p_T(e) > 25$ GeV
- $E_T^{miss} > 25$ GeV
- $N_{cand} = 27370$
- $\mathcal{L} = 42\ pb^{-1}$

- $p_T(\mu) > 20$ GeV
- $E_T^{miss} > 20$ GeV
- $N_{cand} = 8302$
- $\mathcal{L} = 17\ pb^{-1}$





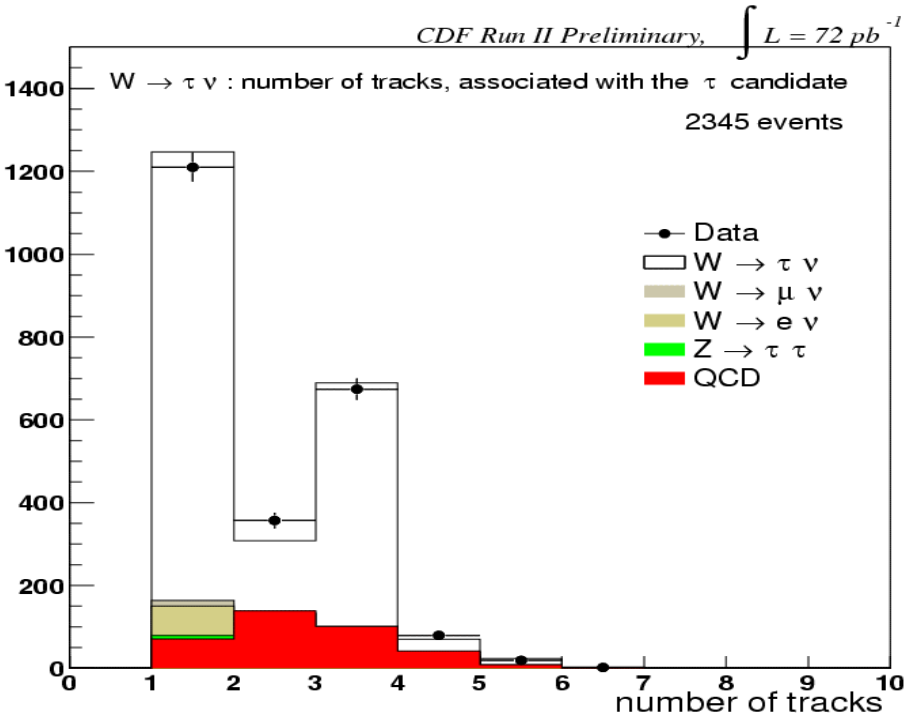
$s_W \bullet Br(W? \ e\nu) = 2.884 \pm 0.021 \pm 0.128 \pm 0.284$ nb

$s_W \bullet Br(W? \ \mu\nu) = 3.226 \pm 0.128 \pm 0.100 \pm 0.322$ nb

stat. syst. lumi.

CDF: W? τ ν

- Look for jet within narrow 10 degree cone
- Isolated within wider 30 degree cone
- $p_T(\tau) > 25$ GeV
- $E_T^{miss} > 25$ GeV
- $N_{cand} = 2345$



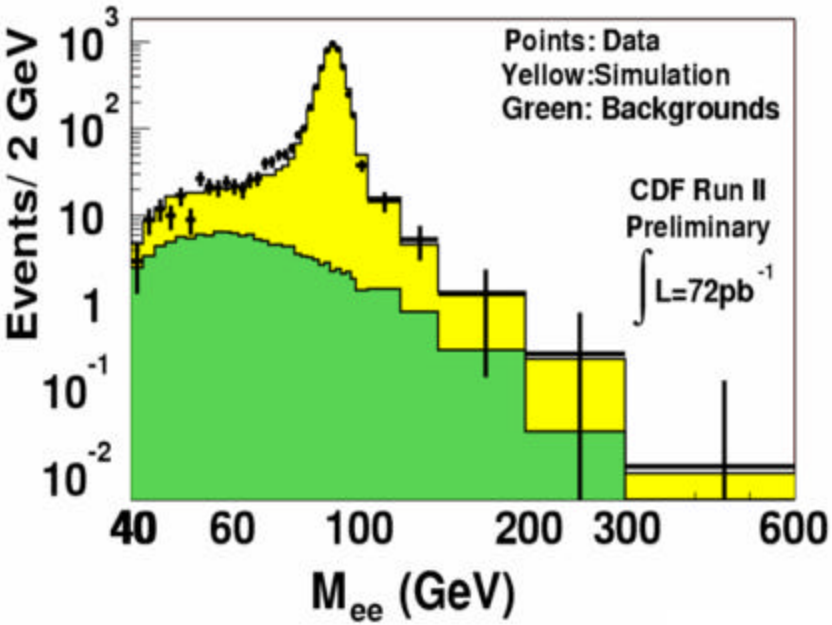
$s_W \cdot Br(W? \ \tau\nu) = 2.62 \pm 0.07 \pm 0.21$

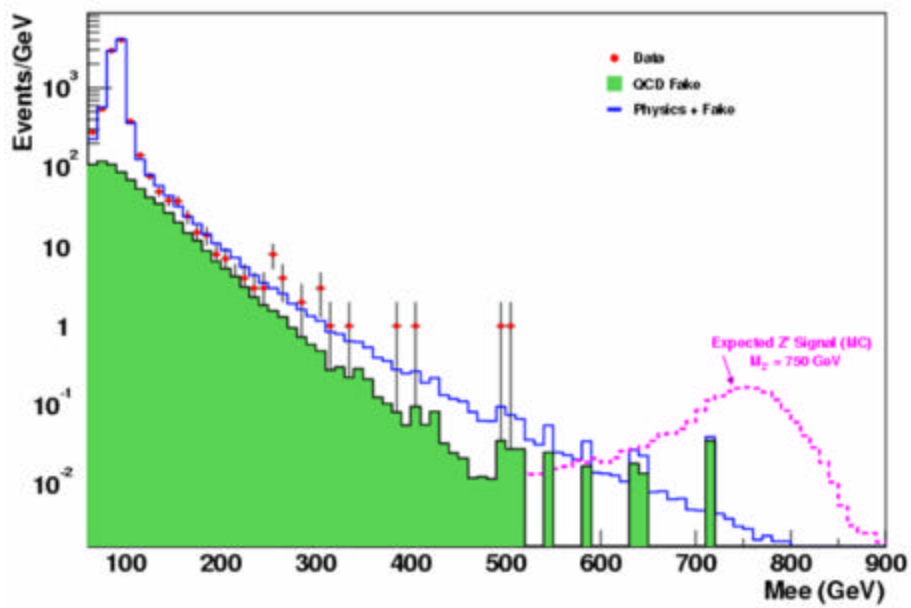
stat. syst. lumi.

Other measurements with W, Z events

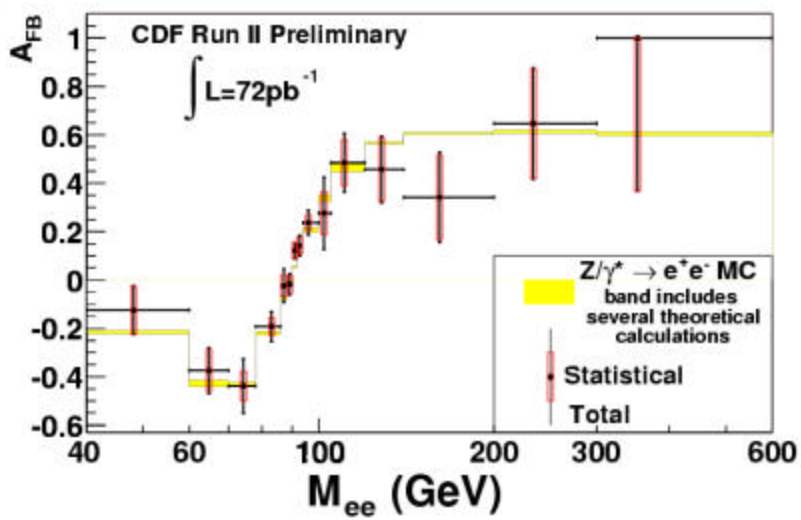
- **High mass tail of Z**

DØ Run II Preliminary

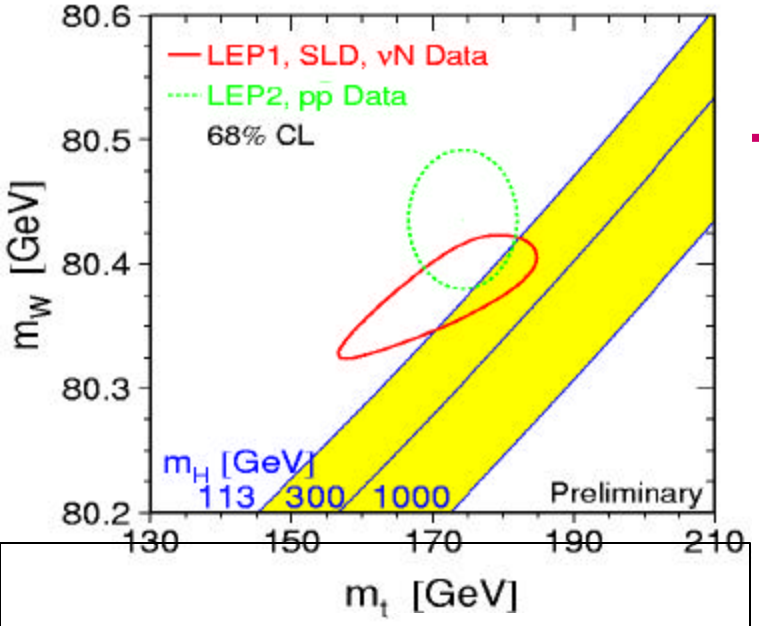


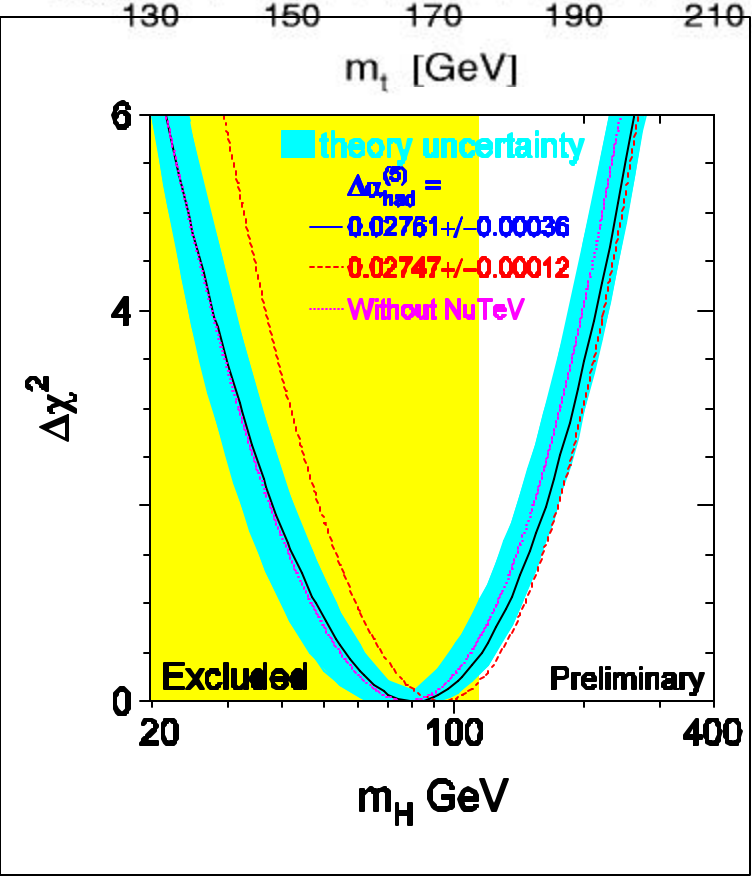


- **Forward-backward asymmetry**



Higgs Search





- Report at LP03 the Results of New Study:

  (W B Bbar channel)

  - 4 to 5 **fb^{-1}** CDF + D0 can exclude SM Higgs up to 130 GeV.

    (range dictated by MSSM).

  - 8 to 10 **fb^{-1}** might find 3 sigma evidence.

B physics

B Physics at the Tevatron

- **Heavy flavor production**
  - **charm cross section**
- **Lifetimes**
- ***B* hadron masses**
- **Branching ratios**
  - $B_s \to K^+K^-$, $\Lambda_b \to \Lambda_c p^-$, $B_s \to D_s p^+$
- **Mixing**
  - B_d, B_s

Notation:

$B_d = B^0 = |\bar{b}d\rangle$

$B_u = B^+ = |\bar{b}u\rangle$

$B_s = |\bar{b}s\rangle$

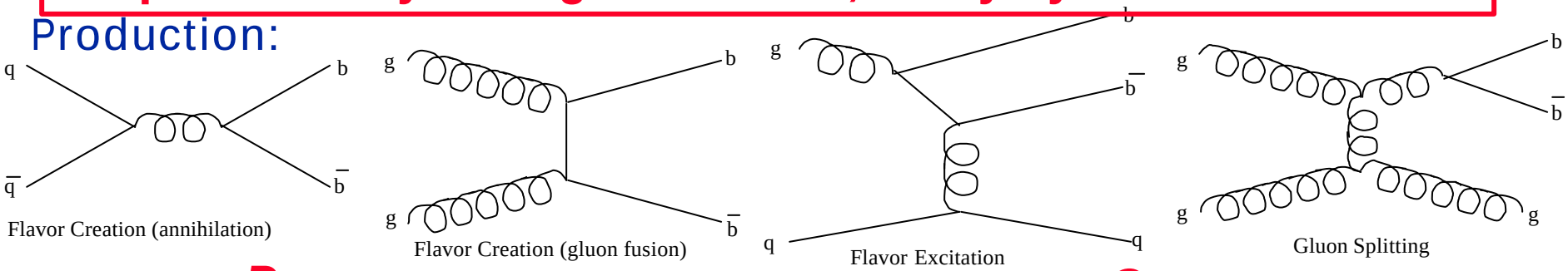
$B_c = |\bar{b}c\rangle$

$\Lambda_b = |udb\rangle$

B Physics at Hadron Machines

***b*'s produced by strong interaction, decay by weak interaction**

Production:



Pros

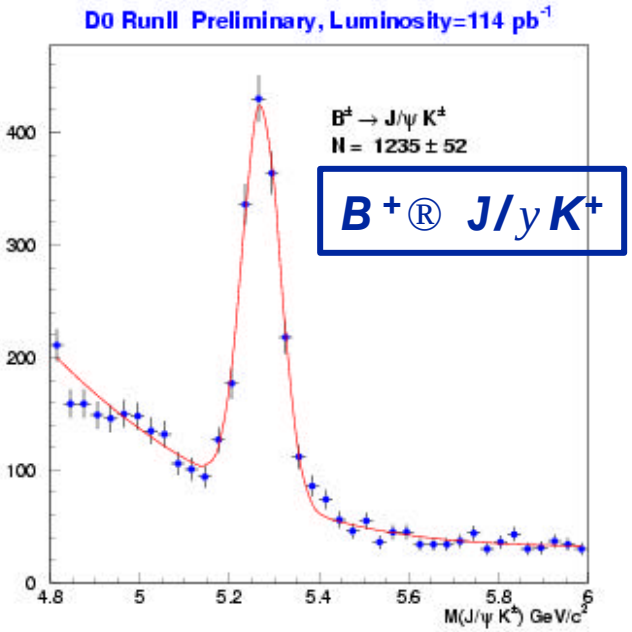
- Enormous cross-section
  - ~100 μbarn total
  - ~3-5 μbarn "reconstructable"
  - **At 4×10^{31}cm^{-2}s^{-1} þ ~150Hz of reconstructable $B\bar{B}$!!**
- All *B* species produced
  - $B_u, B_d, B_s, B_c, \Lambda_b, \ldots$
- Production is incoherent
  - Measure of *B* and *B* not required

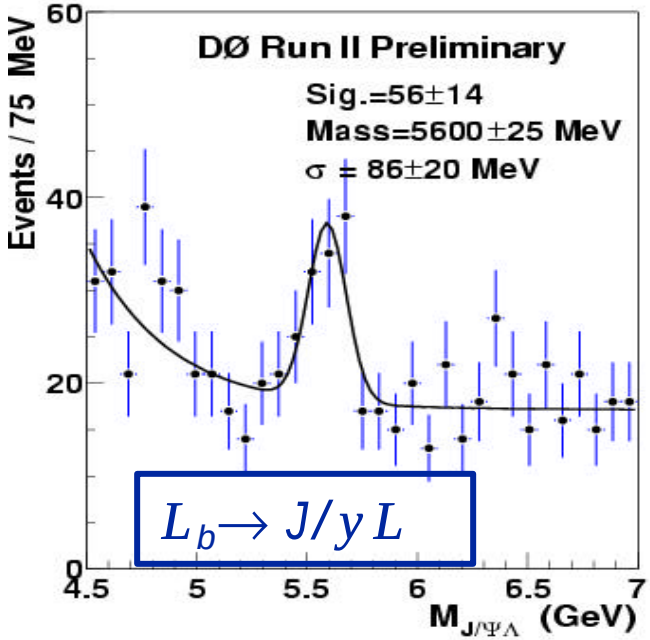
Cons

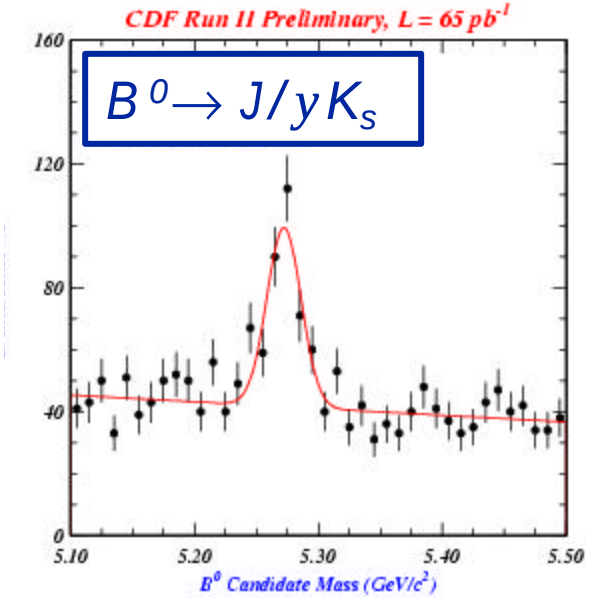
- Large inelastic background
  - Triggering and reconstruction are challenging
- Reconstruct a *B* hadron, ~20-40% chance 2nd *B* is within detector acceptance
- p_T spectrum relatively soft
  - **Typical $p_T(B)$~10-15 GeV for trigger+reconstructed *B*'s**
    …softer than *B*'s at LEP!

Disclaimer: acceptance comments relevant to "central" detectors like DØ and CDF

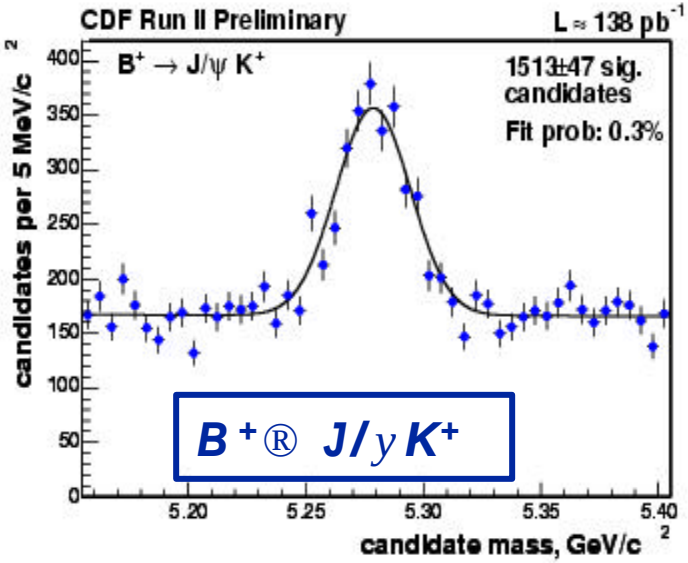
Yields in $B \to J/\psi X$ Modes

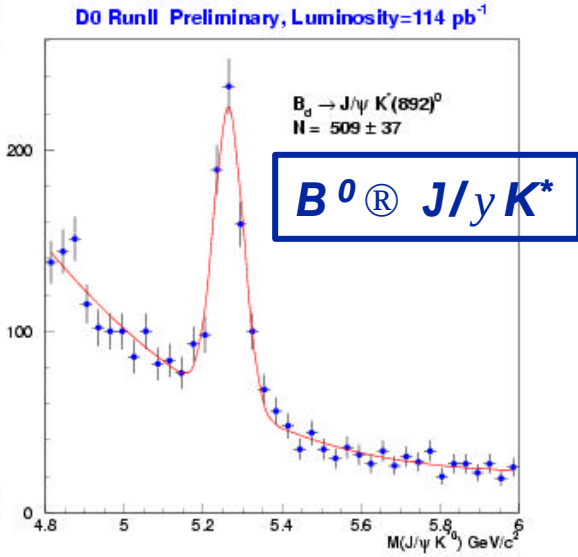






- Trigger on low p_T dimuons (1.5-2GeV/μ)
- Fully reconstruct
  - ✓ J/ψ, $\psi(2s) \to \mu^+\mu^-$
  - ✓ $B^+ \to J/\psi K^+$
  - ✓ $B^0 \to J/\psi K^*$, $J/\psi K_s$
  - ✓ $B_s \to J/\psi f$
  - ✓ $L_b \to J/\psi L$





B_s Lifetime

$B_s \to J/y\ f$, with $J/y \to m^+m^-$ and $f \to K^+K^-$

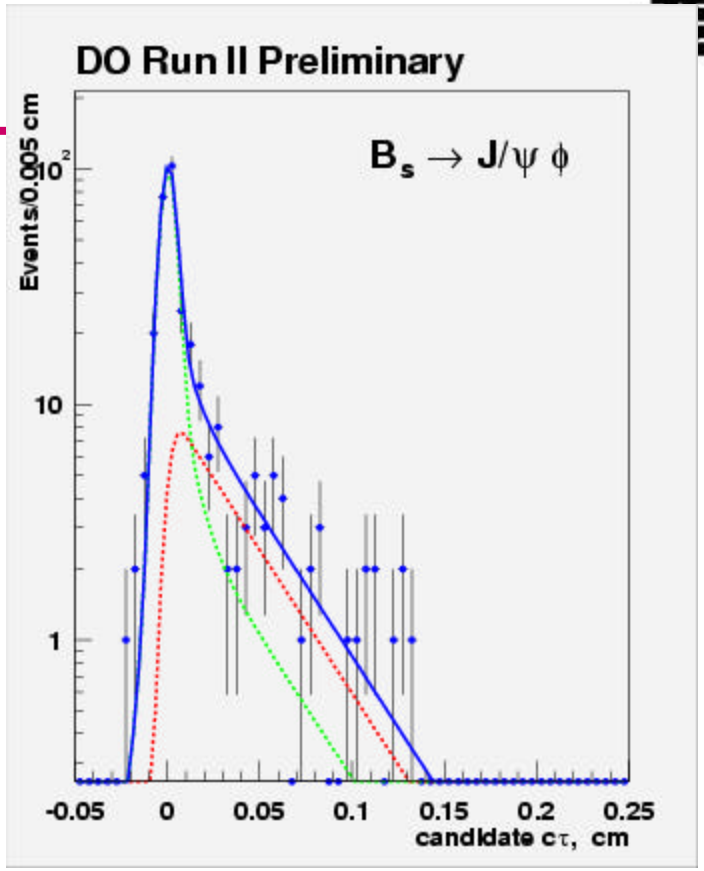
DØ (115pb^{-1}): *(shown here)*

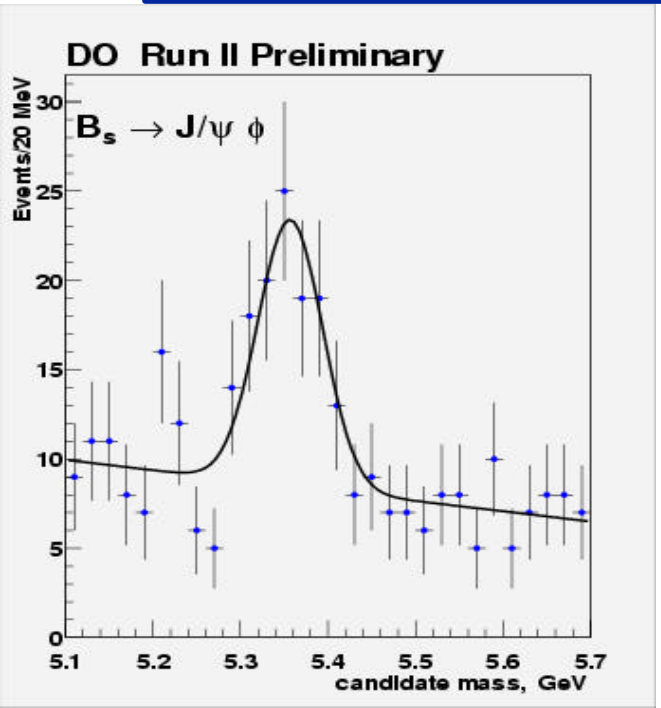
$t(B_s)=1.19\ ^{+0.19}_{-0.16}$ (stat.) ± 0.14(syst.) ps

$t(B_s)/t(B^0) = 0.79 \pm 0.14$ *(uncorrected for CP composition)*

CDF (138pb^{-1}):

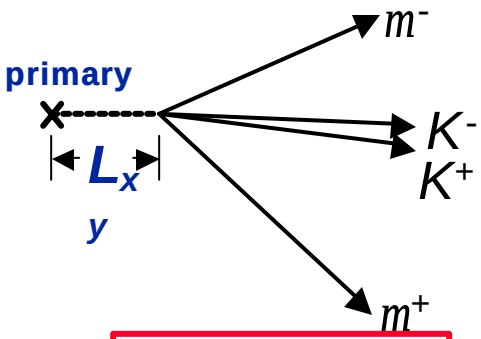
$t(B_s)=1.33 \pm 0.14$(stat.) ± 0.02(syst.) ps





Interesting B_s physics:

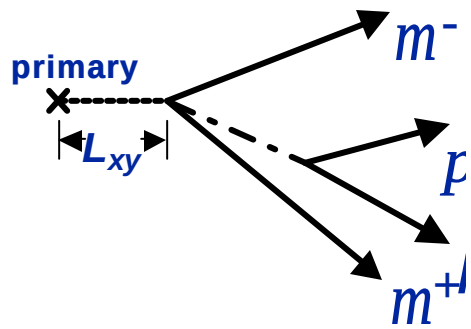
- **Search for CPV in $B_s \to J/y\ f$ ...sensitive to new physics**
- **Width difference** DG
- ***B_s mixing***



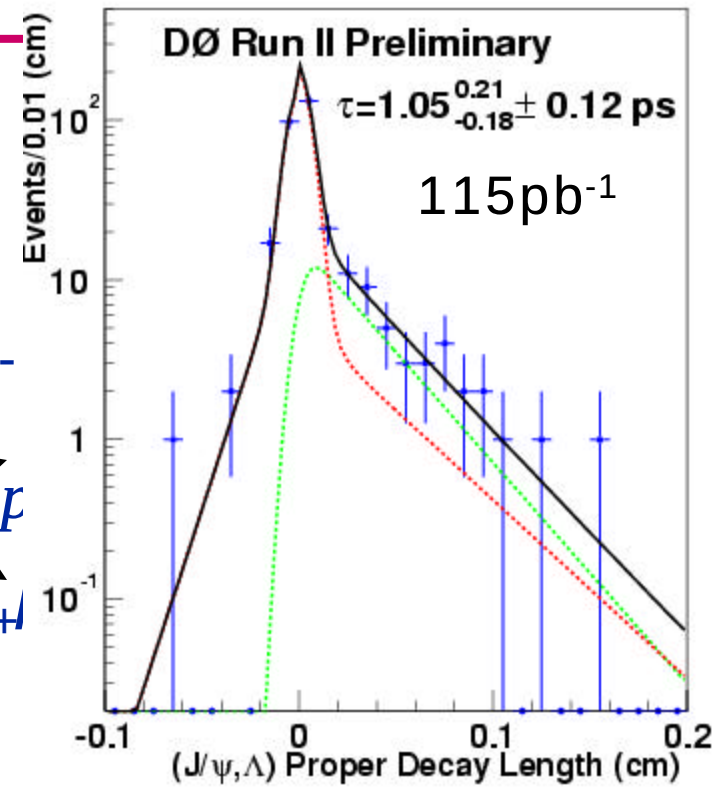
$$ct = \frac{L_{xy}}{bg} = \frac{L_{xy} m_B}{p_T}$$

L_b Lifetime

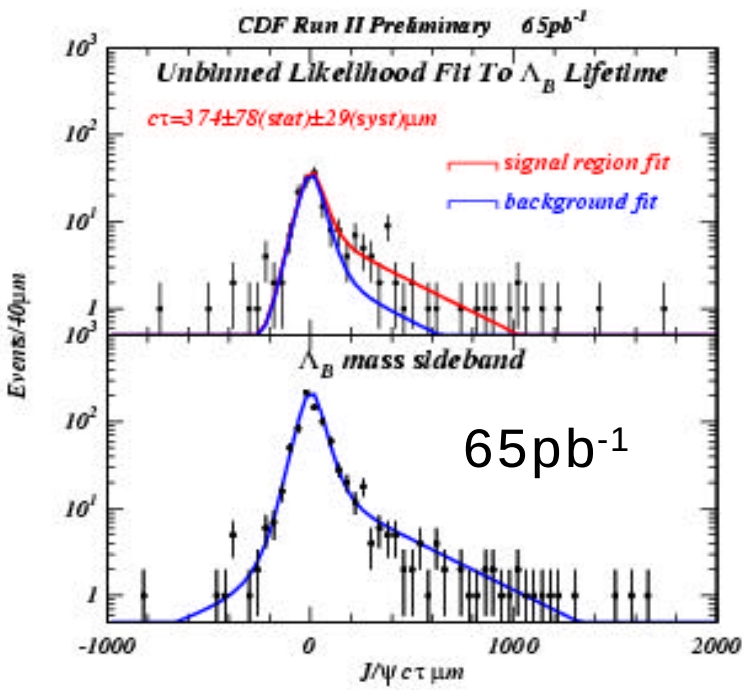
- *Use fully reconstructed* $L_b \to J/y\ L$ *with* $J/y \to m^+m^-$ and $L \to pp^-$
  - *Previous LEP/CDF measurements used semileptonic* $L_b \to L_c l n$
    - *Systematics different*



56±14 signal



CDF 46±9 signal



CDF

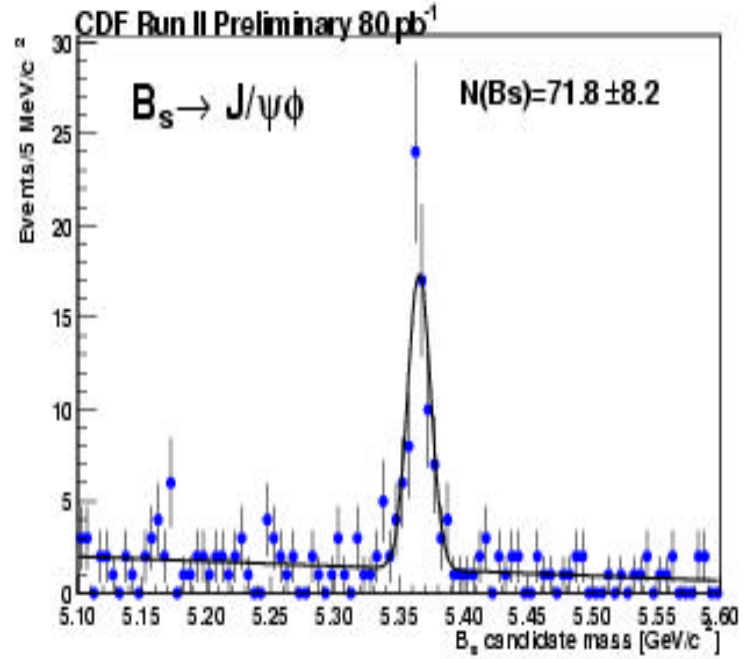
$$t(\Lambda_b) = 1.25 \pm 0.26(stat.) \pm 0.10(syst.)\ \text{ps}$$

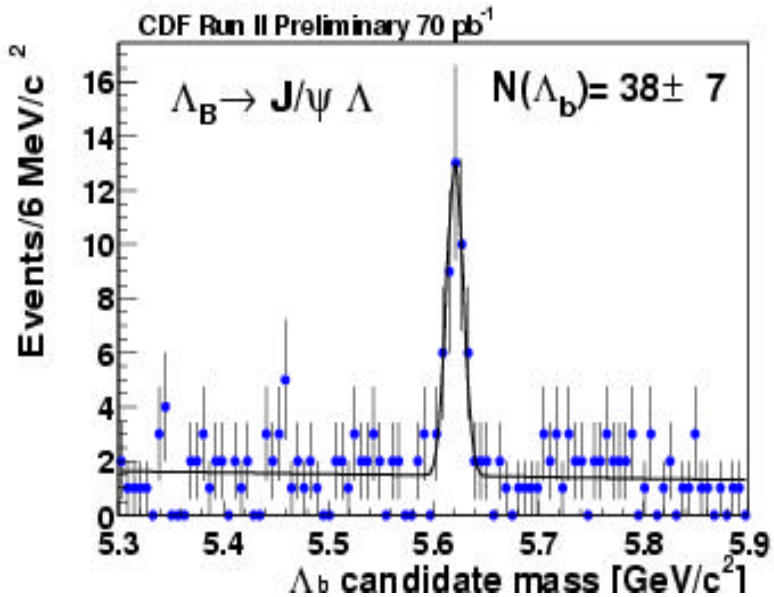
DØ

$$t(\Lambda_b) = 1.05^{+0.21}_{-0.18}(stat.) \pm 0.12(syst.)\ \text{ps}$$

B Hadron Masses

- Measure masses using fully reconstructed $B \to J/y X$ modes
- High statistics $J/y \to m^+m^-$ and $y(2s) \to J/y\, p^+p^-$ for calibration.
- Systematic uncertainty from tracking momentum scale
  - *Magnetic field*
  - *Material (energy loss)*
- *B^+ and B^0 consistent with world average.*
- ***B_s and L_b* measurements are world's best.**

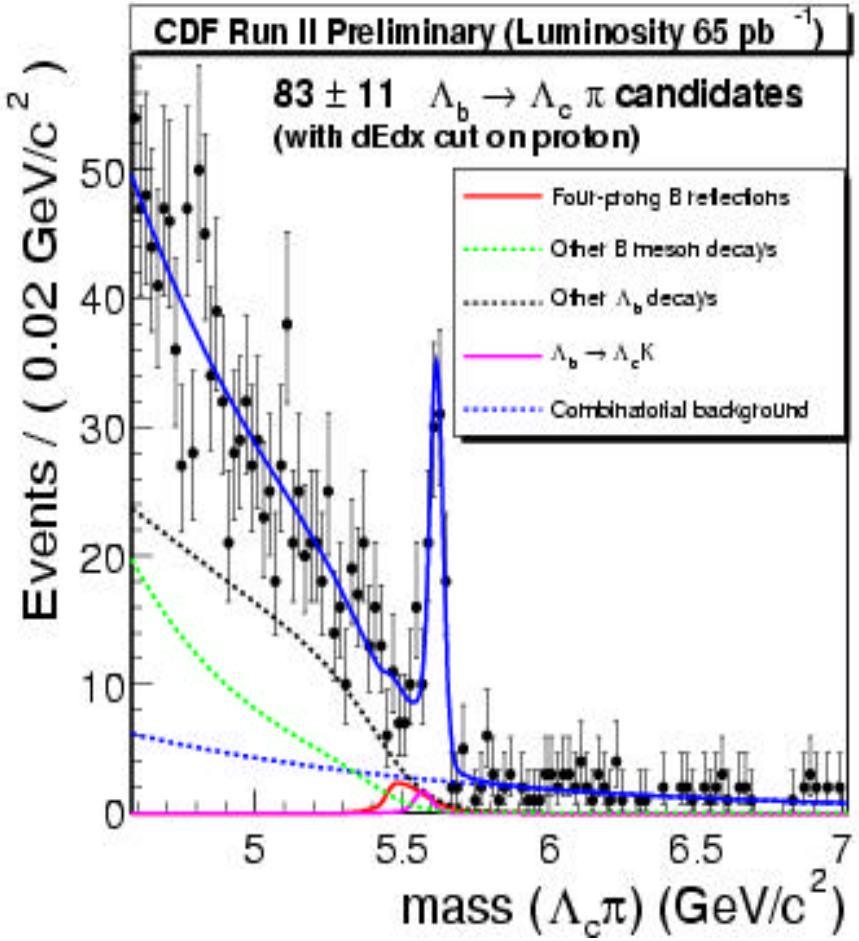




CDF result: $M(B_s)$=5365.50 ±1.60 MeV
World average: $M(B_s)$=5369.6 ±2.4 MeV

CDF result: $M(L_b)$=5620.4 ±2.0 MeV
World average: $M(L_b)$=5624 ±9 MeV

CDF L_b® $L_c p$ with L_c® pKp



Backgrounds: real B decays

Reconstruct π as p: $B_d \to D^- p^+ \to K^+ p^- p^- p^+$

- Use MC to parametrize the shape.
- Data to normalize the amplitude
- Dominant backgrounds are real heavy flavor
- proton particle ID (dE/dx) improves S/B

Fitted signal:

$$N_{\Lambda_b} = 96 \pm 13(stat.)^{+6}_{-7}(syst.)$$

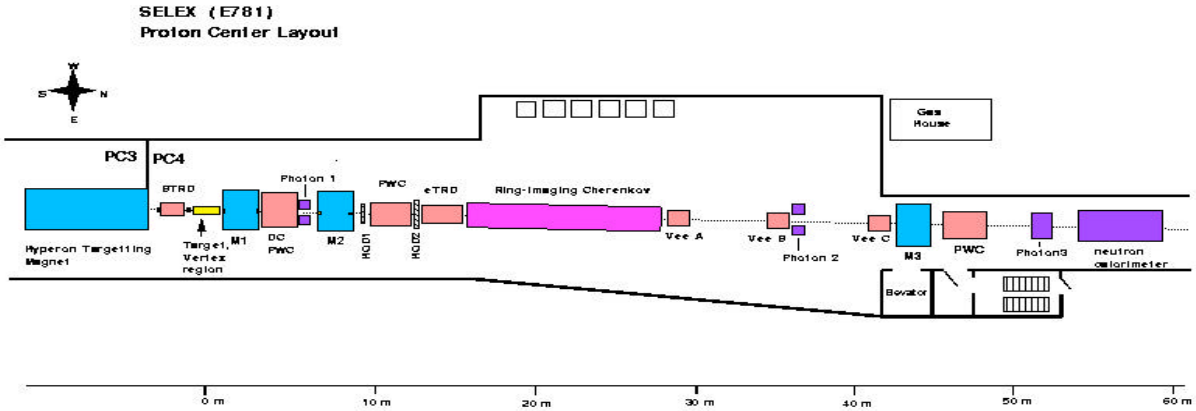
Measure: $$\frac{s_b \times f_{baryon} \times BR(\Lambda_b \to \Lambda^+_c p^-)}{s_b \times f_d \times BR(B^0 \to D^- p^+)}$$

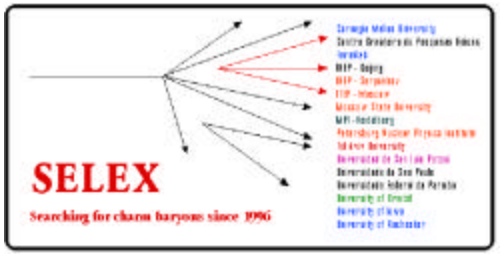
New Result !

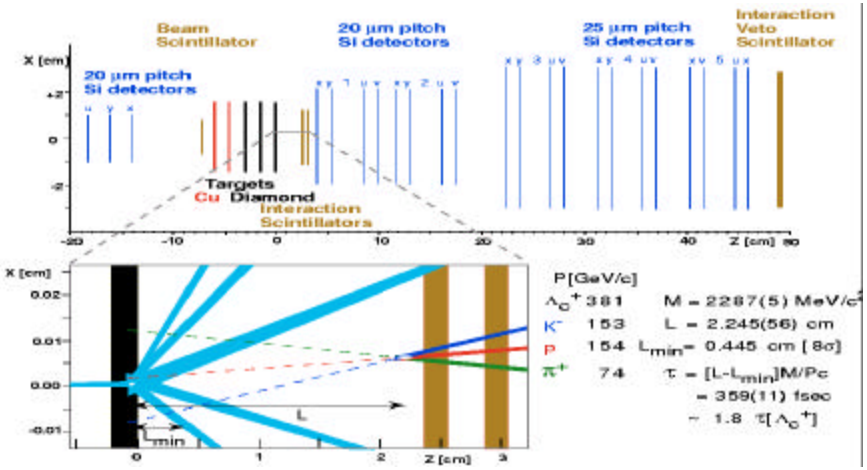
$$BR(\Lambda_b \to \Lambda_c \pi^{\pm}) = (6.0 \pm 1.0(\text{stat}) \pm 0.8(\text{sys}) \pm 2.1(\text{BR}))\ 10^{-3}$$

Fixed Target

Selex Experiment at Fermilab
Charmed Hadroproduction with p^- ,p and S^- beams





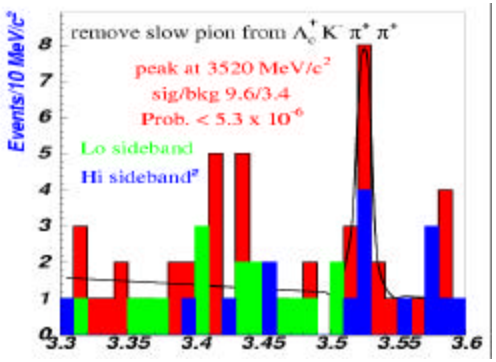


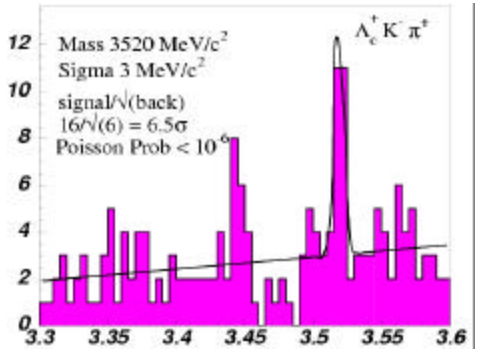
SELEX Experiment

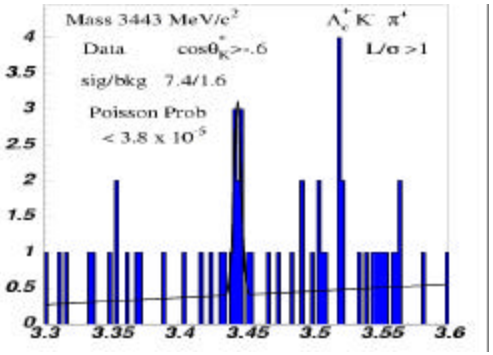
- Forward charm production xf>1
- π^- ,p and Σ^- beams @ 600 GeV/c
- Typical boost ~100
- RICH PID above 22 GeV/c
- 20 plane – 4 view SVX σ>4 μm
- data taken in 1996-7

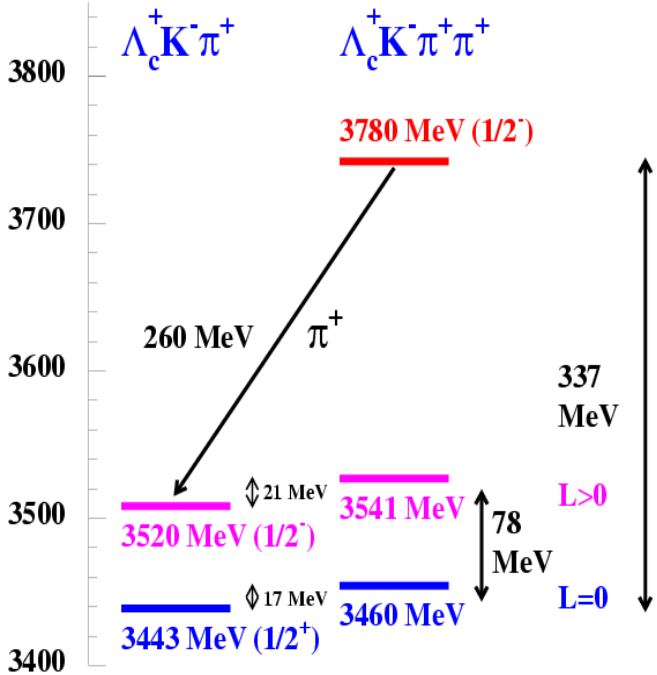
SELEX Doubly Charmed Baryon States

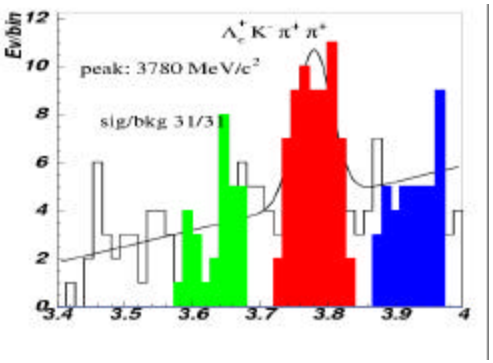
An excited state and pair of isodoublets?

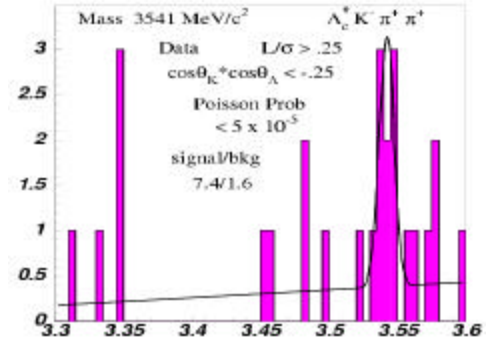


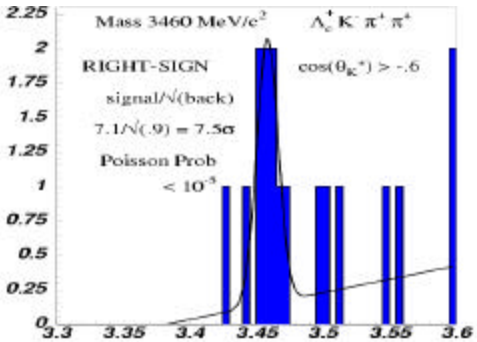












NEUTRINOS

The Neutrino Program

- **DONUT**
  - Observe Tau Neutrinos
- **MiniBooNE**
  - will make possible a decisive check of the Oscillation hypothesis of the LSND anomaly; if confirmed we need more than 3 neutrinos, $\Delta m^2 \sim 1\ eV^2$.
  - Running now!!!
  - 1 GeV ν, 500 m distance
- **MINOS**
  - will observe and measure the atmospheric neutrino oscillation with high statistics and a controlled source;
  - will start operating in FY05.
  - 3-20 GeV ν, 740 km distance

DONUT Status

FNAL E872 Beam dump beam

Status :

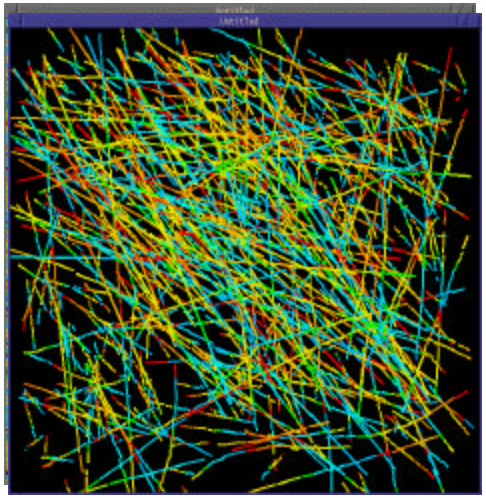
406 neutrino interaction analyzed.

7 n_t CCevent detected

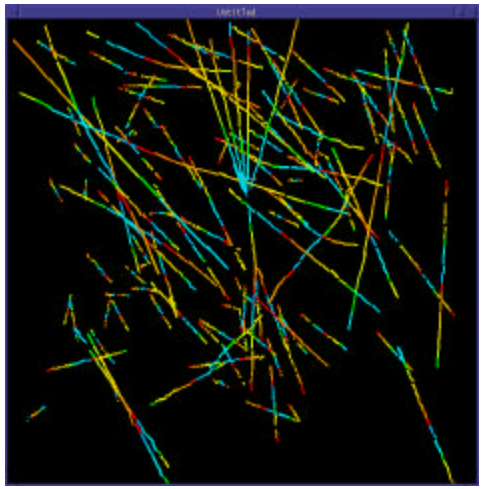
On-going :

Component analysis of the prompt neutrino beam

? $_e$: ? $_\mu$: ? $_t$

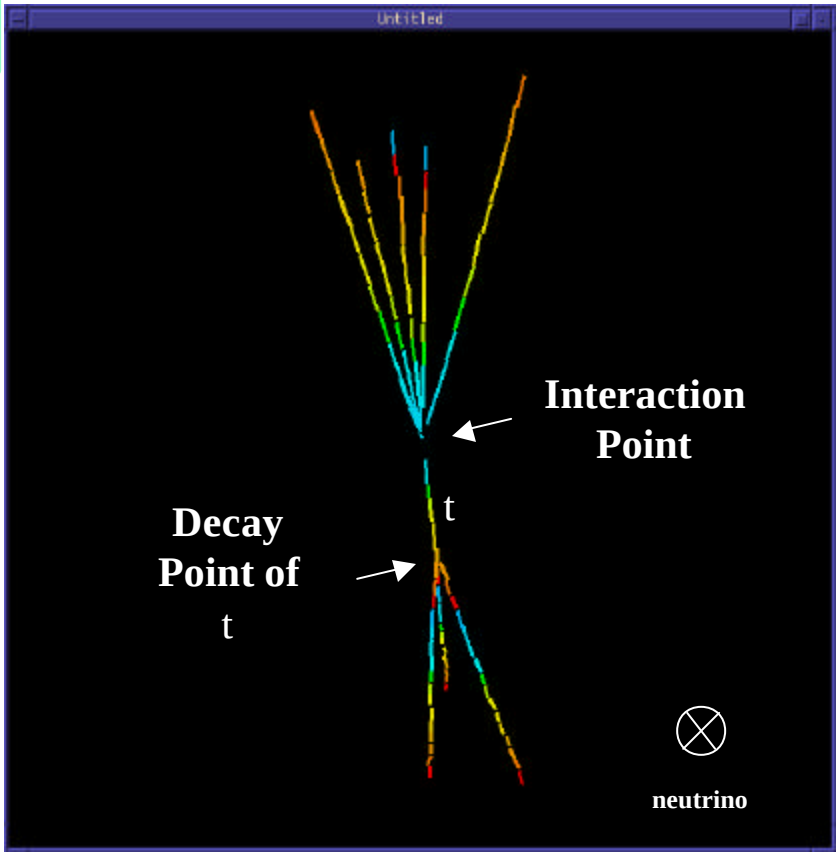


All tracks in the Scanning region (4179 tracks)



Reject passing through tracks (420 tracks remained)

Reject Low momentum tracks (114 tracks remained)



Vertex detection :

Neutrino interaction and decay of short lived particles

Detection of ? $_t$ ^{CC} in DONUT

A very Little Neutrino Phenomenology

If neutrinos have mass then they may oscillate between flavors with the following probability

$$P = \sin^2 2? \sin^2(1.27\Delta m^2 L / E)$$

L is the distance that the neutrino travels (the baseline) - km

E is the neutrino energy - GeV

$\sin^2 2\theta$ is the oscillation mixing angle

Δm^2 is the mass difference squared between neutrino mass eigenstates – eV^2

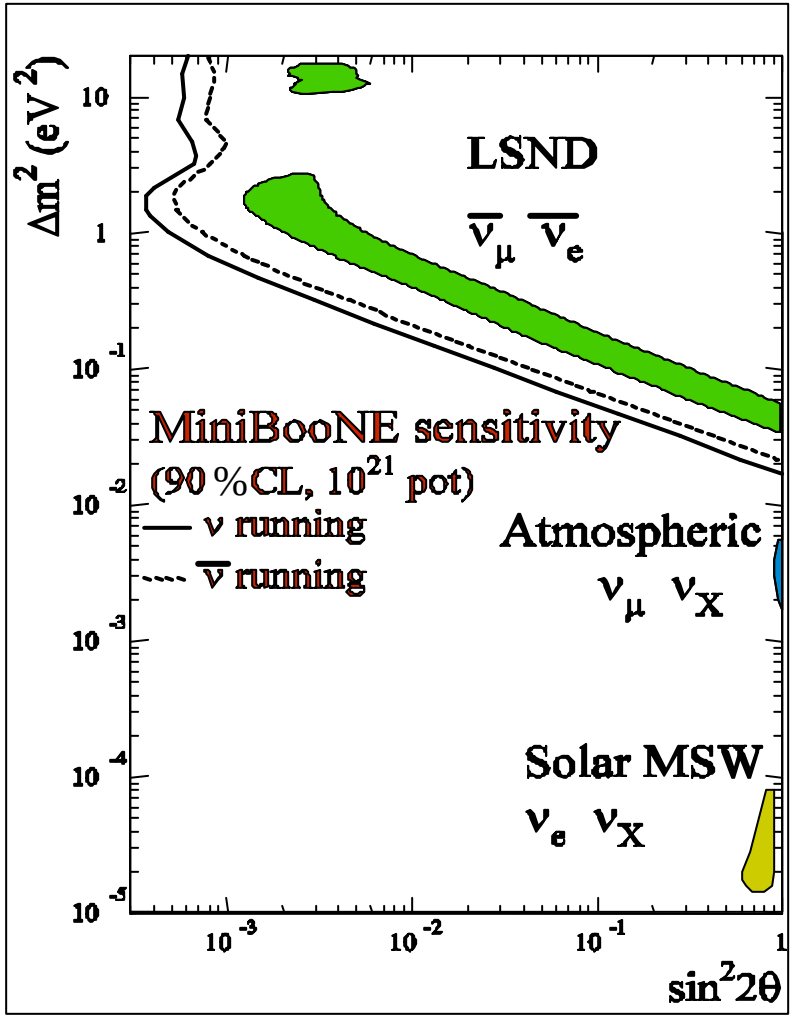
MiniBooNE Goal: Investigate LSND

Taking atmospheric, solar, reactor, and LSND results together … either …

- One or more of the experiments are not seeing oscillations
- or there are >3 neutrinos
  (gives you 3 independent Δm^2 scales)
- or CPT is not a good symmetry
  (gives you different mass scales for $\nu, \bar{\nu}$)

Barenboim, Borissov, Lykken, hep-ph/0212116

- or ???



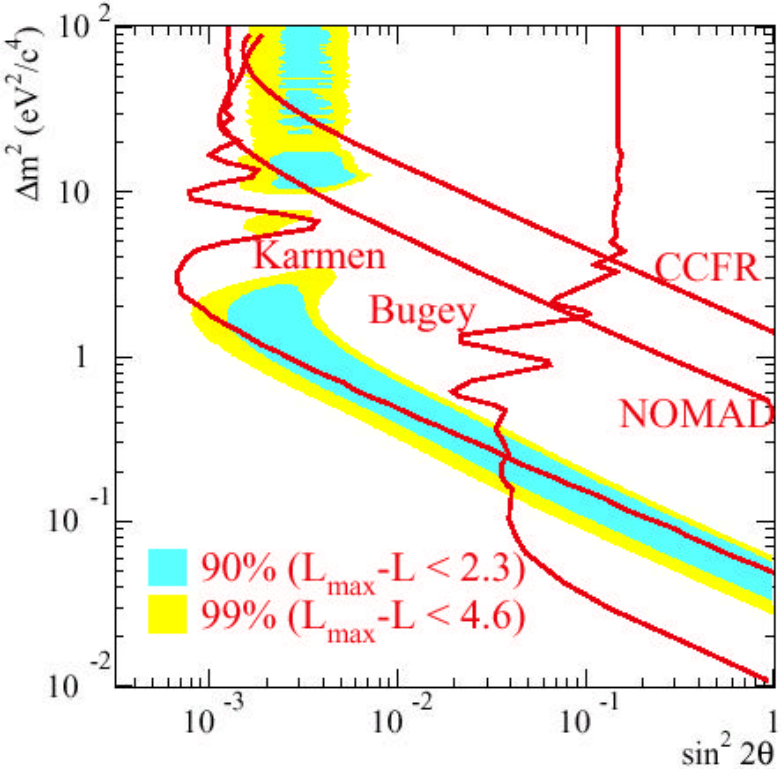
To check LSND want:

- similar L/E
- different systematics
- higher statistics

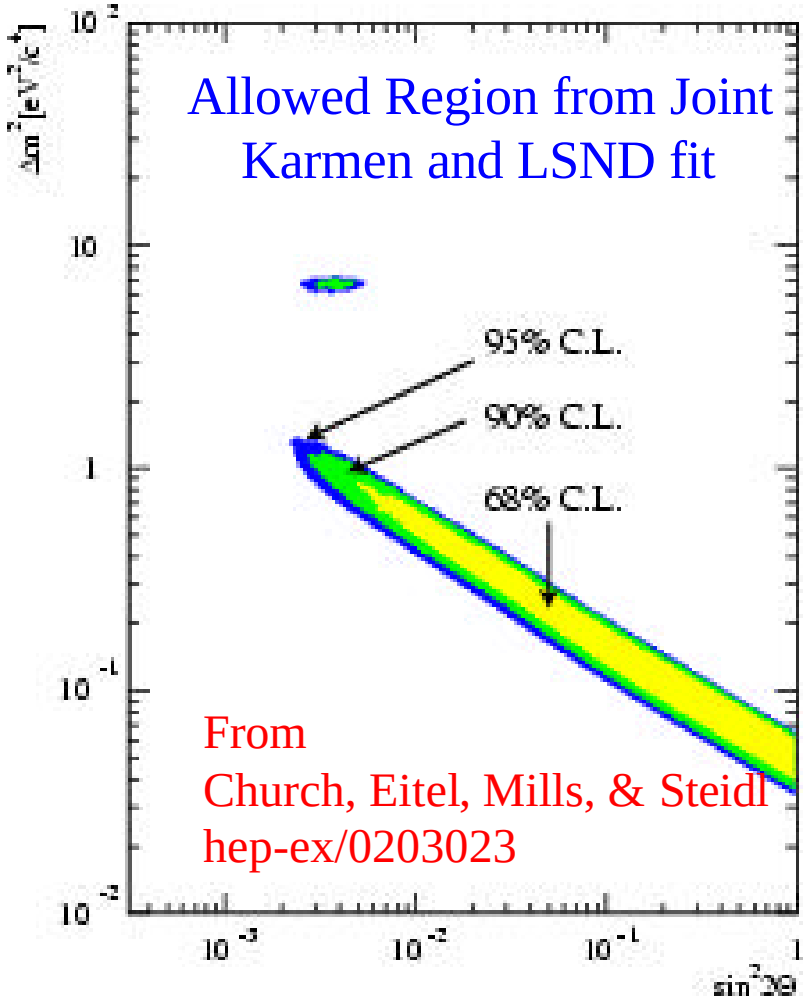
→ MiniBooNE!

The Other Experiments

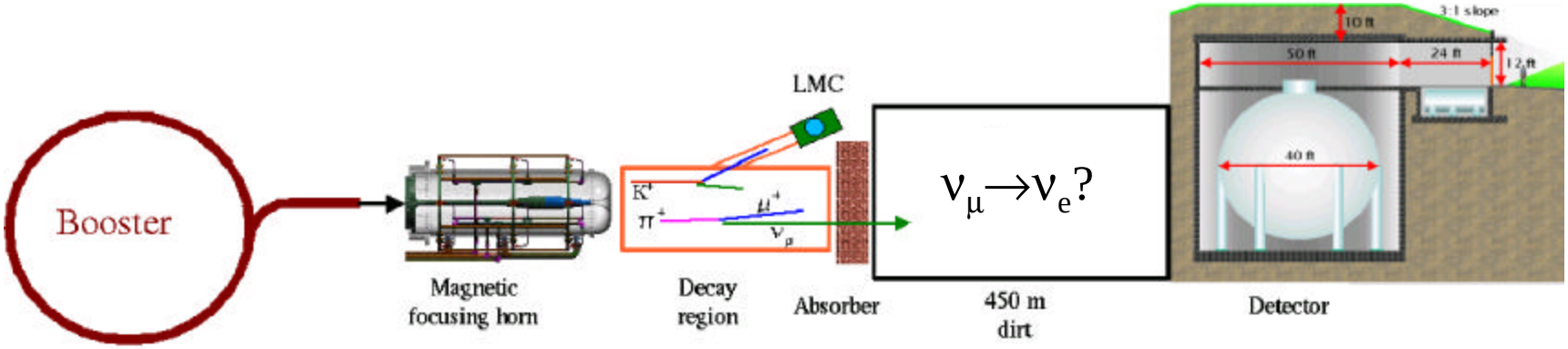
Several other experiments have looked for oscillations in this region.



The most restrictive limits come from the Karmen Experiment.



The MiniBooNE Neutrino Beam



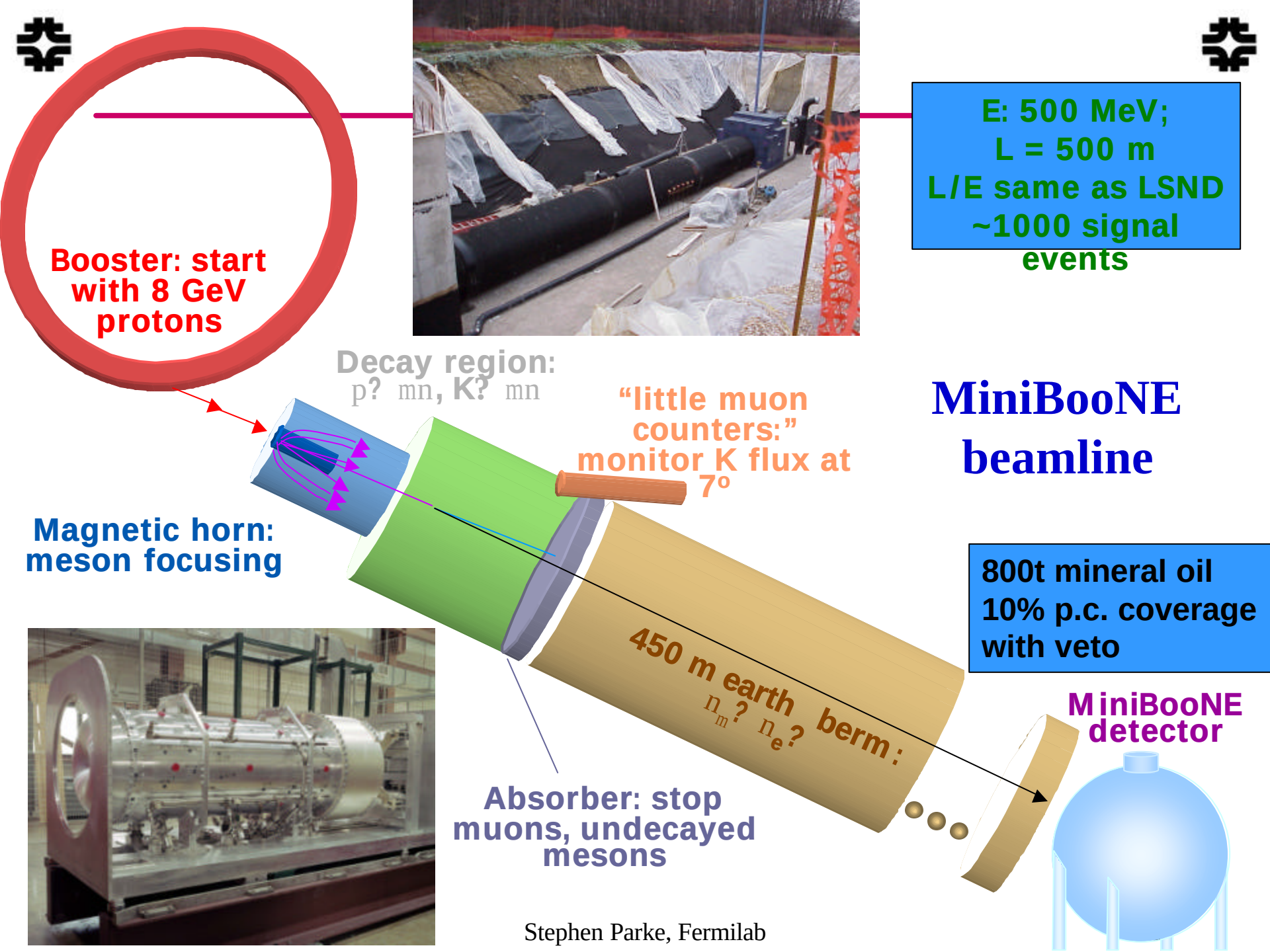
Start with a very intense 8 GeV proton beam from the Booster.

The beam is delivered to a 71 cm long Be target.

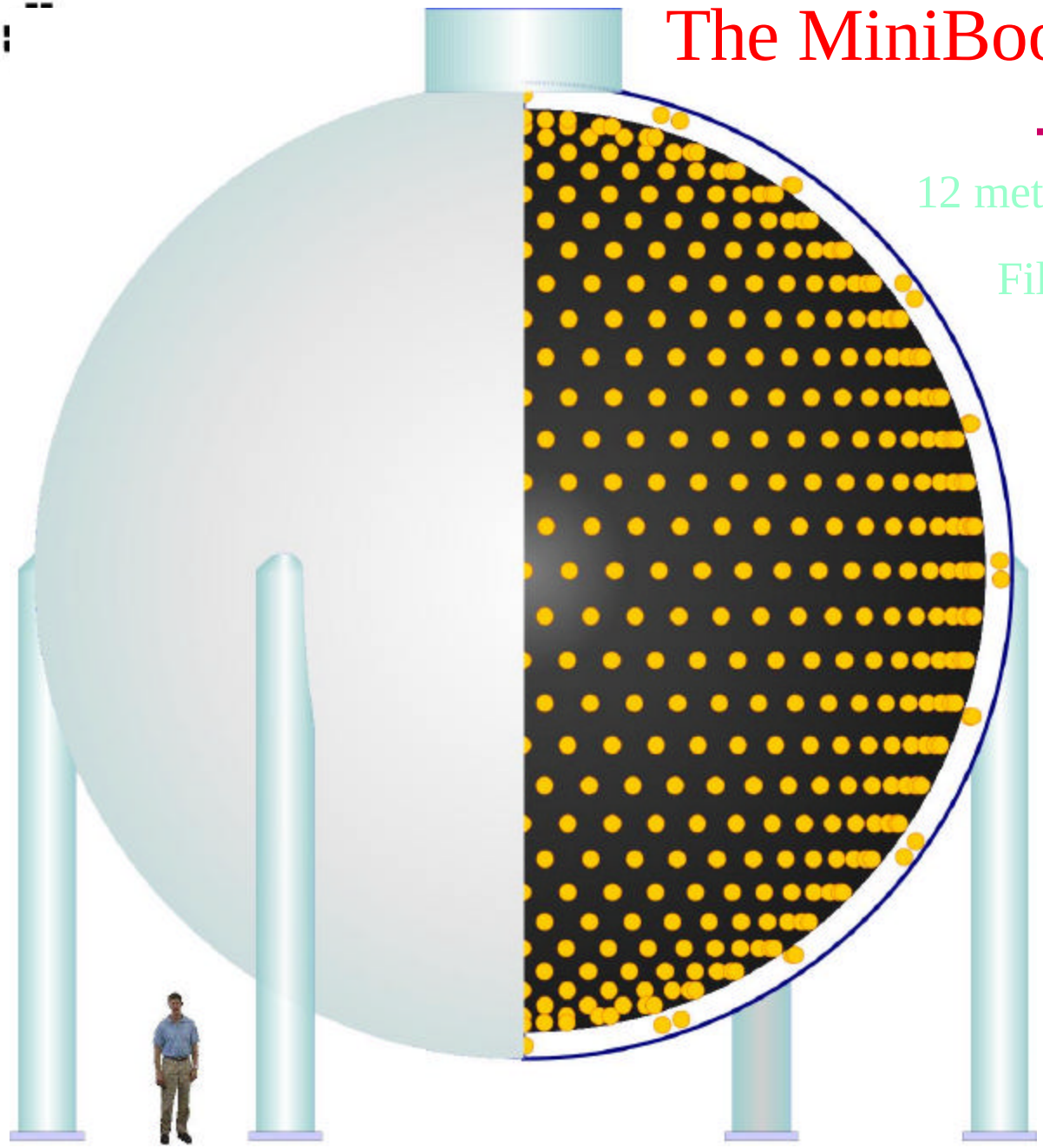
In the target primarily pions are produced, but also some kaons.

- Charged pions decay almost exclusively as $\pi^\pm \rightarrow \mu^\pm \nu_\mu$.
- The decays $K^\pm \rightarrow \pi^0 e^\pm \nu_e$ and $K_L \rightarrow \pi^\pm e^\mp \nu_e$ contribute to background.
- There are also ν_e's from muon decay.

MiniBooNE beamline



The MiniBooNE Detector



12 meter diameter sphere

Filled with 950,000 liters of pure mineral oil — 20+ meter attenuation length

Light tight inner region with 1280 photomultiplier tubes

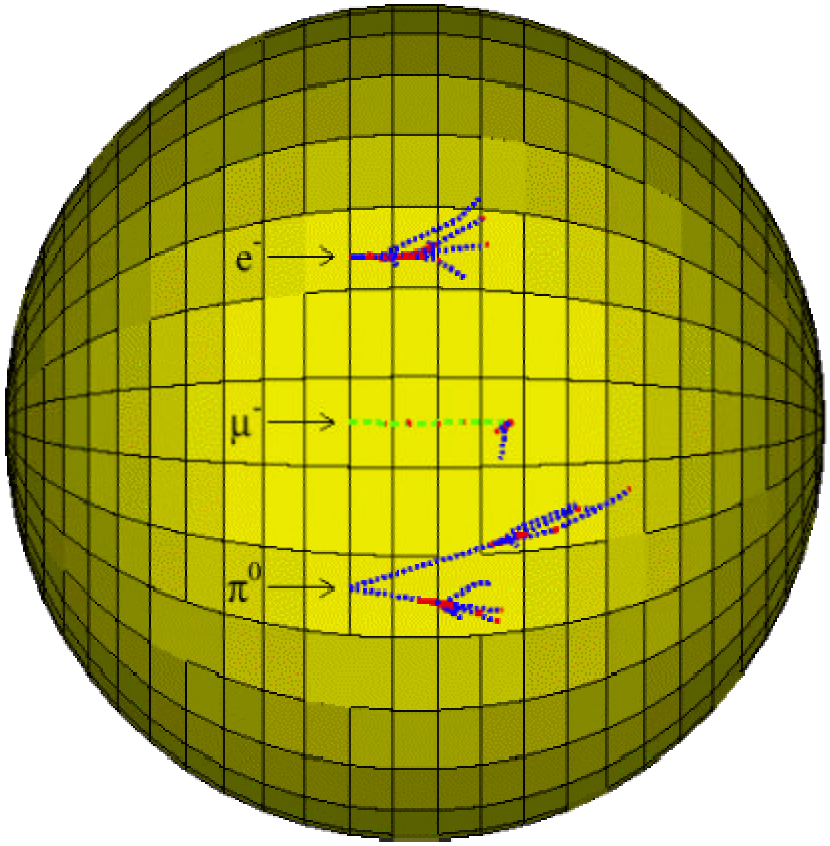
Outer veto region with 240 PMTs.

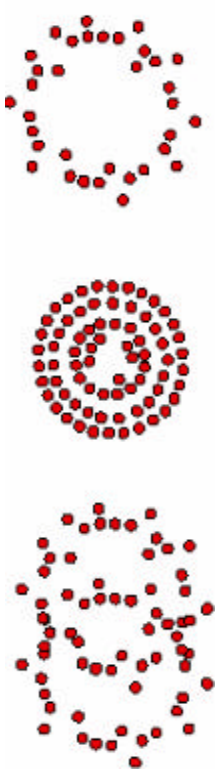
Neutrino interactions in oil produce:

- Prompt Cerenkov light
- Delayed scintillation light

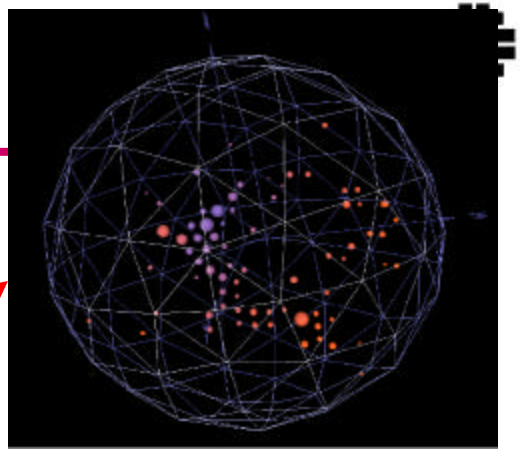
Cerenkov:scintillation ~ 5:1

MiniBooNE Particle ID

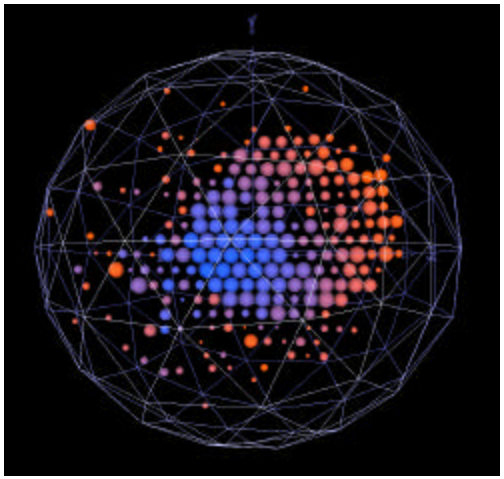




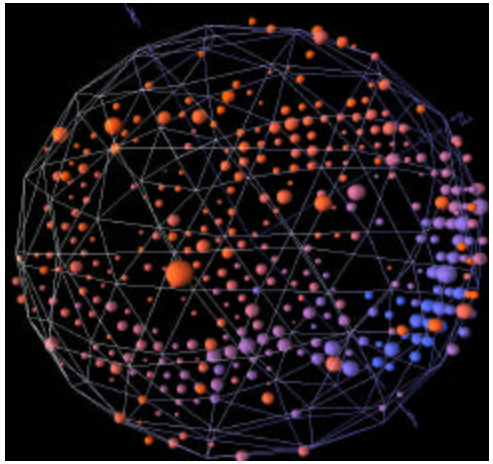
Michel e^- candidate



Beam μ candidate

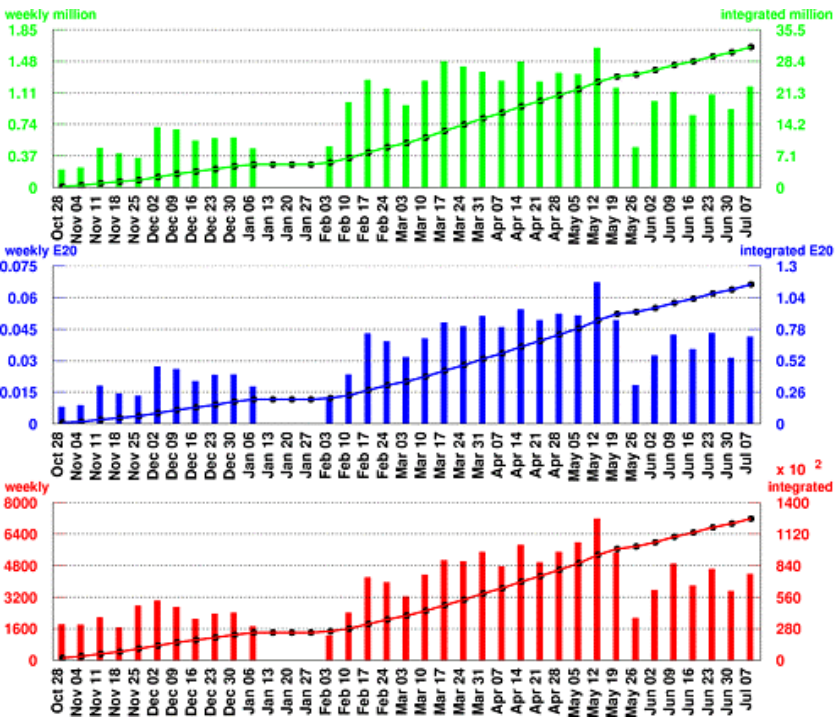


Beam π^0 candidate



Identify electrons (and thus candidate ν_e events) from characteristic hit topology of mineral oil Cherenkov light

Overall MiniBooNE Status



Number of Horn Pulses
To date: 31.58 million
Largest week: 1.63 million
Latest week: 1.18 million

Number of Protons on Target
To date: 1.149 E20
Largest week: 0.0671 E20
Latest week: 0.0413 E20

Number of Neutrino Events
To date: 125818
Largest week: 7192
Latest week: 4364

- Steadily taking data
- Currently at ~10% of 1×10^{21} POT goal
- Have collected >125,000 ν events
- Detector performing well
- Still need more beam!

- Proton rate delivered by Booster has dramatically improved over time

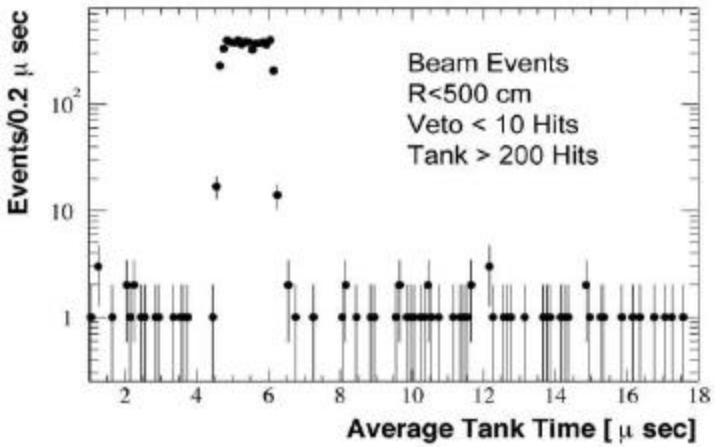
- Further Booster upgrades in the works to reach intended rate
- Detector works beautifully!
- Expect first physics results in the Fall – WIN'03 October

p^0 Background

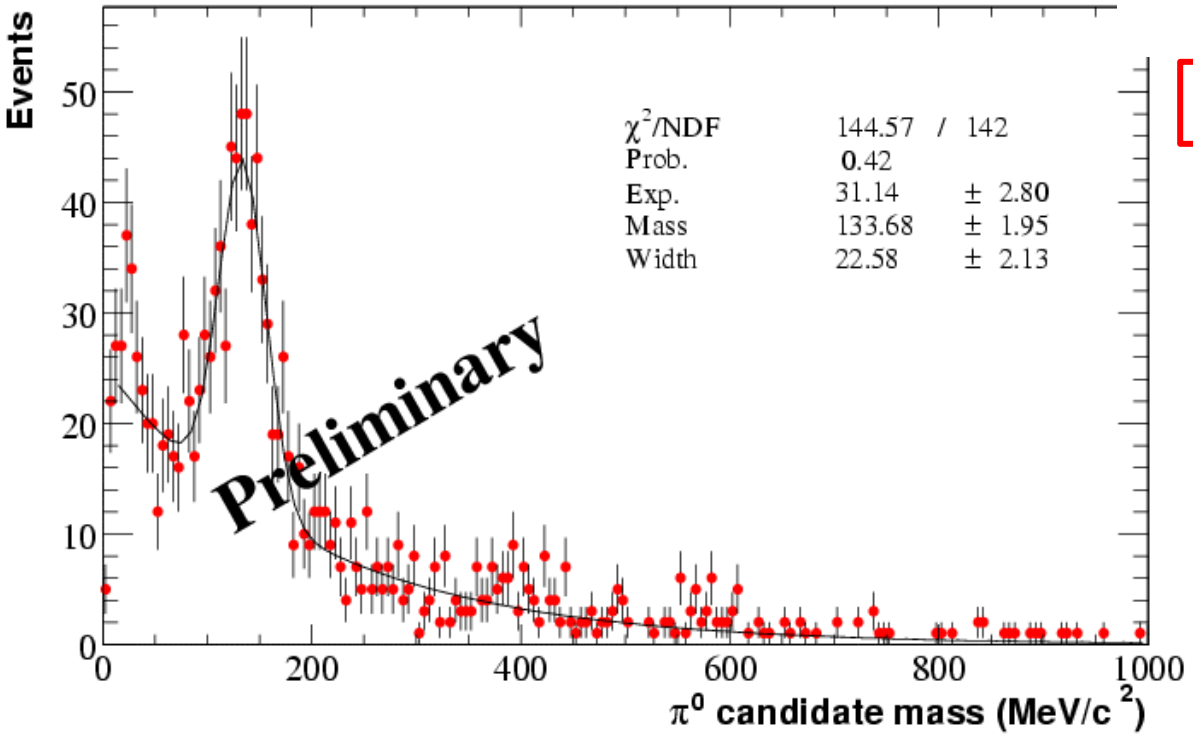
π^0 background to $\nu_\mu \rightarrow \nu_e$ search

$\pi^0 \longrightarrow \gamma\gamma$ can mimic an electron

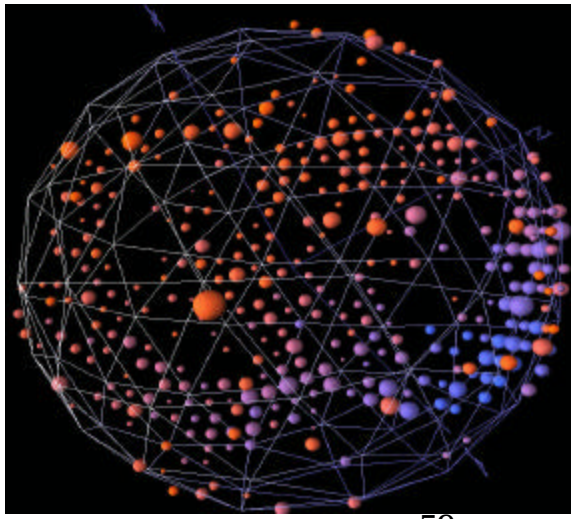
- escaping γ
- asymmetric decays
- ring overlap



non-beam background to ~10^{-3}



π^0 events are a useful calibration source



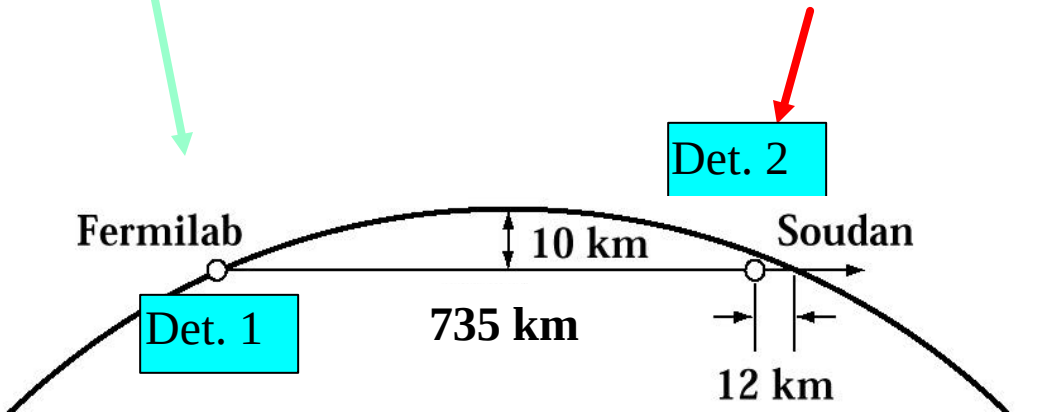
MINOS Physics Goals

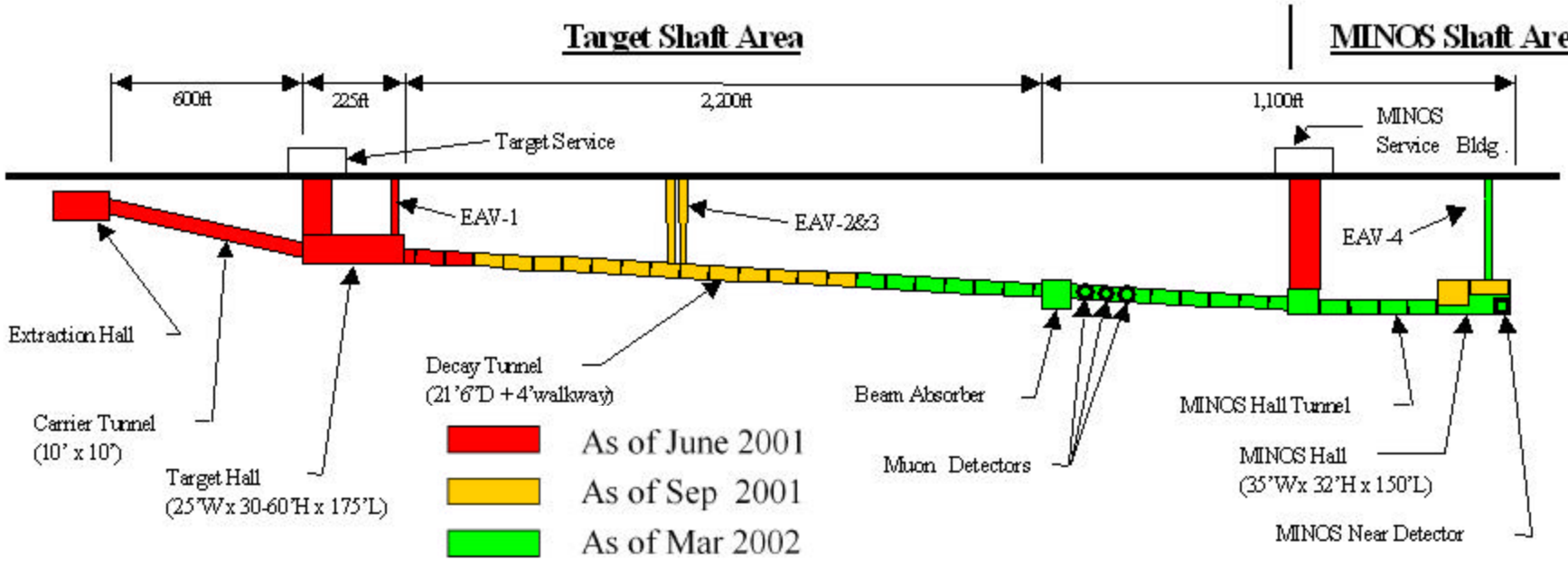
- Demonstrate & Confirm the presence of oscillations.
  - A number of detection channels are available. Best is comparison of near and far Charged Curent energy spectrum. The beamline and detectors are designed to do this with a total systematic error of < 2% per 2 GeV bin.
- Provide precision measurements of oscillation parameters.
- Provide determination of flavor participation to 2%.
- Comparison of oscillation parameters for atmospheric neutrinos and antineutrinos.

The MINOS Experiment

Status

- The installation in the Target Hall will started in September 2002
- The installation in the Near Detector Hall in December. 2002
- The first beam on target in December '04.
- The Far Detector is now complete, with both coils energized and veto shield also finished.
- Taking good atmospheric ν_μ and $\bar{\nu}_\mu$ data.

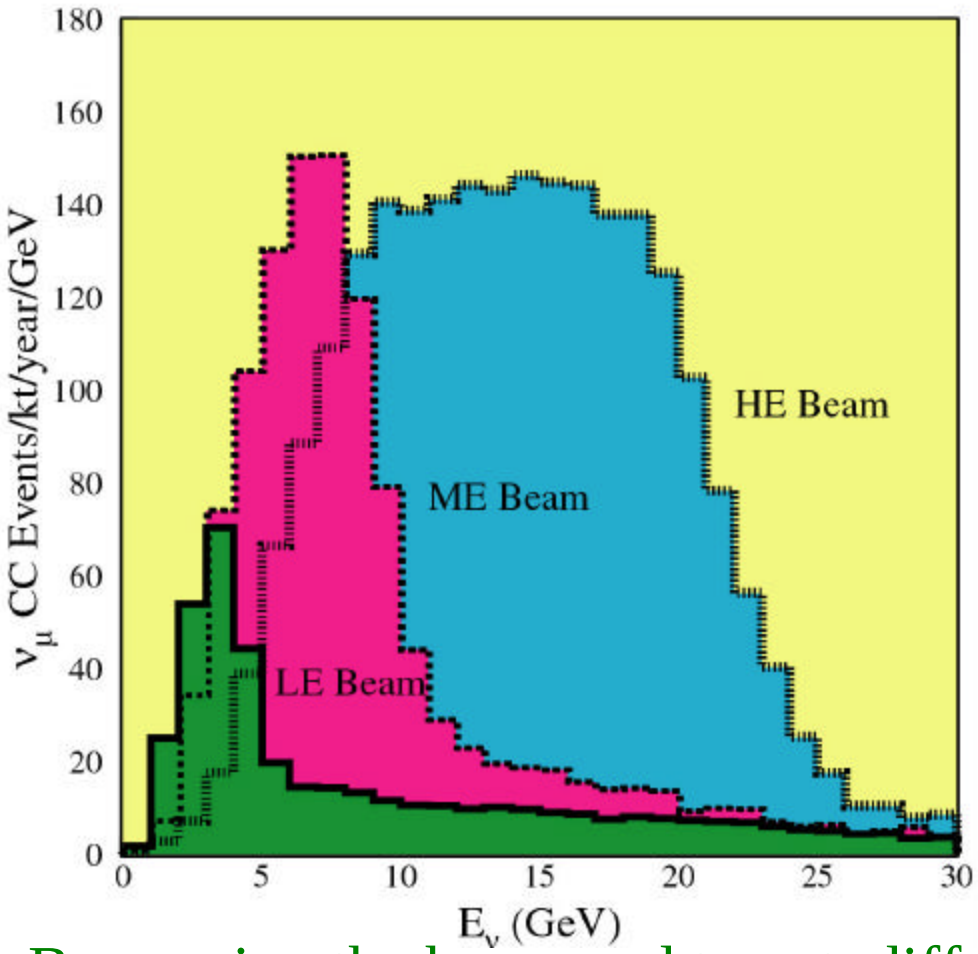




First piece of decay pipe

T

The NuMI Neutrino Energy Spectra



ν_μ CC Events/kt/year

Low	Medium	High
470	1270	2740

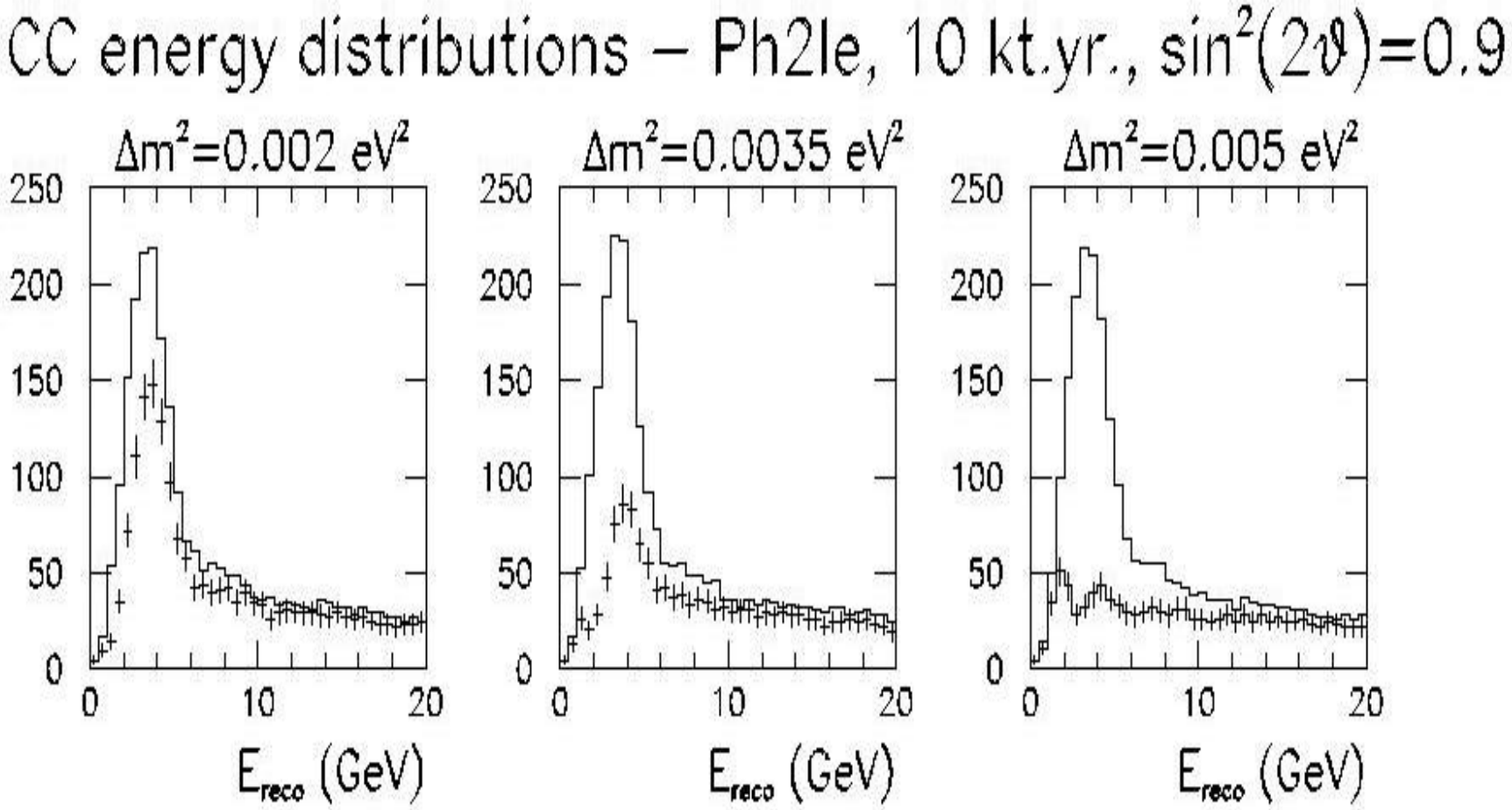
ν_μ CC Events/MINOS/2 year

Low	Medium	High
5080	13800	29600

4×10^{20} protons on target/year
4×10^{13} protons/2.0 seconds

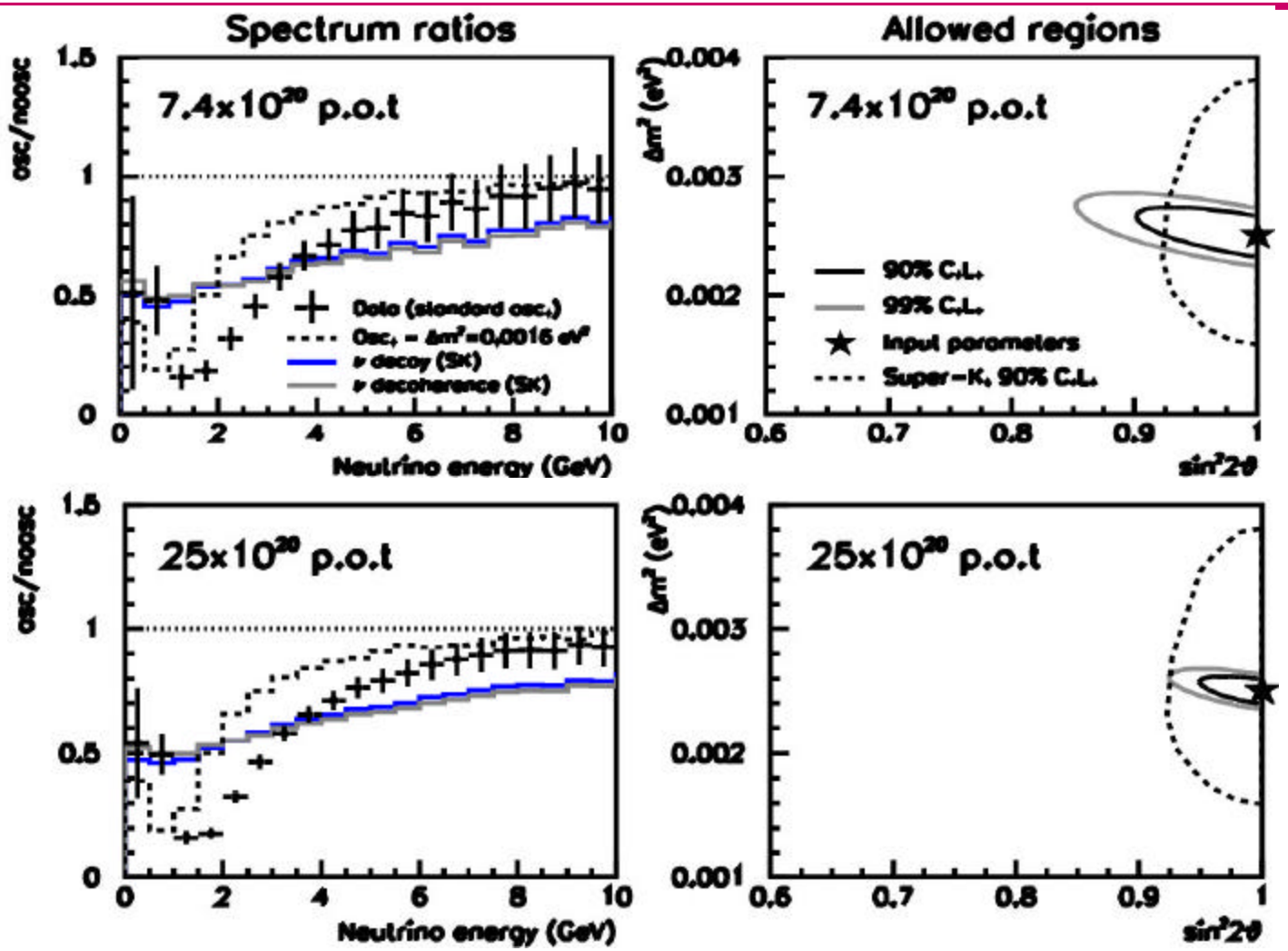
By moving the horns and target, different energy spectra are available using the NuMI beamline. The energy can be tuned depending on the specific oscillation parameters expected/observed.

Charge Current Energy Distributions



Note: 10 kt. Yr. = ~ 2 live years of running. Results still statistics limited at that time.

Measurement of Oscillations in MINOS

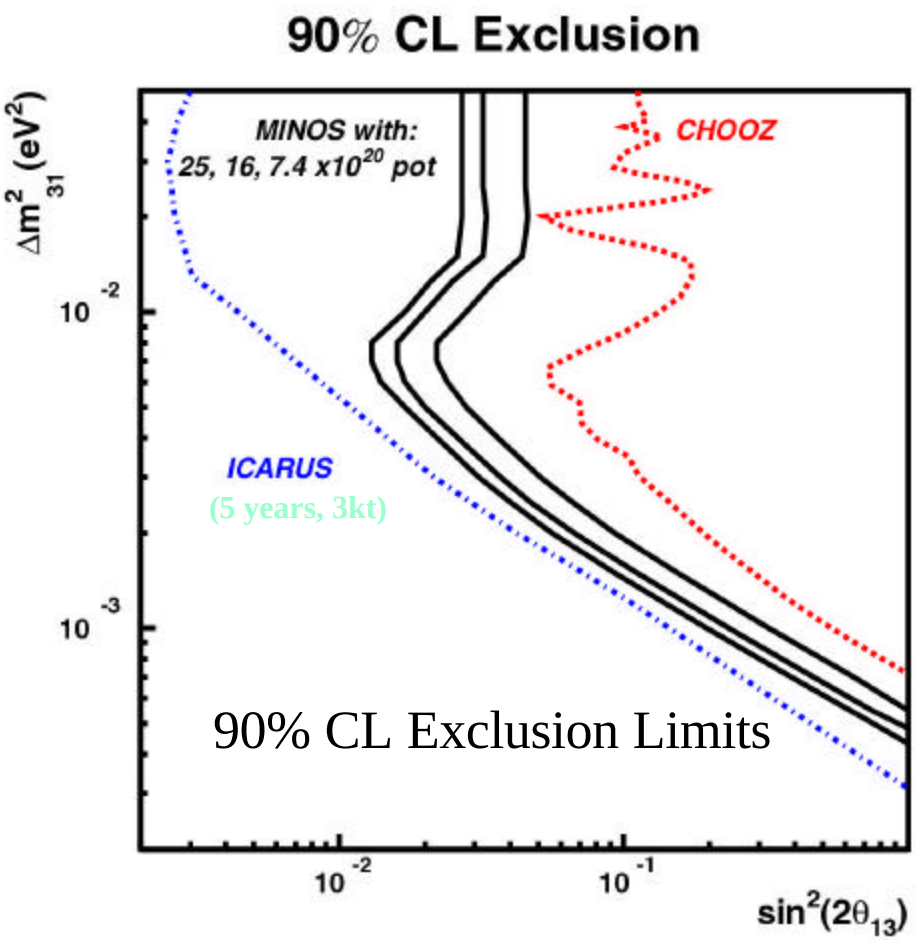


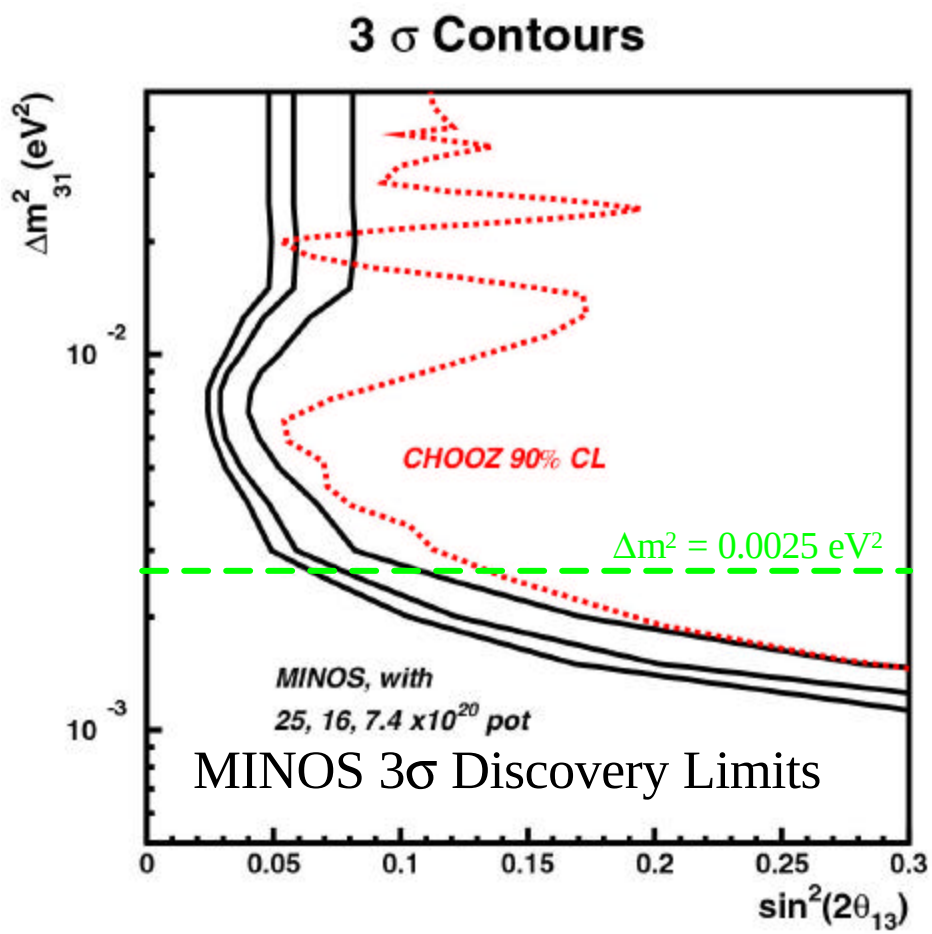
For $Dm^2 = 0.0025\ eV^2$, $\sin^2 2q = 1.0$

Oscillated/unoscillated ratio of number of ν_μ CC events in the far detector vs $E_{observed}$

MINOS 90% and 99% CL allowed oscillation parameter space.

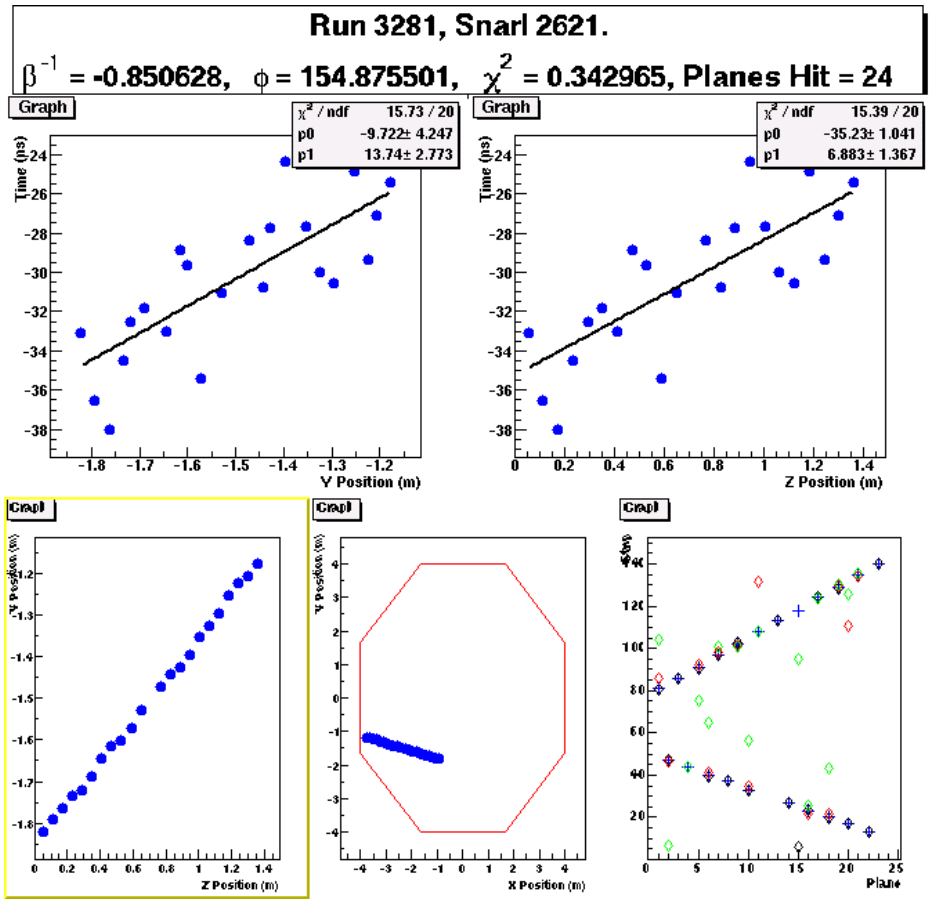
Appearance of Electrons

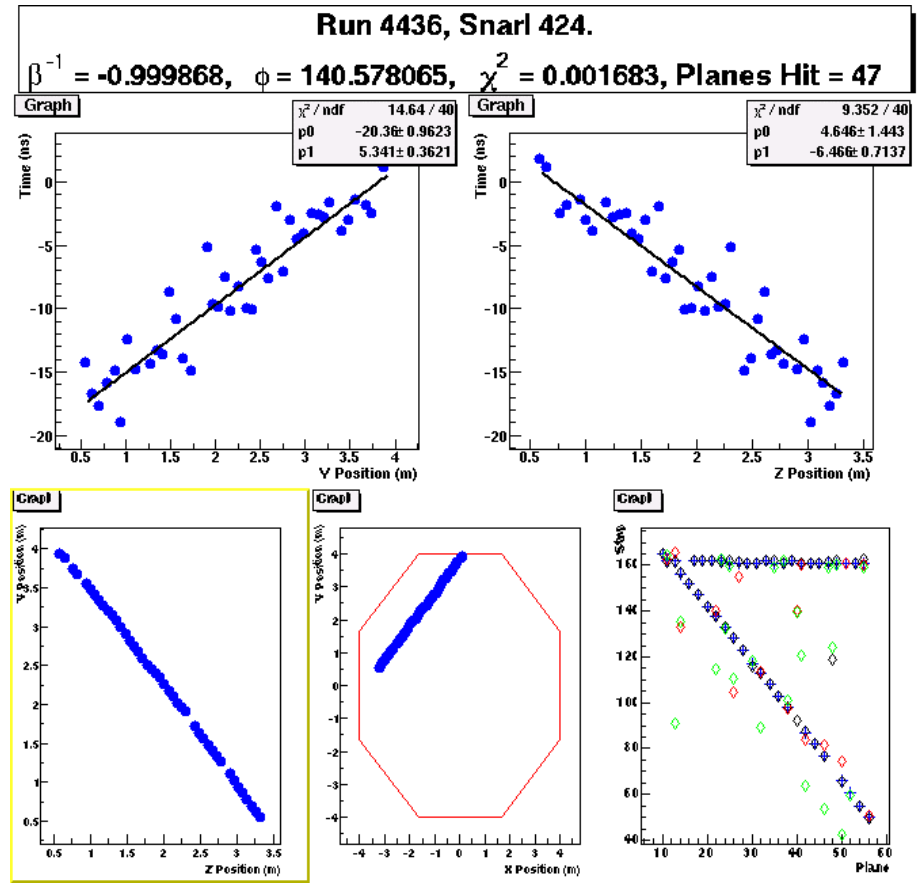




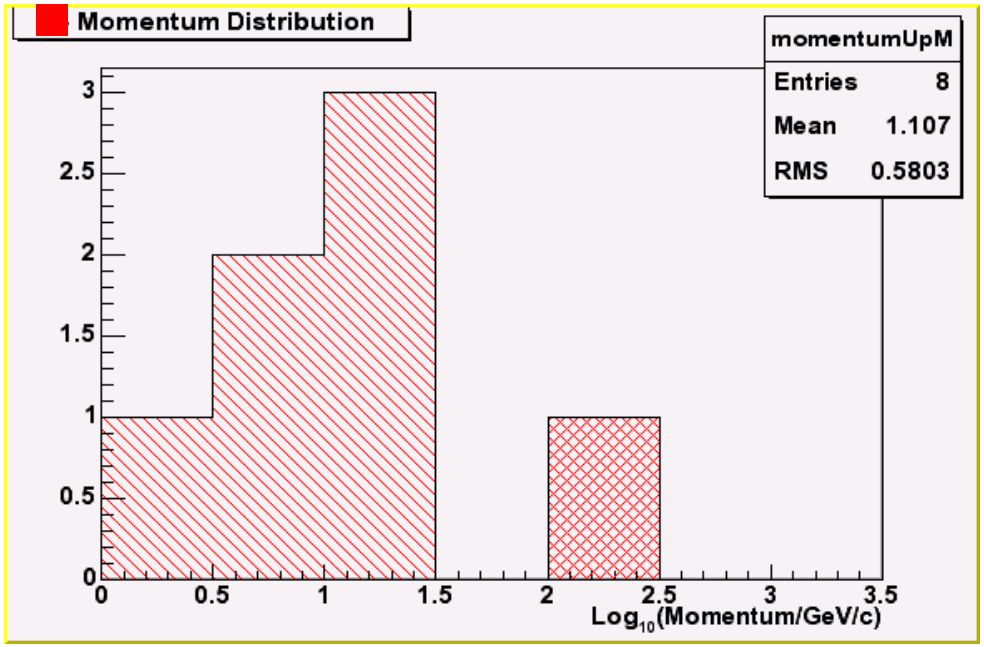
- MINOS sensitivities based on varying numbers of protons on target

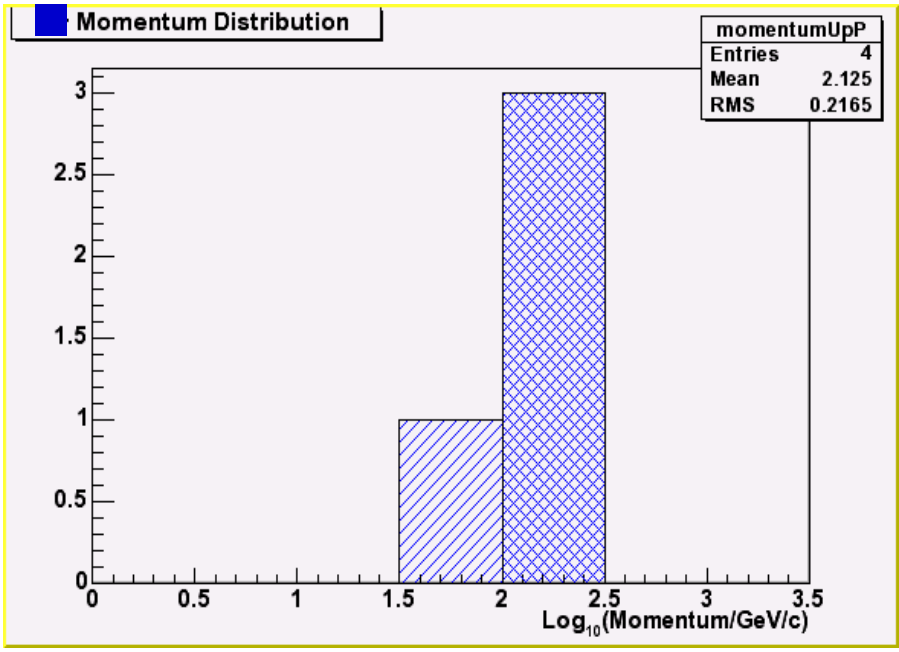
1st and 2nd Neutrino Events at Far Detector





Charge and Momentum of Upgoing Muons





- **One Sign**
- **Other Sign**

THEORY

Theoretical Physics

- **Particle Theory Group: Topics**
  - Beyond Standard Model
    - Supersymmerty, Extra Dimension, Model building
    - Neutrinos
  - Phenomenology
    - Collider Physics, Heavy Flavors
    - QCD Perturbative, Lattice

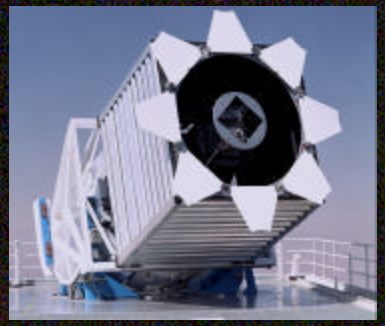
- **Astrophysics Theory Group: Topics**
  - Dark Matter, Dark Energy, inflation, Large-Scale Structure, Cosmic Microwave Background, Gravitational Lensing, Cosmic Rays, Neutrinos

Astro-Physics

The Experimental Particle Astrophysics Program

- Fermilab has an important role in astrophysics experiments, as a partner with NSF, U.S. university groups (DOE and NSF), and foreign institutions:
  - The **Cryogenic Dark Matter Search** (CDMS-II) is going to extend its search for direct detection of cold dark matter with a new facility in the Soudan mine.
  - The **Auger Cosmic Ray Observatory** will study cosmic rays with energy $10^{19} – 10^{21}$ ev at Los Leones, Argentina.
  - The **Sloan Digital Sky Survey** is now operating at Apache Point Observatory, NM and many results are attracting great attention.

Sloan Digital Sky Survey



2.5 m Telescope
Apache Point NM

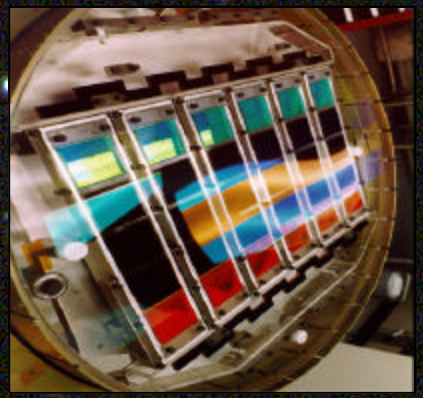
Goals:

1. Image ¼ of sky in 5 bands
2. Obtain redshifts of 1 million galaxies and quasars

Science:

Measure large scale structure of
a) galaxies in 0.2% of the visible universe
b) quasars in 100% of the visible universe

Address fundamental question in cosmology

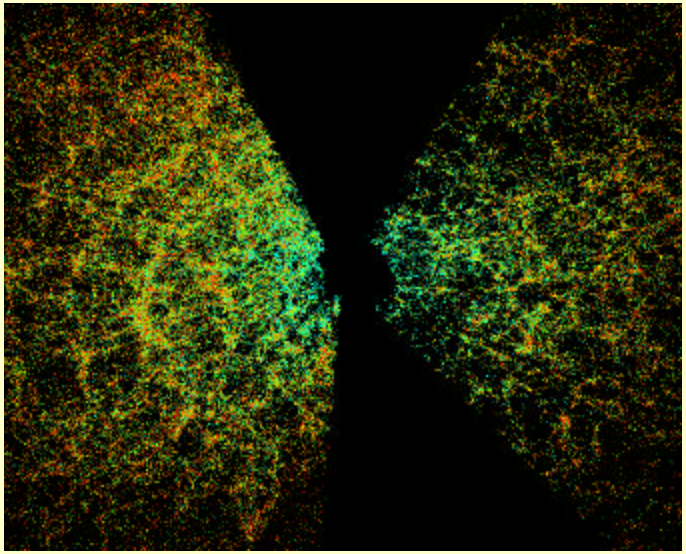


Mosaic Imaging Camera

Status (Aug 2003)

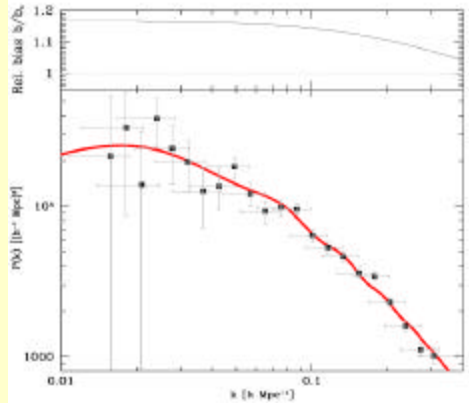
	Baseline	Percent Complete
IMAGING	8452 sq. deg.	**78% as of Aug 6, 2003**
SPECTROSCOPY	1688 tiles	**48% as of Aug 6, 2003**

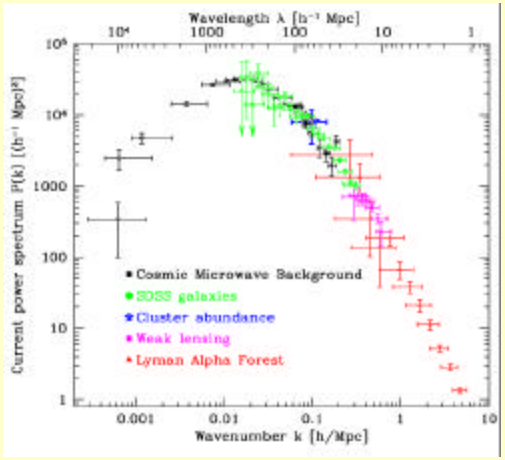
640 Fiber Spectrograph



Distribution of Galaxies around Sun to z=0.15

(Blanton 2003)



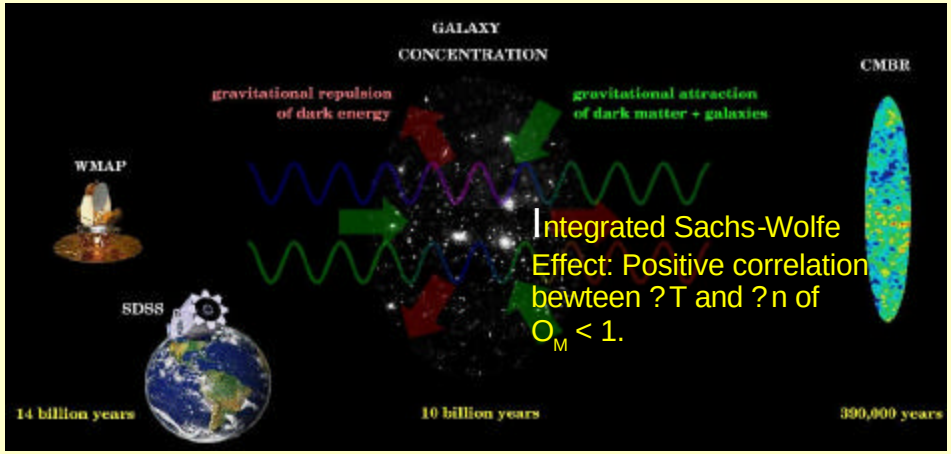


? CDM adjusted to L* galaxy

$O_M h = 0.213 \pm .023$
s_8 (gal) = 0.96 ± .02
n = 0.995

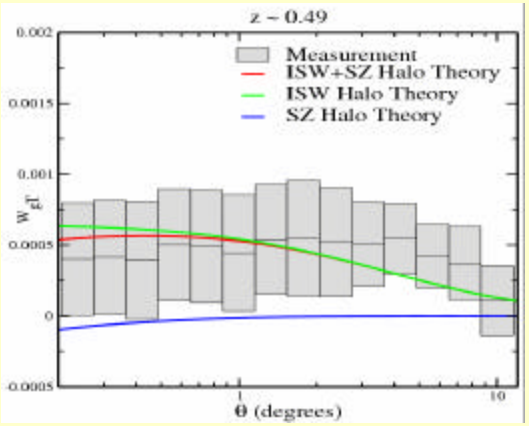
Three-dimensional Power Spectrum

(Tegmark et al 2003)



SDSS vs WMAP: Correlation of temp. fluctuations with galaxy counts

(Scranton et al. 2003)



Strong evidence for dark energy dominated universe (?CDM)

FUTURE PROJECTS

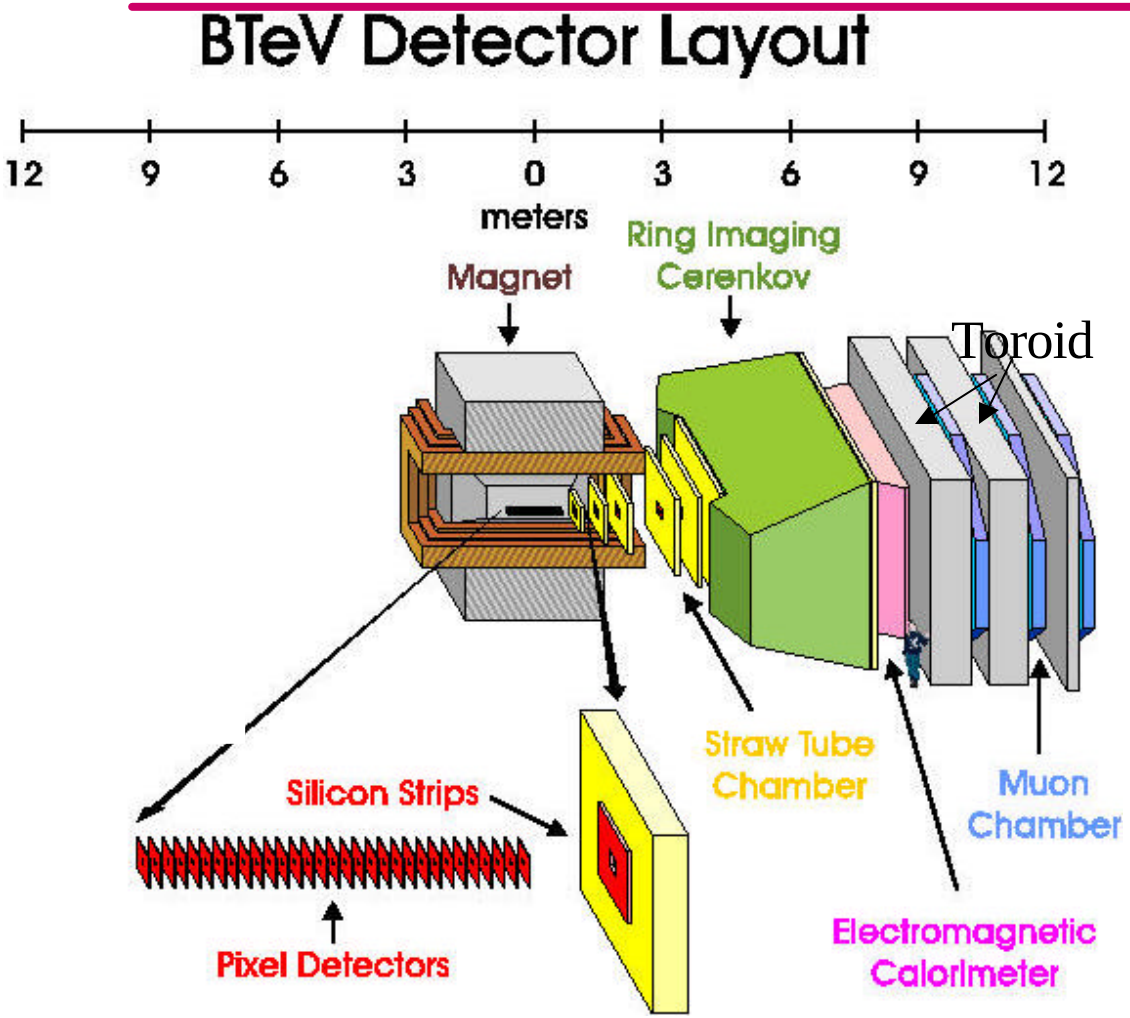
Future Projects: CP Violation

- BTeV
  - Dedicated B-physics Detector at Tevatron Collider
    - The BTeV experiment will exploit the large B meson cross section at the Tevatron to make *precision* measurements of B decays, particularly B_s decays, that have very robust theoretical predictions.

- CKM
  - Precision Measurement of $K^+ \rightarrow p^+ n \bar{n}$
    - The CKM experiment (Charged Kaons at the Main injector) will exploit the large flux of charged kaons produced by the Main Injector proton driver to make a *precision* measurement the ultra-rare $K^+ \rightarrow \pi^+ \nu\nu$ process. (BR ~ 1×10^{-10}).

- NuMI Off-Axis
  - $n_m \rightarrow n_e$
    - Measure Θ_{13}, mass hierarchy and CP violating phase, δ.

Reduced Scope BTeV Spectrometer



Since B's are produced by gluon-gluon fusion, both B's are boosted in the direction of the more energetic gluon, and go into the same arm. If this were not so, tagging would not be efficient with one Arm.

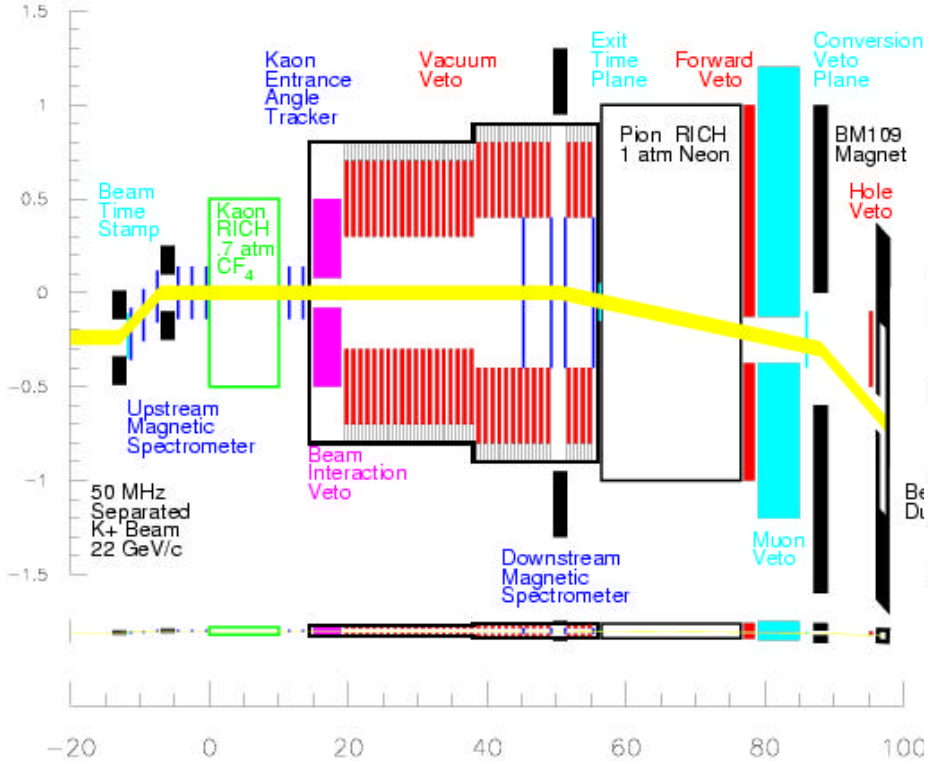
The Re-scoped Version of BTeV 's Stage I approval was recently reconfirmed, unanimously, by the FNAL PAC.

BTeV Physics Reach - 1 Year

Quantity	Uncertainty (s) $\frac{2 \times 10^{32}}{1\text{year}}$
d sin2b	0.018
a	
B-> rp	$^{+/-}4.3^{0}$
g	
B_s-> D_sK	$^{+/-}10^{o}$
B^- ->D^oK^-	$^{+/-}14^{o}$
B^o->Kp	$^{+/-}7^{0}$(plus theory)
Sin(2c)	
B_s->J/y h(')	0.03
pp asym	0.034
x_s (D_sp)	up to 60

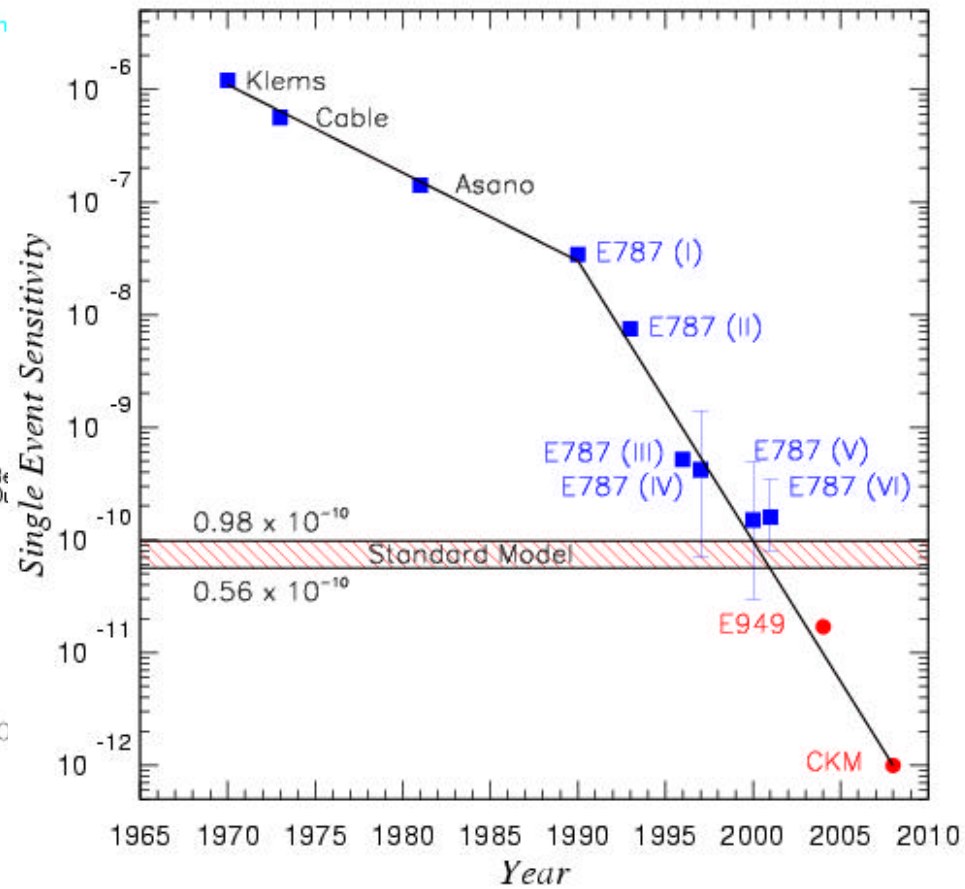
CKM

The CKM Apparatus

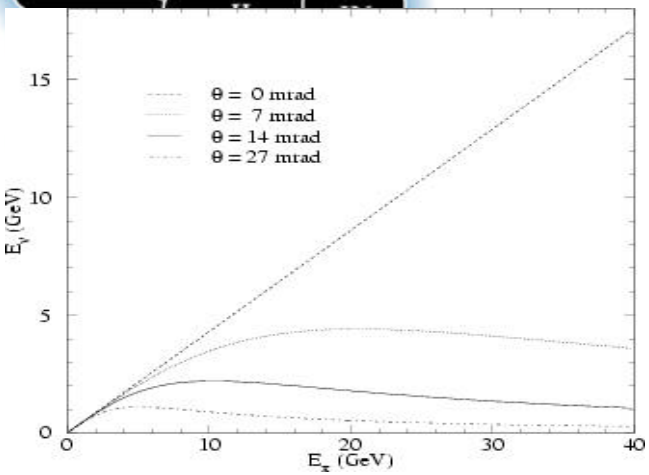


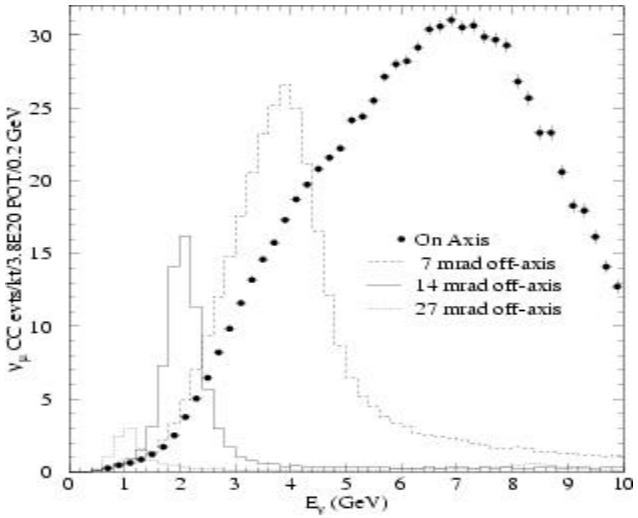
- Decay in flight experiment: 22 GeV/c enriched K^+ beam.
- Philosophy: redundant measurements, proven technology.
- Good, redundant measurements of K^+ and π^+ momenta.
- Good, redundant particle ID for signal and backgrounds.
- Very high-rate, low-mass detectors.

Status of BR($K^+ \to \pi^+ \nu\bar{\nu}$)

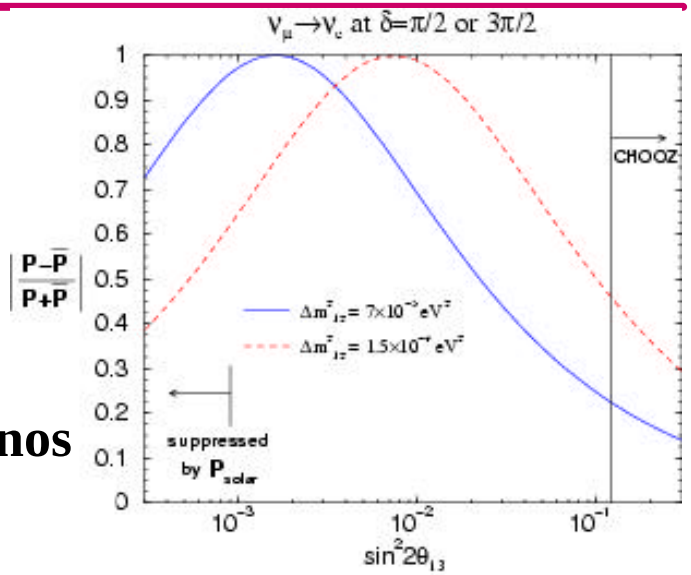


NuMI Off-Axis: $n_m \rightarrow n_e$

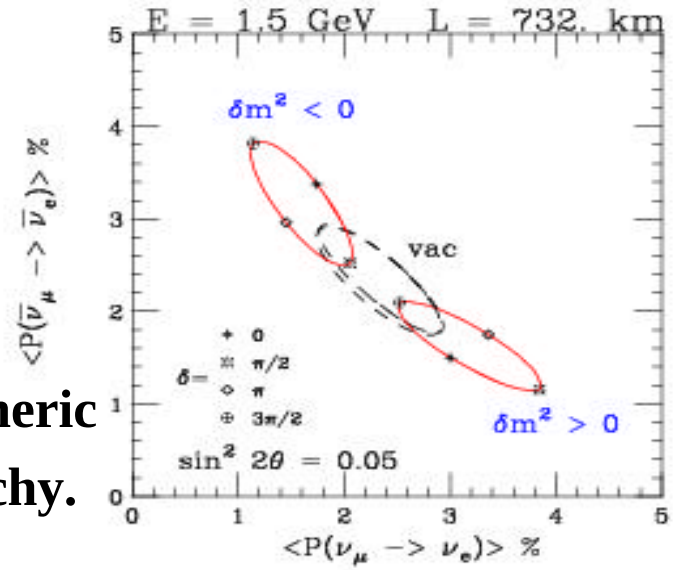




Large Asymmetry Neutrinos Verse Anti-Neutrinos



Matter Effects give NuMI sensitive to The Atmospheric Mass Hierarchy.



OUTLOOK

- **The Fundamental Scales of Mass and Energy**
  - What breaks the electroweak symmetry and sets the electroweak scale of 246 GeV? Top, EW and Higgs.
  - Is there a supersymmetry that is broken at this scale?
- **Neutrinos**
  - What is the pattern of neutrino masses and mixing? CP violation
- **Quarks and CP violation**
  - Are all CP violations consistent with a single source?
- **Cosmological Dark Matter & Dark Energy**.
  - Do new particles make up a significant component of dark matter?
- **Radically New Physics**
  - Eg Are there observable effects of large hidden dimensions?

The Fermilab program will address all of these questions this decade.

Summary

- We have great opportunities for discoveries at Fermilab.
  - An excellent program in the fast-moving area of neutrinos – MiniBOONE, MINOS, NuMI-Off-Axis
  - Exploring a new mass region at the Tevatron
  - Unique experiments in particle astrophysics
  - A big leap in energy scale at the LHC
  - BTeV and CKM which will explore CP violation precisely
- We are also doing R&D on the accelerators needed to advance the field.