# Search for Neutral, Long-lived Particles at DØ

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**Florida State University**

**HEP Seminar**

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**April 17, 2006**

- **Why search?**
- **How?**
- **What did we find?**
- **What does it mean?**

- **Why search?**
- **How?**
- **What did we find?**
- **What does it mean?**

# "Who ordered that?"

*- I.I. Rabi (1937)*

Discovery of the muon

Anderson and Neddermeyer

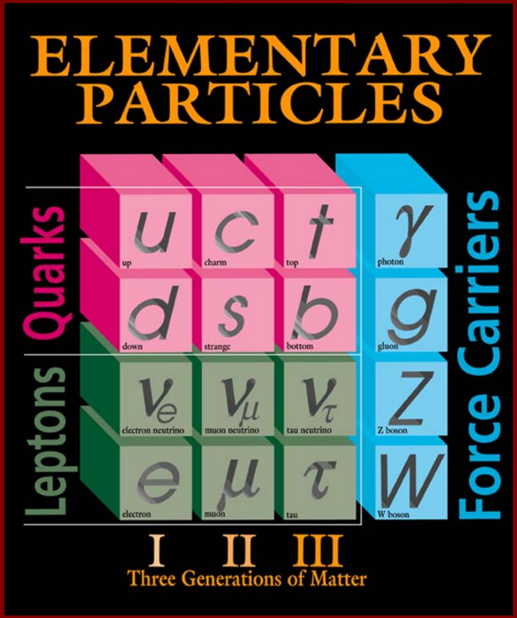
**1937**

Street and Stevenson

Prior to 1937
electron
proton
neutron
photon
positron
hypothesis of neutrino

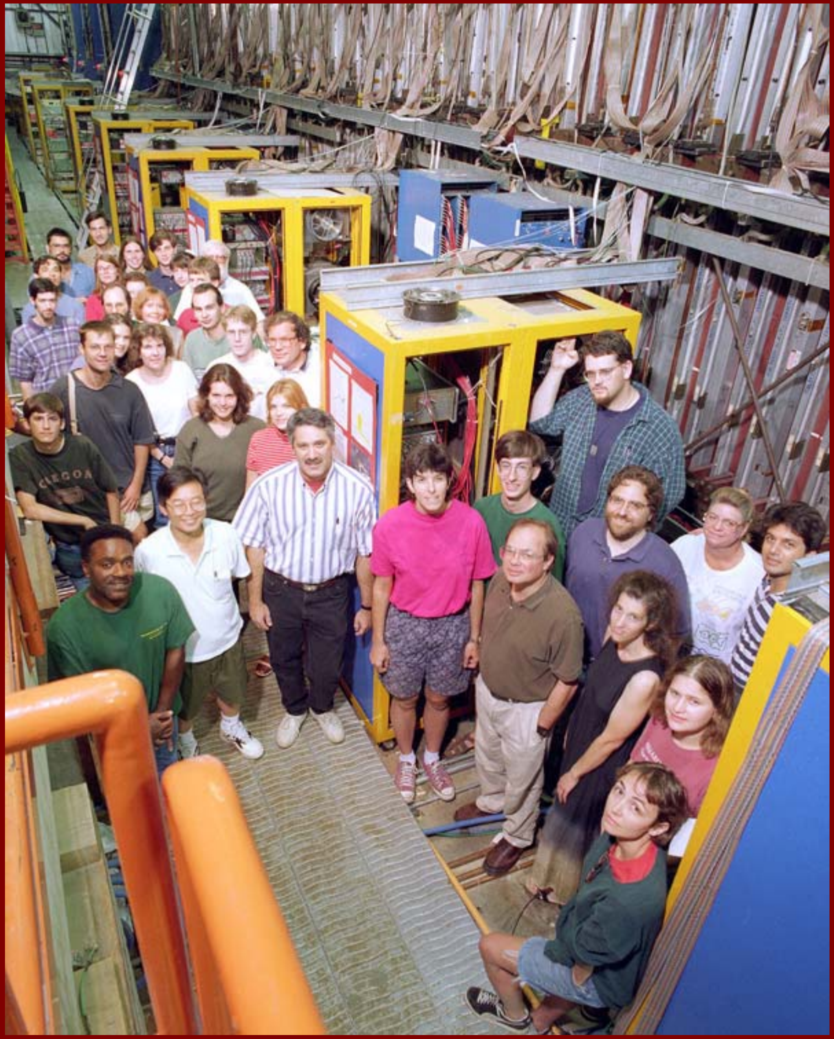
**other examples: strange particles, J/Ψ, tau lepton**

# *The Standard Model*




- **well established**
- **more than 30 years of success**
- **<u>incomplete</u>**

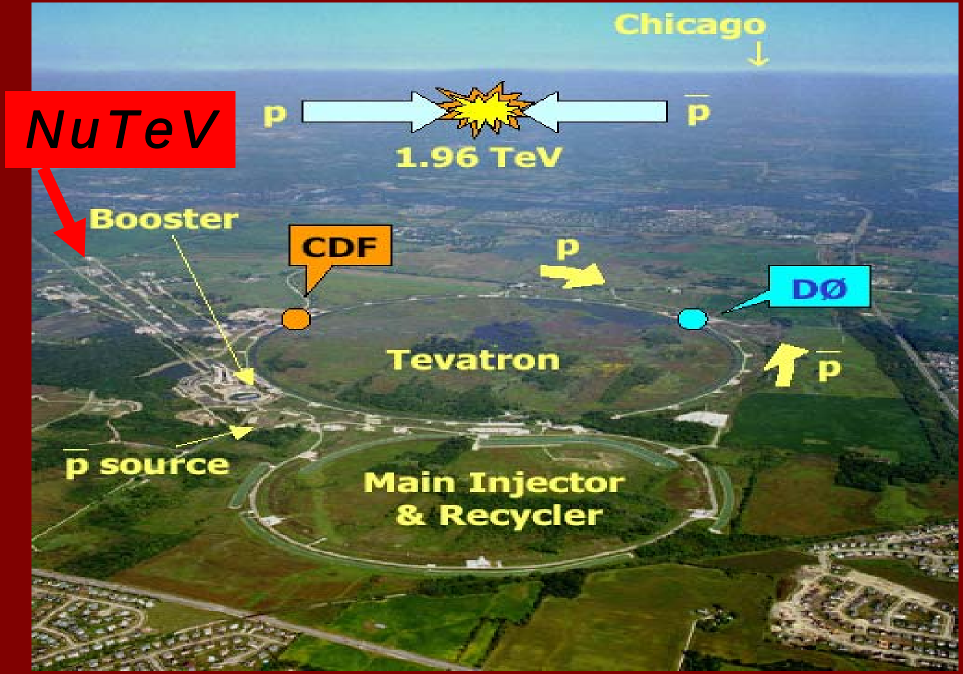
- **E.g.**
  - **We have no deep understanding of the parameters and their values**
  - **We don’t know the meaning of flavor and other quantum numbers.**



# NuTeV

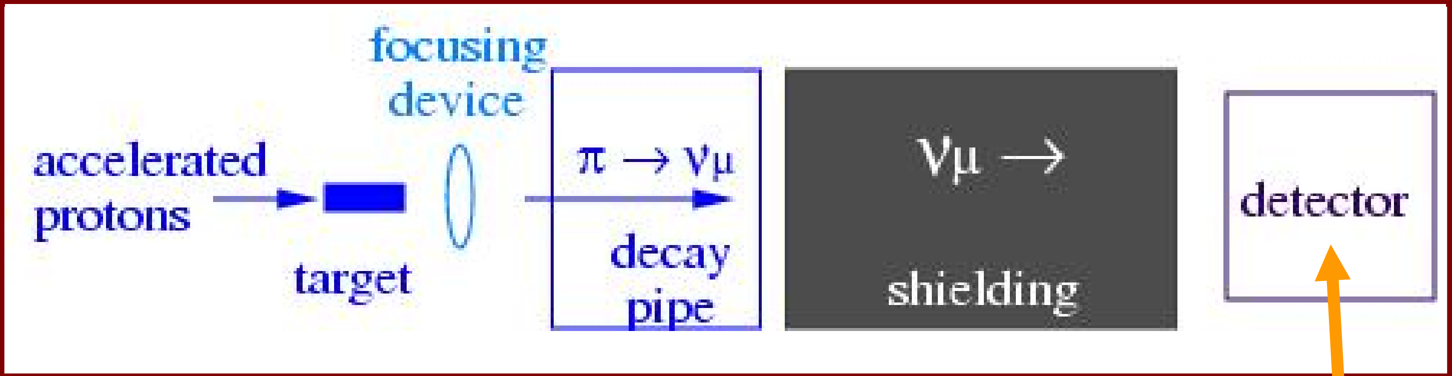
## Neutrinos at the Tevatron

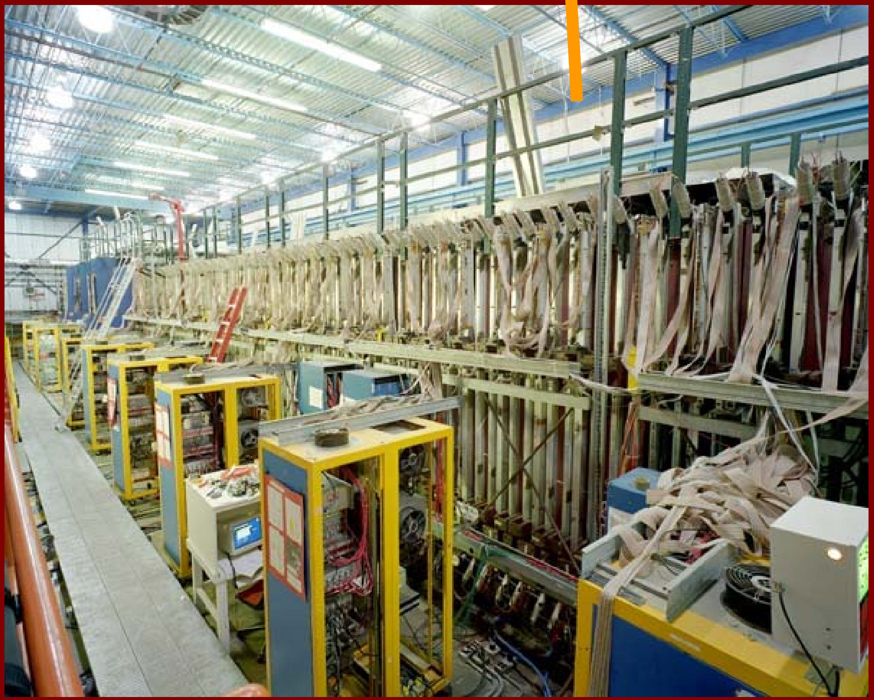
neutrino deep-inelastic scattering
$\sin^2\theta_w$
structure functions
charm production




Fermilab E815
(1996-97)

# *A Neutrino Experiment…*

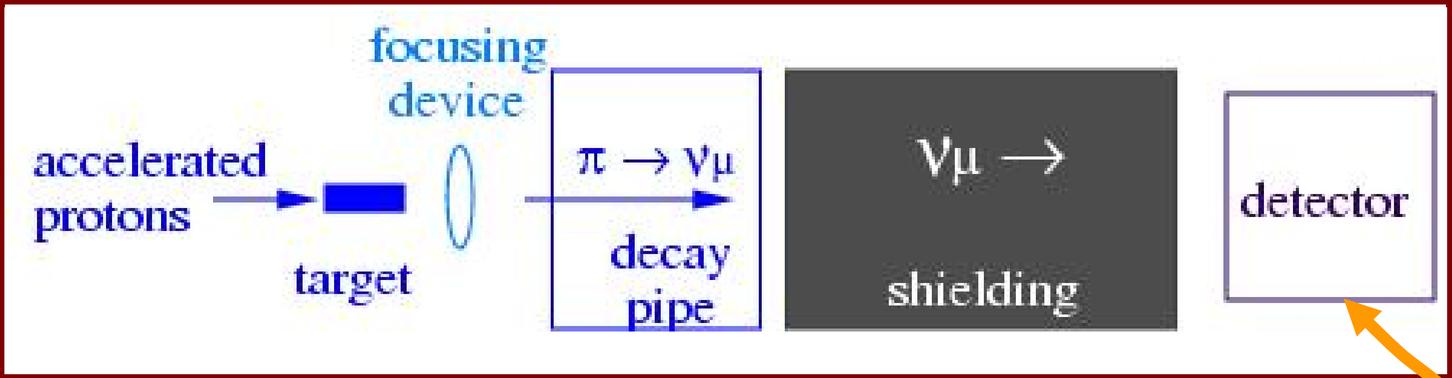


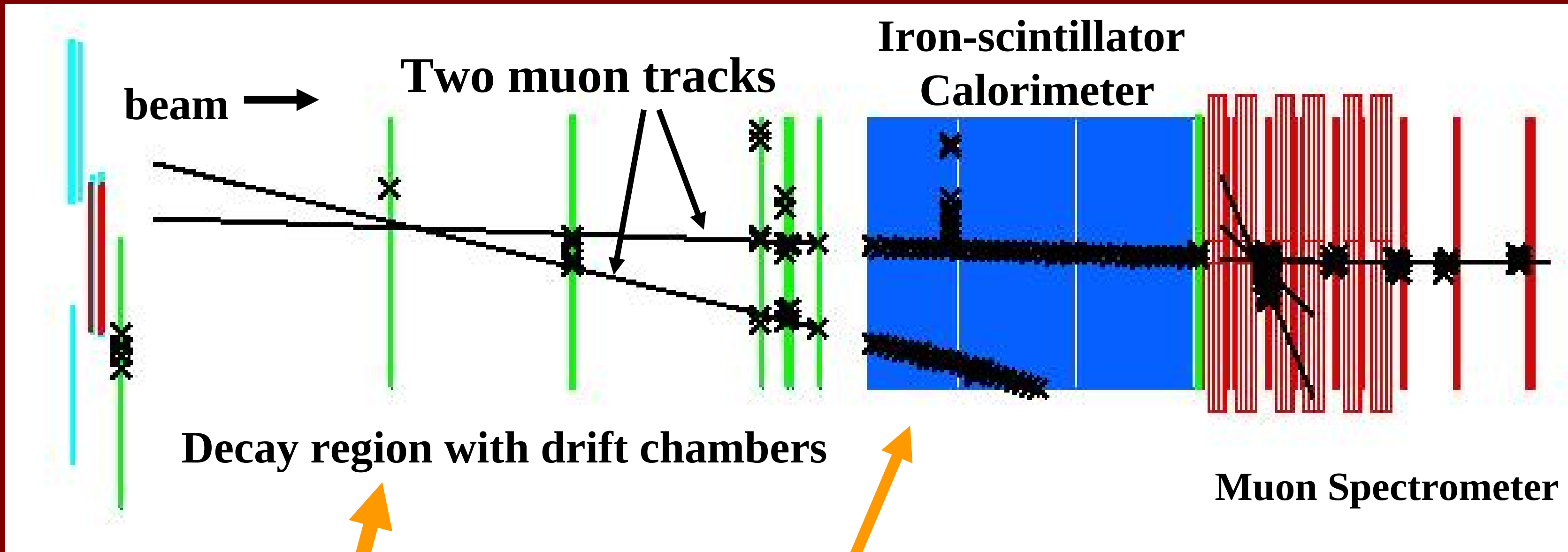
## NuTeV

- $10^{12}$ protons per minute ($10^7$ Watts)
- ~$15 \times 10^9$ neutrinos per minute (in five 2ms pulses)
- 700 ton detector located 1.4 km from neutrino production

# *A Search Experiment…*




- only weakly interacting particles make it to the detector - neutrinos!
- anything else?  (e.g. neutral heavy leptons)
- Goal:
  - look for decay of unstable particles traveling with neutrino beam
  - production is at proton target
  - add another decay region just in front of neutrino detector




# *Search Results…*

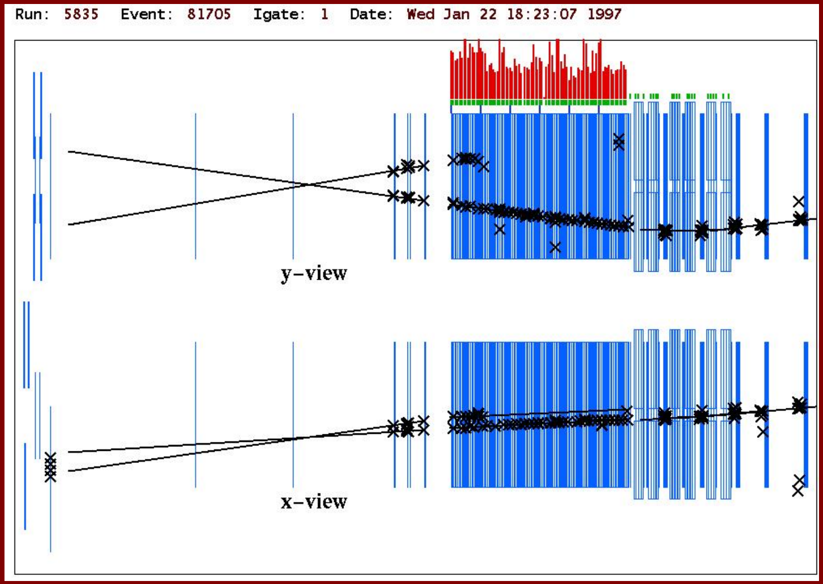
- Neutral Heavy Leptons
  - 0.25<M(NHL)<2.2 GeV
- Karmen anomaly
  - M(ee)=33.9 MeV
- High mass M>2.2 GeV

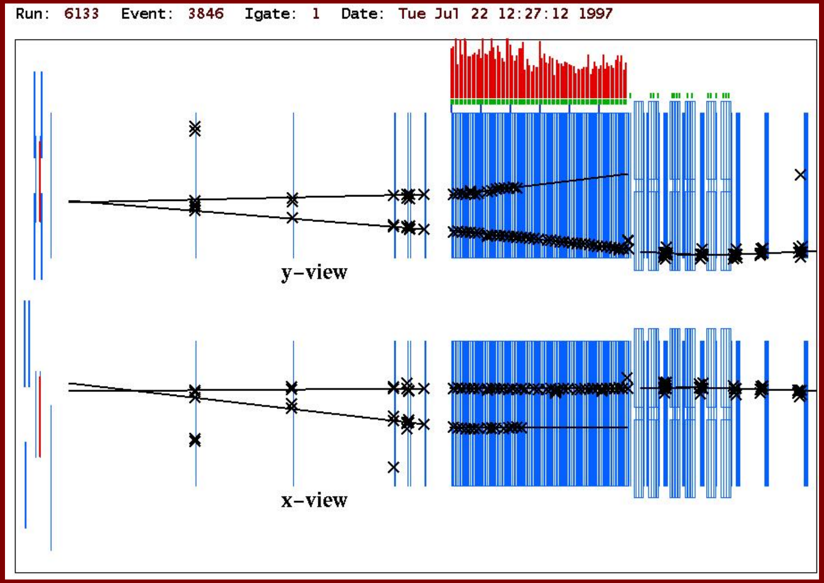
# Third search:

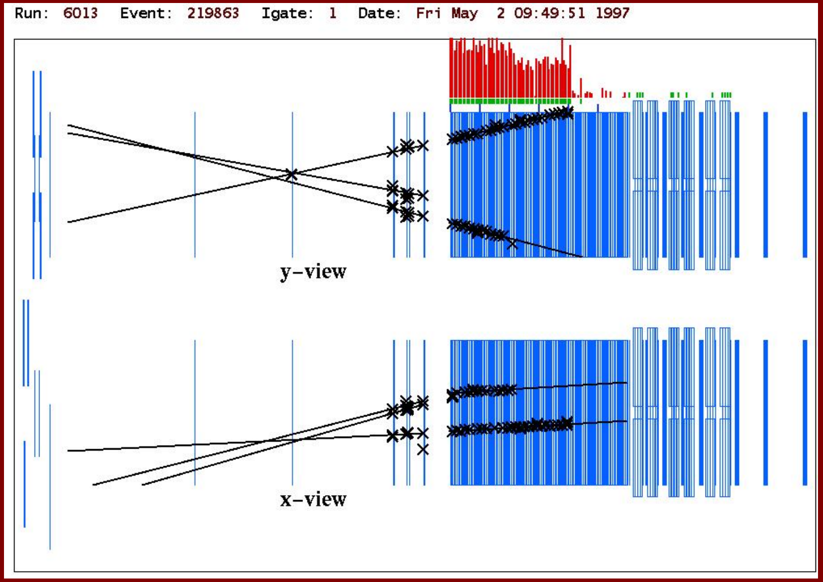
# 3 events found

# Expected background:

# 0.07 ± 0.01 events

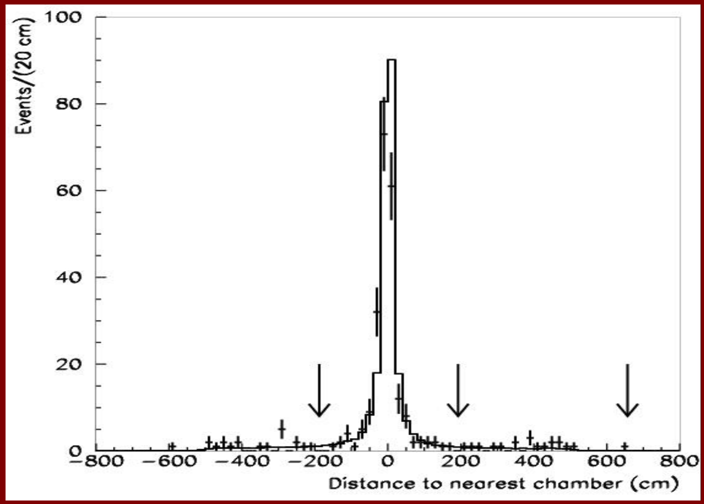


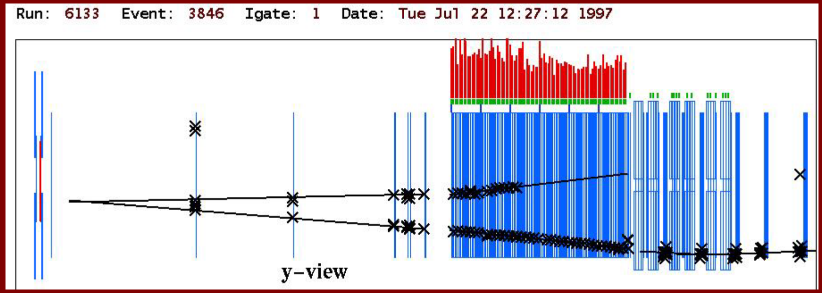



# Interpretation

- Background
  - no known backgrounds are that large
- Signal
  - 3 events >> 0.07 ± 0.01
  - muon energies are asymmetric ($E_1 >> E_2$)





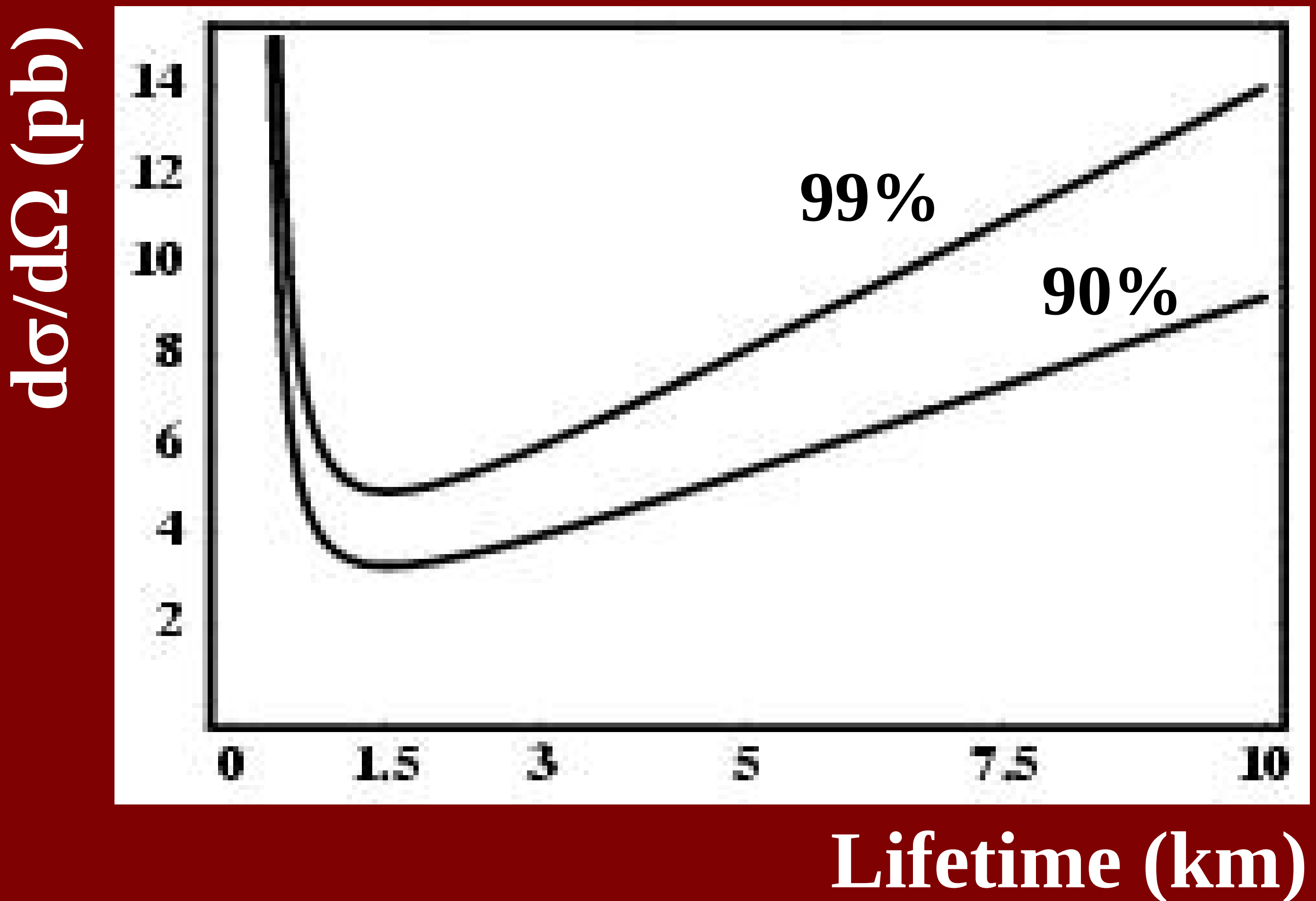
VOLUME 87, NUMBER 4 PHYSICAL REVIEW LETTERS 23 JULY 2001


**Observation of an Anomalous Number of Dimuon Events in a High Energy Neutrino Beam**


T. Adams,[4] A. Alton,[4] S. Avvakumov,[8] L. de Barbaro,[5] P. de Barbaro,[8] R. H. Bernstein,[3] A. Bodek,[8] T. Bolton,[4] J. Brau,[6] D. Buchholz,[5] H. Budd,[8] L. Bugel,[3] J. Conrad,[2] R. B. Drucker,[6] B. T. Fleming,[2] R. Frey,[6] J. A. Formaggio,[2] J. Goldman,[4] M. Goncharov,[4] D. A. Harris,[8] R. A. Johnson,[1] J. H. Kim,[2] S. Koutsoliotas,[2] M. J. Lamm,[3] W. Marsh,[3] D. Mason,[6] J. McDonald,[7] C. McNulty,[2] K. S. McFarland,[3] D. Naples,[7] P. Nienaber,[3] A. Romosan,[2] W. K. Sakumoto,[8] H. Schellman,[5] M. H. Shaevitz,[2] P. Spentzouris,[2] E. G. Stern,[2] N. Suwonjandee,[1] M. Tzanov,[7] M. Vakili,[1] A. Vaitaitis,[2] U. K. Yang,[8] J. Yu,[3] G. P. Zeller,[5] and E. D. Zimmerman[2]

[1]*University of Cincinnati, Cincinnati, Ohio 45221*

# *The conservative approach: set a limit*



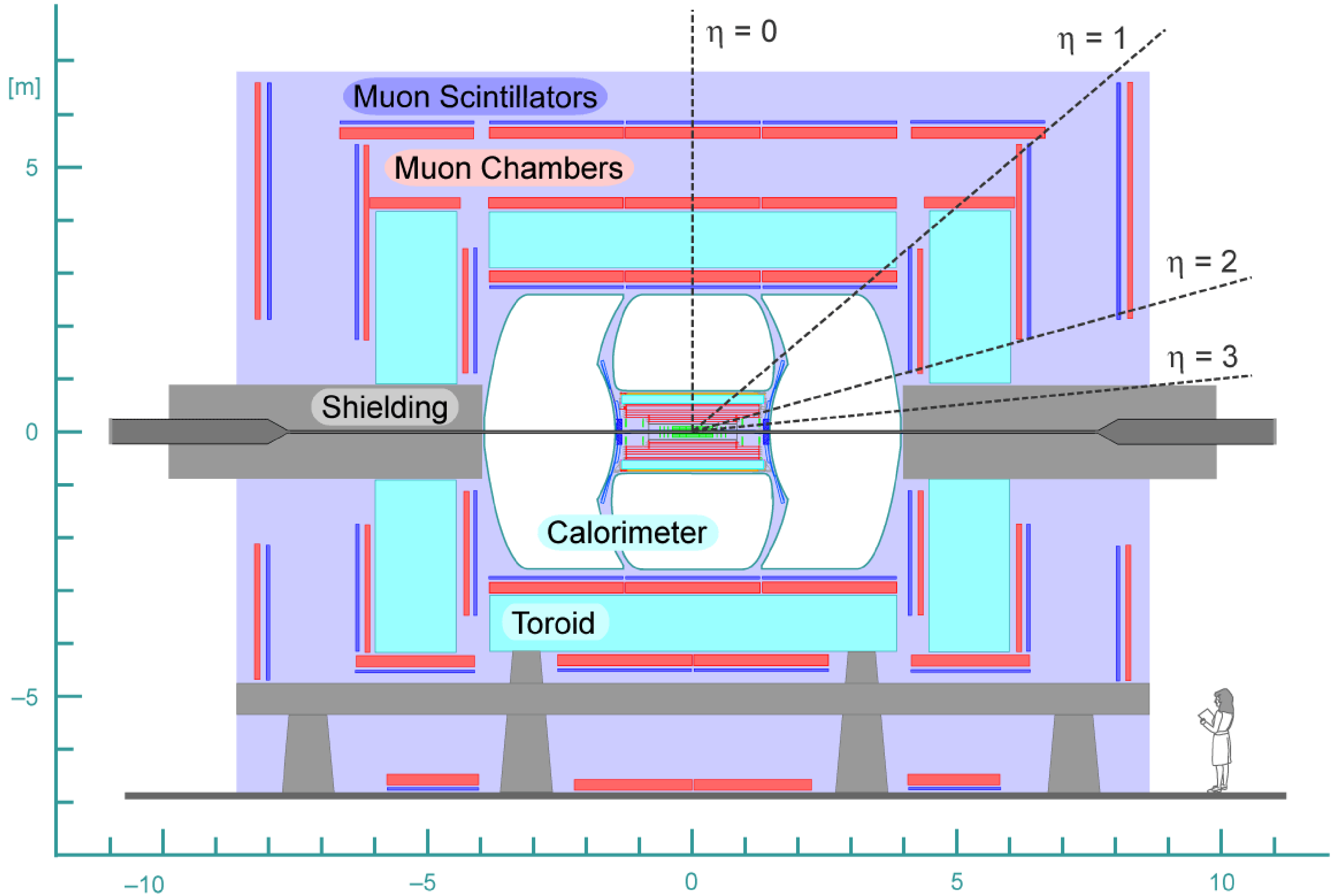
- **Why search?**
- **How?**
- **What did we find?**
- **What does it mean?**

# *What is DØ?*

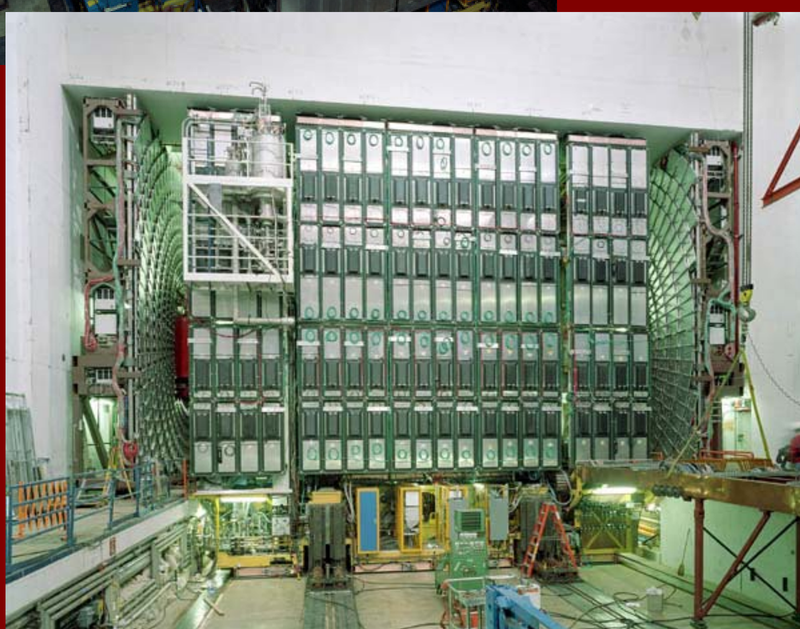
## Fermilab Tevatron

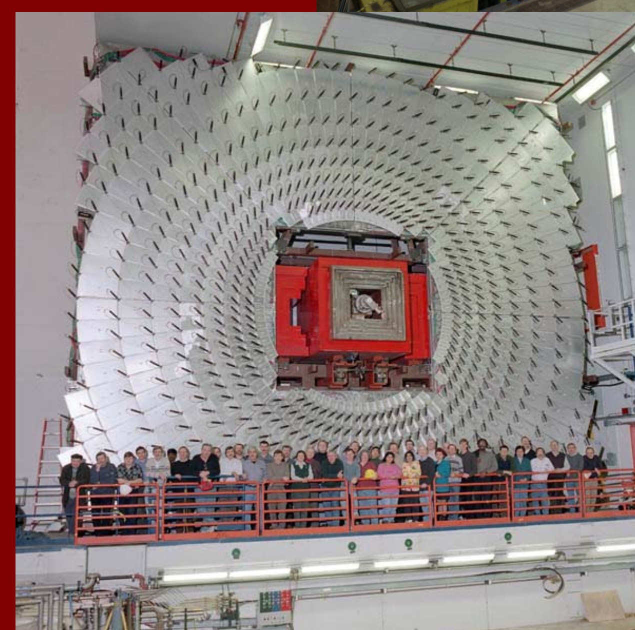
**proton-anti-proton collider**


**DØ is one of two collider experiments**

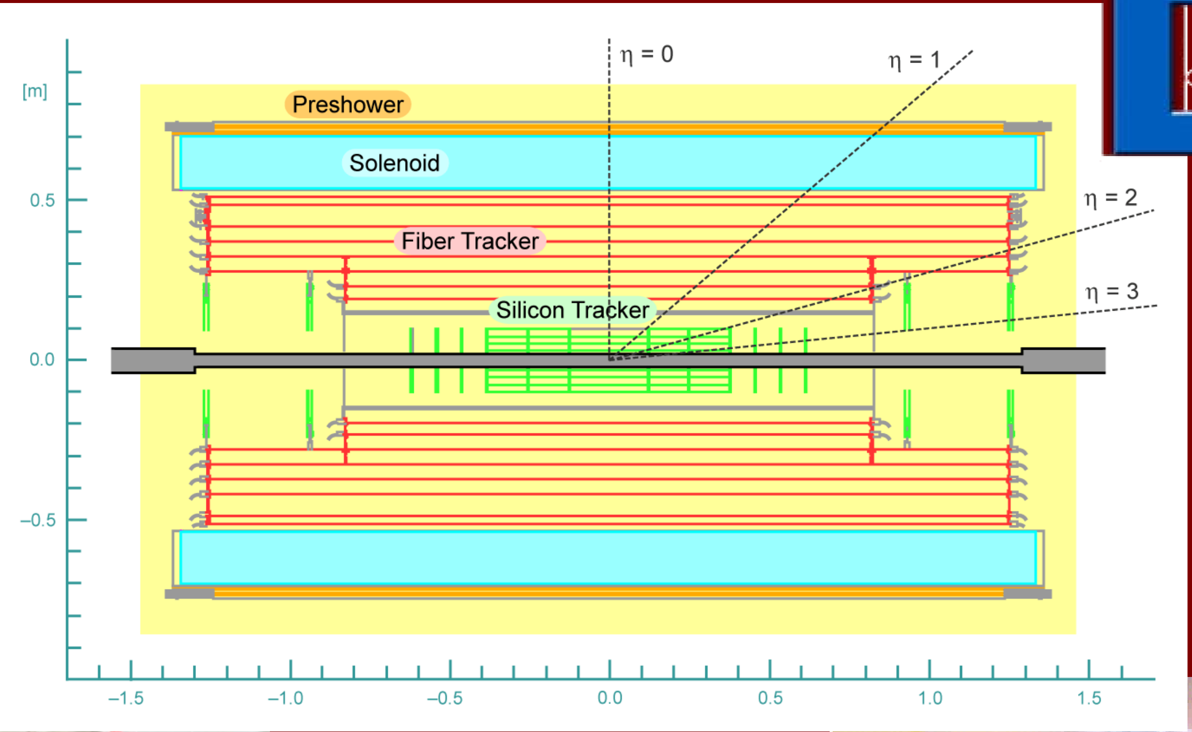

η = 0
η = 1
η = 2
η = 3
[m]
Muon Scintillators
Muon Chambers
Shielding
Calorimeter
Toroid
5
0
–5
–10
–5
0
5
10

# DØ Detector

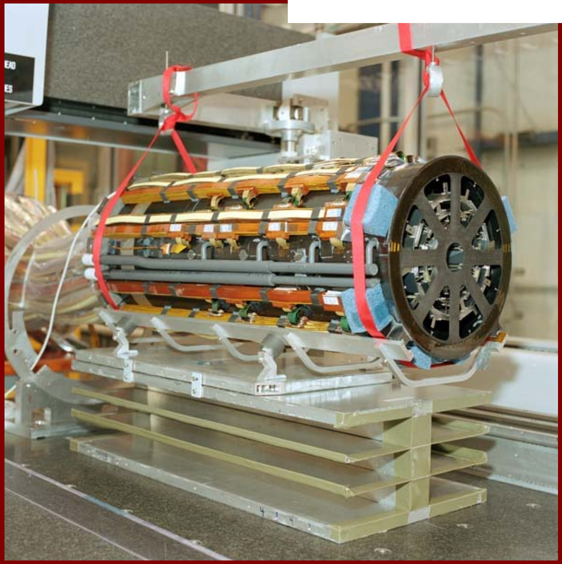




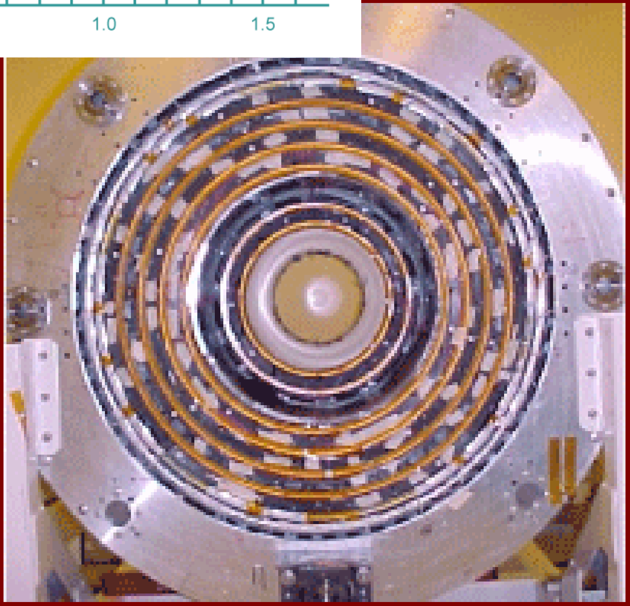
2 Tesla solenoid

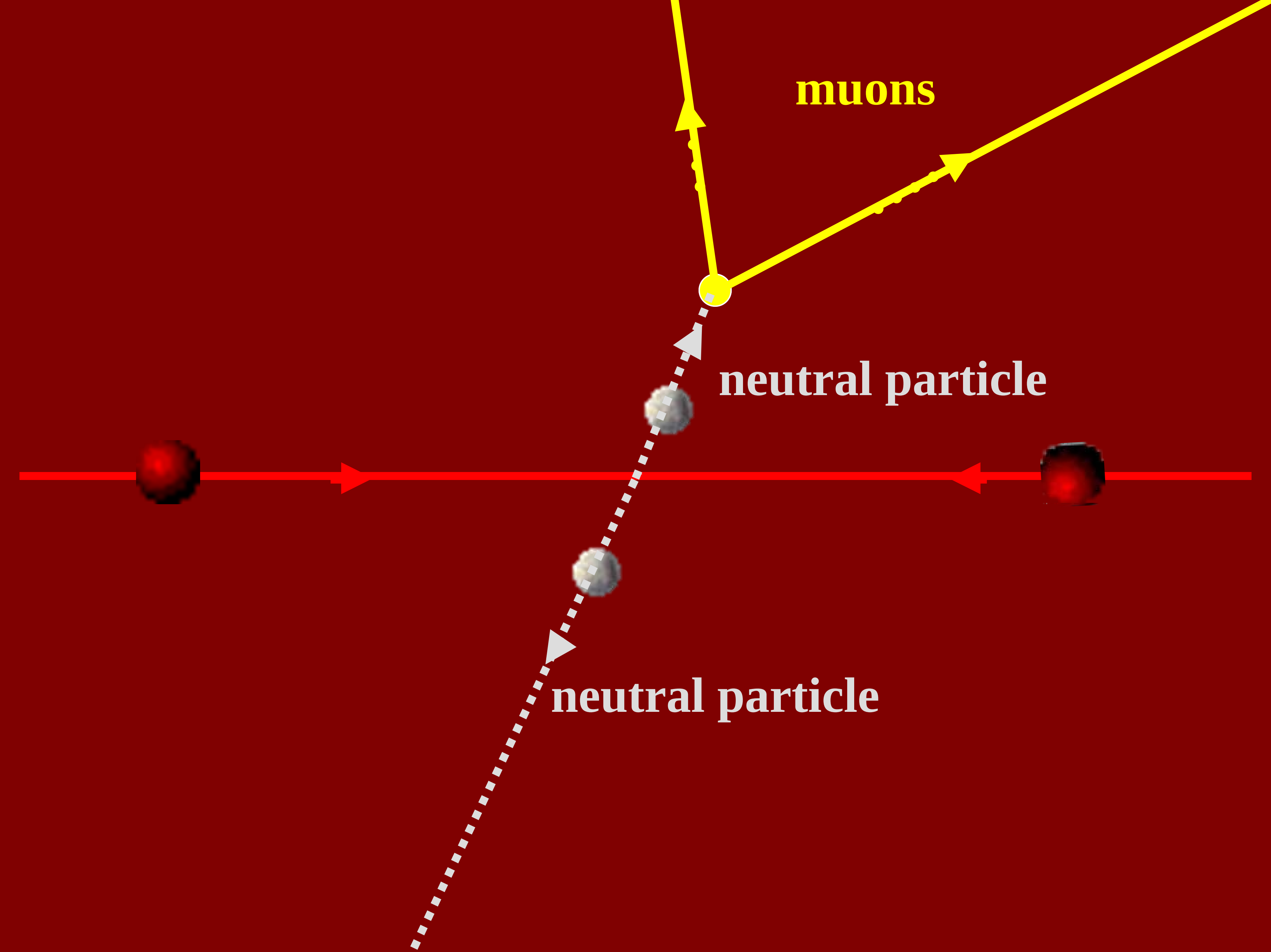



silicon detector



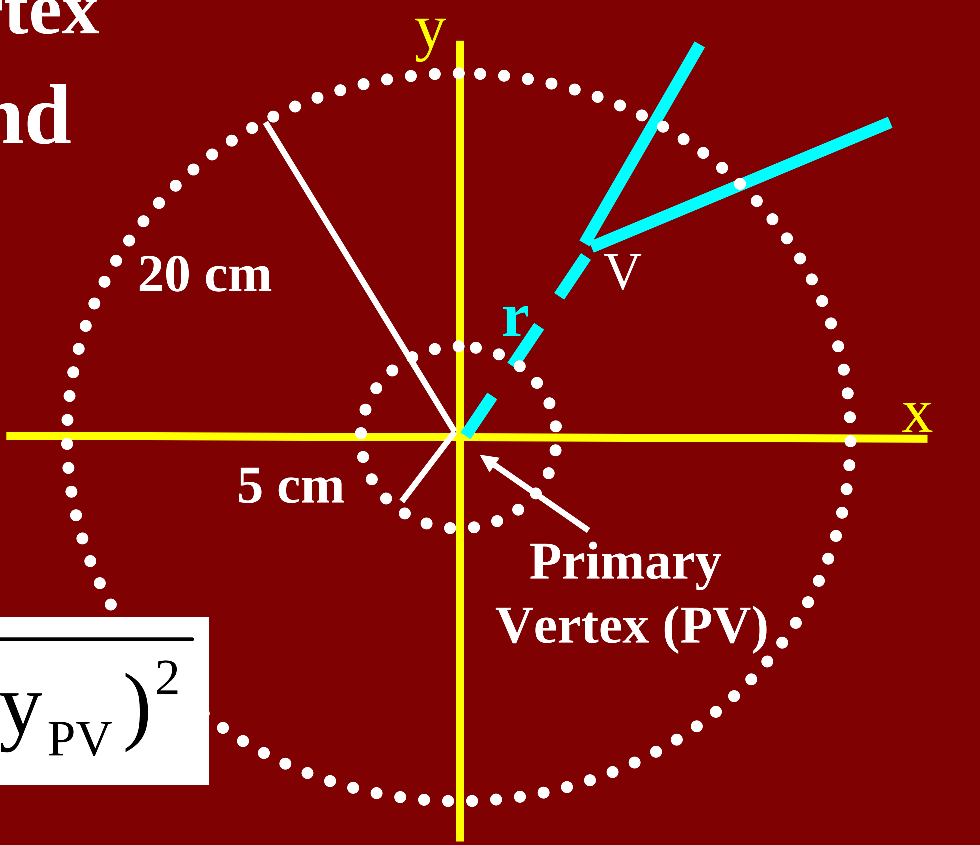
scintillating fiber tracker (CFT)




muons
neutral particle
neutral particle

# *Technique:*

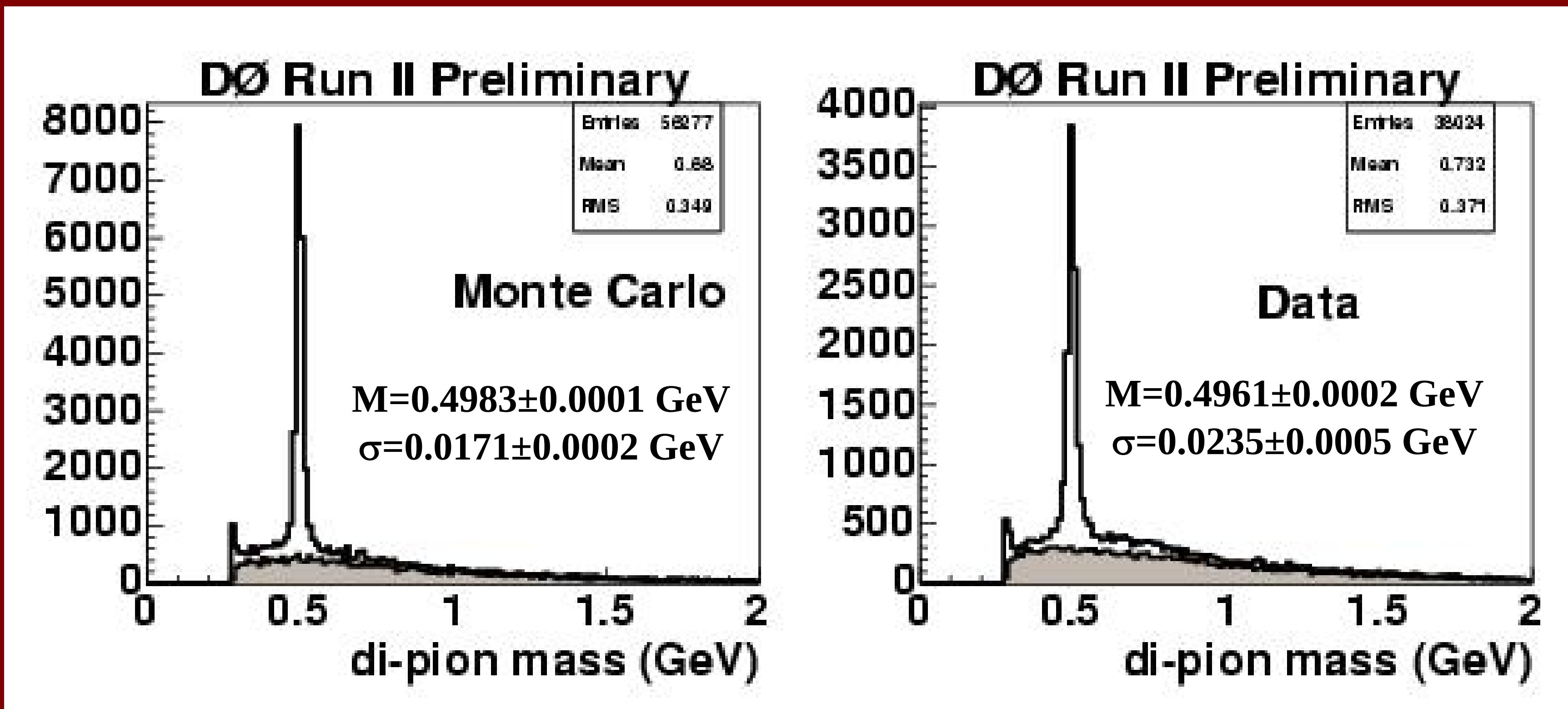
1. **identify events with two muons**
   - **fit to a common vertex**
2. **measure background**
3. **interpret results**




$$r = \sqrt{(x - x_{PV})^2 + (y - y_{PV})^2}$$

# $K_S^0 \rightarrow \pi^+\pi^-$

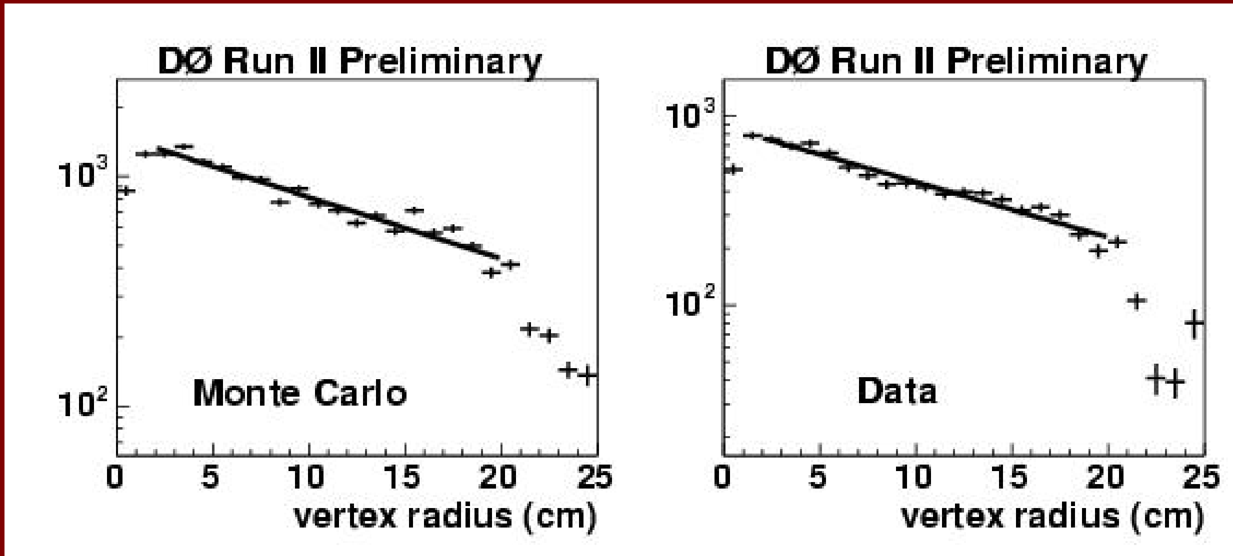
**fit pairs of tracks to common vertex**
**require r>0.5 cm**




**long lifetime = $9.0 \times 10^{-11}$ s**

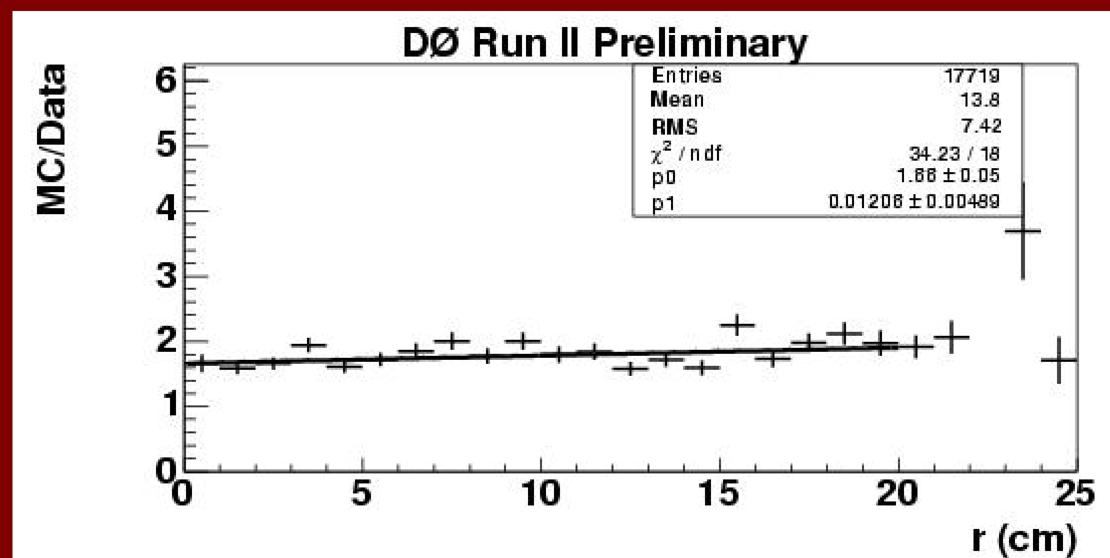
**natural source of neutral, long-lived particles**

# $K_S^0 \rightarrow \pi^+\pi^-$




expected lifetime

MC/Data is flat

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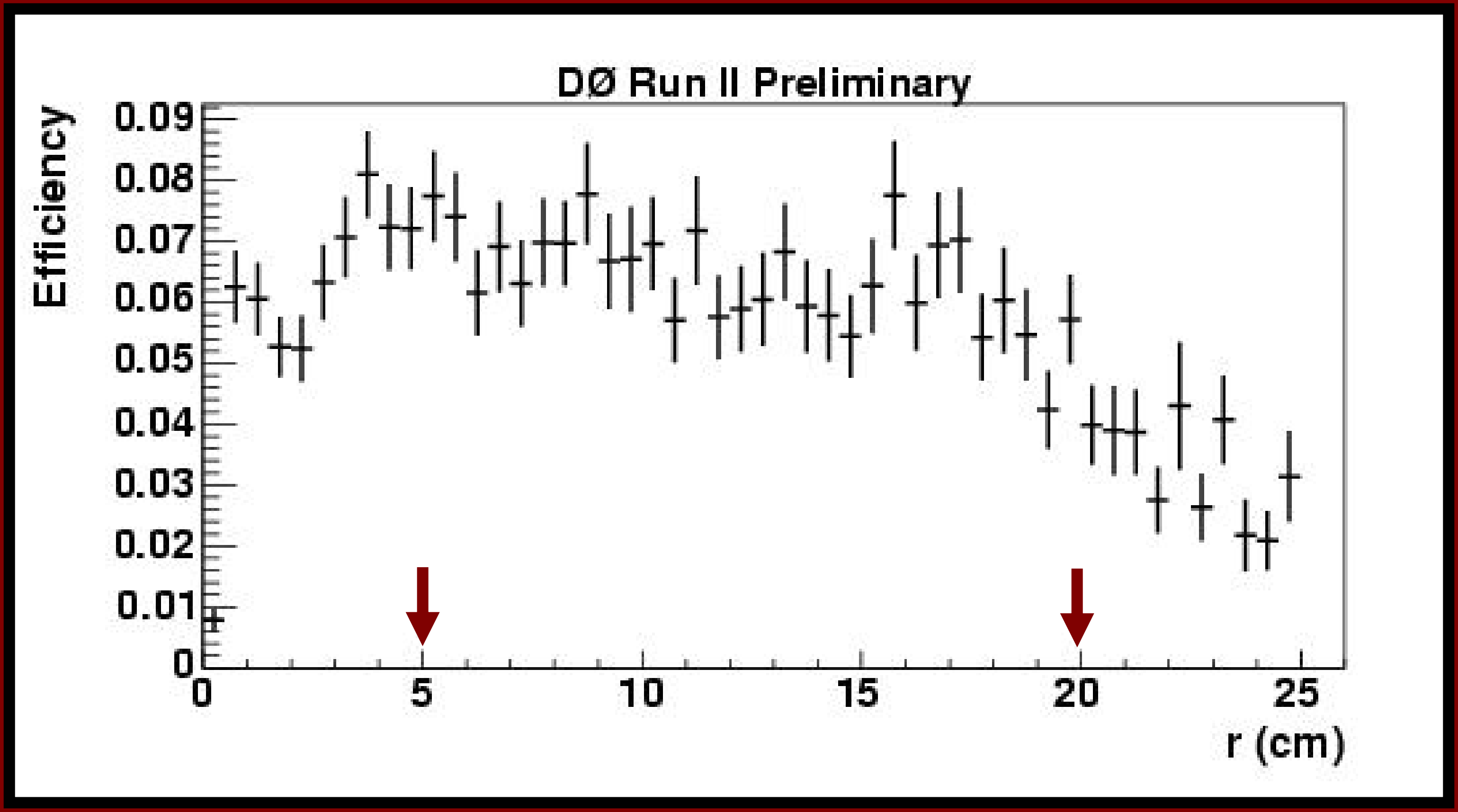
# $K_S^0 \rightarrow \pi^+\pi^-$




efficiency is flat as a function of radius

# *A Possible Signal*

$M_1$ = 3,5,8,10

tanβ = 10 μ = -5000

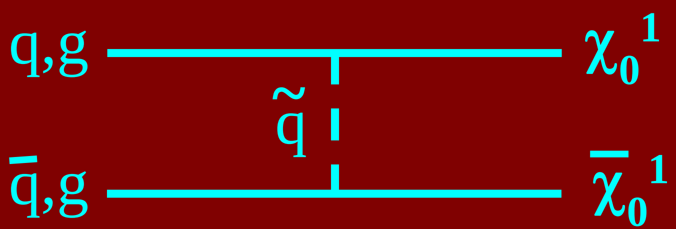
$M_2$ = 200 $m_A$ = 500

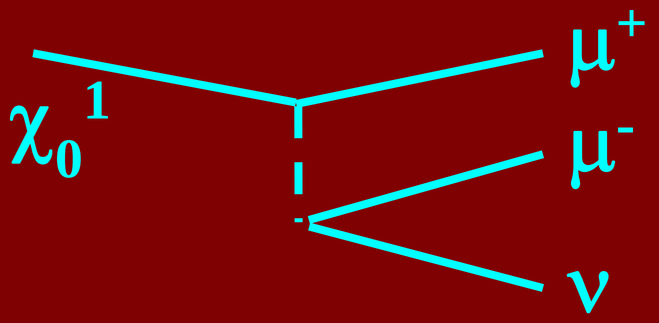
$M_3$ = 400 M(squark) = 300

$\lambda_{122} < 0.01$ M(other) = 1500

**R-parity violating unconstrained minimial supersymmetric model (MSSM)**

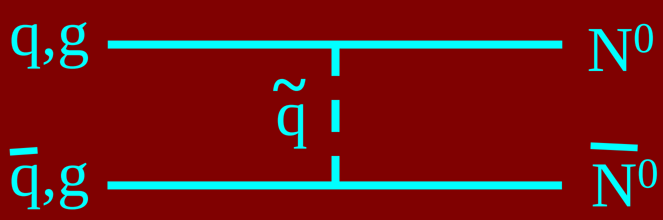
- neutralino ($\chi_0^1$): lightest supersymmetric particle (LSP)
- lifetime depends of a parameter ($\lambda_{122}$)
- small $\lambda_{122}$ = long lifetime

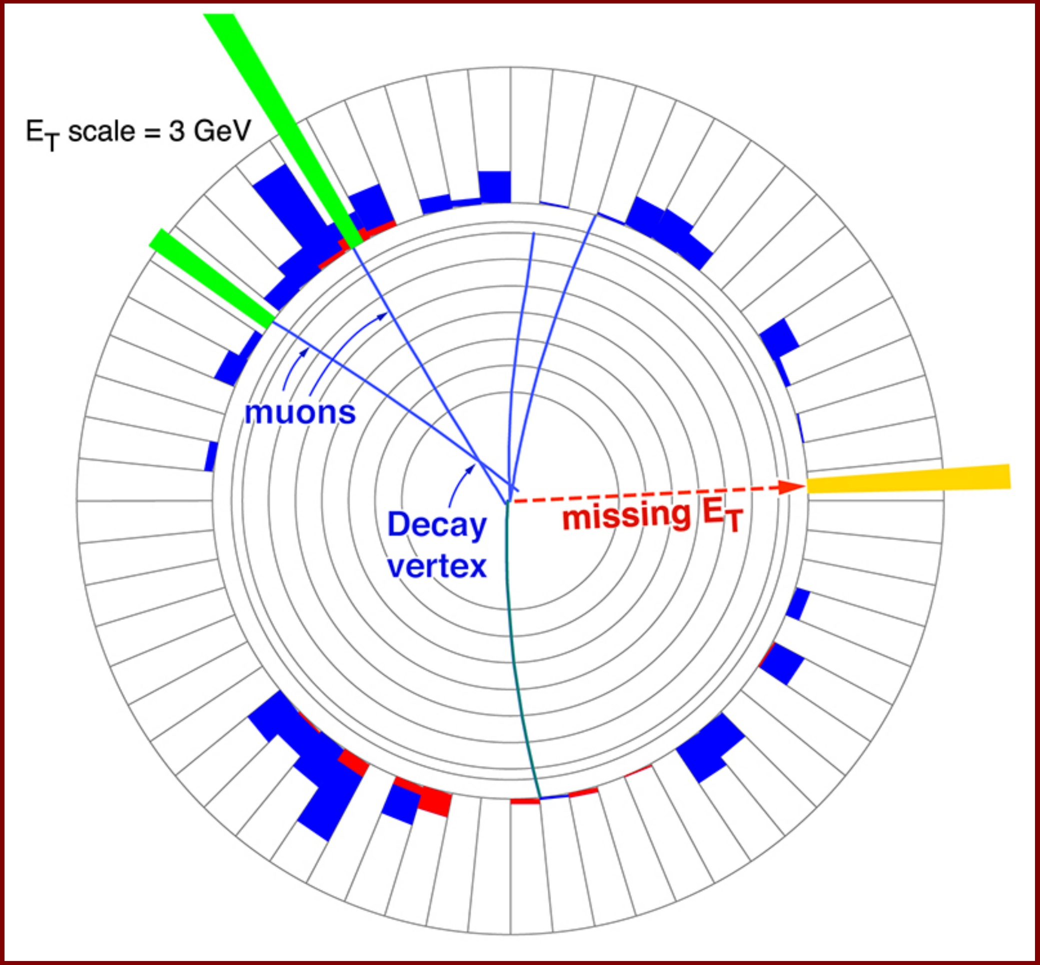



$\chi_0^1 \rightarrow \mu\mu\nu,\ \mu e\nu,\ ee\nu$

# *A Sample Event*
# (simulation)



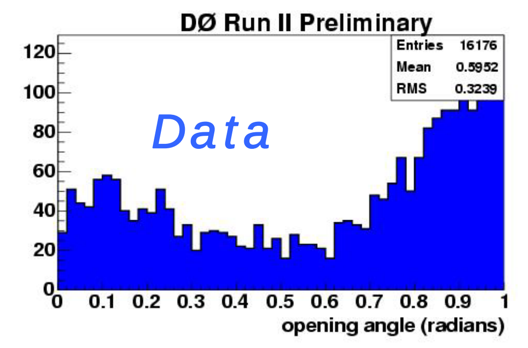
# Event Selection

## Muons

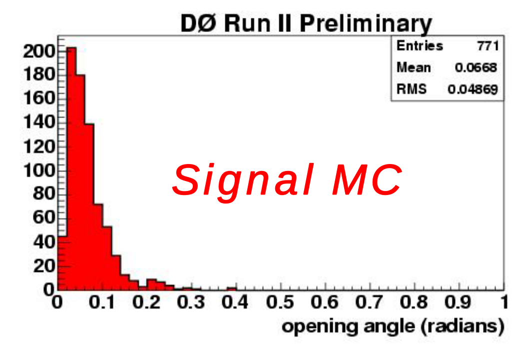
- hits in all 3 layers of muon system
- cosmic ray timing cut
- central track
  - $\chi^2<4$, >13 CFT hits
- isolation
  - Calorimeter
    - $\Sigma E_{cal}(0.1<\Delta R<0.5)$ < 2.5 GeV
  - Tracking system
    - $\Sigma E_{trk}(\Delta R<0.5)$ < 2.5 GeV
- $p_T$>10 GeV

## Events

- dimuon trigger
- >1 muon
  - opposite signed
  - opening angle < 0.5 rad
- primary vertex
  - $|v_{x,y}|$<0.3 cm
  - $|v_z|$<60cm



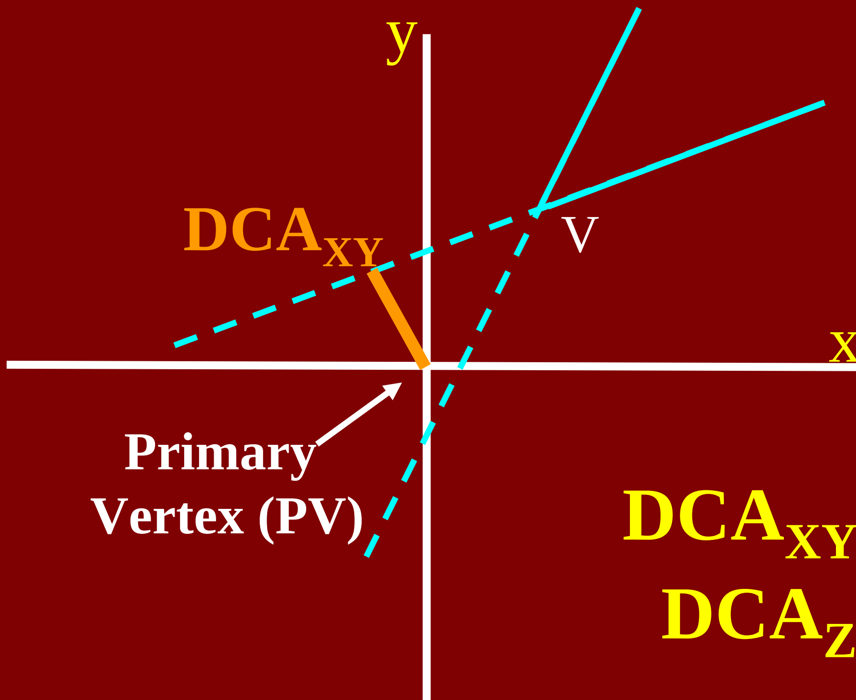

opening angle

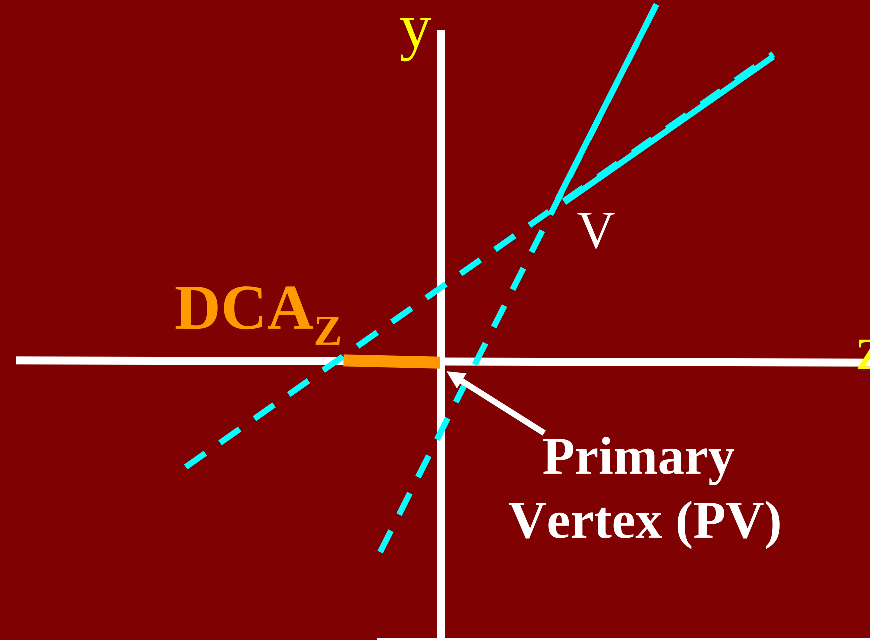



**Luminosity**

**383 ± 25 $pb^{-1}$**

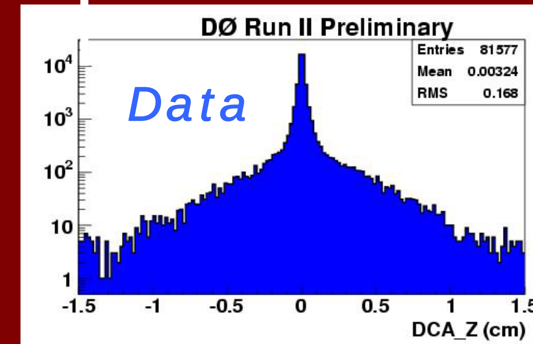
# *Distance of Closest Approach*

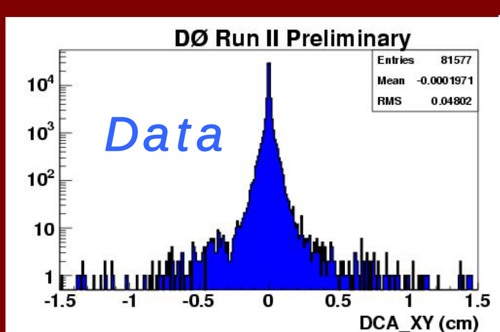


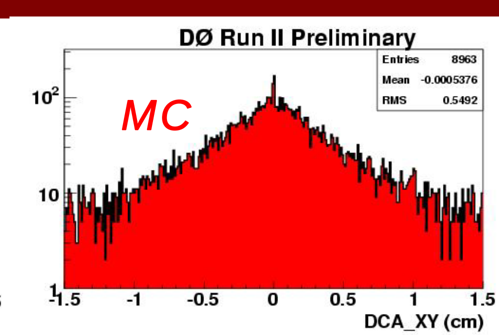



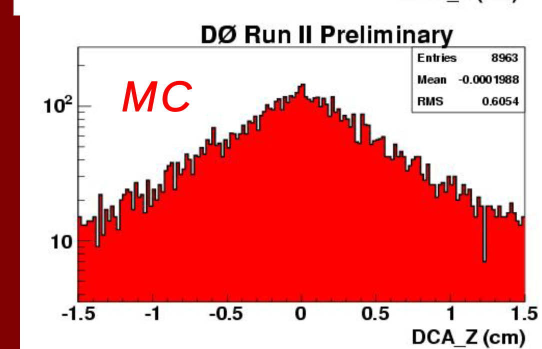

**DCA$_{XY}$ > 0.01 cm**

**DCA$_Z$ > 0.1 cm**



# Event Selection

## Muons

- segments in all 3 muon layers
- cosmic ray timing cut
- central track
  - $\chi^2<4$, >13 CFT hits
- isolation
  - $\Sigma E_{cal}(0.1<\Delta R<0.5) < 2.5$ GeV
  - $\Sigma E_{trk}(\Delta R<0.5) < 2.5$ GeV
- $p_T>10$ GeV
- $DCA_{XY}>0.01$ cm
  $DCA_Z>0.1$ cm

## Events

- dimuon trigger
- >1 muon
  - opposite signed
  - opening angle < 0.5 rad
- primary vertex
  - $|v_{x,y}|<0.3$ cm
  - $|v_z|<60$cm
- dimuon vertex
  - $\chi^2 < 4$
  - $r > 6\sigma_r$
  - $5 < r < 20$ cm

- **Why search?**
- **How?**
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# *How to estimate the background:*

| | | ***Criterion #1*** Fail | Pass |
|---|---|---|---|
| ***Criterion #2*** | Fail | **Sample 1A** | **Sample 1B** |
| | Pass | **Sample 2A** | **Sample 2B** |

$$\frac{\text{Sample 2A}}{\text{Sample 1A}} = \frac{\text{Sample 2B}}{\text{Sample 1B}}$$

final signal sample

## *Vertex Radius*

| *DCA Criterion* | **0.3 < r < 5 cm** | **5 < r < 20 cm** |
|---|---|---|
| **1 muon passes 1 muon fails** | **Sample 1A** *4 events* | **Sample 1B** *1 event* |
| **Both muons pass** | **Sample 2A** *3 events* | **Sample 2B** *???* |

final signal sample

## *Estimated Background:*

$$\text{Sample 2B} = \frac{\text{Sample 2A}}{\text{Sample 1A}} \times \text{Sample 1B} = \frac{3}{4} \times 1 = 0.75 \text{ events}$$

# *How good is this estimate?*

## use complementary samples

- **Loose**
  - **loosen several criteria**
- **1 muon + 1 non-lepton track with isolation**
- **1 muon + 1 non-lepton track without isolation**
- **2 tracks**
  - **0.6<M<0.9 GeV (exclude $K_s$)**
- **MC simulation b+b**
  - **use generated 4-vectors**

*Vertex Radius*

| *DCA Criteria* | | |
|---|---|---|
| | **Sample 1A** | **Sample 1B** |
| | **Sample 2A** | **Sample 2B** |

$$\text{Estimate 2B} = \frac{\text{Sample 2A}}{\text{Sample 1A}} \times \text{Sample 1B}$$

compare estimate with measured value

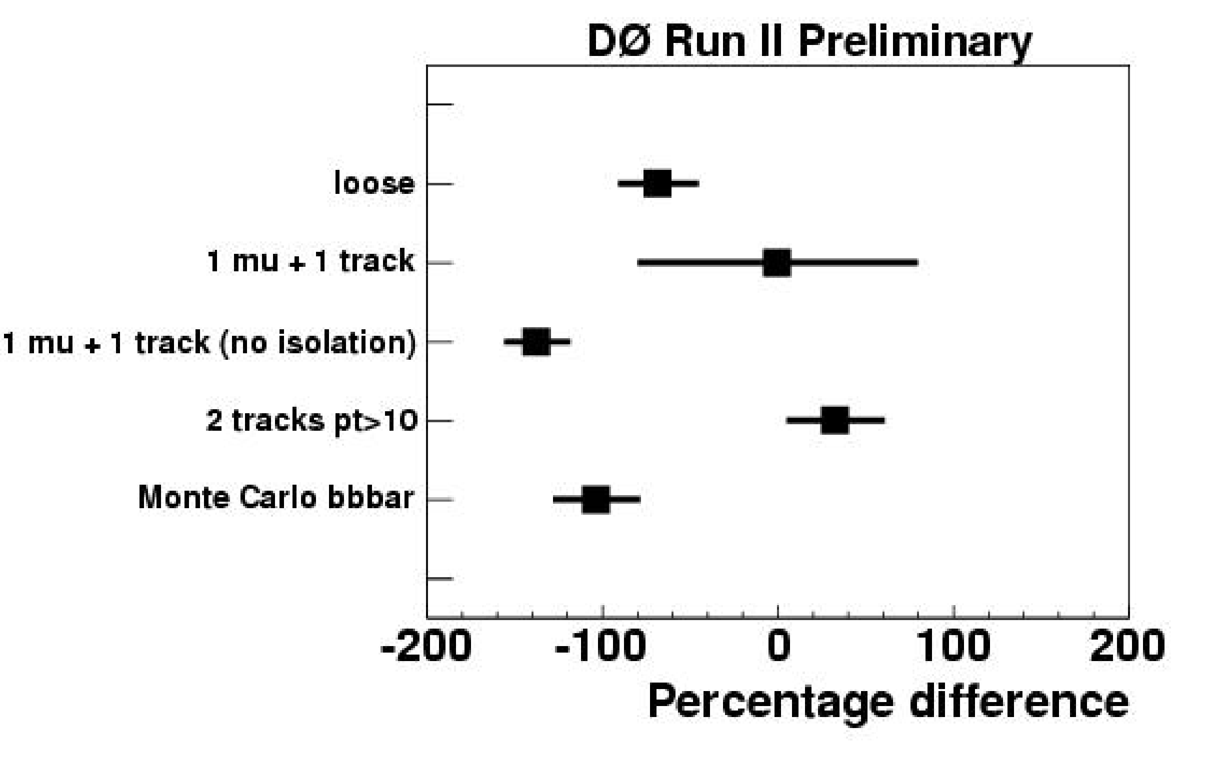
# *How good is this estimate?*

## use complementary samples

evaluate

$$\frac{\text{estimate - observed}}{\text{estimate}}$$

(percentage difference)




assign systematic error of 150%

**background estimate = 0.75 ± 1.1 (stat) ± 1.1 (sys)**

*Found:*

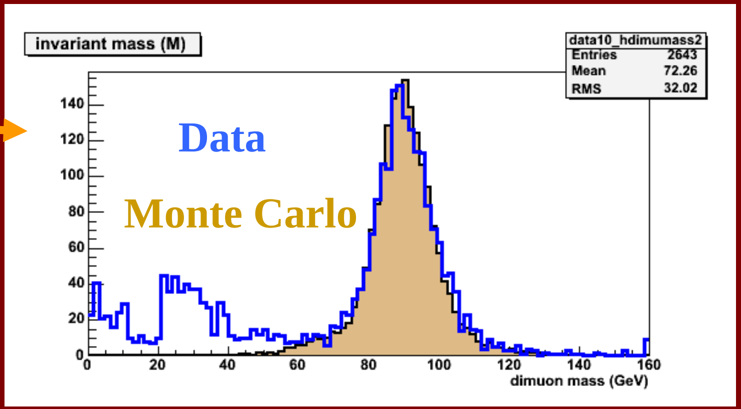
# 0

**events**

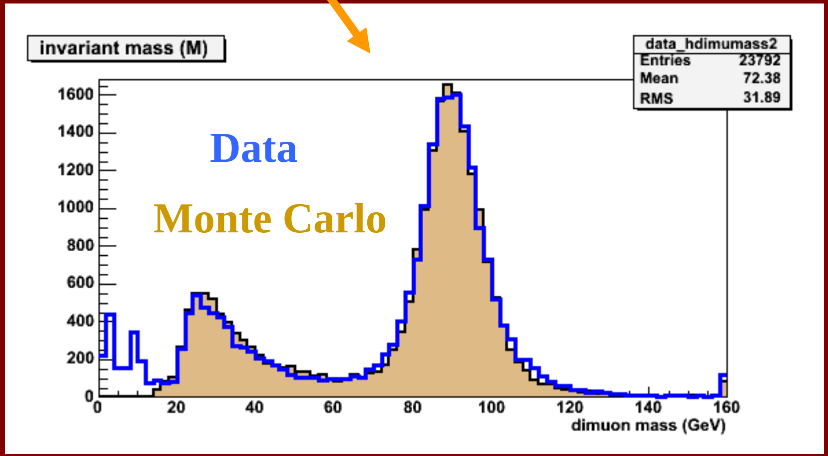
# Data/MC Corrections

- Use Z peak to measure data/MC corrections
  - use a fraction of the dataset

| | |
|---|---|
| Track $\chi^2 < 4$ | $0.94 \pm 0.03$ |
| Ncft > 13 | $0.91 \pm 0.04$ |
| Primary vertex | $0.99 \pm 0.04$ |
| Cal iso < 2.5 GeV | $0.99 \pm 0.04$ |
| Track pT iso < 2.5 GeV | $0.88 \pm 0.04$ |




Test with full dataset



# Acceptance and Error Analysis

| | | |
|---|---|---|
| **luminosity** | **383 ± 25 $pb^{-1}$** | |
| **acceptance** | **0.129 ± 0.005** | (stat) |
| **trigger effic.** (approx) | **0.88 ± 0.05** | |
| **cal quality** | **0.97 ± 0.03** | |
| **track $\chi^2 < 4$** | **0.94 ± 0.03** | |
| **Ncft > 13** | **0.91 ± 0.04** | (Z/DY study) |
| **cal iso < 2.5 GeV** | **0.99 ± 0.04** | |
| **primary vertex** | **0.99 ± 0.04** | |
| **track pT iso < 2.5 GeV** | **0.88 ± 0.04** | |
| **data/MC vertex eff.** | **0.92 ± 0.14** | ($K_s$ analysis) |
| **lumi * acceptance** | **28.7 ± 5.6** | |

- **Why search?**
- **How?**
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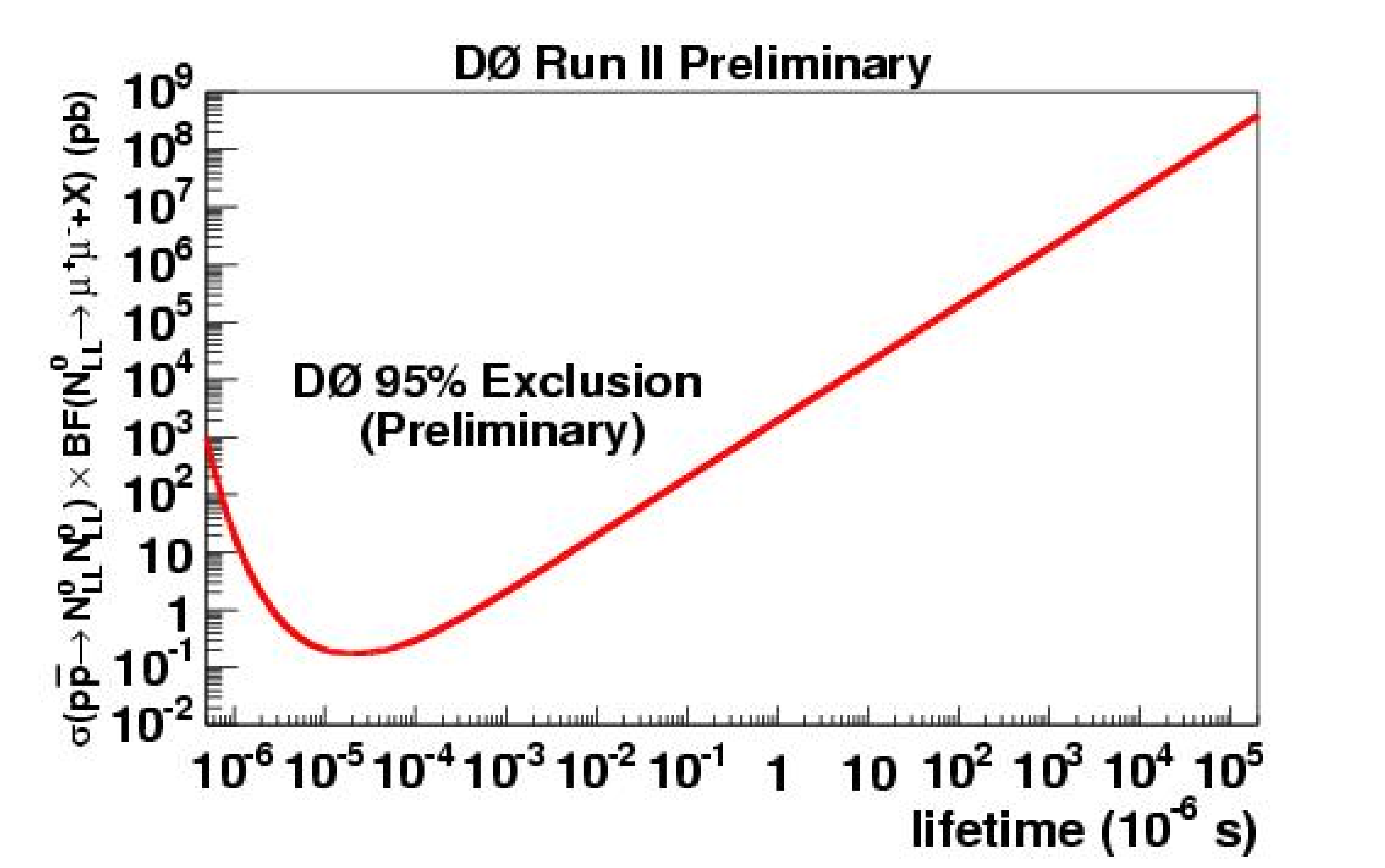
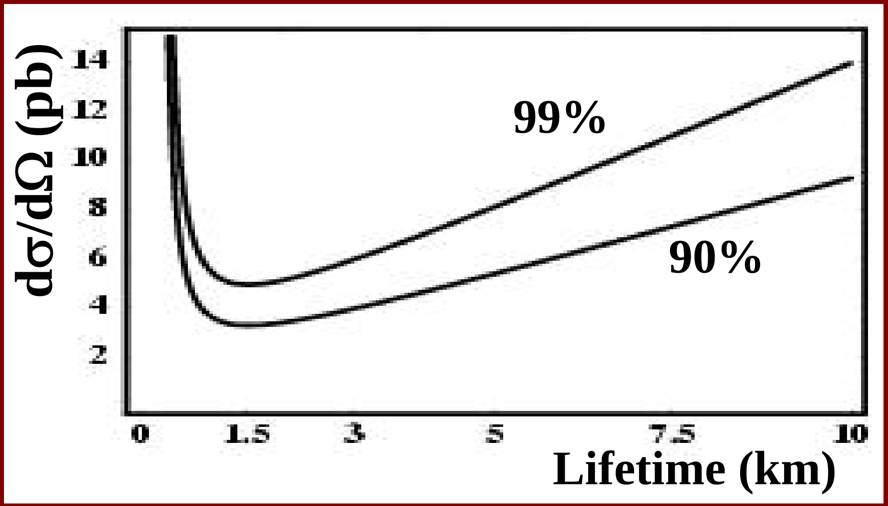
- **What does it mean?**

$N_{DATA}=0 \qquad N_{BKGD}=0.75\pm1.1\pm1.1$

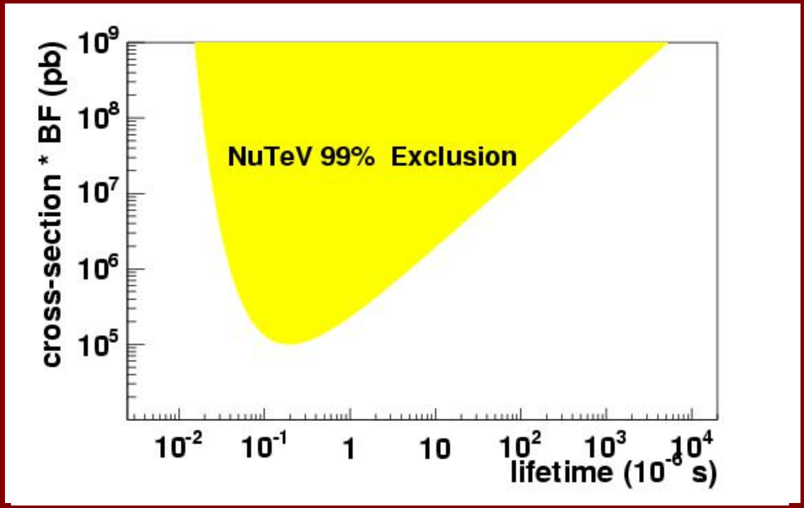


# Conversion of NuTeV

pp at $\sqrt{s}$ = 38 GeV

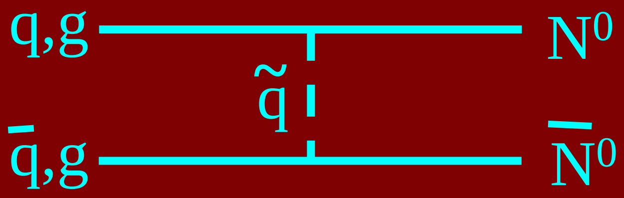


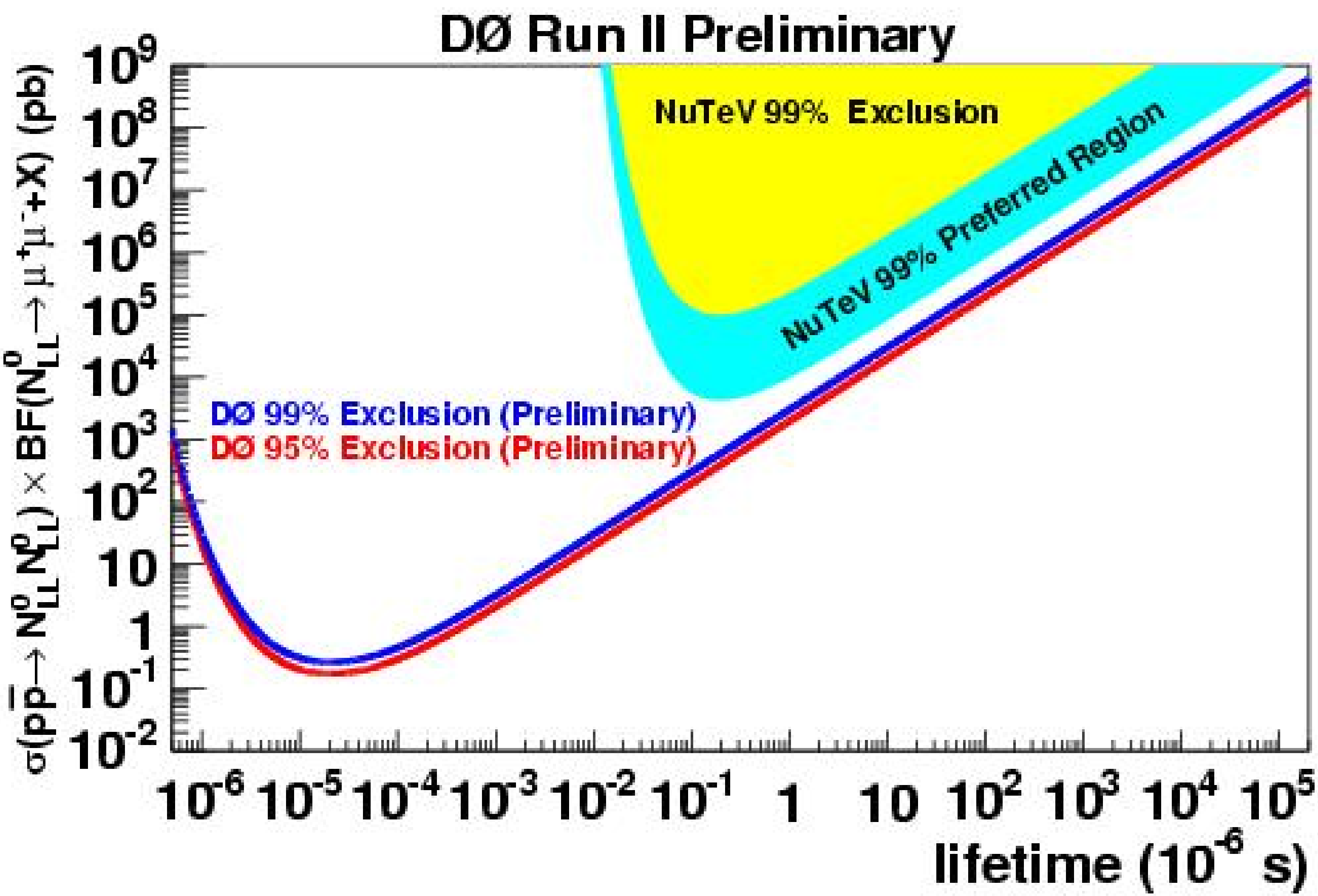

$p\bar{p}$ at $\sqrt{s}$ = 1960 GeV




convert NuTeV → DØ

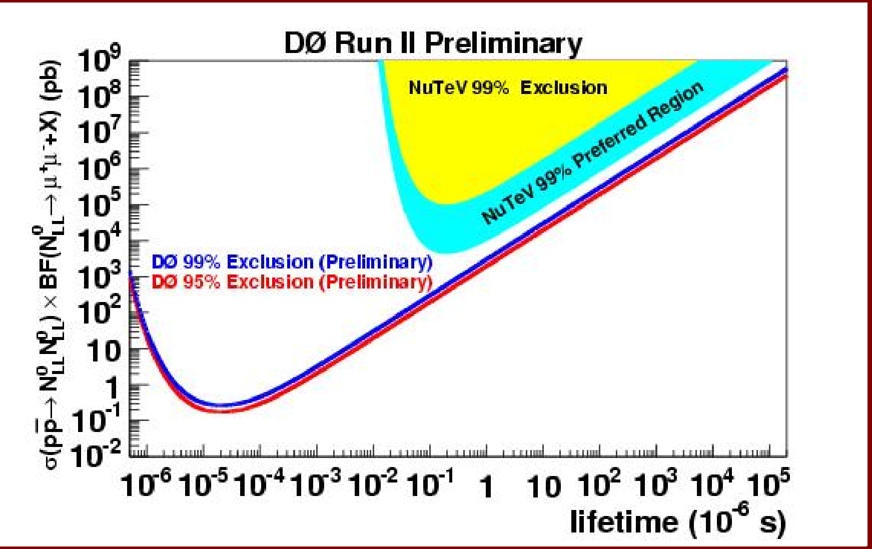
- lifetime: assume average p = 121 GeV (Lorentz boost)
- differential cross-section: multiply by $4\pi$
- cross-section: use signal MC




DØ Run II Preliminary
NuTeV 99% Exclusion
NuTeV 99% Preferred Region
DØ 99% Exclusion (Preliminary)
DØ 95% Exclusion (Preliminary)
$\sigma(p\bar{p}\rightarrow N^0_{LL}N^0_{LL}) \times BF(N^0_{LL}\rightarrow \mu^+\mu^- + X)$ (pb)
lifetime ($10^{-6}$ s)
$10^9$
$10^8$
$10^7$
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
10
1
$10^{-1}$
$10^{-2}$
$10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ 1 10 $10^2$ $10^3$ $10^4$ $10^5$

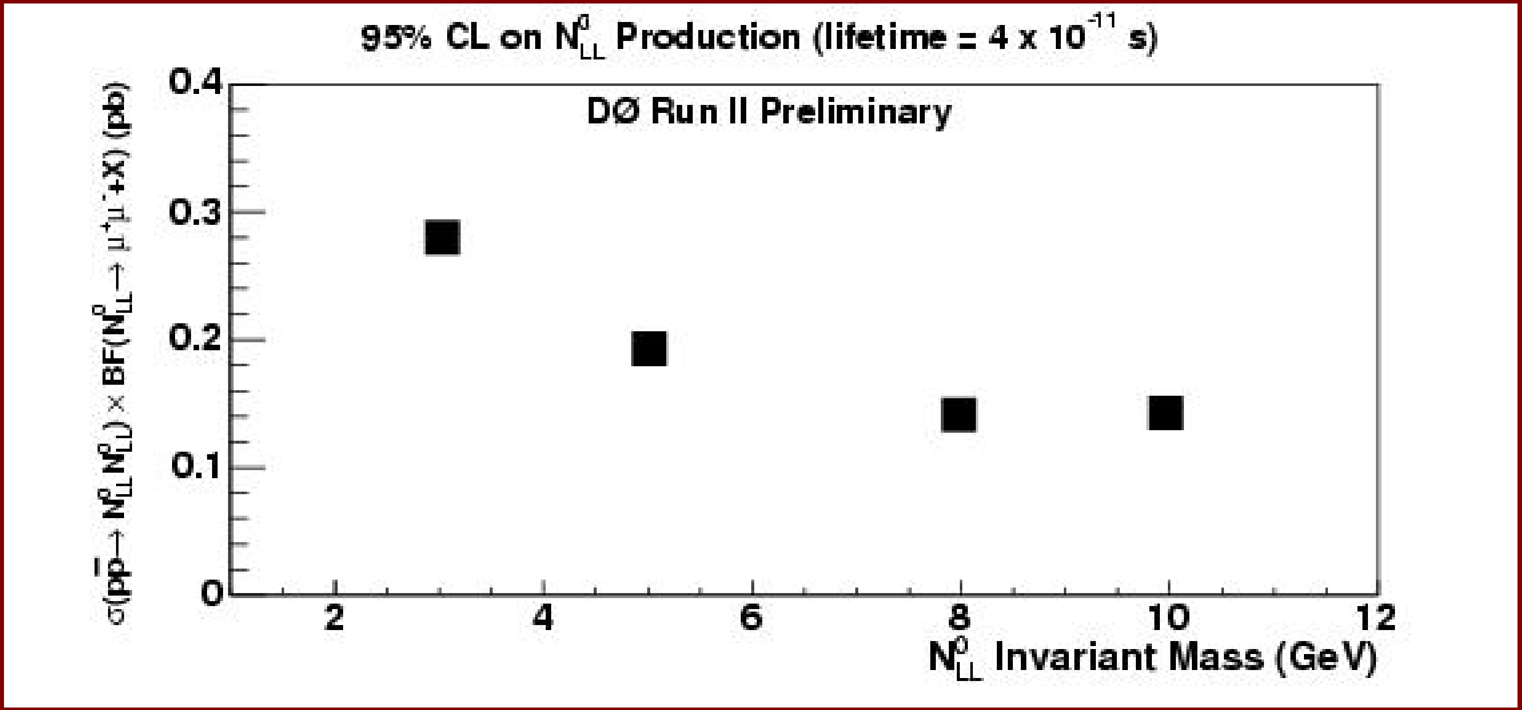
# Summary

- We've used Run II data from DØ to search for neutral, long-lived particles
  - new technique
  - new search direction for collider physics



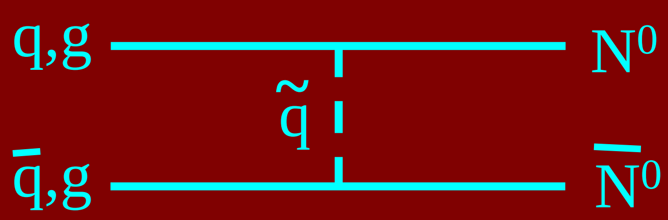

- No events observed
  - background estimate $0.75 \pm 1.1 \pm 1.1$ events

**Put limits on interpretation of NuTeV excess of dimuon events**




limit as a function of particle mass

# Signal Monte Carlo




$M_1$ = 3,5,8,10

tanβ = 10 — $\mu$ = -5000

$M_2$ = 200 — $m_A$ = 500

$M_3$ = 400 — M(squark) = 300

$\lambda_{122}$ = 0.01 — M(other) = 1500

## RPV unconstrained MSSM

- LSP: neutralino (3-10 GeV)
- small $\lambda_{122}$ = long lifetime (m or km)
  - decay in region: radius = 0-25 cm

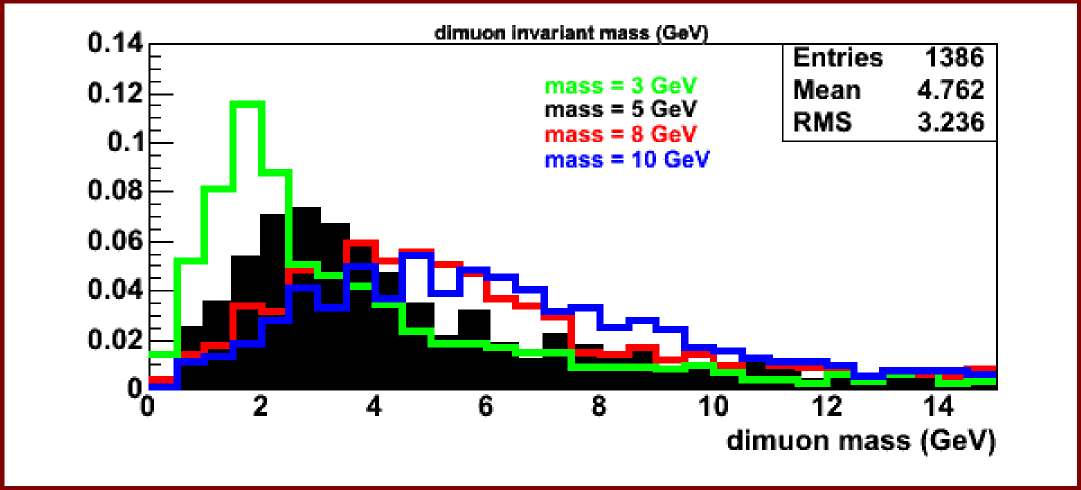
$\sigma$ = 0.022-0.025 pb

$\chi_0^1 \rightarrow \mu\mu\nu, \mu e\nu, ee\nu$

p14.07.00 simulation

p14.06.01 recon

minbias = 0.4 events



# *Use data to estimate background*

Two cuts:
define 4 samples

For background:

$$\frac{\text{Sample 1A}}{\text{Sample 2A}} = \frac{\text{Sample 1B}}{\text{Sample 2B}}$$

$$\frac{\text{Sample 1A}}{\text{Sample 1B}} = \frac{\text{Sample 2A}}{\text{Sample 2B}}$$

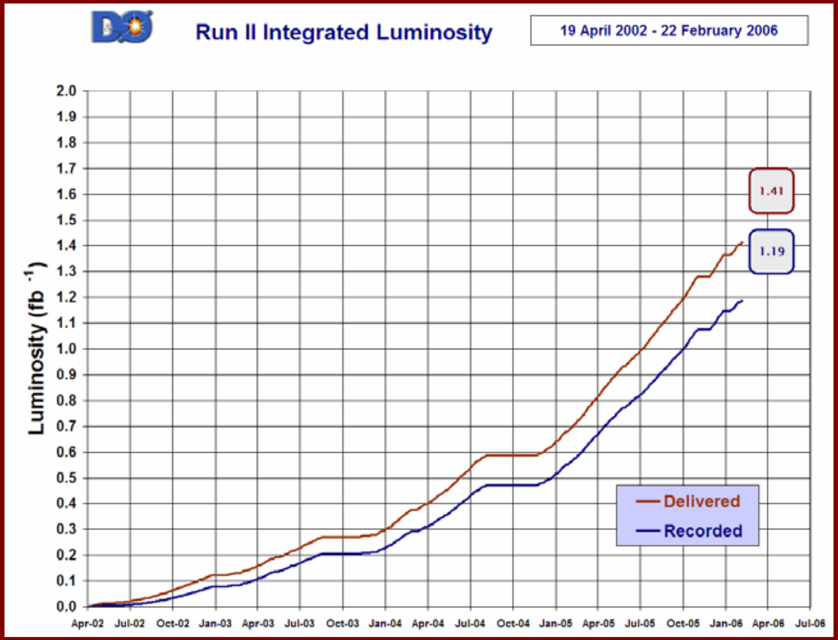
***Criteria #1***

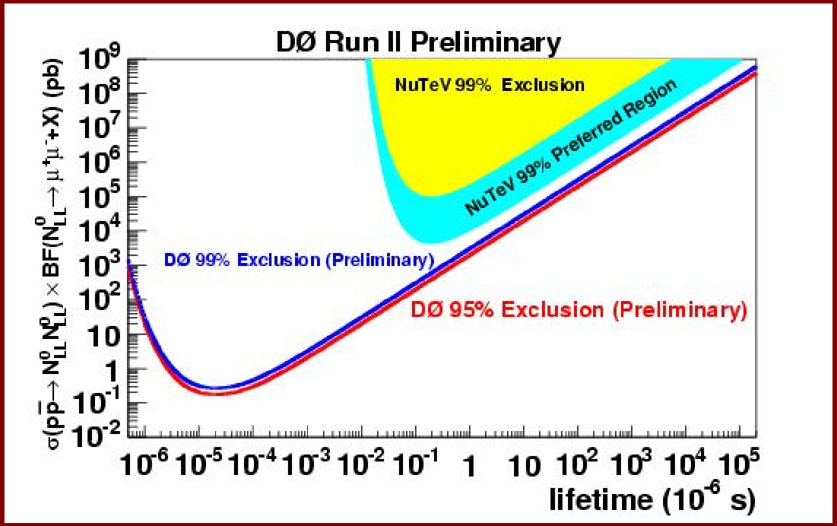
| ***Criteria #2*** | Fail | Pass |
|---|---|---|
| Fail | **Sample 1A** | **Sample 1B** |
| Pass | **Sample 2A** | **Sample 2B** |

final signal sample

$$\text{Sample 2B} = \frac{\text{Sample 2A}}{\text{Sample 1A}} \times \text{Sample 1B}$$

- **DØ has just completed a 5 year data-taking period**
  - **upgrade underway**
  - **more data to come**
- **We've expanded our capabilities and addressed a significant outstanding experimental result**



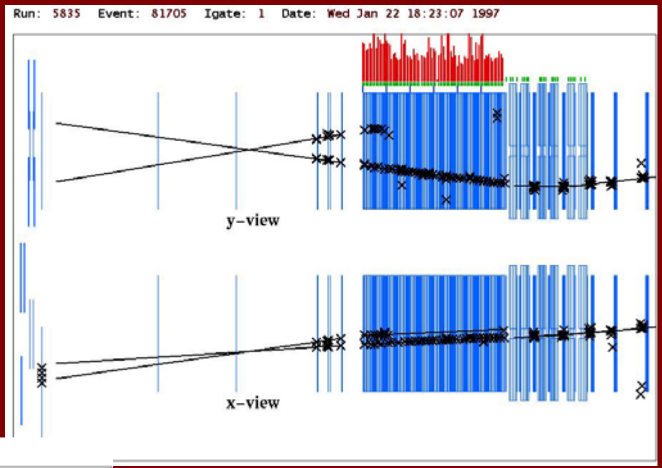



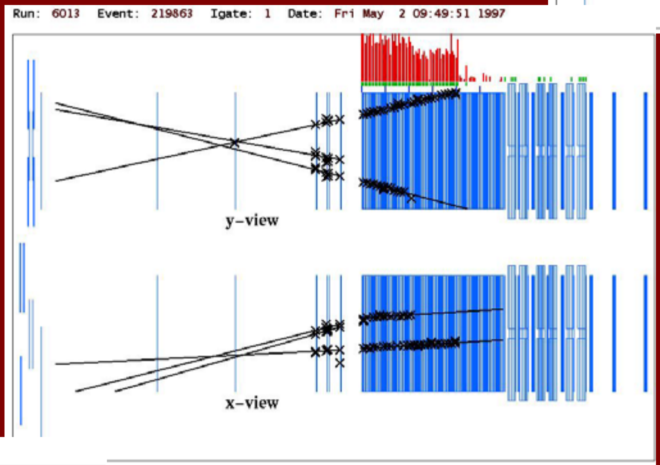
# Third search:

3 events found

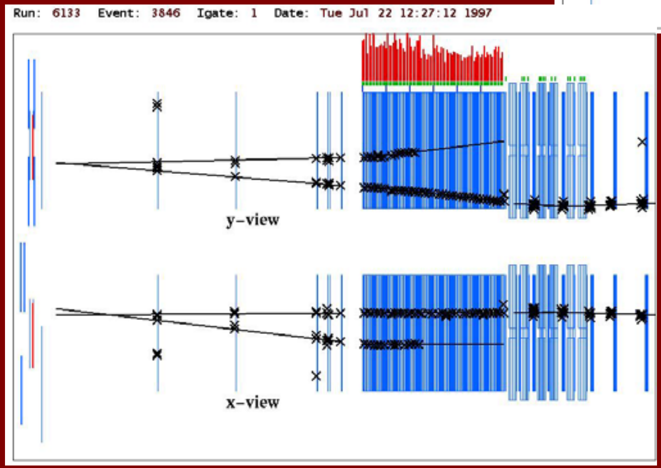
Expected background:

0.07 ± 0.01 events




Decay to
two muons



- **Why do searches?**
- **Why search for neutral, long-lived particles?**
- **How to search for neutral, long-lived particles at D0?**
- **What did we find?**
- **What does it mean?**

# “Who ordered that?”

***- I.I. Rabi (1937)***

Discovery of the muon

Anderson and
Neddermeyer

**1937**

Street and Stevenson

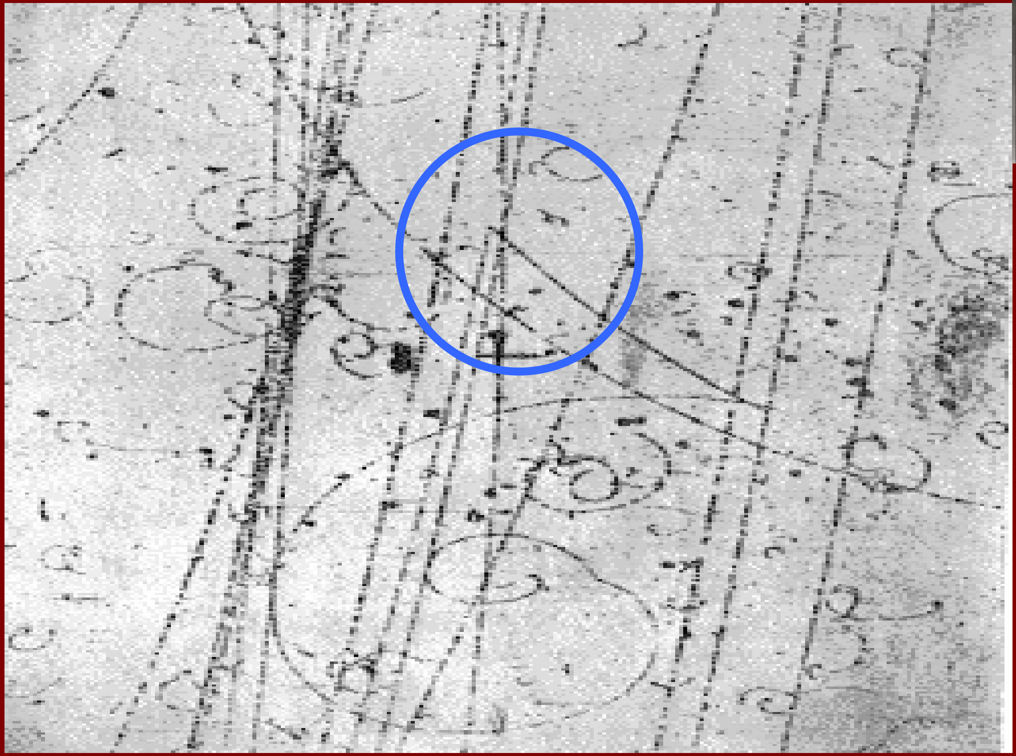
Prior to 1937
electron
proton
neutron
photon
positron
hypothesis of neutrino

other examples: strange particles,
J/Ψ, tau lepton

1947
New unstable particle

Called “vee” or strange particles

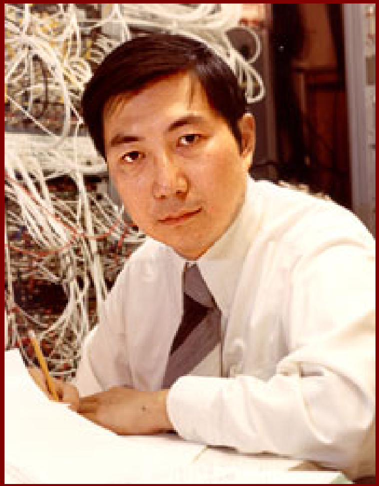
mass ½ of proton

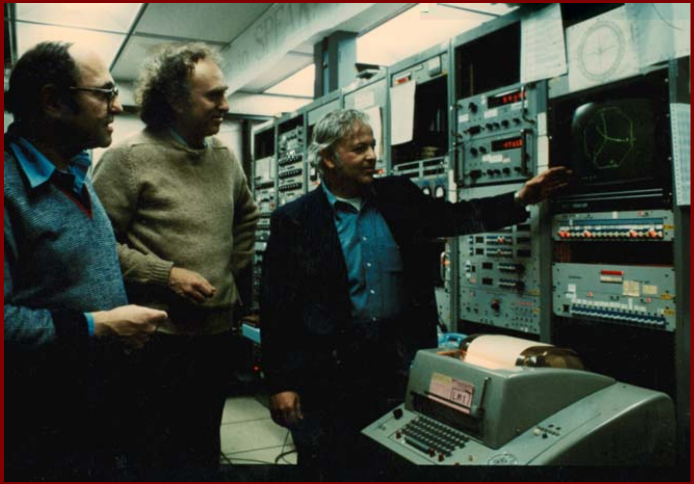


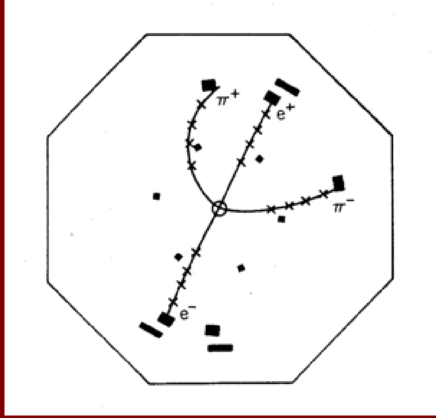
Rochester and Butler

**University of Manchester 1947**

# *November Revolution - 1974*








J/Ψ

first charm meson

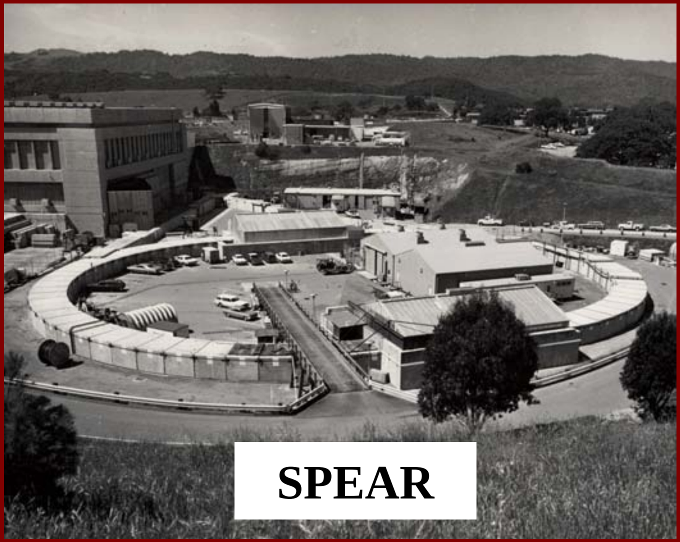
now: 4 leptons

and 4 quarks

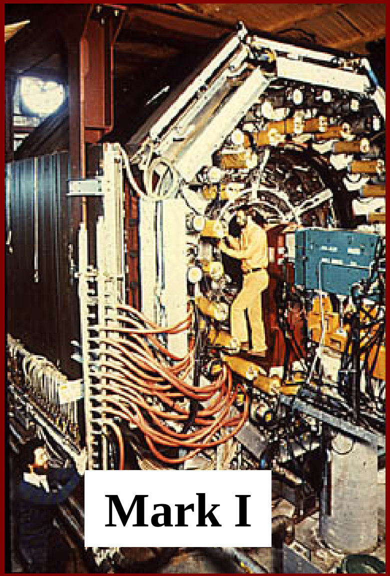
Tau lepton

symmetry

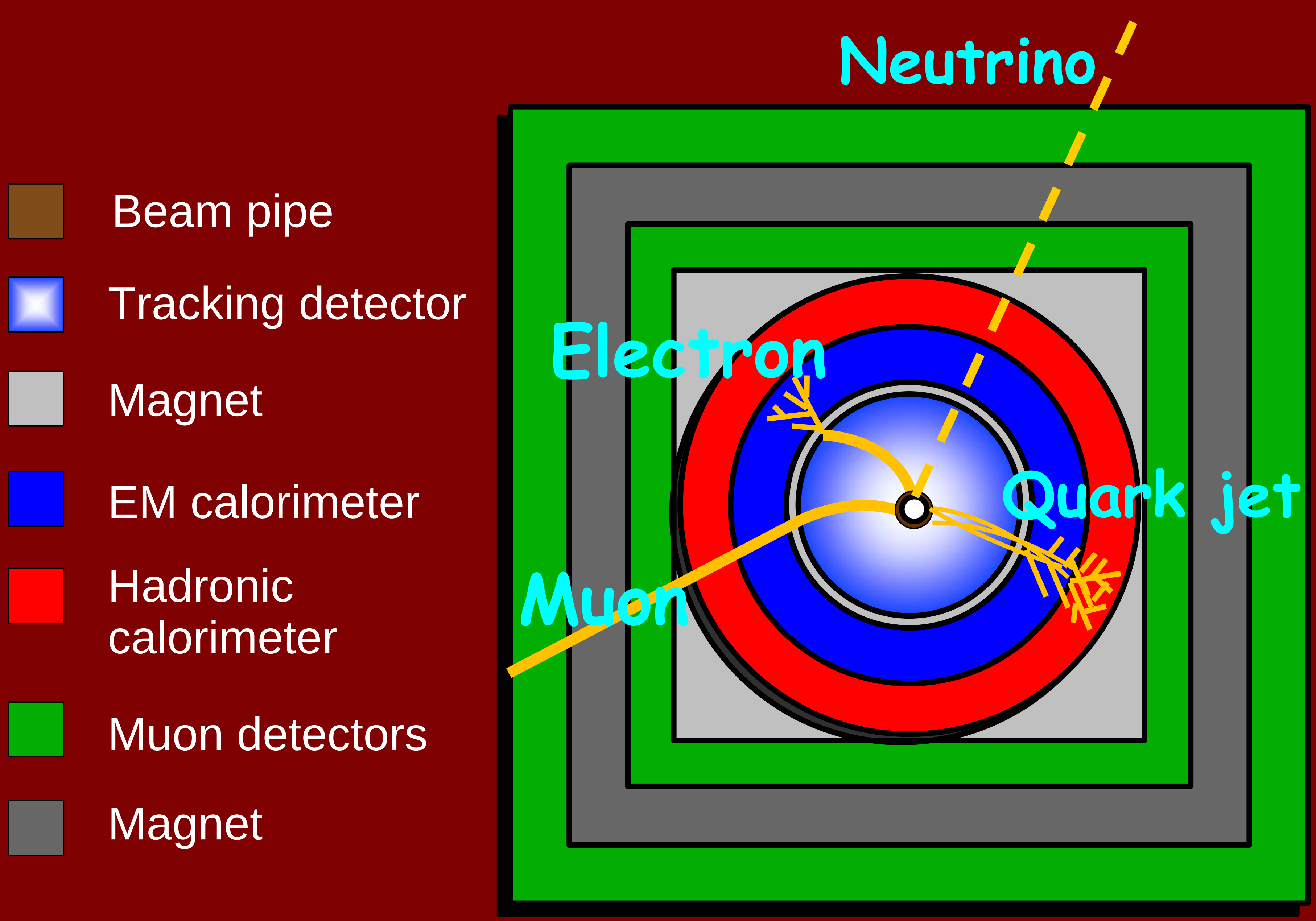
destroyed



**SPEAR**



**Mark I**


Beam pipe
Tracking detector
Magnet
EM calorimeter
Hadronic calorimeter
Muon detectors
Magnet
Neutrino
Electron
Quark jet
Muon

# Fermilab
# Result of the Week

***Fermilab Today***

**http://www.fnal.gov/pub/today/index.html**

# Observation of an Anomalous Number of Dimuon Events in a High Energy Neutrino Beam

T. Adams,[4] A. Alton,[4] S. Avvakumov,[8] L. de Barbaro,[5] P. de Barbaro,[8] R. H. Bernstein,[3] A. Bodek,[8] T. Bolton,[4] J. Brau,[6] D. Buchholz,[5] H. Budd,[8] L. Bugel,[3] J. Conrad,[2] R. B. Drucker,[6] B. T. Fleming,[2] R. Frey,[6] J. A. Formaggio,[2] J. Goldman,[4] M. Goncharov,[4] D. A. Harris,[8] R. A. Johnson,[1] J. H. Kim,[2] S. Koutsoliotas,[2] M. J. Lamm,[3] W. Marsh,[3] D. Mason,[6] J. McDonald,[7] C. McNulty,[2] K. S. McFarland,[3] D. Naples,[7] P. Nienaber,[3] A. Romosan,[2] W. K. Sakumoto,[8] H. Schellman,[5] M. H. Shaevitz,[2] P. Spentzouris,[2] E. G. Stern,[2] N. Suwonjandee,[1] M. Tzanov,[7] M. Vakili,[1] A. Vaitaitis,[2] U. K. Yang,[8] J. Yu,[3] G. P. Zeller,[5] and E. D. Zimmerman[2]

# Evidence for Anomalous Lepton Production in $e^+$–$e^-$ Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

*Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305*

(Received 18 August 1975)

We have found events of the form $e^+ + e^- \to e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

$$e^+ + e^- \to e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

of the detector, or particles very difficult to detect such as neutrons, $K_L{}^0$ mesons, or neutrinos. Most of these events are observed at center-of-