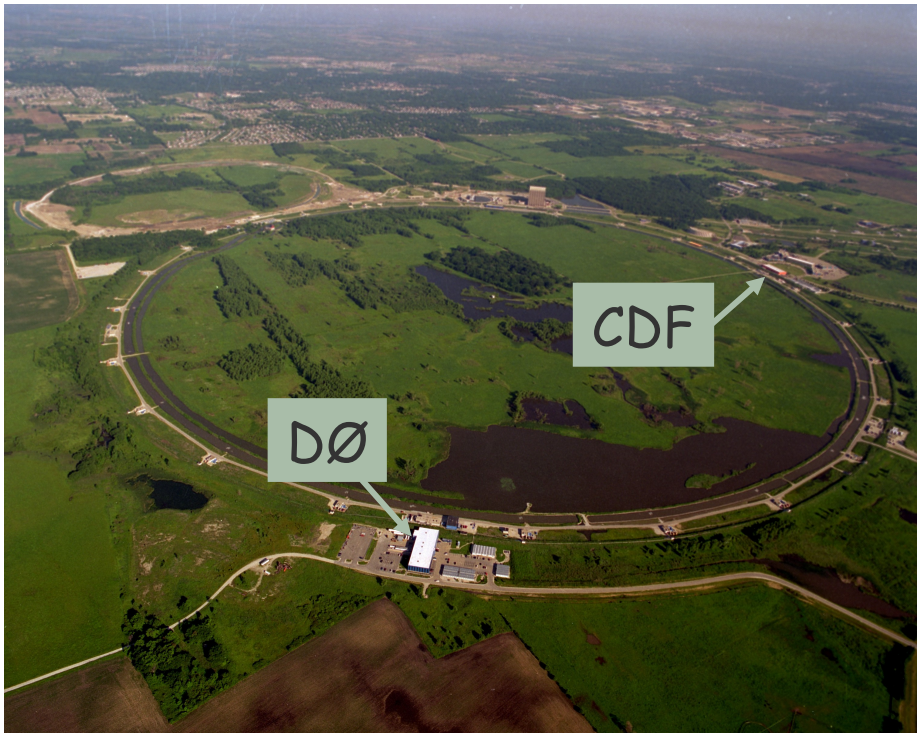
# Long-lived Particles: Tevatron Legacy

**Andy Haas (NYU)**

LHC Long-Lived Particle Mini-Workshop
CERN - May 12, 2016
https://indico.cern.ch/event/517268/timetable/



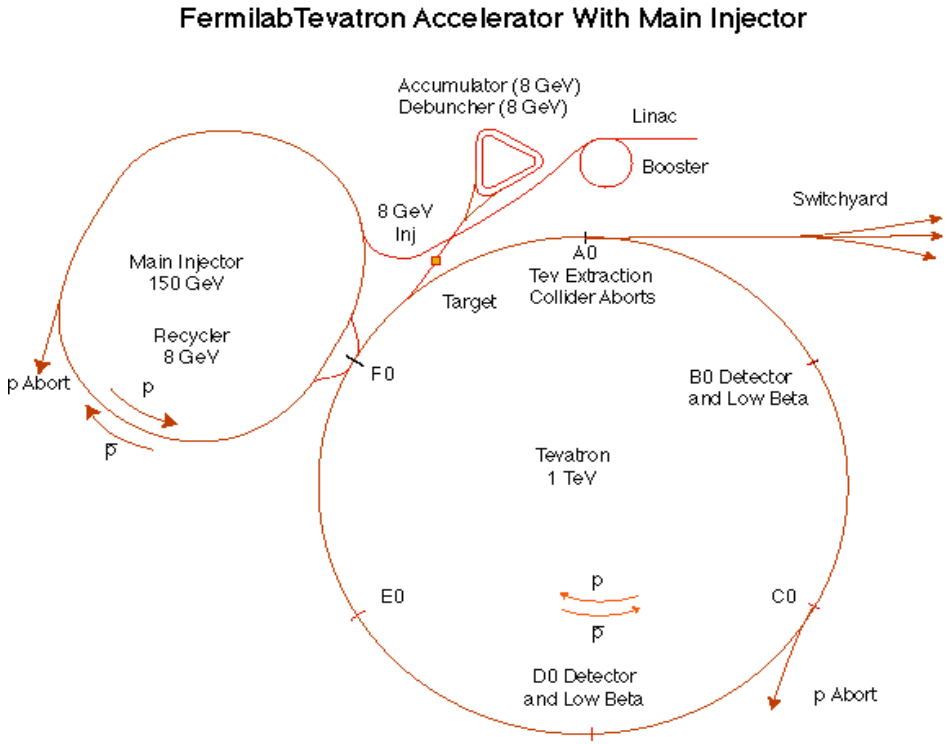

NEW YORK UNIVERSITY

(member from 1998-2012)

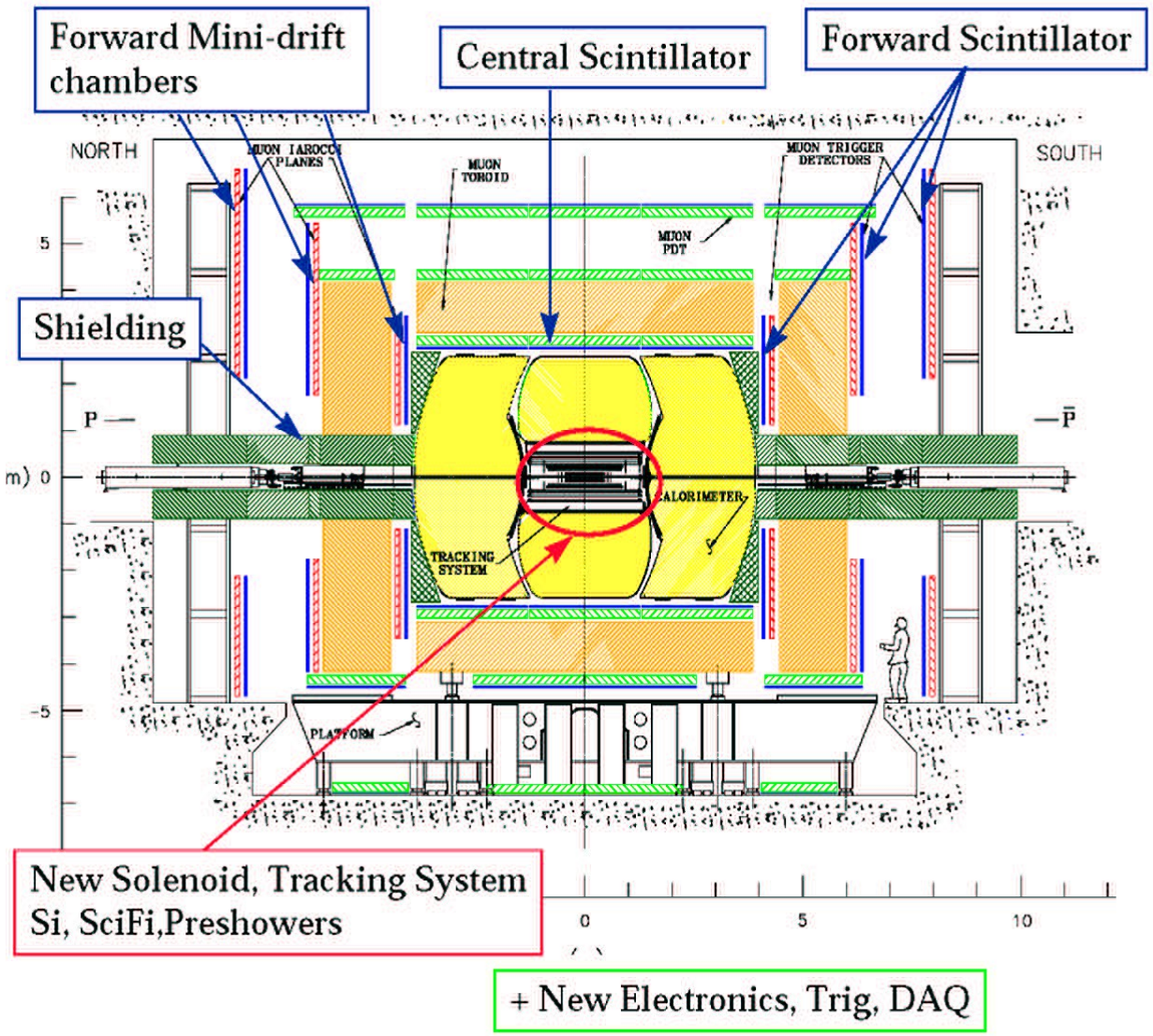
(member from 2004-

# The Teva-what?

- Was the highest energy particle collider in the world, until LHC ~2010
- 1.96 TeV center-of-mass energy, *proton anti-proton* (~15% of LHC)
- Typical luminosity of ~3e32 $cm^{-2}s^{-1}$ (~3% of LHC)
- Run1 (1.8 TeV) discovered top quark in 1995 (~20 candidates, ~100/pb)
- Run2 (1.96 TeV): ~10/fb from 2002-2012 (*almost* found Higgs($\rightarrow$bb))




# The DØ Detector (and there was also CDF)




## Retained from Run I

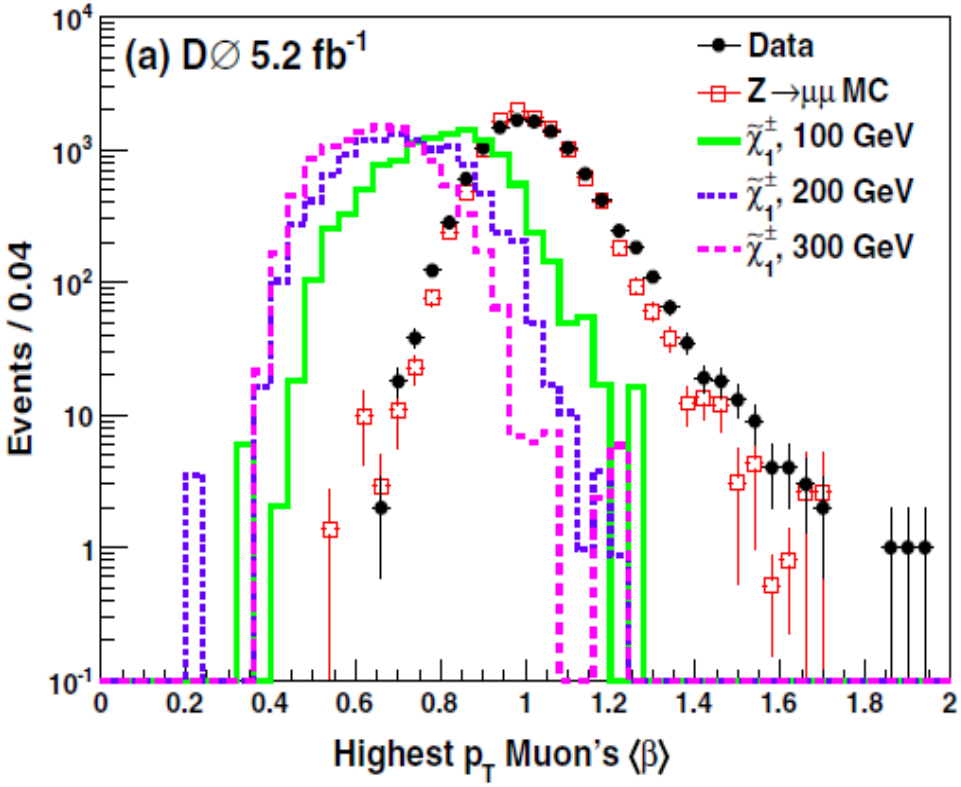
LAr calorimeter
Central muon detector
Muon toroids

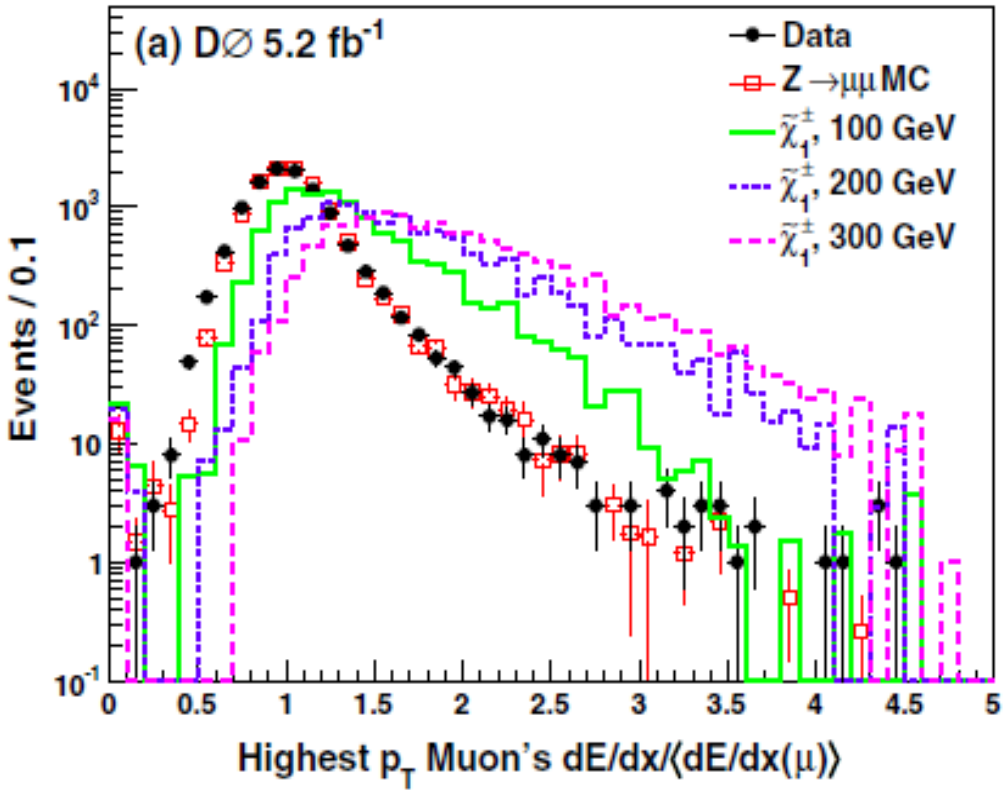
## New for Run II

Magnetic tracker
2 Tesla solenoid
Silicon micro-strip tracker
Scintillating fiber tracker
Pre-shower detectors
Forward muon detector
Forward proton detector
Front-end electronics
Trigger and DAQ

# CDF/D0: long-lived charged massive particles

- Could be R-hadrons, staus, etc.
- Will look like muon, but slow $\rightarrow$ use timing and dE/dx in silicon
- Look for pairs of them, or singles (model-dependent)
- D0 had several searches, based on time-of-flight in the muon system** as well as silicon dE/dx




****My first project on D0, as an undergrad, in 1997-98!**

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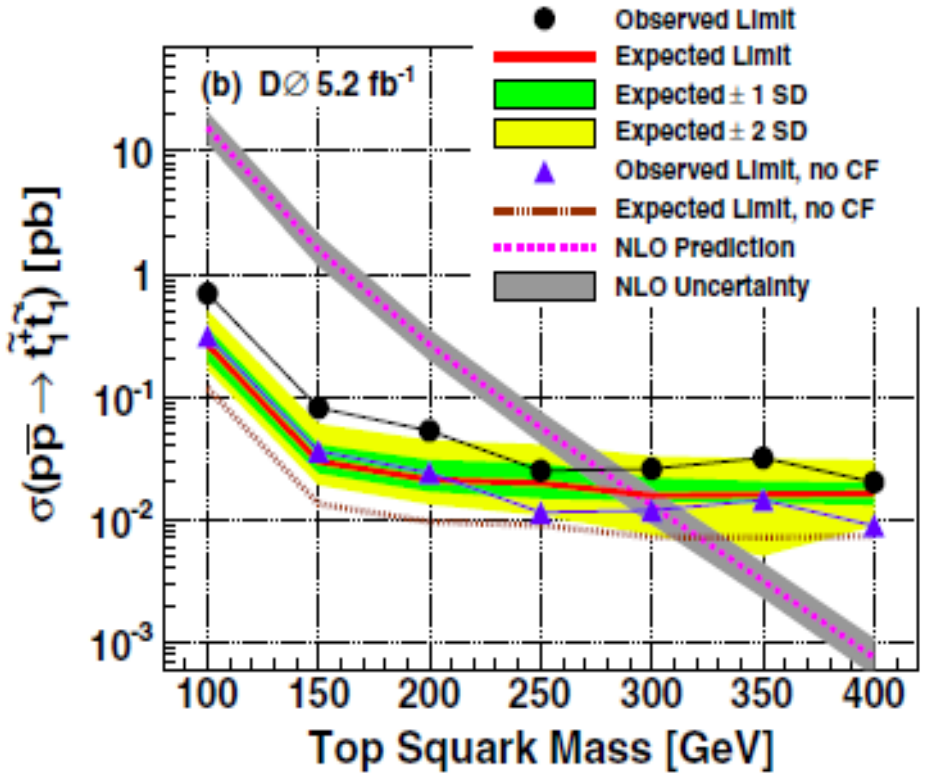
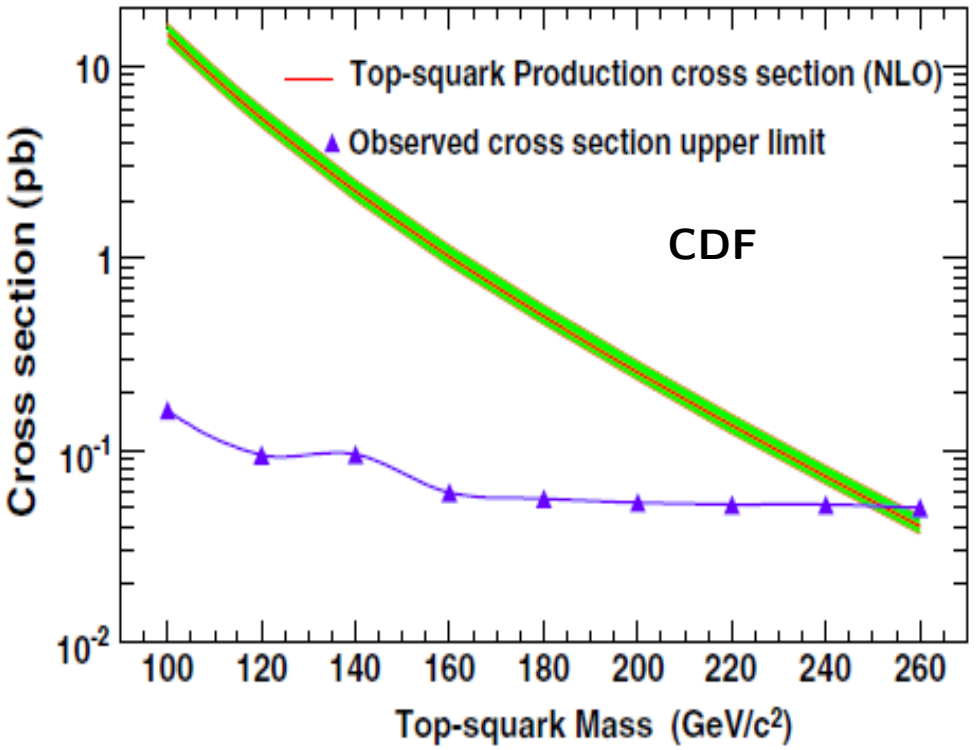
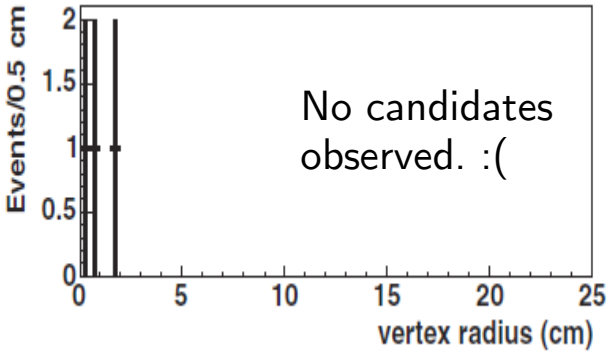
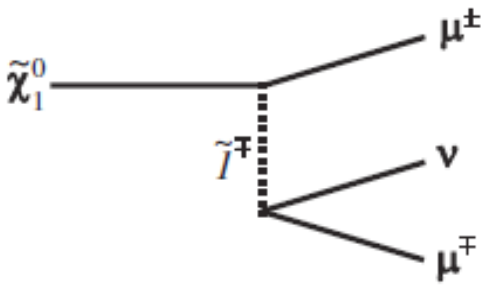


# D0: Long-lived $N^0 \rightarrow$ mumu decay

- Look for a di-muon vertex displaced from the interaction point
  - Low background (no conversions, like in ee), easy trigger
- Vertex radius >5 cm from beamspot
  - Below that was background from b-decays



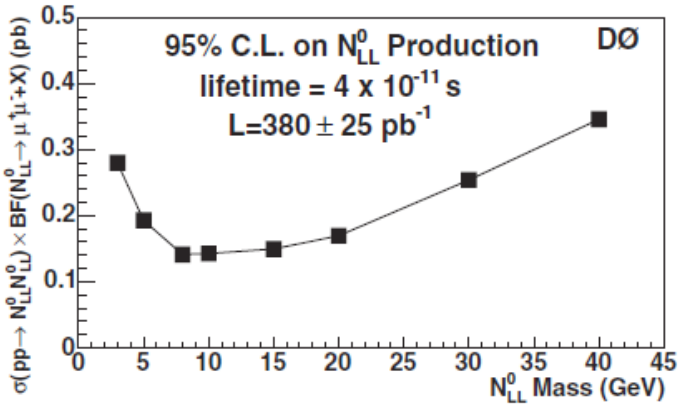
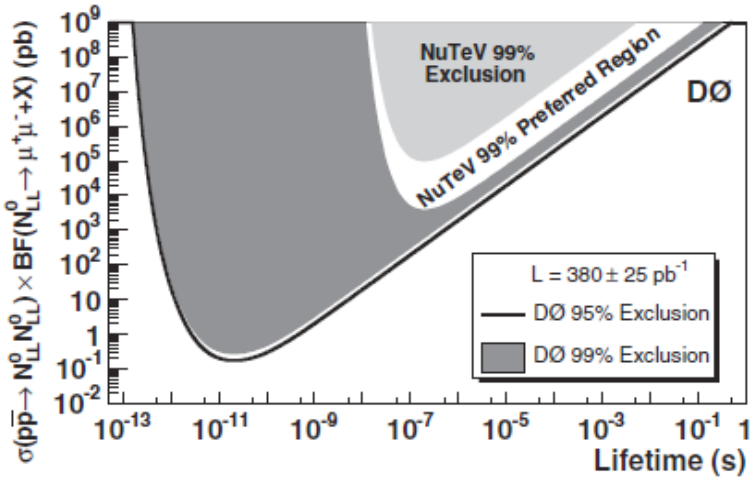



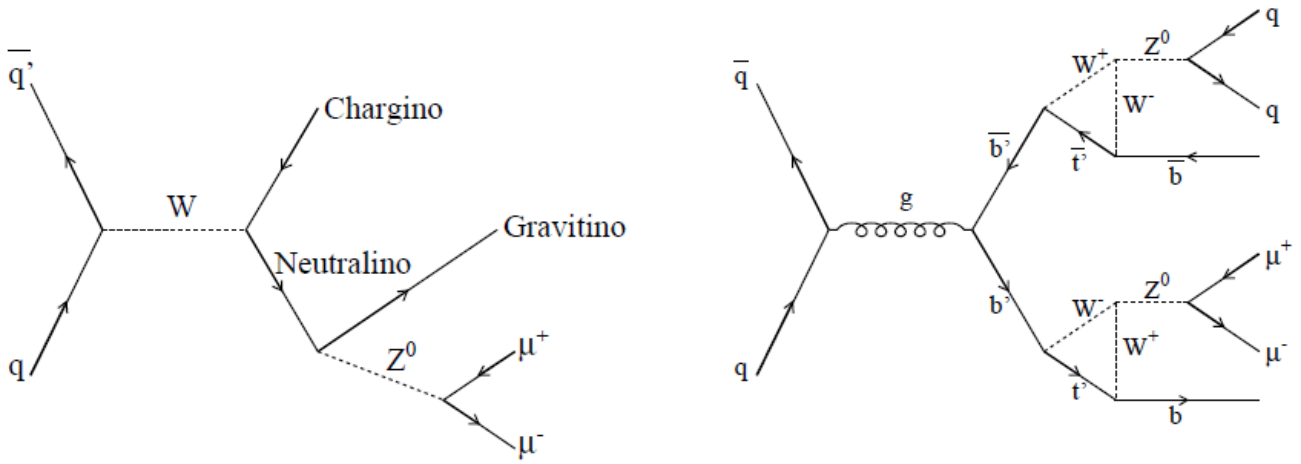

FIG. 4. Limits on $N^0_{LL}$ pair production as a function of its mass. The limit is for a lifetime of $4 \times 10^{-11}$ s.



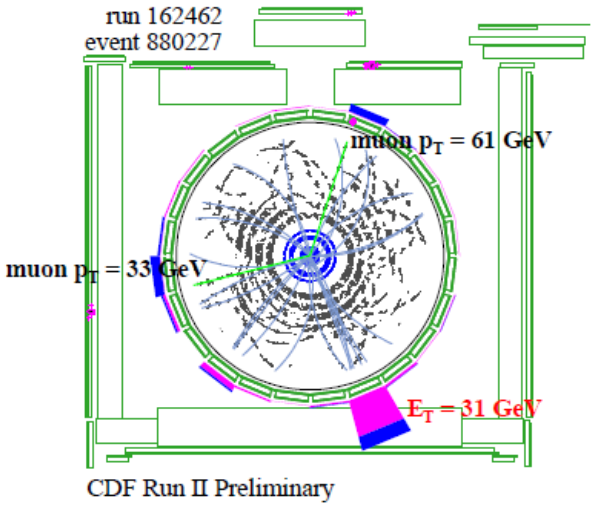

- Sensitive to RPV neutralino$\rightarrow\mu\mu\nu$, etc.
- Motivated by NuTev anomaly of dimuon events (3 observed, 0.07±0.01 expected!)

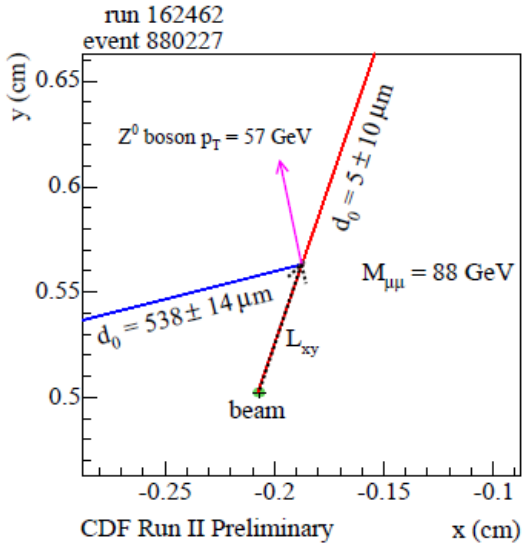
# CDF: Displaced Z → mumu

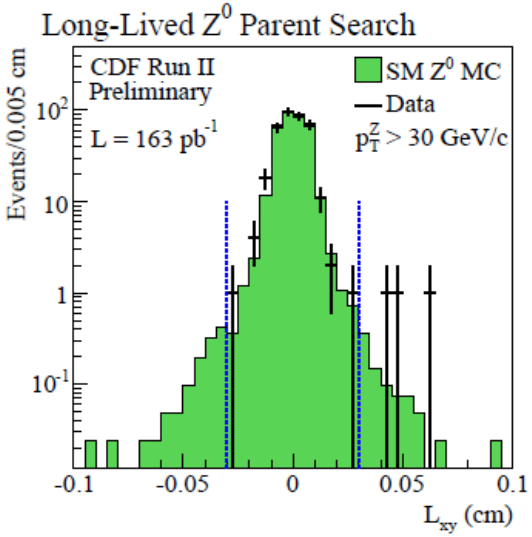
- Displaced Z → mumu, motivated by various SUSY models




- Require Z pT>30 GeV reduces backgrounds
  - ~1 +- 1 events expected, 3 observed



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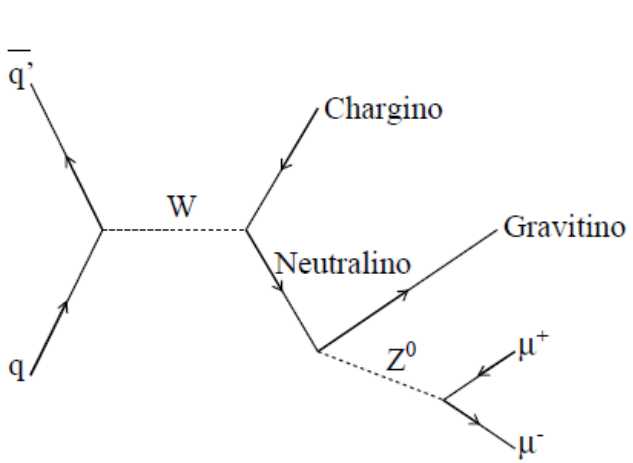
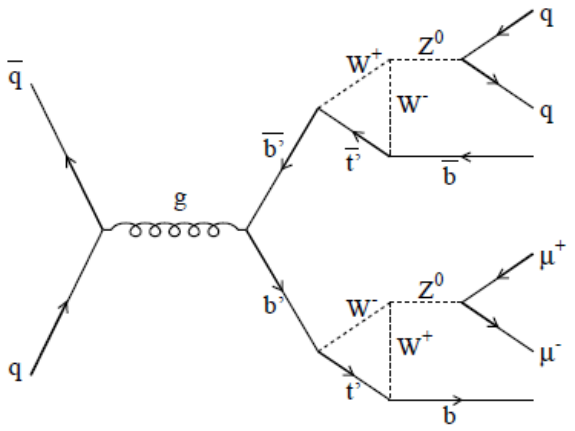
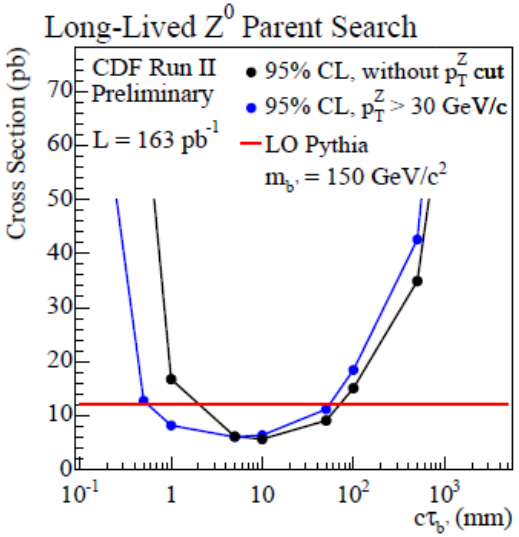
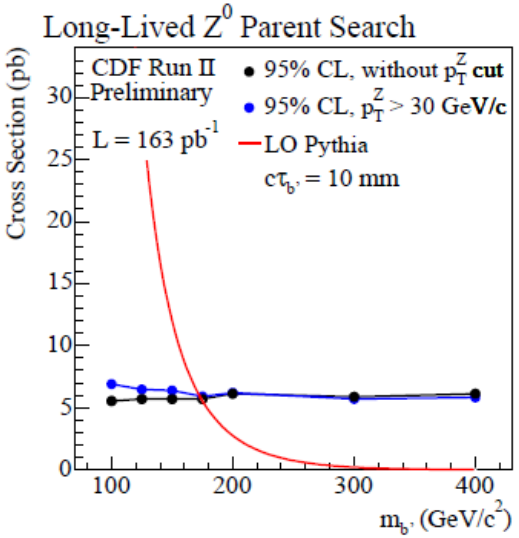
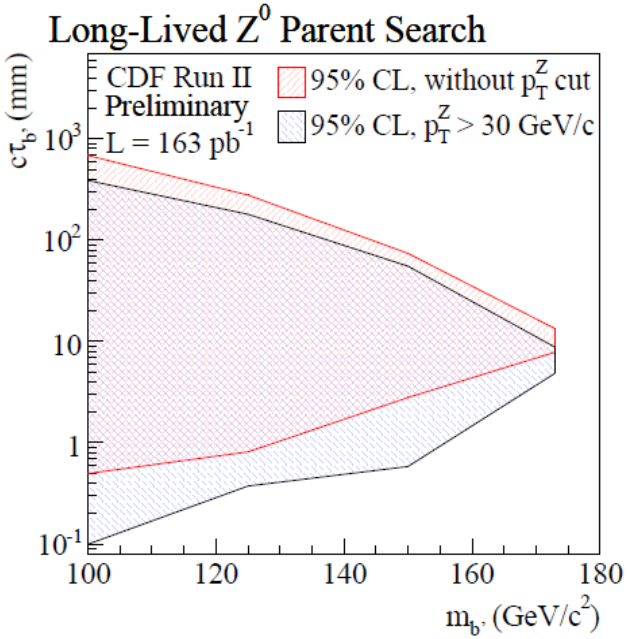



- Set limits on b' as function of lifetime...



# CDF: Neutralinos to "late" photon + MET

- Photons appear "late" due to neutralino moving slow and due to kinked path of neutralino decay...

- CDF had nice timing in their EM calor. Resolution about 0.6 ns ! (ATLAS is about 3x better, 10 years later.)

*Preselection requirements*

$E_T^\gamma > 30$ GeV, $\not\!\!E_T > 30$ GeV

Photon ID and fiducial, $|\eta| < 1.0$

Good vertex, $\sum_{\text{tracks}} p_T > 15$ GeV/$c$

$|\eta^{\text{jet}}| < 2.0$, $E_T^{\text{jet}} > 30$ GeV

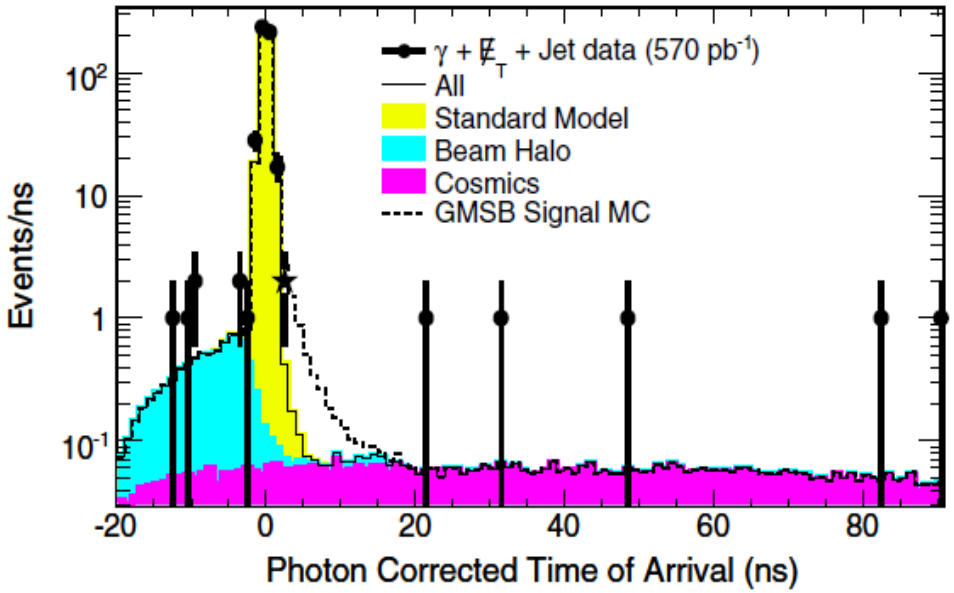
Cosmic ray rejection

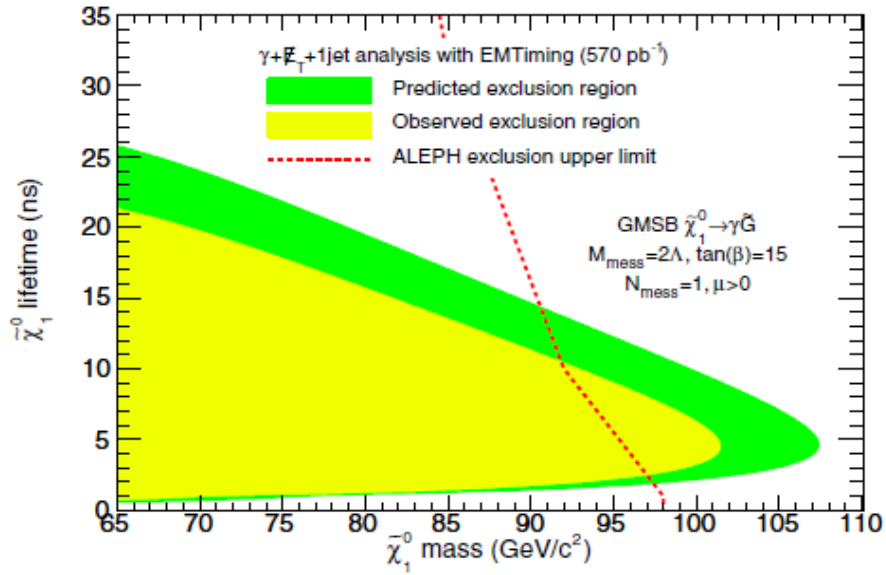
*Requirements after optimization*

$\not\!\!E_T > 40$ GeV, $E_T^{\text{jet}} > 35$ GeV

$\Delta\phi(\not\!\!E_T, \text{jet}) > 1$ rad

2 ns $< t_c^\gamma <$ 10 ns



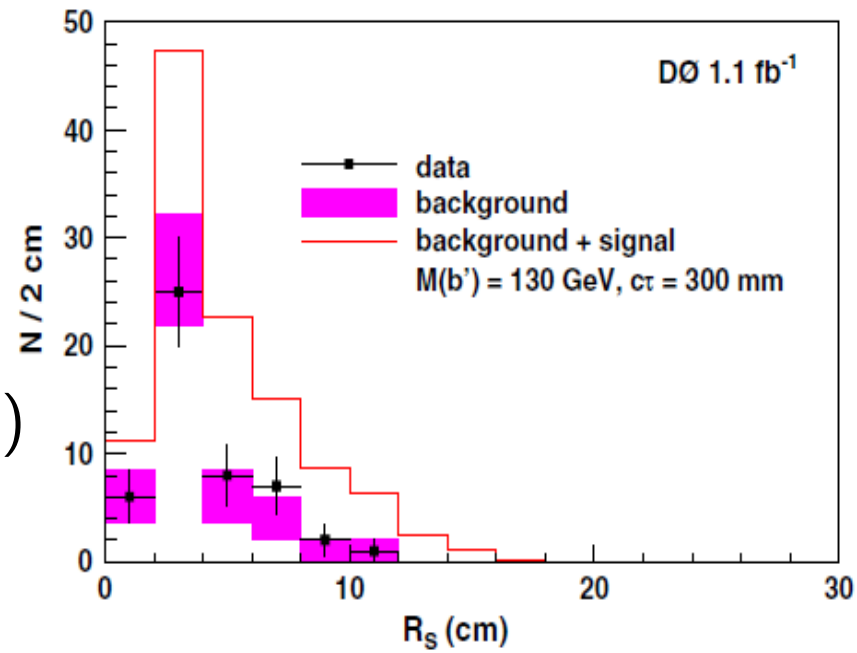
# D0: Displaced decay to electrons or photons

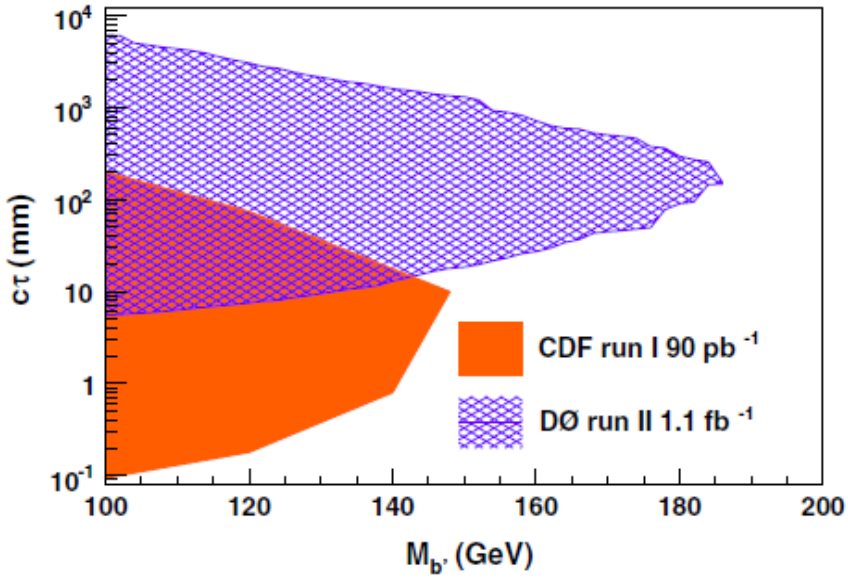
- D0 had segmentation in the EM calor. Measure direction (in eta) of showers

  (ATLAS has even better segmentation, but has not done this search yet (?))

- Look for a pair of electrons (or photons) (can't tell the difference, since there's no track out there at large radii) from a common displaced vertex

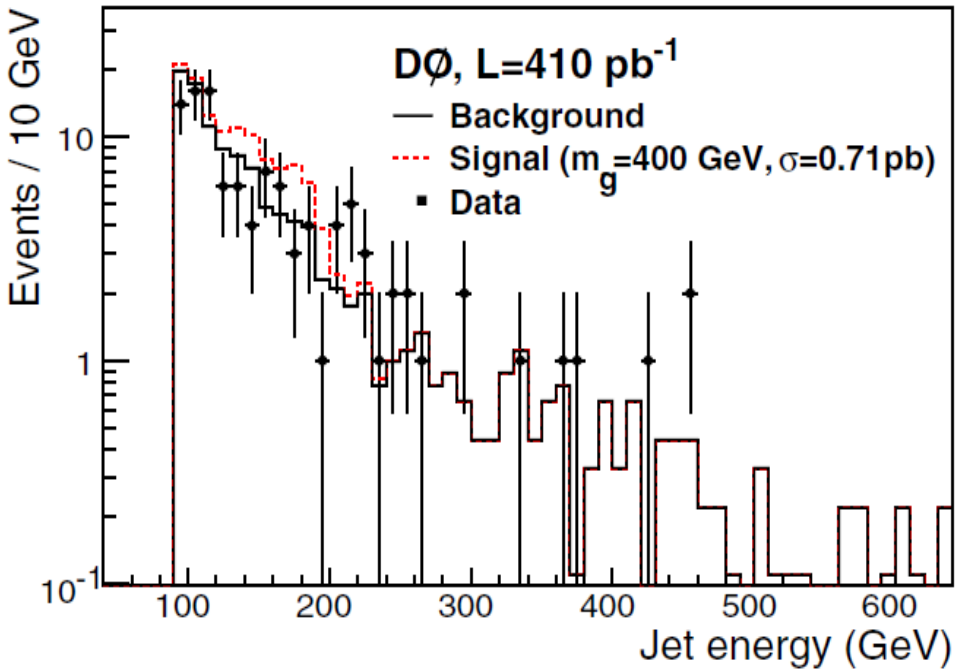
- Similar sensitivity as CDF's displaced b'→Z→mumu search, but peak sensitivity at ~10x larger lifetime

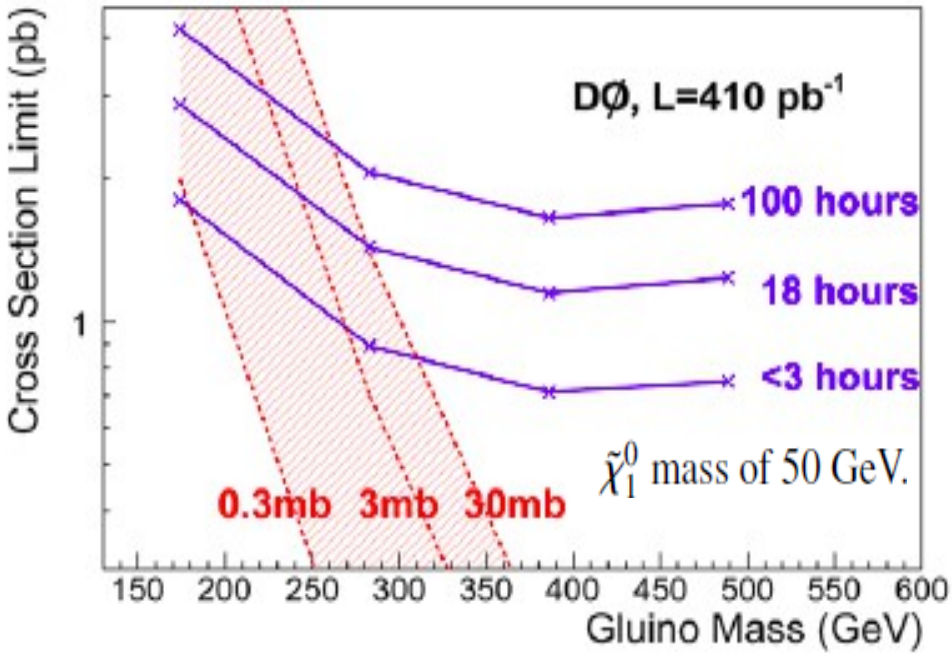


# D0: Stopped Gluinos

- First direct search for particles (R-hadrons) stopping in the calorimeter, and then decaying later (out of time with collisions)
- Was <1 event / bunch crossing, so could use standard crossings, but require no inelastic collision (based on forward trigger scintillators
  - LHC analyses must use empty bunch crossings / abort gap
- Backgrounds were mainly cosmics, and small beam-halo
  - Vetoed double-diffractive events using PV, MET



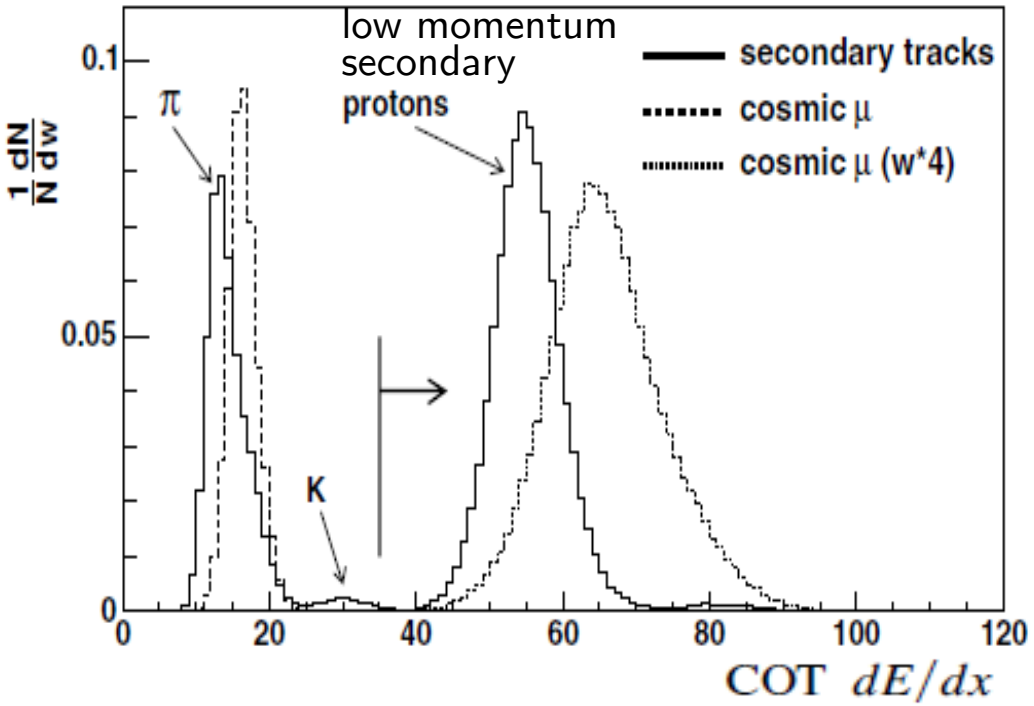



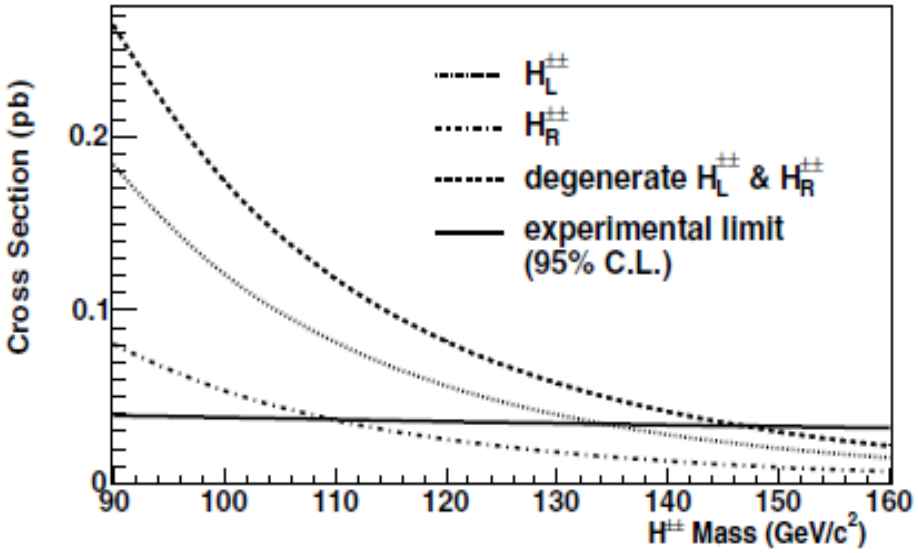
# CDF: Search for highly ionizing tracks ($H^{++}$)

- Use dE/dx in the central outer tracker (COT)
- 2 tracks with pT>18 GeV, >1 matching a muon segment

- Very low background
- No events observed

| Background | Loose Search | Tight Search |
|---|---|---|
| Jet | $<3 \times 10^{-5}$ | $<3 \times 10^{-6}$ |
| $Z \to ee$ | $<1 \times 10^{-11}$ | $<2 \times 10^{-14}$ |
| $Z \to \mu\mu$ | $<4 \times 10^{-7}$ | $<4 \times 10^{-12}$ |
| $Z \to \tau\tau$ | $<8 \times 10^{-9}$ | $<8 \times 10^{-9}$ |
| Data | 0 | 0 |

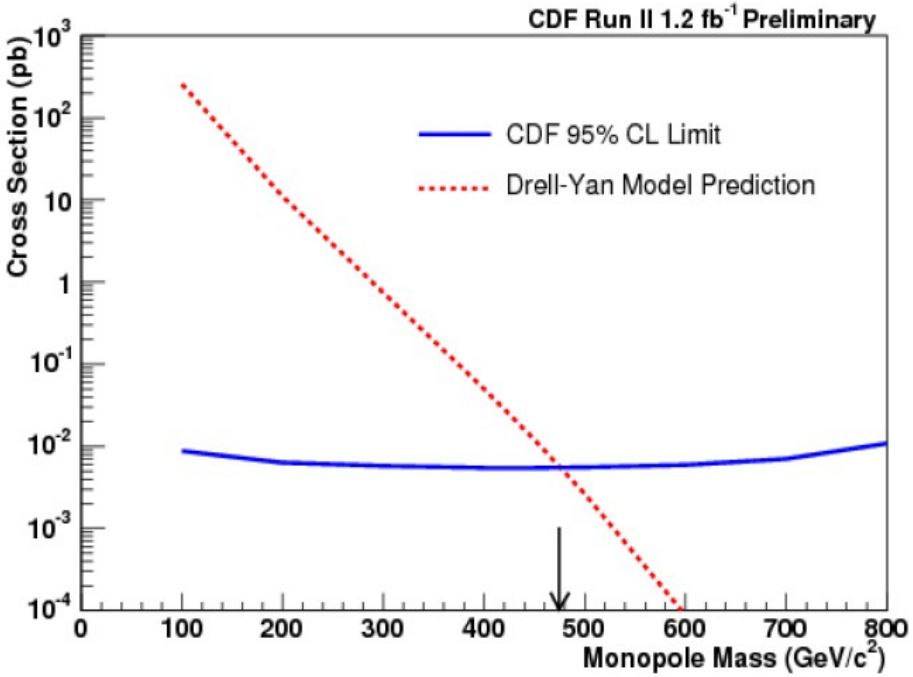


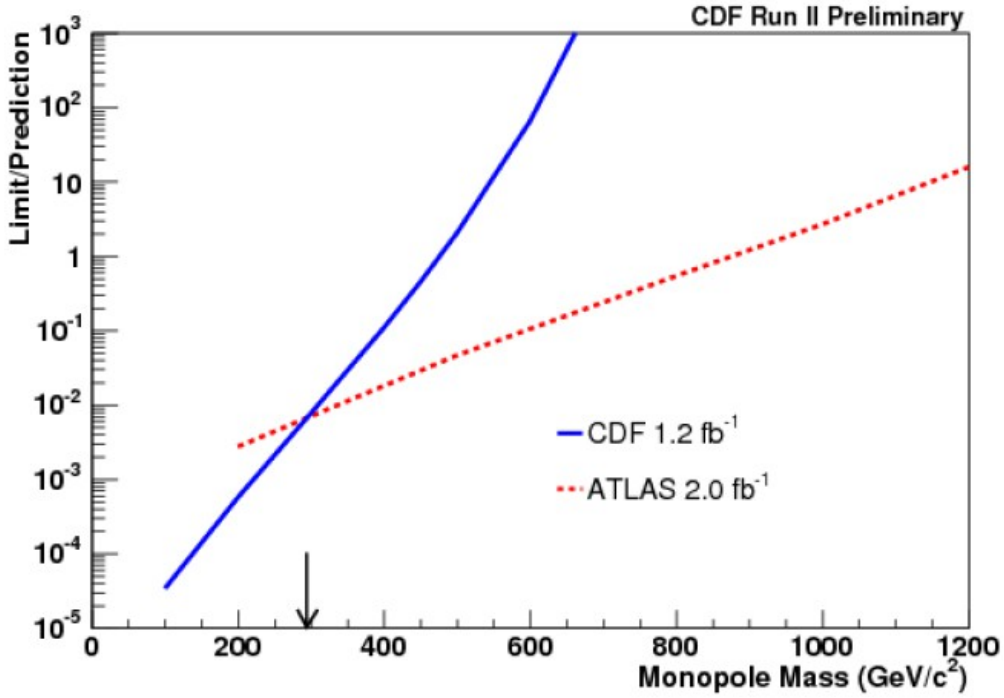



# CDF: Search for monopoles

- Special time-of-flight trigger, require large ionization
- Offline: require no r-phi curvature (no electric charge) and large COT ionization

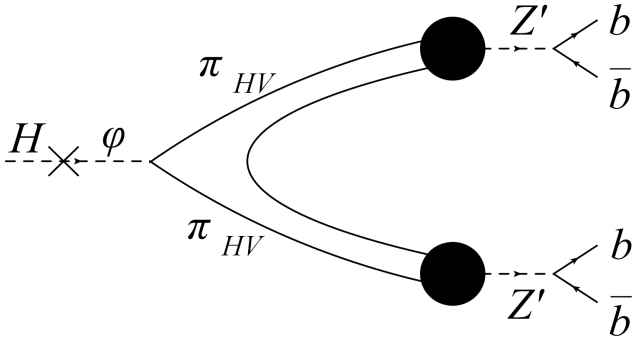
- Expect 0.04±0.02 events of background (mostly from jets)
  Observe 0 events
- More sensitive than *predicted* ATLAS reach at low monopole mass



# D0: Hidden-Valley Higgs decays → bb vertices

- Trigger on low-pt muon (from b decay)
- Look for pairs of displaced vertices with
  - >3 tracks, 1.6 < radius < 20 cm
  - Mass > 2.5 GeV
  - Acollinear decay products (to reduce inelastic collisions)
  - Not in "detector material"



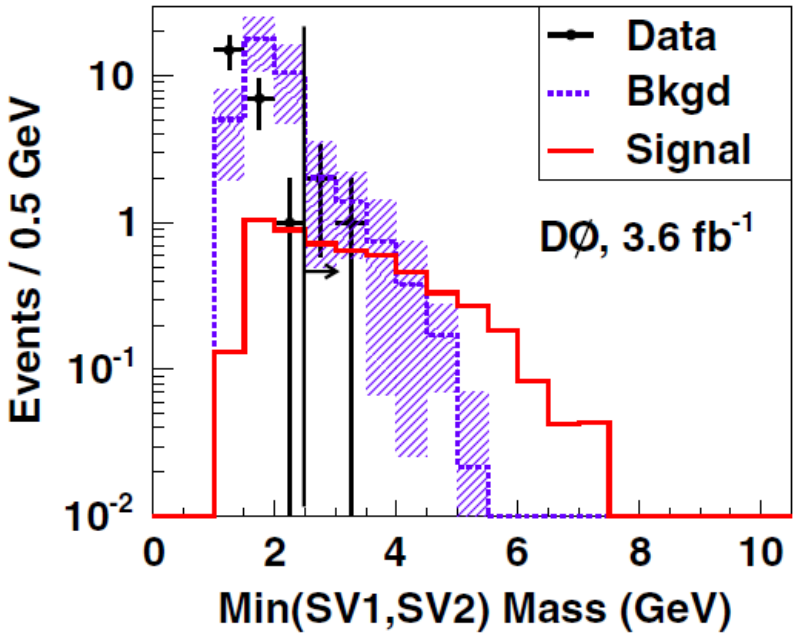
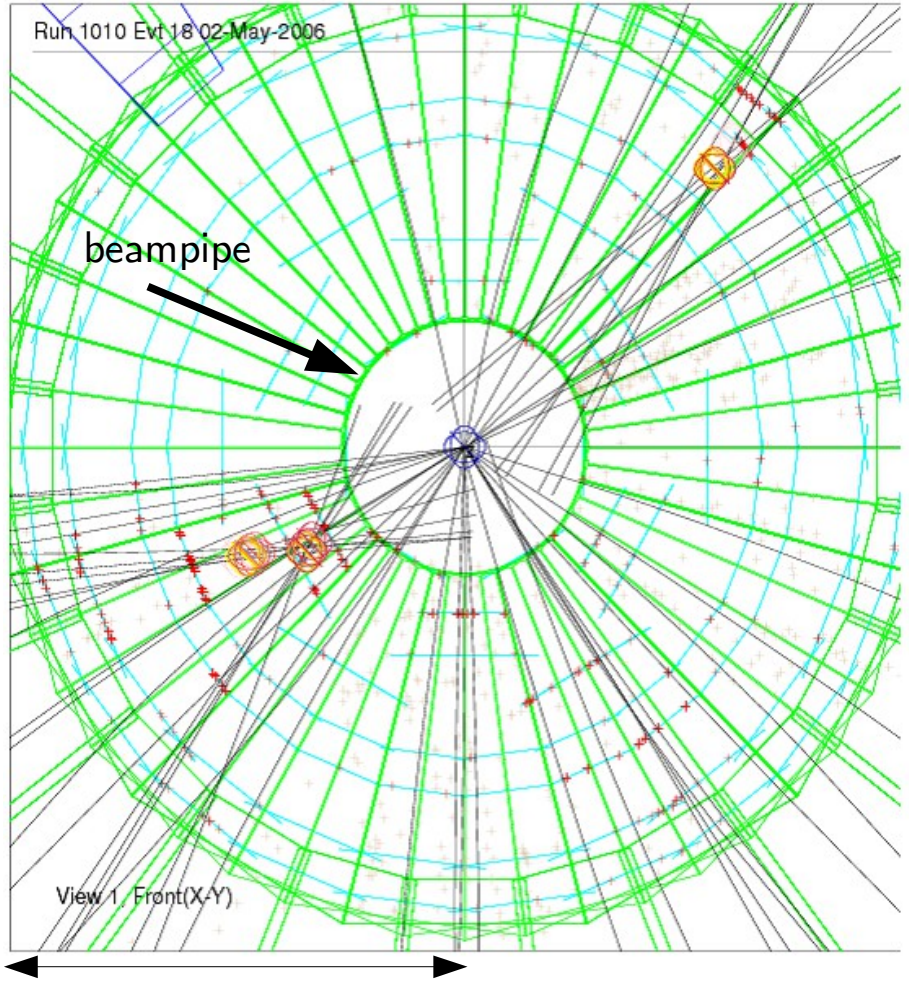




FIG. 2 (color online). The minimum mass of the two SVs, for data, background MC, and signal MC events with $M_H$ = 120 GeV, $m_{\mathrm{HV}}$ = 15 GeV, and $L_d$ = 5 cm. The hatched region shows the uncertainty on the background MC events.



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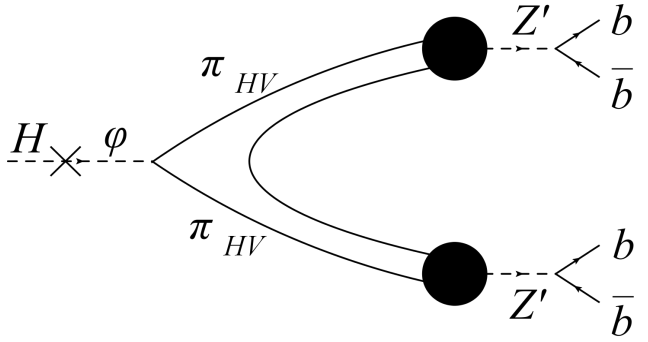
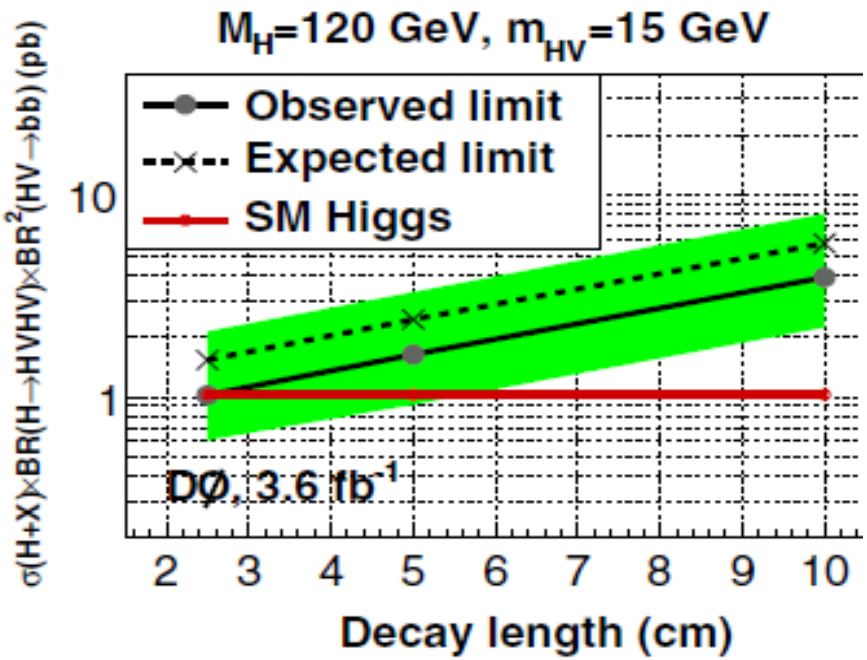
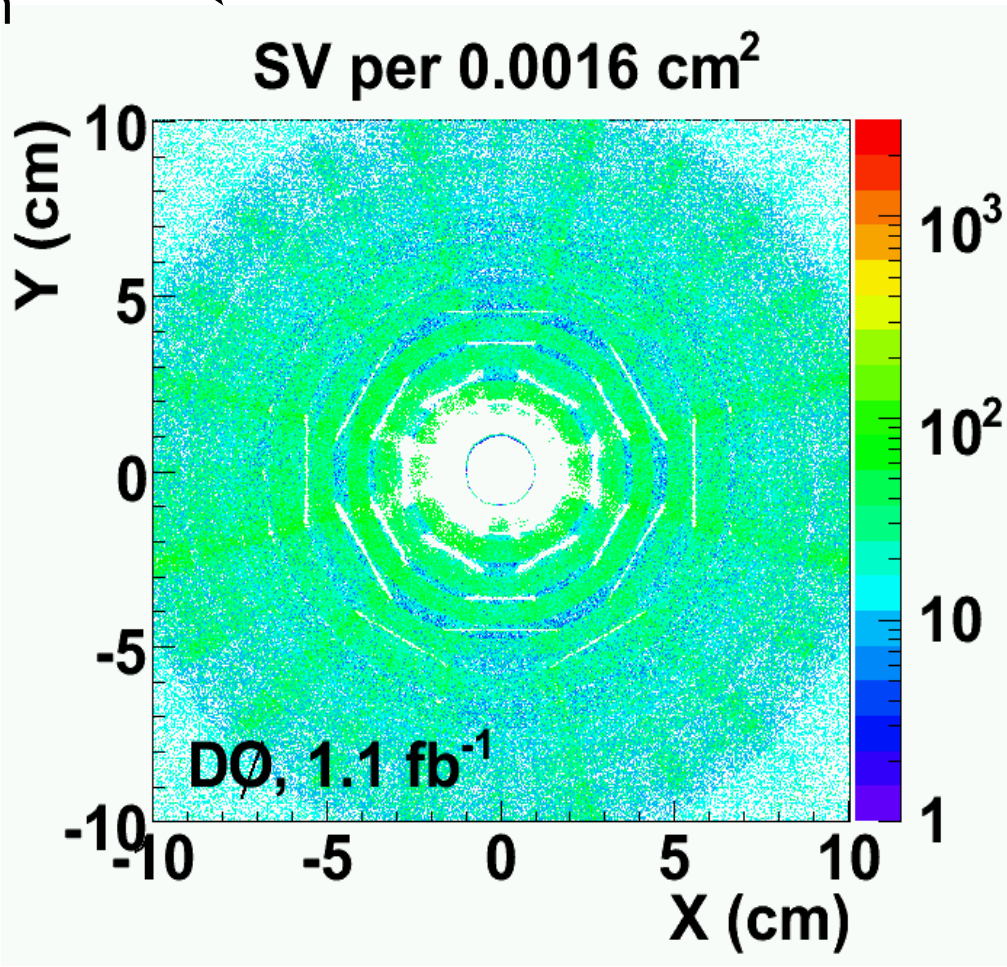



**Material veto map**

- Set limits vs. $m_{HV}$ and decay length
- Could barely exclude 100% BR of Higgs → HV... but reasonable in 2009!



# Summary

- Many LLP analyses familiar today done (often first) at the Tevatron!
  - Long-lived charged massive particles
  - LLP decays to displaced muons or late electrons/photons
  - Stopped gluinos
  - Highly-ionizing tracks / monopoles
  - Hidden-Valley Higgs decays $\rightarrow$ hadronic vertices in the tracker

- Many familiar tools:
  - Timing, dE/dx, calorimeter pointing, vertexing, material veto...

  - Resolutions typically a factor of ~few worse than LHC
  - Smaller efficiency and forward coverage, higher fake rates
  - 396 ns and almost no pileup :)

# Summary

Fun times! Just a few hundred people per experiment for everything...
Detector running, software, computing, simulation, analysis, etc.!


Usually the "LLP group" was you,
until you finished your analysis. :)

# D0 LLP references

- http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#np

- Search for Long-Lived Particles Decaying into Electron or Photon Pairs
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.101.111802
- Search for Neutral, Long-Lived Particles Decaying into Two Muons
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.97.161802
- Search for Stopped Gluinos
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.99.131801
- Search for Resonant Pair Production of Neutral Long-Lived Particles Decaying to bbbar
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.103.071801
- Search for charged massive long-lived particles
  - http://journals.aps.org/prd/pdf/10.1103/PhysRevD.87.052011

# CDF LLP references

- http://www-cdf.fnal.gov/physics/exotic/exotic.html

- Search for Dirac monopoles
  - http://www-cdf.fnal.gov/physics/exotic/r2a/20140619.monopole/index.html
- Search for Heavy Long-Lived Particles that Decay to Photons
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.99.121801
- Search for Long-Lived Massive Charged Particles
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.103.021802
- Search for Long-Lived Parents of the Z Boson
  - http://www-cdf.fnal.gov/physics/exotic/r2a/20040826.mumulxy_longlifez/note_7244.pdf
- Search for Long-Lived Doubly Charged Higgs Bosons
  - http://journals.aps.org/prl/pdf/10.1103/PhysRevLett.95.071801