Unusual Signatures at Hadron Colliders

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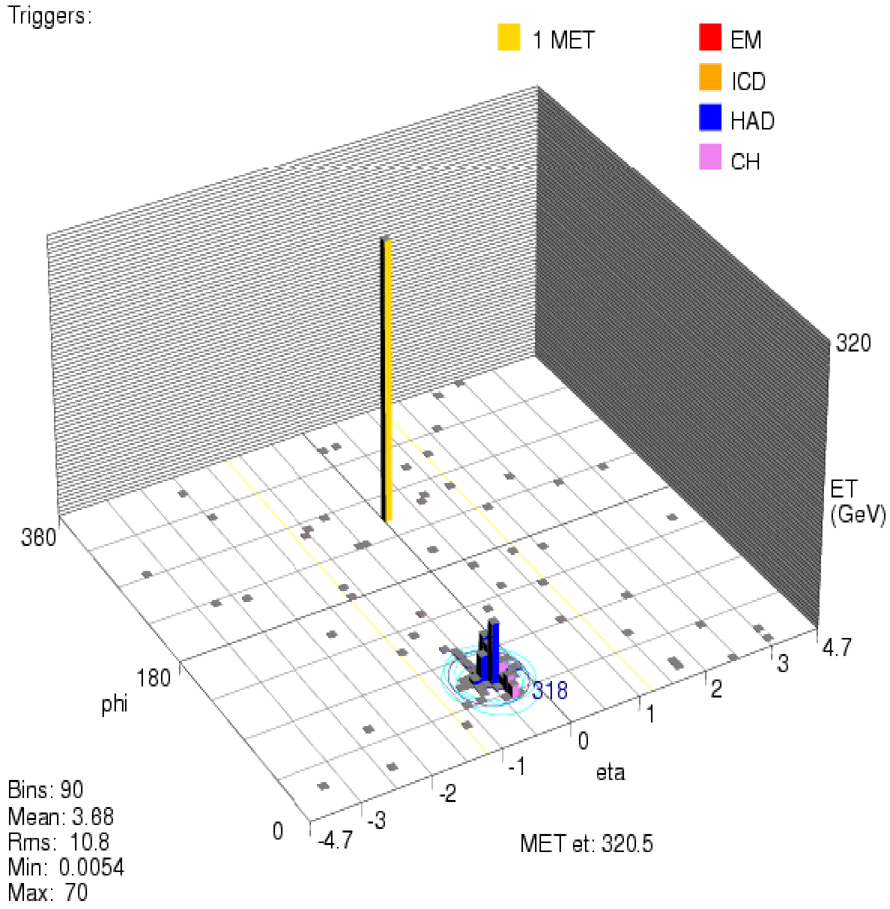


Introduction

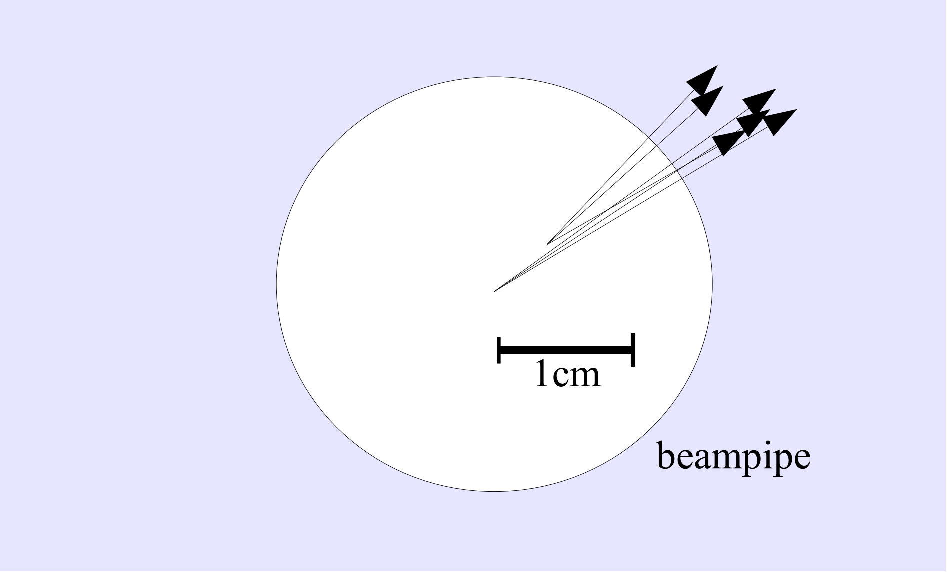
Most known particles decay quickly

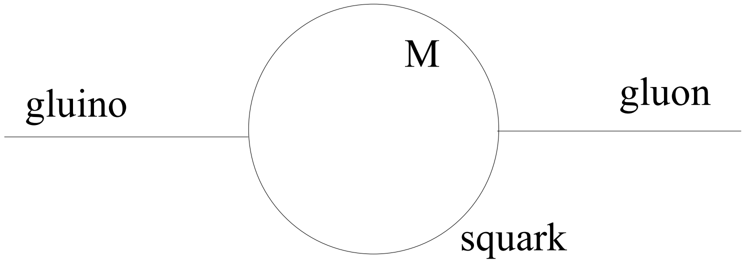
Exception, weak-decays:

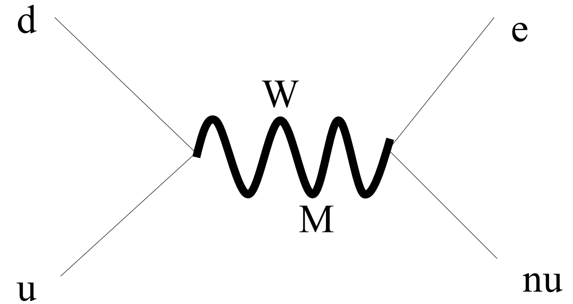
- b, tau ~ mm
- s ~ cm's to km's
- muon, neutron ~ even longer

New particles could be short or *long* lived

- Decay only possible through a heavy virtual intermediate?







Introduction

New long-lived particles look unusual

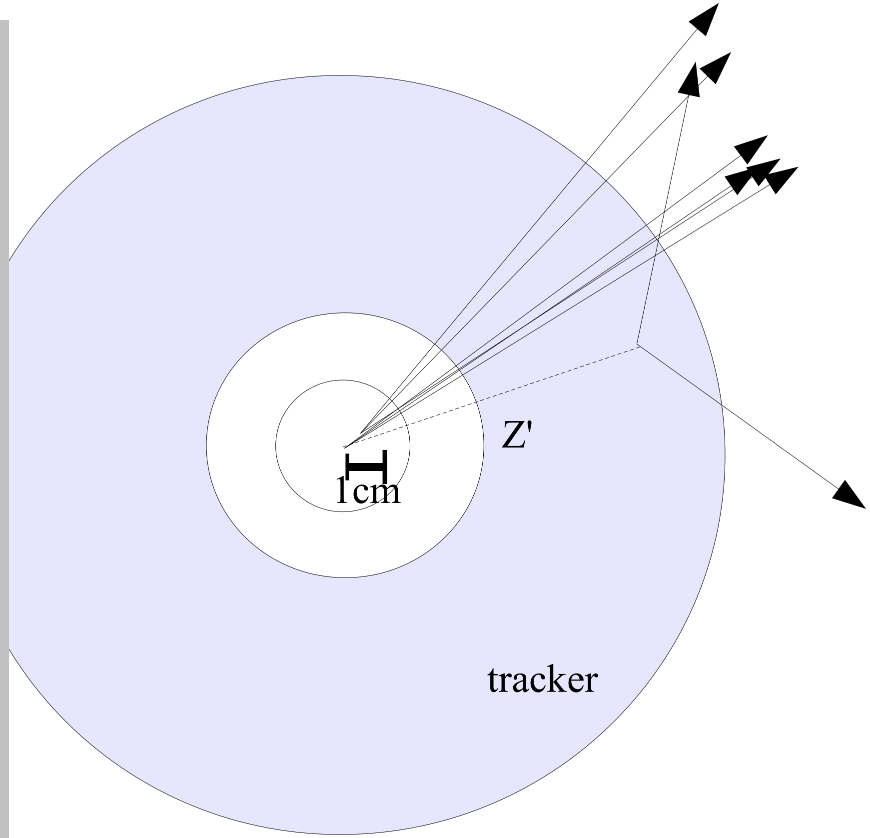
- *Dedicated analysis, triggers, and (sometimes) detectors required!*
- Difficult, but interesting
- Not my day job (I do Higgs)!

Two examples of long-lived particles in this talk:

- Stopped gluino
- Neutral scalar -> b+b

Many more possibilities:

- Magnetic monopoles
- Charged heavy long-lived particle
- Long-lived particles decaying to photon, Z
- ...



SU/SY

Normal SUSY has the mass of scalars near the EW scale

- Stabilize the Higgs mass

Higgs mass is stabilized by something else?

- Anthropic principle?

Scalars not protected by symmetries

- could be heavy (GUT-scale)

Fermions protected by chiral symmetries

- gluinos, neutralinos still light (Weak-scale)

Still get all the other nice things from SUSY

- Unification of gauge forces (doesn't depend on scalar masses!)
- Dark matter
- The right symmetries for string theory, at high energy

And a bonus! Suppression of stuff we *don't* see!

- FCNC's, EDM's, stop quarks, tri-leptons, etc...

Stopped Gluinos

Gluino is long-lived
-> *hadronizes* into "R-hadrons"

Some lose enough momentum through ionization
-> *stop in the calorimeters*

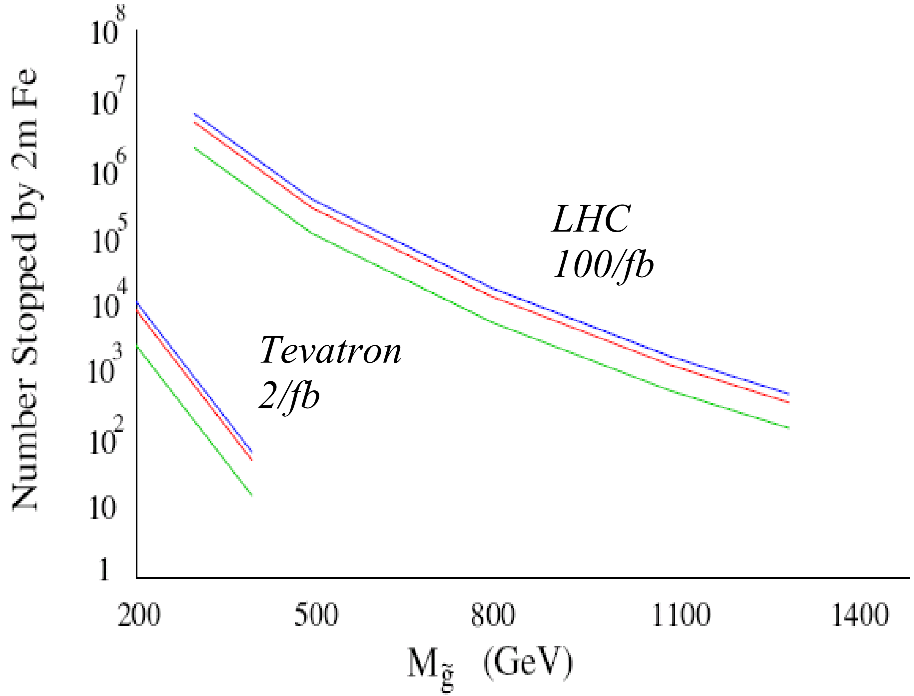
- Decay *later* into gluon+LSP
- Lifetime depends on M_{SUSY}
- See hep-ph/0506242, J. Wacker

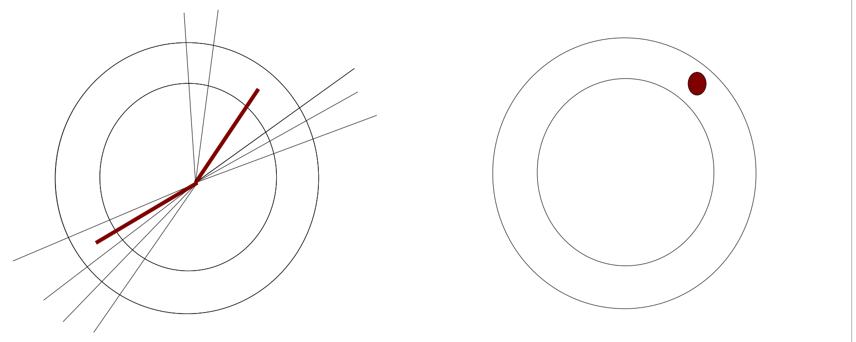
Signature:

- large, isolated energy deposit in the calorimeter
- rest of the "event" very empty

First search where the decay is *in a different bunch crossing* than the production!

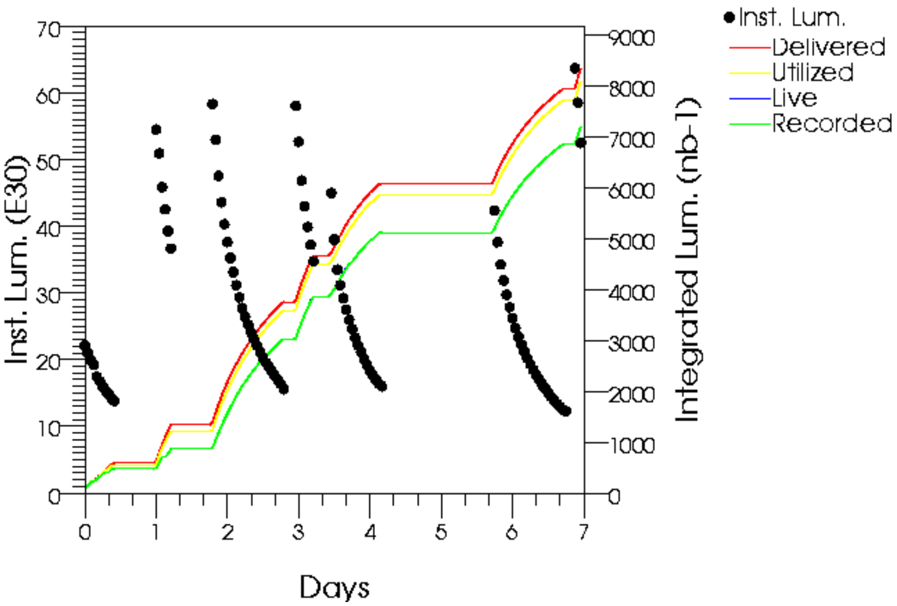
~500 stopped gluinos in 2/fb for m_g=300 GeV
~5 stopped gluinos in 2/fb for m_g=500 GeV

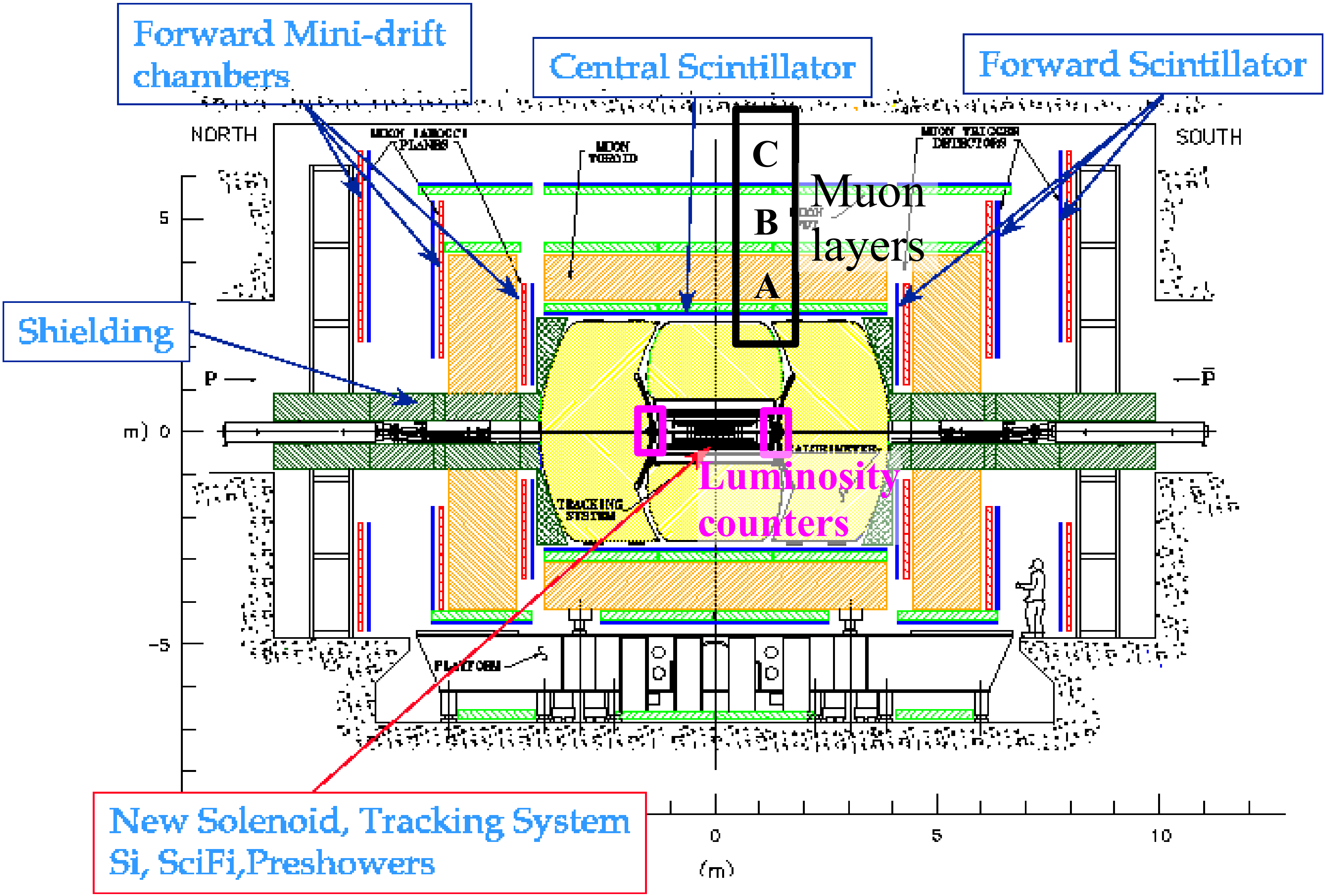




The Tevatron at Fermilab

- 1 km radius p-pbar super-synchrotron
- World's most powerful: 1.96 TeV
- 36 bunches of p/pbar, 396 ns crossing period
- About one "store" per day
- ~3/fb on tape so far




Forward Mini-drift chambers
Central Scintillator
Forward Scintillator
NORTH
SOUTH
C
B
A
Muon layers
Shielding
P
P̄
TRACKING SYSTEM
PLATFORM
Luminosity counters
New Solenoid, Tracking System
Si, SciFi,Preshowers
5
0
-5
10
(m)

Stopped Gluino Simulation

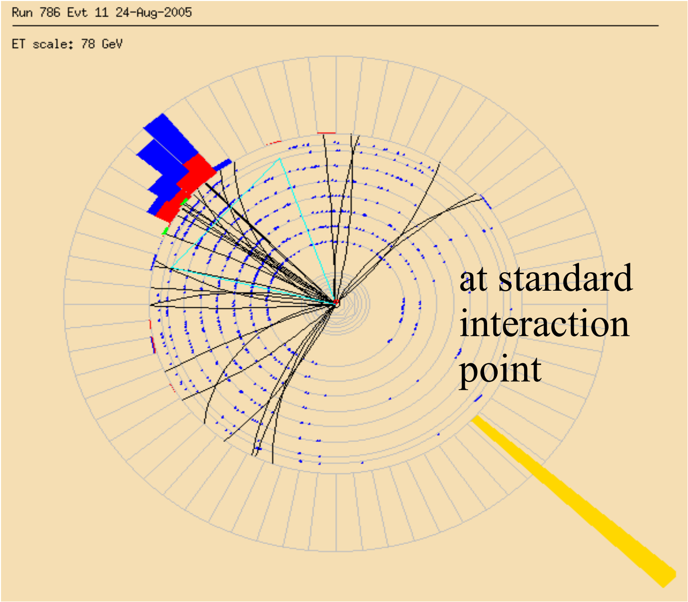
The stopped gluino decay produces a single high-energy gluon (balanced by missing energy)

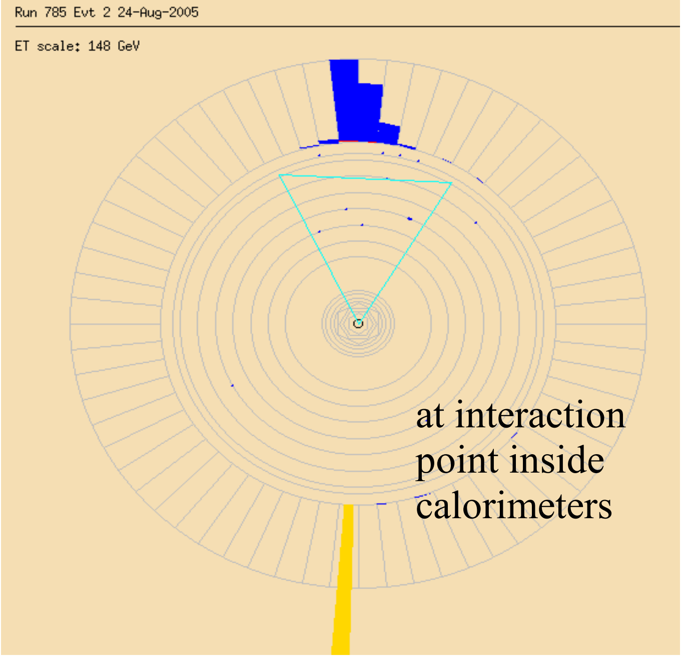
Simulate using Pythia and our detector simulation

Decay location is in the middle of the calorimeter

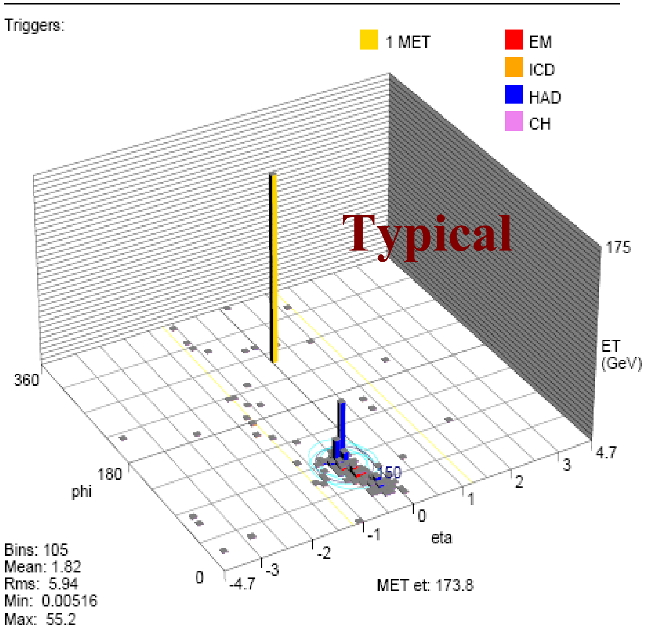
- Custom modifications needed
- Further weighting of events by vertex location to match the distribution expected from stopping gluinos

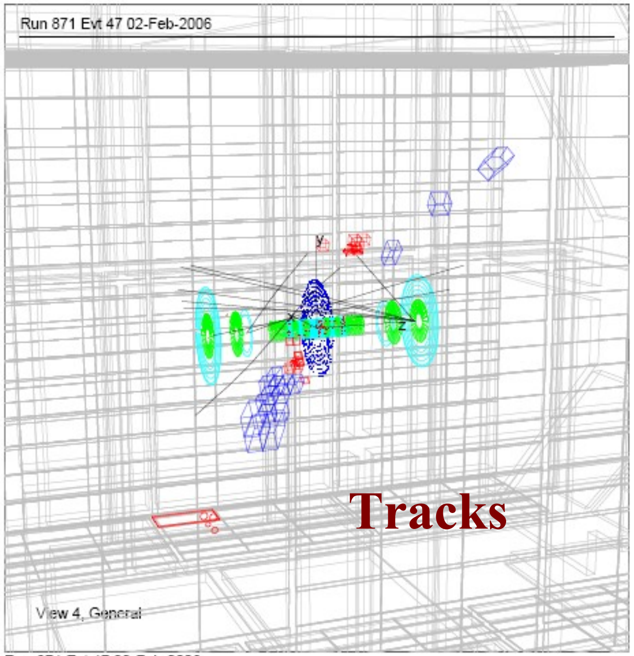
ATLAS simulates the full production, stopping, and decay - fancy!

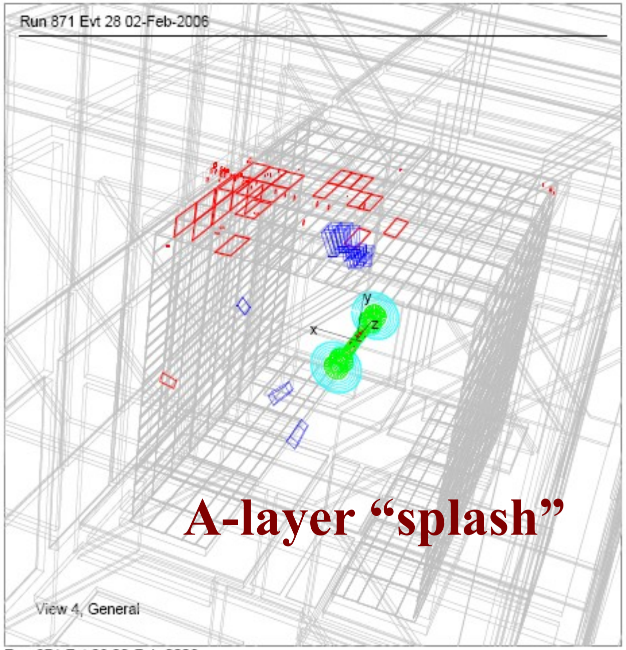


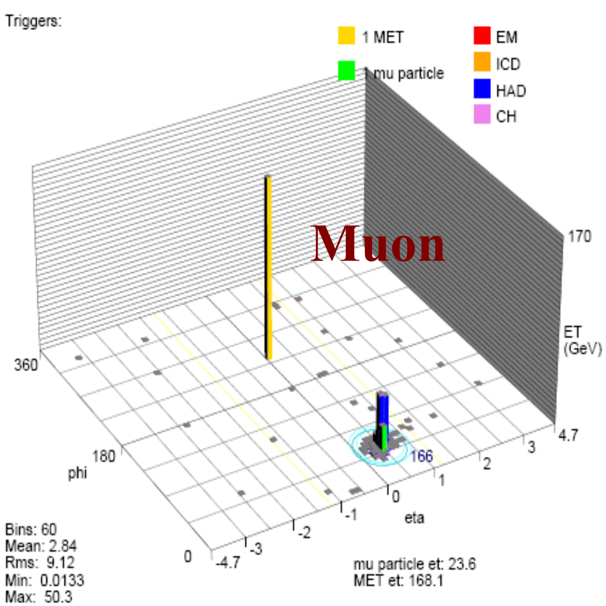


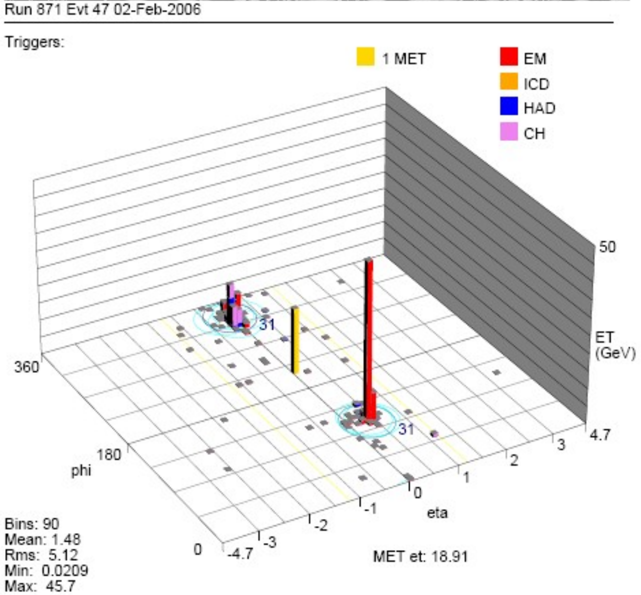
Simulation

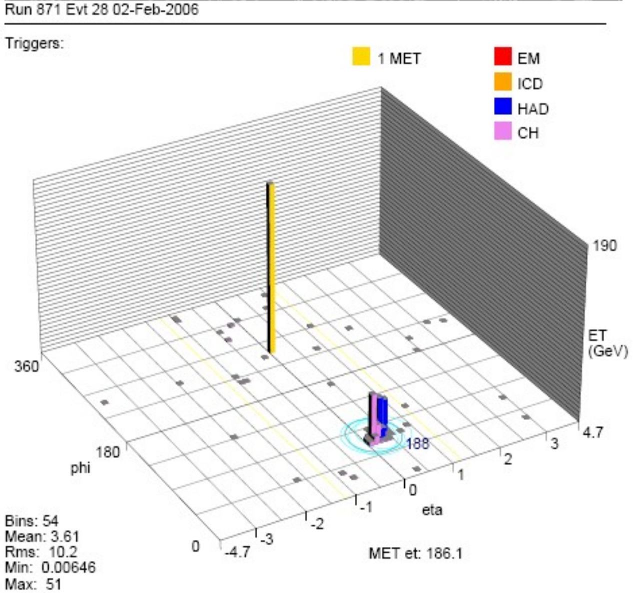

Triggers:
1 MET
EM
ICD
HAD
CH
Typical
175
ET (GeV)
360
180
phi
0
4.7
3
2
1
0
-1
-2
-3
-4.7
eta
150
Bins: 105
Mean: 1.82
Rms: 5.94
Min: 0.00516
Max: 55.2
MET et: 173.8


Run 871 Evt 47 02-Feb-2006
Tracks
View 4, General
Run 871 Evt 47 02-Feb-2006


Run 871 Evt 28 02-Feb-2006
A-layer "splash"
View 4, General
Run 871 Evt 28 02-Feb-2006


Triggers:
1 MET
mu particle
EM
ICD
HAD
CH
Muon
170
ET (GeV)
360
180
phi
0
4.7
166
eta
Bins: 60
Mean: 2.84
Rms: 9.12
Min: 0.0133
Max: 50.3
mu particle et: 23.6
MET et: 168.1


Triggers:
1 MET
EM
ICD
HAD
CH
50
ET (GeV)
360
180
phi
0
4.7
31
31
eta
Bins: 90
Mean: 1.48
Rms: 5.12
Min: 0.0209
Max: 45.7
MET et: 18.91


Triggers:
1 MET
EM
ICD
HAD
CH
190
ET (GeV)
360
180
phi
0
4.7
188
eta
Bins: 54
Mean: 3.61
Rms: 10.2
Min: 0.00646
Max: 51
MET et: 186.1

Signal Distributions

Gluino jets look like normal jets...

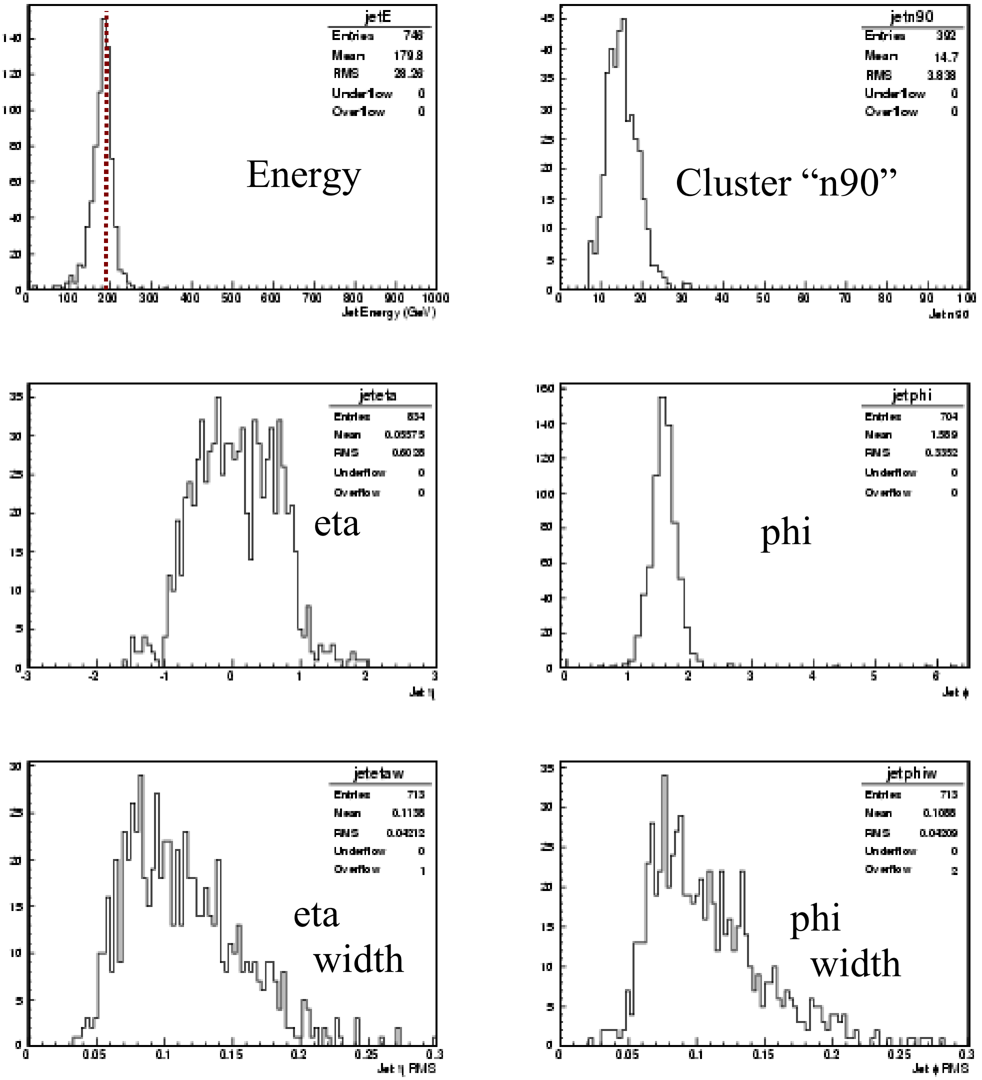
- They are wide (phiwidth,etawidth > 0.08)
- *Good discriminant against muon-induced showers !*

Peak in the jet energy, related to gluino and neutralino masses:

$$E = (M_{\tilde{g}}^2 - M_{\tilde{\chi}_1^0}^2)/2M_{\tilde{g}}$$

Plots from mG=400 GeV sample

E (jet) = (400^2-90^2)/(2*400) ~ 190 GeV



Data Sample

Want an empty event with a large calorimeter shower

Use “GAPSN” triggers – already in place for diffractive physics

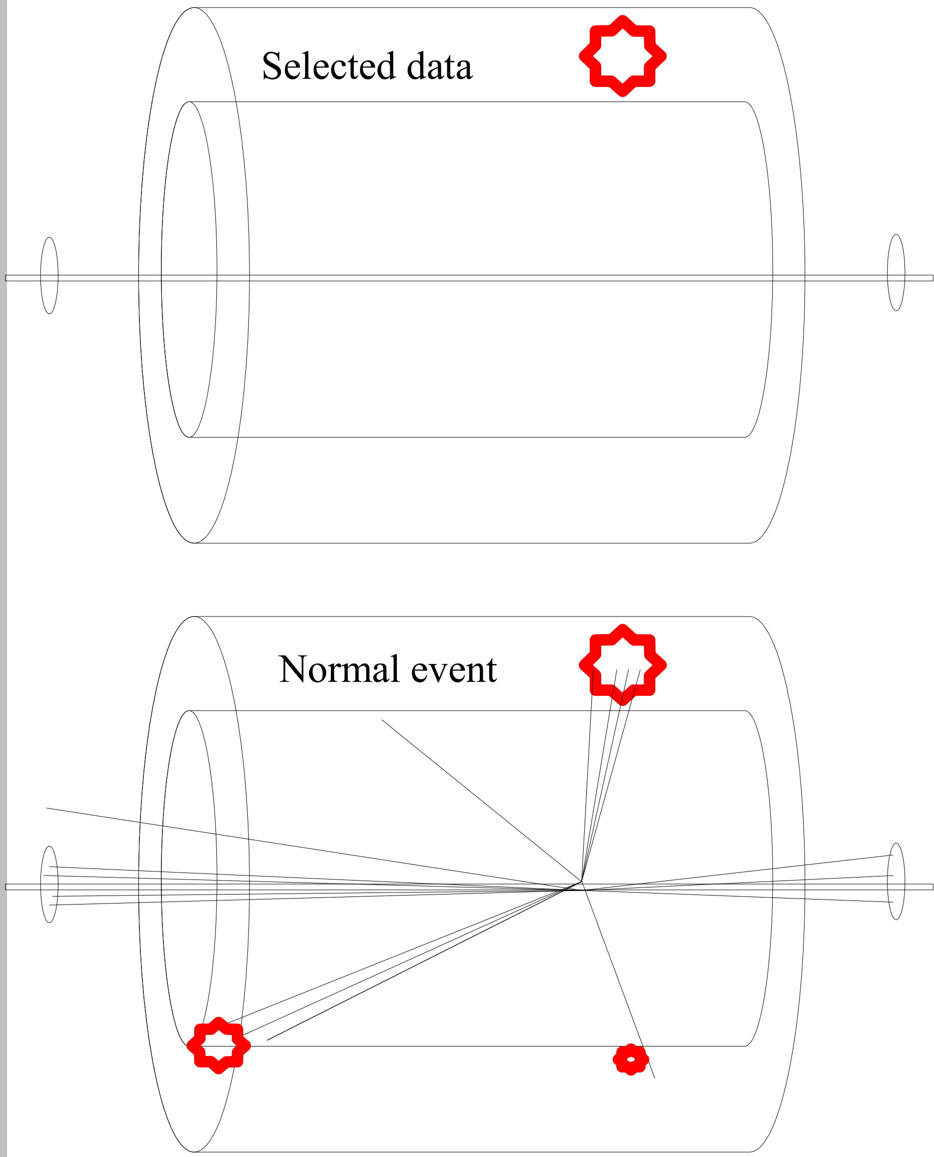
- Require *no hits in either the North or South luminosity counters (scintillators)*
- Require a E_T > 45 GeV “jet”

Offline pre-selection cuts:

- Require one jet with E>90 GeV
- Veto on any other jets (above E_T of 8 GeV)
- No vertex found using tracking detectors

~1 million events

- *What are all these?*



Cosmic Muons

A major background, due to high rate

Usually at least one (BC layer) muon segment

- Two chances to see the muon

Showers in the calorimeter can be quite large (>1TeV!)

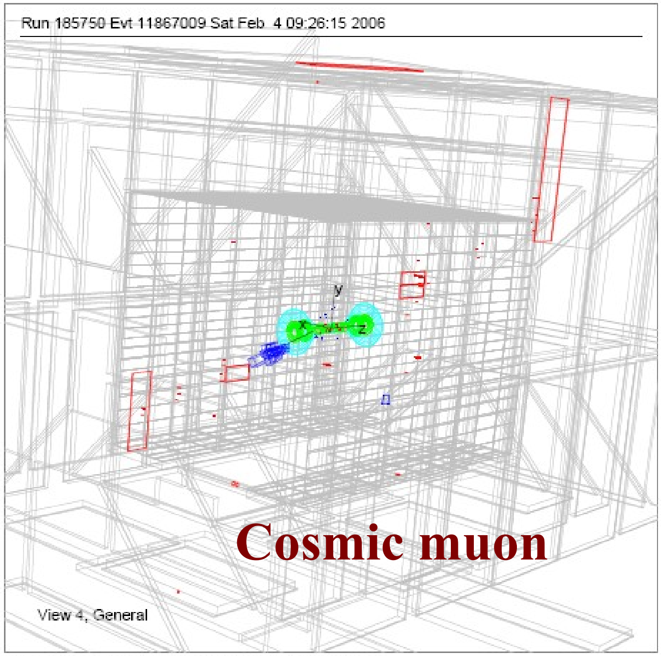
Hard Bremsstrahlung photon is dominant

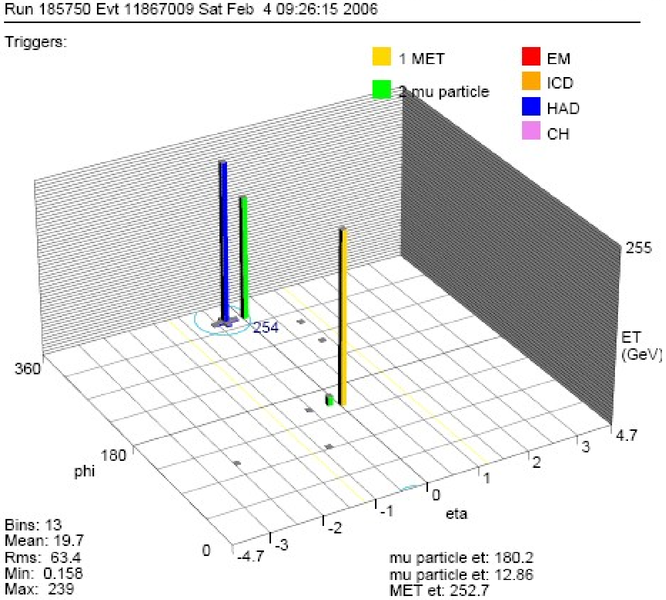
- Narrower showers than “jets”:
  - More energy in single cells (n90 < 5)
  - Smaller phi- and eta-width (<0.08)

But *hadronic* showers are also possible

Visible MIP trail from muon about half the time

- No dedicated algorithm available
- A difficult reconstruction problem
- Can be faked by gluino jets as well
- Not used in the analysis





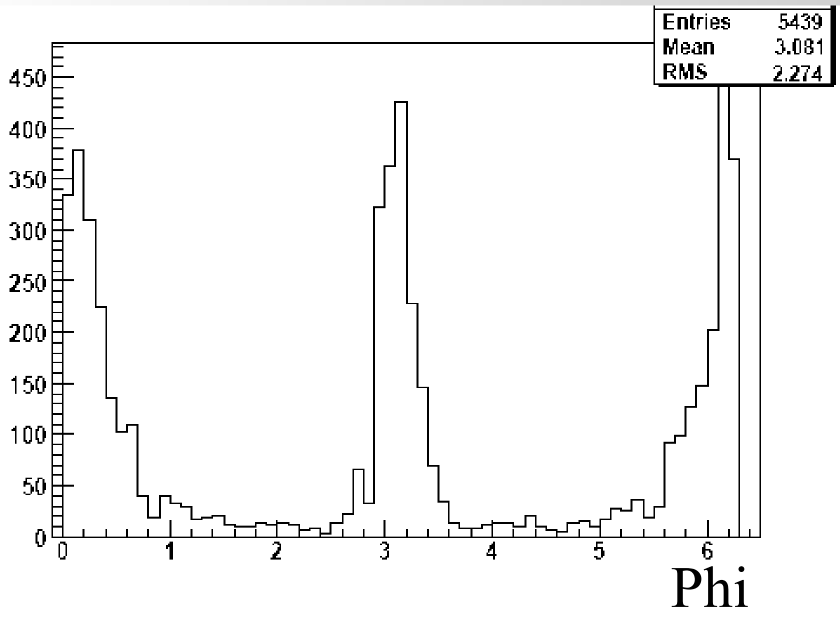
Beam Muons

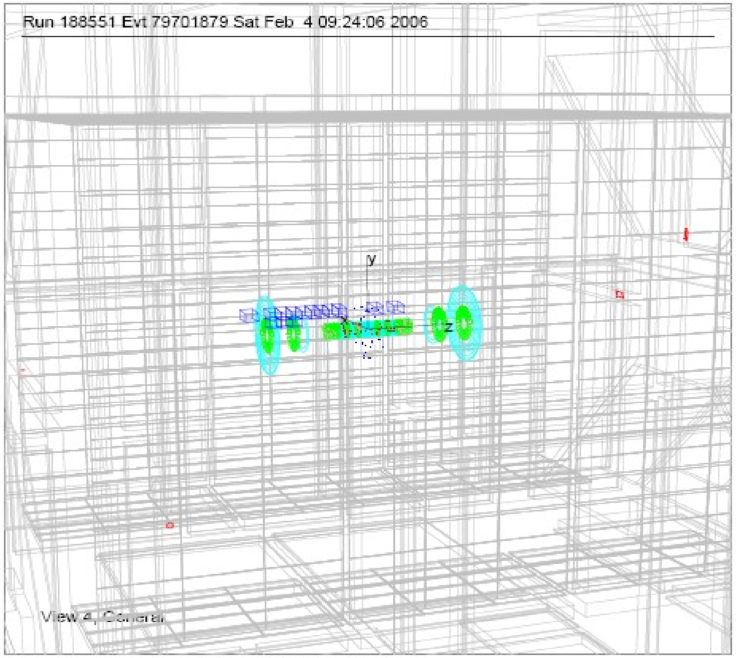
Protons (or anti-protons) hit gas or the beampipe and create pions, which decay to muons

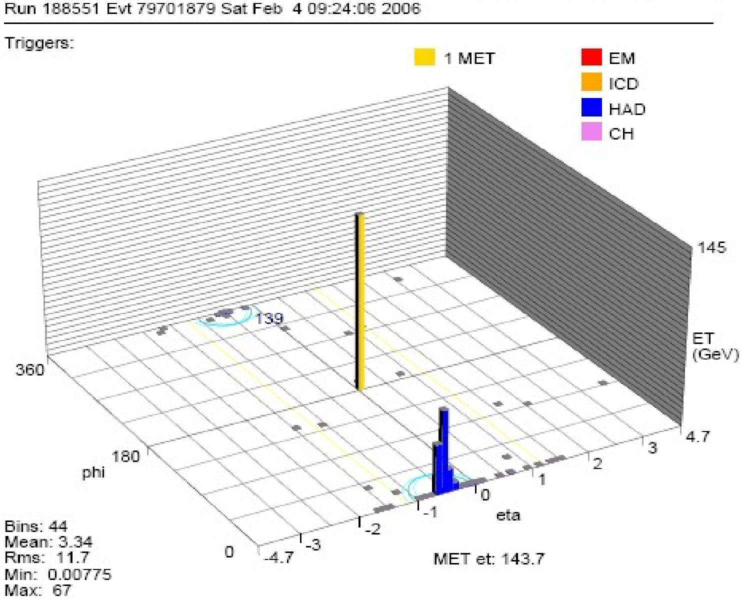
In the plane of the beam!

The shower is very narrow in phi (<0.08) but relatively wide in eta (>0.05)

Often a forward muon segment, or scintillator hits… "in time" (|t|<10ns)







Beam Muons

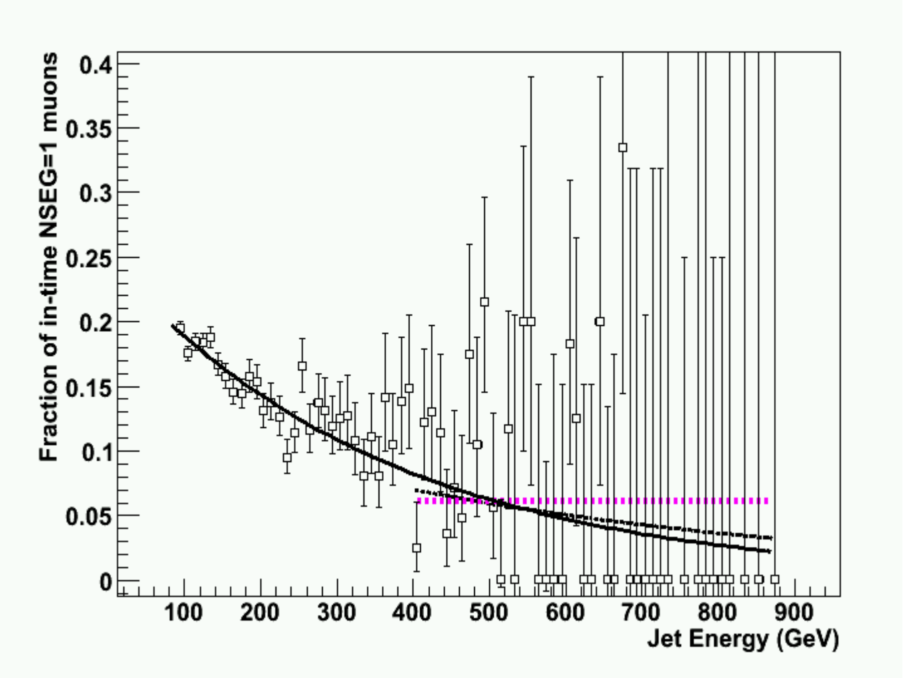
Negligible contribution to the wide-shower data

But narrow-shower data contain a contribution from beam muons

Study the properties of beam muons by looking at “in time” vs. “out of time” muons

Beam muons are removed *from the narrow-shower data* by requiring:

- not in regions around integer values of phi/pi
- looking at high energy showers

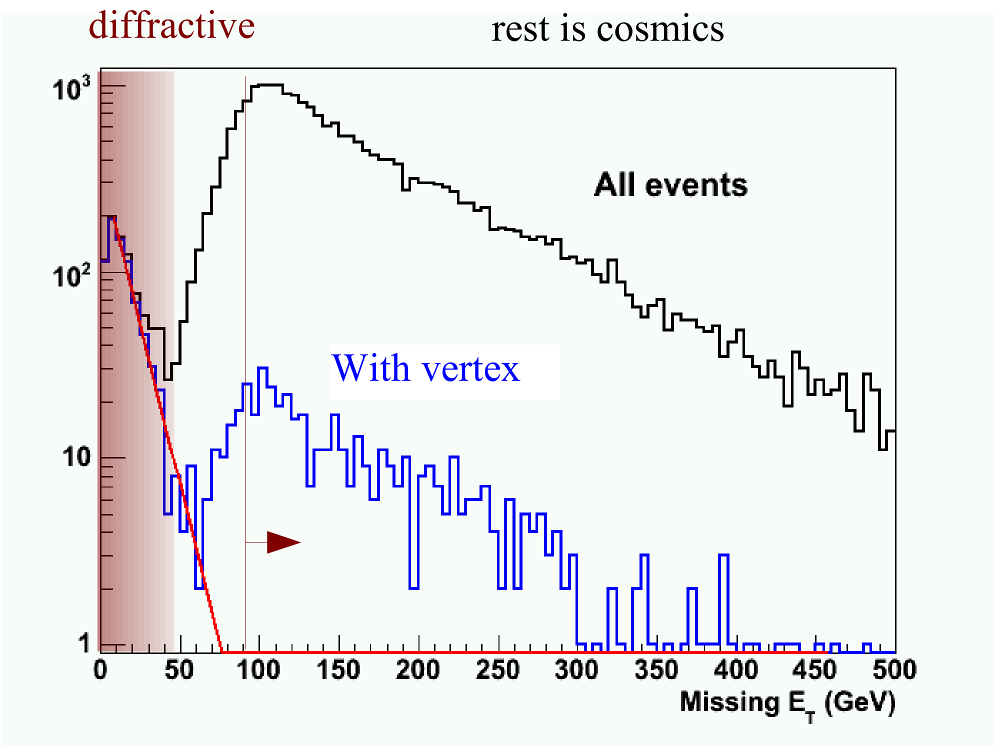


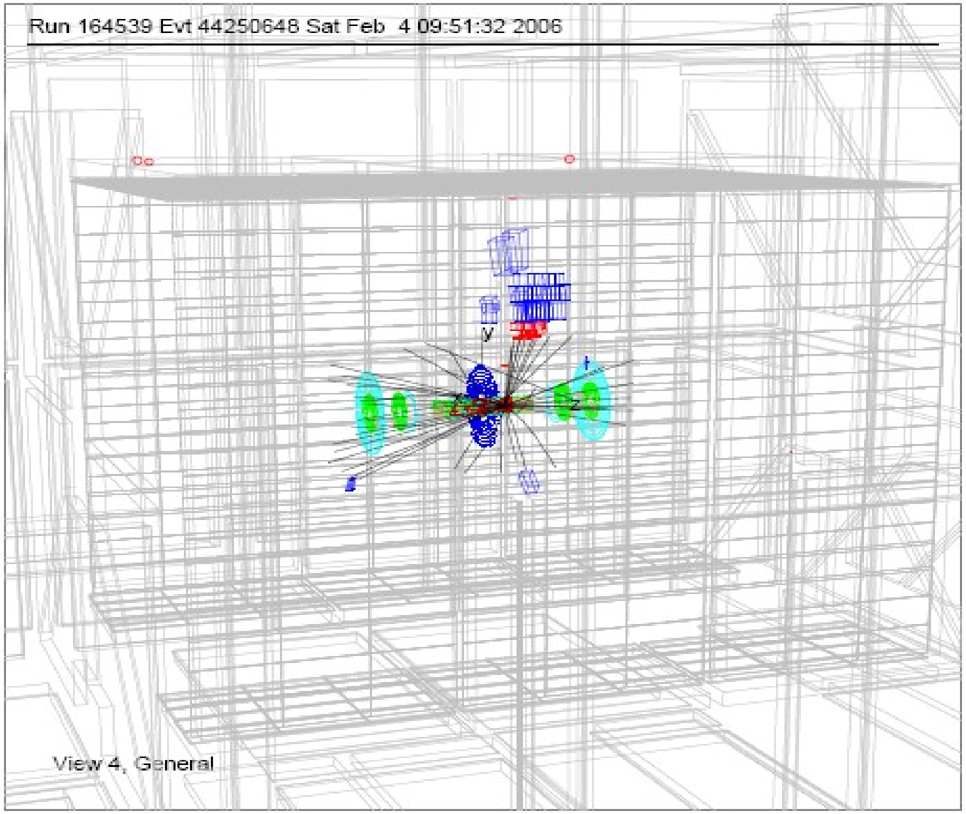
Diffractive Background

Double-diffractive events?

- Require no Primary Vertex
- Require large MET (1 jet, E>90 GeV)

Negligible background after cuts





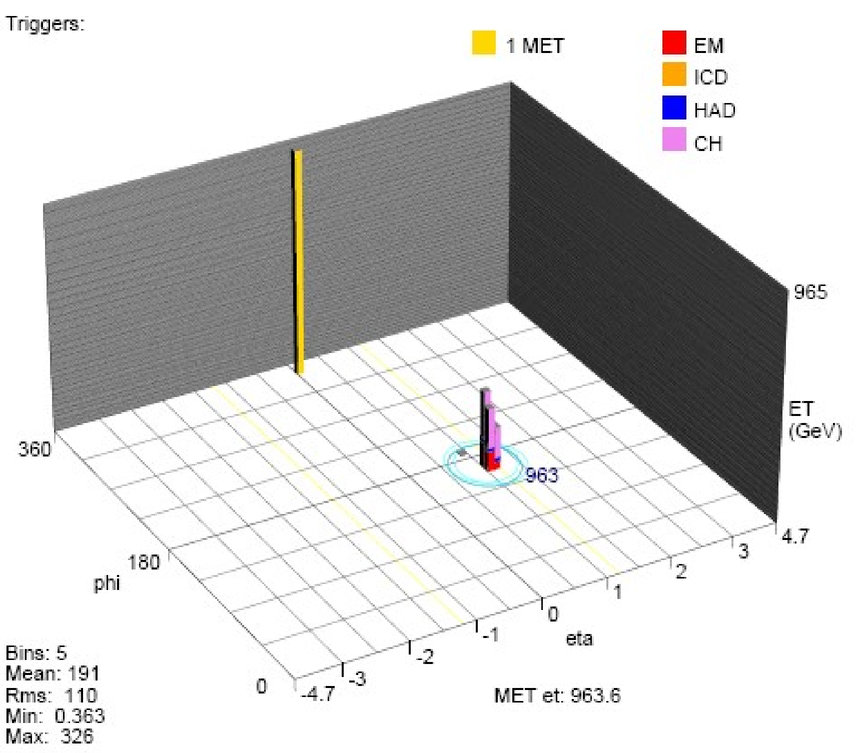
Detector “Problems”

Detector problems tend to be

- in isolated eta-phi regions
- in isolated data-taking periods

They really don't look like jets at all

No sign of remaining detector issues after cuts



Cosmic Neutrons

Cosmic neutrons reach sea-level...

No muon segment, wide shower!

Rate is 1/1000th of cosmic muons at the same energy... ~1/hour on detector

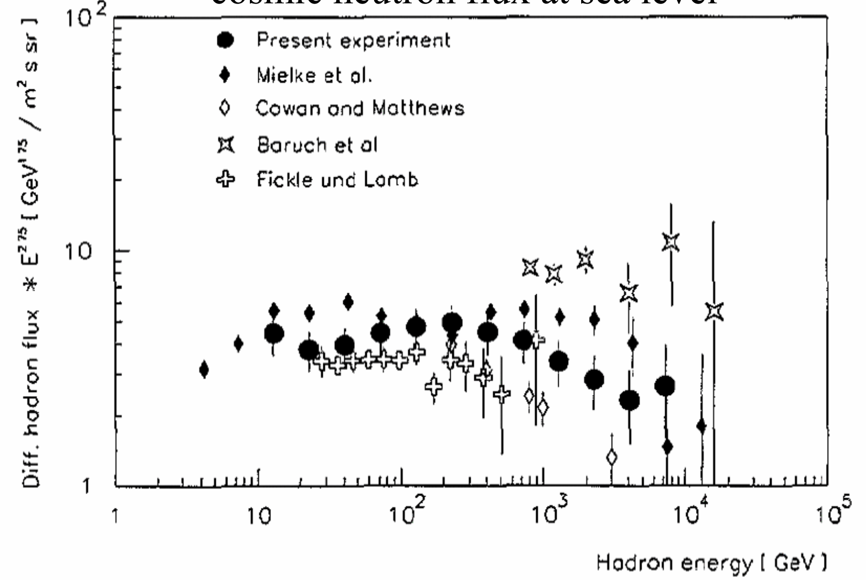
Have to get through the iron toroids

Neutrons would deposit most of their energy in the Coarse Hadronic calorimeter (on the outside)

- We don't trigger on CH energy

No excess of wide-shower no-muon events on the outside of the calorimeter is seen

cosmic neutron flux at sea level



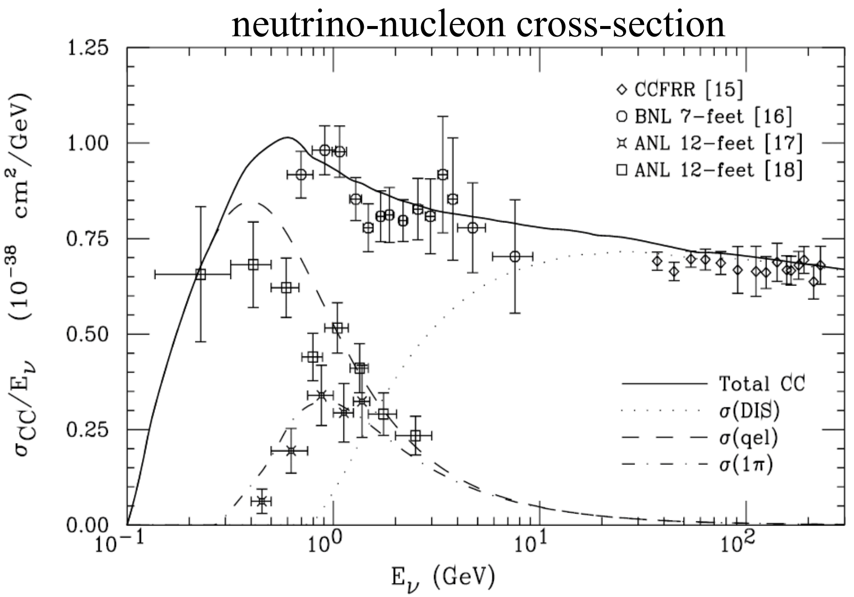
Cosmic Neutrinos

Neutrinos would be a small background:

- Assuming a 1/1 ratio of muons/neutrinos from cosmic sources:

  0.1 Hz / 0.1% Brem *
  6e23 * 17g/cm^3 / 238 g/mole *
  400cm *
  10e-38cm^2/GeV *
  500 GeV =

10e-8Hz = ***0.1/year***



Candidate Selection

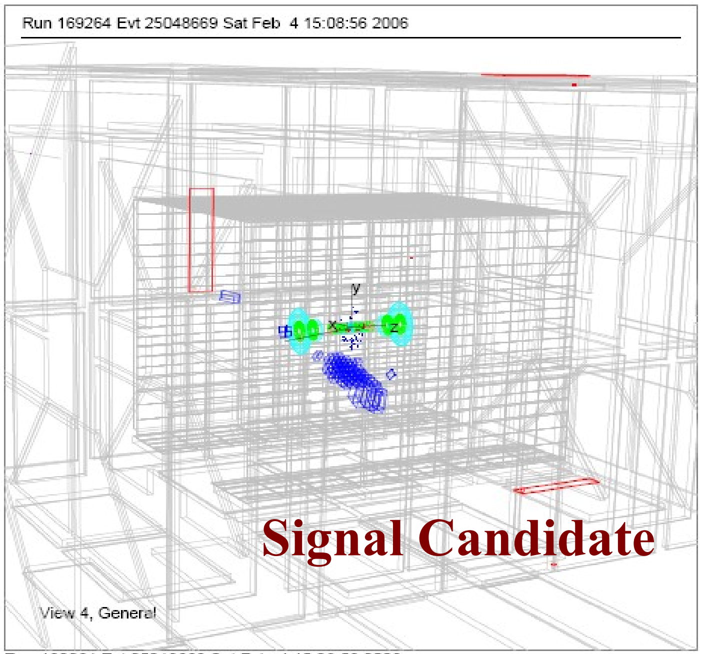
"Wide jet showers":

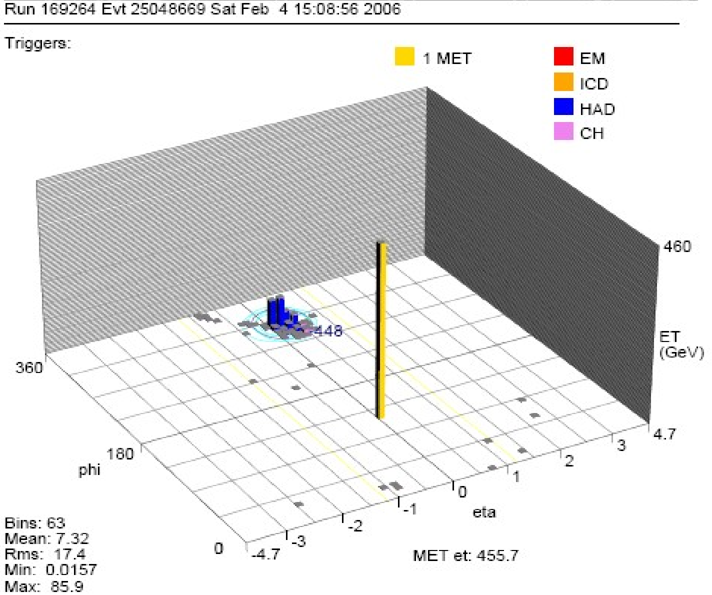
- d_eta > 0.08 and d_phi > 0.08
- n90 >= 10

"No-muon showers"

- No B,C -layer muons
- dphi between A-layer muons <1.5
- dphi (muon, jet) <1.5

A candidate signal event passes both the "wide-jet" and "no-muon" criteria



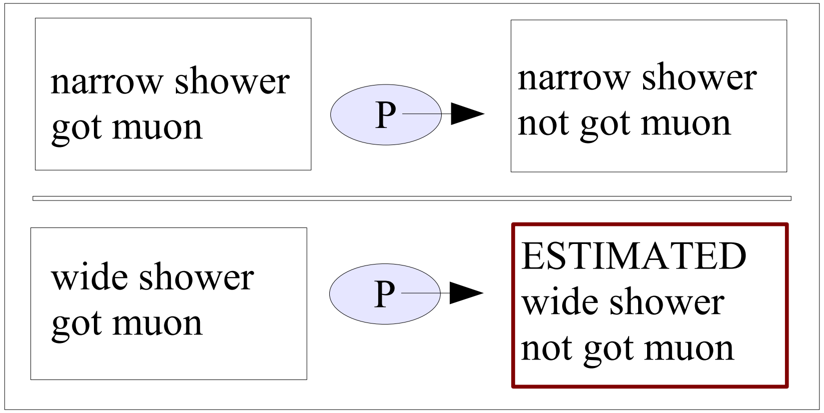


Cosmic Background Estimation

Want to know the fraction of wide-showering, cosmic muon events for which we don't reconstruct the muon

- Detector inefficiency / acceptance

Measure probability to lose muon in the *narrow-showering*, cosmic muon data sample



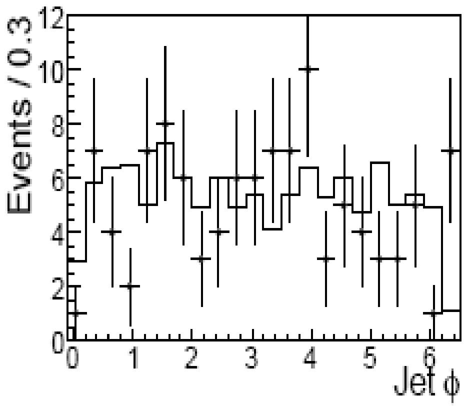
Data / Background Comparison

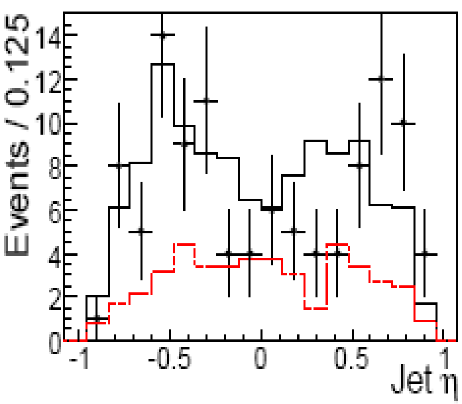
Remove beam-muon contribution to narrow-jet data

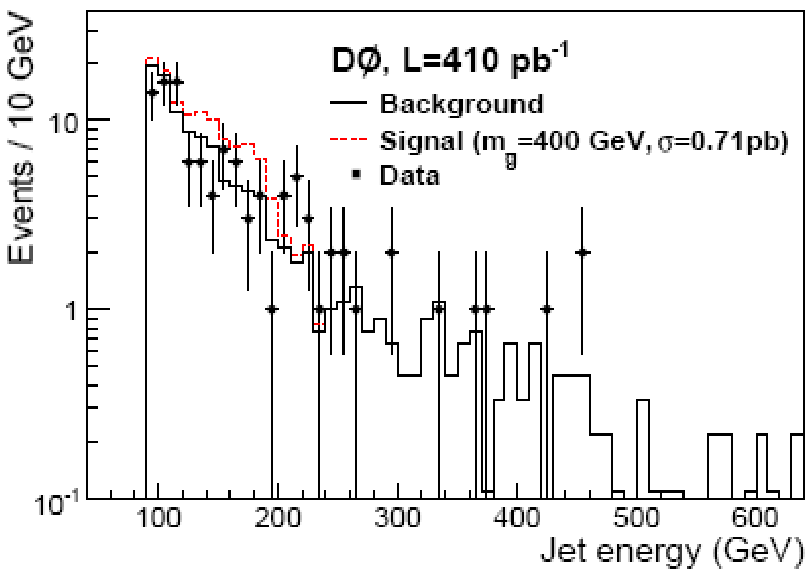
Left with a cosmic-muon narrow-shower data sample

Measure P_nomu = 0.11+-.01

Good data/background agreement in wide-shower energy spectrum





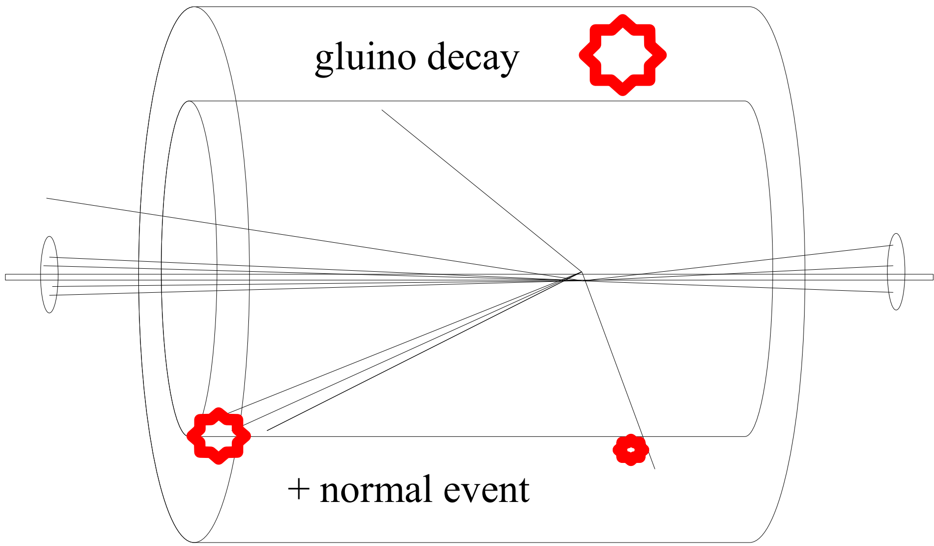


Signal Efficiency

Trigger "dead" if a ppbar collision takes place during the stopped gluino decay

Efficiency measured relative to a non-GAP high-ET jet trigger -> ~60%

- Averaged over all luminosities
- Corrections made for non-linear effects due to luminosity profile

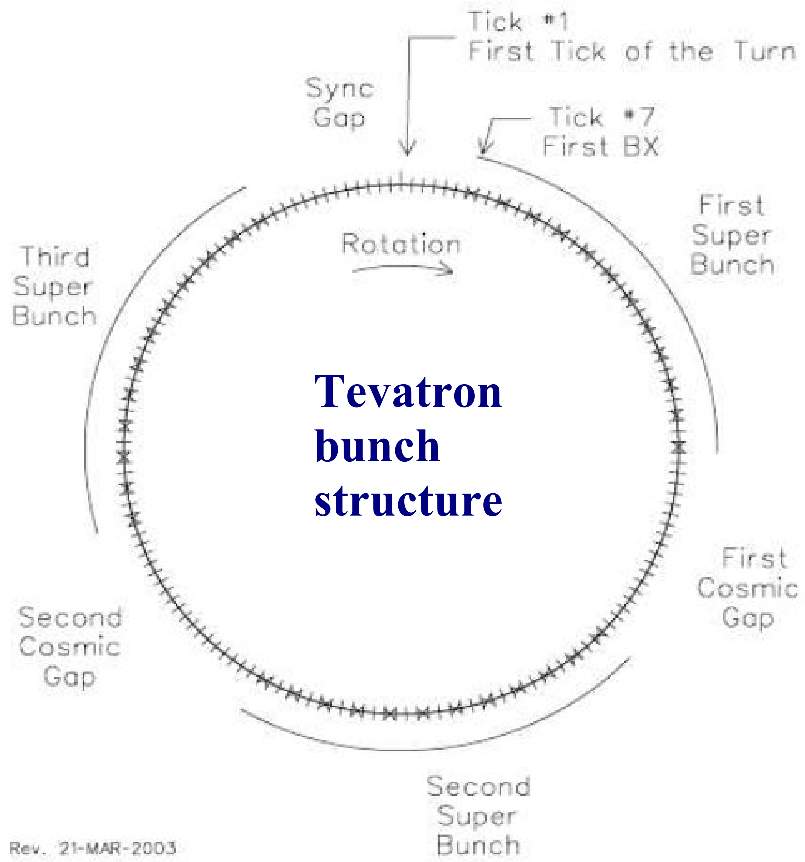


Signal Efficiency

Trigger is "dead" in the "gaps"

Just count the bunch crossings:

- 22% due to "cosmic gaps"
  -> could be recovered
- 11% in "sync gap"
  -> *not* recoverable

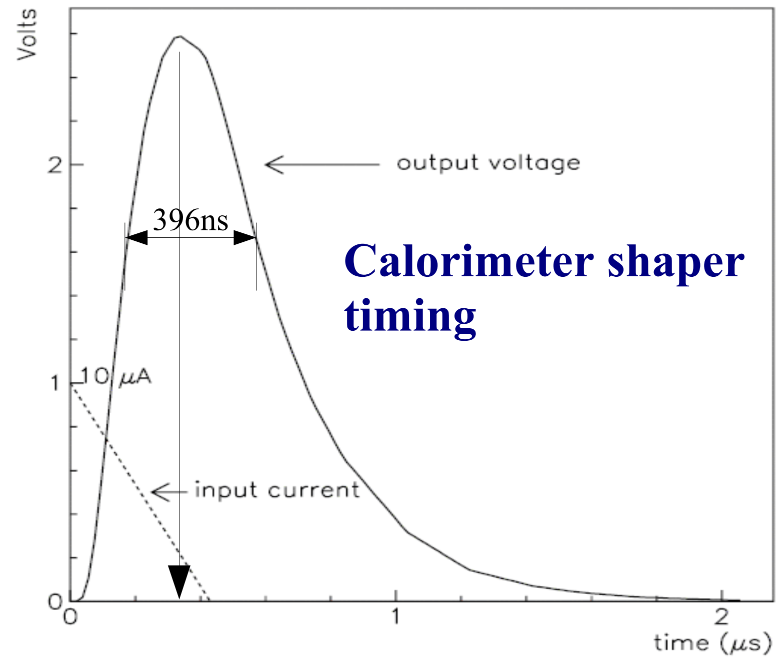


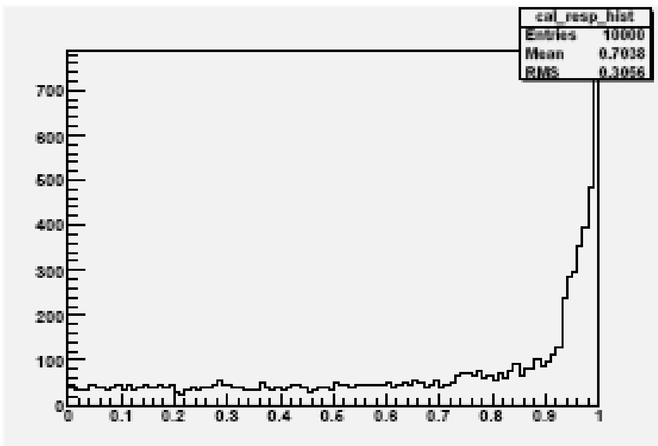
Out-of-time Calorimeter Energy

- Calorimeter electronics sample the shaped pulse in each cell only *once per 396ns – at the assumed signal peak*
- Out of time energy under-estimated!

- Look at cosmic muon events within the muon scintillator timing window
- Compare to the number of cosmic muons *observed* outside the window

- Simulate using info from calibration pulses





Visible jet energy fraction

Stopped Gluino Limits

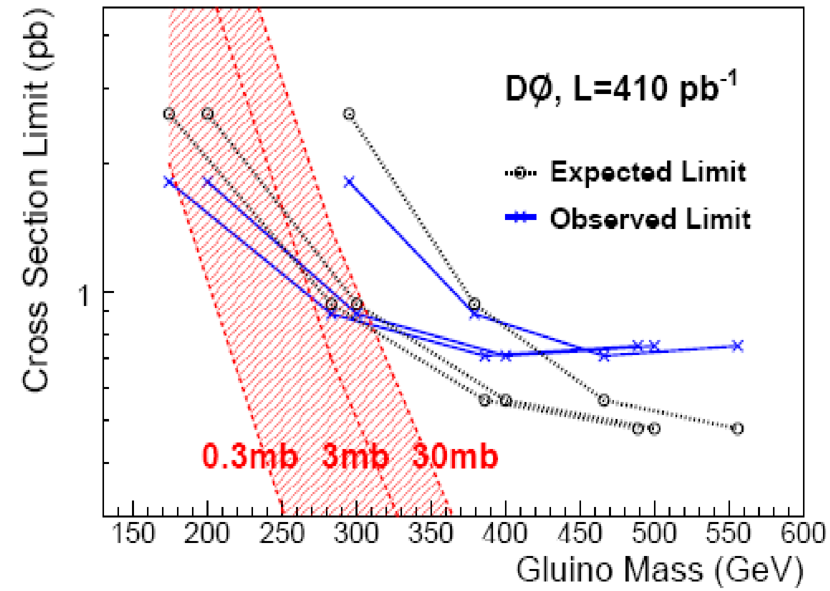
- Four jet energy ranges were chosen
- Count the number of signal, background, and data events in each energy range
- Set limits using Bayesian calculator
- Translate to limits on gluino mass, for given neutralino masses

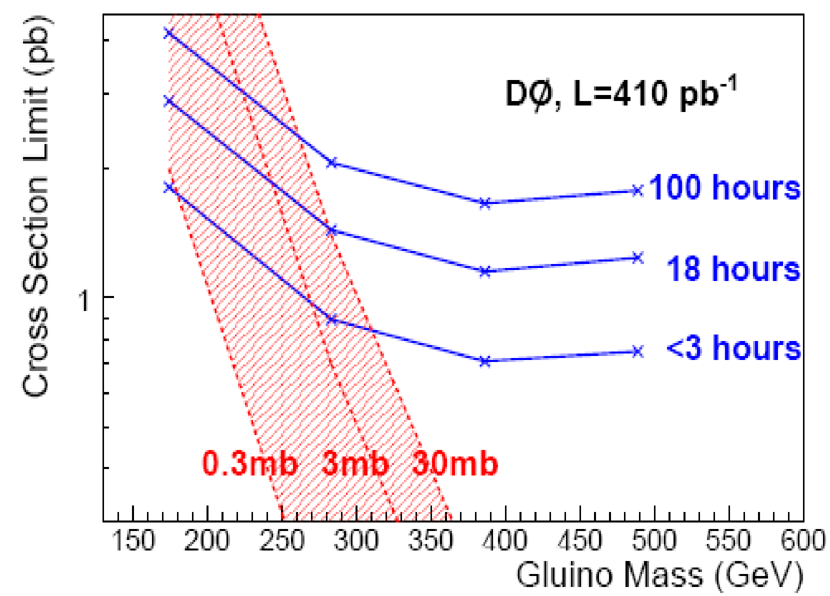
$$M_g = E + \sqrt{E^2 + M_{LSP}^2}$$

- Determine dependence on gluino lifetime
- Compare to theory predictions

Energy (GeV)	Data	Bgnd.	Eff.(%)	Exp. (pb)	Obs. (pb)
92.5–104.6	30	37±3.7	1.7±0.34	2.61	1.81
112.4–156.6	39	40±4.0	4.9±0.98	0.94	0.89
141.3–213.0	34	31±3.1	6.8±1.36	0.56	0.71
168.7–270.6	32	26±2.6	7.2±1.44	0.48	0.75

Phys. Rev. Lett. 99, 131801 (2007)





Future Stopped Gluino Searches

~10x more integrated luminosity on tape

Higher instantaneous luminosity

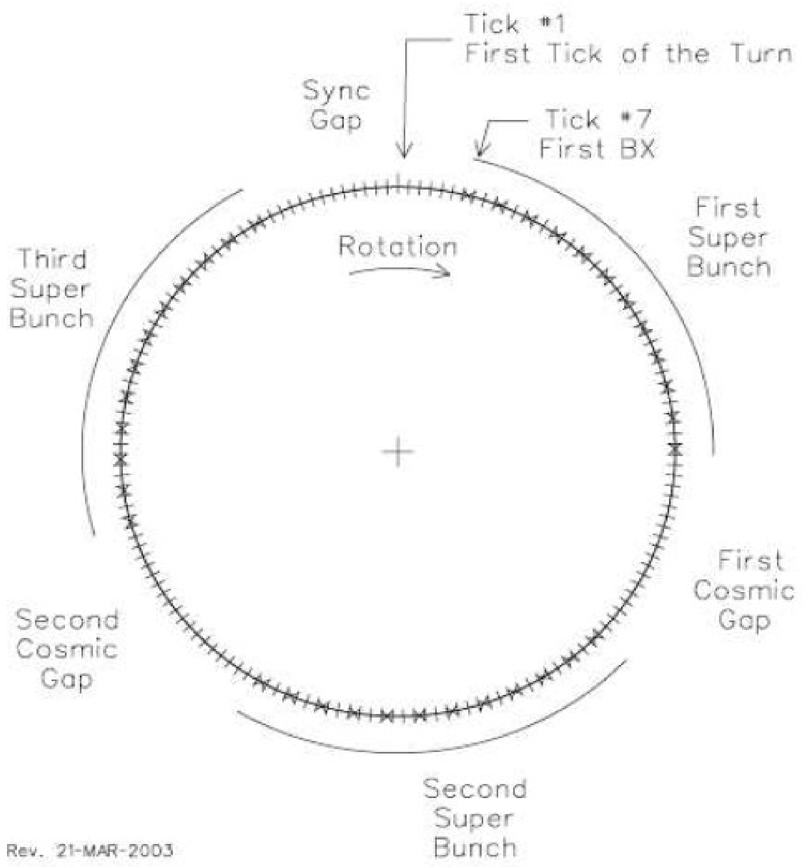
- proportionally less cosmic background!

But new trigger is needed
-> few empty crossings!

- Trigger during empty crossings
-> looking into this possibility at D0

~30% of gluinos have a pair-produced partner which also stopped

- *time-coincidence* of candidates



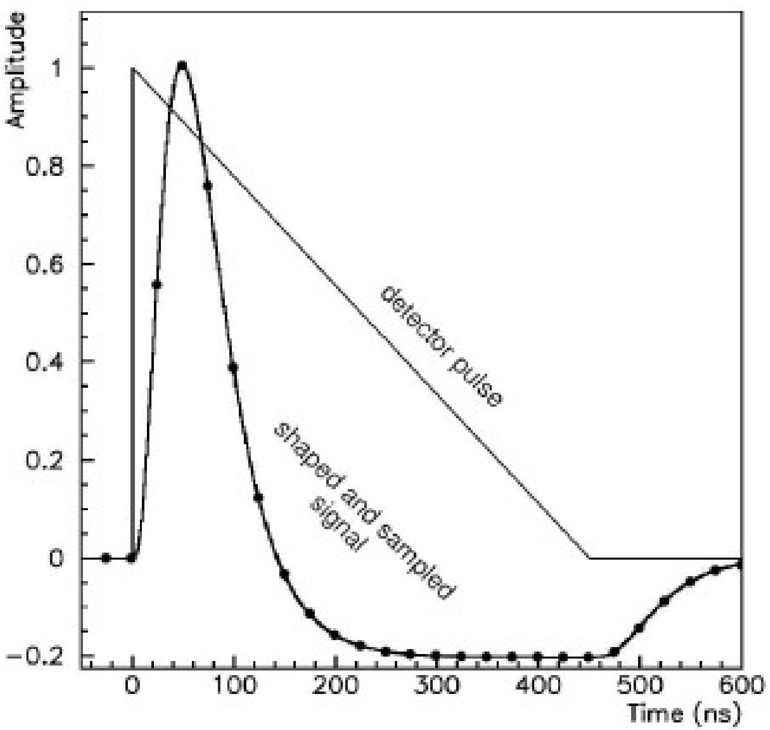
Future Stopped Gluino Searches

Some things get easier at ATLAS

- 14 TeV -> larger signal cross-section
- Higher bunch-crossing rate (25-75 vs. 396ns) and inst. luminosity
- Underground cavern (1/100th the cosmic rate)
- But no Iron toroid magnet
- *5 samples per crossing in LAr electronics*

But search faces new challenges

- Must trigger during empty crossings!
- How empty will empty crossings be?
- Beam-muon background?
- Cavern background?
- ...



Hidden Valley

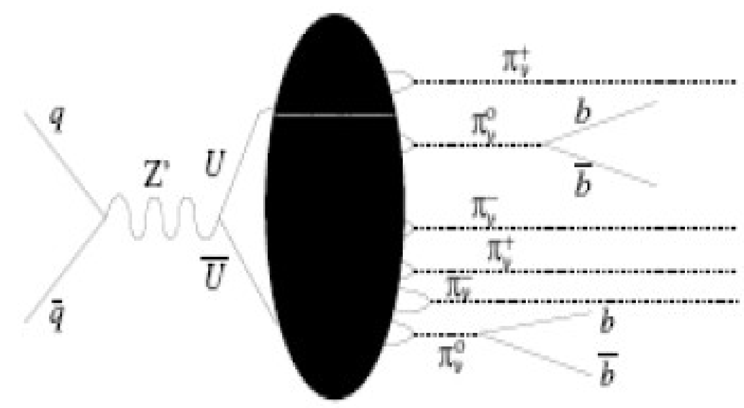
Neutral, long-lived scalars

Prefer to decay to heavier things

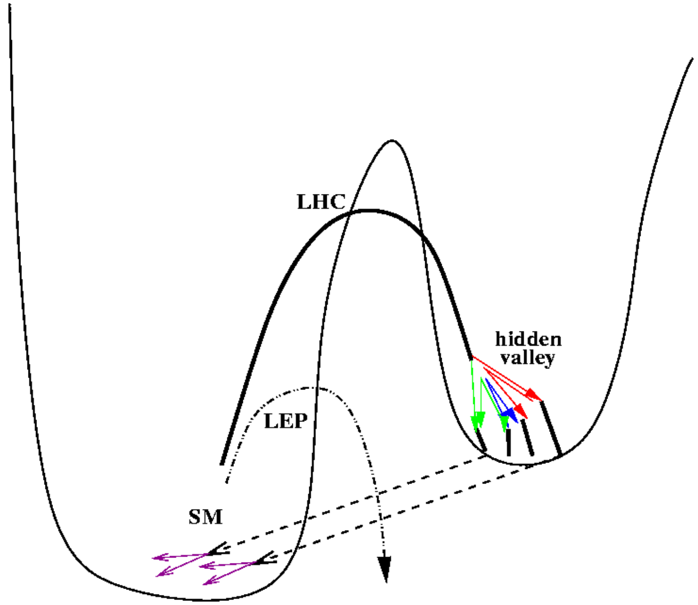
- Helicity suppressed
- like pion -> mu

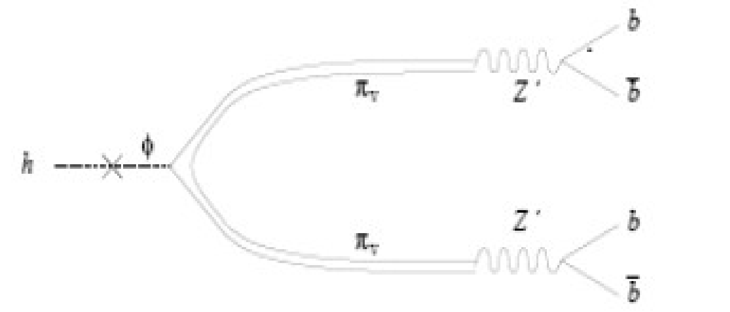
Study decay to bb

Strassler et al., hep-ph/0604261



A "v-hadron" event





1: Higgs decay to v-hadrons, each of which decays to $b\bar{b}$.

Hidden Valley Signal

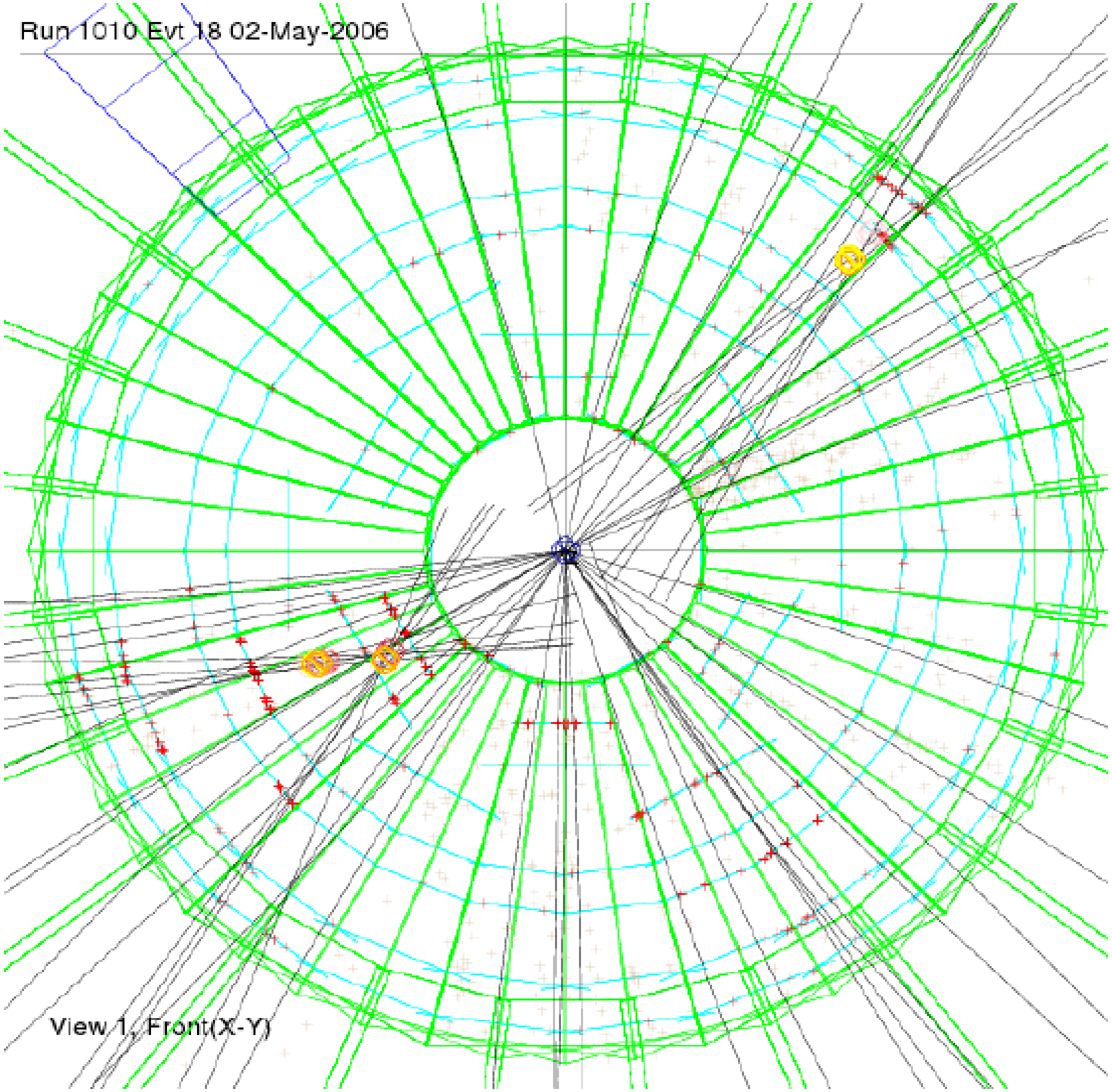
b-b vertex far from the beam

- >4 cm in XY
- Beyond distance from direct b production

Maybe another on the other side of the event

- Depends on lifetime

Can trigger on muon from the decay of a b-quark



Vertices in Data

Many vertices at large radius!

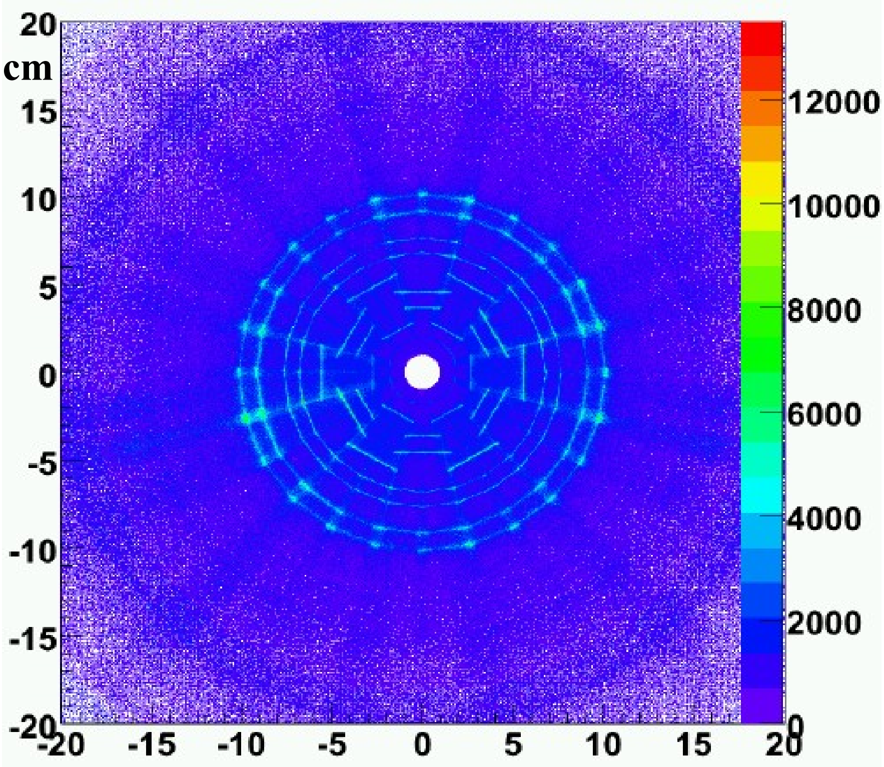
- *Dominated by material interactions with the detector*

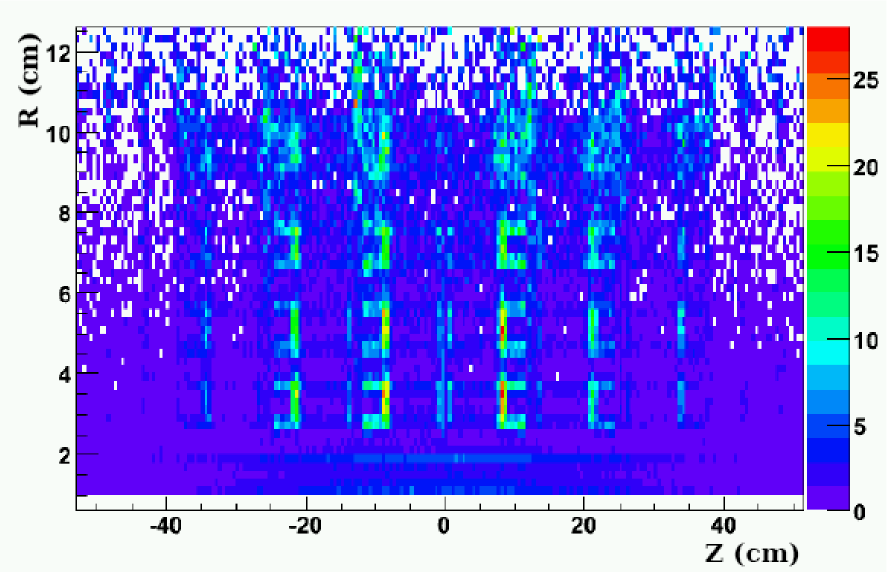
For low number of tracks (<4)

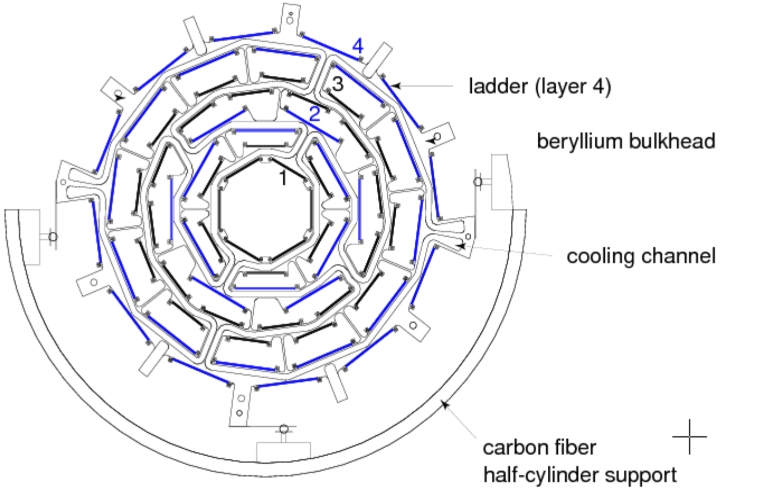
- Photon conversions
- In-flight decays (of known particles)

For high number of tracks (>5)

- Nuclear scattering...



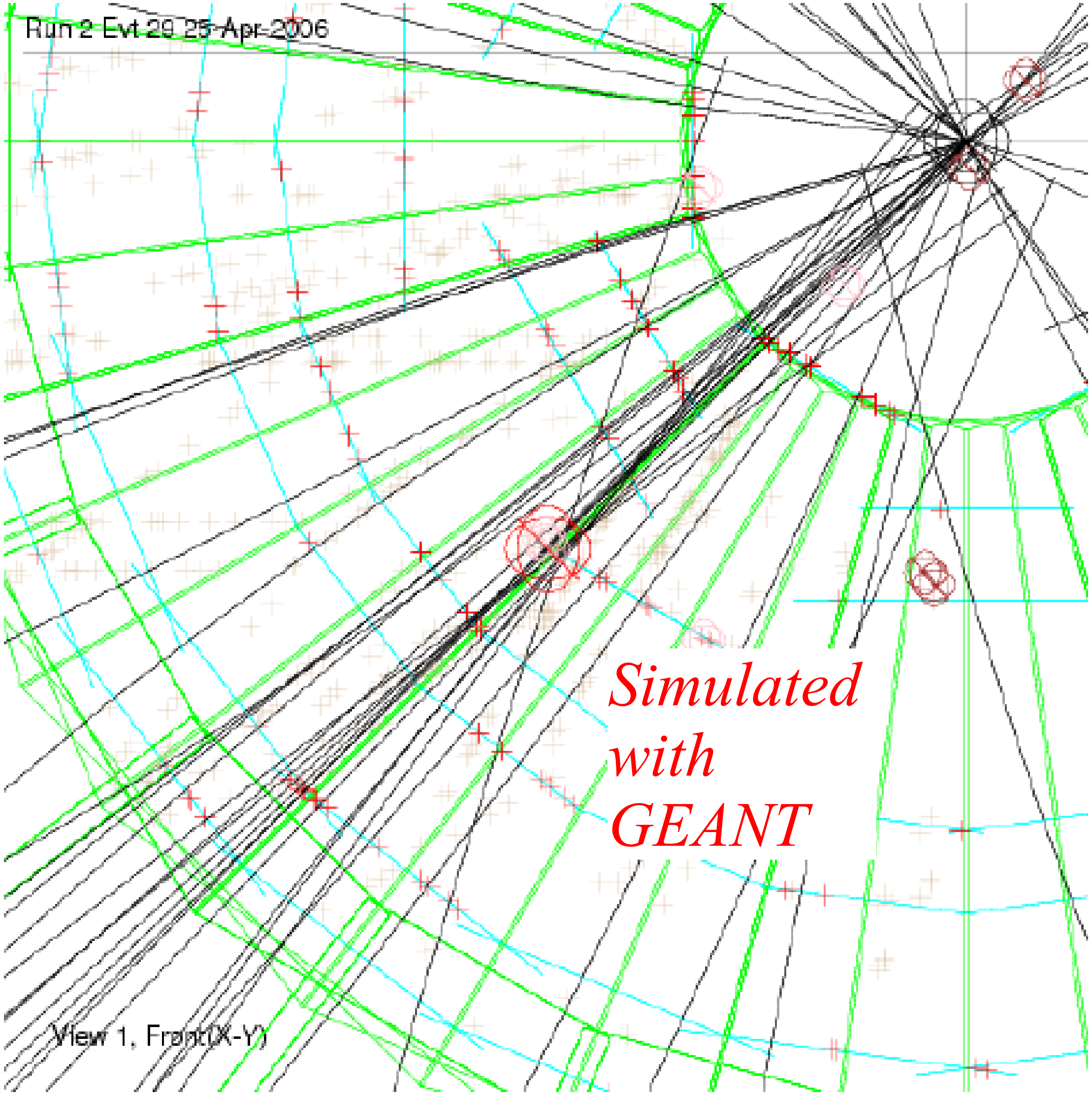




Background Simulation

GEANT does a good job of simulating these nuclear interactions!

Distributions of vertex mass, number of tracks, angles, etc. are in good agreement



Example event:
(material interaction, 6 tracks recoed)

heavy=0: x y z = -4.132 -4.036 24.15
parent's x y z = 0.0001604 -0.002776 19.68
dist = 5.774, isinoutputchunk =1

name = pi+[31.1], parent = K_L0 with pT (Epxpypz)= 69.05 (87.37 -49.42 -48.23 53.53) GeV

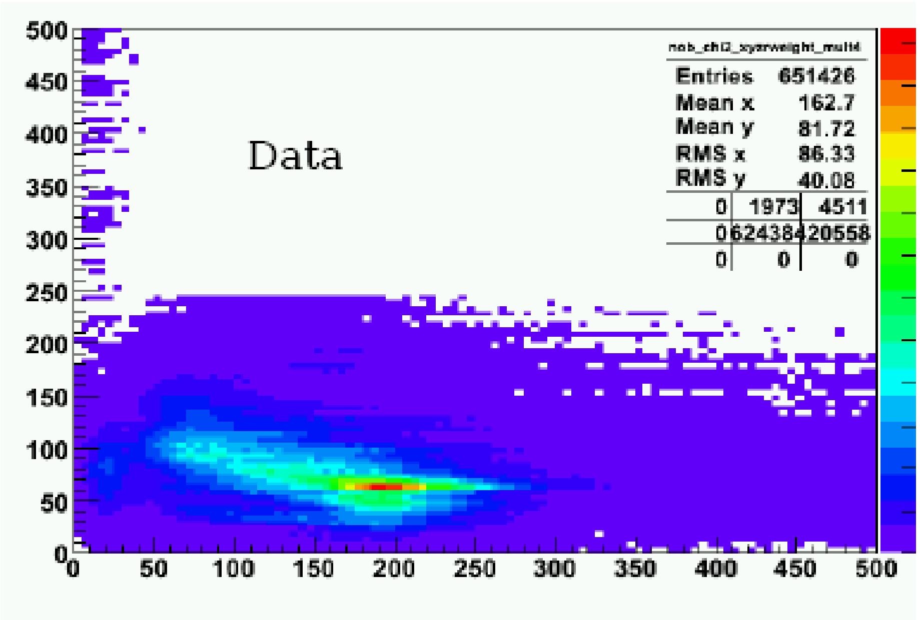
additional daugters: K-[17.0] pi-[8.1] pi+[2.8] pi+[2.5] pi0[1.9] pi0[1.5] pi+[1.4] pi+[1.3] pi+[1.2] K_S0[1.1] proton[1.1] pi-[0.1]

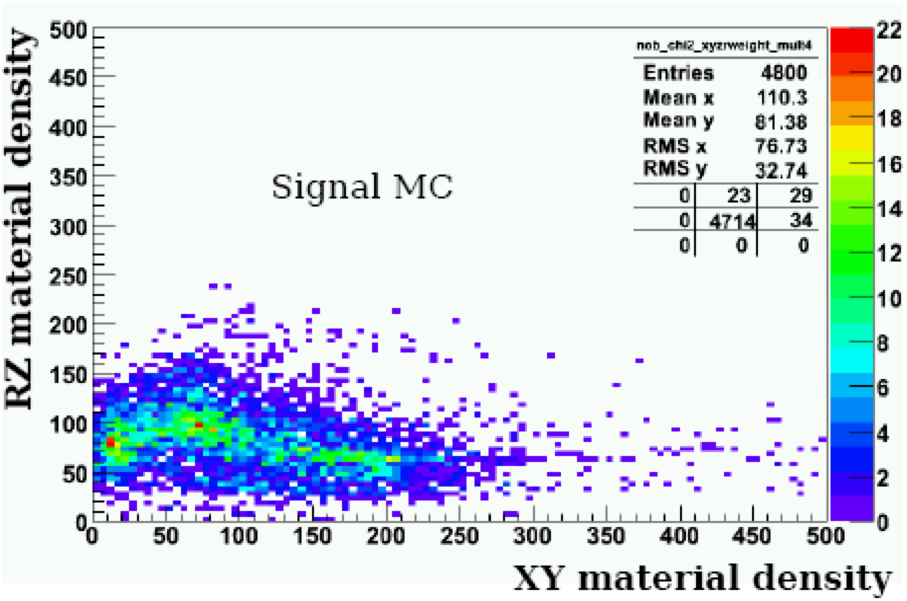
Analysis Plans

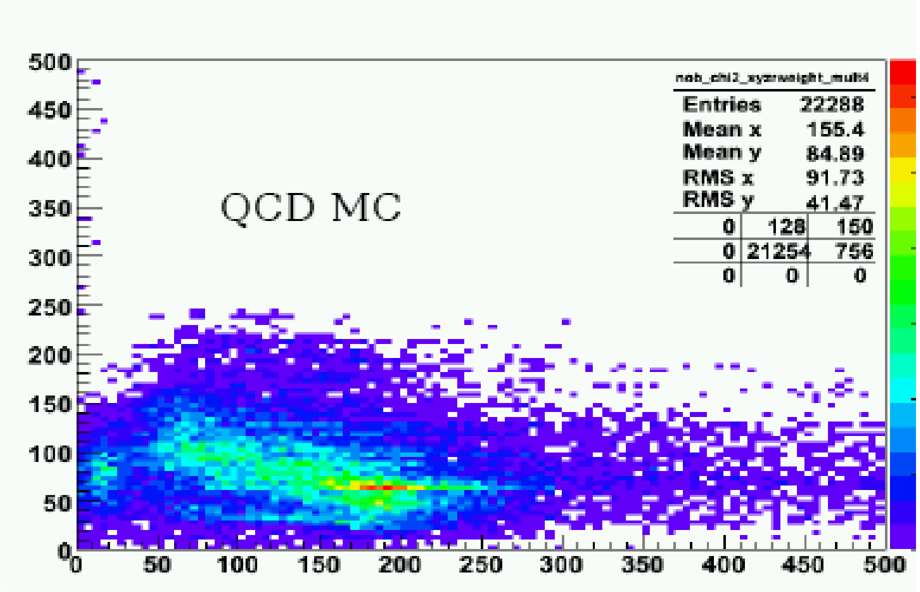
Still finalizing the analysis selections
- Will depend on particle mass and lifetime

Several handles to separate S / B
- Track multiplicity, angles, mass…
- Near detector material?
- Muon matched to far vertex?

Could require a second far vertex



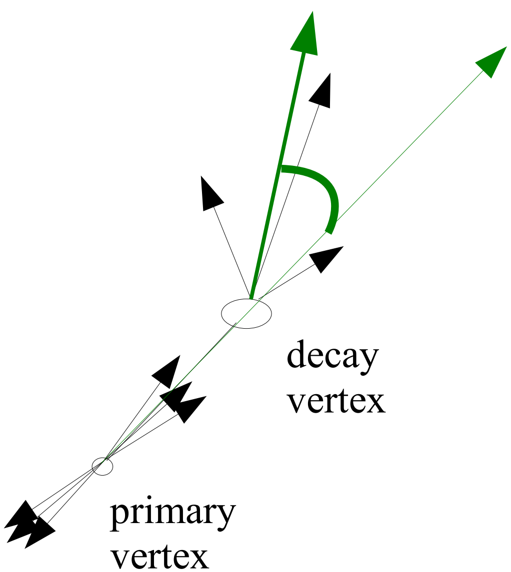


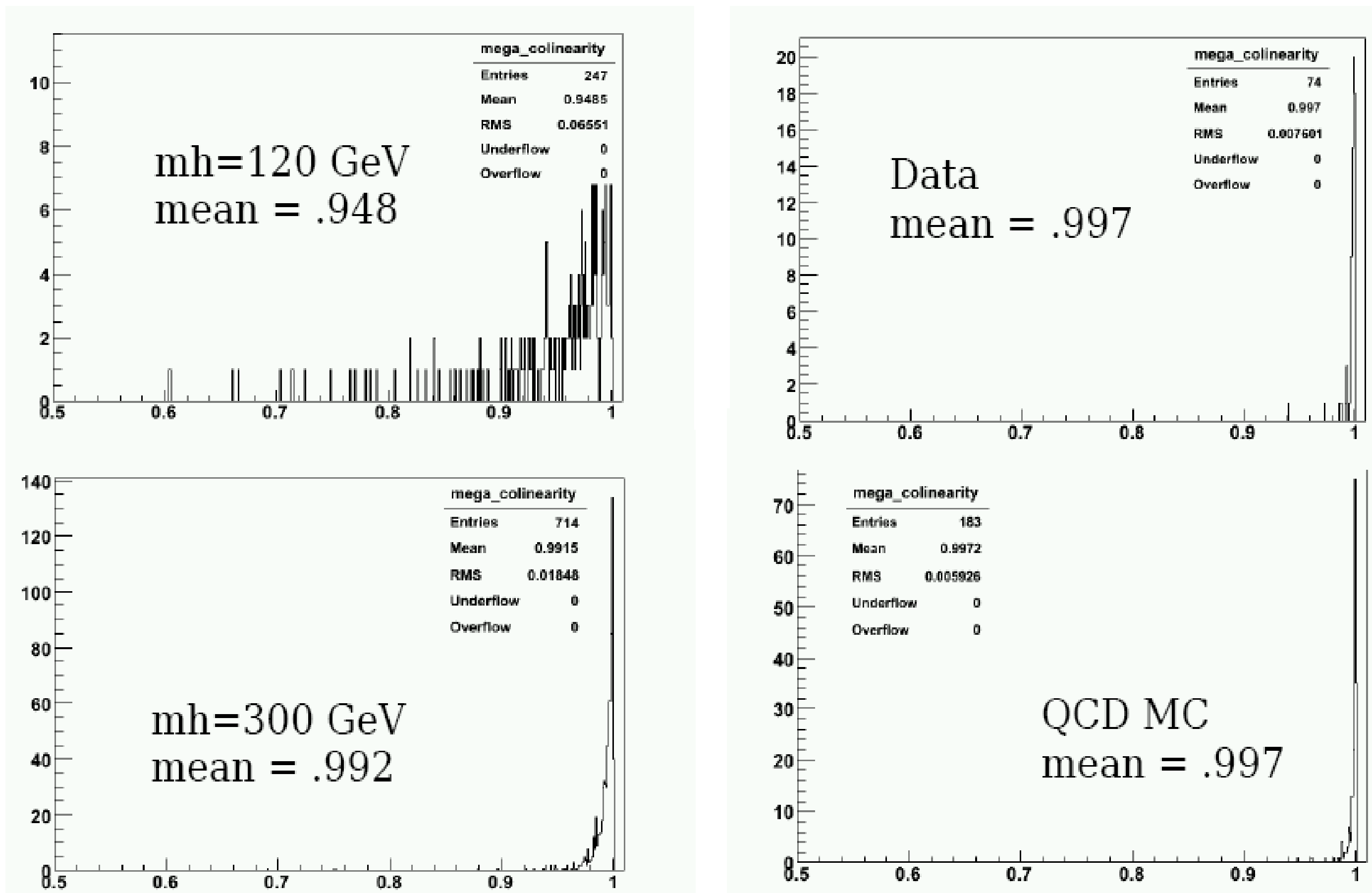


Far Vertex Collinearity

Angle between vertex momentum (sum of its tracks' momenta) and vertex direction

Good discrimination for slow-moving, *low mass* decays

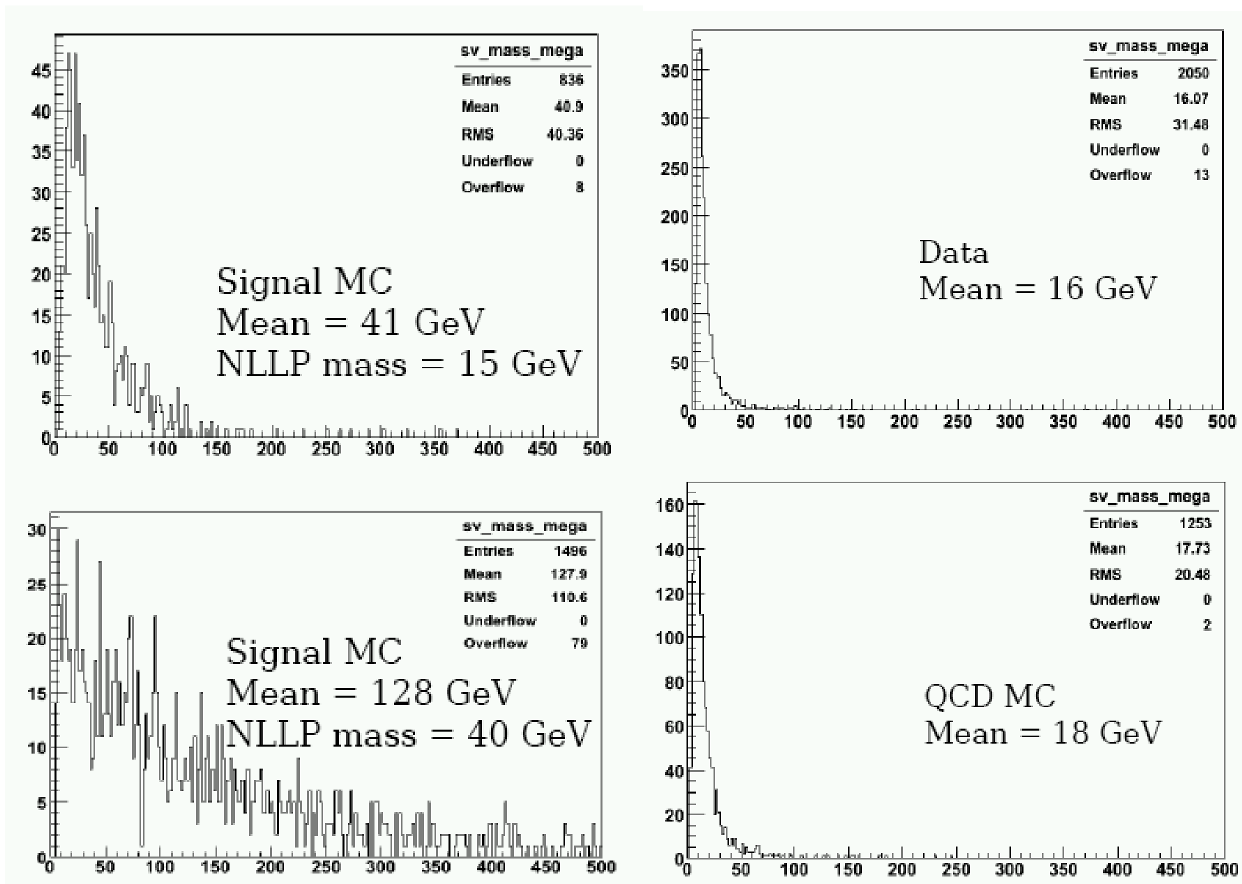




Far Vertex Mass

Invariant mass (^2) of the tracks' 4-momenta (assuming they are pions)

Good discrimination, especially for *high mass* decays



Conclusions

Many models of new physics predict particles with unusual properties

- Long lifetime is *one* example
  - Stopping gluinos
  - Long-lived scalars -> bb

Specialized analyses are required

- Typically interesting and fun!

Shame to miss a signal that the detector is capable of seeing

Room for finding weird things at the Tevatron is narrowing

Studies are being extended to LHC

- Large ATLAS hidden-valley group