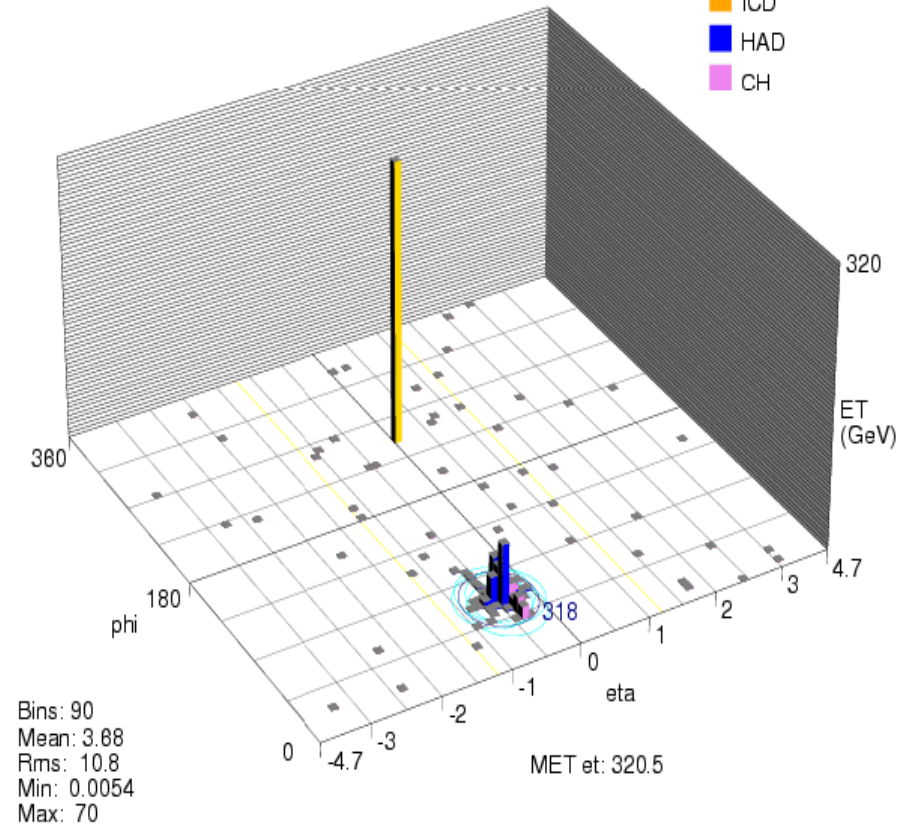
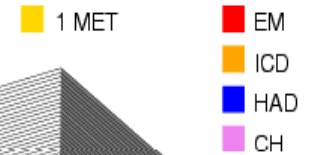




Results of the Search for Stopped Gluinos using the DØ Detector

Triggers:



Andy Haas
Columbia U. / Nevis Labs

DØ / ATLAS

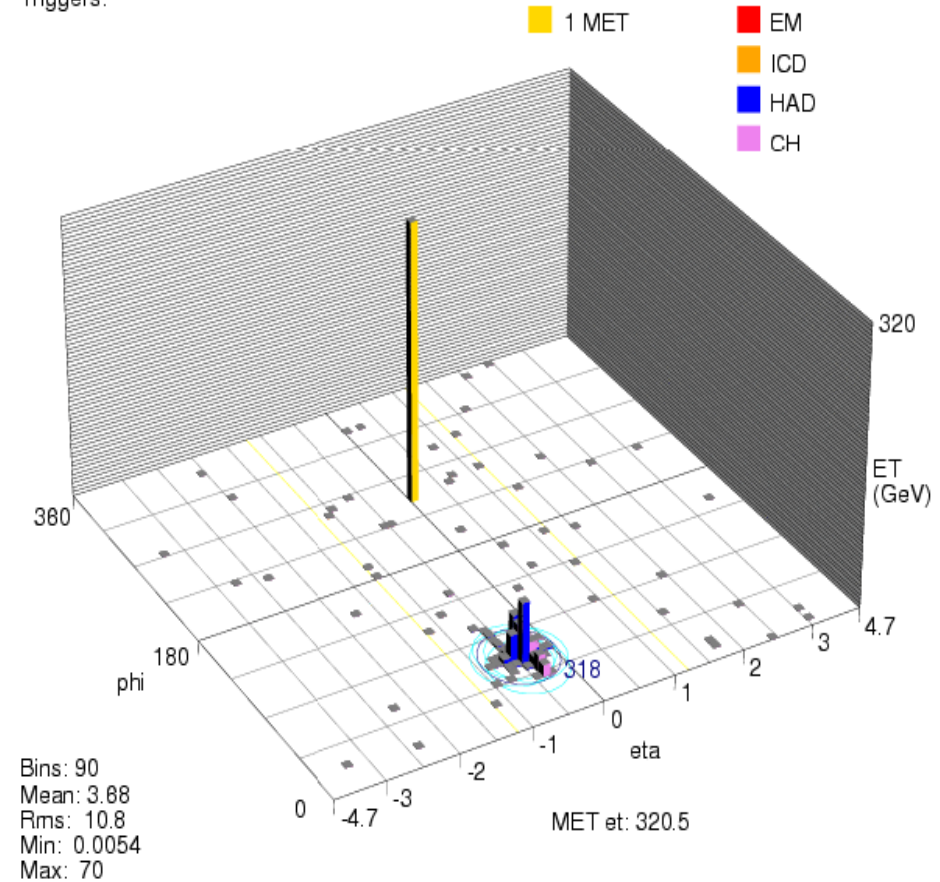
Columbia Seminar
Oct. 18, 2006

Outline

- What's a stopped gluino?
- The Tevatron and D0 detector
- Simulating the stopped gluino signal
- The data used
- Background types
- Event selection
- Estimation of remaining background
- Comparison of data to remaining background
- Signal efficiency
- Systematic uncertainties
- Limits on stopped gluinos
- Future improvements

Run 183228 Evt 67444580 Sa: Feb 4 15:08:13 2006

Triggers:



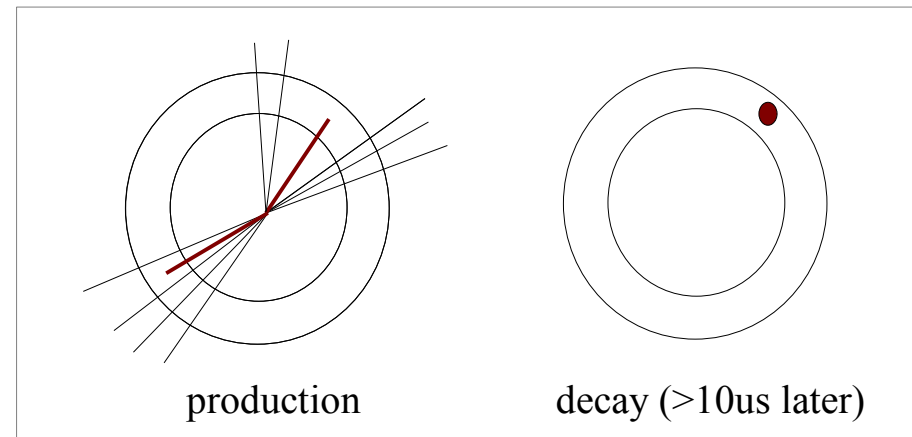
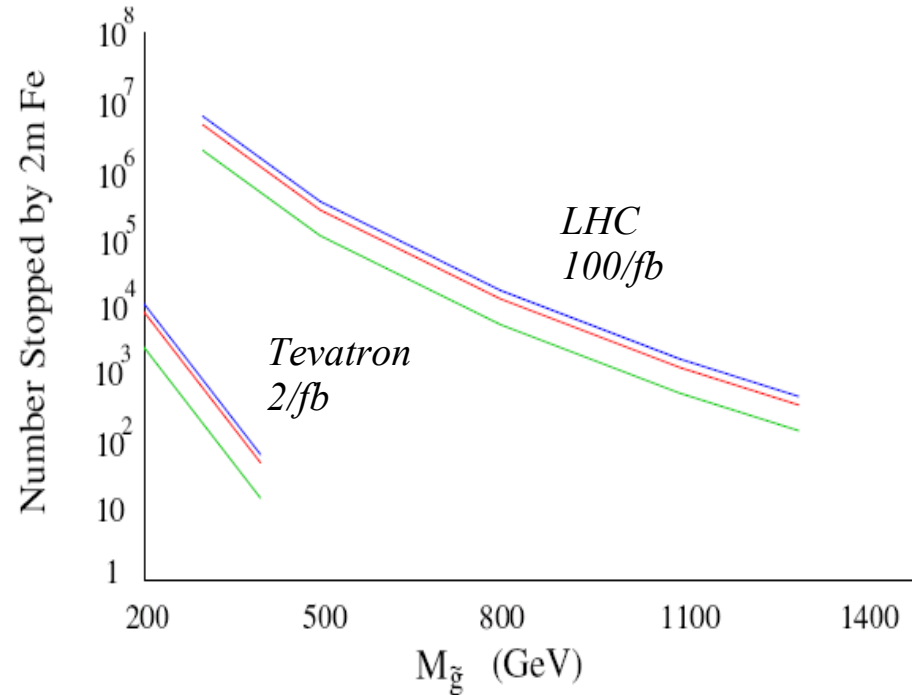
SU/SY

- You've heard of Supersymmetry
 - gluons \leftrightarrow gluinos
 - so *gluinos* are neutral, but colored, and spin $\frac{1}{2}$
- What's "Split Supersymmetry"?
 - Normal SUSY has the mass of scalars near the EW scale
 - This prevents the Higgs mass from being unstable due to loop corrections
 - This was kind of the point of SUSY to begin with!
 - But what if the Higgs mass is stabilized by something else?
 - Chance! \rightarrow Anthropic principle \rightarrow works for the cosmological constant, why can't it work for the Higgs mass???
 - Then the scalars could be very heavy \rightarrow near the GUT scale
 - But fermions are protected by chiral symmetries \rightarrow gluinos are still "light"
- You still get all of the other nice things from SUSY
 - Unification of gauge forces (doesn't depend on scalar masses!)
 - Dark matter (there's still a neutralino \rightarrow spin $1/2$)
 - The right symmetries for string theory, at high energy
- And even a bonus!
 - Natural suppression of all the normal SUSY stuff we *don't* see! :)
 - FCNC's, EDM's, stop quarks, tri-leptons, etc...

What's a Stopped Gluino?

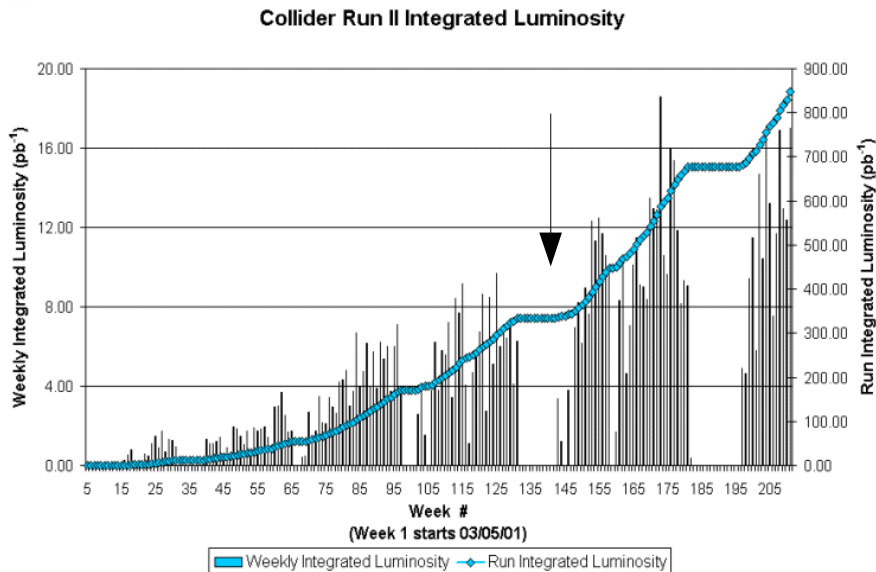
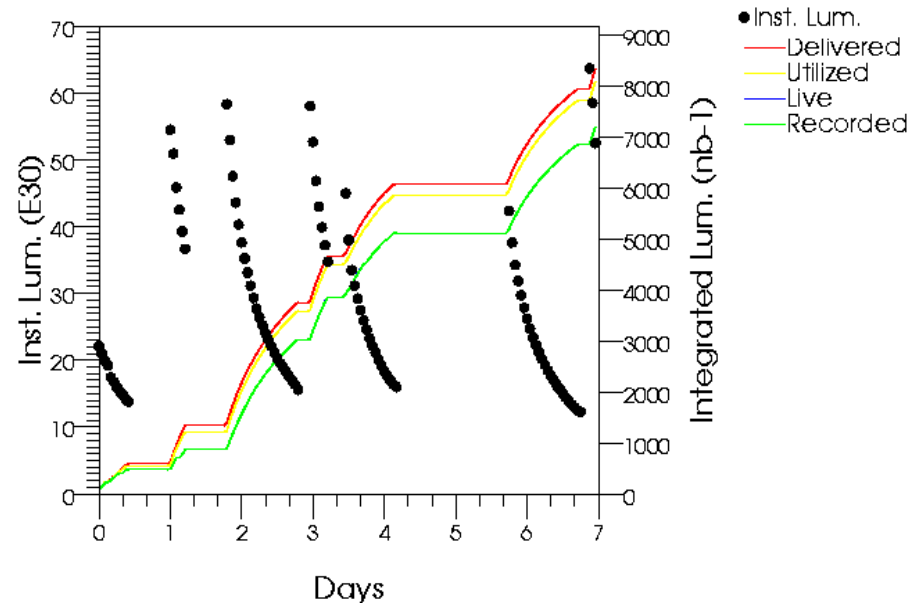
- $p\bar{p}$ -> gluino pair production
- Split SUSY -> heavy scalars -> long-lived gluino !
- Gluinos *hadronize* into "R-hadrons"
- Some charged R-hadrons lose enough momentum through ionization to stop in the calorimeters
 - They later decay into gluon+LSP (or maybe $q\bar{q}$ +LSP)
(BR to gluon+LSP assumed to be 100% for this analysis.)
 - Lifetime depends on M_{SUSY} but is $>10\text{ns}$ if $M_{\text{SUSY}} > 10^6 \text{ GeV}$
(Lifetime assumed to be $>10\mu\text{s}$ and $<\sim 1\text{hour}$ for this analysis.)
 - See *hep-ph/0506242, J. Wacker et al.*
- Signature:
 - large, isolated energy deposit in the calorimeter
 - rest of the "event" should be very empty
 - no tracks or primary vertex
- An interesting "final-state" which has not been carefully explored before experimentally!

~ 500 stopped gluinos in 2/fb for $m_g = 300 \text{ GeV}$
 ~ 5 stopped gluinos in 2/fb for $m_g = 500 \text{ GeV}$



The Tevatron at Fermilab

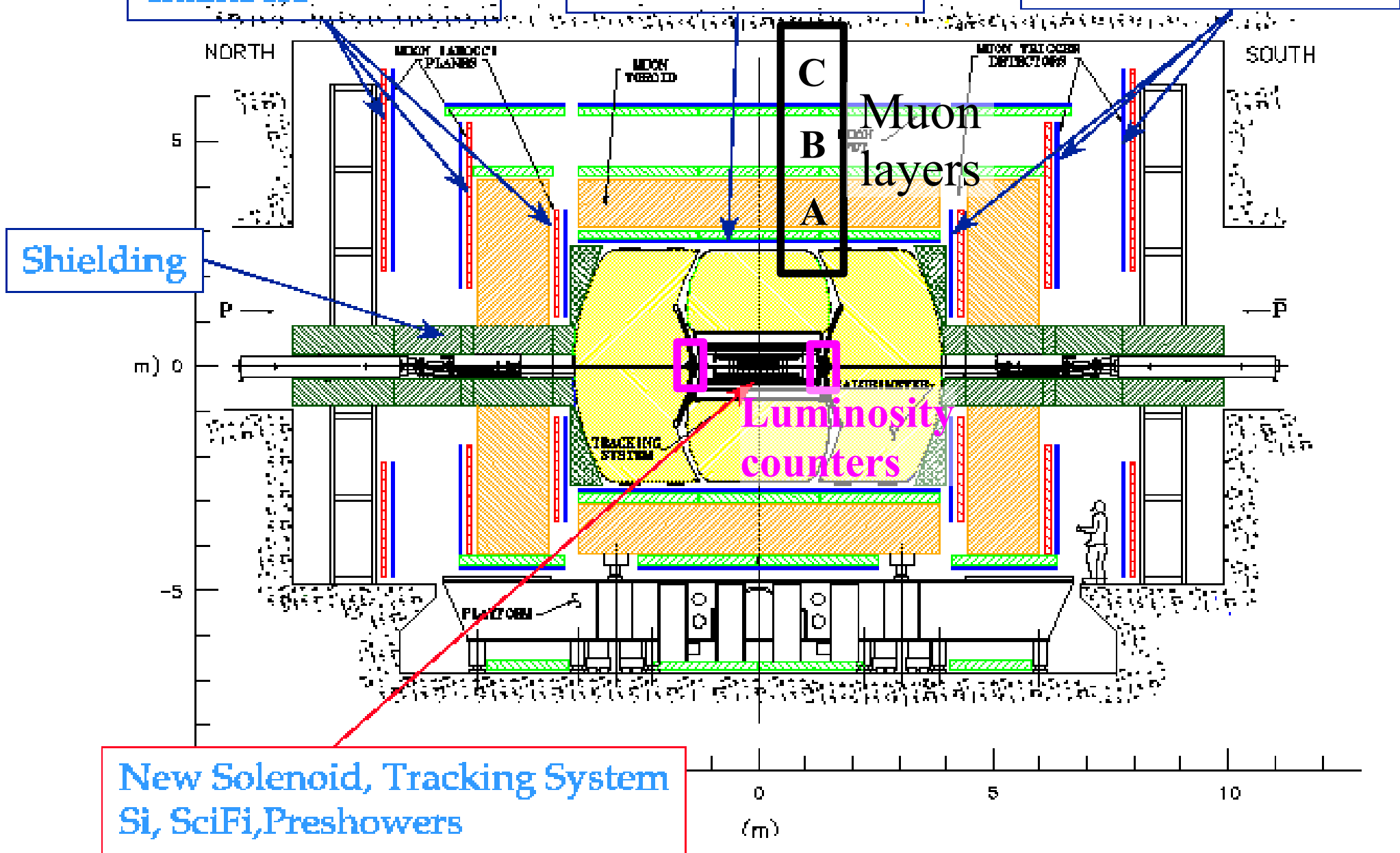
- 1 km radius p-pbar super-synchrotron
- World's most powerful: 1.96 TeV
- 36 bunches of p/pbar, 396 ns crossing period
- 25 cm RMS interaction region
- About one "store" per day
- Inst. luminosity $\sim 40 \times 10^{31} / \text{cm}^2 / \text{s}$
- About 20/pb per (good) week
- $>1/\text{fb}$ on tape so far
- This analysis uses just the first 0.35/fb



Forward Mini-drift chambers

Central Scintillator

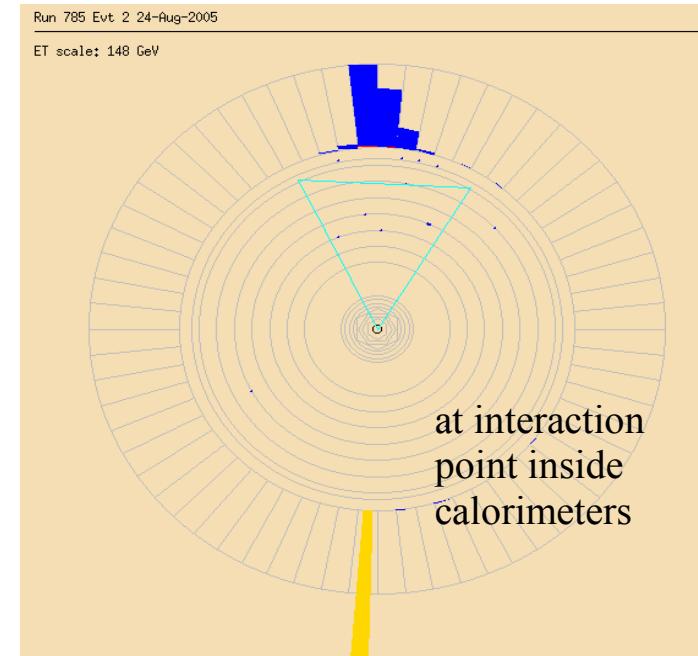
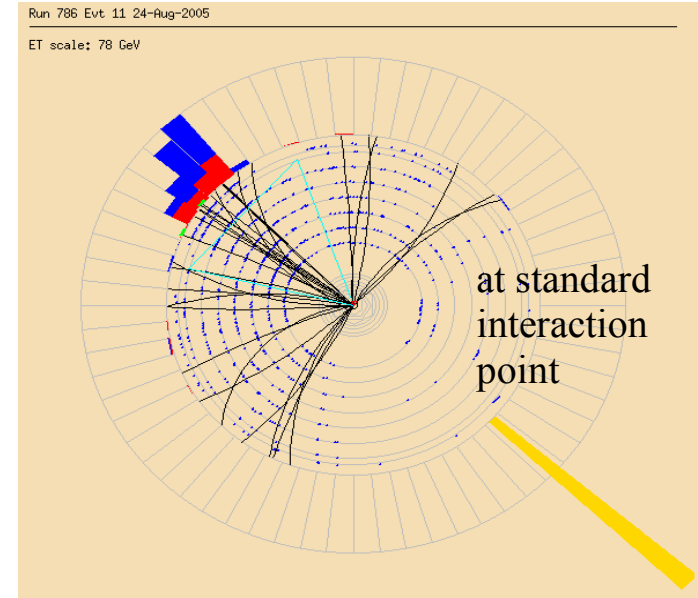
Forward Scintillator



New Solenoid, Tracking System
Si, SciFi, Preshowers

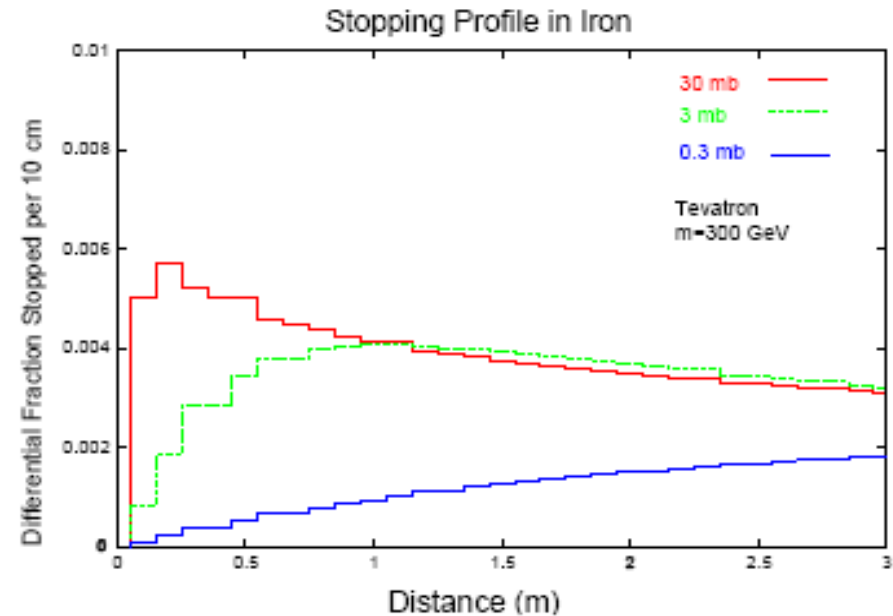
Signal Simulation

- The stopped gluino decay produces a single high-energy gluon (balanced by missing energy)
- Model with Pythia Z+g/q (MSEL=13) and force Z->nunu
 - 1000 events each, with M ~ 200,300,400,500
 - $|\eta| < 0.1$, but rotated jet to *random 3D direction*
 - Boost along Z removed
 - Switch off ISR and multiple parton interactions (no underlying event)
 - Remove remaining beam particles by removing in MCKineChunk if $|p_z/E| > .95$
- Decay location chosen to be Gaussian-distributed: $(x,y,z) = (0 \pm 20, 120 \pm 20, 0 \pm 80)$ cm
 - In the middle of the calorimeter!
- Then, further weighting of events by vertex location to match the distribution expected from stopping gluinos

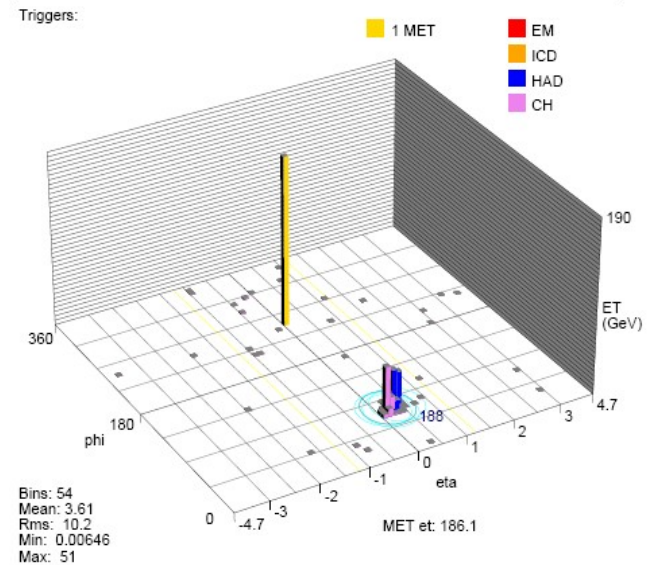
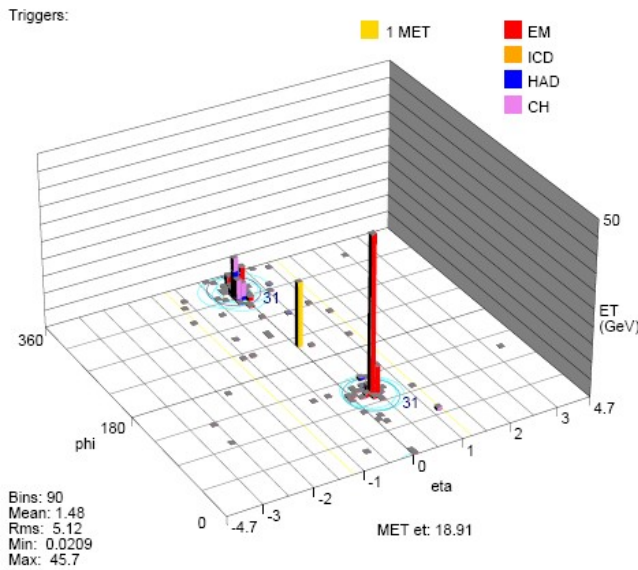
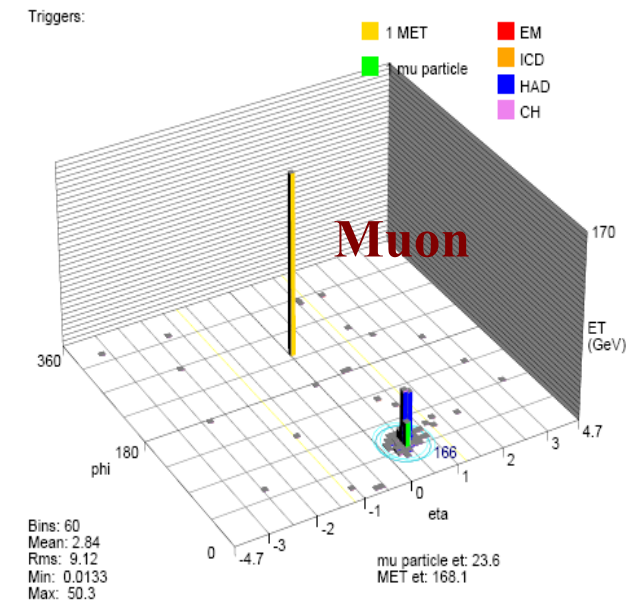
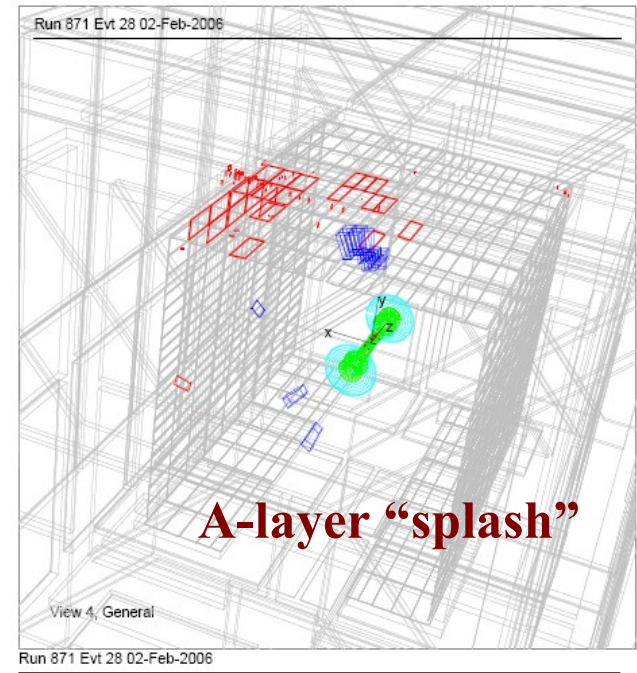
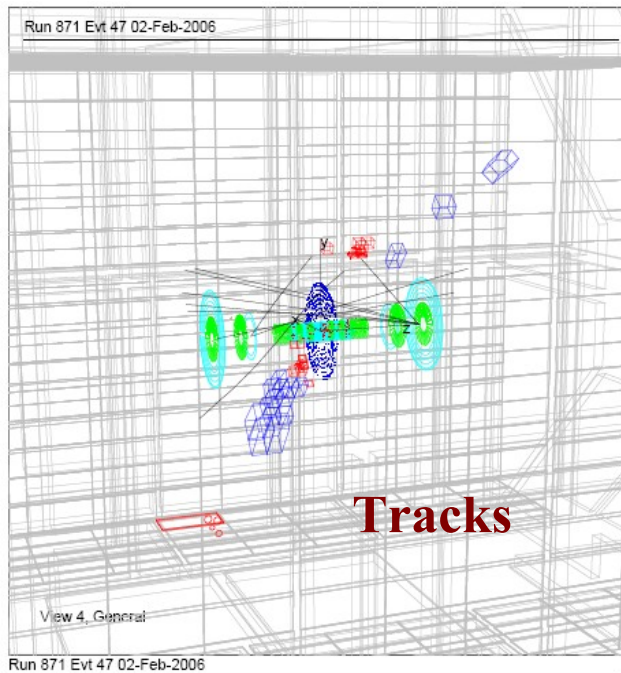
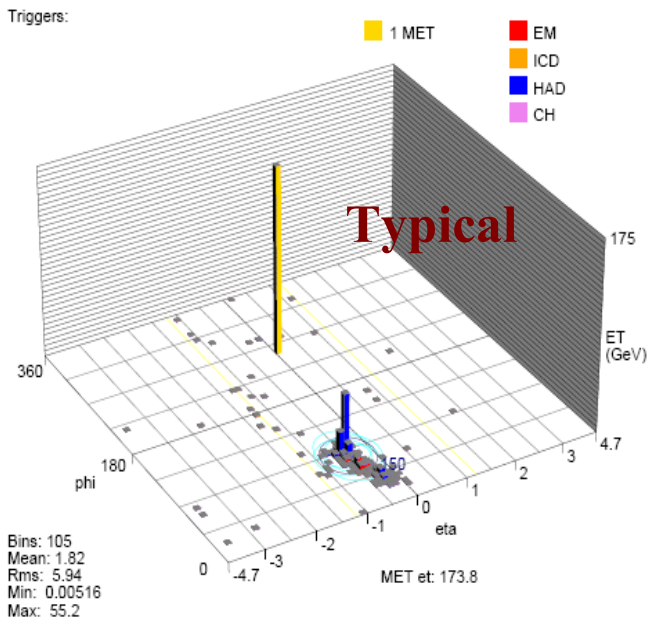


Signal Simulation

- Events are weighted such that “r” is proportional to the 3mb “Wacker distribution”
 - Other distributions (0.3 -> 30mb) are used for systematic uncertainties
- Gluinos produced near threshold at Tevatron, and also those near rest are most likely to stop
 - Isotropically distributed, proportional to $\cos(\theta) : \tanh(\eta)$
 - Events are weighted such that $z : \tanh(\eta)$



Simulation

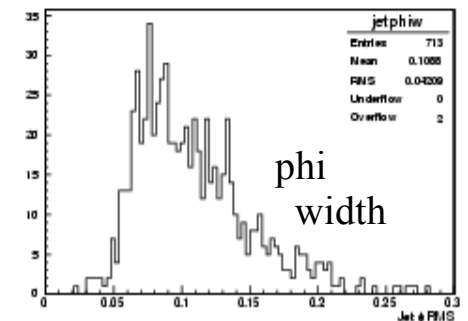
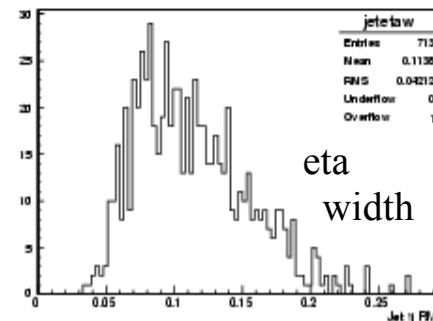
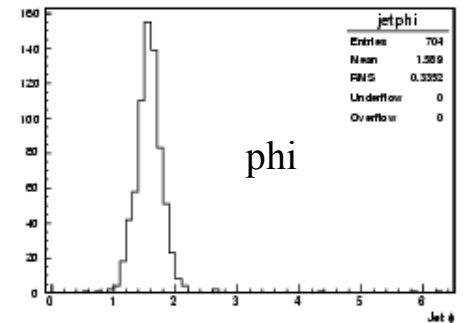
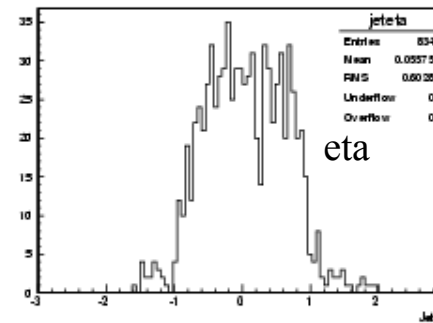
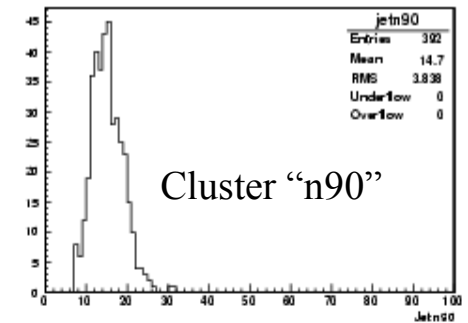
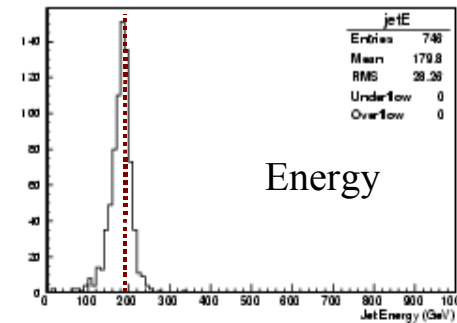


Signal Distributions

- Gluino jets look much like normal jets...
 - They are fairly wide (phiwidth, etawidth > 0.08)
 - *Good discriminant against muon-induced showers!*
- Gluino jets often (30% of the time) have significant leakage / punch-through into the inner muon layer (“A-layer splash”)
 - They may be near the outside of the calorimeter when they decay
- About 10% of the time, a particle (maybe a muon) gets into the BC-layers, forming a good muon segment
- Rarely (<5% of the time) the jets are not contained and shoot back through the tracking volume to the other side of the calorimeter
 - A few tracks are reconstructed (with large impact parameters)
- Sometimes two jets are reconstructed, near each other in dR (about 10-20% of the time)
- Unfortunately, all these odd signatures are also present in the background, at similar rates!

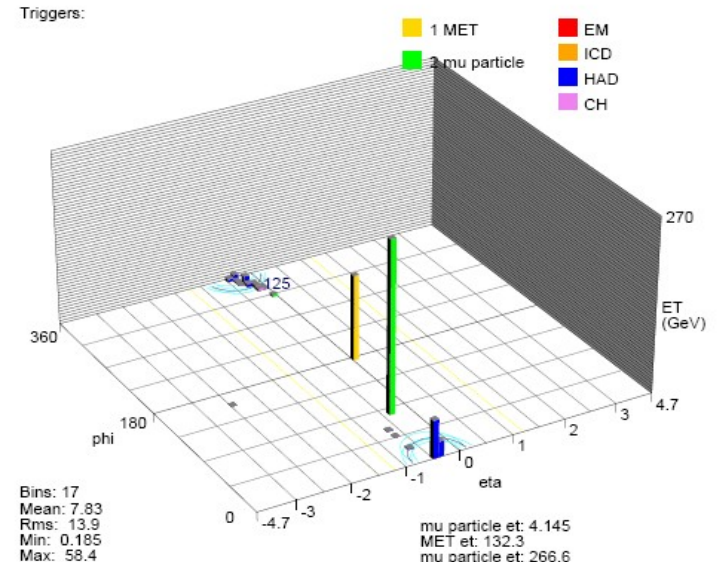
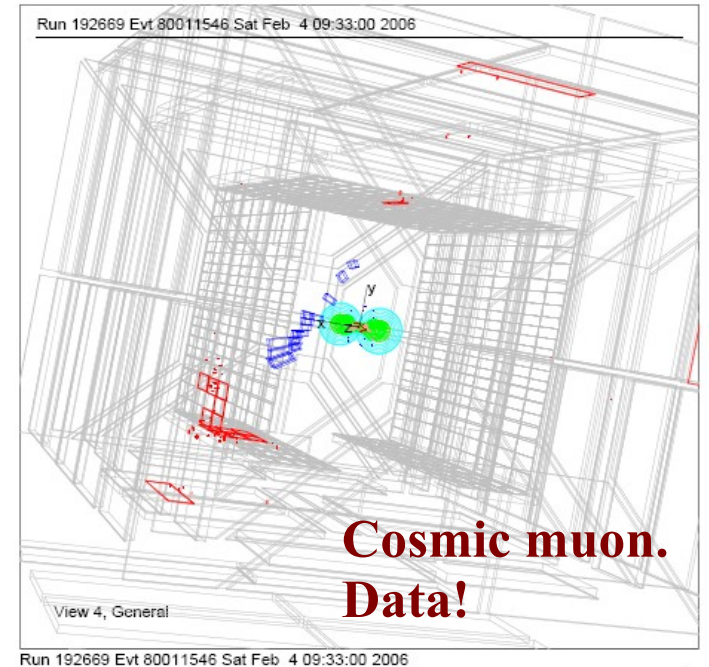
Plots from mG=400 GeV sample

$$E(\text{jet}) = (400^2 - 90^2) / (2 * 400) \sim 190 \text{ GeV}$$



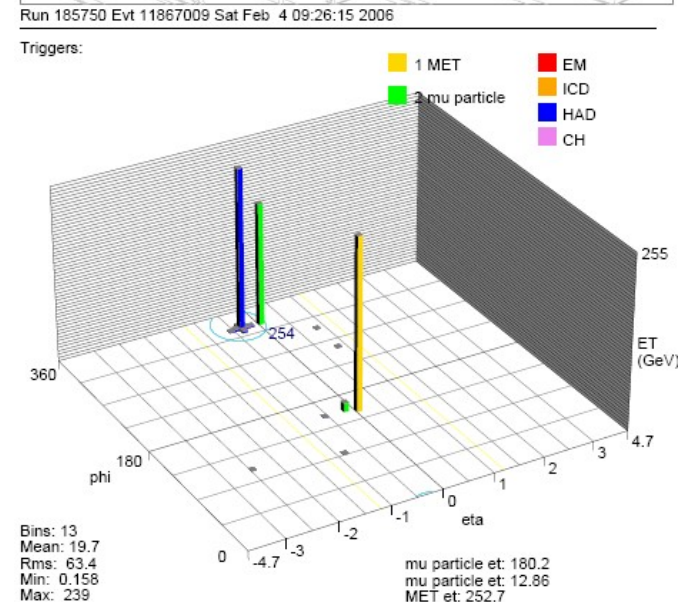
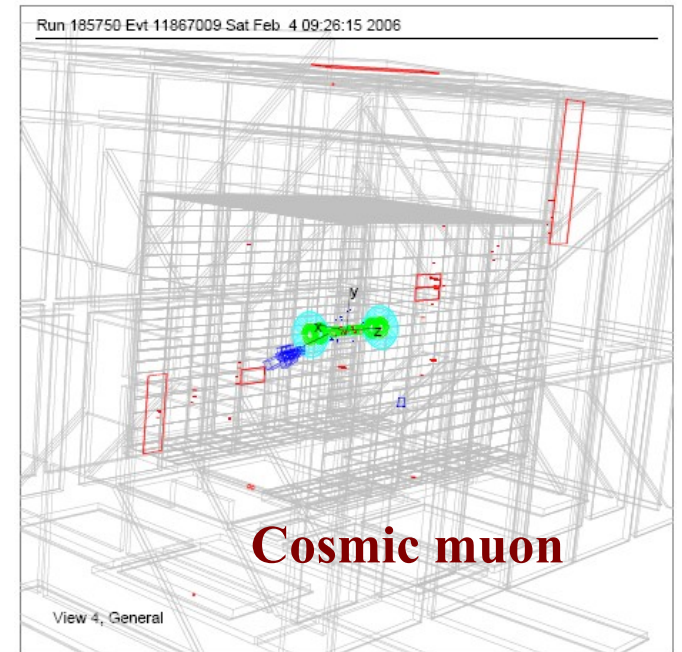
Data and Backgrounds

- Data:
 - Use “GAPSN” triggers – already in place for diffractive physics
 - Require *no hits in either the North or South luminosity counters (scintillators)*
 - Also require a $ET > 45$ GeV jet
 - 7.9M events, $\sim 0.5\text{Hz}$ (!)
- Pre-selection cuts:
 - Good muon and tracking runs
 - 0.5 cone jets (JCCB) (no selection criteria, no JES)
 - Require one jet with $E > 90$ GeV
 - Veto on any other jets (above ET of 8 GeV)
- Backgrounds remaining:
 - Cosmic muons
 - Beam muons (halo)
 - Diffractive events from beam
 - Detector problems, fake energy
 - Other : cosmic neutrons / neutrinos?



Cosmic Muons

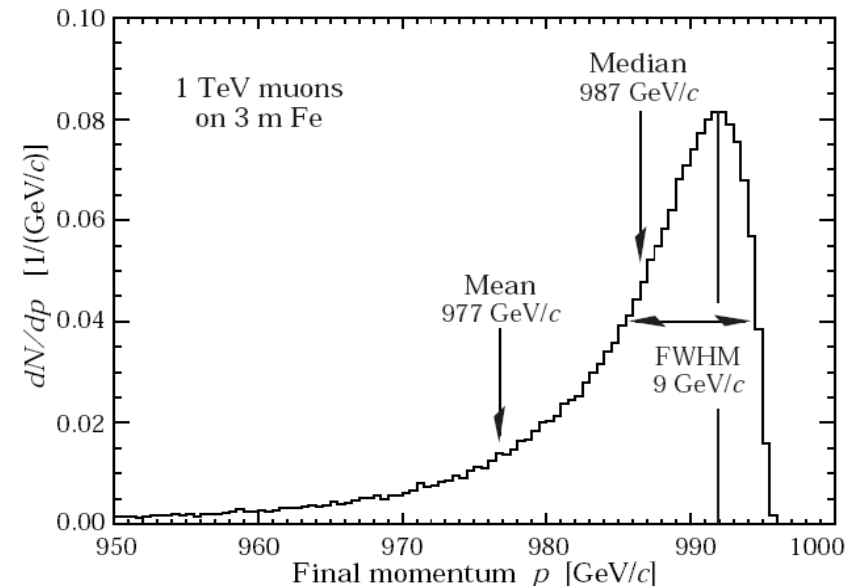
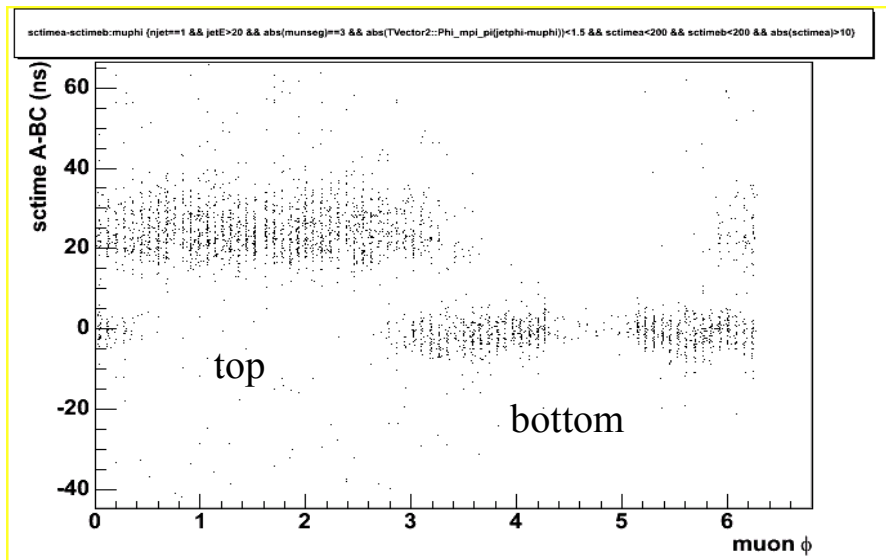
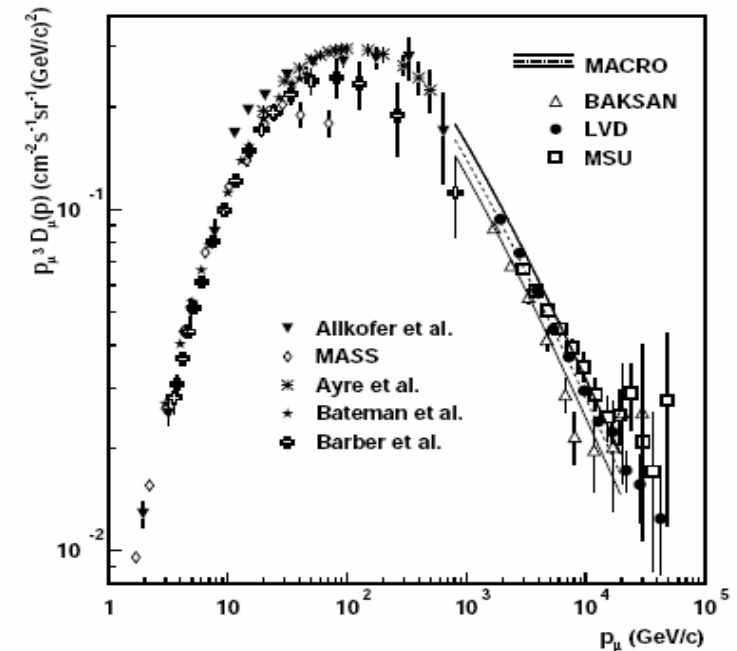
- These, along with “beam-muons” are the major background, due to their high rate
- Usually there's at least one good (BC layer) muon segment
 - There's two chances to see the muon (on the way in, and going out)
- Showers in the calorimeter can be quite large ($>1\text{TeV!}$)
- Hard Bremsstrahlung photon is the dominant process at high energy loss
 - Narrower showers than “jets”:
 - More energy in single cells ($n_{90} < 5$)
 - Smaller phi- and eta-width (<0.08)
- A visible MIP trail about half the time...
 - No dedicated algorithm available for identifying them
 - A difficult reconstruction problem!
 - Can be faked by gluino jets as well
 - Not used in the analysis



Cosmic Checks

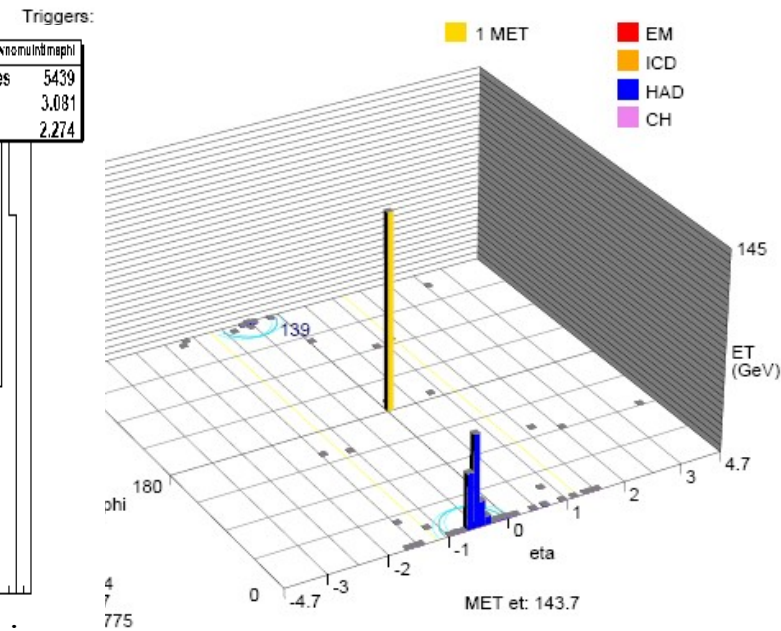
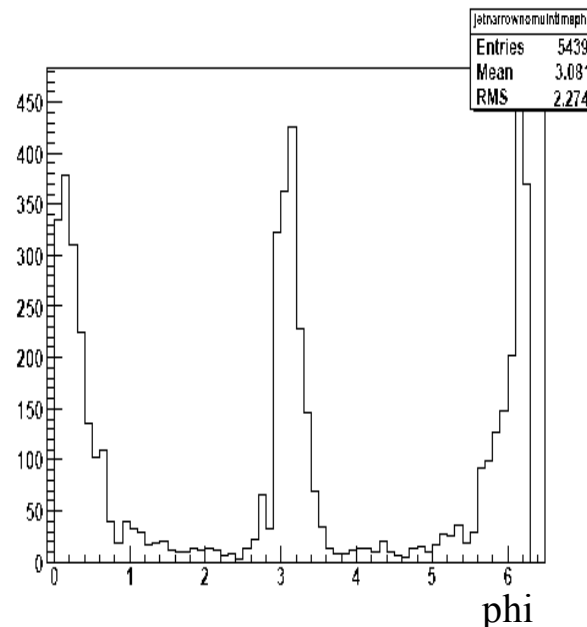
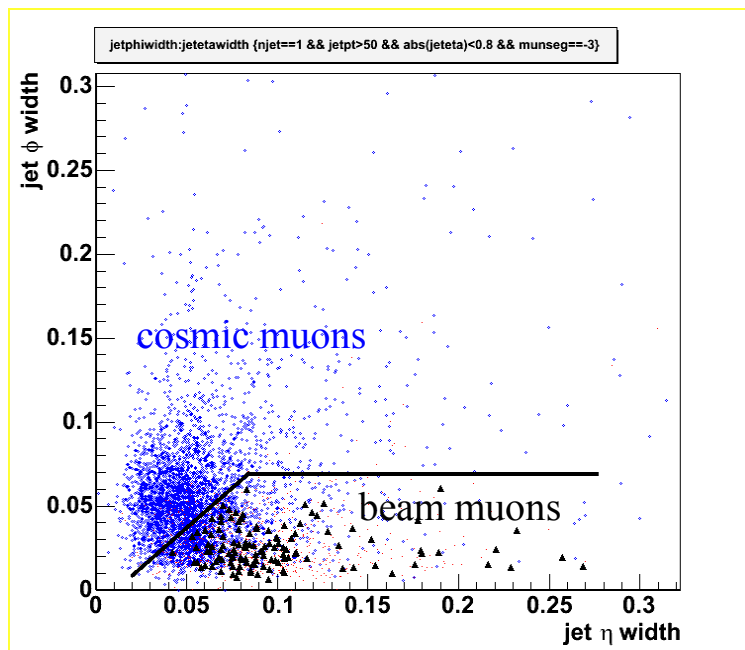
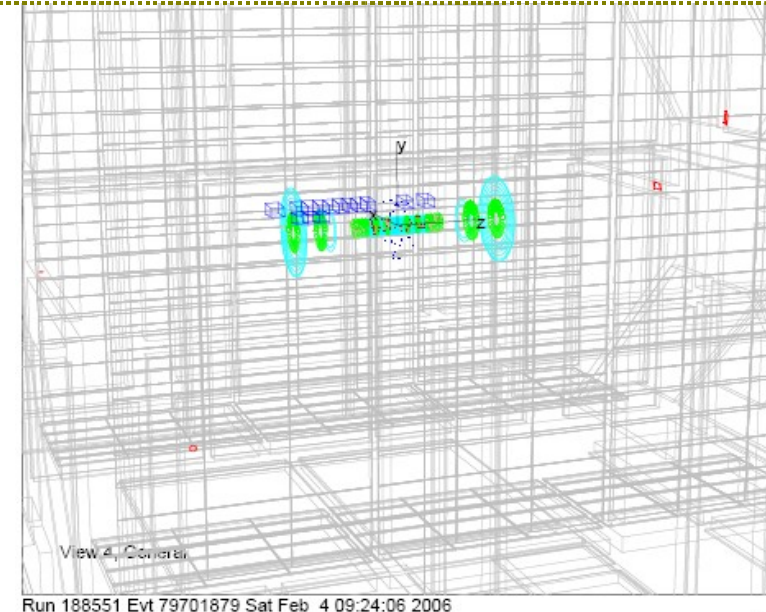
- The observed rate is consistent with expectations
 - Spectrum at sea-level is known:
About $10^{-3}/\text{cm}^2/\text{s}$ above 100 GeV
 - Rate of hard Bremsstrahlung is known:
About 0.1% will lose $>10\%$ of their energy
 - $10\text{m}^2 \times 10^{-3}/\text{cm}^2/\text{s} \times 0.1\% = 0.1\text{Hz}$
- The muon and shower distributions are reasonable
 - Phi, Eta, and timing of muon scintillators

Muons are coming from the sky, and are being blocked by the earth!



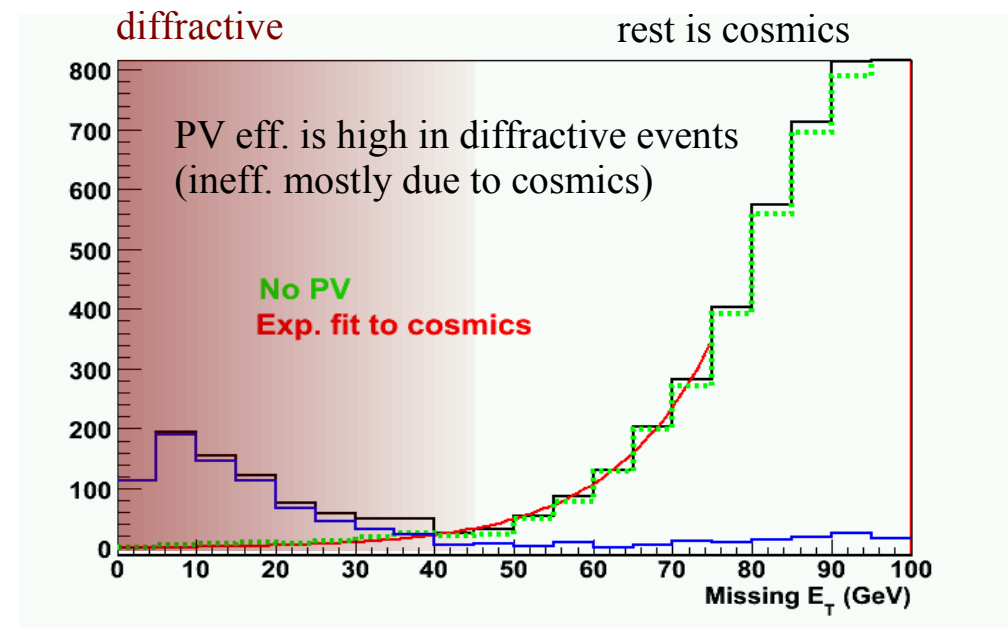
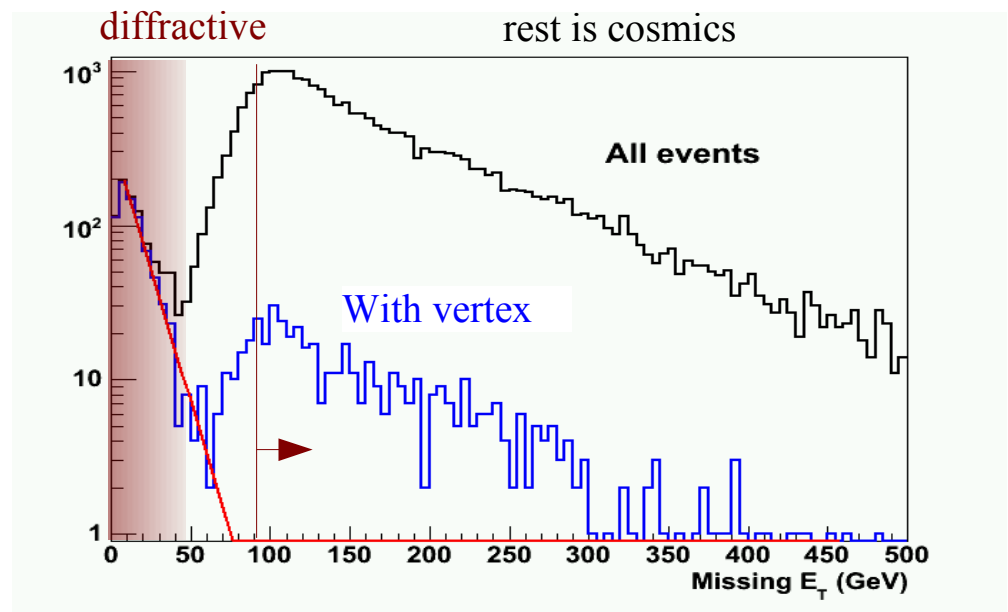
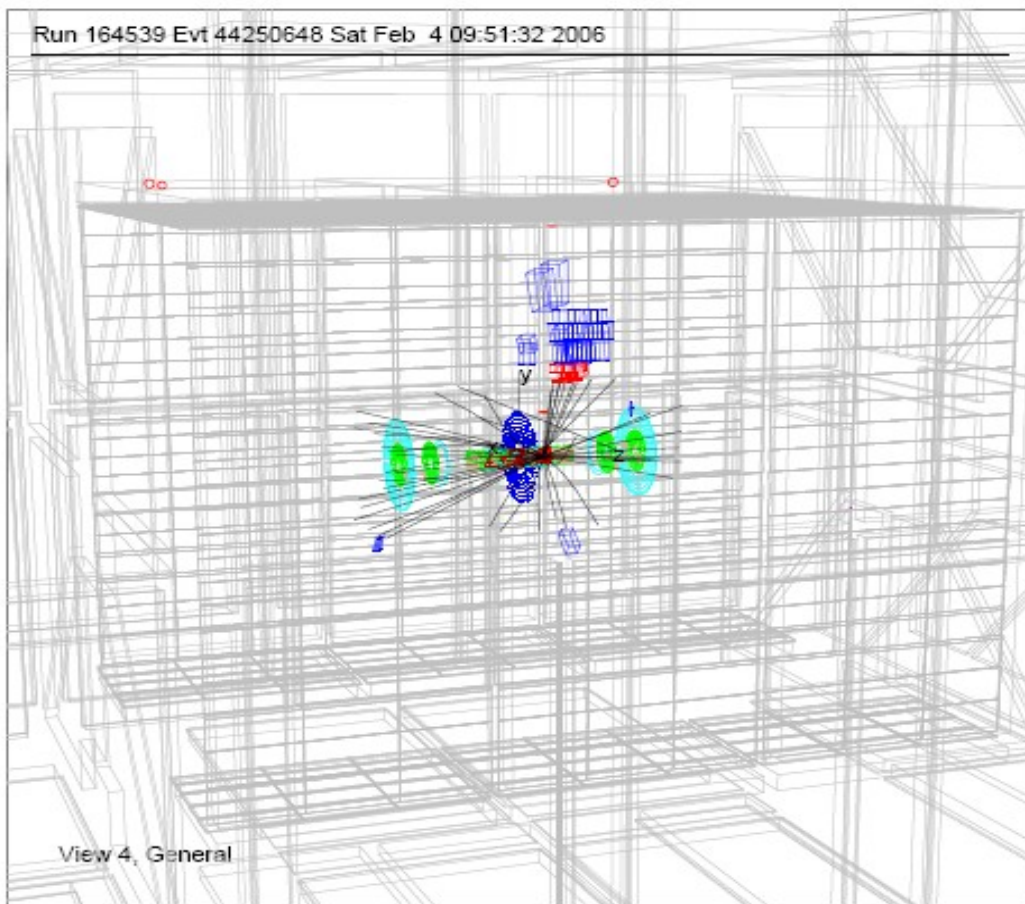
- There are a large number of “beam muon” events (about as many as cosmic muons)
- Often a forward muon segment, or scintillator hits, or MDT hits...
 - scintillators are “in time” ($|t| < 10\text{ns}$)
- Protons (or anti-protons) hit gas or the beampipe and create pions, which decay to muons
- Why are they focused at integer values of ϕ/π ?
 - Accelerator magnet configuration ?
 - Plane of the beam ?
 - Muon shielding at D0 and/or CDF ?
- The shower is very narrow in ϕ (< 0.08) but relatively wide in η (> 0.05)

Beam Muons



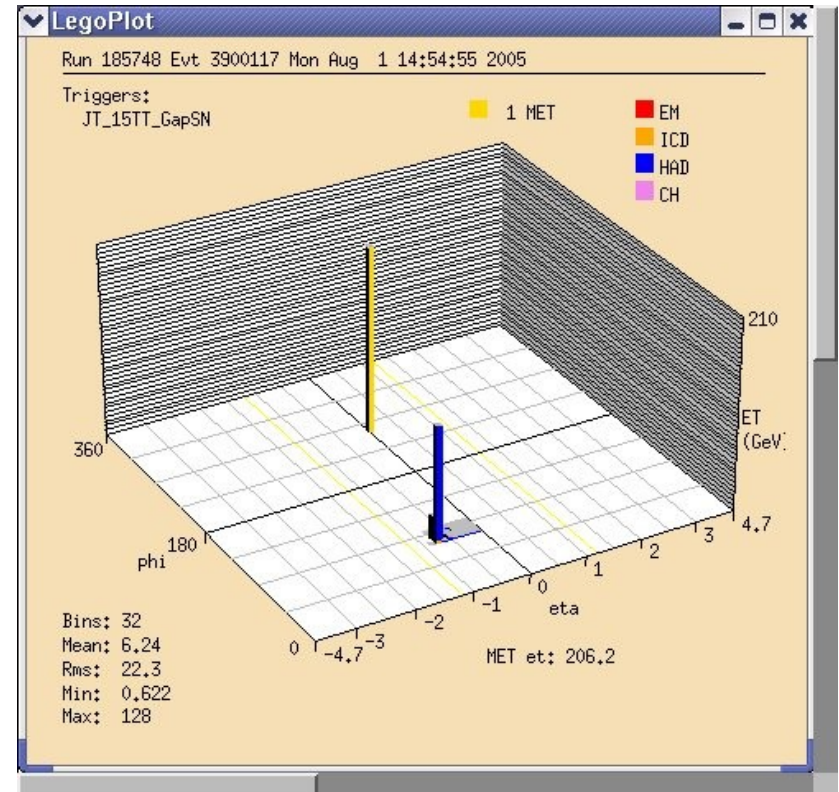
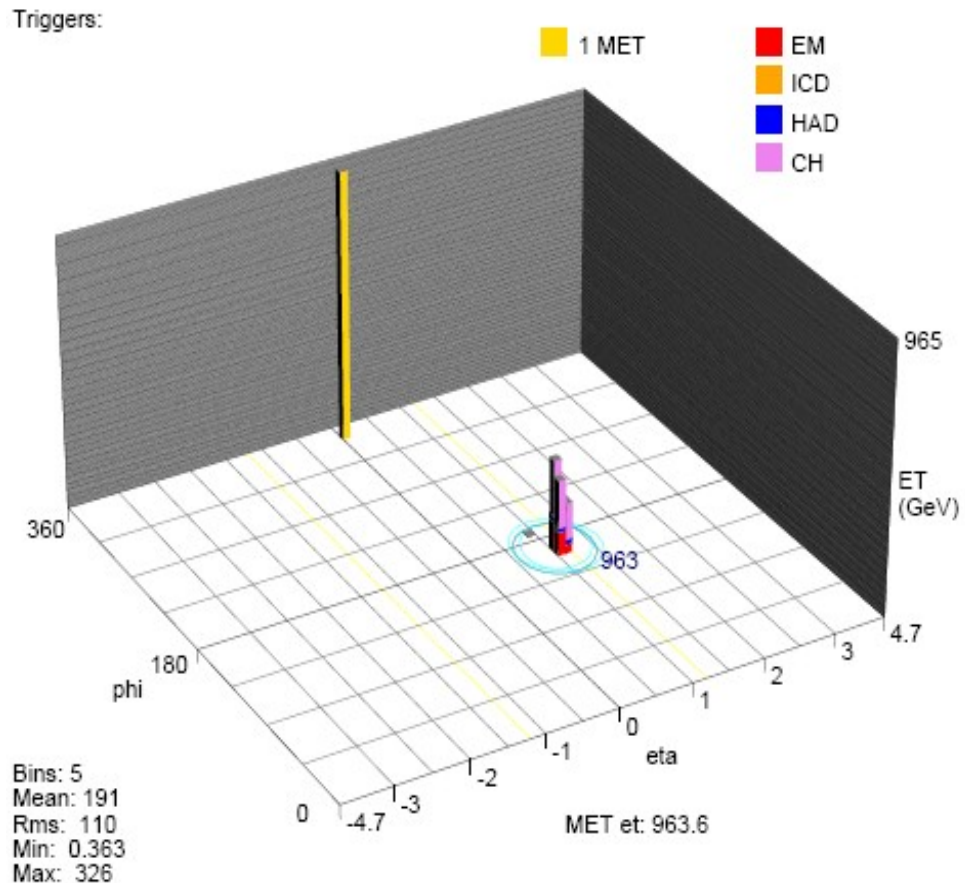
Diffractive Background

- Could double-diffractive events slip through?
 - Require no Primary Vertex
 - Require large MET (1 jet, $E > 90$ GeV)
- No sign of this background after cuts



Detector “Problems”

- Detector problems tend to be in isolated eta-phi regions or isolated data-taking periods
 - These can be removed
- They really don't look like jets at all
- No sign of remaining detector malfunctions after cuts



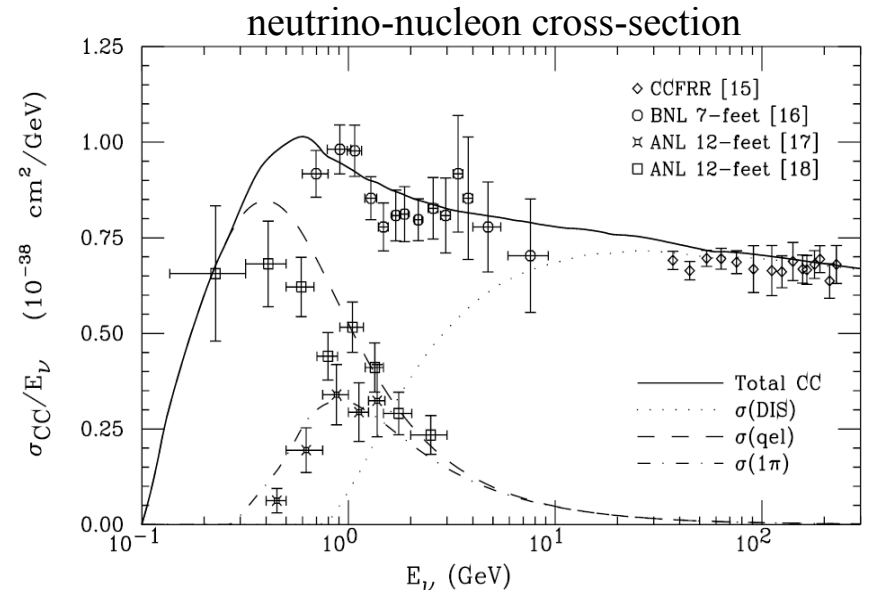
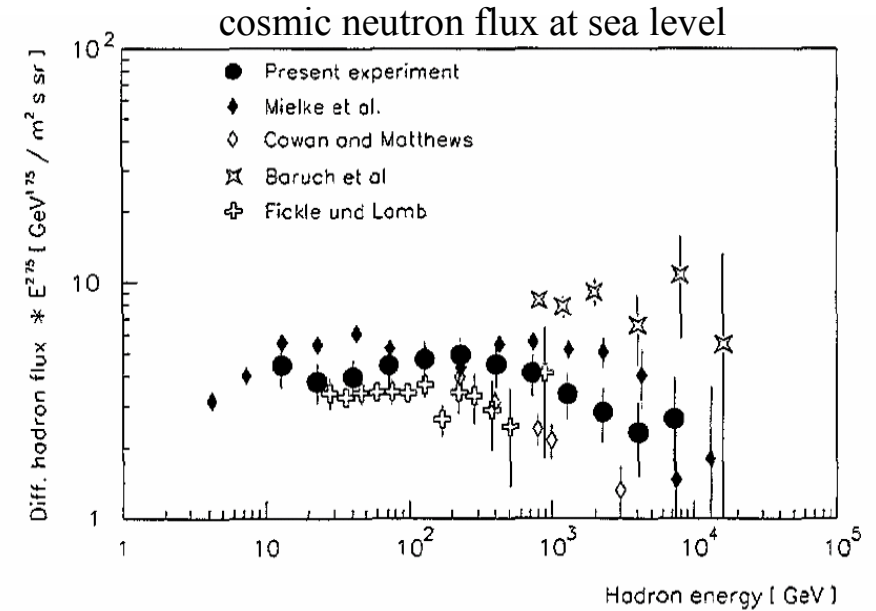
There are ~100 of these events with
 a “jet” at $\eta \approx .7$ and $\phi \approx 1.35$
 Not in any isolated set of runs...

Other Backgrounds

- Cosmic neutrons reach sea-level...
No muon segment, no MIP trail, wide shower!
- The rate is 1/1000th of cosmic muons at the same energy... i.e. ~1/hour on detector
- They would have to get through the iron toroids
 - This seems difficult
- Neutrons that did get through would deposit most of their energy in the Coarse Hadronic calorimeter (on the outside)
 - This would be a good discriminant
 - We don't trigger on CH energy
- **No excess of wide no-muon showers on the outside of the calorimeter is seen**
- **Neutrinos (!) would be a small background:**
 - Assuming a 1/1 ratio of muons/neutrinos from cosmic sources:

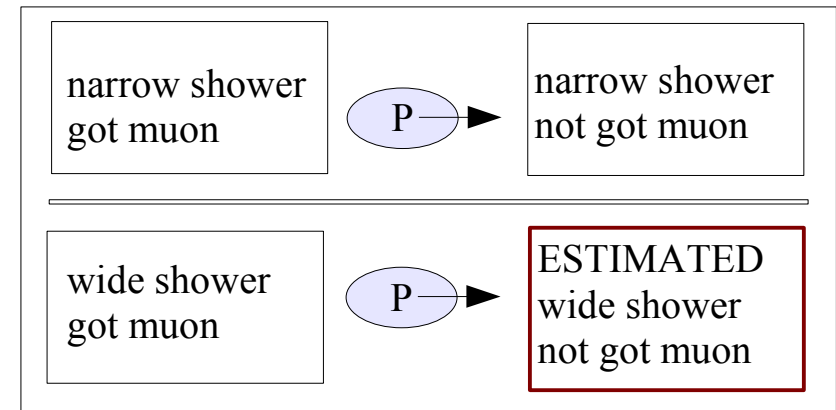
$$0.1 \text{ Hz} / 0.1\% \text{ Brem} * 6e23 * 17\text{g/cm}^3 / 238 \text{ g/mole} * 400\text{cm} * 10e-38\text{cm}^2/\text{GeV} * 500 \text{ GeV} =$$

$$10e-8\text{Hz} = 0.1/\text{year}$$



Background Estimation

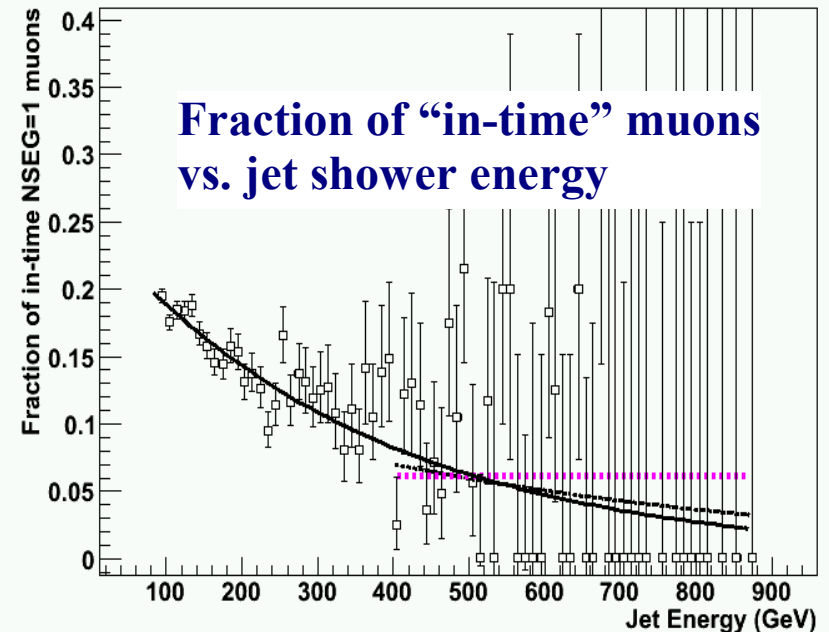
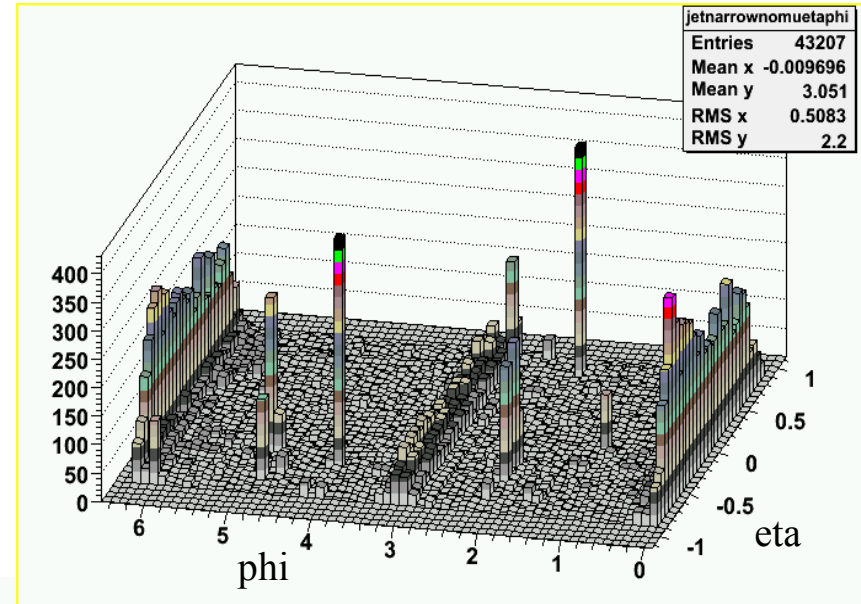
- We want to know the fraction of wide-showering, cosmic muon events for which we *don't* reconstruct the muon
 - This is our background!
- Probability to not reconstruct a cosmic muon in the muon system, $P(\text{nomu})$, is independent of how that muon showers in the calorimeter
- If this is true, then we can:
 1. measure $P(\text{nomu})$ in the narrow jet sample (etawidth and phiwidth < 0.08) - that we know are cosmics
 2. apply $P(\text{nomu})$ to the wide-shower sample (etawidth and phiwidth > 0.08) containing reconstructed muons - that we also know are cosmics - to obtain an estimate of the background
- *Sounds nice, but there's some tricky details...*



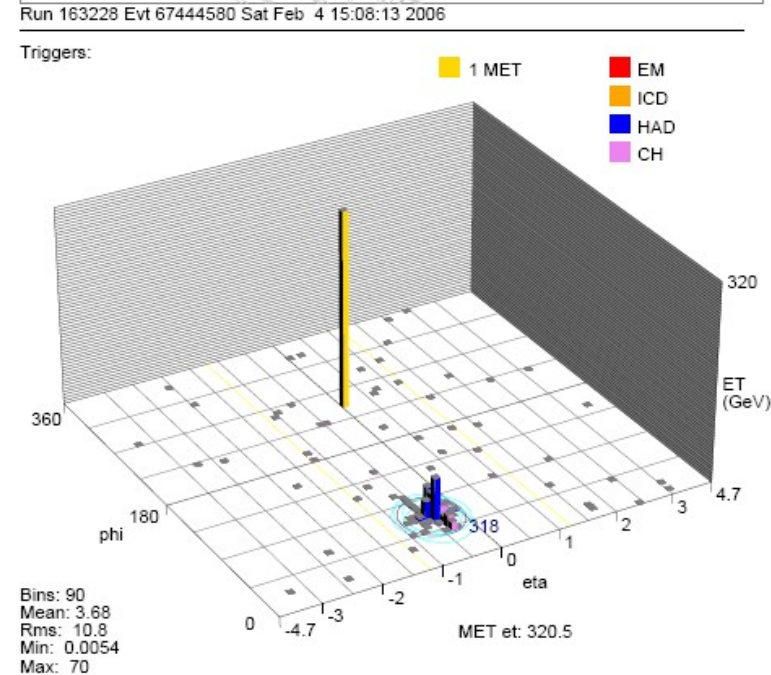
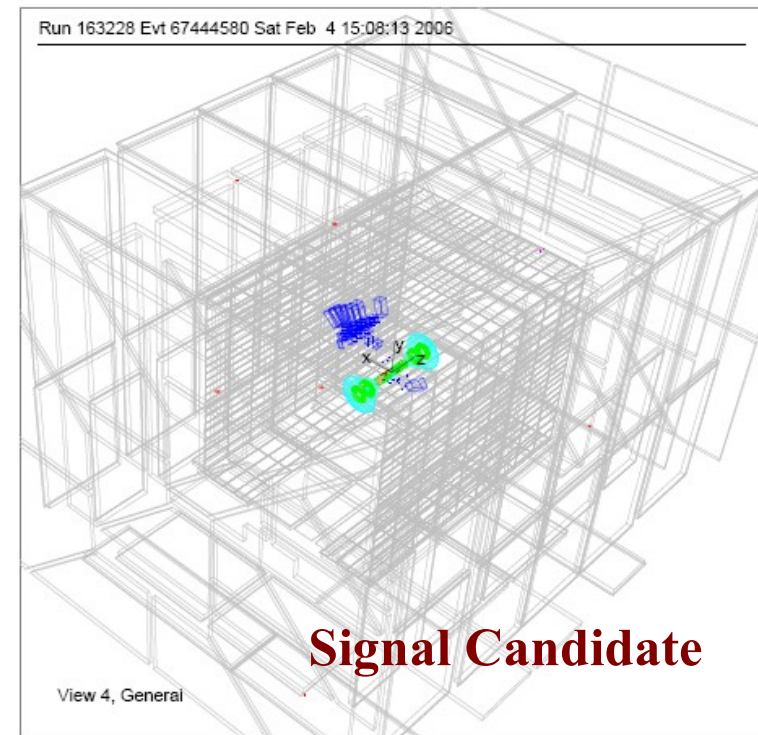
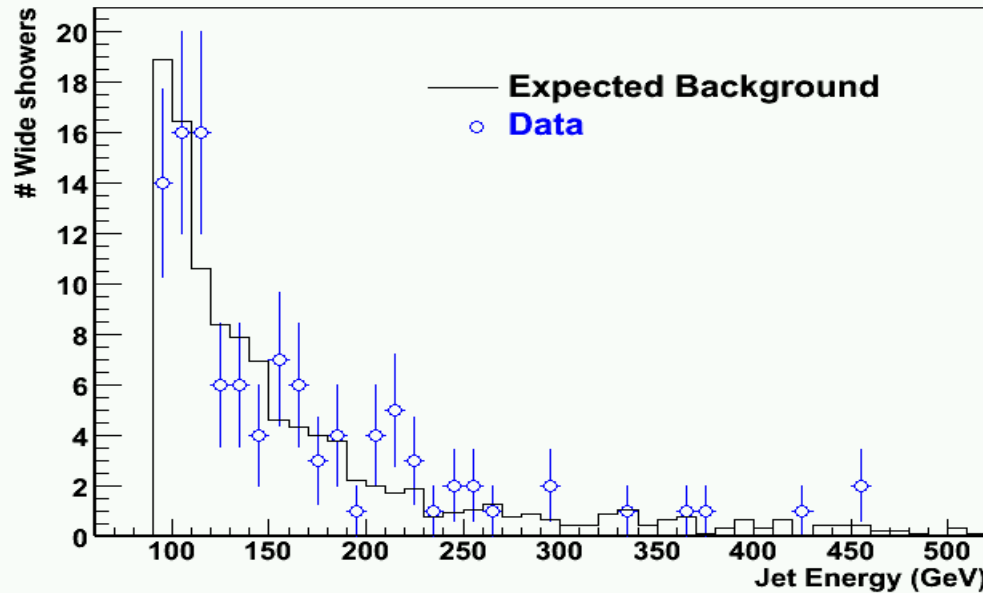
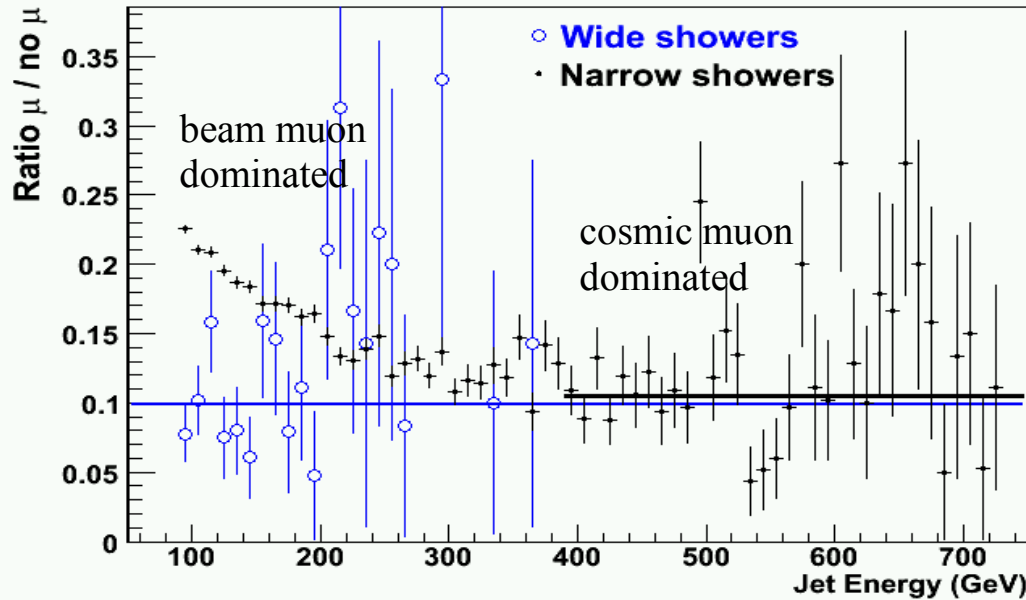
These are all cosmic muon events...

Narrow Cosmic Showers

- The narrow shower sample has some detector effects (hot spots) not present in the wide jet sample
 - Simply don't consider any hot spots when deriving $P(\text{no mu})$
 - If a bin of the eta/phi histogram is > 50 , ignore the region corresponding to that bin
- The narrow jets contain a contribution from beam muons, which have a different energy spectrum, come into the detector at strange angles, and therefore have a different $P(\text{no mu})$
 - Fortunately, we can study the properties of beam muons, and their difference from cosmics, by looking at “in time” vs. “out of time” muons!
- Beam muons are removed by requiring:
 - not in regions around integer values of ϕ/π
 - looking at high energy showers (beam muons' energy spectrum falls off faster than cosmics)

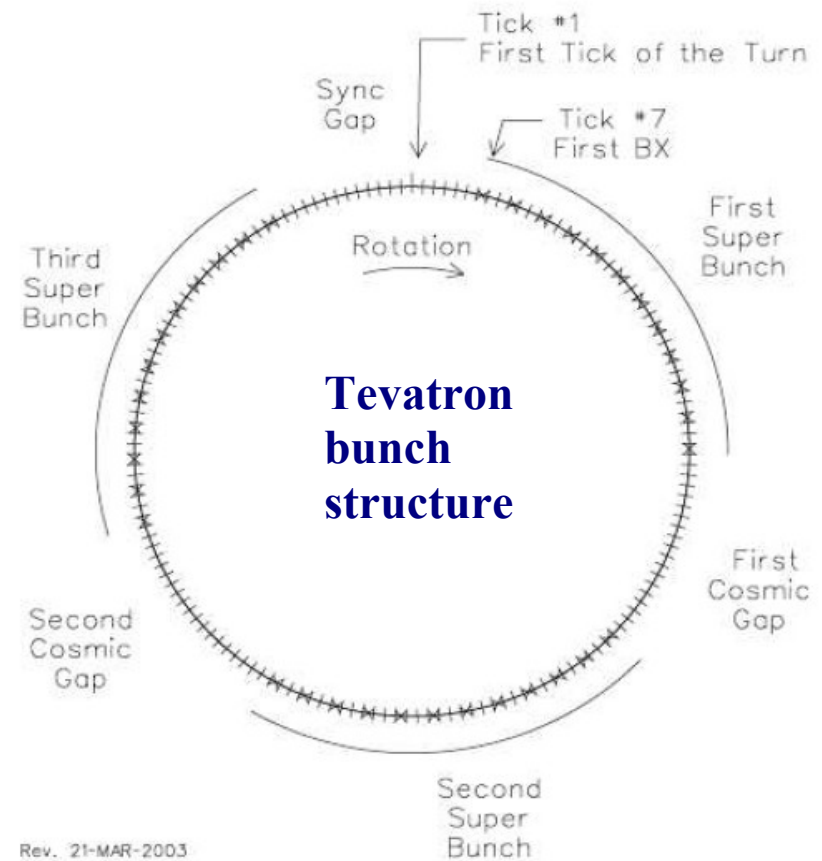


Data vs. Background



Signal Efficiency

- The events have high energy deposits
 - jet trigger eff. $\sim 100\%$
 - But we also require a GAPSN... which is dead if there is a min-bias interaction, or we're in a trigger gap
- GAPSN efficiency measured w.r.t. a non-GAP high-ET jet trigger
 - Averaged over all inst. luminosities
 - Corrections made for non-linear effects due to inst. luminosity profile
- Inefficiency due to bunch structure is simple:
 - Just count the bunch crossings we're live for
 - 22% due to "cosmic gaps" could be recovered
 - 11% in "sync gap" is *not* recoverable

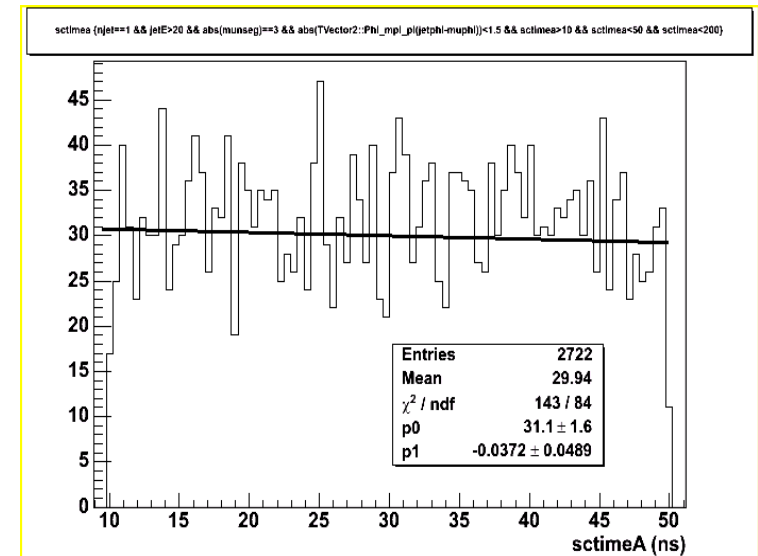
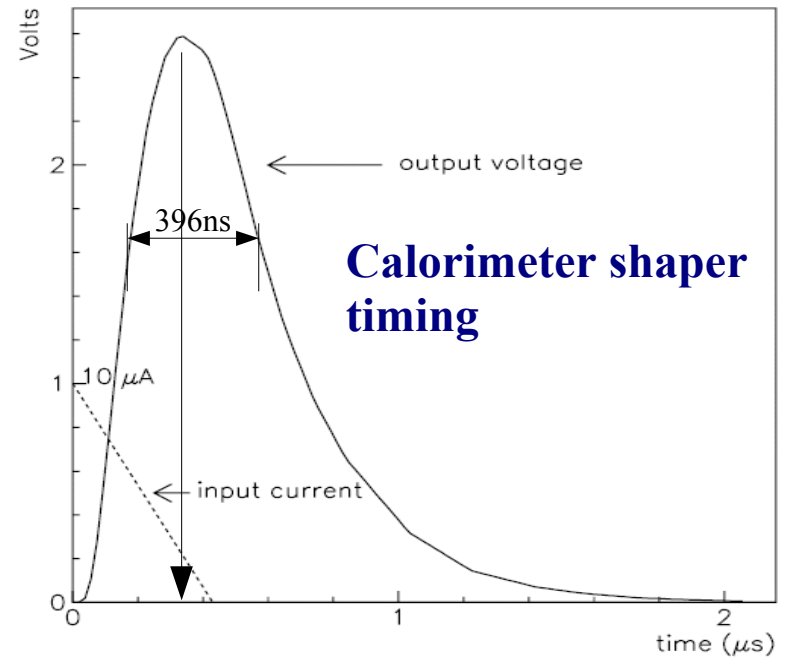


Sample	1 Jet	$ \eta $	$E > 90$	No PV	$W. < .25$	$W. > .08$	n90	No mu
200	0.91	0.91	0.30	0.98	1.00	0.57	0.85	1.00
300	0.87	0.89	0.97	0.97	1.00	0.50	0.86	0.96
400	0.83	0.89	0.99	0.96	0.99	0.56	0.89	0.97
500	0.81	0.91	0.99	0.97	0.99	0.56	0.85	0.97

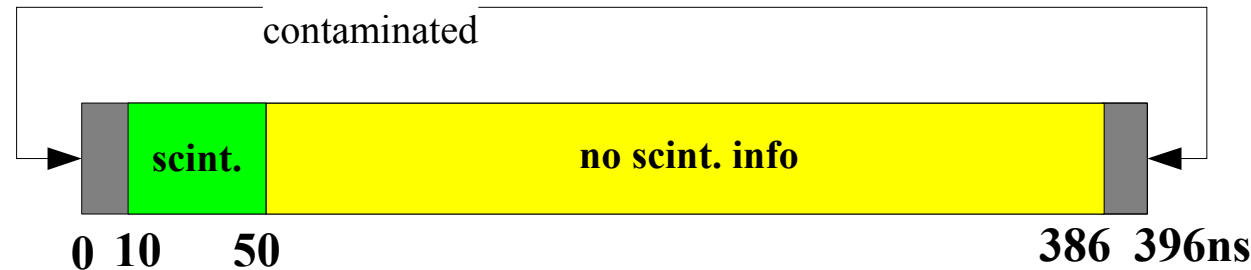
Source	Efficiency
GAPSN Trigger	.6
Trigger gaps	.68
Total	0.41

Out-of-time Calorimeter Energy

- The energy deposits are “out of time”!
- Calorimeter electronics sample the shaped pulse in each cell only *once per 396ns* – at the assumed *signal peak*
- Out of time energy will be under-estimated
- No falloff seen in plot of energy vs. shower time (as measured using muon scintillators – resolution $\sim 5\text{ns}$)
 - Unfortunately, muon timing only good from $-10 \rightarrow 50 \text{ ns}$... limited by electronics
- Look at cosmic muon events within the muon scintillator timing window, and compare to the number of cosmic muons *observed* outside the window
- If the calorimeter energy is lower, we won't observe events as often when they are outside the window (either due to trigger inefficiency or energy falling below offline 90 GeV threshold)
- Determine effect to be an average $15 \pm 5\%$ decrease in measured energy



beam-muon
contaminated



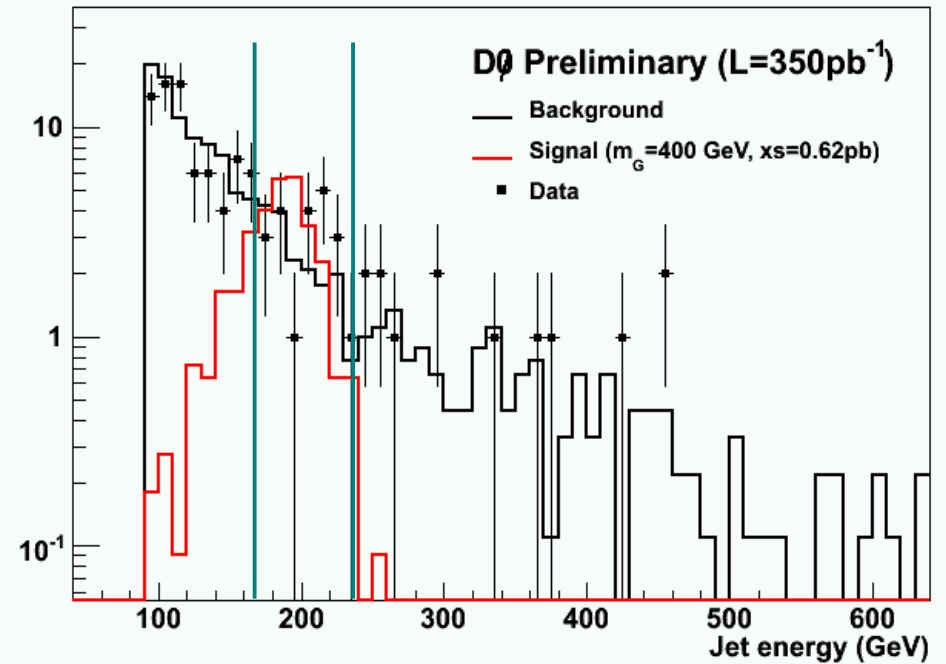
Systematic Uncertainties

- Systematics on signal efficiency come from various sources
 - Geometrical / kinematic
 - jet shape cuts
 - jet energy cut
 - 2nd jet veto
 - eta cut
 - muon cuts
 - Data / MC calorimeter response
 - Simulation of the out-of-time response
 - Trigger efficiency
 - The GAPSN requirement – inefficiency due to min-bias overlap – dependent on luminosity profile
- The background of wide-cosmic-showers has a normalization of $\pm 10\%$, due to statistics of the narrow-cosmic-shower sample at high energy
- There's an uncertainty on the total integrated luminosity of 6.5%

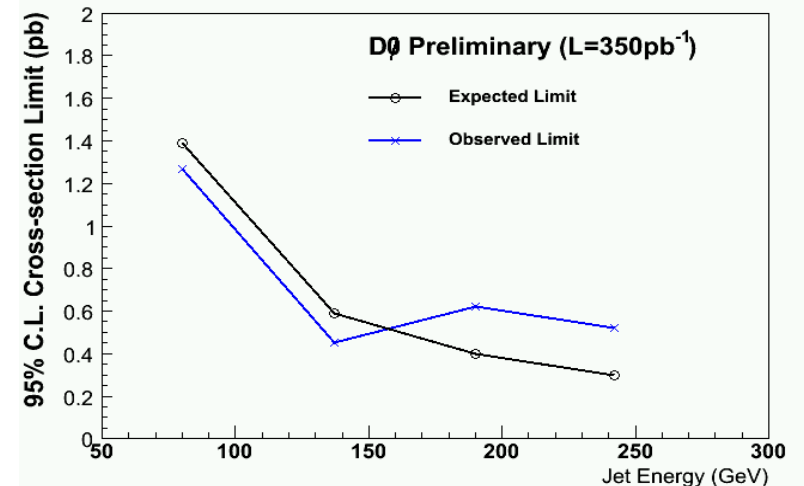
Source	Uncertainty
Geometrical/Kinematic Acceptance	0.2
Min-bias Overlap	0.15
Total	0.25

Limits

- 4 jet energy ranges were chosen, corresponding to the energies of the jets in the various signal mass samples
 - $M - \text{RMS}/2 < E < M + \text{RMS} * 2$
 - Asymmetric because of exponentially falling background and symmetric signal
 - ~80% of signal events passing cuts are accepted in the energy range
- Overall efficiency is around 10%
- Count the number of signal, bkgd., data events in each of the energy ranges
- Set limits using Bayesian calculator



Jet E Range (GeV)	Data	Bgnd.	Eff.	Exp. Limit (pb)	Obs. Limit (pb)
94.6-111.6	46	48.18	0.05	1.39	1.27
126.8-171.8	32	37.84	0.10	0.59	0.45
169.3-233.8	27	21.56	0.11	0.40	0.62
214.2-286.6	14	9.57	0.10	0.30	0.52

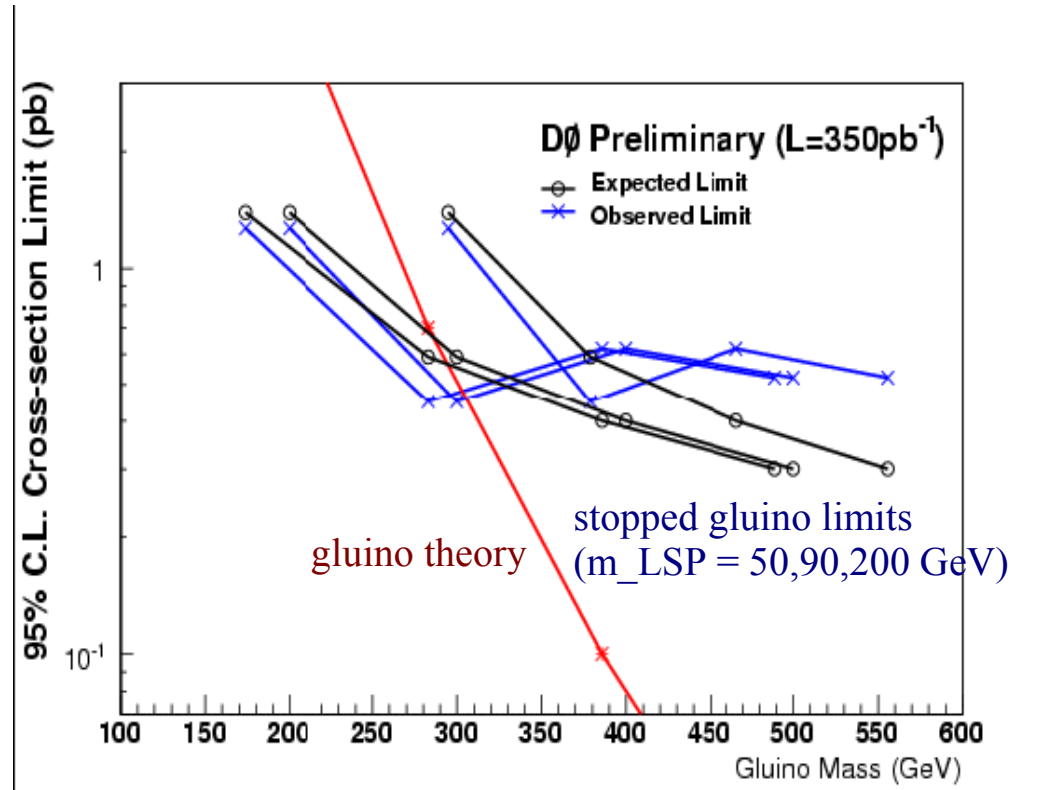


Glauino Limits

- There is only one observable (E), and two model parameters (mG, mLSP)
- Given the simulated values of E, translate to other mG, choosing 3 fixed values of mLSP = 50,90,200 GeV

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

- Compare to theoretical prediction, which is a function of mG



Limits for mLSP=90 GeV

Jet E (GeV)	Gluino Mass (GeV)	Observed Limit (pb)	Theoretical CS (pb)
80	200	1.27	5
137	300	.45	.5
190	400	.62	.05
242	500	.52	.01

Improvements

- The following have been done, but are under review (will be in the publication)
 - Limits can be set as a function of gluino lifetime
 - A model of stores has been created, and limits have been set up to 100 hours
 - Care has been taken in modeling the out-of-time calorimeter energy response
 - Instead of just modeling the average loss of efficiency, the resolution effects are taken into account
 - Data/MC energy scale differences are taken into account
 - Somewhat important since we're using *uncorrected* jet energies
- There's 4x more integrated luminosity on tape
 - And it's at higher instantaneous luminosity -> proportionally less cosmic background
- But a new trigger is needed at high luminosity, since min-bias overlap is introducing significant inefficiency for the GAP trigger
- Jet showers are sometimes wide in both phi and eta, but are narrow in some other linear combination of phi and eta... need to reconstruct the *minimal shower width*
 - This would require a dedicated study, but could reduce backgrounds by ~2x
- Since ~30% of gluinos have a pair-produced partner which also stopped, the *time-coincidence* of candidates should be studied

Conclusions

- First search (that I know of!) for out-of-time jets appearing from within a calorimeter
 - A very challenging analysis...
 - Non-standard signal simulation (“beam” inside calorimeter!)
 - Many signal efficiencies and backgrounds were studied for the first time
 - New method for estimating the remaining cosmic background
- Limits were set in the stopped gluino model on mG vs. $mLSP$
 - Analysis is already sensitive to $mG \sim 300$ GeV
- There are still several ways to improve the sensitivity of the analysis
- Things only get easier at ATLAS ?
 - 14 TeV
 - Underground cavern ($1/10^{\text{th}}$ the cosmic rate)
 - Higher bunch-crossing rate (25-75 vs. 396ns) and inst. luminosity (100x)
 - 5 samples per crossing in LAr electronics $\rightarrow \sim 1$ ns time resolution
- But will pose new challenges...
 - Trigger?
 - More overlap with previous events
 - No Iron toroid magnet