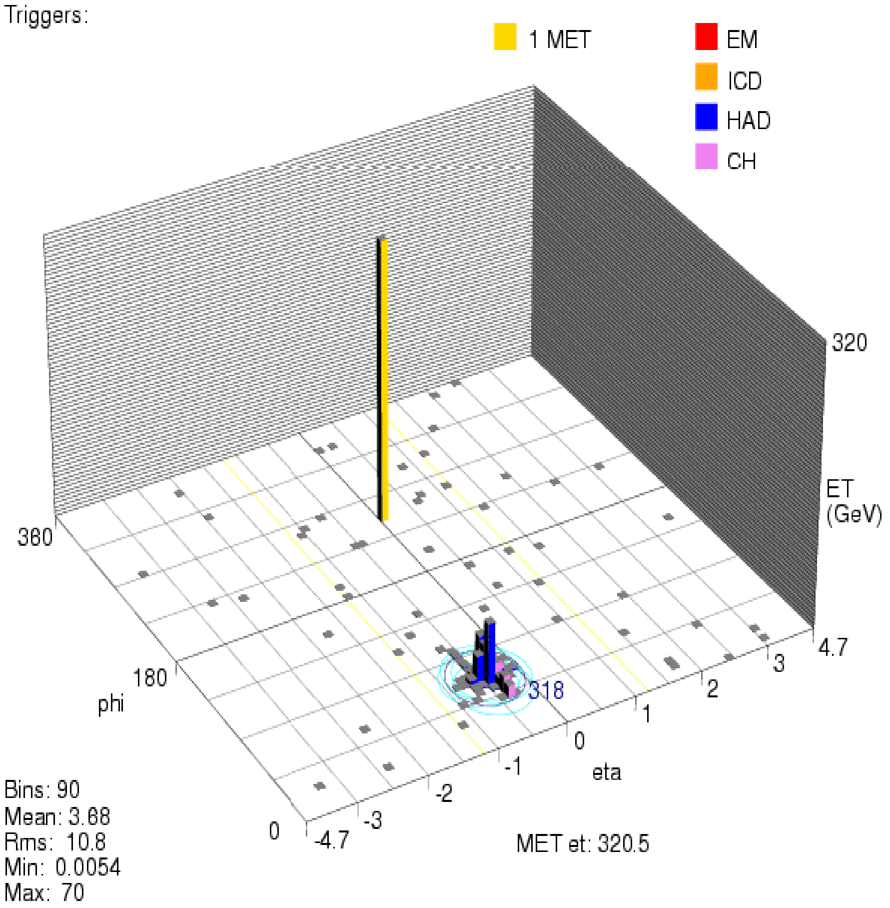
The Search for Stopped Gluinos



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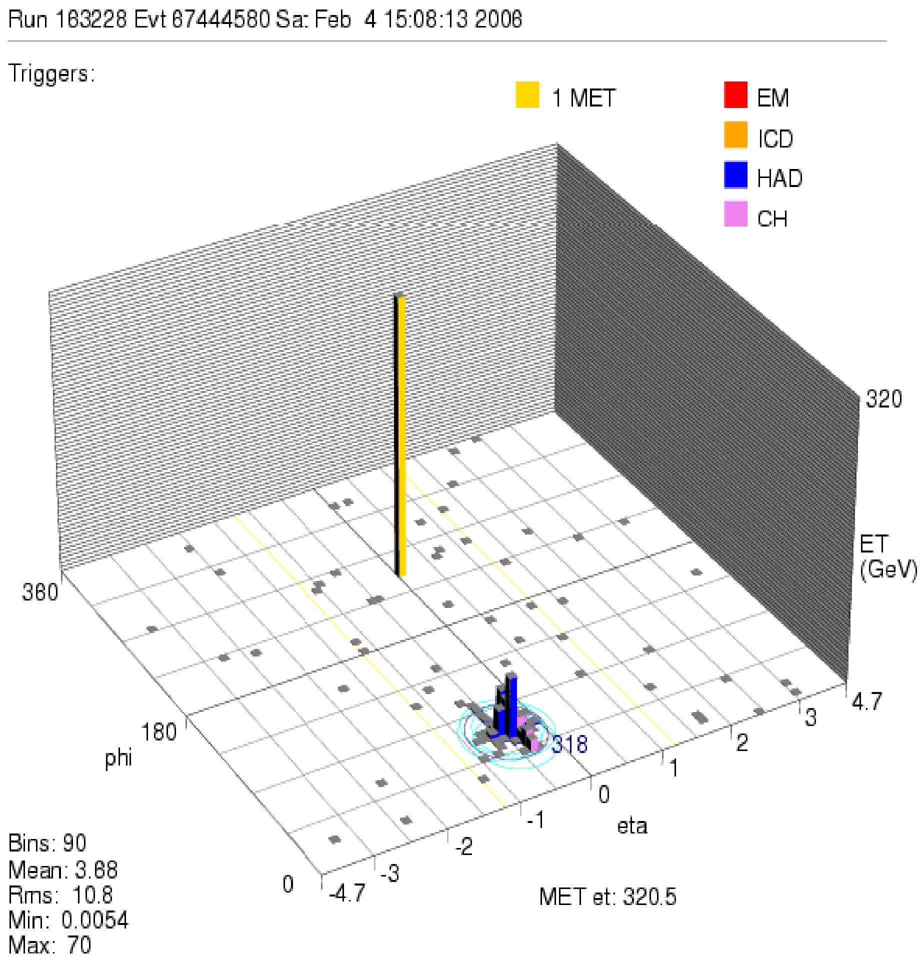
All D0 Meeting
Feb. 2, 2007

Outline

- What's a stopped gluino?
- 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



SU/SY

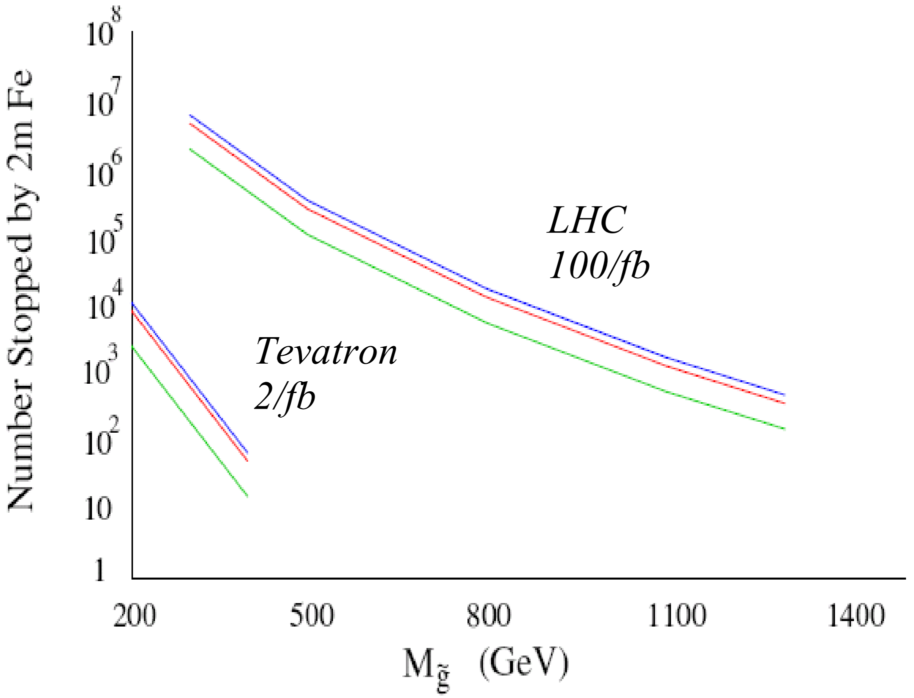
- Supersymmetry
  - gluons <-> gluinos
    - *gluinos* are neutral, colored, but spin ½
- Split Supersymmetry
  - Normal SUSY has the mass of scalars near the EW scale
    - This prevents the Higgs mass from being unstable due to loop corrections
      - This was kind of the point of SUSY to begin with!
  - But what if the Higgs mass is stabilized by something else?
    - Chance! -> Anthropic principle.
    - Works for the cosmological constant, why not the Higgs mass?
  - Scalars should be very heavy -> near the GUT scale
  - Fermions are protected by chiral symmetries -> 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 “light” neutralino -> 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...

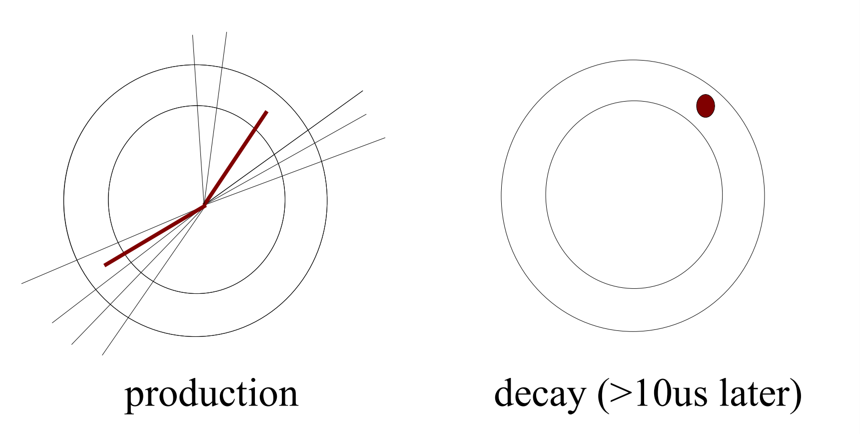
What's a Stopped Gluino?

- ppbar -> 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 qqbar+LSP) *(BR to gluon+LSP assumed to be 100% for this analysis.)*
  - Lifetime depends on M_{SUSY} but is >10ns if M_{SUSY} >10^6 GeV *(Lifetime assumed to be >10 us and <100 hours 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 GeV

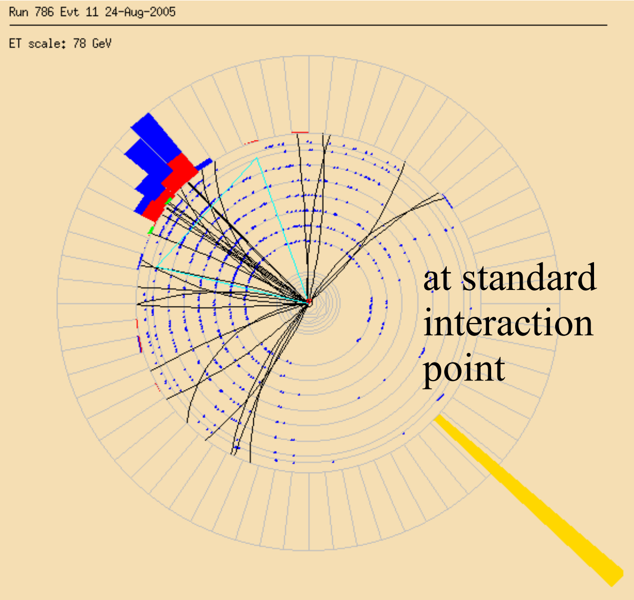
~5 stopped gluinos in 2/fb for m_g=500 GeV



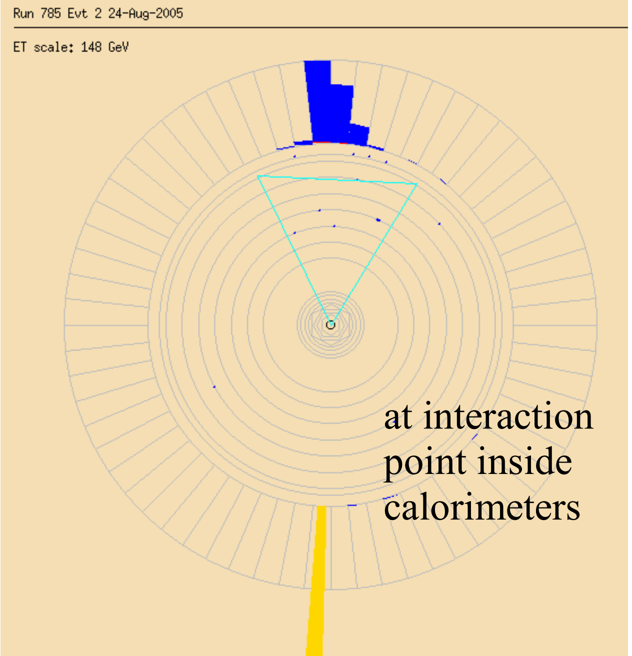


Signal Simulation

- 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 |pz/E|>.95
- Decay location chosen to be Gaussian-distributed: (x,y,z)=(0+-20, 120+-20, 0+-80) cm
  - In the middle of the calorimeter
- Then, further weighting of events by decay location to match the distribution expected from stopping gluinos…



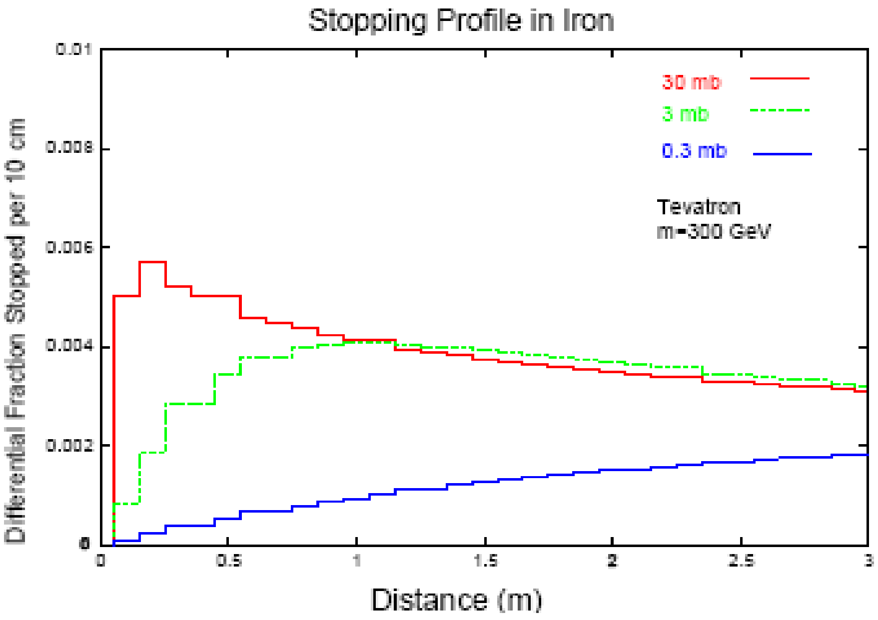
at standard interaction point



at interaction point inside calorimeters

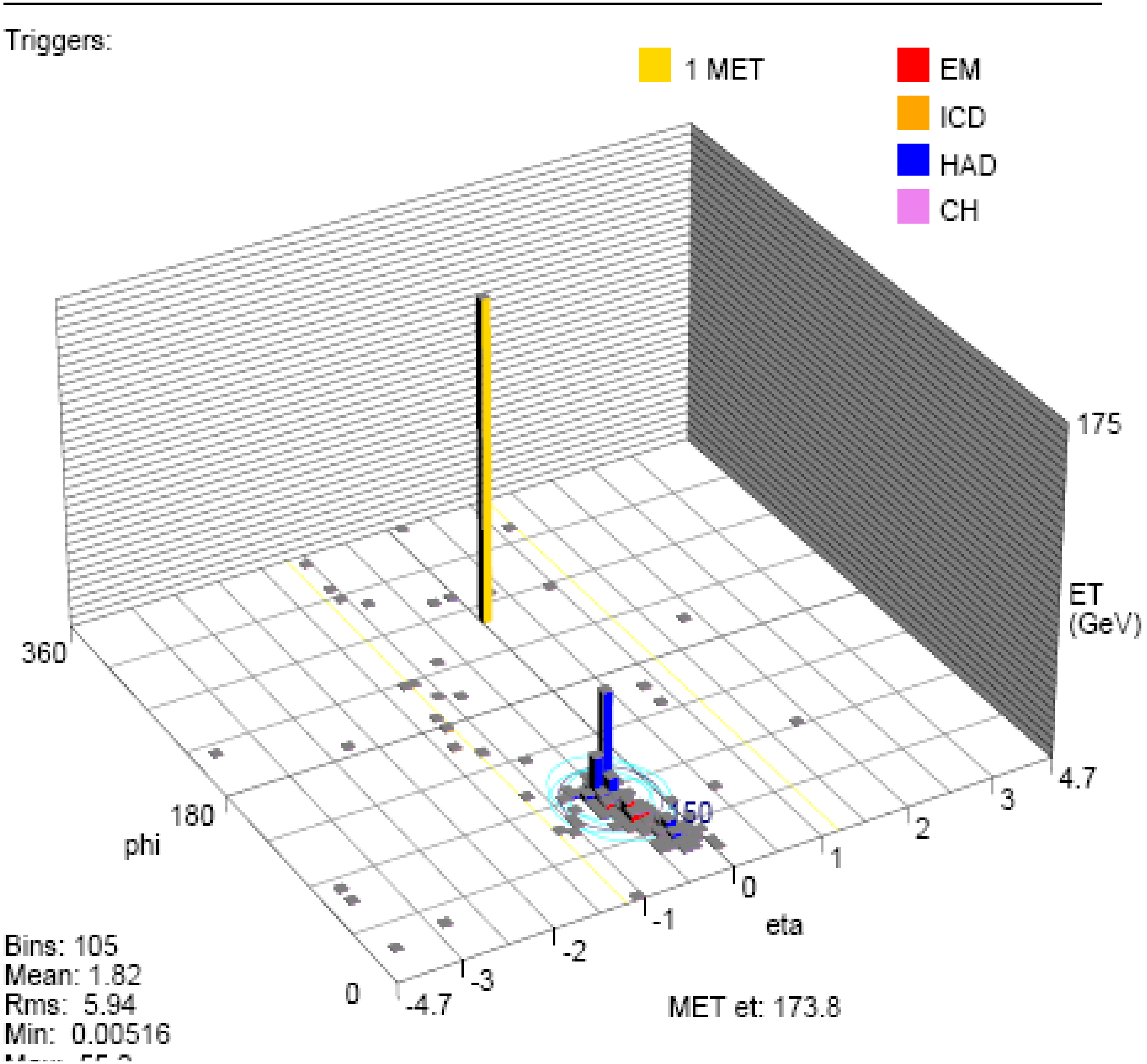
Signal Simulation

- The expected radial distribution in the calorimeter is not well known theoretically
  - Depends on the conversion rate from neutral->charged R-hadrons in matter
- Events are weighted such that “r” is proportional to an average of the distributions expected for 0.3 -> 30mb
  - Nearly flat
- 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 is proportional to tanh(eta)



Getting a Feel for Gluinos

Typical

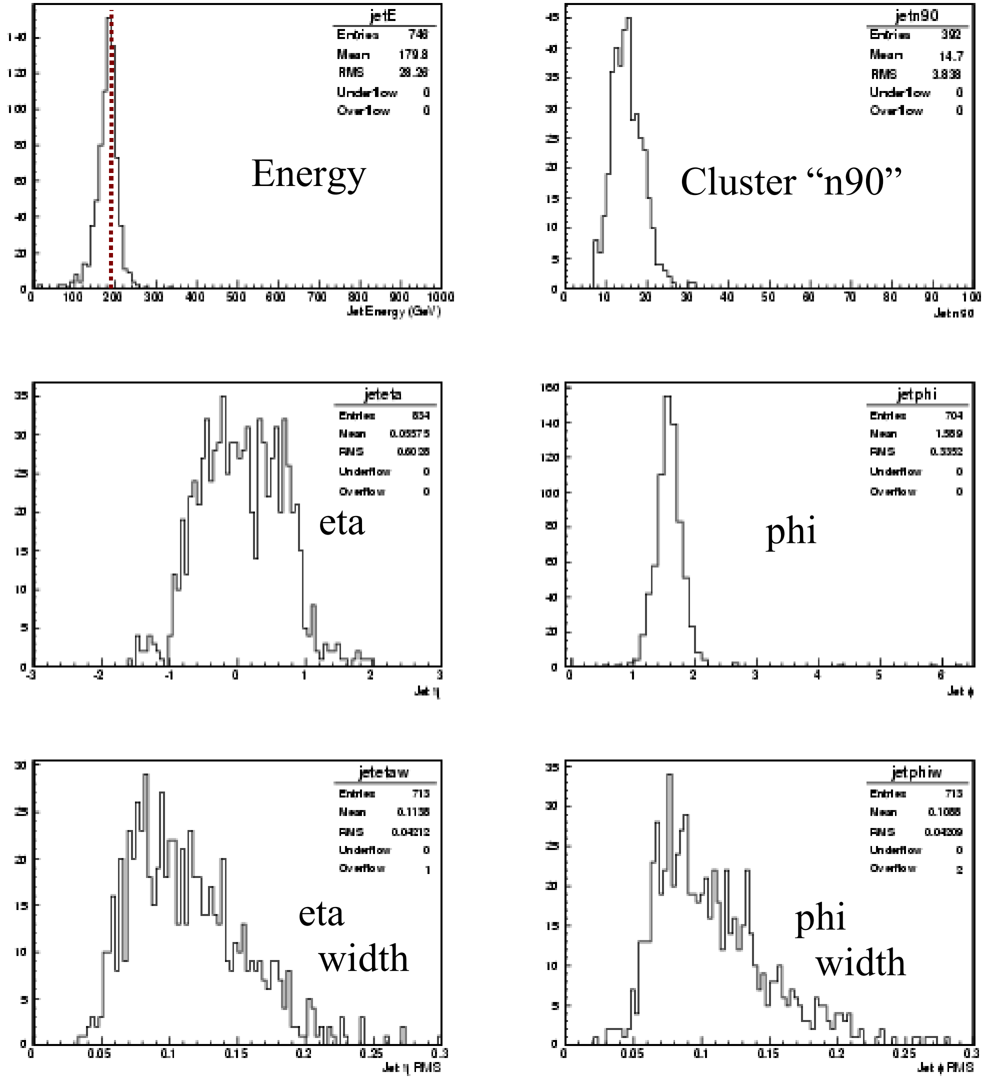


Signal Distributions

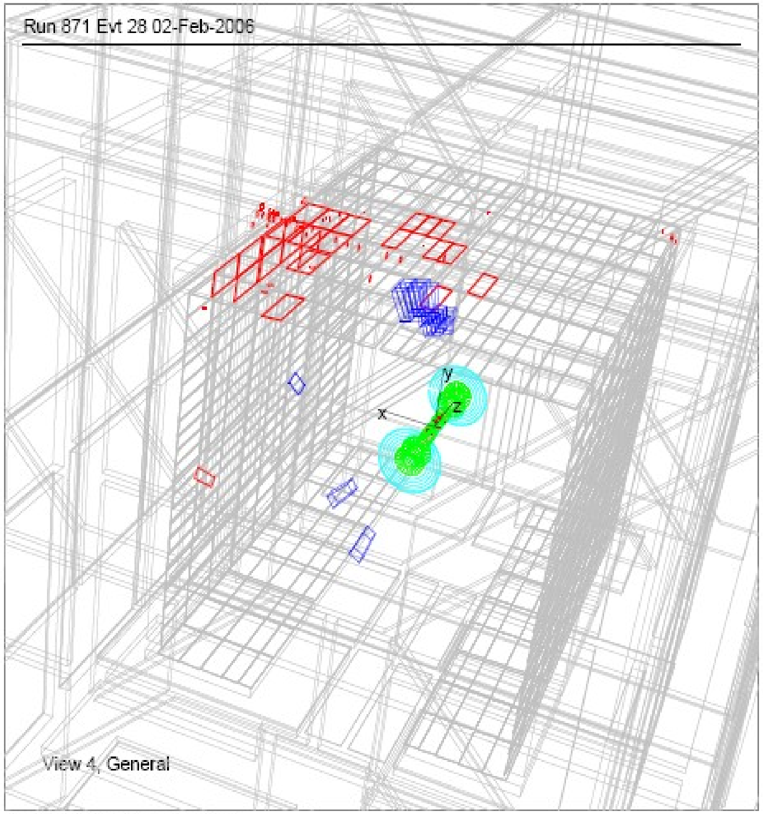
- Gluino jets look much like normal jets…
  - They are fairly wide (phiwidth,etawidth > 0.08)
  - *Good discriminant against muon-induced showers !*
- Gluino jets often (30% of the time) have significant leakage / punch-through into the inner muon layer ("A-layer splash")
  - They may be near the outside of the calorimeter when they decay
  - About 10% of the time, a particle (sometimes a real 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
- Sometimes two jets are reconstructed, near each other in dR (about 10-20% of the time)

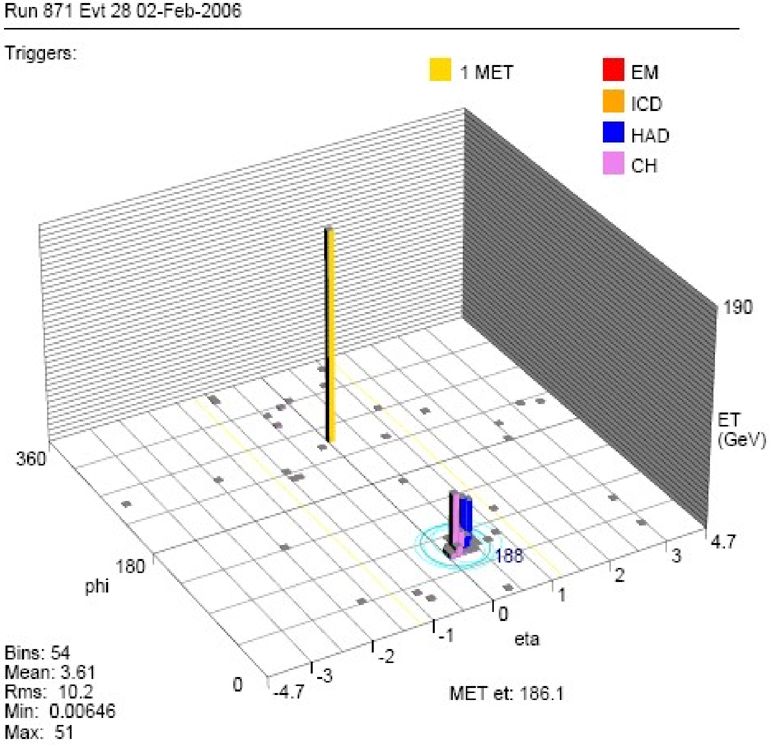
Plots from mG=400 GeV sample

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

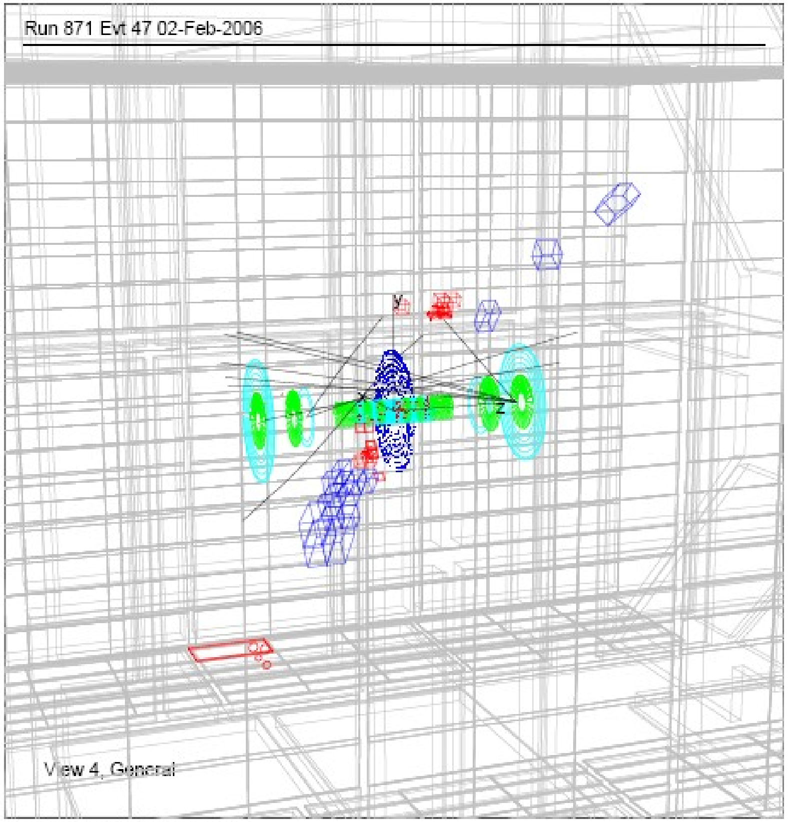


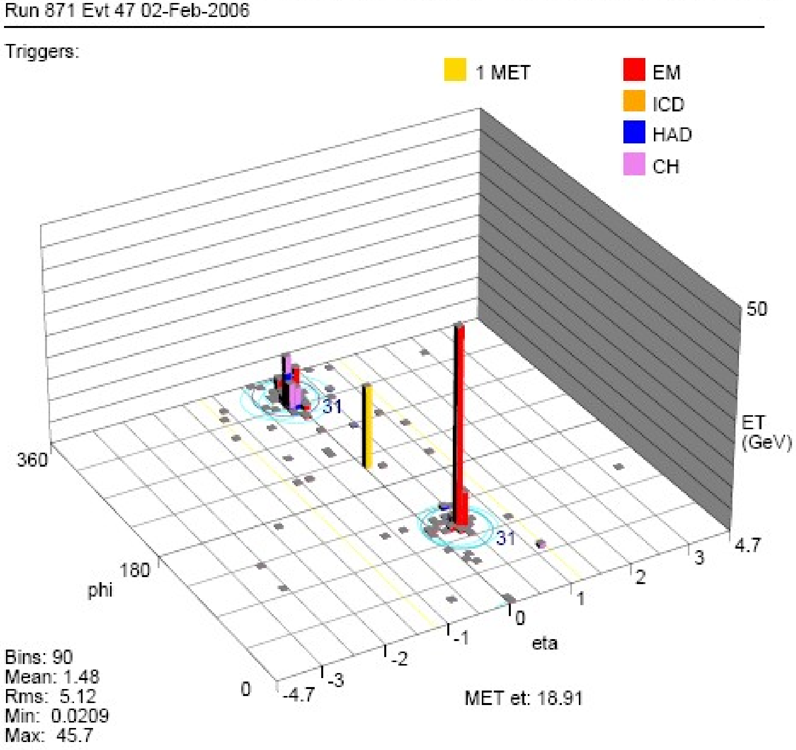
A-layer “splash”





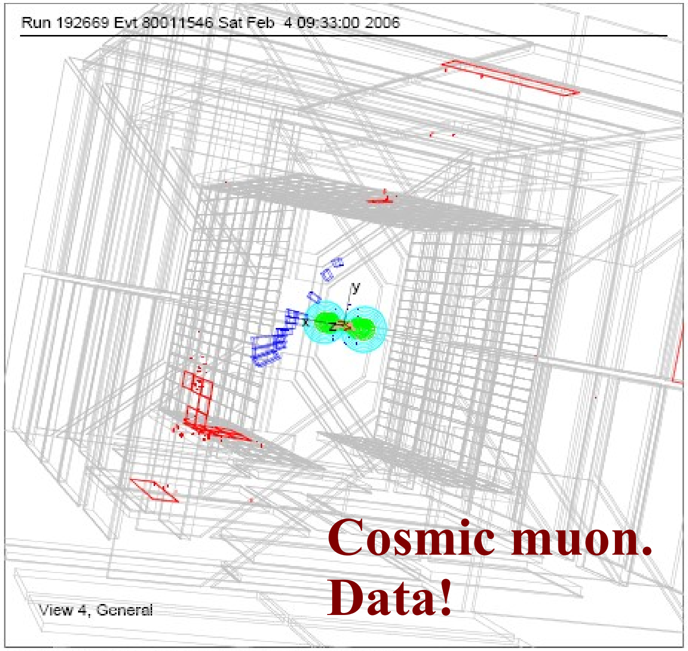
Tracks


Run 871 Evt 47 02-Feb-2006
y
x
z
View 4, General

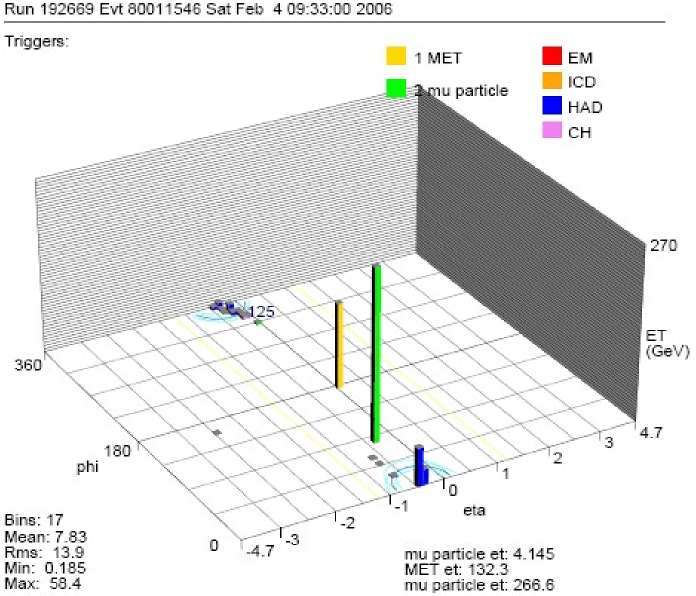

Run 871 Evt 47 02-Feb-2006
Triggers:
🟨 1 MET
🟥 EM
🟧 ICD
🟦 HAD
🟪 CH
50
ET
(GeV)
360
180
phi
0
31
31
-4.7
-3
-2
-1
0
1
2
3
4.7
eta
MET et: 18.91
Bins: 90
Mean: 1.48
Rms: 5.12
Min: 0.0209
Max: 45.7

Data and Backgrounds

- Data -> p14 PASS2:
  - 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, ~0.5Hz (!)
- Pre-selection cuts:
  - Good muon, calorimeter, 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

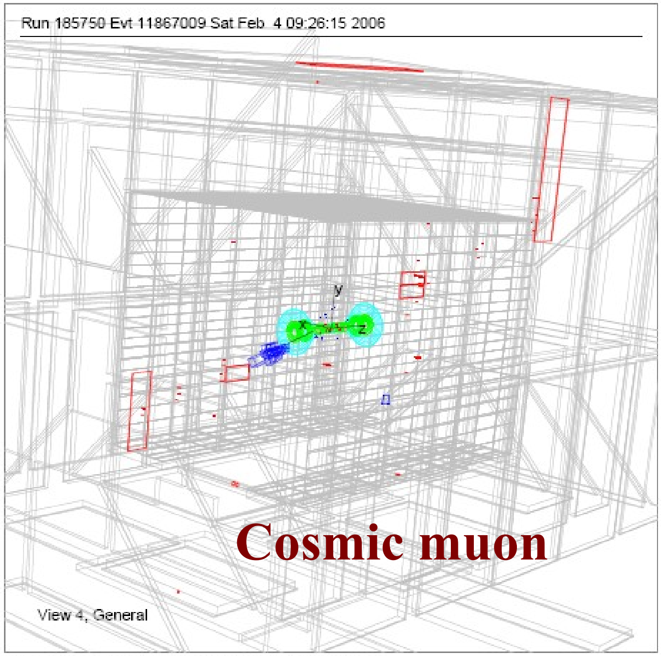


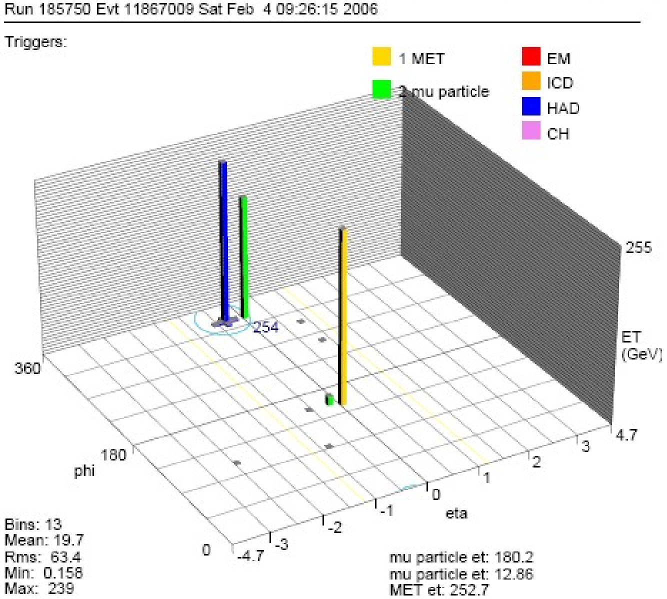
Cosmic muon. Data!



Cosmic Muons

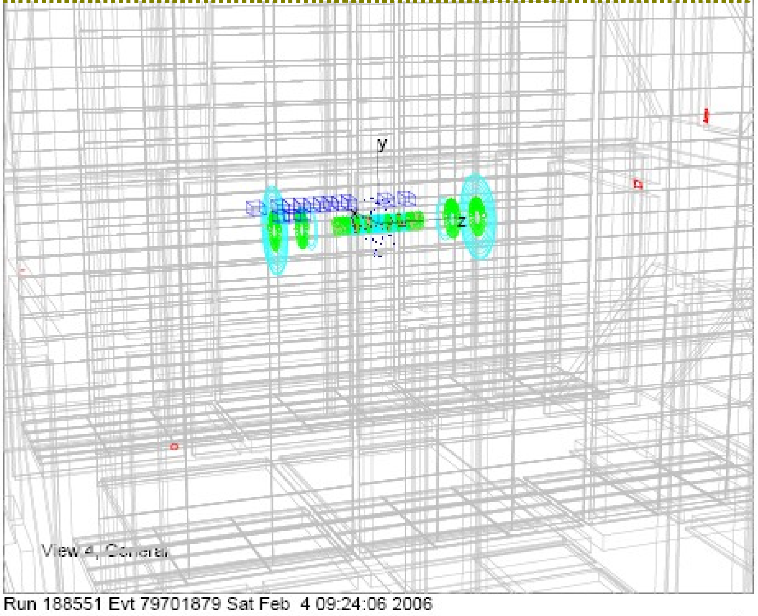
- These are the major background
- Usually there's at least one good (BC layer) muon
  - There's two chances to see the muon (on the way in, and going out)
- Showers in the calorimeter can be quite large (>1TeV!)
- Hard Bremsstrahlung photon is the dominant process at high energy loss
  - Narrower showers than “jets”:
    - More energy in single cells (n90 < 5)
    - Smaller phi- and eta-width (<0.08)
- A visible MIP trail about half the time...
  - No algorithm available for identifying them (unless they are projective)
  - A difficult reconstruction problem!
  - Can be faked by gluino jets as well
  - Not used in the analysis

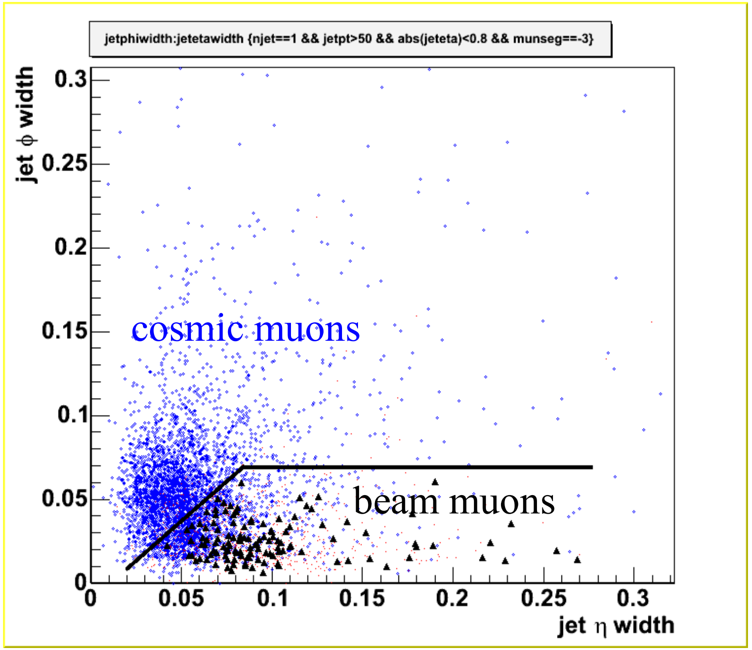


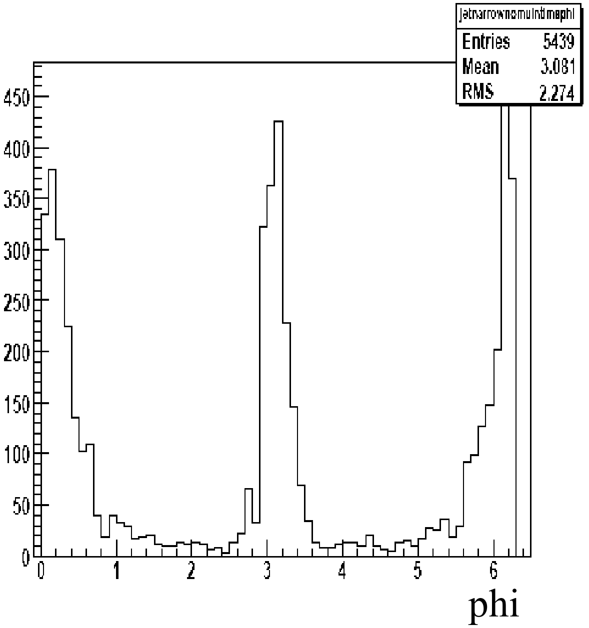


Beam Muons

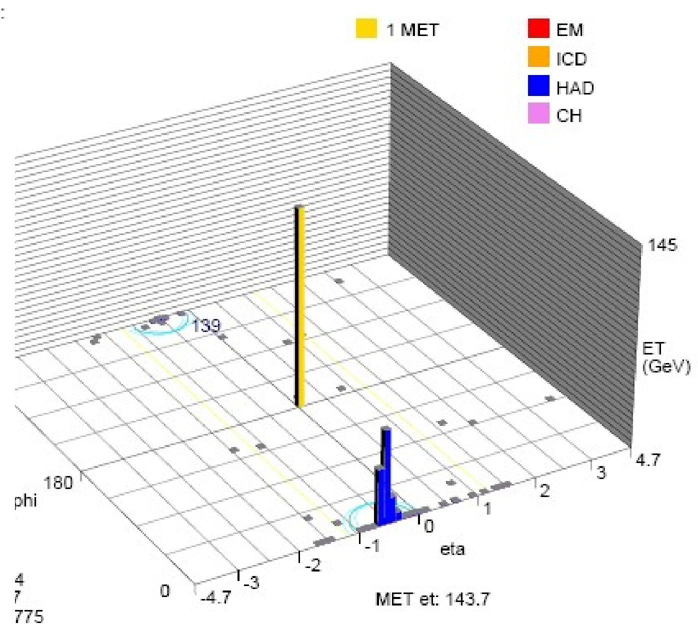
- There are a large number of “beam muon” events (about as many as cosmic muons)
- Often a forward muon segment, or scintillator hits
  - in time with the beam! (|t|<10ns)
- Protons (or anti-protons) hit gas or the beampipe and create pions, which decay to muons
- Why are they focused at integer values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





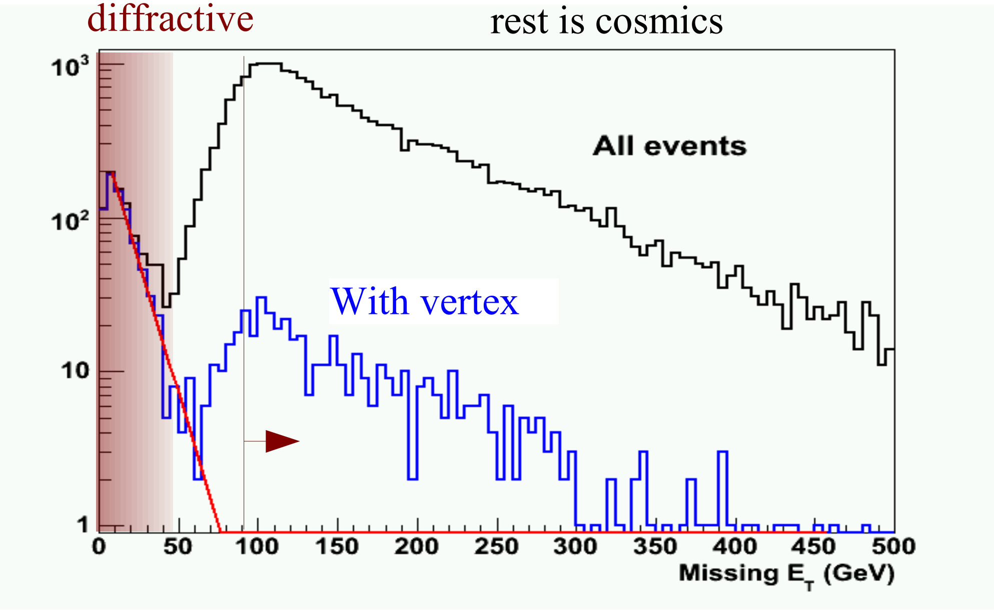


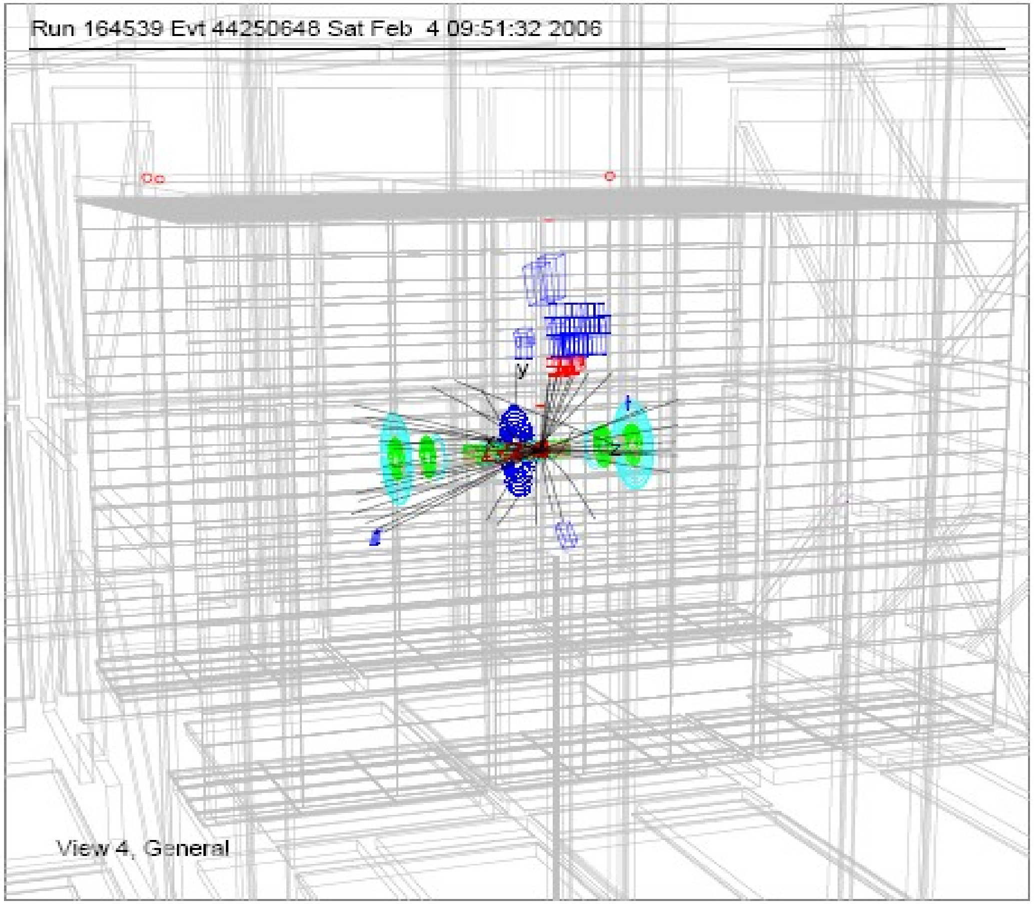
Triggers:



Diffractive Background

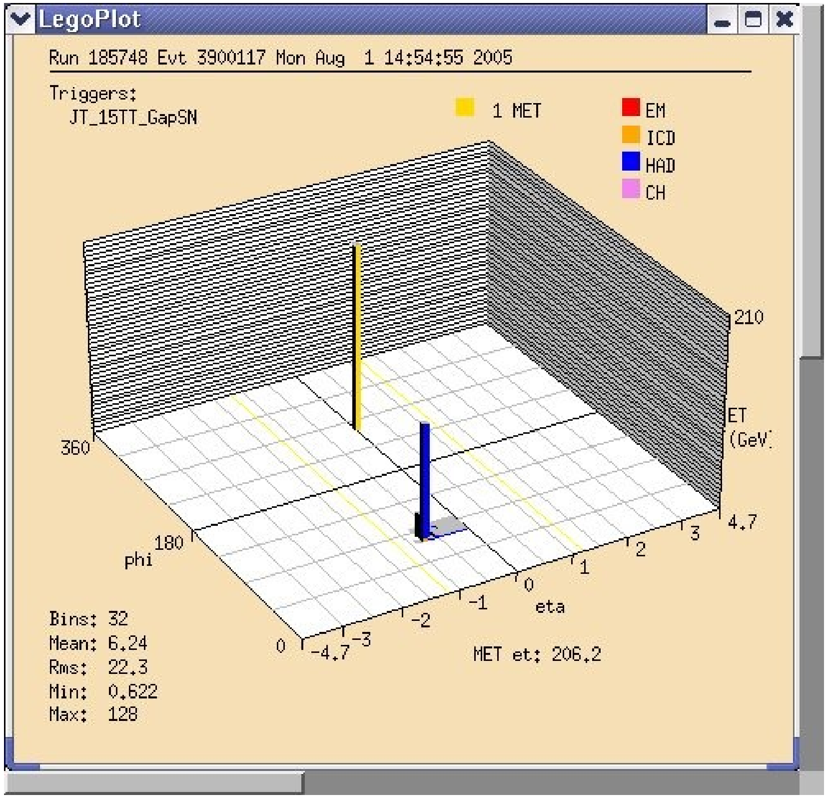
- Could "double-diffractive" events slip through?
  - Require no Primary Vertex
  - Require large MET (1 jet, E>90 GeV)
- Background is negligible after these cuts



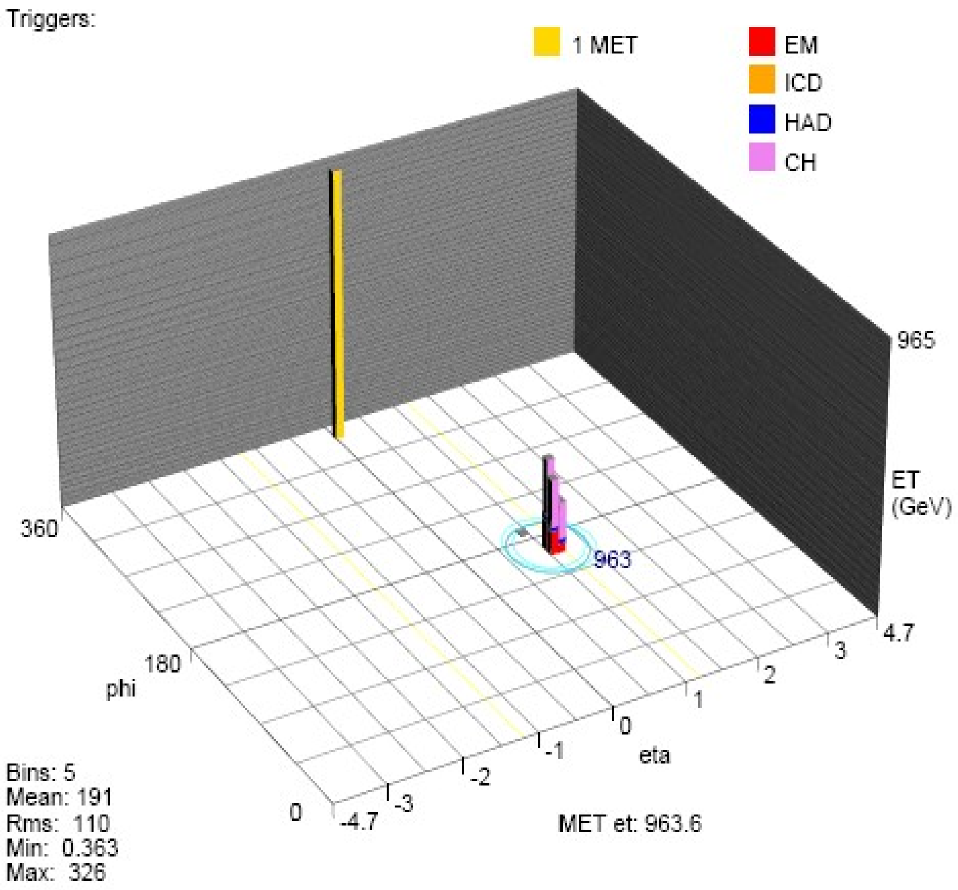


Detector “Problems”

- 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
- Background is negligible after these obvious problems have been removed



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

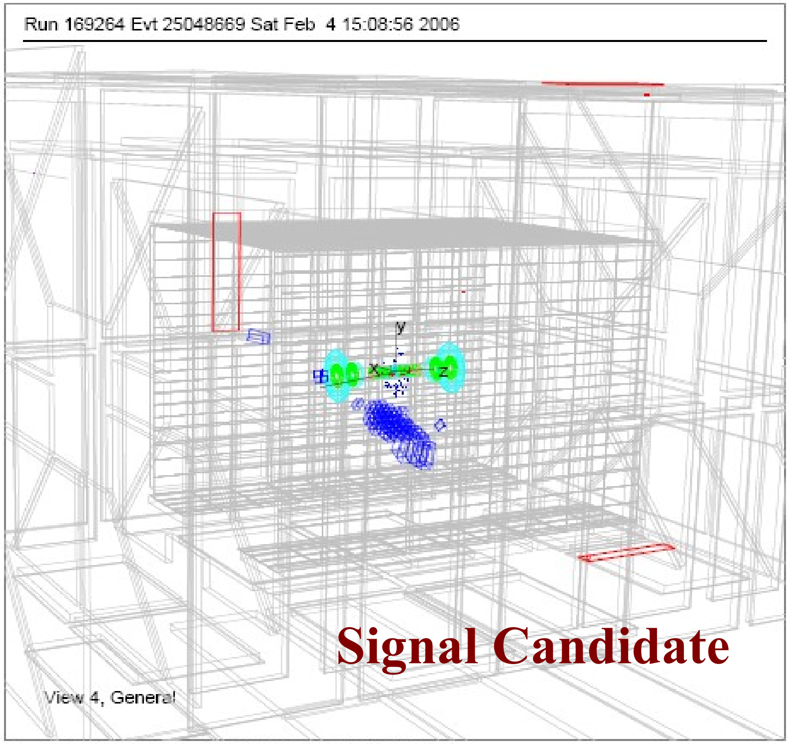


Event Selection

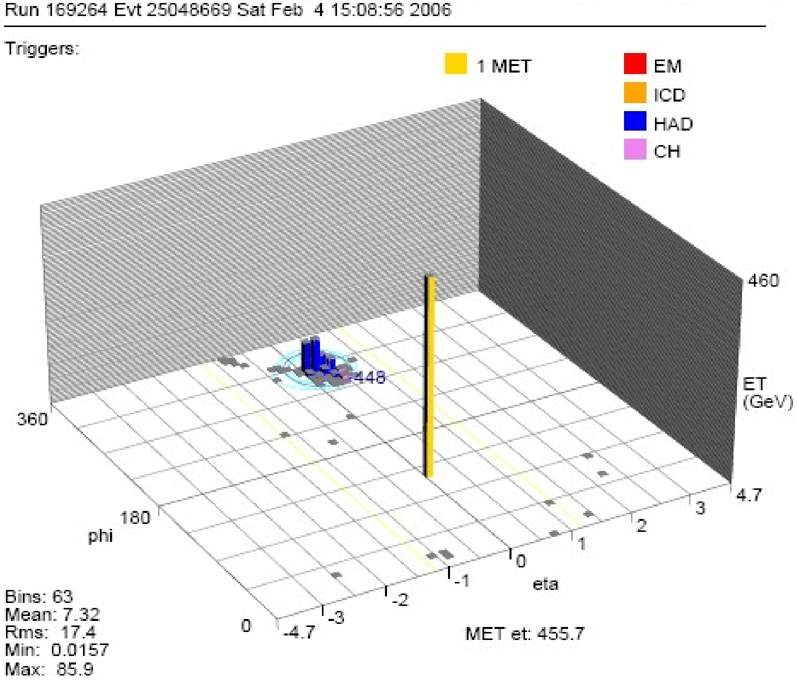
- Jet |eta|<0.9 (gluinos stop centrally, and forward calorimeters had more DQ problems)
- No Primary Vertex (remove diffractive events)

- "Wide jet showers":
  - d_eta > 0.08 and d_phi > 0.08
    - muon-showers tend to be narrow
  - n90 >= 10
    - muon showers tend to have most of their energy in a few cells
- "No-muon showers"
  - No |NSEG|=2,3 muons
  - dphi between any A-layer muons < 1.5
    - Accept A-layer muon splash, but reject back-to-back A-layer muons
  - dphi (muon, jet) < 1.5
    - Accept A-layer splash, but only if it is geometrically consistent with the jet

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



Signal Candidate



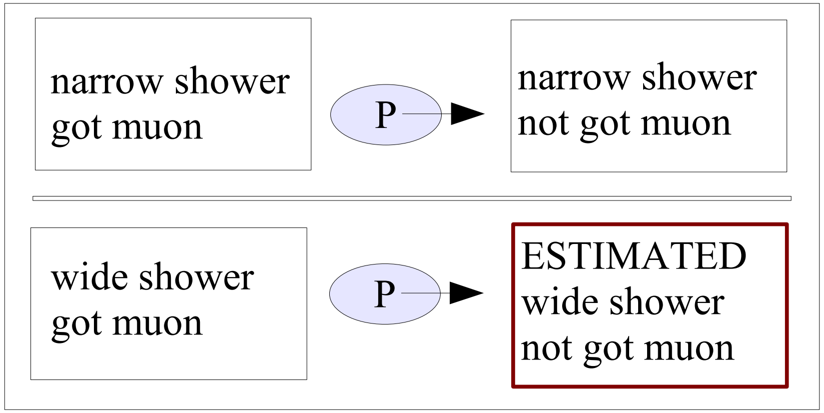
Background Estimation

- Background is wide-showering, cosmic-muon type events for which we *don't* reconstruct the muon

- Probability to not reconstruct a cosmic muon in the muon system, P(nomu), is independent of how that muon showers in the calorimeter

  1. measure P(nomu) in the narrow jet sample
     -- we know these are cosmics --
  2. apply P(nomu) to the wide-shower sample containing reconstructed muons
     -- we know these are also cosmics --

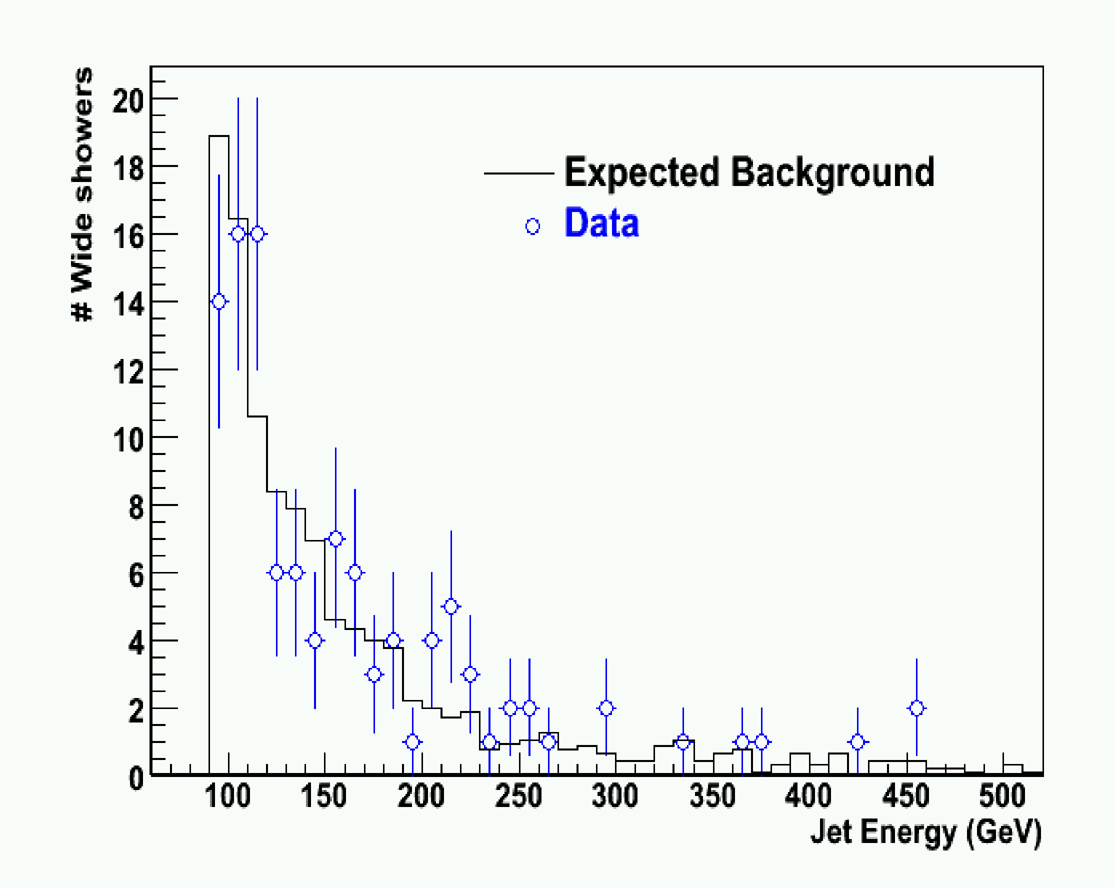
- All other backgrounds have been argued to be negligible after proper cuts
  - This is *conservative* when setting limits...

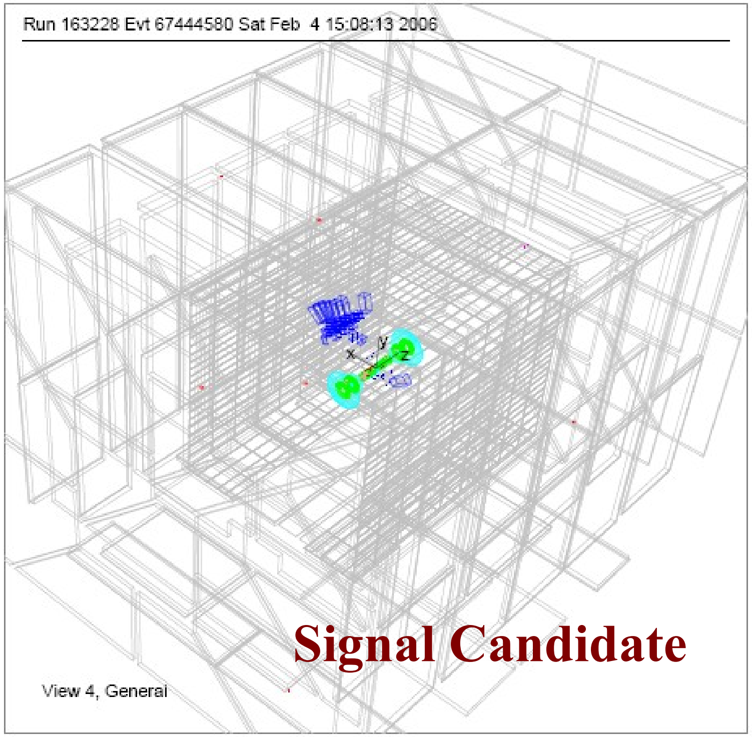


narrow shower got muon → P → narrow shower not got muon

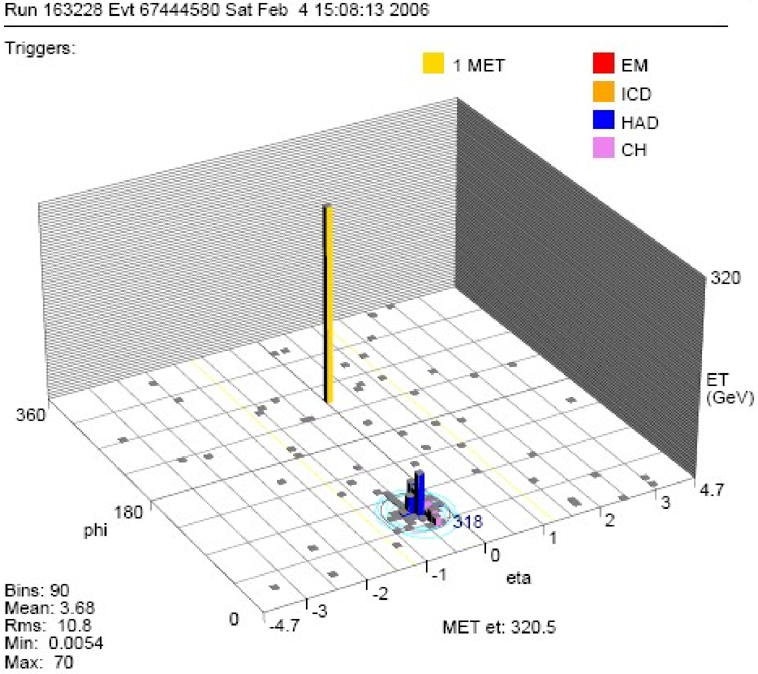
wide shower got muon → P → ESTIMATED wide shower not got muon

Data vs. Background



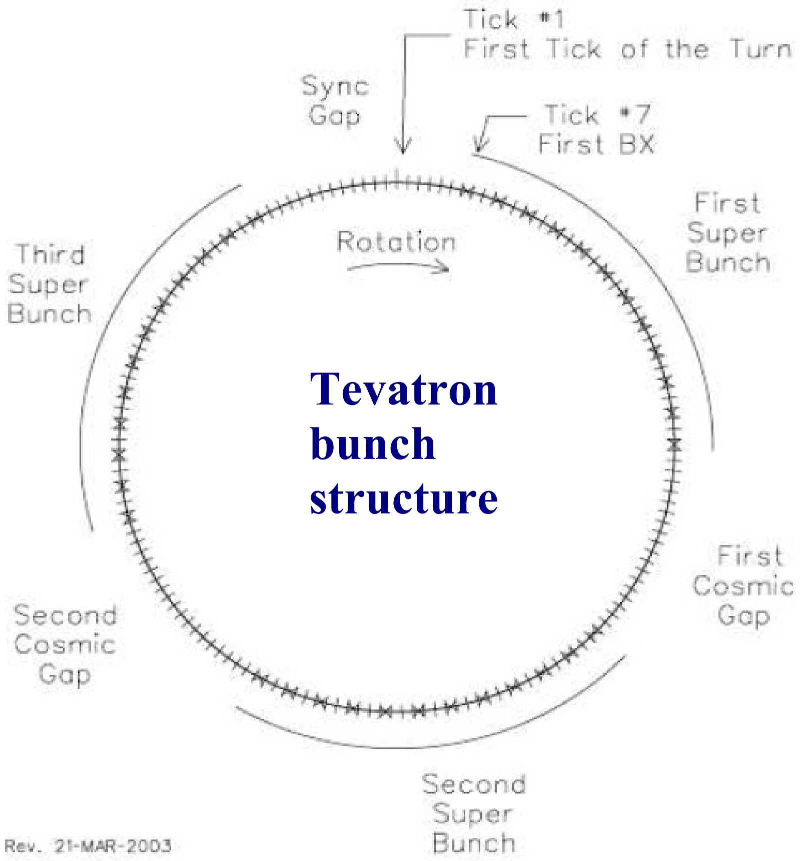


Signal Candidate



Signal Efficiency

- The events have high energy deposits
  - Jet trigger efficiency ~100%
  - But we also require a GAPSN… which is dead if
    - min-bias interaction
    - 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:
  - 22% due to “cosmic gaps” could be recovered
  - 11% in “sync gap” is *not* recoverable



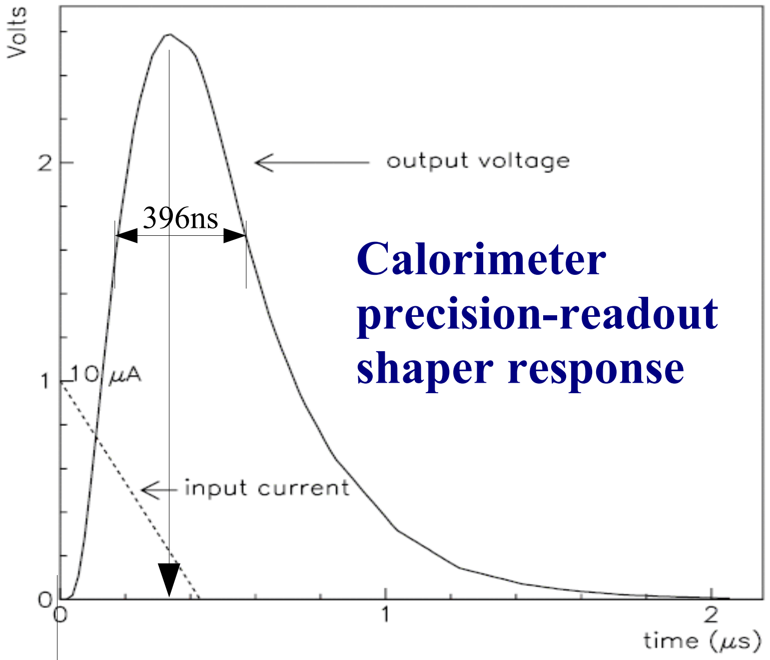
Tevatron bunch structure

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

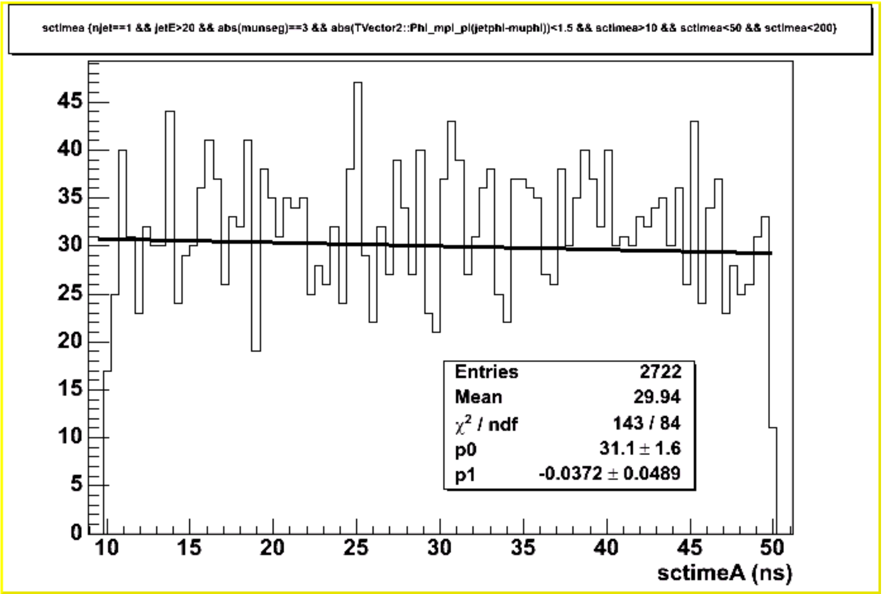
Source	Efficiency
GAPSN Trigger	.6
Trigger gaps	.68
Total	0.41

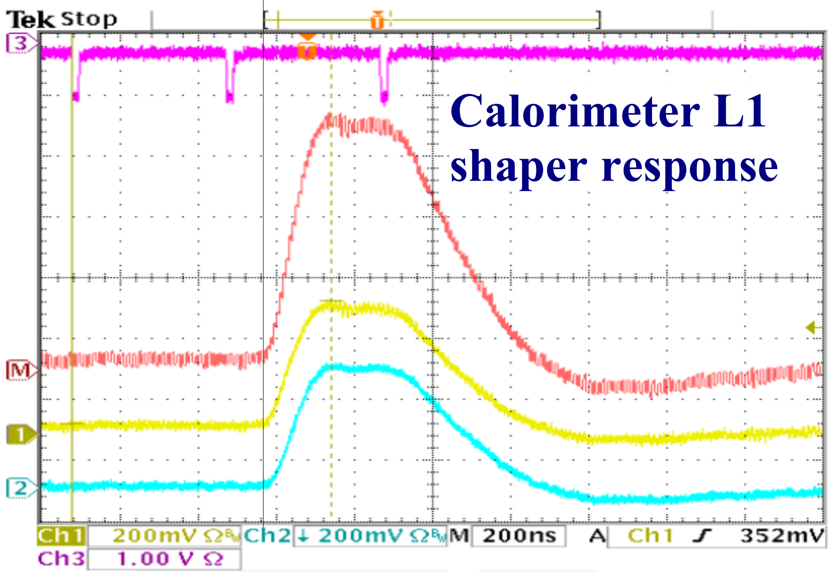
Out-of-time Calorimeter Energy

- The energy deposits are “out of time”!
- Calorimeter electronics sample the shaped pulse only *once per 396ns – at the assumed signal peak*
- Out of time energy will be under-estimated
  - Also need to consider *baseline subtraction*
- L1 response important for deciding which crossing gets triggered
- No falloff seen in plot of energy vs. shower time (as measured using muon scintillators)
  - Unfortunately, muon timing only good from -10 -> 50 ns… limited by electronics



Calorimeter precision-readout shaper response





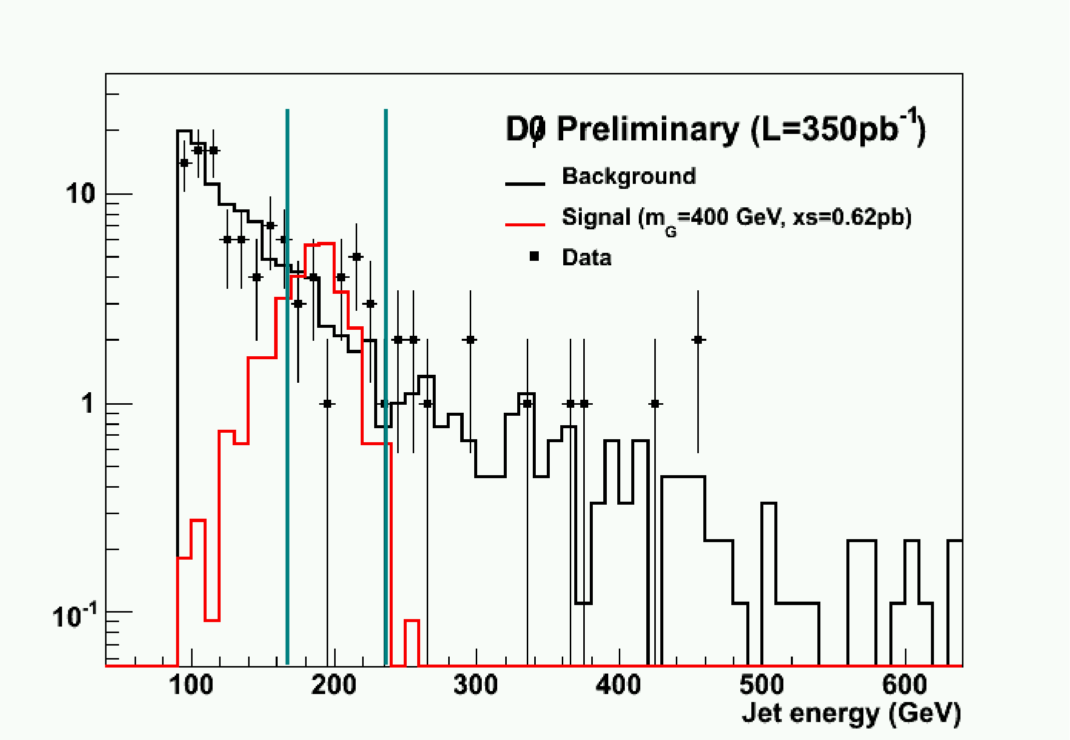
Calorimeter L1 shaper response

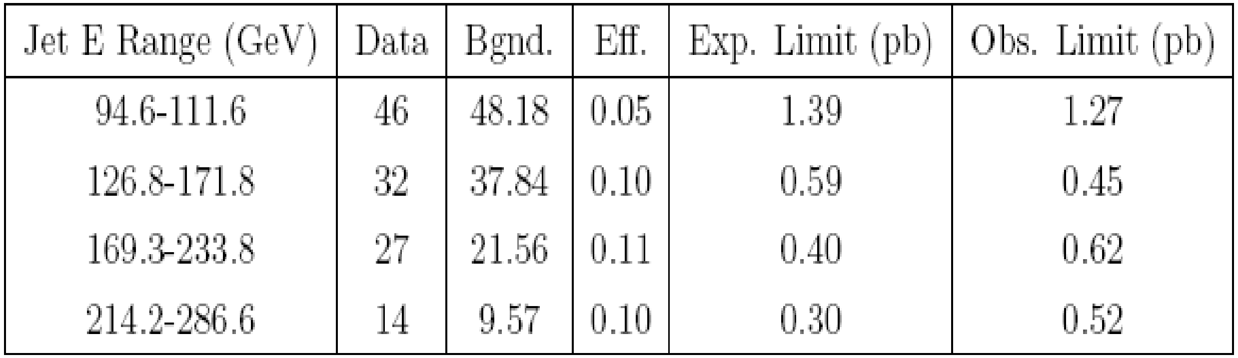
Systematic Uncertainties

- Systematics on signal efficiency come from various sources
  - Geometrical / kinematic (20%)
    - jet shape cuts
    - jet energy cut
    - 2nd jet veto
    - eta cut
    - muon cuts
  - Calorimeter response
    - Data/MC (9%)
    - Out-of-time response (12%)
  - Trigger efficiency (5-15%, depends on gluino lifetime...)
    - The GAPSN requirement
    - Inefficiency due to min-bias overlap
    - Dependence on luminosity profile
- Background normalization (10%)
- Luminosity (6.5%) - still using old value!

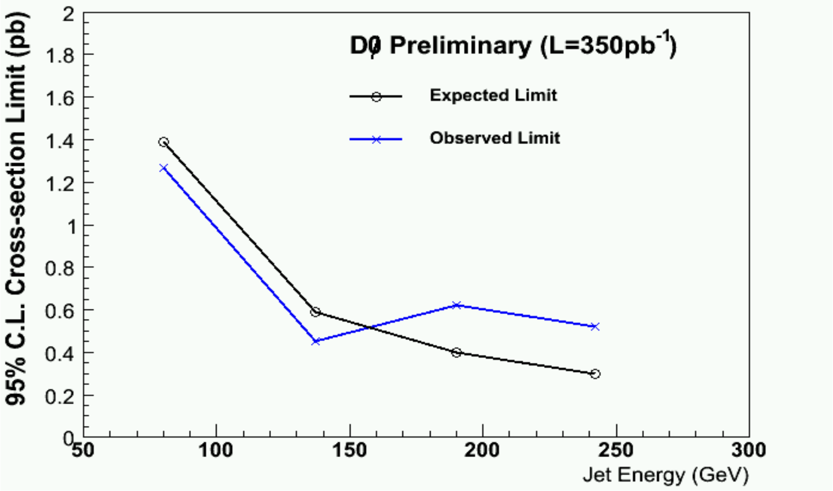
Limits

- 4 jet energy ranges were chosen, corresponding to the energies of the jets in the various signal mass samples
  - M-RMS/2 < E < M+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, bknd., data events in each energy range
- 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

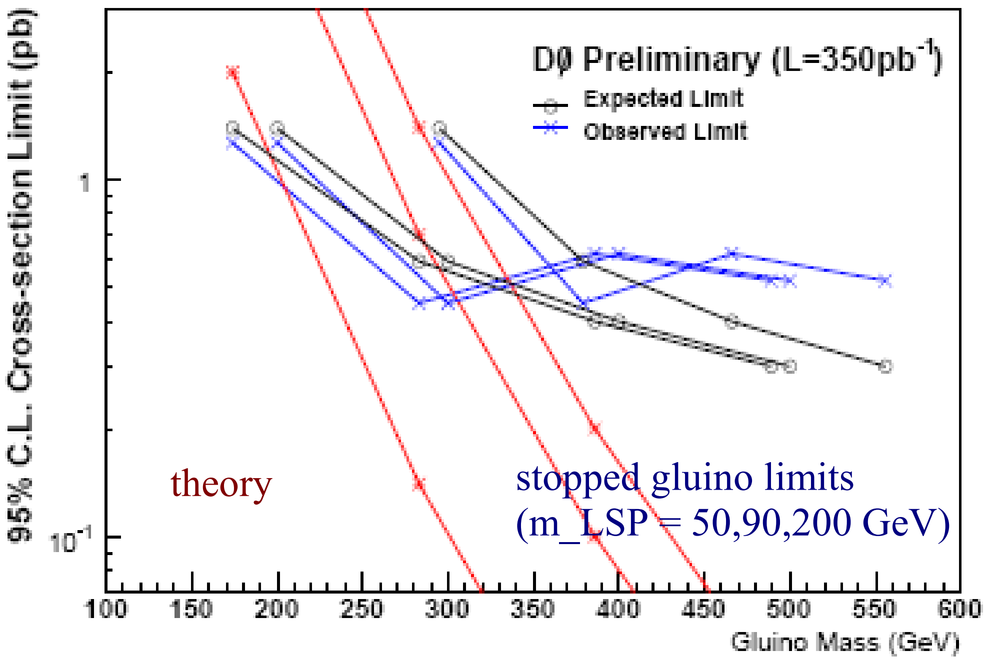


Gluino Limits

- 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



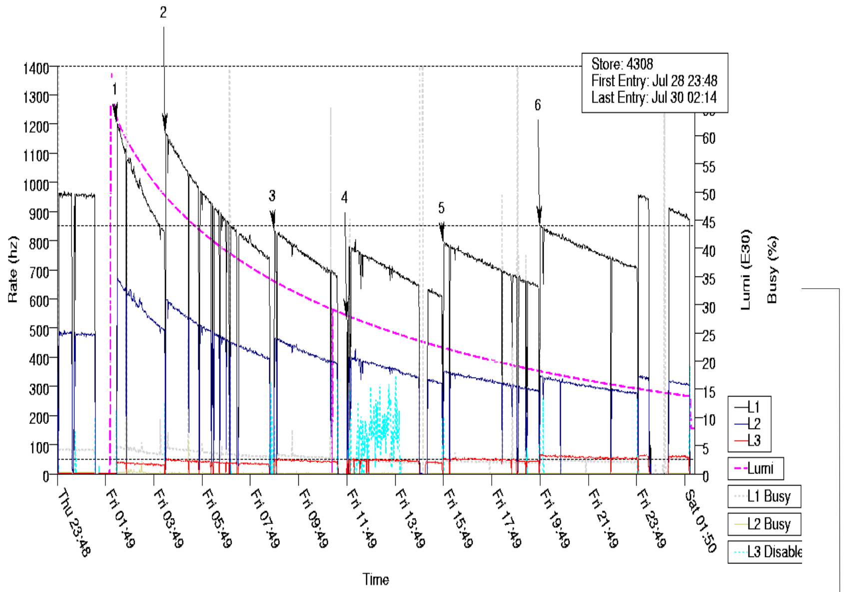
Assumes a short gluino lifetime...

Limits for mLSP=90 GeV

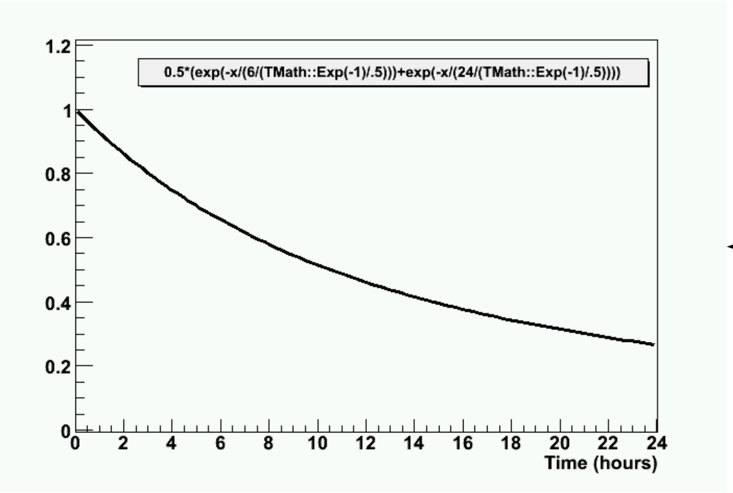
Jet E (GeV)	Gluino Mass (GeV)	Observed Limit (pb)	Theoretical CS (pb)
80	200	1.27	5
137	300	.45	.5
190	400	.62	.05
242	500	.52	.01

Gluino Lifetime

- Preliminary results assumed the gluino lifetime was < ~ 3 hours
  - Longer than this, and luminosity differences between the creation time and decay time start to become significant!
    - Production rate is dependent on luminosity at production time
    - Trigger efficiency is dependent on current luminosity at decay time
- These effects are now modeled, up to 100 hours
- Method:
  1) Choose production time randomly, according to inst. lum. distribution
  2) Choose decay time = production time + random contribution from half-life distribution
  3) Figure out if we're still taking data:
     assume a 24 hour store
     assume a 50% chance of another store starting, at least 6 hours later
  4) Calculate the GAPSN efficiency at the current decay time
     - modeled by exp(-0.3*lum),
     where lum is the relative inst. luminosity)

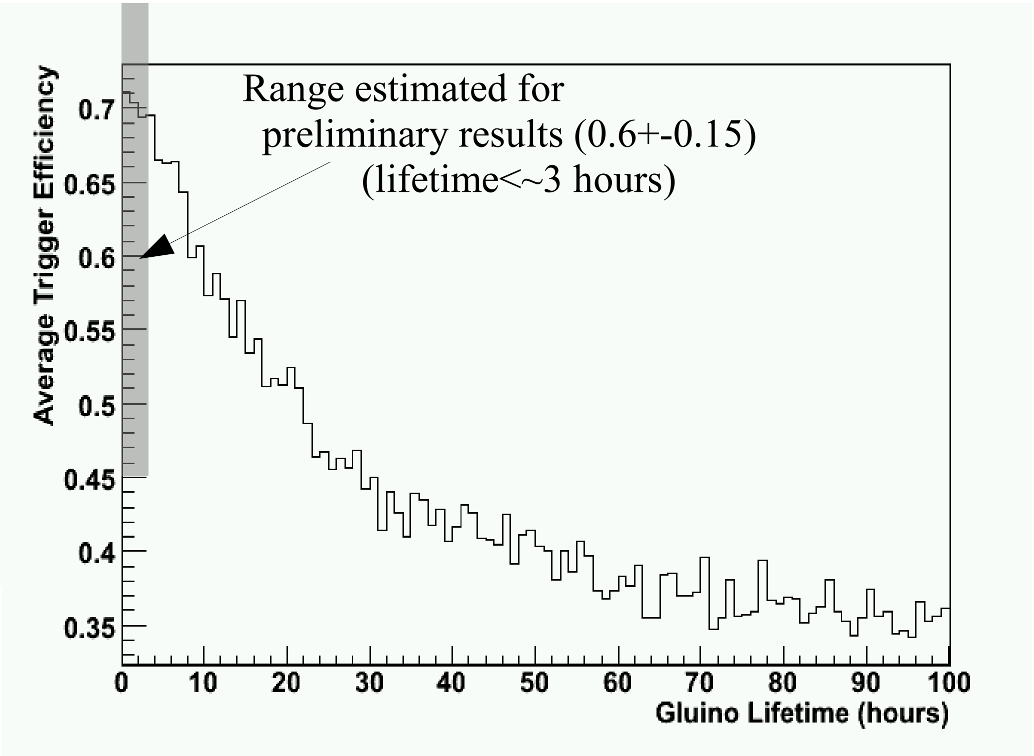


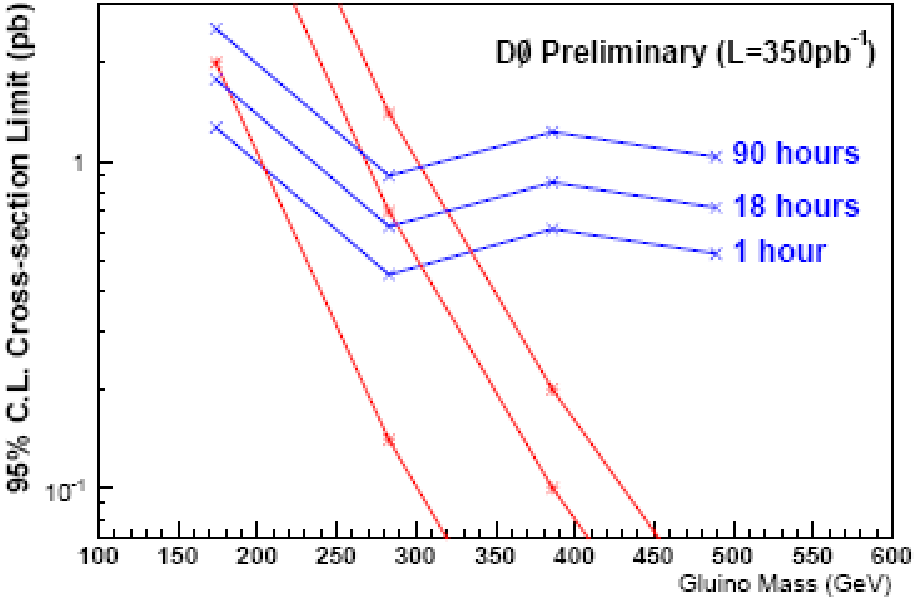
Translate to ROOT



Gluino Lifetime

- Get an estimate of the trigger efficiency which depends on the gluino lifetime
- The efficiency for small lifetime (70%) is consistent with the original estimate used for preliminary results (60+-15%)
- Limits can be set on stopped gluino cross-section, as a function of gluino lifetime, for an assumption of the LSP mass (50 GeV – the best-case scenario):





Conclusions

- **First search for out-of-time jets appearing from within a calorimeter**
  - A very challenging analysis...
  - Non-standard signal simulation
  - Many signal efficiencies and backgrounds were studied for the first time
- *Thanks to all who have helped me to understand the detector, the MC, and the physics!*
  - Peter Tamburello, John Parsons, Dean Schamberger, Dan Edmunds, J.F. Grivaz, Arnd Meyer, Catherine Biscarat, Yuri Gershtein, Dave Cuts, and anyone I'm forgetting...
  - Theorists: Jay Wacker and Matt Strassler

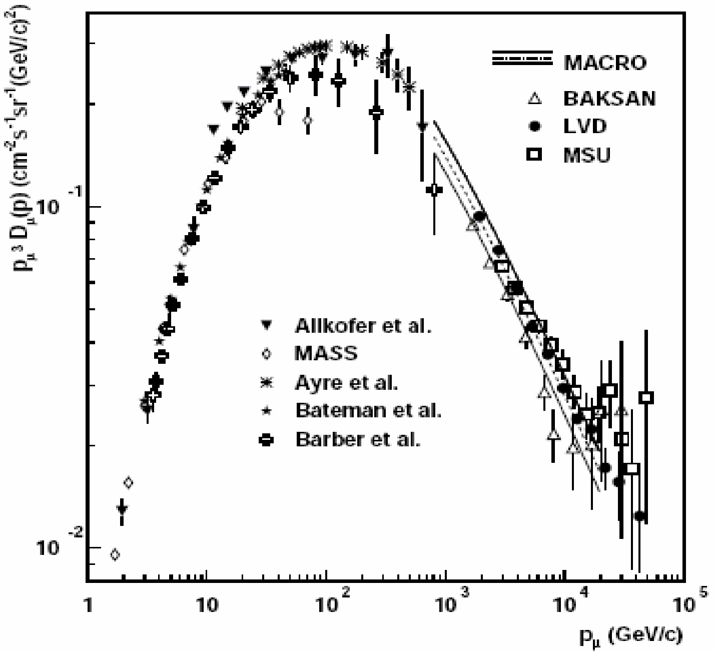
- **Data agrees well with the cosmic muon background**
- Limits on the cross-section for stopping gluinos vs. mG
  - for various mLSP, and as a function of gluino lifetime (up to 100 hours)
- Compare to the *expected* cross-section from theory
  - sensitive to mG ~ 300 GeV, but there is large theory uncertainty

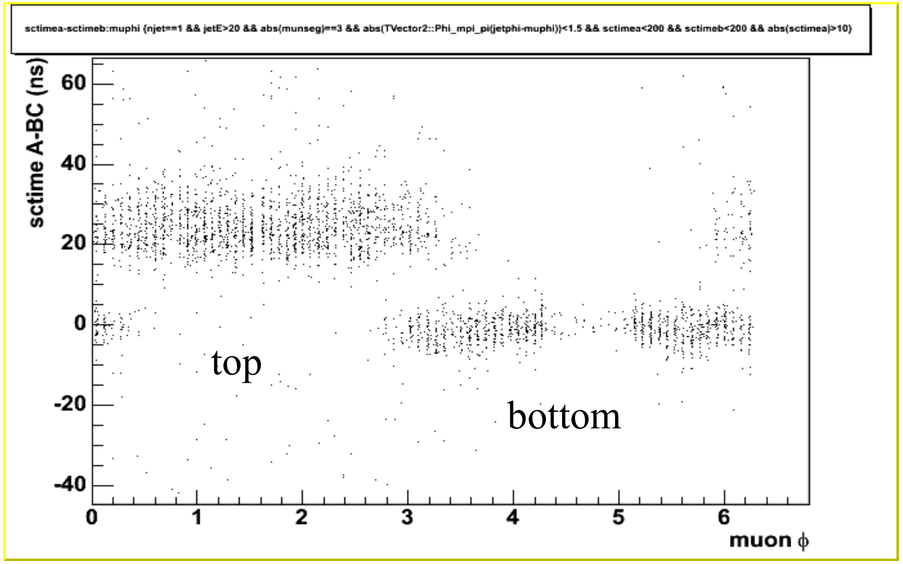
- Finalizing treatment of out-of-time calorimeter response
- **PRL is under EB review**

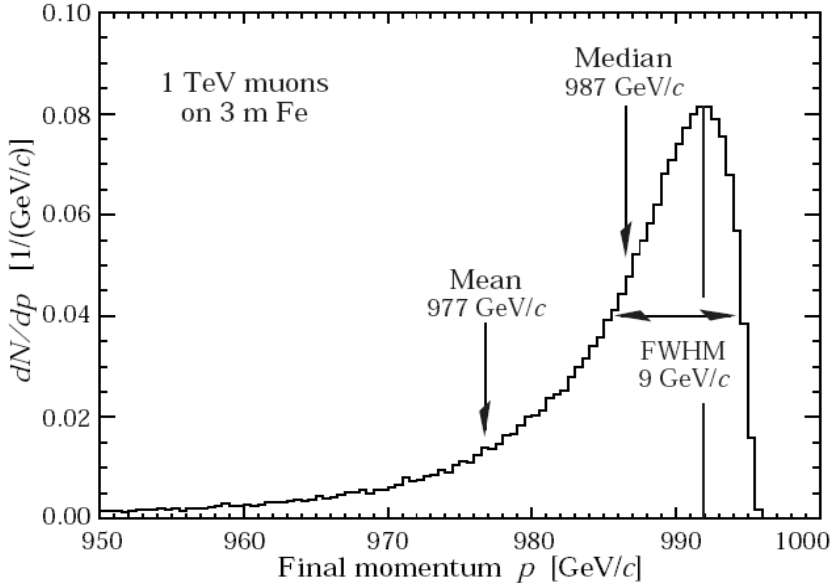
Cosmic Checks

- The observed rate is consistent with expectations
  - Spectrum at sea-level is known: About 10^{-3}/cm^2/s above 100 GeV
  - Rate of hard Bremsstrahlung is known: About 0.1% will lose >10% of their energy
  - 10m^2 x 10^{-3}/cm^2/s x 0.1% = 0.1Hz
- 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!





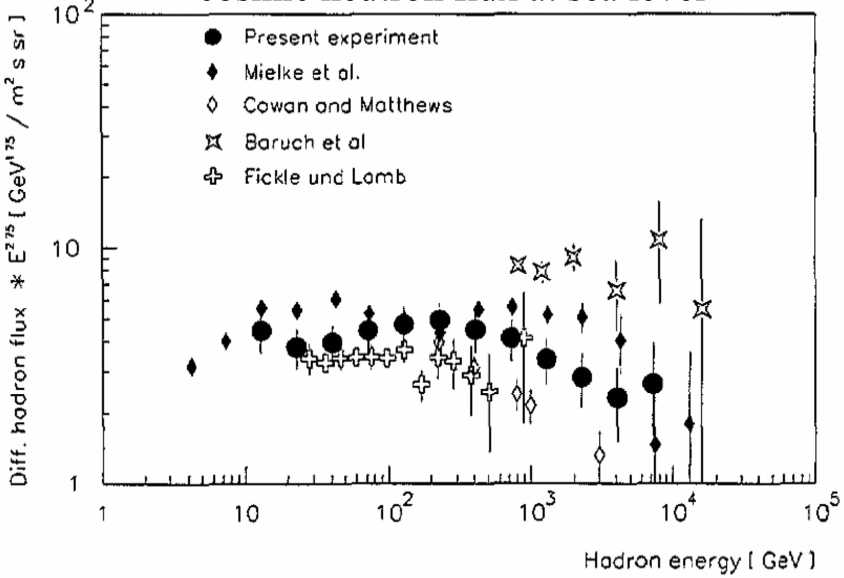


Other Backgrounds

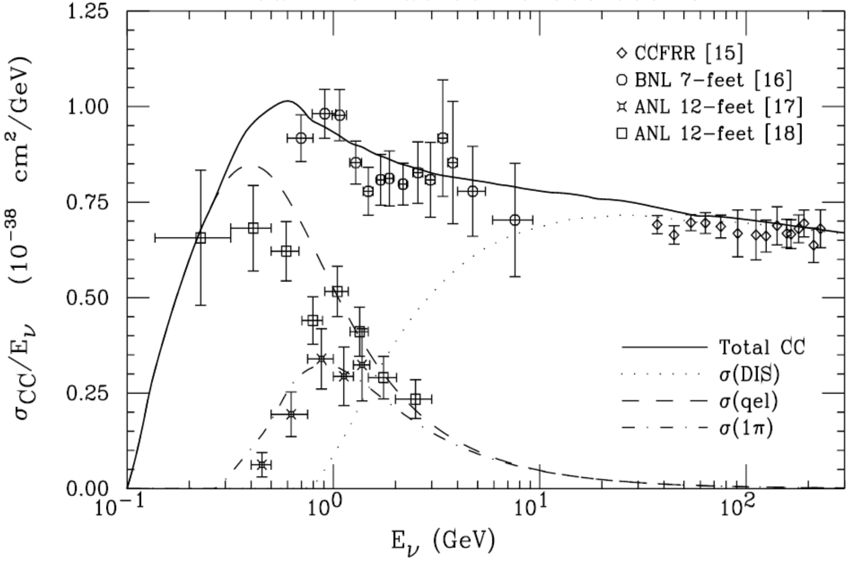
- Cosmic neutrons reach sea-level… No muon segment, no MIP trail, wide shower!
- The rate is 1/1000th of cosmic muons at the same energy… i.e. ~1/hour on detector
- They would have to get through the iron toroids
  - This seems difficult
- Neutrons that did get through would deposit most of their energy 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 Hz / 0.1% Brem * 6e23 * 17g/cm^3 / 238 g/mole * 400cm * 10e-38cm^2/GeV * 500 GeV =
    10e-8Hz = 0.1/year

cosmic neutron flux at sea level

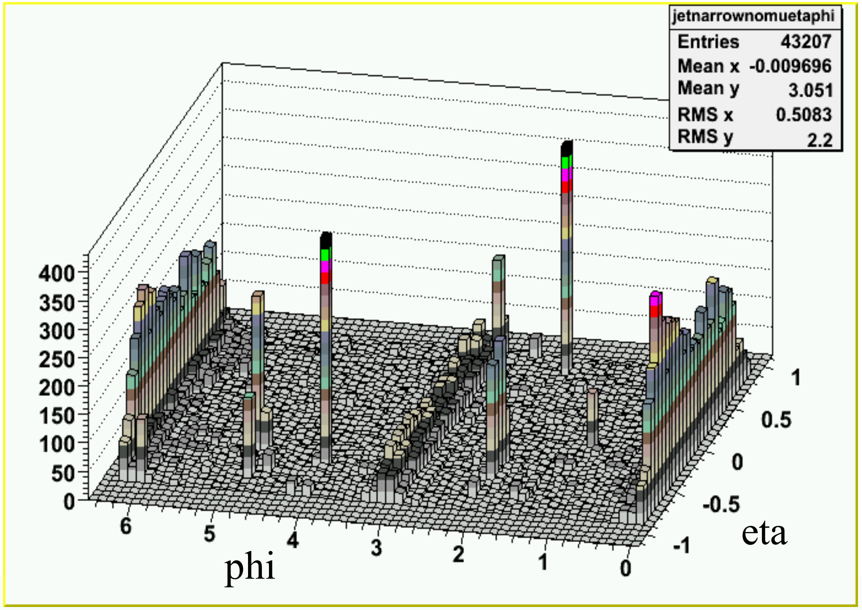


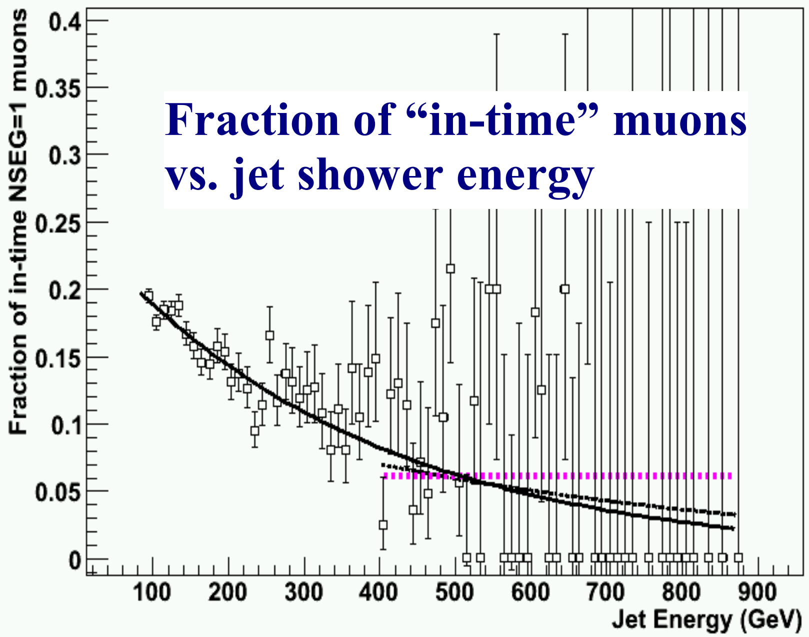
neutrino-nucleon cross-section



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(nomu)
  - 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(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 phi/pi
  - looking at high energy showers (beam muons' energy spectrum falls off faster than cosmics)




Fraction of "in-time" muons vs. jet shower energy

Background Estimation / Beam-muons