The DØ Trigger and the Search for SuperSymmetry

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The DØ Run I Trigger

- Old Run I system consisted of three major levels of triggering:
  - L0 : scintillator trigger
  - L1 : hardware trigger based on fast sums from calorimeter and muon detectors
  - L3 : software trigger running on a farm of ~50 CPUs
- L2 trigger added later
  - Refined electron candidates in calorimeter
  - Finer granularity hardware information from muon detector
- L1/L2 accept rate was 150Hz
- Event size of 450kB

The DØ Trigger

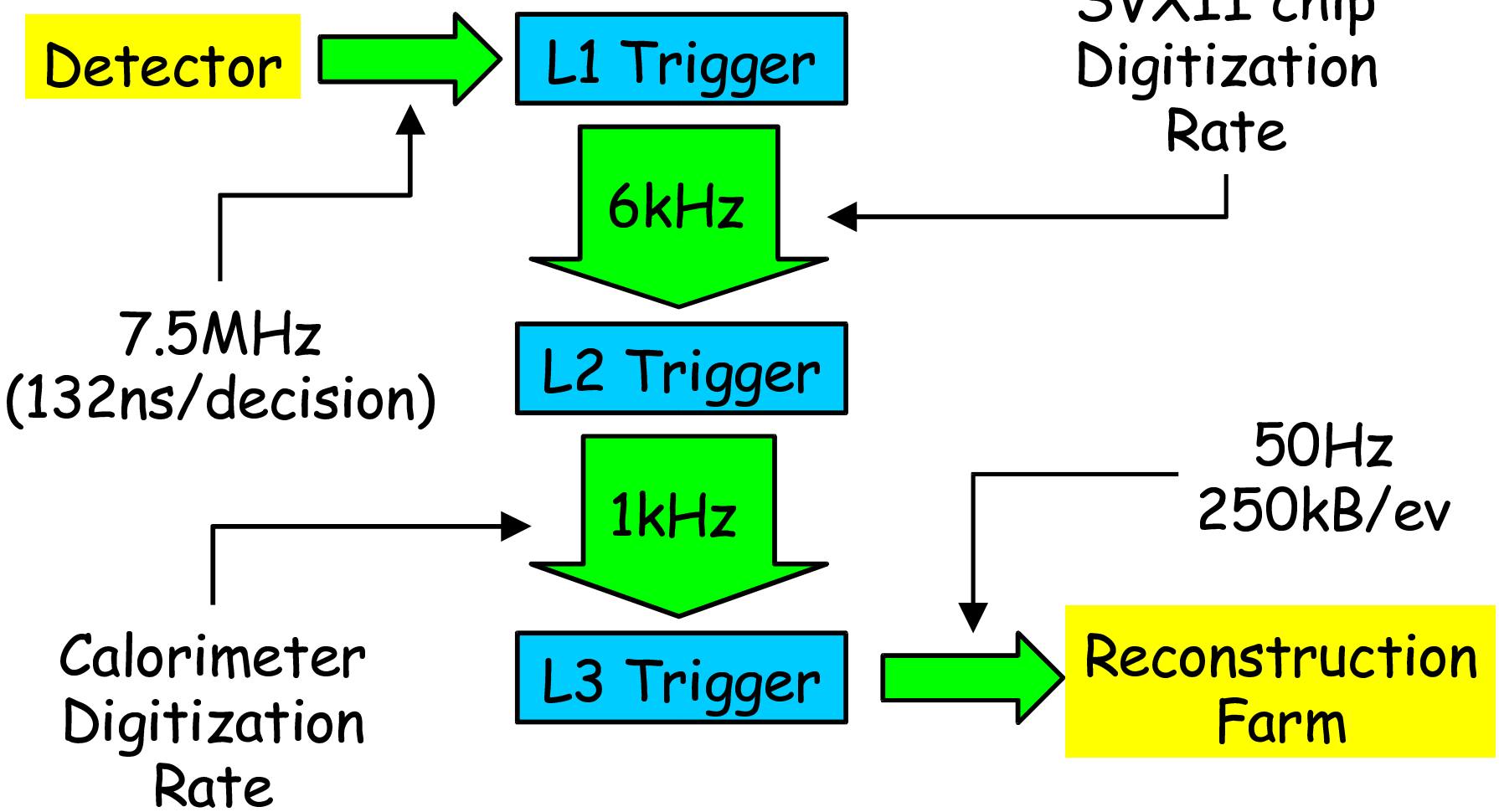
- For Run II the Tevatron has been significantly upgraded
  - Increase in luminosity to $5 \times 10^{32} cm^{-2} s^{-1}$
- Beam crossing interval reduced to 396/132ns (compared to 3.5μs in Run I)
- ...and so has the DØ detector
  - Inner 2T superconducting solenoid
  - New tracking detectors
    - Silicon, Fibre Tracker and Pre-shower
  - Upgraded muon detector

The DØ Trigger Upgrade

- Trigger needed to be significantly upgraded to meet the challenge:
  - Include tracking information from new detectors
  - Expand the L2 trigger to examine all triggers and to have detector specific pre-processing engines
  - Increase the bandwidth and processing power of the L3 workstation farm
- This talk concentrates on L2

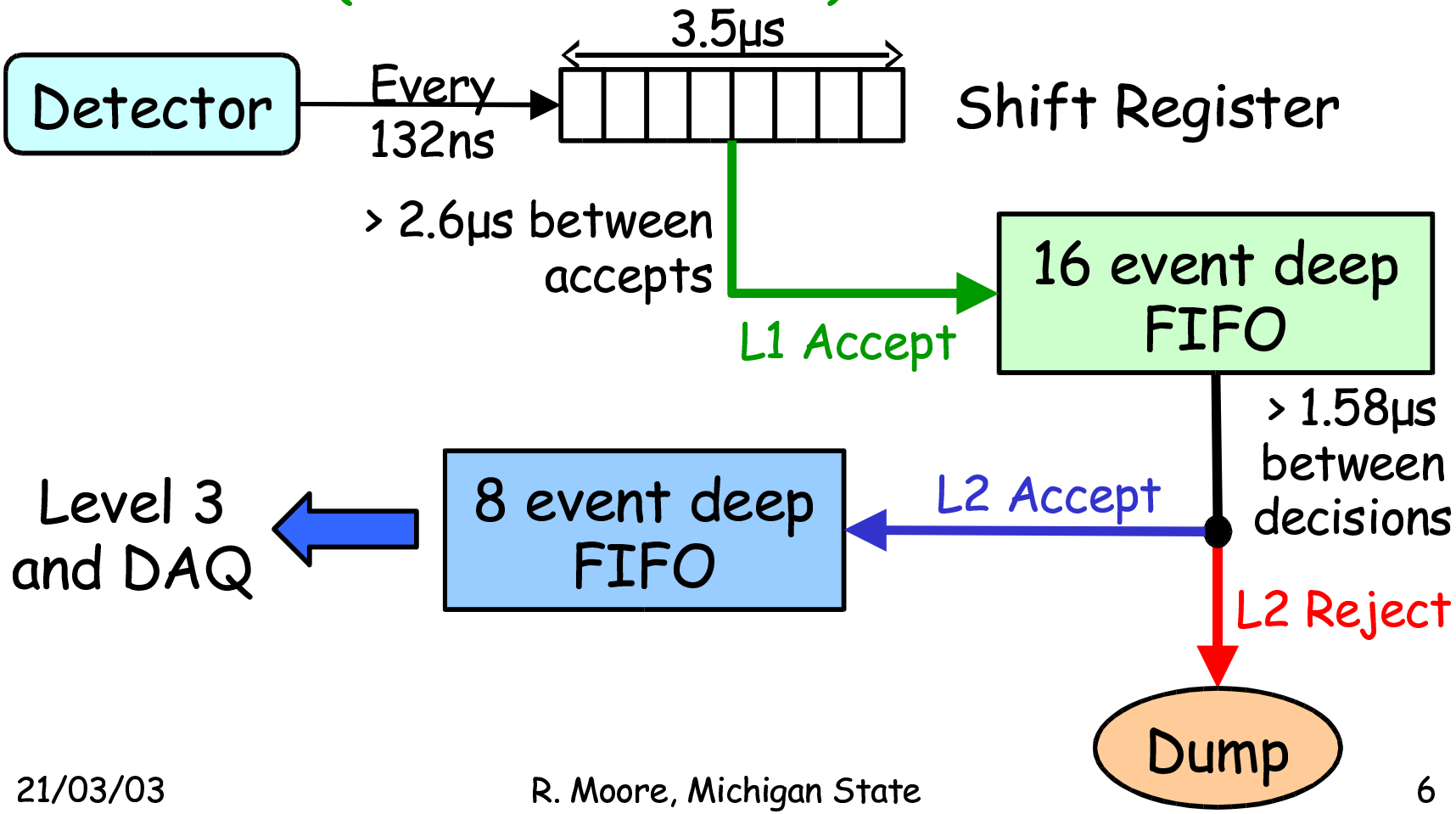
The DØ Trigger

- DØ Trigger split into 3 levels
  - "L0" trigger fires every beam crossing



The L1 Trigger

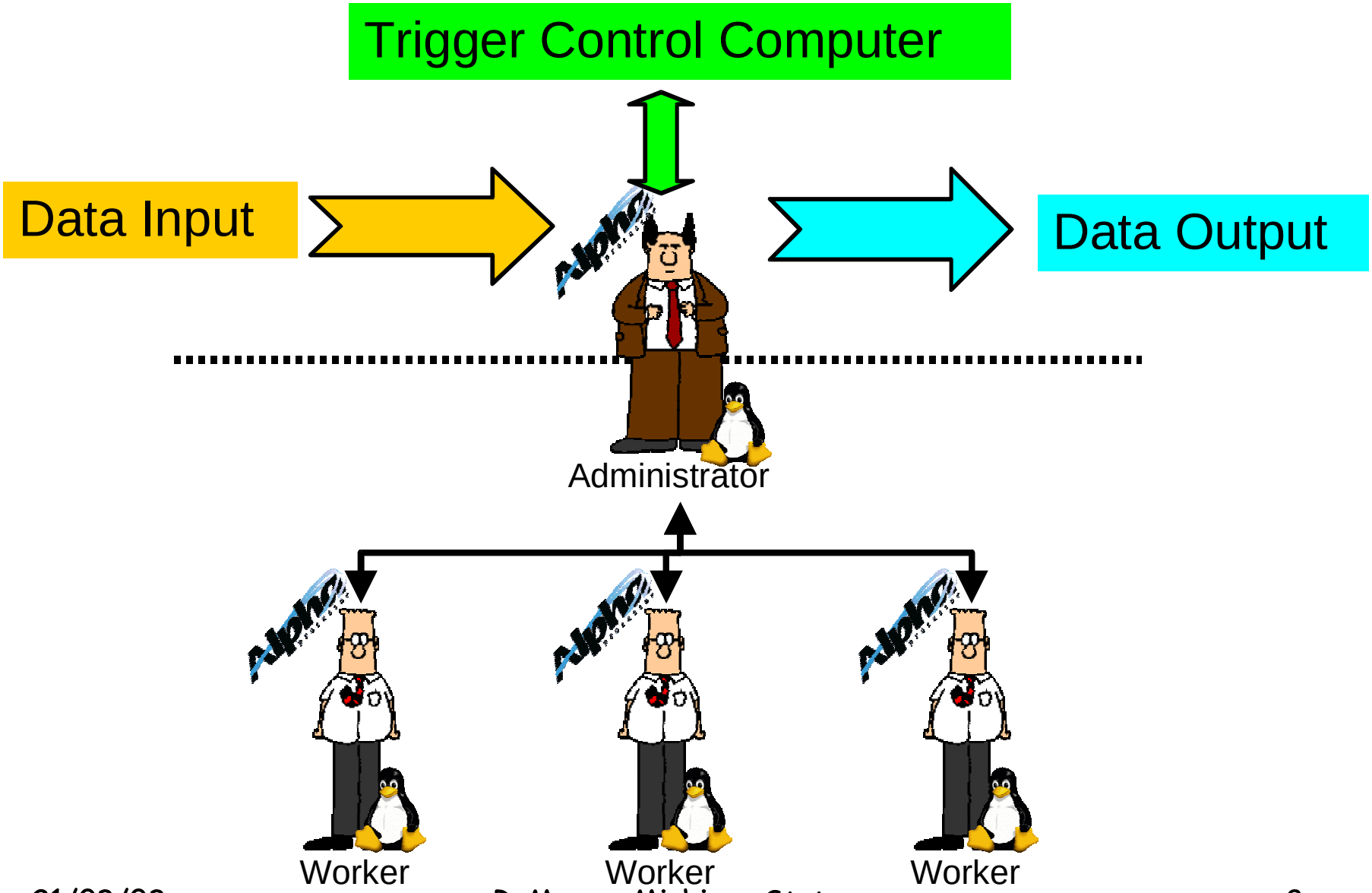
- L1 trigger pure hardware, 128 trigger bits
  - Each subdetector provides 16 or 32 bits every 132ns
  - Combined (AND/OR network) to make 128 decisions



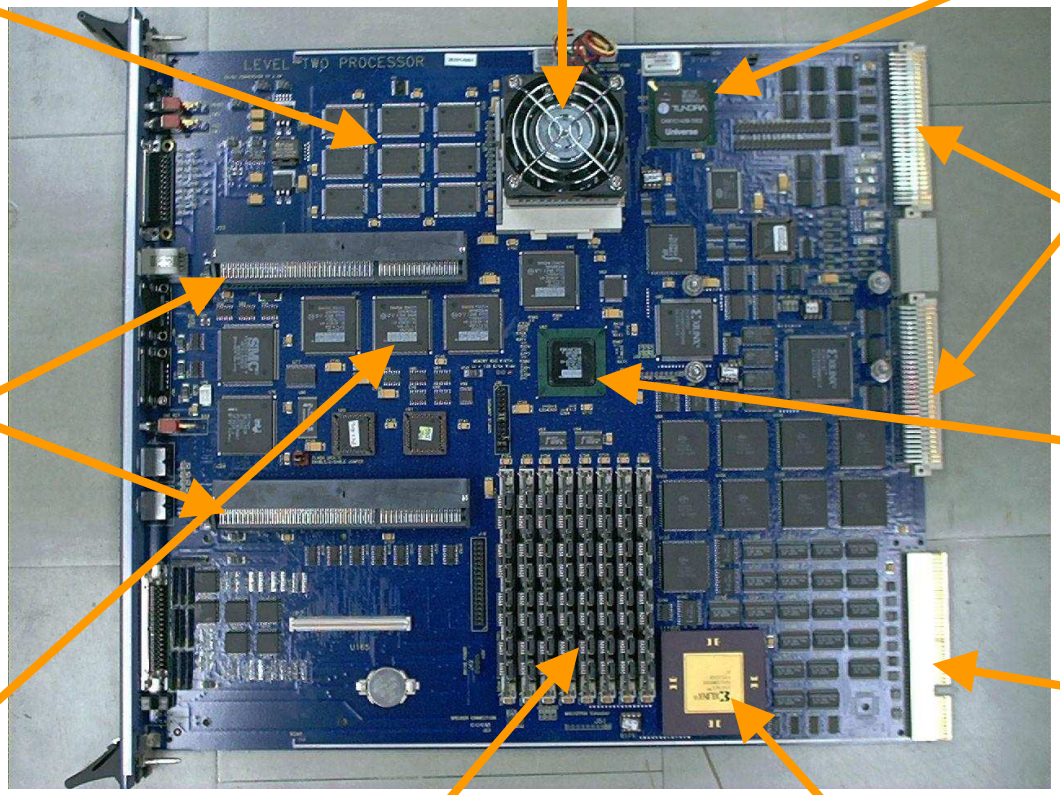
The L2 Trigger

- L2 Trigger software and hardware hybrid
  - Hardware for dataflow, software for processing
- Must respond to events in order received
  - Workstation farm not good at this
  - Use single, powerful CPUs: 500MHz Alpha
- Two stage design
  - Pre-processors format and sort L1 data
  - Global processor correlates information across the whole detector
- 2-4 Alphas in a crate
  - Administrator: handles I/O, monitoring etc.
  - 1-3 workers: process data

Alphas in a Crate



The Alpha Card



L3 Cache Memory

CPU (+fan)

PCI-VME Bridge

VME Bus

PCI Slots

CPU-PCI Interface

Magic Bus

Data Switches

Main Memory

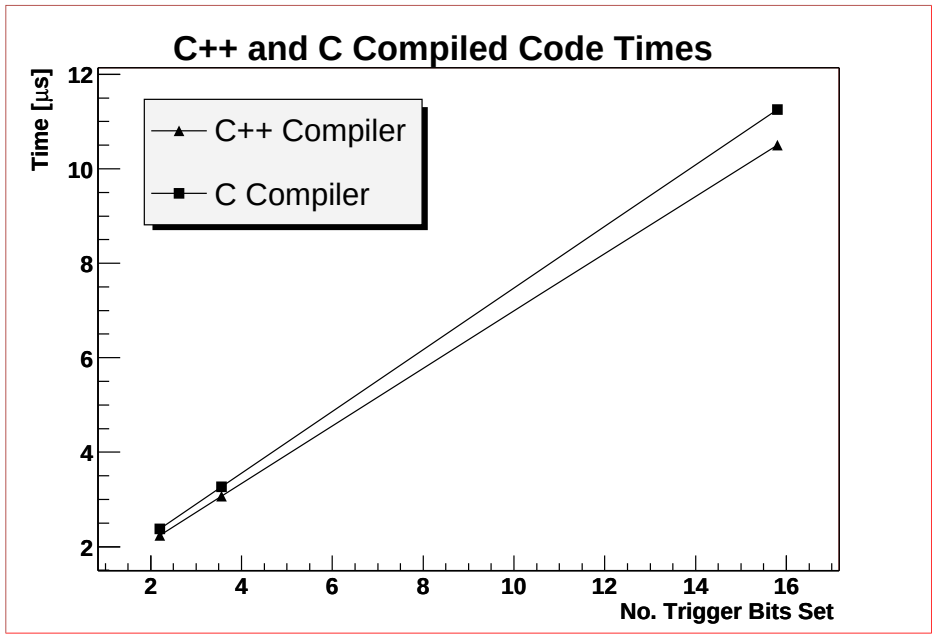
PCI-MBus PIO

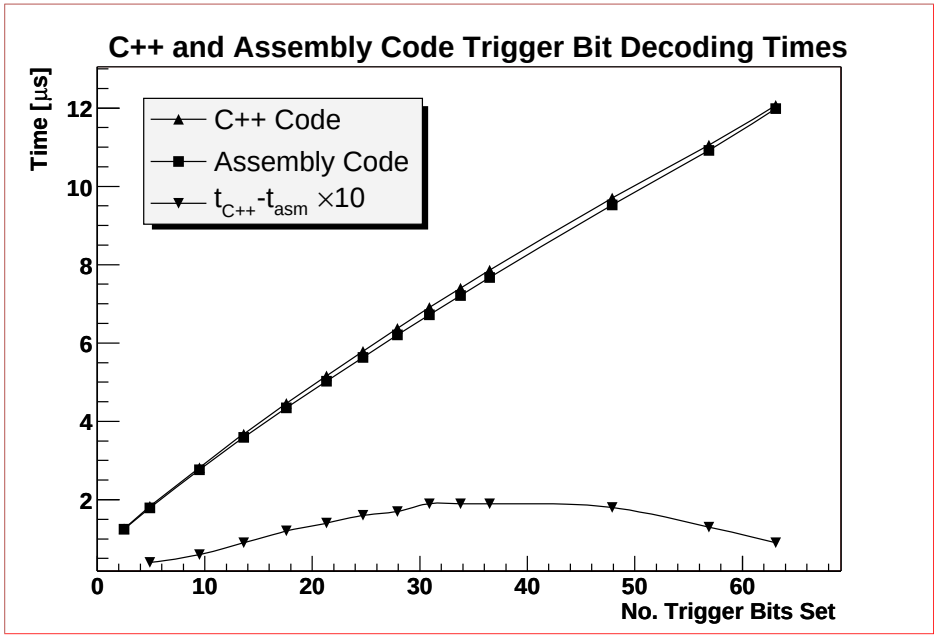
The L2 Software

- Alpha boards run patched Linux 2.2.16 kernel
  - Custom kernel modules for device drivers
- Written in C++, use Digital/Compaq C++ compiler
  - Time budget < 100 μs
  - No dynamic memory allocation or RTTI (for speed)
  - Virtual functions, exceptions very restricted
- Code very portable
  - Run same code in trigger simulation as online
  - Easy to port to the new "Beta" processors
- Dynamically configurable state machine: flexible
  - Single executable for all crates
  - Very useful to adapt to multiple hardware setups

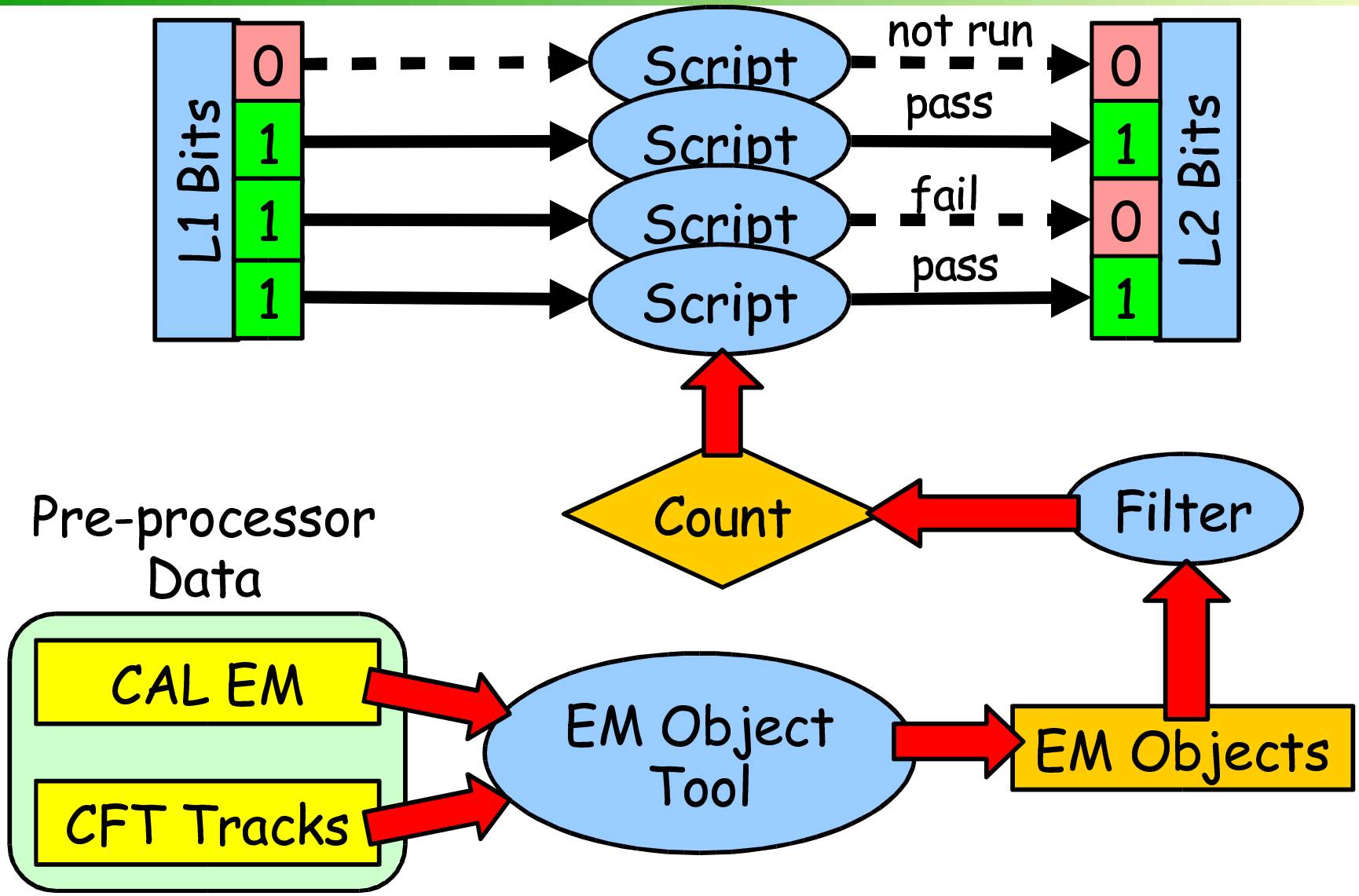
The L2 Software Timing

- Bit search algorithm timings for C,C++ and Asm
  - C++ compiler better optimizer than C compiler
  - Minimal gains from using assembly code (~few %)
    - Compilers REALLY good at optimizing code for CPU!
  - Use Digital/Compaq/HP C++ compiler...not GNU C++





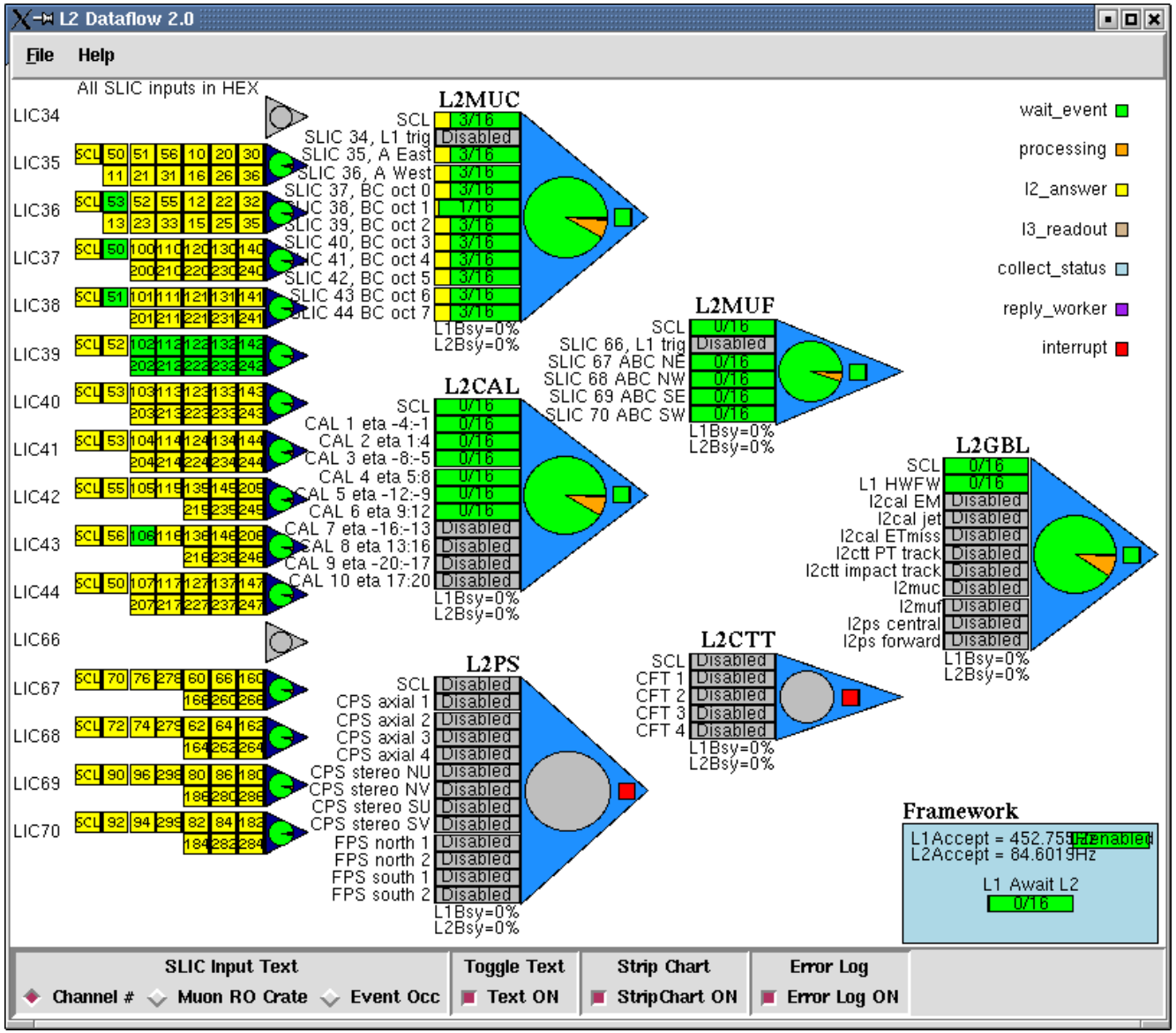
L2 Global Design



L2 Status

- Main production run of Alphas had problems...
  - Manufacturer failed to bake boards and components
- Used spare parts to have second production run
  - Several parts obsolete: unable to obtain more
  - Reduced to running one Alpha per crate
- Made up for some of loss in software
  - Dropped MET Calorimeter preprocessor
  - Rewrote Calorimeter Jet and EM algorithms
  - Framework signifcantly faster than anticipated
- Original estimate with one Alpha ~2.2kHz rate
  - Currently run at 3-4.4kHz depending on trigger setup
- Replacing Alphas with commerical 933MHz P-III Compact PCI boards and custom VME extender: factor 3 faster

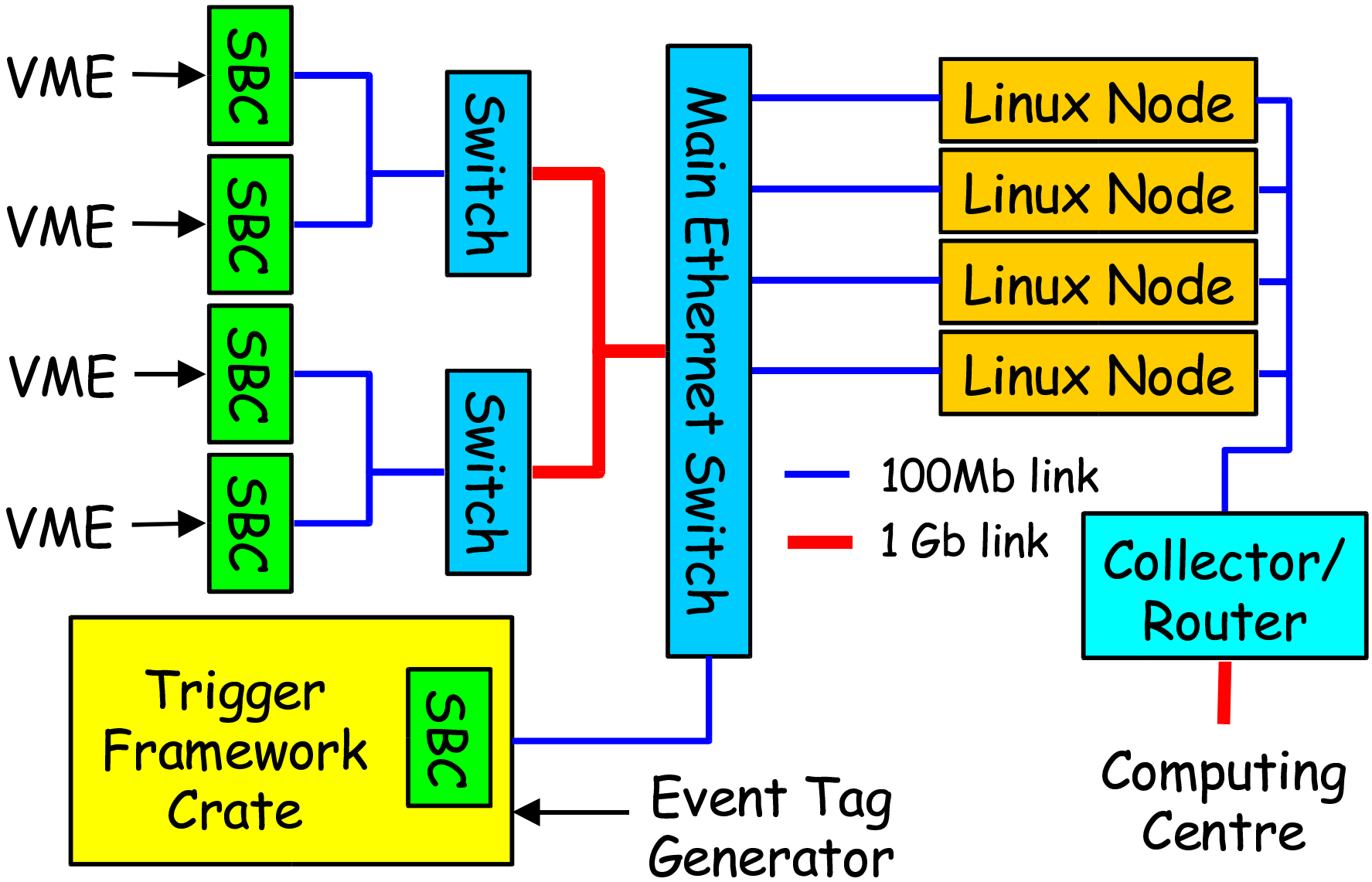
L2 Monitoring



The L3 Trigger

- Pure software trigger, includes DAQ
  - Reads out entire detector
  - Runs speed optimzed reconstruction
- Crates readout using Linux SBCs
  - Event builder is the ethernet switch
- Linux nodes run L3 trigger software on full event
  - 256 different triggers possible
- After processing passed events are output into several exclusive streams
  - Collected and written to computing centre for storage and full reconstruction

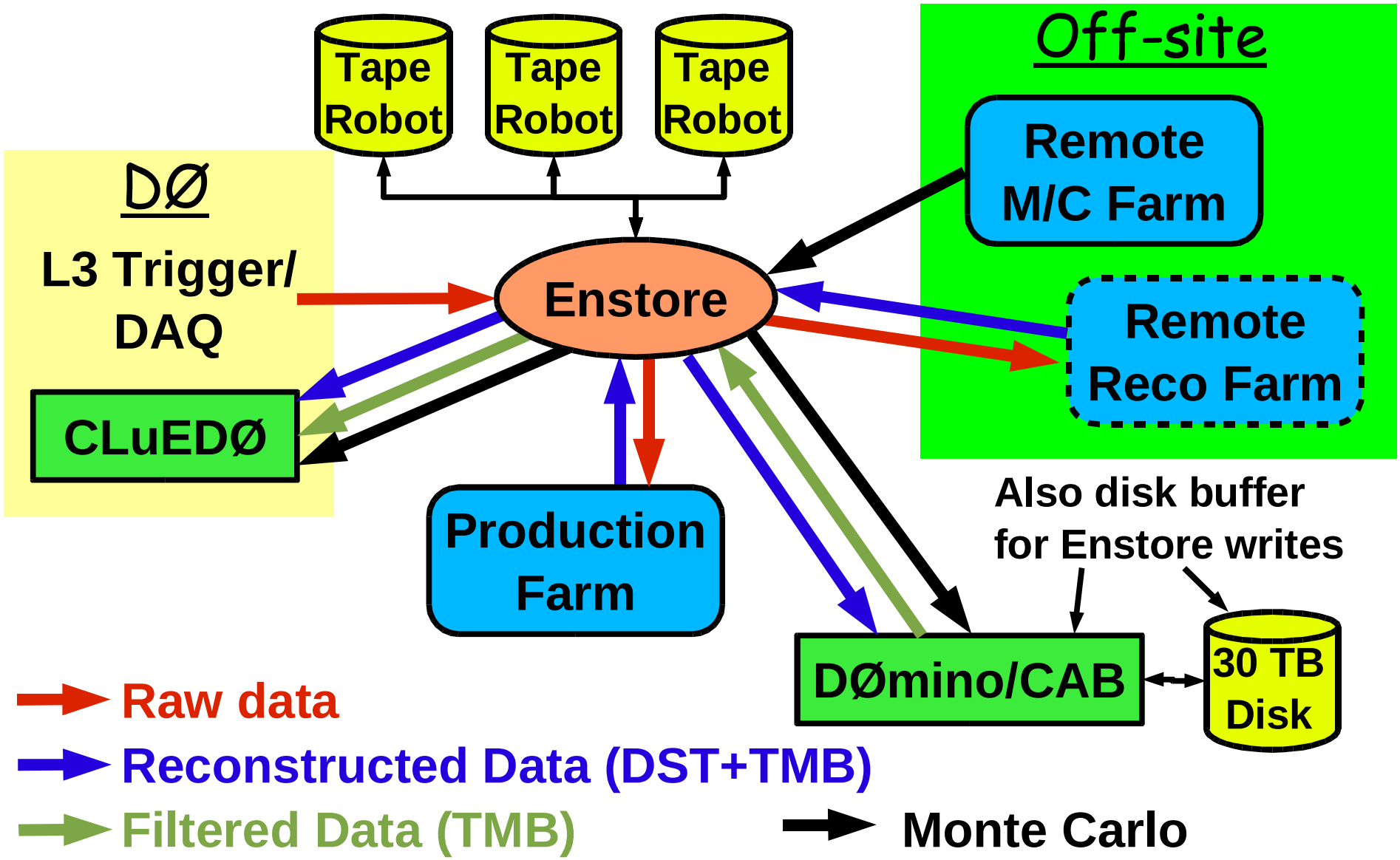
The L3 Trigger



Offline Dataflow

- All events are written directly to tape
  - Fermilab developed ENSTORE system used
    - Interfaces to multiple tape robots
    - Allows easy migration to new tapes/robots...very useful!!!
- Events reconstructed by Linux production farm
  - Writes output back to tape and disk cache on dØmino
    - DØmino is SGI mainframe 192 x 300MHz CPUs, 30TB disk
- Monte Carlo generation done off-site
  - Major European contribution: UK, NL, CZ, FR + UTA
- Two facilities for user-level analysis
  - CluedØ: Linux desktops, current main provider for DØ
  - CAB: Linux backend to dØmino, just up and running

Offline Dataflow



Managing I/O: SAM

- All DØ I/O managed by program called SAM
  - "Sequential Access by Metadata"
  - One of the first production GRID programs
- Central database of all DØ data and MC files
  - Contains description of the files (how created etc.)
  - Contains all known locations of the file
- SAM stations have local disk cache
  - Central DB keeps track of files in local caches
- Users use SAM to search for and fetch files
  - SAM gets files from 'best' location
- Access priority to limited resources e.g. tape drives managed by SAM

CLuEDØ

- Cluster of all DØ Linux desktops
  - 250+ nodes, 500+ users, > 12TB disk on servers
- Designed to fill gaps in DØ computing plan
  - Needed analysis CPU and disk space
    - DØmino central server 300MHz CPUs, not expandable
    - Desktop CPUs (at time) 800MHz (and a lot cheaper!)
  - Cheap: FNAL had serious computing budget cutbacks
    - IDE disks >3 times cheaper Fibre channel for DØmino
    - Allowed institutes to contribute resources
    - Harness already existing desktop CPUs (free CPU!)
  - No FNAL support: team of post-docs and students
  - Code development platform

Features

- PBS batch system to schedule jobs
  - Integrated with new CAB system
- Home grown cluster management program: CLuMP
  - Stores cluster configuration in LDAP database
  - Auto-generates configuration files on all nodes
    - Uses simplified python interface
  - Greatly simplifies adding machines and users
    - Less mistakes, easier for new sysadmins
- CluedØ SAM station
  - Fetch and store files from the central DØ store
- CluedØ is currently the major source of all DØ analysis CPU, slowly sharing load with CAB

Analysis

- DØ currently has three data formats:
  - Raw data, Reconstructed (DST) and Thumbnail (TMB)
  - TMB small enough to keep on disk (10kB/event)
- DST and TMB can be converted into ROOT files
  - DST uses ROOT-tuple format: detector debugging
  - TMB uses ROOT tree format: physics analysis
- Common environment for analysing TMB data within ROOT not yet decided on
  - Write your own ROOT format
  - MOAN: Matched Object Analysis Network
    - Processor based "lego brick" approach, can use TMB & DST
  - Truffle: similar to MOAN but nicer CLI...in development

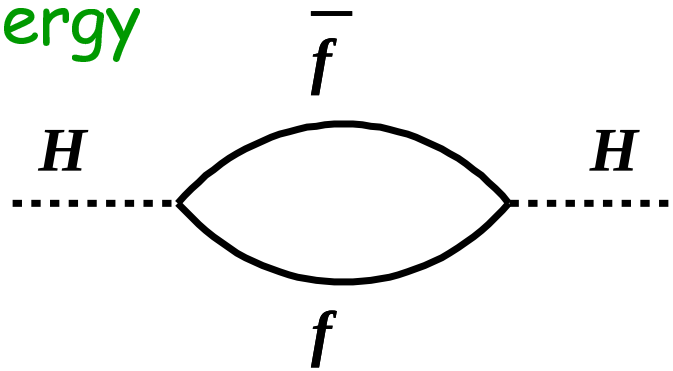
Supersymmetry

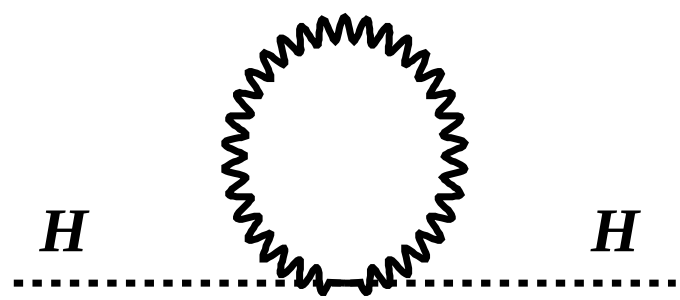
- Proposed symmetry between Fermions and Bosons
- Extends Standard Model by adding super-partners for each SM particle
  - squarks, sleptons, gluinos...
- Requires a Higgs doublet
  - three neutral and two charged Higgs
- Broken symmetry: haven't seen any SUSY particles
  - i.e. squarks and quarks not mass degenerate

SM Particles		SUSY Particles	
Name	*Symbol*	*Name*	*Symbol*
gluon	g	gluino	$\tilde{g}$
charged Higgs	$H^{\pm}$	charginos	$\tilde{\chi}^{\pm}_{1,2}$
W boson	$W^{\pm}$		
light Higgs	h	neutralinos	$\tilde{\chi}^{0}_{1-4}$
heavy Higgs	H		
pseudoscalar Higgs	A		
Z boson	Z		
photon	γ		
graviton	G	gravitino	$\tilde{G}$
quarks	q	squarks	$\tilde{q}$
leptons	l, ν	sleptons	$\tilde{l}, \tilde{\nu}$

Hierarchy Problem

- SM particles contribute to Higgs mass via loop diagrams
  - Contributions diverge quadratically with increasing energy





- In SM no new physics until gravity becomes important at Planck scale (~10^{19}GeV)
  - so Higgs mass contributions will be large
- ...but need M_{Higgs}~<1TeV/c^2 to prevent W^+W^- scattering cross-section breaking unitarity

Hierarchy Problem

- So Higgs mass contributions are ~30 orders of magnitude higher than the Higgs mass!
  - Cancellation to an incredibly precise level needed
  - Not impossible but very artifical
- Supersymmetry solves hierarchy problem by cancelling loop diagrams
  - Super-particles also contribute to Higgs mass
  - Cancels out quadratic divergence
- For this to work expect to see SUSY particles with masses < 1TeV/c^2
- SUSY is not the only possible solution to problem
  - Large extra dimensions lower M_{Planck} to few TeV/c^2

Other Motivations for SUSY

- Dark Matter candidate (not all SUSY models)
  - Add in extra requirement: R parity conservation
  - All particles carry 'R' quantum number
    - SM particles have R=+1, SUSY particles have R=-1
    - Must create SUSY particles in pairs
    - Conserve R: product of all R's must be constant
  - Implies lightest SUSY particle is stable
    - Candidate for non-baryonic dark matter (WMAP result)
  - SUSY not required to have R parity conservation
- SUSY alters running of coupling constants
  - Makes them all converge at single point
- Required for Superstring theories

SUSY Breaking

- Several models for how SUSY is broken
  - Reduce number of free parameters from soft SUSY breaking (> 100) to a more manageable number
    - soft=break mass degeneracy w/o causing quadratic divergence
- mSUGRA: Minimal Super Gravity
  - SUSY breaking occurs at an unreachable mass scale
    - Hidden sector, mass scale M_{SUSY}
  - Fields in this hidden sector interact with SUSY particles via gravity causing SUSY breaking
- Gauge mediated SUSY breaking
  - SUSY break mediated through gauge interactions by messenger fields at $M_m \ll M_{planck}$

GMSB

- Parameters defining GMSB models:
  - $\Lambda = F/M_m$: scale of SUSY masses
  - $M_m > \Lambda$: messenger mass scale
  - N_5 : equivalent number of 5+5 messenger fields
  - $\tan\beta$: ratio of Higgs vacuum expectation values
  - sign(μ) : sign Higgsino mass parameter
  - $C_{grav} \geq 1$: ratio of gravitino mass to value it would have is SUSY breaking scale were F
- Lightest SUSY Particle (LSP) is an almost massless gravitino ($M_G \ll 1$eV)

GMSB Signal

- Phenomenology depends on next lightest sparticle
  - If this is the lightest neutralino then: $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$
  - Signal $\gamma\gamma$ + missing E_T
- Model: $M_m=2\Lambda$, $N_5=1$, $\tan\beta=15$, $\mu > 0$
- Neutralino lifetime not fixed
- Long lifetime case
  - Photons do not point to the production vertex
    - Centre of EM shower in different calorimeter layers can be used to determine the photon's track
- Short lifetimes
  - Decay of neutralino close to production vertex

GMSB Backgrounds

- Mis-measured E_T backgrounds
  - QCD+direct photons or jets faking photons [dominant]
  - Drell-Yan with e faking photon
- True missing E_T backgrounds
  - $W\gamma \rightarrow e\nu\gamma$ (neutrino gives missing E_T) [dominant]
  - W+jet$\rightarrow e\nu$+"γ" (jet fakes γ: can contain lots π^0)
  - $Z \rightarrow \tau\tau \rightarrow ee\nu\nu$
  - t-tbar, WW, WZ etc.

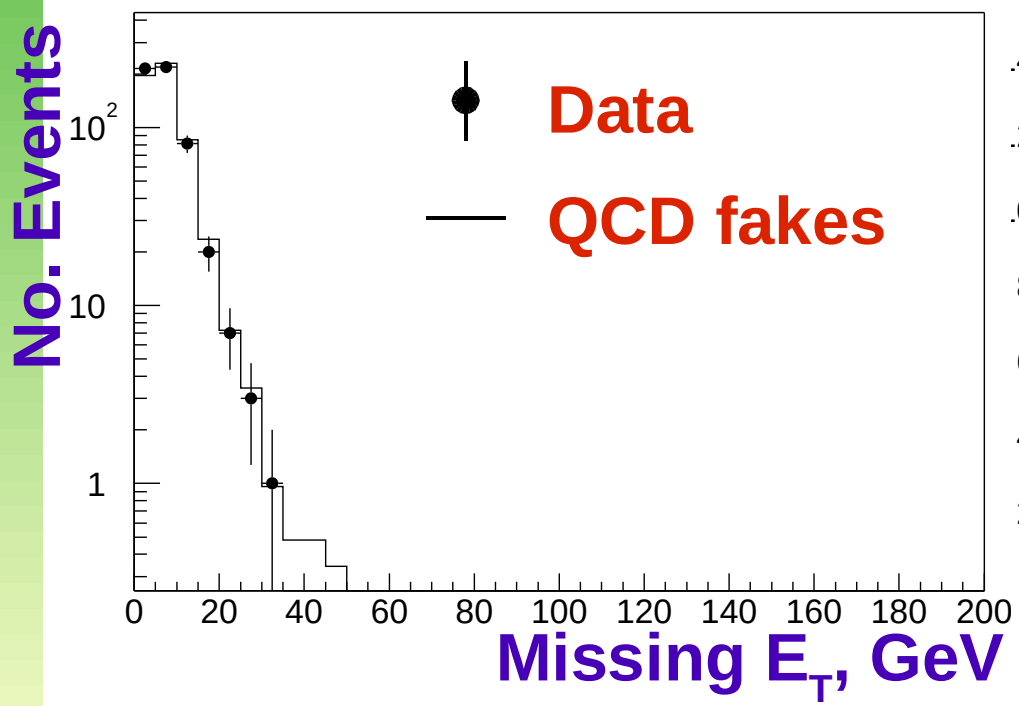
$\gamma\gamma$ + Missing E_T Events

- Integrated luminosity of the sample $42pb^{-1}$
- 2 EM Objects with $E_T > 20GeV$, $|\eta|<1.1$ (CC)
  - $e^{\pm}$ if track $p_T > 10GeV/c$ within 50mrad in φ
- Photon pointing: $|z_1-z_2| \leq 45cm$ z_n=z vertex of γ_n
  - Determines primary vertex to correct MET
- Need to consider jets because of missing E_T criteria, use $\Delta R=0.7$ cone algorithm
  - Uncorrected $E_T > 10GeV$; $0.05 < \text{EM Fraction} < 0.95$
  - n90 > 1 (no. cells containing 90% jet energy)
  - $\Delta\varphi$(MET,lead jet)<2.5 rad (jet mis-measurement)
  - No jets in the ICD region (gap between CC and EC)

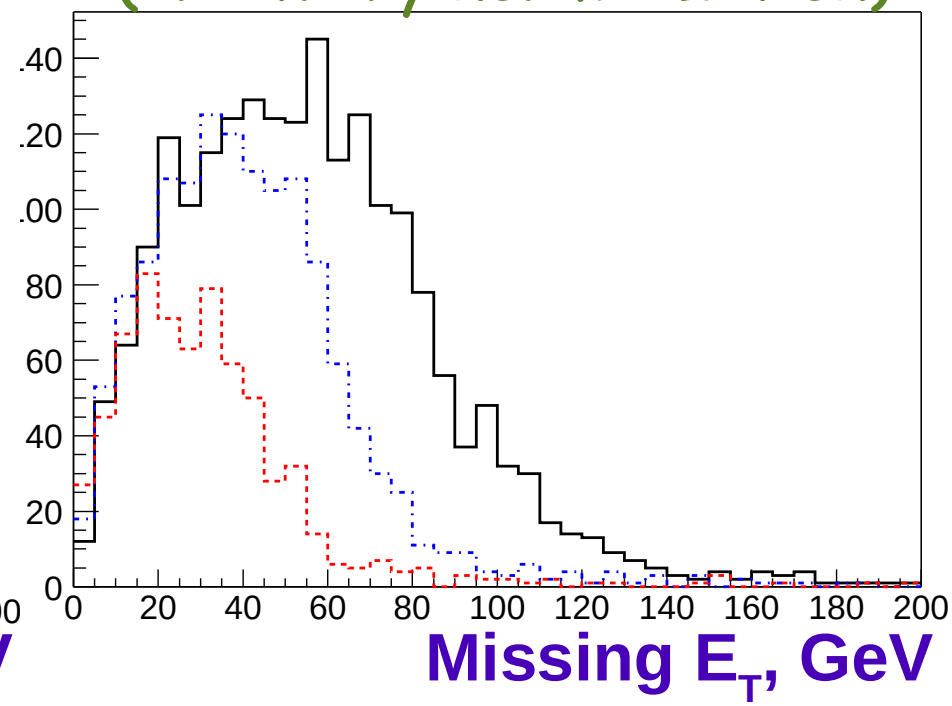
γγ + Missing E_T Events

- 545 Events pass cuts
- Background dominated by fake γ from QCD

γγ Data and QCD Background Missing E_T

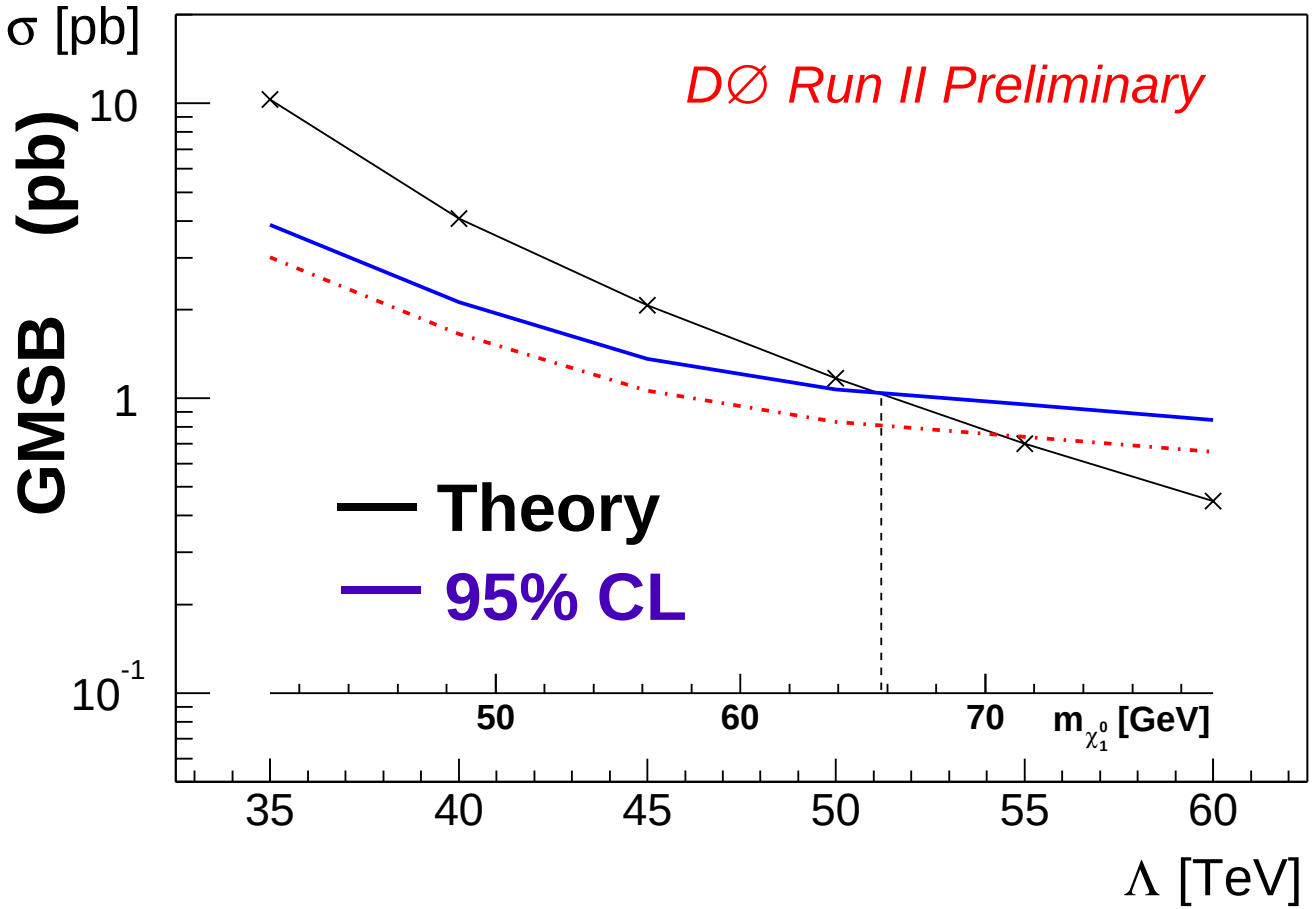


Signal MC Missing ET
Λ =35,45 and 60 TeV
(arbitrary normalization)



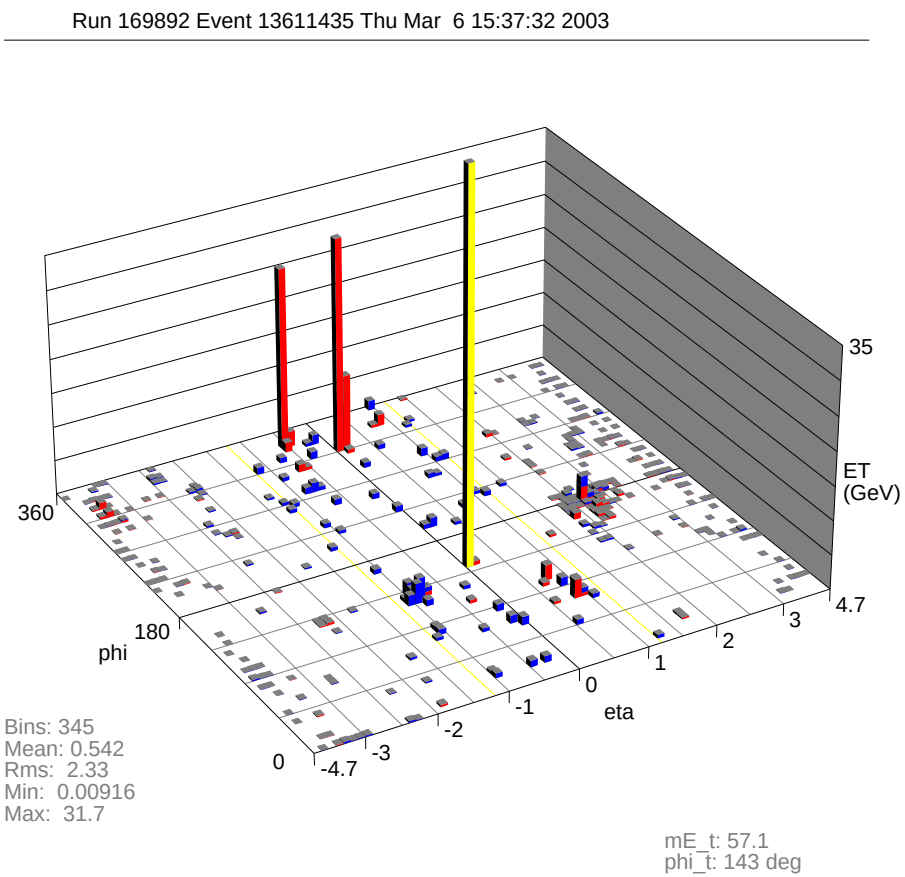
GMSB Limits

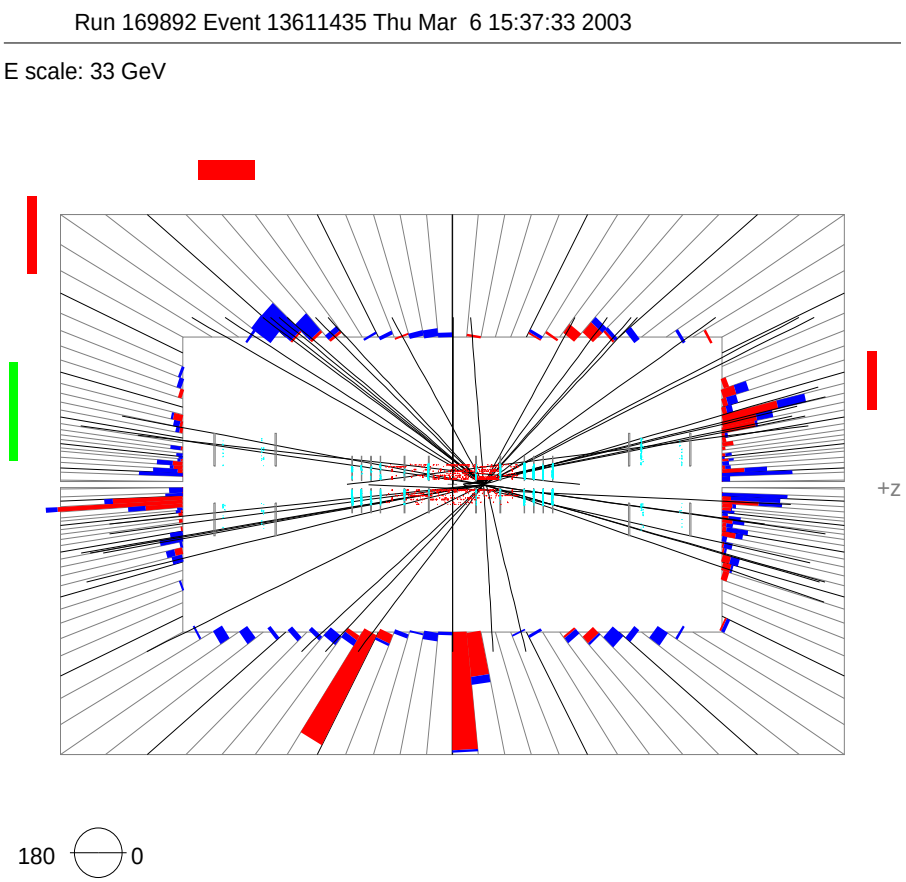
- Set limits for Λ amd M_m of models considered
  - m(neutralino)> 66 GeV/c^2, Λ> 52 TeV
  - Run I limit m(neutralino)> 75 GeV/c^2



Candidate Event

- Highest Missing E_T candidate





mSUGRA

- mSUGRA reduces number of extra SUSY parameters to 4 + sign
  - $m_0, m_{1/2}$: common scalar and gaugino masses at M_{SUSY} scale
  - $\tan\beta$: ratio of Higgs vacuum expectation values
  - A_0, sign(μ) : common trilinear coupling, Higgsino mass parameter
- Lightest SUSY Particle (LSP) is lightest neutralino

mSUGRA Signal

- One signature for mSUGRA is three leptons
  - From production of chargino and neutralino + decay

$$p\overline{p} \rightarrow \widetilde{\chi}_2^0 \widetilde{\chi}_1^{\pm} + X; \quad \widetilde{\chi}_2^0 \rightarrow l^+ l^- \widetilde{\chi}_1^0; \quad \widetilde{\chi}_1^{\pm} \rightarrow l^{\pm} \widetilde{\chi}_1^0$$

  - "Golden mode" for SUSY
    - Very low background from SM
- DØ good place to look for tri-lepton signature
  - Highest energy currently available: if they exist, SUSY particles are heavy otherwise they would already have been seen
  - Good muon coverage
    - $|\eta| < 2.0$, 3 planes, minimal gaps for supports
  - Very good calorimetry (for electron mode)

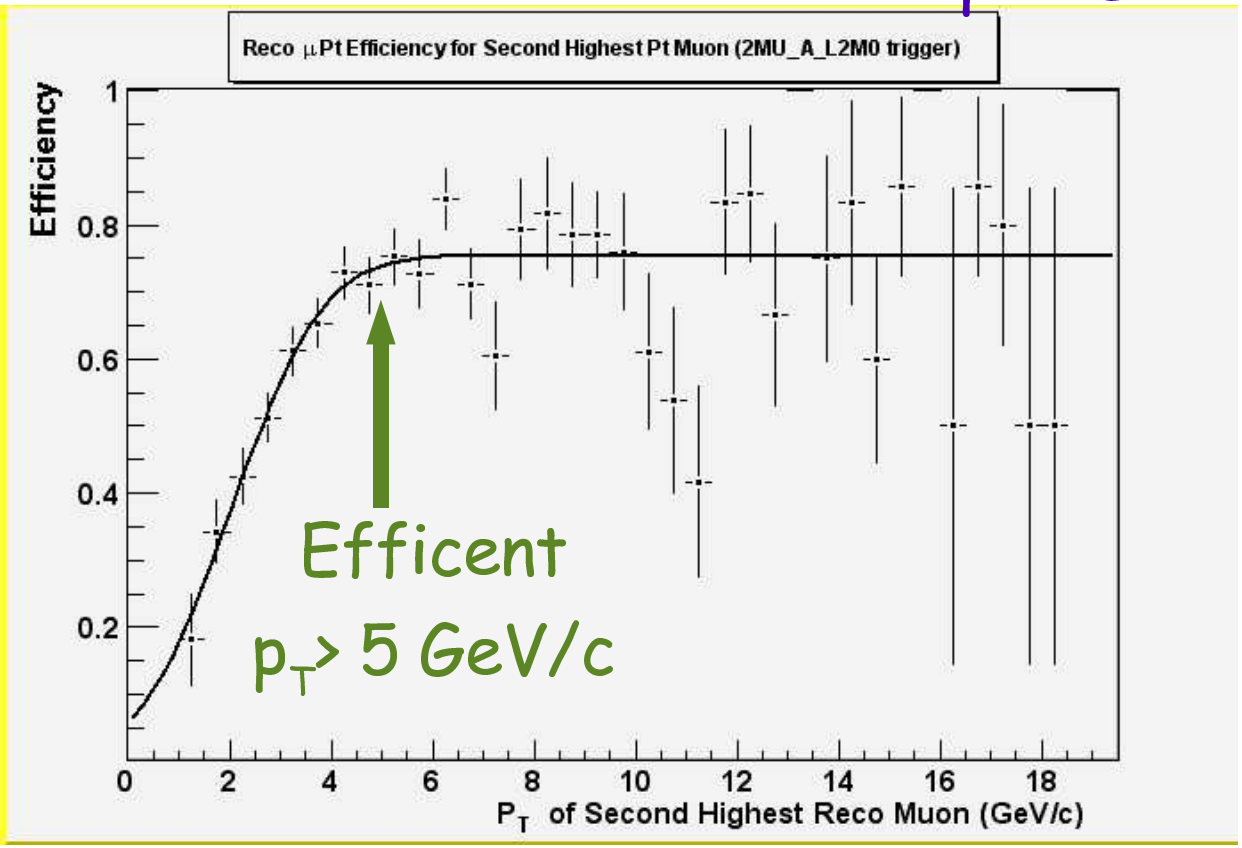
mSUGRA Di-leptons

- Low acceptance if all three leptons are required
  - Require two like-sign leptons instead
  - Increases acceptance, keeps backgrounds low
- ...but understanding backgrounds harder
  - Need to include low p_T muons (SUSY mass difference)
  - Tight cut on μ isolation required to kill background
  - Use minimal cuts: signal varies over parameter space
- Current status of di-muon analysis presented
  - No official results yet...Summer conferences
  - Backgrounds need better understanding
    - Sign mis-id needs full quantitative analysis
    - Non-isolated muons more than current MC predictions

Di-muon Trigger

- Measure di-muon trigger turn on (L1+L2 only)
  - Select events with calorimeter trigger and 2 reconstructed muons
  - Also apply $|\eta|<1.8$ and detector supports cut
  - Count fraction of times di-muon trigger fired as function of second leading muon p_T

20pb^{-1} Data

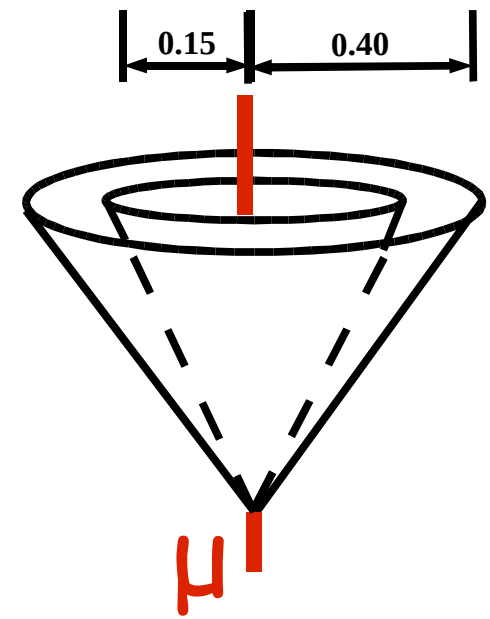


Backgrounds

- Two major sources of background
  - q-qbar: b-bbar contribution dominant
    - σ_{tt} low and c-cbar doesn't give like-sign muons
  - di-boson: WZ, ZZ
  - Also considered W+jets
- b-bbar high σ but μ associated with jet $b \rightarrow \mu \nu_{\mu} c$
  - Remove by cutting on muon isolation
- Di-boson (WZ,ZZ)
  - Low cross-section but muons are isolated
  - Reduce by invariant mass cut
- Need a very good understanding of muon isolation to remove b-bbar background

Muon Isolation

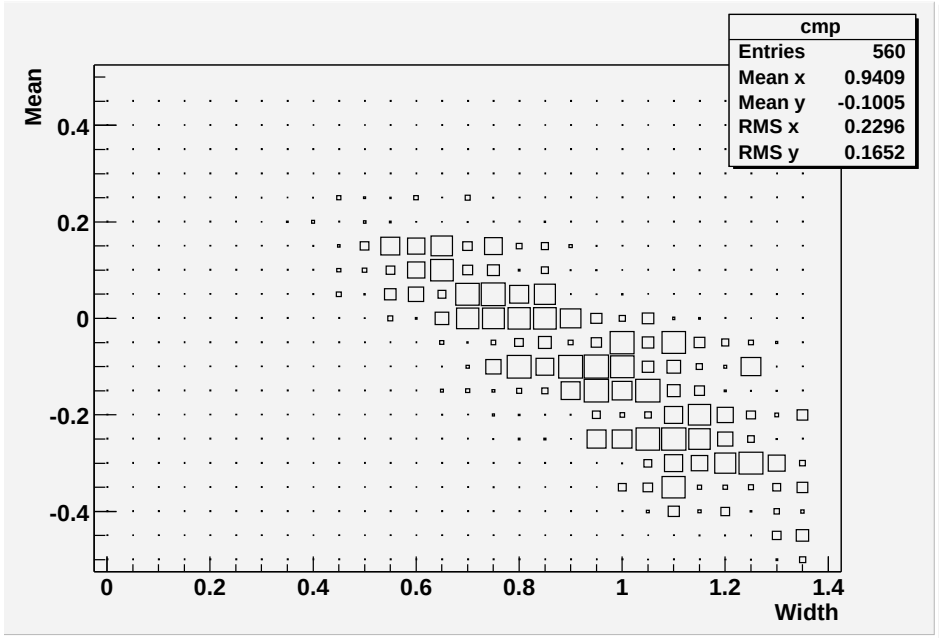
- Muon isolation defined by subtracted calorimeter energy in two cones around muon
  - E in Cone($\Delta R < 0.4$) - E in Cone($\Delta R < 0.15$)
  - Avoids reliance on jet algorithms
- Compare MC vs. data for isolated μ
  - $Z \rightarrow \mu^+\mu^-$ (high p_T) and $\Upsilon \rightarrow \mu^+\mu^-$ (low p_T)
- Observe significantly more halo energy in data than Monte Carlo
  - Warm regions/cells in calorimeter
- Need to correct MC isolation by adding energy
  - Choose gaussian; require isolation > 0



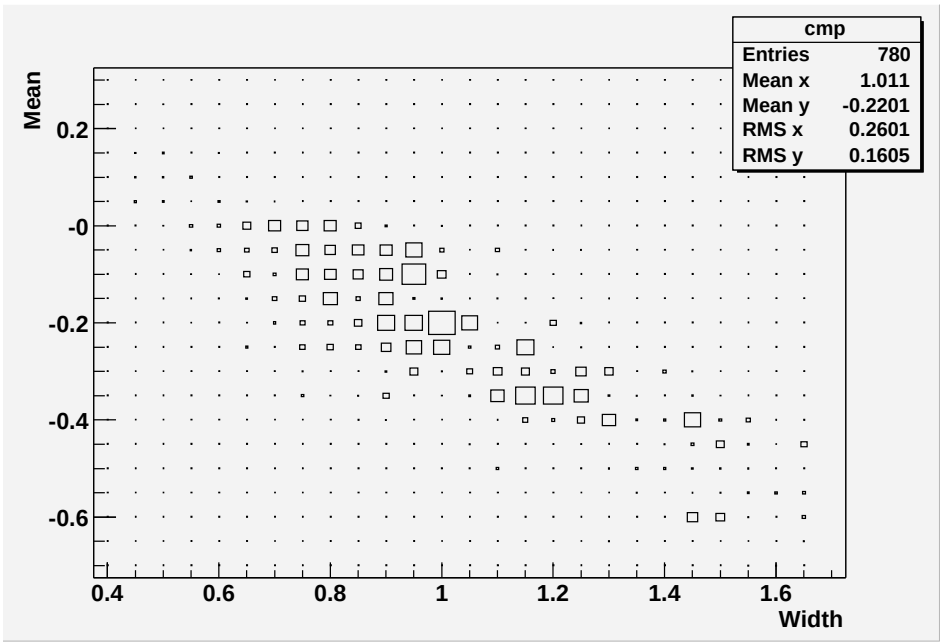
Muon Isolation

- Optimize smearing
  - Vary mean and width of gaussian
  - Use Kolmogorov statistic to compare to data
- Best fit is: mean=-0.1, width=1.0

$Z \rightarrow \mu^+\mu^-$



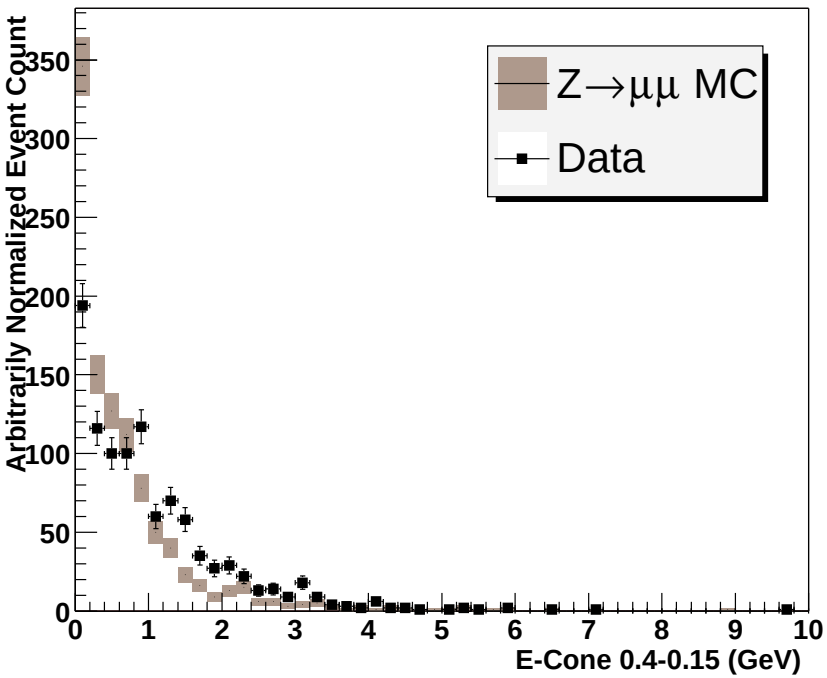
$\Upsilon \rightarrow \mu^+\mu^-$



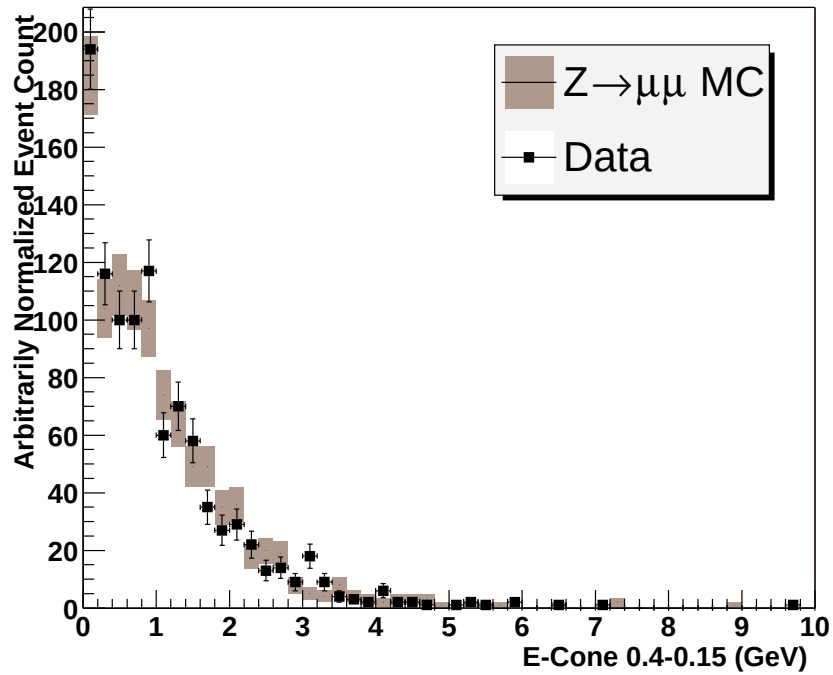
Muon Isolation

- Comparison of before and after smearing for Z
- Z selected from data by requiring:
  - 2 muons with $p_T > 10$ GeV/c, $75 < M_{\mu\mu} < 105$ GeV/c^2

No Smearing



With Smearing



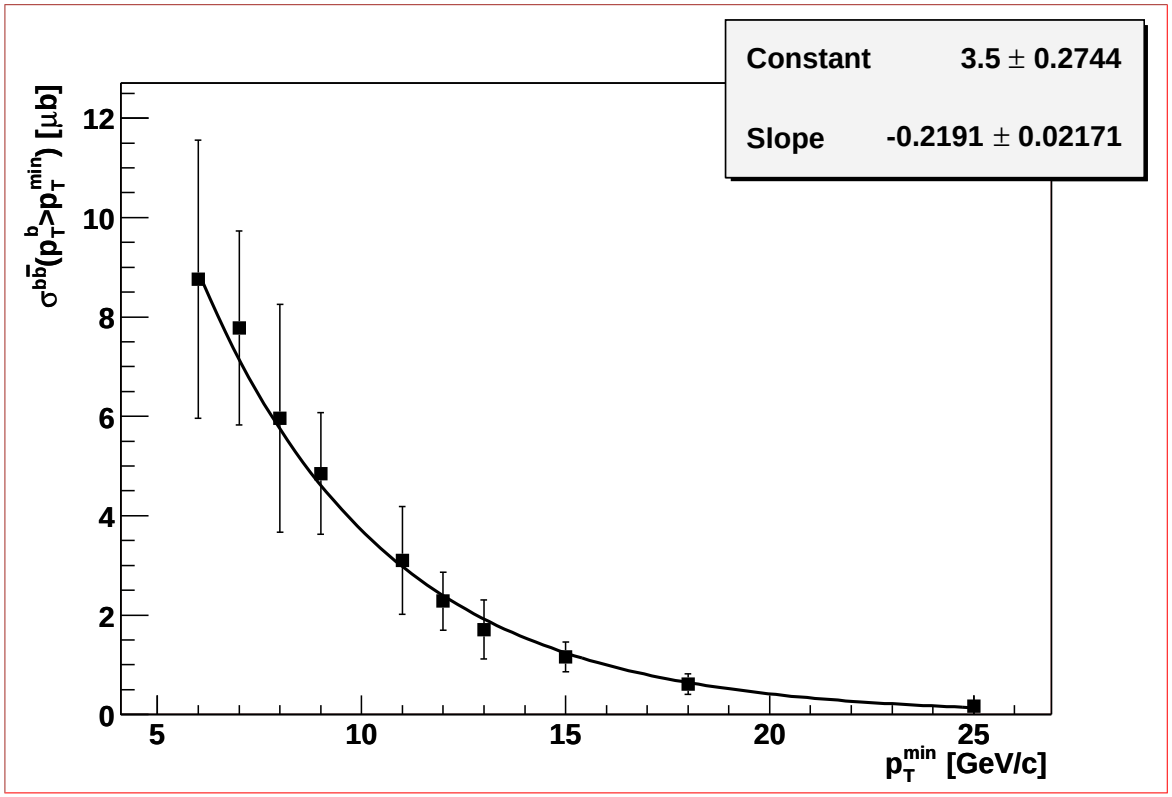
b-bbar MC Cross-section

- Pythia MC cross-section for b-bbar significantly disagrees with Run I measurement
  - Pythia: $\sigma_{bb}(p_T>10GeV/c)=1.75\ \mu b$
  - Run I: $\sigma_{bb}(p_T>10GeV/c)=4.47\pm1.65\ \mu b$
    - Scaled from 1.8TeV (Run I) using Pythia ratio: $\sigma_{1.96}/\sigma_{1.8}$

Fit: $\sigma_{bb}=e^{a+mx}$

Single and dimuon

Run I data points



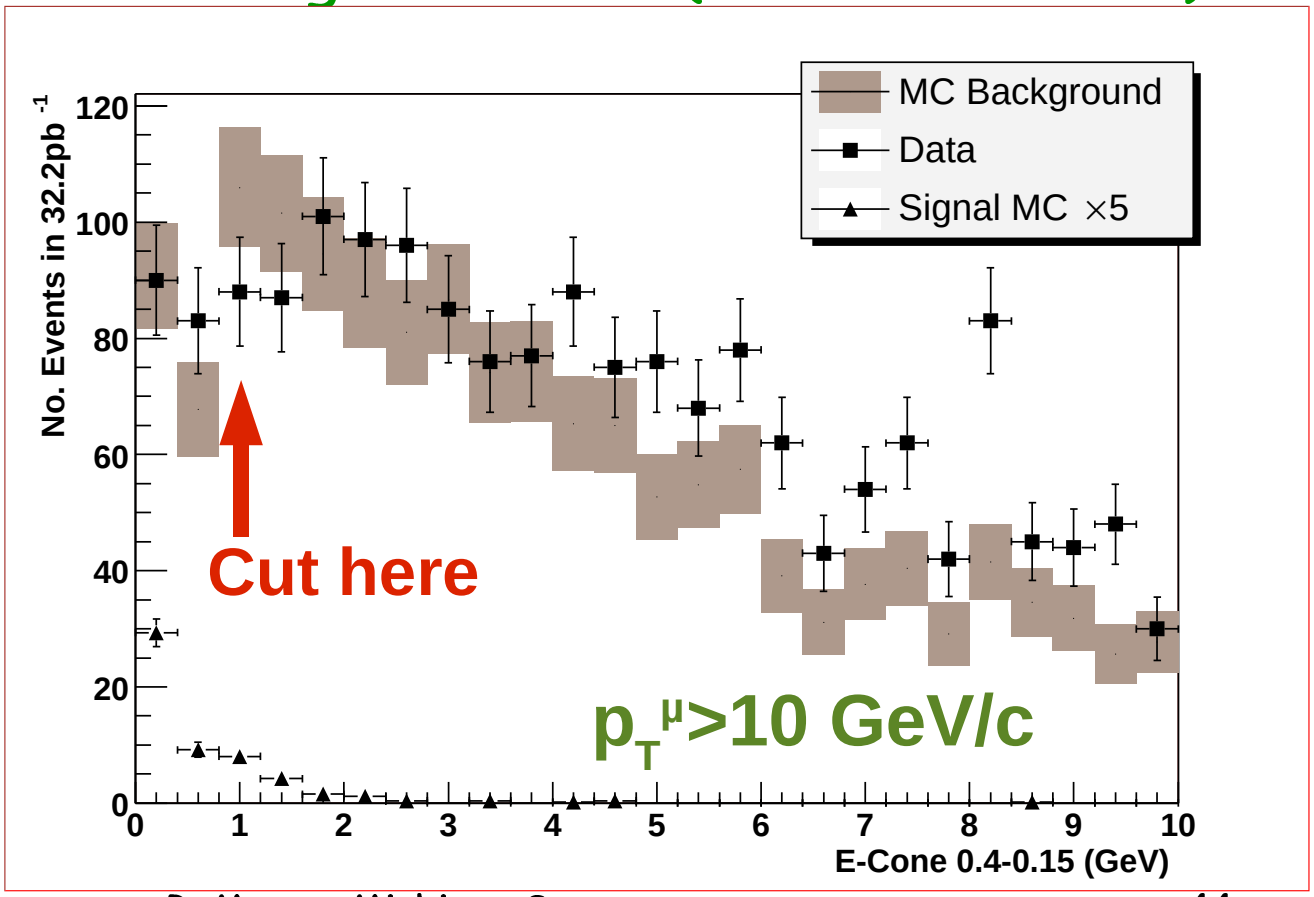
MC and Data μ Isolation

- Compare MC and data muon isolation
  - Like-sign events with 2 muons $p_T > 5$ GeV/c
  - Observe excess at large isolation (i.e. not isolated)

Total MC background correctly normalized

32.2pb^{-1} data

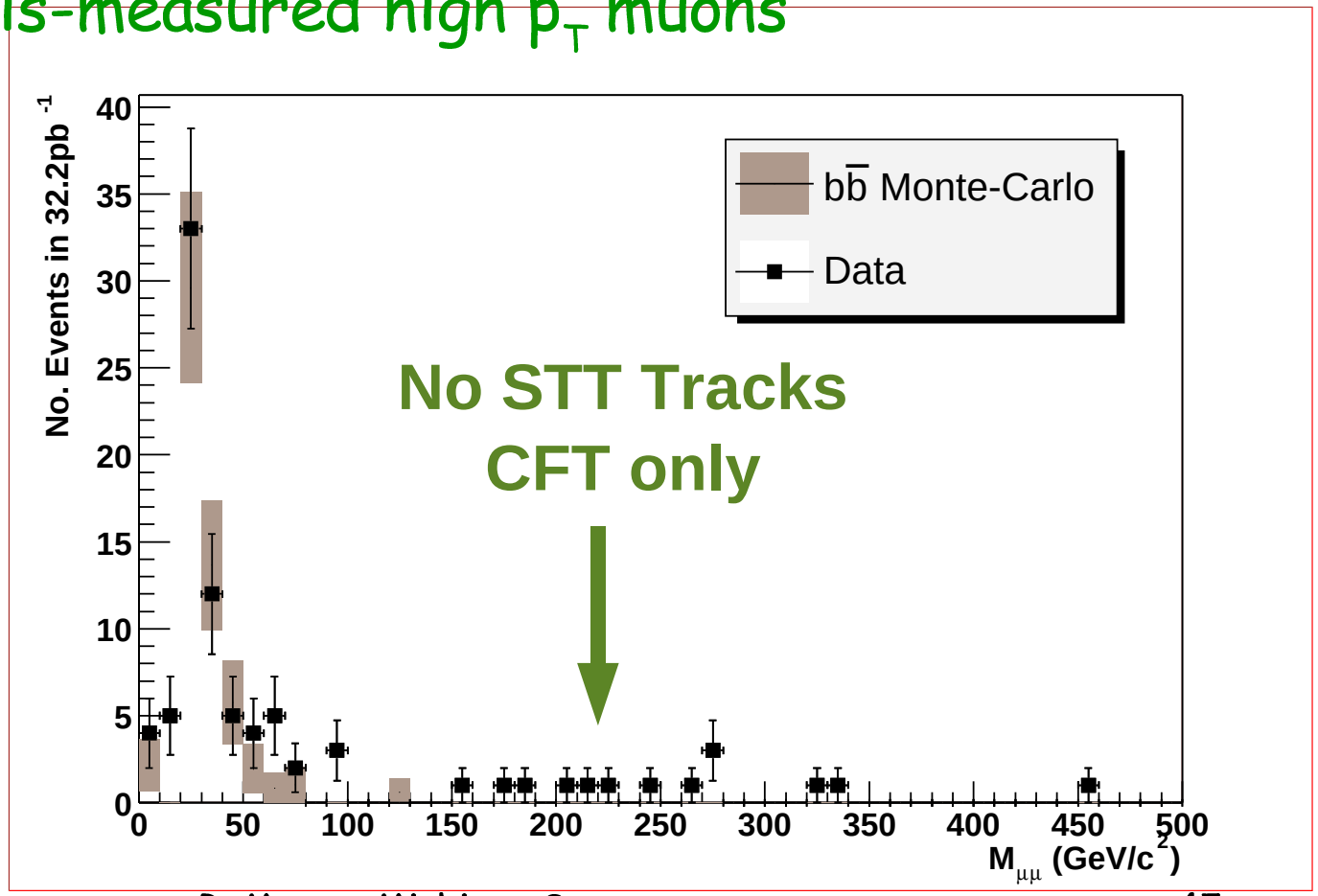
Cut at 1 GeV, $p_T > 10$GeV/c



μμ Invariant Mass Cut

- Final cut: $15 < M_{\mu\mu} < 75$ GeV/c^2
  - Removes sign mis-id at J/Ψ, Υ and Z resonances
  - Removes mis-measured high p_T muons

Events with
2 muons with
E-cone
Iso < 6.0 GeV



Current Results

- Not yet reliable: need to demonstrate better understanding of the backgrounds
  - Data: 4±2 events; Background: $2.3^{+2.8}_{-1.5}$ events
  - MC Signal: 0.41±0.12 events
    - $m_0=m_{1/2}=100 GeV/c^2$, $\tan\beta=3$, $\mu=+$, $A_0=0$

MC Process	σ (μb)	Generated $\times 1,000$	I Lum (pb^{-1})	Final No. Events
$b\bar{b}$	4.47	141,000	31.5	2.3±1.5
$c\bar{c}$	2.29	210,000	91.7	<1.0
$t\bar{t}$	5.86×10^{-6}	5	853.2	<0.1
W+jets	5.96×10^{-4}	4,250	7,133	<0.021
WZ	2.39×10^{-6}	10	4,184	<0.048
ZZ	1.07×10^{-6}	10	9,346	<0.010
Signal	3.57×10^{-6}	3	840.3	0.41±0.12
Data	–	–	32.2	4±2

Lot Still to do...

- Need to understand b-bbar background better
  - Try using data control sample selected by using $\Delta\varphi$ between the muons
    - For b-bbar this peaks at π, for SUSY it is flat
- New reconstruction tracking algorithm soon...
  - Better (understood) tracking efficiency
    - Currently have to apply ~65-90% weight to MC muons
    - Will allow far better understanding of tracking isolation
  - Better correction for CFT only tracks
- Quantatative analysis of sign mis-id background
- MC Scan of mSUGRA parameter space
  - Needed to set limits...or make measurements!

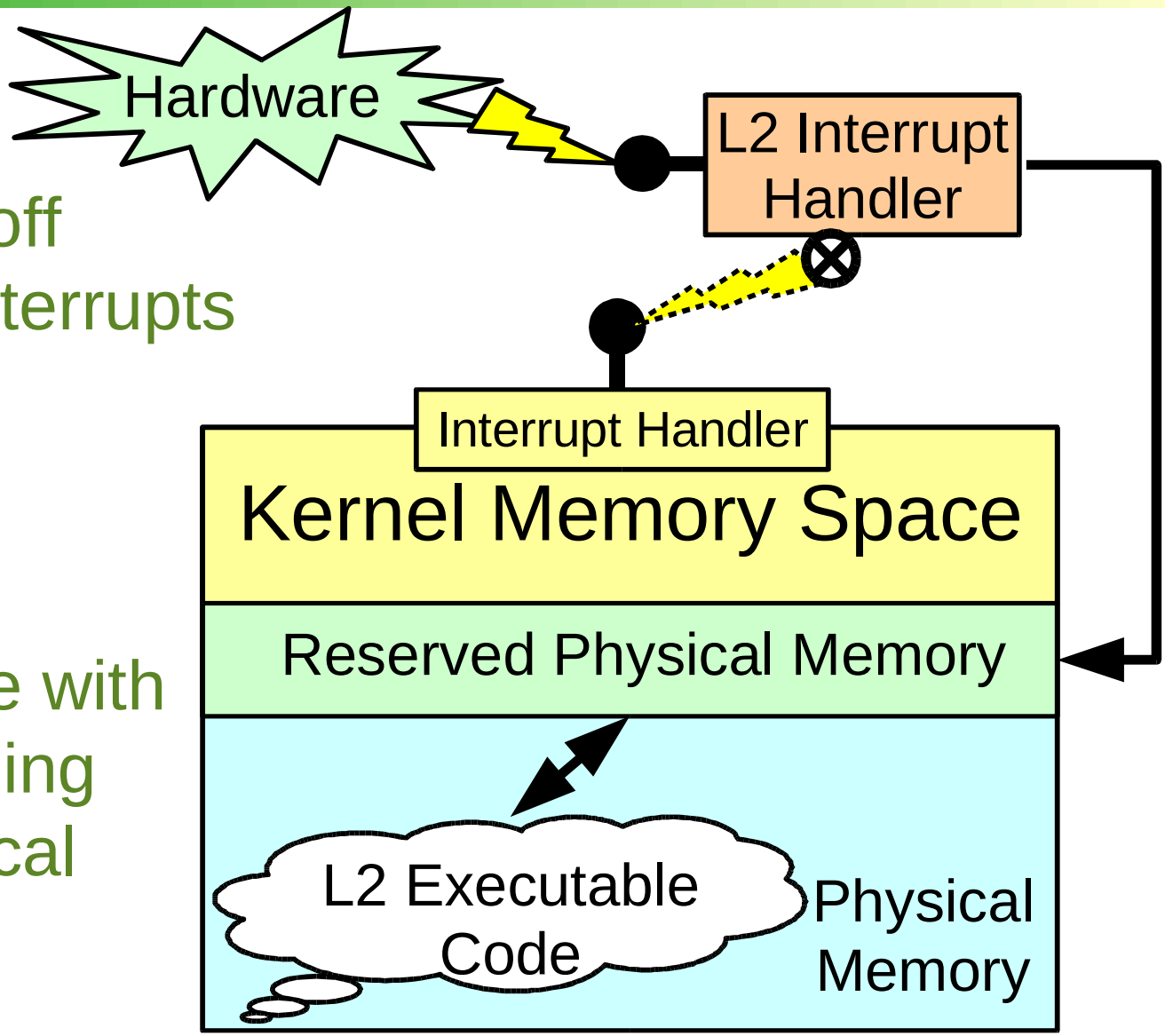
Conclusions

- Trigger is up and working well!
  - L2 beta upgrade within next few months
    - Sufficient to carry on to end of Run IIb
- Offline Analysis framework in place
  - Testbed for new GRID technologies
  - Gaining experience that will be useful for LHC experiments
- Physics results starting to come...
  - Some analyses close to Run I sensitivity
  - Summer conferences will be interesting...
    - Twice Run I luminosity (~200pb^{-1})

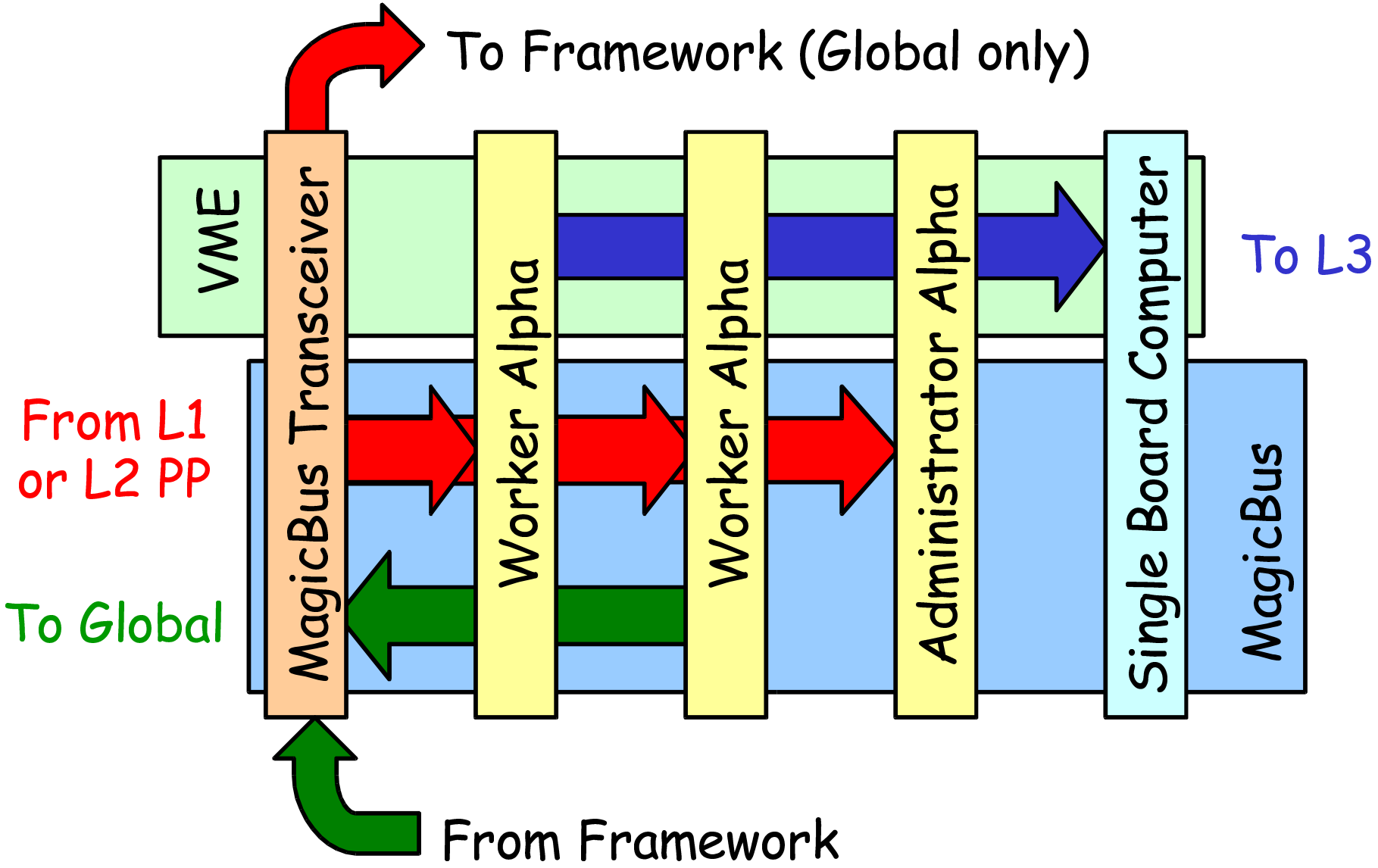
L2 Kernel

Switch turns off all or some interrupts to the kernel

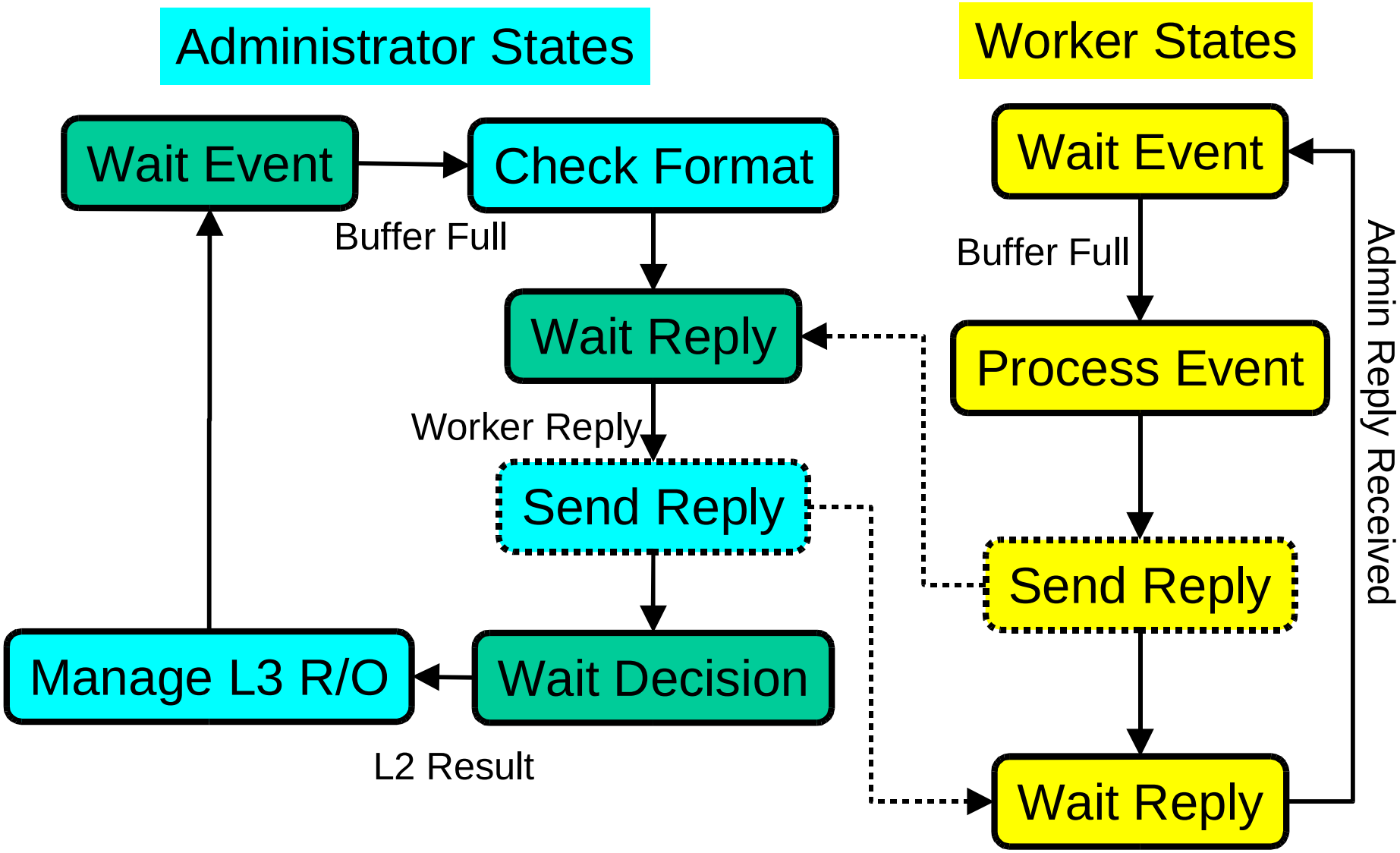
Communicate with processes using shared physical memory



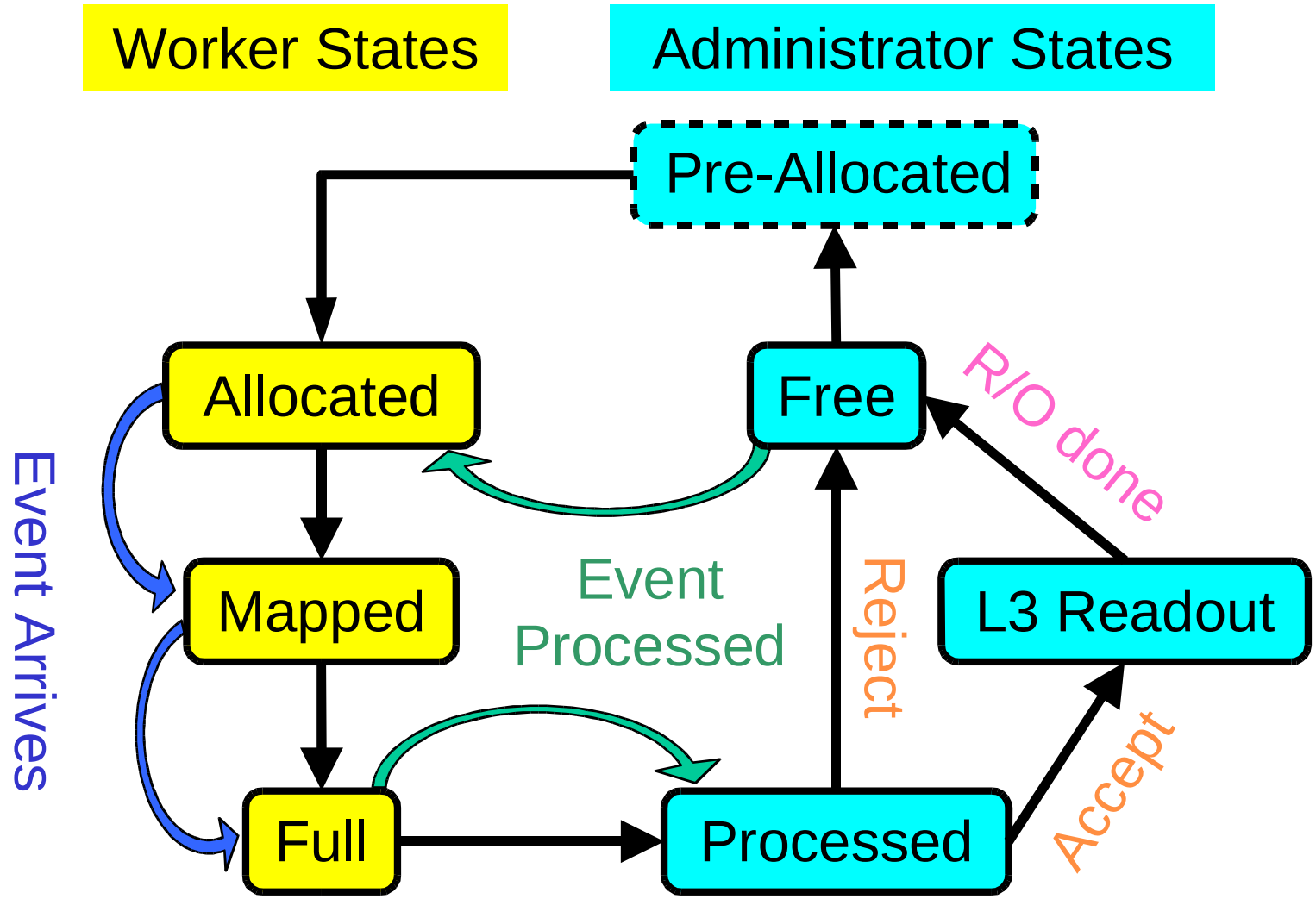
L2 Dataflow


To Framework (Global only)
VME
MagicBus Transceiver
Worker Alpha
Worker Alpha
Administrator Alpha
Single Board Computer
To L3
From L1
or L2 PP
To Global
MagicBus
From Framework

Main L2 Program States



L2 Buffer States



System Administration

- Unique system administration scheme
  - User (physicist) administered (no FNAL support)
  - Divided into sub-clusters by office building
  - Grad students and post-docs contributed from different institutes
    - Counts as official DØ service work
  - Each institute has local admin with root access to just their institutes machines
- Several major benefits of this scheme
  - Admins are users too: problems get fixed fast!
  - Very accessible to users: several in each building
  - Split support load so no one person gets swamped
    - Two people in overall charge