# CDF Trigger System

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Experimental Particle Physics Seminar
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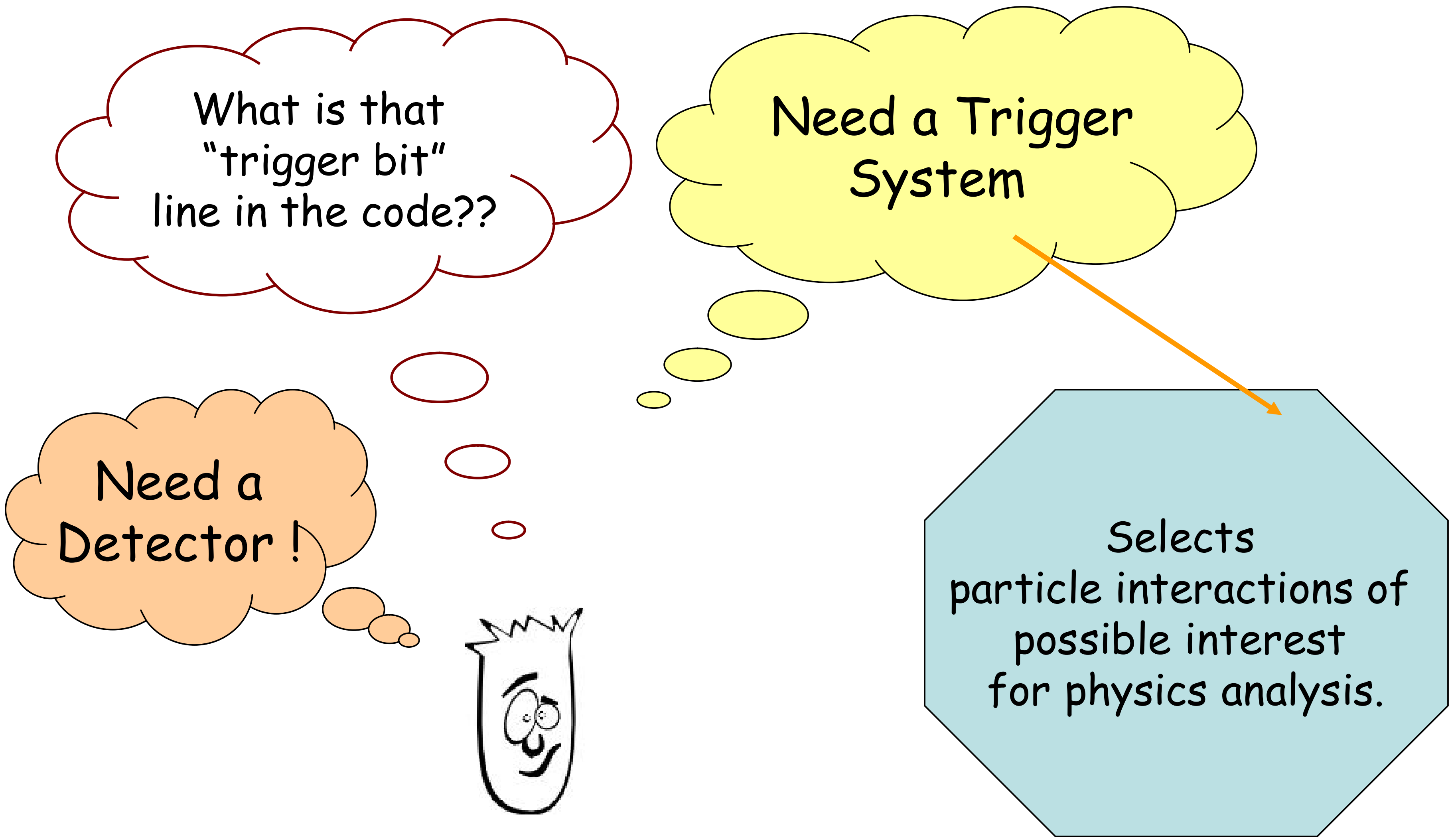
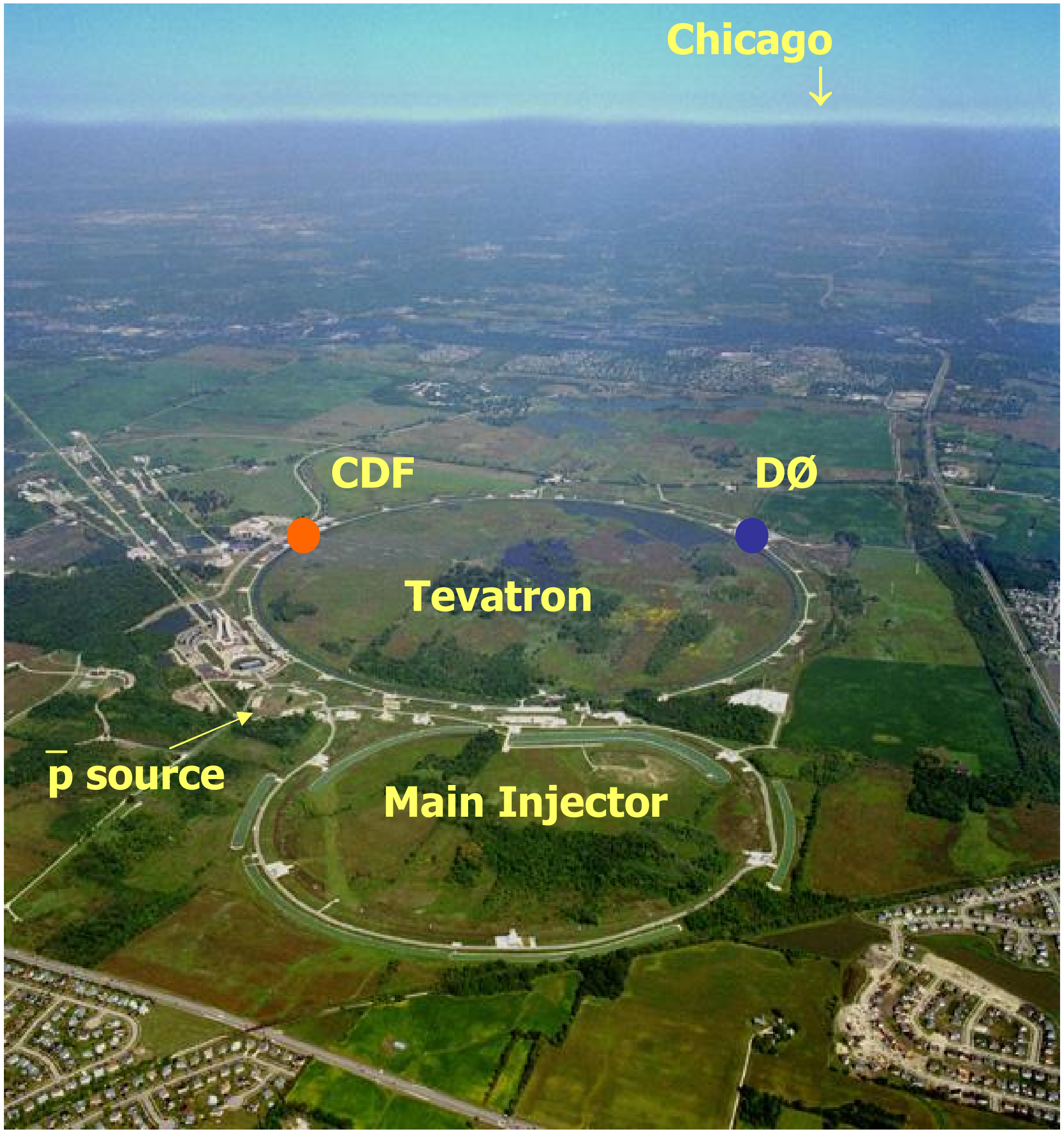
# How to get my top quark event?



# The Tevatron




- Highest energy collider
- Collide protons and anti-protons at CDF and D0
- With a 1.96 TeV Center of mass energy
- 396ns between bunch crossings

# Why is trigger so important?

- Tevatron provides collisions at a rate of ~1.7MHz
- Event size ~ 1/4 MB
- actual CDF output to tape 20MB/s

Trigger rejects 99.995% of crossings !

Select events of interest, but :

- $\sigma_{Inel}$ ~ 50mb
- For example $\sigma_{top}$ ~ 7pb
- That is a ~1/$10^{10}$ factor !!!

Need a trigger system that, keeps with high efficiency events of interest while rejecting unwanted ones

# But do not forget !

CDF is a multipurpose detector

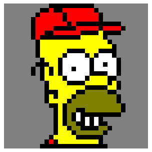
broad physics program including

- Top - precision EW program
- Search for new phenomena
- Tests of perturbative QCD
- B physics

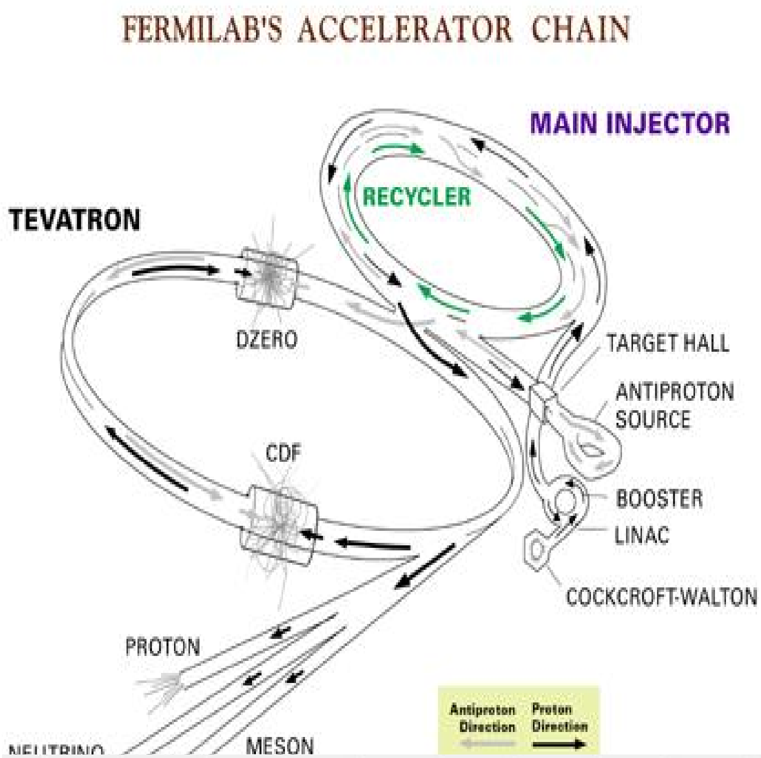
Cross sections vary by a factor of ~ $10^{10}$

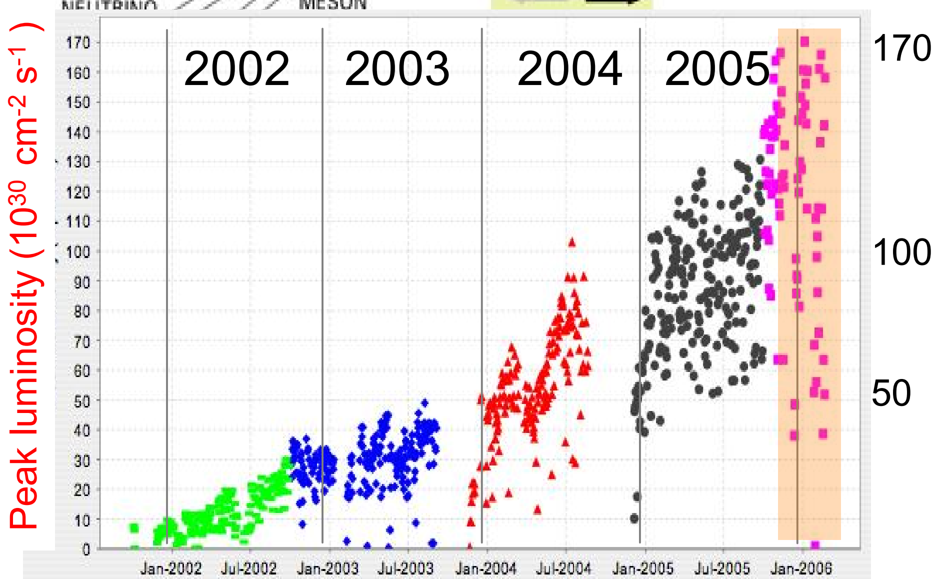
Try to accommodate all !

We want happy experimentalist faces…



# Multiple interactions




36 x 36 bunches
1.7MHz crossing rate
⇓
At High Luminosity:
Multiple interactions !

$$L \cdot \sigma_{inel} = f_{BC} \cdot \mu$$

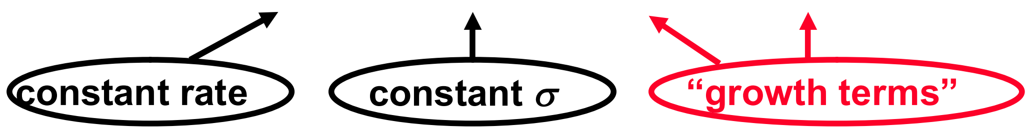
$L$ = Instantaneus Luminosity
$f_{BC}$ = frequency of bunch crossing
$\mu$ : average # of $p\bar{p}$ interaction per BC

$$\mu = 1.8 \leftrightarrow L \sim 5 \cdot 10^{31}\ cm^{-2} s^{-1}$$
$$\mu = 3.5 \leftrightarrow L \sim 10^{32}$$
$$\mu = 7.1 \leftrightarrow L \sim 2 \cdot 10^{32}$$

# Trigger Cross Sections

- For any process: rate $R = L\sigma$ (L = instantaneous luminosity, $\sigma$ = cross section.)
  - For a physics process, $\sigma$ is independent of $L$.
- For trigger cross sections, we observe:

$$\sigma = A/L + B + CL + DL^2$$




  - $A$, $B$, $C$, $D$ are constants depending upon trigger.
  - High purity triggers typically have $C \sim D \sim 0$.
  - Two effects cause extra powers of L:
    - **Overlapping objects from different interactions.**
    - **Fakes that are luminosity dependent.**

- Rates: $R = L\sigma = A + BL + CL^2 + DL^3$

# Efficiency and Dead-time

- Goal of trigger is to maximize collection of data for physics process of interest:
  - Aim for high efficiency !
- For each process, look for:

$$\varepsilon_{trigger} = \text{Ngood(accepted)/Ngood(Produced)}$$

- And watch the dead-time !
- Trigger Dead-time:
  - Due to fluctuations, incoming rate is higher than processing one $\rightarrow$ valid interactions are rejected due to system busy
- Buffering incoming data could reduce dead-time
- But dead-time always incurred if
  - <incoming rate> > 1/<processing time> !

# Detectors

- Arrange different types of detectors in layers surrounded interaction point
- Starting from center moving outwards:
  - Tracking volume within a magnetic field:

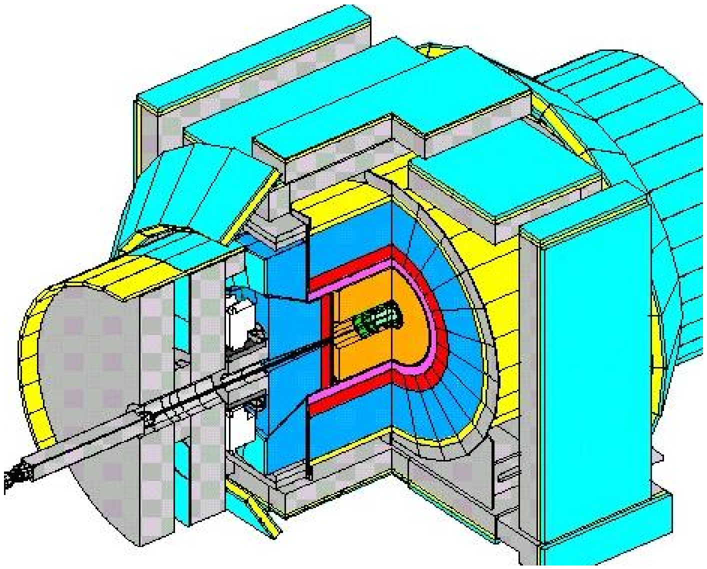
    To measure  trajectory of charged particles with high precision

    Particle ID: Time-Of-Flight
  - Calorimeter usually divided in Electromagnetic and Hadronic

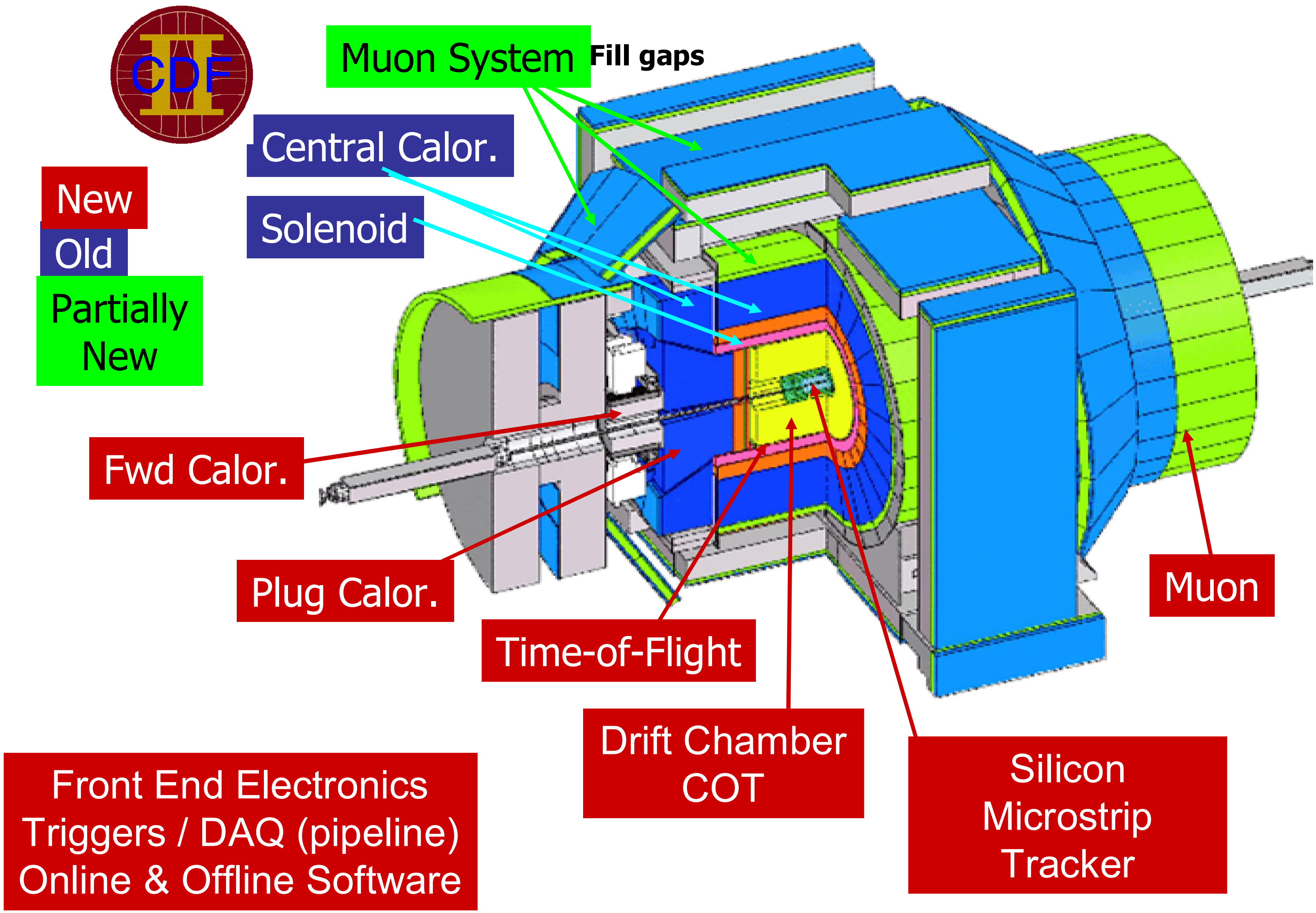
    Absorbs and detects almost all strongly and electromagnetically interacting particles
  - Muon chambers

    Momentum of muons which make

    it through the calorimeter



# CDF detector



# Signatures for triggering

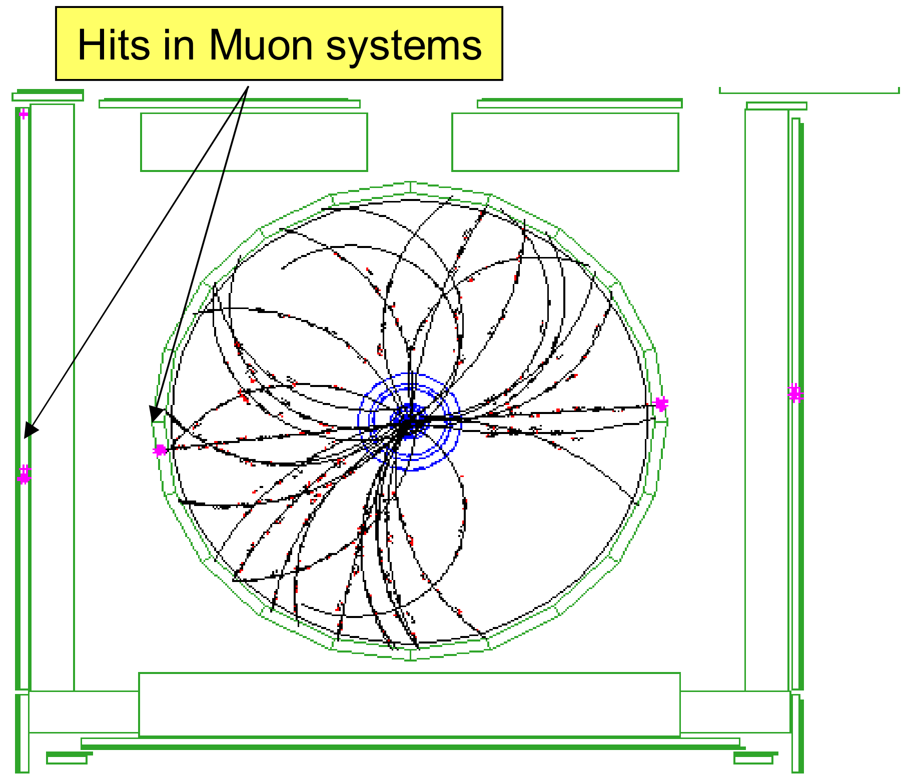
## Accept specific decays modes

High $P_T$ leptons from W, Z, top

## Look for muon candidate:

Mu hit + track matching

--> simplest example




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

# CDF Trigger Implementation

- To obtain high efficiency while large background rejection:
  - Multiple Trigger Levels
- Reject in steps with successively more complete information
- In each step, reject a sufficient fraction of events to not  incurred in high dead-time at next stage

- Basic Idea:

L1 – fast (~few μs) with limited information, hardware based

L2 – moderately fast (~10s of μs), hardware/software

L3 – Commercial processor(s)

# Some examples

- Calorimeter triggers:
  - Single Tower trigger at L1
  - Tower clustering at L2
  - Jet algorithm at L3

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Track triggers

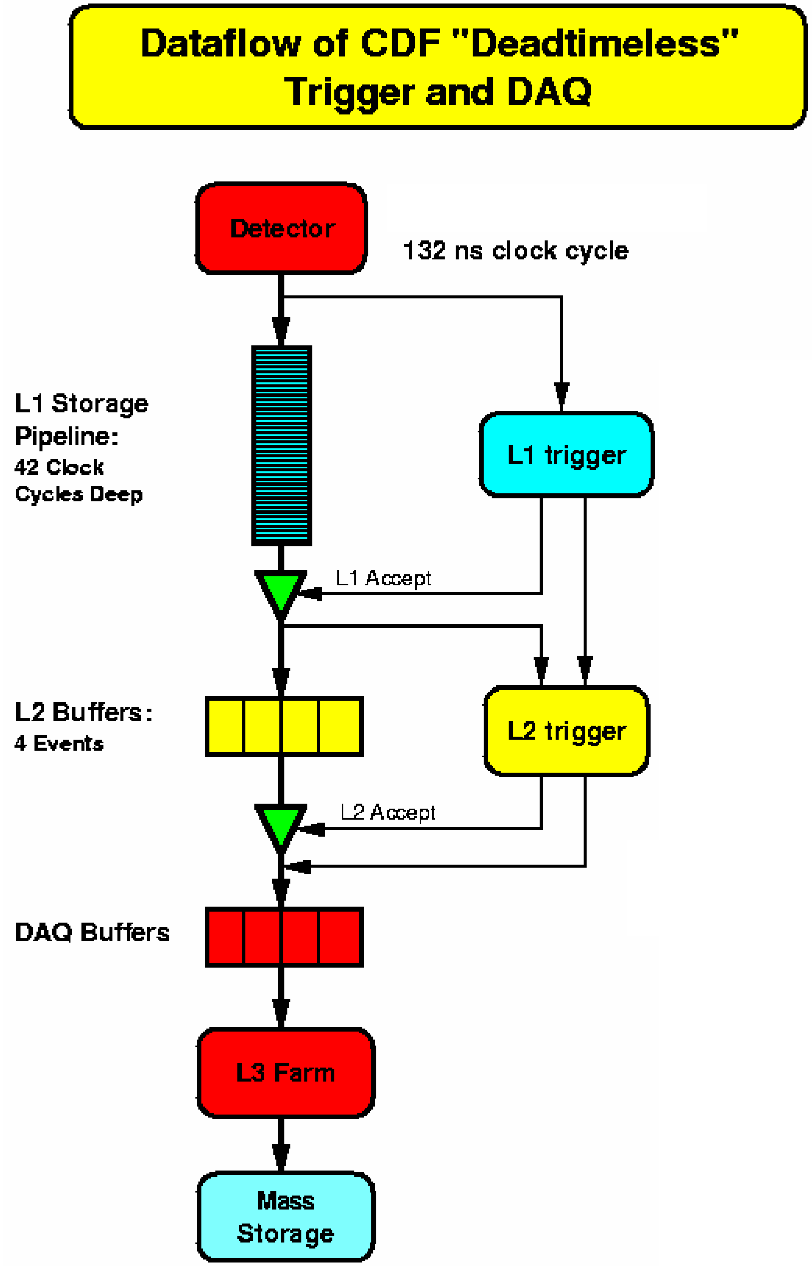
$\eta = -\ln(\tan(\theta/2))$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

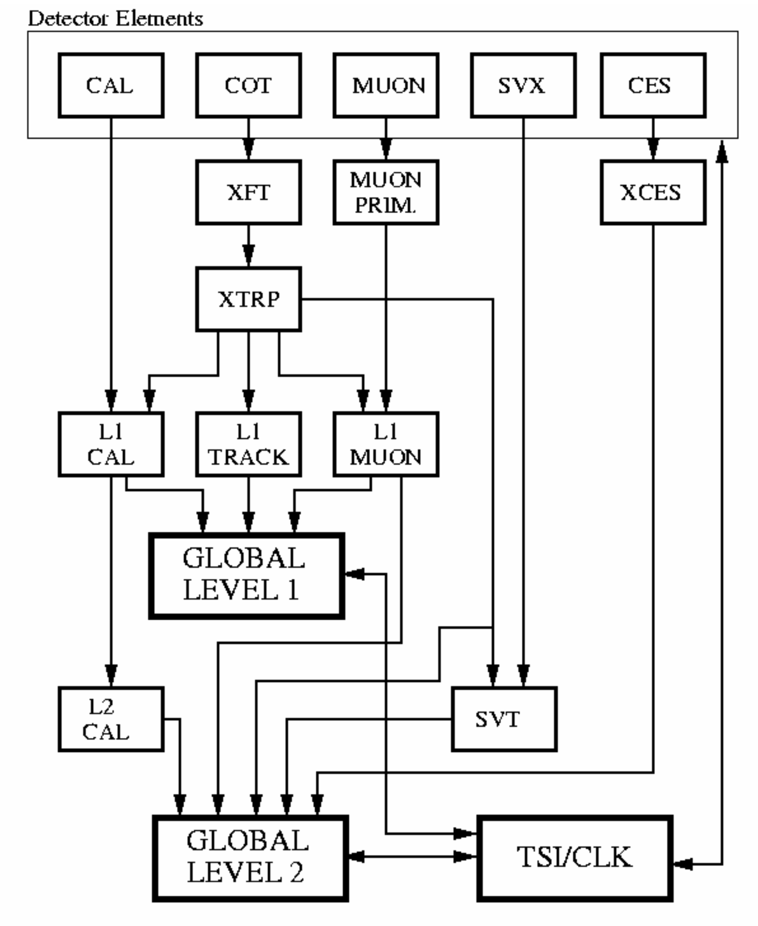
- COT provides track information at L1
- Silicon information is added at L2 (SVT) to measure impact parameter $\sigma(d) = 35\mu m$

## CDF has implemented a 3 level trigger

- Level-1 is a synchronous hardware trigger
  - Processing in parallel pipelined operation
  - L1 decision always occurs at a fixed time (~5μs after beam collision)
  - Input rate = 1.7MHz
    L1A rate ~ up to 35KHz
- Level-2 is a combination of hardware and software trigger (asynchronous)
  - Average Level-2 processing time is ~30μs
  - L2A rate ~ up to 600Hz
- Level-3 is purely a software trigger
  - Massive PC farm running offline-type code
  - Reconstruct complete events
  - L3A rate ~ 100Hz
- Total Data rejection factor 1 : 20000



# What do we trigger on?




- Various trigger subsystem generates primitives that we can "cut" on

- Available trigger primitives are:
  At L1:
  - Central tracking (XFT $p_T$>1.5GeV),
  - Calorimeter (EM and HAD) :
    Electron (Cal +XFT),
    Photon (Cal),
    Jet (EM+HAD)
  - Missing Et, SumEt,
  - Muon (Muon + XFT)

L1 can output
64
different triggers

At L2:
- L1 information
- SVT (displaced track, d0)
- Jet cluster
- Isolated cluster
- Calorimeter ShowerMax

# Combining Physics interests with System bandwidth limitations

Goals:

- Be efficient !
- Keep low dead-time

Three Level system

But, how to

- Accommodate broad physics program
- And cope with increasing luminosity

Very dynamic job !!!

- Lots of work from trigger hardware and trigger database working group….

# What is a Trigger Table?

- Trigger table is how our "trigger menu" is called:
  - "list" of selection criteria
  - Each item on the menu:
    - Is called Trigger Path
    - has three courses: L1, L2 and L3 "recipes":
      - Set of cuts-parameter/instructions particular of each level.
  - *An event is stored if one or more trigger path criteria are met.*
- Each time data taking starts ("a run"), the whole content is communicate to the system
- For bookkeeping, all "menus" and "recipes" are store in a specially designed Database .

# Trigger Tables (II)

- Number of paths we are using: 185 !
- Just some examples of what we could include....

@ L =1.5 $10^{32} cm^{-2} s^{-1}$

Higher rate than available bandwidth (← Single tower, TWO TRACKS)

| Signature (L1 objects, raw rates) | Cross section (nb) | Rate(Hz) |
|---|---|---|
| Single tower ($E_t$ >5 GeV) | 0.4 x$10^6$ | 60K |
| TWO TRACKS ($p_t$>2) | 2 x$10^6$ | 300K |
| Muon ($p_t$>8, 0.6<\|$\eta$\|<1.) | 750 | 120 |
| **L2 triggers** | | |
| Muon ($p_t$>15, 0.6<\|$\eta$\|<1.) | 360 | 50 |
| 2 Jets (+Missing Et) | 360 | 50 |
| Central Electron ($E_t$>16 $p_t$>8) | 170 | 23 |
| Dimuon ($p_t$>2GeV) | 220 | 30 |

# Signal/Backup

- Mentioned examples are not only used to look for that "special" signature (signal) one is interested in
- They are also used for calibration/efficiencies/background studies
- Term backup is misleading…
- For example, for top analyses, need to:
  - Measure L1/L2/L3 signal trigger efficiency
  - Calibrate b-tagging efficiency
  - Calibrate jet energy scale

# The Challenge

To build the table…:

- Try to accommodate all physic interests within system bandwidth limitation
- Physics priorities are important
- Good ideas help to keep physics alive at high luminosities:
  - Improve purity
- Also important to optimize low luminosity range, where more bandwidth is available
- Try to keep low dead-time

Not a simple problem, not a unique solution !

# Dynamic prescale

For large rate backup triggers, a prescale can be applied

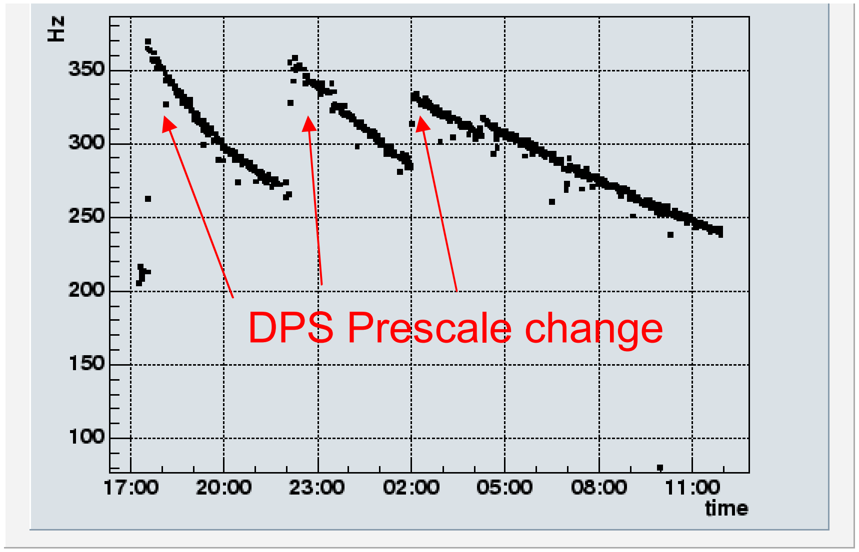
- Prescale (PS) means to only accept a predetermined fraction of events
- The fraction is a fixed value for all luminosities (parameter stored in table for each particular trigger)
- Value determined accordingly to needed statistics (and system availability)

Trigger cross sections grow with luminosity $\rightarrow$ as luminosity falls during a run trigger resources are freed up.

- What if we could change the prescale value while data taking?

- Dynamic prescales up and running since late 2002
- Applied to triggers with high growth term

L2Accept Rate (Hz)



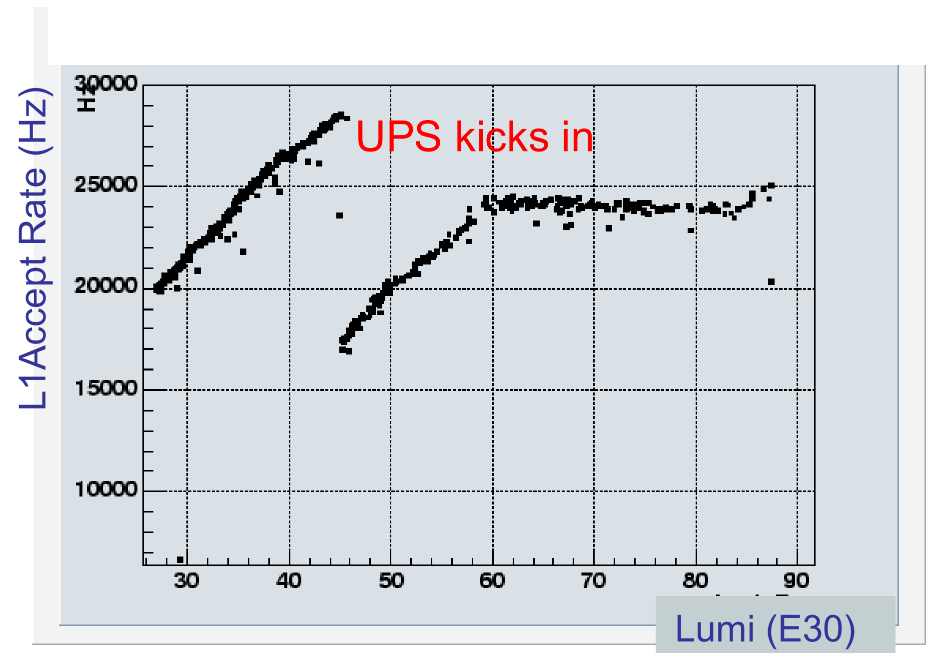

Dynamic prescale (DPS) is a feedback system

- Reduces the prescales as luminosity falls
- Changes happen based on rates information accumulated on a time scale of minutes and amount of change depends on available trigger bandwidth at a given time

The feedback can be also done at the μsec scale !

→ This is what we call the “Uber Prescale (UPS)”, it is still DPS.

-Enabling high rate L1 triggers whenever the system is idling. (effectively look at buffer occupancy)
-In trigger table since 2004
-Applied to high rate L1 track trigger




One simple approach:
Luminosity enable (DPS based on just luminosity):
Turns on/off a particular trigger at a given Instantaneous Luminosity.
In table since 2005.

# Hardware improvements

- Hardware improvements are a key to maintain system alive, especially at high luminosities
- Example: reduction in Level 2 execution time improves the bandwidth for L1A

- Examples are:
  - L2 Pulsar upgrade for L2 decision crate (UPenn big contributor!)
  - L2 SVT upgrade

# Level 2 Decision Crate Upgrade

- The L2 Decision Crate is the heart of L2
- Receives data from 7 preprocessors

  ( L1 Trigger, Calorimeter, Calorimeter isolation, ShowerMax (electrons), Muon, L1 Track (XFT) and L2 Silicon Tracking )
- Processor runs L2 algorithm and makes L2 Trigger decision

Upgraded from

- 6 flavors of custom interface boards
- Custom Alpha processor
- Data to processor on Custom Bus

to

- Pulsar board as universal interface
- Use CERN S-LINK technology
- Linux PC

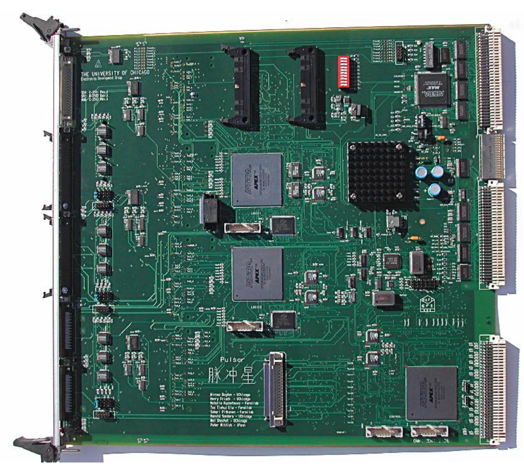
  Easily to upgrade when faster processor becomes available

• Full upgrade in place since September 2005.

• Has already shown high reliability

• Flexibility allows for future improvements to cope with increase of luminosity

• Average gain ~20 μsec



# L2 SVT upgrade

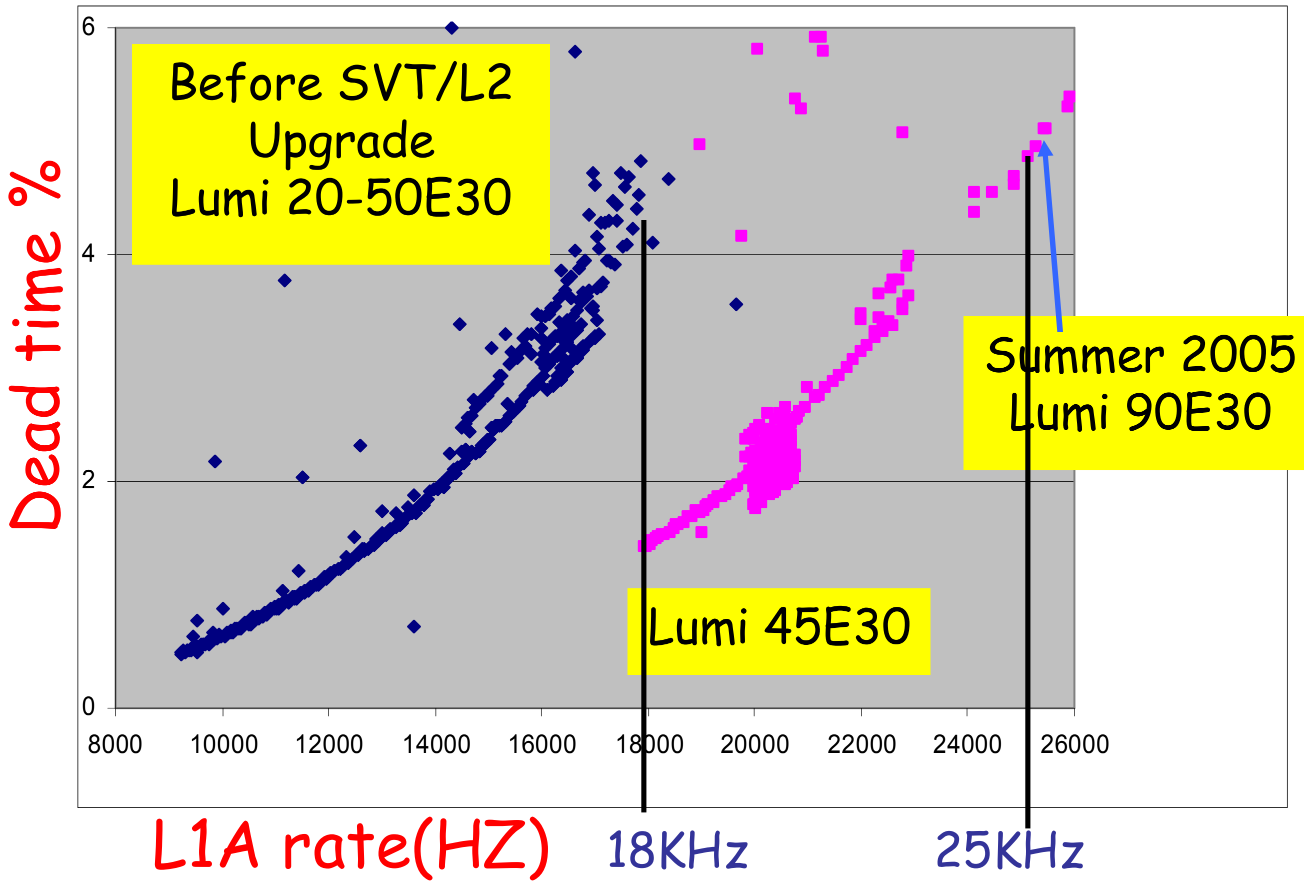
- Helped to reduce the L2 latency by speeded up SVT execution

Done by improved capabilities:

1. Improved pattern recognition
2. Faster track fitting

Using Pulsars

+7kHz (+40%) L1A bandwidth @ double inst. lumi.



# High Luminosity effects

Cross section grows with luminosity:

$$\sigma = A/L + B + CL + DL^2$$

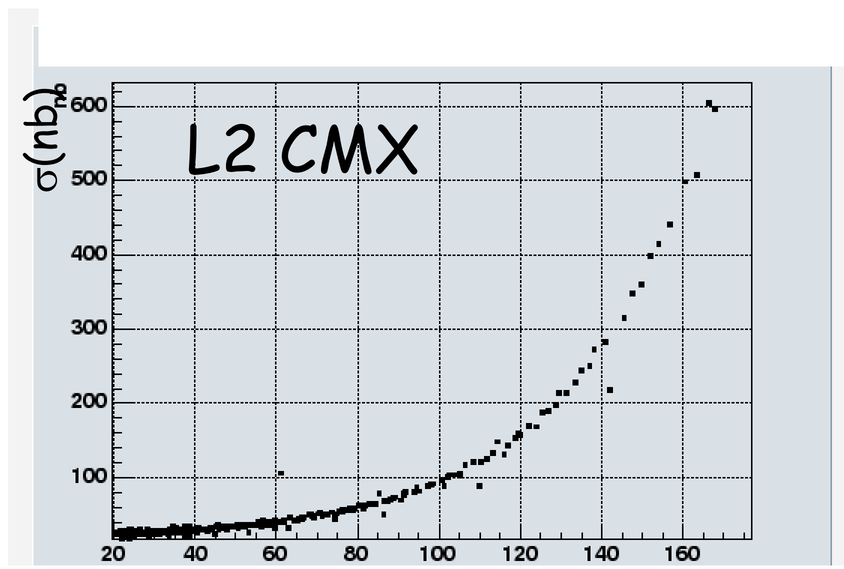
Two examples:

- Jet Triggers:
  - Current L2 Clustering algorithm sensitive to detector occupancy
- Fake Tracks:

Track trigger rates growing rapidly with luminosity

Dominant component comes from fake tracks

Muon + track pointing to it

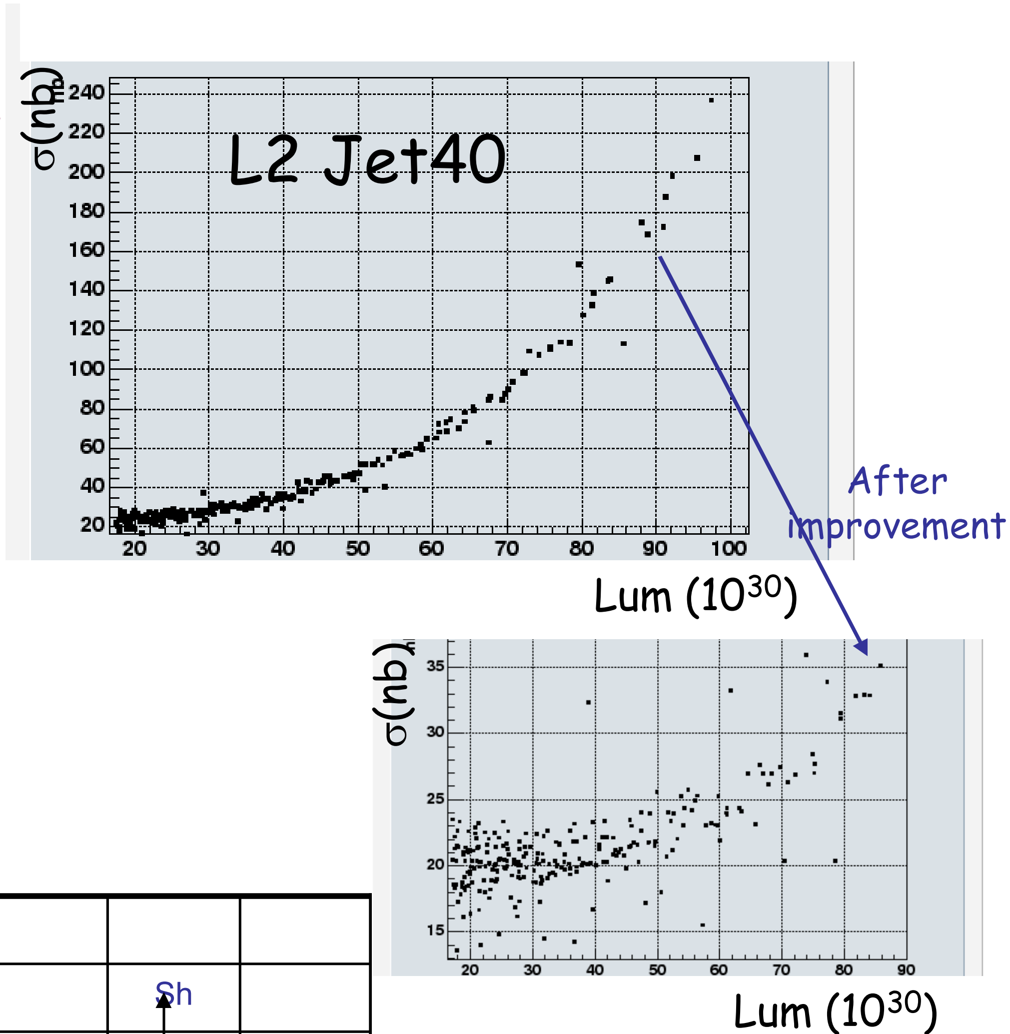



Lum ($10^{30}$)

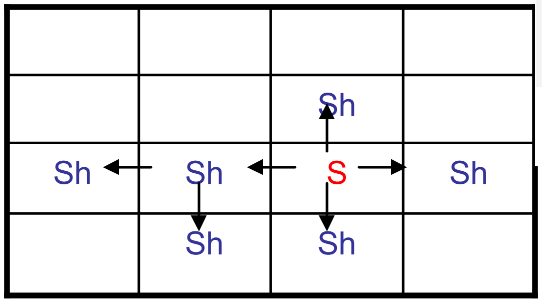
# L2 Jet Trigger

## Observed high growth term

- Calorimeter is divided in trigger towers (0.2x15° $\eta$-$\phi$) and energy information is sent to L2 Calorimeter trigger boards.
- This energy is clustered and check against trigger threshold.
- The clustering process is as follows:



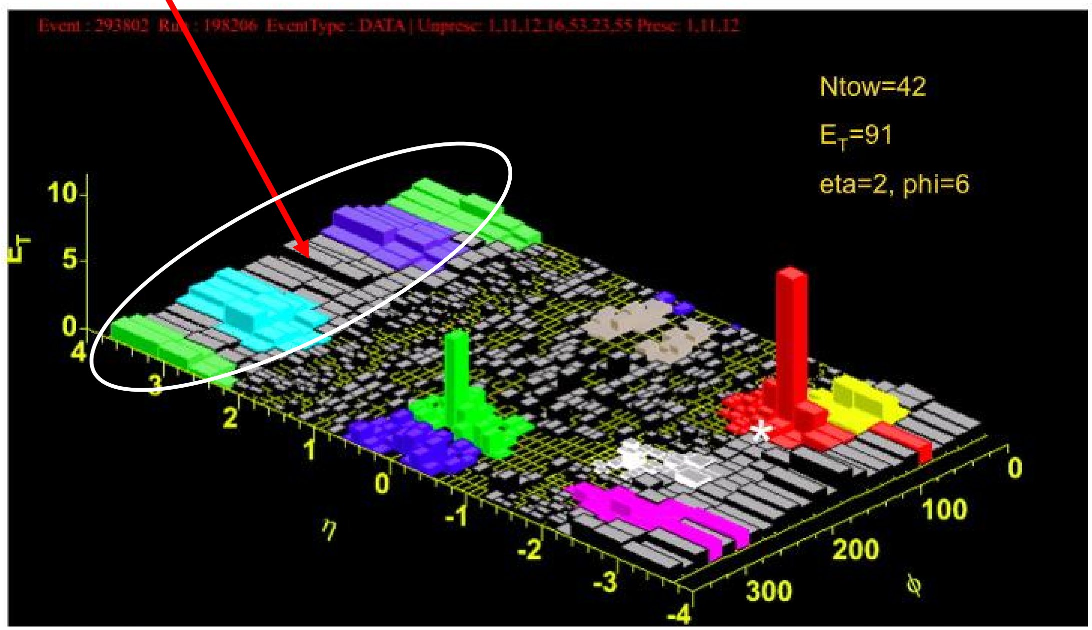

Find "seed" tower ($E>E_s$)
Look for adjacent shoulder towers ($E>E_{Sh}$)
Continue until no shoulder is found



# L2 Jet triggers (II)

- Found that rate increased due to "large" clusters in azimuth in forward region → "Ring of Fire"
- Solved by increasing shoulder threshold

- *As Luminosity increases, this could happen on other Calorimeter regions*
- Not only a rate problem, could cause inefficiencies on triggers that require many jets (for example top hadronic)




- Possible solutions:
  - –Increase threshold on other regions too ( what about efficiency?)
  - –Improve clustering algorithm (Pulsar based system is flexible enough)

# Fake tracks

Extra occupancy due to increase of number of interactions per crossing → more chance for confusion:

- Fake tracks
- Worse resolution

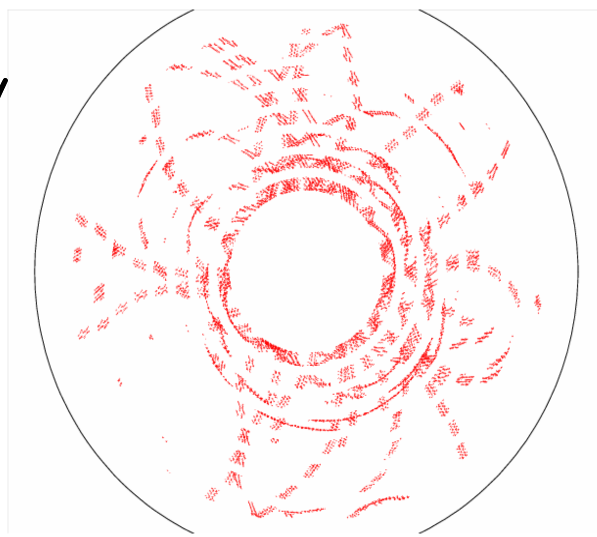
•Currently only using 4 axial layers (only 2D information)

•XFT Upgrade will add stereo (z) information from 3 outer layers

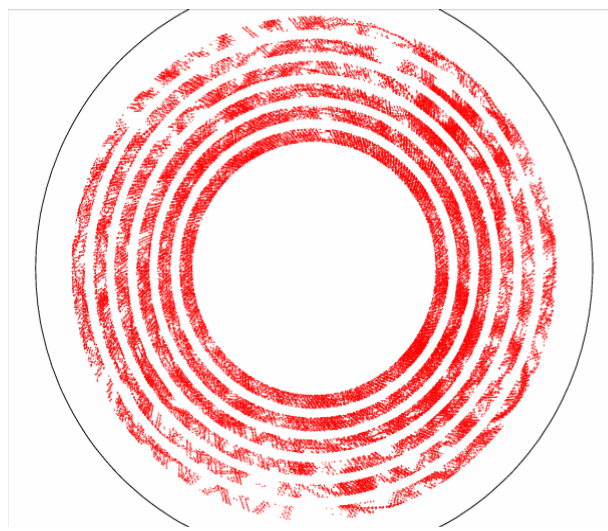
•Expect to reduce fakes by ~ x5 (trigger dependent)

COT occupancy

Random Inelastic Interactions (Simulation)

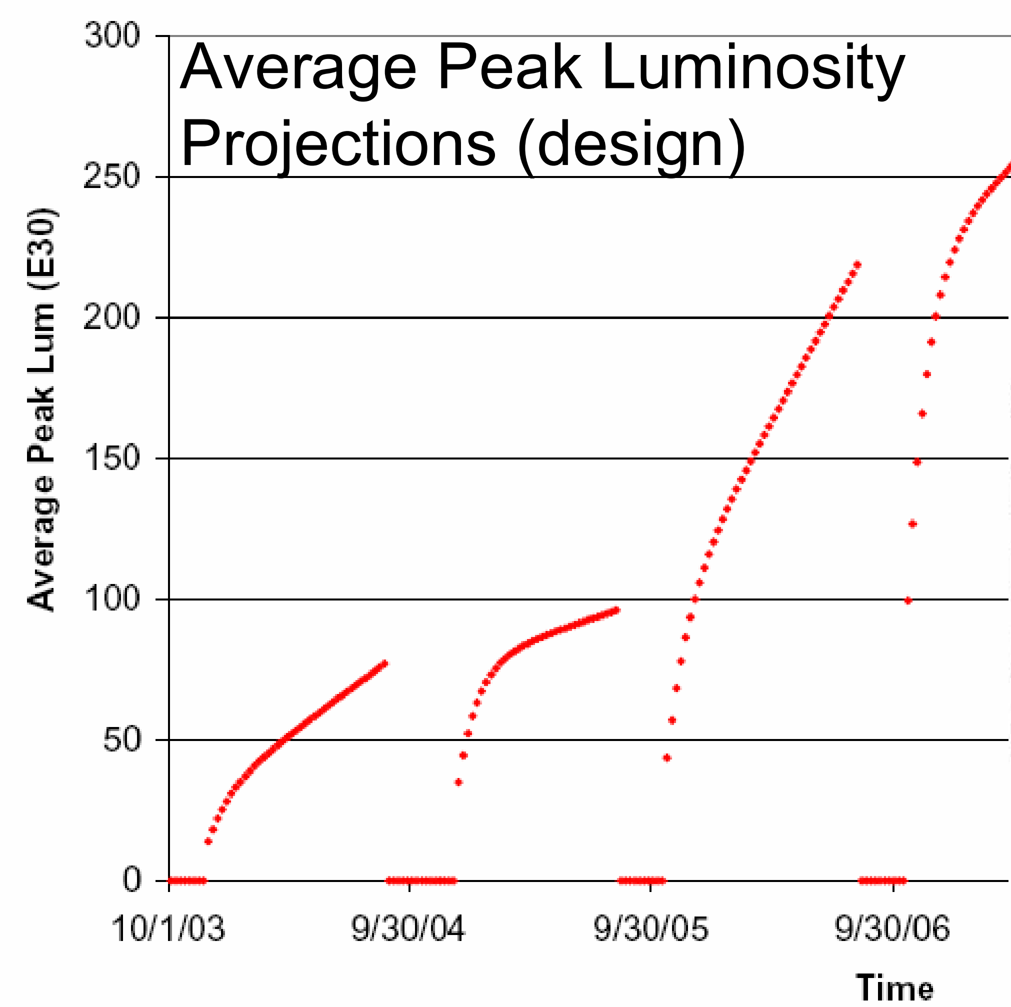


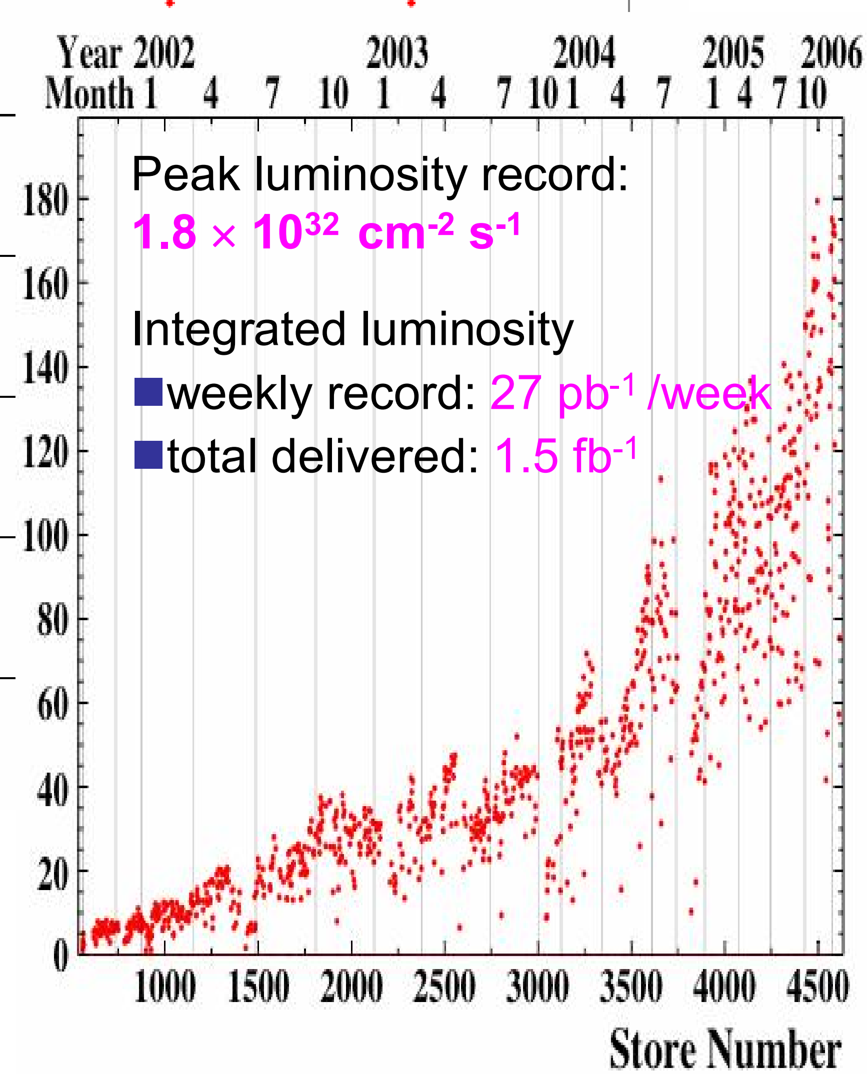
Luminosity ~ 3E31



Luminosity ~ 4E32

# Tevatron performance



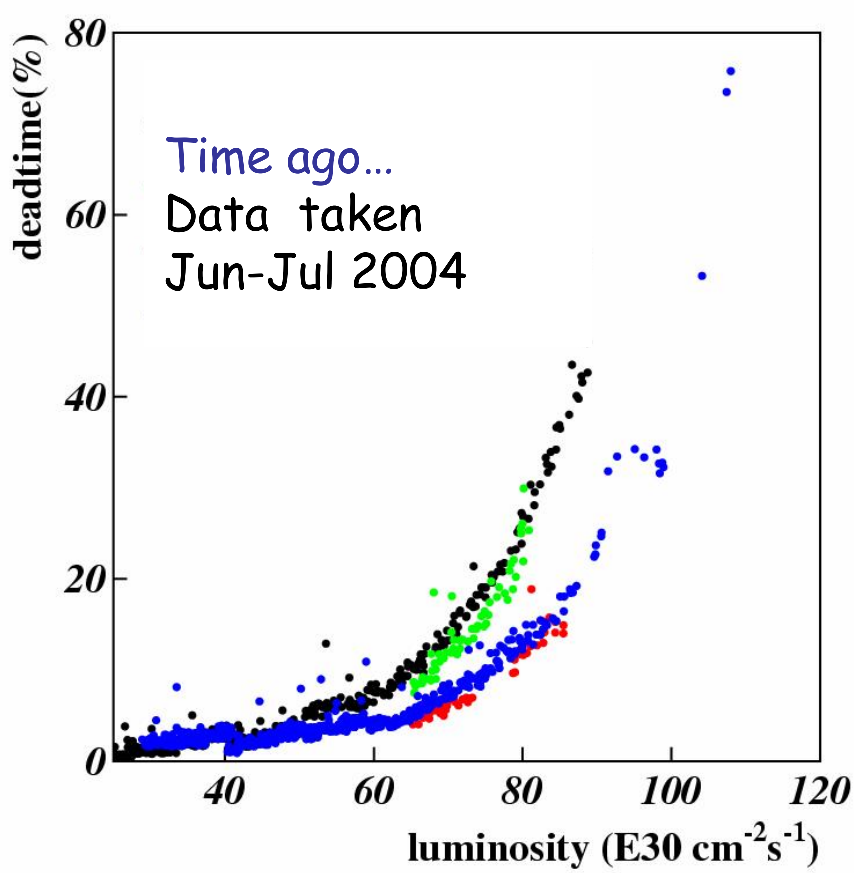




Exciting and challenging
times to come !!!!

# How CDF is doing?

Used to have two tables (high and medium-low Lum)

**Now , only one table for whole luminosity range !**



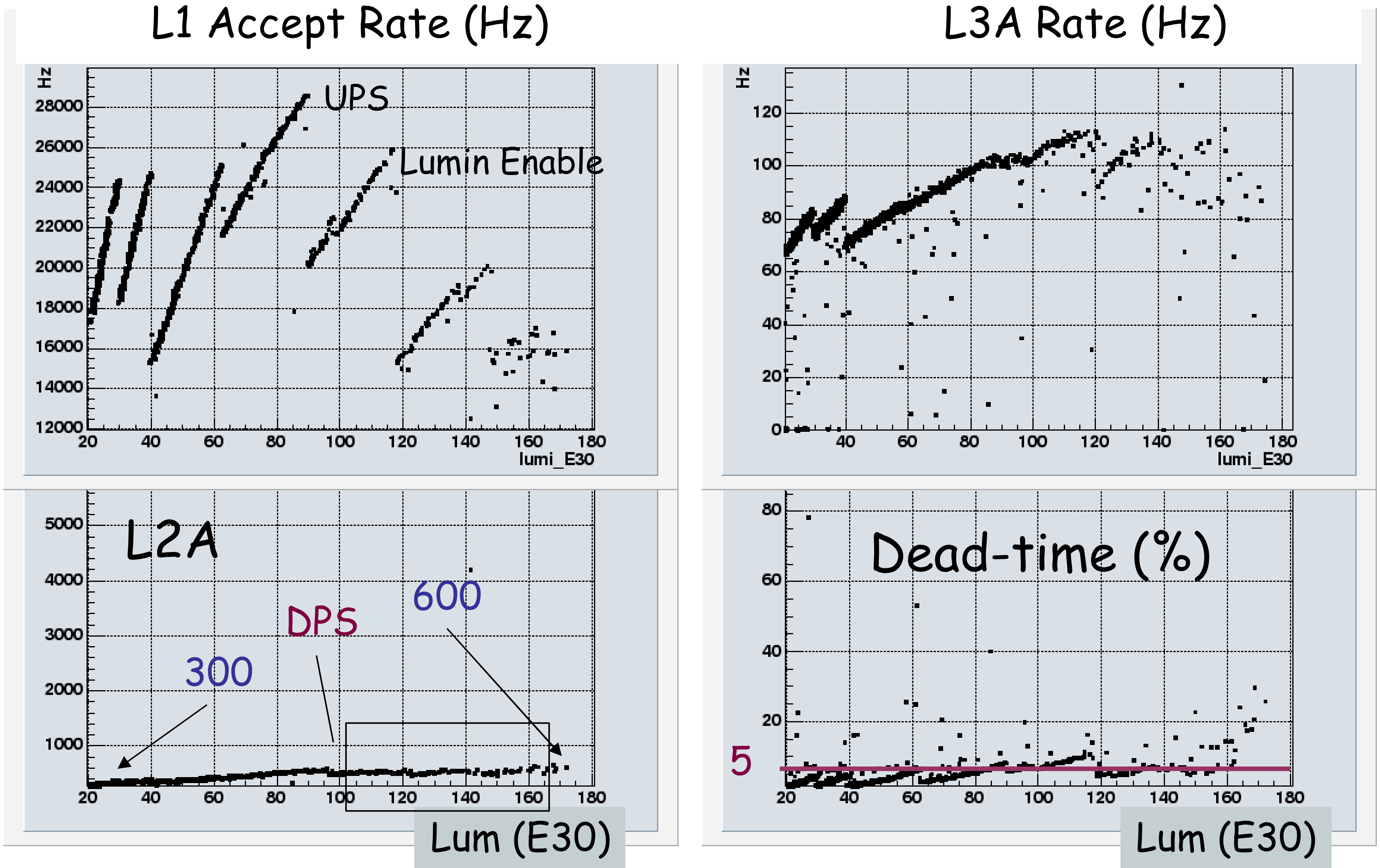

| 2006 | L1 | L2 | L3* |
|---|---|---|---|
| Triggers | 56 | 131 | 185 |
| Max In/Out (Hz) | 1.7M/ 35k | 600 | ~100 |

* L3 means Trigger paths

<Dead-time> ~5%

Collaboration Effort !

## Feb 2006 (run 211554-Online plots)




# 1.3fb$^{-1}$ data on tape to analyze !

# Summary

- Trigger is very important and interesting at hadron colliders
- Trigger is also very challenging, make it even more interesting
- One of the best places for young physicists to get trained on large experiment

Be a trigger person, Join the fun !!!

# Top Charge Measurement at CDF

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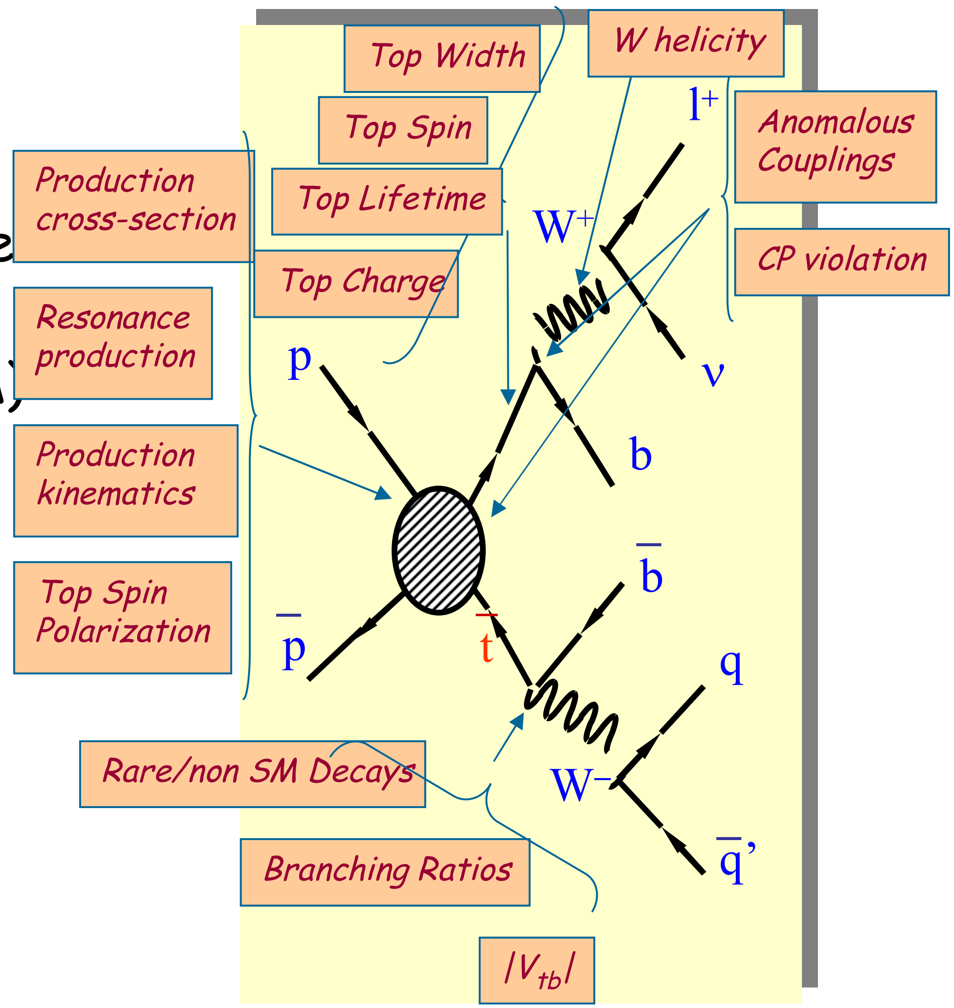
Experimental Particle Physics Seminar
April 25, 2006

# Top Properties
## Why top charge?

Since discovery, many efforts to measure properties (mass, cross section, …)

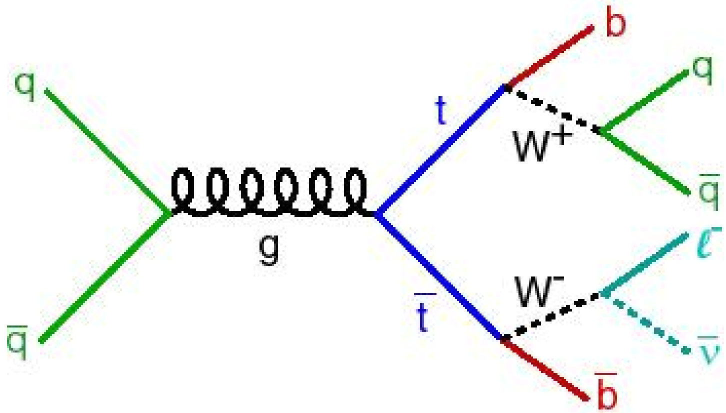
- Not yet measured electric charge at CDF
- Is it +2/3 as standard model (SM) predicts?
- Is there an alternative?
  - exotic quark of charge Q= -4/3
  - top mass predicted at $m_t$ ~274GeV/c$^2$




*hep-ph/9810531, hep-ph/9909537

hep-ph/0106341

# Top production and decay




➢At Tevatron, top quarks are primarily produced in pairs

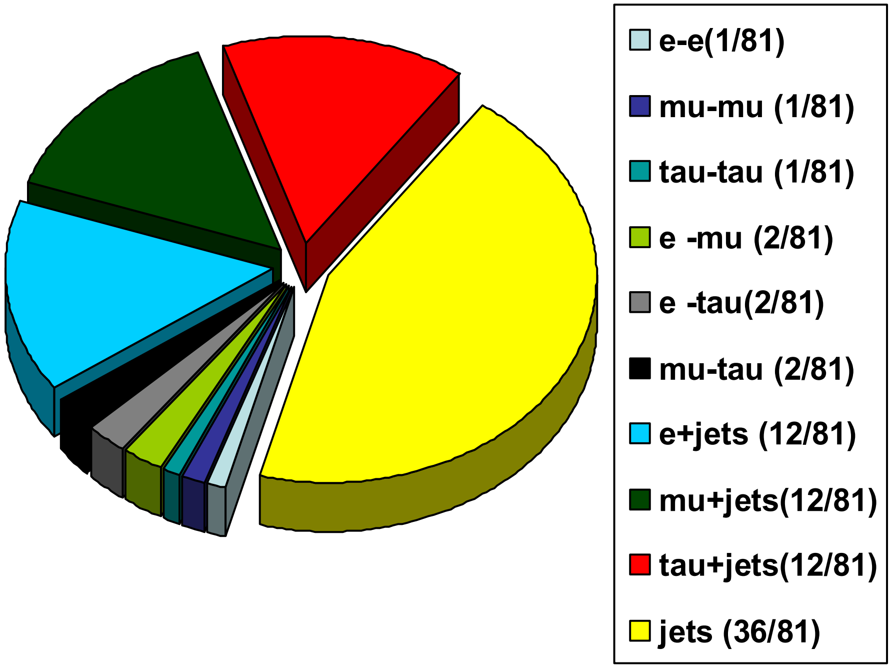
$$\sigma(\bar{p}p \rightarrow t\bar{t} \ @ \ M_{top} = 175 GeV) \approx 6.7 \text{ pb}$$

**One top pair per $10^{10}$ inelastic collisions !!**

## Top Decay

**t→Wb ~ 100%**
**2 b jets**
**Final state determined by W decay**

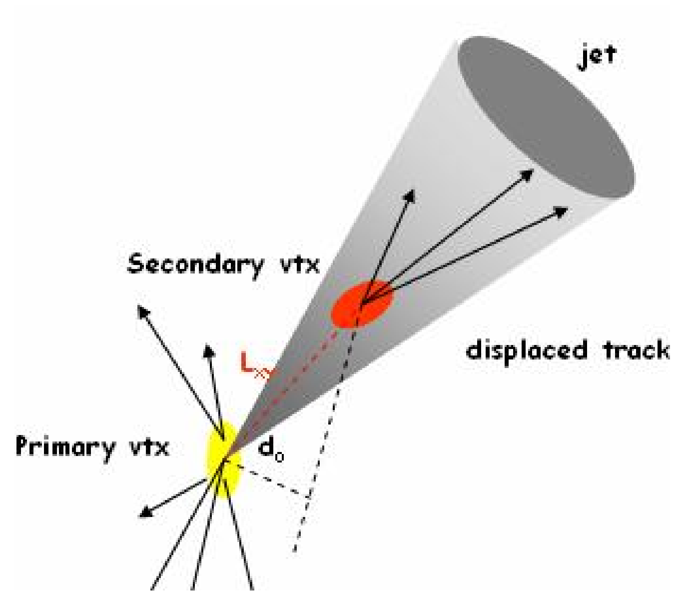
**Dilepton:**
Both W's decay via W→lν (l=e or μ, 5%)
**Lepton+jets:**
One W decays via W→lν (l=e or μ, 30%)
**All hadronic:**
Both W's decay via W→qq (44%)



# Event Selection

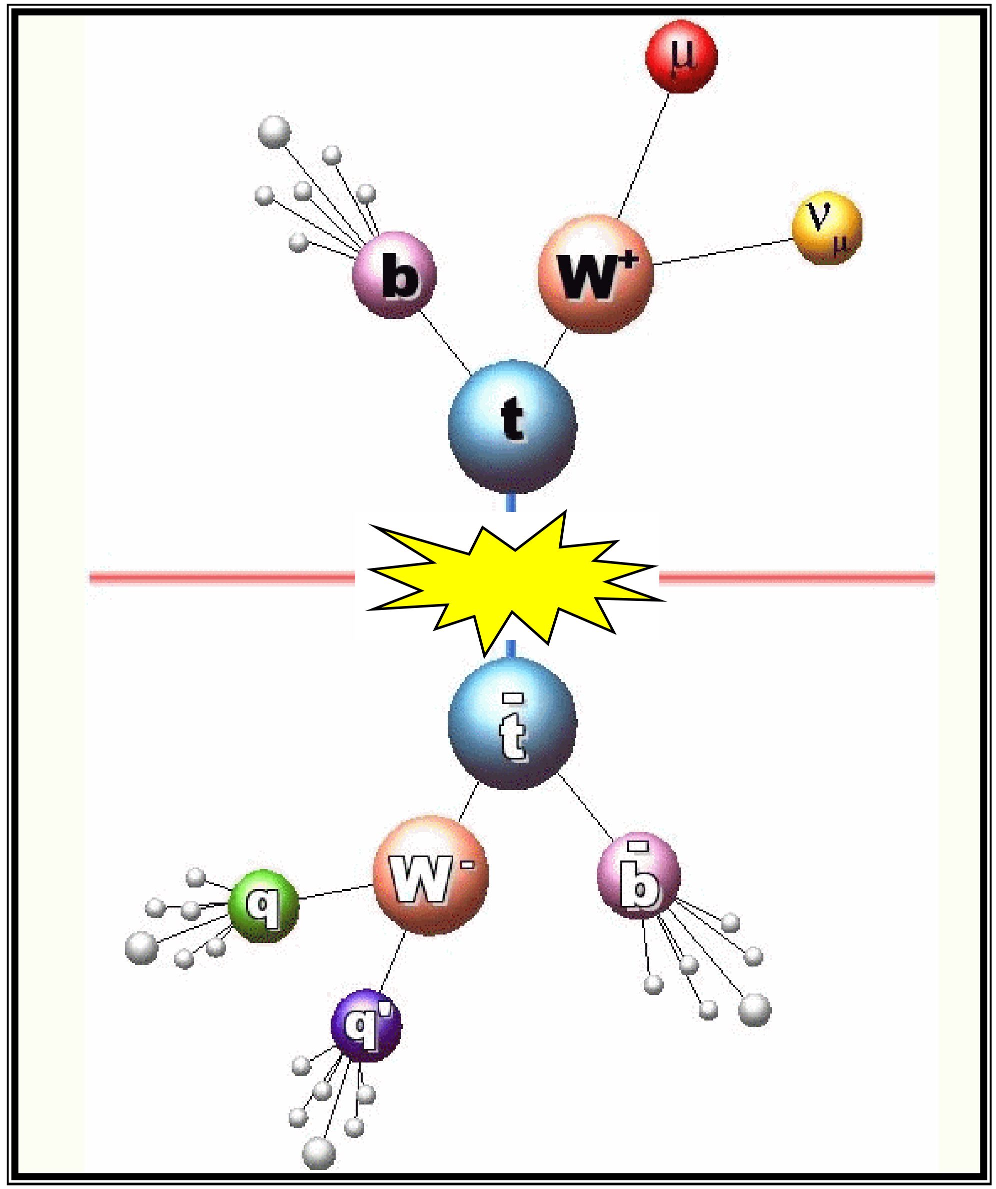
- Use data collected by looking for central electron and muons
- Use Dilepton and Lepton + jets final states.
  - DIL: 2 leptons Et>20 GeV, 2 jets Et>15 GeV (basic selection)
  - L+J: leton Et>20GeV, 4 jets Et>15GeV (basic selection)
  - What about the b jets on the event !?
  - find those jets using a secondary vertex algorithm:
    - b quarks are long lived
    - Can be "tagged" by looking for the decay vertex
    - Find displaced tracks in jet (cone 0.4)
  - Efficiency ~50% (loose tagger)
  - Wrong assignment (mistags) ~1%

Only used for L+J case



# Measuring the sign of the top charge

- If what we observed is an exotic quark of Q=-4/3 :
  - Expect $W^-b$ instead of $W^+b$
- What do we need?:
  - Charge of W (charge of lepton)
  - Assignment of b jet to the W
  - Flavor of b jet (is it a b or anti-b?)



# Method and performance

- Let's define:
  - $N^+$ = # events assigned as $W^+b$ and $N^-$ = # events assigned as $W^-b$
  - Asymmetry (A) :

$$A = \frac{N^+ - N^-}{N^+ + N^-}$$

- But paring and flavor tagging mismeasurement distort the assignment of $N^+$ or $N^-$

$$\text{Purity } P = \frac{N_{Right}}{N_{Right} + N_{Wrong}}$$

$N_{Right}$ : # correctly assigned events

$$\text{Dilution } D = \frac{N_{Right} - N_{Wrong}}{N_{Right} + N_{Wrong}} \quad , \quad D = 2P - 1$$

- Relation between "true" asymmetry and the measured one:

$$A_{true} = \frac{A_{meas}}{D}$$

- And the uncertainty on $A_{true}$ :

$$\sigma_A \propto 1 \Big/ \sqrt{\left(\varepsilon D^2 N\right)}$$

$\varepsilon$: efficiency
of the various applied selection criterion

Need to optimize $\varepsilon D^2$ !!!!

# Reconstructing the event

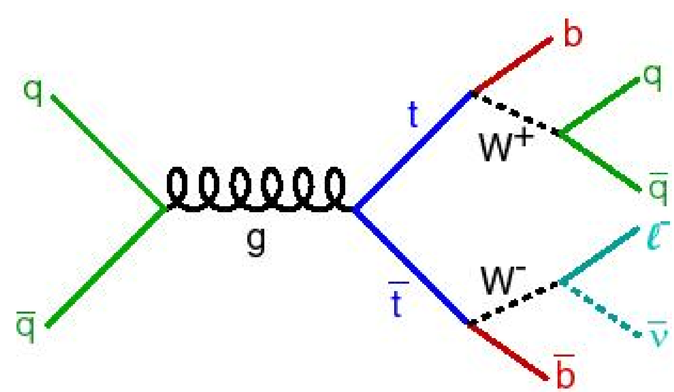
## Lepton + jets

Kinematic fitter :

- Using kinematic information, $\chi^2$ fitter $\rightarrow$ assign jets to partons
- 4 jets events $\rightarrow$ 12 jet-parton assignment
- By requiring 2 b tagged jets $\rightarrow$ only 2 combinations
  ( improve also Signal to Background ratio )
- Select assignment with smallest $\chi^2$
- Optimized by requiring events with $\chi^2 < 9$.
  (same cut used by top mass analysis)

$\varepsilon$=57%  P=82%  $\varepsilon D^2$=0.24

(Signal MC)

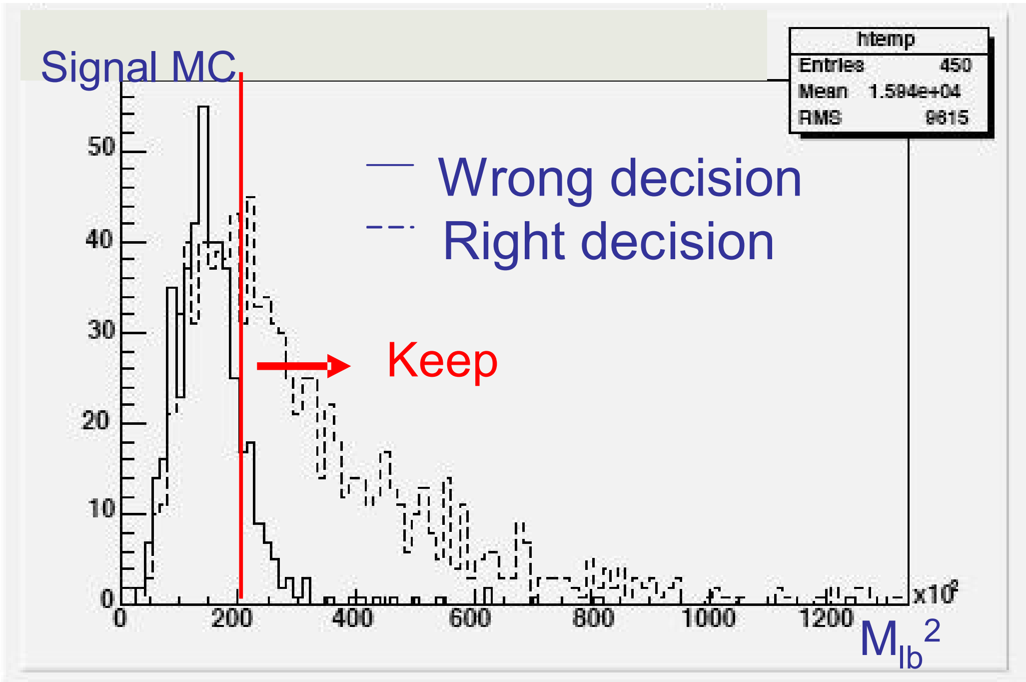


# Dilepton

- Assign b jets to the 2 most energetic jets
- Determine invariant mass lepton-bjet ($M_{lb}$)
- 2 combinations, 4 $M_{lb}$ values
- Select events with $M_{lb}^2 > 22000\ GeV/c^2$
- And used the combination that do not include $M_{lb\ max}$

$\varepsilon$=40% P=94% $\varepsilon D^2$=0.31

(Signal MC)



# B Flavor Tagging

- Is it b or anti-b? Correlation with b-jet charge?

Used momentum weighted charge of associated tracks

$$JetQ = \frac{\sum_i q_i (\hat{n} \cdot \vec{p}_i)^w}{\sum_i (\hat{n} \cdot \vec{p}_i)^w}$$

$\hat{n}$ : *jet axis*

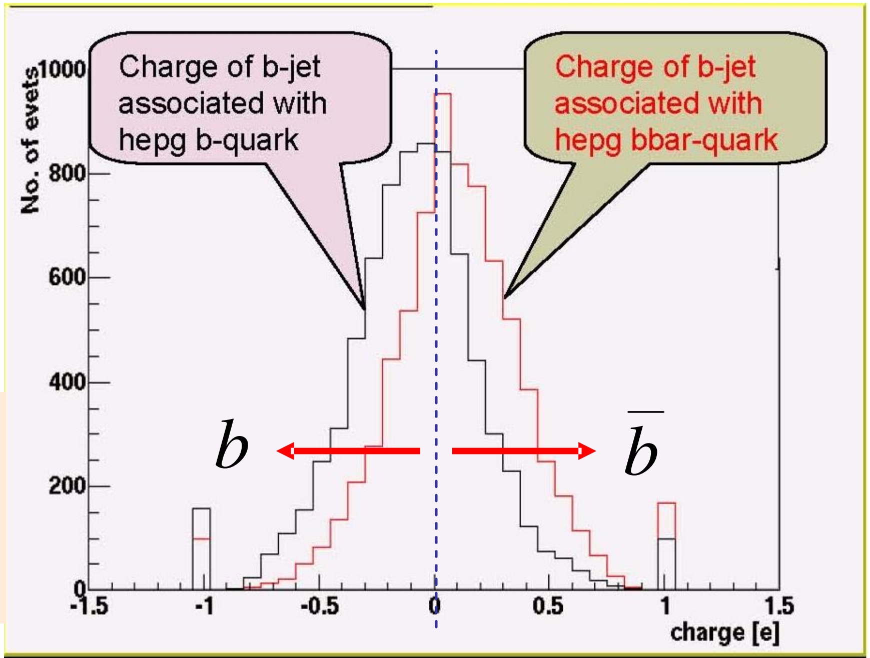
$\vec{p}$ : *track momentum*

**Optimized with:**

$w$ = 0.5

$p_T$ > 0.5 *GeV*

Highest 10 $p_T$ tracks




- Requiring Opposite sign between b jets.

Dilepton: ε=49% P=73% εD²=0.1 (Signal MC)

Lepton+jets: ε=53% P=74% εD²=0.13

# Background studies

- Some events are not "top" but "look" like it
- Studied same backgrounds than other top analyses
- But not only need number of them:

are they more likely to mimic +2/3 or -4/3 events? ⟺ Is the fraction of $N^+$ events ($f^+$) 50% ?

| Lepton + jets : 26 events after eff. (signal, scaled to 1fb$^{-1}$) | | | |
|---|---|---|---|
| Background | Expected # of events | $N_B/N_T$ (%) | Fraction $f^+$ |
| W+HF | 2.7 | 22 | 0.52±0.01 |
| QCD | | 31 | |
| Diboson | | 2 | |
| Mistags | | 40 | |
| Single Top | | 5 | |
| **Dilepton : 9.4 events after eff. (signal, scaled to 1fb$^{-1}$)** | | | |
| Drell-Yan | 6.4 | 70 | 0.5 |
| Fakes | | 22 | |
| Diboson | | 8 | |

# Sensitivity studies

- Use Profile Likelihood (eliminate dependence on nuisance parameters) $\rightarrow$ function of $f^{+}$ (fraction of 2/3 assigned events).
- How likely is the data consistent with the SM (%CL)?
- Studies showed strong dependence on purity of data ($p_s$)
- Weak dependence on number and asymmetry of background

Need to do a good job measuring $p_s$ !

# Summary

- Have developed and optimized a method to determine top charge for first time at CDF.
- Studied backgrounds and sensitivity
- Working on precise measurement of purity on data and studying systematics
- Plan to have a result for $1fb^{-1}$ for summer conferences

# Backup

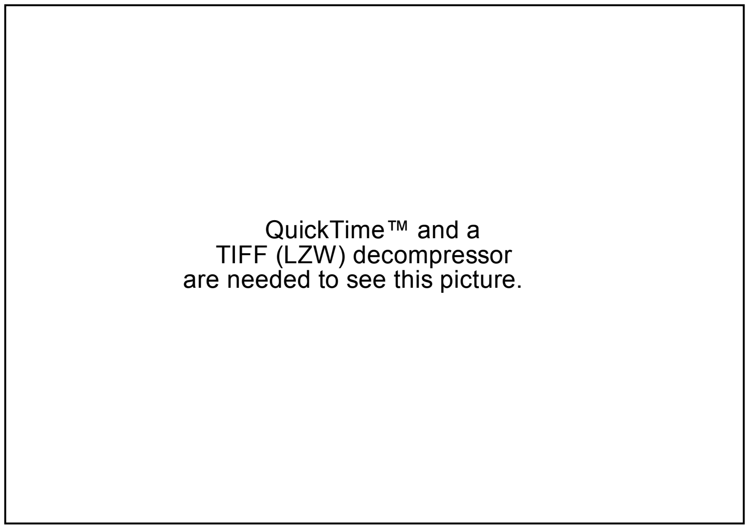
# Statistical Treatment

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Z. Gunay's talk
APS

# Purity on Data




- Double tagged events
- Look for semileptonically decay (muon)
- Jet Charge applied on away jet
- Get number of Opposite Sign (OS) events where $Q_{away}\, Q\mu < 0$

Correct for:

- $B \rightarrow c \rightarrow \mu$
- Mixing
- Background (use $Pt_{rel}$ to cut or fit)

Give same sign (SS) events