Physics at the Tevatron Collider: Lecture #1

Darien Wood

Northeastern University

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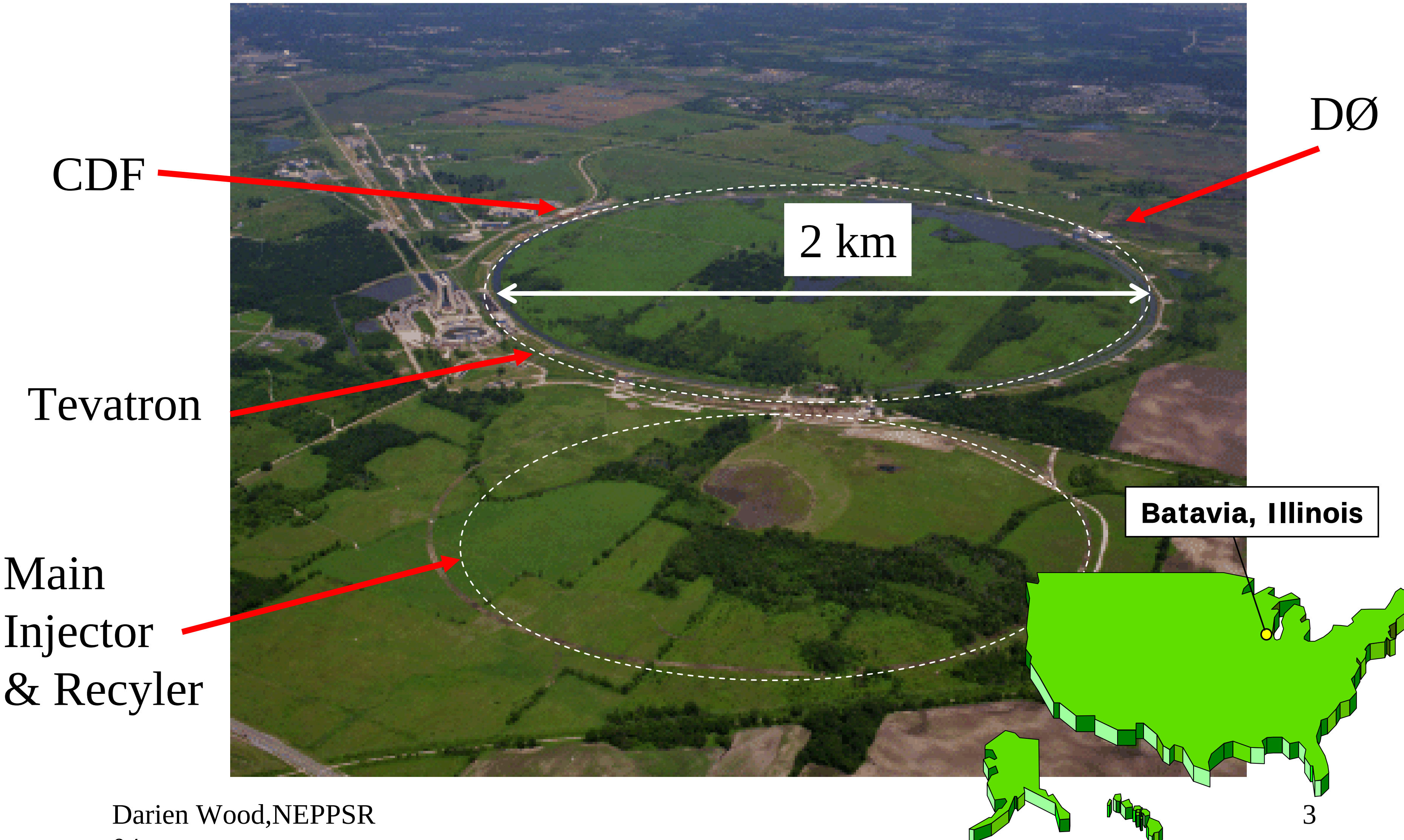
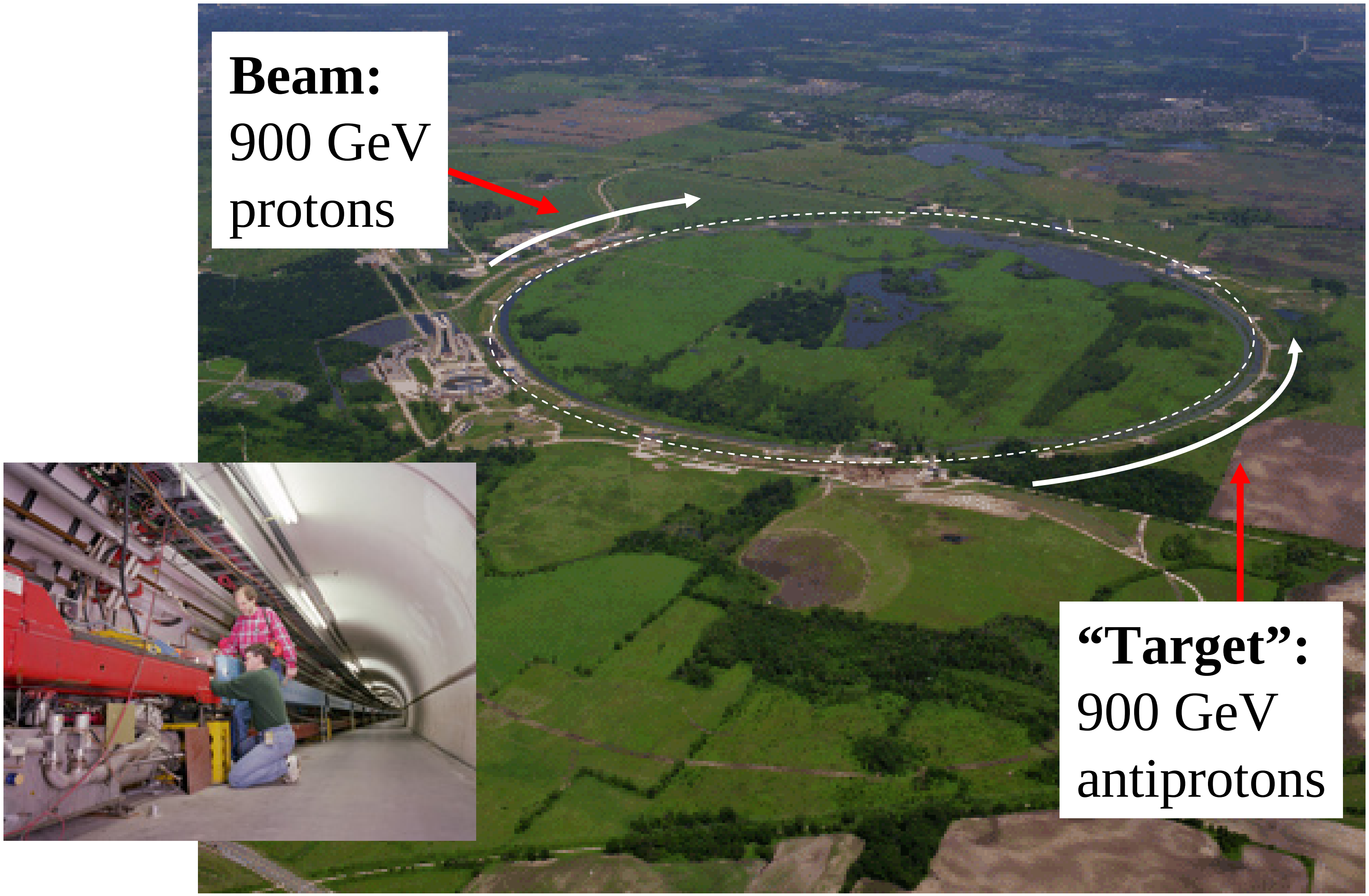
Lecture #1

- Quick tour of the Tevatron
- Basics of hadron collisions
  - Partons and parton distribution functions
  - Kinematic variables
  - Cross sections and rates of important processes
- Motivating example: top quark physics
- Generic measurement and identification of objects
  - Jets
  - electrons, photons, hadrons, muons, neutrinos
- CDF and DØ detectors
  - electrons and photons
  - muons
  - missing transverse energy
  - b-tagging
  - triggering

Tevatron Collider: Fermilab

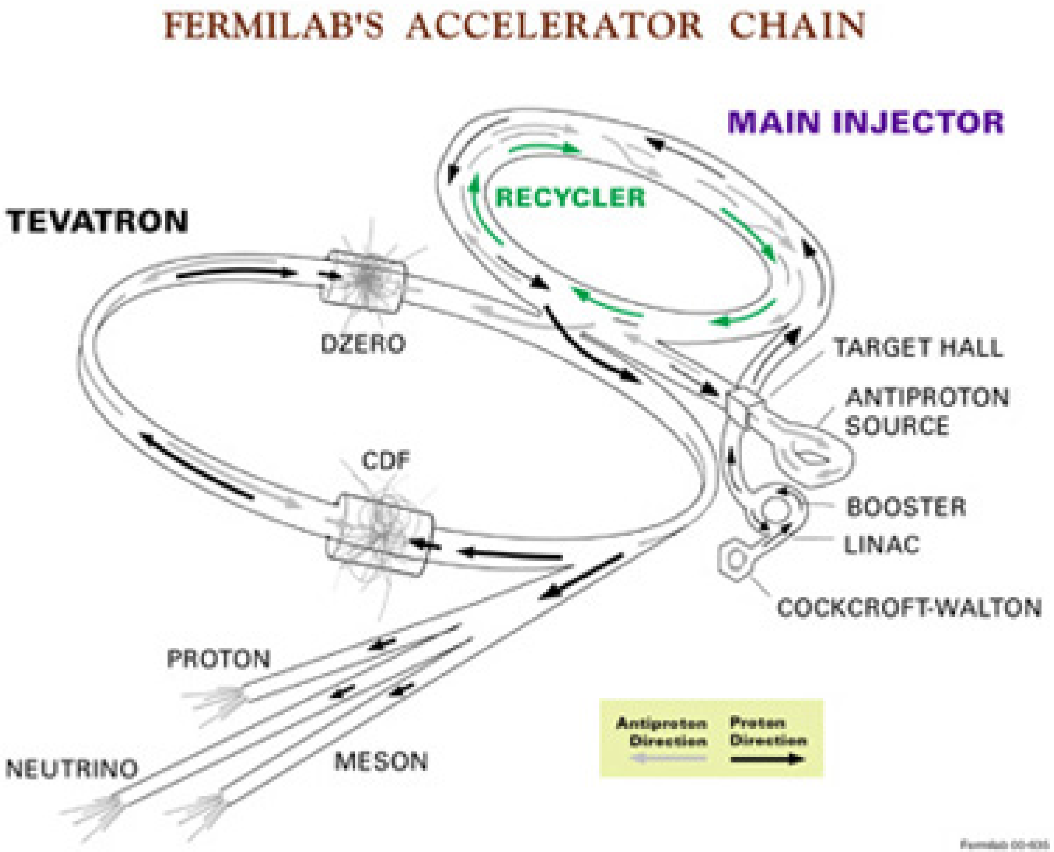


Tevatron Collider



Collision energy = 1.8 TeV

Antiprotons

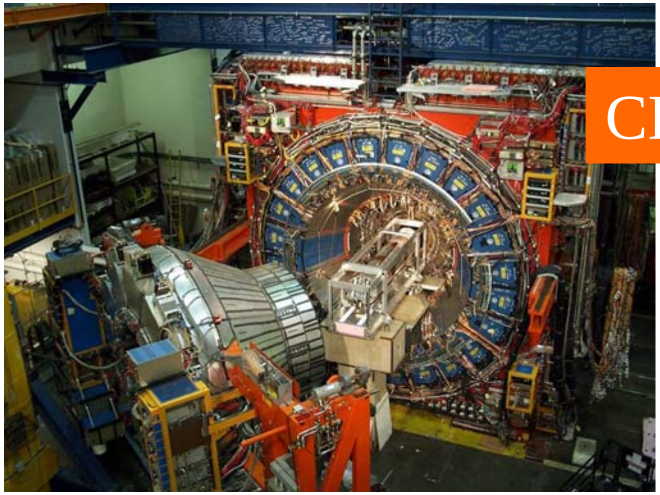


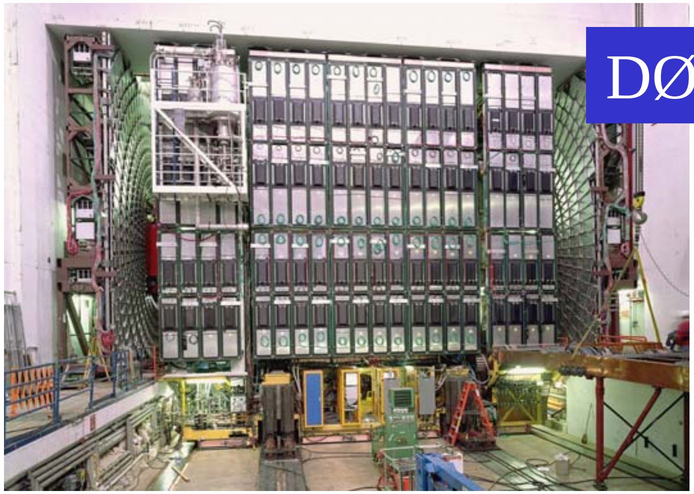
Antiprotons are created in collisions of the proton beam with a nickel target, then collected,
cooled, and stored.

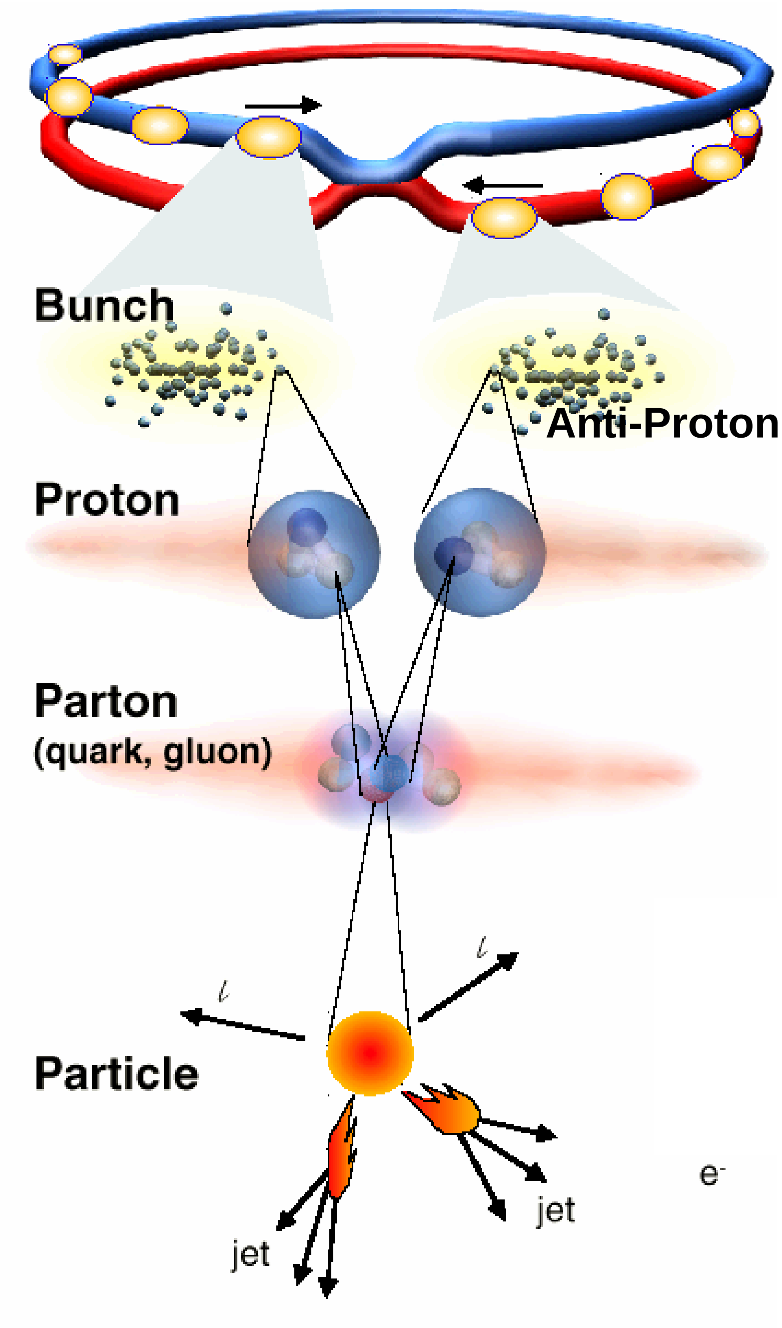
~2x10^{12} antiprotons stored

The Detectors

- Much more discussion later
- Important features to keep in mind for now
  - Collisions take place at the (approximate) center of the detectors
  - Detectors must have apertures in the forward and backward directions for the beams to enter and exit
  - Detectors try to measure momentum and or energy of particles produced in collison







Tevatron in #'s

Tevatron parameters (2003):

Proton Anti-proton 36x36 bunches

Protons/bunch 10^{11}
Anti-protons/bunch 10^{10}

Beam Energy 0.98 TeV/beam

Luminosity $\sim10^{32}$ cm^{-2} s^{-1}

bunch crossing time 396 ns

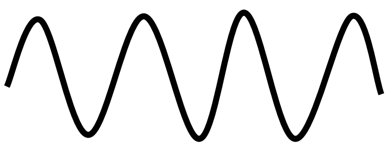
Collision Rate 2.5 MHz

Brief History of the Tevatron Collider

- 1983: Tevatron accelerator began operations
- 1985: First collisions of the Tevatron Collider
- 1986-1989: "Run 0" of the collider
  - Center-of-mass energy: 1.8 TeV
  - Integrated luminosity ~4.5 pb^{-1}
  - CDF detector only
- 1992-1996: "Run I" of the collider
  - 1.8 TeV
  - Integrated luminosity ~100 pb^{-1}
  - Both CDF and DØ detectors
  - Top quark discovery
- 2001-present: "Run II"
  - 1.96 TeV
  - Upgraded CDF and DØ detectors
  - Integrated luminosity ~500 pb^{-1} so far…
  - Anticipate 4-8 fb^{-1} by the end of Run II (~2009)

Hadron collisions

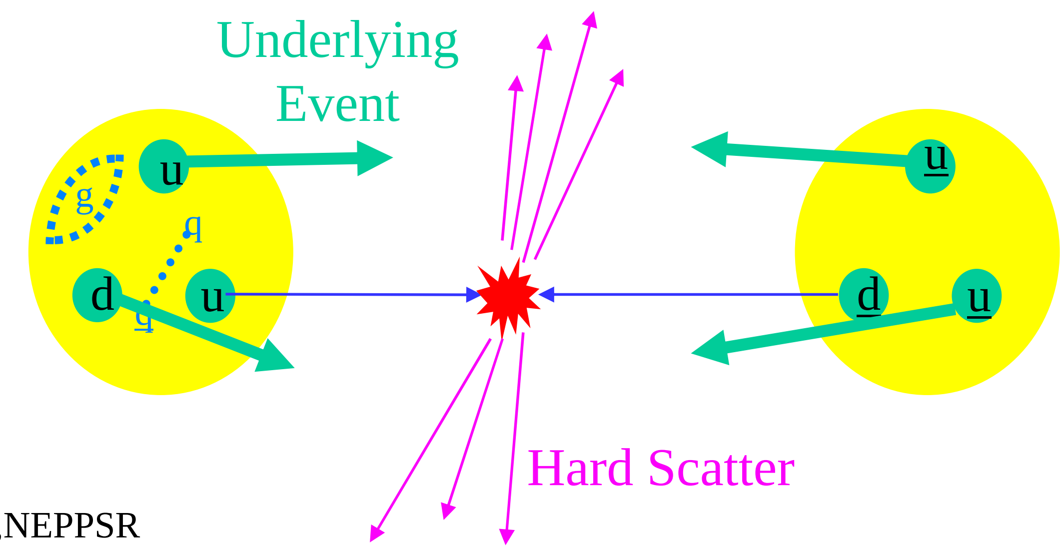
(too) Simple minded calculation: deBroglie wavelength of proton



$$\lambda = \frac{hc}{pc} = \frac{1.2\text{GeV}\cdot\text{fm}}{980\text{GeV}} \approx 10^{-18}\,\text{m}$$

Much smaller than the size of a (anti)proton (~10^{-15}m)

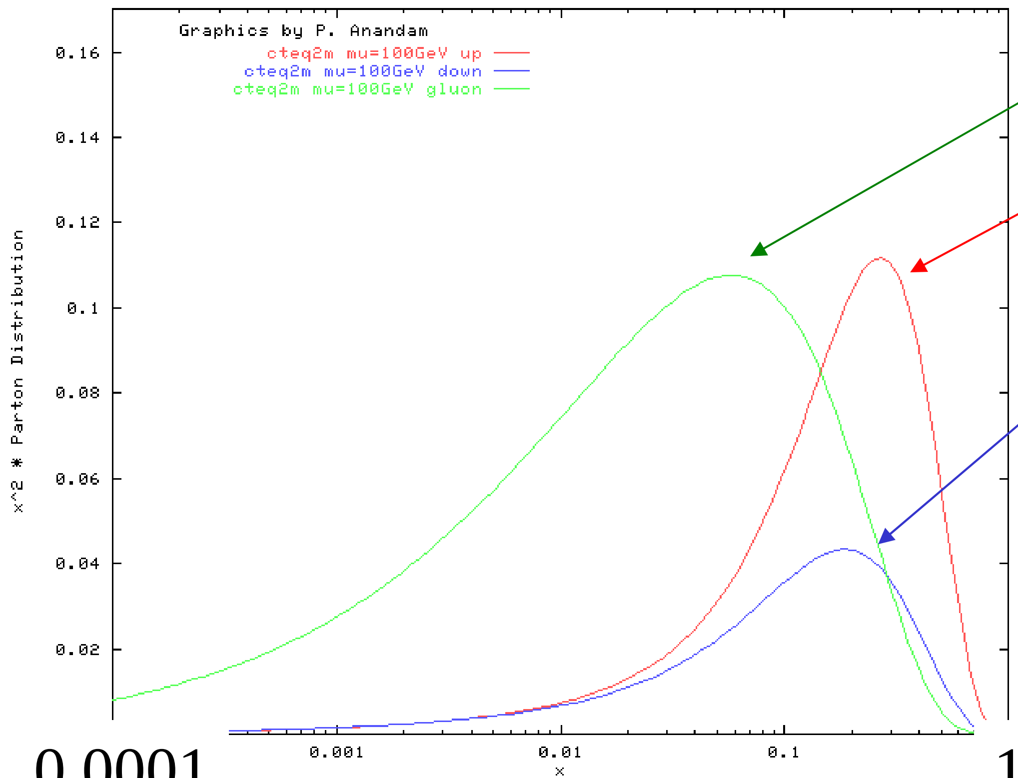
⇒hard scatter involves only one parton (q,g) from each



Parton distribution functions

- Probability of finding a parton (quark or gluon) with a fraction *x* of the (anti)proton's momentum is given by the pdf, $f(x,Q^2)$ for a momentum scale Q

x^2*pdf



gluon

up

down

(on a log scale area under x^2*pdf shows momentum fraction)

0.0001

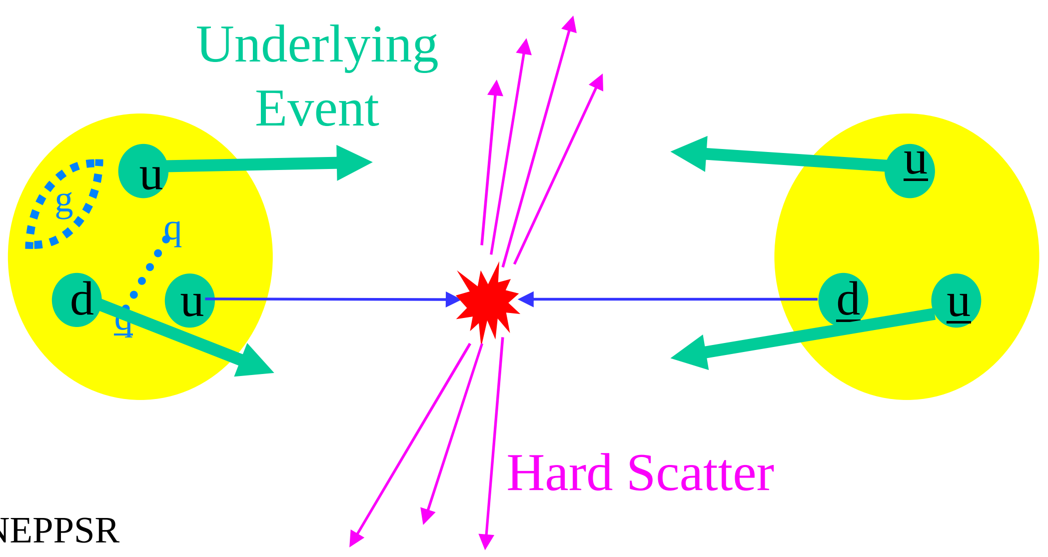
1

Log scale

From website zebu.oregon.edu/~parton/partongraph.html

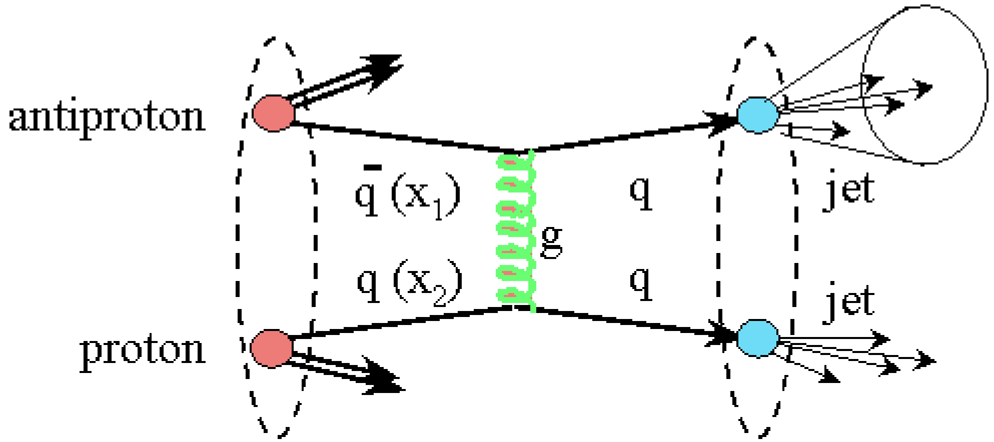
Hadron collisions: experimental consequences

- Energy involved in “hard scatter” is less (typically <10%) than the full proton-antiproton center-of-mass energy
- “hard scatter” system is generally
  - Not at rest along the beam direction $\sum p_z \neq 0$
  - Nearly at rest transverse to the beam direction $\sum \vec{p}_T \approx 0$
- Additional particles & energy are present from the “underlying event”



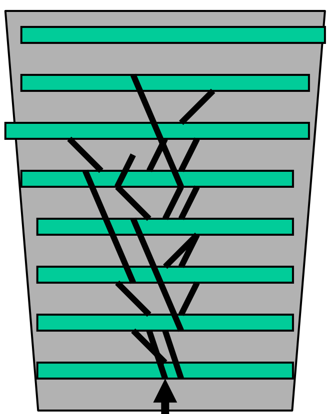
Most common high-pt process: jet production

Quarks are not free, so what emerges is a collimated jet of hadrons along the original quark or gluon direction



As seen by the calorimeter:

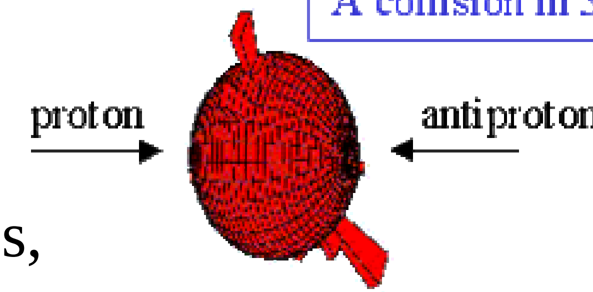
A single calorimeter cell



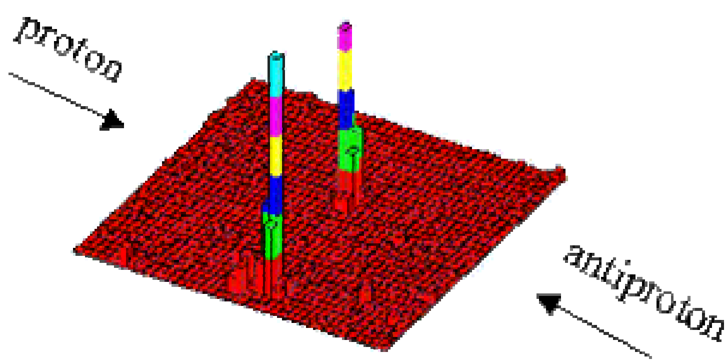
DØ: Uranium plates, with liquid Argon in the gaps

CDF: Iron plates with plastic scintillator in the gaps

A collision in 3D



The same collision in 2D



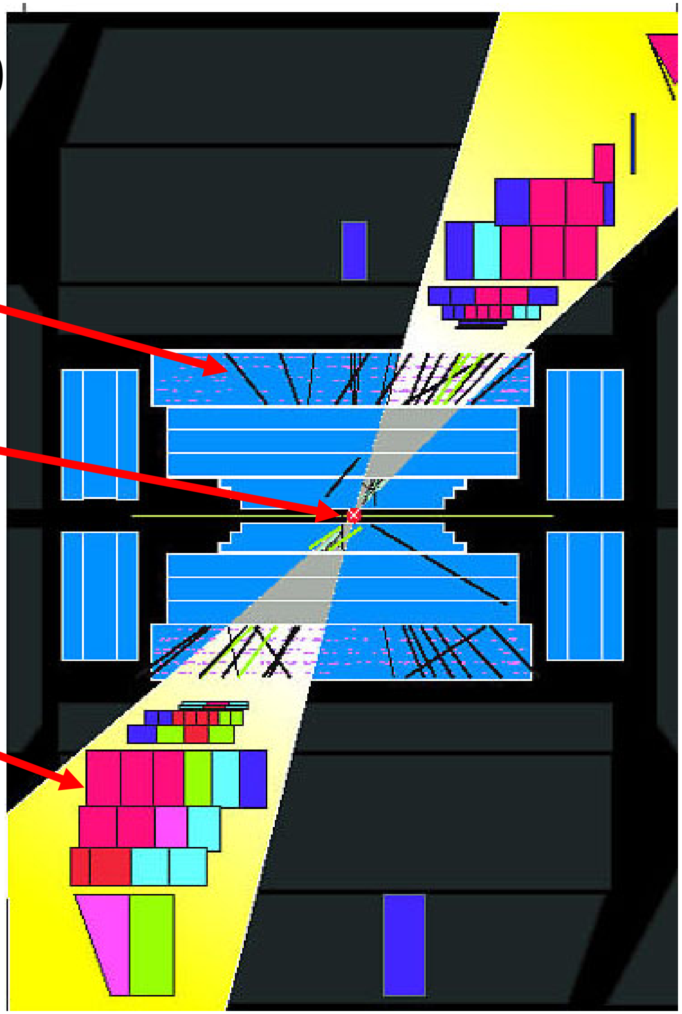
An event observed in the detector:

(2-dimensional slice)

Charged tracks

Point of collision

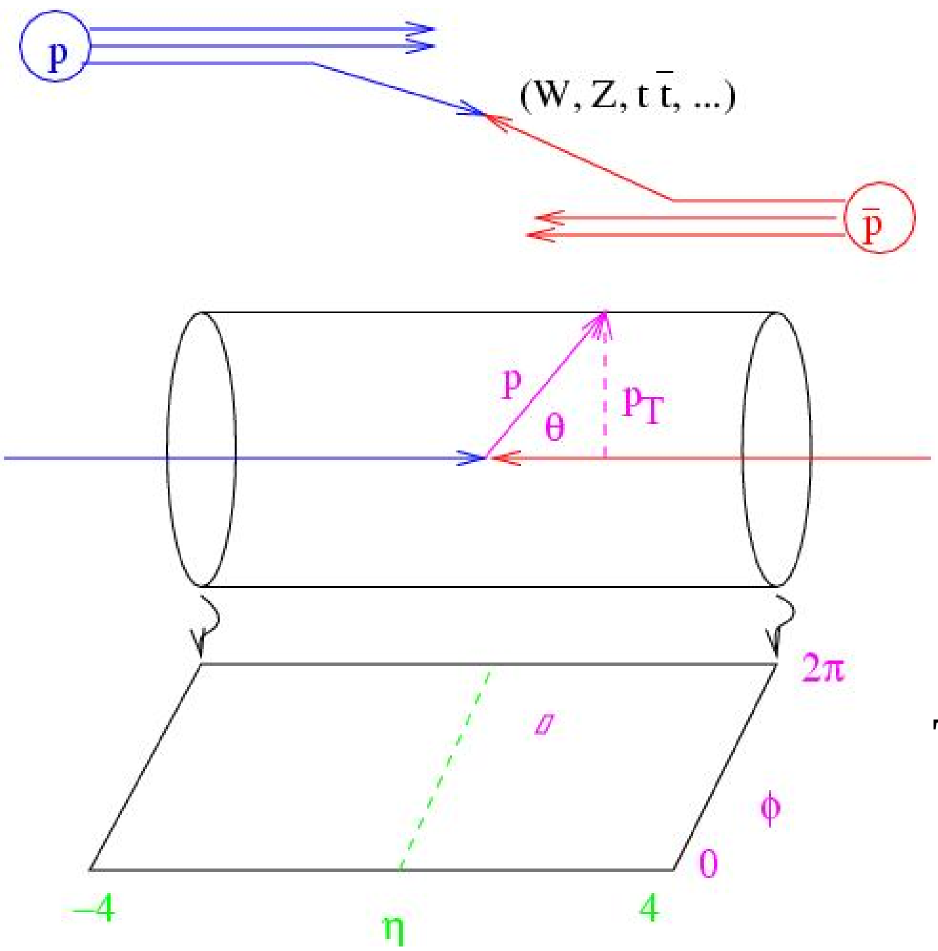
Colors correspond to energy deposited in a “cell” of the calorimeter



Note that energy is concentrated in two narrow cones, or jets.

“Simple cone algorithm”: sum all energy in a cone around jet axis

Coordinate system



Beam axis : z

Azimuth: φ

Rapidity:

$$y = \frac{1}{2}\ln\left(\frac{E + p_z}{E - p_z}\right)$$

pseudorapidity:

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

Transverse momentum:

$$p_T = p\sin\theta = \sqrt{p_x^2 + p_y^2}$$

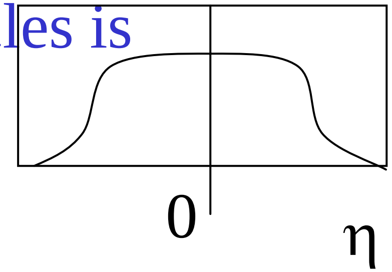
Phase space variables: eta, phi, and p_T

- Recall that the hard scatter system is generally in motion in the z-direction with respect to the laboratory frame
- Under a boost in the z-direction:
  - p_T is invariant
  - ϕ is invariant
  - Rapidity itself is not invariant, but all differences in rapidity are invariant

$$y \rightarrow y - \tanh^{-1} \beta$$

$$y_1 - y_2 \rightarrow y_1 - y_2$$

- At a given p_T, the expected density of particles is (approximately) uniform in eta and phi.
  - In contrast to e+e$^-$, where $\cos\theta$ is flat

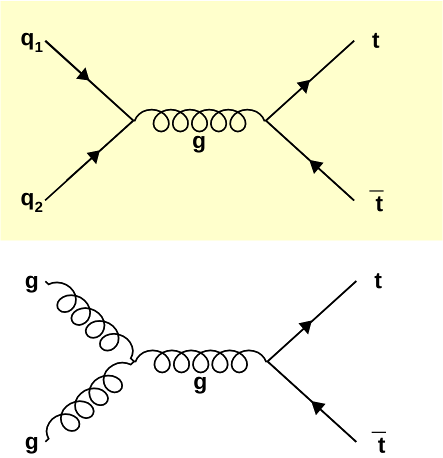


Typical production rates for p-pbar at 2 TeV

Final state	Cross section (pb)	Rate at L=10^{32} $cm^{-2}s^{-1}$
"minimum bias"	$4x10^{10}$	4 MHz
2 jets	$4x10^{6}$	400 Hz
4 jets	$1.6x10^{5}$	16 Hz
6 jets	6000	0.6 Hz
W	30000	3 Hz
Z	9000	0.9 Hz
WZ	3.5	$3.5x10^{-4}$ Hz (1.3/hour)
t tbar	**7.5**	**$7.5x10^{-4}$ Hz (3/hour)**

Top quark production and decay

- in proton anti-proton collisions at Tevatron energies, top quarks are primarily produced in pairs (Strong interactions)



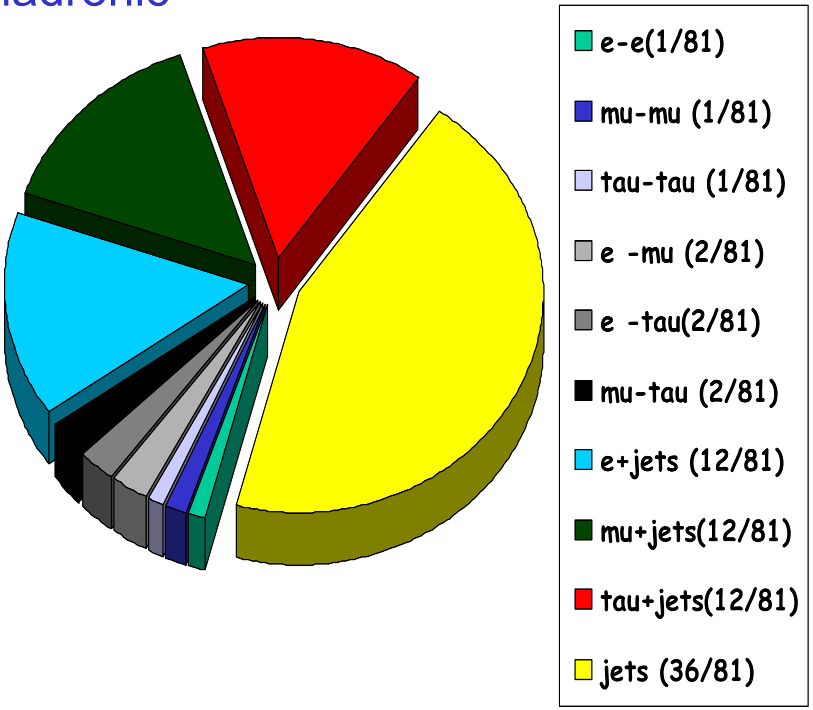
Single top production (Electroweak interactions): not yet observed

- lifetime very short ($\approx 10^{-24}$s), Br($t \rightarrow Wb$)=100%

  Both W's decay via $W \rightarrow l\nu$ (l=e or μ; 5%)
  dilepton

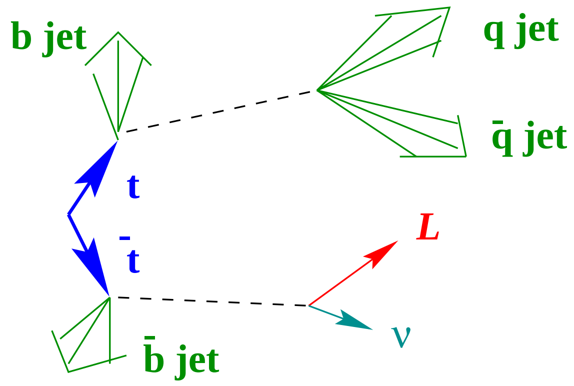
  One W decays via $W \rightarrow l\nu$ (l=e or μ; 30%)
  lepton+jets

  Both W's decay via $W \rightarrow qq$ (44%)
  all hadronic

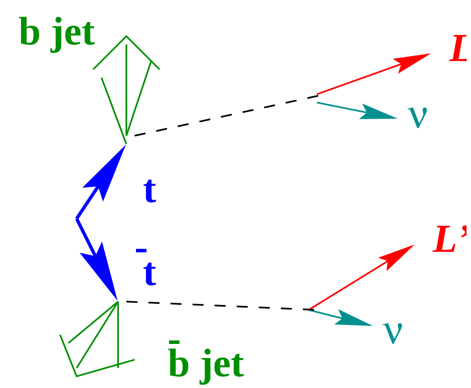


Top quark

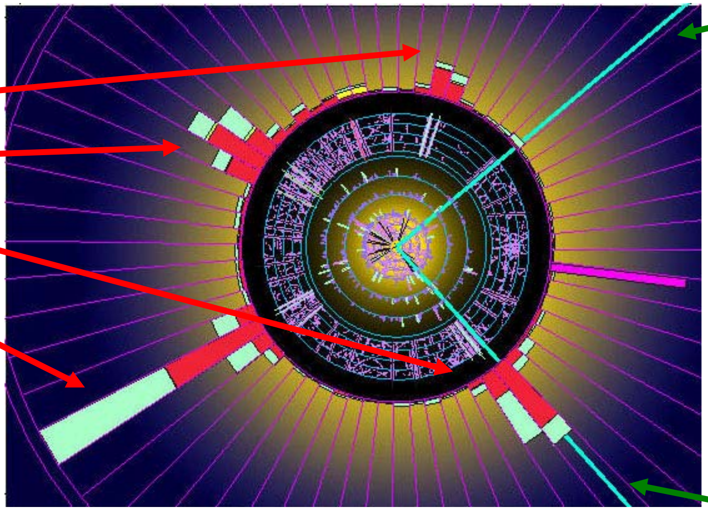
lepton+jets



dilepton



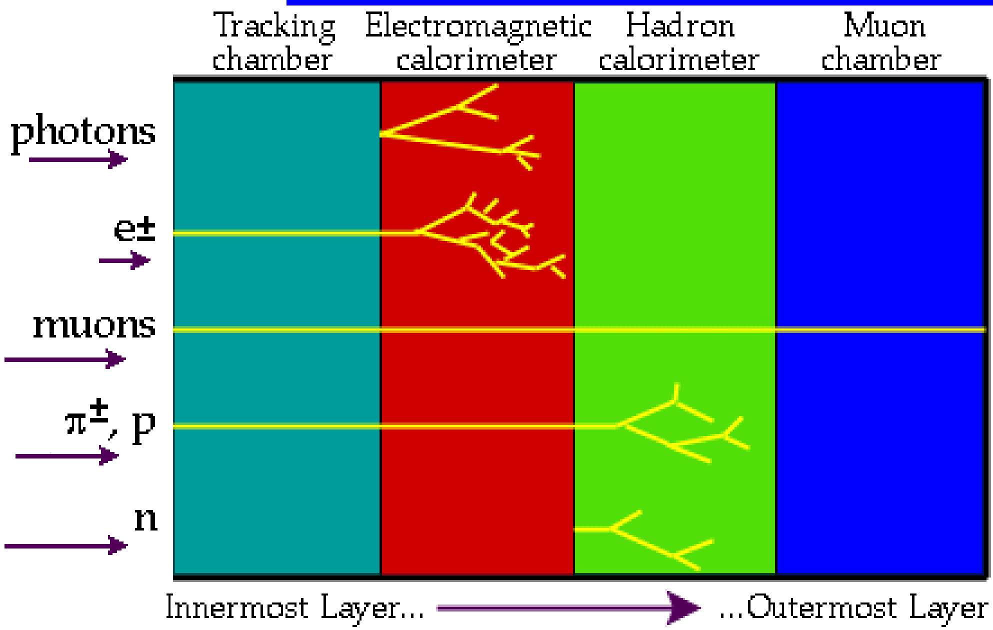
Uses all parts of the detector

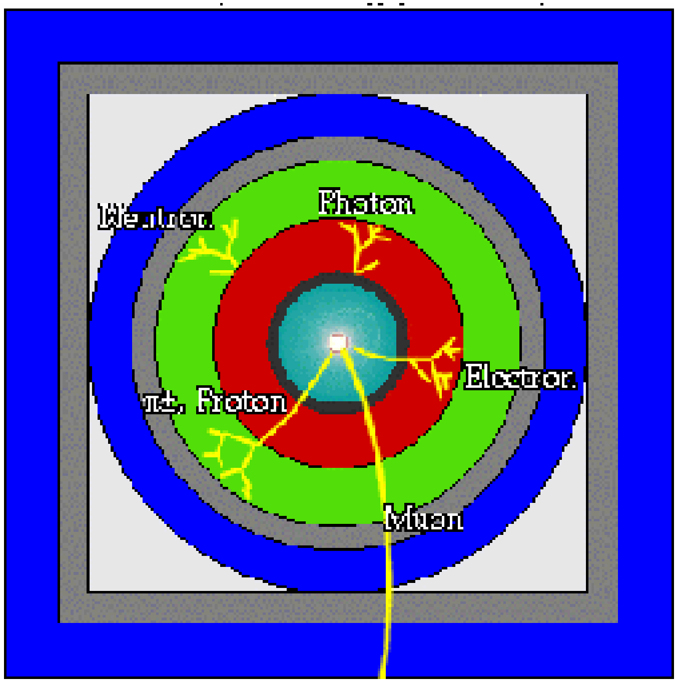


Hadron collider detector principles

- Strong interaction dominates
  - Typically ~20 charged tracks per event, mostly pions
  - Not easy to distinguish among various light hadrons (pions, kaons, …) but often you don't care
  - Isolated leptons are a signature of something interesting and or unusual
    - EM or weak interaction
    - Decay of heavy object
- Basic distinguishable objects: jets, photons, electrons, muons, (taus), neutrinos
- Often useful to be able to separate jets from heavy quarks (b-jets, c-jets) from those from light quarks and gluons

A Generic Detector System





Tracking chambers ⇒ trajectory of charged particles
Calorimeters ⇒ measure energy
Electromagnetic: e, photon
Hadronic: pion, K, proton,neutrons…
Muon Chambers ⇒ measure muon trajectory
Magnets ⇒ charged particles bend in magnetic fields. Bend depends on charge and momentum

what's missing?

Calorimeter Wish list

An ideal calorimeter should:

- measure the **energy** of each particle coming into it (except muons and neutrinos) with good **resolution**
- measure the **position** of the energy deposition, so that it can be associated with a momentum vector
- be able to **distinguish** different types of particle from each other by the way they "shower" inside the calorimeter
  - electrons & photons
  - hadrons (protons, pions, kaons, etc.) or jets of hadrons
  - muons
  - neutrinos

Wish list continued

- completely **contain** all particles (except muons and neutrinos) [“hermeticity”]
- have a constant, stable energy **calibration**
- have the **same** energy response for hadrons and electrons
- have a fine **segmentation** to be able to distinguish nearby particles (also important in being able to examine the transverse size of a shower)

DØ detector

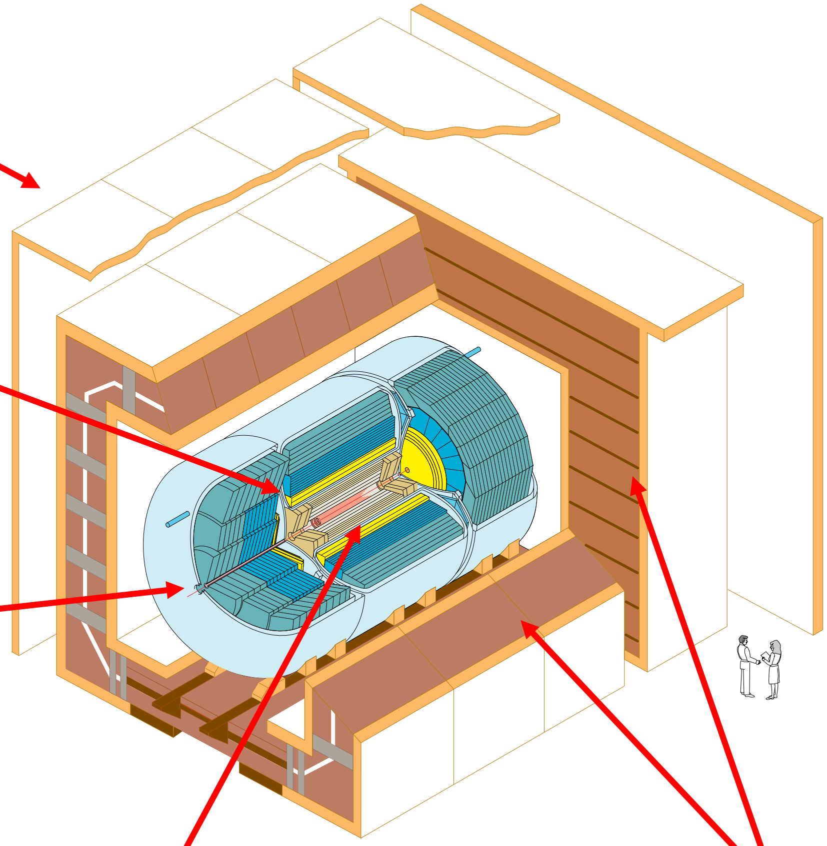
Muon Spectrometer

Solenoid magnet

Uranium/Liquid Argon Calorimeter

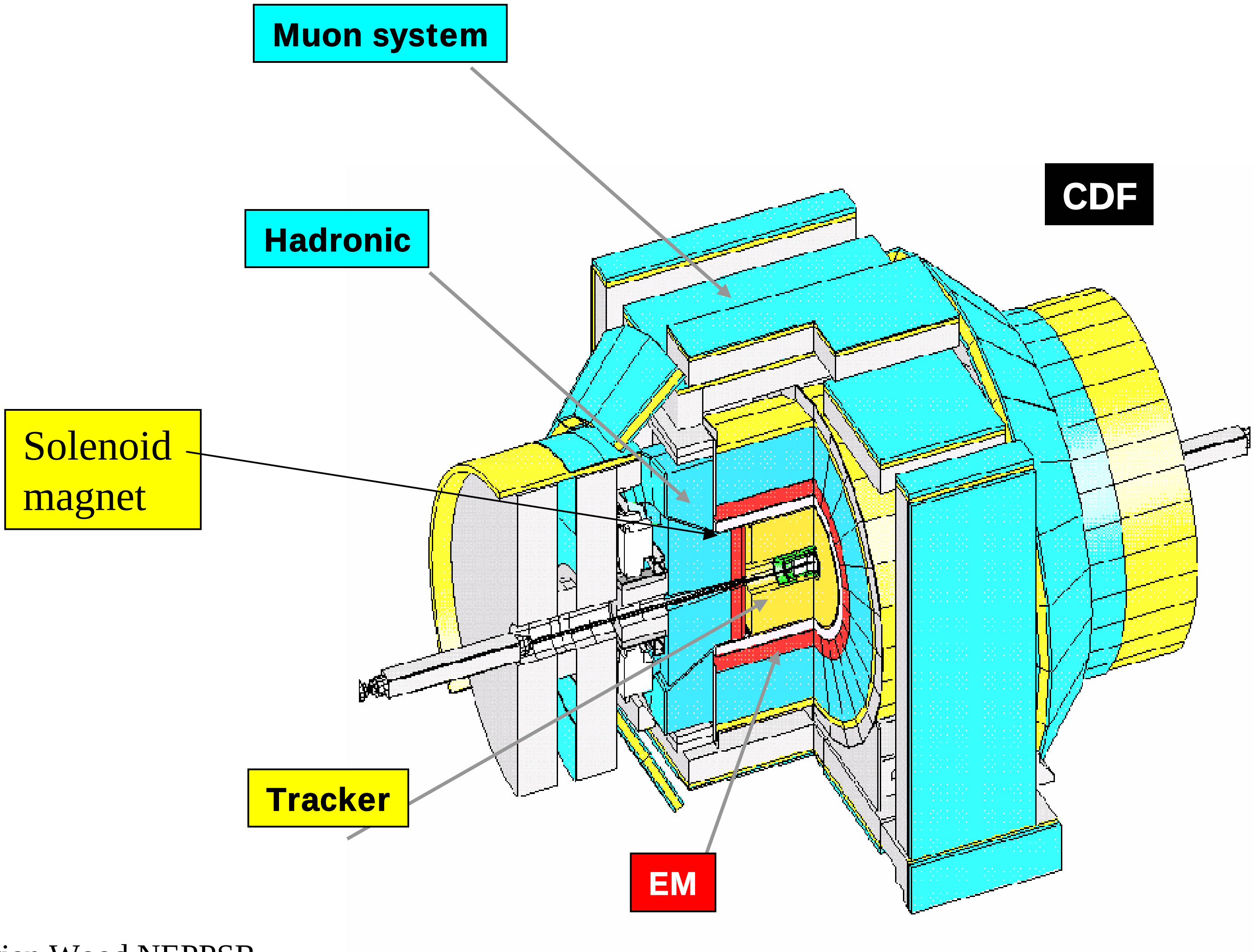
Charged particle tracking

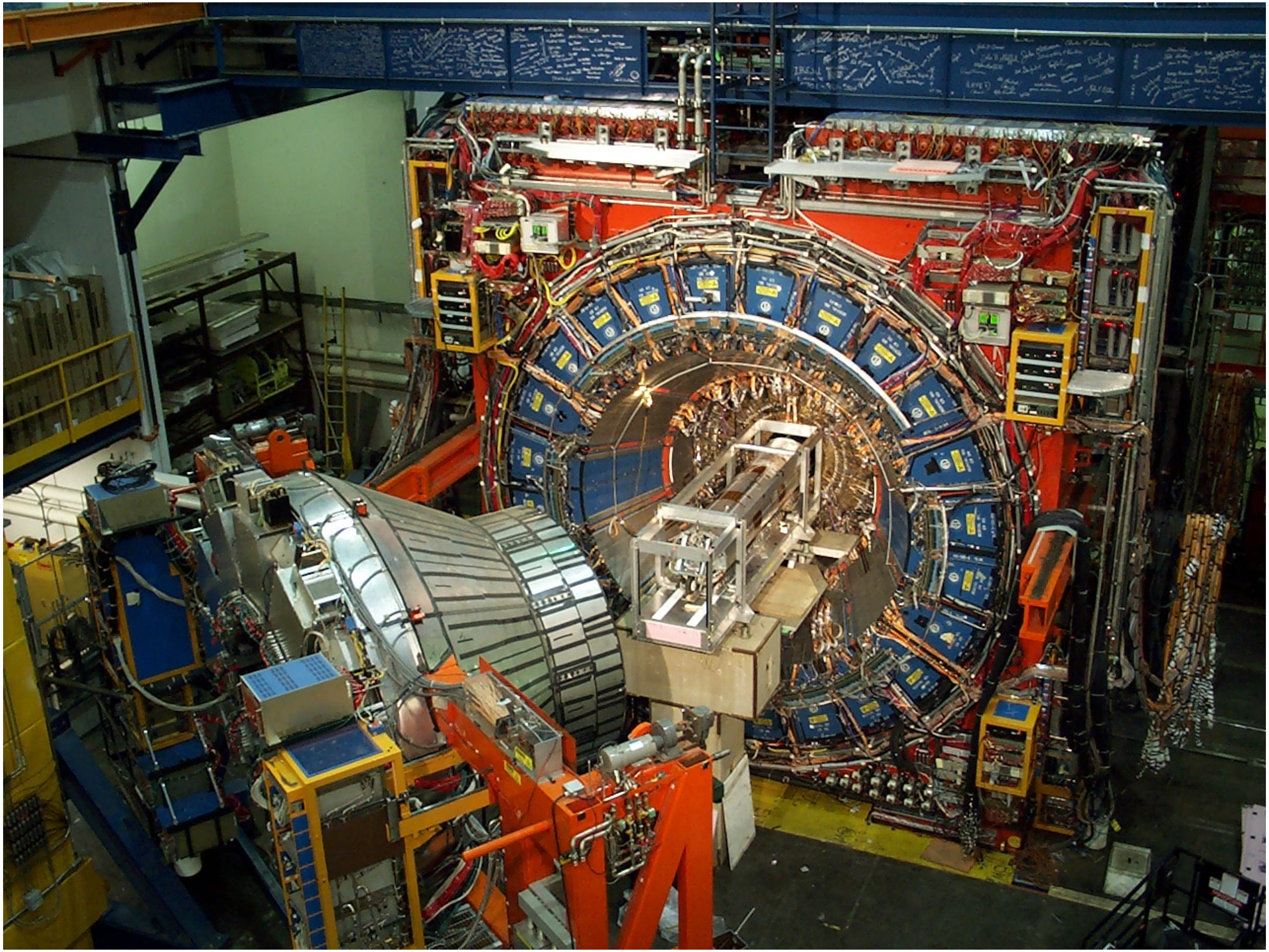
Toroid magnets



DØ detector, before the closing of the collision hall

CDF Detector



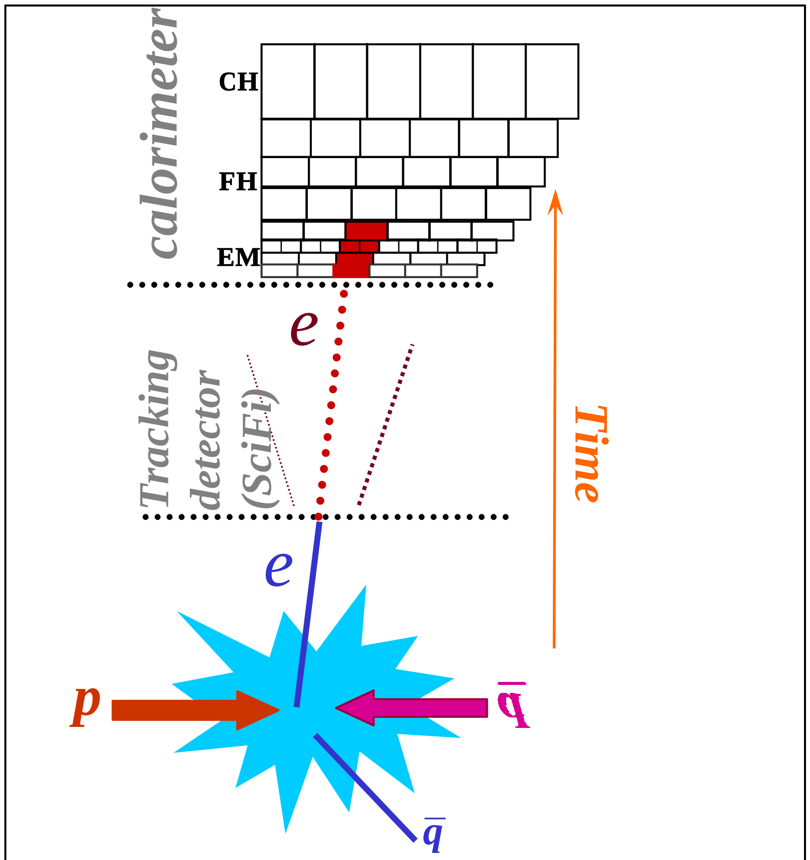


CDF detector, with the plug calorimeter retracted

CDF and DØ

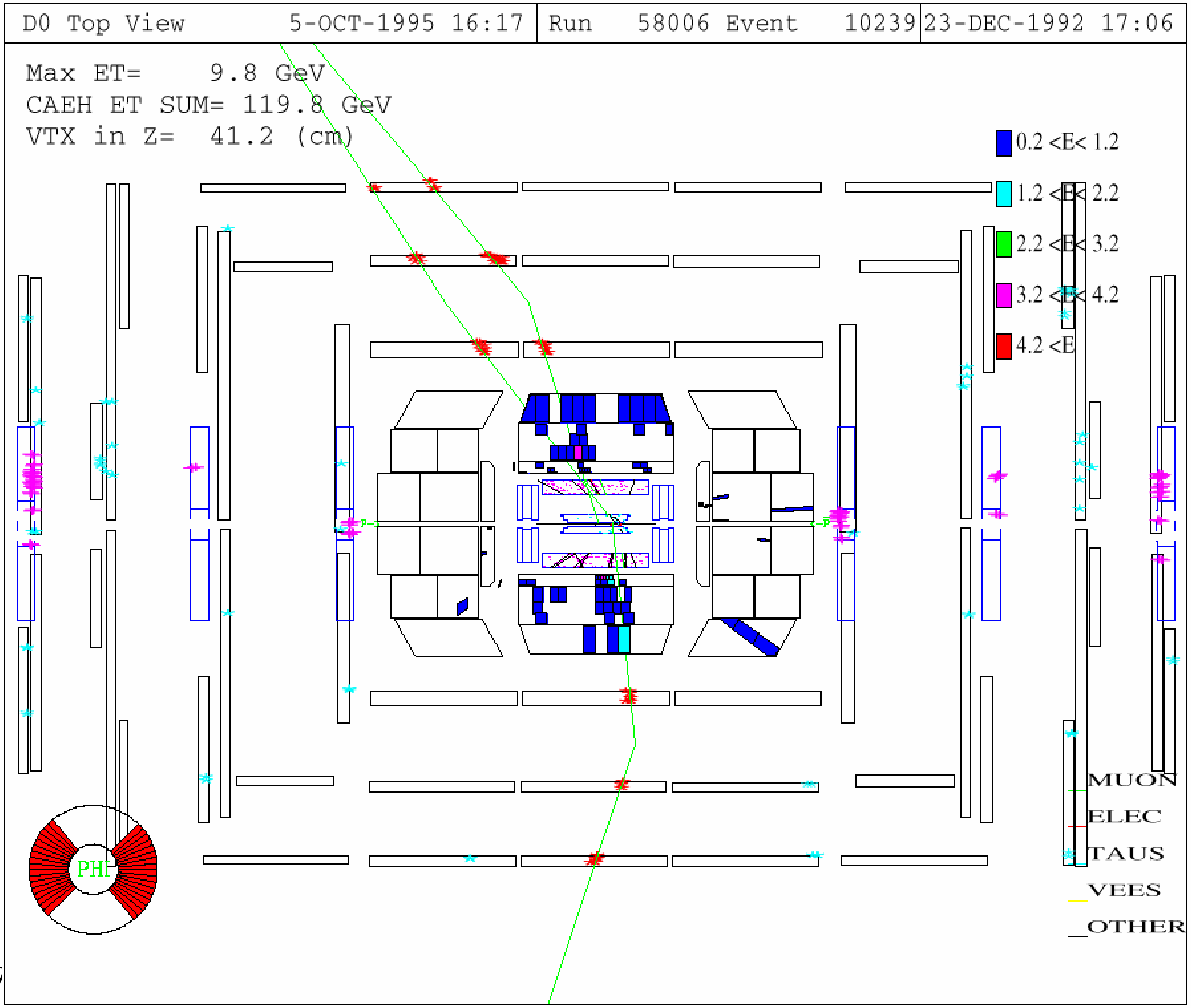
- Common to both detectors
  - Silicon microstrip detector (tracking, vertex)
  - Magnetic tracker
  - Central solenoid magnet
  - Preshower detectors
  - Electromagnetic calorimeter
  - Hadronic calorimeter
  - Iron absorber
  - Muon detectors
- CDF highlights
  - Large radius (1.5m) tracker: good momentum resolution
  - Time-of-flight system
- DØ highlights
  - Hermetic, dense calorimeter
  - More complete muon coverage with magnetized iron toroids

Electrons and photons

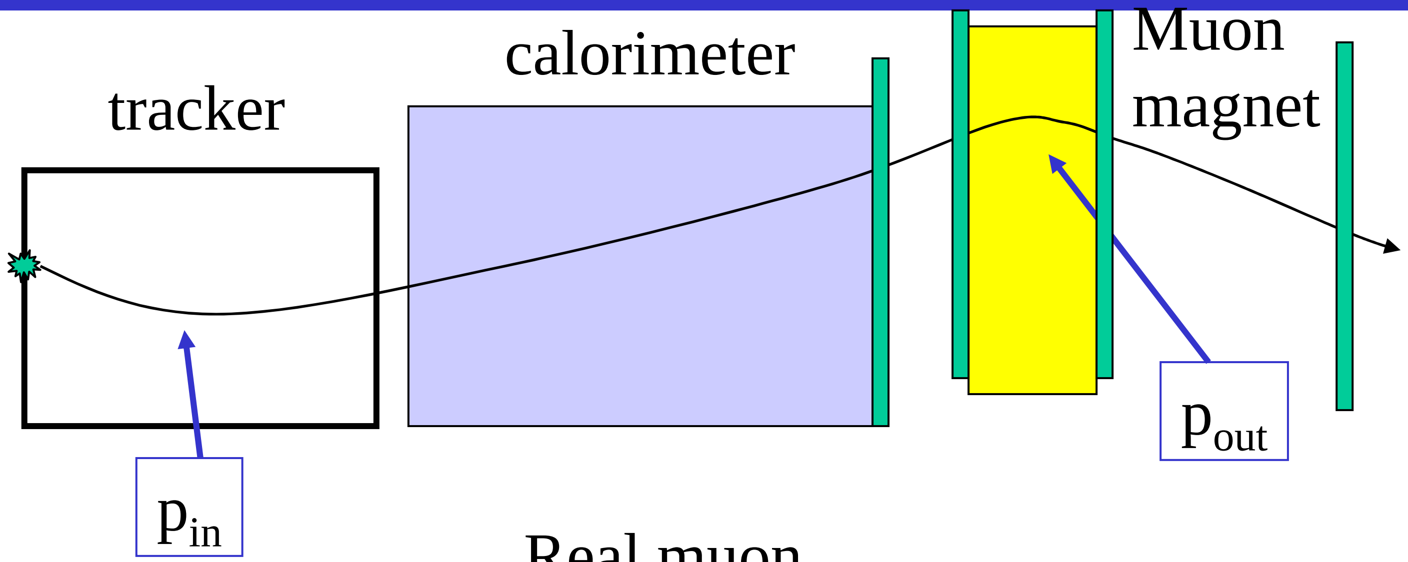


- In the calorimeter
  - Narrow cluster of energy in EM (front) section
  - Little or no energy in Had (back) section
- In the tracker
  - **Photon**: no track (no hits)
  - **Electron**: track with momentum matching energy of calorimeter cluster
- Fake backgrounds
  - Jets with most of their energy in π^0('s)
  - **Photon:** electron with missing track
  - **Electron:** photon conversion

Identifying Muons



Muon Signal

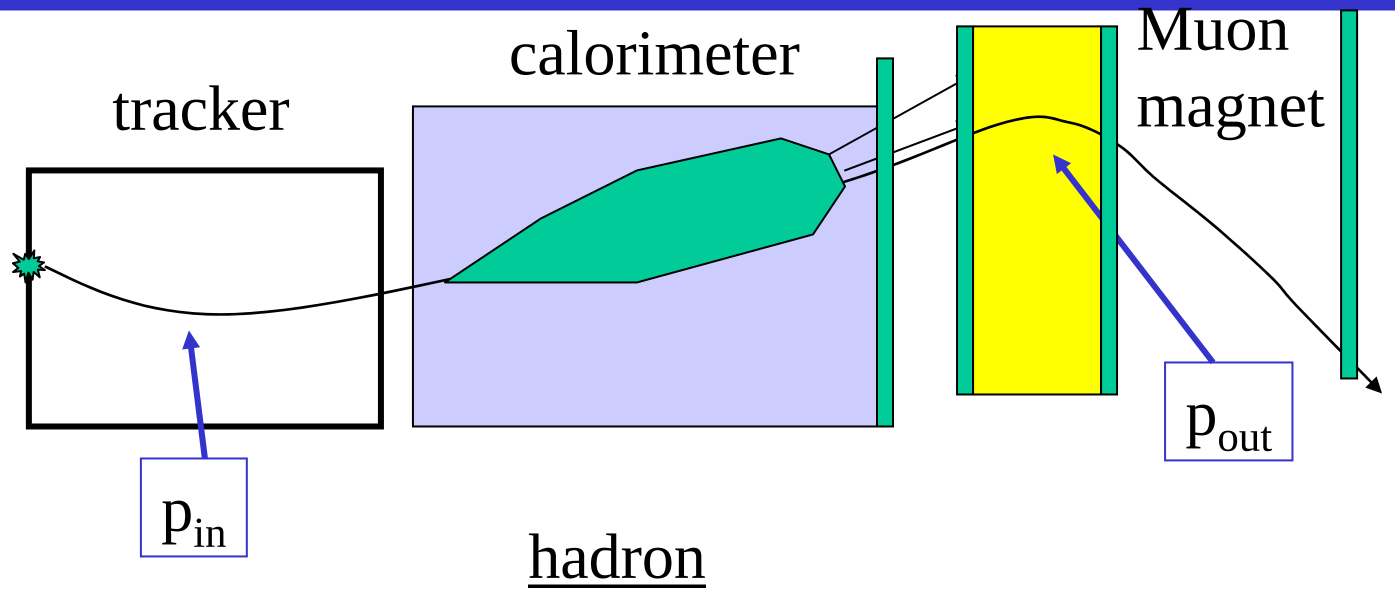


Real muon

$p_{in} \approx p_{out} + E_{loss}$ (muon ID tool)

Better resolution comes from tracker; p_{out} dominated by multiple scattering (or showering)

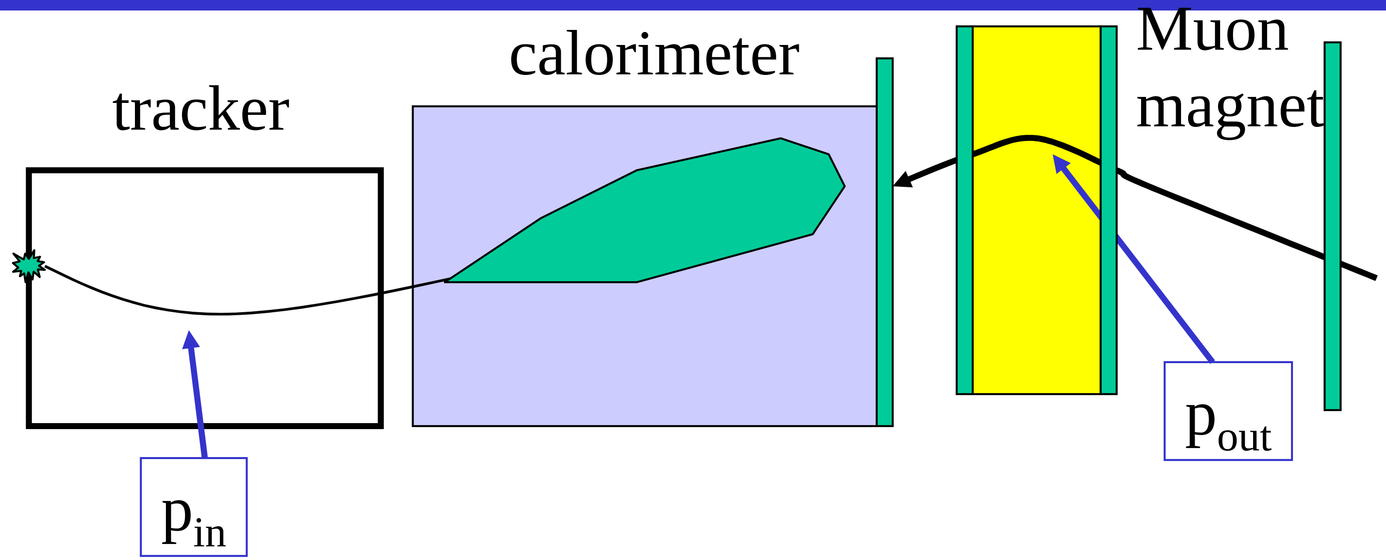
Muon background 1: punchthrough/decay



$p_{in} >> p_{out} + E_{loss}$

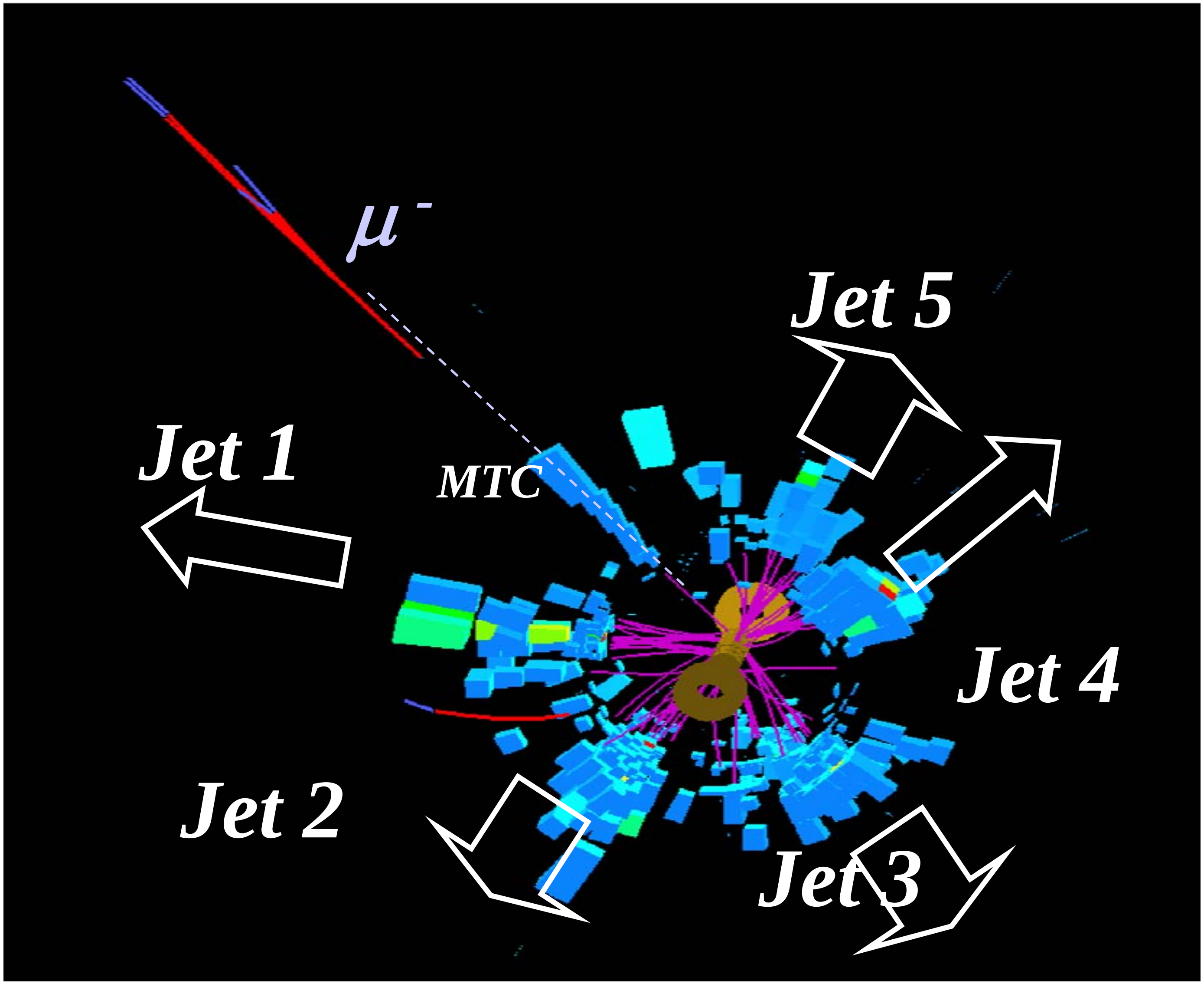
Outer decay/p.t. track points back to parent hadron, but momenta do not match.

Muon background 2: halo/backscatter



p_{in} ? $p_{out}+E_{loss}$

Good timing (scintillator) can get rid of most of these



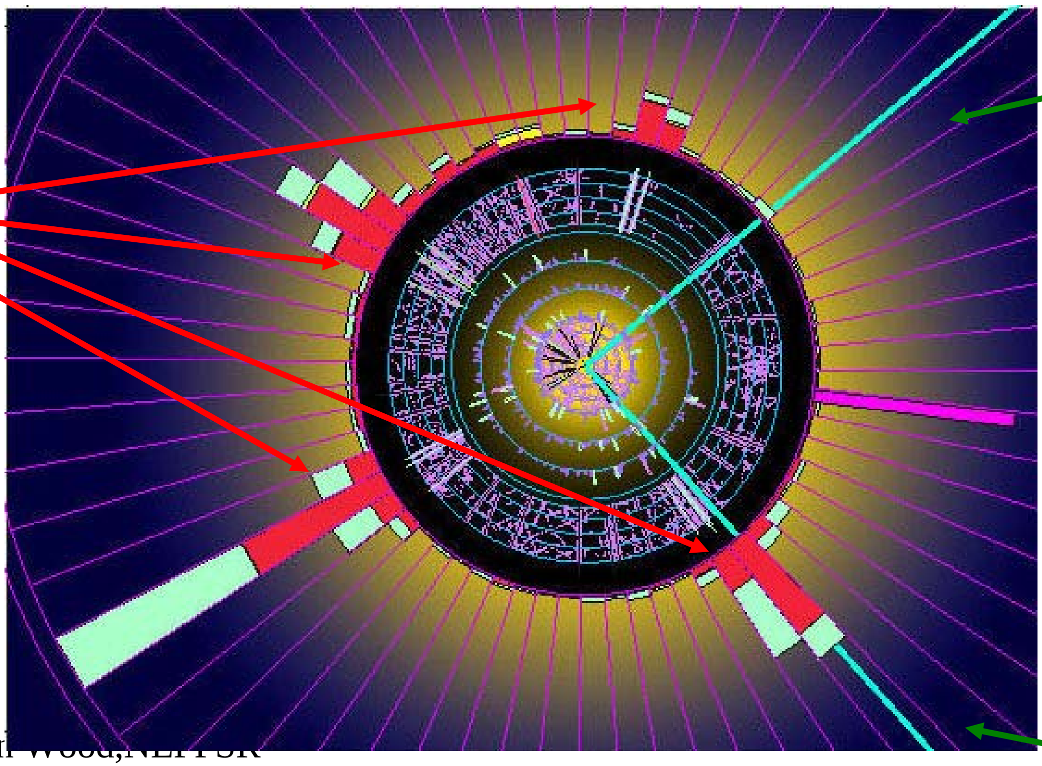
DØ top to μ+jets Candidate Event

Missing Transverse Energy ($\not{E}_T$)

Example: top quark candidate (ttbar →μνjjjj)
[transverse view]

$$\vec{\not{E}}_T = -\sum \vec{E}_T(cal) - \sum p_T(muons)$$

jets



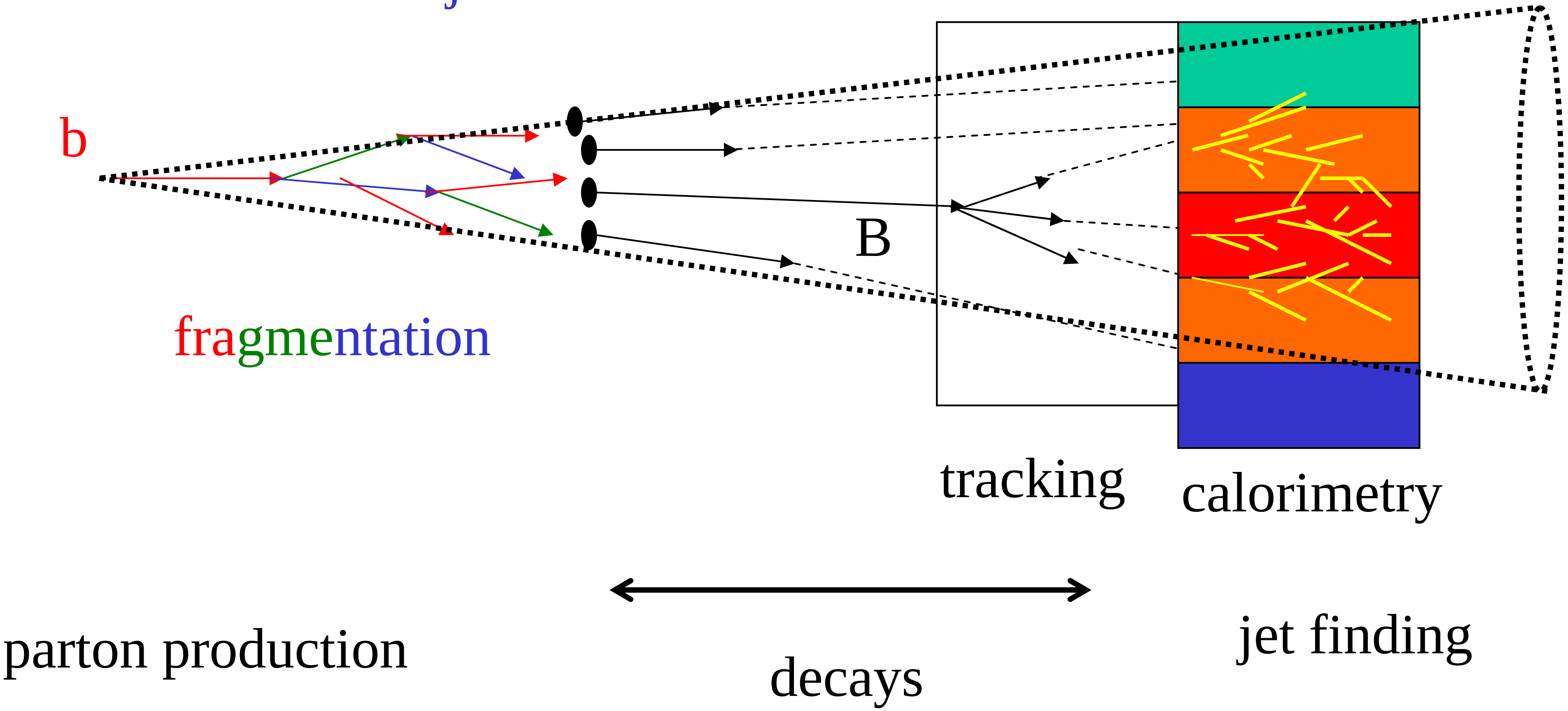
Muon from W decay

Missing momentum from neutrinos

Muon from b-quark decay

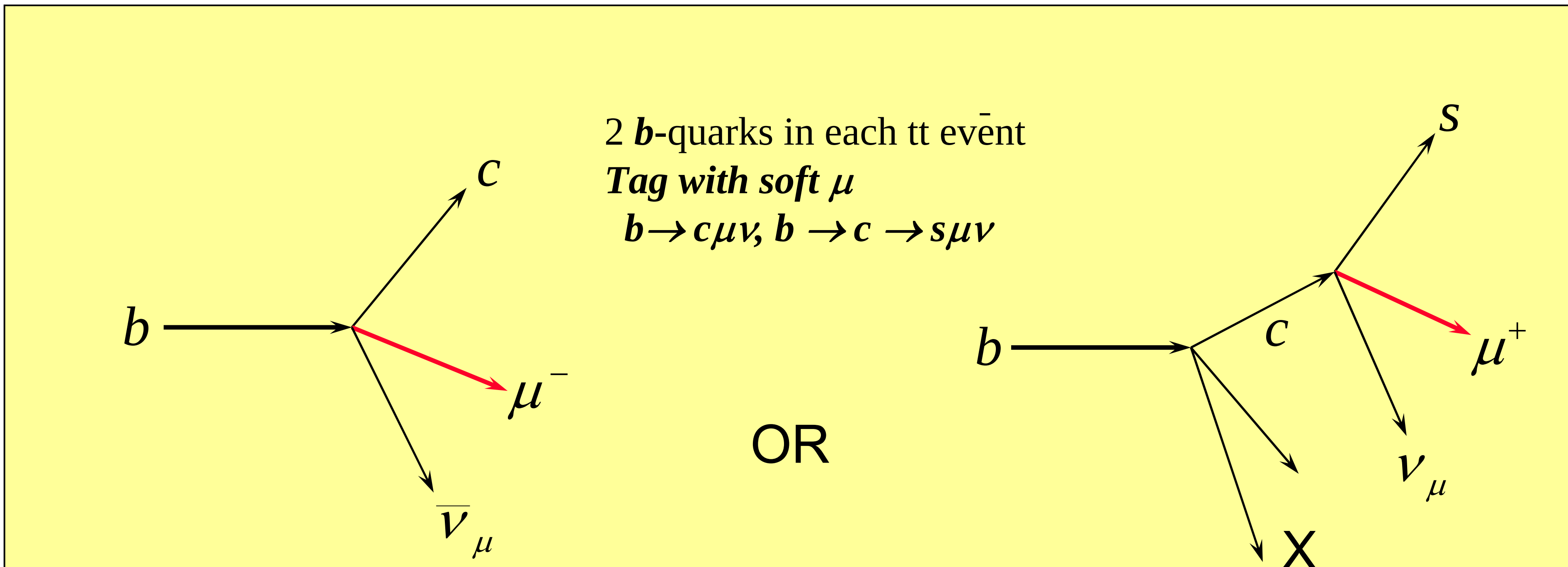
b-quark jets

- Recall the steps between production of a quark and detection of a jet:



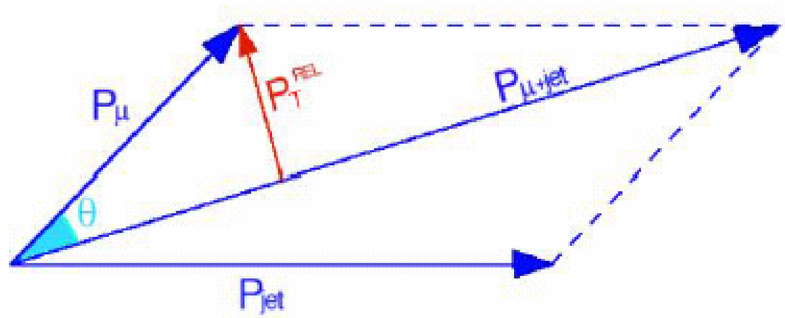
Identifying the b quark

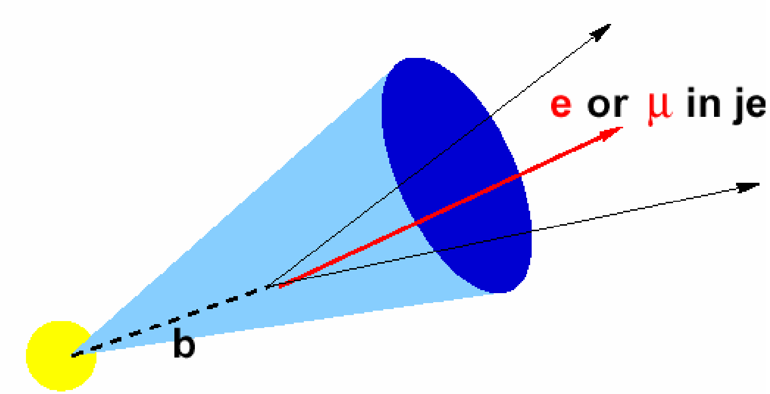
1 **Semileptonic decays of the b-quark**
example: B(b →μ + X) ≈ 20% ⇒ detect muons in jets



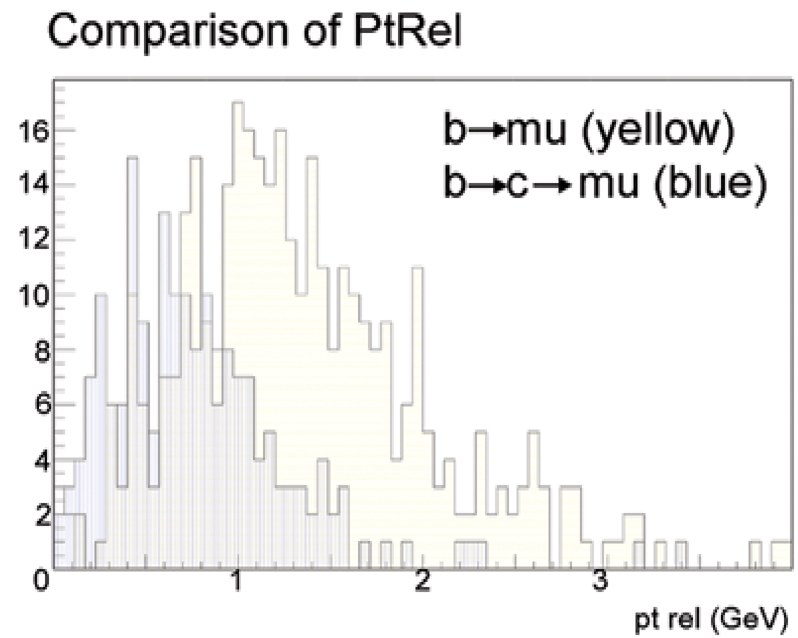
Soft lepton tag

- These leptons have a softer p_T spectrum than leptons from W/Z
  - are not isolated

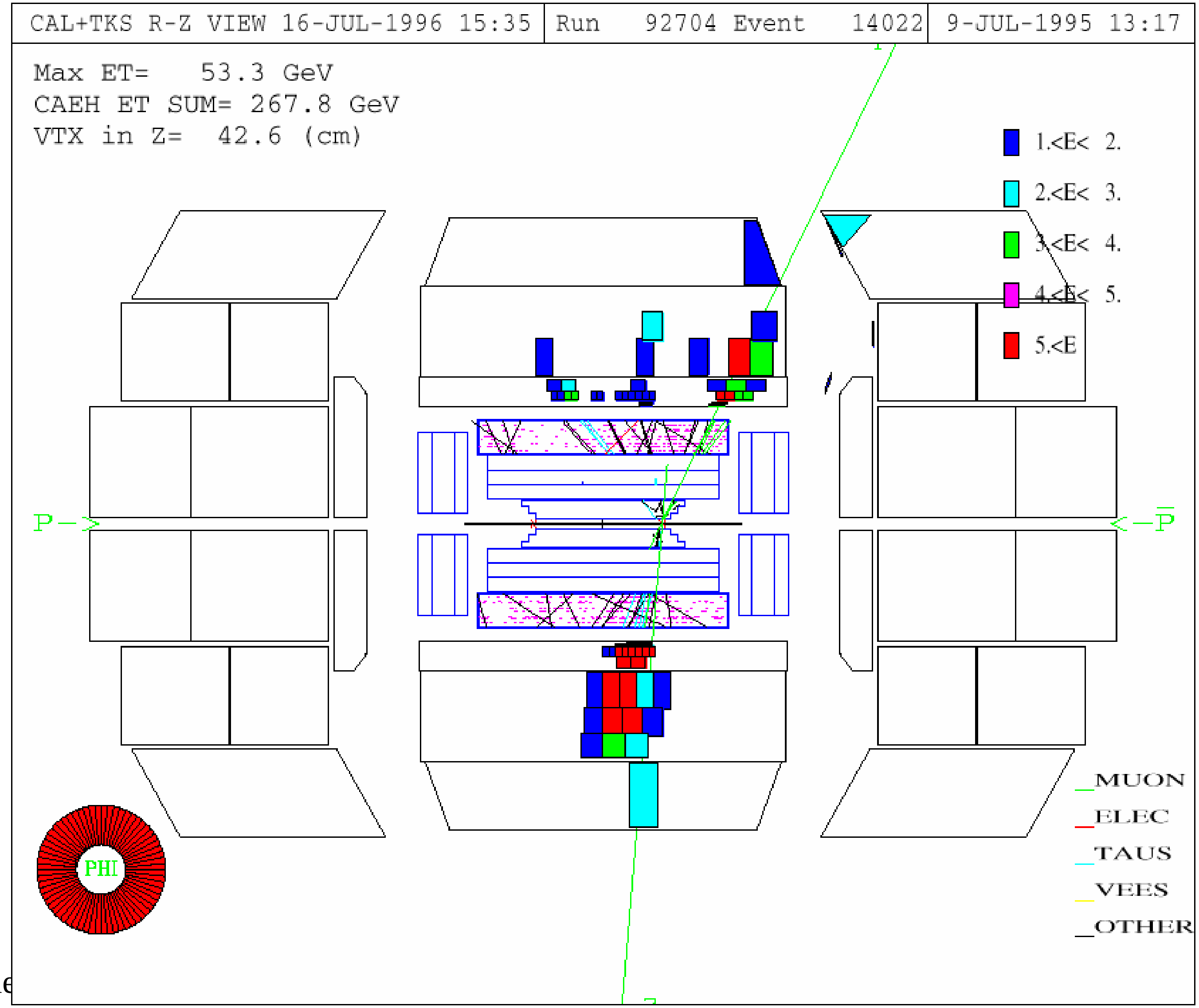




- $b \to \ell \nu c$ (BR ~ 20%)
- $b \to c \to \ell \nu s$ (BR ~ 20%)

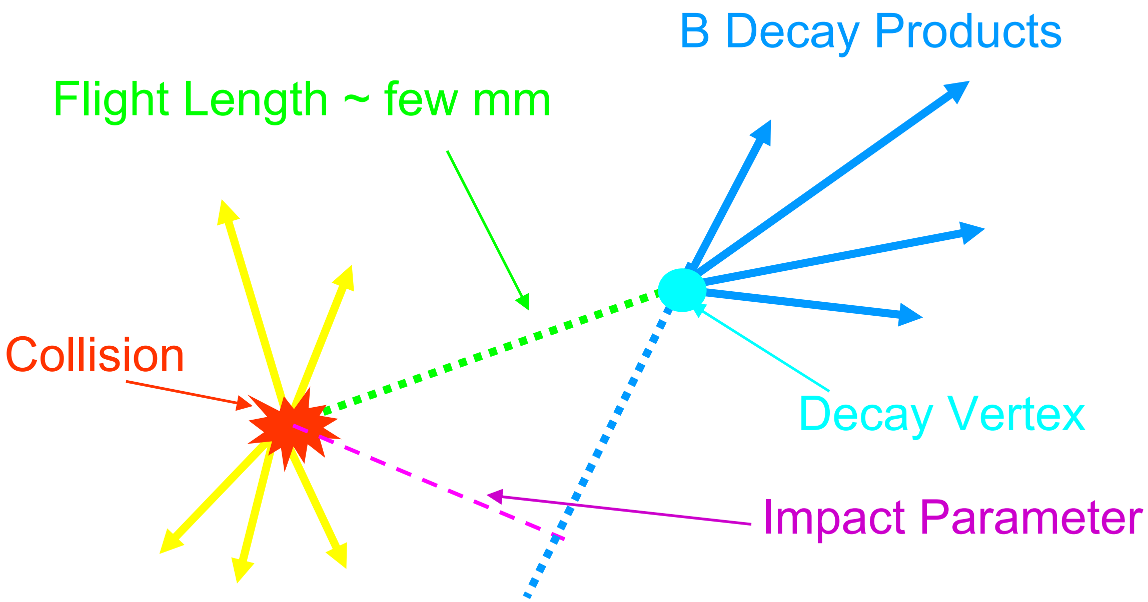


Top Event with b-jet (D0)



Identifying the b quark

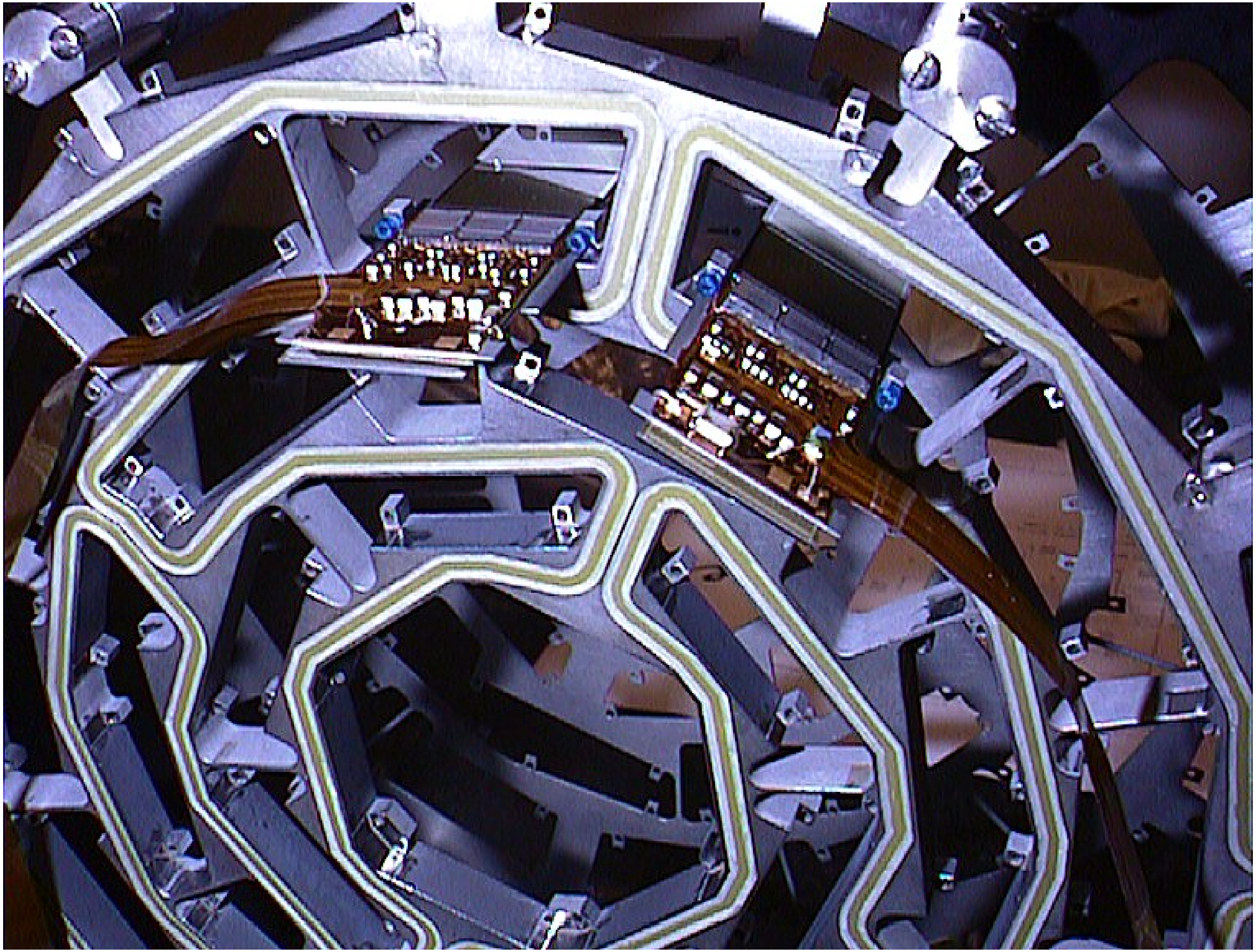
2 **life time ≈ 1.5 ps ⇒ cτ ≈ 0.5 mm (short, but not too short)**



precise tracking close to primary collision point
⇒silicon microstrip detectors

Decaying particles: examples

Particles	Lifetime	$c\tau$	Lifetime signature
W,Z,top	$<10^{-23}$ s	~0	Decay immediately
$\pi^0(\rightarrow\gamma\gamma)$	8×10^{-16} s	25 nm	Decay length undetectable
τ	2.9×10^{-13} s	87 μm	Inside beam pipe; hard even with SMT
$D^0/D^\pm/D_s$	$0.4\text{-}1.0\times10^{-12}$ s	150-350 μm	Inside beam pipe; possible w/ SMT
$B^0/B^\pm/B_s$/b-baryon	$\sim1.5\times10^{-12}$ s	450 μm	Inside beam pipe; possible w/ SMT
$K^0_s(\rightarrow\pi\pi)$	0.8×10^{-10} s	2.7 cm	decays in outer tracking chamber
$K^\pm$, $\pi^\pm$, $\mu^\pm$	$>10^{-8}$ s	>3 m	reach cal without decaying

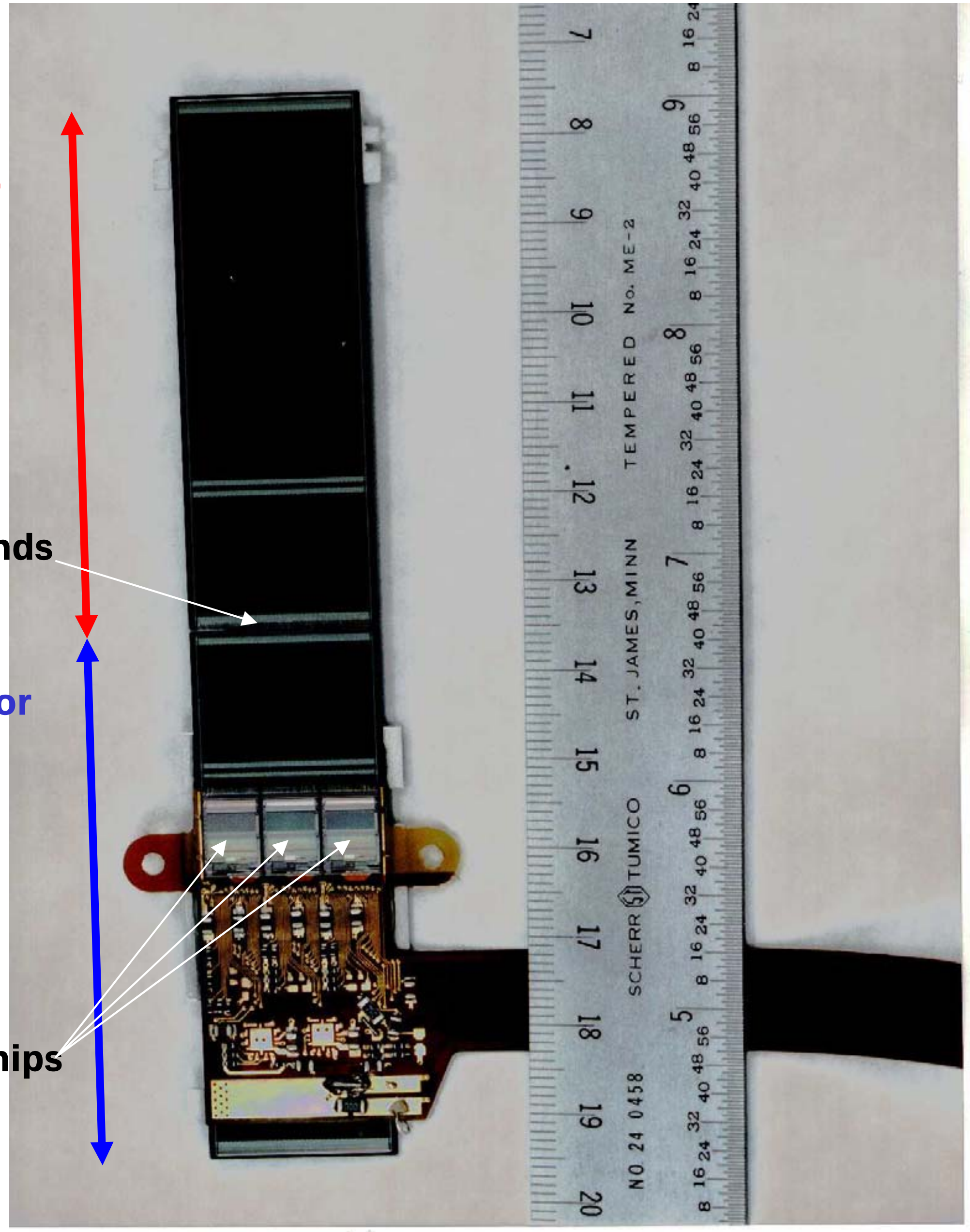


Silicon sensor

Wire bonds

Silicon sensor

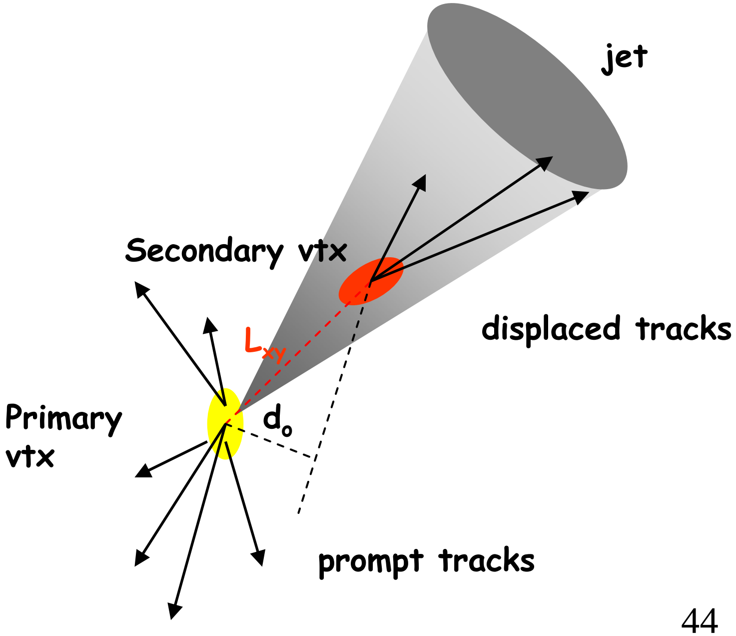
SVX2e readout chips



HDI (flex circuit readout)

Lifetime signature for b-jets

- Long lifetime of B hadrons
  - cτ~450μm + boost
  - Travel ~3 mm before decay with large charged track multiplicity
- Two ways of looking for lifetime tags
  - A reconstructed vertex, displaced from the primary vertex
  - Presence of track(s) with large impact parameter, d_0

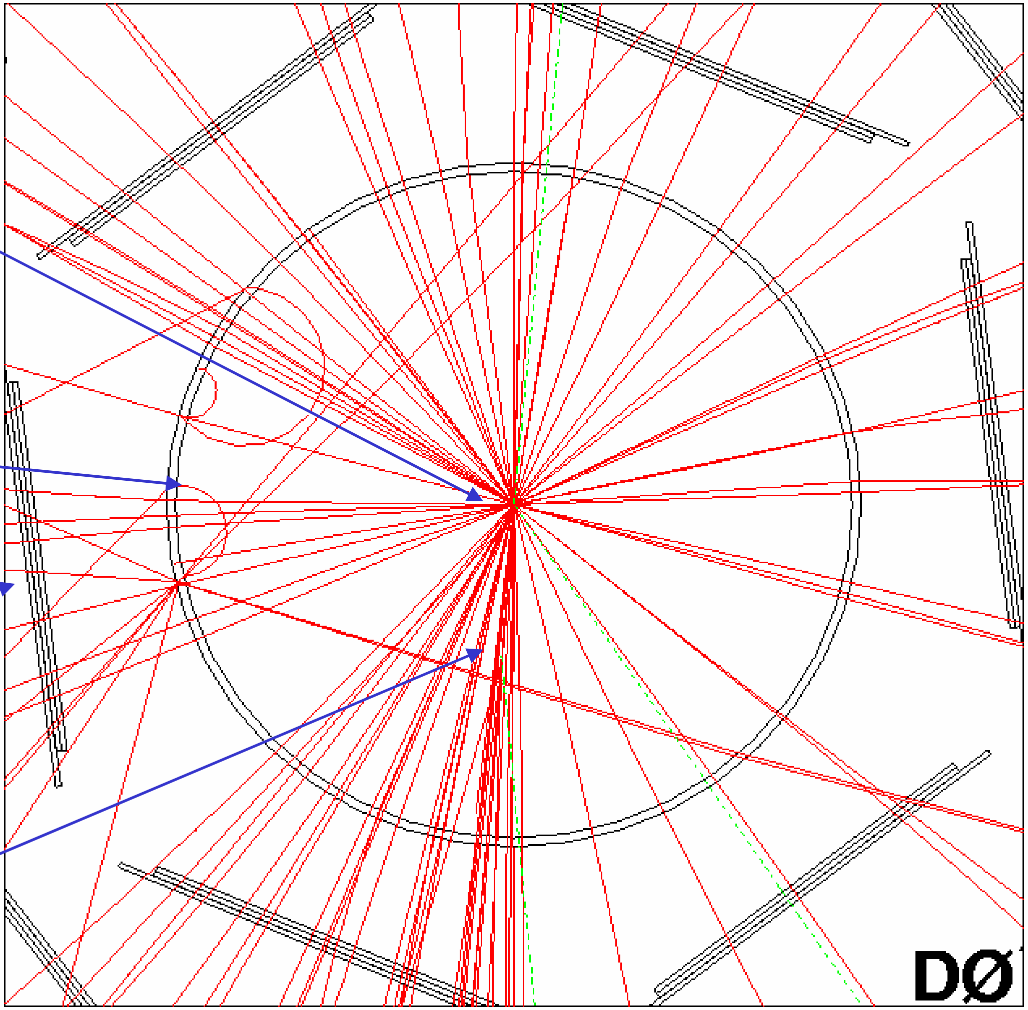


Interaction point ("primary vertex")

Beampipe

Silicon detector

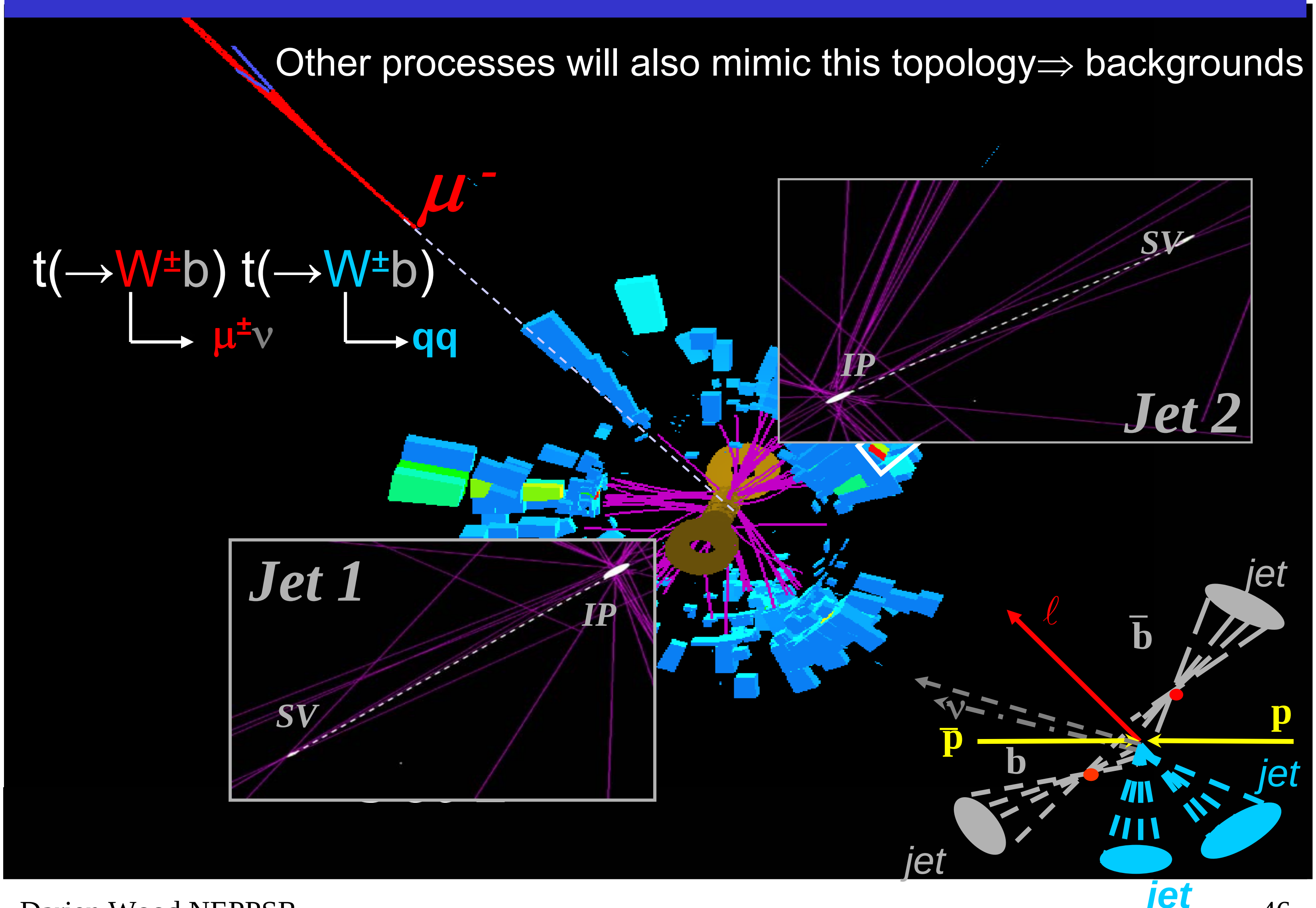
B decay ("secondary vertex")



This green track clearly does not originate at the primary vertex

1 inch

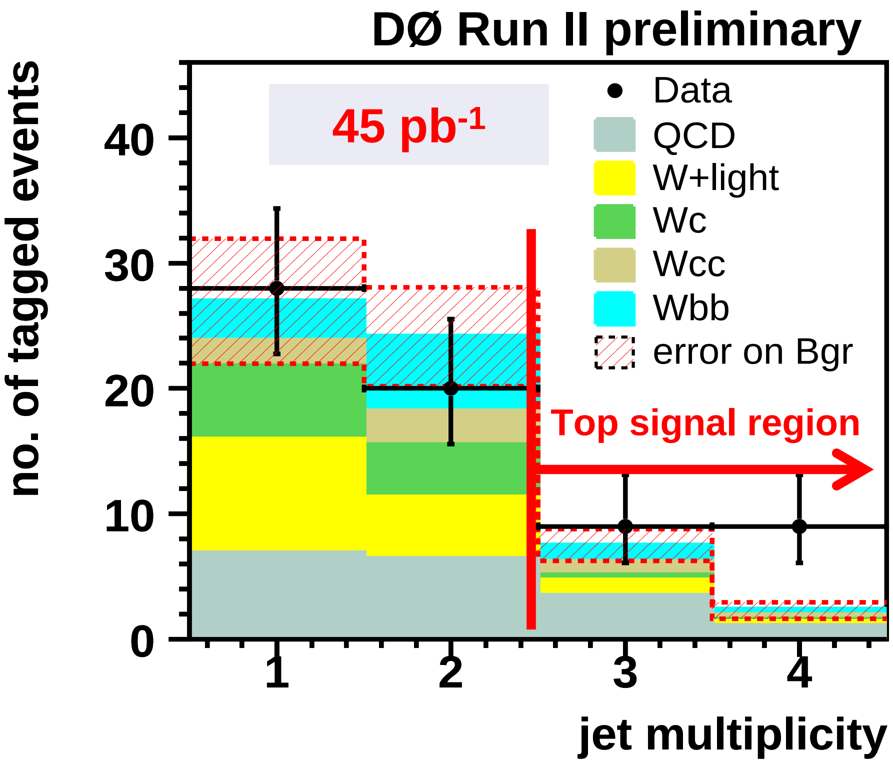
t-tbar candidate event with b-tags

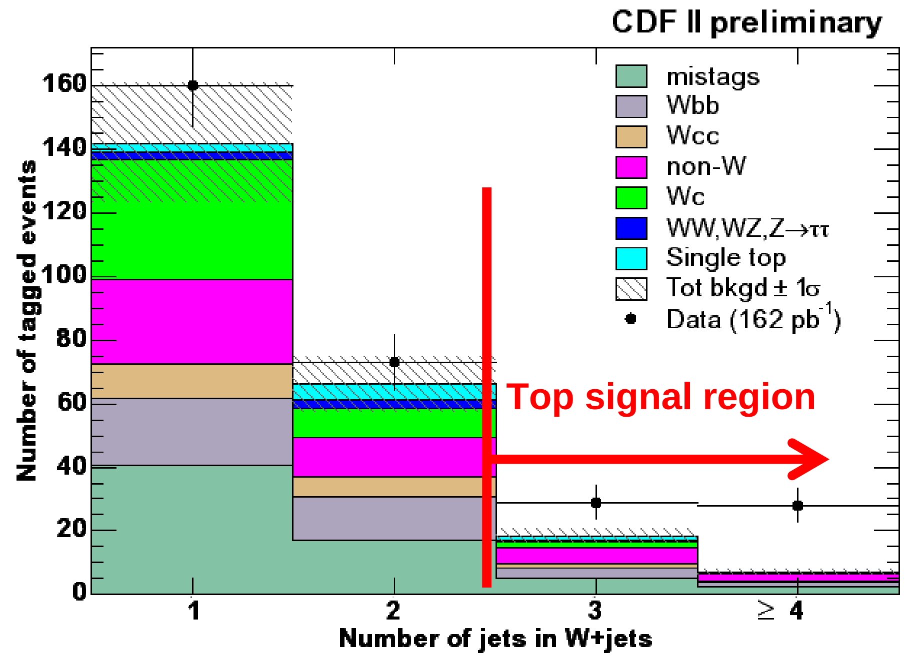


Background to b-tagging

- soft lepton tag
  - fake leptons (in light-quark/gluon jets)
  - c-quark jets
  - $K^{\pm}, \pi^{\pm}$ decays in flight (in light-quark/gluon jets)
  - chance overlap of light-quark/gluon jet and lepton
- lifetime tag
  - mismeasured tracks in light-quark/gluon jet
  - c-quark jets
  - K_s, Λ decays in light-quark/gluon jets

Top signal and background (Run II)





$$t\bar{t} \rightarrow l\nu b\bar{b}q\bar{q}$$

"lepton+jets" w/ b-tag

One of the best for mass determination

Triggering

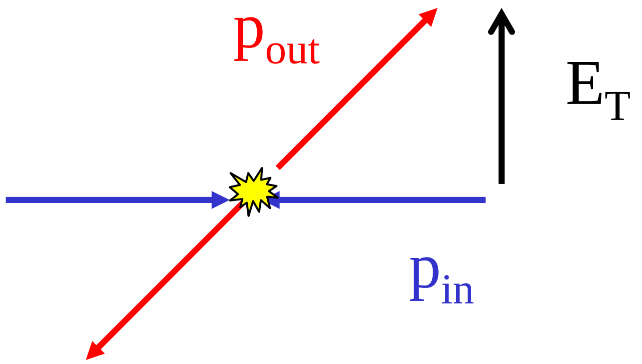
- A few relevant numbers:
  - Bunch collision rate: 2.5 MHz
  - Inelastic interaction rate at $L=10^{32}$: 4 MHz
  - Data size of each event: ~0.5 Megabytes
  - Rate at which data can be recorded: ~50 Hz
- Clearly, most of the events have to be discarded before they are recorded (record 1 crossing in 50,000)
- Events that are discarded are real physics (jet production, low p_T b-quarks, low-mass lepton pairs…)
  - Need to make choices about physics
  - Different from e^+e^- colliders, where generally all real interactions can be recorded
- **Triggers have a big, important job at hadron colliders**

Typical production rates for p-pbar at 2 TeV

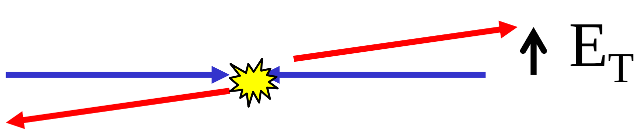
Final state	Cross section (pb)	Rate at $L=10^{32}$ $cm^{-2}s^{-1}$
"minimum bias"	$4x10^{10}$	4 MHz
2 jets	$4x10^{6}$	400 Hz
4 jets	$1.6x10^{5}$	16 Hz
6 jets	6000	0.6 Hz
W	30000	3 Hz
Z	9000	0.9 Hz
WZ	3.5	$3.5x10^{-4}$ Hz (1.3/hour)
t tbar	7.5	$7.5x10^{-4}$ Hz (3/hour)

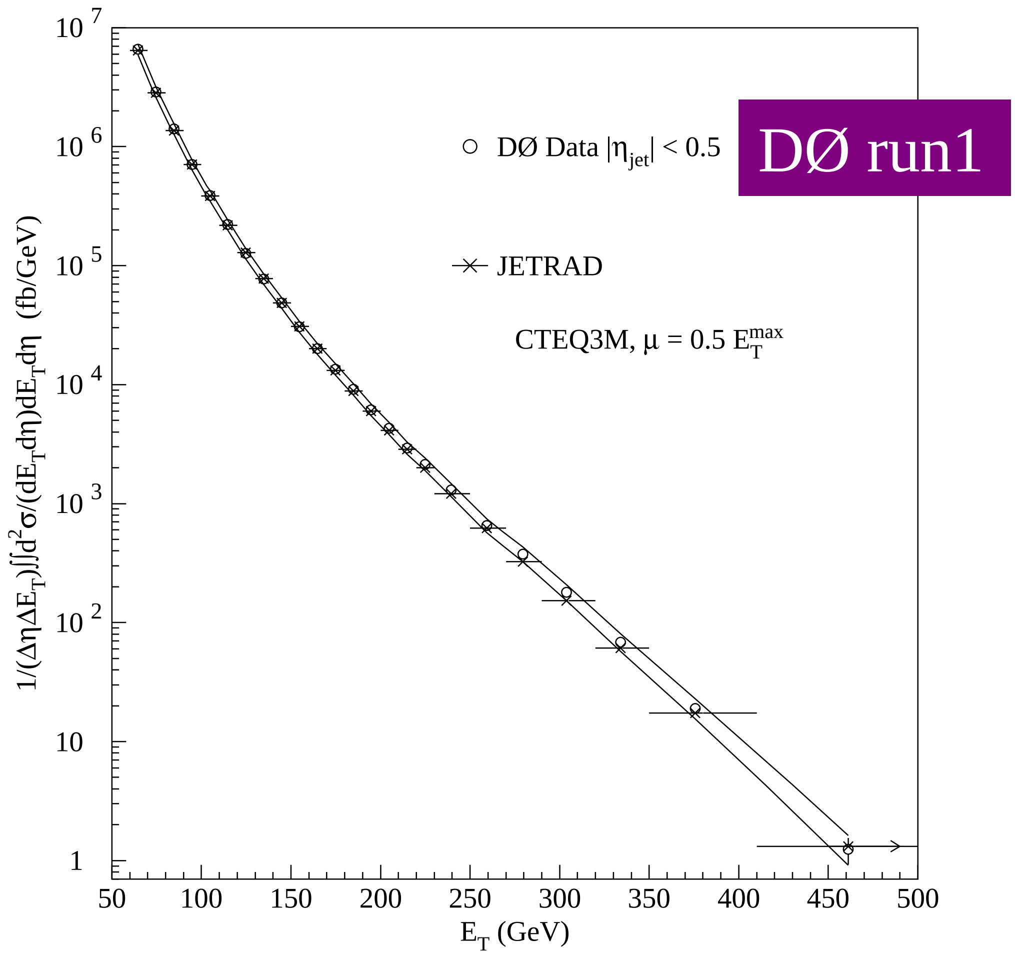
Spectrum of jet transverse energy

Hard collision:

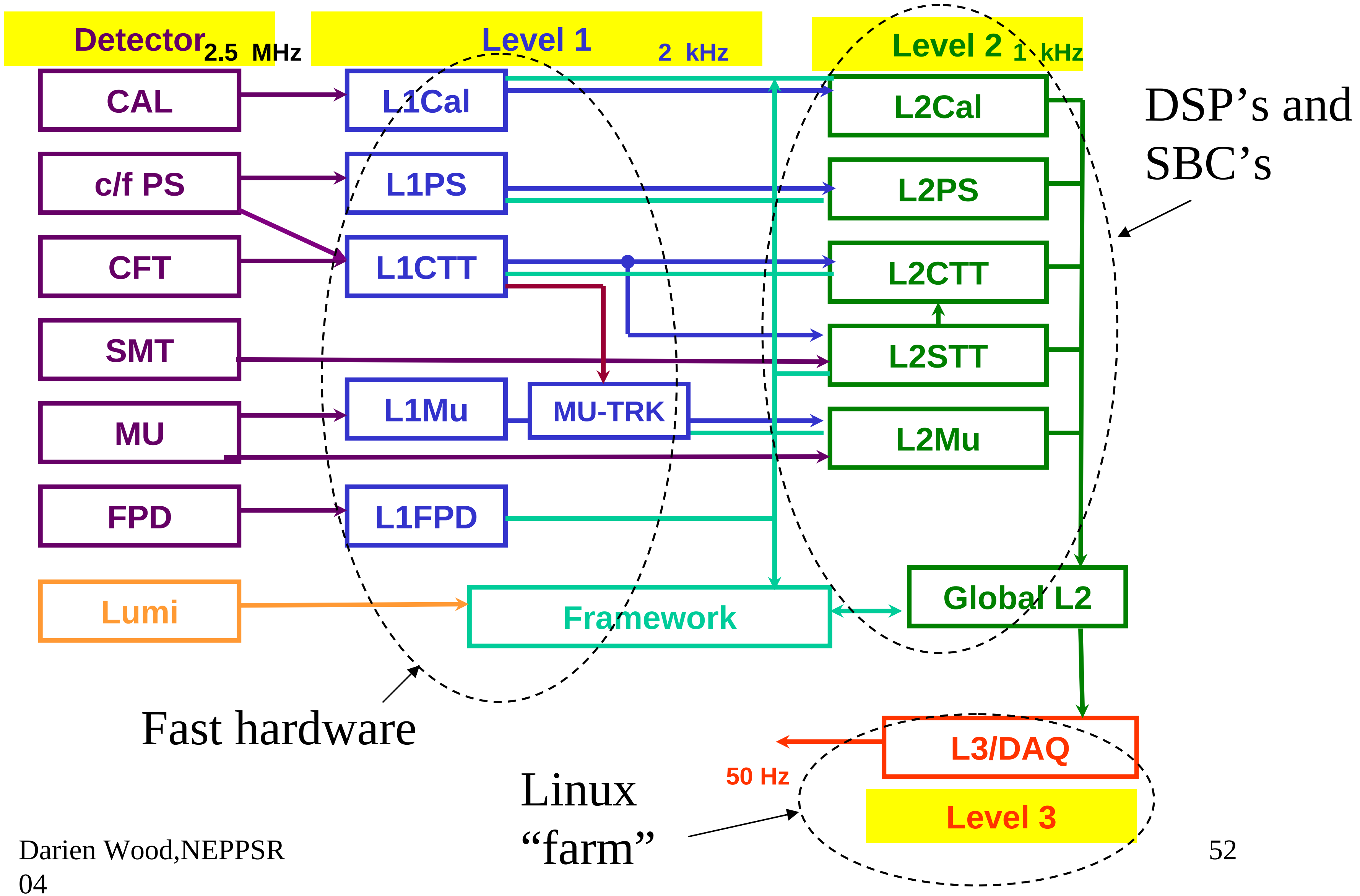


soft collision:





The DØ Trigger System (current)

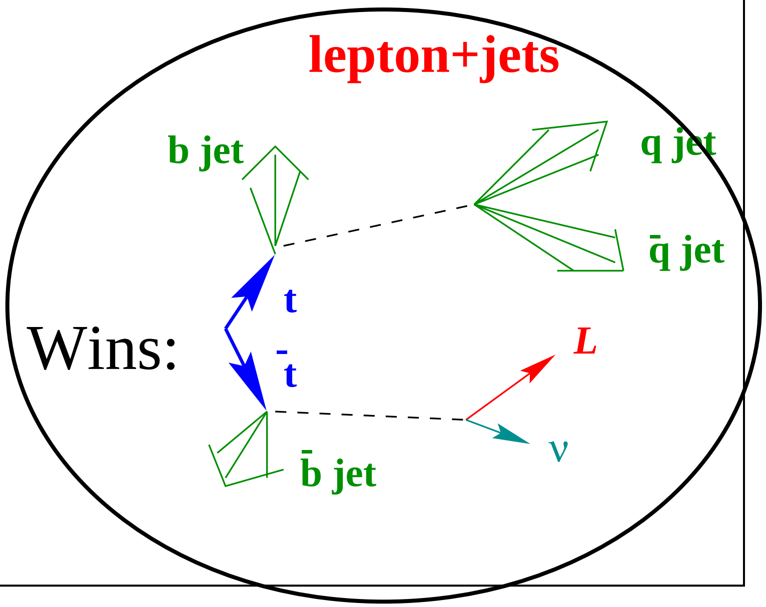


Example of a trigger condition

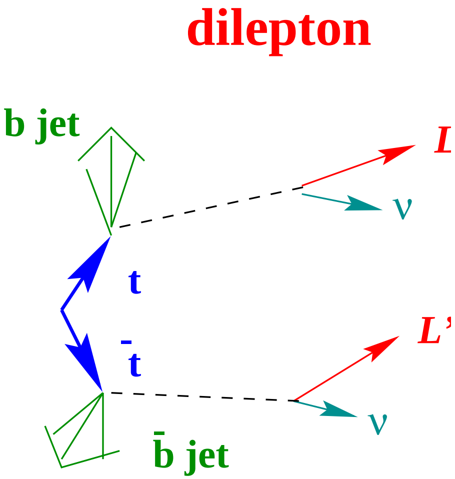
- Name: MUJ1_JT15HA_TK10 (one of 378 triggers)
- Purpose: trigger on top$\rightarrow$muon+jets (among others)
- Level 1
  - 2-layer coincidence of muon scintillator and of muon wire chambers
  - At least two "towers" (0.2 eta X 0.2 phi) with E_T above 3 GeV
  - Rate: 70 Hz
- Level 2:
  - Fast reconstruction muon track (no momentum cut)
  - Fast jet cluster with E_T above 8 GeV
  - Rate: 55 Hz
- Level 3:
  - Reconstructed jet above 15 GeV, and sum of missing E_T and scalar E_T > 50 GeV
  - Charged track with p_T>10 GeV
  - Rate: ~1 Hz

Top quark mass measurement

- advantages
  - 2nd largest branching ratio
  - only one neutrino

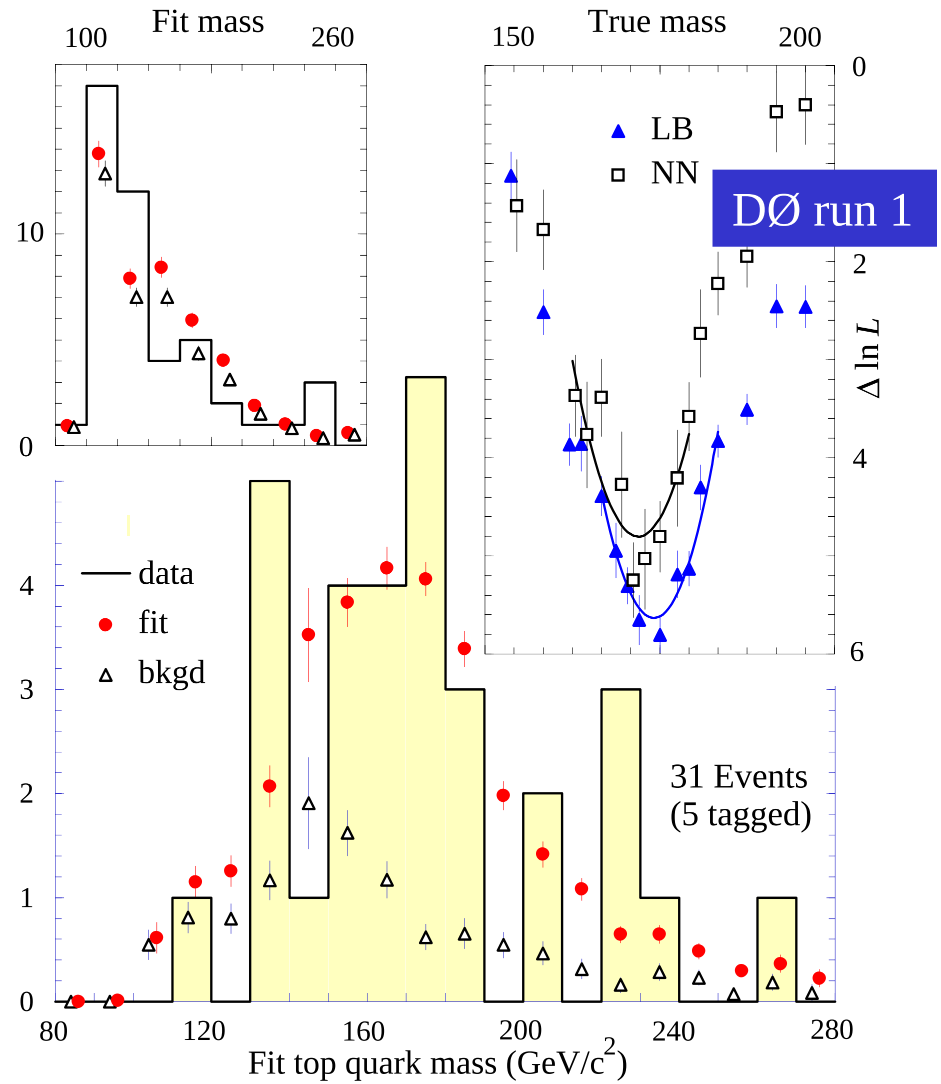


- advantages
  - low background
  - better energy resolution for leptons than for jets

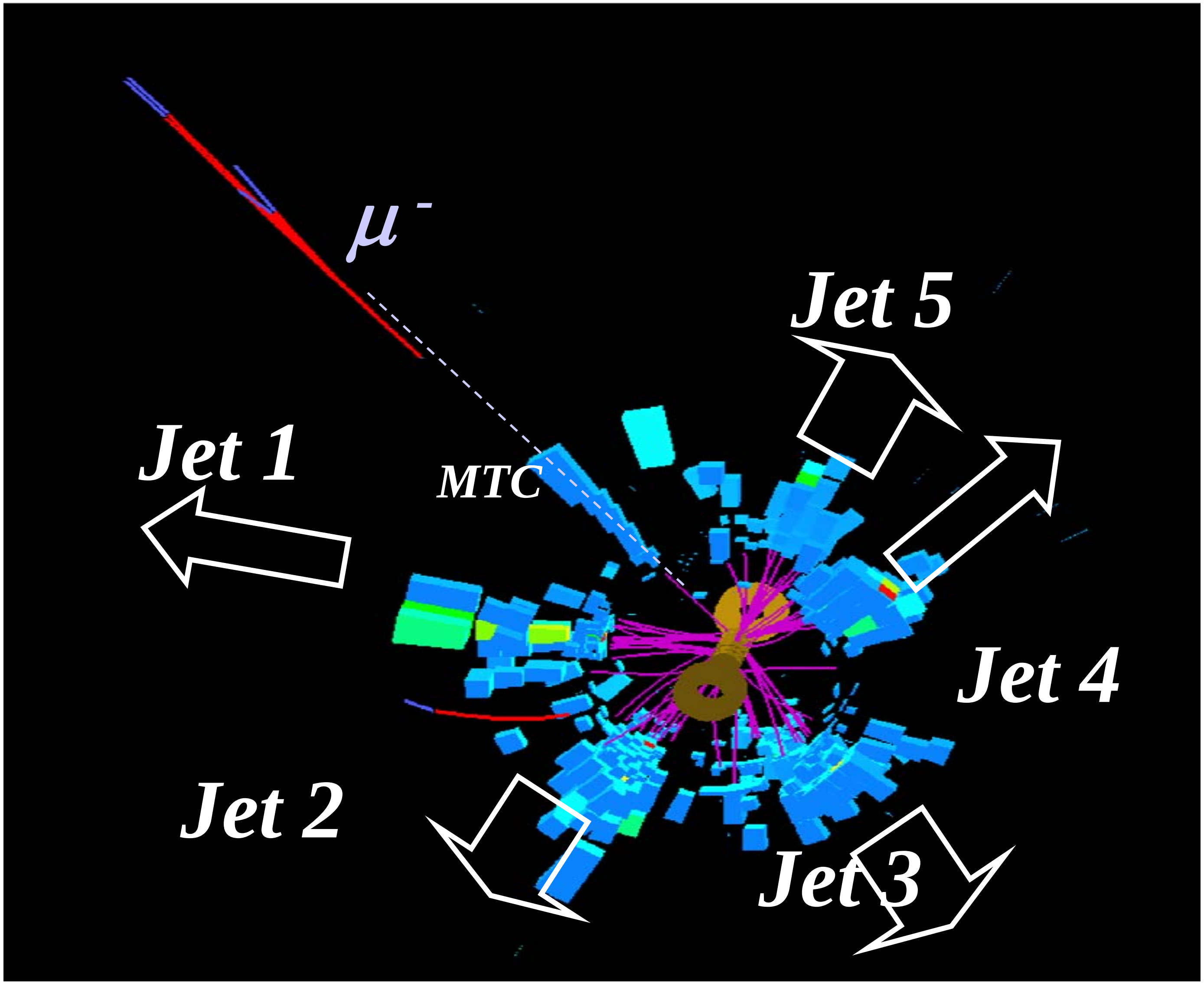


Technique #1: one mass per event

- Lepton+4jets channel: all final state variables (18) are measured except for $p_z(\nu)$
- Three additional constraints:
  - $m(qq) = m_W$
  - $m(l\nu) = m_W$
  - $m(bqq) = m(bl\nu)$
- Twice over-constrained fit: (17+3-18)
- For each event, select jet permuation with best fit (lowest chisquared)
- Make distribution of masses, and fit to singnal(m_t) + bkg



$$m_t = 173.3 \pm 5.6(\text{stat}) \pm 5.5(\text{sys})\text{GeV}$$



DØ top to μ+jets Candidate Event

Technique #2: optimized matrix element weighting

Likelihood method using most available information

Measured — to be estimated — resolutions, reconstruction effects

$$P(x;\alpha)=\frac{1}{\sigma}\int d^n\sigma(y;\alpha)\,dq_1\,dq_2\;f(q_1)\,f(q_2)\,W(x,y)$$

Matrix Element — PDF's

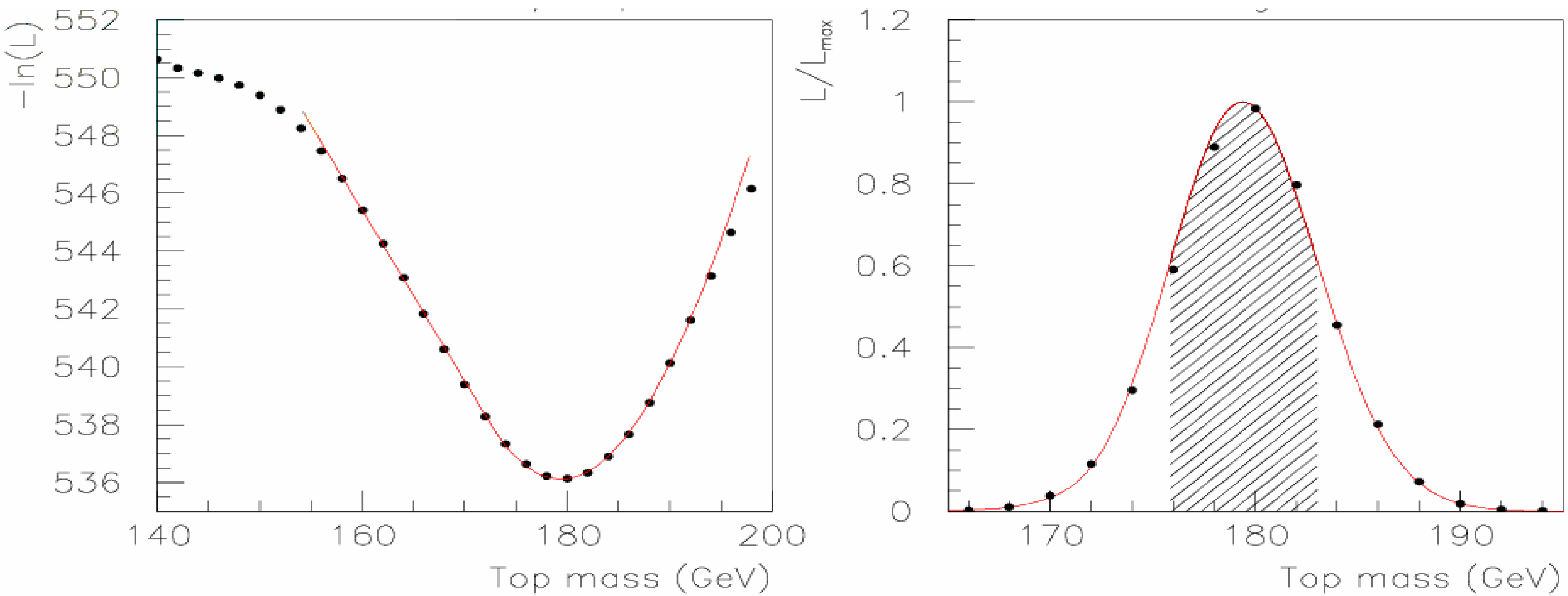
LO ME used, 4 jets required exclusively, additional cut on background probability (to improve purity) → 22 events

$$-\ln L(\alpha)=-\sum_{i=1}^{N}\left\{\ln\left[c_1P_{t\bar{t}}(x_i;\alpha)+c_2P_{bkg}(x_i)\right]\right\}$$
$$+N\int A(x)\left[c_1P_{t\bar{t}}(x;\alpha)+c_2P_{bkg}(x)\right]dx$$

Acceptance

Likelihood definition: estimate signal and background fractions and m_{top}

Results of matrix element weighting



$$m_{top} = 180.1 \pm 3.6\,(\text{stat}) \pm 3.9(\text{sys})\,\text{GeV}/c^2$$

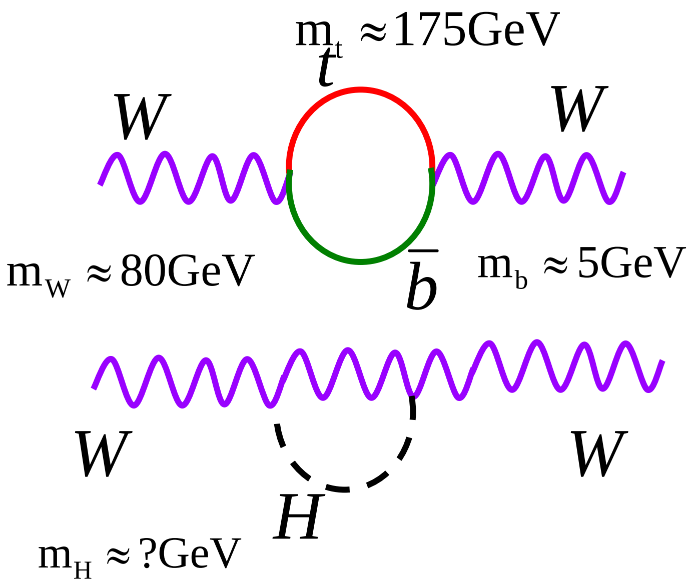
large improvement on the statistical uncertainty (~2.4× stats)

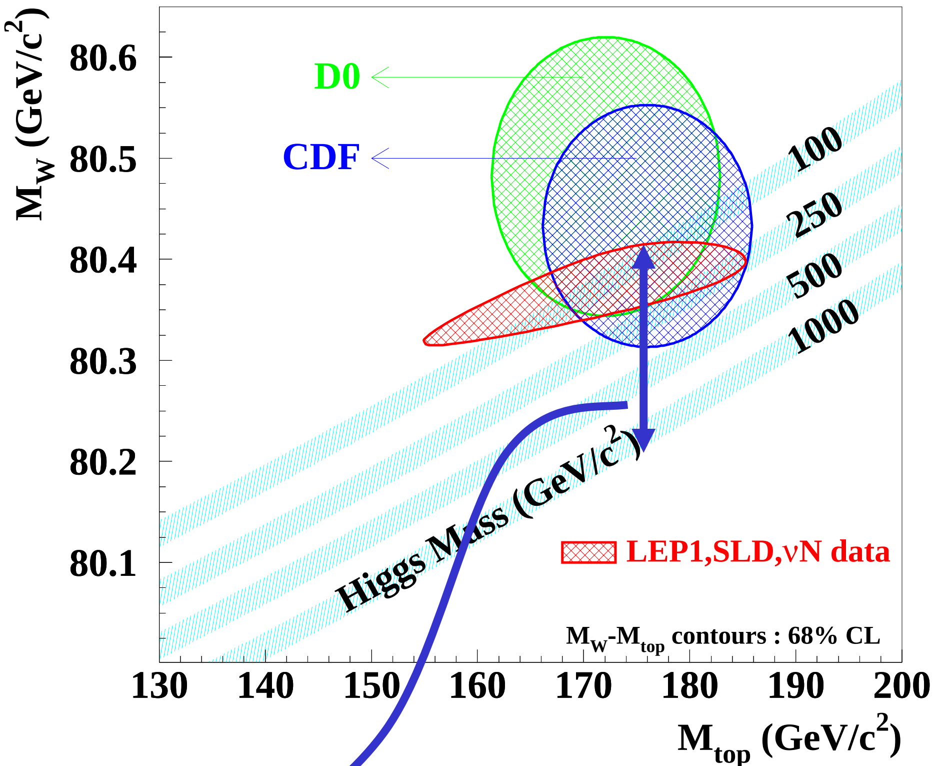
NEW World average: $m_{top} = 178.0 \pm 4.3\,\text{GeV}/c^2$

Run 2 mass analyses under way.
With 2 fb^{-1} data: $\delta m_{top} \approx$ 1-2GeV

Largest systematic error: Jet energy calibration: 3.3 GeV

Virtual Effects on W mass





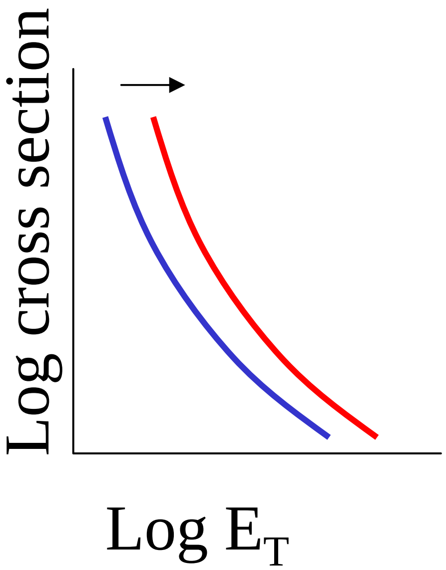
- One piece of evidence missing: the Higgs particle responsible for the mass of all known particles
- Finding the Higgs (or not): verify a prediction or declare clear evidence for new physics

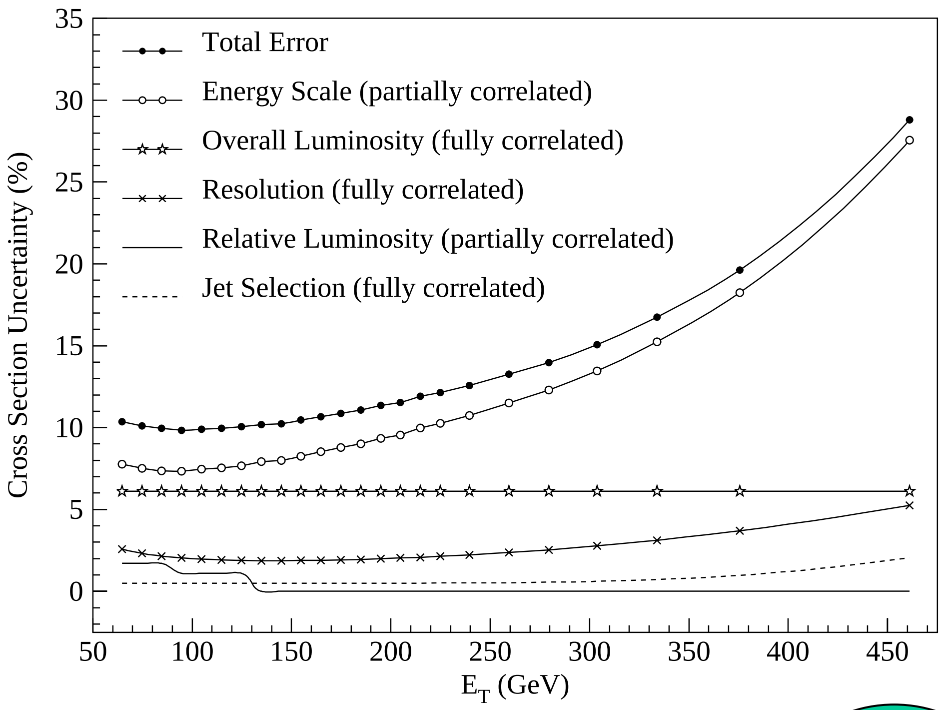
Mass shift from virtual Higgs effects (?)

Interesting features of top mass analysis

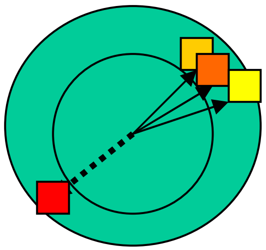
- small number of events
  - fitting techniques refined to make maximum use of limited statistics
- substantial background
  - fitting has to be robust in the presence of background
- complicated event topology
  - kinematic fitting
  - consideration of multiple permutations of object assignments

Jet energy calibration





A small shift in energy scale calibration gives a large shift in cross section



Jet energy calibrated in situ with photon+jet events