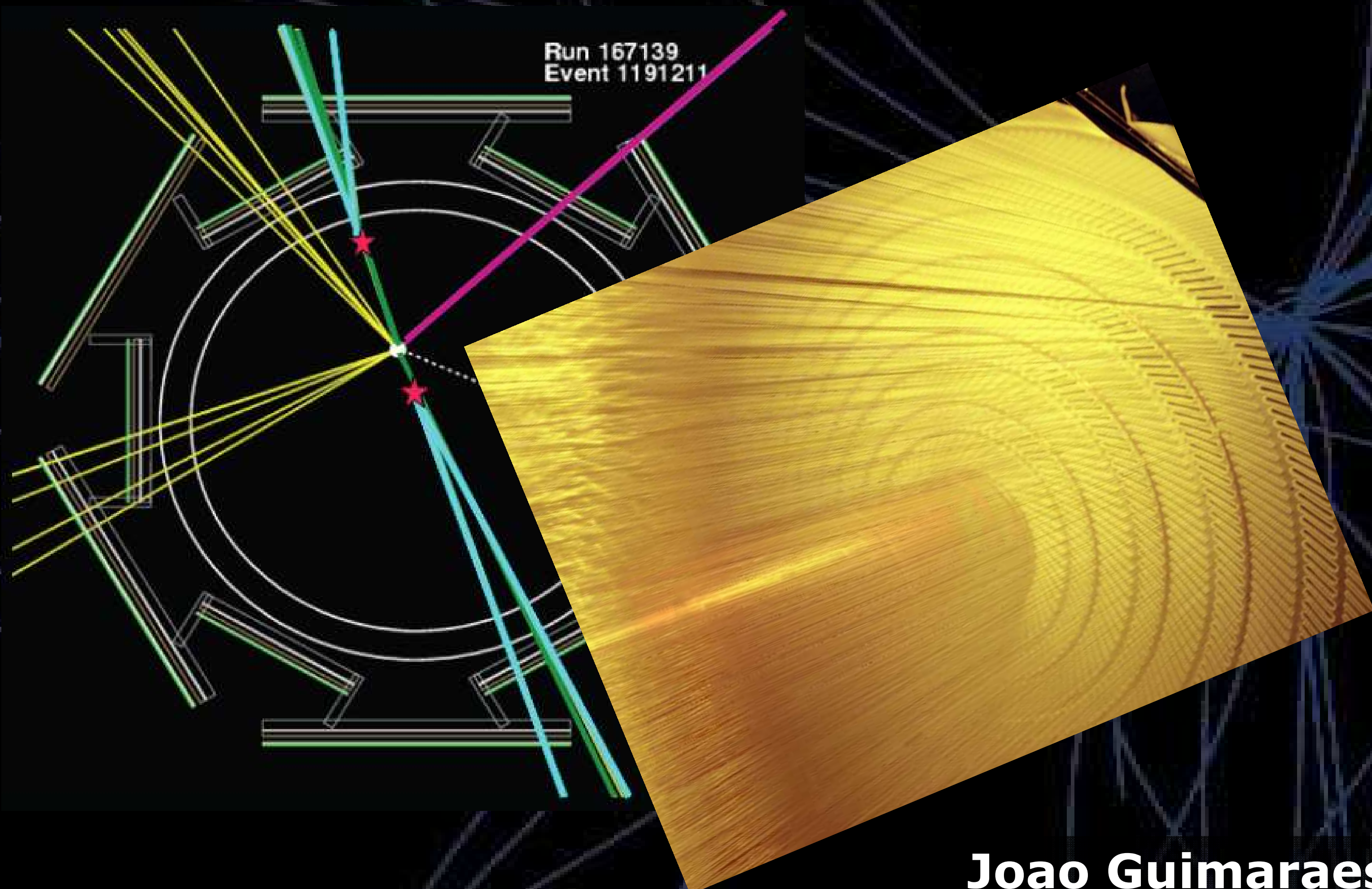
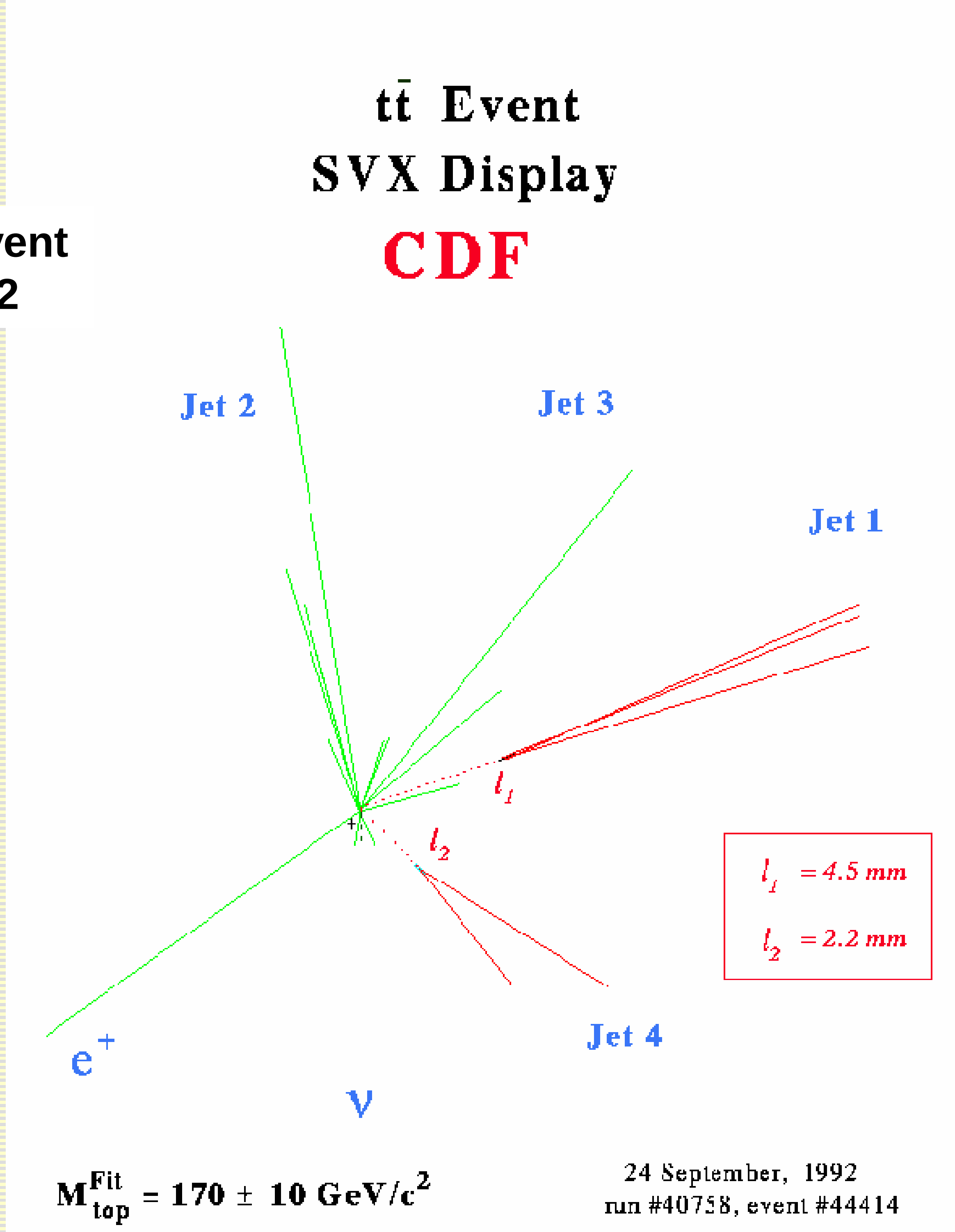
Physics at Hadron Colliders



NEPPSR 2006

Joao Guimaraes da Costa
Harvard University

First top-quark event
September 1992



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NEWS RELEASE

News Release - March 2, 1995

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PHYSICISTS DISCOVER TOP QUARK

Batavia, IL--Physicists at the Department of Energy's Fermi National Accelerator Laboratory today (March 2) announced the discovery of the subatomic particle called the top quark, the last undiscovered quark of the six predicted by current scientific theory. Scientists worldwide had sought the top quark since the discovery of the bottom quark at Fermilab in 1977. The discovery provides strong support for the quark theory of the structure of matter.

FERMILAB-PUB-95/022-E
CDF/PUB/TOP/PUBLIC/3040

Observation of Top Quark Production in $\bar{p}p$ Collisions

Abstract

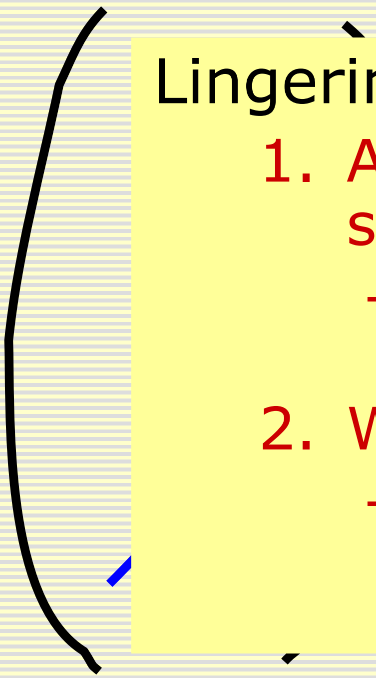
We establish the existence of the top quark using a 67 pb^{-1} data sample of $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab (CDF). Employing techniques similar to those we previously published, we observe a signal consistent with $t\bar{t}$ decay to $WWb\bar{b}$, but inconsistent with the background prediction by 4.8σ. Additional evidence for the top quark is provided by a peak in the reconstructed mass distribution. We measure the top quark mass to be 176 ± 8(stat.) ± 10(sys.) GeV/c^2, and the $t\bar{t}$ production cross section to be $6.8^{+3.6}_{-2.4}$ pb.

$\times$ 35 m_b

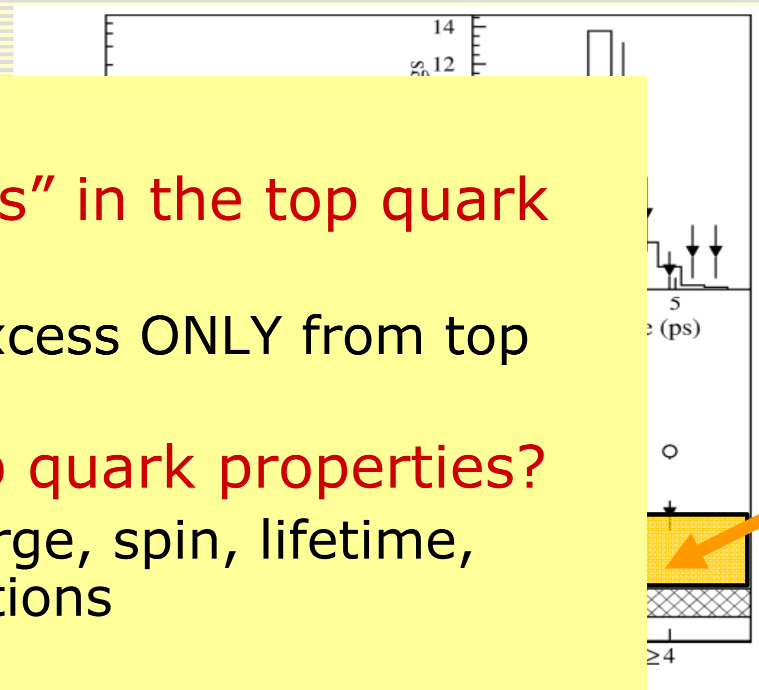
The Top Quark

1989-1995: ~110 pb-1 (Run I)
A few dozen events

Theorist View



Experimentalist View



Lingering Questions:

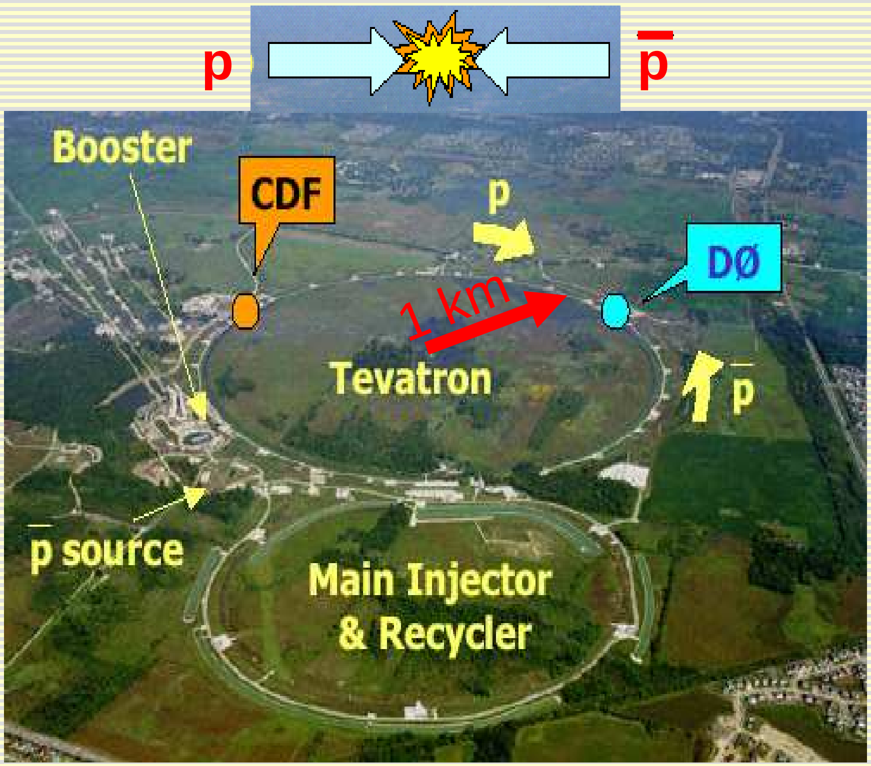
1. Any "New Physics" in the top quark sample?
   – Is the event excess ONLY from top production?
2. What are the top quark properties?
   – Top mass, charge, spin, lifetime, branching fractions

Is "Top" really Top?

Hadron Colliders

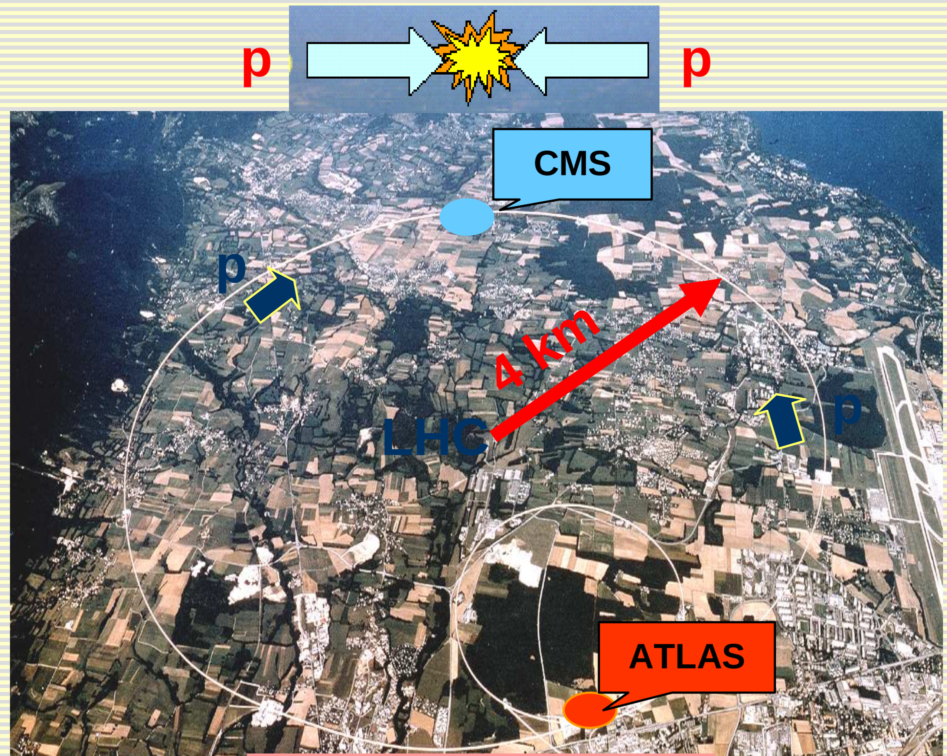
Tevatron
highest energy collider today

1.96 TeV



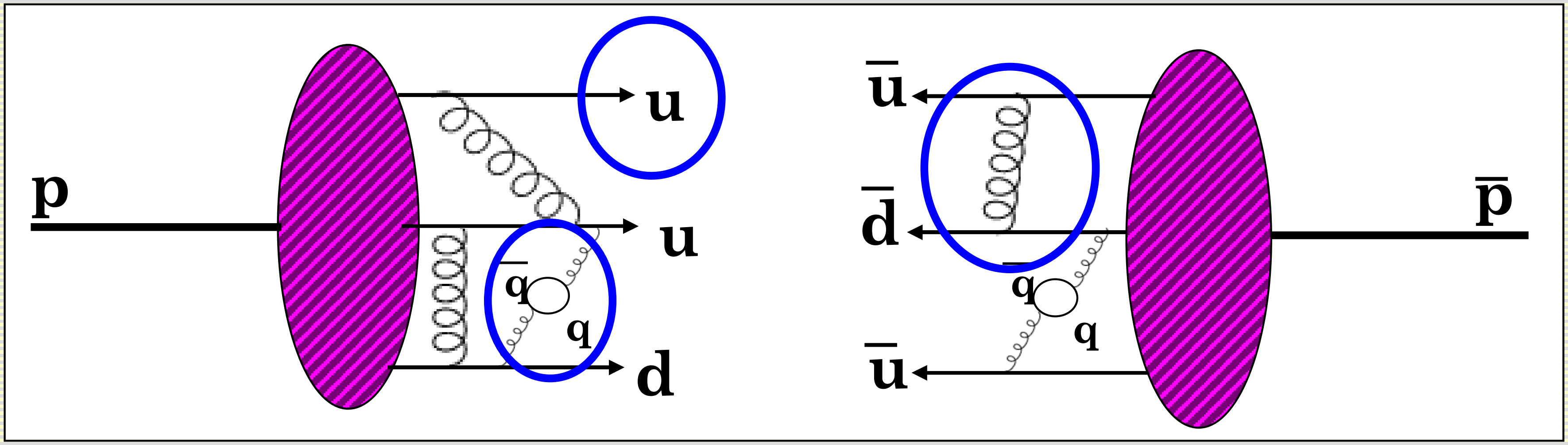
LHC
highest energy collider starting 2008

14 TeV

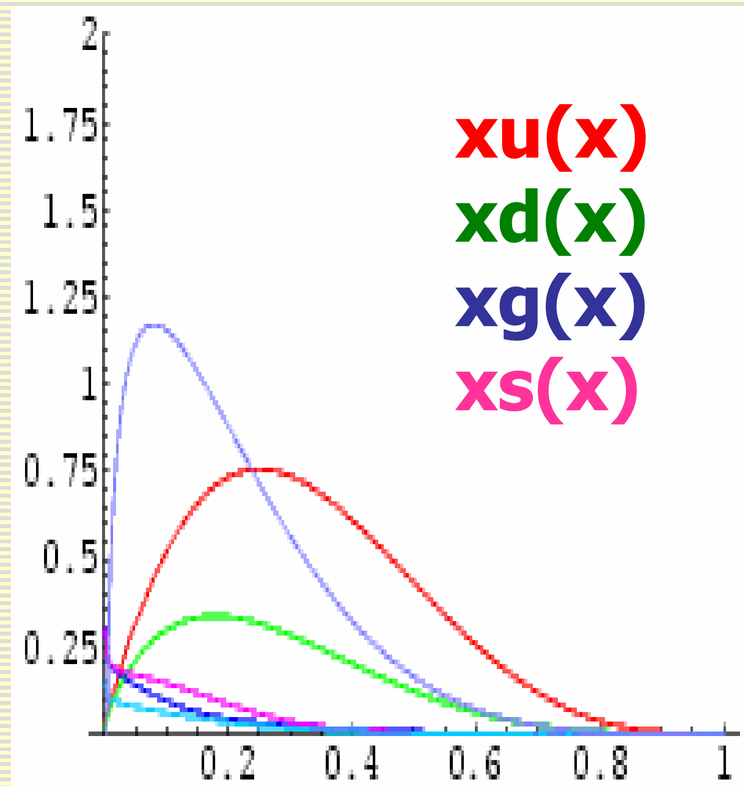


x 30-50 luminosity

Hadron Collider Basics

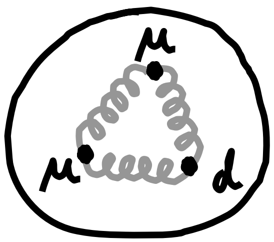


- Hadrons are composite
  - Really collide broad band of constituent partons
    - Valence + Sea quarks
    - Gluons
    - Momentum fraction carried by parton given by measured parton distribution functions (PDFs)
  - parton–parton CM energy ~ 1/6 beam–beam CM energy
  - Additional particles from “underlying event

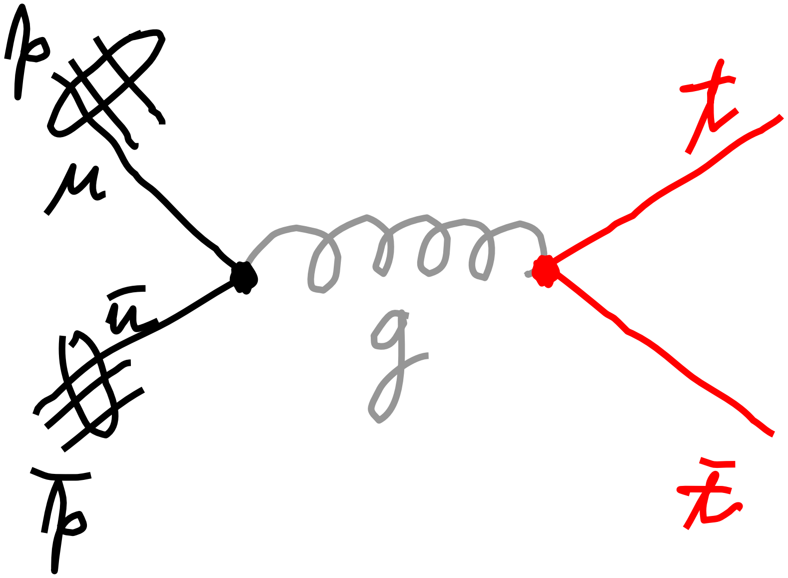


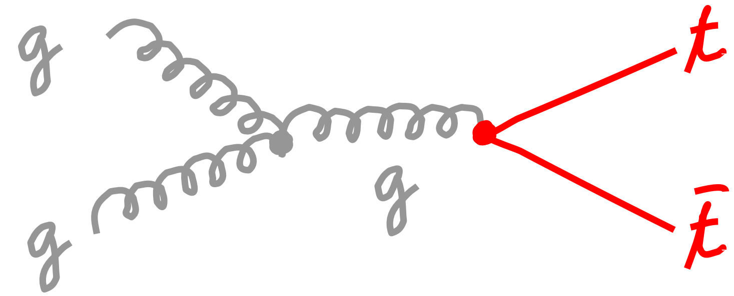
Top Quark Production at Hadron Colliders

Proton

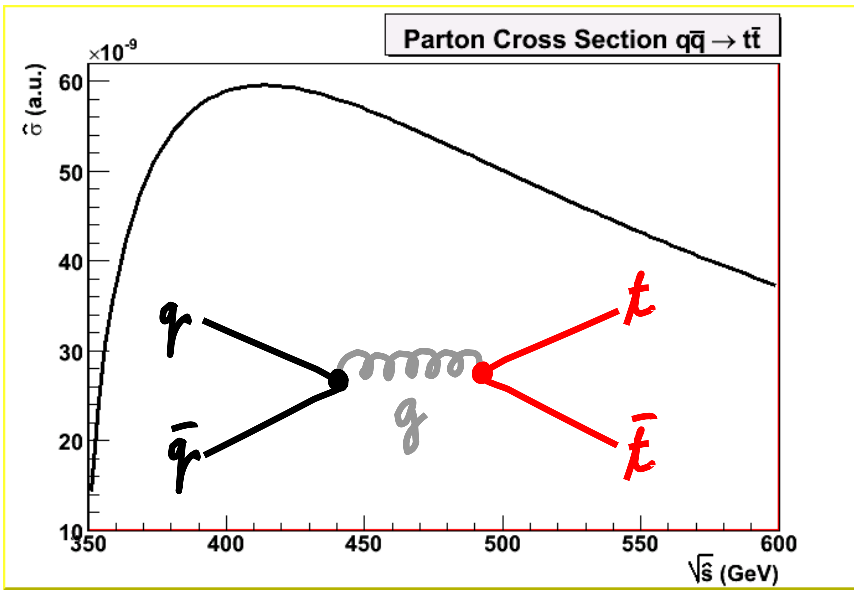


$$x = \frac{p_{parton}}{p_{proton}}$$





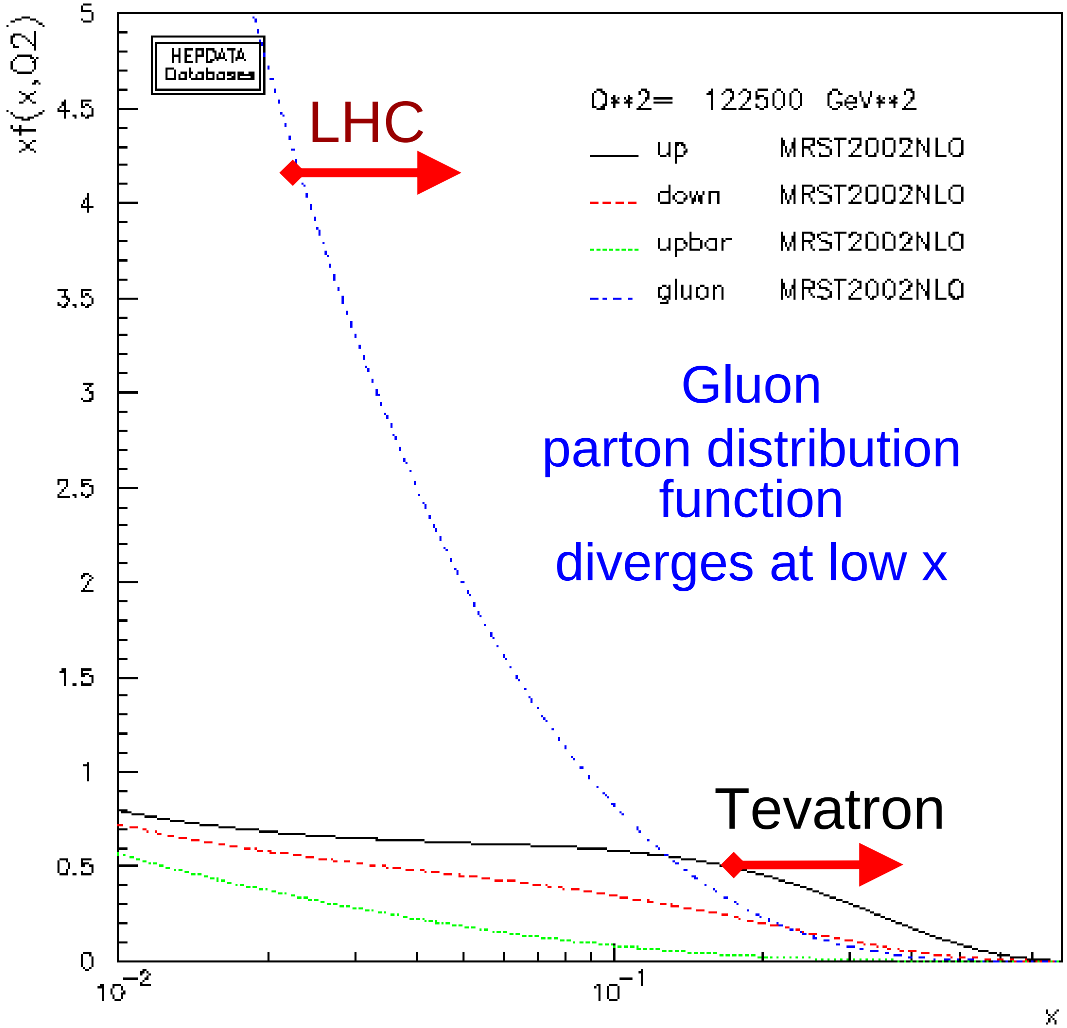
$$\sigma(p\bar{p} \rightarrow t\bar{t}) = \sum_{i,j} \int dx_i F_i\left(x_i, \mu^2\right) \int dx_j F_j\left(x_j, \mu^2\right) \hat{\sigma}_{ij}\left(\hat{s}, \mu^2, M_{top}\right)$$



Hard scattering cross-section

Parton Distribution Functions

Parton distribution function: $xF(x,\mu^2)$



$$x = \frac{p_{parton}}{p_{proton}}$$

Effective center of mass energy

$$\sqrt{\hat{s}} < \sqrt{s}$$

$$\sqrt{\hat{s}} > 2m_{top}$$

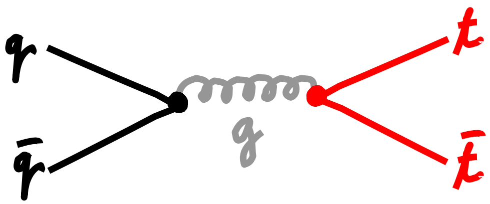
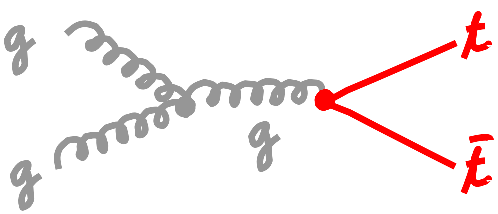
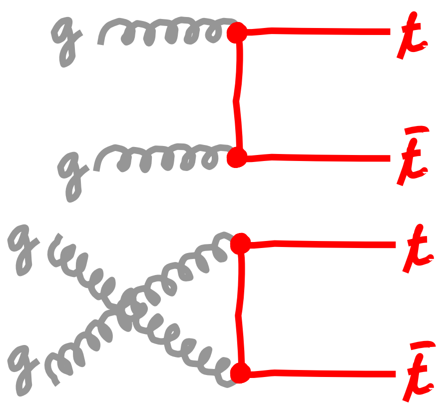
$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} = x\sqrt{s}$$

$$x_1 \approx x_2$$

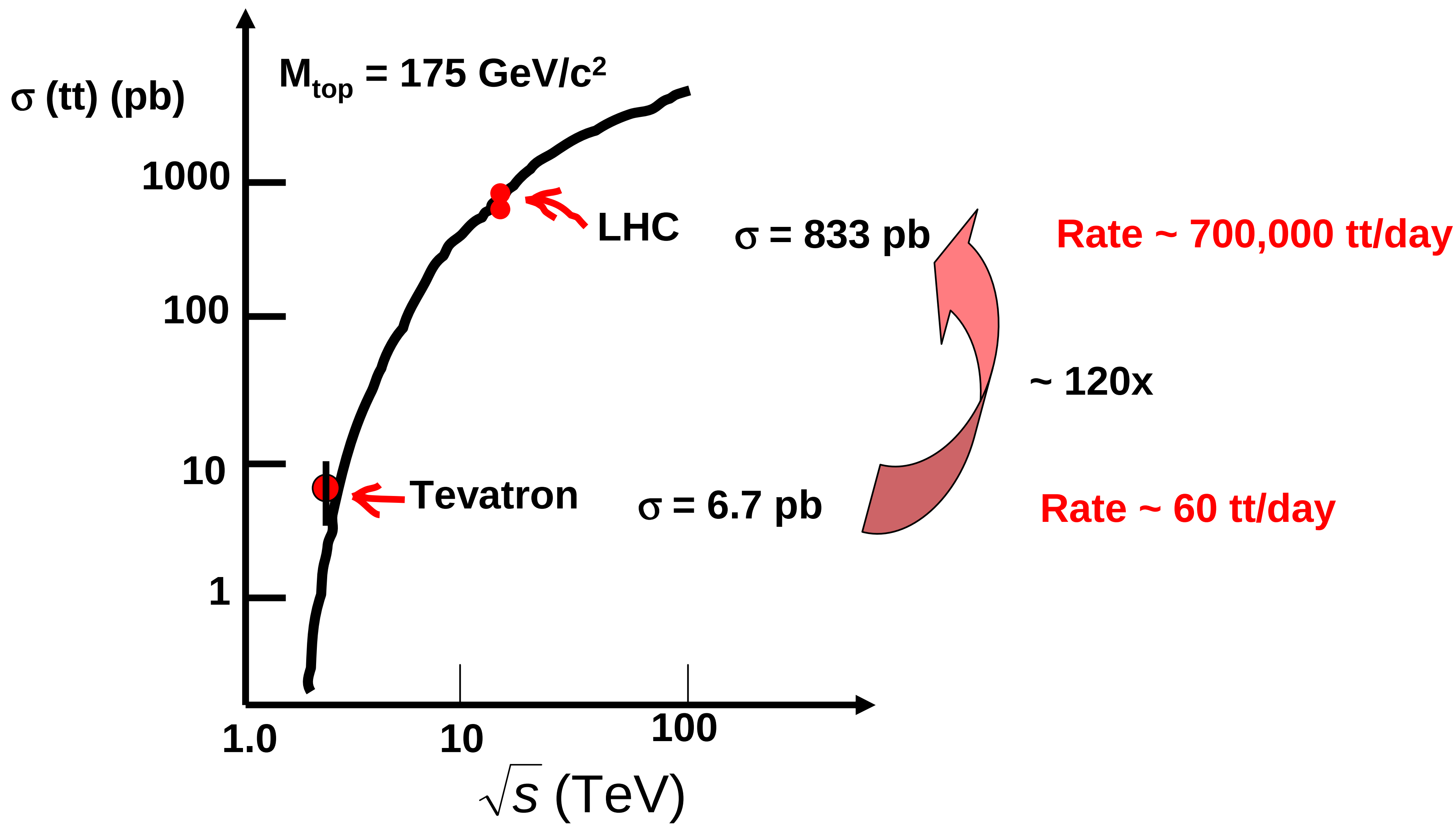
TeV $x \geq \dfrac{2m_{top}}{\sqrt{s} = 1.96\,TeV} = 0.18$

LHC $x \geq \dfrac{2m_{top}}{\sqrt{s} = 14\,TeV} = 0.025$

Top Quark Pair Production

	Tevatron $\sqrt{s} = 1.96\,TeV$	**LHC** $\sqrt{s} = 14\,TeV$
	**85%**	**10%**
 	**15%**	**90%**

Theoretical Cross Section

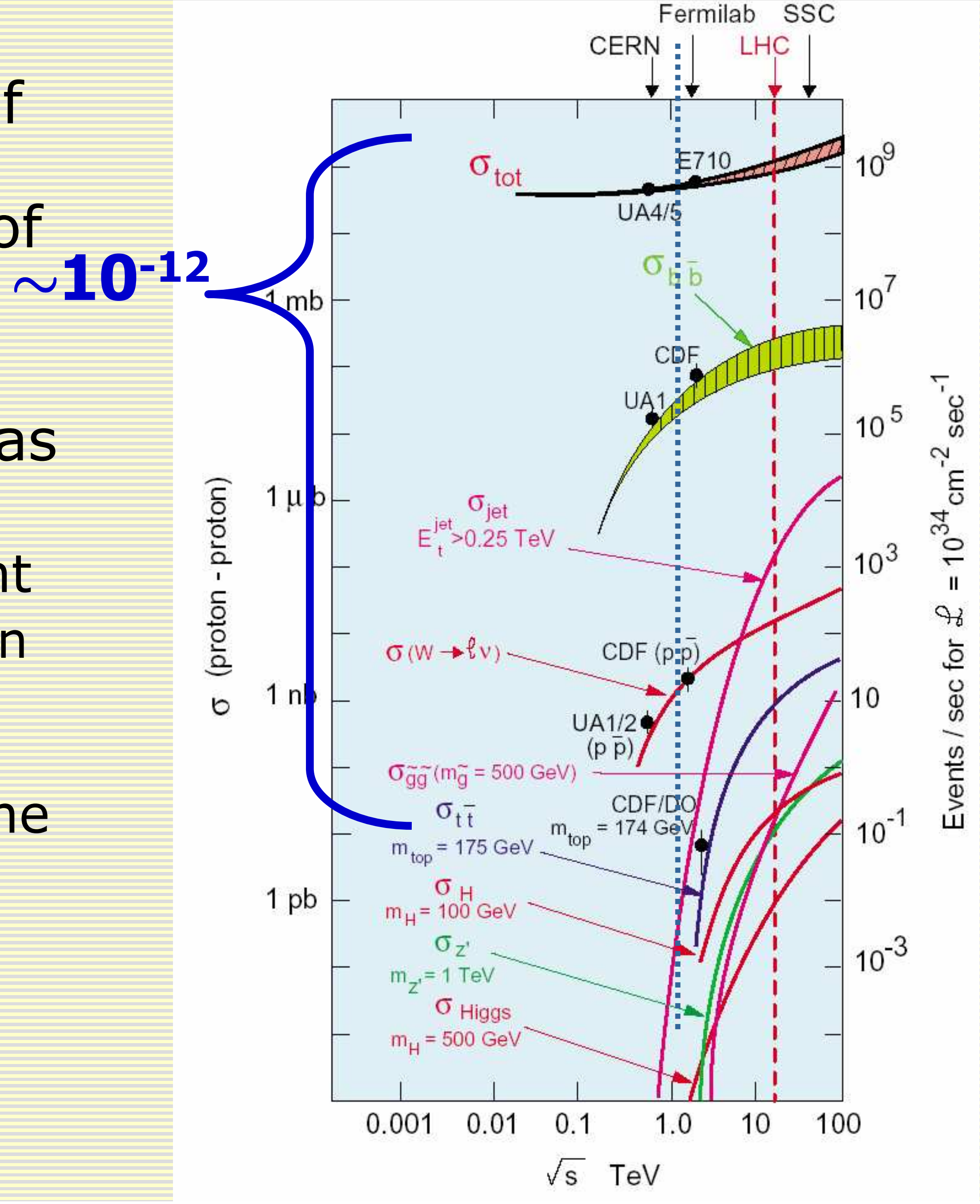


Cacciari et al.
JHEP 0404:068 (2004)
Kidonakis & Vogt
PRD 68 114014 (2003)

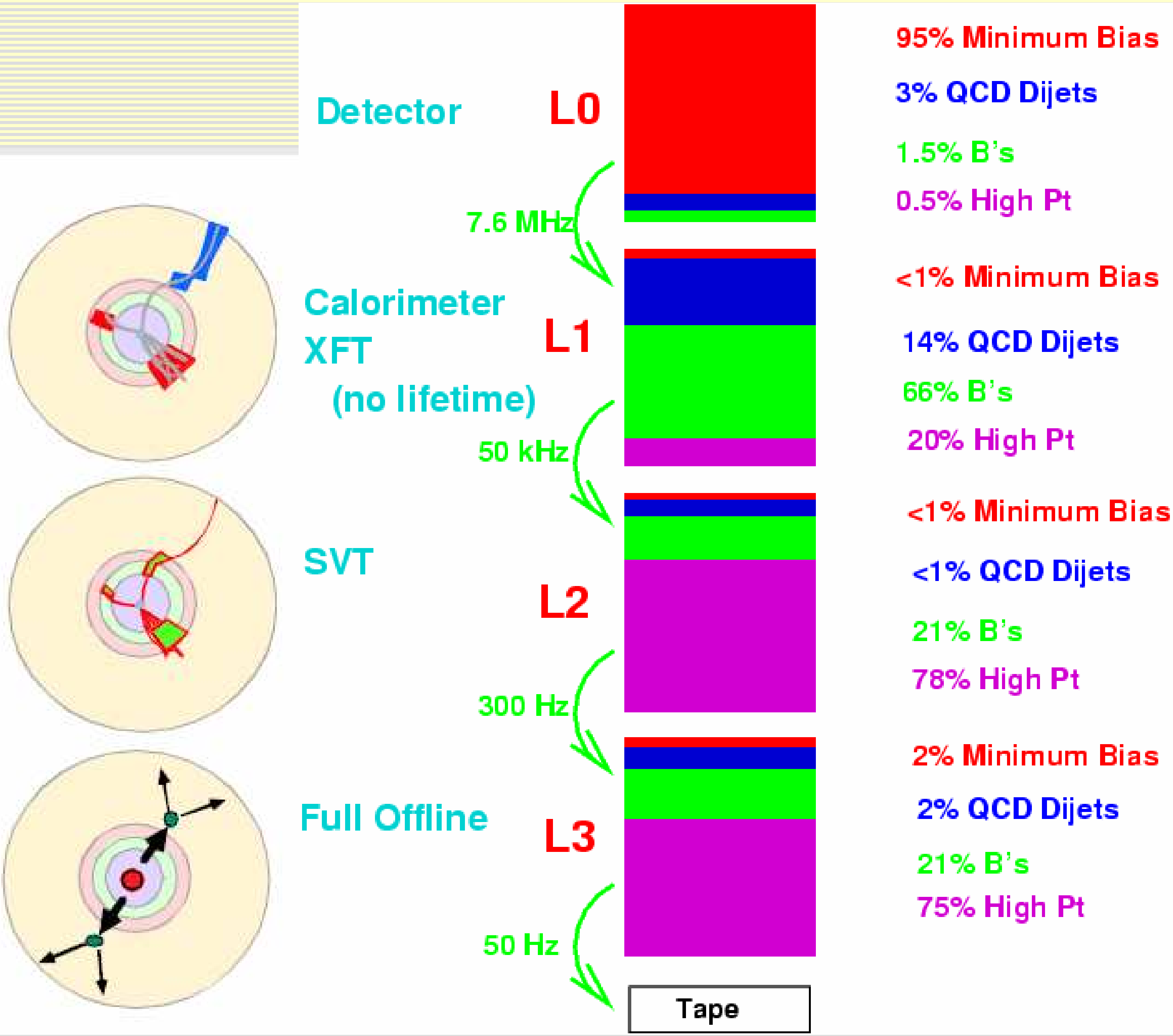
Hadron Colliders – Challenges

- Probability for "soft" QCD interactions many orders of magnitude greater than hard scattering processes of interest

- Analysis of collision data has added complications
  - No beam energy constraint
    - Momentum conservation constraint only in transverse plane
  - Possibility of more than one interaction per beam crossing
  - Incoming partons may radiate gluons



Trigger



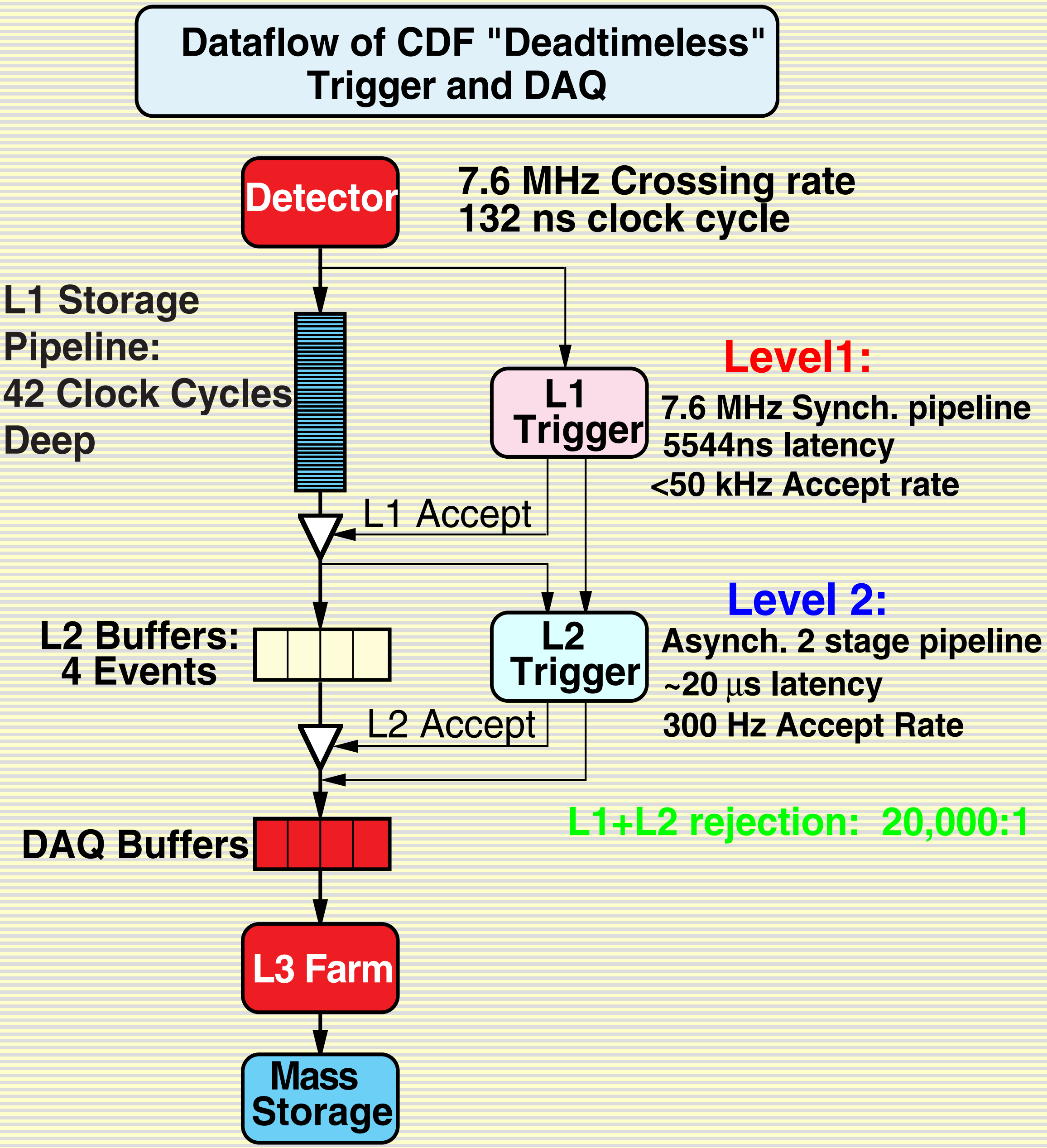
Soft QCD

QCD Dijets

B physics

High p_T

Trigger and Data Acquisition



In modern experiments, acquire LOTS of data in very short time:

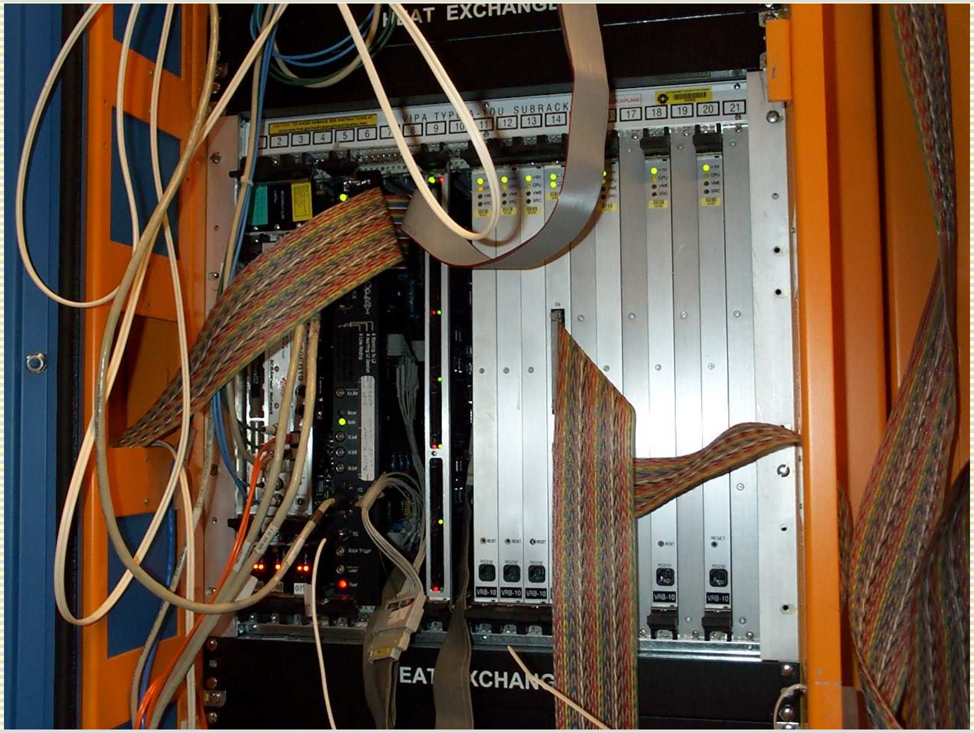
- Proton-anti-proton collisions happen at the Tevatron every 396 ns ~ 7 MHz.
- CDF has about 1 Mio electronic channels

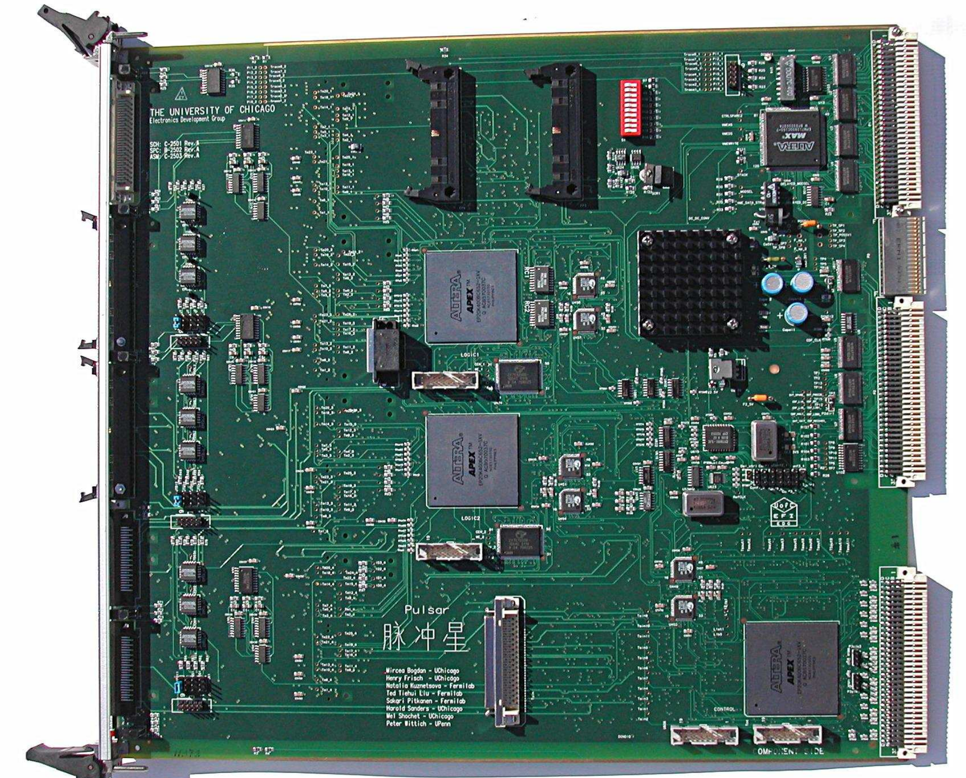
  ⇒O(1 TBit/sec)

  ⇒ Electronics and network can't handle that – need to select interesting events at pallatable rate

  ⇒ Need a Trigger

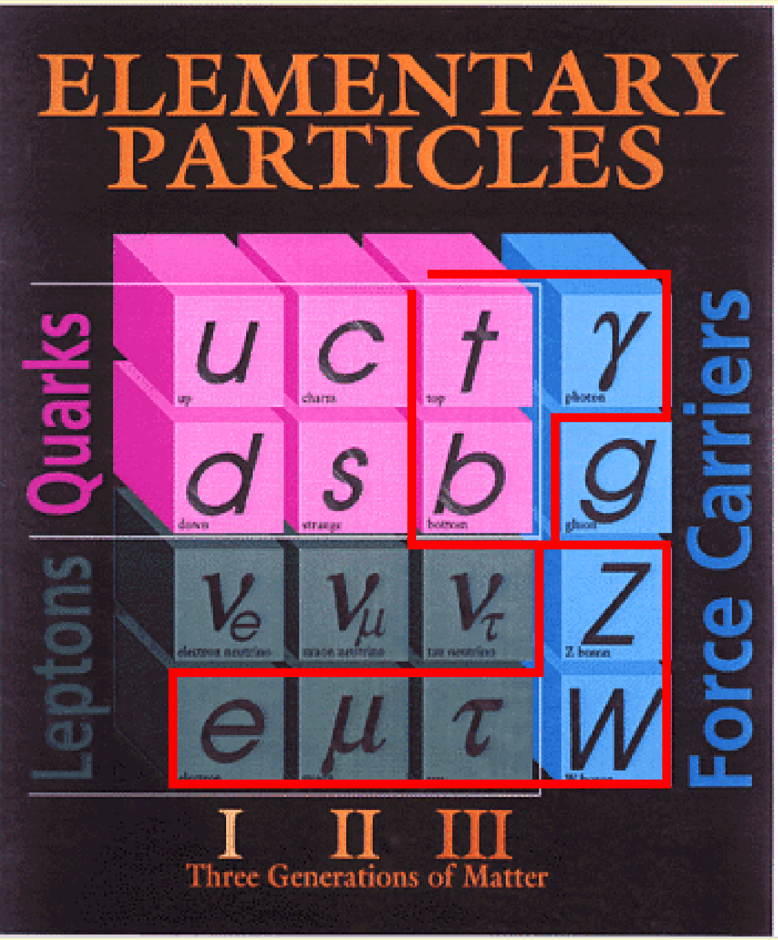
A CDF VME crate





Pulsar PCB, top side

Theoretical High-Energy Physics



- 4 forces carried by gauge bosons
  - Electromagnetism (g)
  - Weak (W,Z)
  - Strong (gluon)
  - Gravity (Graviton)

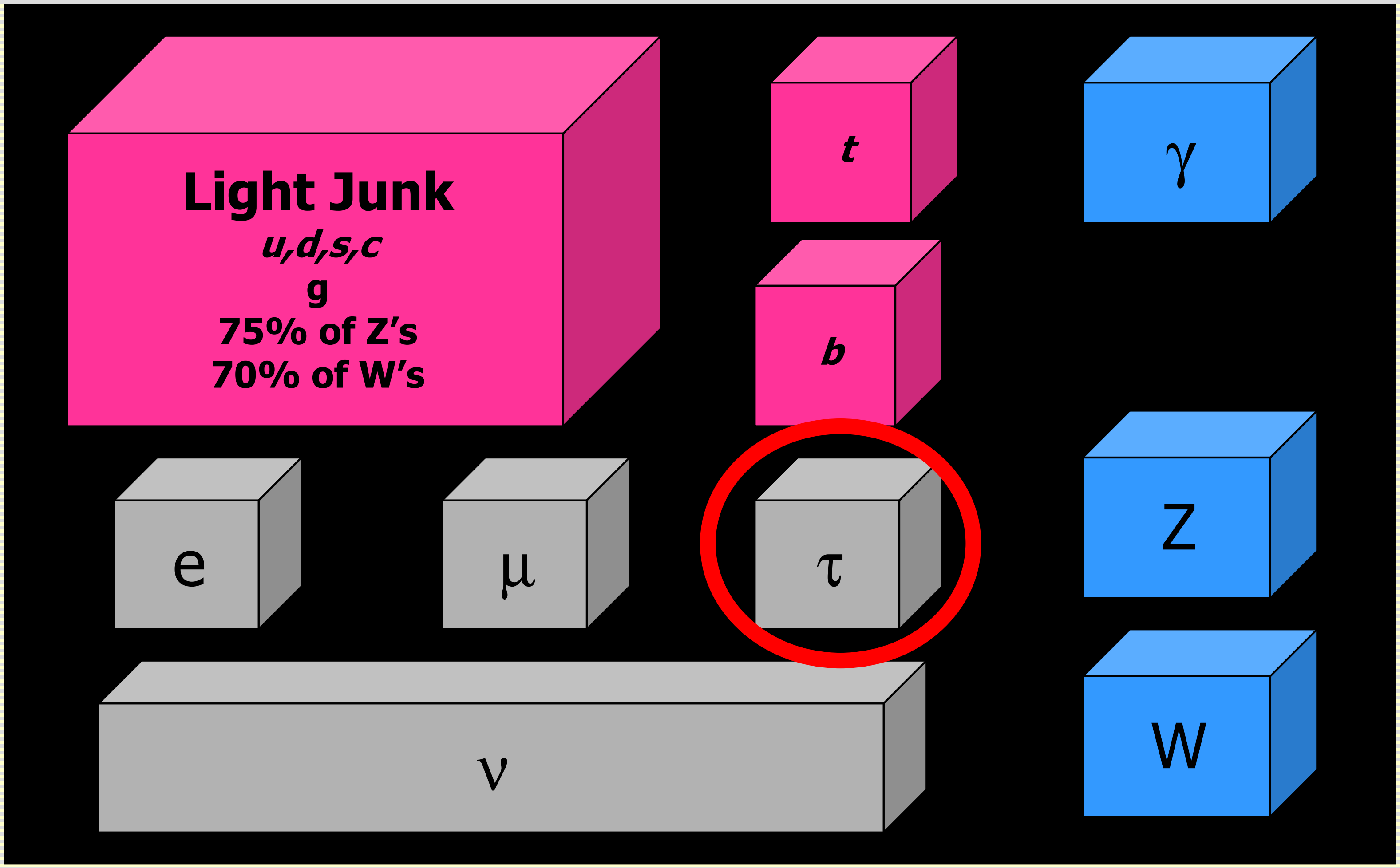
Electroweak

GUT?

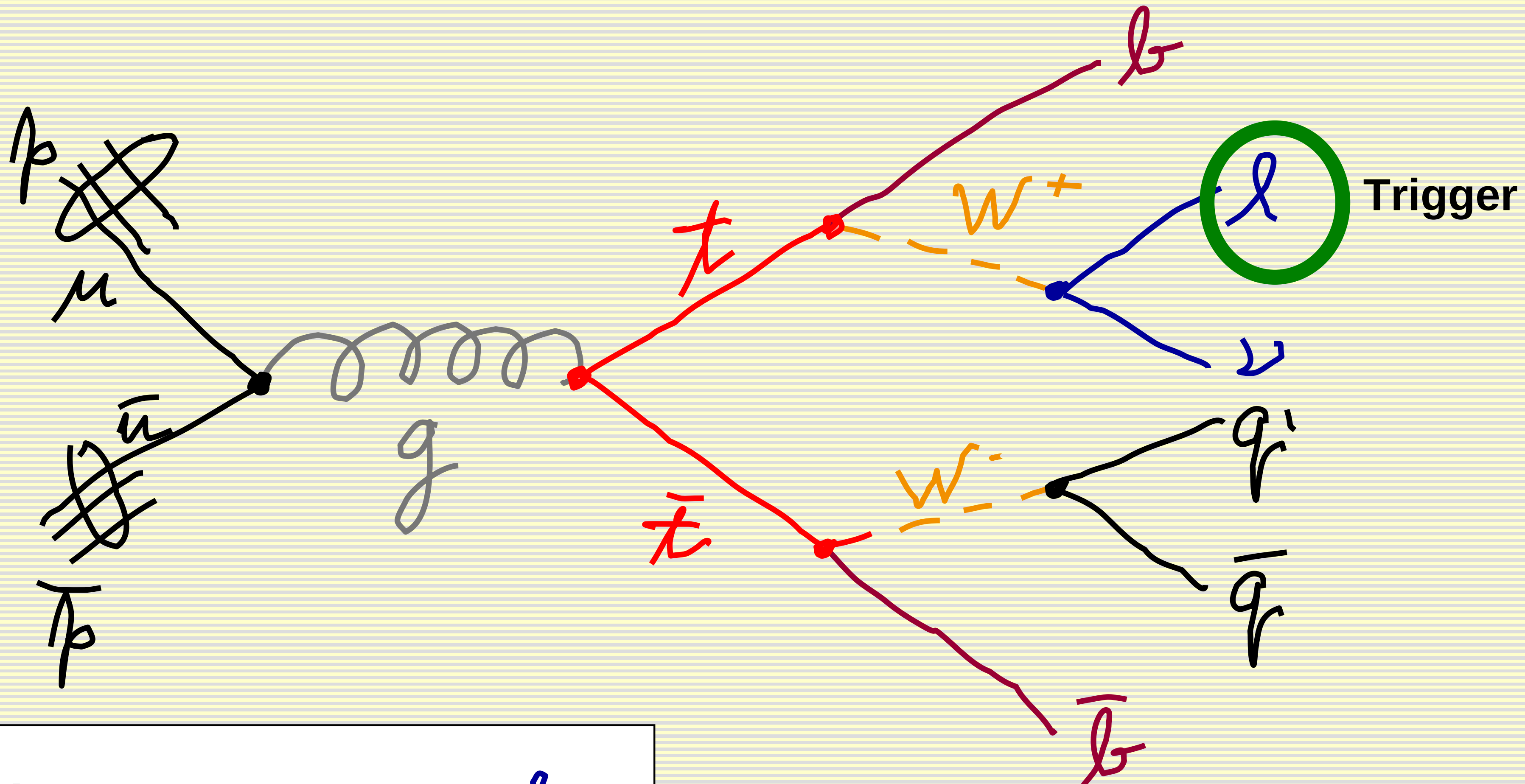
?

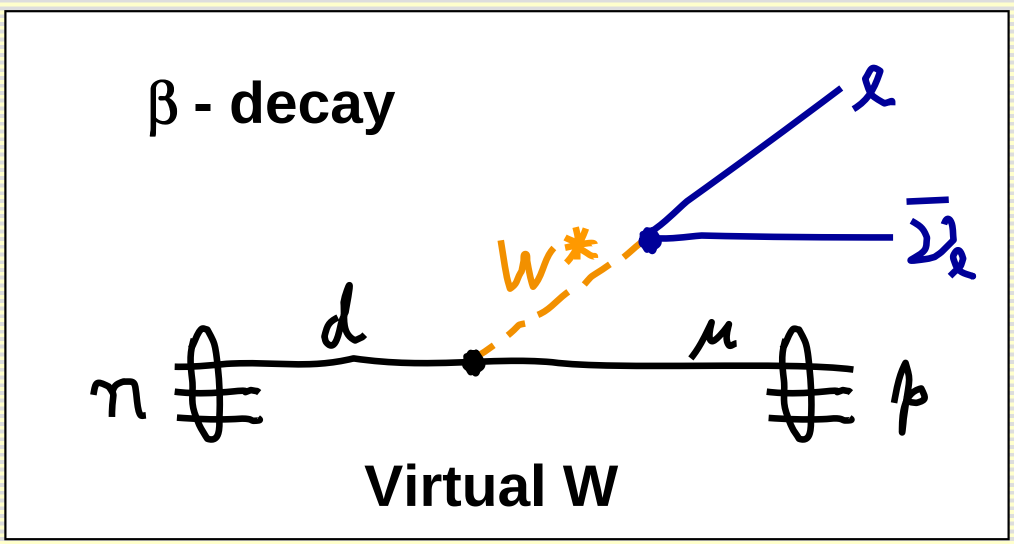
Strings?
SUSY?
Extra dimensions?

Experimental
Hadron-Collider Physics



The Top Event



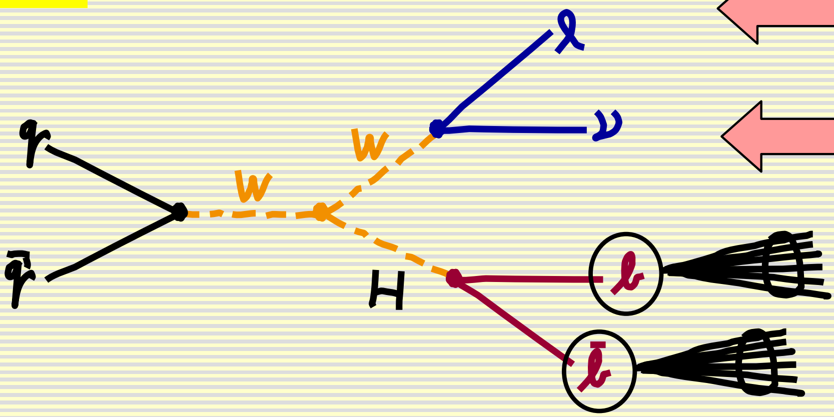


Always:

2 jets are b-quark jets

Physics Signatures

Higgs

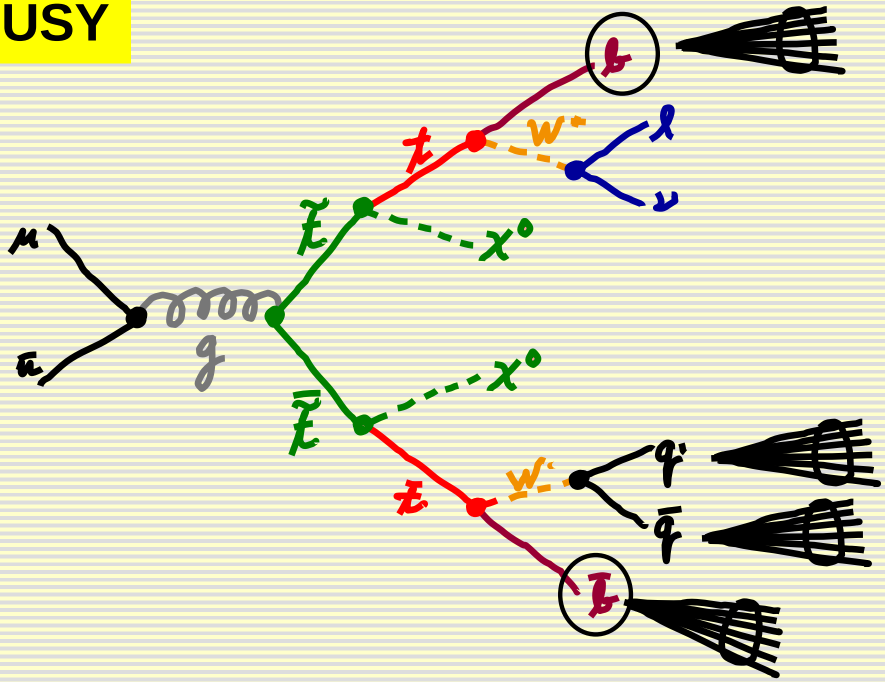


Ionization detectors (charged particles)

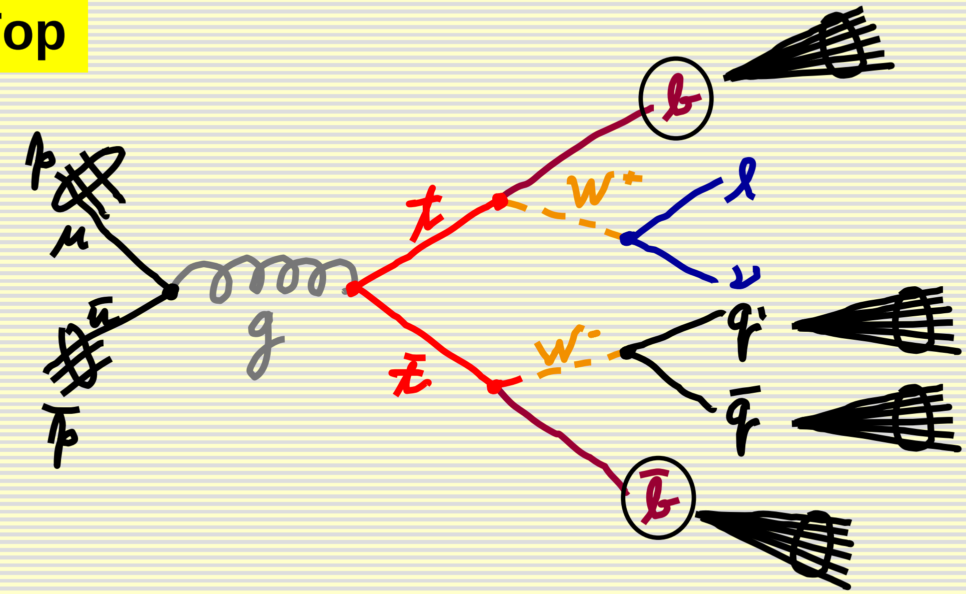
Missing transverse energy

Jets

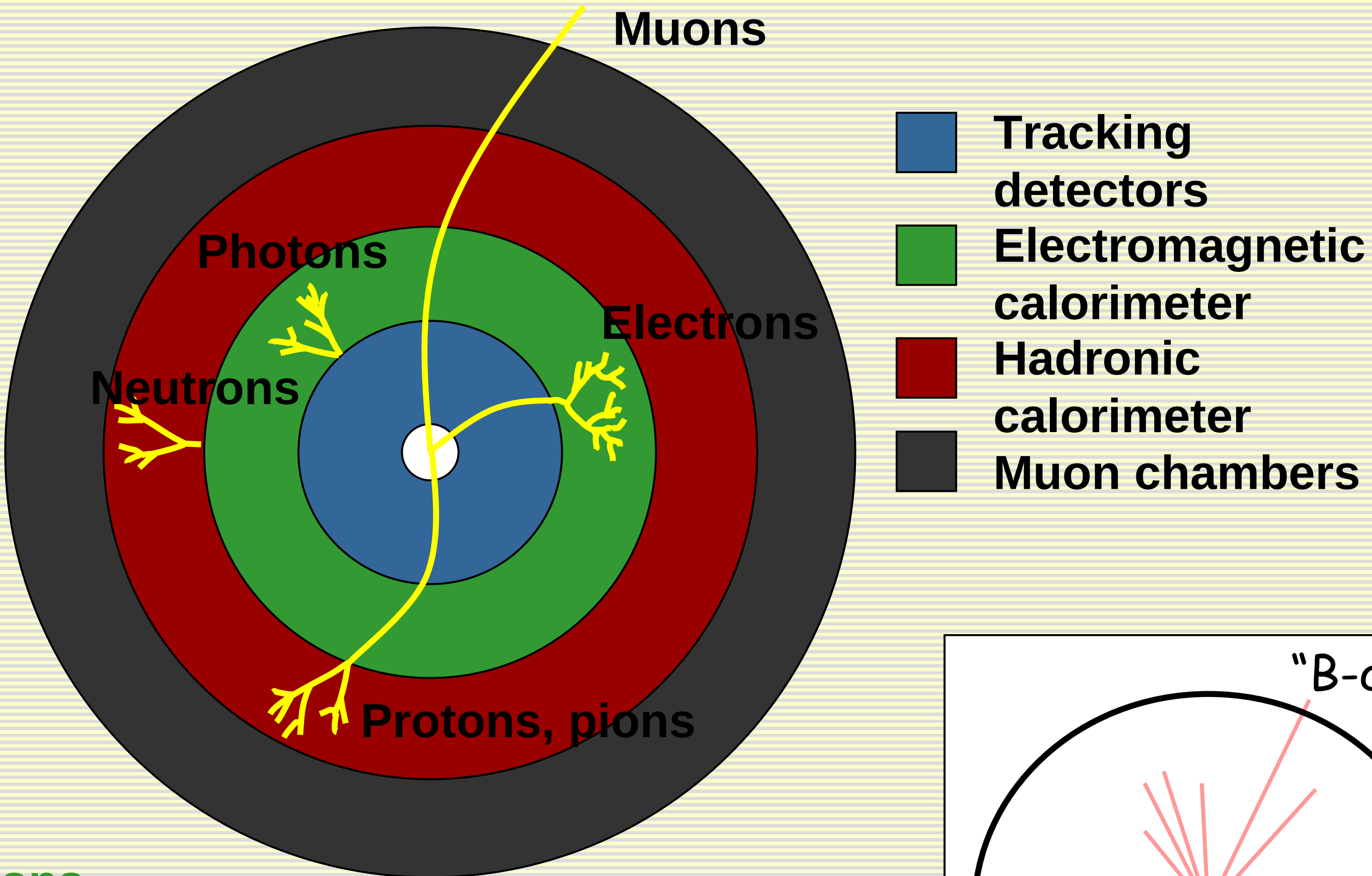
SUSY

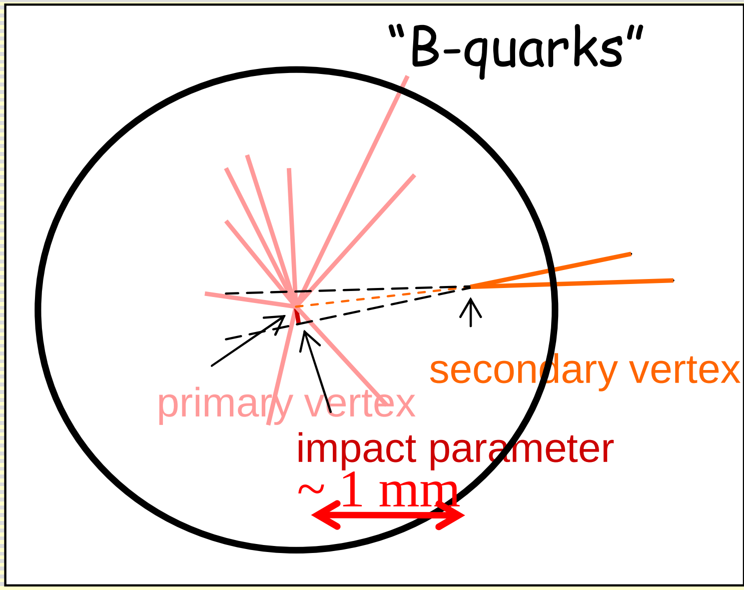


Top

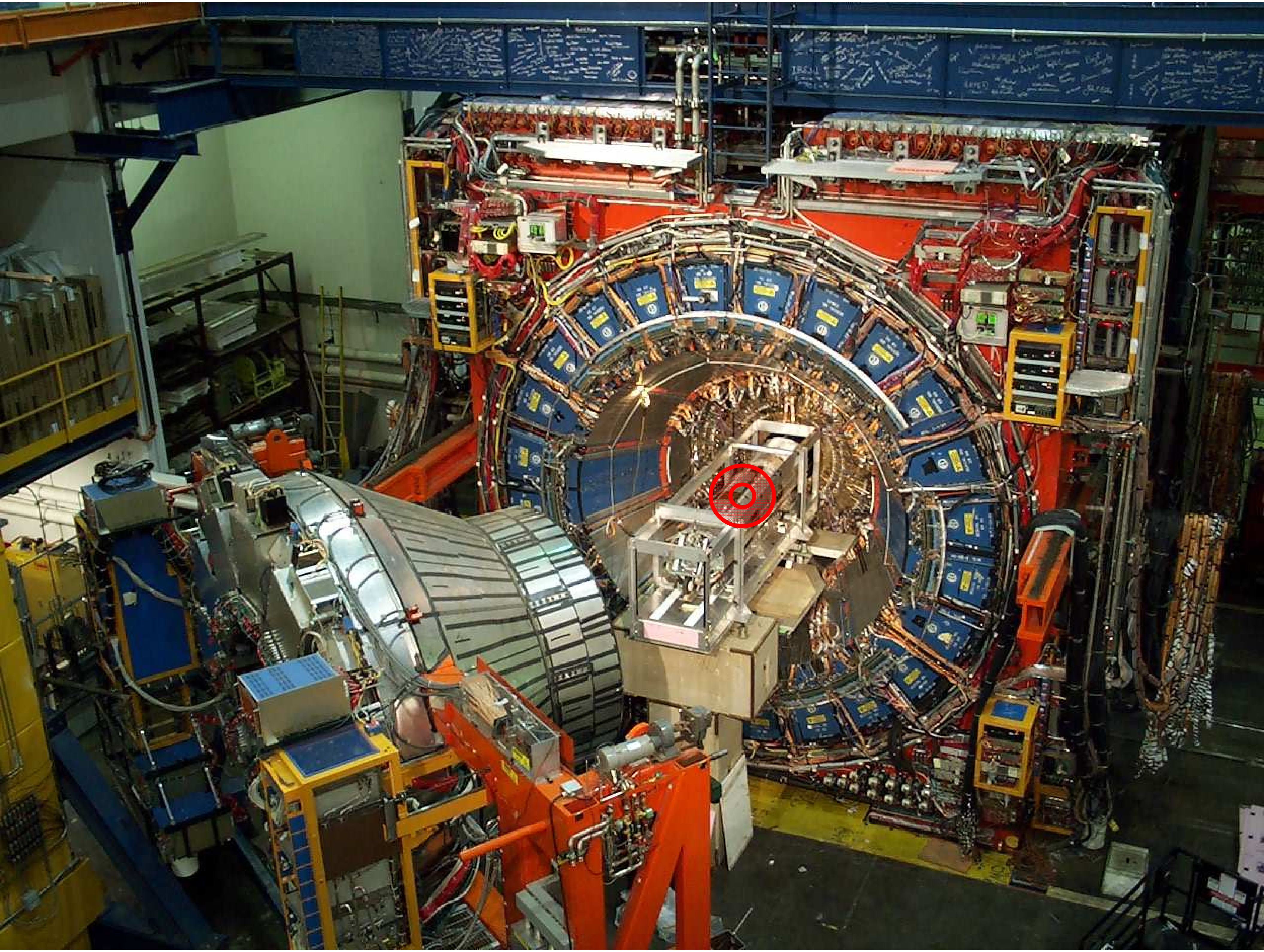


How We Detect Different Particle?

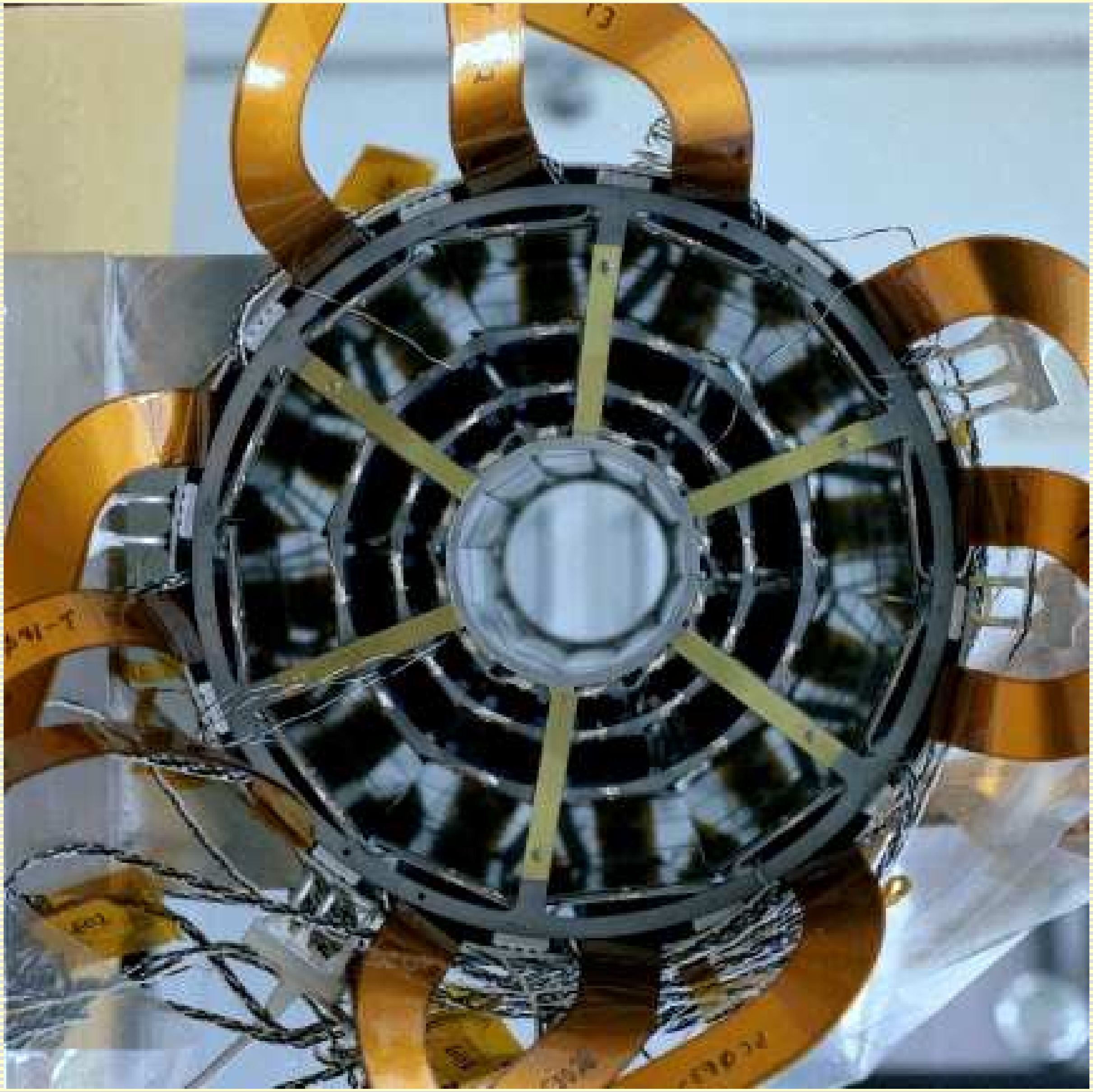




- Quarks/gluons
  - **Detected in collimated flows of hadrons → Jets**
- Neutrinos
  - **Detected indirectly → Missing energy**



Silicon Detector in Top Quark Discovery



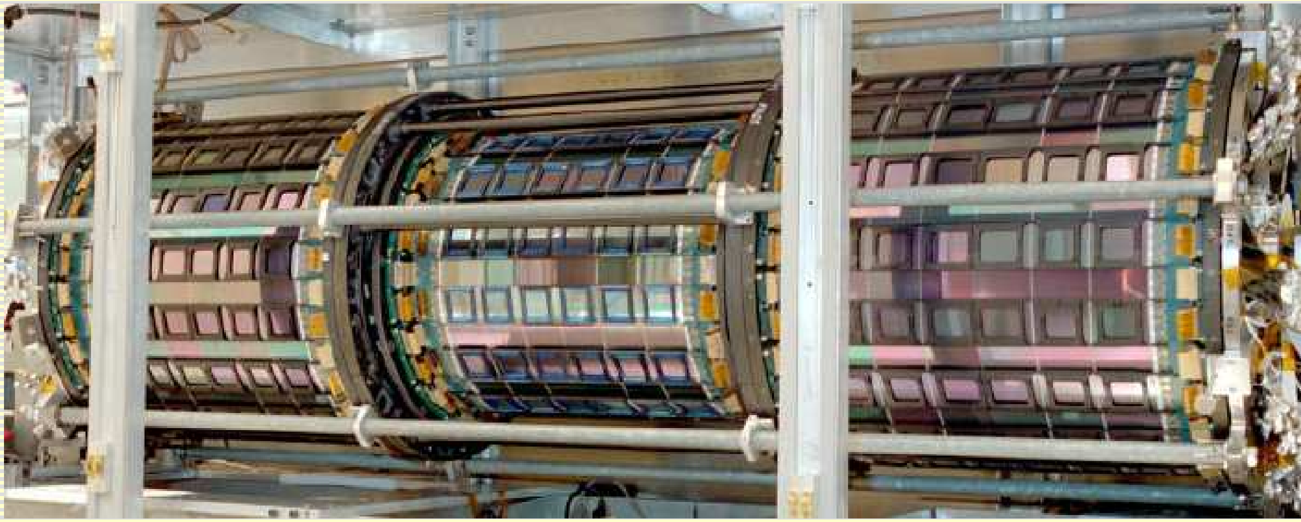
New detection technique

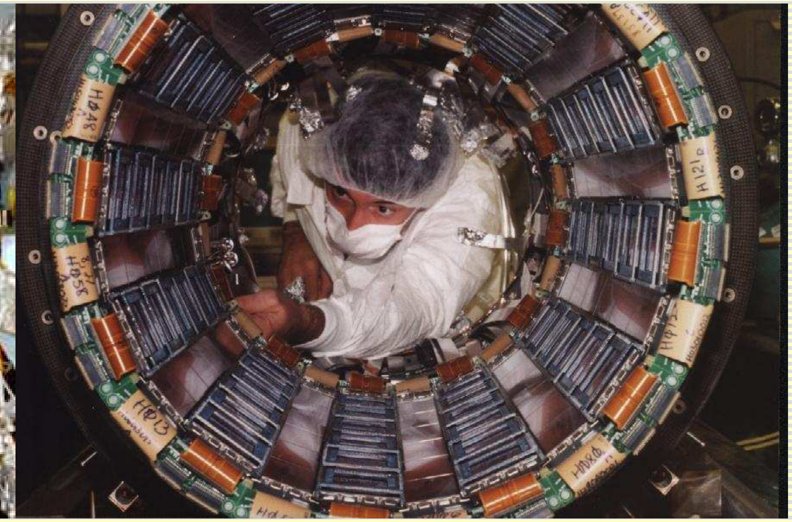
⇩

Top quark discovery

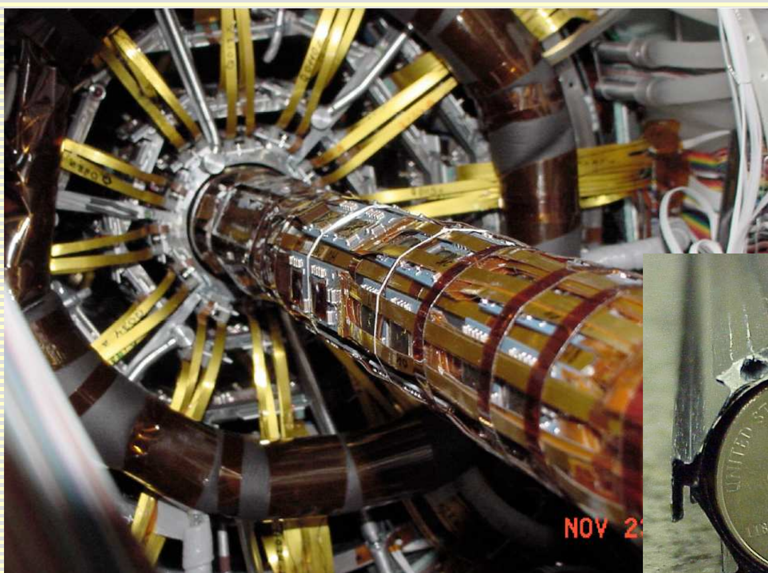
4 Silicon Layers

The New Silicon Detector





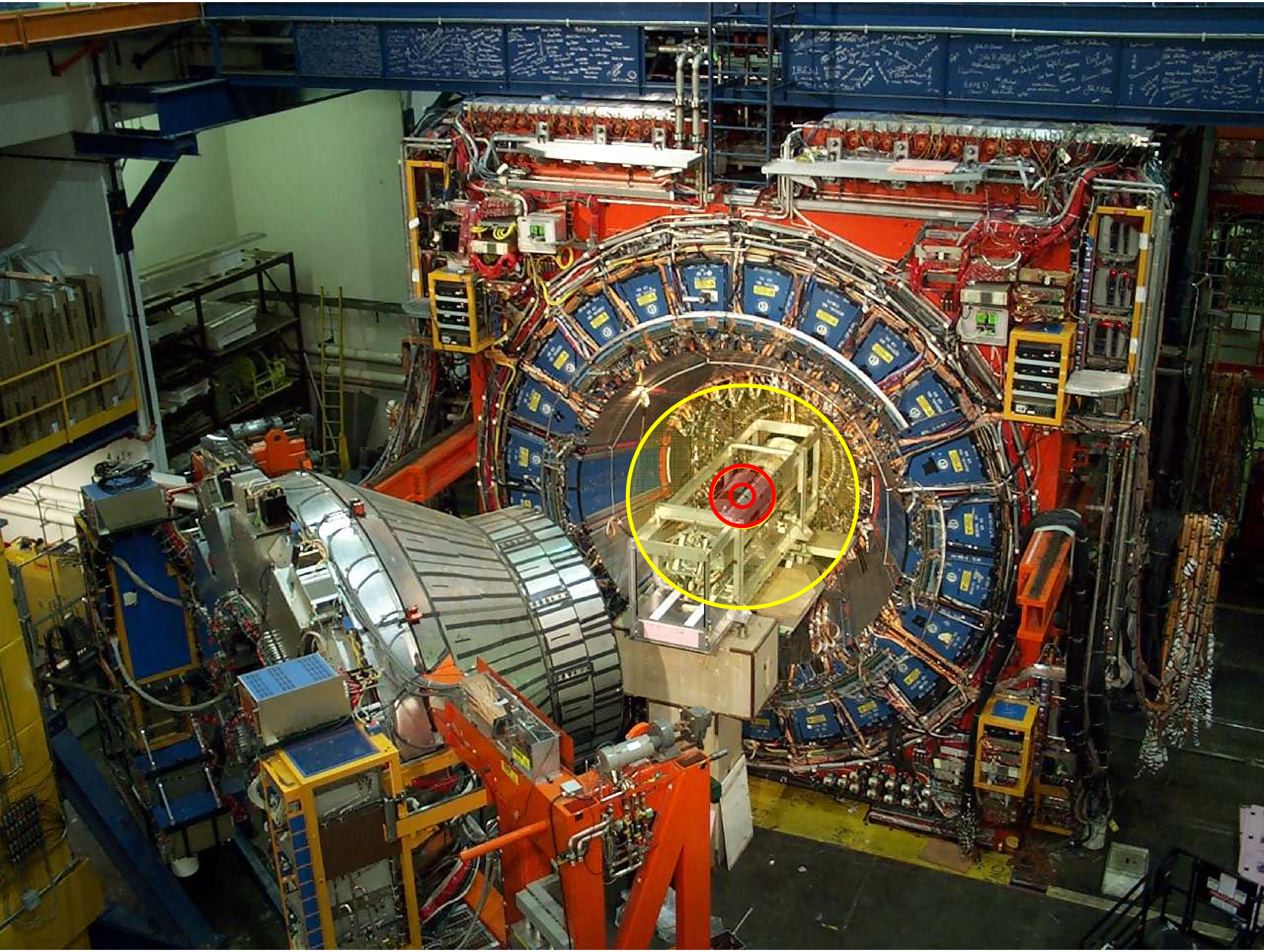
1.9 meter



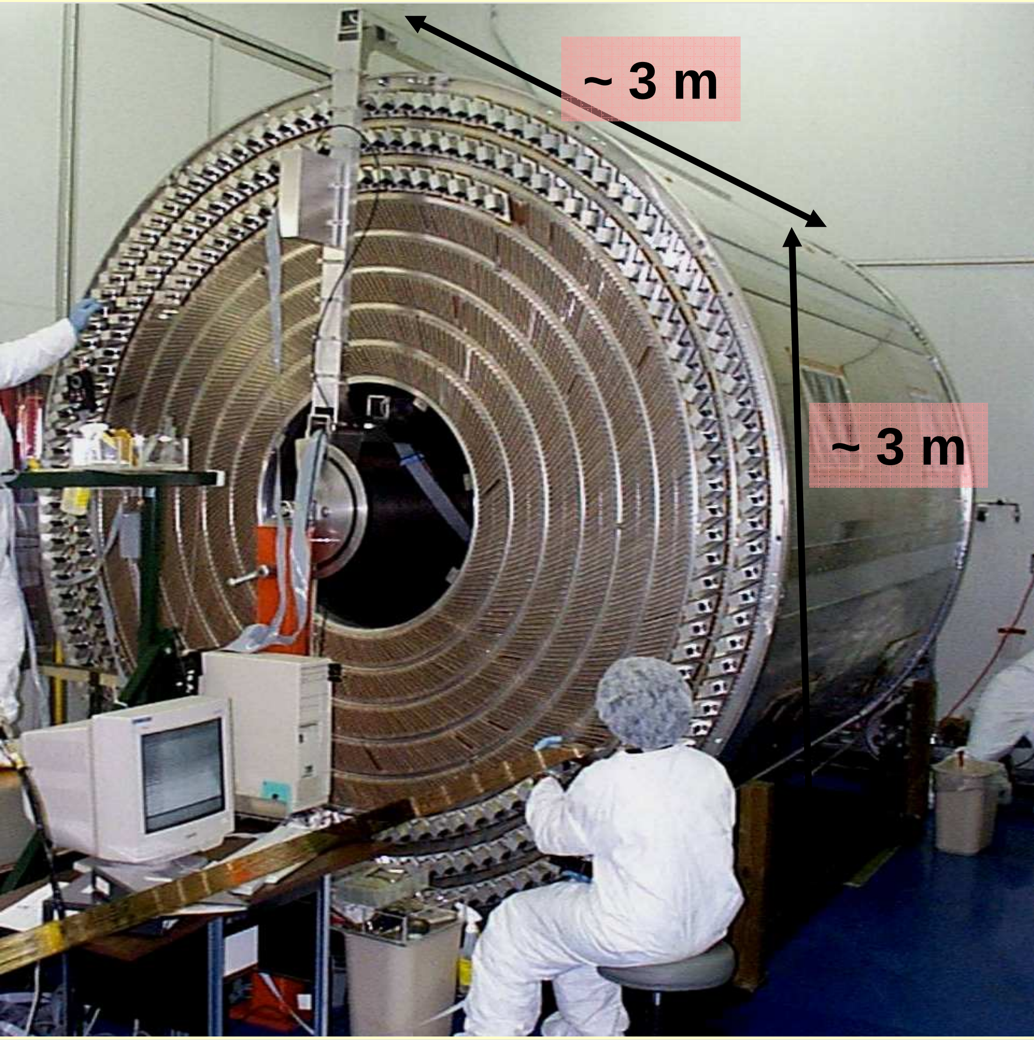
7- 8 Silicon Layers

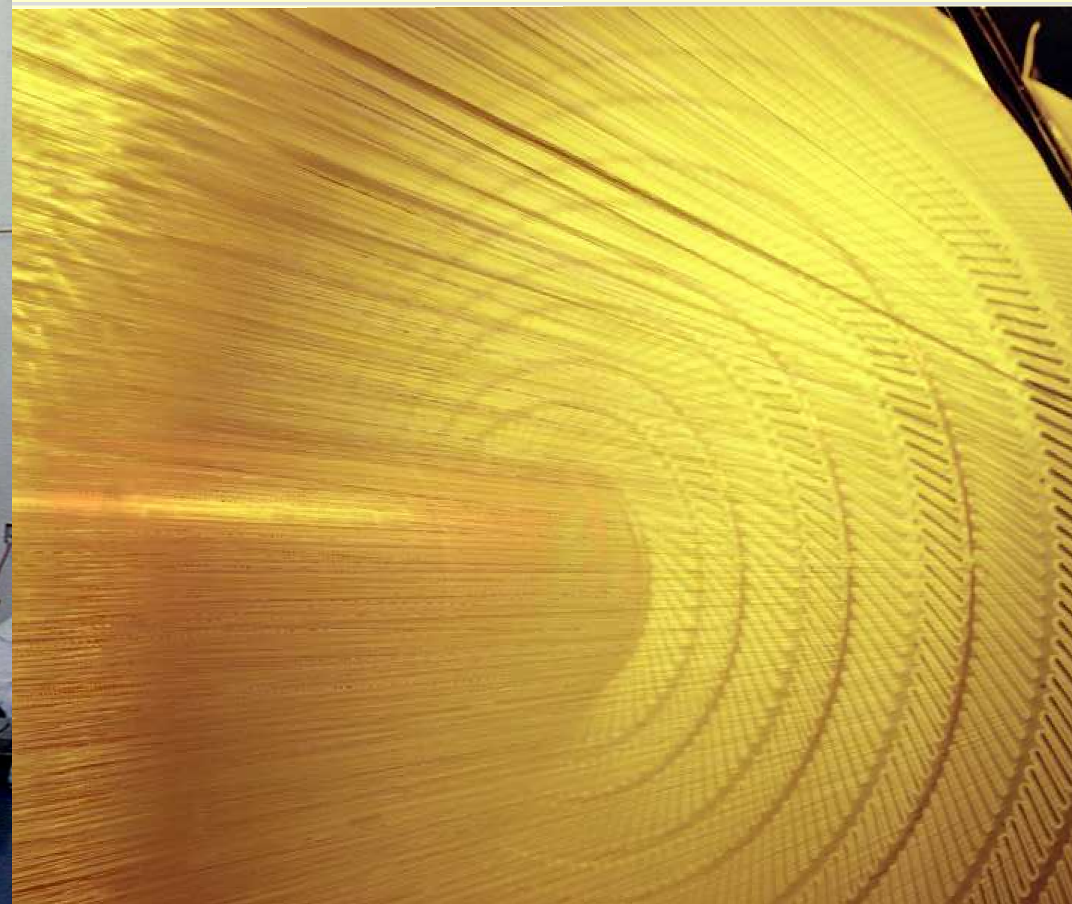
Readout channels
48,000 → 730,000

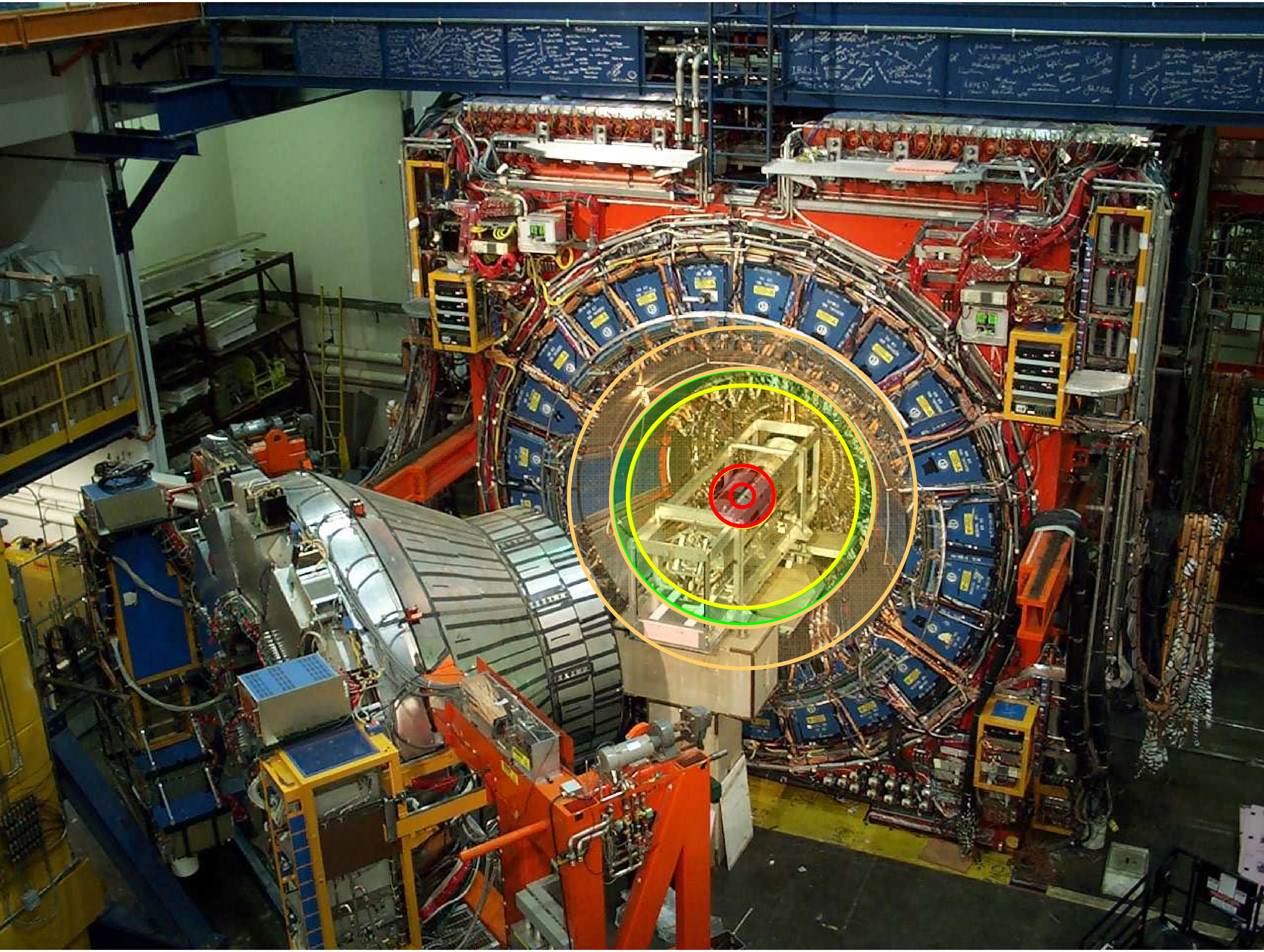
Beampipe
(the size of a quarter)



30,000 high-voltage human-hair-thick Gold-plated Tungsten wires in Argon-Ethane gas

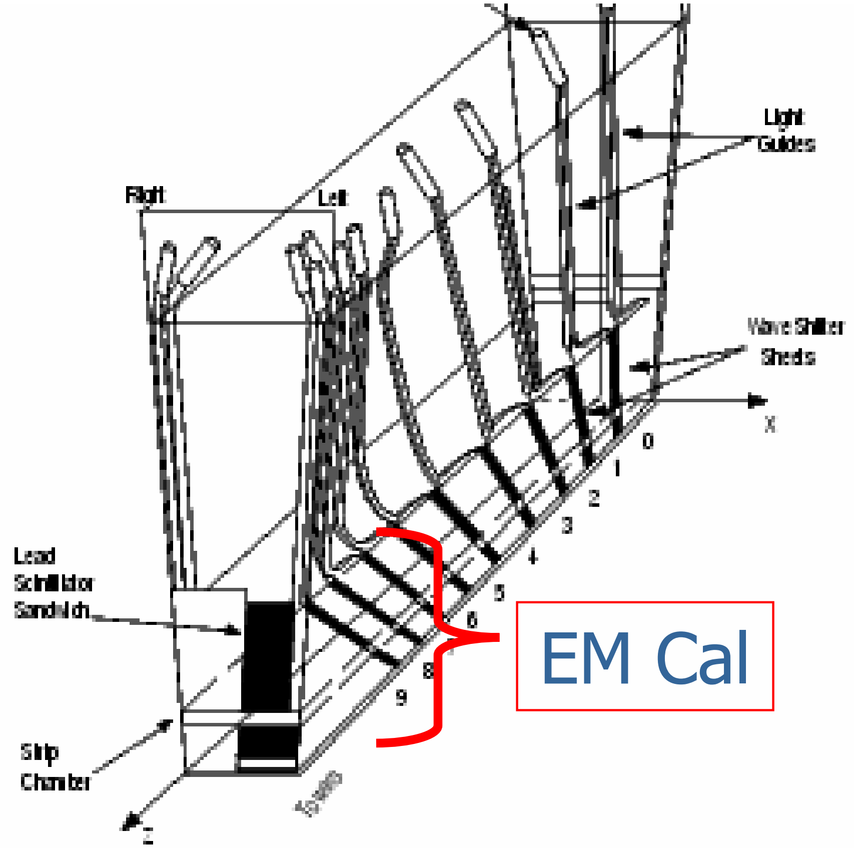


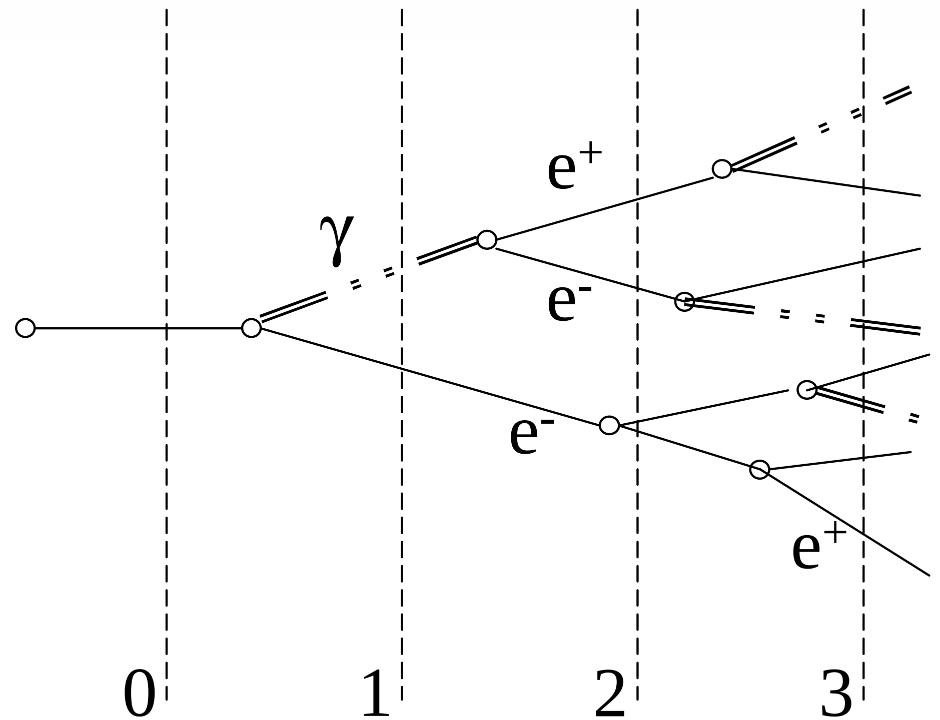




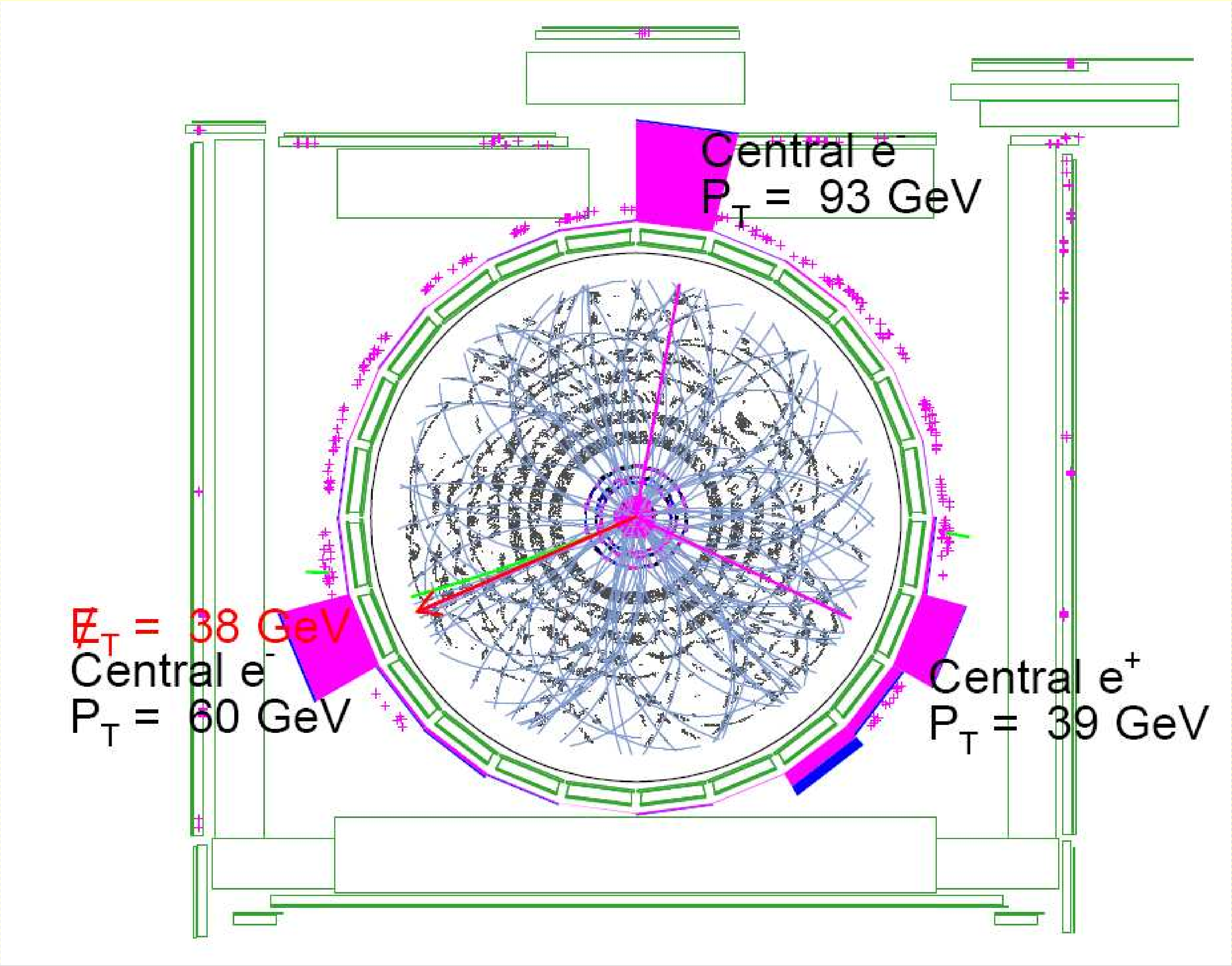
Calorimeter (EM)

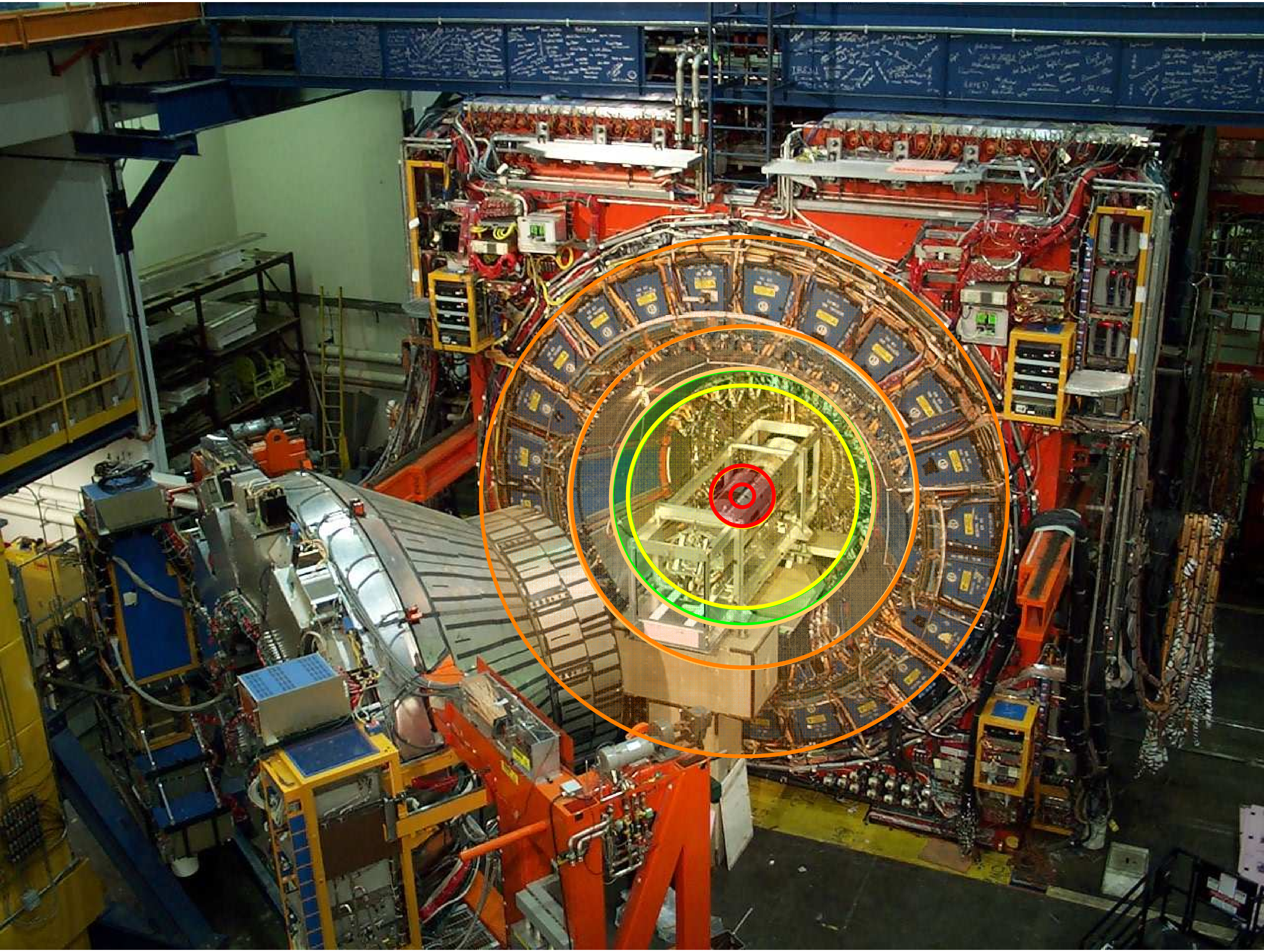
- Lead-scintillator sandwich
  - Lead initiates γ conversion, bremsstrahlung
  - Scintillators detect low-energy ionizing electrons and positrons
    - Light guides bring scintillator light out to PMTs
  - 18 radiation lengths
    - 1/8" Pb, 5mm scintillator
- Total ionization proportional to initial energy of e, γ





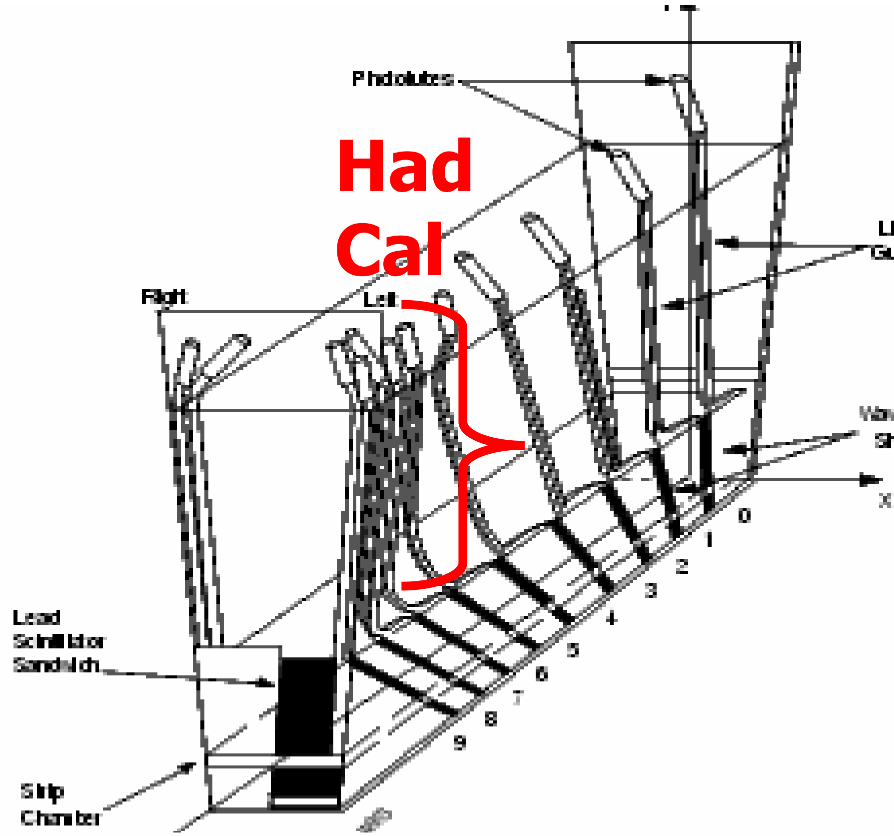
Clean Event: ZW→eeeν

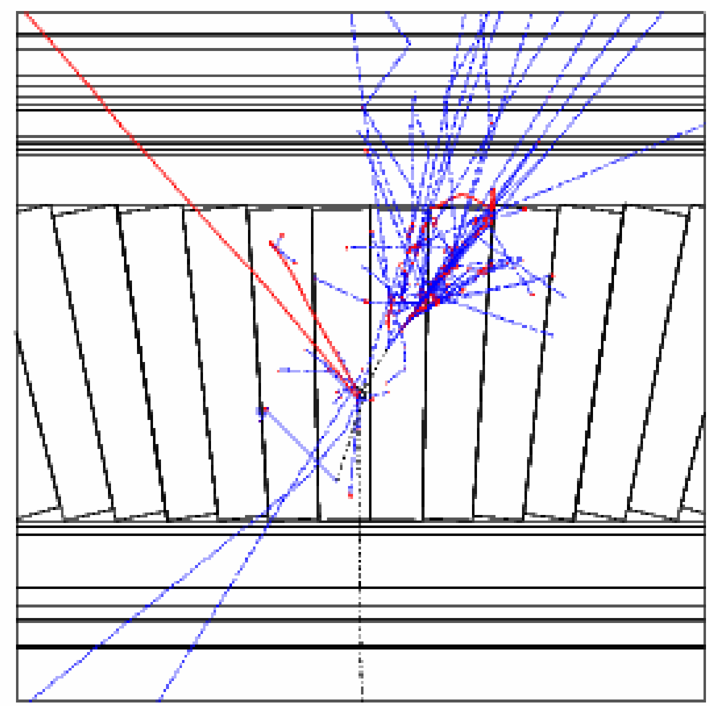




Calorimeter (Had)

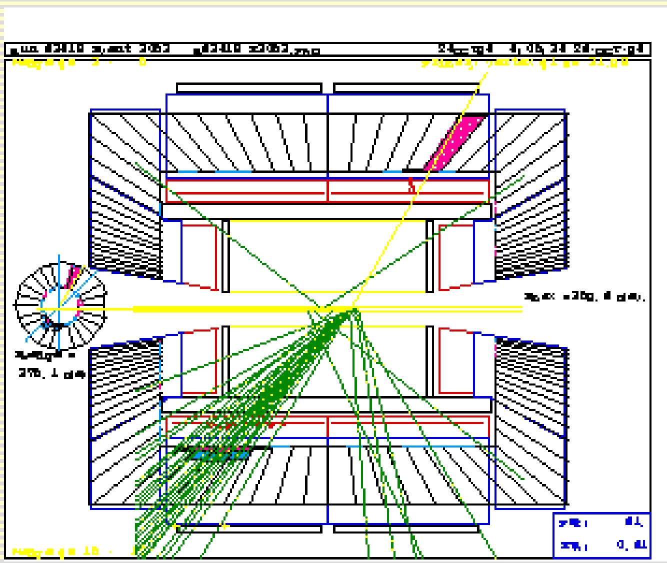
- Steel-scintillator sandwich
  - Undergo nuclear interactions in material
  - Some (highly variable) energy loss due to nuclear binding energy, neutrons
  - Some EM component (π^0), some ionizing track (p, $\pi^{\pm}$)
- Huge variation event-to-event in detected energy for same energy particle
  - Very wide resolution

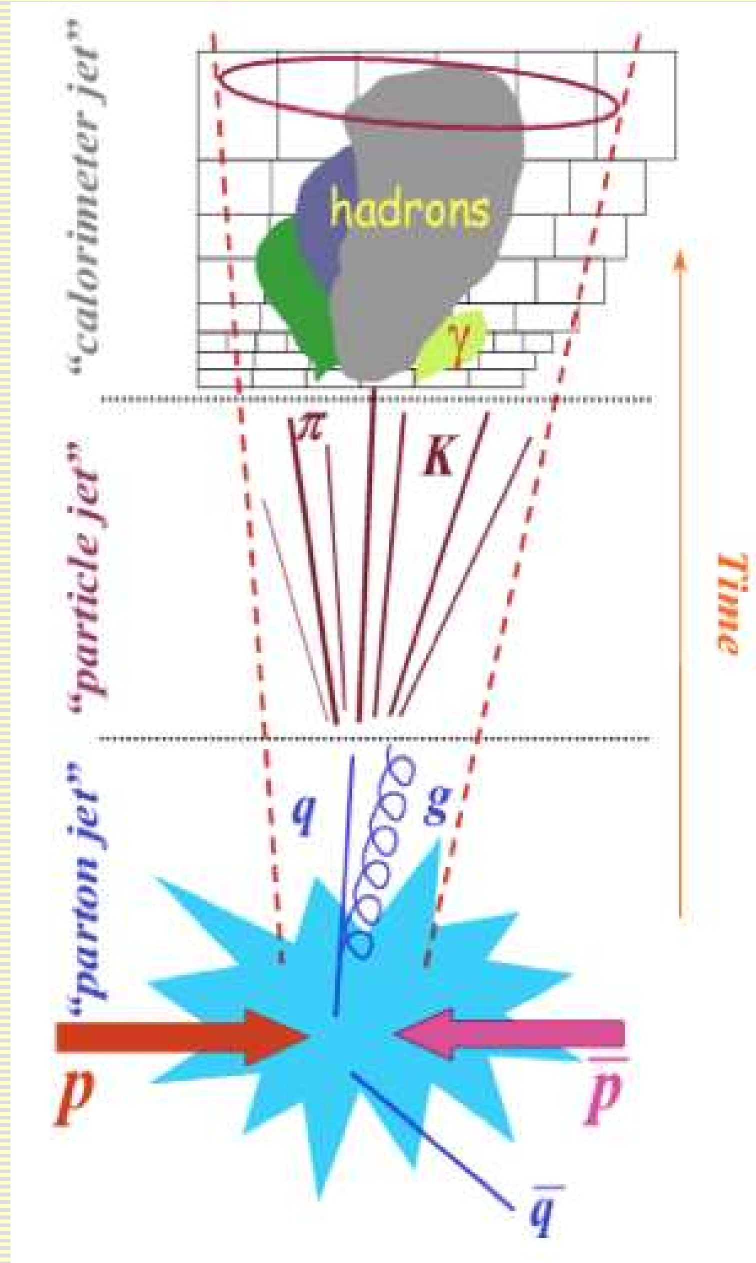




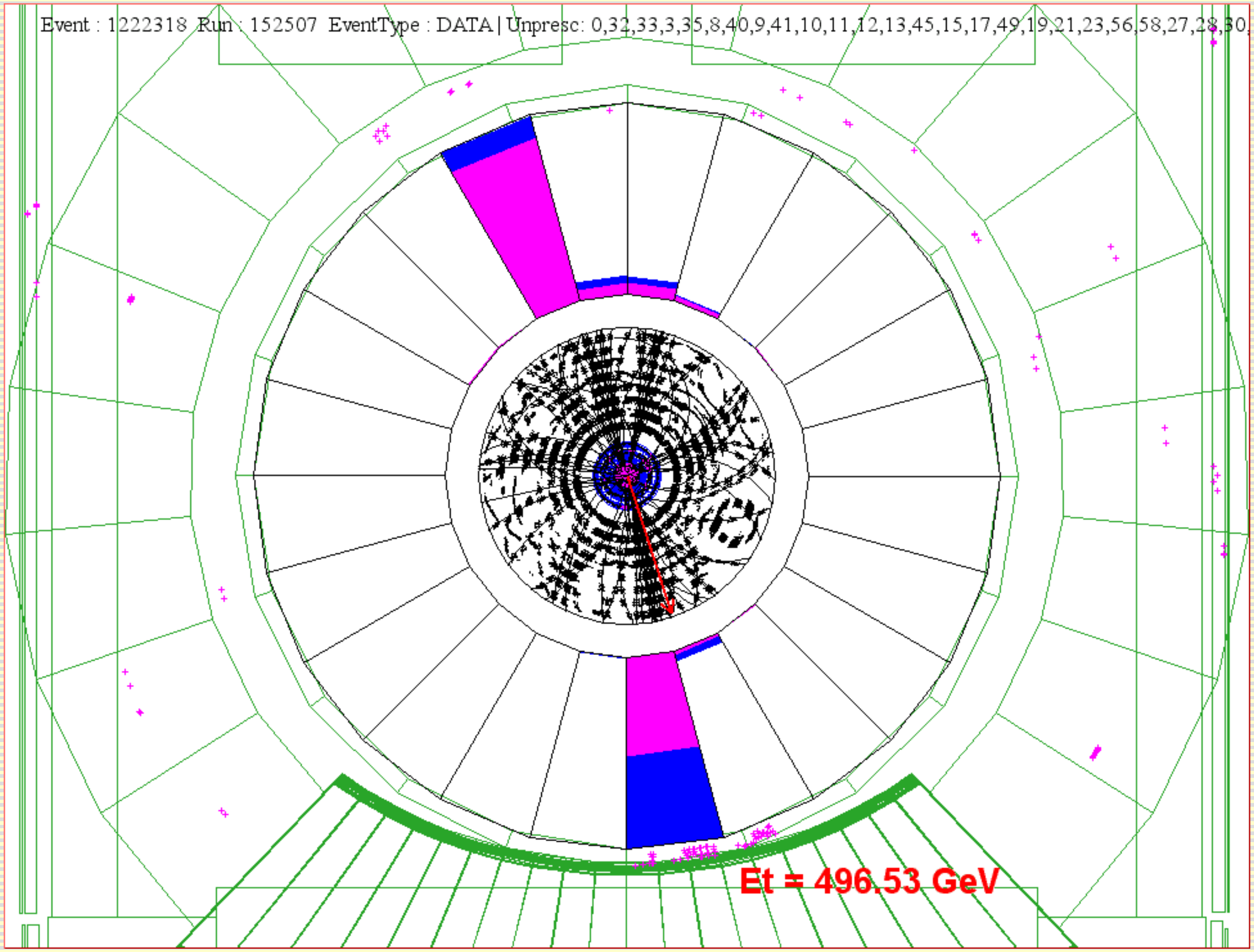
Reconstruction of Jets

- Quarks or gluons in final state hadronize, create flow of particles
- Reconstructed as a cluster of energy in the calorimeter
- Momentum of tracks is not used to reconstruct the kinematics of the jet

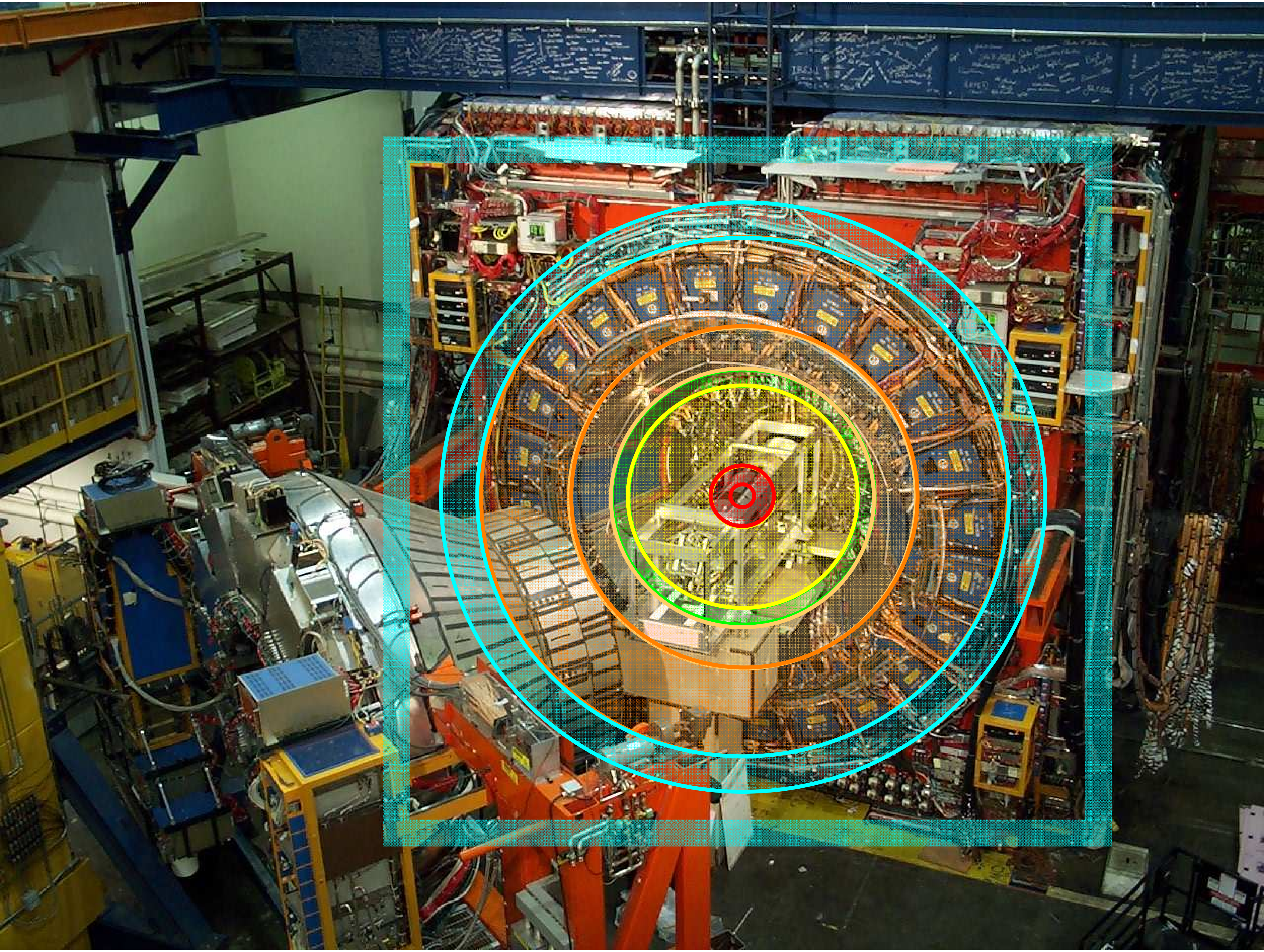




Dijet event

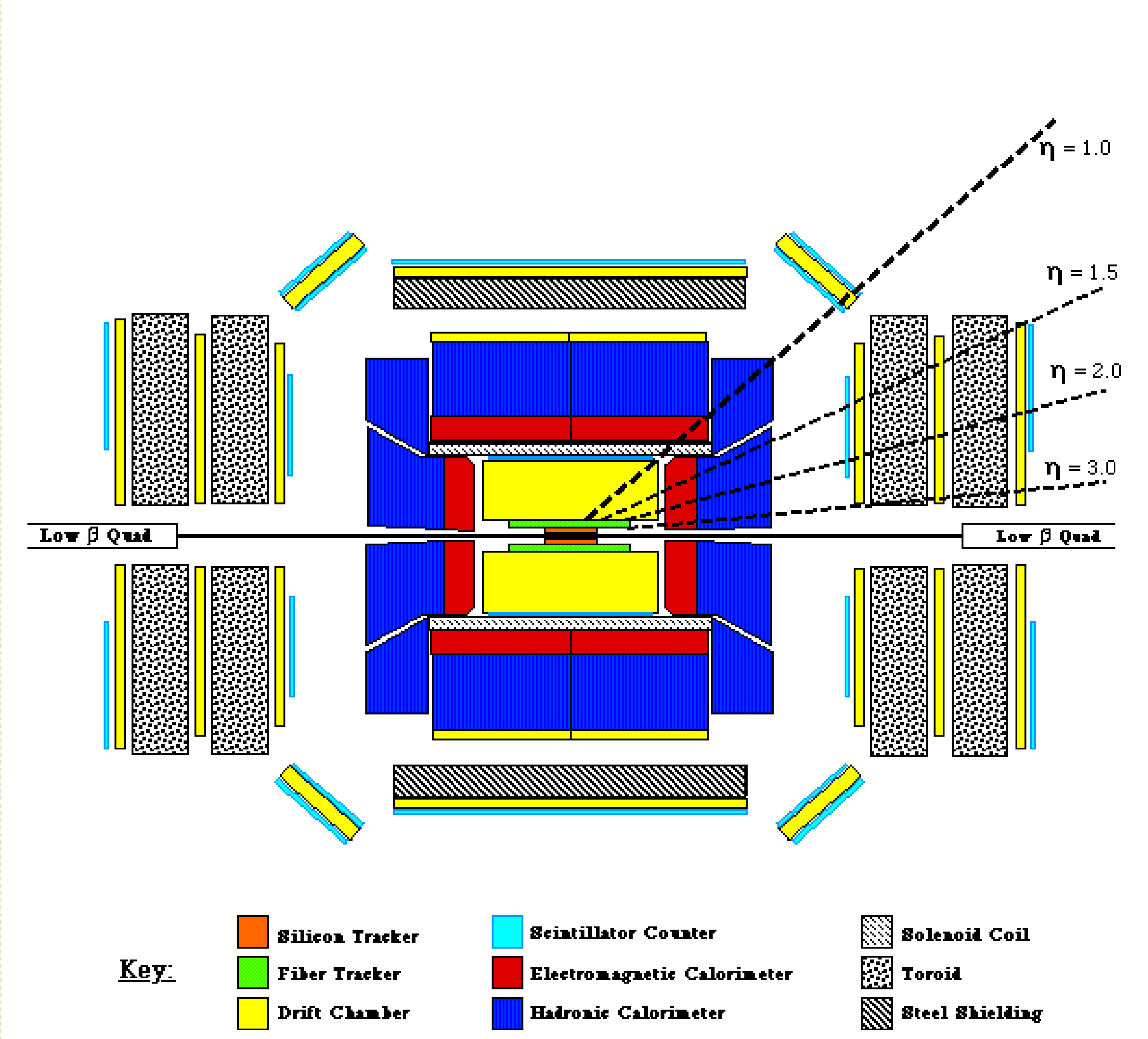


m_{jj}=1364 GeV
(70% of CM energy!)

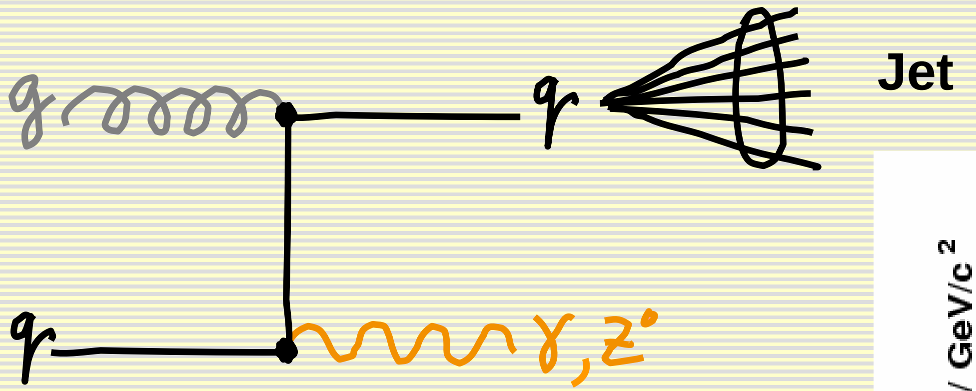


Muon Chambers

- Consists of drift tubes and scintillators (triggering)
- Steel outside hadron calorimetry
  - 60 cm-1m

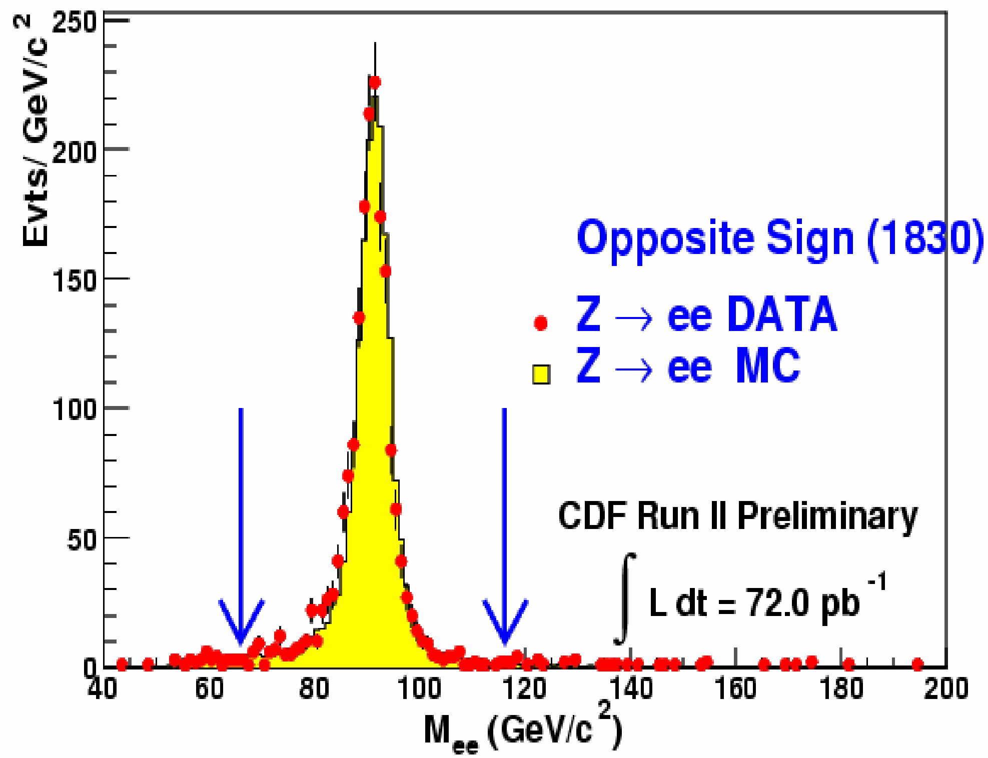


Energy Balance and Jets

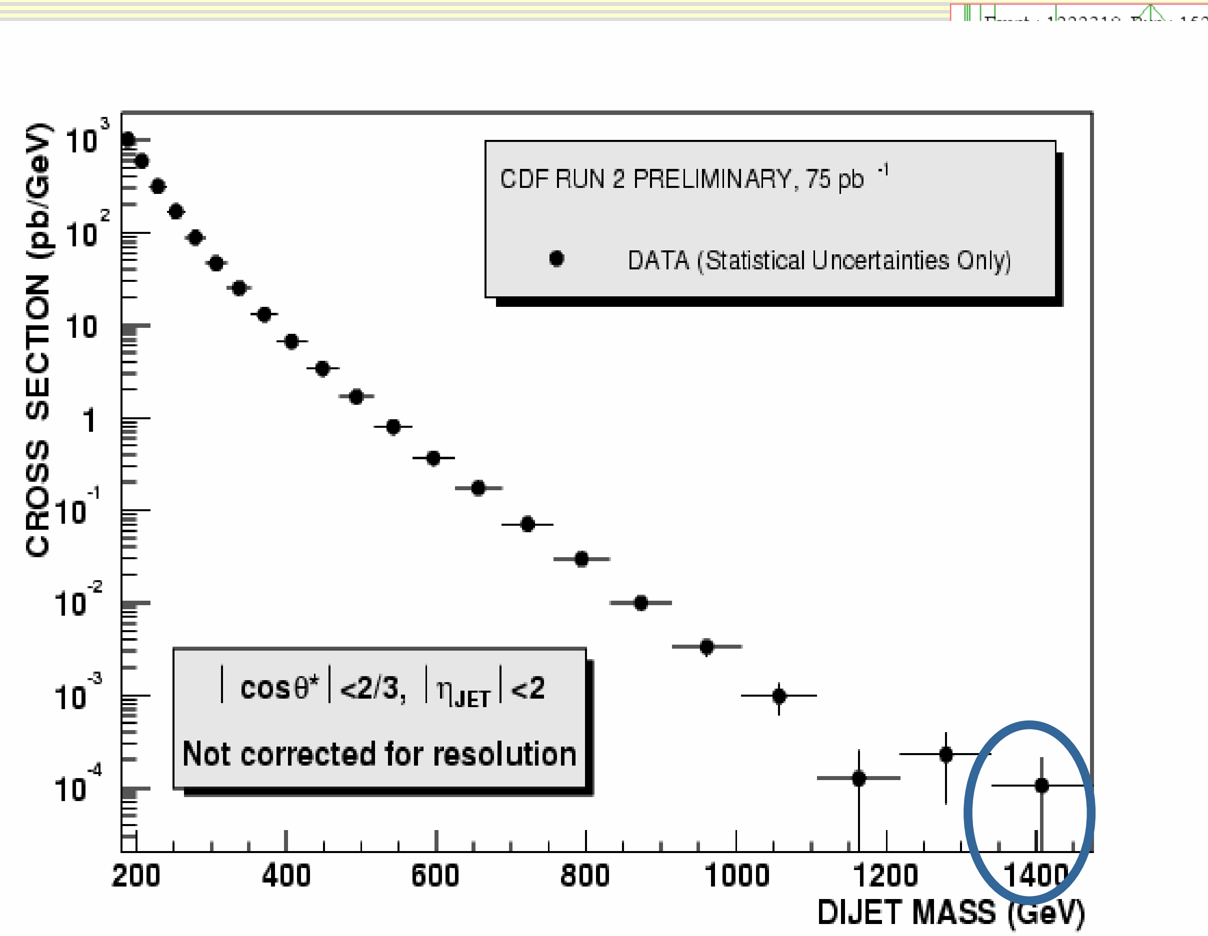


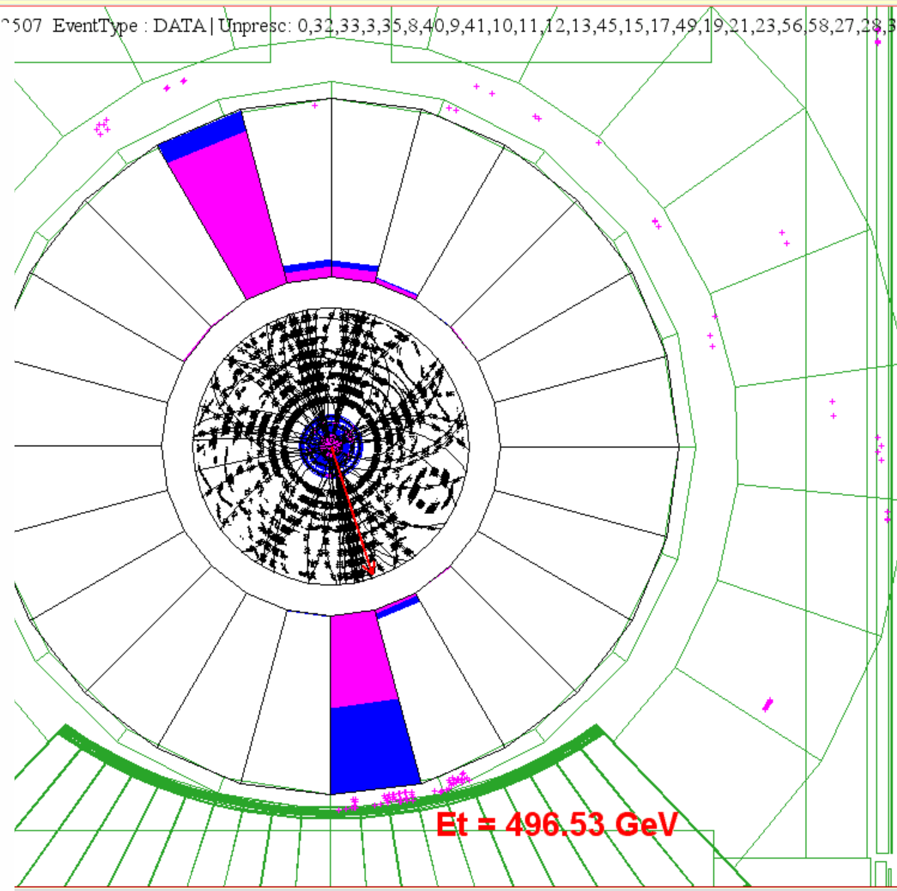
$Z \rightarrow ee$ mass sets EM scale

Photon-jet mass sets had scale



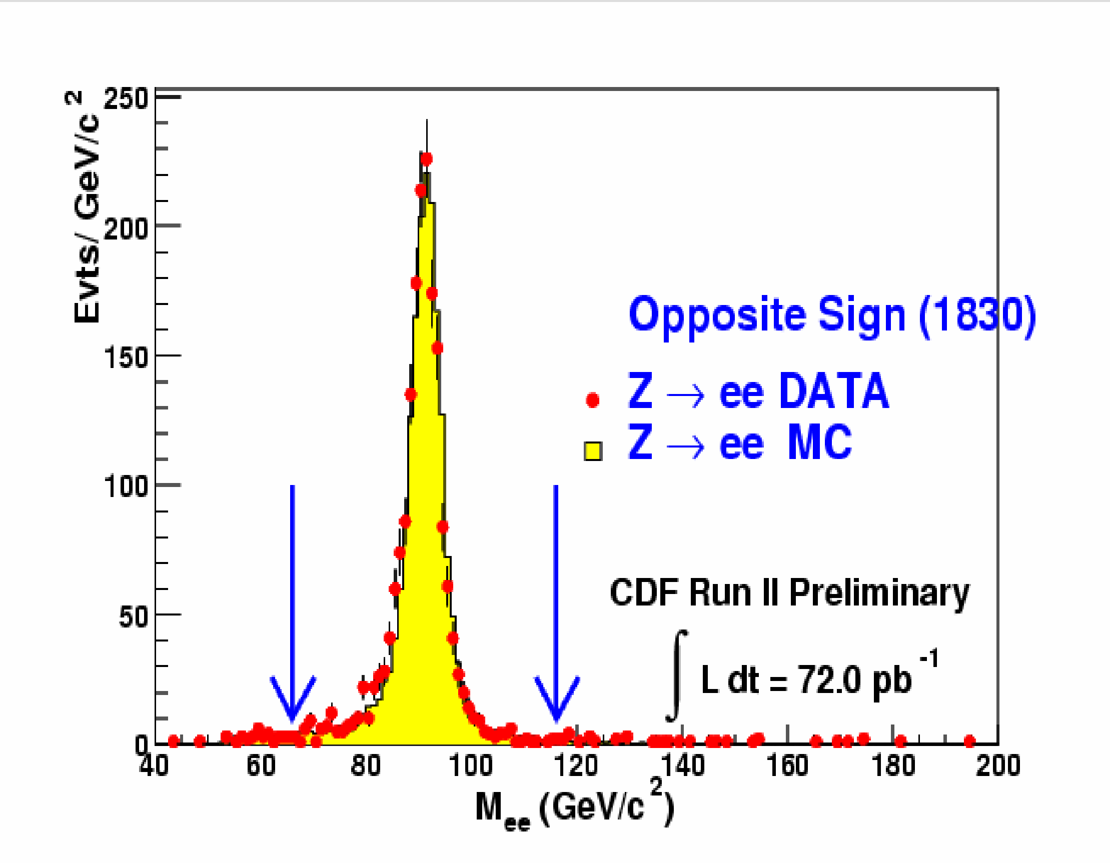
High Jet ET Cross-Section

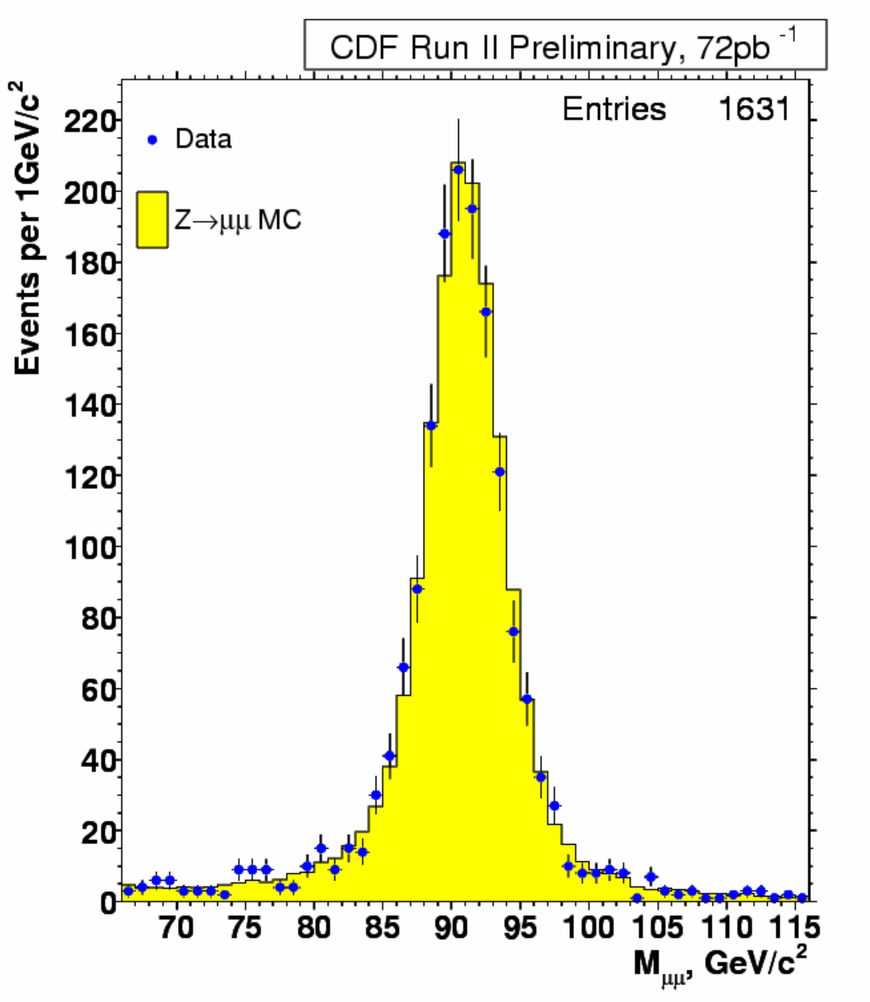




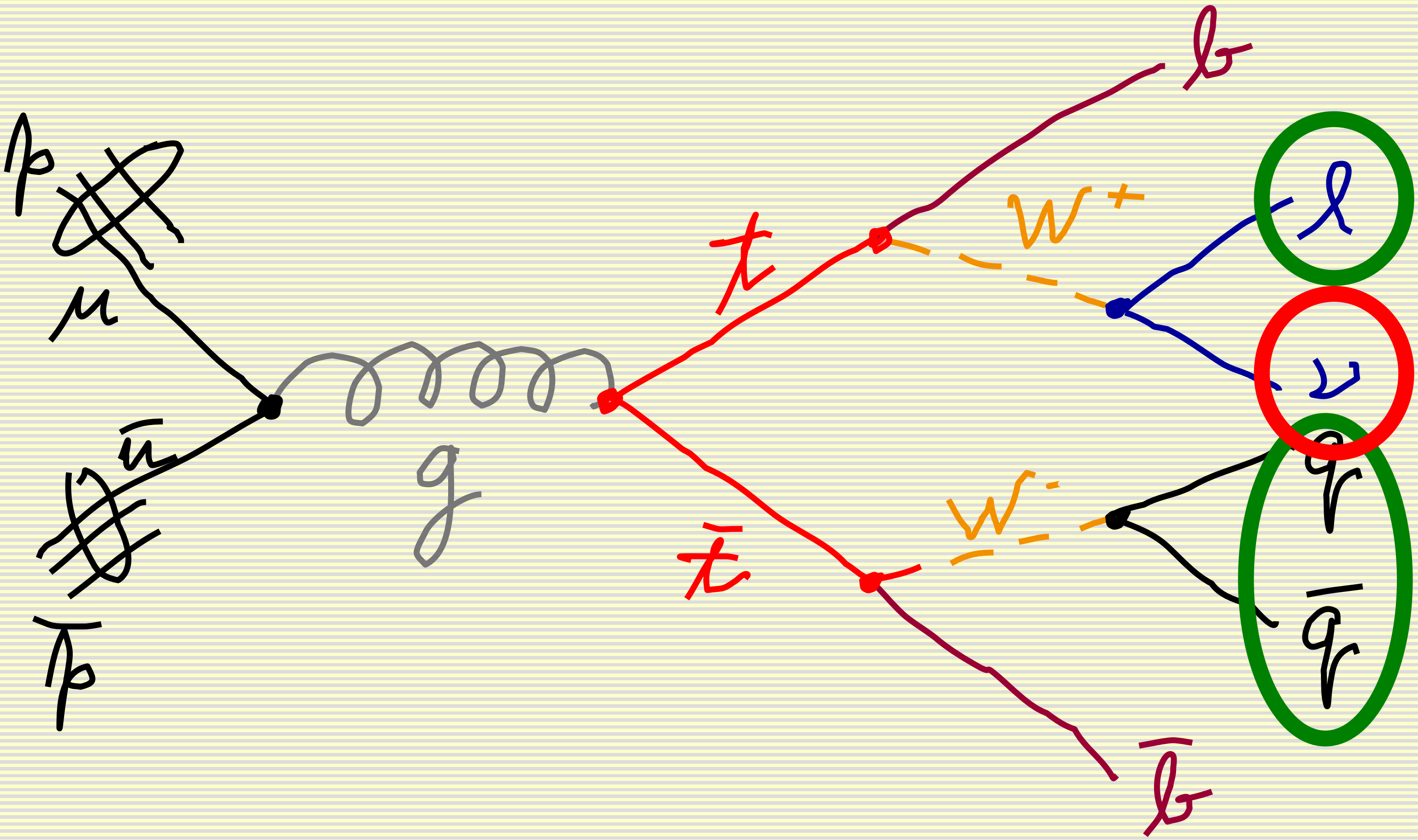
m_{jj}=1364 GeV
(70% of CM energy!)

Find Z's: Measure cross section





The Top Event



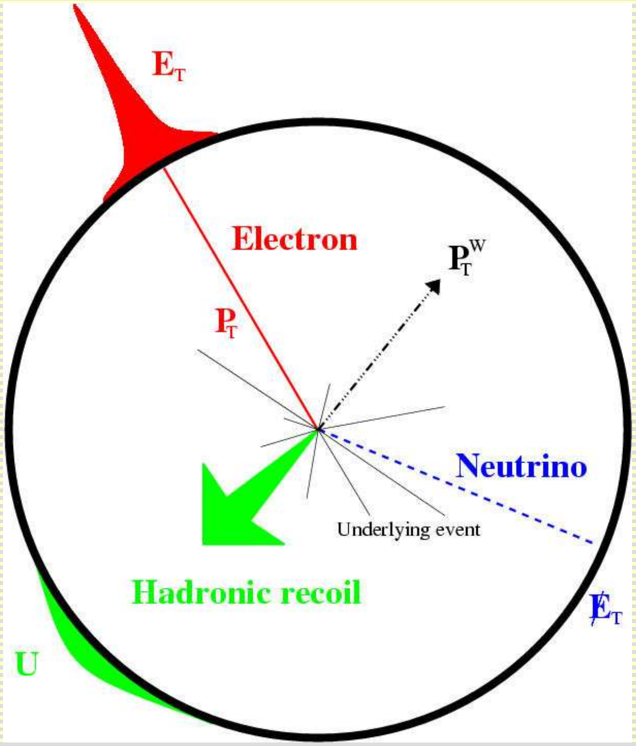
Electron or Muon

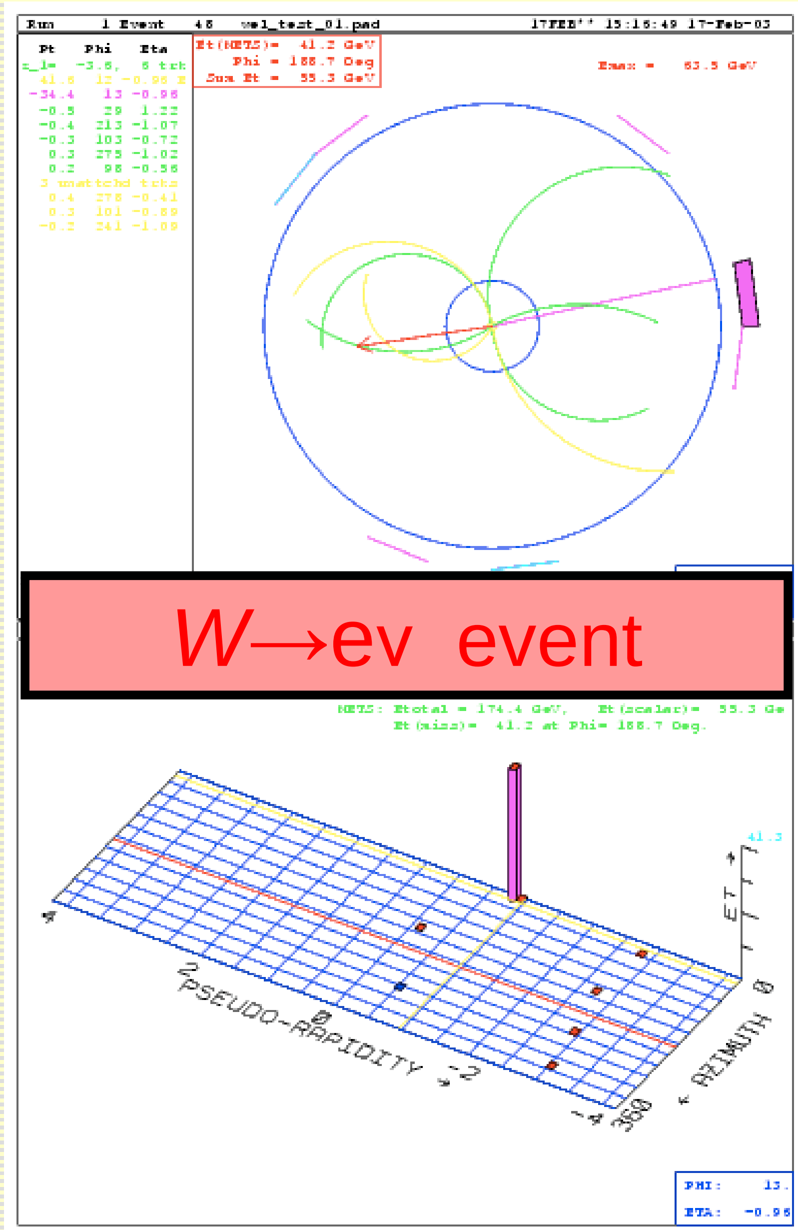
Quarks

↓

Jets

Missing Energy Signature

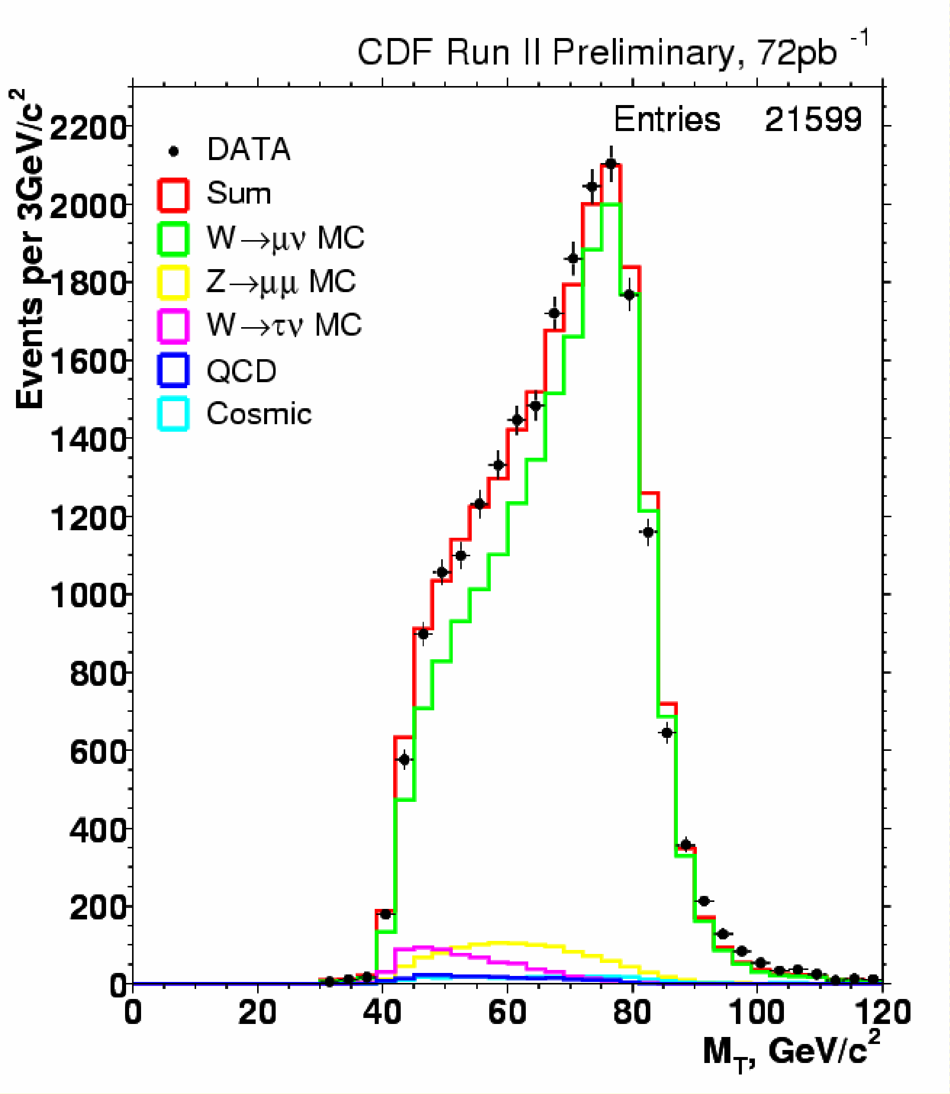




- Sum over energy transverse to the beam axis
- Any imbalance is attributed to undetected particles
  - "Missing E_T" (MET)

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

Finding W's

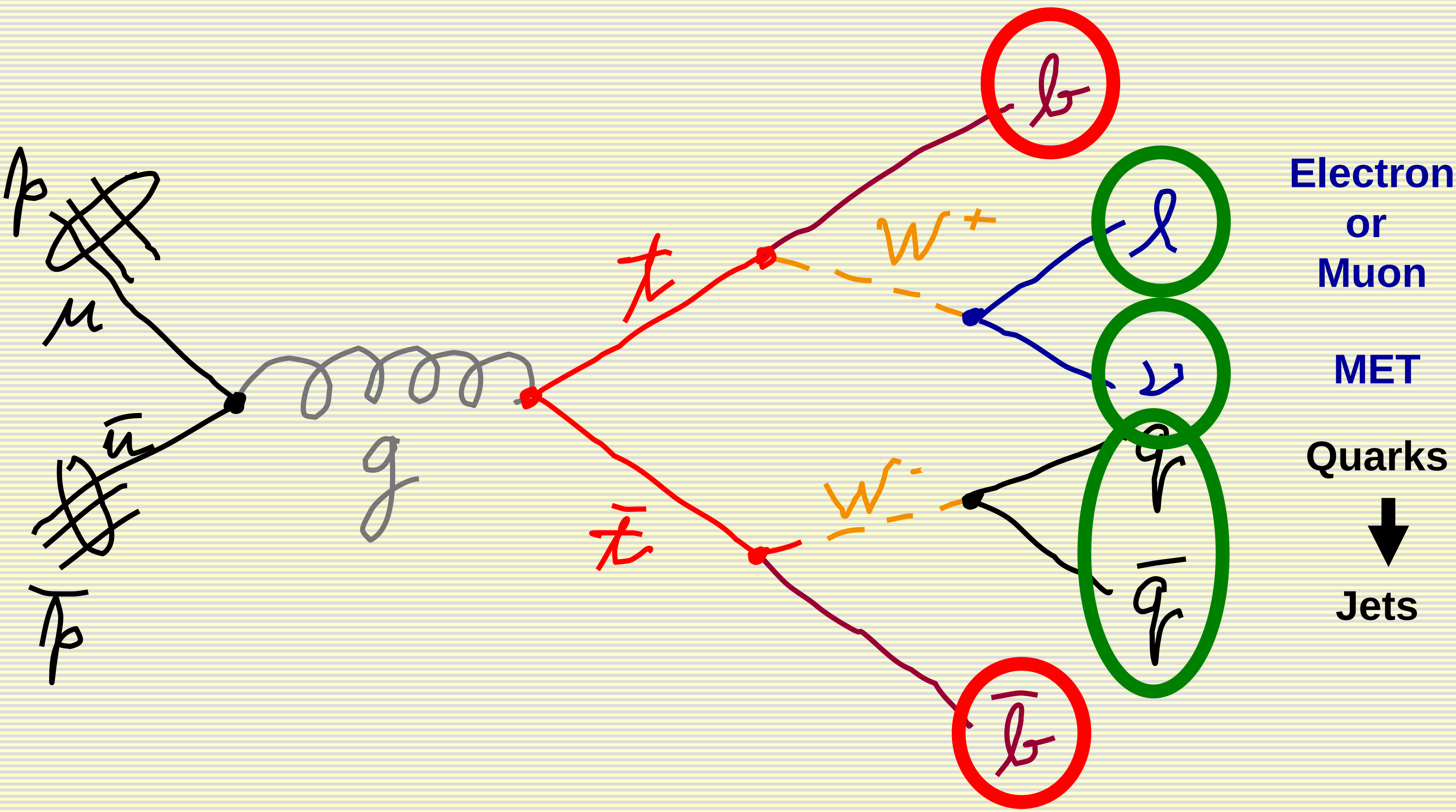


- A W is
  - A high-pT isolated lepton
  - Large MET

$$m_T^W \equiv \sqrt{p_T^\ell p_T^\nu \left(1 - \cos(\phi_\ell - \varphi_\nu)\right)}$$

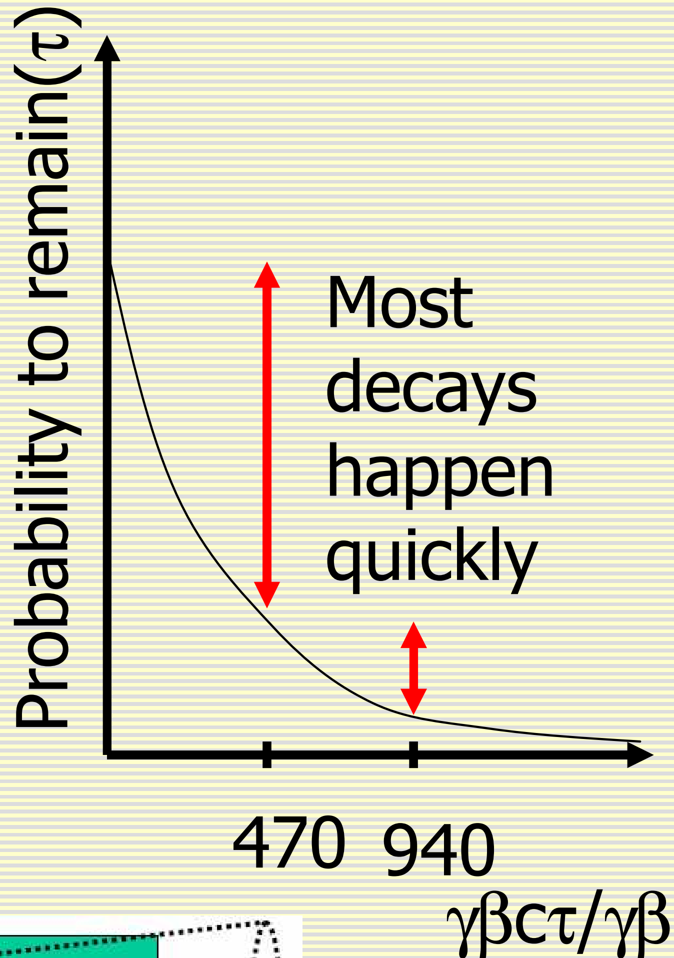
- Robust even though only observing in transverse plane
- Edge ("jacobian edge") tells you mass
- Slope of edge tells p_T(2nd order), resolution, Γ_W
- Tail tells you Γ_W

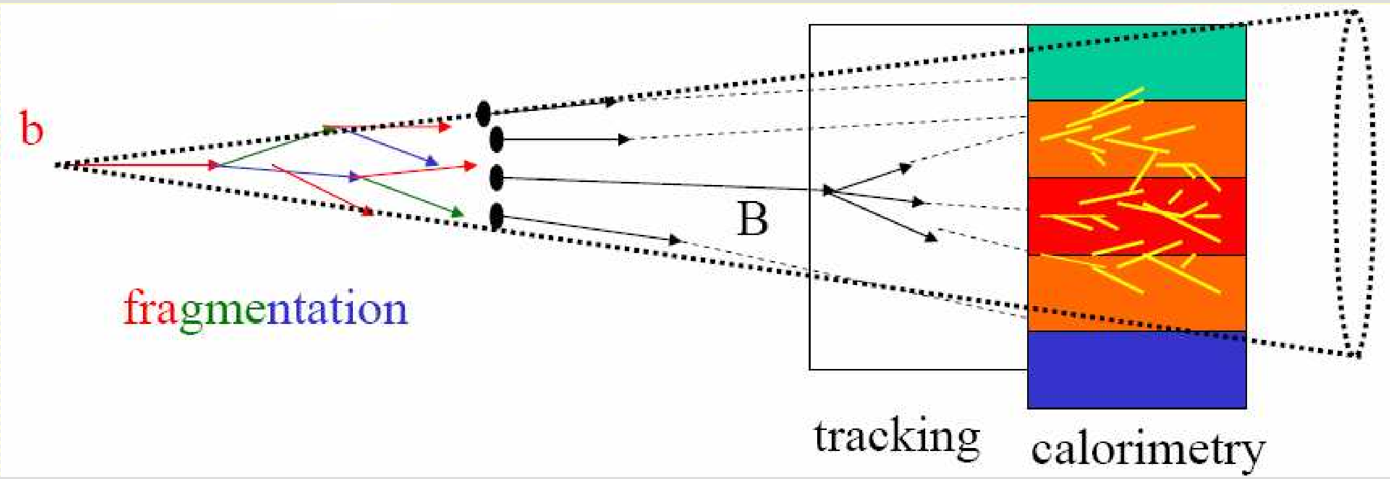
The Top Event



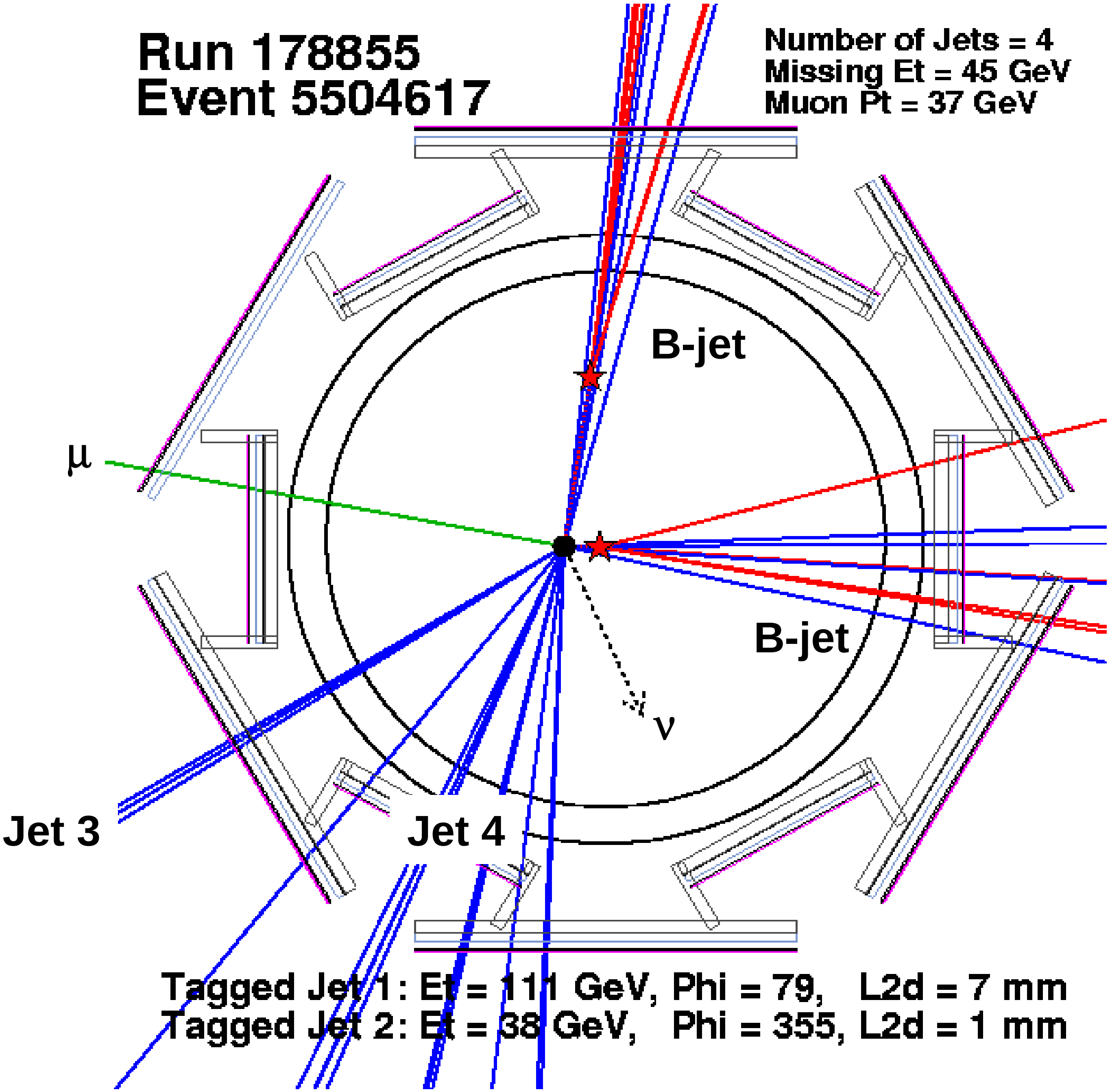
The b-quark → B-Jet

- Massive (~ He nucleus)
- Unstable
  - Spontaneously decays with probability given by its half-life : τ_b is 1.6 x 10^{-12} s
  - Average proper distance traveled before decay given by $\gamma\beta c\tau_b$ is ~470$\gamma\beta$ μm





Top Event Display from CDF: Tagging b-quarks



b-quarks have long lifetime ($c\tau$ = 460 μm)

$d = \beta\gamma c\tau$

B mesons travel few mm before decaying

Displaced Vertex Tagging

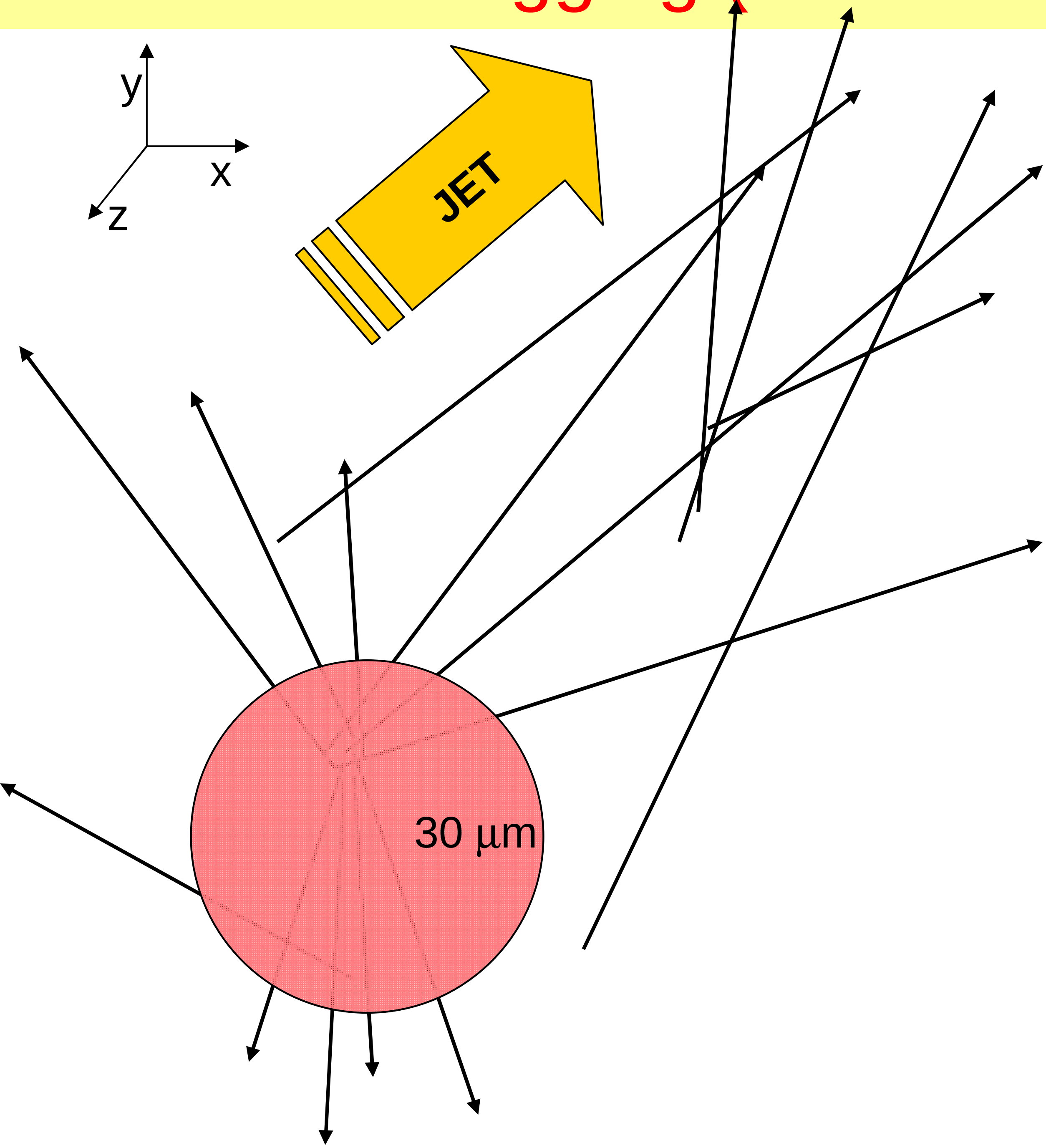
$b \rightarrow c l \nu$ (BR ~ 20%)

$c \rightarrow s l \nu$ (BR ~ 20%)

Soft Lepton Tag

4x lower efficiency
7x larger fake rate

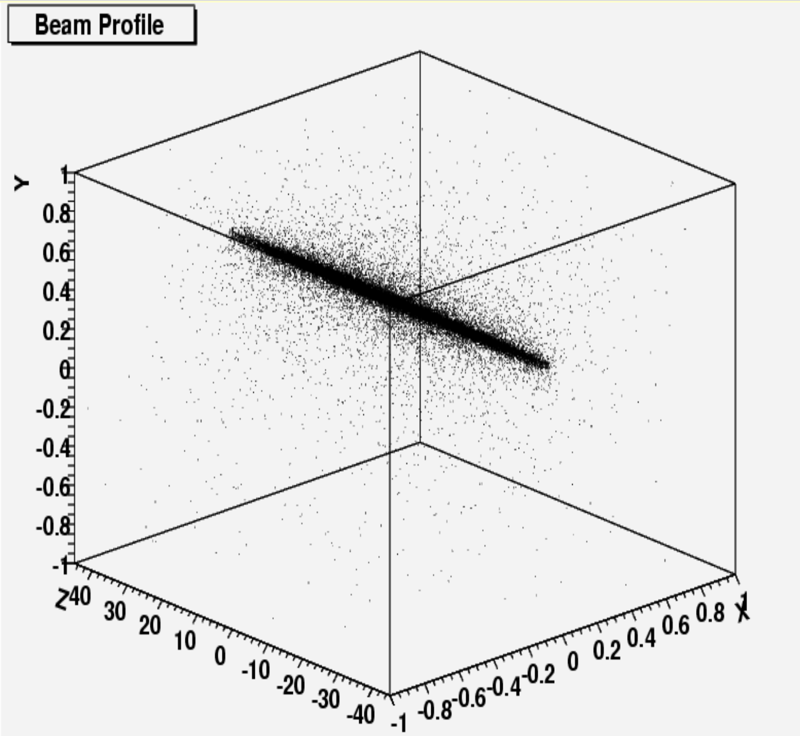
B-tagging (Secondary Vertex)

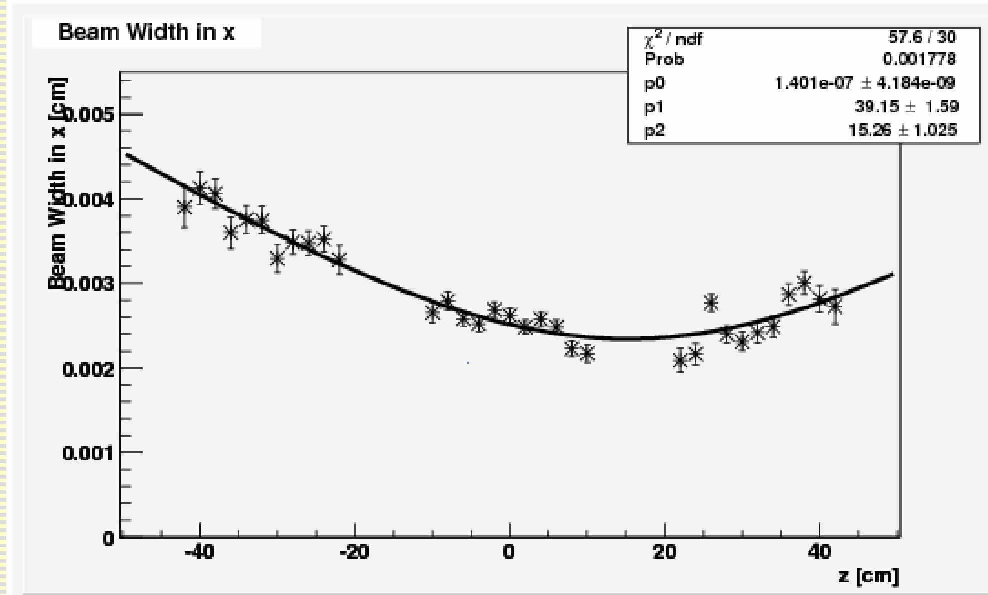


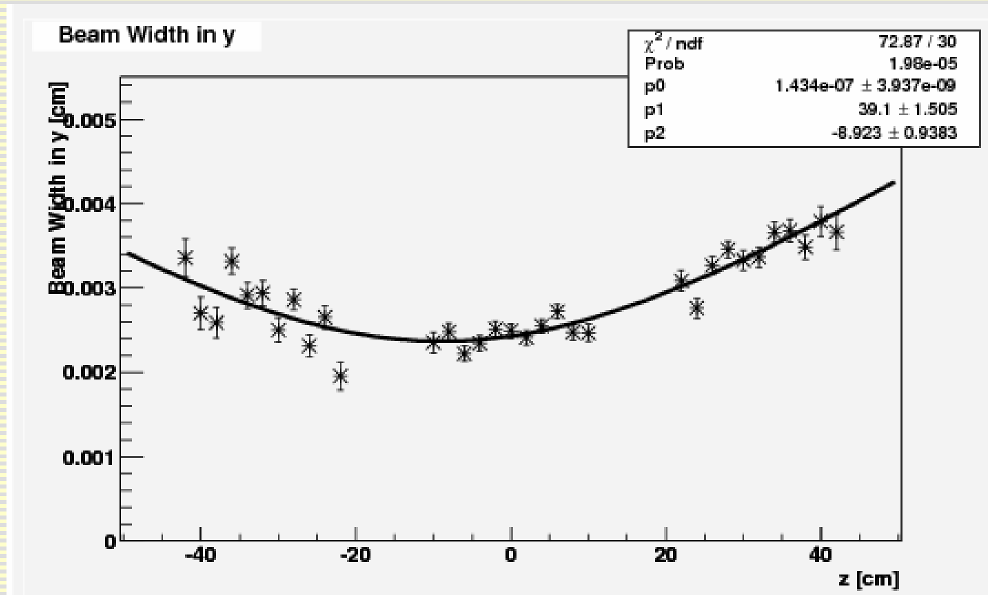
Start with set of tracks and general location of luminous region

The Beam

- Beamline very long
  - Luminous region σ~30cm



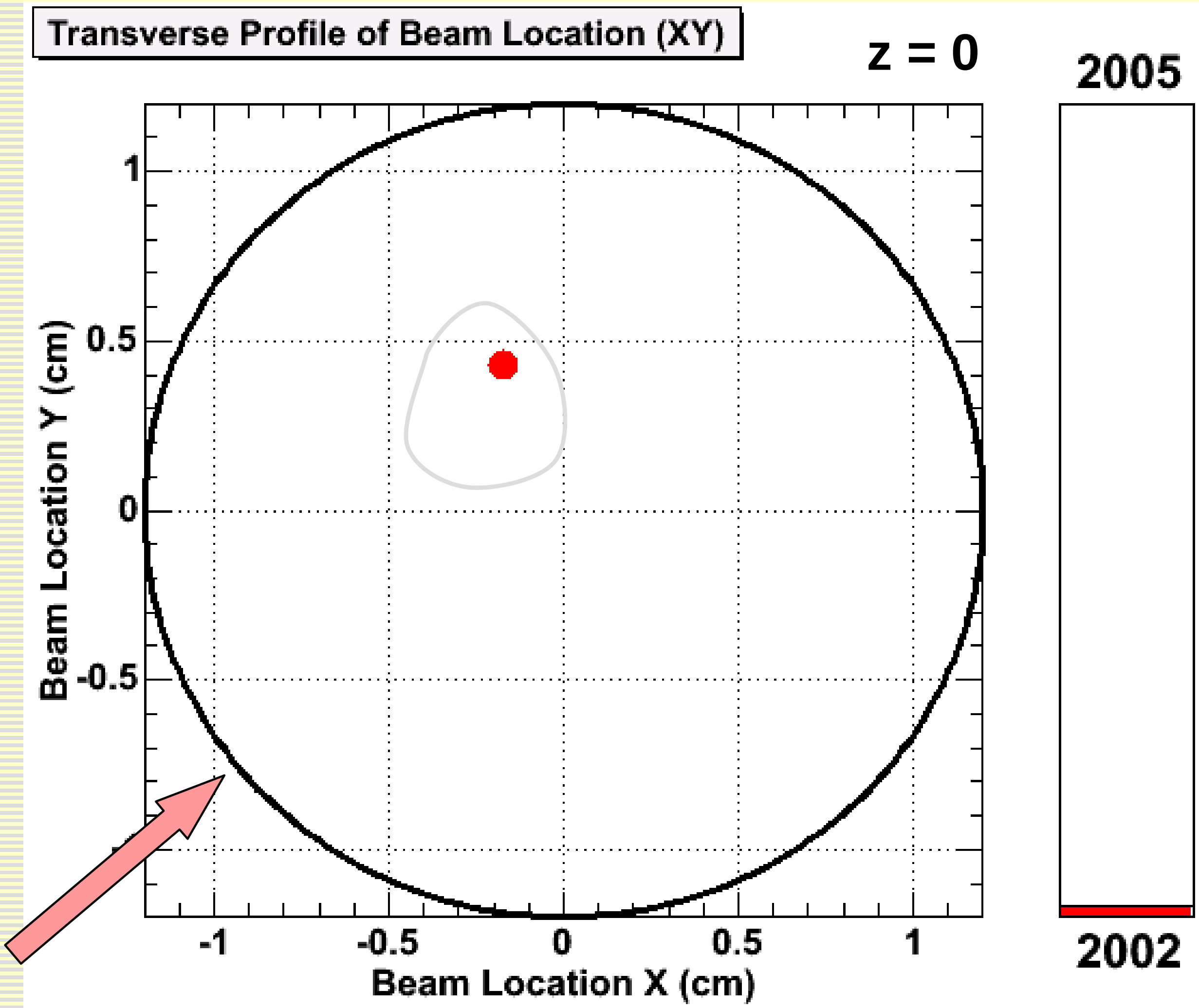




- Hadronic interactions have large cross sections
  - Multiple interactions in same bunch crossing not uncommon

The luminous region at CDF

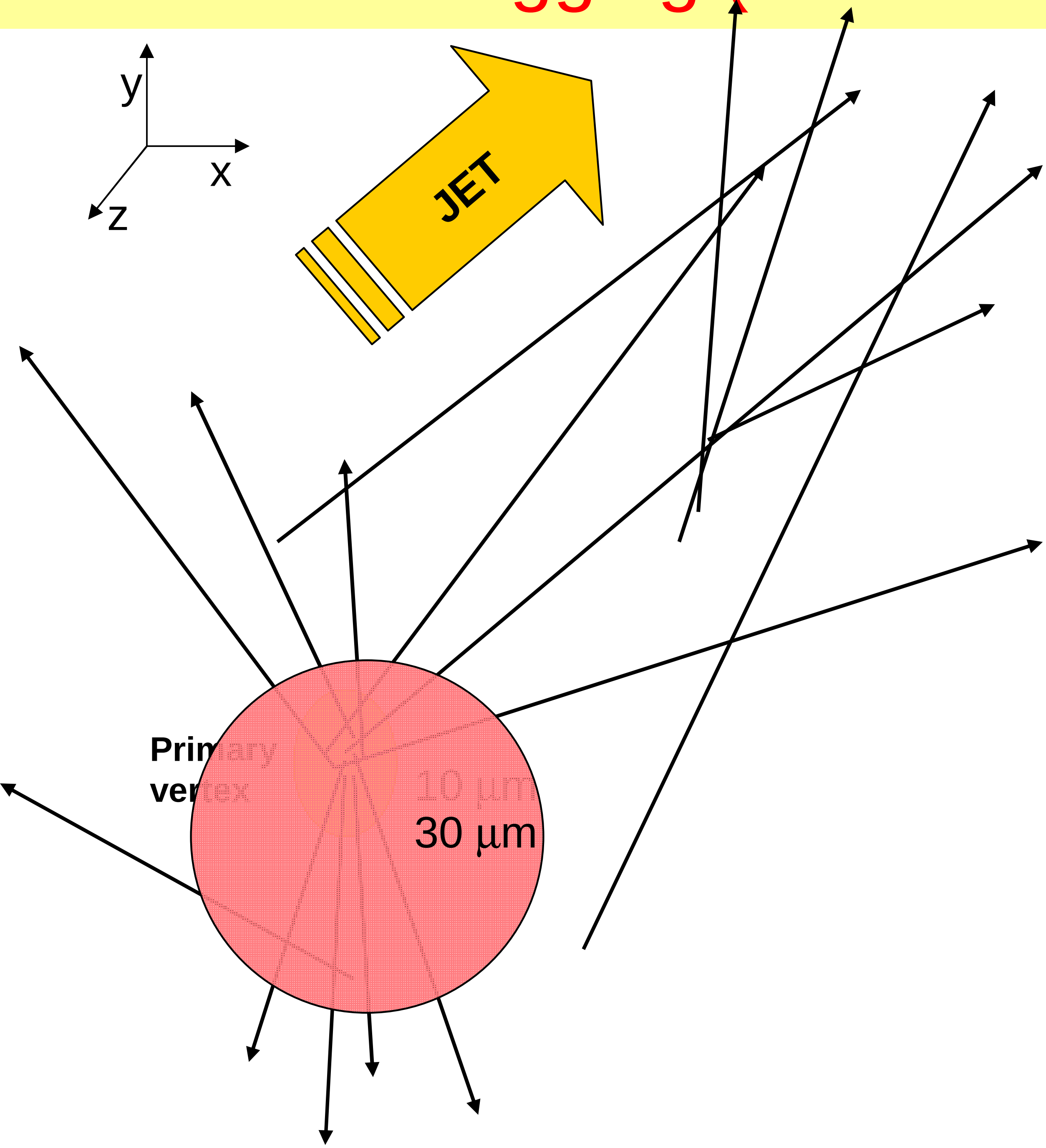
- Average location of the $p\bar{p}$ interaction point per run size magnified 30x (real size 30 μm)



Beam pipe

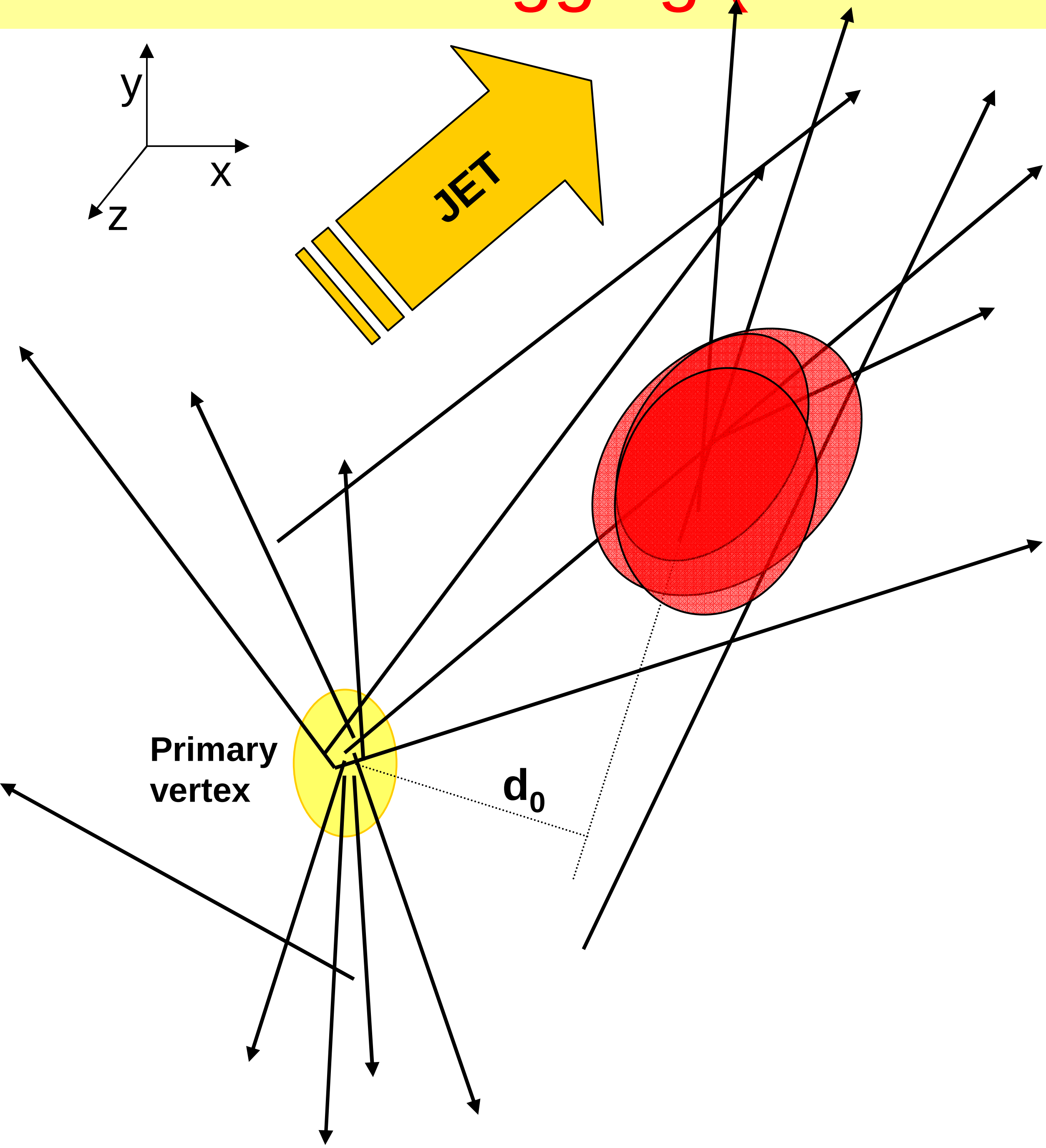
z direction along beampine (proton direction)

B-tagging (Secondary Vertex)



Start with set of tracks and general location of luminous region
Find event-by-event primary vertex

B-tagging (Secondary Vertex)



Start with set of tracks and general location of luminous region

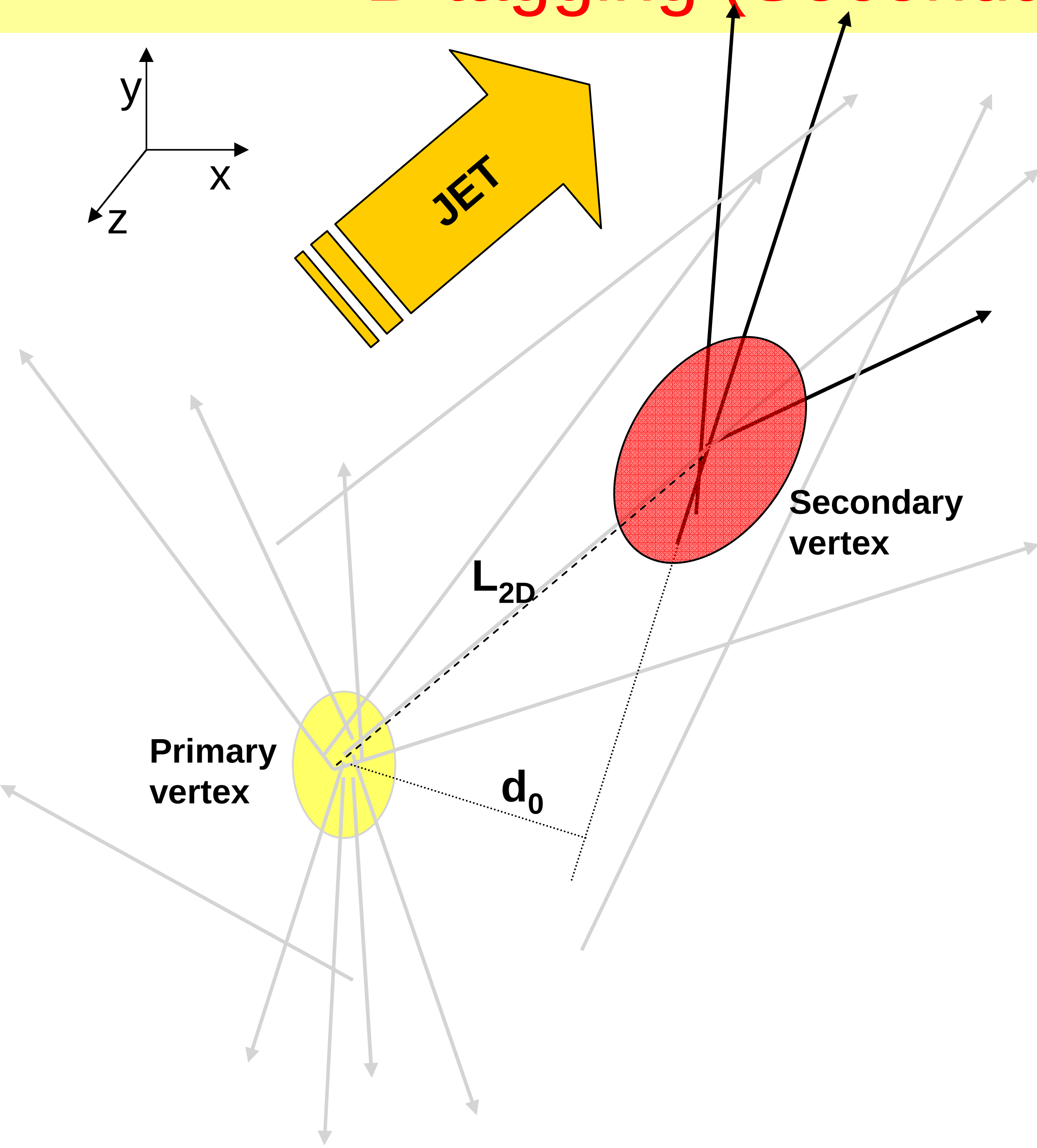
Find event-by-event primary vertex

Select tracks with large impact parameter inside jet

Make a seed for secondary vertex and form vertex

Iterate:
removing tracks with worst chi2

B-tagging (Secondary Vertex)

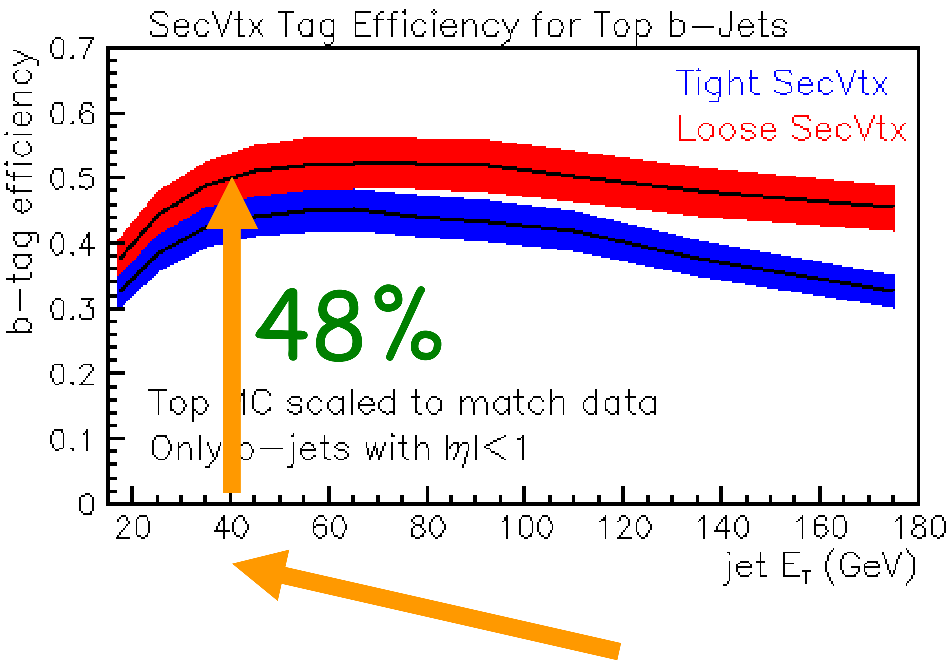


Start with set of tracks and general location of luminous region
Find event-by-event primary vertex
Select tracks with large impact parameter inside jet
Make a seed for secondary vertex and form vertex
Iterate: removing tracks with worst chi2
Got a vertex! Check if L_{2D} is large enough

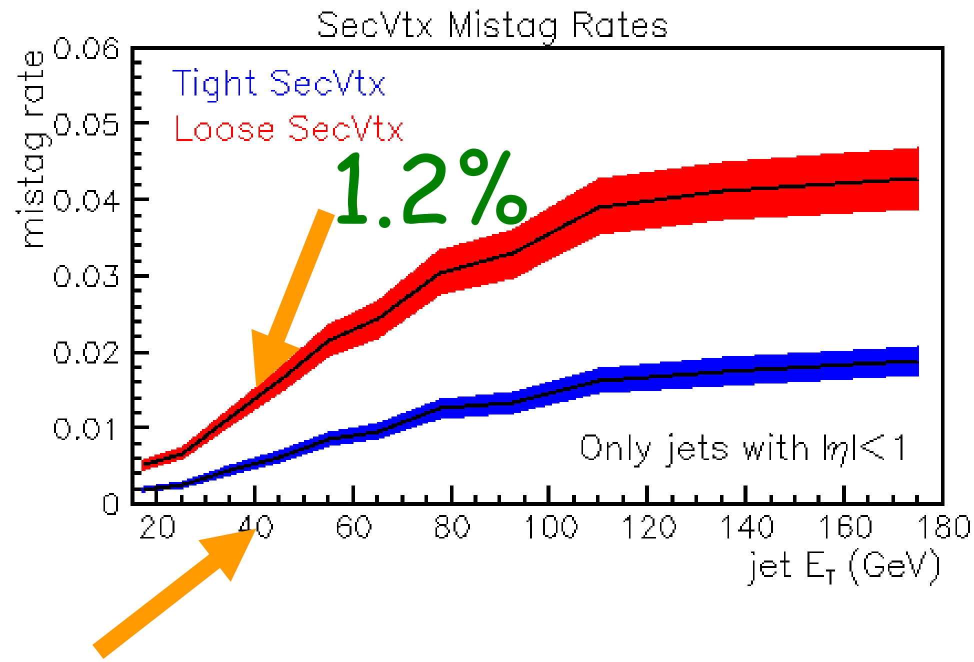
$$\frac{L_{2D}}{\sigma_{L_{2D}}} > 7.5$$

Secondary Vertex Tagging

Efficiency



Mistag rate

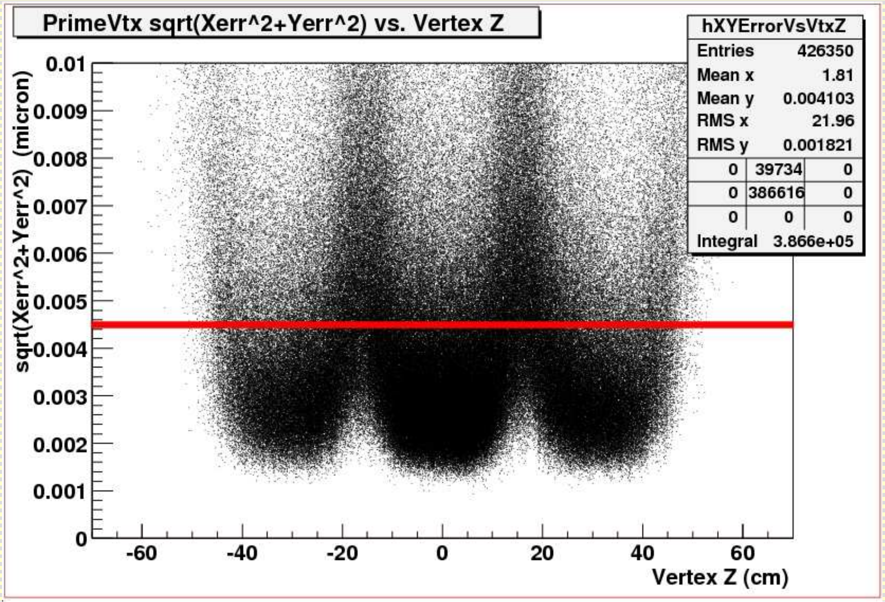


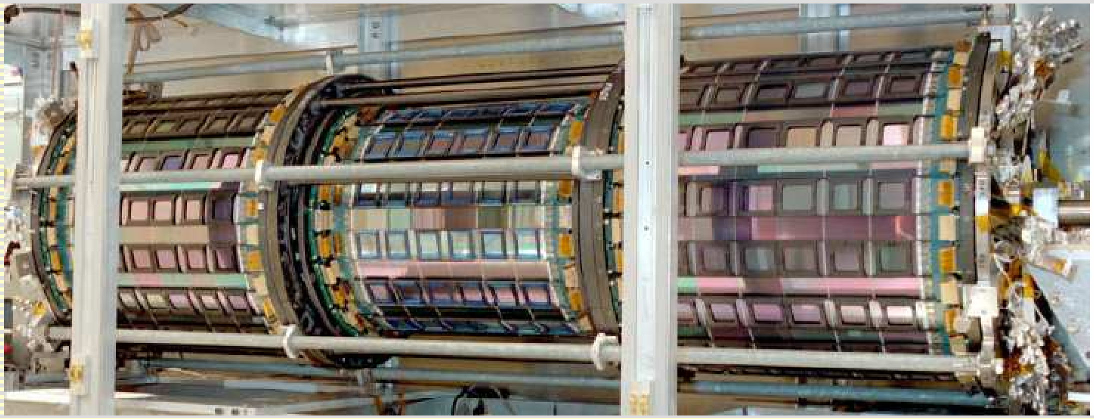
Typical top E_T ~40 GeV

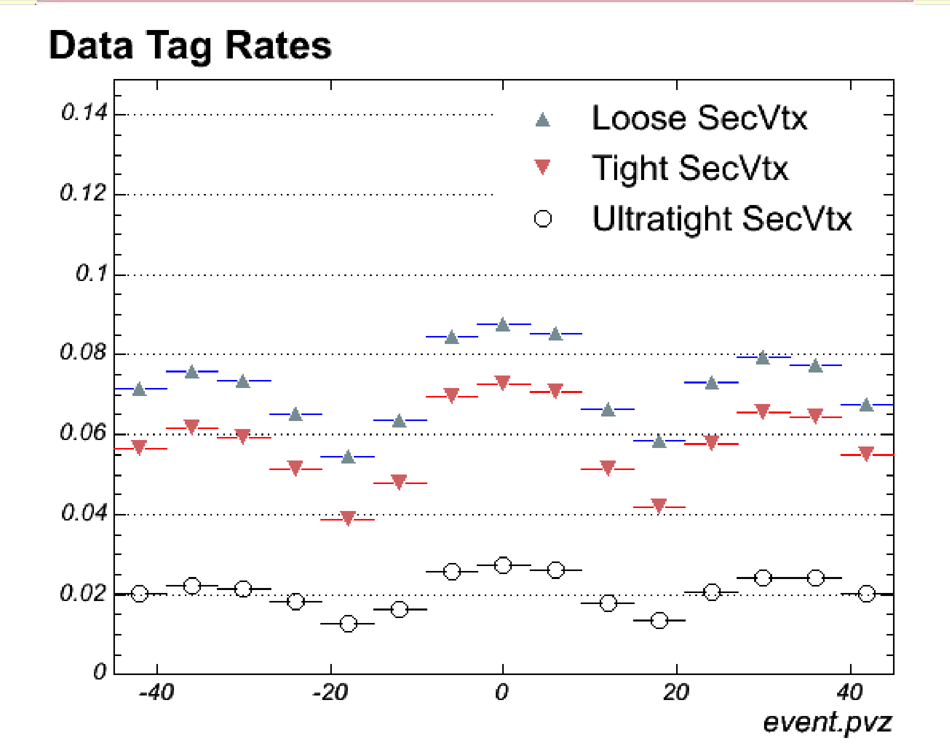
Top b-tag efficiency/event : 69% (2 b’s)

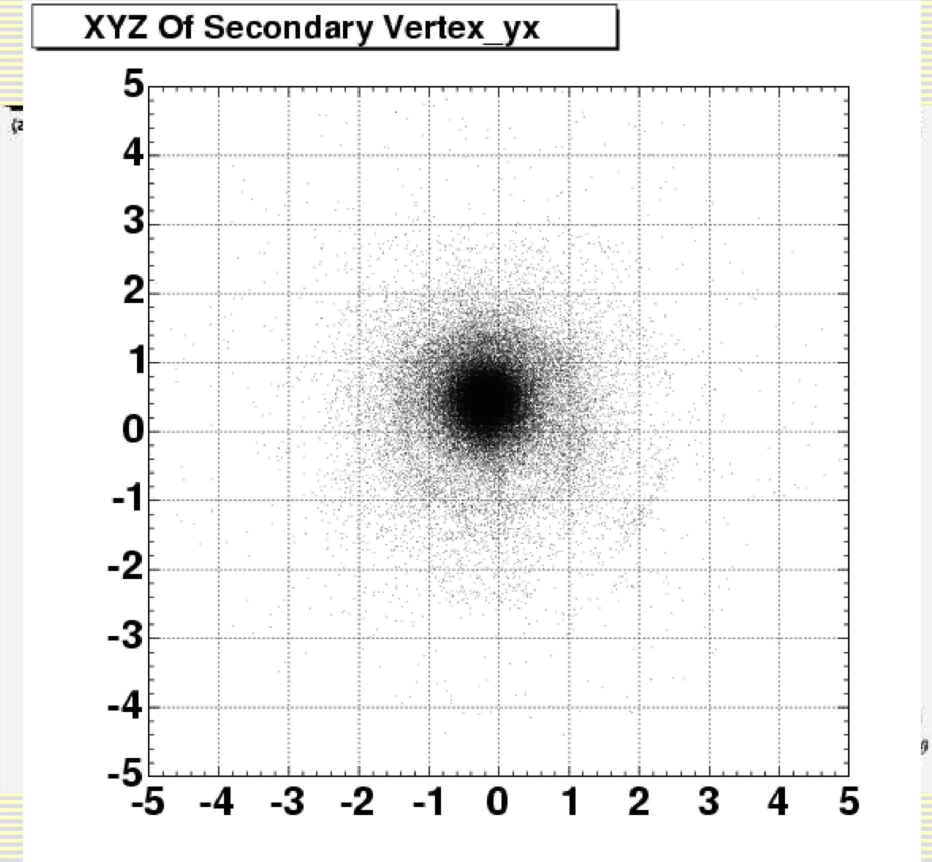
Fake rate/event : ~4%

Problems: Multiple scattering in material

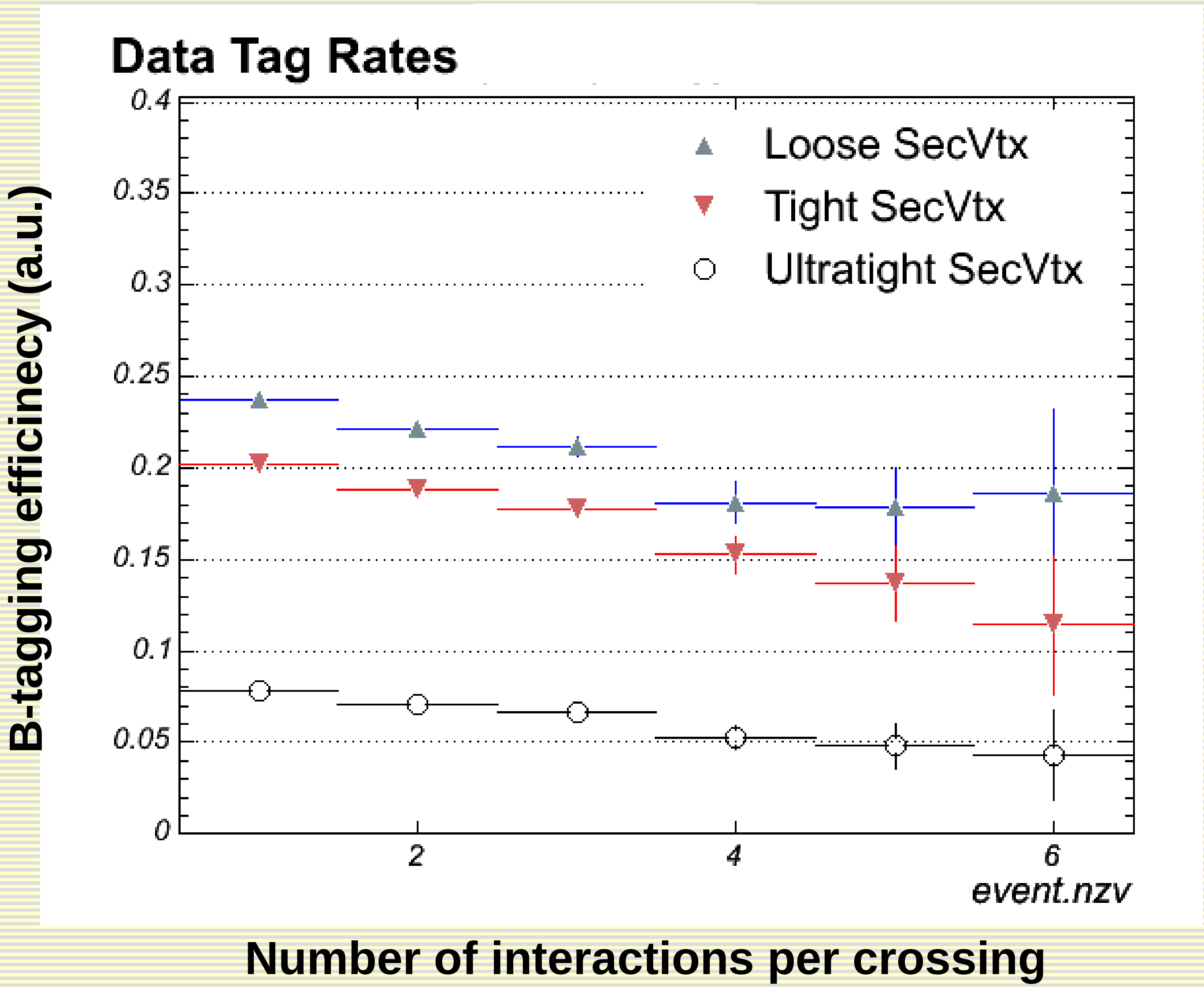




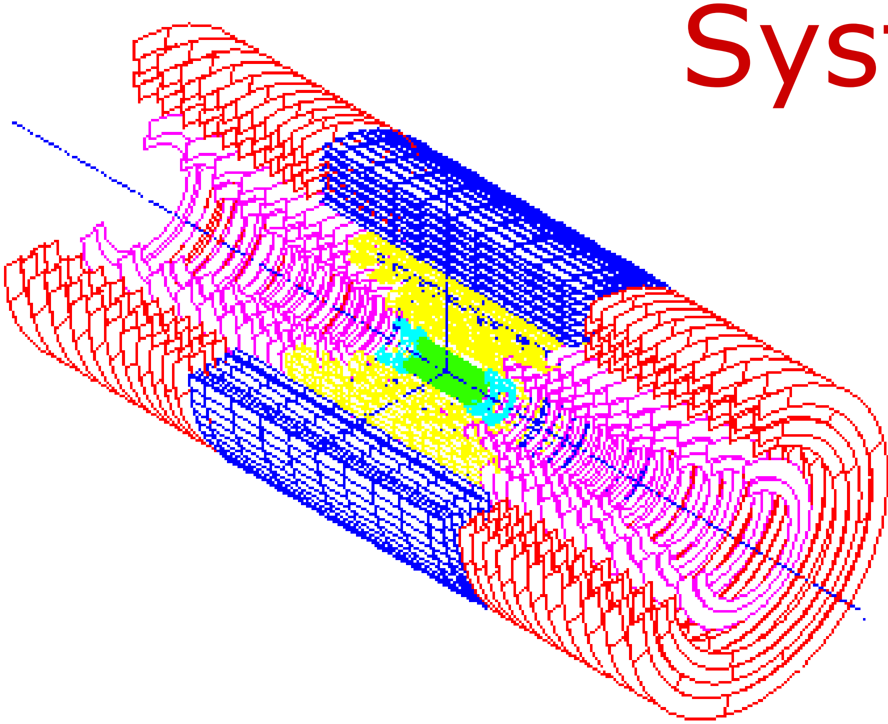




Problems: Effects from multiple interactions



Large 'Contemporary' Silicon Systems



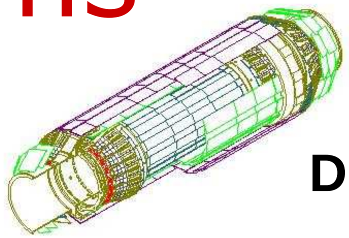
CMS Silicon Tracker (~2007)

~12,000 modules

~ 223 m^2 silicon area

~25,000 silicon wafers

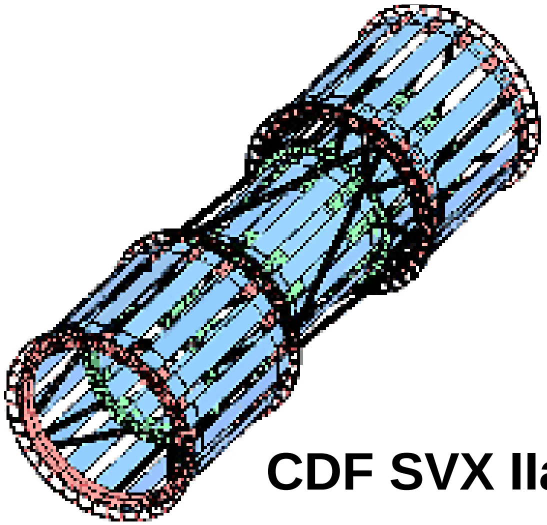
~ 10M readout channels



DELPHI (1996)

~ 1.8m^2 silicon area

175 000 readout channels

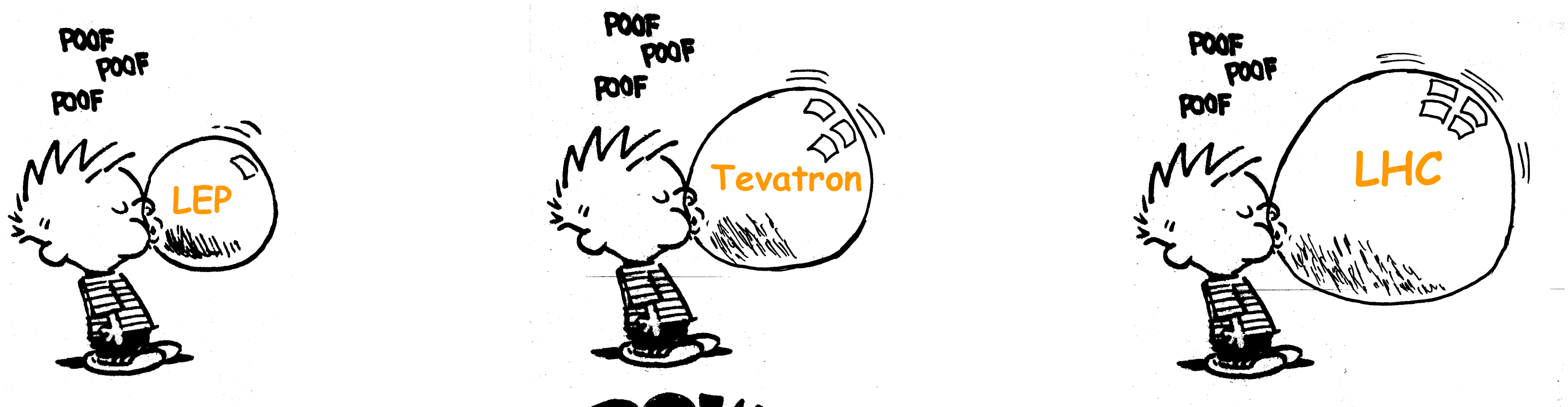


CDF SVX IIa (2001-)

~ 11m^2 silicon area

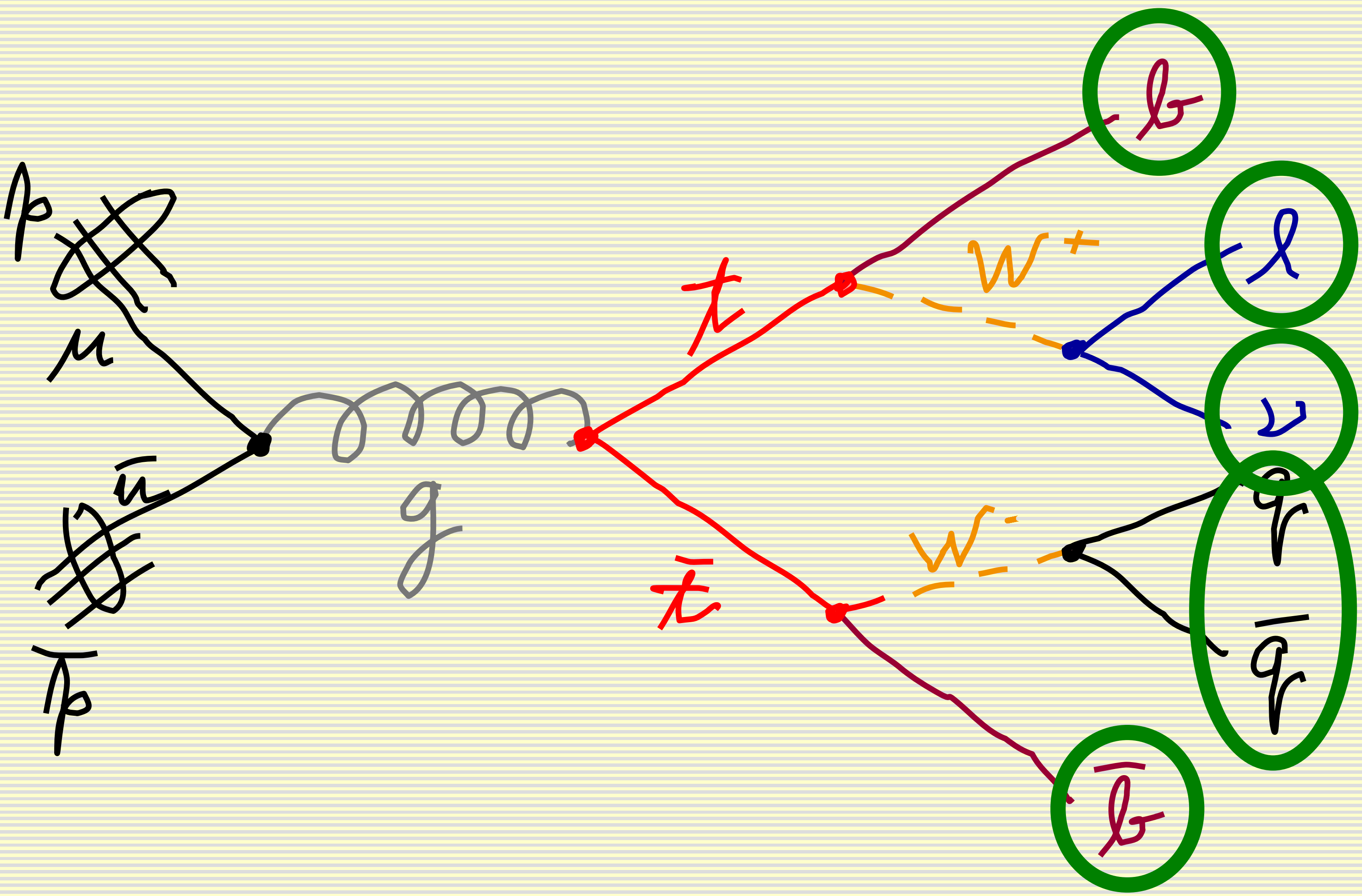
~ 750 000 readout channels

Large Silicon Detector Systems ….



P.Collins, ICHEP 2002

The Top Event



Electron
or
Muon

MET

Quarks

↓

Jets

Cross Section Measurement

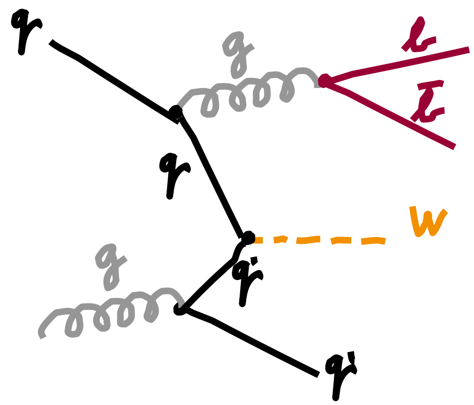
$$\sigma_{t\bar{t}} = \frac{N_{obs} - \widehat{N}_{bkg}}{\epsilon_{pretag} \times \epsilon_b \times \int \mathcal{L} dt}$$

- N_{obs} : Number of observed events
- N_{bkg} : Number of expected background events
- ε_{pretag} : Efficiency before tagging (incl Acc and BR)
  - ε_{pretag} ~ 7.5%
- ε_{btag} : Event tagging efficiency
  - ε_{pretag} ~ 69%
  - $\int$ L dt : Integrated luminosity

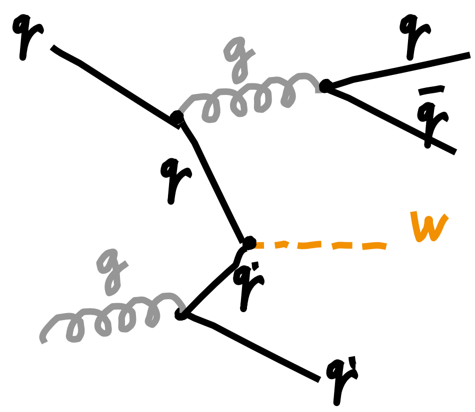
Backgrounds

– W + jets

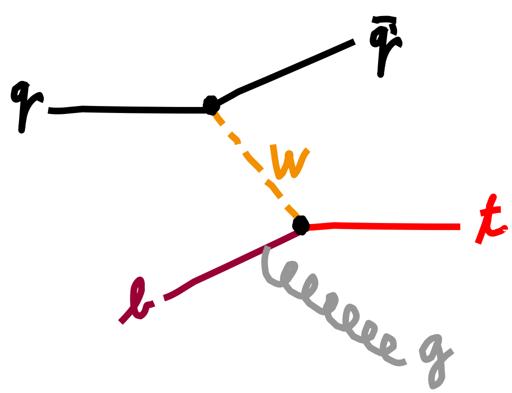
- Wbb,Wcc,Wc

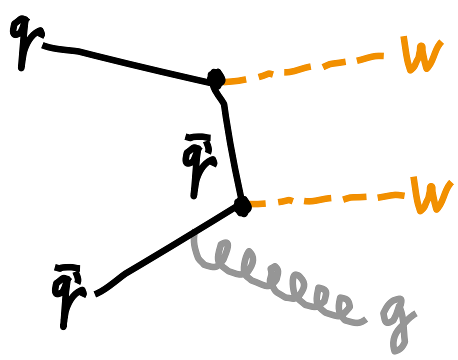


- W+ light jet + fake b



– Single top, WW, WZ, Z→ τ τ

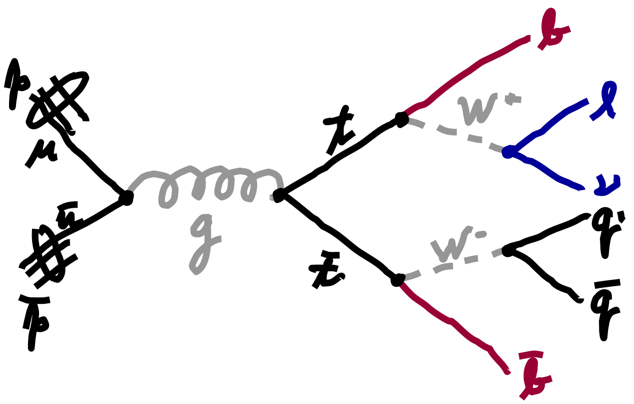




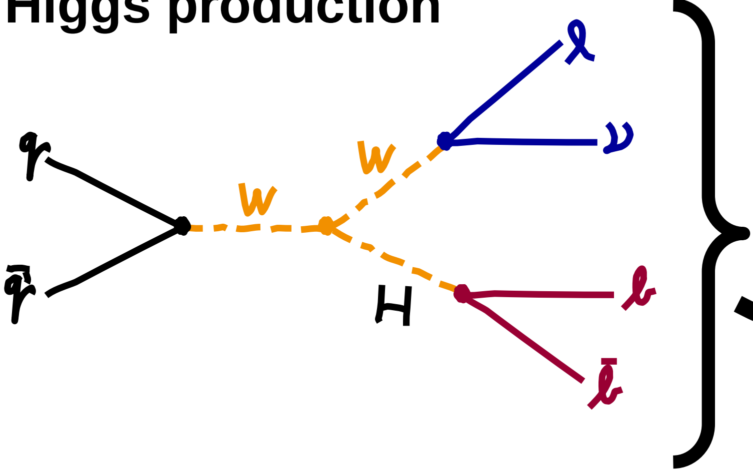
– Non-W

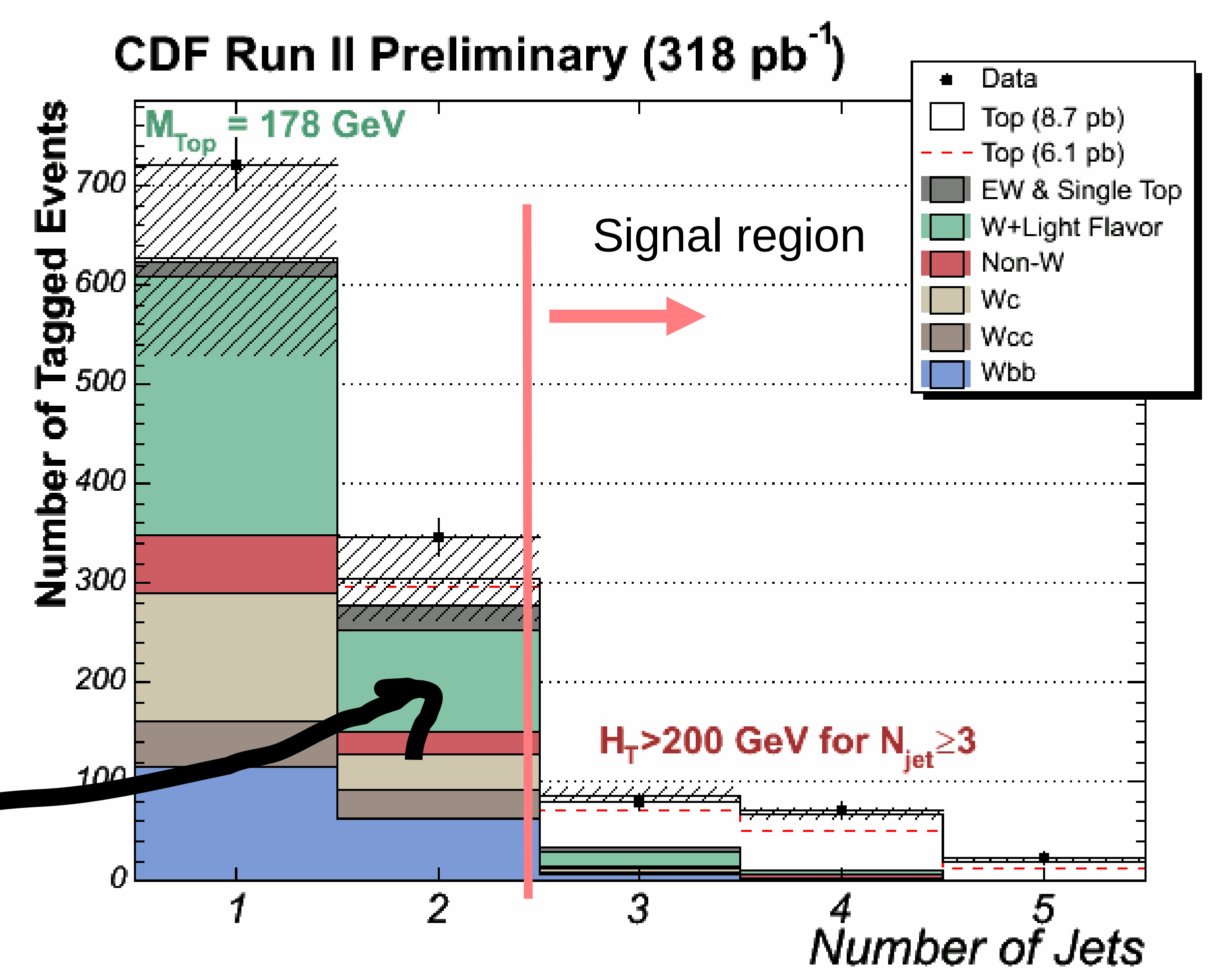
- Fake W-bosons

Top Cross Section (Single Tag)



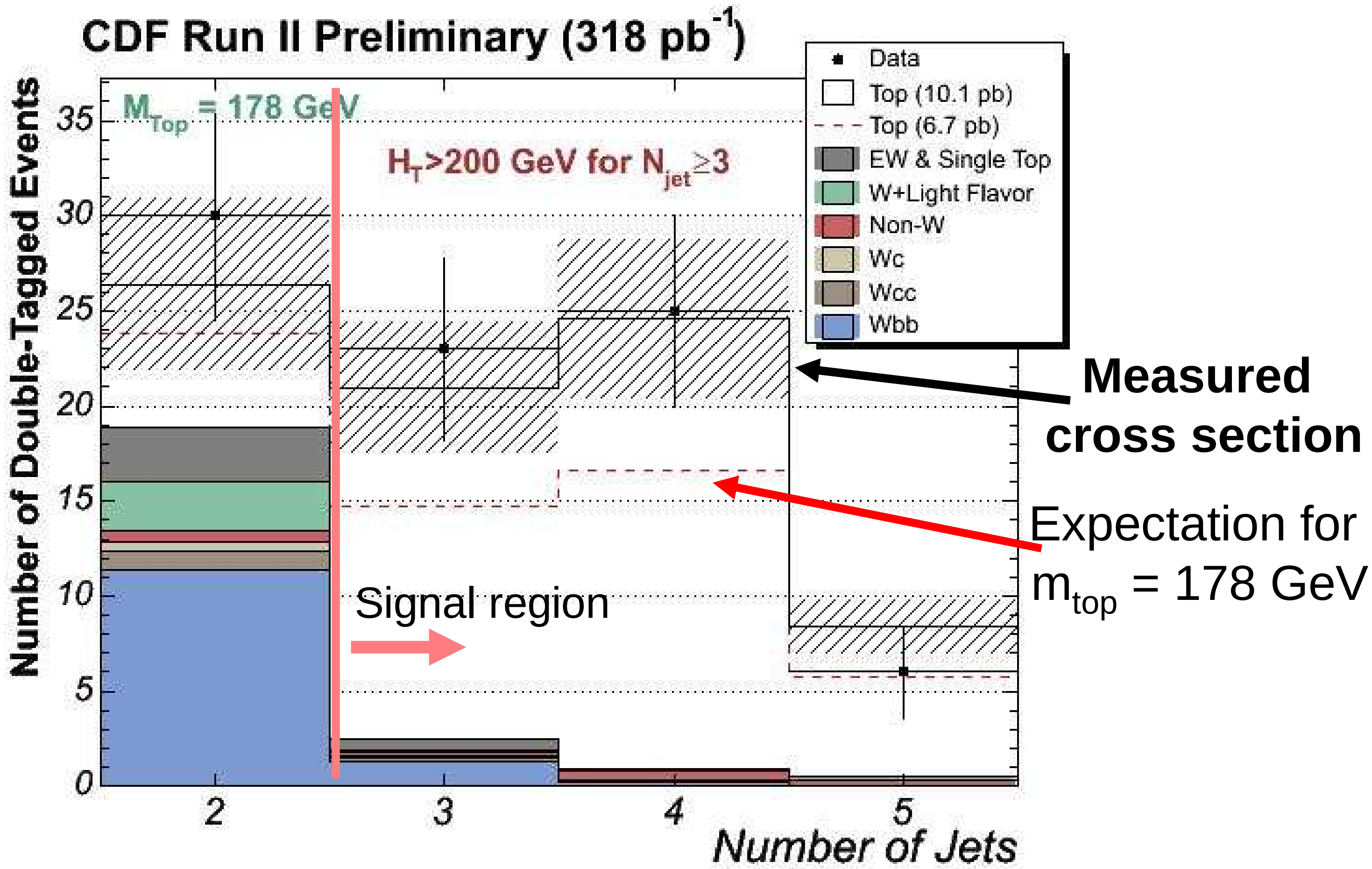
Higgs production





Sample	Events	*tt* fraction	σ(*tt*)
Loose Tagger	174	73%	$8.7^{+0.9}_{-0.9}\,{}^{+1.2}_{-0.9}$ pb

Top Cross Section (Double Tags)



Sample	Events	*tt* fraction	σ(*tt*)
Loose Tagger	54	92%	$10.1^{+1.6}_{-1.4}{}^{+2.1}_{-1.4}$ pb

Top in radiative corrections

Electromagnetic constant:
measured in atomic transitions, e^+e^- machines

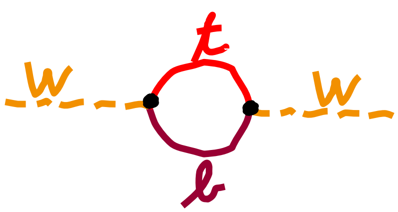
Weinberg angle:
measured at LEP/SLC

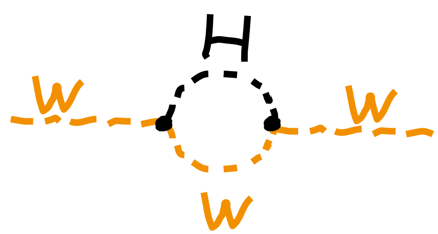
$$m_W = \left(\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}\right)^{\frac{1}{2}} \frac{1}{\sin\theta_W\sqrt{1-\Delta r}}$$

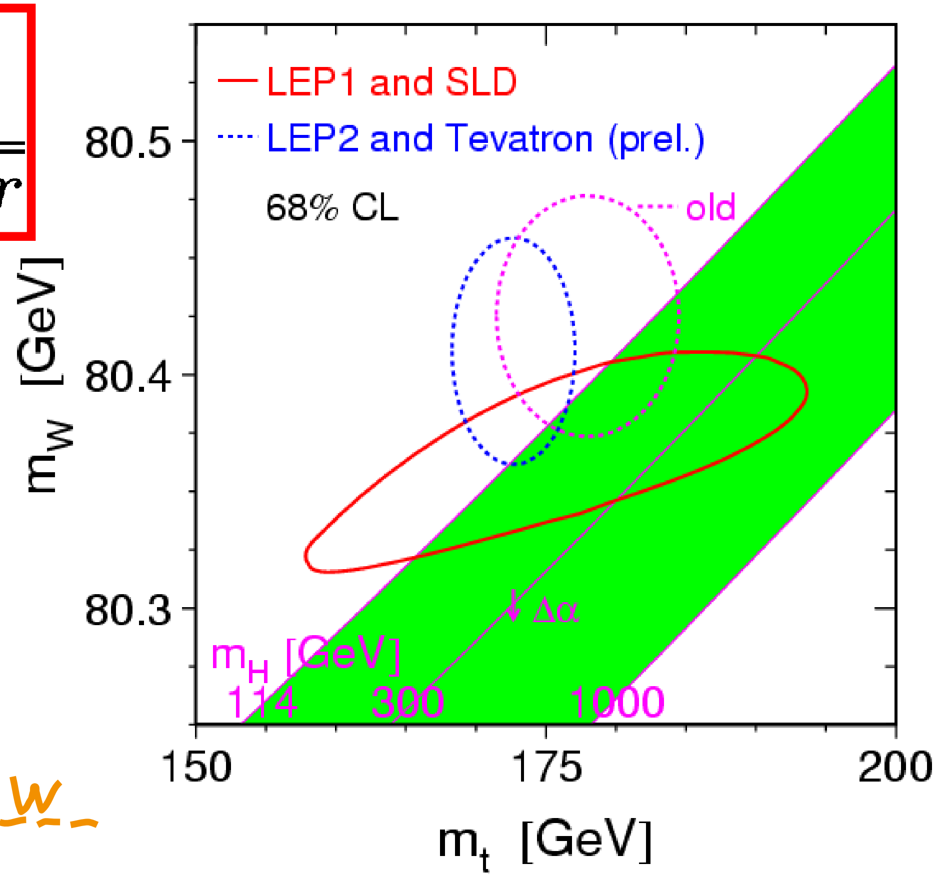
Fermi constant:
measured in muon decay

Radiative corrections

$$\Delta r \sim f(m_{top}^2, \ln m_H)$$



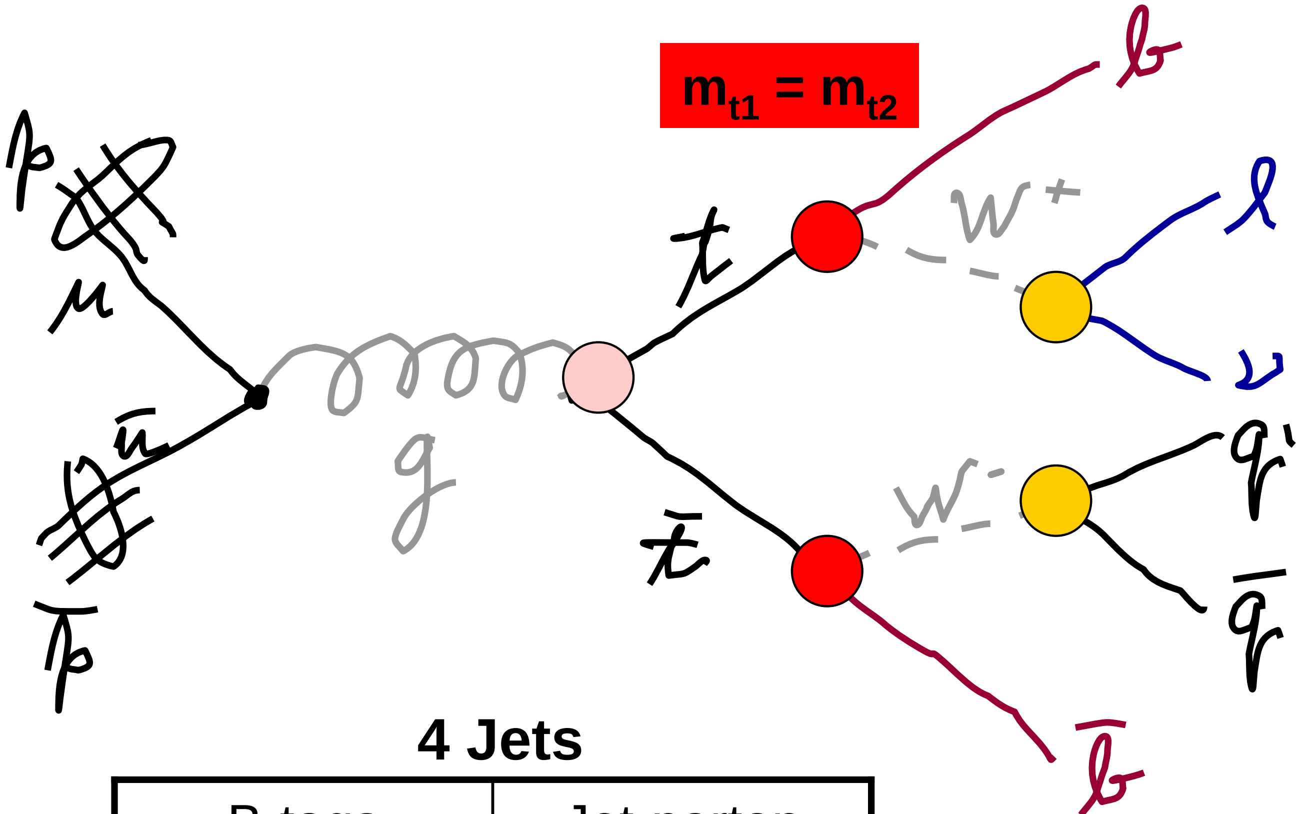




Top Mass Reconstruction

Lepton + Jets

Kinematical Fit



P_T balance

$m_{l\nu} = m_W$

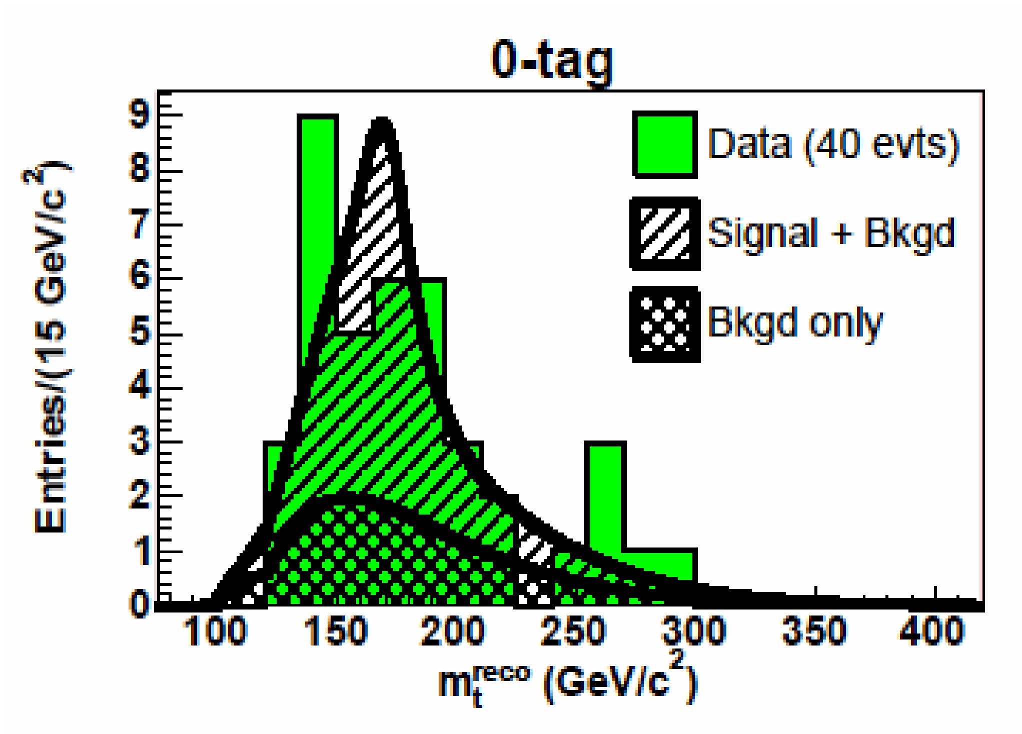
$m_{jj} = m_W$

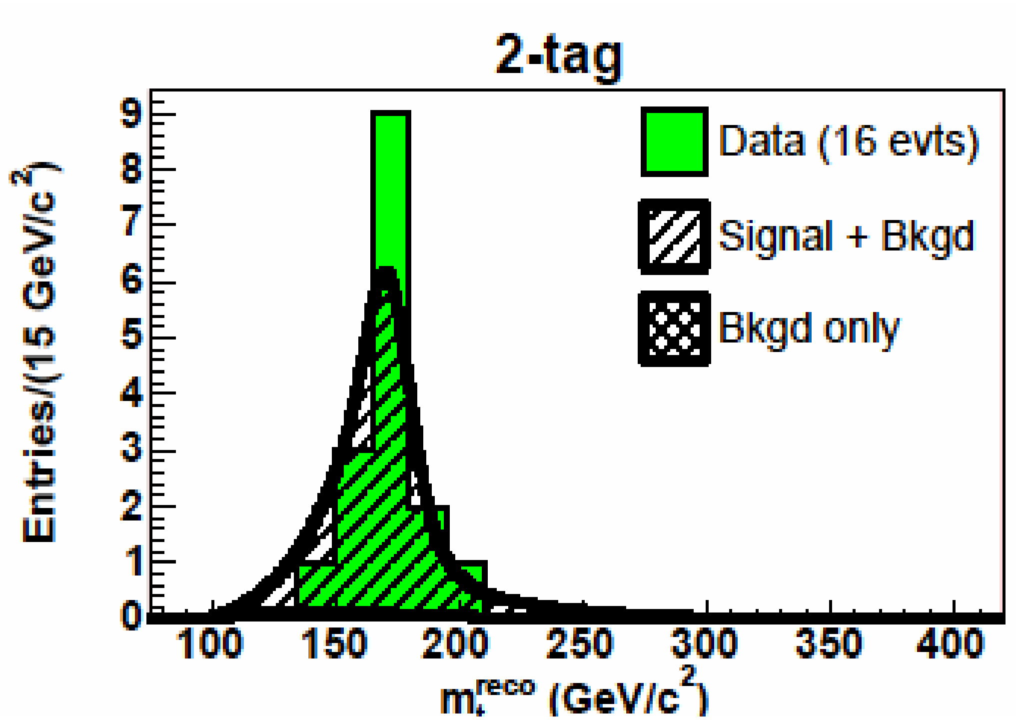
4 Jets

B-tags	Jet-parton combinations
0	12
1	6
2	2

x 2 neutrino P_z solutions

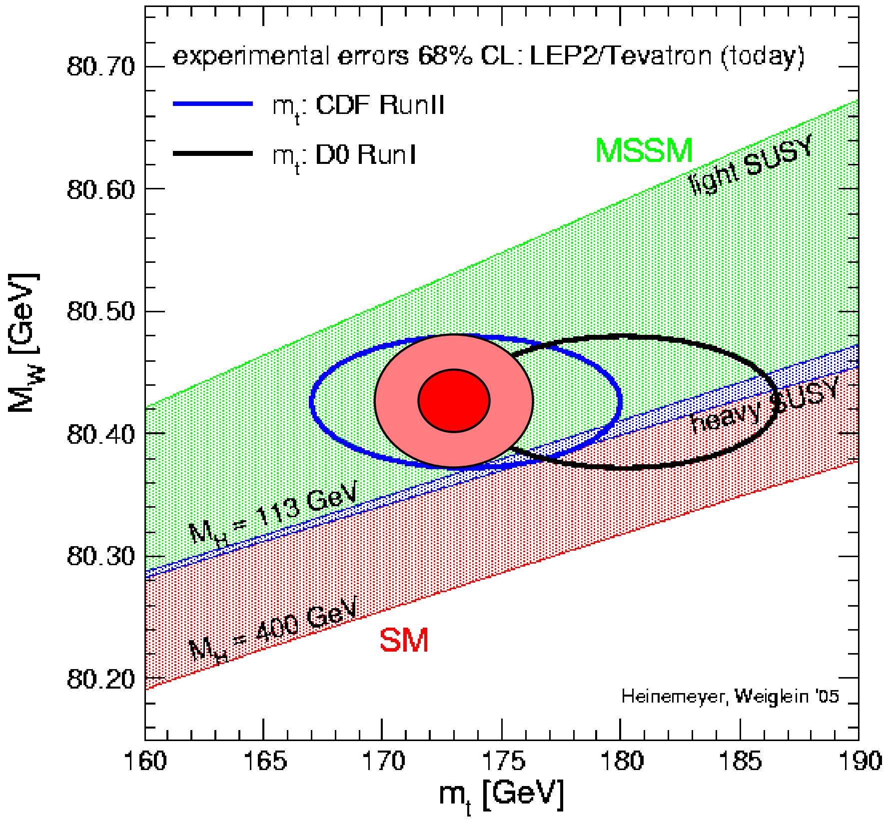
Top Mass Measurement





Effect on Higgs Mass Expectations

World Average: $m_{top} = 172.5 \pm 2.3$ GeV/c^2 (CDF + D0)



$\Delta m_{top} = 3.1\%$

$m_{top} = 178.0 \pm 4.3$ GeV
$m_H = 114^{+69}_{-45}$ GeV
$m_H < 260$ GeV @ 95% C.L.

$m_{top} = 172.5 \pm 2.3$ GeV
$m_H = 89^{+42}_{-32}$ GeV
$m_H < 207$ GeV @ 95% C.L.

$\Delta m_H = 22\%$

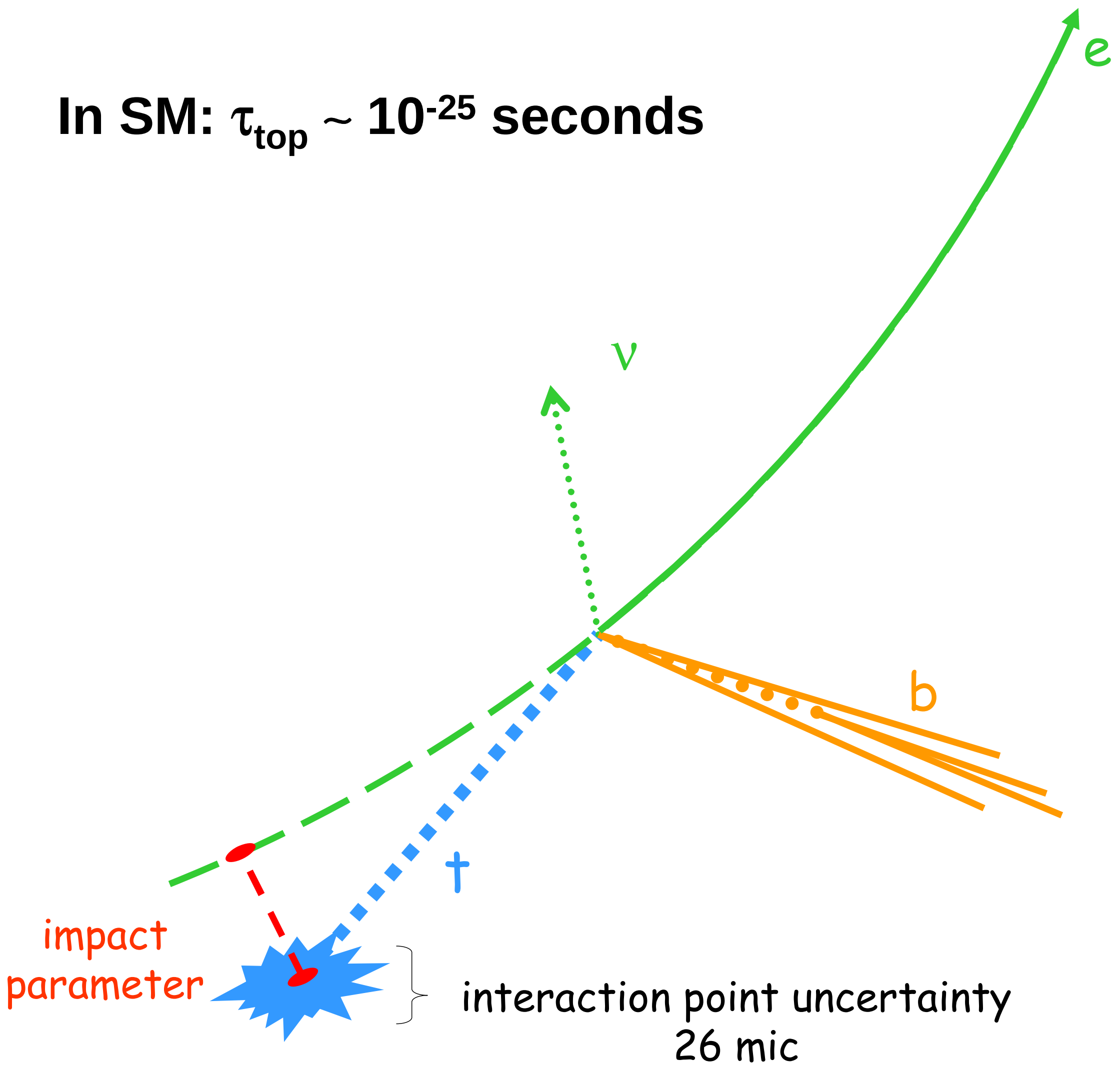
Future Prospects:

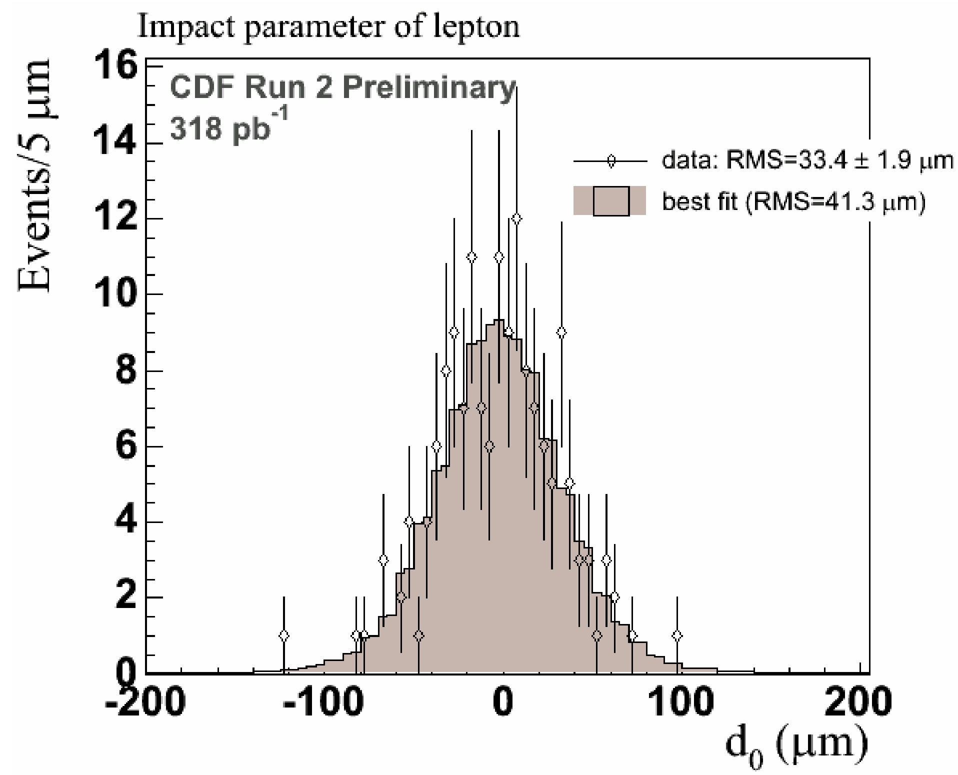
- $\Delta m_{top} < 1.5$ GeV/c^2
- $\Delta m_W < 25$ MeV/c^2

$$\frac{\Delta M_H}{M_H} < 30\%$$

Top Lifetime: Direct Measurement

In SM: $\tau_{top} \sim 10^{-25}$ seconds



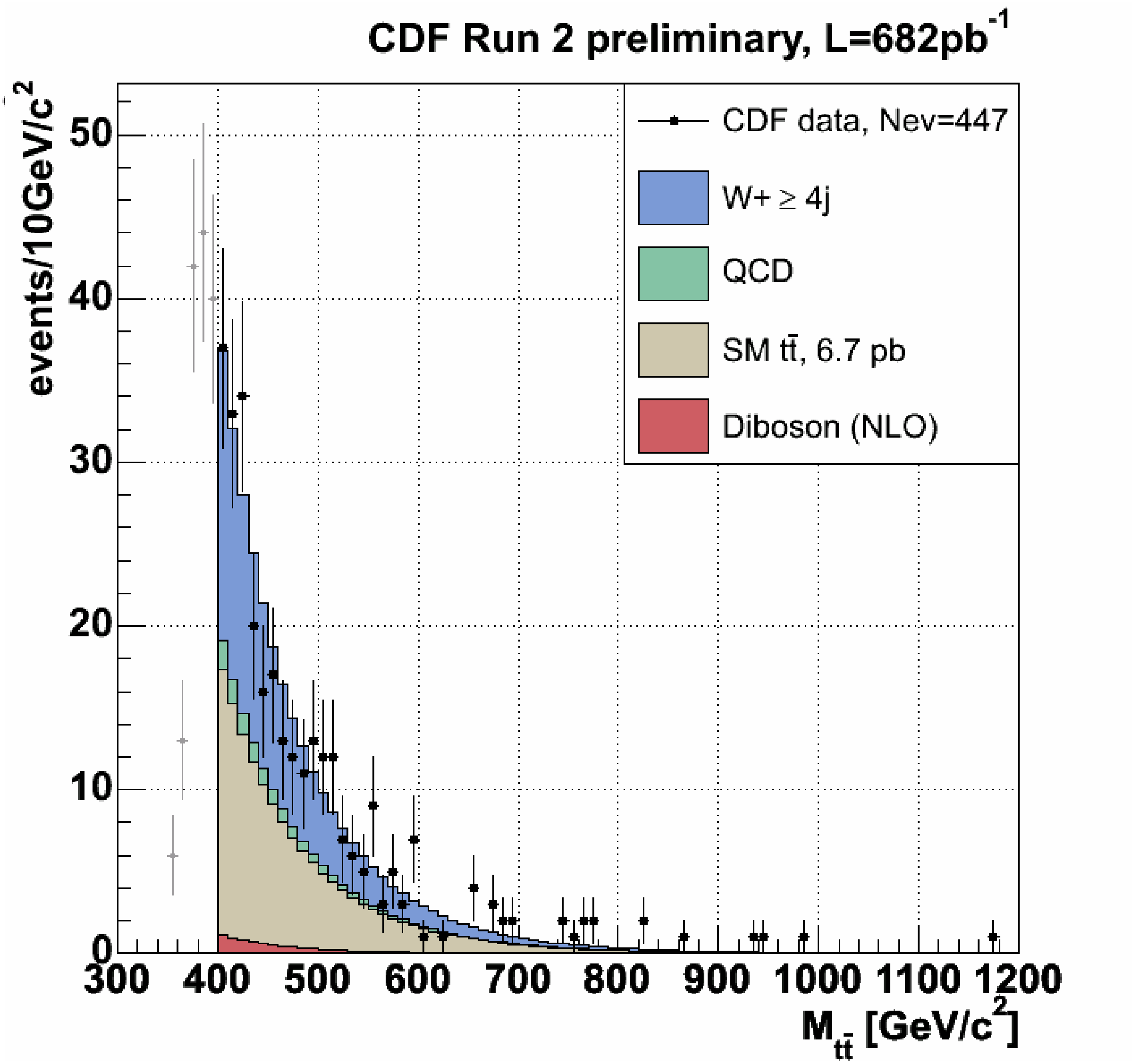


$\tau_{top} < 17.5 \times 10^{-14}$ seconds
@ 95% C.L. (CDF)

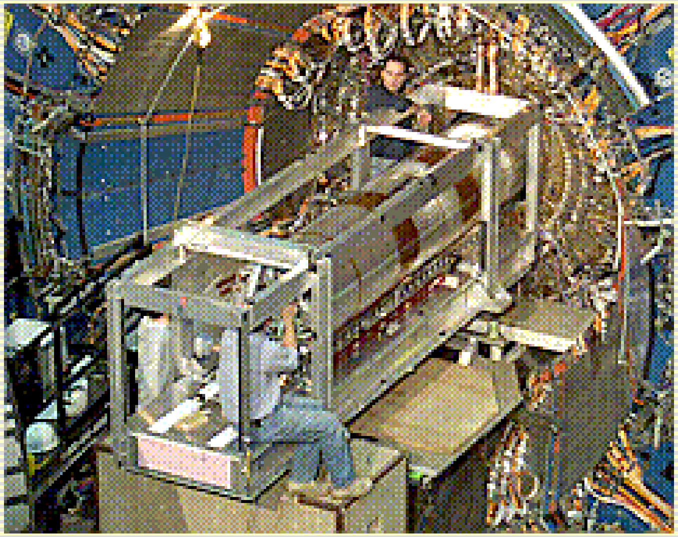
Toponium? Mass Resonance?

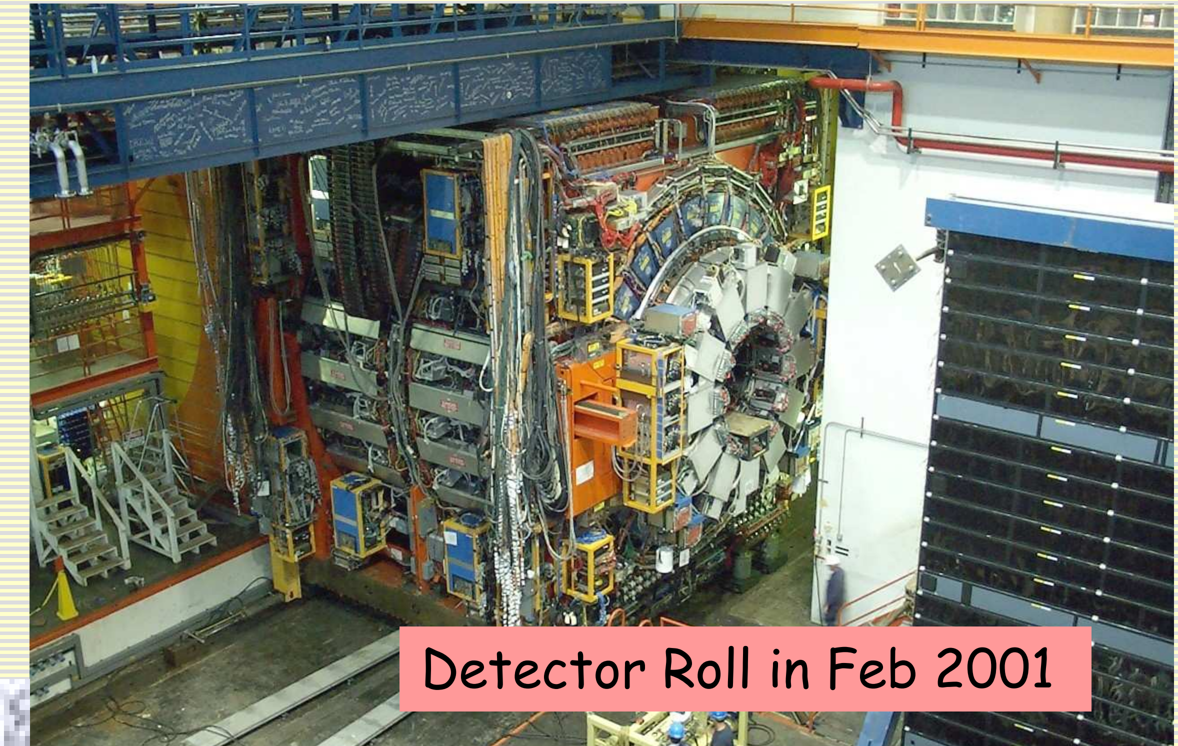
Hadronization:

$\tau \sim 10^{-23}$ seconds



CDF II at Work!

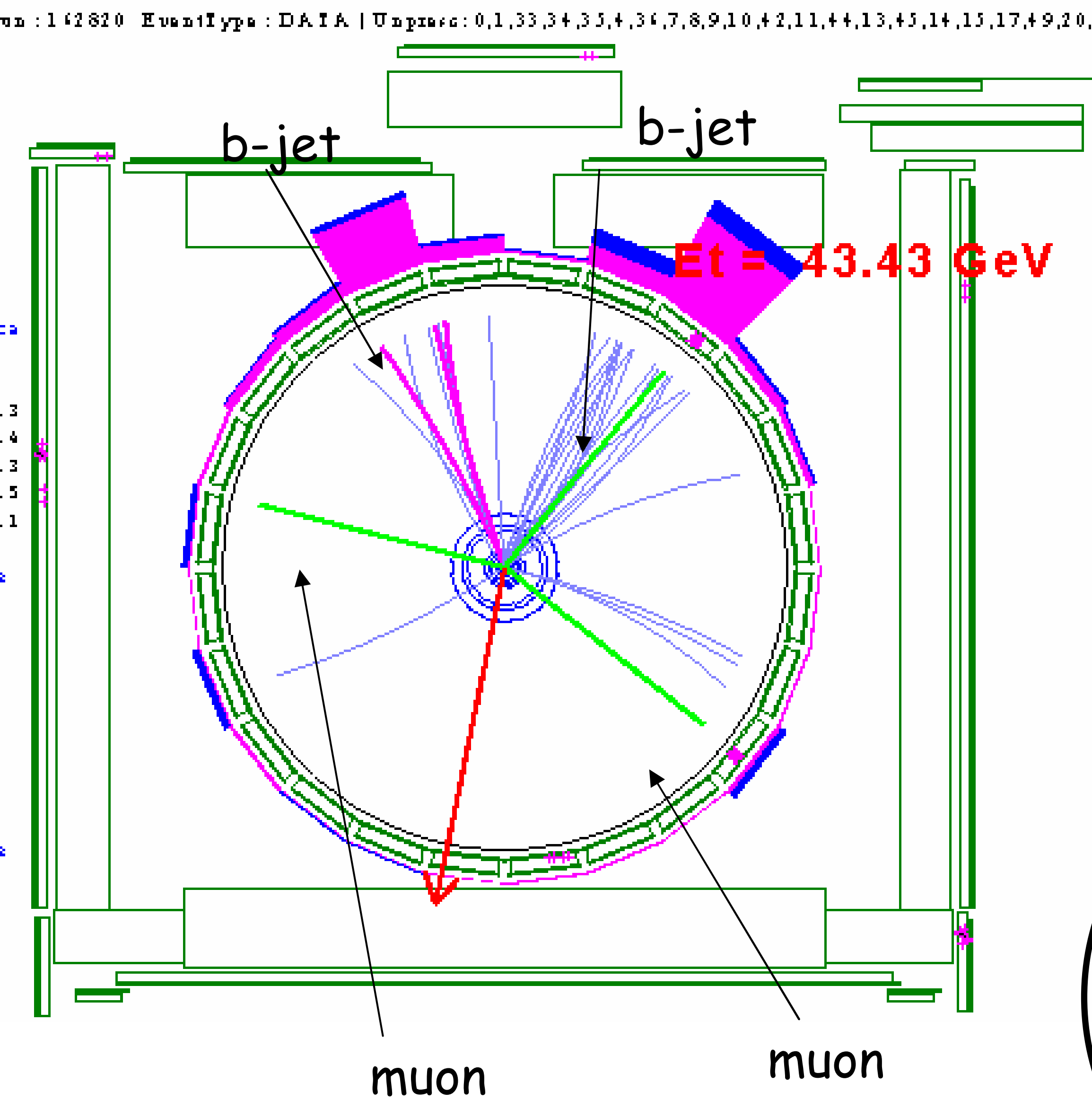




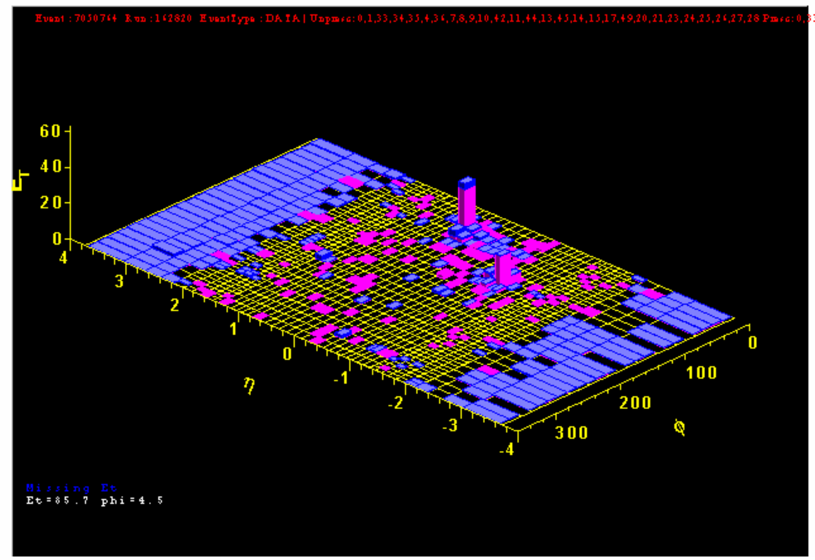
Detector Roll in Feb 2001

There is a control room, too.

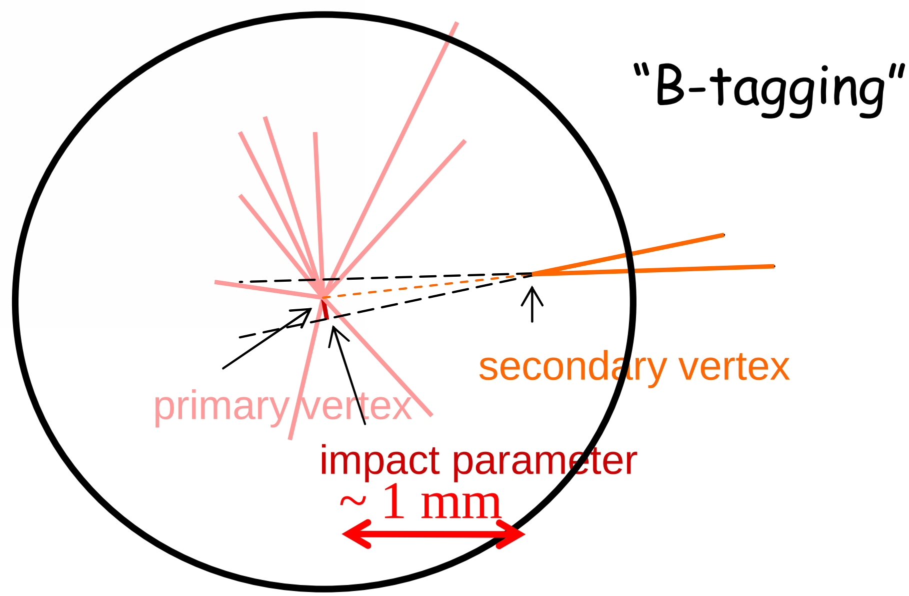
A Real Event...



b-jet
b-jet
Et = 43.43 GeV
muon
muon



E_T
60
40
20
0
η
φ
100
200
300
Missing Et
Et=85.7 phi=4.5



"B-tagging"
secondary vertex
primary vertex
impact parameter
~ 1 mm