

Title: Top Quark: The Elusive Truth

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Abstract: The top quark is the heaviest known type of quark, and possibly the last. Particle physicists sometimes refer to it as the "truth" quark, not always with tongue in cheek. The top quark might be just an ordinary quark, no stranger than the "strange" one, but it might hold the key to major questions of Nature through its connection to the origin of mass, the Higgs boson, and cosmic dark matter. At the Fermi National Accelerator Laboratory outside Chicago, hundreds of these heavy quarks have been observed and some first snapshots of their behavior have been obtained. At the Large Hadron Collider at CERN, millions of the heavy quarks will be produced. This lecture will review current knowledge of the top quark and explain how this knowledge has been obtained through experiments at the giant particle accelerators. Future experiments, which might reveal the top quark's deeper mysteries, will also be described.

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# QUANTUM TO COSMOS

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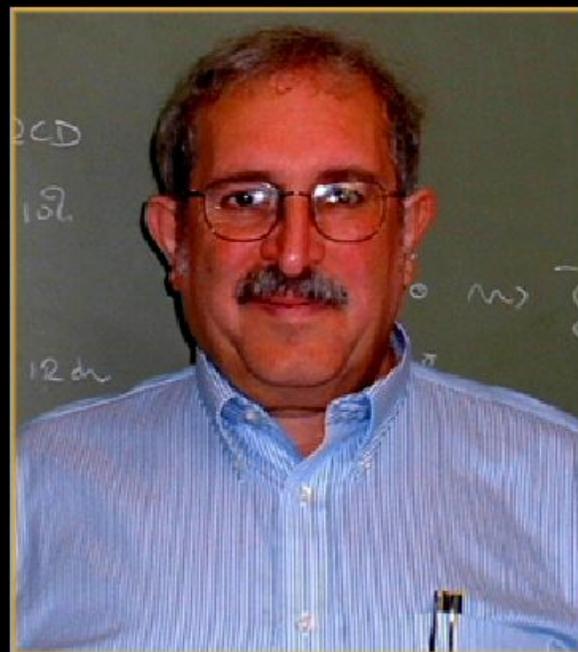
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# TOP QUARK: THE ELUSIVE TRUTH

Michael E. Peskin, SLAC National Laboratory, Stanford



# Top Quark: the Elusive Truth

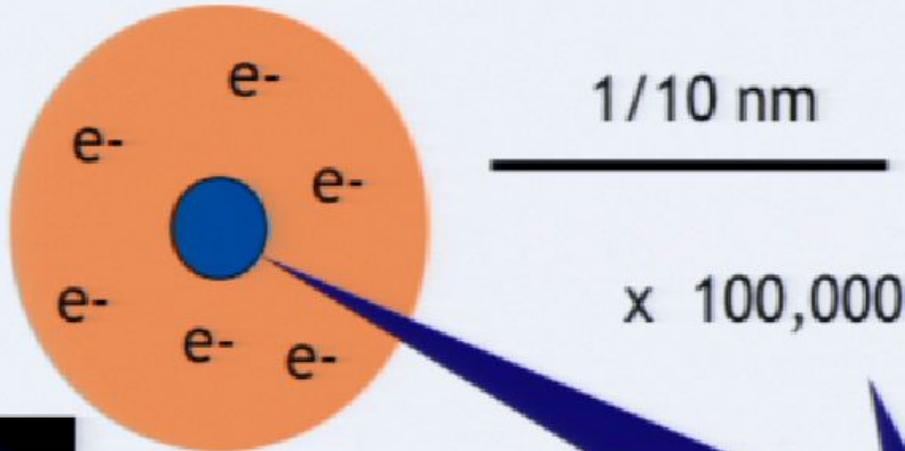
How to recognize a Top Quark

Evidence for the Top Quark

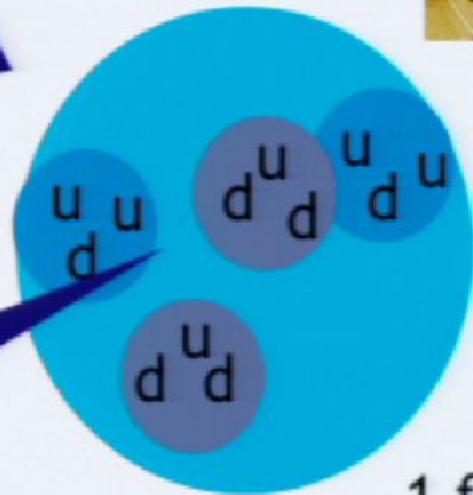
Quantum Patterns

Quantum Patterns of the Top

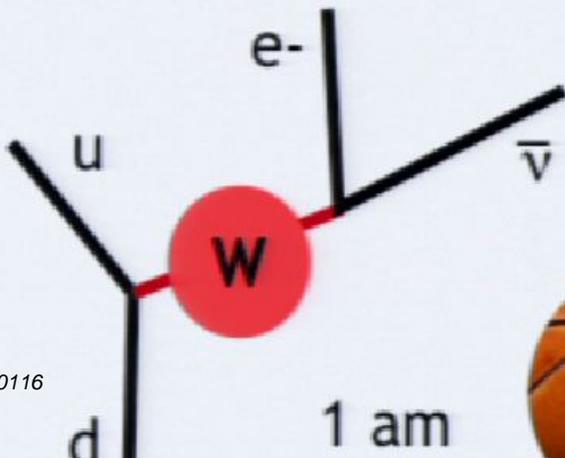
Top and the Problem of Mass



x 100,000



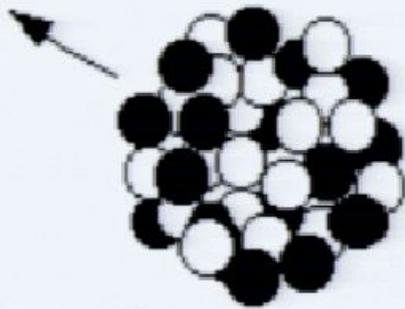
x 1000



# Beta Particle Radiation



Daughter  
Nucleus  
Calcium-40



Parent Nucleus  
Potassium-40



Antineutrino



Beta Particle

d



e



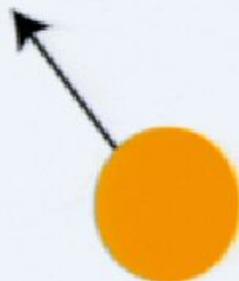
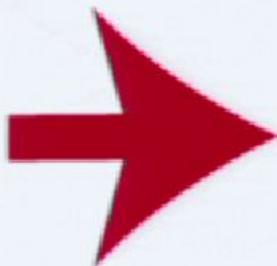
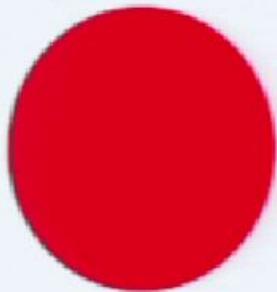
u



$\bar{\nu}_l$



b



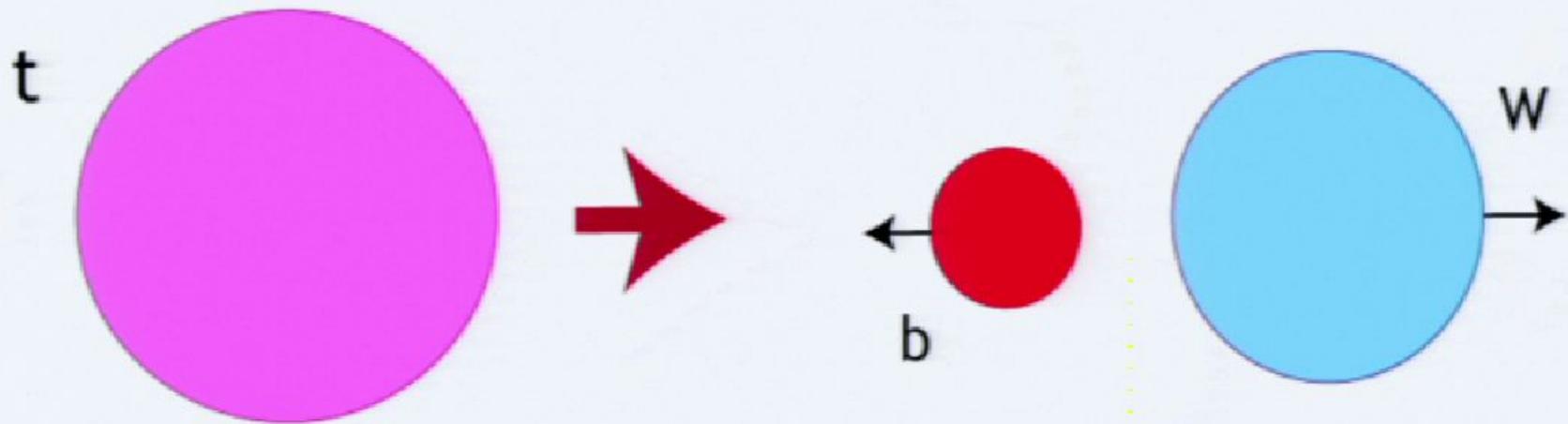
e



c



$\bar{\nu}$



top  $\Rightarrow$  b + W

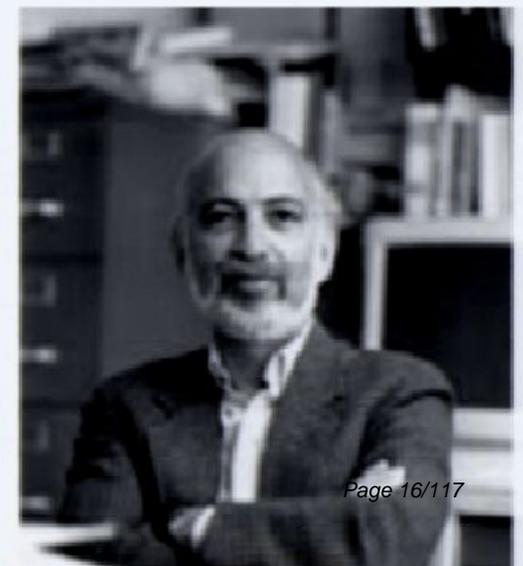
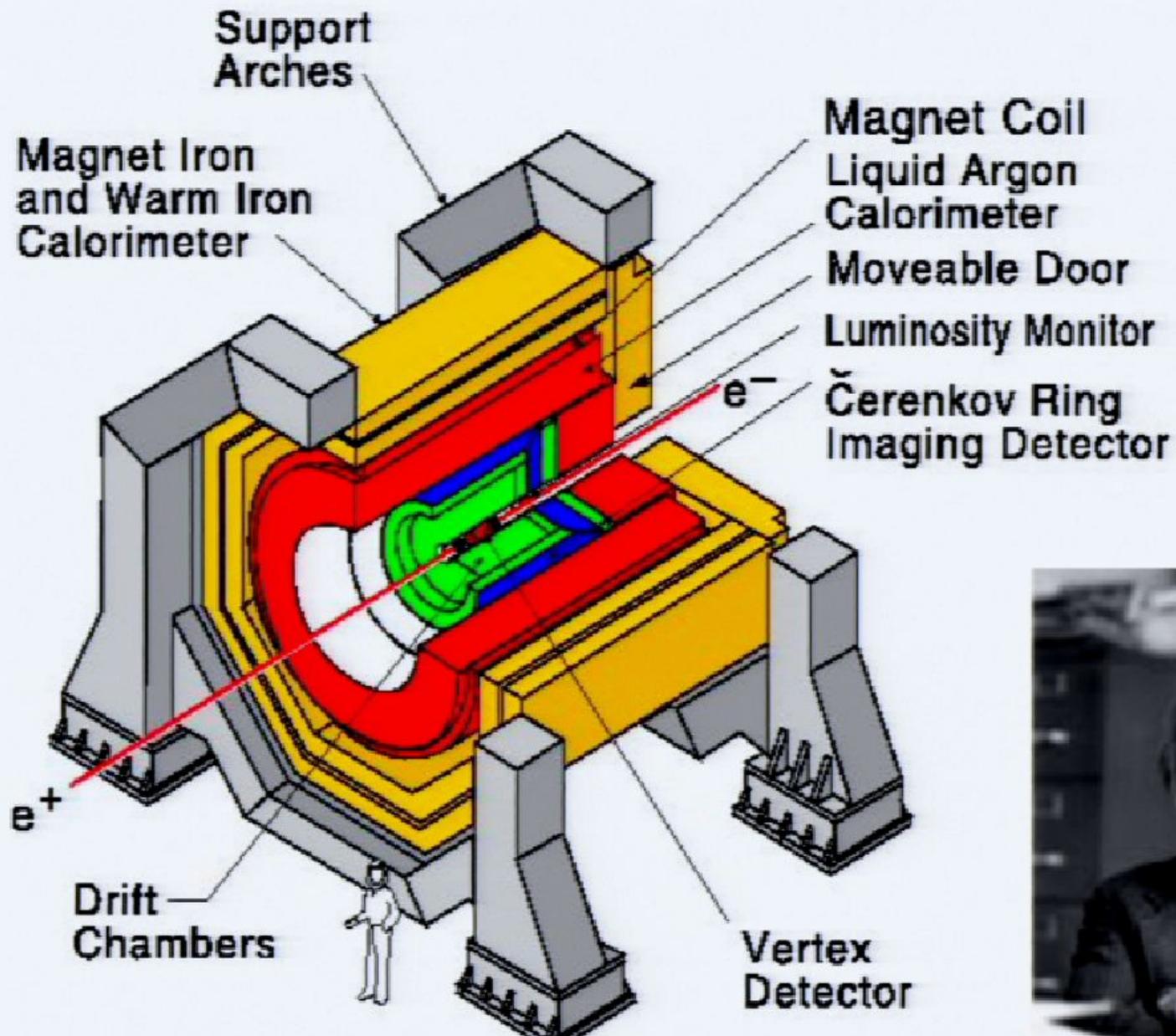
$\Rightarrow$  b + q +  $\bar{q}$

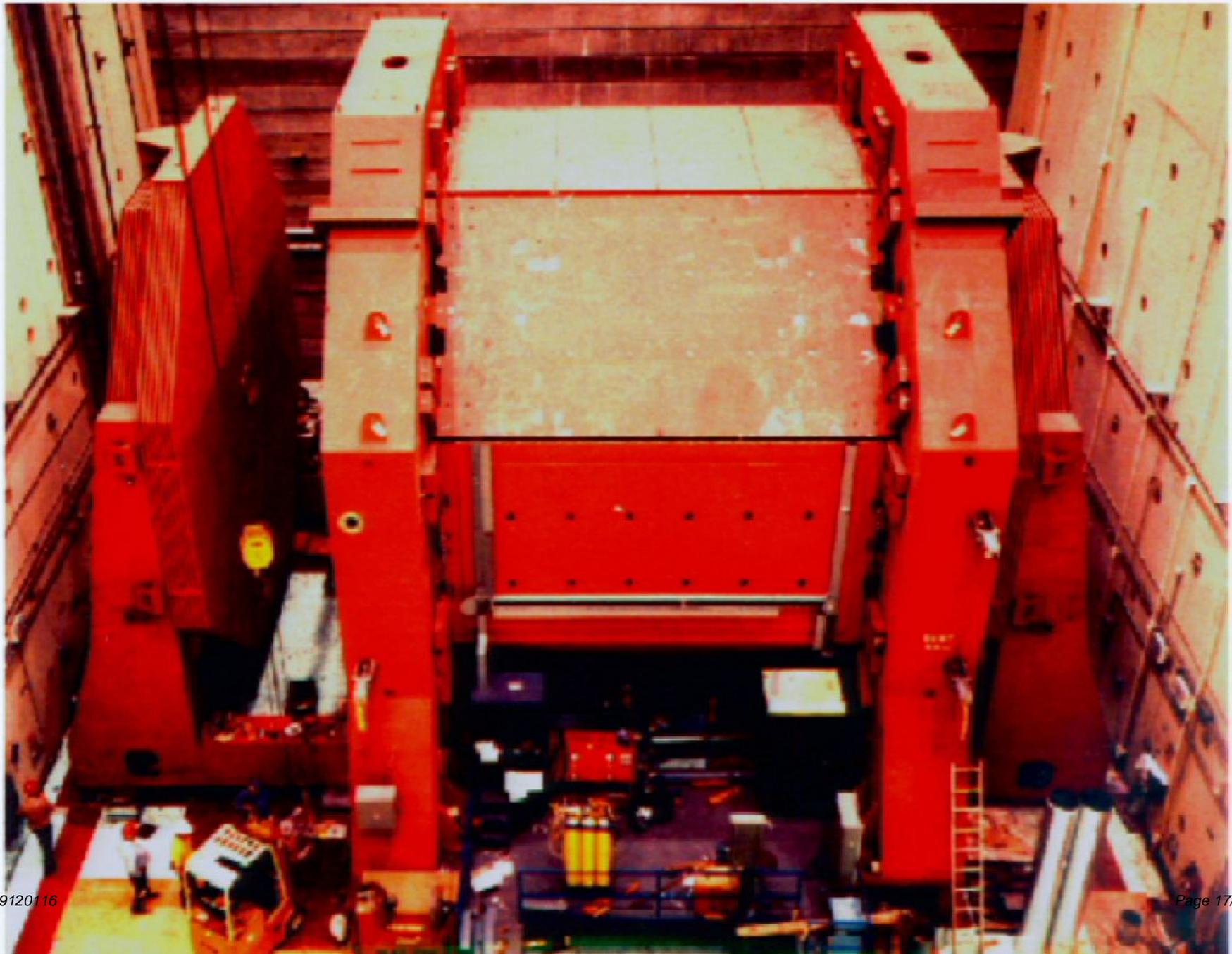
$\Rightarrow$  b + e +  $\bar{\nu}$

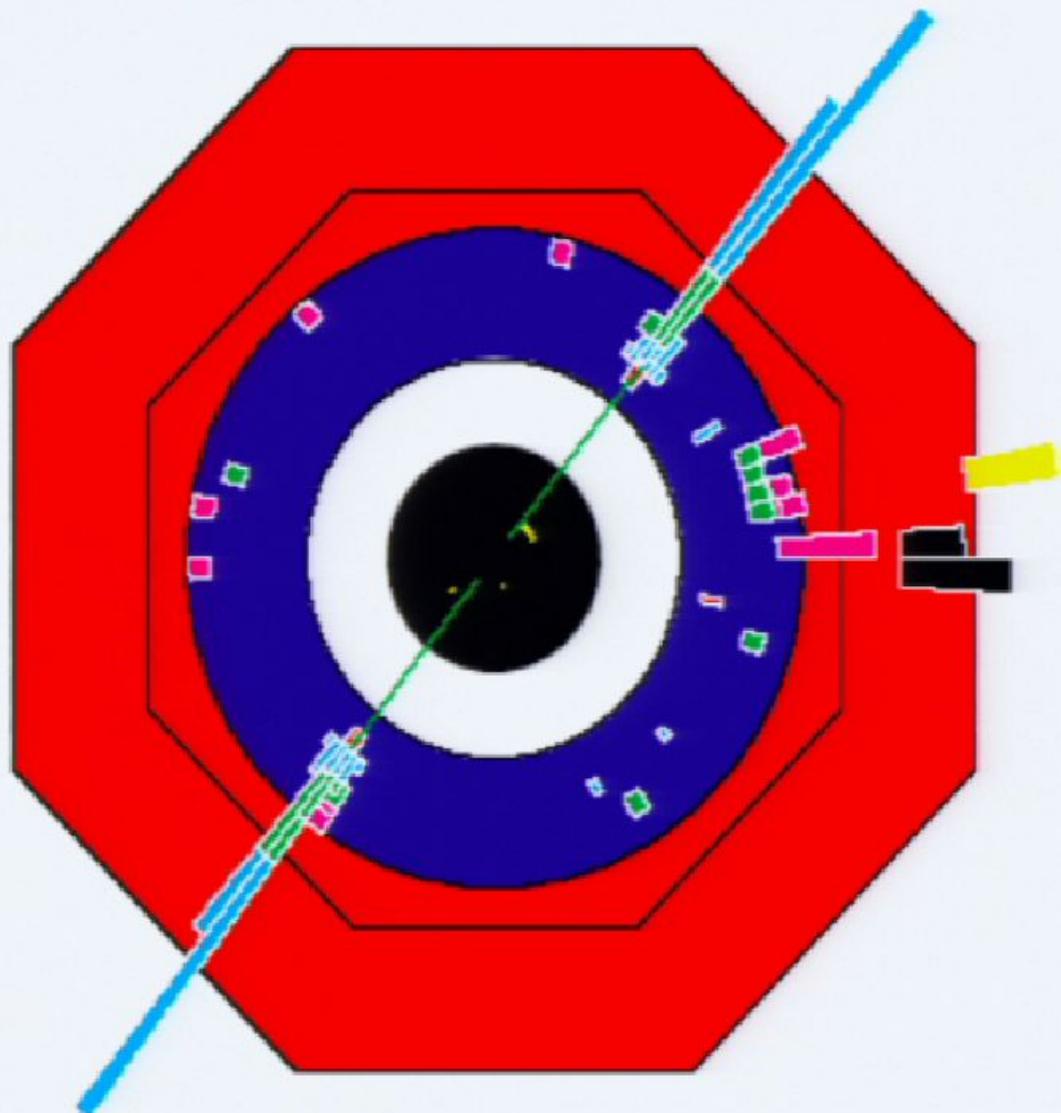
But what does a quark actually look like ?

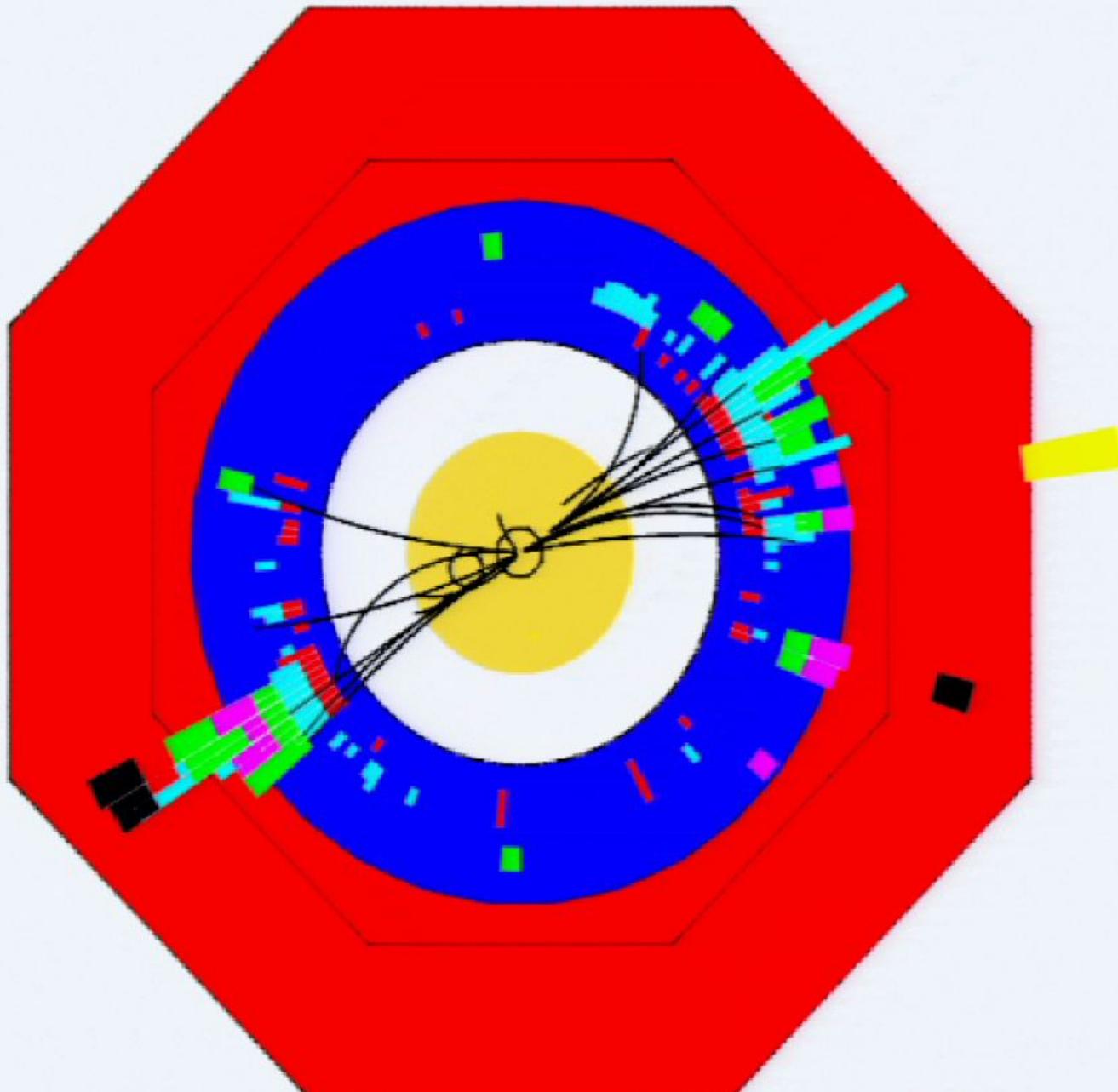


# SLD

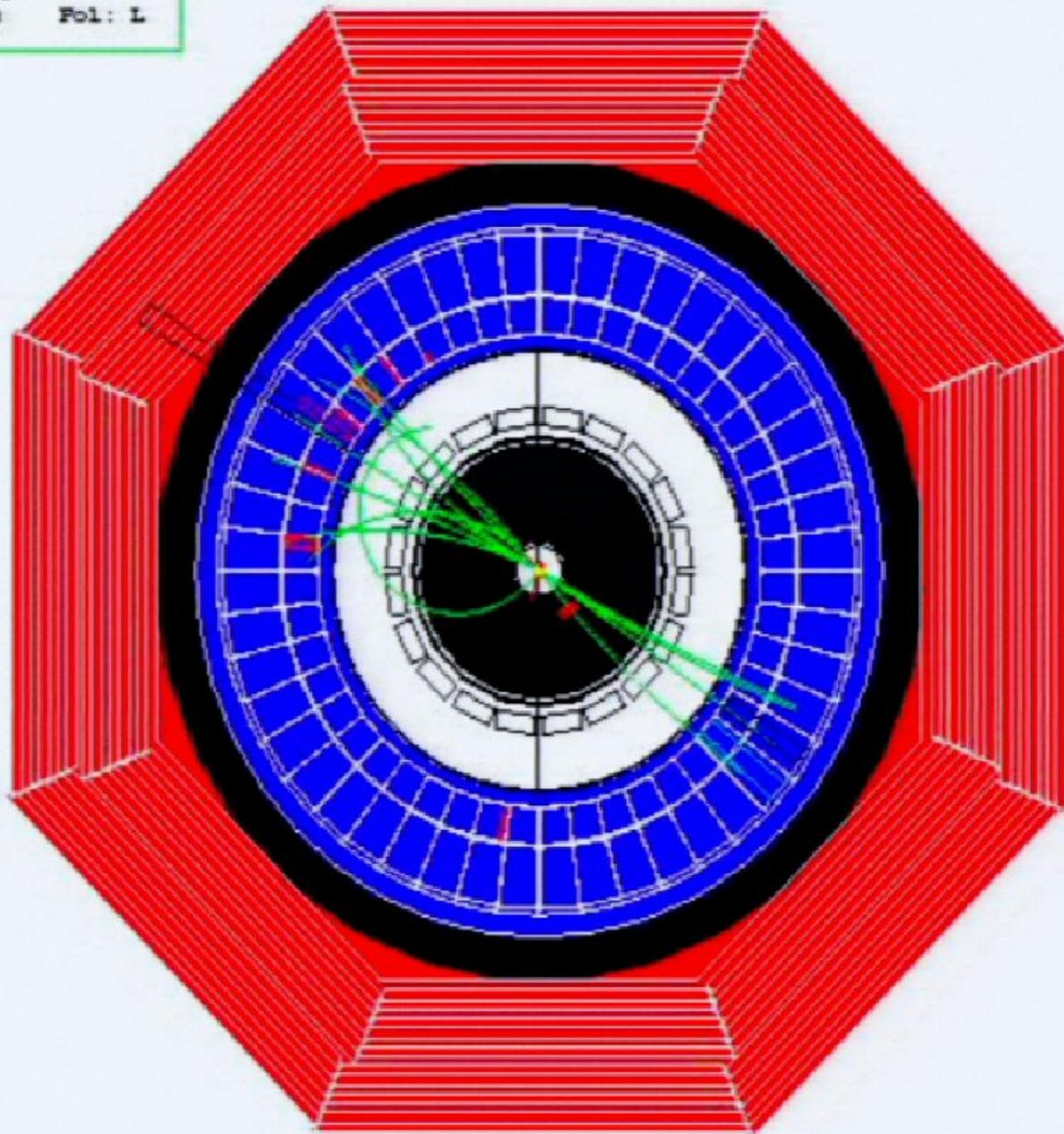






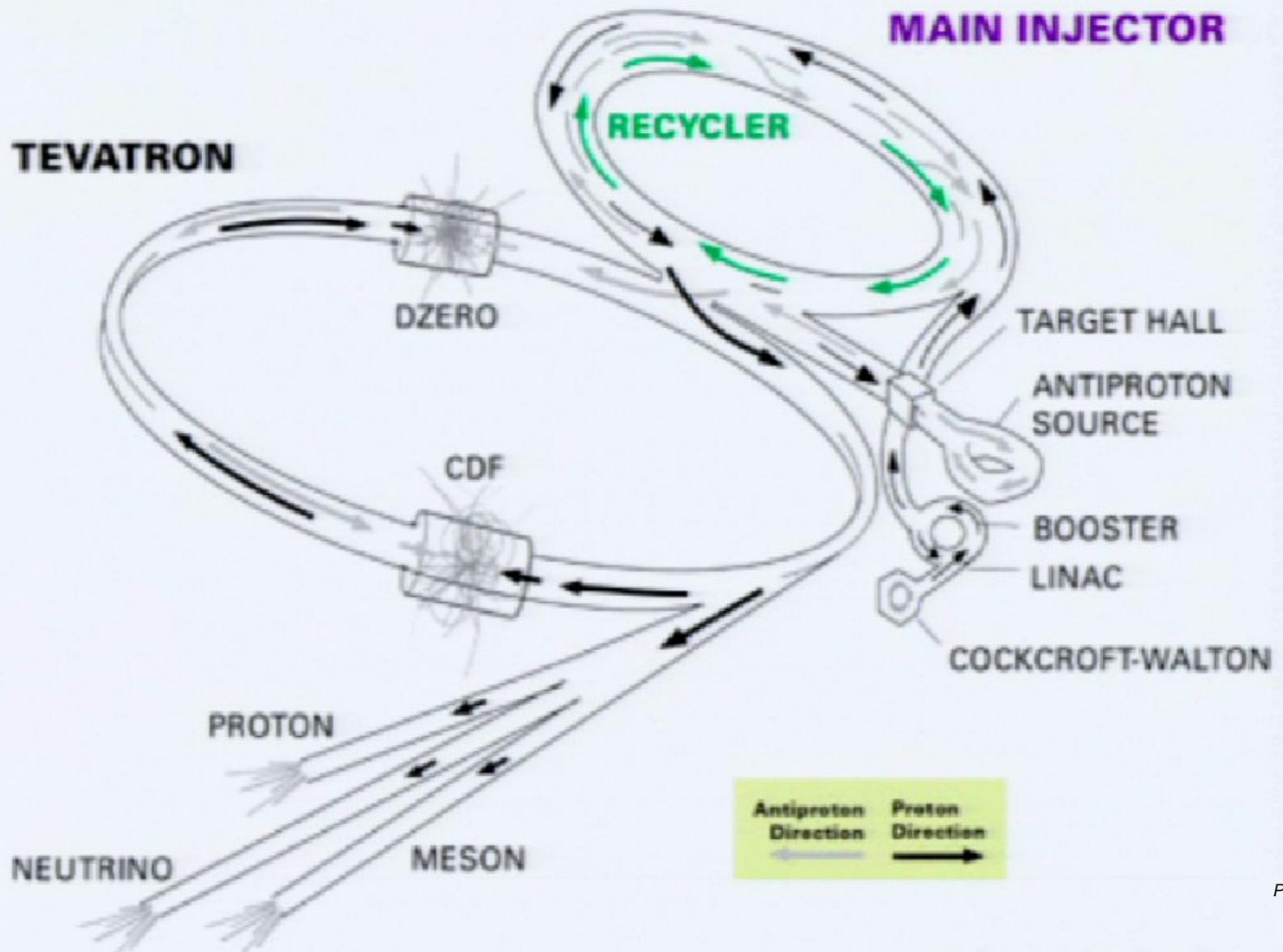


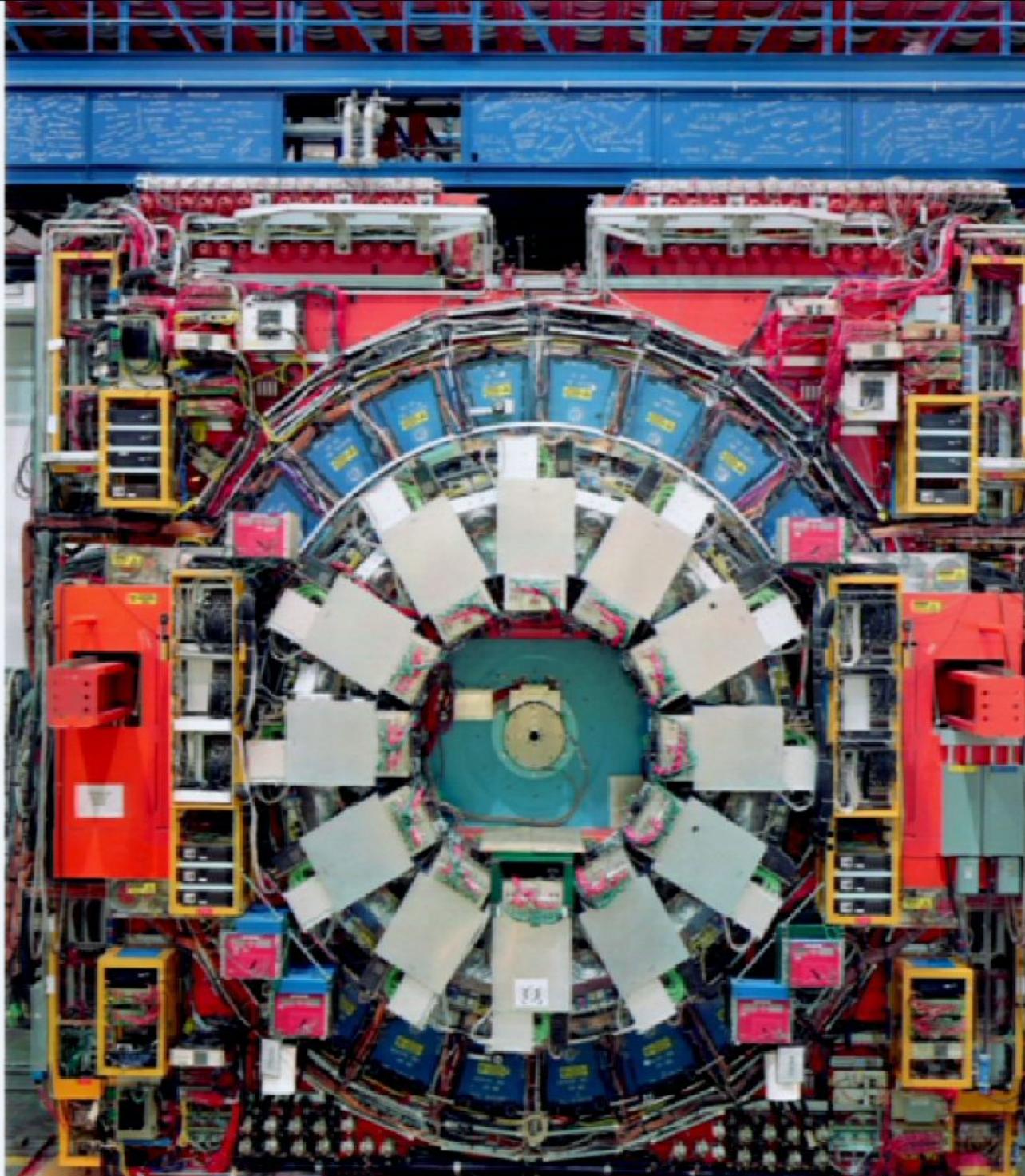
Run 12576, EVENT 2540  
4-JUL-1992 19:18  
Source: Run Data Fol: 1



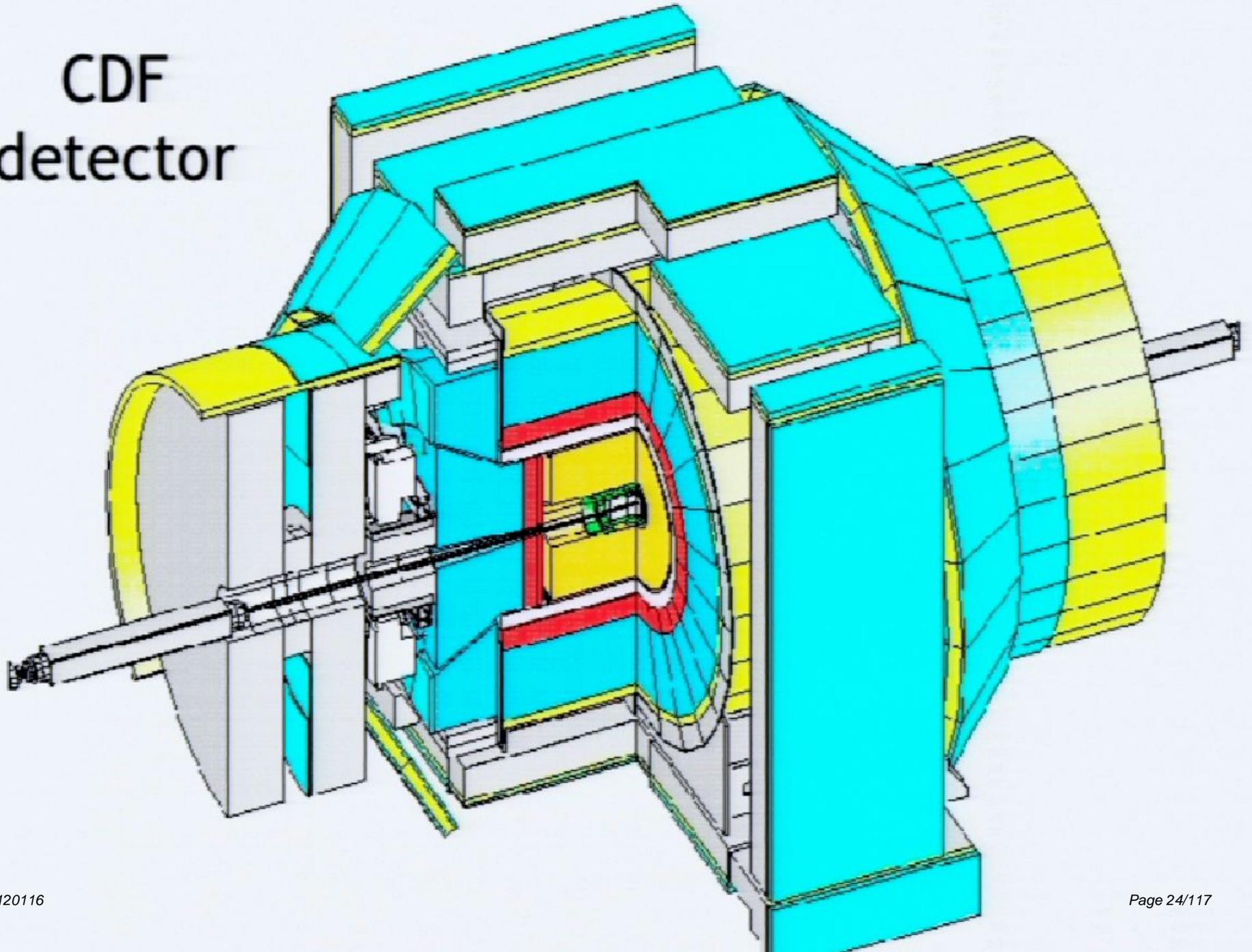


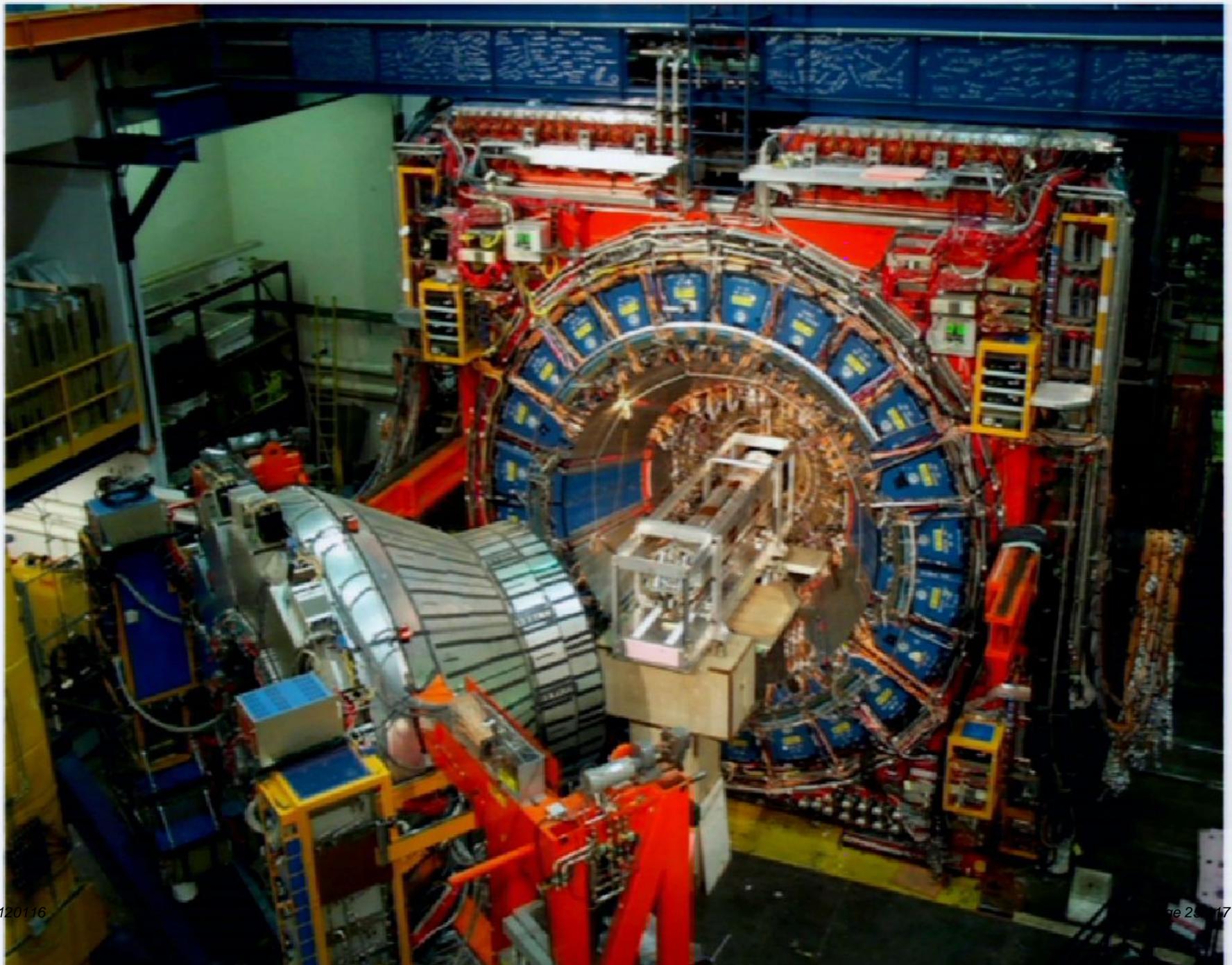
# FERMILAB'S ACCELERATOR CHAIN





# CDF detector





each time the protons go around

probability of proton-antiproton collision

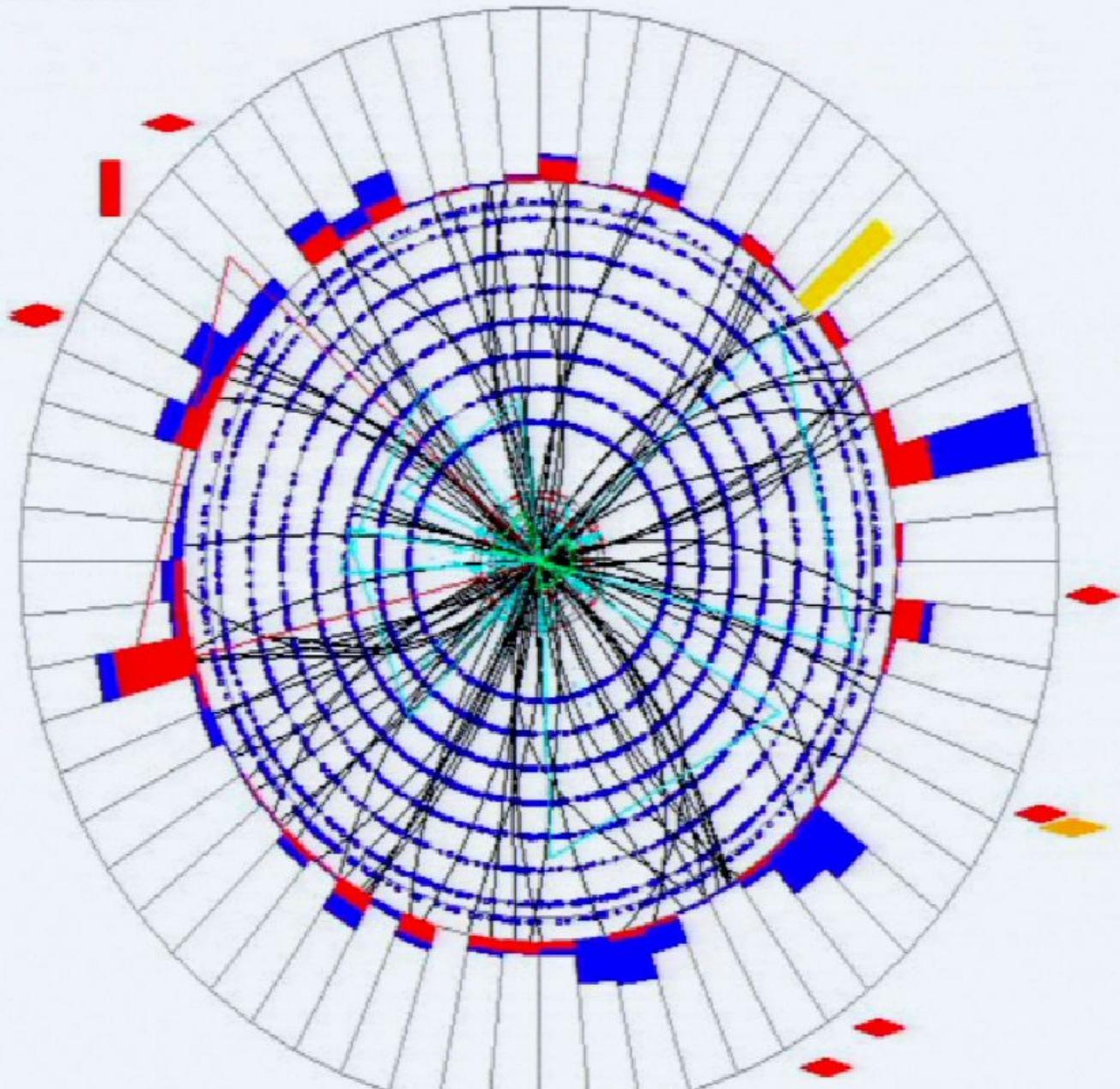
1

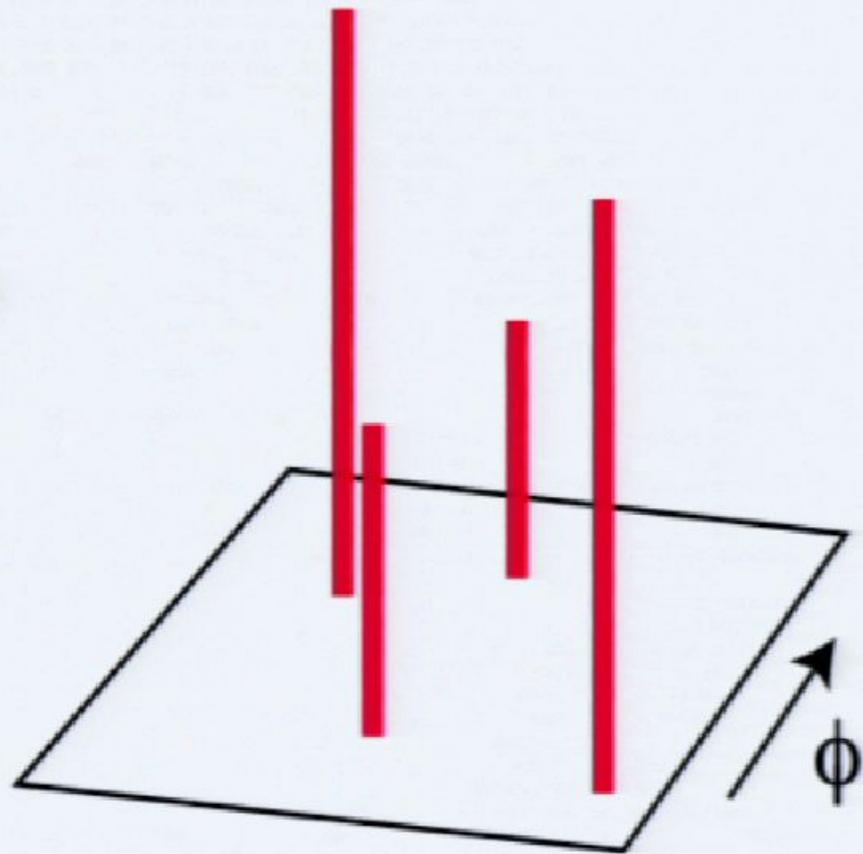
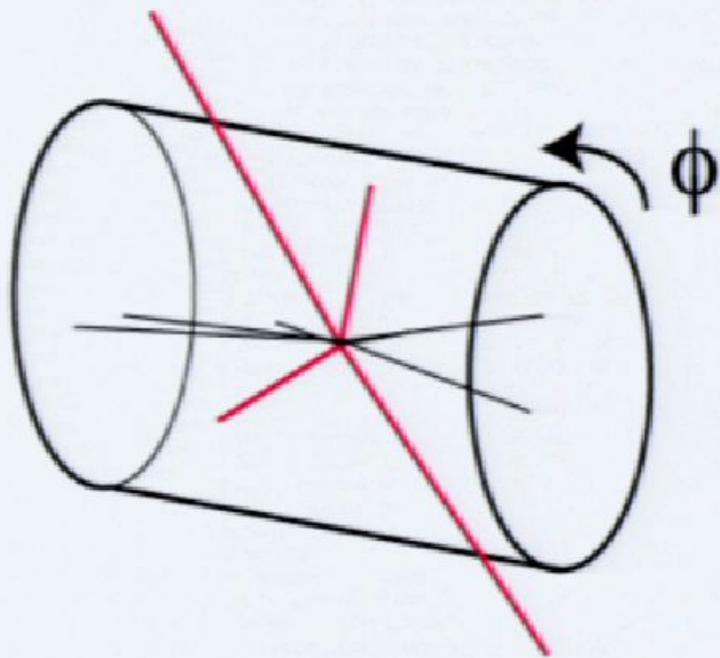
probability of producing top + antitop

1 in 10 billion

Run 223385 Evt 9802792 Thu Jul 20 17:14:11 2008

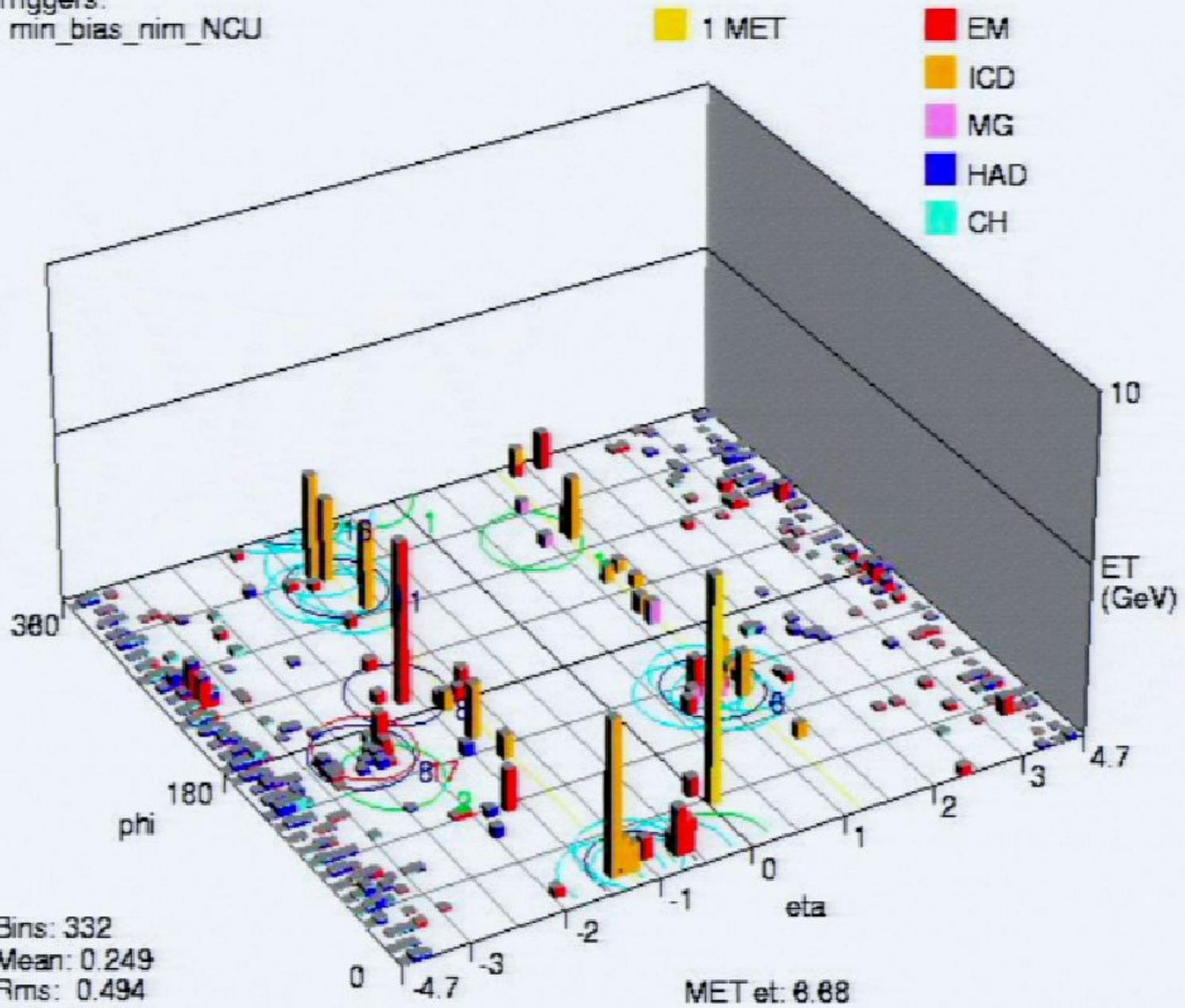
ET scale: 10 GeV





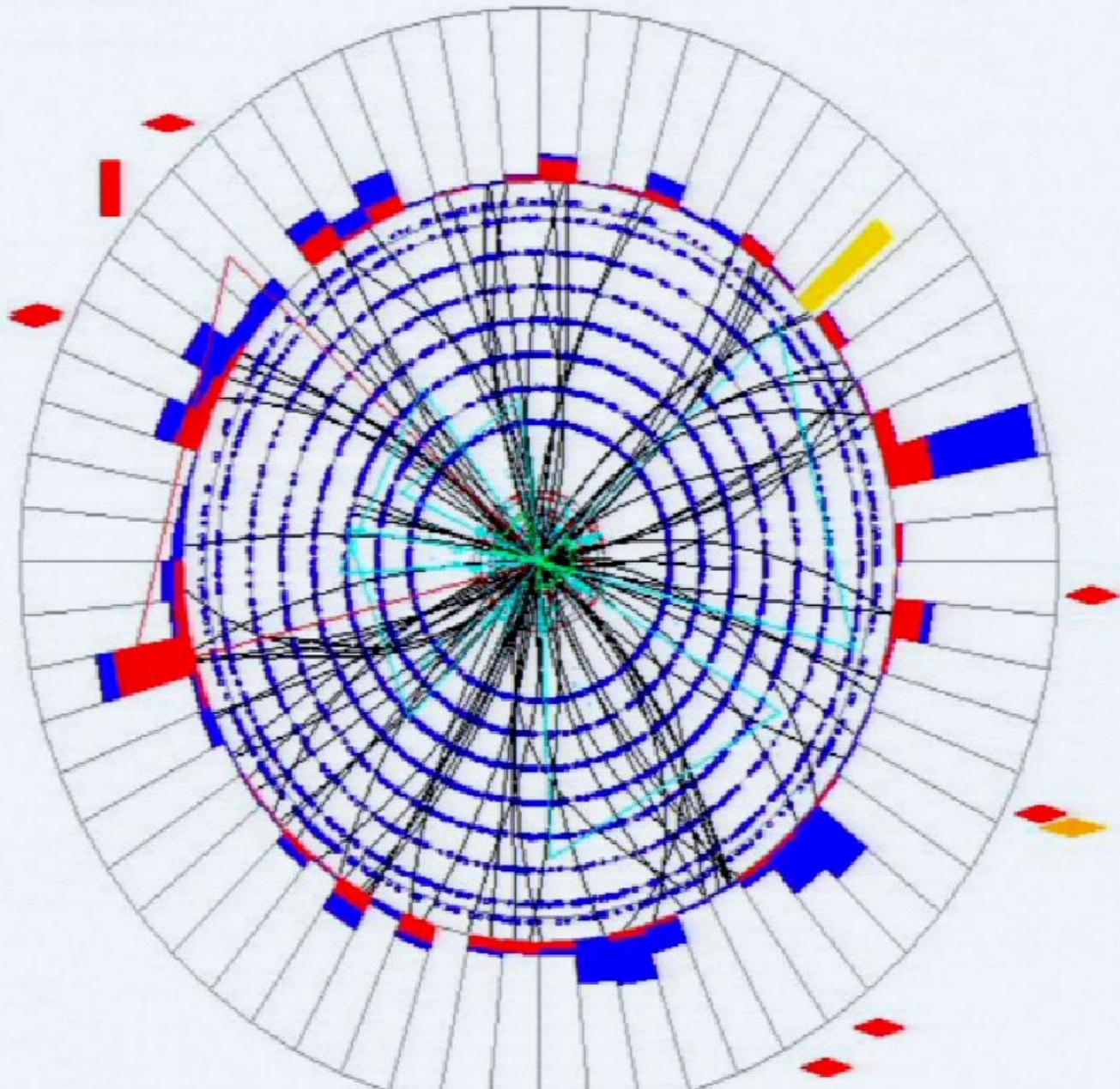
Run 223385 Evt 9802792 Thu Jul 20 17:14:11 2006

Triggers:  
min\_bias\_nim\_NCU



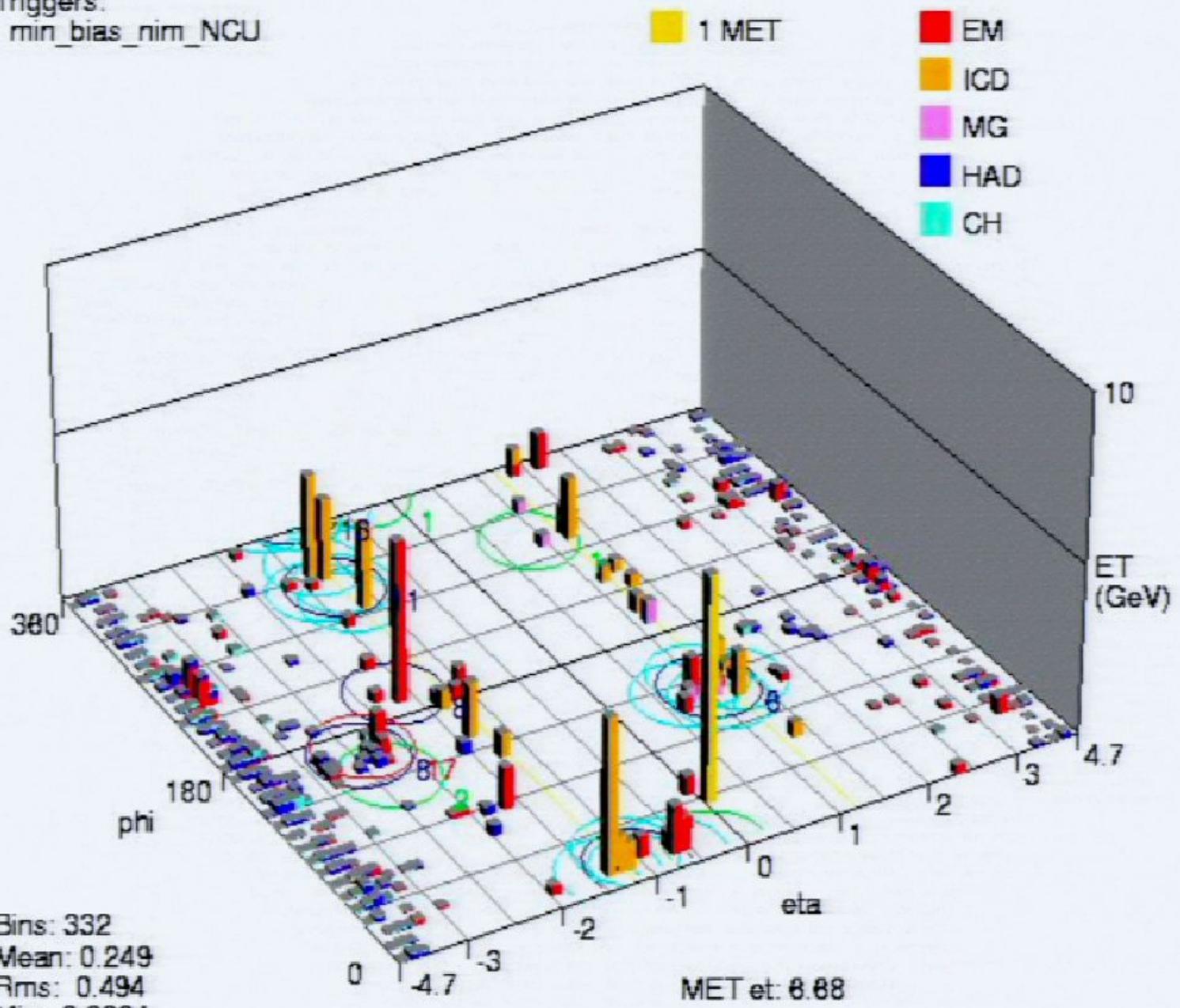
Run 223385 Evt 9802792 Thu Jul 20 17:14:11 2008

ET scale: 10 GeV



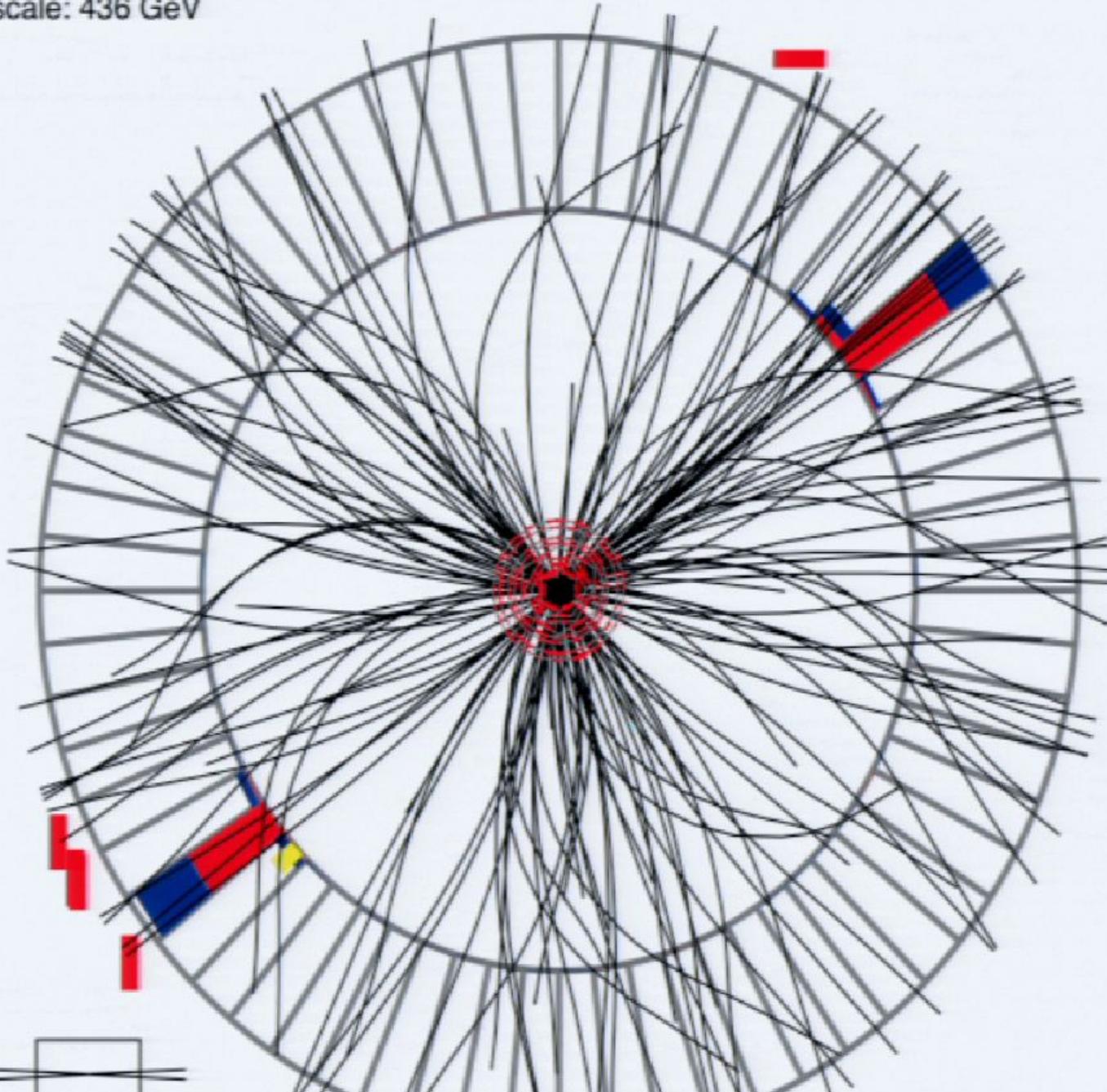
Run 223385 Evt 9802792 Thu Jul 20 17:14:11 2006

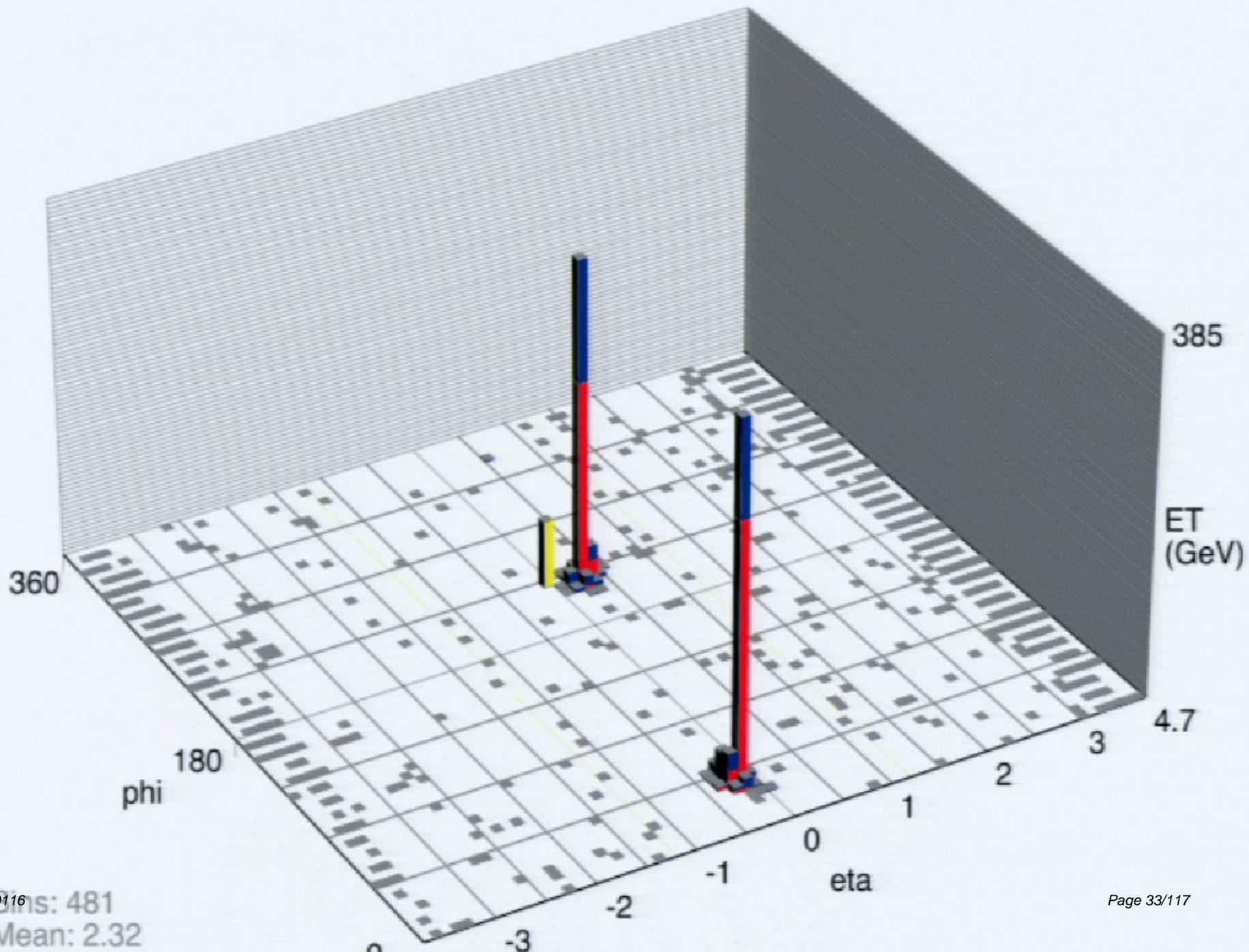
Triggers:  
min\_bias\_nim\_NCU



Run 178796 Event 67972991 Fri Feb 27 08:34:15 2004

ET scale: 436 GeV





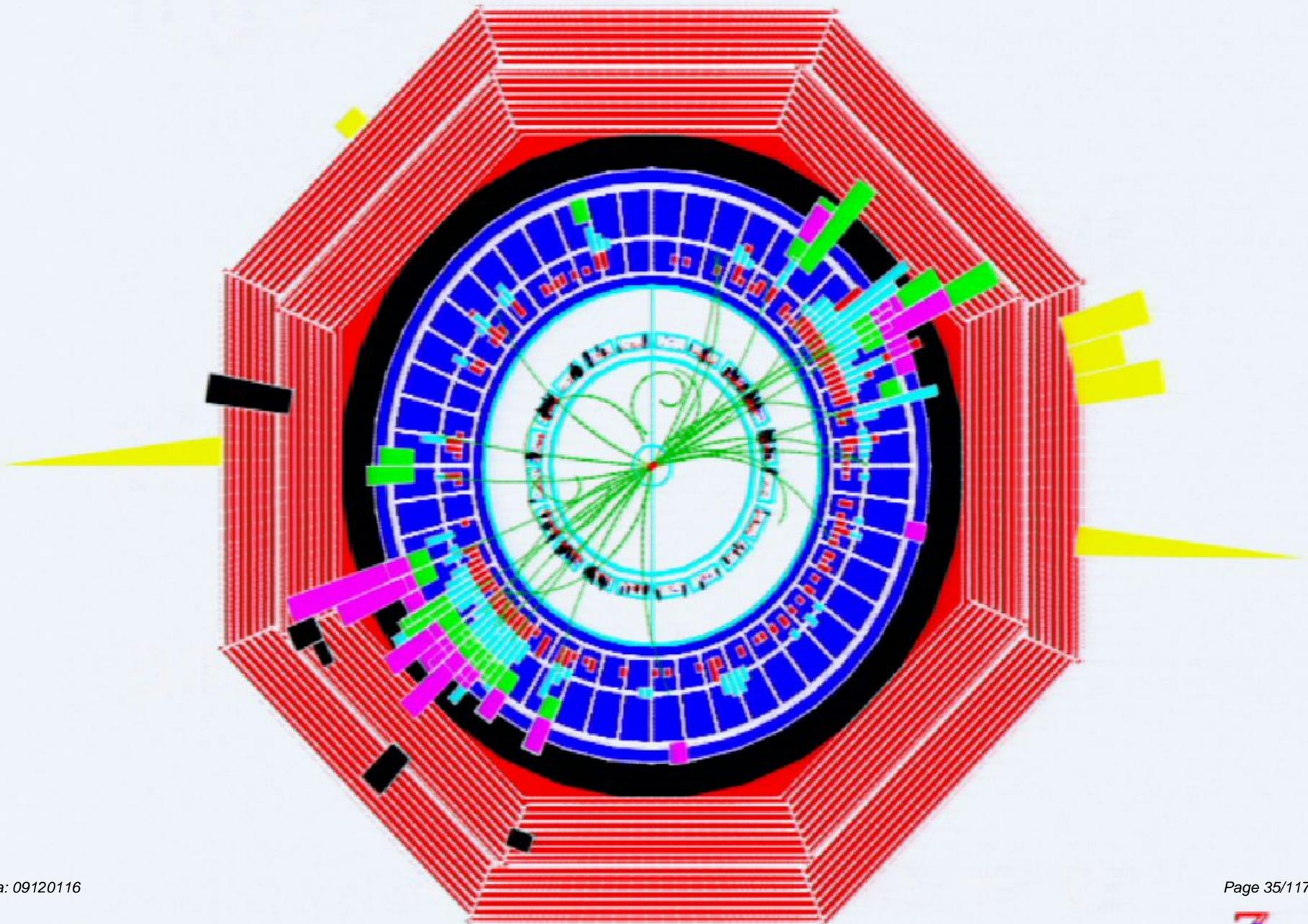
top  $\Rightarrow$  **b** + W

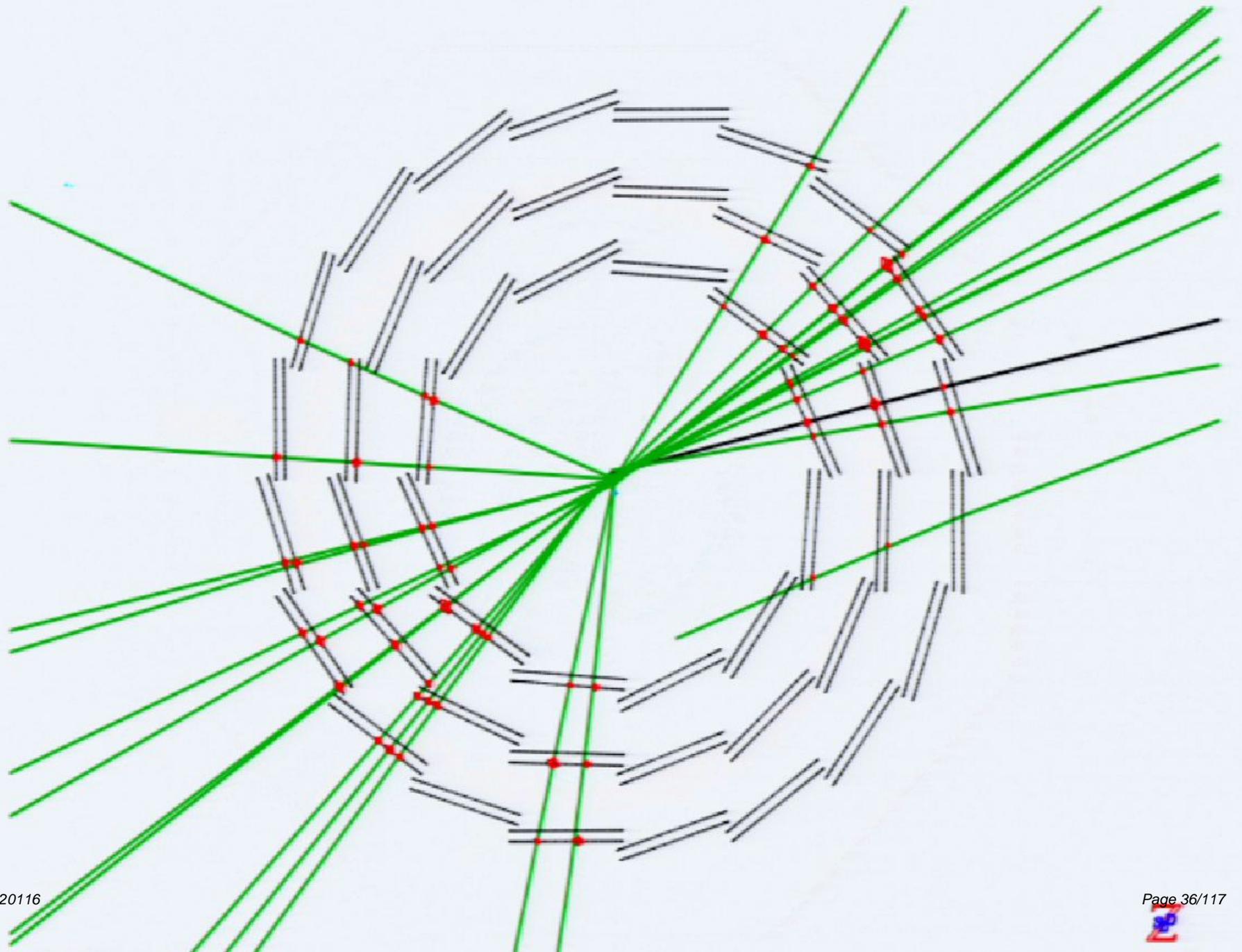
$\Rightarrow$  **b** + q +  $\bar{q}$

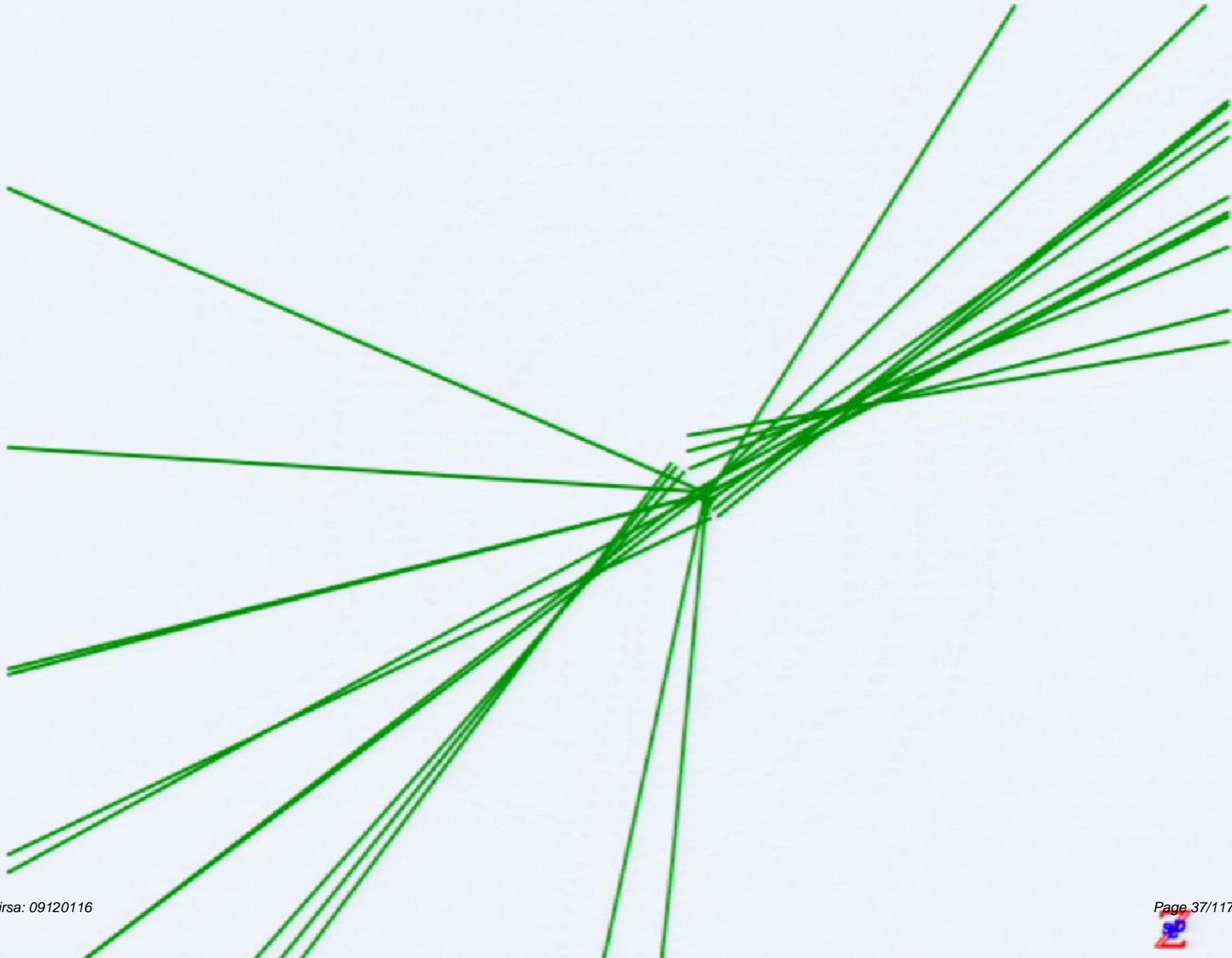
plus

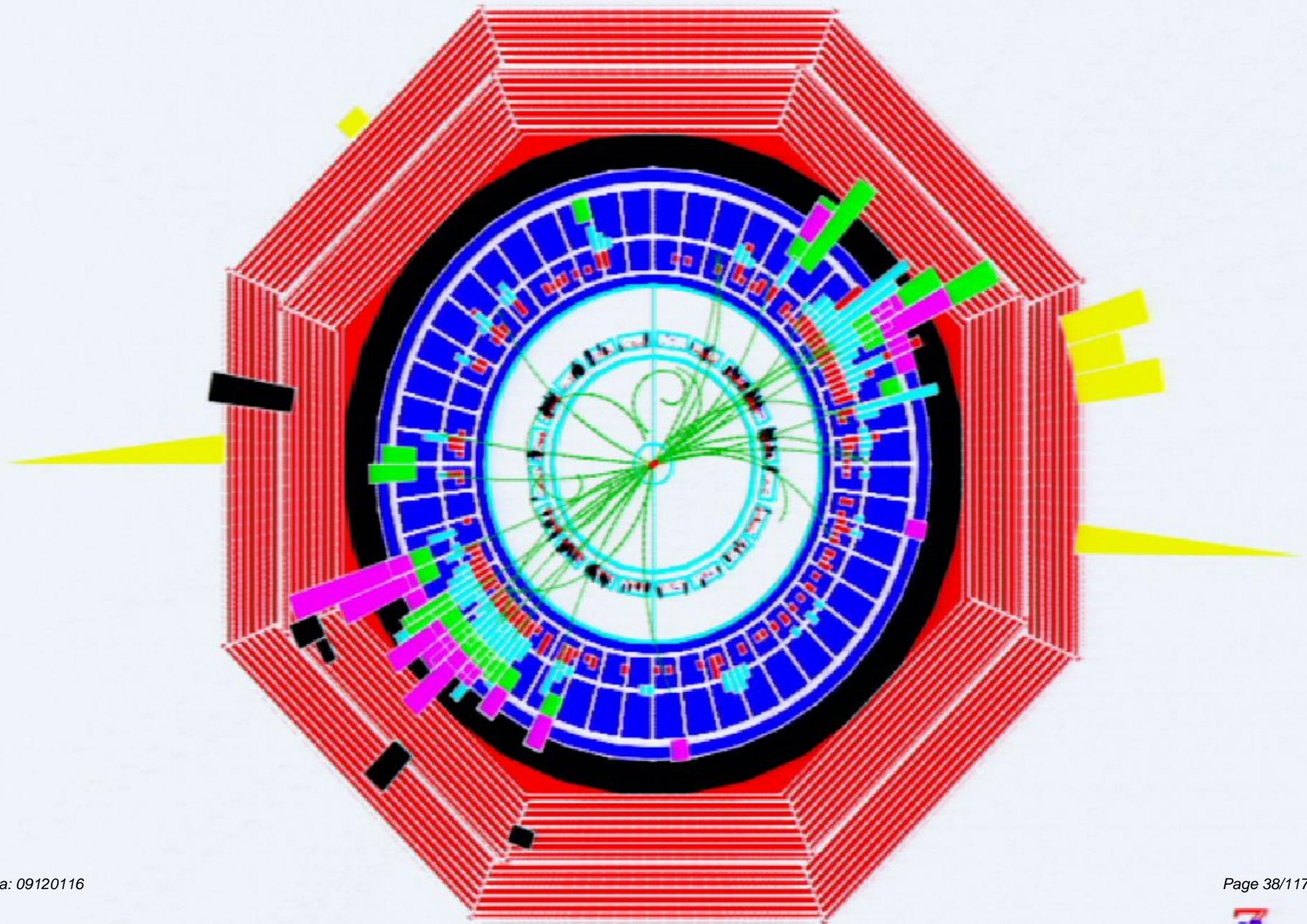
antitop  $\Rightarrow$   $\bar{b}$  +  $W^-$

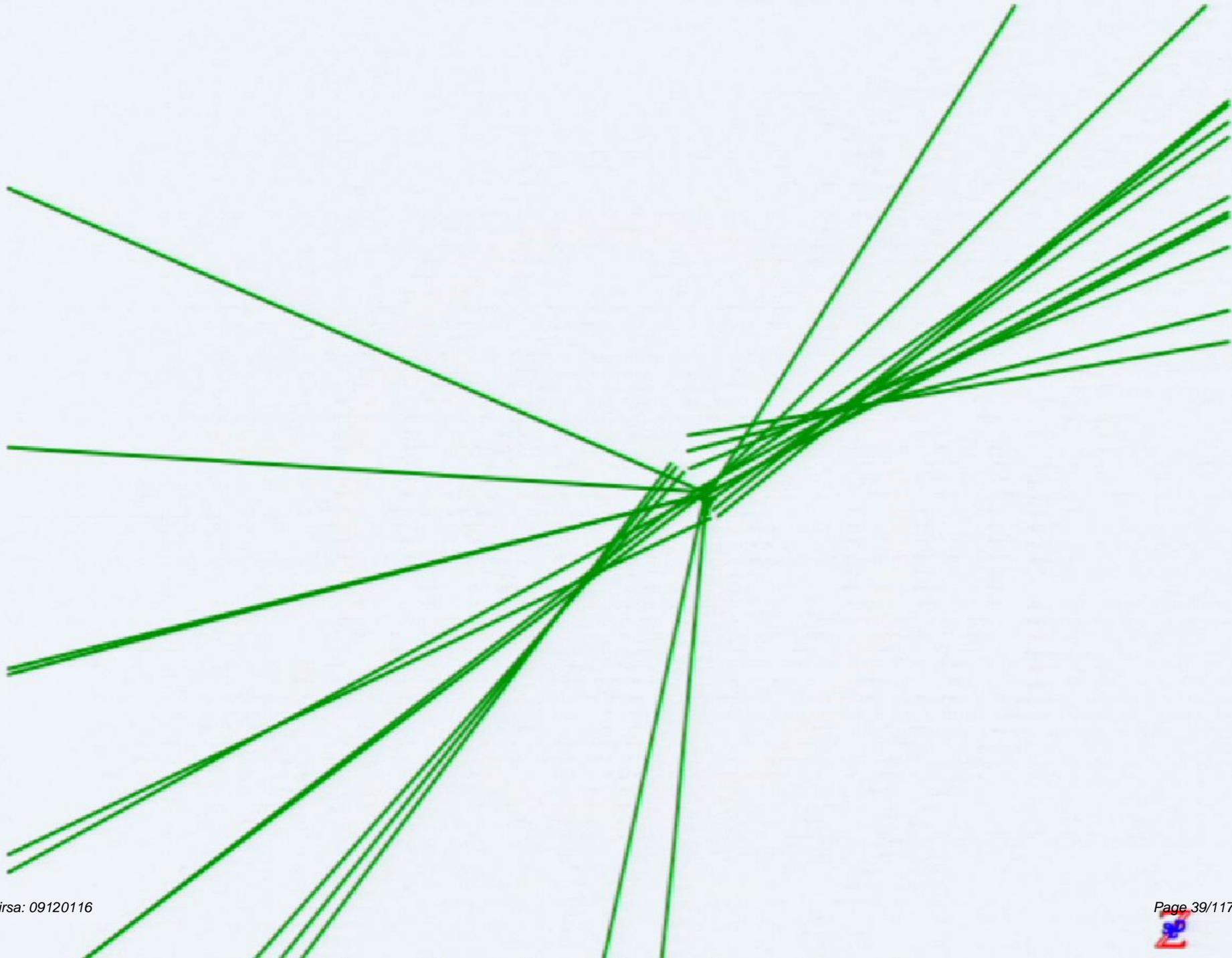
$\Rightarrow$   $\bar{b}$  + e +  $\nu$



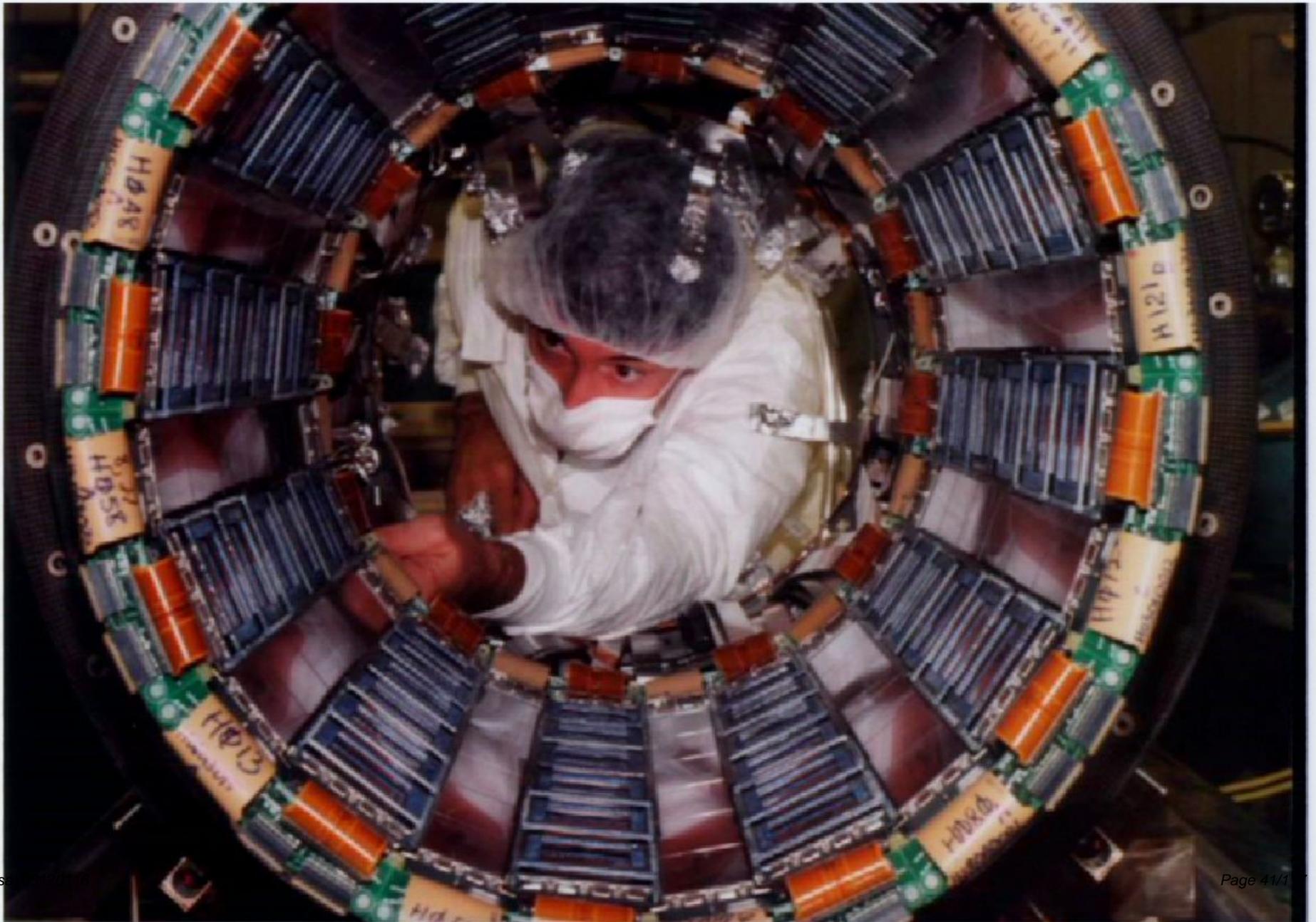






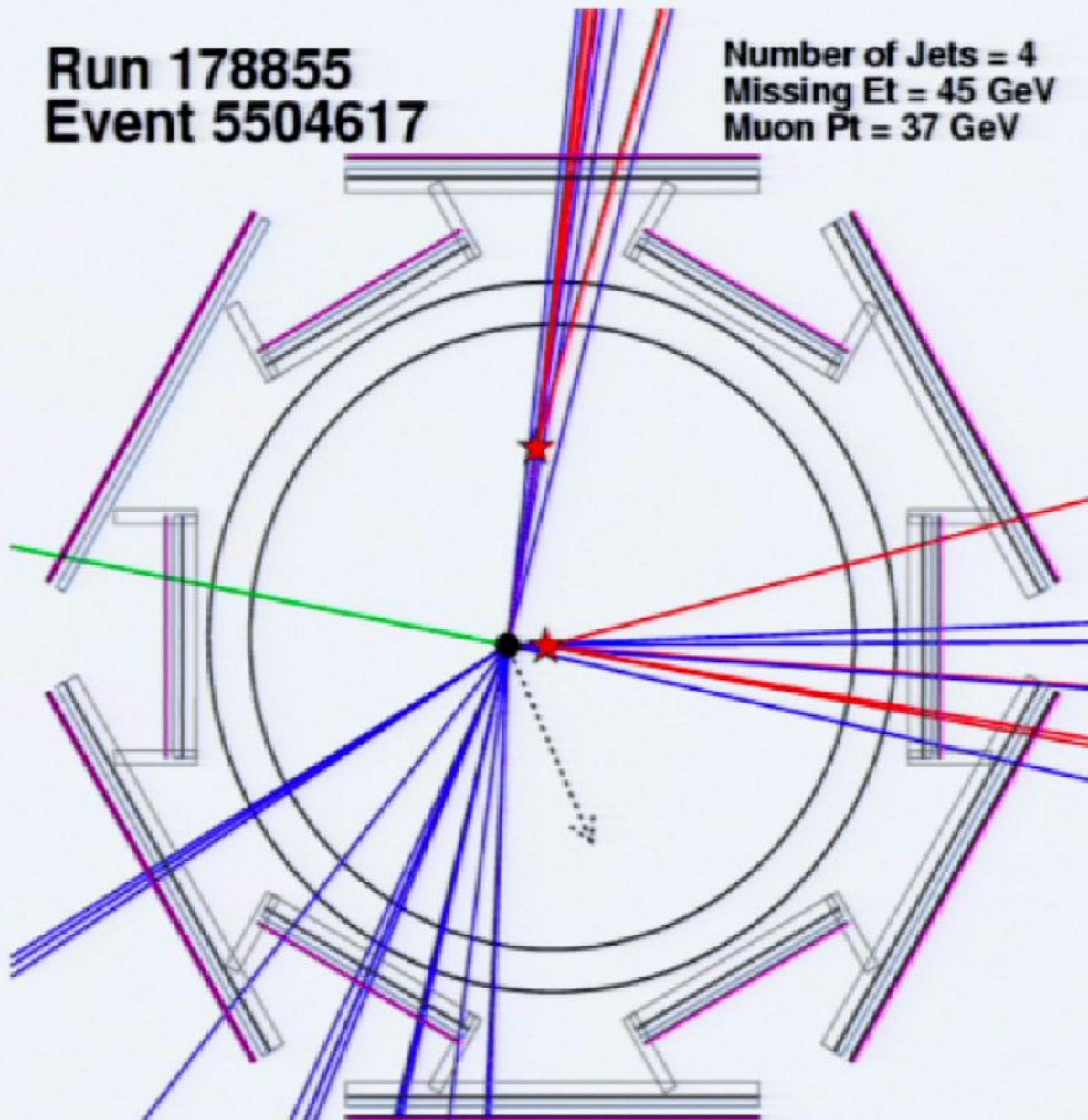






**Run 178855  
Event 5504617**

**Number of Jets = 4  
Missing Et = 45 GeV  
Muon Pt = 37 GeV**



**Tagged Jet 1: Et = 111 GeV, Phi = 79, L2d = 7 mm  
Tagged Jet 2: Et = 38 GeV, Phi = 355, L2d = 1 mm**

# e + 4 jet event

40758\_44414

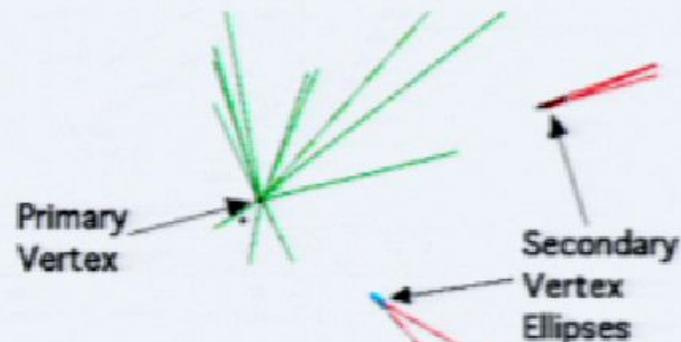
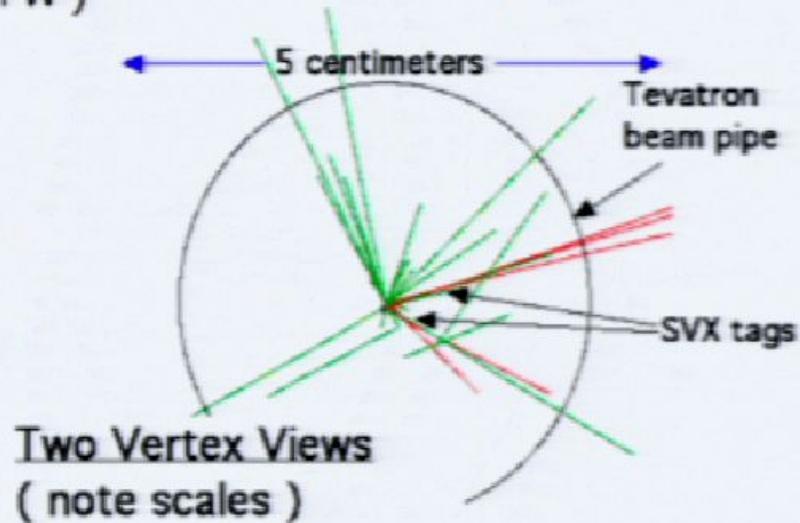
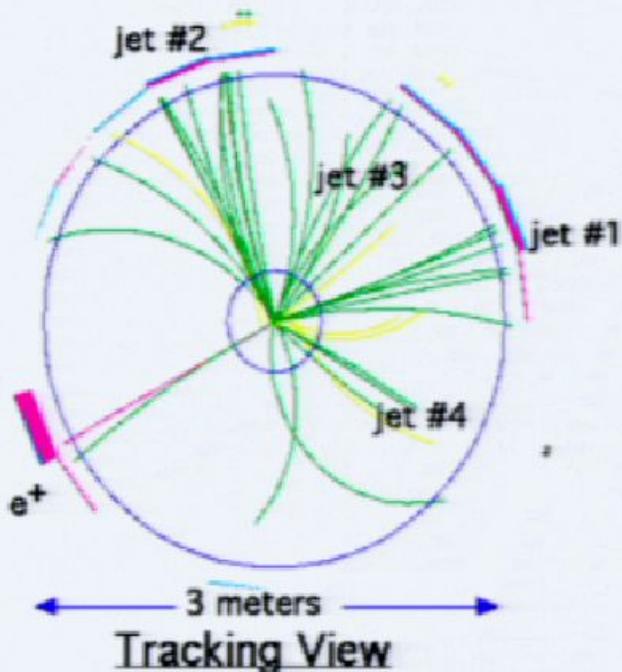
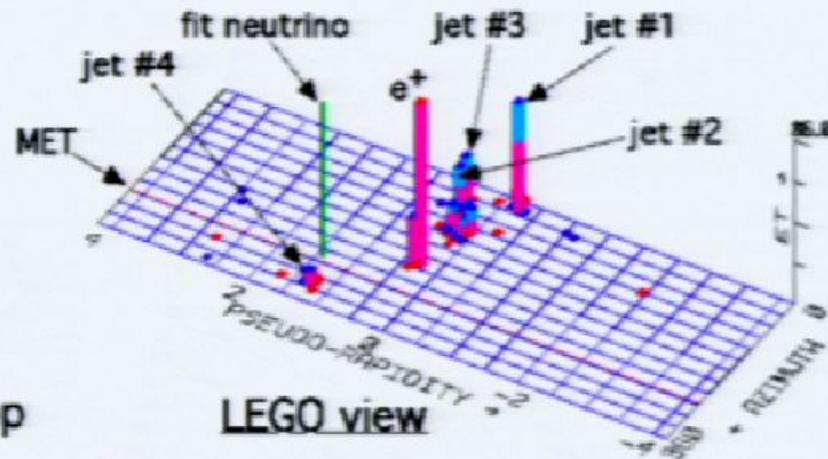
24-September, 1992

TWO jets tagged by SVX

fit top mass is  $170 \pm 10$  GeV

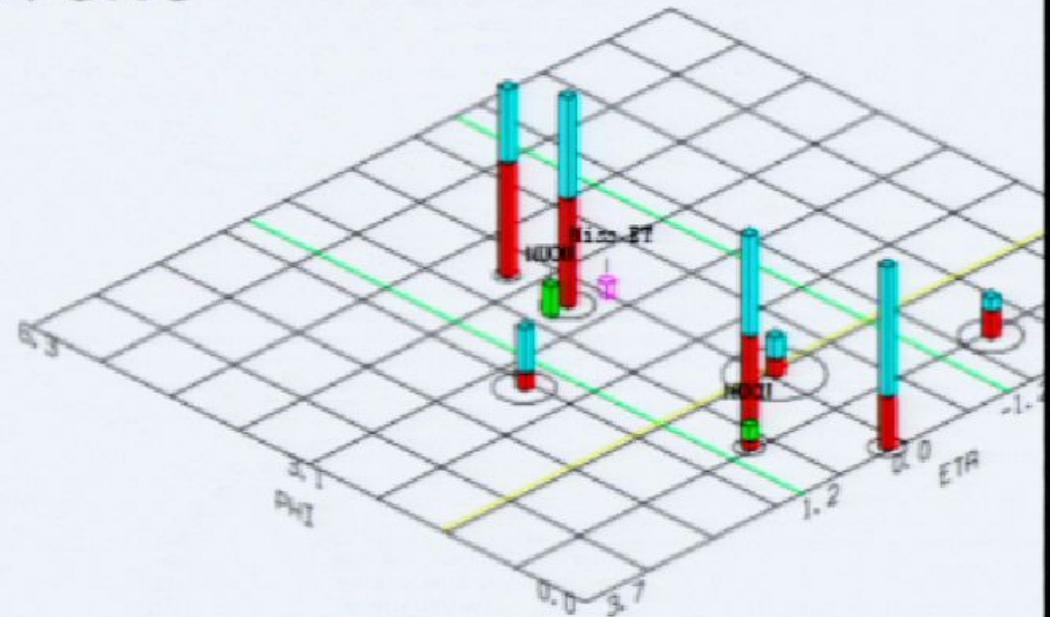
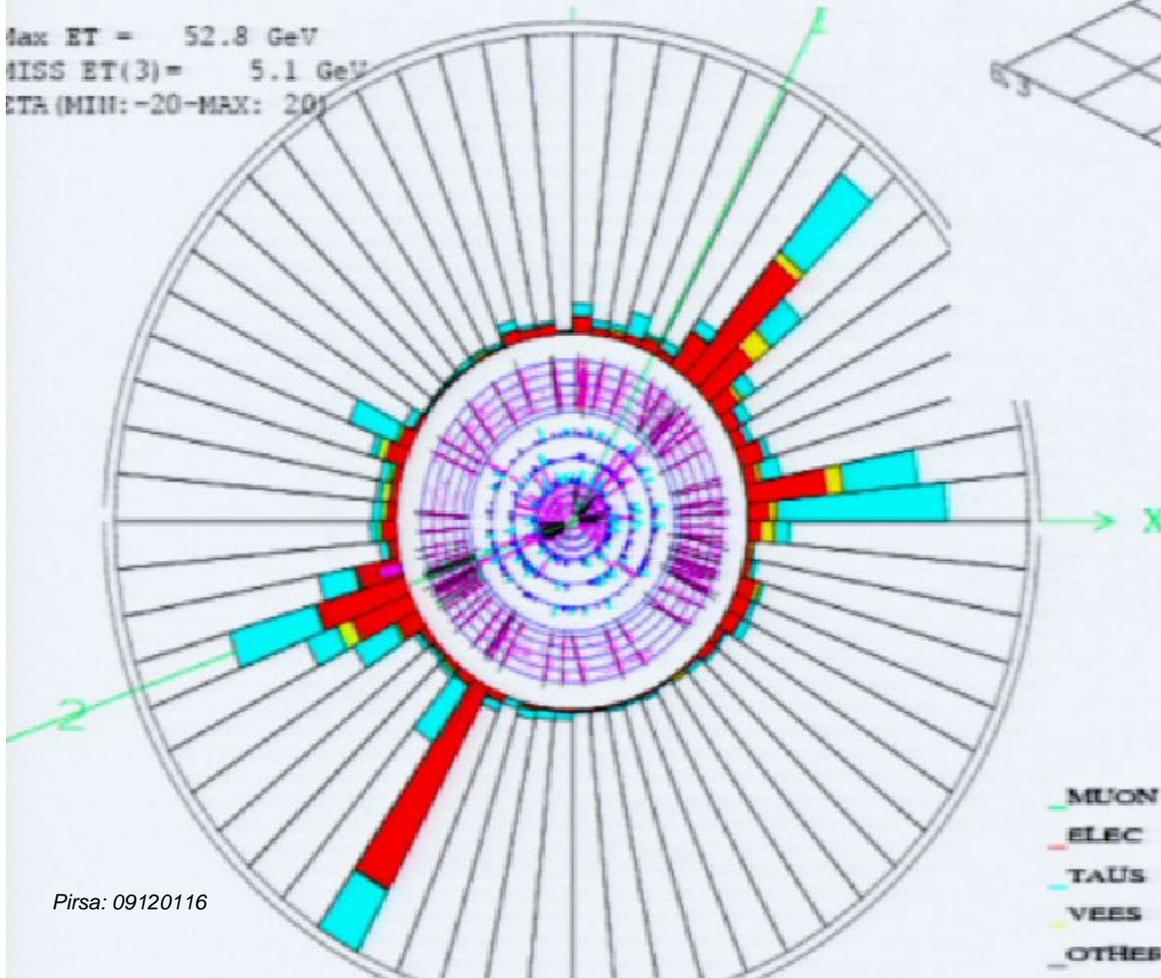
$e^+$ , Missing  $E_t$ , jet #4 from top

jets 1,2,3 from top ( 2&3 from W )



# D0 6-jet top quark event

Max ET = 52.8 GeV  
MISS ET(3) = 5.1 GeV  
ETA (MIN: -20-MAX: 20)



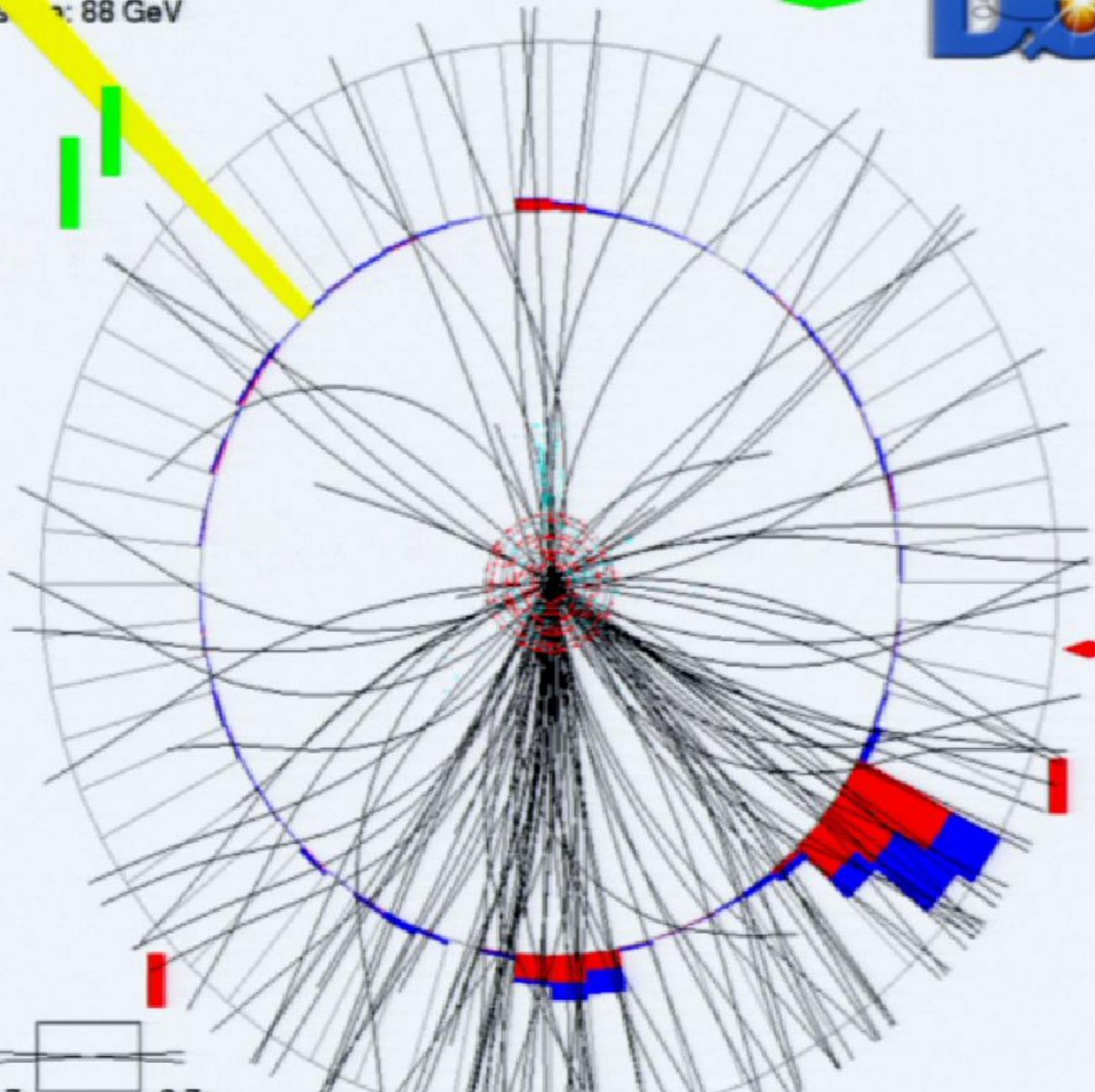
How do I know it is not

W + gluon + gluon + gluon

$\Rightarrow$  b +  $\bar{b}$

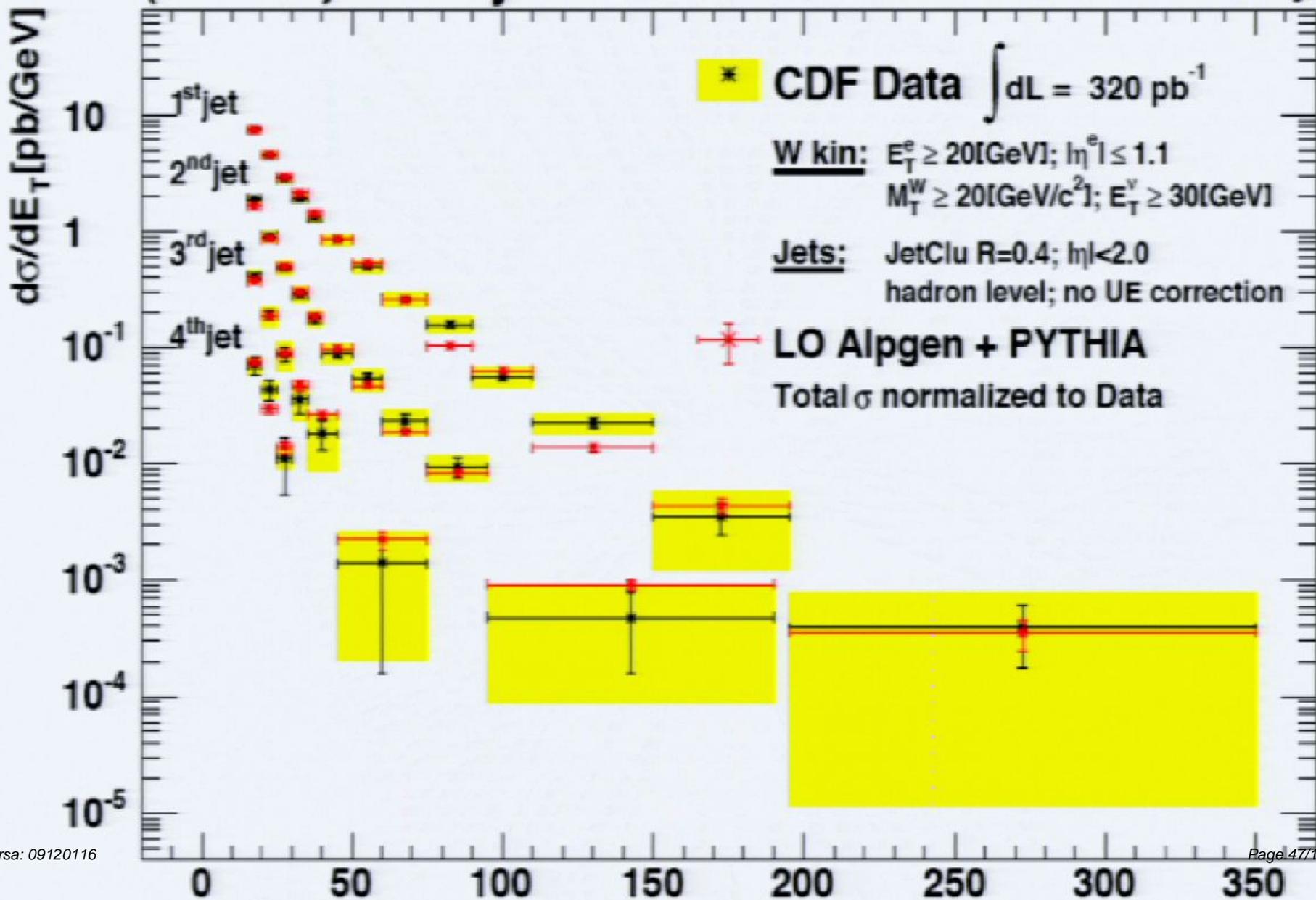
? ? ?

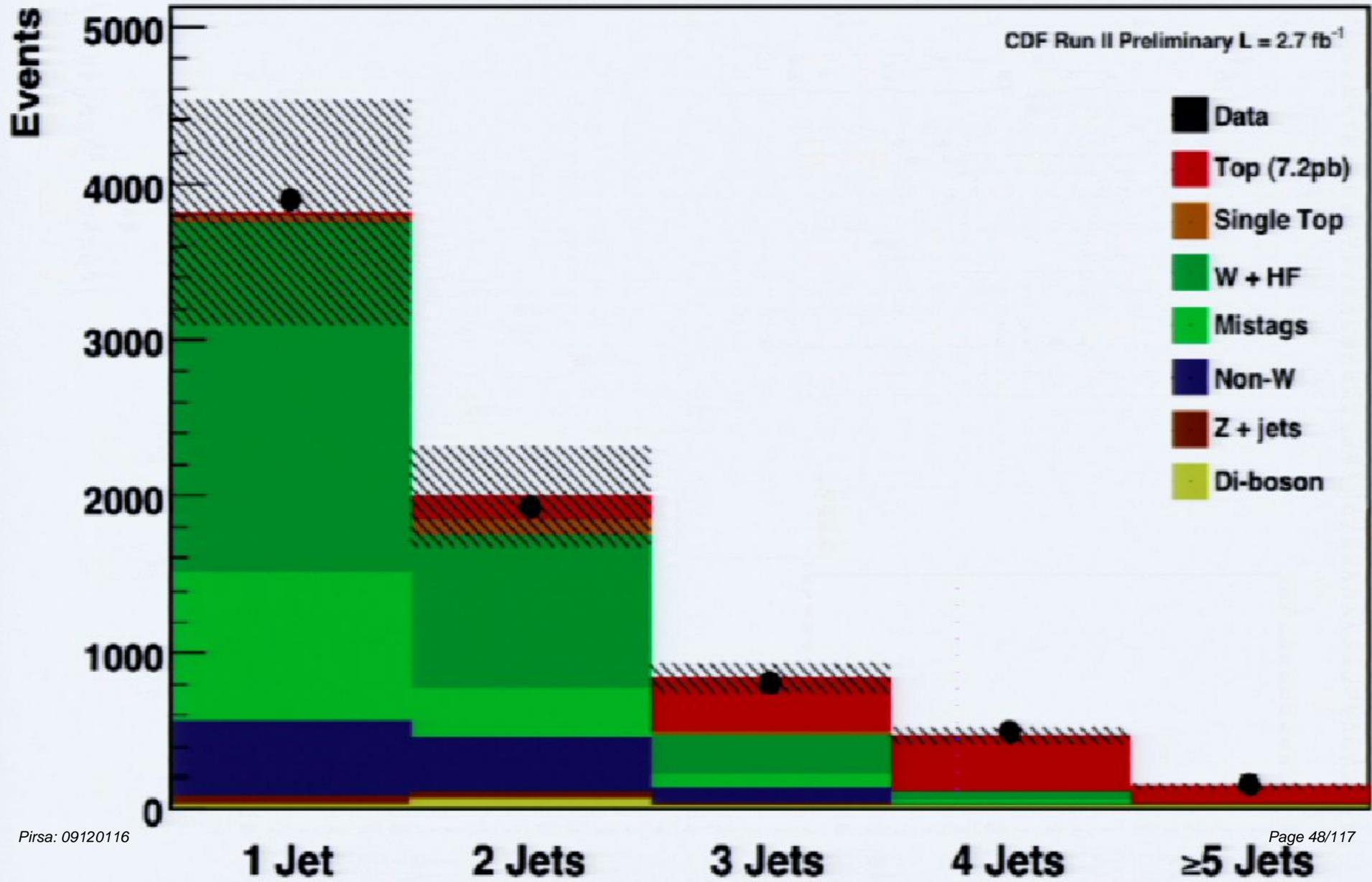
ET s: 88 GeV

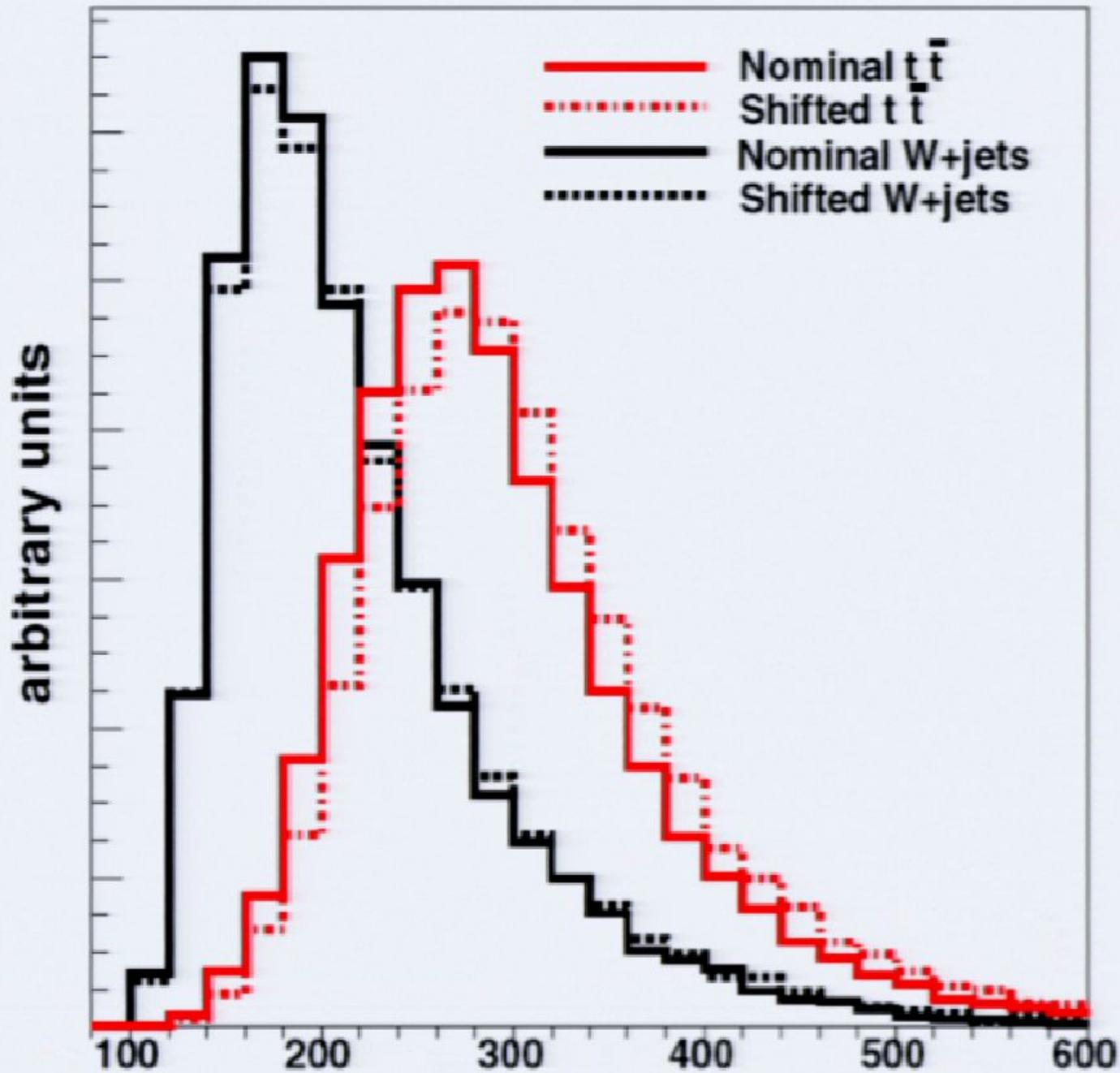


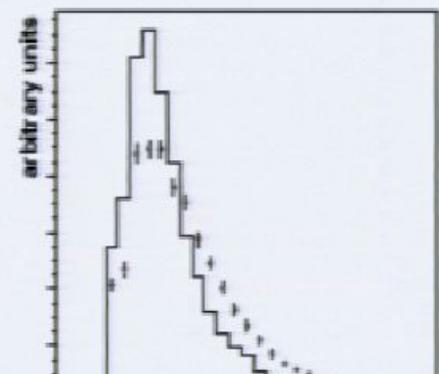
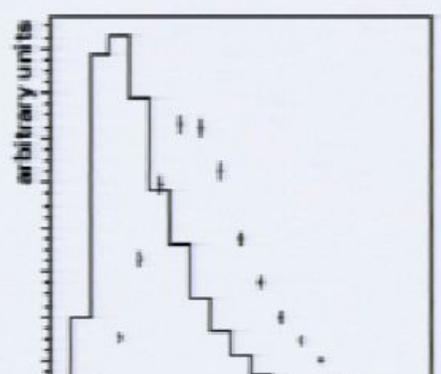
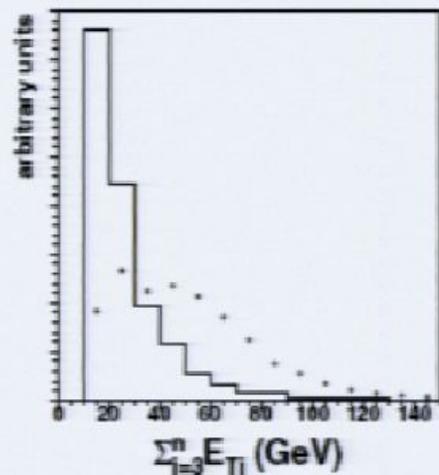
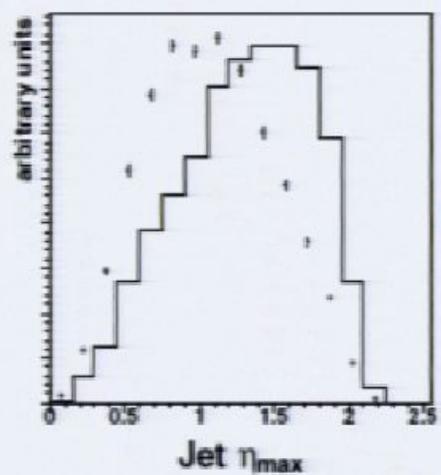
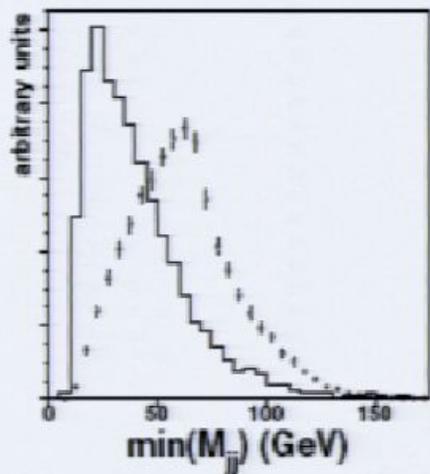
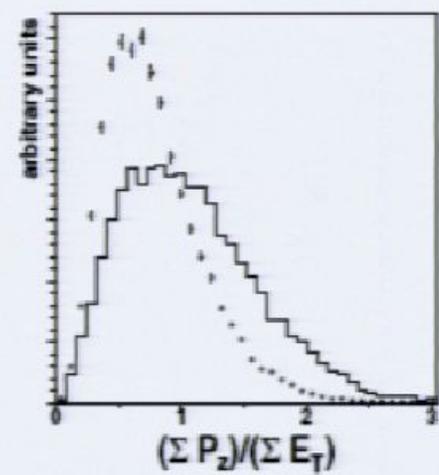
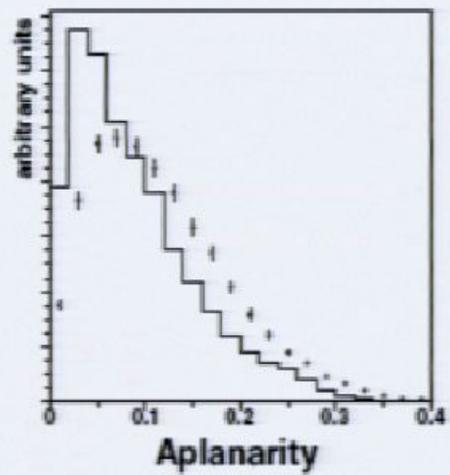
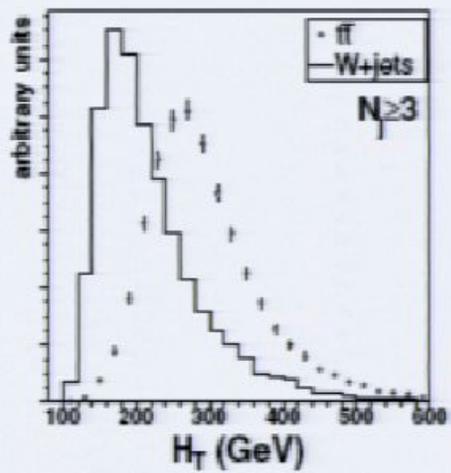
# $(W \rightarrow e\nu) + \geq n$ jets

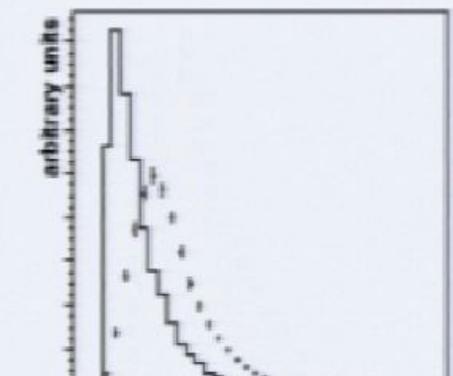
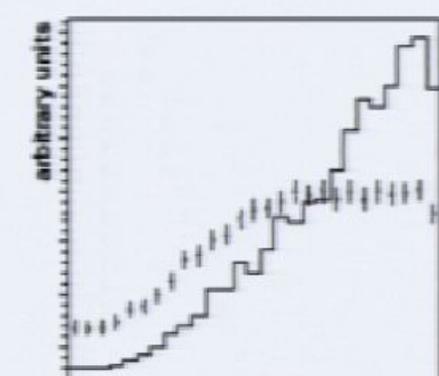
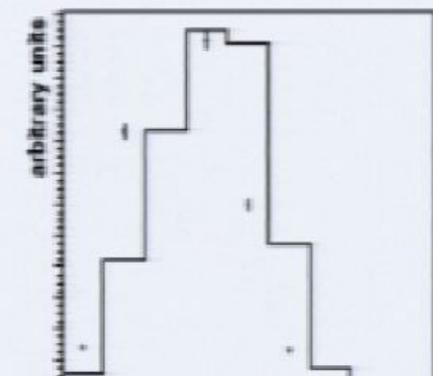
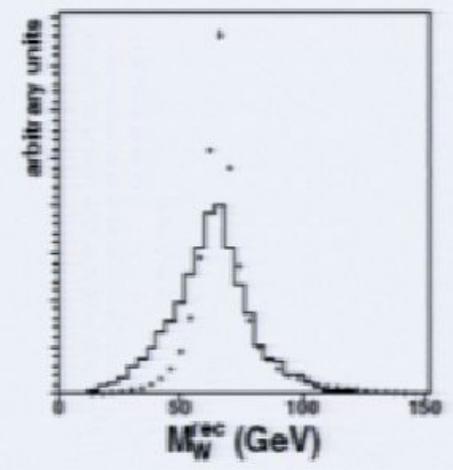
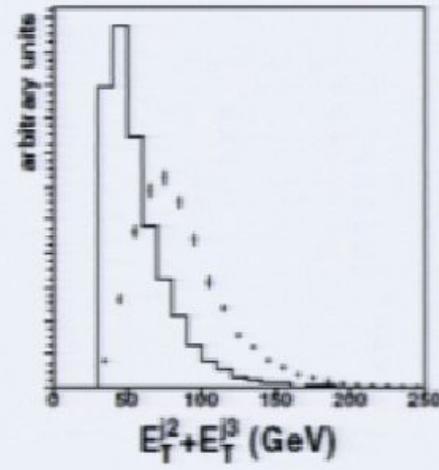
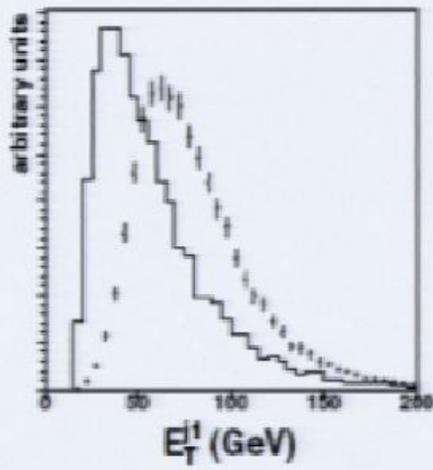
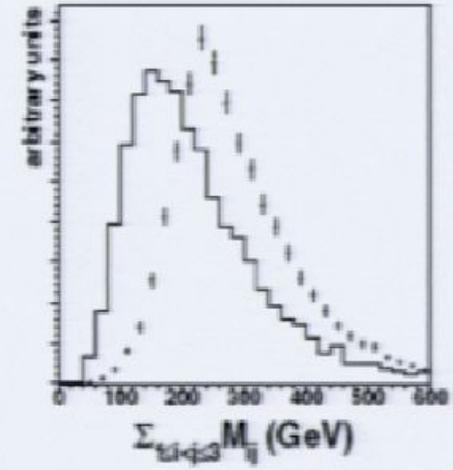
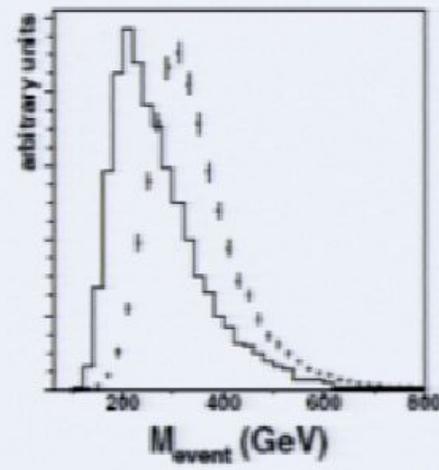
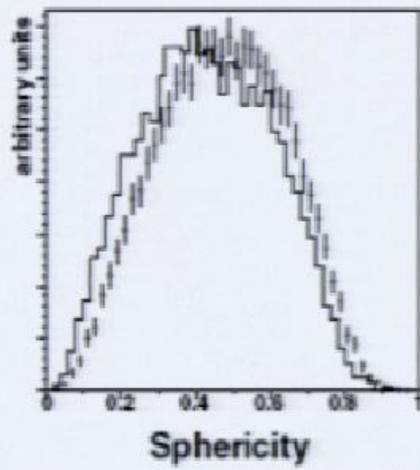
CDF Run II Preliminary



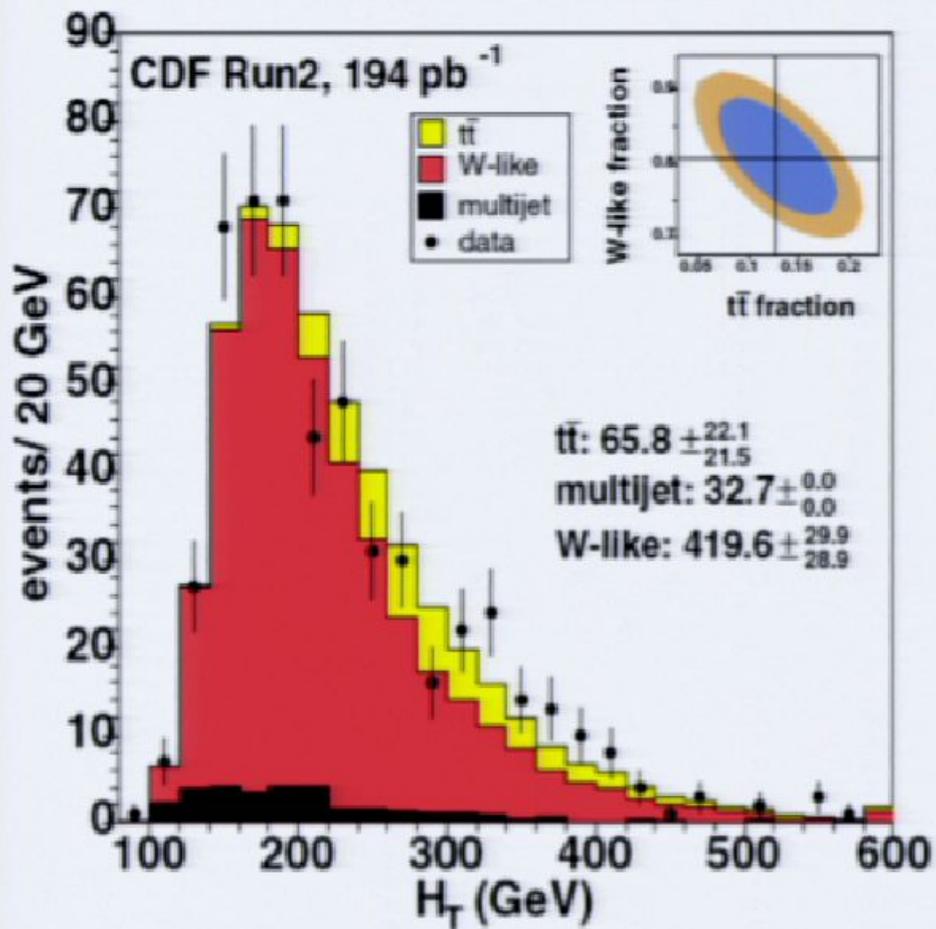




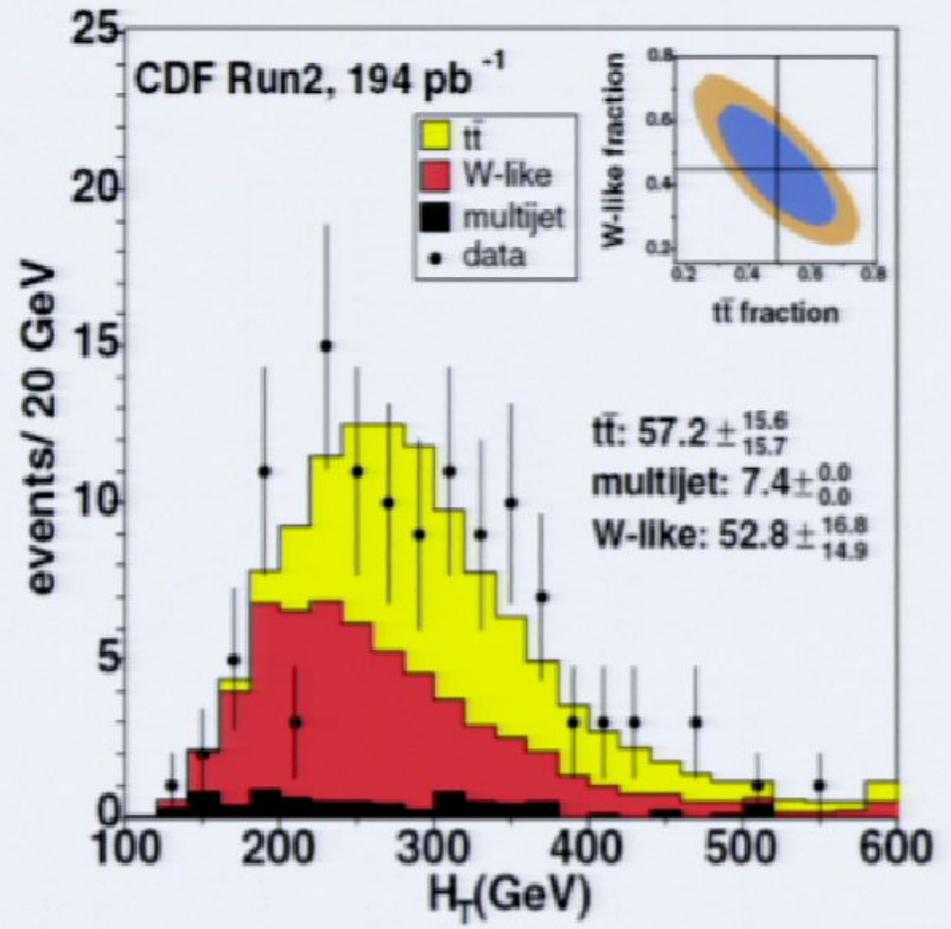




# W + 3 jets



# W + 4 jets



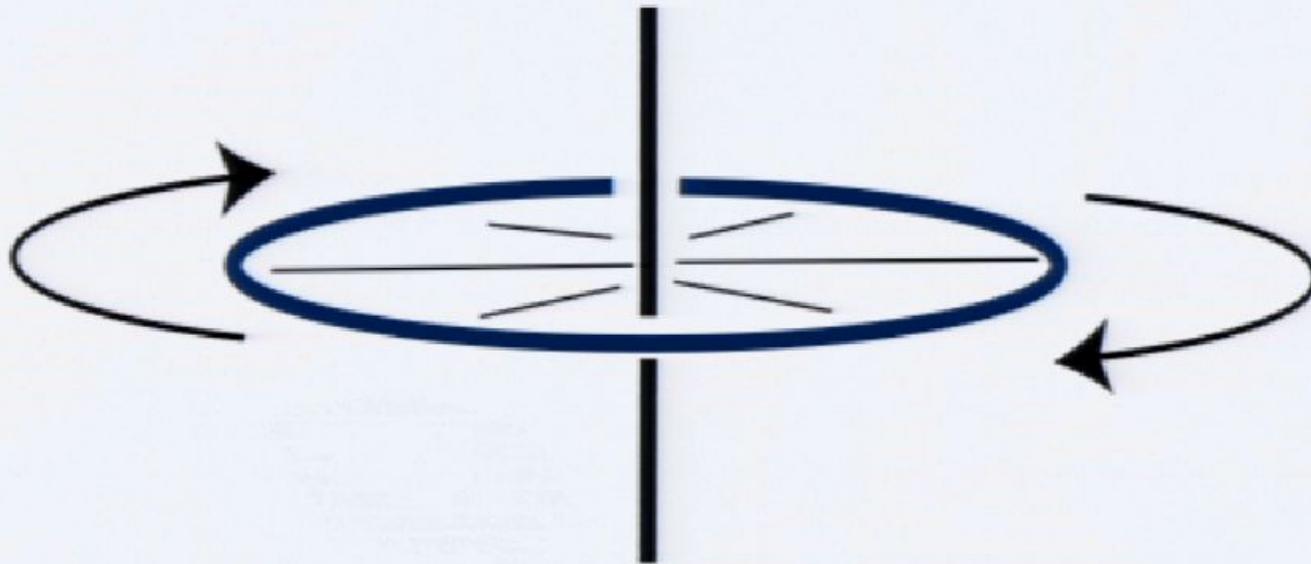
Once we have the top quarks,  
what do we do with them ?

To talk about this, we need to study

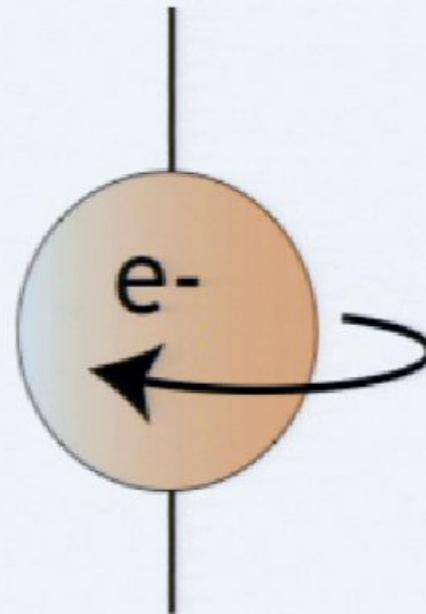
**Quantum Patterns**



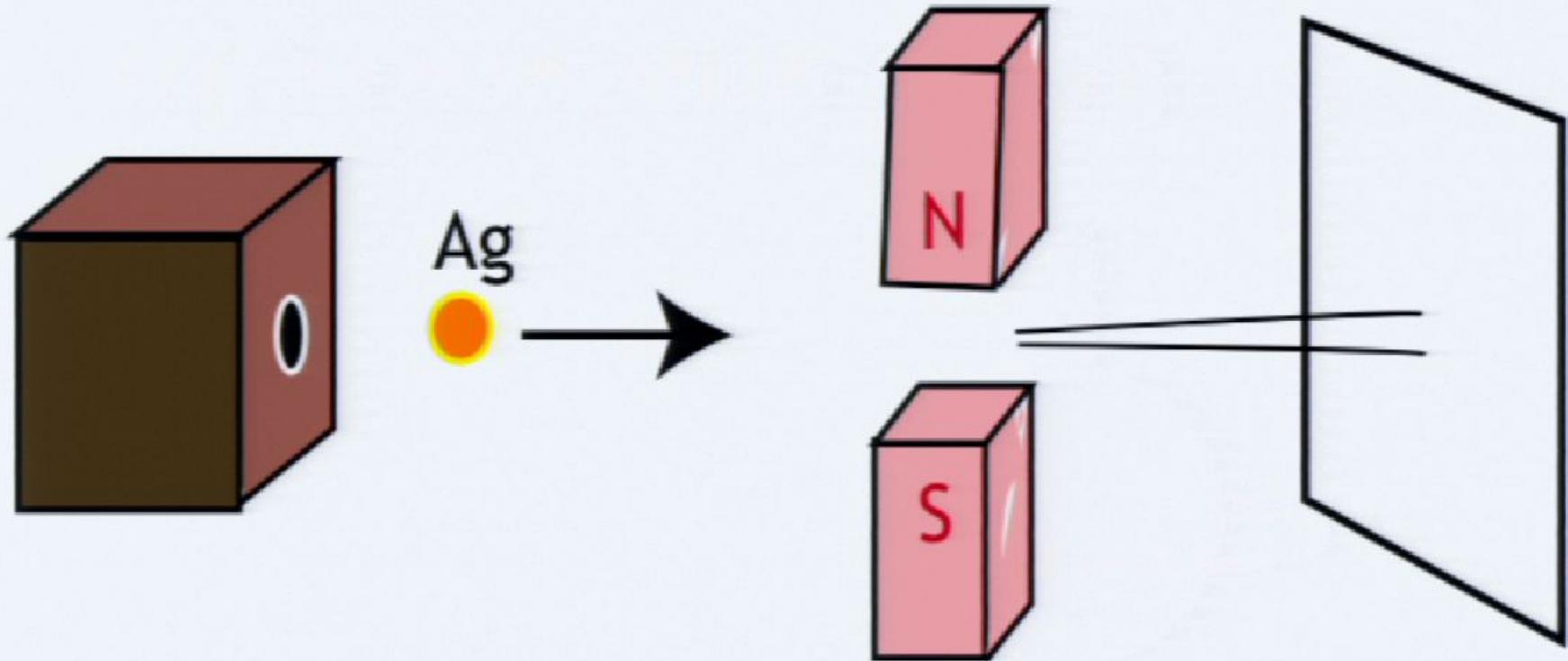
# Quantum Mechanics of Angular Momentum



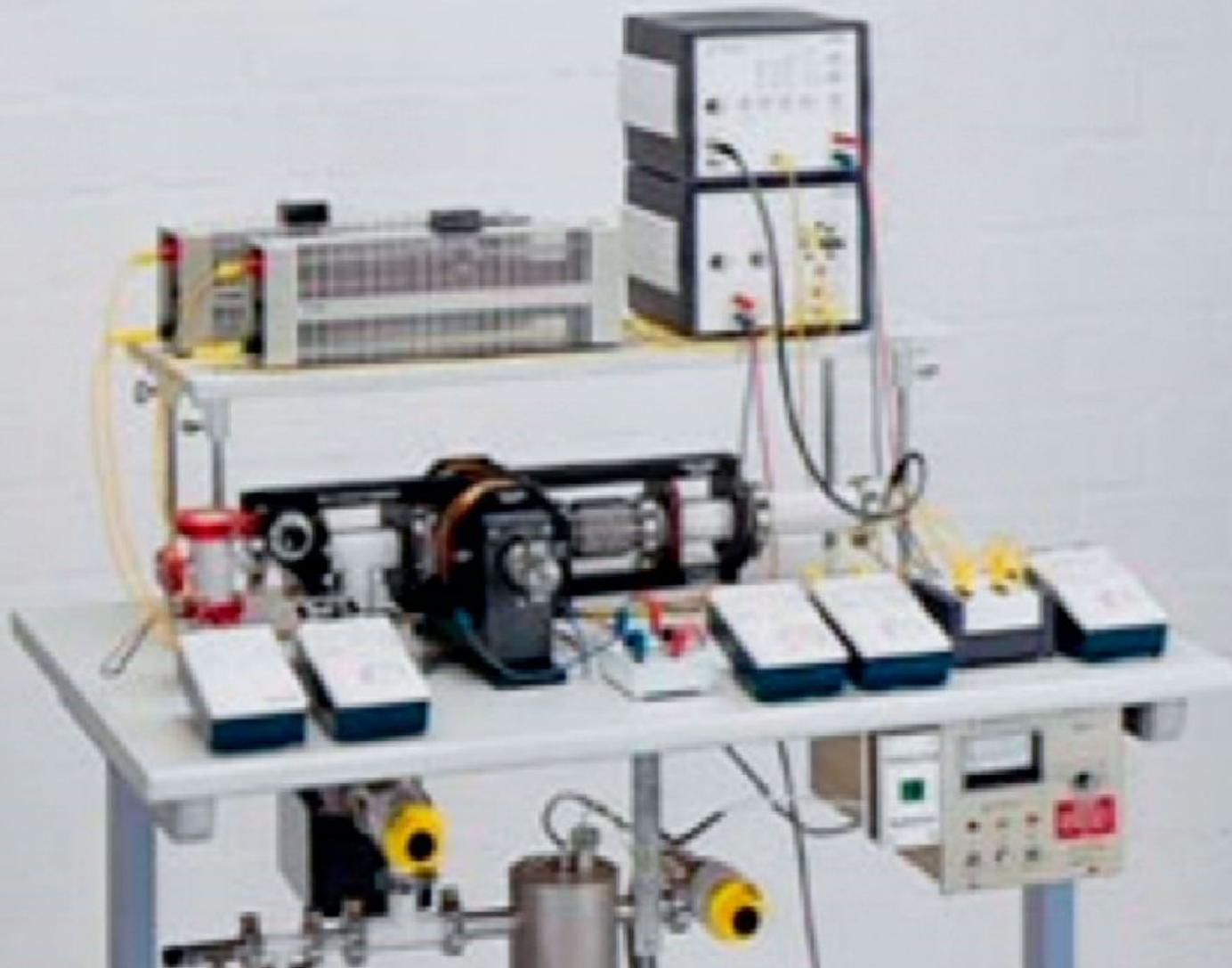
Elementary particles have internal  
angular momentum (“spin”)



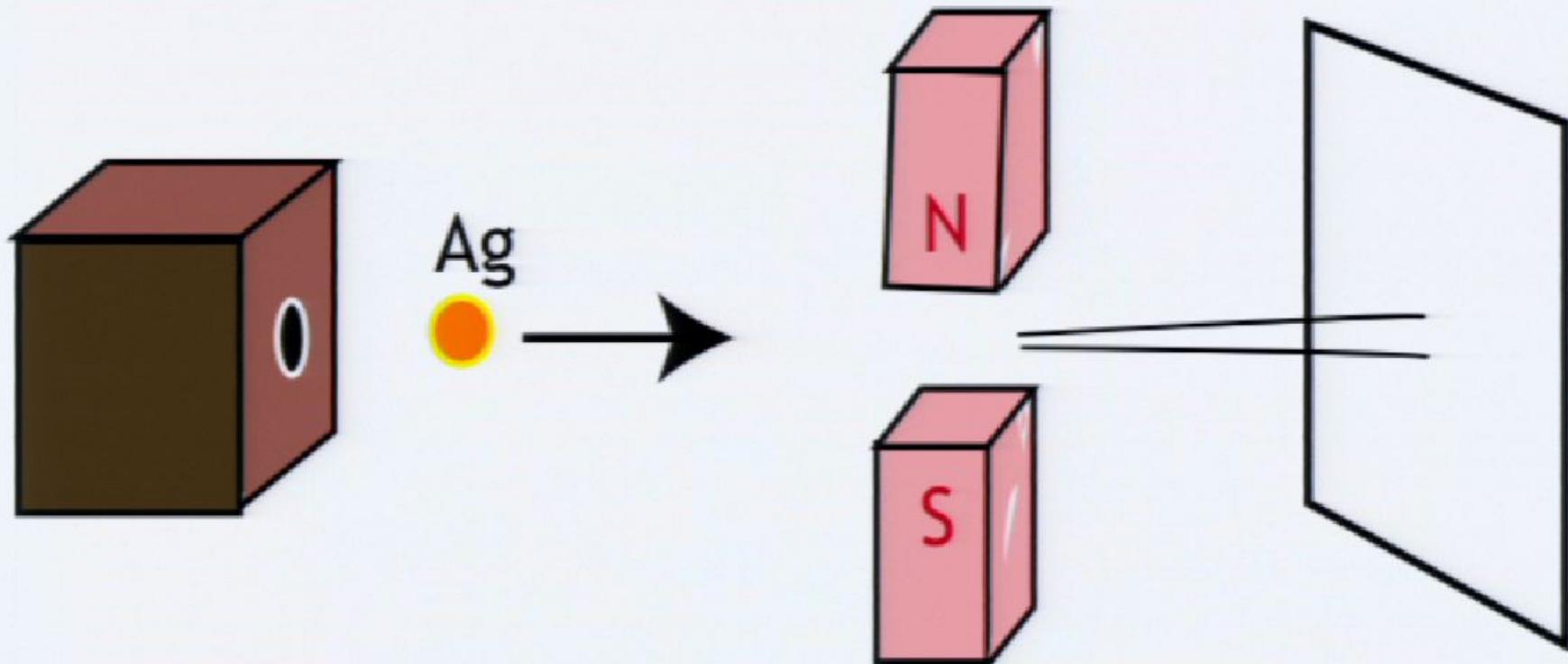
# Stern-Gerlach experiment 1922



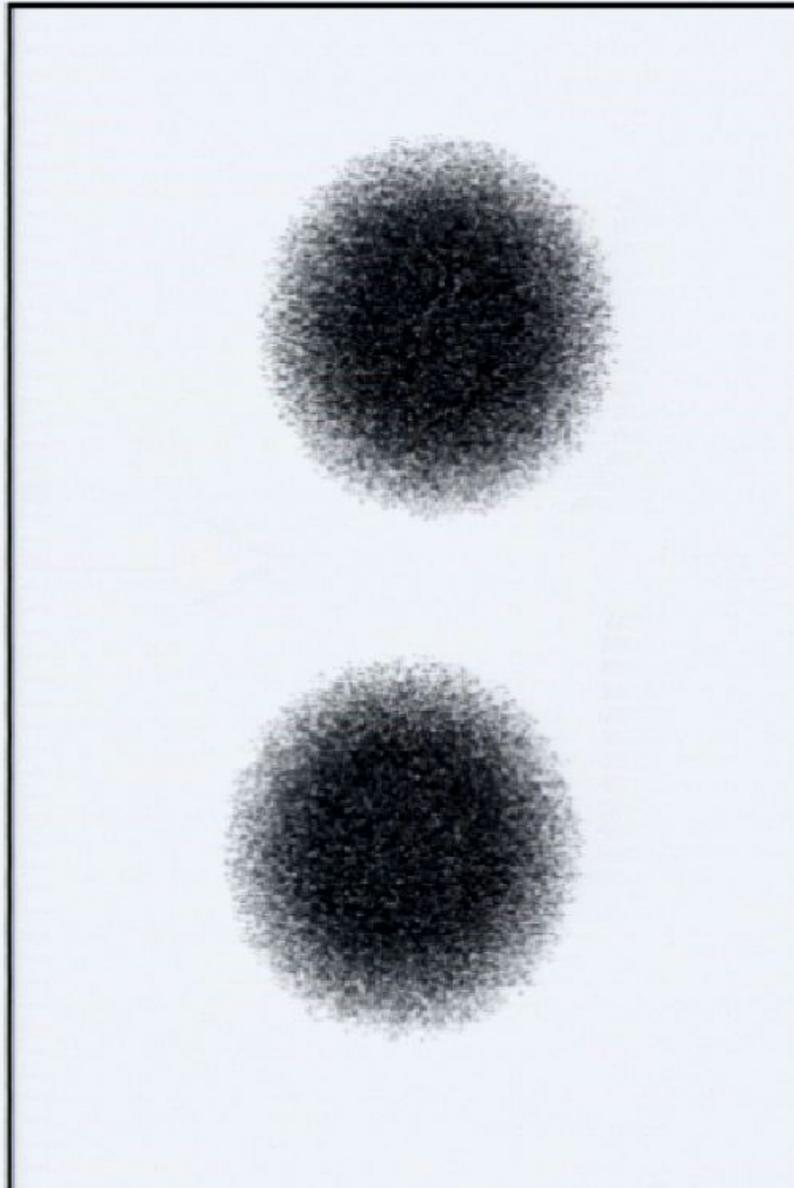
Here is a modern version of the experiment.



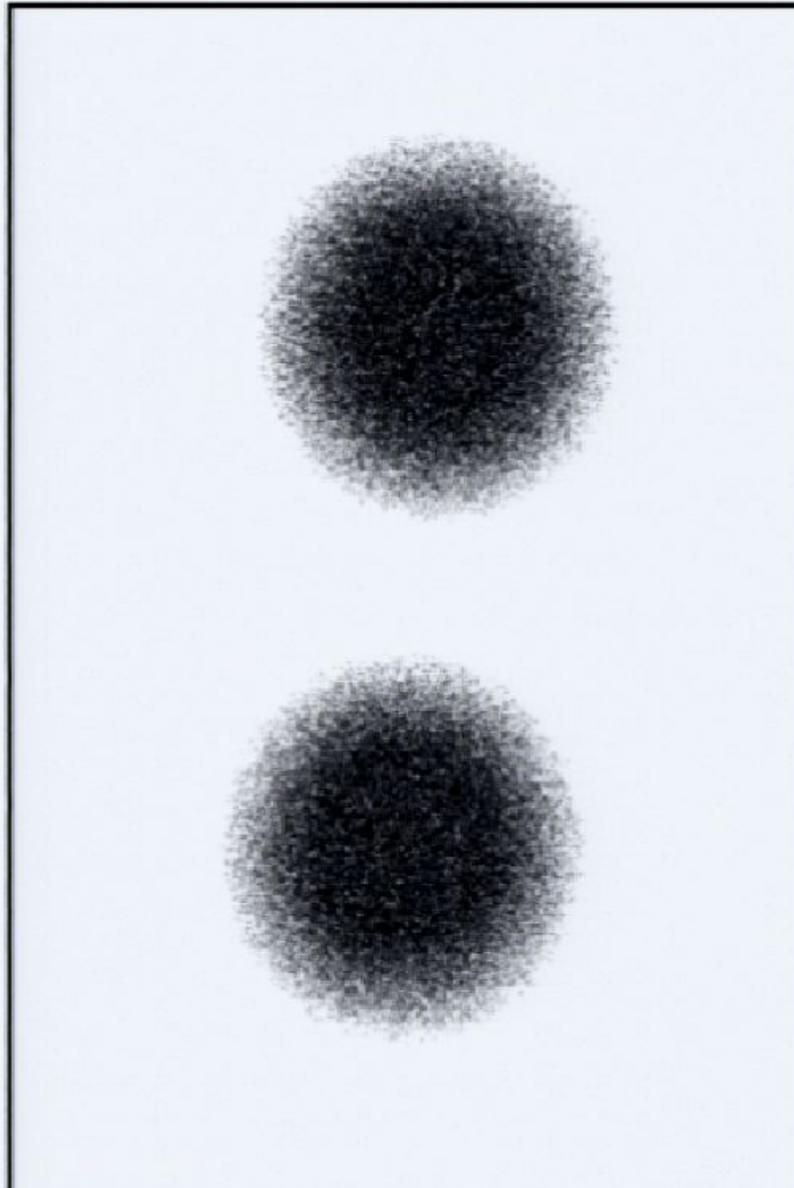
# Stern-Gerlach experiment 1922



Here is the result of the experiment:

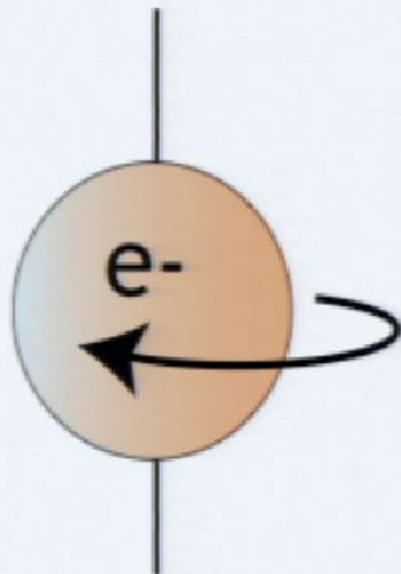


Here is the result of the experiment:

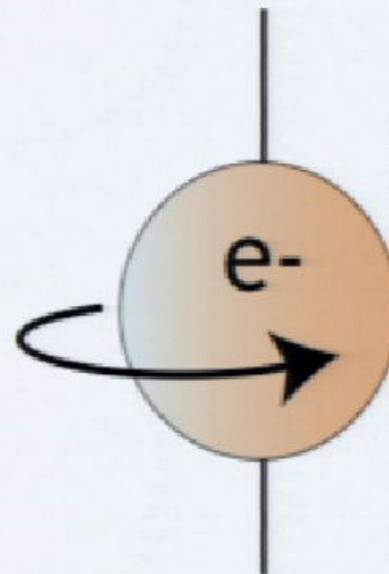


The electron has spin =  $\frac{1}{2}\hbar$

in one of two orientations

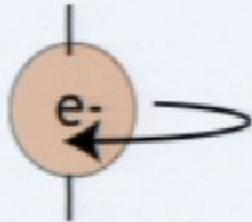


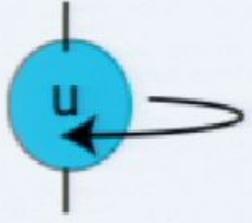
spin down

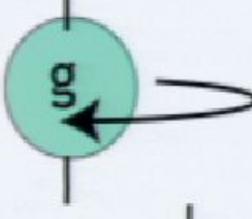


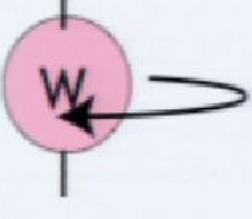
spin up

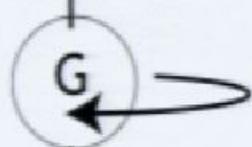
# The spin of a particle is the key to its identity:

electron  spin 1/2

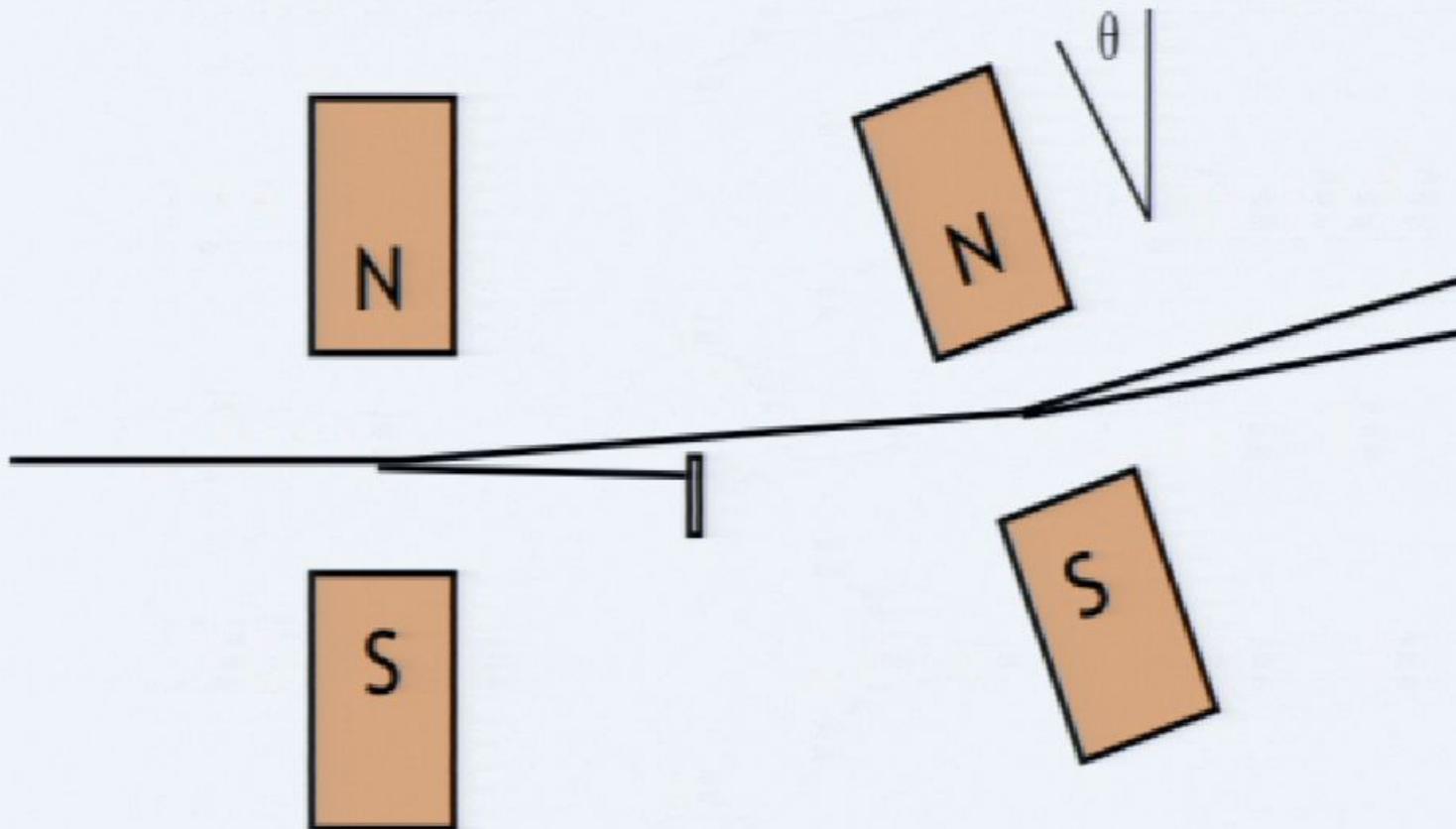
quark  spin 1/2

gluon  spin 1

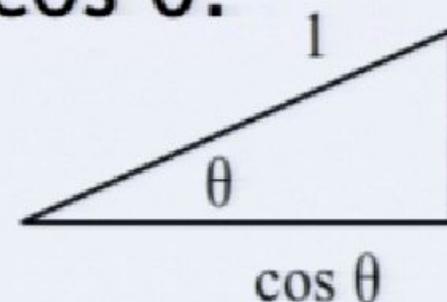
W boson  spin 1

graviton  spin 2

What happens when we do two **sequential** Stern-Gerlach selections?

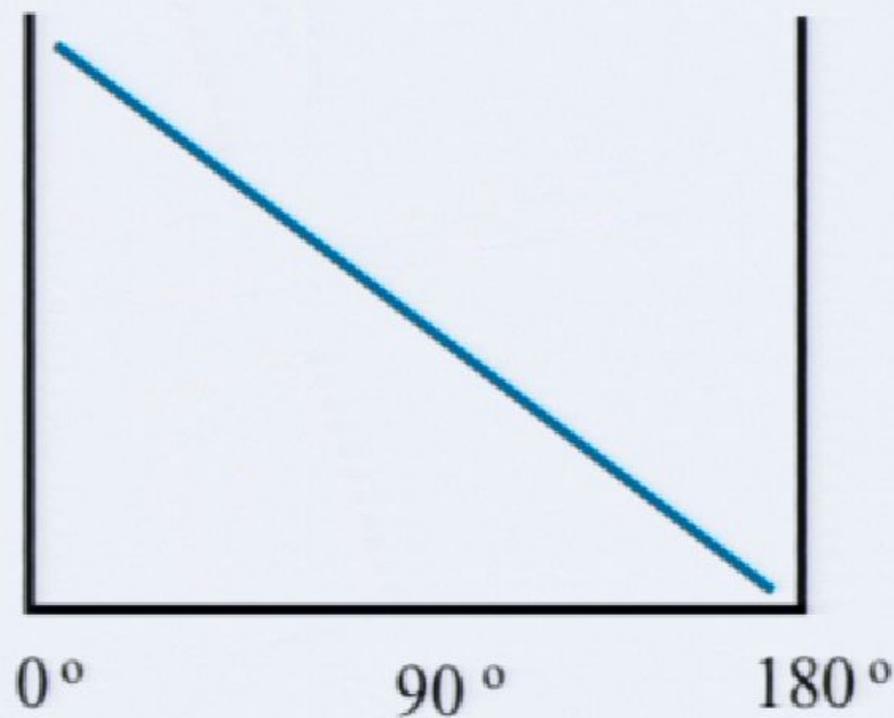


The probability of being in the top beam is a simple mathematical function of  $\cos \theta$ .



For spin 1/2

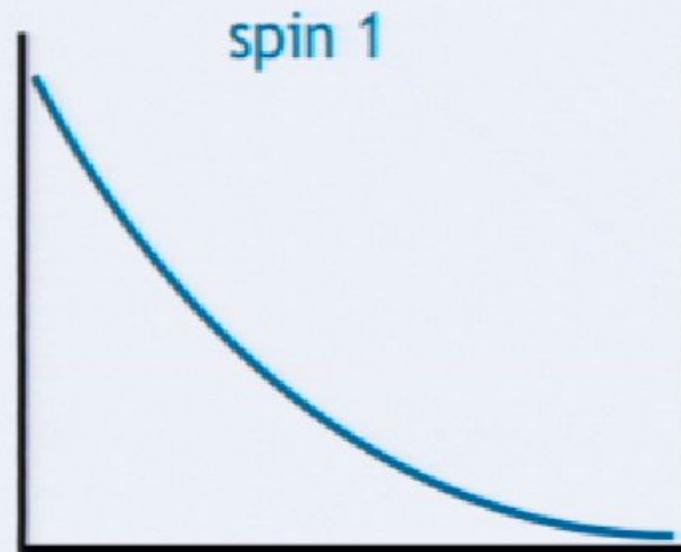
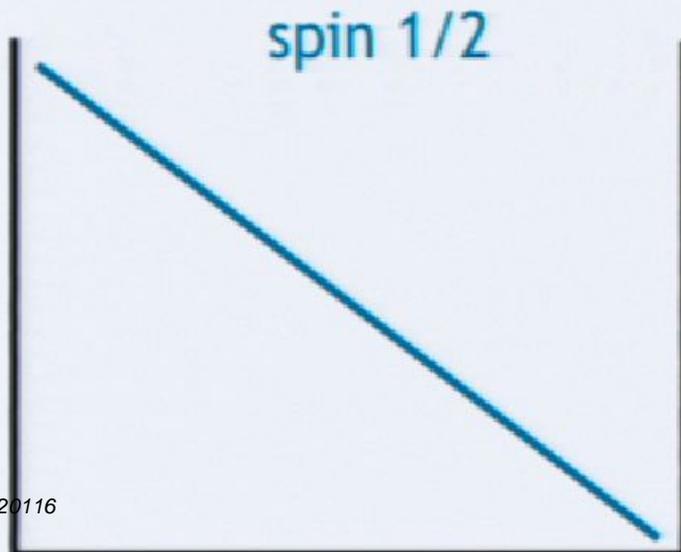
$$P(\theta) = (1 + \cos \theta)/2$$



There is a characteristic pattern for each value of the spin.

$$\text{spin } \frac{1}{2} : P(\theta) = (1 + \cos \theta)/2$$

$$\text{spin } 1 : P(\theta) = (1 + \cos \theta)^2/4$$



Quantum patterns are part of the territory of “Bell’s inequality”,

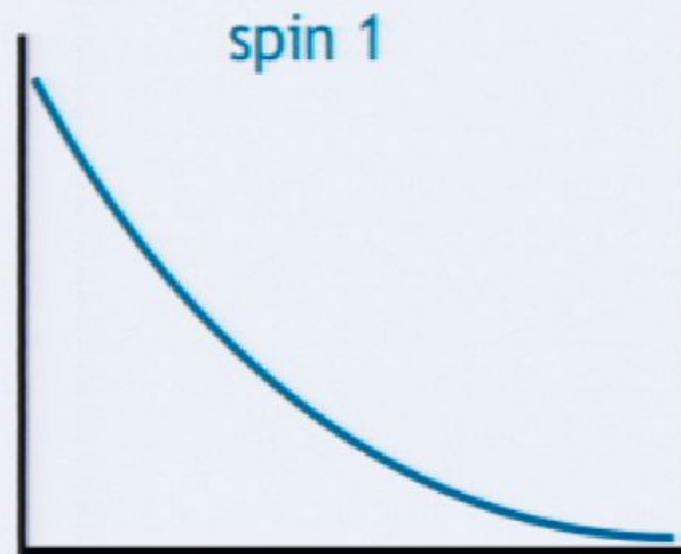
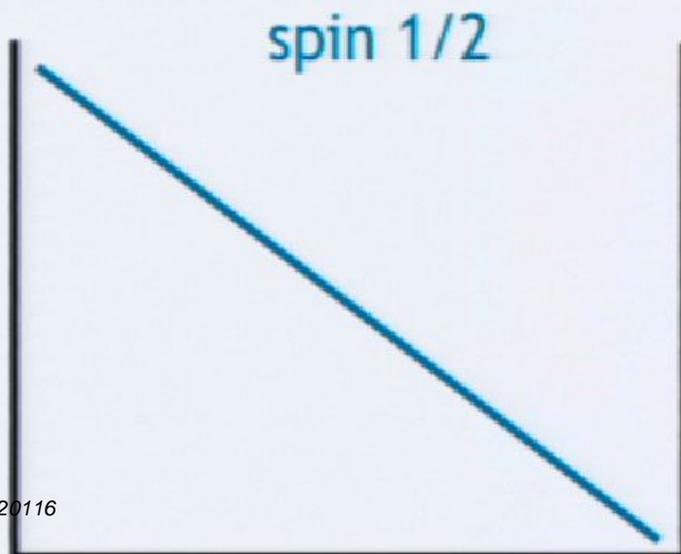
the proof that quantum mechanics is not governed by hidden variables with classical probabilities.

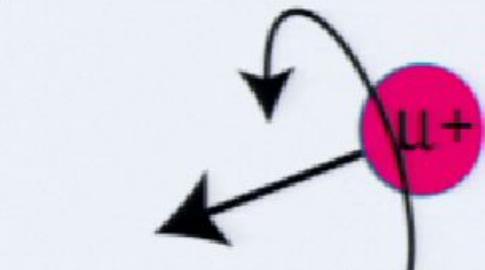
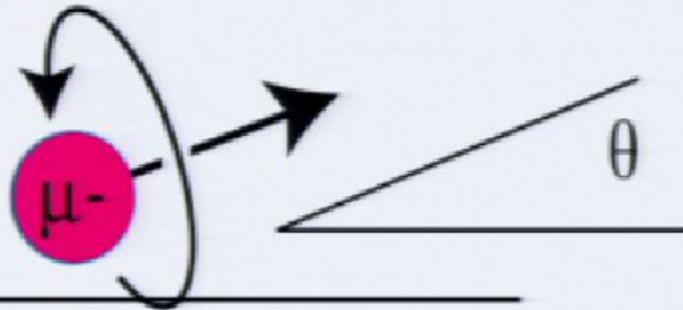
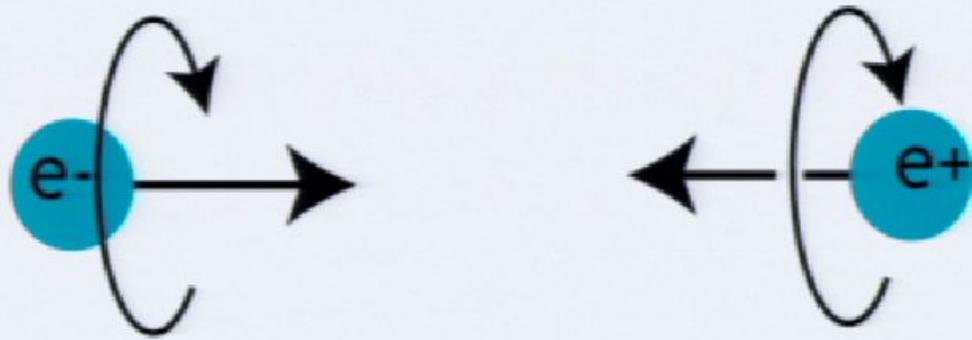


There is a characteristic pattern for each value of the spin.

$$\text{spin } \frac{1}{2} : P(\theta) = (1 + \cos \theta) / 2$$

$$\text{spin } 1 : P(\theta) = (1 + \cos \theta)^2 / 4$$



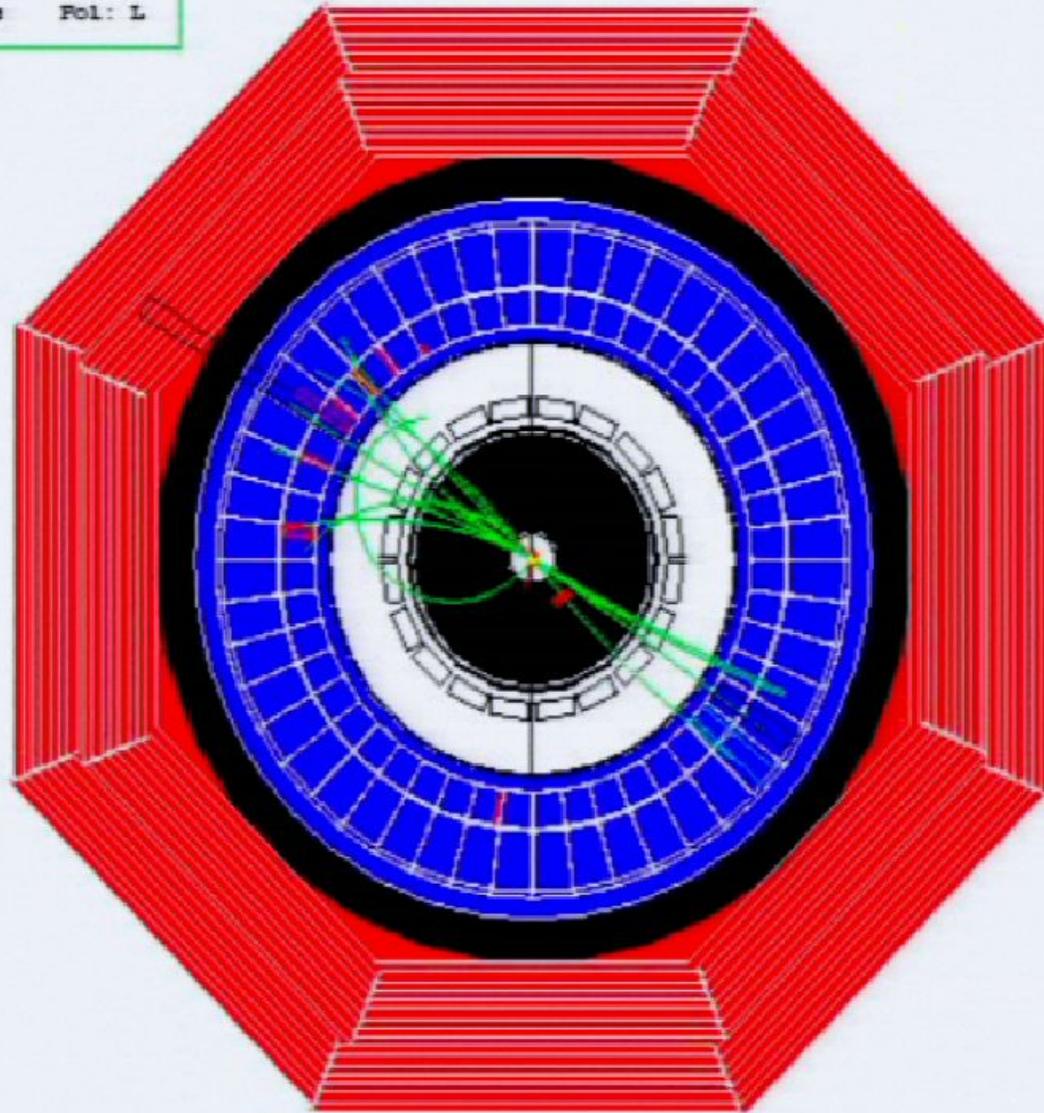


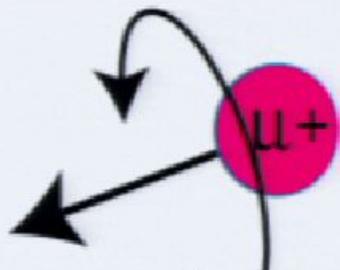
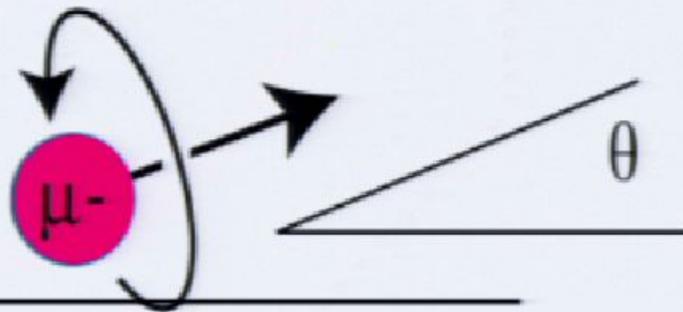
Quantum patterns are part of the territory of “Bell’s inequality”,

the proof that quantum mechanics is not governed by hidden variables with classical probabilities.



Run: 12576, EVENT: 2540  
4-JUL-1992 19:18  
Source: Run Data Pol: L

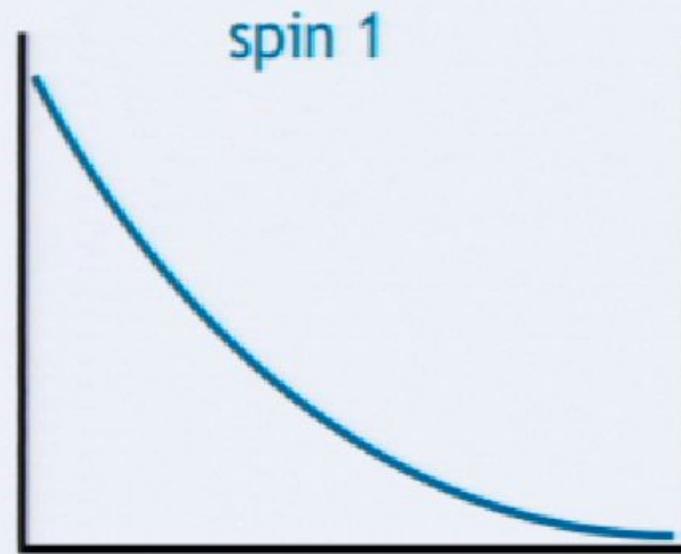
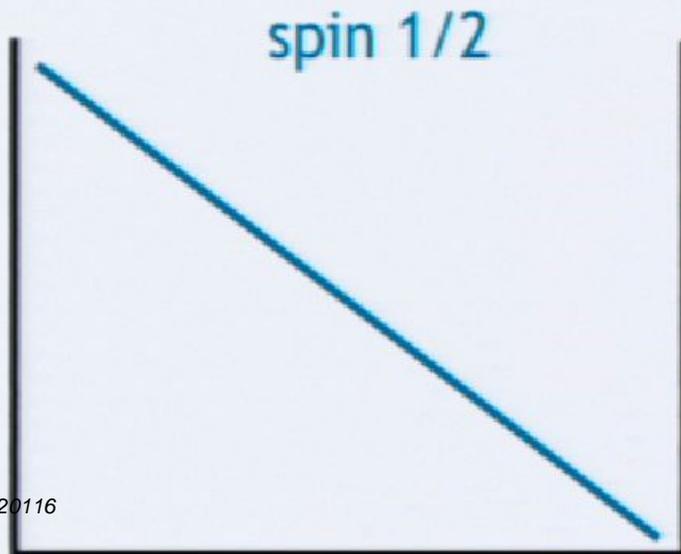




There is a characteristic pattern for each value of the spin.

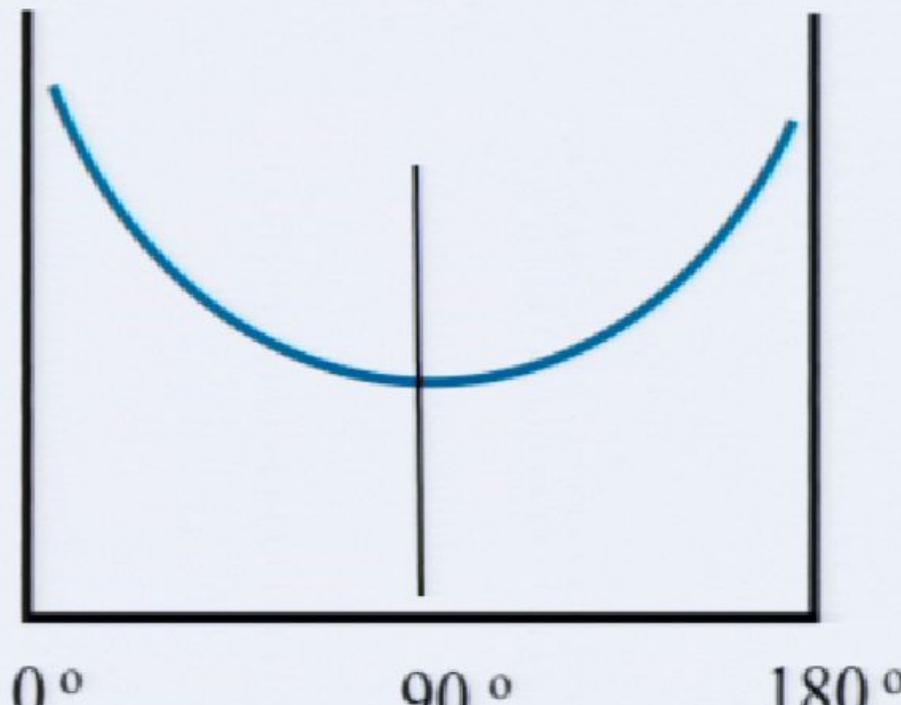
$$\text{spin } \frac{1}{2} : P(\theta) = (1 + \cos \theta) / 2$$

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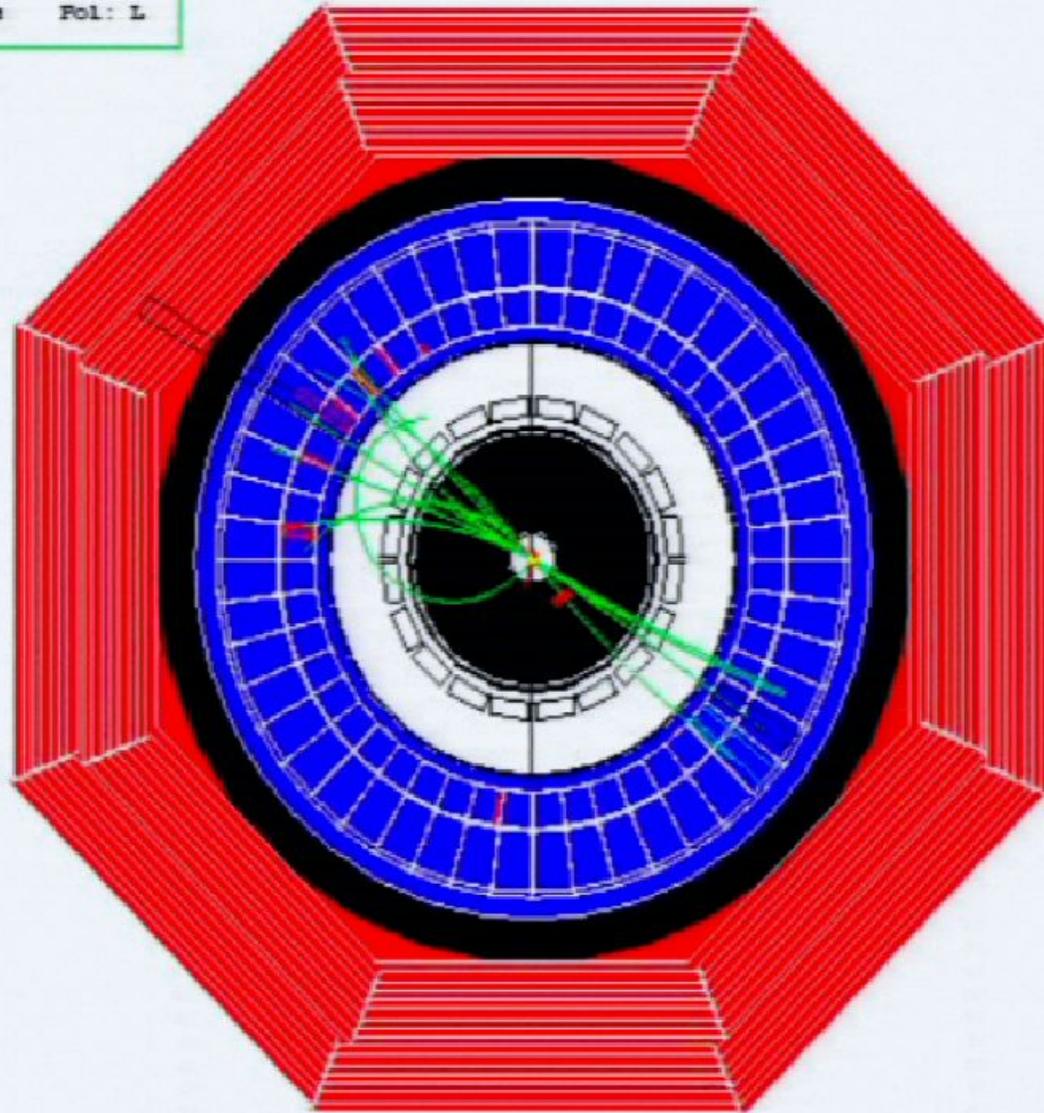


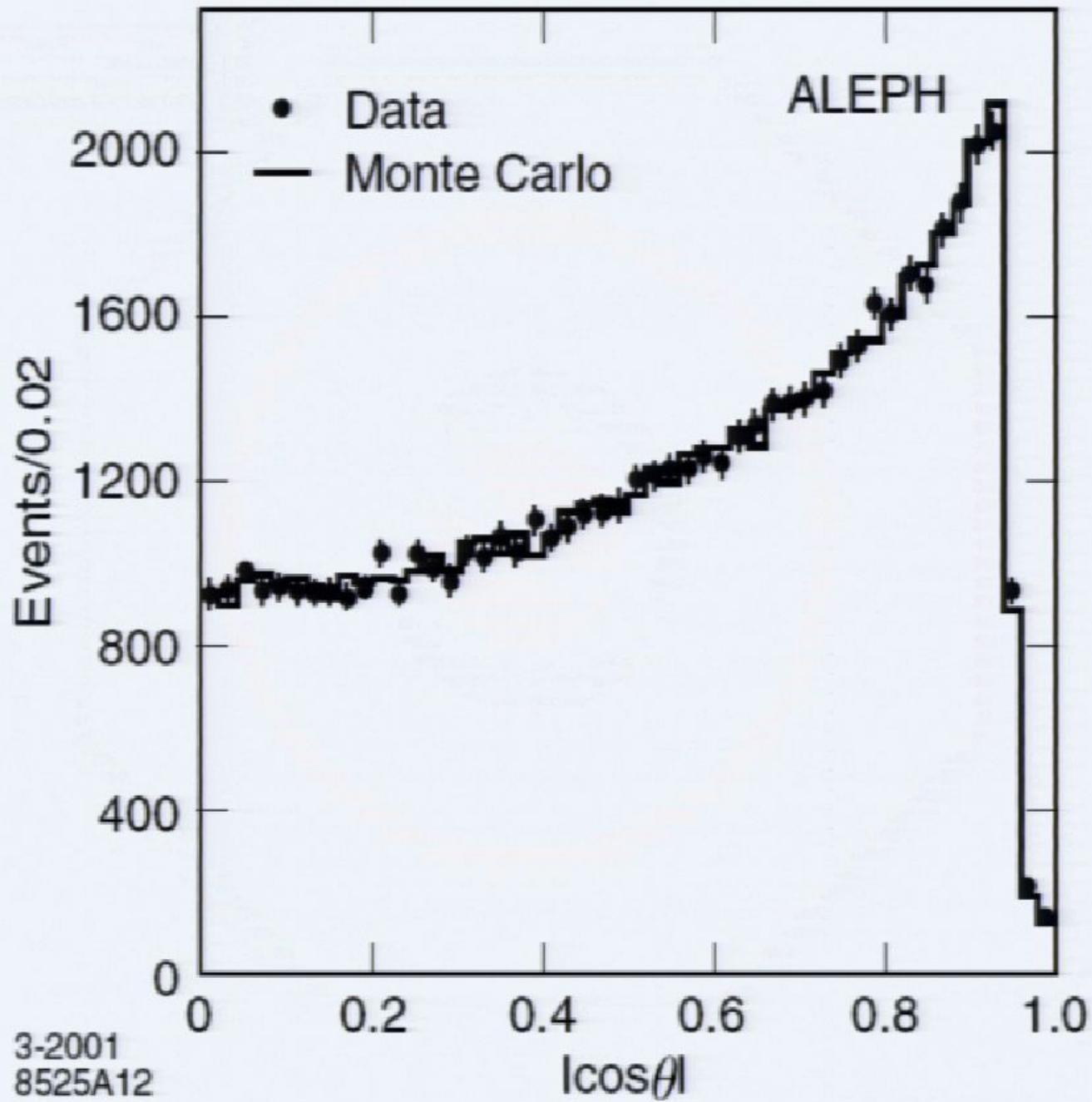
The probability of this collision is proportional to

$$\frac{(1 + \cos \theta)^2}{4} + \frac{(1 - \cos \theta)^2}{4} = \frac{1 + \cos^2 \theta}{2}$$



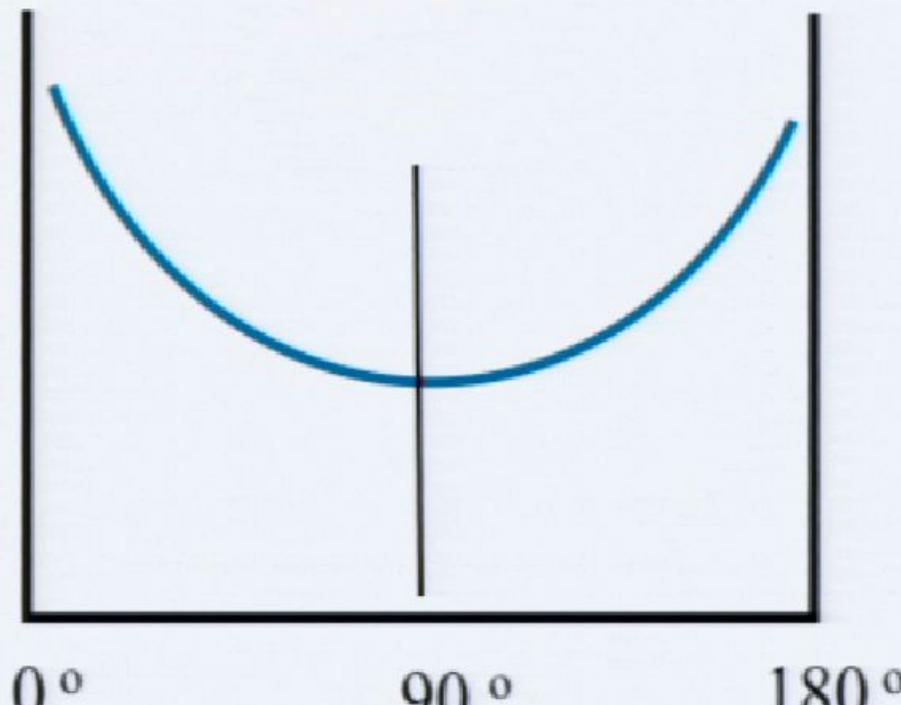
Run: 12576, EVENT: 2540  
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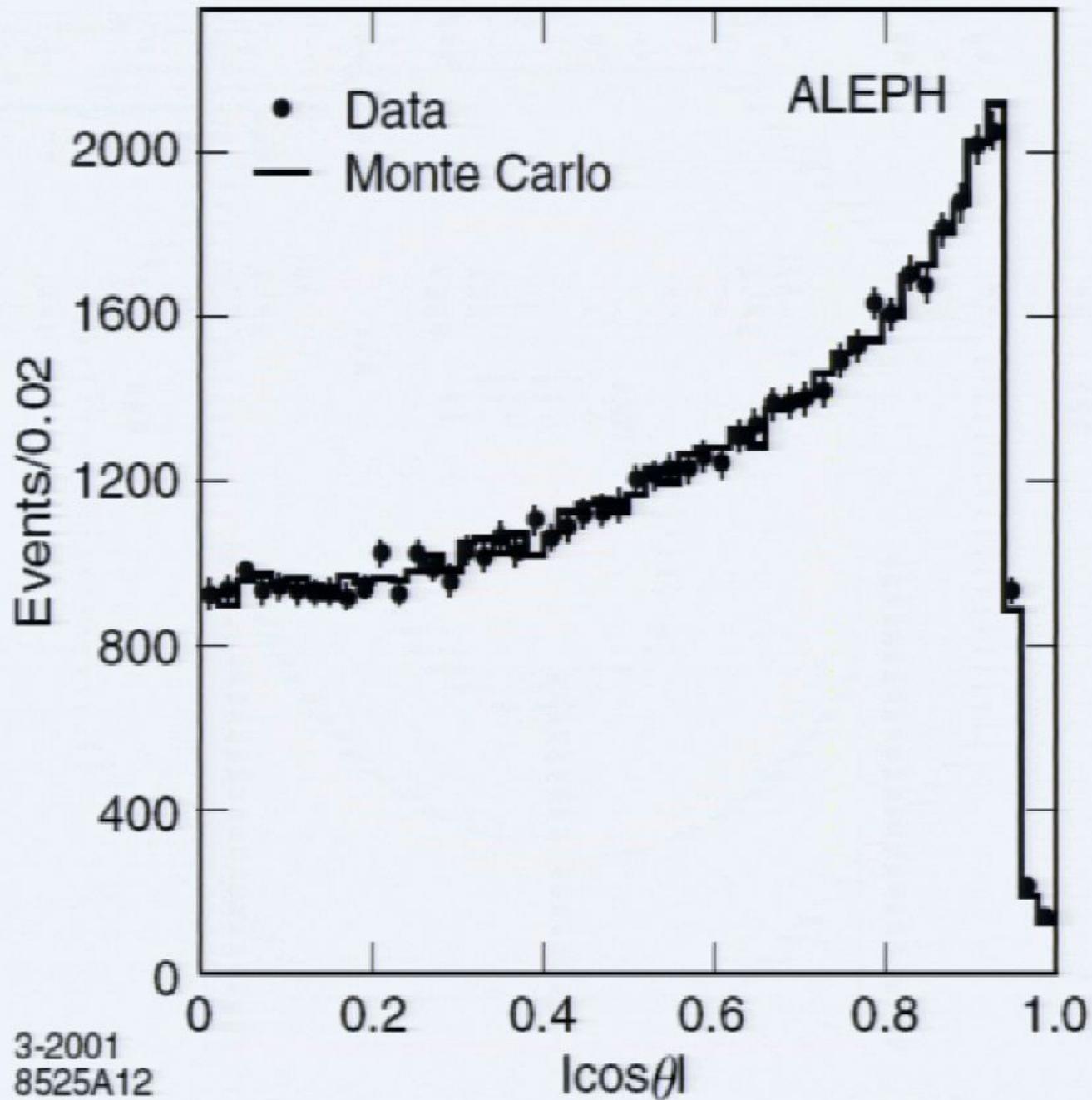


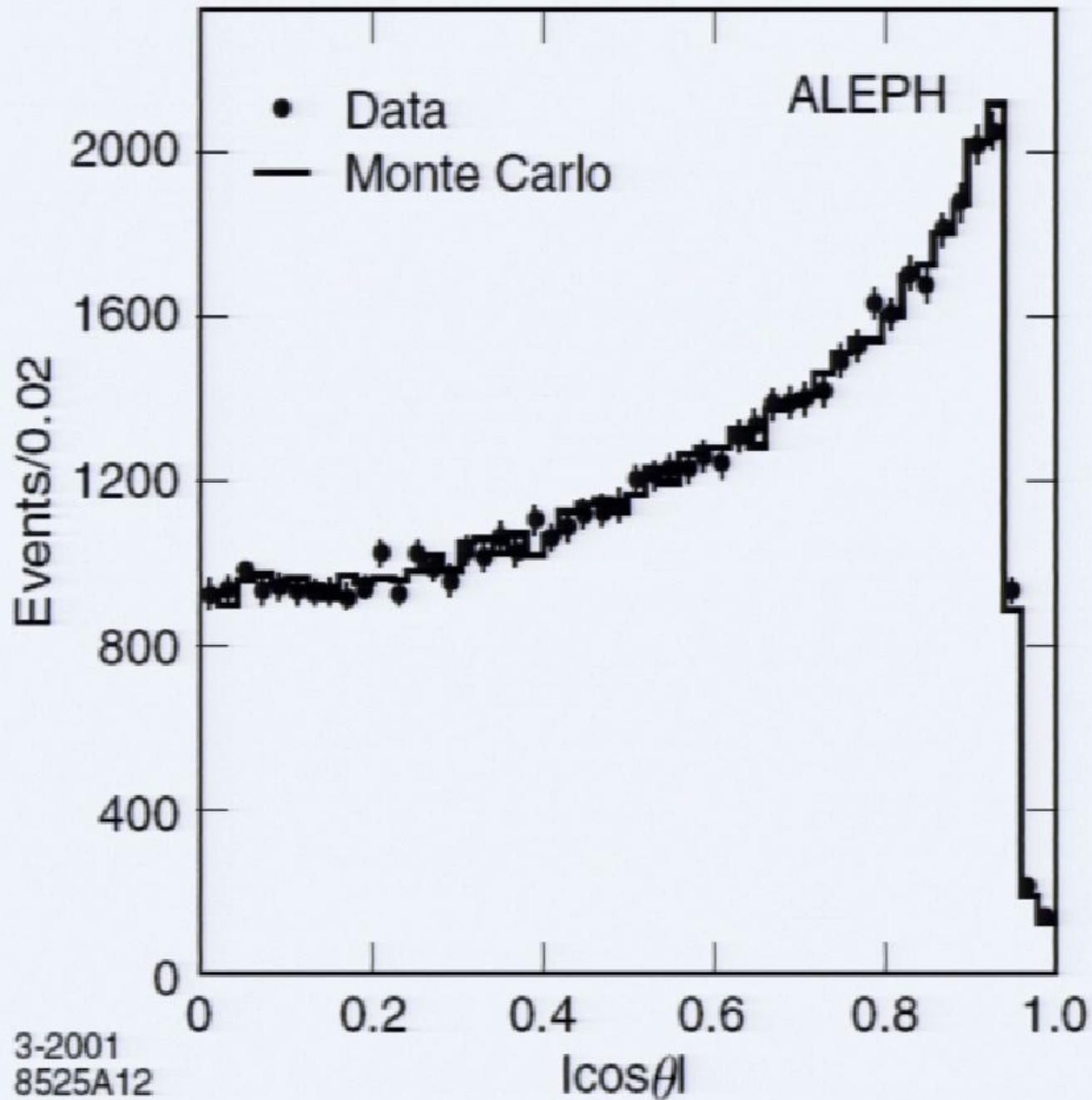


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What are the patterns for the  
top quark ?

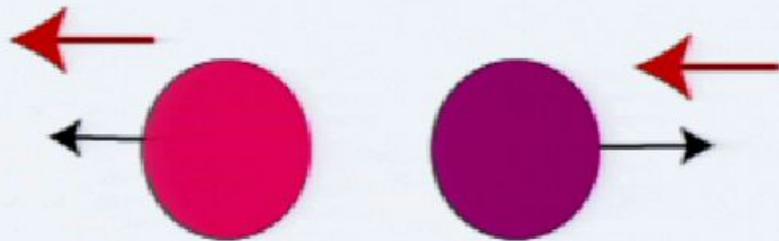


What are the patterns for the  
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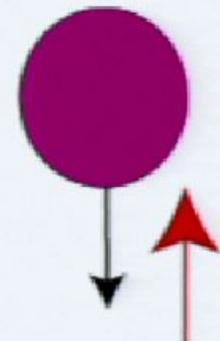
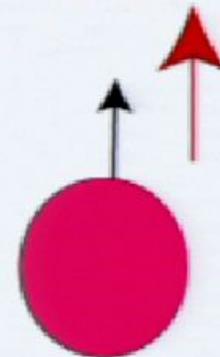


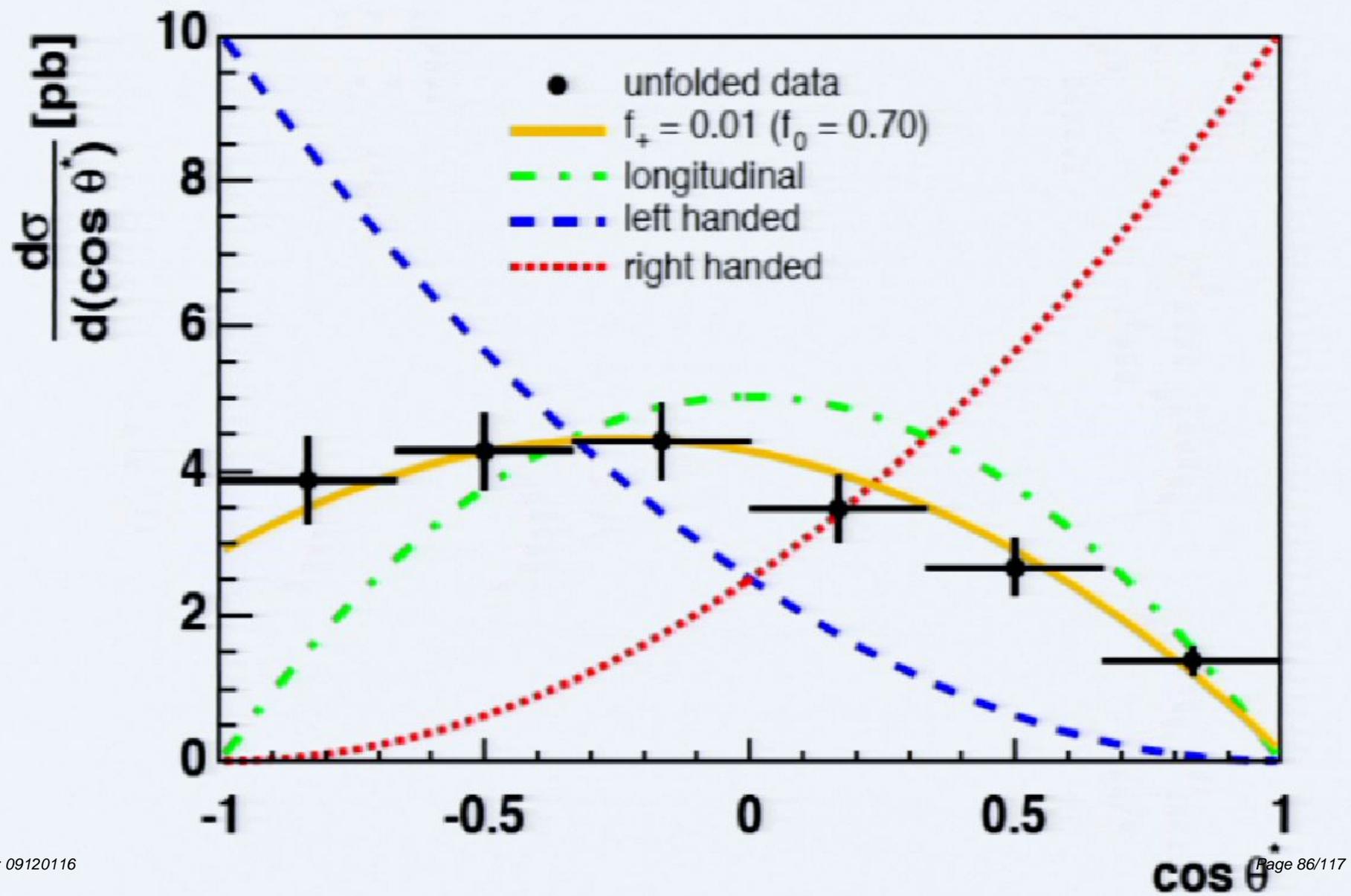


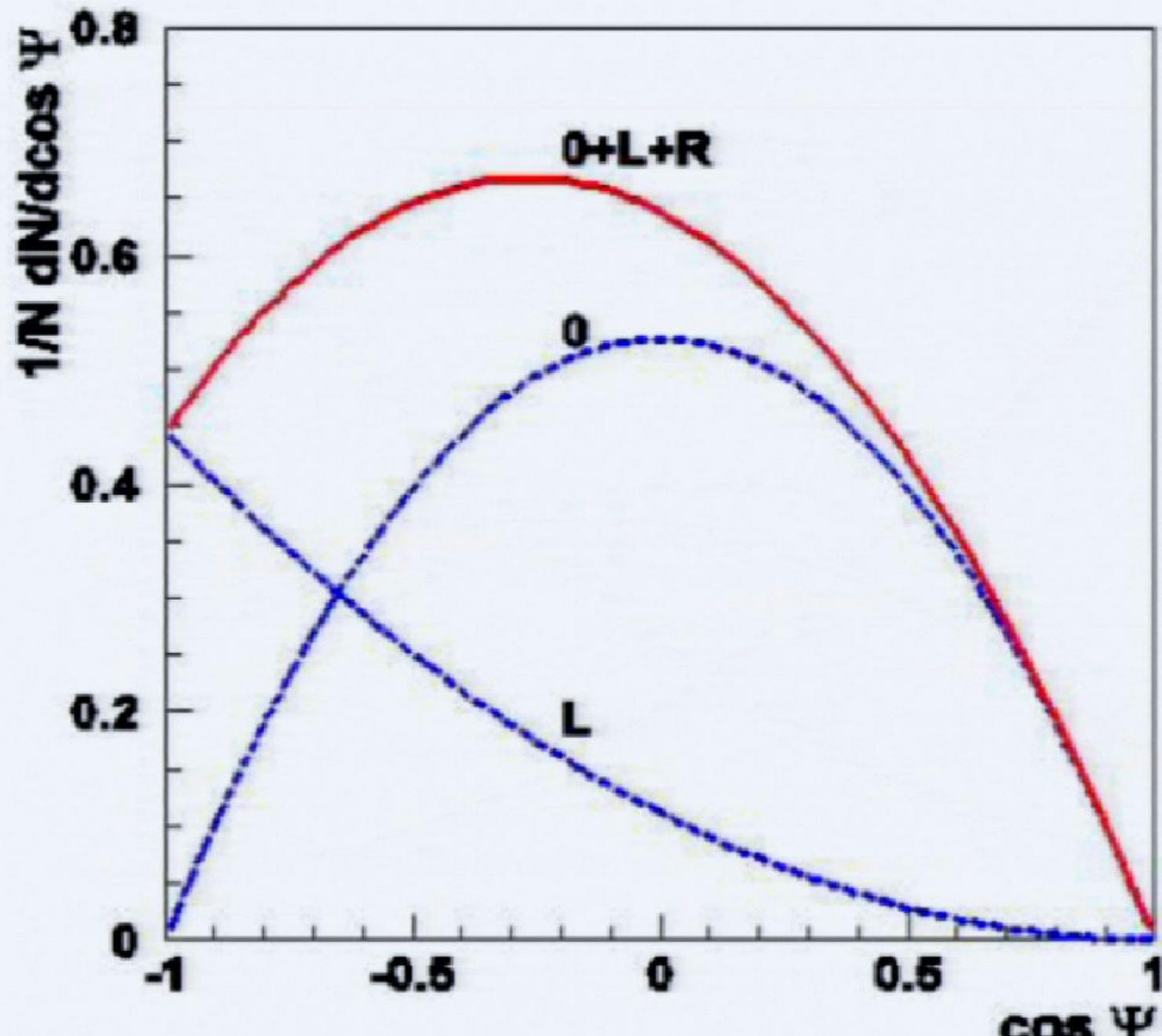
$W_L$

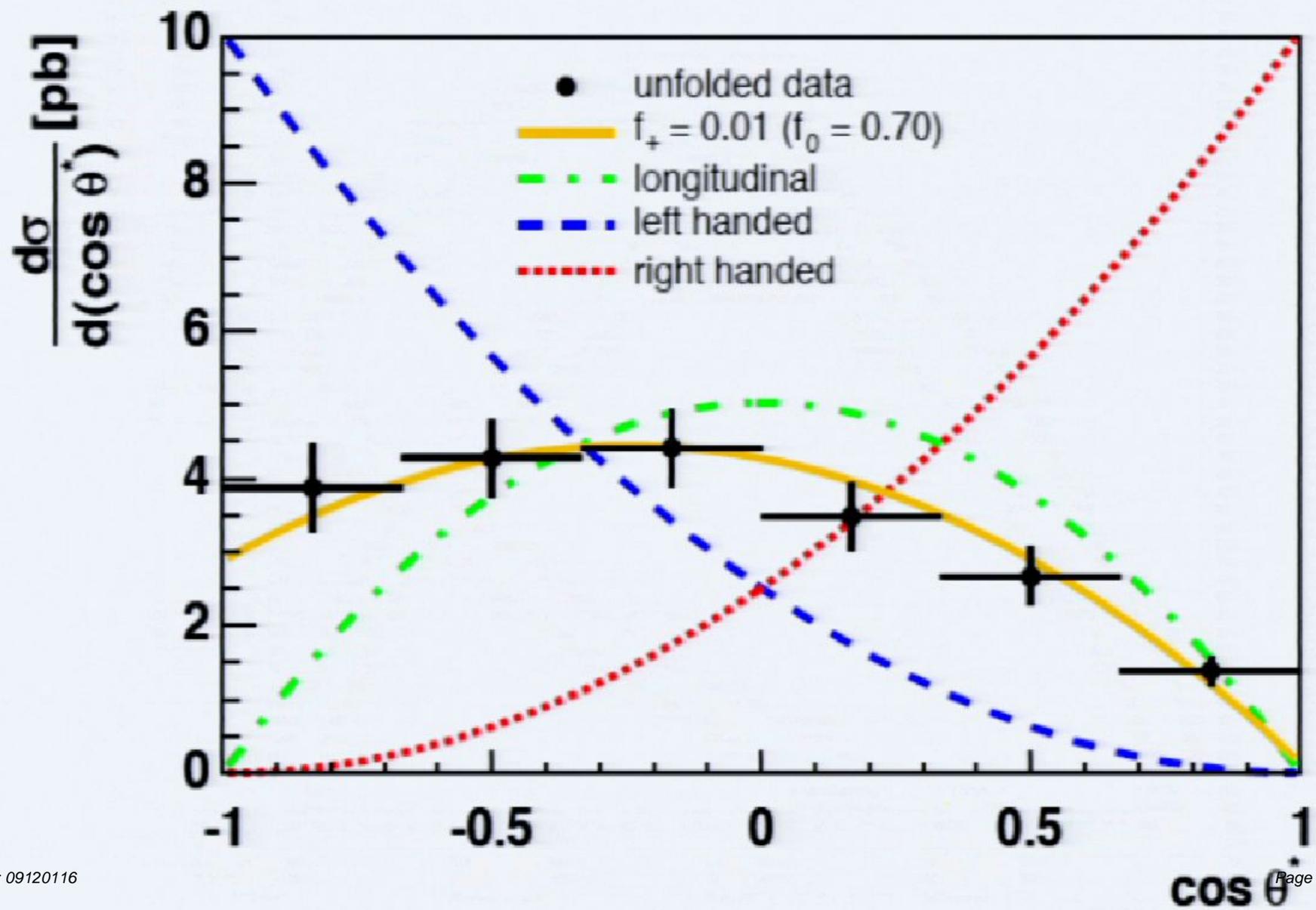


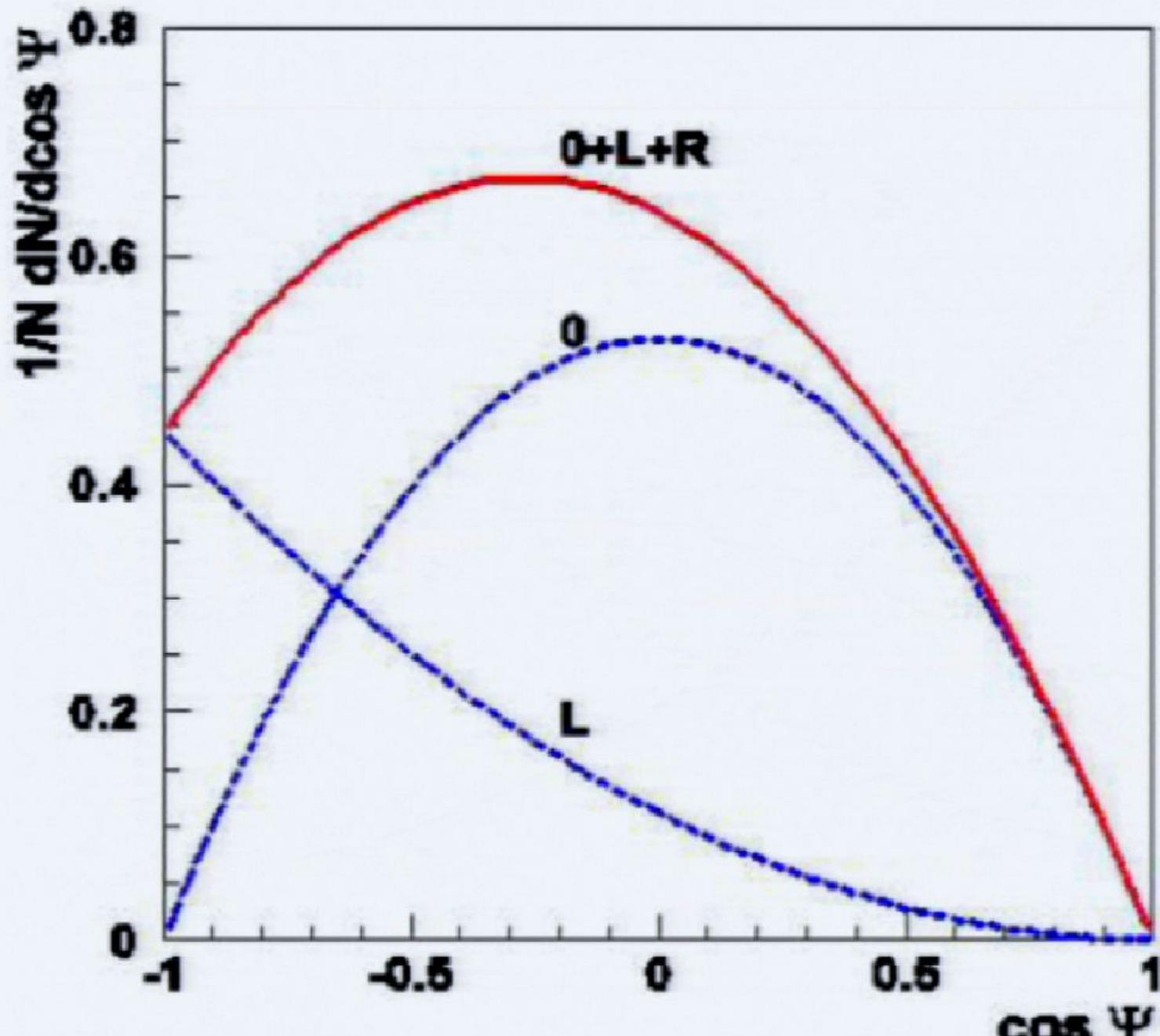
$W_0$











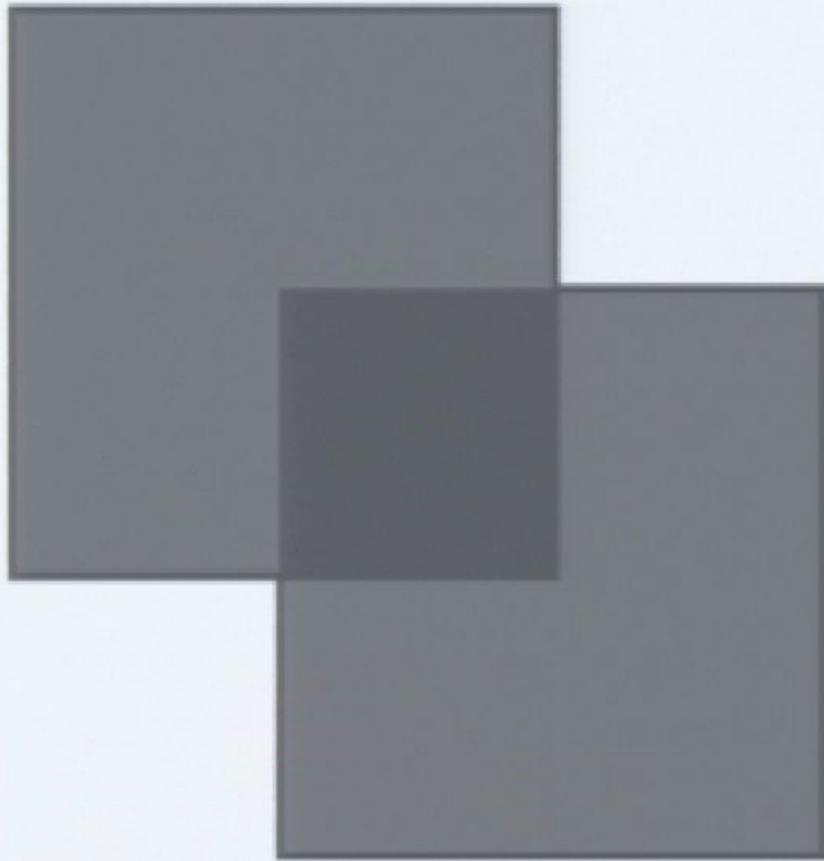
Why so much  $W(0)$

and so little  $W(L)$  ?

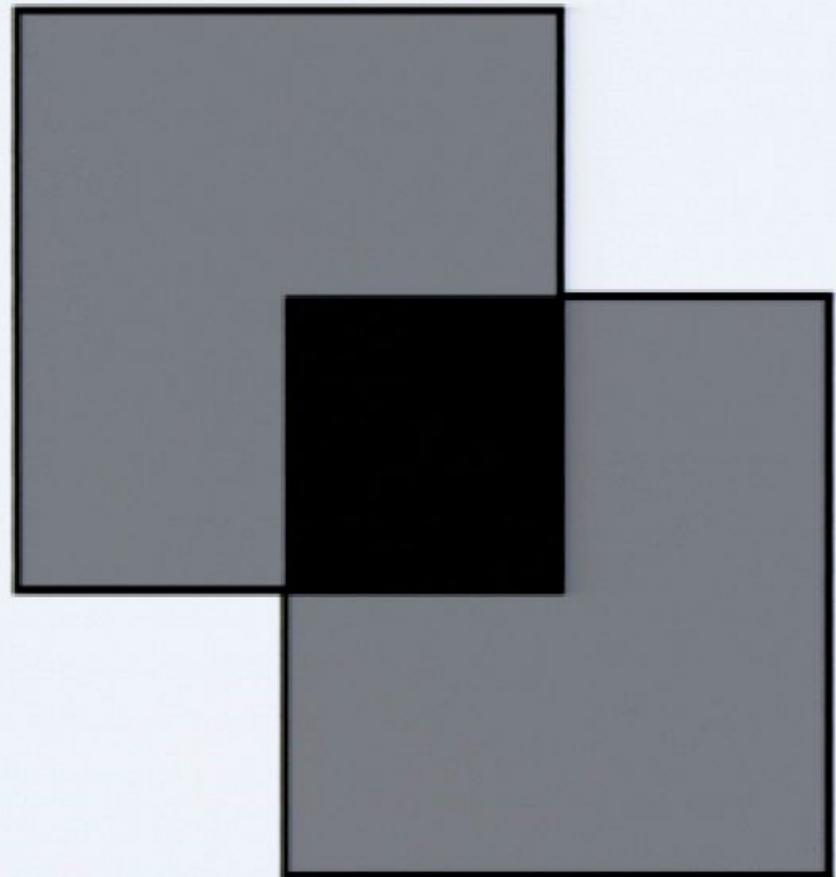
The business of  $W$  having three polarization states is very weird.

Photons have only two polarization states.



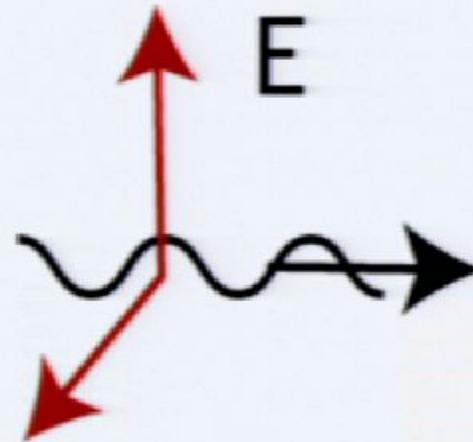


**Parallel axes.**

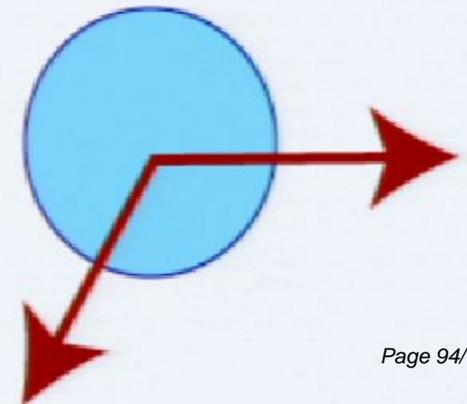
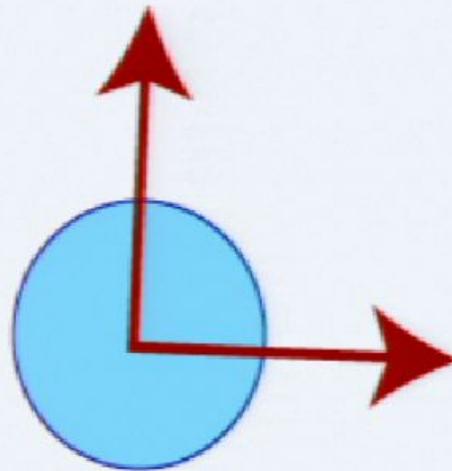
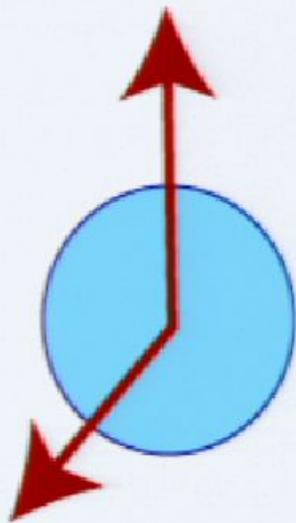


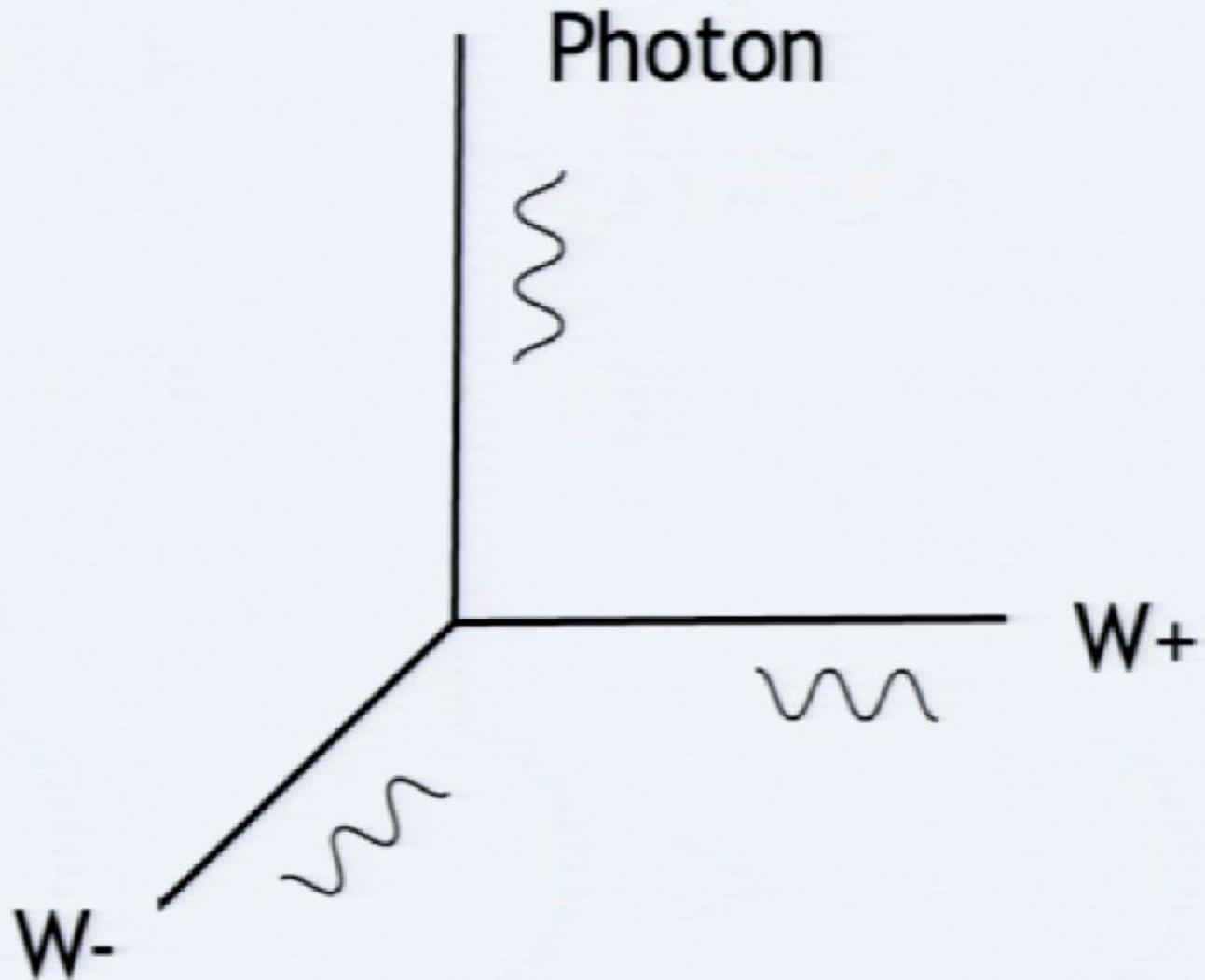
**Crossed axes.**

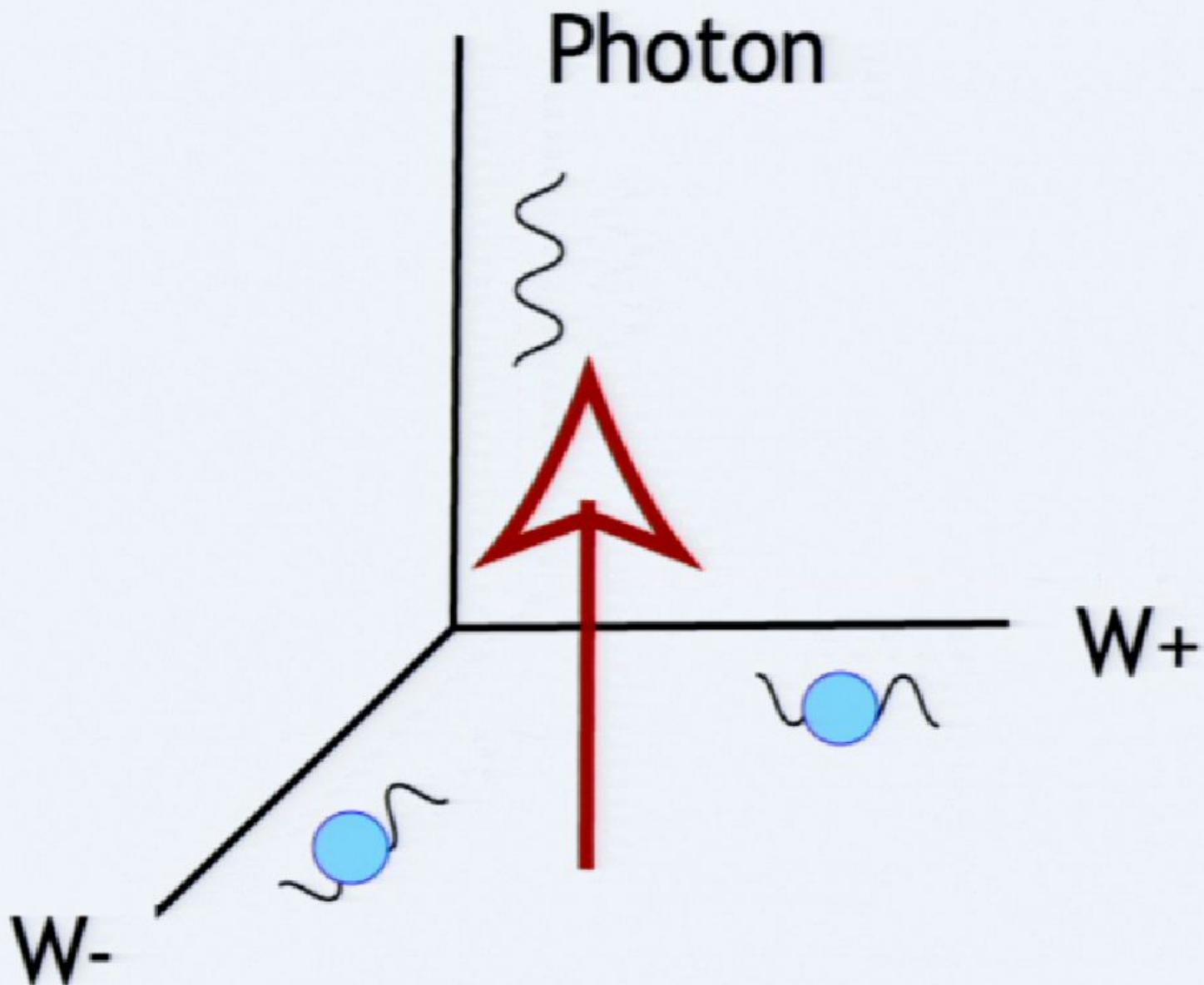
photon

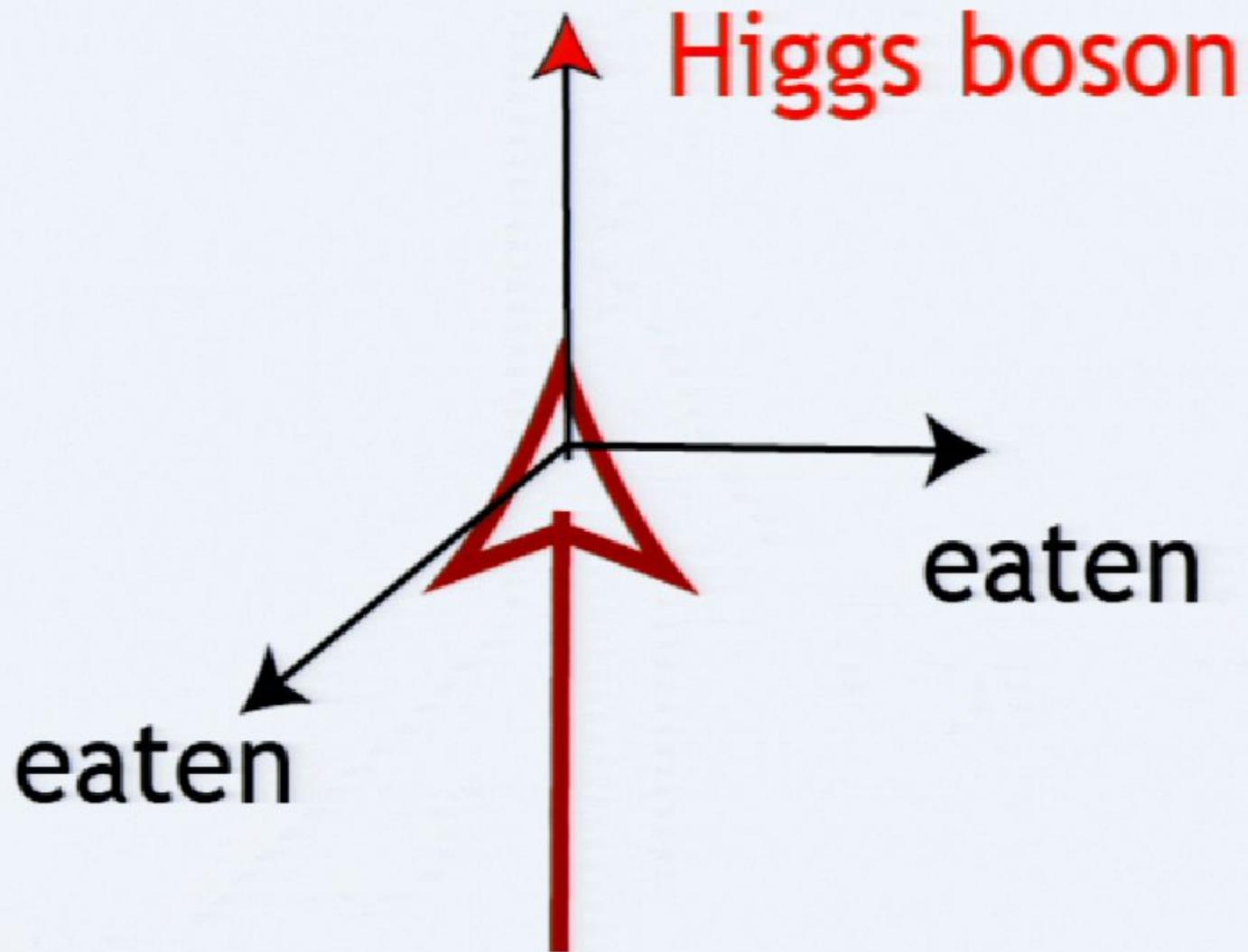


W boson









The top is the **heaviest** quark,  
the **most coupled** to the Higgs boson,  
thus, the most coupled to  **$W(0)$** .

And, also,

**the best probe of the truth of this story.**



# CERN Large Hadron Collider

7 TeV protons

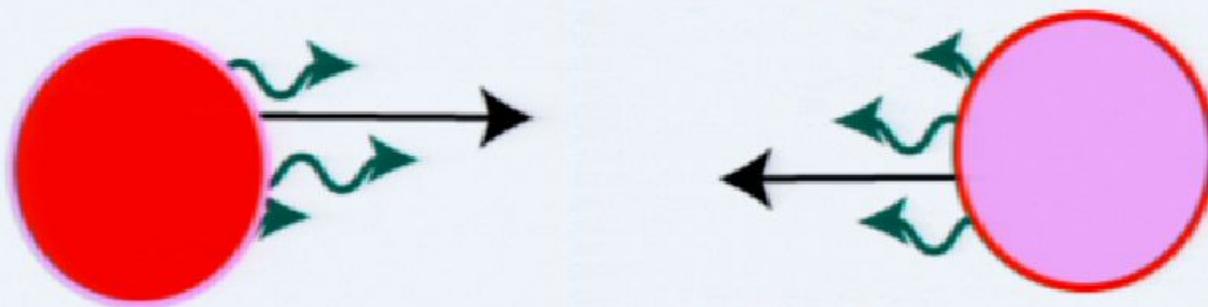
(ECM = 14 TeV)

27 km  
circumference  
tunnel

Fermilab  
Tevatron

2 TeV

10,000 top quarks

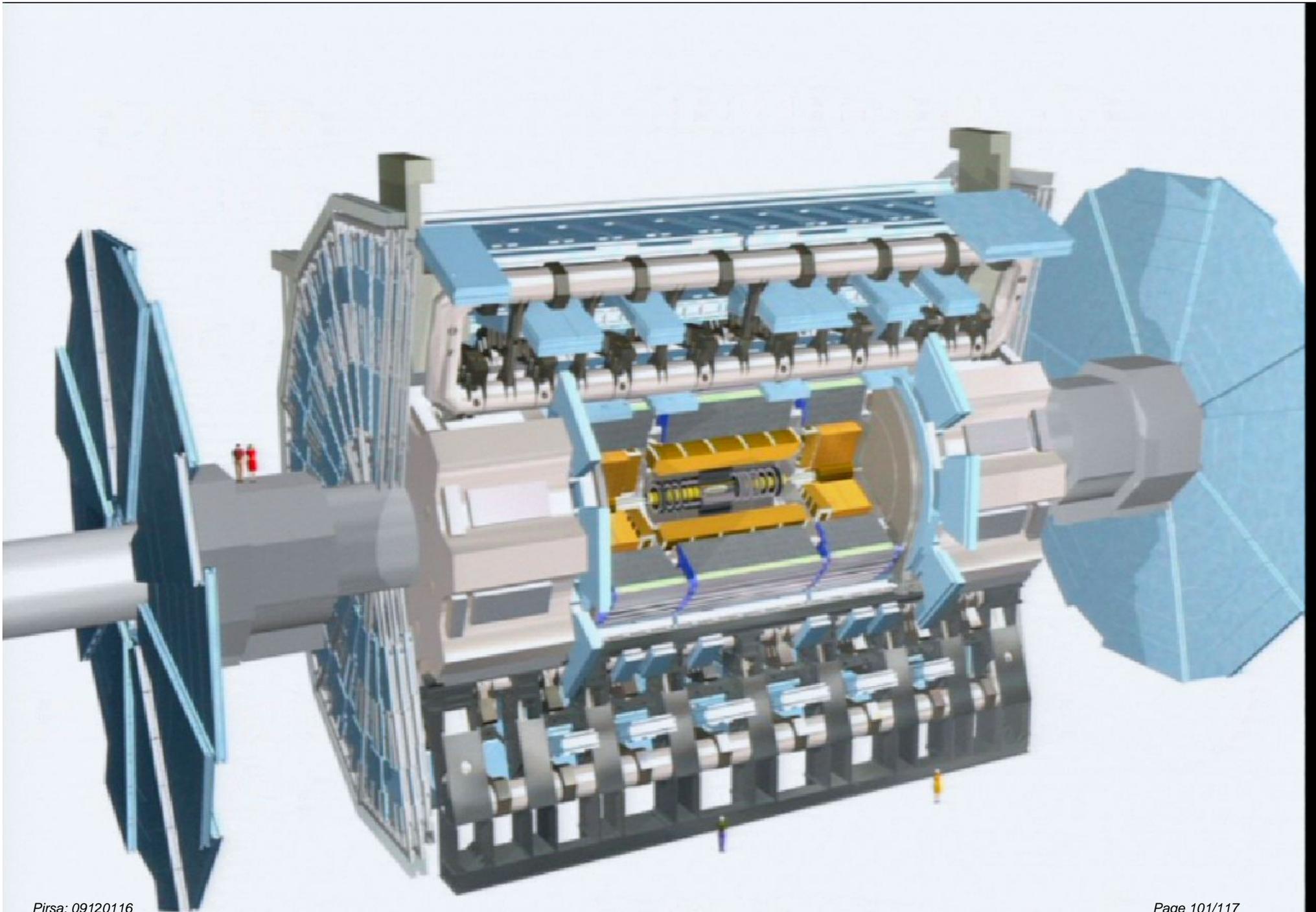


CERN  
Large Hadron  
Collider

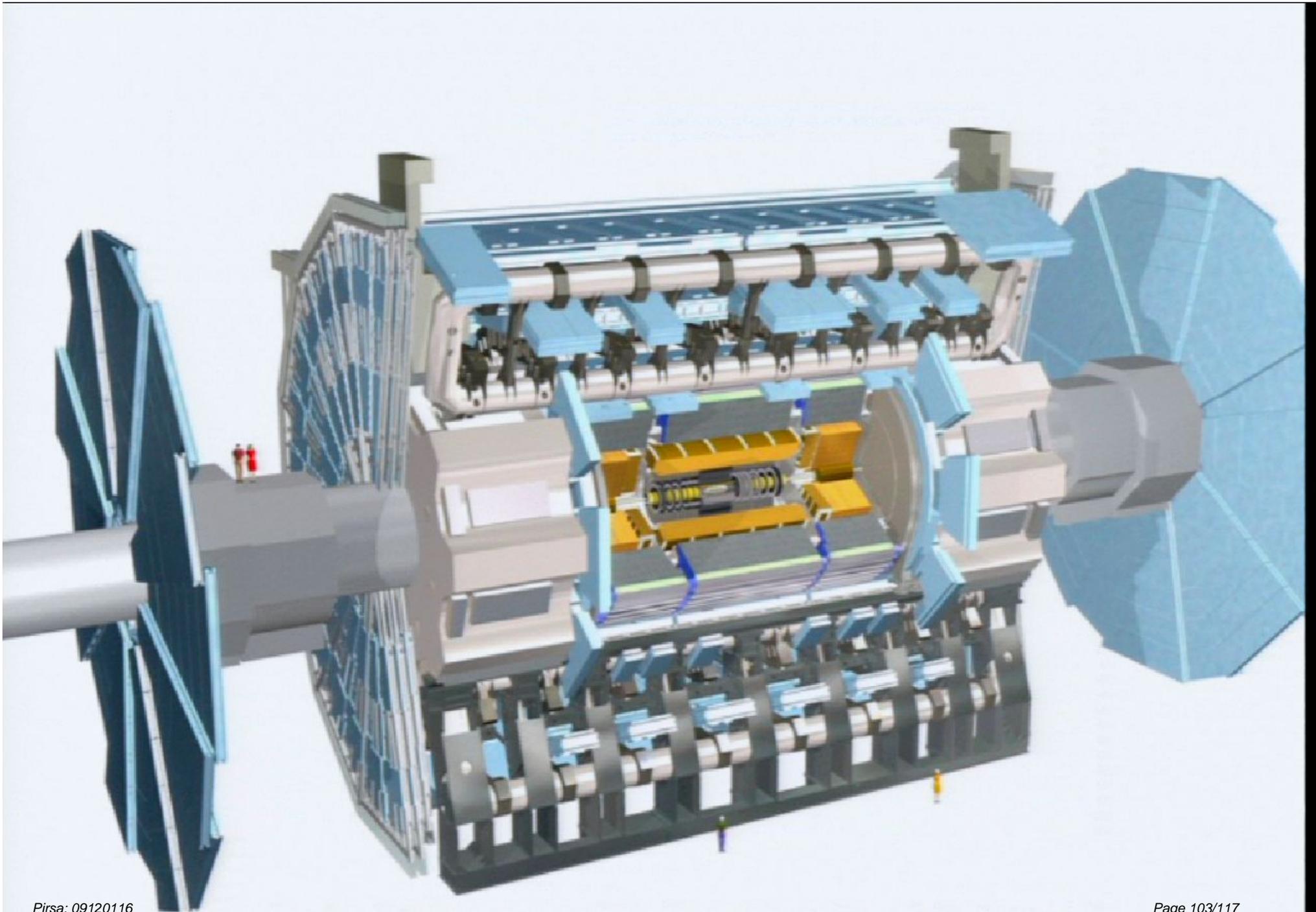
14 TeV

10,000,000 top quarks

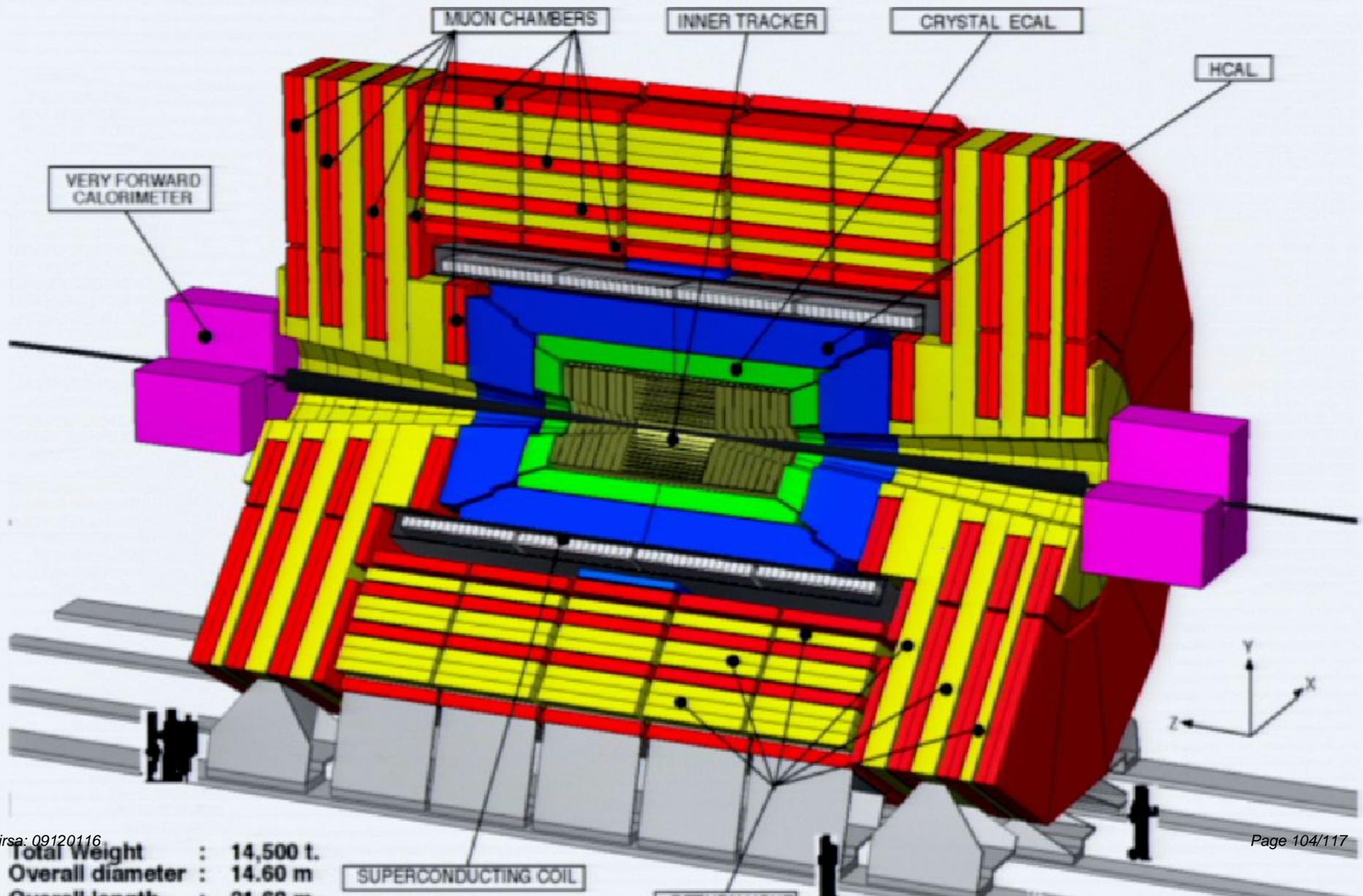


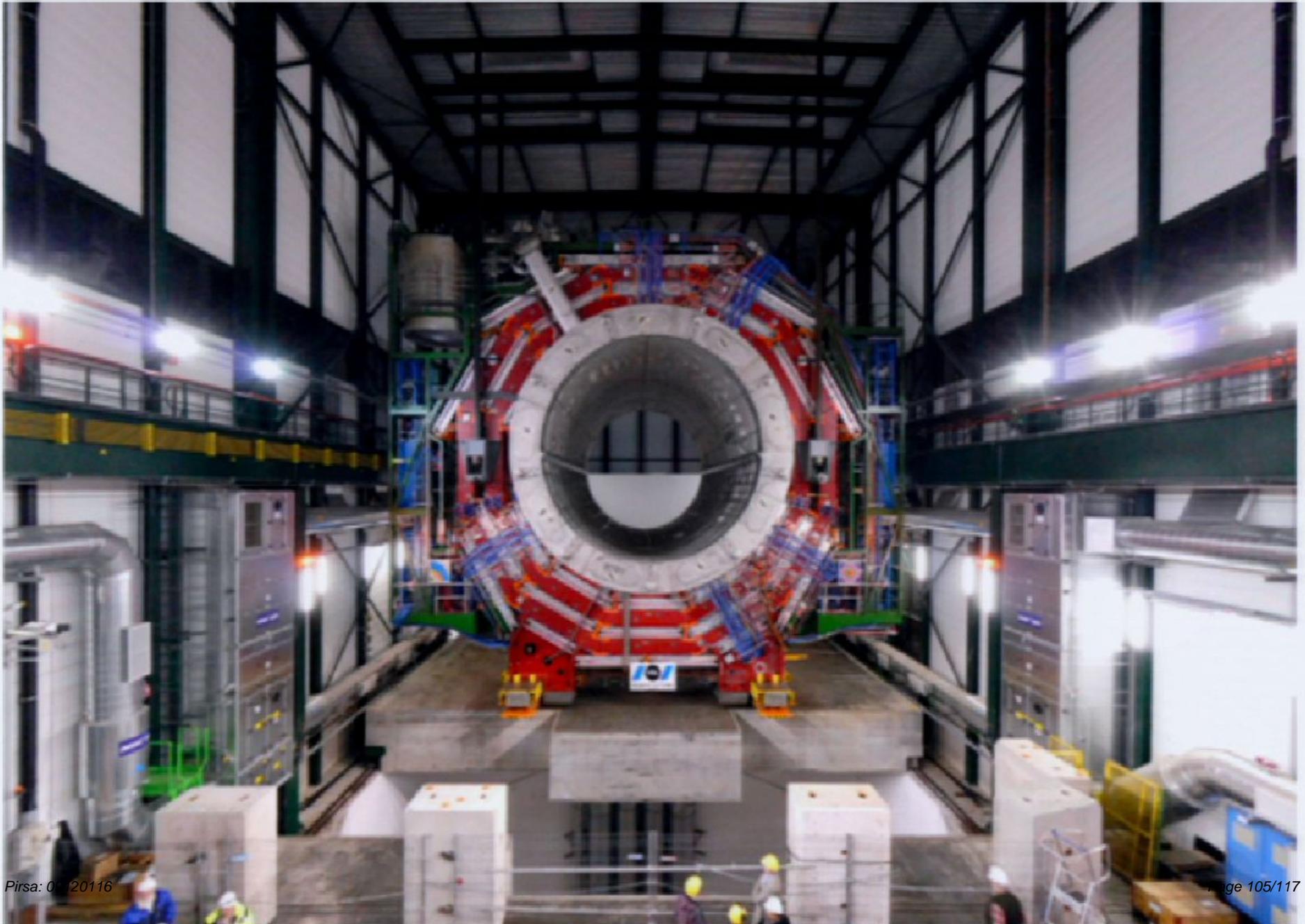


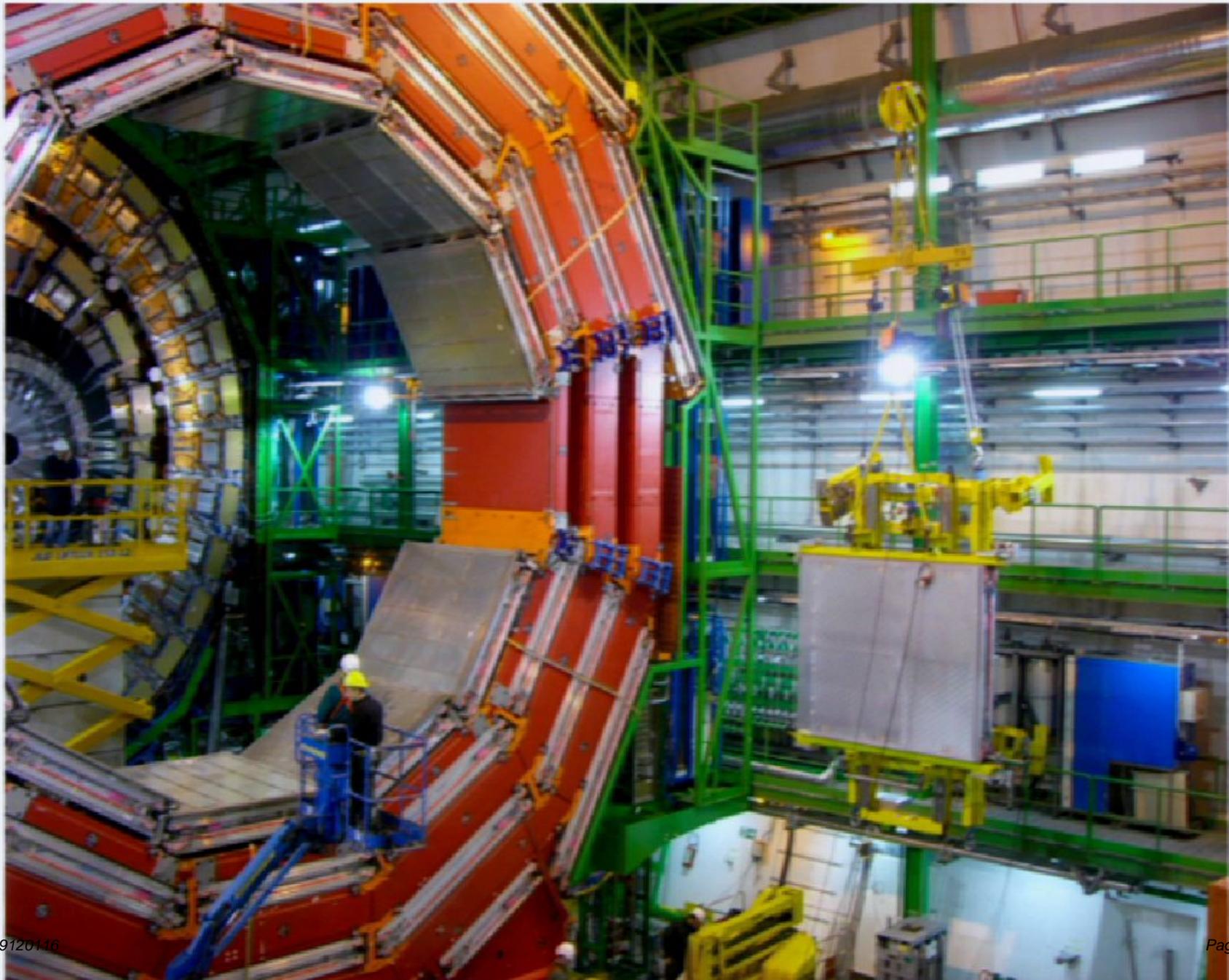




# A Compact Solenoidal Detector for LHC

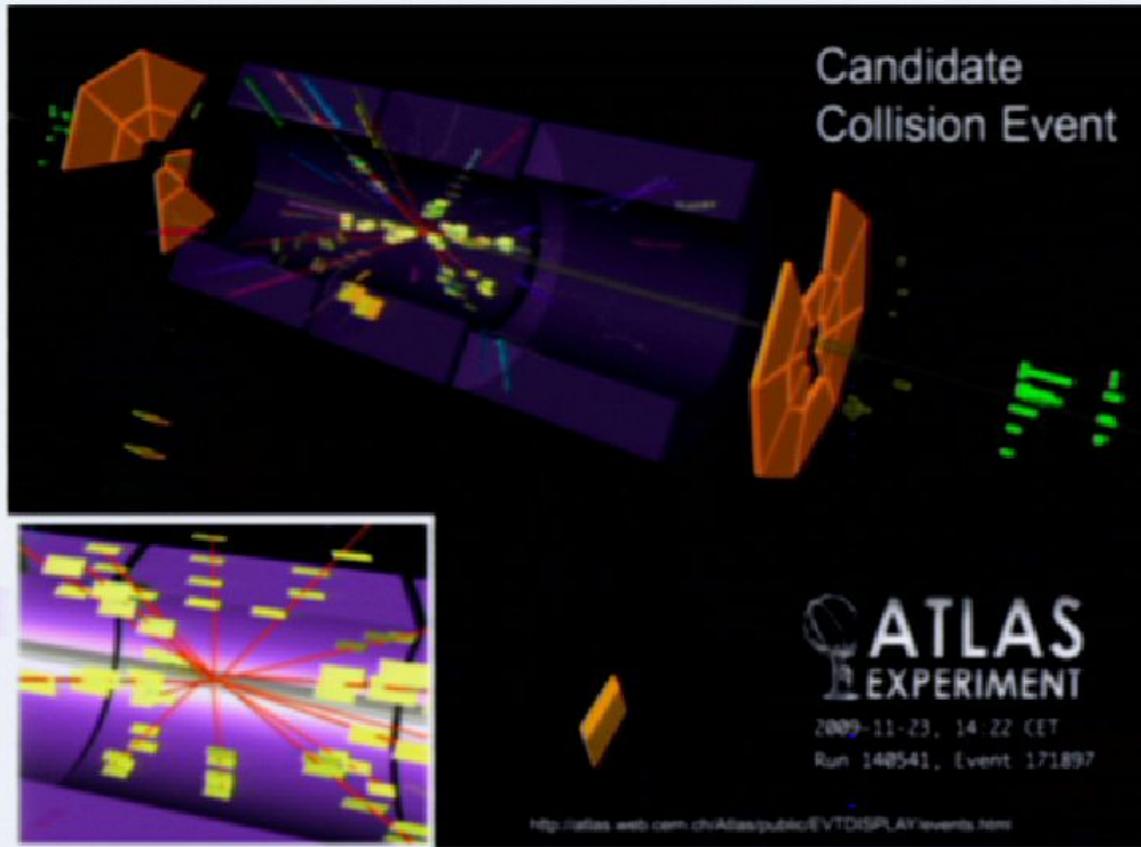






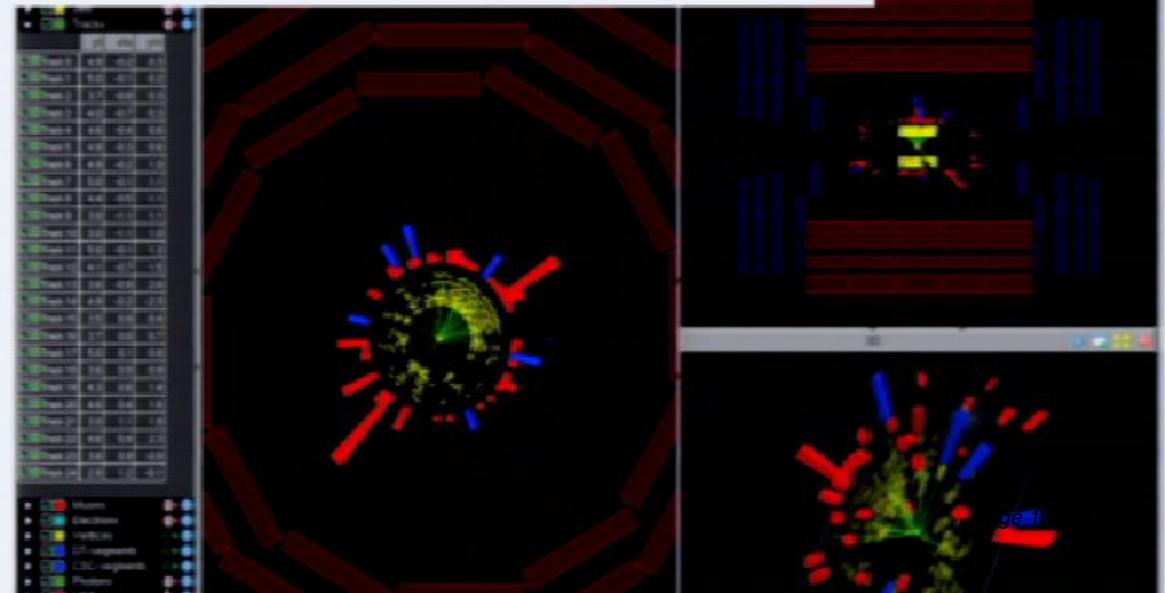
November  
23

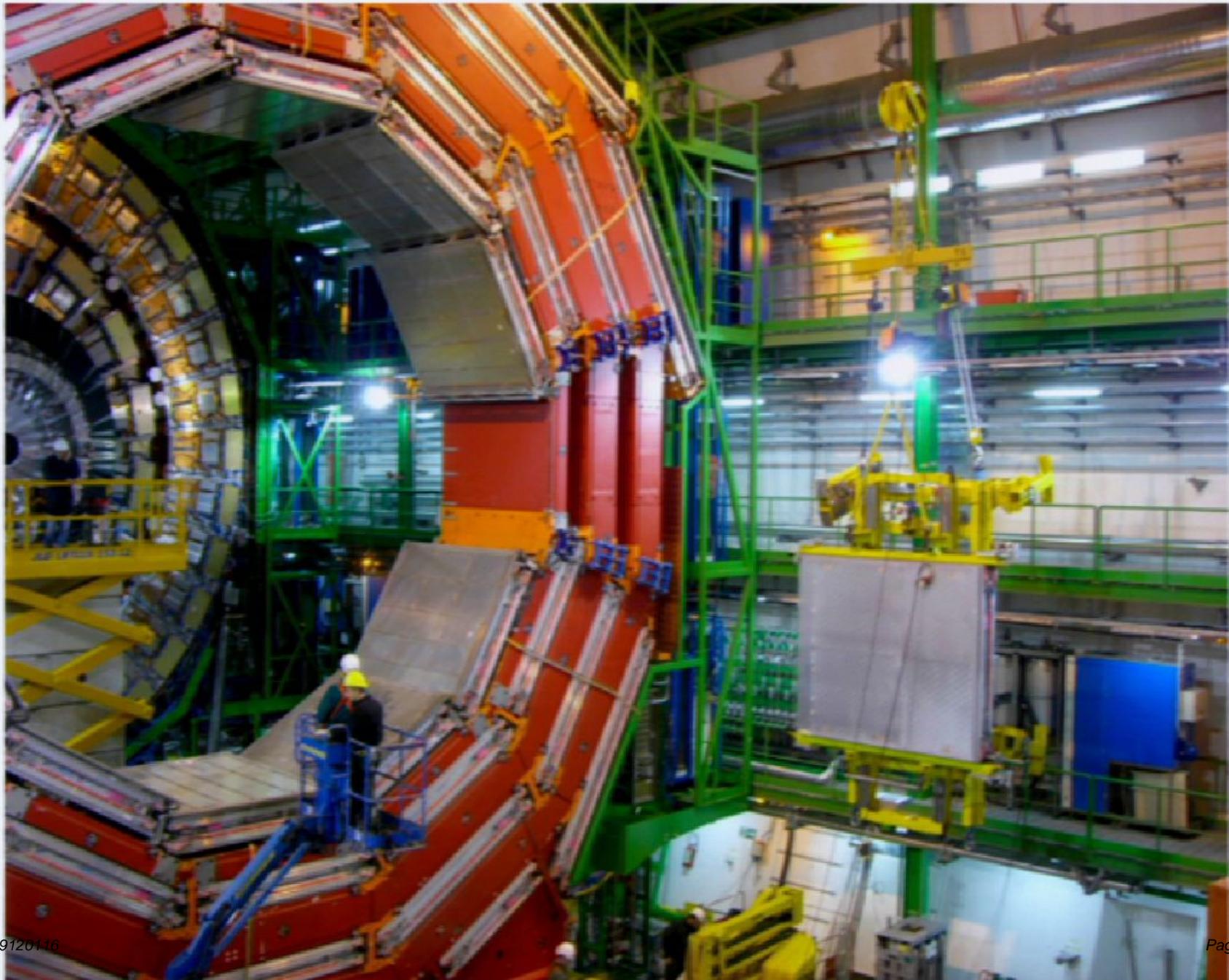
First  
collisions in  
ATLAS and  
CMS!



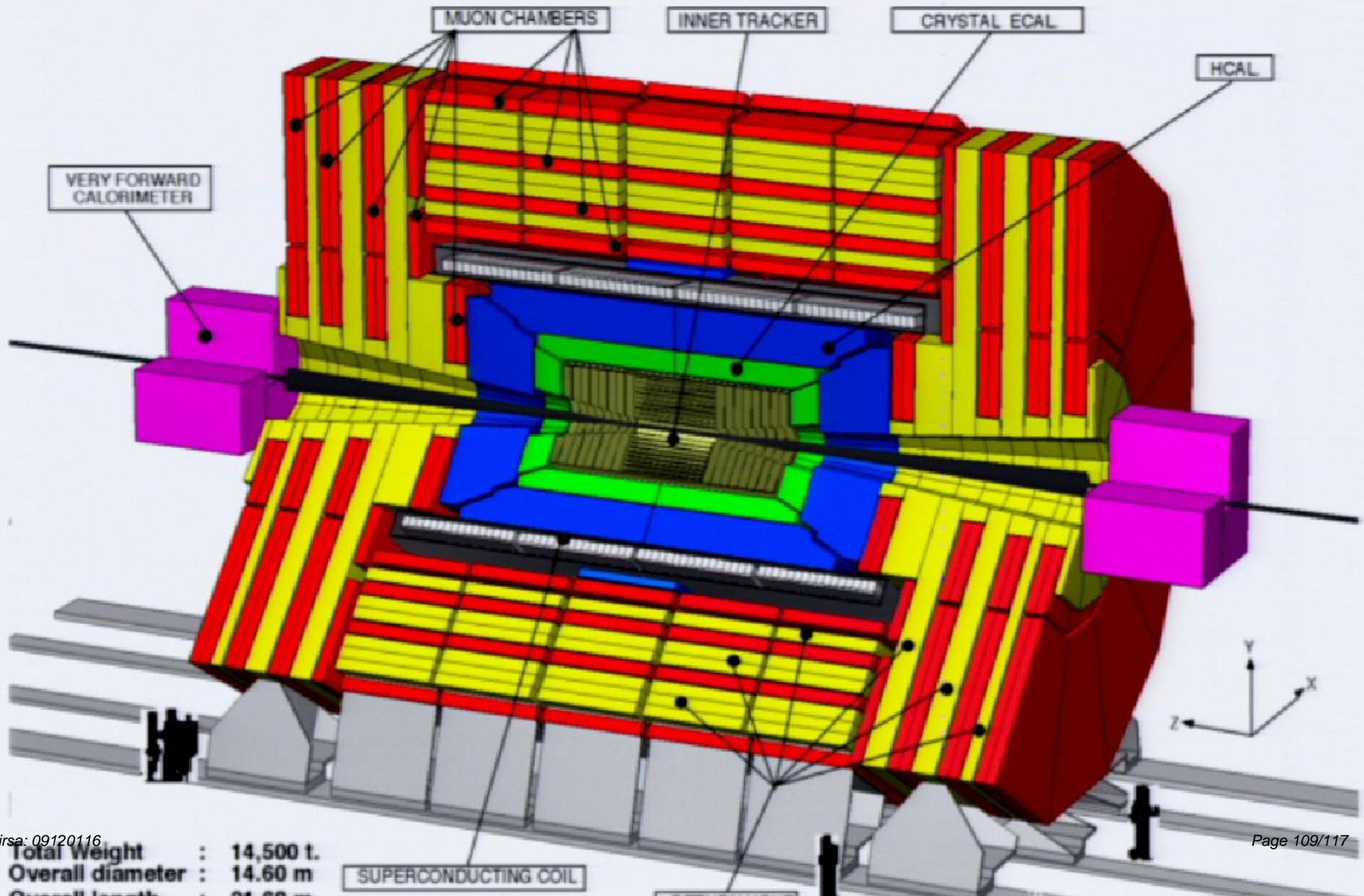
November  
30

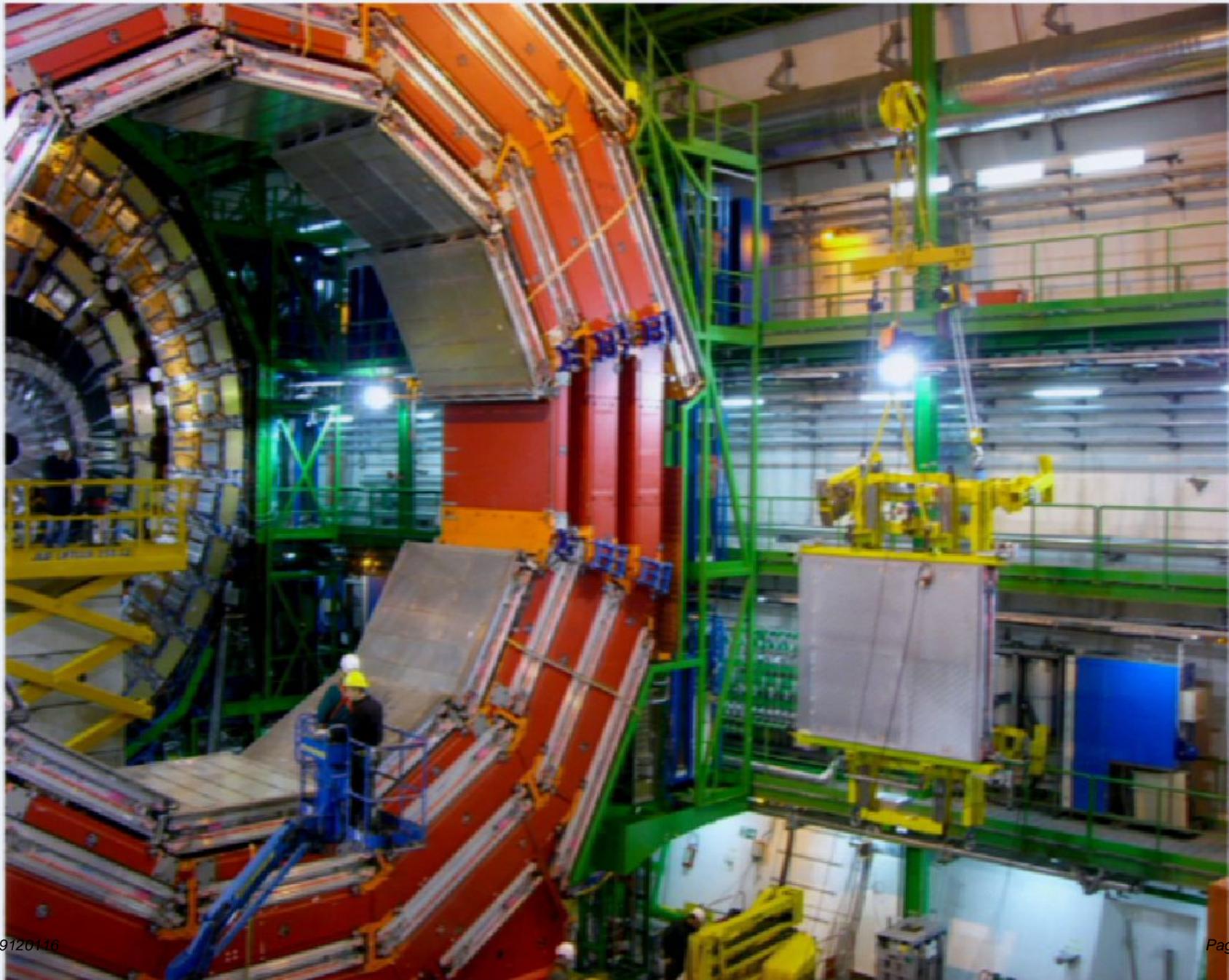
Pirsa: 09120116  
2.36 TeV





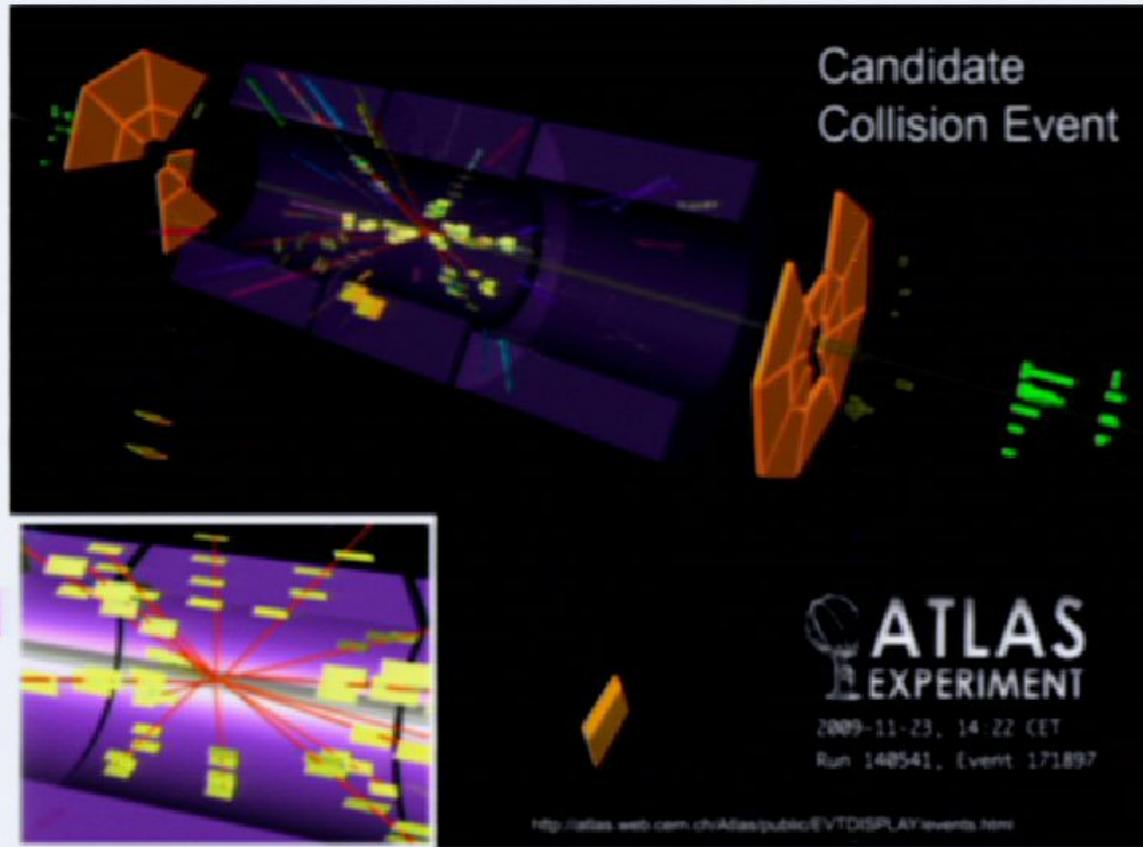
# A Compact Solenoidal Detector for LHC





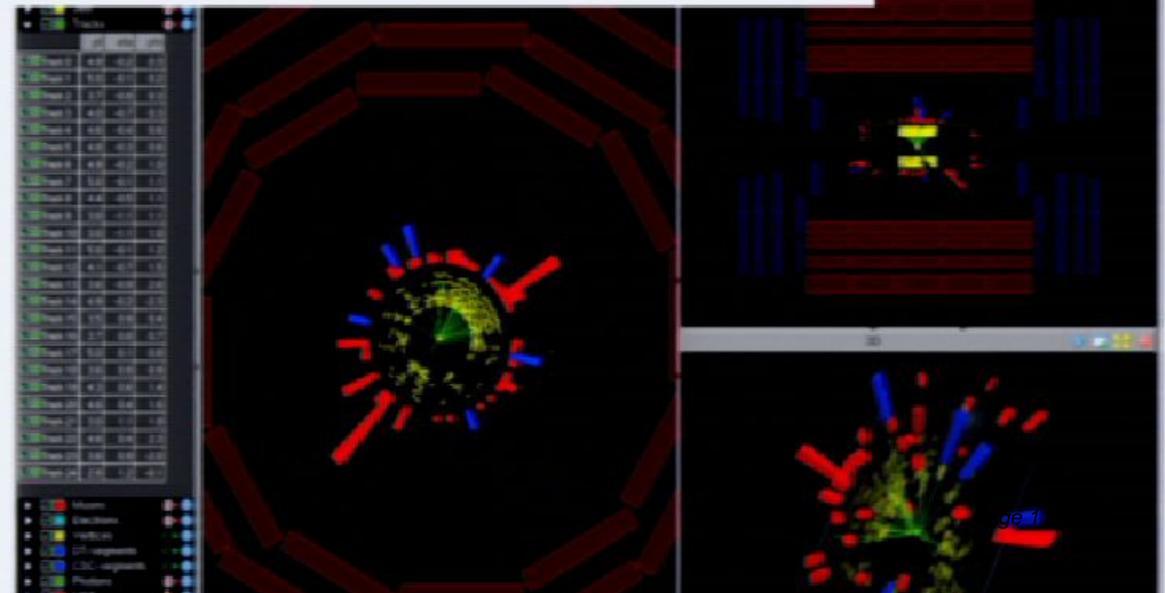
November  
23

First  
collisions in  
ATLAS and  
CMS!



November  
30

Pirsa: 09120116  
2.36 TeV



We will search for top  
and for the truth.

We look forward to many  
surprising and profound  
discoveries.



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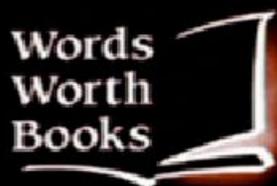
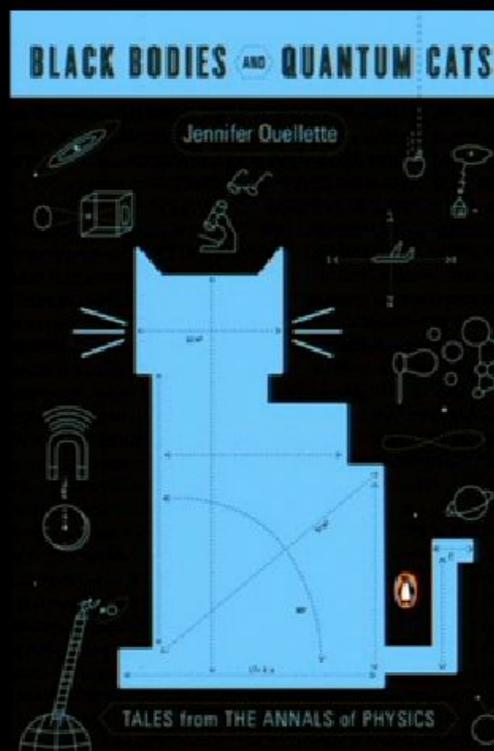


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# 750215



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