Chapter 8: Experiment

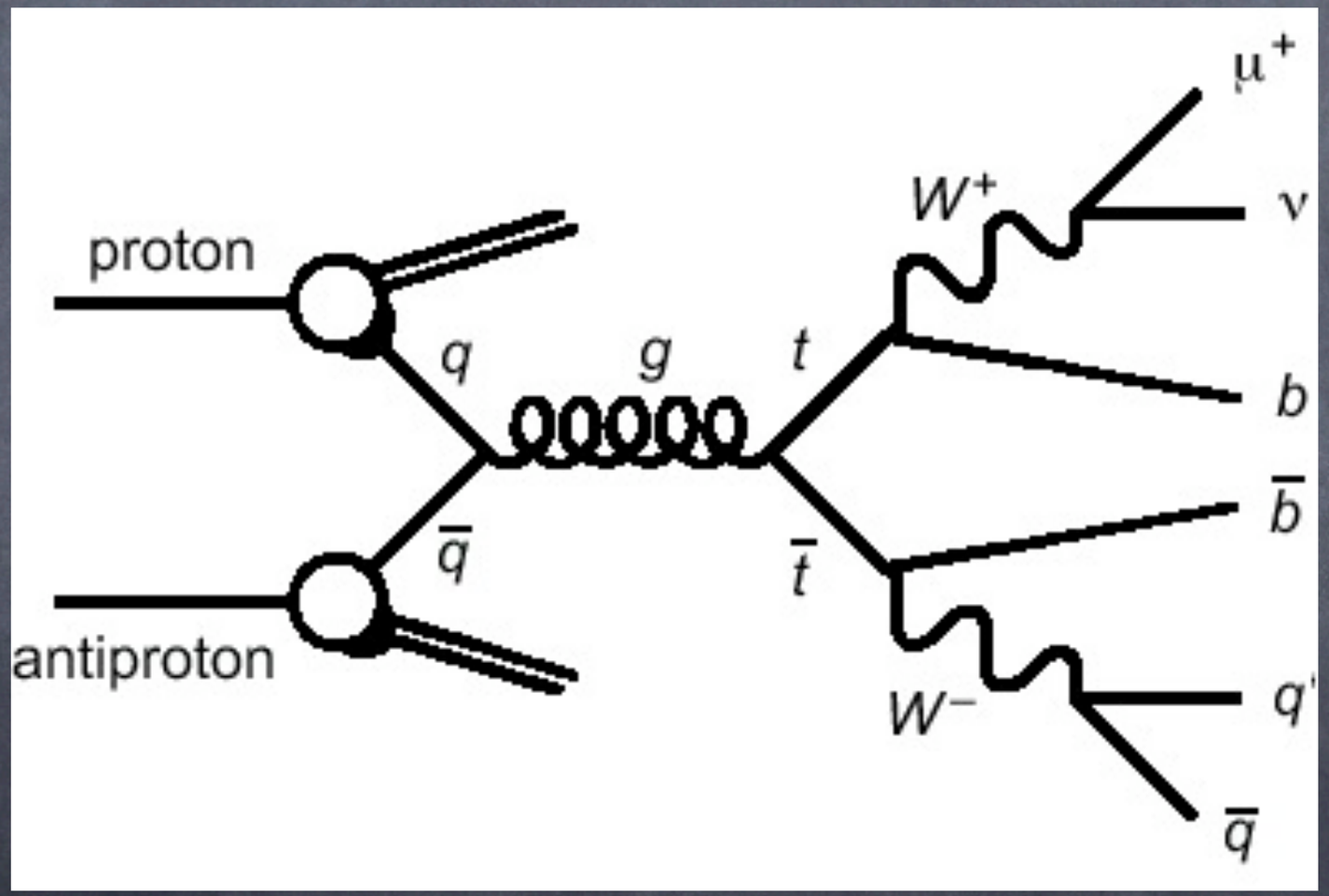
Fermilab

Fermilab

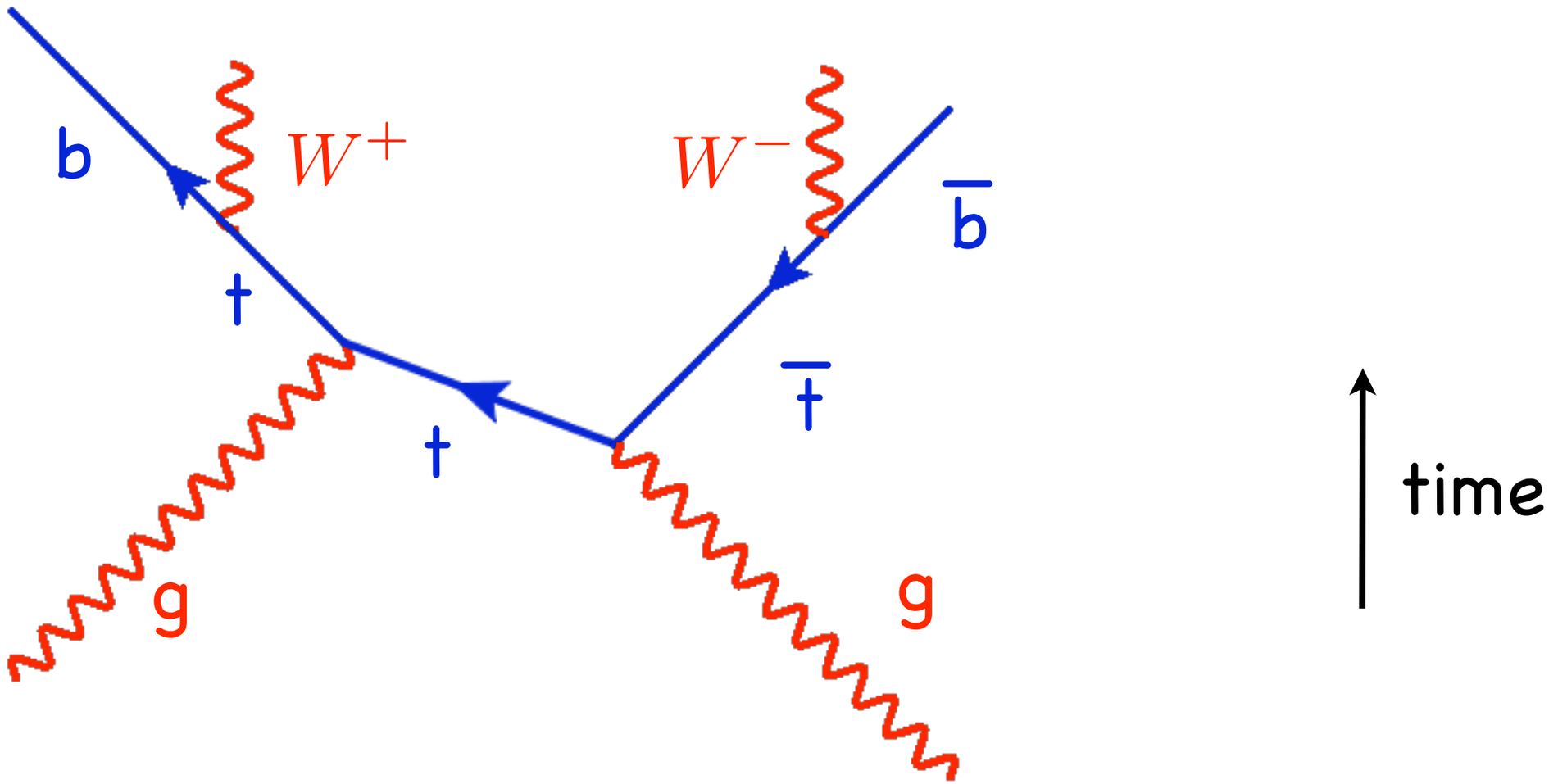
Fermilab CDF

Fermilab: D0

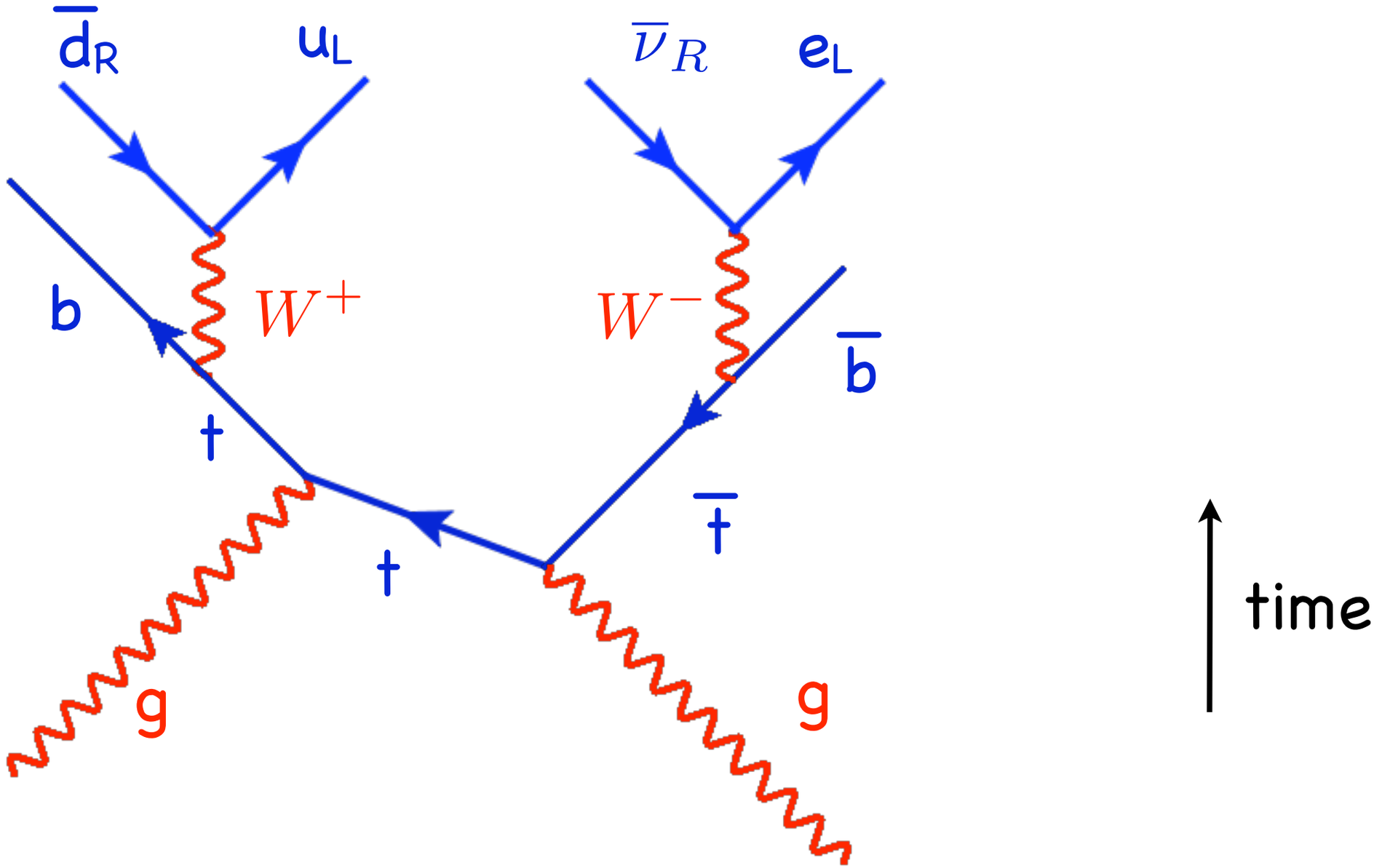
top quark production



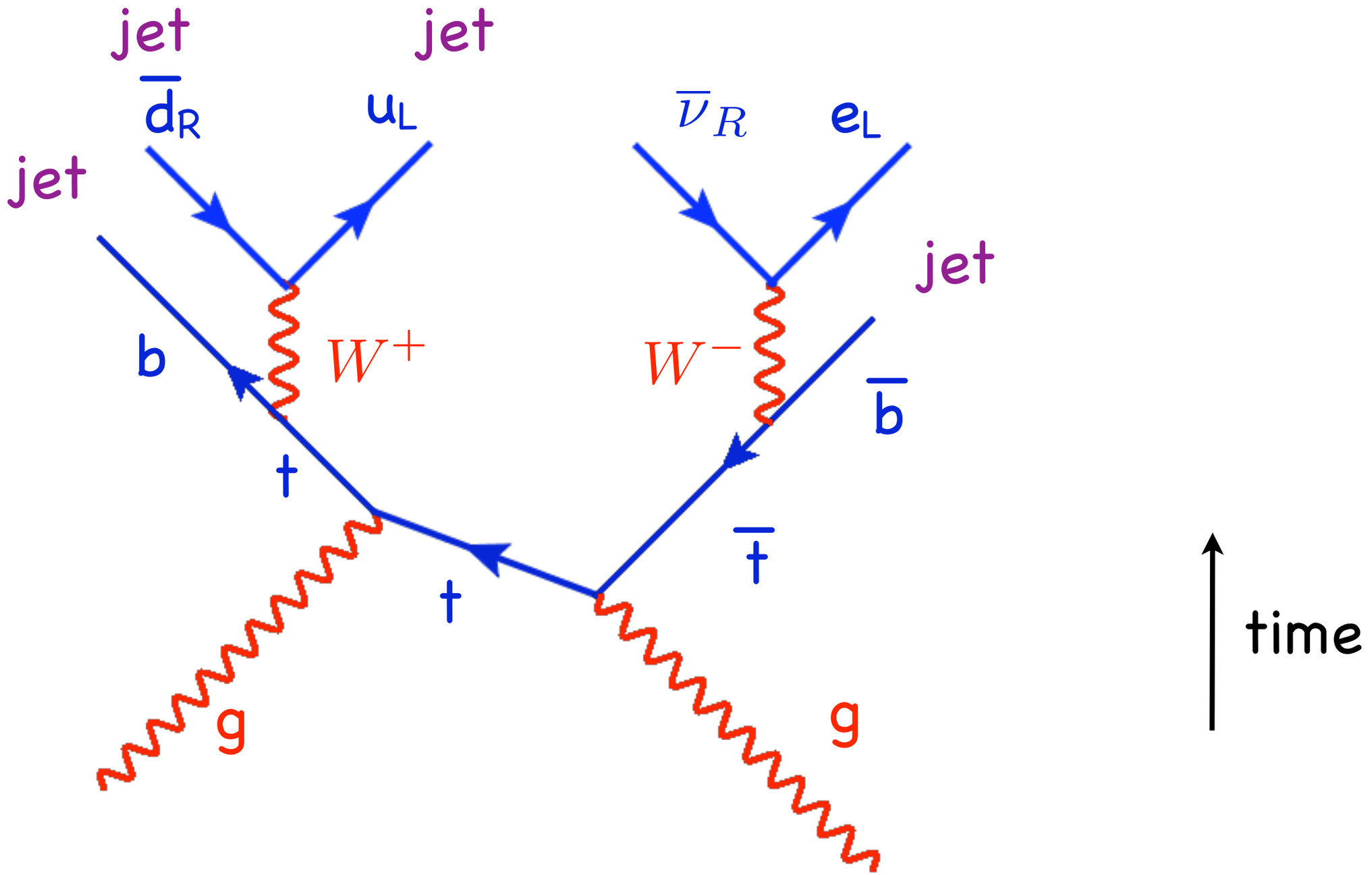
Top Quarks



Top Quarks

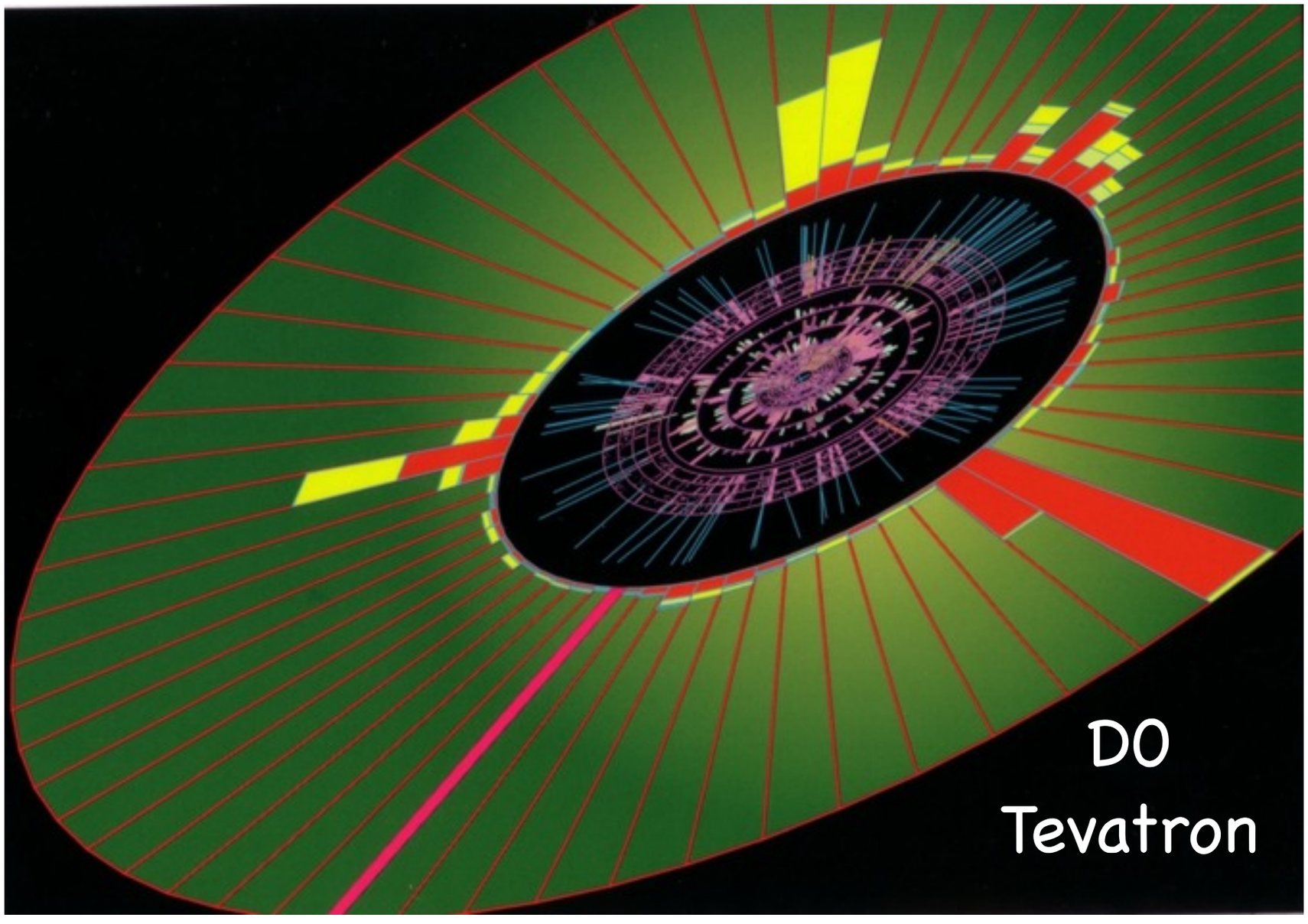

$\overline{d}_R$
u_L
$\overline{\nu}_R$
e_L
b
W^+
W^-
$\overline{b}$
t
$\overline{t}$
t
g
g
time

Top Quarks


jet
jet
$\overline{d}_R$
u_L
jet
b
W^+
t
t
g
$\overline{\nu}_R$
e_L
jet
W^-
$\overline{b}$
$\overline{t}$
g
time

Top Quarks

jet jet jet



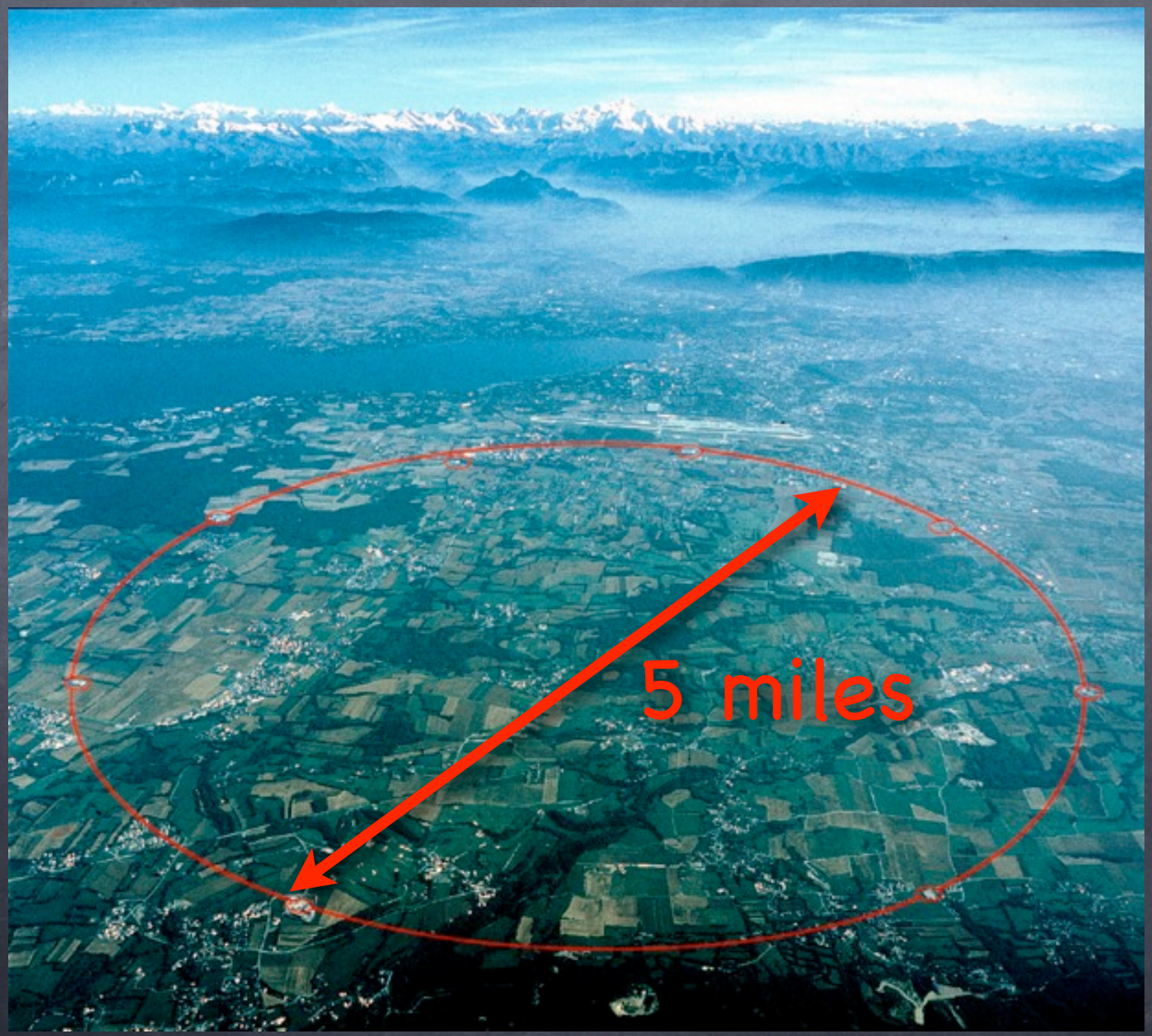
jet

e_L

missing momentum

CERN and LEP

CERN and LEP



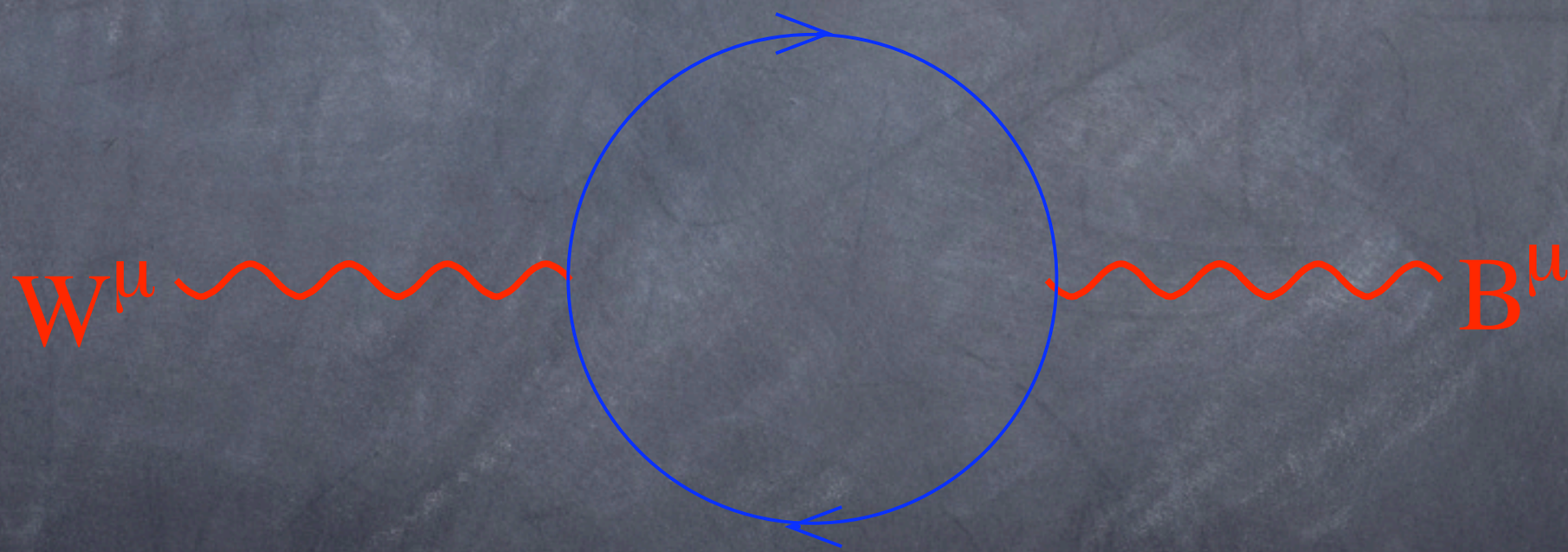
Rubbia and Van der Meer

1984 Nobel Prize

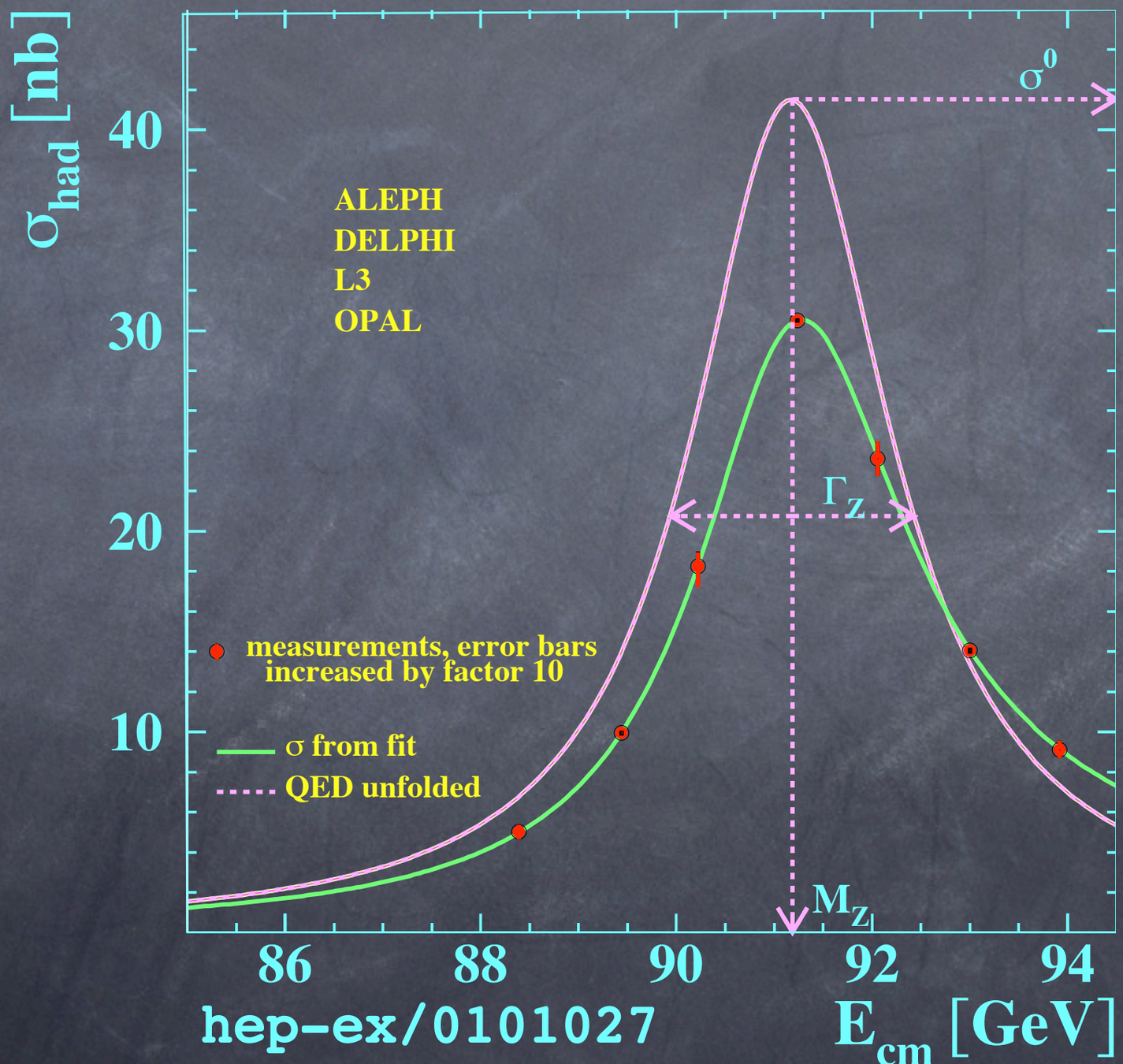
Tim Berners-Lee

inventor of HTML and WWW

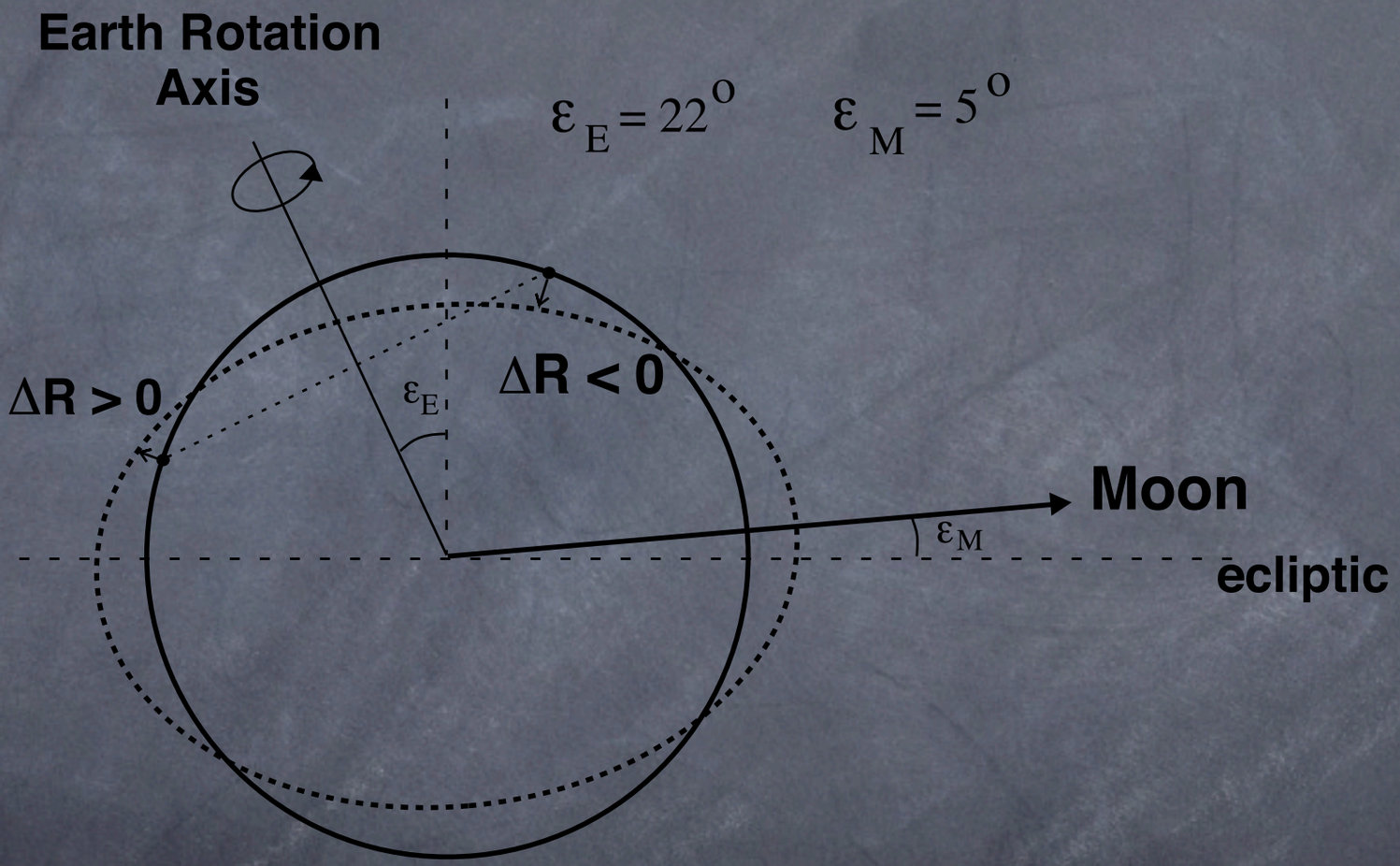
Precision Measurements



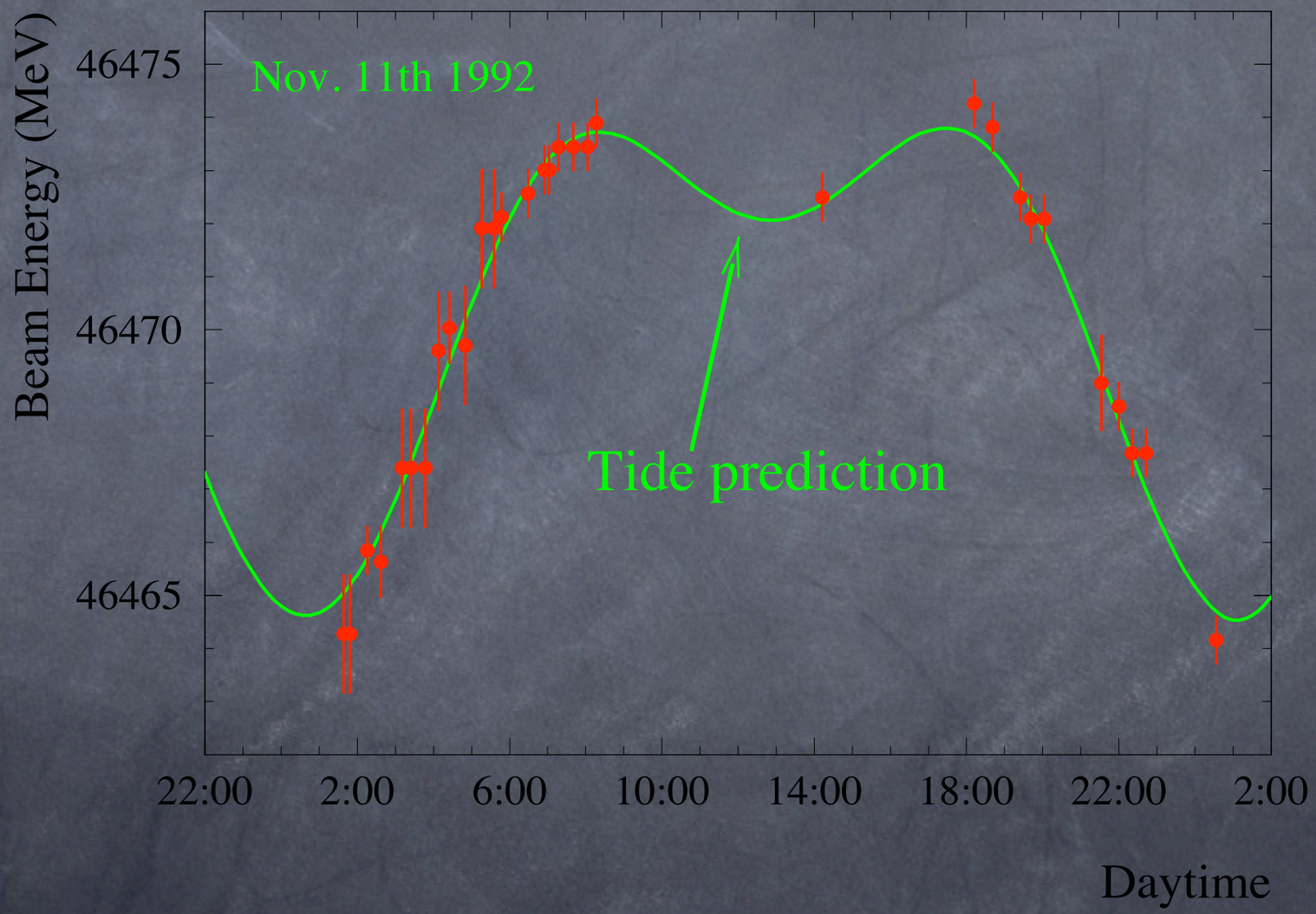
Precision Measurements



Land Tides

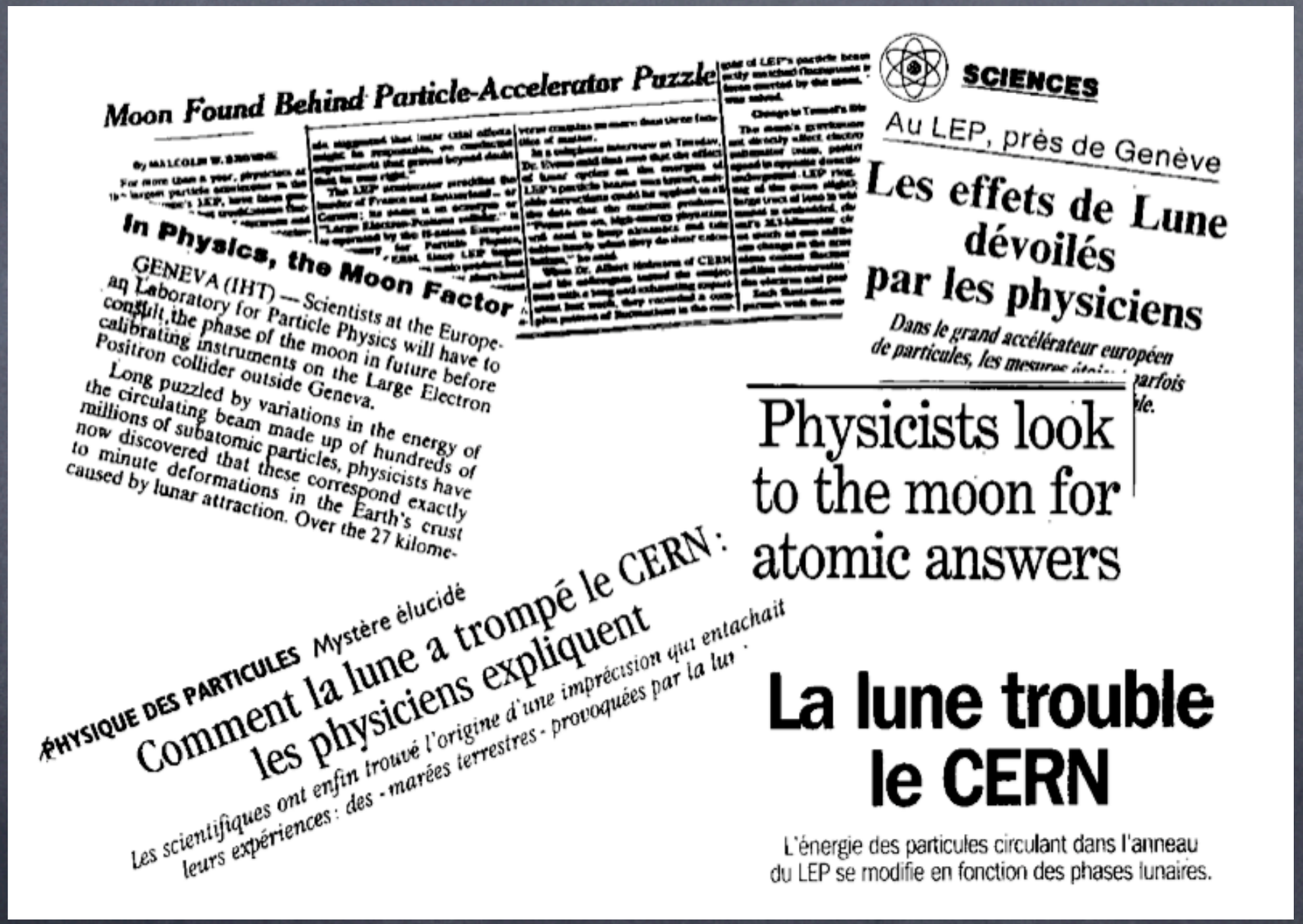

Earth Rotation Axis
$\varepsilon_E = 22^o$
$\varepsilon_M = 5^o$
ΔR > 0
ΔR < 0
ε_E
Moon
ε_M
ecliptic

LEP: Tides



The total strain is 4×10^{-8} ($\Delta C = 1$ mm)

LEP: Moon



Moon Found Behind Particle-Accelerator Puzzle

In Physics, the Moon Factor

GENEVA (IHT) — Scientists at the European Laboratory for Particle Physics will have to consult the phase of the moon in future before calibrating instruments on the Large Electron Positron collider outside Geneva.

Long puzzled by variations in the energy of the circulating beam made up of hundreds of millions of subatomic particles, physicists have now discovered that these correspond exactly to minute deformations in the Earth's crust caused by lunar attraction. Over the 27 kilome-

SCIENCES

Au LEP, près de Genève

Les effets de Lune dévoilés par les physiciens

Dans le grand accélérateur européen de particules, les mesures

Physicists look to the moon for atomic answers

PHYSIQUE DES PARTICULES Mystère élucidé

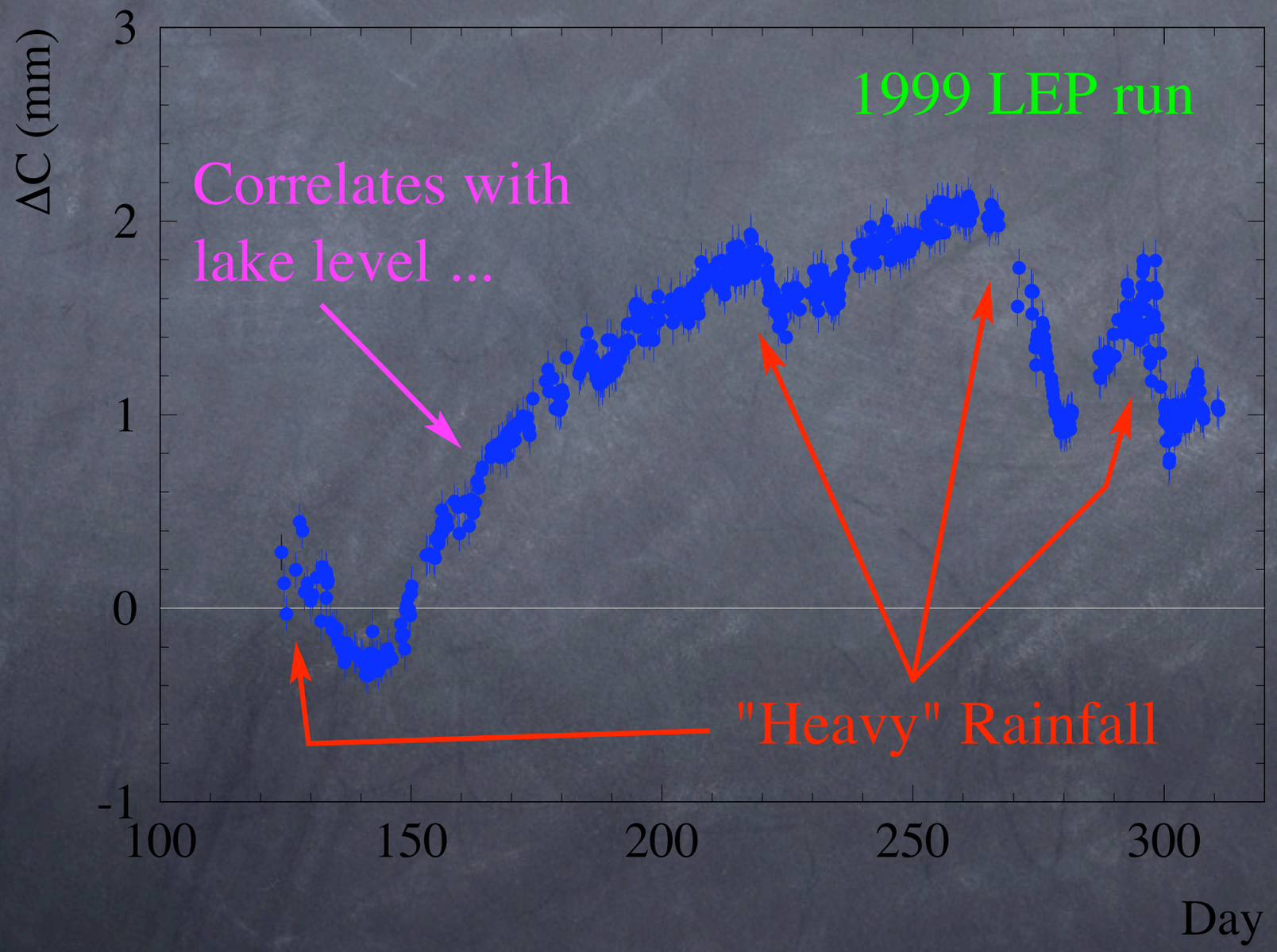
Comment la lune a trompé le CERN: les physiciens expliquent

Les scientifiques ont enfin trouvé l'origine d'une imprécision qui entachait leurs expériences: des - marées terrestres - provoquées par la lu

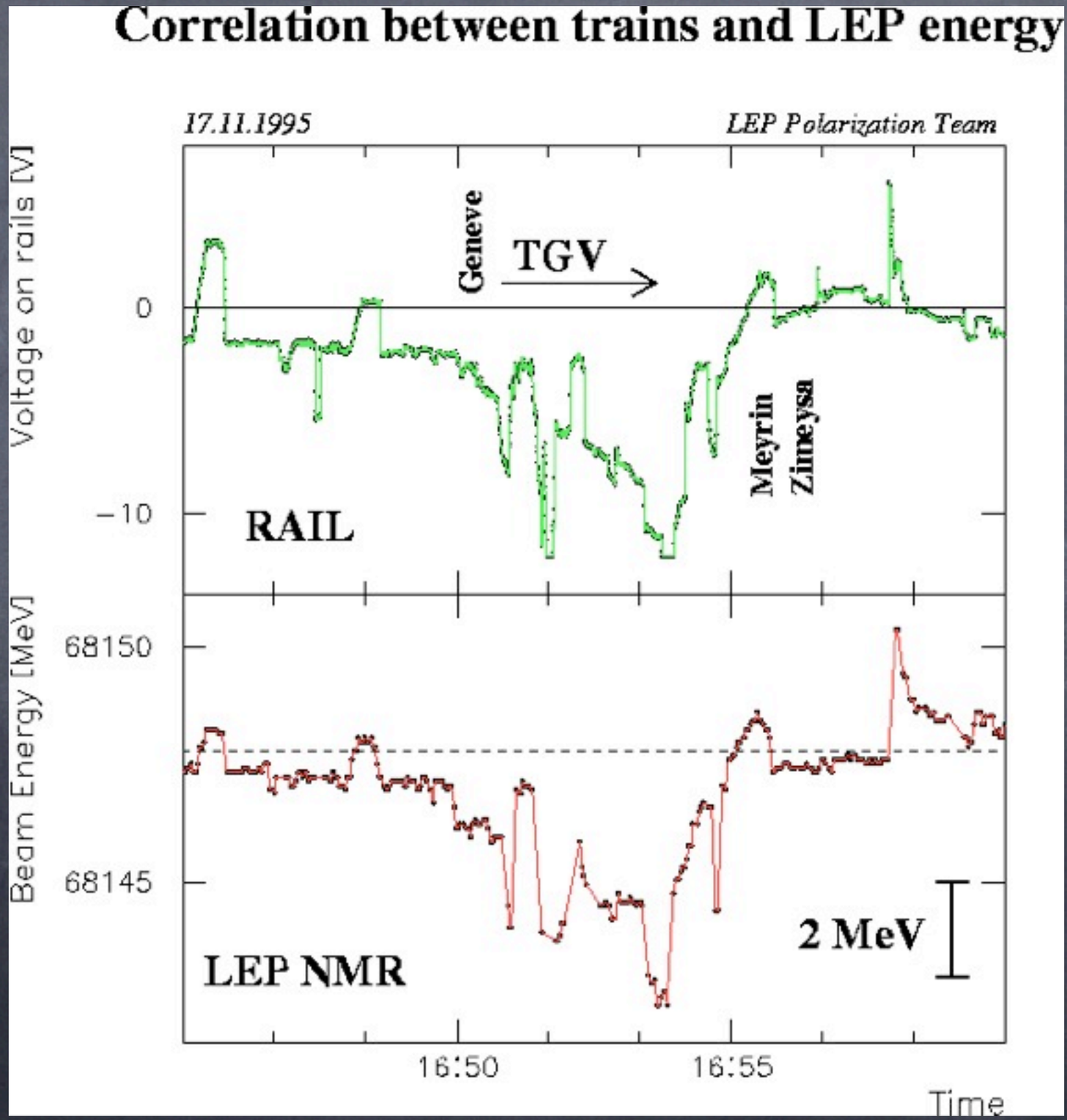
La lune trouble le CERN

L'énergie des particules circulant dans l'anneau du LEP se modifie en fonction des phases lunaires.

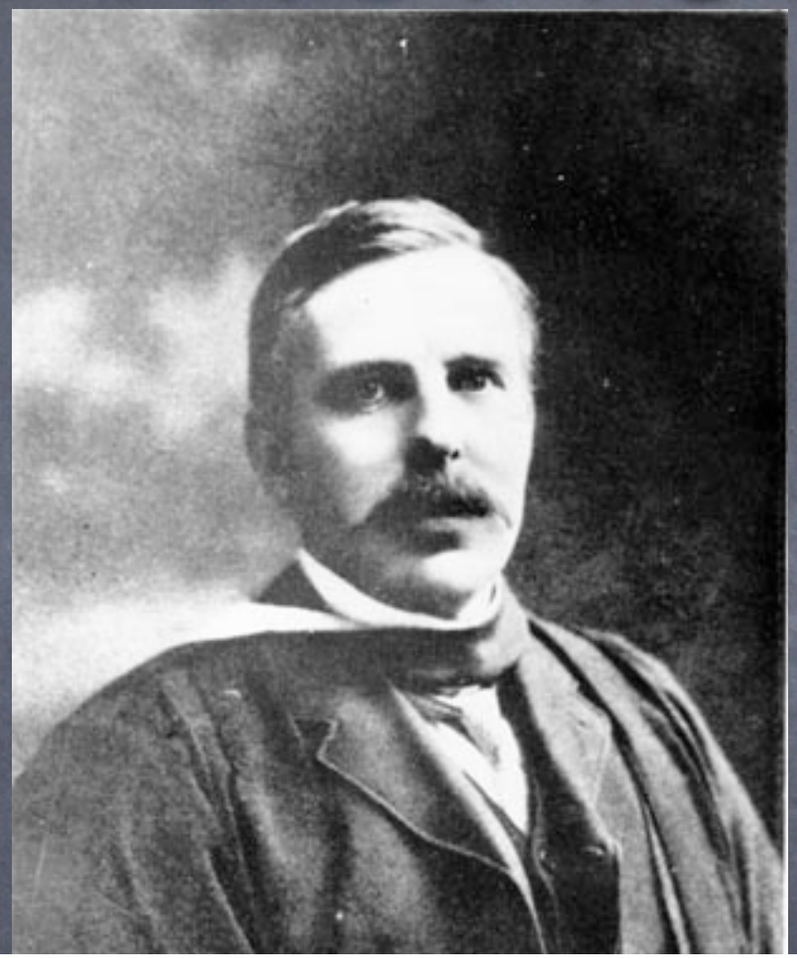
LEP: Rain

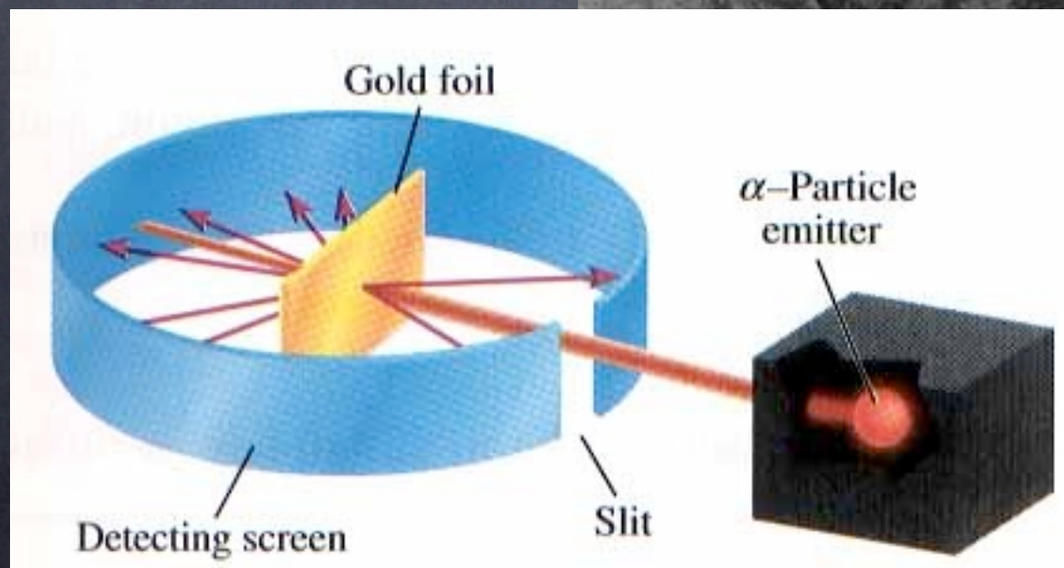

ΔC (mm)
3
2
1
0
-1
100
150
200
250
300
Day
1999 LEP run
Correlates with
lake level ...
"Heavy" Rainfall

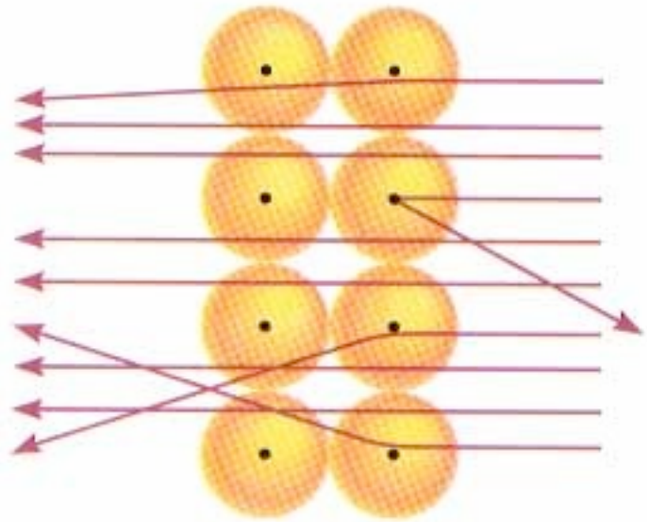
LEP: Trains


Correlation between trains and LEP energy
17.11.1995
LEP Polarization Team
Voltage on rails [V]
0
−10
Geneve
TGV
Meyrin
Zimeysa
RAIL
Beam Energy [MeV]
68150
68145
2 MeV
LEP NMR
16:50
16:55
Time

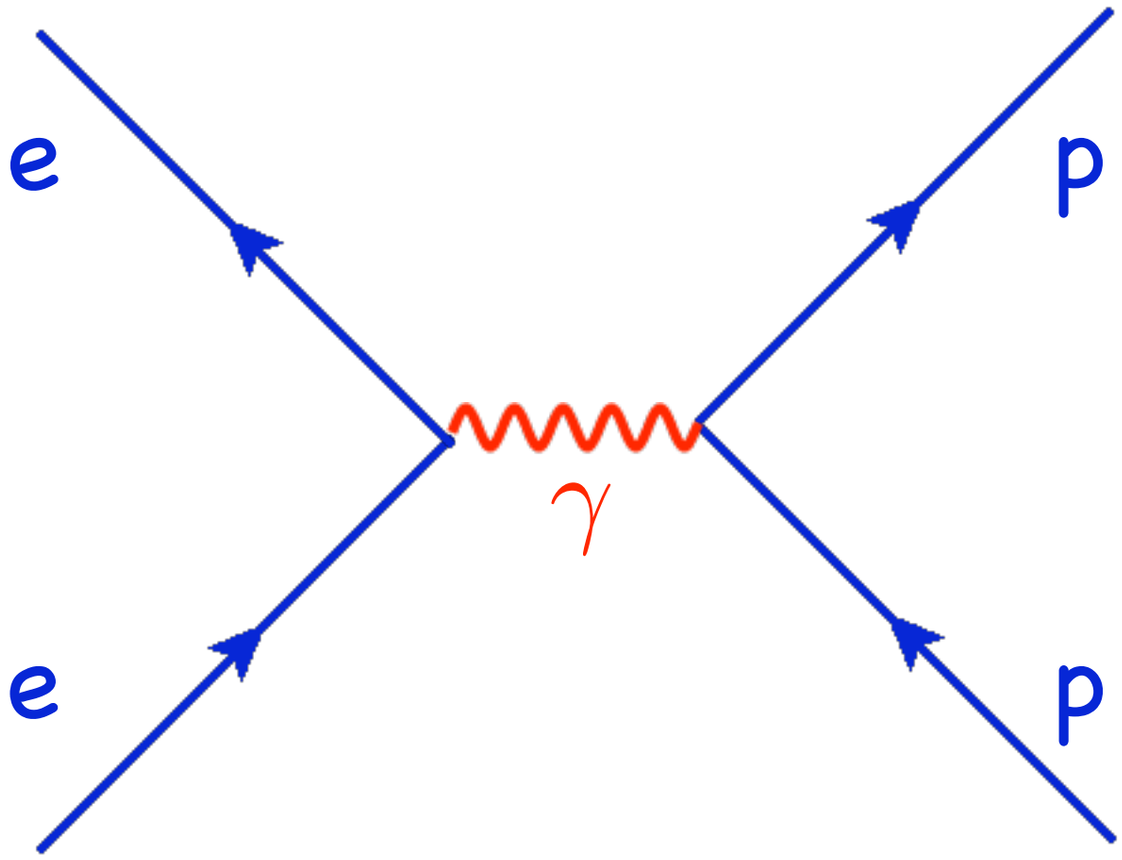
Rutherford





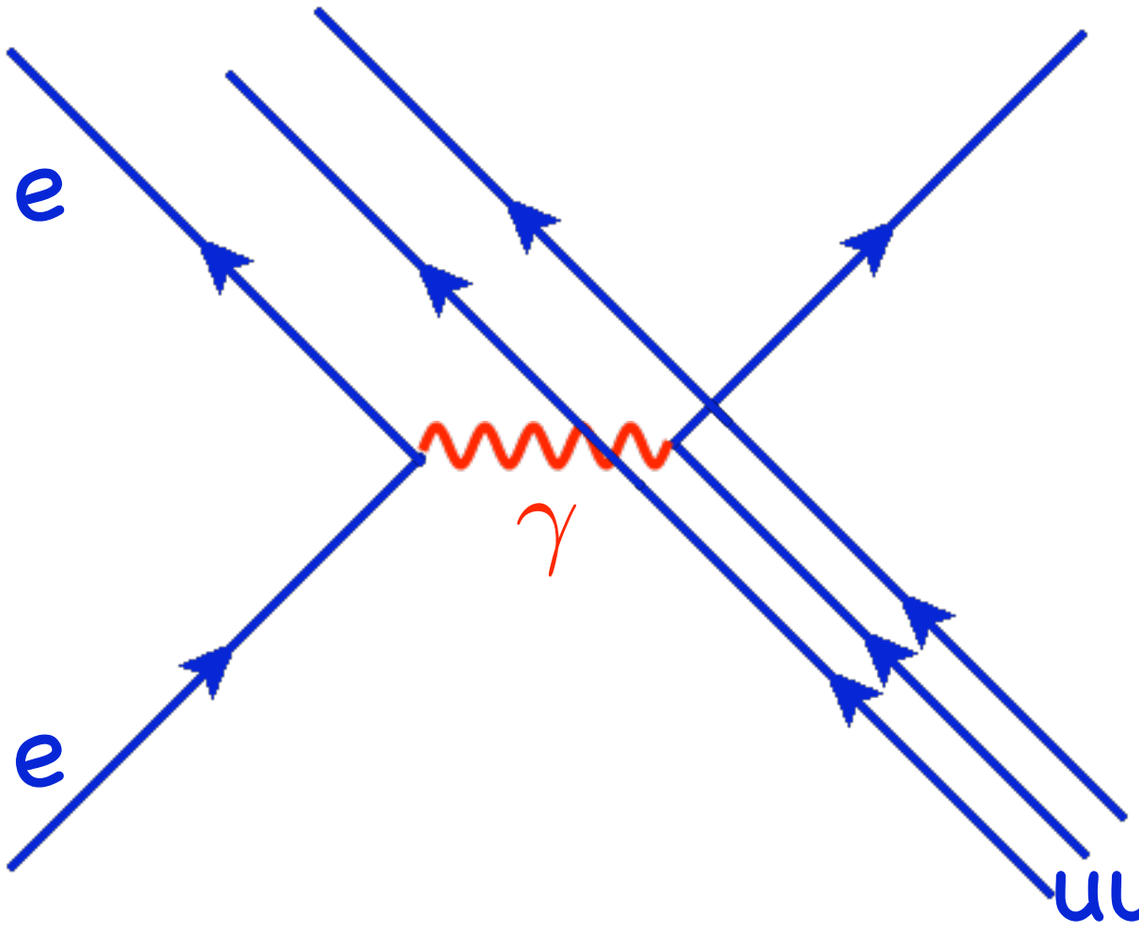


Low Energy



low energy photon cannot
resolve proton structure

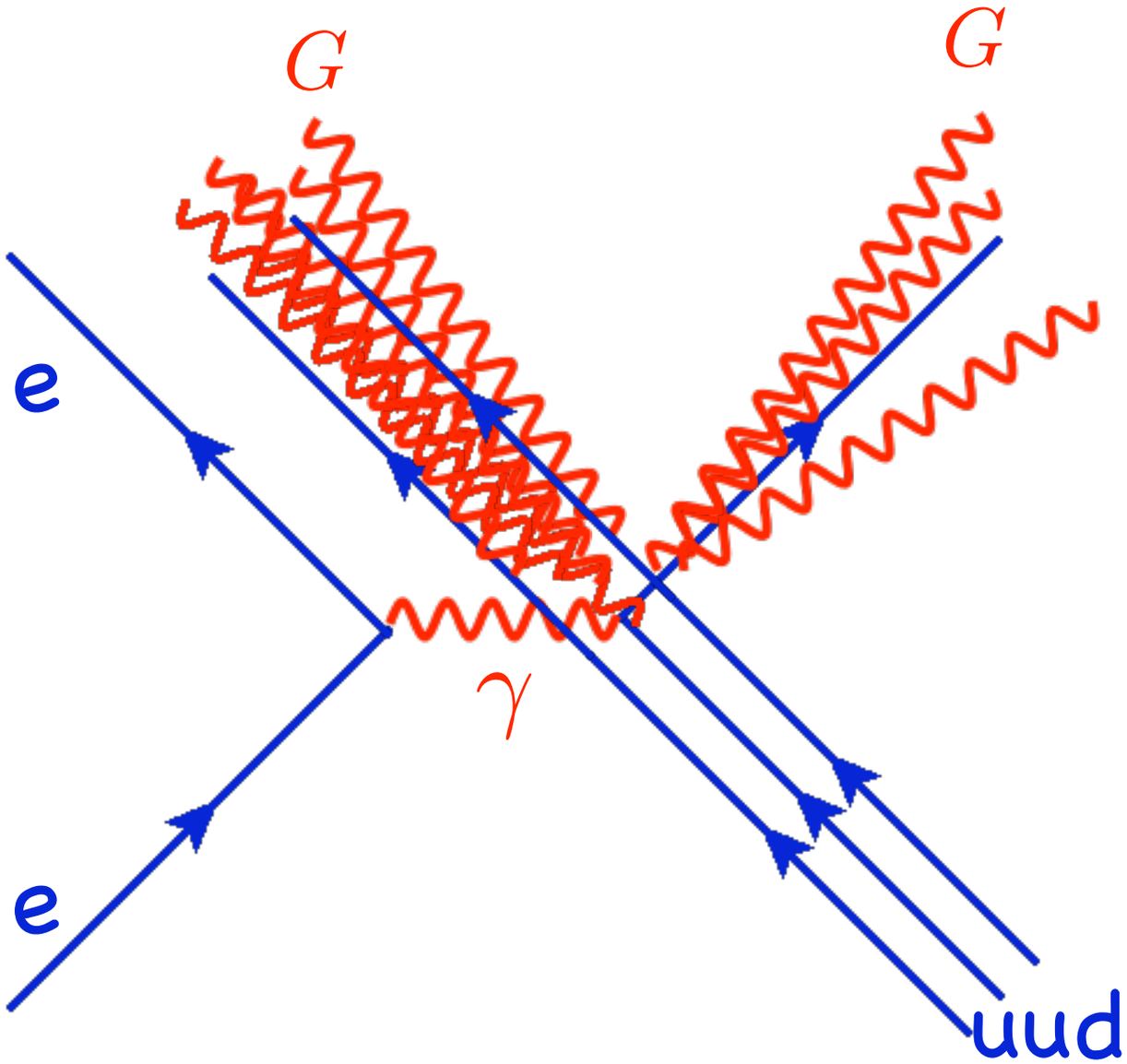
SLAC–MIT Experiment



1968

high energy photon resolves quarks

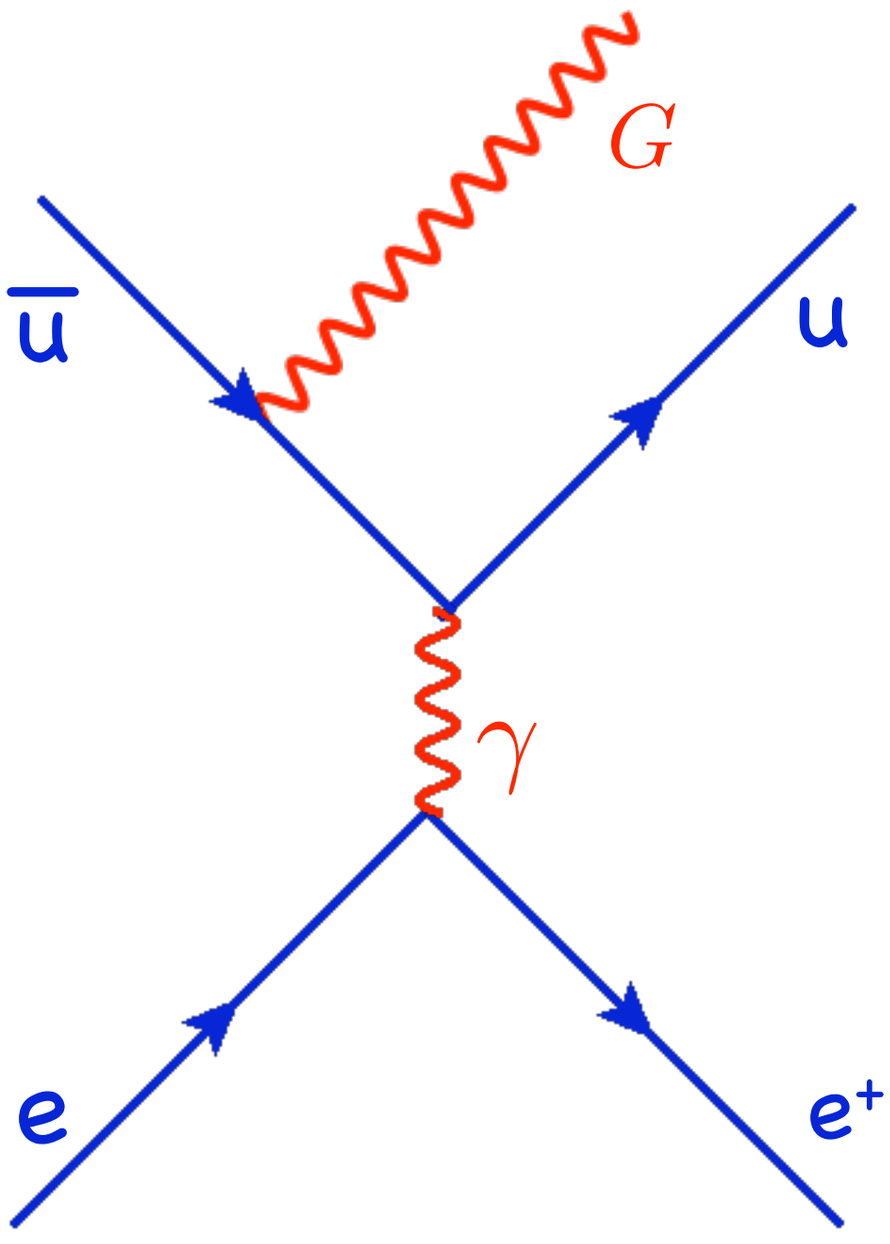
SLAC-MIT Experiment



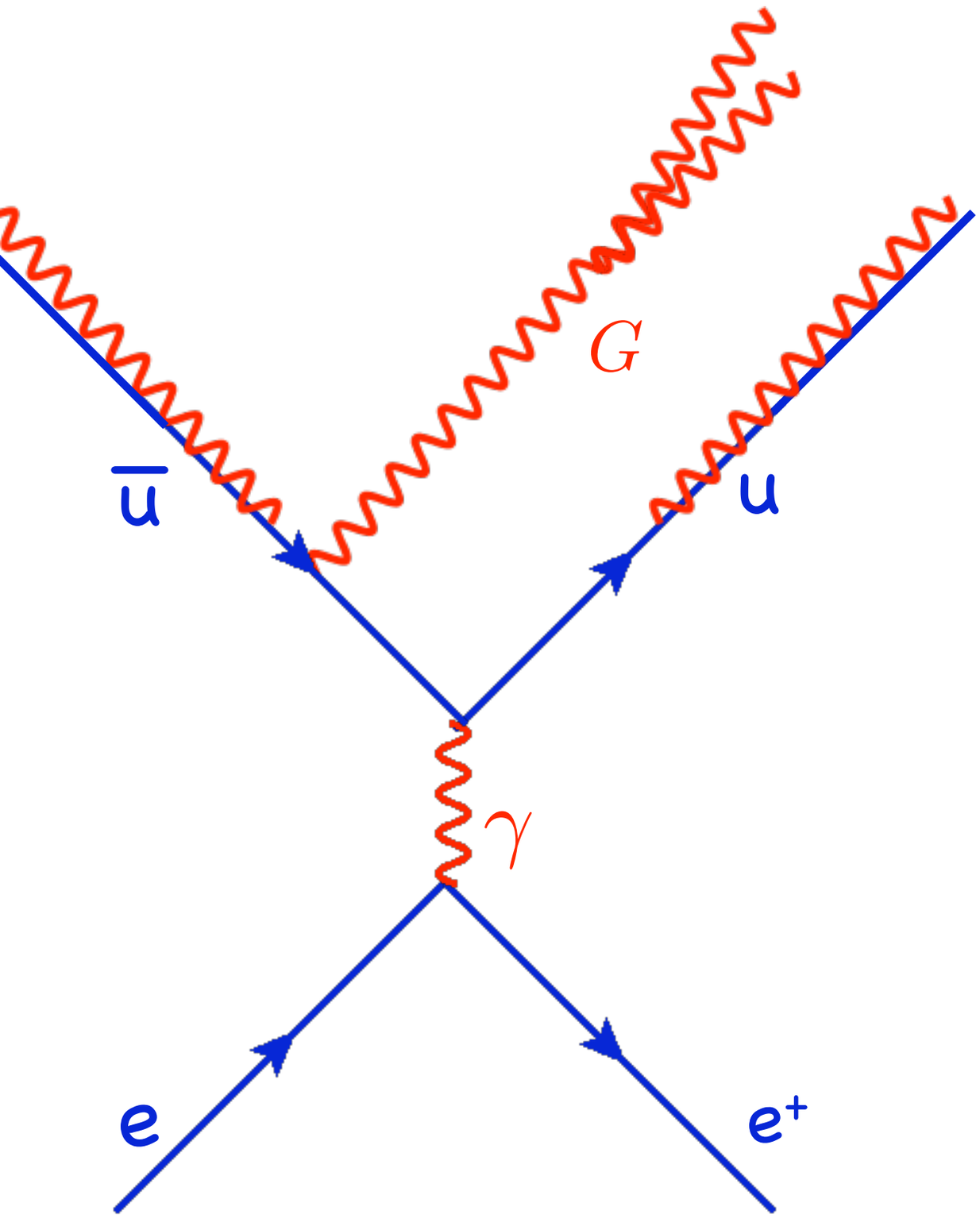
1968

high energy photon resolves quarks

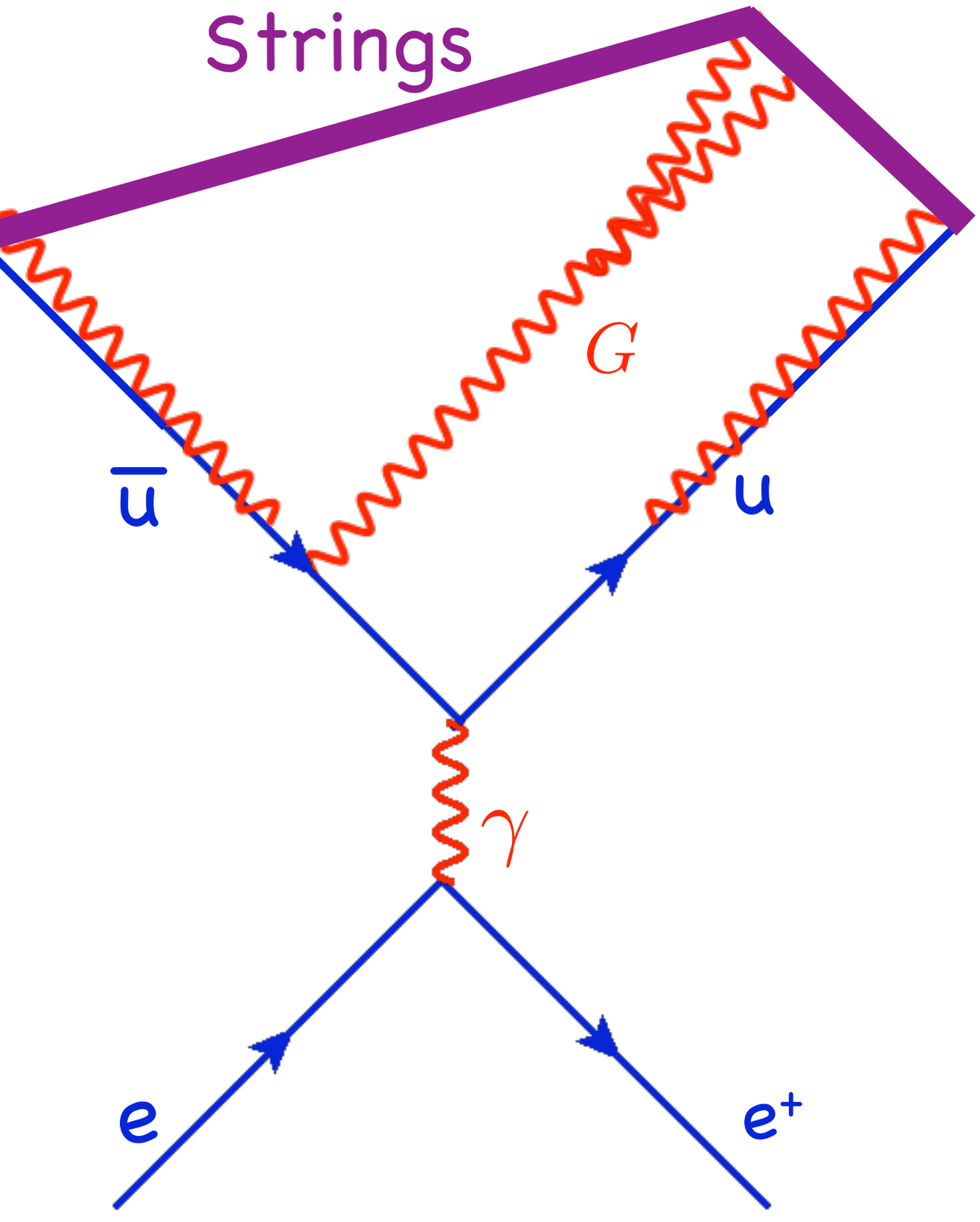
Jets



Jets

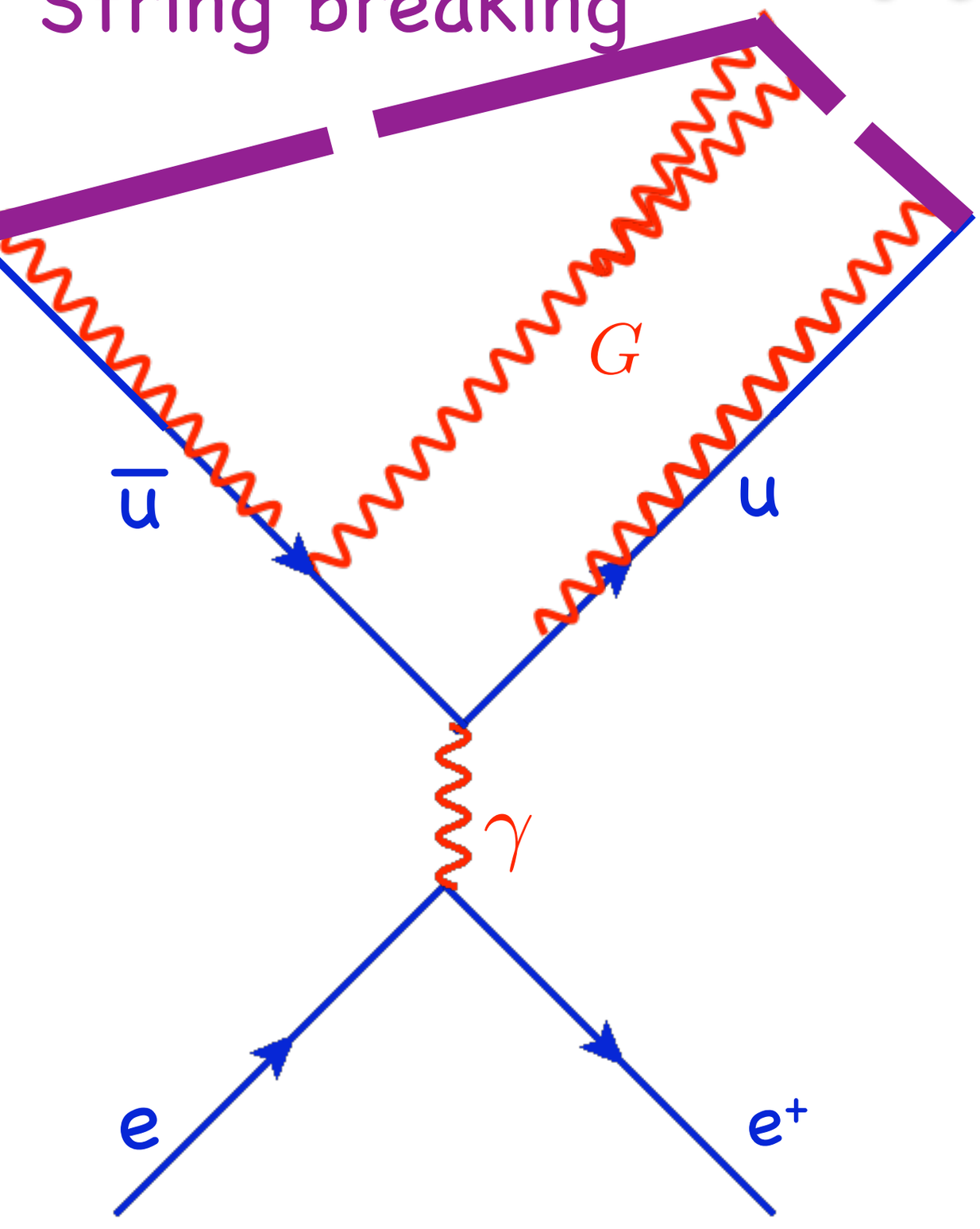


Jets

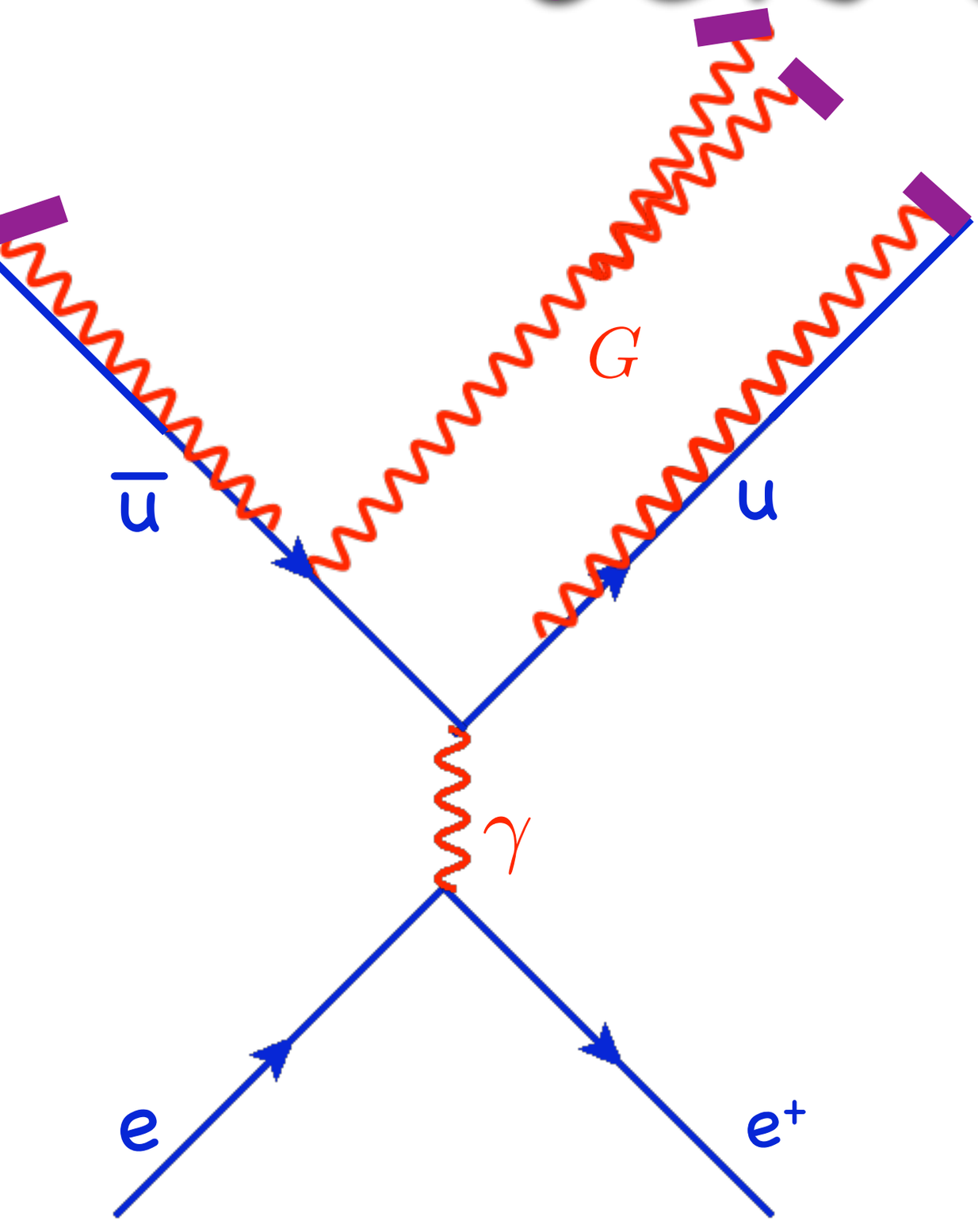


Hadrons

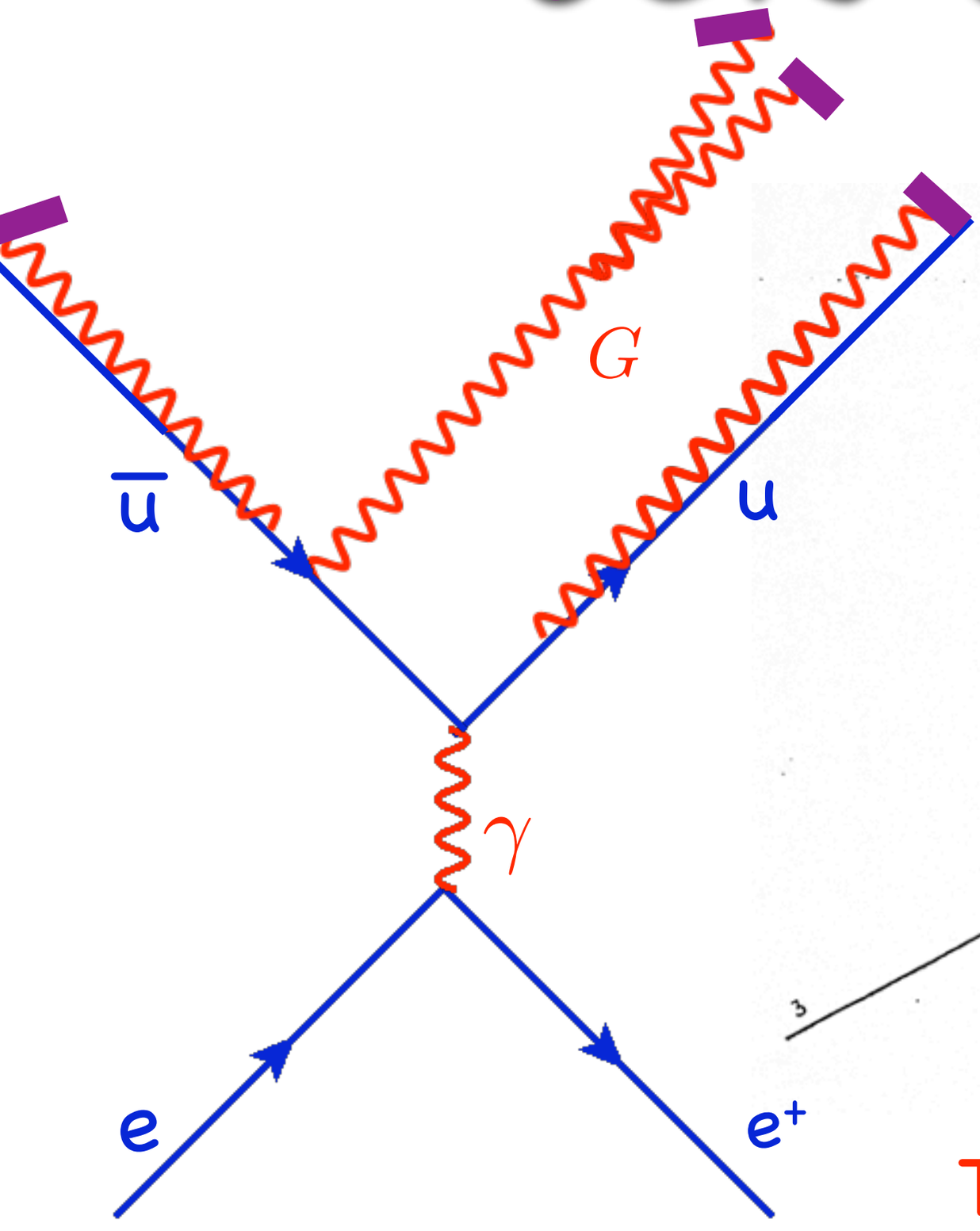
String breaking

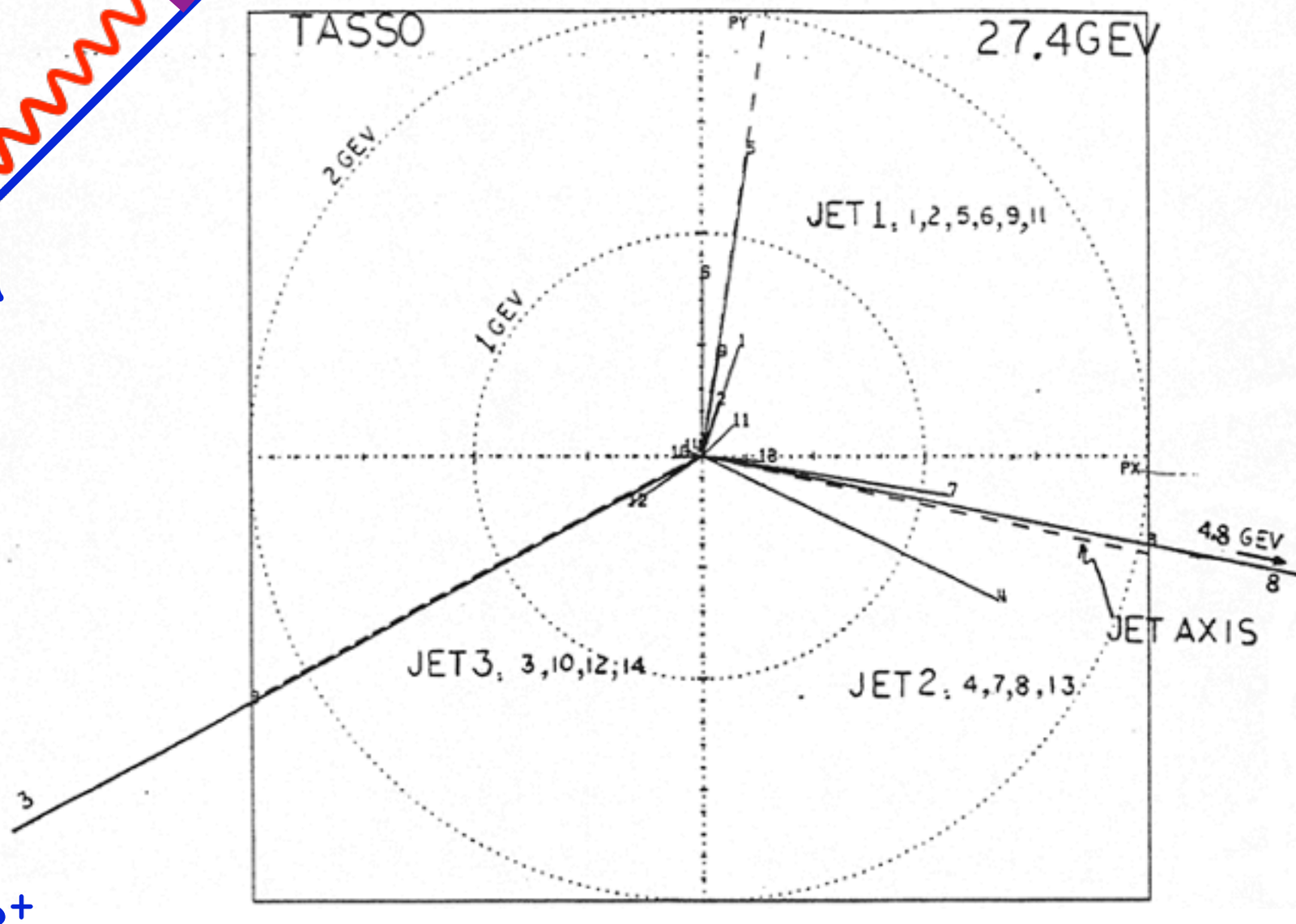


Jets of Hadrons



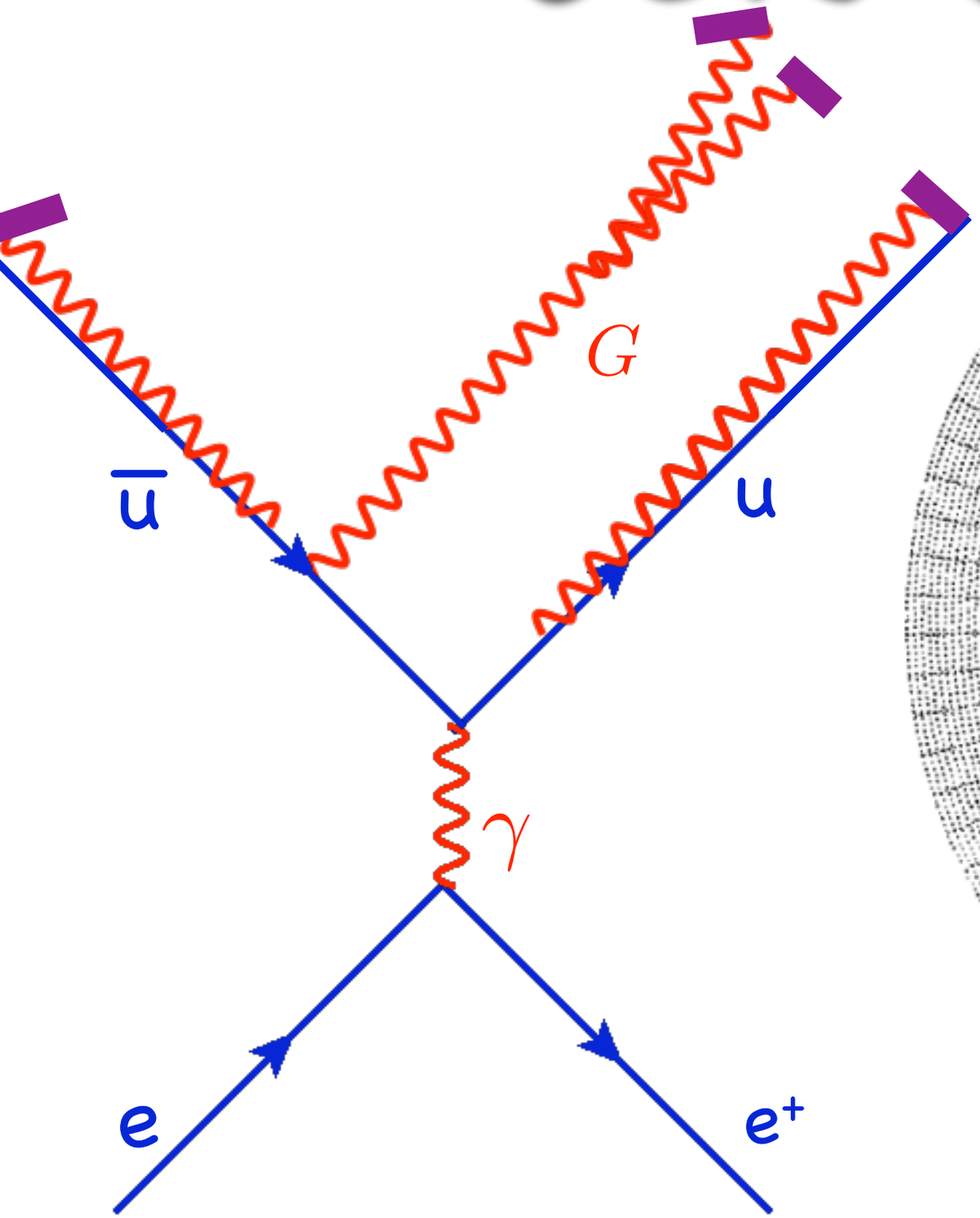
Jets of Hadrons

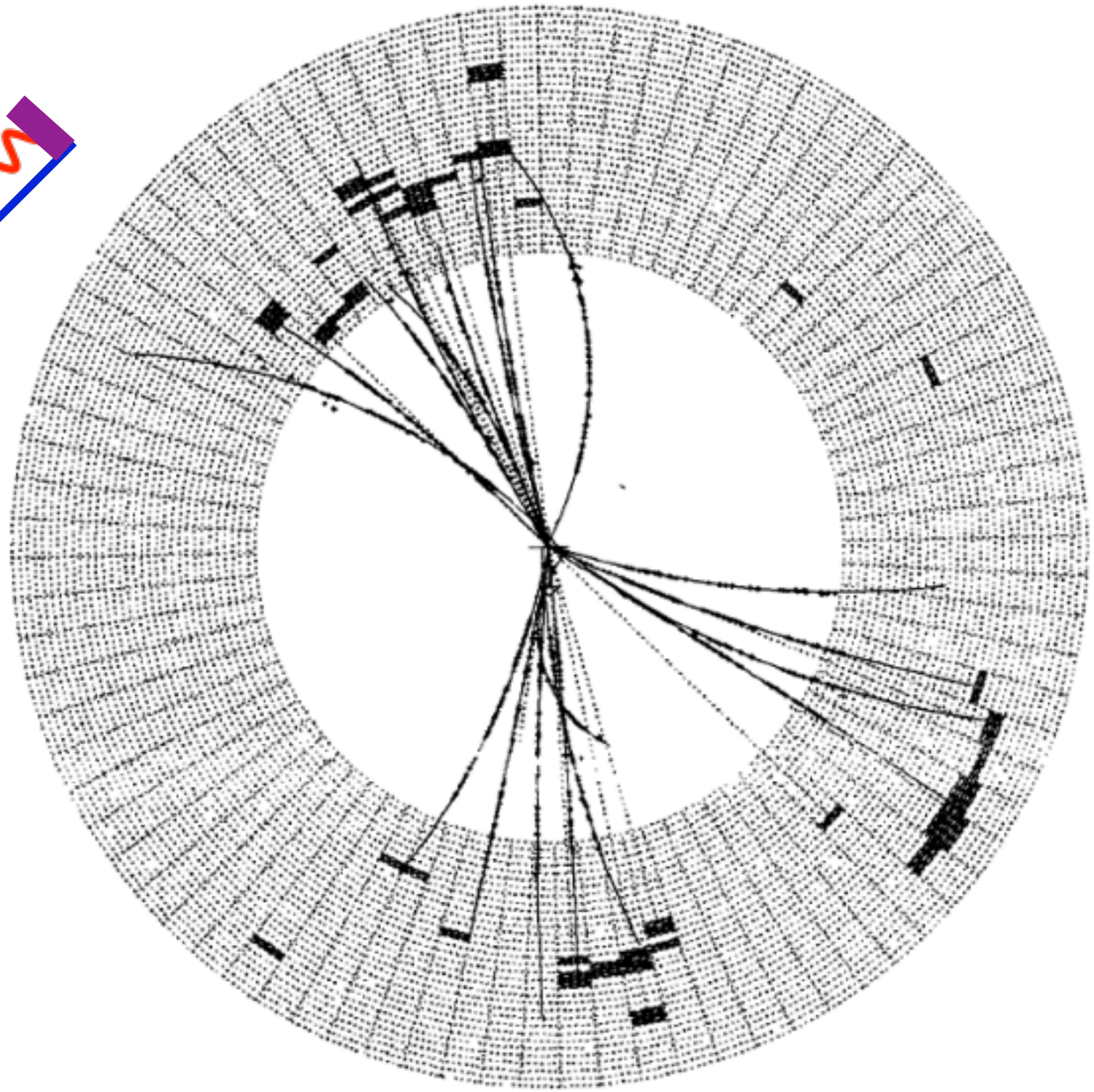




TASSO detector at PETRA

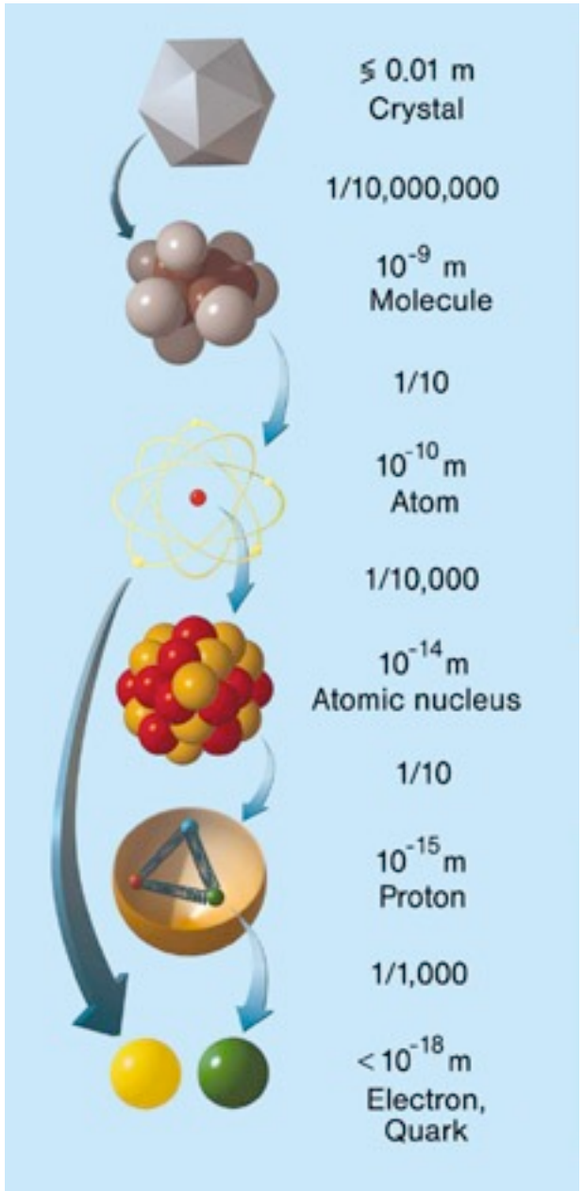
Jets of Hadrons





JADE detector at PETRA

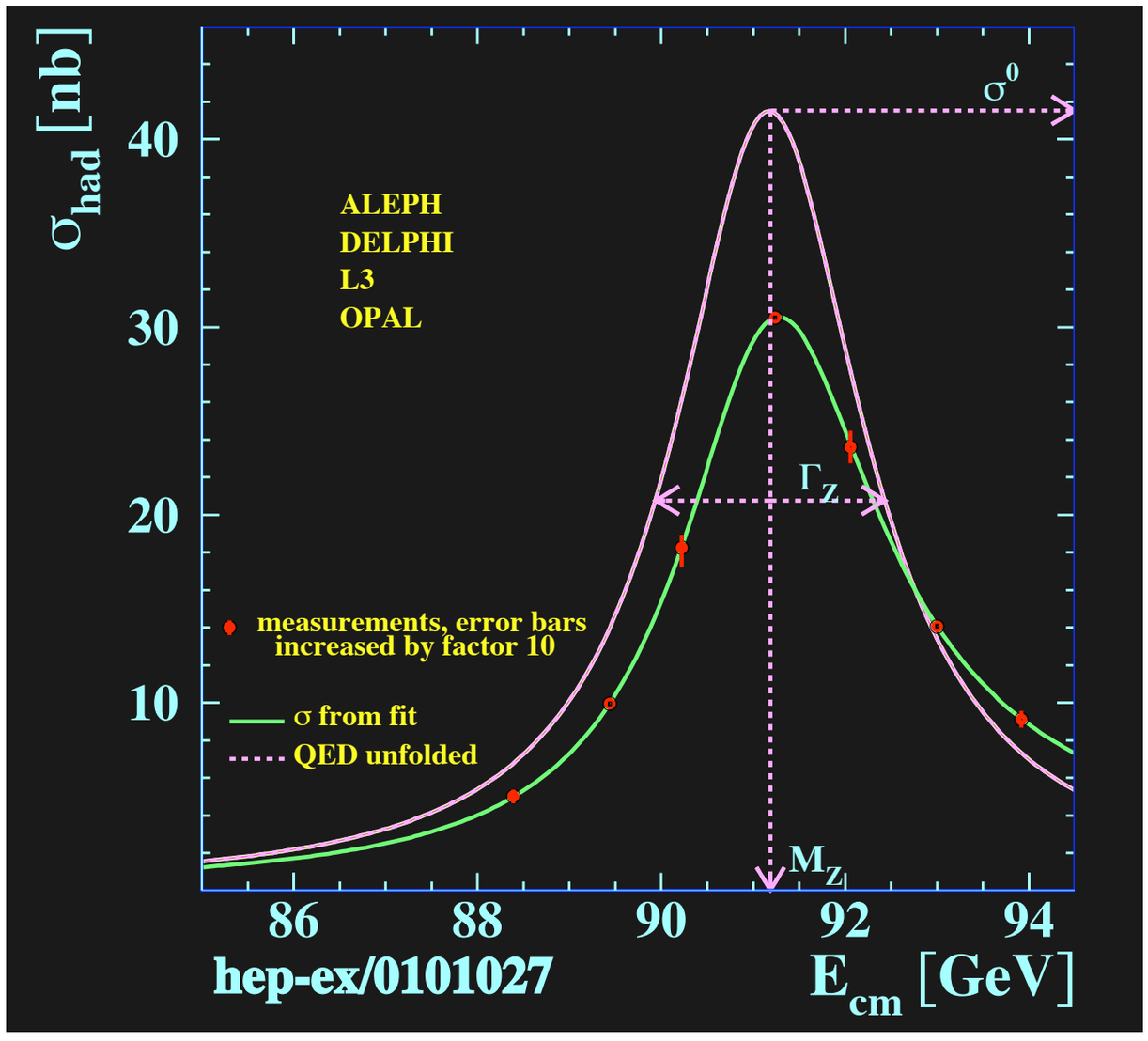
Weak Scale



$$\frac{1}{100000000}\,A$$

250 GeV

SM Weak Interactions



- ☑ consistent with all precision data
- fine-tuned to 1 part in 10^{30}
- must be incomplete

Phenomenology

proton-proton collisions produce
mainly lots of hadrons

Garden Variety Hadrons

particle	mass	main decay	lifetime
π^0	$135\,\mathrm{MeV}$	$\to \gamma\,\gamma$	$8 \times 10^{-17}\,\mathrm{s}$
$\pi^\pm$	$140\,\mathrm{MeV}$	$\to \mu\,\nu_\mu$	$3 \times 10^{-8}\,\mathrm{s}$
$K^\pm$	$494\,\mathrm{MeV}$	$\to \mu\,\nu_\mu$	$10^{-8}\,\mathrm{s}$
η	$548\,\mathrm{MeV}$	$\to \gamma\,\gamma$	$5 \times 10^{-19}\,\mathrm{s}$
ρ^0	$775\,\mathrm{MeV}$	$\to \pi\,\pi$	$4 \times 10^{-24}\,\mathrm{s}$
p	$938\,\mathrm{MeV}$	$-$	$> 10^{38}\,\mathrm{s}$
n	$940\,\mathrm{MeV}$	$\to p\,e^-\,\bar{\nu}_e$	$886\,\mathrm{s}$
B^0	$5,280\,\mathrm{MeV}$	$\to K^\pm + \text{ hadrons}$	$2 \times 10^{-12}\,\mathrm{s}$

Cross Sections

events/s = cross section x luminosity

$$\frac{\Delta N}{\Delta t} = \sigma L$$

σ traditionally measured in barns

$$1\,b = 10^{-28}\,\mathrm{m}^2 = 100\,\mathrm{fm}^2$$

typical nuclear cross section

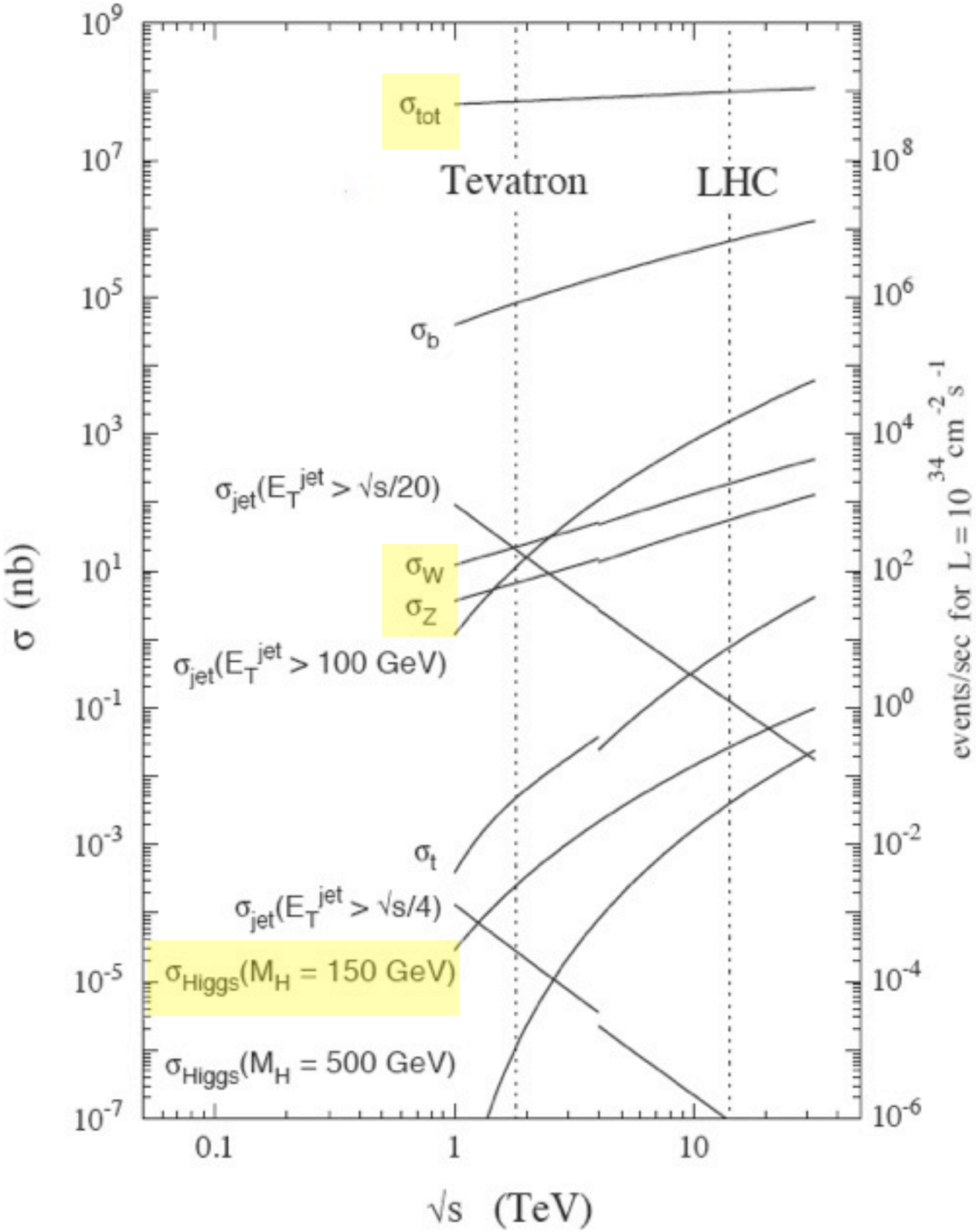
Cross Sections

$$\sigma_{QCD} \sim (1\,\mathrm{fm})^2 = 10^7\,\mathrm{nb}$$

$$\sigma_{weak} \sim \frac{1}{M_W^2} = \frac{1}{(80\,\mathrm{GeV})^2} = 60\,\mathrm{nb}$$

$$\sigma_{higgs} \sim \frac{1}{(16\pi^2 m_{top})^2} = 10^{-3}\,\mathrm{nb}$$

Cross Sections



Travel Distances

$$E = \gamma\, m = 10\,\mathrm{GeV}$$

particle	mass	distance
ρ^0	$775\,\mathrm{MeV}$	$2 \times 10^{-14}\,\mathrm{m}$
η	$548\,\mathrm{MeV}$	$3 \times 10^{-9}\,\mathrm{m}$
π^0	$135\,\mathrm{MeV}$	$2 \times 10^{-6}\mathrm{m}$
B^0	$5,280\,\mathrm{MeV}$	$10^{-3}\,\mathrm{m}$
$K^\pm$	$494\,\mathrm{MeV}$	$60\,\mathrm{m}$
$\pi^\pm$	$140\,\mathrm{MeV}$	$640\,\mathrm{m}$
n	$940\,\mathrm{MeV}$	$3 \times 10^{12}\,\mathrm{m}$
p	$938\,\mathrm{MeV}$	$> 10^{47}\,\mathrm{m}$

Travel Distances

$$E = \gamma\, m = 10\,\mathrm{GeV}$$

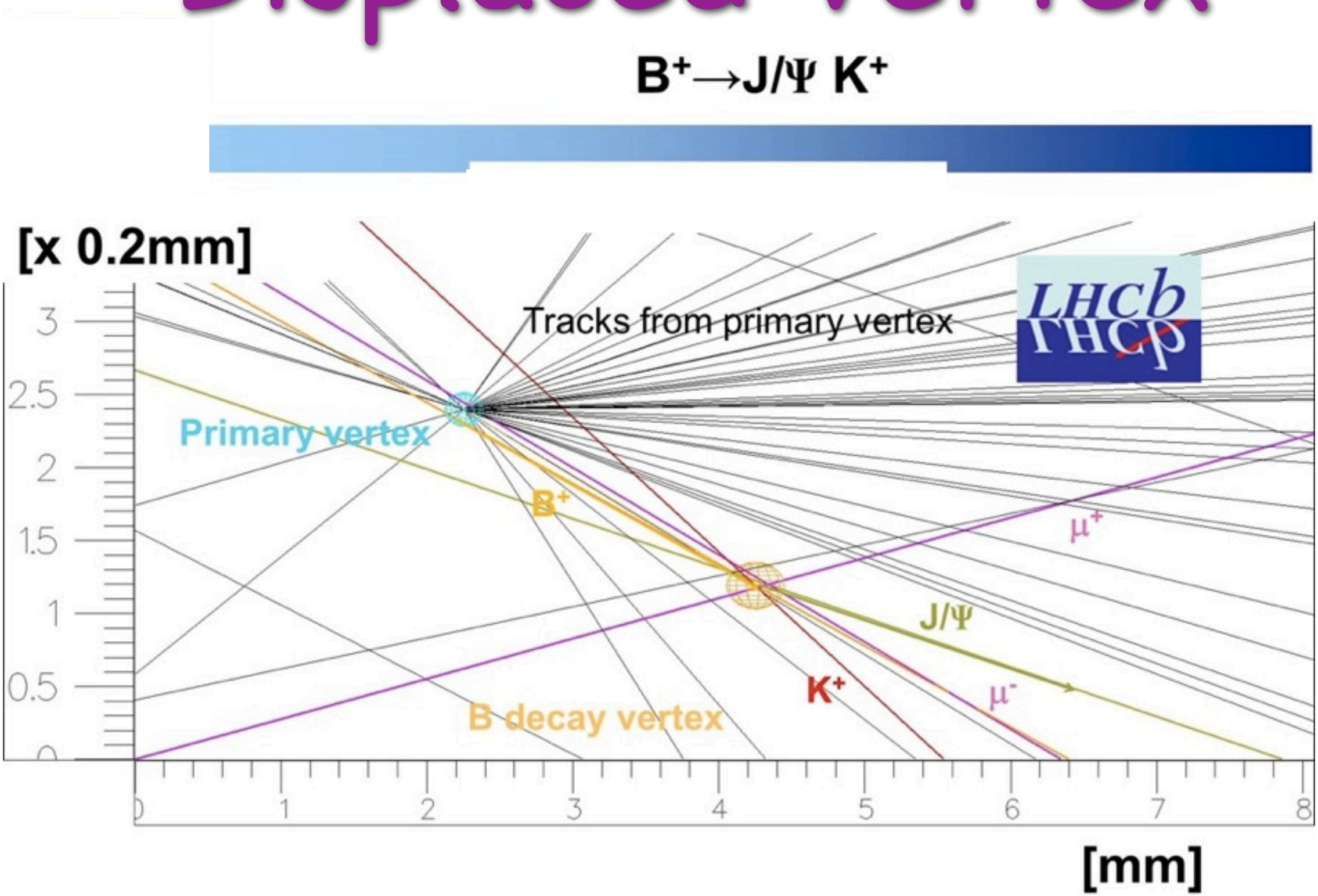
particle	mass	distance	
ρ^0	$775\,\mathrm{MeV}$	$2 \times 10^{-14}\,\mathrm{m}$	
η	$548\,\mathrm{MeV}$	$3 \times 10^{-9}\,\mathrm{m}$	
π^0	$135\,\mathrm{MeV}$	$2 \times 10^{-6}\mathrm{m}$	
B^0	$5,280\,\mathrm{MeV}$	$10^{-3}\,\mathrm{m}$	
$K^\pm$	$494\,\mathrm{MeV}$	$60\,\mathrm{m}$	detector stable
$\pi^\pm$	$140\,\mathrm{MeV}$	$640\,\mathrm{m}$	
n	$940\,\mathrm{MeV}$	$3 \times 10^{12}\,\mathrm{m}$	
p	$938\,\mathrm{MeV}$	$> 10^{47}\,\mathrm{m}$	

Travel Distances

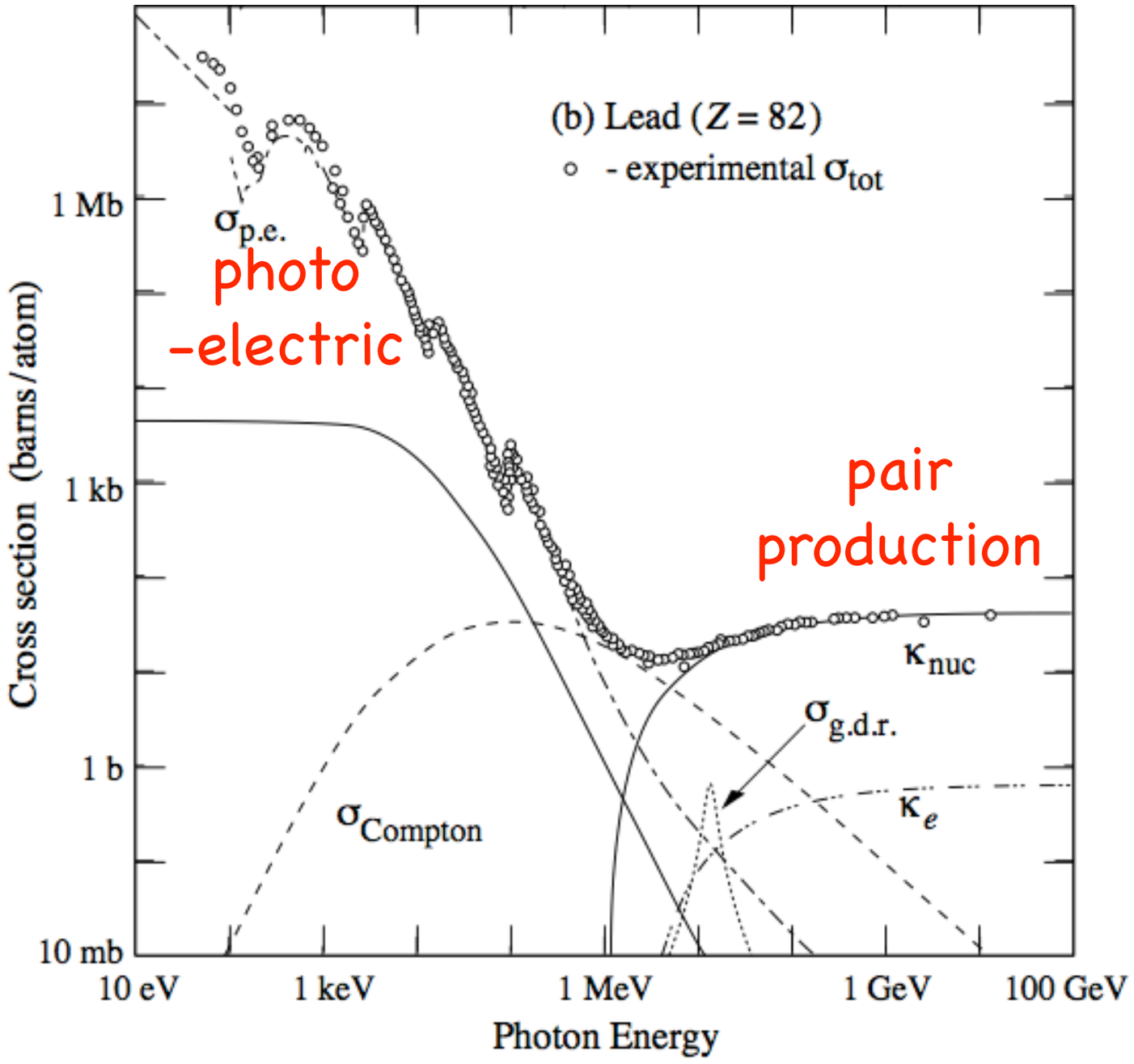
$$E = \gamma\, m = 10\,\mathrm{GeV}$$

particle	mass	distance	
ρ^0	$775\,\mathrm{MeV}$	$2 \times 10^{-14}\,\mathrm{m}$	
η	$548\,\mathrm{MeV}$	$3 \times 10^{-9}\,\mathrm{m}$	
π^0	$135\,\mathrm{MeV}$	$2 \times 10^{-6}\mathrm{m}$	
B^0	$5,280\,\mathrm{MeV}$	$10^{-3}\,\mathrm{m}$	displaced vertex
$K^\pm$	$494\,\mathrm{MeV}$	$60\,\mathrm{m}$	detector stable
$\pi^\pm$	$140\,\mathrm{MeV}$	$640\,\mathrm{m}$	
n	$940\,\mathrm{MeV}$	$3 \times 10^{12}\,\mathrm{m}$	
p	$938\,\mathrm{MeV}$	$> 10^{47}\,\mathrm{m}$	

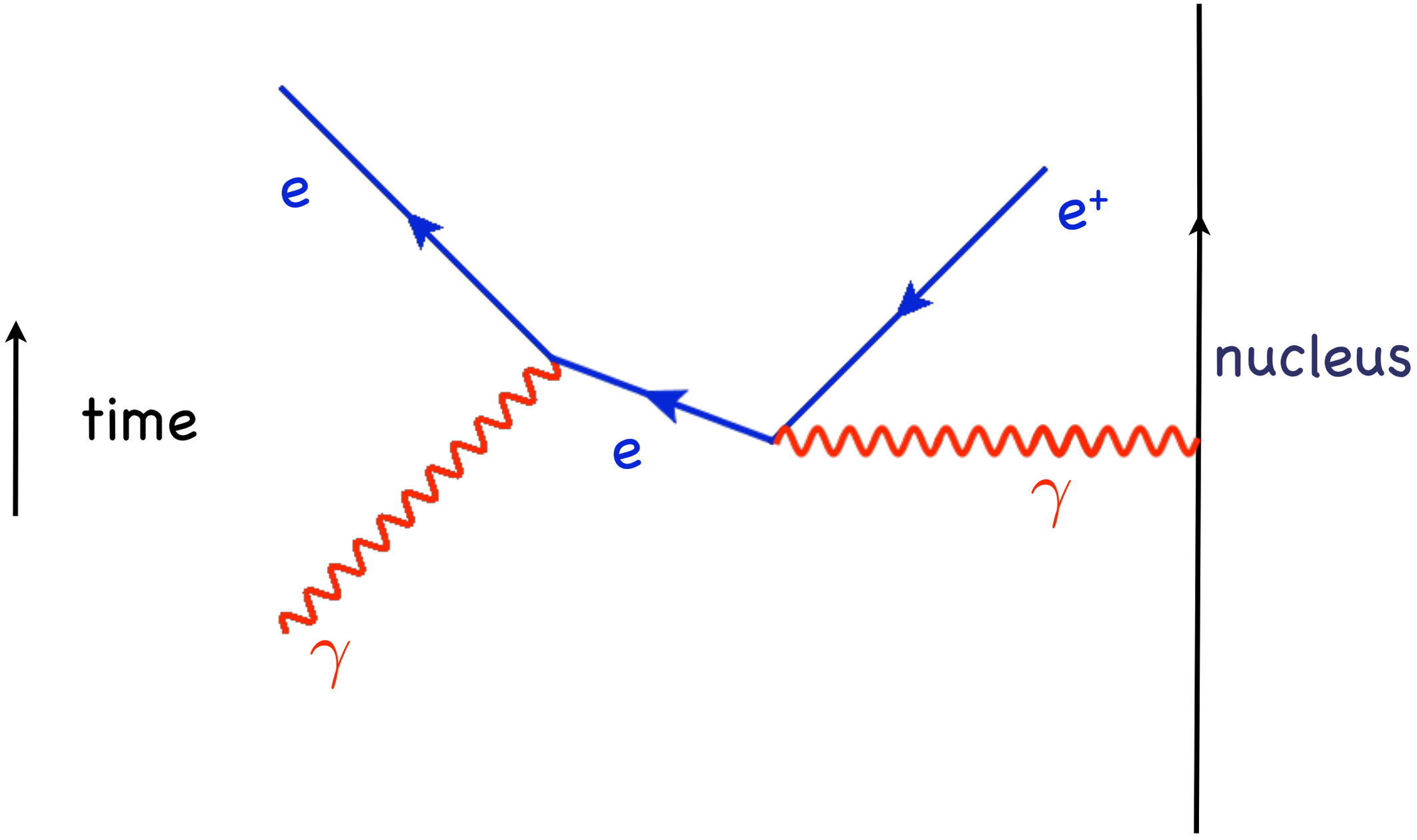
Displaced Vertex



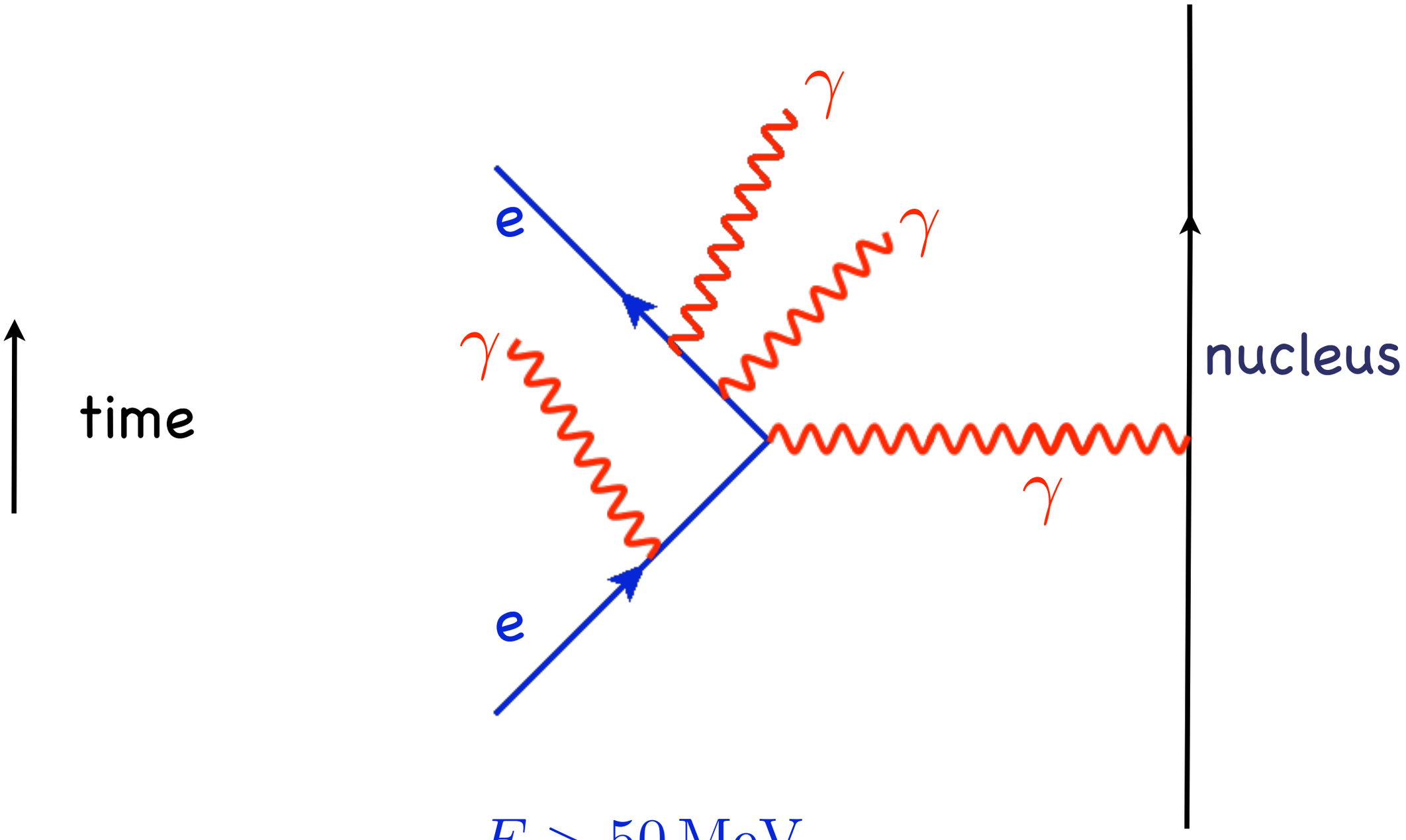
Photon Energy Loss



Pair Production



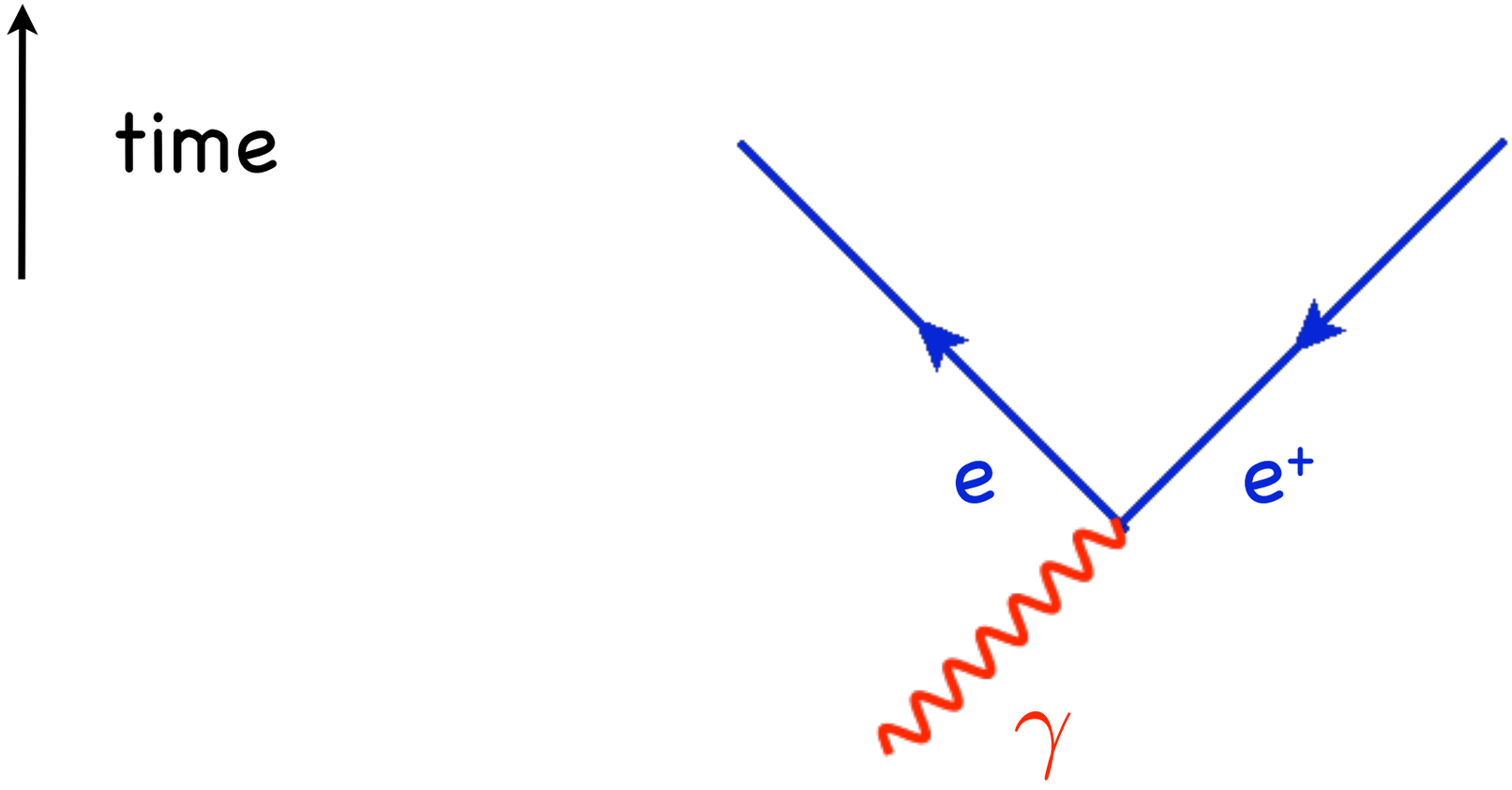
Electron Bremsstrahlung



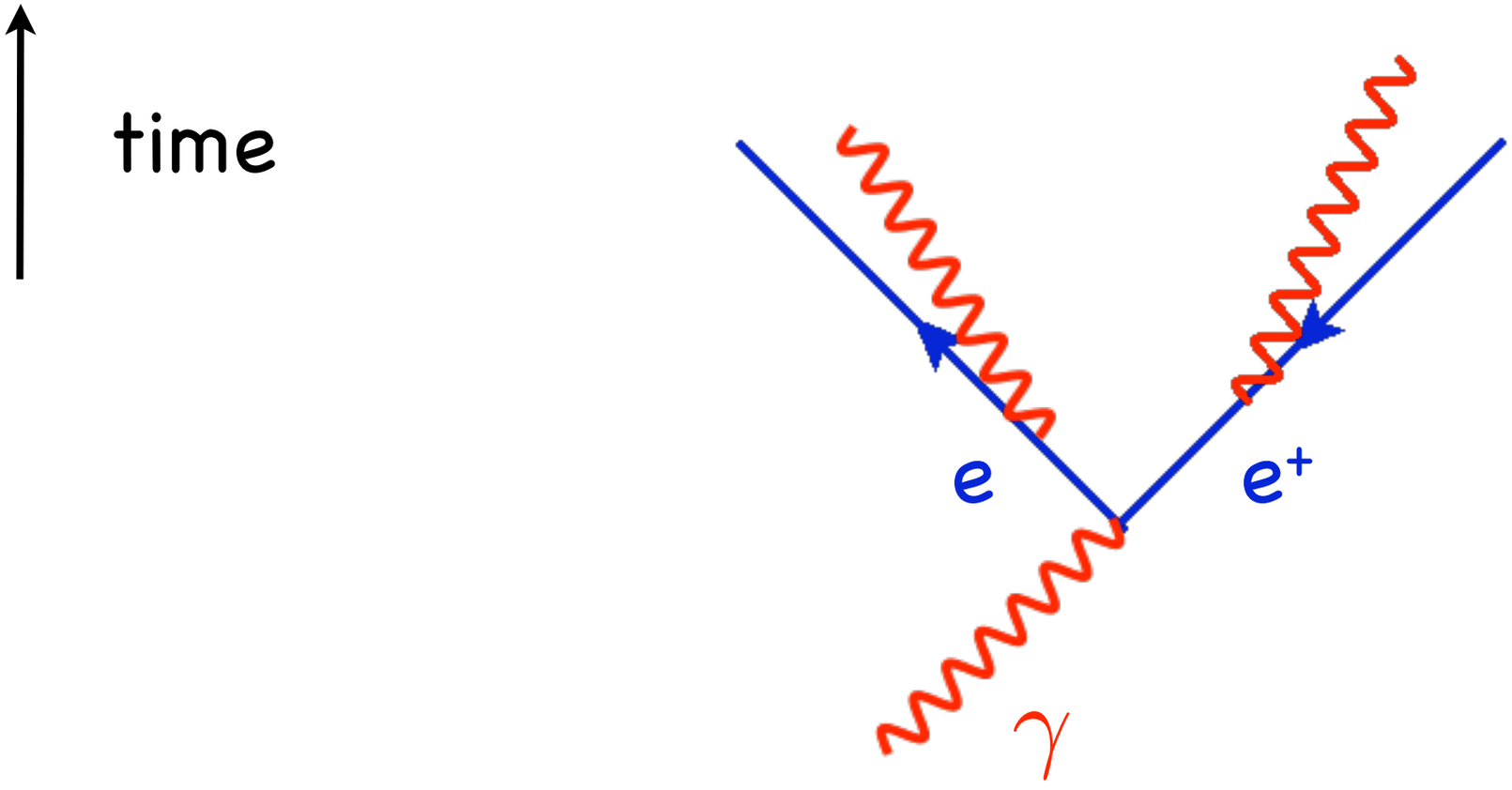
$E > 50\,\mathrm{MeV}$

$\gamma > 100$

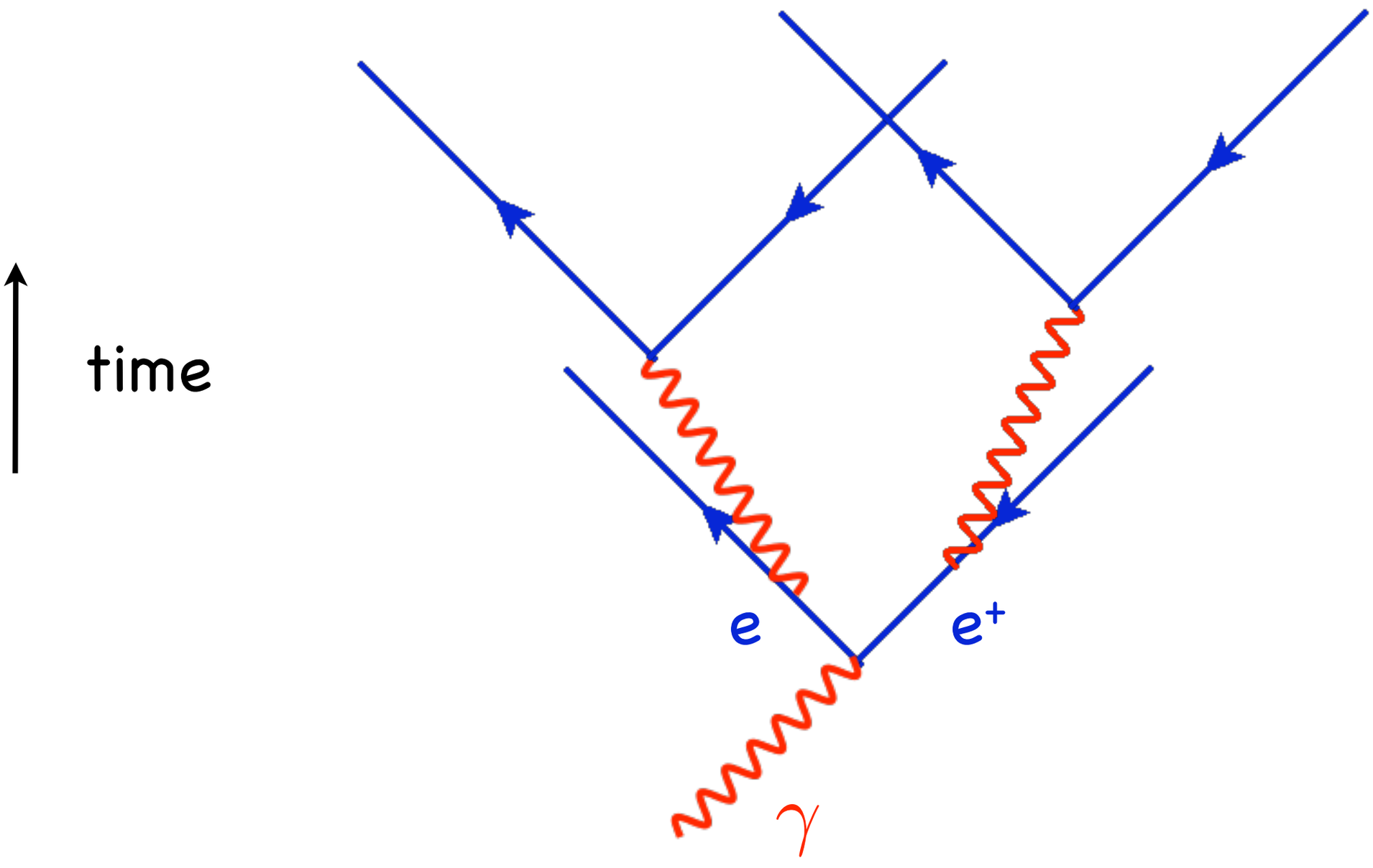
EM Shower



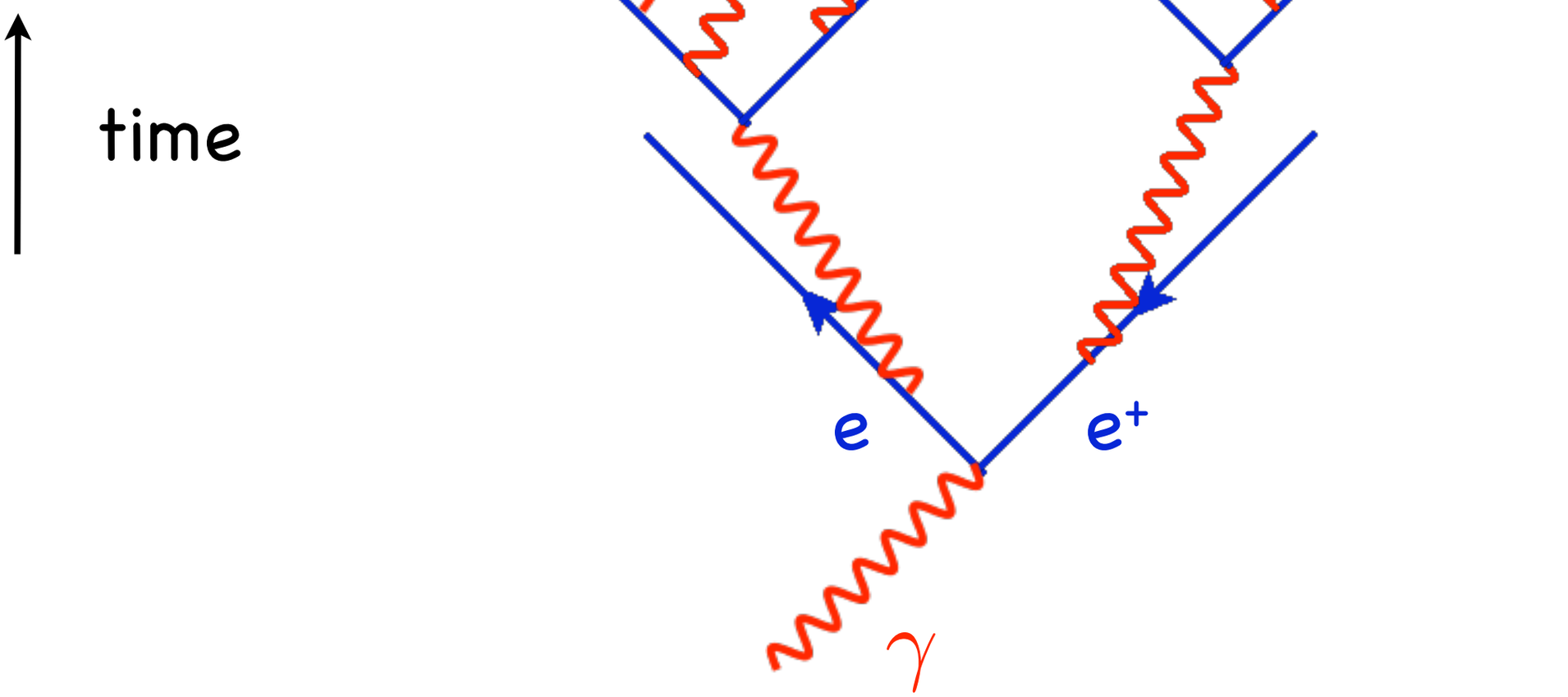
EM Shower



EM Shower

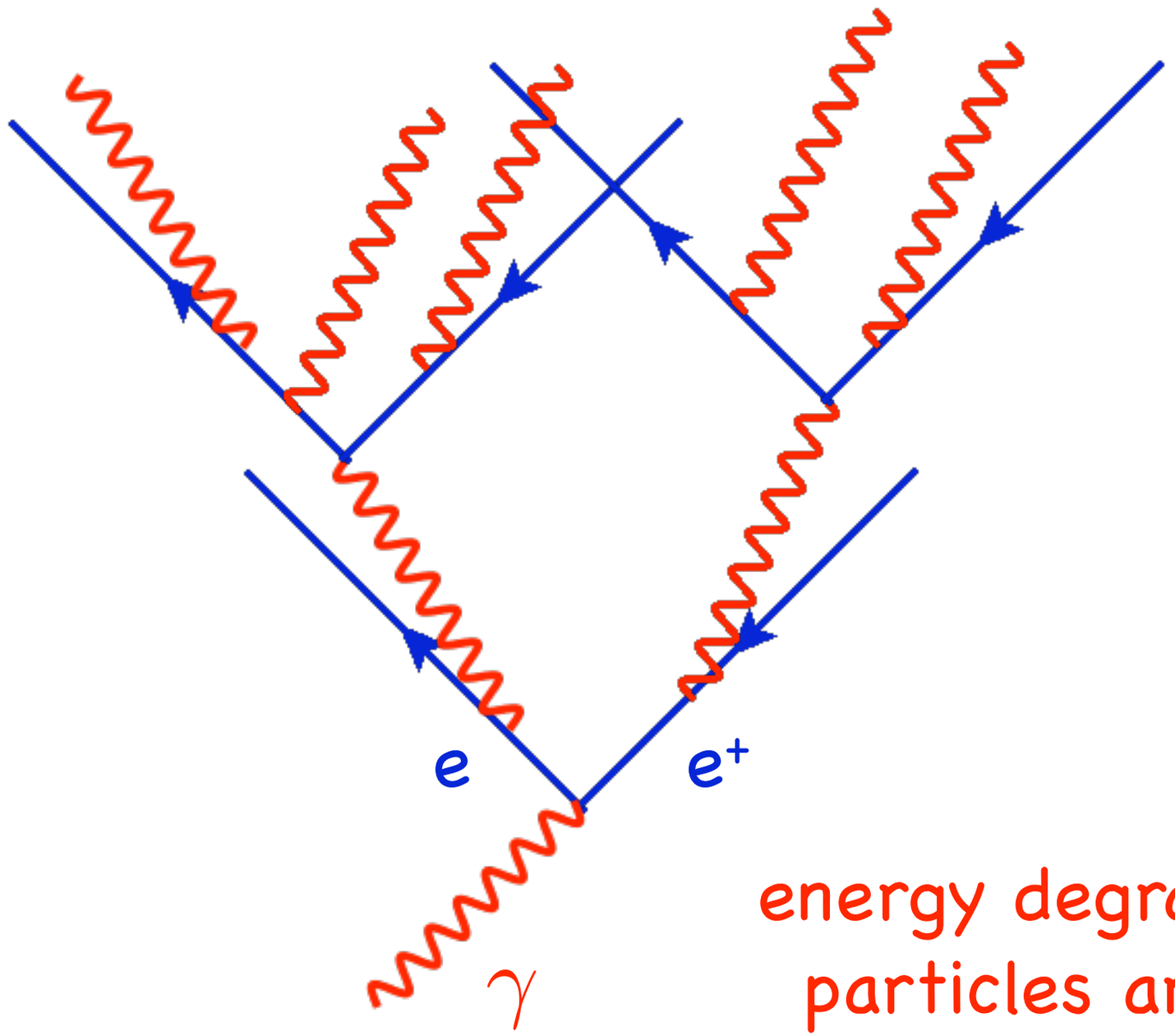


EM Shower



EM Shower

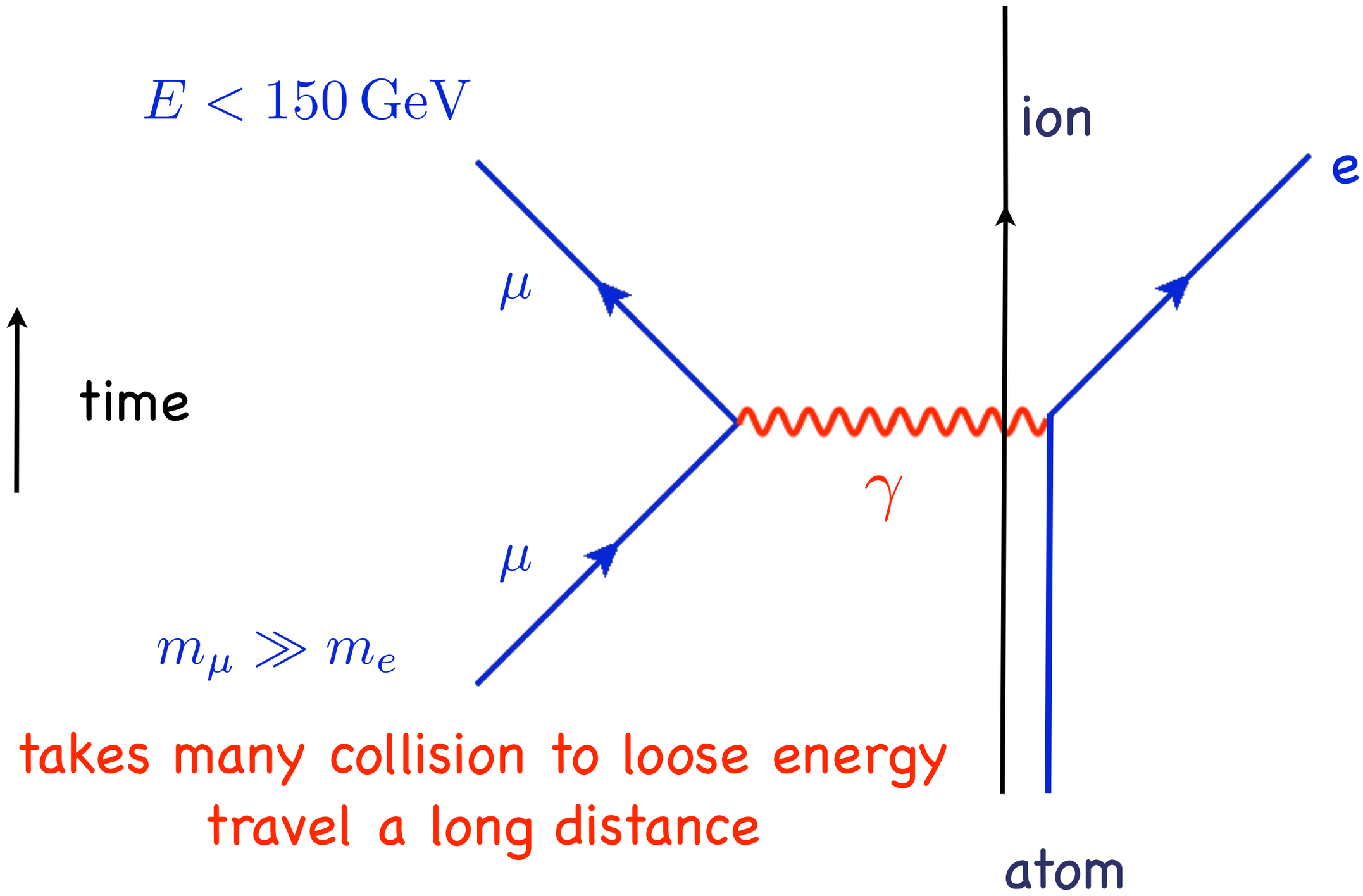
time



energy degrades as more particles are produced

Muons Ionize

$E < 150\,\mathrm{GeV}$

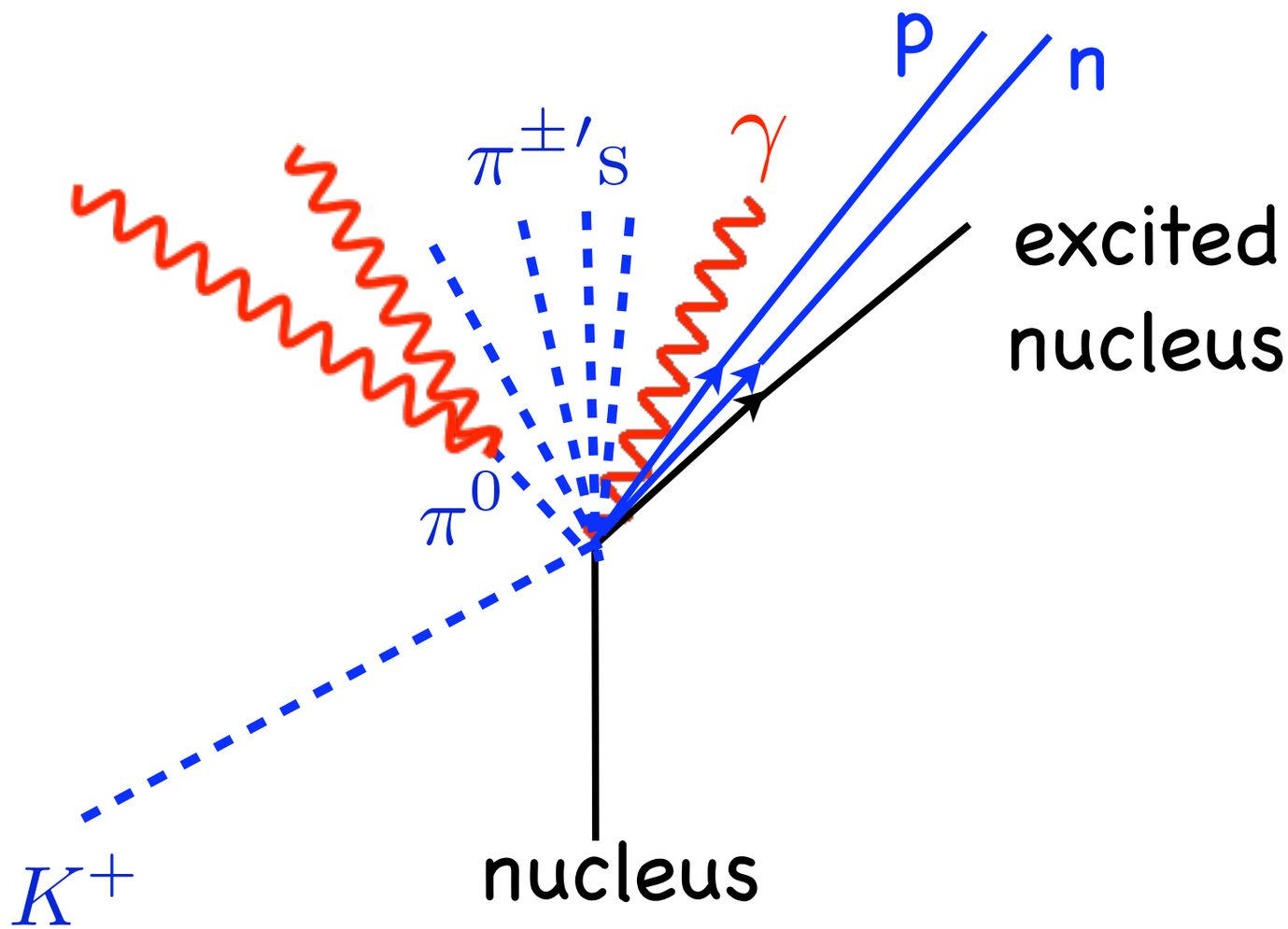


$m_\mu \gg m_e$

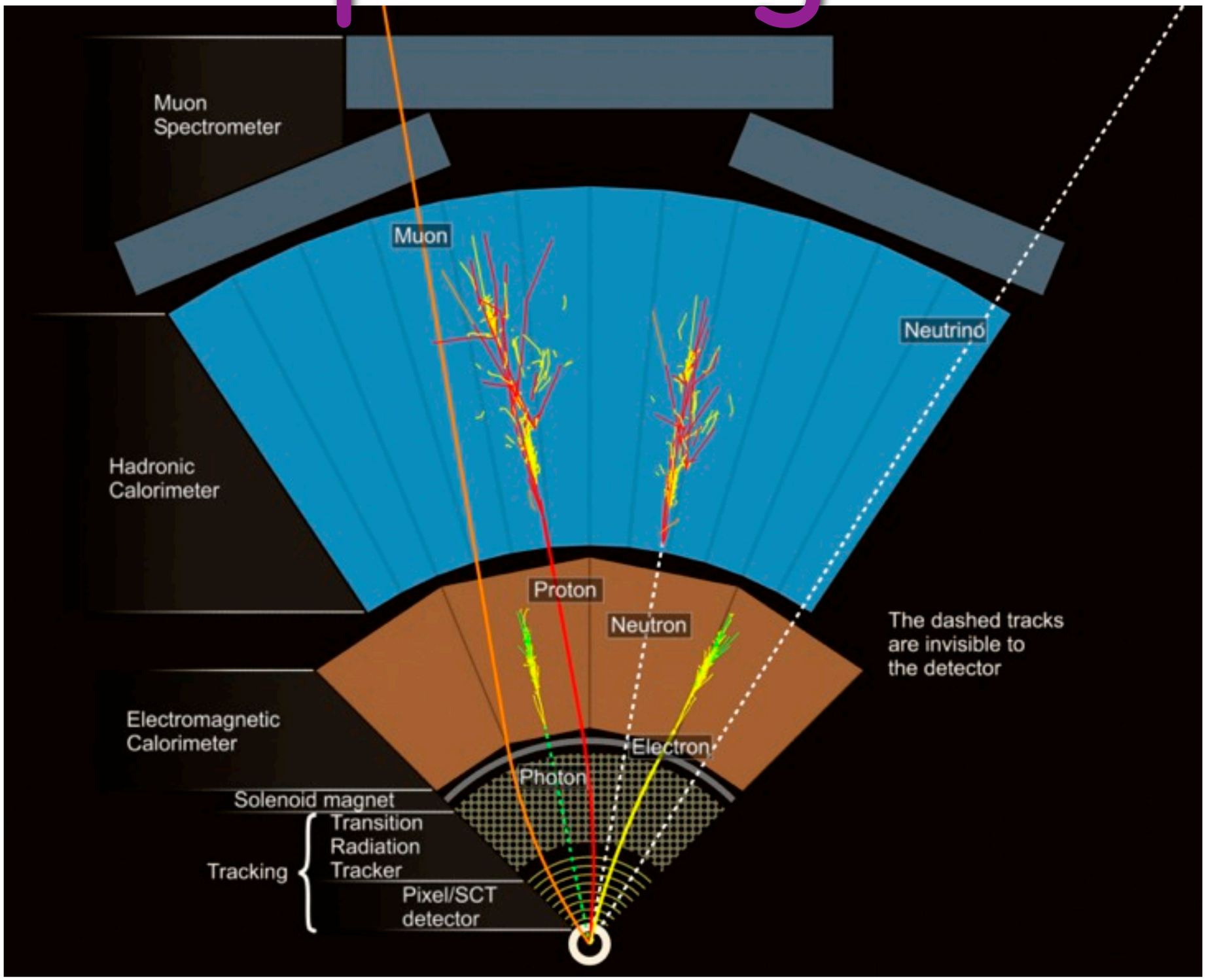
takes many collision to loose energy
travel a long distance

Hadronic Showers

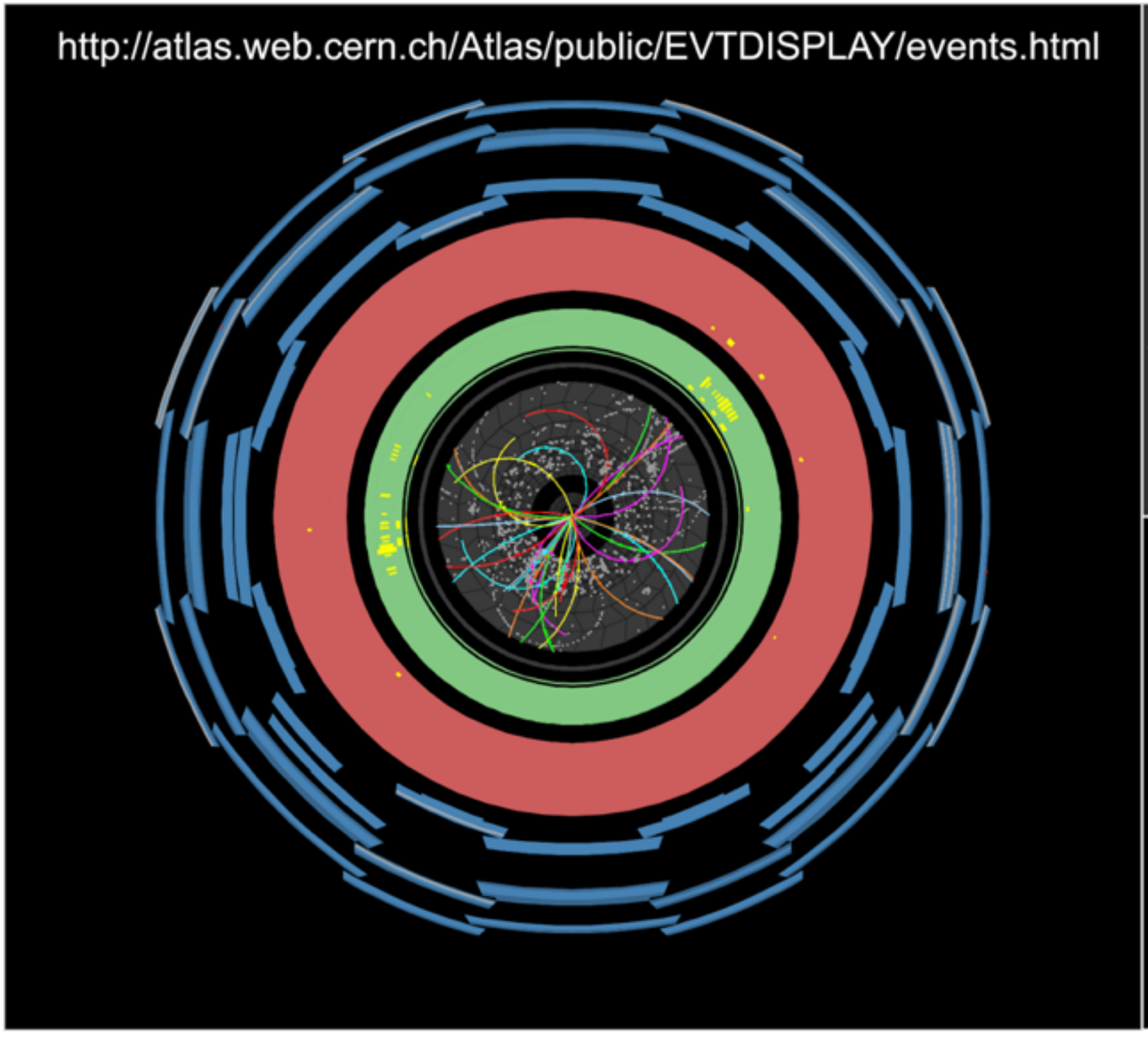
hadrons are heavier than muons
but have strong nuclear interactions
more complicated showers

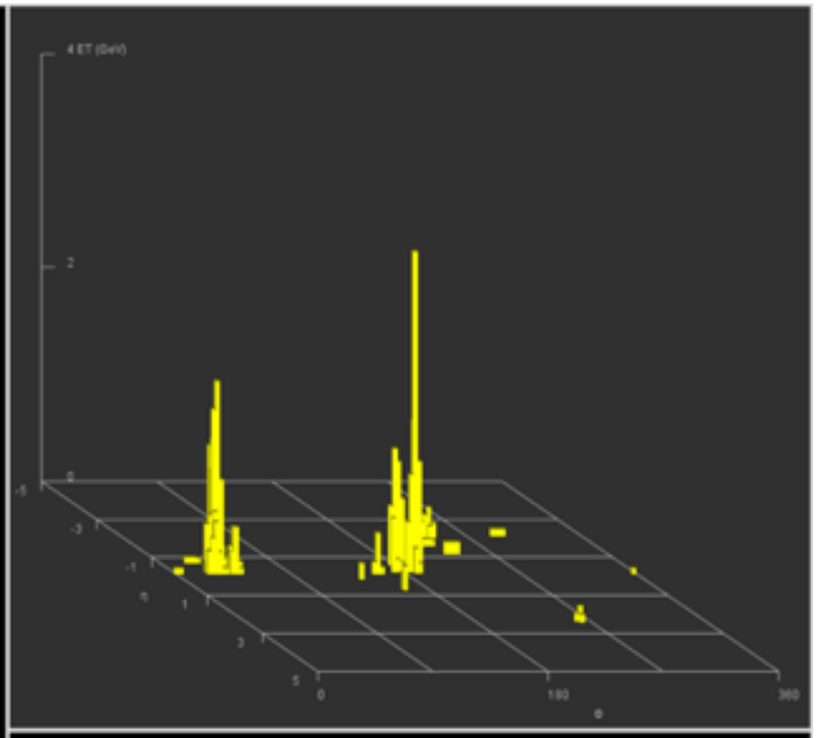


Interpreting Data



Actual Data

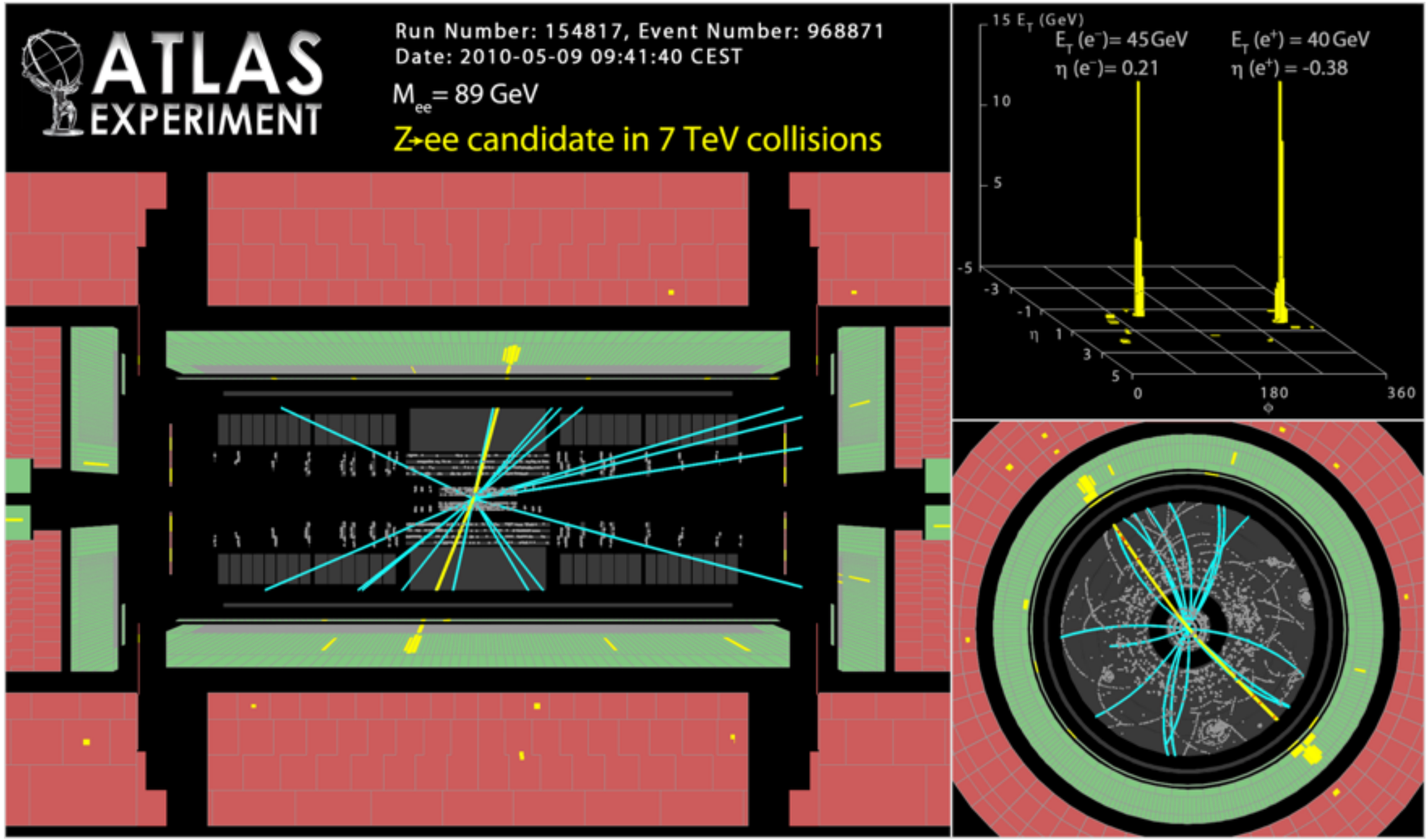




Run Number: 152166, Event Number: 347262

Date: 2010-03-30 13:05:04 CEST

Actual Data


ATLAS
EXPERIMENT
Run Number: 154817, Event Number: 968871
Date: 2010-05-09 09:41:40 CEST
M_{ee} = 89 GeV
Z→ee candidate in 7 TeV collisions
15 E_T (GeV)
E_T (e^-)= 45GeV
E_T (e^+) = 40GeV
η (e^-)= 0.21
η (e^+) = -0.38
10
5
-5
-3
-1
η
1
3
5
0
180
360
φ