Introduction to High Energy Physics
PHY 489/1489
(Introduction to Particle Physics)

R.S.Orr

- Me = Robert S. Orr
    - orr@physics.utoronto.ca, phone 416 978 6029, MP818A
- Office hours – Thursday afternoon 3 -> 5?
- TA – Randy Conklin MP920, rconklin@physics.utoronto.ca
- Prerequisits: PHY354, PHY356
- What you need from mechanics:
    - Special relativity, Relativistic kinematics
    - What is a Lagrangian, what is a Hamiltonian.
    - Partial differential equations, matrices, linear algebra
- What you'll need from Qumtum Mechanics:
    - Dirac notation, completeness, etc
    - Eigenvalue equations – Schroedinger, angular momentum
    - Probability density and current
    - Conserved quantities
    - Commutation and compatible observables
    - Angular momentum, commutators
- I'll remind you about some of this next week

- This is first time that I have done this course for several years. You can find the transparencies from last year (Hiro Tanaka) at

  ttps://sites.phyiscs.utoronto.ca/tanaka/phyiscs-489-1489-2017/

- I'll build a new site as we go along. I don't guarantee to follow Hiro. But his site will still be useful.
- Text book: Modern Particle Physics – Mark Thomson.
- You should read the book. There is a lot in it. I doubt if I will cover all of it. I'll try to tell you which parts I will omit.
- Grading:
  - 4 Problem sets at 10% = 40%
  - Midterm 15%
  - Final 45%
  - Late assignments will not be accepted after solutions posted
  - Hand them in at class on due date, or before 17:00 in my mail box on the 8th floor.

What is this course about?

- Learning enough of the mathematical structure of the standard model to allow you to do calculations and see how they compare with experiment.
- I hope you will also learn enough to appreciate the beauty of this description that we have build up of the most fundamental layer of physical reality.
- To do all this on the basis of relativistic single particle wave functions, without having to learn a lot of quantum field theory. But, in a way that I believe is still correct.

- To learn what we think are the problems inherent in the standard model, and what the future might hold.

- To have a passing acquaintance with accelerator and detectors.
- To understand at some level how experiments are done.

- What we know about the elementary particles depends completely on experiment.
- If there were no experiments, Theory would be idle speculation.
- This is becoming a problem in our field – see JPH441.
- The bulk of our experimental knowledge of the elementary particles has come from electron and proton colliding beam accelerators. I think we expect this to continue. It is the only practical way to reach high energies.
- Fixed target neutrino physics is also important – essentially to understand how lepton basis states mix. I'll tell you what that means later.
- There is a large effort to detect dark matter in underground non-accelerator experiments. So far, without result.

- First let's define some quantities that we measure in experiments. If you don't understand, we will come back to them in relativistic kinematics.
- I won't talk about how detectors work. There is a little about it in Thomson's book. Read it, and ask me about it if you are interested.

WHAT DO EXPERIMENTS ACTUALLY MEASURE?

INITIAL STATE PARTICLES → COLLISION → FINAL STATE PARTICLES

- MEASURE ENERGY MOMENTUM 4-VECTOR FOR ALL OUTGOING CHARGED PARTICLES

  $p = (E, p_x, p_y, p_z)$ ELECTRON, MUON, PROTON ------

FORM LORENTZ INVARIANT COMBINATIONS OF p_i

- INVARIANT MASS = $\sum p_i^2$

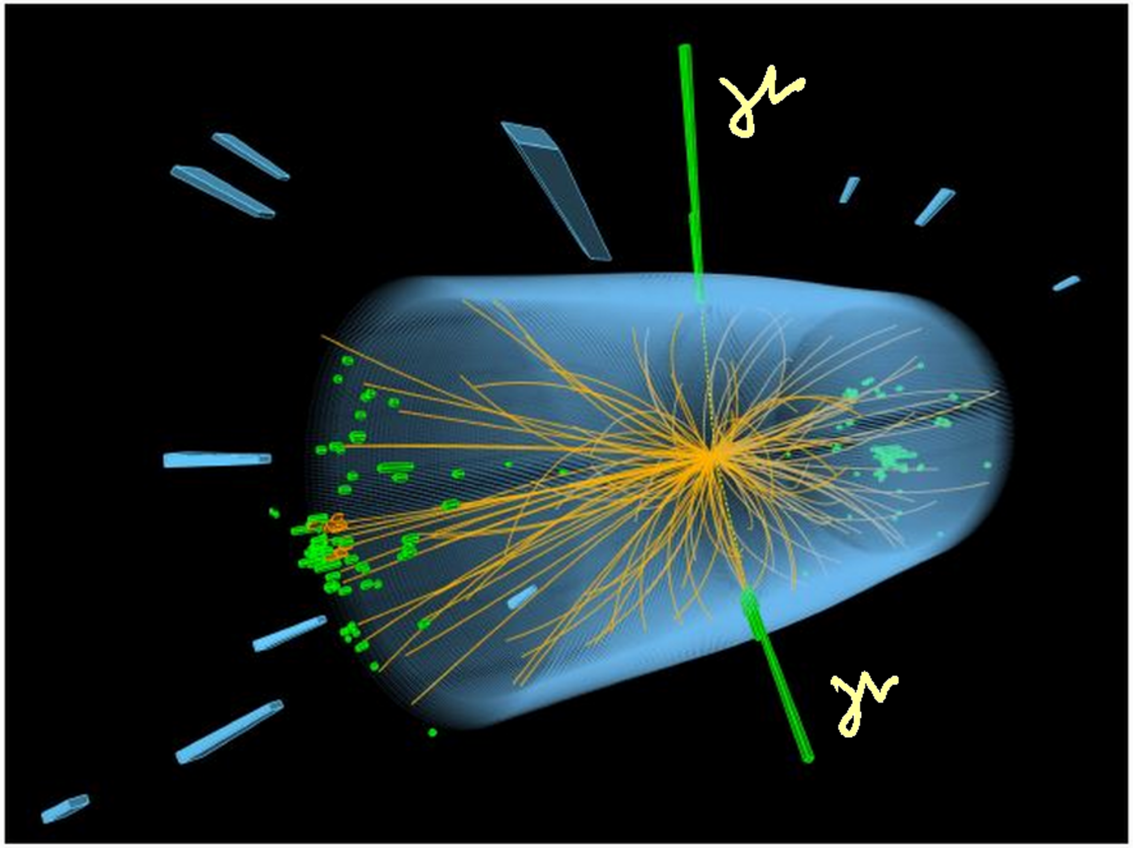
  → DISCOVER NEW STATES eg Higgs

- ANGULAR DISTRIBUTIONS

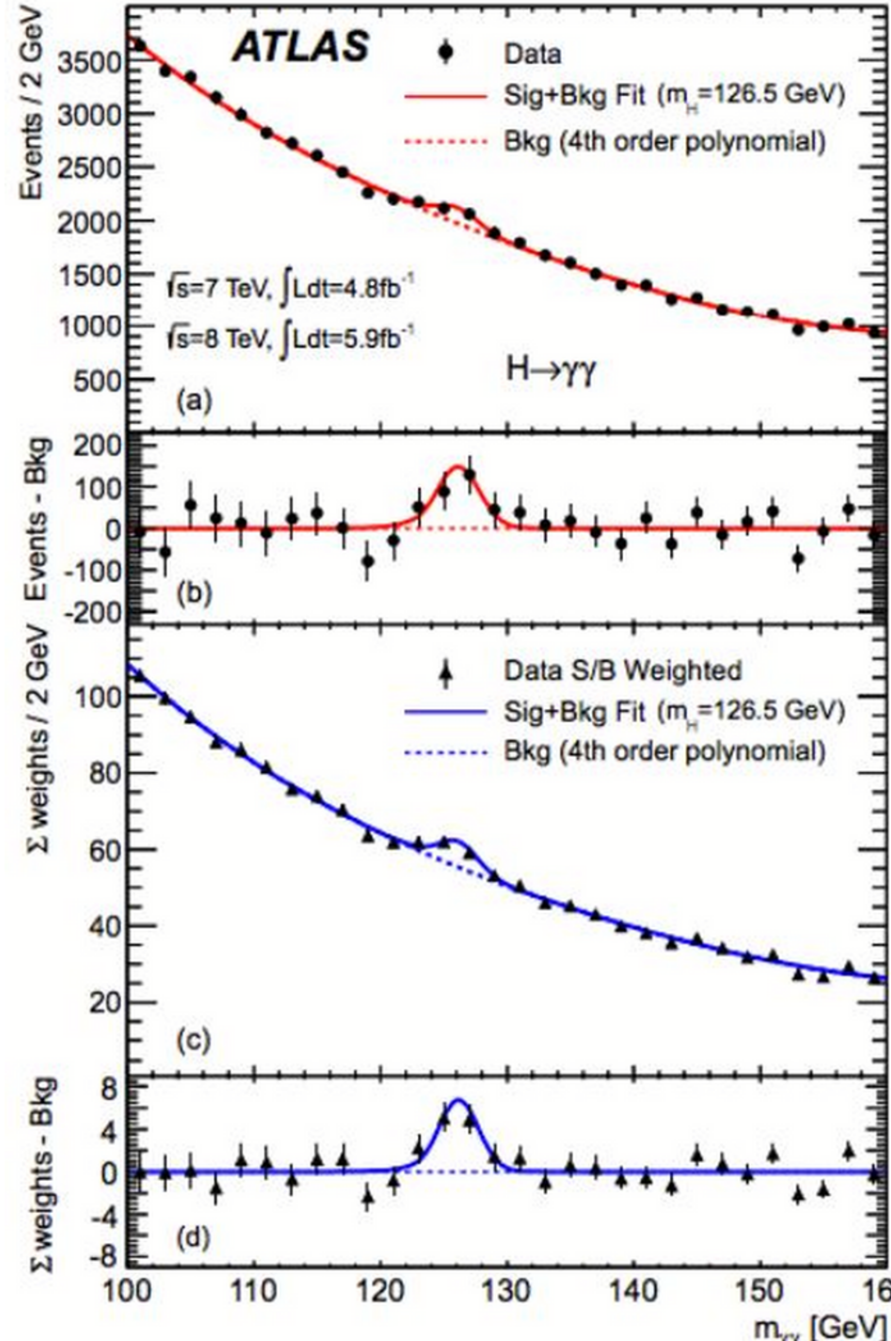
  → PREDICTED BY THEORY

  ↳ TEST THEORY

OBSERVATION OF HIGGS IN ATLAS

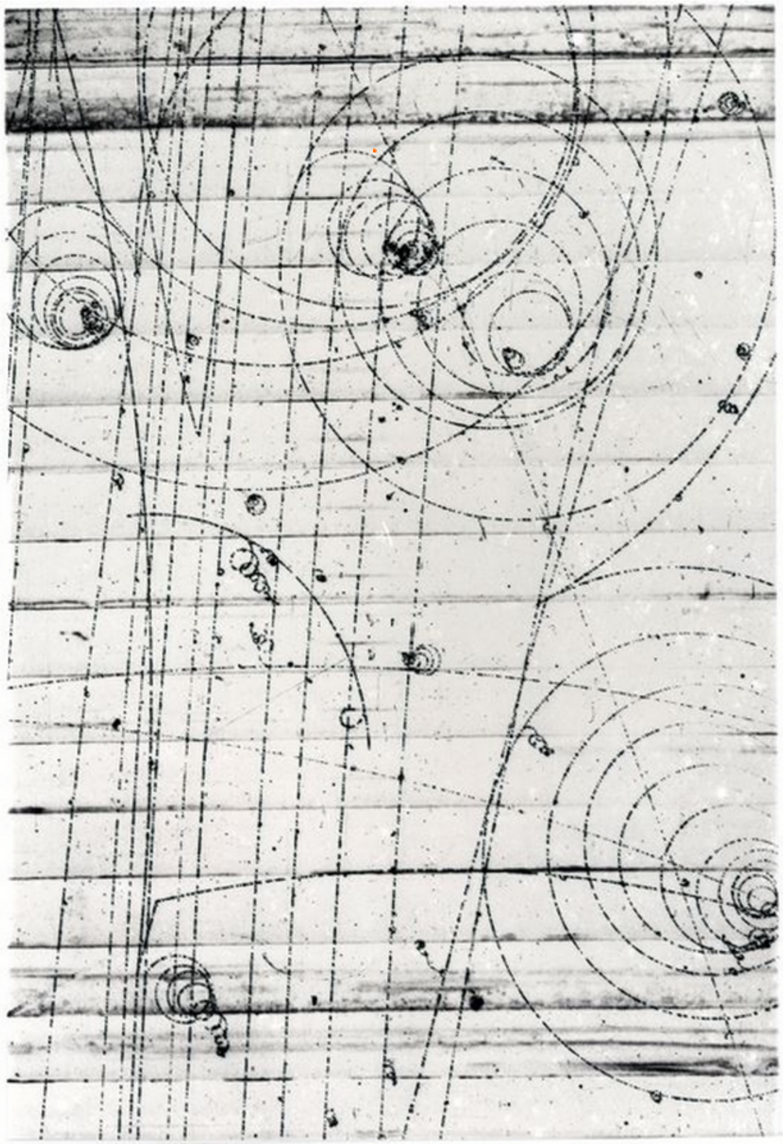


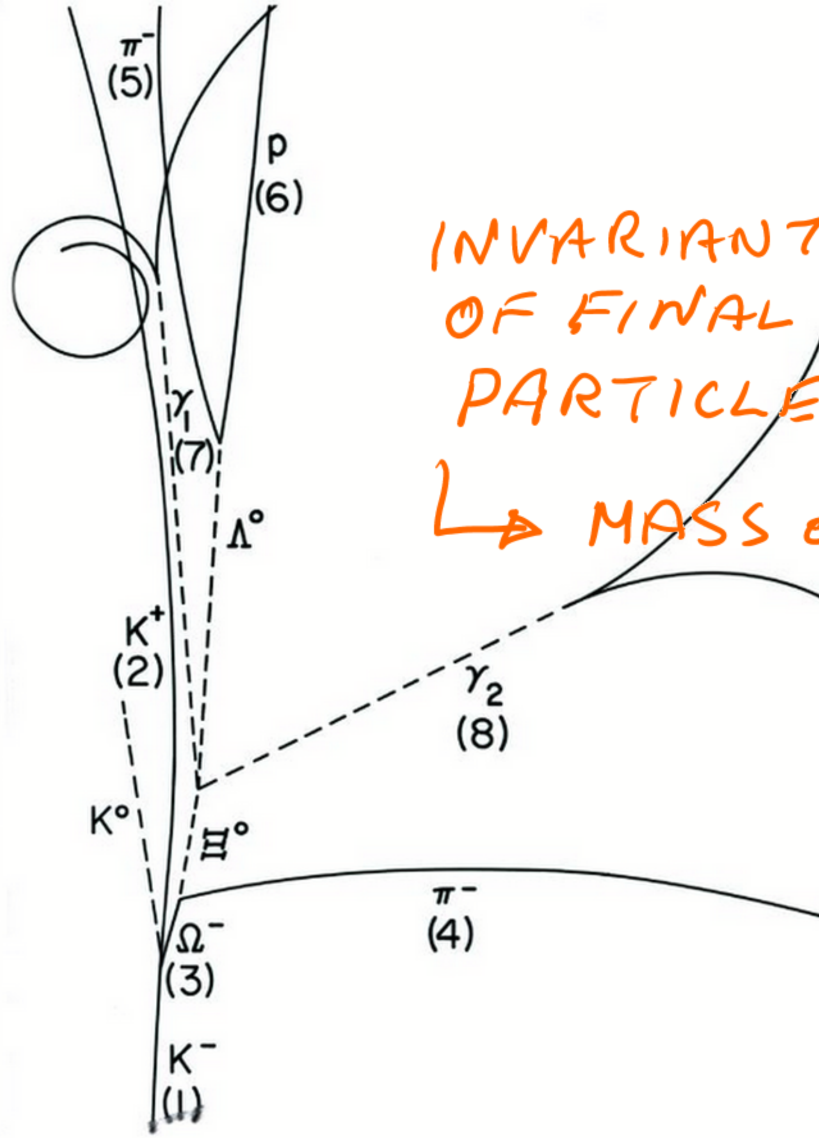
HISTOGRAM INVARIANT MASS OF $\gamma\gamma$ PAIRS



$\gamma\gamma$ INVARIANT MASS

DISCOVERY OF Ω^- IN BUBBLE CHAMBER



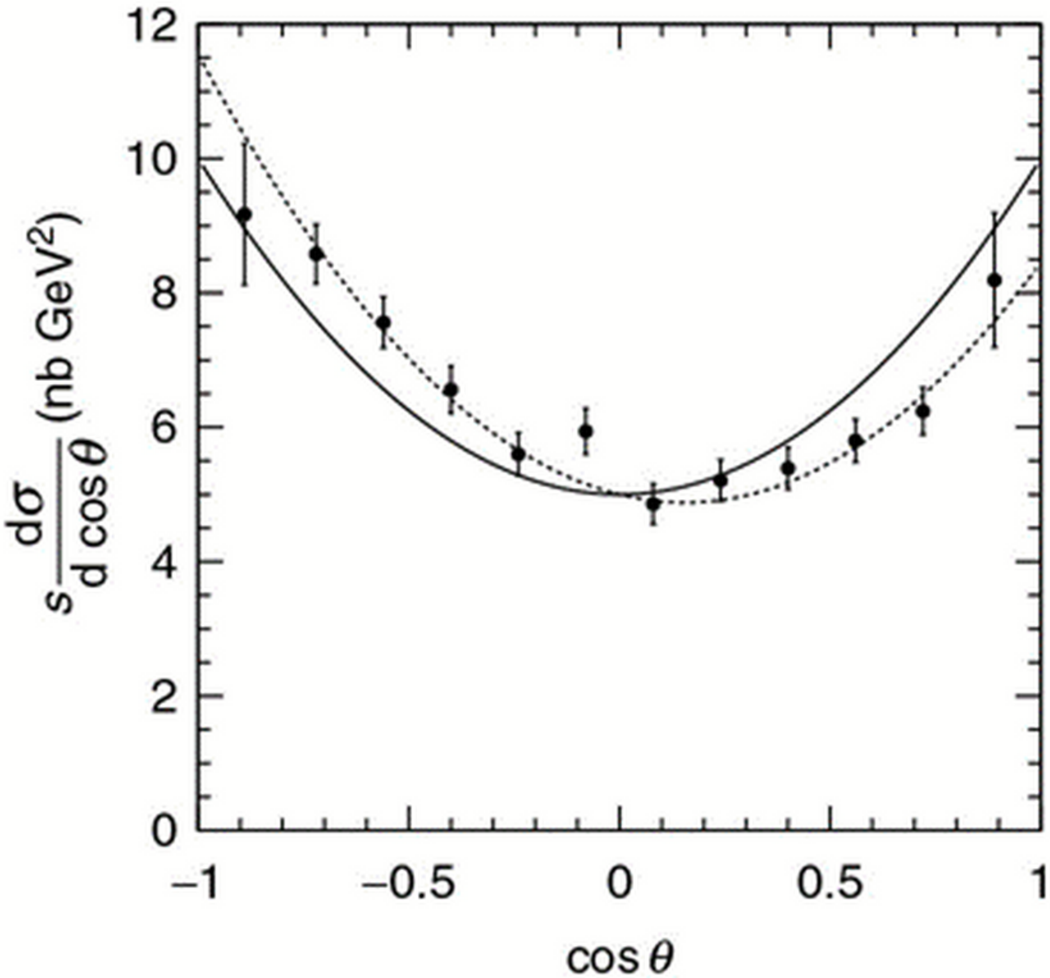


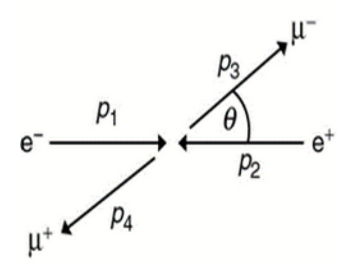
INVARIANT MASS OF FINAL STATE PARTICLES

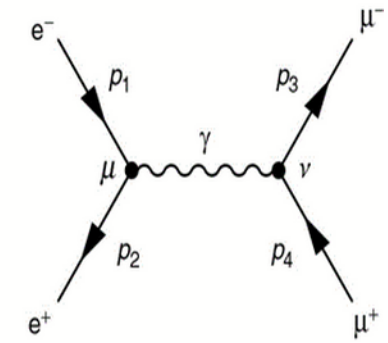
↳ MASS OF Ω

ANGULAR DISTRIBUTION OF $e^+e^- \to \mu^+\mu^-$

QED PREDICTION







WE WILL CALCULATE THIS (CHAPT 6)

- THE PROBABILITY OF SOME PROCESS OCCURRING IS ALWAYS ONE OF THE PREDICTIONS OF THEORY
- THEORY GIVES MATRIX ELEMENT
- RATE OF EVENTS/SEC IS WHAT EXPERIMENT MEASURES

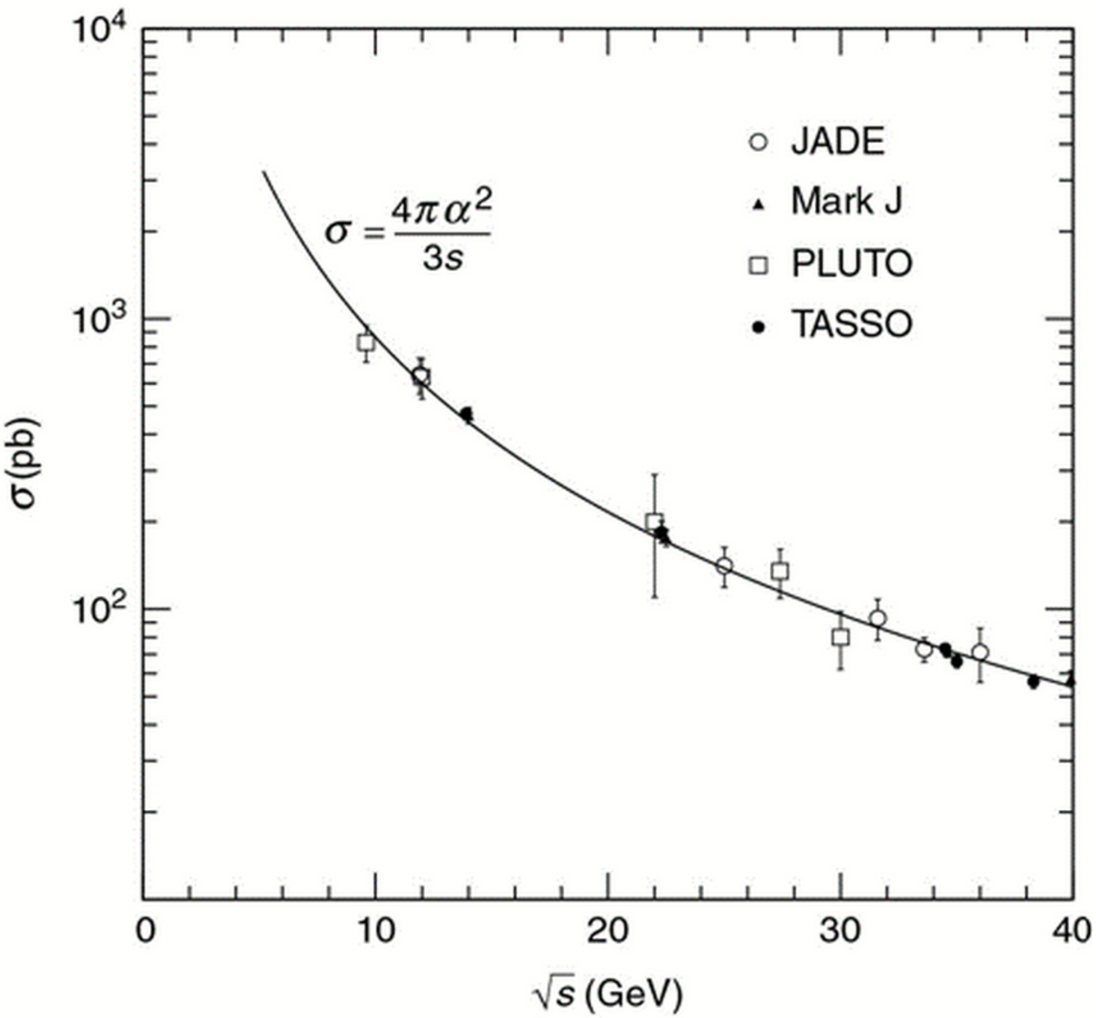
$$\sigma_{THEORY} = (\text{PHASE SPACE}) \times |\mathcal{M}|^2$$

$$\sigma_{EXPT} = (\text{RATE}) \times \text{LUMINOSITY}$$

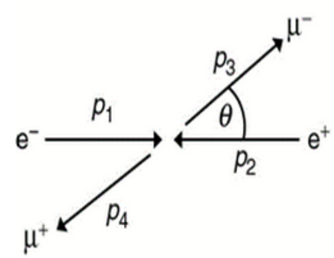
LUMINOSITY ← COLLISIONS/SEC

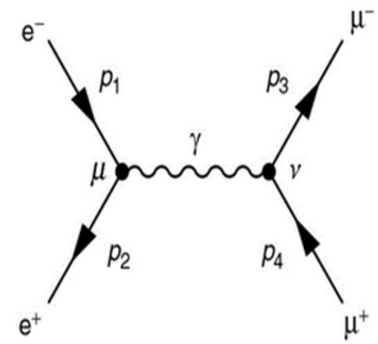
$$\mathcal{L} = f \frac{n_1 n_2}{4\pi \sigma_x \sigma_y} \qquad (1.5)$$

CROSS SECTION VARIATION WITH ENERGY IN $e^+e^- \to \mu^+\mu^-$



WE WILL ALSO CALCULATE THIS





DIRECT OBSERVATION OF QUARKS $e^- p \to e^- X$

(X ← ANYTHING)

DEEP INSIDE THE NUCLEON

STANFORD LINEAR ACCELERATOR

BASED ON MICROWAVE TECHNOLOGY USED BY HOFSTADTER

20 GeV/c
↳ 50 GeV/c

2 MILES LONG

$\$114 \times 10^6$ IN 1965

LHC $\$10^{10}$ IN 2005

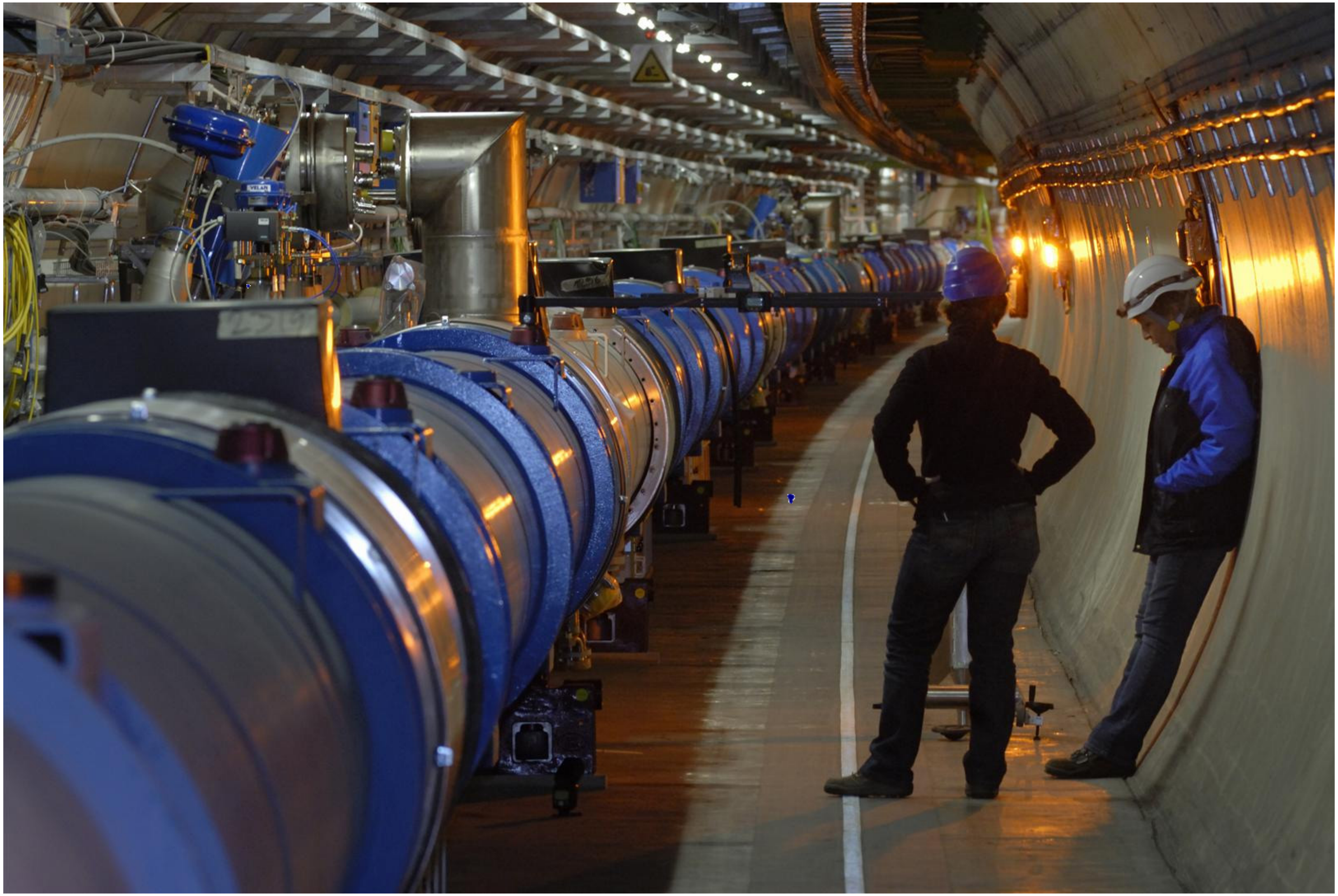
LEP e^+e^- @ 200 GeV

- PRECISION STUDY OF WEAK COUPLINGS
- NUMBER OF NEUTRINO FLAVORS
- LIMITS ON HIGGS MASS

TEVATRON $\bar{p}p$ @ 2000 GeV

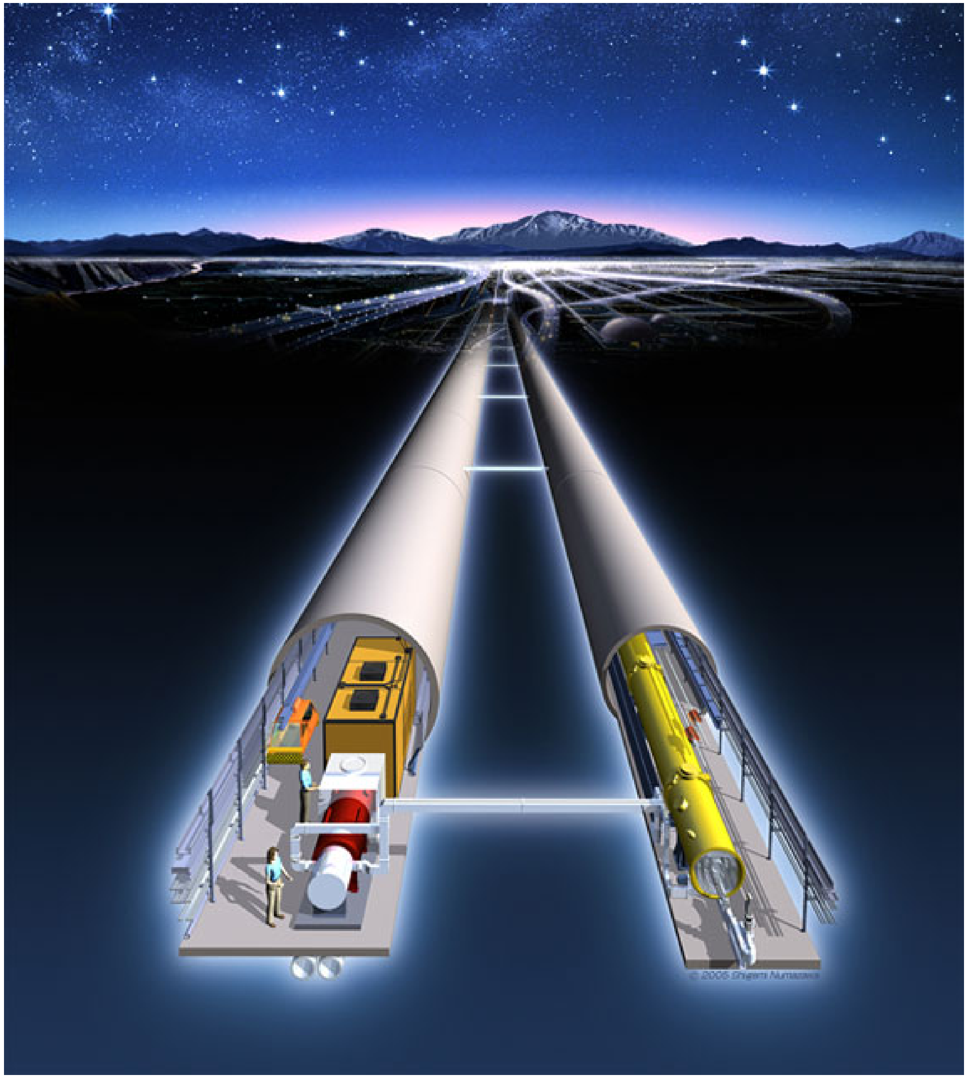
- DISCOVERY OF b-QUARK
- DISCOVERY OF t-QUARK
- SEARCH FOR HIGGS

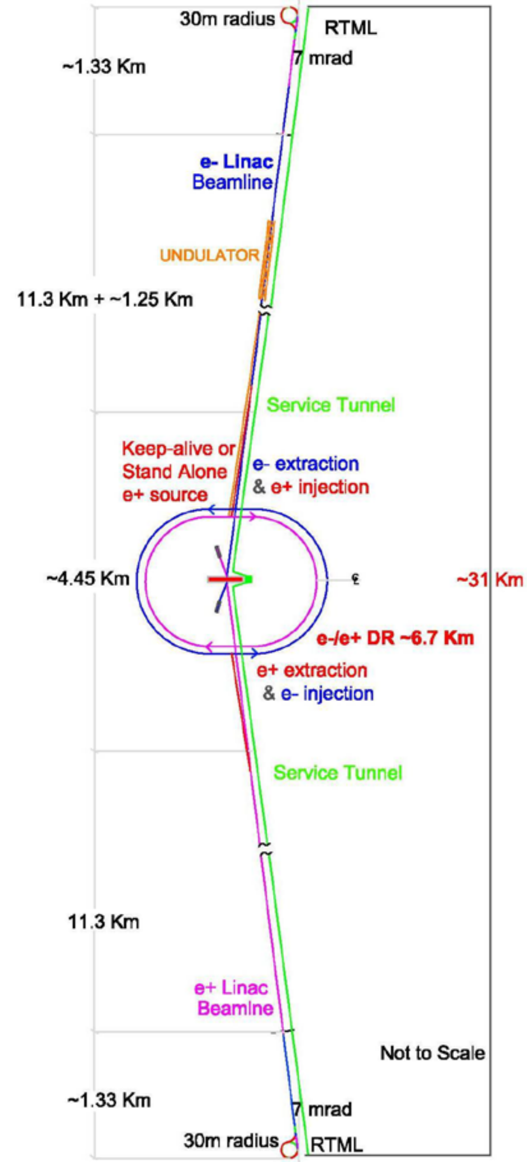
LHC pp @ 14000 GeV



DISCOVERY OF HIGGS SUSY?

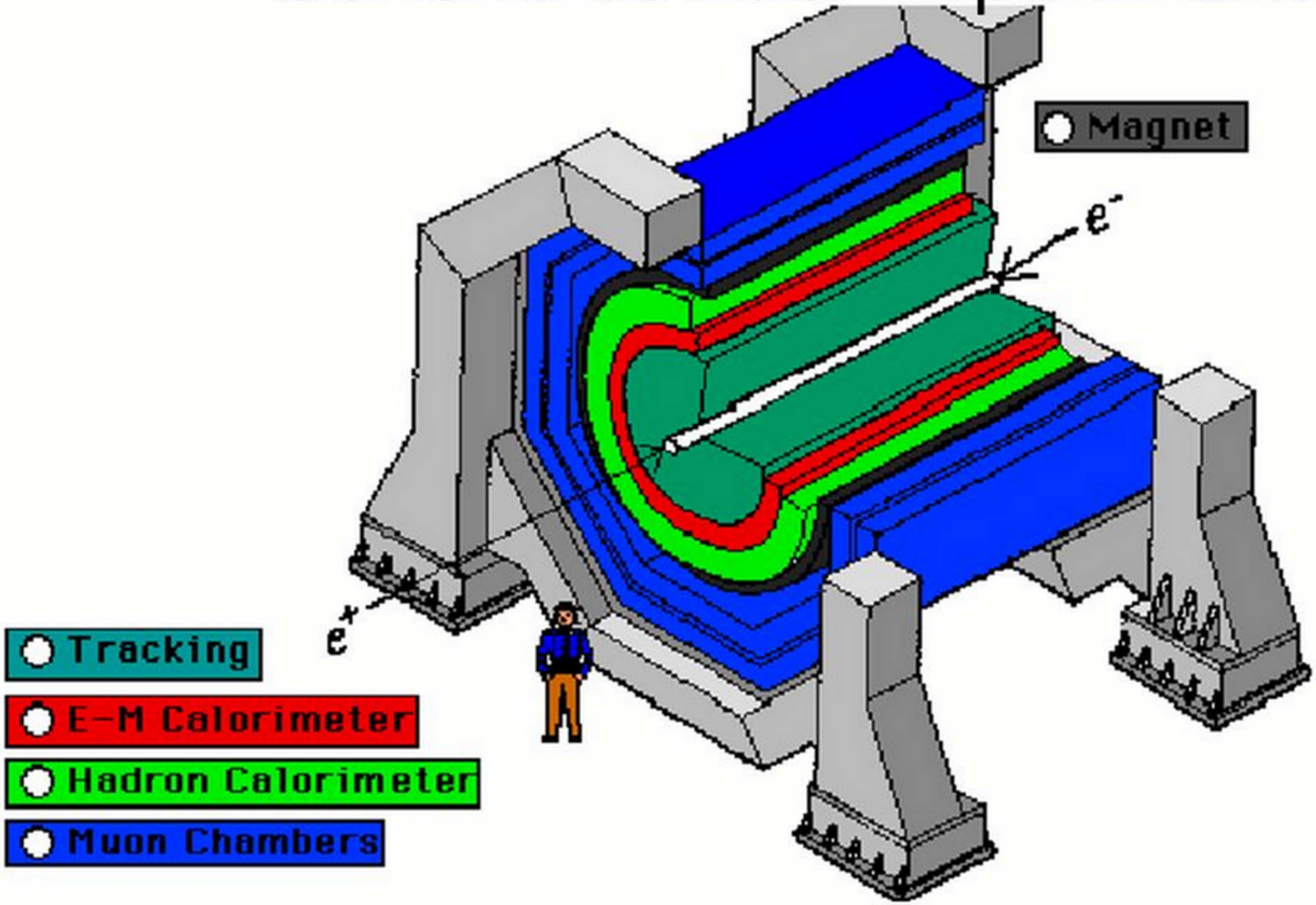
ILC e+e- @ 1000 GeV





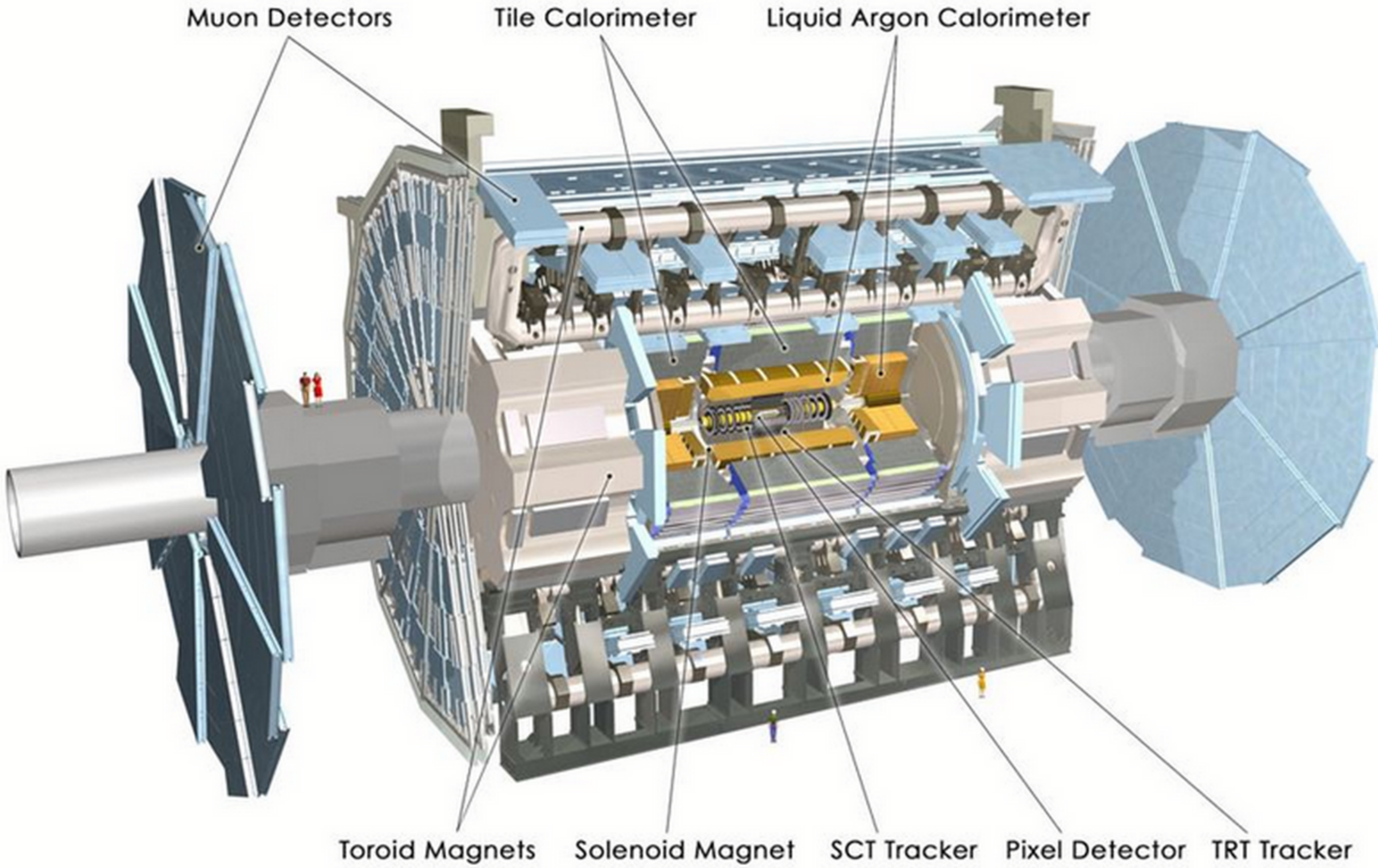
PRECISION STUDY OF HIGGS COUPLINGS

Generic Collider Experiment



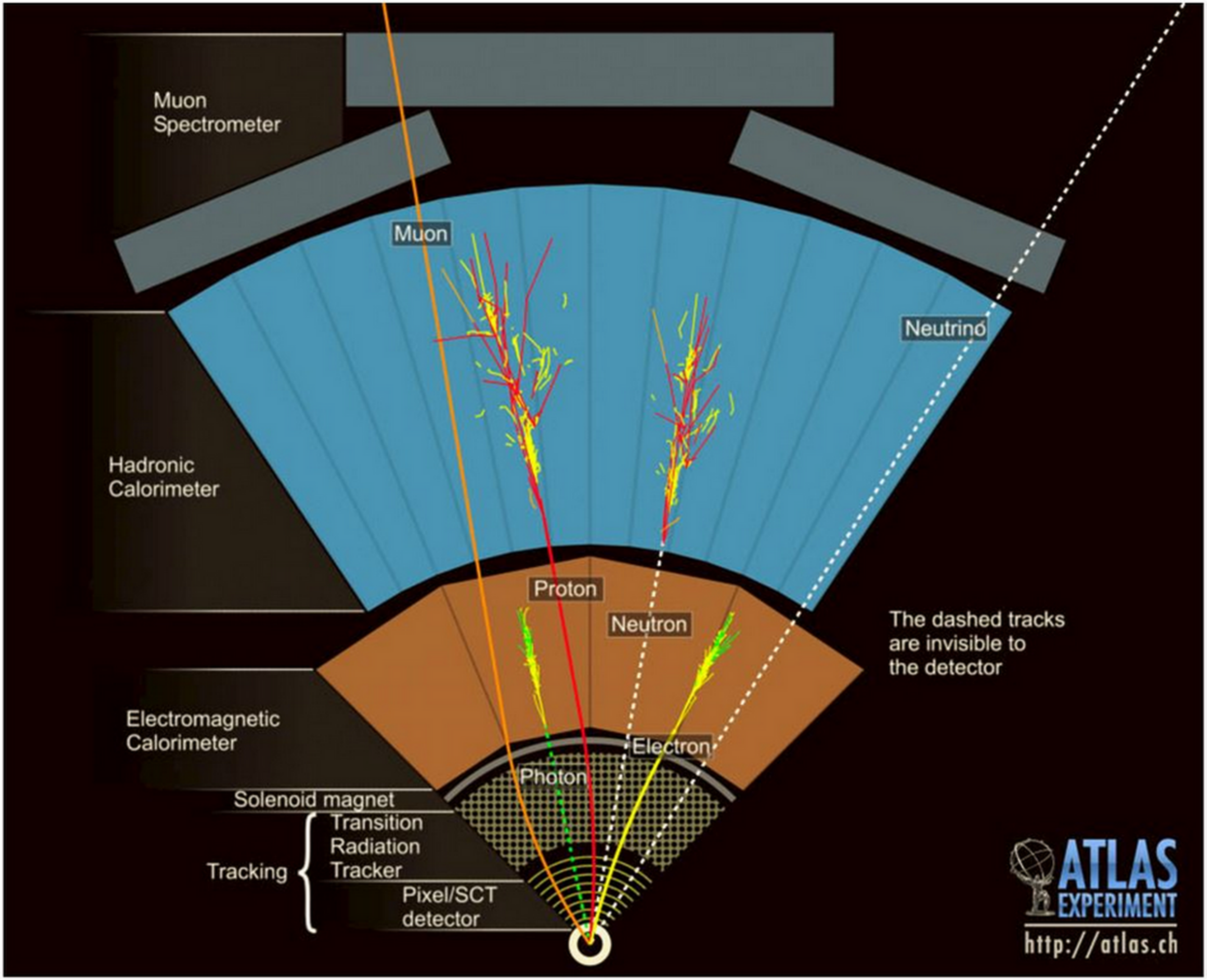
Layers of detector systems around collision point

ATLAS Detector

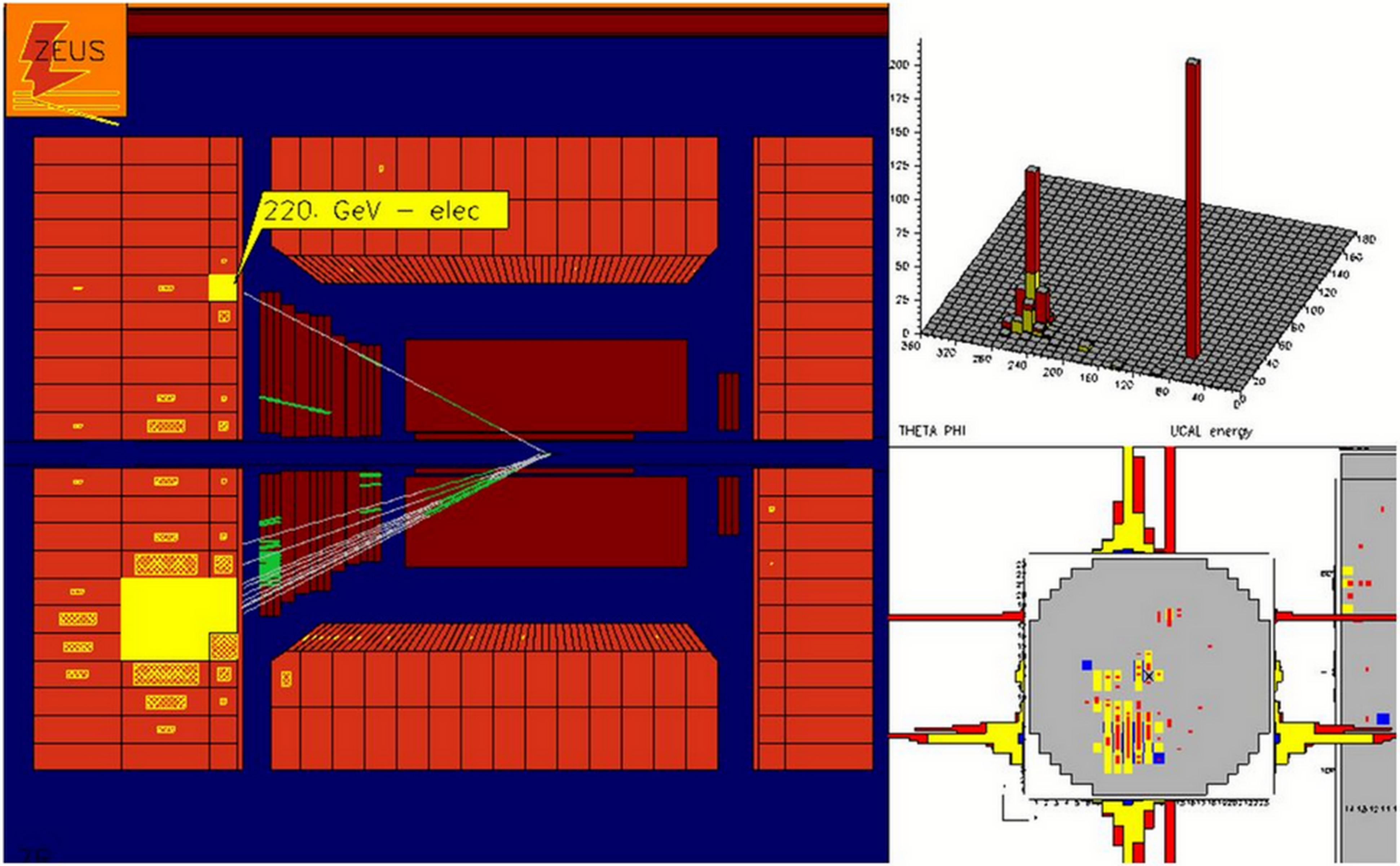


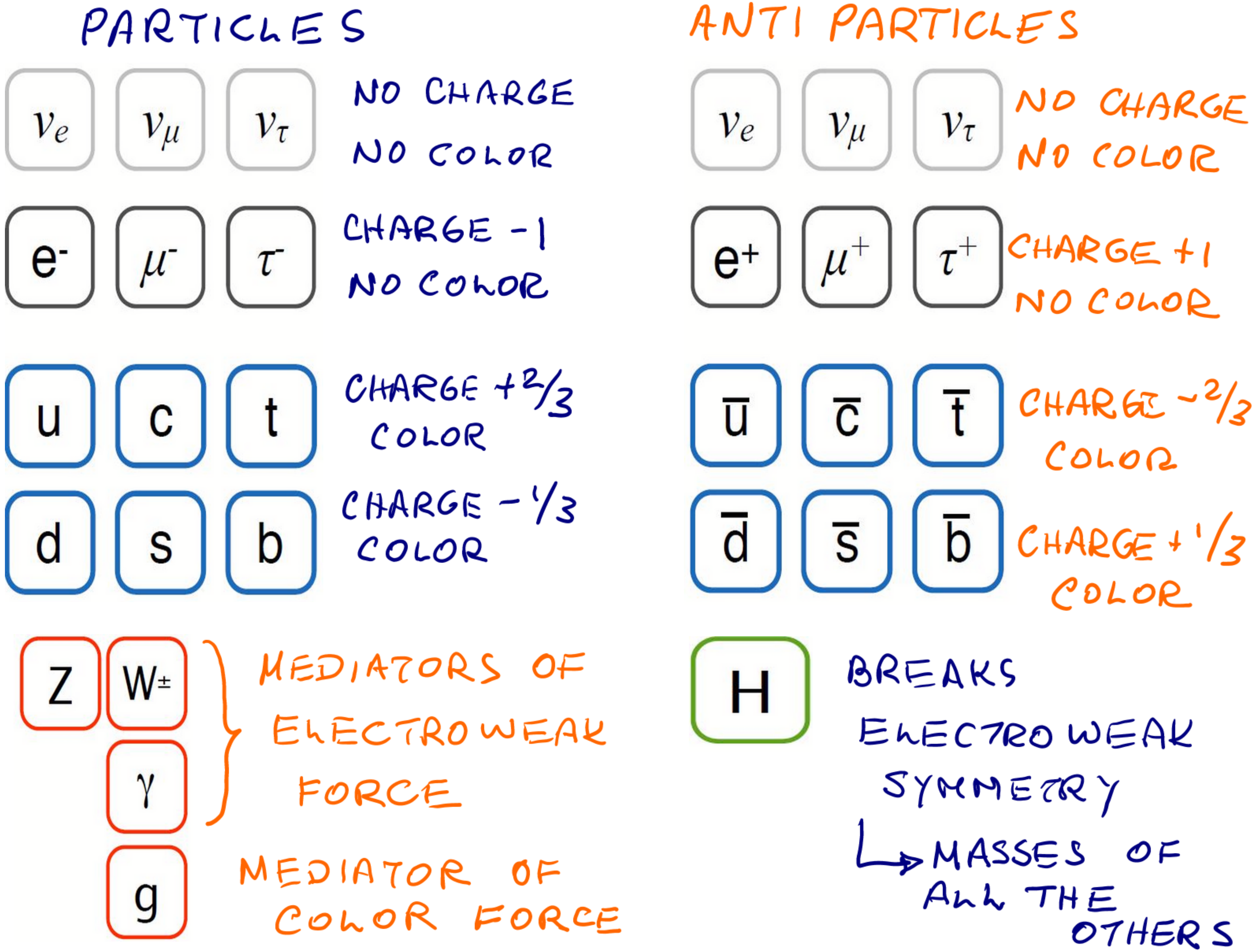
- Different Particles detected by different techniques.
  - Tracks of Ionization – Tracking Detectors
  - Showers of Secondary particles – Calorimeters

ATLAS Detector



ZEUS ep PROTON STRUCTURE

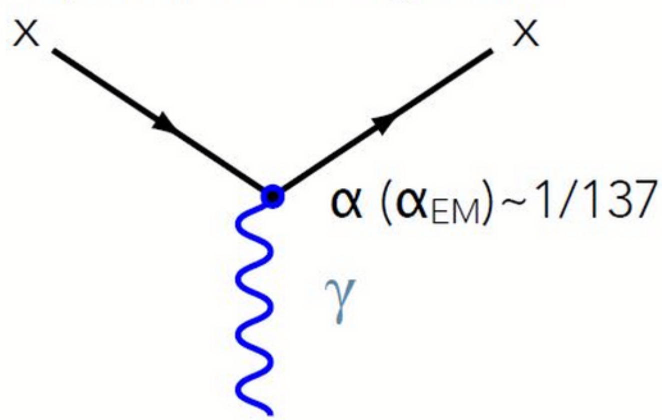




PARTICLES
ANTI PARTICLES
ν_e ν_μ ν_τ
NO CHARGE
NO COLOR
e^- μ^- τ^-
CHARGE −1
NO COLOR
u c t
CHARGE +2/3
COLOR
d s b
CHARGE −1/3
COLOR
ν_e ν_μ ν_τ
NO CHARGE
NO COLOR
e^+ μ^+ τ^+
CHARGE +1
NO COLOR
$\bar{u}$ $\bar{c}$ $\bar{t}$
CHARGE −2/3
COLOR
$\bar{d}$ $\bar{s}$ $\bar{b}$
CHARGE +1/3
COLOR
Z $W^\pm$ γ
MEDIATORS OF ELECTROWEAK FORCE
g
MEDIATOR OF COLOR FORCE
H
BREAKS ELECTROWEAK SYMMETRY
→ MASSES OF ALL THE OTHERS

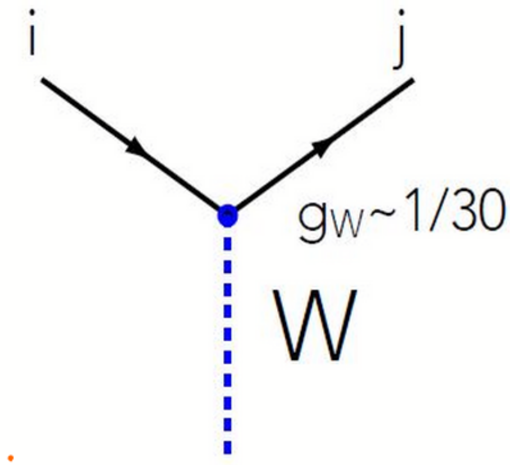
INTERACTIONS ≡ FORCES

electromagnetism
"quantum electrodynamics"



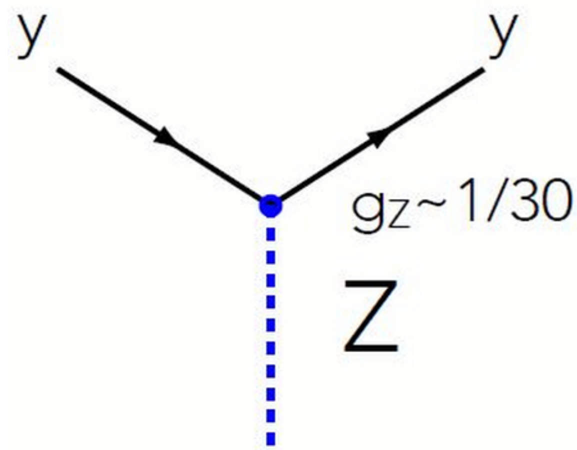
X = CHARGE PARTICLE

weak charged current



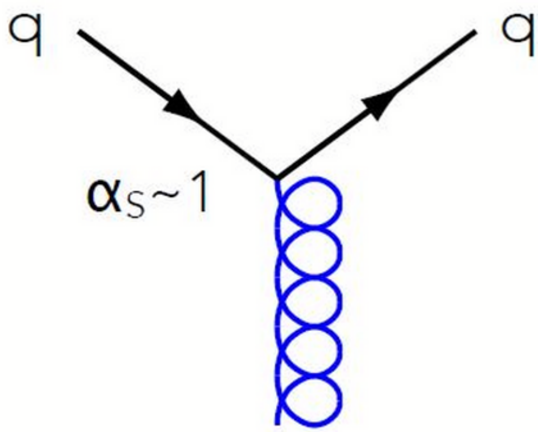
j = CHARGED PARTICLE OR NEUTRINO

weak neutral current



Y = ANY QUARK OR LEPTON

strong interaction
"quantum chromodynamics"



q IS ANY QUARK

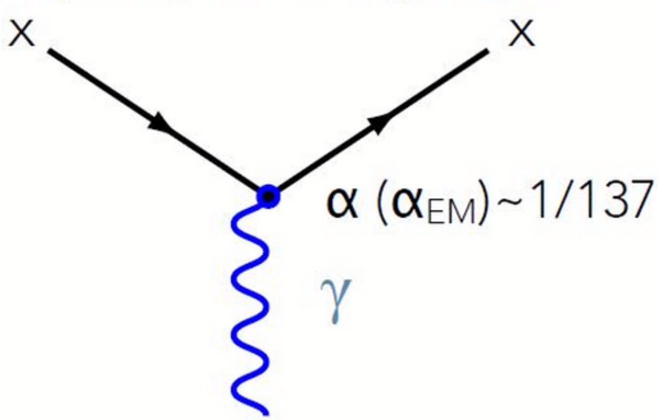
→ PARTICLE

← ANTI PARTICLE

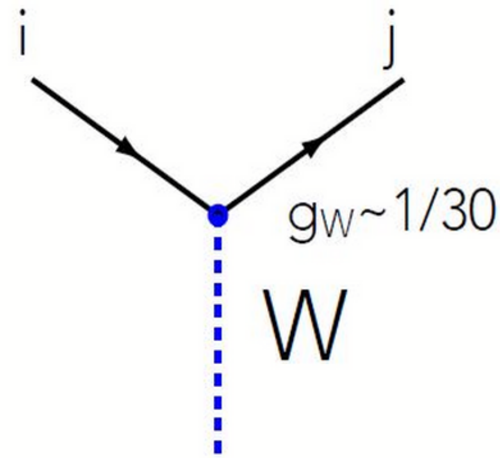
α, g COUPLING STRENGTH AT VERTEX

CONSERVATION LAWS ⟹ SYMMETRIES

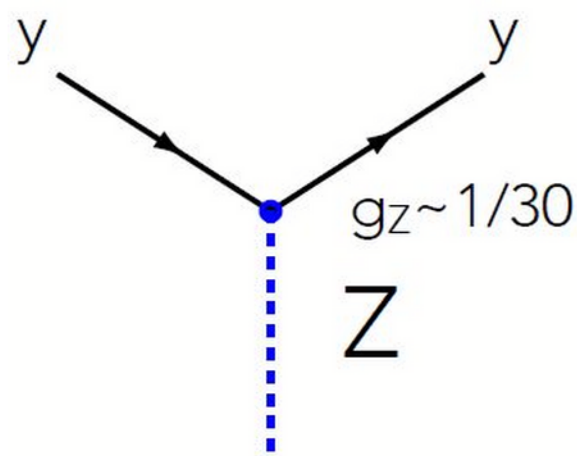
electromagnetism
"quantum electrodynamics"



weak charged current

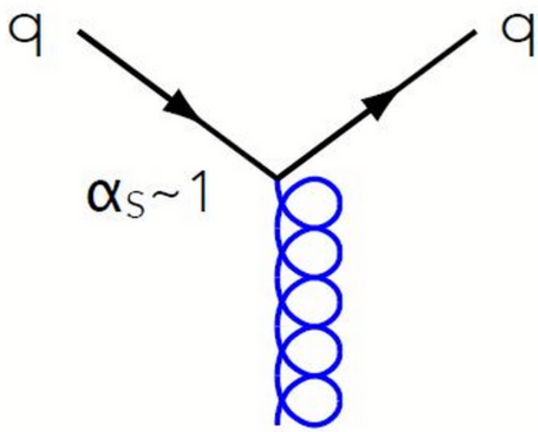


weak neutral current



CLASSICAL → MASS/ENERGY
ANGULAR MOMENTUM

strong interaction
"quantum chromodynamics"



STANDARD MODEL → BUILT INTO DIAGRAMS

- ELECTRIC CHARGE
- LEPTON NUMBER (FLAVOR)
  e, μ, τ

WHICH PARTICLES "SEE" WHICH FORCES?

ν_e ν_μ ν_τ

WEAK INTERACTION (W/Z)

NO ELECTROMAGNETIC OR COLOR

e^- μ^- τ^-

ELECTRO WEAK (γ/W/Z)

NO COLOR INTERACTION

u c t

d s b

ELECTROWEAK

COLOR (GLUON)

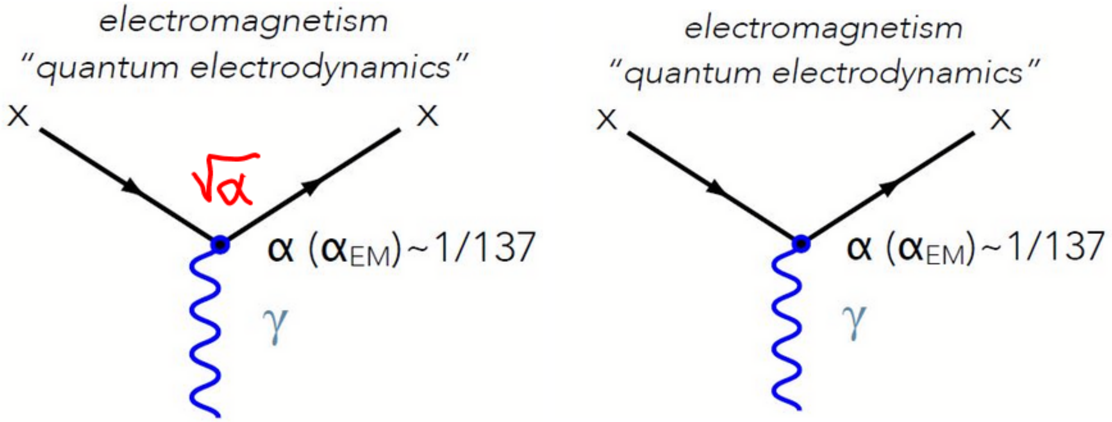
Z $W^\pm$ WEAK

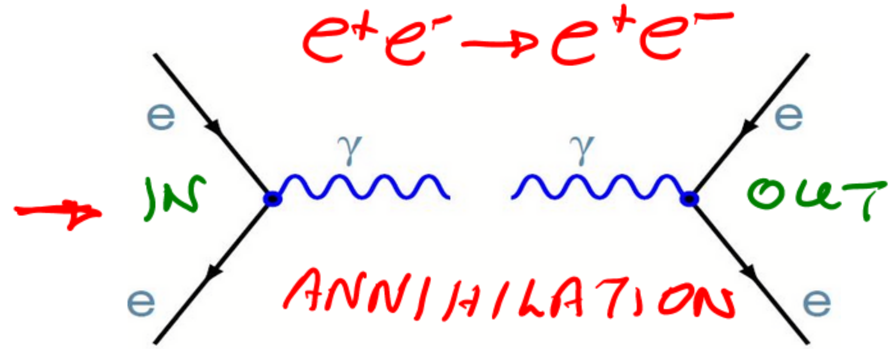
γ EM

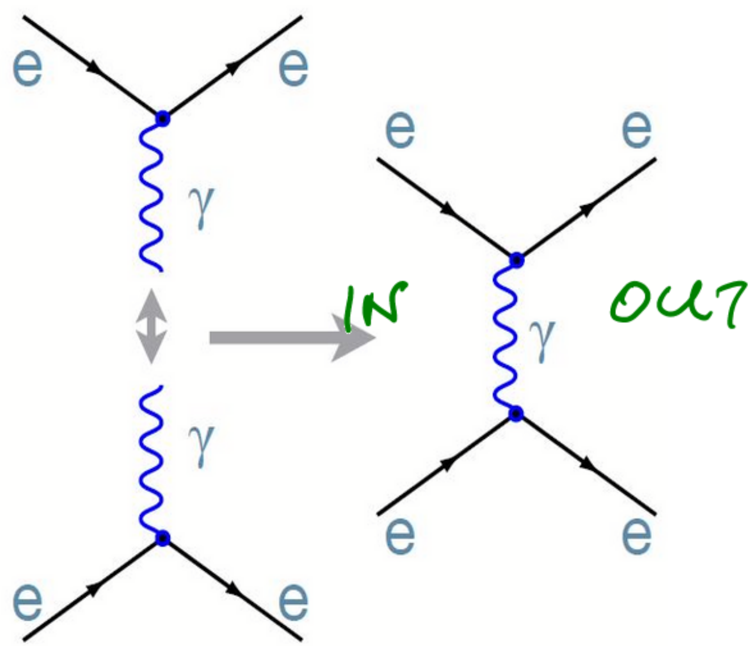
g COLOR

H ELECTRO WEAK INTERACTION

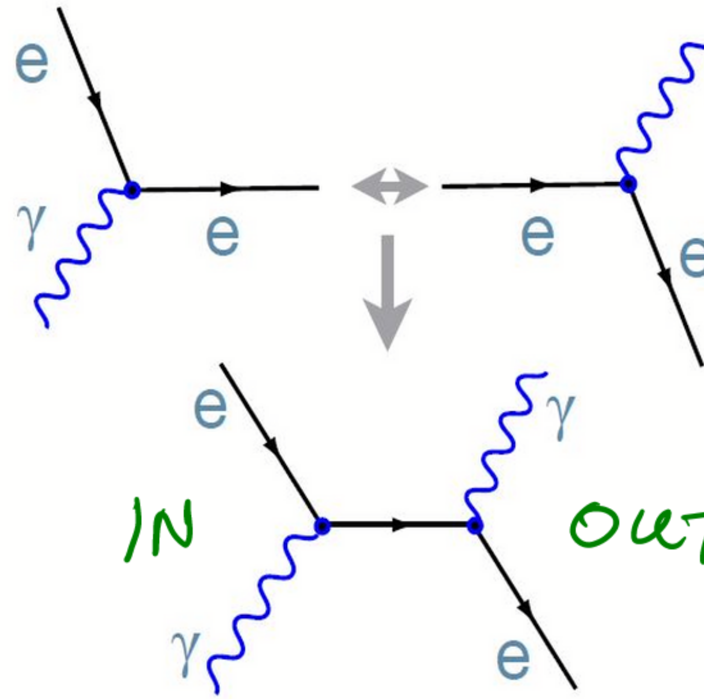
BUILD INTERACTIONS BY COMBINING DIAGRAMS → THEY CAN BE ROTATED







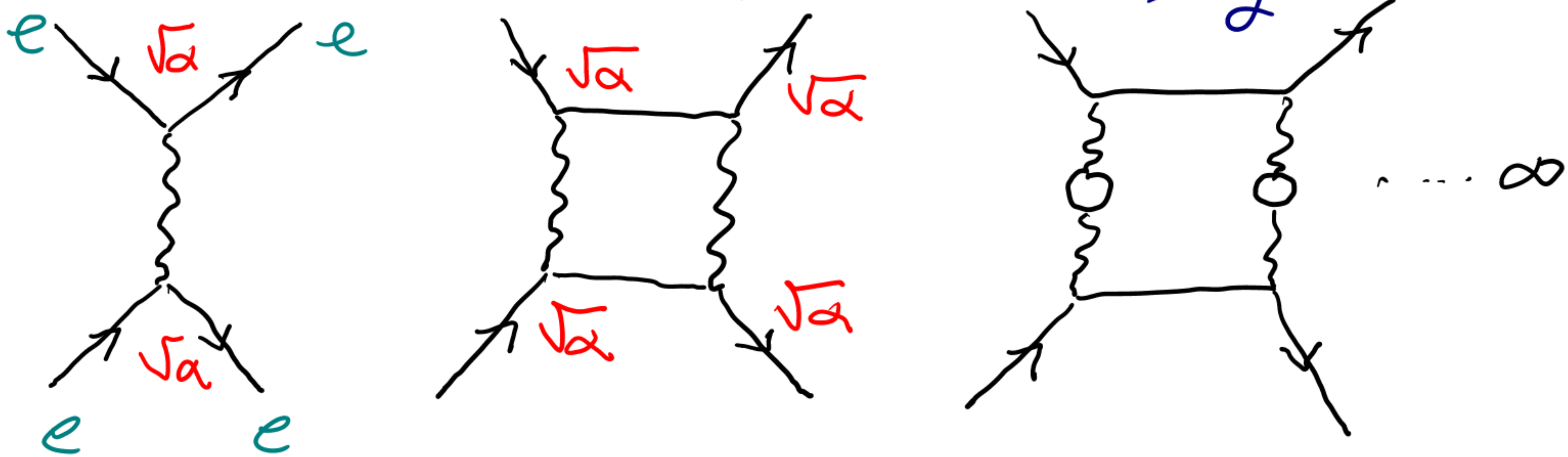
$e^+e^- \rightarrow e^+e^-$ SCATTERING



$e\gamma \rightarrow \gamma e$ COMPTON SCATTER

PERTURBATION THEORY

IN FACT THERE ARE A ∞ NUMBER OF POSSIBLE DIAGRAMS FOR ANY PROCESS, eg



$\sim \alpha = 1/137$ $\quad\sim \alpha^2$ $\quad\sim \alpha^4$

SINCE $\alpha \ll 1$ FIRST TERM GOOD $\sim 1\%$

HIGHER ACCURACY → HIGHER ORDER

WHAT IF COUPLING > 1 ?

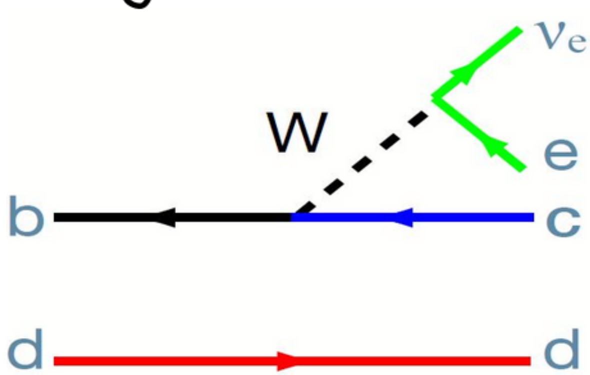
HADRONS

NEVER SEE FREE QUARKS. CONFINED INSIDE COLORLESS HADRONS

- MESONS $q\bar{q}$ $\pi, K, \rho, D, \Upsilon$ ......
- BARYONS qqq $p, n, \Lambda, \Sigma, \Xi$ ......

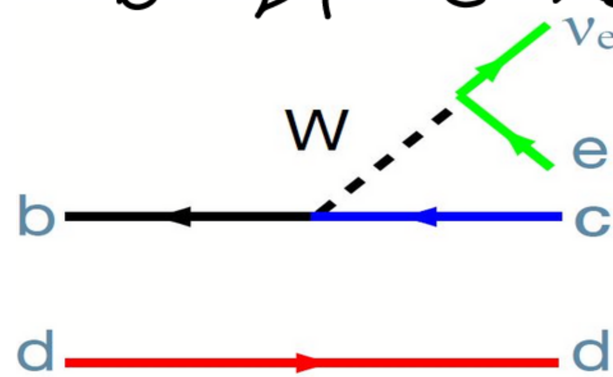
HADRON MASS SPECTRUM LED TO IDEA OF CONSTITUENT QUARKS.

$B_0 \to D^{*-} e^+ \nu_e$



TYPICAL WEAK DECAYS

$B^0 \to \rho^- e^+ \nu_e$



$W^{\pm}$ MEDIATES WEAK "CHARGED CURRENT"

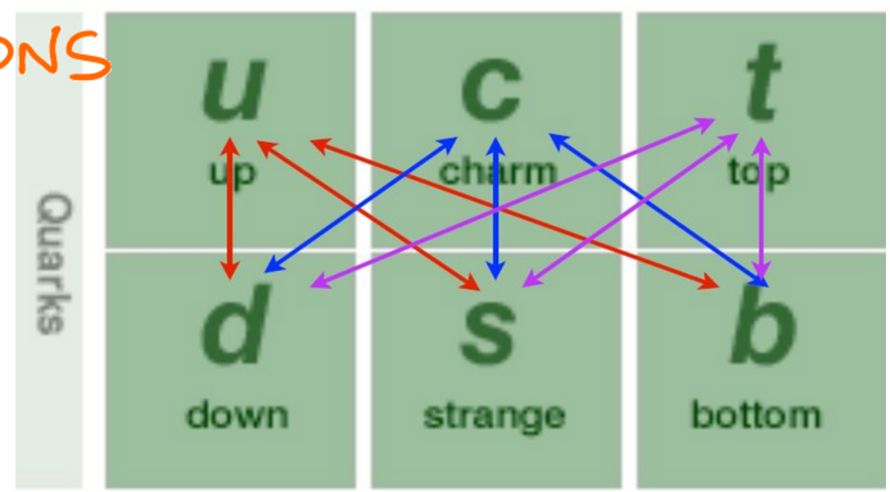
FOR LEPTONS – FLIPS IN GENERATION

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \updownarrow W^{\pm} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \updownarrow W^{\pm} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix} \updownarrow W^{\pm}$$

FOR QUARKS – GENERATION ⟷ GENERATION

TRANSITION PROBABILITY GOES DOWN AS GENERATIONS BECOME FURTHER APART IN MASS.

CKM MATRIX



CDF @ TEVATRON