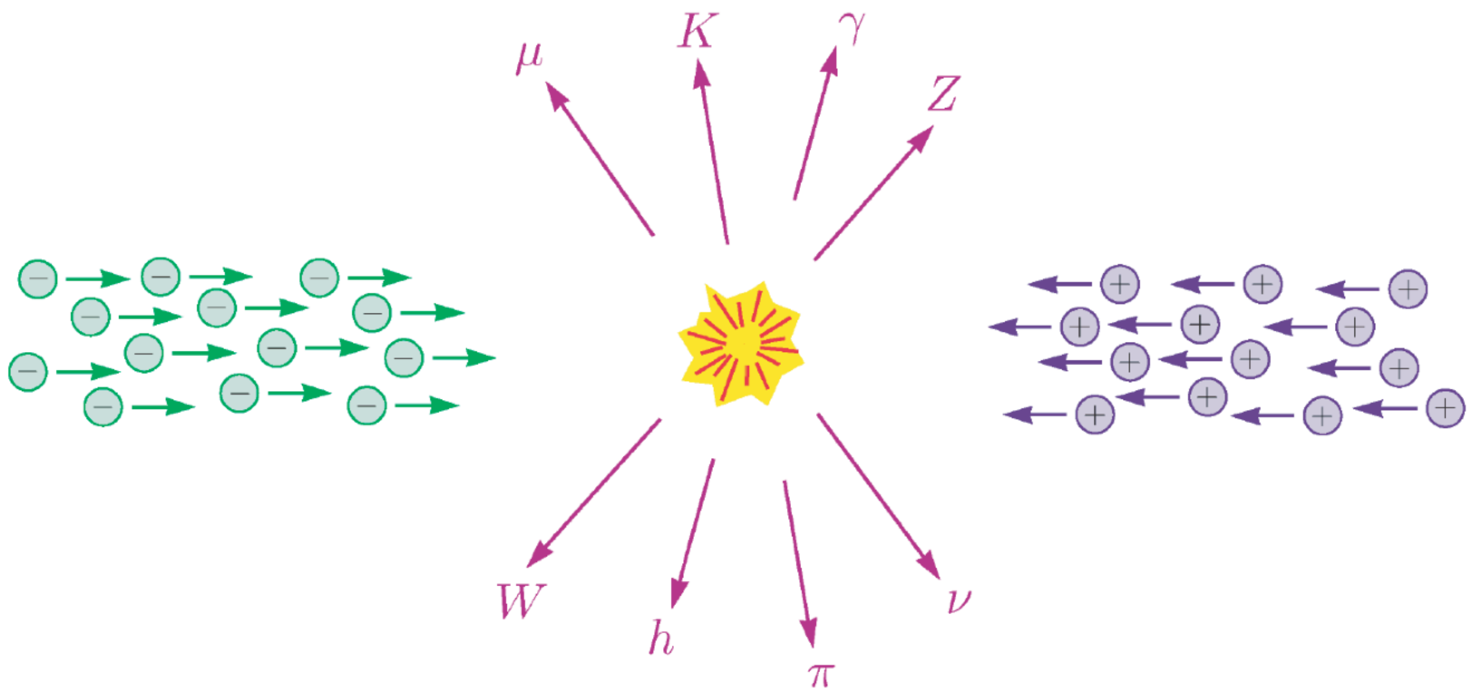
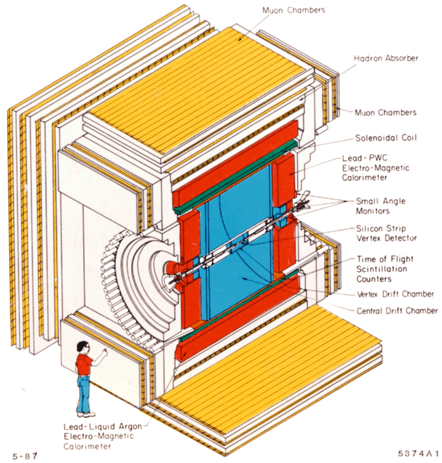
High-Energy Particle Physics

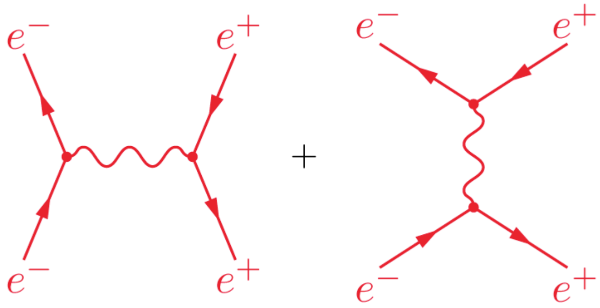


D. Schroeder, 30 November 2012

Outline

- Colliders (storage rings)
- Detectors
- Example reactions
- Feynman diagrams
- The Periodic Table
- Discovering Neptune





Why high energy?

1. Produce massive particles: $E = mc^2$

2. Probe small length scales:

$$\lambda = \frac{h}{p} = \frac{hc}{E}$$

for ultra-relativistic particles

$$= \frac{1240 \text{ eV-nm}}{E} = \frac{1.24 \text{ GeV-fm}}{E}$$


20 GeV electron accelerator
Photo: SLAC


Photo: SLAC

Photo: SLAC

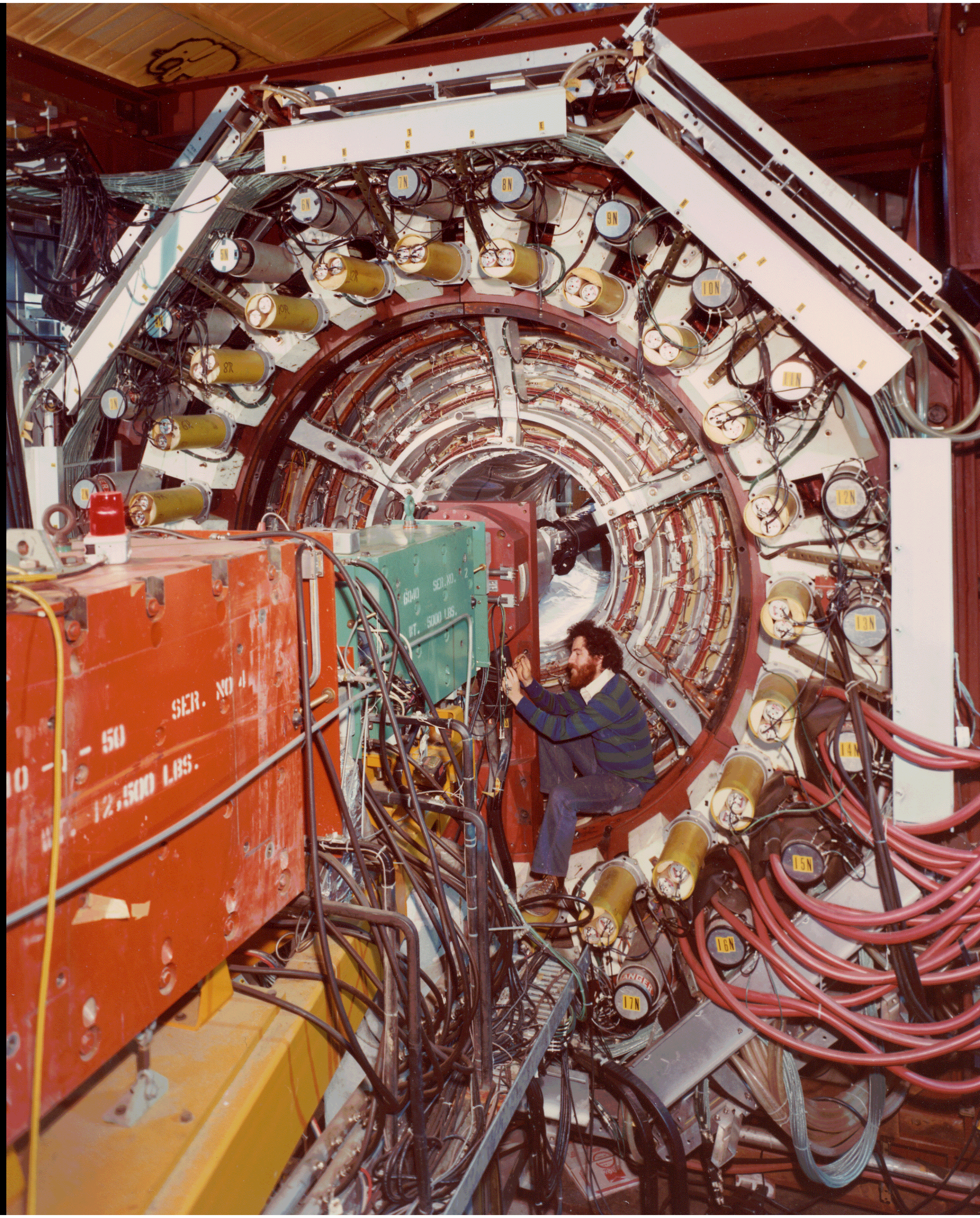


Photo: SLAC

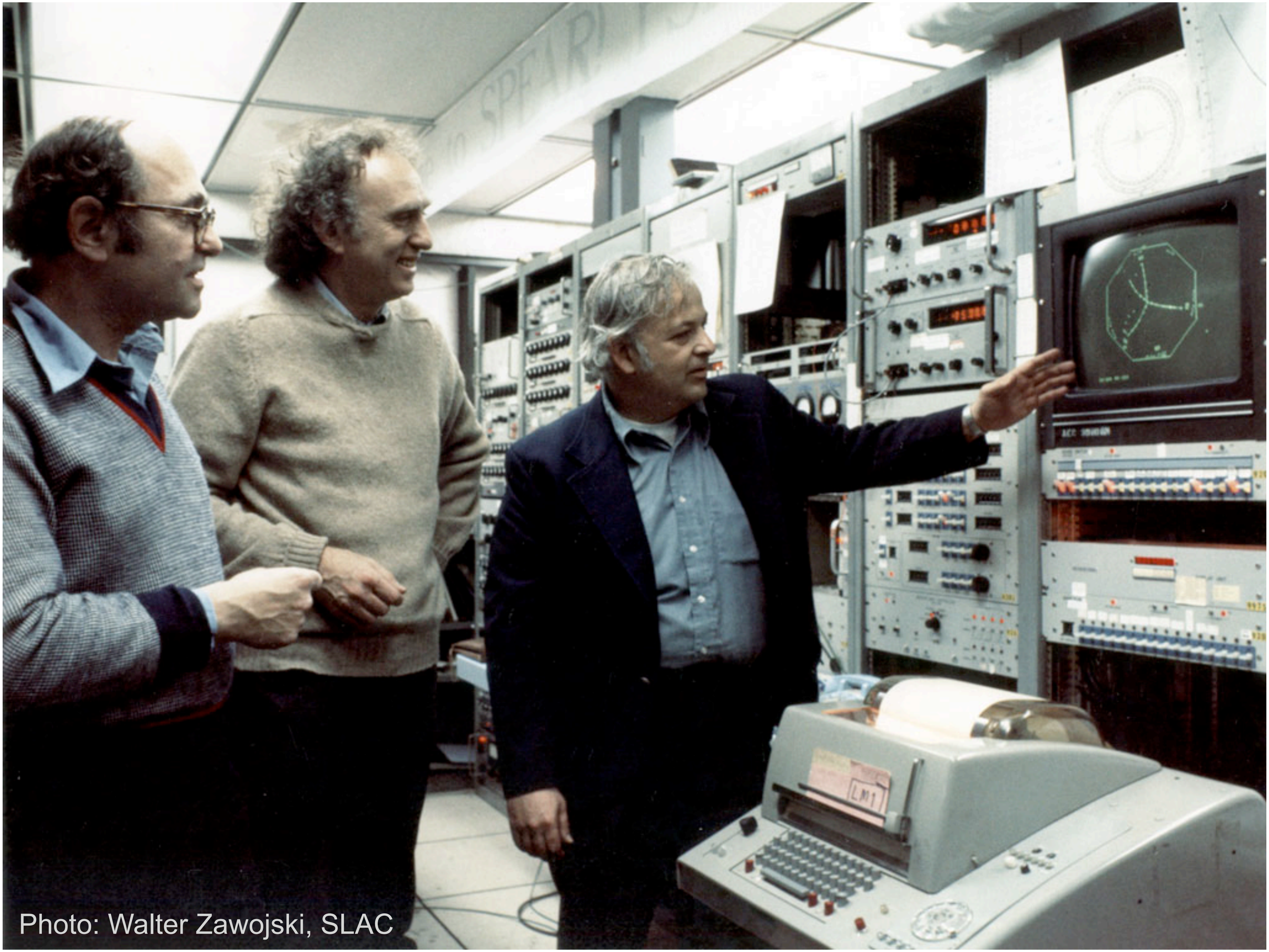


Photo: Walter Zawojski, SLAC


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km
Photo: CERN

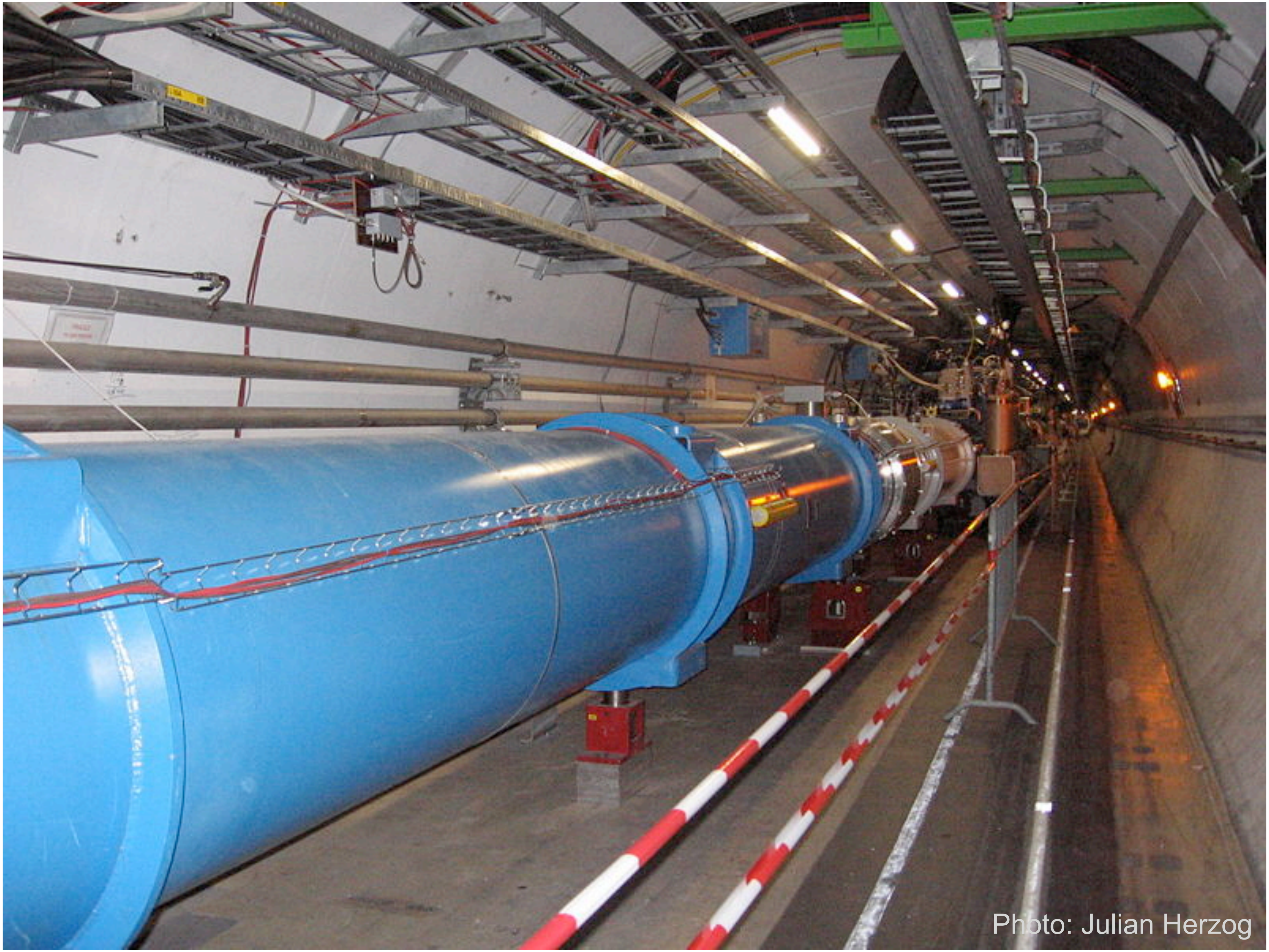


Photo: Julian Herzog

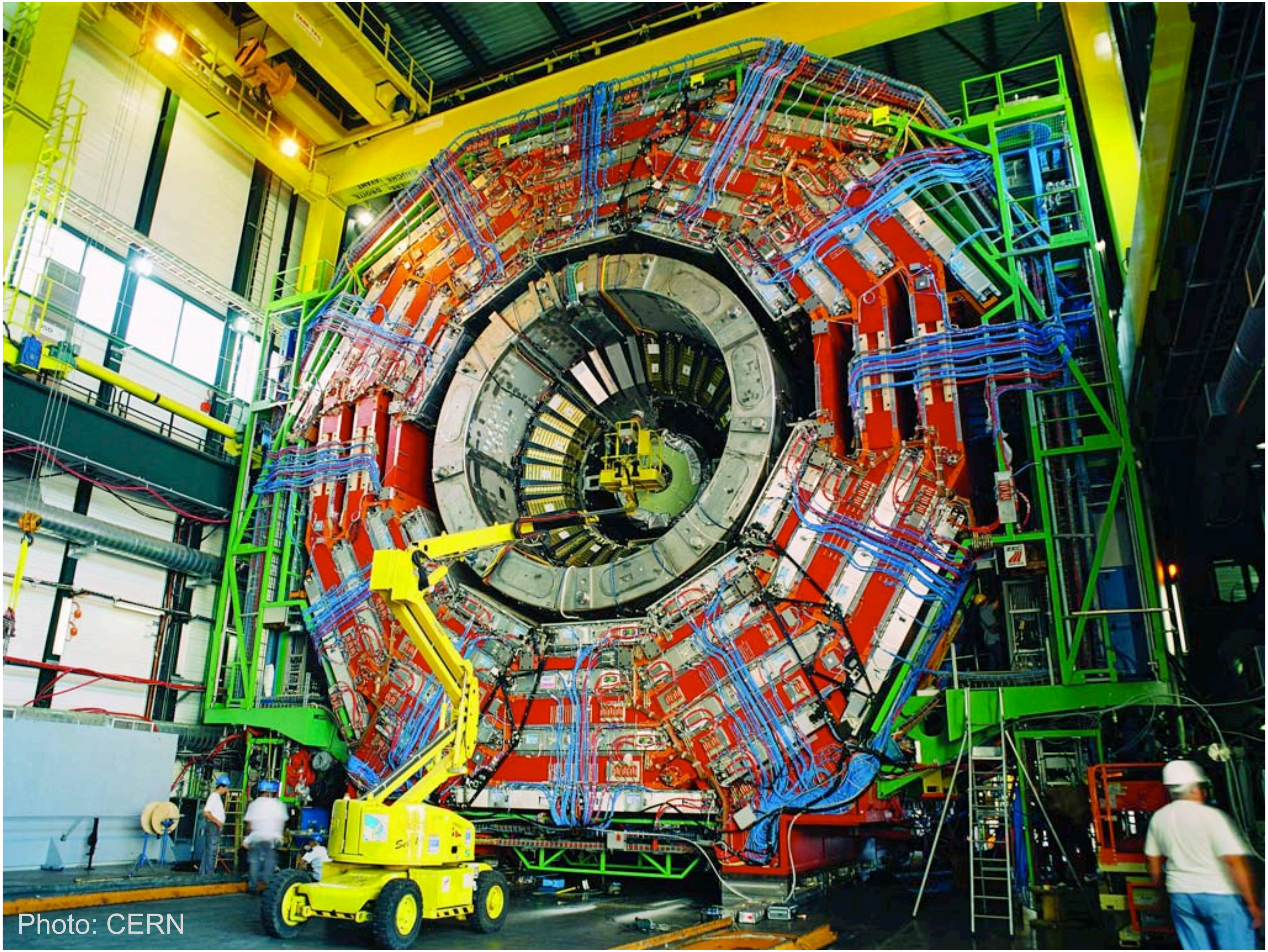


Photo: CERN

How high can the LHC energy be?

Newton's second law: $\vec{F}_B = m\vec{a}$

For circular motion perpendicular to field, $qvB = \dfrac{mv^2}{R}$

But for a relativistic particle, $m\vec{a}$ becomes $\dfrac{d\vec{p}}{dt}$ where $\vec{p} = \dfrac{m\vec{v}}{\sqrt{1-(v/c)^2}} = \gamma m\vec{v}$

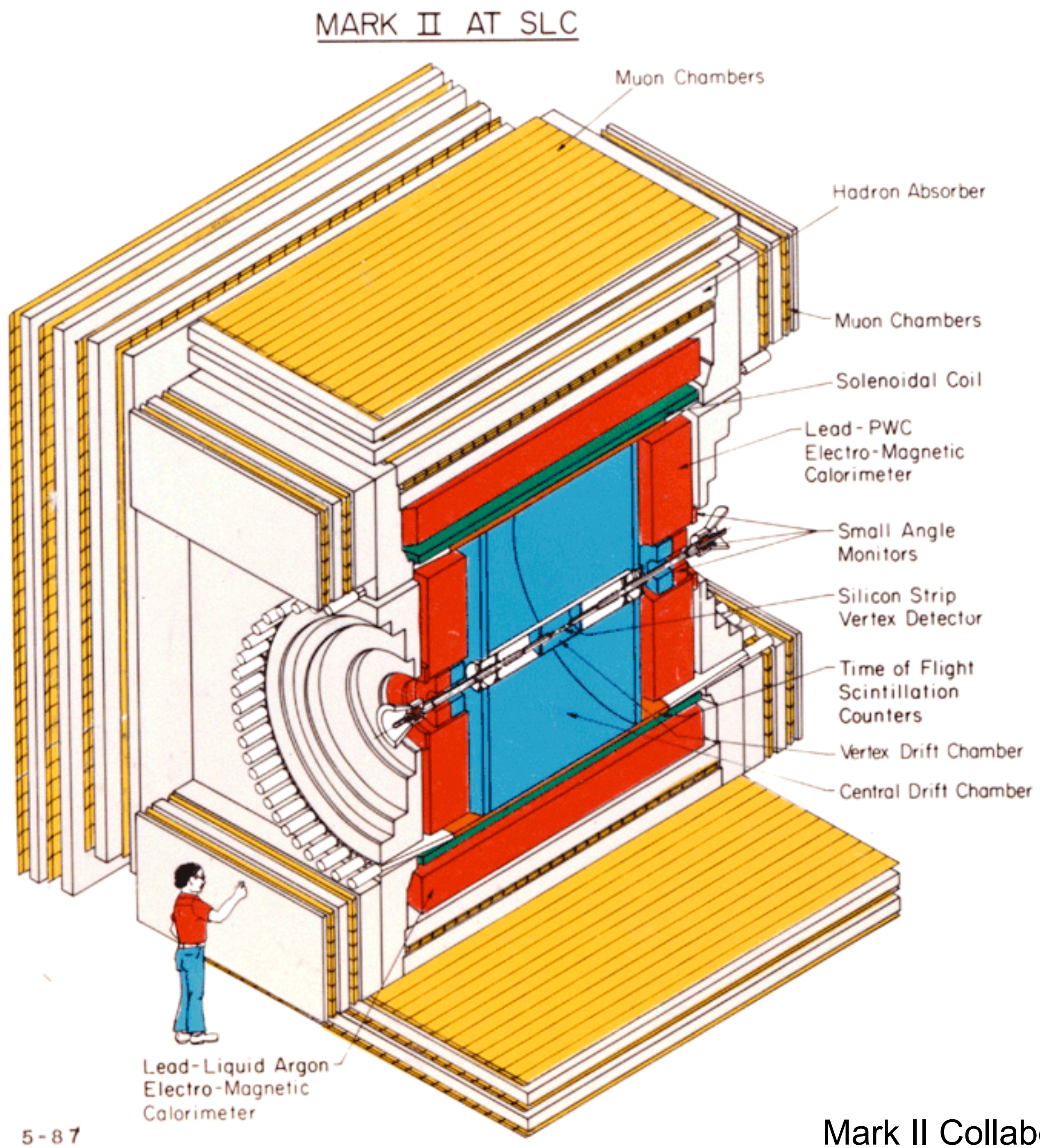
So $qvB = \dfrac{\gamma m v^2}{R} \longrightarrow \gamma m v = qBR$

Since $v \approx c$,

$$E_{\rm max} = \gamma mc^2 = qBR\,c = (1.6\times10^{-19}\ \mathrm{C})(8.3\ \mathrm{T})(4230\ \mathrm{m})(3\times10^8\ \mathrm{m/s}) = 10.5\times10^{12}\ \mathrm{eV}$$

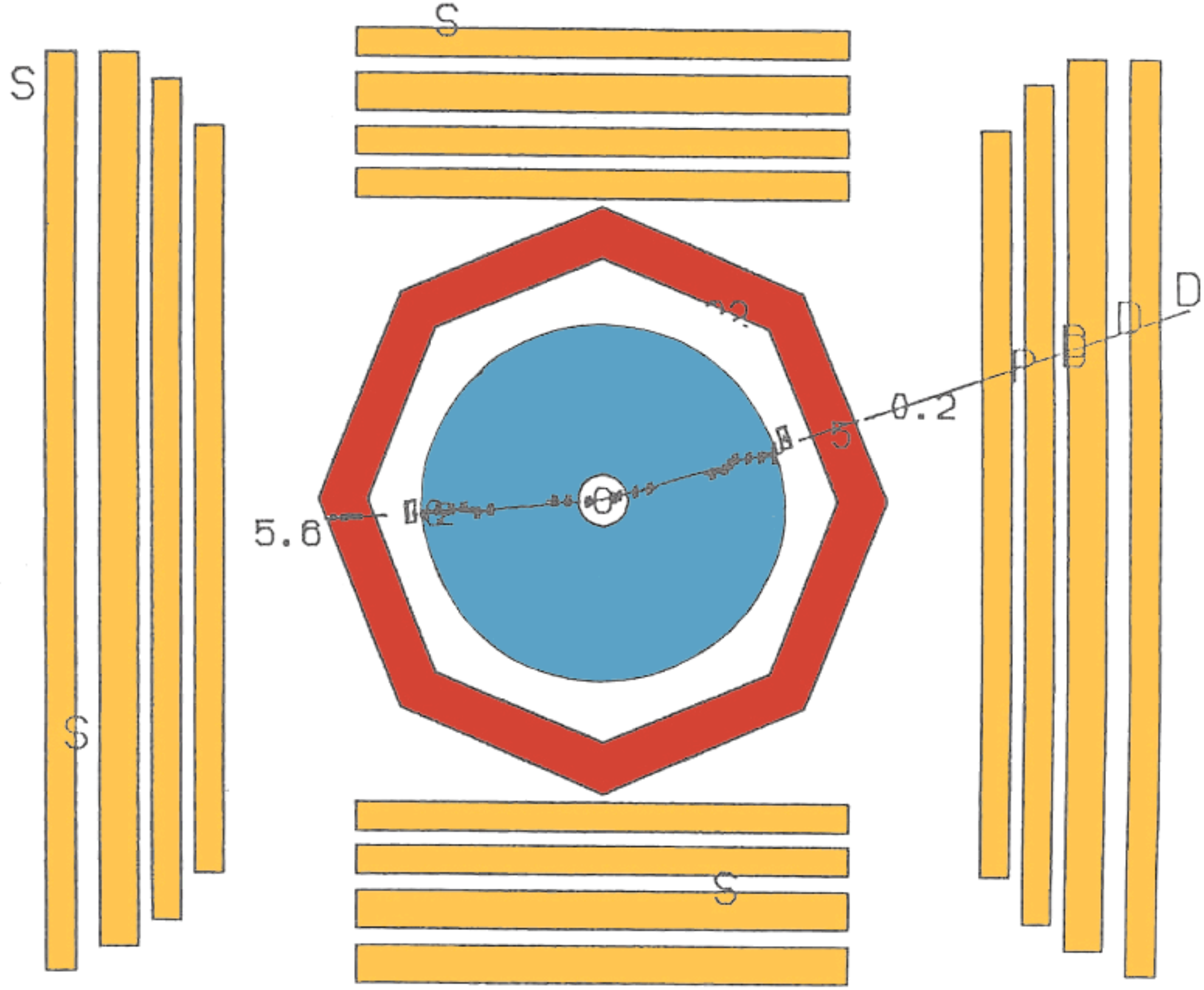
But bending magnets don't fill entire ring, so actually $E_{\rm max} = 7$ TeV

Therefore $\gamma = \dfrac{E}{mc^2} = \dfrac{7000\ \mathrm{GeV}}{0.938\ \mathrm{GeV}} = 7460$ $\qquad \dfrac{v}{c} = \sqrt{1-\dfrac{1}{\gamma^2}} = 0.99999991$



Mark II Collaboration, SLAC

Mark II $e^{+}\mu^{-}$ Event Reconstruction



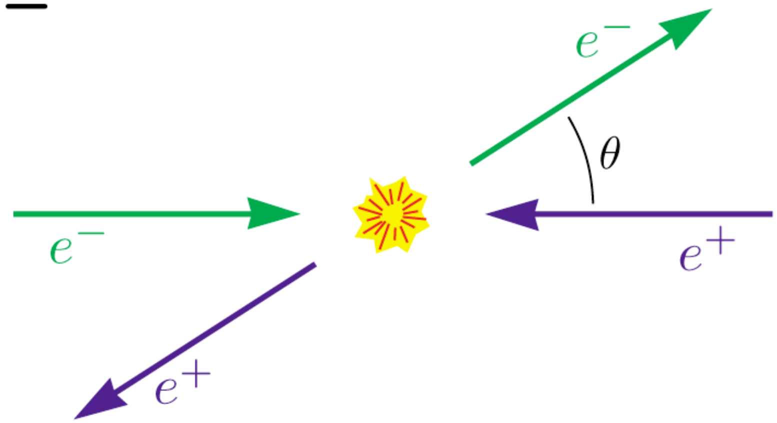
Mark II Collaboration, SLAC

Example 1: $e^+e^- \longrightarrow e^+e^-$

total momentum $= 0$

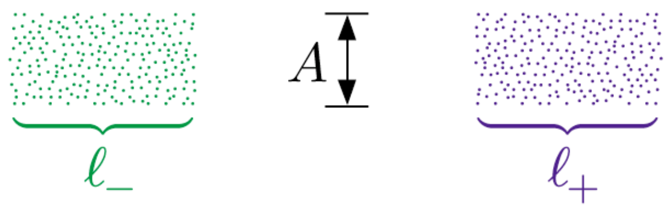
total energy $= 2E$

Probability(E,θ) = **?**



E-dependence follows from dimensional analysis:

density $= \rho_-$



density $= \rho_+$

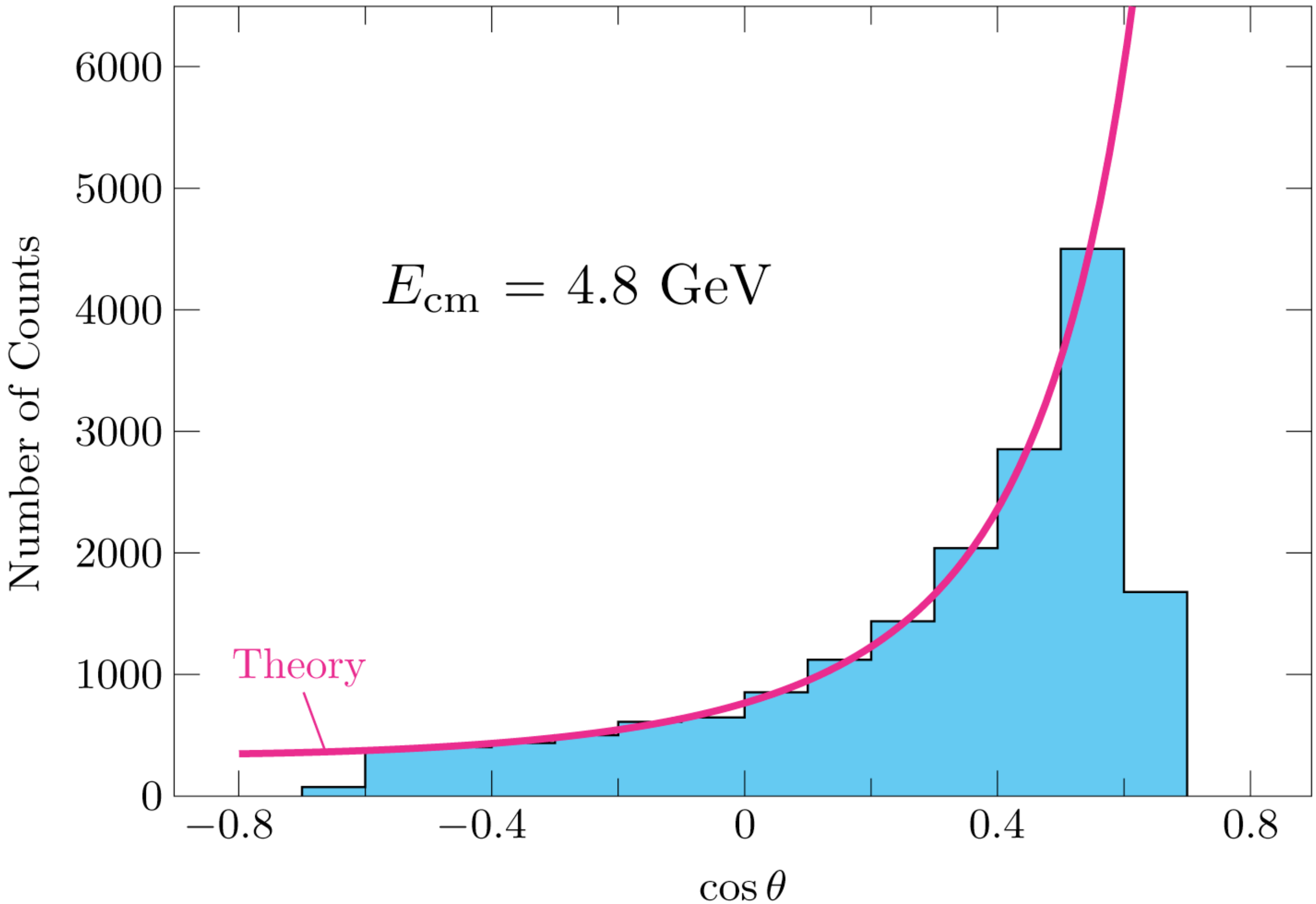
$$\text{Probability} = (\rho_- \, \rho_+ \, \ell_- \, \ell_+ \, A) \times (\text{something with units of length}^2)$$

When $E \gg m_e$, the only relevant length is $\dfrac{\hbar}{p} = \dfrac{\hbar c}{E}$

$$\Longrightarrow \quad \textbf{Probability} \propto \frac{1}{E^2}$$

$e^+e^- \longrightarrow e^+e^-$ at SPEAR

Augustin, et al., PRL 34, 233 (1975)

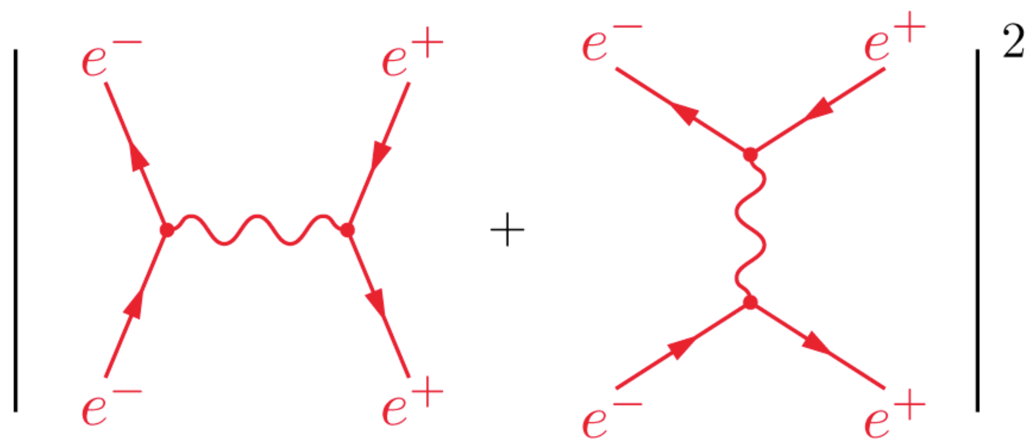


Prediction for $e^+e^- \longrightarrow e^+e^-$ event rate (H. J. Bhabha, 1935):

$$\begin{pmatrix}\text{event}\\ \text{rate}\end{pmatrix} \propto \frac{d\sigma}{d\Omega} = \frac{e^4}{32\pi^2 E_{\text{cm}}^2}\left[\frac{1+\cos^4\frac{\theta}{2}}{\sin^4\frac{\theta}{2}} - \frac{2\cos^4\frac{\theta}{2}}{\sin^2\frac{\theta}{2}} + \frac{1+\cos^2\theta}{2}\right]$$

Interpretation of Bhabha's formula (R. P. Feynman, 1949):

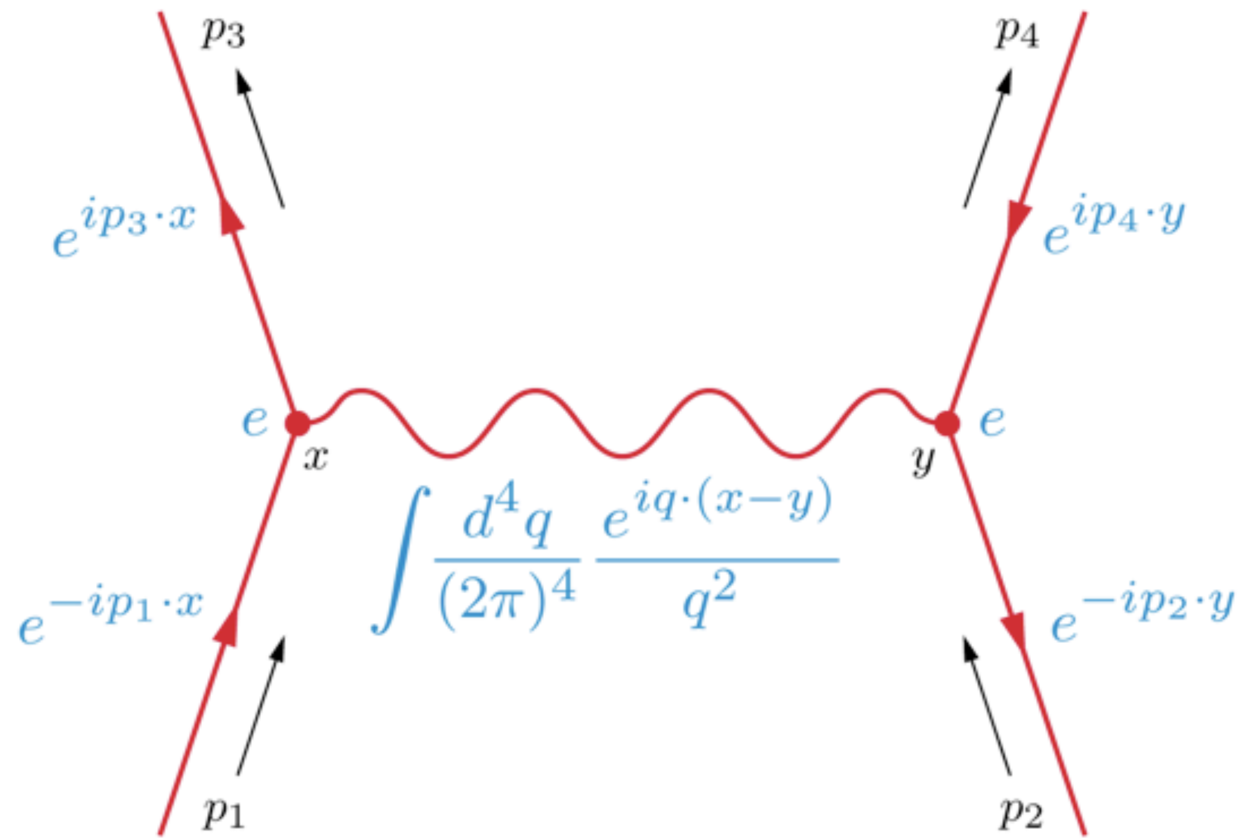
$$= (\text{const.}) \times$$



Each diagram represents a complex number that depends on E and θ.

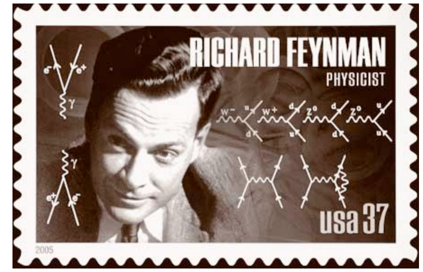
Each vertex represents a factor of the electron's charge, $e = -0.303$.

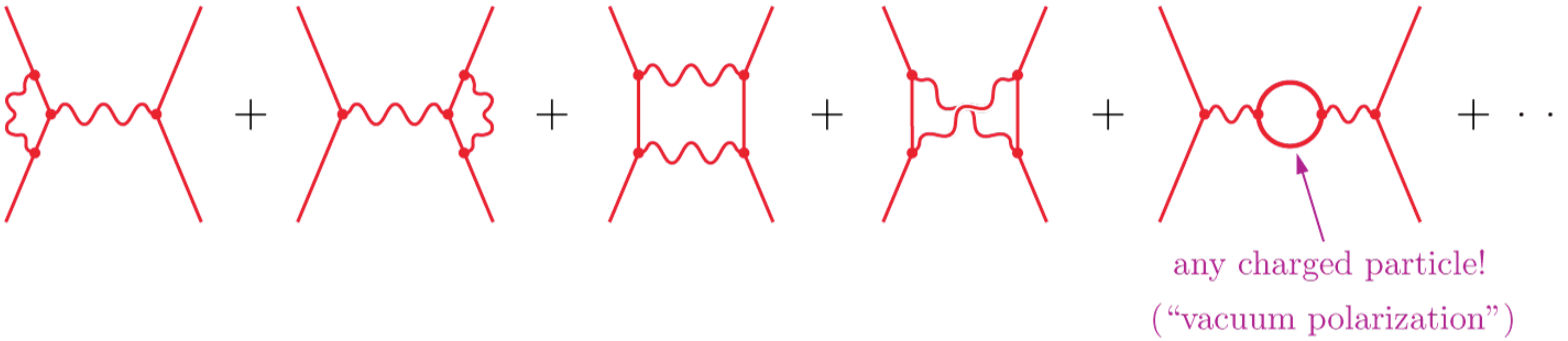
Feynman Rules (neglecting spin, $\hbar = c = 1$)



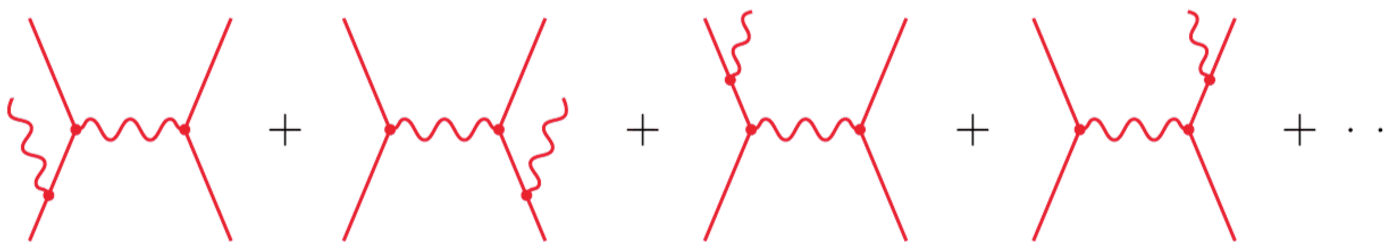
Multiply pieces together, integrate over x and y . . .

Higher-Order Diagrams





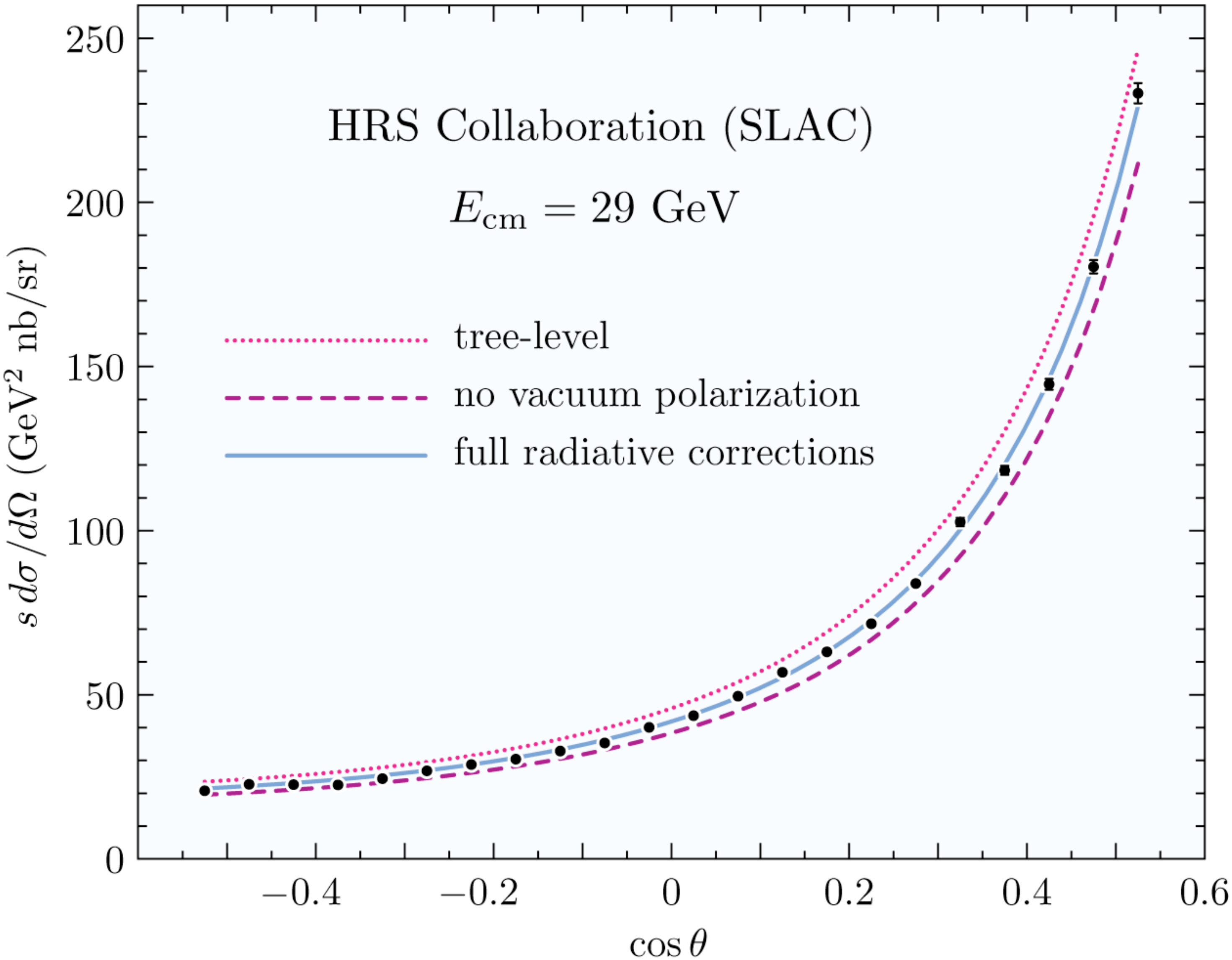
Also:



More vertices $\Longrightarrow$ more factors of e $\Longrightarrow$ smaller value

It Works!

M. Derrick, et al., *Phys. Rev.* D34, 3286 (1986)



THE PERIODIC TABLE

Particles like the electron (fermions, spin 1/2)

Leptons		Quarks (each in 3 "colors")	
e 0.511 MeV	ν_e < 0.000003	d 7	u 3
μ 106	ν_μ < 0.2	s 120	c 1200
τ 1777	ν_τ < 20	b 4300	t 175,000
−1	0	−1/3	2/3 ← charge

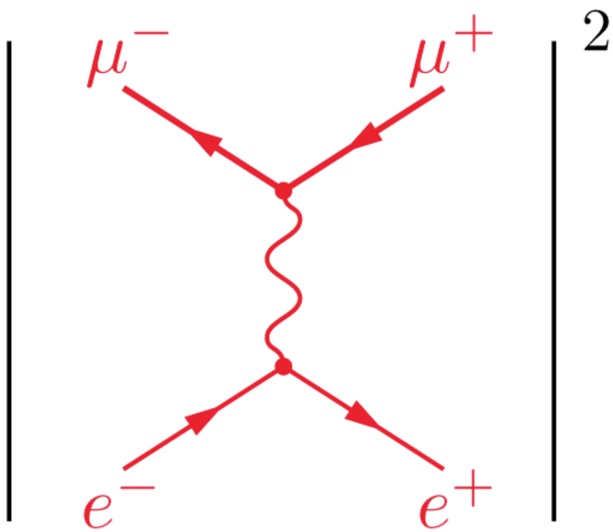
Particles like the photon (bosons, spin 1)

γ 0	photon	"electromagnetism"
g 0	gluon (8 "colors")	"strong interaction"
$W^\pm$ 80,420	Z^0 91,188	"weak interaction"

(Gravity is negligible.)

Example 2: $e^+e^- \longrightarrow \mu^+\mu^-$

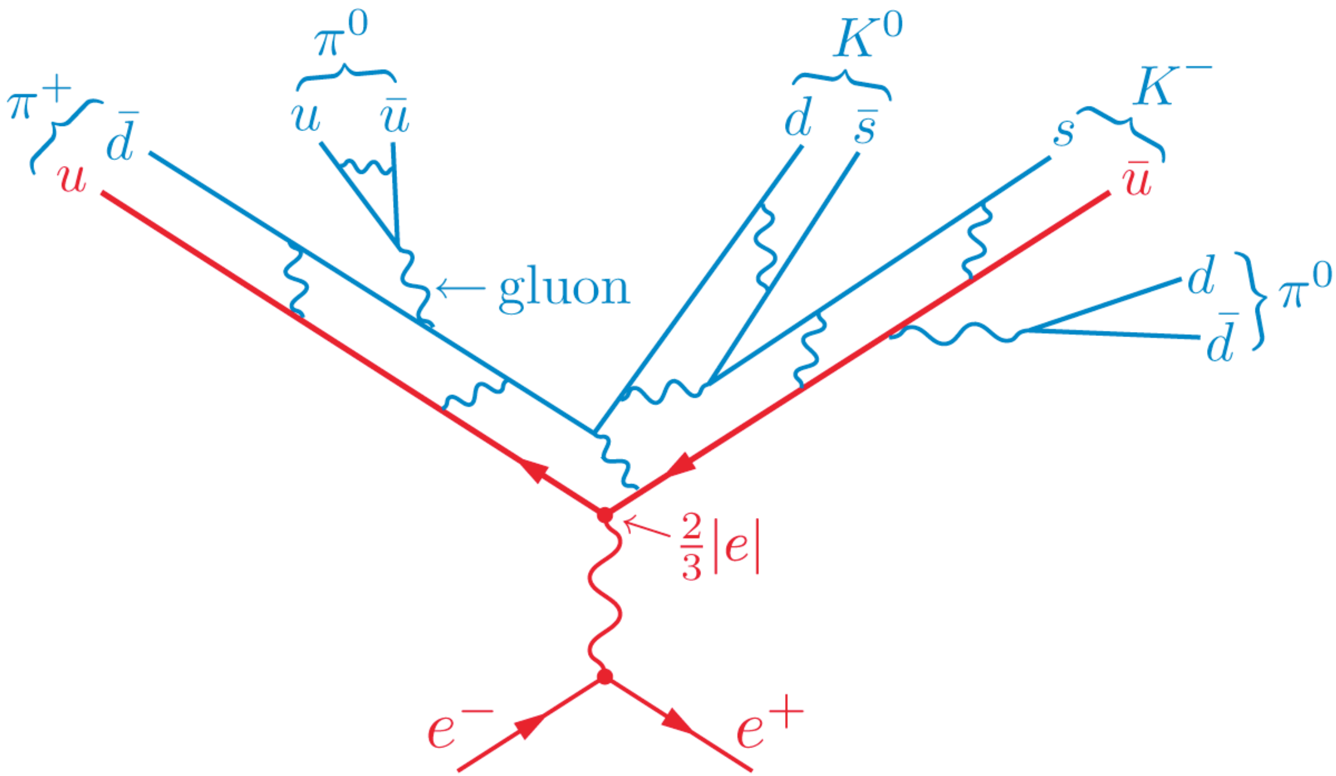
Only one diagram:



$$\left| \; \right|^2 = (\text{const.}) \times \frac{e^4}{E^2}\left(1 + \cos^2\theta\right)$$

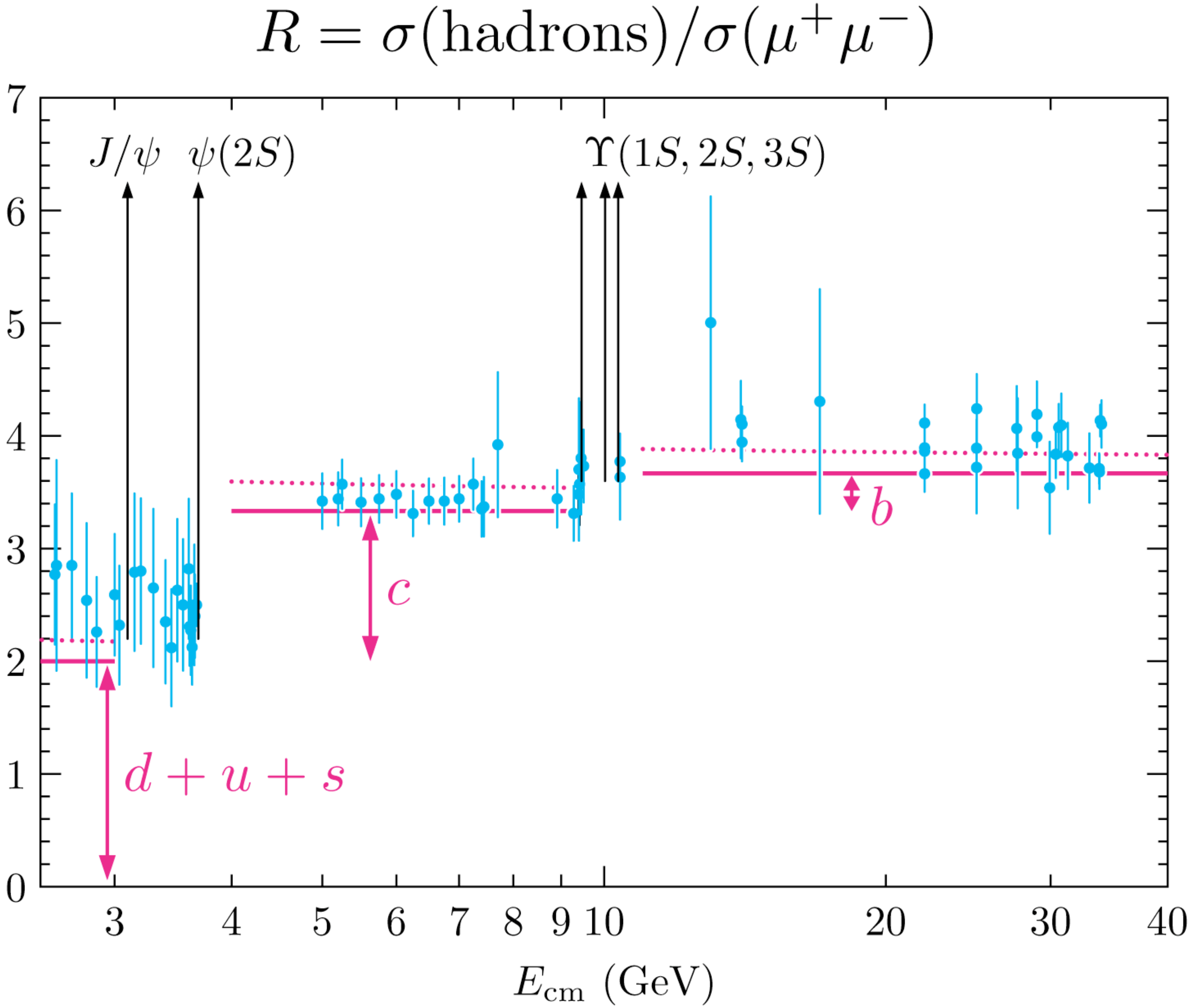
(Same as third term in Bhabha formula, provided that $E \gg m_\mu$.)

Example 3: $\boldsymbol{e^+e^- \longrightarrow q\bar{q} \longrightarrow}$ **hadrons**

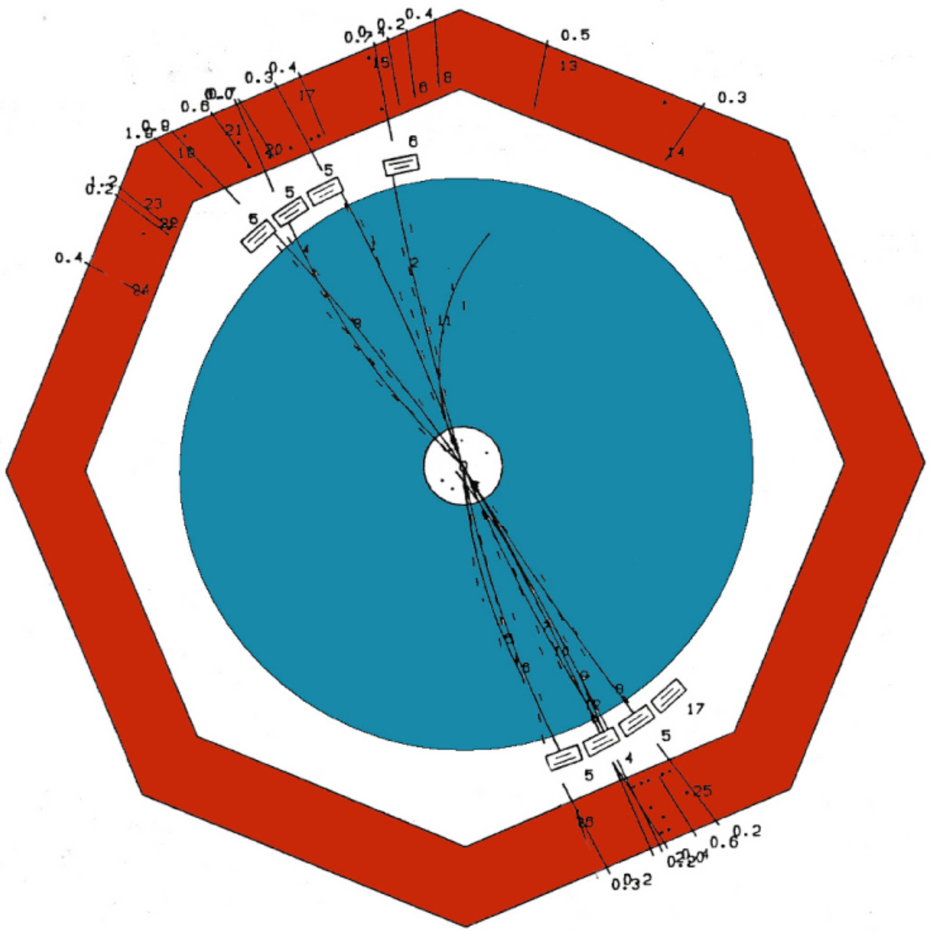


For $10\ \text{GeV} < E_{\text{cm}} < 40\ \text{GeV}$,

$$\frac{e^+e^- \to \text{hadrons}}{e^+e^- \to \mu^+\mu^-} = \underset{\substack{\uparrow \\ \text{colors}}}{3} \times \left[\underset{\substack{\uparrow \\ d}}{\left(\frac{1}{3}\right)^2} + \underset{\substack{\uparrow \\ u}}{\left(\frac{2}{3}\right)^2} + \underset{\substack{\uparrow \\ s}}{\left(\frac{1}{3}\right)^2} + \underset{\substack{\uparrow \\ c}}{\left(\frac{2}{3}\right)^2} + \underset{\substack{\uparrow \\ b}}{\left(\frac{1}{3}\right)^2} \right]$$

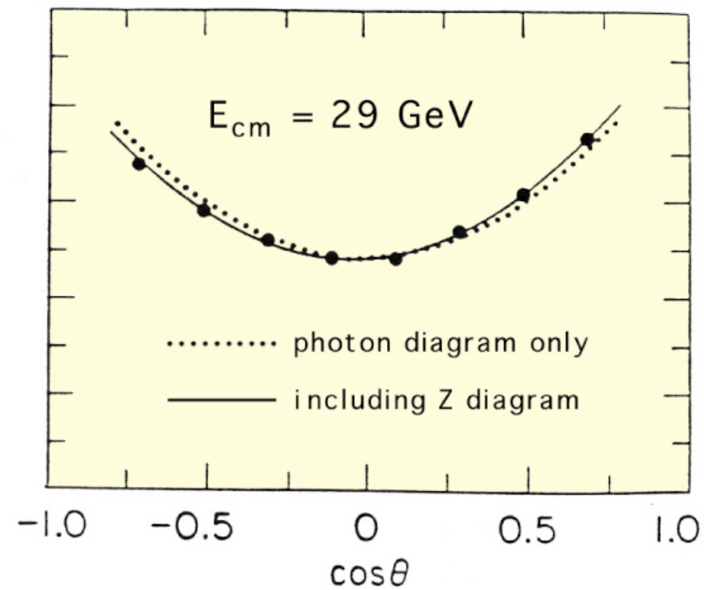

$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$
J/ψ
$\psi(2S)$
$\Upsilon(1S, 2S, 3S)$
c
b
$d + u + s$
E_{cm} (GeV)
0
1
2
3
4
5
6
7
3
4
5
6
7
8
9
10
20
30
40

2-Jet Hadronic Event

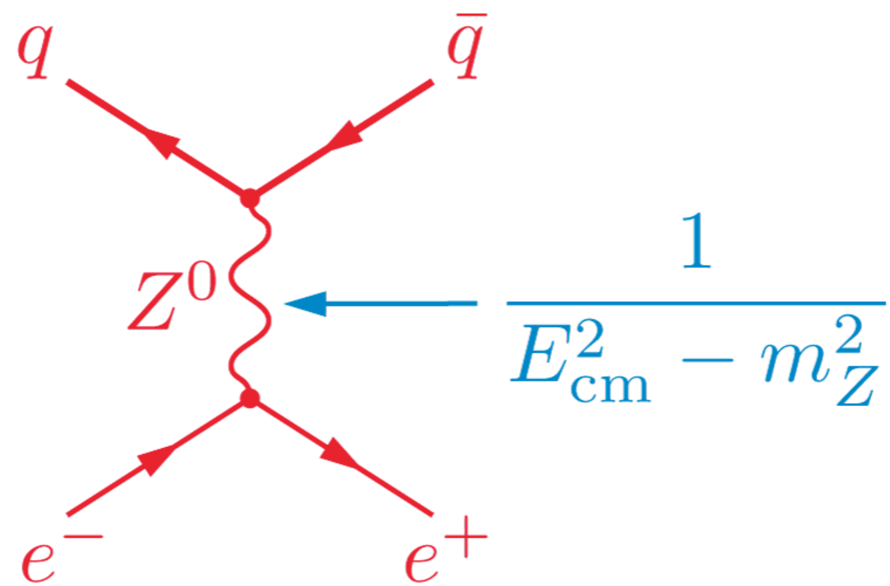


Angular Distribution

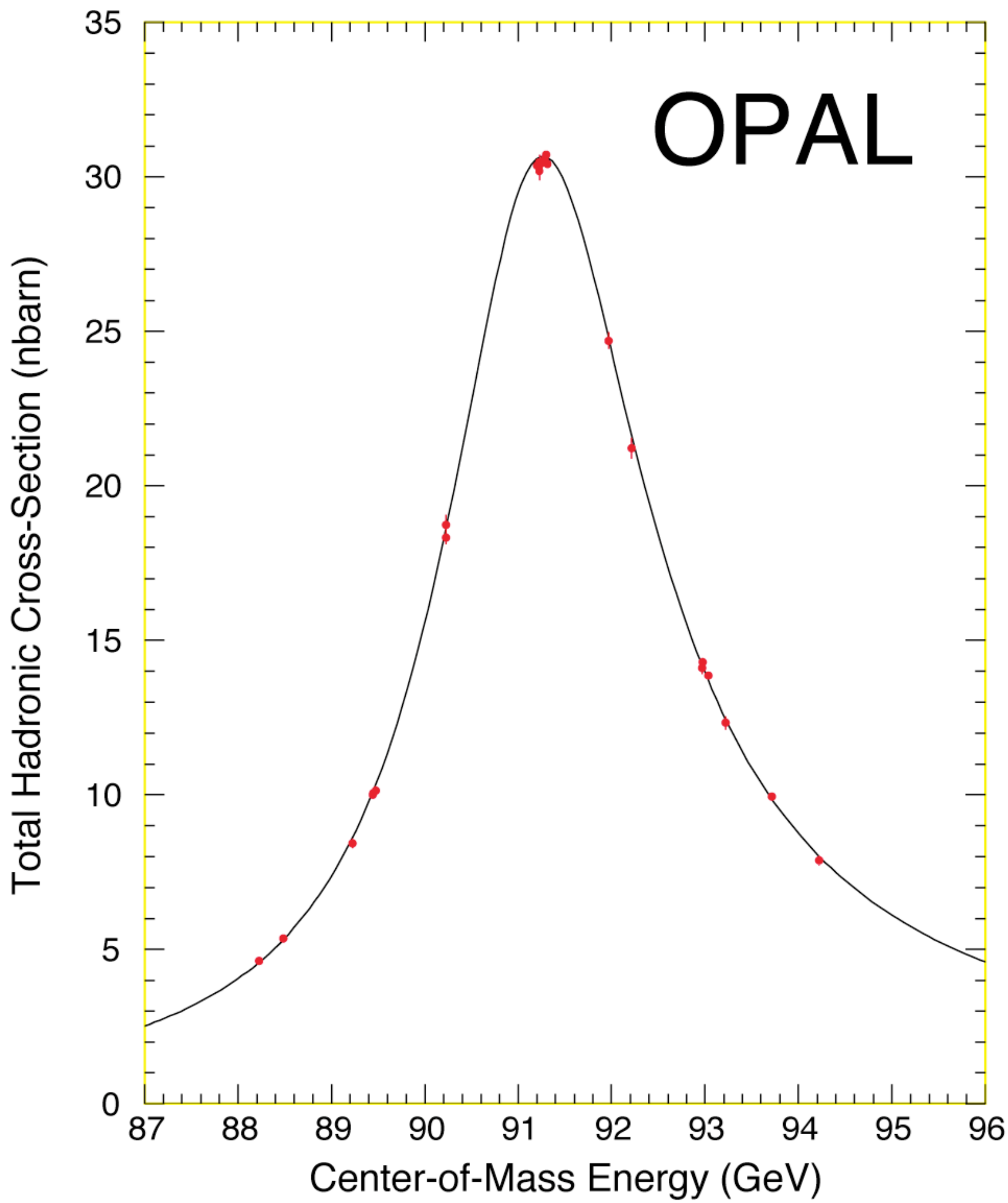
MAC detector (SLAC), 1986



Example 3(b): $e^+e^- \longrightarrow Z^0 \longrightarrow q\bar{q}$

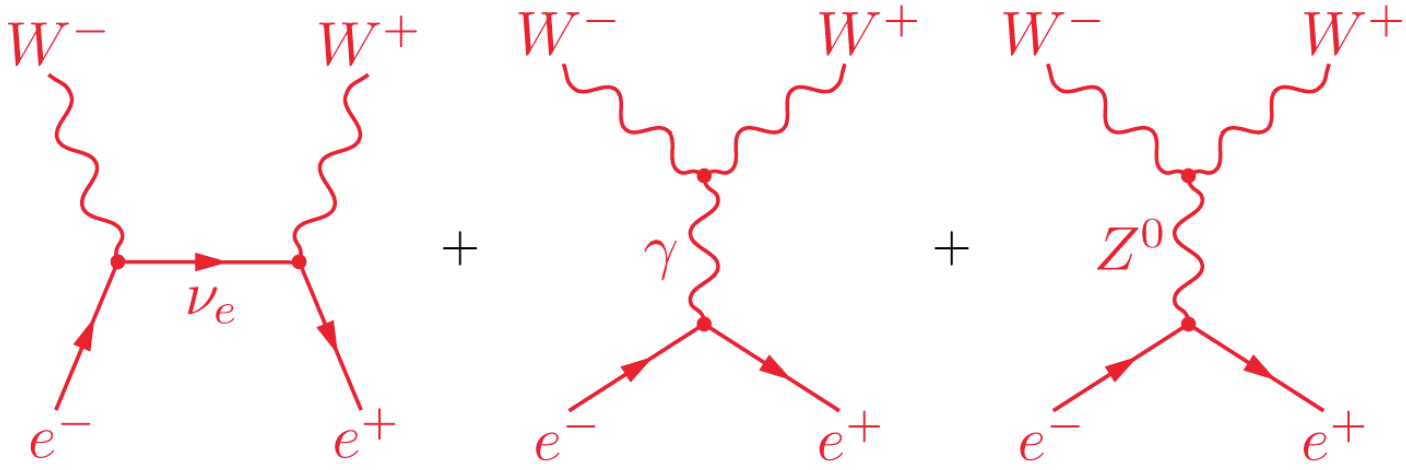


Higher-order diagrams turn ∞ into smooth resonance curve.

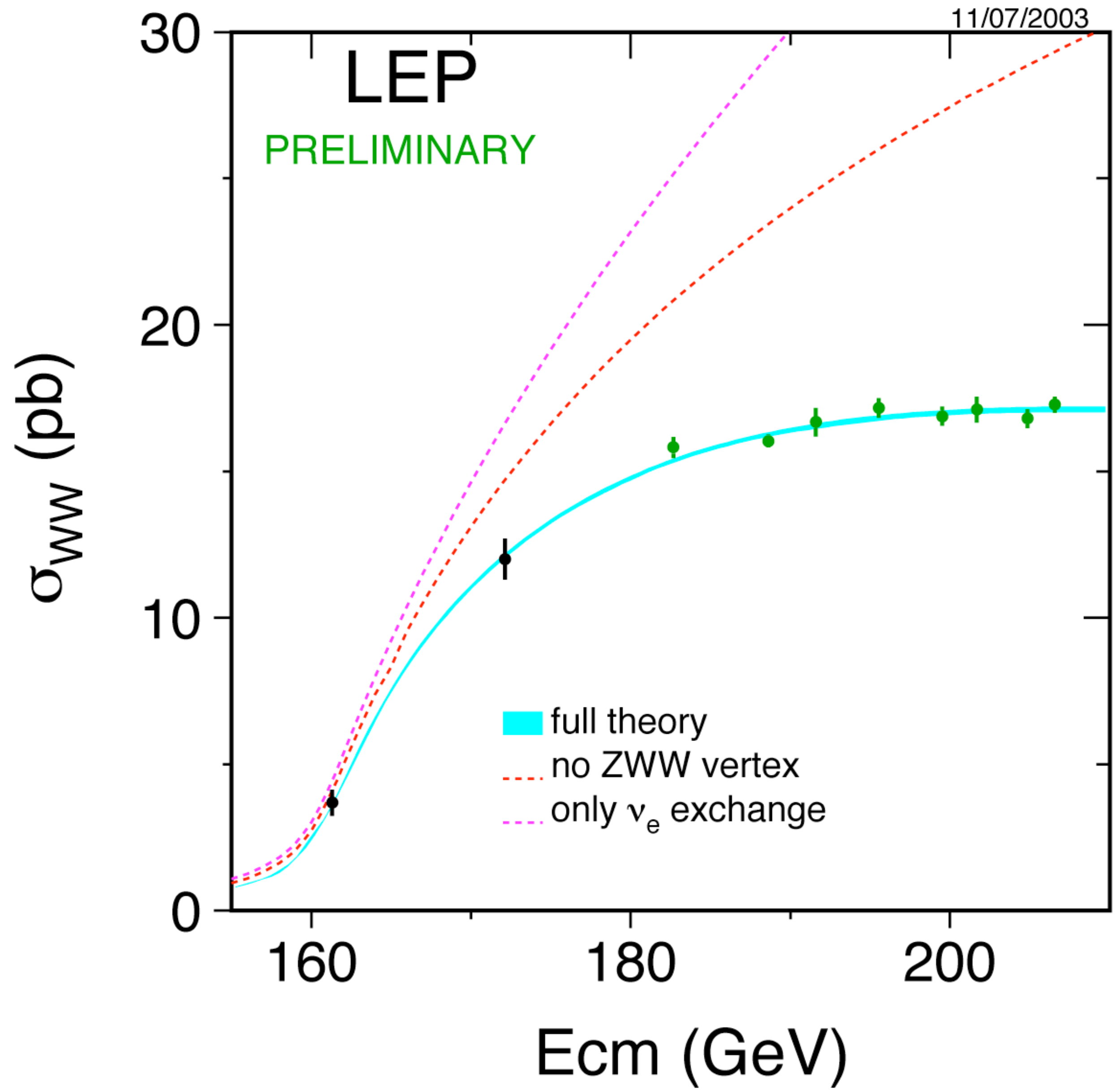


OPAL
Total Hadronic Cross-Section (nbarn)
Center-of-Mass Energy (GeV)
0
5
10
15
20
25
30
35
87
88
89
90
91
92
93
94
95
96

Example 4: $e^+e^- \longrightarrow W^+W^-$

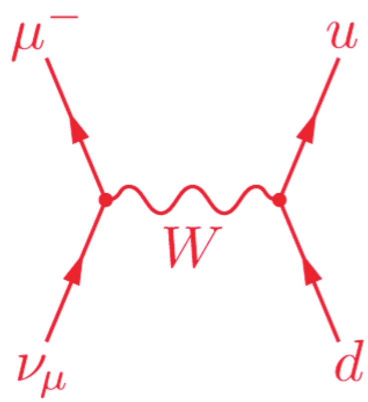


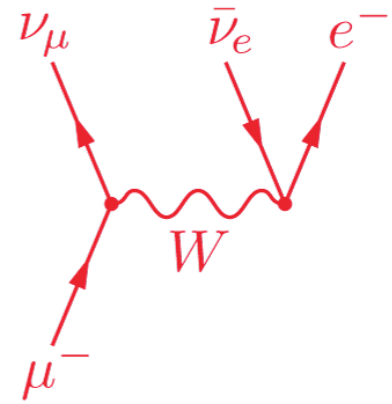
- Requires $E_{\text{cm}} > 2m_W = 160$ GeV



11/07/2003
LEP
PRELIMINARY
30
20
10
0
160
180
200
σ_{WW} (pb)
Ecm (GeV)
full theory
no ZWW vertex
only ν_e exchange

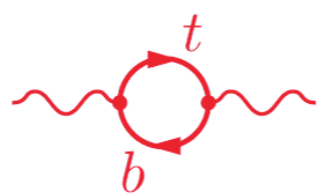
- Direct measurement of m_W can be compared to indirect measurements:



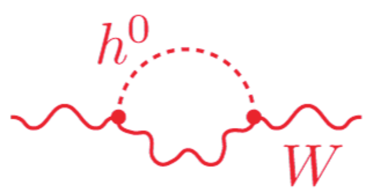


- Corrections from higher-order diagrams must be included,

especially:



- Results disagree, typically by $\sim$1%!
- Simplest solution: new spin-0 "Higgs" particle, $m_h \lesssim 200$ GeV



(Also needed to avoid nonsensical predictions at $E \gtrsim 1000$ GeV)

To learn more…

- R. P. Feynman, *QED: The Strange Theory of Light and Matter*
- R. M. Barnett, et al., *The Charm of Strange Quarks*
- M. Riordan, *The Hunting of the Quark*
- ParticleAdventure.org
- physics.weber.edu/schroeder/feynman