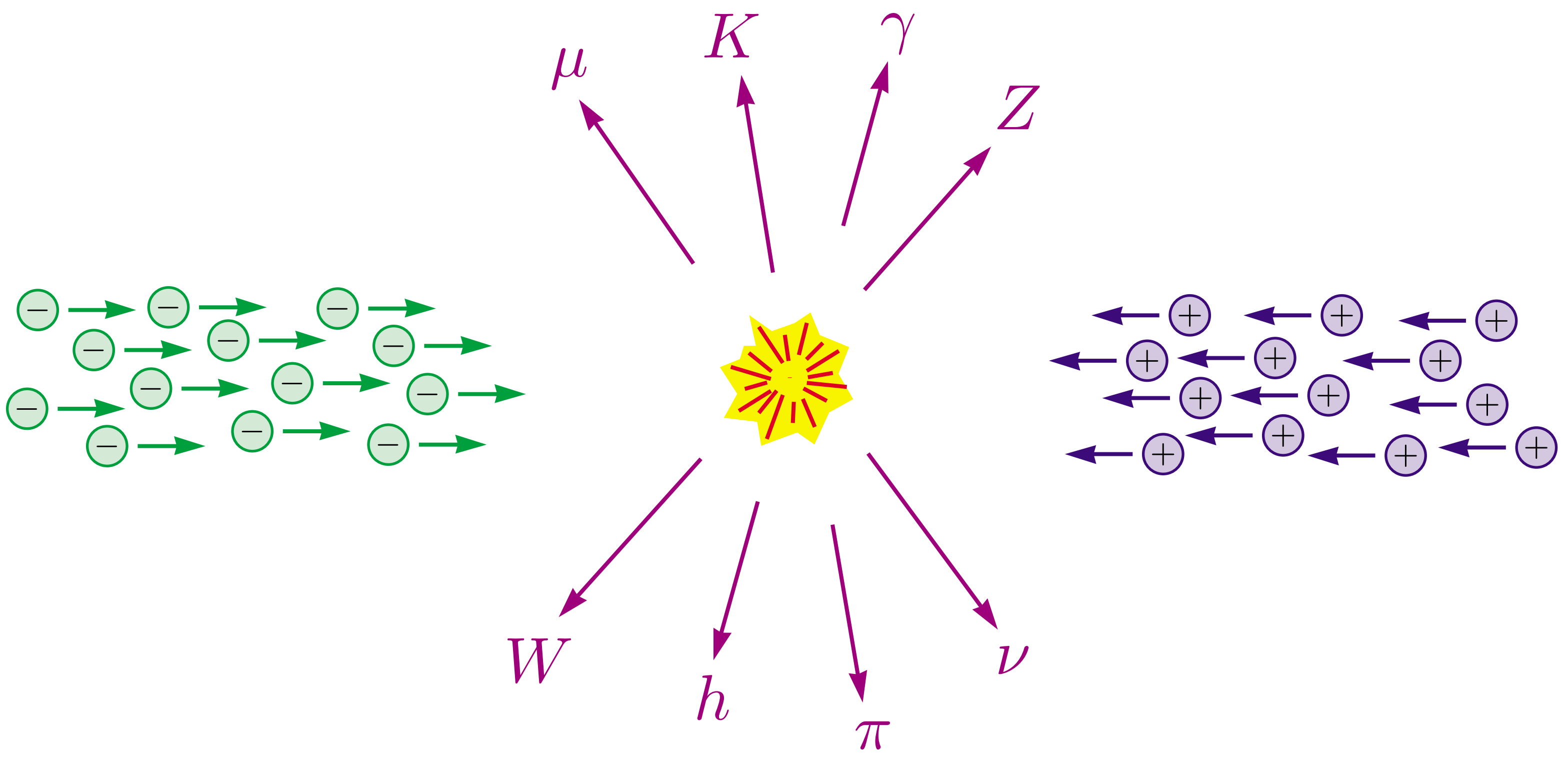
Electron - Positron Annihilation



D. Schroeder, 29 October 2002

OUTLINE

- Electron-positron storage rings
- Detectors
- Reaction examples

$$e^+e^- \longrightarrow e^+e^-$$

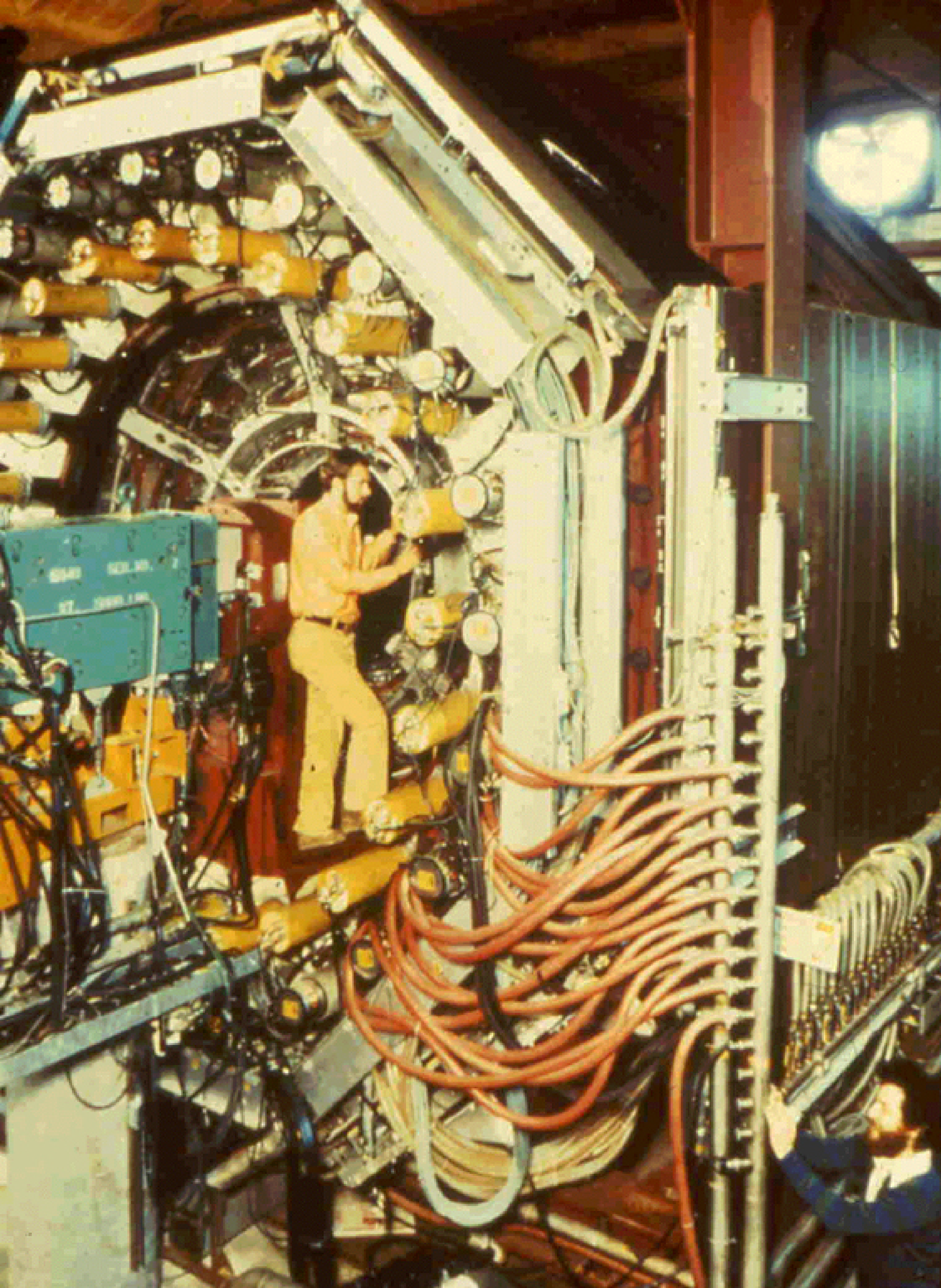
[Inventory of known particles]

$$e^+e^- \longrightarrow \mu^+\mu^-$$

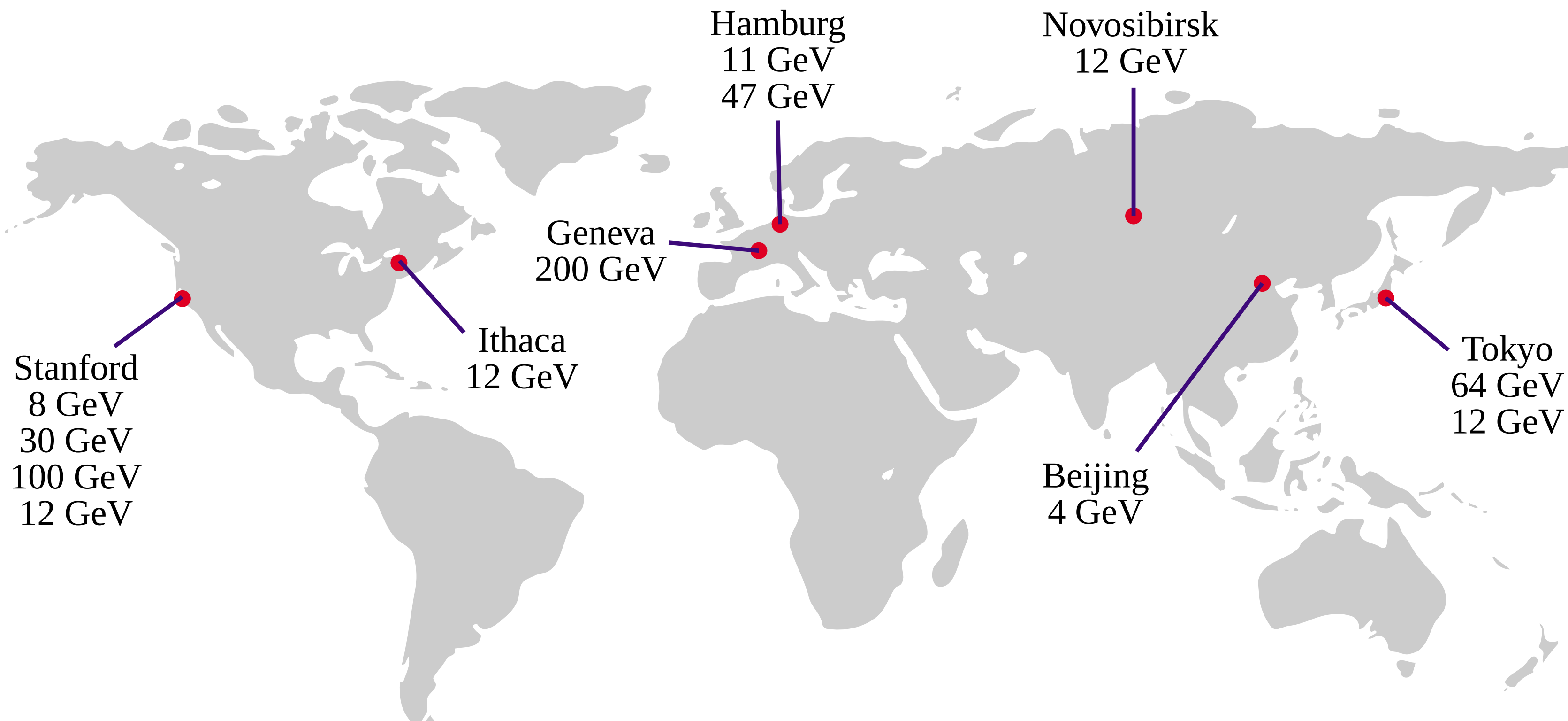
$$e^+e^- \longrightarrow q\,\bar{q}$$

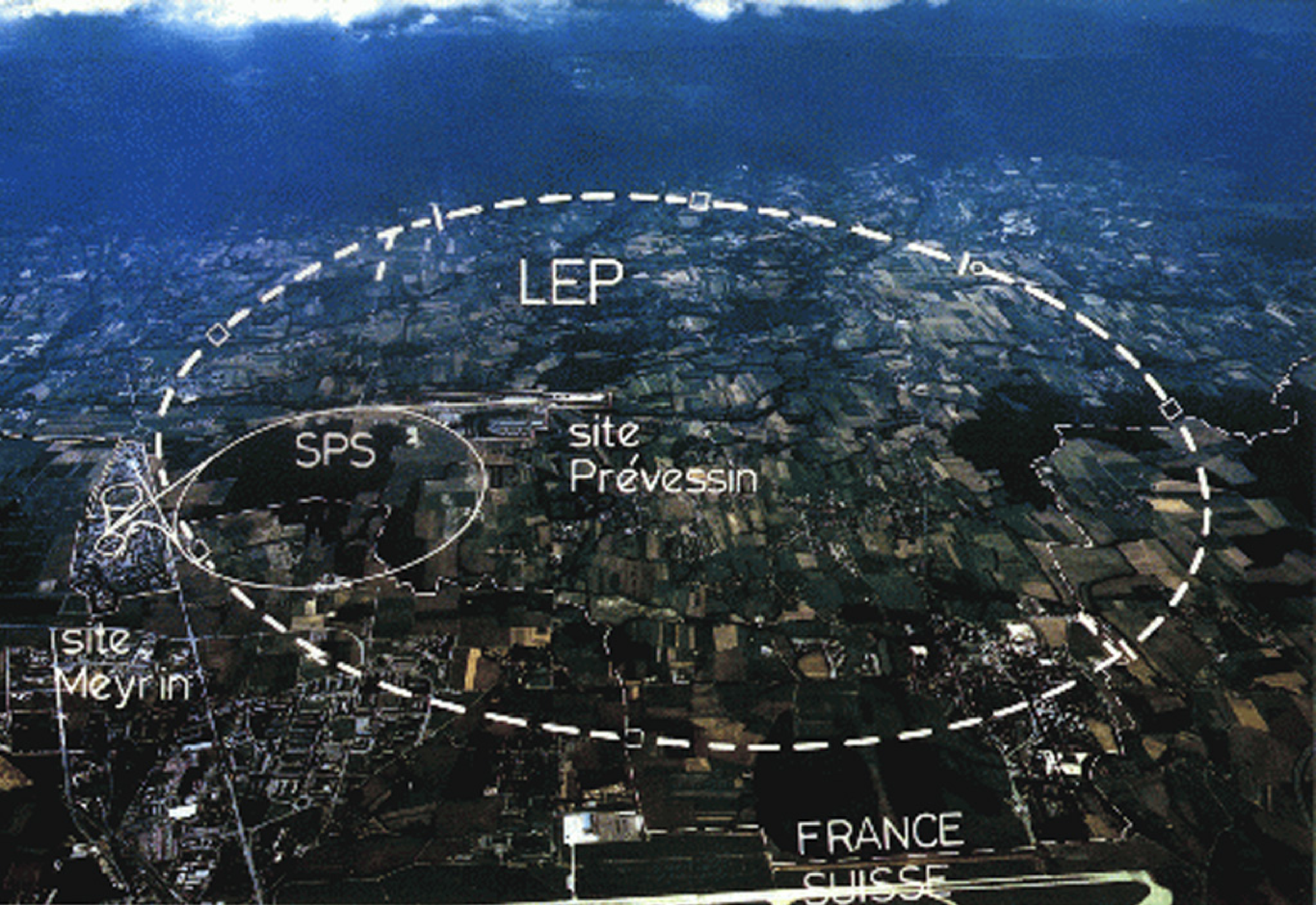
$$e^+e^- \longrightarrow W^+W^-$$

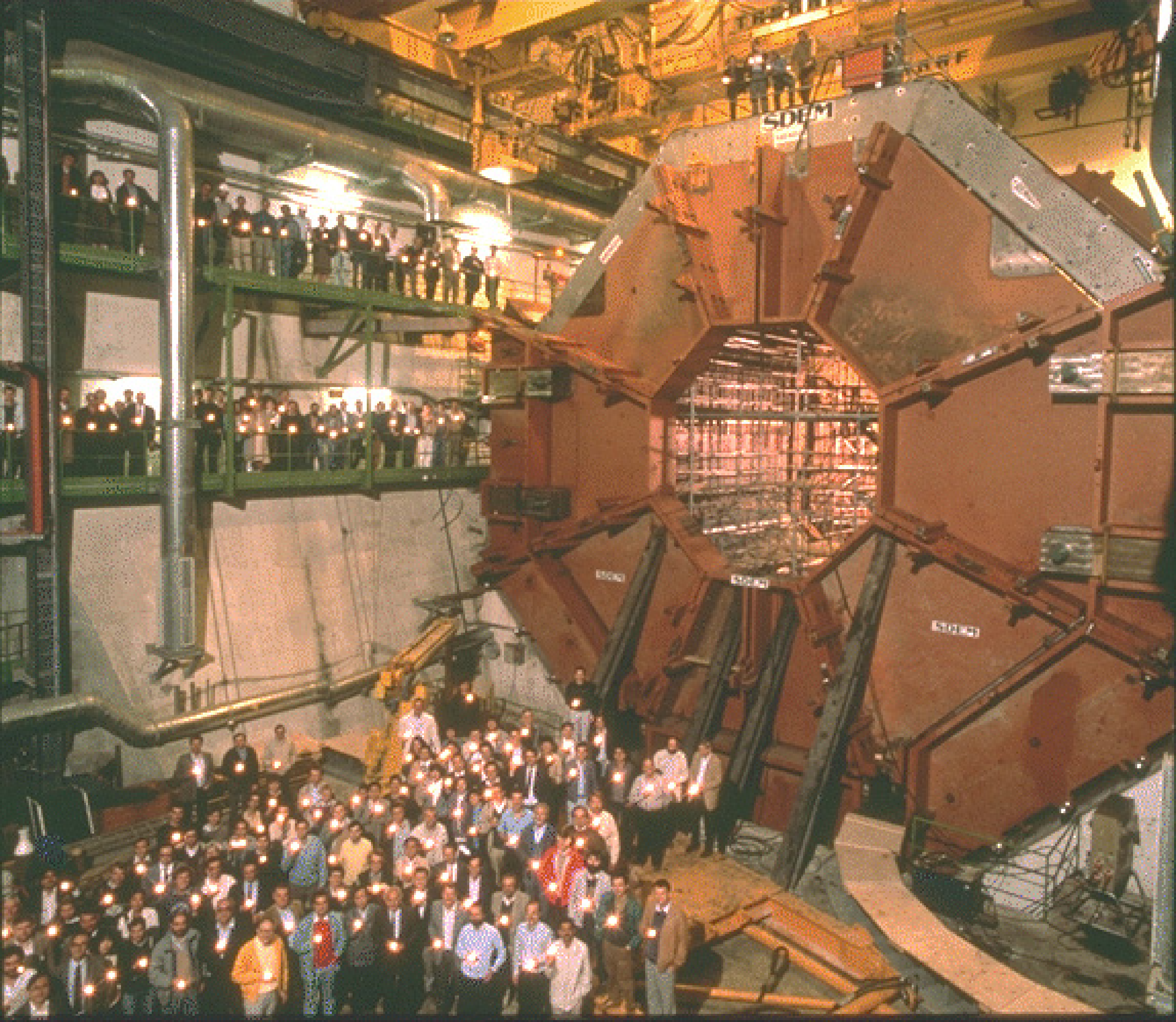
- The future: Linear colliders



Electron-Positron Colliders




LEP
SPS
site Prévessin
site Meyrin
FRANCE
SUISSE


SDEM

Size (R) and Cost (\$) of an e^+e^- Storage Ring

$$\$ = \alpha R + \frac{\beta E^4}{R} \qquad (E = \text{beam energy})$$

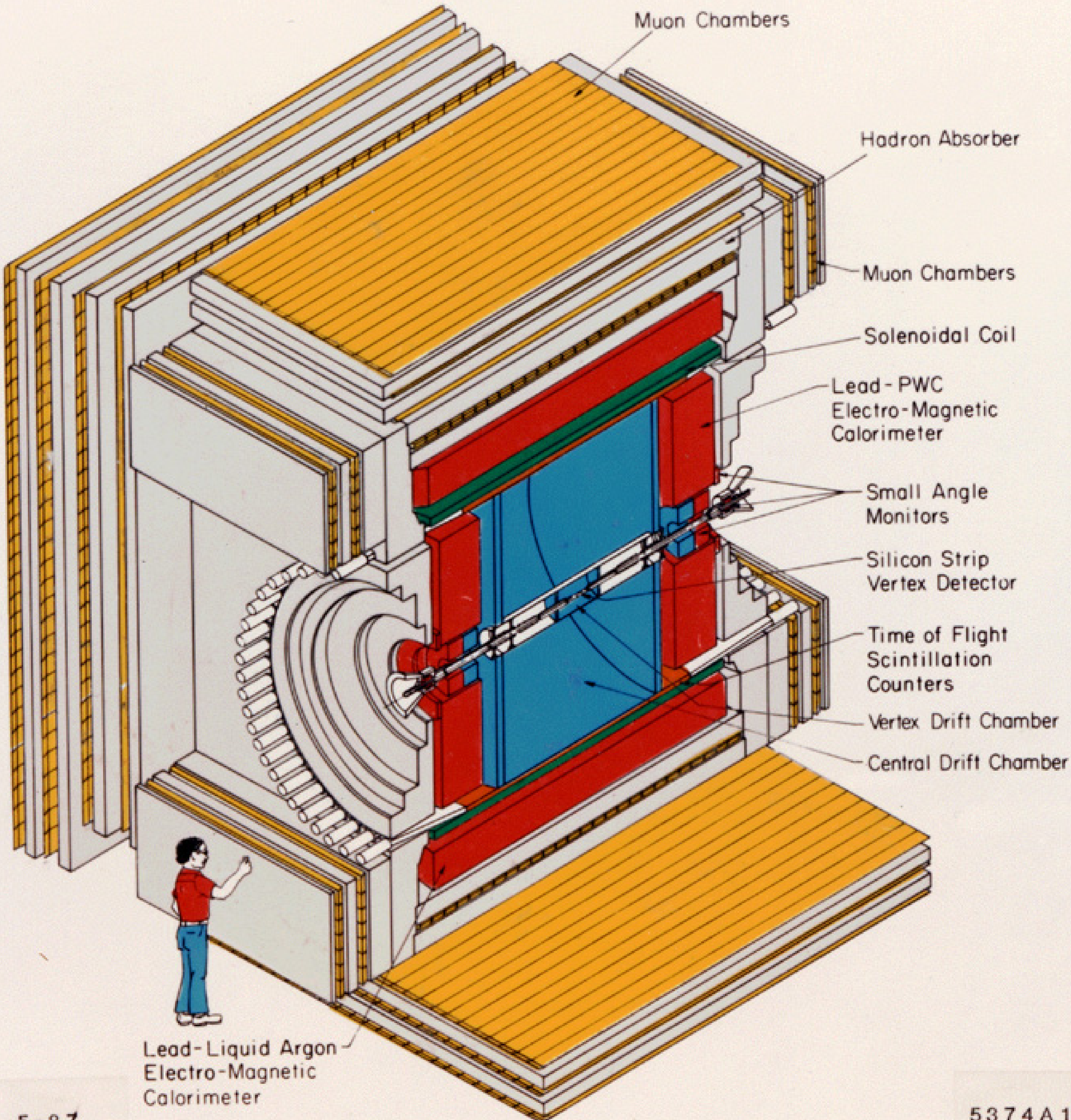
Find minimum \$: $$0 = \frac{d\$}{dR} = \alpha - \frac{\beta E^4}{R^2}$$

$$\Longrightarrow \qquad R = \sqrt{\frac{\beta}{\alpha}}\, E^2, \qquad \$ = 2\sqrt{\alpha\beta}\, E^2$$

SPEAR: $E = 8$ GeV, $R = 40$ m, \$ = 5 million

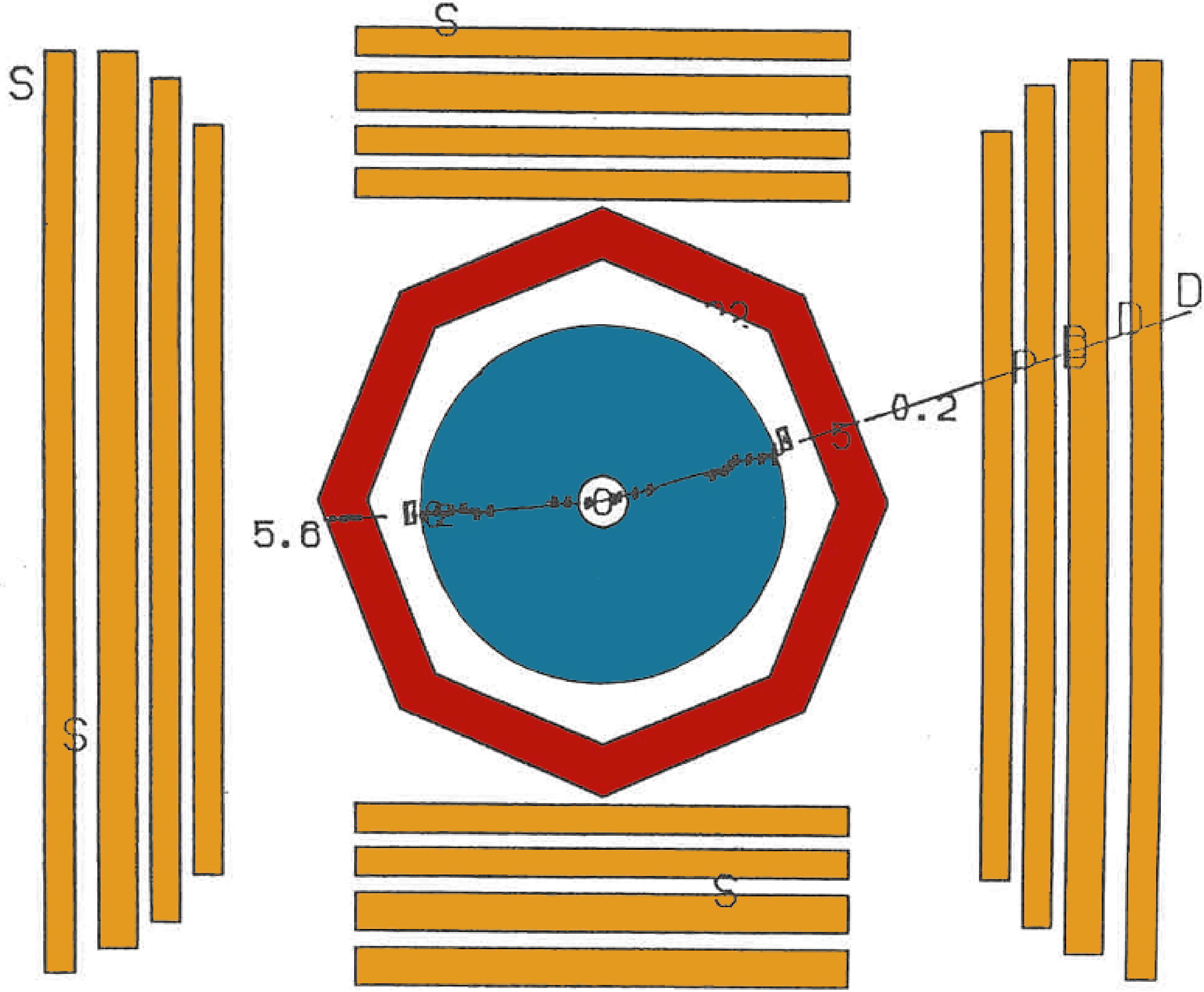
LEP: $E = 200$ GeV, $R = 4.3$ km, \$ = 1 billion

MARK II AT SLC



5-87

5374A1

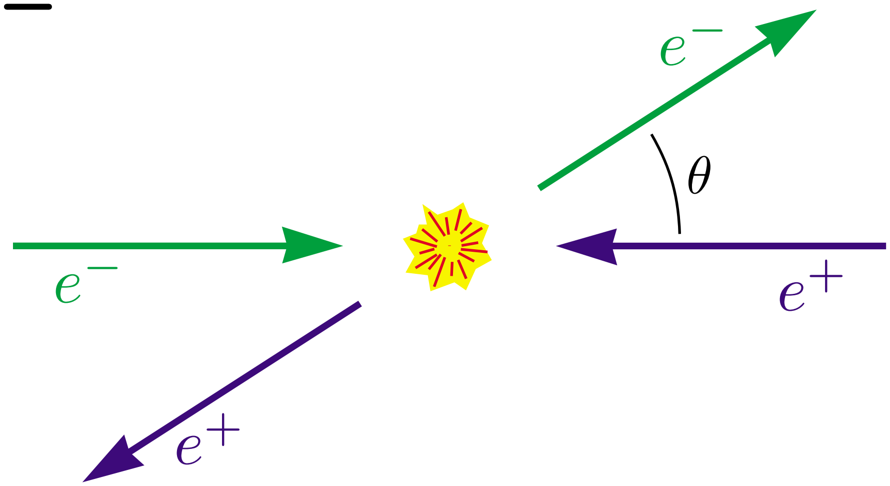

S
S
S
S
D
0.2
5
5.6

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

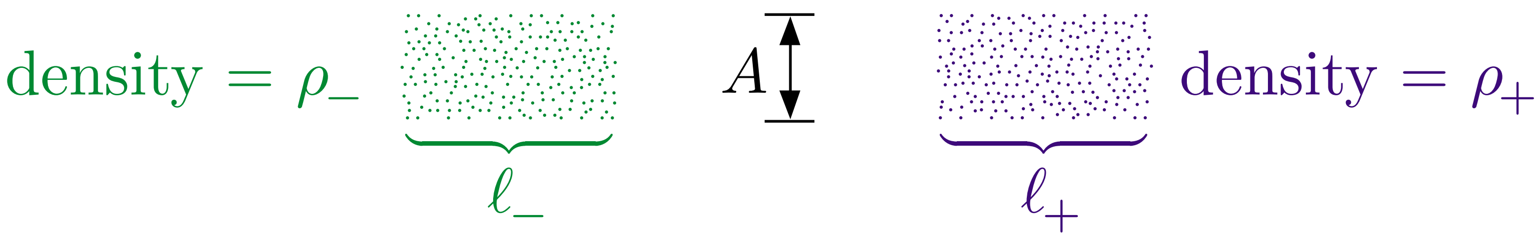
total momentum $= 0$

total energy $= 2E$

Probability$(E,\theta) =$ **?**



E-dependence follows from dimensional analysis:



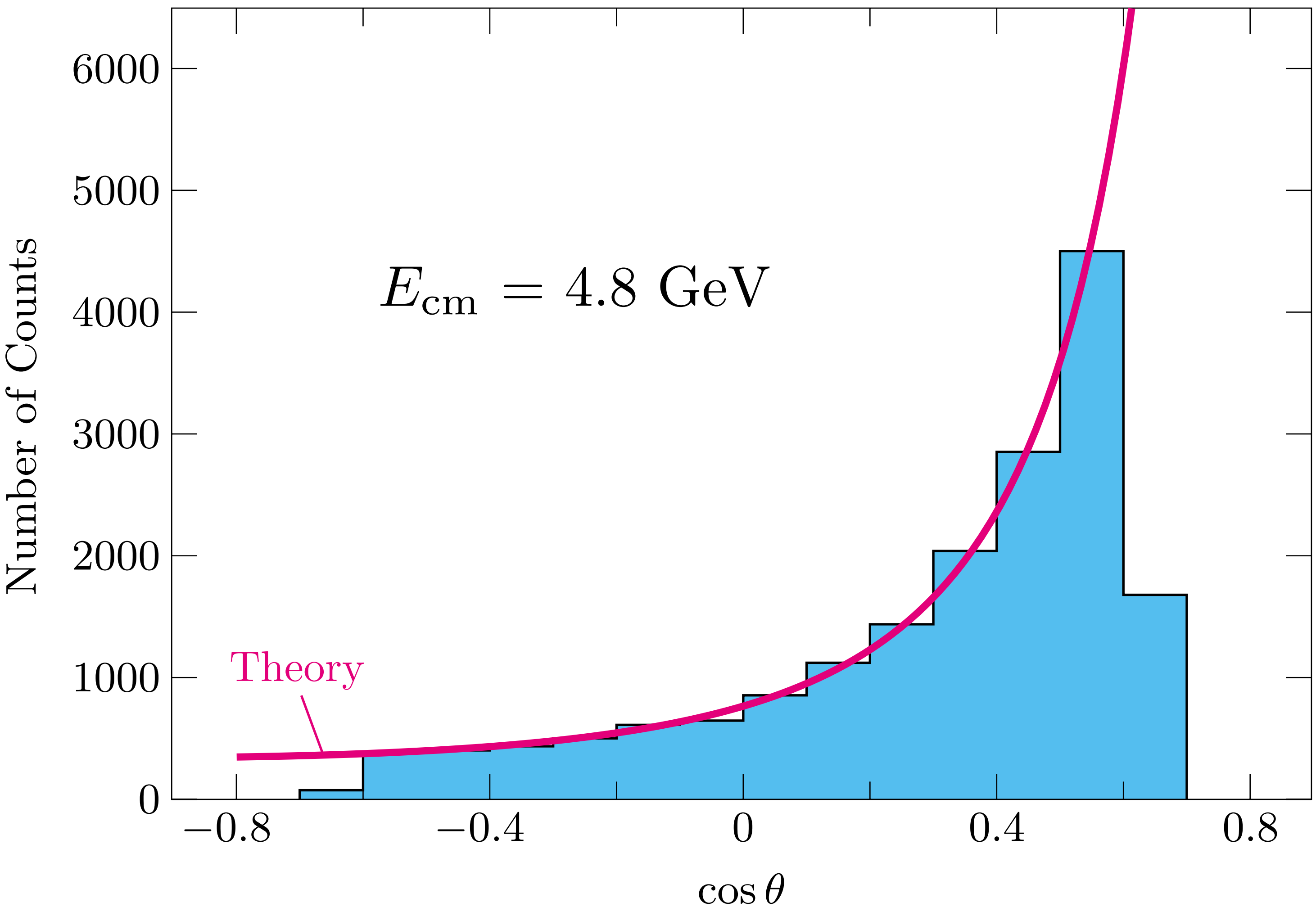
Probability $= (\rho_- \, \rho_+ \, \ell_- \, \ell_+ \, A) \times$ (something with units of length^2)

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)

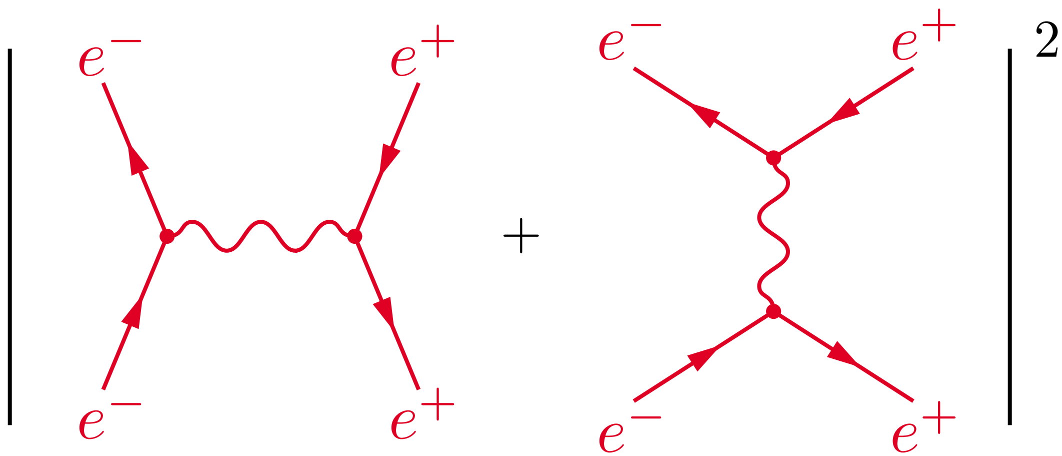


Prediction for $e^+e^- \longrightarrow e^+e^-$ event rate (H. J. Bhabha, 1935):

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

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

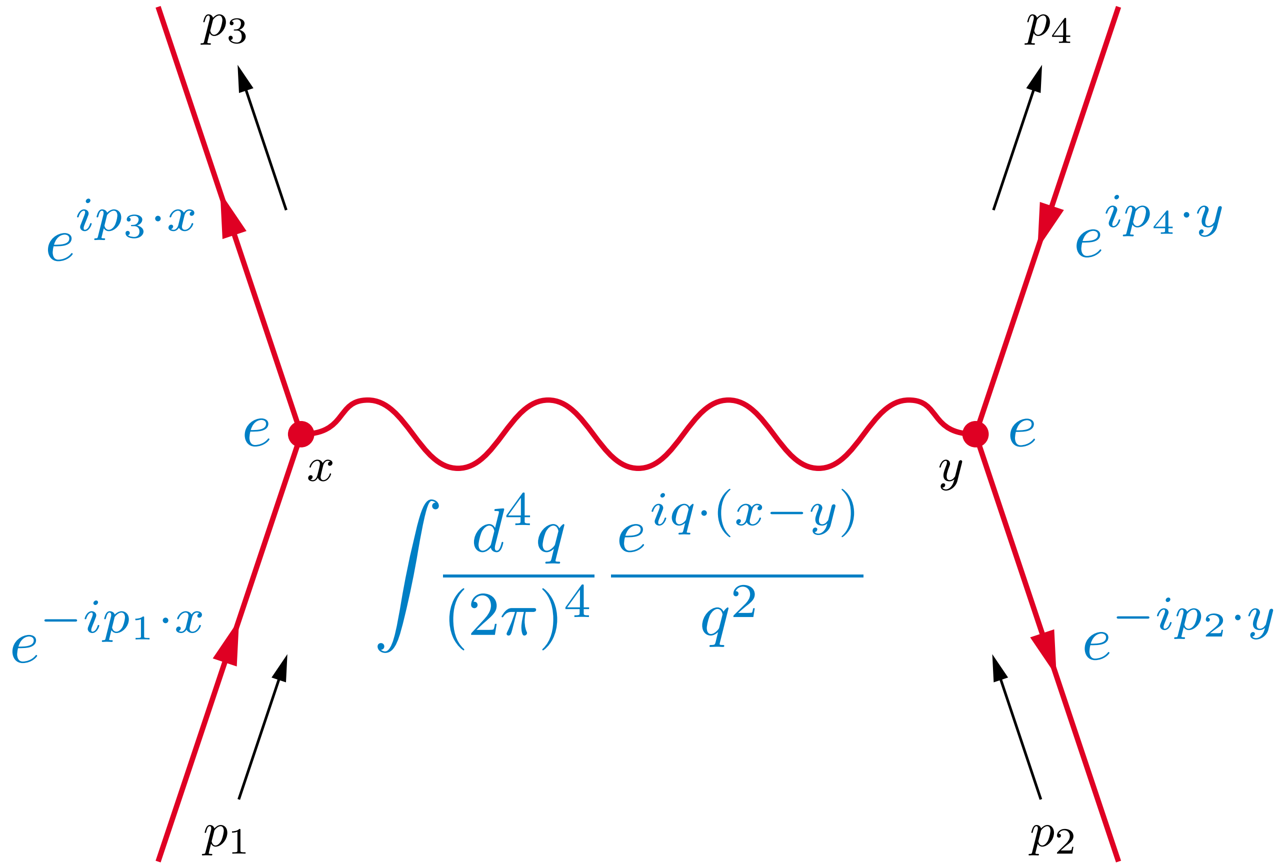
$= (\text{const.}) \times$



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

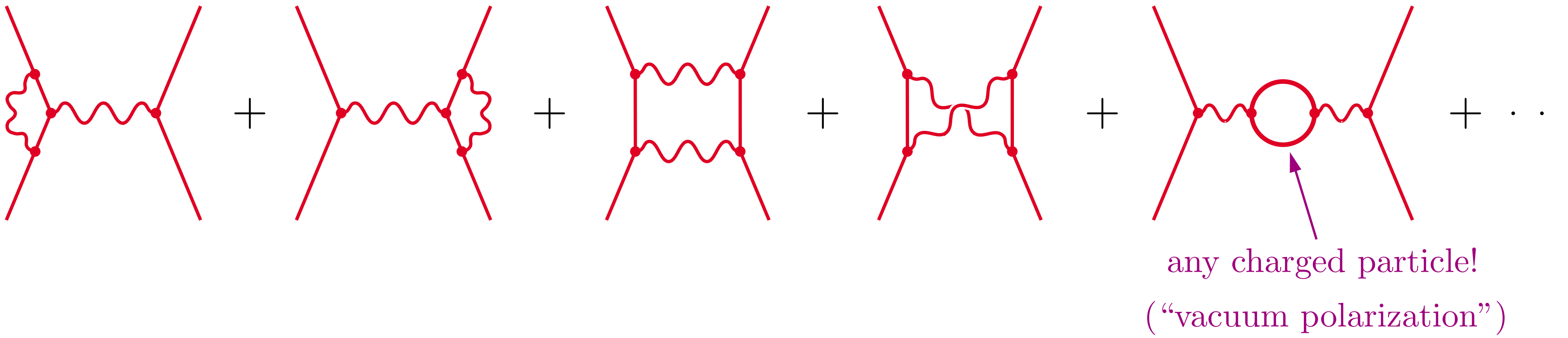
Each vertex represents a factor of the electron's charge, $e = -0.303$.

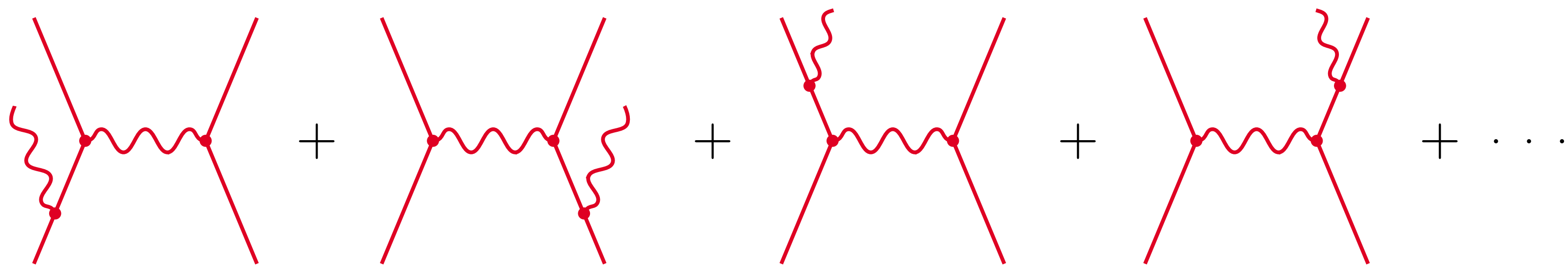
Feynman Rules (neglecting spin, $\hbar = c = 1$)



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

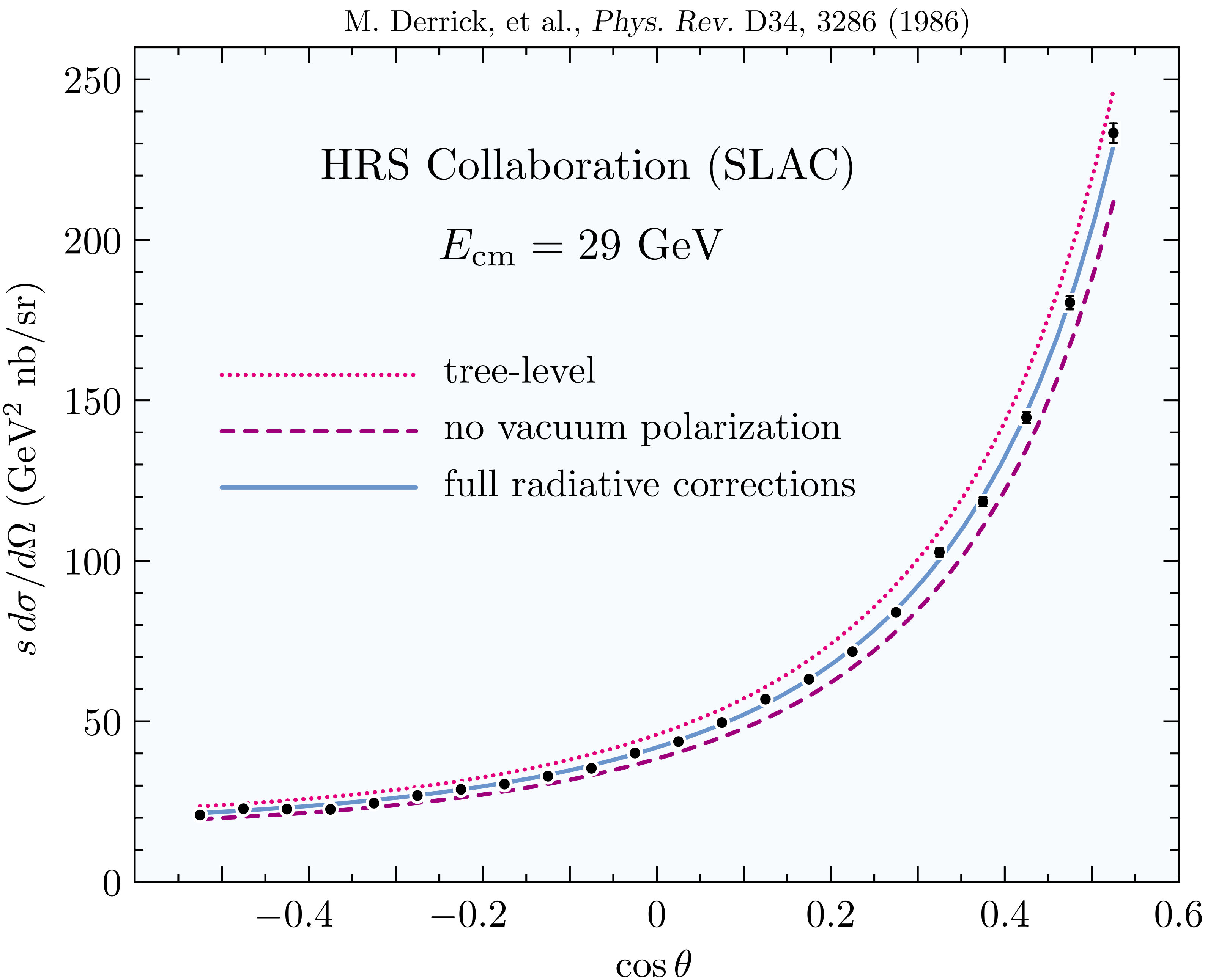
Higher-Order Diagrams



Also: 

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

It Works!


M. Derrick, et al., *Phys. Rev.* D34, 3286 (1986)
HRS Collaboration (SLAC)
$E_{\mathrm{cm}} = 29$ GeV
tree-level
no vacuum polarization
full radiative corrections
$s\, d\sigma/d\Omega$ (GeV^2 nb/sr)
$\cos\theta$
0
50
100
150
200
250
−0.4
−0.2
0
0.2
0.4
0.6

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	$-1/3$	$2/3$	$\leftarrow$ charge

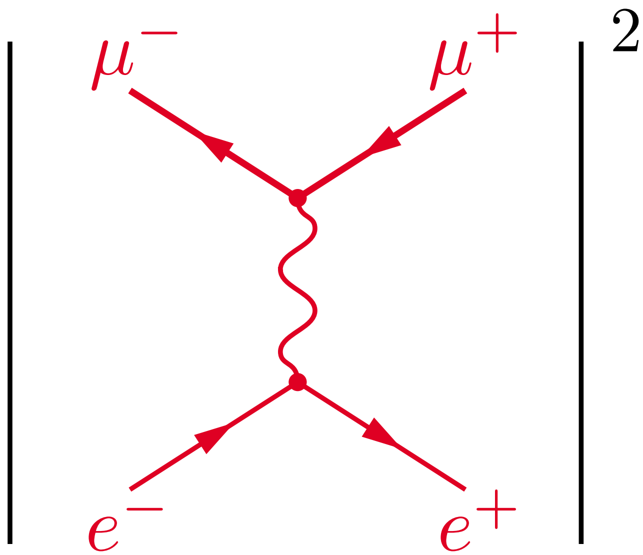
Particles like the photon (bosons, spin 1)

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

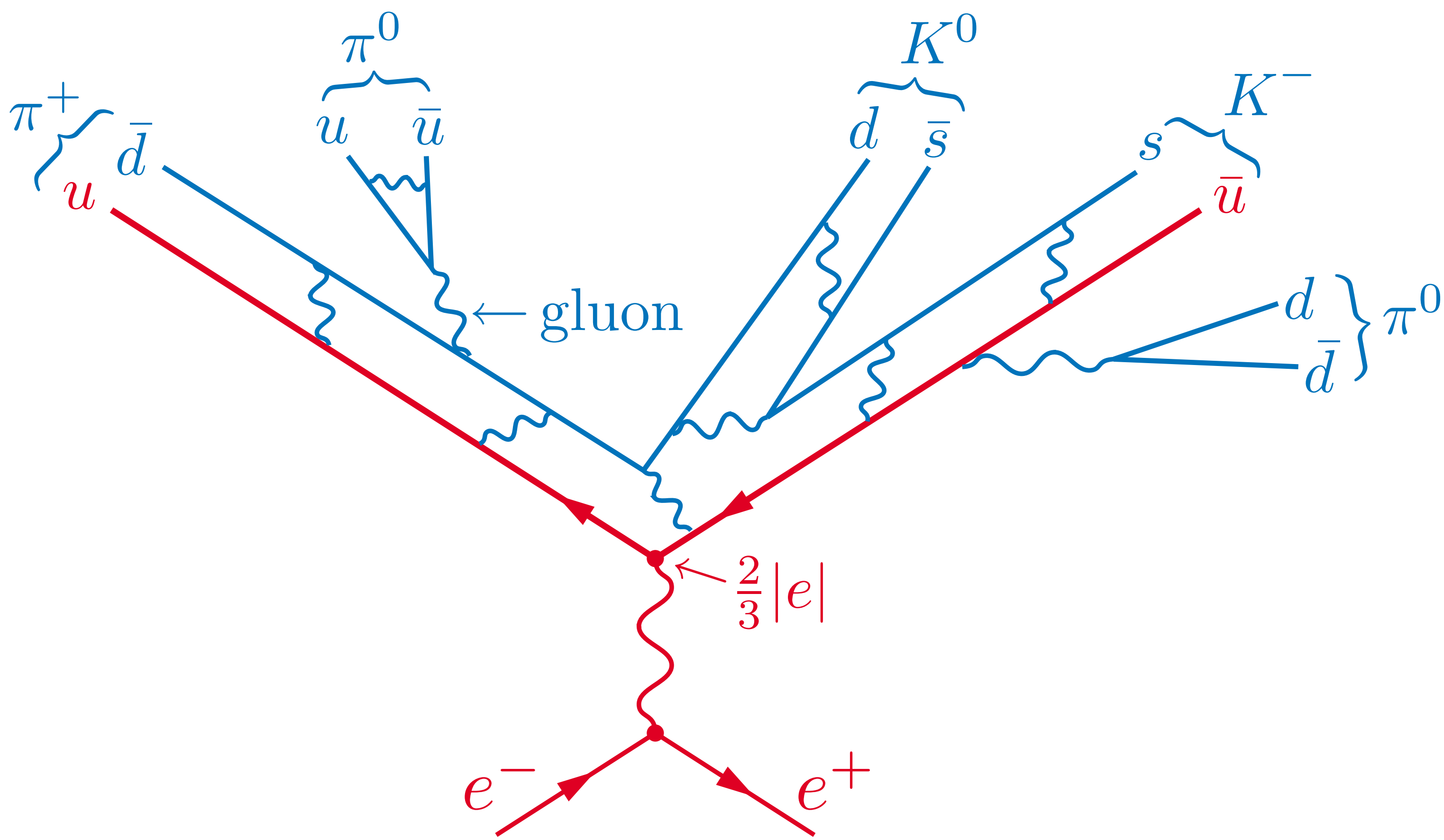
Only one diagram:



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

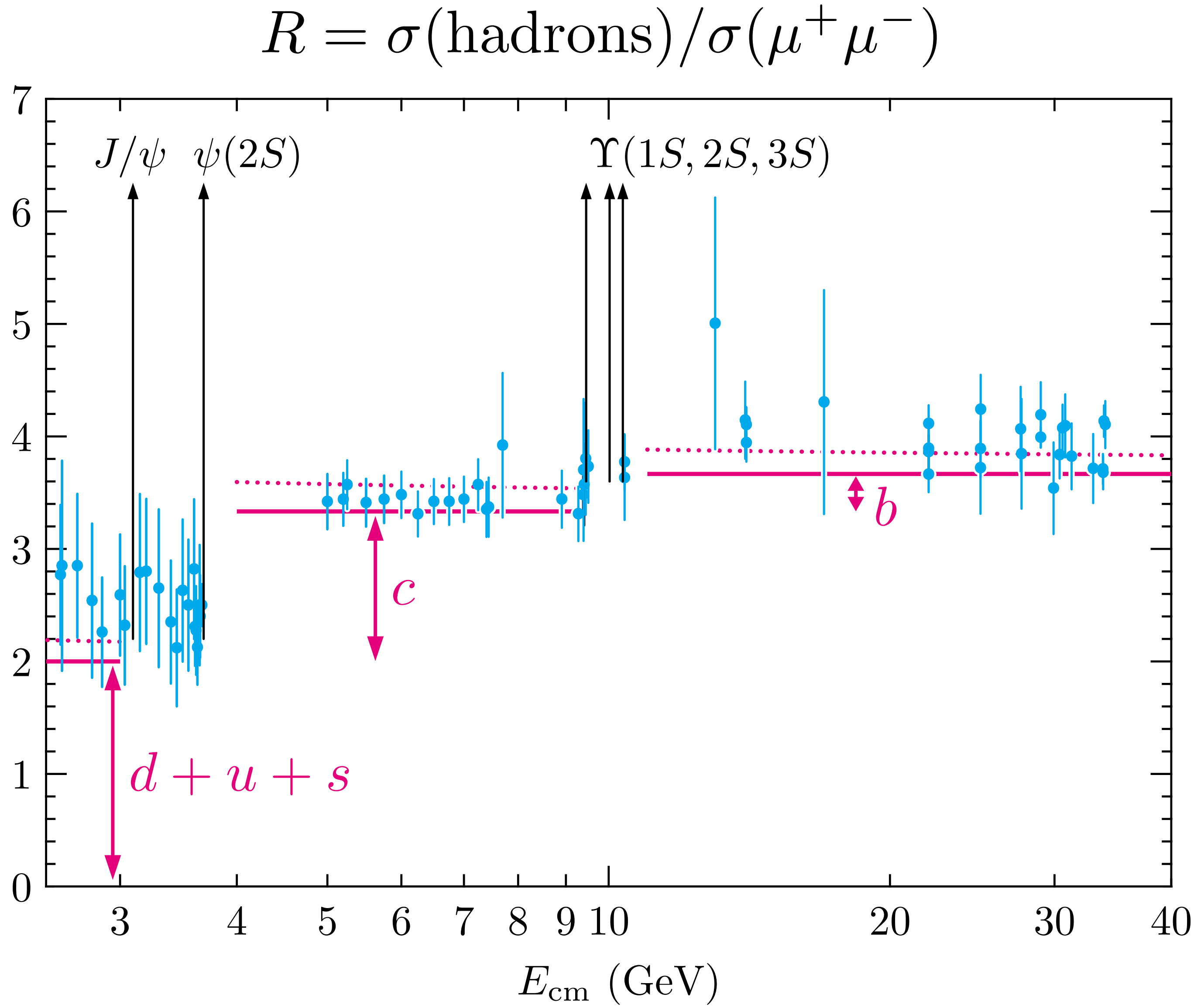
(Same as third term in Bhabha formula, provided that $E \gg m_\mu$.)

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



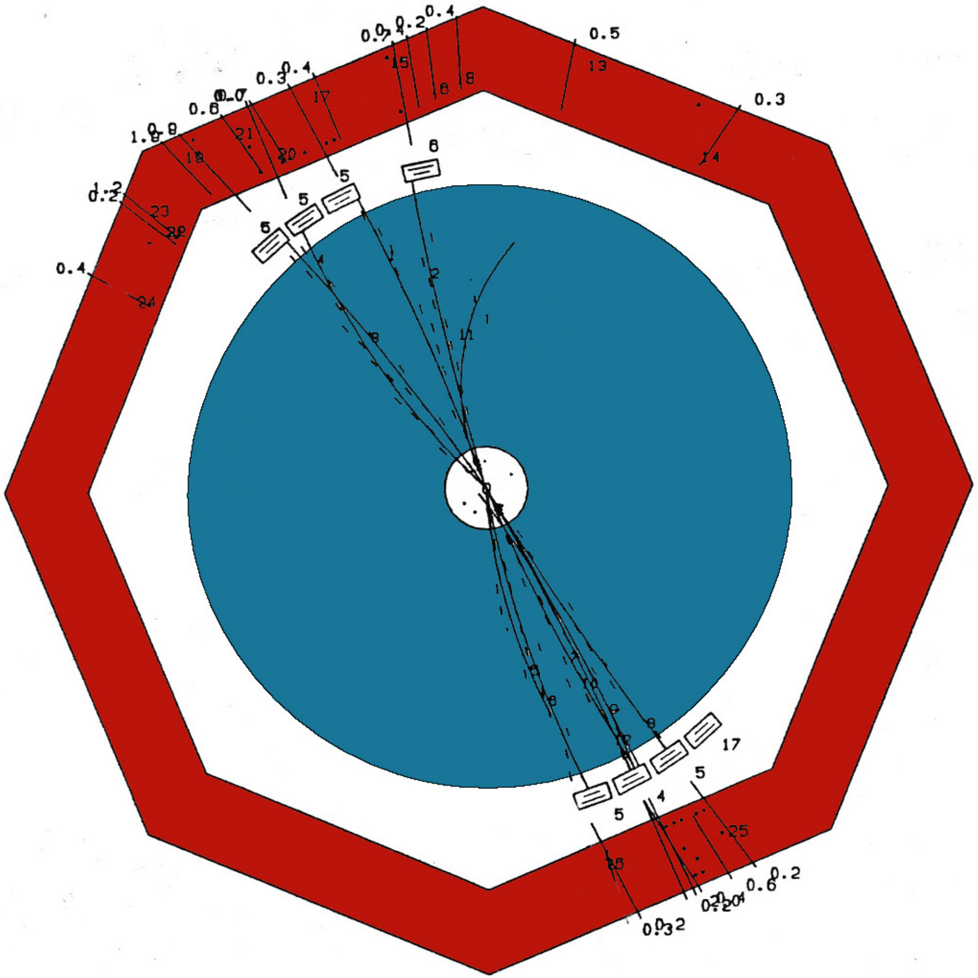
For 10 GeV $< E_{\text{cm}} <$ 40 GeV,

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



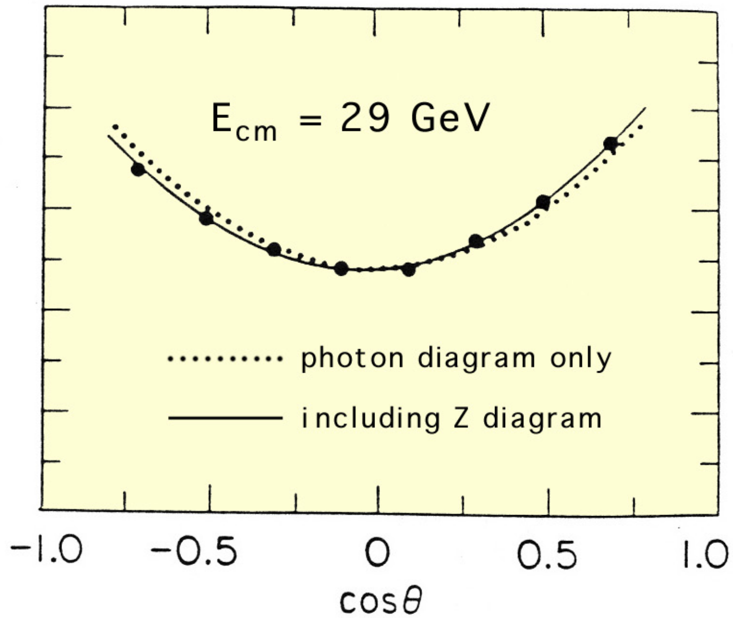
$R = \sigma(\text{hadrons})/\sigma(\mu^+\mu^-)$
J/ψ
$\psi(2S)$
$\Upsilon(1S, 2S, 3S)$
$d + u + s$
c
b
0
1
2
3
4
5
6
7
3
4
5
6
7
8
9
10
20
30
40
E_{cm} (GeV)

2- Jet Hadronic Event

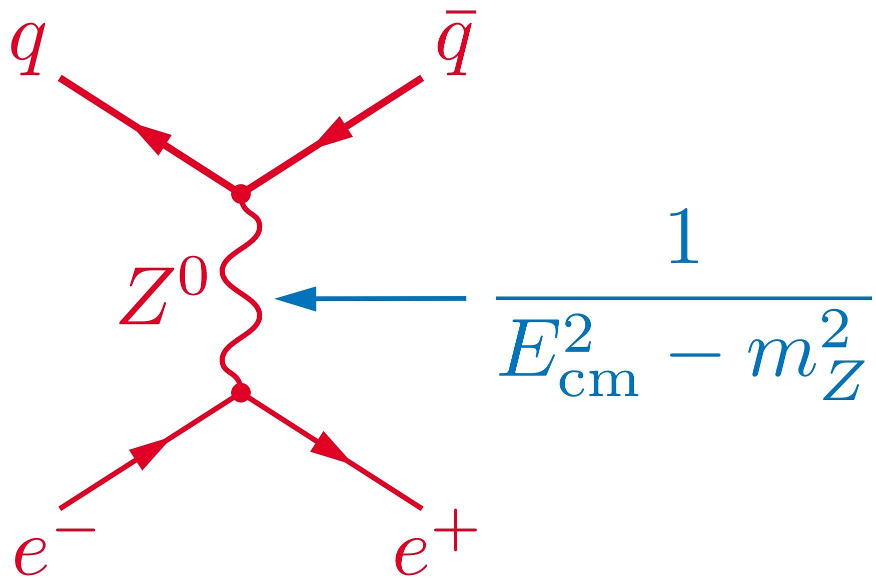


Angular Distribution

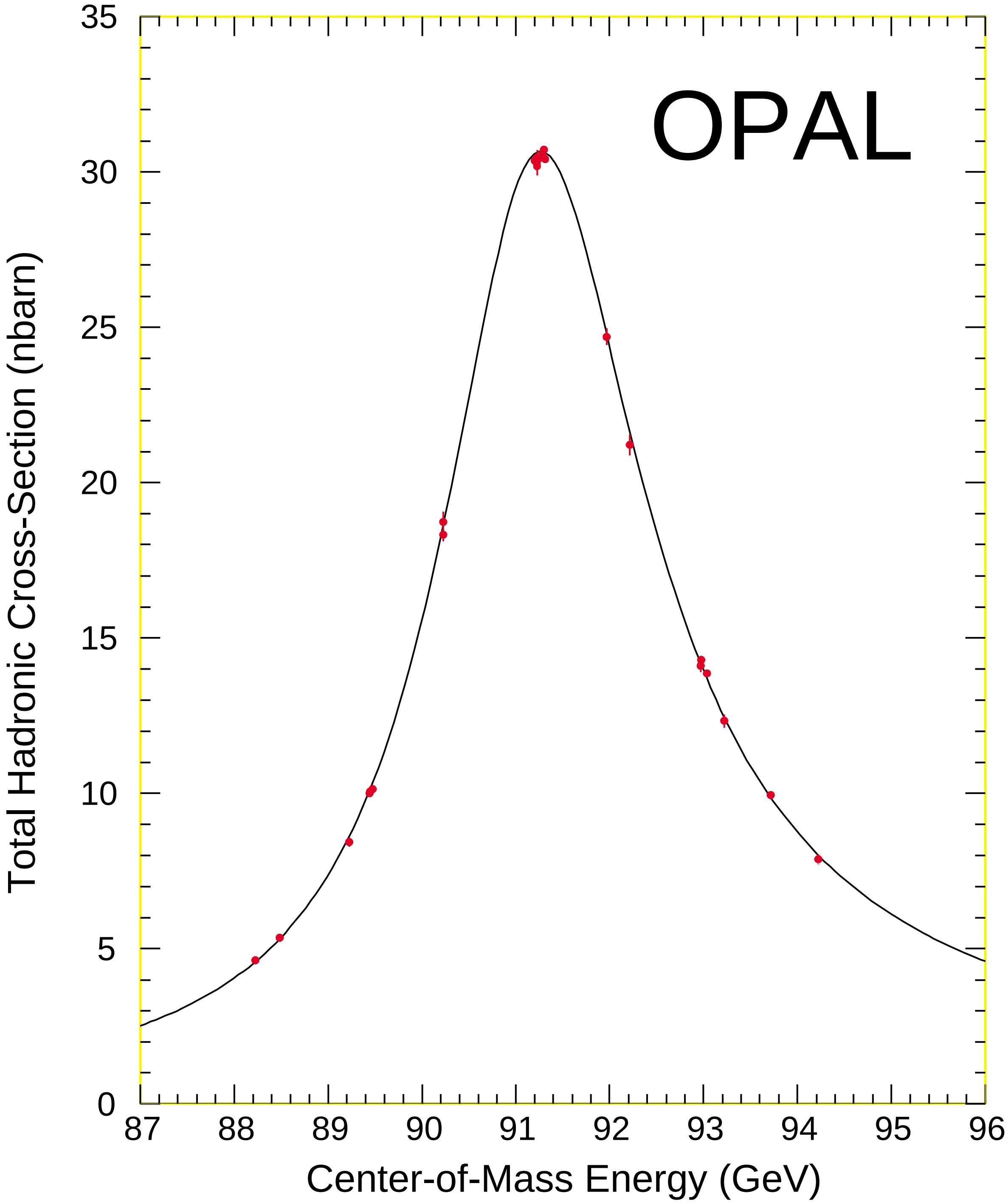
MAC detector (SLAC), 1986



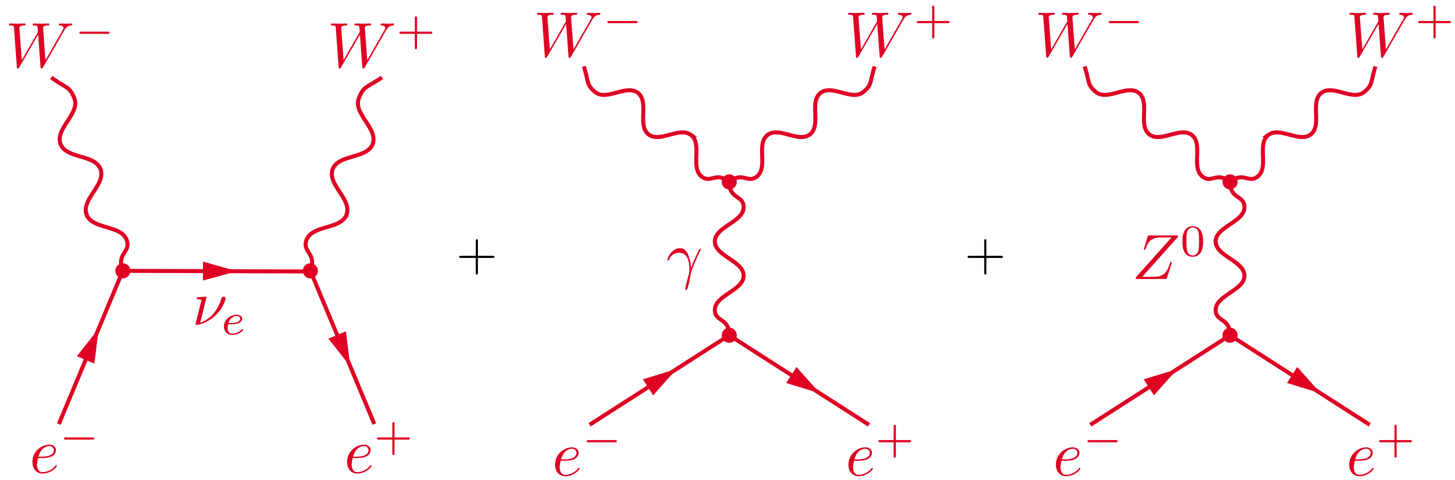
Example 3(b): $\boldsymbol{e^+e^- \longrightarrow Z^0 \longrightarrow q\bar{q}}$



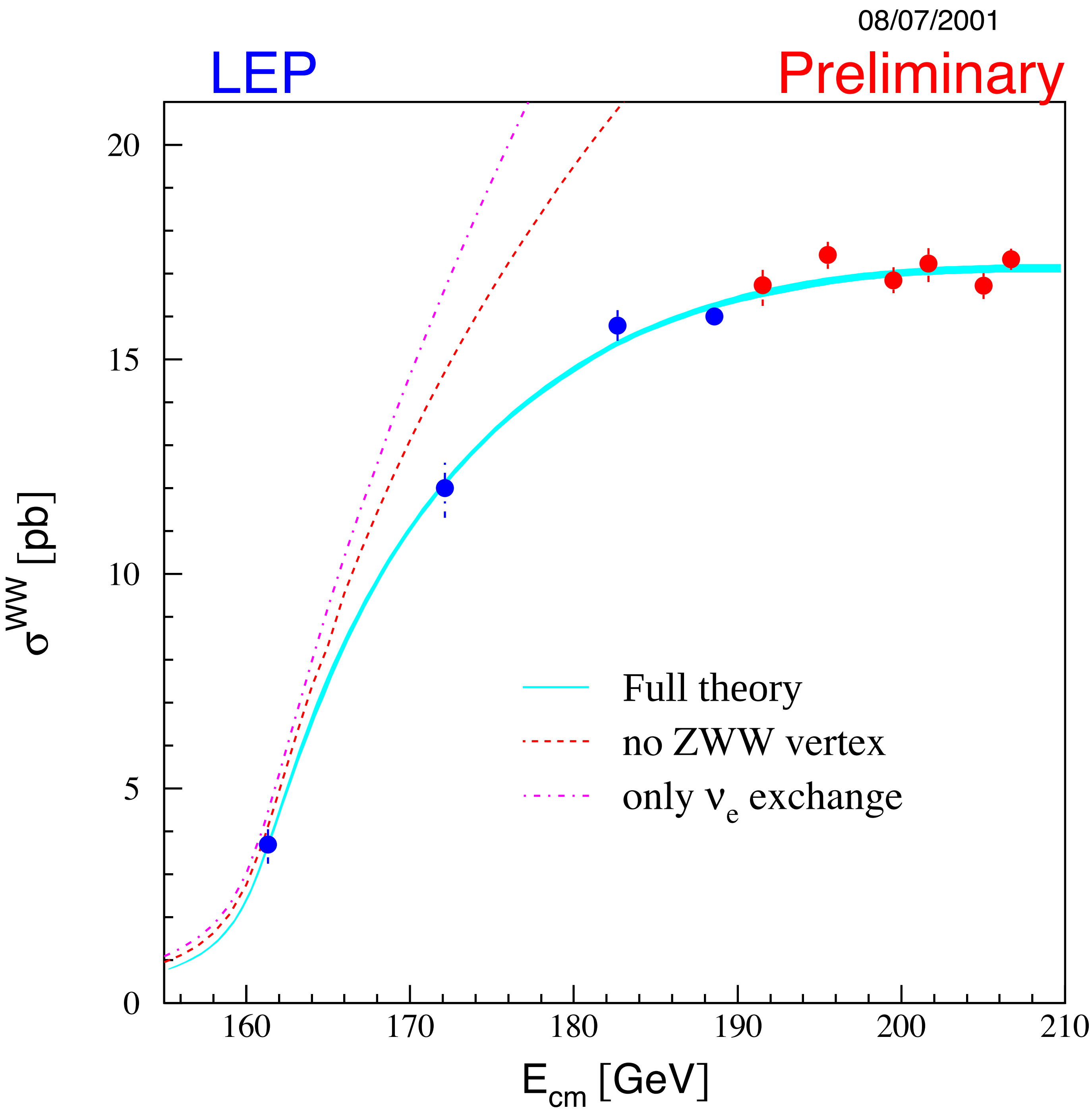
Higher-order diagrams turn ∞ into smooth resonance curve.


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

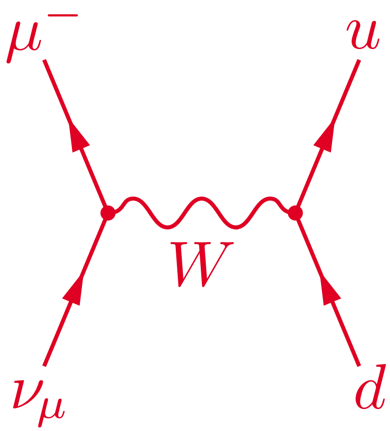
Example 4: $\boldsymbol{e^+e^- \longrightarrow W^+W^-}$

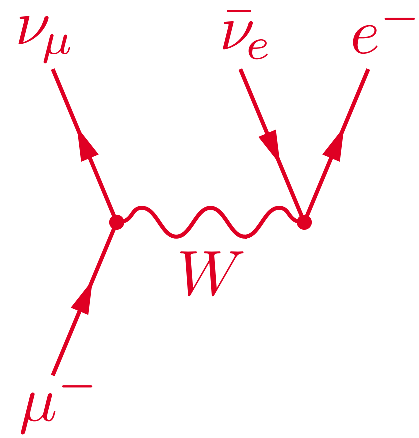


- Requires $E_{\rm cm} > 2m_W = 160$ GeV

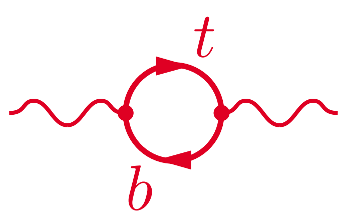

08/07/2001
LEP
Preliminary
20
15
10
5
0
160
170
180
190
200
210
σ^WW [pb]
E_cm [GeV]
Full theory
no ZWW vertex
only ν_e exchange

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

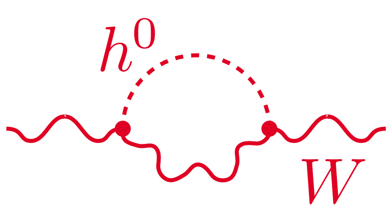




- Corrections from higher-order diagrams must be included,

especially: 

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



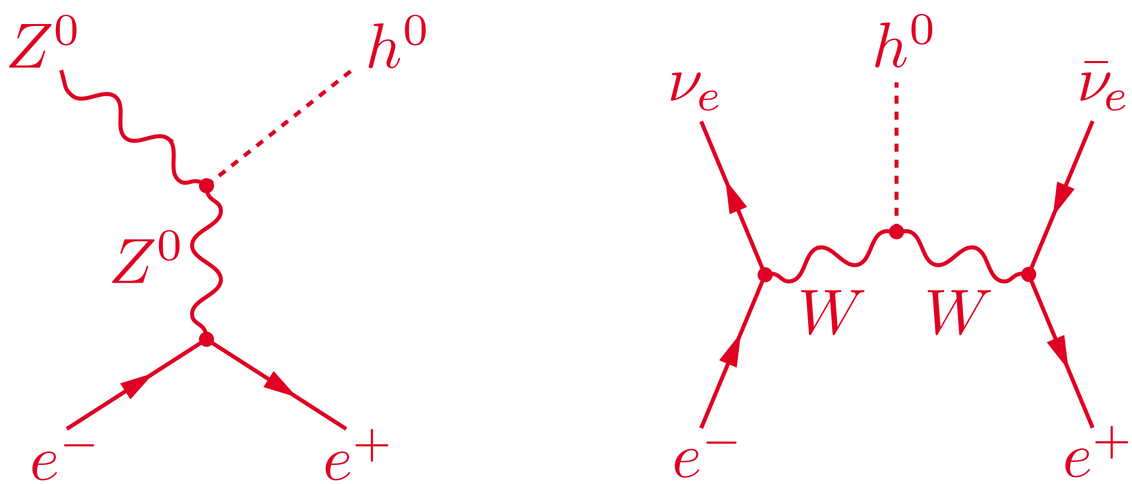
(Also needed to avoid nonsensical predictions at $E \gtrsim 1000$ GeV)

Looking for the Higgs Particle(s)

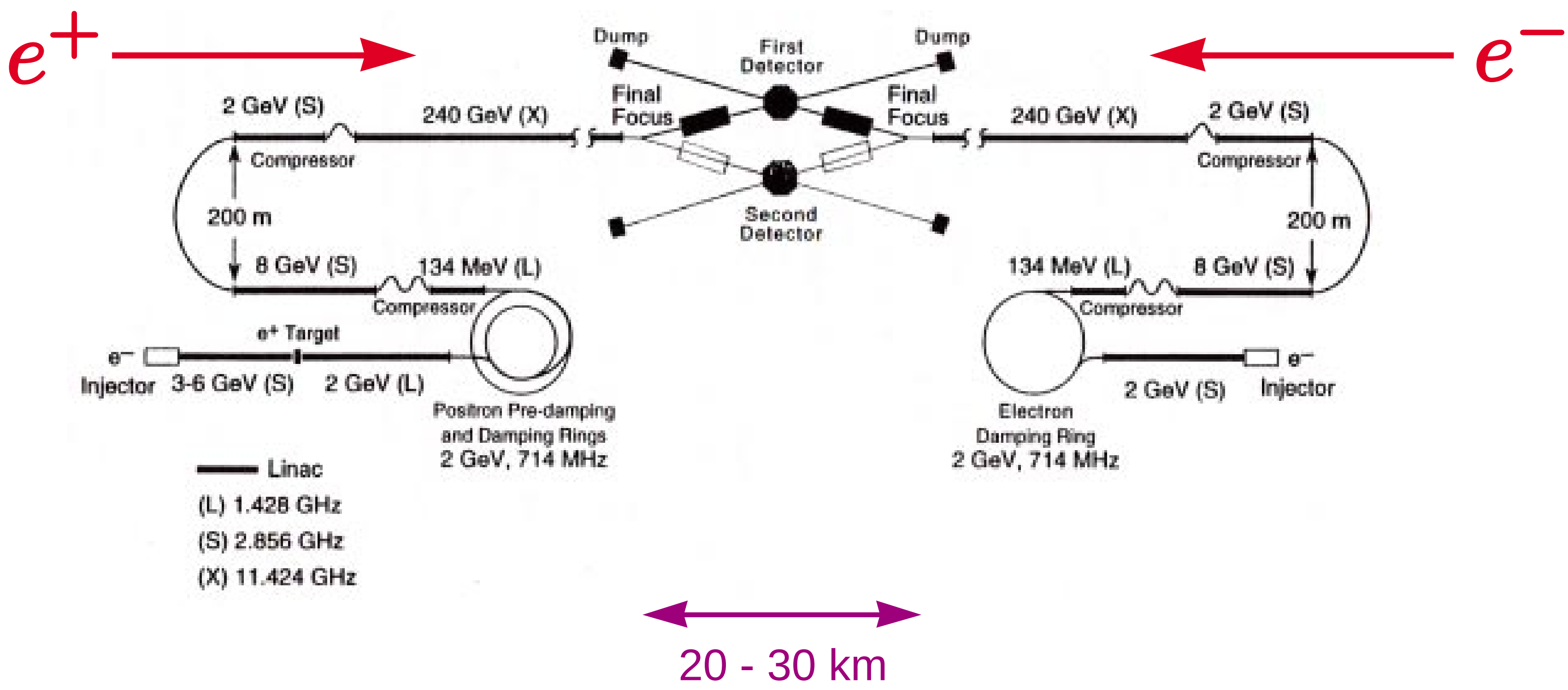
- Tevatron (Fermilab, Chicago): $p\bar{p}$, $E_{\rm cm} = 2000$ GeV
- Large Hadron Collider (CERN, Geneva): pp, $E_{\rm cm} = 14,000$ GeV, 2007

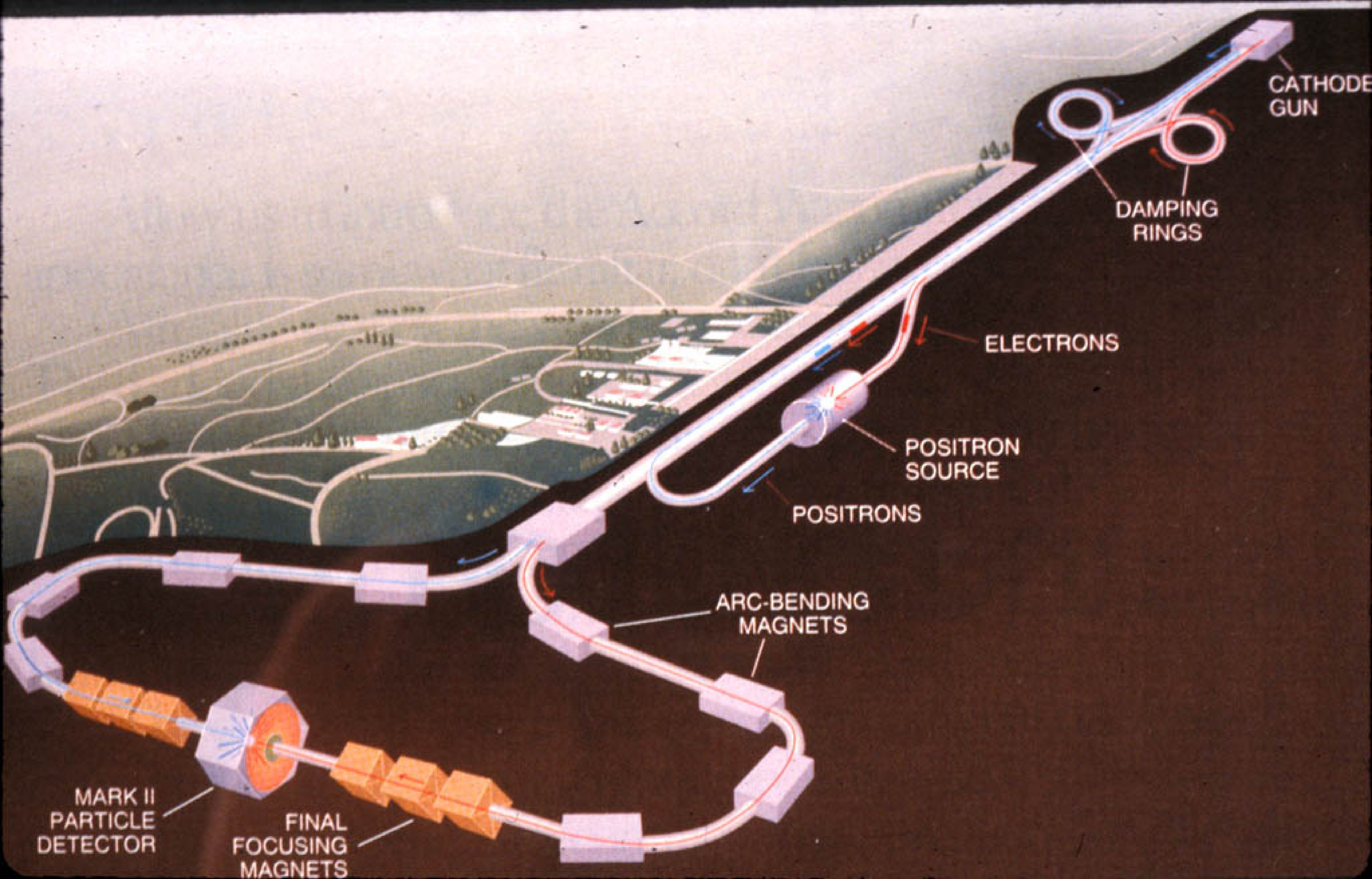
  Discovery likely! Detailed study difficult.

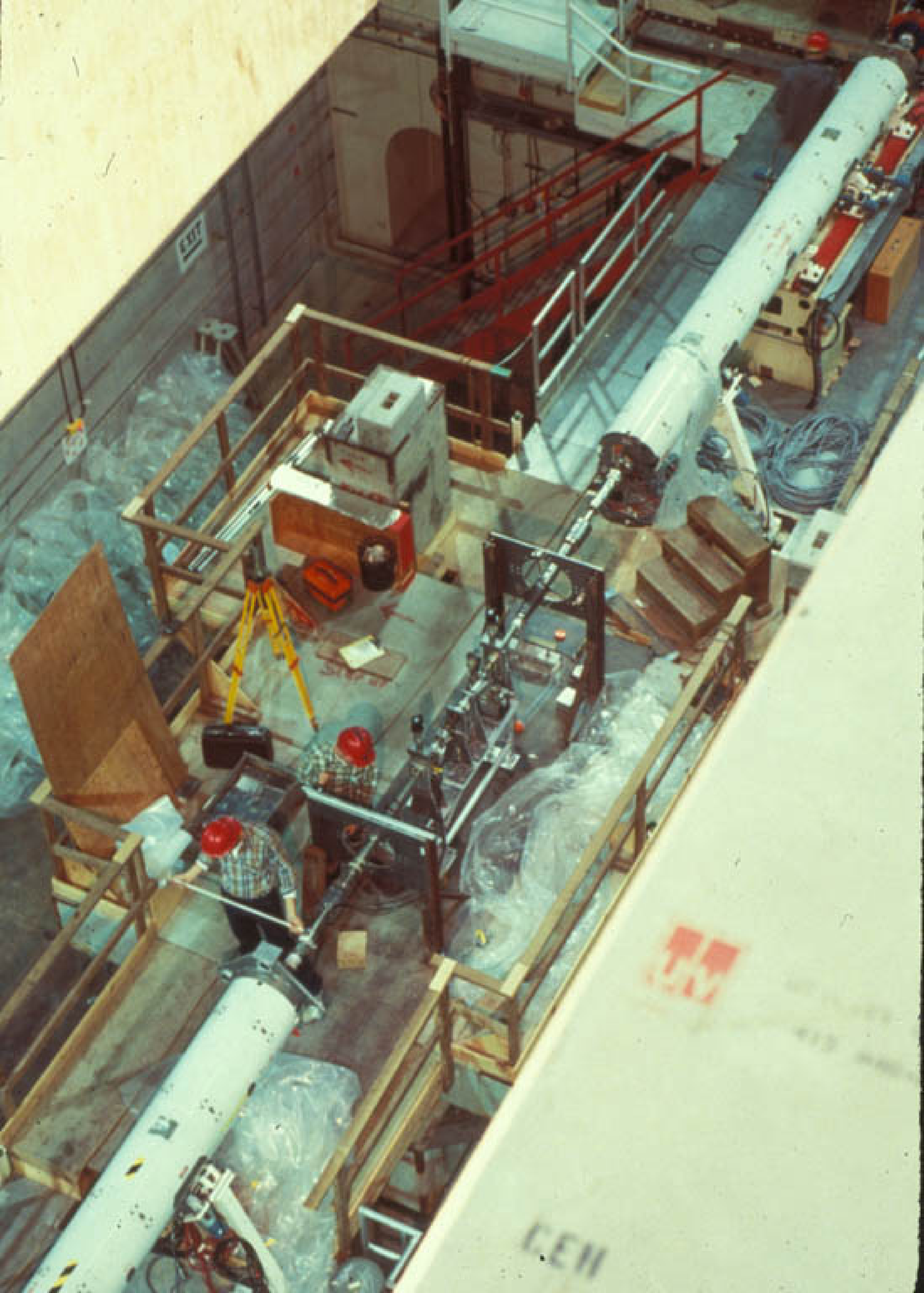
- e^+e^- storage ring, $E_{\rm cm} = 500+$ GeV? Too big, too expensive.
- e^+e^- *linear* collider



The Next Linear Collider




CATHODE GUN
DAMPING RINGS
ELECTRONS
POSITRON SOURCE
POSITRONS
ARC-BENDING MAGNETS
MARK II PARTICLE DETECTOR
FINAL FOCUSING MAGNETS



Suggested Reading

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