Experimental tests of QED:

1. From the matrix element to the measurement
2. e^+e^- scattering experiments
3. Anomalous magnetic moment

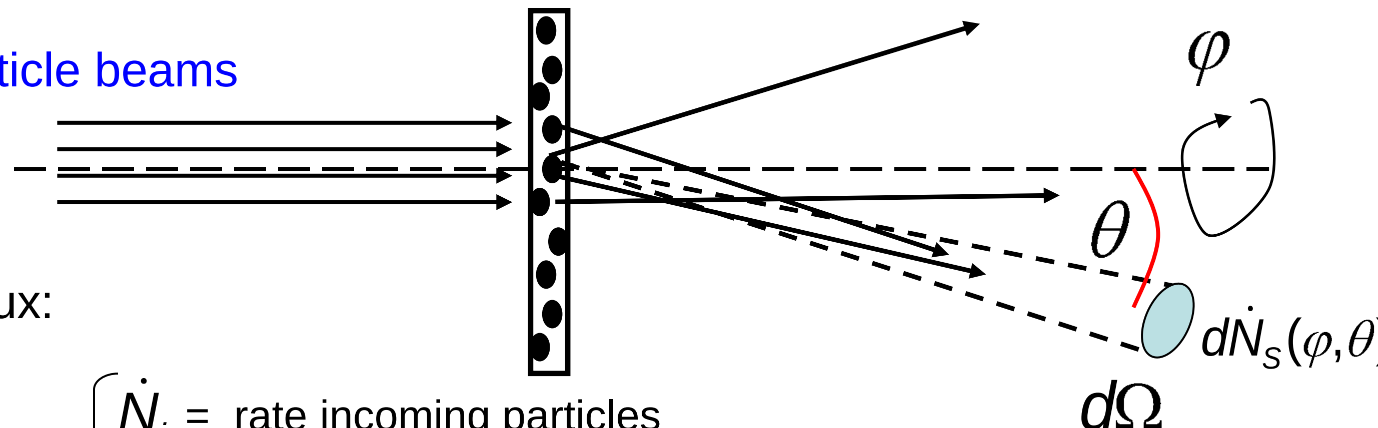
1. From the matrix element to the measurement

1.1 Cross section – experimental definition

$\rightarrow$ Most important observable to describe scattering processes.

Target:
N_t scattering centers

particle beams



Incident particle flux:

$$F = \frac{\dot{N}_i}{A} = n_i v_i$$

- $\dot{N}_i$ = rate incoming particles
- n_i = particle density in beam
- v_i = velocity of particles

Particles rate scattered into $d\Omega(\varphi,\theta)$: $d\dot{N}_s(\varphi,\theta)$

$$d\sigma = \frac{d\dot{N}_s(\varphi,\theta)}{F \cdot N_t} = \frac{d\dot{N}_s(\varphi,\theta)}{\Phi}$$

Differential cross section:

$$\frac{d\sigma(\varphi,\theta)}{d\Omega} = \frac{d\dot{N}_s(\varphi,\theta)}{F N_t \cdot d\Omega} = \frac{d\dot{N}_s(\varphi,\theta)}{\Phi \cdot d\Omega}$$

$N_t=1$

Total cross section:

The total cross section is obtained from the total rate of scattered particles:.

$$\sigma_{tot} = \frac{\dot{N}_s}{\Phi}$$

respectively:

$$\sigma_{tot} = \int \left(\frac{d\sigma}{d\Omega} \right) d\Omega = \frac{1}{\Phi} \int \left(\frac{d\dot{N}_s}{d\Omega} \right) d\Omega$$

$d\cos\theta \, d\varphi$

of scattered particle

Dimension $\sigma = \frac{\text{time}^{-1}}{(\text{time}^{-1} \times \text{area}^{-1})} = \text{area}$

Units: $[\sigma] = 1\,\text{b} = 10^{-28}\text{m}^2$

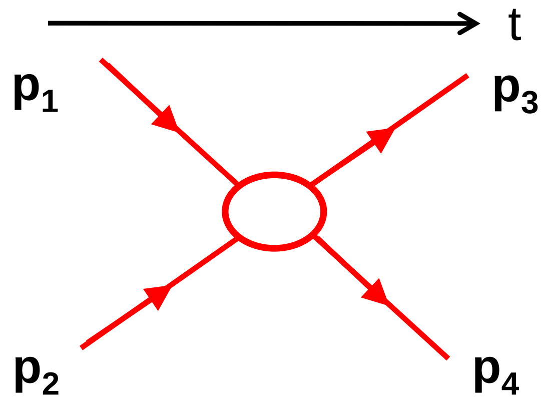
1 b = 1 barn

1.2 Scattering matrix and transition amplitude

Scattering process:

$$1 + 2 \rightarrow 3 + 4$$

$$P_i = p_1 + p_2$$



$$P_f = p_3 + p_4$$

Initial and final states: $\quad |i\rangle \quad \rightarrow \quad |t\rangle$

Scattering operator (S matrix): $\quad \lim_{t \to +\infty} |t\rangle = \mathbf{S} |i\rangle$

Measurement selects specific state f.
Probability S_{fi} to find f: $\quad \langle f | t \rangle = \langle f | \mathbf{S} | i \rangle = S_{fi}$

$$S_{fi} = \delta_{fi} + \mathrm{i}(2\pi)^4 \delta^4 (P_f - P_i) T_{fi}$$

$$T_{fi} = \langle f | \mathbf{T} | i \rangle$$

Probability that collection of states **i** will make the transition to a final state **f**:

$$P_{fi} = |S_{fi}|^2$$

$$P_{fi} = (2\pi)^8 \left[\delta^4(P_f - P_i)\right]^2 |T_{fi}|^2$$

… or to all possible final states **f**:

$$P_{fi} = \sum_f |S_{fi}|^2$$

Final-state phase-space:

The calculation of the transition probability has to consider the number of possible states for each of the out-going particles: $\rightarrow$ phase-space factor

dN_f = number of states within $\vec{p}$ and $\vec{p} + d\vec{p}$:

$$dN_f = \frac{d^3 p_C}{2E_c (2\pi)^3} \cdot \frac{d^3 p_D}{2E_D (2\pi)^3} \cdot \ldots$$

1.3 Amplitude, cross section and phase space

$$d\sigma = \frac{\text{transition rate per unit volume}}{\text{incindent flux}}$$

$$d\sigma = \underbrace{\frac{|S_{fi}|^2 \, dN_f}{VT}}_{w_{fi}} \frac{1}{\Phi}$$

w_{fi}= Transition rate / V

$$w_{fi} = \frac{|S_{fi}|^2 \, dN_f}{VT} = \frac{(2\pi)^8 \left[\delta^4(P_f - P_i)\right]^2 \left|T_{fi}\right|^2}{VT} dN_f$$

$$= \frac{(2\pi)^8 \delta^4(P_f - P_i) \delta^4(0) \left|T_{fi}\right|^2}{VT} dN_f$$

$$= (2\pi)^4 \delta^4(P_f - P_i) \left|T_{fi}\right|^2 dN_f$$

Incident flux Φ:

Lab: 1 ⟶ 2

CMS: 1 ⟶ ⟵ 2 $\vec{p}_1 = -\vec{p}_2$

Lab: $$\Phi\big|_{\text{unit V}} = \rho_1 v_1 N_2/\text{V} = 2\text{E}_1 2E_2 \left(\frac{|\vec{p}_1|}{E_1}\right)$$

CMS: $$\Phi\big|_{\text{unit V}} = 2E_1 2E_2 |\vec{v}_1 - \vec{v}_2| = 2E_1 2E_2 \left|\frac{\vec{p}_1}{E_1} - \frac{\vec{p}_2}{E_2}\right| = 4|\vec{p}_1|(E_1 + E_2)$$

$$= 4\left((p_1 \cdot p_2)^2 - m_1^2 m_2^2\right)^{1/2}$$

Reminder: Normalization of states

$$\langle (p,s) | (p',s') \rangle = \delta_{ss'} (2\pi)^3 2E_p \, \delta(\vec{p} - \vec{p}')$$

States are delta-function in momentum space.

$$= \delta_{ss'} 2E_p \int d^3x \, e^{i(\vec{p}-\vec{p}')\vec{x}} = 2E_p V\big|_{s=s'}$$

Differential cross section:

$$d\Phi_2(P_i, p_C, p_D)$$

$$d\sigma = \frac{|T_{fi}|^2}{4\left((p_1 \cdot p_2)^2 - m_1^2 m_2^2\right)^{1/2}} \overbrace{(2\pi)^4 \delta^4(P_f - P_i) \frac{d^3 p_C}{2E_c (2\pi)^3} \cdot \frac{d^3 p_D}{2E_D (2\pi)^3}}$$

Lorentz invariant phase-space factor for n particles:

$$d\Phi_n(P, \underbrace{p_1, p_2, \ldots, p_n}_{\text{Final state}}) = (2\pi)^4 \delta^4(P - (p_1 + p_2 + \ldots + p_n)) \prod_{final} \frac{d^3 p_f}{(2\pi)^3 2E_f}$$

See also PDG
http://pdg.lbl.gov/2009/reviews/rpp2009-rev-kinematics.pdf

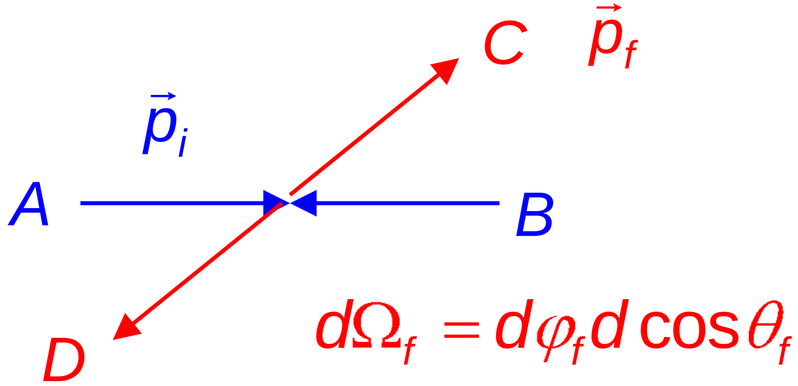
(uses unfortunately different normalization)

Phase space integration for two-particles final-state (CMS)

Center of Mass System:

$\vec{p}_i = \vec{p}_A = -\vec{p}_B \quad \vec{p}_f = \vec{p}_C = -\vec{p}_D$

$s = (E_A + E_B)^2$



$$d\Phi_2 \xrightarrow{\int}$$

$$\int d\Phi_2 = \frac{1}{4\pi^2}\int \delta^3(\vec{p}_C + \vec{p}_D)\delta(E_A + E_B - E_C - E_D)\frac{d^3 p_C}{2E_C}\frac{d^3 p_D}{2E_D}$$

$$\int d\Phi_2 = \frac{1}{4\pi^2}\int \delta^3(\vec{p}_C + \vec{p}_D)\,\delta(E_A + E_B - E_C - E_D)\,\frac{d^3 p_C}{2E_C}\,\frac{d^3 p_D}{2E_D}$$

In the CMS need to integrate only over p_c: $d^3p = d\Omega\, p^2\, dp$

$$\int d\Phi_2 = d\Omega_C \frac{1}{16\pi^2}\int \delta(E_A + E_B - E_C - E_D)\,\frac{|\vec{p}_C|^2\, d|\vec{p}_C|}{E_C E_D}$$

$$\vec{p}_f = \vec{p}_C = -\vec{p}_D$$

With

$$\int \delta[h(\omega)]\, g(\omega)\, d\omega = \left(g \left| \frac{dh}{d\omega} \right|^{-1} \right)_{f=0}$$

and

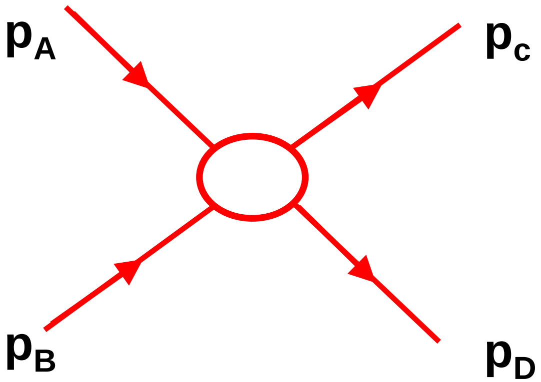
$$h = \sqrt{s} - \sqrt{\vec{p}_C^{\,2} + m_C^2} - \sqrt{\vec{p}_C^{\,2} + m_C^2}$$

$$\Rightarrow \left| \frac{dh}{d|p_C|} \right|_{h=0} = \frac{|\vec{p}_C|\sqrt{s}}{E_C E_D}$$

$$\Rightarrow \int d\Phi_2 = \frac{1}{16\pi^2}\int \frac{|\vec{p}_f|}{\sqrt{s}}\, d\Omega_f$$

1.4 Differential cross section …putting everything together

$$A + B \to C + D$$



CMS

$$d\sigma = \frac{|T_{fi}|^2}{\Phi} d\Phi_2 = \frac{1}{64\pi^2} \cdot \frac{1}{s} \cdot \frac{|\vec{p}_f|}{|\vec{p}_i|} \cdot |T_{fi}|^2 d\Omega_f$$

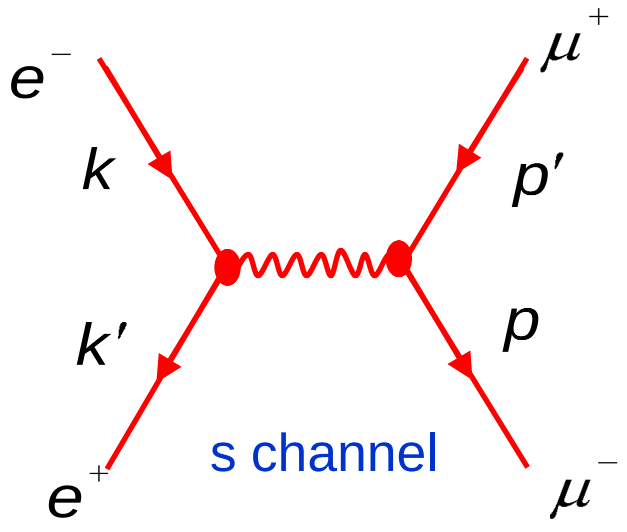
$$\frac{d\sigma}{d\Omega_f} = \frac{1}{64\pi^2} \cdot \frac{1}{s} \cdot \frac{|\vec{p}_f|}{|\vec{p}_i|} \cdot |T_{fi}|^2$$

- The dynamics of the scattering process is contained in the matrix element M_{fi} which can be calculated using Feynman rules
- 1/s dependence of the cross section because of initial/final state kinematics

2. e⁺e⁻ scattering experiments

2.1 Myon pair production

$$e^+ e^- \rightarrow \mu^+ \mu^-$$



$$T_{fi} \sim -\frac{e^2}{q^2} \bar{v}_e(k')\gamma_\mu u_e(k) \cdot \bar{u}_\mu(p)\gamma^\mu v_\mu(p')$$

Spinors decribe a specific spin state of the fermions

For non-polarized ingoing particles and for non-observation of final state spin one observes unpolarized cross sections $\Rightarrow$ need to **average over possible initial spin states** and **sum over all final spin states**.

$$\overline{|T_{fi}|^2} = \frac{1}{4} \cdot \sum_{s_e, s'_e} \sum_{s_\mu, s'_\mu} |T_{fi}|^2$$

Averaging and summing over spins of initial/final state:

$$\overline{|M_{fi}|^2} = \frac{1}{4}\frac{e^4}{s^2} \sum_{s,s',r,r'} |\bar{u}_{\mu,s}(p_3)\gamma^\nu v_{\mu,s'}(p_4)\ \bar{v}_{e,r}(p_2)\gamma_\nu u_{e,r'}(p_1)|^2$$

neglect masses

$$= 8\frac{e^4}{s^2}\left[(p_1p_4)(p_2p_3) + (p_2p_4)(p_1p_3)\right]$$

Lorentz invariant!

By using the Mandelstam variables in the relativistic limit

$$s = (p_1 + p_2)^2 = m^2 + m^2 + 2p_1p_2 \approx 2p_1p_2 \approx 2p_3p_4$$

$$t = (p_1 - p_3)^2 = m^2 + M^2 - 2p_1p_3 \approx -2p_1p_3 \approx -2p_2p_4$$

$$u = (p_1 - p_4)^2 = m^2 + M^2 - 2p_1p_4 \approx -2p_1p_4 \approx -2p_2p_3$$

if masses neglected

$$\overline{|M_{fi}|^2} = 2e^4\frac{t^2 + u^2}{s^2}$$

Remember: matrix element squared can be expressed in s, u, t!

$$\overline{\left|T_{fi}\right|^2}_{e^+e^-\to\mu^+\mu^-}(s,t,u) = 2e^4\,\frac{t^2+u^2}{s^2}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2}\cdot\frac{1}{s}\cdot\left|T_{fi}\right|^2$$

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{32\pi^2}\cdot\frac{1}{s}\cdot\frac{t^2+u^2}{s^2}$$

$$= \frac{e^4}{64\pi^2}\cdot\frac{1}{s}\cdot(1+\cos^2\theta)$$

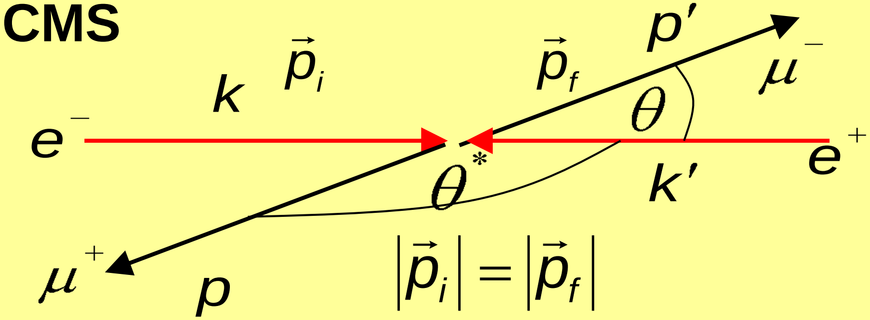
$$e^2 = 4\pi\alpha$$

$$\left.\frac{d\sigma}{d\Omega}\right|_{CMS} = \frac{\alpha^2}{4s}\cdot(1+\cos^2\theta)$$

← 1/s dependence from flux factor

Kinematics for high-relativistic particles

CMS



$$\left|\vec{p}_i\right| = \left|\vec{p}_f\right|$$

$$p^2 = p'^2 = k^2 = k'^2 = 0$$

$$s = (k+k')^2 \approx 4E_i^{\,2}$$

$$t = (k-p)^2 \approx -2kp \approx -2E_i^{\,2}(1-\cos\theta^*) \approx -\frac{s}{2}(1+\cos\theta)$$

$$u = (k-p')^2 \approx -2kp' \approx -2E_i^{\,2}(1-\cos\theta) \approx -\frac{s}{2}(1-\cos\theta)$$

$$\left.\frac{d\sigma}{d\Omega}\right|_{CMS} = \frac{\alpha^2}{4s}\cdot(1+\cos^2\theta)$$

$$\sigma_{tot} = \frac{4\pi\alpha^2}{3s} = \frac{86.86\,\text{nb}\,\text{GeV}^2}{s}$$

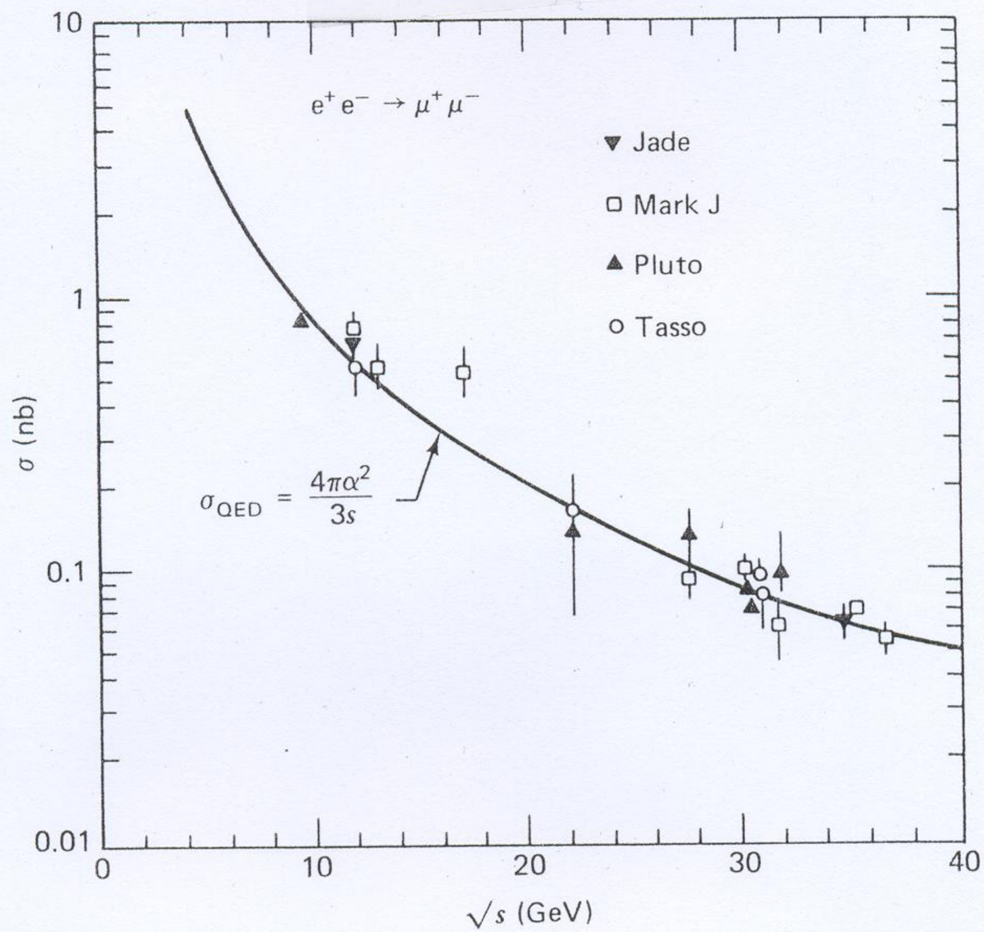
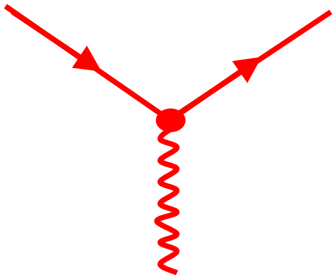


Fig. 6.6 The total cross section for $e^-e^+ \to \mu^-\mu^+$ measured at PETRA versus the center-of-mass energy.

Comments about the angular distribution



Decomposition of the fermion current:

$$\bar{u}\gamma^{\mu}u = (\bar{u}_R + \bar{u}_L)\gamma^{\mu}(u_R + u_L)$$

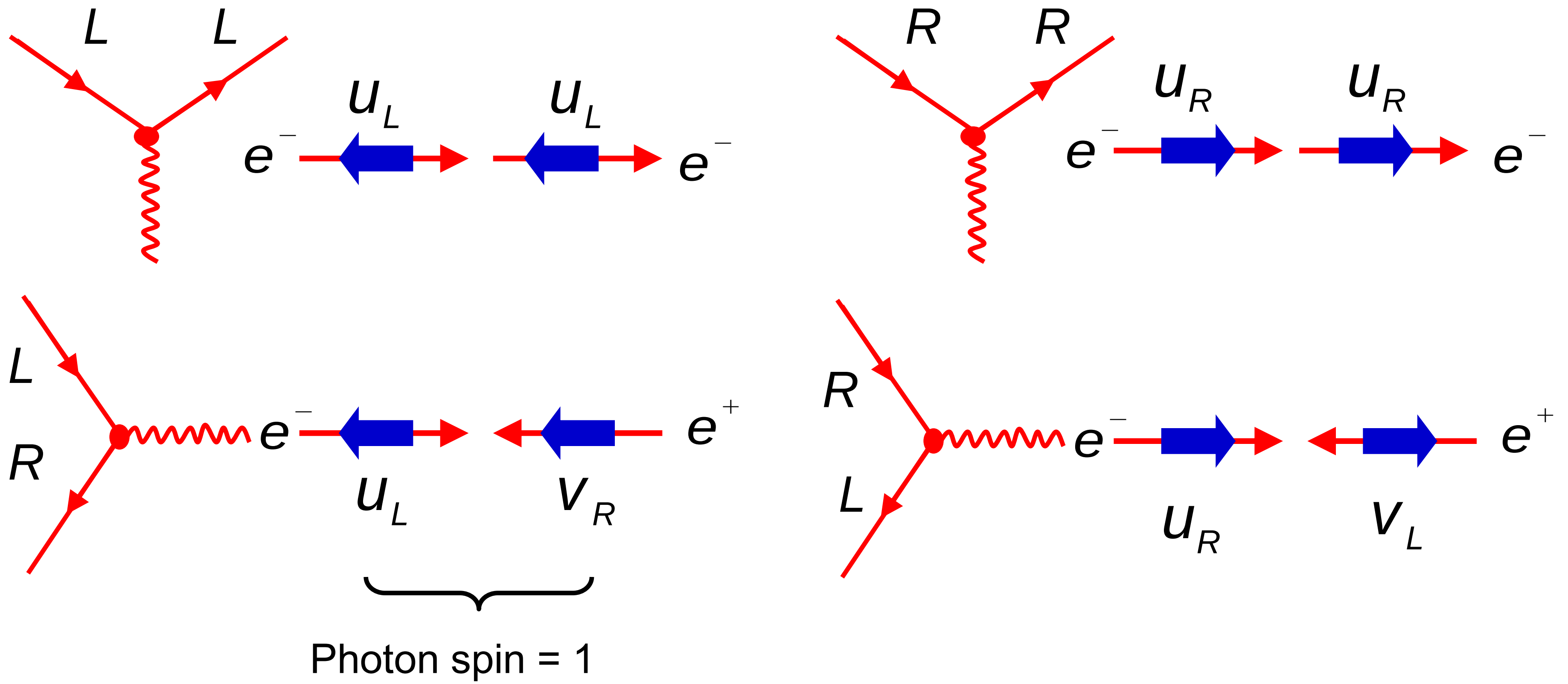
$$= \bar{u}_R\gamma^{\mu}u_R + \bar{u}_L\gamma^{\mu}u_L$$

$$\bar{u}_L = u_L^{\dagger}\gamma^0 = u^{\dagger}\tfrac{1}{2}(\mathbb{1} - \gamma^5)\gamma^0 = \bar{u}\tfrac{1}{2}(\mathbb{1} + \gamma^5)$$

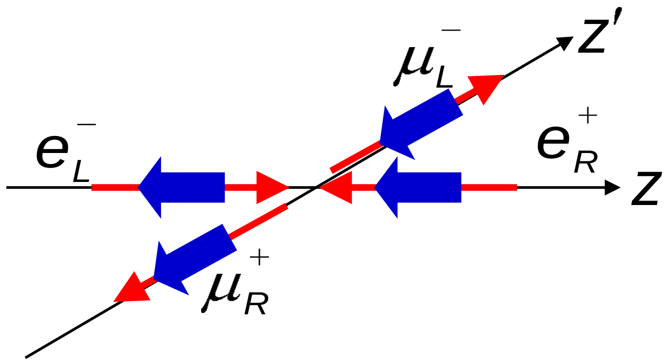
$$\gamma^5\gamma^0 = -\gamma^0\gamma^5 \qquad (\gamma^5)^2 = \mathbb{1}$$

Symbolically – correct only for massless fermions

Vector current $ie\gamma^{\mu}$:



Angular distribution $e^+e^- \to \mu^+\mu^-$



$$d^J_{m'm}$$

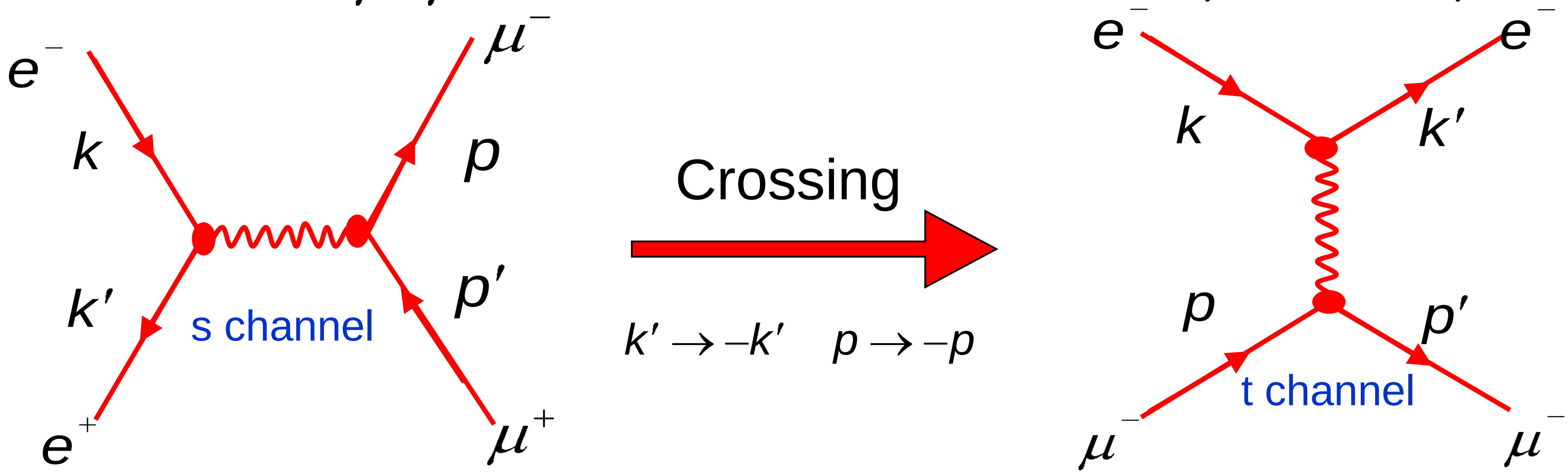
Axis z	rotation →	Axis z'
$J=1$, $m_z=-1$	$\xrightarrow{d^1_{-1-1}}$	$J=1$, $m_{z'}=-1$
$J=1$, $m_z=-1$	$\xrightarrow{d^1_{+1-1}}$	$J=1$, $m_{z'}=+1$

Change of quantization axis

$$\frac{d\sigma}{d\Omega} \sim \left(d^1_{-1-1}\right)^2 + \left(d^1_{+1-1}\right)^2 \sim \frac{1}{4}(1+\cos\theta)^2 + \frac{1}{4}(1-\cos\theta)^2 \sim 1+\cos^2\theta$$

Angular distribution is an effect of vector $ie\gamma^\mu$ coupling!

$$e^+e^- \to \mu^+\mu^- \qquad\qquad e^-\mu^- \to e^-\mu^-$$



$$s = (k + k')^2 \quad \to \quad \tilde{t} = (k - k')^2$$

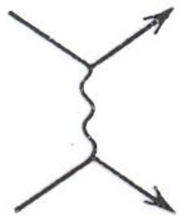
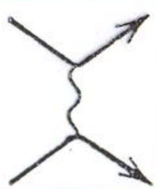
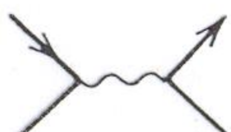
$$t = (k - p)^2 \quad \to \quad \tilde{s} = (k + p)^2$$

$$u = (k - p')^2 \quad \to \quad \tilde{u} = (k - p')^2 = u$$

$$\overline{|M|^2}_{e^+e^- \to \mu^+\mu^-}(s,t,u) \quad = \quad \overline{|M|^2}_{e^-\mu^- \to e^-\mu^-}(\tilde{t},\tilde{s},\tilde{u})$$

$$\overline{|M|^2}_{e^+e^- \to \mu^+\mu^-}(s,t,u) = 2e^4 \frac{t^2 + u^2}{s^2} \quad \Rightarrow \quad \overline{|M|^2}_{e^-\mu^- \to e^-\mu^-}(\tilde{t},\tilde{s},\tilde{u}) = 2e^4 \frac{\tilde{s}^2 + \tilde{u}^2}{\tilde{t}^2}$$

Fermion scattering - Summary

	Feynman Diagrams		$\overline{|\mathcal{M}|^2}/2e^4$		
	Forward peak	Backward peak	Forward	Interference	Backward
Møller scattering $e^-e^- \to e^-e^-$			$\frac{s^2+u^2}{t^2}$ +	$\frac{2s^2}{tu}$ +	$\frac{s^2+t^2}{u^2}$
				$(u \leftrightarrow t$ symmetric)	
(Crossing $s \leftrightarrow u$) ↓	Forward	"Time-like"	Forward	Interference	Time-like
Bhabha scattering $e^-e^+ \to e^-e^+$			$\frac{s^2+u^2}{t^2}$ +	$\frac{2u^2}{ts}$ +	$\frac{u^2+t^2}{s^2}$
$e^-\mu^- \to e^-\mu^-$			$\frac{s^2+u^2}{t^2}$	"Rutherford"	
(Crossing ↓ $s \leftrightarrow t$) $e^-e^+ \to \mu^-\mu^+$					$\frac{u^2+t^2}{s^2}$

2.2 Experimental methods

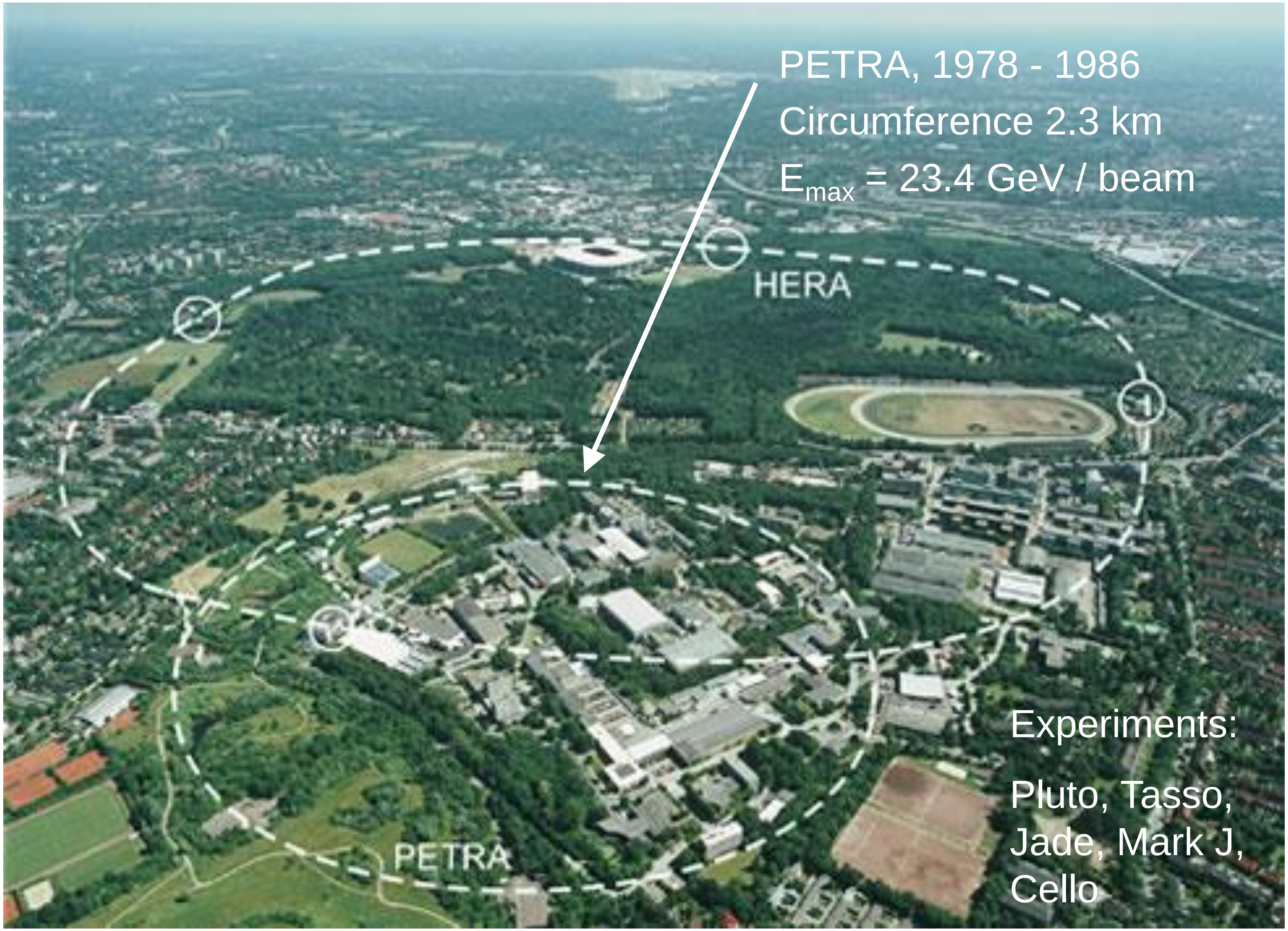
e^+e^- accelerator (selection)

Accelerator	Lab	$\sqrt{s}$	L_{int} / Exper.	
SPEAR	SLAC	2 – 8 GeV		
PEP	SLAC	$\rightarrow$29 GeV	220 - 300 pb^{-1}	
PETRA	DESY	12 - 47 GeV	~20 pb^{-1}	today
TRISTAN	KEK	50 – 60 GeV	~20 pb^{-1}	
LEP	CERN	90 GeV	~200 pb^{-1}	Z physics

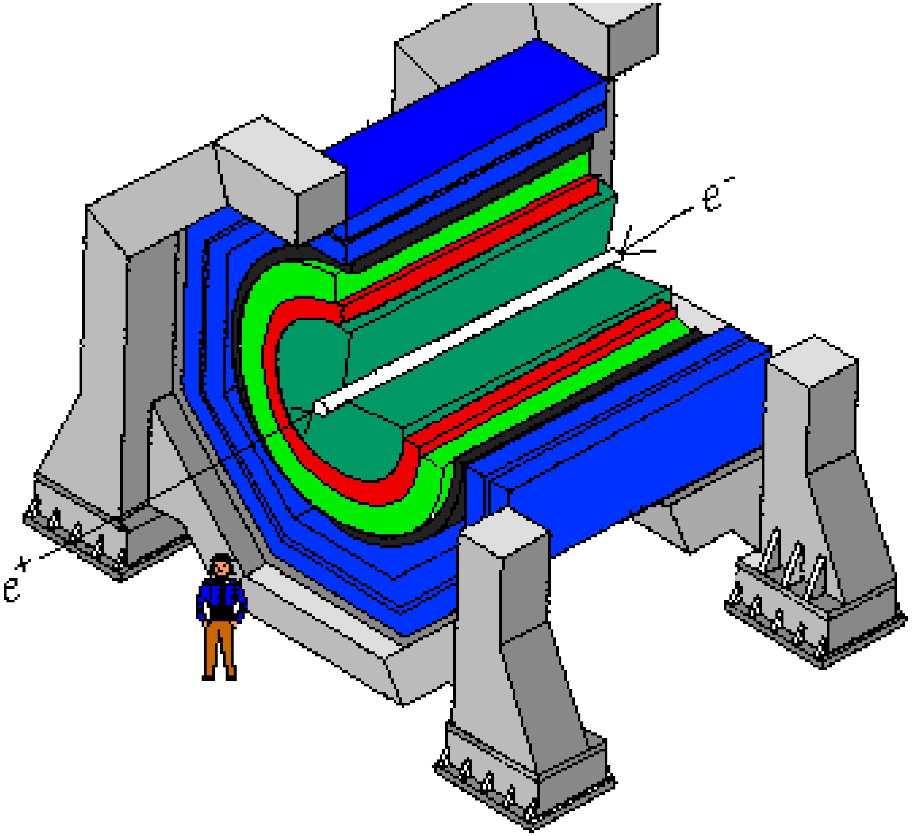
Cross section (experimental definition)

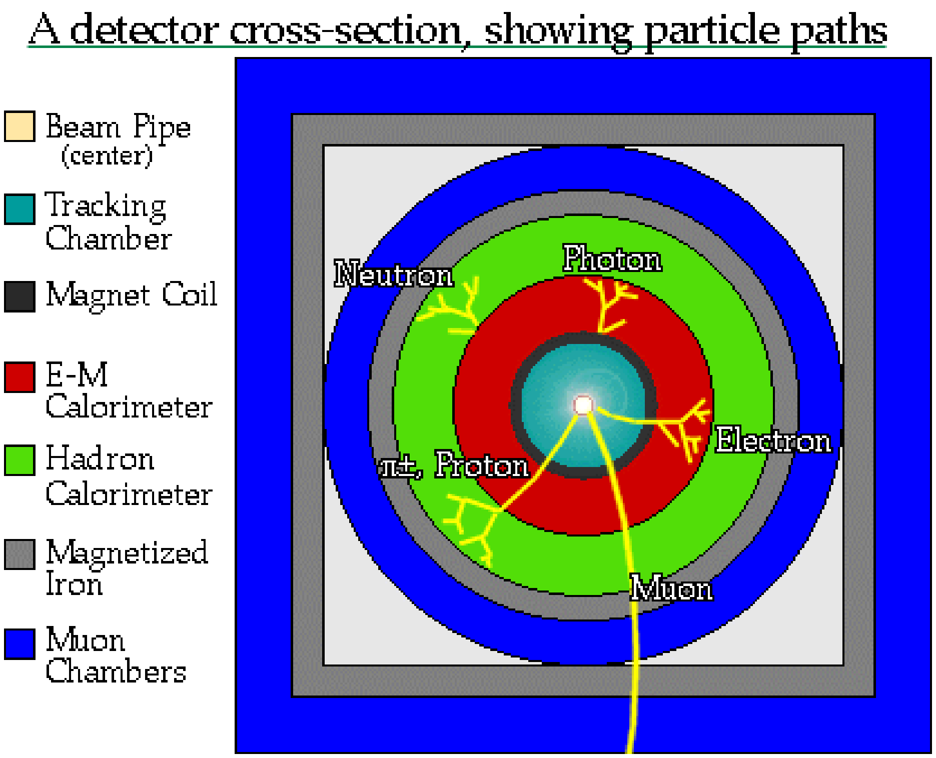
$$\sigma(e^+e^- \rightarrow f\,\bar{f}) = \frac{N_{ff}(1-b)}{\varepsilon\, L_{int}}$$

- N_{ff} number of detected $e^+e^- \rightarrow$ ff events
- b background fraction
- ε acceptance / efficiency
- L_{int} integrated luminosity of collider

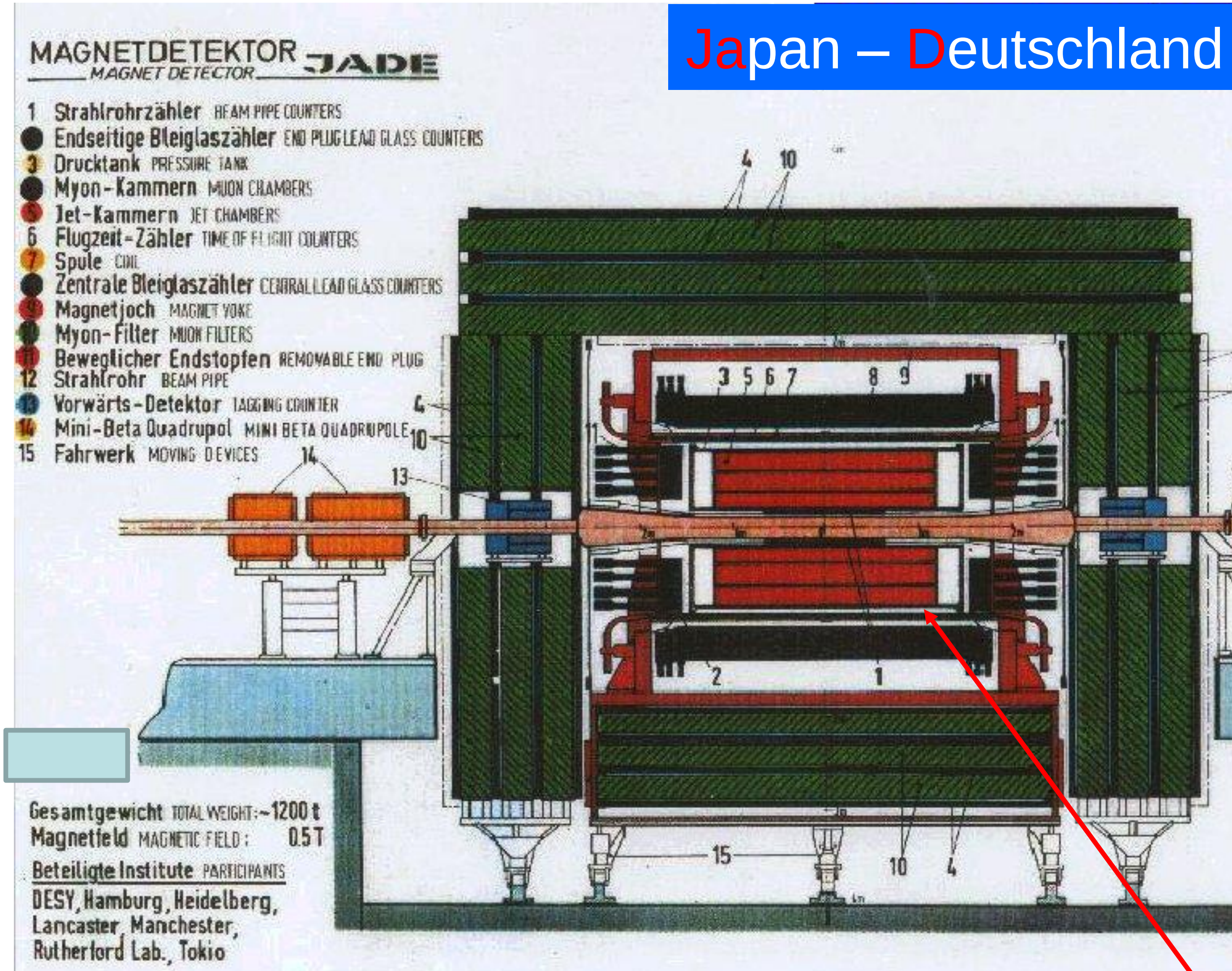

PETRA, 1978 - 1986
Circumference 2.3 km
E_{max} = 23.4 GeV / beam
HERA
PETRA
Experiments:
Pluto, Tasso, Jade, Mark J, Cello

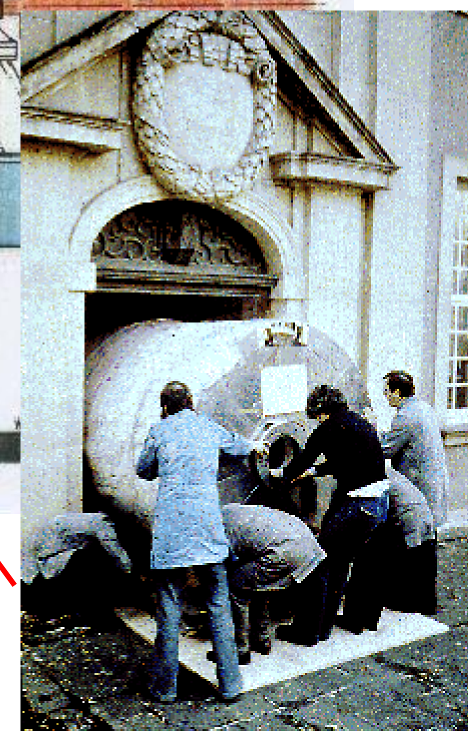
Particle detectors

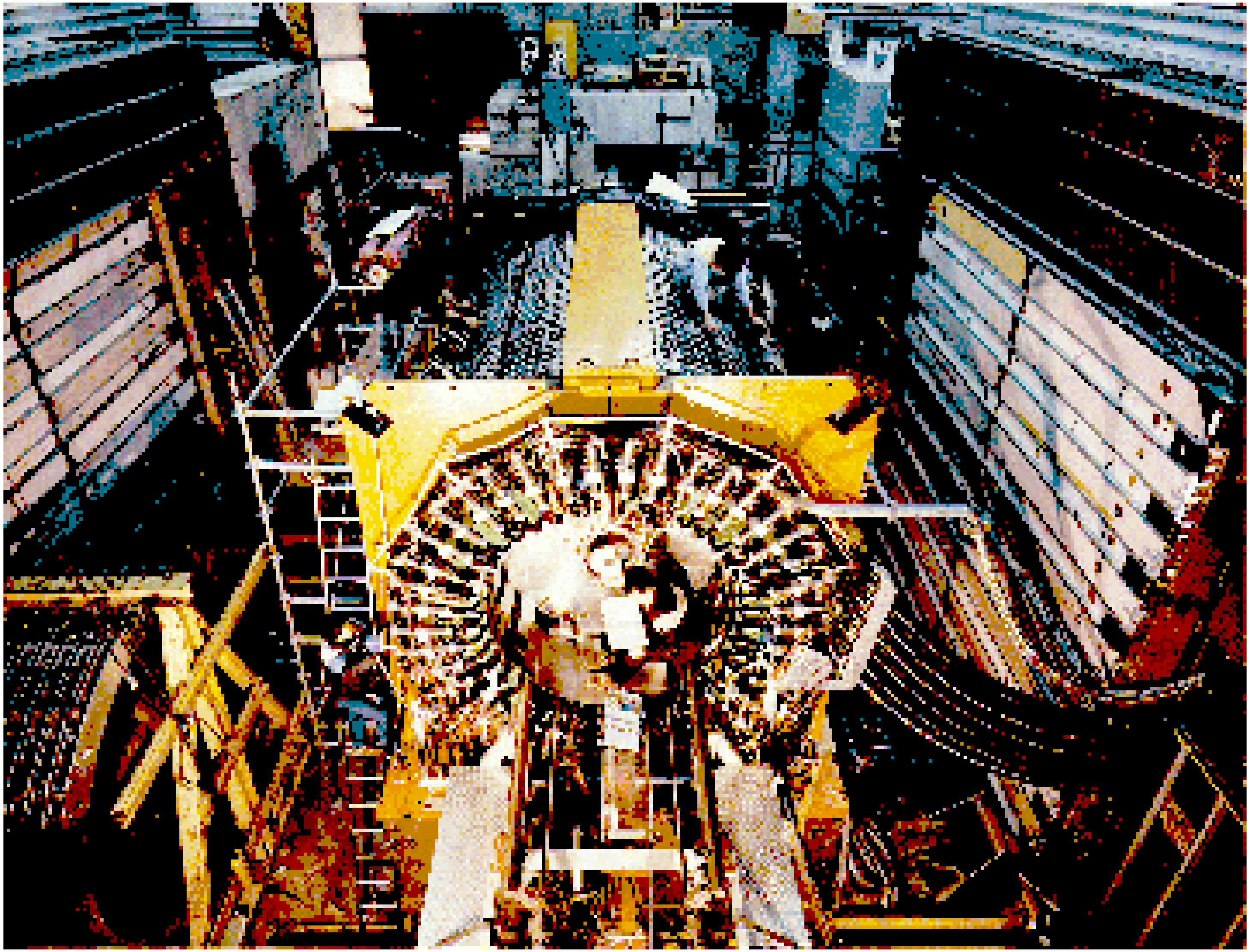




Japan – Deutschland – England

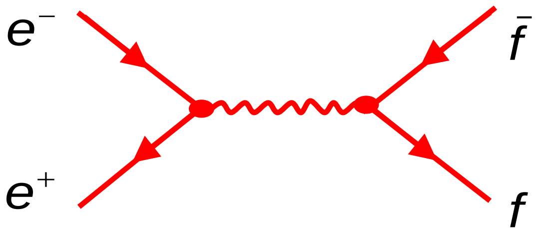


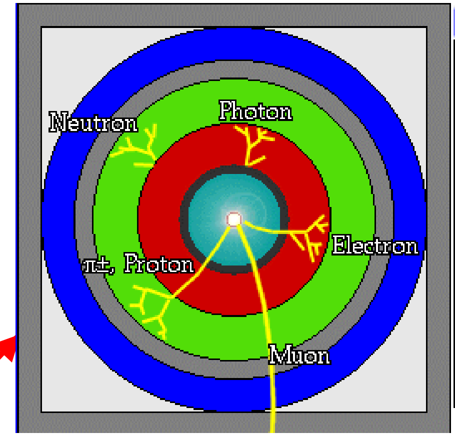


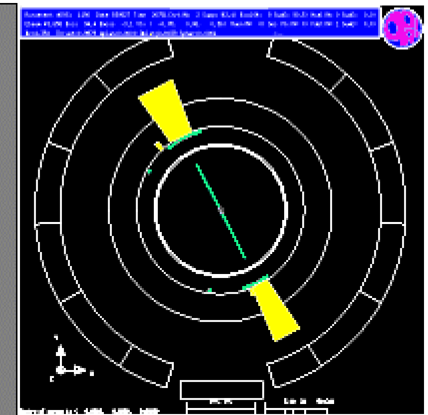


Experimental Signatures:

OPAL / LEP

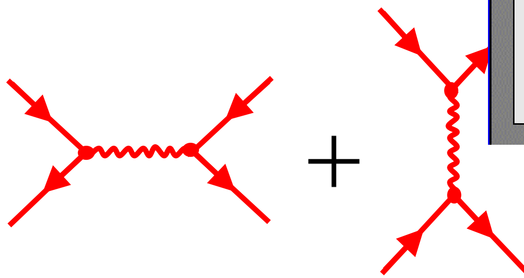


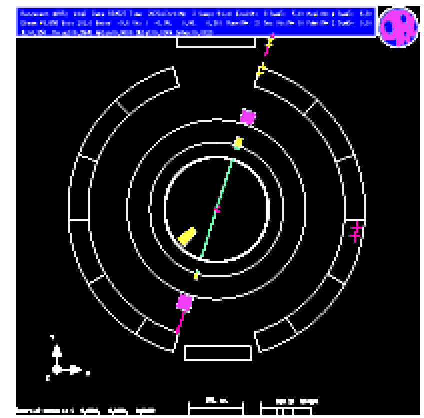




$e^- e^+$

$f\,\bar{f} = e^- e^+$

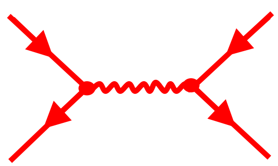


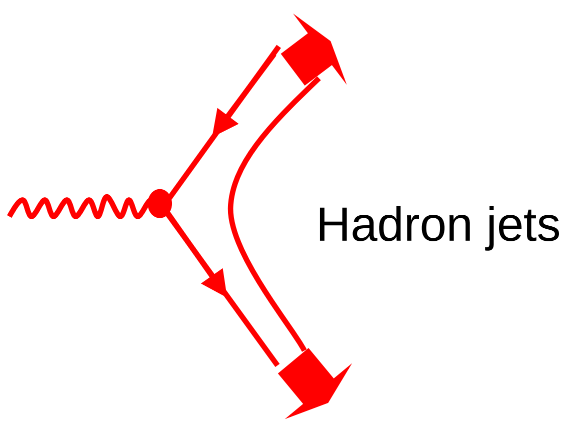


$\mu^- \mu^+$

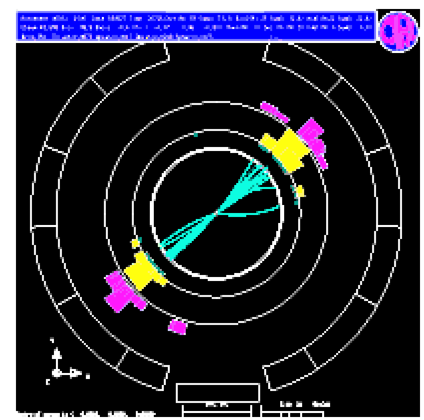
$\mu^- \mu^+$

$\tau^- \tau^+$





$q\,\bar{q}$



$q\,\bar{q}$ mit

$q = u, d, s, c, b, (t)$

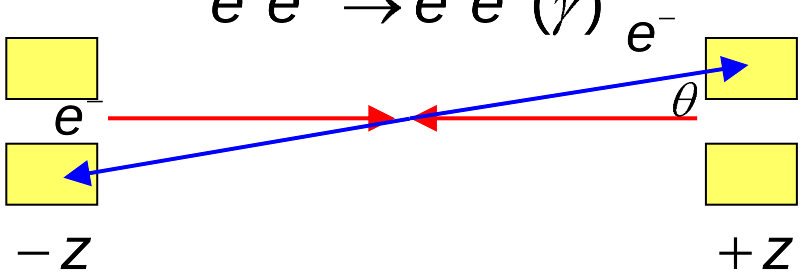
Determination of integrated luminosity

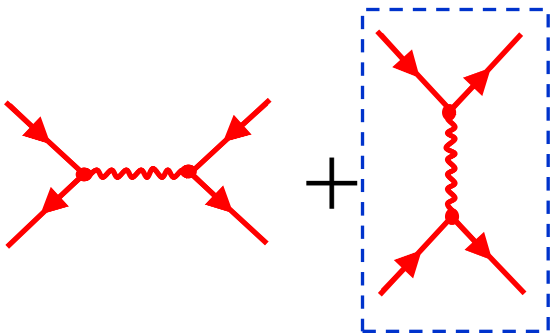
$$\sigma(e^+e^- \to f\,\bar{f}) = \frac{N_{ff}(1-b)}{\varepsilon\, L_{\text{int}}}$$

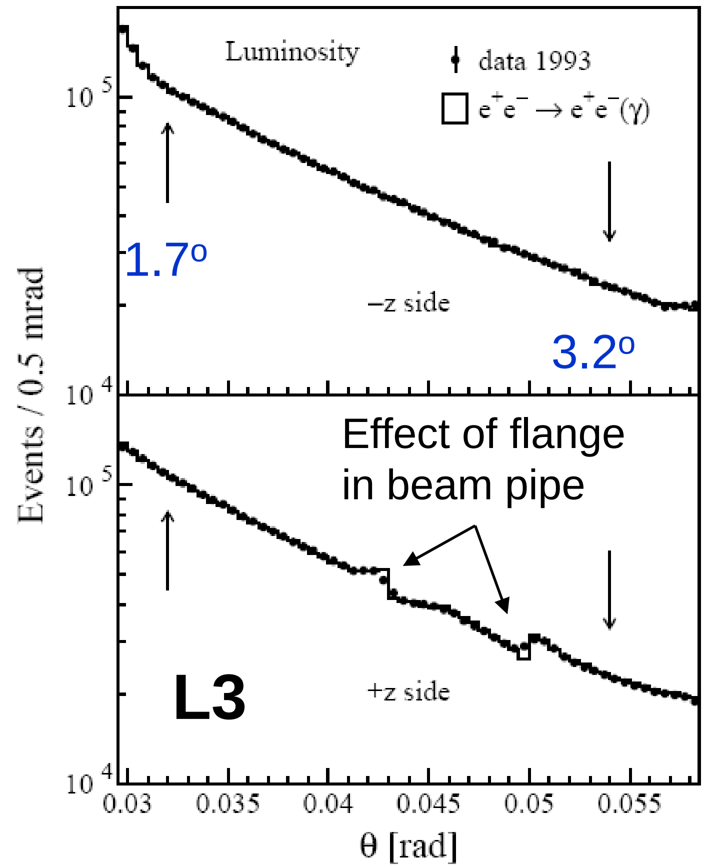
$$L_{\text{int}} = \int L_{ee}(t)\,dt$$

small angle Bhabha scattering
(low momentum transfer):

$$e^+e^- \to e^+e^-(\gamma)$$





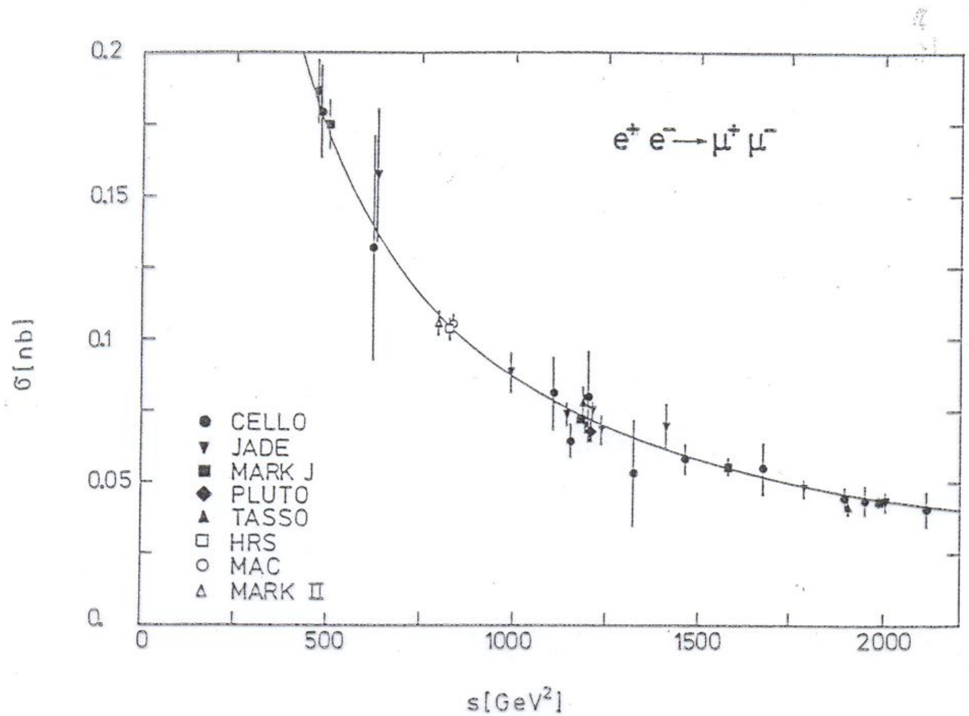


Small angle Bhabha scattering is t channel dominated: theoretical cross section σ_{theo} well known.

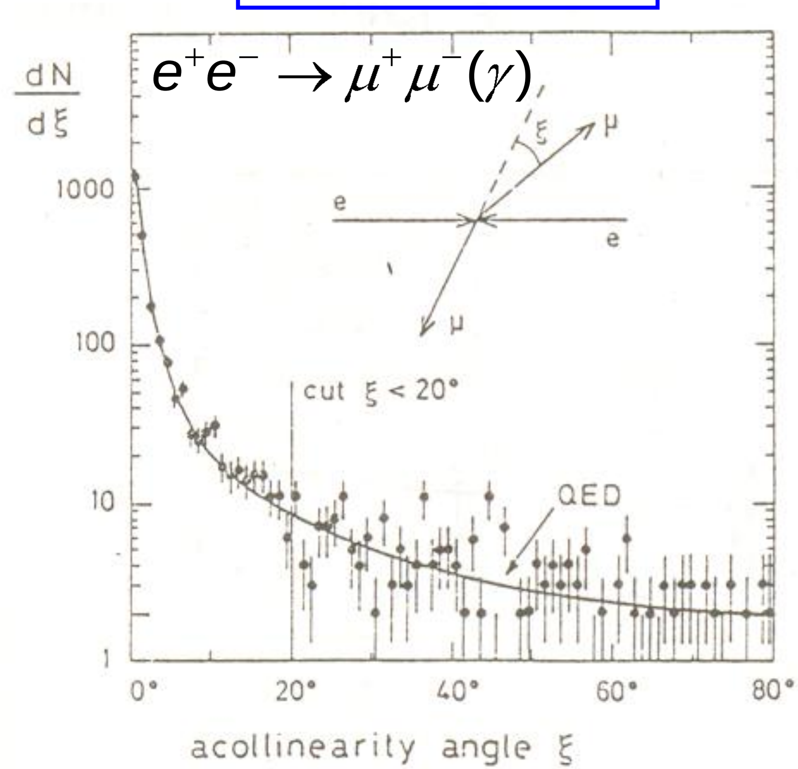
$$L_{\text{int}} = \frac{N_{ee}}{\sigma_{theo}\,\varepsilon}$$

At LEP:
typ. errors < 0.5%

2.3 $e^+e^- \to \mu^+\mu^-$



Acollinearity

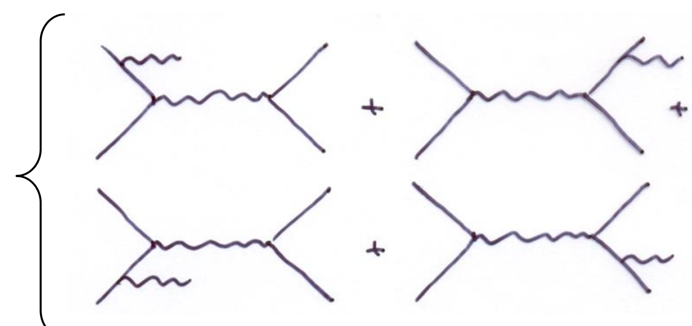


Good agreement with QED!

Quantitative limit for new physics ?

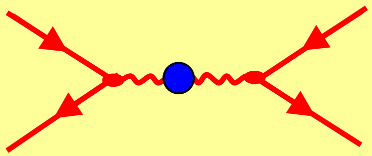
Effect of bremsstrahlung:

There will always be additional photons



Possible deviation from QED:

- additonal heavy photon



Modifies propagator

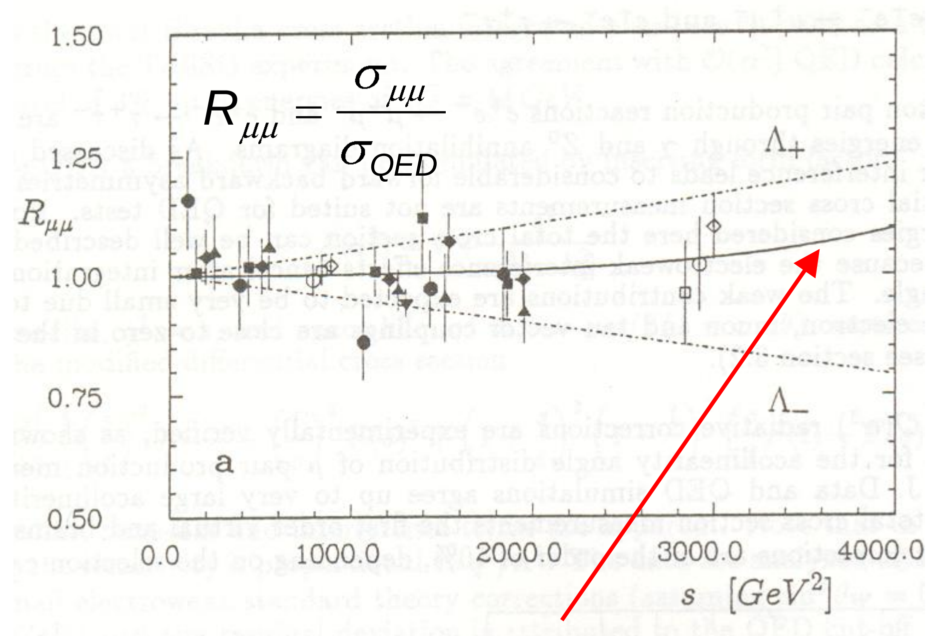
$$\frac{1}{q^2} \rightarrow \frac{1}{q^2} - \frac{1}{q^2 - \Lambda^2} = \frac{1}{q^2}\left(1 - \frac{q^2}{q^2 - \Lambda^2}\right)$$

$$\approx \frac{1}{q^2}\left(1 + \frac{q^2}{\Lambda^2}\right)$$

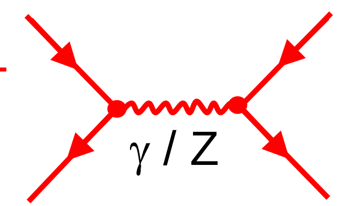
Λ corresponds to the mass of new photon

To also account for possible lower cross sections:

$$\frac{1}{q^2} \rightarrow \frac{1}{q^2}\left(1 \mp \frac{q^2}{q^2 - \Lambda_\pm^2}\right)$$



$$\frac{\sigma_{\mu\mu}^{\gamma+Z}}{\sigma_{QED}}$$



Additional heavy photon:

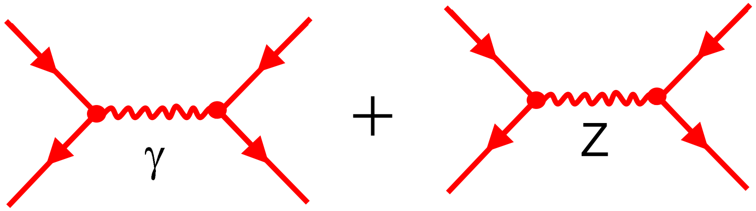
$$\sigma_{\mu\mu} = \frac{4\pi\alpha^2}{s}\left(1 \mp \frac{s}{s - \Lambda_\pm^2}\right)^2$$

→ $\Lambda_\pm > 200\,\text{GeV}$

Confirms "Coulomb law" down to 10^{-18} m

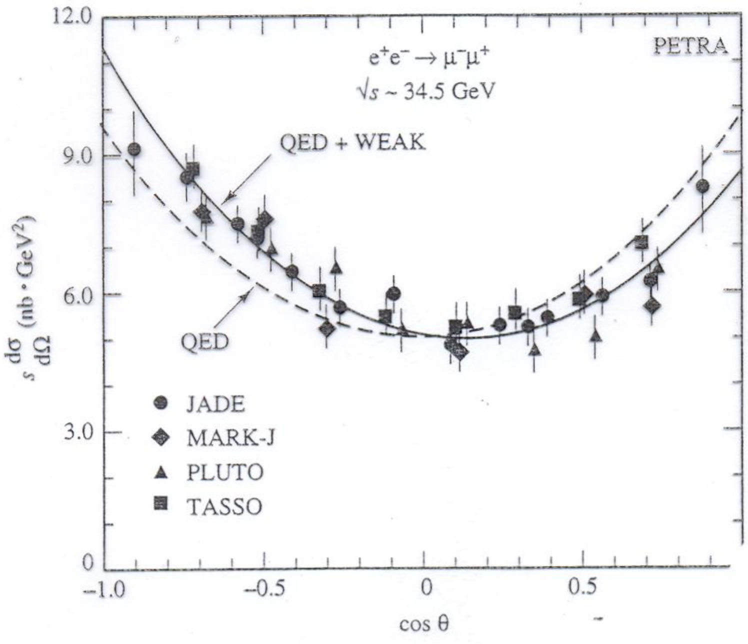
Effect of Z boson exchange

„heavy photon w/ different couplings“



$$\left.\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\cdot(1+\cos^2\theta)\right|_{QED}$$

$$\left.\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\cdot(1+\cos^2\theta + A\cos\theta)\right|_{\gamma+Z}$$

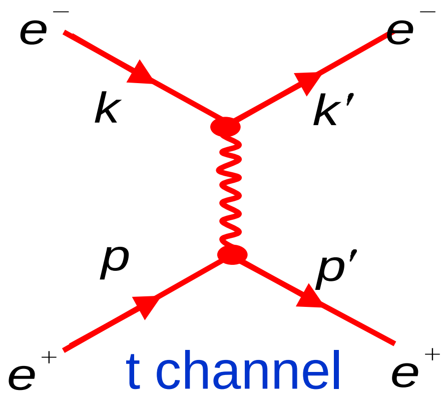
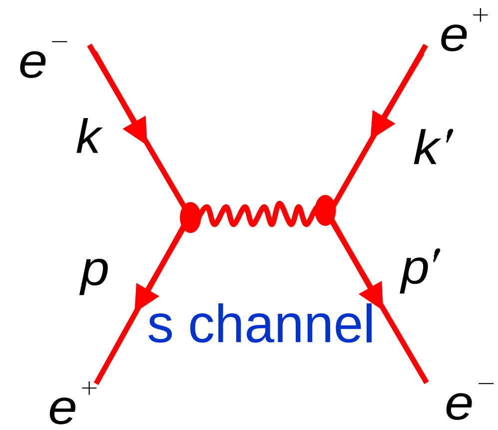


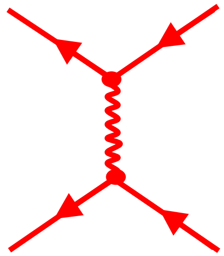
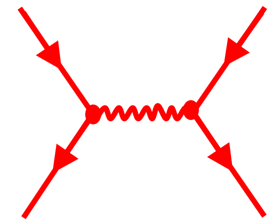
The effect of the “heavy” Z boson is already seen at low energies!

Clear deviation from QED:

⇒Effect of electro-weak γ/Z interference

2.4 Bhabha scattering $e^+e^- \to e^+e^-$

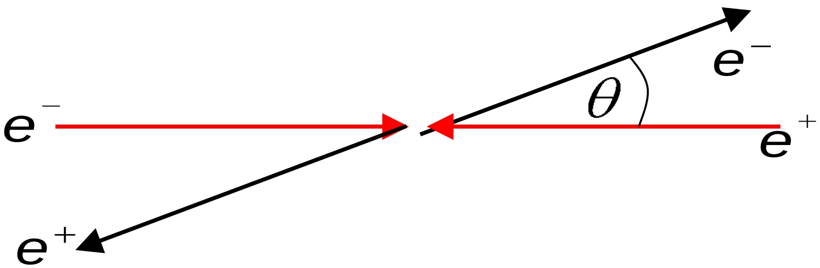
$M =$  $+$ 

$\overline{|M|^2} = \left|\right.$  $\left.\right|^2 +$ interference $+ \left|\right.$  $\left.\right|^2$

$\underbrace{\qquad}_{e^-\mu^- \to e^-\mu^-}$ (first term) $\qquad \underbrace{\qquad}_{e^+e^- \to \mu^+\mu^-}$ (last term)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{s^2+u^2}{t^2} + \frac{2u^2}{ts} + \frac{t^2+u^2}{s^2}\right)$$

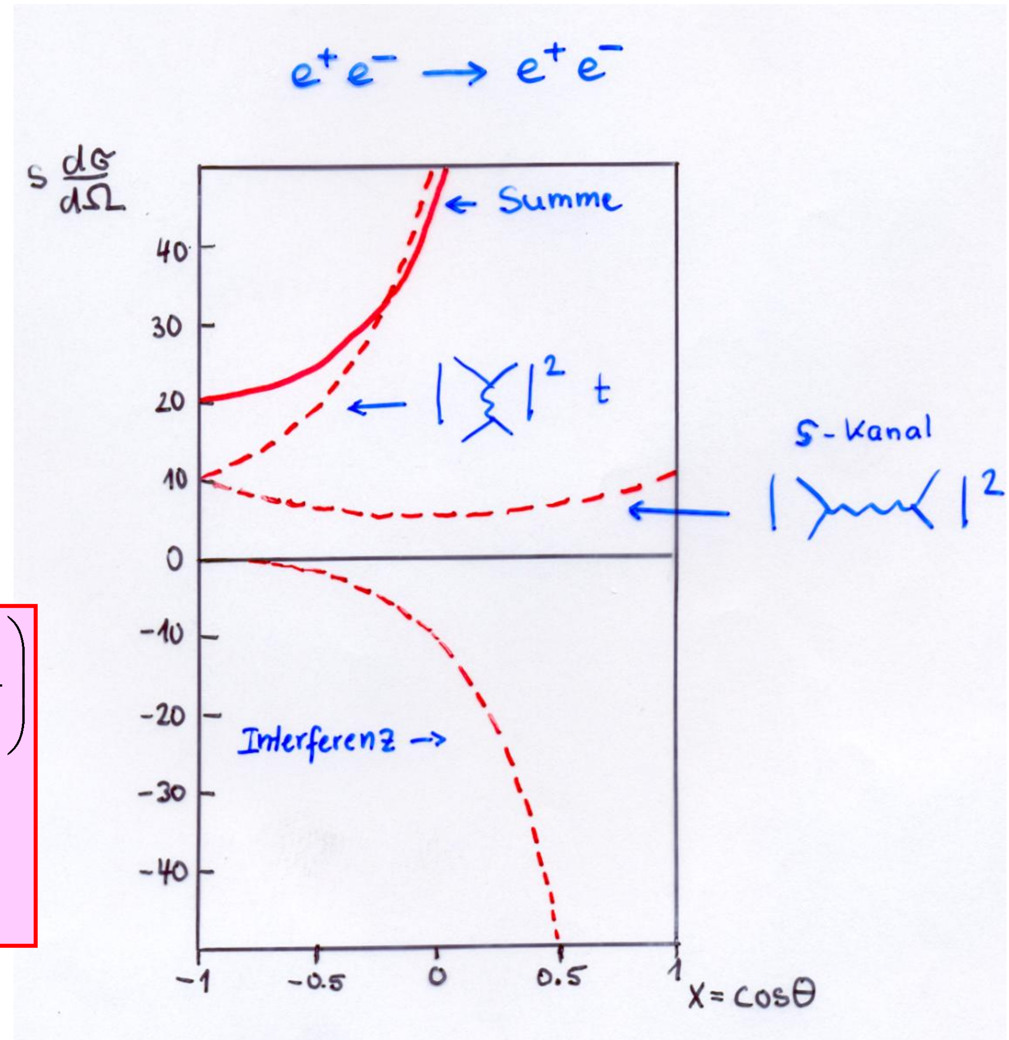
CM system:



with x=cosθ

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{4+(1+x)^2}{(1-x)^2} - \frac{(1+x)^2}{1-x} + \frac{1+x^2}{2}\right)$$

$$= \frac{\alpha^2}{2s}\left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2$$



$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2$$

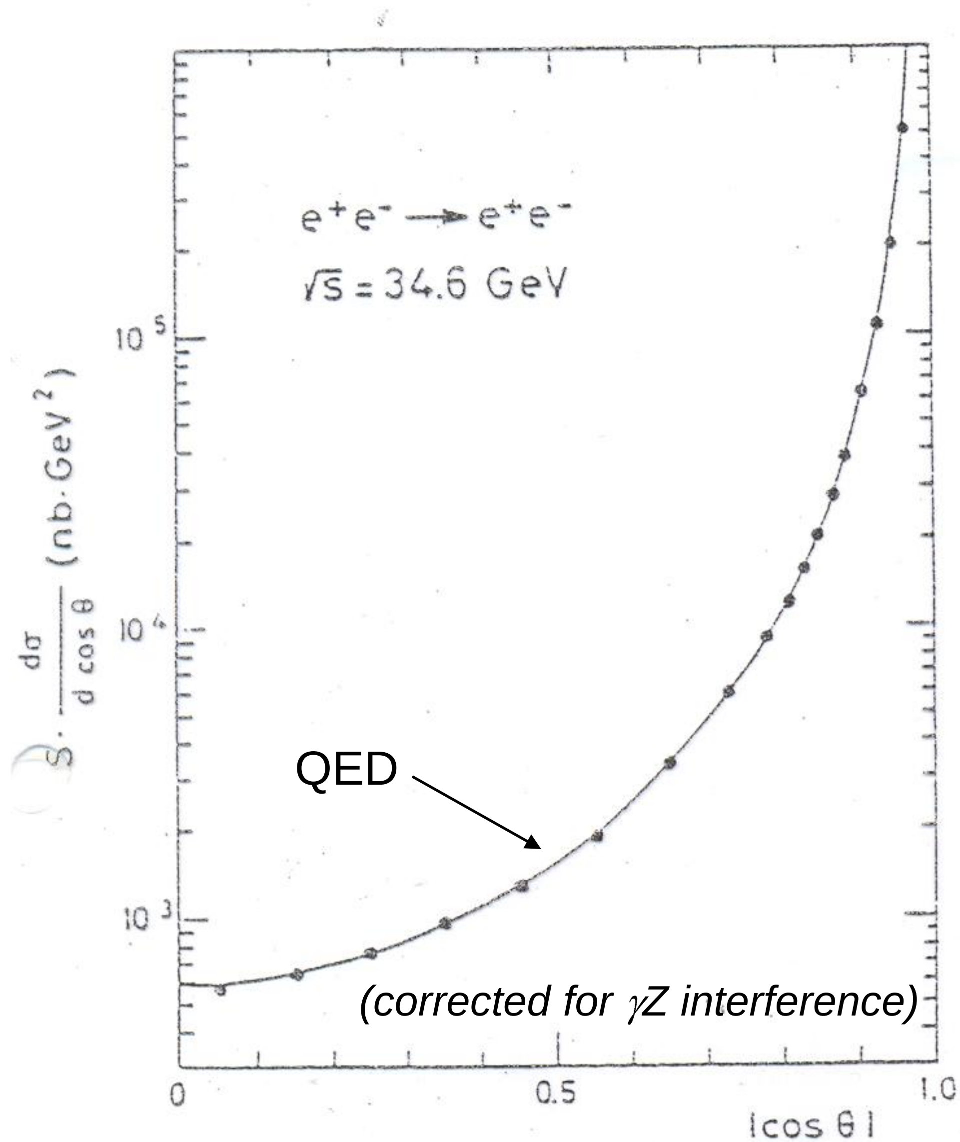
divergent for $\cos\theta \to 1$

Additional „heavy photon“:

$$\frac{1}{q^2} \to \frac{1}{q^2}\left(1 \mp \frac{q^2}{q^2 - \Lambda_\pm^2}\right)$$

$\Rightarrow$ Can be described by form factor:

$$F(q^2) = 1 \mp \frac{q^2}{q^2 - \Lambda_\pm^2}$$



Form factor modifies differential cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{u^2+s^2}{t^2}\left|F(t)\right|^2 + \frac{2u^2}{ts}\left|F(t)F(s)\right| + \frac{u^2+t^2}{s^2}\left|F(s)\right|^2\right)$$

Fit to combined PETRA e^+e^- data:

$\Lambda+$ >435 GeV @ 95% CL

$\Lambda-$ > 590 GeV

In the "space picture" form factor corresponds to modified Coulomb potential at small distances:

$$\frac{1}{r} \rightarrow \frac{1}{r}(1-e^{-\Lambda r})$$

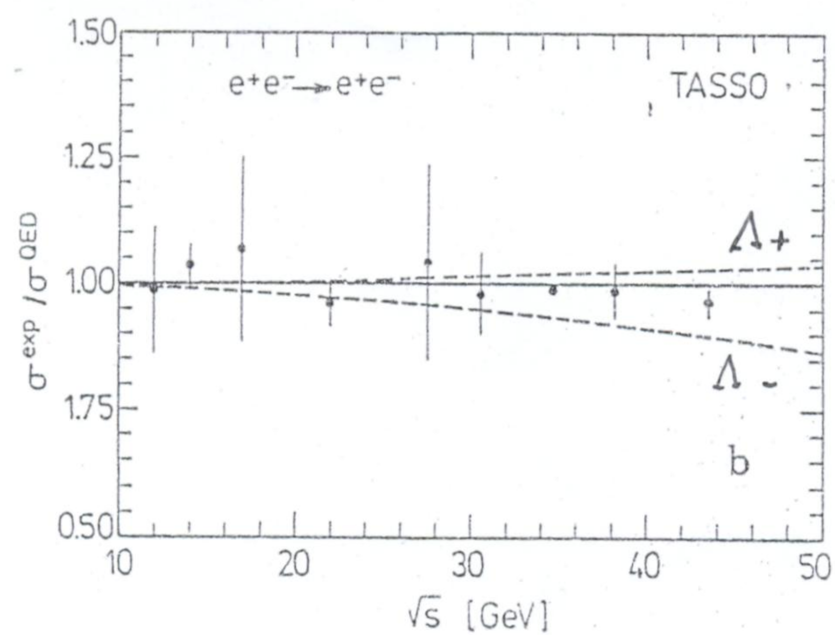
i.e. Λ measures point-like nature of $e\gamma$ interaction (size of electron).

Λ> ~500 GeV ⇔ r_e< 0.197/500 fm

Electr. substructure $< 0.5 \times 10^{-18}$ m

Tasso: Λ_+ >370 GeV

Λ_- > 190 GeV



2.5 Discovery of the Tau-Lepton

MARK I (SLAC), 1975, M.Perl et al.

Nobel Prize 1995 for M.Perl

Evidence for Anomalous Lepton Production in e^+-e^- Annihilation*

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,† G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,‡ B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,§ T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,‖ J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

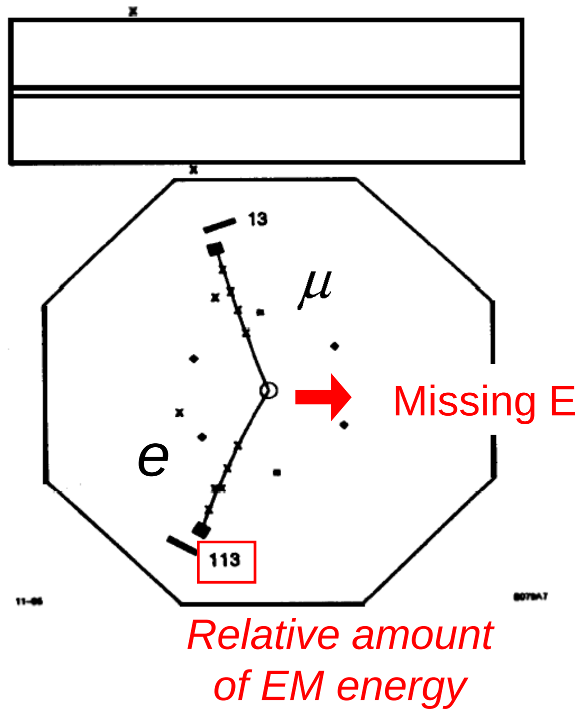
(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp$ + missing energy, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

We have found 64 events of the form

$$e^+ + e^- \rightarrow e^\pm + \mu^\mp + \geq 2 \text{ undetected particles} \quad (1)$$

for which we have no conventional explanation. The undetected particles are charged particles or photons which escape the 2.6π sr solid angle of the detector, or particles very difficult to detect such as neutrons, K_L^0 mesons, or neutrinos. Most of these events are observed at center-of-mass energies at, or above, 4 GeV. These events were found using the Stanford Linear Accelerator Center–Lawrence Berkeley Laboratory (SLAC-



Explanation:

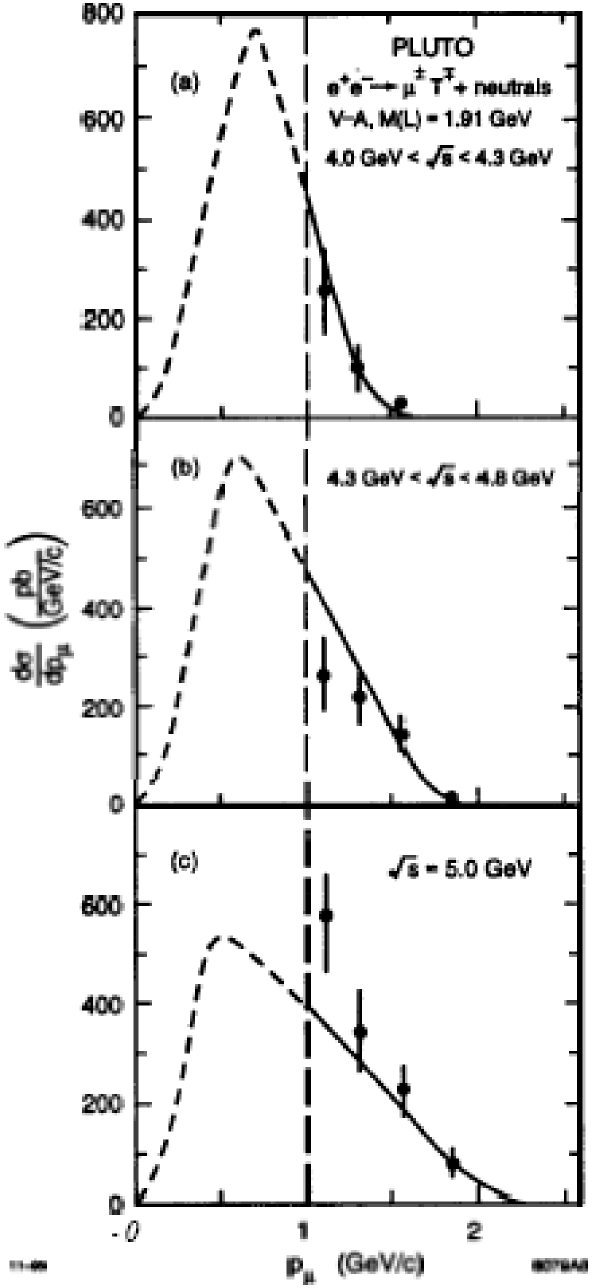
$$e^+e^- \rightarrow \tau^+ \tau^-$$

$$\tau^- \rightarrow e^- \, \bar{\nu}_e \nu_\tau$$

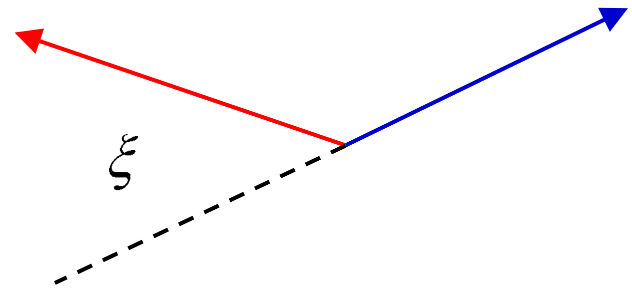
$$\tau^+ \rightarrow \mu^+ \, \nu_\mu \bar{\nu}_\tau$$

A lot of Discussions in 1975:

Are these events really decays of a new 3rd generation heavy lepton ?



1) Large acollinearity confirms tau hypothesis



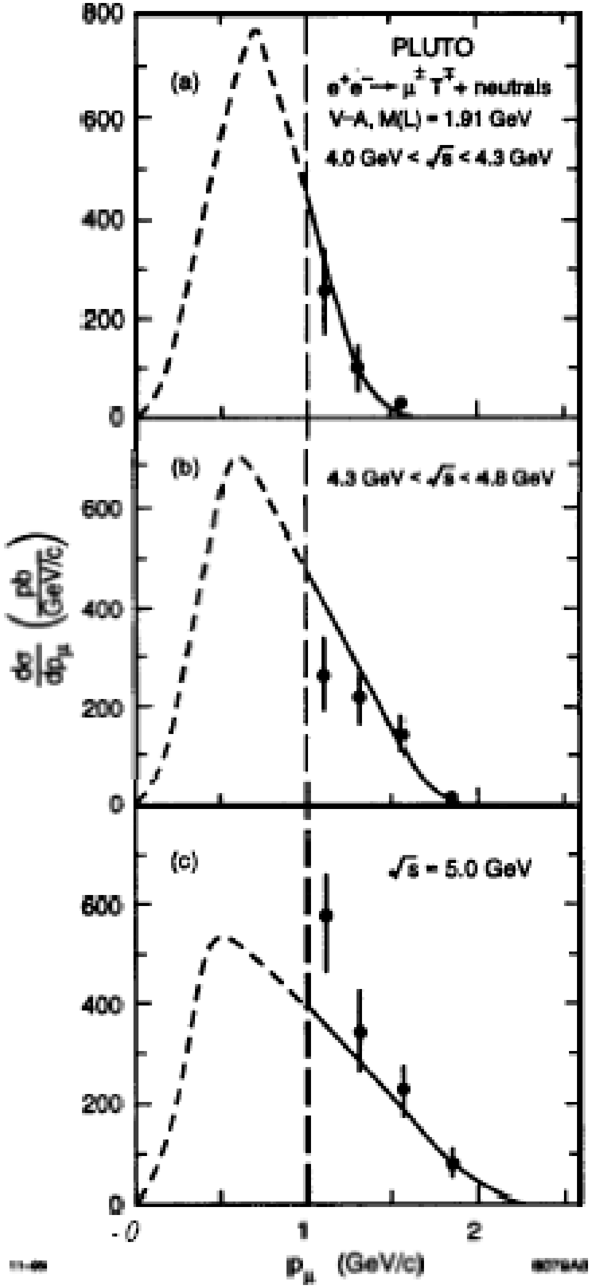
2) Anomalous “single muon events” predicted:

Expectation: $BR(\tau \to e(\mu)\nu\bar{\nu}) \approx 20\%$

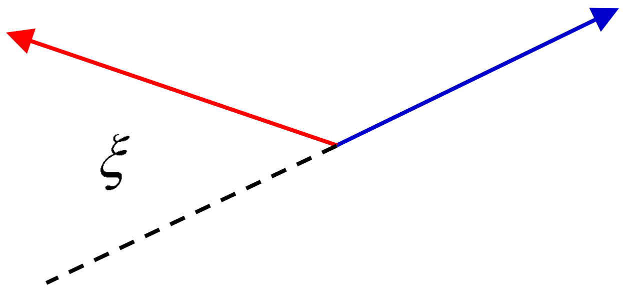
$BR(\tau \to h + \nu) \approx 60\%$

$$e^+ + e^- \to \mu^\pm + h^\mp + \text{missing E}$$

PLUTO (DESY, 1976) confirms the anomalous “single muon events”. Muon spectrum consistent with 3-body tau decay.



1) Large acollinearity confirms tau hypothesis



2) Anomalous “single muon events” predicted:

Expectation: $BR(\tau \rightarrow e\,(\mu)\,\nu\bar{\nu}) \approx 20\%$

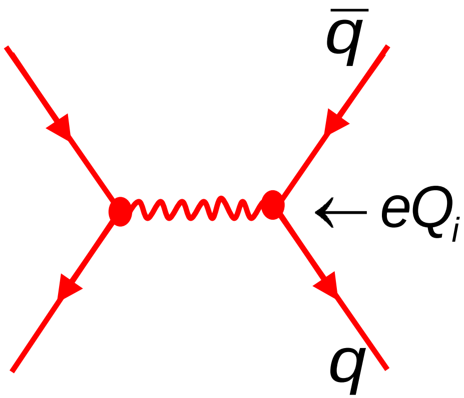
$BR(\tau \rightarrow h + \nu) \approx 60\%$

$\Rightarrow$ $e^+ + e^- \rightarrow \mu^\pm + h^\mp + \text{missing E}$

$\Leftarrow$ PLUTO (DESY, 1976) confirms the anomalous “single muon events”. Muon spectrum consistent with 3-body tau decay.

2.6 $e^+e^- \to$ hadrons

e^+e^- annihilation to a pair of quarks with subsequent hadronization.



$$Q_i = \begin{cases} +\frac{2}{3} \\ -\frac{1}{3} \end{cases}$$

Quarks have fractional charges and carry "color" as additional quantum number.

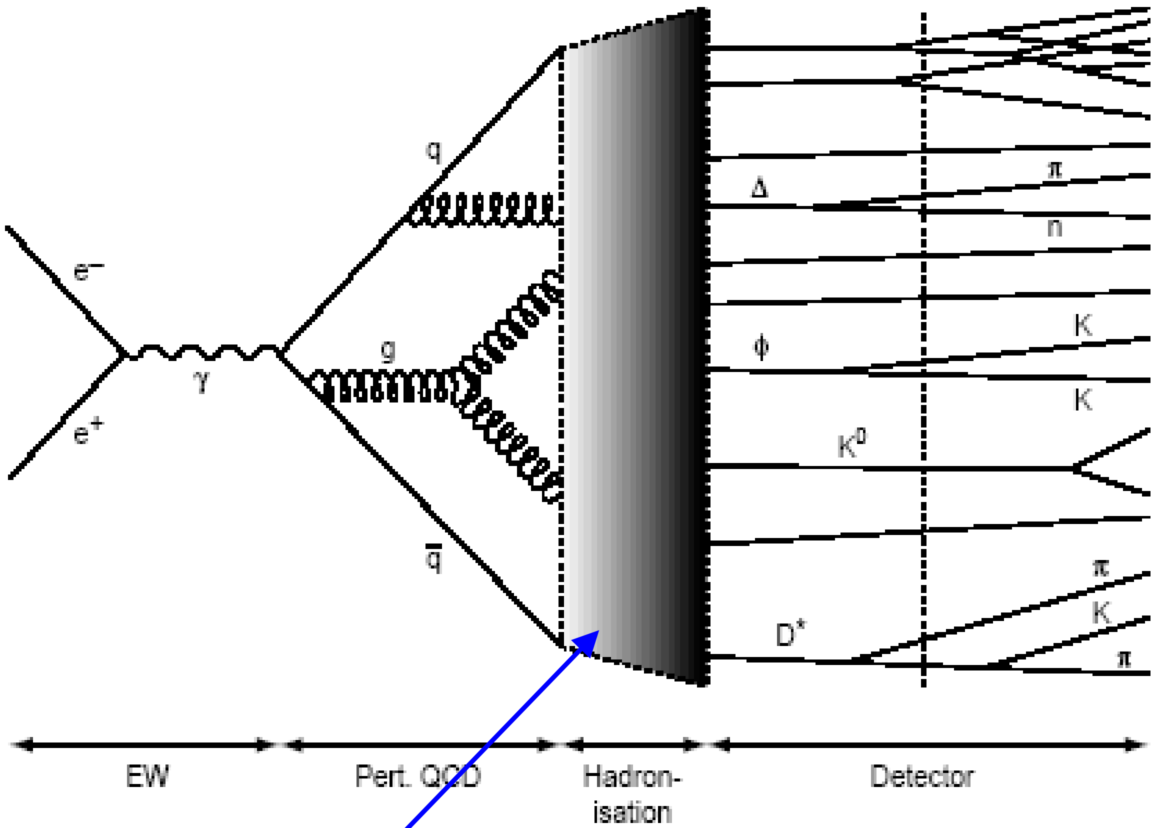
Additional color factor N_C

$$\left.\frac{d\sigma}{d\Omega}\right|_{ee\to hadrons} = \frac{\alpha^2}{4s} \cdot N_C \cdot \sum_{quarks\,i} Q_i^2 (1+\cos^2\theta)$$

Sum over kinematically possible quark flavors: $4m_q^2 < s$

$\sqrt{s}$	Quarks
< ~3 GeV	uds
< ~10 GeV	udsc
< ~350 GeV	udscb
> ~350 GeV	udscbt

From Quarks to Jets

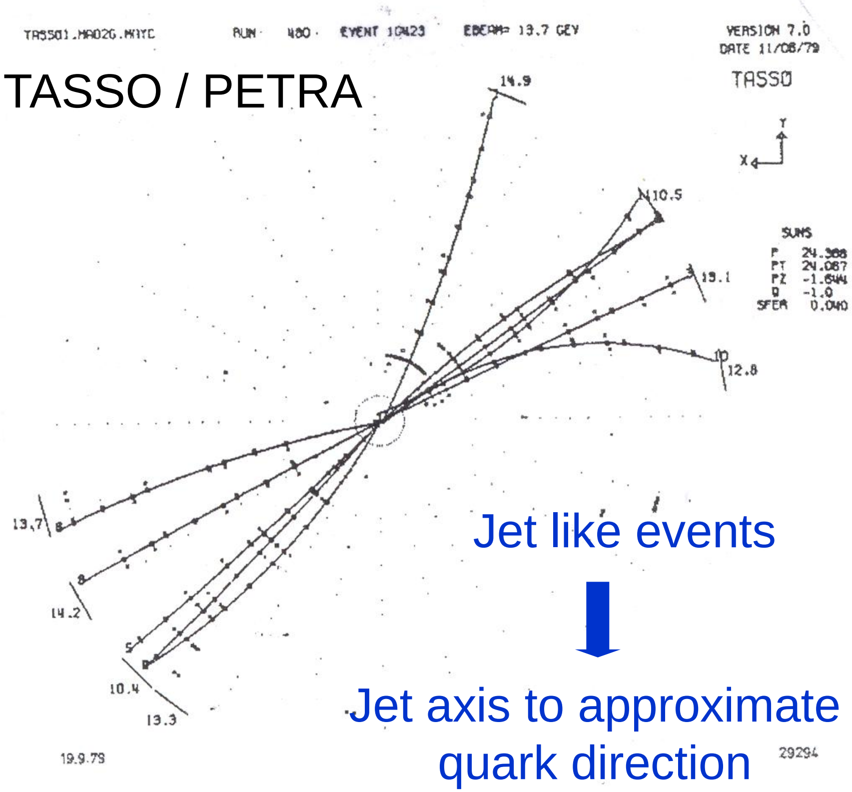


Described successfully by different phenomenological fragmentation models realized as Monte Carlo programs: **PHYTIA, HERWIG**

~ 20 particles at 90 GeV

Quark jets and angular distribution

TASSO / PETRA

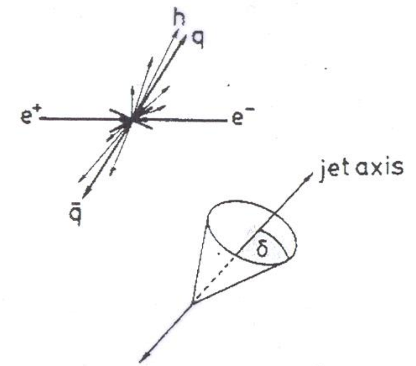


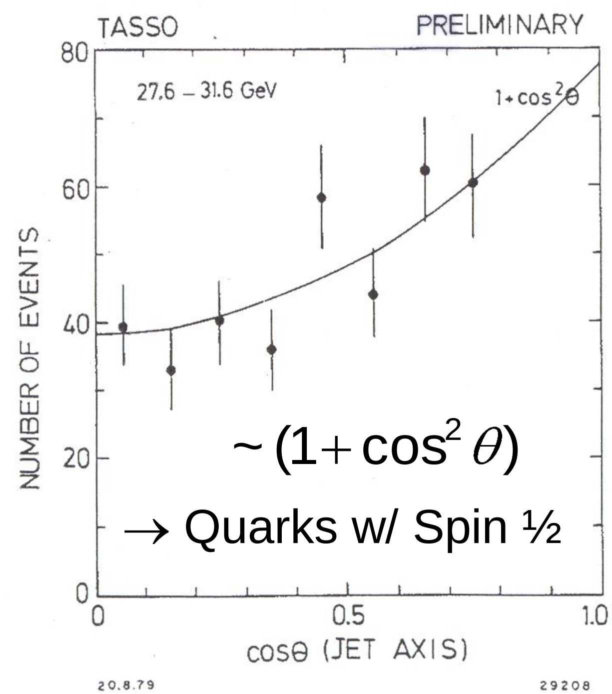
Jet like events

⬇

Jet axis to approximate quark direction

Fig.2 A typical multihadron event at 27.4 GeV recorded in the central detector. The inner 4 layers belong to the proportional chamber, the following 9 are zero degree layers of the drift chamber. The solid bars at the periphery mark time-of-flight counters.





$\sim (1+\cos^2\theta)$

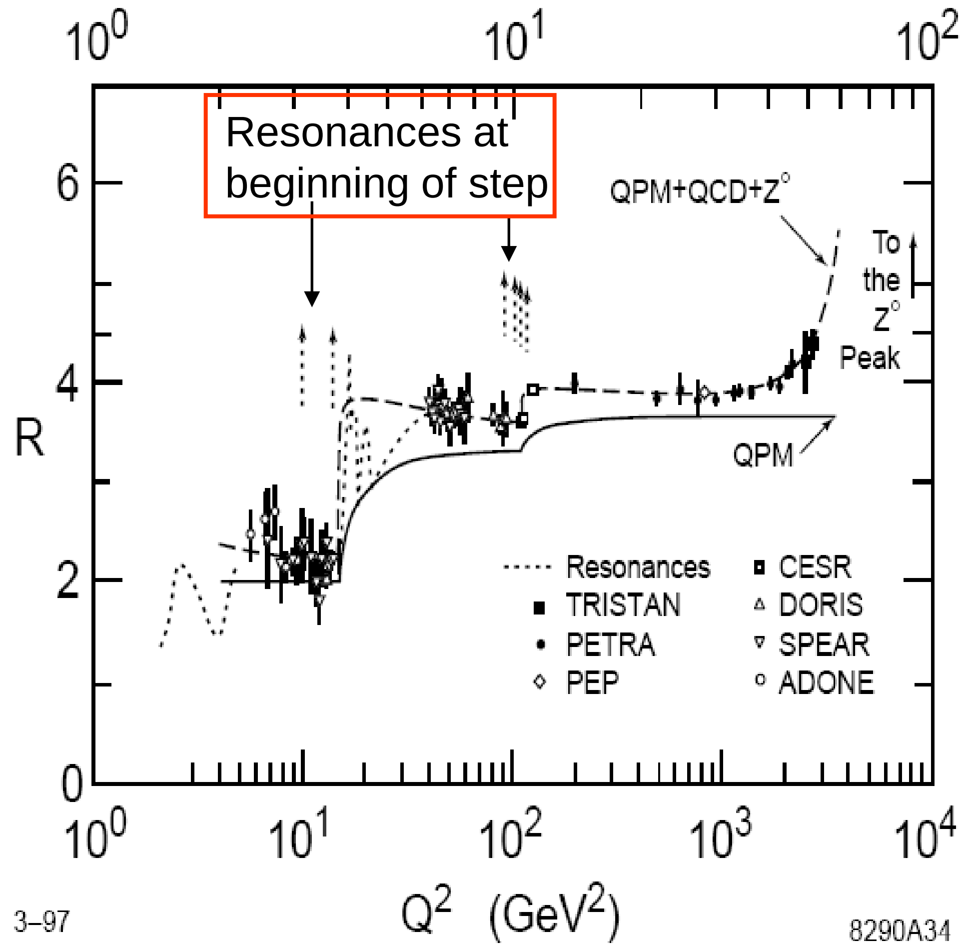
$\rightarrow$ Quarks w/ Spin ½

Fig.7 Angular distribution of the jet axis with respect to the beam.

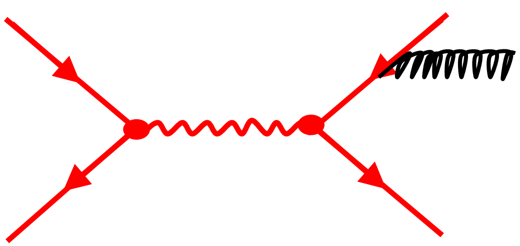
Definition:

$$R_{had} = \frac{\sigma(ee \to hadrons)}{\sigma(ee \to \mu\mu)} = 3 \cdot \sum_i Q_i^2$$

$\sqrt{s}$	Quarks	$R_{had} = 3 \cdot \sum_i Q_i^2$
< ~3 GeV	uds	3·6/9=2.00
< ~10 GeV	udsc	3·10/9=3.33
< ~350 GeV	udscb	3·11/9=3.67
> ~350 GeV	udscbt	3·15/9=5.00



Data lies systematically higher that the prediction from Quark Parton Model (QPM) → gluon bremsstrhl.



$$\sigma(s) = \sigma_{QED}(s)\left[1 + \frac{\alpha_s(s)}{\pi} + 1.411 \cdot \frac{\alpha_s(s)^2}{\pi^2} + \ldots\right]$$

~ 7%