Particle Physics WS 2012/13
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QED Feyman Rules

External Lines

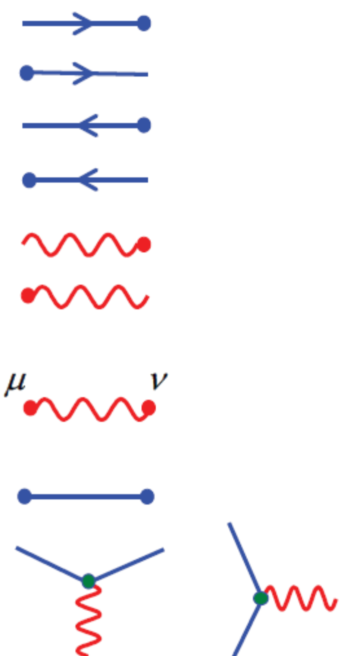
spin 1/2	incoming particle	$u(p)$	
	outgoing particle	$\bar{u}(p)$	
	incoming antiparticle	$\bar{v}(p)$	
	outgoing antiparticle	$v(p)$	
spin 1	incoming photon	$\varepsilon^{\mu}(p)$	
	outgoing photon	$\varepsilon^{\mu}(p)^*$	

Internal Lines (propagators)

spin 1	photon	$-\frac{ig_{\mu\nu}}{q^2}$
spin 1/2	fermion	$\frac{i(\gamma^{\mu}q_{\mu}+m)}{q^2-m^2}$

Vertex Factors

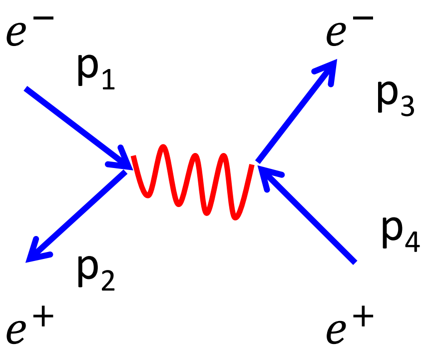
spin 1/2	fermion (charge -|e|)	$ie\gamma^{\mu}$



Matrix Element $-iM$ = **product of all factors**

Starting from elm potential exploiting Fermi's gold rule

⇒ derived QED Feyman Rules



incoming electron $u(p_1)$
incoming positron $\overline{v(p_2)}$ } 1st vertex

outgoing electron $\overline{u(p_3)}$
outgoing positron $v(p_4)$ } 2nd vertex

$$-iM = i\, q_e \overline{v_e(p_2)}\, \gamma^{\mu}\, u_e(p_1) \frac{-ig^{\mu\nu}}{q^2}\, i q_e \overline{u_e(p_3)}\, \gamma^{\nu}\, v_e(p_4)$$

fermion current at 1st vertex — propagator — fermion current at 2nd vertex

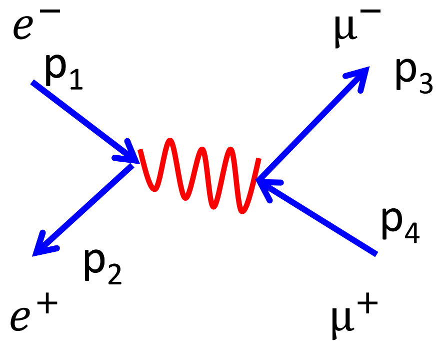
Calculation of cross section $e^+e^- \to \mu^+\mu^-$

Lecture 3, diff. cross-section in CMS: $$\frac{d\sigma}{d\Omega} = \frac{1}{64\,\pi^2 s}\frac{p_f}{p_i}\,|M_{fi}|^2$$

$|\vec{p_1}| = |\vec{p_2}| = p_i$

$|\vec{p_3}| = |\vec{p_4}| = p_f$

$s = (E_1 + E_2)^2$

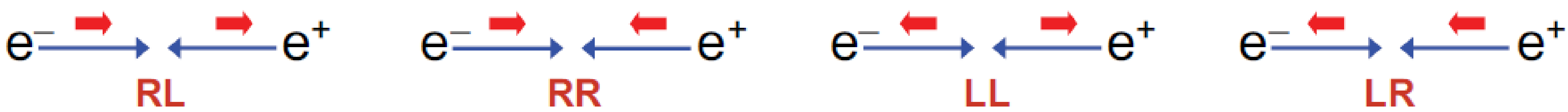


lowest order diagram $M \sim e^2 \sim \alpha_{em}$

(NU: $e=\sqrt{4\pi\alpha}$; $\alpha \sim \frac{1}{137}$)

$$-iM = i\, q_e \overline{v_{e}(p_2)}\, \gamma^\xi u_e(p_1) \frac{-i g^{\xi\nu}}{q^2}\; i q_\mu \overline{u_\mu(p_3)}\, \gamma^\nu v_\mu(p_4)$$

For unpolarized beam need to average over all possible initial helicity combinations.

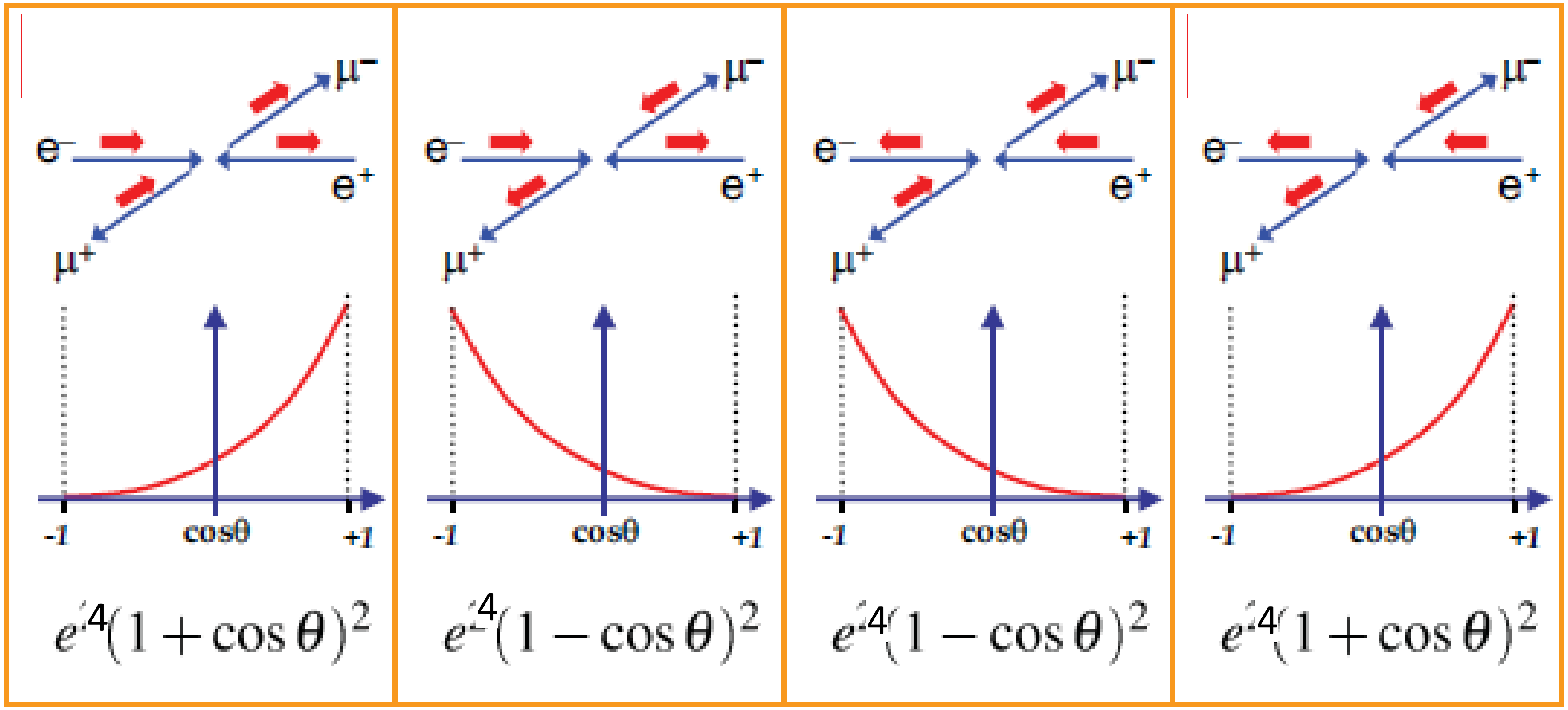


spin averaged matrix element

$$<|M|^2> = \frac{1}{4}\left(|M_{RL\,\to\,XX}|^2 + |M_{RR\,\to\,XX}|^2 + |M_{LL\,\to\,XX}|^2 + |M_{LR\,\to\,XX}|^2\right)$$

Matrix Element Calculation

Computation was done for limit E>>m; note, several helicity combinations vanished!



$|M(RL\rightarrow RL)|^2$ $|M(RL\rightarrow LR)|^2$ $|M(LR\rightarrow RL)|^2$ $|M(LR\rightarrow LR)|^2$

Differential Cross Section

The cross section is obtained by averaging over the initial states and summing over all final states.

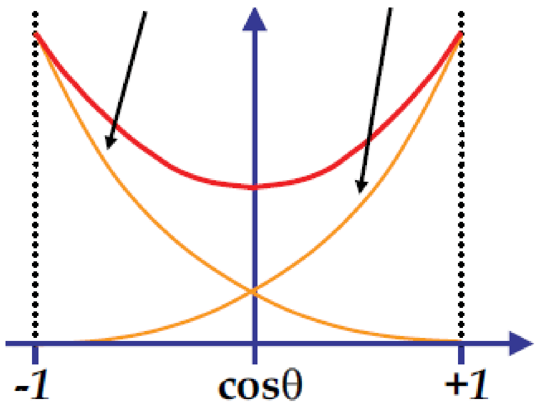
$(E >> m_\mu \rightarrow p_f = p_i)$

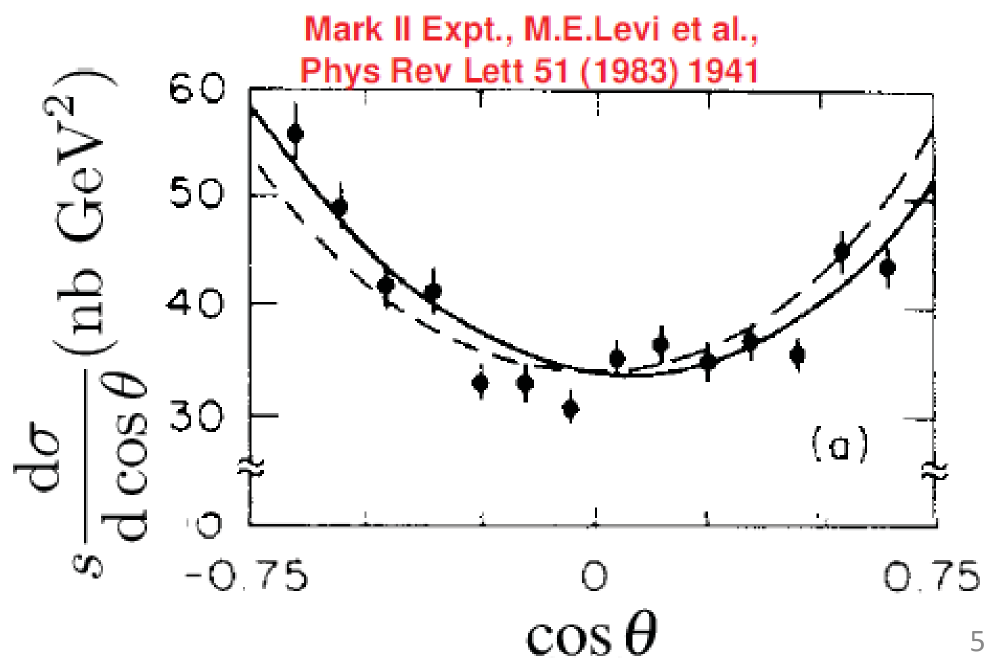
$$\frac{d\sigma}{d\Omega} = \frac{1}{4}\,\frac{1}{64\,\pi^2 s}\,\frac{p_f}{p_i}\sum |M_{fi}|^2$$

$$= \frac{1}{256\,\pi^2\, s}\left(|M(RL\rightarrow RL)|^2 + |M(LR\rightarrow LR)|^2 + |M(RL\rightarrow LR)|^2 + |M(LR\rightarrow RL)|^2 \right)$$

$$= \frac{(4\pi\alpha)^2}{256\,\pi^2\, s}\left(2(1+\cos\theta)^2 + 2(1-\cos\theta)^2\right)$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}(1+\cos^2\theta)$$

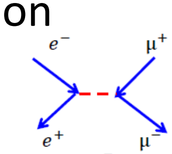




Example: $e^+e^- \rightarrow \mu^+\mu^-$, $\sqrt{s} = 29\ GeV$

- - - pure QED (α^3) calculation

——— QED + Z contribution



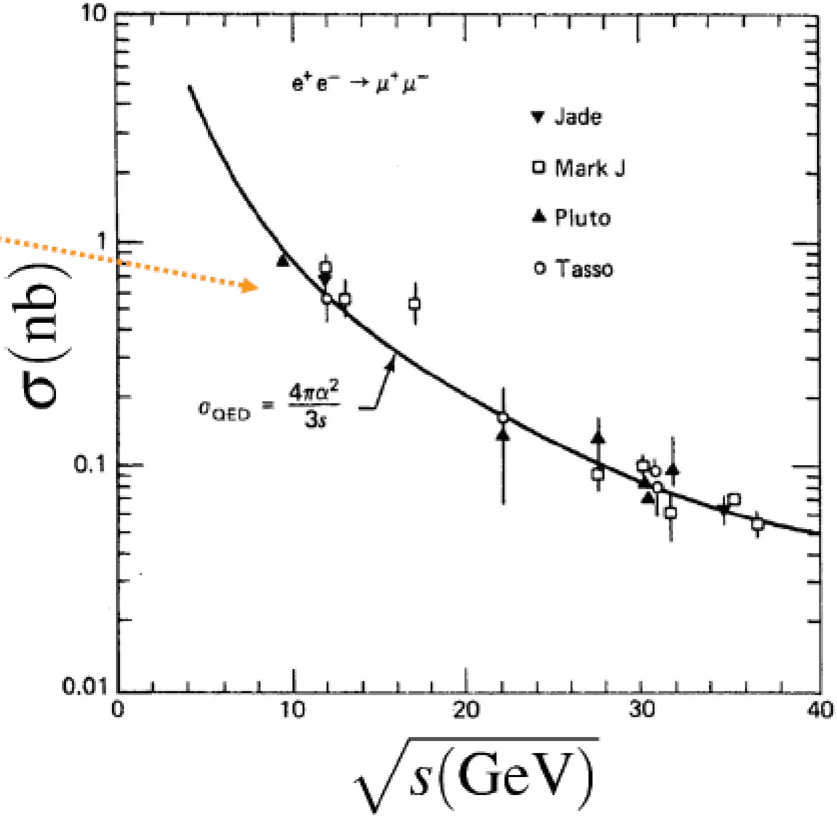
Total Cross Section

Total cross section obtained by intregrating over θ and ϕ using

$$\int (1 + cos^2\theta) d\Omega = 2\pi \int (1 + cos^2\theta)\, d\theta = \frac{16\pi}{3}$$

⇒ total cross section for $(e^+ e^- \rightarrow \mu^+ \mu^-)$: $\boldsymbol{\sigma = \frac{4\pi\alpha^2}{3s}}$

Lowest order computation
provides good description of data



Very impressive result:
from first principle computation
we have reached a 1% precise result!

Helicity and Chirality

$$\Sigma = \begin{pmatrix} \sigma & 0 \\ 0 & \sigma \end{pmatrix} = \begin{bmatrix} \begin{pmatrix} \sigma_1 & \\ & \sigma_1 \end{pmatrix} \\ \begin{pmatrix} \sigma_2 & \\ & \sigma_2 \end{pmatrix} \\ \begin{pmatrix} \sigma_3 & \\ & \sigma_3 \end{pmatrix} \end{bmatrix}$$

helicity operator: h = $\vec{\Sigma}\hat{\vec{p}}$ [H,h] = 0

Helicity is a conserved quantity!

Helicity is not a LI quantity!
($\vec{p}$ is not a LI)

chirality operator: $\gamma^5 = i\,\gamma^0\gamma^1\gamma^2\gamma^3 = \begin{pmatrix} 0 & I \\ I & 0 \end{pmatrix}$

in Dirac representation

$[H,\gamma^5] \neq 0$

Chirality is not a conserved quantity!
Chirality is however LI!

only for E>>m : $\gamma^5 \sim \vec{\Sigma}\vec{p}$

⇒ LH chirality eigenstates ≡ LH helicity eigenstates
RH chirality eigenstates ≡ RH helicity eigenstates

For massive particles (not ultra relativisitc): **helicity states are combination of chirality states!**

Chirality Eigenstates

Only certain combinations of chirality eigenstates take part in elm IA (property of vertex coupling)

$\bar{u}_L \gamma^\mu u_L$, $\overline{u_R} \gamma^\mu u_R$ — Right handed particles with right handed particles; Left handed particles with left handed particles

$\bar{v}_L \gamma^\mu v_L$, $\overline{v_R} \gamma^\mu v_R$ — Right handed antiparticles with right handed antiparticles; Left handed anti particles with left handed antiparticles

$\bar{u}_L \gamma^\mu v_R$, $\overline{v_R} \gamma^\mu u_L$

$\overline{u_R} \gamma^\mu v_L$, $\bar{v}_L \gamma^\mu u_R$ — Right handed particles with left handed antiparticles; Left handed particles with right handed particles

Consider E>>m (ultra relativistic limit), chirality eigenstates = helicity eigenstates

$$\Psi_L = u_{h=-1}\, e^{i(\vec{p}\vec{x}-Et)} \qquad \Psi_R = v_{h=1}\, e^{-i(\vec{p}\vec{x}-Et)}$$

$$\Psi_R = u_{h=+1}\, e^{i(\vec{p}\vec{x}-Et)} \qquad \Psi_L = v_{h=-1}\, e^{-i(\vec{p}\vec{x}-Et)}$$

$$E \to -E$$

$$\vec{p} \to -\vec{p}$$

$$\vec{s} \to \vec{s}$$

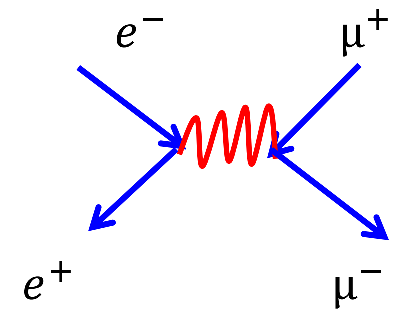
Left handed antiparticles ≡ right handed particles

Right handed antiparticles ≡ left handed particles

Coupling strength for left handed and right handed particles is the same in elm. IA!

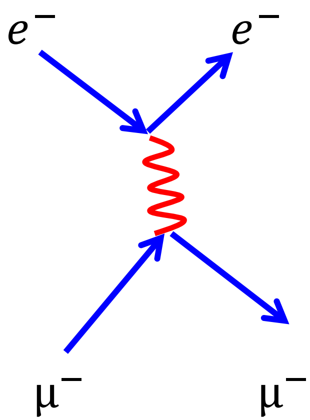
Content of Today

- We do already have $\boldsymbol{e^- + e^+ \to \mu^- + \mu^+}$

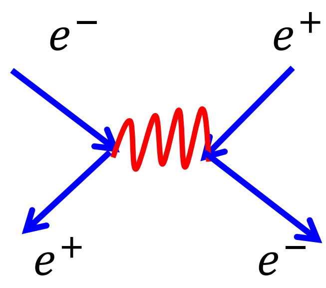


- Calculate cross-section for related process exploiting symmetries and Mandelstam variables

$\boldsymbol{e^- + \mu^- \to e^- + \mu^-}$



and $\boldsymbol{e^- + e^+ \to e^- + e^+}$



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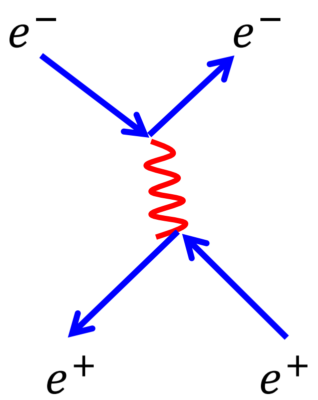


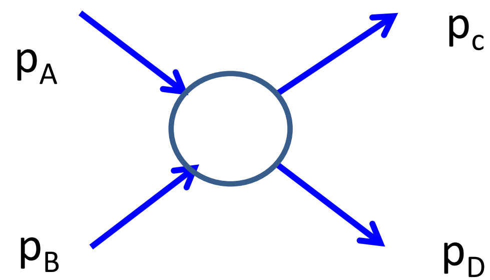
- Test of first order QED computations in e^+e^- collisions at TASSO

- Luminosity measurements exploiting $\mathrm{e^- + e^+ \to e^- + e^+}$

- Discovery of τ lepton in e^+e^- collisions

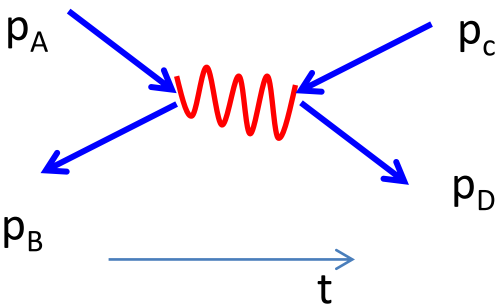
Time and Space Structure of Feynman Diagrams

general 4 prong diagram
(several first order QED diagrams have this structure)



choose CMS system

a) Time like “s” channel process

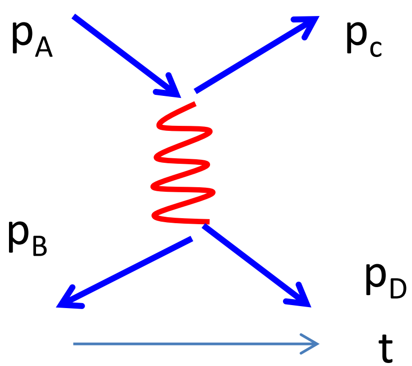


$s = q^2 = (p_A + p_B)^2 = (E_A + E_B)^2 - (\vec{p}_A + \vec{p}_B)^2 \geq (m_A + m_B)^2 > 0$

real photon: $q^2 = E^2 - \vec{p}^{\,2} = 0$

$q^2 > 0$ virtual photon

b) Space like “t” channel process



$t = q^2 = (p_C - p_A)^2 = (E_C - E_A)^2 - (\vec{p}_C - \vec{p}_A)^2$

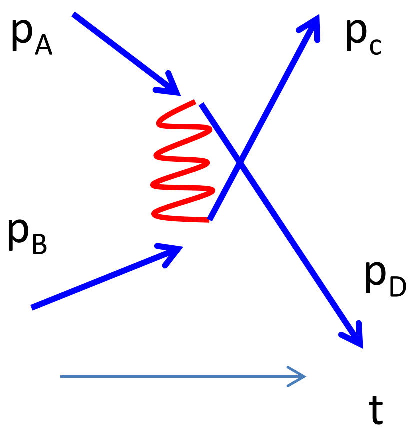
choose A at rest and $m_A = m_C$: $E_C > m_C$

$t = E_c^2 - 2E_c m_A + m_A^2 - \vec{p}_c^{\,2} = m_C^2 - 2E_C m_A + m_A^2 < 0$

$q^2 < 0$ virtual photon

Mandelstam variables

b) "u" channel process



$u = q^2 = (p_D - p_A)^2 < 0$

$q^2 < 0$ virtual photon

Mandelstam variables:

$s = (p_A + p_B)^2 = (p_C + p_D)^2$
$t = (p_C - p_A)^2 = (p_D - p_B)^2$
$u = (p_D - p_A)^2 = (p_C - p_B)^2$

Total cross/section or any LI invariant diff. cross-section can only depend on scalar products of 4-momenta p_A, p_B, p_C, p_D.

$p_i p_j$ → 10 scalars: $p_A p_A$, $p_A p_B$, $p_A p_C$, $p_A p_D$
$p_B p_B$, $p_B p_C$, $p_B p_D$,
$p_C p_C$, $p_C p_D$,
$p_D p_D$

$p_i^2 = E_i^2 - \vec{p}_i^{\,2} = m_i^2$ → four constraints

energy + momentum conservation: $(p_A + p_B = p_C + p_D)$ → four constraints

⇨ 2 independent scalars describe the process, usually 2 of Mandelstam variables are chosen

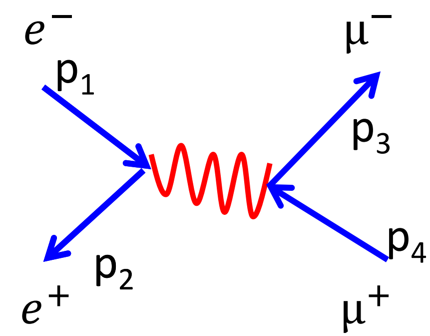
Lorentz Invariant Representation of X-Section

$$<M_{fi}>^2 = \frac{1}{4} \sum |M_{fi}|^2$$

$$= \frac{1}{4}\left(|M(RL\to RL)|^2 + |M(LR\to LR)|^2 + |M(RL\to LR)|^2 + |M(LR\to RL)|^2 \right)$$

$$= \frac{e^4}{4}\left(2(1+\cos\theta)^2 + 2(1-\cos\theta)^2\right)$$

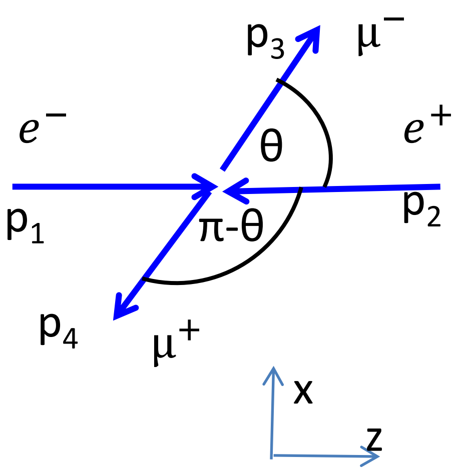
[Θ in CMS, E >> m]



$<M_{fi}>^2$ is LI, would be good to express it in form of LI quantities!

In CMS: $p_1 = (E,0,0,E)$
$p_2 = (E,0,0,-E)$
$p_3 = (E, E\sin\theta, 0, E\cos\theta)$
$p_4 = (E, -E\sin\theta, 0, -E\cos\theta)$

$(p_i \pm p_j)^2 = m_i^2 + m_j^2 \pm 2p_ip_j$
$\sim \pm 2p_ip_j$
E>>m



$p_1p_2 = 2E^2 \sim ½ (p_1+p_2)^2 = \frac{1}{2}s$

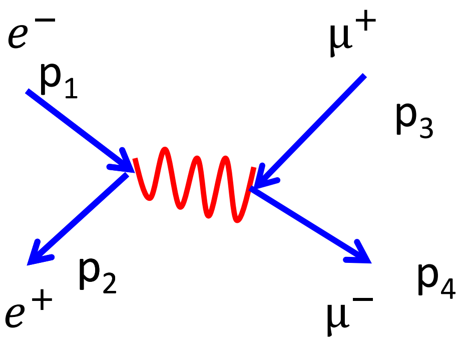
$p_1p_3 = E^2(1+\cos\theta) \sim -½ (p_3-p_1)^2 = -\frac{1}{2}t$

$p_1p_4 = E^2(1-\cos\theta) \sim -½ (p_4-p_1)^2 = -\frac{1}{2}u$

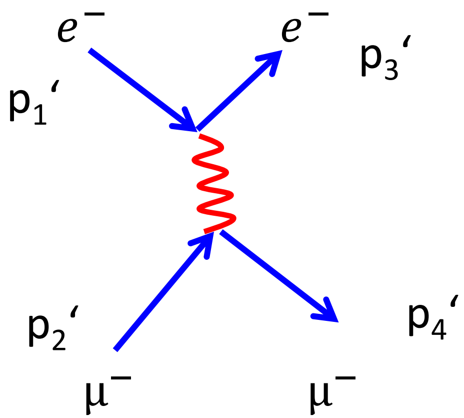
$$<M_{fi}>^2 = 2e^4 \frac{t^2+u^2}{s^2}$$

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

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



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



$p_1 \rightarrow p_1'$

$p_2 \rightarrow -p_3'$

$p_3 \rightarrow -p_2'$

$p_4 \rightarrow p_4'$

$s = (p_1+p_2)^2 \quad \rightarrow \quad (p_1'-p_3')^2 = t'$

$t = (p_3-p_1)^2 \quad \rightarrow \quad (-p_2'-p_1')^2 = s'$

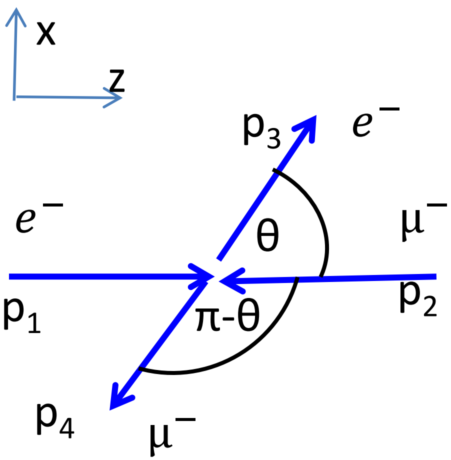
$u = (p_4-p_1)^2 \quad \rightarrow \quad (p_4'-p_1')^2 = u'$

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

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

$e^-\mu^-$ Scattering in CMS

In CMS: $p_1 = (E,0,0,E)$; $p_2 = (E,0,0,-E)$; $p_3 = (E, E\sin\theta, 0, E\cos\theta)$; $p_4 = (E, -E\sin\theta, 0, -E\cos\theta)$



$s = 4E^2$

$t = (p_3-p_1)^2 \sim -2p_3p_1 = -2E^2(1-\cos\theta)$

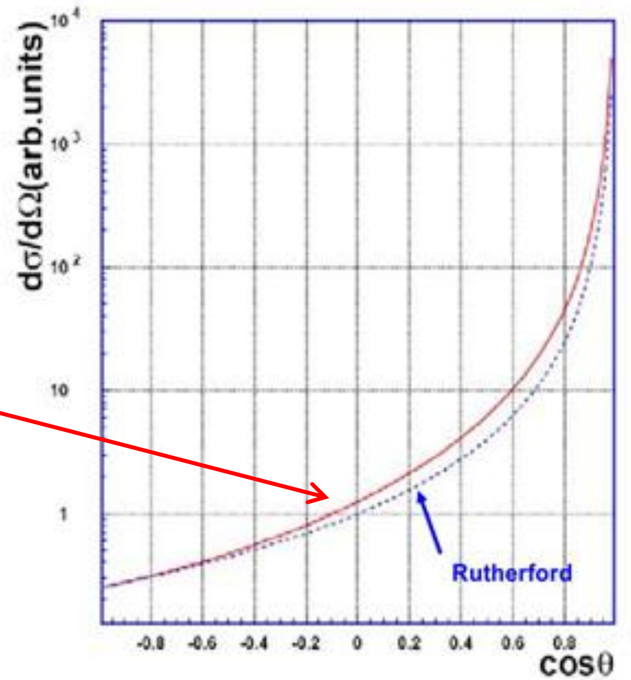
$u = (p_4-p_1)^2 \sim -2p_4p_1 = -2E^2(1+\cos\theta)$

$$<M_{fi}>^2 = 2e^4\frac{s^2+u^2}{t^2} = 2e^4\frac{4+(1+\cos\theta)^2}{(1-\cos\theta)^2}$$

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p_f}{p_i}<M_{fi}>^2$$

$$= \frac{e^4}{8\pi^2 s}\frac{1+\frac{1}{4}(1+\cos\theta)^2}{(1-\cos\theta)^2}$$

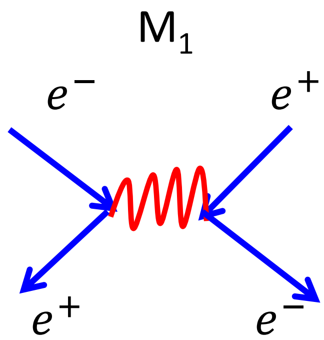
$$= \frac{e^4}{8\pi^2 s}\frac{1+\frac{1}{4}(1+\cos\theta)^2}{4\sin^4\theta/2}$$



sideremark: almost Rutherford, for Rutherford need non-relativisitc computation

Bhabha-Scattering $e^- + e^+ \rightarrow e^- + e^+$

M =



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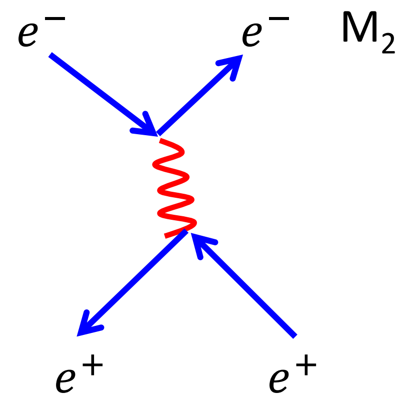
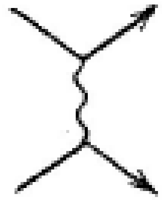
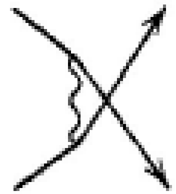
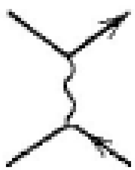
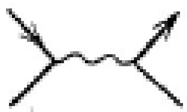
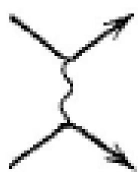
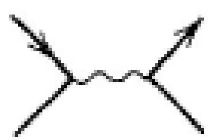


$|M|^2 = \quad |M_1|^2 \quad$ + interference + $\quad |M_2|^2$

same as for $e^- e^+ \rightarrow \mu^- \mu^+$ — same as for $e^- e^+ \rightarrow e^- e^+$

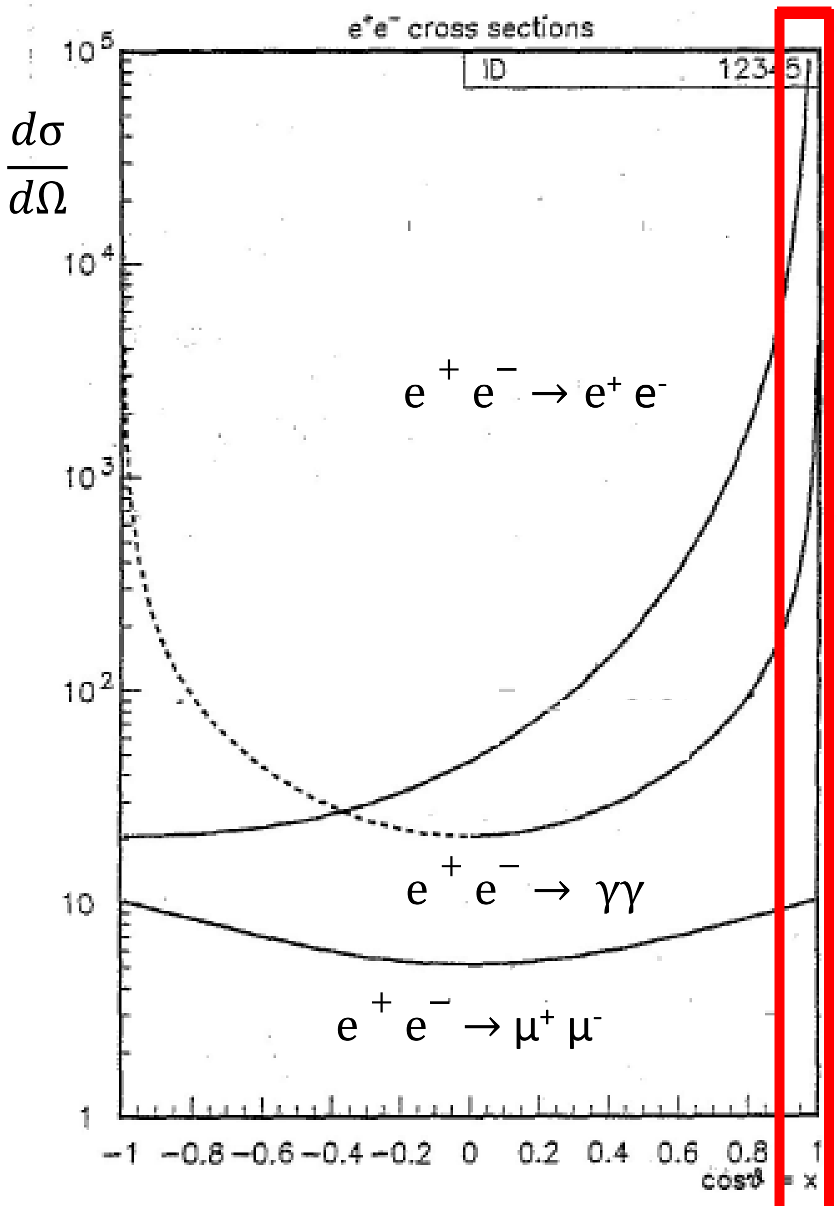
$$\frac{d\sigma}{d\Omega} = \frac{e^4}{8\pi^2 s}\left(\frac{t^2+u^2}{s^2} + \frac{2u^2}{t^2} + \frac{s^2+u^2}{t^2} \right)$$

Leading Order Contributions to Representative QED Processes

	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 $e^-e^+ \to e^-e^+$			$\frac{s^2+u^2}{t^2}$	$+\ \frac{2u^2}{ts}$	$+\ \frac{u^2+t^2}{s^2}$
$e^-\mu^- \to e^-\mu^-$			$\frac{s^2+u^2}{t^2}$		
(Crossing $s \leftrightarrow t$)					
$e^-e^+ \to \mu^-\mu^+$					$\frac{u^2+t^2}{s^2}$

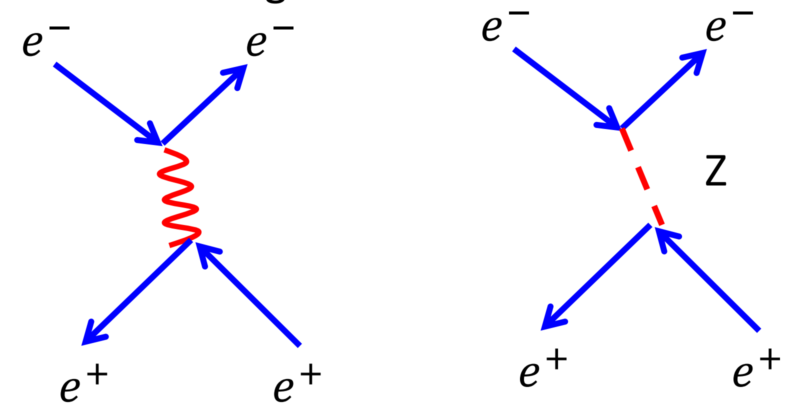
from
Halzen and Martin

Scatter Processes in e^+e^-



exploited for luminosity measurements

Bhabha scattering: t+s channel

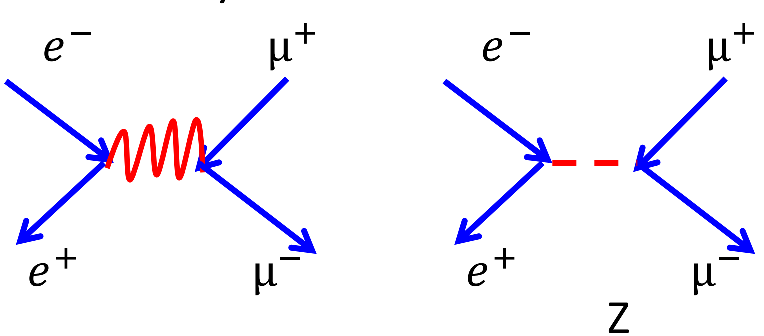


t-channel less sensitiv to contributions from Z exchange, even at larger energies.

QED computation have precision of 10^{-4}

Exploit forward region for luminosity measurements

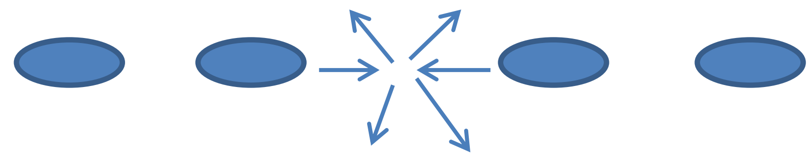
s-channel only



Luminosity Determination at e^+e^- Machines

Interaction rate: $\dot{N}_{IA} = \sigma_{IA} \times L$

Number of observed events: $N_{IA} = \int \sigma_{IA} \times L\, dt = \sigma_{IA} \int L\, dt$



σ_{IA}: interaction cross-section

L: luminosity, depends on machine parameters $[cm^2/s]$

$L_{int} = \int L\, dt$ $[barn^{-1}]$

$$L = \frac{1}{4\pi} \frac{n_B\, f\, n_1\, n_2}{\sigma_x\, \sigma_y}$$

n_1, n_2 : particles per bunch
n_B : number of buches
f : revolution frequency
σ_x, σ_y : beam size at IA point

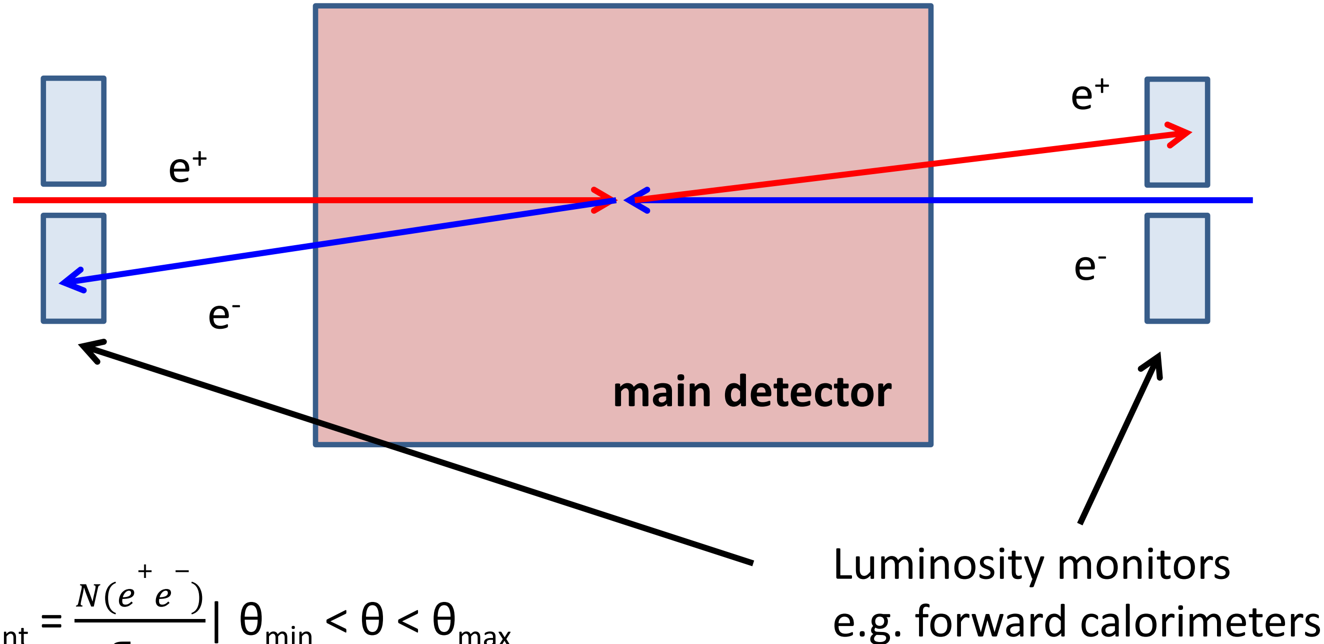
determination of delivered integrated luminosity from machine parameters not precise enough (± 5-10%)

Instead a known reference process with known x-section is used to determine the integrated luminosity

$$L_{int} = \frac{N_{ref}}{\sigma_{ref}}$$

Luminosity Determination at e^+e^- Machines

Reference process for e^+e^- machines: small angle Bhabha scattering, precisely known, very high rate, very little background



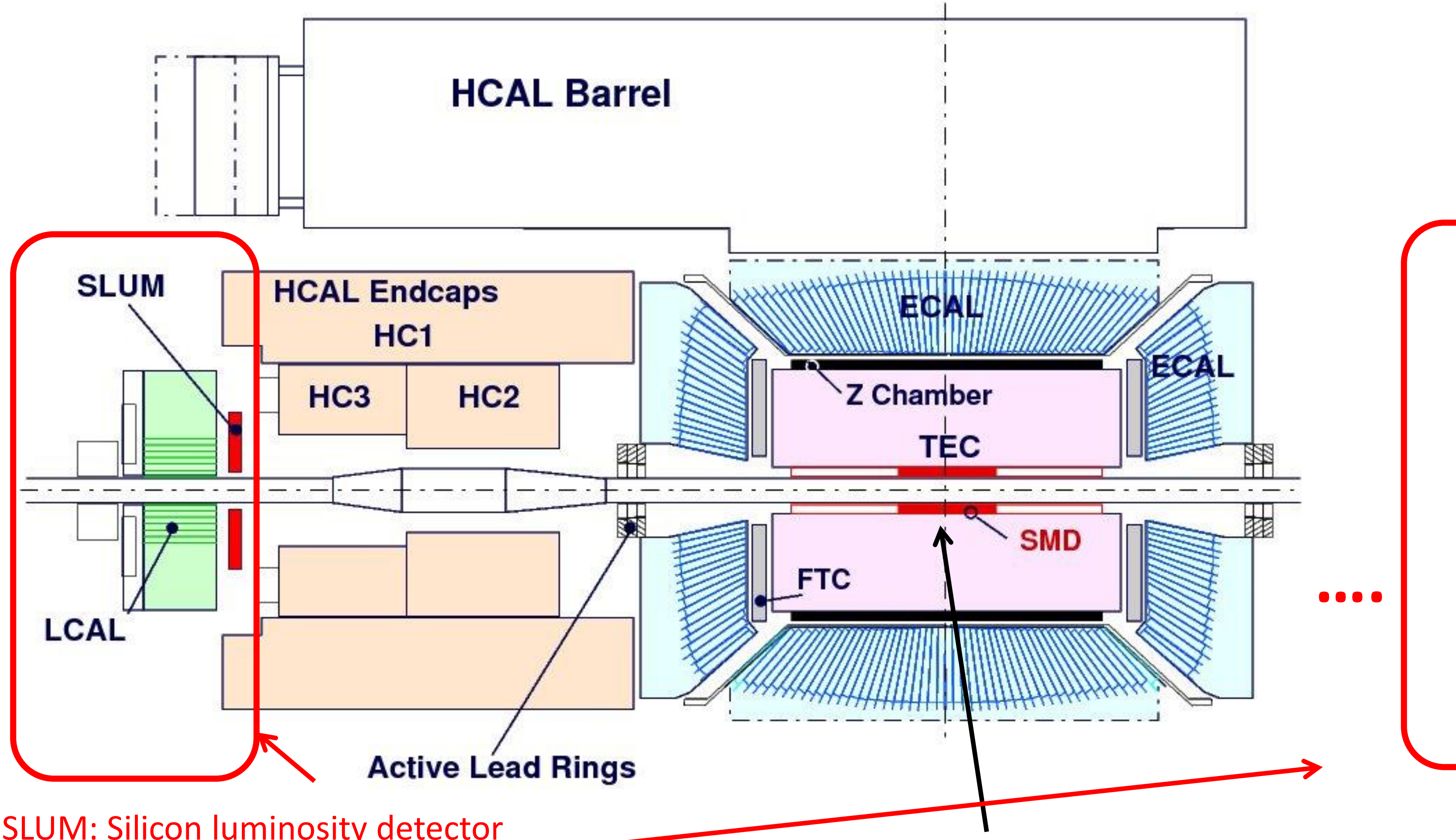
$$L_{int} = \frac{N(e^+e^-)}{\sigma_{ref}} \Big| \ \theta_{min} < \theta < \theta_{max}$$

Typical ranges for angles: $15^\circ < \theta < 35^\circ$

(other standard candle $Z \rightarrow \mu\mu$)

L3 Detector at LEP

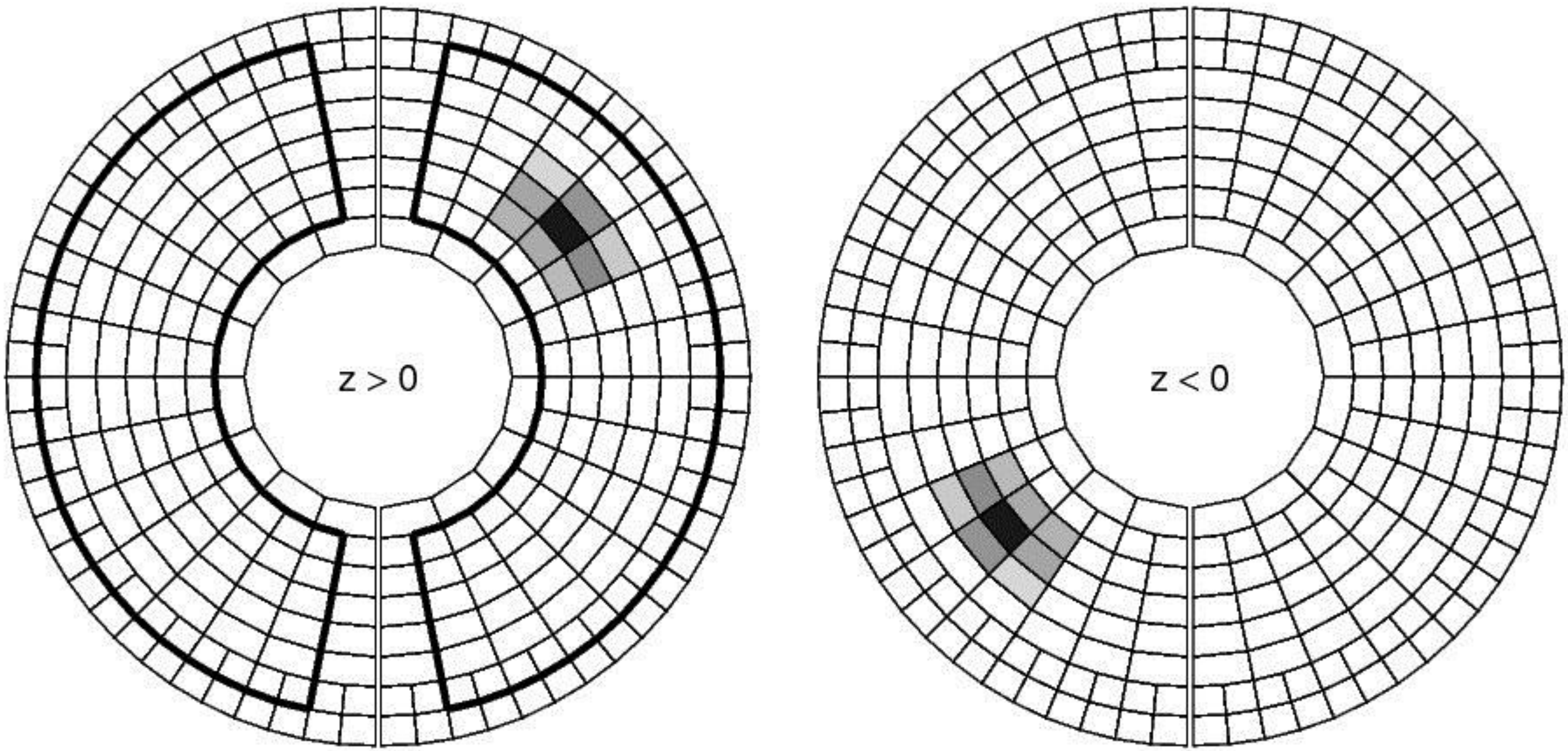
LEP: Large Electron Positron Collider, CERN, E_{CM} = 90 GeV



SLUM: Silicon luminosity detector
LCAL: Luminosity calorimeter

collision center

Bhabha Scattering Event in LEP LCAL



Experimental Test of QED: Tasso Experiment

An aerial view showing the PETRA ring and the current HERA Collider

The PETRA Collider

The TASSO Detector

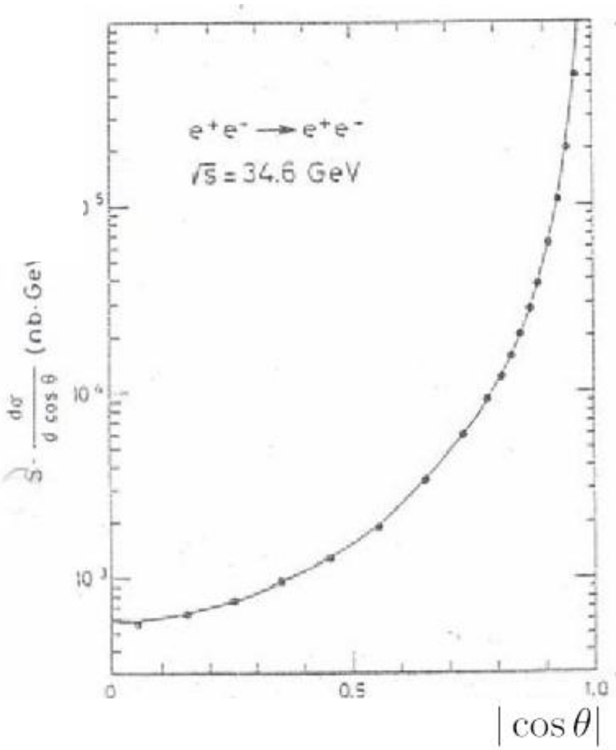
PETRA: Positron-electron collider (DESY, Hamburg), E_{CM} up to 35 GeV

Started data taking in 1976, finished data taking in 1986

Tasso: Two Arm Spectrometer Solenoid

[Tasso experiment is famous for discovery of the gluon]

How to test for possible deviations in $e^+e^- \rightarrow e^+e^-$



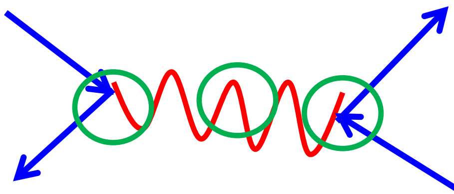
------ theory prediction (dominated by t-channel)

• data points

Perfect agreement! - how to quantify perfect?

Possible deviations from QED:

- Finite extension of lepton
- modified photon propagator



Description and parametrization of deviation by form factor: $F(q^2) = 1 \pm \frac{q^2}{q^2 - \Lambda_{\pm}^2}$

$$\frac{1}{q^2} \rightarrow \frac{1}{q^2} \pm \frac{1}{q^2 - \Lambda_{\pm}^2}$$

In this choice of form factor parameterization $F(q^2)$ describes an add. massive photon which modify the propagator. Parameter $\Lambda_{\pm}$ would correspond to the photon mass of add. photon.

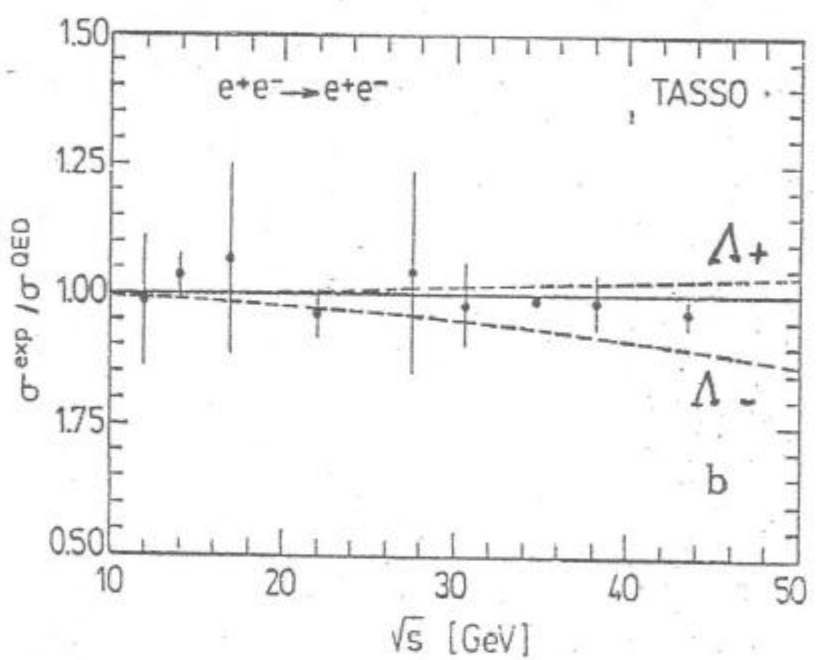
How to test for possible deviations in $e^+e^- \rightarrow e^+e^-$

$$\frac{d\sigma}{d\Omega} = \frac{e^4}{8\pi^2 s}\left(\frac{t^2+u^2}{s^2}|F(t)|^2 + \frac{2u^2}{t^2}|F(t)F(s)| + \frac{s^2+u^2}{t^2}|F(s)|^2 \right)$$

A fit to the Tasso data results in: $\Lambda_+ > 435$ GeV, $\Lambda_- > 590$ GeV @ 95% CL

In the space picture form factor correspond to modified Coulomb potential:

$$\frac{1}{r} \rightarrow \frac{1}{r}(1 + e^{-\Lambda r}) \quad \equiv \text{extended charge}$$



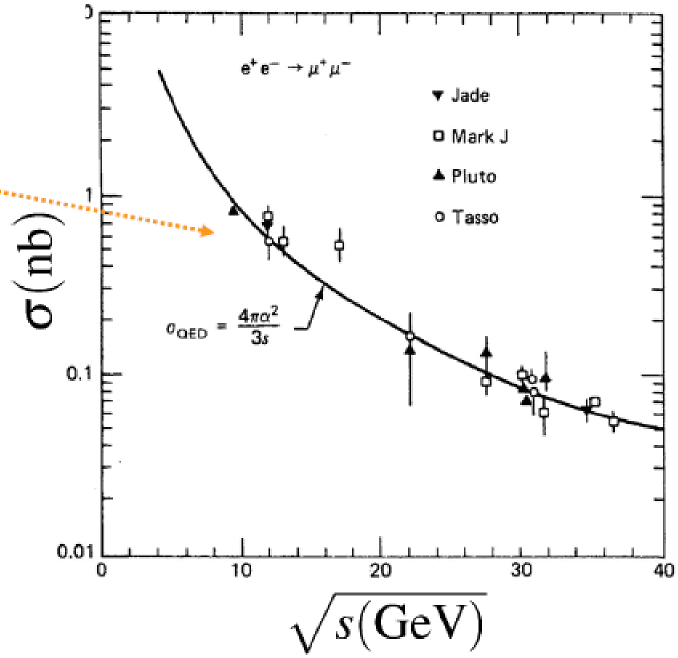
For $\Lambda > 500$ GeV

Point-like electron:

< 0.197 fm/500 = $0.5 \; 10^{-18}$ m

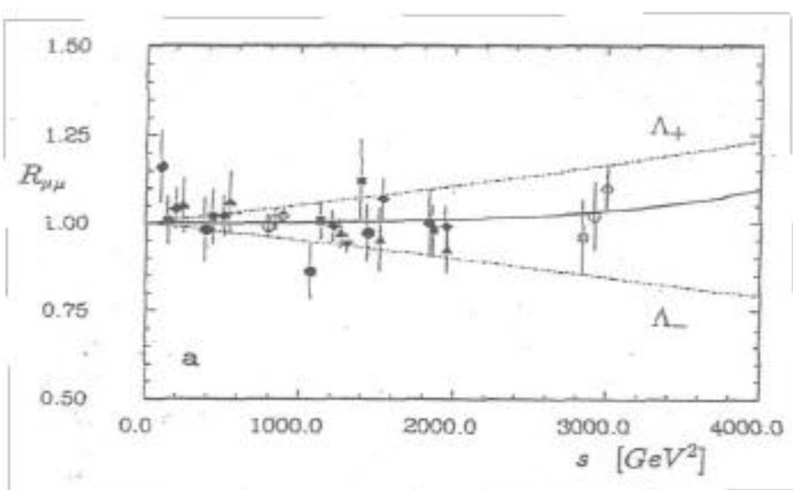
Test of QED in $e^+e^- \to \mu^+\mu^-$

Total cross section
Very good agreement



$$\sigma(e+e- \to \mu+\mu-) = \frac{e^4}{3s}\left(1 \pm \frac{s}{s-\Lambda_\pm^{\ 2}}\right)$$

$$R_{\mu\mu} = \frac{\sigma_{exp}}{\sigma_{th}}$$

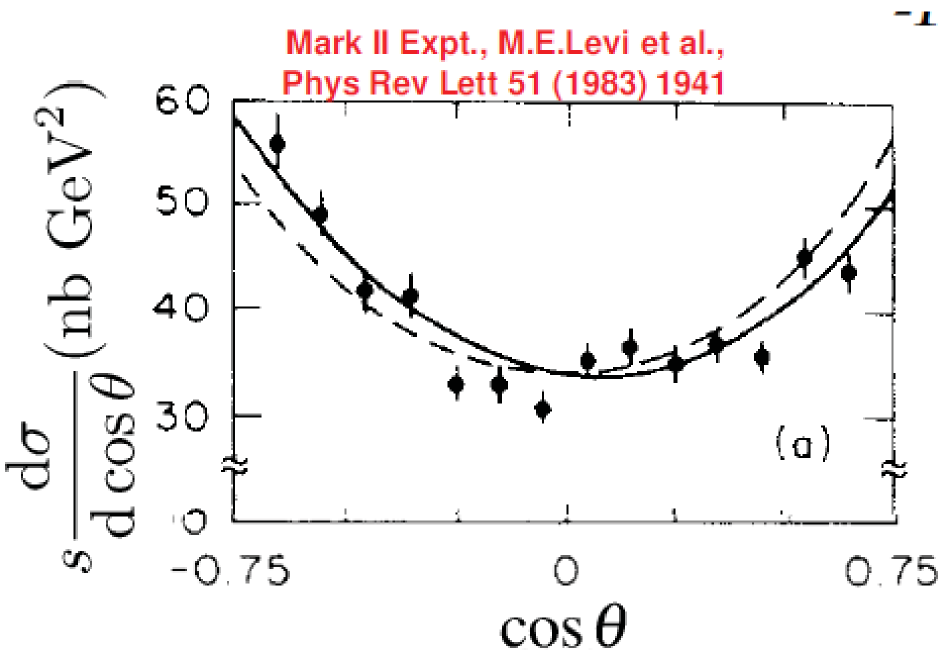


$\Lambda_\pm$ > 250 GeV

muon substructure < 10^{-18} m

Test of QED in $e^+e^- \to \mu^+\mu^-$

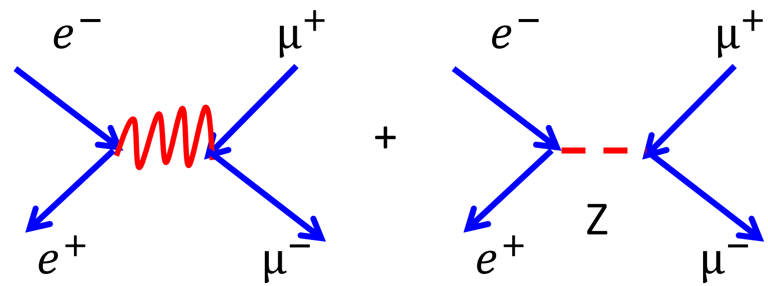
Total cross-section in very good agreement, however angular distribution deviates from QED predictions $\to$ effect of electroweak interference

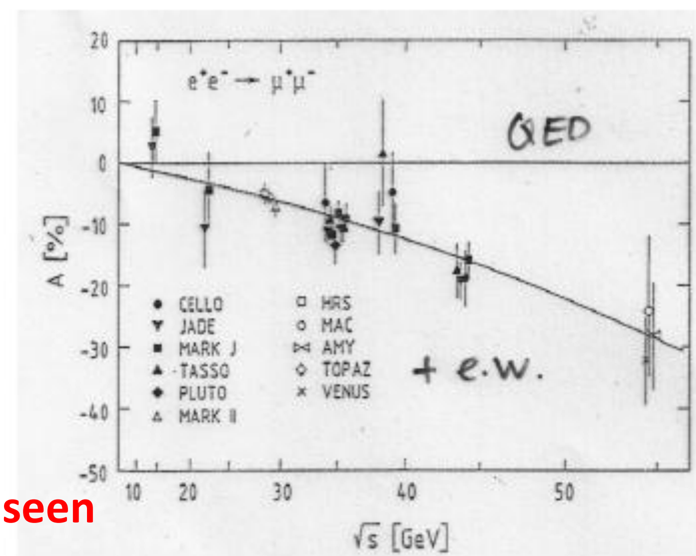


backward region

forward region

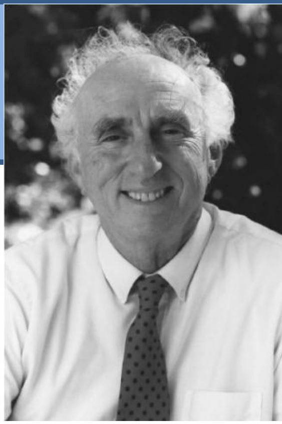
$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$





Due to interference effect of EW contribution already seen at $\sqrt{s}$ = 30 GeV!

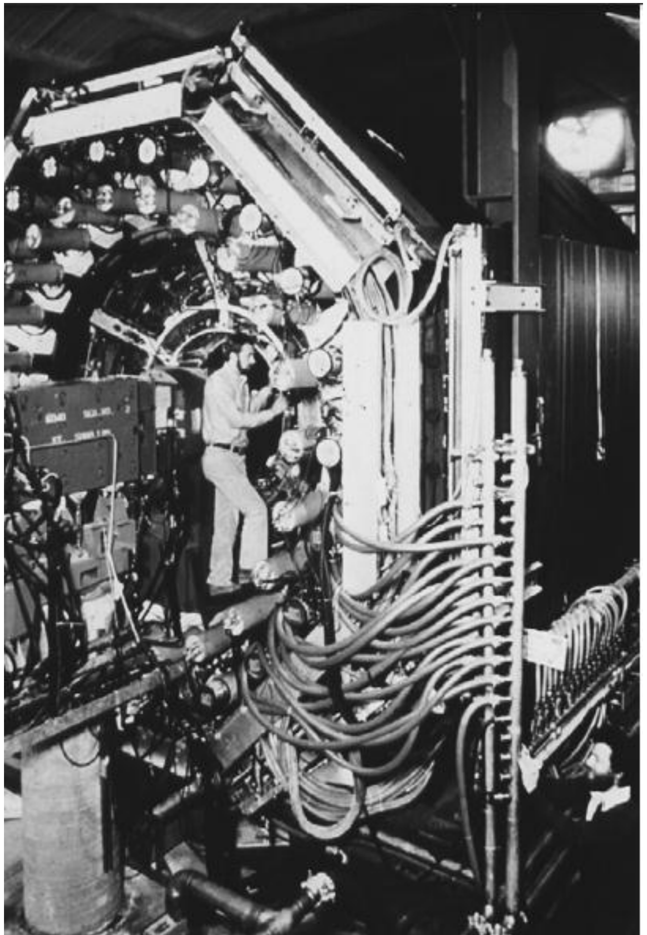
Discovery of the Tau Lepton – 1975



M. L. Perl, leader of
Mark-I experiment
at SLAC
Nobel prize 1995

SPEAR: Standford-positron-electron-accelerator ring

E_{CM} up to 8 GeV



Mark-I experiment

Discovery of the Tau Meson

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 $e^+ + e^- \to e^\pm + \mu^\mp$ + 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

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

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-

physics process:

$e^+ \ e^- \to \tau^+ \ \tau^-$

$\tau^+ \to e^+ \ \bar{\nu}_\tau \ \nu_e$

$\tau^- \to \mu^- \ \bar{\nu}_\mu \ \nu_\tau$

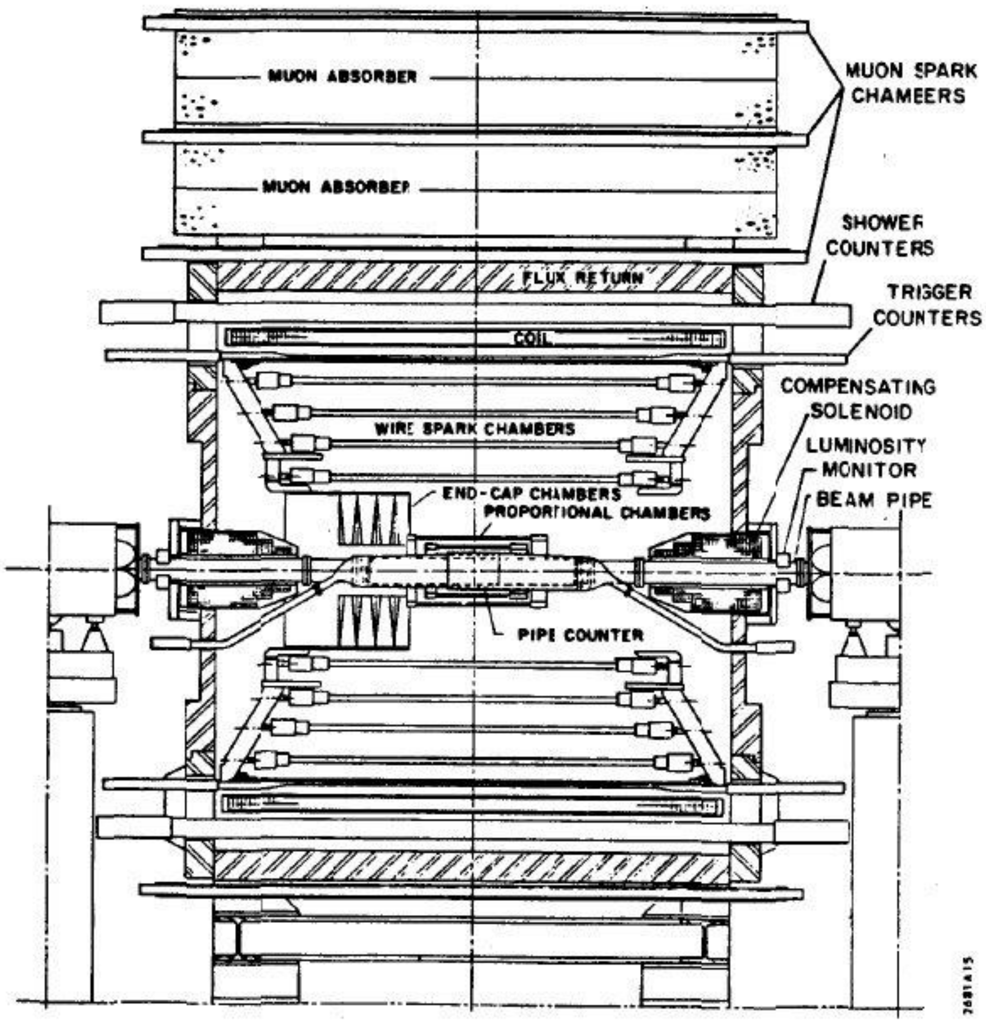
+ CC

Signature in experiment:

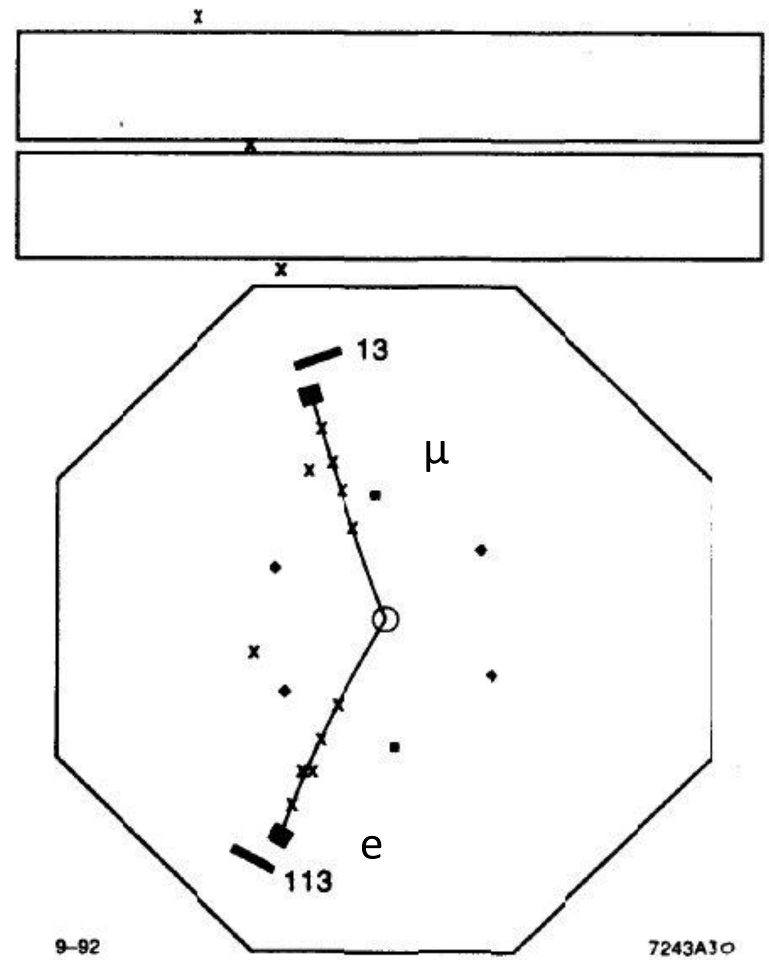
$e^+ \ e^- \to e^\pm \mu^\mp + \geq 2$ undetected particles

in e+e- collisions we know the initial 4 momenta, thus we can check for missing energy in the final state

Mark-I experiment



(a)



(b)

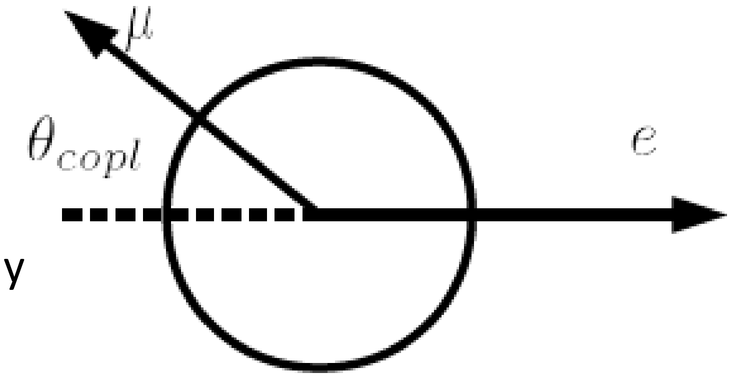
Discovery of the Tau Lepton

signature: $e^+ e^- \to e^{\pm} \mu^{\mp} + \geq 2$ undetected particles

Background process:

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

  with one leg in the final state mis/identified as electron/muon respectively;



cut on θ_{copl}>20˚ reduced this background significantly

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

Very rare decay, cross check: look for same sign $e^-\mu^-$ and $e^+\mu^+$ combinations

- hadron mis-id background (h: hadron)

  $e^+ e^- \to \mu^+ h^- X$, $e^+ e^- \to h^+ e^- X$, $e^+ e^- \to h^+ h^- X$

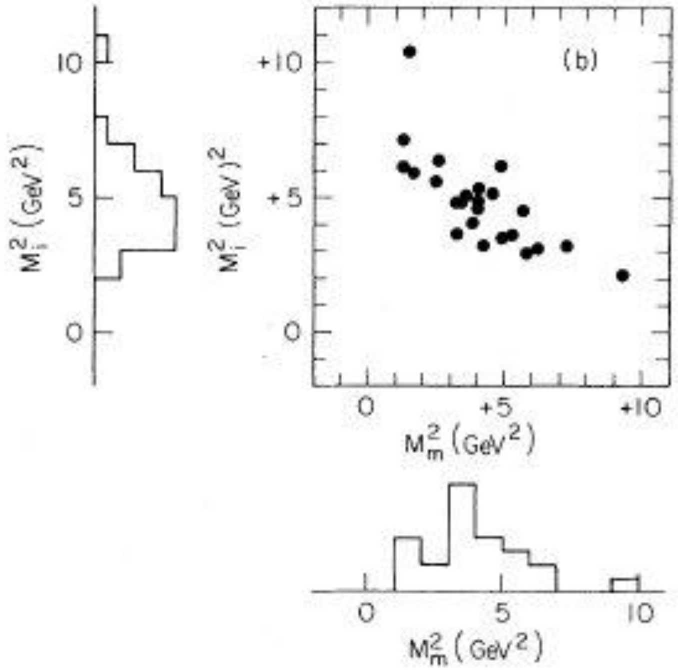
4.7 ± 1.5 background candidates from these sources

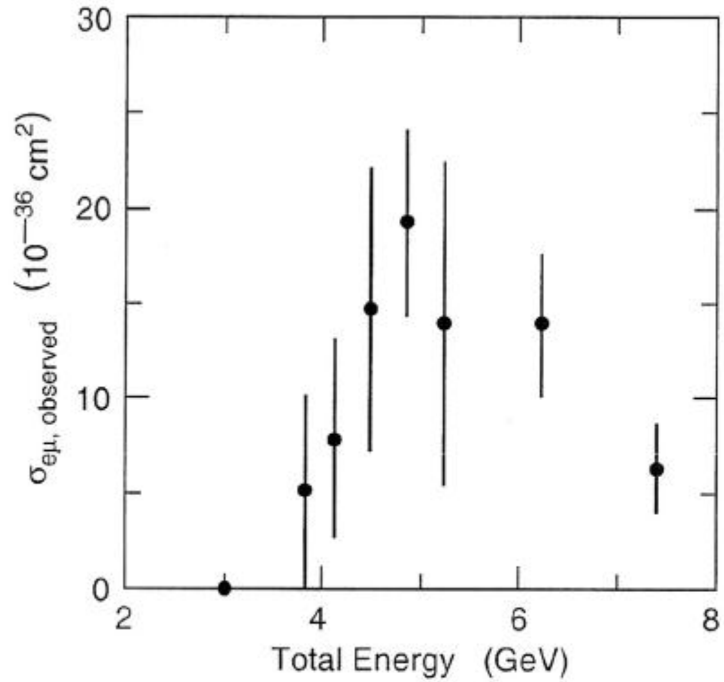
24 signal candidates → clear signal, not compatible with background fluctuations

TABLE I. Distribution of 513 two-prong events, obtained at $E_{c.m.} = 4.8$ GeV, which meet the criteria $|\vec{p}_1| > 0.65$ GeV/c, $|\vec{p}_2| > 0.65$ GeV/c, and $\theta_{copl} > 20°$. Events are classified according to the number N_γ of photons detected, the total charge, and the nature of the particles. All particles not identified as e or μ are called h for hadron.

Particles \ N_γ	0	1	>1	0	1	>1
	Total charge = 0			Total charge = ±2		
e–e	40	111	55	0	1	0
e–μ	24	8	8	0	0	3
μ–μ	16	15	6	0	0	0
e–h	20	21	32	2	3	3
μ–h	17	14	31	4	0	5
h–h	14	10	30	10	4	6

Discovery of the Tau Lepton

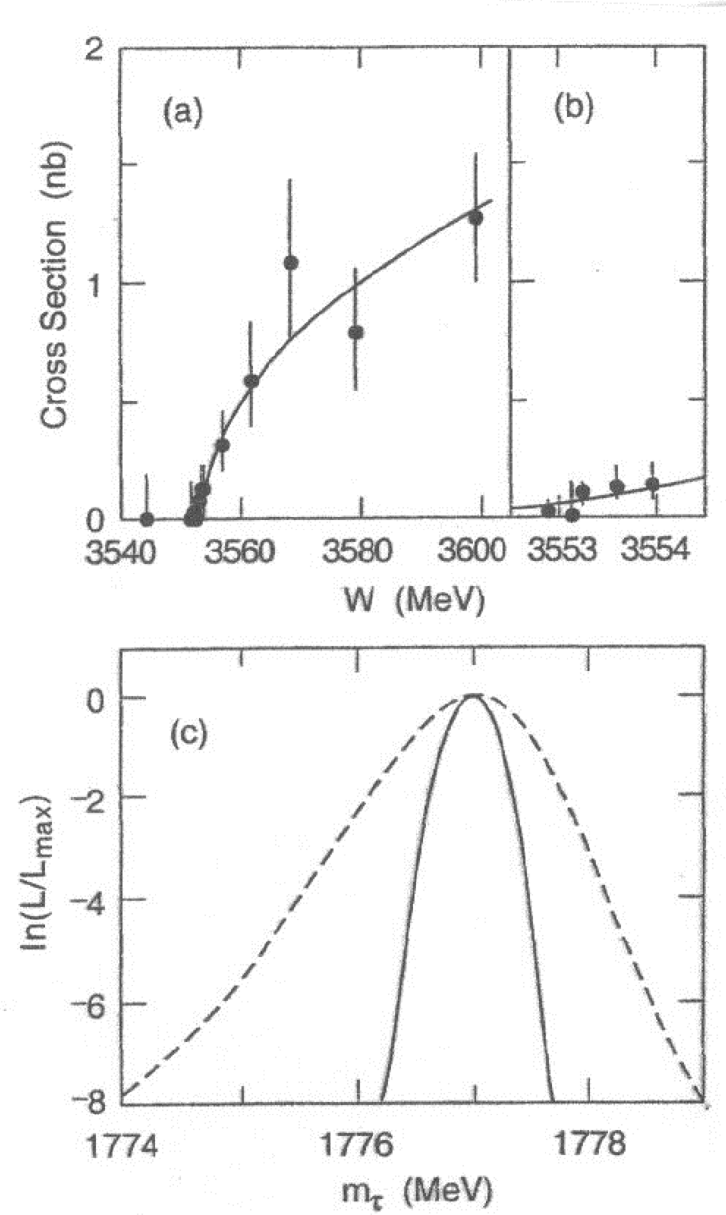




M_m: missing energy
M_i: invariant mass of (e,μ)
No resonance observed, thus at least 2 missing particles in final state

threshold behaviour indicates mass of tau particle $2m_\tau \sim 4$ GeV

Measurement of Tau Mass

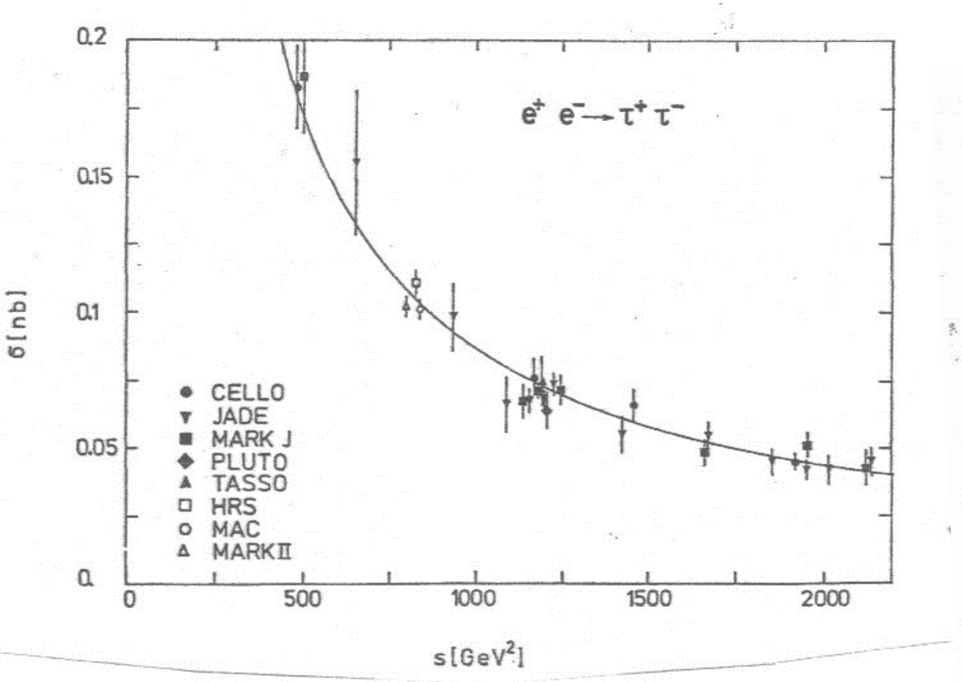


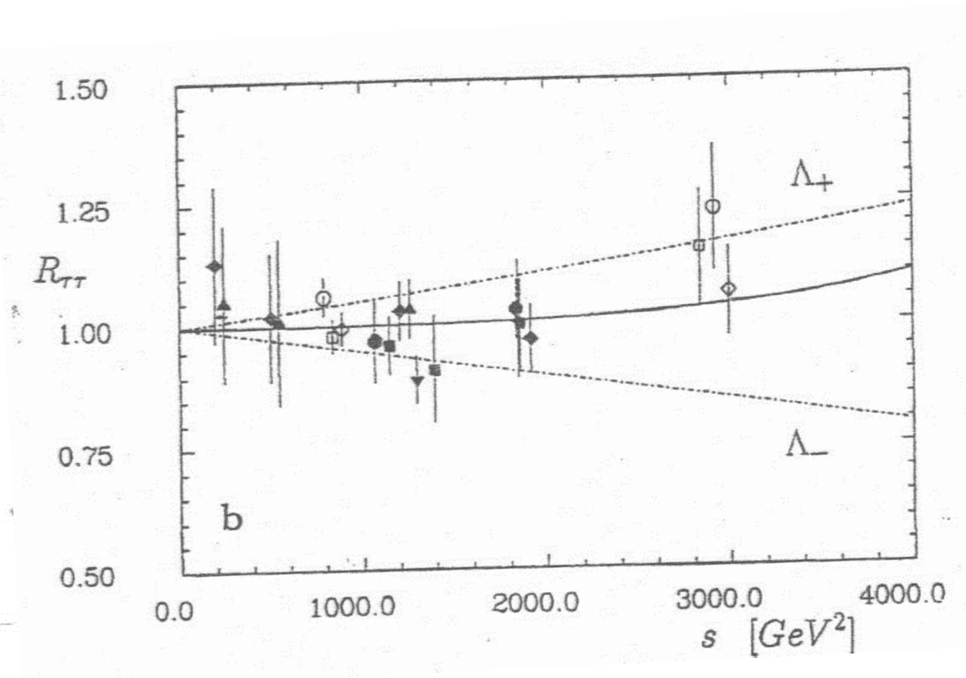
Later measurement at BESS (1994):

$$m_\tau = 1776.96^{+0.18+0.20}_{-0.19-0.16} MeV$$

Point like nature of τ Particle

As for e+e- → μ+μ- 1st order QED prediction
of total cross-section for $e^+e^- \to \tau^+\tau^-$ in wonderful agreement
(differential cross-section suffers from interference
with Z exchange diagram)





Λ± > 200 GeV
→ another point like (elementary) particle

Summary

- Two add. variables (beside all masses and 4 momenta of initial particles) are required to describe scatter process A+B $\rightarrow$ C +D. E.g. use 2 out of 3 (LI) Mandelstam variables

- Symmetry arguments can be used to relate cross-section of different scatter process (technical: swap of Mandelstam variables in cross-section formular)

- First order QED correction describe well the total cross section in data (for $e^+e^- \rightarrow e^+e^-$, $e^+e^- \rightarrow \mu^+\mu^-$, $e^+e^- \rightarrow \tau^+\tau^-$) This is mainly related to the strong supression of higher order diagrams α ~1/137

- Differential cross-section is affected by interference with Z exchange diagram (can be computed as well)

Next time :continue test of QED in e^+e^- scattering

- hadronic resonances in e^+e^- scattering

- higher order corrections and renormalization (running coupling constants)