

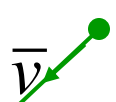



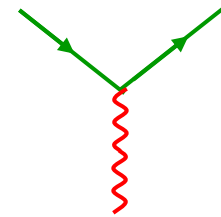


Feynman regels voor QED ($S=1/2$)

Externe lijnen

Deeltje			$\left\{ \begin{array}{l} \text{inkomend: } u \\ \text{uitgaand: } \bar{u} \\ \text{inkomend: } \bar{v} \\ \text{uitgaand: } v \\ \text{inkomend: } \epsilon_\mu \\ \text{uitgaand: } \epsilon_\mu^* \end{array} \right.$
Anti-deeltje			
Foton			

Vertices



$$-i(\sqrt{4\pi}e)\gamma_\mu$$

Propagatoren

Deeltje



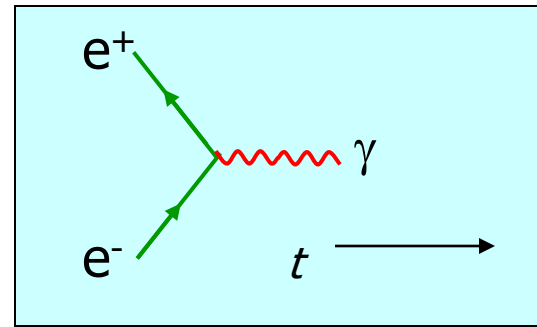
$$\frac{i(\gamma_\mu q^\mu + m)}{q^2 - m^2}$$

Foton

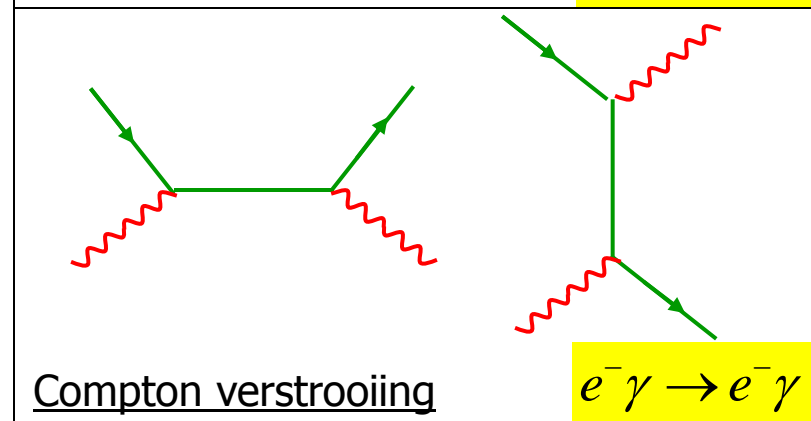
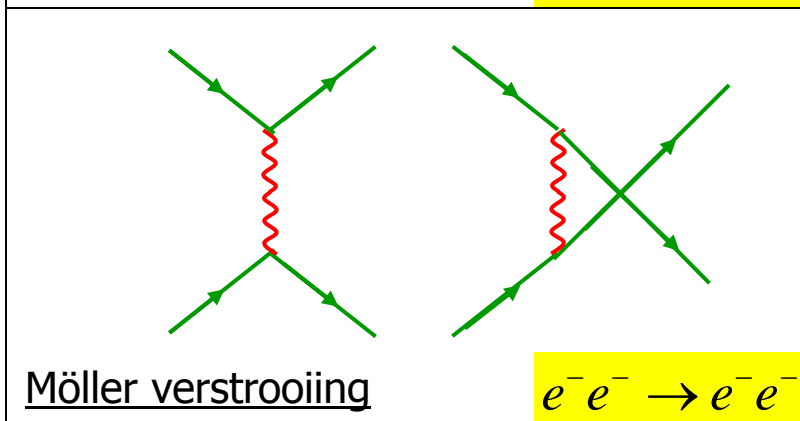
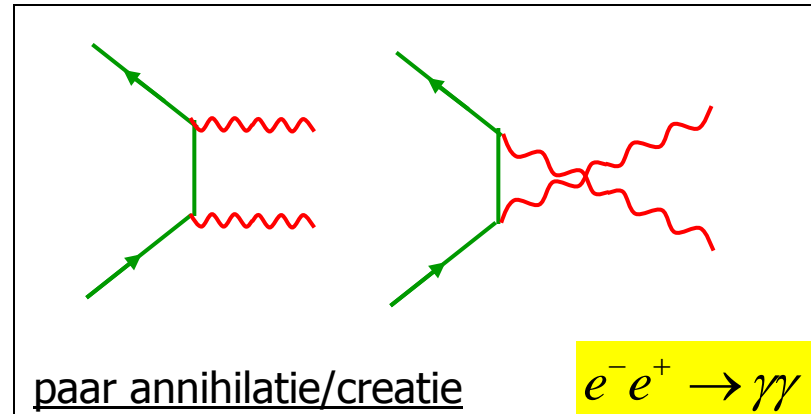
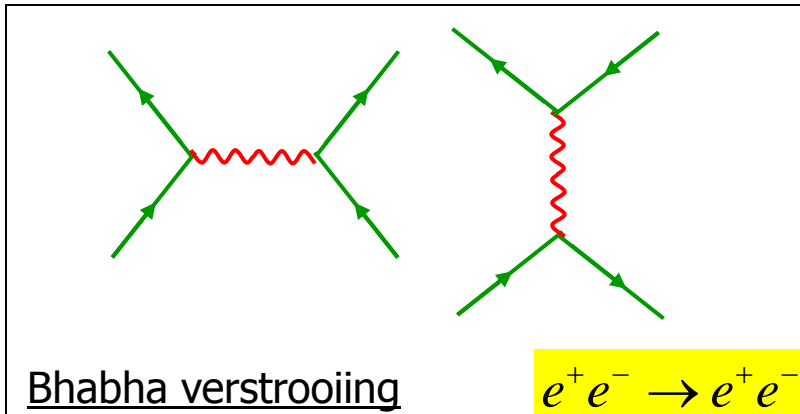


$$\frac{-ig_{\mu\nu}}{q^2}$$

QED



Fundamentele interacties:

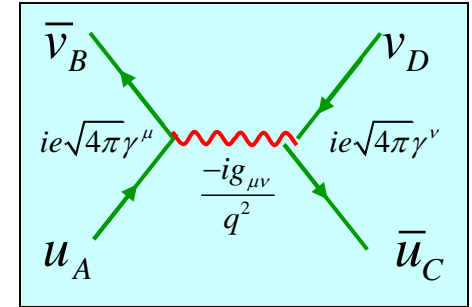


Berekening $e^-e^+ \rightarrow \mu^-\mu^+$

Feynman regels geven

$$-i\mathcal{M} = [ie\sqrt{4\pi}\bar{v}_B\gamma^\mu u_A] \times \frac{-ig_{\mu\nu}}{(p_A + p_B)^2} \times [ie\sqrt{4\pi}\bar{u}_C\gamma^\nu v_D] \Rightarrow$$

$$\mathcal{M} = -4\pi e^2 [\bar{v}_B\gamma^\mu u_A] \times \frac{1}{q^2} \times [\bar{u}_C\gamma_\mu v_D] \quad q = p_A + p_B$$



De spin algebra geeft een spoor

$$|\bar{\mathcal{M}}|^2 = \left(\frac{4\pi e^2}{(k+p)^2}\right)^2 \times \frac{1}{4} \sum [\bar{v}(p)\gamma^\mu u(k)] \times [\bar{u}(k')\gamma_\mu v(p')] \times [\bar{v}(p')\gamma_\nu u(k')] \times [\bar{u}(k)\gamma^\nu v(p)]$$

$$= \left(\frac{4\pi e^2}{(k+p)^2}\right)^2 \times \frac{1}{4} \times (\text{Tr}[(\not{p} - M)\gamma^\mu(\not{k} + m)\gamma^\nu]) \times (\text{Tr}[(\not{p}' - M)\gamma_\nu(\not{k}' + m)\gamma_\mu])$$

$$= \left(\frac{4\pi e^2}{(k+p)^2}\right)^2 \times \frac{1}{4} \times (\text{Tr}[\not{p}\gamma^\mu \not{k}\gamma^\nu] - 4mMg^{\mu\nu}) \times (\text{Tr}[\not{p}'\gamma_\nu \not{k}'\gamma_\mu] - 4mMg_{\mu\nu})$$

$$= \left(\frac{4\pi e^2}{(k+p)^2}\right)^2 \times 4(p^\mu k^\nu + p^\nu k^\mu - [p \cdot k + mM]g^{\mu\nu}) \times (p'_\mu k'_\nu + p'_\nu k'_\mu - [p' \cdot k' + mM]g_{\mu\nu})$$

$$= \left(\frac{4\pi e^2}{(k+p)^2}\right)^2 \times 4(2(p \cdot p')(k \cdot k') + 2(p \cdot k')(p' \cdot k) + \dots)$$

$$\begin{cases} P_A \rightarrow k \\ P_B \rightarrow p \\ P_C \rightarrow k' \\ P_D \rightarrow p' \end{cases}$$

$$\frac{d\sigma}{d\cos\theta}(e^+ + e^- \rightarrow \mu^+ + \mu^-) = \frac{\pi\alpha^2}{8E^2}(1 + \cos^2\theta)$$

Elektron-positron annihilatie

Muon productie

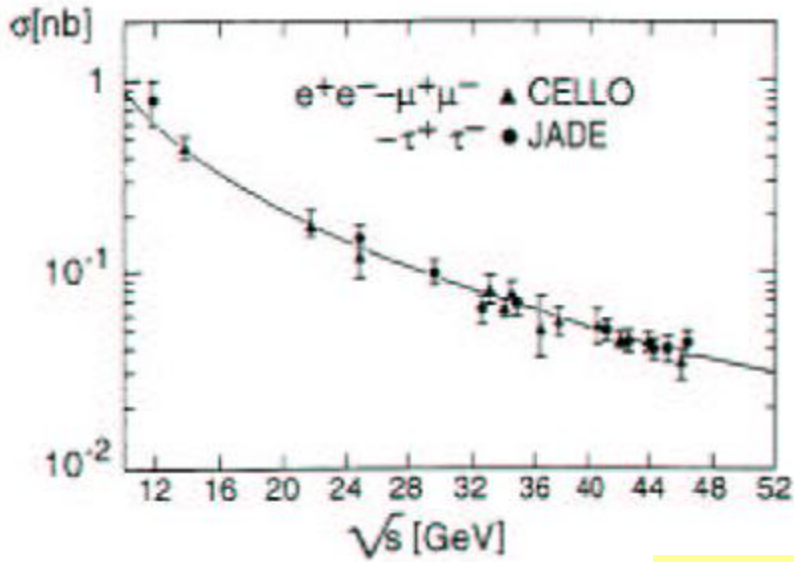
$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

$$\frac{d\sigma}{d\cos\theta}(e^+ + e^- \rightarrow \mu^+ + \mu^-) = \frac{\pi\alpha^2}{8E^2}(1 + \cos^2\theta)$$

spinfactor

integreer

$$\sigma(e^+ + e^- \rightarrow \mu^+ + \mu^-) = \sigma(e^+ + e^- \rightarrow \tau^+ + \tau^-) = \frac{21.7}{E^2} \text{ nanobarns}$$



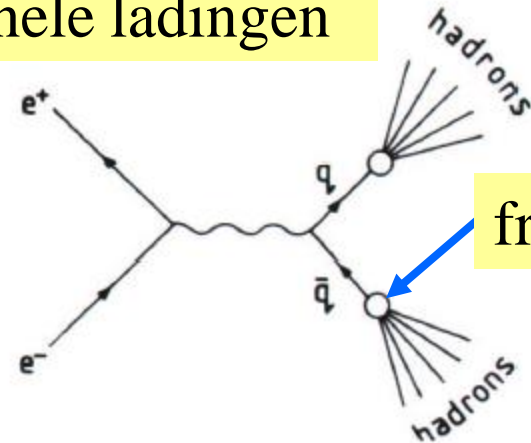
Elektron, muon en tau zijn identiek, afgezien van massa en levensduur

Twee-jet productie

$$\frac{d\sigma}{d\cos\theta}(e^+ + e^- \rightarrow q + \bar{q}) = \frac{3\pi e_q^2 \alpha^2}{8E^2}(1 + \cos^2\theta)$$

kleur

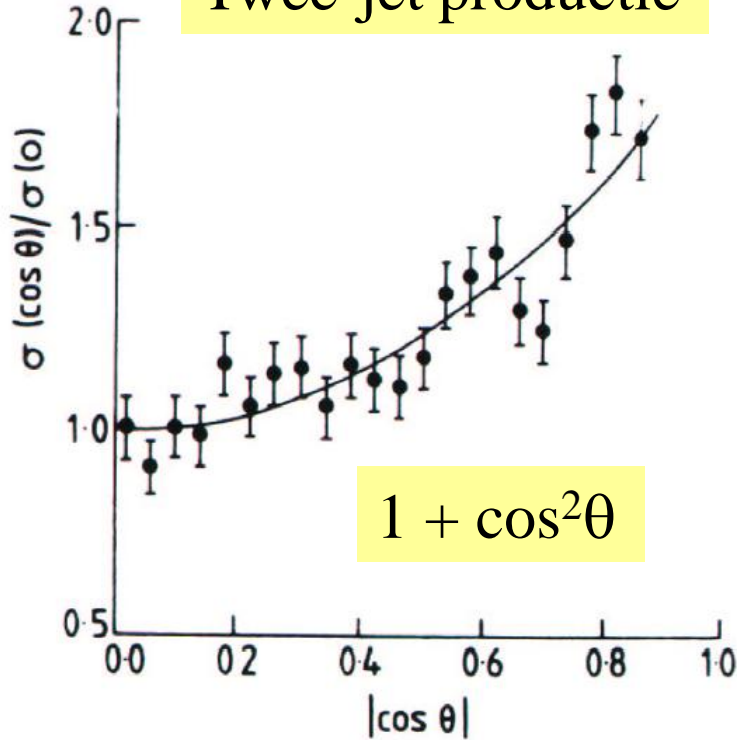
fractionele ladingen



fragmentatie

Elektron-positron annihilatie

Twee-jet productie



$1 + \cos^2\theta$

Quarks hebben spin 1/2

Quarks hebben kleur en fractionele lading

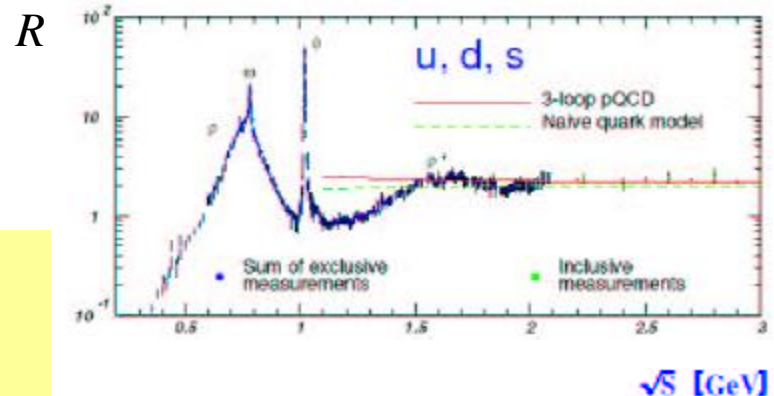
$$R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadronen})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

$$\frac{d\sigma}{d\cos\theta}(e^+ + e^- \rightarrow q + \bar{q}) = \frac{3\pi e_a^2 \alpha^2}{8E^2} (1 + \cos^2\theta)$$

$$\frac{d\sigma}{d\cos\theta}(e^+ + e^- \rightarrow \mu^+ + \mu^-) = \frac{\pi\alpha^2}{8E^2} (1 + \cos^2\theta)$$

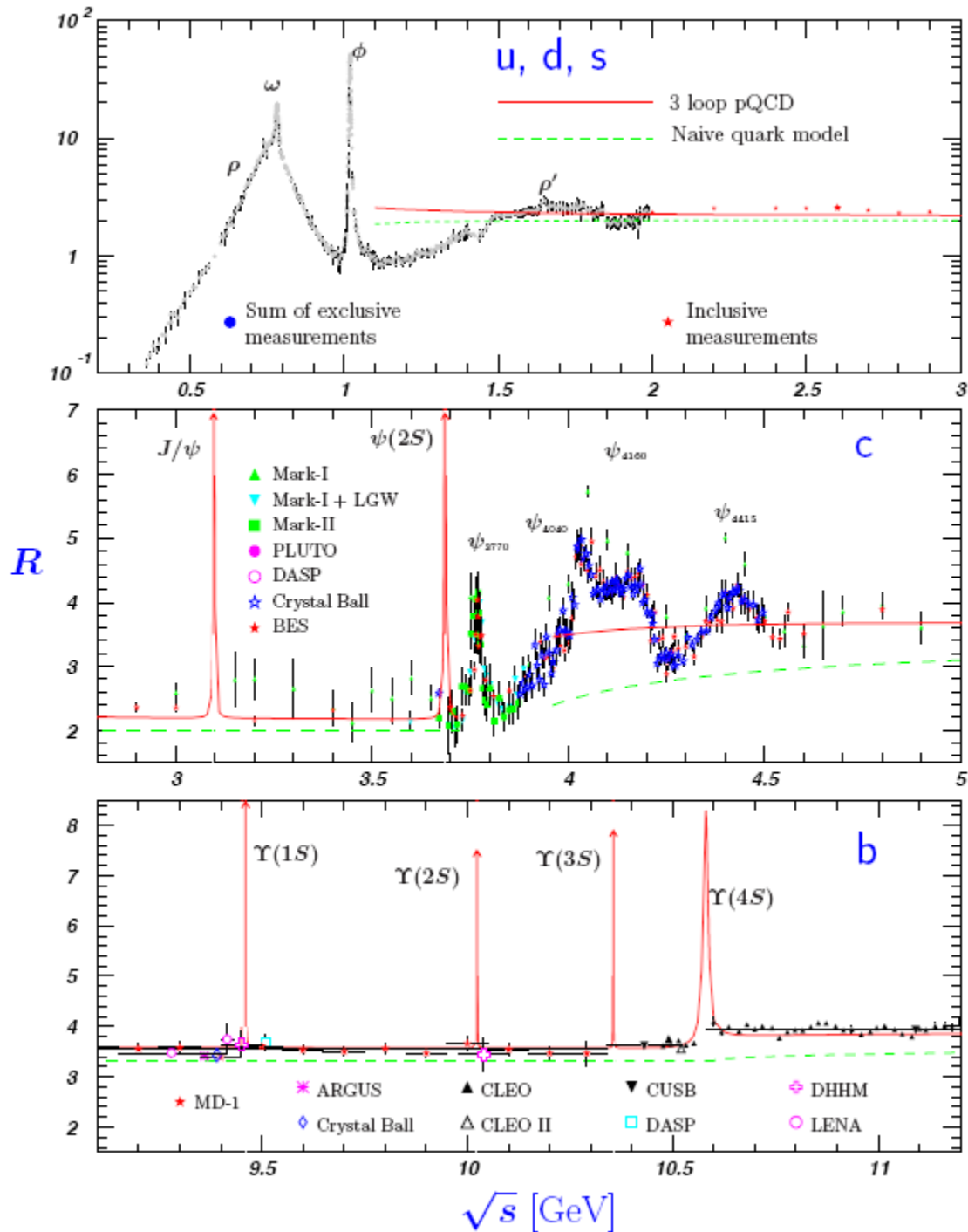
Voor $E < 3.5$ GeV

$$R = 3 \left[\left(\frac{2}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 + \left(-\frac{1}{3}\right)^2 \right] = 2$$



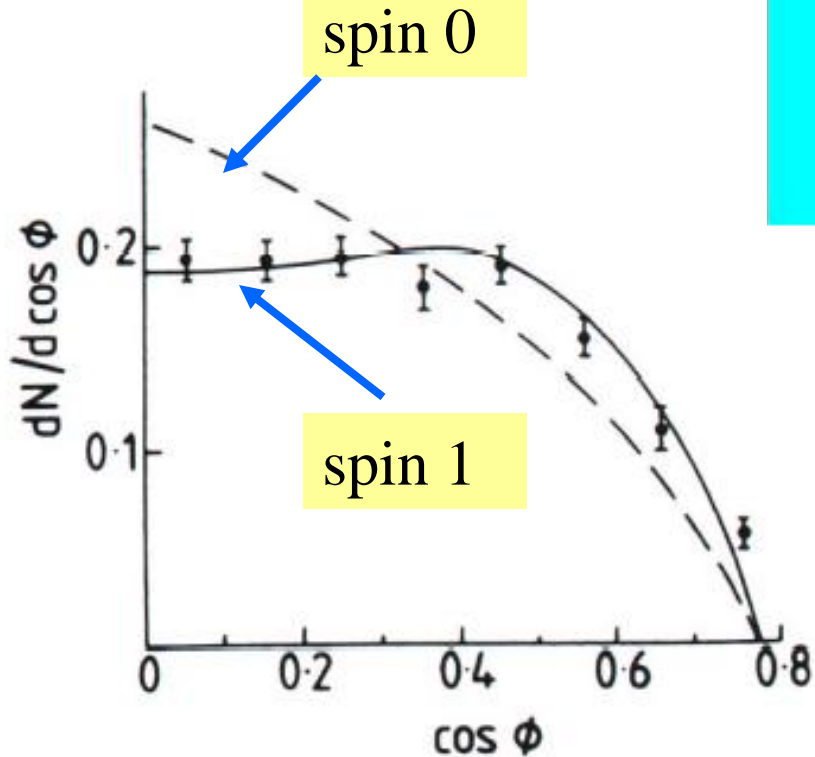
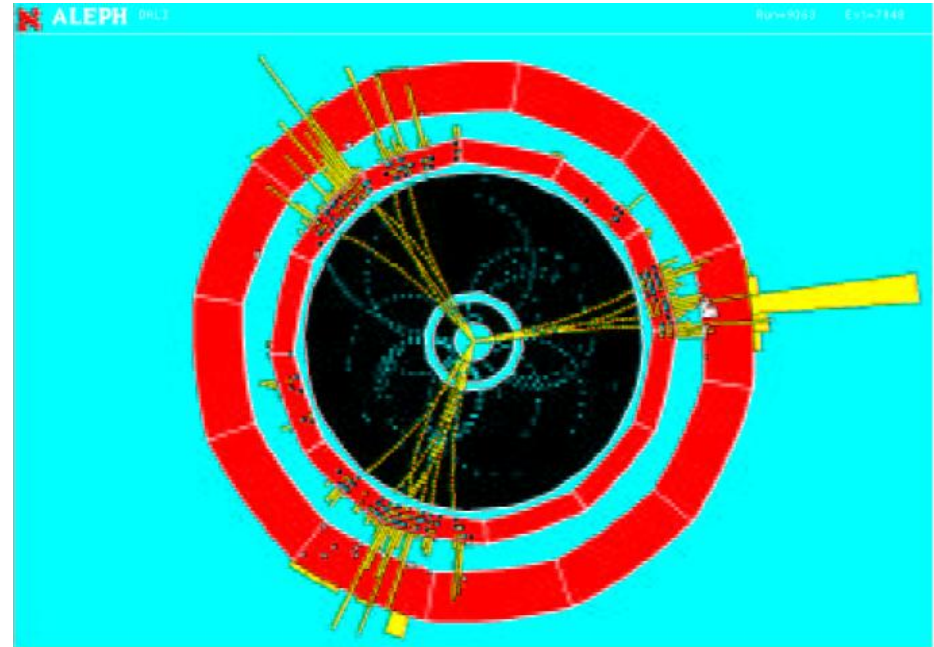
Elektron-positron annihilatie

$$R \equiv \frac{\sigma_{qq}}{\sigma_{\mu\mu}} = \frac{\sum_{\text{quarks}} e^+ e^- \rightarrow q\bar{q}}{e^+ e^- \rightarrow \mu^+ \mu^-}$$



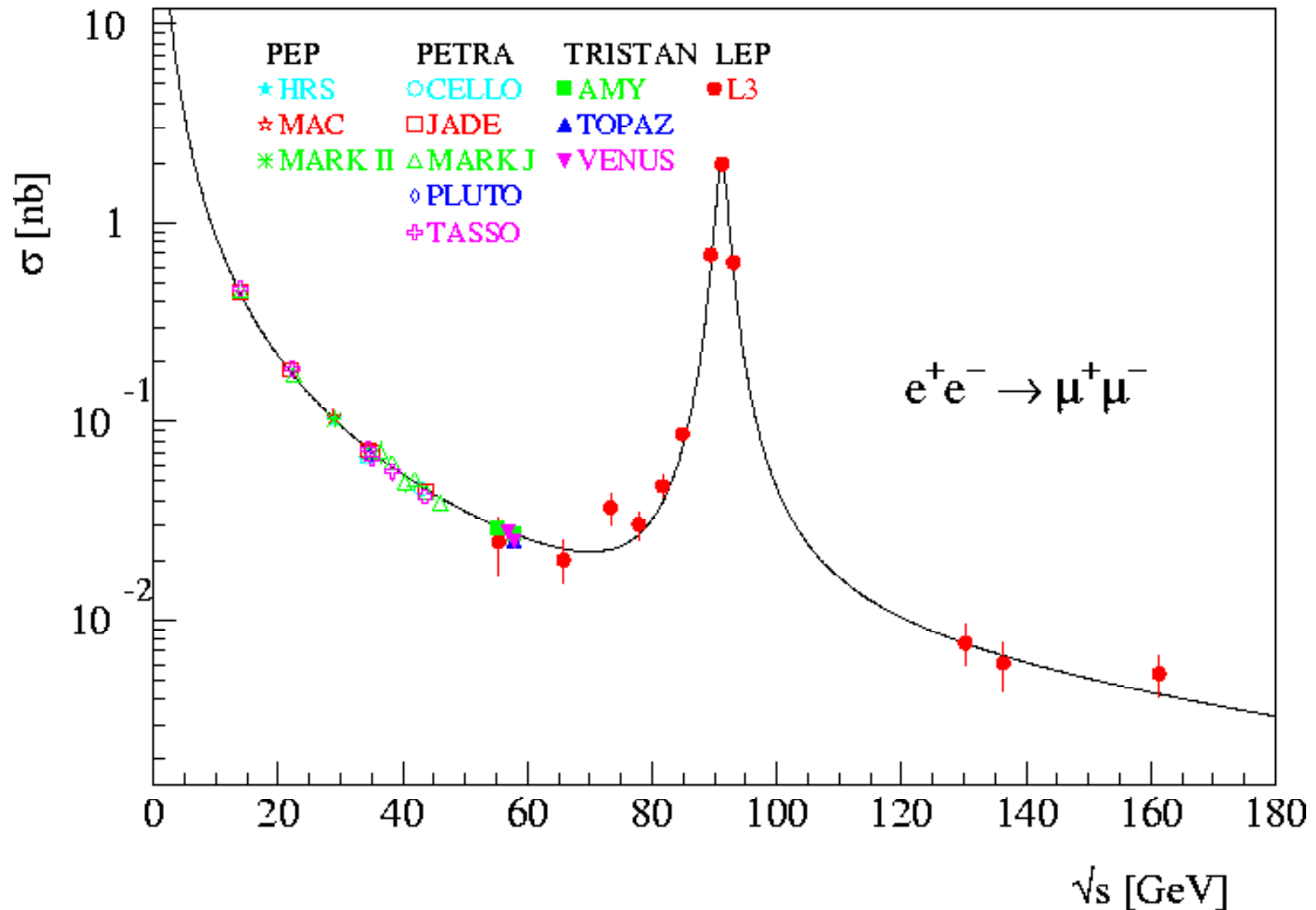
Elektron-positron annihilatie

Drie-jet productie



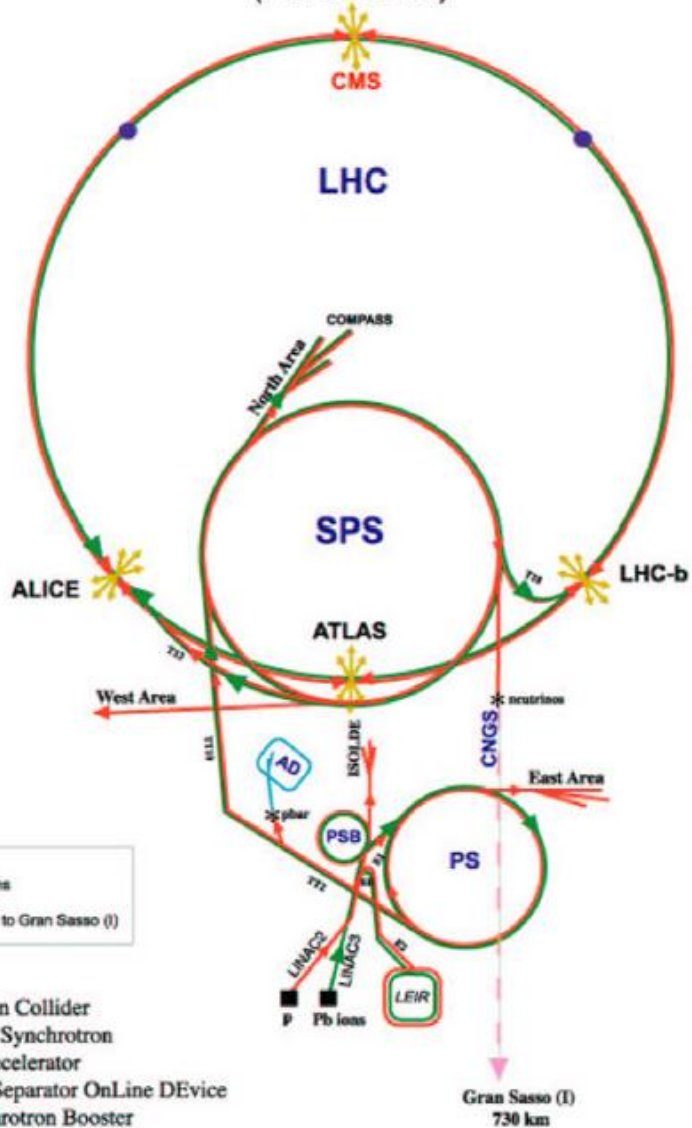
Gluonen hebben spin 1

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

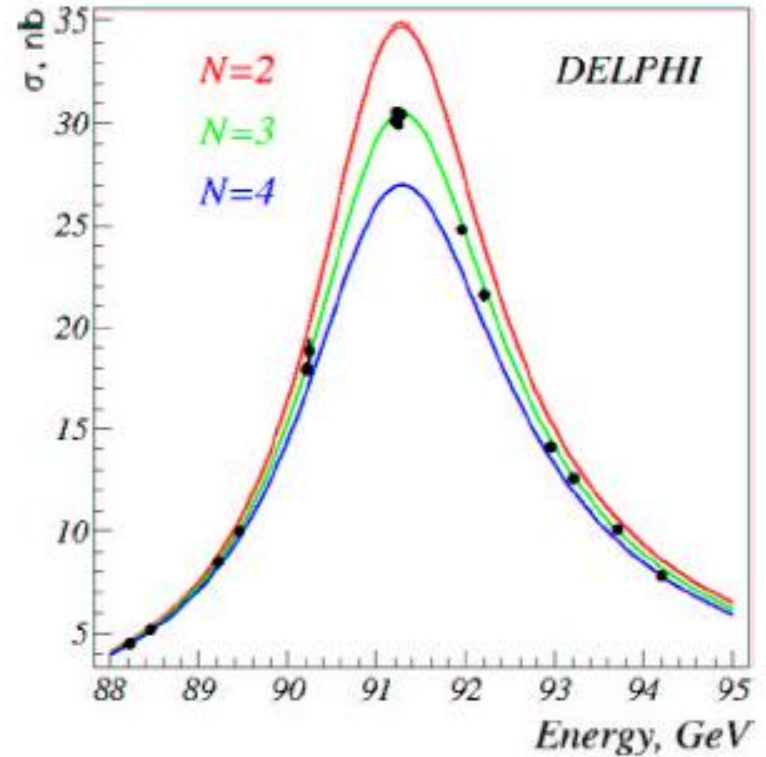


Z^0 -resonantie

CERN Accelerators
(not to scale)



- LHC: Large Hadron Collider
- SPS: Super Proton Synchrotron
- AD: Antiproton Decelerator
- ISOLDE: Isotope Separator OnLine DEvice
- PSB: Proton Synchrotron Booster
- PS: Proton Synchrotron
- LINAC: LINear ACcelerator
- LEIR: Low Energy Ion Ring
- CNGS: Cern Neutrinos to Gran Sasso



e^+e^- verstrooiing

Drie generaties!

Rudolf LEY, PS Division, CERN, 02.09.96
 Revised and adapted by Antonella Del Rosso, ITT Div.,
 in collaboration with B. Desforges, SL Div., and
 D. Mangiarini, PS Div. CERN, 23.05.01