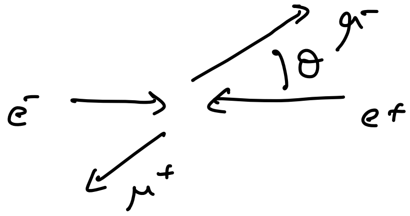
$e^+e^- \to \mu^+\mu^-$

$q\bar{q}$ (hadrons)



$$\sigma(e^+e^- \to \mu^+\mu^-) = \frac{16\pi}{3}\frac{\alpha^2}{s} = \frac{86.8 \text{ nb}}{s[\text{GeV}^2]}$$

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

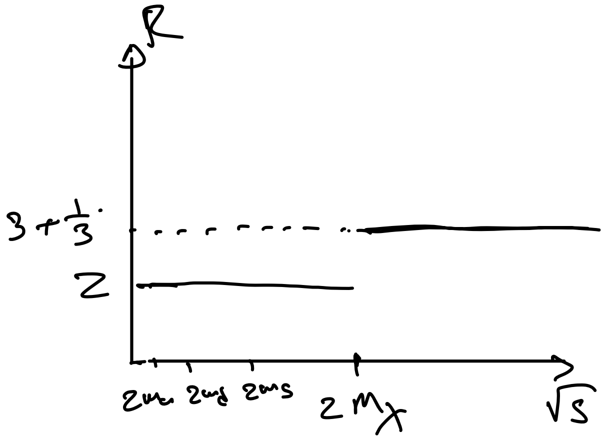
$$\sigma(e^+e^- \to q\bar{q}) = \sum_{i \text{ flavors}} \sigma(e^+e^- \to \mu^+\mu^-) \times Zq_i^2 \times N_c$$

$$2m_i \leq \sqrt{s}$$

$\sqrt{s} = 2E_{\text{beam}}$.

$$R = \frac{\sigma(e^+e^- \to q\bar{q})}{\sigma(e^+e^- \to \mu^+\mu^-)} = \sum_i Zq_i^2 N_c$$

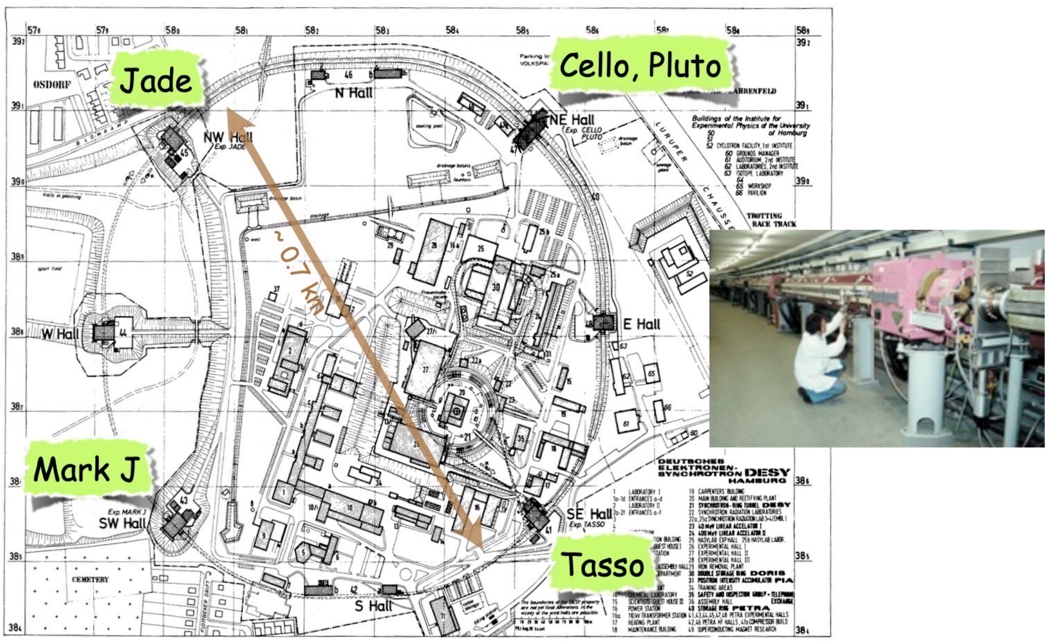
$\sqrt{s} \geq m_u, m_d, m_s \Rightarrow R = 2.$



For $\sqrt{s} < 2m_X$

q_X: charge $\frac{2}{3}$ New quark X with $q = \frac{2}{3}e$

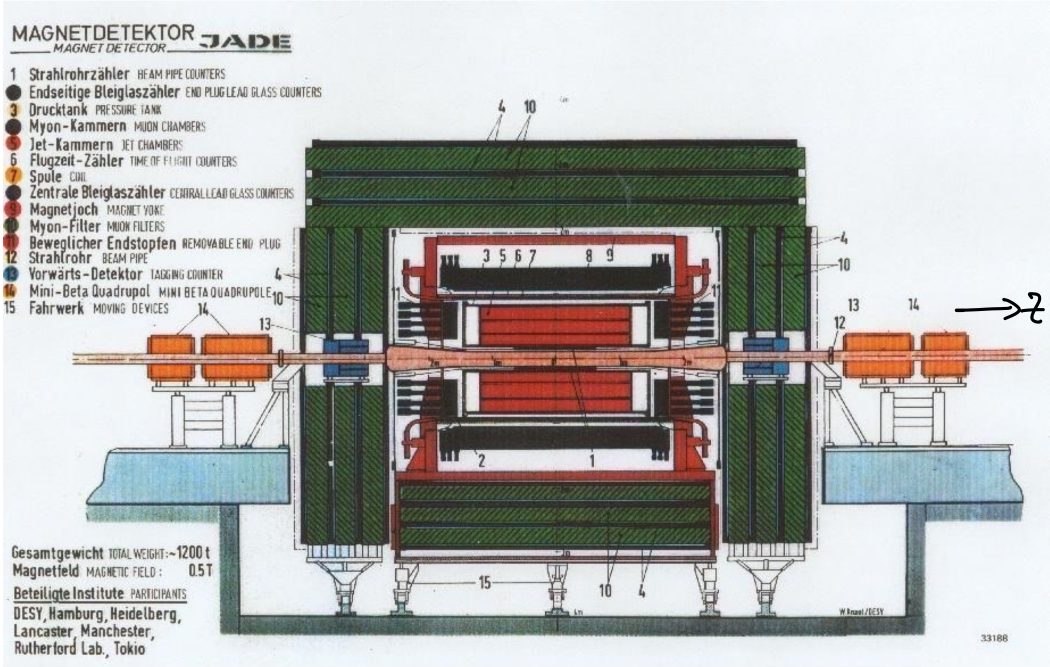
$$R(\sqrt{s} \geq 2m_X) = R + N_c \times \left(\frac{2}{3}\right)^2 = 2 + 3 \times \frac{4}{9} = 2 + \frac{4}{3} = 3 + \frac{1}{3}$$



PETRA @ DESY
near Hamburg

$12 \to 46.7$ GeV
$\sqrt{s}$

$1976 \to 1986$

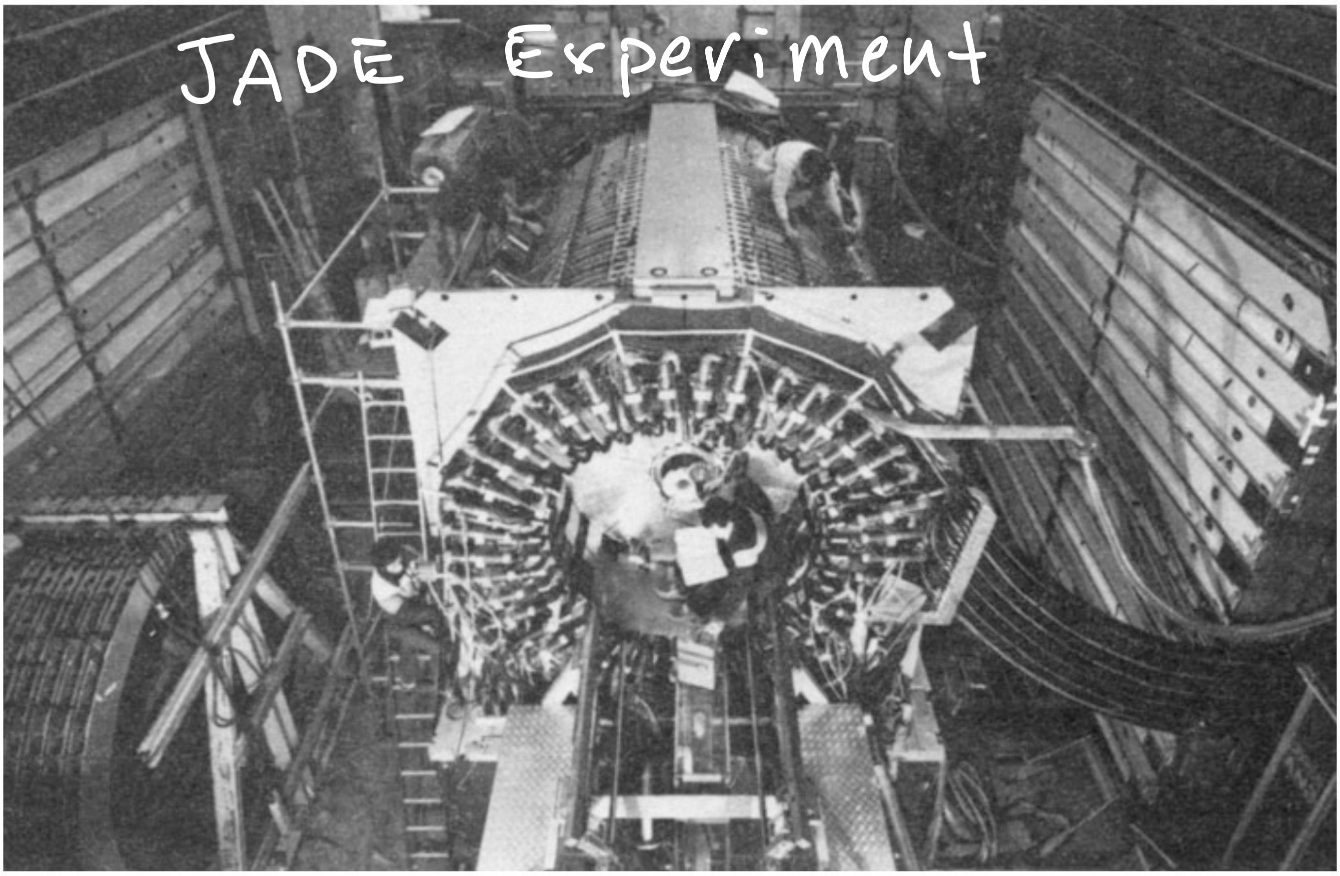


JADE Detector

JApan.

Deutschland

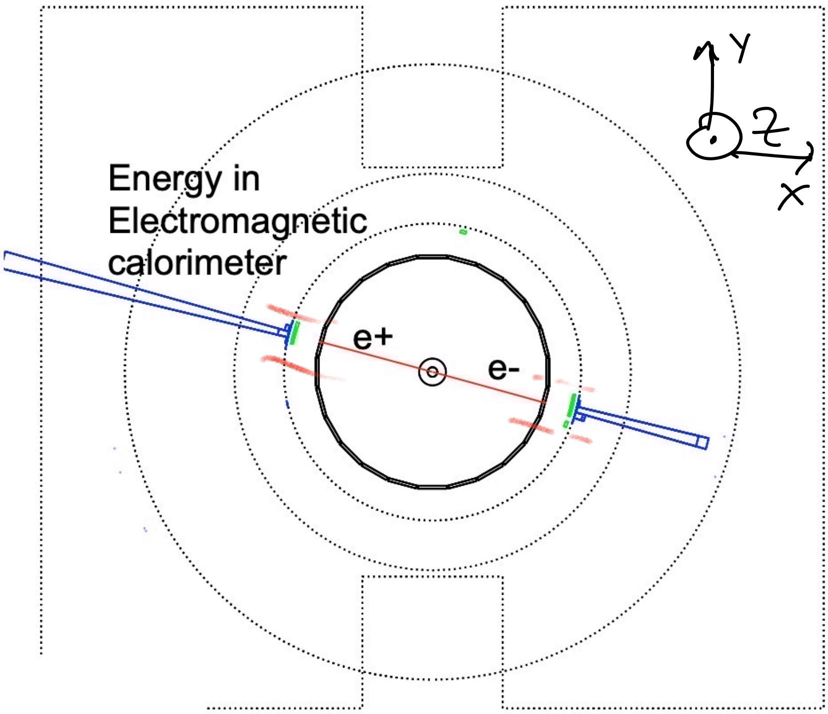
England



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

$\mu^+\mu^-$

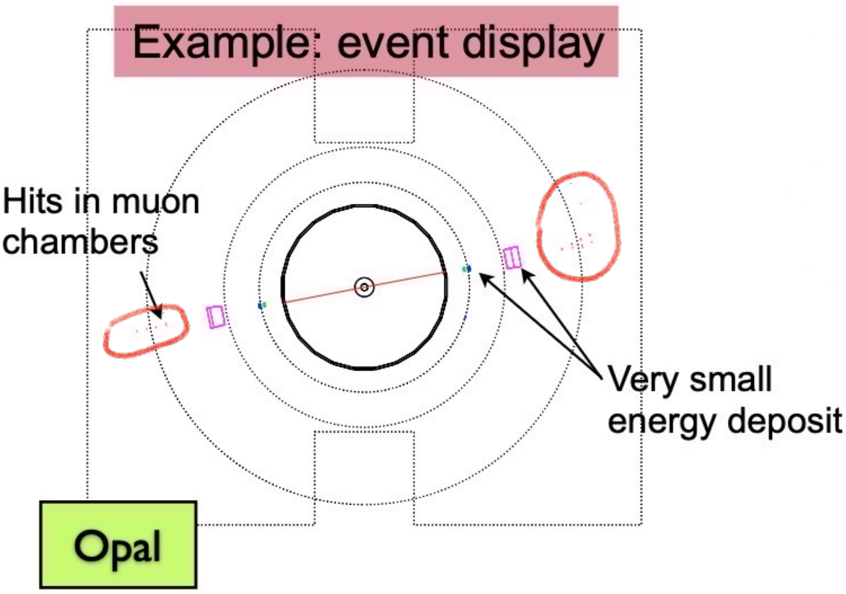
$q\bar{q}$ (hadrons)



e^+e^-:

2 charged tracks

+ 2 large energy EM deposits.

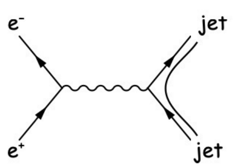


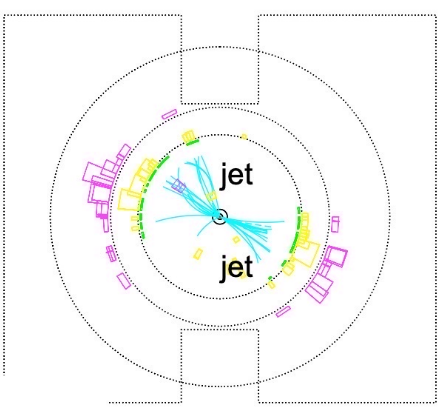
$\mu^+\mu^-$

2 charged tracks.

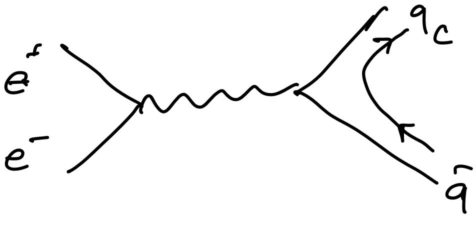
small EM deposit

+ signal in muon chambers

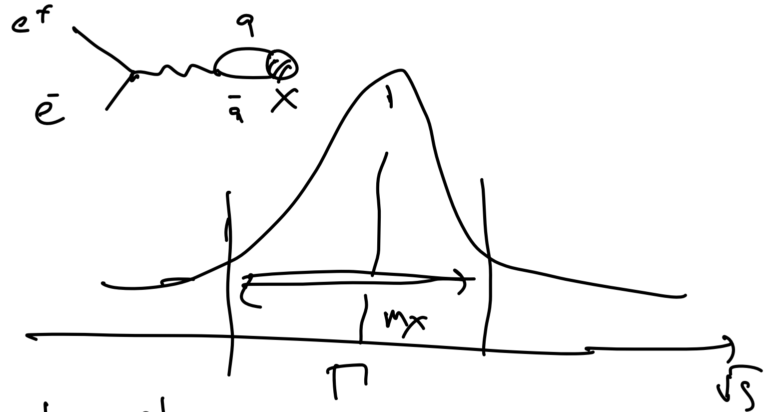




$q\bar{q}$ (hadrons)



$q_c \bar q_{\bar c}$ bound state with mass m_X



machine has $\sqrt{s} = 2E$

$\sigma(e^+e^- \to X \to f\bar f)$

$\sqrt{s} \approx m_X \Rightarrow$ produce X at rest.

$$\sigma(e^+e^- \to X \to f\bar f) = \frac{16\pi}{s} \frac{(2J+1)}{(2S_a+1)(2S_b+1)} \frac{\Gamma_{e^+e^-}}{\Gamma_{tot}} \frac{\Gamma_{f\bar f}}{\Gamma_{tot}} \frac{\Gamma_{tot}^2}{(m_X-\sqrt{s})^2 + \Gamma_{tot}^2/4}$$

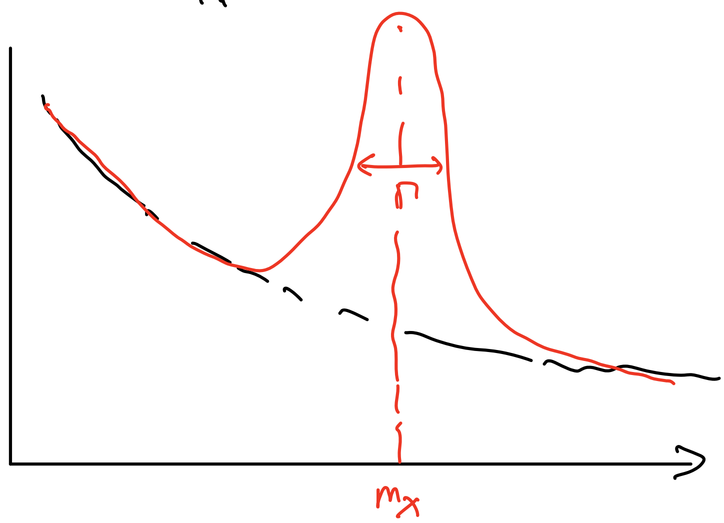
J: angular momentum of X

S_a, S_b : spin of incoming beams (in this case $S_a = S_b = 1/2$)

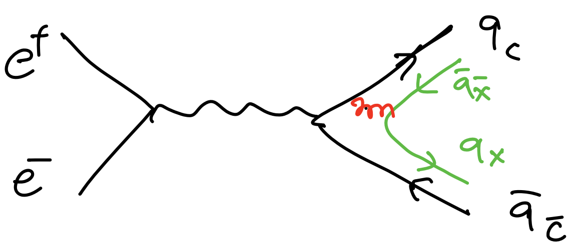
$X: \longrightarrow$

$f\bar f$	$\Gamma_{f\bar f}$	$m_X \geq 2m_e, 2m_f$
$e^+ \bar e$	$\Gamma_{e^+e^-}$	
$a\ b$	Γ_{ab}	
$\vdots$		

$\Gamma_{tot} = \Gamma_{ee} + \Gamma_{f\bar f} + \Gamma_{ab} + \dots$ all decays of X

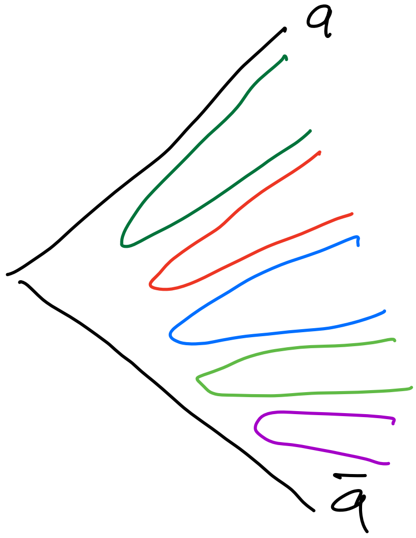


2nd case: $\sqrt{s} \neq m_X$ ($> m_X + \Gamma$, $< m_X - \Gamma$)

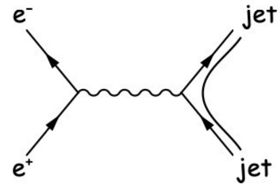


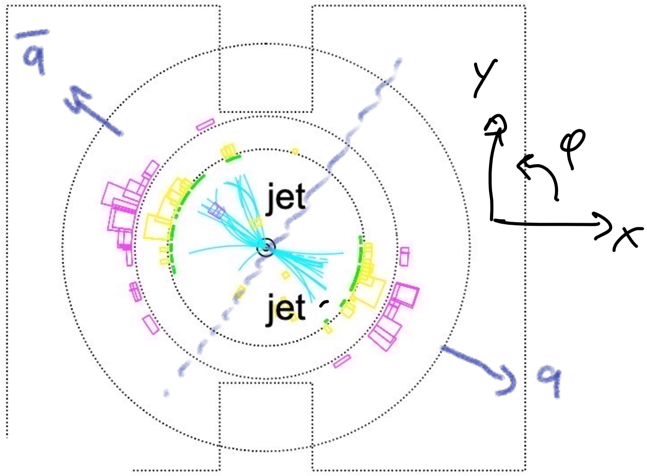
$(q\bar q_x)$ meson.

$(q_x \bar q)$ meson



$e^+e^- \longrightarrow N$ hadrons.



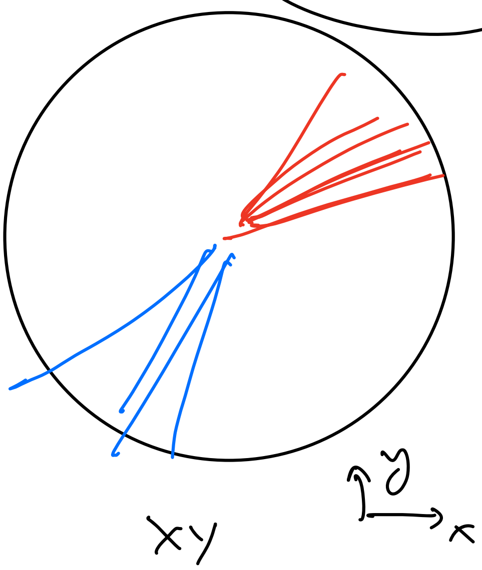


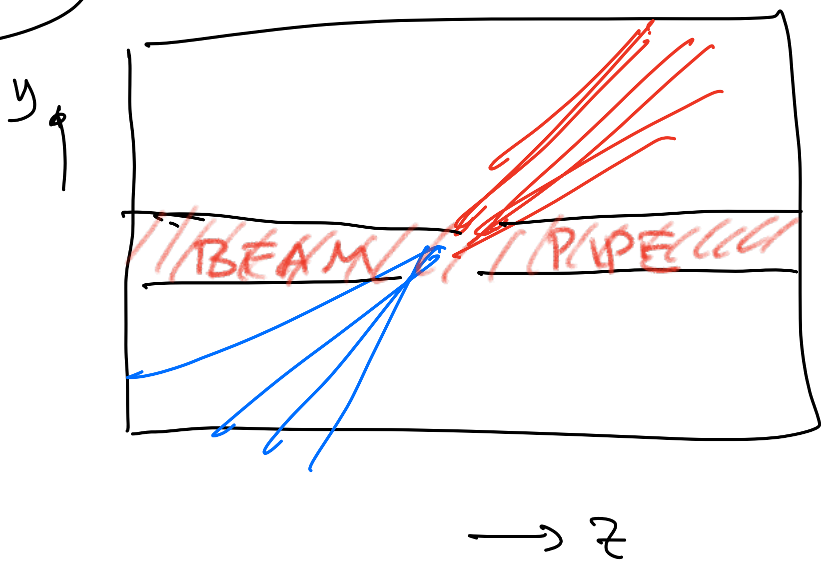
$\sqrt{s} = m_X$

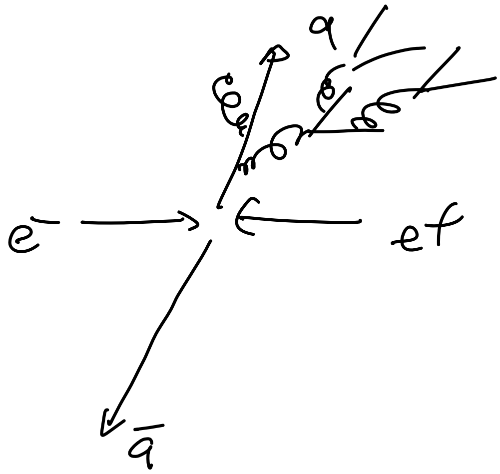
$e^+e^- \longrightarrow q\,\bar{q}$ $\quad \sigma_X : e^+e^- \to X.$

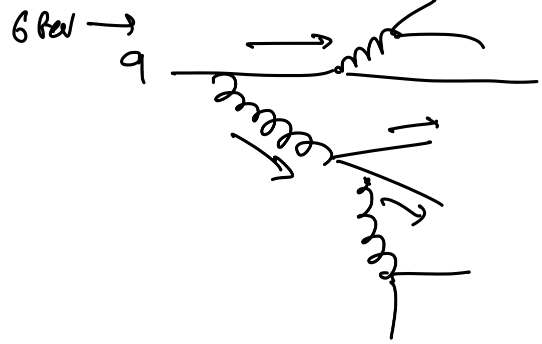
$\sigma_{ME} : e^+e^- \to$ jets.

$$\frac{d\sigma}{d\Omega} \propto (1 + \cos^2\theta)$$









$$e^+e^- \longrightarrow \begin{array}{ll} e^+e^- & \sigma_1 \ (\sigma_{Bhabha}) \\ \mu^+\mu^- & \sigma_2 \\ \text{hadrons.} & \sigma_3 \\ \tau^+\tau^- & \sigma_4. \end{array}$$

$N_{events} = \sigma_{tot} \ \mathcal{L}_{inst} \cdot \Delta t$

Δt ↪ time of measurements.

$\mathcal{L}_{inst}$ ↪ parameter of the machine

N_{events}: $\mu^+\mu^-$, e^+e^-, hadrons.

$$N_{e^+e^-} = \sigma_1 \times \mathcal{L}_{inst} \times \Delta t$$

$$N_{\mu^+\mu^-} = \sigma_2 \times \mathcal{L}_{inst} \times \Delta t$$

$$N_{had} = \sigma_3 \times \mathcal{L}_{inst.} \times \Delta t$$

$$\Rightarrow \mathcal{L}_{inst} = \frac{N_{e^+e^-}}{\sigma_1 \times \Delta t}$$

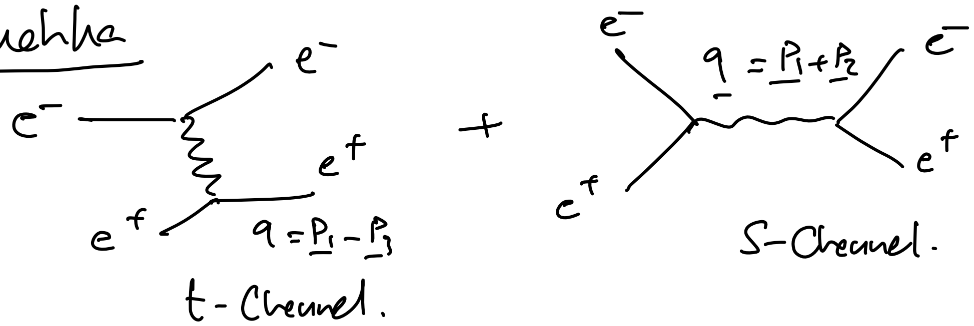
σ_1 ↪ comes from theory with high precision.

$$N_{had} = \sigma_3 \times \frac{N_{e^+e^-}}{\sigma_1^{(th)} \cancel{\int \mathcal{L}}} \cancel{\int \mathcal{L}}$$

$\Rightarrow$ measure σ_3

Knowledge of Bhabha cross section $\Rightarrow$ measure $\mathcal{L}_{inst}$.

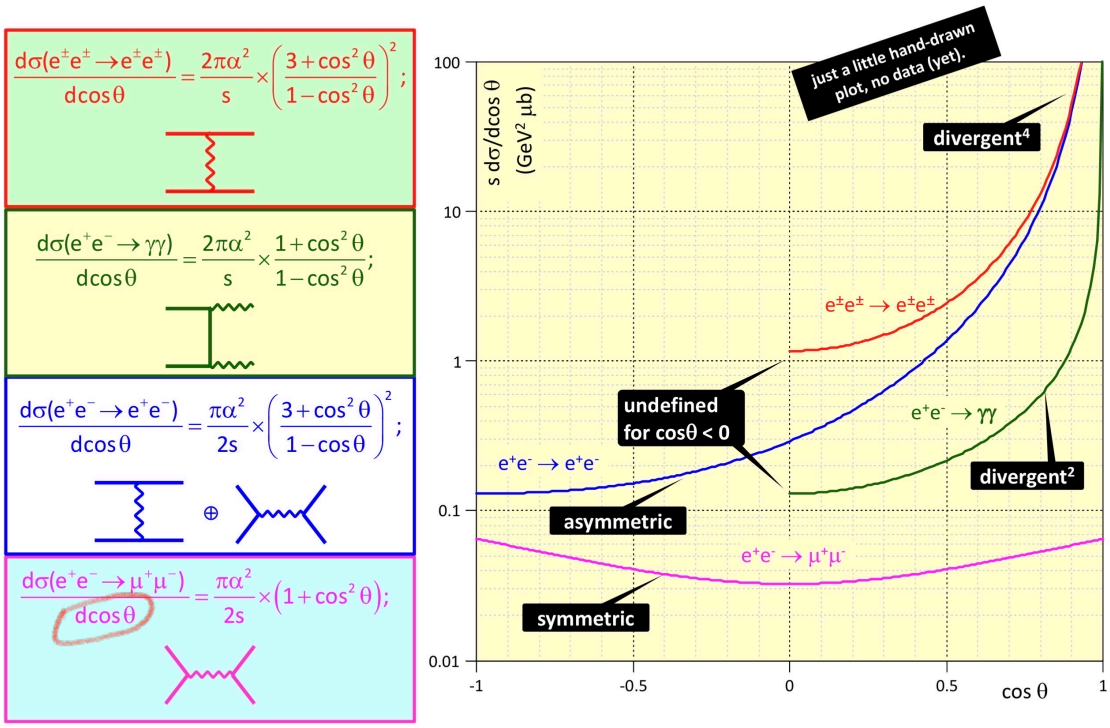
Bhabha



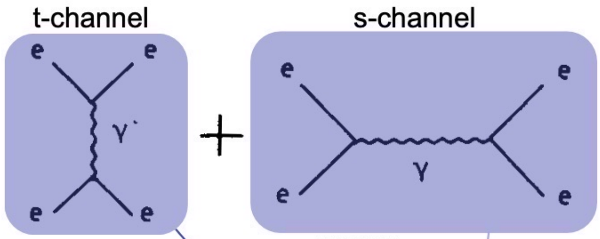
$$\sigma(e^+e^- \to e^+e^-) \propto |\mathcal{M}_t^{e^+e^-} + \mathcal{M}_s^{e^+e^-}|^2$$

$$= |\mathcal{M}_t|^2 + |\mathcal{M}_s|^2 + \mathcal{M}_t \mathcal{M}_s^* + \mathcal{M}_s \mathcal{M}_t^*$$

$$\frac{d\sigma}{d\Omega}(e^+e^- \to \mu^+\mu^-) \propto (1 + \cos^2\theta)$$

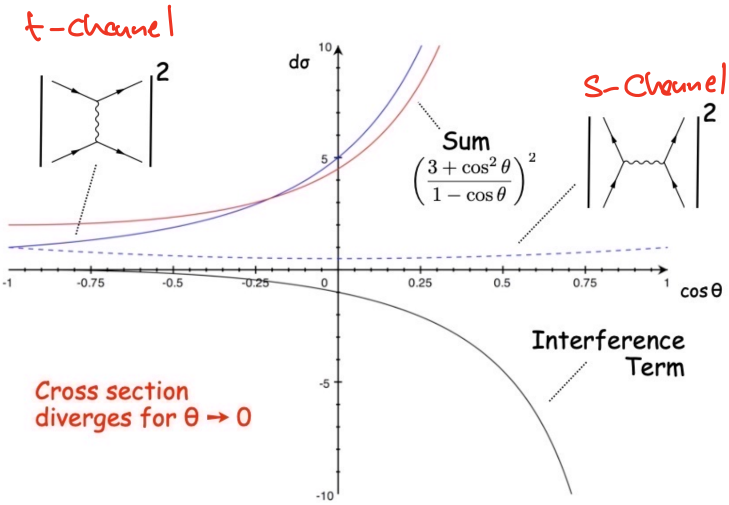


$$d\Omega = 2\pi \sin\theta \, d\theta = 2\pi \, d\cos\theta$$



$$\frac{d\sigma_0}{d\Omega} = \frac{\alpha^2}{2s}\left(\frac{q'^4+s^2}{q^4} + \underbrace{\frac{2q'^4}{q^2 s}}_{\text{interference term}} + \frac{q'^4+q^4}{s^2}\right)$$

$$= \frac{\alpha^2}{4s}\left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2$$



- limits of $d\sigma/d\cos\theta$ for $\cos\theta \to 1$ (i.e. $\theta \to 0$):

$e^\pm e^\pm \to e^\pm e^\pm$: $\frac{2\pi\alpha^2}{s}\left(\frac{3+1}{\sin^2\theta}\right)^2 = \left(\frac{2\pi\alpha^2}{s}\right)\left(\frac{16}{\theta^4}\right)$;

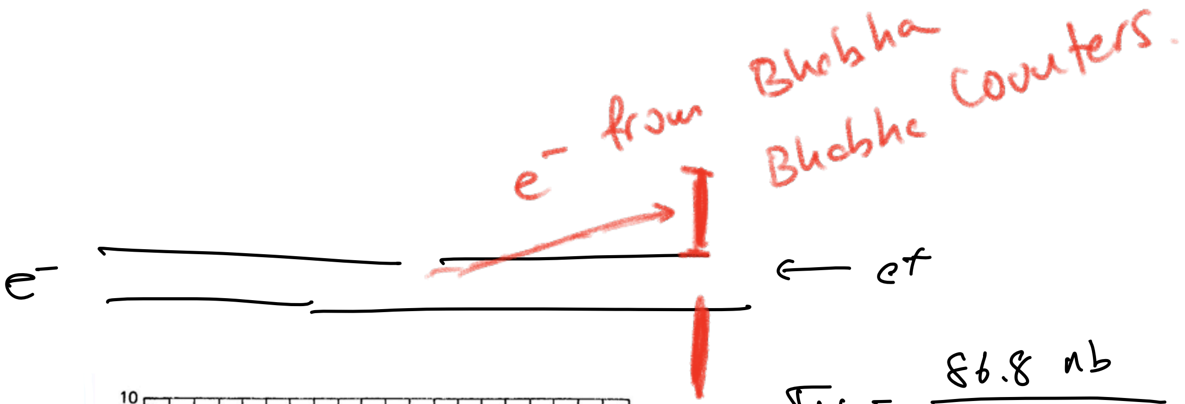
$e^\pm e^\pm \to \gamma\gamma$: $\frac{2\pi\alpha^2}{s}\frac{1+1}{\sin^2\theta} = \left(\frac{2\pi\alpha^2}{s}\right)\left(\frac{2}{\theta^2}\right)$;

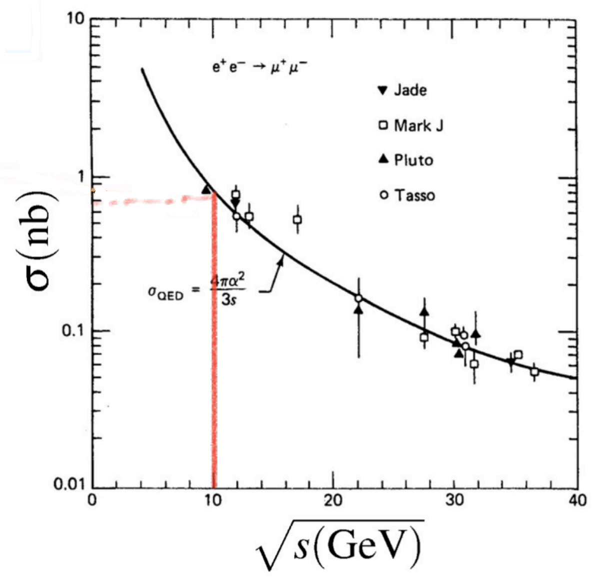
$e^+e^- \to e^+e^-$: $\frac{\pi\alpha^2}{2s}\left(\frac{3+1}{2\sin^2(\theta/2)}\right)^2 = \left(\frac{2\pi\alpha^2}{s}\right)\left(\frac{16}{\theta^4}\right)$;

$e^+e^- \to \mu^+\mu^-$: $\frac{\pi\alpha^2}{2s}(1+1) = \left(\frac{2\pi\alpha^2}{s}\right)\left(\frac{1}{2}\right)$.

from above expressions use $\sin\frac{\theta}{2} = \varepsilon$ and keep upto ε^4

Divergence of Bhabha for $\theta \to 0$.





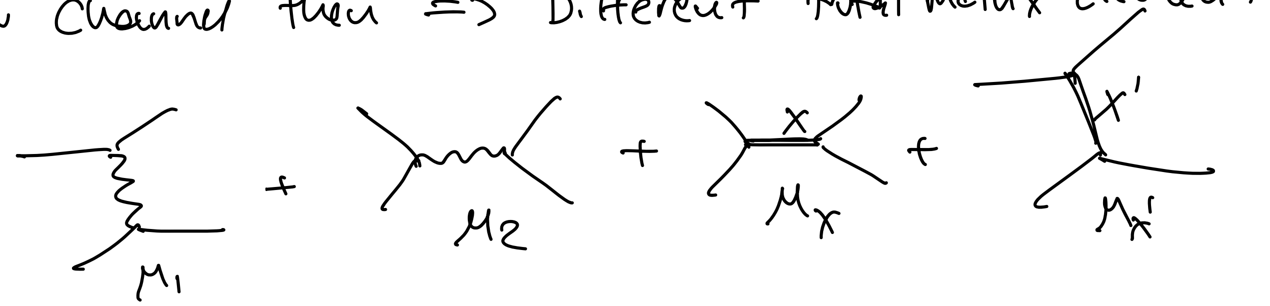
$$\sigma_{tot} = \frac{86.8 \text{ nb}}{s\,[\text{GeV}^2]}.$$

$s = 100$ GeV. $\Rightarrow \sqrt{s} = 10.$

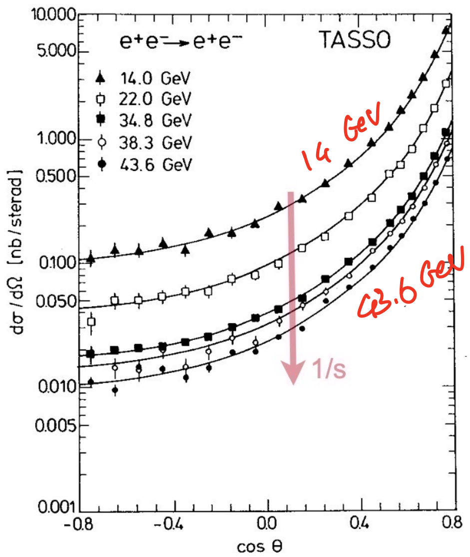
$\Rightarrow \sigma_{tot} = 0.87$ nb.

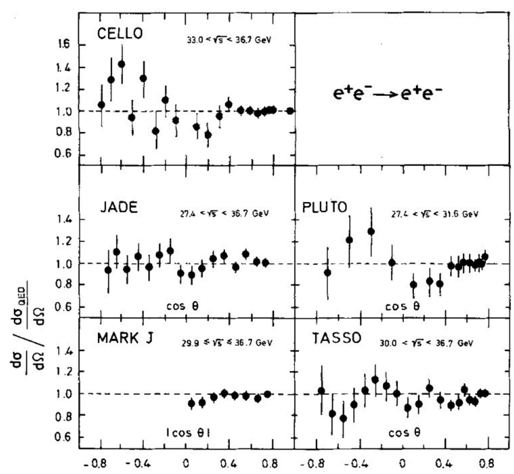
If a new channel then $\Rightarrow$ Different total matrix element

$\mathcal{M}_{tot} =$



$$|\mathcal{M}_{tot}|^2 \propto |\mathcal{M}_1|^2 + |\mathcal{M}_2|^2 + |\mathcal{M}_x|^2 + |\mathcal{M}_{x'}|^2 +$$
$$2\mathcal{M}_1\mathcal{M}_2 + 2\mathcal{M}_1\mathcal{M}_x + 2\mathcal{M}_1\mathcal{M}_{x'} - \cdots$$
$$+ \cdots$$



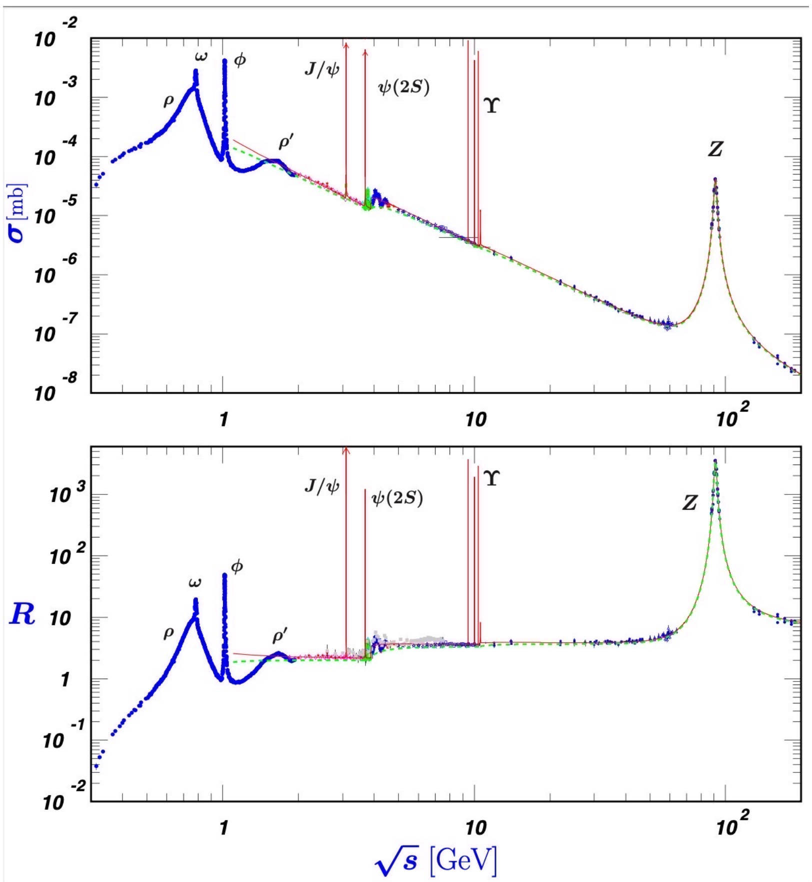


Ratio between measured cross section and QED calculation

$\sigma_{Bhabha} \propto \frac{1}{s}(\text{—})$

$$\text{Ratio} = \frac{\text{meas } \sigma}{\text{Th } \sigma}$$

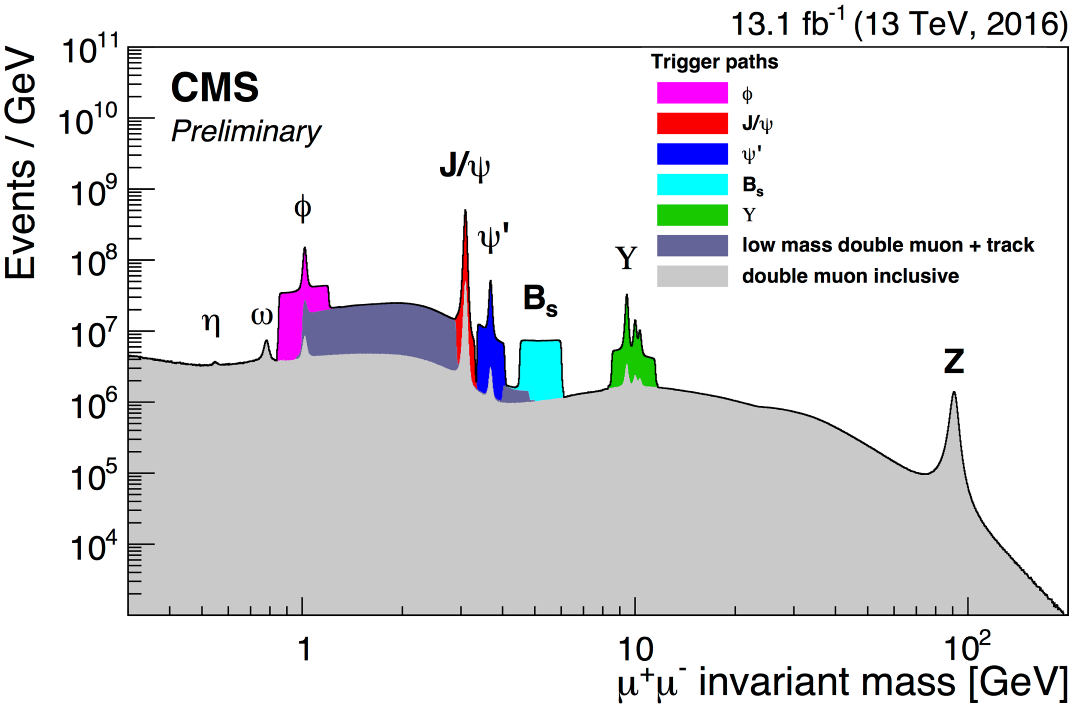
$\sim 1 \Rightarrow$ agreement between theory calculation and exp. meas.

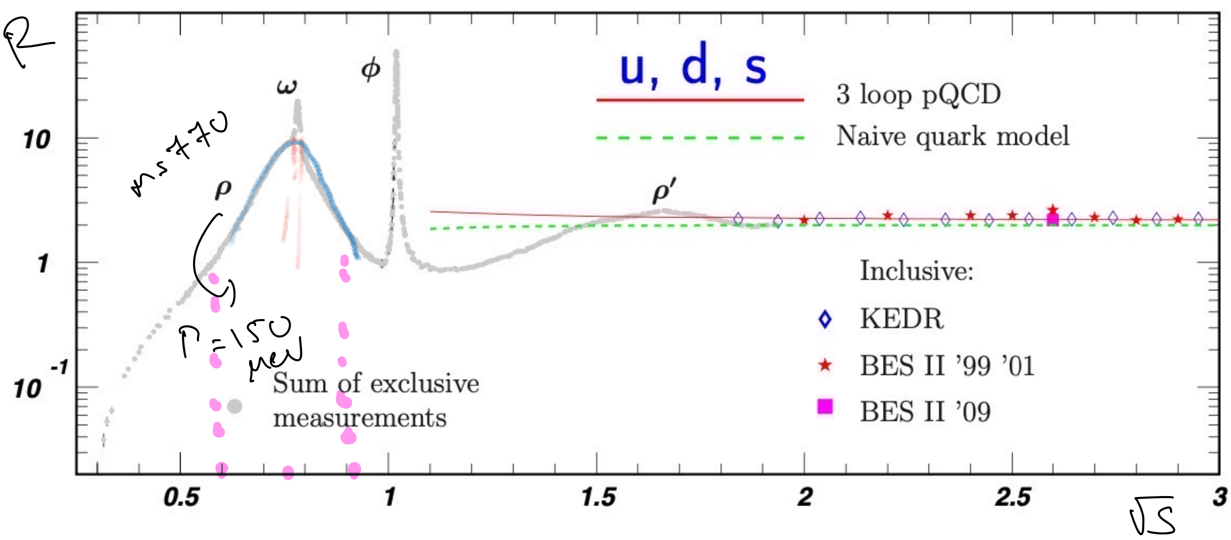


$$\sigma = \frac{86.8 \text{ nb}}{s\ [\text{GeV}^2]}$$

$$R = \frac{\sigma(e^+e^- \to had)}{\sigma(e^+e^- \to \mu^+\mu^-)}$$

$$= \sum_i Zq_i^2 N_c$$





$R = 2$ compatible with 3 flavours and $N_c = 3$

$\omega(782)$ $\Gamma = 8.7$ MeV   mass $= 782$ MeV.

$\rho(770)$ $\Gamma = 150$ MeV. ρ, ω $u\bar{u}, d\bar{d}$

$\sqrt{s} \simeq m_\rho - m_\omega$

$\phi(1020)$ $\Gamma = 4$ MeV $\phi \sim s\bar{s}$

$\rho' = \rho(1570)$ $\Gamma = 165$ MeV.