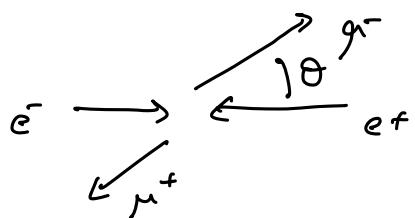


$$e^+ e^- \rightarrow \mu^+ \mu^-$$

$\bar{q} \bar{q}$ (hadrons)



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

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

$$\sigma(e^+ e^- \rightarrow q\bar{q}) = \sum_{\text{flavors.}} \delta(e^+ e^- \rightarrow \mu^+ \mu^-) \times Z_q^2 \times N_c$$

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

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

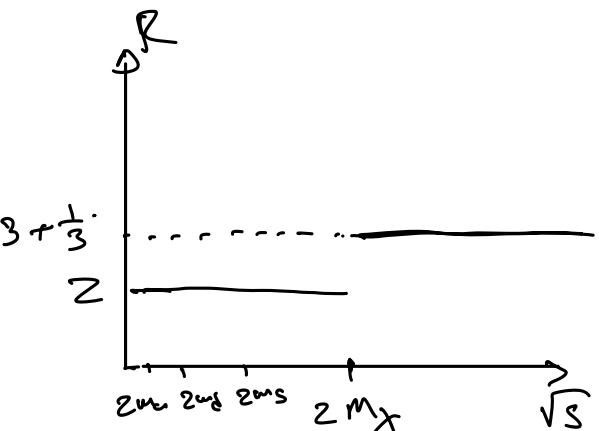
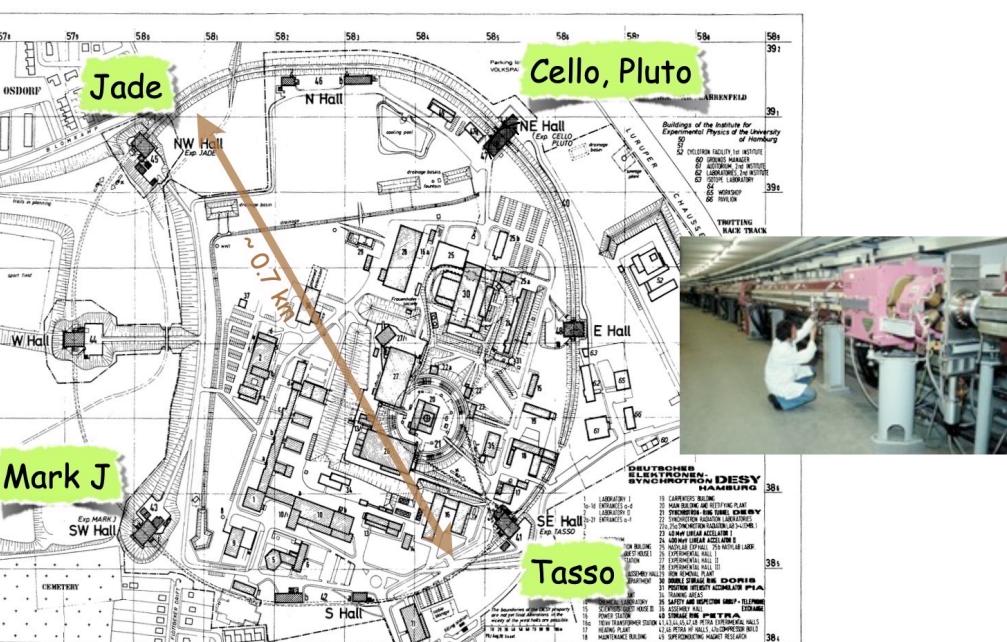
$$R = \frac{\sigma(e^+ e^- \rightarrow q\bar{q})}{\sigma(e^+ e^- \rightarrow \mu^+ \mu^-)} = \sum_i Z_q^2 N_c$$

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

$$\text{For } \sqrt{s} < 2m_X$$

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

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



PETRA @ DESY
near Hamburg

$12 \rightarrow 66.7 \text{ GeV}$
 \sqrt{s}

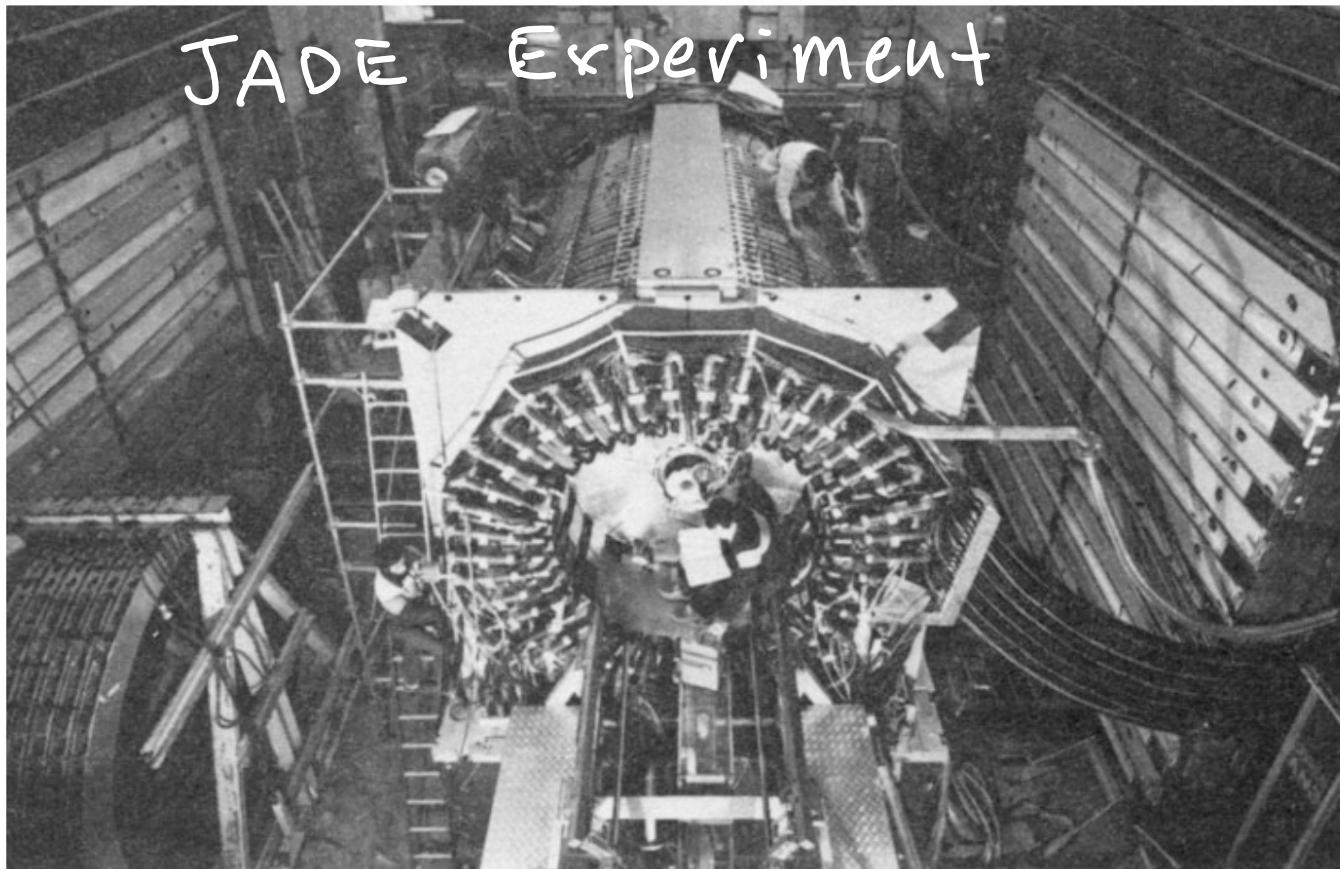
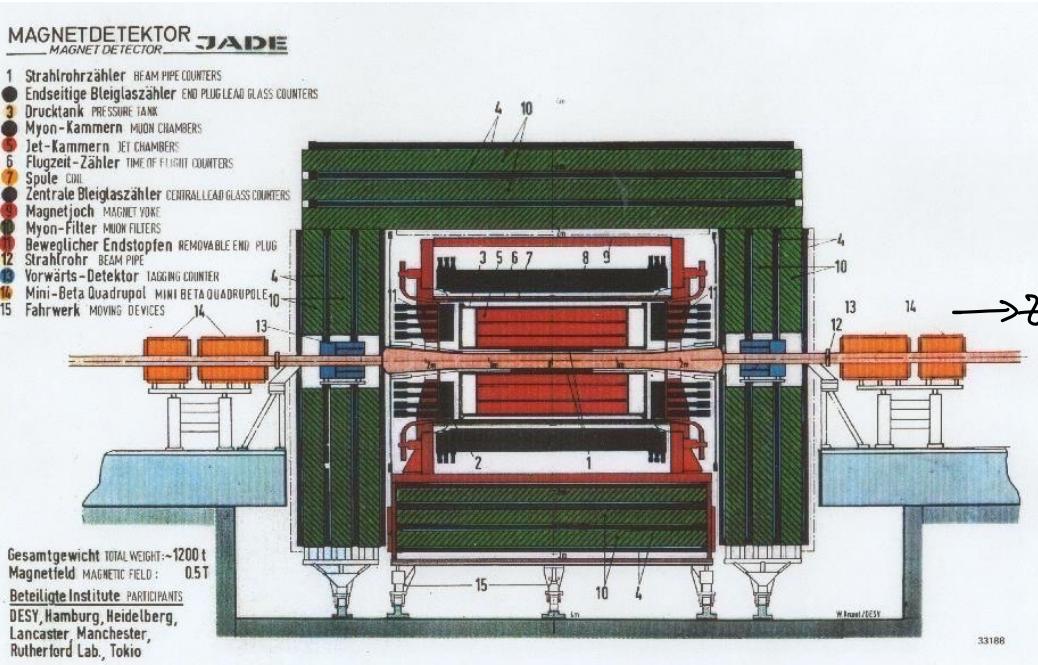
$1976 \rightarrow 1986$

MAGNETDETEKTOR JADE

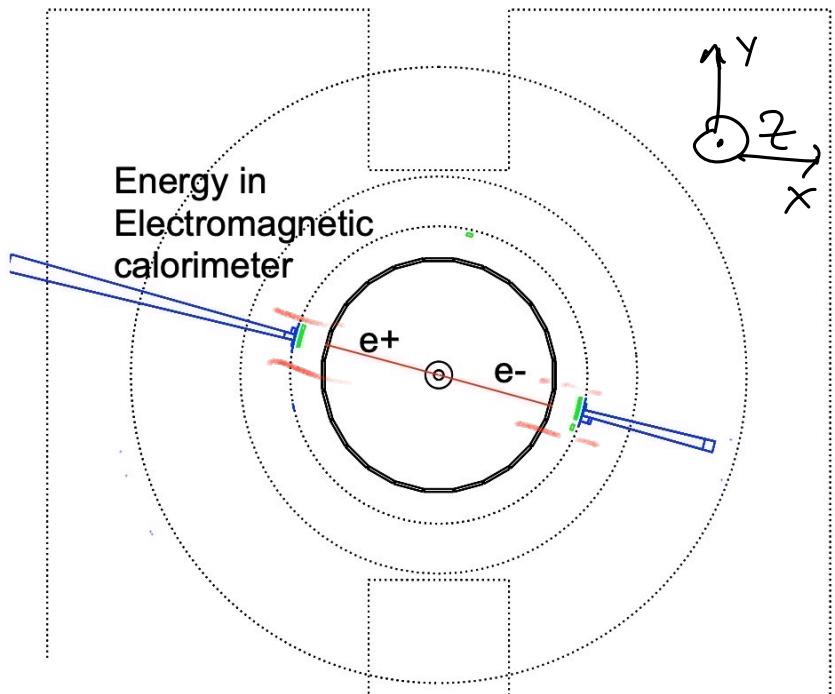
- 1 Strahlrohrzähler BEAM PIPE COUNTERS
- 2 Endseitige Bleiglaszähler END PLUG LEAD GLASS COUNTERS
- 3 Drucktank PRESSURE TANK
- 4 Myon-Kammern MUON CHAMBERS
- 5 Jet-Kammern JET CHAMBERS
- 6 Flugzeit-Zähler TIME OF FLIGHT COUNTERS
- 7 Spule COIL
- 8 Zentrale Bleiglaszähler CENTRAL LEAD GLASS COUNTERS
- 9 Magnetjoch MAGNET YOKE
- 10 Myon-Filter MUON FILTERS
- 11 Beweglicher Endstopfen REMOVABLE END PLUG
- 12 Strahlrohr BEAM PIPE
- 13 Vorwärts-Detektor TAGGING COUNTER
- 14 Mini-Beta Quadrupol MINI BETA QUADRUPOLE
- 15 Fahrwerk MOVING DEVICES

Gesamtgewicht TOTAL WEIGHT: ~1200 t
 Magnetfeld MAGNETIC FIELD: 0.5 T
 Beteiligte Institute PARTICIPANTS:
 DESY, Hamburg, Heidelberg,
 Lancaster, Manchester,
 Rutherford Lab, Tokio

JADE Defector
 Japan.
 Deutschland
 England

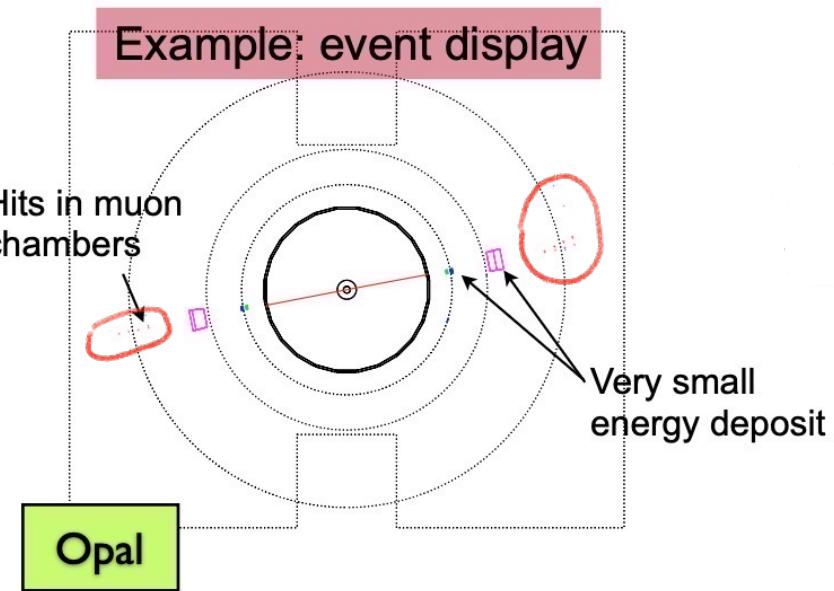


$$\begin{aligned}
 e^+ e^- &\rightarrow e^+ e^- \\
 &\quad \mu^+ \mu^- \\
 &\quad q\bar{q} (\text{hadrons})
 \end{aligned}$$

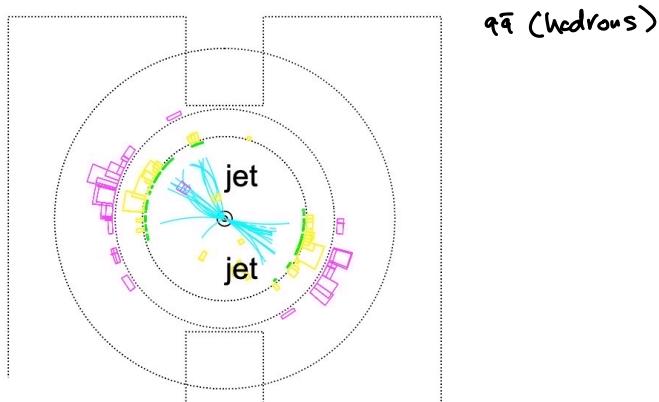
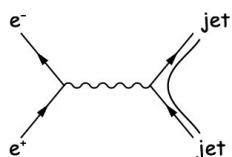


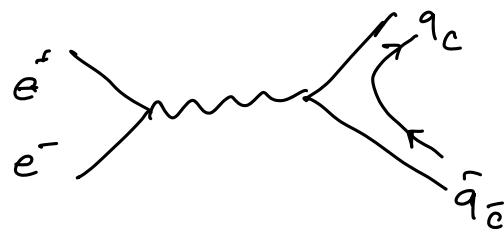
$e^+ e^-$:

2 charged tracks
+ 2 large energy deposits.



$\mu^+ \mu^-$
2 charged tracks.
small EM deposit +
Signal in muon
chambers

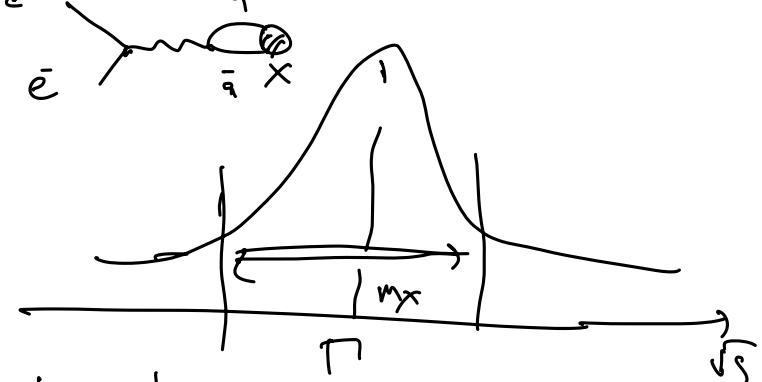




$q\bar{q}_c$ bound state with mass M_X

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

$$\Gamma(e^+e^- \rightarrow X \rightarrow f\bar{f})$$



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

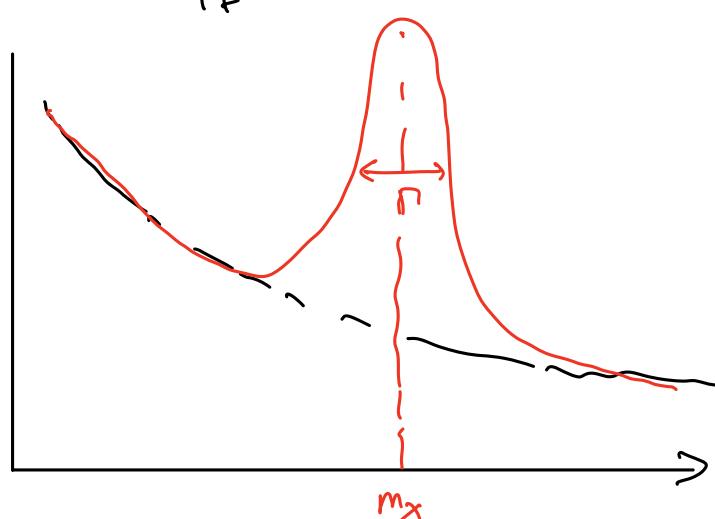
$$\Gamma(e^+e^- \rightarrow X \rightarrow f\bar{f}) = \frac{16\pi}{s} \frac{(2J+1)}{(2S_a+1)(2S_b+1)} \frac{\Gamma_{e^+e^-}}{\Gamma_{\text{tot}}} \frac{\Gamma_{f\bar{f}}}{\Gamma_{\text{tot}}} \frac{\Gamma_{\text{tot}}^2}{(m_X - \sqrt{s})^2 + \Gamma_{\text{tot}}^2/4}$$

J : angular momentum of X

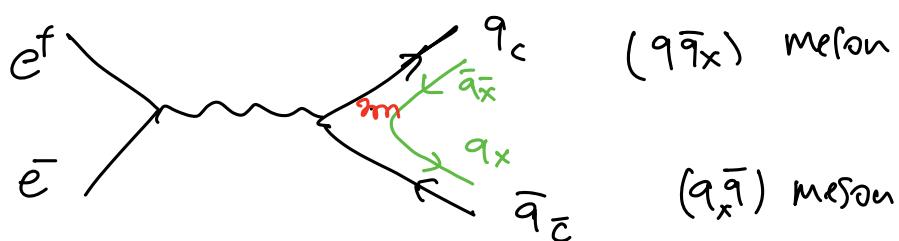
S_a, S_b : spin of incoming beams (in this case $S_a = S_b = 1/2$)

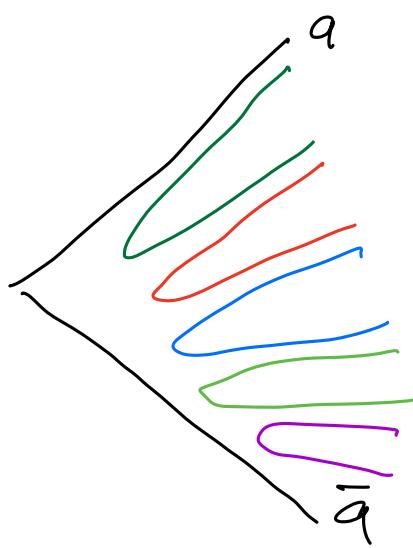
$X: \longrightarrow$	$f\bar{f}$	$\Gamma_{f\bar{f}}$	$m_X > 2m_e, 2m_f$
	e^+e^-	$\Gamma_{e^+e^-}$	
	$a\bar{b}$	$\Gamma_{a\bar{b}}$	
	\vdash		

$\Gamma_{\text{tot}} = \Gamma_{ee} + \Gamma_{f\bar{f}} + \Gamma_{a\bar{b} \text{ etc.}}$ all decays of X

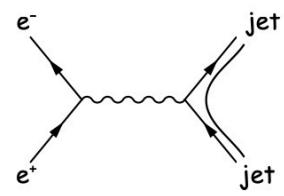


2nd case: $\sqrt{s} \neq m_X$ ($> m_X + \Gamma$, $< m_X - \Gamma$)





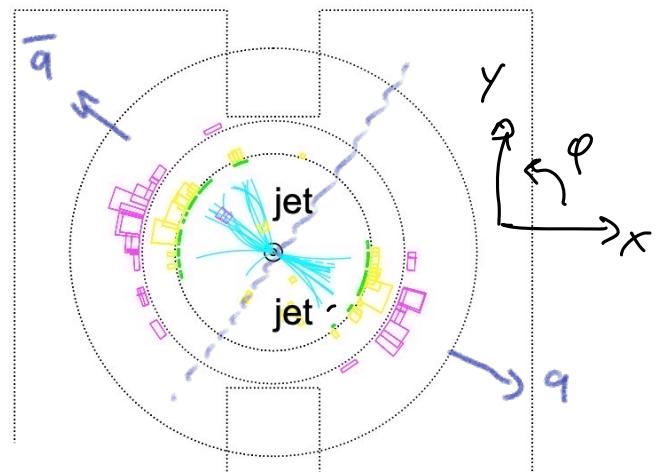
$e^+e^- \rightarrow N \text{ hadrons.}$



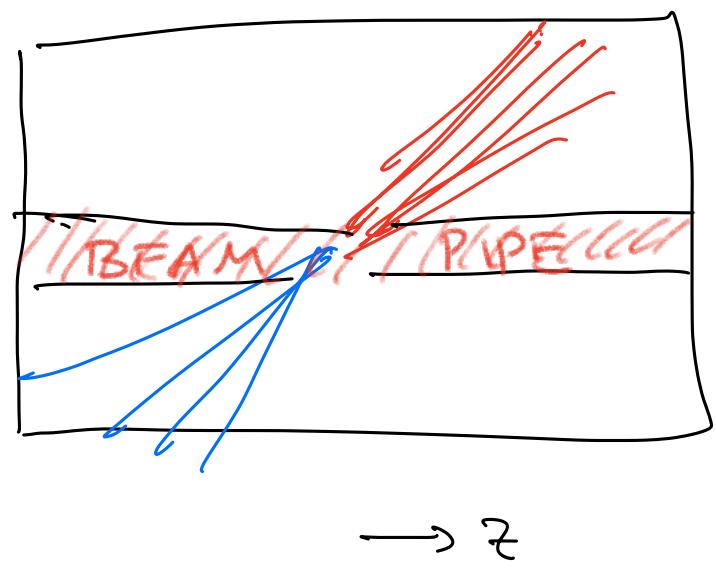
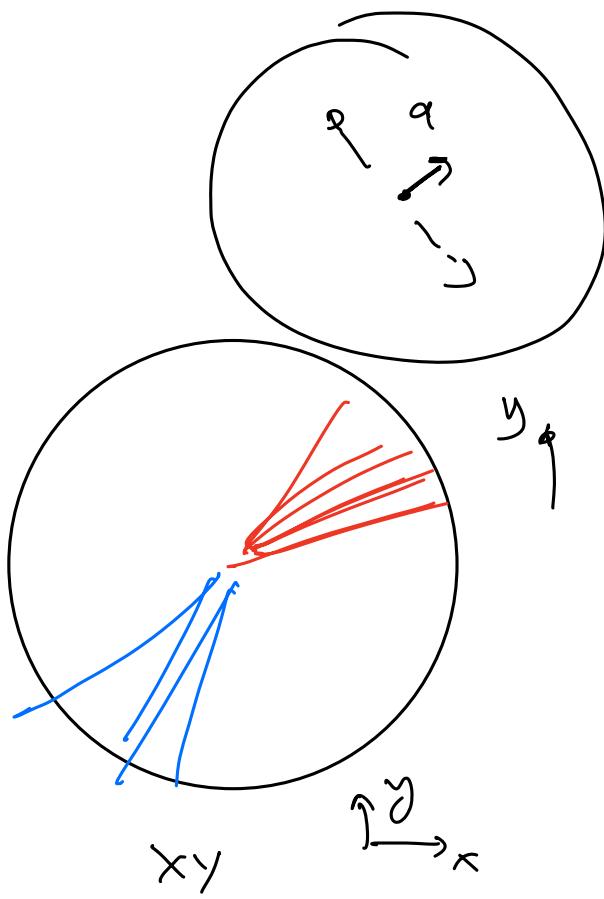
$$\sqrt{s} = m_X$$

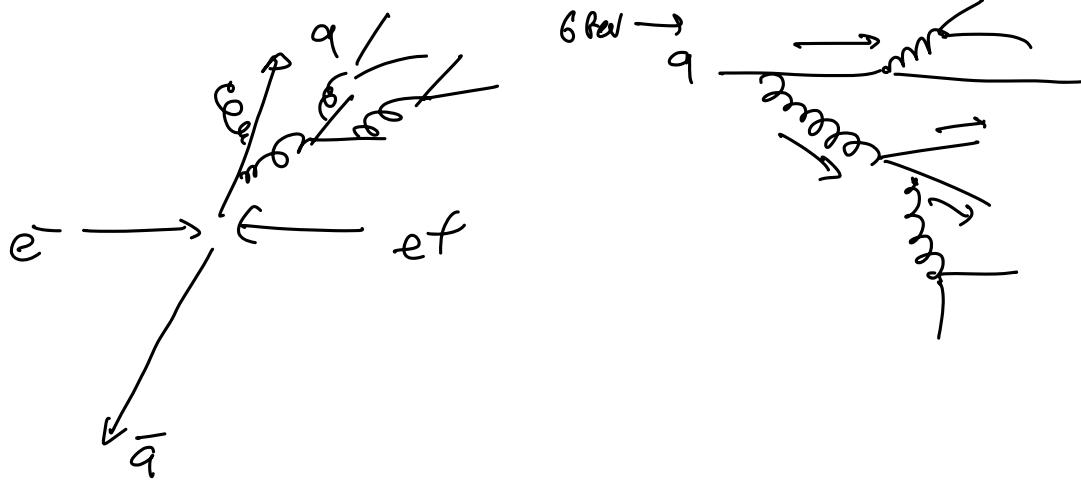
$e^+e^- \rightarrow q\bar{q}$ $\sigma_x: e^+e^- \rightarrow x.$

$\sigma_{N\ell}: e^+e^- \rightarrow j\ell\nu.$



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





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

$$\frac{\text{Nevents}}{\mu^+\mu^- \quad e^+e^- \quad \text{hadrons}} = \sigma_{\text{pt}} \cdot L_{\text{inst}} \cdot \Delta t$$

↗ time of measurements.
 ↗ parameter of the machine

$$N_{e^+e^-} = \sigma_1 \times L_{\text{inst}} \times \Delta t$$

$$N_{\mu^+\mu^-} = \sigma_2 \times L_{\text{inst}} \times \Delta t$$

$$N_{\text{had}} = \sigma_3 \times L_{\text{inst}} \times \Delta t$$

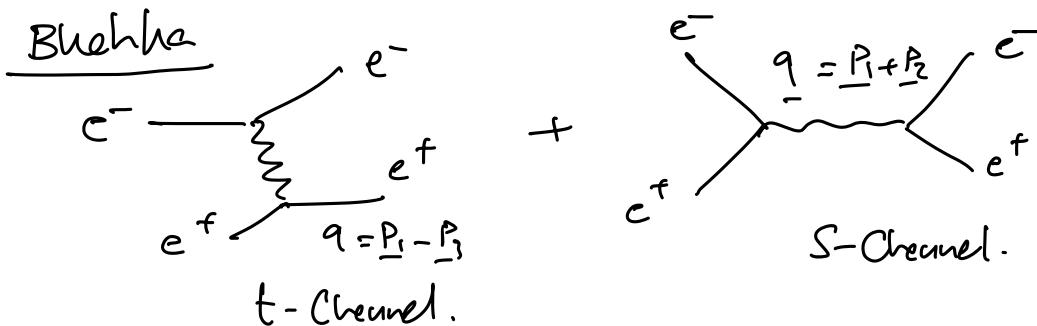
$$\Rightarrow L_{\text{inst}} = \frac{N_{e^+e^-}}{\sigma_1 \times \Delta t}$$

↙ comes from theory with high precision.

$$N_{\text{had}} = \sigma_3 \times \frac{N_{e^-}}{\sigma_1^{(\text{had})}} \quad \cancel{\text{OK}}$$

\Rightarrow measure σ_3

Knowledge of Bhabha cross section \Rightarrow measure $\sigma_{\text{inst.}}$



$$\sigma(e^+e^- \rightarrow e^+e^-) \propto |\mu_t^{e^+e^-} + \mu_s^{e^+e^-}|^2$$

$$= |\mu_t|^2_f |\mu_s|^2_f + \mu_t \mu_s^* + \mu_s \mu_t^*$$

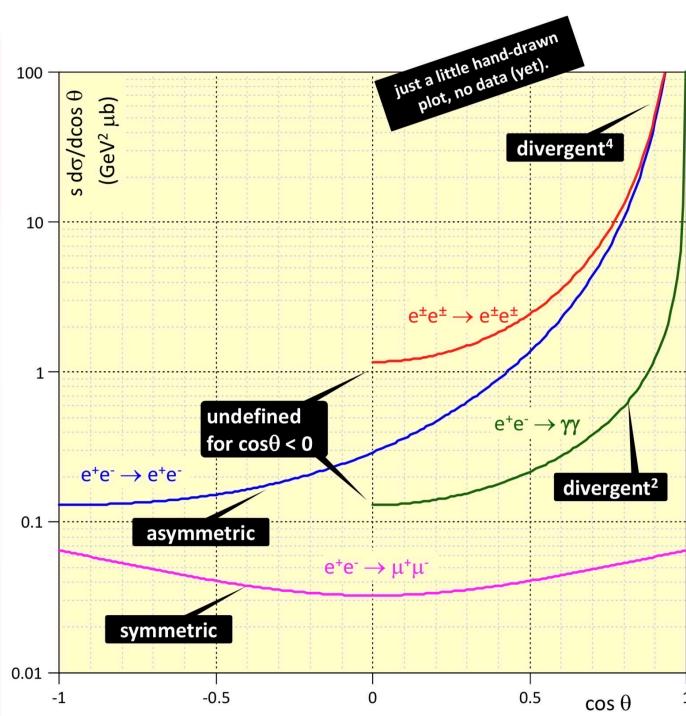
$$\frac{d\sigma}{d\cos\theta}(e^+e^- \rightarrow \gamma + \gamma) \propto (1 + \cos^2\theta)$$

$$\frac{d\sigma(e^\pm e^\pm \rightarrow e^\pm e^\pm)}{d\cos\theta} = \frac{2\pi\alpha^2}{s} \times \left(\frac{3 + \cos^2\theta}{1 - \cos^2\theta} \right)^2;$$

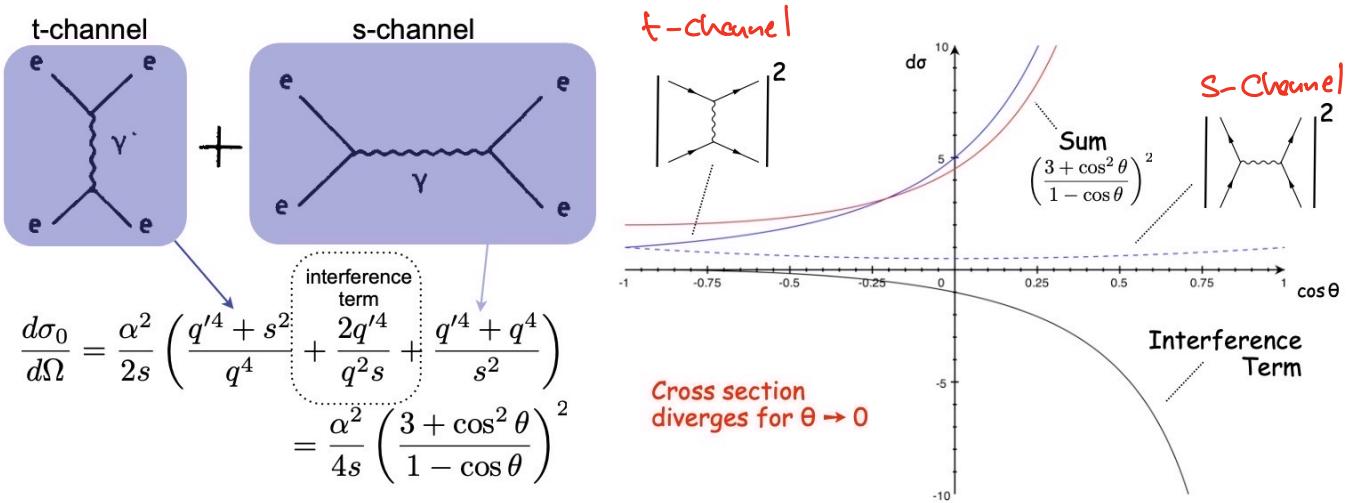
$$\frac{d\sigma(e^+e^- \rightarrow \gamma\gamma)}{d\cos\theta} = \frac{2\pi\alpha^2}{s} \times \frac{1 + \cos^2\theta}{1 - \cos^2\theta};$$

$$\frac{d\sigma(e^+e^- \rightarrow e^+e^-)}{d\cos\theta} = \frac{\pi\alpha^2}{2s} \times \left(\frac{3 + \cos^2\theta}{1 - \cos\theta} \right)^2;$$

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



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



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

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

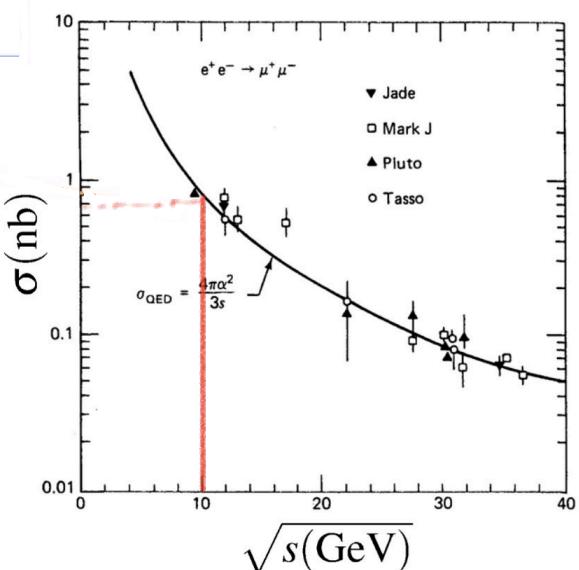
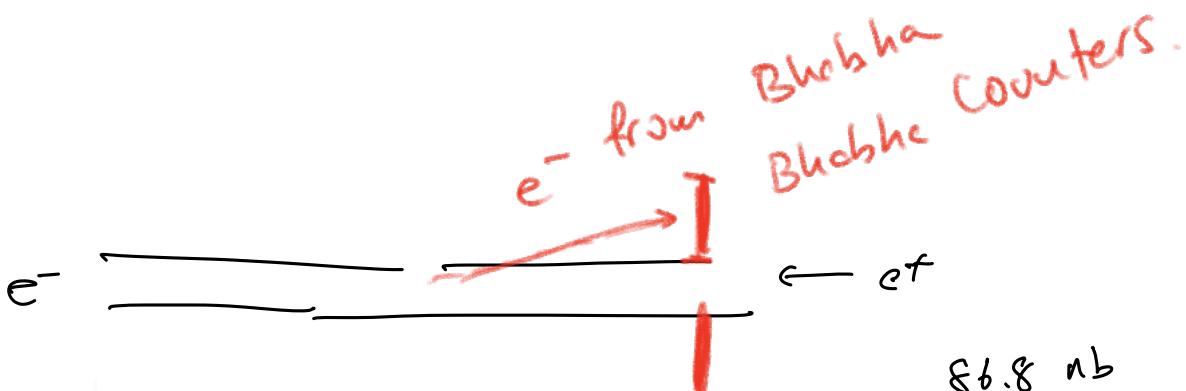
$$e^\pm e^\pm \rightarrow \gamma\gamma: \frac{2\pi\alpha^2}{s} \frac{1+1}{\sin^2 \theta} = \left(\frac{2\pi\alpha^2}{s} \right) \left(\frac{2}{\theta^2} \right);$$

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

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

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

Divergence of Bremsstrahlung
for $\theta \rightarrow 0$.



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

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

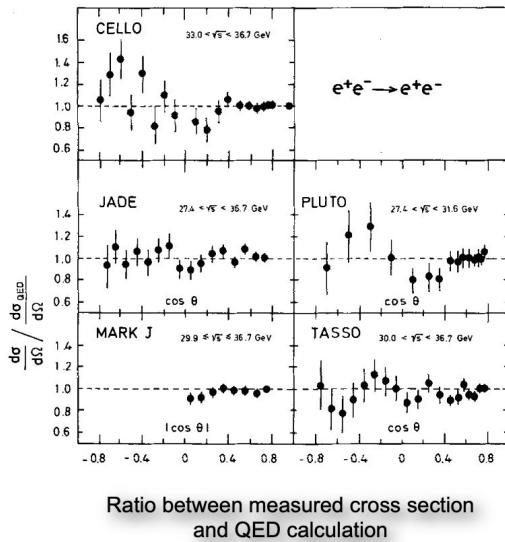
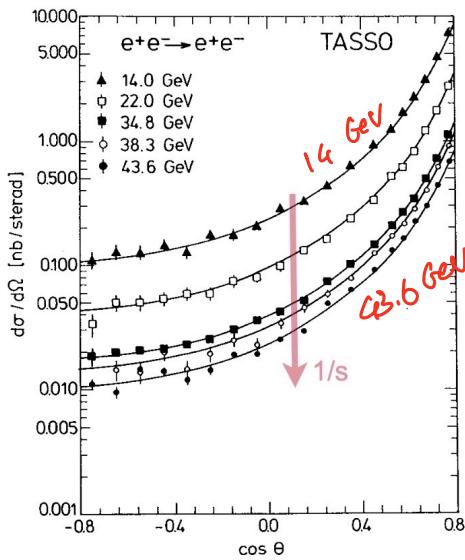
$$\Rightarrow \sigma_{tot} = 0.87 \text{ nb.}$$

If a new channel then \Rightarrow different total matrix element

$$M_{\text{tot}} = M_1 + M_2 + M_X + M_{X'}$$

$$|M_{\text{tot}}|^2 \propto (M_1^2 + M_2^2 + M_X^2 + |M_{X'}|^2 + 2M_1M_2 + 2M_1M_X + 2M_1M_{X'} -$$

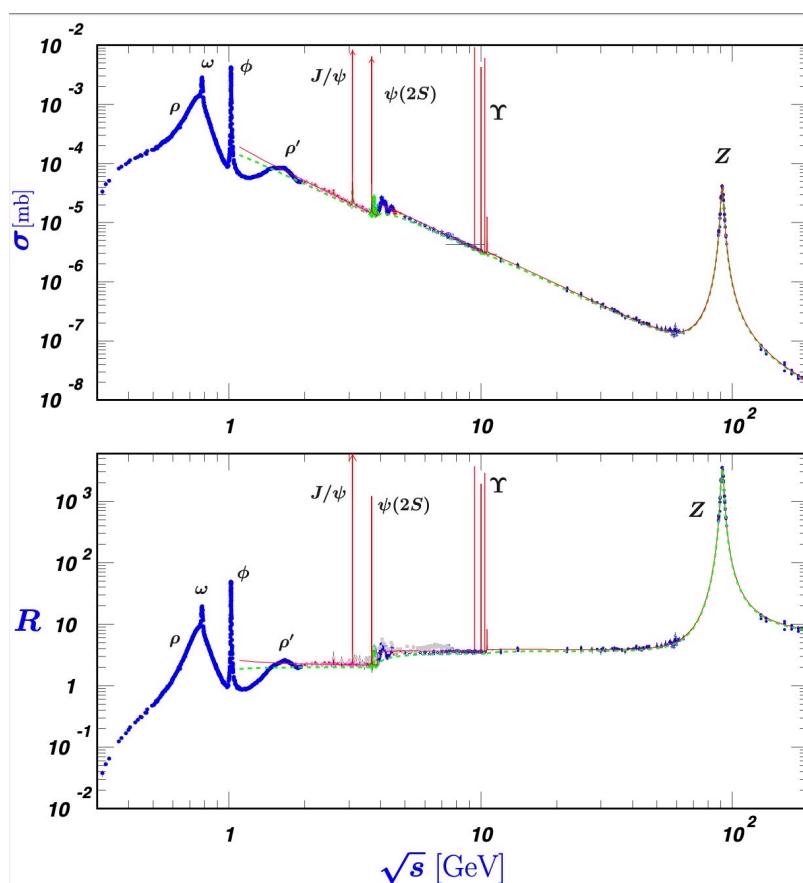
+ —



$$\sigma_{\text{Brems}} \propto \frac{1}{s} (-)$$

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

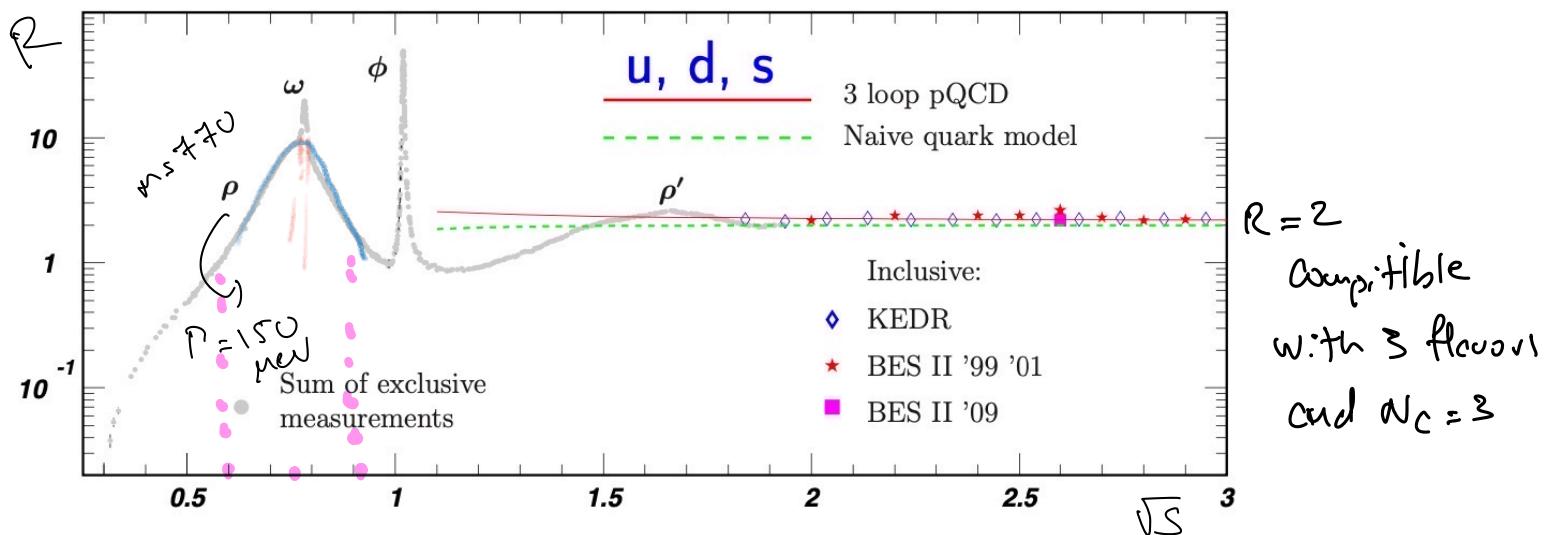
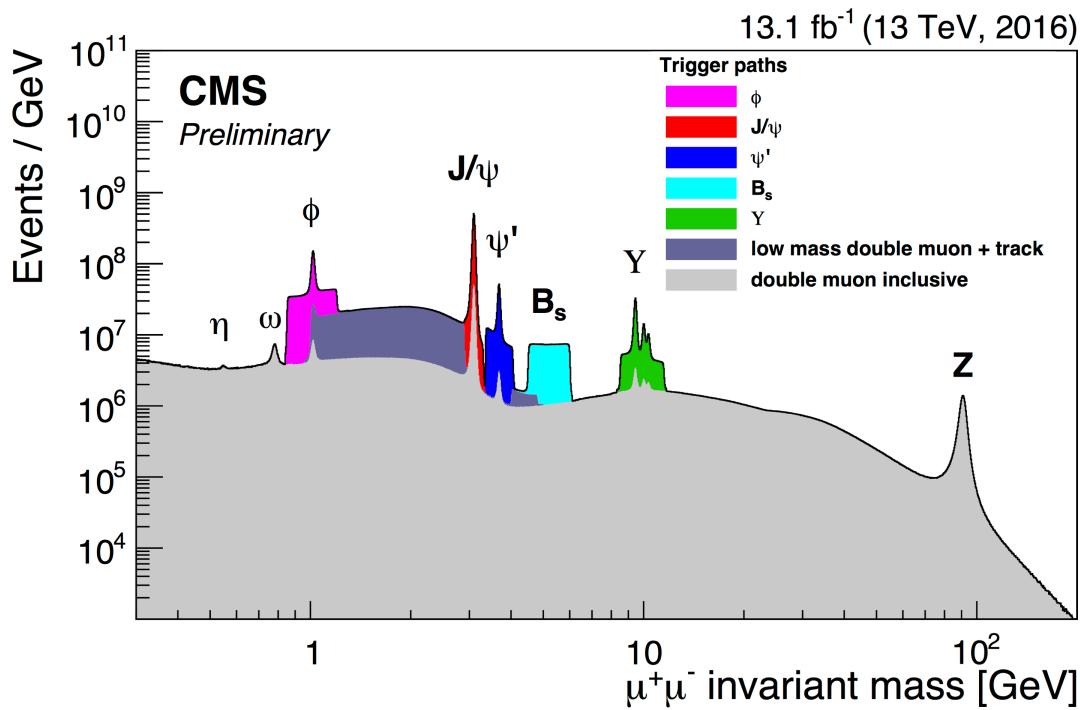
$\approx 1 \Rightarrow$ agreement
between theory
calculation
and exp. meas.



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

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

$$= \sum_i Z g_i^2 N_c$$



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

$\rho(770)$ $\Gamma = 150 \text{ MeV}$. $\rho_c \omega$ $u\bar{u}, d\bar{d}$

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

$\phi(1020)$ $\Gamma = 4 \text{ MeV}$ $\phi \approx S\bar{S}$

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