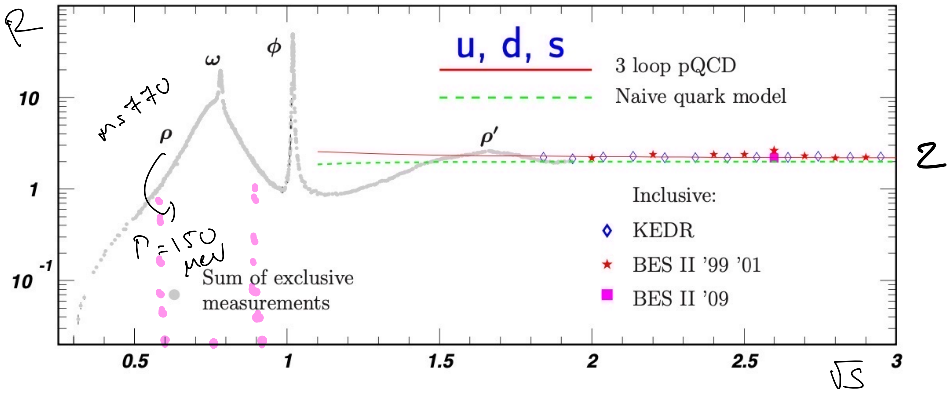
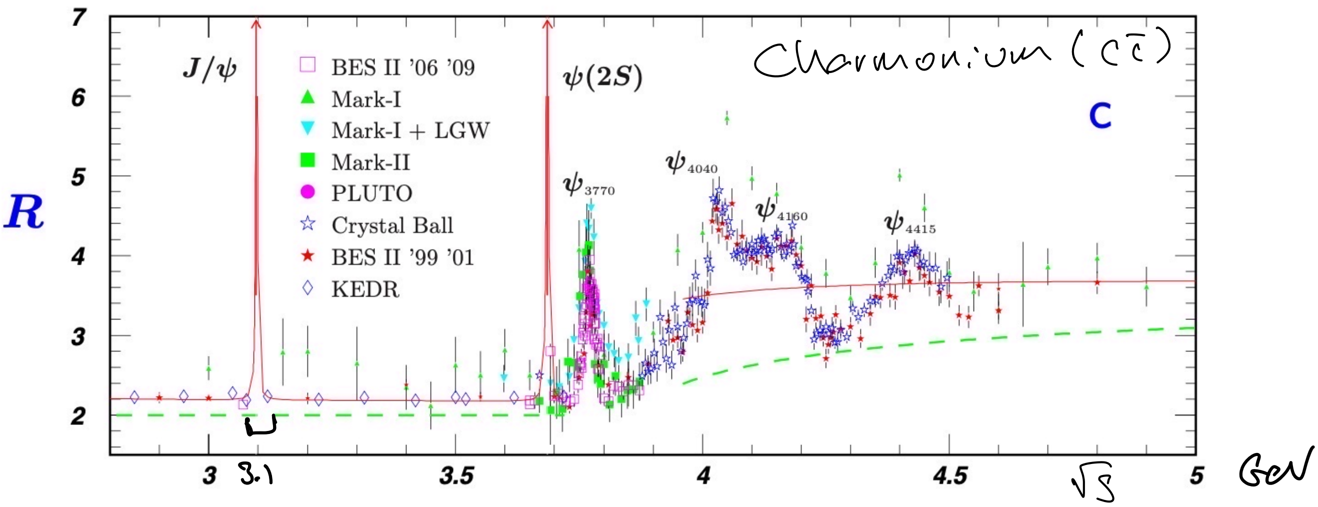


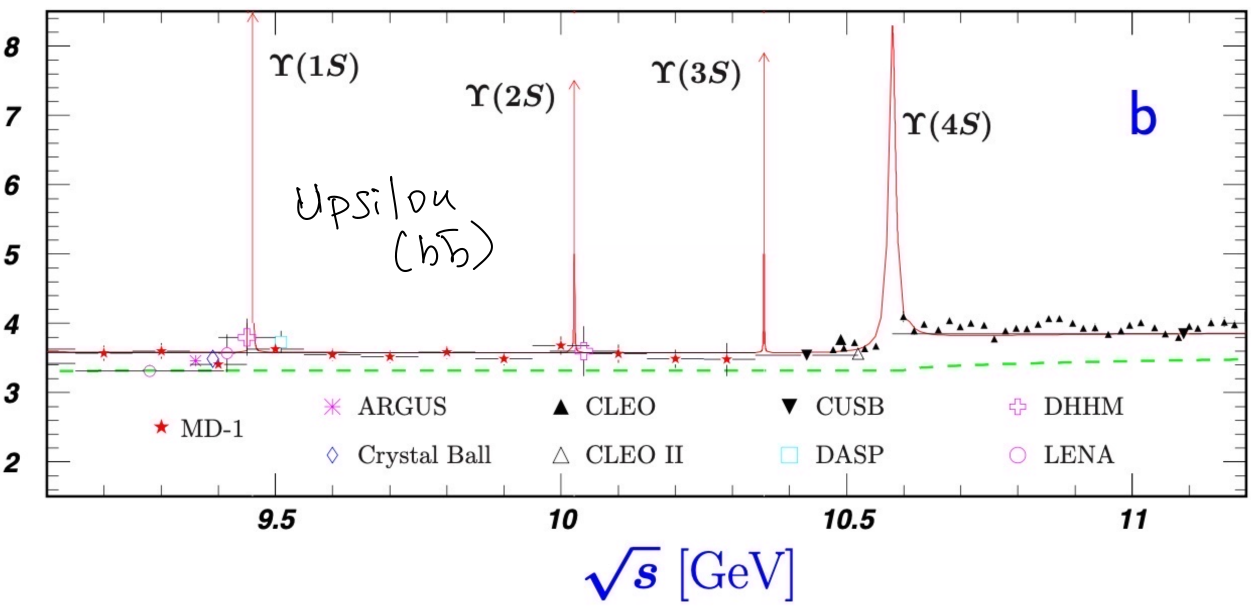
$2 \Rightarrow$ indirect indication of 3 quarks. and $N_c = 3$

resonances of u, d, s quarks.

$$R = R(\sqrt{s})$$



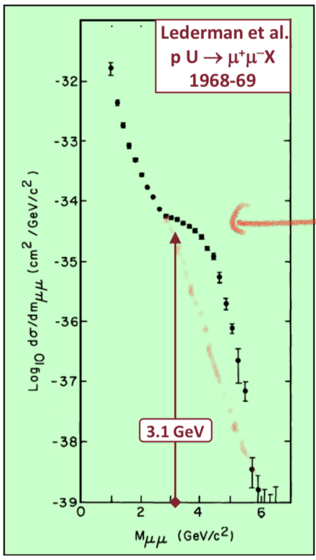
$$R = N_c \times \Sigma_i \, Z q_i^2$$



Between 5 → 9 GeV of $\sqrt{s}$ $\quad R = N_c \times \left[\underset{u}{\left(\frac{2}{3}\right)^2} + \underset{d}{\left(\frac{1}{3}\right)^2} + \underset{s}{\left(\frac{1}{3}\right)^2} + Z_c^2 \right]$

From measurement of $R \Rightarrow$ a 4^{th} quark with charge $Z = +\frac{2}{3}$

End of 1960's indication of c quark

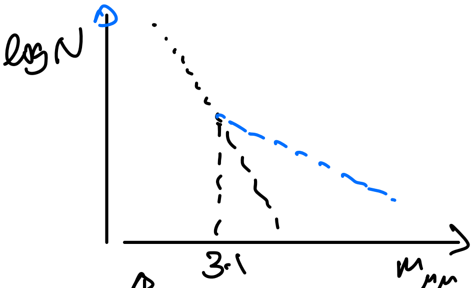


p + target → $(\mu^+\mu^-) + X$

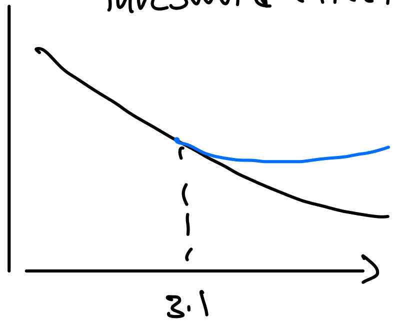
look at invariant mass of $\mu^+\mu^-$.

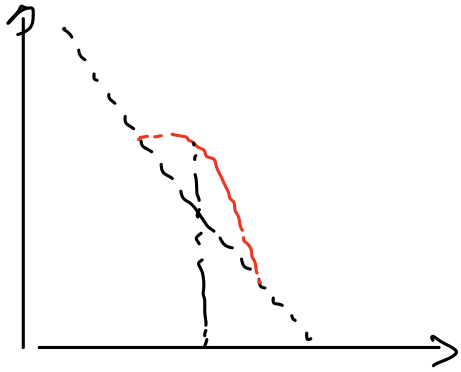
shoulder

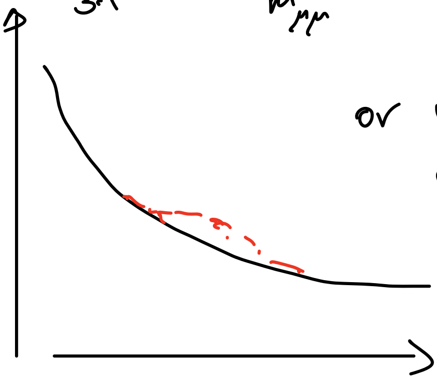
2 possibilities



Threshold effect







or wide peak on top of background

1970: GIM mechanism (Glashow - Iliopoulos - Maiani) in $K^0 \to \mu^+\mu^-$ (weak decay)

To Discover new quark ⇒ 2 ways.

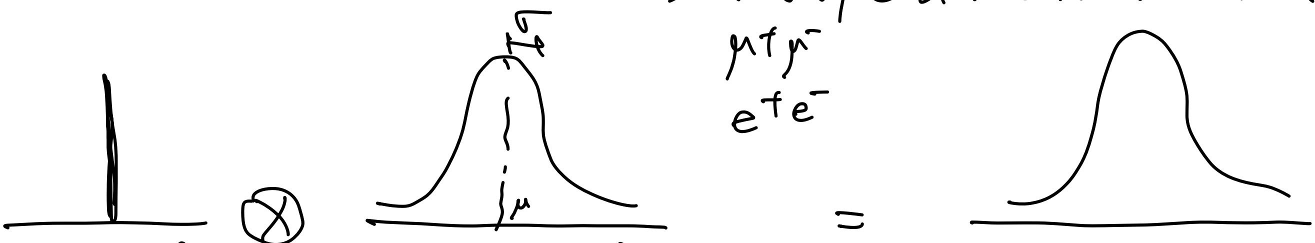
1) $e^+e^- \to x\bar{x}$

2) p + target → $(x\bar{x}) + Y$

↳ known / and measurable final states.

$\mu^+\mu^-$

e^+e^-



physics $\delta(x-x_0)$ ⊗ $G(x'-\mu,\sigma)$ = $G(x-x_0-\mu,\sigma)$

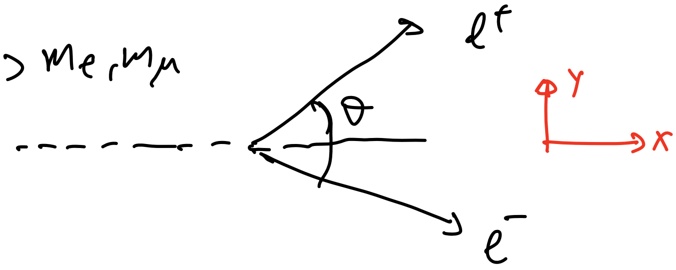
μ: offset or bias of detector

We want $\mu = 0$

Experimental quantity observed

Better resolution in e^+e^- or $\mu^+\mu^-$

$E_i >> m_e, m_\mu$



$\underline{p}^+ = (E^+, E^+\cos\frac{\theta}{2}, E^+\sin\frac{\theta}{2}, 0)$

$\underline{p}^- = E^-, E^-\cos\frac{\theta}{2}, -E^-\sin\frac{\theta}{2}, 0)$

$$m_{\ell\ell}^2 = (E^+ + E^-)^2 - (\vec{p}^+ + \vec{p}^-)^2 = 4E^+E^-\sin^2\frac{\theta}{2}$$

$$2\sin^2\frac{\theta}{2} = 1 - \cos\theta$$

$\sigma_m^2 = \sigma_E^2 \oplus \sigma_\theta^2$ Experimental resolution

Need both energy and angle for good m_{ee} peak.

$p + \text{target} \longrightarrow X + Y$ $\quad Y = p, \pi^+, \pi^-, \pi^0 - -$

$\hookrightarrow \mu^+\mu^-$

$m_\pi = 140$ MeV

$m_\mu = 106$ MeV

$p = 1$ GeV

$\Rightarrow E_{\pi,\mu} \simeq$ are the same.

Thick material to stop hadrons: cement, concrete, metal

hadronic interaction + ionization

decay length: $= \underbrace{\beta\gamma}c\tau$.

$$\beta\gamma = \frac{p}{m} = \frac{1\text{ GeV}}{100\text{ MeV}} = 10$$

$\tau = 10^{-6}$ s

$c = 3\times10^{8}$ m/s.

$\beta\gamma c\tau = 2\times10^{-5}\times 3\times10^{8}$ m

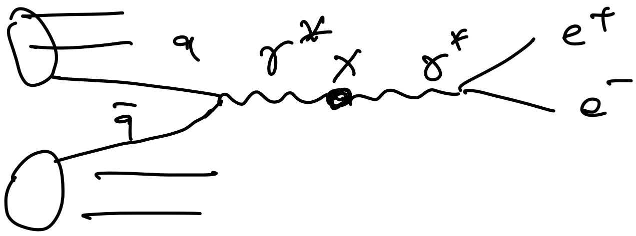
muons undergo muon scattering $\Rightarrow$ Bad angular resolution

$\Rightarrow$

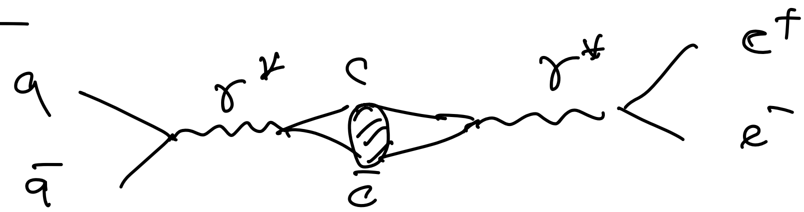
November Revolution 1974:

1) $p + Be \longrightarrow (e^+e^-) + X$

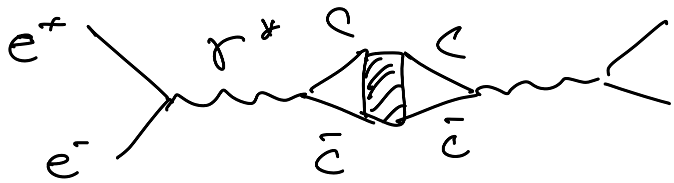
$\hookrightarrow$ Resonance. Sam Ting: Brookhaven Alternating Gradient Synch.



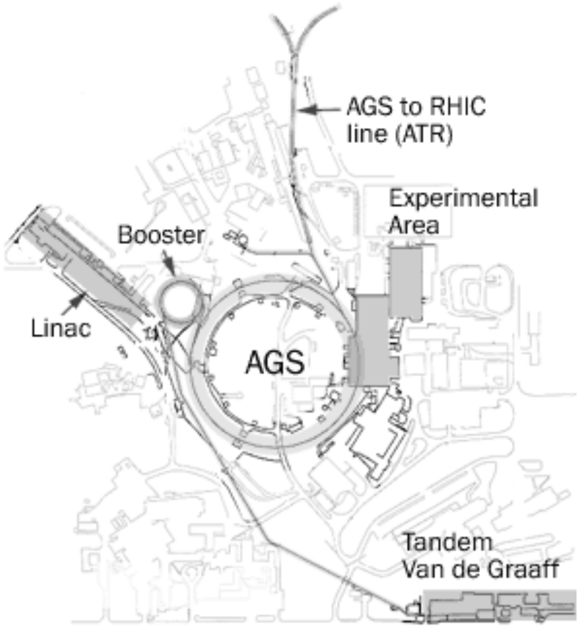
Burton Richter: SLAC.
SPEAR
Stanford
positron
electron
asym
ring

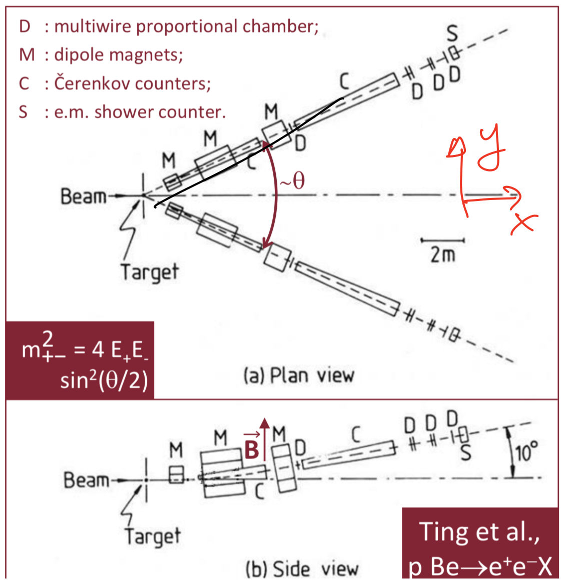


2) $e^+e^- \to J/\psi \to e^+e^-,\ \mu^+\mu^-,$ hadrons.

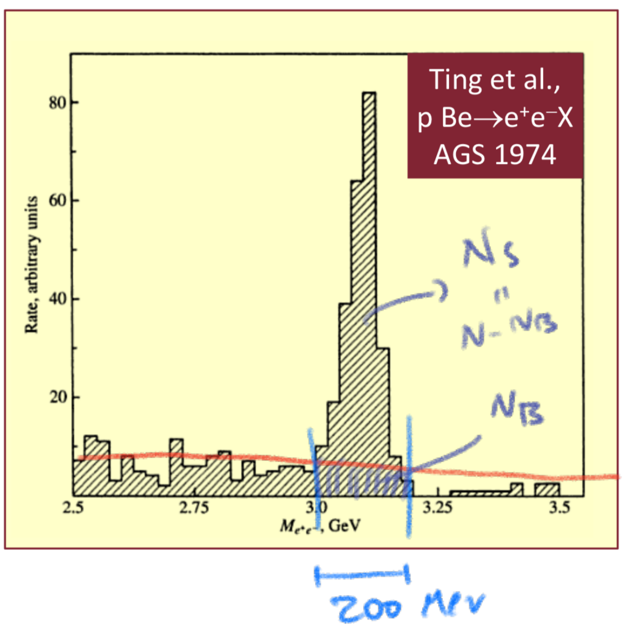


Brookhaven





$$m_{e^+e^-} = 4E^+E^- \sin^2\frac{\theta}{2}$$



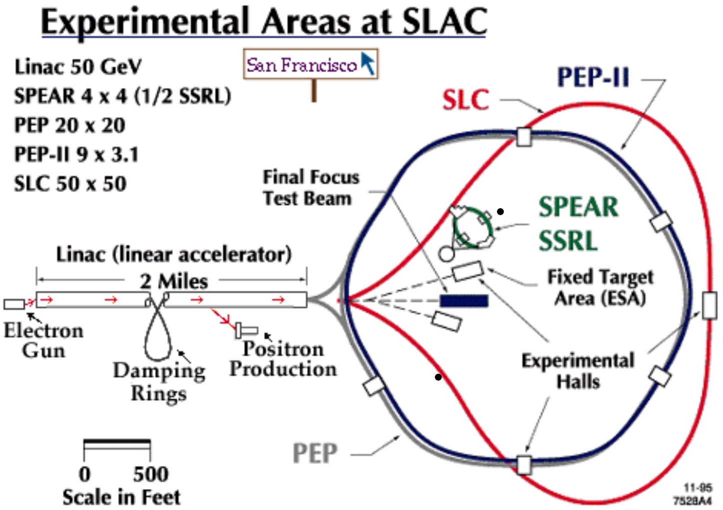
observed width dominated by experimental resolution.

$m \sim 3.1$ GeV

$\sigma_{Gauss} \simeq 30$ MeV

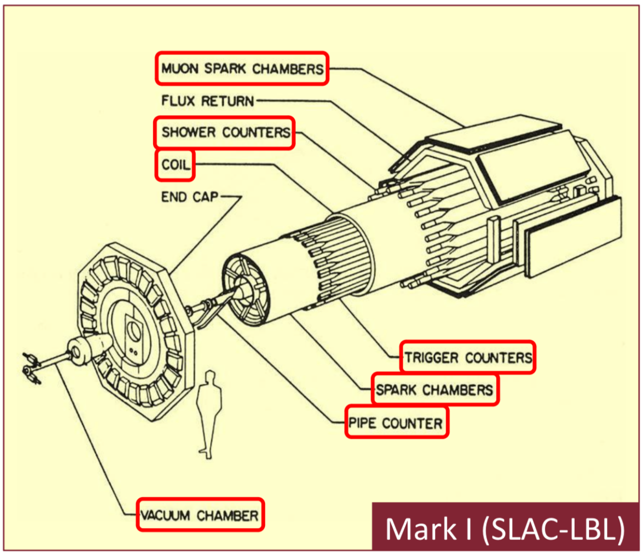
$$\frac{N_S}{\sqrt{N_B}} = \frac{N_{tot} - N_B}{\sqrt{N_B}}$$

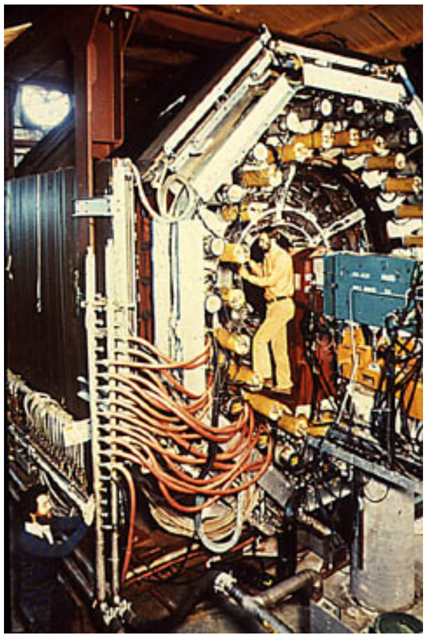
SLAC experiment



$e^+e^- \to e^+e^-, \mu^+\mu^-$, had.

$\sqrt{s}$: 2.5 → 7.5 GeV



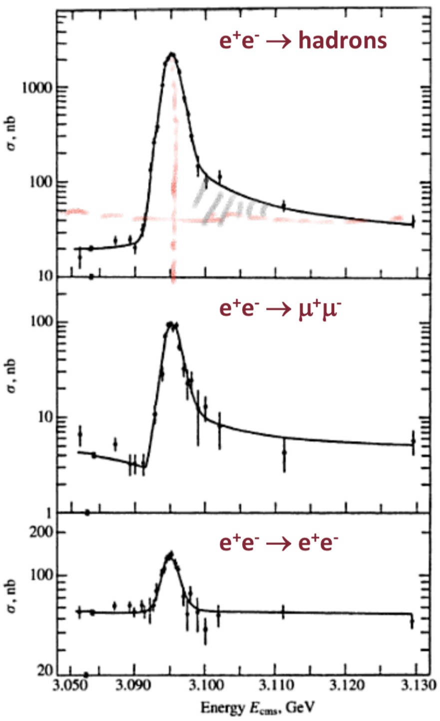


scan 2.5 → 7.5 in steps of 200 MeV

in 1974 Nov → 2.5 MeV steps

scan near 3.1 GeV

production cross section of a new resonance:



Tiny: decay of a new resonance.

why right shoulder > left shoulder

$\Gamma(e^+e^- \to X)$

$\sqrt{s} = \sqrt{s_0}$ nominal $\sqrt{s}$

$\sqrt{s_{eff}} \le \sqrt{s_{nom.}}$ because of Bremsstrahlung

$$\sigma(e^+e^- \to x) \propto \frac{16\pi}{s} \frac{2J+1}{(2S_a+1)(2S_b+1)} \frac{\Gamma_{ee}}{\Gamma_{tot}} \frac{\Gamma_{ff}}{\Gamma_{tot}} \frac{\Gamma_{tot}^2}{(x-x_0)^2 + \Gamma_{tot}^2/4}$$

$\sqrt{s}_{nom.} > m_X$ (right shoulder) $\qquad \sqrt{s}_{eff} = \sqrt{s}_{nom} - \Sigma$ ↳ Bremss.

properties of new resonance:

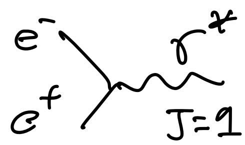
mass = 3.1 GeV $\qquad \Gamma_{tot} = 0.087$ MeV

hypothesis: $X = c\bar{c}$ bound state $\quad c$: is the new charm quark.

$e^+e^- \to \gamma^* \to X \to e^+e^-$

Ting: J $\qquad$ Richter: ψ $\qquad$ Today: J/ψ

$J_X^{PC} = 1^{--}$ same as photon.



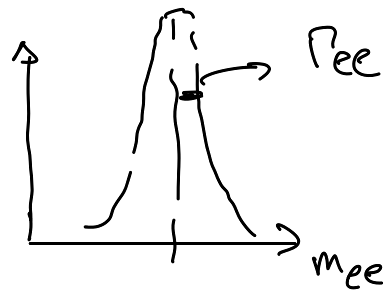
if X is ground state $\Rightarrow L=0$.

$J=1 \to S=1$

what is total width Γ?

p + Target $\to (X) + Y$
↳ e^+e^-

$\Rightarrow$ cannot determine Γ_{tot}



In e^+e^- experiment:

$$\sigma(e^+e^- \to \text{hadrons}) \propto \frac{\Gamma_{ee}}{\Gamma_{tot}} \frac{\Gamma_{had}}{\Gamma_{tot}}$$

$$\sigma(e^+e^- \to \mu^+\mu^-) \propto \frac{\Gamma_{ee}}{\Gamma_{tot}} \frac{\Gamma_{\mu\mu}}{\Gamma_{tot}}.$$

$$\sigma(e^+e^- \to e^+e^-) \propto \frac{\Gamma_{ee}^2}{\Gamma_{tot}^2}$$

4 unknowns: $\Gamma_{ee}, \Gamma_{\mu\mu}, \Gamma_{had}, \Gamma_{tot}$

3 observables: σ_{ee} $\sigma_{\mu\mu}$ σ_{had}. $\qquad \Rightarrow \Gamma_{tot} = 0.087$ MeV

1 constraint: $\Gamma_{tot} = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{had}$.

10 days later new resonance