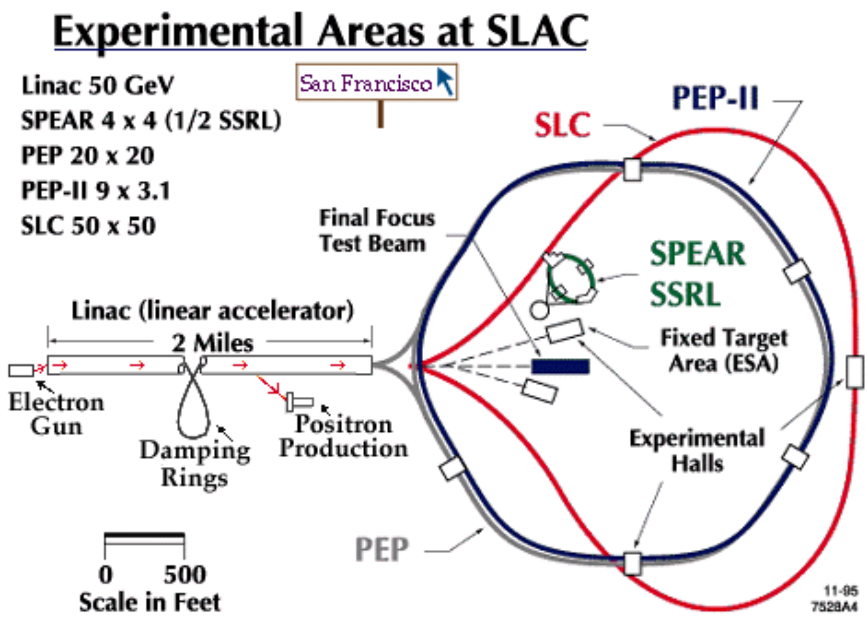
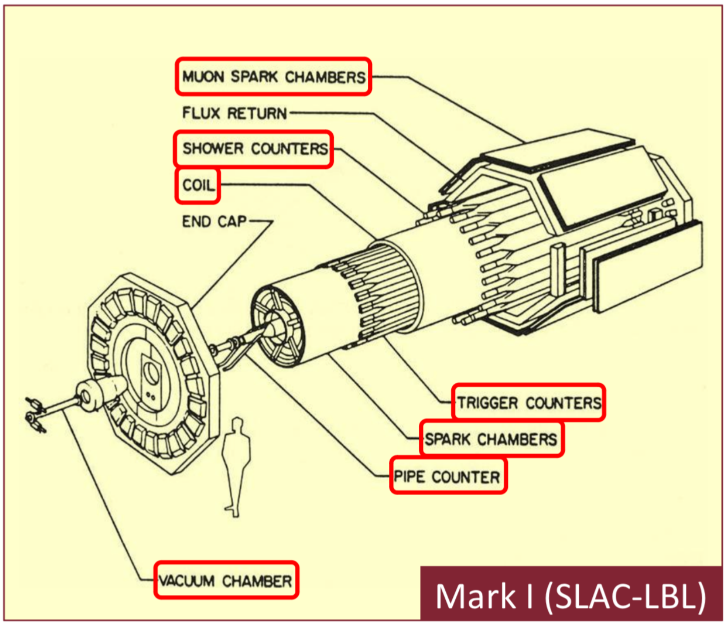
ψ @ SLAC by Richter

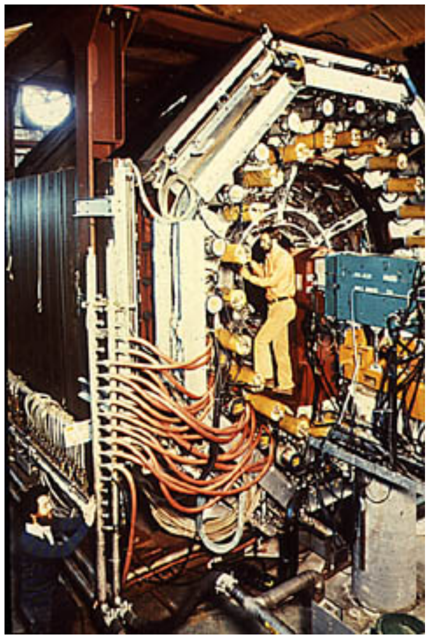
SPEAR

e^+e^- collider

$\sqrt{s}$: 2.5 → 7.5 GeV







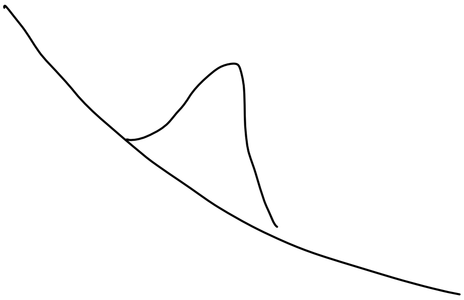
e^+e^- collisions scanning $\sqrt{s}$.

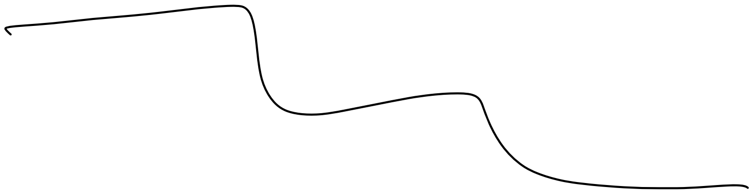
2.5 7.5 GeV

$N = \sigma \cdot \mathcal{L} \cdot \Delta t$

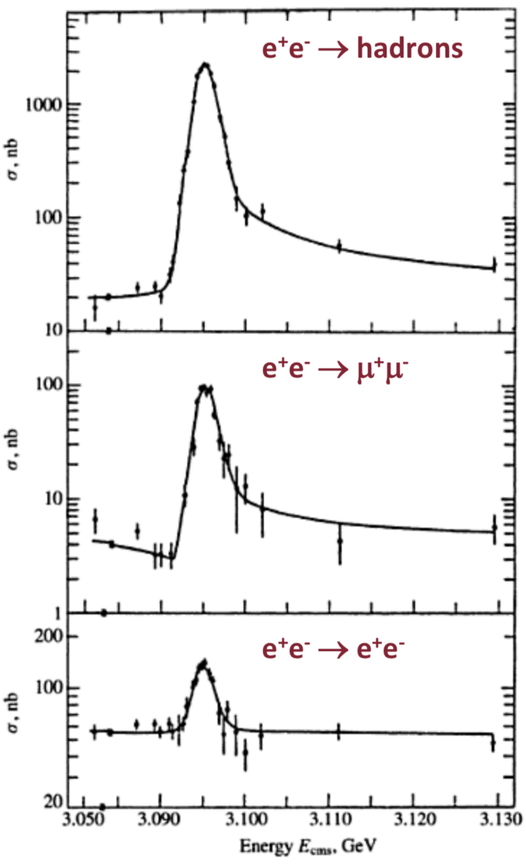
At the beginning steps of 200 MeV.

2.5 → 2.7 → 2.9 → 3.1 → 3.3. GeV $\sqrt{s}$





Nov. 1974 : 200 → 2.5 MeV steps. energy scans



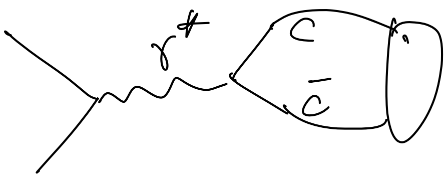
More hadrons > leptons.

$e^+e^- \to$ had. $\qquad e^+e^- \to \ell^+\ell^-$

Richter: ψ

$e^+e^- \to \gamma^* \to J/\psi \to \ell^+\ell^-$

$J^P = 1^-$



J/ψ

Hypothesis J/ψ bound state of $c\bar{c}$ $\qquad m = 3.1$ GeV

$q\bar{q}$ quarkonium $\qquad$ today 3097 MeV

$M_{c\bar{c}} = 2m_c - B \to m_c \simeq 1.5$ GeV

$$\sigma(ee \to J/\psi \to f\bar{f}) = \frac{(2J_R+1)}{(2\frac{1}{2}+1)(2\frac{1}{2}+1)} \frac{4\pi}{|\vec{p}_{in}|^2} \frac{\Gamma_{ee}}{\Gamma_{tot}} \frac{\Gamma_{f\bar{f}}}{\Gamma_{tot}} \frac{\Gamma_{tot}^2}{(\sqrt{s}-M_{R})^2+\Gamma_{tot}^2/4}.$$

$|\vec{p}_{in}| \simeq E$ $\qquad s = 4E^2$

$\frac{3}{4}$ $\qquad \frac{4\pi}{\frac{s}{4}} = \frac{16\pi}{s}$

$\frac{4\pi}{3} \; \frac{1}{s}$

$\Gamma_{ee} : \Gamma(J/\psi \to ee)$ $\qquad \Gamma_{f\bar{f}} : \Gamma(J/\psi \to f\bar{f})$ $\qquad f = \mu, q$

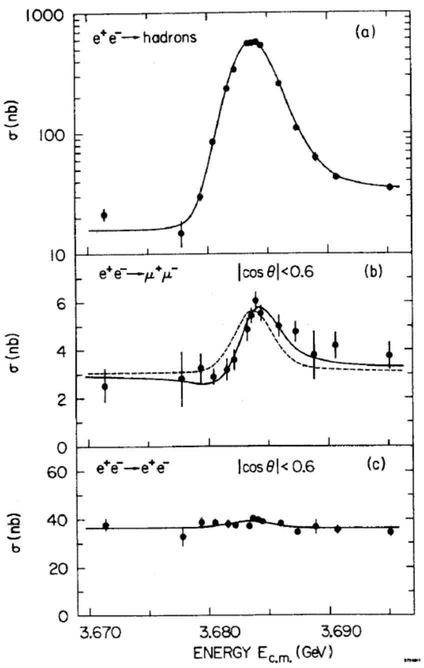
$\Gamma_{tot} = \Gamma_e + \Gamma_\mu + \Gamma_{had}$. assum.

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

Measurement: $\sigma_{ee}, \sigma_{\mu\mu}, \sigma_{had}$ and assume $\Gamma_{tot} = \Gamma_{ee}+\Gamma_{\mu\mu}+\Gamma_{had}$

$\Gamma_{tot} = 0.087$ MeV

10 days later: ψ'



Shoulder?

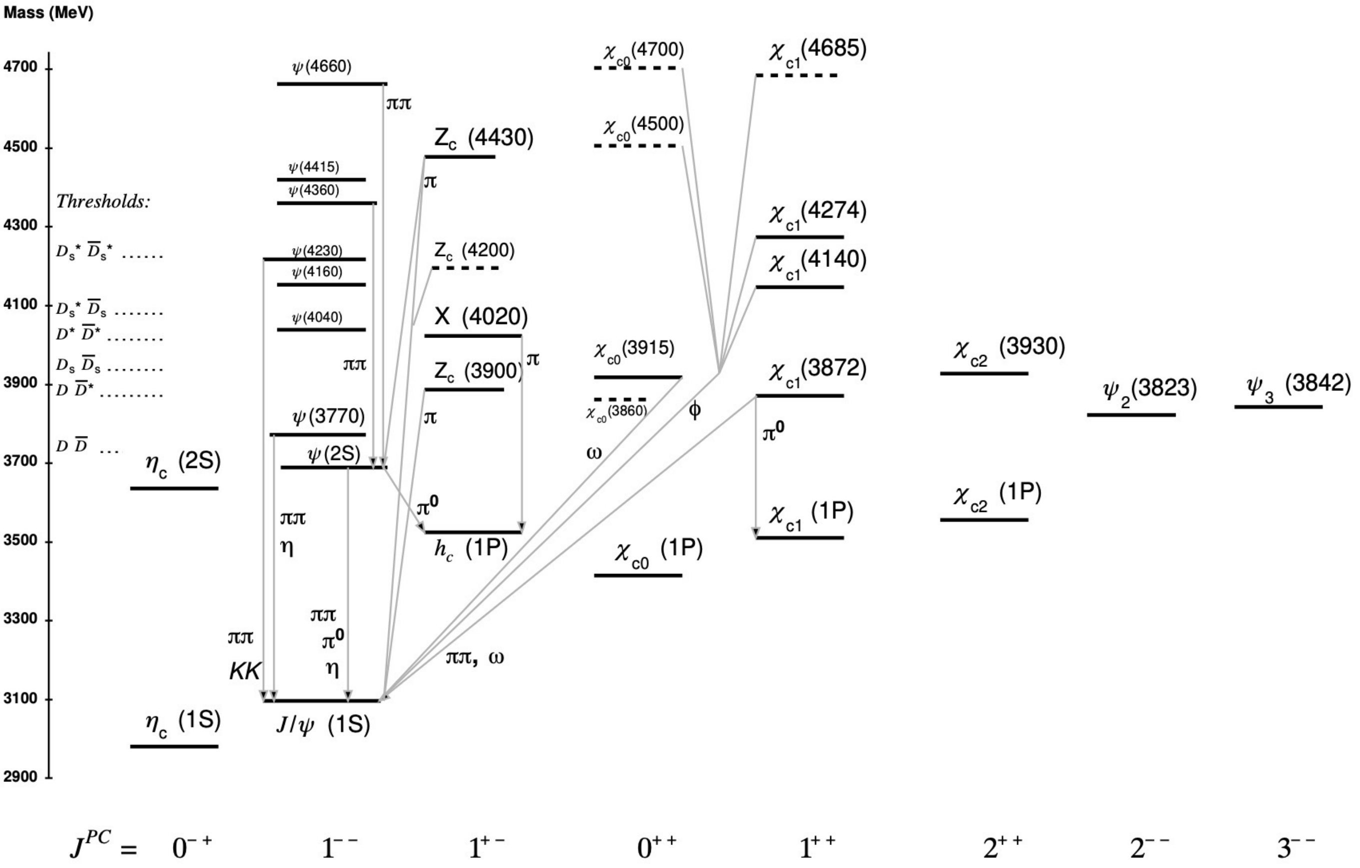
$e^+e^- = \sqrt{s_1}$

$e^+e^- = \sqrt{s_2} = \sqrt{s_1} + \varepsilon$

synch. rad. $\quad e^+e^- \to \sqrt{s_1}$

$J/\psi \qquad \psi(1S) \qquad$ of $c\bar{c}$ bound state.

$\psi' \qquad \psi(2S)$



$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + Kr$ $c \overset{r}{—} \bar{c}$

Charmonium $c\bar{c}$

Mesons $q_1\bar{q}_2$ $c\bar{q}$ $q = u, d, s.$

charmed mesons. (open charm)

1976: Discovery of $c\bar{d} = D^+$ $m \simeq 1.8$ GeV

J/ψ Γ 87 keV

$\psi(2S)$ 294 keV

$J/\psi(1S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(87.7 ± 0.5) %	
Γ_2	virtual $\gamma \to$ hadrons	(13.50 ± 0.30) %	
Γ_3	ggg	(64.1 ± 1.0) %	
Γ_4	γgg	(8.8 ± 1.1) %	
Γ_5	e^+e^-	(5.971 ± 0.032) %	
Γ_6	$e^+e^-\gamma$	[a] (8.8 ± 1.4) $\times 10^{-3}$	
Γ_7	$\mu^+\mu^-$	(5.961 ± 0.033) %	

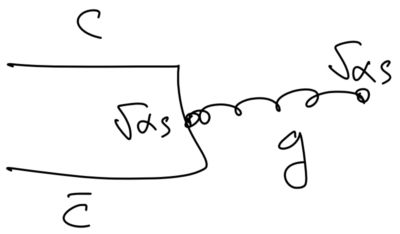
$\psi(2S)$ $J^P = 1^-$

$\psi(2S)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	hadrons	(97.85 ±0.13) %	
Γ_2	virtual $\gamma \to$ hadrons	(1.73 ±0.14) %	S=1.5
Γ_3	ggg	(10.6 ±1.6) %	
Γ_4	γgg	(1.03 ±0.29) %	
Γ_5	light hadrons	(15.4 ±1.5) %	
Γ_6	K_S^0 anything	(16.0 ±1.1) %	
Γ_7	e^+e^-	(7.93 ±0.17) $\times 10^{-3}$	
Γ_8	$\mu^+\mu^-$	(8.0 ±0.6) $\times 10^{-3}$	
Γ_9	$\tau^+\tau^-$	(3.1 ±0.4) $\times 10^{-3}$	
	Decays into $J/\psi(1S)$ and anything		
Γ_{10}	$J/\psi(1S)$ anything	(61.4 ±0.6) %	
Γ_{11}	$J/\psi(1S)$ neutrals	(25.38 ±0.32) %	
Γ_{12}	$J/\psi(1S)\pi^+\pi^-$	(34.68 ±0.30) %	
Γ_{13}	$J/\psi(1S)\pi^0\pi^0$	(18.24 ±0.31) %	
Γ_{14}	$J/\psi(1S)\eta$	(3.37 ±0.05) %	
Γ_{15}	$J/\psi(1S)\pi^0$	(1.268±0.032) $\times 10^{-3}$	

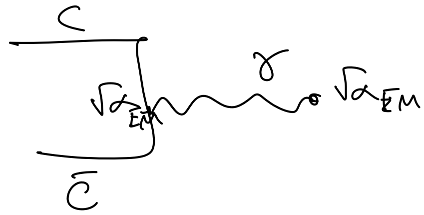
$\Gamma_{decay} \propto |M|^2 \rho(E_f)$

If strong interaction kinem. possible $\Rightarrow$ hadronic decay dominates.



$M \sim \alpha_s$

$\alpha_s \simeq 0.1$



$M \sim \alpha_{EM} \sim \frac{1}{137}$

Charmonium Decay

$Q\bar{Q}$ $\quad Q = c, s \quad q = u, d$

mesons $\quad q_1\bar{q}_2 \quad Q\bar{q}$

$Q\bar{Q} \longrightarrow Q\bar{q} \quad \bar{Q}q$

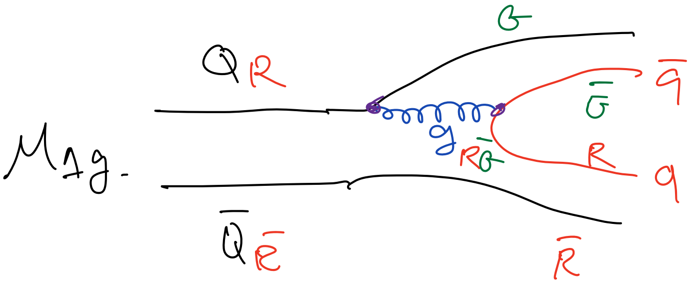
$\phi = (s\bar{s})$

$s\bar{s} \longrightarrow s\bar{u} \quad \bar{s}u \quad K^- K^+$

$\qquad\qquad \bar{d} \quad d \quad \bar{K}^0 K^0$

$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.1 ± 0.5) %	S=1.3
Γ_2	$K_L^0 K_S^0$	(33.9 ± 0.4) %	S=1.2
Γ_3	$\rho\pi + \pi^+\pi^-\pi^0$	(15.4 ± 0.4) %	S=1.2
Γ_4	$\rho\pi$		
Γ_5	$\pi^+\pi^-\pi^0$		
Γ_6	$\eta\gamma$	(1.301 ± 0.025) %	S=1.2
Γ_7	$\pi^0\gamma$	$(1.32 \pm 0.05) \times 10^{-3}$	
Γ_8	$\ell^+\ell^-$	—	



QED $\quad \bar{u}\gamma^\mu u$

$Q^a \quad \lambda^{ab} \quad Q^b$

Gluons: $3 \times \bar{3} = 1 + 8$

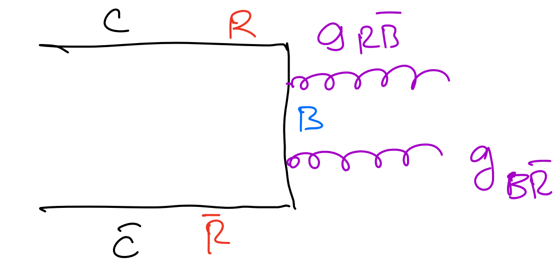
$R\bar{B}, R\bar{G}, B\bar{R}, B\bar{G}, G\bar{R}, G\bar{B} + - -$

$c\bar{c} \longrightarrow c\bar{u} \quad \bar{c}u \quad D^0 \quad \bar{D}^0$

$\qquad\qquad \bar{d} \quad d \quad D^+ \quad D^-$

$M \quad 3.1 \qquad 1.8 \quad 1.8 \qquad Q = m_{J/\psi} - 2m_D < 0$

$J/\psi \to D\bar{D}$ Not kinematically possible



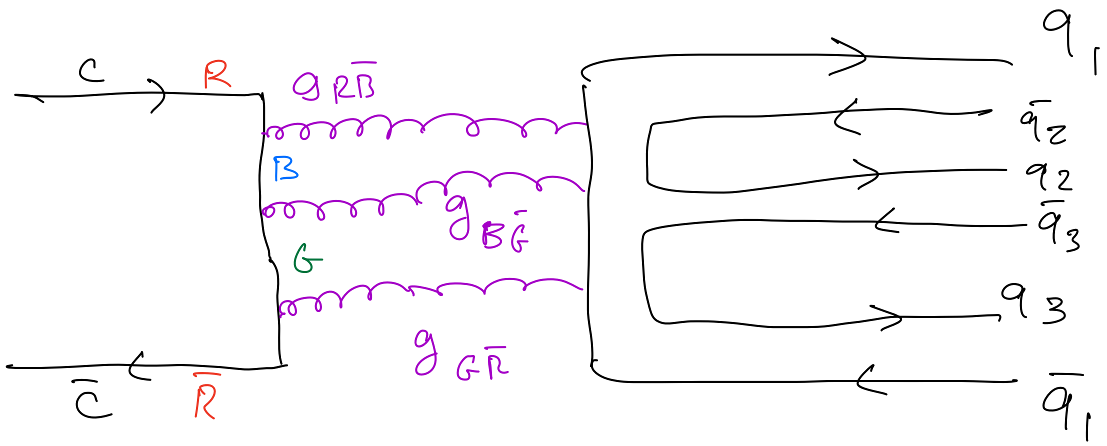
$\mathbb{C}$ parity.

C_g Final state gg.

$\mathbb{C}_f = (C_g)^2 = +1$

Initial state $\mathbb{C}_{c\bar{c}} = C_\gamma = -1$.

$\Rightarrow$ $\mathbb{C}$ parity violation

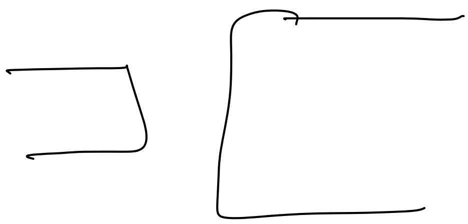


$c\bar{c} \to q\bar{q}$

$Q\bar{Q} \to g$ $\mathcal{M} \sim \alpha_s$

$Q\bar{Q} \to 3g$ $\mathcal{M} \sim \alpha_s^3$ suppressed compared to 1g exchange.

OZI Rule empirical.



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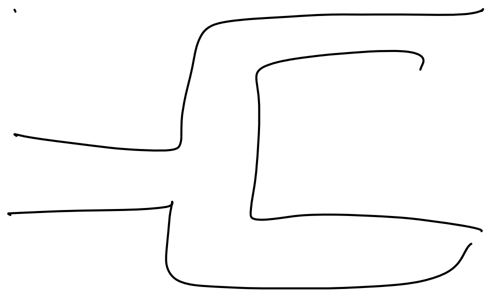

favored.

Okubo-Zweig-Iizuka 1966

$J/\psi \to ggg \to \pi^+ \pi^- \pi^0$