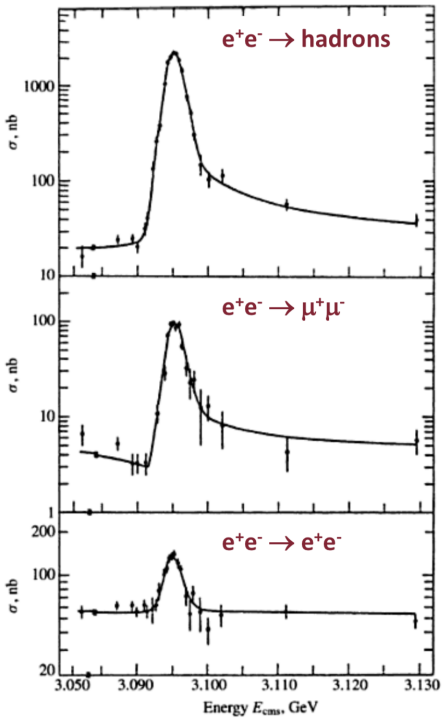
$e^+e^- \to$ hadrons, $\mu\mu$, ee $\Rightarrow$ discovery of J/ψ, $\psi(2S)$

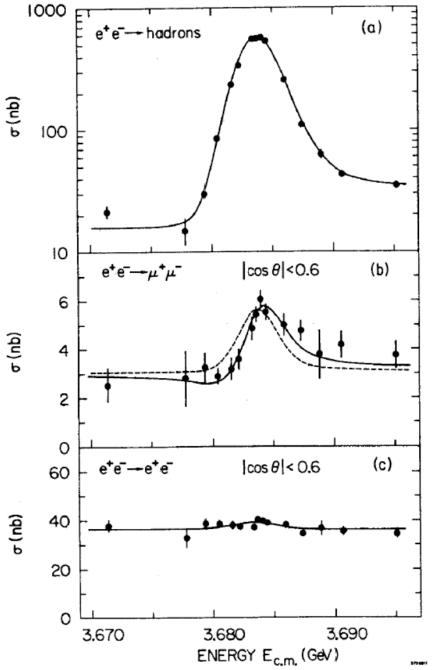
J/ψ



$M \simeq 3.1$ GeV

$\Gamma \simeq 87$ KeV

$\psi(2S)$



$M \simeq 3.7$ GeV

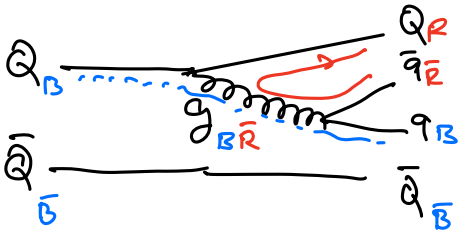
$\Gamma \simeq 294$ KeV

ρ: $M = 770$ MeV $\quad \Gamma \simeq 150$ MeV.

$\phi(1020)$ = $\quad M = 1020$ MeV $\quad \Gamma = 4$ MeV

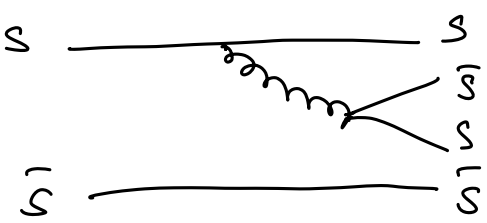
particle $Q\bar{Q}$ $\quad Q = s, c$ $\quad \phi \sim s\bar{s}$ $\quad J/\psi = c\bar{c}$

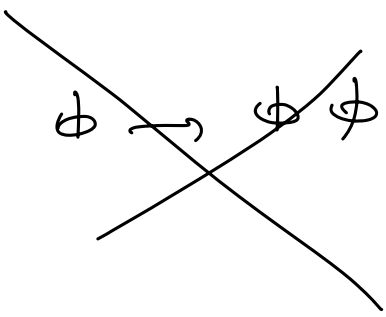
Strong decay of $Q\bar{Q}$



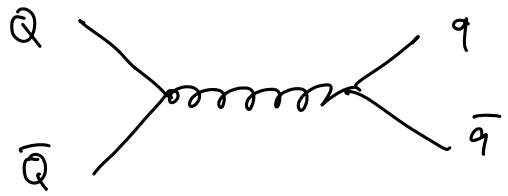
$q = u, d,$

$Q\bar{q} \longrightarrow (Q\bar{q}) + (\bar{q}q)$ $\quad Q = s, c$ $\quad q = u, d$





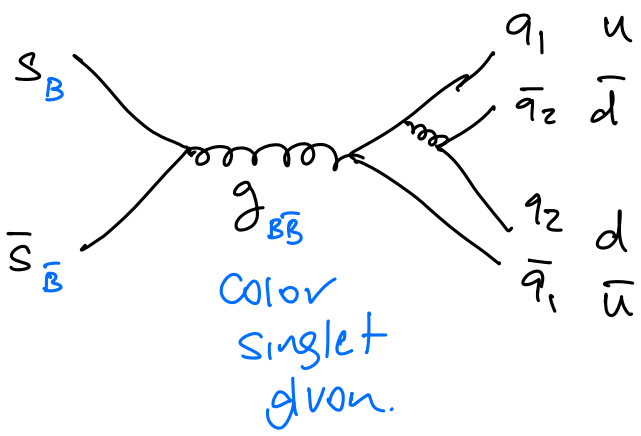
what about annihilation channel?



$\phi \to \pi^0$ NO

violates E-mom. conservation.

$Q = s$ $\quad q = u$



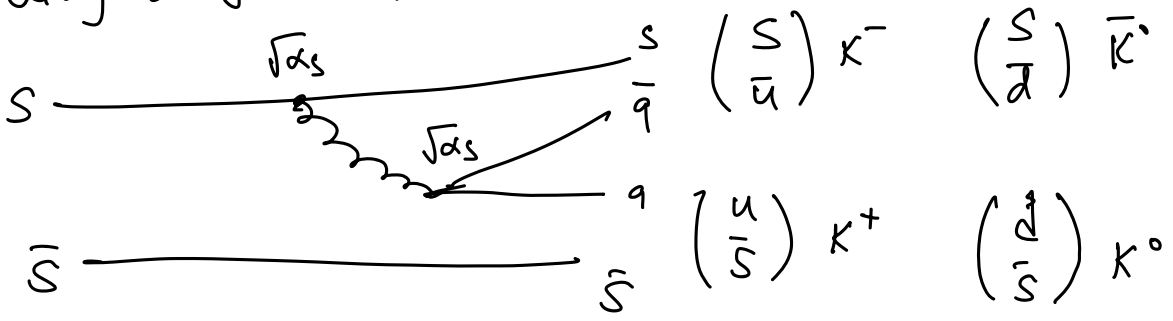
$q_1, q_2 = u, d$

$\phi \to \pi^+\pi^-$

Color singlet gluon.

we have 8 colored gluons $\Rightarrow$ NO $s\bar{s} \to$ gluon.

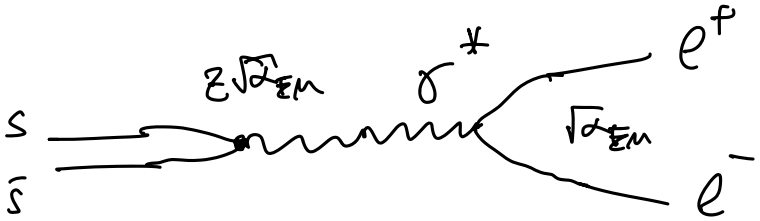
only decays of ϕ :



$\phi(1020)$ DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^- ✓	(49.1 ±0.5) %	S=1.3
Γ_2	$K^0_L K^0_S$ ✓	(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 ±0.05) $\times 10^{-3}$	
Γ_8	$\ell^+\ell^-$ ✓	—	

No direct measurement available. See Phys. Rev. Lett 86, 1898 (2001)



$M_{EM} \sim z\alpha_{EM}$

$\alpha_{EM} \sim 1/137$

$$\Gamma(a \to b+c) \propto |\mathcal{M}_{a\to bc}|^2 \underbrace{\rho(E_f = E_i)}_{\text{phase space}}$$

$\phi \to K^+K^-$ $\quad m_K \simeq 495$ MeV $\quad Q = 1020 - 2\times 495$ MeV

$\to \ell^+\ell^-$ $\quad m_e = 0.5$ MeV $\quad Q = 1020 - 1$

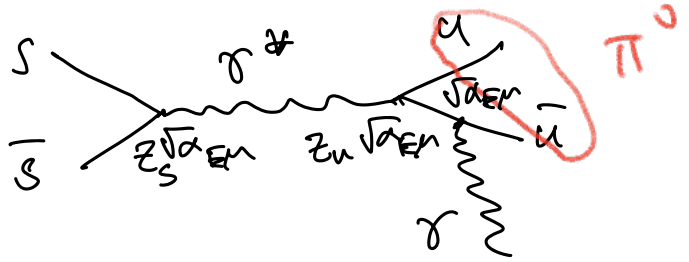
$\mathcal{M}_{EM} \sim z\alpha_{EM}$ $\quad \alpha_{EM} \simeq \frac{1}{137}$

$\mathcal{M}_{QCD} \sim \alpha_s$ $\quad \alpha_s \simeq 0.1$

$\Gamma_{EM} \lesssim \frac{1}{100}\,\Gamma_{strong}$

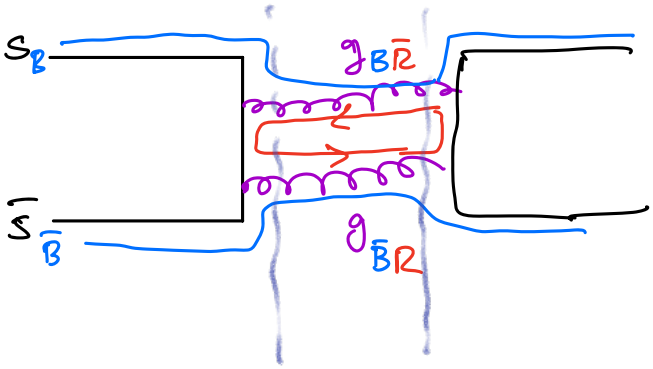
How $\phi \to \pi^0\gamma$ delay.

$\pi^0 = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$



$\mathcal{M} \sim z_s z_u \alpha_{EM}^{3/2}$

Rest frame of ϕ $\qquad \gamma \leftarrow \phi \rightarrow \pi^0$

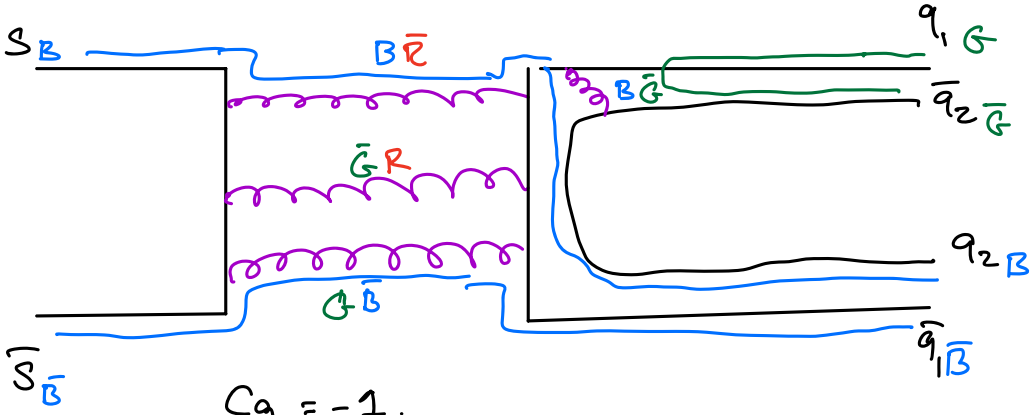


$Q\bar{Q} \to$ 2 gluons.

C parity $\qquad C(s\bar{s}) = -1$

$C(gg) = [C(g)]^2 = +1.$

$\Rightarrow$ C-parity violation $\Rightarrow$ not possible.



$q_1 q_2 = u, d.$

$C_g = -1.$

$s\bar{s} \to ggg$ conserves C-parity.

$\phi \to \pi^+\pi^-,\ \pi^0\pi^0$

G-parity = $C \times I_2$ rotation.

I_2 rotation: $\pi^+ \to (\ )\pi^-$

ϕ & $I^G = 1^-$ $\qquad J^{PC} = 1^{--}$

$s\bar{s}$ $\qquad G = (-1)^{I+S} = -1$ $\qquad L=0,\ S=1$

vector meson octet

$I=0.$
$S=1$ $\qquad C = (-1)^{L+S} = -1.$

$\pi^\pm$: $\quad I^G = 1^{-1}$ $\qquad J^P = 0^-$

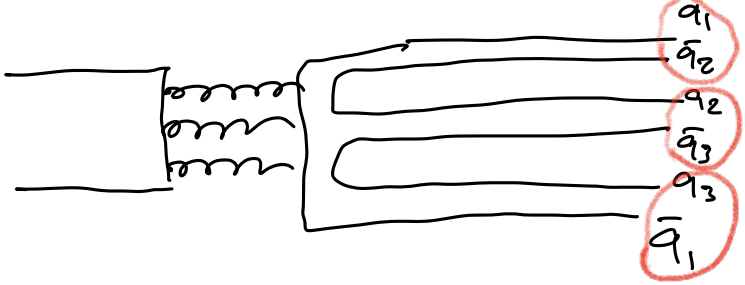
π^0: $\quad I^G = 1^{-1}$ $\qquad J^{PC} = 0^{-+}$

$L=0.$
$S=0$ $\qquad G = (-1)^{I+S} = -1.$ $\qquad C = (-1)^{L+S} = +1.$
$I=1$

	$\phi \to$	π^+	π^-
P	-1	(-1)	(-1)
G	-1	(-1)	(-1)

$\Rightarrow \phi \to \pi\pi$ not allowed by G parity conserv.

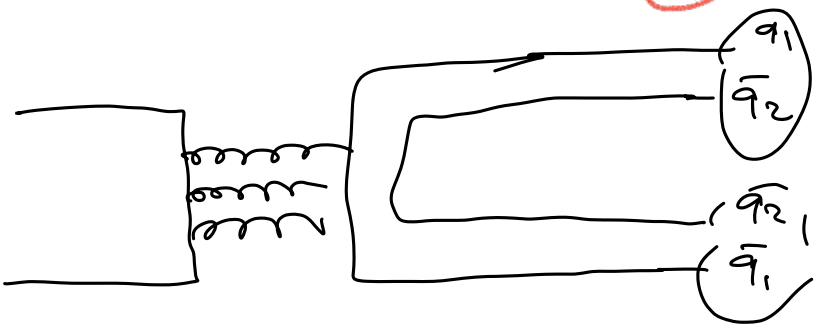
	$\phi \to$	π^0	π^0
G	(-1)	(-1)	(-1)



$q_1, q_2, q_3 = u, d$

$\pi^+ \pi^0 \pi^0$ NO

$\pi^+ \pi^- \pi^0$ OK



$q_1, q_2 = u, d.$

$S=1$

$S=0.$

$\rho(770)$: u, d

$\rho^+ \to \pi^+ \pi^0$

$\rho^0 \to \pi^+ \pi^-$

$I^G = 1^+$

$G = (-1)^{I+S}$

$S=1.$

$\phi \to \rho^+ \pi^-$

$G \quad -1 \qquad (+1)\ (-1)$

$\rho^0 \ \pi^0$

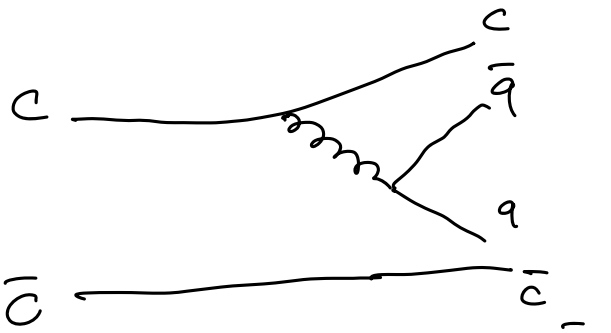
$(+1)\ (-1)$

$\phi \to \rho\ \pi$

$\hookrightarrow \pi\pi\pi$

$\phi(1S\bar{S})$ $\Gamma = 4$ MeV.

$J/\psi(c\bar{c})$: $\Gamma = 87$ KeV



$J/\psi \to D^0 \bar{D}^0$

Charmed mesons.

$q = u, d, s$

$c\bar{q}$

$\begin{pmatrix} c \\ \bar{u} \end{pmatrix} D^0$ $\begin{pmatrix} c \\ \bar{d} \end{pmatrix} D^+$

$\begin{pmatrix} u \\ \bar{c} \end{pmatrix} \bar{D}^0$ $\begin{pmatrix} d \\ \bar{c} \end{pmatrix} D^-$

$m_{D^0} \simeq 1.864$ GeV

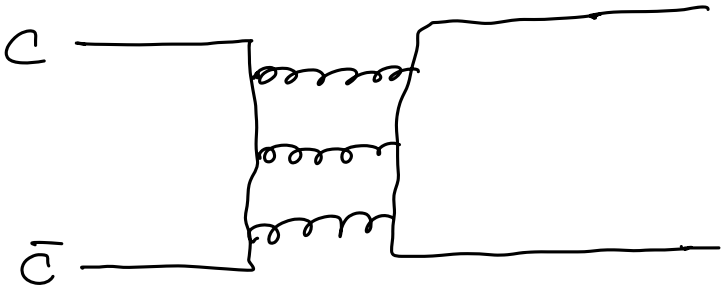
$m_{J/\psi} = 3.1$ GeV $< 2 \times m_D$

$\Rightarrow$ Kinematically not allowed

J/ψ(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) %	

only decays of J/ψ ⇒ need 3 gluons.



$J/\psi = c\bar{c}$ $\quad I^G = 0^-$ $\quad J^{PC} = 1^{--}$

$S = 1.$

$G = (-1)^{I+S} = -1$

⇒ $J/\psi \to \pi\pi\pi$

no 1g decay channel ⇒ decay suppressed ⇒ $\Gamma = 87$ keV

$\psi(2S)$ $\Gamma = 296$ keV $\quad m = 3.7$ GeV.

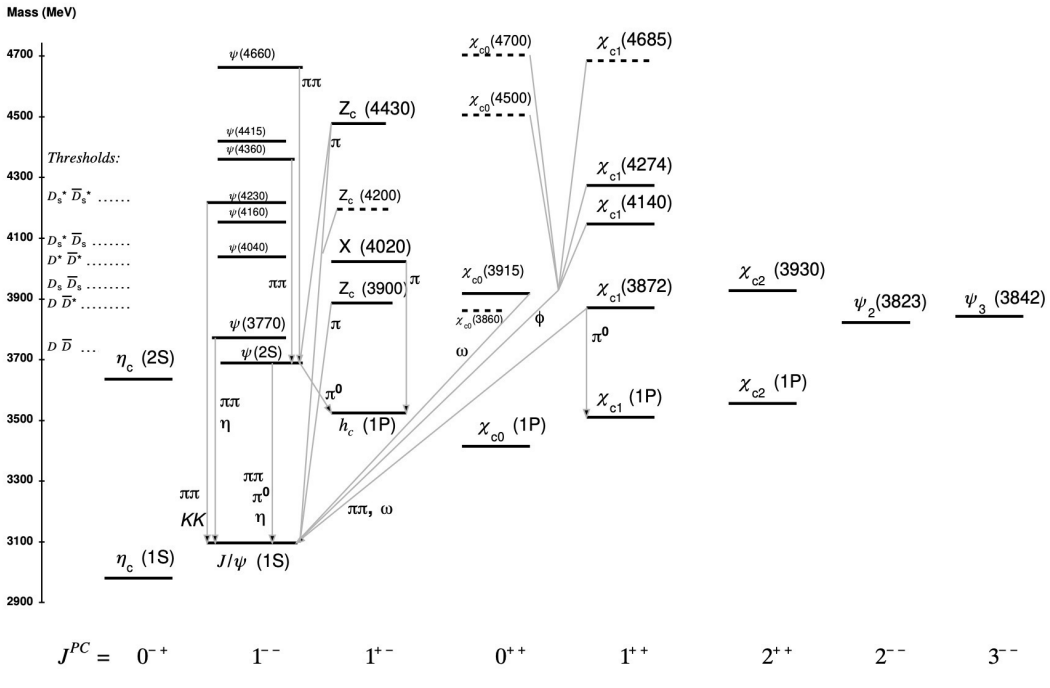
$J/\psi \equiv \psi(1S)$ $\quad c\bar{c}$

$\psi(2S)$ $\quad c\bar{c}$

ψ(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^0_S 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) $\times 10^{-3}$	

Charmonium ($c\bar{c}$) resonances

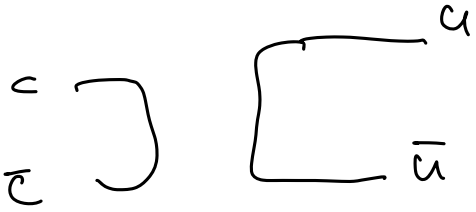


$c\bar{c}$ similar to hydrogen or positronium (e^+e^-)

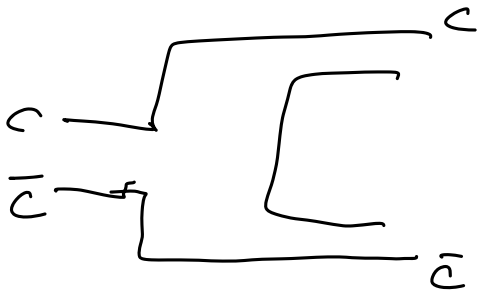
To compute the energy level $V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + Kr$ $\quad K>0.$

Narrowness of J/ψ $\Rightarrow$ OZI Rule. 1966.

Okubo - Zweig - Iizuka.



Disconnected color lines



Connected color lines.

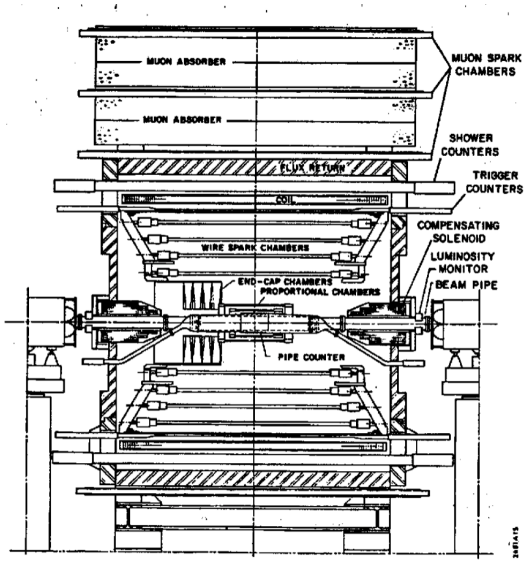
Favored
if kinematically allowed.

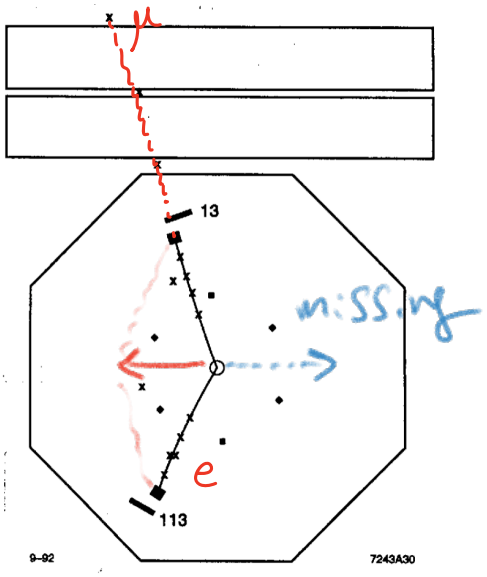
SPEAR @ SLAC 1976

Discovery of τ lepton.

Mark I detector

$e^+e^- \longrightarrow$





$e^+e^- \longrightarrow \mu^+ e^-$ unbalanced.

$e^+e^- \longrightarrow \tau^+\tau^-$

$\tau^- \hookrightarrow e^- \bar{\nu}_e \nu_\tau$

$\tau^+ \hookrightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$

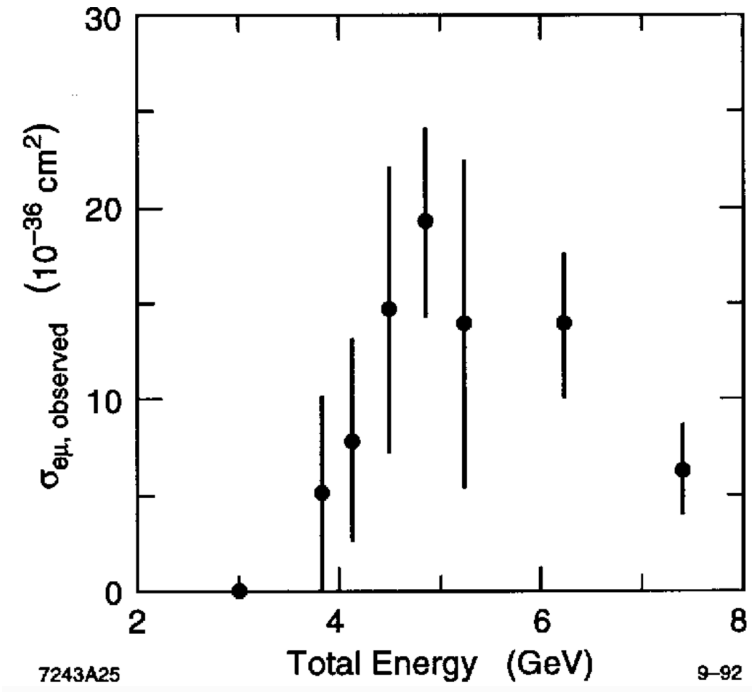
missing energy/momentum.

$\sqrt{s} \geq 2 \times m_\tau$ also see imbalance e^+e^-

$\mu^+\mu^-$

$e^-\mu^+$

$e^+\mu^-$



threshold effect.

$\Downarrow$

$m_\tau = 1.78$ GeV

$\tau \longrightarrow$ hadrons possible.