

# Quarks and Hadrons

- Properties of hadrons
- Pions and nucleons
- Strange particles
- Charm and beauty
- Breit-Wigner distribution
- Exotics

# Quark Flavors

3 pairs  
Called  
generations

Fractional  
charge

See PDG for updates on mass  
<http://pdg.lbl.gov/2014/reviews/rpp2014-rev-quark-masses.pdf>

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
<b>u</b> up	0.003	2/3
<b>d</b> down	0.006	-1/3
<b>C</b> charm	1.3	2/3
<b>S</b> strange	0.1	-1/3
<b>t</b> top	175	2/3
<b>b</b> bottom	4.3	-1/3

# Quark Flavor Interactions

	Strong	EM	Weak	Gravity
u	✓	✓	✓	✓
d	✓	✓	✓	✓
c	✓	✓	✓	✓
s	✓	✓	✓	✓
t	✓	✓	✓	✓
b	✓	✓	✓	✓

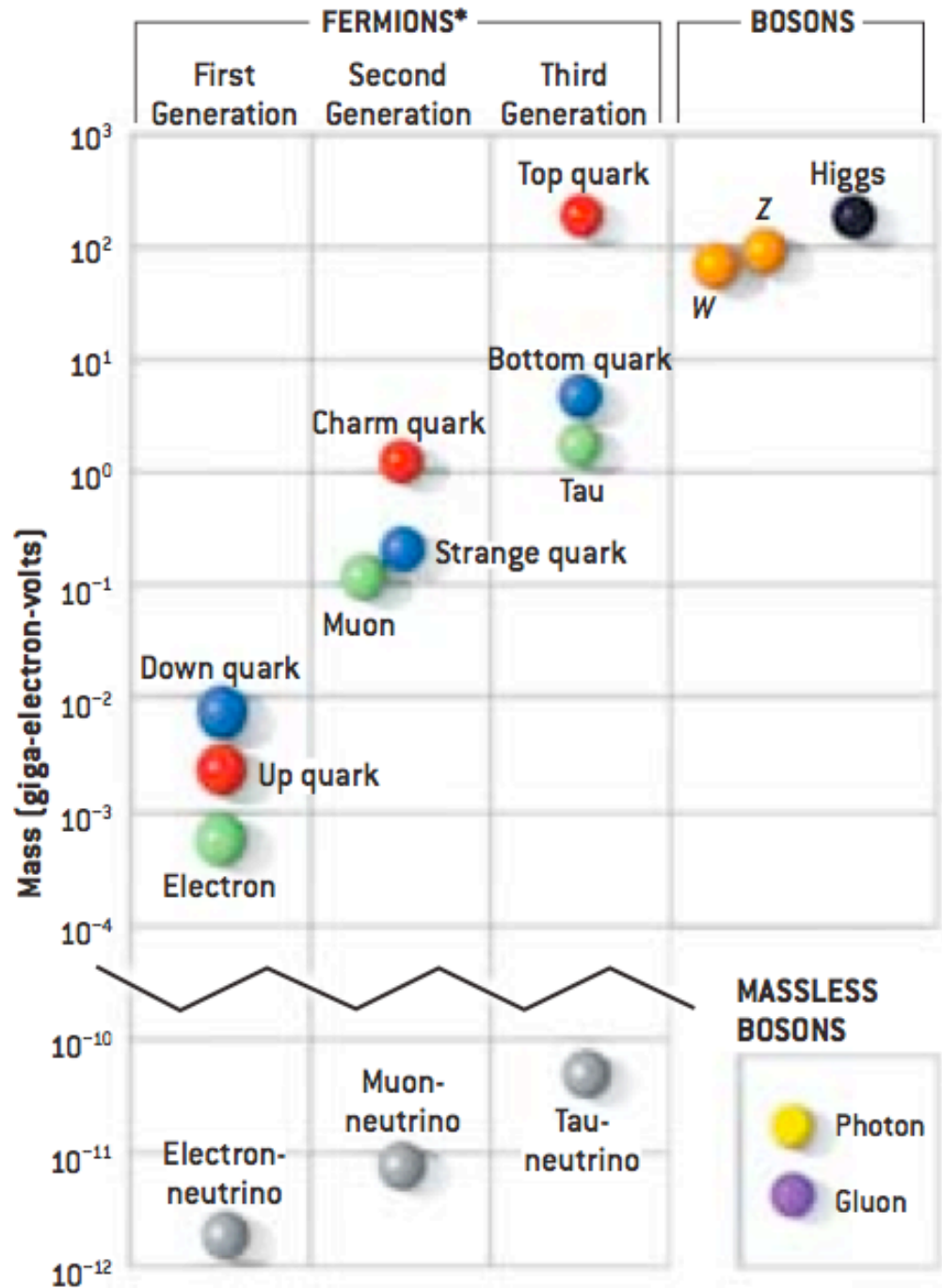
# Quark Flavors

	Quantum Number	Rest Mass, GeV
up, down	$I = 1/2$	$m_u \approx m_d \approx 0.3$
strange	$S = -1$	$m_s \approx 0.50$
charm	$C = +1$	$m_c \approx 1.50$
bottom	$B = -1$	$m_b \approx 4.5$
top	$T = +1$	$m_t \approx 173$

Particles comprised of these quarks will have masses determined roughly by the rest masses of the quarks (internal interactions alter the mass some)

The strong interaction conserves each of the flavor quantum numbers

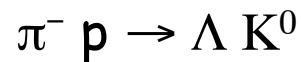
# Mass Spectrum of Standard Model Particles



J. Brau

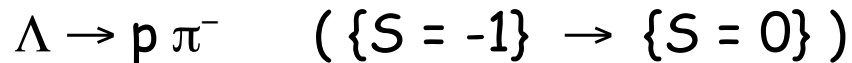
# Quark Flavor Conservation

- Strange production and decay is a good example of how the quark flavor conservation law works
- Strange particles are always produced in pairs in strong interactions:

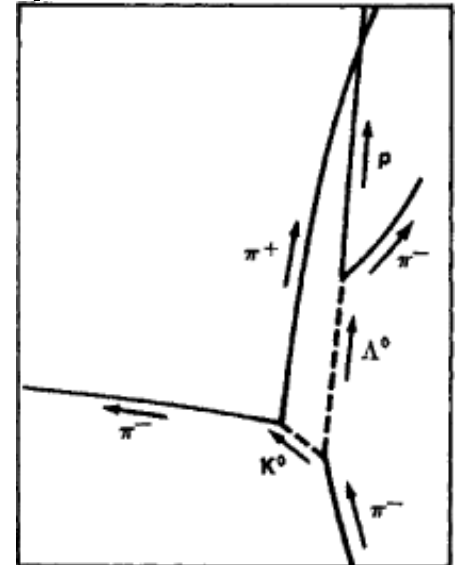


- $S(\Lambda) = -1$ , contains strange quark
- $S(K) = +1$ , contains antistrange quark
- this is a strong interaction and therefore has a large cross section

- In the decays of strange particles, the strangeness may vanish:



- this process is not allowed by the strong interaction, therefore must involve the weak interaction, and is therefore slow.



# Baryons and Mesons

- Quarks have never been observed in isolation in nature, in bound states of three quarks or a quark and an antiquark
  - baryon =  $QQQ$  {three quark state}
  - meson =  $Q\bar{Q}$  {quark antiquark pair}
- Baryons and mesons are collectively referred to as hadrons and comprise all of the strongly interaction particles
- Baryons have half-integer spin ( $1/2, 3/2, 5/2, \dots$ ) and mesons integer spin ( $0, 1, 2, \dots$ )
- Note - exotics =  $Q\bar{Q}Q\bar{Q}$  or  $QQQ\bar{Q}\bar{Q}$

# Baryon Number

- Baryon number of quark is  $1/3$ ,  
and baryon number of anti-quark is  $-1/3$
- so  $B \equiv 1/3 [N(q) - N(\bar{q})]$
- Baryons have baryon number 1,  
anti-Baryons have baryon number -1,  
and mesons have baryon number 0

# Baryons and antibaryons

**Baryons  $qqq$  and Antibaryons  $\bar{q}\bar{q}\bar{q}$**   
 Baryons are fermionic hadrons.  
 There are about 120 types of baryons.

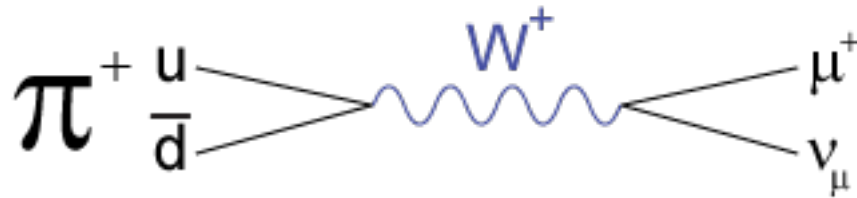
Symbol	Name	Quark content	Electric charge	Mass $\text{GeV}/c^2$	Spin
<b>p</b>	proton	<b>uud</b>	1	0.938	1/2
<b><math>\bar{p}</math></b>	anti-proton	<b><math>\bar{u}\bar{u}\bar{d}</math></b>	-1	0.938	1/2
<b>n</b>	neutron	<b>udd</b>	0	0.940	1/2
<b><math>\Lambda</math></b>	lambda	<b>uds</b>	0	1.116	1/2
<b><math>\Omega^-</math></b>	omega	<b>sss</b>	-1	1.672	3/2

# Quark Mass

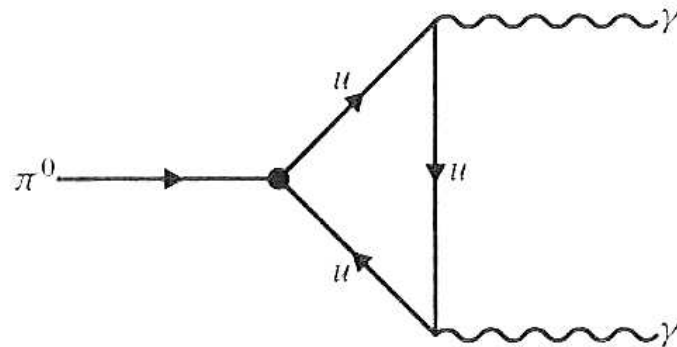
- There are two ways of describing the quark mass:
  - constituent quark mass (used in Perkins)
    - $m(u) \approx 0.31 \text{ GeV}$        $m(d) \approx 0.31 \text{ GeV}$
  - current quark mass
    - $m(u) \approx 0.003 \text{ GeV}$        $m(d) \approx 0.006 \text{ GeV}$
- Consider the mass of the two light mesons, the pion and the rho, both composed of  $u\bar{d}$ 
  - $m(\text{pi}) = 0.14 \text{ GeV}$
  - $m(\text{rho}) = 0.77 \text{ GeV}$
  - constituent quark picture requires large spin-orbit interaction energy to explain difference

# Pions

- Lightest mesons are  $\pi^\pm$  (140),  $\pi^0$  (135), where the mass in MeV is indicated
- $\pi^\pm$  decays to  $\mu^\pm \nu$  with  $\tau = 2.6 \times 10^{-8}$  sec,



- $\pi^0$  decays to  $\gamma\gamma$  with  $\tau = 0.8 \times 10^{-16}$  sec



# Strange Particles

- The same year in which pions were discovered (1947), particles which were produced through the strong interaction, but decayed via the weak interaction were found in cosmic rays - these were deemed "strange particles" because of this behavior.
- Associated production
  - Strange particles are produced copiously on a time scale of  $10^{-23}$  sec., but decay slowly on a time scale of  $10^{-10}$  sec.
  - This suggests (Pais) the production mechanism is entirely different from the decay mechanism
  - Produced in pairs with property(strangeness) that is conserved by strong interactions, but not conserved by weak interaction
  - eg.  $\pi^- + p \rightarrow K^+ + \Sigma^-$  or  $\pi^- + p \rightarrow K^0 + \Lambda$

# Strange Particles

- Kaons
  - $K^0(498) = d\bar{s}$        $K^+(494) = u\bar{s}$
  - $\bar{K}^0(498) = s\bar{d}$        $K^-(494) = s\bar{u}$
- Lambda
  - $\Lambda(1116) = sud$
- Sigma
  - $\Sigma^+(1189) = suu$
  - $\Sigma^0(1193) = sud$
  - $\Sigma^-(1197) = sdd$

# Strong Interactions & Strange Decays

- Decay of the  $\Sigma$  baryons

Baryon	Composition	Q-value, MeV	Decay Mode	Lifetime, s
$\Sigma^0$ (1192)	uds	77	$\Lambda\gamma$	$10^{-19}$
$\Sigma^+$ (1189)	uus	116	$p\pi^0$	$10^{-10}$
$\Sigma^0$ (1385)	uds	135	$\Lambda\pi^0$	$10^{-23}$

# Strong Interactions & Strange Decays

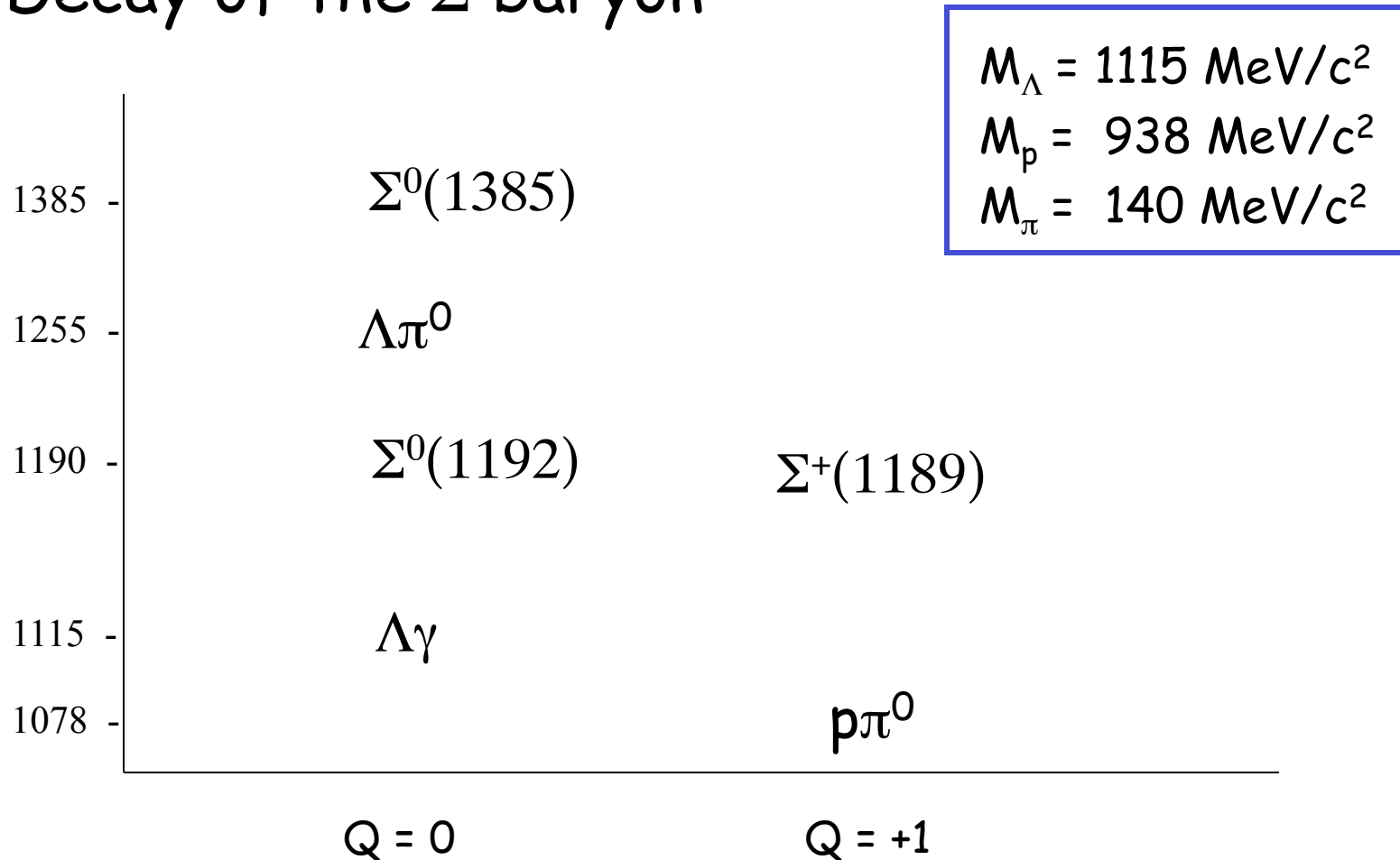
- Decay of the  $\Sigma$  baryons

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$\Sigma^0$ (1385)	uds	135	$\Lambda\pi^0$	$10^{-23}$

- why is the  $\Sigma^0$  (1192) 3 MeV heavier than the  $\Sigma^+$  (1189) ?
- why does the  $\Sigma^+$  (1189) live a billion times longer than the  $\Sigma^0$  (1192) ?

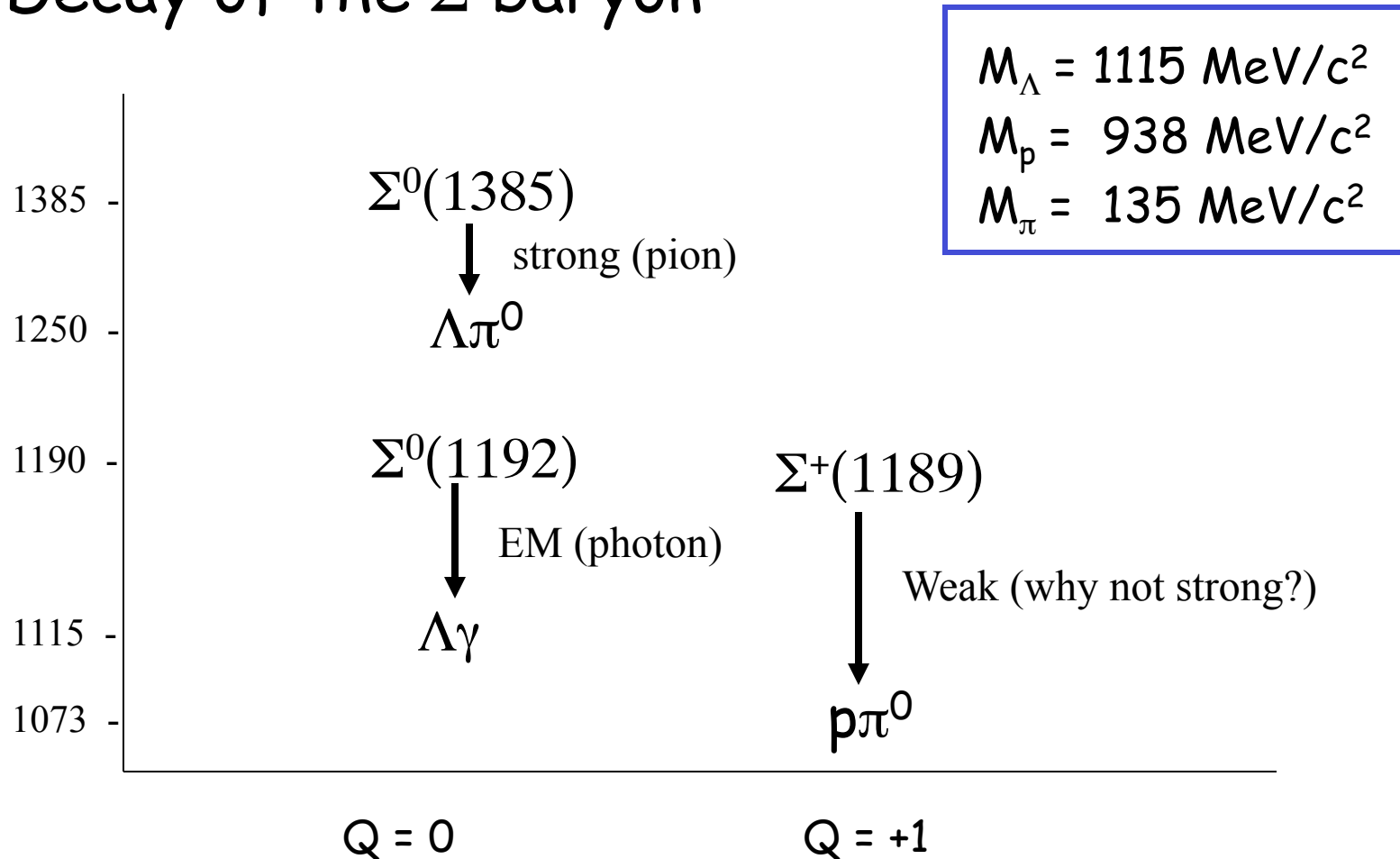
# Strong Interactions & Strange Decays

- Decay of the  $\Sigma$  baryon



# Strong Interactions & Strange Decays

- Decay of the  $\Sigma$  baryon



# Strong Interactions & Strange Decays

- Decay of the  $\Sigma$  baryons

Baryon	Composition	Q-value, MeV	Decay Mode	Lifetime, s
$\Sigma^0$ (1192)	uds	77	$\Lambda\gamma$ (EM)	$10^{-19}$
$\Sigma^+$ (1189)	uus	116	$p\pi^0$ (weak)	$10^{-10}$
$\Sigma^0$ (1385)	uds	135	$\Lambda\pi^0$ (strong)	$10^{-23}$

- strong

- $\Sigma^0$  (1192) cannot decay strongly because  $M_\Lambda + M_\pi = 1250 \text{ MeV}/c^2$
- $\Sigma^+$  (1189) cannot decay strongly (same reason)

- EM

- $\Sigma^+$  (1189) cannot decay Emly because there is no lighter charged, strange baryon ( $\Sigma^+$  (1189) is lightest charged, strange baryon)

## Strong Interactions & Strange Decays

- The ratios of the decay rates give an approximate indication of the relative strengths of the interactions:

$$\{\tau[\Sigma^0(1192)] / \tau[\Sigma^0(1385)]\}^{1/2} \approx 100 \approx \alpha_s / \alpha$$

- Since  $\alpha = 1/137$ ,  $\alpha_s \approx 1$

# Charm and Beauty

- In 1970, three quarks explained all known hadrons.
- During the 1970' s, two more quarks were discovered
  - charm, 1974
  - bottom, 1977
- In 1995, the top quark was finally observed

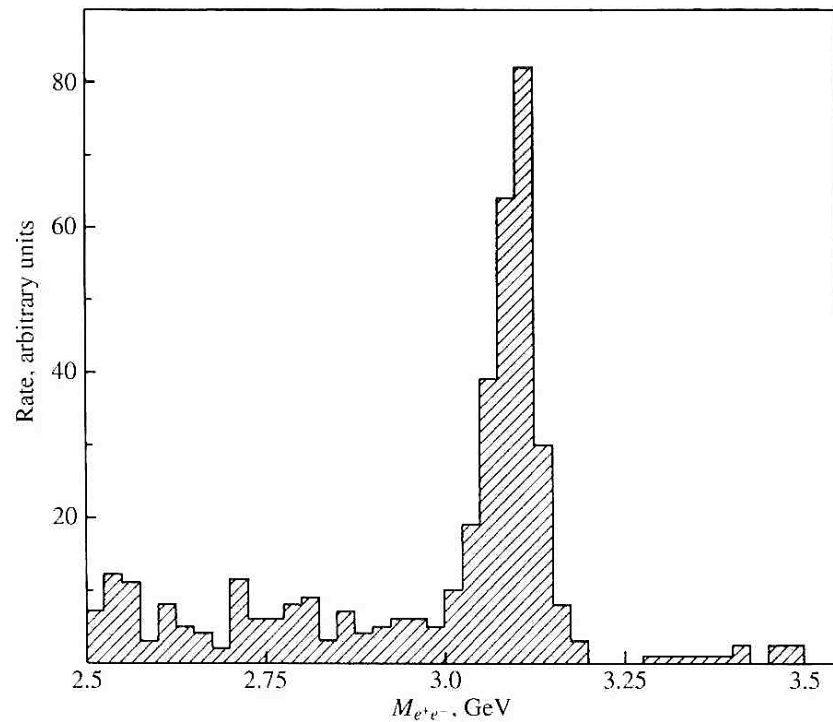
Flavor	I	$I_3$	S	C	$B^*$	T	Q/e
u	1/2	1/2	0	0	0	0	+2/3
d	1/2	-1/2	0	0	0	0	-1/3
s	0	0	-1	0	0	0	-1/3
c	0	0	0	1	0	0	+2/3
b	0	0	0	0	-1	0	-1/3
t	0	0	0	0	0	1	+2/3





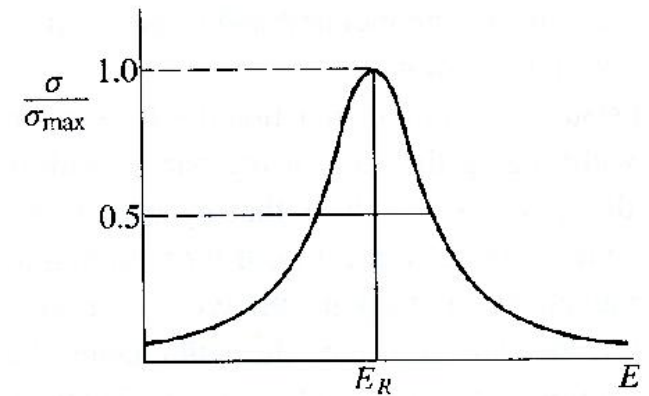
# Discovery of Charm

- 1974
  - BNL:  $p + \text{Be} \rightarrow \text{J}/\psi + \text{anything}$   
 $\quad \quad \quad \downarrow$   
 $\quad \quad \quad e^+e^-$



# Breit-Wigner Distribution

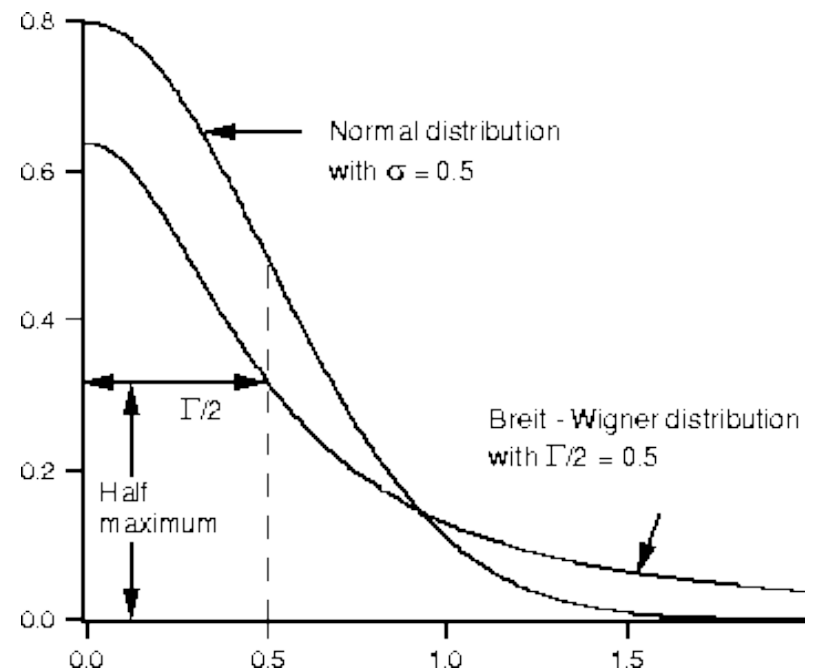
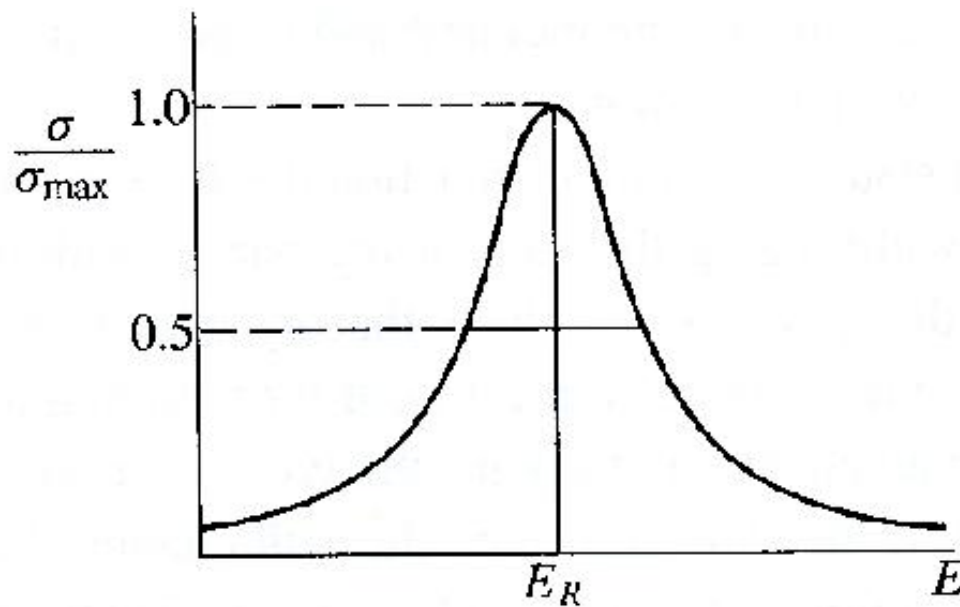
- When two particles collide, they can form an unstable, broad state, known as a “resonance”.
- The cross section which measures the probability of forming the resonant state follows the Breit-Wigner distribution:



$$\sigma(E) = \sigma_{\max} \frac{\Gamma^2/4}{(E - E_R)^2 + \Gamma^2/4}$$

# Breit-Wigner Distribution

$$\sigma(E) = \sigma_{\max} \frac{\Gamma^2/4}{(E - E_R)^2 + \Gamma^2/4}$$



# Breit-Wigner Distribution

- $\psi(t) = \psi_0 e^{-\Gamma/2t} e^{-iE_0 t}$
- Fourier Transform:
- $$\begin{aligned}\psi(E) &= \int \psi(t) e^{iEt} dt = \int \psi_0 e^{-\Gamma/2t} e^{-iE_0 t} e^{iEt} dt \\ &= \int \psi_0 e^{i[(E - E_0) + i\Gamma/2]t} dt\end{aligned}$$
- $\psi(E) \sim 1/[E - E_0 + i\Gamma/2]$
- $|\psi(E)|^2 \sim 1/[(E - E_0)^2 + \Gamma^2/4]$

# Breit-Wigner Distribution

- When spin and angular momentum are taken into consideration

$$\sigma = \frac{4\pi \lambda^2 (2J + 1)}{(2s_a + 1)(2s_b + 1)} \frac{\Gamma^2/4}{[(E - E_R)^2 + \Gamma^2/4]}$$

where  $\lambda$  is the wavelength of the scattered and scattering particle in their common CMS

$$\lambda = h/p$$

# Breit-Wigner Distribution

$$\sigma = \frac{4\pi\lambda^2(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma^2/4}{[(E-E_R)^2 + \Gamma^2/4]}$$

- Elastic scattering

$$\sigma = \frac{4\pi\lambda^2(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma_{el}^2/4}{[(E-E_R)^2 + \Gamma^2/4]}$$

- General scattering ( $i \rightarrow j$ )

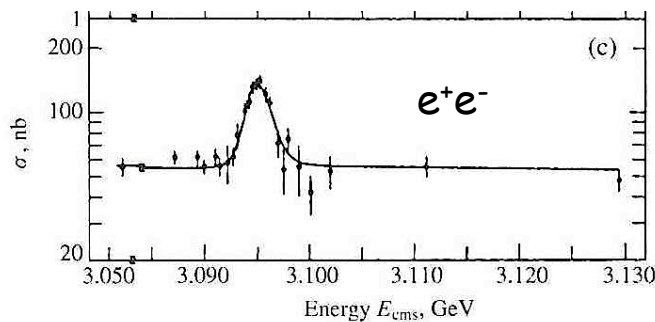
$$\sigma = \frac{4\pi\lambda^2(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma_i\Gamma_j/4}{[(E-E_R)^2 + \Gamma^2/4]}$$

# Discovery of Charm

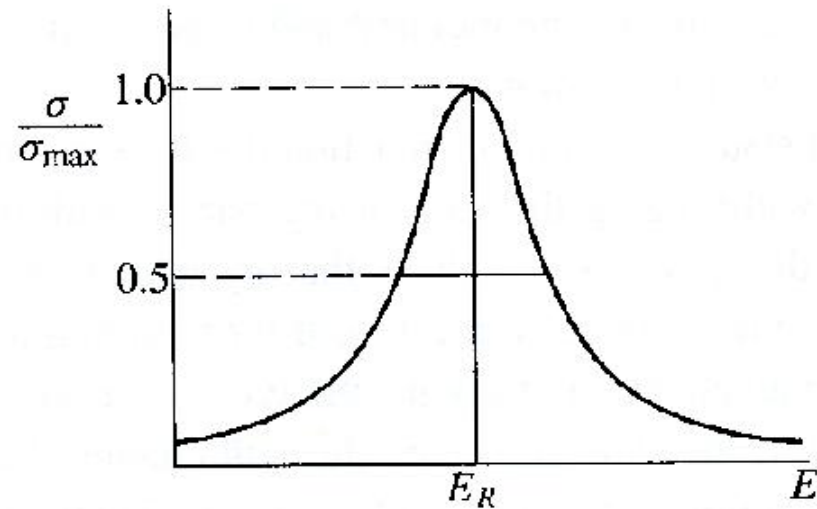
- Total width from integral of the cross section:

$$\sigma = \frac{4\pi\lambda^2(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma_i\Gamma_j/4}{[(E-E_R)^2 + \Gamma^2/4]}$$

$$\int \sigma(E) dE$$



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# Discovery of Charm

- Total width from integral of the cross section:

$$\sigma = \frac{4\pi\kappa^2(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma_i\Gamma_j/4}{[(E-E_R)^2 + \Gamma^2/4]}$$

$$\int \sigma(E) dE \qquad \Gamma_i = \Gamma_j = \Gamma_{ee}$$

Let  $x = 2(E-E_R)/\Gamma$ ,  $dx = 2dE/\Gamma$ ,  $dE = (\Gamma/2) dx$

$$2J+1=3 \quad \text{and} \quad 2s_a+1=2s_b+1=2$$

$$\int \sigma(E) dE = 3\pi/2 \kappa^2 (\Gamma_{ee}/\Gamma)^2 \Gamma \int \frac{dx}{(1+x^2)}$$



# Discovery of Charm

- Total width from integral of the cross section:

$$\sigma = \frac{4\pi\lambda^2(2J+1)}{(2s_a+1)(2s_b+1)} \frac{\Gamma_i\Gamma_j/4}{[(E-E_R)^2 + \Gamma^2/4]}$$

$$\int \sigma(E) dE = 3\pi^2/2 \lambda^2 (\Gamma_{ee}/\Gamma)^2 \Gamma = 800 \text{ nb MeV}$$

$$\Gamma_{ee}/\Gamma = 0.06$$

$$\lambda = \hbar c/pc = 197 \text{ MeV-fm}/1550 \text{ MeV}$$

$$\Gamma = 0.093 \text{ MeV} \quad (\text{very narrow})$$

Ref: Particle Data Group

# Discovery of Charm

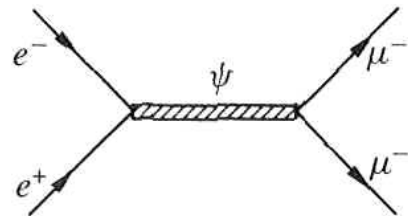
- Vector mesons:

	$\Gamma$	.
$\rho(776 \text{ MeV})$	150	MeV
$\omega(784 \text{ MeV})$	8.4	MeV
$J/\psi(3100 \text{ MeV})$	0.093	MeV

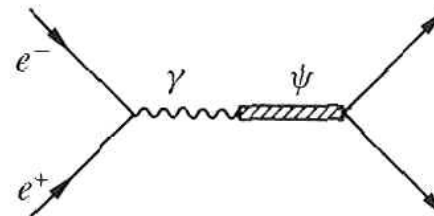
	$\Gamma_{ee}$	
$\rho(776 \text{ MeV})$	6.8	keV
$\phi(1020 \text{ MeV})$	1.4	keV
$\omega(784 \text{ MeV})$	0.6	keV
$J/\psi(3100 \text{ MeV})$	5	keV

# Discovery of Charm

- Shape of the resonance was consistent with  $J^P = 1^-$ 
  - interference of the direct and virtual photon channels



(a)



(b)

$m=0$

$j=$

- ratio of decay modes  
(such as  $\rho^0\pi^0$  and  $\rho^-\pi^+$ )  
shows  $J/\psi$  is  $I=0$  state

	2	1	0
1, -1	$\sqrt{\frac{1}{6}}$	$\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{3}}$
0, 0	$\sqrt{\frac{2}{3}}$	0	$-\sqrt{\frac{1}{3}}$
-1, 1	$\sqrt{\frac{1}{6}}$	$-\sqrt{\frac{1}{2}}$	$\sqrt{\frac{1}{3}}$

# Discovery of Charm

- $\psi(3700) \rightarrow \psi(3100) \pi^+ \pi^-$

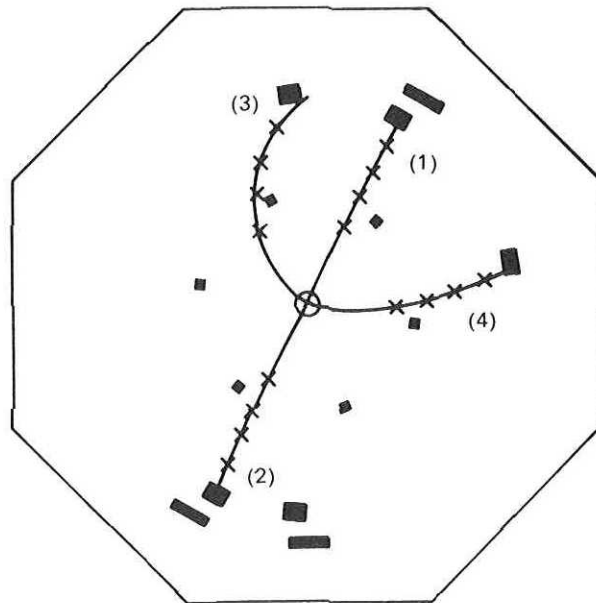
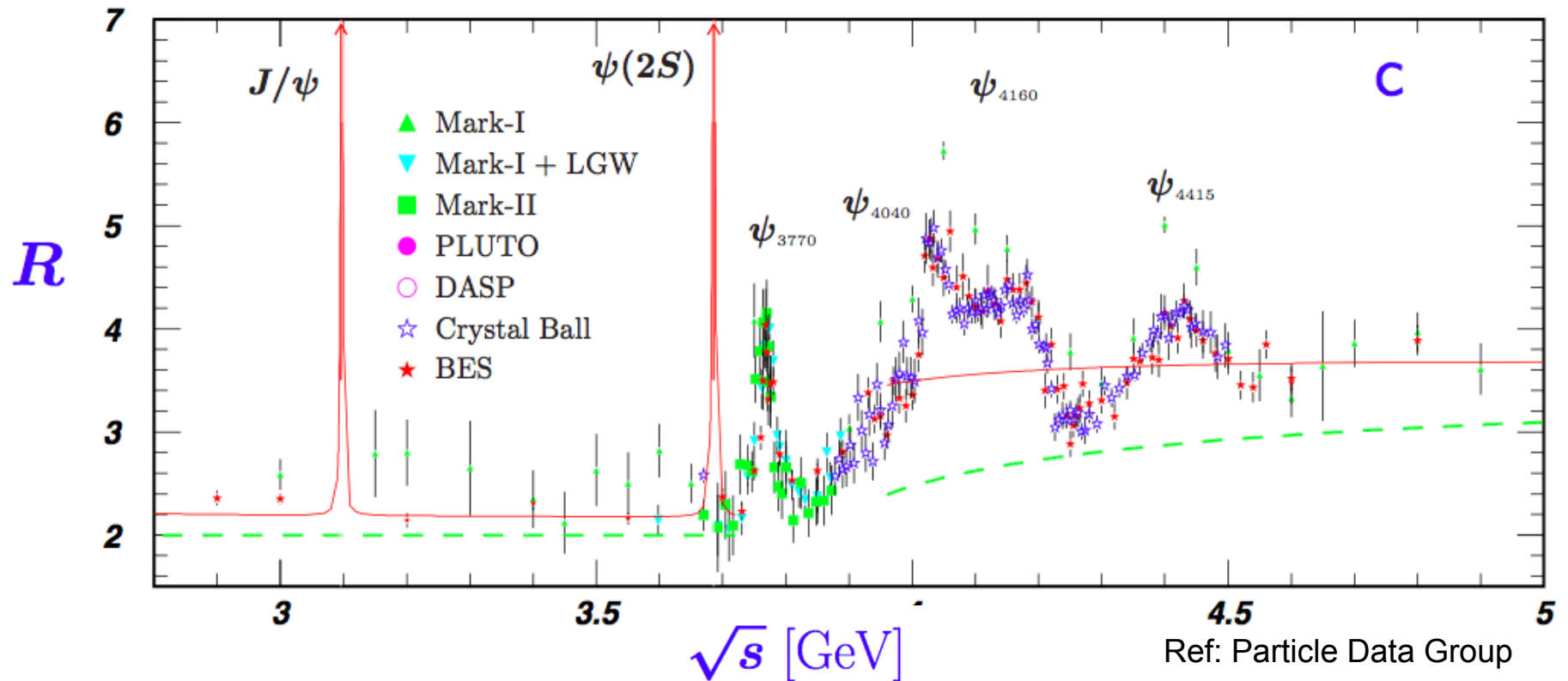


Fig. 4.4. Example of the decay  $\psi(3.7) \rightarrow \psi(3.1) + \pi^+ + \pi^-$  observed in a spark chamber detector. The  $\psi(3.1)$  decays to  $e^+ + e^-$ . Tracks (3) and (4) are due to the relatively low energy (150 MeV) pions, and (1) and (2) to the 1.5 GeV electrons. The magnetic field and the SPEAR beam pipe are normal to the plane of the figure. The trajectory shown for each particle is the best fit through the sparks, indicated by crosses. (From Abrams *et al.* 1975.)

# Discovery of Charm



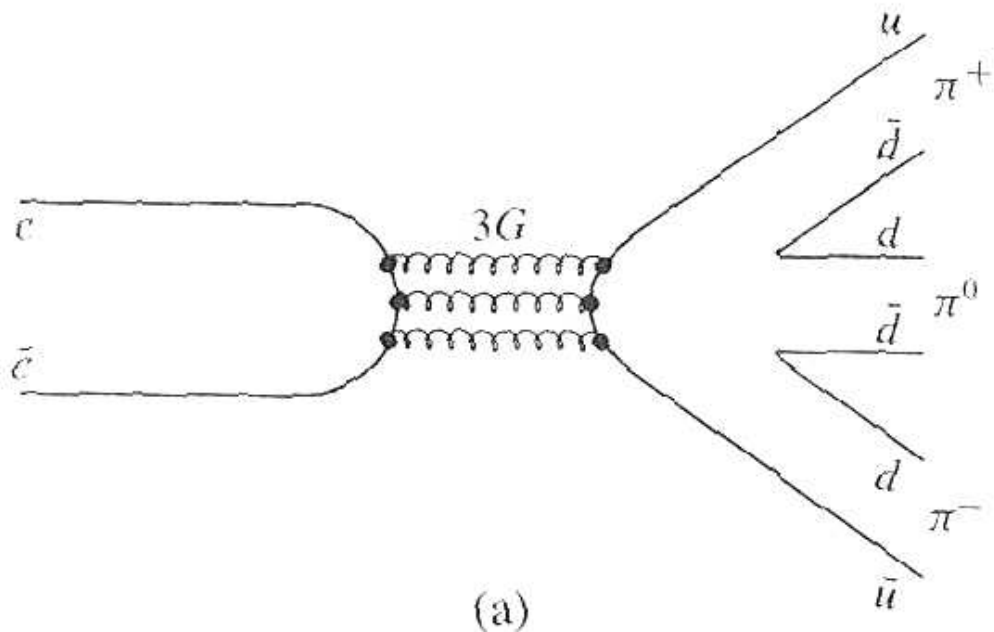
$R = \sigma(e^+ e^- \rightarrow \text{hadrons}) / \sigma_{\text{PT}}(e^+ e^- \rightarrow \mu^+ \mu^-)$   
 - consider  $e^+ e^- \rightarrow \text{hadrons}$  as  $e^+ e^- \rightarrow Q\bar{Q}$ ,  
 summed over all quarks

$$\begin{aligned}
 \sigma_{\text{PT}}(e^+ e^- \rightarrow \mu^+ \mu^-) &= 4\pi\alpha^2 / 3s \\
 &= 87\text{nb} / s(\text{GeV}^2) \\
 &\text{(point cross section)}
 \end{aligned}$$

# Discovery of Charm

- Narrowness of  $\psi(3100)$  and  $\psi(3700)$  explained by QCD,  $3G$  exchange required

Colorless,  
and  $C$  parity odd



# Discovery of Charm

- For heavier charmonium states, open charm decay modes open up  $\rightarrow$  broader resonances

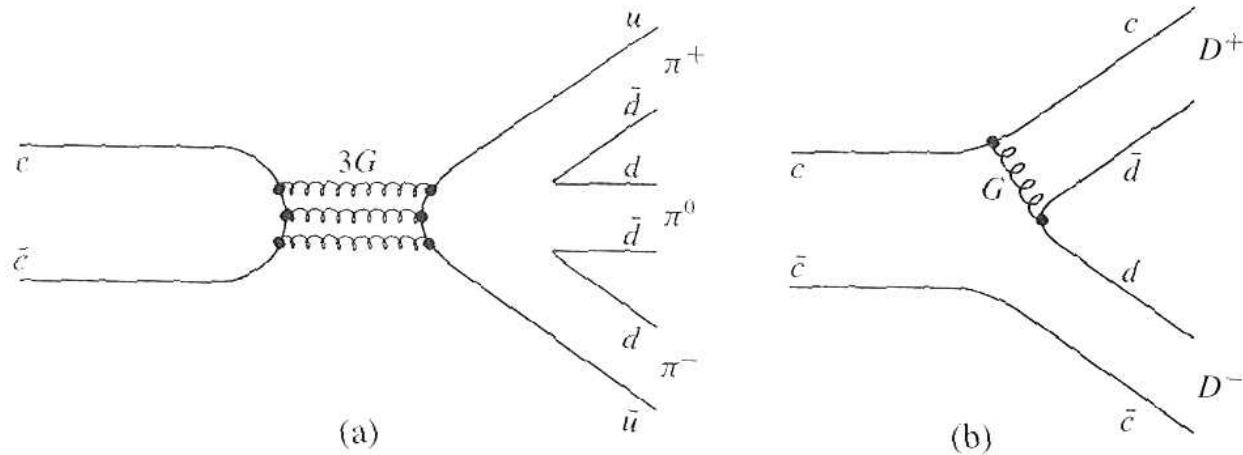


Fig. 4.5. Quark diagrams for charmonium decay. (a)  $\Psi(3100) \rightarrow 3\pi$ ,  $\Gamma = 0.076$  MeV; (b)  $\Psi(3770) \rightarrow D\bar{D}$ ,  $\Gamma = 24$  MeV. Diagram (b) is favoured but forbidden by energy conservation for charmonium states  $\psi(3.1)$  and  $\psi(3.7)$  with masses below threshold  $2M_D = 3.75$  GeV. The 'OZI forbidden' diagram (a) is therefore the only one allowed for hadronic decay of these low-mass states.

# Discovery of Charm

$\psi(3100)$	$\Gamma = 0.093 \text{ MeV}$	
$\psi(3700)$	$\Gamma = 0.30 \text{ MeV}$	Open charm
$\psi(3770)$	$\Gamma = 27 \pm 1 \text{ MeV}$	threshold
$\psi(4040)$	$\Gamma = 80 \pm 10 \text{ MeV}$	
$\psi(4160)$	$\Gamma = 103 \pm 8 \text{ MeV}$	
$\psi(4415)$	$\Gamma = 62 \pm 20 \text{ MeV}$	

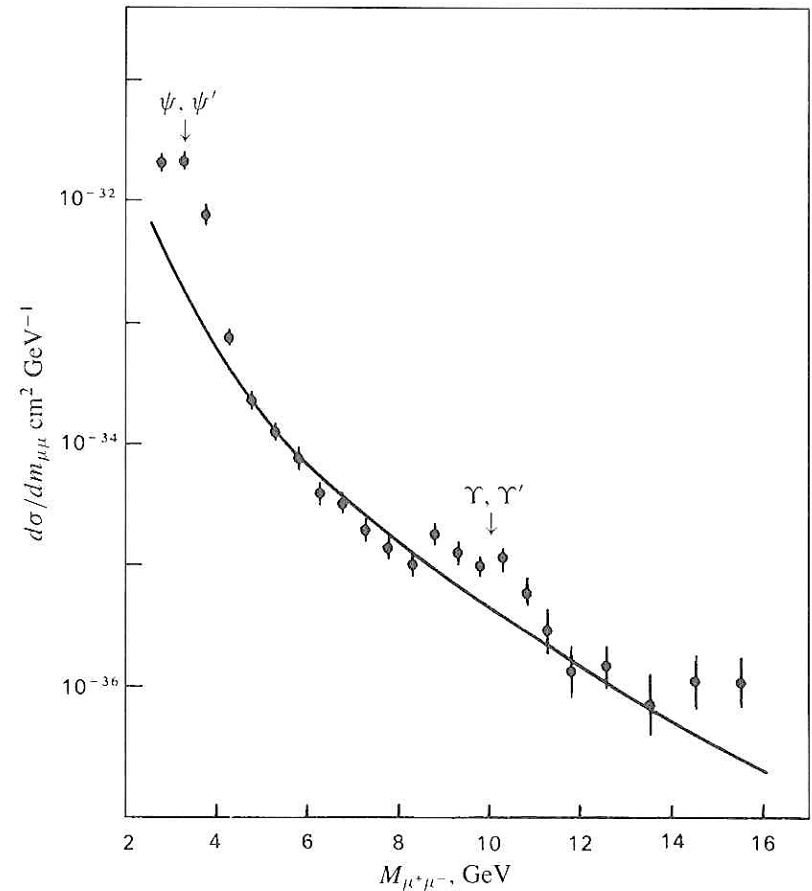
Ref: Particle Data Group

# Open Charm

- $D^+(1869) = c\bar{d}$   $C=+1$
- $D^0(1865) = c\bar{u}$   $C=+1$
- $D^-(1869) = d\bar{c}$   $C=-1$
- $\bar{D}^0(1865) = u\bar{c}$   $C=-1$
- $D_s^+(1969) = c\bar{s}$   $C=+1, S=+1$
- $D_s^-(1969) = s\bar{c}$   $C=-1, S=-1$
  
- $\Lambda_c^+(2285) = cdu$   $C=+1$
  
- $\tau(\text{charm}) \sim 10^{-13} \text{ sec}$

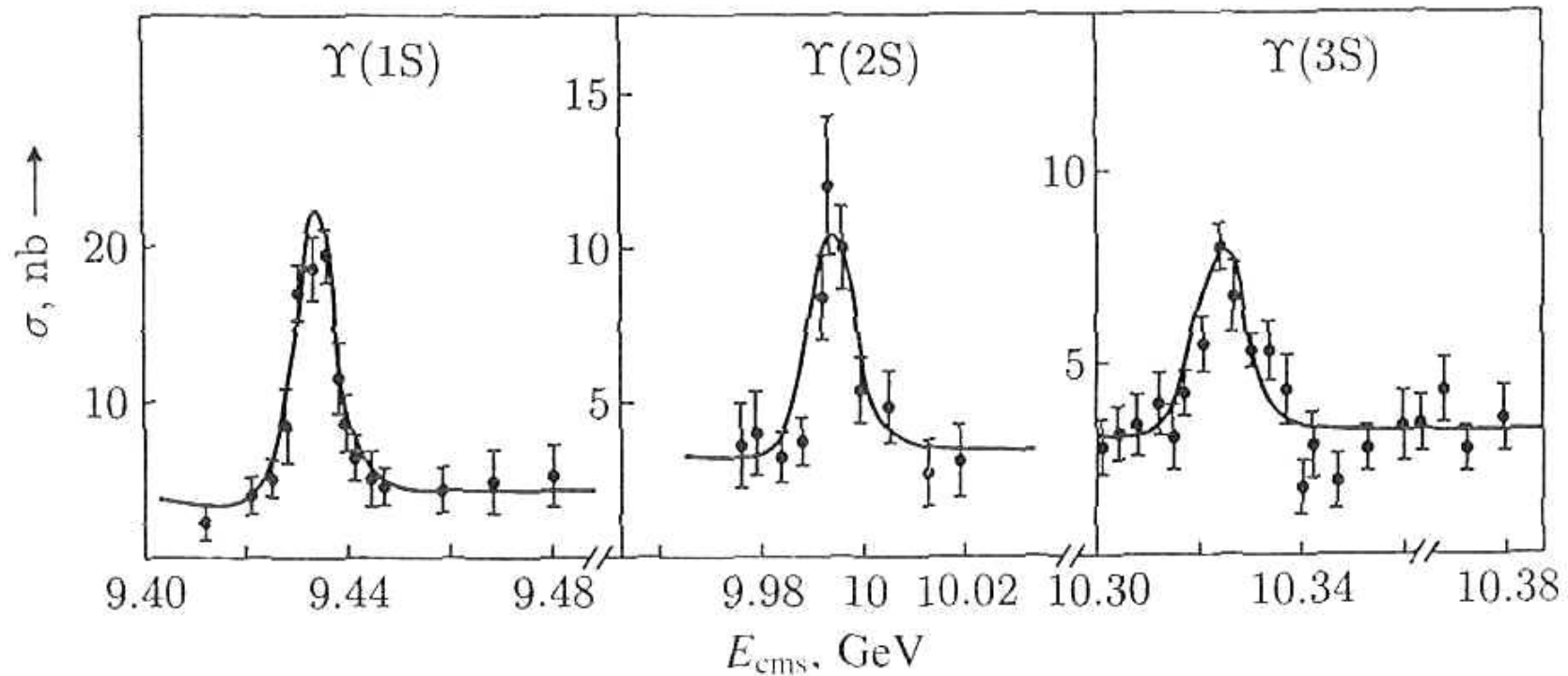
# Discovery of Beauty

- 1977
  - history repeats itself
  - another narrow resonance
  - this time at Fermilab
  - $p+\text{Be} \rightarrow \mu^+\mu^- + \text{anything}$
  - $p+\text{Cu} \rightarrow \mu^+\mu^- + \text{anything}$
  - $p+\text{Pt} \rightarrow \mu^+\mu^- + \text{anything}$
  - 400 GeV protons

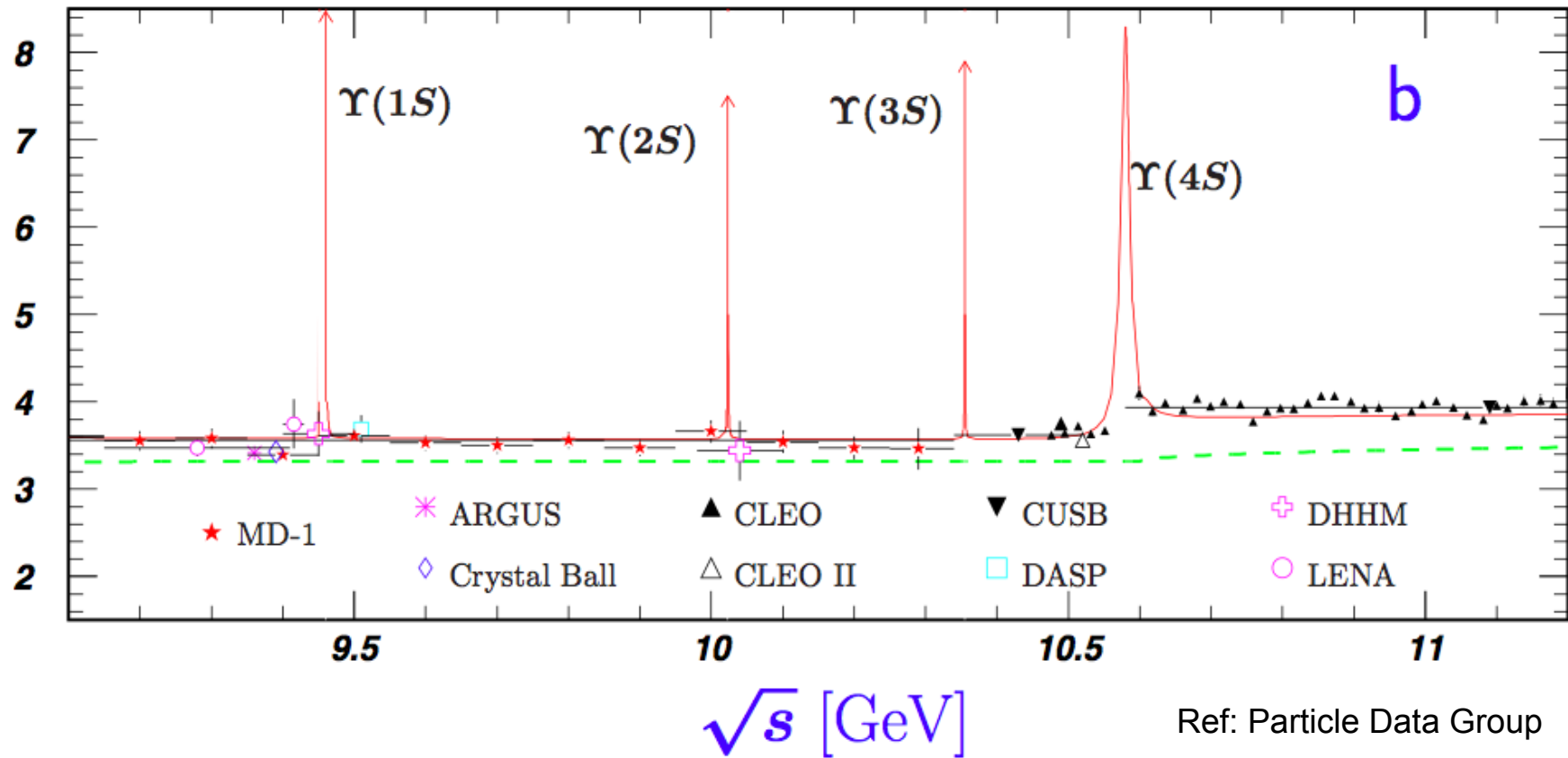


# Discovery of Beauty

- Electron-positron colliders refine measurements:
  - DORIS at DESY, CLEO at Cornell



# Discovery of Beauty



# Discovery of Beauty

	Mass (MeV)	$\Gamma_{ee}$ (keV)	$\Gamma$ (MeV)
$\Upsilon(1S)$	9460	1.34	0.054
$\Upsilon(2S)$	10023	0.61	0.032
$\Upsilon(3S)$	10355		0.020
$\Upsilon(4S)$	10579	0.27	$20.5 \pm 2.5$

Ref: Particle Data Group

# Naked Bottom

- $B^+(5278) = u\bar{b}$   $B=+1$
- $B^0(5279) = d\bar{b}$   $B=+1$
- $B^-(5278) = b\bar{u}$   $B=-1$
- $\bar{B}^0(5279) = b\bar{d}$   $B=-1$
  
- $\Lambda_b^0(5624) = udb$   $B=-1$
- $\Xi_b^0(5792) = usb$   $B=-1, S=-1$
- $\Xi_b^-(5792) = dsb$   $B=-1, S=-1$
  
- $\tau(\text{beauty}) \sim 10^{-12} \text{ sec}$

# Exotics

- The allowed combinations of  $S$  and  $Q$

for  $qqq$  baryons and  $q\bar{q}$  mesons

BARYONS

$S$	$Q$
0	2, 1, 0, -1
-1	1, 0, -1
-2	0, -1
-3	-1

MESONS

$S$	$Q$
1	1, 0
0	1, 0, -1
-1	0, -1

- Exotic QNs can be formed by  $qqqq\bar{q}$  or  $qq\bar{q}\bar{q}$  or only gluons (glueballs)