Particle Physics - Chapter 3
Heavy flavors – e^+e^- low energy

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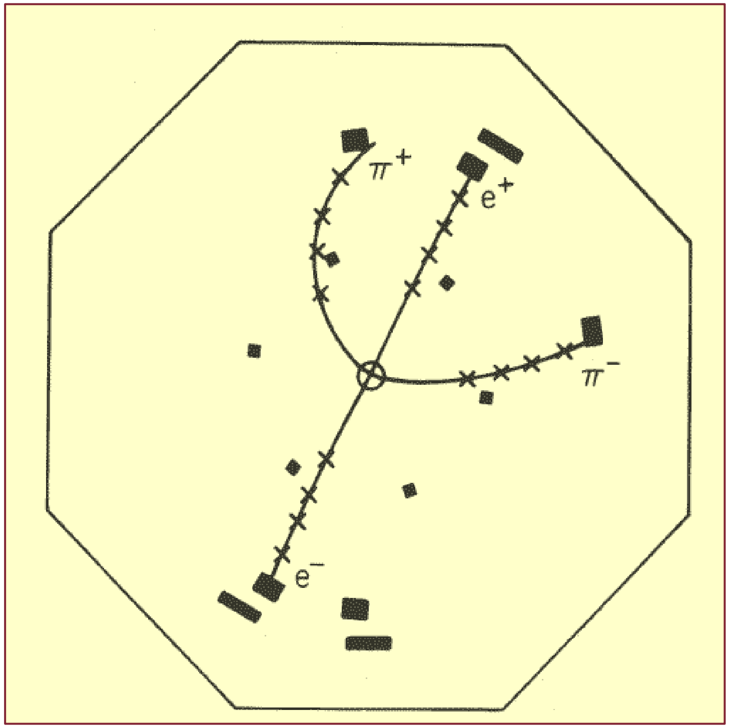
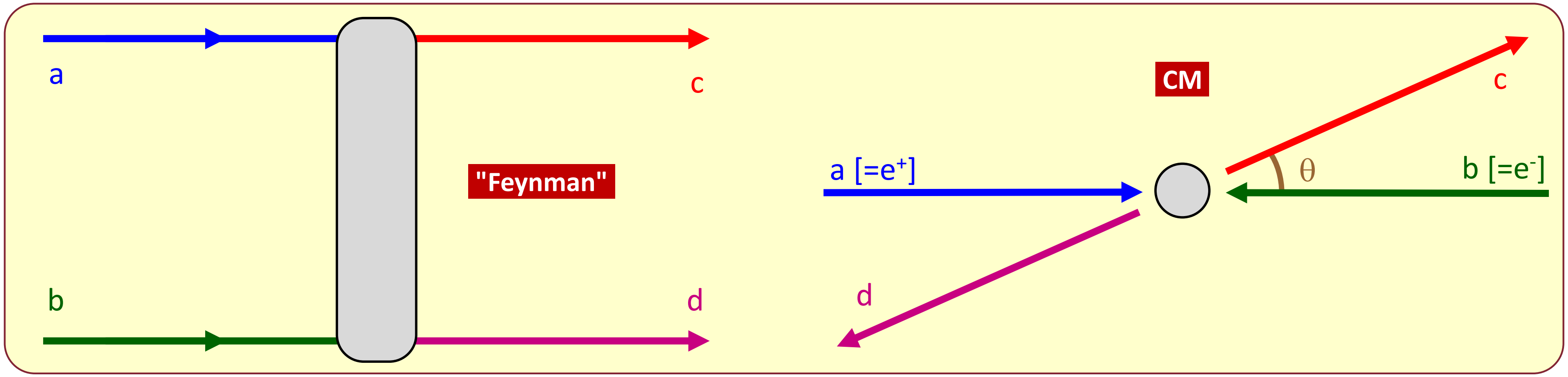
3 – Heavy flavors – e^+e^- low energy



much of h.f. studies have been performed in e^+e^- collisions; therefore this chapter contains also a discussion of this subject.

Mandelstam variables$^{(*)}$



The Mandelstam variables s, t, u:

CM system

- $p_a = [E, \quad p, \quad 0, \quad 0];$
- $p_b = [E, \quad -p, \quad 0, \quad 0];$
- $p_c = [E, p\cos\theta, p\sin\theta, \quad 0];$
- $p_d = [E, -p\cos\theta, -p\sin\theta, \quad 0];$

s,t,u L-invariant

- $s \equiv (p_a + p_b)^2 = (p_c + p_d)^2 = 4E^2;$
- $t \equiv (p_a - p_c)^2 = (p_b - p_d)^2 \approx -\frac{1}{2}\, s\,(1 - \cos\theta) = -s \sin^2(\theta/2);$
- $u \equiv (p_a - p_d)^2 = (p_b - p_c)^2 \approx -\frac{1}{2}\, s\,(1 + \cos\theta) = -s \cos^2(\theta/2);$
- $s + t + u = 0$ (→ 1+1 independent variables, e.g. $[E,\theta]$, $[s, t]$, $[\sqrt{s},\theta]$).

Lorentz-invariant variables for 2→2 processes.

Assume $E \gg m_i$, for the masses of all 4 bodies (otherwise, look for the formulæ in [PDG]).

Q. : what about φ (the azimuth) ?
A. : if nothing in the dynamics is φ-dependent (e.g. the spin direction), then the cross-section must be φ-symmetric.

$^{(*)}$ **NOT** specific of h.f. or e^+e^-; here just for convenience.

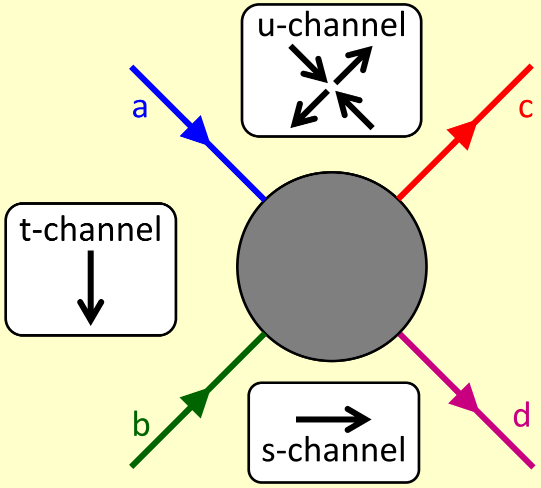
Mandelstam variables: $m_i \neq 0$

General case ab → cd, masses NOT negligible:

[p_i and p_j are 4-mom, $p_i p_j$ = dot product]

- $s \equiv (p_a + p_b)^2 = (p_c + p_d)^2 = m_a^2 + m_b^2 + 2p_a p_b;$
- $t \equiv (p_a - p_c)^2 = (p_b - p_d)^2 = p_a^2 + m_c^2 - 2p_a p_c;$
- $u \equiv (p_a - p_d)^2 = (p_b - p_c)^2 = p_a^2 + m_d^2 - 2\ p_a p_d;$
- $s + t + u = m_a^2 + m_b^2 + m_c^2 + m_d^2 +$
  $+ 2p_a(p_a + p_b - p_c - p_d) =$
  $= m_a^2 + m_b^2 + m_c^2 + m_d^2 = \Sigma_i\ m_i^2.$

In addition, the ***crossing symmetry*** *correlates the processes which are symmetric wrt time (s-, t-, and u-channels [see box]). If the c.s. is conserved in the interaction, the same amplitude is valid for all the channels, in their appropriate physical domains (an example on next page).*



s-channel	$ab \to cd$	$(\bar{p}p \to \bar{n}n)$
t-channel	$a\bar{c} \to \bar{b}d$	$(\bar{p}n \to \bar{p}n)$
u-channel	$a\bar{d} \to \bar{b}c$	$(\bar{p}\bar{n} \to \bar{p}\bar{n})$

an old approach (1950-80), now almost forgotten, especially important for strong interactions at low energies (see the example $\bar{p}p \to \bar{n}n$), where the dynamics was not calculable (still is not).

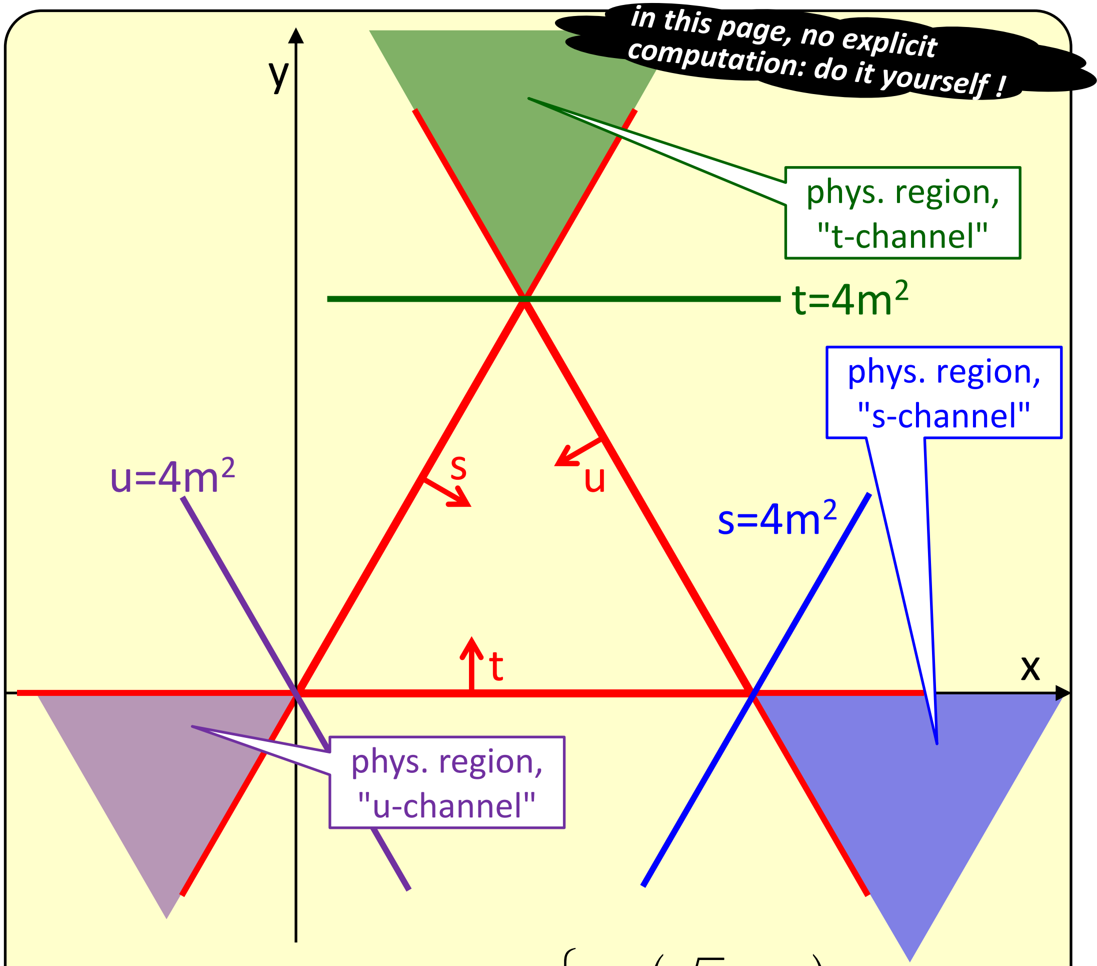
Mandelstam variables: example

Example : $m_a = m_b = m_c = m_d = m$;

- $s = 4E^2 \geq 4m^2$;
- $t = -4p^2\sin^2(\theta/2)$;
- $u = -4p^2\cos^2(\theta/2)$;

$$\left.\begin{matrix} s = 4E^2 \geq 4m^2; \\ t = -4p^2\sin^2(\theta/2); \\ u = -4p^2\cos^2(\theta/2); \end{matrix}\right\} s + t + u = 4m^2;$$

- in a xy plane draw an equilateral triangle of height $4m^2$, and label s-t-u the three sides and the lines through them (drawn in red);
- remember Viviani's theorem and its extension ("*the sum of the signed distances between a point and the lines of a triangle is a constant*");
- find the physical regions (i.e. the allowed values of s-t-u) for the given process (i.e. the "s-channel") and for the t and u channels;
- among s-t-u, only two variables are independent → the "space of the parameters" is 2D.



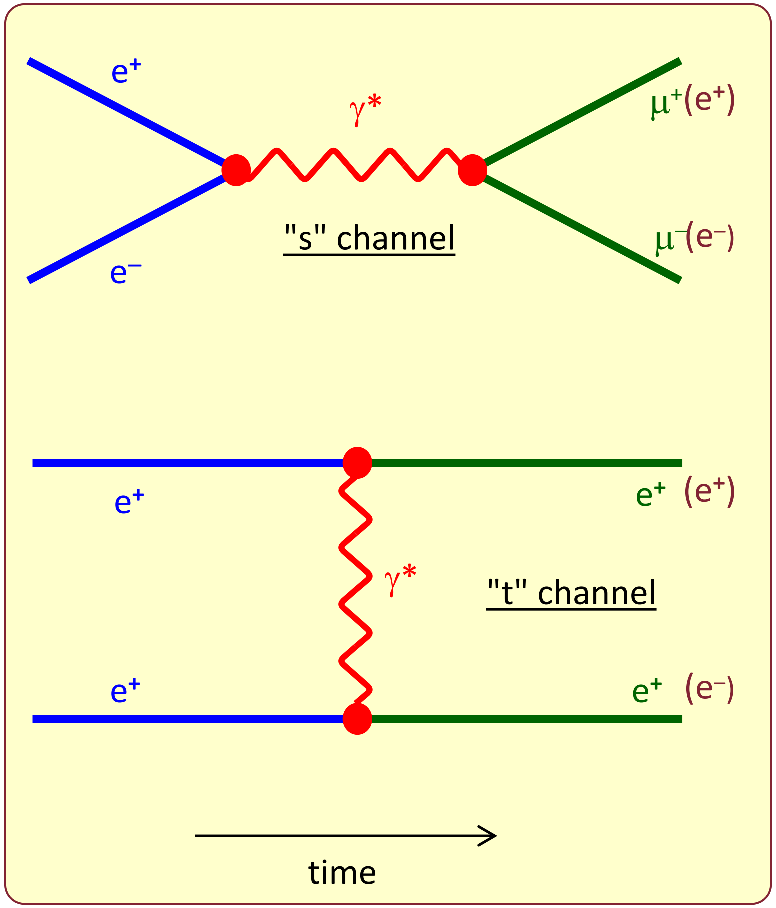
in this page, no explicit computation: do it yourself !

$$\begin{cases} x = \dfrac{4m^2 + s - u}{\sqrt{3}} \\ y = t = 4m^2 - s - u \end{cases} \rightarrow \begin{cases} s = \left(\sqrt{3}x - y\right)/2 \\ t = y \\ u = 4m^2 - \left(\sqrt{3}x + y\right)/2. \end{cases}$$

Mandelstam variables: s vs t

- in a "s-channel" process (e.g. $e^+e^- \to \mu^+\mu^-$), the |4-momentum|^2 of the mediator γ^* is exactly s [i.e. m(γ^*) = $\sqrt{s}$, $\sqrt{s} > 0$];
- in a "t-channel" process (e.g. $e^+e^+ \to e^+e^+$), the |4-momentum|^2 of the mediator (γ^* also in this case) is t [t < 0 !!!] ;
- some processes (e.g. $e^+e^- \to e^+e^-$, called "Bhabha scattering") have more than one Feynman diagrams; some of them are of type s and some others of type t; in such a case we say it is a sum of "s-type diagrams" and "t-type diagrams" + the interference,

... although, *needless to say*, on an event-by-event basis, the observer does **NOT** know whether the event was *s* or *t*.



This discussion is over-simplified, e.g. "the u-channel" is not even mentioned. However, it is sufficient for the experimental results of this chapter.

Mandelstam variables: 1/s

- in absence of polarization, the cross sections of a process "X" does NOT depend on the azimuth φ :

$$\frac{d\sigma_{"X"}}{d\Omega} = \frac{1}{2\pi}\frac{d\sigma_{"X"}}{d\cos\theta} = \frac{s}{4\pi}\frac{d\sigma_{"X"}}{dt}.$$

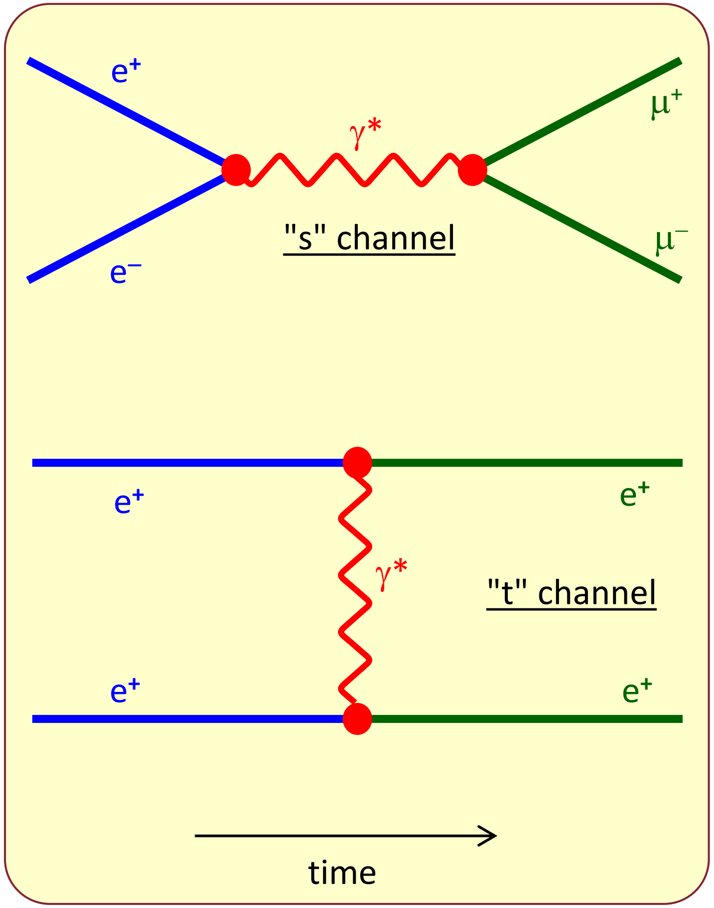
- for $m^2 << s$, if $\mathcal{M}_{"X"}$ is the matrix element of the process$^{(*)}$:

$$\frac{d\sigma_{"X"}}{dt} = \frac{\left|\mathcal{M}_{"X"}\right|^2}{16\pi s^2}.$$

- in lowest order QED, if $m^2 << s$:

$$\frac{d\sigma_{"X"}}{d\cos\theta} = \frac{\left|\mathcal{M}_{"X"}\right|^2}{32\pi s} = \frac{\alpha^2}{s} f(\cos\theta).$$

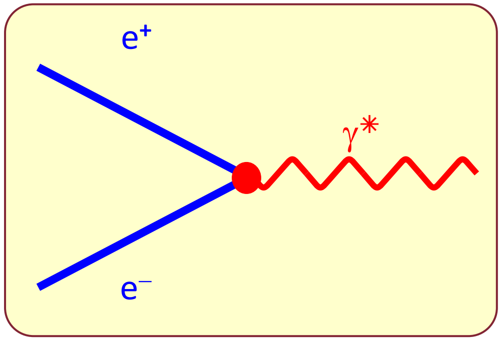
- when θ → 0, cos θ → 1 :
  - s-channel : f(cos θ) → constant;
  - t-channel : f(cos θ) → ∞.



(*) also by dimensional analysis :
$[c = \hbar = 1]$, $[\sigma] = [\ell^2]$; $[t] = [s] = [\ell^{-2}]$;
therefore, in absence of any other dimensional scale,
σ [and dσ/dΩ] = [number] × 1/s.

Collisions e^+e^- : initial state

- At low energy$^{(*)}$, the main processes happen with annihilation into a virtual γ^*.
- The initial state is :
  - charge = 0;
  - lepton (+ baryon + other additive) number = 0;
  - spin = 1 ("γ^*");
- CM kinematics :
  - e^+ [E, p, 0, 0];
  - e^- [E, −p, 0, 0];
  - γ^* [2E,0, 0, 0];
  - $m(\gamma^*) = \sqrt{s} = 2E$ [virtual photon, short lived].

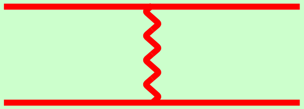
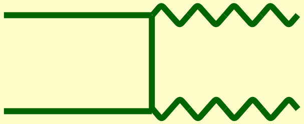
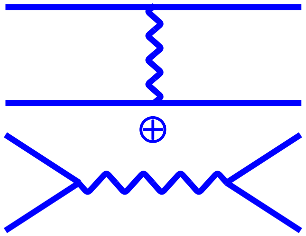
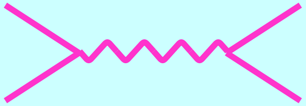


In this chapter, we will stay in the "low energy" regime.

$^{(*)}$ "low energy" ($m_f << \sqrt{s} = E_{CM} = 2E = m_{\gamma*} << m_Z$), where m_f are the masses of all (initial+final) fermions. When $E_{CM} \sim m_Z$, a $Z^{(*)}$ may also be formed; the process $e^+e^- \to Z$ resonates at $\sqrt{s} = m_Z$ and becomes dominant (see Collider Physics, § LEP).

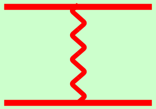
Collisions e^+e^- : QED cross sections

Consider some QED processes in lowest order [$\sqrt{s} \ll m_Z$, only γ^* exchange] :

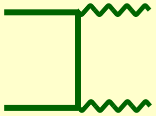
➢ $e^\pm e^\pm \to e^\pm e^\pm$		$\frac{d\sigma(e^\pm e^\pm \to e^\pm e^\pm)}{d\cos\theta} = \frac{2\pi\alpha^2}{s} \times \left(\frac{3+\cos^2\theta}{1-\cos^2\theta}\right)^2;$
➢ $e^+e^- \to \gamma\gamma$		$\frac{d\sigma(e^+e^- \to \gamma\gamma)}{d\cos\theta} = \frac{2\pi\alpha^2}{s} \times \frac{1+\cos^2\theta}{1-\cos^2\theta};$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

Collisions e⁺e⁻ : QED dσ/dcosθ

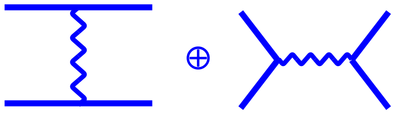
$$\frac{d\sigma(e^\pm e^\pm \to e^\pm e^\pm)}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\times\left(\frac{3+\cos^2\theta}{1-\cos^2\theta}\right)^2;$$



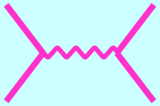
$$\frac{d\sigma(e^+e^- \to \gamma\gamma)}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\times\frac{1+\cos^2\theta}{1-\cos^2\theta};$$

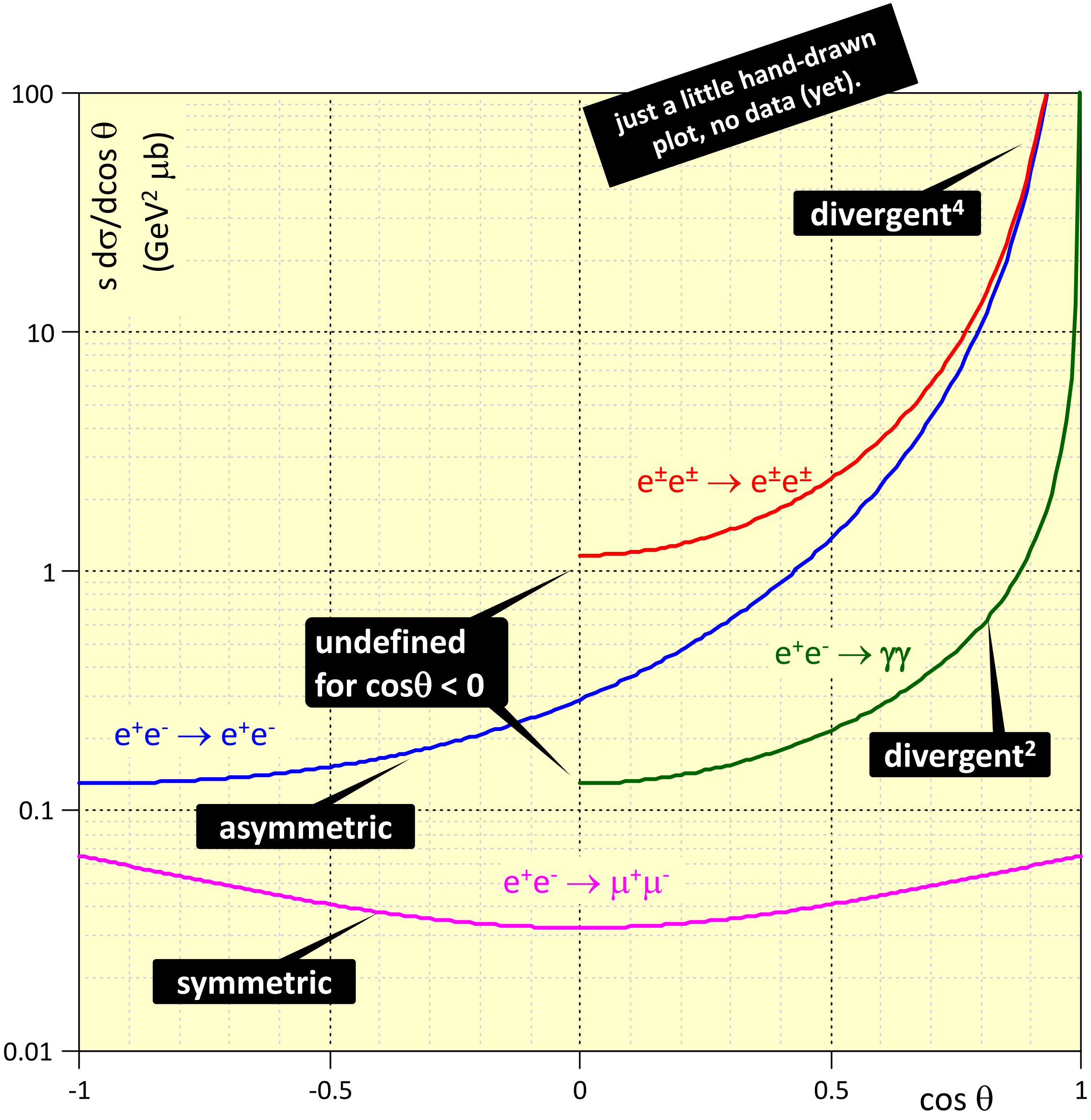


$$\frac{d\sigma(e^+e^- \to e^+e^-)}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\times\left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2;$$



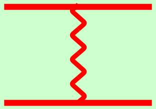
$$\frac{d\sigma(e^+e^- \to \mu^+\mu^-)}{d\cos\theta} = \frac{\pi\alpha^2}{2s}\times\left(1+\cos^2\theta\right);$$



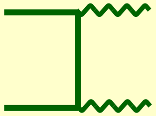


Collisions e^+e^- : QED $d\sigma/d\cos\theta$

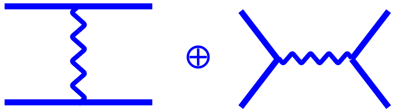
$$\frac{d\sigma(e^\pm e^\pm \to e^\pm e^\pm)}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\times\left(\frac{3+\cos^2\theta}{1-\cos^2\theta}\right)^2;$$



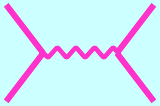
$$\frac{d\sigma(e^+e^- \to \gamma\gamma)}{d\cos\theta} = \frac{2\pi\alpha^2}{s}\times\frac{1+\cos^2\theta}{1-\cos^2\theta};$$



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



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



some little gymnastics:

- compute a value, just to understand:

$$s\frac{\sigma(e^+e^- \to e^+e^-)}{d\cos\theta}\bigg|_{\substack{s=1\text{GeV}^2\\ \cos\theta=-1}} = (\hbar c)^2\, 2\pi\alpha^2 =$$

$$\approx \frac{0.389\times10^3\times2\times3.14}{137^2} \approx 0.13\ \text{GeV}^2\mu\text{b}.$$

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

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

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

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

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

Collisions e^+e^- : $e^+e^- \to \mu^+\mu^-, q\bar{q}$

- kinematics, computed in CM sys, $\sqrt{s} >> m_e, m_\mu$:

e^+ $(E, \quad p, \quad 0, \; 0);$

e^- $(E, \quad -p, \quad 0, \; 0);$

μ^+ $(E, \; p\cos\theta, \; p\sin\theta, \; 0);$

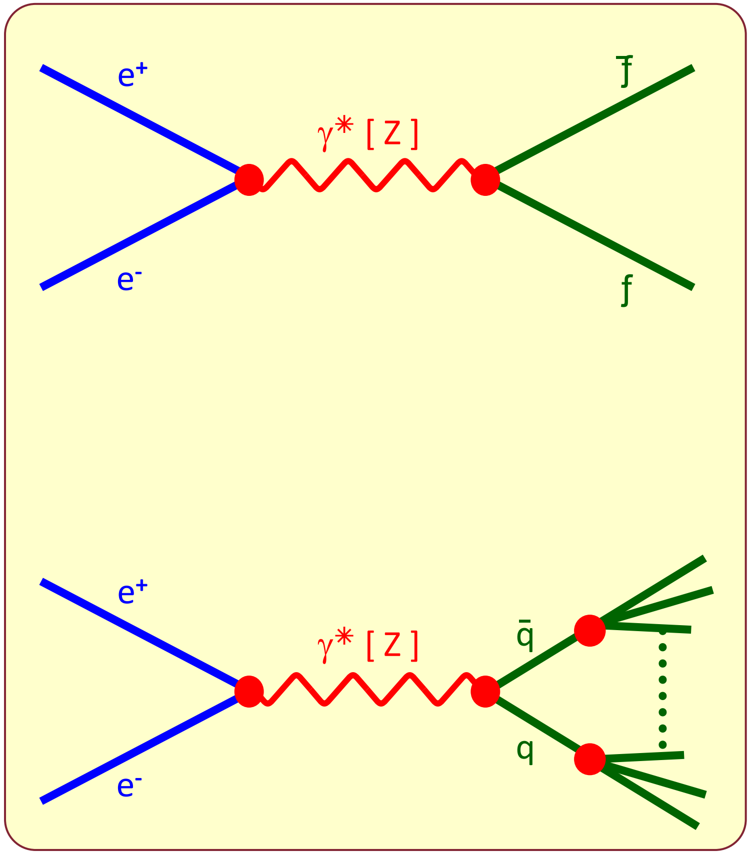
μ^- $(E, -p\cos\theta, -p\sin\theta, \; 0);$

$p \approx E = \sqrt{s}/2;$

$\vec{p}(e^+) \cdot \vec{p}(\mu^+) \approx E^2 \cos\theta \approx s \cos\theta / 4;$

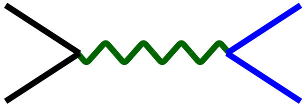
$p(e^+)\, p(\mu^+) \approx E^2 (1 - \cos\theta) = s \sin^2(\theta/2) = -t;$

- the case $e^+e^- \to q\bar{q}$ is similar at parton level; however free (anti-)quarks do NOT exist → quarks hadronize, producing collimated jets of hadrons [+ *subtleties due to the fact that hadrons and leptons, unlike quarks, are color singlets with integer charge*] .



Collisions e^+e^- : $\sigma(e^+e^- \to \mu^+\mu^-, q\bar{q})$

- $e^+e^- \to \mu^+\mu^-$



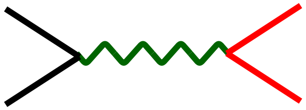
$$\sigma_{\mu\mu} = \int_{-1}^{1} d\cos\theta \left[\frac{d\sigma_{\mu\mu}}{d\cos\theta}\right] = \frac{\pi\alpha^2}{2s}\int_{-1}^{1} d\cos\theta\left(1+\cos^2\theta\right) = $$

$$= \frac{4\pi\alpha^2}{3s} = \frac{86.8\text{ nb}}{s[\text{GeV}^2]} = \frac{21.7\text{ nb}}{E^2_{\text{beam}}[\text{GeV}^2]}.$$

$[1+\cos^2\theta] = P_1^{\text{Legendre}}(\cos\theta)$

[spin 1 → 2 spin ½]

- $e^+e^- \to q\bar{q}$



$$\frac{d\sigma_{q\bar{q}}}{d\cos\theta} = \frac{d\sigma_{\mu\mu}}{d\cos\theta}\times c_f e_f^2 = \frac{\pi\alpha^2}{2s}c_f e_f^2\left(1+\cos^2\theta\right);\ c_f = \begin{Bmatrix} 3 & \text{quarks} \\ 1 & \text{leptons} \end{Bmatrix} \quad [\text{color}]$$

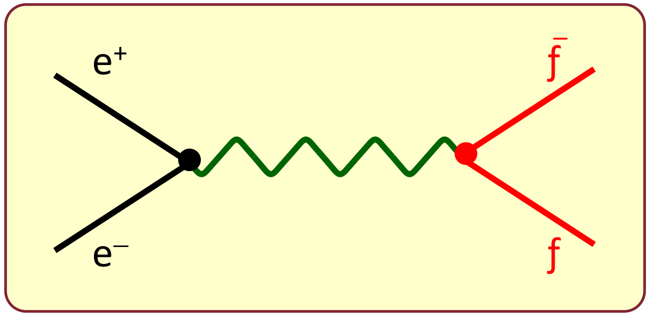
$$\sigma_{q\bar{q}} = \sigma_{\mu\mu} c_f e_f^2 = \frac{4\pi\alpha^2}{3s} c_f e_f^2; \qquad e_f = \begin{Bmatrix} 1 & \text{leptons} \\ 2/3 & u\ c\ t \\ -1/3 & d\ s\ b \end{Bmatrix} \quad [\text{charge}].$$

In the approx $m_e << \sqrt{s}$, $m_f << \sqrt{s}$ (i.e. light quarks). If m_f NOT negligible,use the complete formula [see next slide].

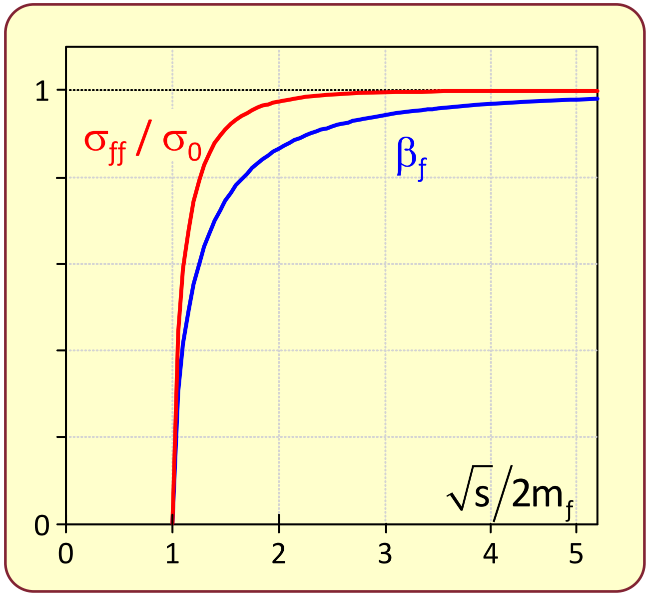
Collisions e^+e^- : $m_f > 0$

Previous formulæ NOT correct if m_f NOT negligible, e.g. near the threshold for the production of heavy quarks/leptons, $\sqrt{s} \approx 2m_f$.

→ list (no proof) the formulæ for $e^+e^- \to f\bar{f}$ $(2m_e << \sqrt{s} \approx 2m_f)$:



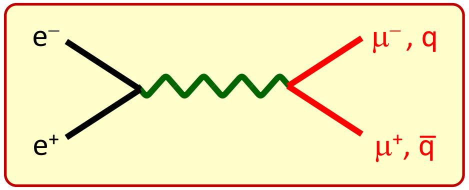
- $\beta_f = \sqrt{1 - \frac{4m_f^2}{s}}$ (see blue curve);
- $\frac{d\sigma_{f\bar{f}}}{d\cos\theta} = \frac{\pi\alpha^2 c_f e_f^2}{2s} \beta_f \left[\left(1 + \cos^2\theta\right) + \left(1 - \beta_f^2\right)\sin^2\theta \right]$;
- $\sigma_{f\bar{f}} = \boxed{\frac{4\pi\alpha^2}{3s}} \beta_f \frac{3 - \beta_f^2}{2} = \boxed{\sigma_0} \beta_f \frac{3 - \beta_f^2}{2}$ (see red curve).



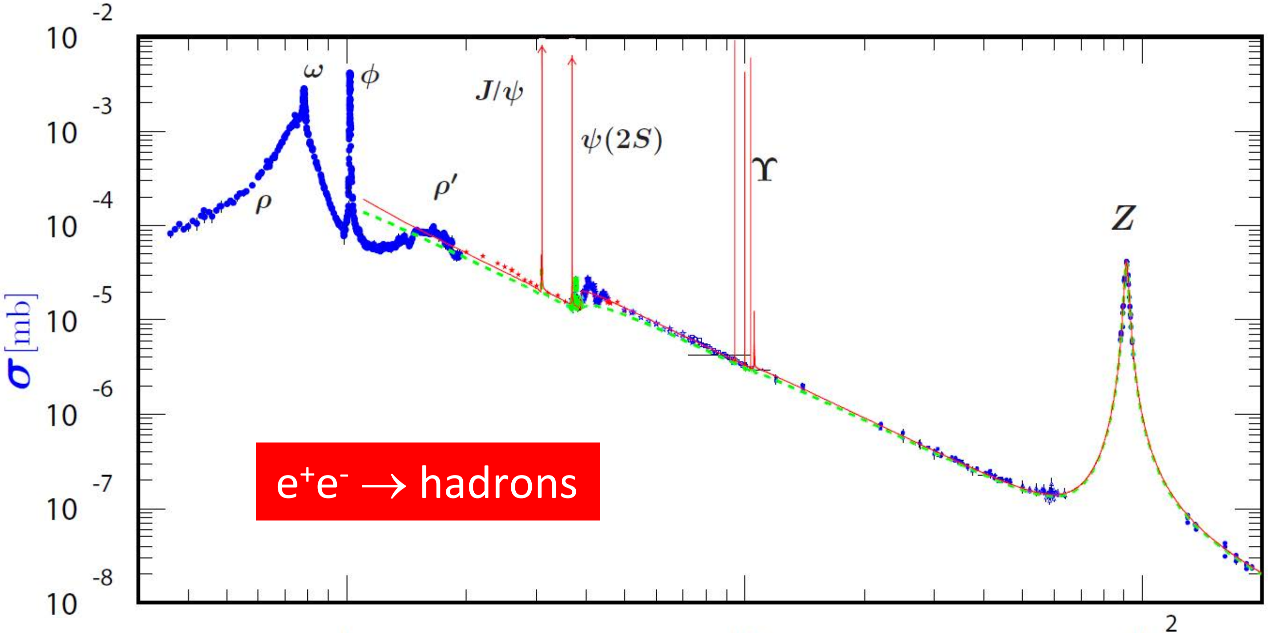
Clearly:

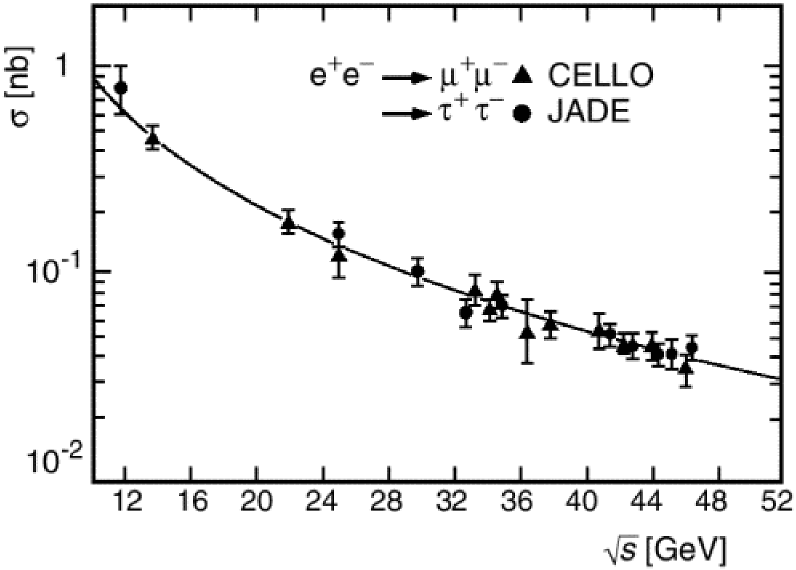
- $\sqrt{s} < 2m_f \to$ no f production;
- $\sqrt{s} \gg 2m_f \to 2m_f / \sqrt{s} \to 0, \ \beta_f \to 1, \ \sigma_{f\bar{f}} \to \sigma_0$.

Collisions e^+e^- : $\sigma_{\text{large}\sqrt{s}}(e^+e^- \to \mu^+\mu^-, q\bar{q})$



$$\sigma_{\mu\mu} = \frac{4\pi\alpha^2}{3s} = \\ = \frac{86.8\ \text{nb}}{s[\text{GeV}^2]} = \frac{21.7\ \text{nb}}{E^2[\text{GeV}^2]}.$$



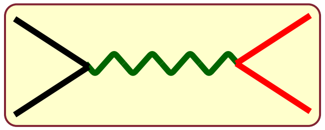


- the continuum, for $0.5 \le \sqrt{s} \le 50$ GeV, agrees well with the predicted $1/s$ [the line in log-log scale];
- + resonances $q\bar{q}$ [the bumps];
- for $\sqrt{s} > 50$ GeV [e.g. LEP] it is dominated by the Z formation in the s-channel.

Collisions e^+e^- : $R = \sigma(q\bar{q})/\sigma(\mu^+\mu^-)$

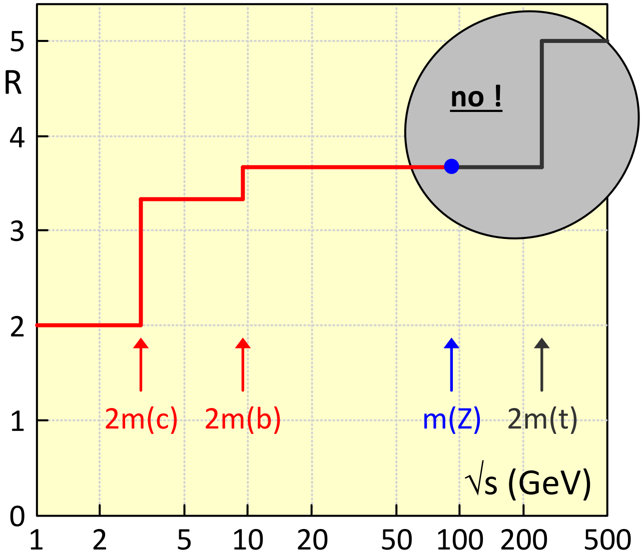
- define the quantity, both simple conceptually and easy to measure:

$$\boxed{R = \frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)} = 3\sum\nolimits_{\text{quarks}} e_i^2 = R\left(\sqrt{s}\right);}$$



en passant, a powerful test of the existence of the color quantum number

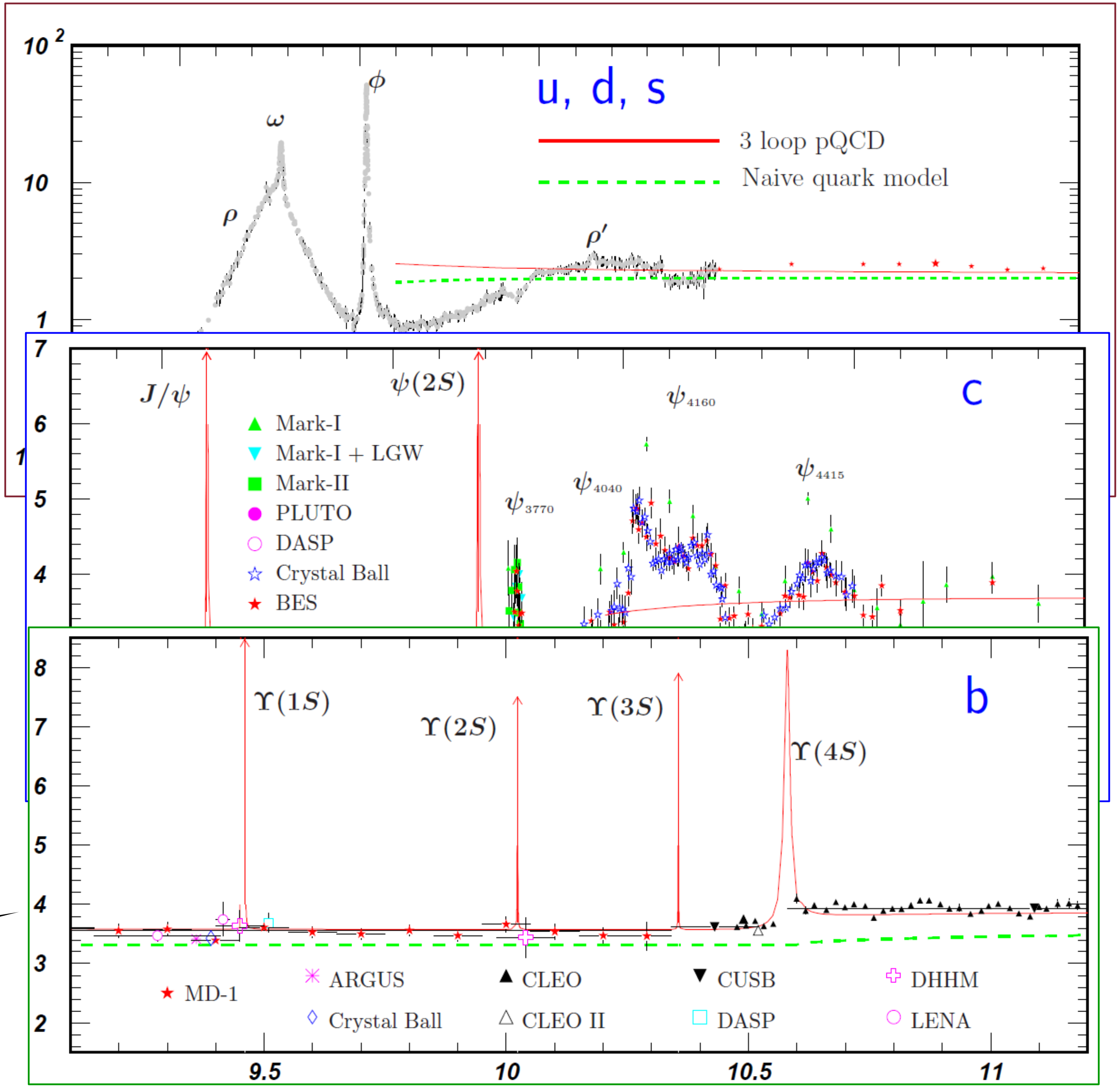
- sum over all the quarks, produced at energy $\sqrt{s}$ (i.e. $2m_q < \sqrt{s}$) :
  - $0 < \sqrt{s} < 2\,m_c$: $R = R_{uds} = 3 \times [\,({}^{2}/_{3})^2 + ({}^{-1}/_{3})^2 + ({}^{-1}/_{3})^2\,] = 2$;
  - $2\,m_c < \sqrt{s} < 2\,m_b$: $R = R_{udsc} = R_{uds} + 3 \times ({}^{2}/_{3})^2 = 3 + {}^{1}/_{3}$;
  - $2\,m_b < \sqrt{s} < 2\,m_t$: $R = R_{udscb} = R_{udsc} + 3 \times ({}^{-1}/_{3})^2 = 3 + {}^{2}/_{3}$;
  - ~~$2\,m_t < \sqrt{s} < \infty$: $R = R_{udscbt} = R_{udscb} + 3 \times ({}^{2}/_{3})^2 = 5$~~;
- but reality is more complicated :
  - the step at $\sqrt{s} = 2m_q$ is rounded [*see before*];
  - $q\bar{q}$ resonances are formed at $\sqrt{s} \approx 2m_q$; their decay modes affects the measurement of R;
  - at $\sqrt{s} \approx m_Z$ [and $\sqrt{s} \approx 2m_W$] the weak interactions change completely the scenario → for $\sqrt{s} \geq 50$ GeV, R has a different explanation [*e.g. LEP*];
  - also notice that $m_Z < 2m_t$; therefore the "t step" happens at higher $\sqrt{s}$ than the Z resonance.



Collisions e^+e^- : R vs √s (small √s)

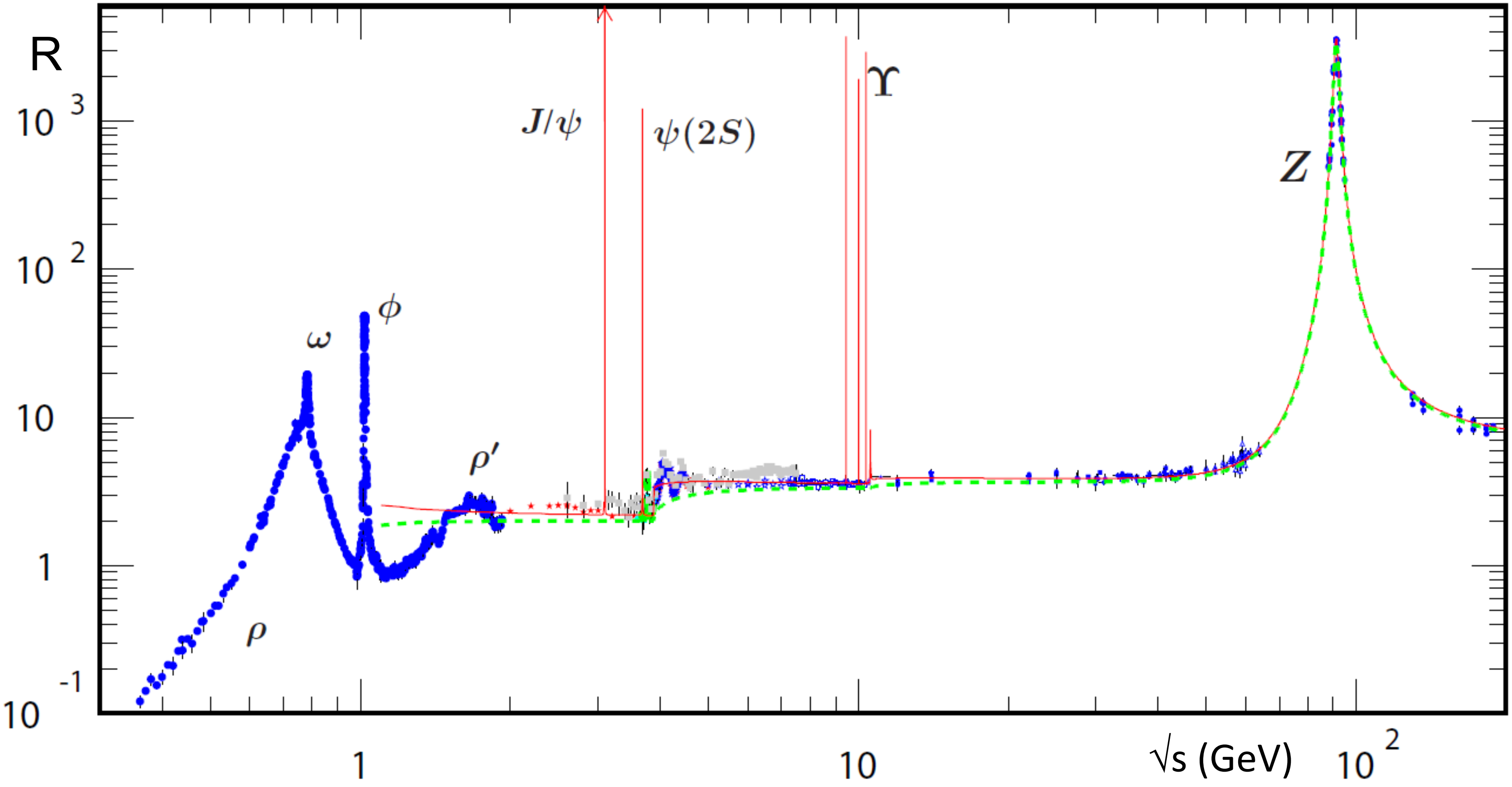
Plot R vs √s (=2E):

- resonances $u\bar{u}$, $d\bar{d}$, $s\bar{s}$ at 1-2 GeV (only those with $J^P=1^-$) (→"vector dominance");
- step at $2m_c$ (J/ψ);
- step at $2m_b$ (ϒ);
- slow increase at √s > 50 GeV (Z, next slide);
- [lot of effort required, as demonstrated by the number of detectors and accelerators];
- strong evidence for the color (factor 3 necessary).



plots from [PDG, 588]

Collisions e^+e^- : R vs √s (large √s)

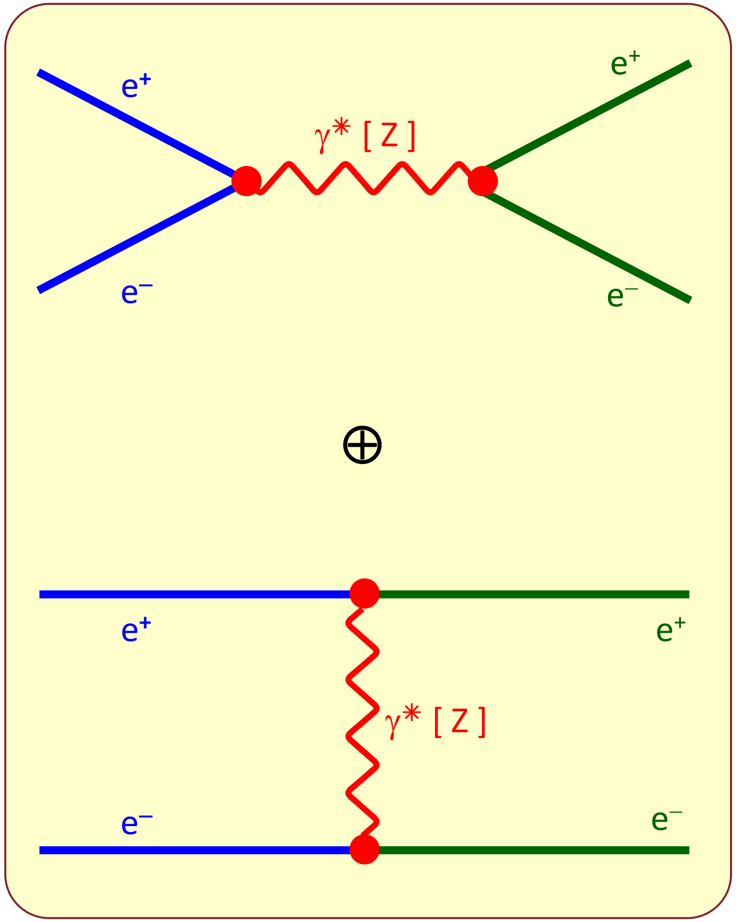


- The full range 200 MeV < √s < 200 GeV (3 orders of magnitude !!!).
- For √s > 50 GeV new phenomenon: electroweak interactions and the Z pole.

Collisions e^+e^- : $e^+e^- \rightarrow e^+e^-$

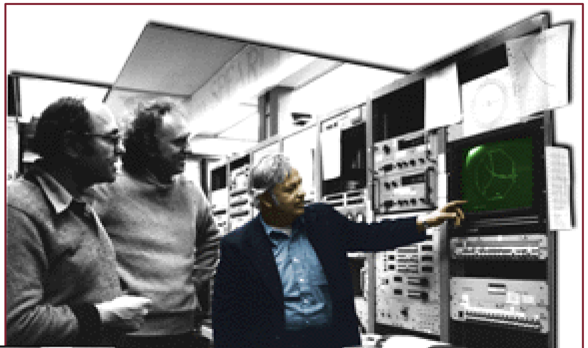
The case $e^+e^- \rightarrow e^+e^-$ (Bhabha scattering) is different, as seen before:

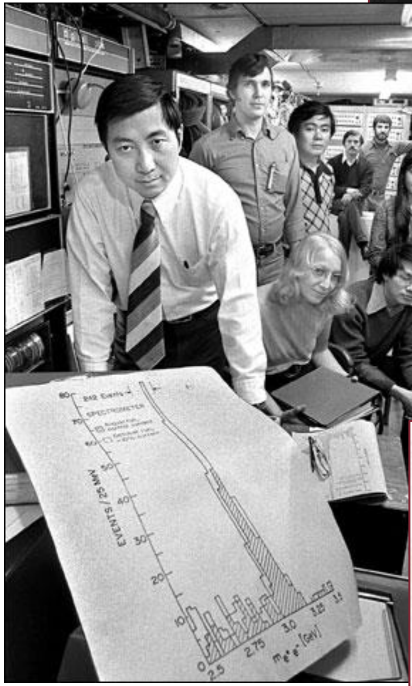
- two Feynman diagrams with a spin-1 boson exchange (γ^* [+ Z at higher energy]) :
    - s-channel, similar to $\mu^+\mu^-$;
    - t-channel, like e^+e^+;
    - interference between the two diagrams [four at higher energies];
- the angular distribution (see before) reflects these differences;
- [*il va sans dire que*] on an event-by-event basis it is NOT possible to determine whether an event belongs to s- or t-channel; however, different regions of the final state parameter space are actually dominated by s- or t-channel [*therefore physicists speak of "s-channel" physics (e.g. the formation of resonances) or t-channel physics (e.g. Bhabha at small* θ)].



The November Revolution

- The u,d,s quarks have not been predicted; in fact the mesons and baryons have been discovered, and later interpreted in terms of their quark content [§ 1];
- ***Some theoreticians had predicted another quark, based on*** **(no $K^0 \to \mu^+\mu^-$)*, but people did not believe it.***
- In November 1974, the groups of Burton Richter (SLAC) and Samuel Ting (Brookhaven) discovered simultaneously a new state with a mass of $\approx$ 3.1 GeV and a tiny width, much smaller than their respective mass resolution.
- Ting & coll. had the name "J", while Richter & coll. called it "ψ". Today's name is "J/ψ".
- We split the discussion : start with the hadronic experiment.
- The width was measured, after some time, to be 0.087 MeV, a surprisingly small value for a resonance of 3 GeV mass.





the two experiments are quite different: we will review first the "J" and then the "ψ".

The November Revolution : J

- The group of Ting at the AGS proton accelerator measured the inclusive production of e^+e^- pairs in interactions of 30 GeV protons on a plate of beryllium :

  $$p\ Be \rightarrow e^+ e^- X.$$

- The experiment was searching mass resonances with $J^P = 1^-$ ($= \gamma$), decaying into (e^+e^-) pairs with the "Drell-Yan" process [*see later*].

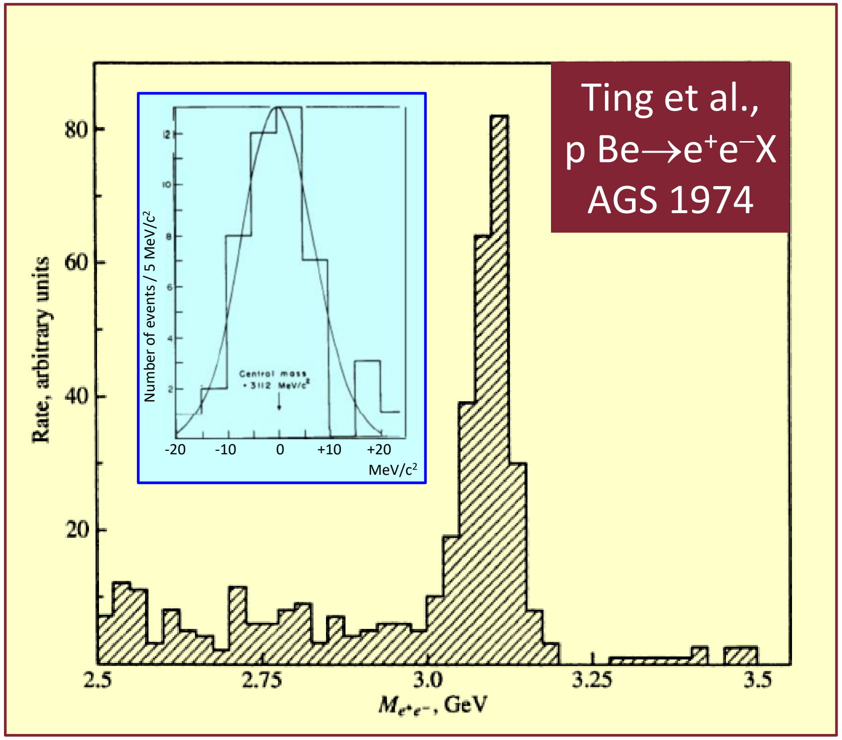
- The key feature of the experiment was the very good resolution in $m(e^+e^-)$:

  $$\Delta m(e^+e^-) \approx 10\ \text{MeV}.$$

- This resolution allowed for a much higher sensitivity wrt other previous exp.'s (e.g. Lederman's), which studied $\mu^+\mu^-$ pairs in the same range. Lederman had a "shoulder" in $d\sigma/dm(\mu^+\mu^-)$, but no conclusive evidence [*next slide*].

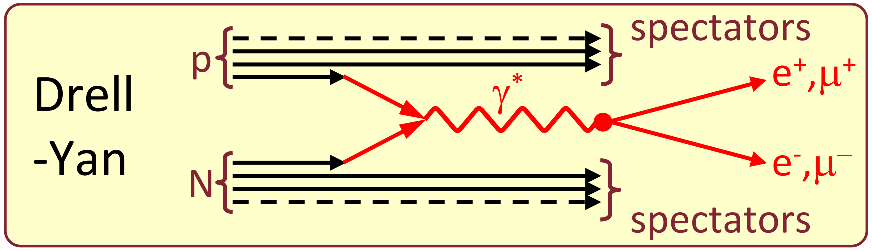
- Ting called the new particle "J", because of the e.m. current.

Measured quantum numbers of the J:
- mass ~3.1 GeV;
- width < 5 MeV (see fig., it is $\sigma_{meas.}$, not Γ_{BW});
- charge = 0;
- $J^P = 1^-$;
- no meas. of isospin, Γ, other decay modes …

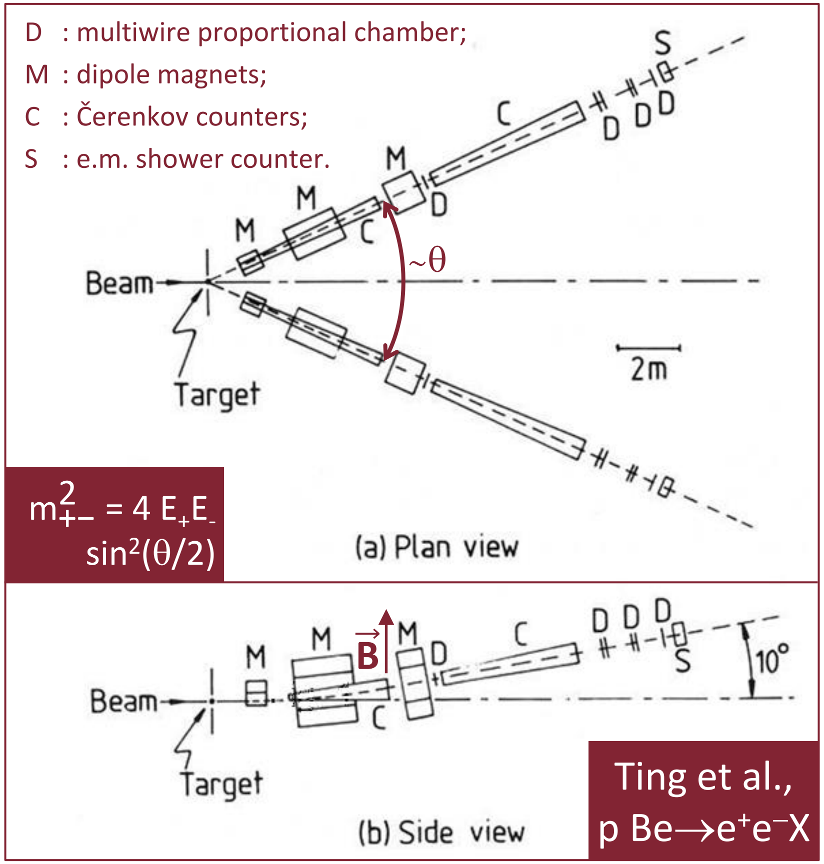


Ting et al.,
$p\ Be \rightarrow e^+e^-X$
AGS 1974

The November Revolution : the J experiment



- The Ting experiment used a two arm magnetic spectrometer, to measure separately the electron and the positron.
- Leptonic events are rare → very intense beams (2×10^{12} ppp $^{(*)}$) → high rejection power (~10^8) to discard hadrons, that can fake e^+e^- or $\mu^+\mu^-$.
- Advantage in the $\mu^+\mu^-$ case: μ penetration → select leptons from hadrons with a thick absorber in a large solid angle → larger acceptance, higher counting rate.
- Disadvantage : thick absorber → multiple scattering → worst mass resolution.
- Benefit in the e^+e^- case: electron identification with Čerenkov counter(s) + calorimeters → simpler setup.
- Disadvantage : small instrumented solid angle → smaller yield.


D : multiwire proportional chamber;
M : dipole magnets;
C : Čerenkov counters;
S : e.m. shower counter.

$m^2_{+-} = 4 E_+E_- \sin^2(\theta/2)$

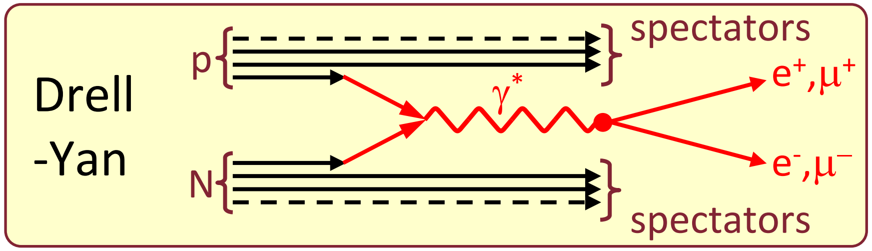
(a) Plan view

(b) Side view

Ting et al.,
p Be→e^+e^-X

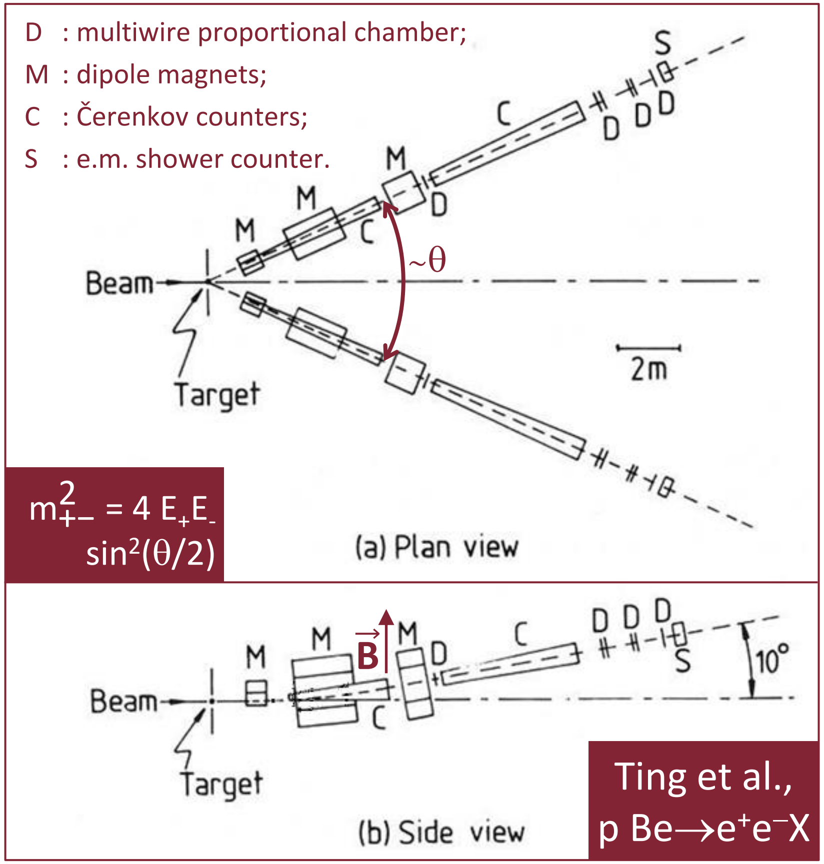
$^{(*)}$ "ppp" : "particles (or protons) per pulse", i.e. once per accelerator cycle every few seconds; it is the typical figure of merit of a beam from an accelerator.

The November Revolution : the J exp.



"p, θ independent concept"
→ vary $|\vec{B}|$

$$
\begin{aligned}
p^+ &= \left[E^+,\ p^+\cos(\theta/2),\ p^+\sin(\theta/2),\ \ 0\right] = \\
&\approx \left[E^+,\ E^+\cos(\theta/2),\ E^+\sin(\theta/2),\ \ 0\right] \\
p^- &\approx \left[E^-,\ E^-\cos(\theta/2),\ -E^-\sin(\theta/2),\ 0\right]; \\
\boxed{m^2_{+-}} &= (p^+ + p^-)^2 = \cancel{m}^2 + \cancel{m}^2 + 2p^+\cdot p^- = \\
&\approx 2E^+E^-\left[1 - \cos^2(\theta/2) + \sin^2(\theta/2)\right] = \\
&\boxed{= 4E^+E^-\sin^2(\theta/2)}.
\end{aligned}
$$



$m^2_{+-} = 4\,E_+E_-\,\sin^2(\theta/2)$

Ting et al.,
p Be→e^+e^-X

The November Revolution : $\Delta m_{c\bar{c}}$

Problem (see previous slides)

Three similar exp. distributions:

$d\sigma(\text{hadron Nucleus} \to \ell^+ \ell^- X) / dm_{\ell\ell}$.

Similar dynamics:

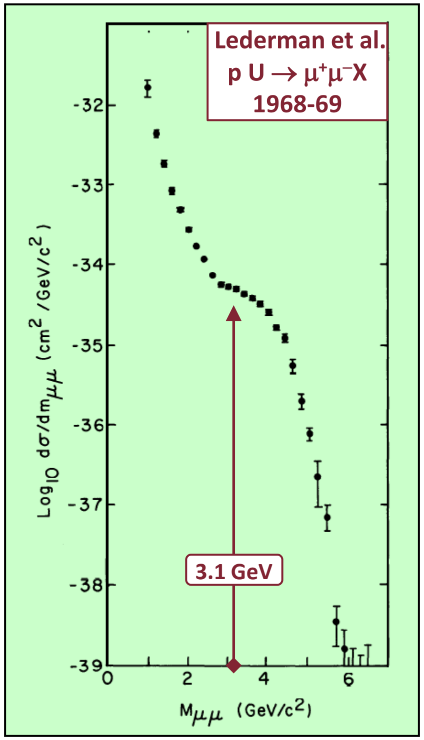
- continuum, exponentially falling [*yes, even in Ting's plot*];
- resonance(s) on top [*look Michelini's*].

Differences:

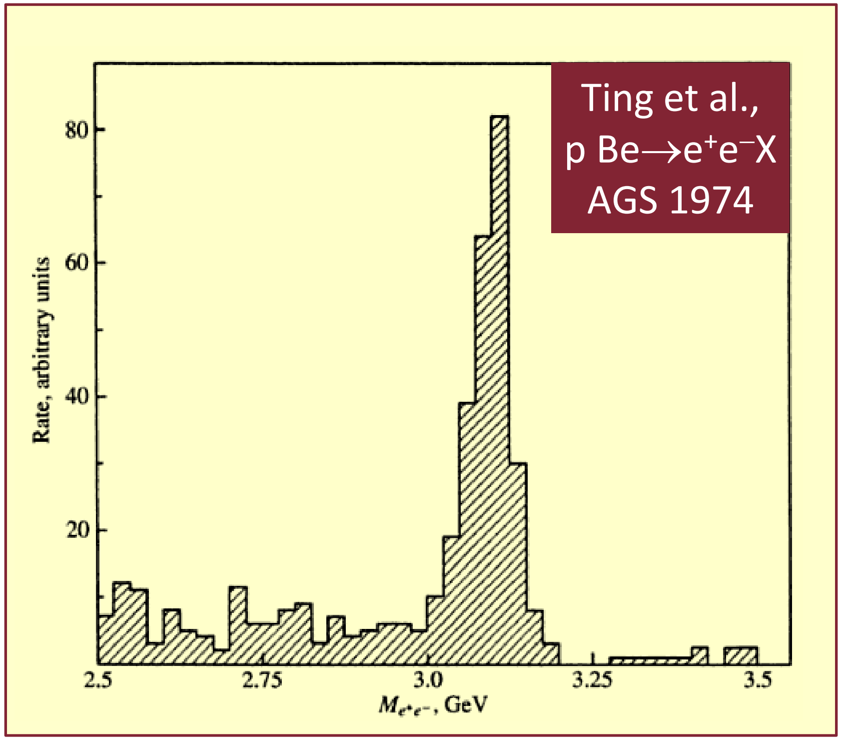
- $m_{\ell\ell}$ resolution [*!!! why ?*];
- horizontal scale (i.e. mass interval);
- vertical scale (i.e. resonance size)

Please comment on:

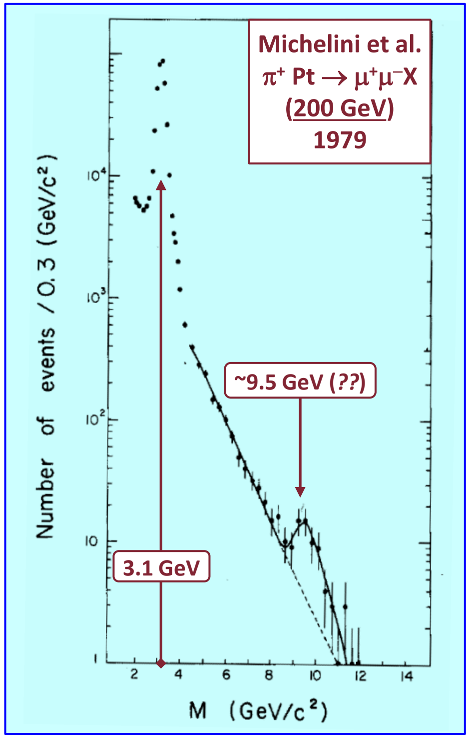
- effect of these differences on ratio resonance/continuum (→ discovery ?);
- "quality" of the experiments.



Lederman et al.
$p\,U \to \mu^+\mu^- X$
1968-69



Ting et al.,
$p\,Be \to e^+e^- X$
AGS 1974

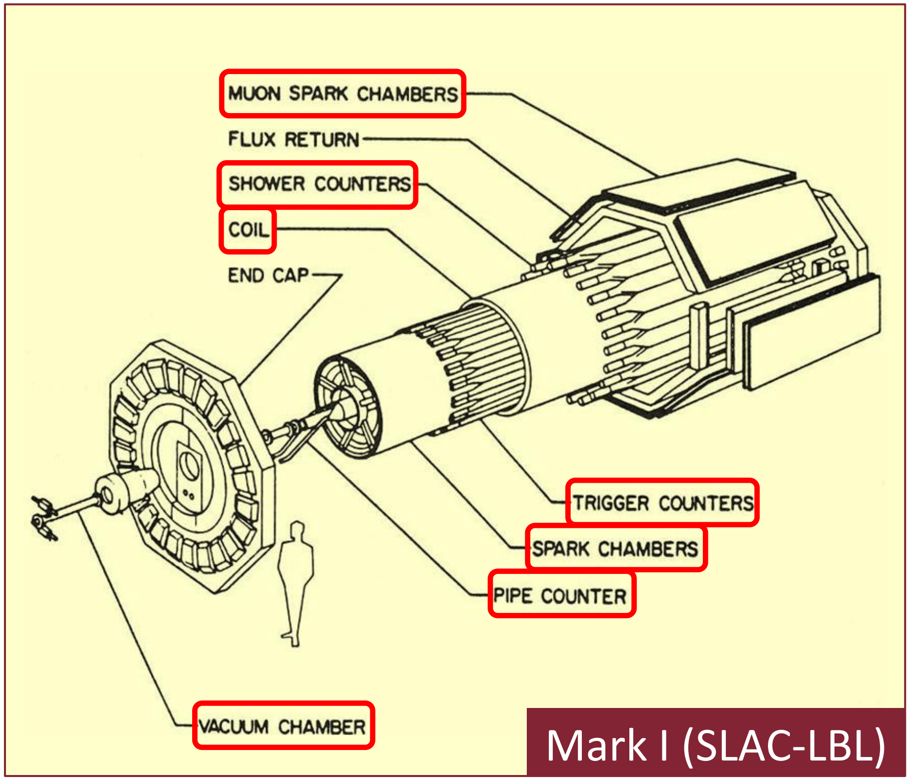


Michelini et al.
$\pi^+ Pt \to \mu^+\mu^- X$
(200 GeV)
1979

The November Revolution : Mark I

[back to 1974 : they did not know]

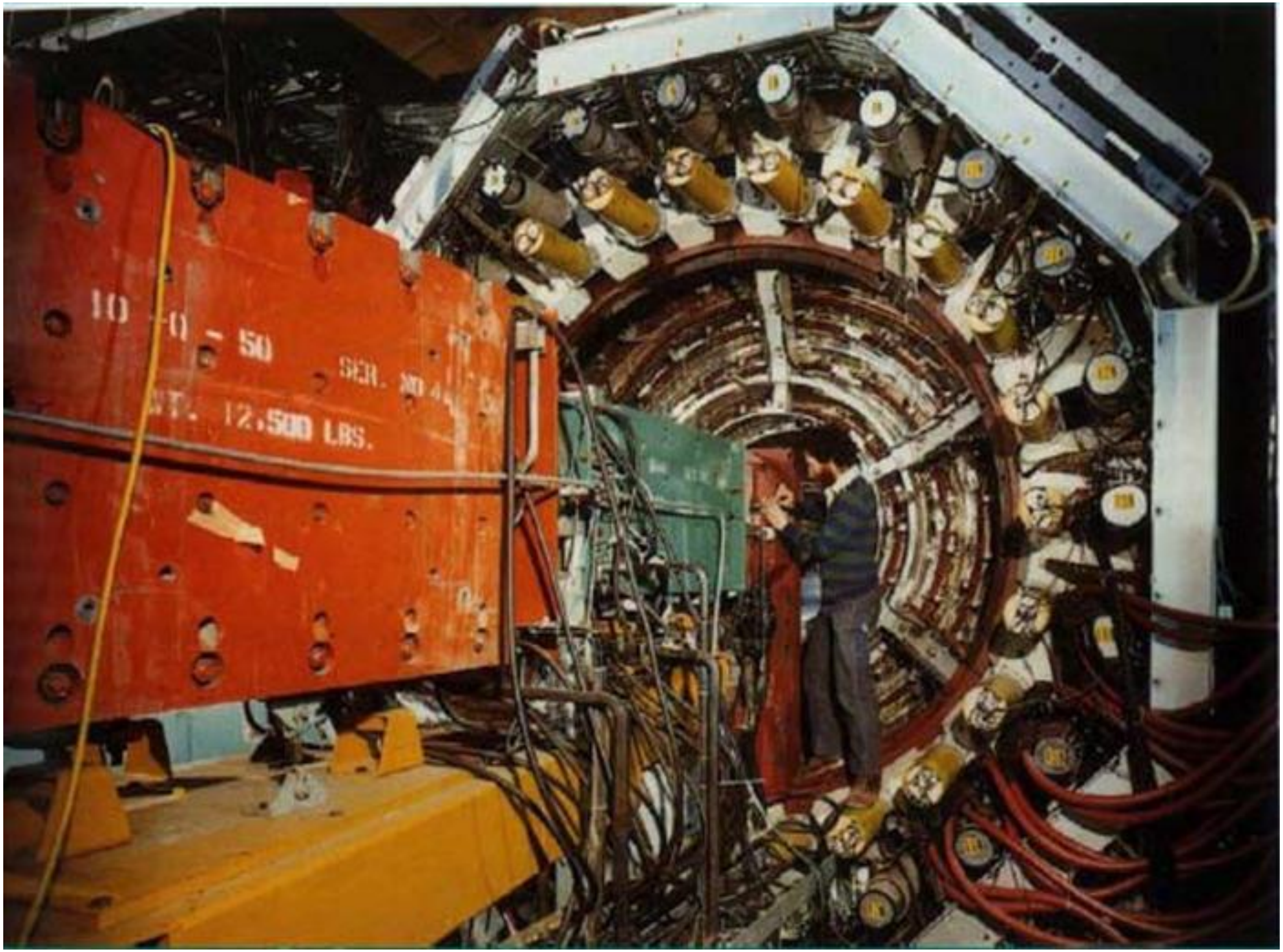
- Mark I at the e^+e^- collider SPEAR was studying collisions at $\sqrt{s}$ = 2.5 ÷ 7.5 GeV.
- The detector was made by a series of concentrical layers ("onion shaped").
- Starting from the beam pipe :
  - magnetostrictive spark chambers (tracking),
  - time-of-flight counters (particles' speed + trigger),
  - coil (solenoidal magnetic field, 4.6 kG),
  - electromagnetic calorimeter (energy and identification of γ's and $e^\pm$'s),
  - proportional chambers interlayered with iron plates (identification of $\mu^\pm$'s).



Mark I (SLAC-LBL)

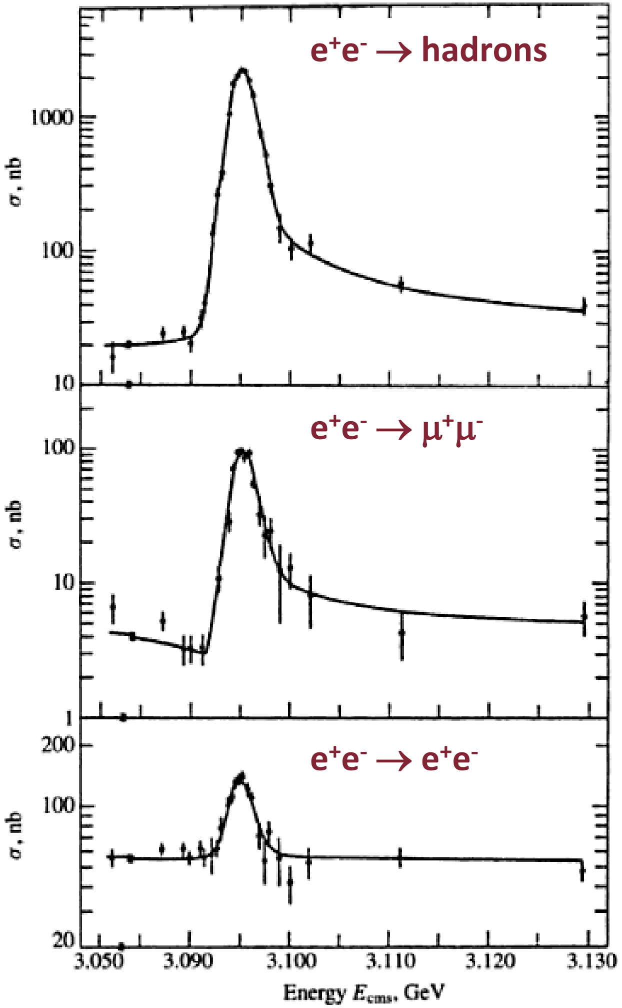
- [*Notice the strong similarity among all the Collider detectors : CMS – 40 years later – has the same "onion" structure, with a scale factor > 10, i.e. a volume ~1000 times larger. However, ATLAS is different*].

The November Revolution : Mark I at SLAC



The November Revolution : ψ

- In 1974, up to the highest available energies, $R = \sigma(e^+e^- \to \text{hadrons}) / \sigma(e^+e^- \to \mu^+\mu^-) \approx 2$.
- Measurements at the Cambridge Electron Accelerator (CEA, Harvard) in the region of energies of SPEAR had found $R \cong 6$ (a mixture of continuum and resonances). Also ADONE at LNF, which could reach an energy just sufficient, was not pushed to its max energy [*At the time the large amount of information carried by R was not completely clear*].
- At the novel Collider SPEAR, the scanning in energy was performed in steps of 200 MeV.
- The measured cross-section appeared to be a constant, NOT with expected trend $\propto 1/s$.
- When a drastic reduction in the step (200 → 2.5 MeV) increased the "resolving power", a resonance appeared, with width compatible with the beam dispersion (even compatible with a δ-Dirac).
- The particle was called "ψ" (see fig. on page 2).


inside Mark I acceptance and normalized to Bhabha.

Charmonium: J/ψ properties

- After some discussion, the correct interpretation emerged :
  - the resonance, now called J/ψ, is a bound state of a new quark, called **charm** (c), and its antiquark;
  - the c had been proposed in 1970 to exclude FCNC [GIM mechanism, § *4*];
  - the J/ψ has $J^P = 1^-$ [*next slide*];
  - the name "charmonium" is an analogy with positronium ("onium" : bound state particle-antiparticle);
- The cross-section (Breit-Wigner) for the formation of a state (J_R = 1) from e^+e^- ($S_a = S_b = ½$), followed by a decay into a final state, shows that [*see* § *intro.*]:

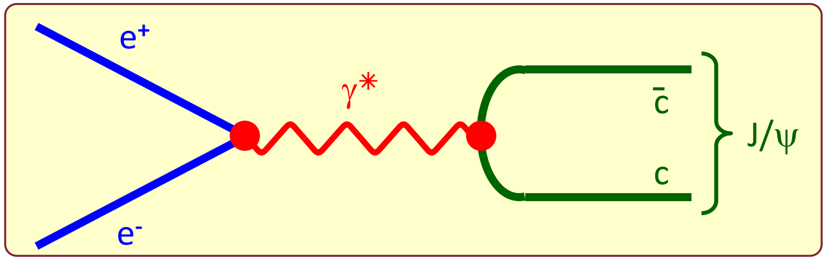
$$\boxed{\begin{aligned}&\sigma(ab \to J/\psi \to f\bar{f}, \sqrt{s}) = \\ &= \frac{16\pi}{s}\frac{(2J_R+1)}{(2S_a+1)(2S_b+1)}\left[\frac{\Gamma_{ab}}{\Gamma_R}\right]\left[\frac{\Gamma_{f\bar{f}}}{\Gamma_R}\right]\left[\frac{\Gamma_R^2/4}{\left(\sqrt{s}-M_R\right)^2+\Gamma_R^2/4}\right]\end{aligned}}$$

- $\sigma(e^+e^- \to J/\psi \to f\bar{f}, \sqrt{s}) =$

$$= \frac{12\pi}{s}\left[\frac{\Gamma_e}{\Gamma_{tot}}\right]\left[\frac{\Gamma_f}{\Gamma_{tot}}\right]\frac{\Gamma_{tot}^2/4}{\left(m_{J/\psi} - \sqrt{s}\right)^2 + \Gamma_{tot}^2/4};$$

- $\Gamma_f =$ width for the $\left(J/\psi \leftrightarrow f\bar{f}\right)$ coupling;
- $\Gamma_{tot} = \Gamma_e + \Gamma_\mu + \Gamma_{had}$ = full width of J/ψ;
- $\Gamma_f / \Gamma_{tot} = BR(J/\psi \to f\bar{f})$ [very useful].

- After 1974, many exclusive decays have been precisely measured, all confirming the above picture; the last PDG has 227 decay modes; the present most precise value of the mass and width is
  m(J/ψ) = 3097 MeV, Γ_{tot}(J/ψ) = 93 keV.



Charmonium : J/ψ quantum numbers

At SPEAR they were able to measure many of the J/ψ quantum numbers :

- the resonance is asymmetric (the right shoulder is higher); therefore there is interference between J/ψ formation and the usual γ^* exchange in the s-channel; therefore the J/ψ and the γ have the same $J^P = 1^-$;
- from the cross section, by measuring σ_{had}, σ_μ and σ_e, they have 3 equations + a constraint (see the box, three $\sigma_f + \Gamma_{tot}$) for the 4 unknowns (three $\Gamma_f + \Gamma_{tot}$); therefore they measured everything, obtaining a Γ_{tot} very small (~90 keV, a puzzling results, see next slides);
- the equality of the BR ($J/\psi \to \rho^0\pi^0$) and ($\to \rho^\pm\pi^\mp$) implies isospin I = 0;
- the J/ψ decays into an odd (3, 5) number of π, not ~~in an even (2, 4) number~~; this fact has two important consequences :
  - the G-parity is conserved in the decay (so the J/ψ decays via strong inter.). 𝔾
  - G-parity = -1 [also $(-1)^{I+\ell+s} = -1$].

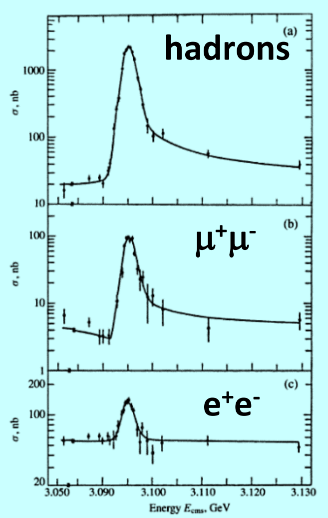
$$\sigma(e^+e^- \to J/\psi \to f\bar{f}) =$$

$$= \frac{3\pi}{s}\frac{\Gamma_e\Gamma_f}{\left(m_{q\bar{q}} - \sqrt{s}\right)^2 + \Gamma^2_{tot}/4}$$

$$= \sigma_f(\Gamma_e, \Gamma_f, \Gamma_{tot}, \sqrt{s});$$

measure $\sigma_{had}, \sigma_{\mu\mu}, \sigma_{ee}$;

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

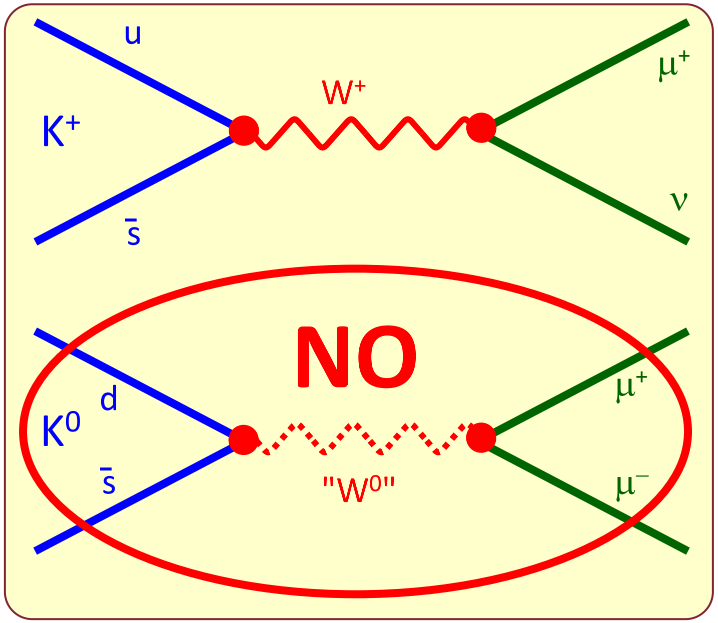


4 equations (f = had, μ, e + Γ_{tot}), 4 unknowns;
NO direct measurement of "width" required, but assume that ALL decays detected (e.g. no ν)

Charmonium : the GIM mechanism

- The weak neutral current processes between quarks of different flavor (FCNC, "Flavor Changing Neutral Current") are strongly suppressed [e.g. $\Gamma(K^0_L \to \mu^+\mu^-) << \Gamma(K^\pm \to \mu^\pm\nu)$].
- This fact was explained in 1970 by S. Glashow, J. Iliopoulos and L. Maiani by introducing the **charm quark** (*Phys. Rev. D2, 1285*);
- they predicted:
  - a fourth quark (c), identical to the u quark (but $m_c >> m_u$), carrying a new quantum number C, "charm";
  - as for the strangeness, C is conserved in strong and electromagnetic interactions and violated in weak interactions;
  - the lightest charmed mesons are $c\bar{q}$ or $\bar{c}q$ pairs (q = uds), and have a mass of 1500 - 2000 MeV and $J^P = 0^-$;
  - these mesons decay weakly; because of their larger mass, their lifetimes are $\mathcal{O}$(ps), an order of magnitude shorter than those of the K mesons;
  - the positive meson with open charm ($c\bar{d}$, now called D^+) decays preferably in final states with negative strangeness ($c \to sf\bar{f}$, $\Delta S = \Delta C$).

[*see* § *4 for more details*]



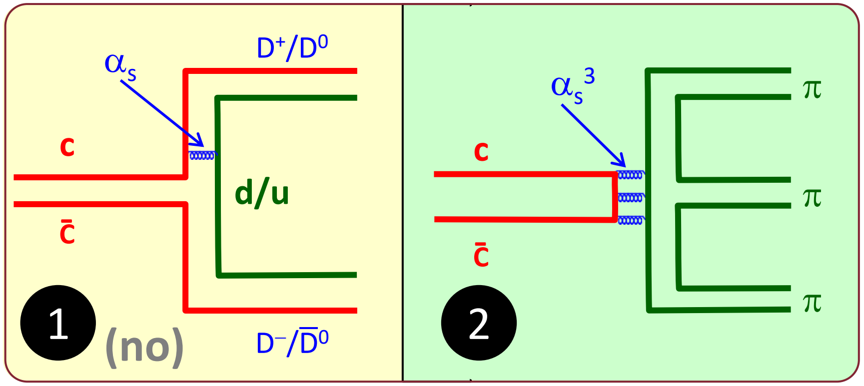
Charmonium : QCD decay

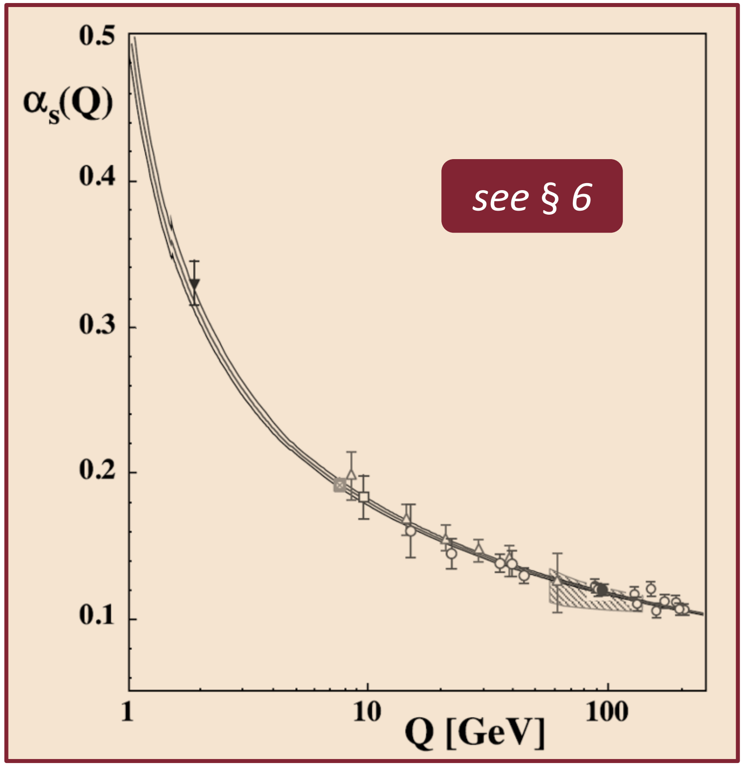
$Q\bar{Q}$ states$^{(*)}$ [e.g. ϕ ($s\bar{s}$), J/ψ ($c\bar{c}$), Υ ($b\bar{b}$)] :

- decay preferentially ① [($Q\bar{Q}$) → ($Q\bar{q}$) ($\bar{Q}q$)], e.g. $\phi \to \bar{K}K$, i.e. [($s\bar{s}$) → ($\bar{d}s$) ($d\bar{s}$)];
- $J/\psi \to D^+D^-$ (or $D^0\bar{D}^0$) [($c\bar{c}$) → ($\bar{d}c$) ($d\bar{c}$) or ($\bar{u}c$) ($u\bar{c}$)] forbidden ($m_{J/\psi} < 2m_D$);
- then $c\bar{c}$ annihilate into gluons ($J/\psi \to \pi$'s ②):
  - 1 gluon forbidden by color;
  - 2 gluons forbidden by C-parity [$C_{2g} = +1$; $C_{J/\psi} = C_\gamma = -1$];
  - 3 gluons allowed :

$$\Gamma(Q\bar{Q} \to 3g \to \pi's) = \frac{160(\pi^2 - 9)}{81 m^2_{Q\bar{Q}}} \alpha_s^3 |\psi(0)|^2 ;$$

- The value α_s^3 (and its "running" [§ *6*]) produces a smaller width for larger masses :
  - $\alpha_s^3(m^2_\phi) \approx 0.5^3 = .125$;
  - $\alpha_s^3(m^2_{J/\psi}) \approx 0.3^3 = .027$;
  - $\alpha_s^3(m^2_\Upsilon) \approx 0.2^3 = .008$.





see § 6

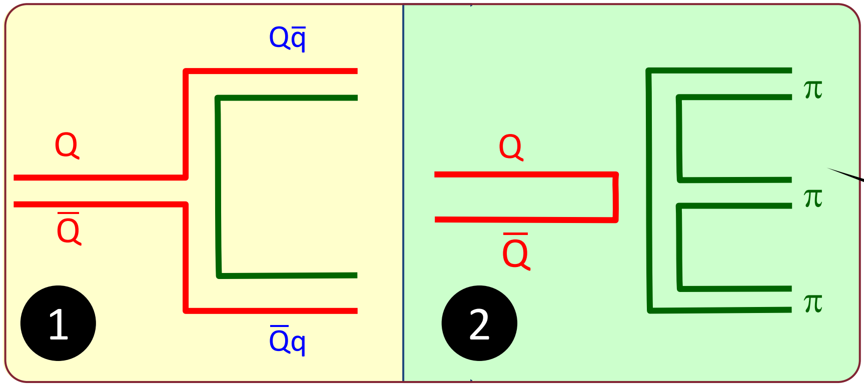
(*) in these slides: q = u/d, Q = s/c".

Charmonium : the Zweig rule (OZI)

The "Zweig rule" was set out empirically in a qualitative way before the advent of QCD :

- compare $(\phi \to 3\pi) \leftrightarrow (\phi \to KK) \leftrightarrow (\omega \to 3\pi)$;
- in the decay of a bound state of heavy quarks Q, the final states without Q's ("decays with disconnected diagrams" ②) have suppressed amplitude wrt "connected decays" ①;
- if only the decays ② are kinematically allowed (ex. J/ψ or Υ), the total width is small and the bound state is "narrow";

1963-1966 :
Susumu Okubo
(大久保 進
Ōkubo Susumu),
George Zweig,
Jugoro Iizuka (飯塚)



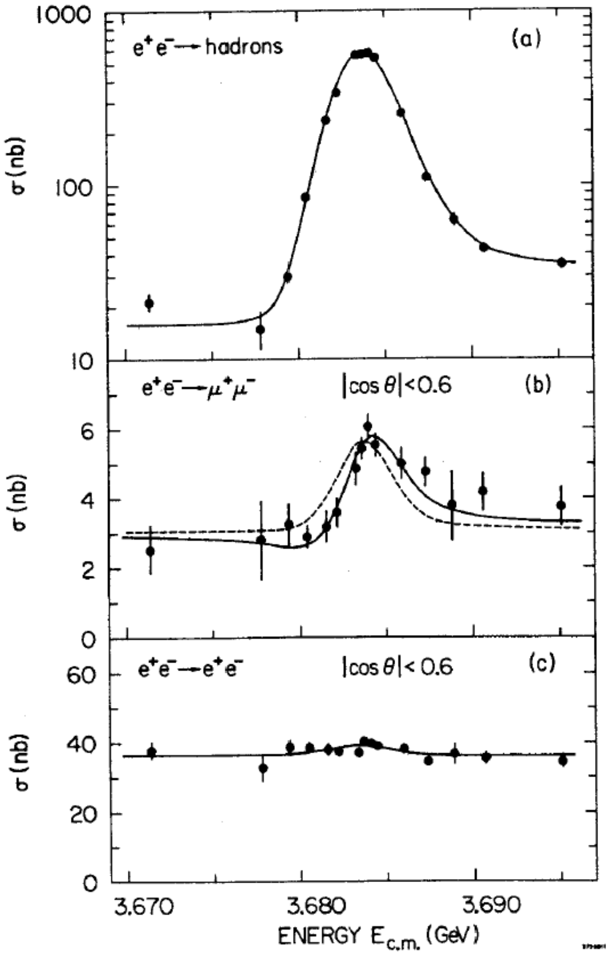
before the QCD advent, gluons were not considered.

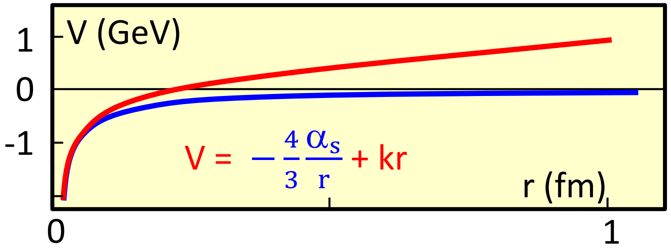
Charmonium: ψ'

- After the discovery of the J/ψ, at SPEAR they performed a systematic energy scanning with a very small step. After ten more days a second narrow resonance was found, called ψ', with the same quantum numbers of the J/ψ.
- The analysis shows that the J/ψ was the 1S state of cc̄, while the ψ' is the 2S.
- Both particles have $J^P = 1^-$, I=0.
- The next page gives a scheme of the cc̄ levels.
- They offer a reasonable agreement with the solution of the Schrödinger equation of a hypothetical QCD potential [*see* § *Standard Model*]

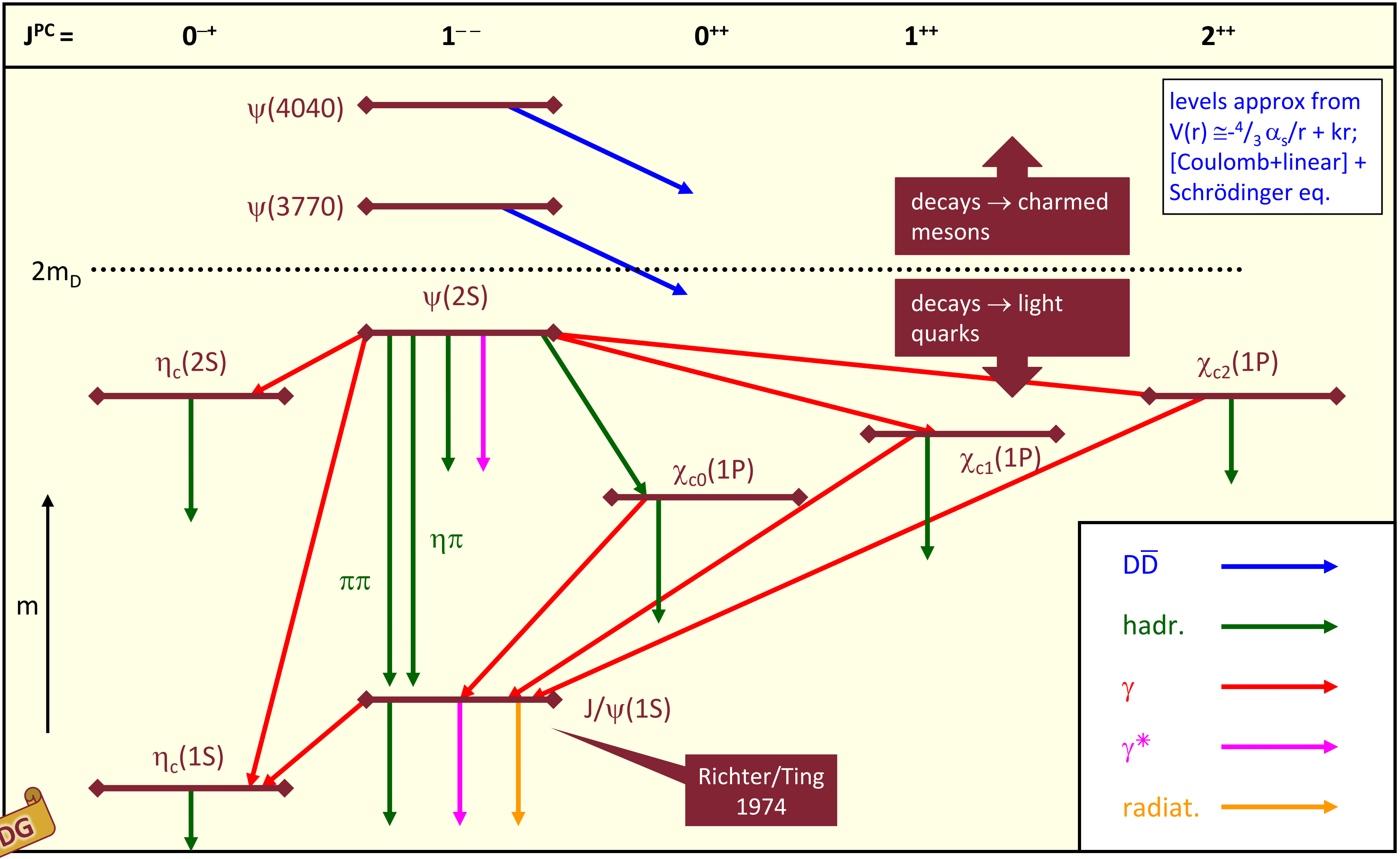
$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + kr = -\frac{A}{r} + Br.$$

- Notice that this approximation should become more realistic for heavier quarks, when the non-relativistic limit gets better.





Charmonium : c$\bar{c}$ levels



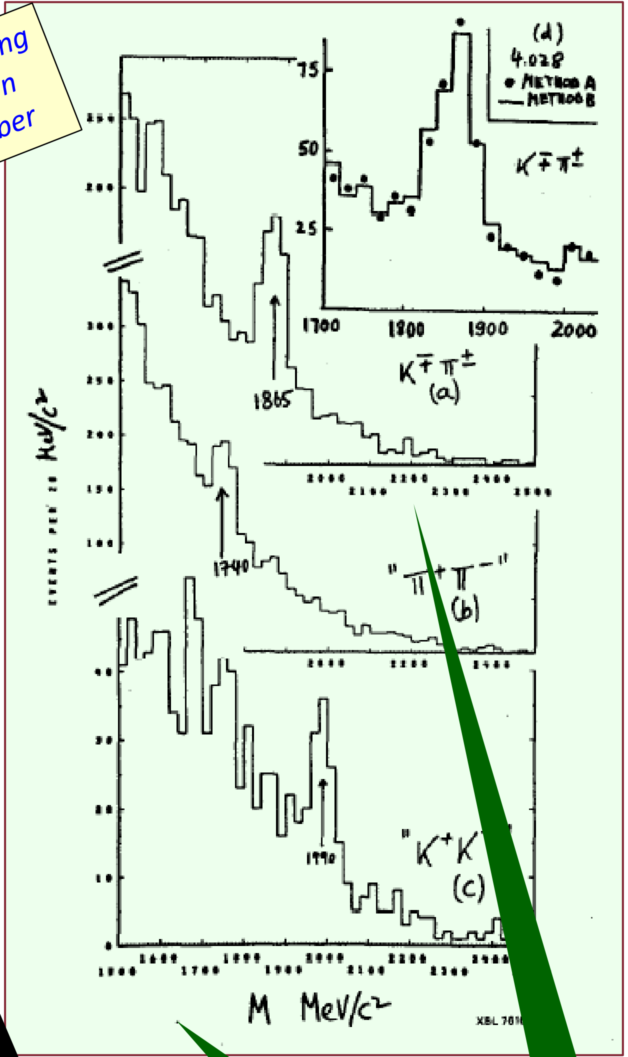
levels approx from $V(r) \cong -{}^{4}/_{3}\, \alpha_s/r + kr$; [Coulomb+linear] + Schrödinger eq.

Open charm : discovery

- If the J/ψ is a bound $c\bar{c}$ state, then mesons $c\bar{q}$ and $\bar{c}q$ must exist, with a mass $\approx m_{J/\psi}/2 + 100 \div 200$ MeV [$3690/2 < m_D < 3770/2$ MeV].
- In 1976, the Mark I detector started the search for charmed pseudoscalar mesons (D^0 $\bar{D}^0$), the companions of π's and K's.
- They looked at $\sqrt{s} = 4.02$ GeV in the channels

  $$e^+e^- \rightarrow D^0\,\bar{D}^0\,X^0; \quad \rightarrow D^+\,D^-\,X^0.$$

- According to theory, D-mesons lifetimes are small, with a decay vertex not resolved (*with 1976 detectors*) wrt the e^+e^- one.
- Therefore the strategy of selection was the presence of "narrow peaks" in the combined mass of the decay products.
- A first bump at 1865 MeV with a width compatible with the experimental resolution was observed in the combined mass ($K^\pm\pi^\mp$), corresponding to the D^0 and $\bar{D}^0$ decay.



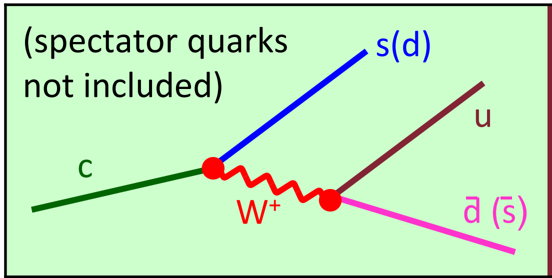
handwriting by Gerson Goldhaber

Today's technology allows for it !!!

They were afraid of K/π exp. misidentification → mass is computed with all particle hypotheses.

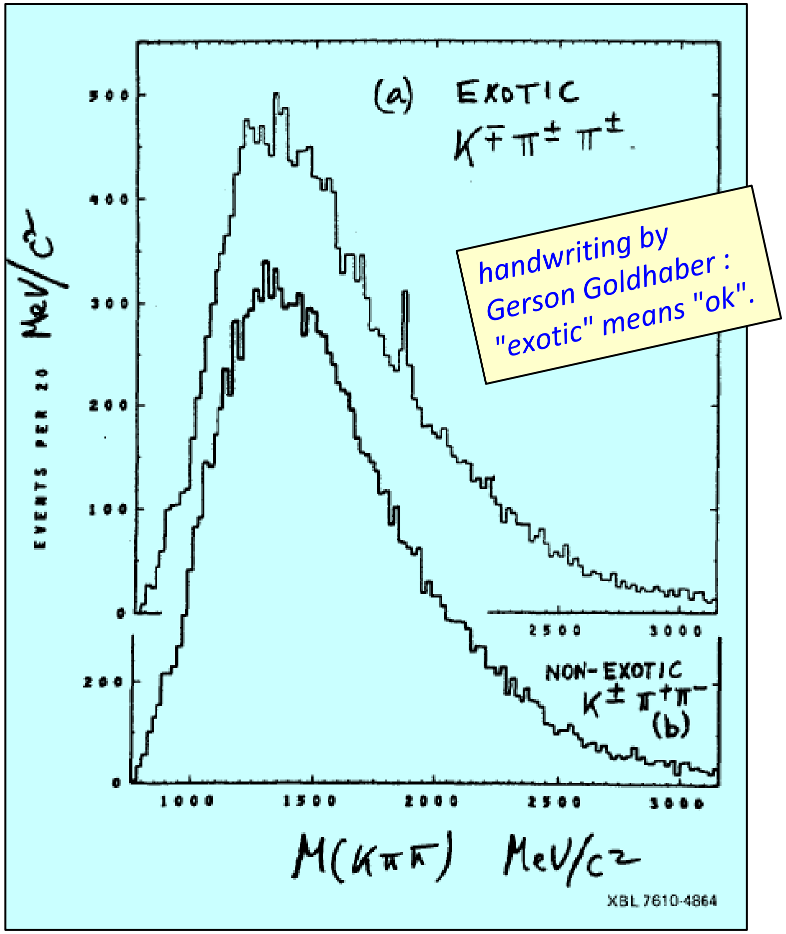
Open charm: "C-allowed, suppressed"

- Also the mass ($K^{\mp}\pi^{\pm}\pi^{\pm}$) had a bump at 1875 MeV, corresponding to the D^{+} and D^{-} decays.
- Moreover, in perfect agreement with the GIM predictions, no bump was found in ($K^{\pm}\pi^{+}\pi^{-}$), which is forbidden ("Cabibbo doubly suppressed", in this language).
- i.e. mainly $D^{+} \rightarrow K^{-}\pi^{+}\pi^{+}$, $D^{-} \rightarrow K^{+}\pi^{-}\pi^{-}$ (!!!).



the c quark decays through its Cabibbo couplings (see):
[c↔s, u↔d] ∝ cos θ_c = "big"
[c↔d, u↔s] ∝ sin θ_c = "small"

⅔	-⅓	⅔	⅓	K/π	"Cabibbo" dependence	
c →	s	u	$\bar{d}$	$\bar{K}(n\pi)$	$\propto \cos^2\theta_c$	"allowed"
	s	u	$\bar{s}$	$\bar{K}K(n\pi)$	$\propto \sin\theta_c \cos\theta_c$	"suppressed"
	d	u	$\bar{d}$	$(n\pi)$	$\propto \sin\theta_c \cos\theta_c$	"suppressed"
	d	u	$\bar{s}$	$K(n\pi)$	$\propto \sin^2\theta_c$	("suppressed")^2



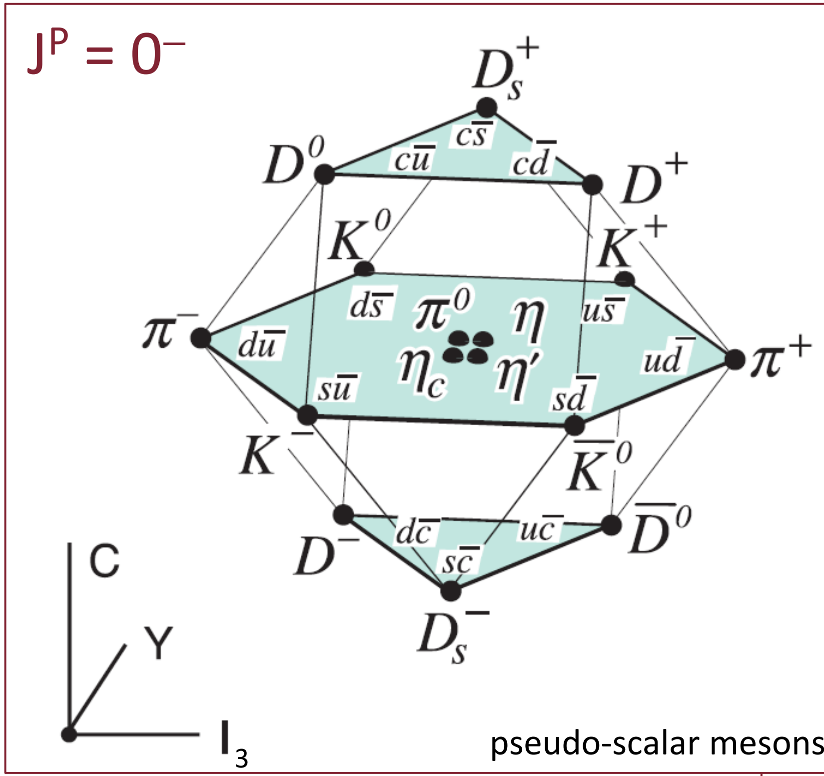
handwriting by Gerson Goldhaber : "exotic" means "ok".

the so-called "$\Delta S = \Delta C$" rule :

$c \rightarrow \bar{K}$: (C : +1 → 0) ↔ (S : 0 → −1)

$\bar{c} \rightarrow K$: (C : −1 → 0) ↔ (S : 0 → +1)

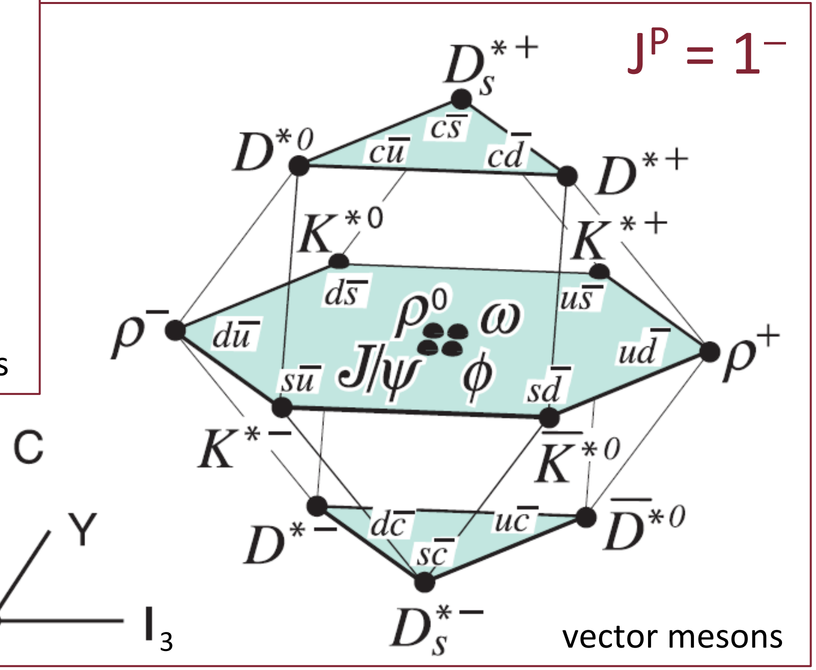
Open charm: meson multiplets



pseudo-scalar mesons

$\underline{\text{SU(3)}}_{\text{flavor}} \rightarrow \underline{\text{SU(4)}}_{\text{flavor}}$

With 4 quarks, the SU(3) nonets become 16-multiplets in a 3-D space. However, the c quark has a large mass, so $\text{SU(4)}_{\text{flavor}}$ is much more broken that $\text{SU(3)}_{\text{flavor}}$.

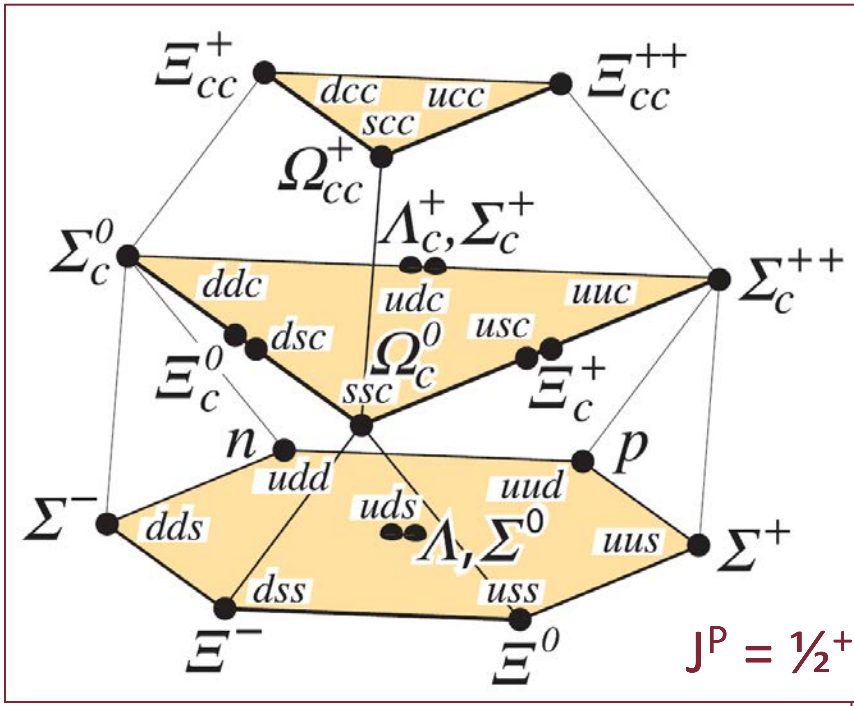


vector mesons

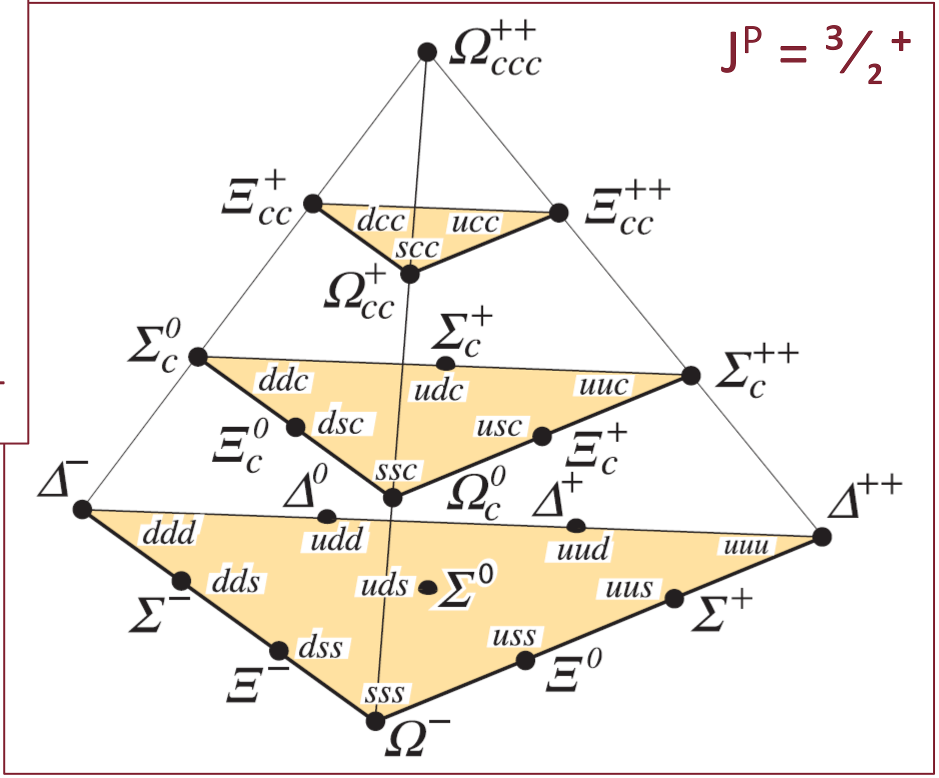
$4 \otimes \bar{4} = 15 \oplus 1.$

Open charm : baryon multiplets

SU(4)$_{flavor}$ baryons



$J^P = ½^+$



$J^P = {}^3/_2{}^+$

The 3rd family

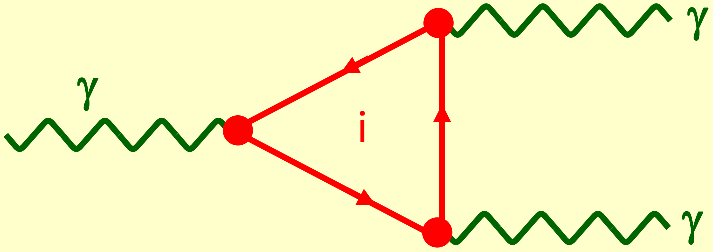
- "who ordered that ?" [*I.I.Rabi about the* μ];
- in modern terms : "why consecutive families of quarks/leptons, differing only in mass ? why/how they mix ?" [*see* § *4-5*]
- as of today, nobody knows : the number of families and the mixing matrix are free parameters of the SM [*maybe one day some theory bSM will constrain it*];
- "non-QCD" constraints in the SM:
  - ➢ families must be complete : the existence of a single member (e.g. the ν or the ℓ^-) implies the existence of all the others, to avoid **anomalies** (Adler-Bell-Jackiw); it requires $\Sigma_i\ e_i = 0$, where the sum runs on all members i and colors c of the family F [*see box*];
  - ➢ the Z full width Γ^Z_{tot} constrains the number of "light ν's" [*Coll. Phys.* § *LEP*] ;

➢ in the SM, (at least) three families are necessary to generate a natural mechanism of CP violation in the quark decays [*see* § *K*^{0}];

➢ in the SM, n_F is free, but n_c must be 3.

$$\left\{\begin{array}{ccc} \begin{pmatrix} e^- \\ \nu_e \end{pmatrix} & \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} & \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \\ \begin{pmatrix} u \\ d \end{pmatrix} & \begin{pmatrix} c \\ s \end{pmatrix} & \begin{pmatrix} t \\ b \end{pmatrix} \end{array}\right. \qquad \begin{array}{ll} e_i = -1 & ,c = 1 \\ e_i = 0 & ,c = 1 \\ e_i = 2/3 & ,c = 3 \\ e_i = -1/3 & ,c = 3 \end{array}$$

$$\boxed{\sum\nolimits_F \left(\sum\nolimits_i e_i\right) = n_F \times \left\{ \begin{array}{c} (-1)+(0)+ \\ +3_c \times \left[\left(\frac{2}{3}\right)+\left(\frac{-1}{3}\right)\right] \end{array} \right\} = 0}.$$



The τ lepton : discovery

The analysis of Mark I data produced another beautiful discovery : the τ lepton (M. Perl won the 1995 Nobel Prize):

- the selection followed a method well known, pioneered at LNF-Frascati : the "unbalanced pairs $e^\pm\mu^\mp$" :

$$e^+e^- \to \tau^+\tau^-$$

$$\left.\begin{array}{l} \hookrightarrow \mu^-\bar{\nu}_\mu\nu_\tau \\ \hookrightarrow e^+\nu_e\bar{\nu}_\tau \end{array}\right\} \to \mu^- e^+ \ \text{(\underline{unbalanced})}$$

(+ CC μ^+e^-).

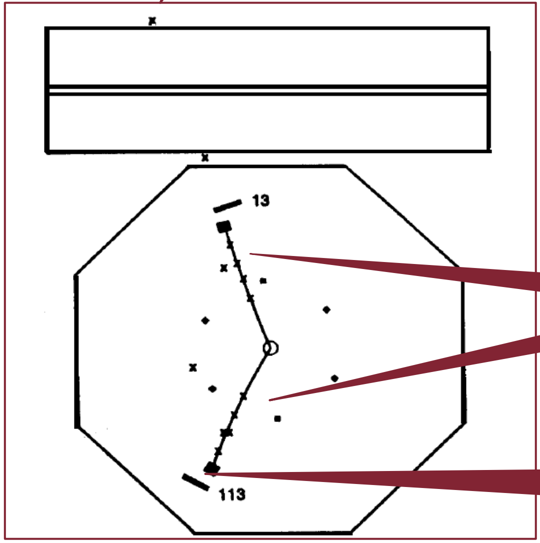
- events from this process are extremely clean and free from background [*see fig.*];
- the e^+e^- / $\mu^+\mu^-$ unbalanced pairs, which have to be present in the correct number

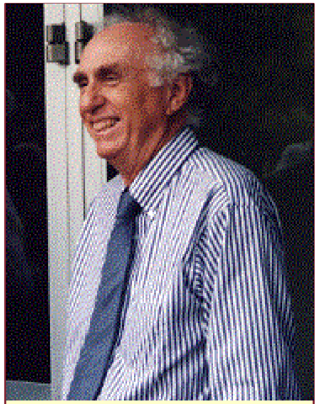
$$N_{unb}(e^+e^-) = N_{unb}(\mu^+\mu^-) =$$

$$= N(e^+\mu^-) = N(e^-\mu^+),$$

are only used to cross-check the sample.

In principle the τ lepton has very little to do with the c quark. However collider, detector, energy, selection and analysis are closely linked. Therefore, in experimental reviews, the τ lepton is usually treated together with the charm quark.



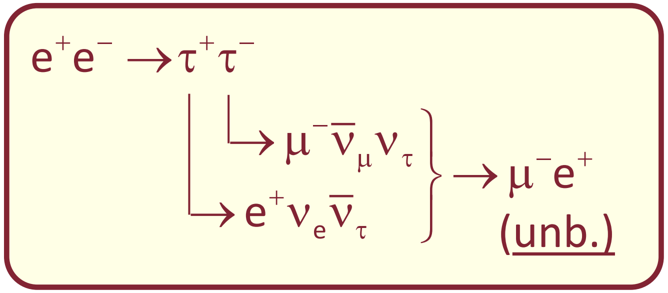


Martin Perl

The τ lepton : identification

Simple method: the yield of $e^{\pm}\mu^{\mp}$ pairs vs $\sqrt{s}$: it immediately points to the threshold $\sqrt{s} = 2m_\tau$.

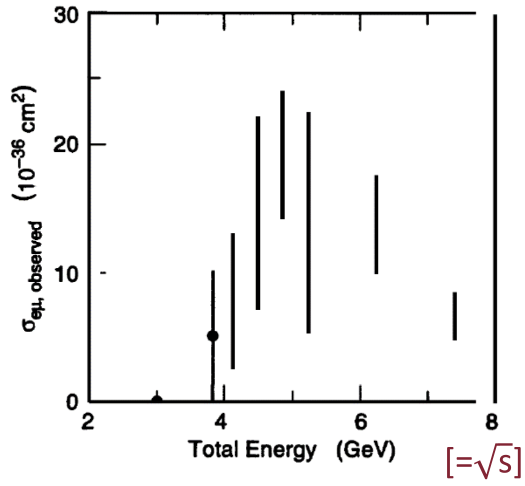
- therefore : $m_\tau \approx 1780$ MeV.
  [best present value 1776.8 MeV]
- why is the $\tau^{\pm}$ a lepton ?
  - at the time, the evidence came from the lack of any other plausible explanation;
  - today, the evidence is solid :
    - the Z and W decays into ($e\ \mu\ \tau$) with the same BR and angular distribution;
    - the τ lifetime and decays have been measured and found in agreement with predictions …
- the discovery of the τ started the hunt for the particles of the new (3rd) family, still unknown:
  - the ν_τ (possibly mixed with the others);
  - the pair of quarks q_{up} q_{down}, similar to ud (now called **top** and **bottom**).



$$e^+e^- \to \tau^+\tau^-$$

$$\left.\begin{array}{l} \hookrightarrow \mu^-\bar{\nu}_\mu\nu_\tau \\ \hookrightarrow e^+\nu_e\bar{\nu}_\tau \end{array}\right\} \to \mu^- e^+$$

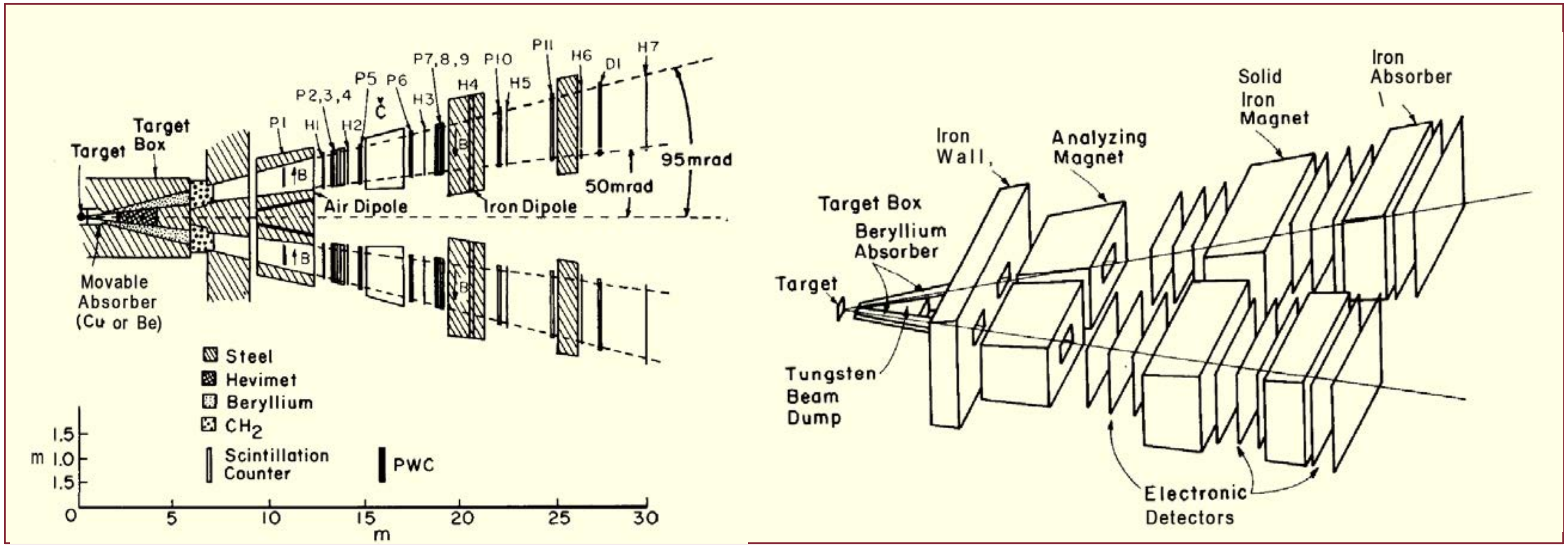
(unb.)



The b quark : discovery

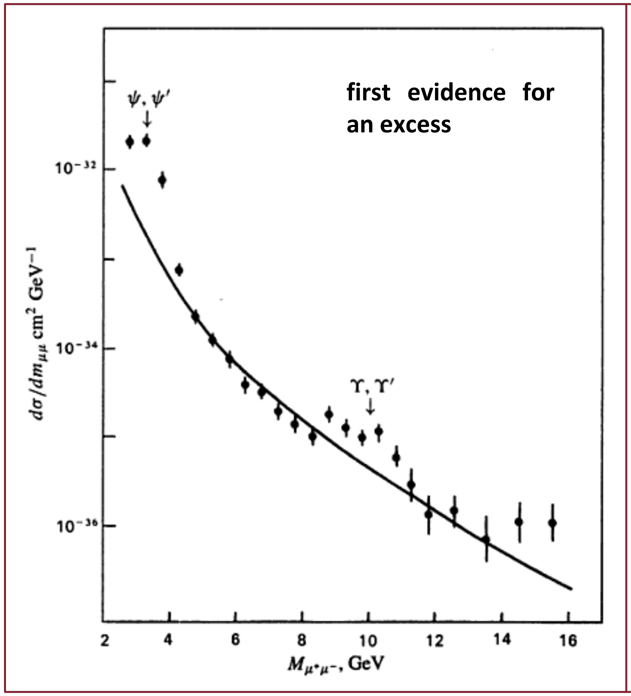
- The down quark of the 3rd family was called b (= beauty, bottom).
- In 1977 Leon Lederman and collaborators built at Fermilab a spectrometer with two arms, designed to study $\mu^+\mu^-$ pairs produced by interactions of 400 GeV protons on a copper (or platinum) target.
- The reaction under study was again the Drell-Yan process. As already pointed out, this type of events is rare, therefore requiring intense beams (in this case 10^{11} ppp) and high rejection power against charged hadrons.

Leon Lederman

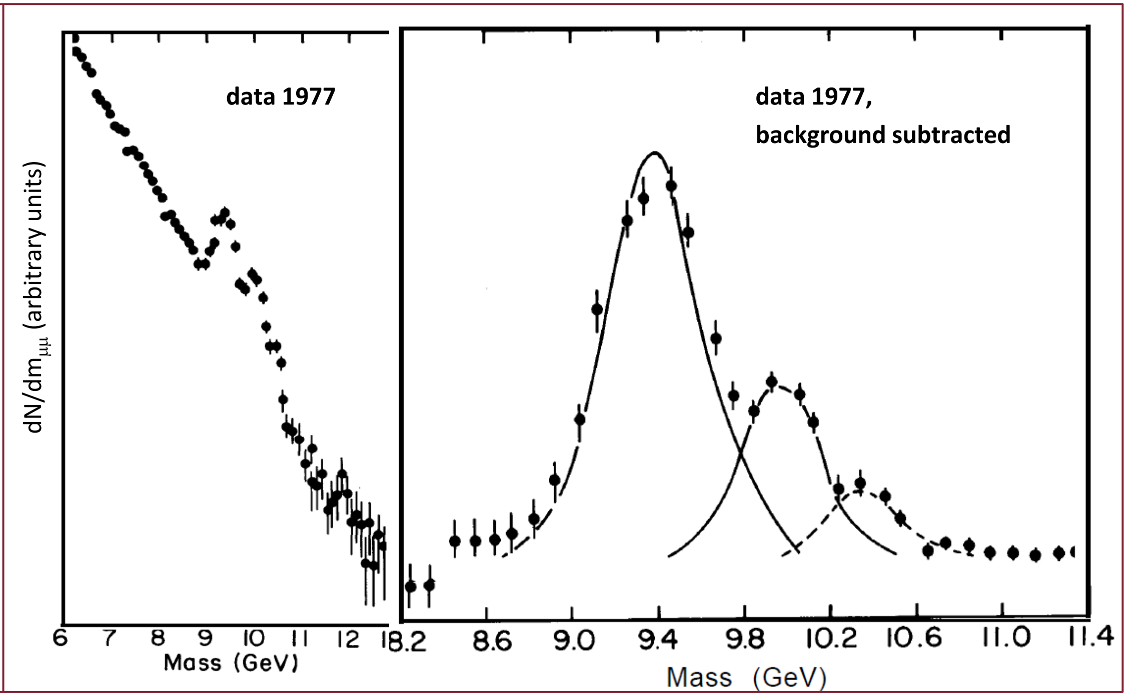


The b quark : dσ/dm

- The usual price of the absorber technique is a loss of resolution in the muon momenta, which was $\Delta m_{\mu\mu} / m_{\mu\mu} \approx 2\%$.
- The figures show the distribution of $m_{\mu\mu}$. Between 9 and 10 GeV : there is a clearly visible excess.
- When the $\mu\mu$ continuum is subtracted, the excess appears as the superimposition of three separate states.
- The states, called ϒ(1S), ϒ(2S), ϒ(3S) are bound states b$\bar{b}$.



first evidence for an excess

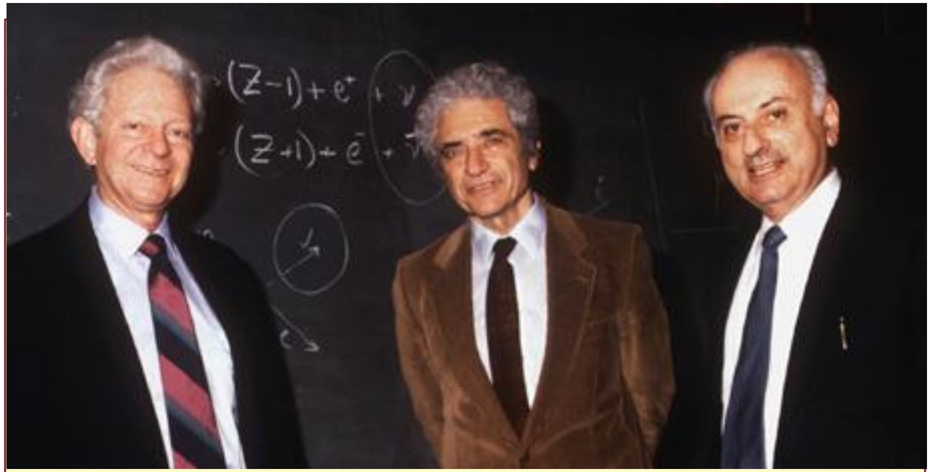


data 1977

data 1977, background subtracted

The b quark : open b

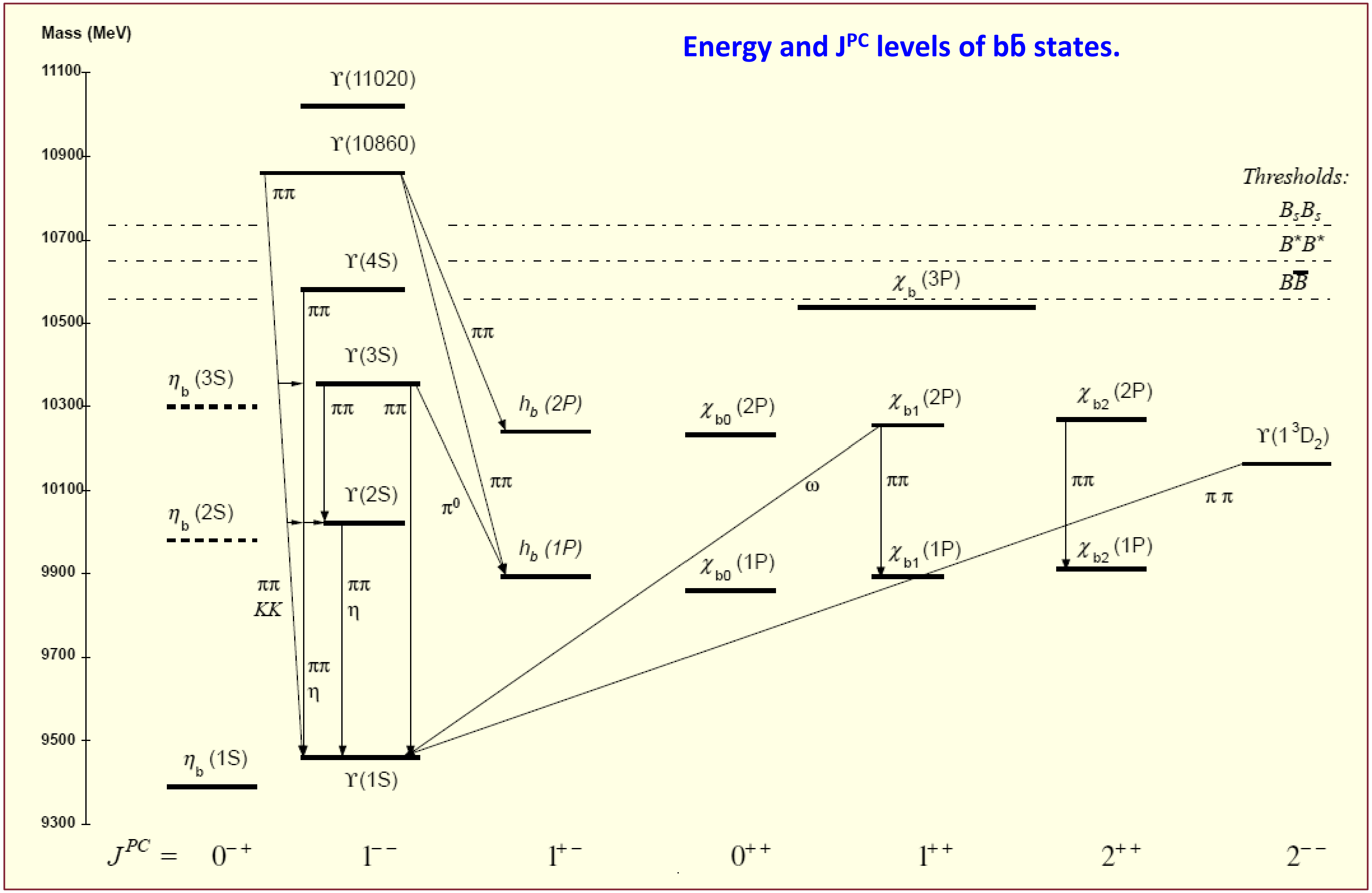
- Precision measurement, carried out at DESY and Cornell with e^+e^- Colliders, soon confirmed the results. After two years, also "open beauty", i.e. bound states $b\bar{q}$, was identified and called $B^{0,\pm}$.
- The figure in the next page shows an updated compilation of the $b\bar{b}$ states.
- Bottomonium (beauty in not used anymore, *don't know why*) is a very interesting system. Recently, a lot of studies (BaBar, Belle) have been performed on the $\mathbb{CP}$ violation in the $B^0\bar{B}^0$ system (similar to the K^0's, but different from the charms) [*see* § K^0].
- *Leon Lederman together with Mel Schwartz and Jack Steinberger got the 1988 Nobel Prize, NOT for his $b\bar{b}$ discovery, but for his neutrino studies (the "two neutrino experiment" in 1962).*



Leon Lederman Jack Steinberger Mel Schwartz

Nobel laureates 1988

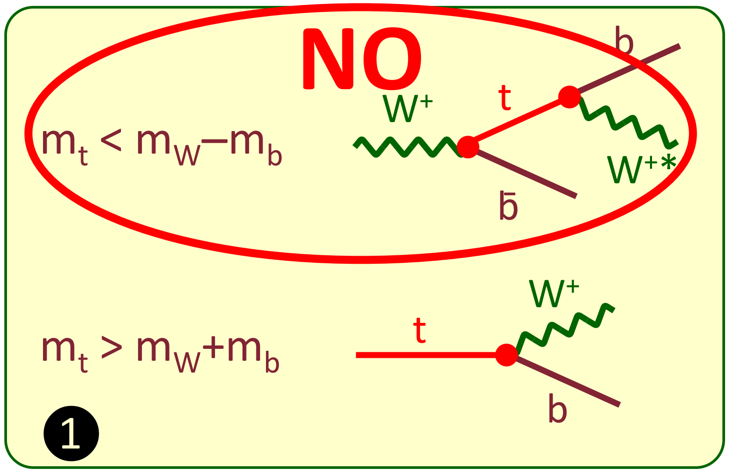
The b quark : bottomonia

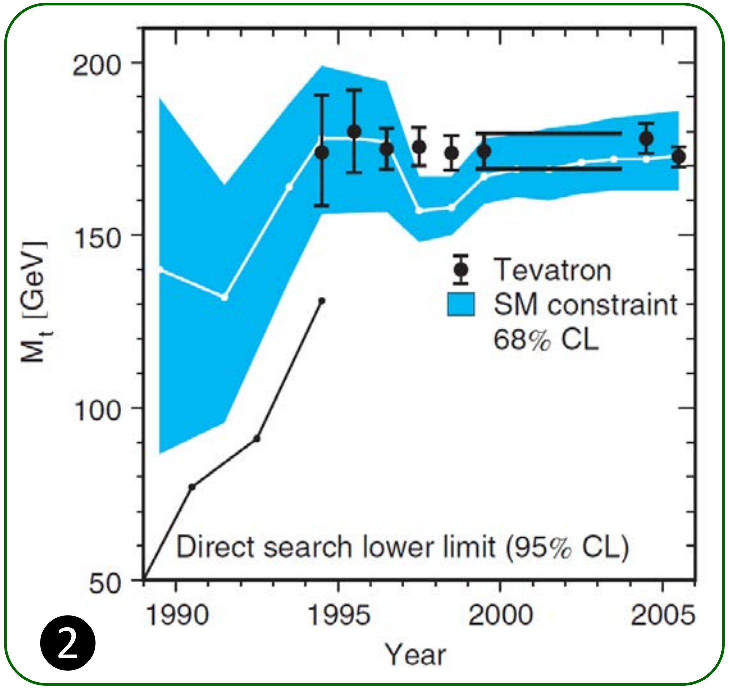


Energy and J^{PC} levels of $b\bar{b}$ states.

The t quark : search

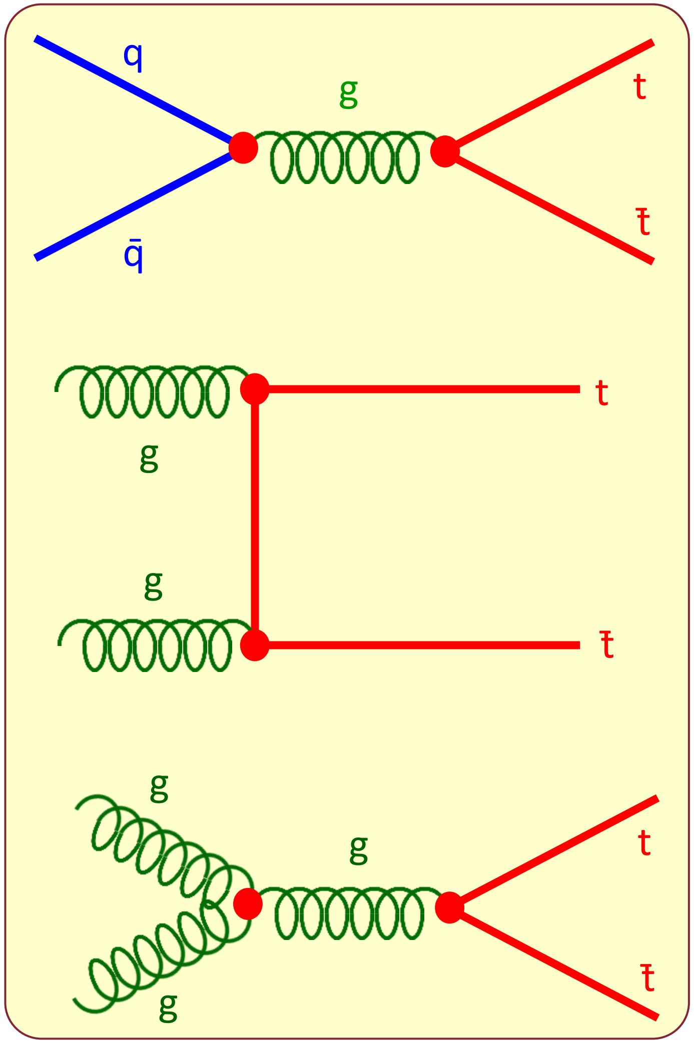
- The top quark was directly searched in hadron (Sp$\bar{p}$S, Fermilab) and lepton (Tristan, LEP) colliders, but was NOT found until 1990's;
- at the time the mass limit was $m_t \geq 90$ GeV;
- at $m_t \approx m_W \pm m_b$ ($\approx$ 80 GeV), the search changes: the "golden discovery channel" moves from ($W^+ \to t\bar{b} \to W^{+*} b\bar{b}$) to ($t \to W^+ b$) [fig. ❶];
- m_t was first *computed* from the radiative corrections for m_W and m_Z [*Coll.Phys.* § *LEP*];
- the LEP data, together with all other e.w. measurements, allowed for a prediction of $m_t \approx 175$ GeV [fig. ❷];
- in the 1990's the search was finally concluded at the Tevatron, by the CDF and D0 experiments.
- At present, we measure $m_t = 173 \pm 0.4$ GeV.

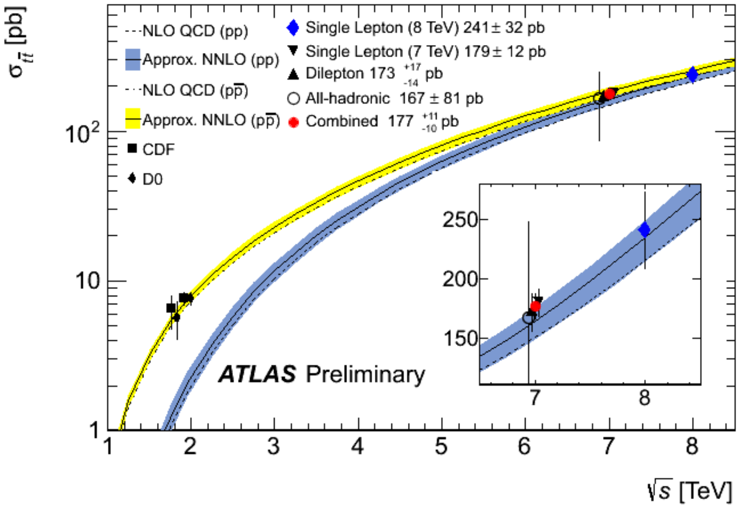




The t quark : production

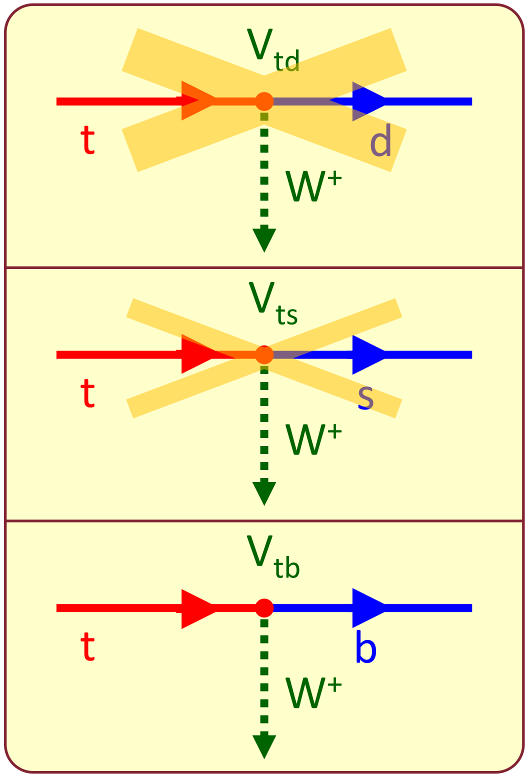
- in a hadronic collider [*see Coll.Phys.*], the top is produced in pairs, via hadronic interactions;
- in pp and p̄p the PDF of initial state partons are different (valence / sea): the qq̄ channel decreases from 90% (p̄p at Tevatron, √s=1.8 TeV) to 5% (pp at LHC, √s=14 TeV) [*qualitatively understandable*];
- in the same range, the total cross section increases from 5 to 600 pb [*also quite understandable*].

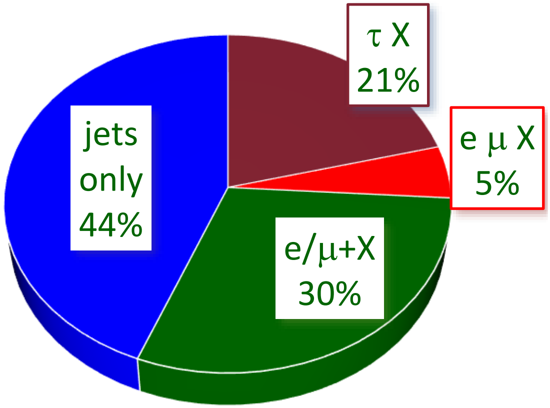




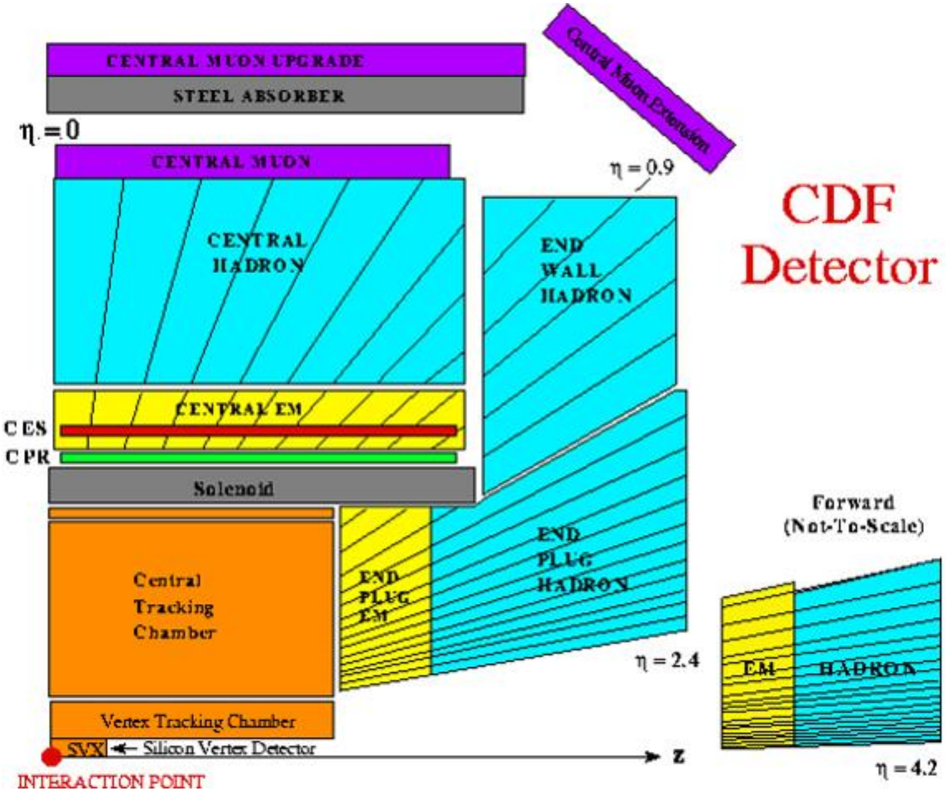
The t quark : decay

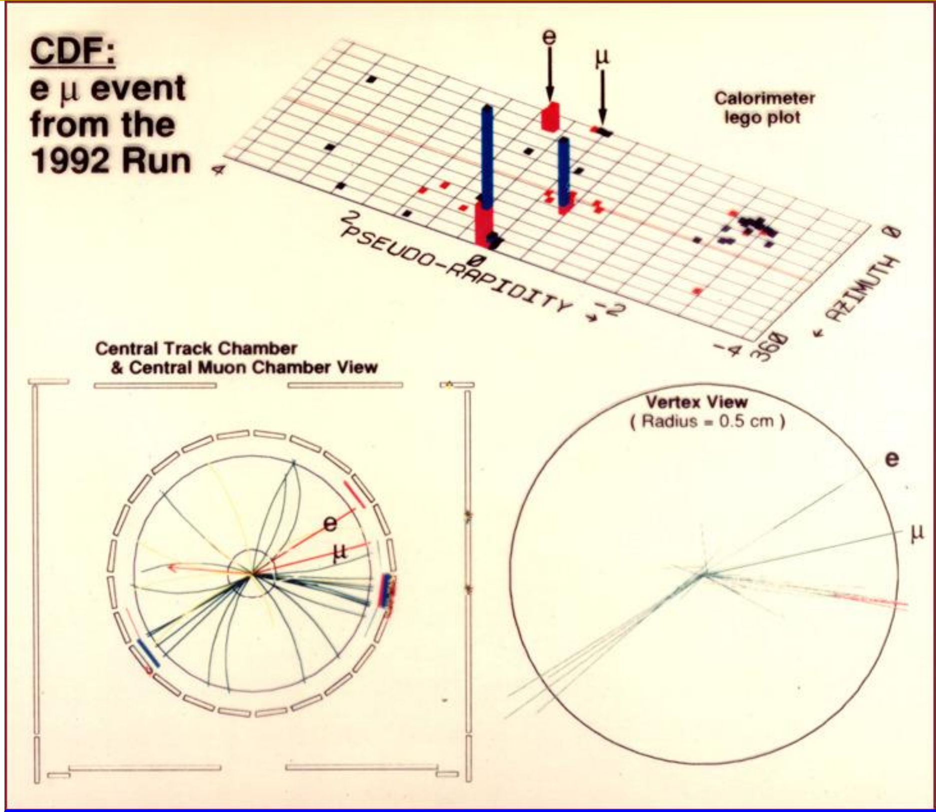
- the top quark decays weakly in a (real) W and a "down-type" quark (q=d/s/b), with a coupling $\propto V_{tq}$ [CKM, see § 5];
- therefore the most common decay is $t \to bW^+$ ($\bar{t} \to \bar{b}W^-$);
- since $\Gamma \approx G_F m_t^3 / (8\pi\sqrt{2}) \sim 2$ GeV, $\tau_t \sim 4 \times 10^{-25}$ s [¿ "*m^3*" ?];
- therefore the top decays *before* any hadronic process (hadronization, toponium formation) may happen;
- in turn the W decays "democratically" [*see Coll.Phys.*] into all the ($\ell\nu$) ($q\bar{q}$) pairs (hadrons × 3 because of color);
- in summary, the decays for ($t\bar{t} \to W^+ W^- X$) are :
  - both W's into e/μ : the golden channel, but rare;
  - only one W into e/μ : more common, less easy;
  - both W's into quarks (i.e. jets) : most common, difficult;
  - (one or more) $\tau^\pm$ in the final state : ν's → almost impossible with present technology.





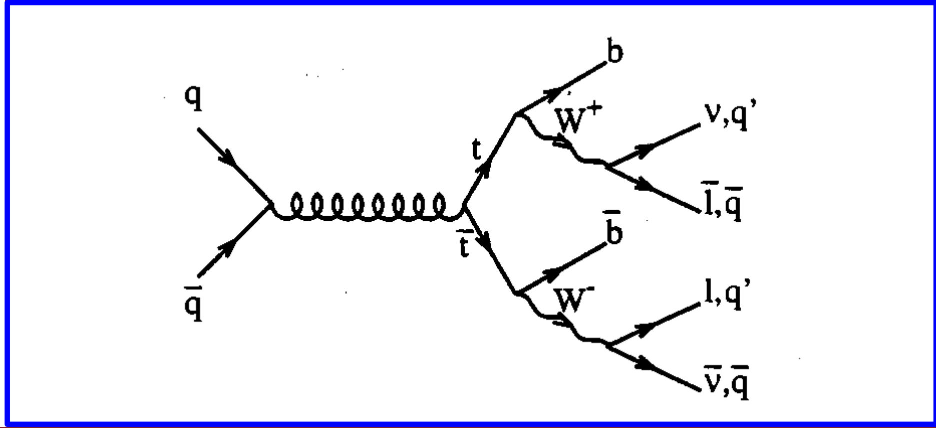
The t quark : discovery (1992-4)





main tools for tt̄ events at Tevatron (1992-4) :

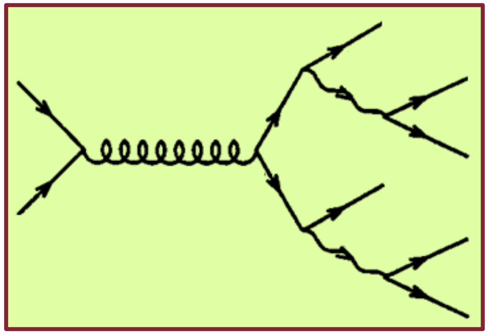
- multibody final states;
- lepton id ($e^\pm$, $\mu^\pm$);
- secondary b vertices;
- mass fits.



The t quark : results (1992-4)

- in may 1994, with 20 pb^{-1} of data, the CDF collaboration was able to claim the top "evidence" (3σ) and, one year after, its "discovery" (5σ);

- [for the latest results on top, see Coll.Phys. § LHC].



○	**data before b-tag**
▼	**data after b-tag**
↕	**[t-signal]**
▭	**computed background**

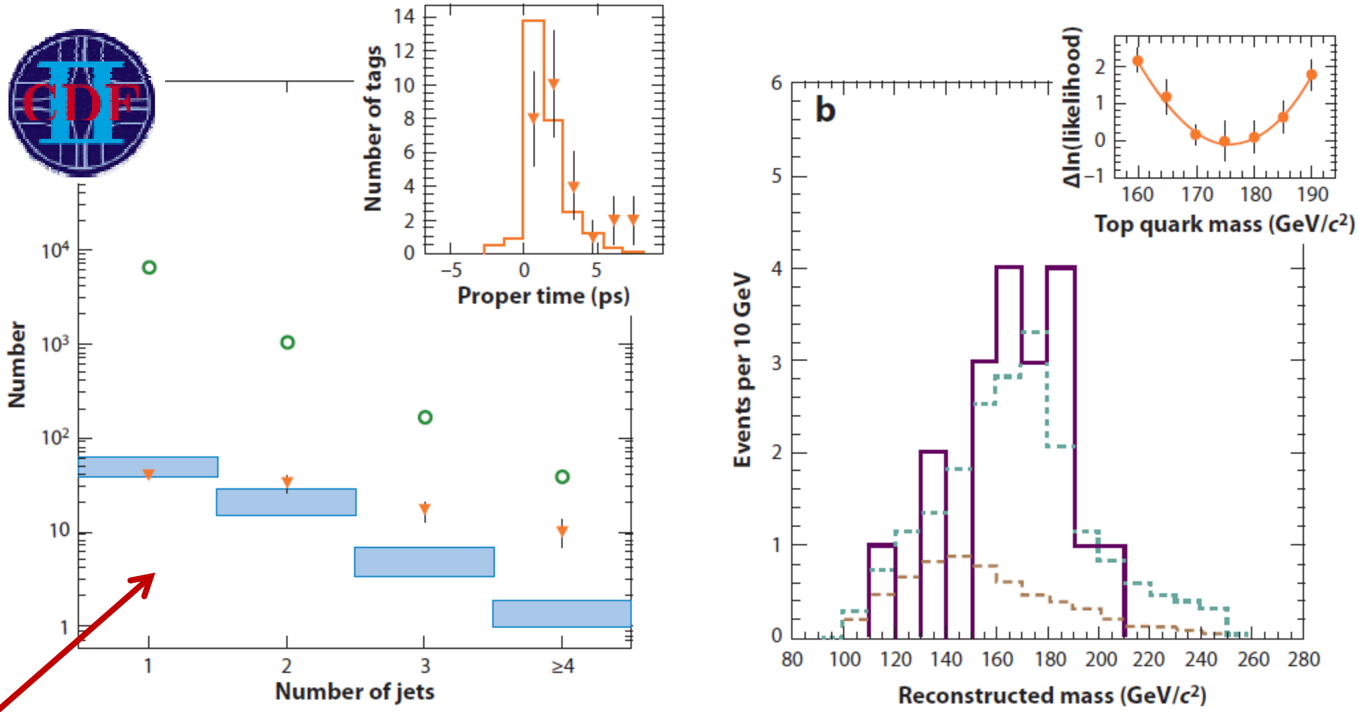


Figure 10

(*a*) Number of CDF events before secondary vertex *b* tagging (*circles*), number of tags observed (*triangles*), and expected number of background tags (*hatch marks*) versus jet multiplicity. (*Inset*) The secondary vertex proper time distribution for events with three or more jets (*triangles*) compared with the expectation for *b* quark jets in top quark decay. (*b*) CDF reconstructed mass distribution for *b*-tagged events with at least four jets (*solid line*). Also shown are the background shape (*dashed purple line*) normalized to the expected number of background events and the sum of the background and top quark contributions (*dotted green line*). (*Inset*) The likelihood fit used to determine the top quark mass. Modified from Abe et al. 1995 (115) with permission.

Summary

Finally, a simple table with all the quarks and their quantum numbers [antiquarks have same I and opposite $\mathcal{B}$, Q, I_3, S, C, B,

	d	u	s	c	b	t
$\mathcal{B}$: baryon number	⅓	⅓	⅓	⅓	⅓	⅓
Q : electric charge	–⅓	+⅔	–⅓	+⅔	–⅓	+⅔
I : Isospin	½	½	0	0	0	0
I_3 : Isospin 3-component	–½	+½	0	0	0	0
S : strangeness	0	0	–1	0	0	0
C : charm	0	0	0	+1	0	0
B : bottomness	0	0	0	0	–1	0
T : topness	0	0	0	0	0	+1

Gell-Mann – Nishijima (revised) formula : $Q = I_3 + ½ (\mathcal{B} + S + C + B + T)$.

conventional rules:

- **in Gell-Mann–Nishijima all +ve;**
- **I_3 –ve for d / +ve for u;**
- **S/B –ve for s/b;**
- **C/T +ve for c/t;**

(if different rule, please stay consistent).

Is this the REAL end of the story, i.e. no other quark exists ?

- the SM does not answer: discoveries or mass limits are left to the experiments;
- LEP measurement of n_ν [see];
- present mass limits [mainly LHC];
- a bSM theory could predict the number of families (or any other constraint).

References

1. [BJ, 10];
2. [Bettini, 4];
3. [YN1 14], [YN2 11.9]
4. the process $e^+e^- \rightarrow f\bar{f}$: [MQR 14];
5. the CKM mixing and the GIM mechanism : [§ 4] and refs. therein;
6. the LEP fit to m_t : [§ 6];
7. Tevatron results : Ann. Rev. Nucl. Part. Sci. 2013. 63:467–502 [*notice that the LEP fit to m_t is NOT mentioned*].

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End of chapter 3