Hadrons in QCD

- SU(3)_color Symmetry
- Bound hadronic states and confinement
- Running of alpha
- asymptotic freeedom
- $e^+e^- \rightarrow$ hadrons (R_had)
- Tests of QCD and hadron decays

SU(3) Group Representation

$$r=\begin{pmatrix}1\\0\\0\end{pmatrix} \qquad g=\begin{pmatrix}0\\1\\0\end{pmatrix} \qquad b=\begin{pmatrix}0\\0\\1\end{pmatrix}$$

8 generators (N*N-1)

$$\lambda_1=\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix},\quad \lambda_2=\begin{pmatrix}0&-i&0\\i&0&0\\0&0&0\end{pmatrix}\quad \lambda_3=\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix},$$

$$\lambda_4=\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix},\quad \lambda_5=\begin{pmatrix}0&0&-i\\0&0&0\\i&0&0\end{pmatrix},\quad \lambda_6=\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix},$$

$$\lambda_7=\begin{pmatrix}0&0&0\\0&0&-i\\0&i&0\end{pmatrix},\quad \lambda_8=(1/\sqrt{3})\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}.$$

structure constants:

$f^{123}=1$,

$f^{147}=-f^{156}=f^{246}=f^{257}=f^{345}=-f^{367}=½$

$f^{458}=f^{678}=½\sqrt{3}$

Fundamental Represenation of SU(3)

$$\frac{1}{\sqrt{3}}(|R\bar{R}\rangle + |G\bar{G}\rangle + |B\bar{B}\rangle)$$

$|G\bar{B}\rangle$

$|R\bar{B}\rangle$

$-|G\bar{R}\rangle$

$\frac{1}{\sqrt{2}}(|G\bar{G}\rangle - |R\bar{R}\rangle)$

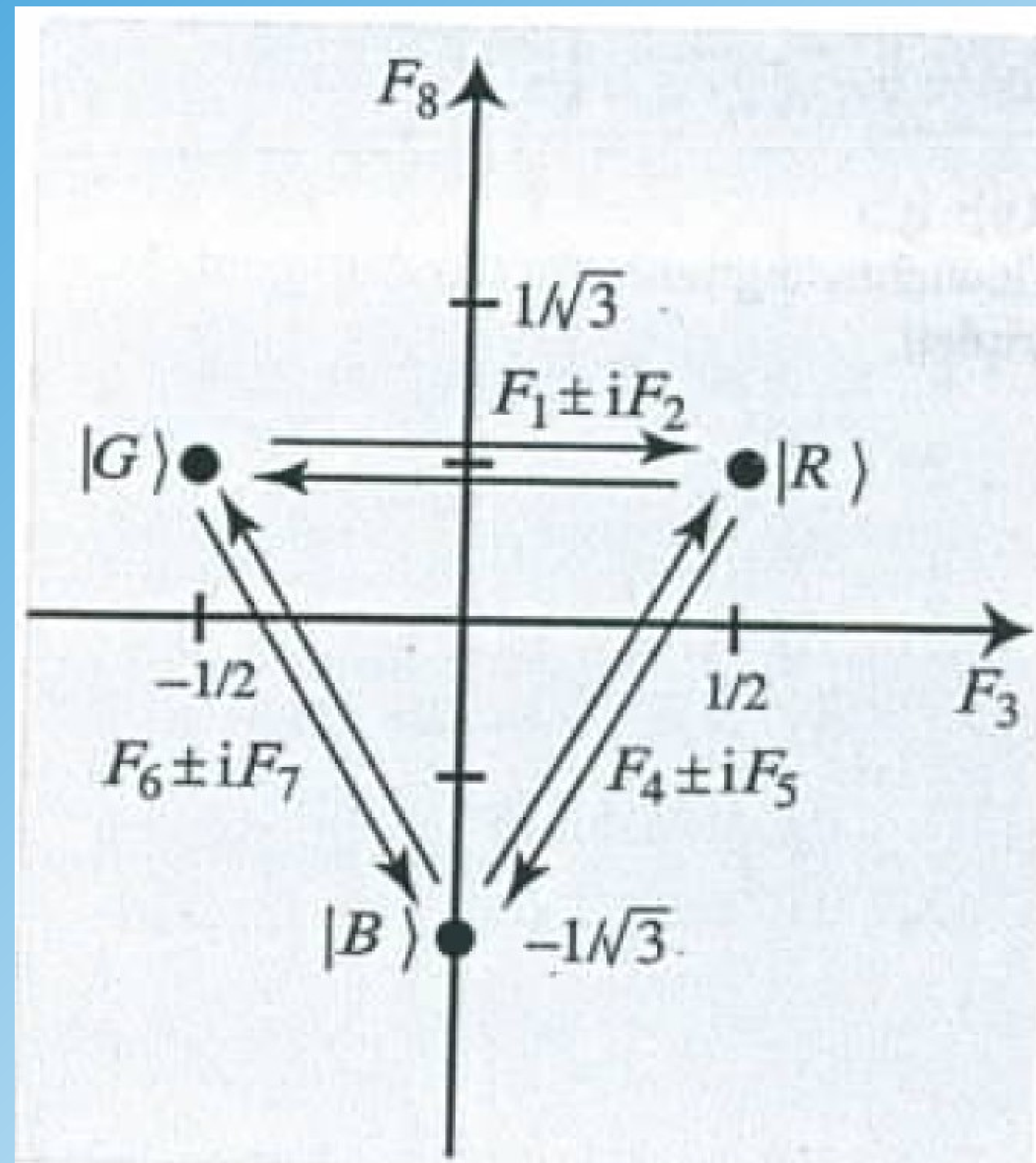
$\frac{1}{\sqrt{6}}(|R\bar{R}\rangle + |G\bar{G}\rangle - 2|B\bar{B}\rangle)$

$|R\bar{G}\rangle$

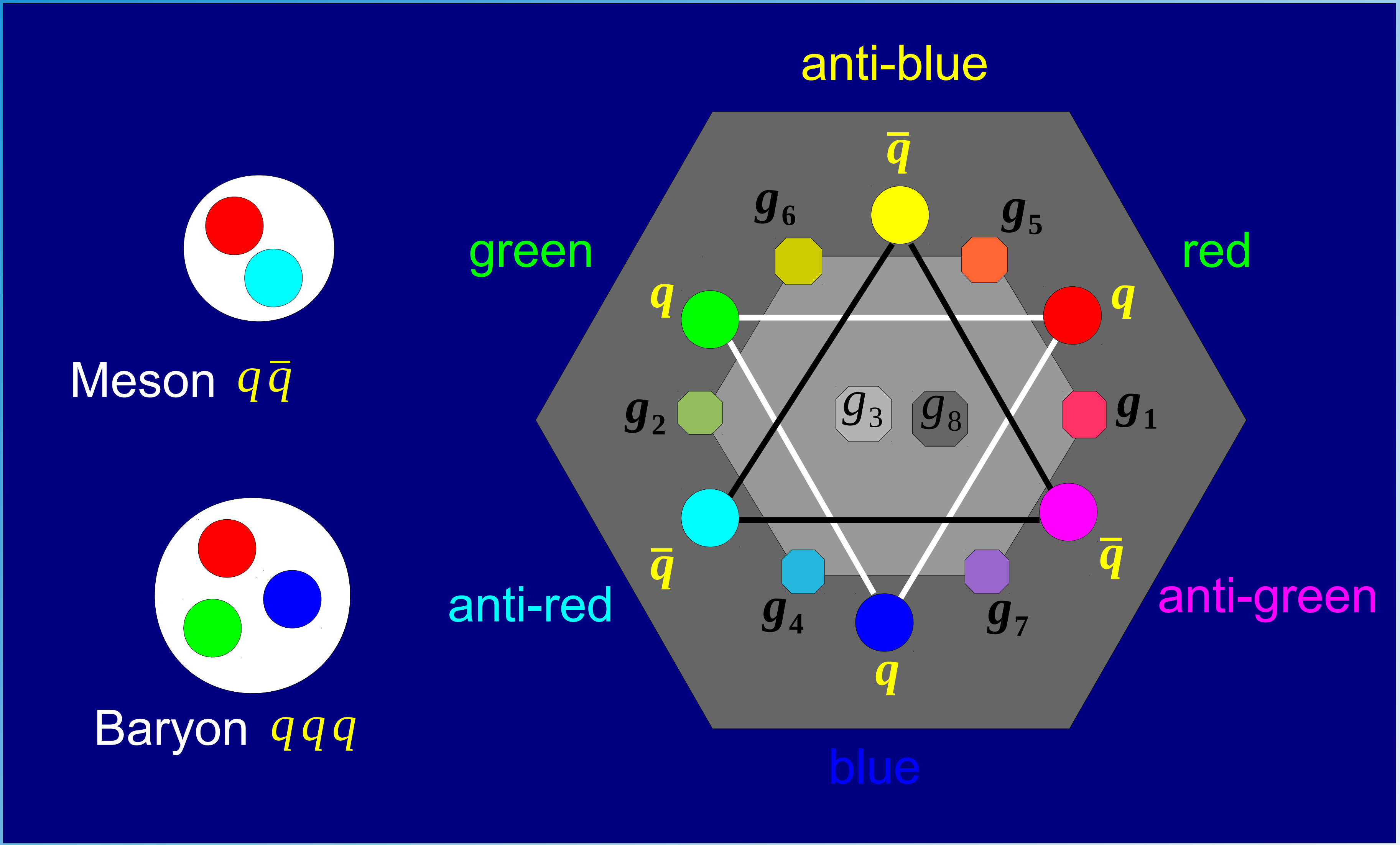
$-|B\bar{R}\rangle$

$|B\bar{G}\rangle$

8 traceless combinations

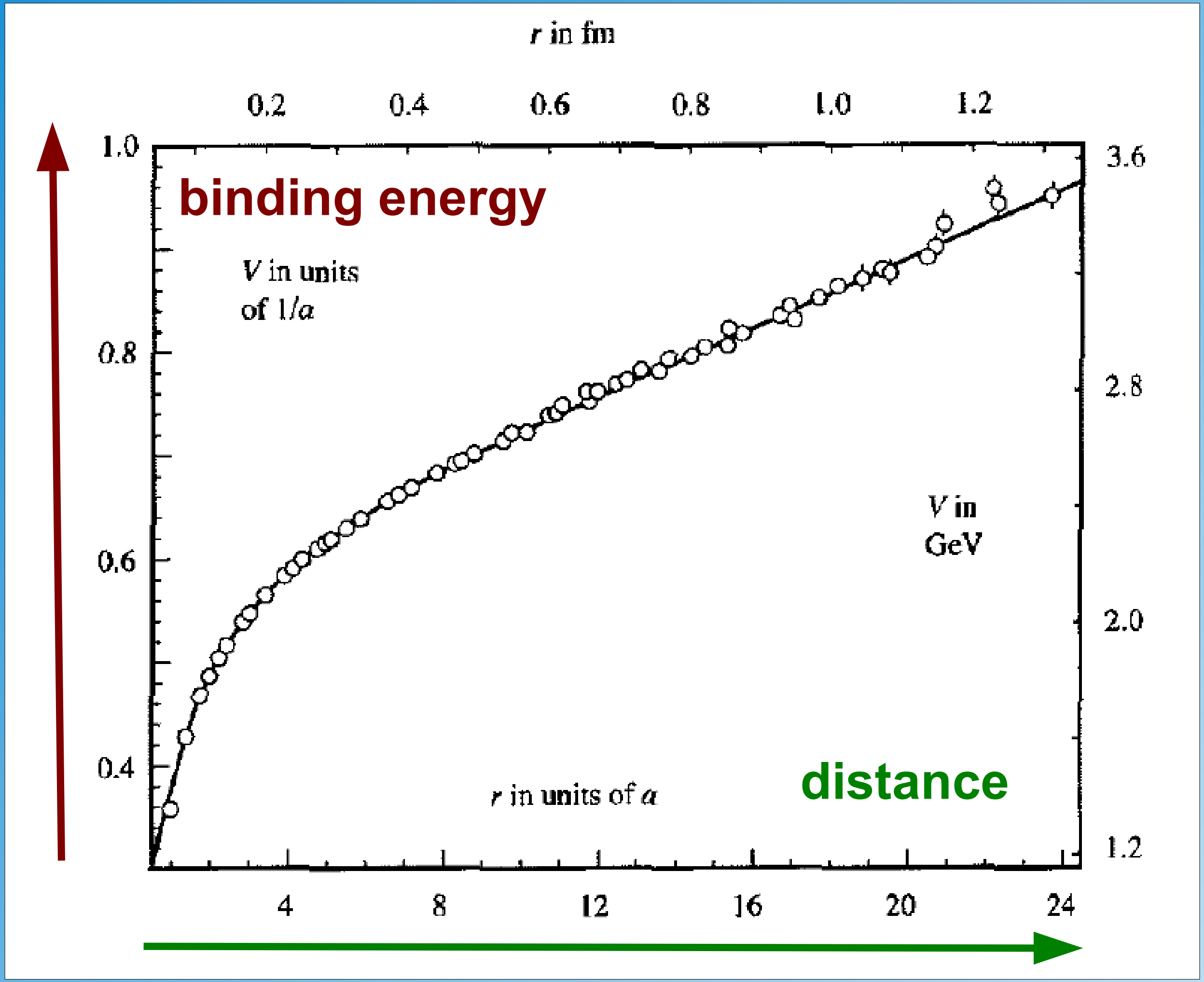


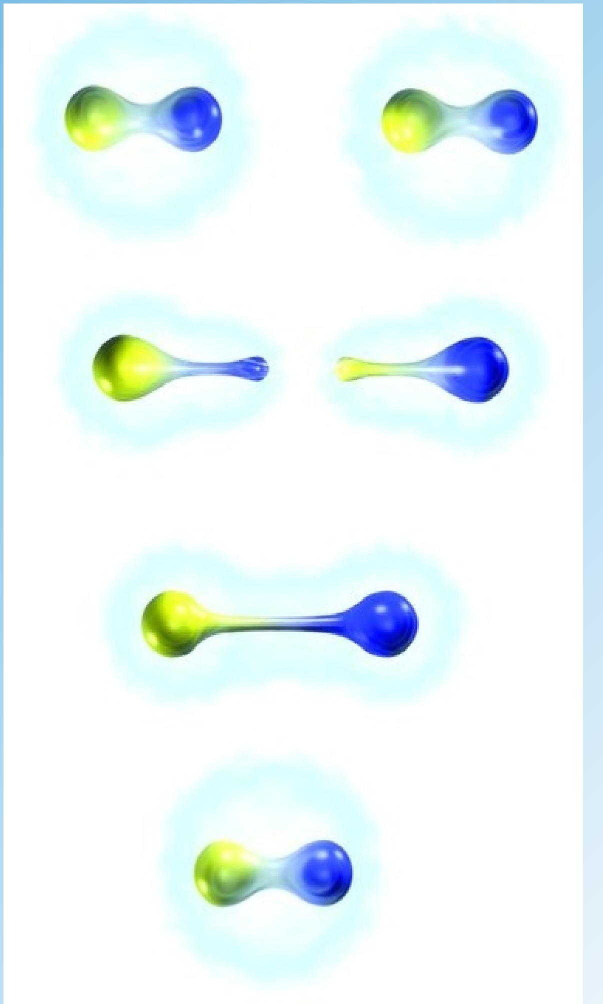
Quantum Chromodynamics



Confinement

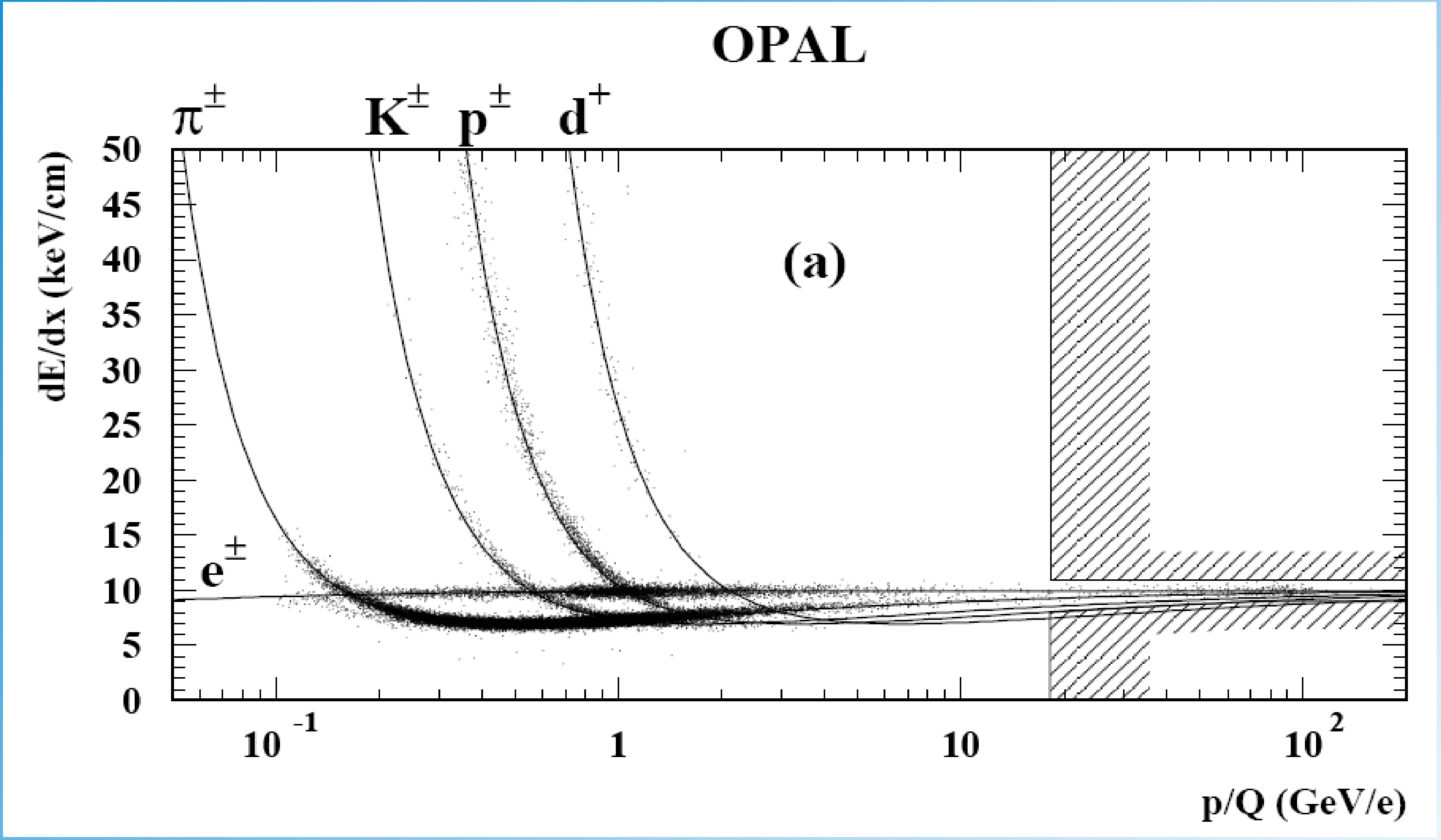
The force between two quarks is 50000 N !!!





consequence: free quarks or gluons are not observable

Search for Free Quarks



- study of ionisation losses

$SU(3)_C$ Octets and Decuplets

$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$

Singlet anti-symmetric

$\frac{1}{\sqrt{6}}(|RGB\rangle - |RBG\rangle + |BRG\rangle - |BGR\rangle + |GBR\rangle - |GRB\rangle)$

Decuplet symmetric

$|RRR\rangle$

$\frac{1}{\sqrt{3}}(|RRG\rangle + |RGR\rangle + |GRR\rangle)$

$\frac{1}{\sqrt{3}}(|RGG\rangle + |GRG\rangle + |GGR\rangle)$

$|GGG\rangle$

$\frac{1}{\sqrt{3}}(|RRB\rangle + |RBR\rangle + |BRR\rangle)$

$\frac{1}{\sqrt{6}}(|RGB\rangle + |RBG\rangle + |BRG\rangle + |BGR\rangle + |GBR\rangle + |GRB\rangle)$

$\frac{1}{\sqrt{3}}(|GGB\rangle + |GBG\rangle + |BGG\rangle)$

$\frac{1}{\sqrt{3}}(|RBB\rangle + |BRB\rangle + |BBR\rangle)$

$\frac{1}{\sqrt{3}}(|GBB\rangle + |BGB\rangle + |BBG\rangle)$

$|BBB\rangle$

Octet anti-symmetric

$\frac{1}{\sqrt{2}}(|GRG\rangle - |GGR\rangle)$

$\frac{1}{\sqrt{2}}(|RRG\rangle - |RGR\rangle)$

$\frac{1}{\sqrt{2}}(|GBG\rangle - |GGB\rangle)$

$\frac{1}{2}(|RBG\rangle - |RGB\rangle + |GBR\rangle - |GRB\rangle)$

$\frac{1}{\sqrt{12}}(|RGB\rangle - |RBG\rangle + |GBR\rangle - |GRB\rangle + 2|BGR\rangle - 2|BRG\rangle)$

$\frac{1}{\sqrt{2}}(|RBR\rangle - |RRB\rangle)$

$\frac{1}{\sqrt{2}}(|BBG\rangle - |BGB\rangle)$

$\frac{1}{\sqrt{2}}(|BBR\rangle - |BRB\rangle)$

Octet mixed

$\frac{1}{\sqrt{6}}(|GGR\rangle + |GRG\rangle - 2|RGG\rangle)$

$\frac{1}{\sqrt{6}}(-|RRG\rangle - |RGR\rangle + 2|GRR\rangle)$

$\frac{1}{\sqrt{6}}(|GGB\rangle + |GBG\rangle - 2|BGG\rangle)$

$\frac{1}{\sqrt{12}}(|RGB\rangle + |RBG\rangle + |GRB\rangle + |GBR\rangle - 2|BRG\rangle - 2|BGR\rangle)$

$\frac{1}{\sqrt{6}}(|RRB\rangle + |RBR\rangle - 2|BRR\rangle)$

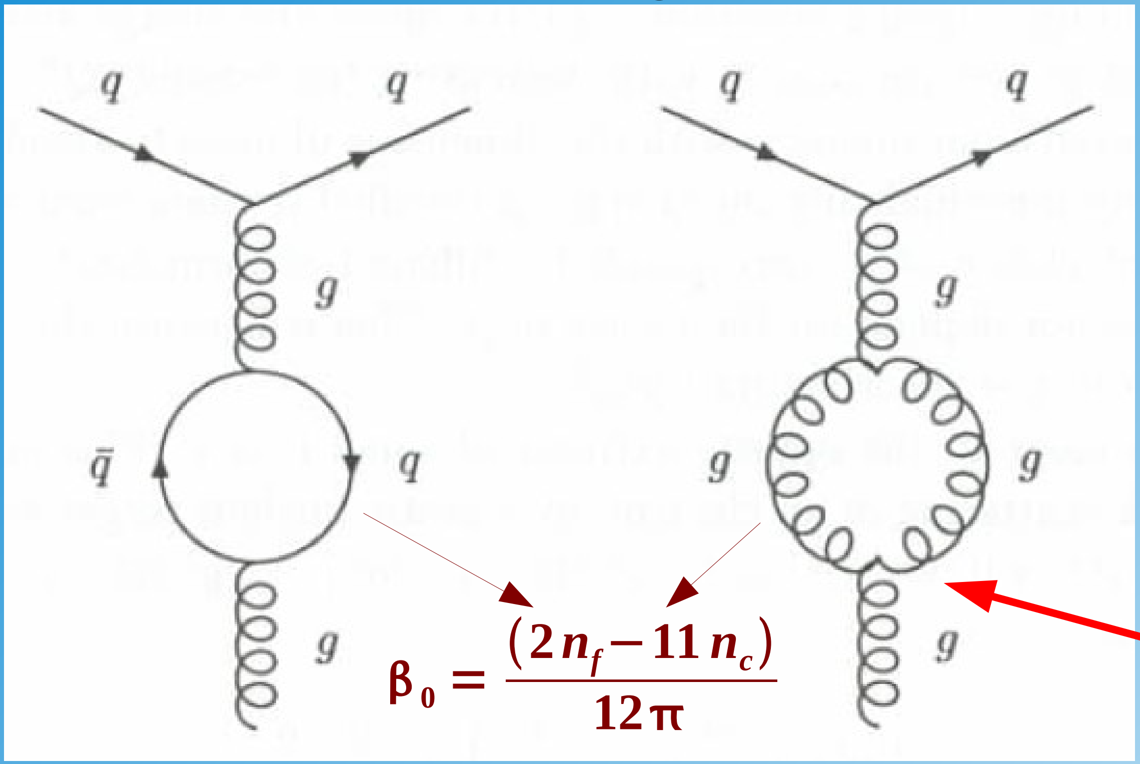
$\frac{1}{\sqrt{6}}(-|BGB\rangle - |BBG\rangle + 2|GBB\rangle)$

$\frac{1}{\sqrt{6}}(-|BRB\rangle - |BBR\rangle + 2|RBB\rangle)$

$\frac{1}{2}(|GRB\rangle + |GBR\rangle - |RGB\rangle - |RBG\rangle)$

QCD Vacuum Polarisation

The vacuum as „magnetic medium“



$$\beta_0 = \frac{(2n_f - 11n_c)}{12\pi}$$

„diamagnetic“
(isolator)

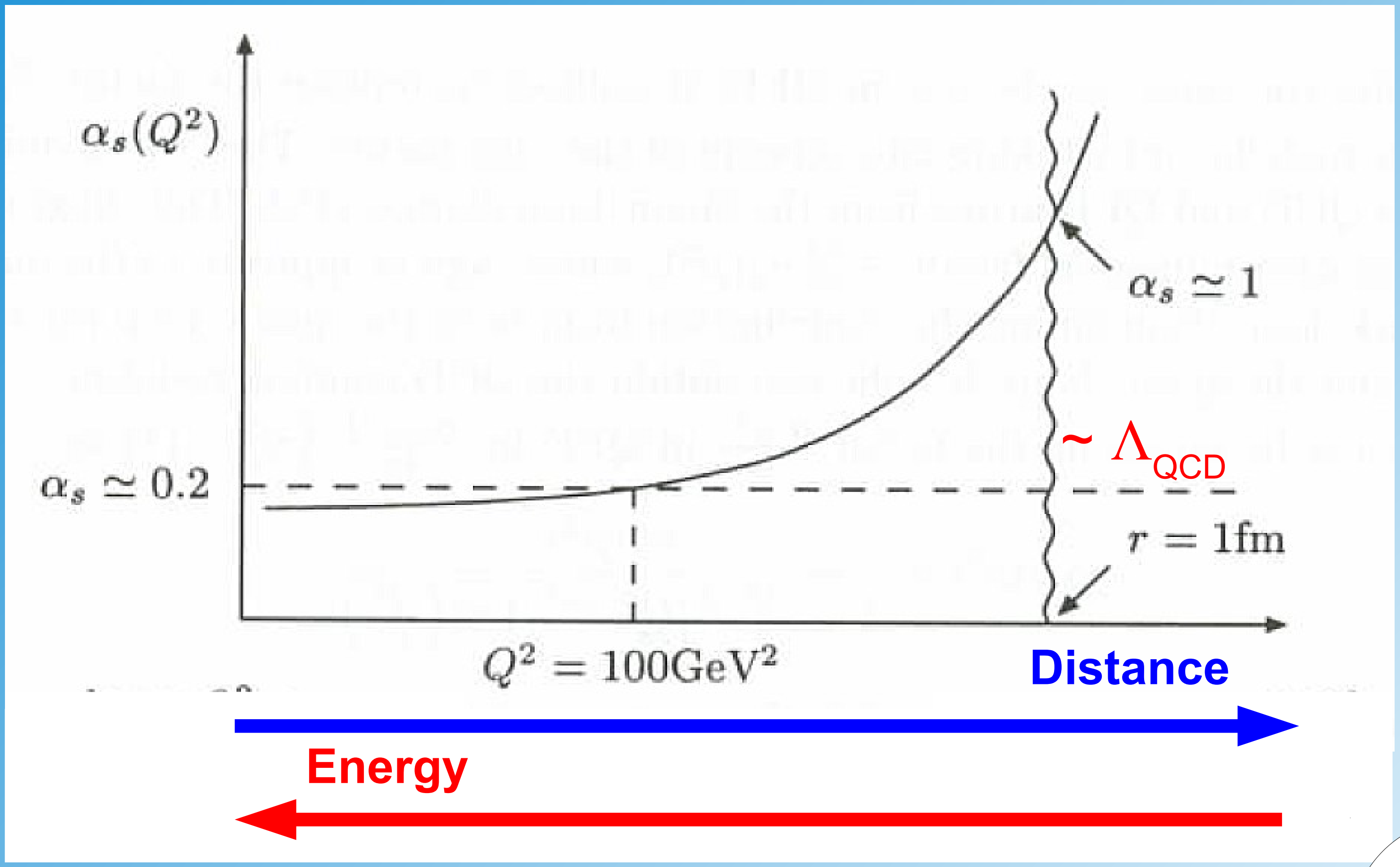
„paramagnetic“
(magnet)

$$\alpha(Q^2) = -\frac{1}{\beta_0 \log(Q^2/\Lambda^2)}$$

$$\beta_0 < 0$$

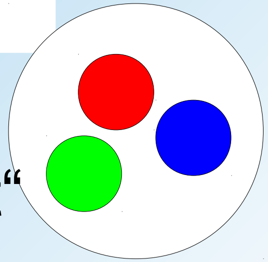
(asymptotic freedom)

Running of alpha$_s$



„Asymptotic Freedem“

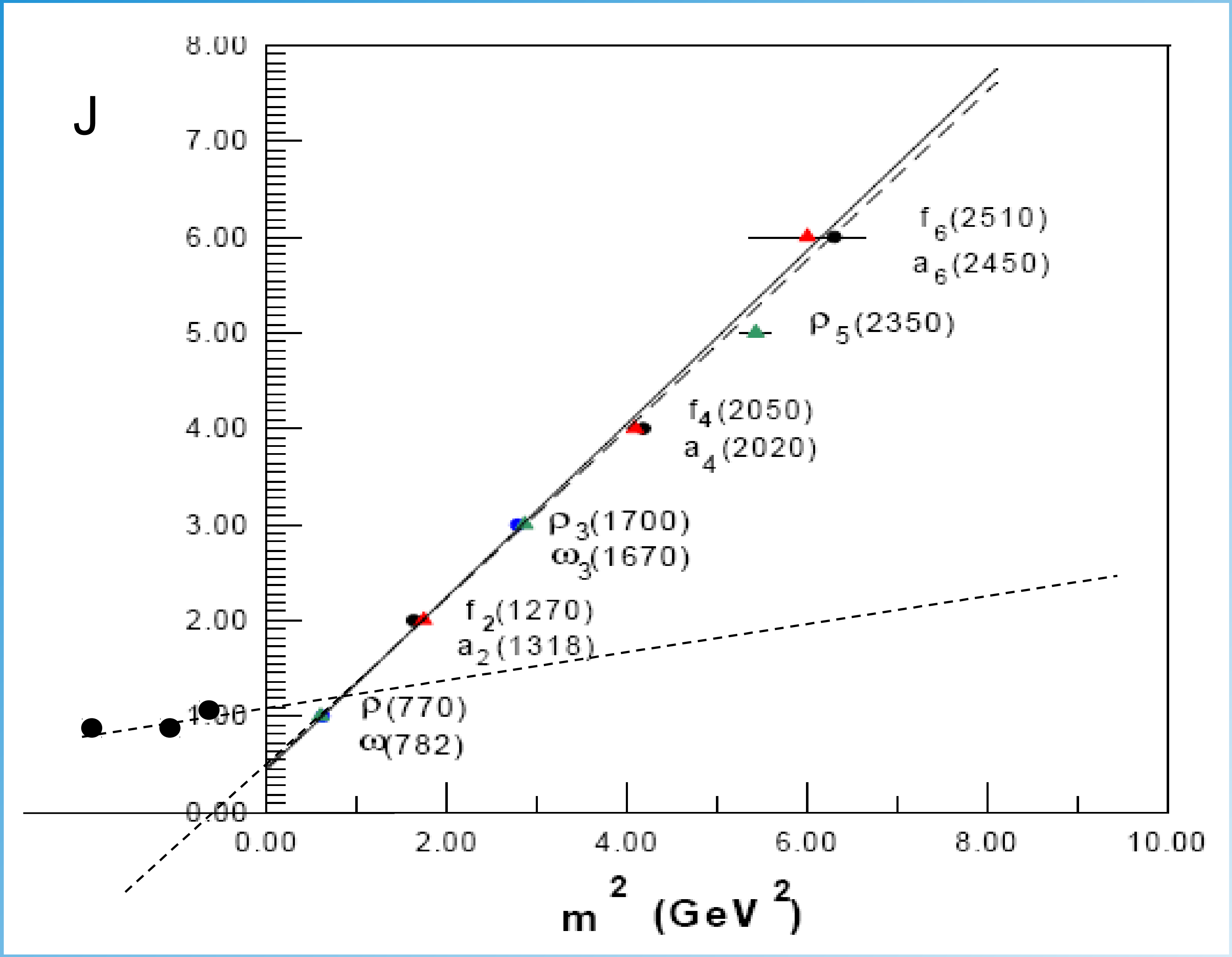
„Confinement“



„Asymptotic Freedom“

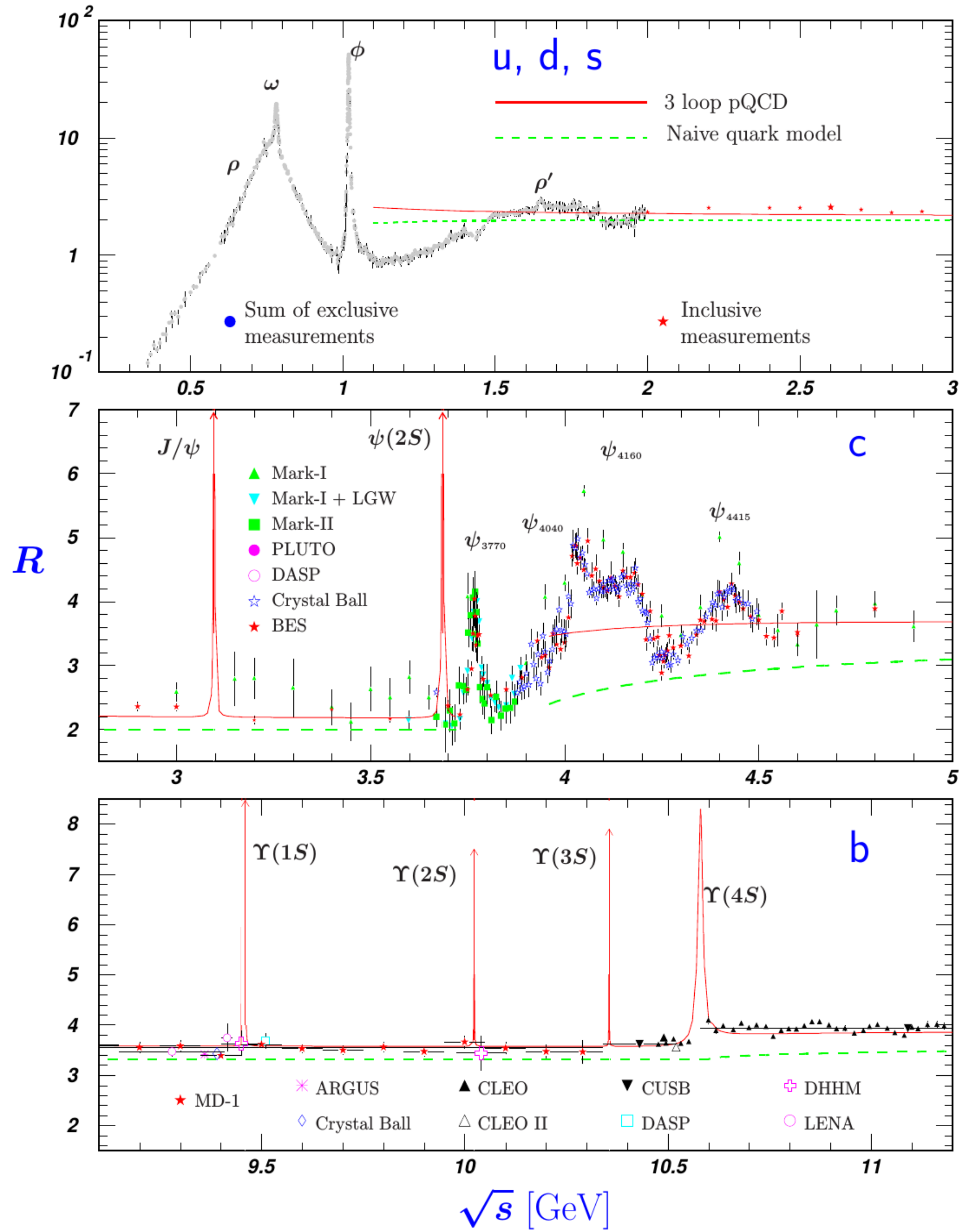
„Oh Brother, where art thou?“ (2000)

Chew Frautschi-Plot

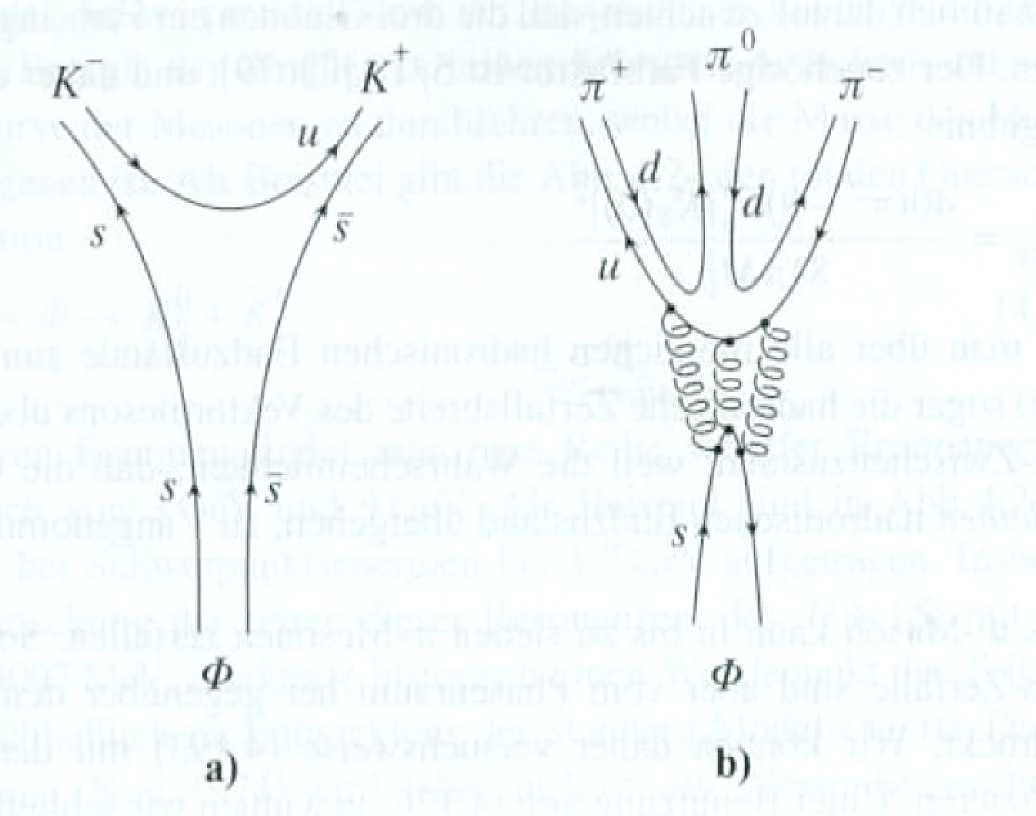


Measurements of R_had

$$R_{had} = \frac{e^+ e^- \to hadrons}{e^+ e^- \to \mu^+ \mu^-}$$



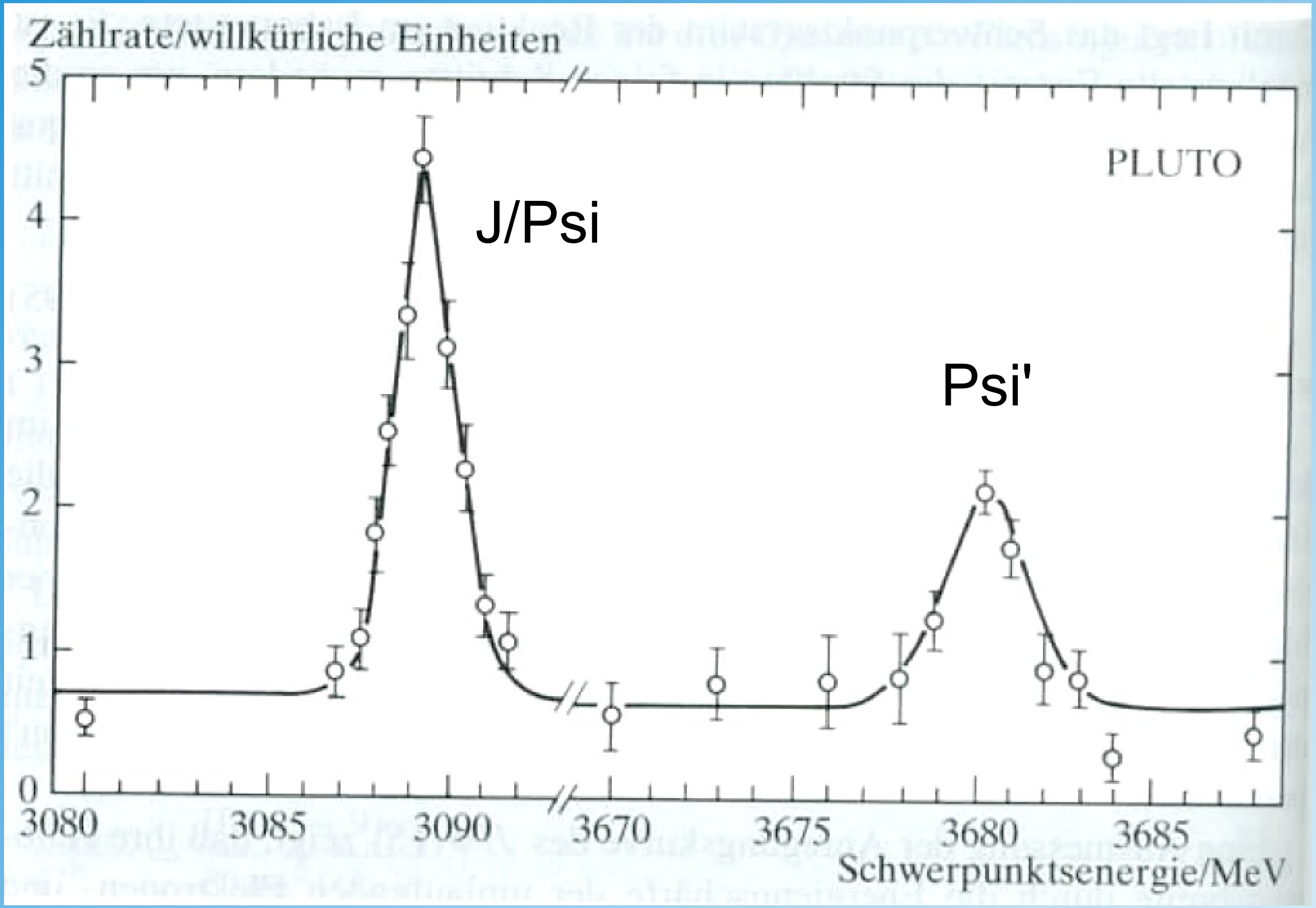
Phi Decays



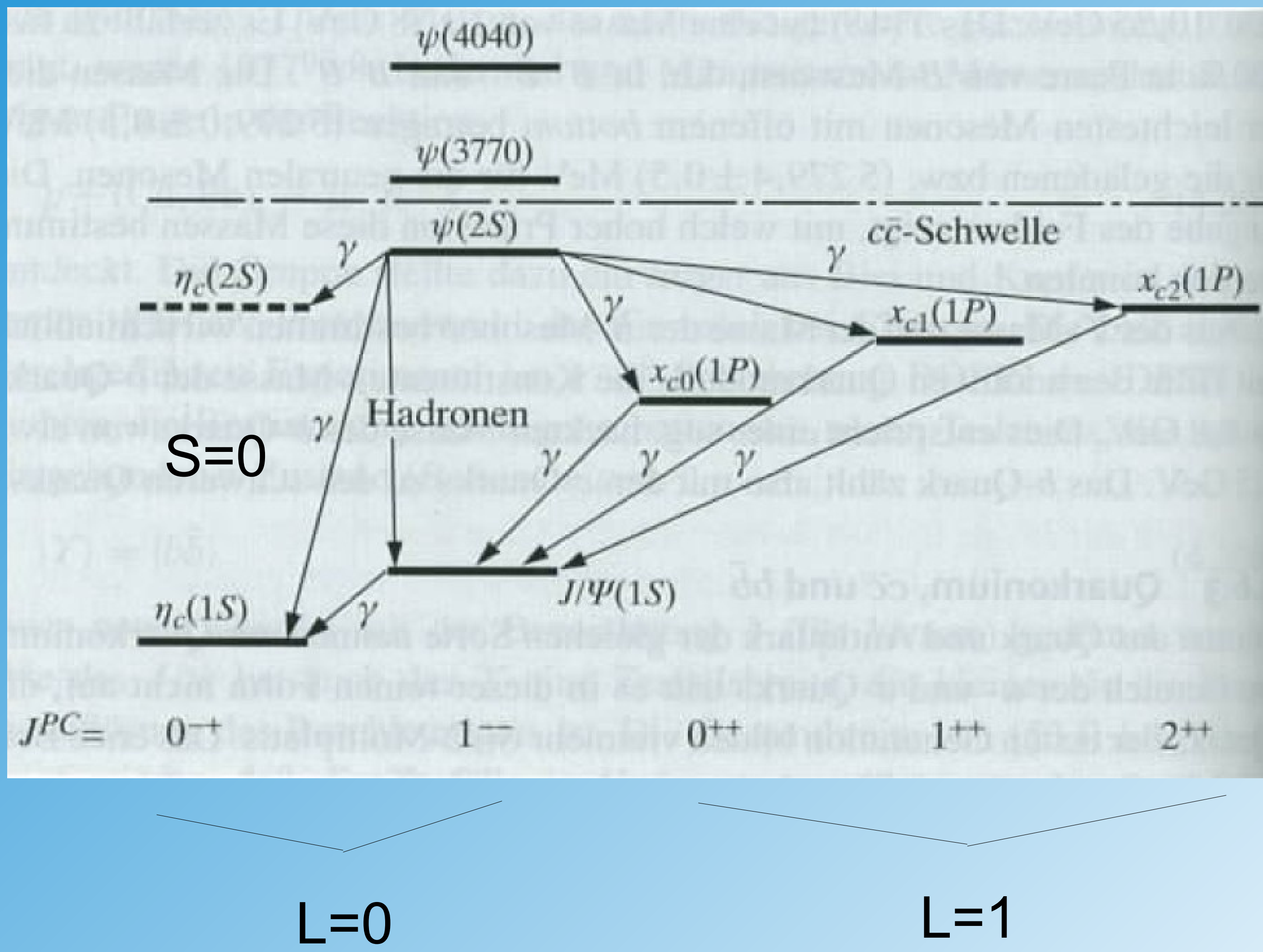
dominant if allowed

OZI (Zweig) rule

Charmonium Resonances

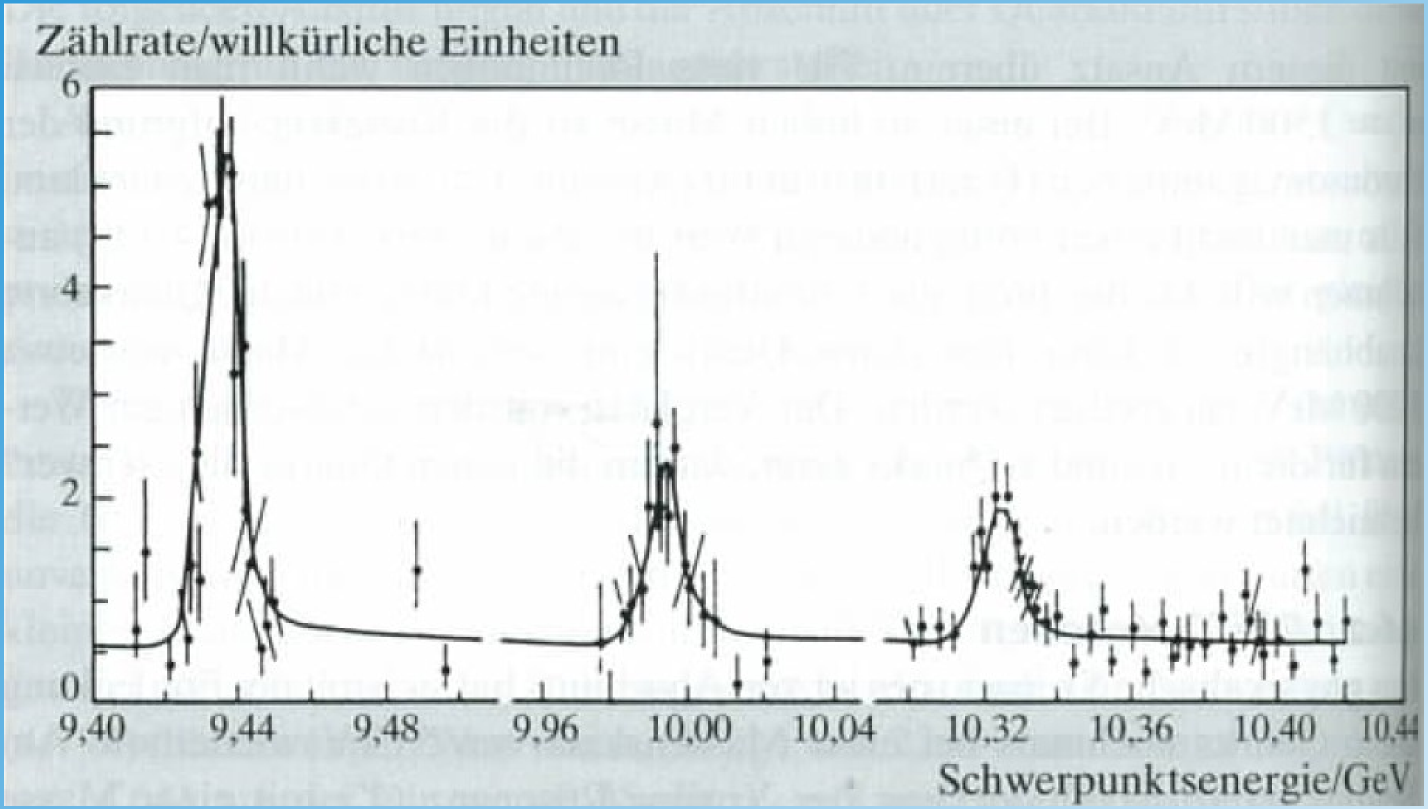


Charmonium

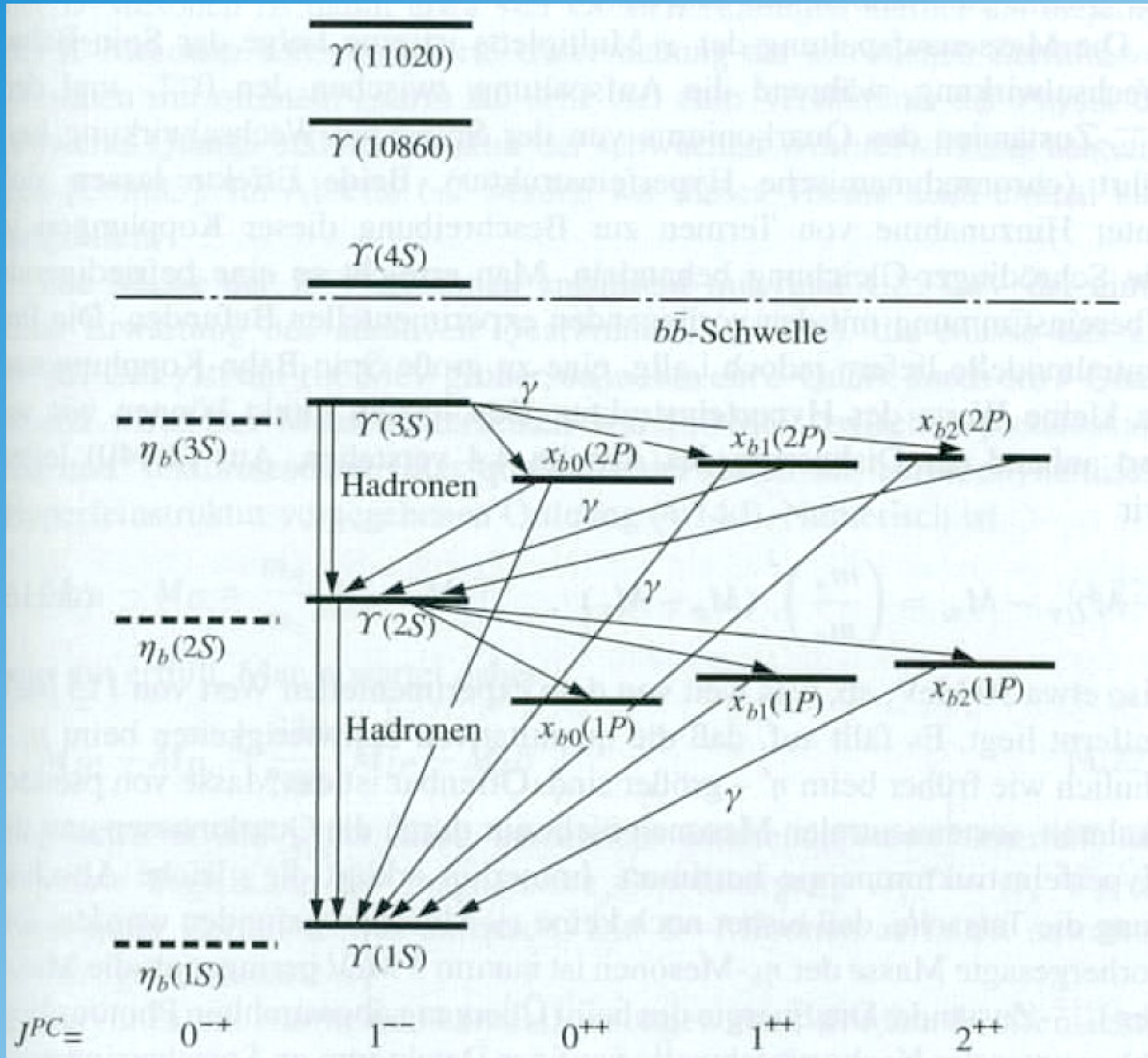


ψ(4040)
ψ(3770)
ψ(2S)
$c\bar{c}$-Schwelle
$\eta_c(2S)$
$\chi_{c2}(1P)$
$\chi_{c1}(1P)$
$\chi_{c0}(1P)$
Hadronen
γ
S=0
J/Ψ(1S)
$\eta_c(1S)$
$J^{PC}=$ 0^{-+} 1^{--} 0^{++} 1^{++} 2^{++}
L=0
L=1

Bottomium Resonances



Bottomium



Υ(11020)
Υ(10860)
Υ(4S)
$b\bar{b}$-Schwelle
γ
$\eta_b(3S)$
Υ(3S)
$\chi_{b0}(2P)$
$\chi_{b1}(2P)$
$\chi_{b2}(2P)$
Hadronen
γ
γ
$\eta_b(2S)$
Υ(2S)
$\chi_{b0}(1P)$
$\chi_{b1}(1P)$
$\chi_{b2}(1P)$
Hadronen
γ
$\eta_b(1S)$
Υ(1S)
$J^{PC}=$ 0^{-+} 1^{--} 0^{++} 1^{++} 2^{++}