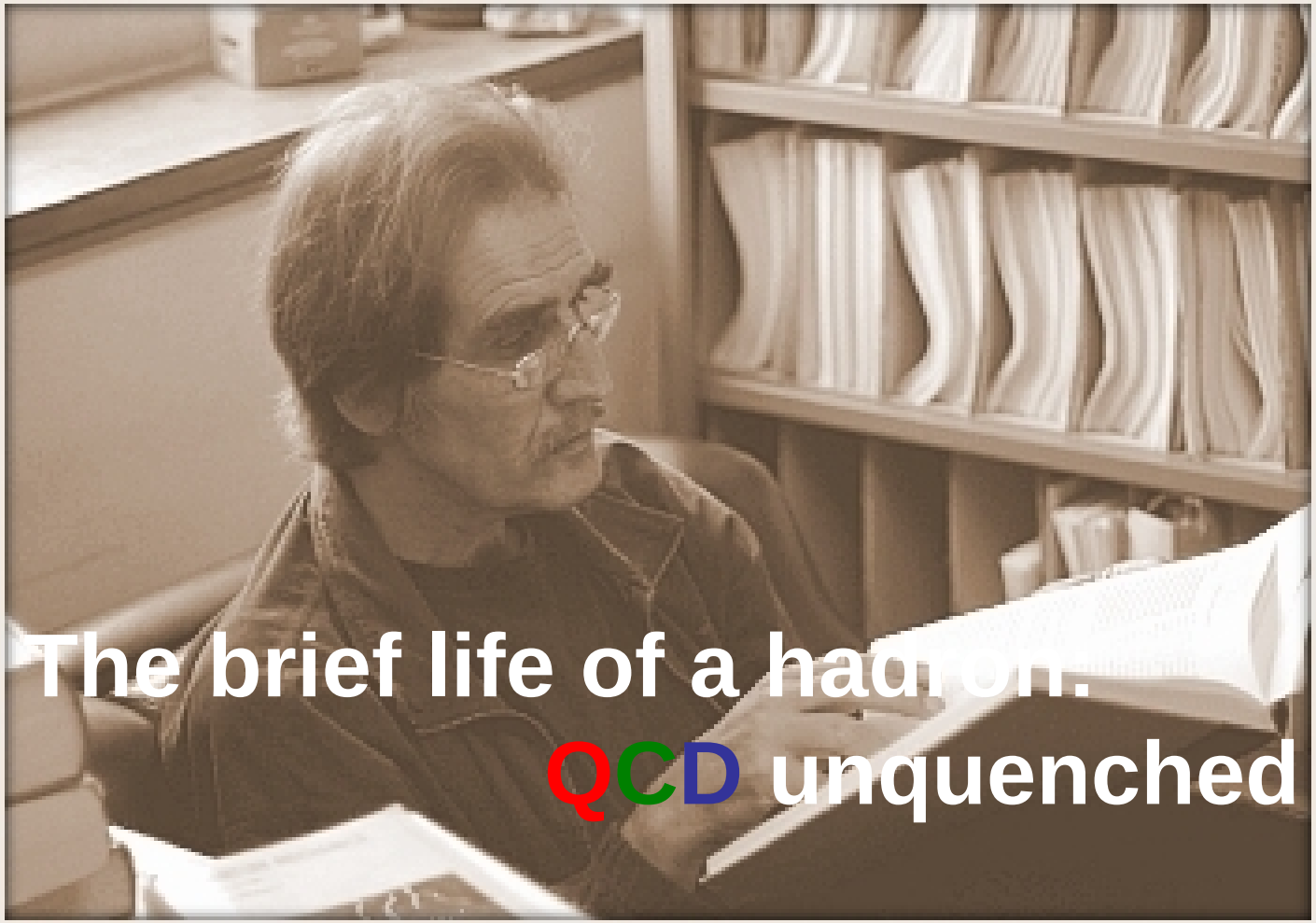
EEF 70

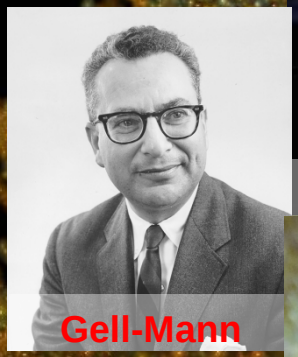


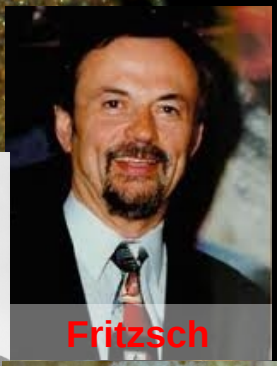
Michael Pennington
Coimbra 2014

Glimpsing colour
in a world of black & white

QCD

$$\mathcal{L}_{QCD} = \sum_{\substack{q=u,d,s,\\ c,b,t}} \bar{q} \left(i\gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

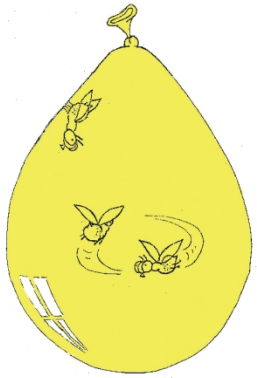

Gell-Mann


Fritzsch

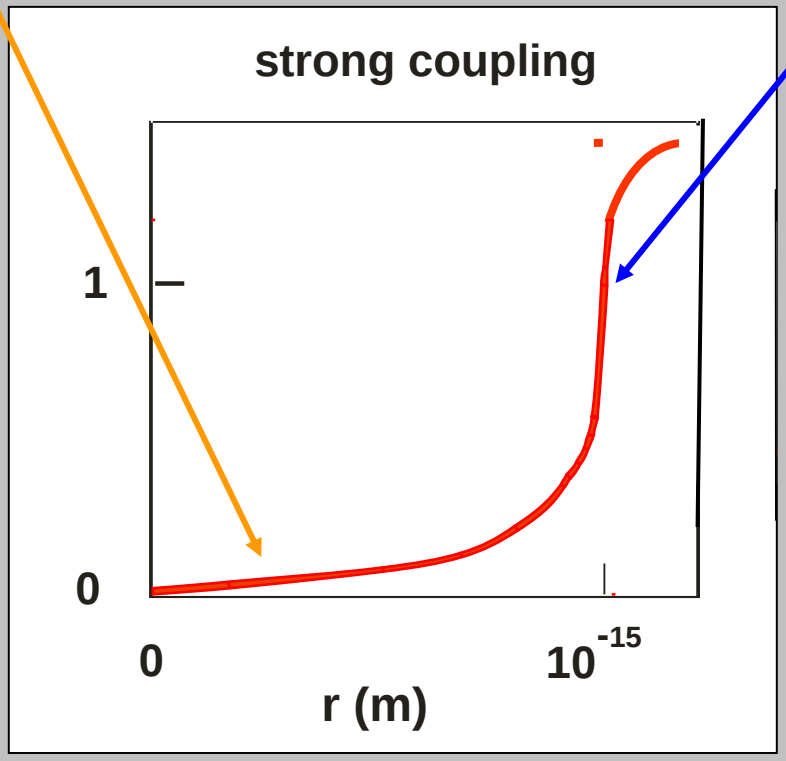
Leutwyler

QCD

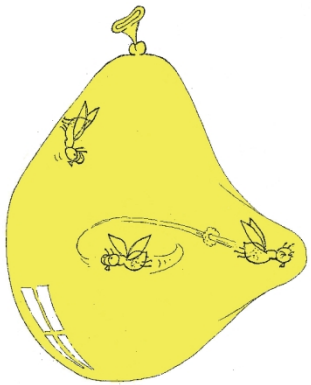
asymptotic freedom



pQCD



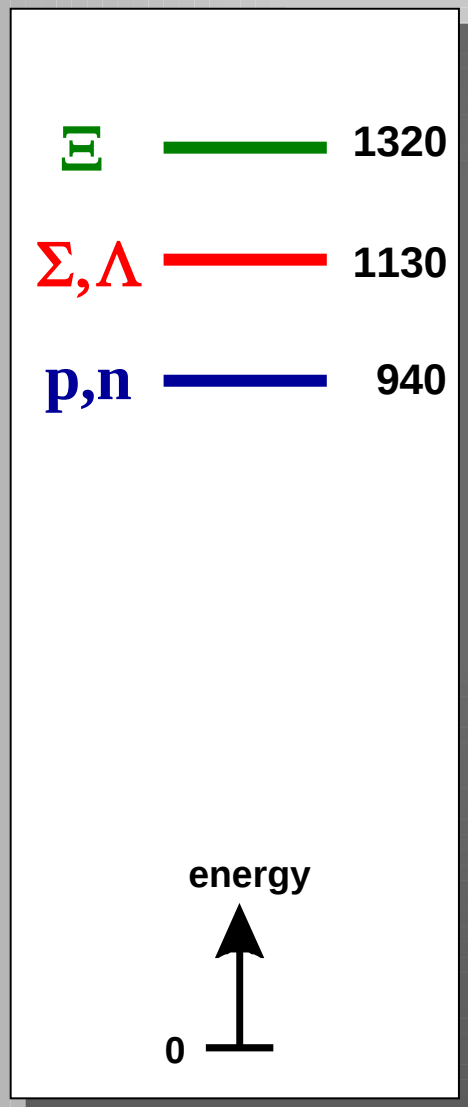
confinement

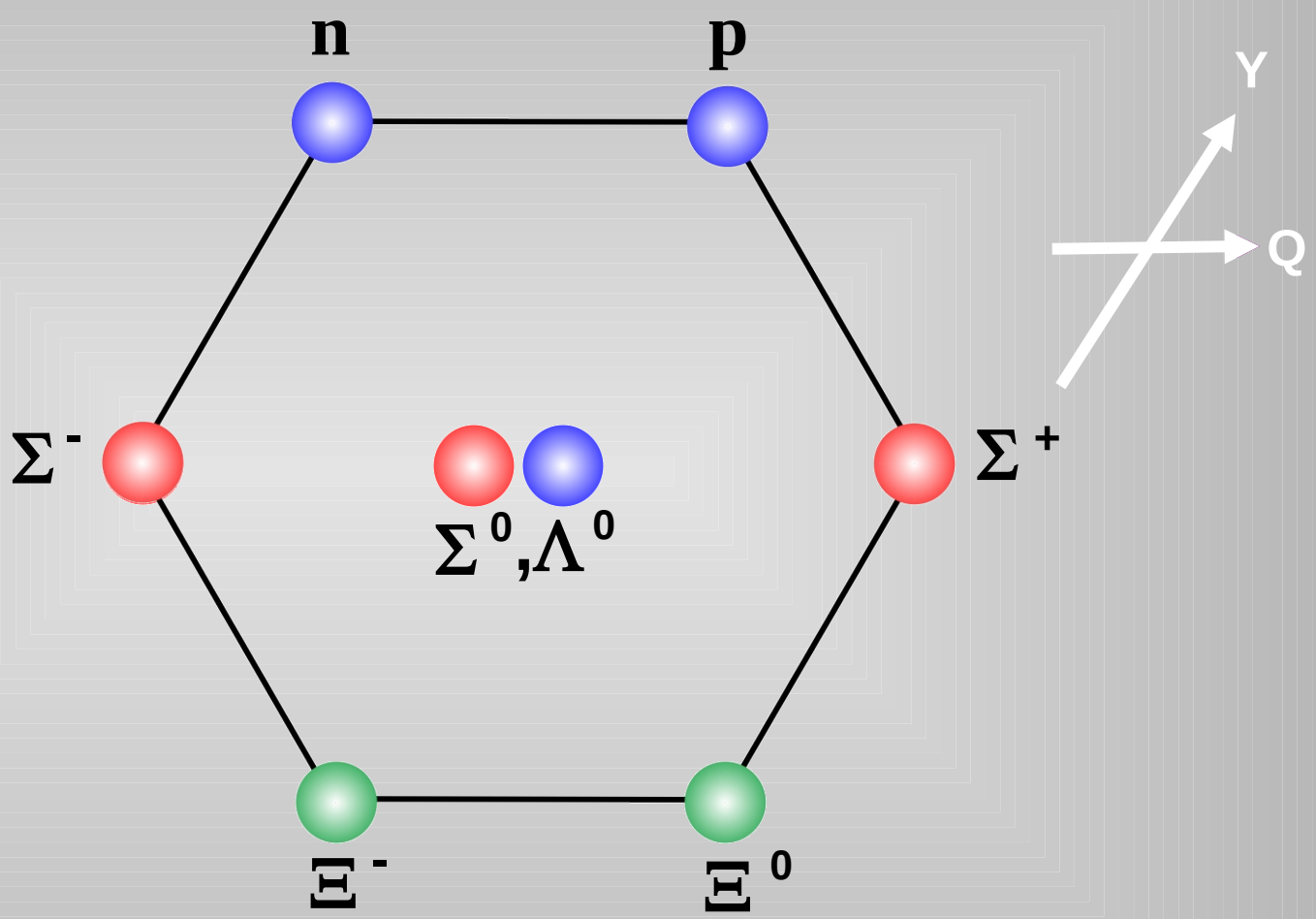


strong QCD

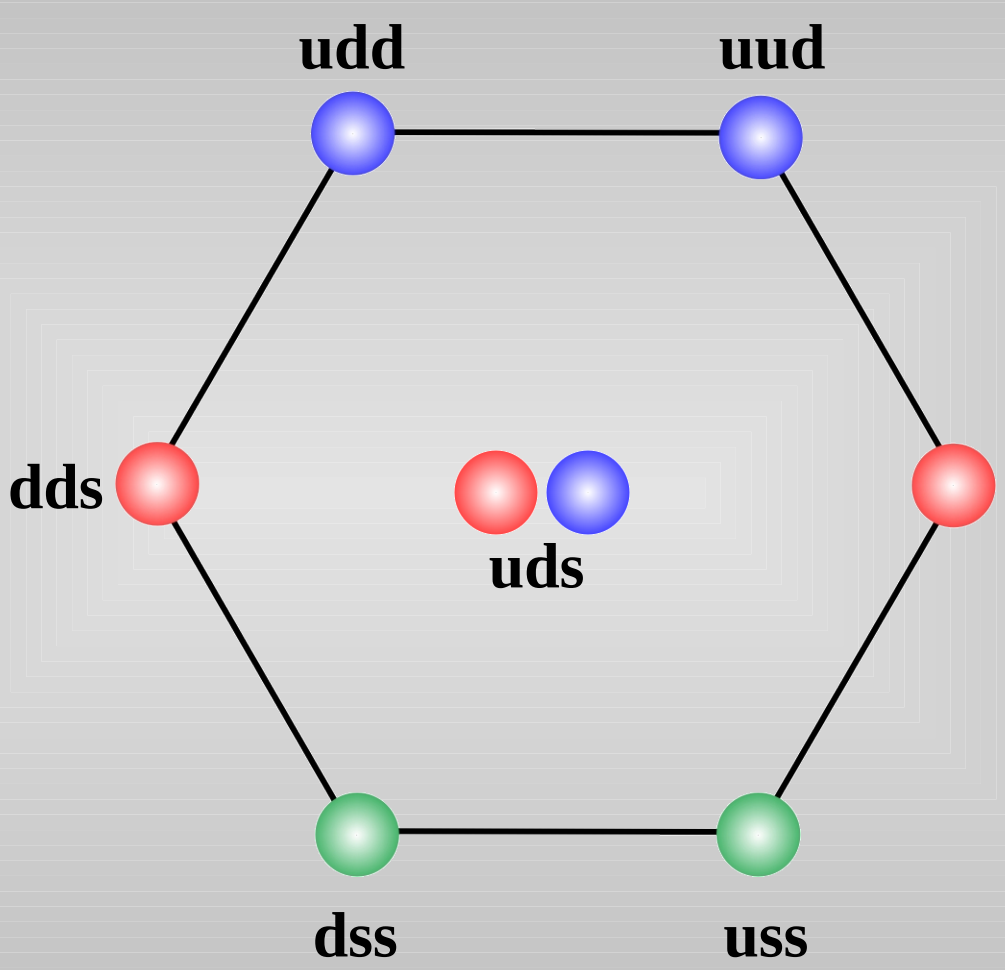
Hadron spectrum

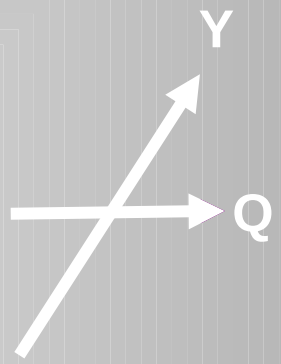
Baryon octet

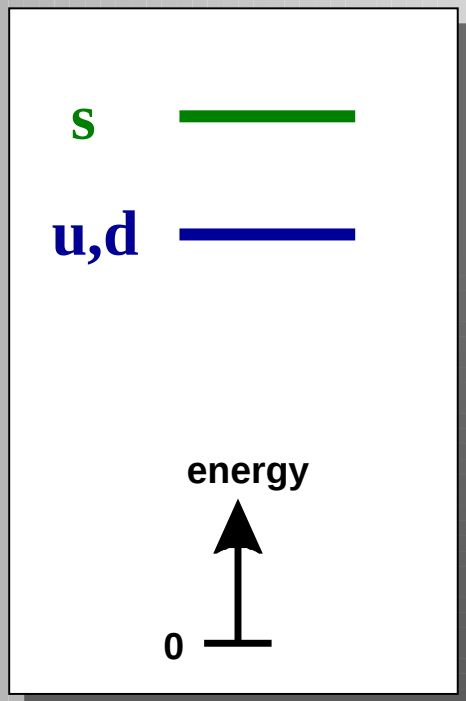


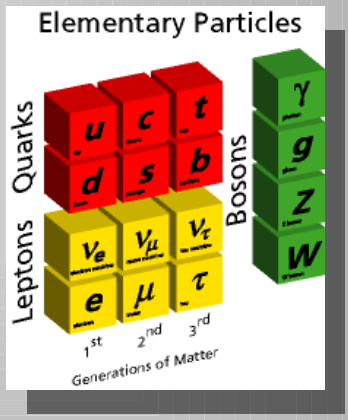


Baryon octet

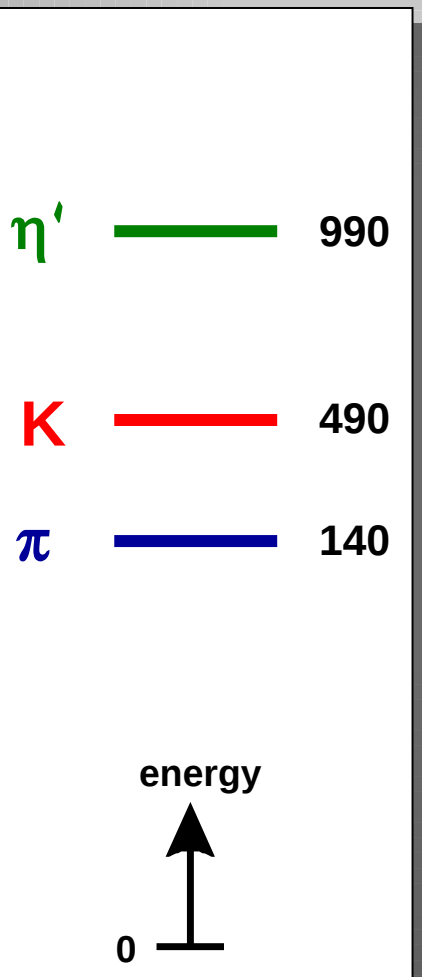


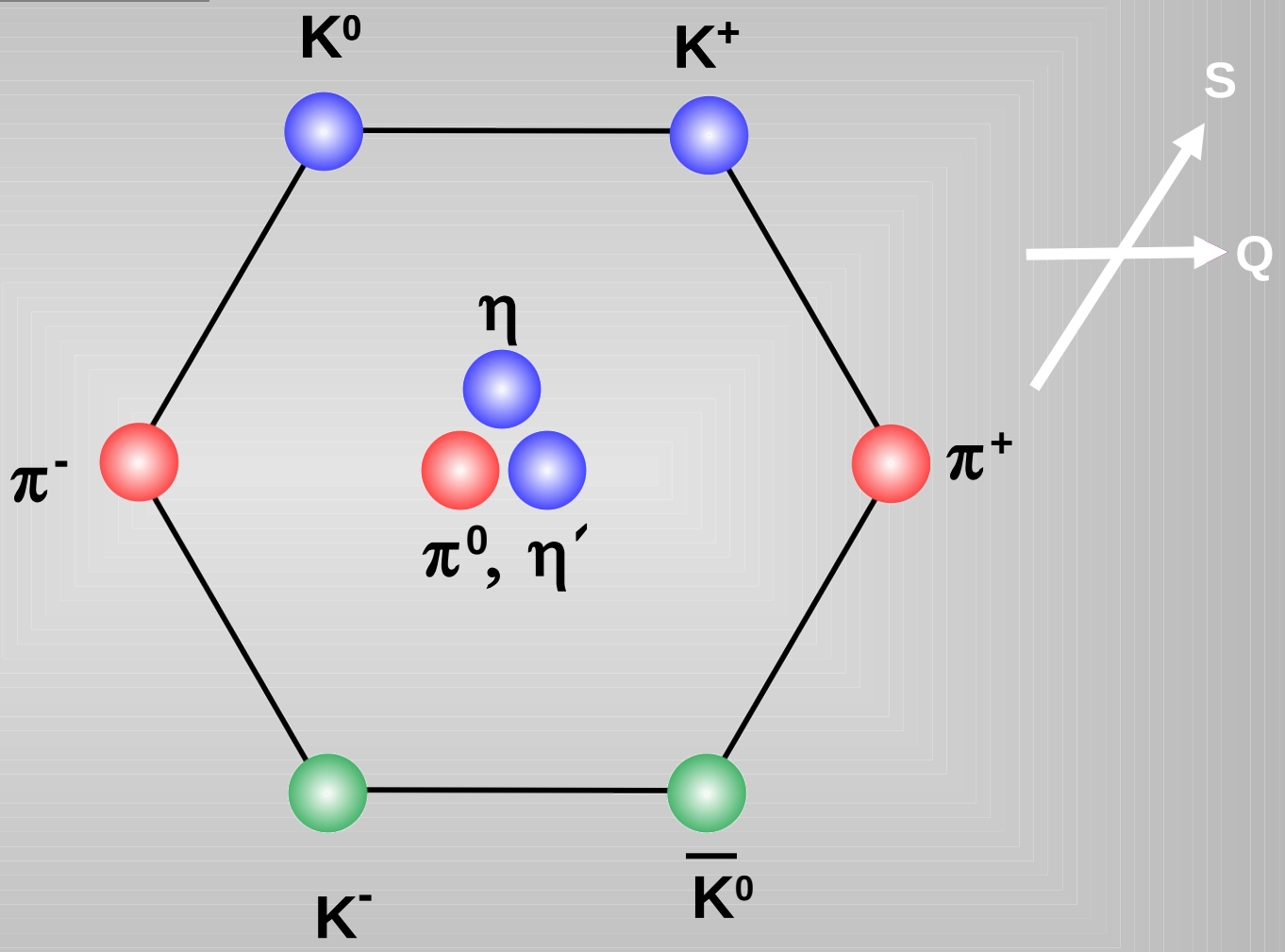






Meson nonet





Ground States

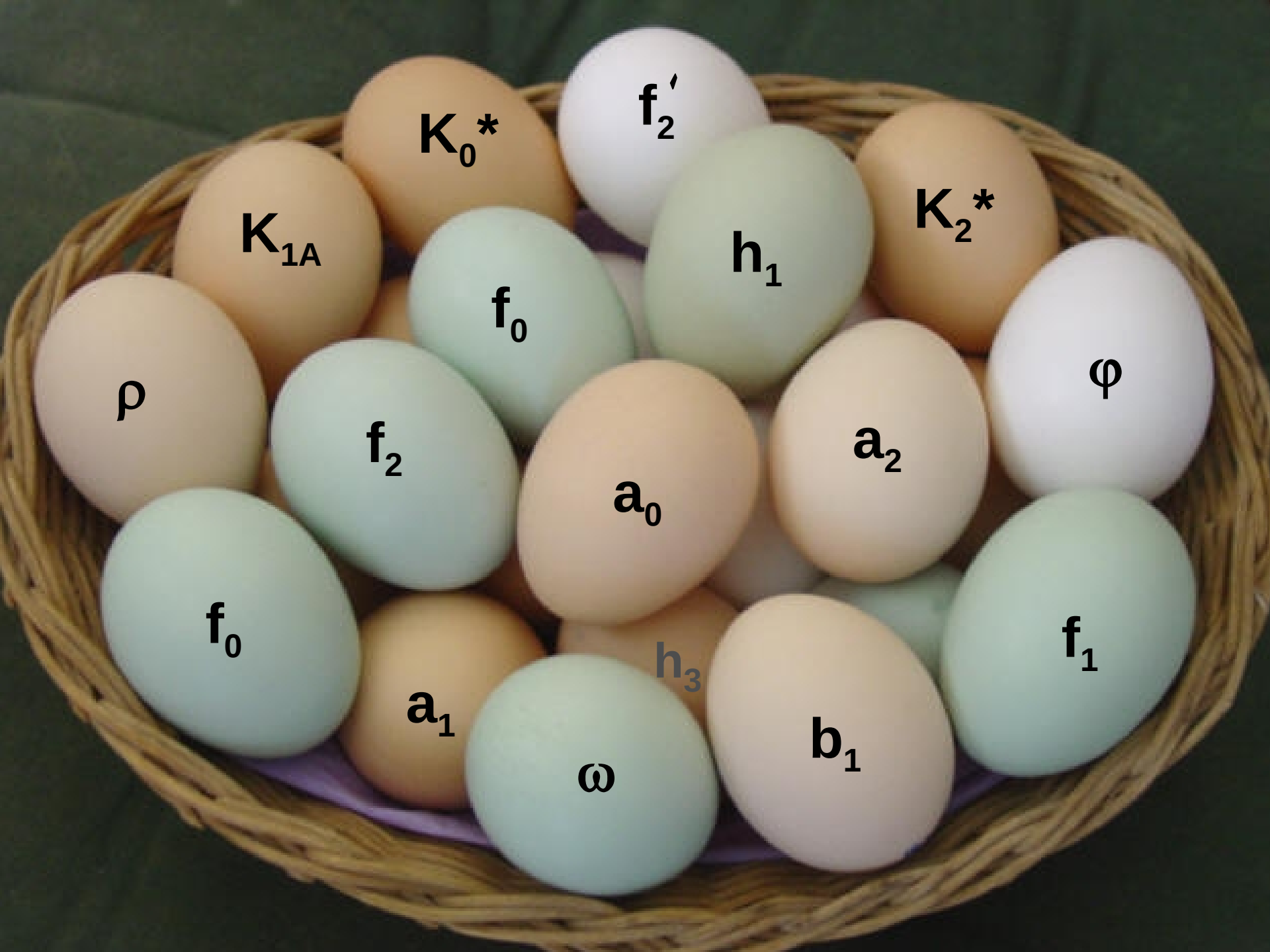
colour wave-functions

$$\pi^+ = \frac{1}{\sqrt{N_c}} \left[u\bar{d} + u\bar{d} + u\bar{d} + u\bar{d} + \ldots \right.$$

$N_c = 3$

$$p = \frac{1}{\sqrt{6}} \left[uud + uud + uud \right.$$

$$\left. - uud - uud - uud \right.$$


K_0^*
f_2'
K_{1A}
h_1
K_2^*
f_0
ρ
φ
f_2
a_0
a_2
f_0
h_3
f_1
a_1
b_1
ω

Meson spectrum

J^{PC}

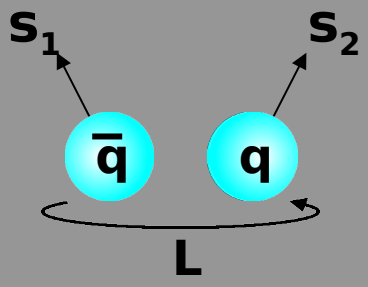
radial

L=3: 4^{++}, 3^{++}, 2^{++}, 3^{+-}

L=2: 3^{--}, 2^{--}, 1^{--}, 2^{-+}

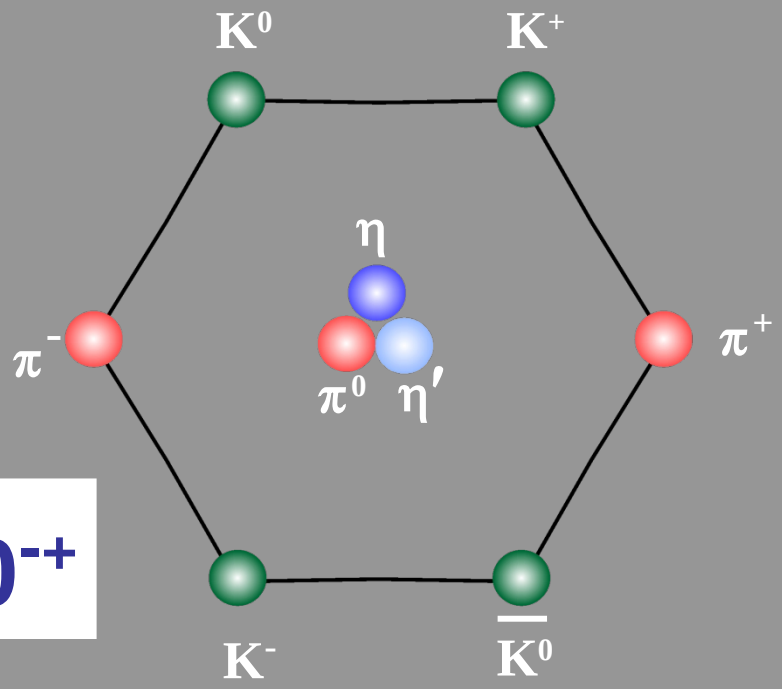
L=1: 2^{++}, 1^{++}, 0^{++}, 1^{+-}

L=0: 1^{--}, 0^{-+}

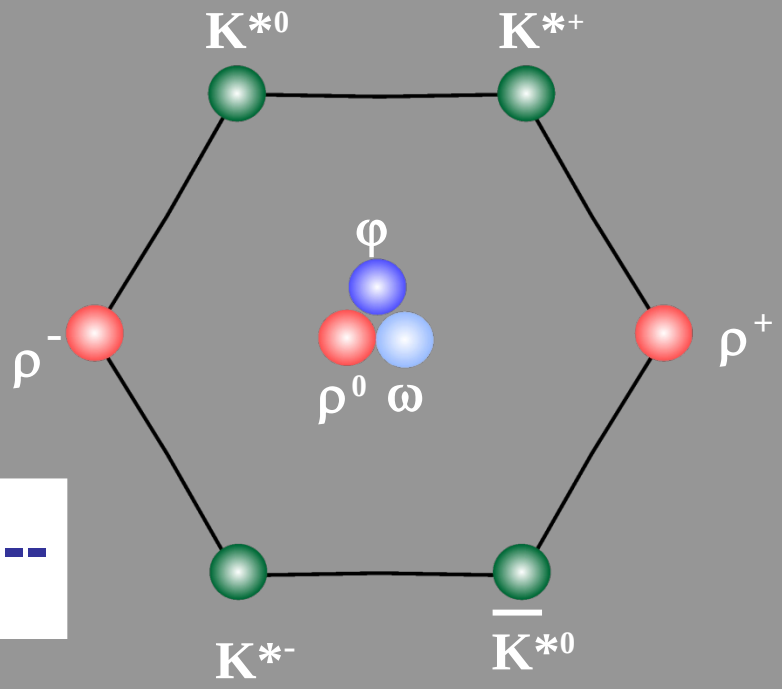


S = 0, 1

Meson spectrum

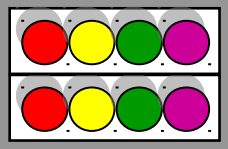


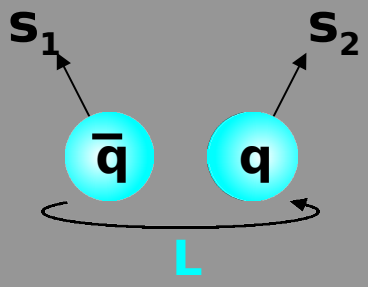
0^{-+}



1^{--}

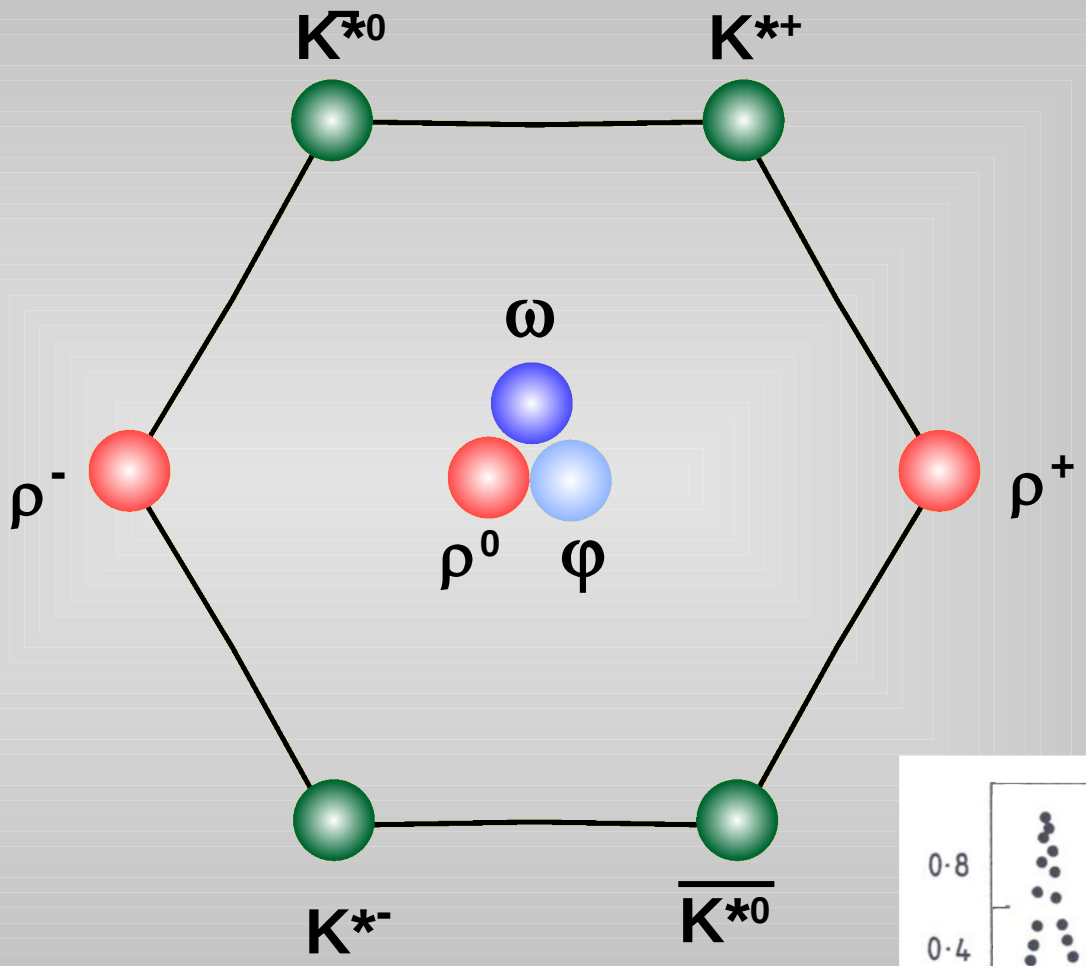
L=0 1^{--} 0^{-+}



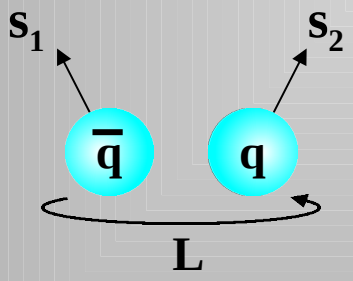


S = 0, 1

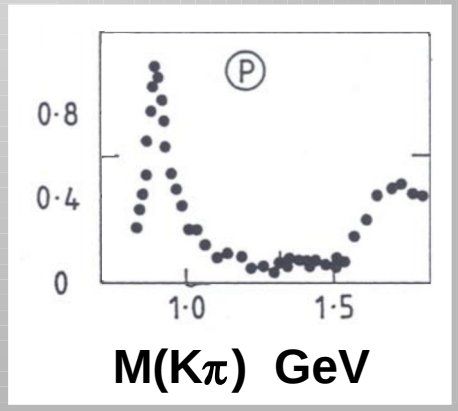
Vector multiplet



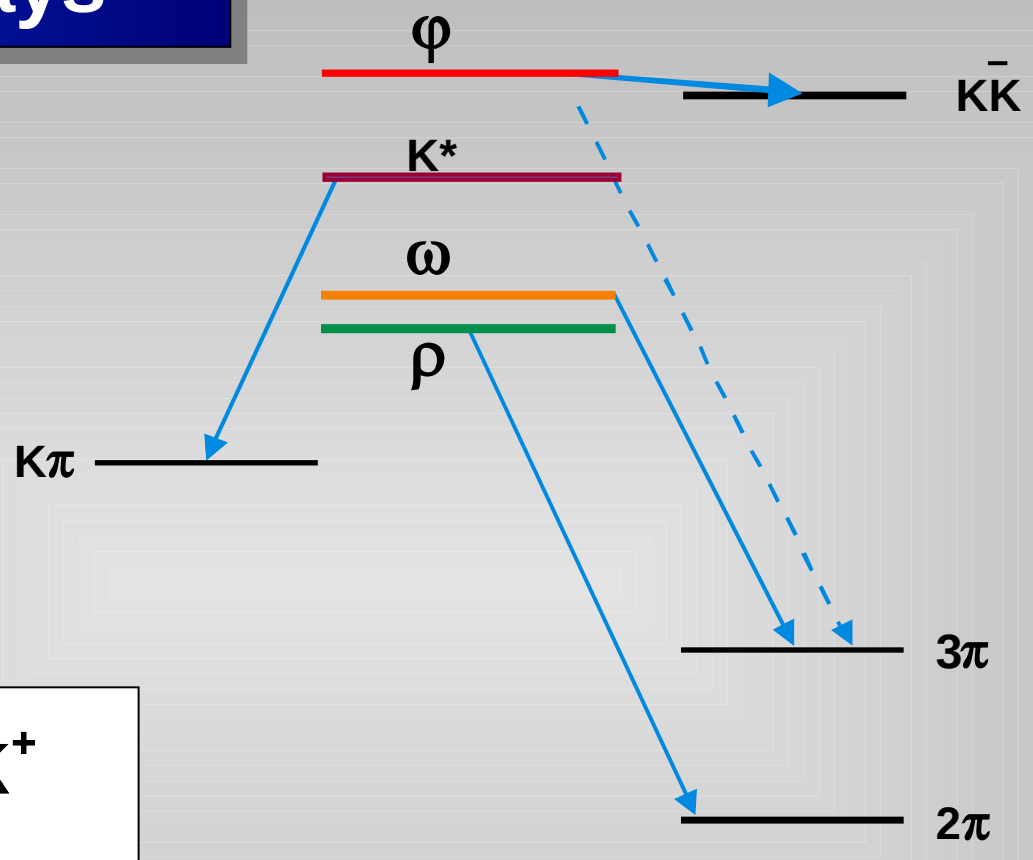
$J^{PC} = 1^{--}$

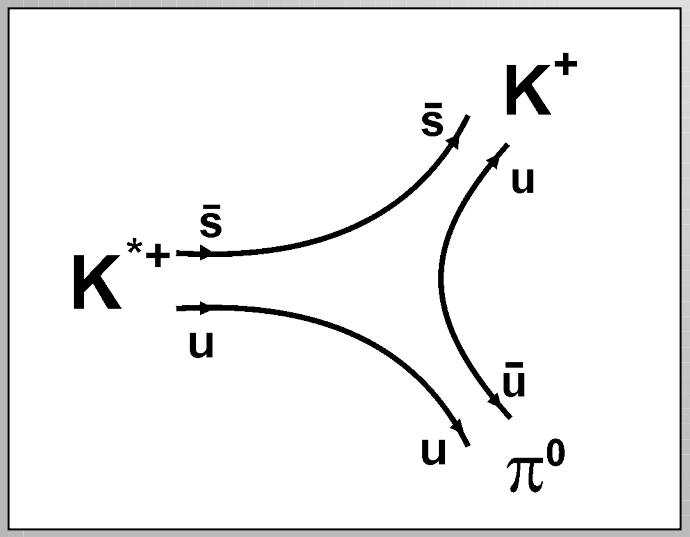


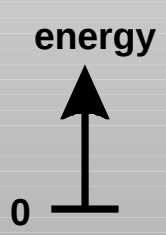
S = 1, L = 0



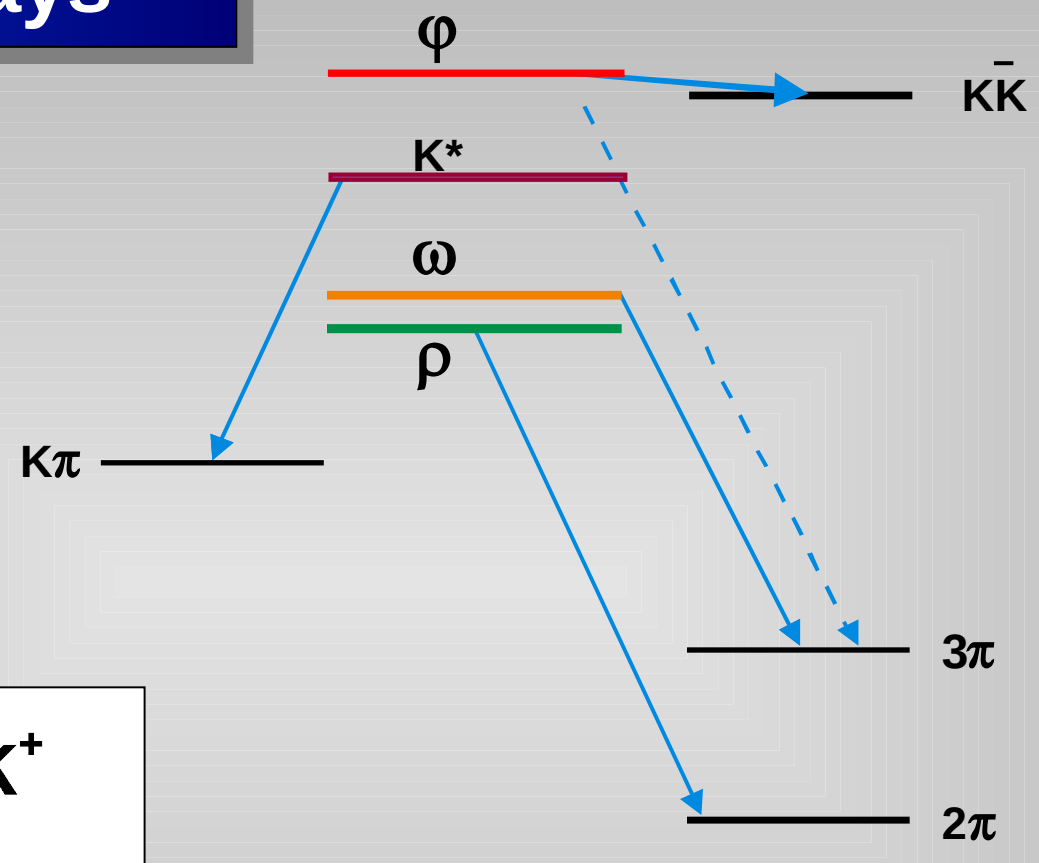
Vector decays

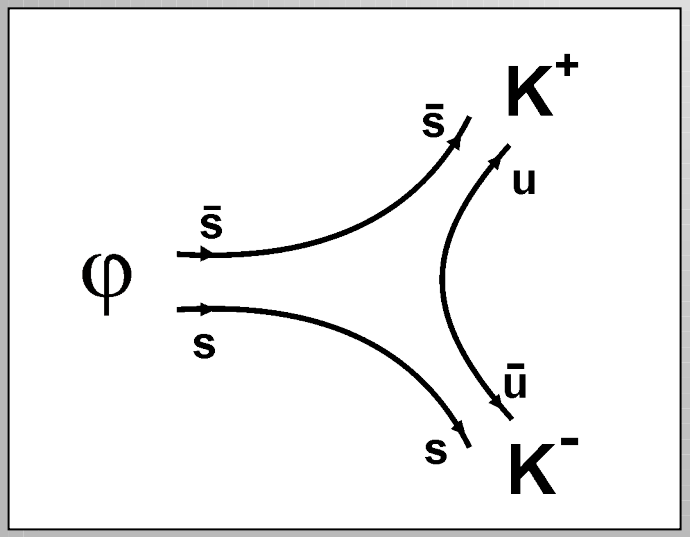


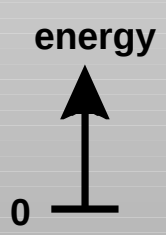




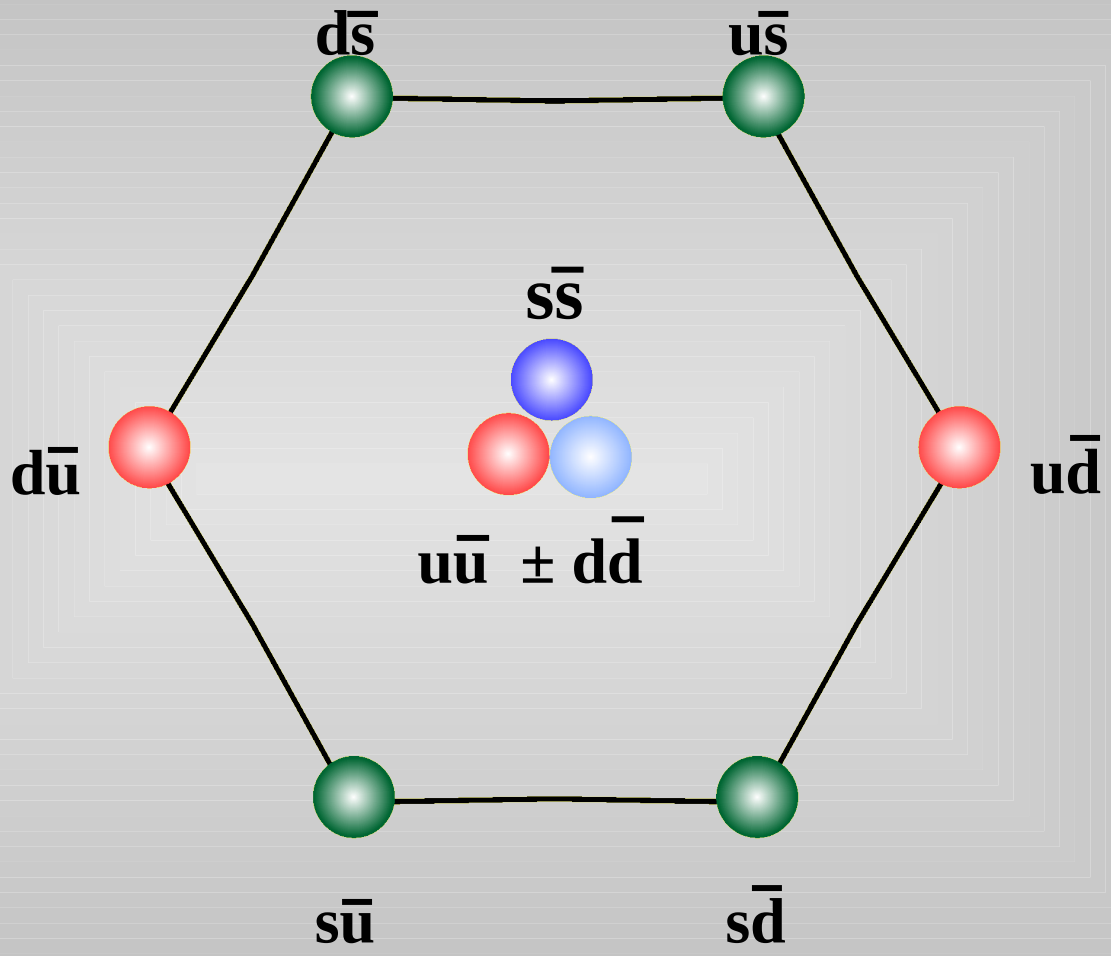
Vector decays



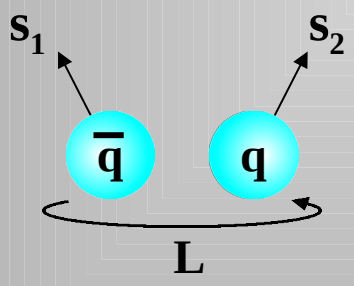




Vector multiplet

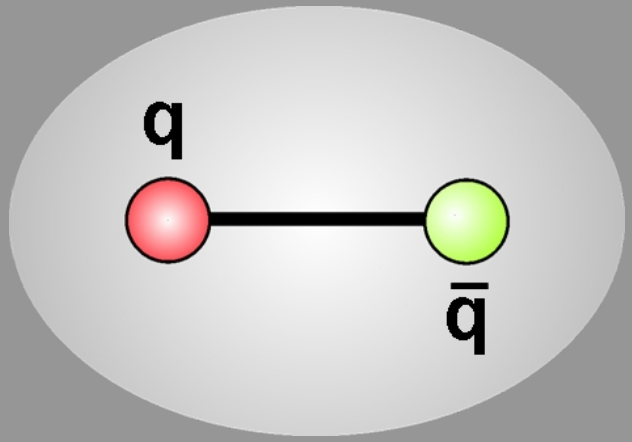


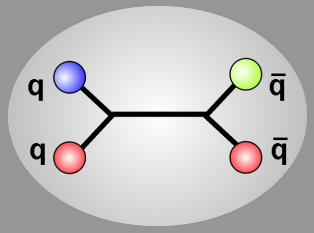
$J^{PC} = 1^{--}$

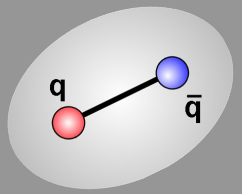


S = 1, L = 0

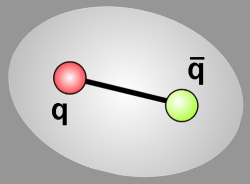
ρ(770)





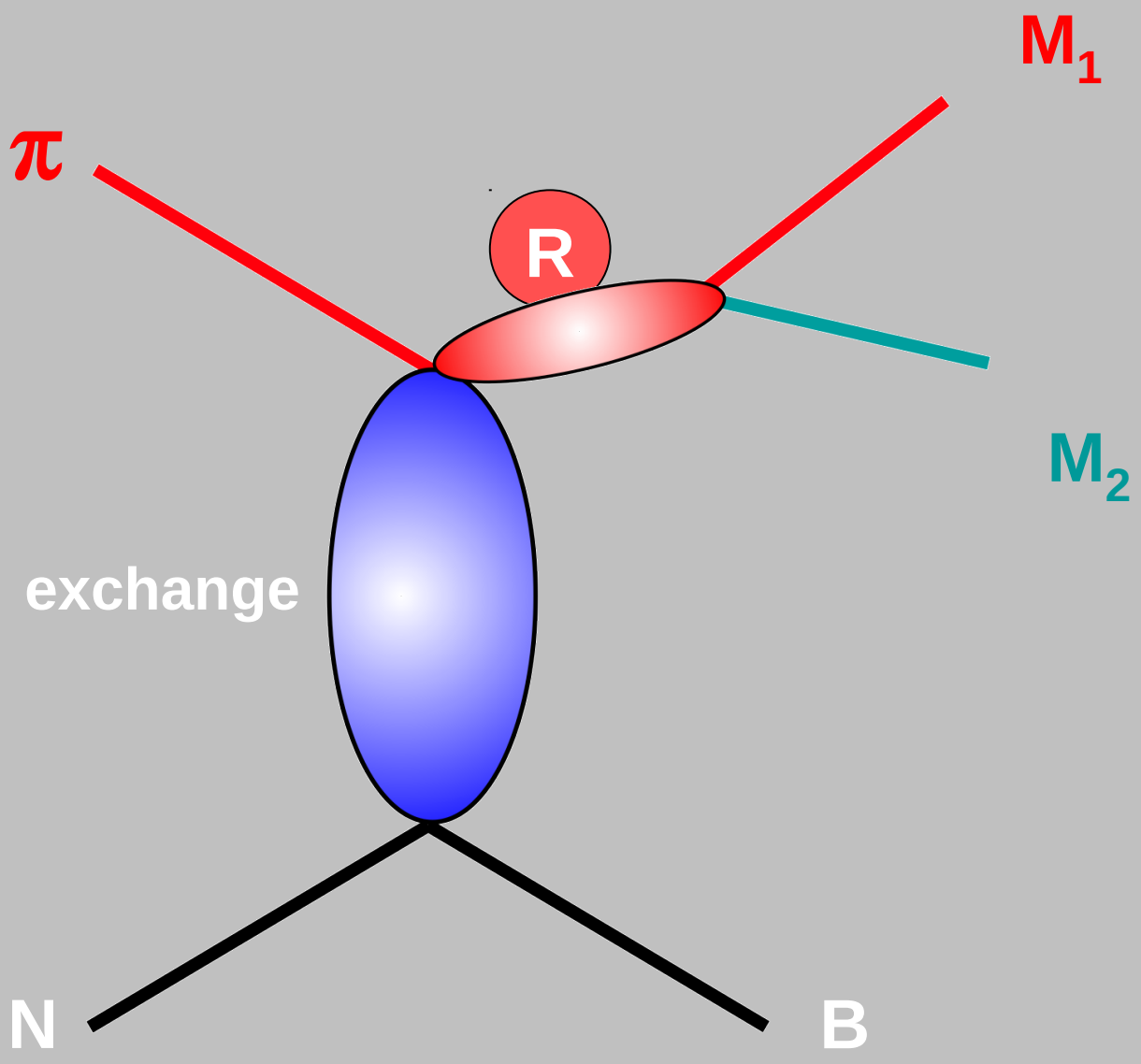


π^+



π^-

Hadroproduction



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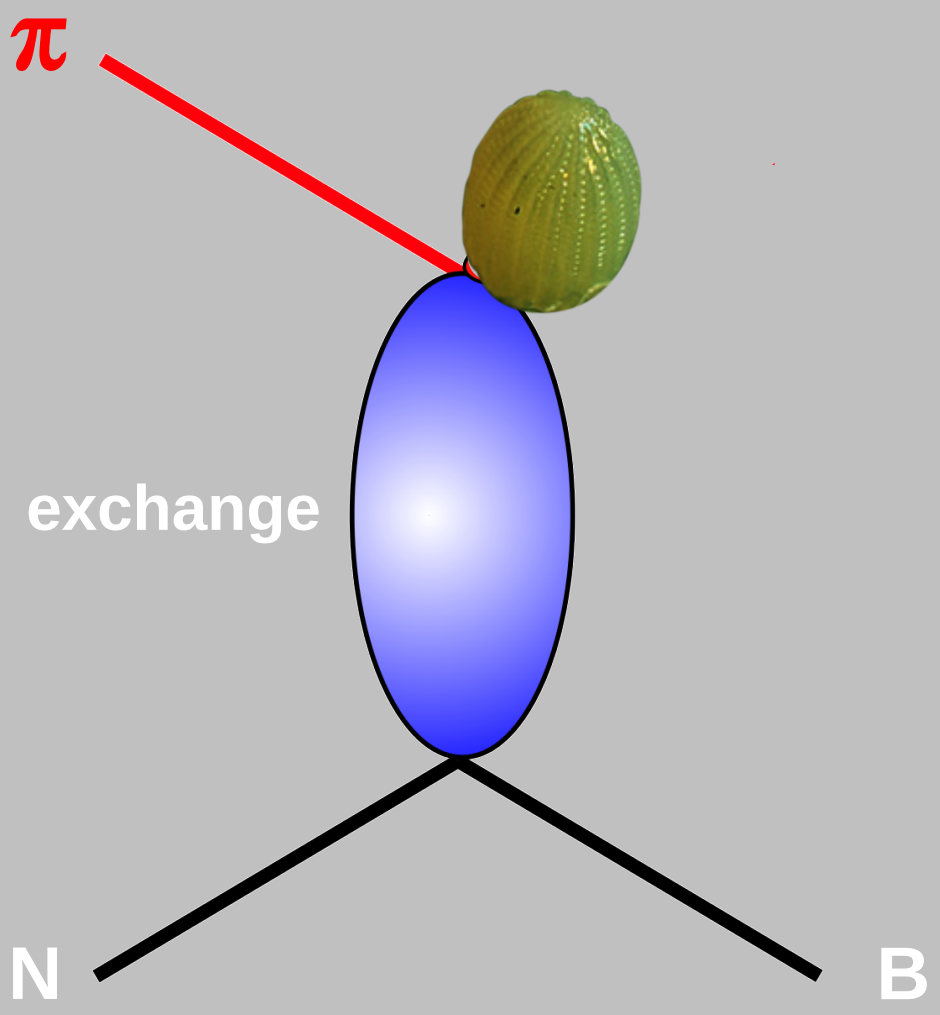

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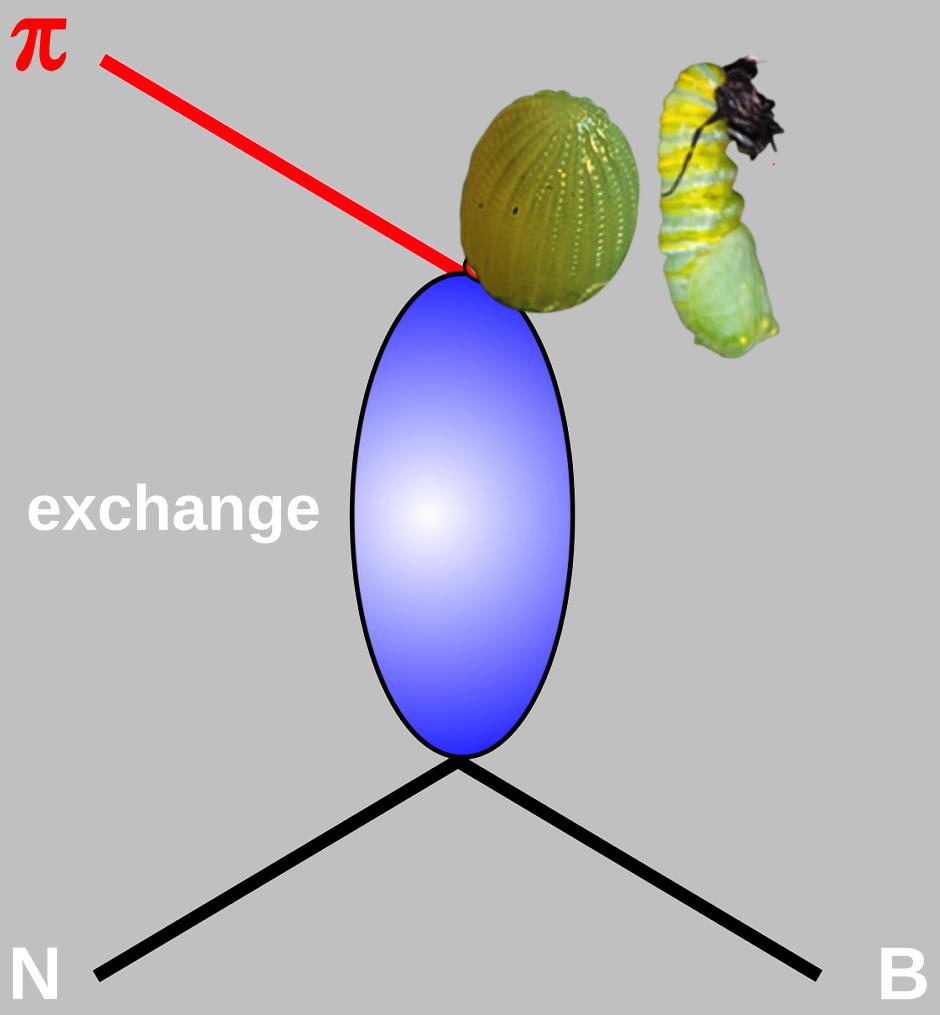

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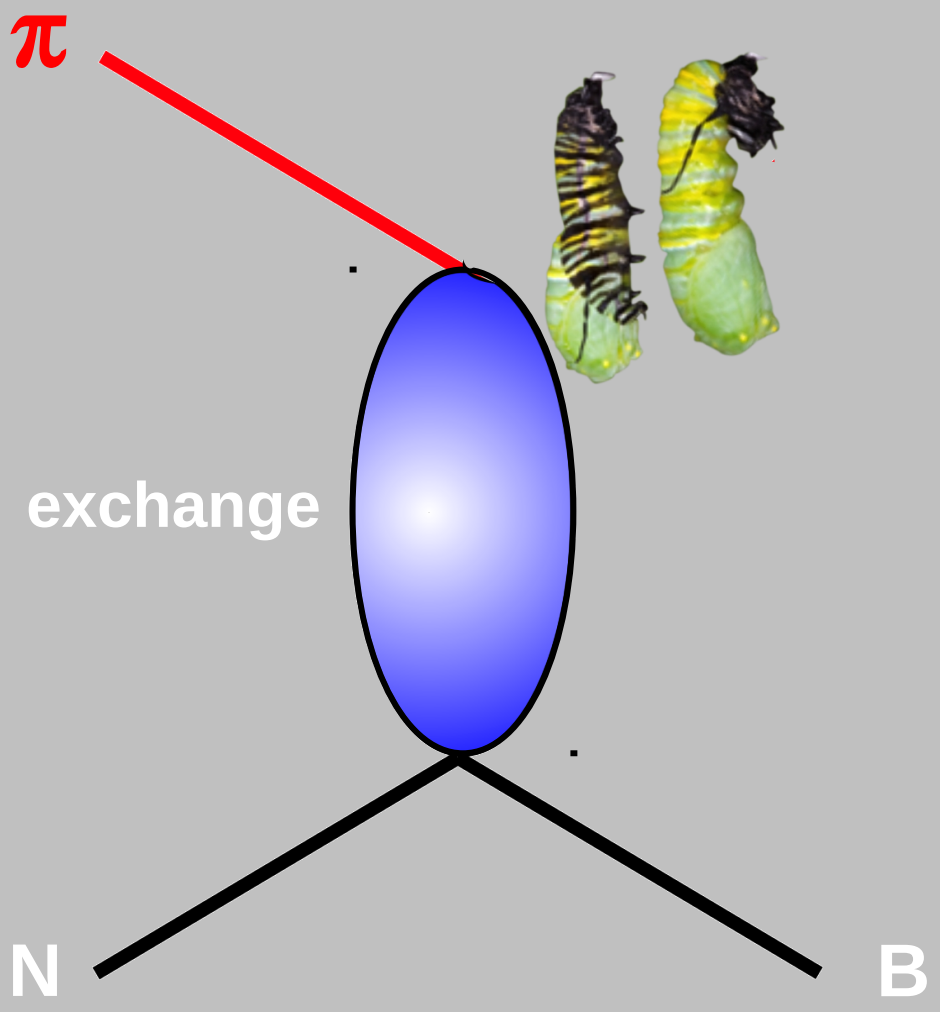

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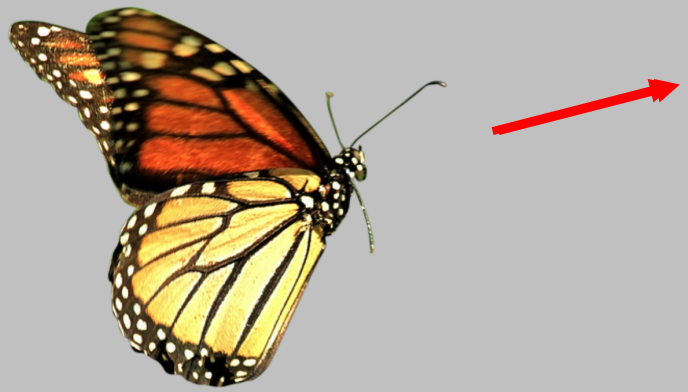

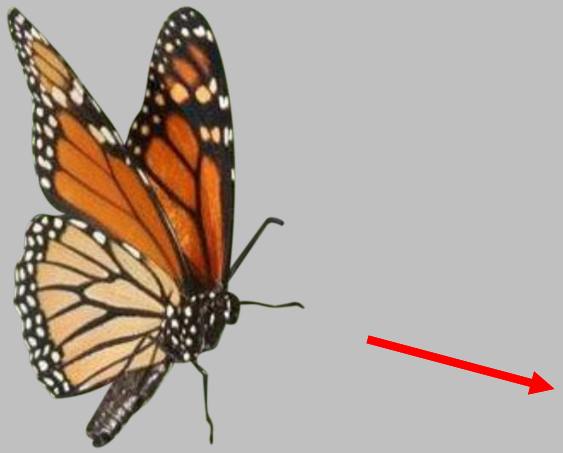

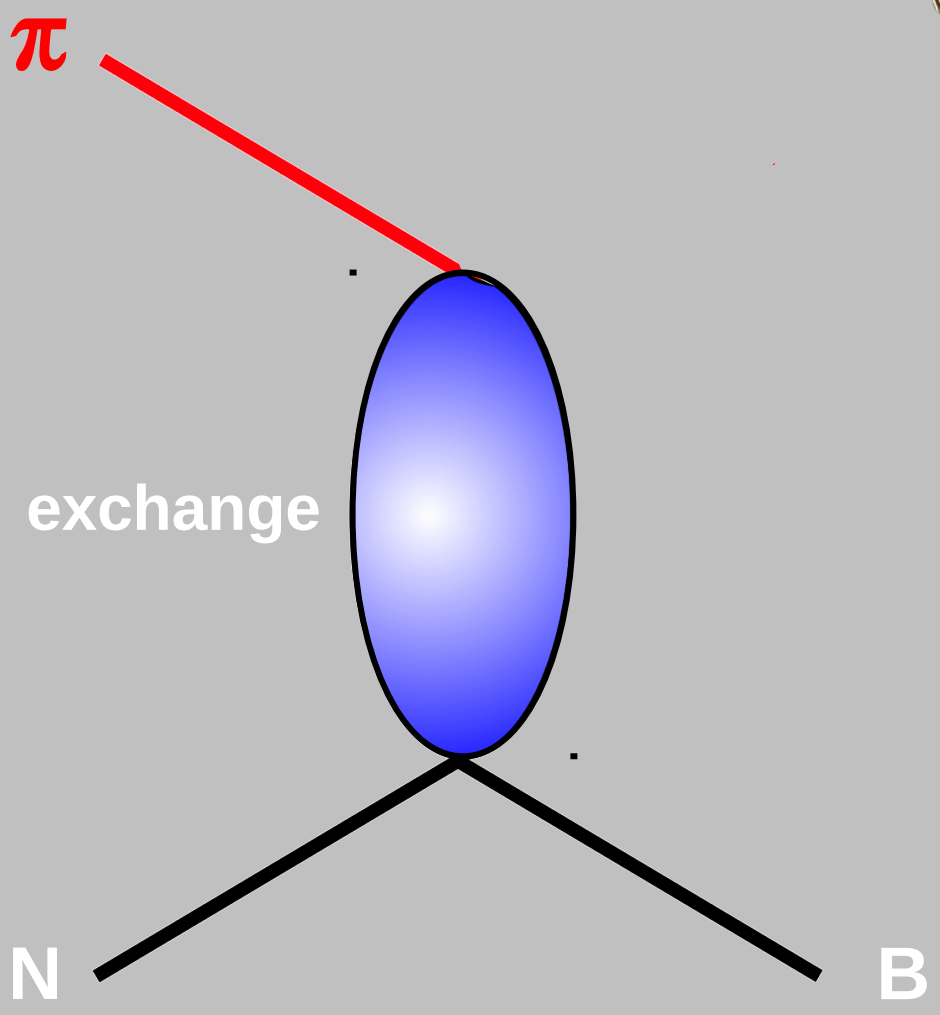

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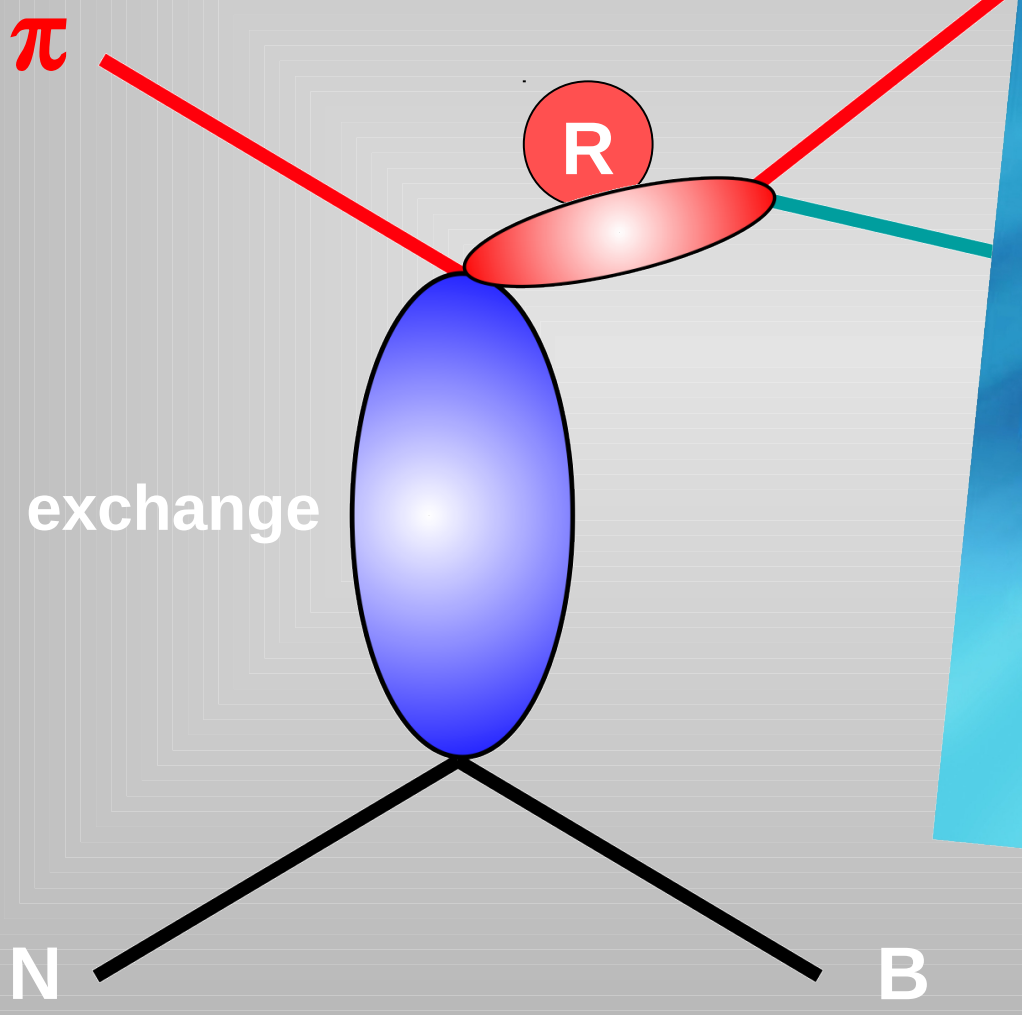
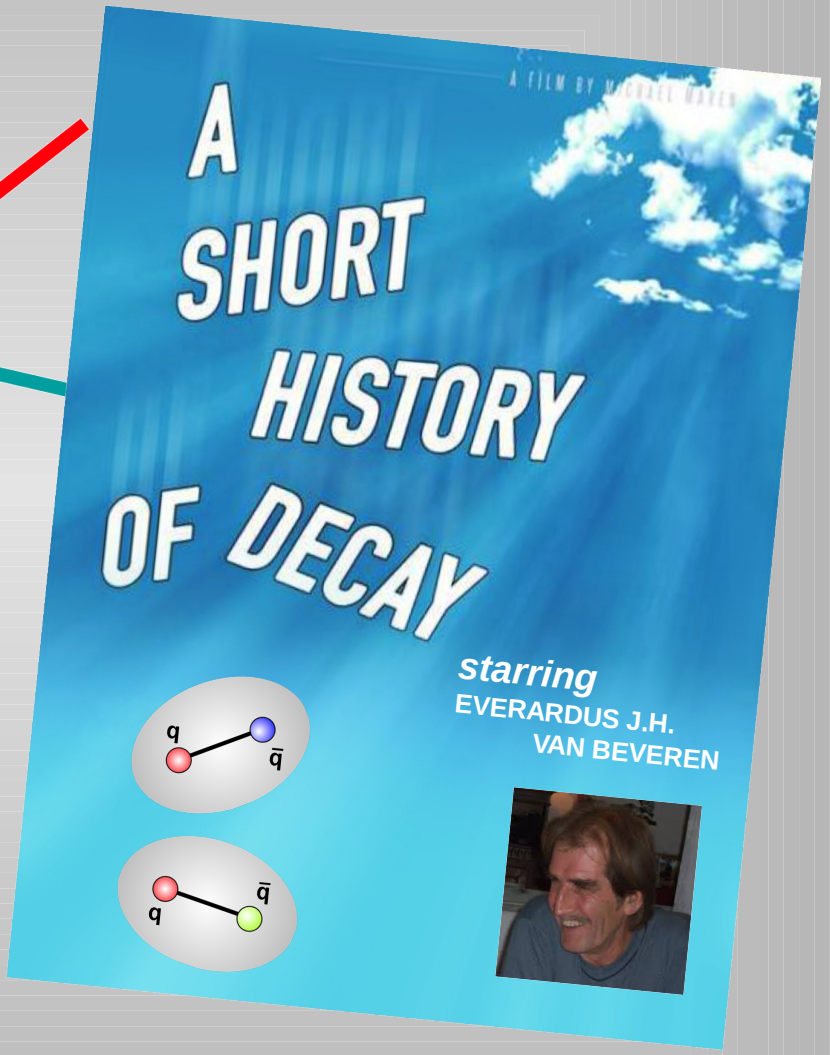
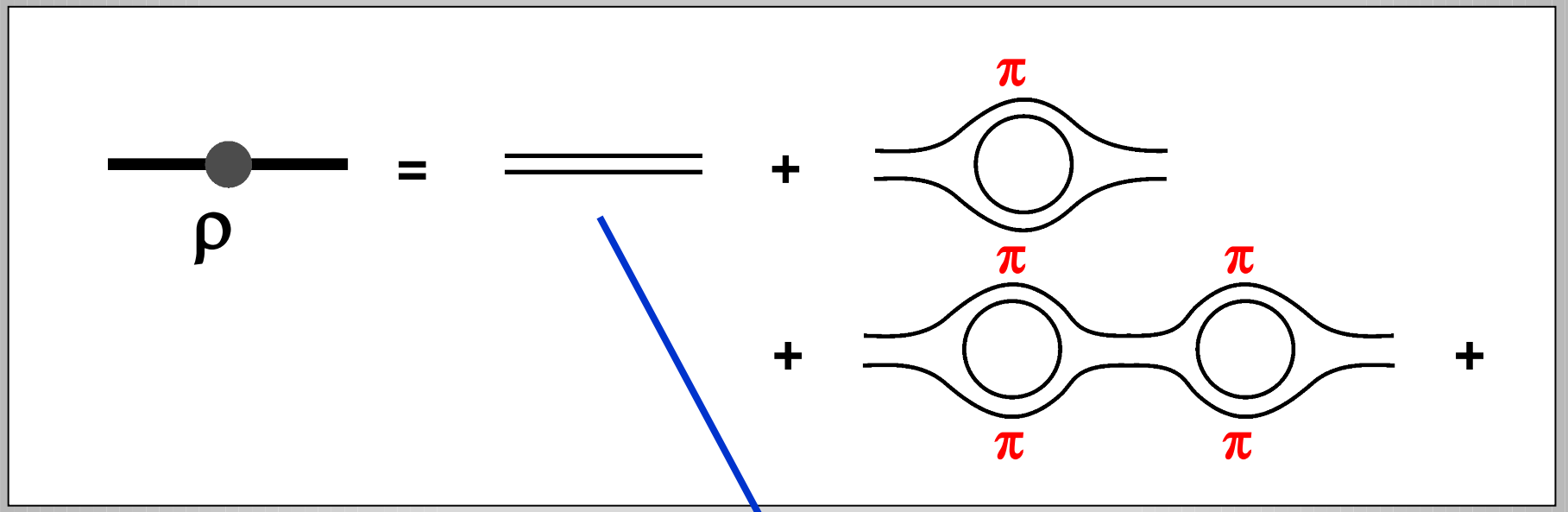
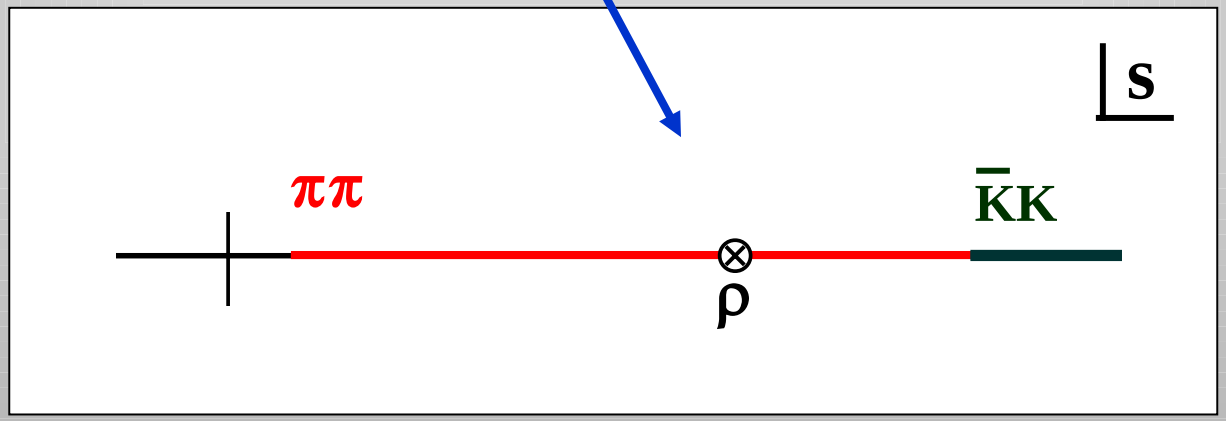




Vector multiplet

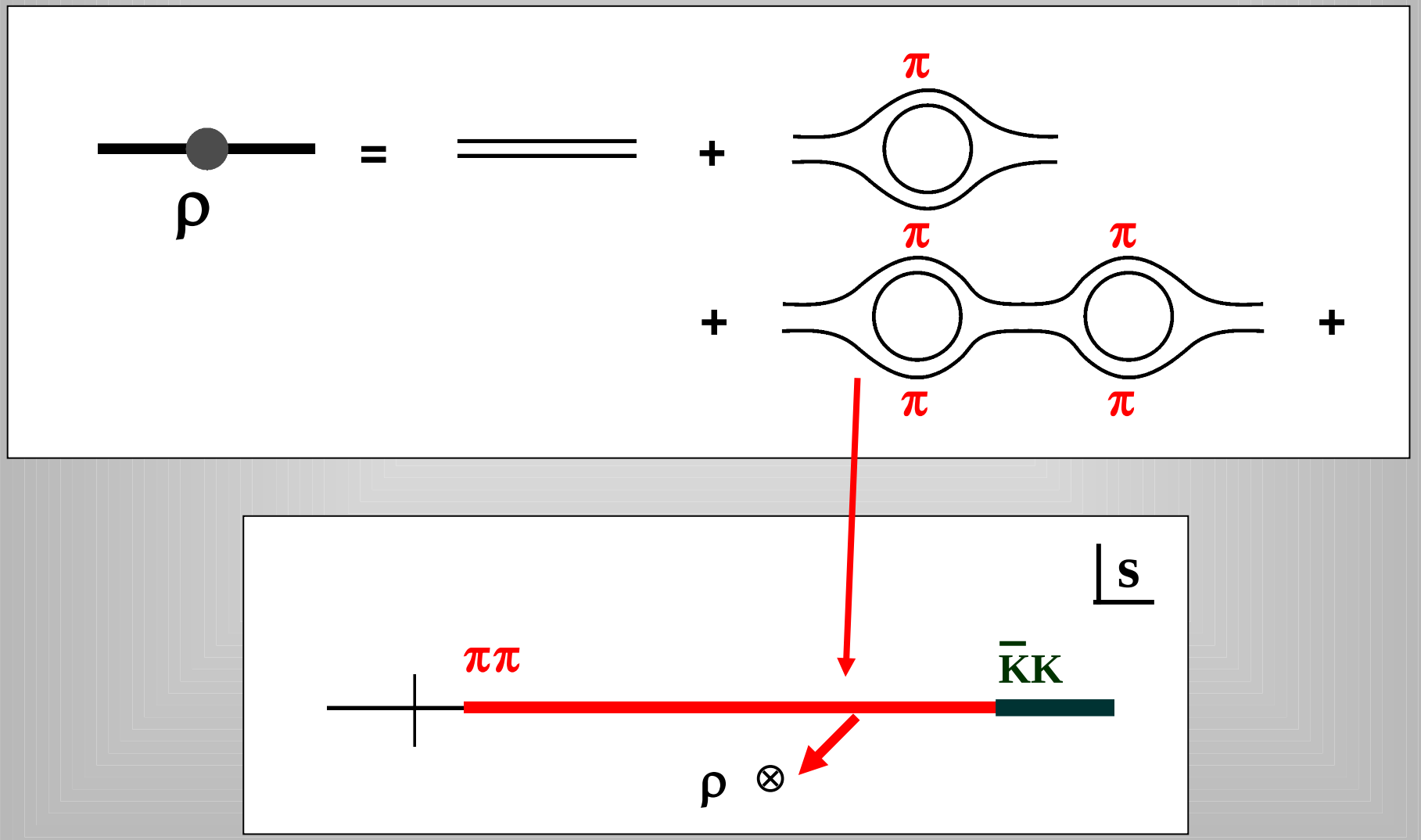
shifting of masses

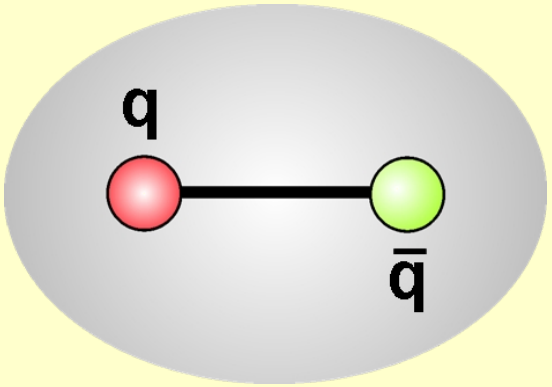


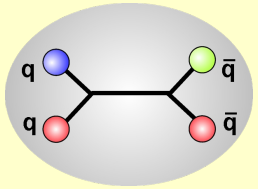


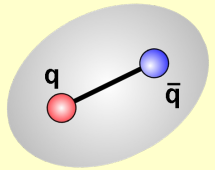
Vector multiplet

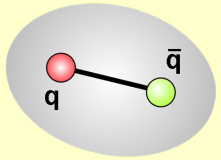
shifting of masses

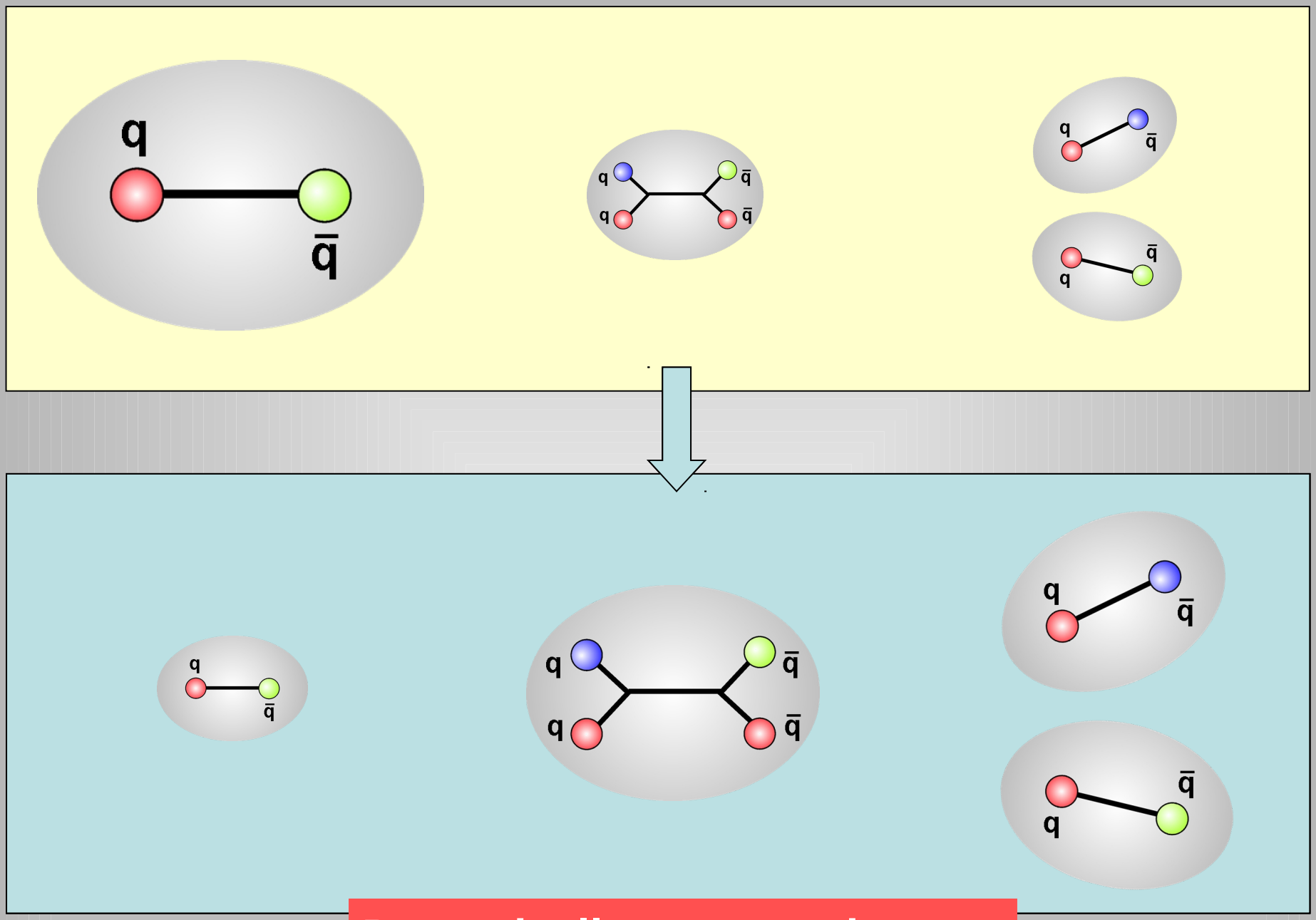



q
q̄


q
q
q̄
q̄


q
q̄


q̄
q


q
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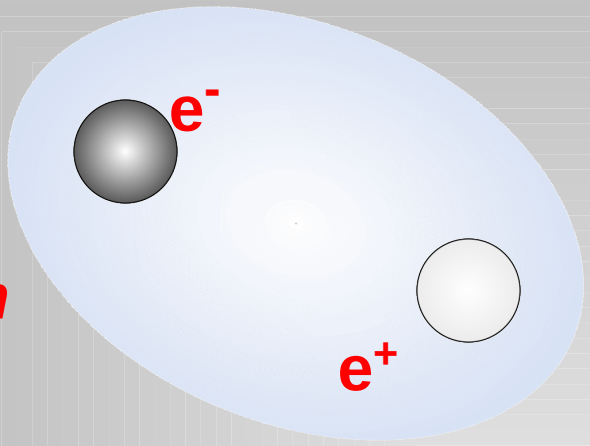
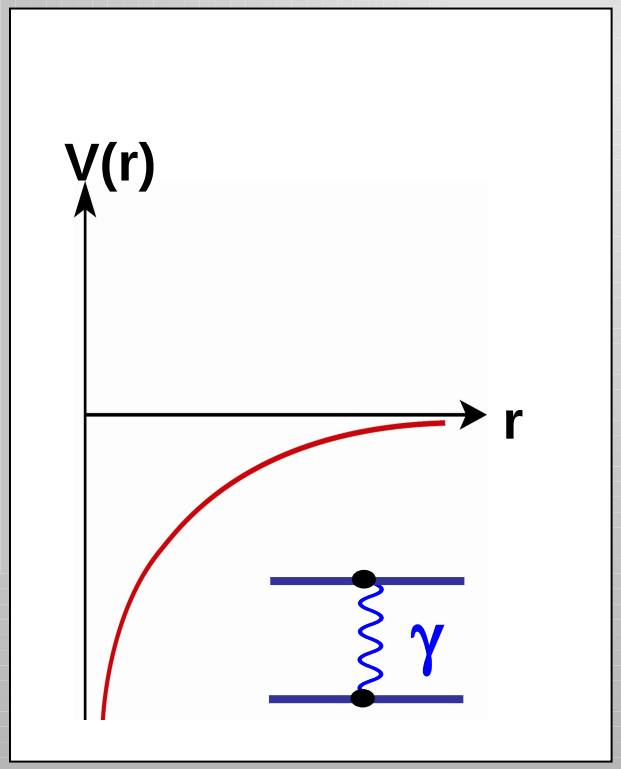
Dynamically generated states

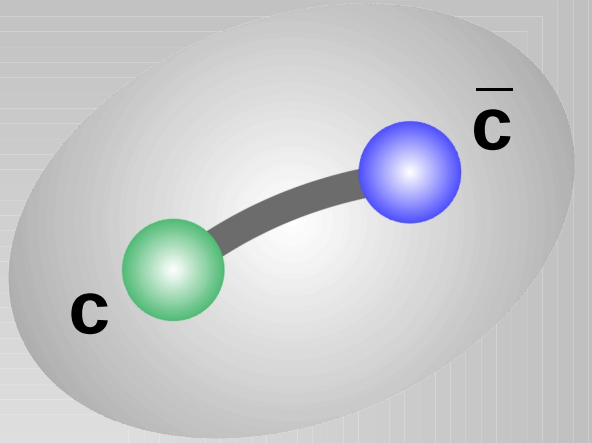
positronium



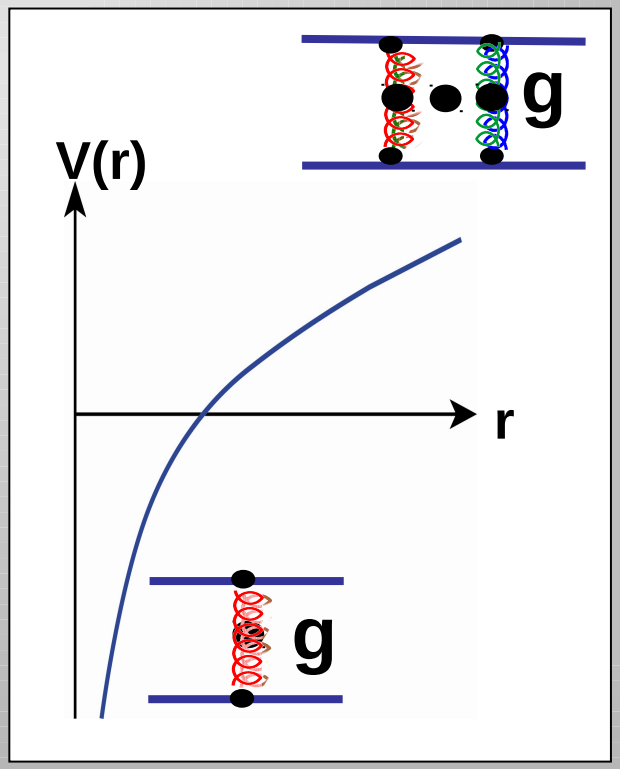
0.1 *nm*



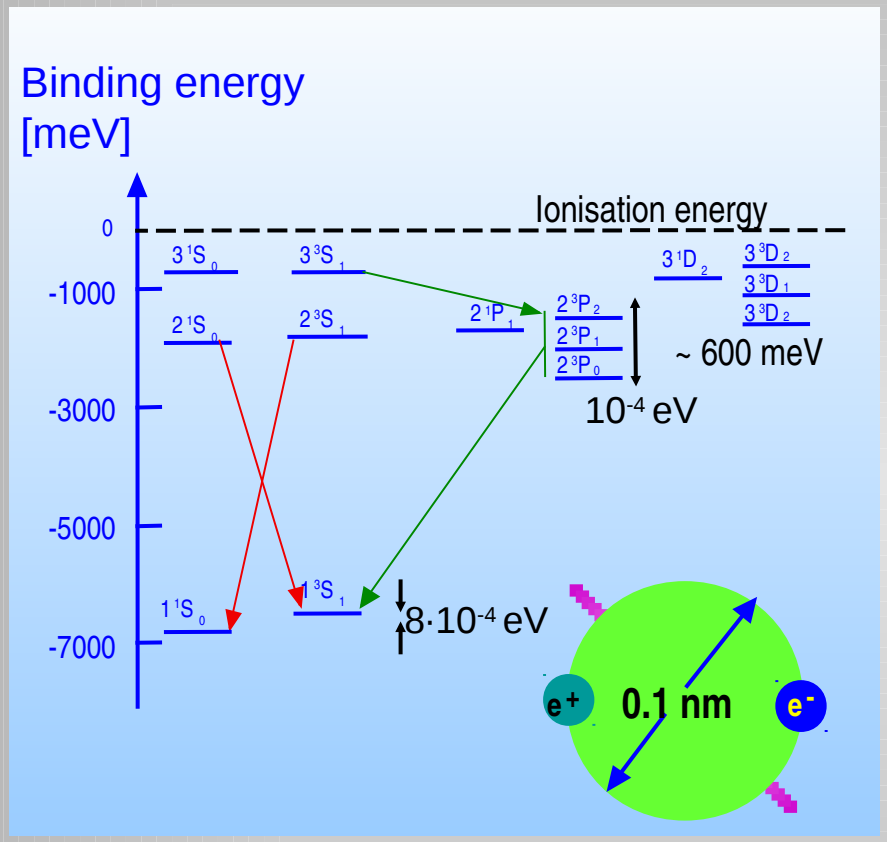
charmonium



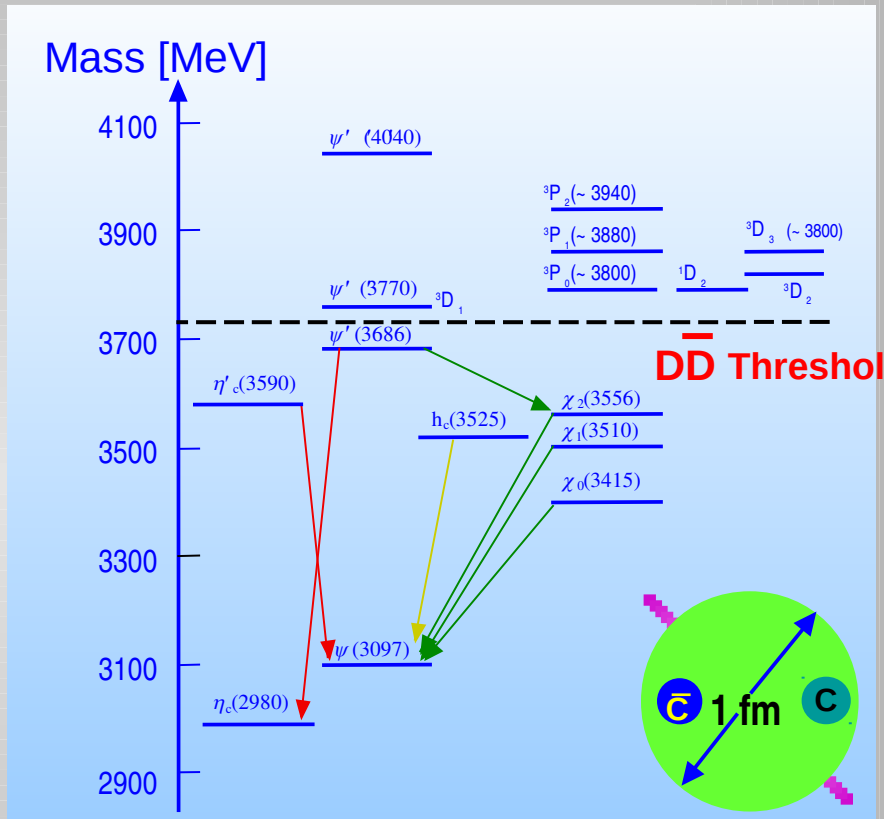
1 *fm*



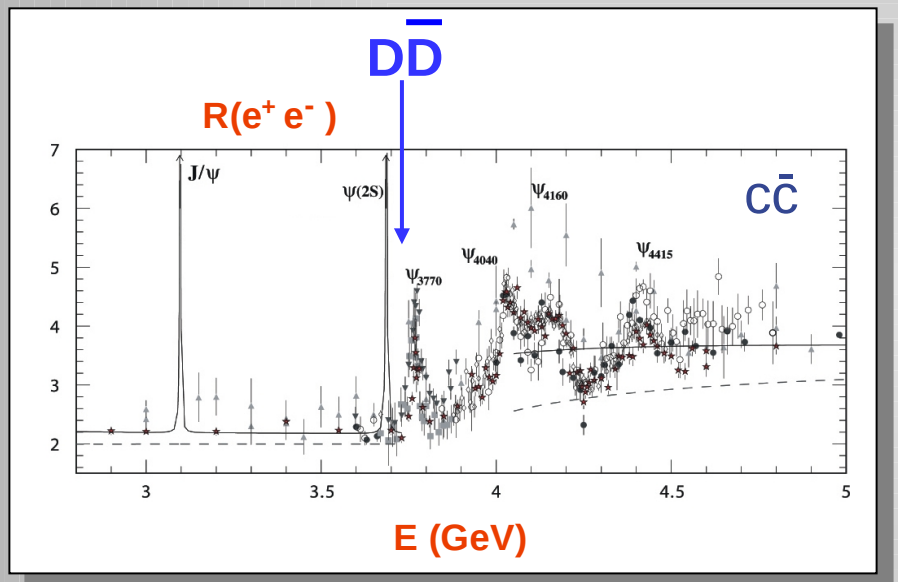
positronium

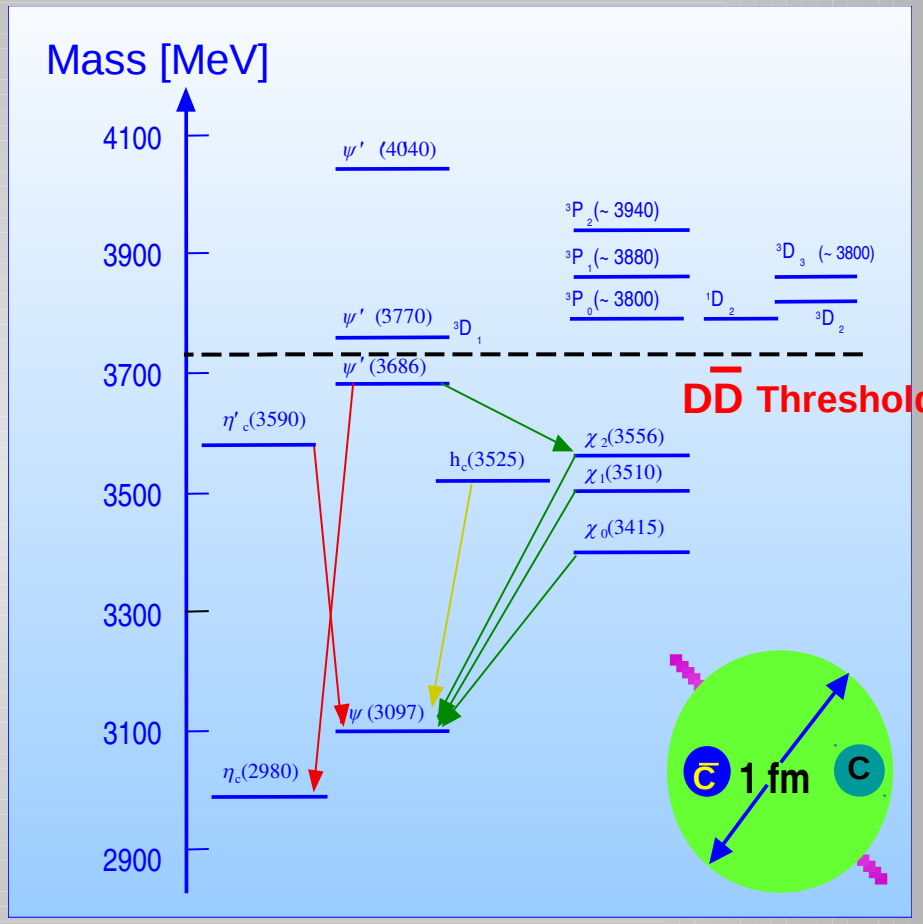


charmonium

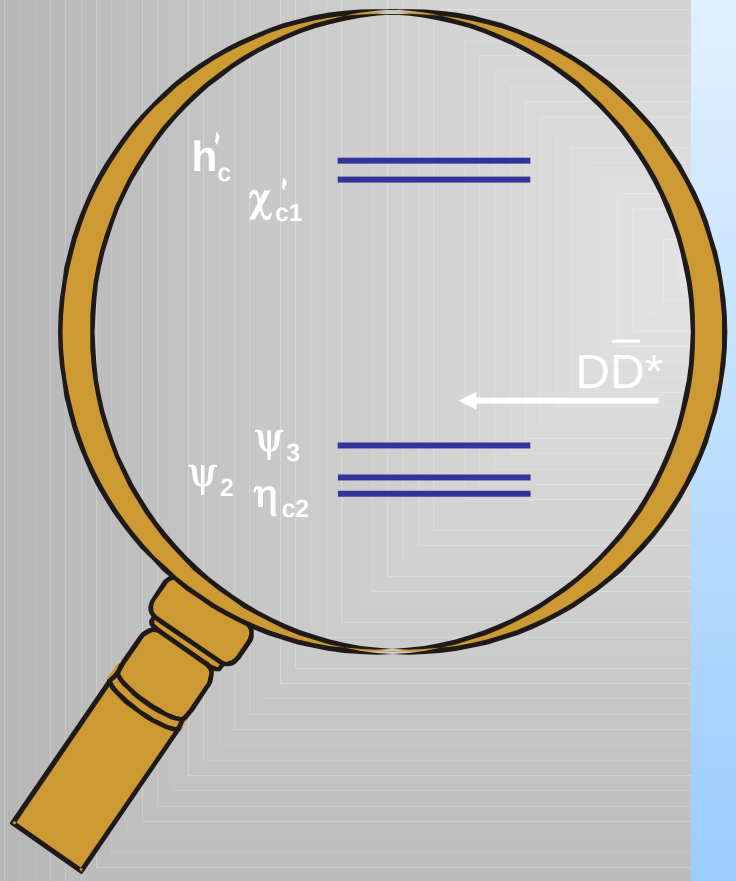


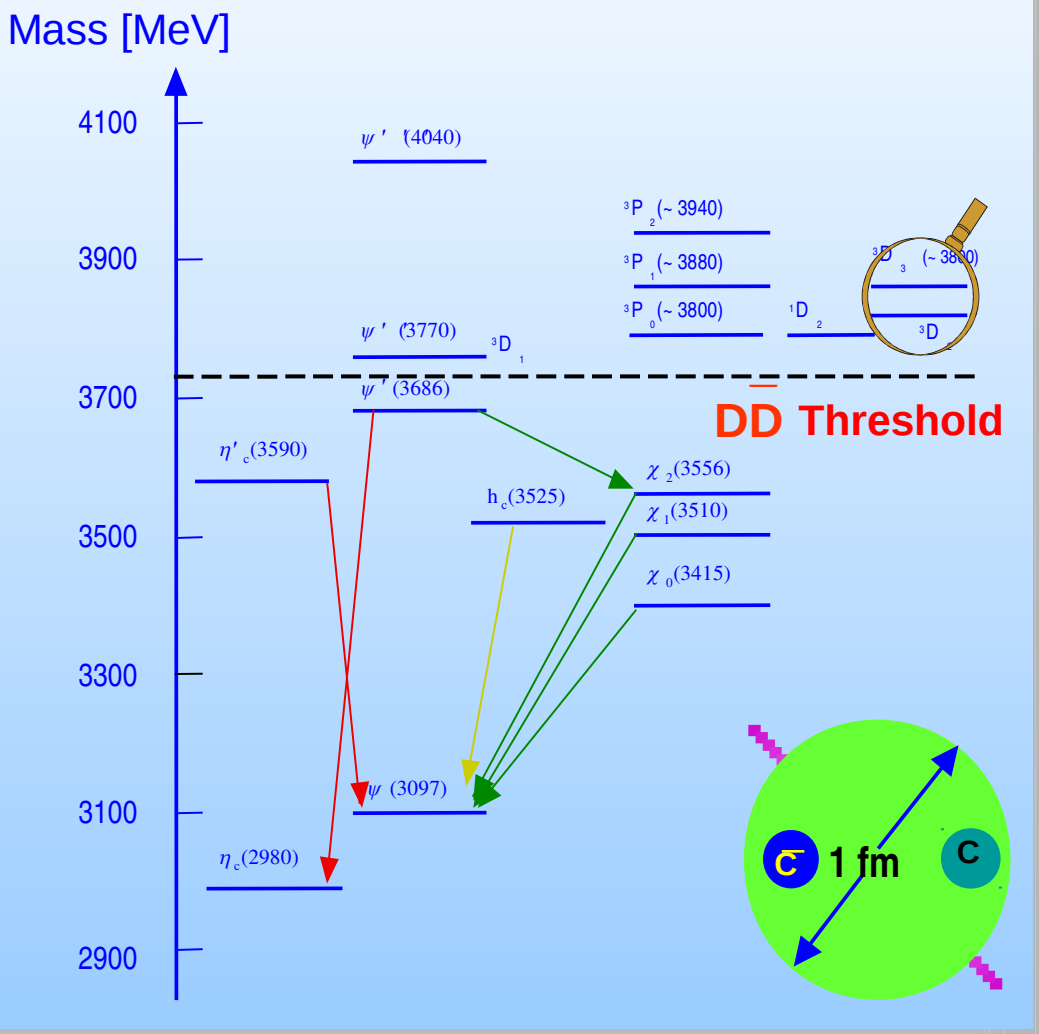
charmonium


DD̄
R(e+ e-)
J/ψ
ψ(2S)
ψ3770
ψ4040
ψ4160
ψ4415
cc̄
E (GeV)


Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ′ (4040)
ψ′ (3770)
3D1
ψ′ (3686)
η′c(3590)
hc(3525)
χ2(3556)
χ1(3510)
χ0(3415)
ψ (3097)
ηc(2980)
3P2(~ 3940)
3P1(~ 3880)
3P0(~ 3800)
1D2
3D3 (~ 3800)
3D2
DD̄ Threshold
c̄
1 fm
c

charmonium


h'c
χ'c1
DD̄*
ψ3
ψ2
ηc2


Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ ' (4040)
3P2 (~ 3940)
3P1 (~ 3880)
3P0 (~ 3800)
1D2
3D3 (~ 3850)
3D1
ψ ' (3770)
ψ ' (3686)
DD̄ Threshold
η'c(3590)
hc(3525)
χ2(3556)
χ1(3510)
χ0(3415)
ψ (3097)
ηc(2980)
c
1 fm
c̄

THE XYZ AFFAIR

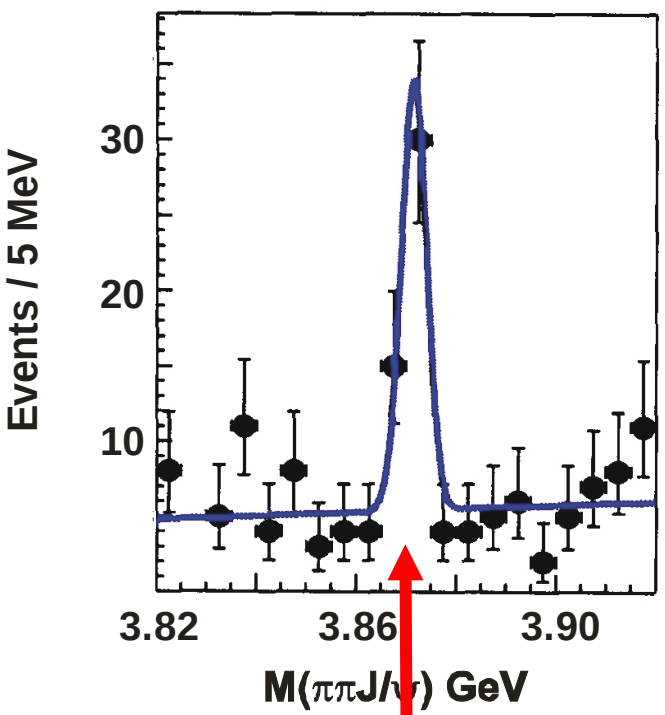
D_s D_s X Y Z Z_b

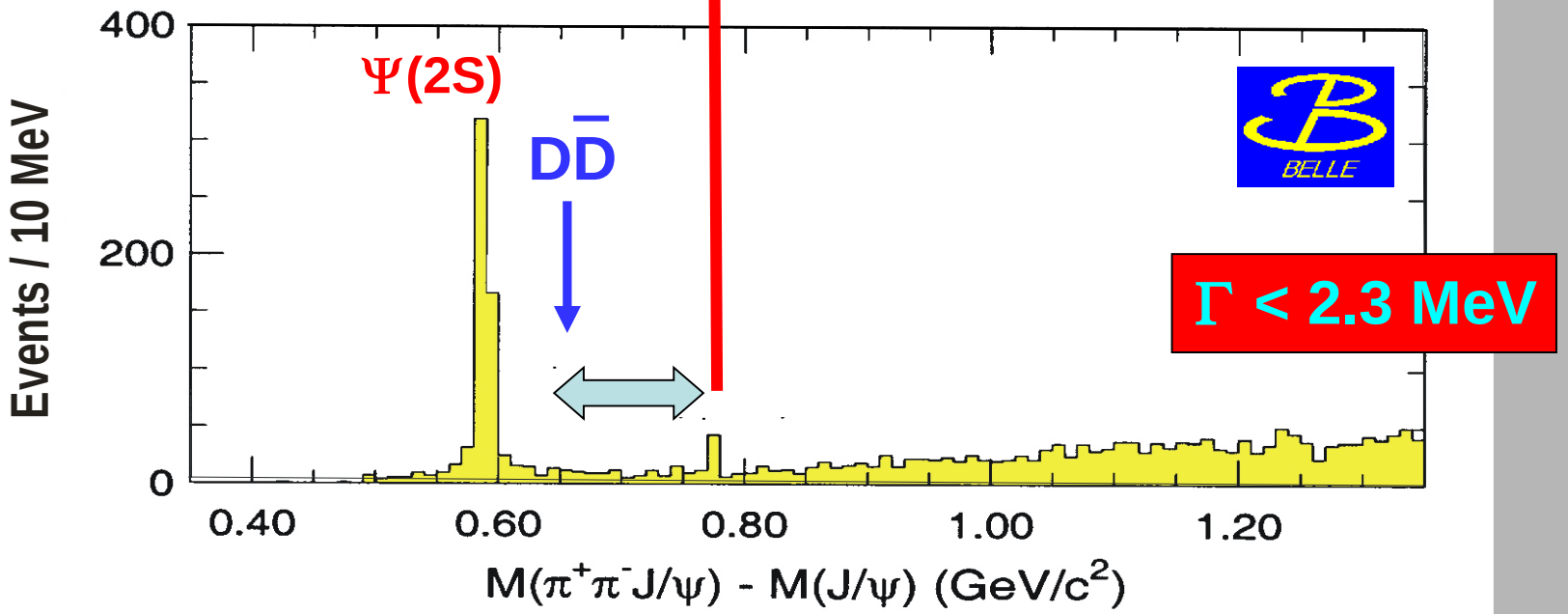
X(3872)

304M B's

$B \rightarrow KX$

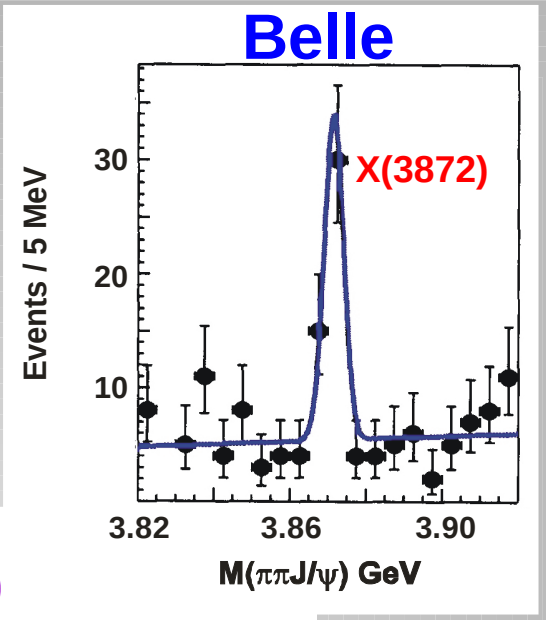
$X \rightarrow \pi^+\pi^- J/\psi$

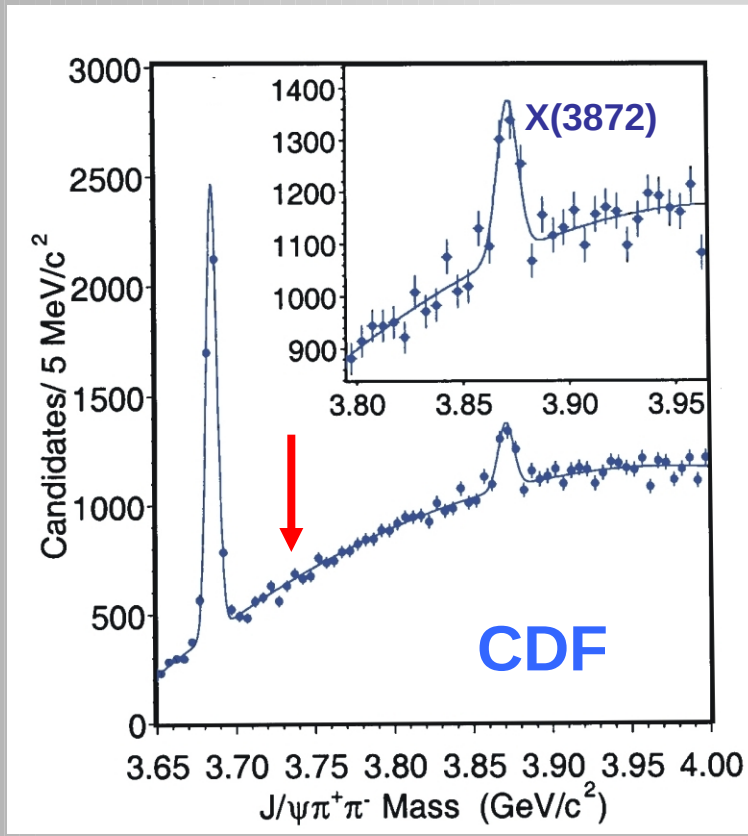


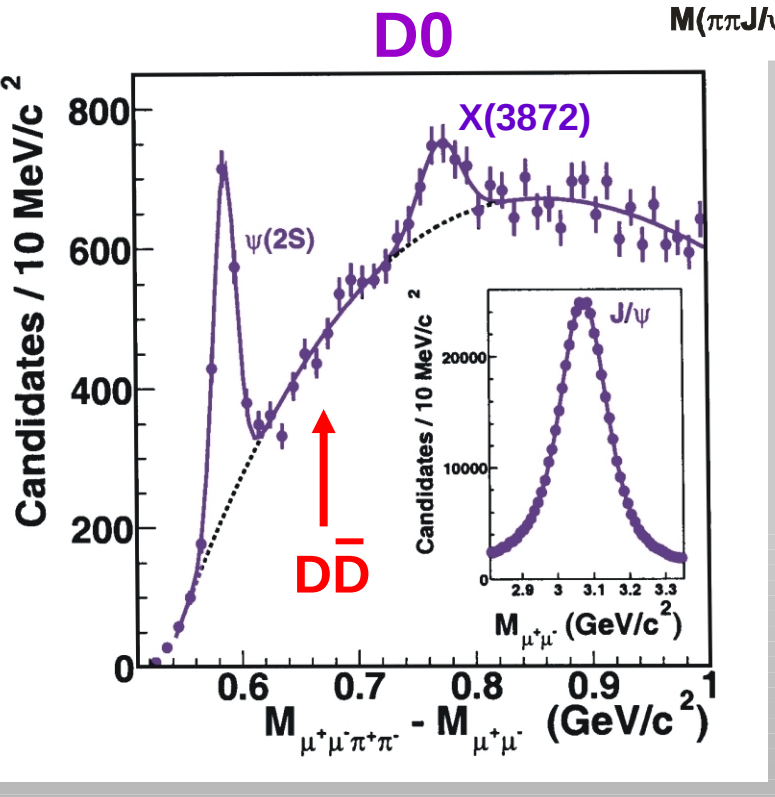


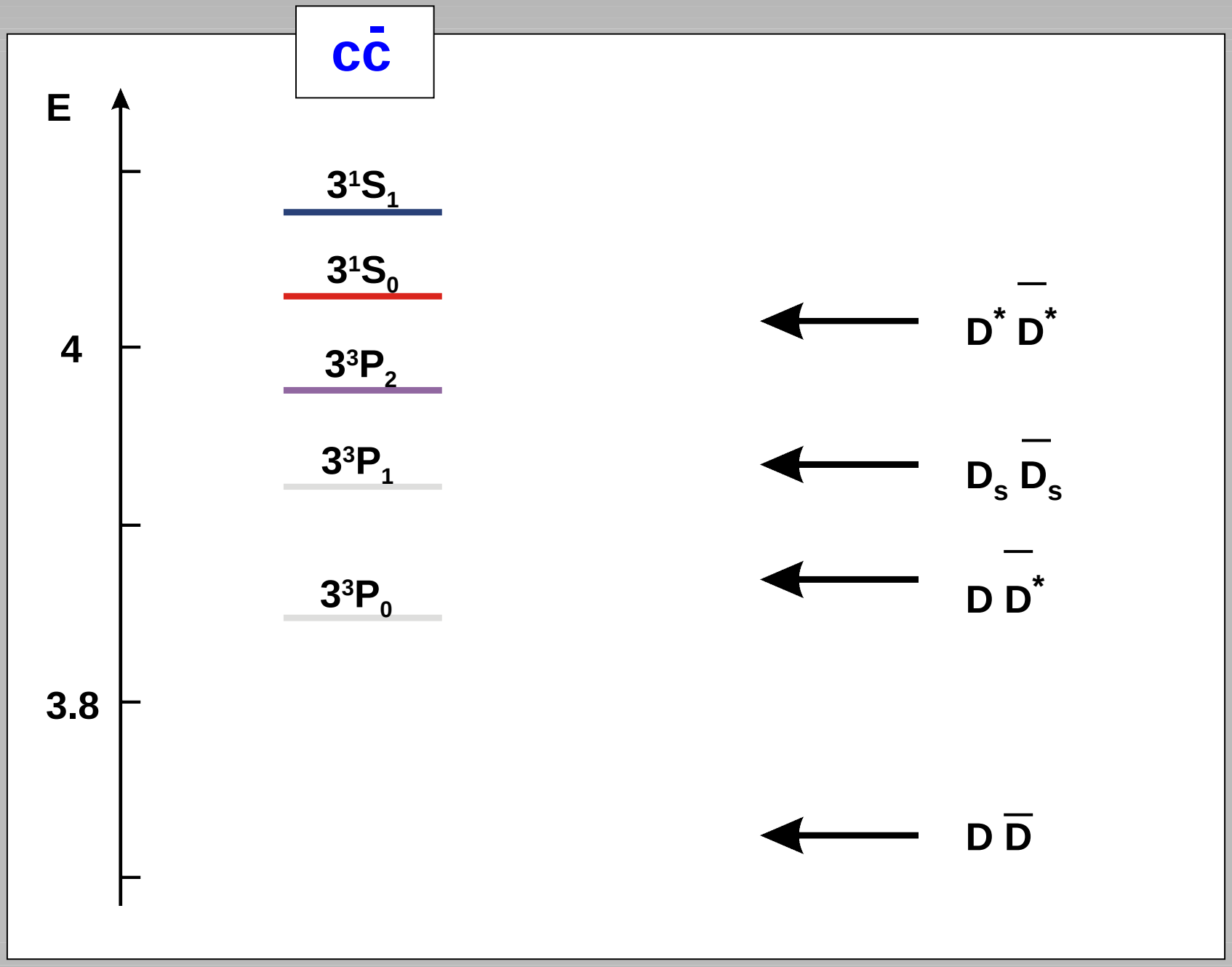
X(3872)

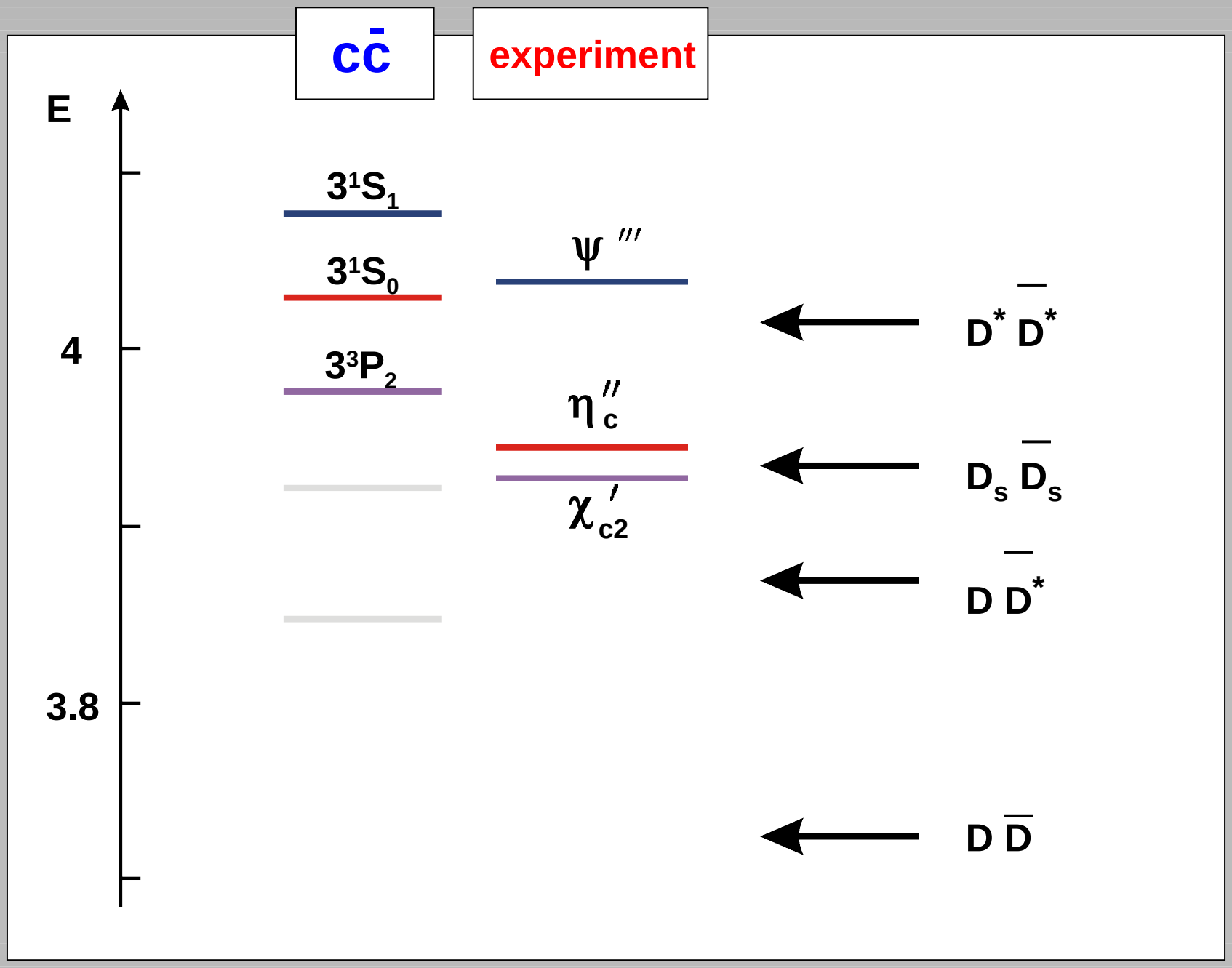
$J^{PC} = 1^{++}$, LHCb

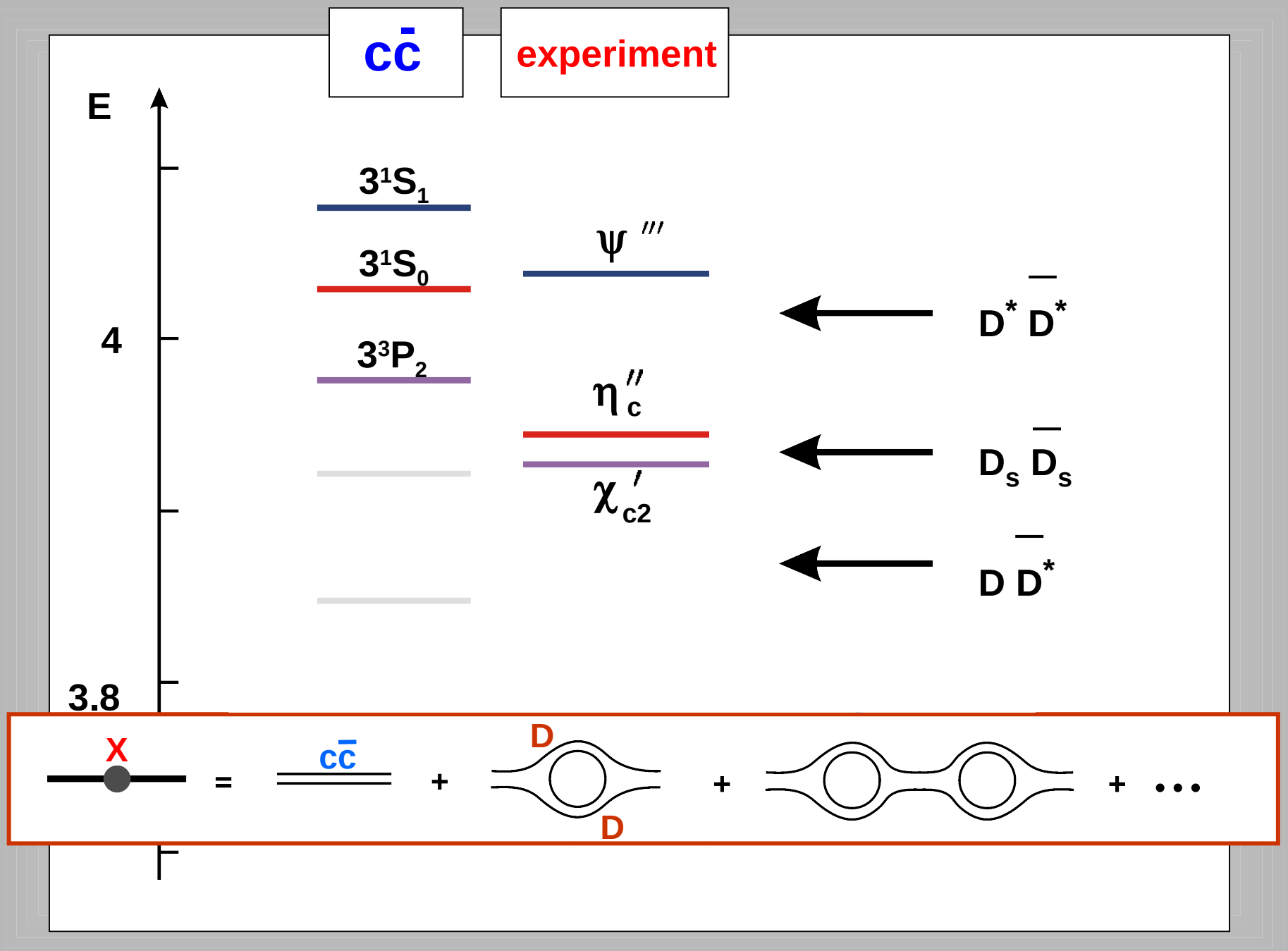


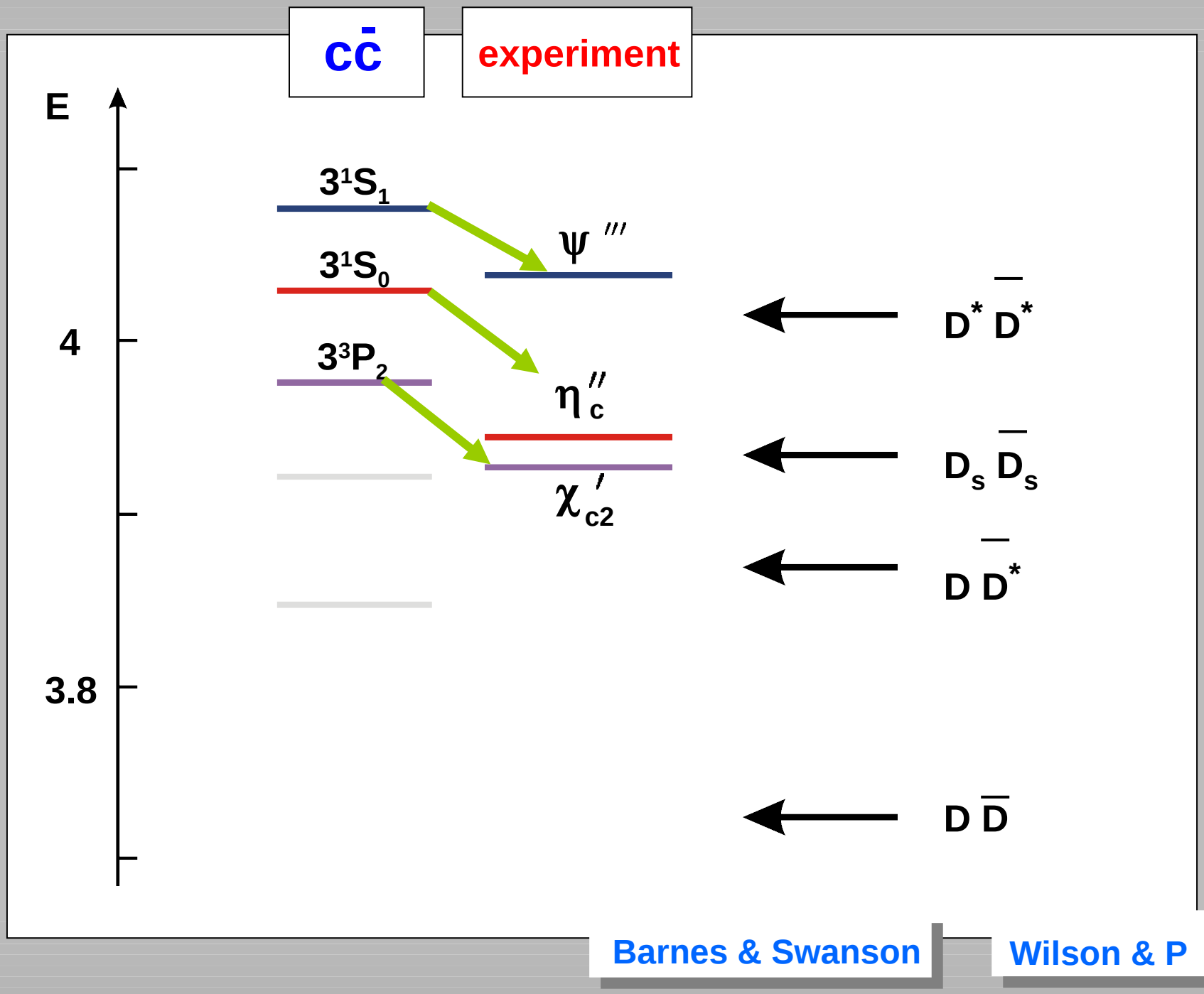


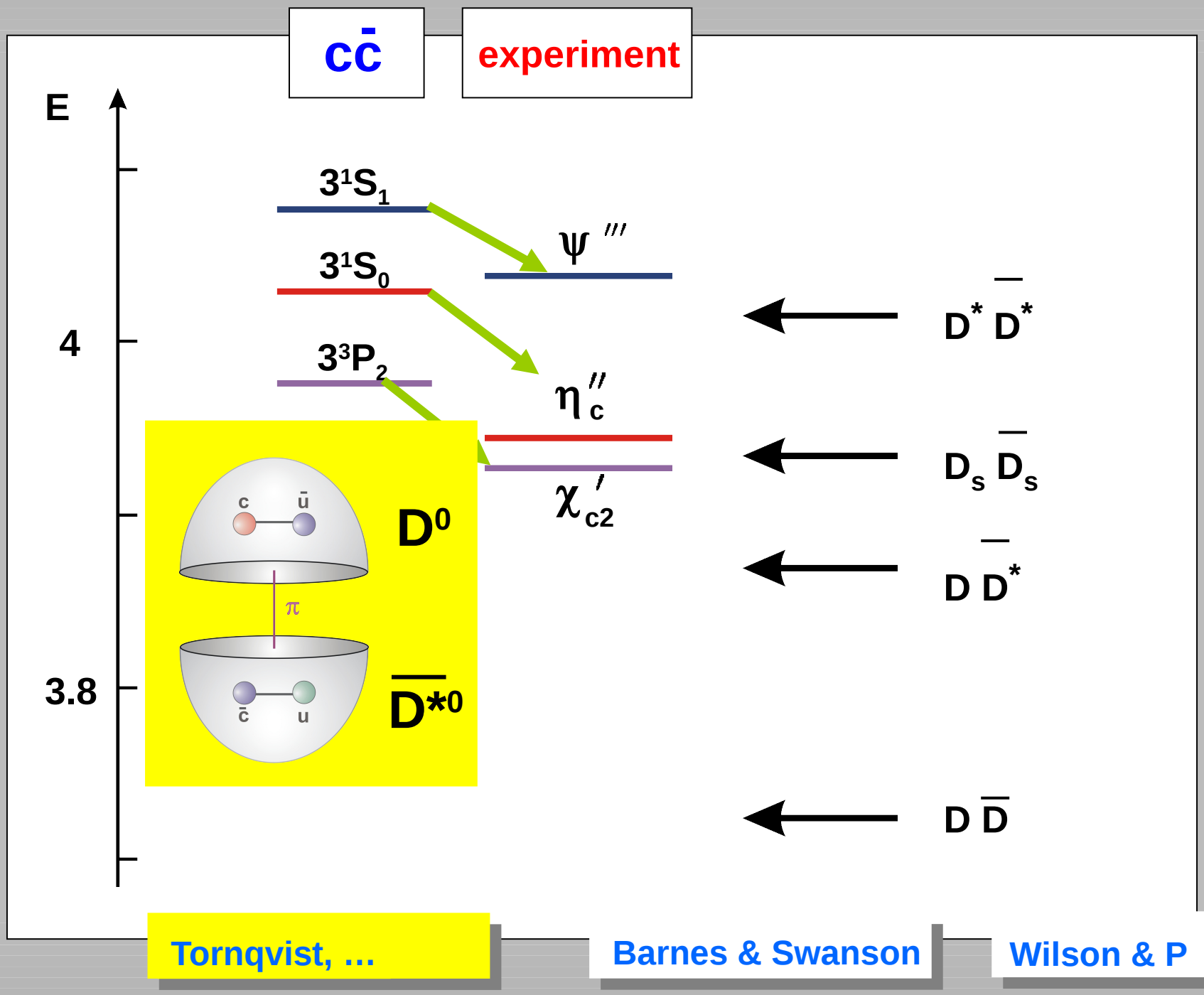



$c\bar{c}$
E
4
3.8
3^1S_1
3^1S_0
3^3P_2
3^3P_1
3^3P_0
$D^* \bar{D}^*$
$D_s \bar{D}_s$
$D \bar{D}^*$
$D \bar{D}$


cc̄
experiment
E
4
3.8
3¹S₁
3¹S₀
3³P₂
ψ‴
η″c
χ′c2
D* D̄*
Ds D̄s
D D̄*
D D̄


cc̄
experiment
E
4
3.8
3¹S₁
3¹S₀
3³P₂
ψ‴
η″c
χ′c2
D* D̄*
Ds D̄s
D D̄*
X
=
cc̄
+
D
D
+
+ • • •


cc̄
experiment
E
4
3.8
3¹S₁
3¹S₀
3³P₂
ψ‴
η″c
χ′c2
D* D̄*
Ds D̄s
D D̄*
D D̄
Barnes & Swanson
Wilson & P


cc̄
experiment
E
4
3.8
3¹S₁
3¹S₀
3³P₂
ψ‴
η″c
χ′c2
D*D̄*
DsD̄s
DD̄*
DD̄
D⁰
D̄*⁰
c
ū
c̄
u
π
Tornqvist, …
Barnes & Swanson
Wilson & P

experiment

D_s

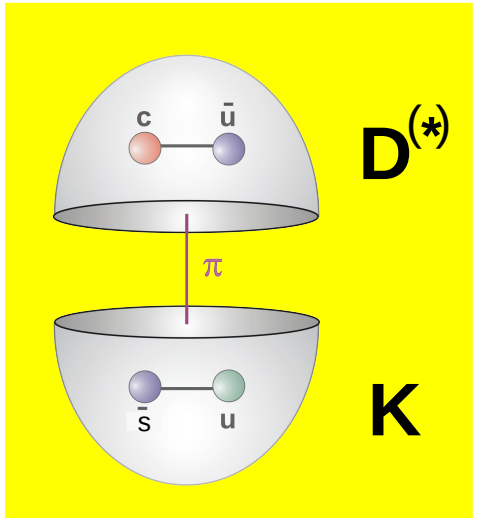
E

2.6

2.5

2.4

2.3

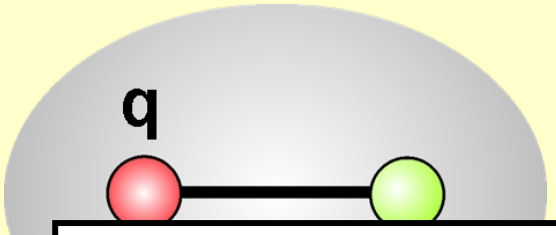


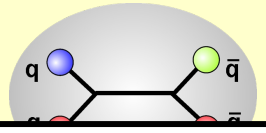
$D_s^*(2460)$

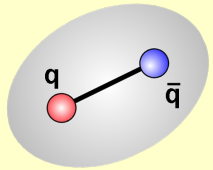
$D_s(2317)$

D*K

DK



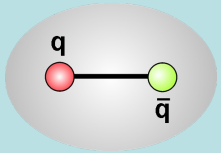


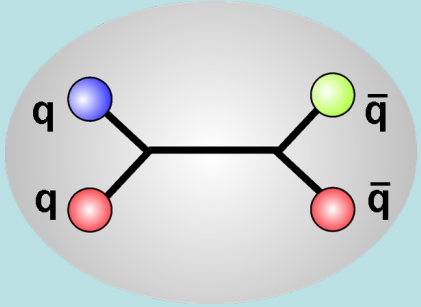


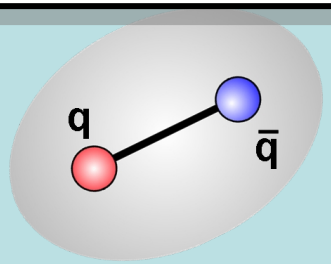
$X(3872)$ is not a true molecule

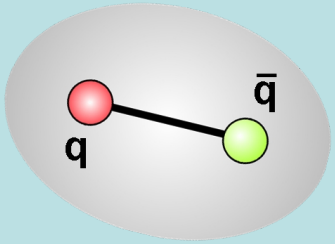
Susana Coito[1], George Rupp[1], and Eef van Beveren[2]

[1] Centro de Física das Interacções Fundamentais, Instituto Superior Técnico, Technical University of Lisbon, P-1049-001 Lisbon, Portugal
[2] Centro de Física Computacional, Departamento de Física, Universidade de Coimbra, P-3004-516 Coimbra, Portugal



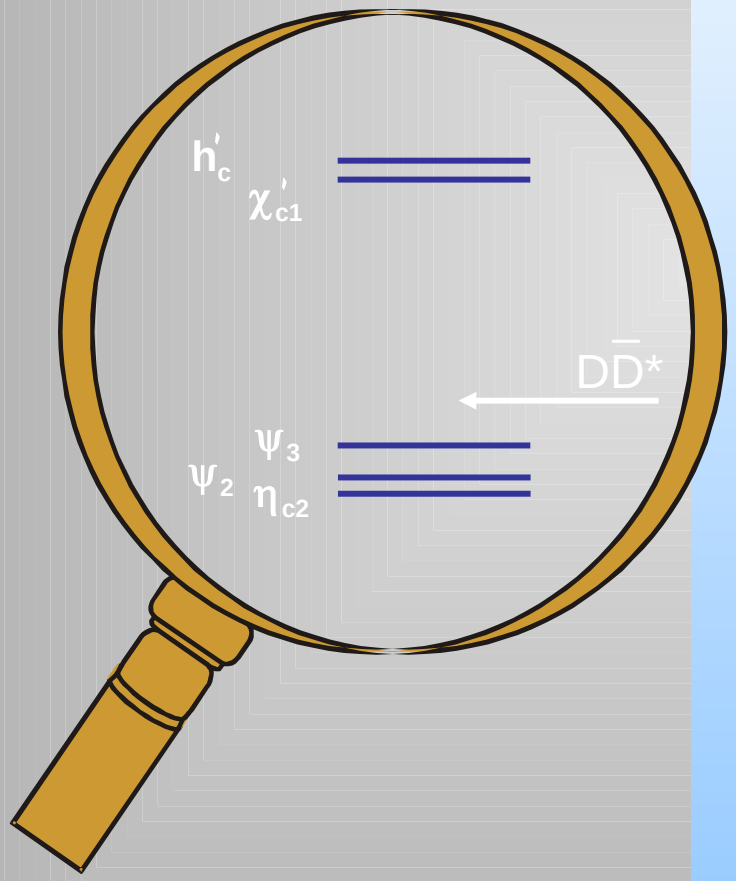


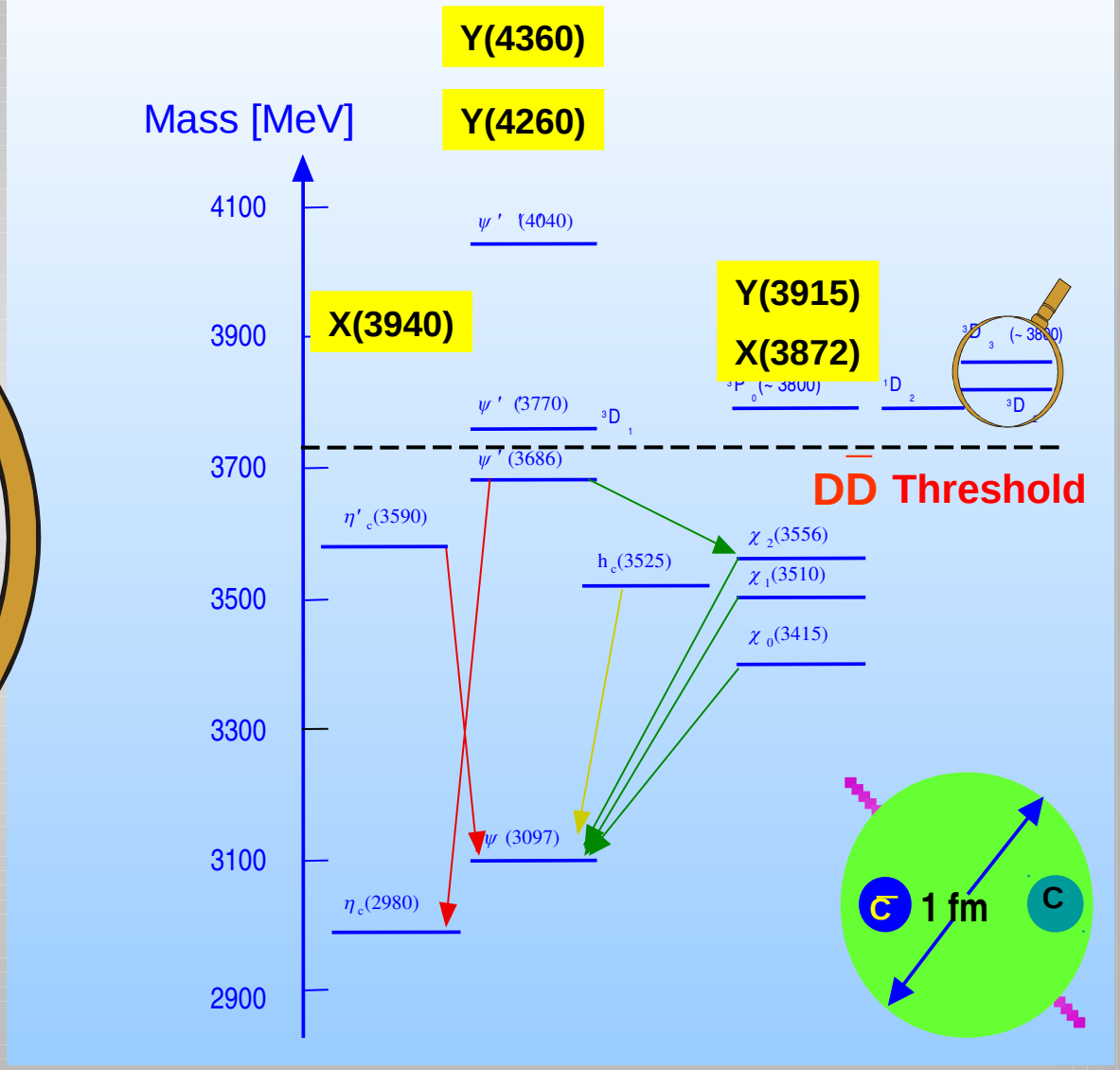




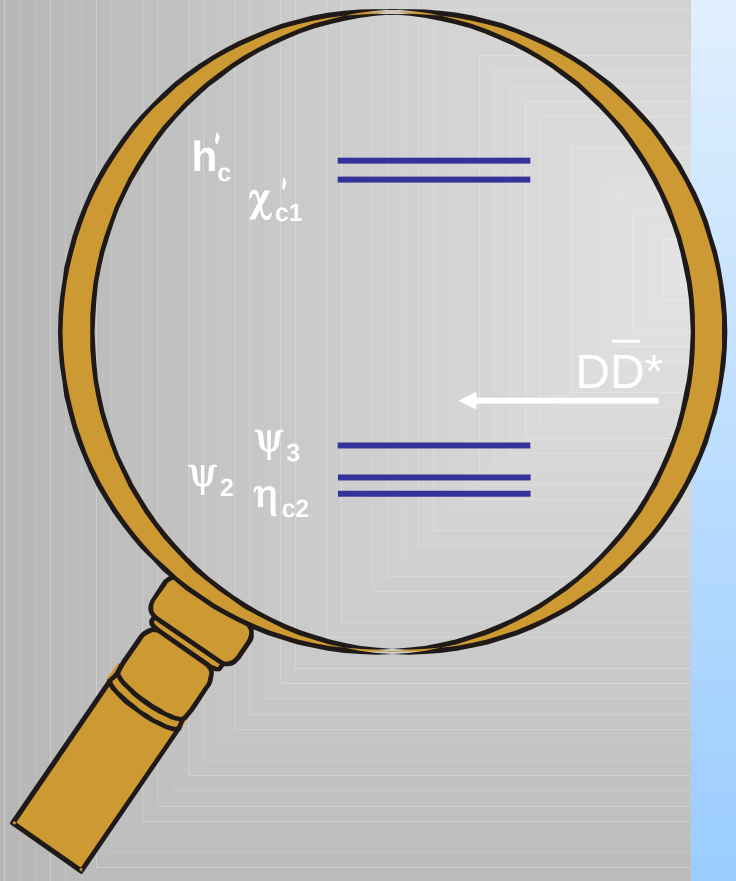
Dynamically generated states

charmonium


h'c
χ'c1
DD̄*
ψ3
ψ2
ηc2


Y(4360)
Y(4260)
Mass [MeV]
4100
3900
3700
3500
3300
3100
2900
ψ ' (4040)
X(3940)
Y(3915)
X(3872)
ψ ' (3770)
3D1
ψ ' (3686)
DD̄ Threshold
η'c(3590)
hc(3525)
χ2(3556)
χ1(3510)
χ0(3415)
ψ (3097)
ηc(2980)
c
1 fm
c

charmonium



Z_c^+

Z(4430)

Y(4360)

Mass [MeV]

Y(4260)

Z(4250)

4100

ψ' (4040)

Z(4060)

Y(3915)

X(3940)

3900

Z(3900)

X(3872)

ψ' (3770)

3D1

3700

ψ' (3686)

DD̄ Threshold

η'c(3590)

χ2(3556)

hc(3525)

χ1(3510)

3500

χ0(3415)

3300

ψ (3097)

3100

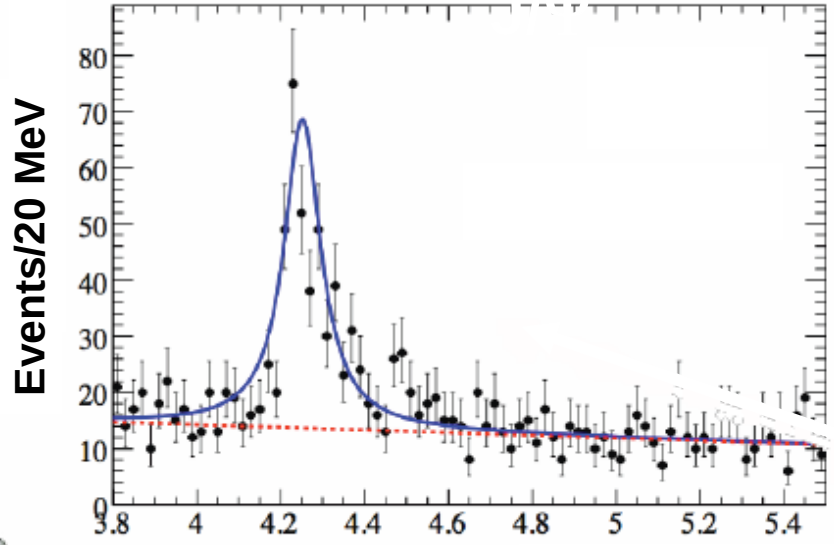
ηc(2980)

2900

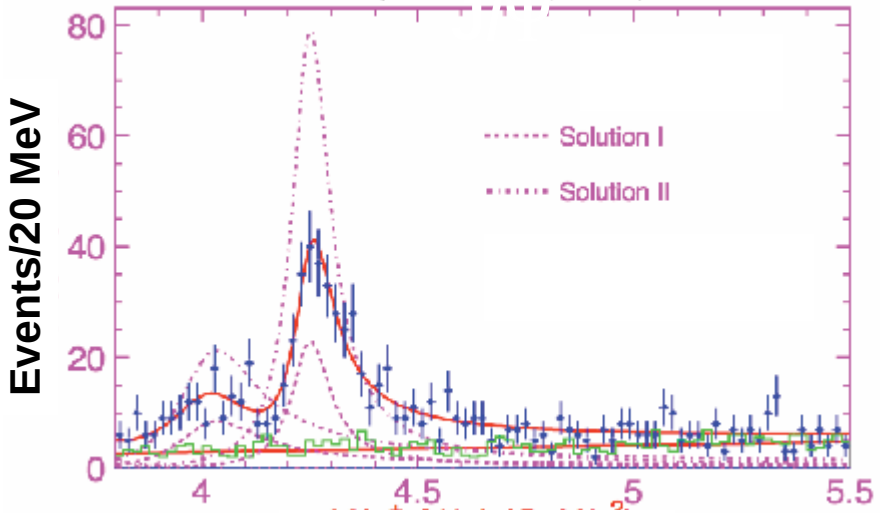
c c̄ 1 fm c̄

Y (4260)

$e^+e^- \longrightarrow \pi^+\pi^-$

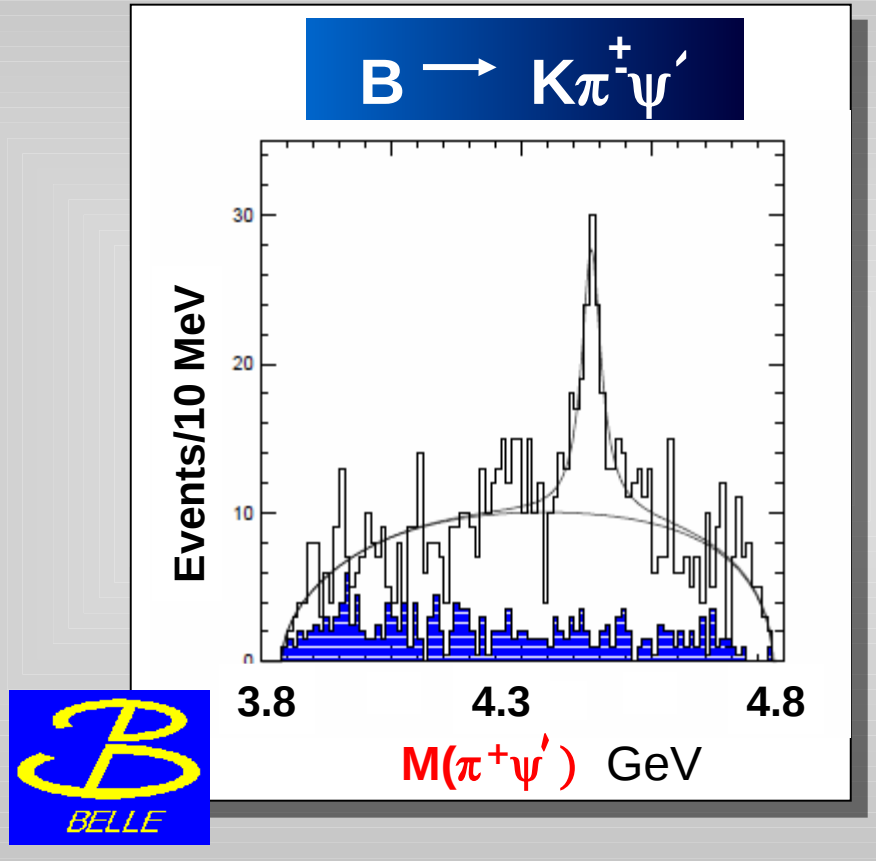


$e^+e^- \longrightarrow \pi^+\pi^-$



BELLE

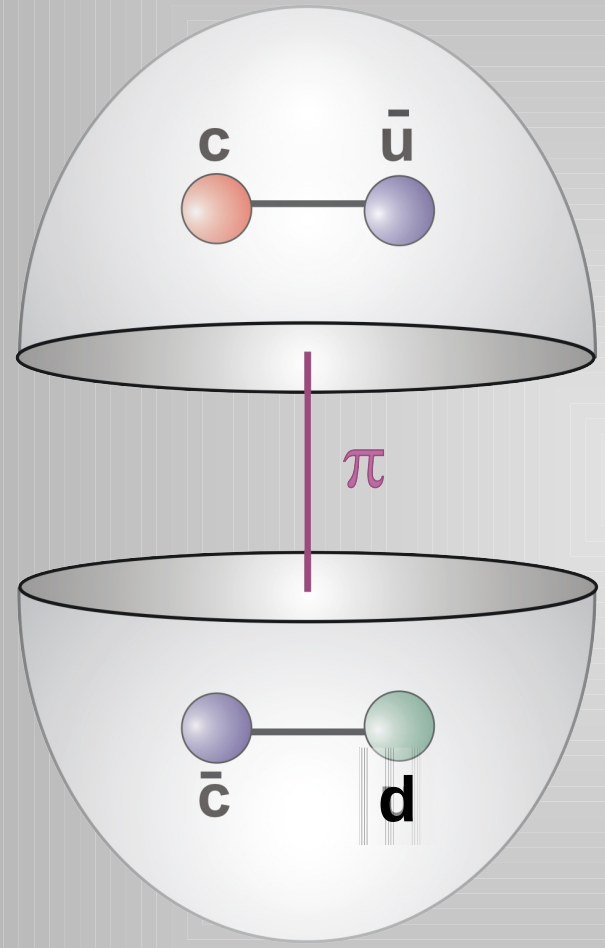
$Z_c^{\pm}(4430)$

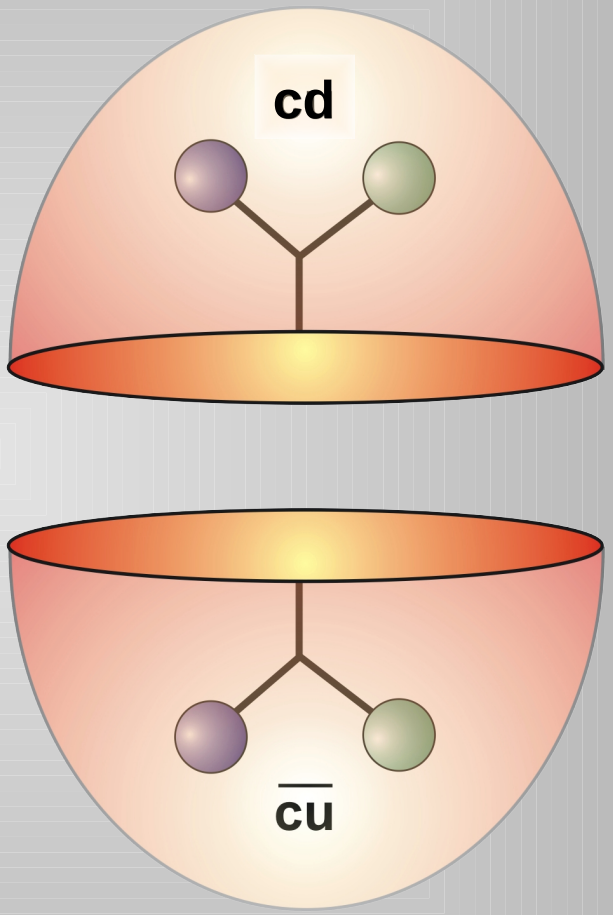


Z_c^-

molecule

tetraquark

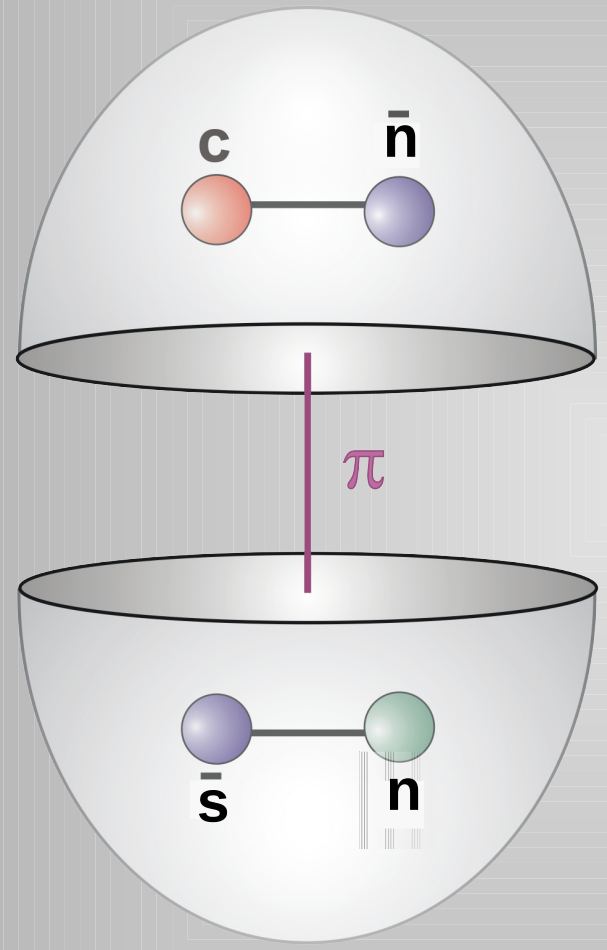


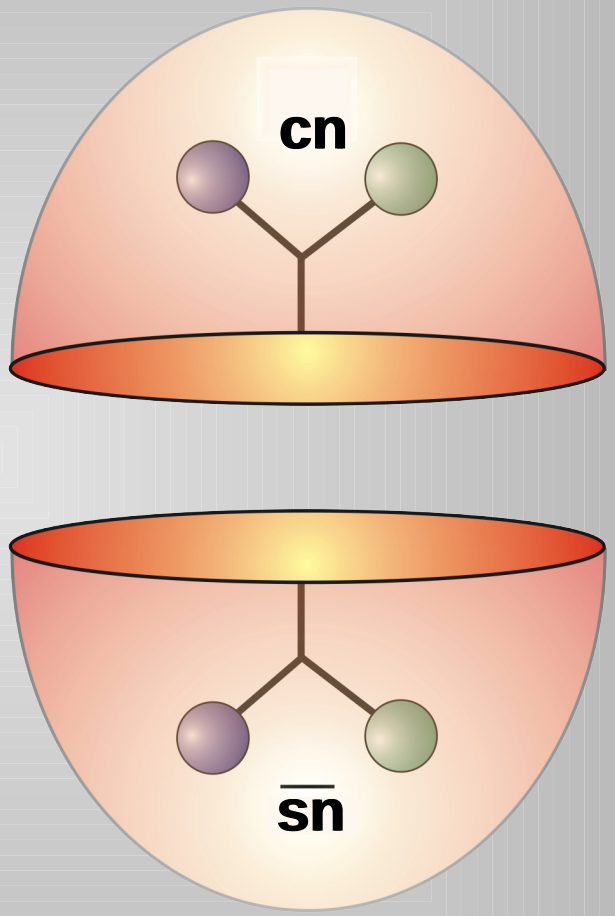


$D_s^{(*)+}$

molecule

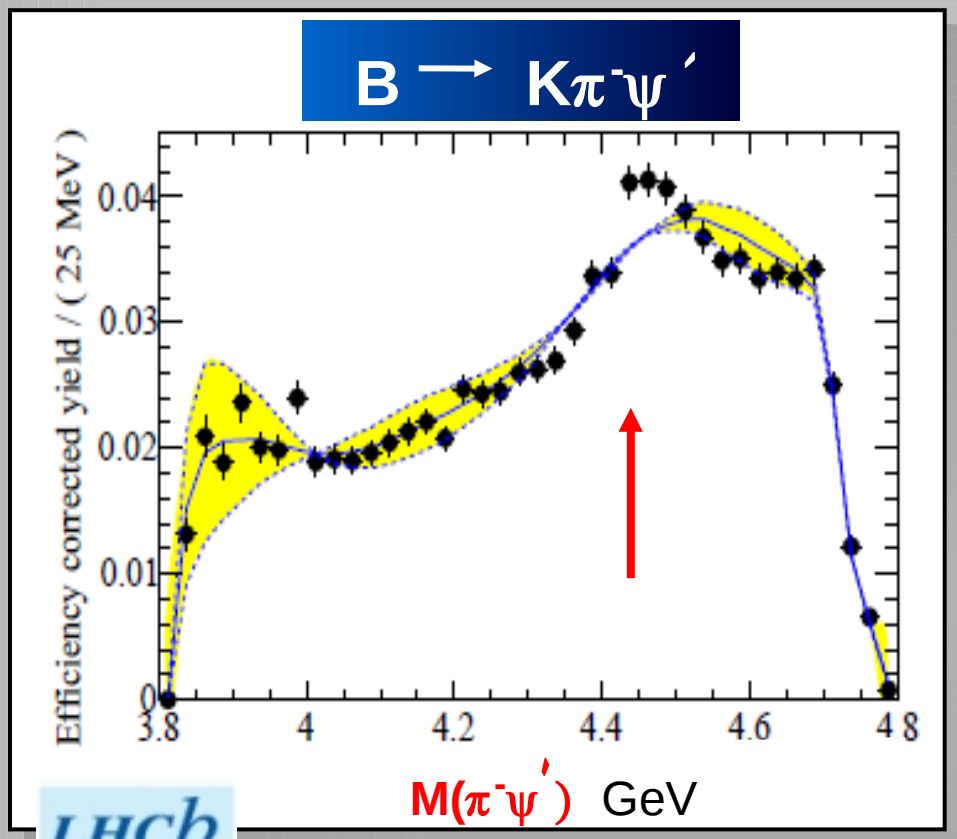
tetraquark

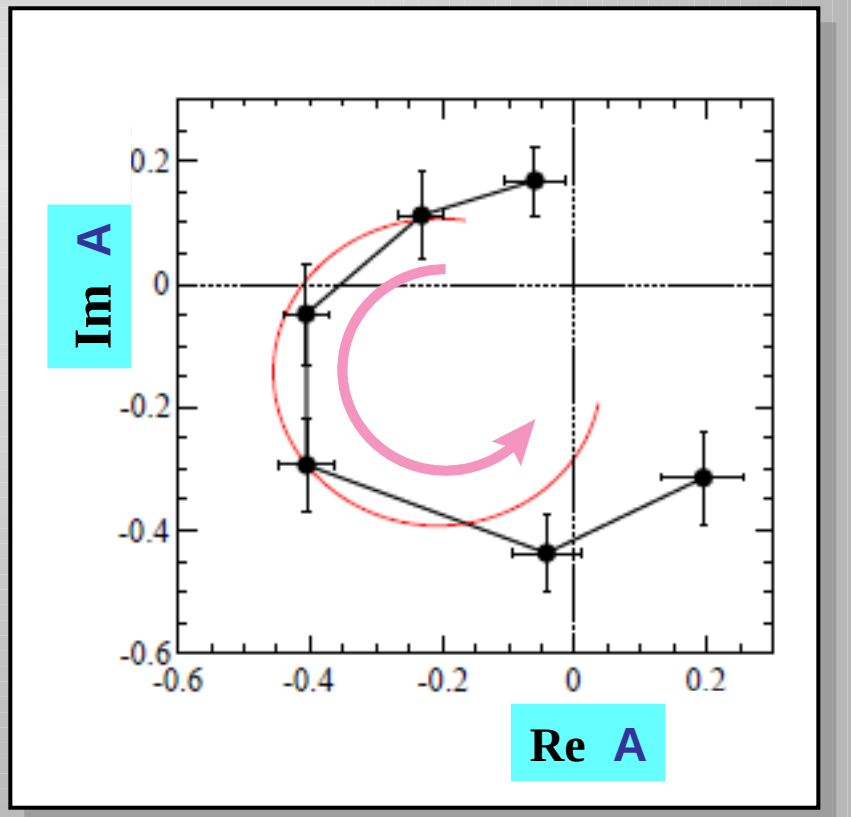


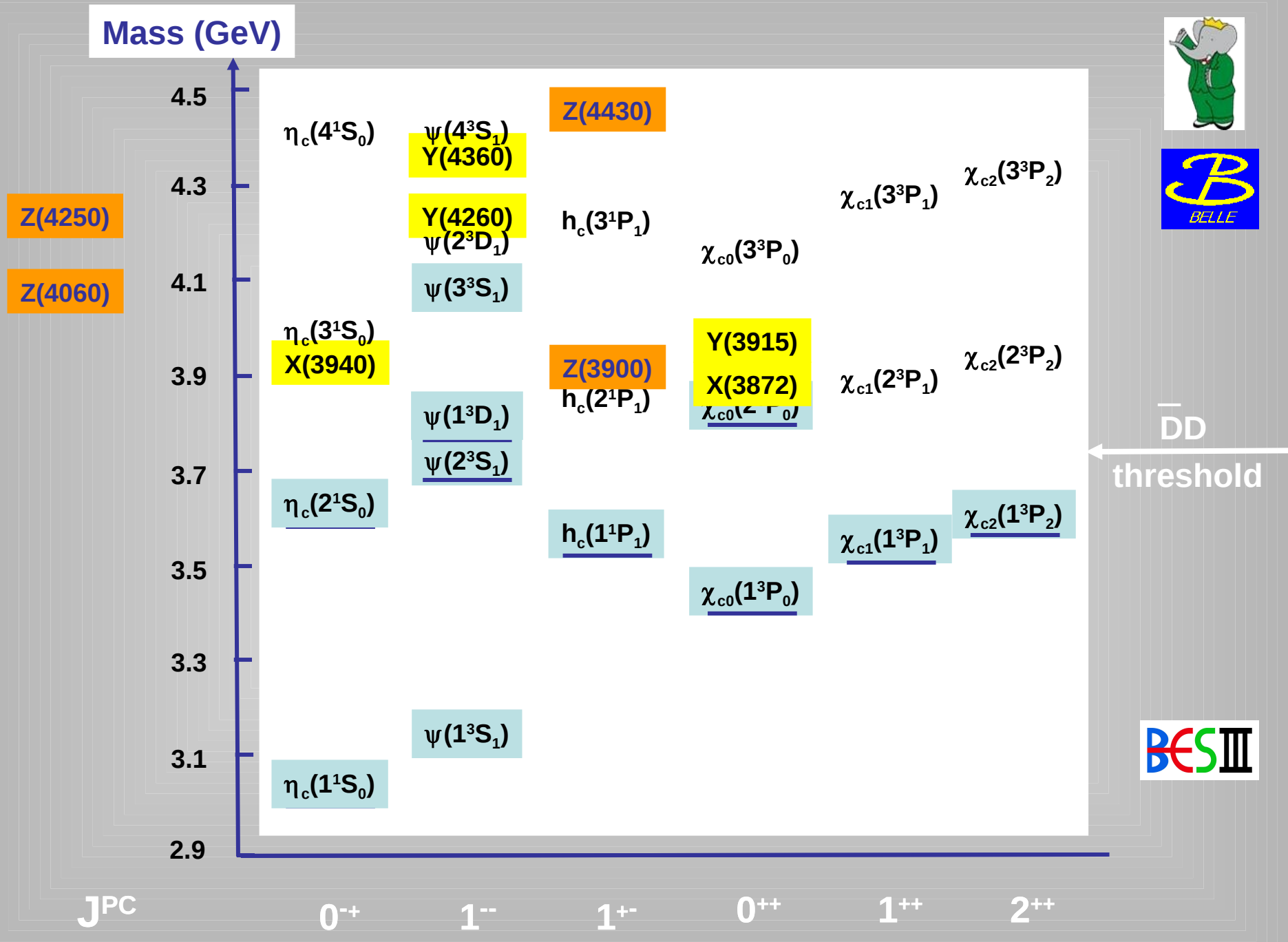


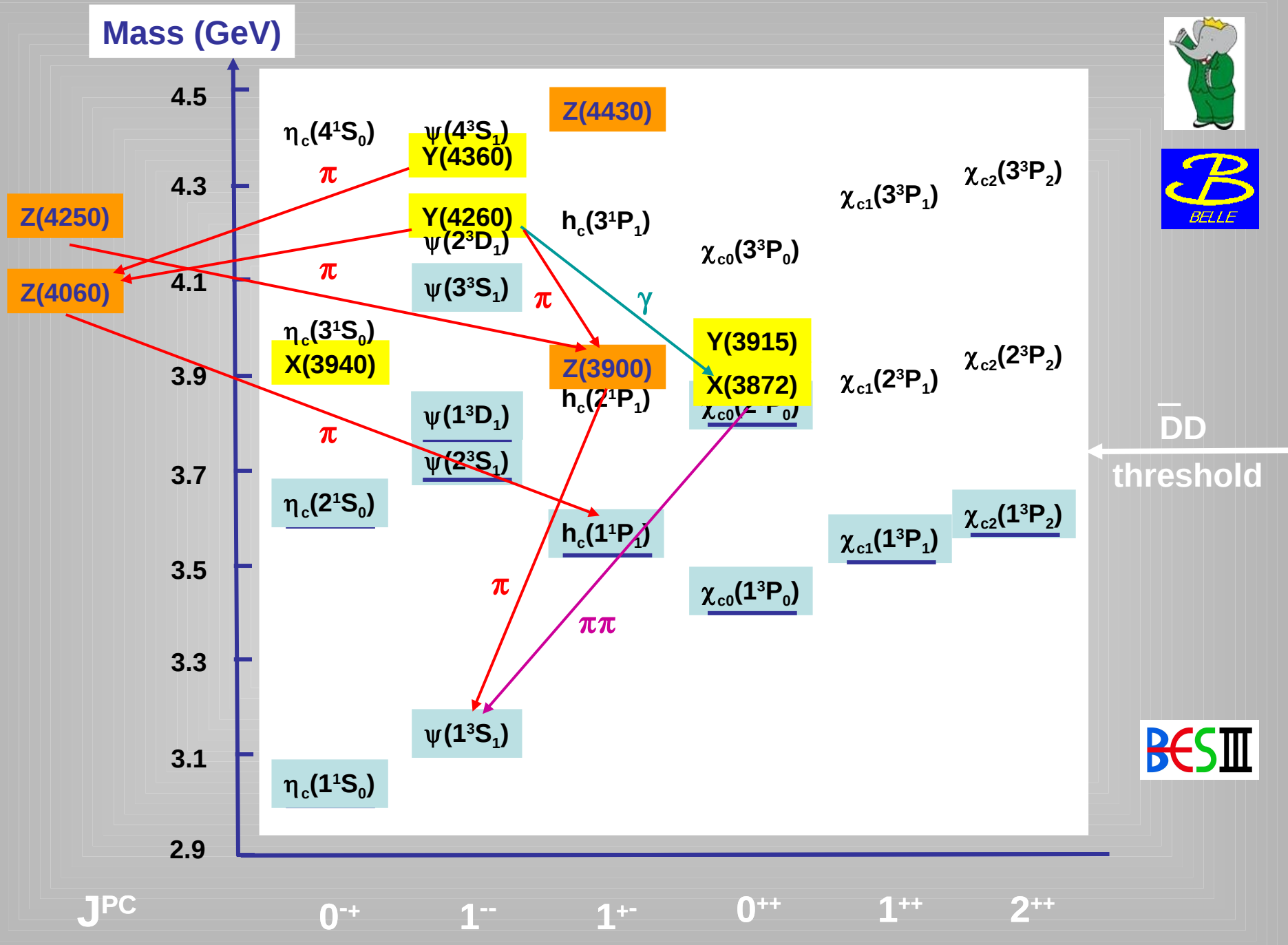
n = u, d

$Z_c^-(4430)$


B → Kπ⁻ψ′
Efficiency corrected yield / (25 MeV)
0.04
0.03
0.02
0.01
0
3.8
4
4.2
4.4
4.6
4.8
M(π⁻ψ′) GeV
LHCb

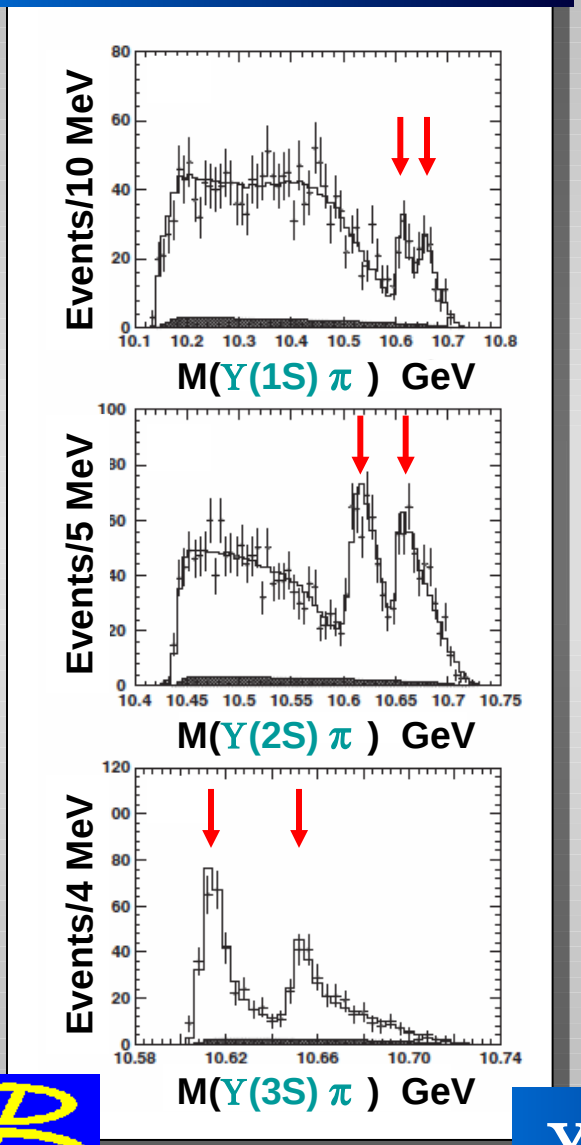

Im A
0.2
0
-0.2
-0.4
-0.6
-0.6
-0.4
-0.2
0
0.2
Re A


Mass (GeV)
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
Z(4250)
Z(4060)
$\eta_c(4^1S_0)$
$\psi(4^3S_1)$
Y(4360)
Z(4430)
Y(4260)
$\psi(2^3D_1)$
$h_c(3^1P_1)$
$\chi_{c1}(3^3P_1)$
$\chi_{c2}(3^3P_2)$
$\chi_{c0}(3^3P_0)$
$\psi(3^3S_1)$
$\eta_c(3^1S_0)$
X(3940)
Z(3900)
Y(3915)
X(3872)
$h_c(2^1P_1)$
$\chi_{c1}(2^3P_1)$
$\chi_{c2}(2^3P_2)$
$\psi(1^3D_1)$
$\psi(2^3S_1)$
$\eta_c(2^1S_0)$
$h_c(1^1P_1)$
$\chi_{c1}(1^3P_1)$
$\chi_{c2}(1^3P_2)$
$\chi_{c0}(1^3P_0)$
$\psi(1^3S_1)$
$\eta_c(1^1S_0)$
J^{PC}
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
$\bar{D}D$
threshold
BELLE
BESIII


Mass (GeV)
4.5
4.3
4.1
3.9
3.7
3.5
3.3
3.1
2.9
Z(4250)
Z(4060)
ηc(4¹S0)
ψ(4³S1)
Y(4360)
Z(4430)
Y(4260)
ψ(2³D1)
ψ(3³S1)
hc(3¹P1)
χc0(3³P0)
χc1(3³P1)
χc2(3³P2)
ηc(3¹S0)
X(3940)
Z(3900)
hc(2¹P1)
Y(3915)
X(3872)
χc1(2³P1)
χc2(2³P2)
ψ(1³D1)
ψ(2³S1)
ηc(2¹S0)
hc(1¹P1)
χc1(1³P1)
χc2(1³P2)
χc0(1³P0)
ψ(1³S1)
ηc(1¹S0)
π
γ
ππ
DD
threshold
JPC
0-+
1--
1+-
0++
1++
2++
BELLE
BESIII

Z_b's

$\Upsilon(5S) \rightarrow (\Upsilon(nS)\pi)\pi$



$M = 10607.2 \pm 2.0$ MeV
$\Gamma = 18.4 \pm 2.4$ MeV

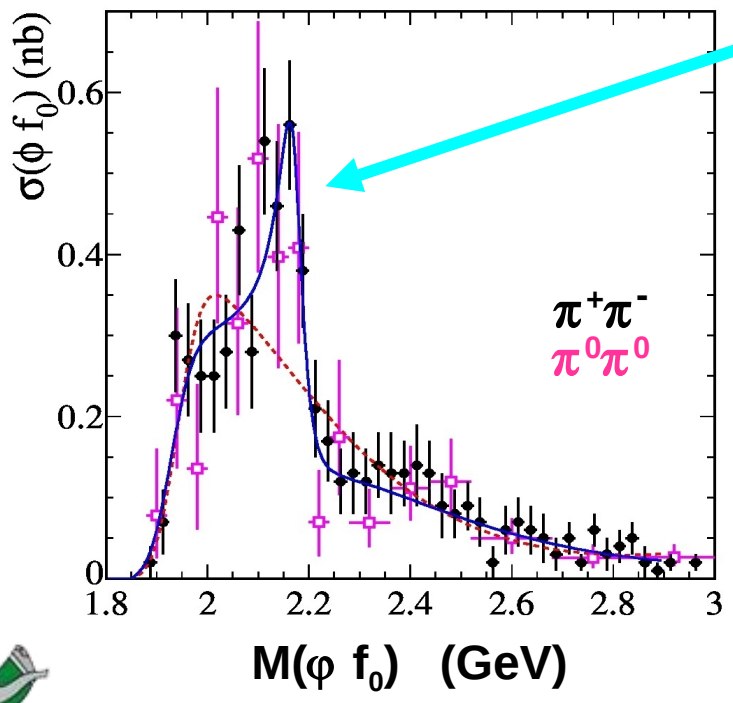
$M = 10652.2 \pm 1.5$ MeV
$\Gamma = 11.5 \pm 2.2$ MeV

n = 1,2,3
m = 1,2

$\Upsilon(5S) \rightarrow (h_b(mP)\pi)\pi$

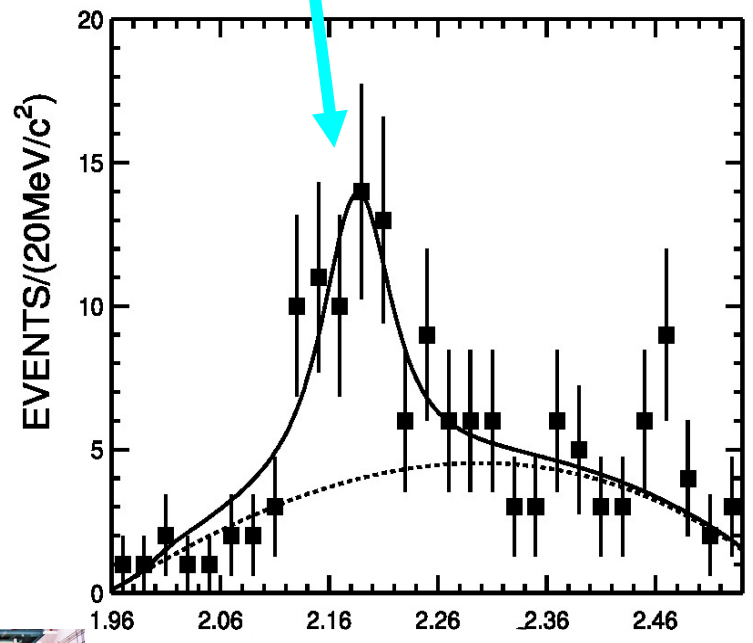
BELLE

$e^+e^- \longrightarrow \gamma_{ISR}\,(\varphi\, f_0)$



Y (2175)

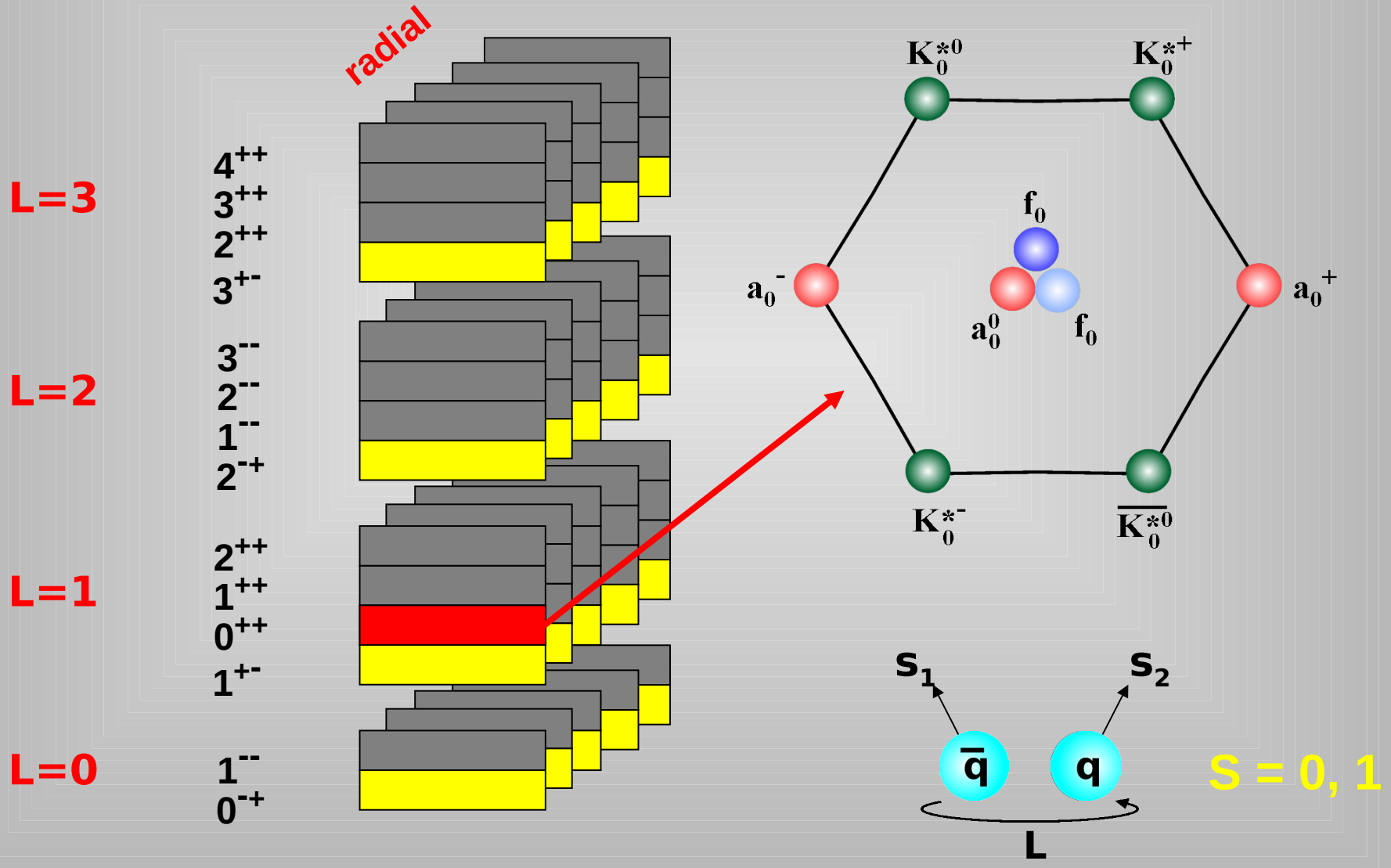
$J/\Psi \longrightarrow \eta\,(\varphi\, f_0)$



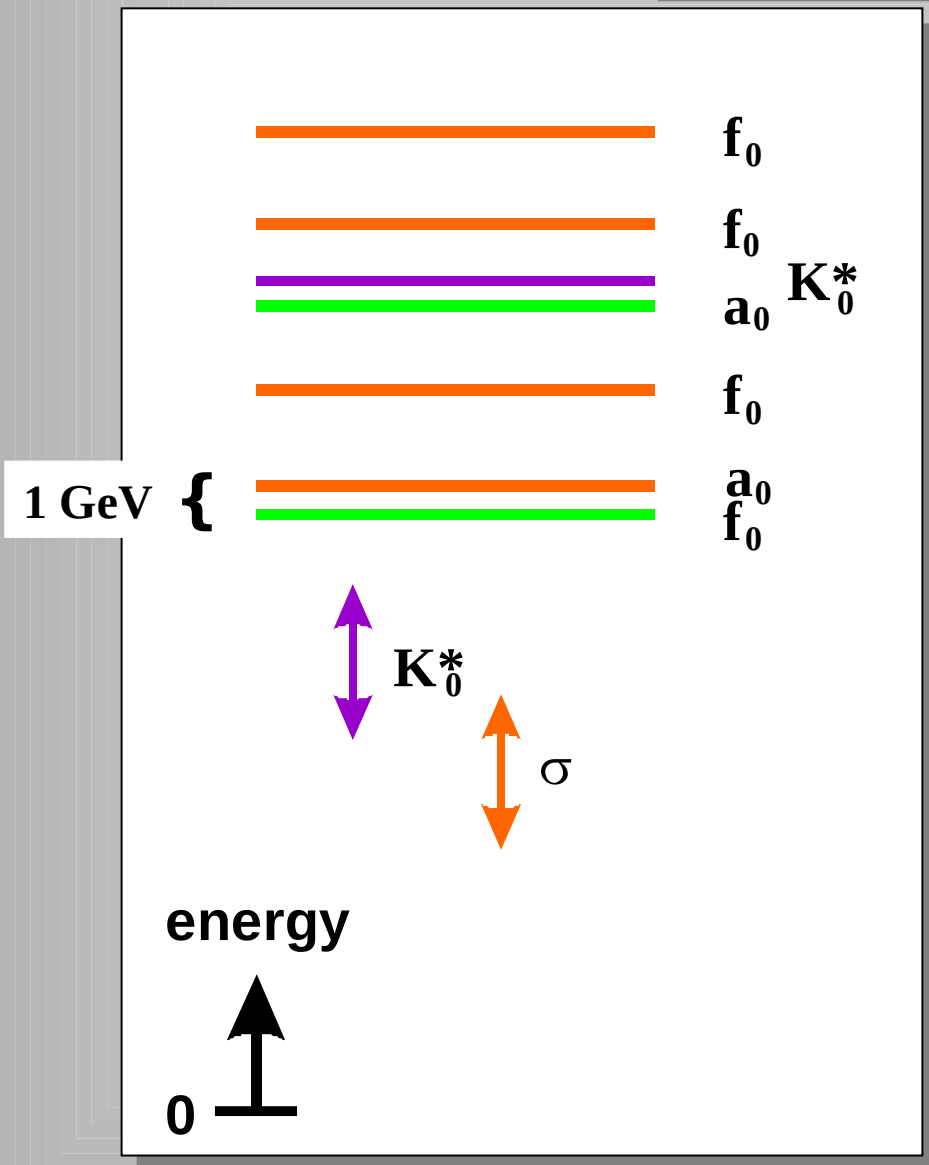
More Surprising States?

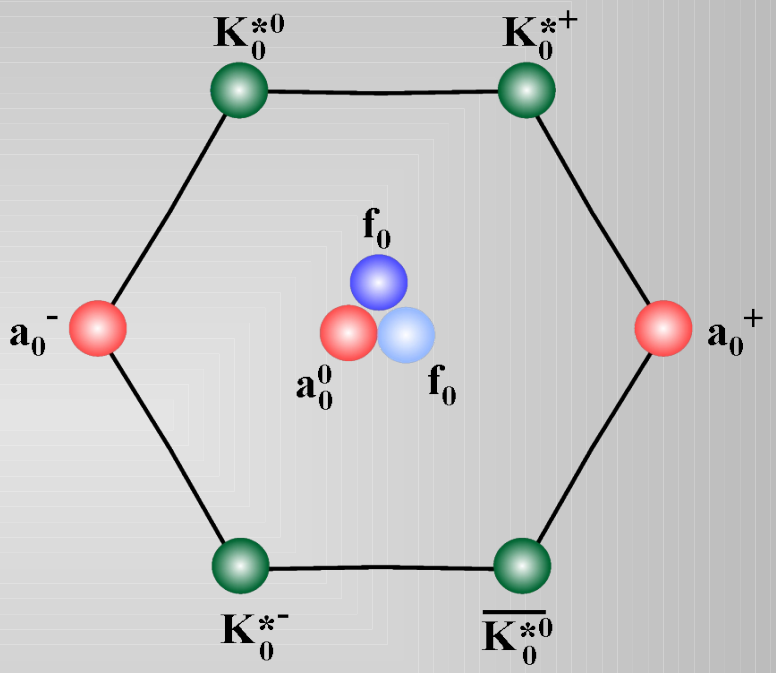
Meson spectrum

0^{++}

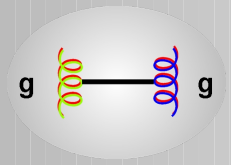


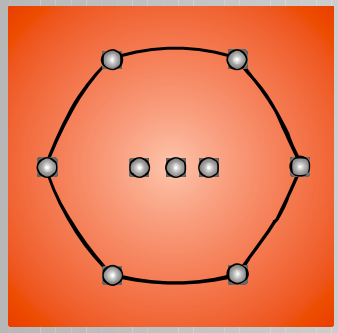
Scalar multiplet

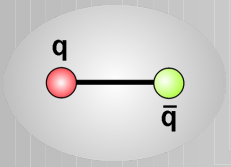


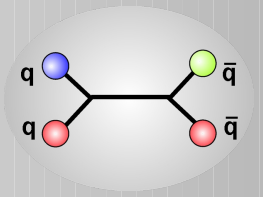


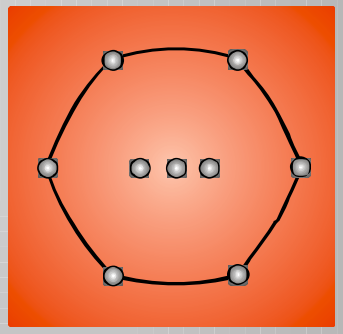
Scalar mesons











gg — f_0

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

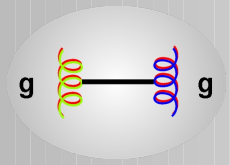
$\bar{s}s\bar{n}n$ — a_0 / f_0

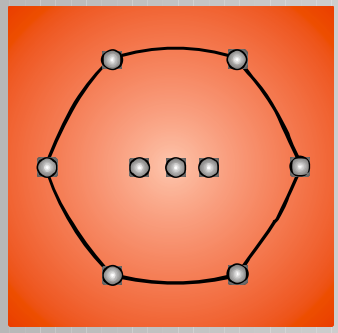
$\bar{s}n\bar{n}n$ — K_0 κ

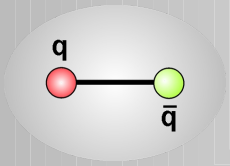
$\bar{n}n\bar{n}n$ — f_0 σ

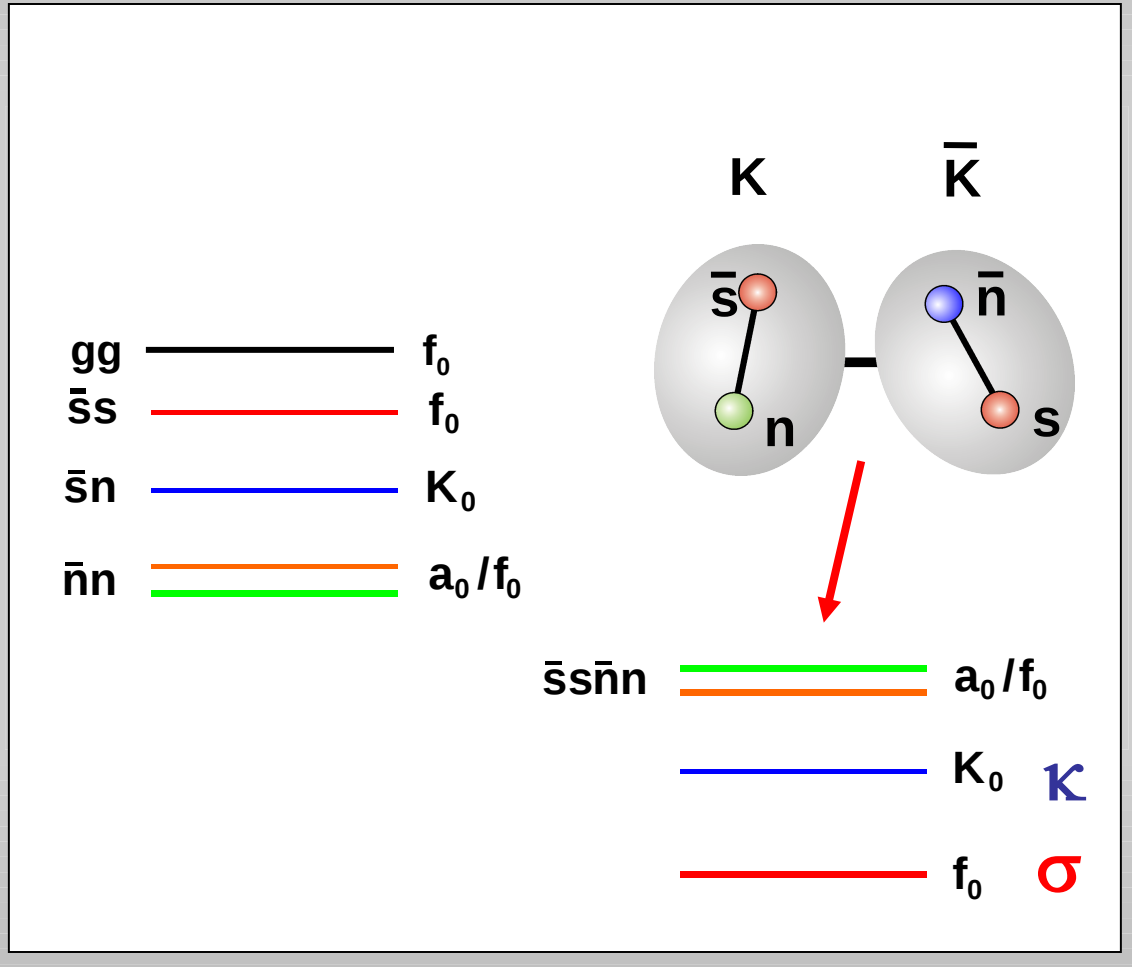
$n = u,d$

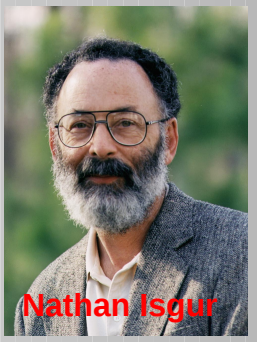
Scalar mesons





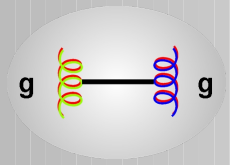


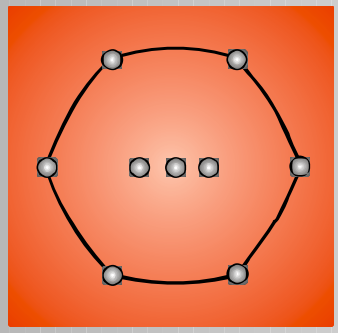


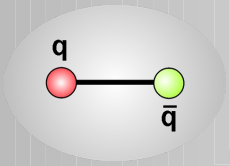


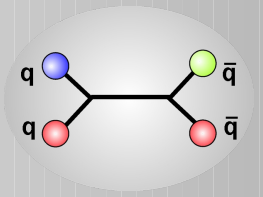
n = u,d

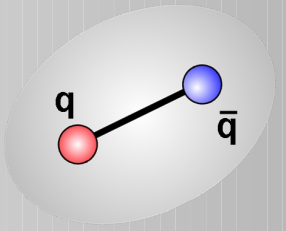
Scalar mesons

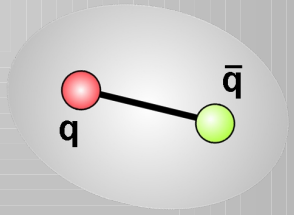


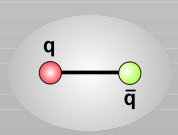


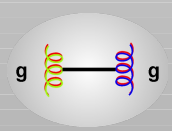


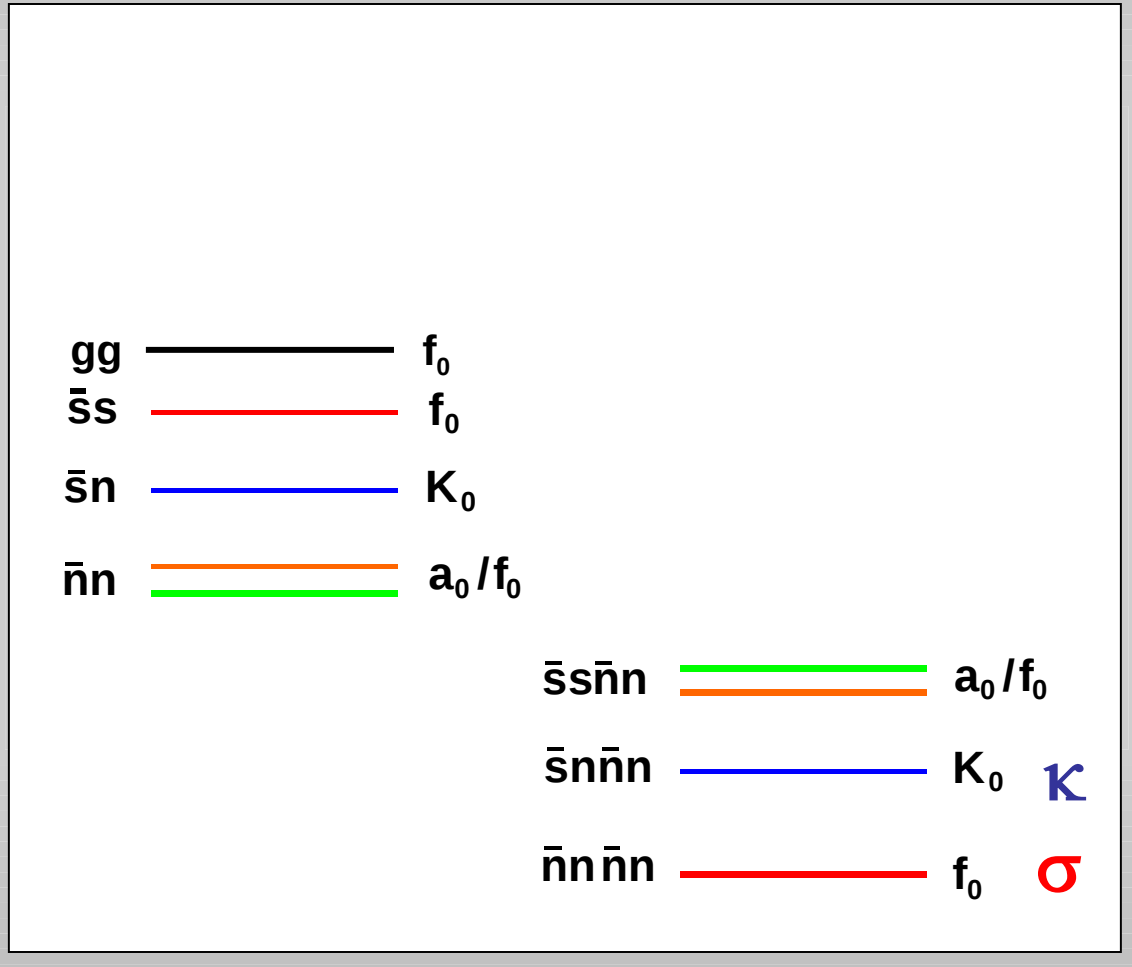






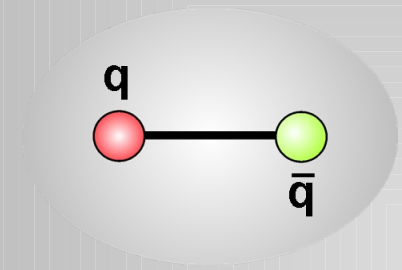




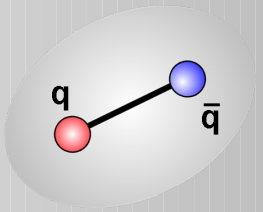


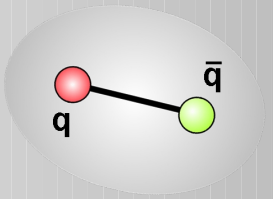
$f_0(980)$

?

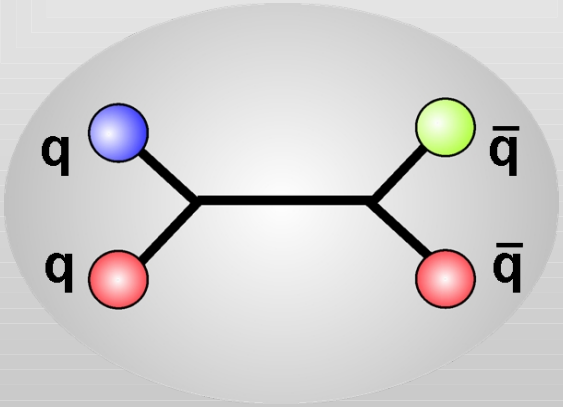


K

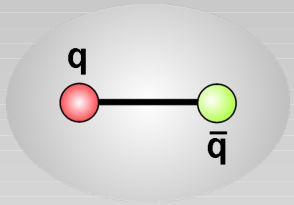


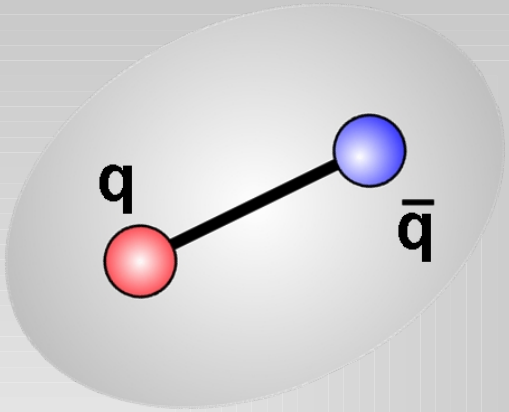


$\bar{K}$

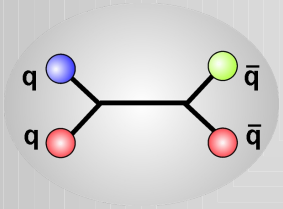


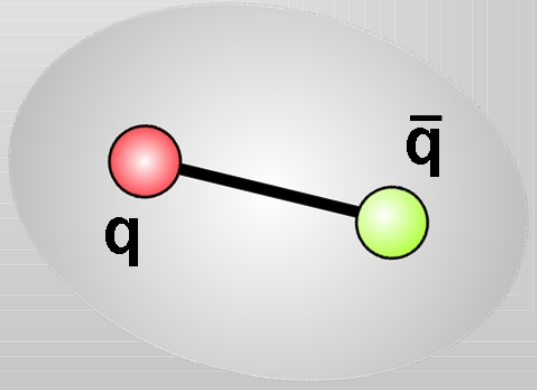
$f_0(980)$





K



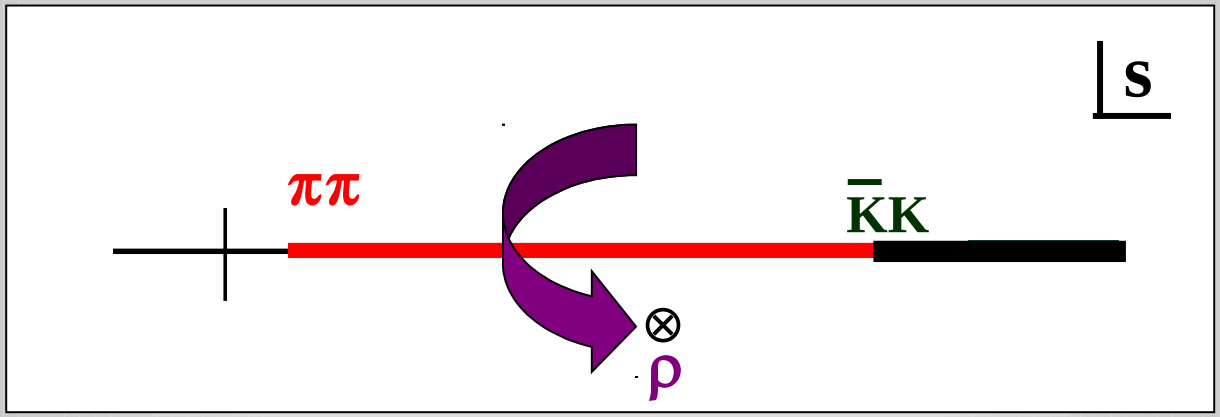


$\bar{K}$

?

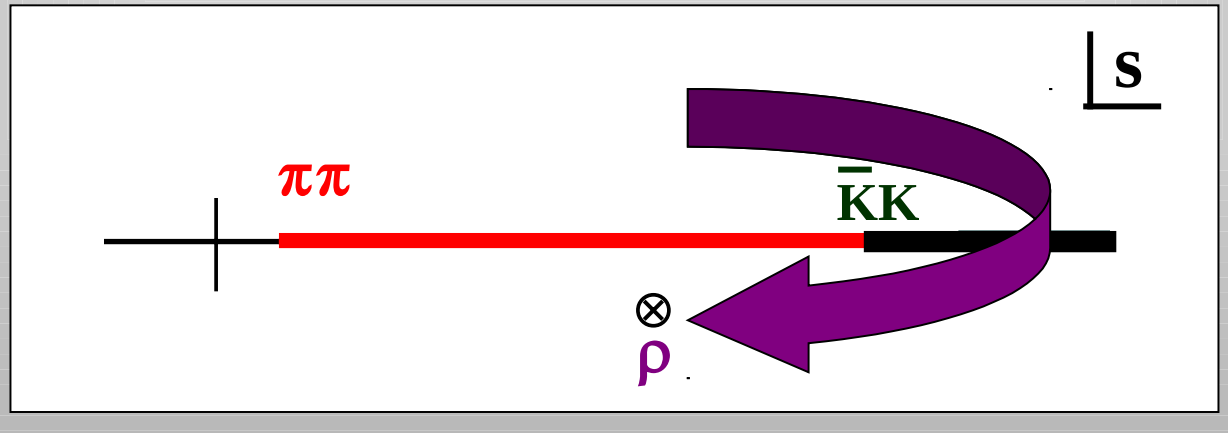
Vector meson

poles in complex plane



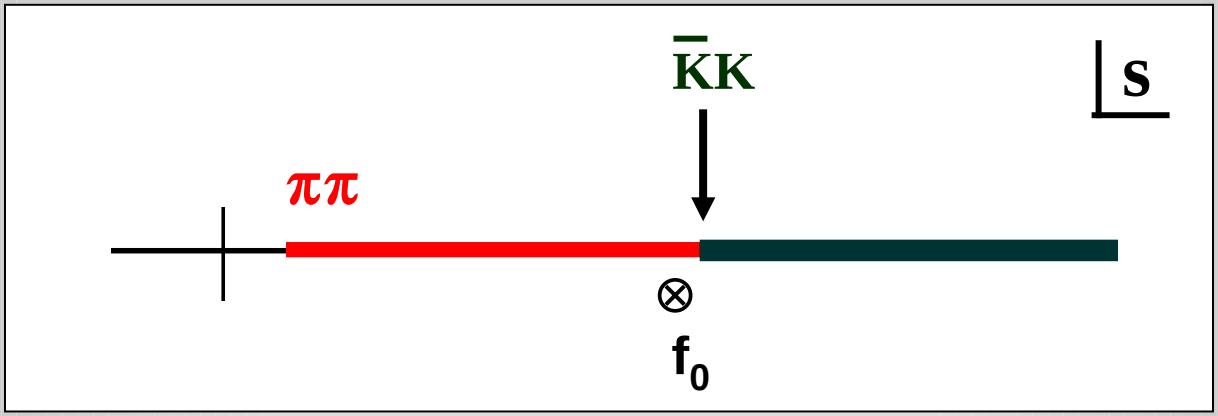
shadow pole

mirror pole



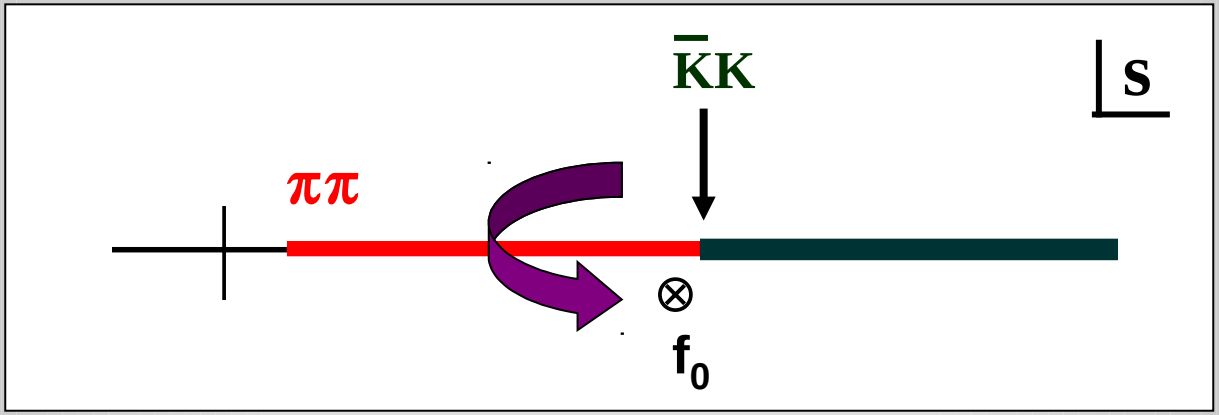
Scalar meson

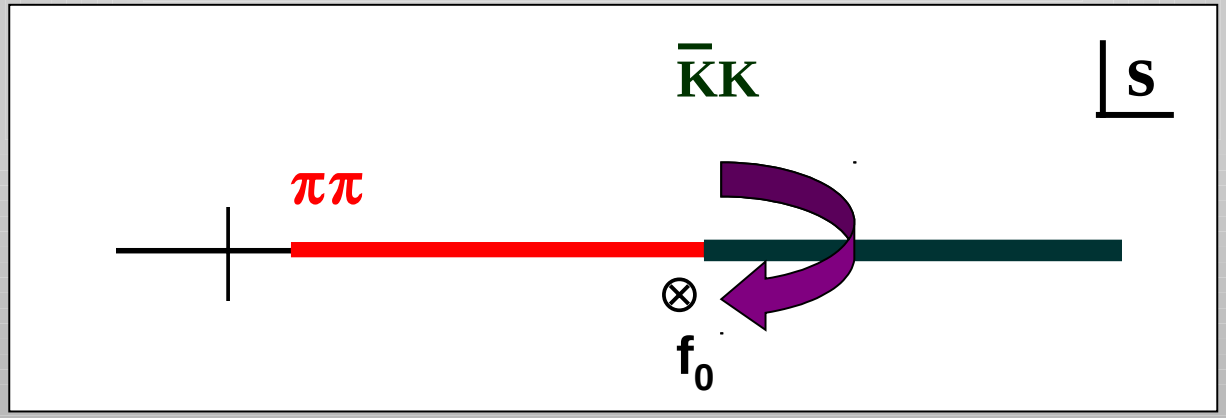
poles in complex plane



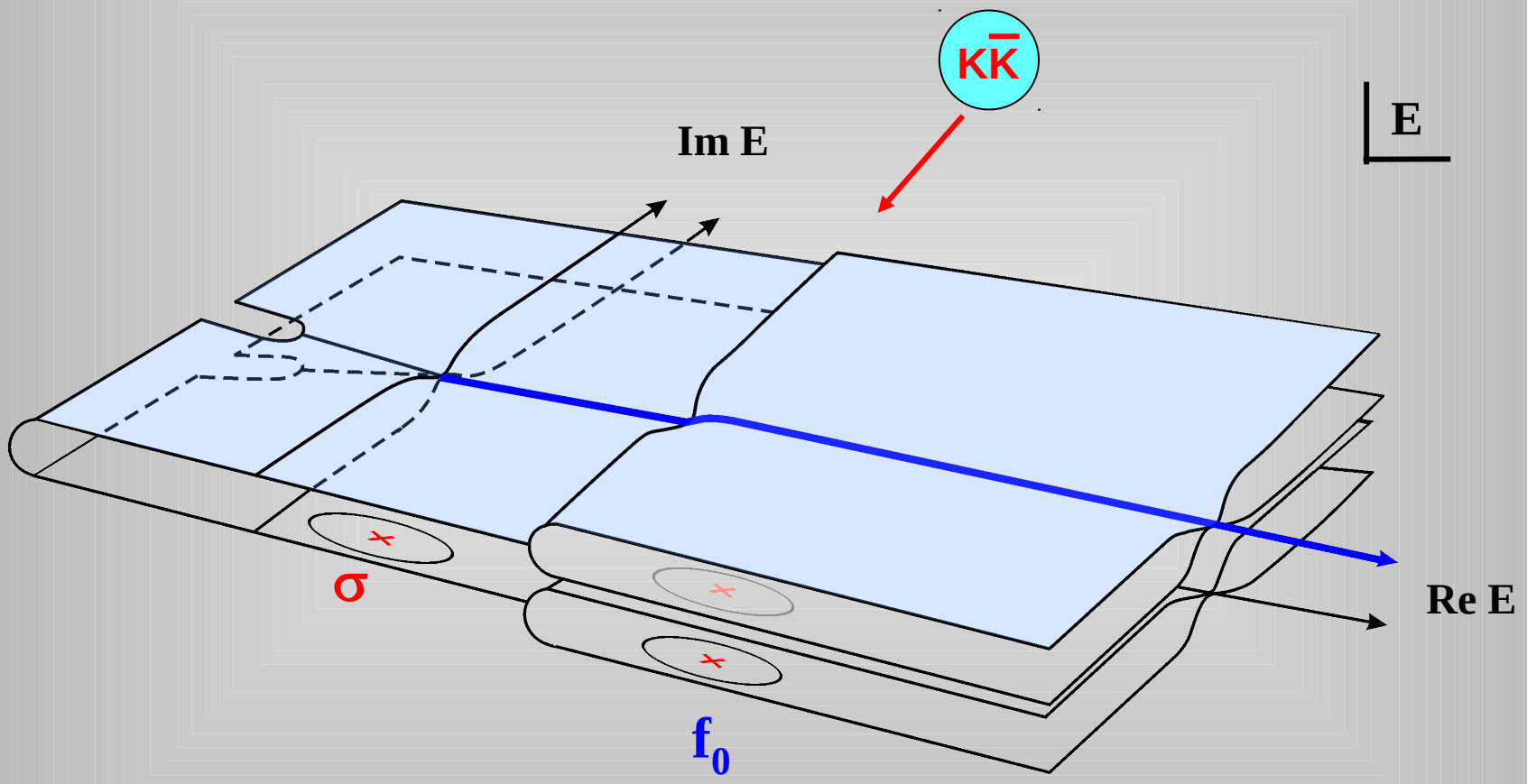
Scalar meson

poles in complex plane



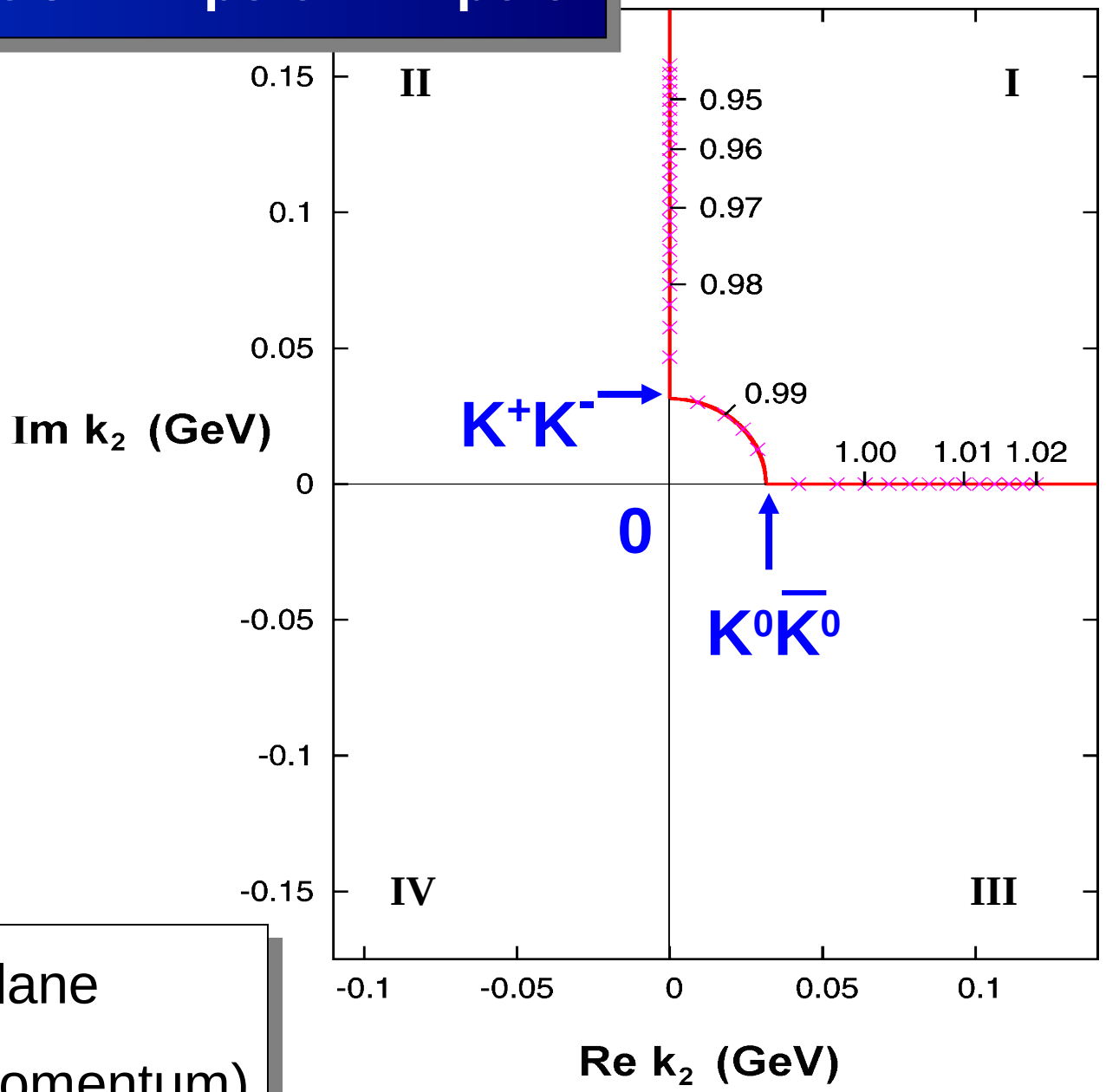


Quark state v Molecule



Weinberg
Morgan

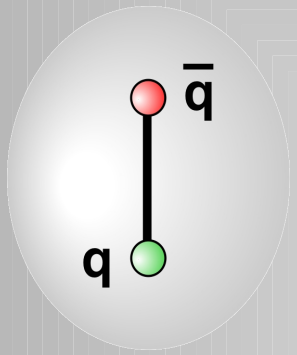
Jost function: 1 pole v 2 pole

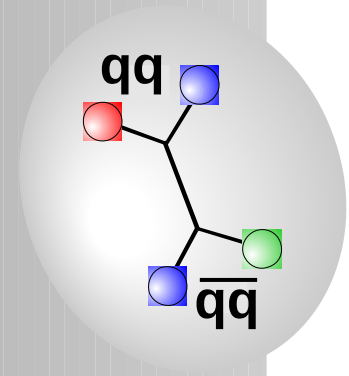


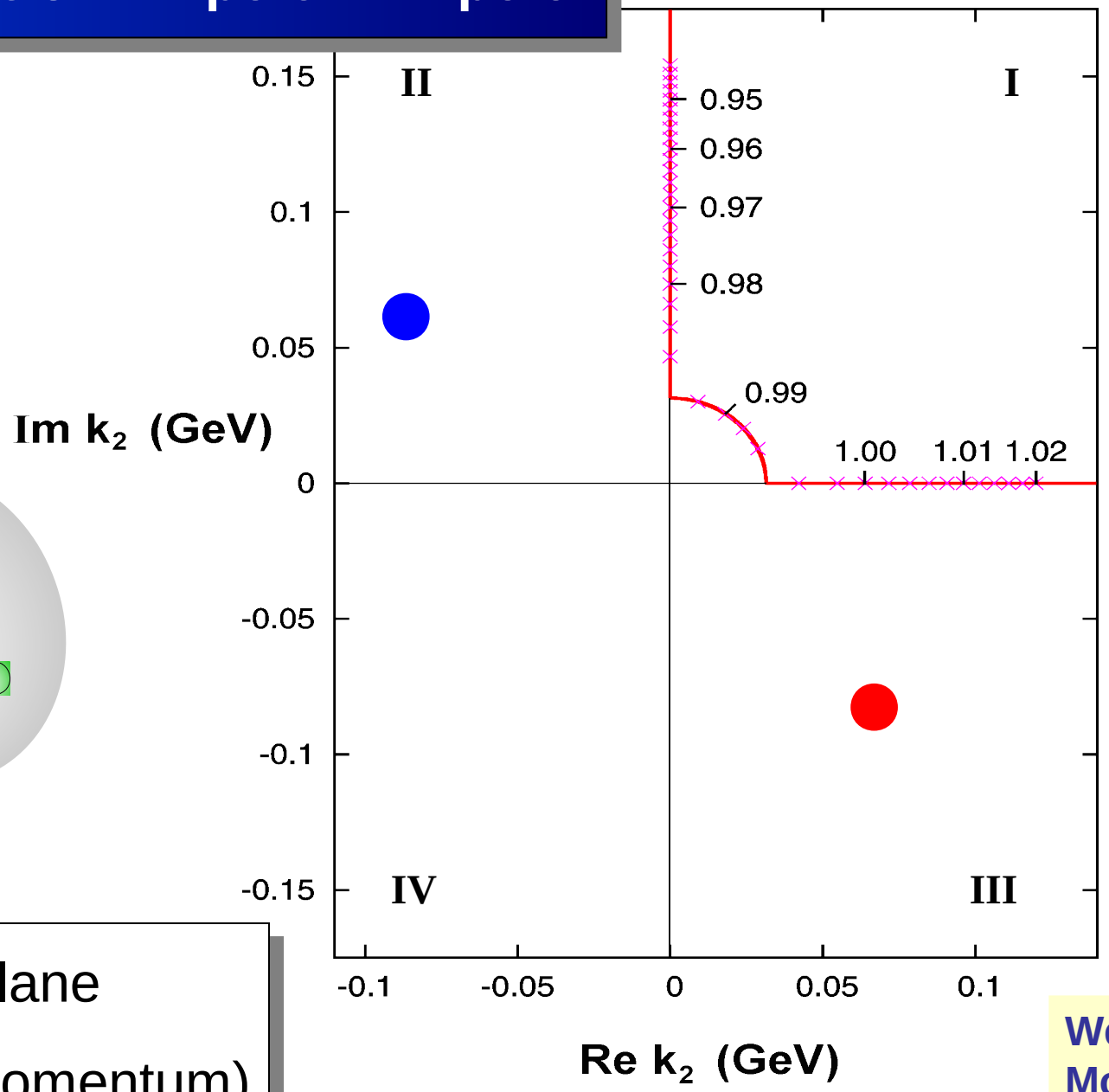
k_2 plane

($K\bar{K}$ c.m. momentum)

Jost function: 1 pole v 2 pole





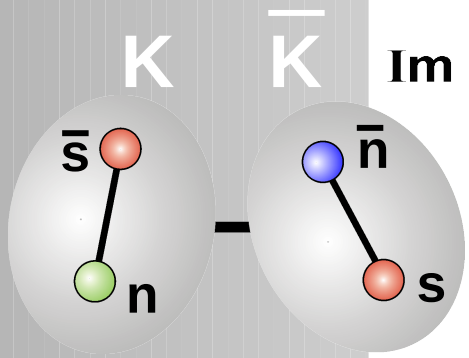


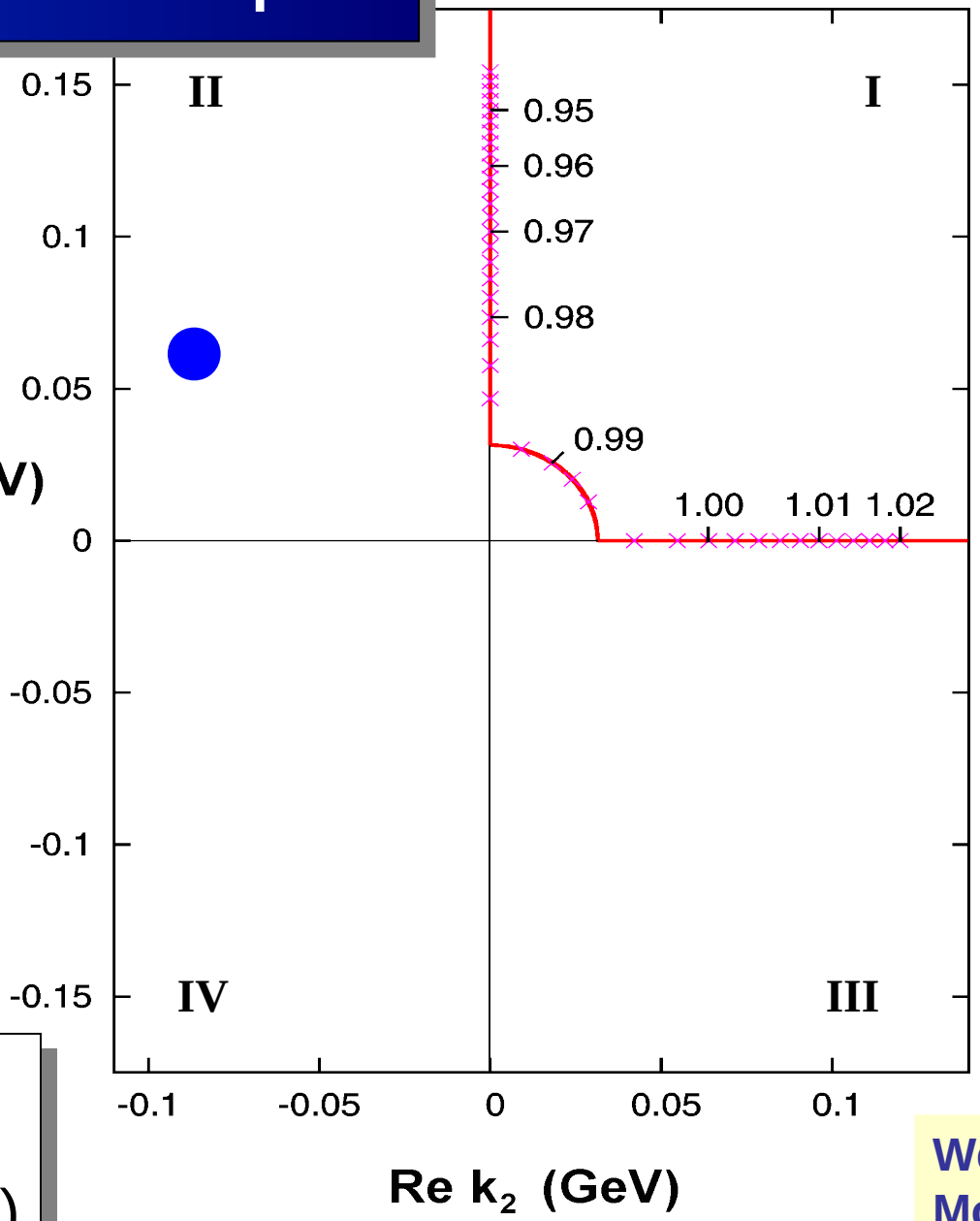
k_2 plane

($\bar{K}K$ c.m. momentum)

Weinberg
Morgan

Jost function: 1 pole v 2 pole



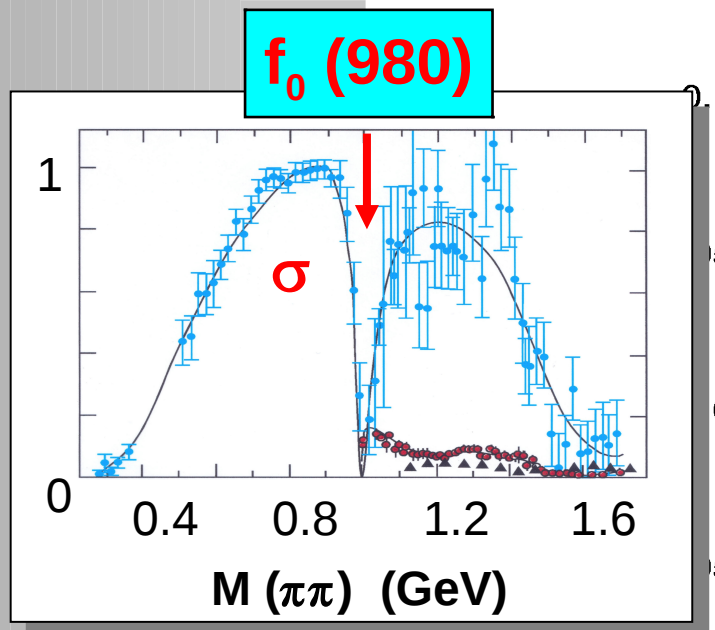


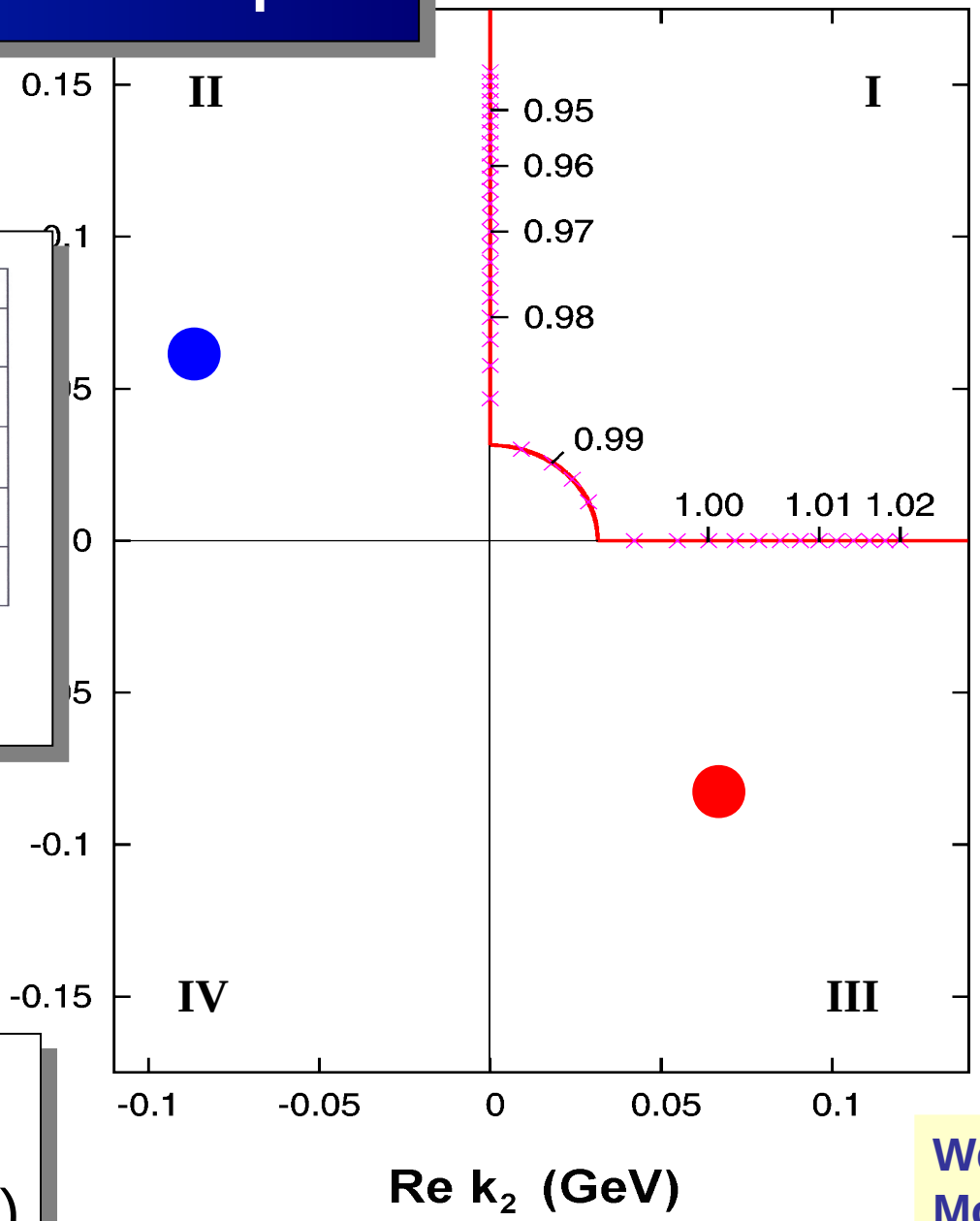
k_2 plane

($\bar{K}K$ c.m. momentum)

Weinberg
Morgan

Jost function: 1 pole v 2 pole



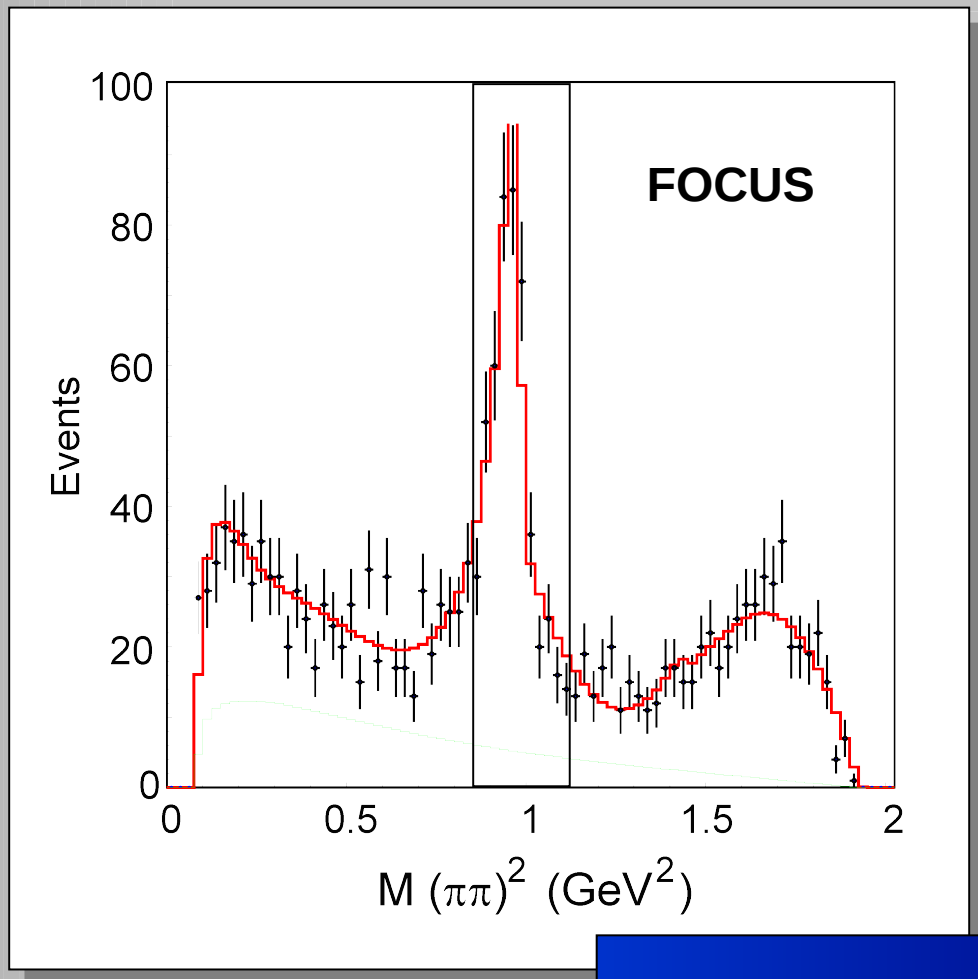


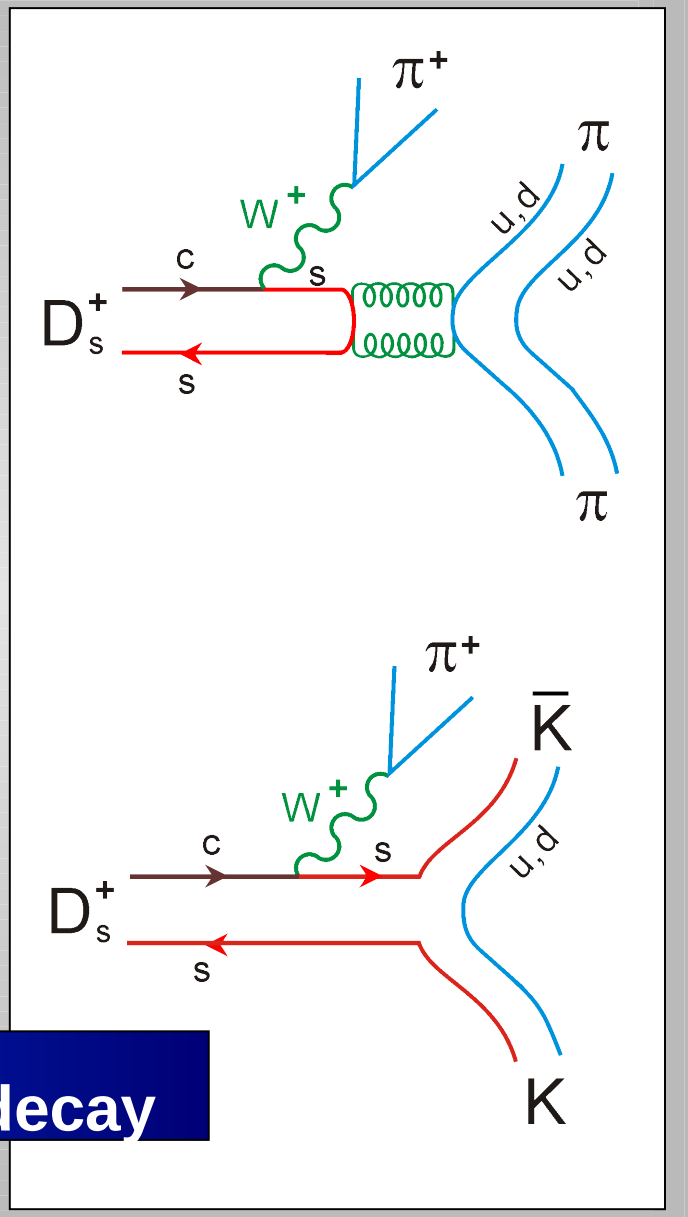
k_2 plane

($K\bar{K}$ c.m. momentum)

Weinberg
Morgan

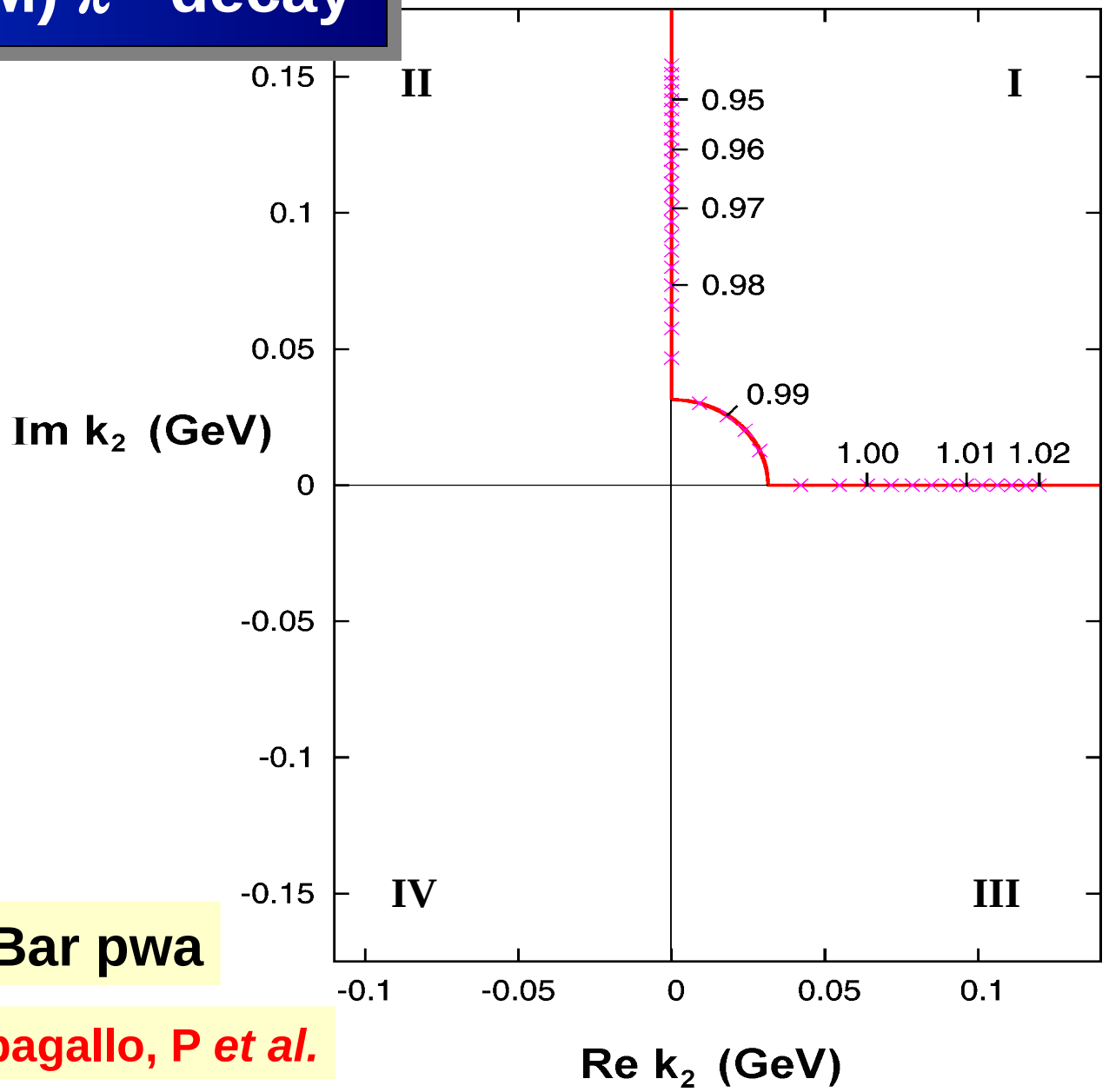
Heavy flavour decays





$D_s \rightarrow (MM)\,\pi$ decay

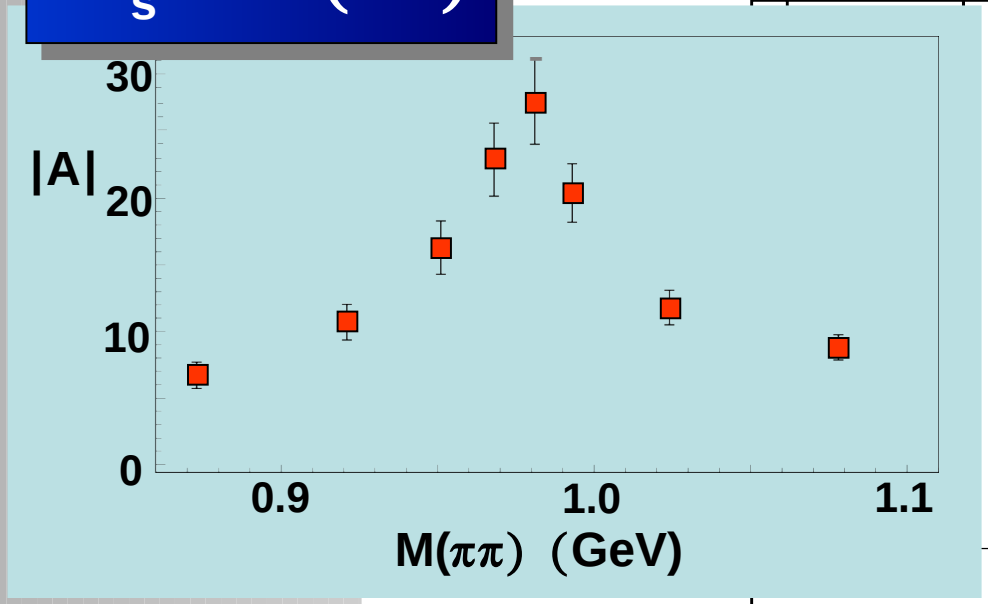
$D_s \rightarrow (MM)\,\pi$ decay

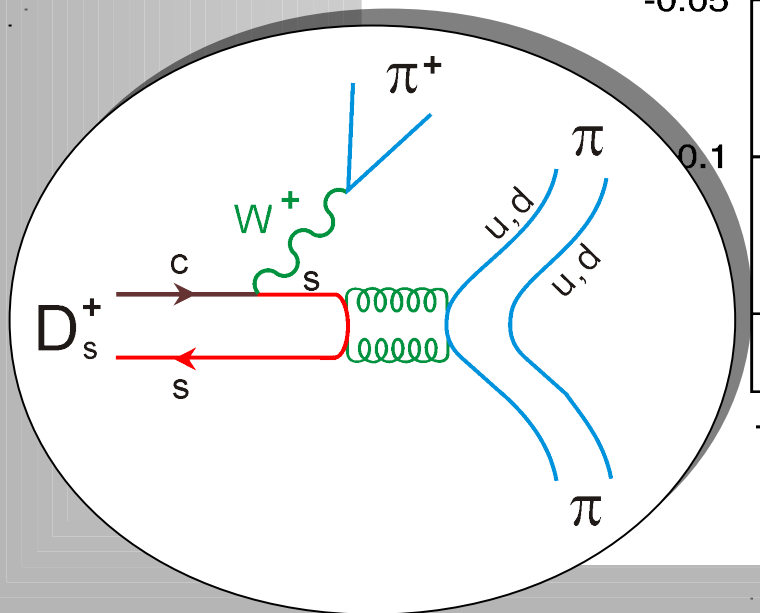


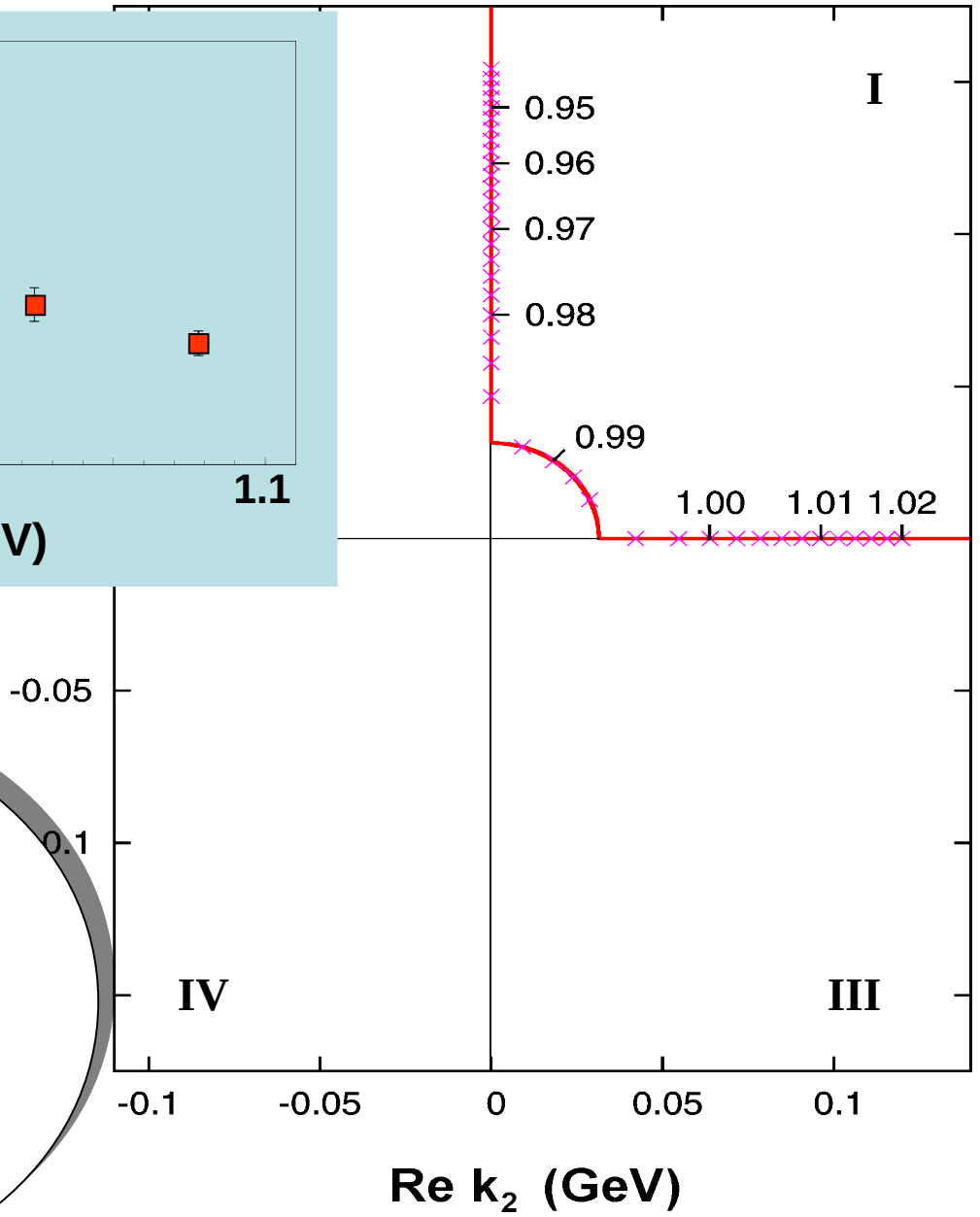
BaBar pwa

Pappagallo, P *et al.*

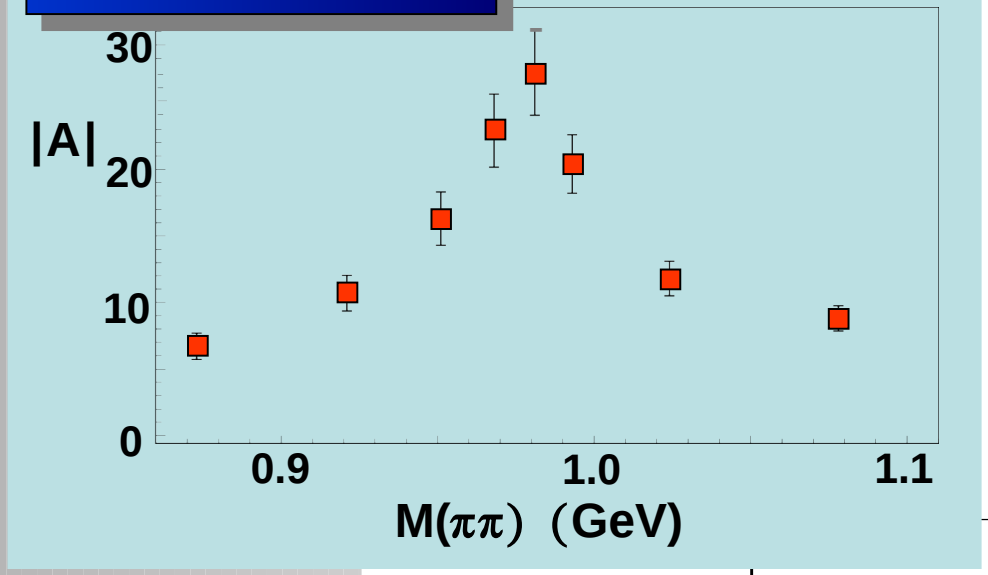
$D_s \to \pi(\pi\pi)$

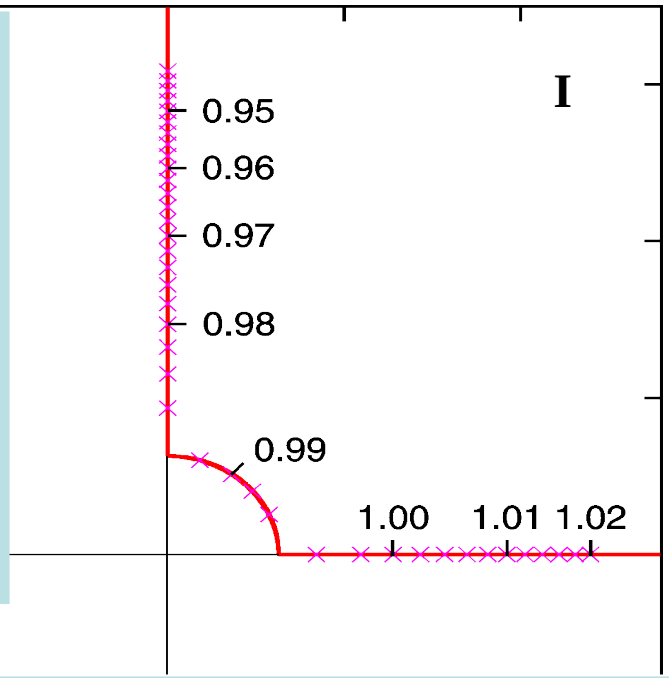

30
20
10
0
|A|
0.9
1.0
1.1
M(ππ) (GeV)

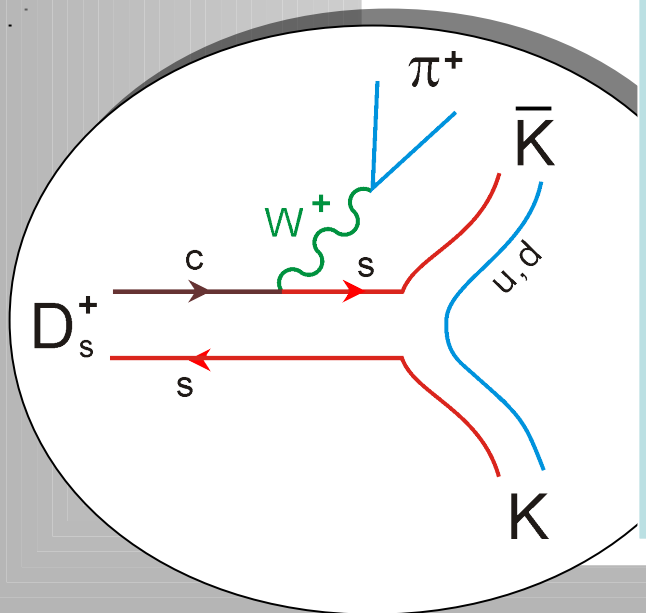

π+
π
W+
c
s
u,d
u,d
D+s
s
π

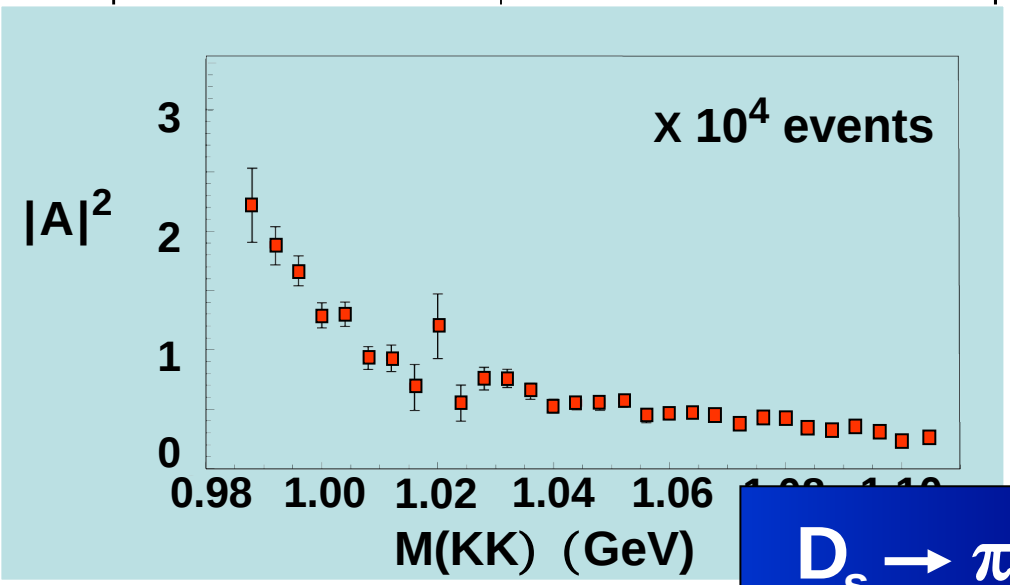

I
IV
III
0.95
0.96
0.97
0.98
0.99
1.00
1.01
1.02
-0.05
0.1
-0.1
-0.05
0
0.05
0.1
Re k2 (GeV)

$D_s \to \pi\,(\pi\pi)$



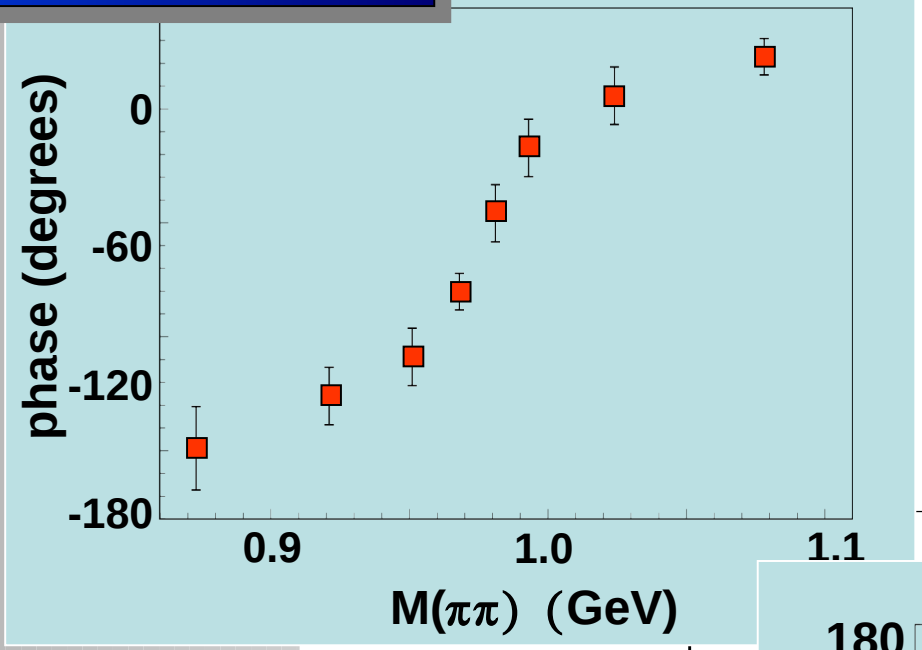


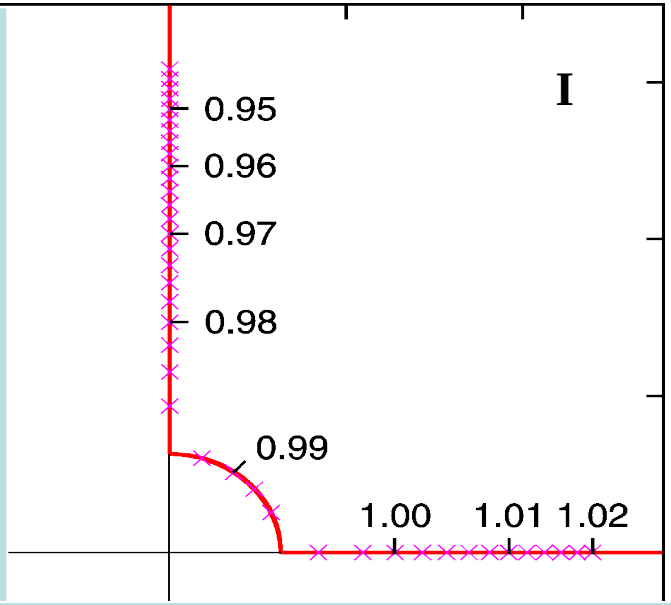


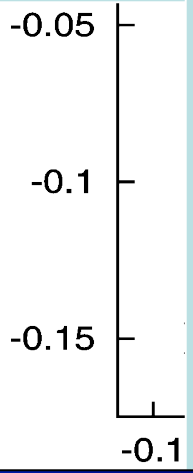


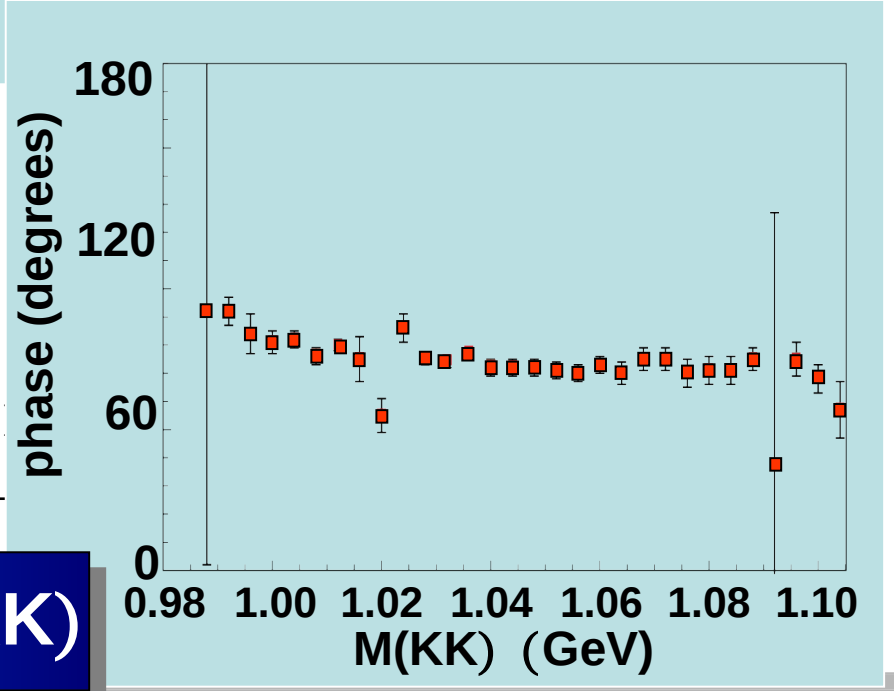
$D_s \to \pi\,(KK)$

$D_s \rightarrow \pi\,(\pi\pi)$



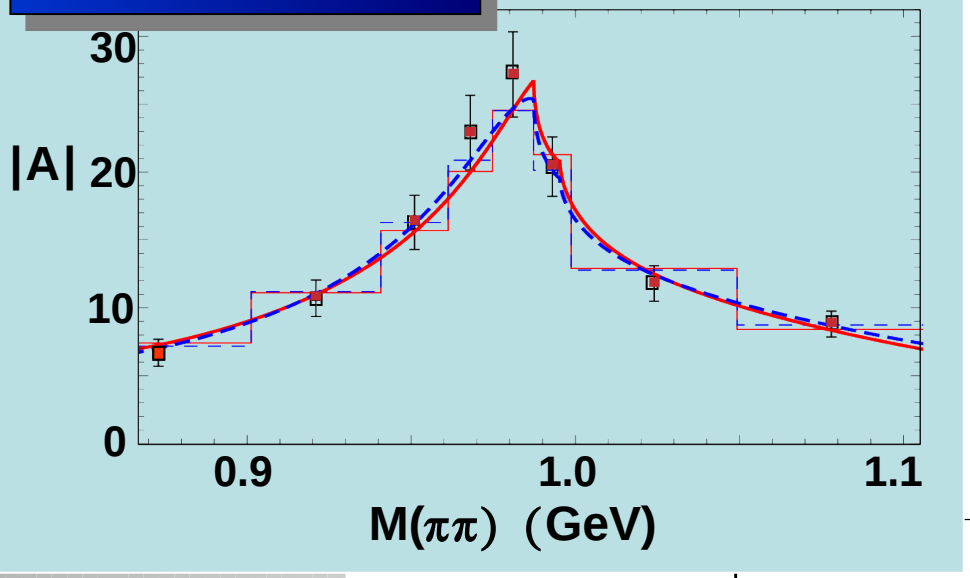


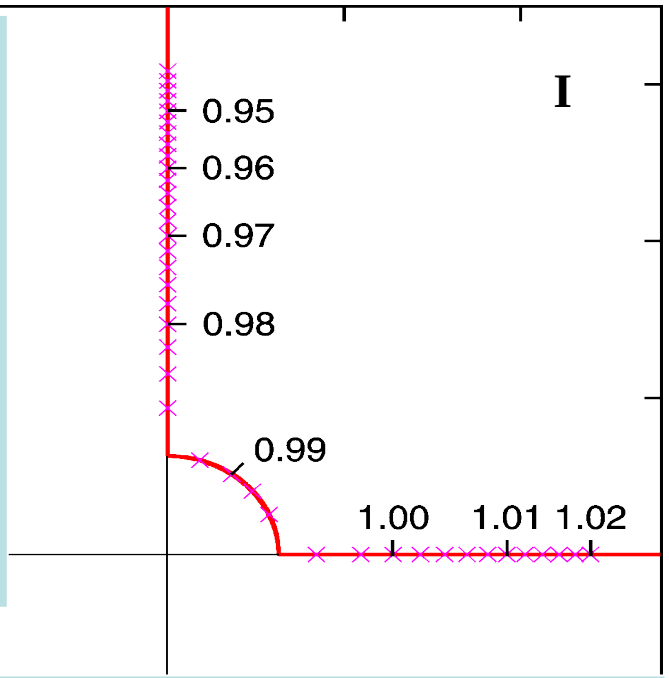


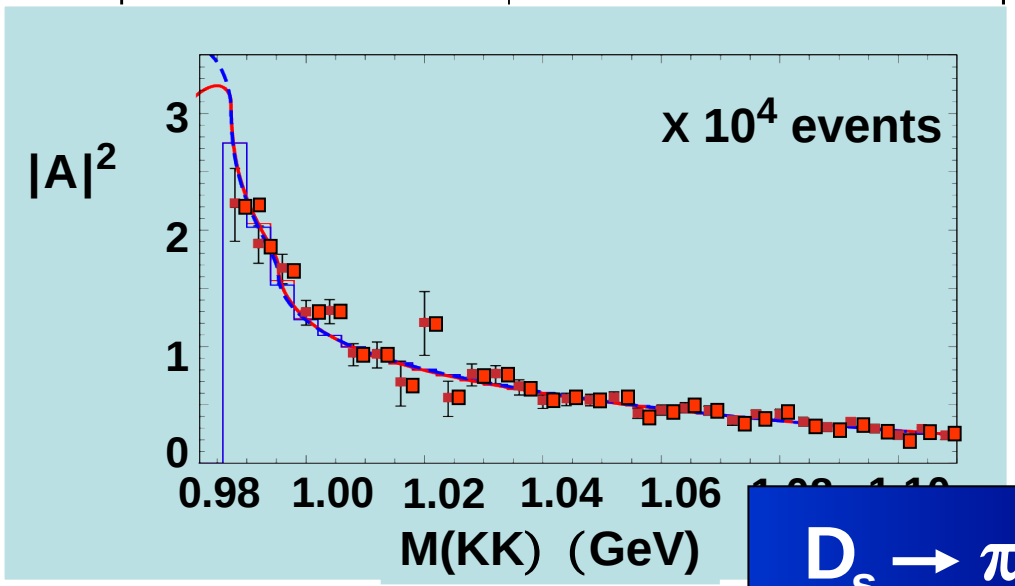


$D_s \rightarrow \pi\,(KK)$

$D_s \rightarrow \pi\,(\pi\pi)$

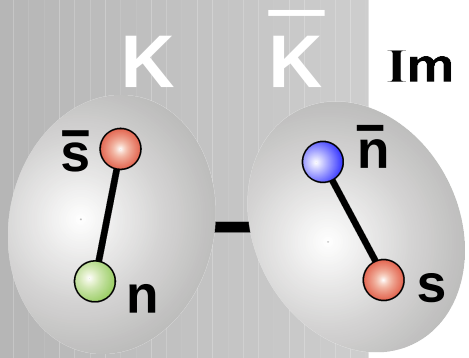


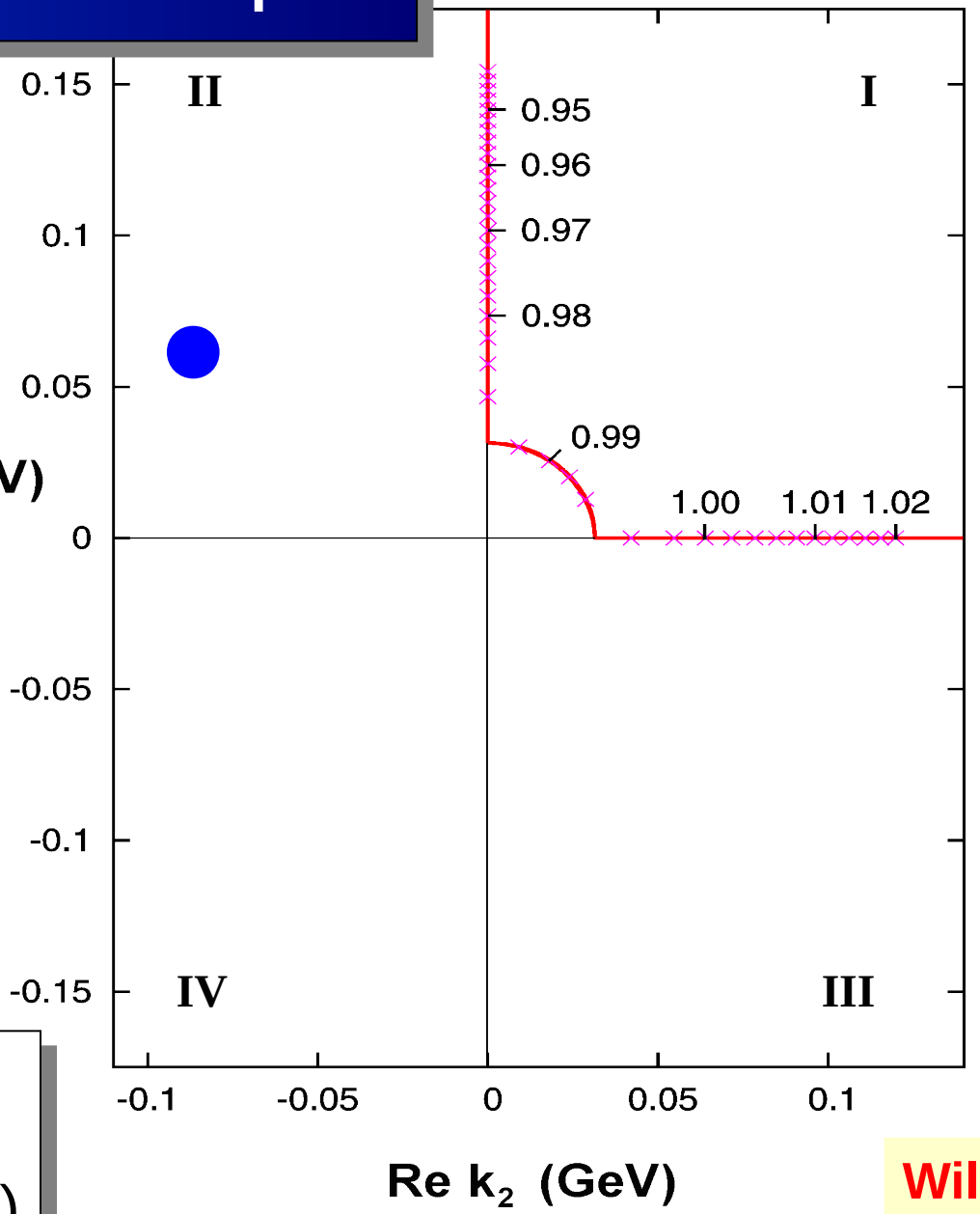




$D_s \rightarrow \pi\,(KK)$

Jost function: 1 pole v 2 pole



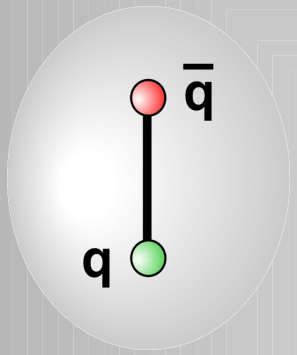


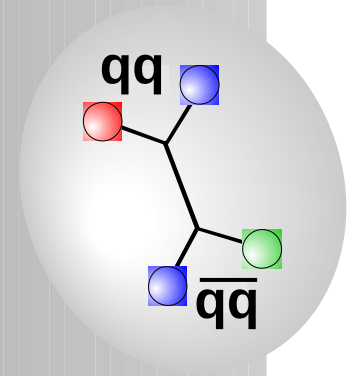
k_2 plane

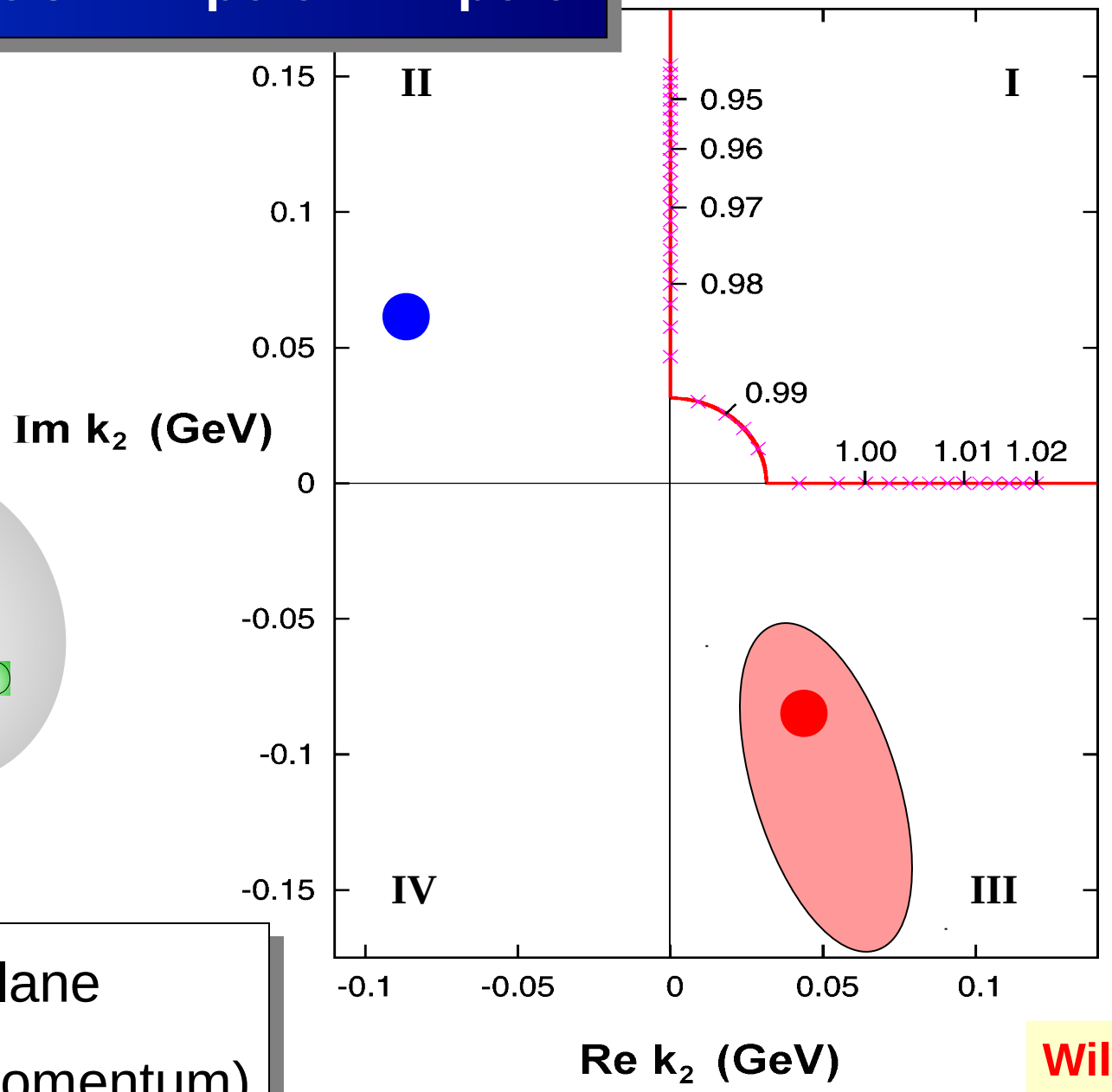
($\bar{K}K$ c.m. momentum)

Wilson & P

Jost function: 1 pole v 2 pole





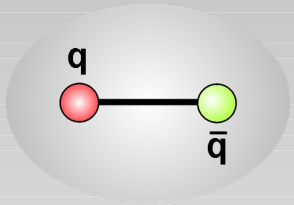


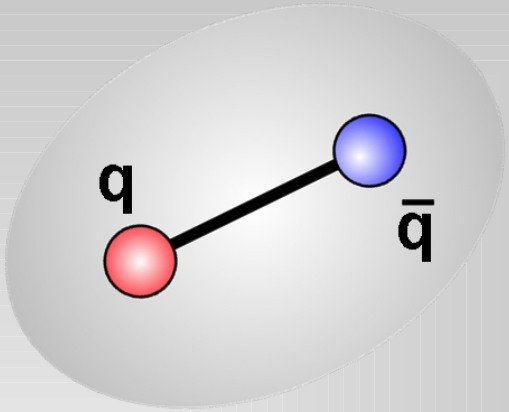
k_2 plane

($\bar{K}K$ c.m. momentum)

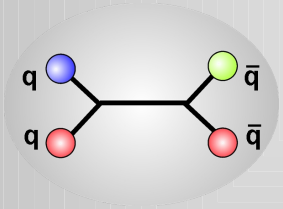
Wilson & P

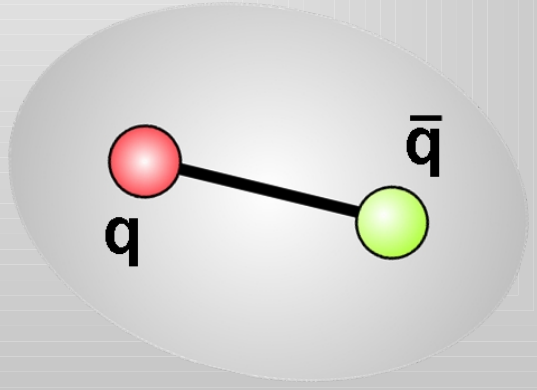
$f_0(980)$





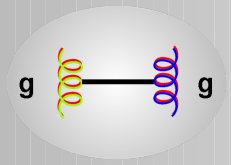
K

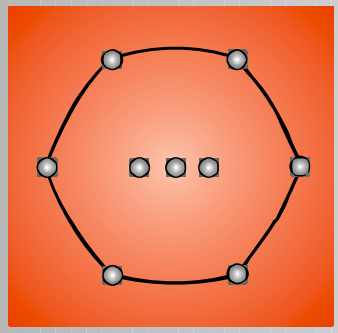


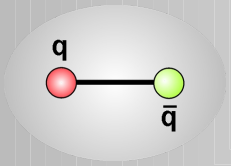


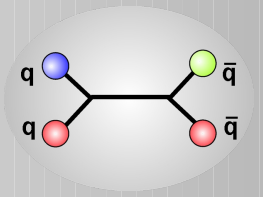
$\bar{K}$

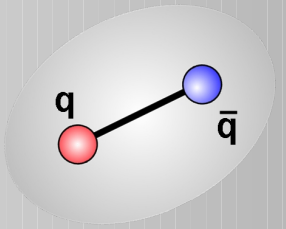
Scalar mesons

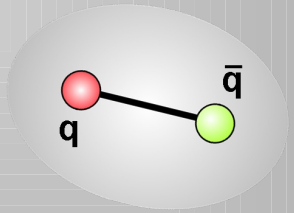


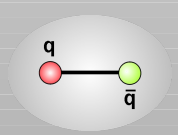


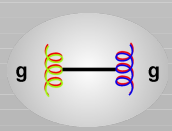












gg — f_0

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

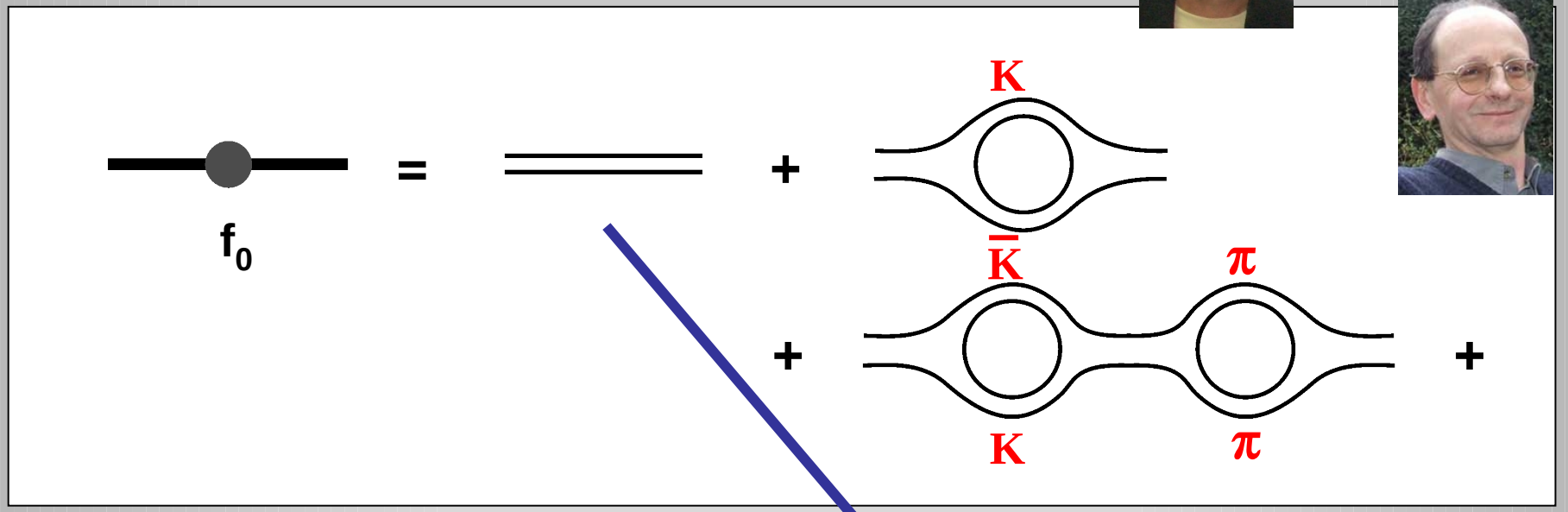
$\bar{s}s\bar{n}n$ — a_0 / f_0

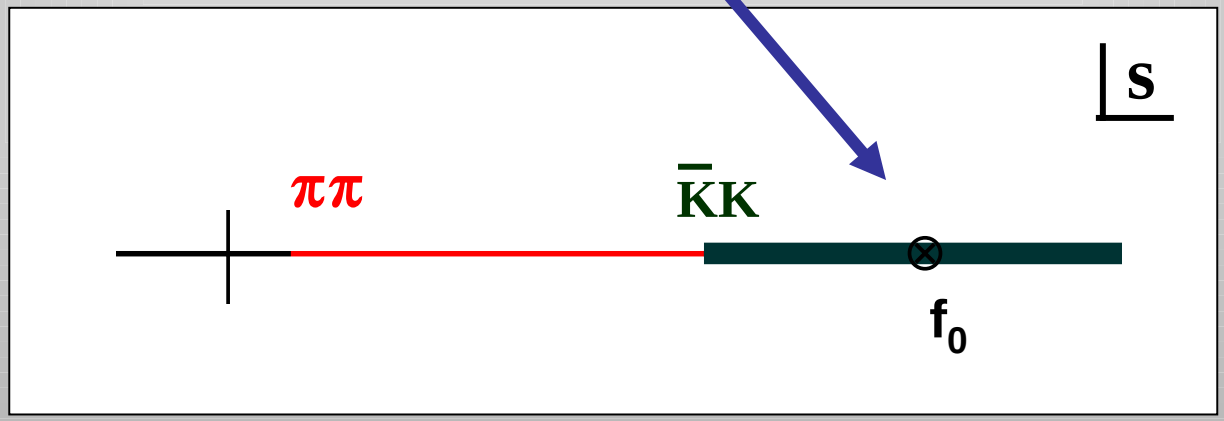
$\bar{s}n\bar{n}n$ — K_0 κ

$\bar{n}n\bar{n}n$ — f_0 σ

Scalar multiplet

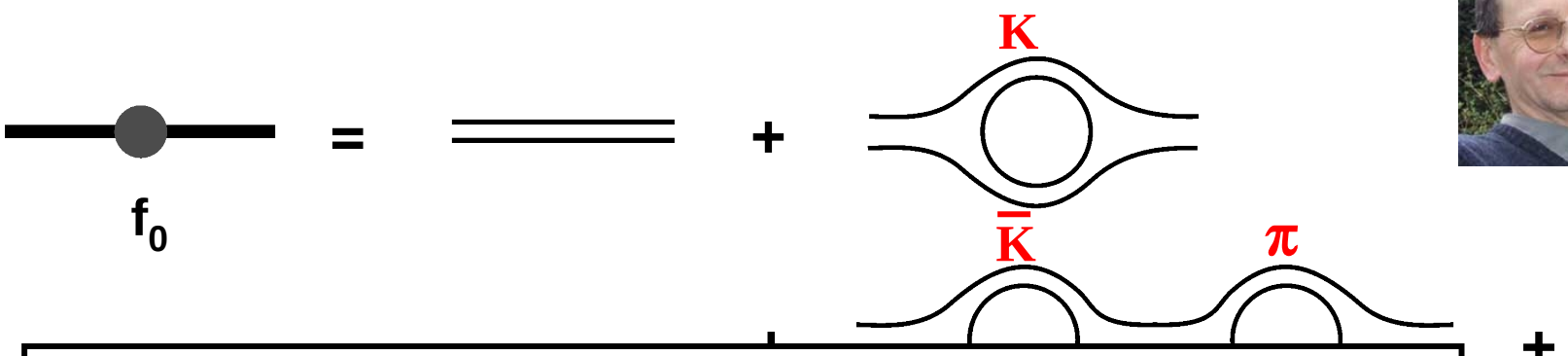
van Beveren
Rupp





Scalar multiplet

van Beveren
Rupp



dyn

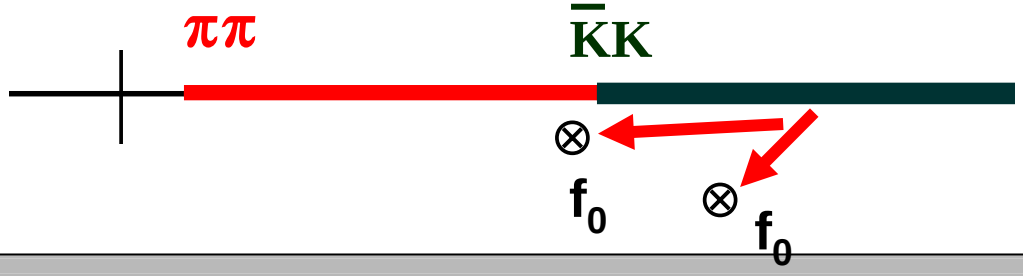
A Low Lying Scalar Meson Nonet in a Unitarized Meson Model

E. van Beveren [1], T.A. Rijken [1], K. Metzger [1], C. Dullemond [1], G. Rupp [2], and J.E. Ribeiro [3]

[1] Institute for Theoretical Physics, University of Nijmegen, NL-6525 ED Nijmegen, The Netherlands
[2] Zentrum für Interdisziplinäre Forschung, Universität Bielefeld, D-4800 Bielefeld 1, Federal Republic of Germany
[3] Centro di Fisica da Materia Condensada, Av. do. Prof. Gama Pinto, 2, P-1699 Lisbon, Portugal

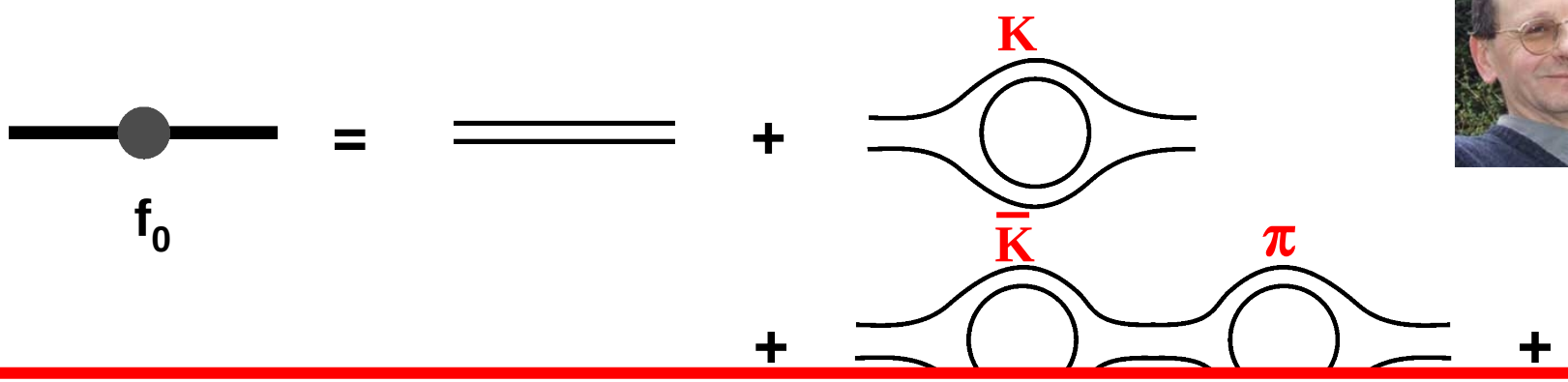
Received 27 August 1985; in revised form 13 December 1985

$\bar{s}s$



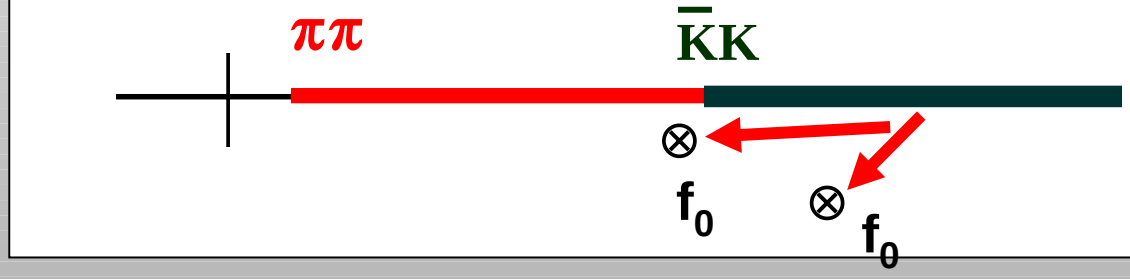
Scalar multiplet

van Beveren
Rupp



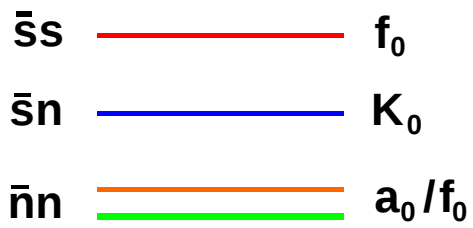
$$\mathcal{L}_{QCD} = \sum_{q=\,u,d,s,\,c,b,t} \bar{\psi}_q \left(i \gamma_\mu D^\mu - m_q \right) \psi_q - \frac{1}{4} \mathcal{F}_{\mu\nu} \mathcal{F}^{\mu\nu}$$

$\bar{s}s$

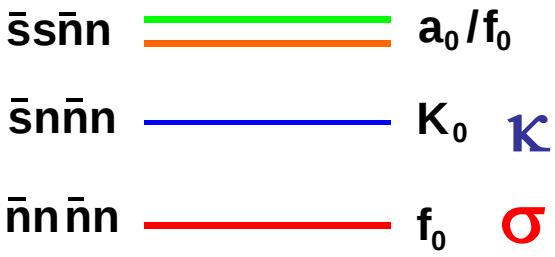


Scalar multiplet

$q\bar{q}$



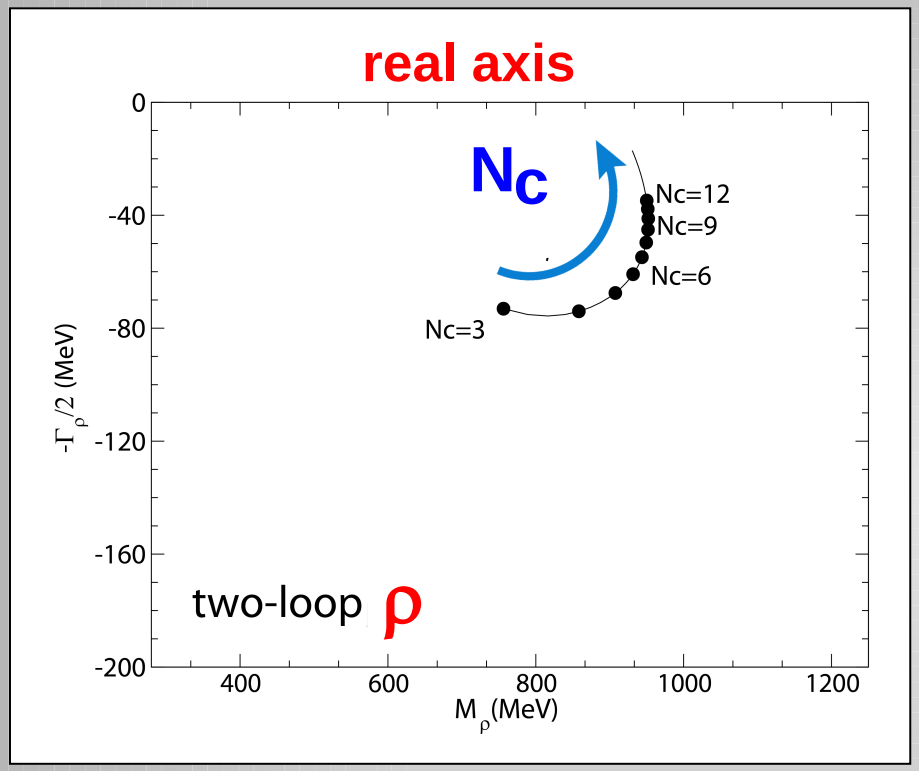
$q\bar{q}q\bar{q}$

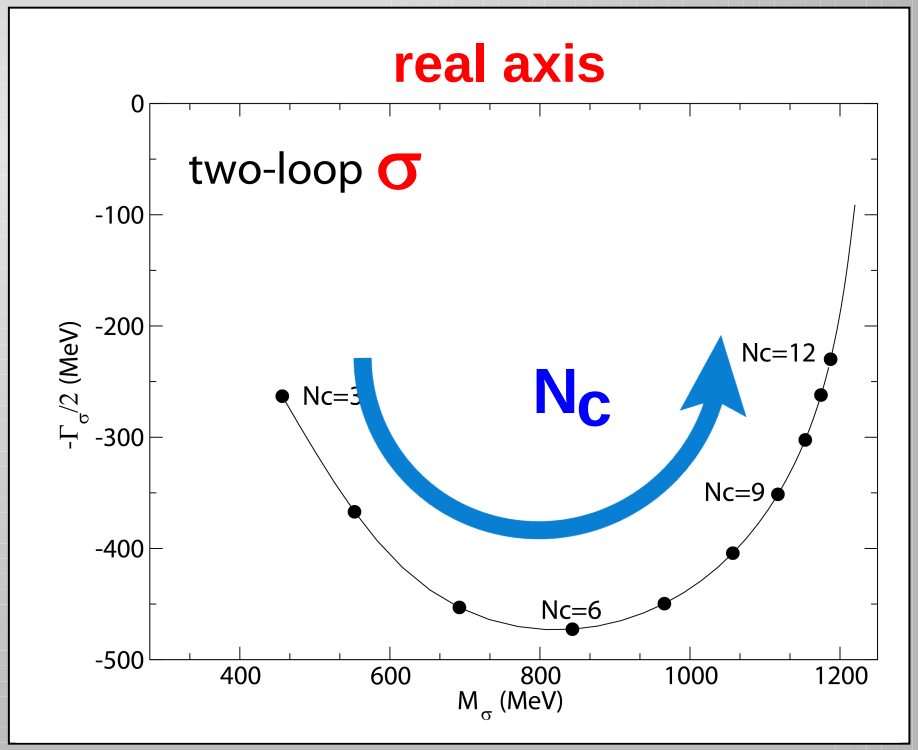


N_c large → stable

N_c large → meson continuum

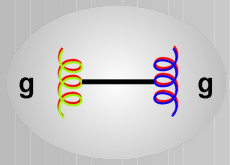
1 / N_c @ two loops

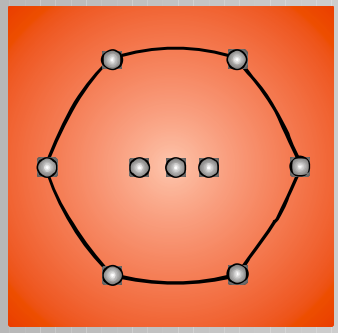


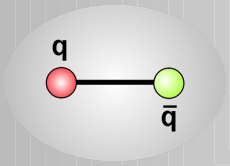


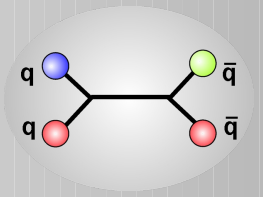
Pelaez, Ruiz de Elvira, Wilson & P

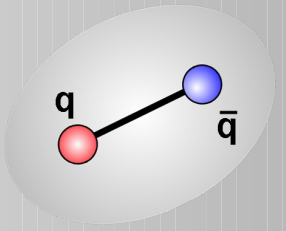
Scalar mesons

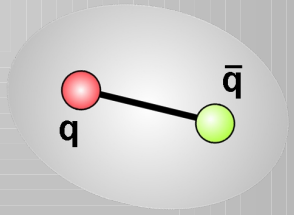


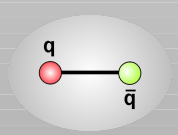


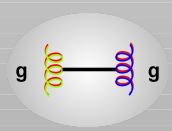












gg — f_0

$\bar{s}s$ — f_0

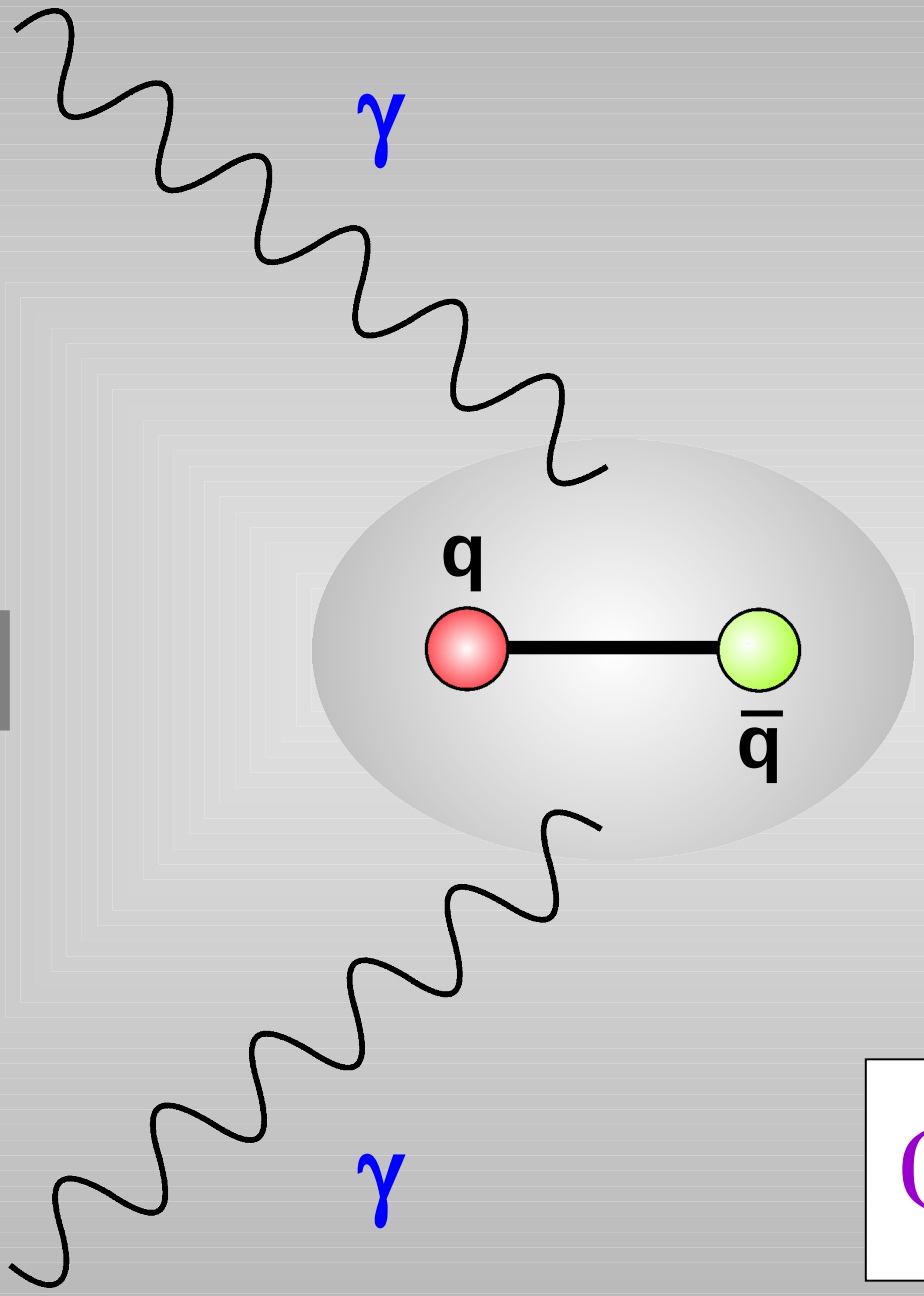
$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

$\bar{s}s\bar{n}n$ — a_0 / f_0

$\bar{s}n\bar{n}n$ — K_0 κ

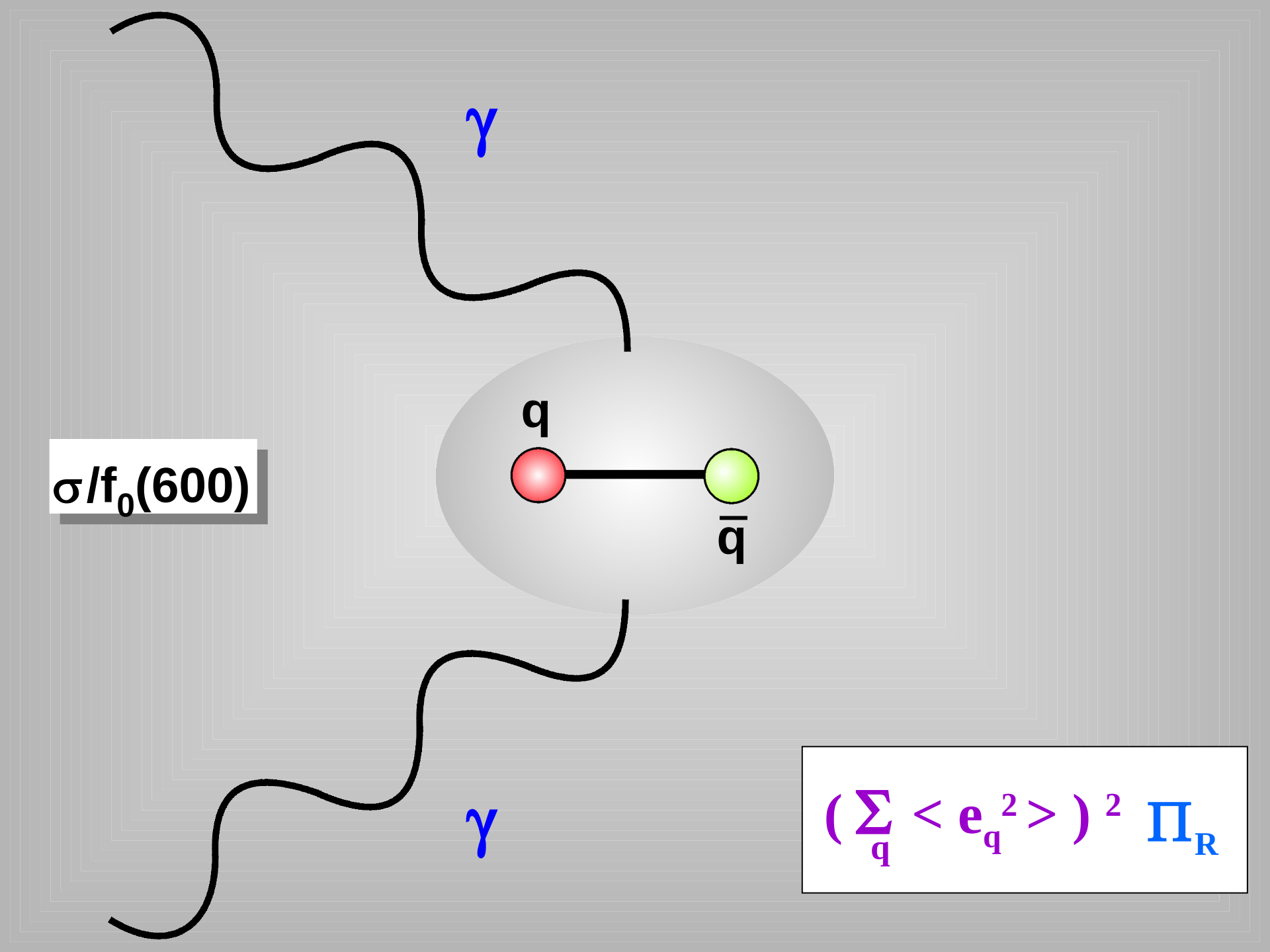
$\bar{n}n\bar{n}n$ — f_0 σ

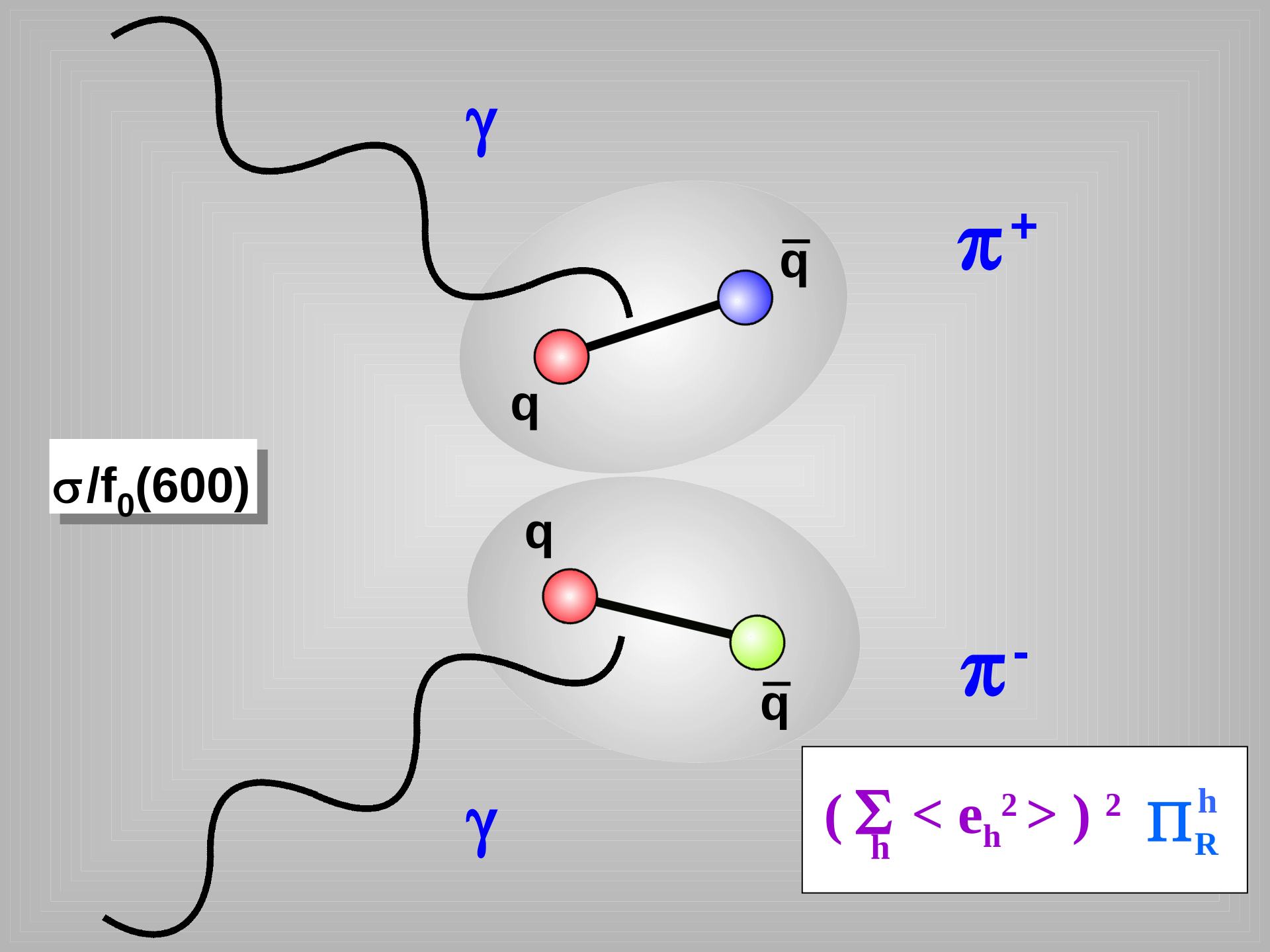


$q\bar{q}$

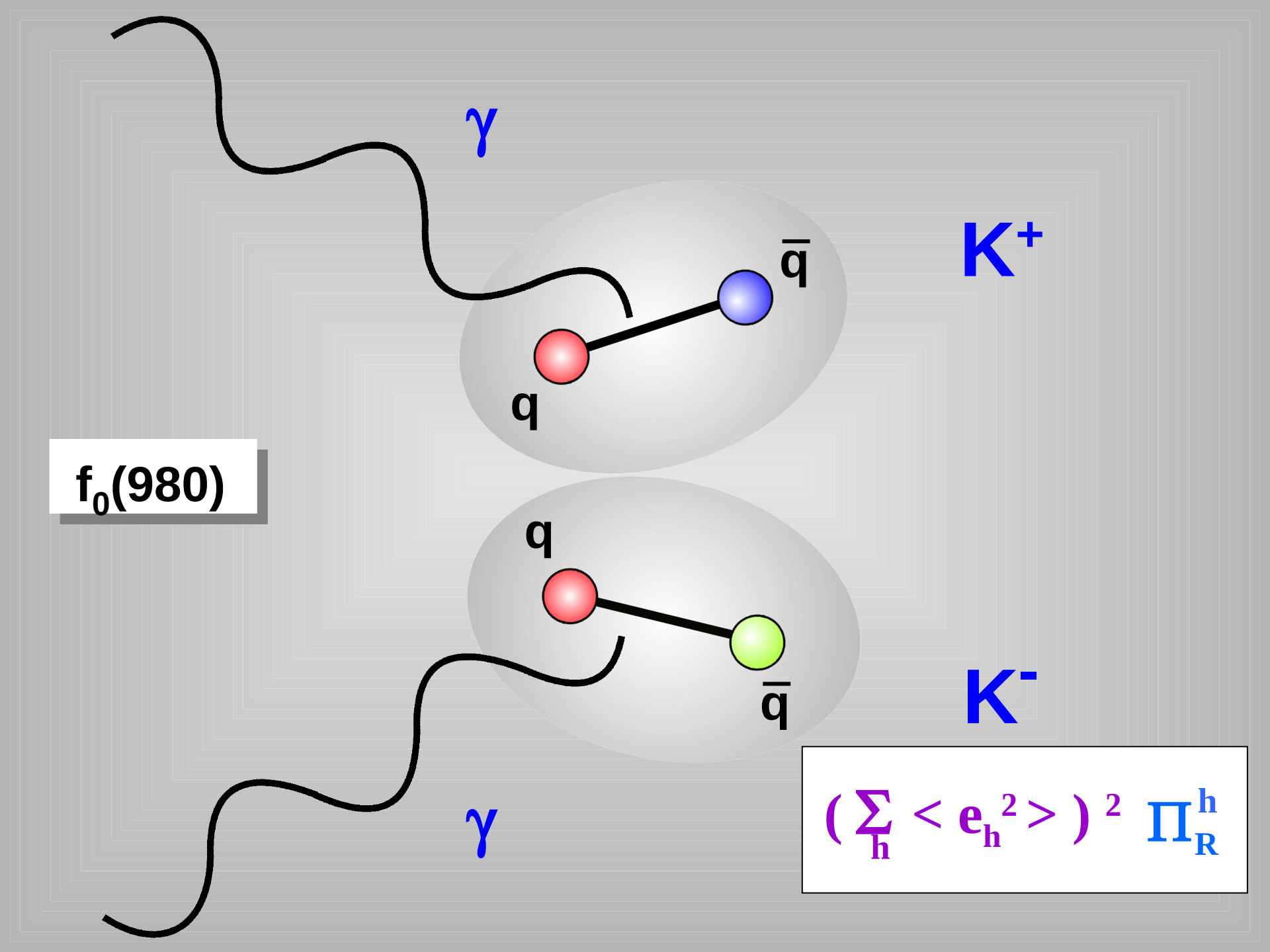
$|\Psi(0)|^2$

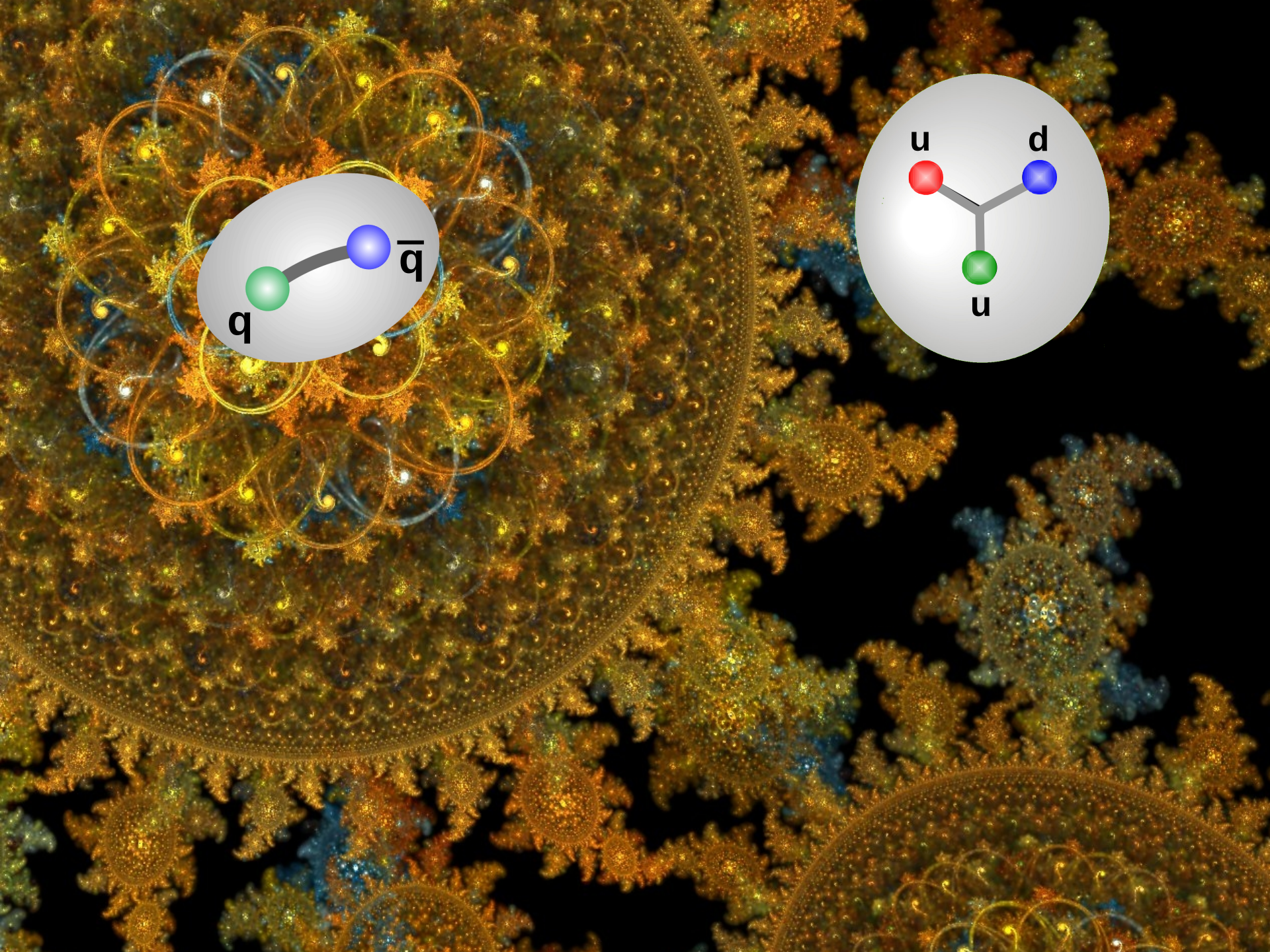
$$\left(\sum_q \langle e_q^2 \rangle\right)^2 \Pi_R$$

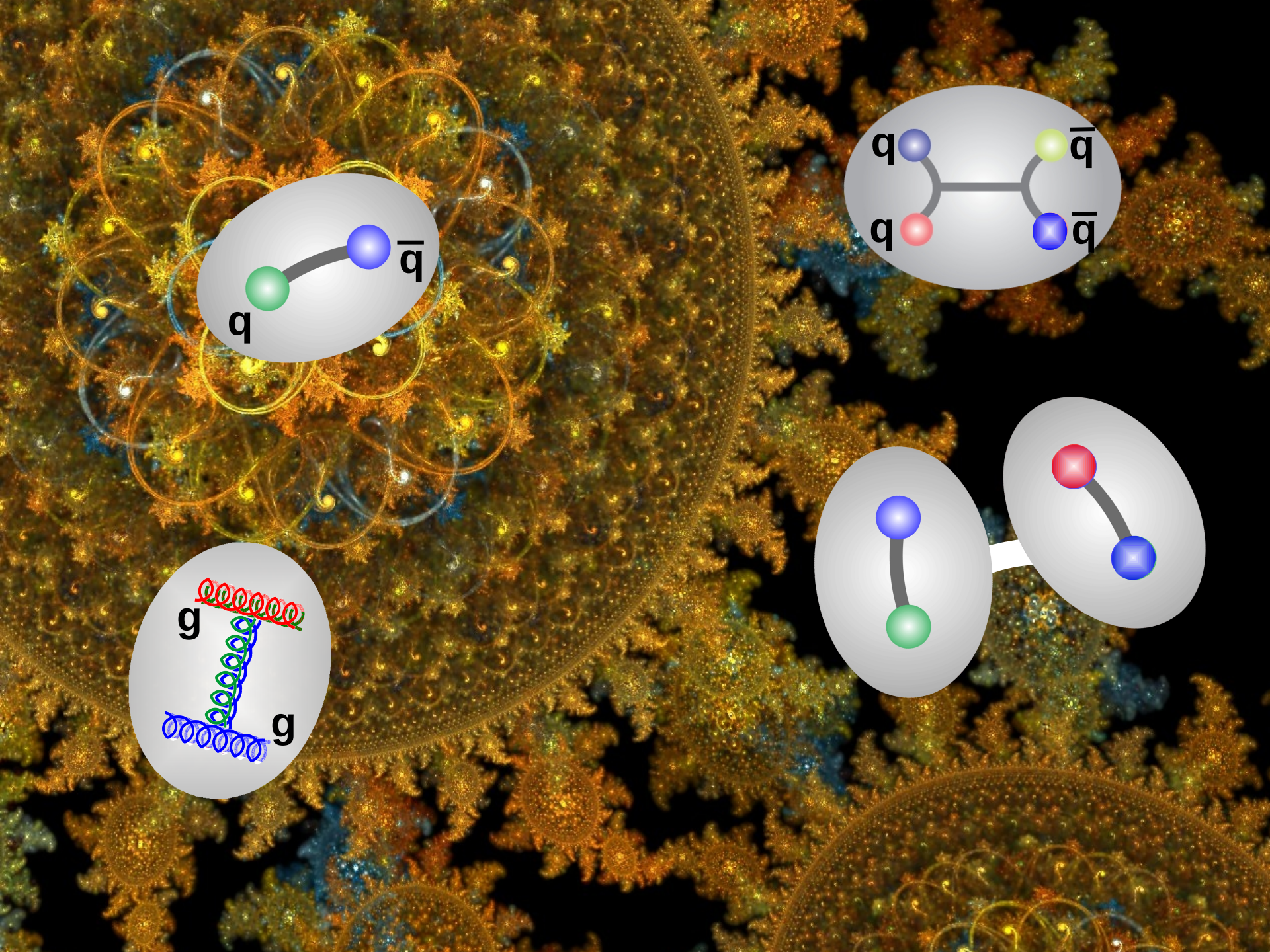

γ
σ/f0(600)
q
q̄
γ
(Σ_q <e_q^2>)^2 Π_R

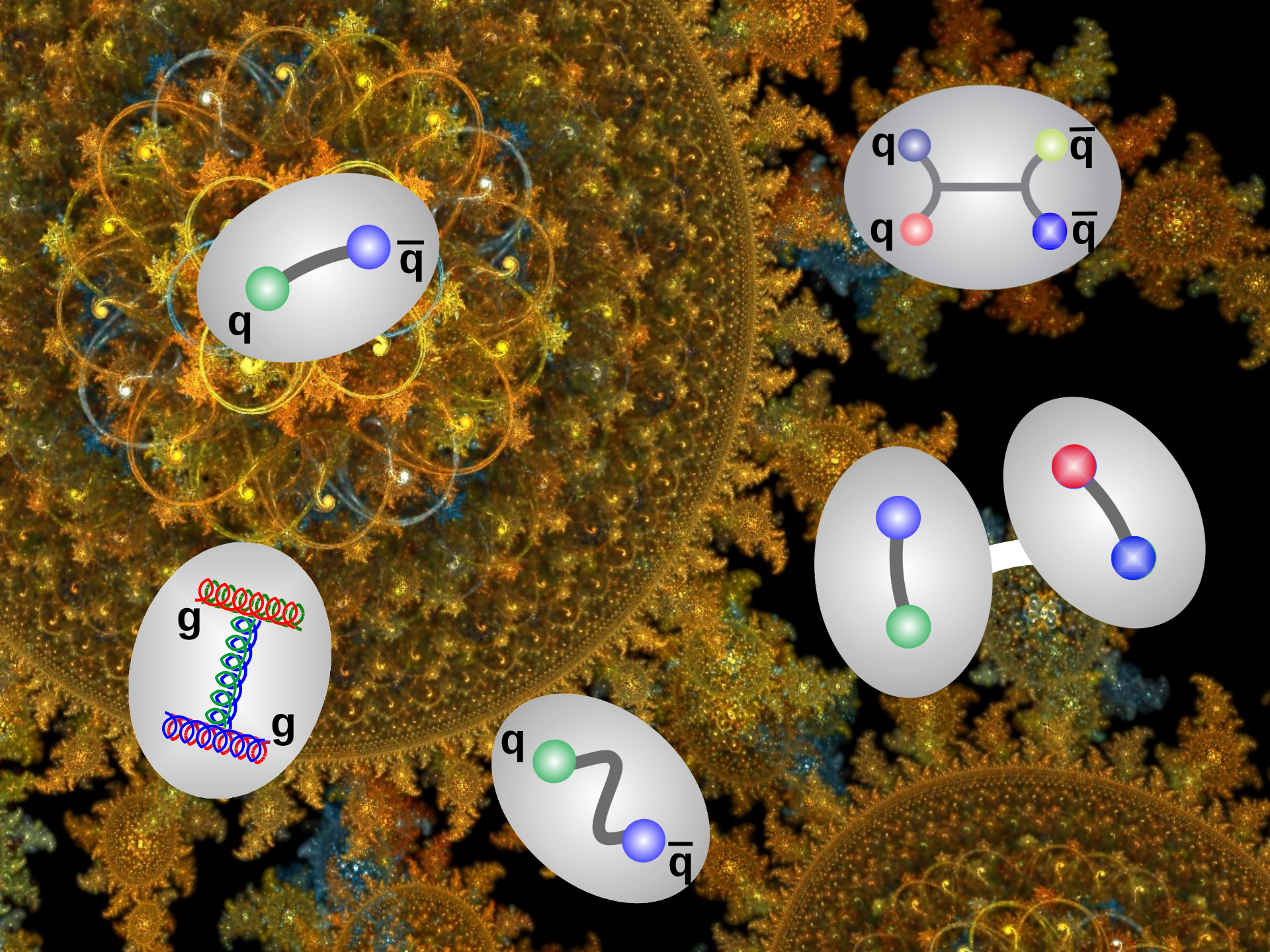


$$\left(\sum_h \langle e_h^2 \rangle\right)^2 \Pi_R^h$$


γ
$\bar{q}$
K^+
q
$f_0(980)$
q
$\bar{q}$
K^-
γ
$\left(\sum_h \langle e_h^2 \rangle\right)^2 \Pi_R^h$


q
$\overline{q}$
u
d
u


q
$\bar{q}$
q
$\bar{q}$
q
$\bar{q}$
g
g

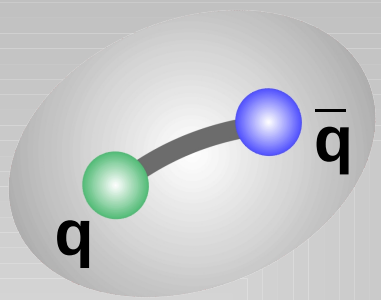

q
q̄
q
q̄
q
q̄
g
g
q
q̄

meson spectrum

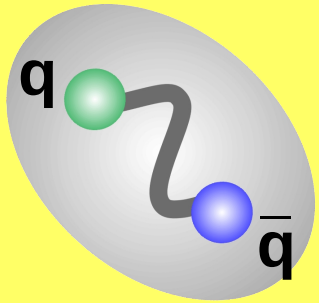
allowed J^{PC}

0^{--}	0^{-+}	0^{+-}	0^{++}
1^{--}	1^{-+}	1^{+-}	1^{++}
2^{--}	2^{-+}	2^{+-}	2^{++}
3^{--}	3^{-+}	3^{+-}	3^{++}
4^{--}	4^{-+}	4^{+-}	4^{++}

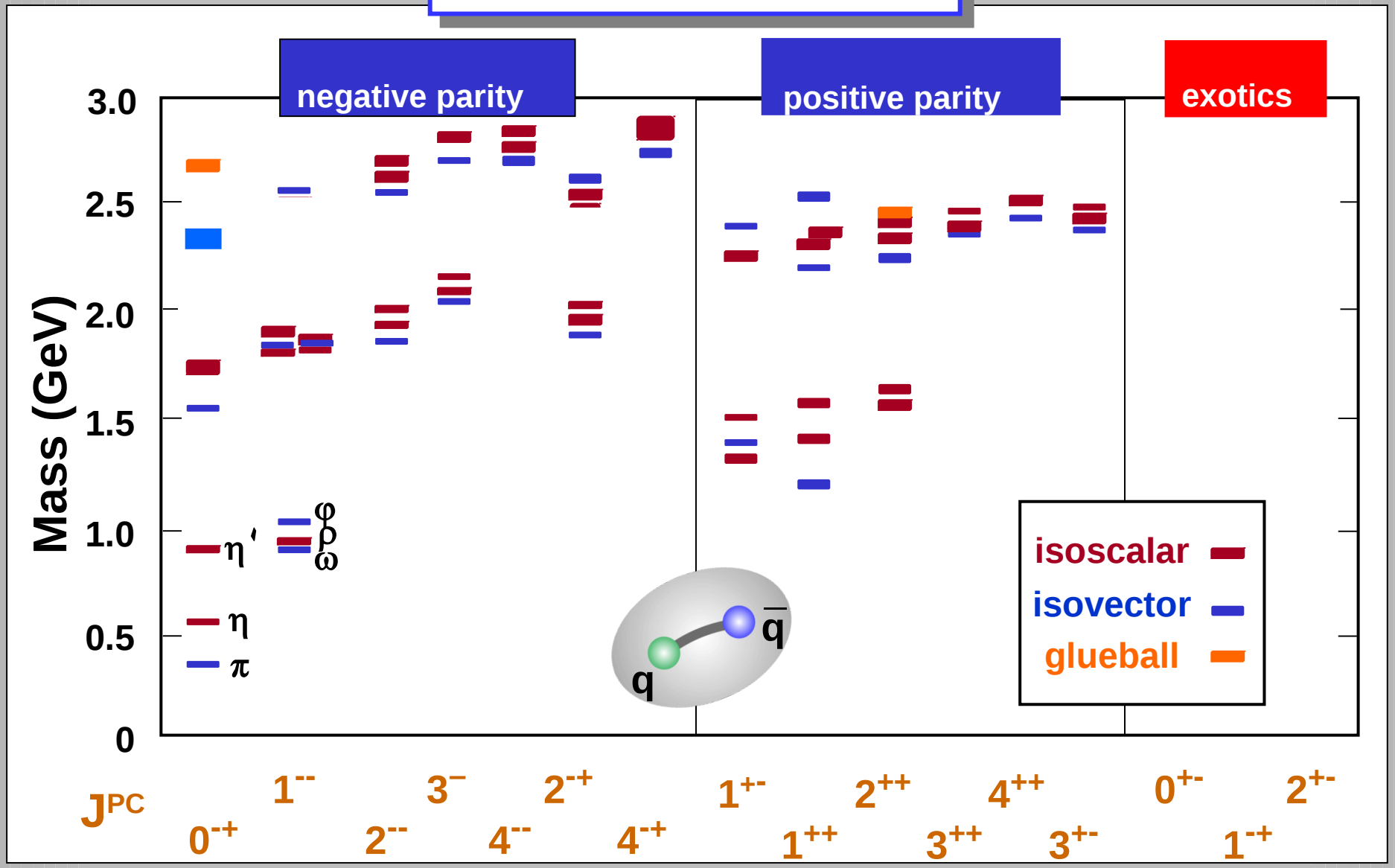
. . .



$J^{PC} \rightarrow$ not $\bar{q}q$



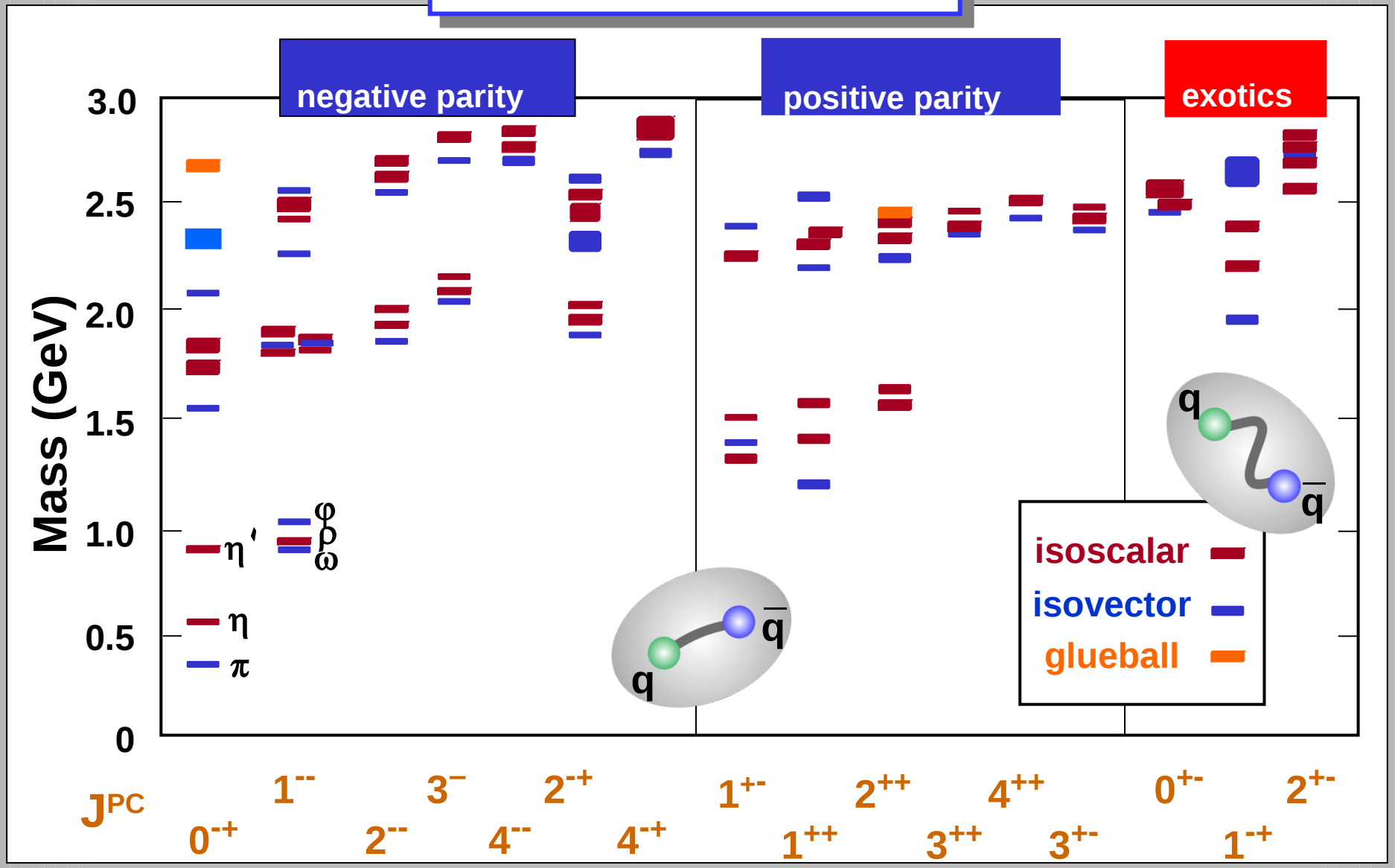
Meson spectrum



Dudek *et al*

m_π = 396 MeV

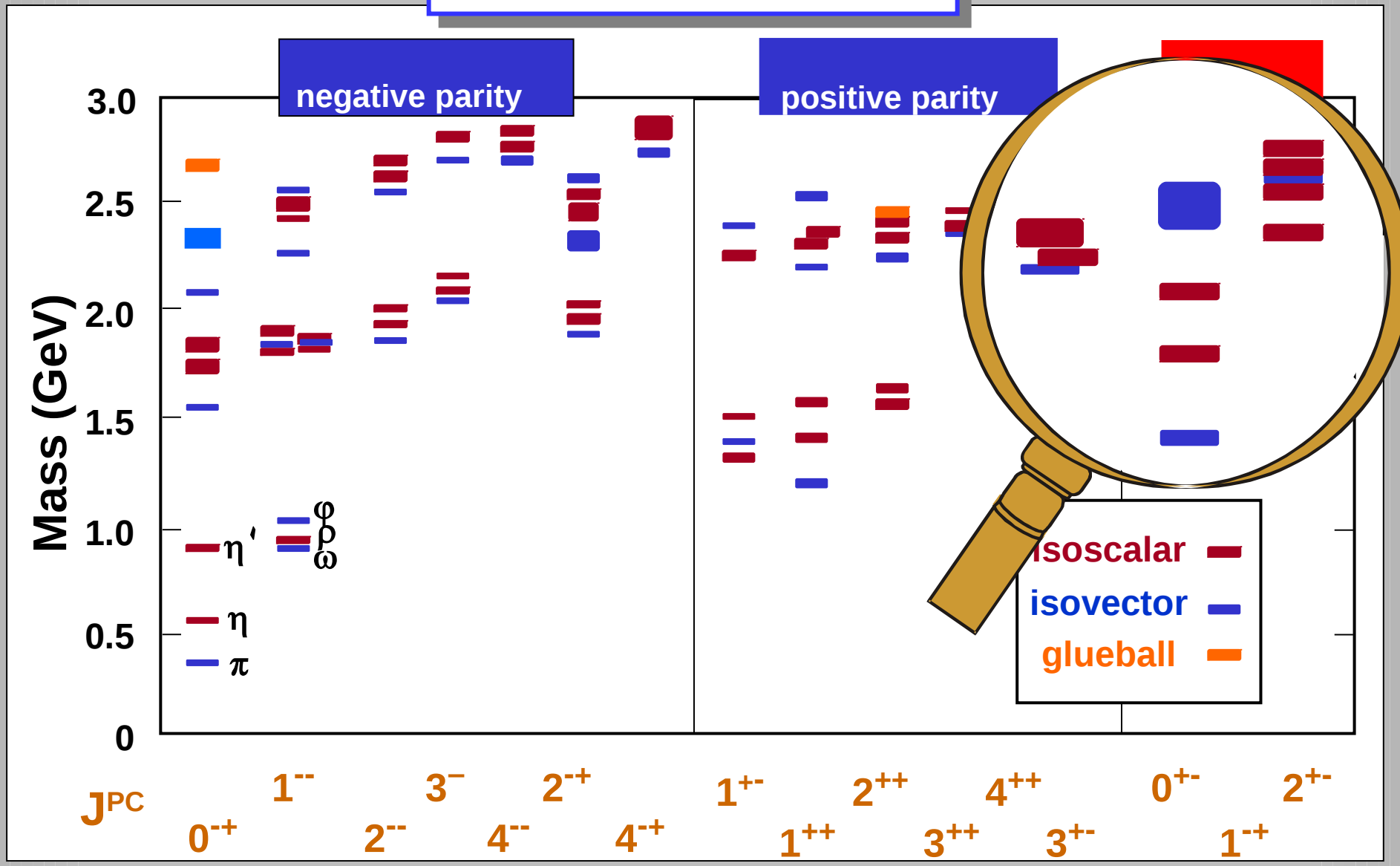
Meson spectrum



Dudek *et al*

m_π = 396 MeV

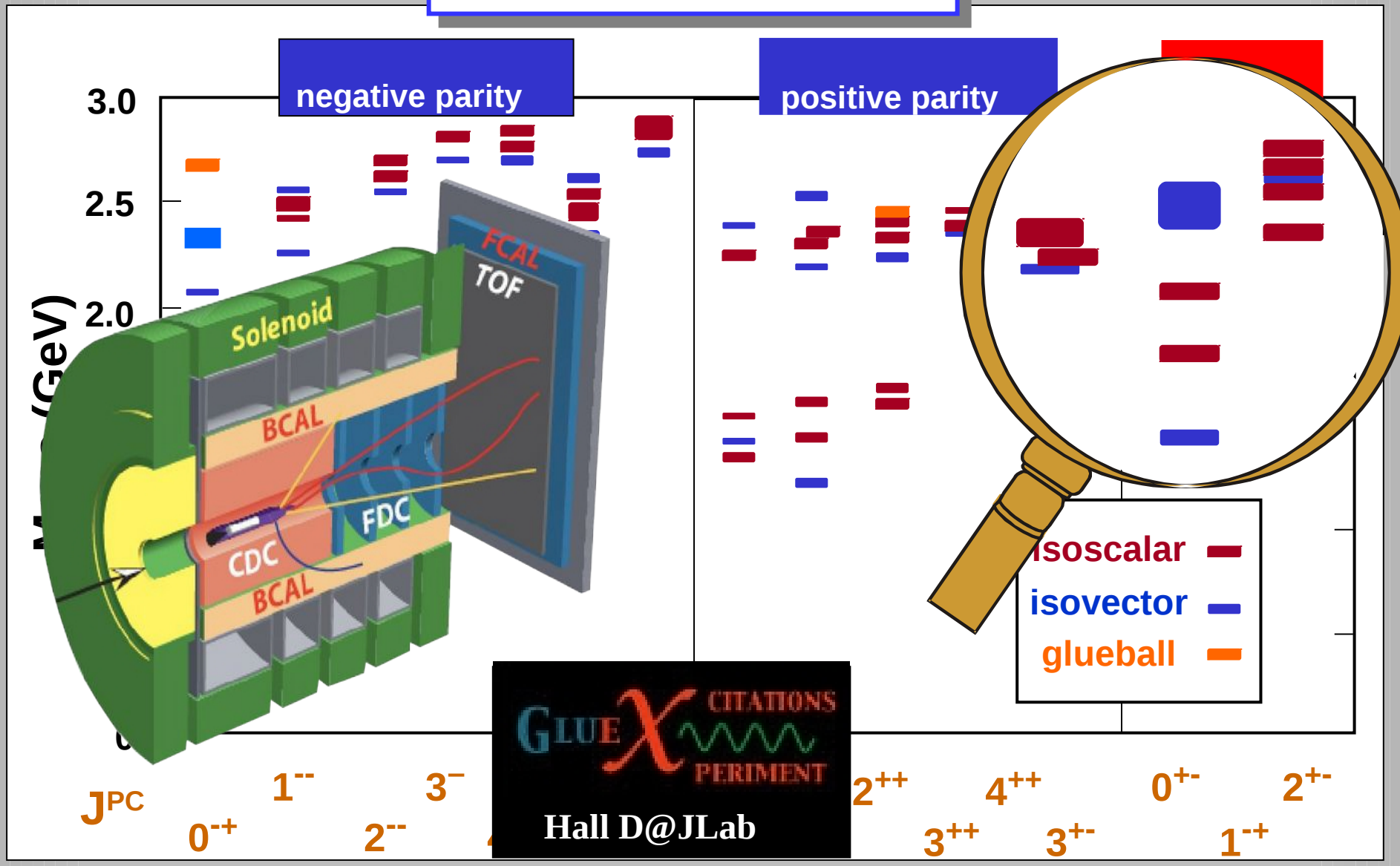
Meson spectrum



Dudek *et al*

m_π = 396 MeV

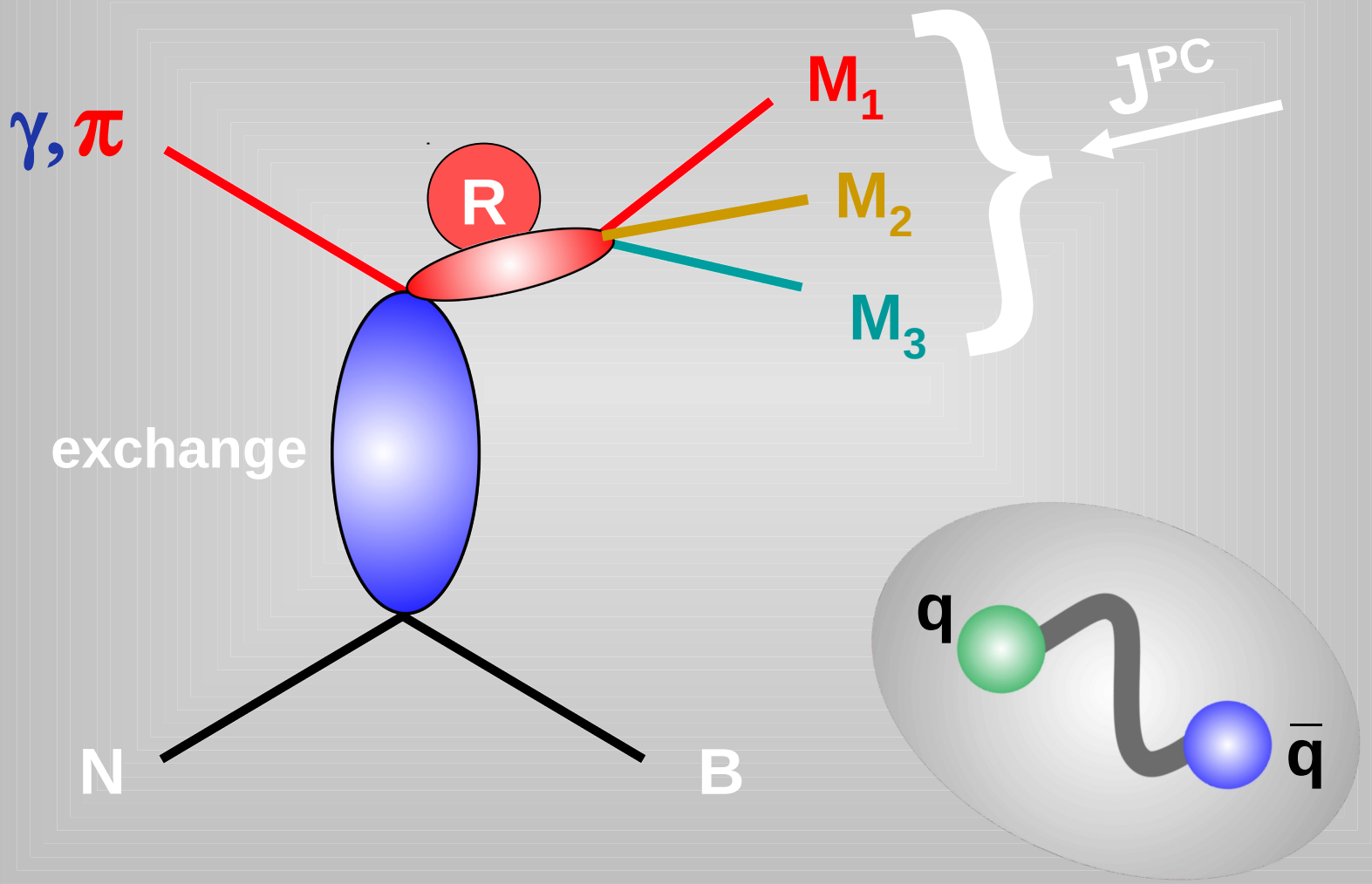
Meson spectrum



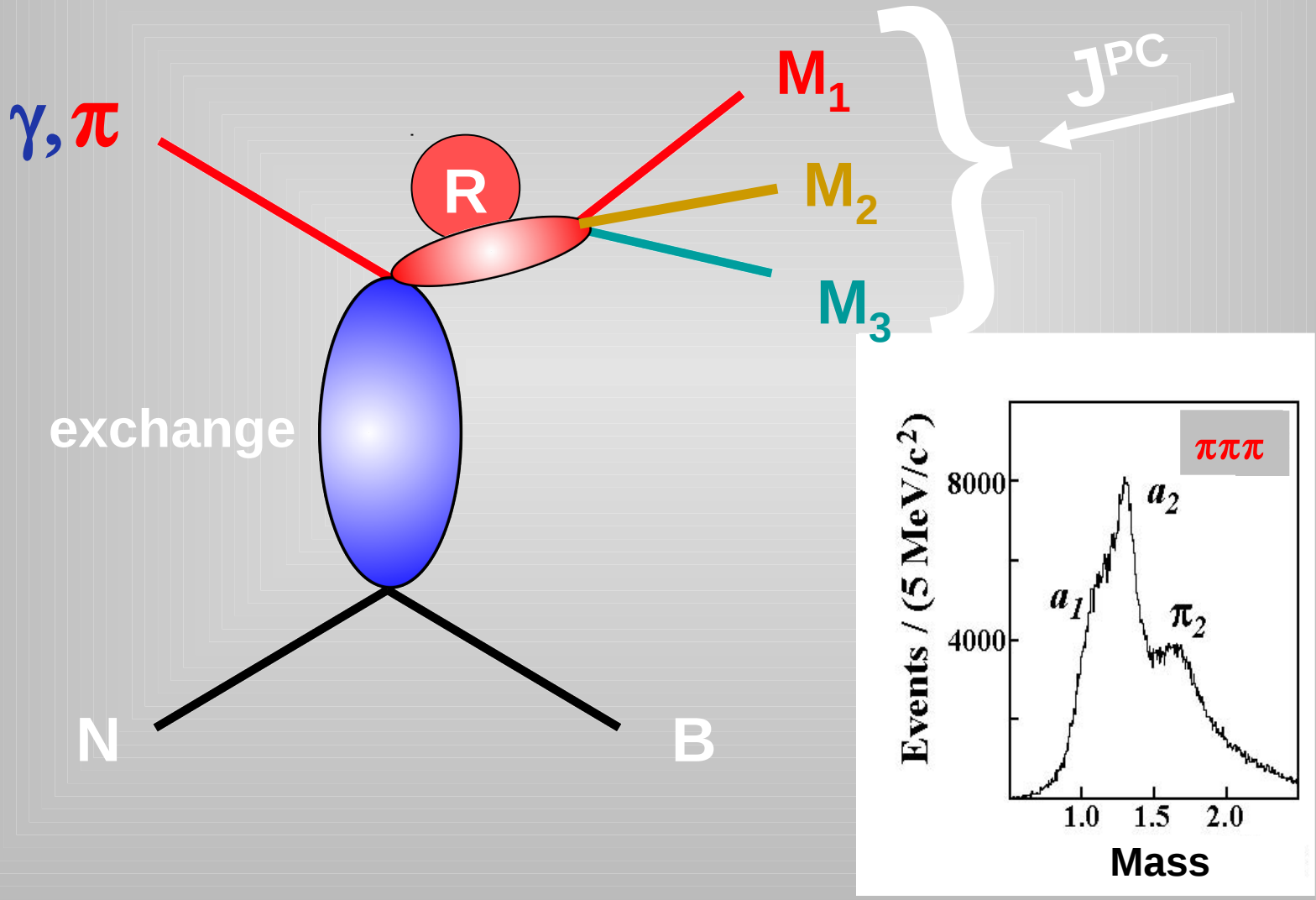
Dudek *et al*

m_π = 396 MeV

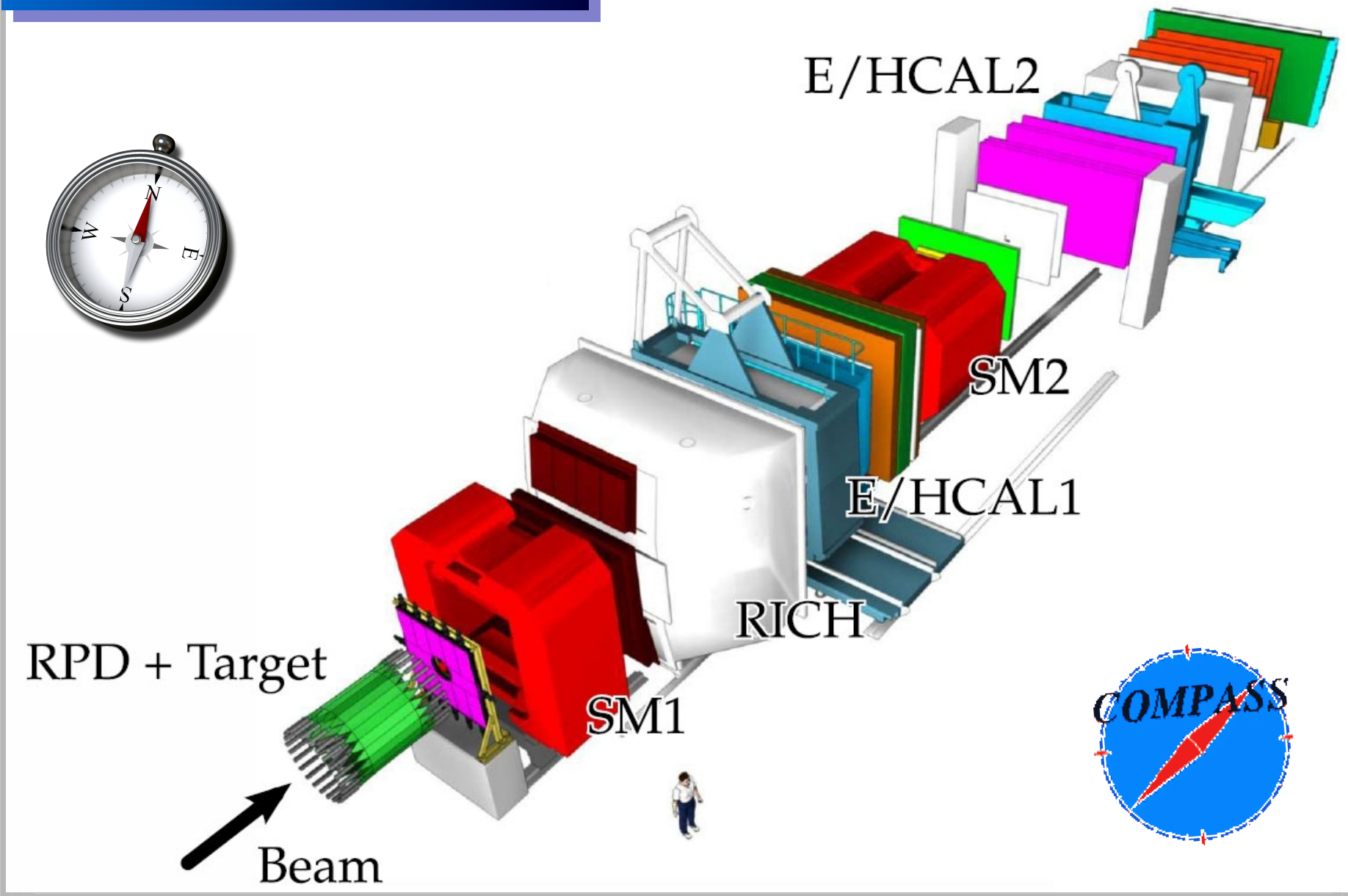
Amplitude Analysis



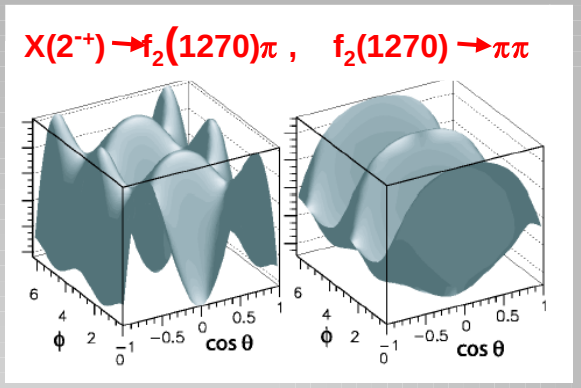
Amplitude Analysis

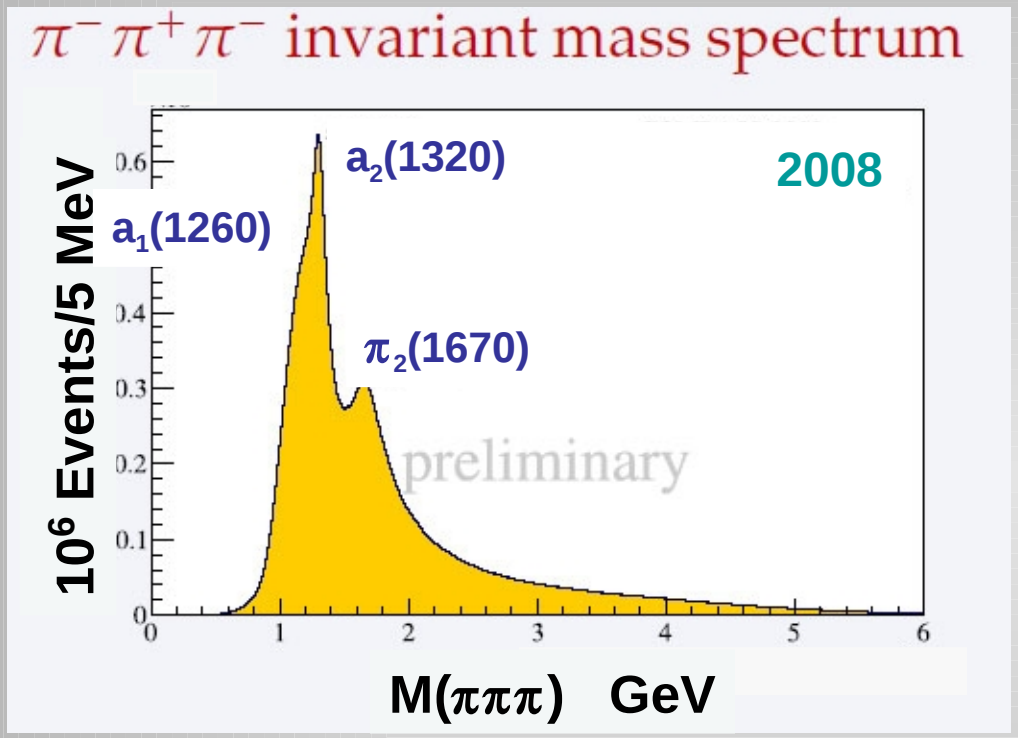


COMPASS @ CERN



COMPASS @ CERN

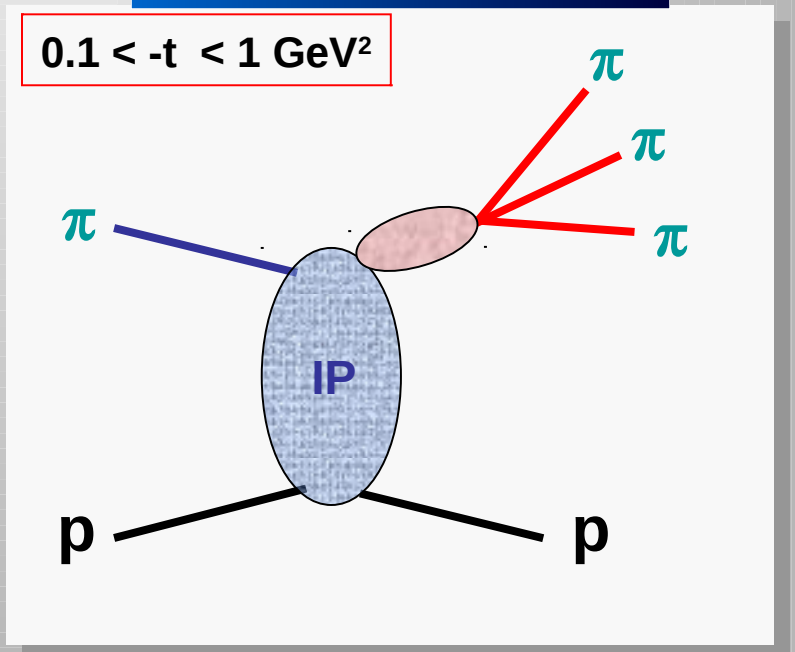




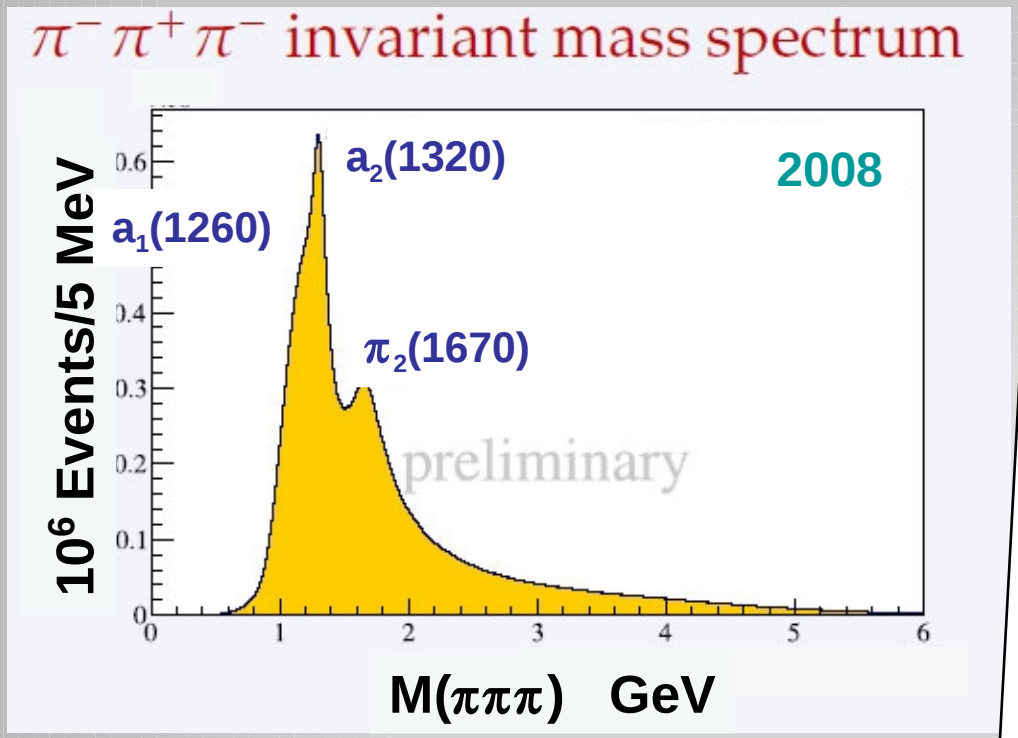
192 GeV beam 96M 3π events

PWA: 52 waves

$\pi^- p \longrightarrow \pi^-\pi^+\pi^- p$



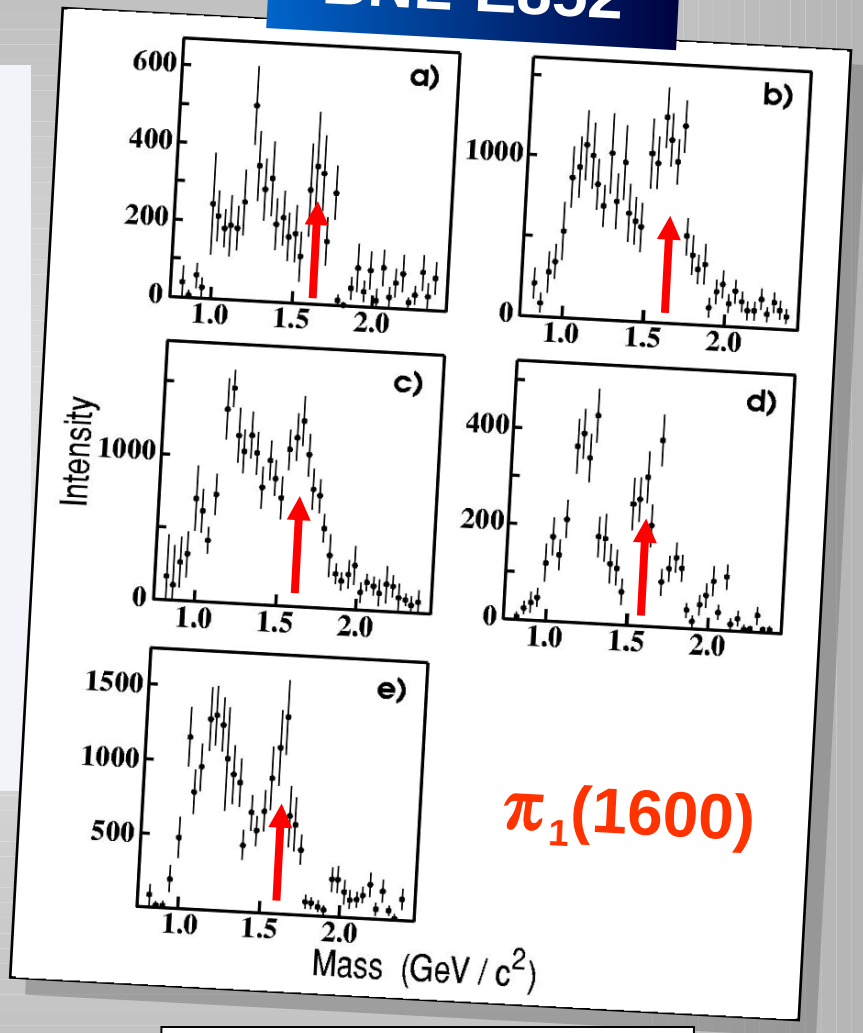
COMPASS @ CERN



192 GeV beam 96M 3π events

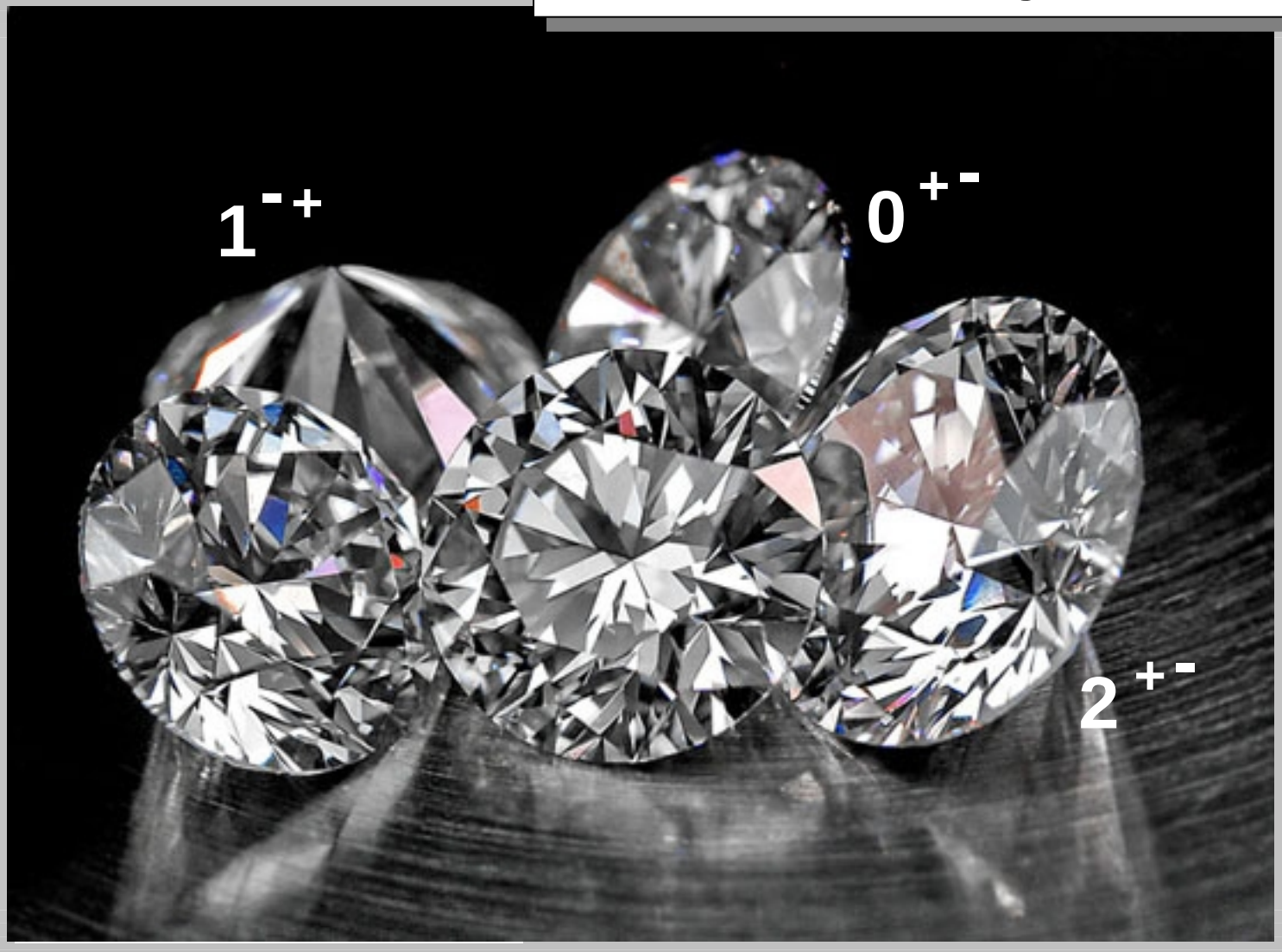
PWA: 12 waves

BNL-E852

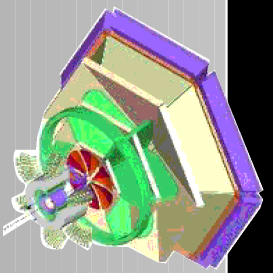


variation of 1^{-+} with unquenching

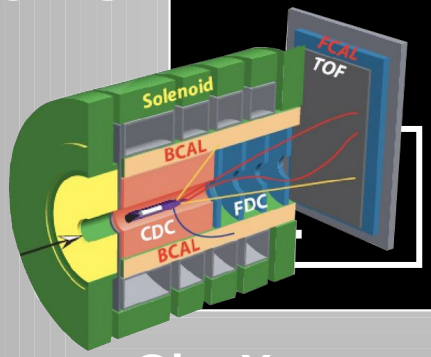
Precision analysis tools



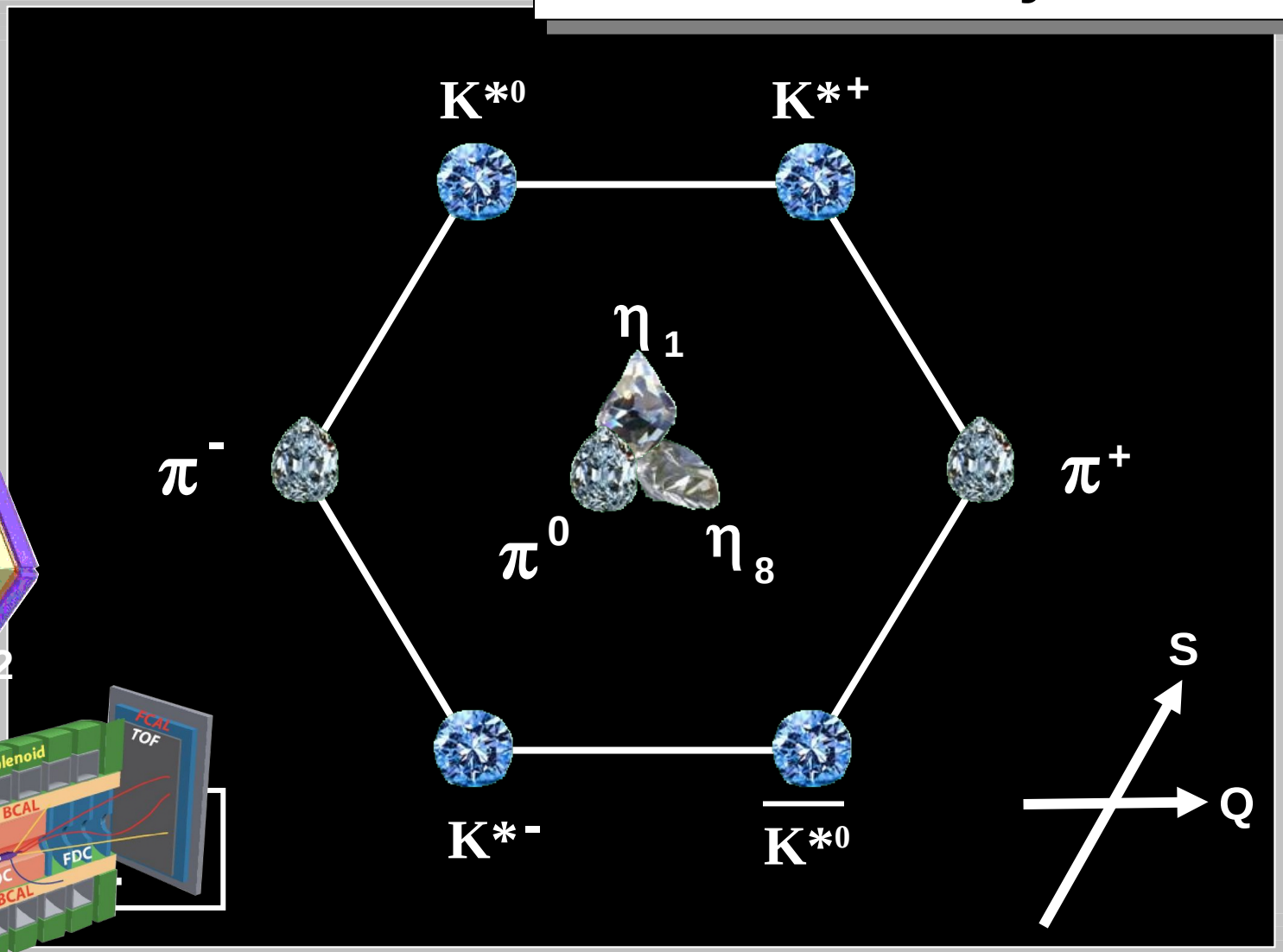
Precision analysis tools

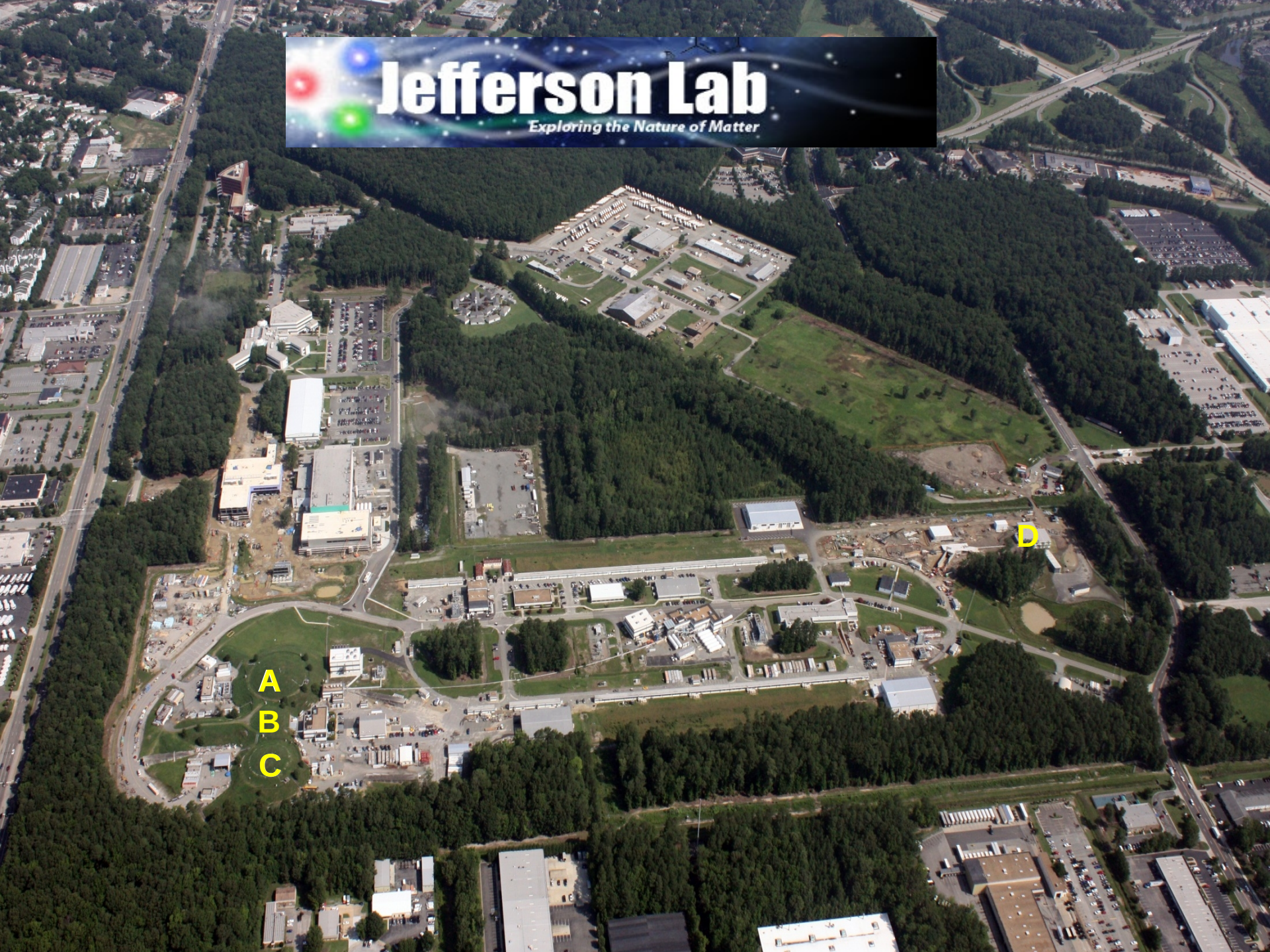


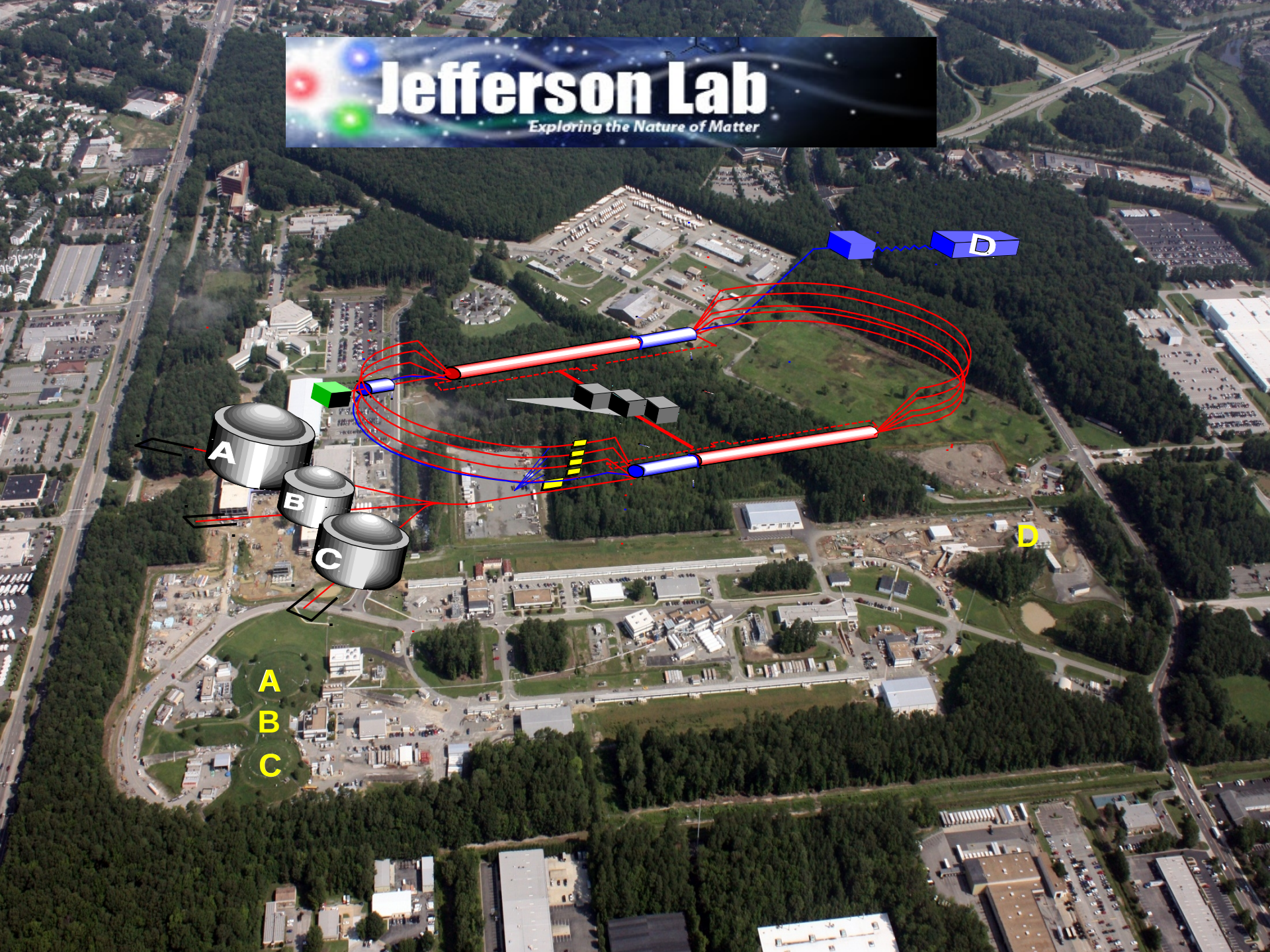
CLAS12



GlueX

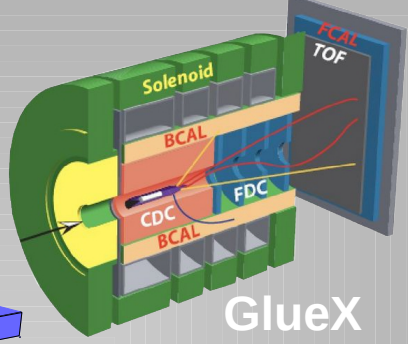



Jefferson Lab
Exploring the Nature of Matter
A
B
C
D

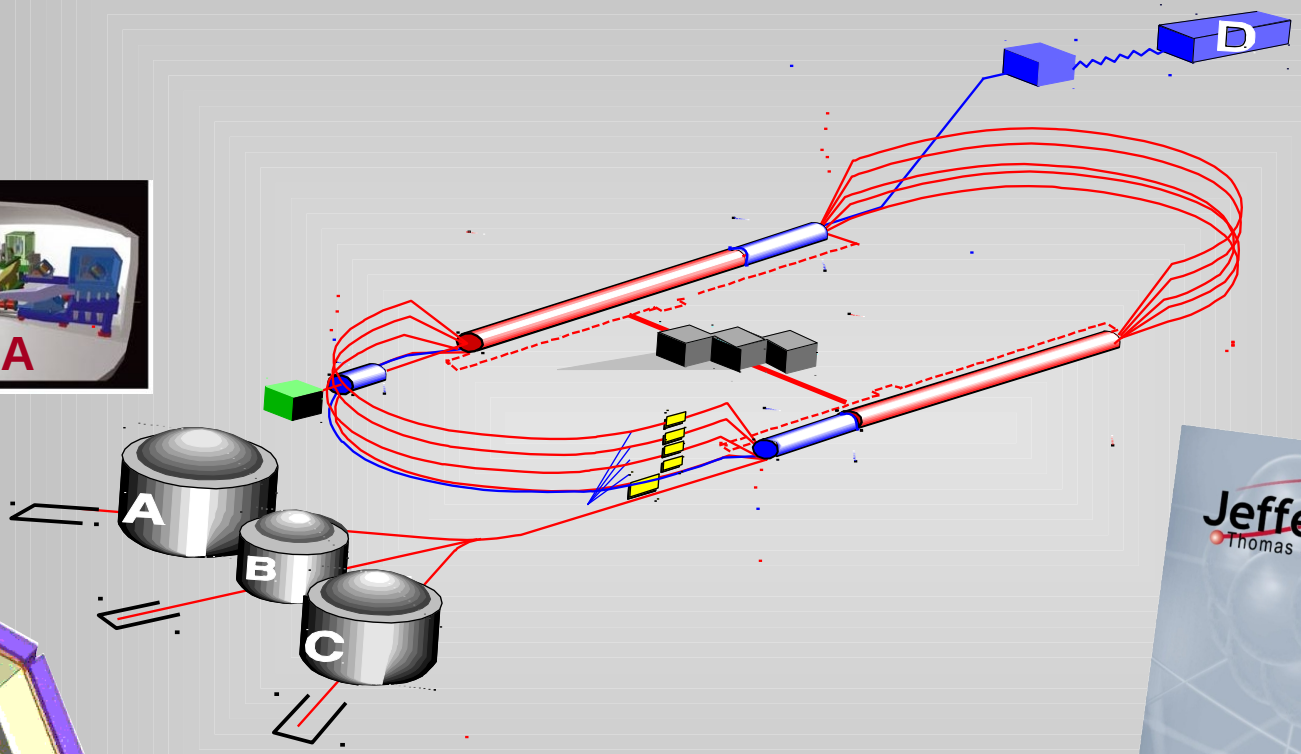

Jefferson Lab
Exploring the Nature of Matter
D
A
B
C
D
A
B
C

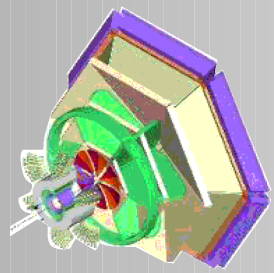
Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter

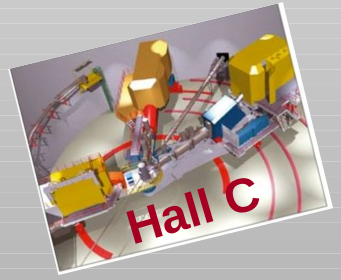


GlueX





CLAS12

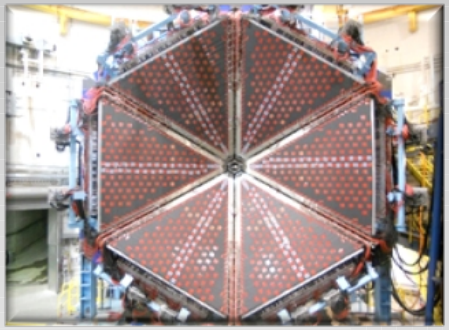


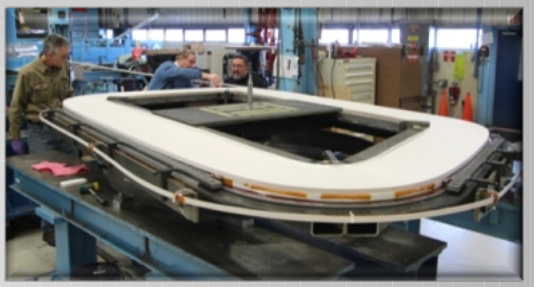
Jefferson Lab 12 GeV upgrade

Exploring the Nature of Matter

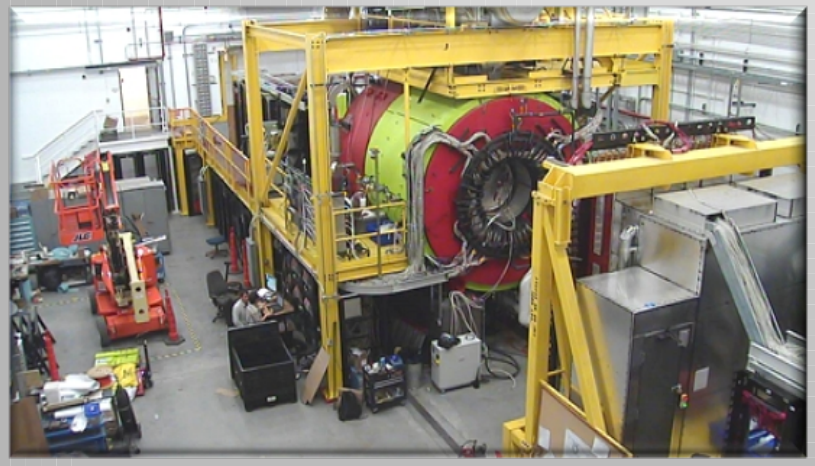
Accelerator 99% complete

Hall B 73% complete



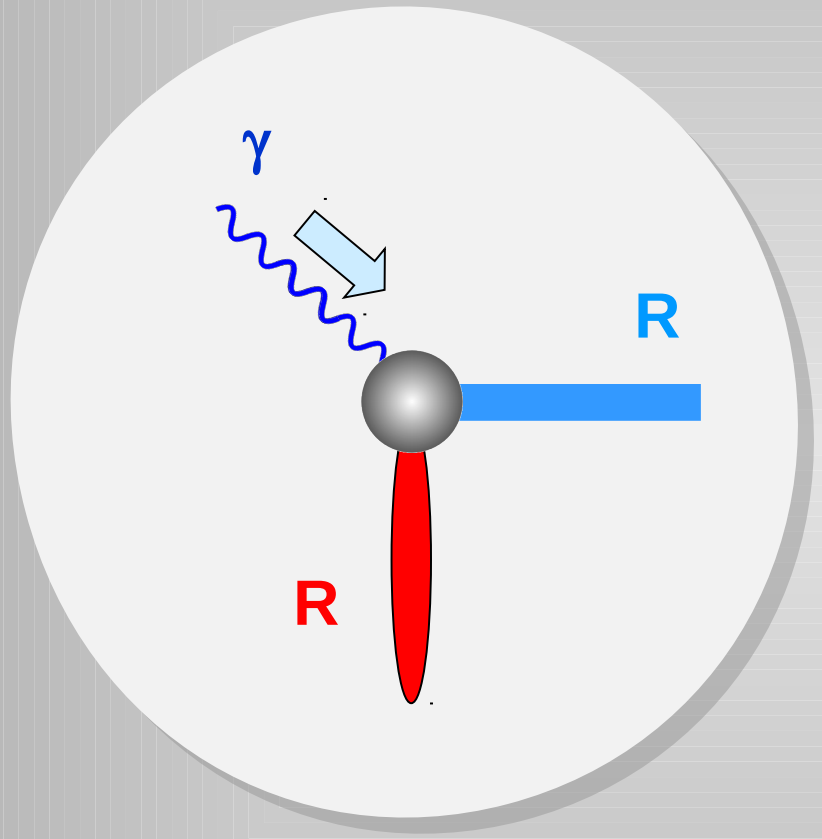


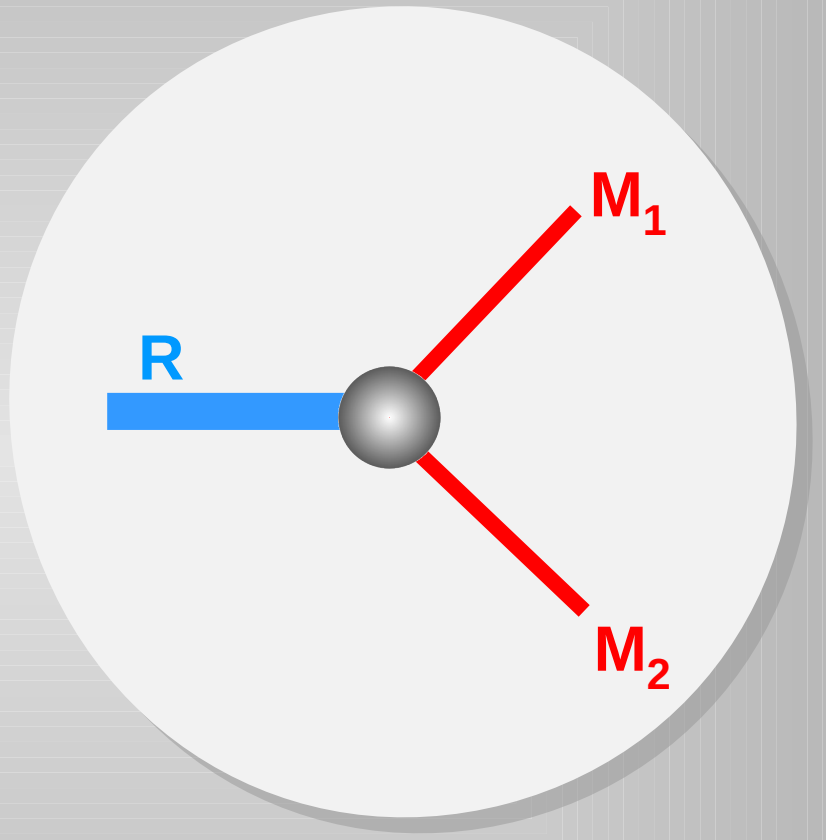
Hall D 97% complete



Hall C 73% complete

Calculating on the lattice



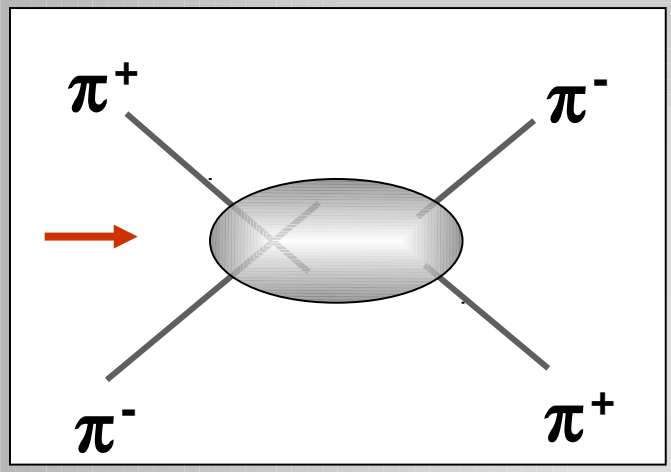


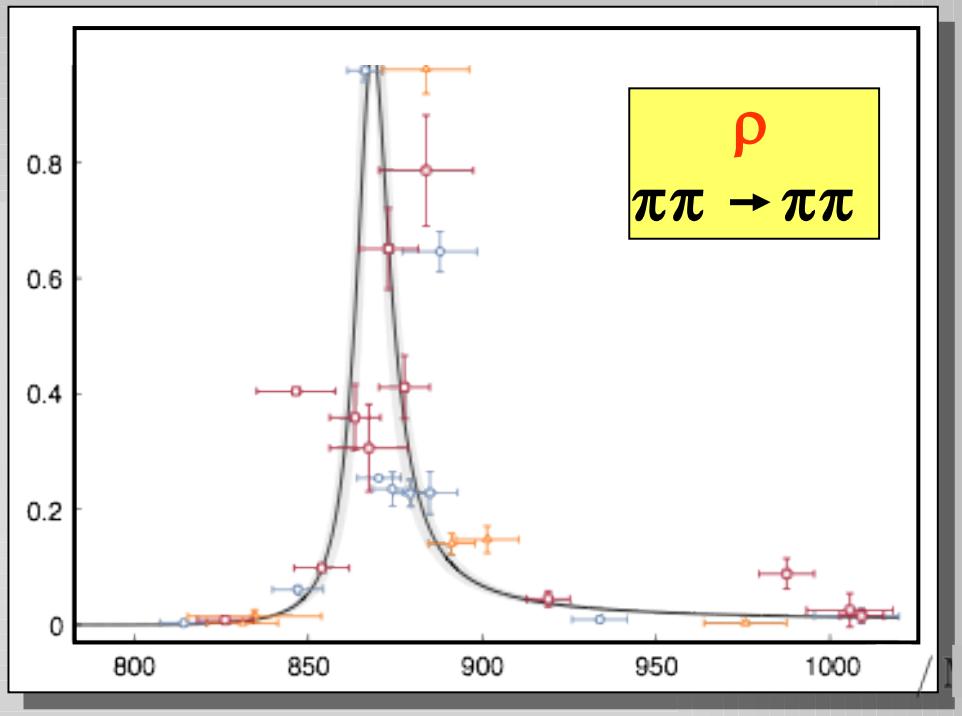
e.g. $\gamma\,\pi_R \rightarrow \pi_1$

e.g. $\pi_1 \rightarrow \rho\,\pi$

normalize photoproduction cross-sections

Scattering on the lattice

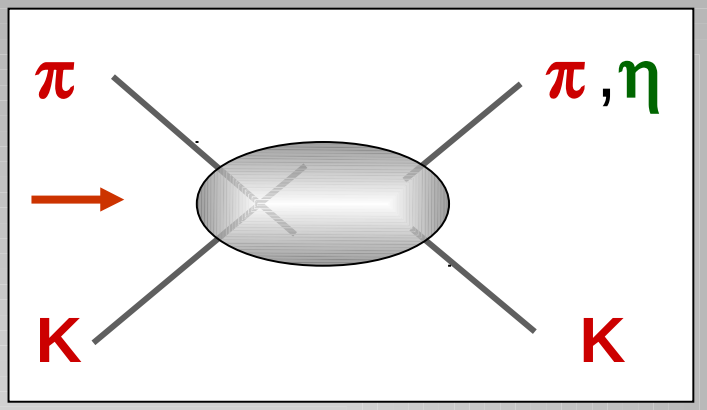


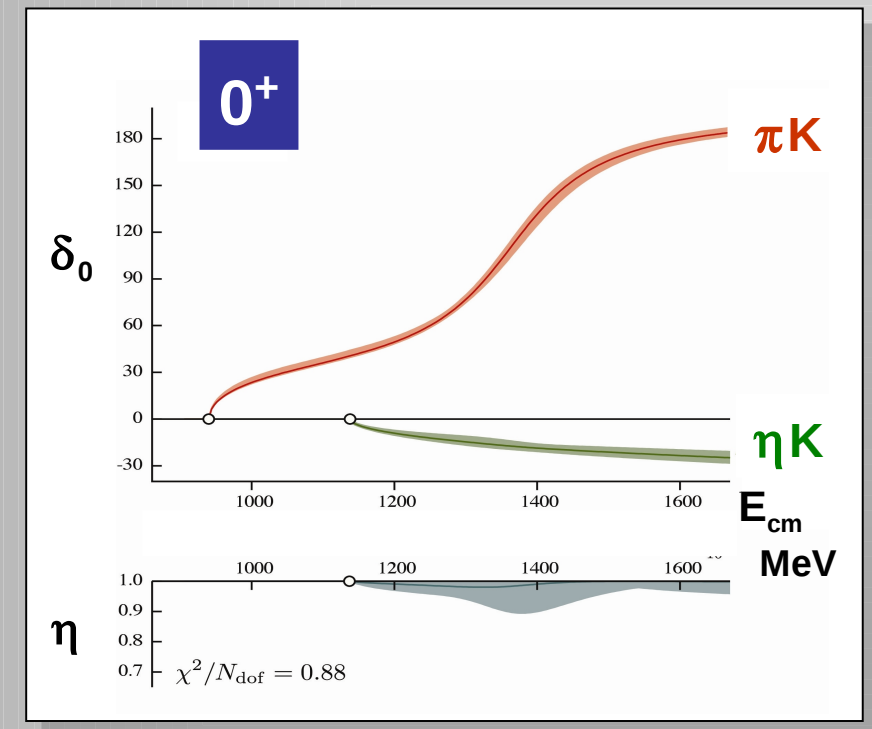


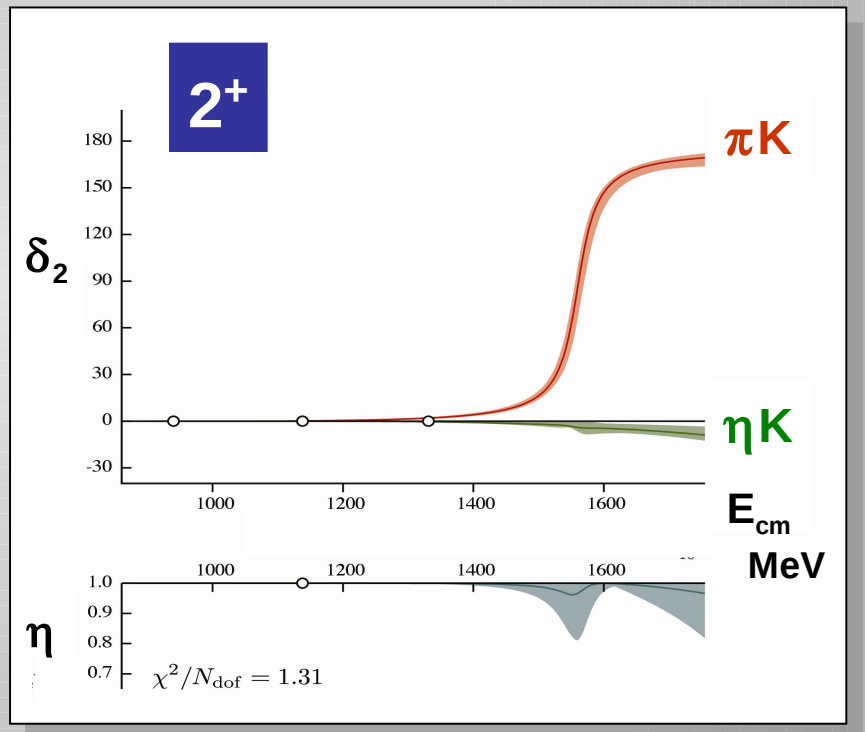
m_π = 396 MeV

Hadron Spectrum Collaboration

Scattering on the lattice

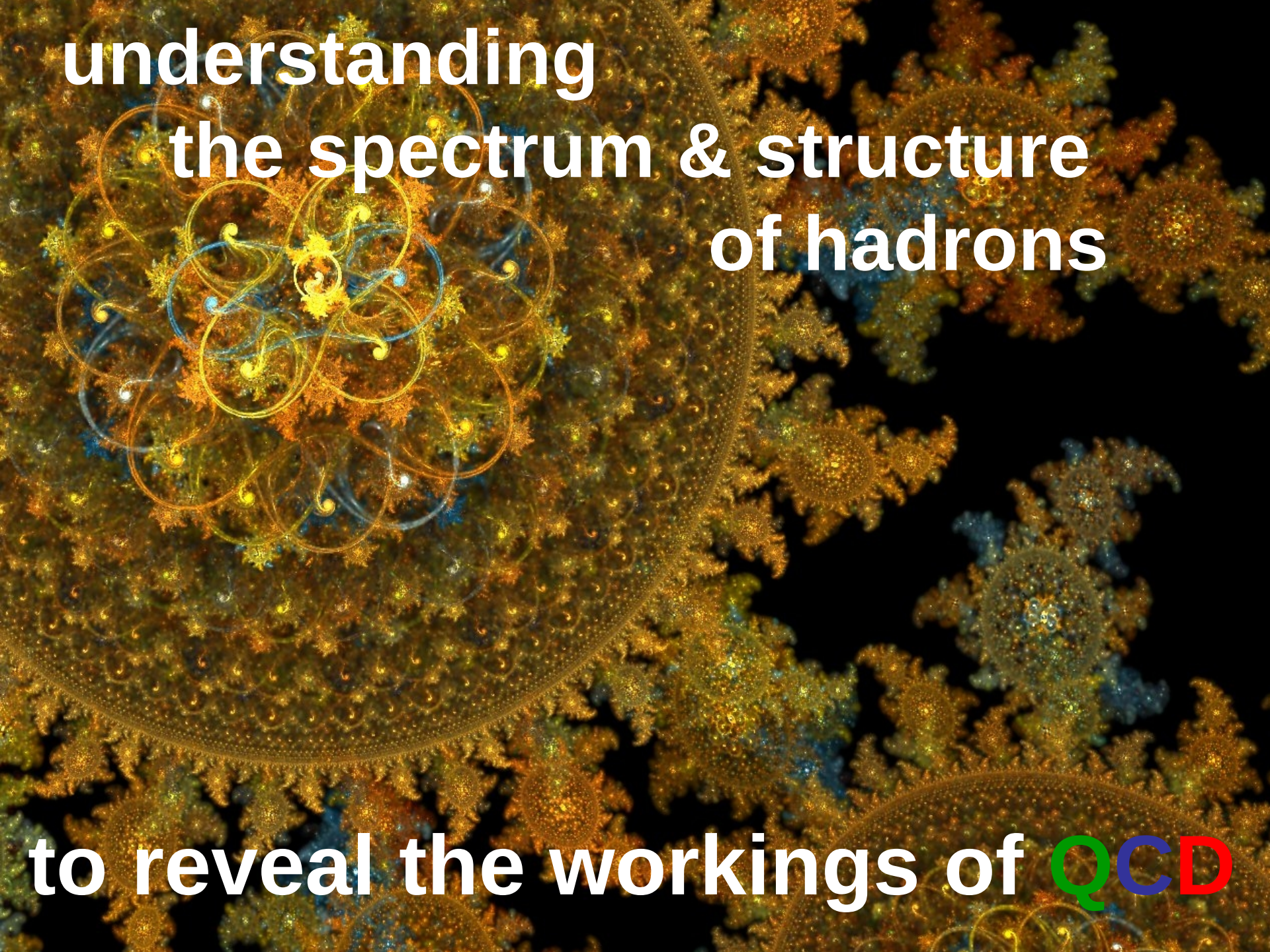






m_π = 396 MeV

Dudek, Edwards, Thomas, Wilson


understanding
the spectrum & structure
of hadrons
to reveal the workings of QCD