Resonances in QCD

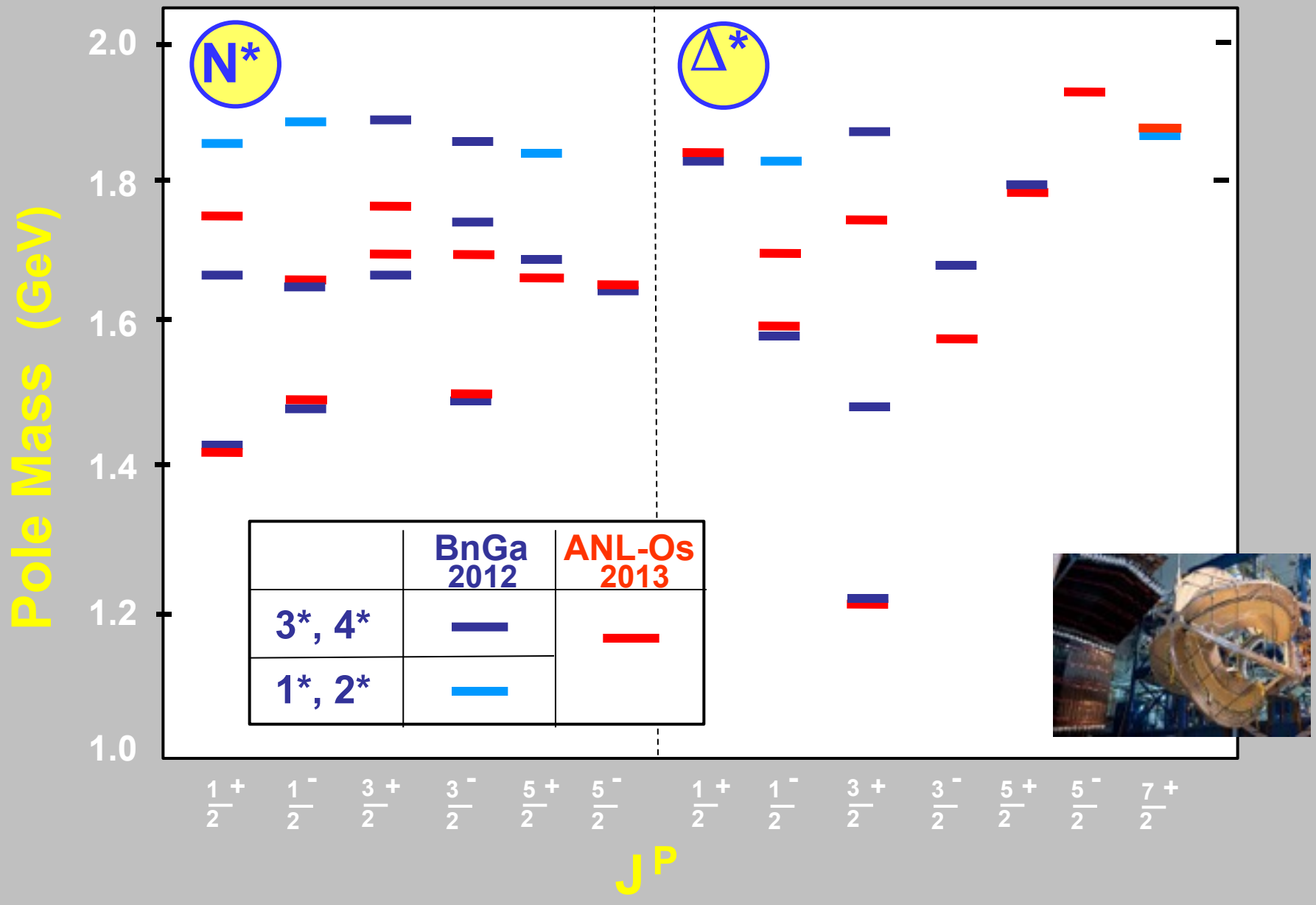
Hadrons: effective degrees of freedom

how do these depend on flavor, *s,c,b*

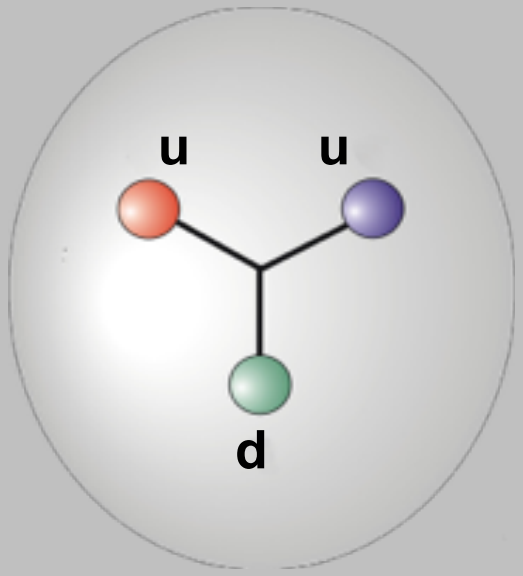
Hadron interactions: universality

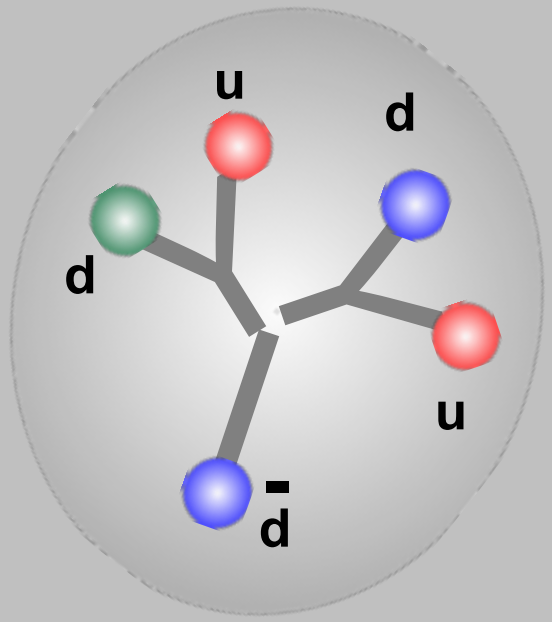
$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b,t} \bar{q} \left(i \gamma_\mu D^\mu - m_q \right) q - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}$$

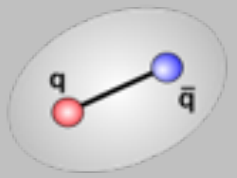
Baryon spectrum from ANL-Osaka & Bonn-Ga



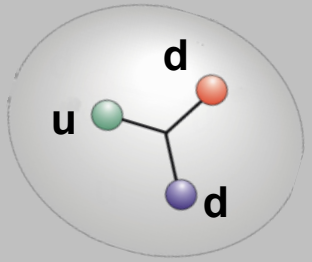
N*(1440)



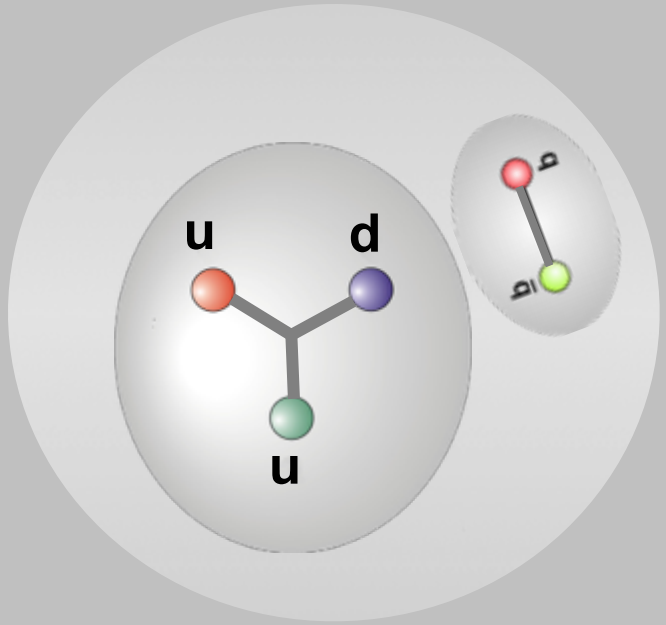




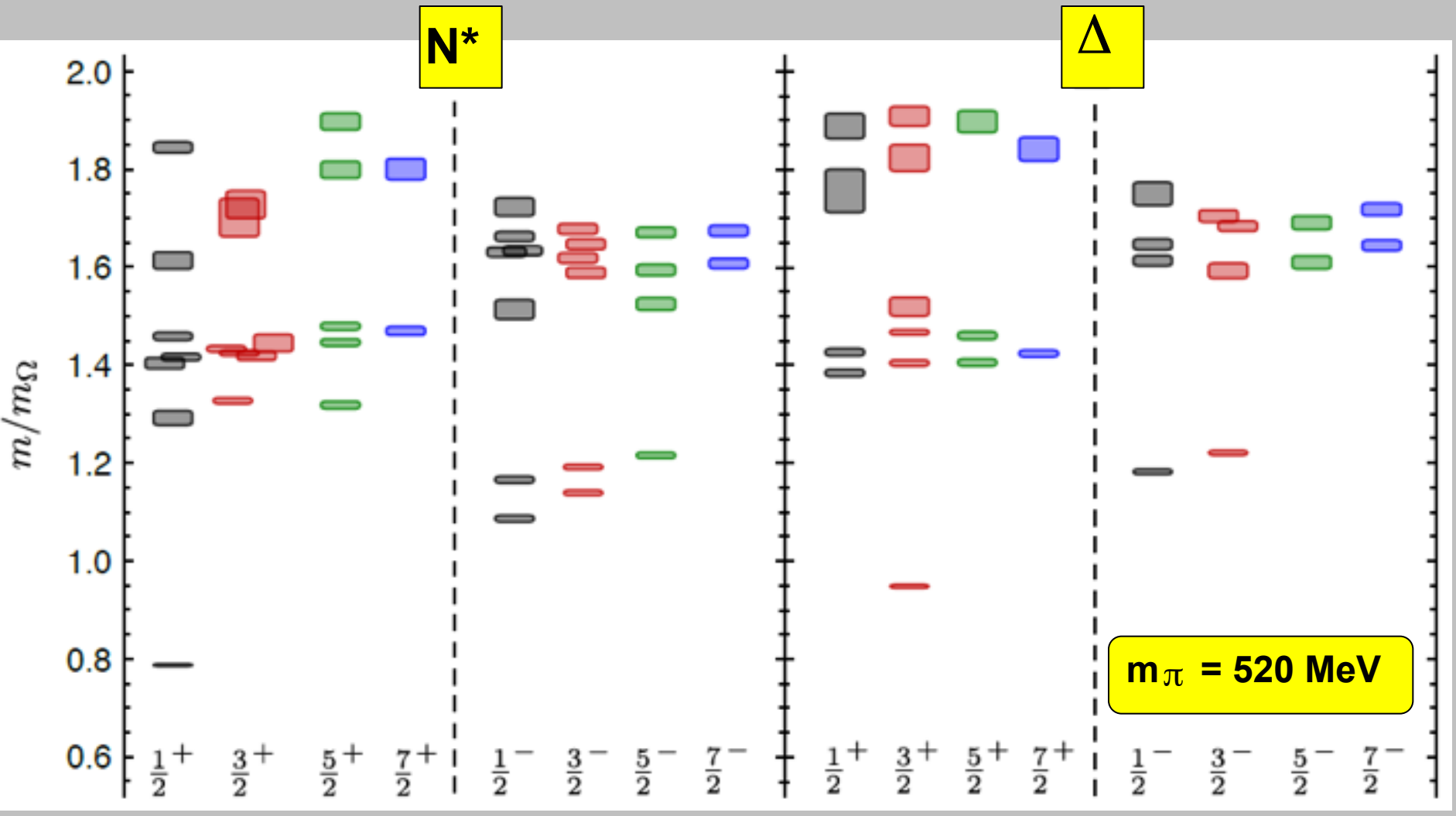
π



N



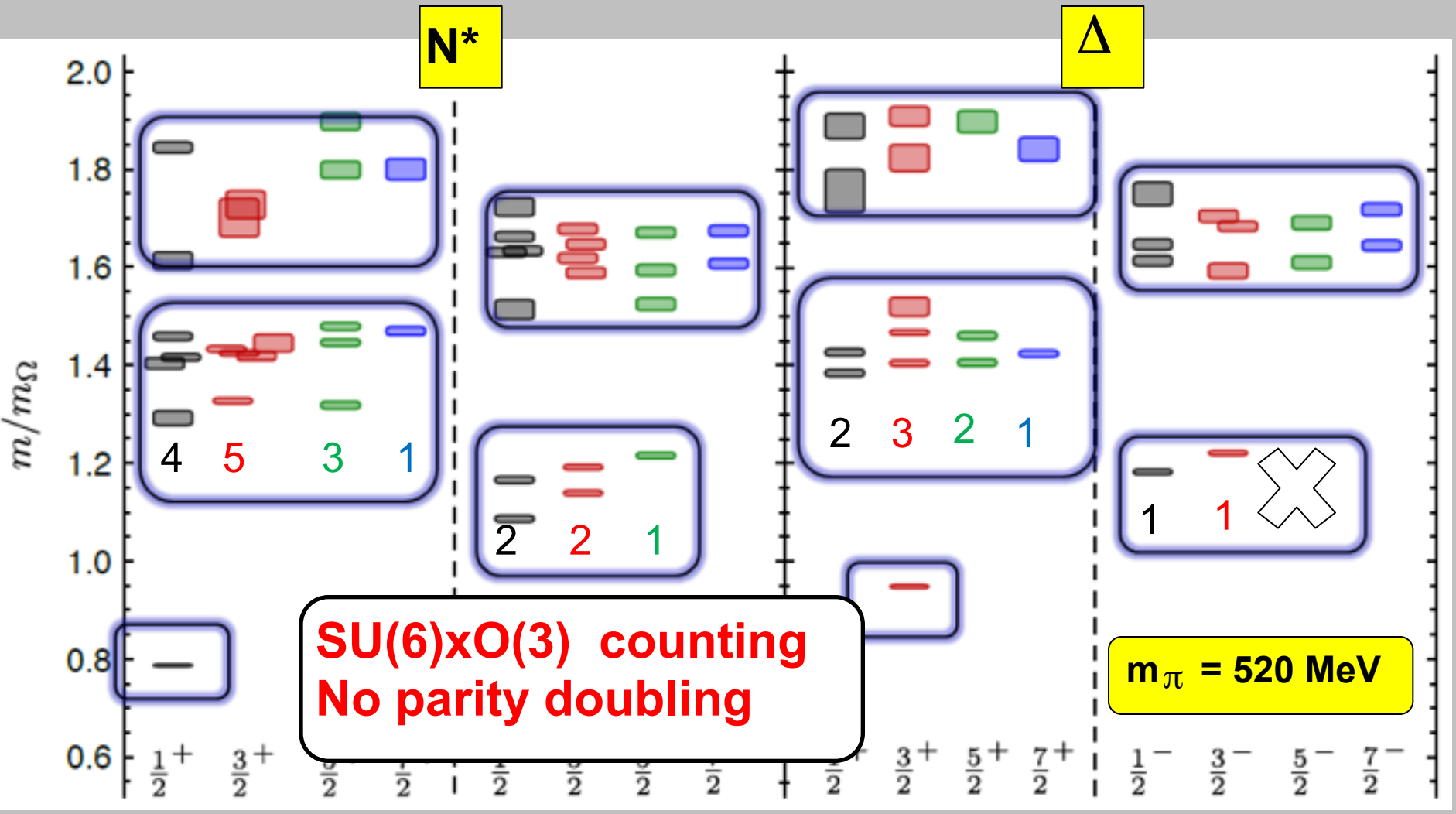
Spin identified N* and Δ states



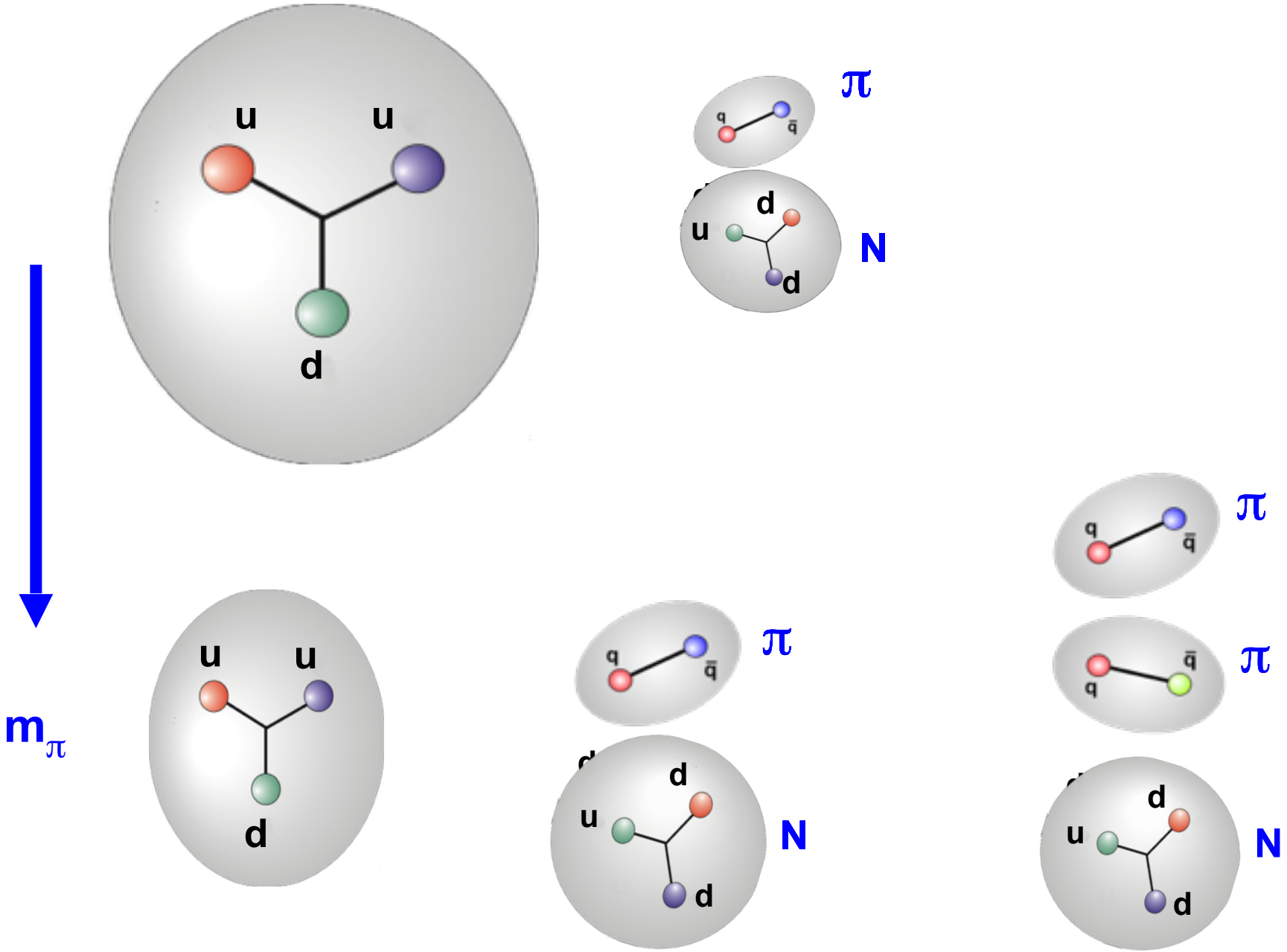
Modelling

Edwards, Dudek, Wallace & Richards

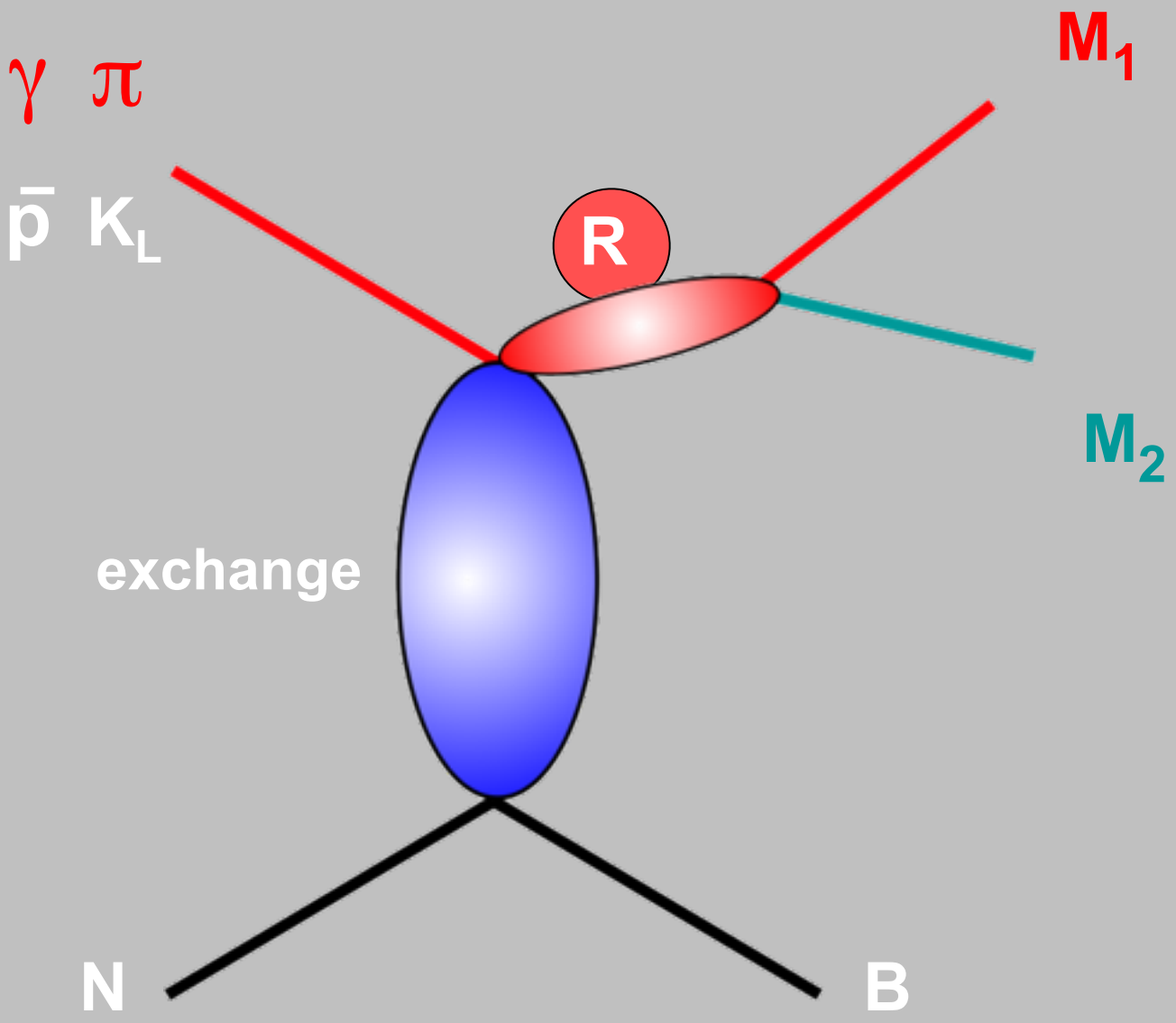
Spin identified N* and Δ states

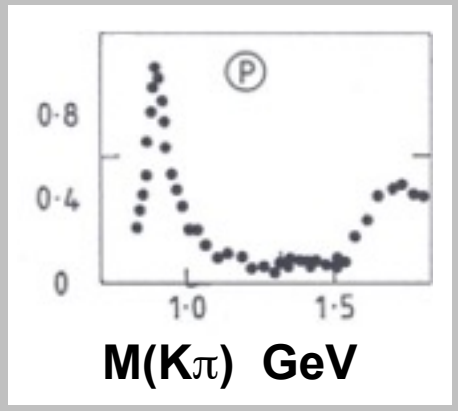


Edwards, Dudek, Wallace & Richards


u
u
d
π
q
q̄
d
u
d
N
m_π
u
u
d
π
q
q̄
π
q
q̄
q
d
u
d
N
π
q
q̄
π
q
q̄
d
u
d
N

Hadroproduction





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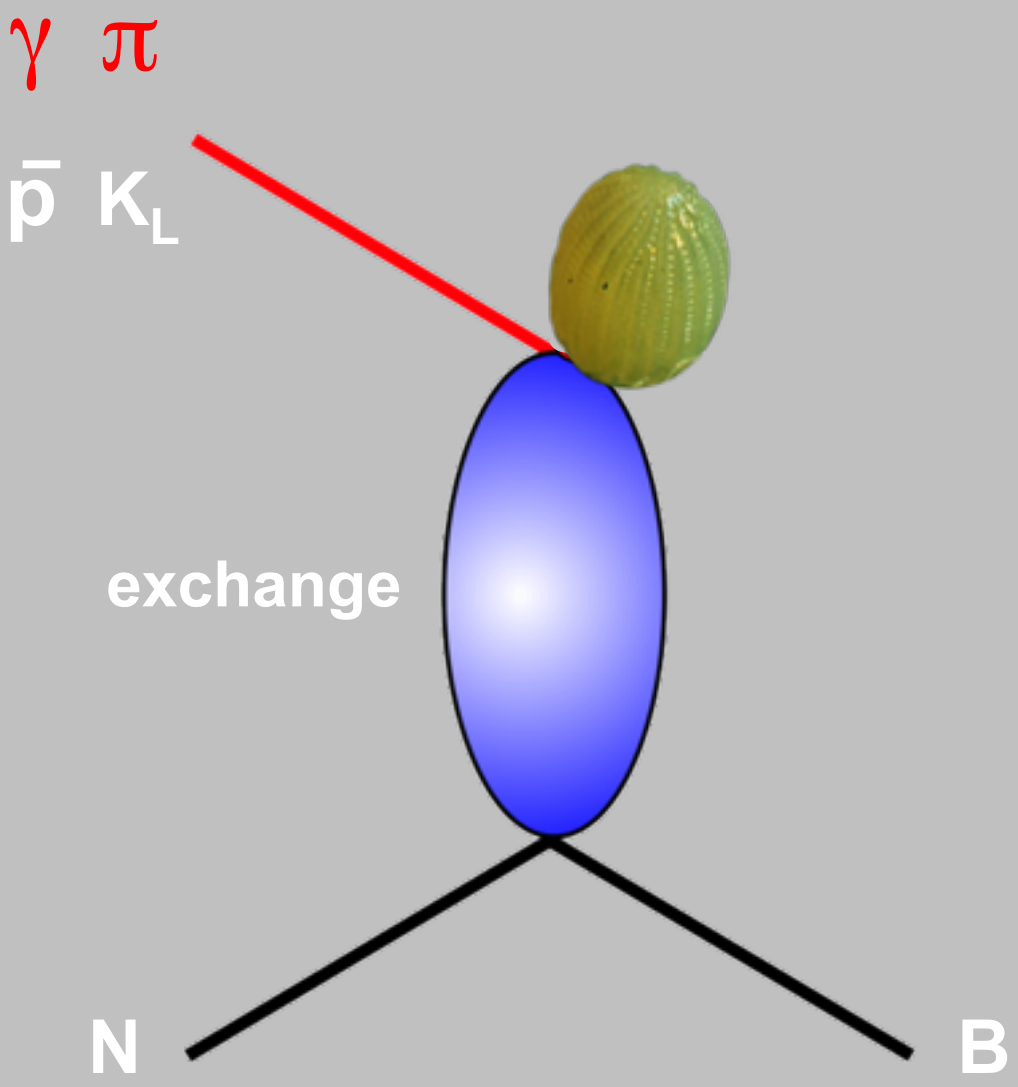

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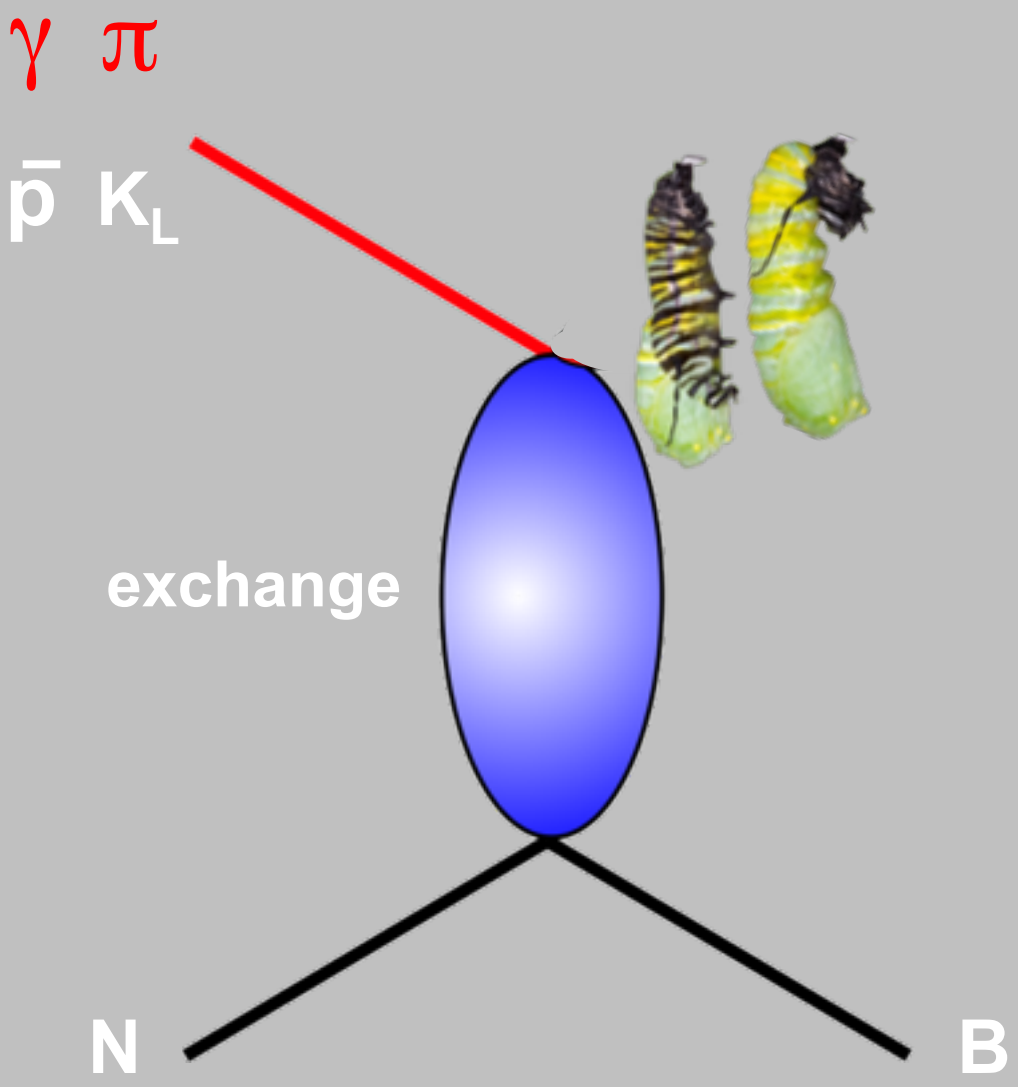

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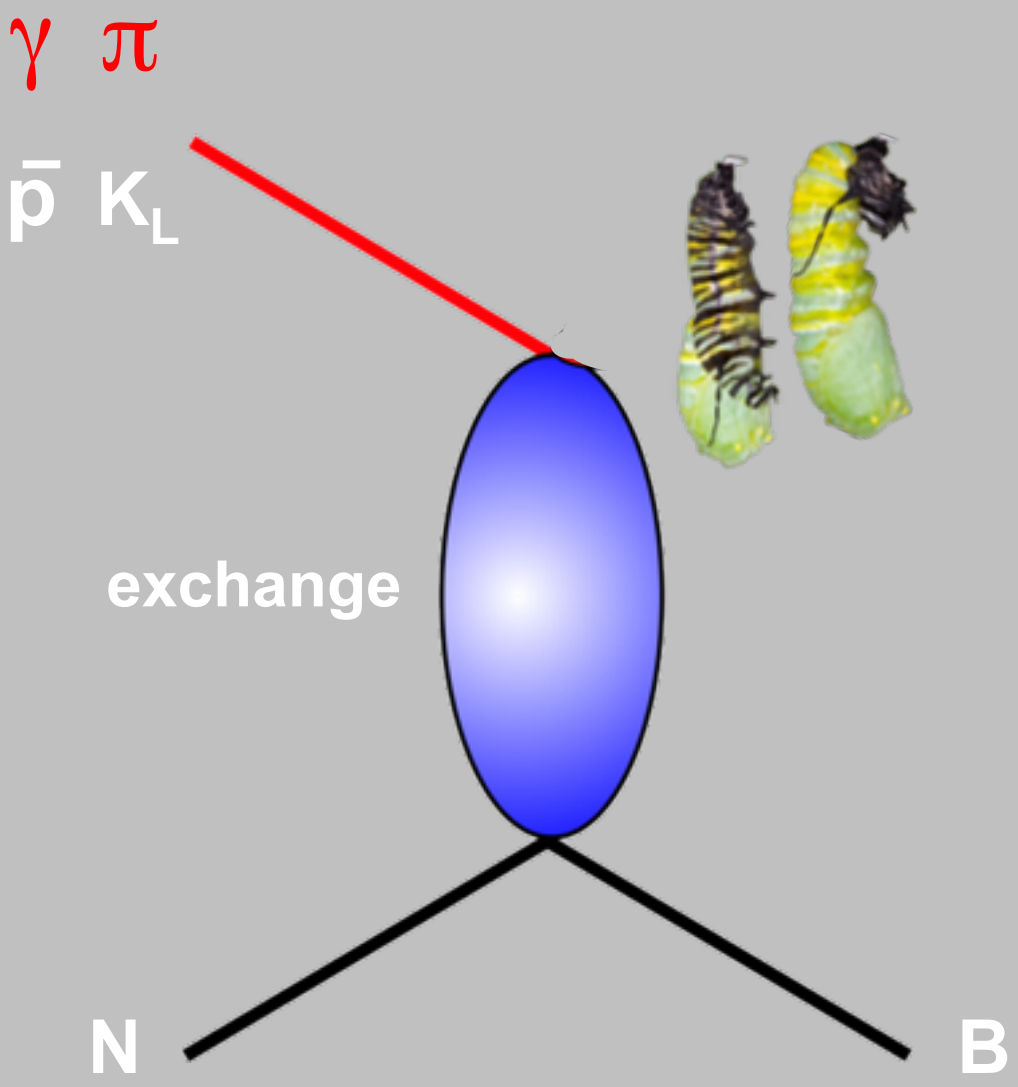

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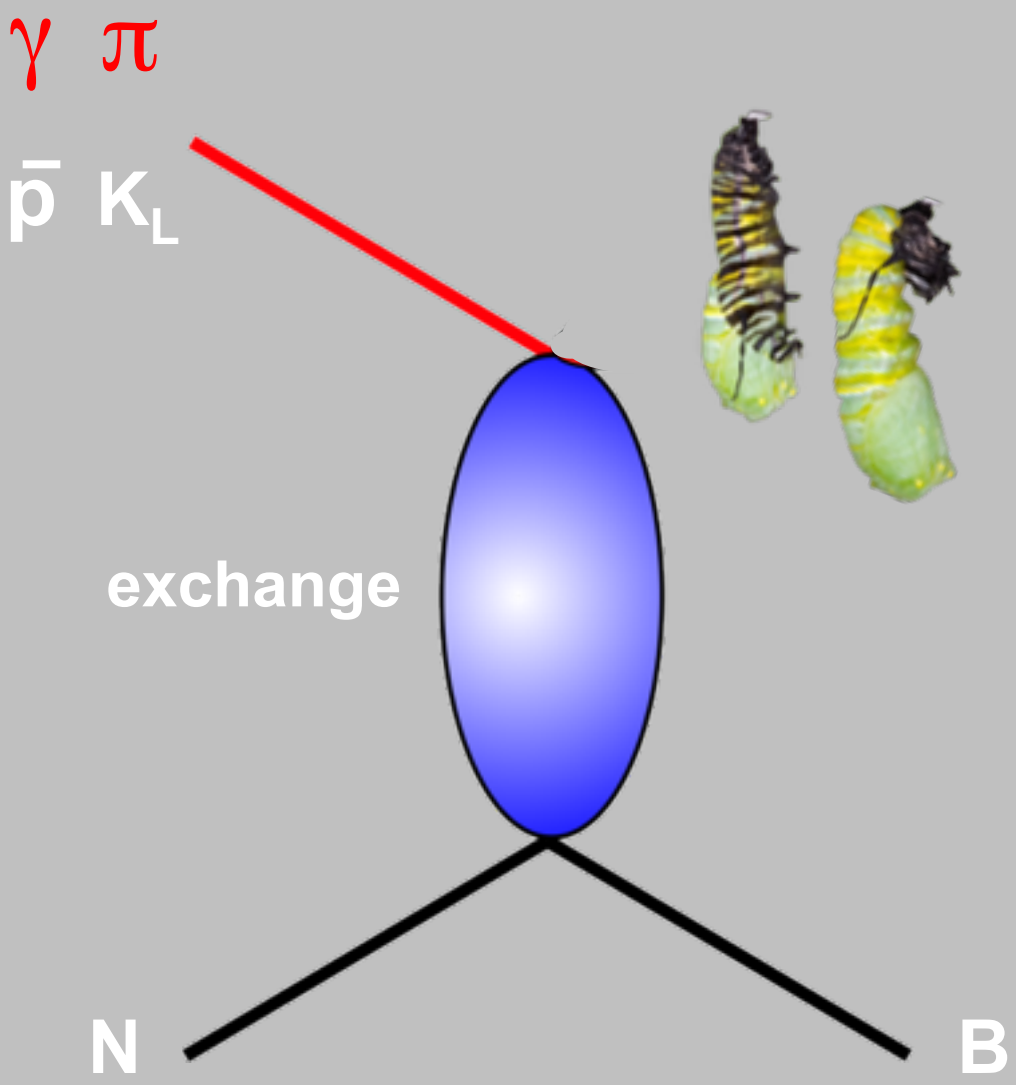

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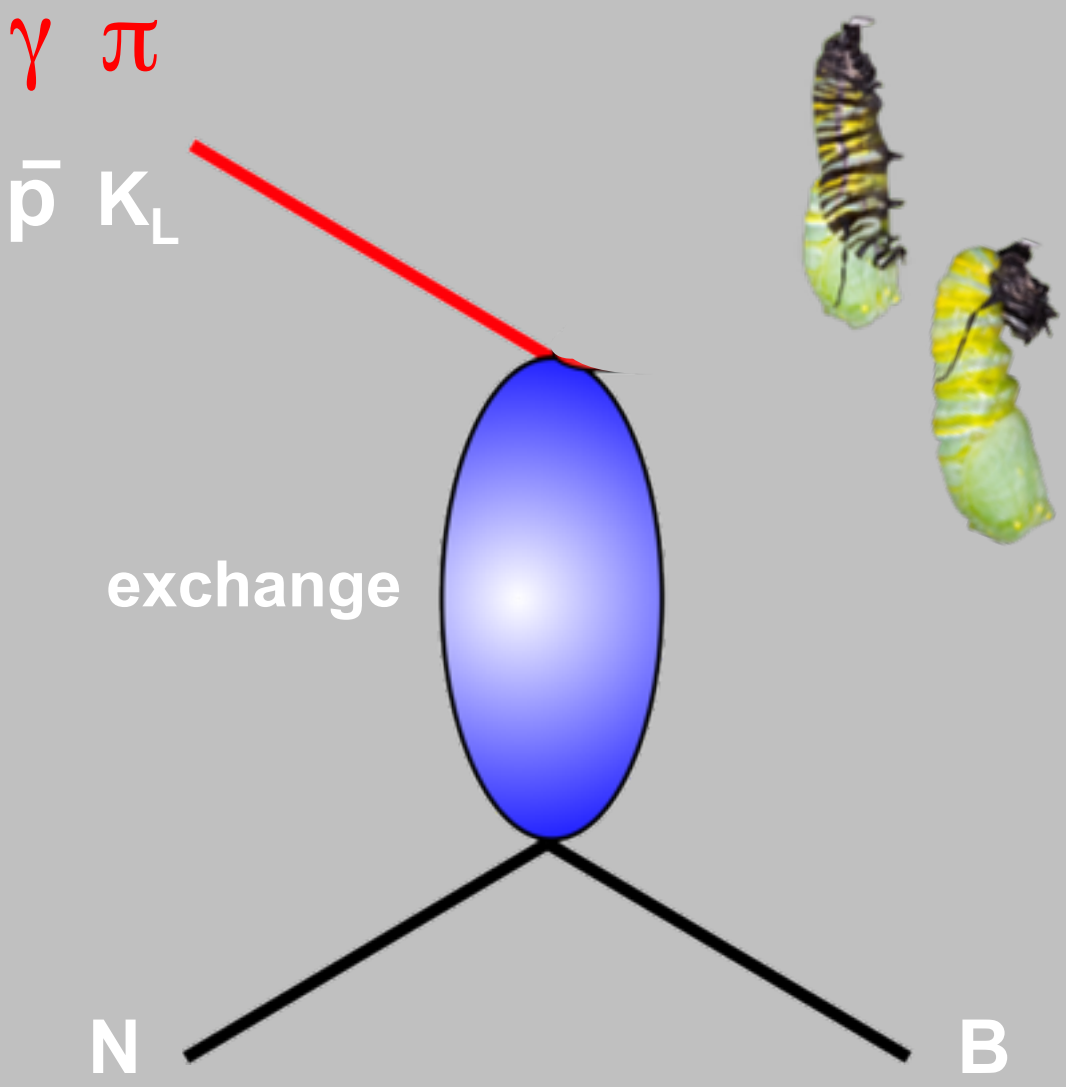

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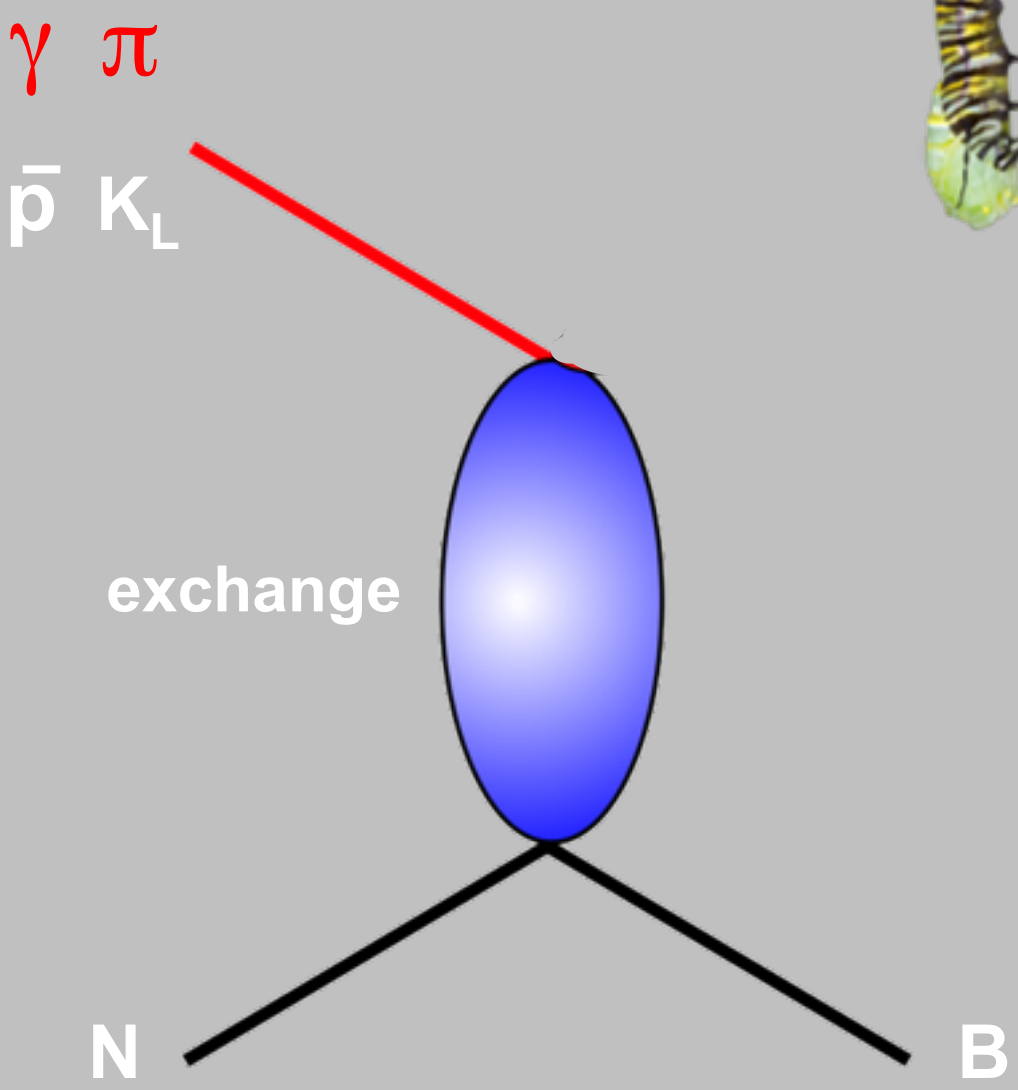
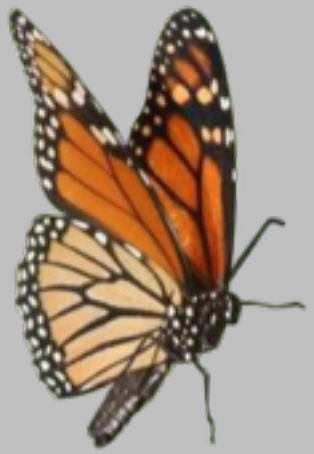
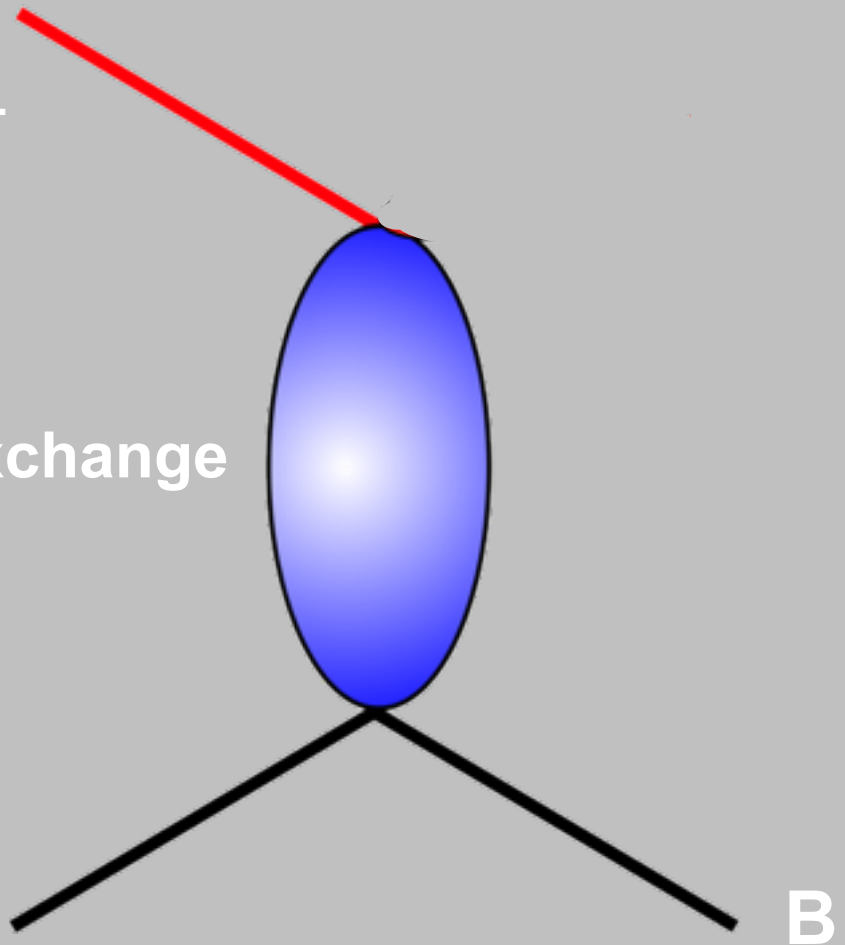


Hadroproduction

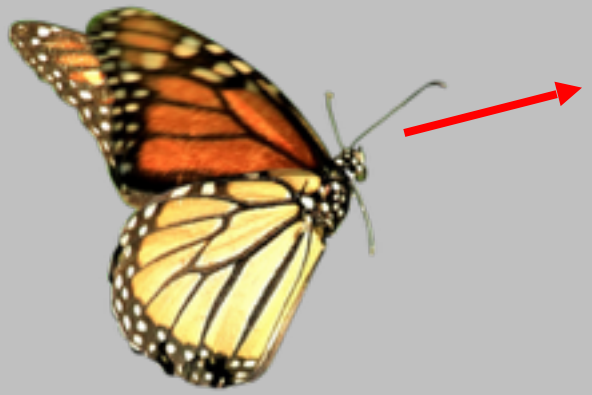
γ π

$\bar{p}$ K_L



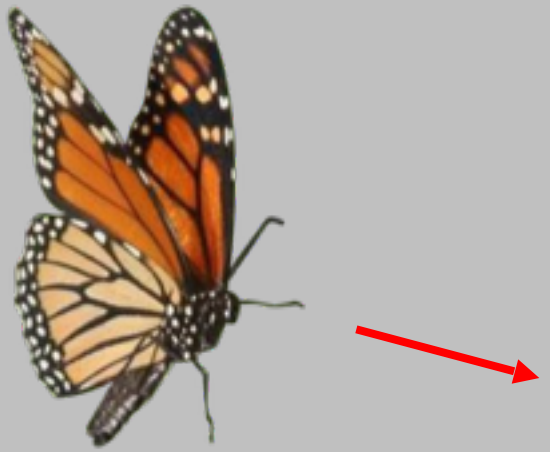


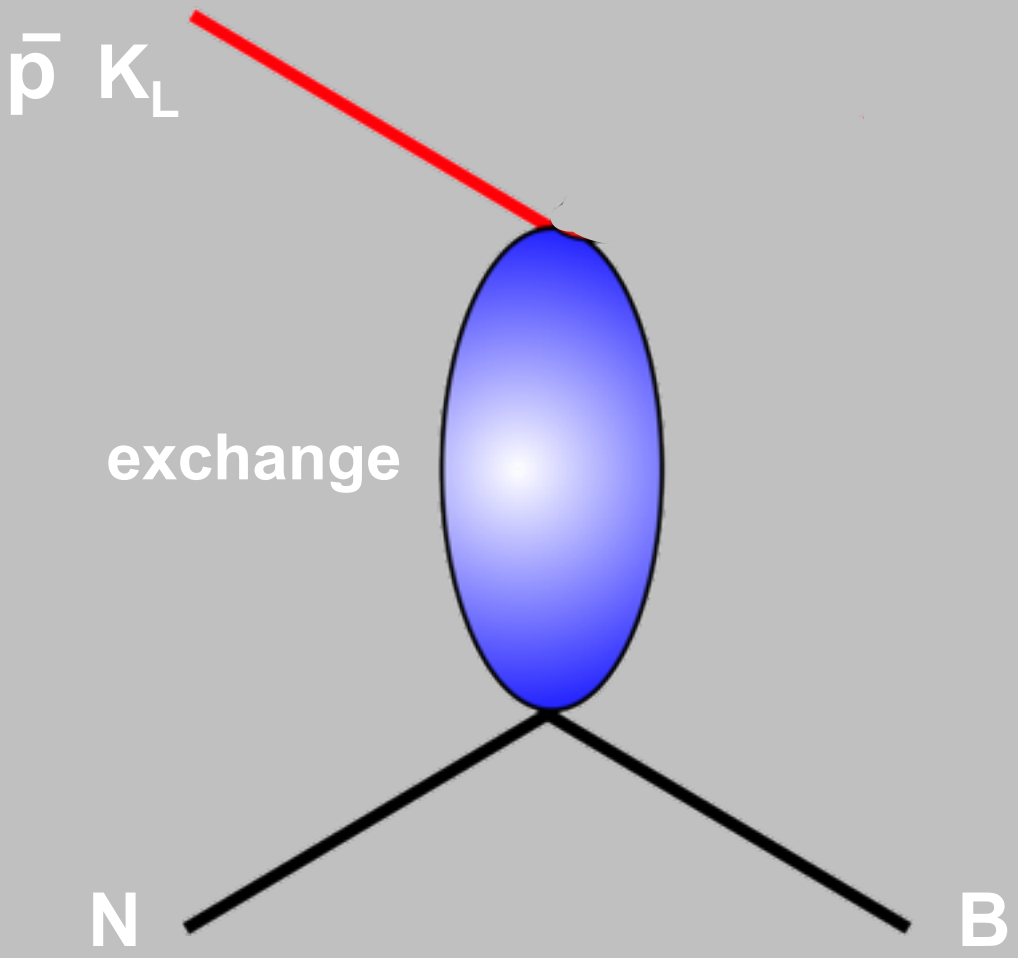
Hadroproduction



γ π

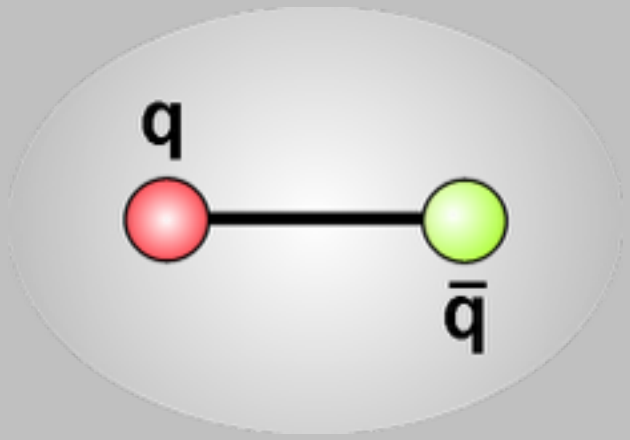
$\bar{p}$ K_L

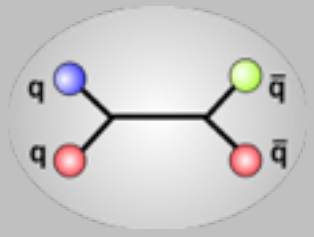


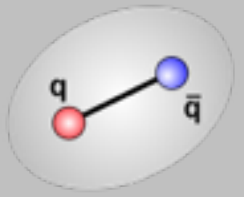


K*(892)

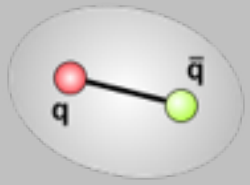
$J^{PC} = 1^{--}$





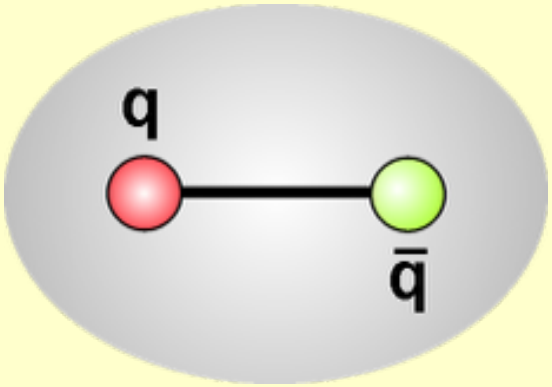


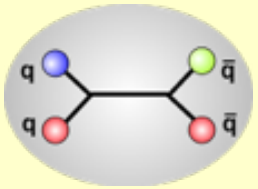
K^+

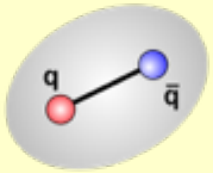


π^-

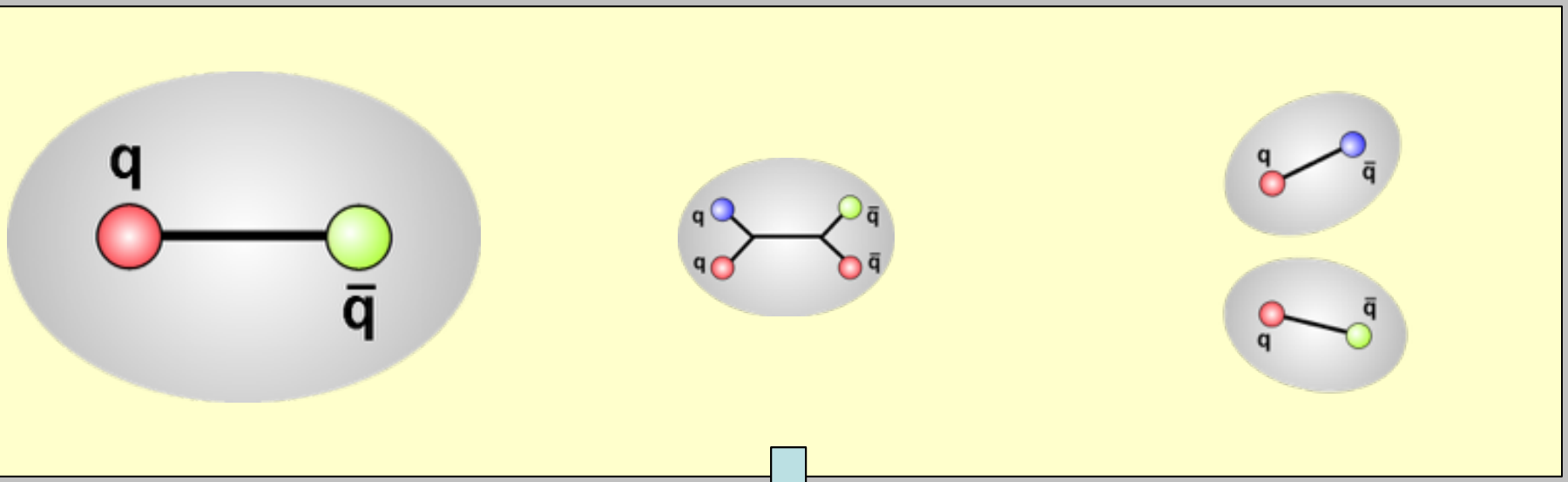
degrees of freedom


q
q̄

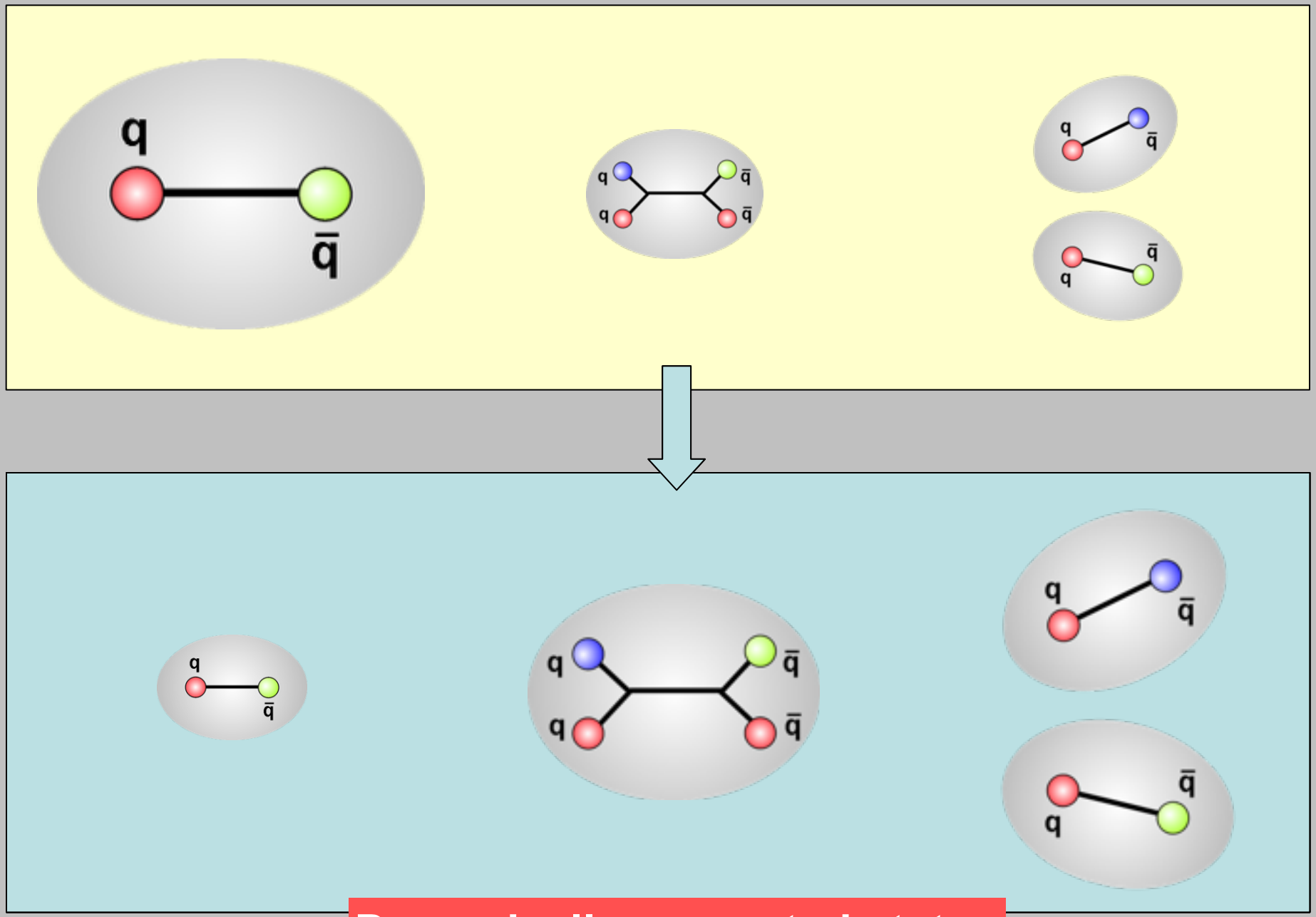

q
q̄
q
q̄


q
q̄


q̄
q

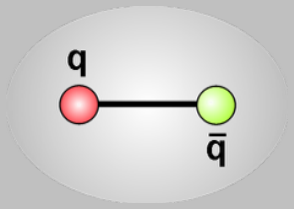


Degrees of freedom

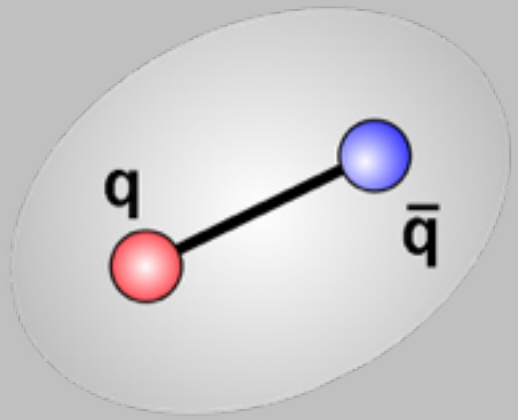

q
q̄
q
q
q̄
q̄
q
q̄
q
q̄
q
q̄
q
q̄
q
q̄
Dynamically generated states

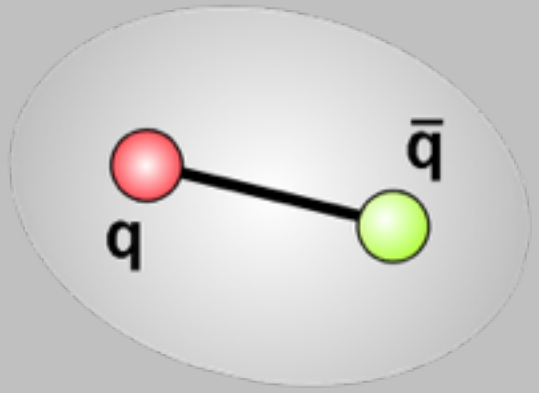
κ (600)

$J^{PC} = 0^{+}_{+}$



K



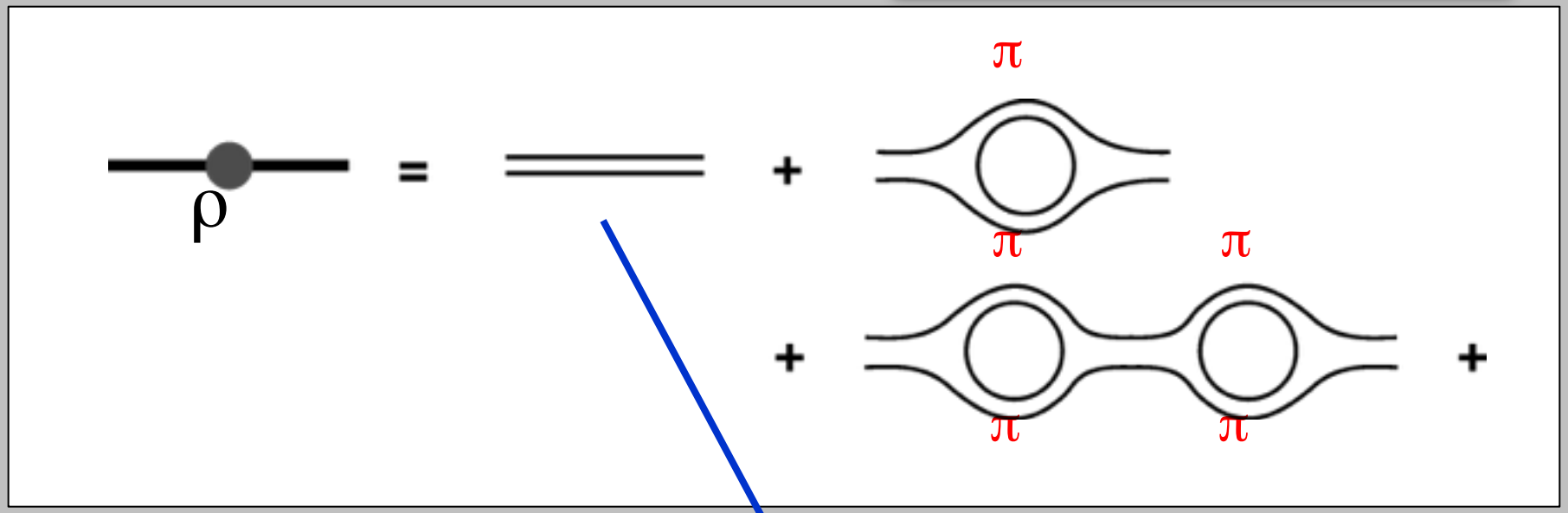


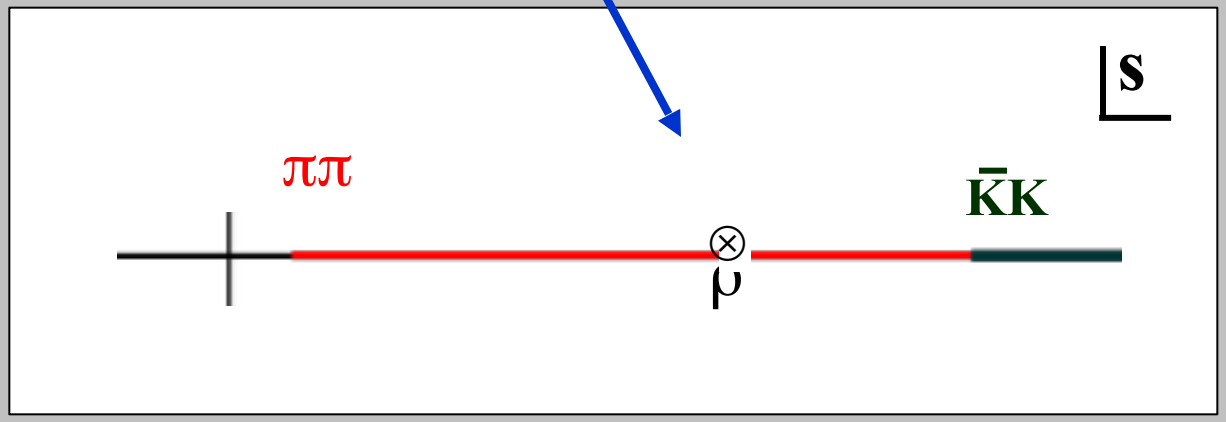
π

X,Y,Z,...

Vector multiplet

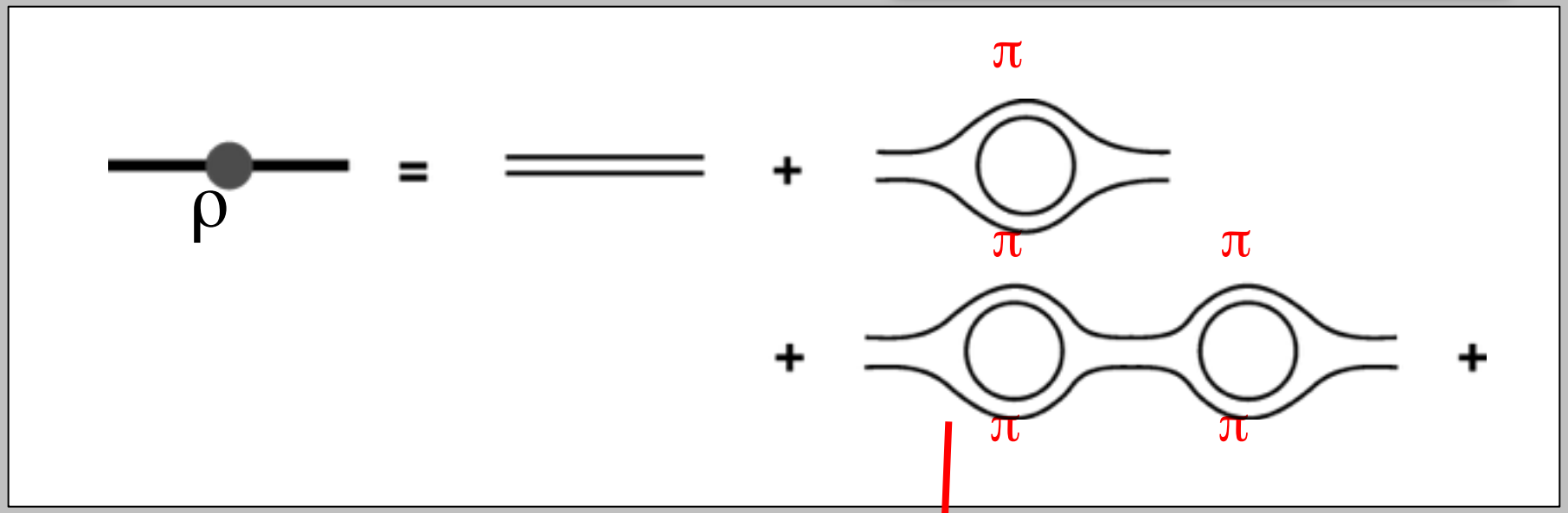
shifting of masses

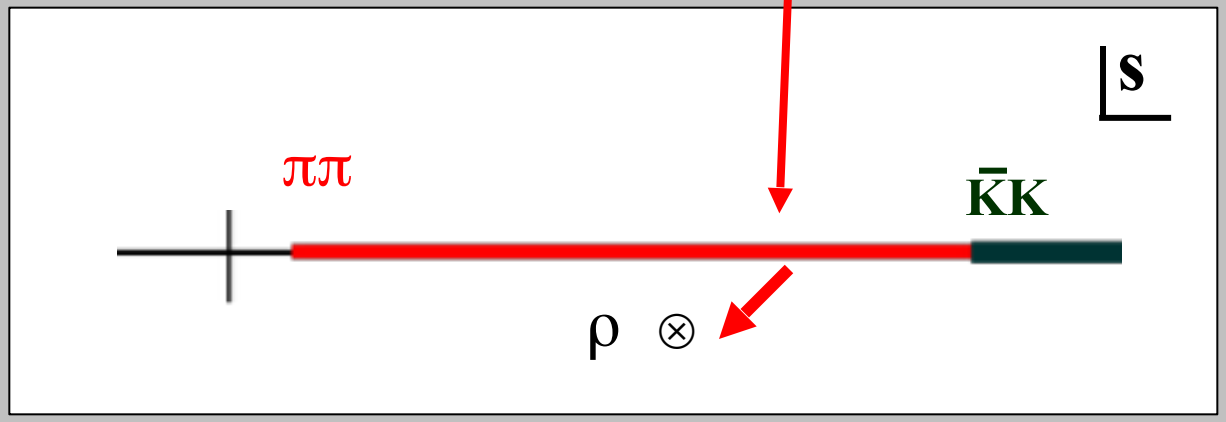




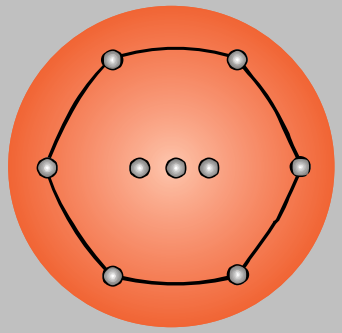
Vector multiplet

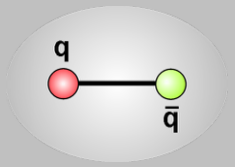
shifting of masses

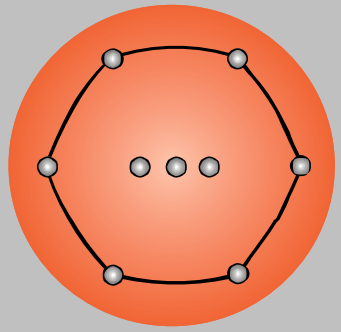




Scalar mesons







$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0 / f_0

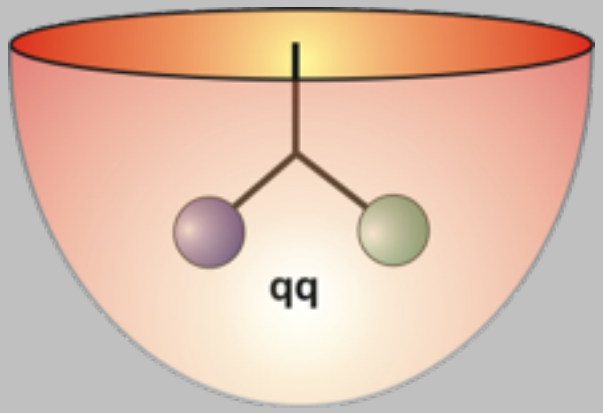
$\bar{s}s\bar{n}n$ — a_0 / f_0

$\bar{s}n\bar{n}n$ — K_0 κ

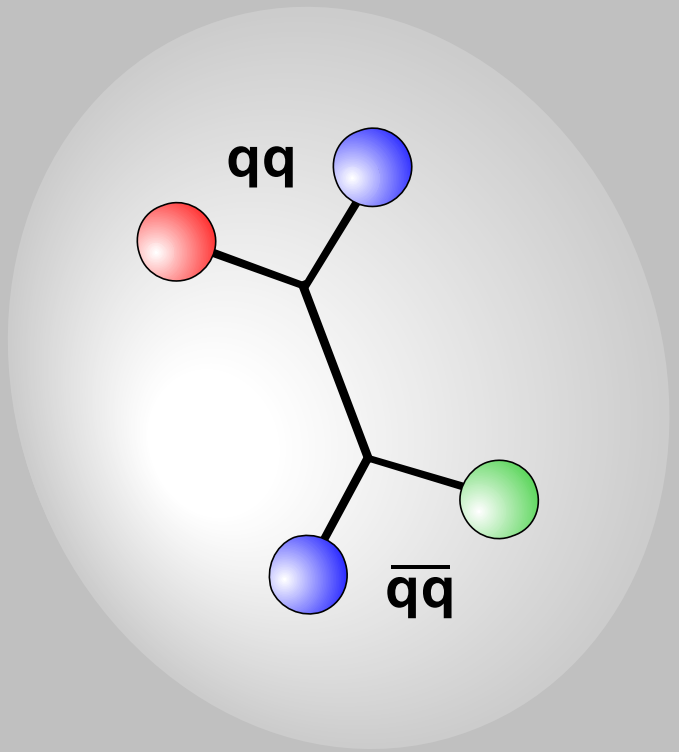
$\bar{n}n\bar{n}n$ — f_0 σ

$n = u,d$

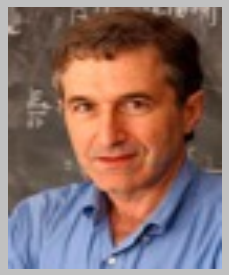
diquarks: color



tetraquark



Jaffe & Wilczek

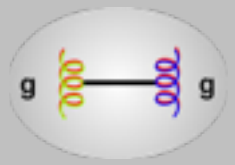


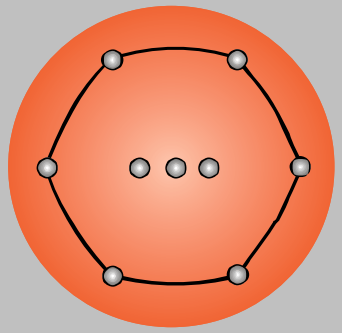
Scalar diquarks

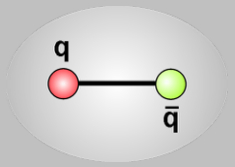
[ud] [us] [ds]

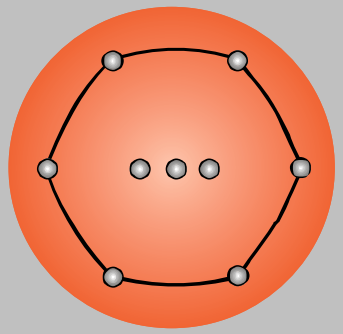
[cd] [cu] [cs]

Scalar mesons









gg — f_0

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0/f_0

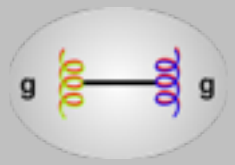
$\bar{s}s\bar{n}n$ — a_0/f_0

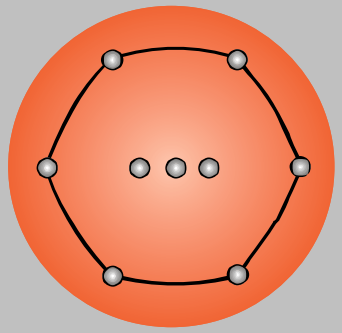
$\bar{s}n\bar{n}n$ — K_0 κ

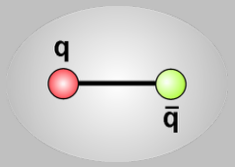
$\bar{n}n\bar{n}n$ — f_0 σ

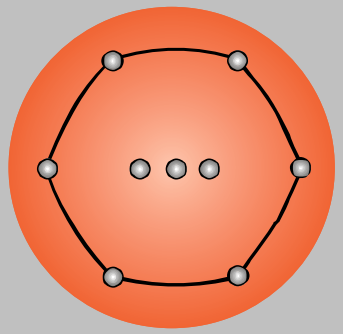
n = u,d

Scalar mesons









gg — f_0

$\bar{s}s$ — f_0

$\bar{s}n$ — K_0

$\bar{n}n$ — a_0/f_0

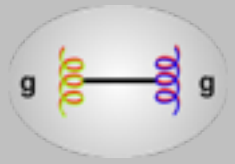
$\bar{s}s\bar{n}n$ — a_0/f_0

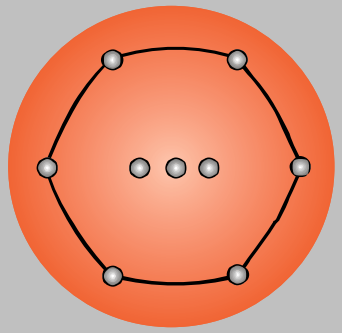
$\bar{s}n\bar{n}n$ — K_0 κ

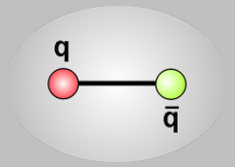
$\bar{n}n\bar{n}n$ — f_0 σ

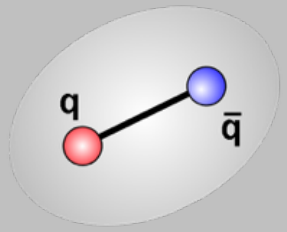
n = u,d

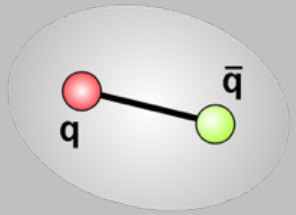
Scalar mesons

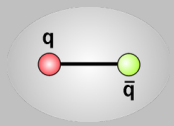


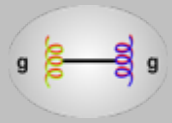












gg — f_0

$\bar{s}s$ — 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

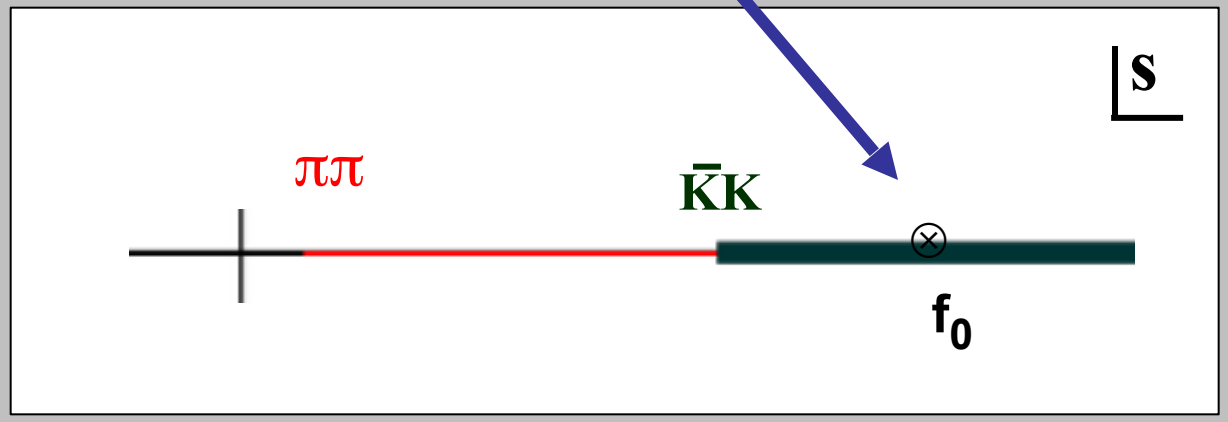
$\bar{n}n\bar{n}n$ — f_0 σ

Scalar multiplet

Van Beveren

Rupp

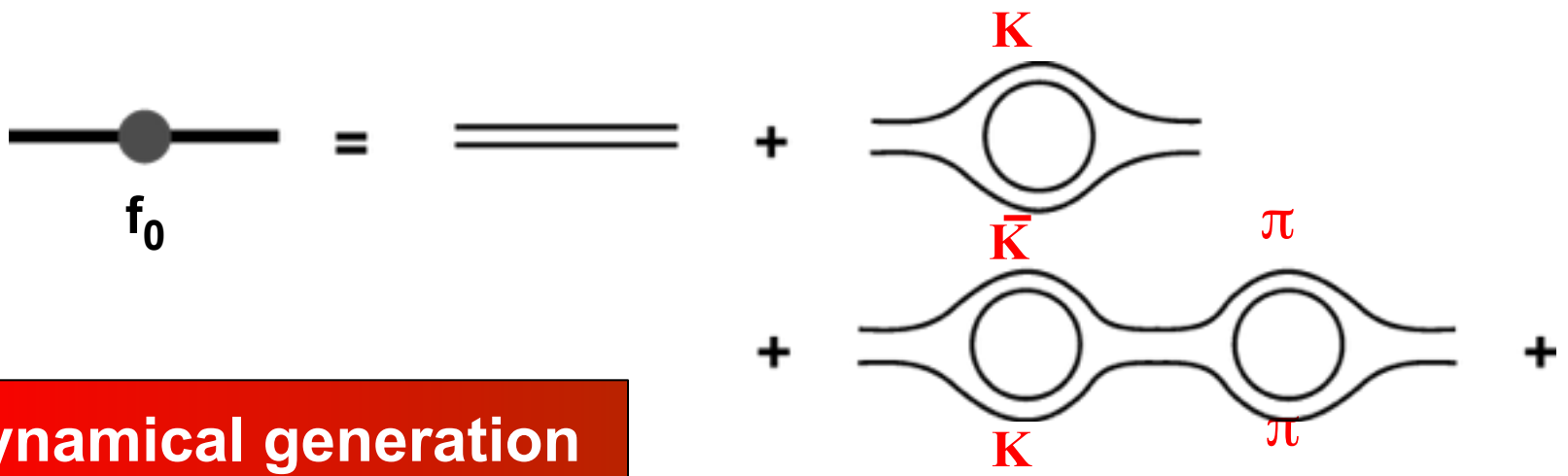
+Tornqvist



s̄s

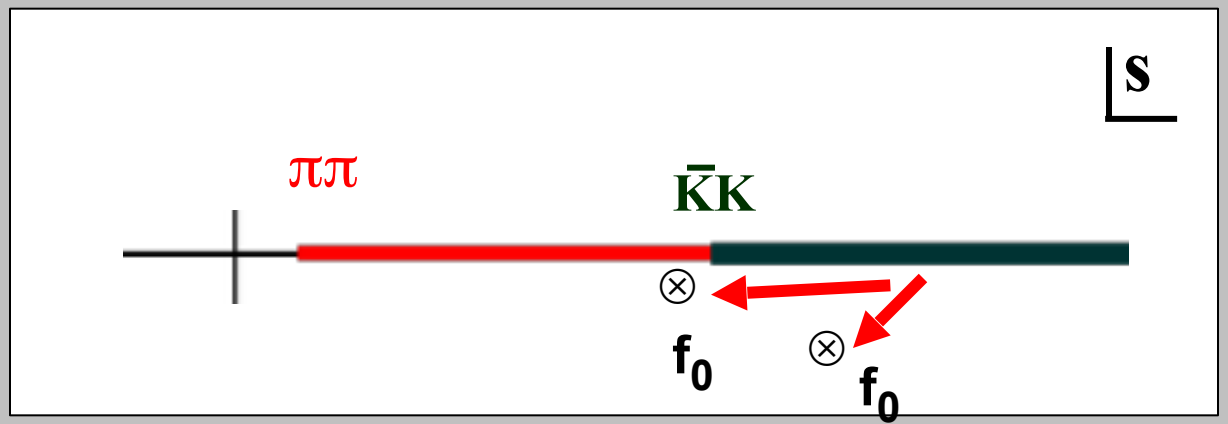
Scalar multiplet

shifting of masses



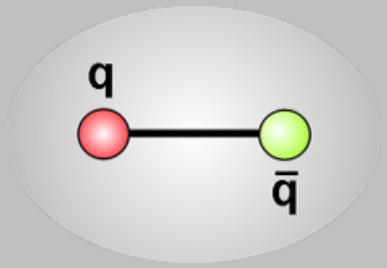
dynamical generation

$\bar{s}s$

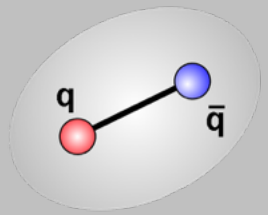


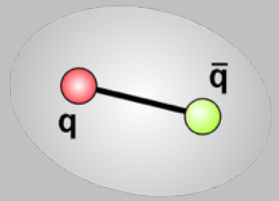
$f_0(980)$

?



K

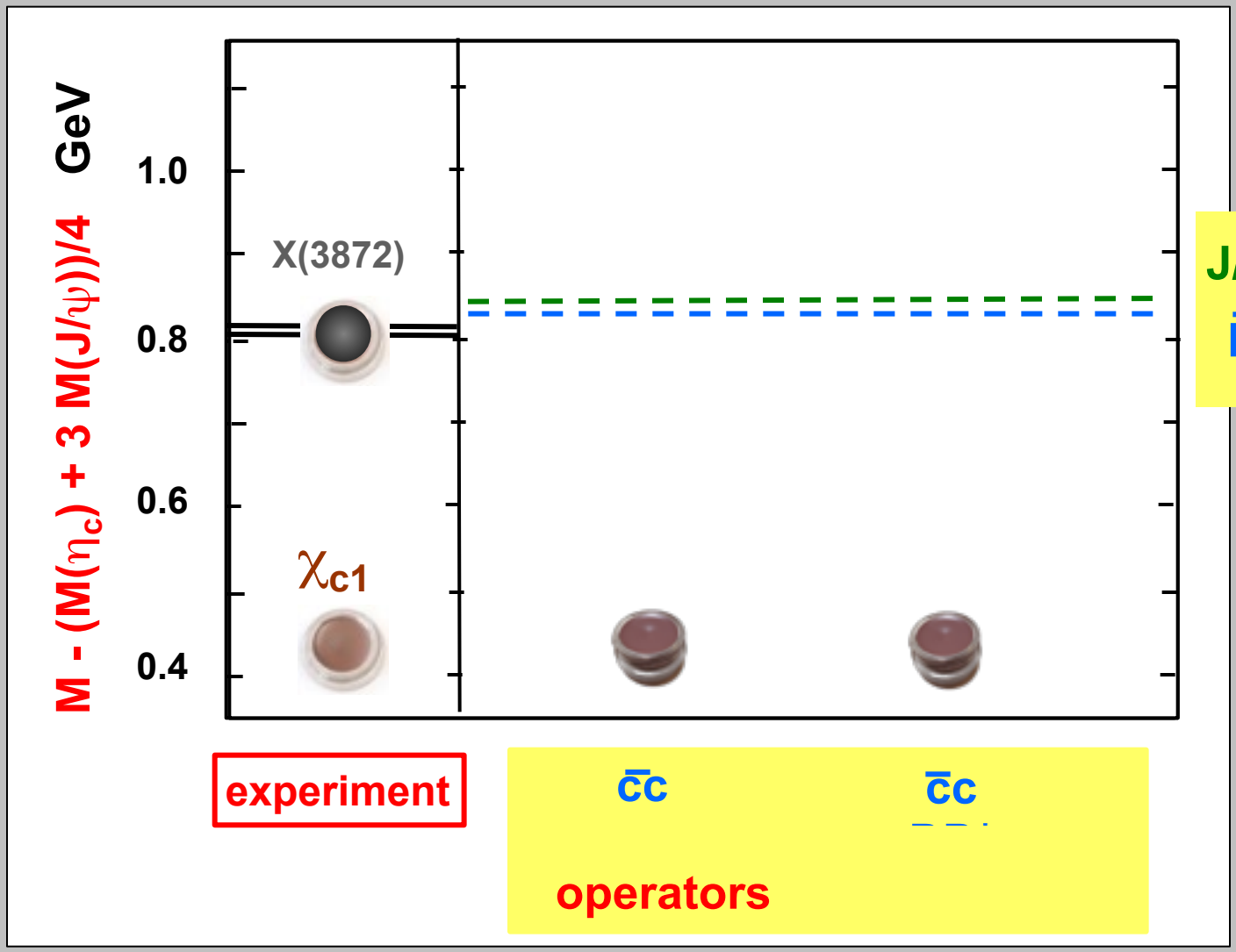




$\bar{K}$

X(3872) & 1^{++} charmonium

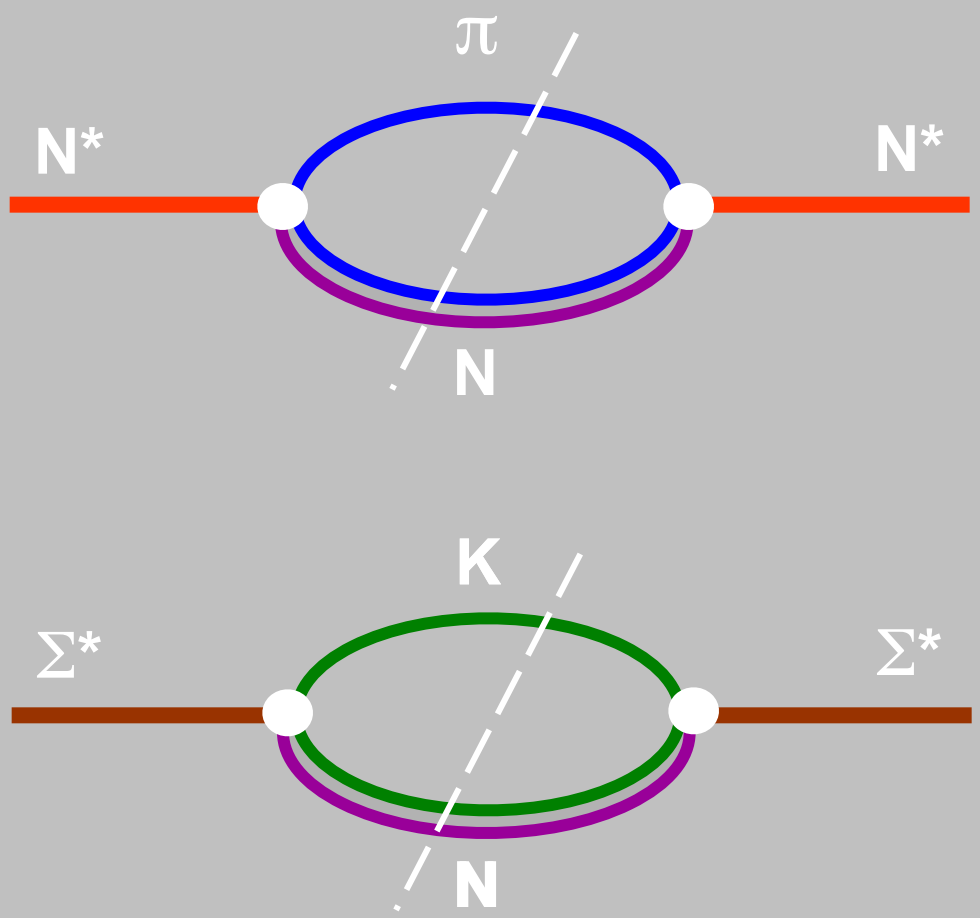
m_π 296 MeV



Prelovsek & Leskovec

Lee, De Tar, Na, Mohler

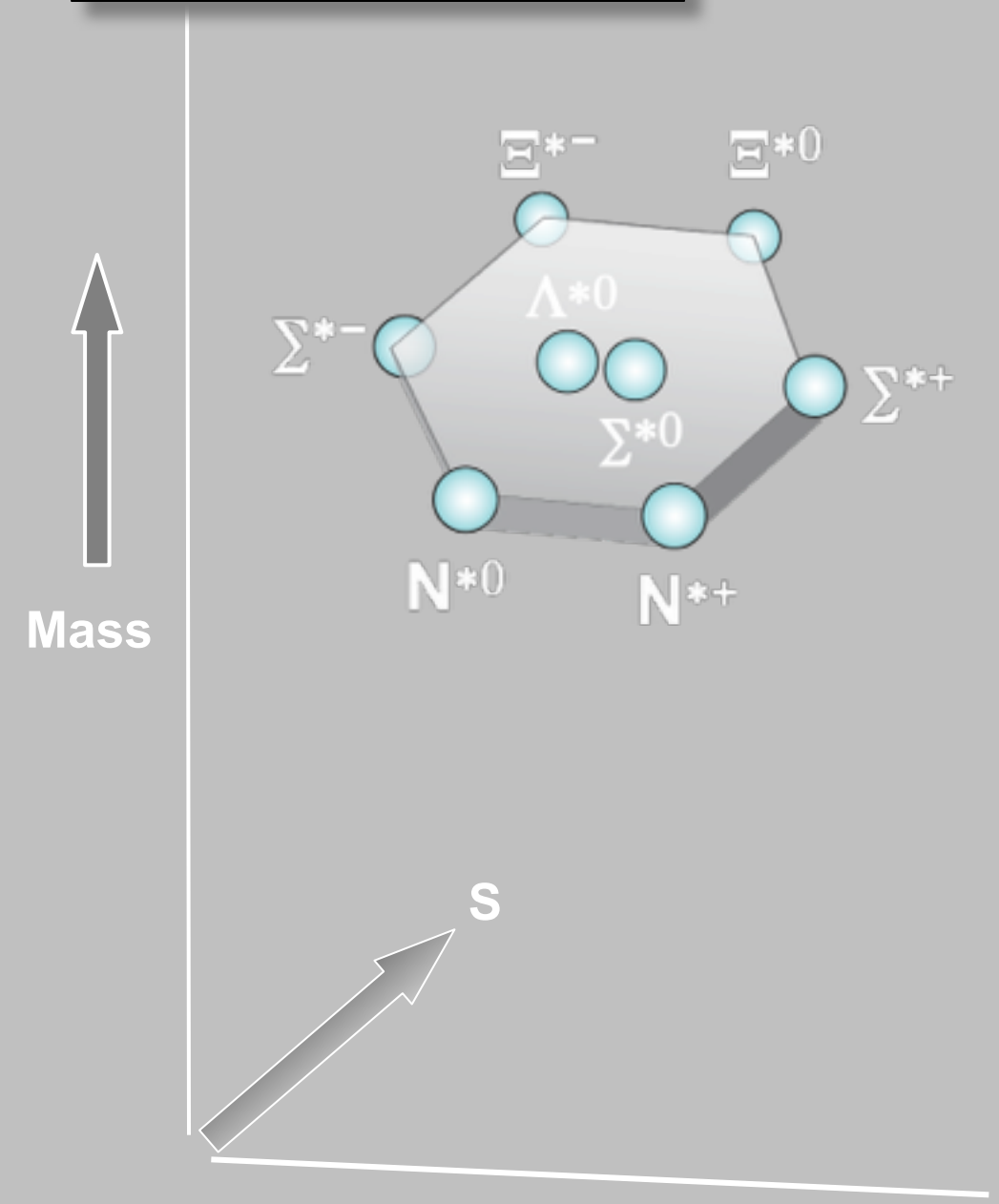
Contributions to baryon decays



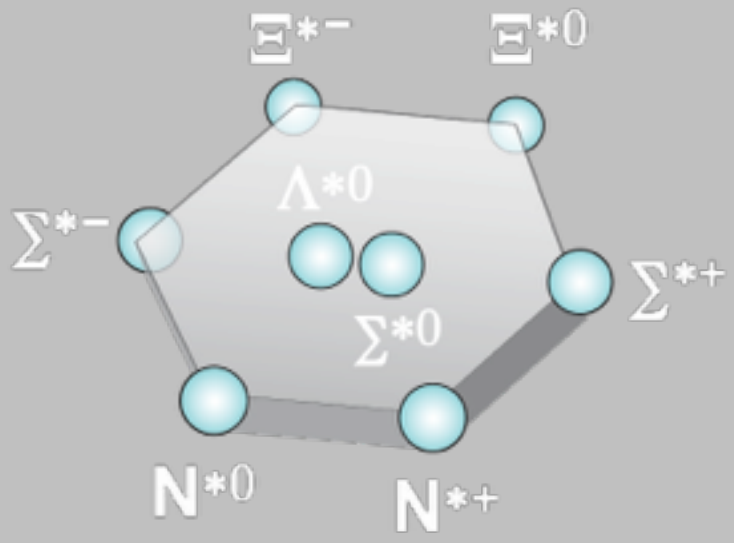
when S-wave interactions

shift most from quark model simplicity

Baryon octet



Baryon octet



Mass

S

decay channels

$K\Sigma$

$\pi\Xi$

KN

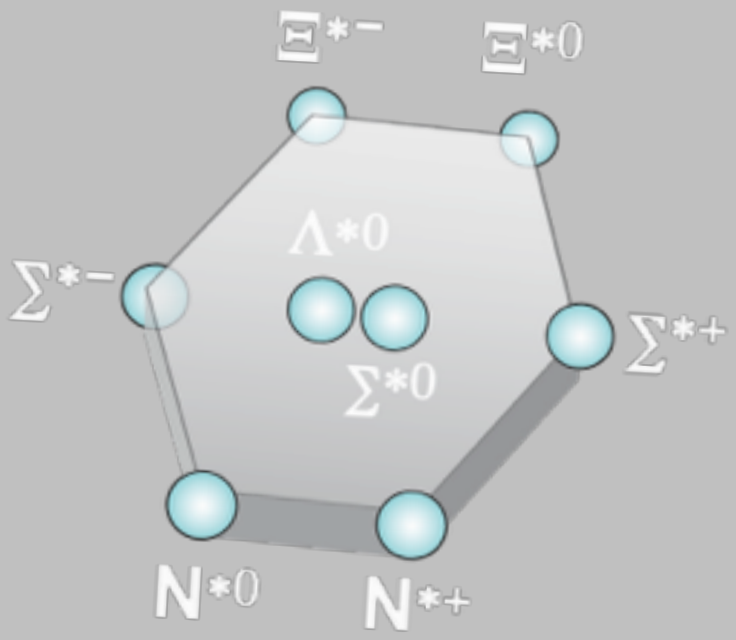
$\pi\Sigma$

$\pi\Delta$

$\pi\pi N$

πN

Baryon octet



Mass

S

decay channels

$K\Sigma$

$\pi\Xi$

KN

$\pi\Sigma$

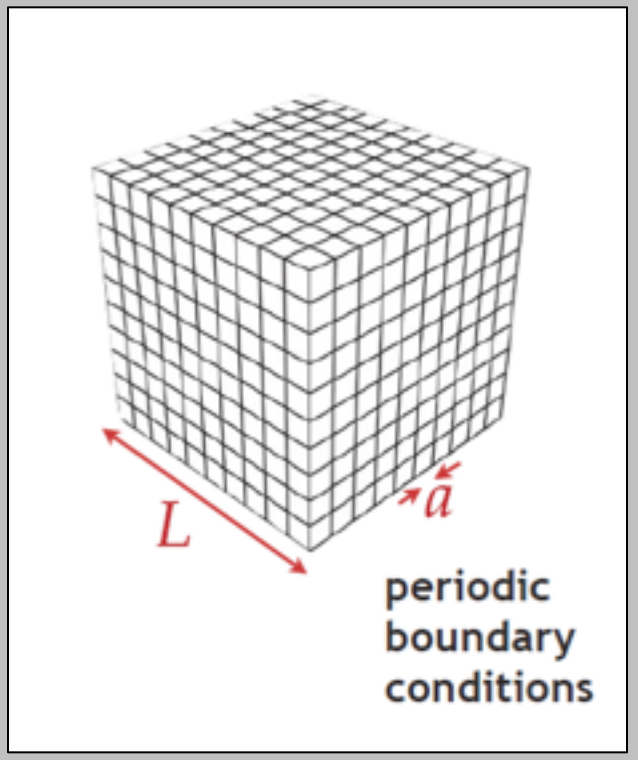
$\pi\Delta$

$\pi\pi N$

πN

Scattering in a box: LQCD

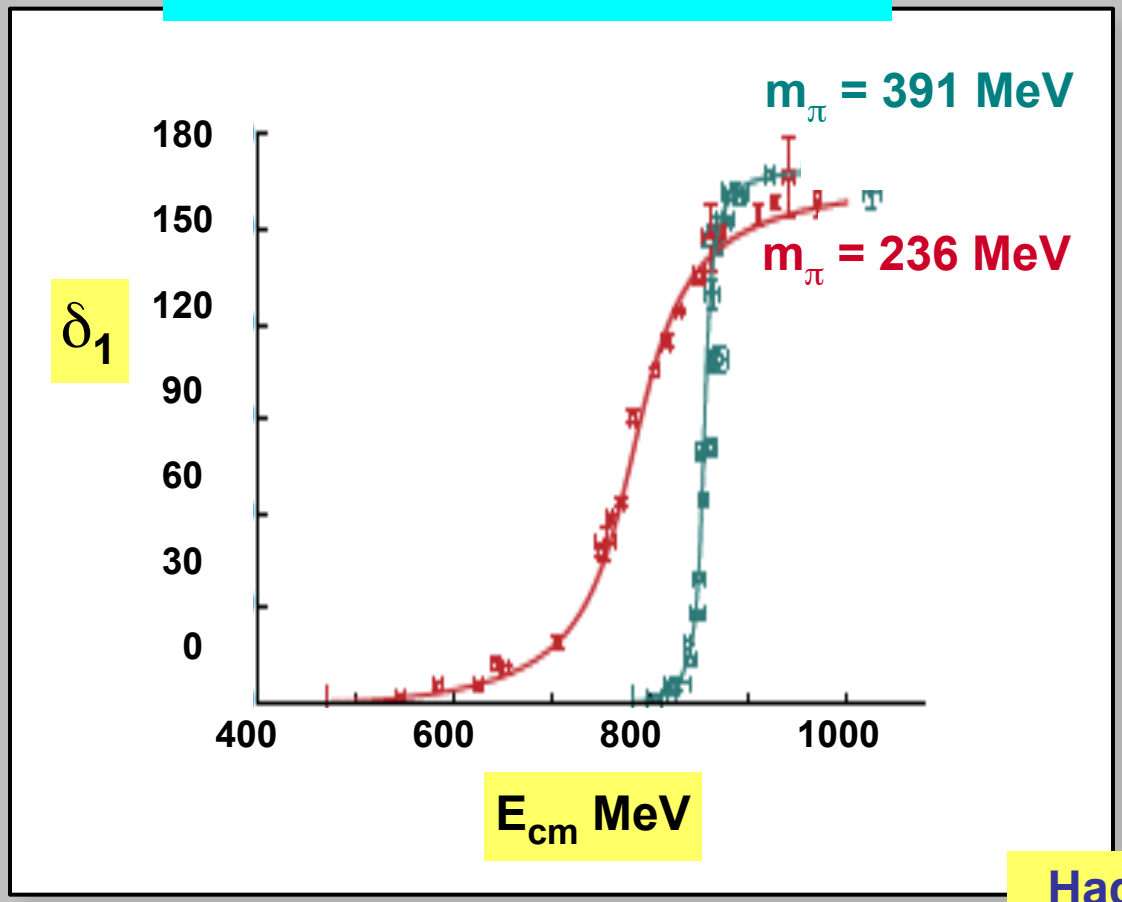
From his ‘90 “Thesis”

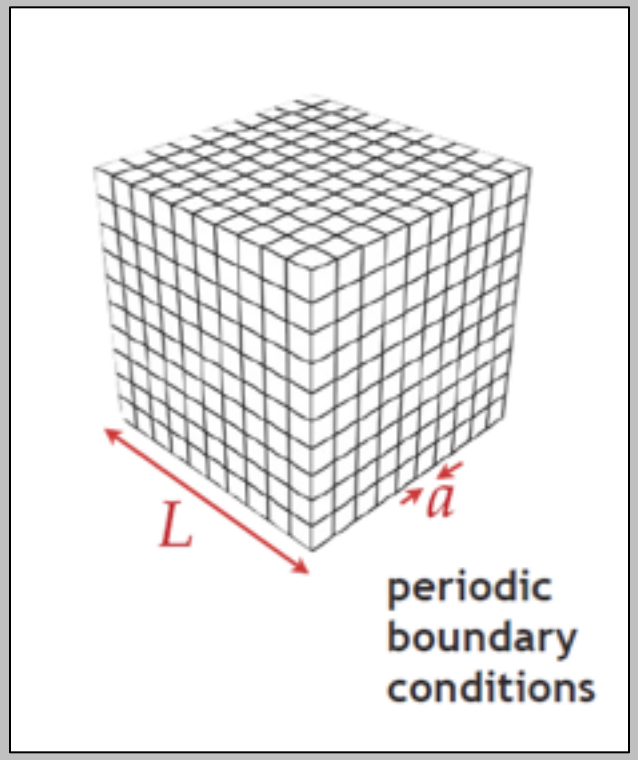


how to connect the finite to the infinite

Scattering in a box: LQCD

$I = J = 1 \quad \pi\pi \rightarrow \pi\pi$

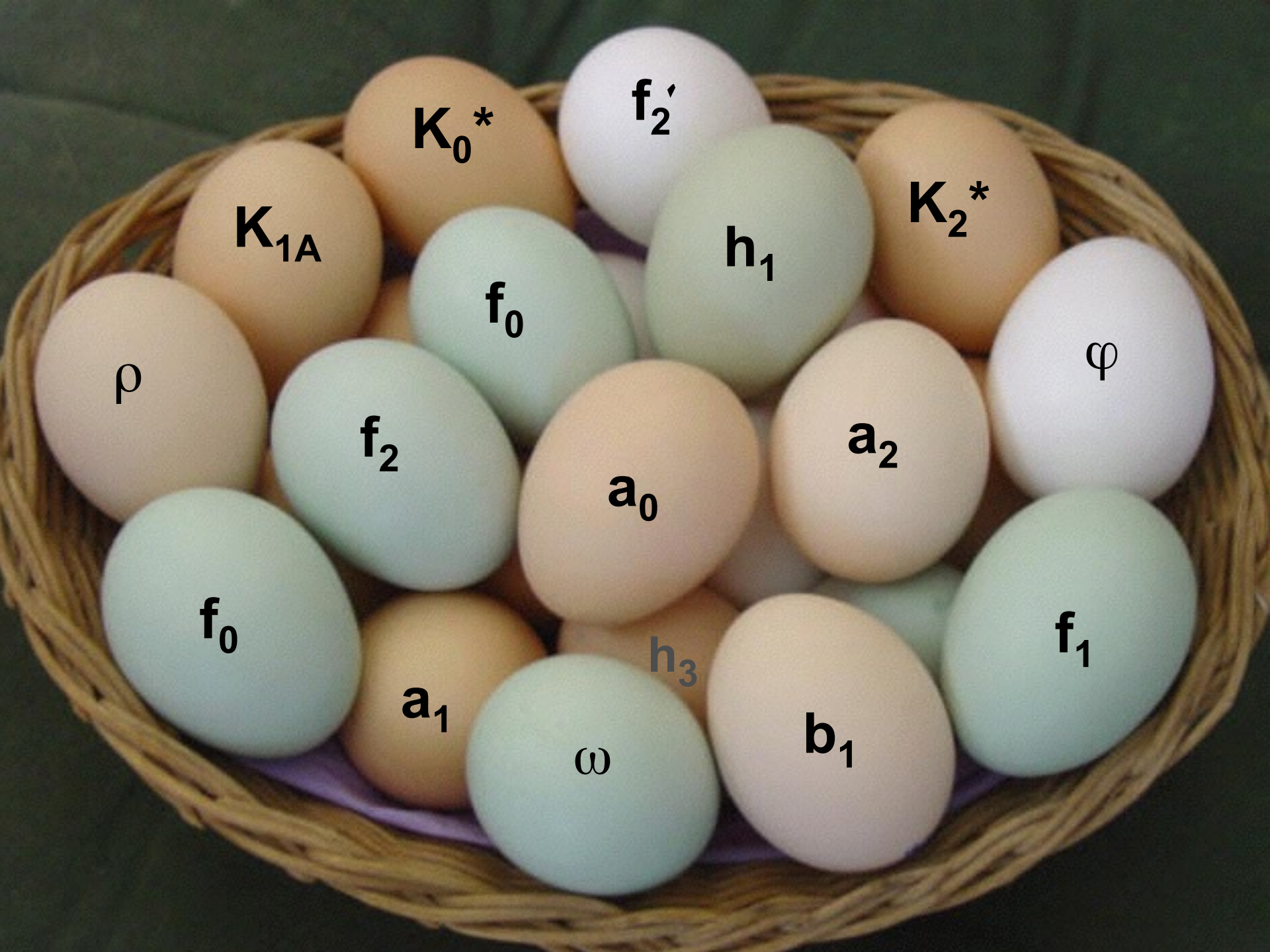




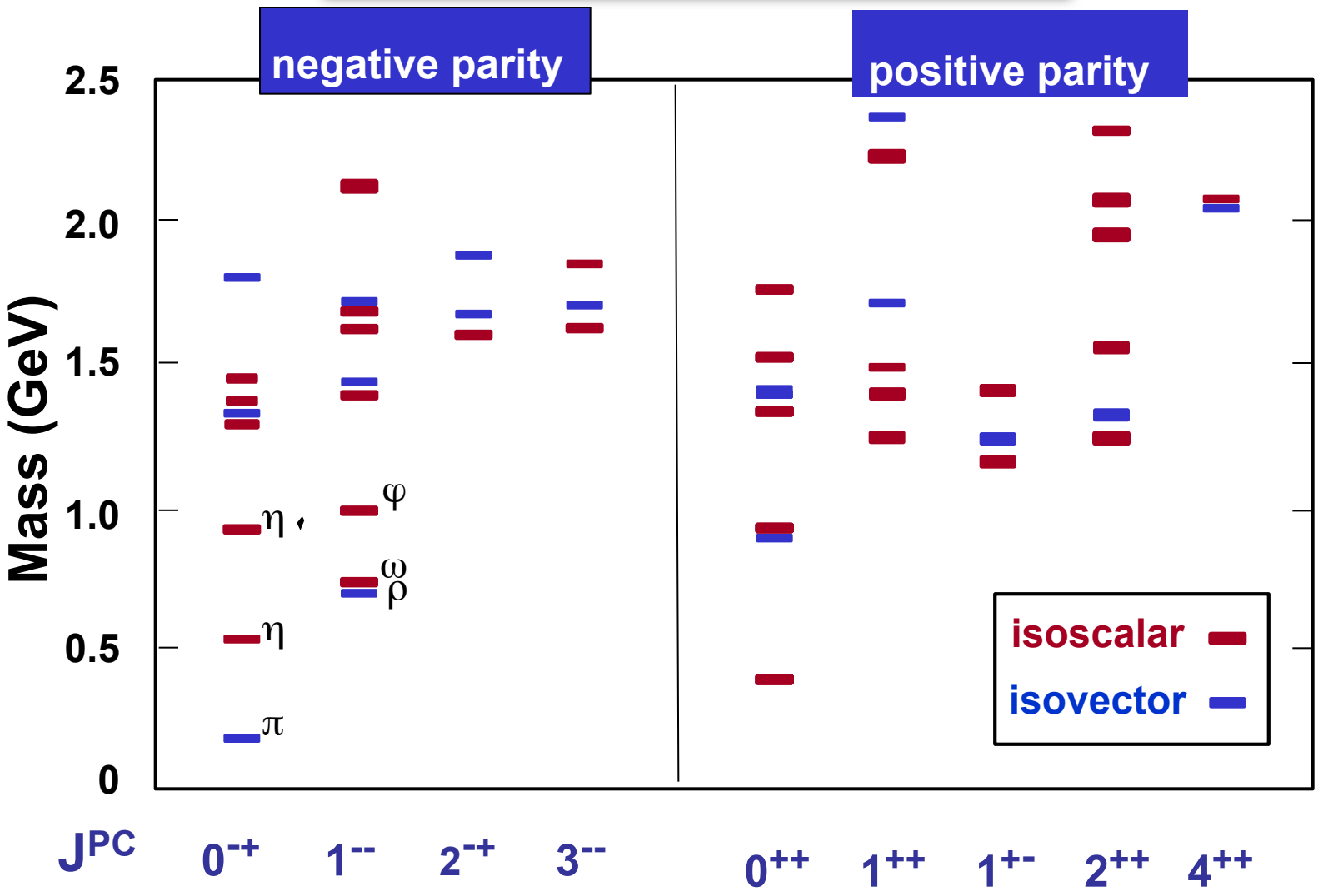
Lüscher method applied

Hadron Spectrum Collaboration
Wilson *et al.*

Lifecycle of a hadron

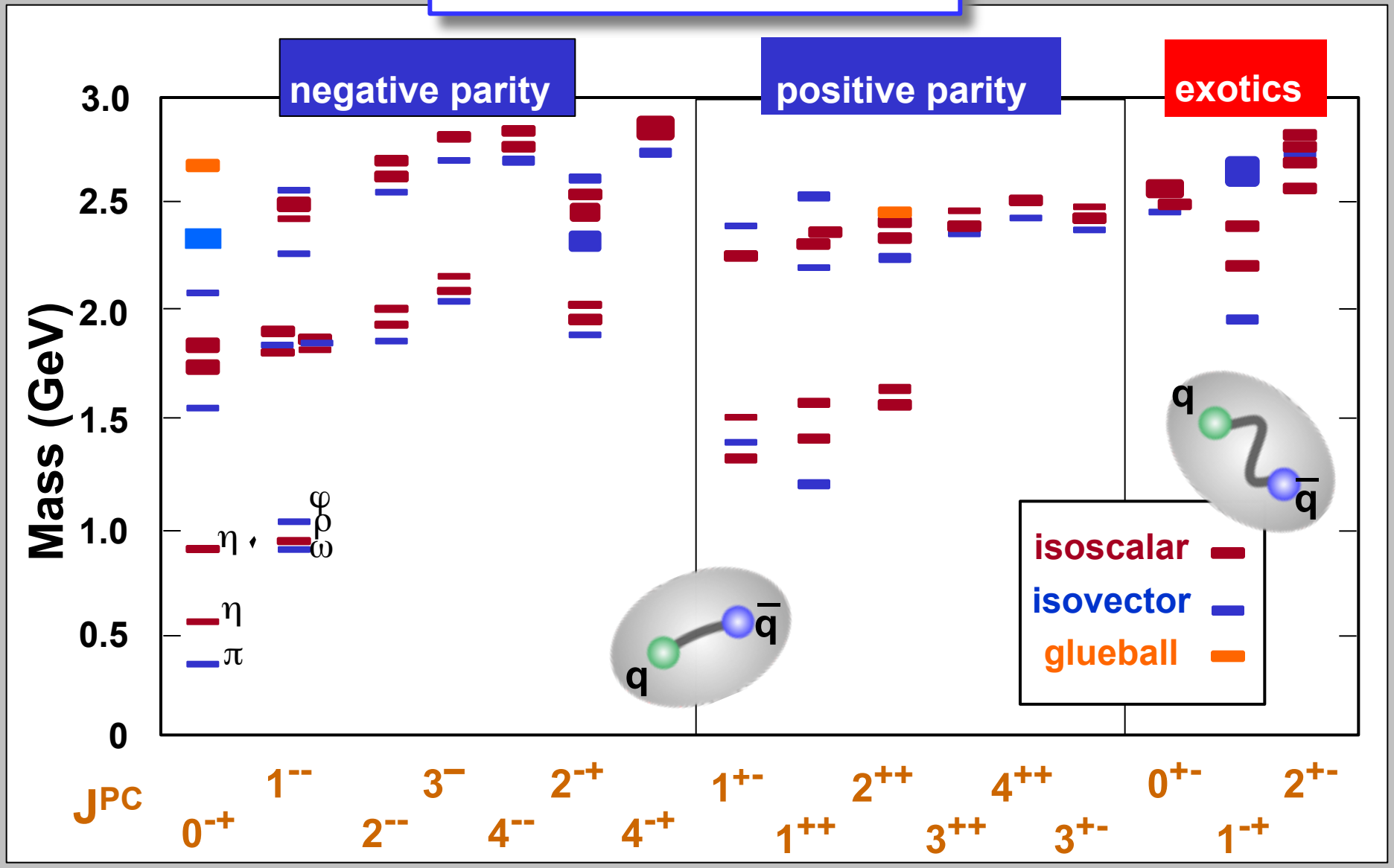

K_0^*
f_2'
K_{1A}
K_2^*
h_1
f_0
ρ
φ
f_2
a_2
a_0
f_0
f_1
h_3
a_1
b_1
ω

Light Meson Spectrum



PDG particle data group

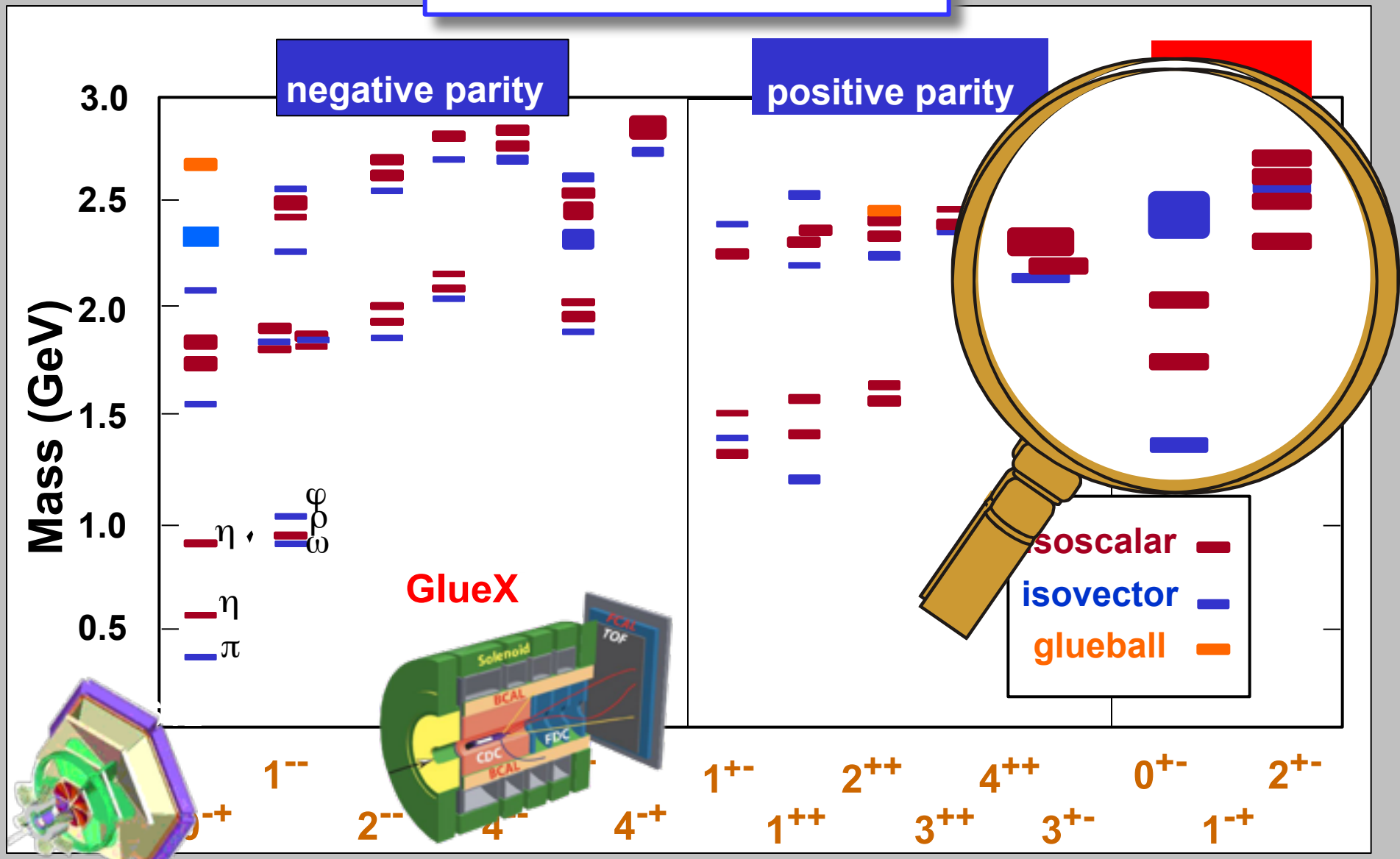
Meson spectrum



Dudek *et al*

m_π = 396 MeV

Meson spectrum



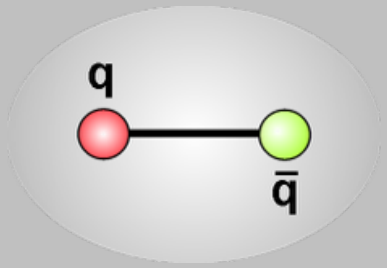
CLAS12

Dudek *et al*

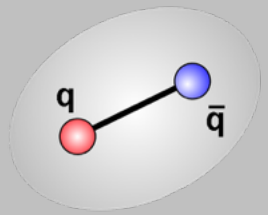
m_π = 396 MeV

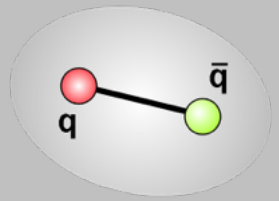
$f_0(980)$

?



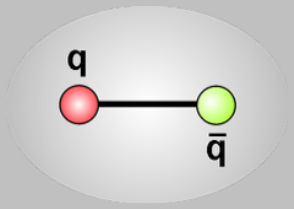
K

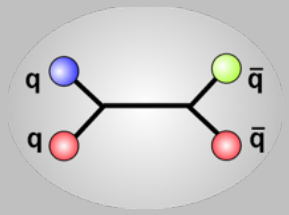




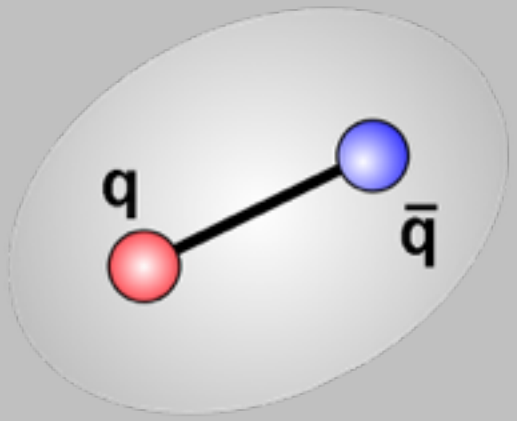
$\bar{K}$

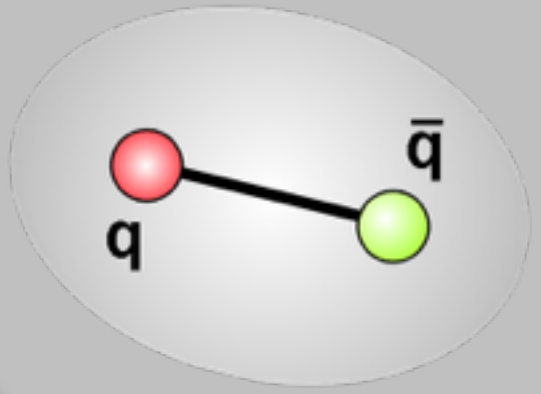
$f_0(980)$





K

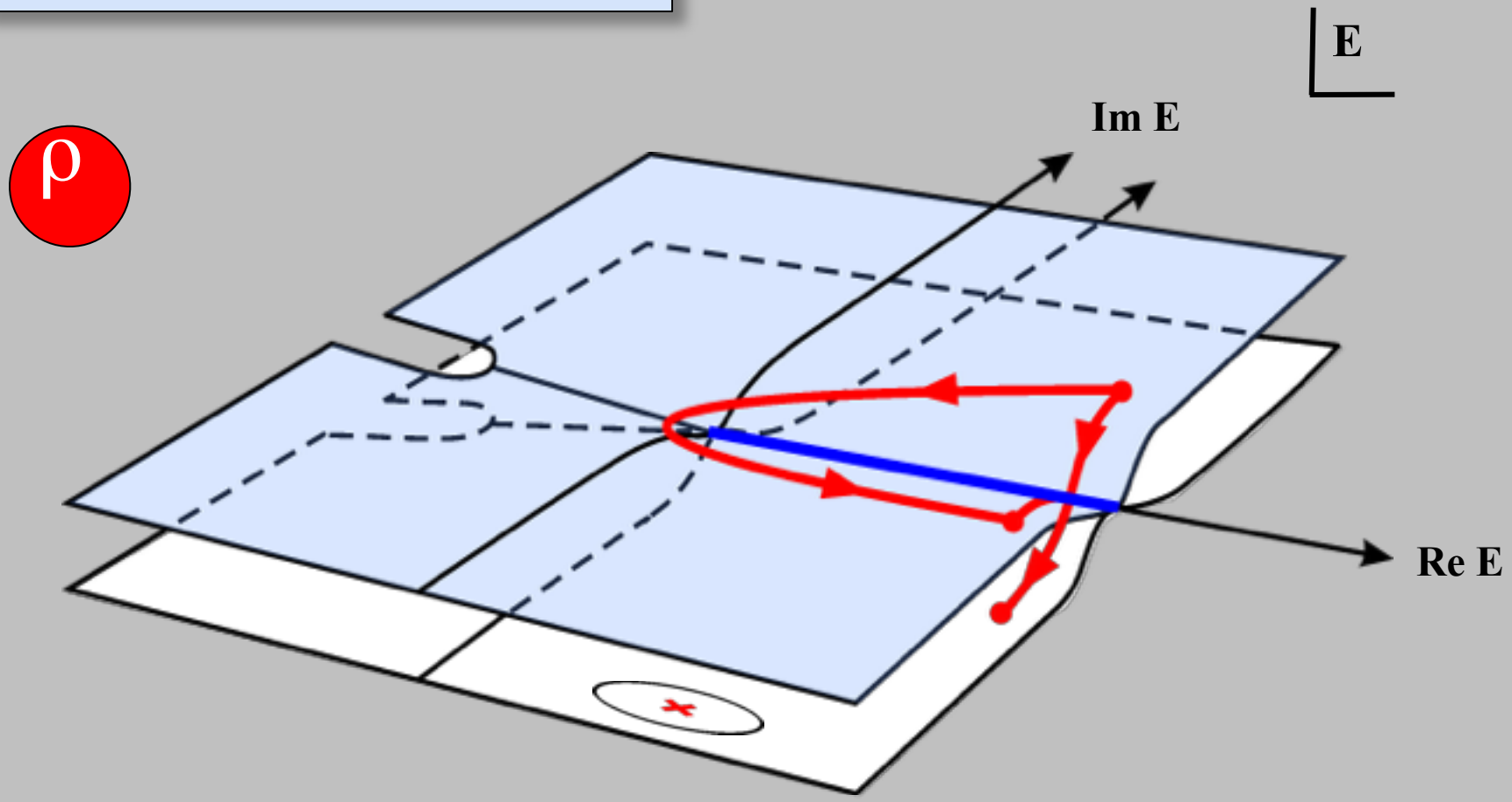




K̄

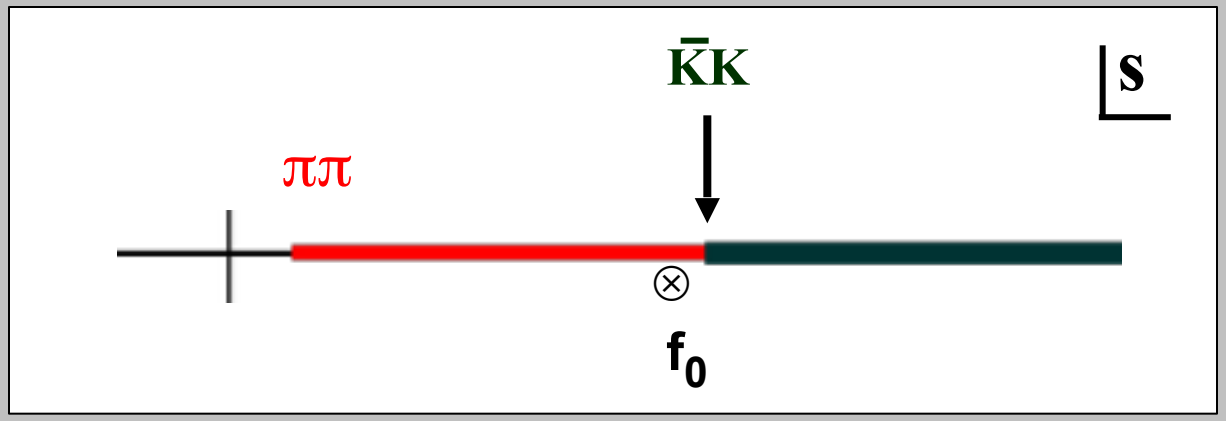
?

Into the complex plane



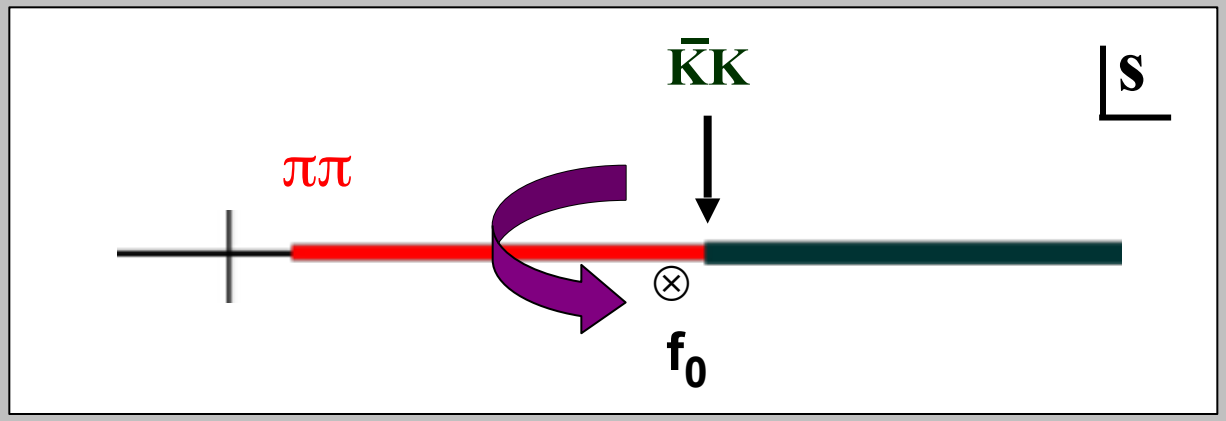
Scalar meson

poles in complex plane

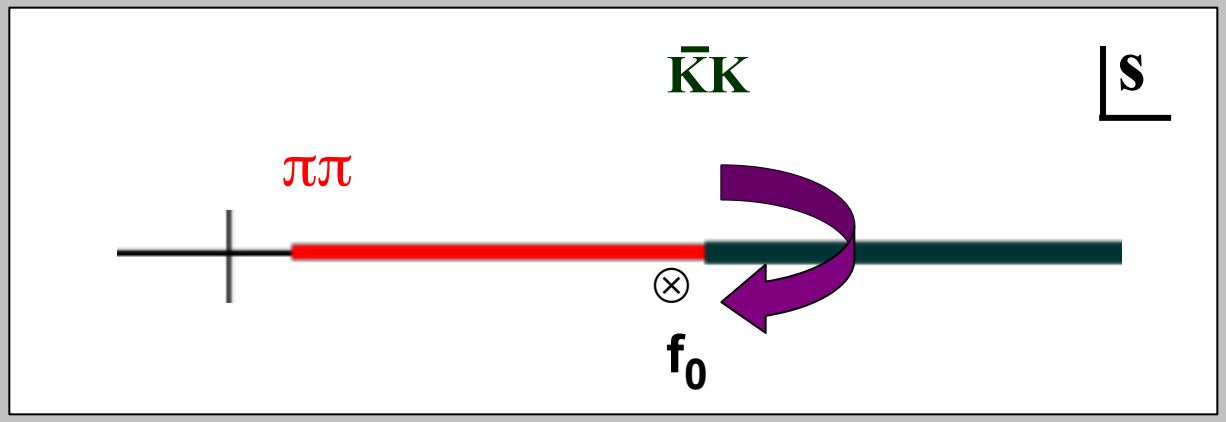


Scalar meson

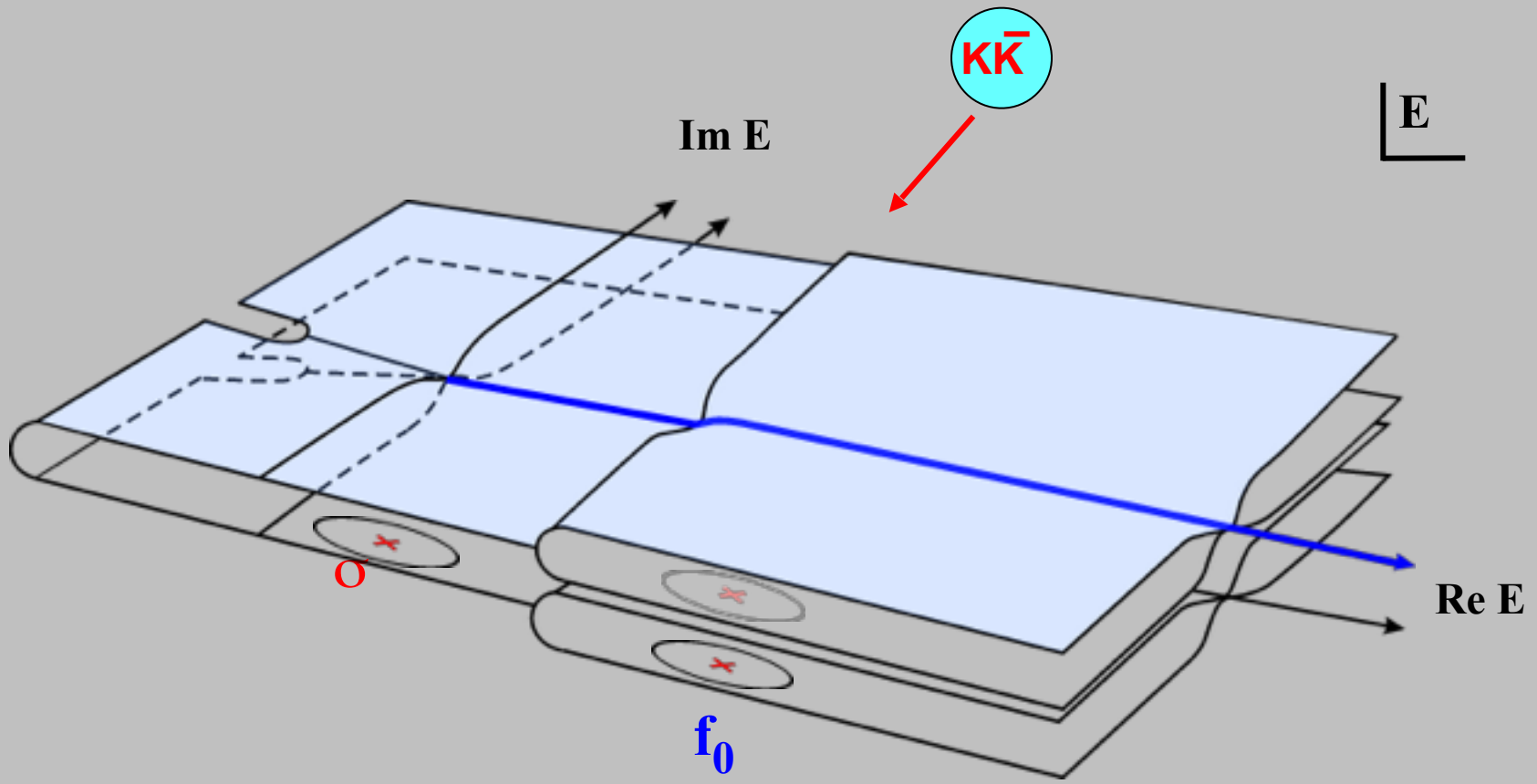
poles in complex plane



Is there a mirror pole?

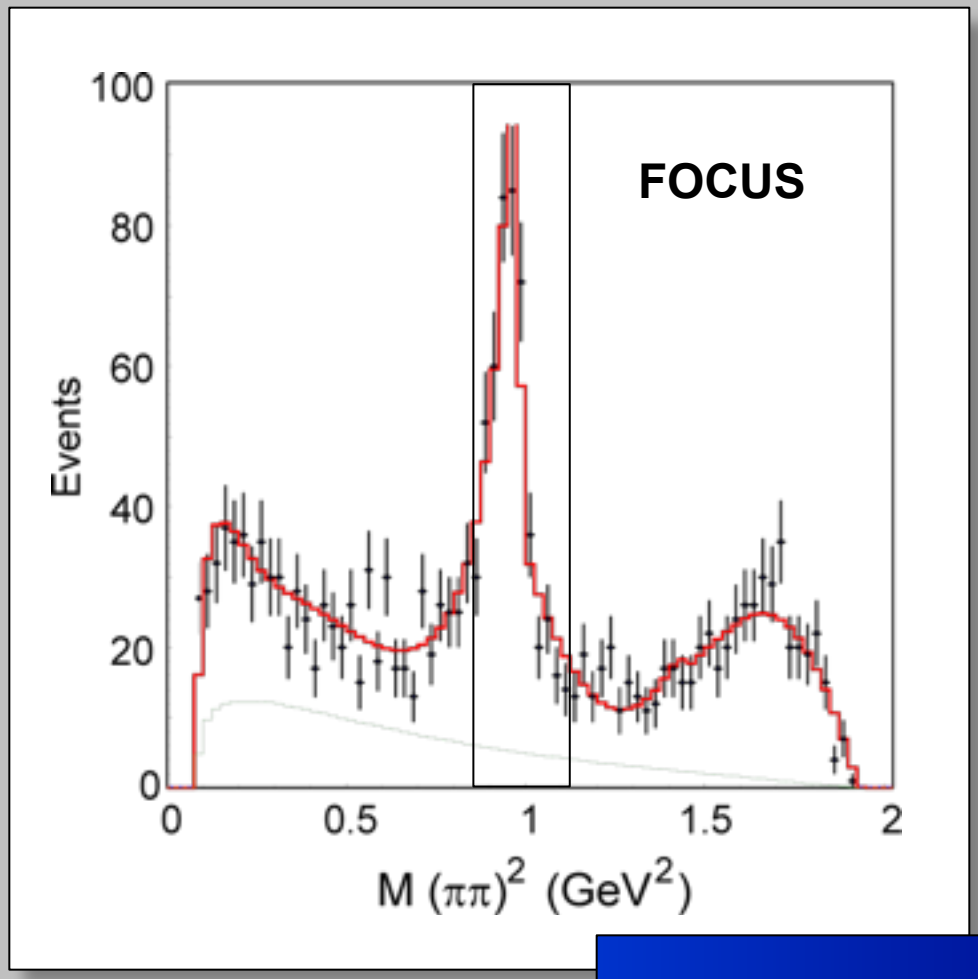


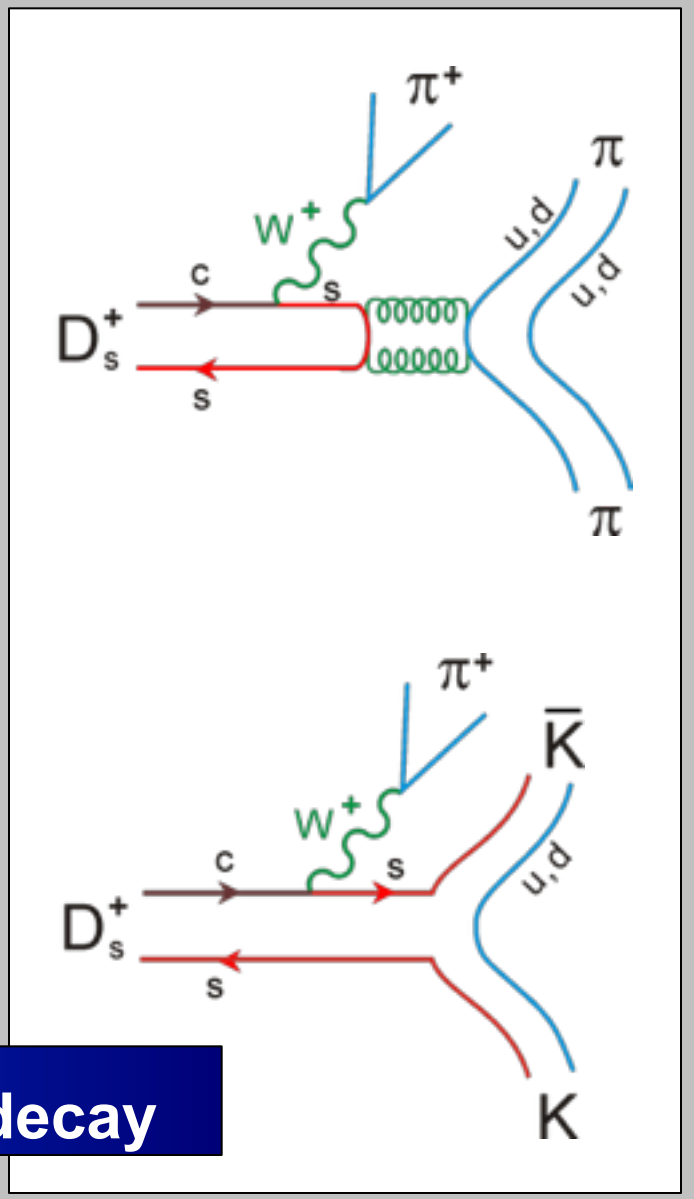
Quark state v Molecule



Weinberg
Morgan

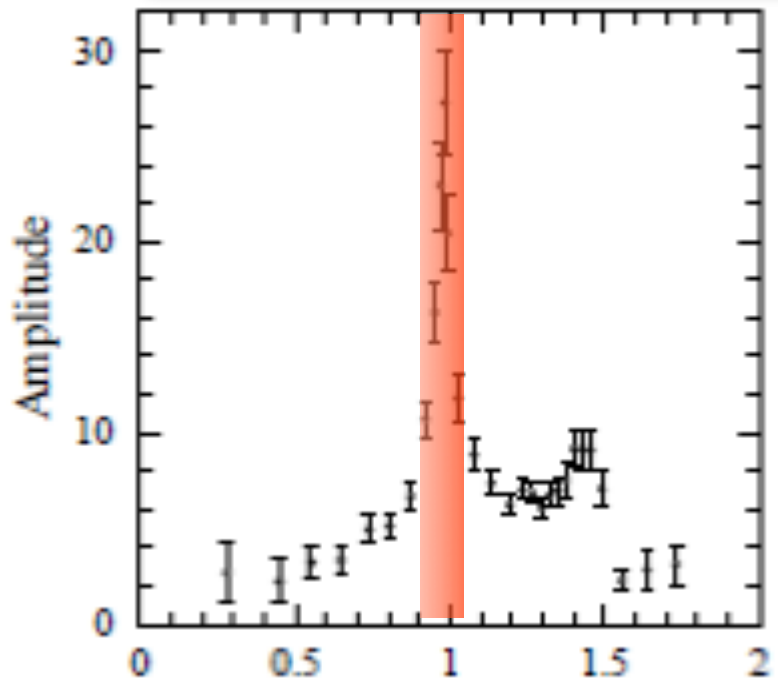
Heavy flavor decays



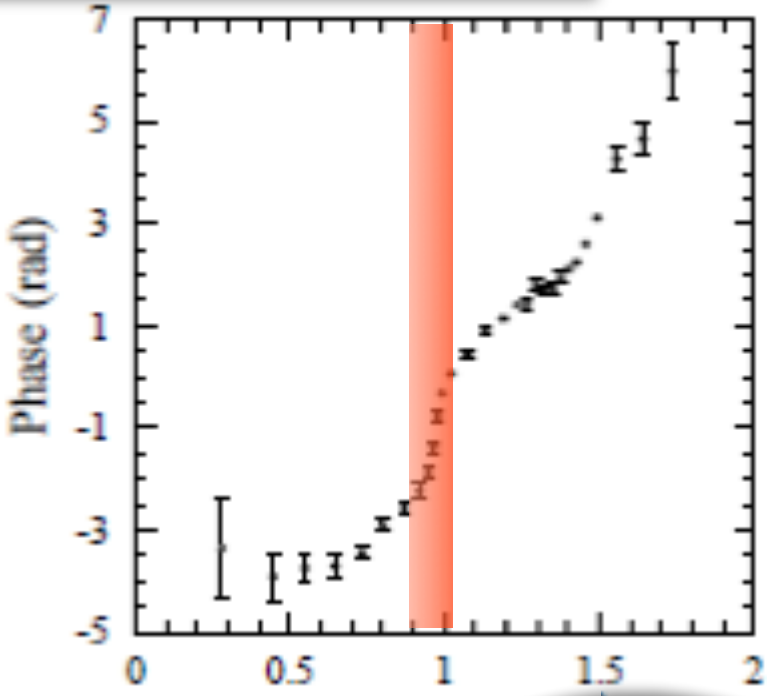


$D_s \rightarrow (MM)\,\pi$ decay

$\pi\pi$ S-wave in $D_s \to \pi(\pi\pi)$ decay



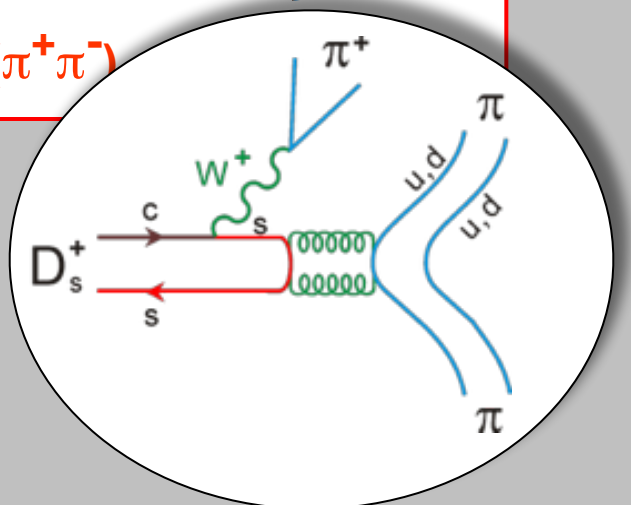
$M(\pi^+\pi^-)$ GeV



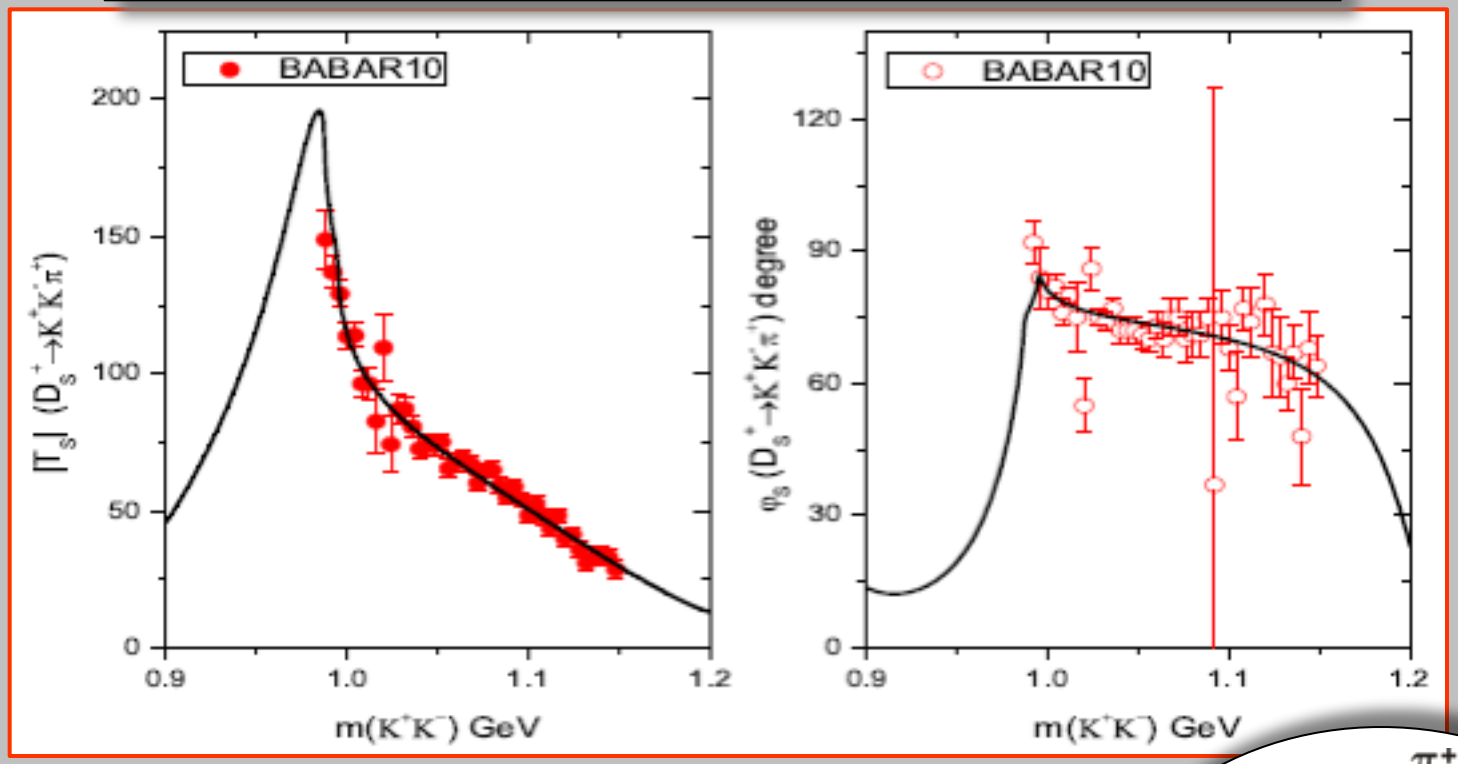
$M(\pi^+\pi^-)$

BaBar pwa

Pappagallo, P *et al.*

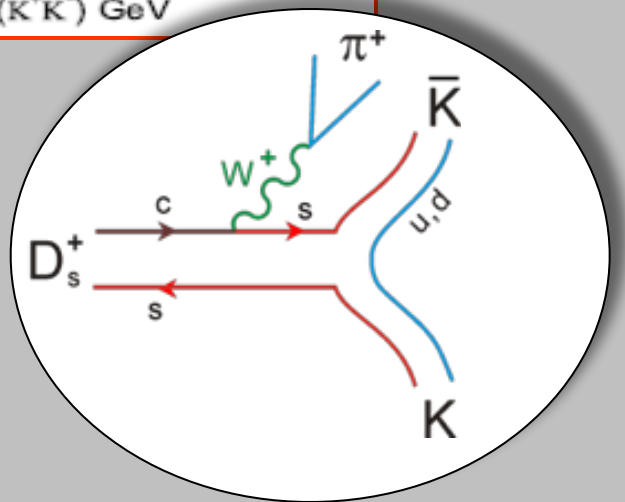


$\bar{K}K$ S-wave in $D_s \to \pi(\bar{K}K)$ decay

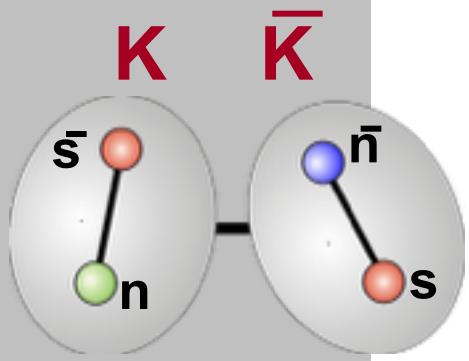


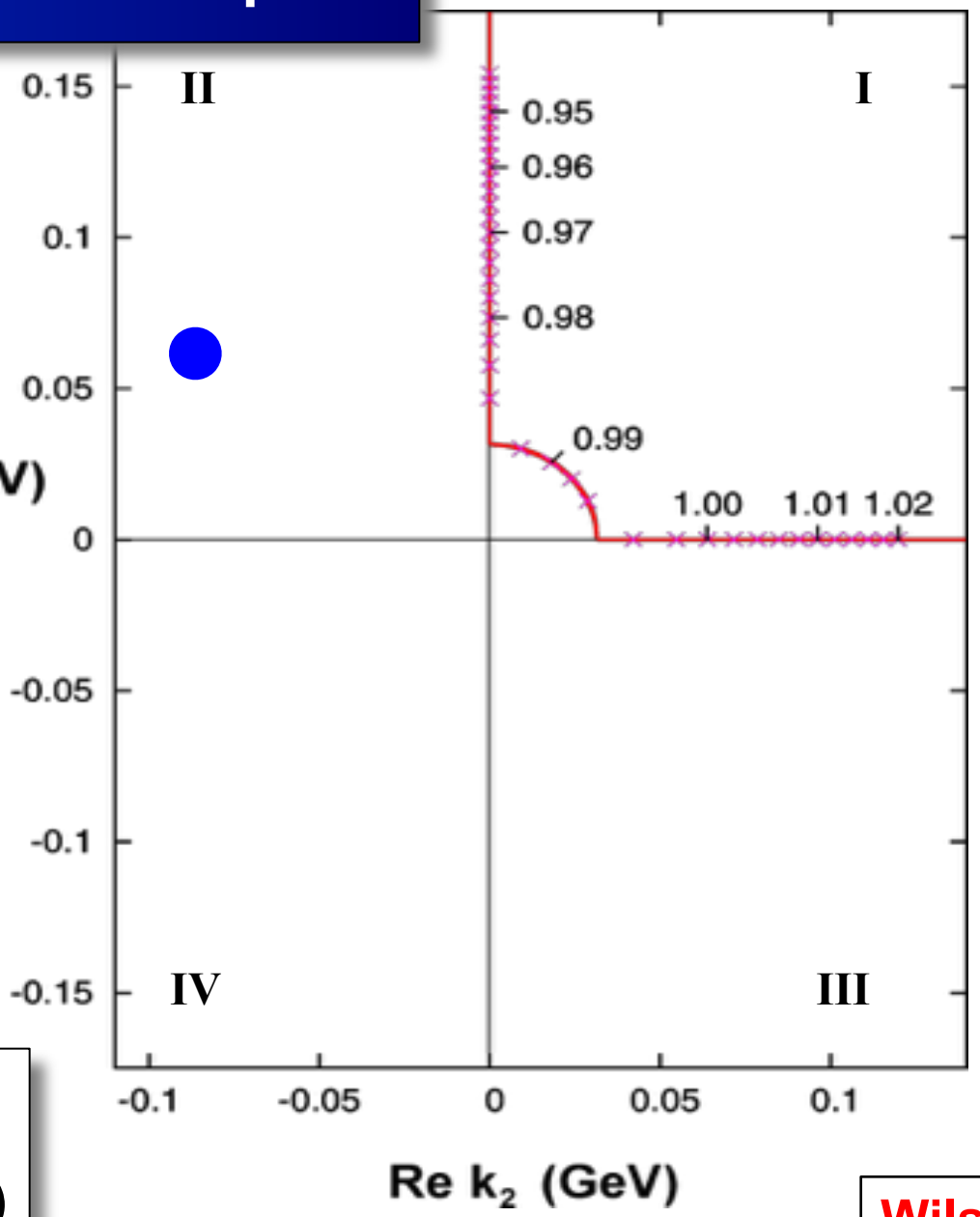
BaBar pwa

Pappagallo, P *et al.*



Jost function: 1 pole v 2 pole



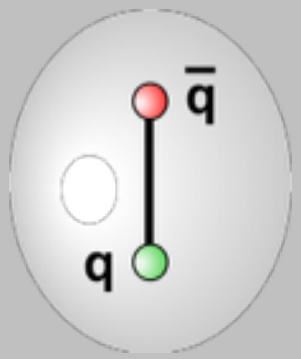


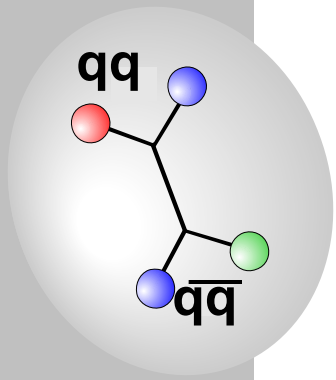
k_2 plane

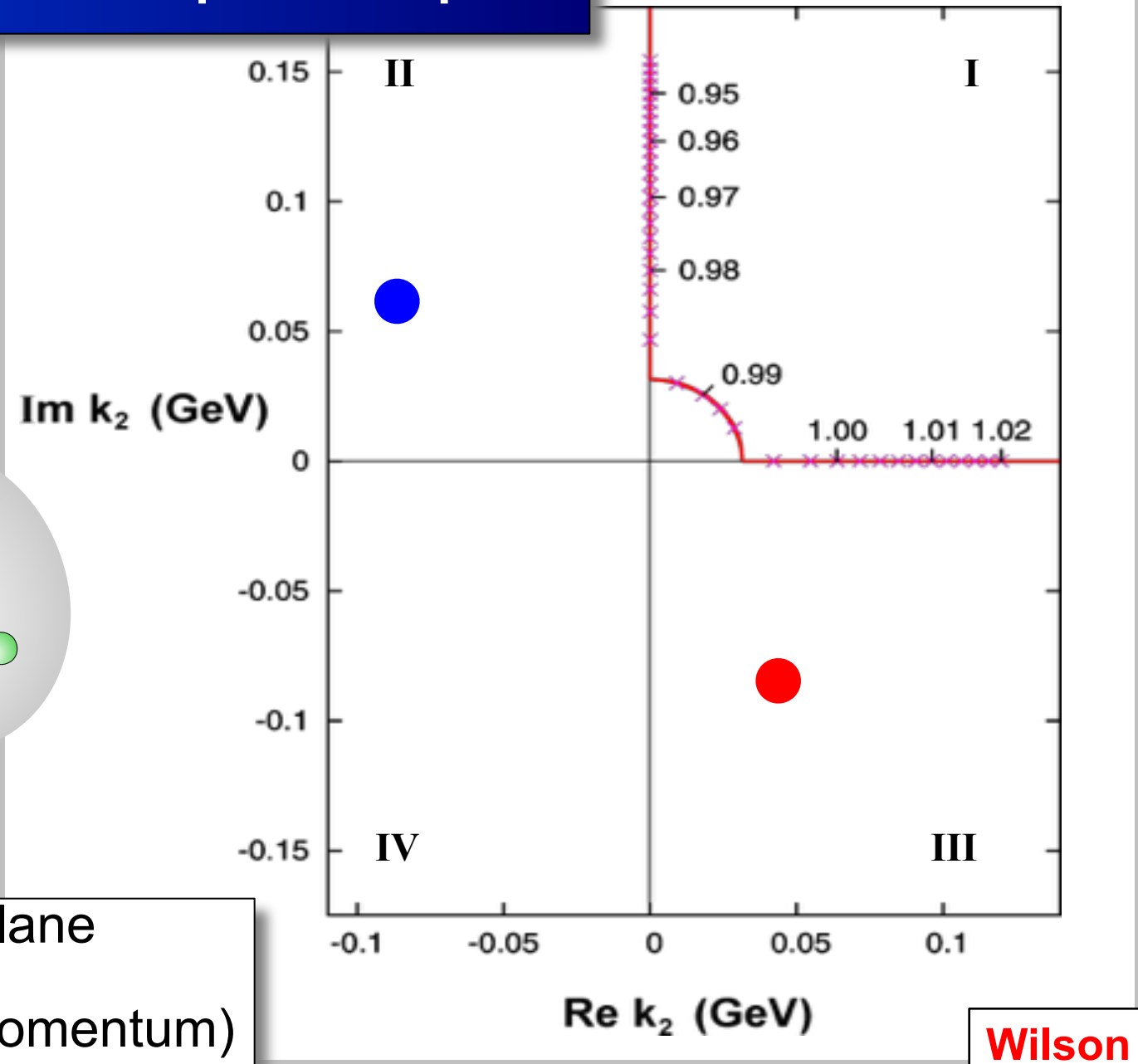
(K$\bar{K}$ c.m. momentum)

Wilson & P

Jost function: 1 pole v 2 pole





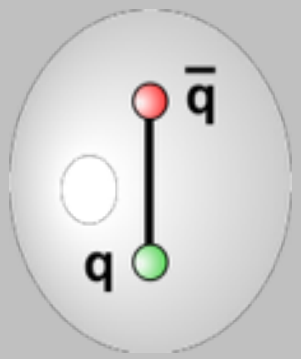


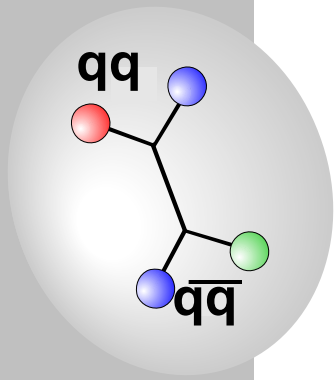
k_2 plane

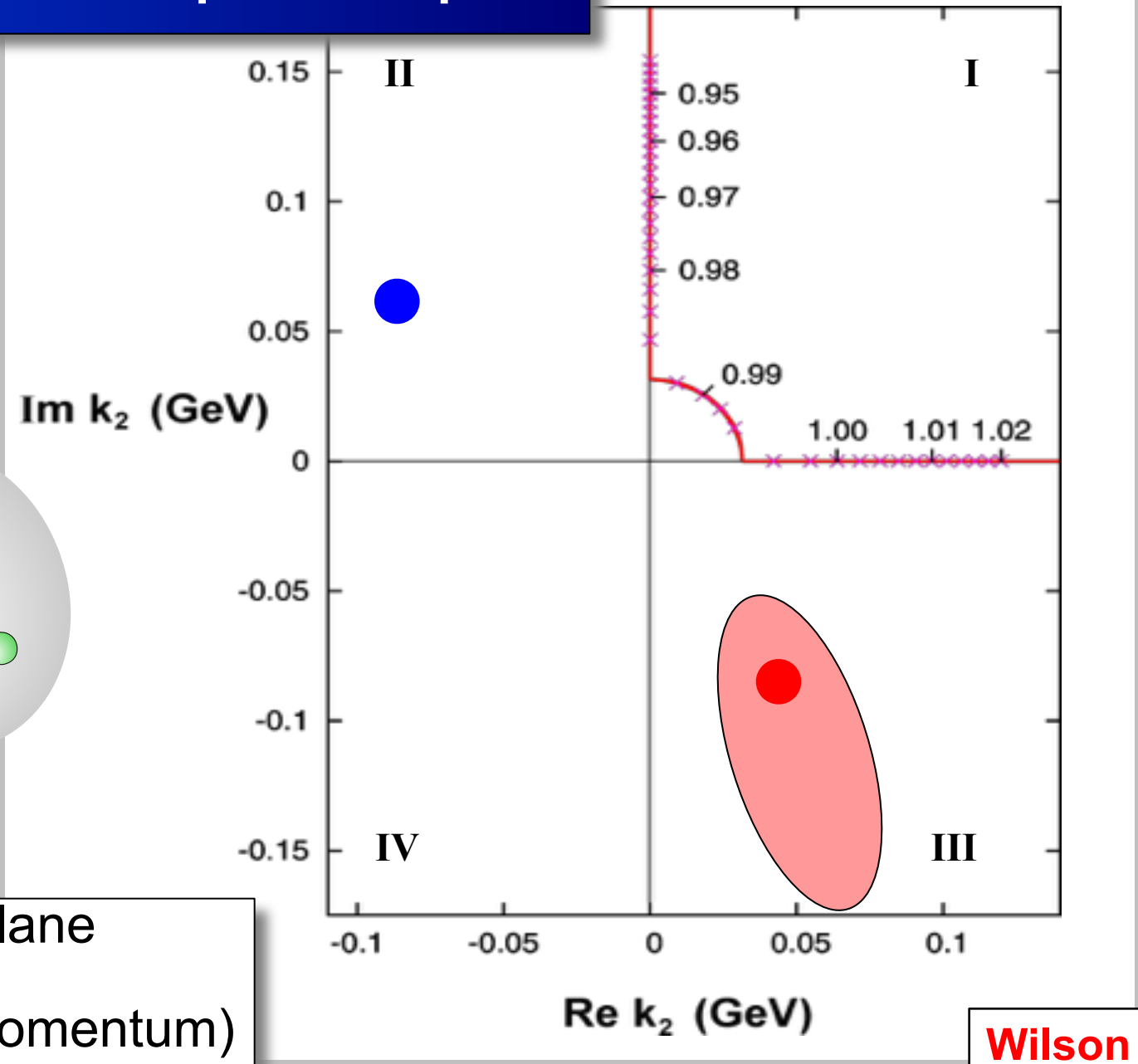
($K\bar{K}$ c.m. momentum)

Wilson & P

Jost function: 1 pole v 2 pole





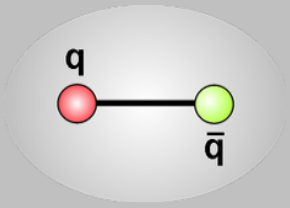


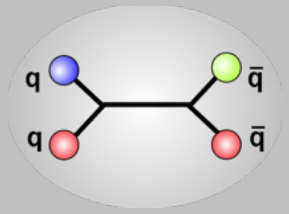
k_2 plane

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

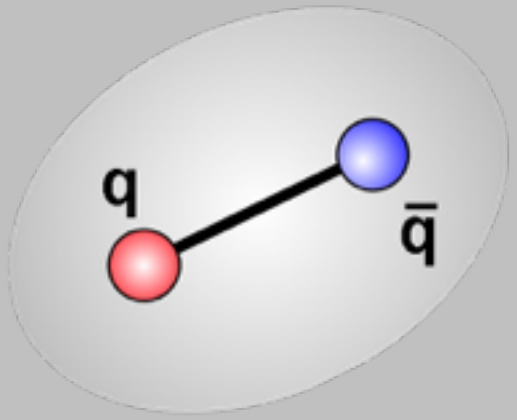
Wilson & P

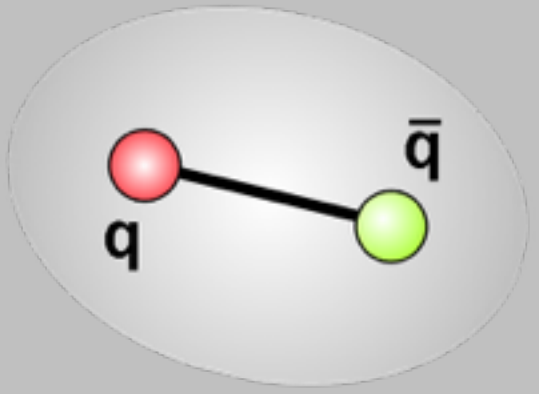
$f_0(980)$





K

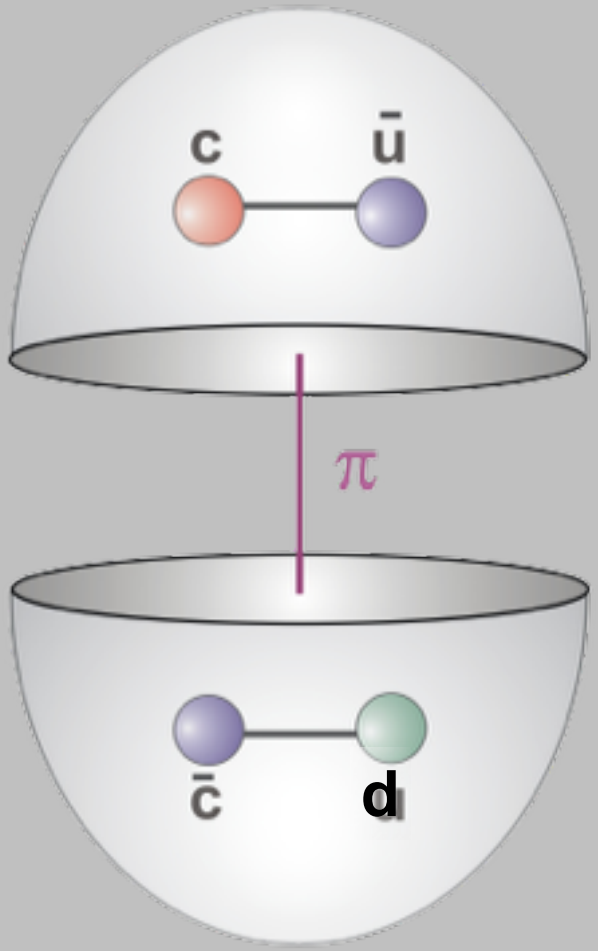




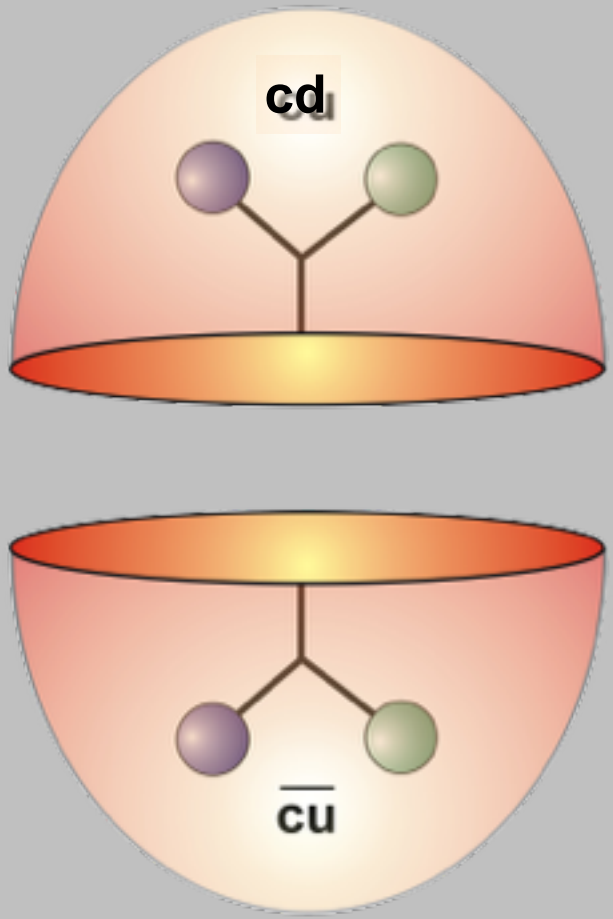
K̄

Z_c^-

molecule

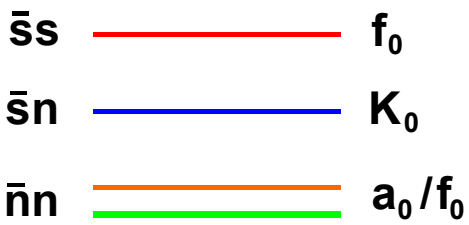


tetraquark

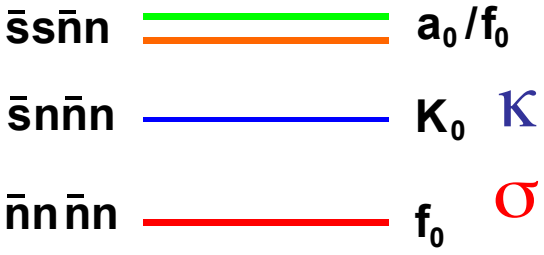


Scalar meson multiplets

$q\bar{q}$



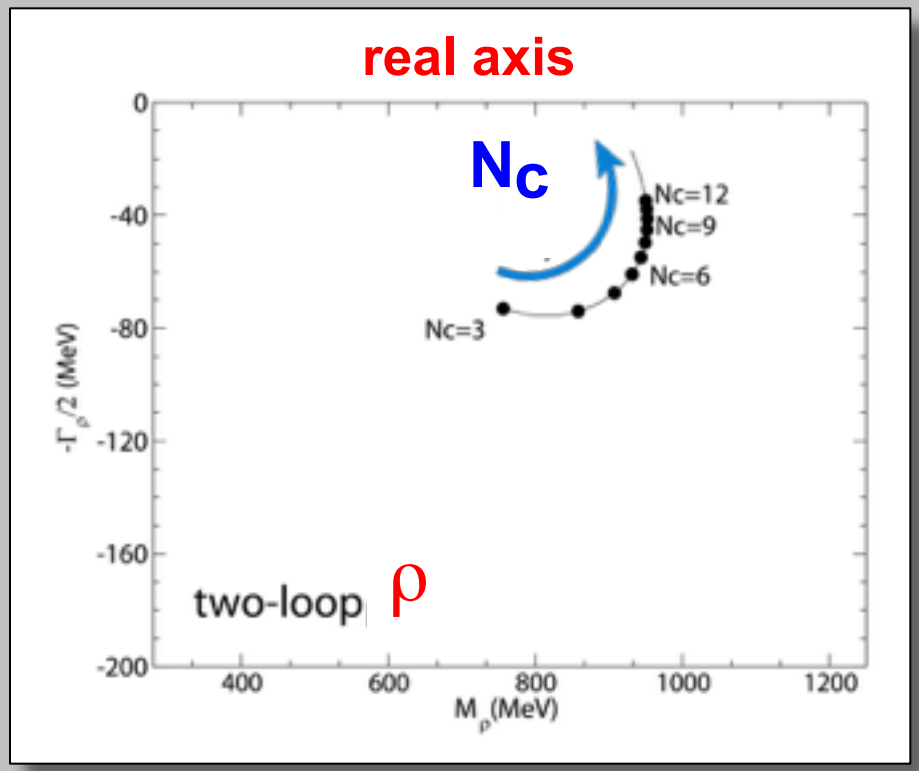
$q\bar{q}q\bar{q}$

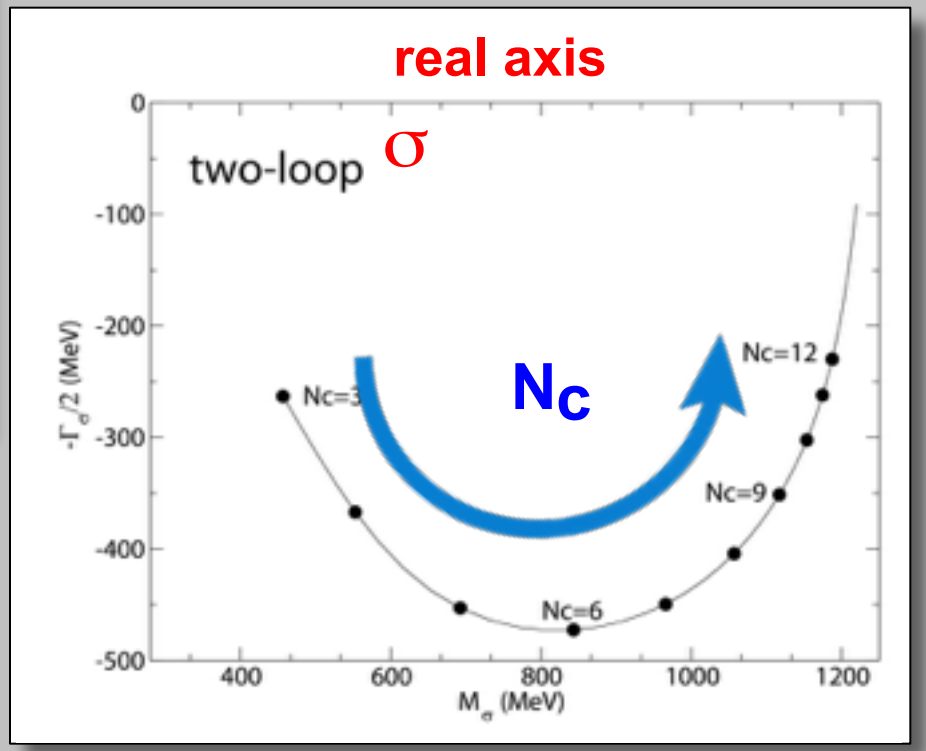


N_c large ⟶ stable

N_c large ⟶ meson continuum

1 / N_c @ two loops





Pelaez, Ruiz de Elvira, Wilson & P