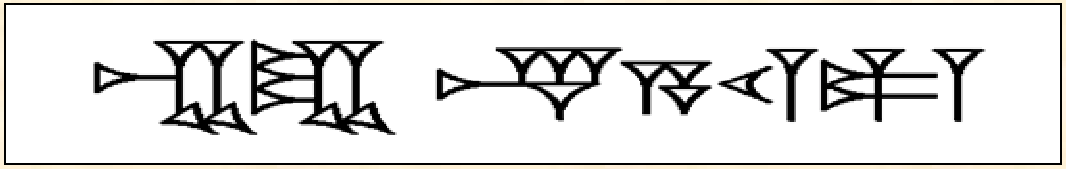
In the debris of hadron interactions lies the beauty of QCD

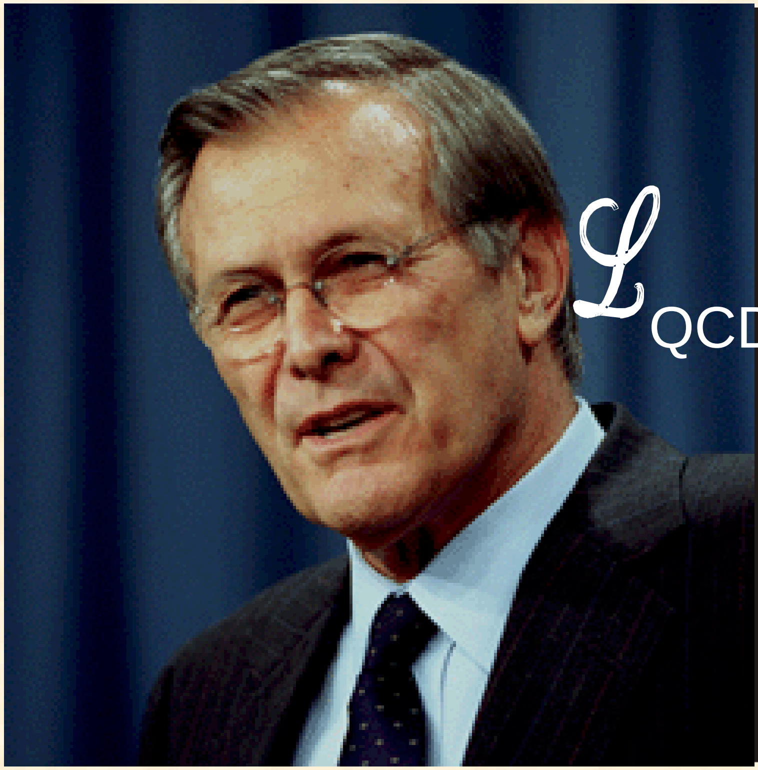
Book of QCD



Workshop on
Gluonic Excitations
JLab, May 2003

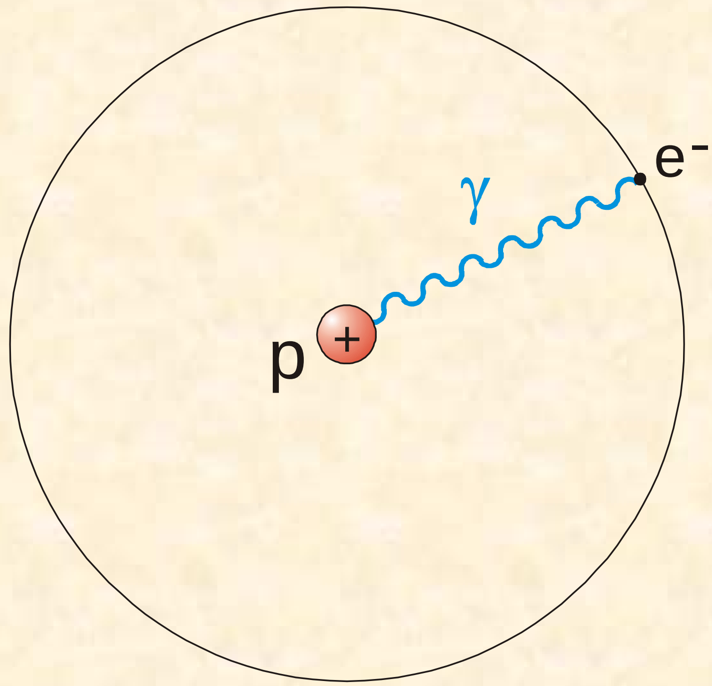
QCD

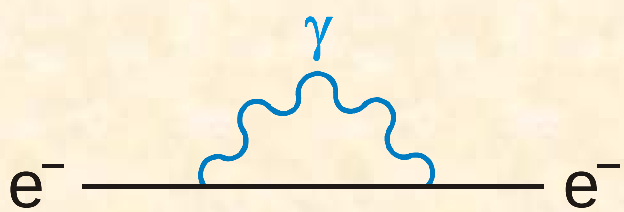
1971

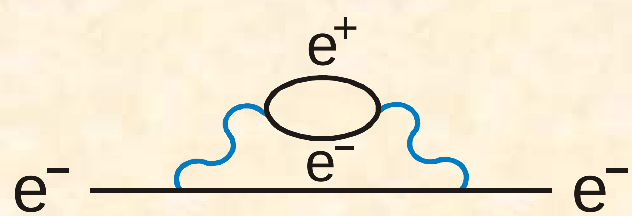


$$\mathcal{L}_{QCD} = \sum_{q=u,d,s,c,b} q\,(i\,\gamma_\mu D^\mu - m_q)q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

QED

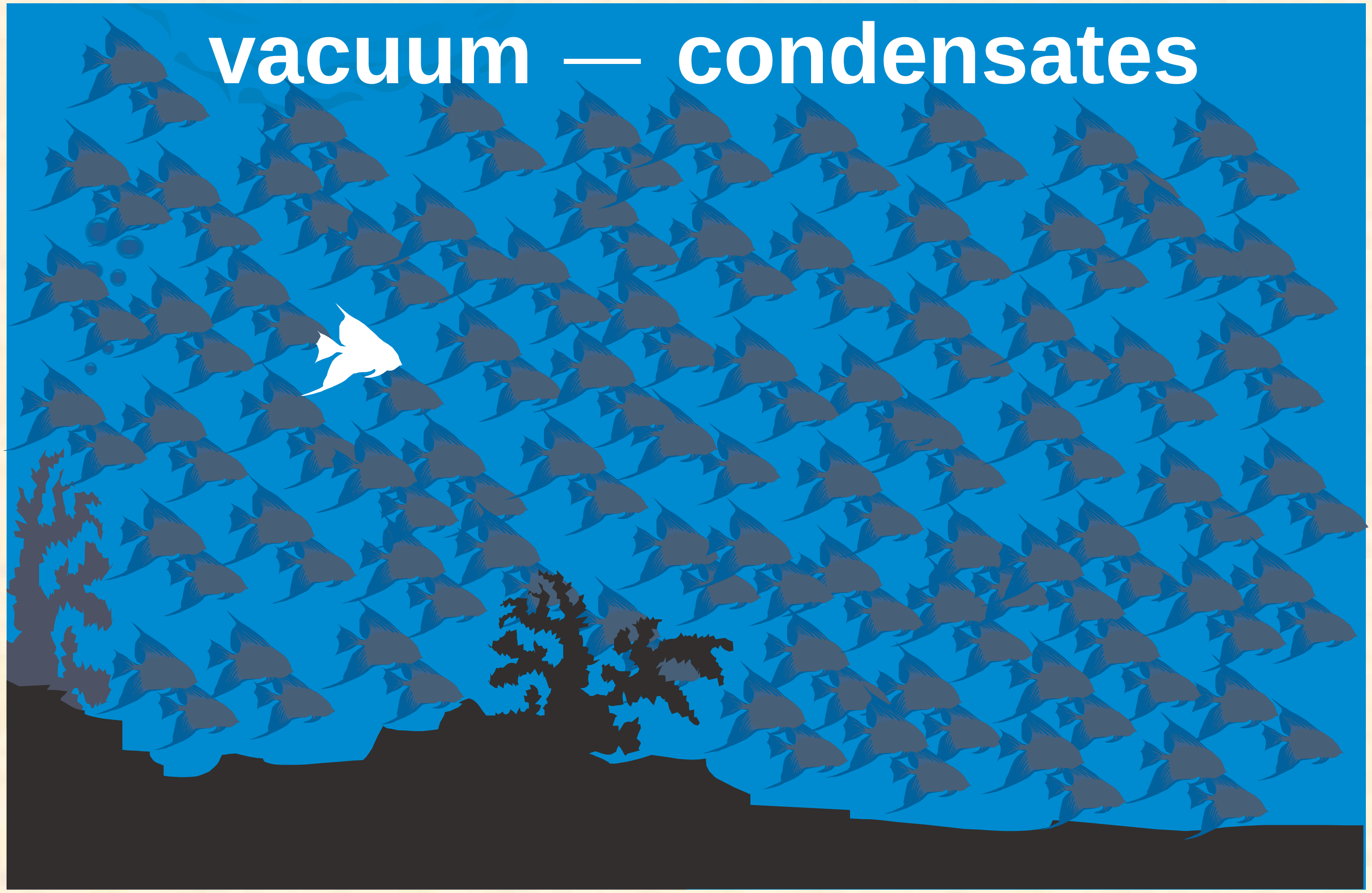




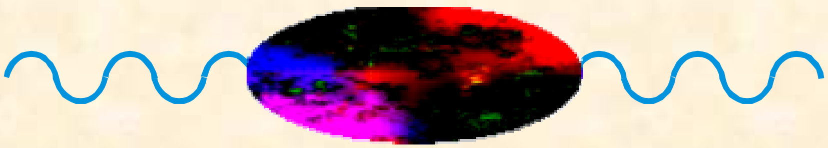


vacuum

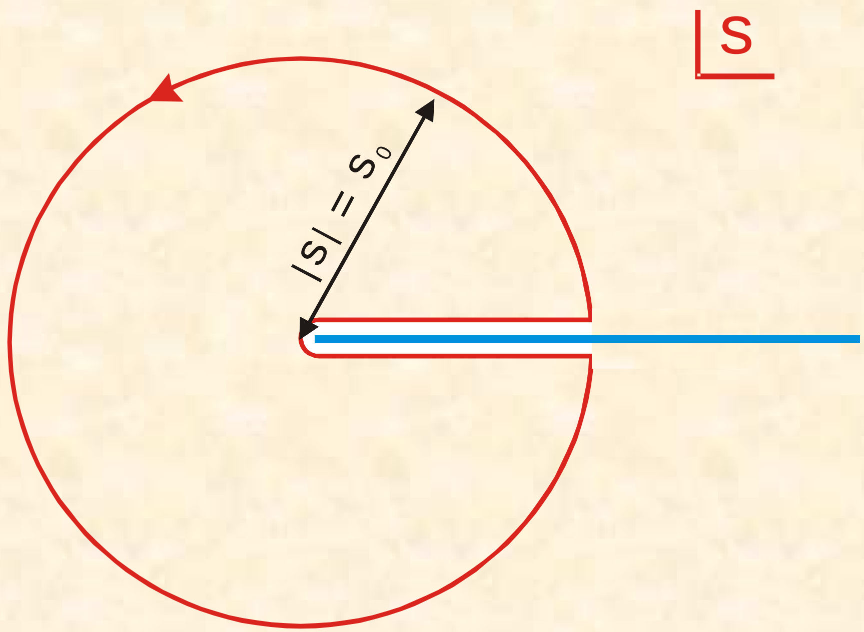
vacuum — the Dirac sea


vacuum — condensates

QCD sum rules

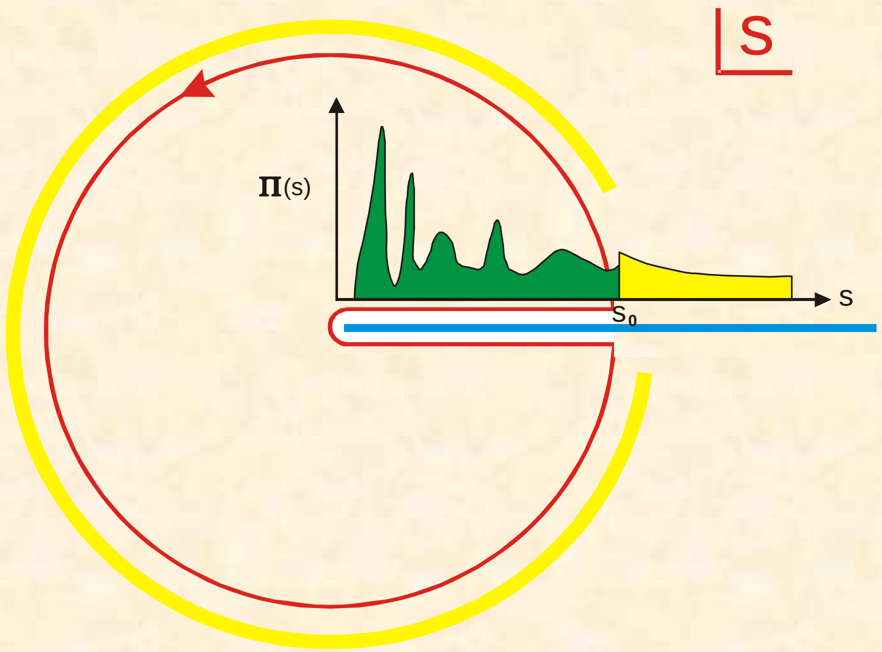


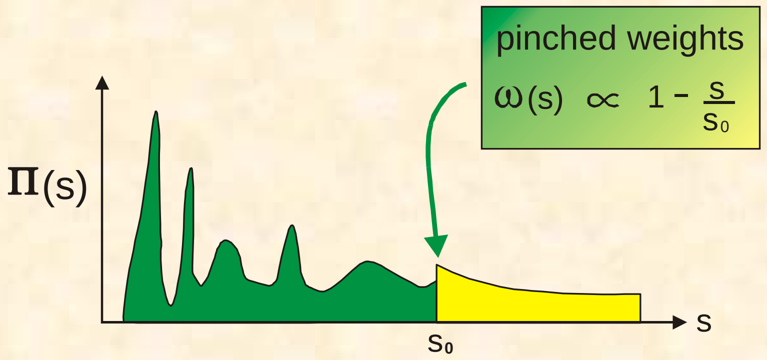
current correlator



$$\oint ds\, \omega(s)\, \Pi(s) \;=\; 0$$

$$2i \int_0^{s_0} ds\, \omega(s)\, \mathrm{Im}\, \Pi(s) = -\oint ds\, \omega(s)\, \Pi(s)$$





$$m_q = \frac{1}{2}(m_u + m_d)$$

		m_q(1 GeV) (MeV)	m_q(2 GeV) (MeV)
Chetyrkin *et al.* 99	Pseudoscalar Sum Rule	5.7 + 1.2	4.0 + 0.8
Prades 98		6.4 + 1.3	4.5 + 0.9
Maltman & Kambor 01		5.6 + 0.8	3.9 + 0.6
Cherry & Pennington 01	Scalar Sum Rules	4.5 + 0.6	3.2 + 0.4
JLQCD 99	Quenched Lattice QCD	6.0 + 0.4	4.2 + 0.3
QCDSF 99		6.3 + 0.3	4.4 + 0.2
APE 99		6.8 + 0.7	4.8 + 0.5
CP-PACS 00		6.2 + 0.2	4.4 + 0.1
SESAM 98	Unquenched Lattice QCD	3.9 + 0.2	2.7 + 0.1
CP-PACS 00		4.9 + 0.3	3.5 + 0.2
QCDSF - UKQCD 01		5.0 + 0.3	3.5 + 0.2
SESAM 01		6.4 + 2.4	4.5 + 1.7

3 - 5 MeV

$$\langle q\bar{q} \rangle$$

		$\langle \bar{q}q \rangle$(1GeV)	$\langle \bar{q}q \rangle$(2GeV)
Narison 89	Pseudoscalar Sum Rules	$-(224 + 8\ \text{MeV})$	$-(203 + 7\ \text{MeV})$
Dosch & Narison 98	*D*-decay Sum Rules	$-(193 - 262\ \text{MeV})^3$	$-(212 - 289\ \text{MeV})^3$
Giusti *et al* 99	Quenched Lattice QCD	$-(222 + 11\ \text{MeV})^3$	$-(245 + 12\ \text{MeV})^3$
Hernández *et al* 01		$-(252 + 11\ \text{MeV})^3$	$-(278 + 12\ \text{MeV})^3$
MILC 01		$-(263 + 5\ \text{MeV})^3$	$-(290 + 6\ \text{MeV})^3$

$-(270\ \text{MeV})^3$

m_s

		m_s(1 GeV) (MeV)	m_s(2 GeV) (MeV)
Jamin & Munz 95	Scalar	$189 + 32$	$133 + 23$
Chetyrkin *et al* 97	Sum Rules	$206 + 19$	$145 + 13$
Colangelo *et al* 97		$125 - 160$	$88 - 113$
Maltman 99		$159 + 11$	$112 + 8$
Jamin *et al* 01		$141 + 23$	$99 + 16$
Dominguez *et al* 98	Pseudoscalar Sum Rules	$155 + 25$	$109 + 18$
Pich & Prades 99	τ-decay	$164 + 33$	$115 + 23$
Kambor & Maltman 00	Sum Rules	$159 + 23$	$112 + 16$
Chen *et al* 01		160^{+28}_{-35}	113^{+20}_{-25}
JLQCD 99	Quenched	$151 + 10$	$106 + 7$
ALPHA - UKQCD 99	Lattice QCD	$138 + 6$	$97 + 4$
QCDSF 99		$149 + 6$	$105 + 4$
APE 99		$158 + 13$	$111 + 9$
CP-PACS 00		156^{+4}_{-6}	110^{+3}_{-4}
RBC 00		$153 + 44$	$108 + 31$
MILC 99	Unquenched	$160 + 16$ (m_K) $178 + 13$ (m_ϕ)	$113 + 11$ (m_K) $125 + 9$ (m_ϕ)
APE 00	Lattice QCD	$159 + 21$ (m_K) $153 + 37$ (m_ϕ)	$112 + 15$ (m_K) $108 + 26$ (m_ϕ)
CP-PACS 00		125^{+6}_{-9} (m_K) 128^{+7}_{-15} (m_ϕ)	88^{+4}_{-6} (m_K) 90^{+5}_{-11} (m_ϕ)
JLQCD 00		$128 + 6$ (m_K) $151 + 10$ (m_ϕ)	$91 + 4$ (m_K) $106 + 7$ (m_ϕ)
QCDSF + UKQCD 00		$128 + 7$ (m_K)	$90 + 5$ (m_K)
SESAM 01		$131 + 118$ $(m_{K,\phi})$	$92 + 83$ $(m_{K,\phi})$

90 - 130 MeV

quarks, gluons

QCD

$SU(N_f)$

$$\mathcal{L}_{QCD} = \sum_{q=u,d} \bar{q}\,(i\,\gamma_\mu D^\mu - m_q)\,q - \frac{1}{4} G^{\mu\nu} G_{\mu\nu}$$

$m_u, m_d \simeq$ 1-5 MeV $\ll \Lambda_{QCD}$

$SU(N_f) \times SU(N_f)$

hadrons

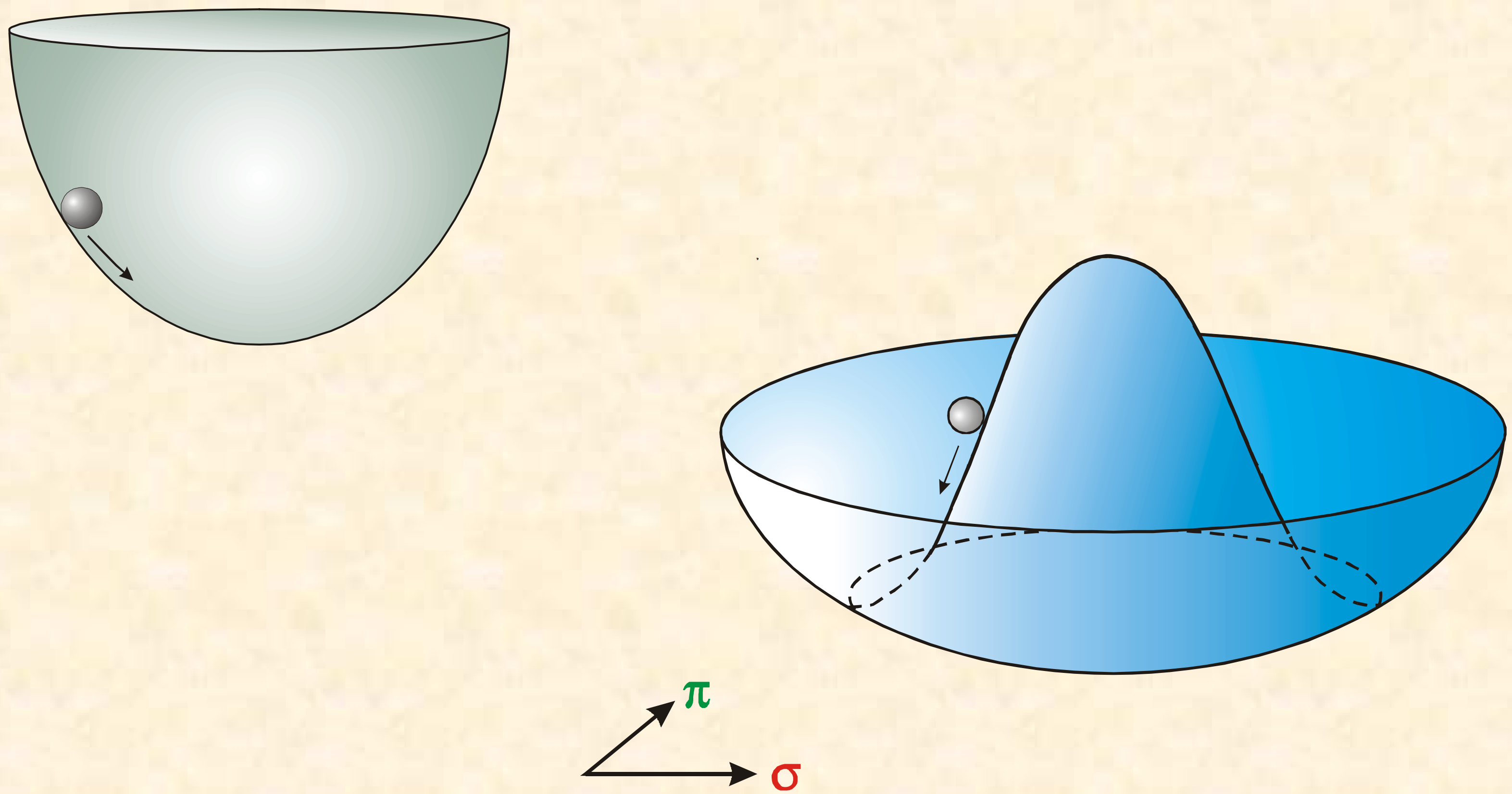
effective Lagrangian

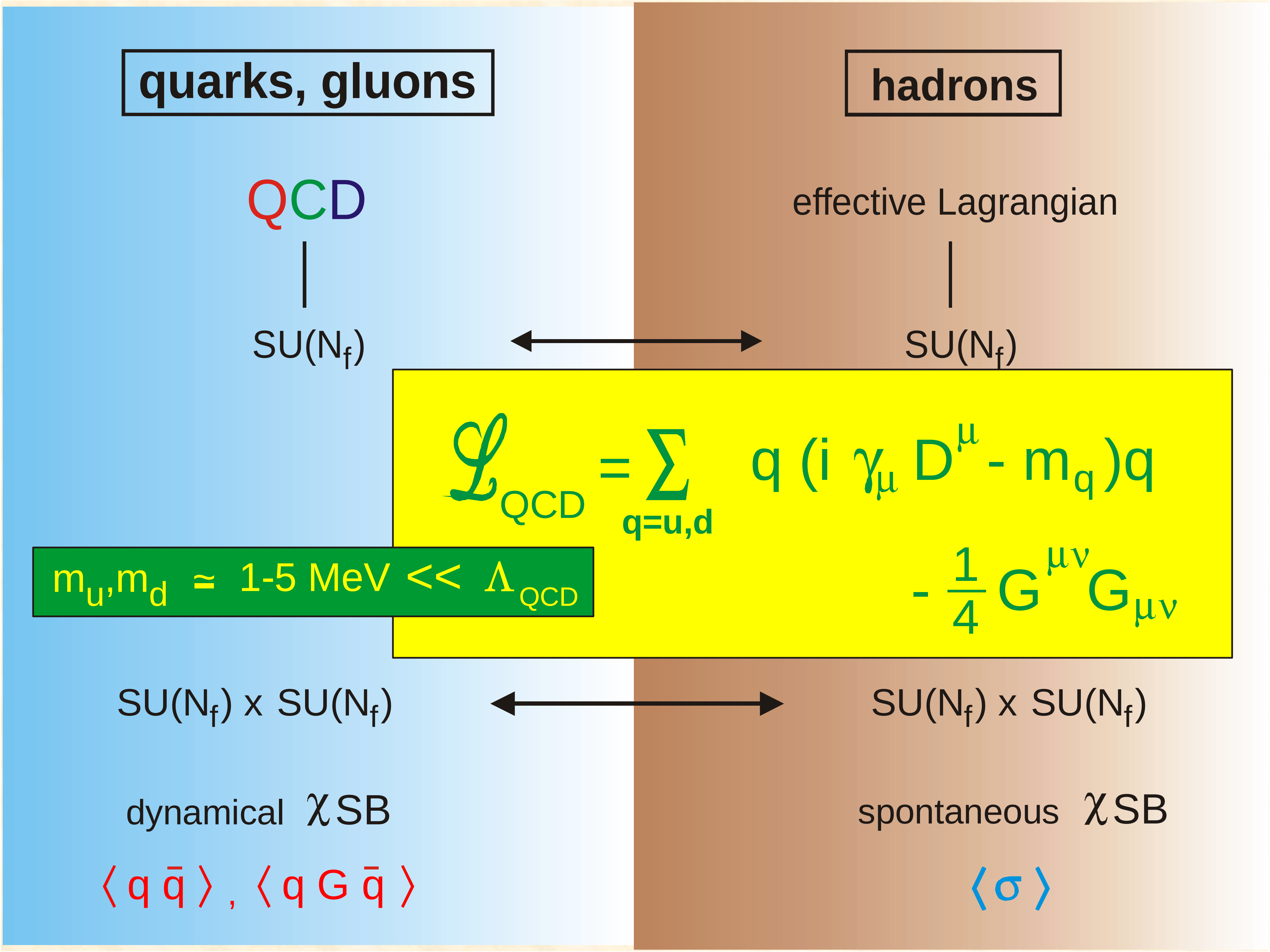
$SU(N_f)$

$SU(N_f) \times SU(N_f)$

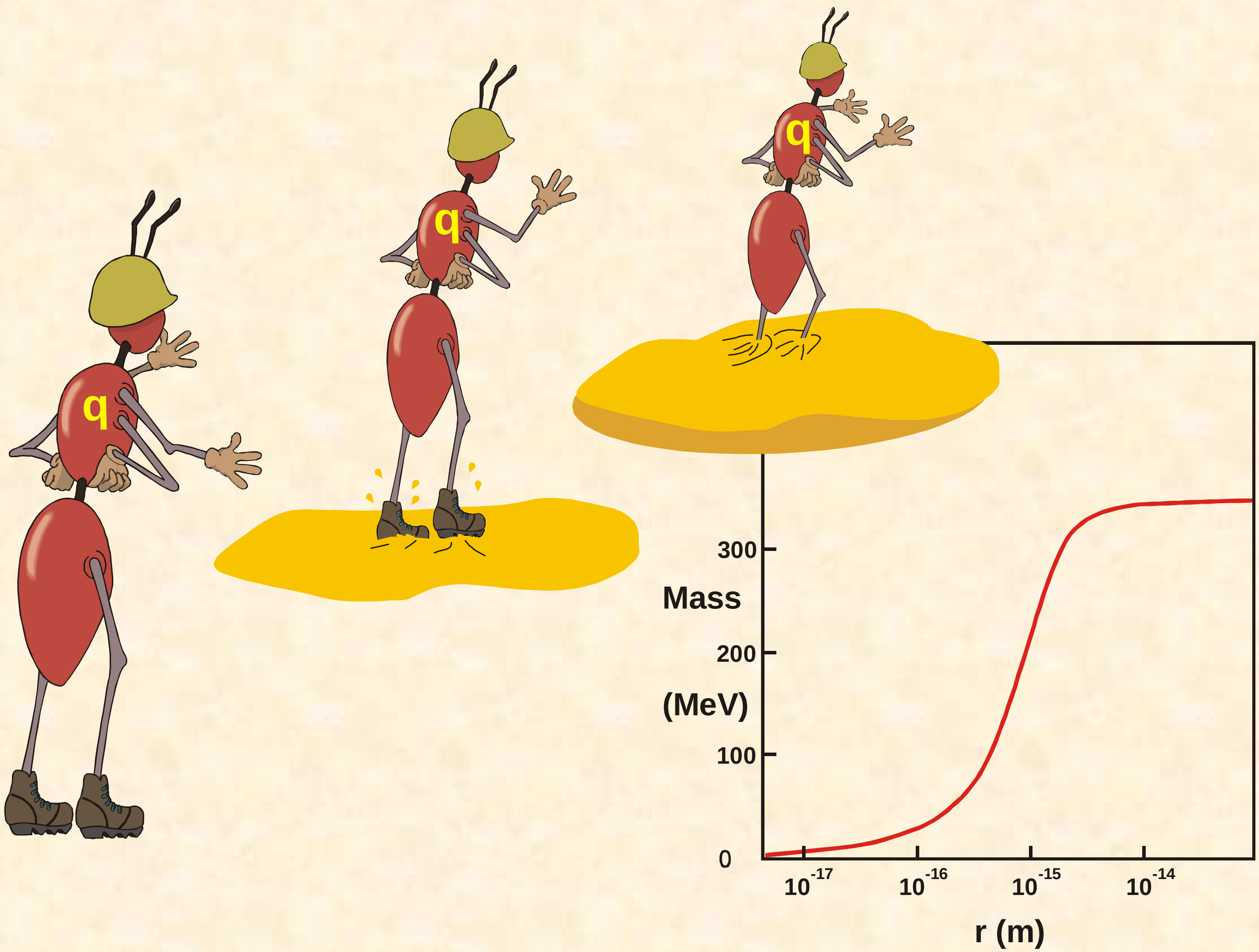
spontaneous χSB

Ground State – Vacuum

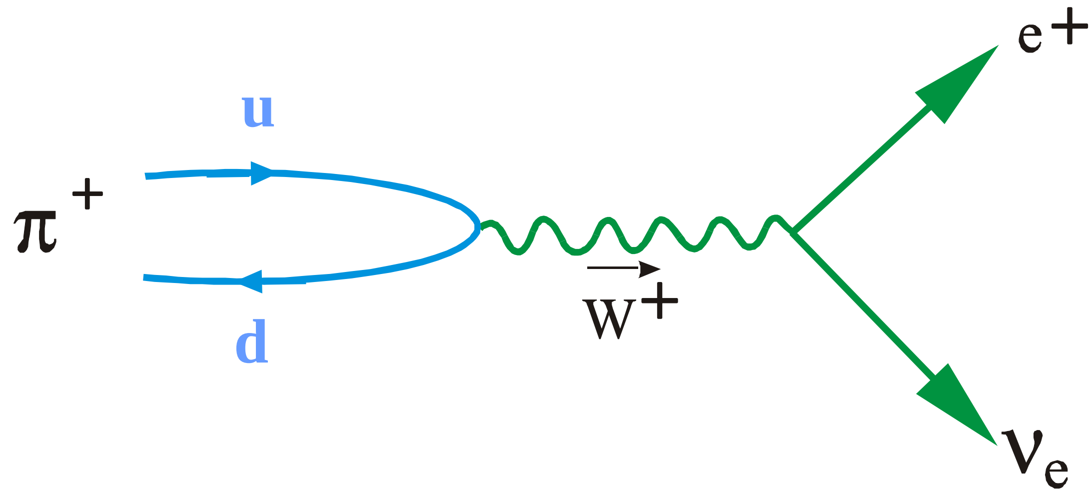


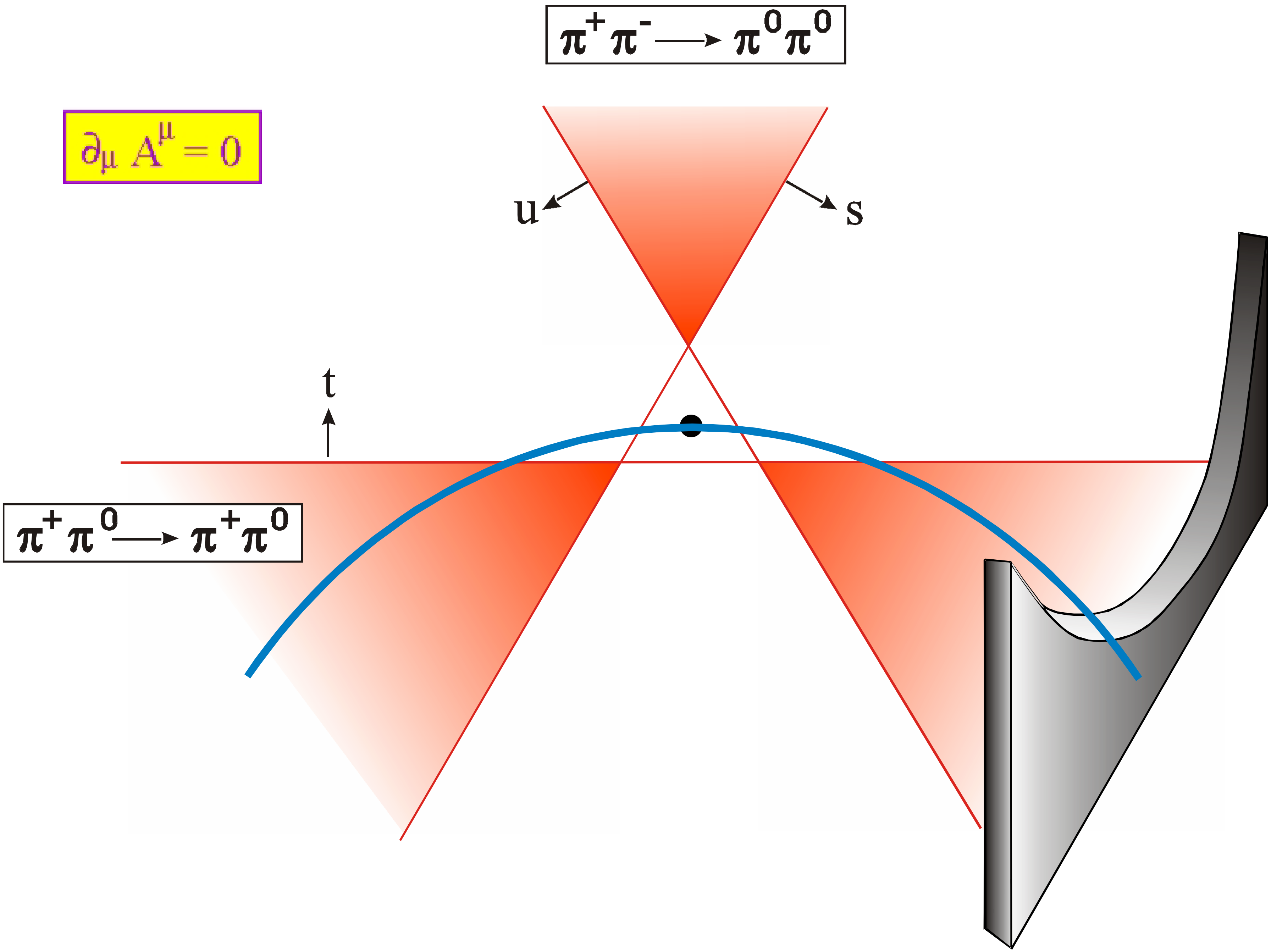

quarks, gluons
hadrons
QCD
effective Lagrangian
SU(N_f)
SU(N_f)
ℒ_QCD = Σ_{q=u,d} q̄ (i γ_μ D^μ - m_q) q - 1/4 G^{μν} G_{μν}
m_u, m_d ≃ 1-5 MeV << Λ_QCD
SU(N_f) x SU(N_f)
SU(N_f) x SU(N_f)
dynamical χSB
spontaneous χSB
⟨q q̄⟩ , ⟨q G q̄⟩
⟨σ⟩

u/d quarks propagating

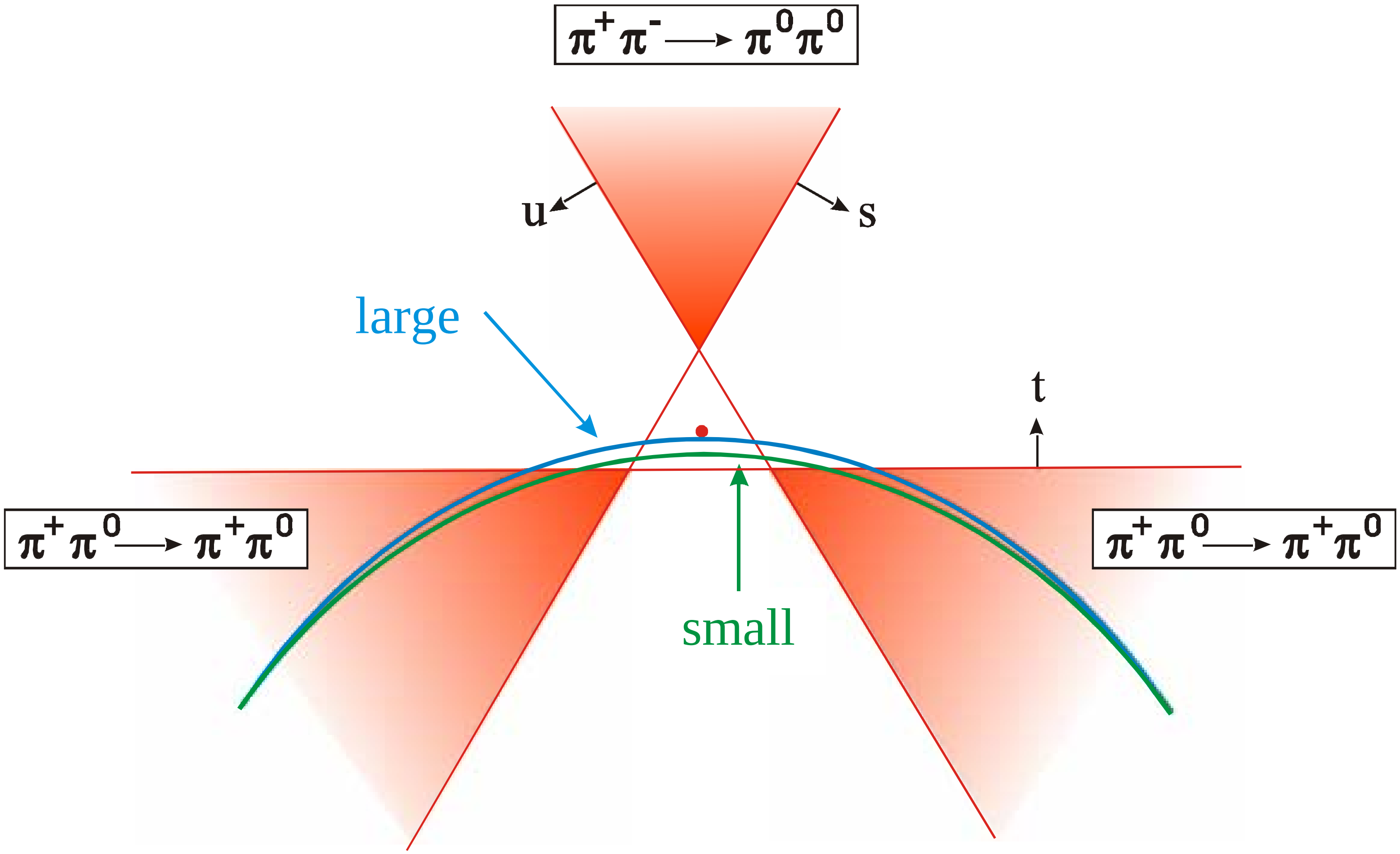


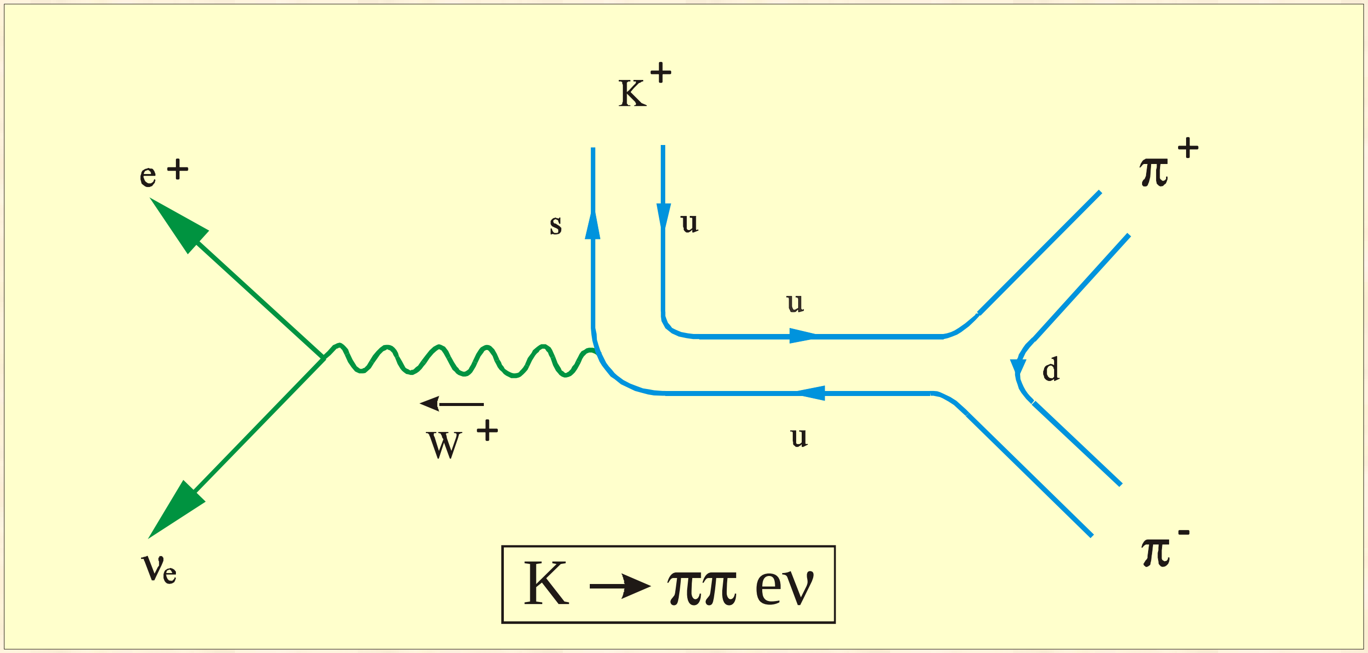
$\partial_\mu A^\mu = 0$



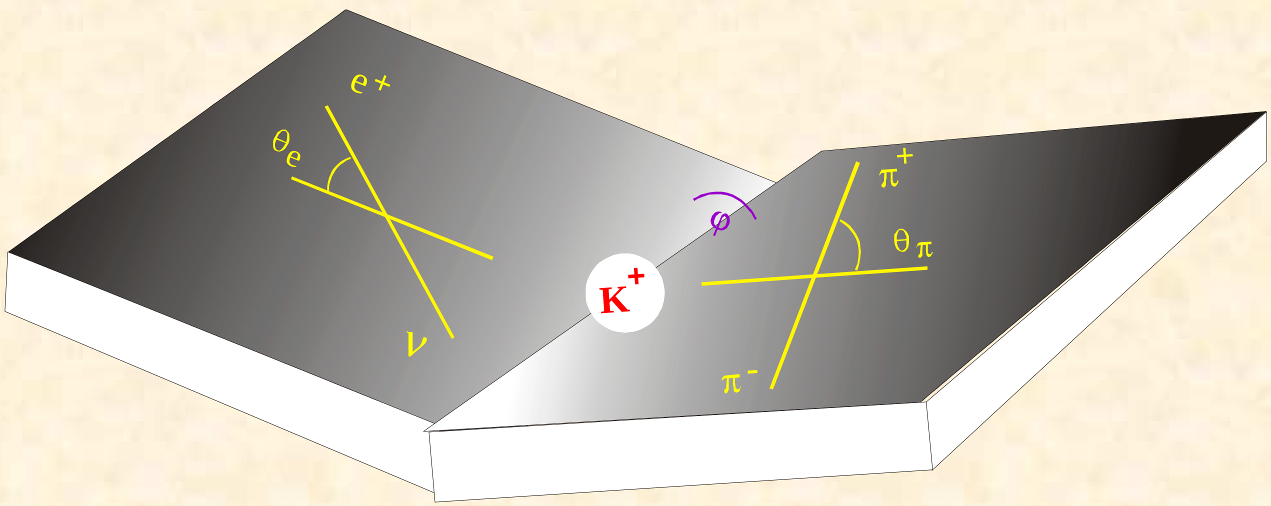


$\pi^+\pi^- \longrightarrow \pi^0\pi^0$
$\partial_\mu A^\mu = 0$
u
s
t
$\pi^+\pi^0 \longrightarrow \pi^+\pi^0$

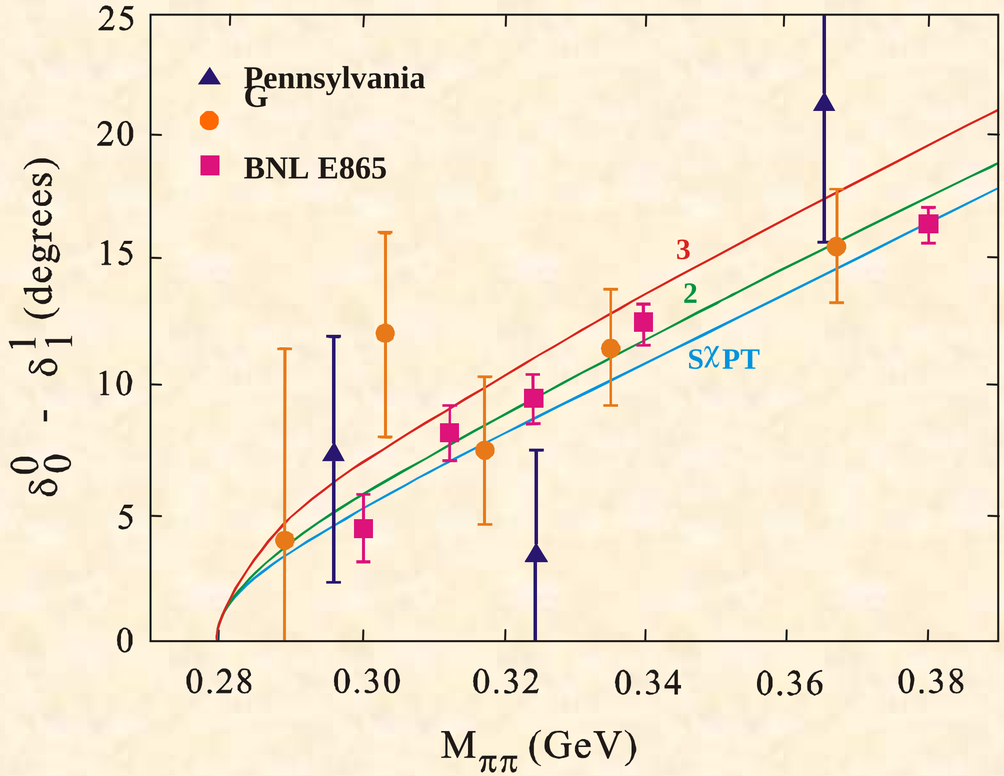

$\pi^+\pi^- \longrightarrow \pi^0\pi^0$
u
s
large
t
$\pi^+\pi^0 \longrightarrow \pi^+\pi^0$
small
$\pi^+\pi^0 \longrightarrow \pi^+\pi^0$



K +
e +
s
u
π +
u
d
W +
u
ν e
π -
K → ππ eν



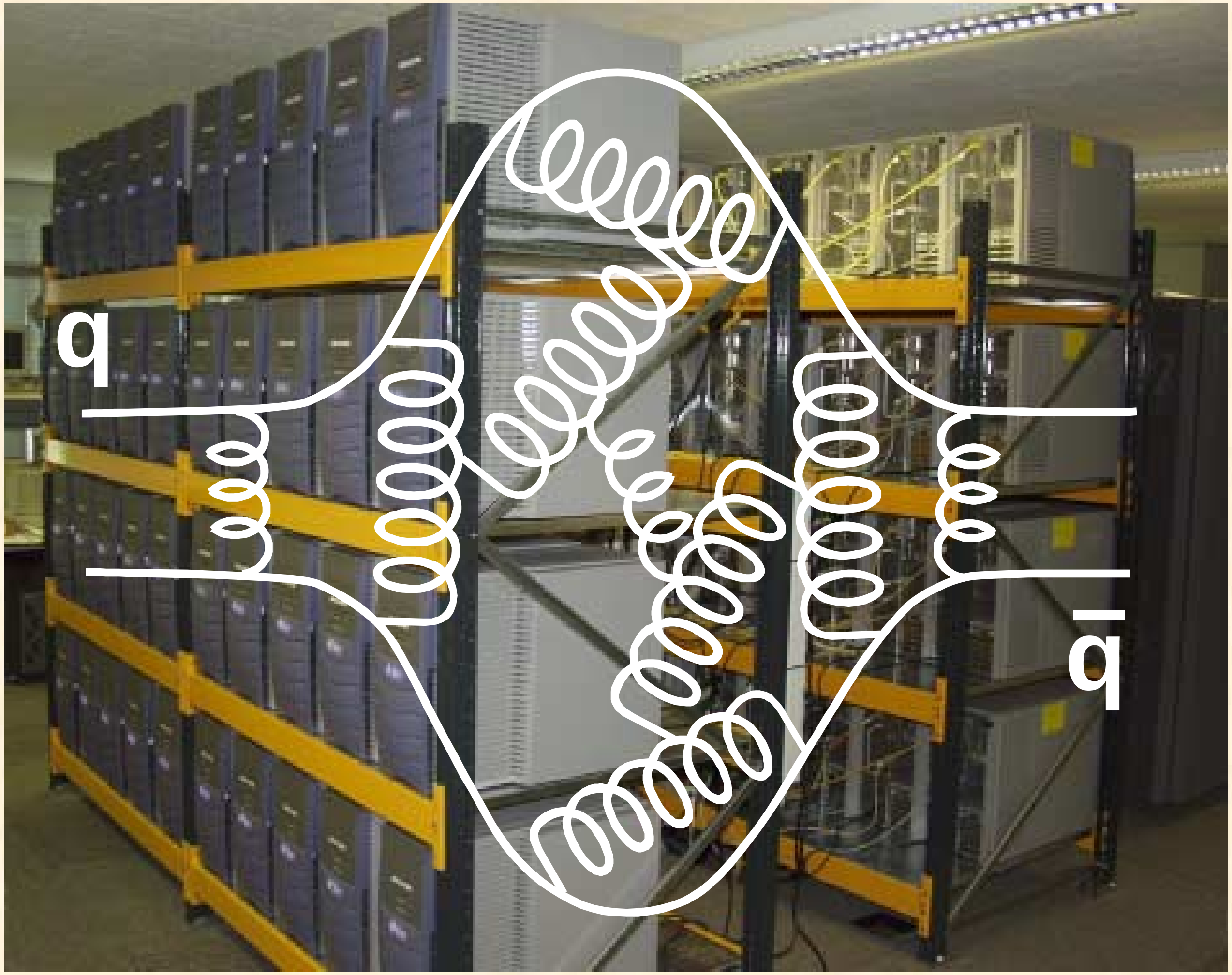
e +
θe
ν
φ
K+
π+
θπ
π -



GMOR $m_\pi{}^2 F_\pi{}^2 = -\,(m_u + m_d)\,\langle q\bar{q}\rangle + \ldots$

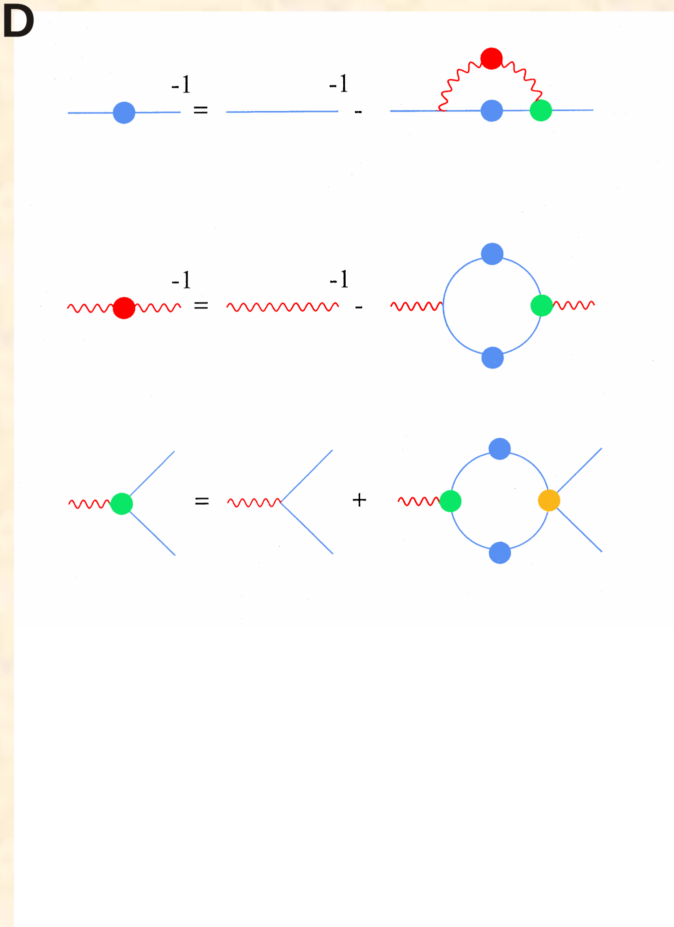
$\langle q\bar{q}\rangle = -(270\ \mathrm{MeV})^3$

Lattice QCD

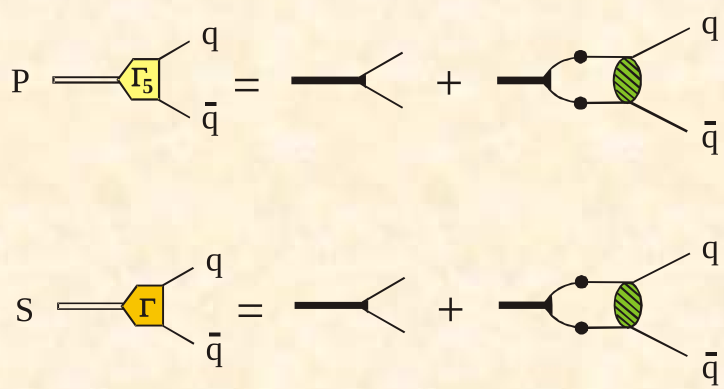


Schwinger-Dyson Equations

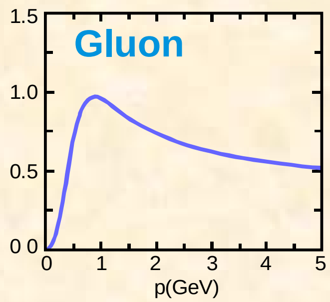
QED

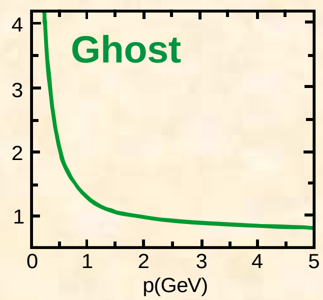


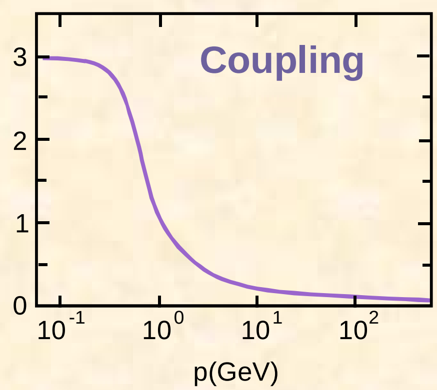
Bound State Equations

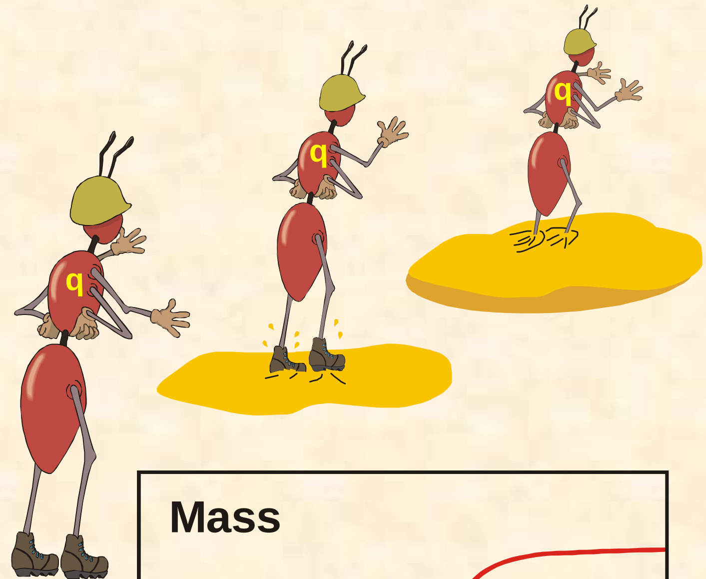


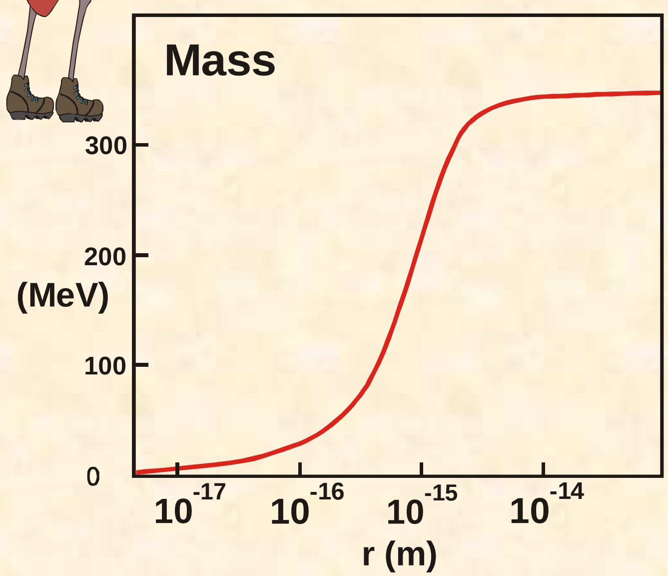
calculating the masses of u/d quarks



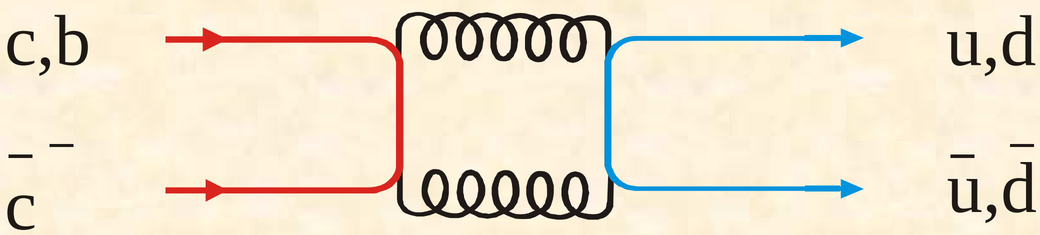






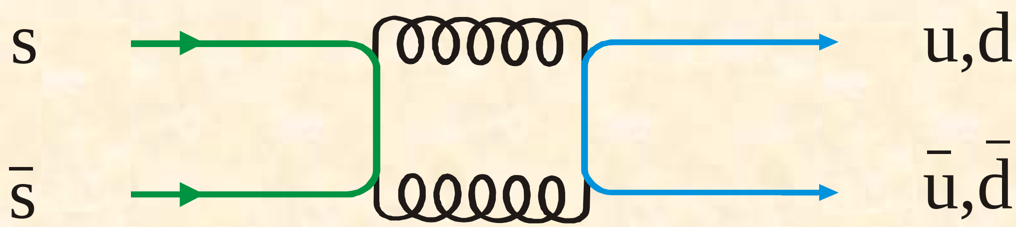


Flavour structure of QCD



Suppressed

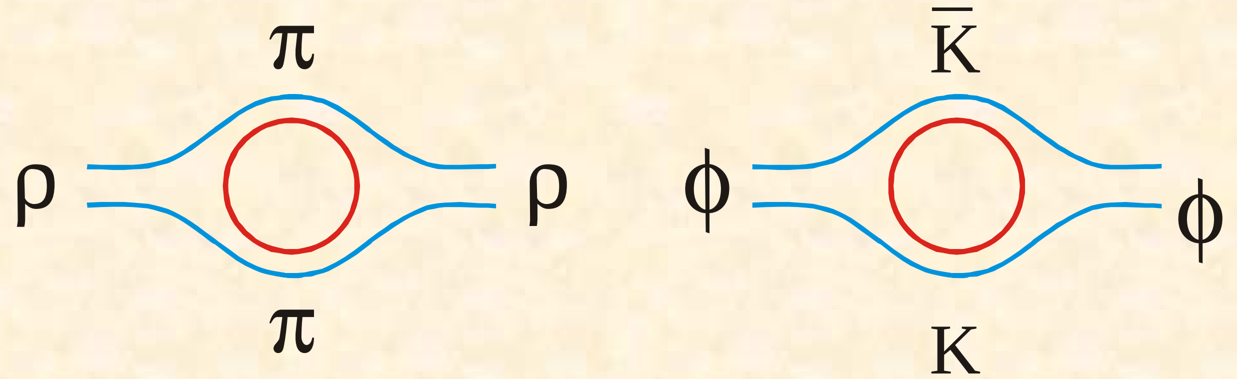
$N_c = 3, N_c \rightarrow \infty$



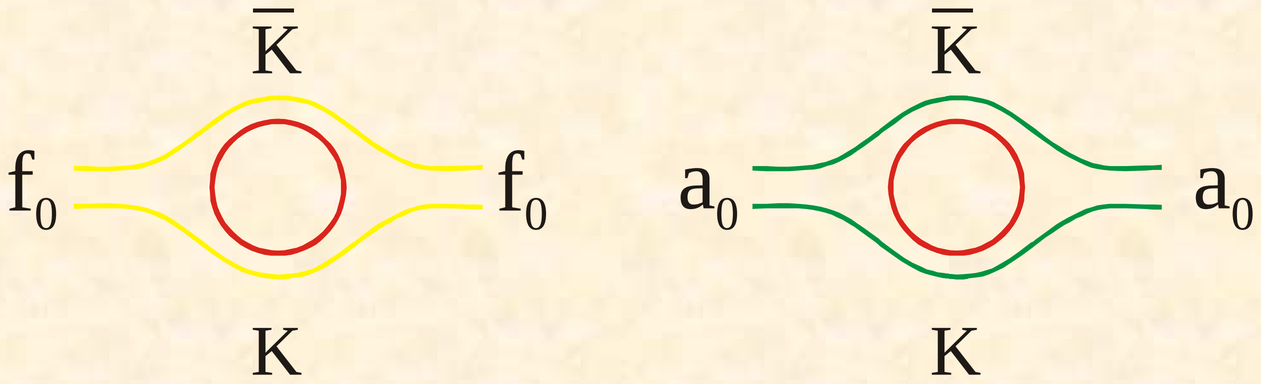
Suppression?

$N_c = 3, N_c \rightarrow \infty$

quark model = hadron world?

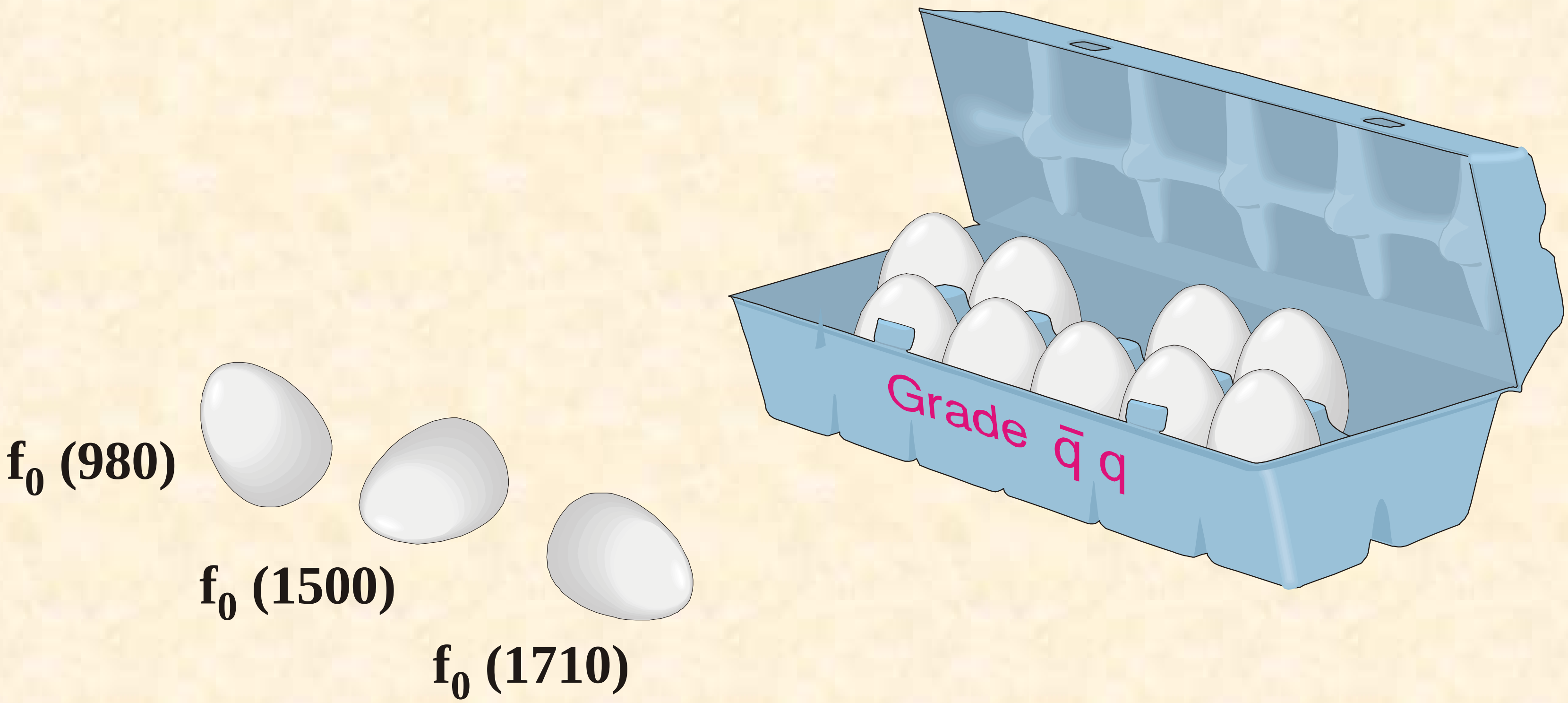


unquenching unimportant

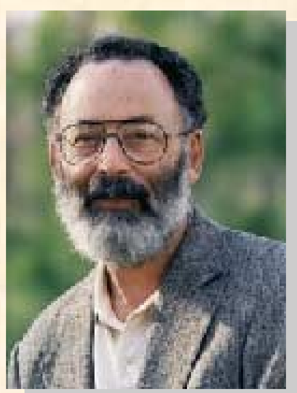


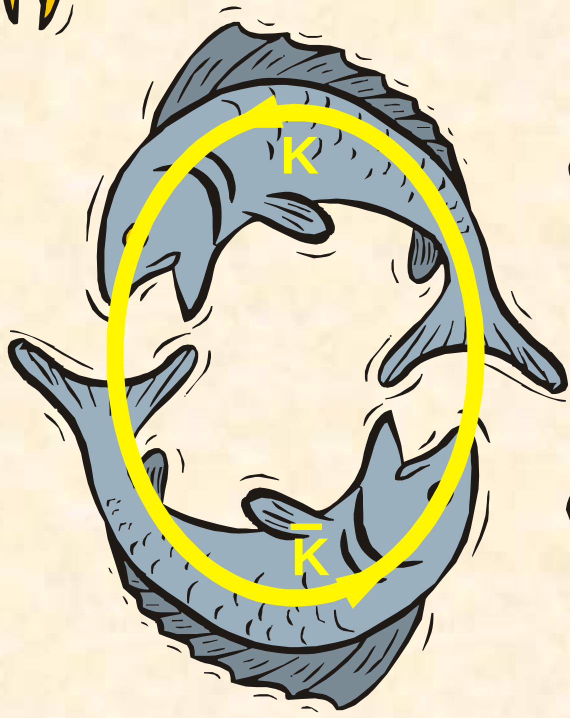
unquenching important

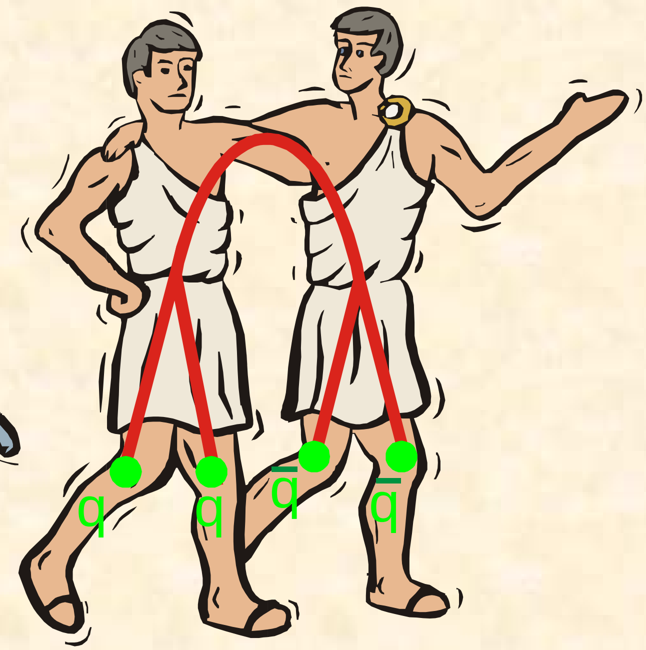
Which f_0 is in which nonet?

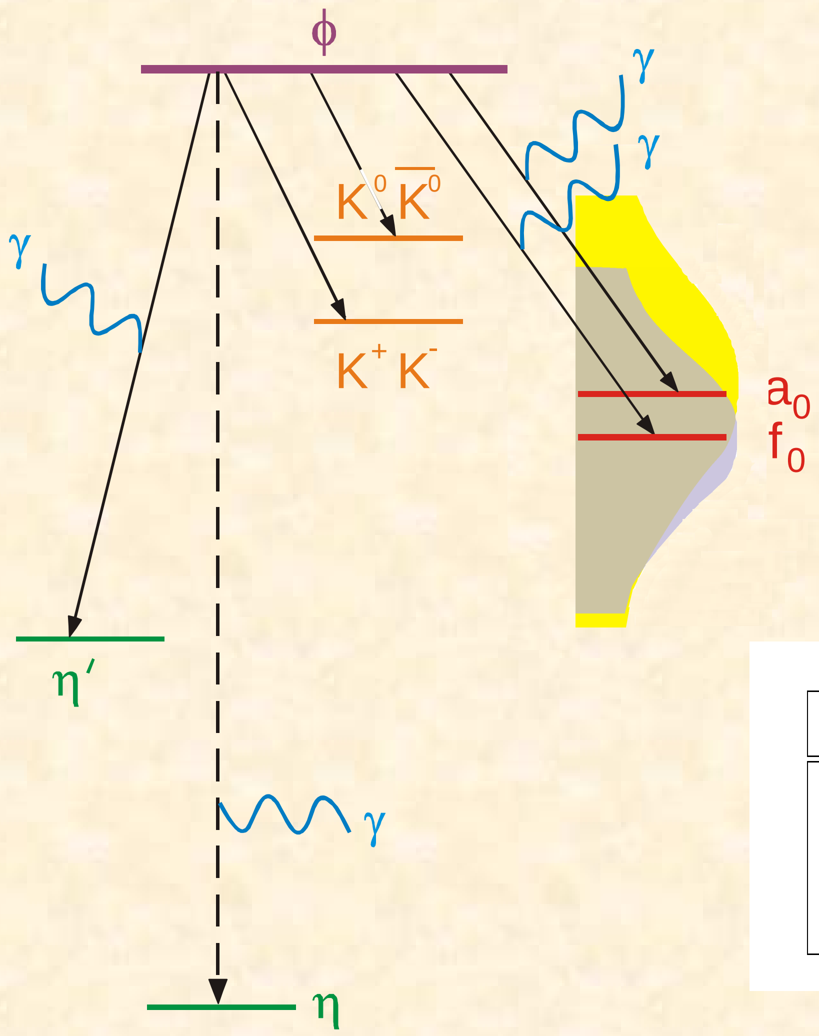


Which is the $f_0(980)$?



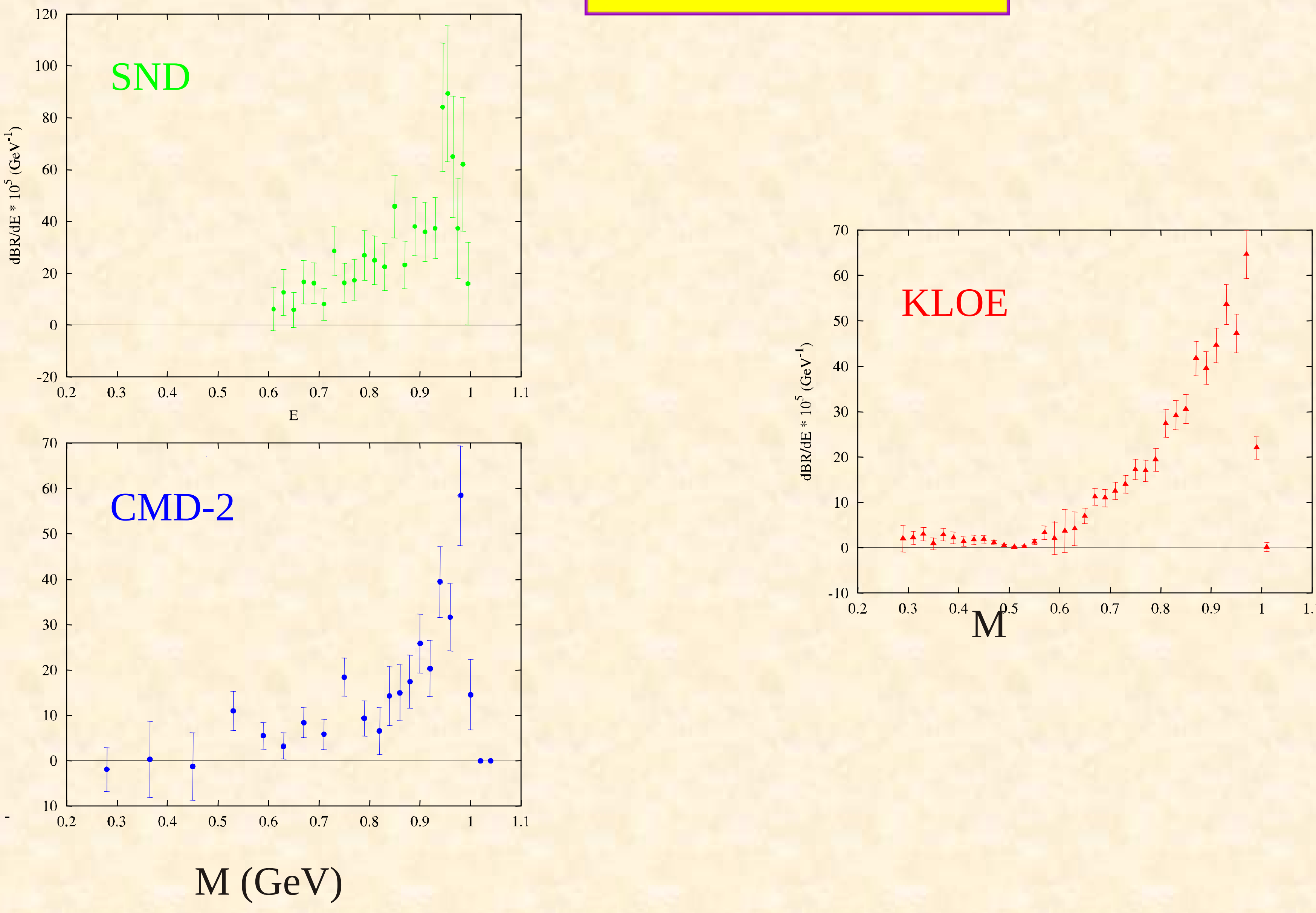




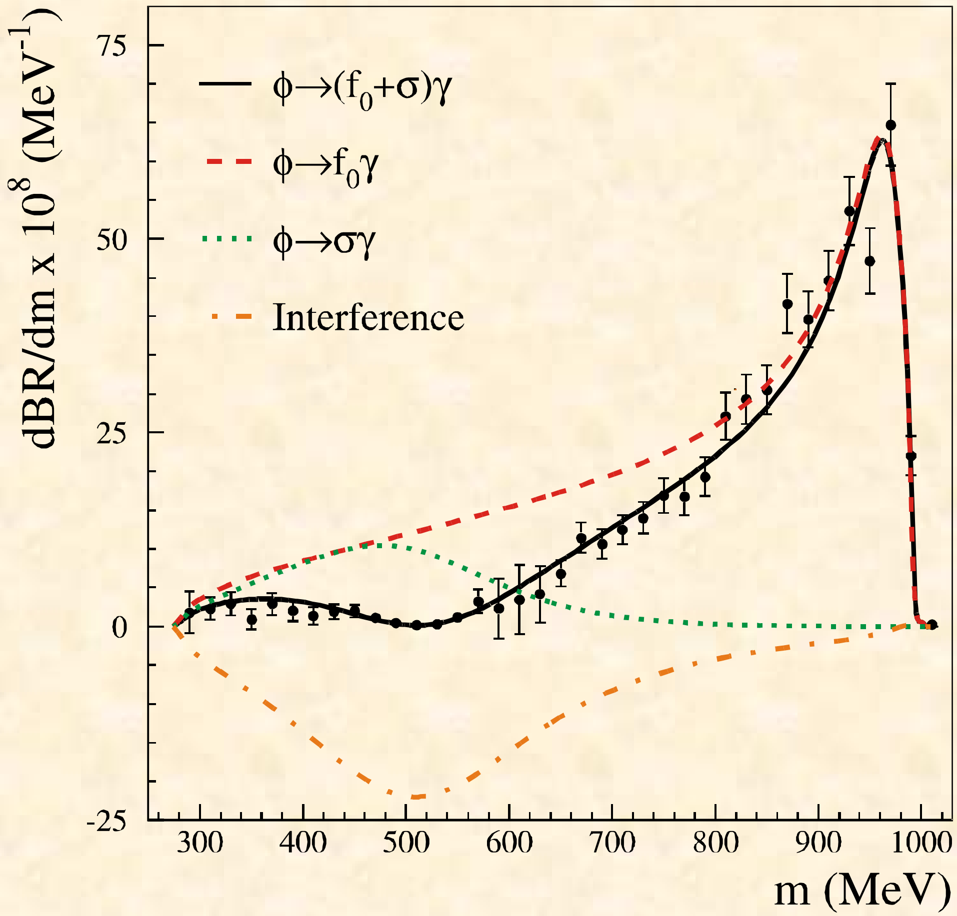


Composition	$BR(\phi \to \gamma f_0(980))$
$qq\overline{qq}$	$O(10^{-4})$
$s\overline{s}$	$O(10^{-5})$
$K\overline{K}$	$< O(10^{-5})$

$\varphi \rightarrow \gamma\,(\pi\pi)$



KLOE: $\varphi \to \gamma(\pi^0\pi^0)$



$BR(\phi \to f_0\gamma) \cdot 10^4$

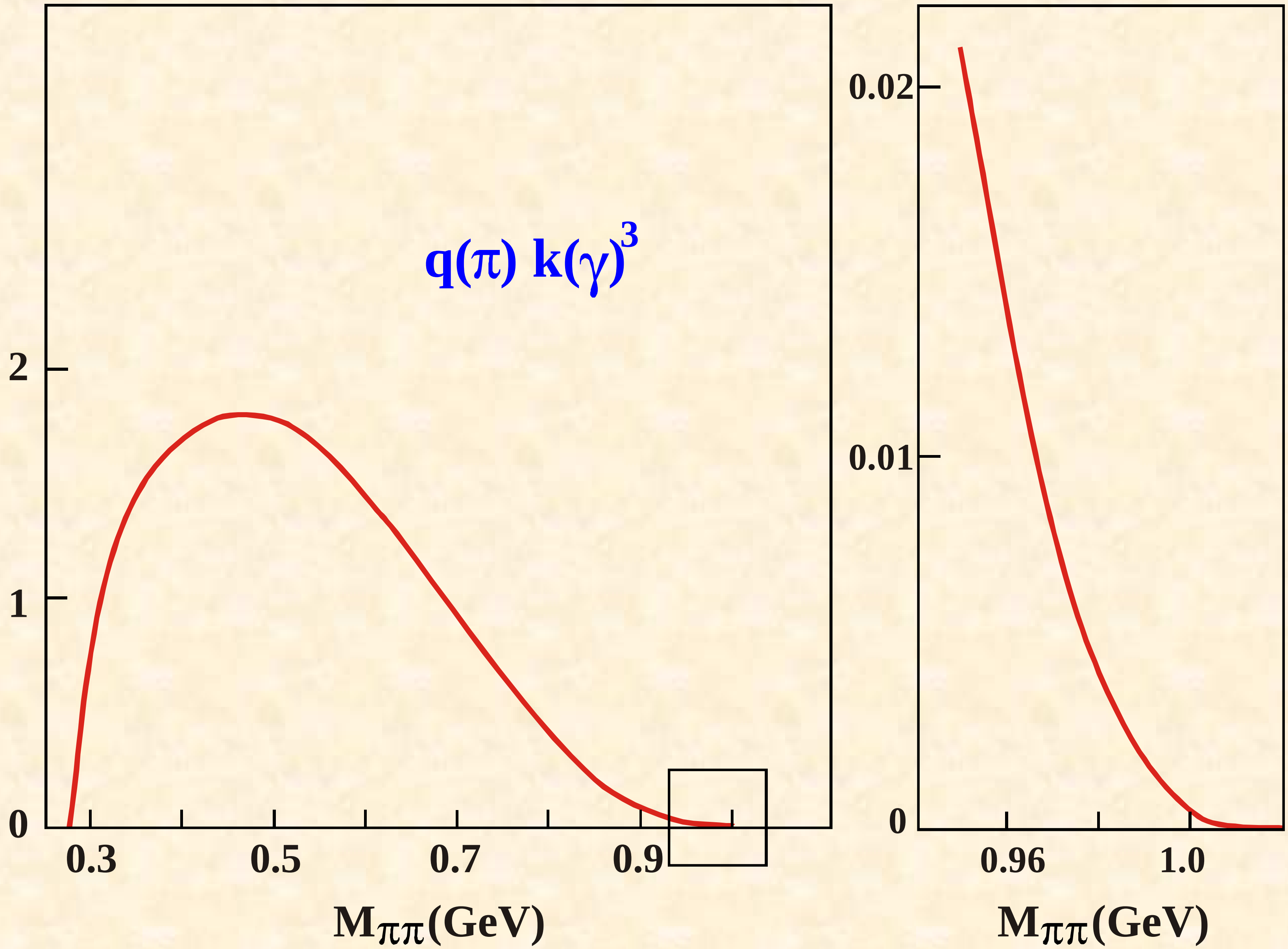
(4.47 ± 0.21)

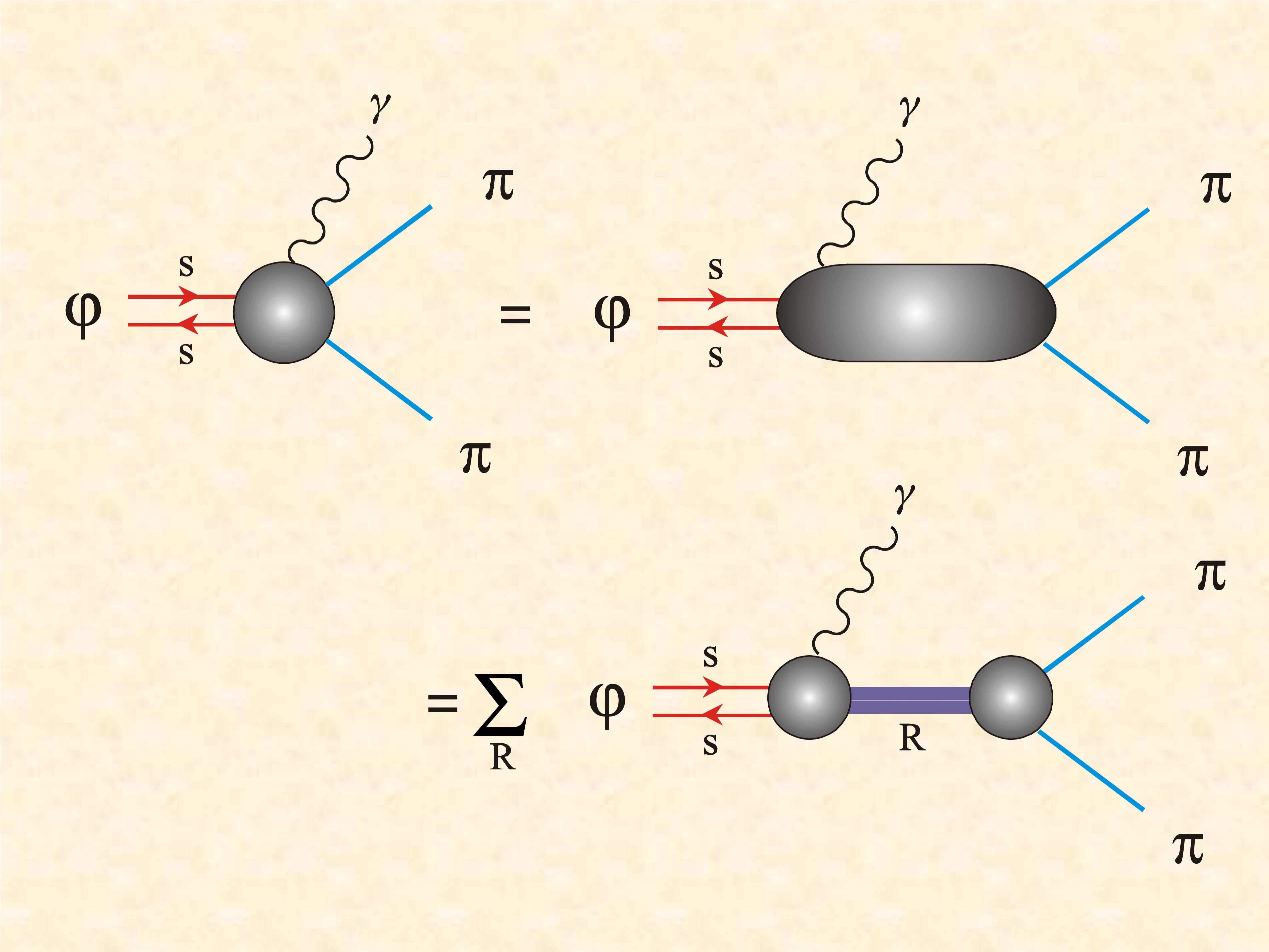
Fermilab E791

$m_\sigma = 478$ MeV,

$\Gamma_\sigma = 324$ MeV

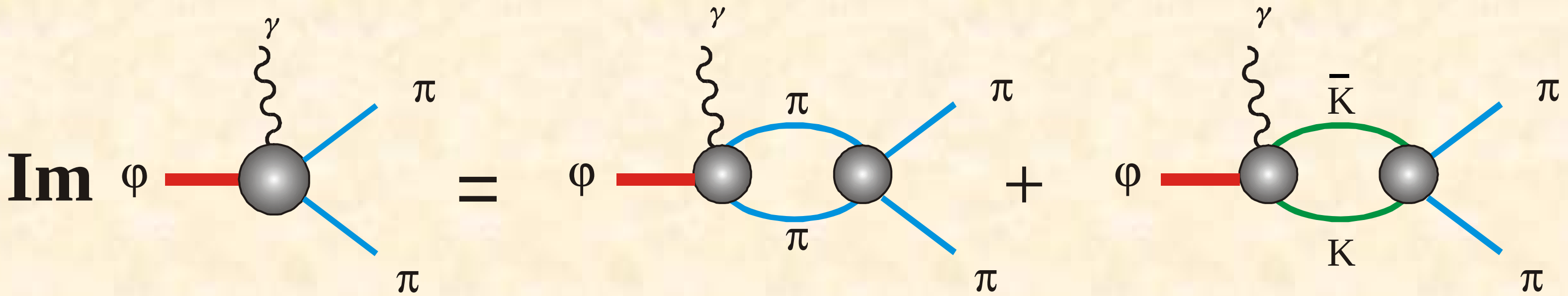
$\varphi \rightarrow \gamma(\pi\pi)$




γ
π
s
φ
s
π
=
γ
π
s
φ
s
π
γ
π
= Σ
R
s
φ
s
R
π

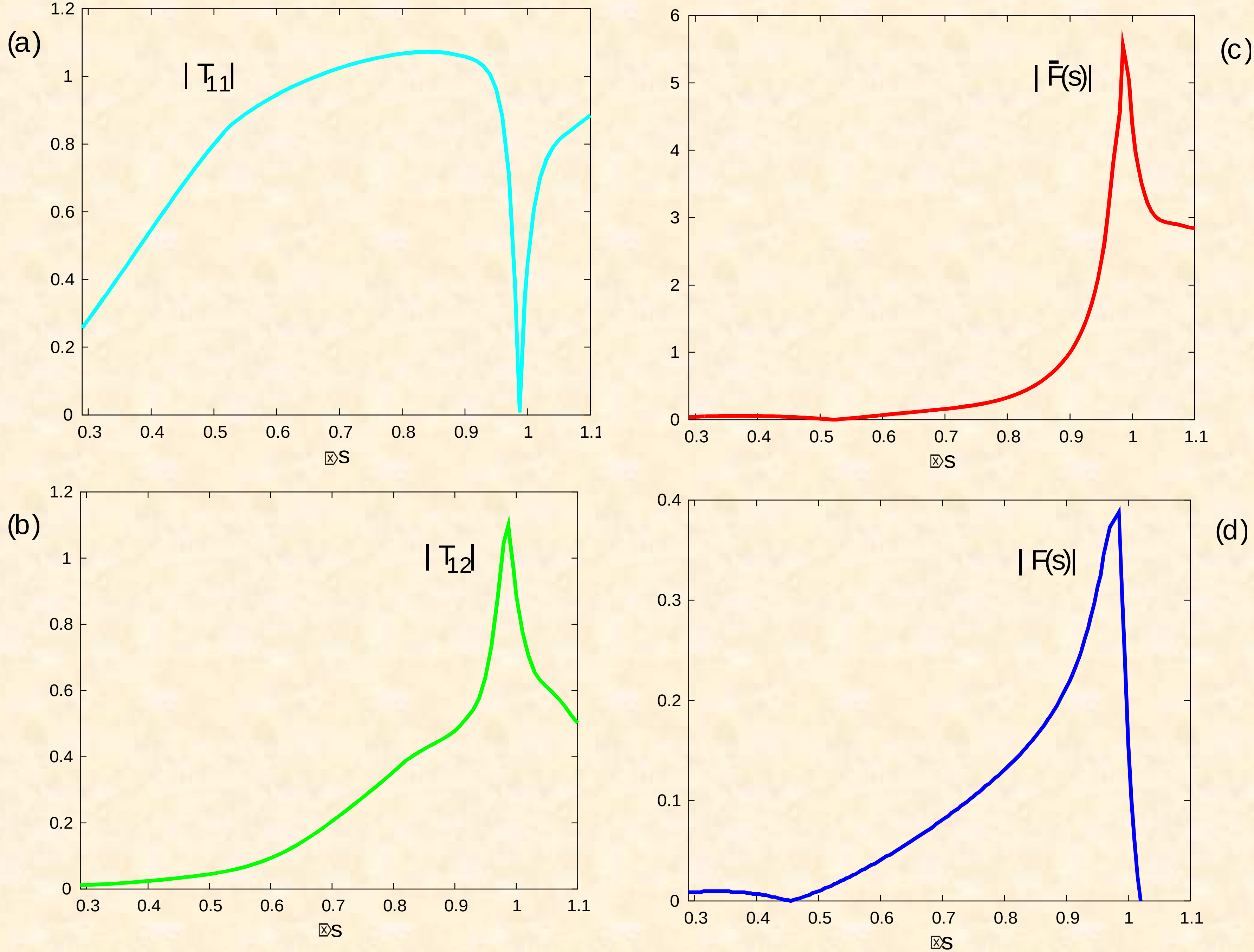
UNITARITY

If NO $\phi\pi$ strong interaction

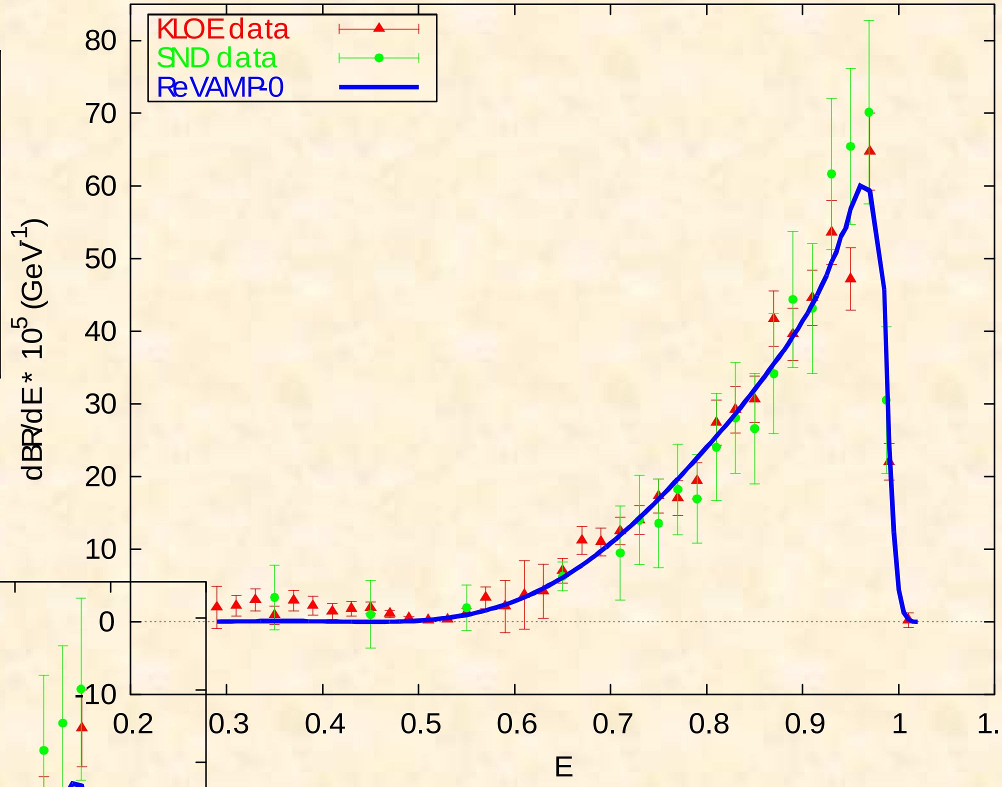


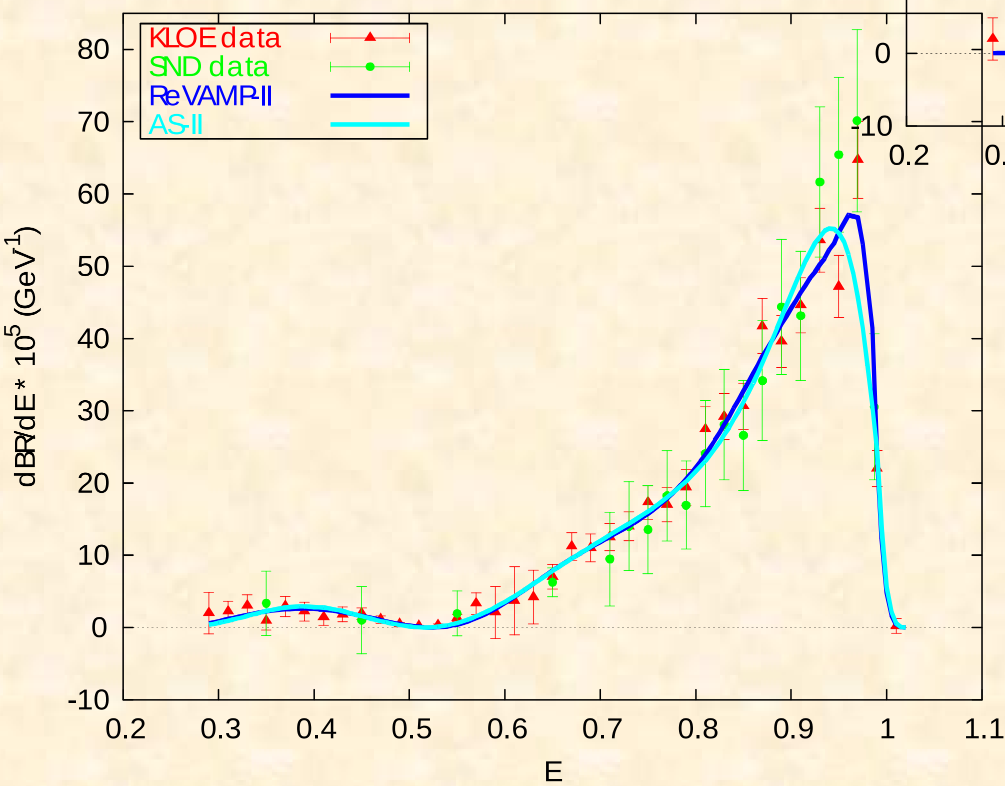
$$\mathcal{F}(\phi \to \gamma\pi\pi; s) = \alpha_1(s)\,\mathcal{T}(\pi\pi \to \pi\pi) + \alpha_2(s)\,\mathcal{T}(\overline{K}K \to \pi\pi)$$

$$\frac{d\Gamma}{dM} = \rho(s)\,|\mathcal{F}(s)|^2$$

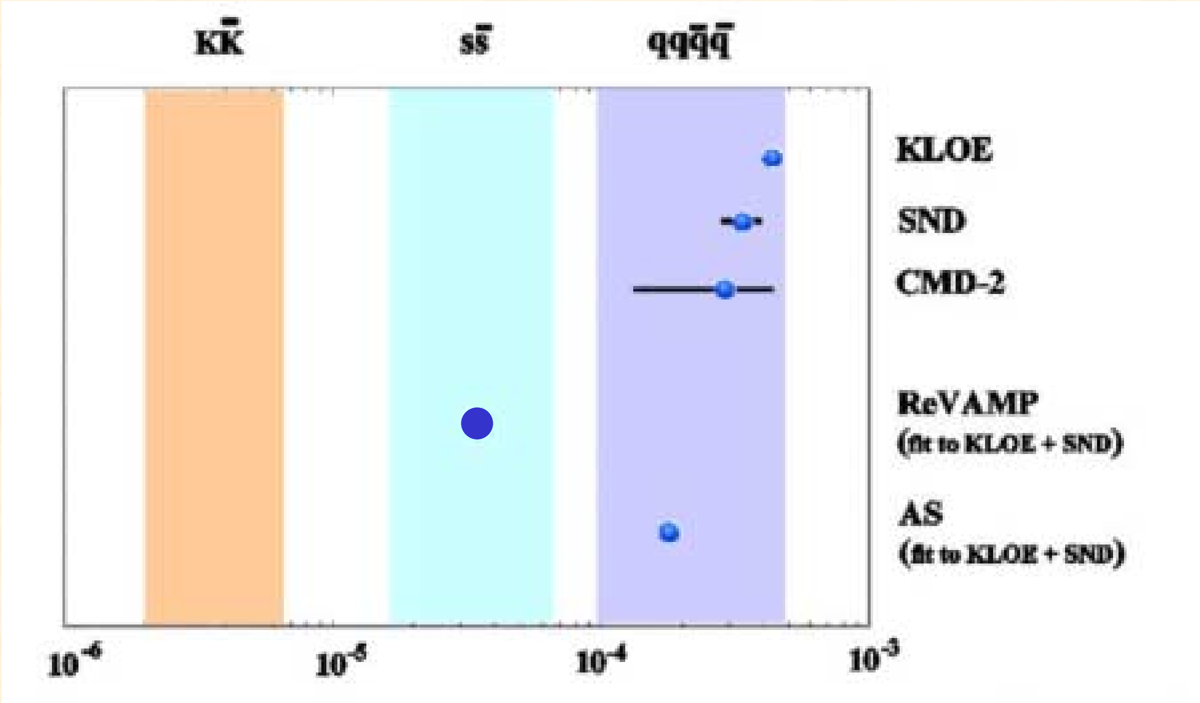

(a)
| T11|
(b)
| T12|
(c)
| F̄(s)|
(d)
| F(s)|
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
s

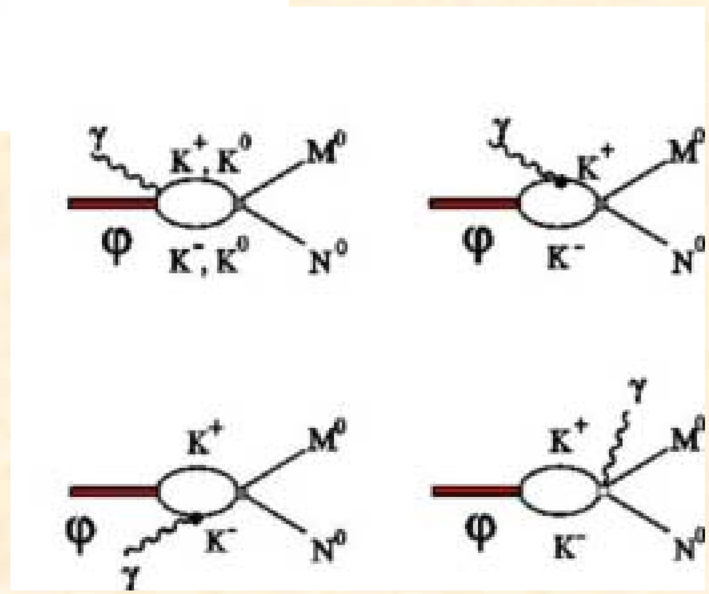
	$BR(\phi \to f_0 \gamma) \cdot 10^4$
KLOE	(4.47 ± 0.21)
SND	$(3.12 \pm 0.30 \pm 0.36)$
CMD-2	$(2.90 \pm 0.21 \pm 1.54)$
ReVAMP (fit to KLOE SND data)	0.31



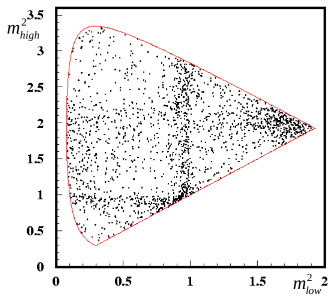


AS (fit to KLOE SND data)	1.92


KK̄
ss̄
qqq̄q̄
KLOE
SND
CMD-2
ReVAMP
(fit to KLOE + SND)
AS
(fit to KLOE + SND)
10^-6
10^-5
10^-4
10^-3

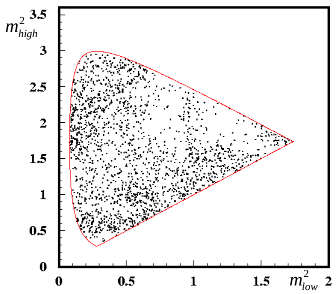

γ
K+, K0
K-, K0
M0
N0
φ
K+
K-

$D_s \to \pi\pi\pi$



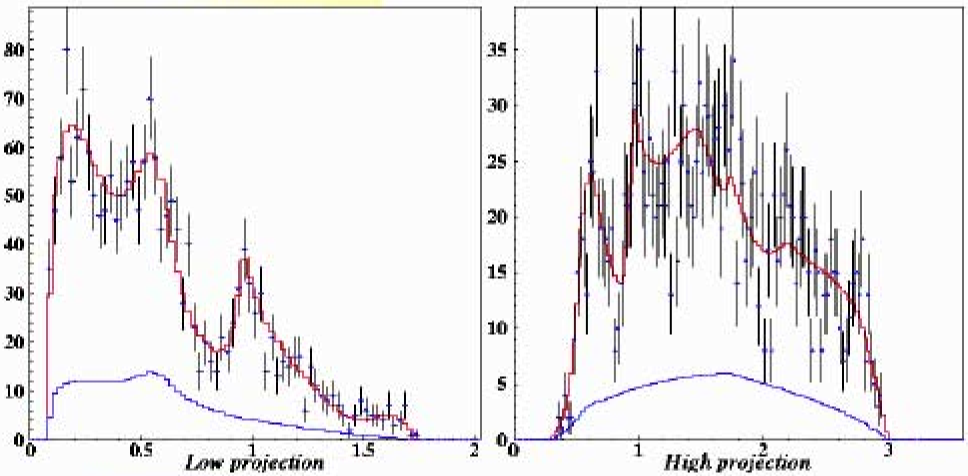
FOCUS
Fermilab E687 upgrade

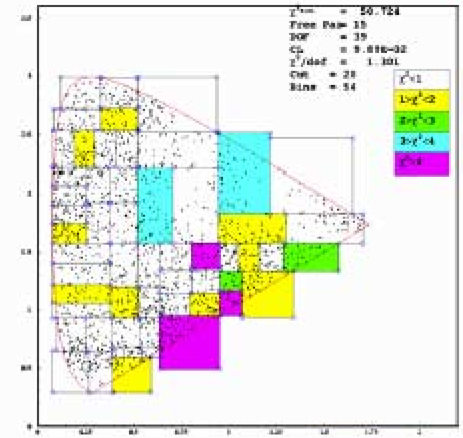
$D^+ \to \pi\pi\pi$



Preliminary

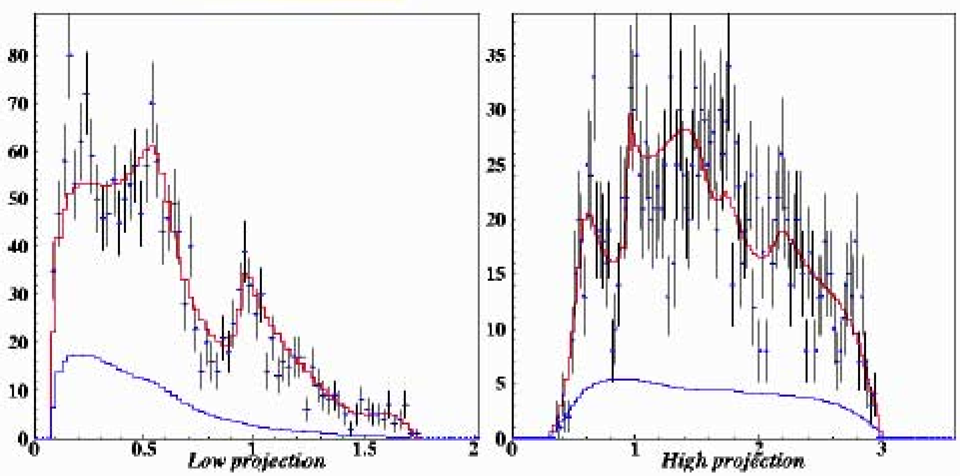
With $f_0(400)$

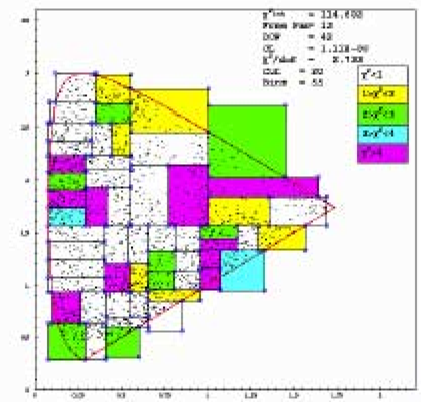




C.L. ~ 1 0%

Without $f_0(400)$





~ 10^{-8} %

Isobar approach

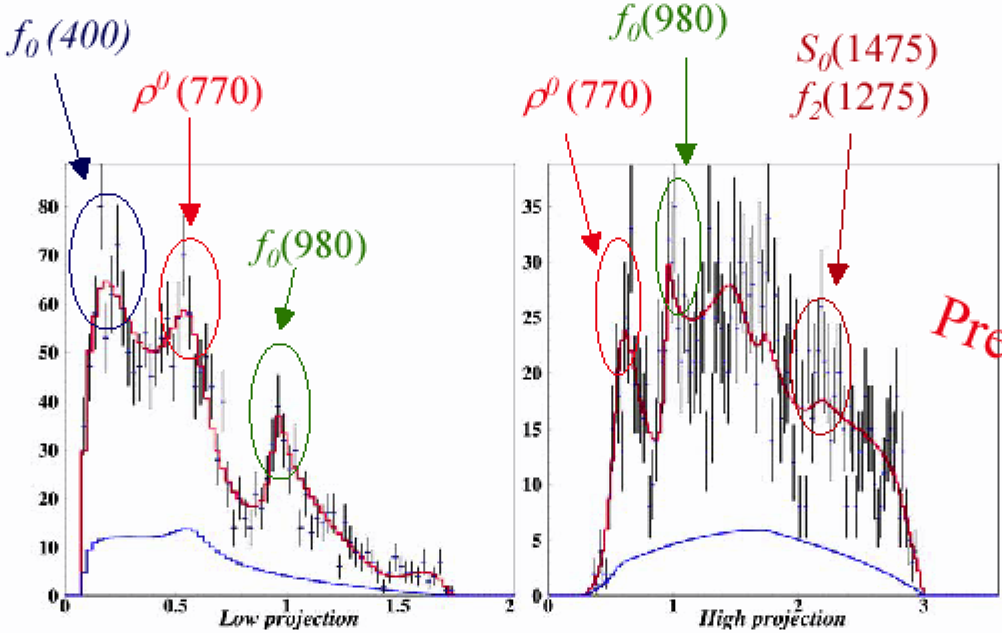
Single BW for $f_0(400)$

$m = 443 \pm 27\ MeV$
$\Gamma = 443 \pm 80\ MeV$

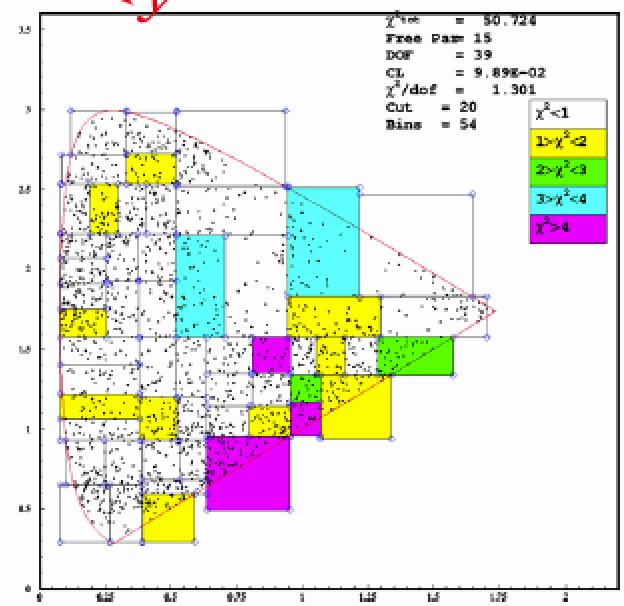
E791 Results :

$m = 478^{+24}_{-23} \pm 17\ MeV$

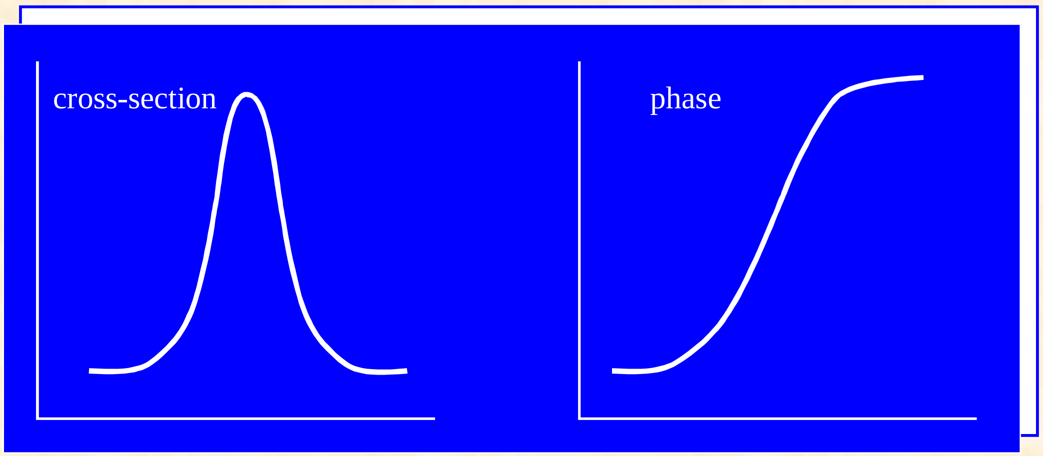
$\Gamma = 324^{+42}_{-40} \pm 21\ MeV$

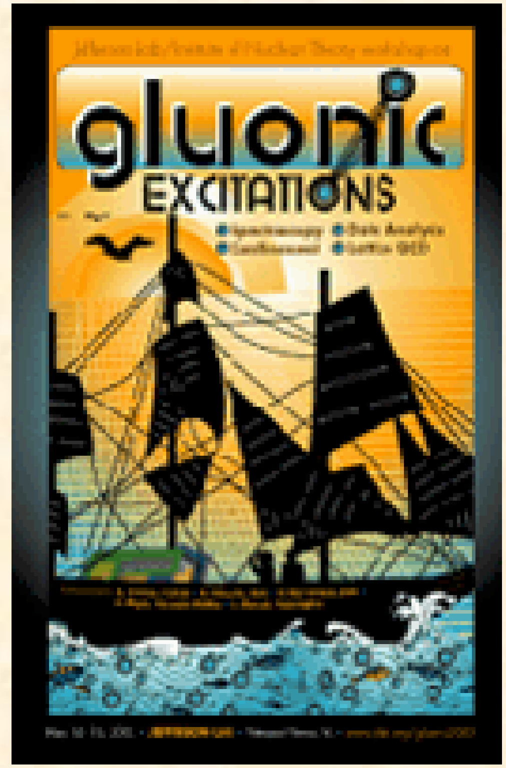


Preliminary



resonances	fit fraction (%)	phase ϕ_j	amplitude a_j
NR	9.8 ± 4.3	0 (*fixed*)	1 (*fixed*)
$\rho^0(770)$	32.8 ± 3.8	62.9 ± 16.8	1.830 ± 0.408
$f_2(1275)$	12.3 ± 2.1	-213.3 ± 17.7	1.120 ± 0.306
$f_0(980)$	6.7 ± 1.5	-145.9 ± 17.7	0.827 ± 0.239
$S_0(1475)$	1.8 ± 1.2	242.3 ± 25.8	0.425 ± 0.208
$f_0(400)$	18.9 ± 5.3	-96.9 ± 30.7	1.389 ± 0.468





States in the spectrum - poles of the S-matrix universal with definite quantum numbers

Comprehensive Analyses