$D^*_{s0}(2317)$ and $D^*_{s1}(2632)$ require $K^*_0(800)$ and $\rho'(1250)$

prepared for the
341. WE-Heraeus-Seminar

Exotic States: Challenges for QCD

January, 17-21 (2005)
Physikzentrum, Bad Honnef (Germany)

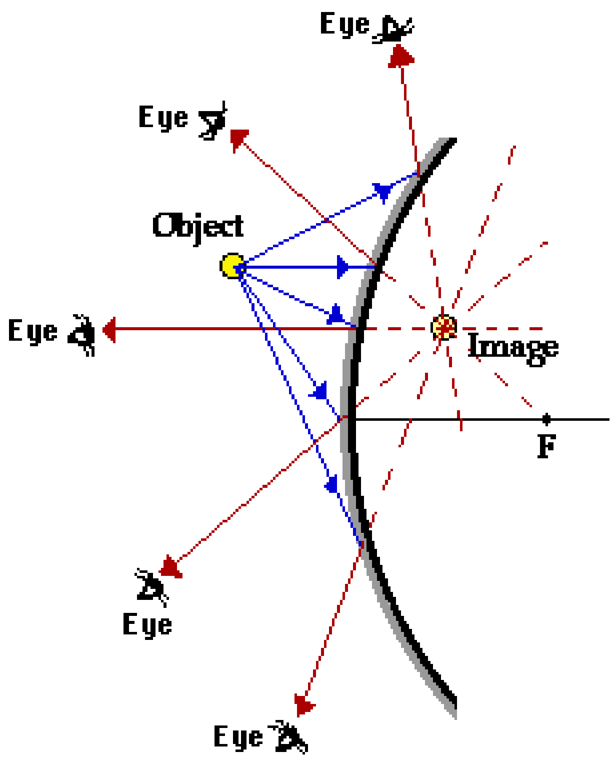
Eef van Beveren
George Rupp

Miss QCD
and her little fellow Electroweak
Bad Honnef, January 17th, 2005

Miss QCD, now in her early thirties, embarrassed by the very thought that from the not-exactly-faithful candidates, soon she should select a partner for life.

Wrong Picture

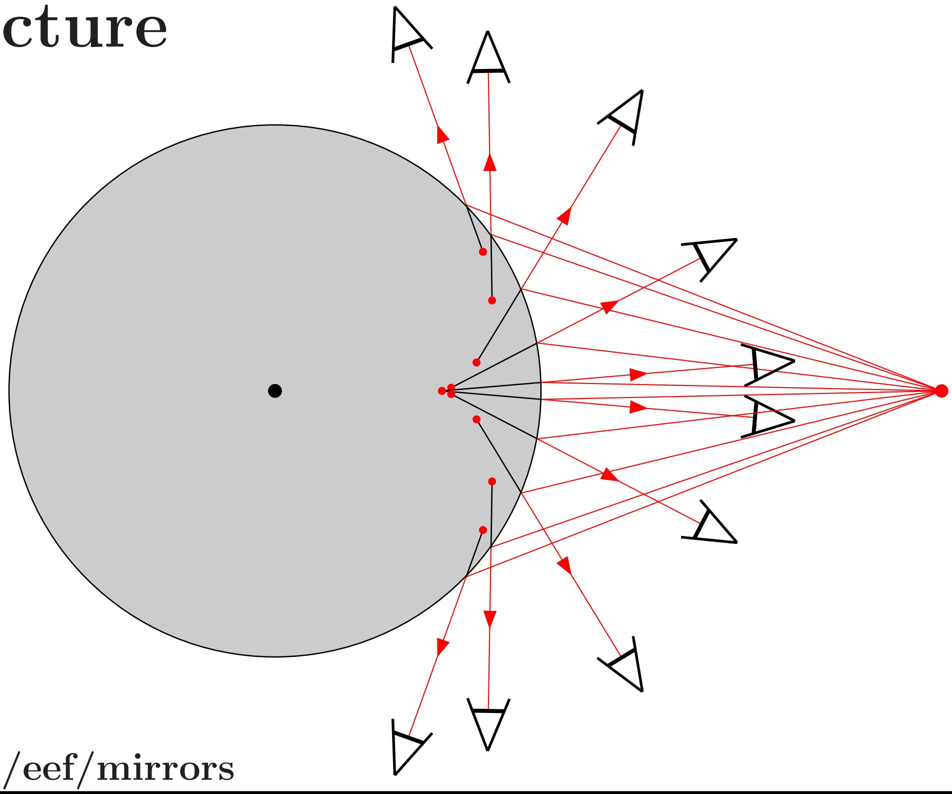
The same object
seen through
a spherical mirror
from different angles,
does NOT result
in the same
reflection image.



picture from
high-school physics tutorial

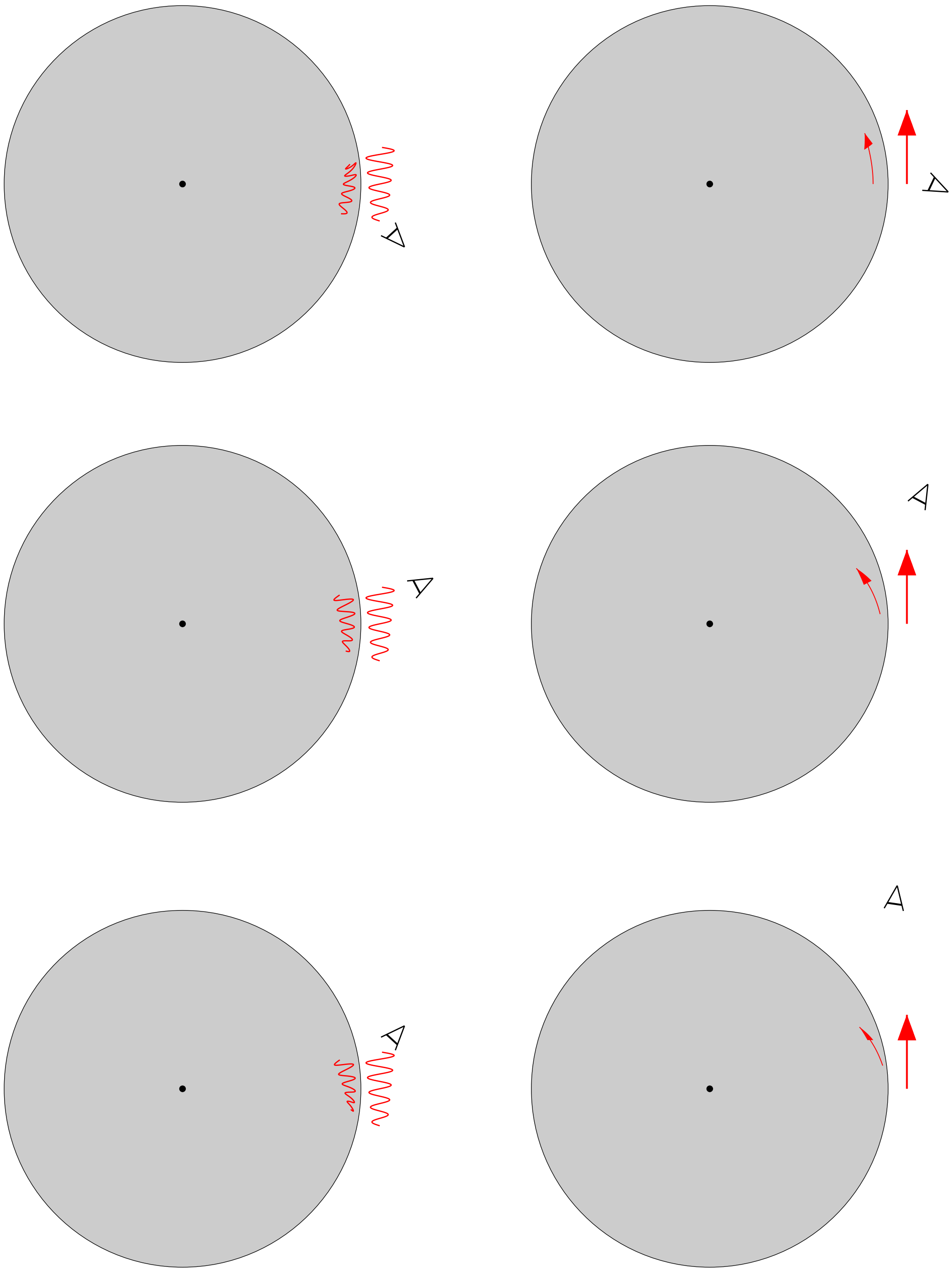
Correct Picture

different angle
different image



http://cft.fis.uc.pt/eef/mirrors

The image is deformed
and depends on one's angle of view



contrary to what is told high-school students.

the object: **STRONG INTERACTIONS**

the mirror: **QCD**

the different angles:

quark-antiquark bound states

multiquark bound states

lattice QCD

linear sigma model

chiral perturbation theory

hadronic decay

hadronic scattering

electron-positron scattering

two-photon scattering

In the debris of hadron interactions
lies the beauty of QCD.
(Michael Pennington 2003-2004)

Quark-Antiquark Bound States

QCD-inspired potential

the Richardson Potential

incorporates

asymptotic freedom

short-range 0ne-gluon exchange

and

confinement

properties

the resulting Spectrum

has a ground state

and

an infinity

of angular and radial excitations

Example: Hans Hersbach, nucl-th/9305010

Ia 4 (3) parameters

Ib 3 (3) parameters

II 5 (4) parameters

+ constituent quark masses ($m_u = m_d$).

Hans Hersbach
nucl-th/9305010

Bottonium: $b\bar{b}$ $J^{PC} = 1^{--}$ or ${}^{2s+1}L_J = {}^3S_1/{}^3D_1$				
Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
Υ	9.460	9.493	9.434	9.441
Υ'	10.023	10.011	10.018	10.022
	10.160	10.131	10.171	10.160
Υ''	10.355	10.346	10.348	10.365
		10.423	10.444	10.451
Υ'''	10.580	10.614	10.599	10.626
		10.672	10.670	10.688
Υ^{iv}	10.865	10.846	10.811	10.844
		10.893	10.868	10.892
Υ^{v}	11.019	11.054	11.000	11.035

Charmonium: $c\bar{c}$ $J^{PC} = 1^{--}$ or ${}^{2s+1}L_J = {}^3S_1/{}^3D_1$				
Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
J/Ψ	3.097	3.099	3.104	3.117
Ψ'	3.686	3.655	3.646	3.665
Ψ''	3.770	3.766	3.780	3.775
Ψ'''	4.040	4.051	4.017	4.028
Ψ^{iv}	4.159	4.124	4.105	4.097
Ψ^{v}	4.415	4.376	4.319	4.314
		4.430	4.384	4.364

Hans Hersbach
nucl-th/9305010

Light unflavoured mesons: u/d quarks. $J^{PC} = 1^{--}$ or $^{2s+1}L_J = {}^3S_1/{}^3D_1$				
Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
ρ	0.768	0.754	0.762	0.867
	1.290	1.365	1.345	1.387
ρ'	1.465	1.474	1.477	1.460
ρ''	1.700	1.806	1.786	1.764
		1.865	1.864	1.807
ρ'''	2.100	2.162	2.151	2.065
ρ^{iv}	2.150	2.200	2.206	2.096

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Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
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a_0'	1.320	1.517	1.464	1.510

Strange mesons (Kaons): s, u/d quarks. $J^P = 0^-$ or ${}^{2s+1}L_J = {}^1S_0$				
Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
K	0.495	0.762	0.723	0.781

Strange mesons (Kaons): s, u/d quarks. $J^P = 1^-$ or ${}^{2s+1}L_J = {}^3S_1$				
Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
K^*	0.894	0.891	0.876	0.955
$K^{*\prime}$	1.412	1.504	1.455	1.477
$K^{*\prime\prime}$	1.714	1.618	1.588	1.553
		1.945	1.890	1.852

Strange mesons (Kaons): s, u/d quarks. $J^P = 0^+$ or ${}^{2s+1}L_J = {}^3P_0$				
Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}
K_0^*	1.429	1.177	1.112	1.115
		1.674	1.587	1.604
$K_0^{*\prime}$	1.950	2.074	1.989	1.955

Different Example

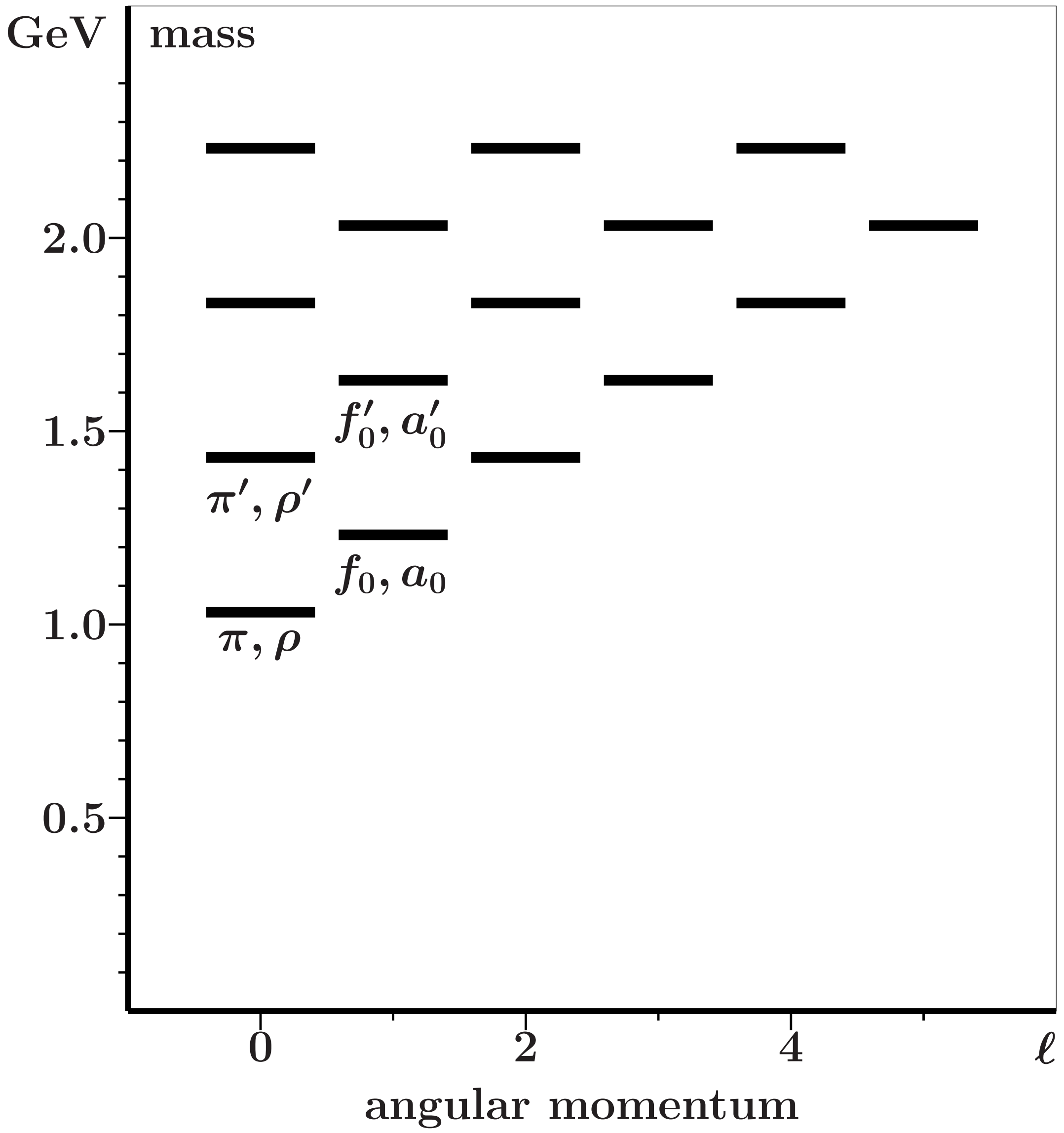
flavor-independent HARMONIC OSCILLATOR

Based on the OBSERVED property

of EQUAL level spacings for ALL flavors

Resulting Spectrum for mesons

1 parameter (ω) + constituent quark masses ($m_u = m_d$).



Harmonic Oscilator

Bottonium: $b\bar{b}$

$J^{PC} = 1^{--}$ or $^{2s+1}L_J = {}^3S_1/{}^3D_1$

Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}	H.O.
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		10.672	10.670	10.688	10.87
Υ^{iv}	10.865	10.846	10.811	10.844	11.25
		10.893	10.868	10.892	11.25
Υ^{v}	11.019	11.054	11.000	11.035	11.63

Charmonium: $c\bar{c}$

$J^{PC} = 1^{--}$ or $^{2s+1}L_J = {}^3S_1/{}^3D_1$

Name	M^{exp}	M^{Ia}	M^{Ib}	M^{II}	H.O.
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$K^{*\prime\prime}$	1.714	1.618	1.588	1.553	1.58
		1.945	1.890	1.852	1.96

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K_0^*	1.429	1.177	1.112	1.115	1.39
		1.674	1.587	1.604	1.77
$K_0^{*\prime}$	1.950	2.074	1.989	1.955	2.15

The obvious conclusion

that

a flavor-independent harmonic oscillator

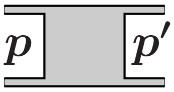
does not yield the meson spectrum

is WRONG,

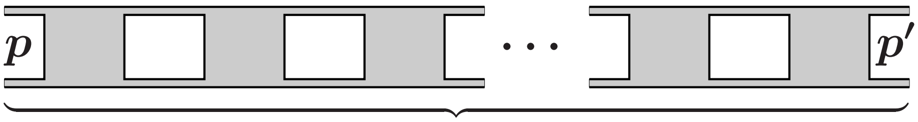
it just needs one more ingredient!

Quark Exchange

couples $Q\bar{Q}$ to Meson-Meson

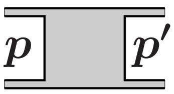
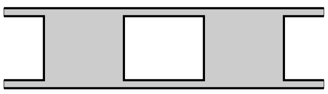
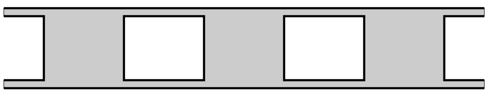
$\langle \vec{p}|\, V \,|\vec{p}\,'\rangle =$  $= \langle \vec{p}|\, V_t \,\left(E(p) - H_c\right)^{-1}\, V_t \,|\vec{p}\,'\rangle$

$$\langle \vec{p}|\, (V G_f)^{N+1}\, |\vec{p}\,'\rangle =$$

$=$ 

$N+1$ times

$$\langle \vec{p}|T|\vec{p}\,'\rangle =$$

$=$  $+$  $+$  $+\cdots$

Meson-Meson Scattering

Partial-wave K matrix*

$$K_\ell(p) = \frac{\pi\lambda^2\mu p \displaystyle\sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p)\,\mathcal{J}_{n\ell}(p)}{E(p)-E_{n\ell_c}}}{\pi\lambda^2\mu p \displaystyle\sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p)\,\mathcal{N}_{n\ell}(p)}{E(p)-E_{n\ell_c}} - 1}$$

$E_{n\ell_c}$ = radial spectrum quark-antiquark

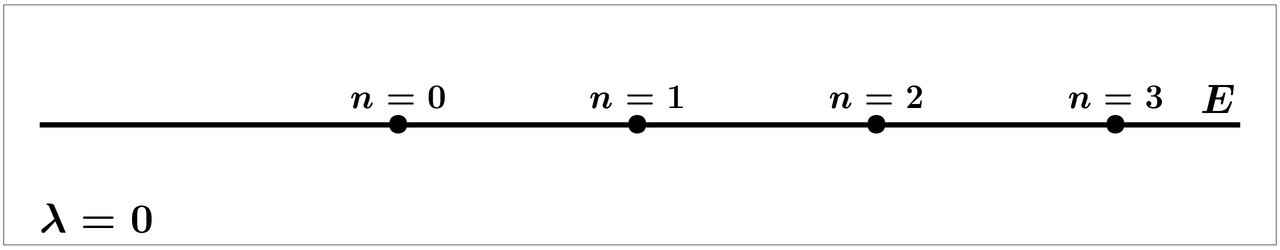
*Phys. Rev. D21, 772 (1980)

*AIP Conf. Proc. 687, 86-95 (2003) [arXiv:hep-ph/0306155]

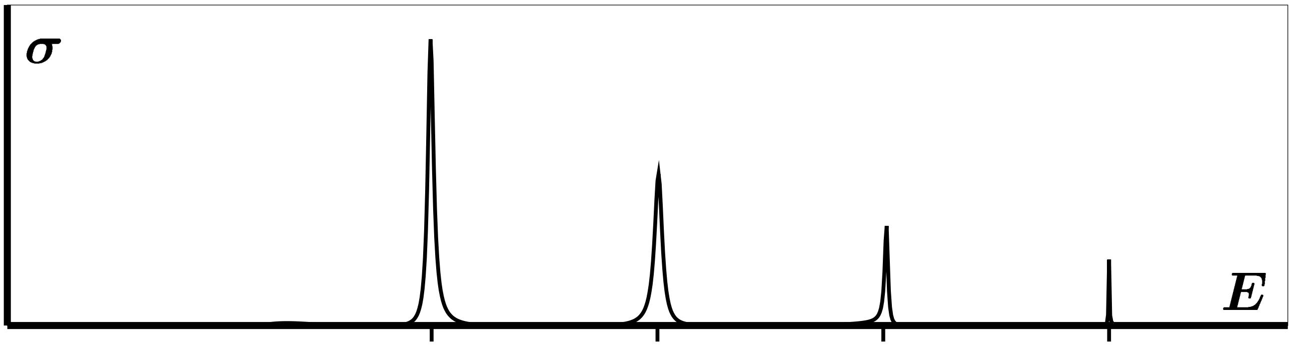
Two more parameters for the description of V_t:

λ - intensity

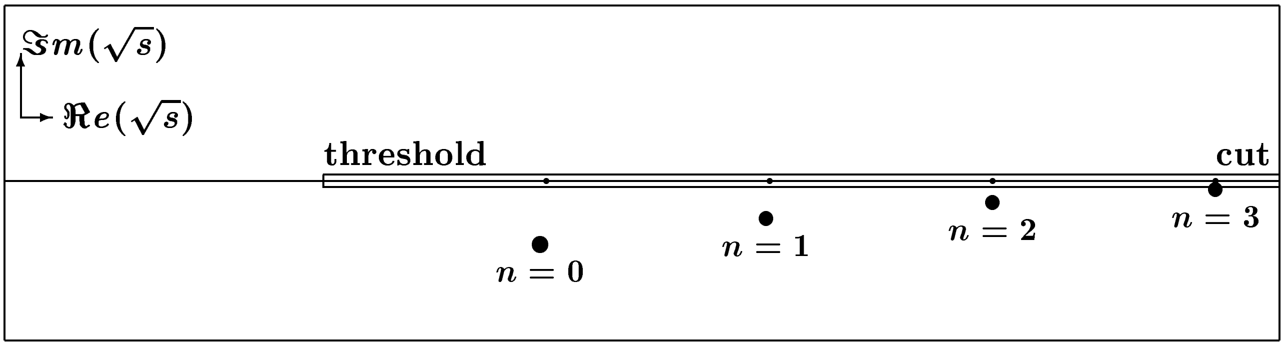
a - shape



The spectrum of confinement for fixed ℓ_c



Elastic meson-meson scattering (λ small)

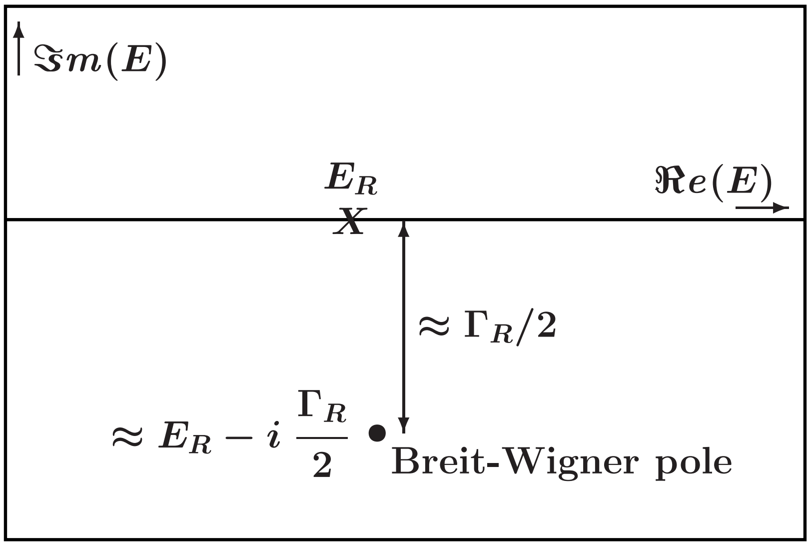


Scattering-matrix poles (λ small)

Near a Breit-Wigner Resonance (λ small)

$$K_\ell(s) \approx \frac{\Gamma_R/2}{E_R - \sqrt{s}}$$

$E_R \approx$ central resonance mass
$\Gamma_R \approx$ resonance width



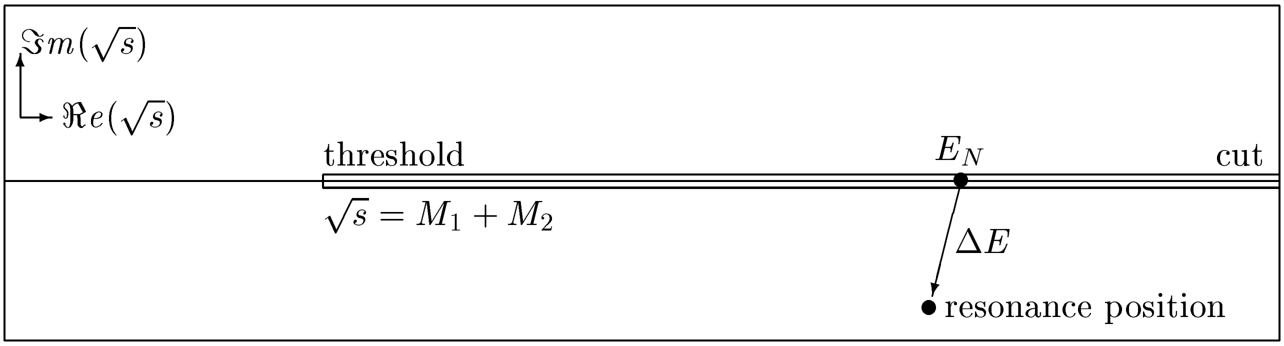
complex $E(p)$ plane

Our resonance expression:

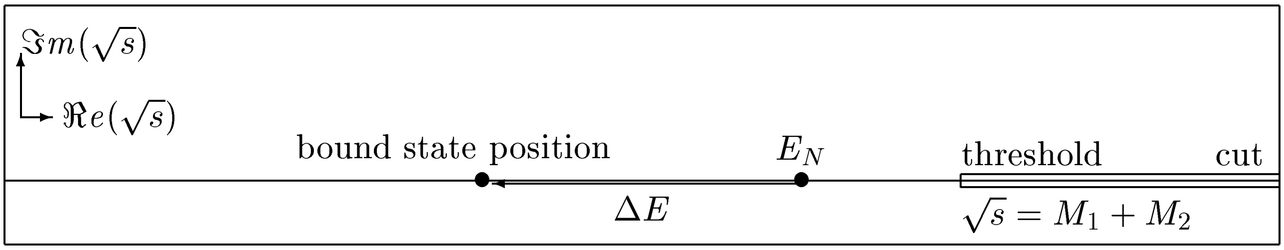
$$\boldsymbol{K_\ell(p) = \frac{\pi\lambda^2\mu p \sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p)\,\mathcal{J}_{n\ell}(p)}{E(p)-E_n}}{\pi\lambda^2\mu p \sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p)\,\mathcal{N}_{n\ell}(p)}{E(p)-E_n} - 1}}$$

There are two cases:

1. $\boldsymbol{E_N}$ above threshold



2. $\boldsymbol{E_N}$ below threshold



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		1.674	1.587	1.604	1.65
$K_0^{*\prime}$	1.950	2.074	1.989	1.955	1.80

Approximation in our expression
for a better contact with experiment

$$K_\ell(p) \;\approx\; \frac{2\lambda^2\;\mu\;pa\;j_\ell^2(pa)\;\sum\limits_{n\,=\,0}^{\infty}\dfrac{\left|\mathcal{F}_n(a)\right|^2}{E(p)-E_n}}{2\lambda^2\;\mu\;pa\;j_\ell(pa)\;n_\ell(pa)\;\sum\limits_{n\,=\,0}^{\infty}\dfrac{\left|\mathcal{F}_n(a)\right|^2}{E(p)-E_n}\;-\;1}$$

λ = coupling constant
p = relative meson-meson linear momentum
$E(p)$ = total invariant meson-meson mass
E_n = n-th level of the confinement spectrum (ω)
μ = reduced meson-meson mass
j_ℓ = spherical Bessel function
n_ℓ = spherical Neumann function
$\mathcal{F}_n$ = quark-antiquark confinement wave function
a = $q\bar{q}$ separation distance (≈ 0.5 fm)

and a further approximation

$$\lambda^2\sum_{n\,=\,0}^{\infty}\frac{\left|\mathcal{F}_n(a)\right|^2}{E-E_n}\;\approx\;\lambda^2\left(\sum_{n\,=\,0}^{N}\frac{B_n}{E-E_n}-1\right)$$

with a redefinition of λ

Eliminating parameters

by recombining 2 quarks and 2 antiquarks within a harmonic oscillator model for confinement.

Zeit. Phys. C 21, 291 (1984)

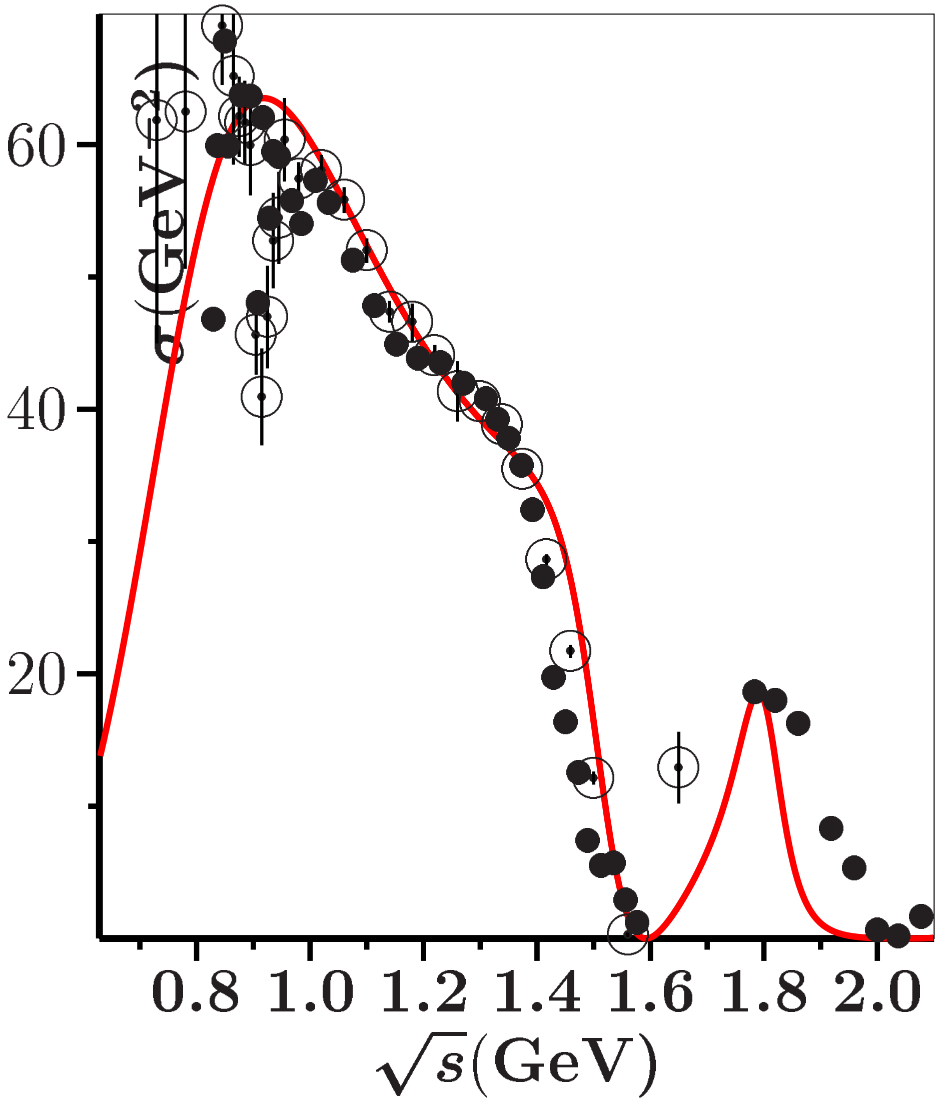
$$\lambda^2 \sum_{n=0}^{\infty} \frac{\left|\mathcal{F}_n(a)\right|^2}{E - E_n}$$

turns, for $K\pi$ elastic $I = \frac{1}{2}$ S-wave scattering, into

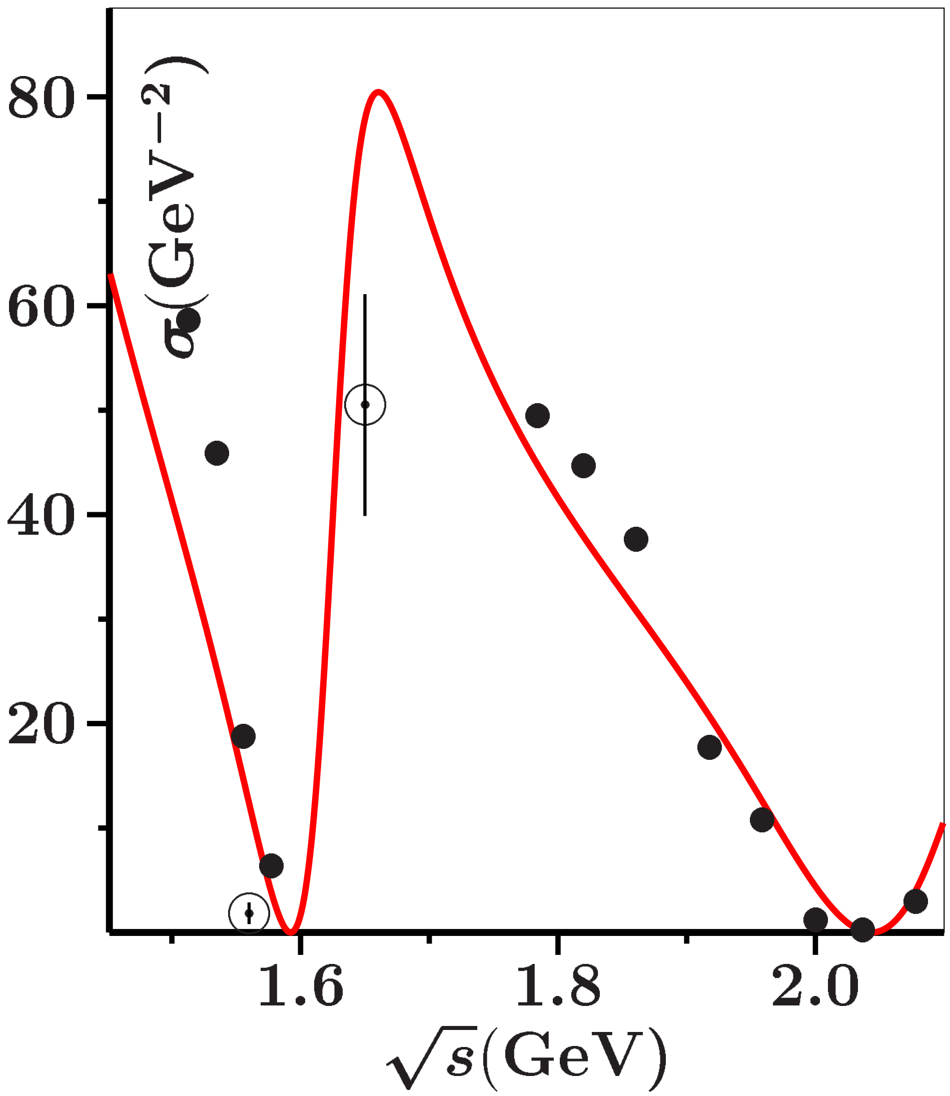
$$\sum_{n=0}^{\infty} \quad \frac{(n+1) \times 4^{-n}}{E - (1.31 + n \times 0.38)} \quad \text{GeV}^2$$

$(n+1) \times 4^{-n}$ represents the matrix element for the coupling of an excited scalar $u\bar{s}$ pair to a $\pi^0 K^+$ pair in S wave.

The reason for this number to drop fast with n, is that the higher the radial excitation, the more the level degeneracy in the 4-particle harmonic oscillator. Hence, the smaller the coupling to a specific channel.

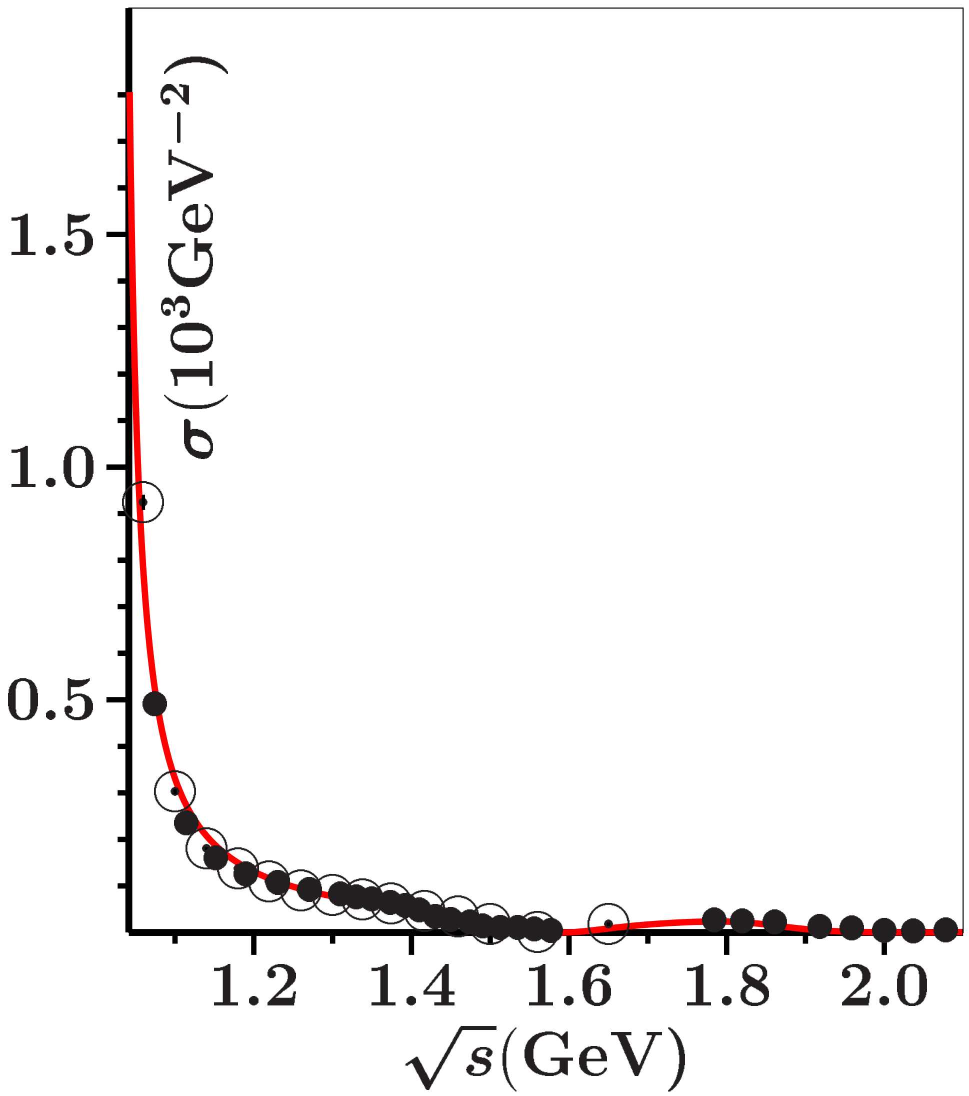


$$\pi^0 K^+ \rightarrow \pi^0 K^+$$



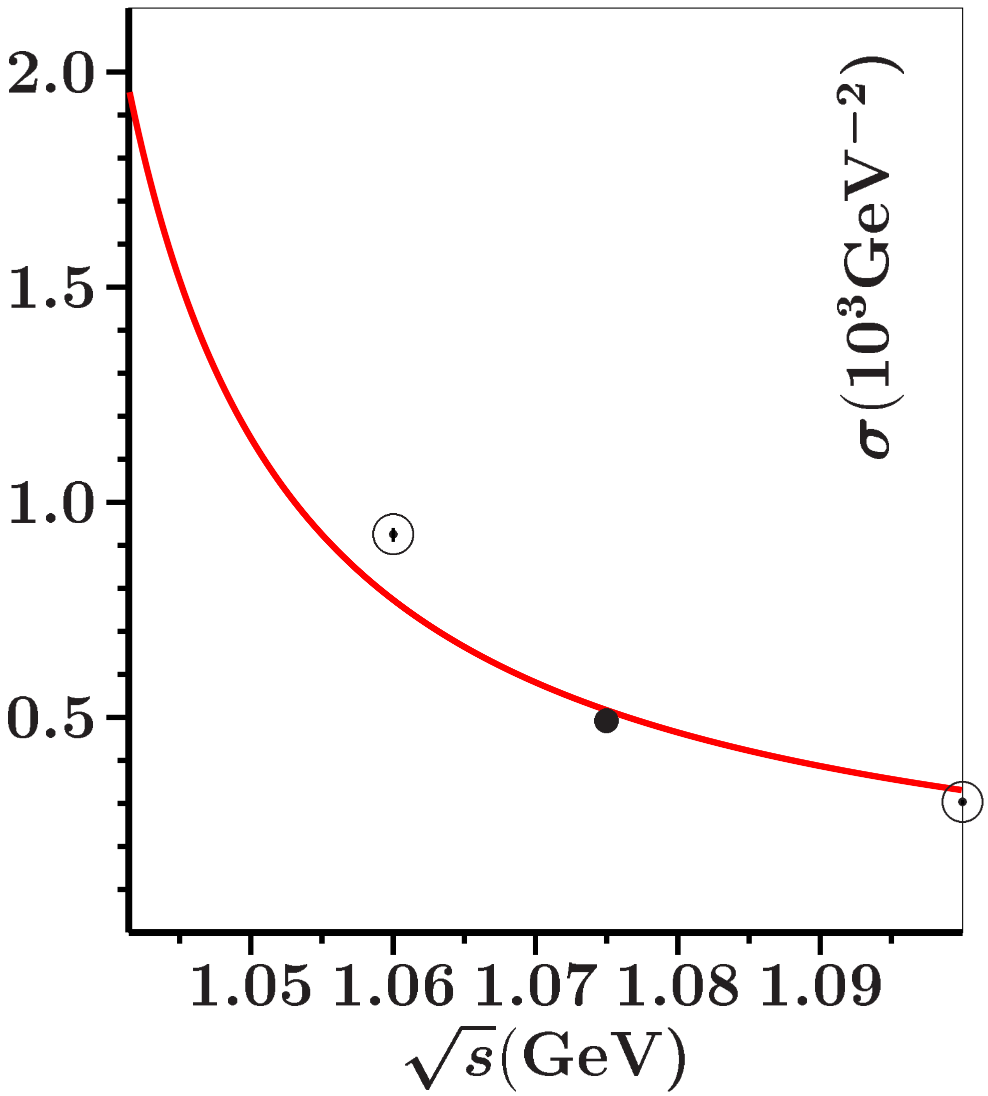
$$\eta' K^+ \to \eta' K^+$$

Data = $\pi^0 K^+$ phase shifts and $\eta' K^+$ kinematics

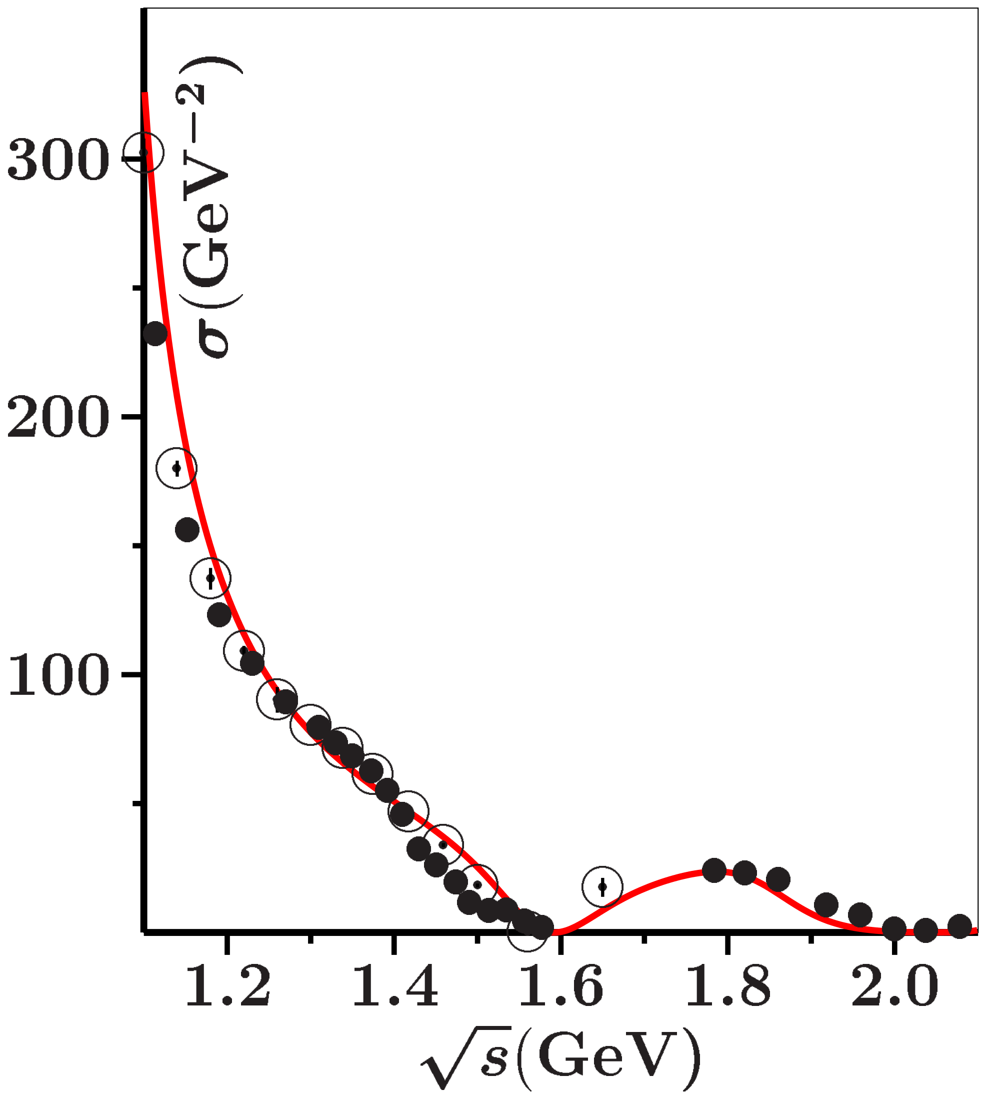


$$\eta K^+ \rightarrow \eta K^+$$

Data = $\pi^0 K^+$ **phase shifts and** ηK^+ **kinematics**



detail of $\eta K^+ \rightarrow \eta K^+$



detail of $\eta K^+ \to \eta K^+$

CONCLUSION(S)

The expression

$$K_\ell(p) \approx \frac{2\lambda^2\ \mu\ pa\ j_\ell^2(pa) \displaystyle\sum_{n=0}^{\infty} \frac{|\mathcal{F}_n(a)|^2}{E(p)-E_n}}{2\lambda^2\ \mu\ pa\ j_\ell(pa)\ n_\ell(pa) \displaystyle\sum_{n=0}^{\infty} \frac{|\mathcal{F}_n(a)|^2}{E(p)-E_n} - 1}$$

seems a good approximation for data analysis.

Full off-shell T matrix:

- hep-ph/0304105 (δ-shell for V_t)
- hep-ph/0306155 (in the appendix, more general)

Many-channel analysis of light scalar mesons:

- Zeitschrift für Physik C30, 615 (1986)
(postscript version available through Spires)

Advantages

Full scattering amplitude

Unexpected extra resonances

"Adler" zeroes

S/D interchange

$$K_\ell(p) \; = \; \frac{\pi\lambda^2\mu p \displaystyle\sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p) \; \mathcal{J}_{n\ell}(p)}{E(p) - E_{n\ell_c}}}{\pi\lambda^2\mu p \displaystyle\sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p) \, \mathcal{N}_{n\ell}(p)}{E(p) - E_{n\ell_c}} \; - \; 1}$$

reproduces the full meson-meson scattering amplitude, not just isolated and moreover non-existing $q\bar{q}$ bound states.

$$K_\ell(p) = \frac{\pi\lambda^2\mu p \sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p)\ \mathcal{J}_{n\ell}(p)}{E(p) - E_{n\ell_c}}}{\pi\lambda^2\mu p \sum_{n=0}^{\infty} \frac{\mathcal{J}^*_{n\ell}(p)\ \mathcal{N}_{n\ell}(p)}{E(p) - E_{n\ell_c}} - 1}$$

contains scattering poles which are NOT directly related to the confinement spectrum of $E_{n\ell_c}$:

$f_0(600)$, $K_0^*(800)$, $a_0(980)$, $f_0(980)$,
$D_0^*(2140)$, $D_{s0}^*(2317)$, ...

Zeit. Phys., C30, 615 (1986) (scalar nonet)

Phys. Rev. Lett. 91, 012003 (2003) (D_{s0} states)

$$
K_\ell(p) \;=\; \frac{\pi\lambda^2\mu p \sum\limits_{n=0}^{\infty} \dfrac{\mathcal{J}^*_{n\ell}(p)\;\mathcal{J}_{n\ell}(p)}{E(p)-E_{n\ell_c}}}{\pi\lambda^2\mu p \sum\limits_{n=0}^{\infty} \dfrac{\mathcal{J}^*_{n\ell}(p)\,\mathcal{N}_{n\ell}(p)}{E(p)-E_{n\ell_c}} \;-\; 1}
$$

contains kinematical zeroes at almost the same complex energies as "Adler" zeroes.

hep-ph/0412078

Preliminary

$$K_\ell(p) = \frac{\pi\lambda^2\mu p \sum\limits_{n=0}^{\infty} \dfrac{\mathcal{J}^*_{n\ell}(p)\ \mathcal{J}_{n\ell}(p)}{E(p) - E_{n\ell_c}}}{\pi\lambda^2\mu p \sum\limits_{n=0}^{\infty} \dfrac{\mathcal{J}^*_{n\ell}(p)\ \mathcal{N}_{n\ell}(p)}{E(p) - E_{n\ell_c}} - 1}$$

seems to interchange the order of dominantly S and dominantly D resonances for $J^{PC} = 1^{--}$ scattering:

$\rho(1290)$ and $D^*_{s1}(2632)$

seem to be dominantly D.

$K_0^*(800)$ or κ

$I(J^P) = \frac{1}{2}(0^+)$

OMITTED FROM SUMMARY TABLE

The existence of this state is controversial.

$K_0^*(800)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
722±60		[1] BUGG	03	RVUE	$11\ K^- p \to K^- \pi^+ n$
797±19±43	15090	[2] AITALA	02	E791	$D^+ \to K^- \pi^+ \pi^+$
905^{+65}_{-30}		[3] ISHIDA	79B	RVUE	$11\ K^- p \to K^- \pi^+ n$

1 T-matrix pole. Reanalysis of ASTON 88 data.
2 Not seen by KOPP 01 using 7070 events of $D^0 \to K^- \pi^+ \pi^0$. Possibly seen by LINK 02E in $D^+ \to K^- \pi^+ \mu^+ \nu_\mu$.
3 Reanalysis of ASTON 88 using interfering Breit-Wigner amplitudes.

$K_0^*(800)$ WIDTH

VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
772±100		[4] BUGG	03	RVUE	$11\ K^- p \to K^- \pi^+ n$
410±43±87	15090	[5] AITALA	02	E791	$D^+ \to K^- \pi^+ \pi^+$
545^{+235}_{-110}		[6] ISHIDA	79B	RVUE	$11\ K^- p \to K^- \pi^+ n$

4 T-matrix pole. Reanalysis of ASTON 88 data.
5 Not seen by KOPP 01 using 7070 events of $D^0 \to K^- \pi^+ \pi^0$. Possibly seen by LINK 02E in $D^+ \to K^- \pi^+ \mu^+ \nu_\mu$.
6 Reanalysis of ASTON 88 using interfering Breit-Wigner amplitudes.

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