... after an intense discussion

1 Connection between resonances and QCD

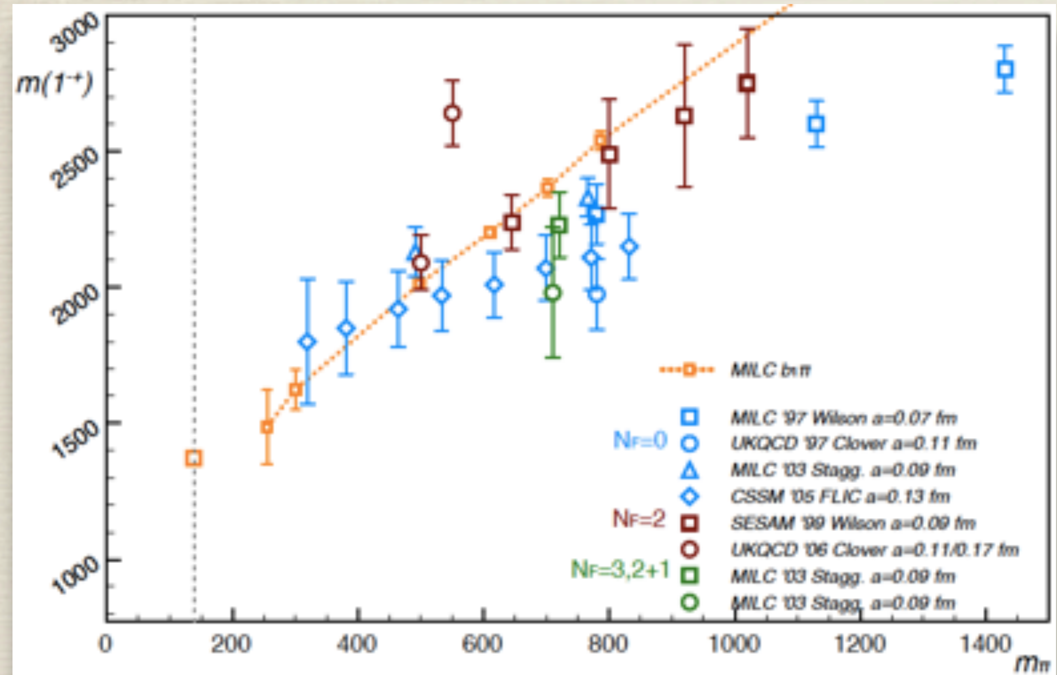
2 Connection between real (data) and imaginary (resonances) worlds

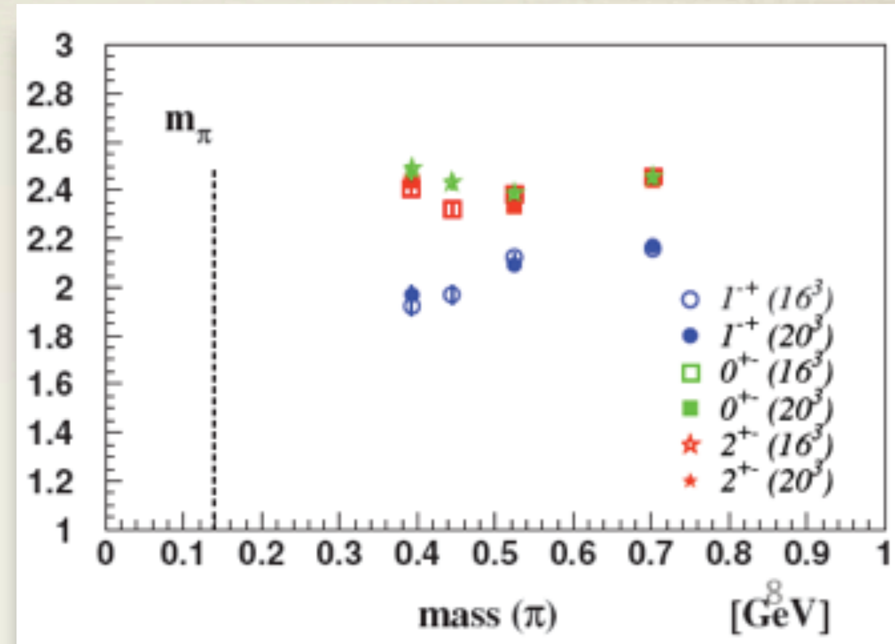
Hybrid Mesons

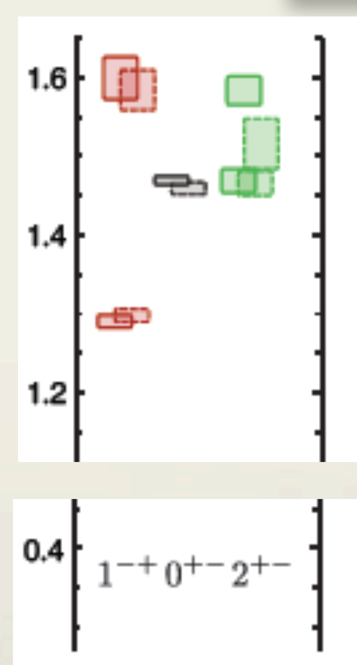
Adam Szczepaniak
Indiana University

* (Selected) aspects on theory and phenomenology
    * Structure of gluonic excitations
* (Selected) aspects of PWA

$$1^{-+}_{S_{Q\bar{Q}}=1} = \frac{0^{++}}{2} + \rho \;\sim 0.8\text{ GeV} + 0.77\text{ MeV} \sim 1.6\text{ GeV}$$







Charmonium 1^{-+}

Ref.	Method	ΔM (GeV)
MILC 97	W	1.34(8)(20)
MILC 99	SW	1.22(15)
CP-PACS 99	NR	1.323(13)
JKM 99	LBO	1.19

Excitations in excess of 1GeV

* $J^{PC} = 1^{-+}$ lowest state

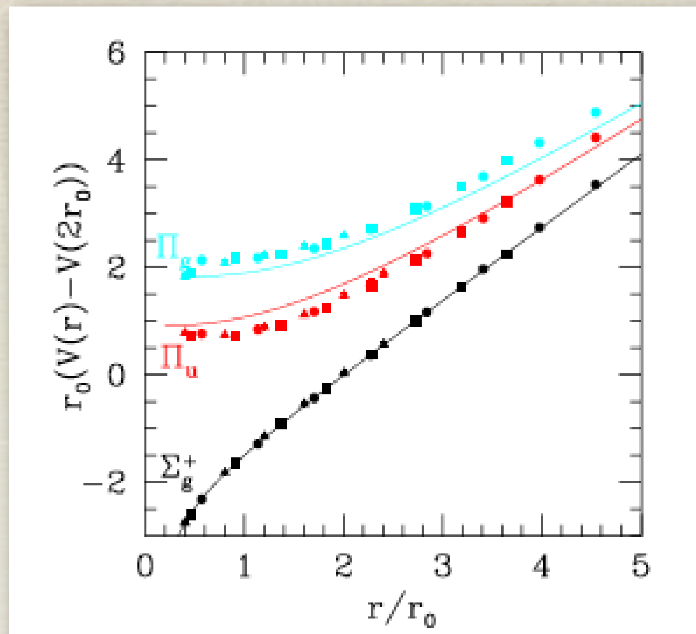
  Higher masses have also been resolved

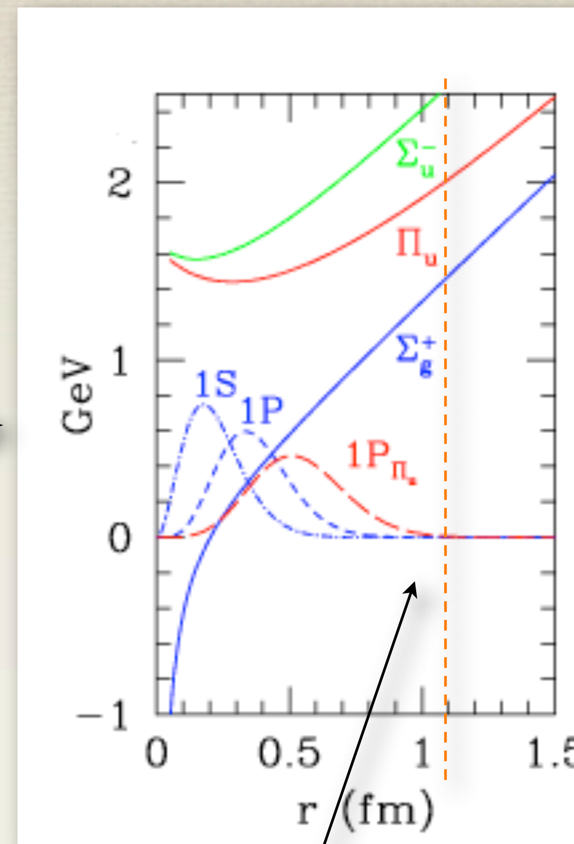
  Chiral extrapolations 100-200 MeV (Thomas,APS)

  In large-Nc same as for ordinary mesons O(1/Nc) (Cohen)

  Preliminary (toy) lattice compuation of widths agrees with models (Michael,McNeile) (Burns,Close)

more on widths





Bali (00)

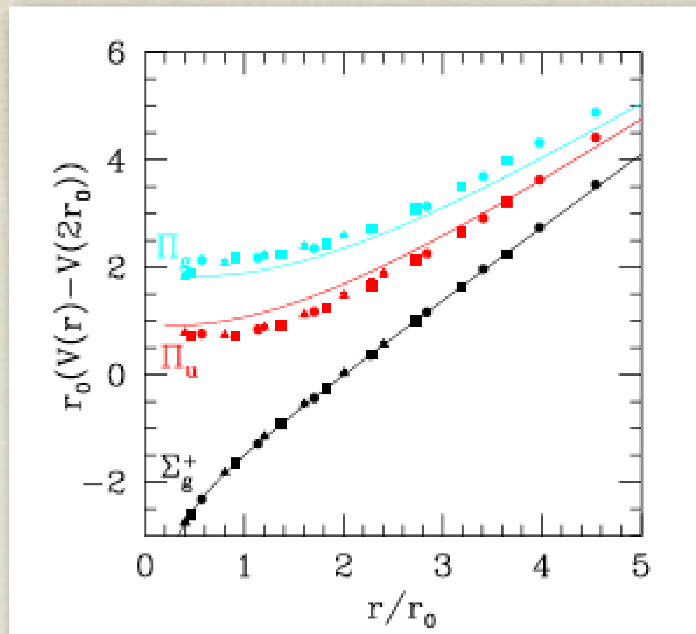
1^{-+} (1.8 GeV)	$b_1\,\pi$	$f_1\,\pi$	$\rho\,\pi$	
PSS	S 73 D 1	S 9 D 0.04	P 13	Γ MeV
IKP	S 51 D 11	S 14 D 7	P 12	

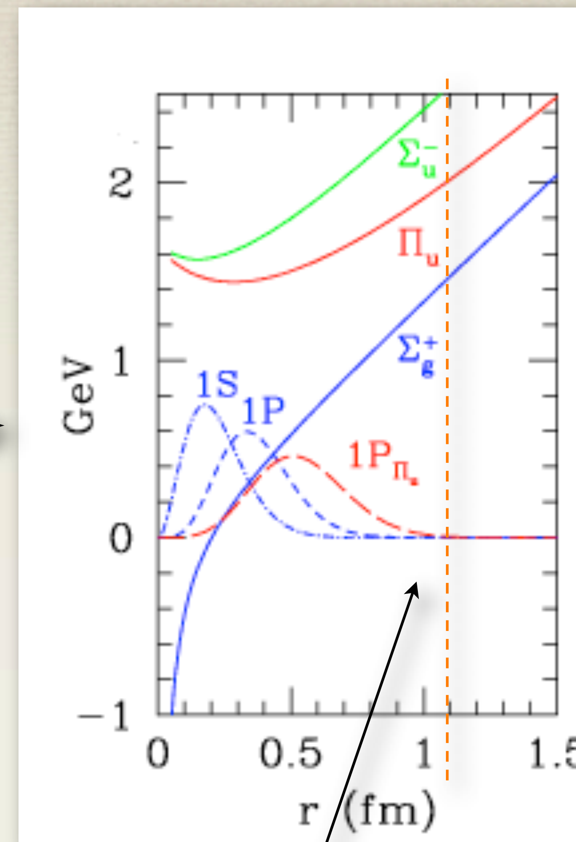
Isgur, Kokosky, Paton (85)
Close, Page (95)
Page, Swanson, Szczepaniak (99)
Close, Dudek (04)

- Low lying states expected below string breaking !

- Unusual decay modes in the flux tube model

more on widths





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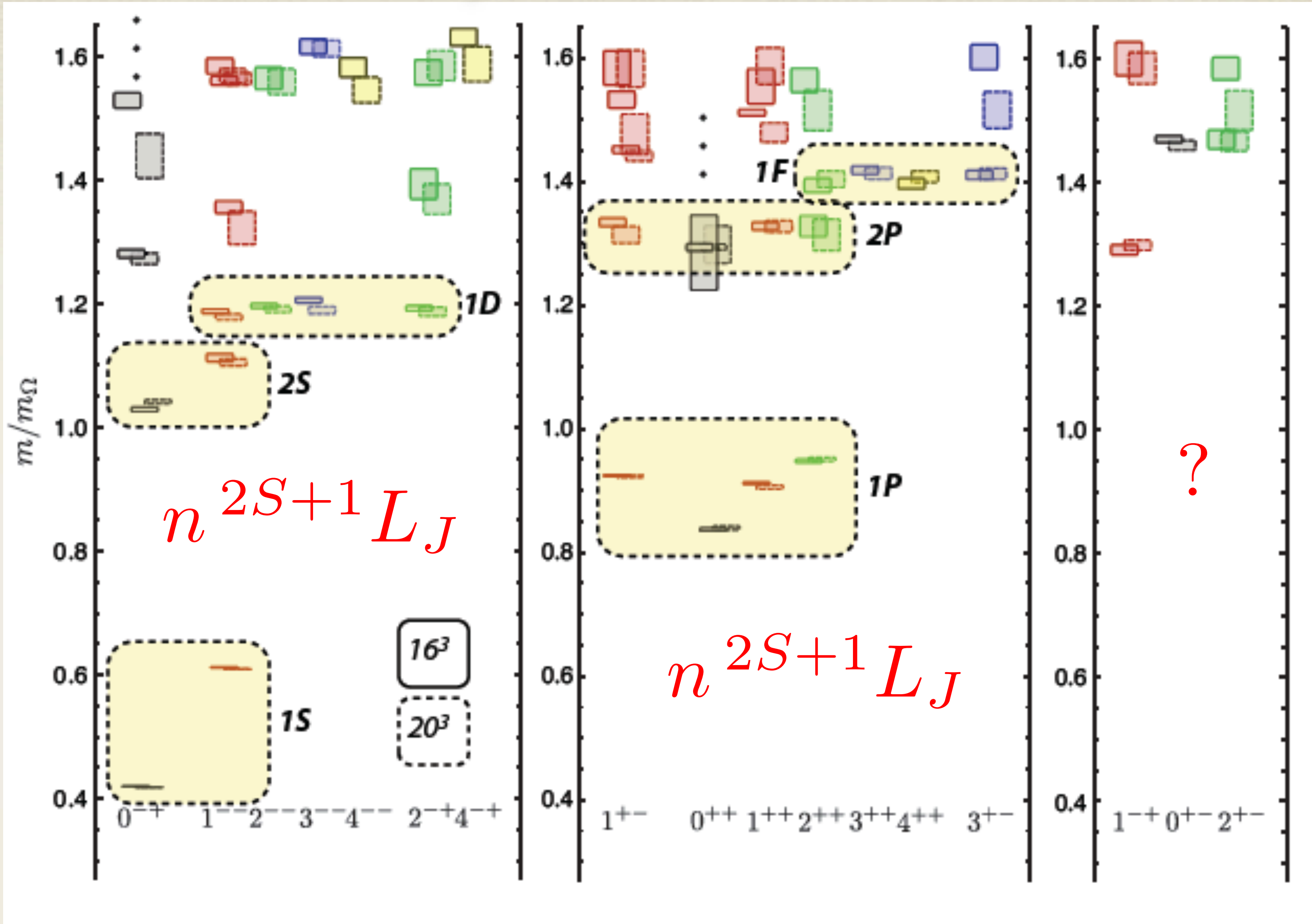
- Low lying states expected below string breaking !
- In large-N_c same as for ordinary mesons $O(1/N_c)$
- Unusual decay modes in the flux tube model

Structure

* normal meson spectrum seems to be very quark model-like !

J.Dudek at al.
Phys.Rev.D82:0345
08,2010



$$\bar{q}(x)\Gamma^i q(x) \sim b^\dagger(k)\sigma^i d(-k)$$

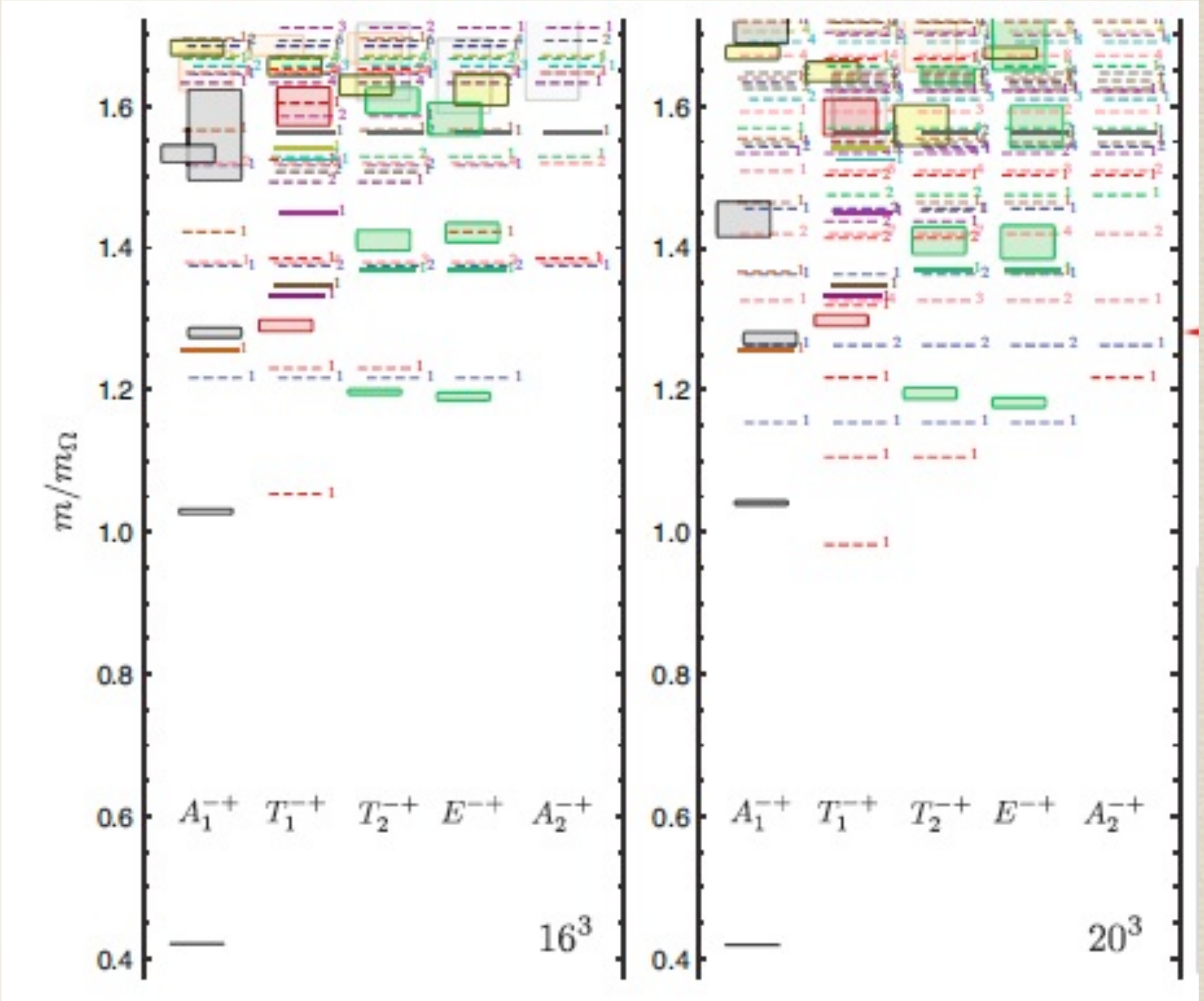
$$\bar{q}(x)F_{ij}(x)q(x) \sim b^\dagger(k)\vec{k}\times\vec{a}(q)d(-q-k)$$

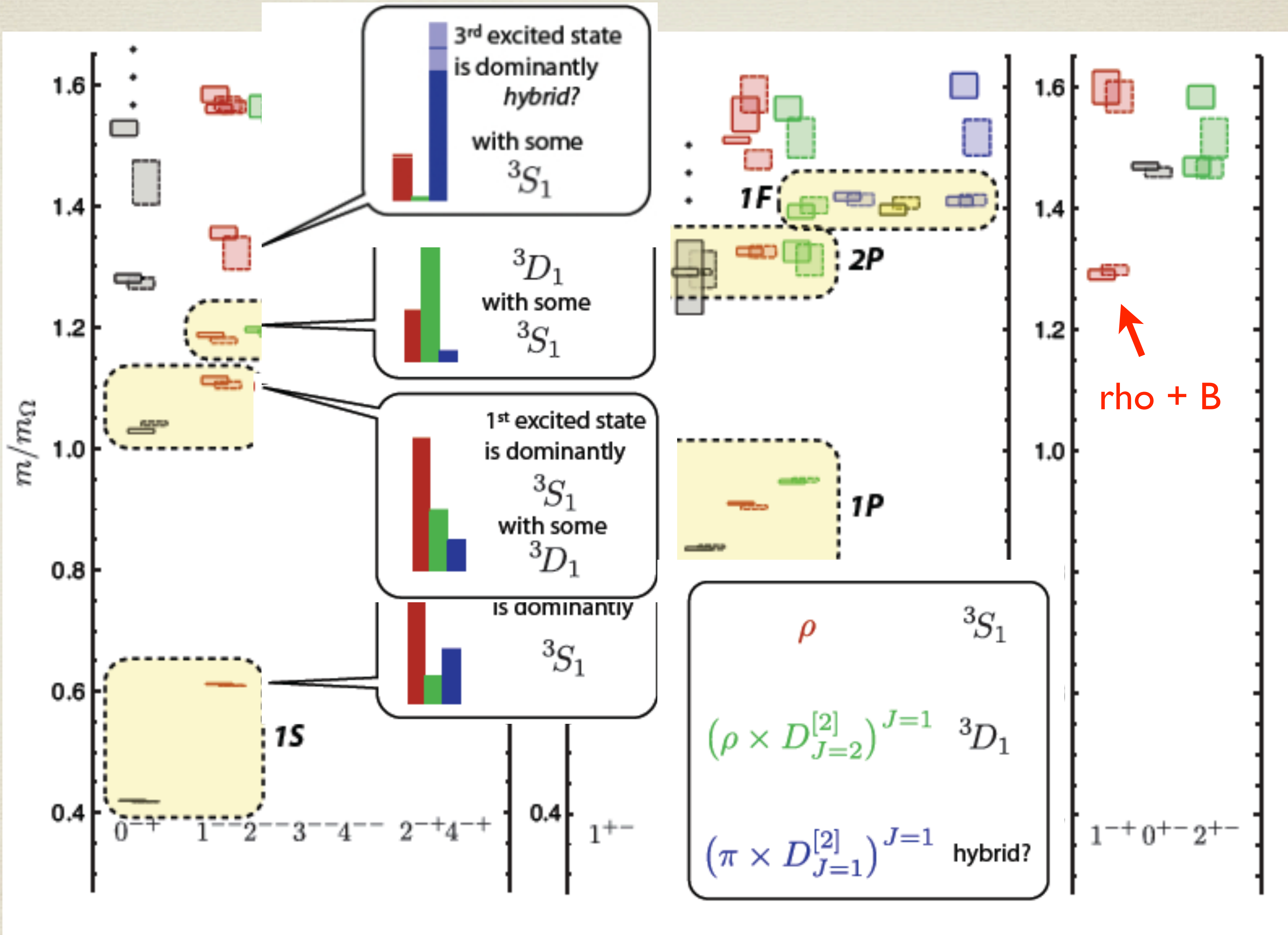
to determine structure study

$\langle \text{Vacuum}|O[q,g]|\ \text{Meson}\rangle$

in unquenched lattice lowest energies correspond to continuum states

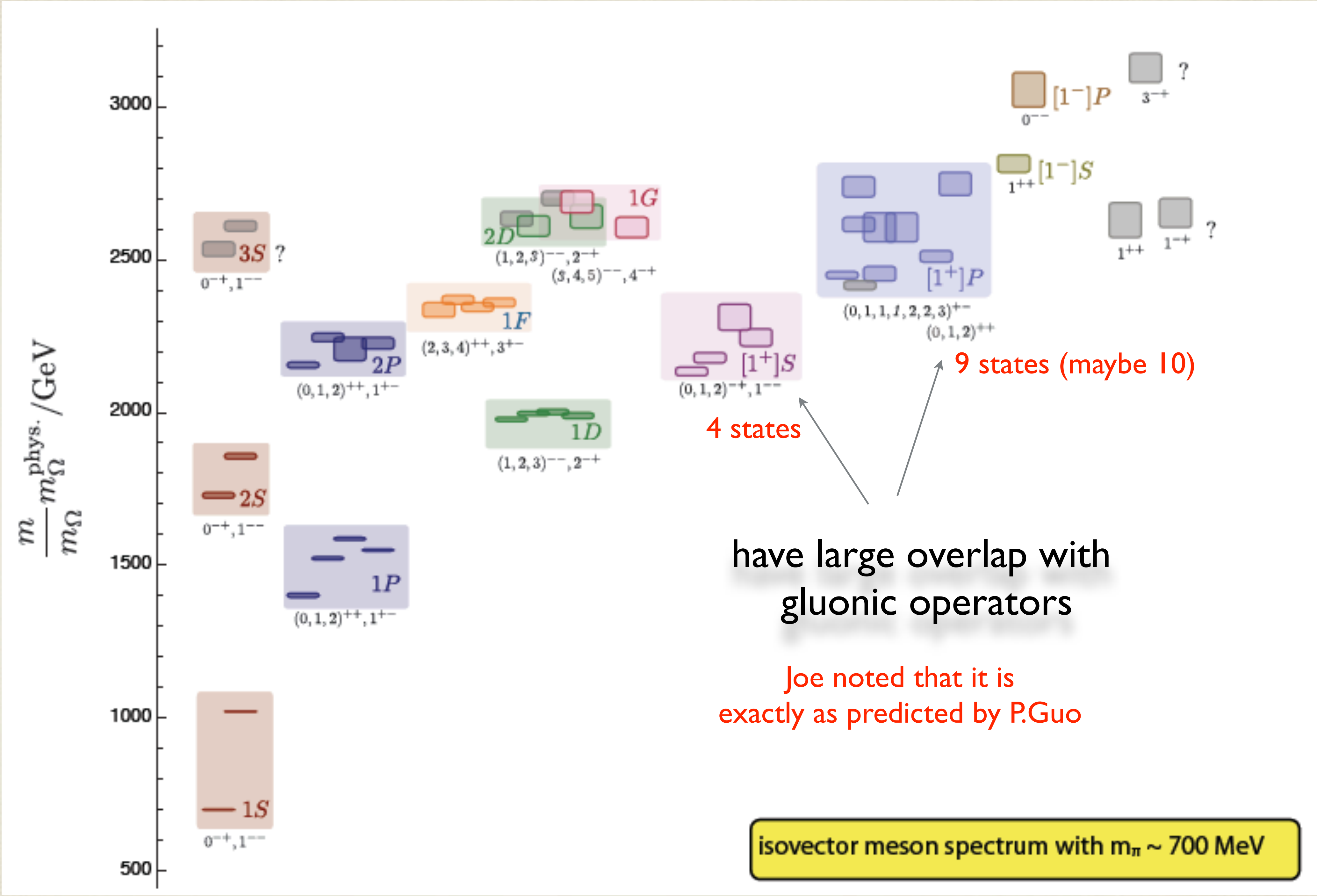
- On finite volume multi-meson state and single hadron states are discrete.
- If there are single hadron states, use volume dependence to disentangle
- Continuum states can have any J,P,C but not single hadron states
- The choice of operators minimizes overlap with multi-meson states





3rd excited state is dominantly hybrid? with some $^3S_1$
$^3D_1$ with some $^3S_1$
1st excited state is dominantly $^3S_1$ with some $^3D_1$
is dominantly $^3S_1$
ρ $^3S_1$
$(\rho \times D^{[2]}_{J=2})^{J=1}$ $^3D_1$
$(\pi \times D^{[2]}_{J=1})^{J=1}$ hybrid?
1S
1P
2P
1F
rho + B
m/m_Ω
0^{-+} 1^{--} 2^{--} 3^{--} 4^{--} 2^{-+} 4^{-+}
1^{+-}
1^{-+} 0^{+-} 2^{+-}

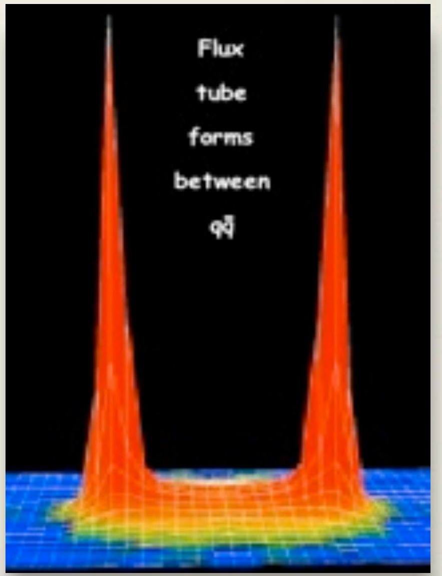
* state of the art full spectrum



Gluon structure models

Bag Model

Flux tube model



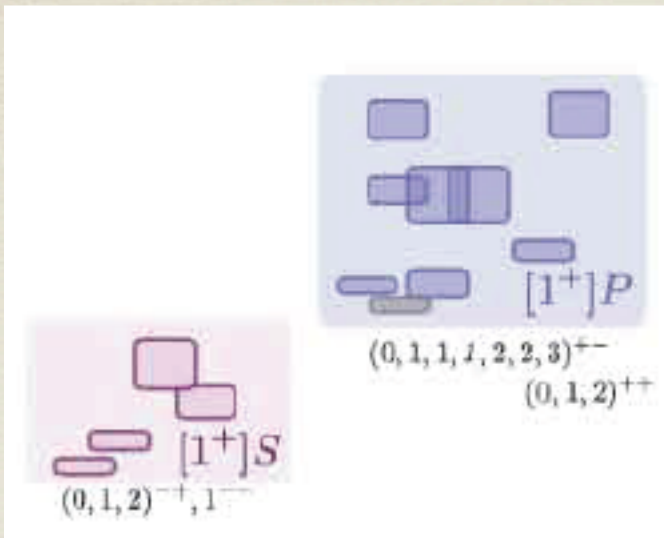
Gluon structure models

And The Winer Is !

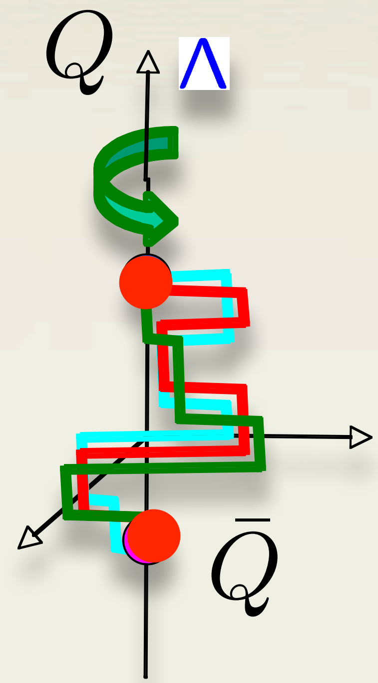
Quasi-particles

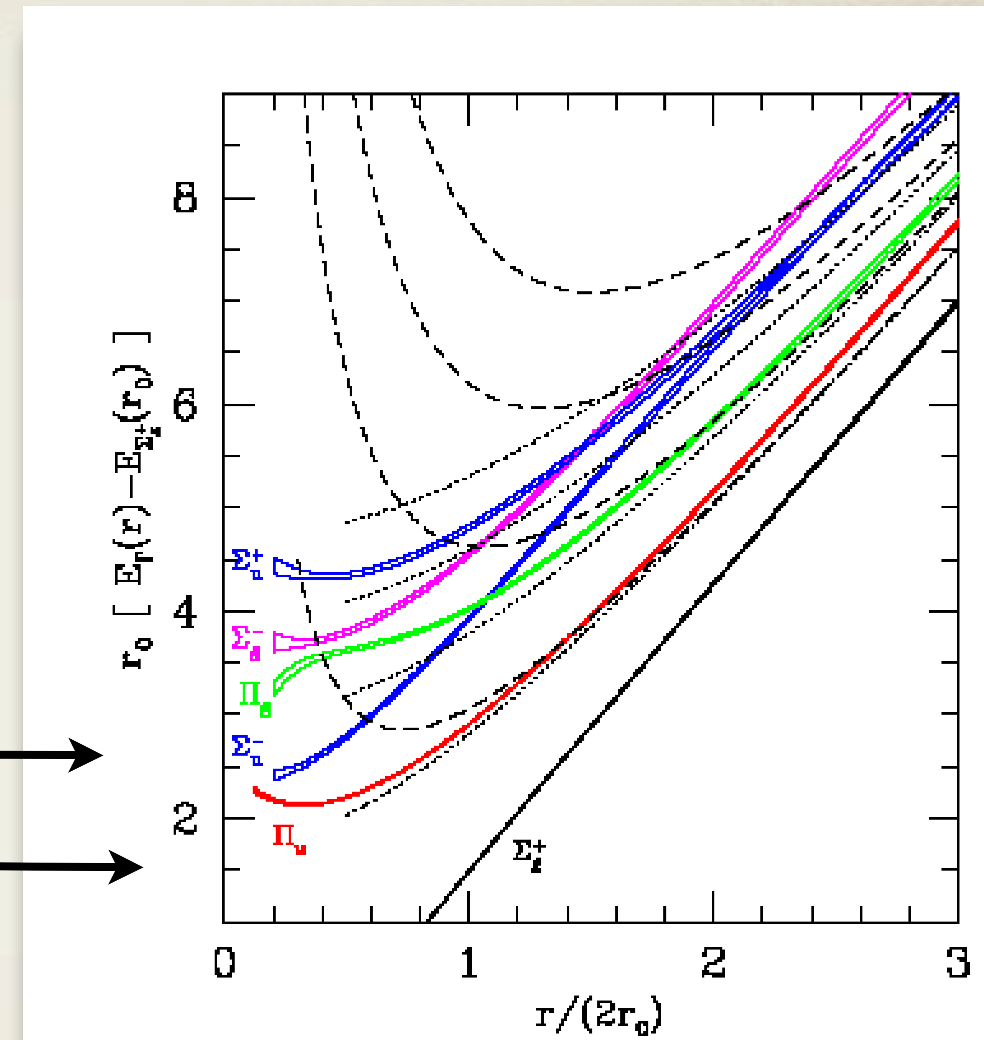
A "good" gluon structure model should describe all these :

* exotic and crypto-exotic mesons



* adiabatic potentials (axial symmetry)

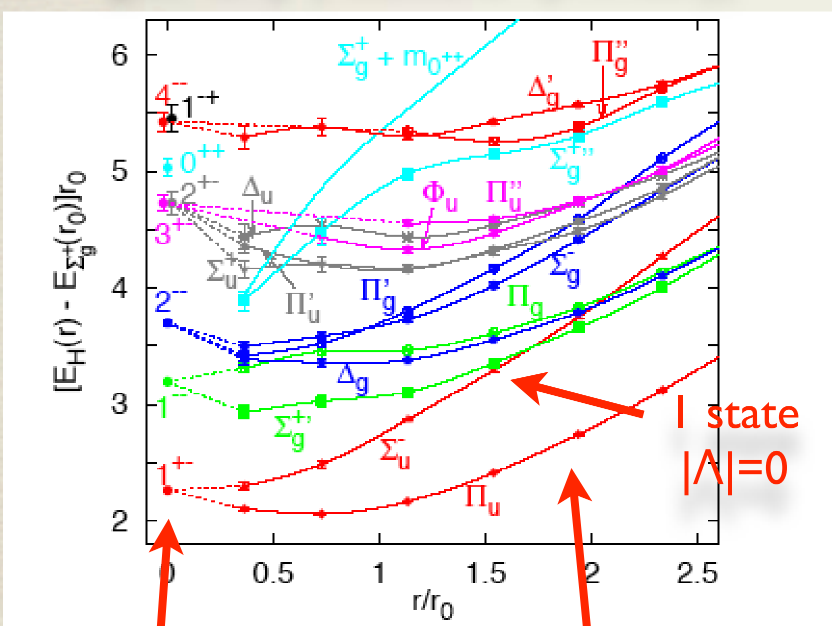




$PC = +1$

$PC = -1$

* glue lump (rotational symmetry)



3 states
M=±1,0 !

2 states
$|\Lambda|=\pm 1$

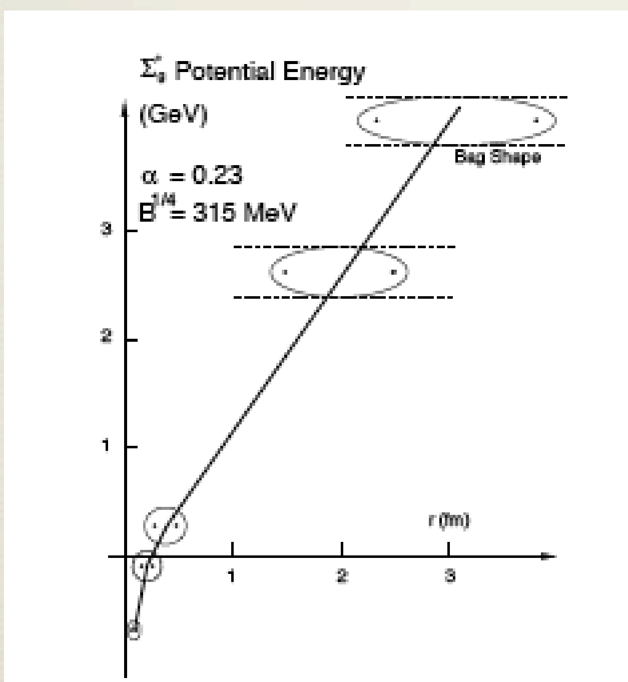
$$\Lambda^Y_{PC} = (\Sigma, \Pi, \Delta, \cdots)^{\pm}_{u,g}$$

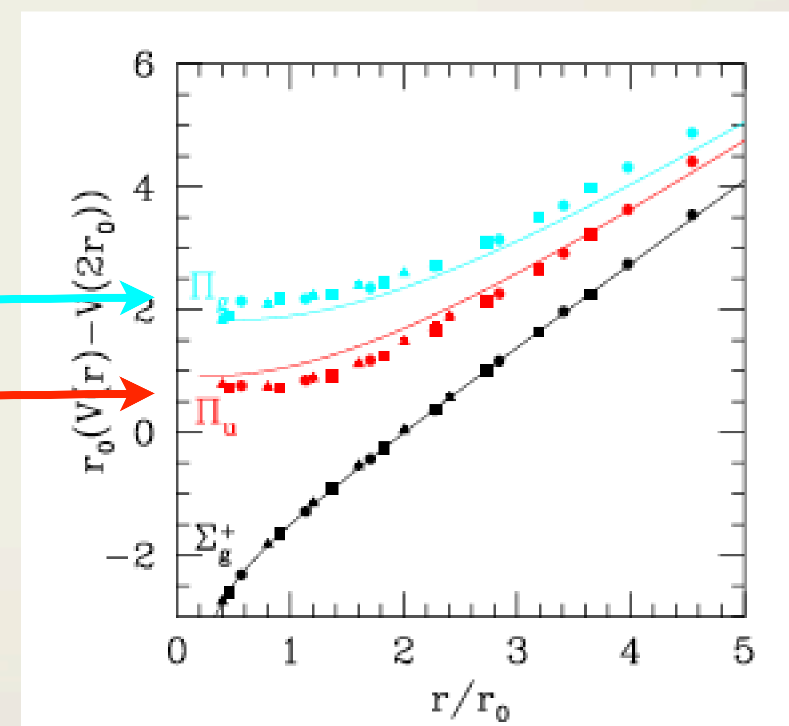
$a = 1$ fm	$q\bar{q}(J^P = 1^-)$	g, $J^{PC} = 1^{+-}$	g, $J^{PC} = 1^{--}$
E	810 MeV	550 MeV	900 MeV

shifts the energy scale

$E_{q\bar{q}} + E_g + E_{\rm Bag} + E_{\rm Vac} + E_{\rm QCD}$	$\pi_0/\eta_0(0^{-+})$	$\pi_1/\eta_1(1^{+-})$	$\rho_1/\omega_1(1^{--})$	$\pi_2/\eta_2(2^{-+})$
Barnes,Close [GeV]	1.1	1.3		
Chanowitz,Sharp [GeV]	1.4	1.8	1.6	2.0

$\pi(1300)/\eta(1300)$ $\rho(1450), \rho(1700)$ $\omega(1420), \omega(1650)$ $\pi_2(1670)$ $\pi_2(2100)$

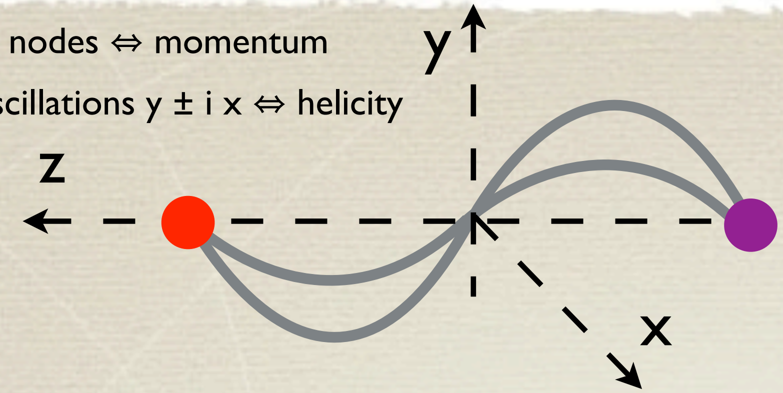




Juge, Kuti, Morningstar

m nodes ⇔ momentum

oscillations y ± i x ⇔ helicity

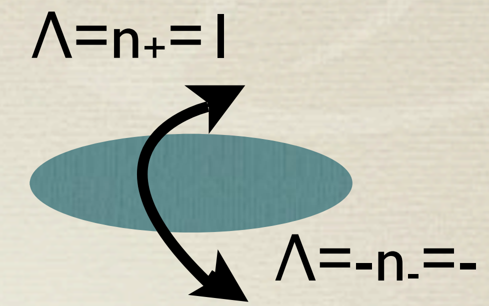


$n_\pm(m)$ = number of m-momentum modes of helicity ±

$N = \sum_m m\,[n_+(m) + n_-(m)]$ total momentum

$\Lambda = \sum_m [n_+(m) - n_-(m)]$ spin projection on the z axis

for example the lowest energy mode N=1 |Λ|=1 (0-nodes)



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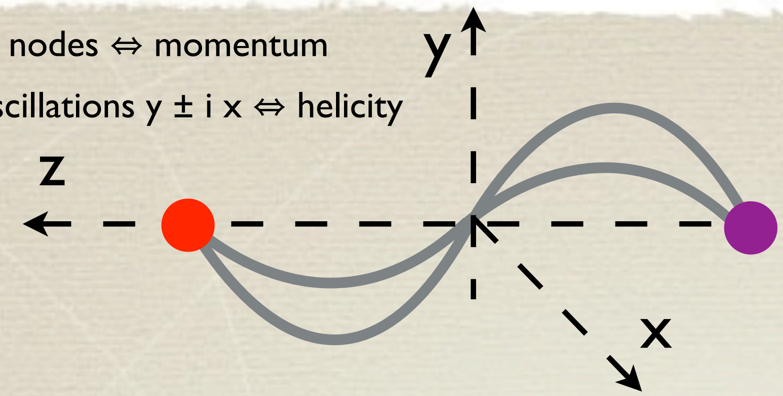

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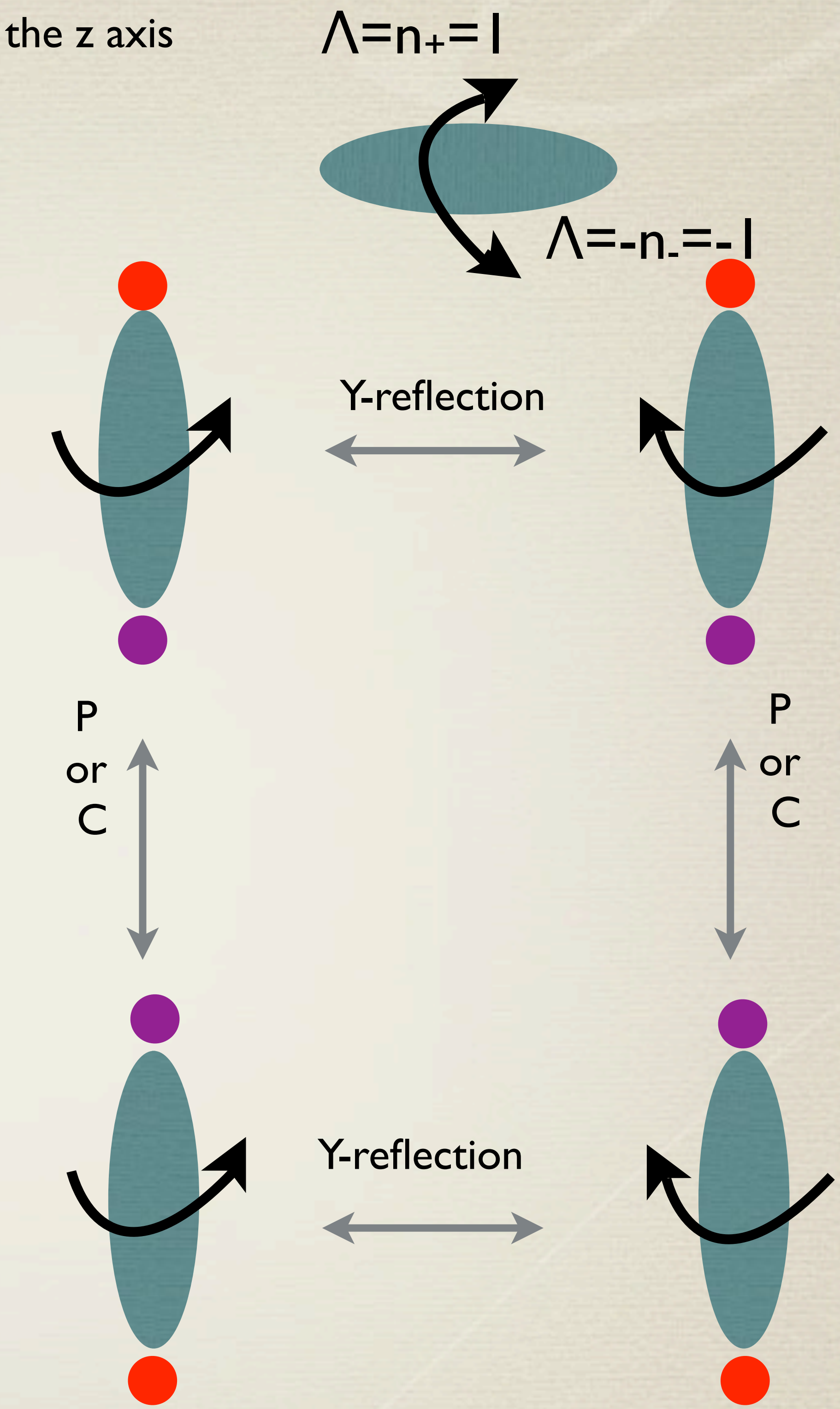

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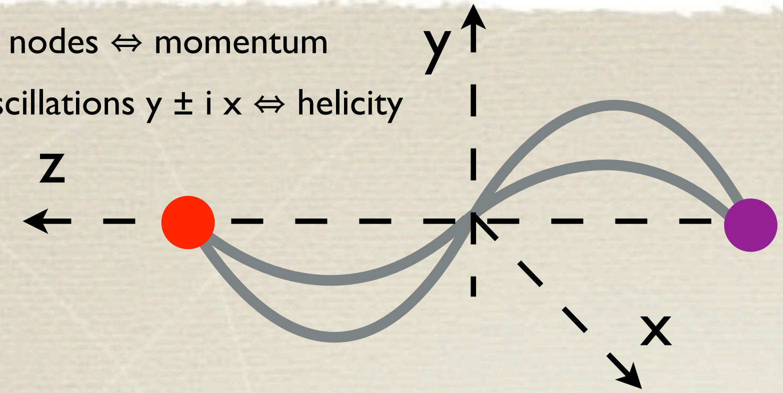

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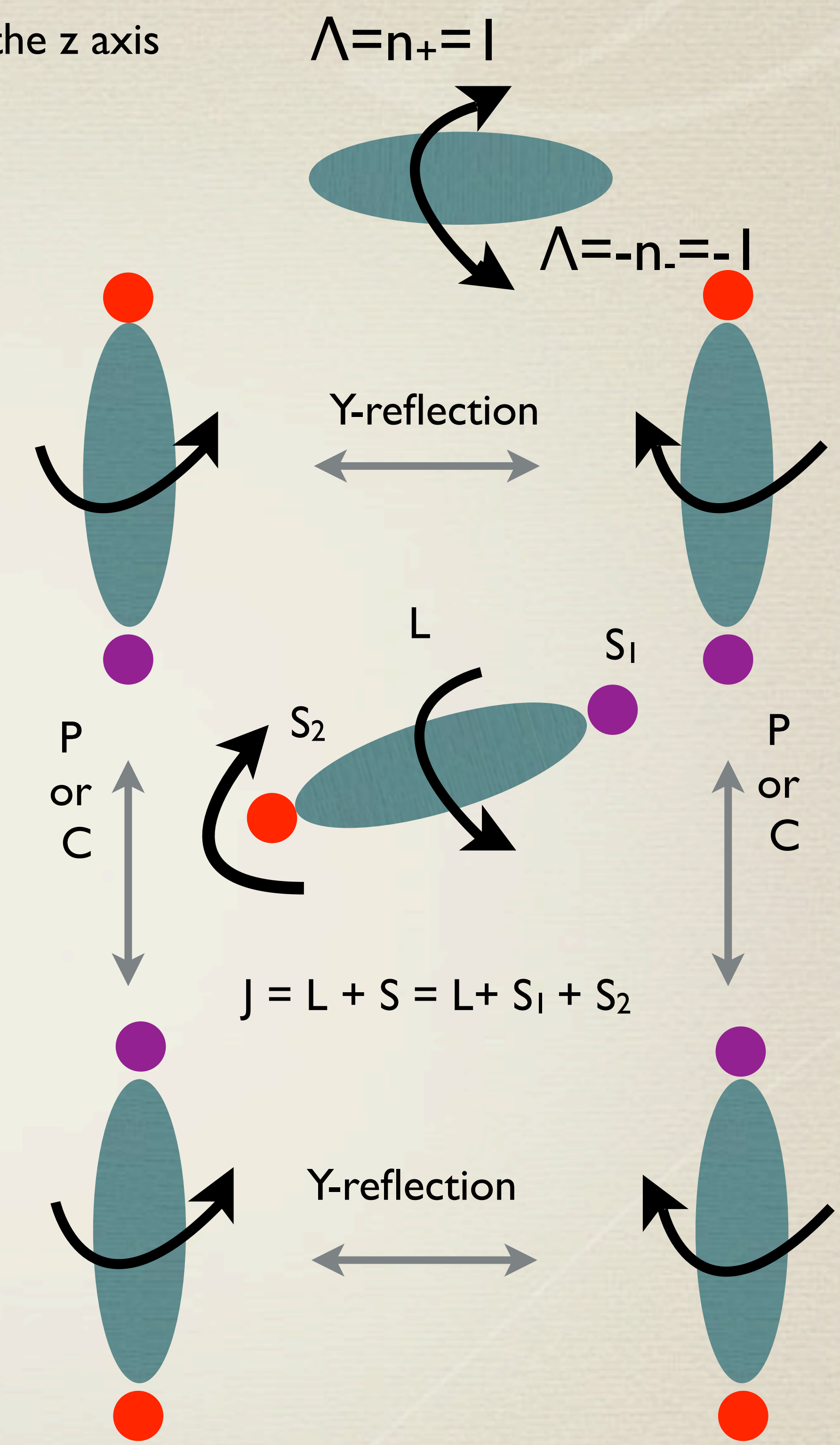

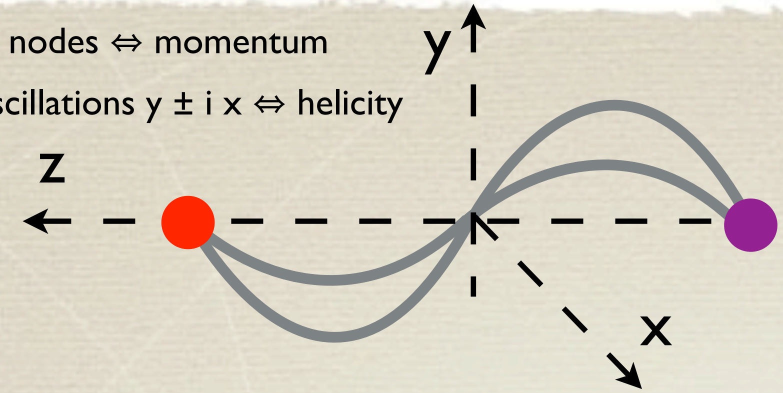

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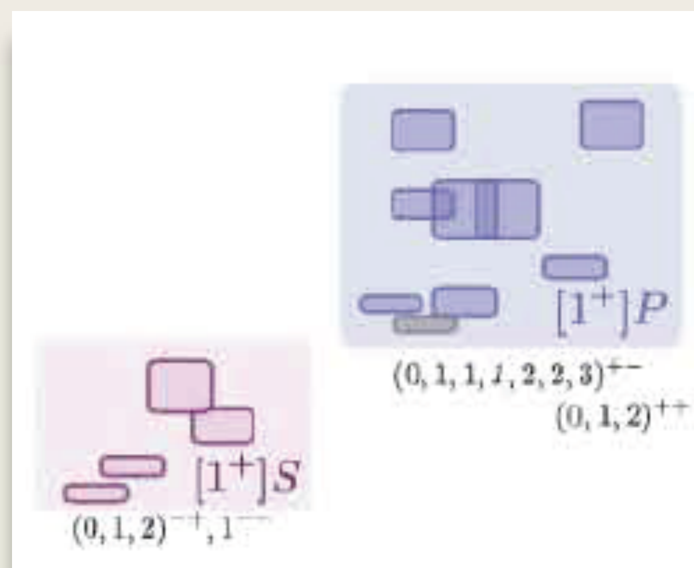
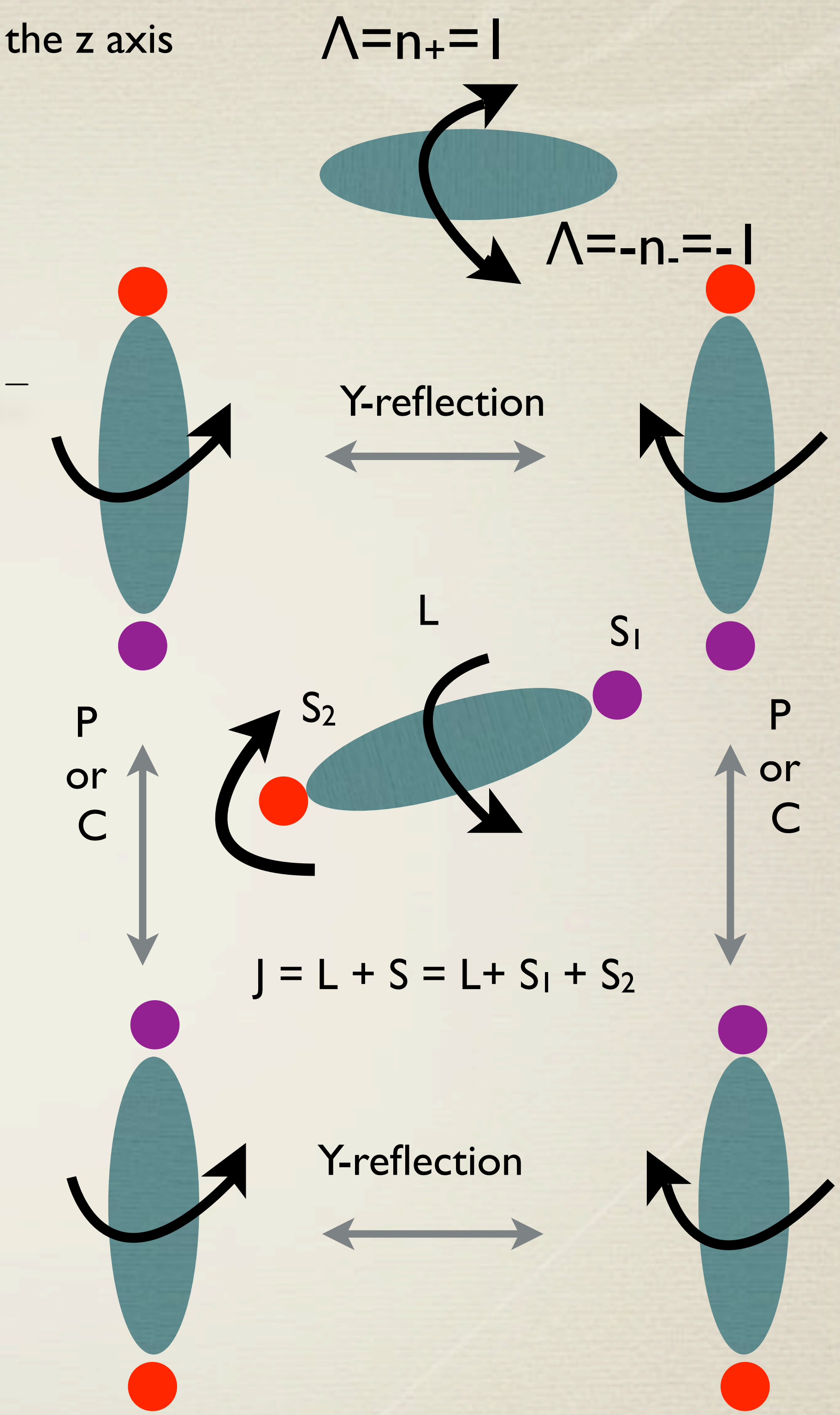
degenerate in FT

$$P = +1 \; C = -1$$
$$P = -1 \; C = +1$$

$$\begin{array}{lcll} S=0 & & 1^{--} & 1^{++} \\ S=1 & J^{PC} = & (0,1,2)^{-+} & (0,1,2)^{+-} \end{array}$$



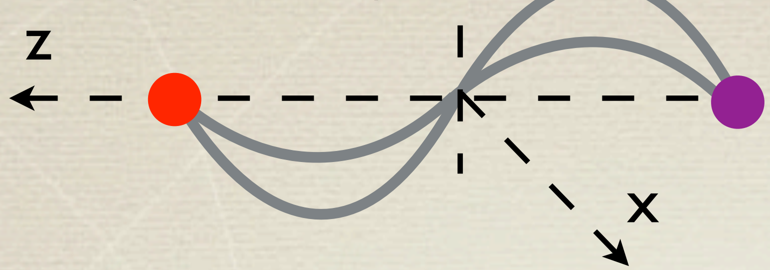


lattice and FT
do not agree !

problem with the rigid rotor

m nodes ⇔ momentum

oscillations y ± i x ⇔ helicity



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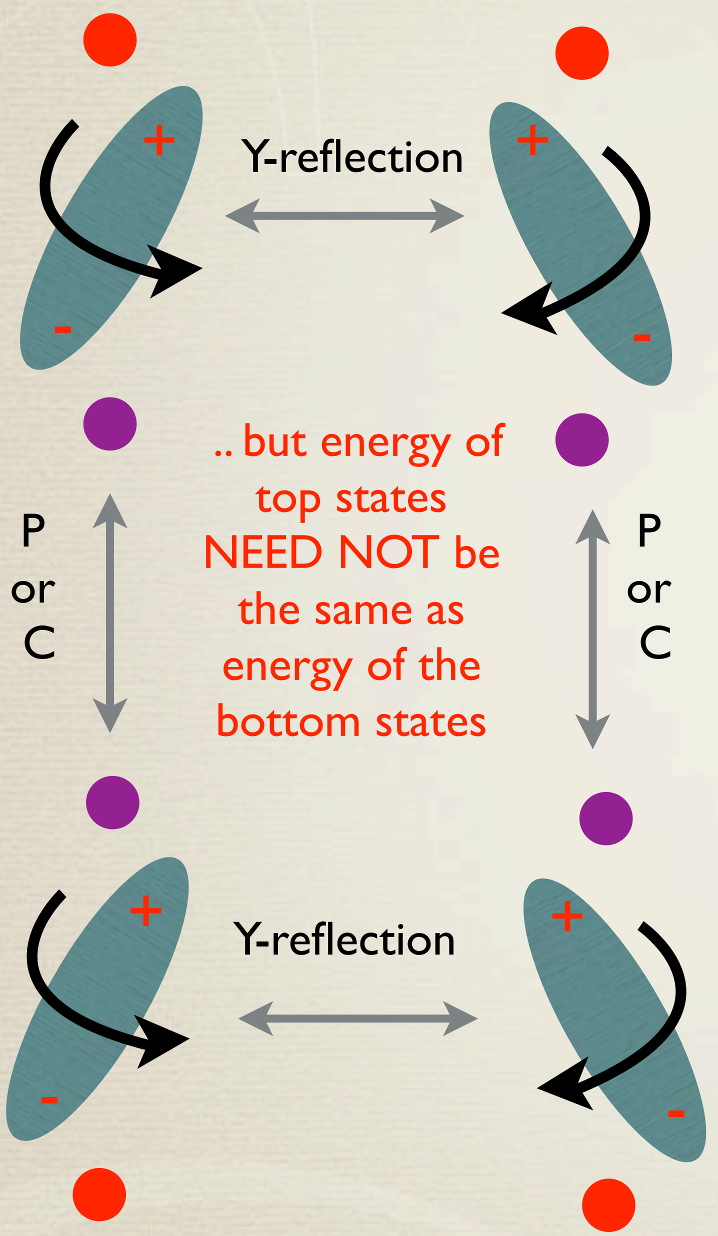
for example the lowest energy mode N=1 |Λ|=1 (0-nodes)

degenerate in FT

$P = +1\ C = -1$
$P = -1\ C = +1$

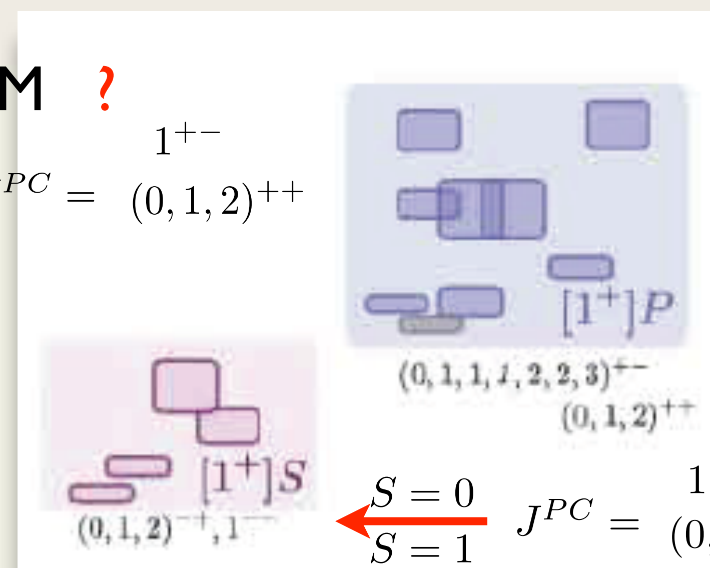
Top two states have the same energy.

$$S = 0 \qquad J^{PC} = \begin{matrix} 1^{--} & 1^{++} \end{matrix}$$
$$S = 1 \qquad (0,1,2)^{-+} \quad (0,1,2)^{+-}$$



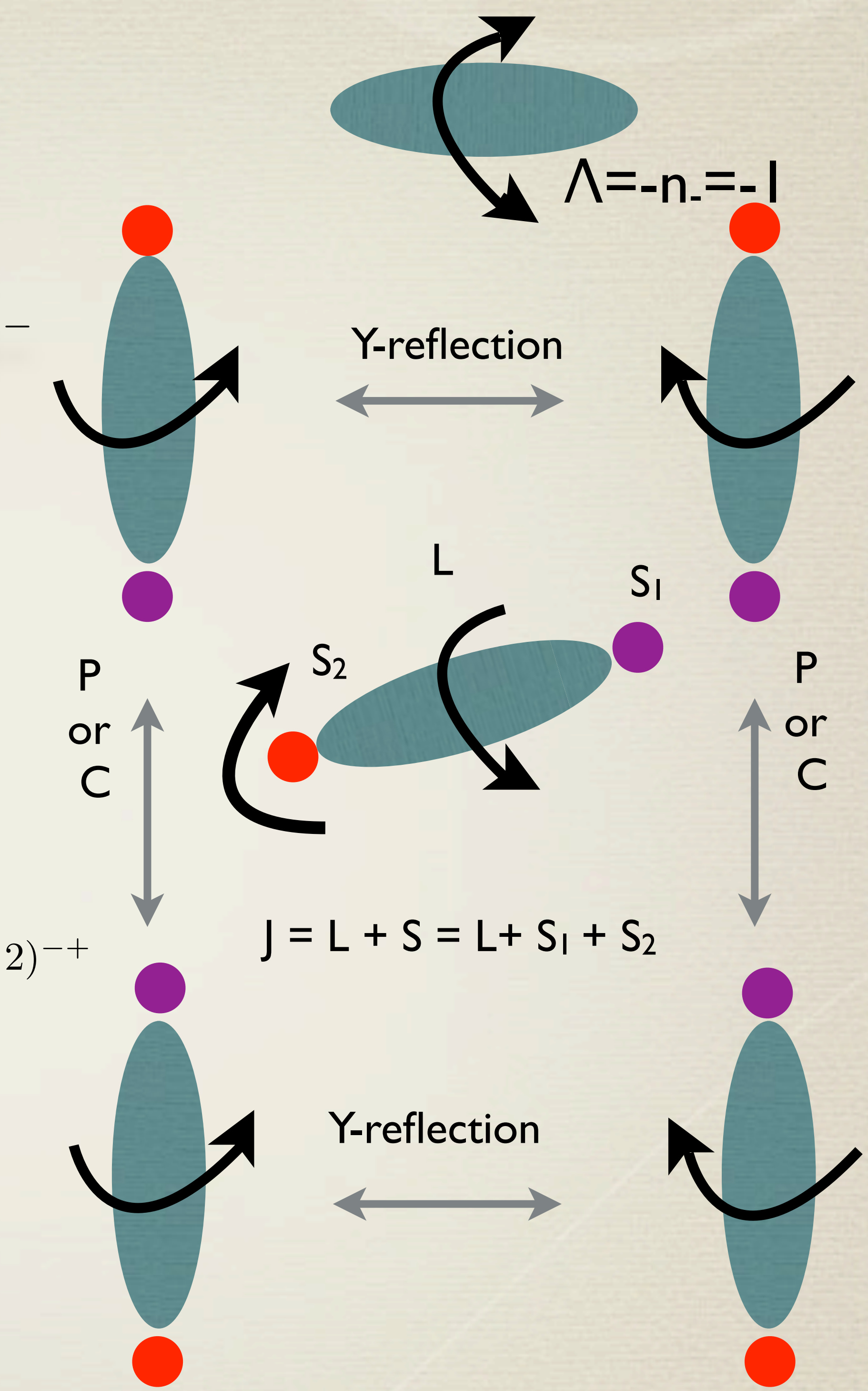
TM ?

$$S = 0 \quad J^{PC} = 1^{+-}$$
$$S = 1 \quad (0,1,2)^{++}$$



$$S = 0 \quad J^{PC} = 1^{--}$$
$$S = 1 \quad (0,1,2)^{-+}$$

TE



lattice and FT
do not agree !

problem with the rigid rotor

Bottom two states have the same energy,

Solving for hadrons QCD

Solving for hadrons QCD $H_{QCD}[p,q]\Psi_n(q) = E_n\Psi_n(q)$

$$q \to \vec{A}^a_T(\vec{x}) \quad a = 1 \cdots N_C^2 - 1 \quad \Psi_n(q) \to \Psi_n(A)$$

Solving for hadrons QCD

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$$\Psi_{vac}(q) = e^{-\frac{1}{2}\int B(x)K(x,y)B(y)} \to e^{-\frac{1}{2}\int B\frac{1}{\sqrt{\vec{\nabla}^2}}B}$$

AS (Indiana)
H.Reinhard (Tuebingen)

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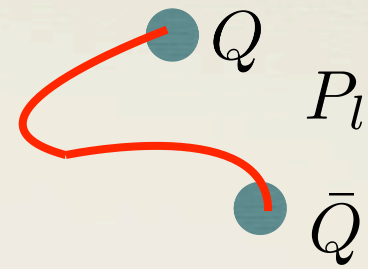
in QCD gauge invariant variables are Wilson lines => periodicity (center symmetry)



$$P_l e^{ig\int d\vec{l}\vec{A}^a(l)T^a}$$

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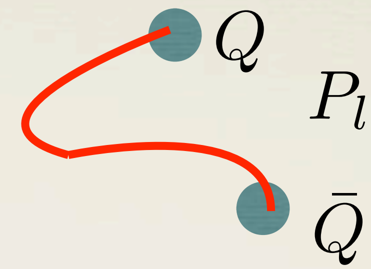

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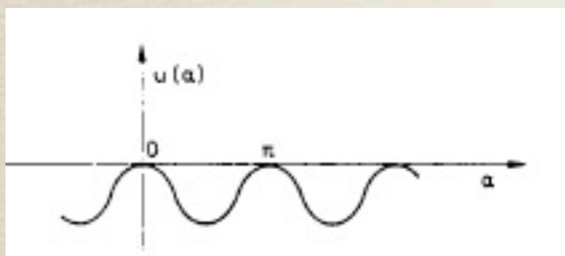

tunneling between equivalent potential minima instantons -> vortices, monopoles

vacuum = monopole gas

quark and gluons propagate in a monopole background -> screening

(H.Metevosyan, AS)

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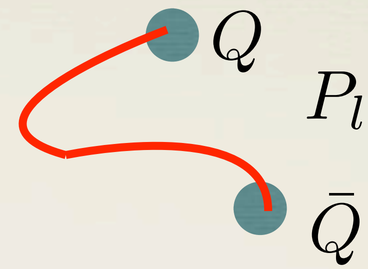

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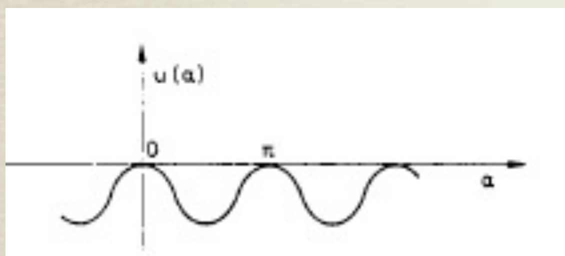

tunneling between equivalent potential minima instantons -> vortices, monopoles

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(btw: "one gluon exchange kernel" is not responsible for confinement the monopole gas is!)

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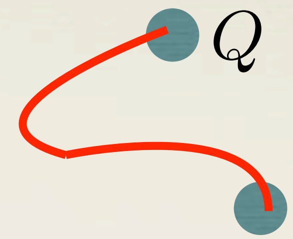

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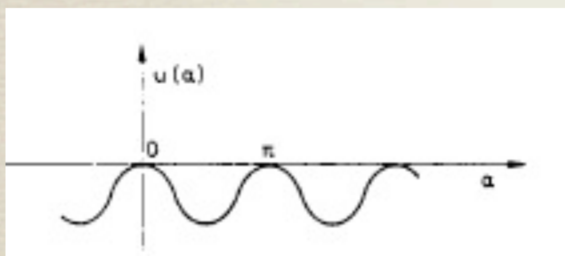
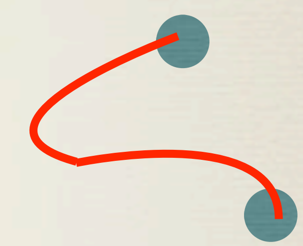


tunneling between equivalent potential minima instantons -> vortices, monopoles

$$|Q\bar{Q}\rangle_{true} = \sum \Bigg|$$  $$\Bigg\rangle$$

from interaction between string an monopoles (dual super conductor)

vacuum = monopole gas

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(H.Metevosyan, AS)

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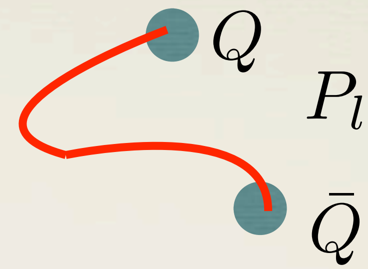
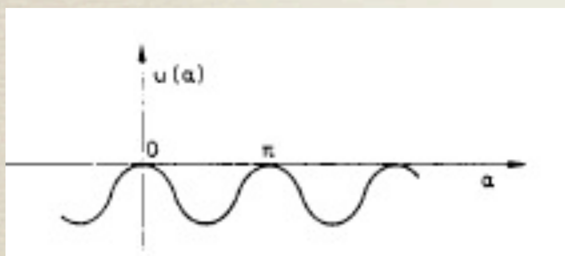
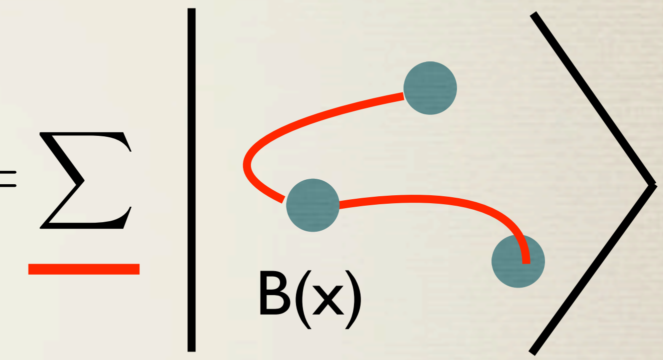


$$P_l e^{ig\int d\vec{l}\vec{A}^a(l)T^a}$$



tunneling between equivalent potential minima instantons -> vortices, monopoles

$$|Q\bar{Q}g\rangle_{true} = \sum$$



vacuum = monopole gas

quark and gluons propagate in a monopole background -> screening

(H.Metevosyan, AS)

Solving for hadrons QCD

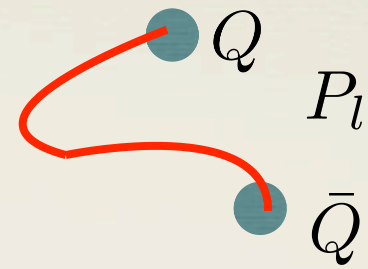
$$H_{QCD}[p,q]\Psi_n(q) = E_n\Psi_n(q)$$

$$q \to \vec{A}^a_T(\vec{x}) \qquad a = 1 \cdots N_C^2 - 1 \qquad \Psi_n(q) \to \Psi_n(A)$$

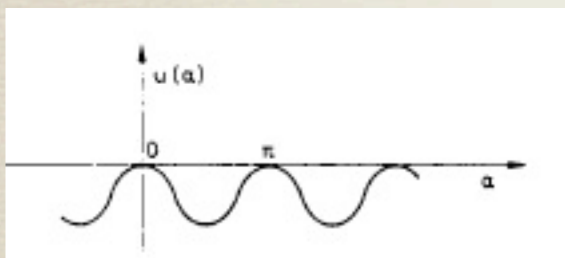
$$\Psi_{vac}(q) = e^{-\frac{1}{2}\int B(x)K(x,y)B(y)} \to e^{-\frac{1}{2}\int B\frac{1}{\sqrt{\vec{\nabla}^2}}B}$$

AS (Indiana)
H.Reinhard (Tuebingen)

in QCD gauge invariant variables are Wilson lines => periodicity (center symmetry)

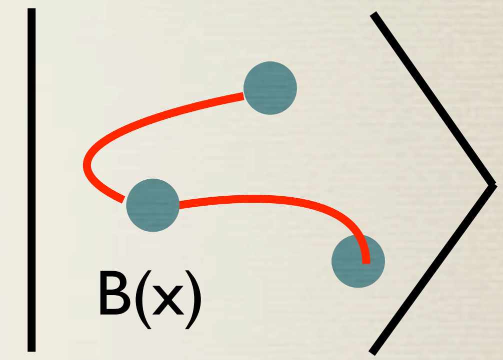


$$P_l e^{ig\int d\vec{l}\vec{A}^a(l)T^a}$$



tunneling between
equivalent potential minima
instantons -> vortices,
monopoles

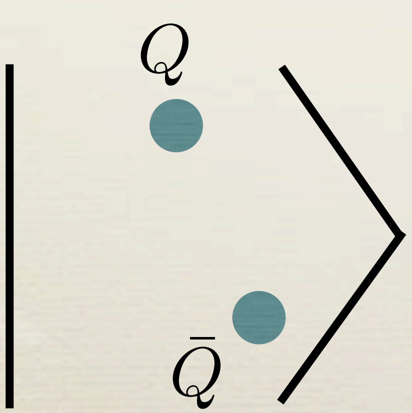
$$|Q\bar{Q}g\rangle_{true} = \sum$$



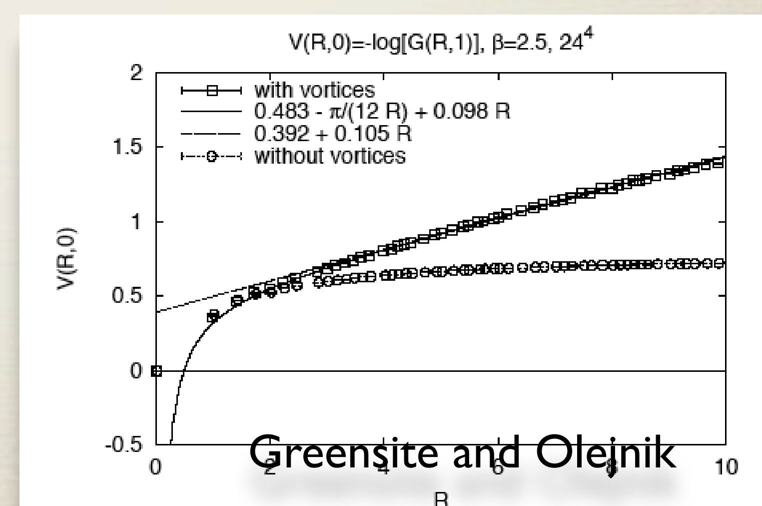
vacuum = monopole gas

quark and gluons propagate
in a monopole background
-> screening
(H.Metevosyan, AS)

$$|Q\bar{Q}\rangle_{var} =$$



Coulomb energy is over-confining and it also because of the monopole gas.



Solving for hadrons QCD

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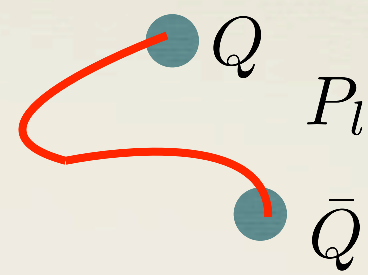
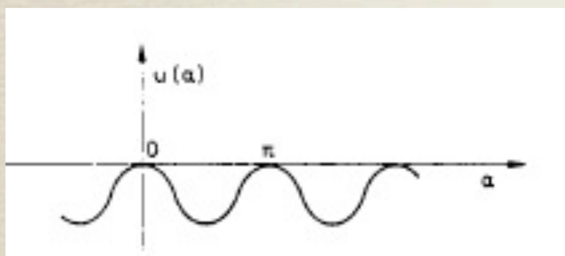


$$P_l e^{ig\int d\vec{l}\vec{A}^a(l)T^a}$$



tunneling between
equivalent potential minima
instantons -> vortices,
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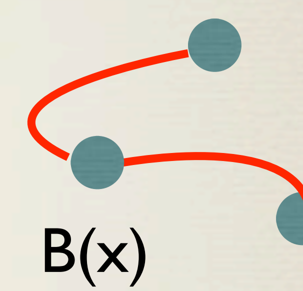
$$|Q\bar{Q}g\rangle_{true} = \underline{\sum} \Big|$$  $$\Big\rangle$$

vacuum = monopole gas

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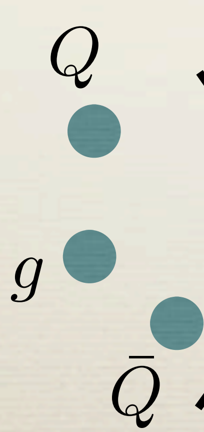
(H.Metevosyan, AS)

$$|Q\bar{Q}g\rangle_{var} = \Big|$$  $$\Big\rangle$$

Gluon propagator and Monopoles

$$\langle A(\vec{k})A(-\vec{k})\rangle = D(|\vec{k}|) \to \frac{1}{2|\vec{k}|}$$

IR suppression from monopole screening

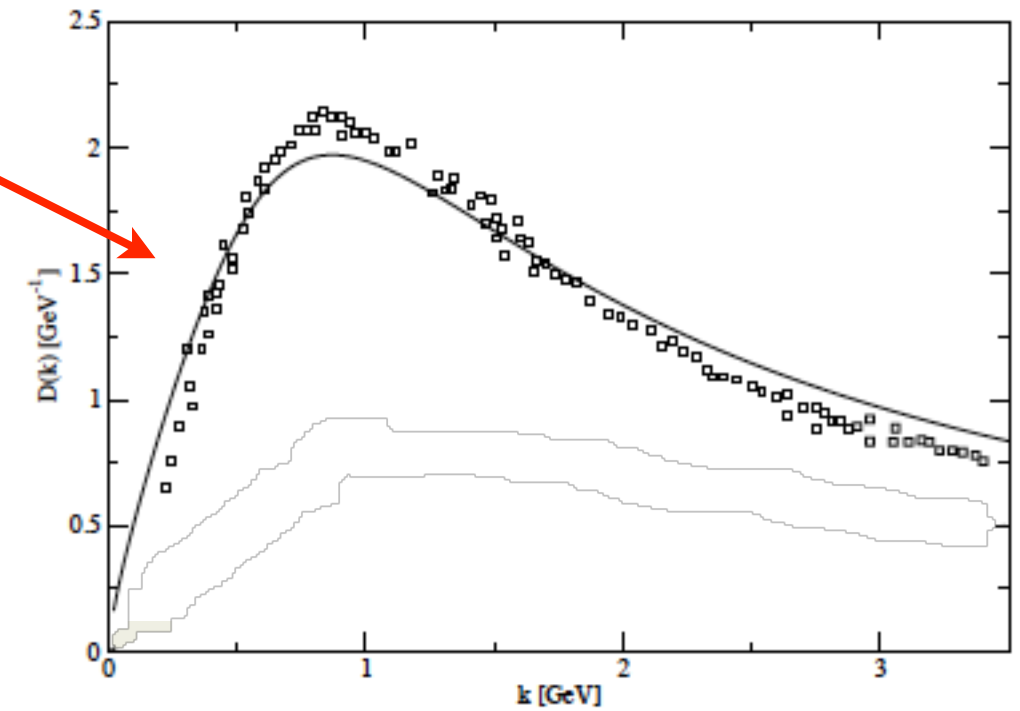


FIG. 1: Comparison of our gluon propagator with that obtained from lattice computations [52]

(H.Metevosyan, AS)

Coulomb Gauge

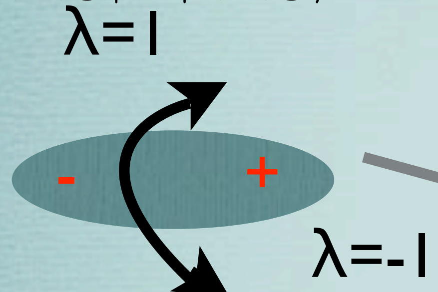
$$H = H_D + H_{YM} + H_C$$

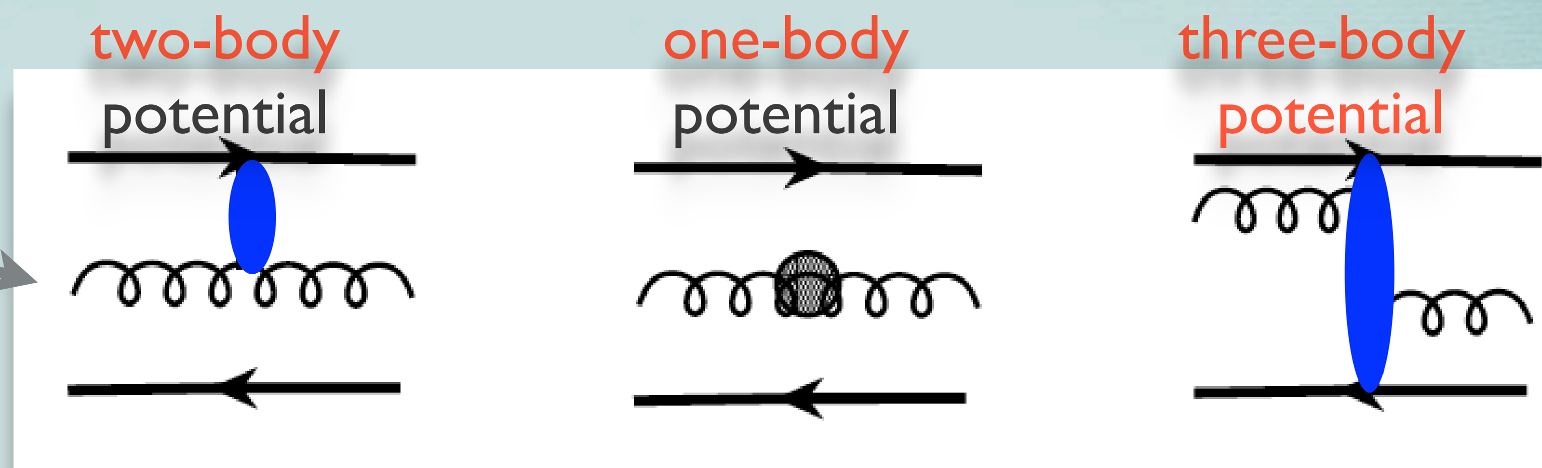
$$K = \frac{1}{2}\frac{g}{\nabla \cdot D}(-\nabla^2)\frac{g}{\nabla \cdot D}$$

$$H_C = \int d\mathbf{x}d\mathbf{y}\,\rho^a(\mathbf{x})K[\mathbf{x},\mathbf{y},\mathbf{A}]_{ab}\rho^b(\mathbf{y})$$

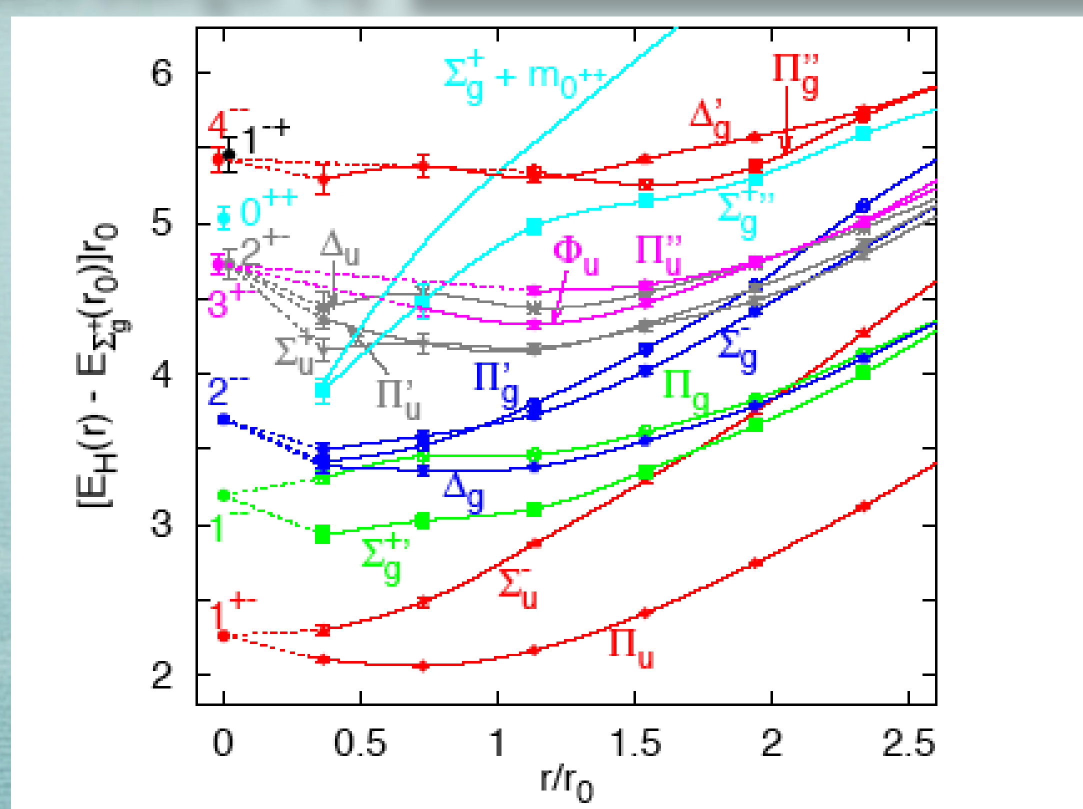
and using variational states $|Q\bar{Q}\rangle_{var}, |Q\bar{Q}g\rangle_{var}$ $\quad H|J^{PC}\rangle = E(R)|J^{PC}\rangle$

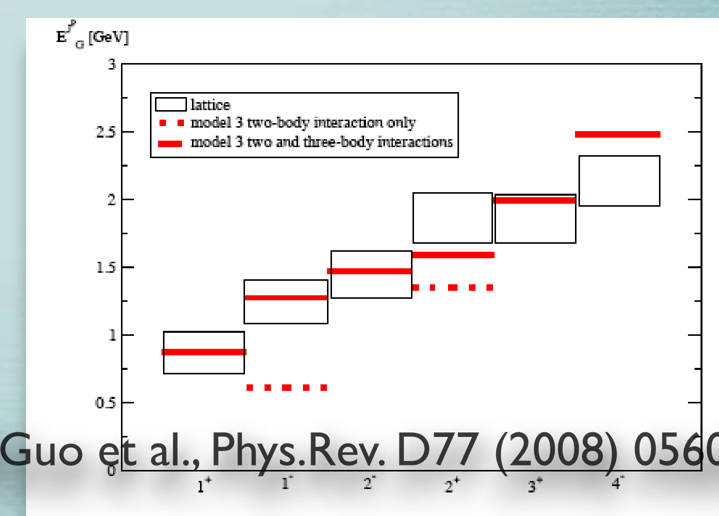
$\langle Q\bar{Q}g|H|Q\bar{Q}g\rangle =$





one-body Schrodinger eq.





P.Guo et al., Phys.Rev. D77 (2008) 056005

non-relativistic hybrids

expected degeneracies

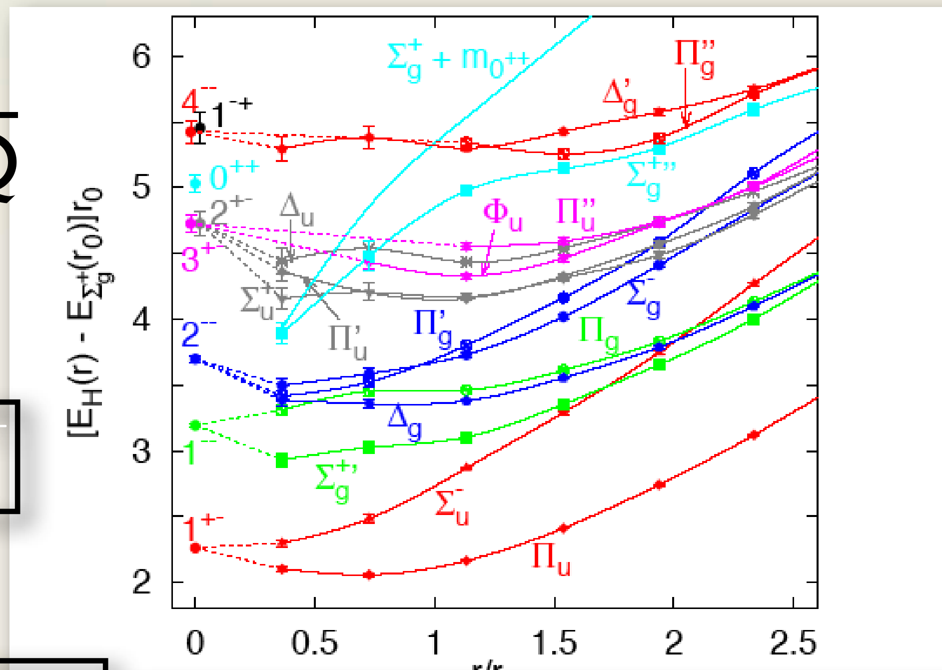
- ✱ $Q\bar{Q}$ in L=0,S=0,1
- ✱ coupled to 1^{--} glue in the relative L=1 state => $J_g^{PC} = 1^{+-}$

J^{PC} glue ↓ $\qquad$ J^{PC} $Q\bar{Q}$ ↓

$$1^{+-} \times 0^{-+}_{S_{Q\bar{Q}}} = \boxed{1^{--}}$$

$$1^{+-} \times 1^{--}_{S_{Q\bar{Q}}=1} =$$

$$\boxed{0^{-+}, 1^{-+}, 2^{-+}}$$

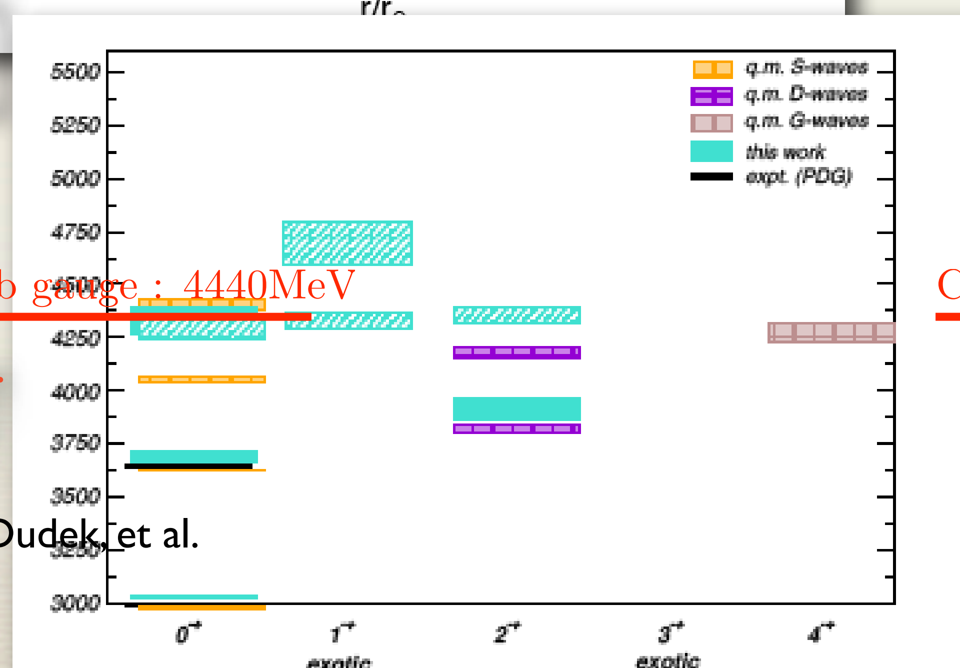


✱ experiment

Y(4260) (Belle,BaBar)

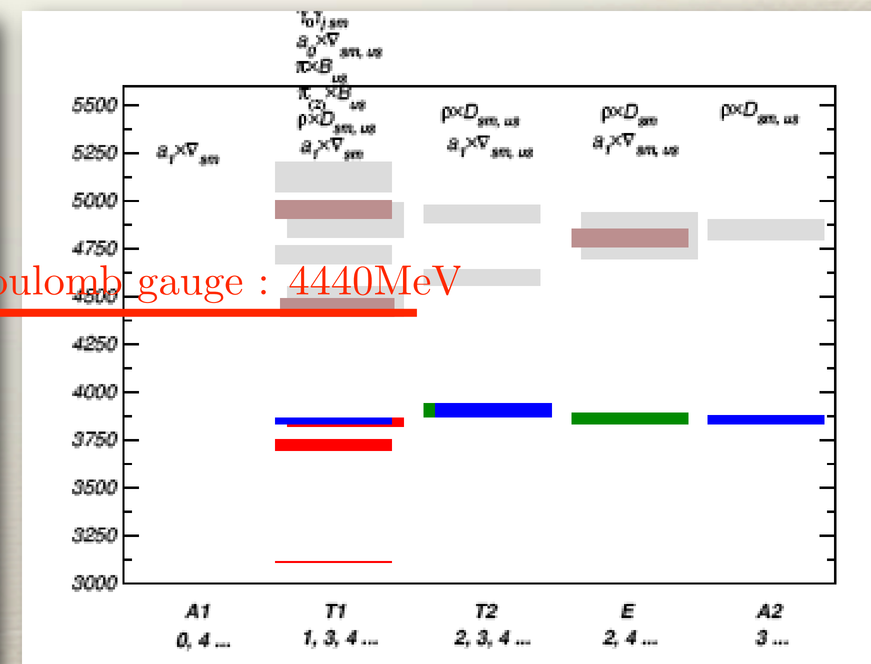
P.Guo et al., Phys.Rev. D78 (2008) 056003

Coulomb gauge : 4440MeV



J.Dudek, et al.

Coulomb gauge : 4440MeV



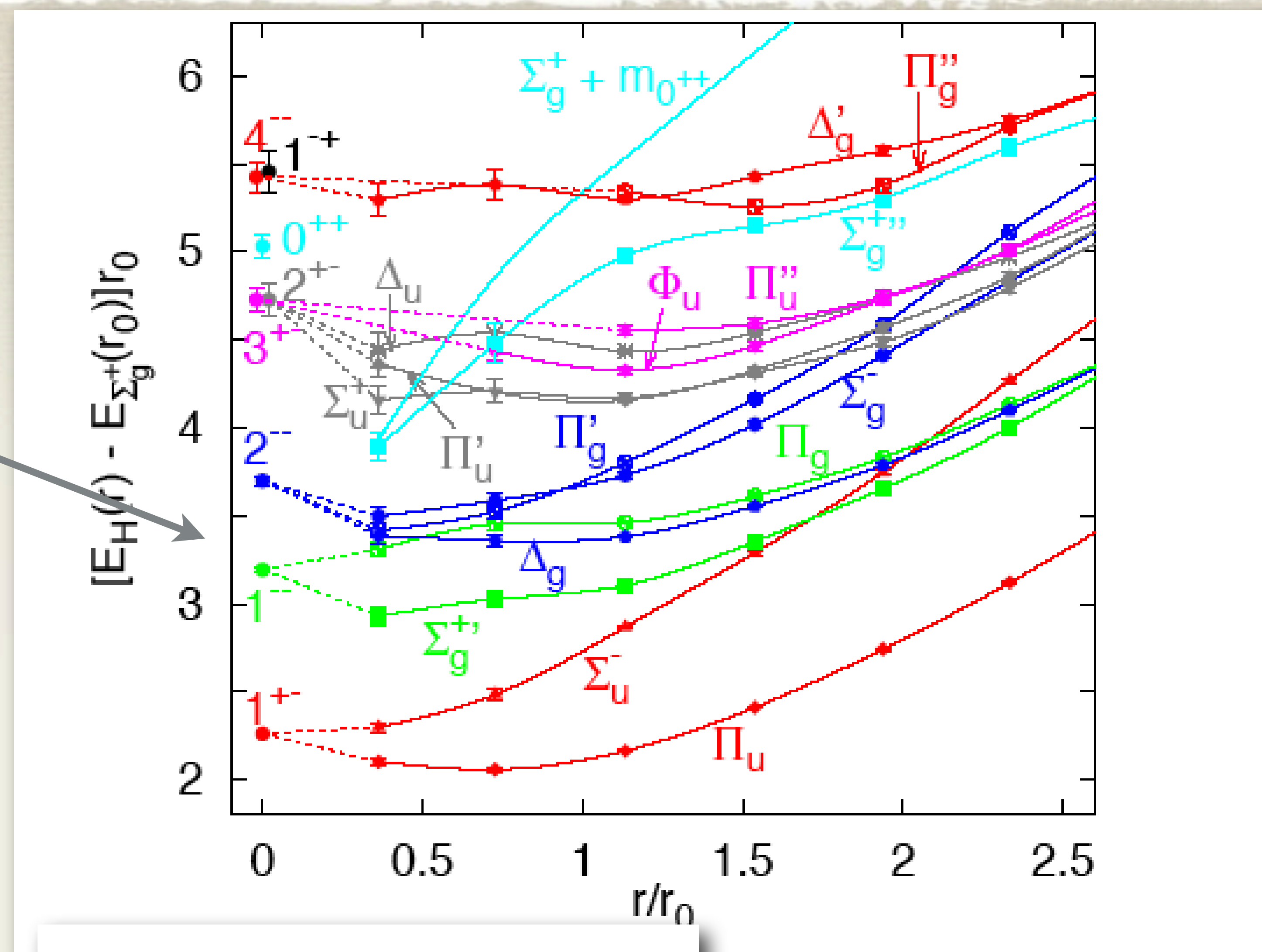
$$|hybrid\rangle = |J J_g L_{Q\bar{Q}} S\rangle$$

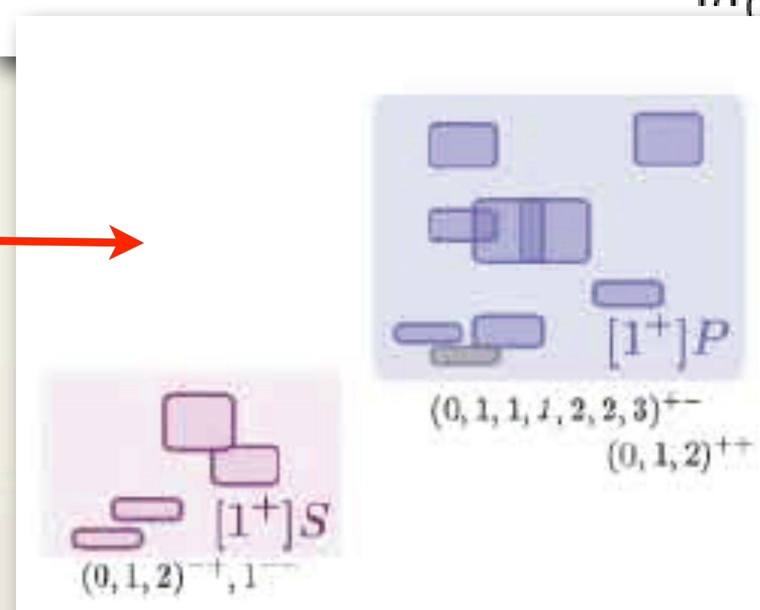
$J_g^{PC} = 1^{--}$

	$S=0$	$S=1$
$L=0$	1^{+-}	$(0,1,2)^{++}$
$L=1$	$(0,1,2)^{-+}$	$(0,1^3,2^2,3)^{--}$

$J_g^{PC} = 1^{+-}$

	$S=0$	$S=1$
$L=0$	1^{--}	$(0,1,2)^{-+}$
$L=1$	$(0,1,2)^{++}$	$(0,1^3,2^2,3)^{+-}$





observed lattice pattern in perfect agreement with QCD CG even for light quarks

Exotic story $\pi^- p \to \eta \pi^0 N$
$\to \eta \pi^- p$

$(\eta\pi^0)$ in P-wave has $J^{PC}=1^{-+}$!

$\pi^- p \to \eta\pi^- p$	$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2 $\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2
$\pi^- p \to \eta\pi^0 n$	New results: No consistent B-W interpretation possible but a weak $\eta\pi$ interaction exists and can reproduce the exotic wave
$\pi^- p \to \eta'\pi^- p$	$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2 $\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2
$\pi^- p \to \rho^0\pi^- p$	$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2 $\Gamma = 168 \pm 20^{+150}_{-12}$ MeV / c^2

$\pi^- p \to b_1 \pi p$
$\pi^- p \to f_1 \pi p$

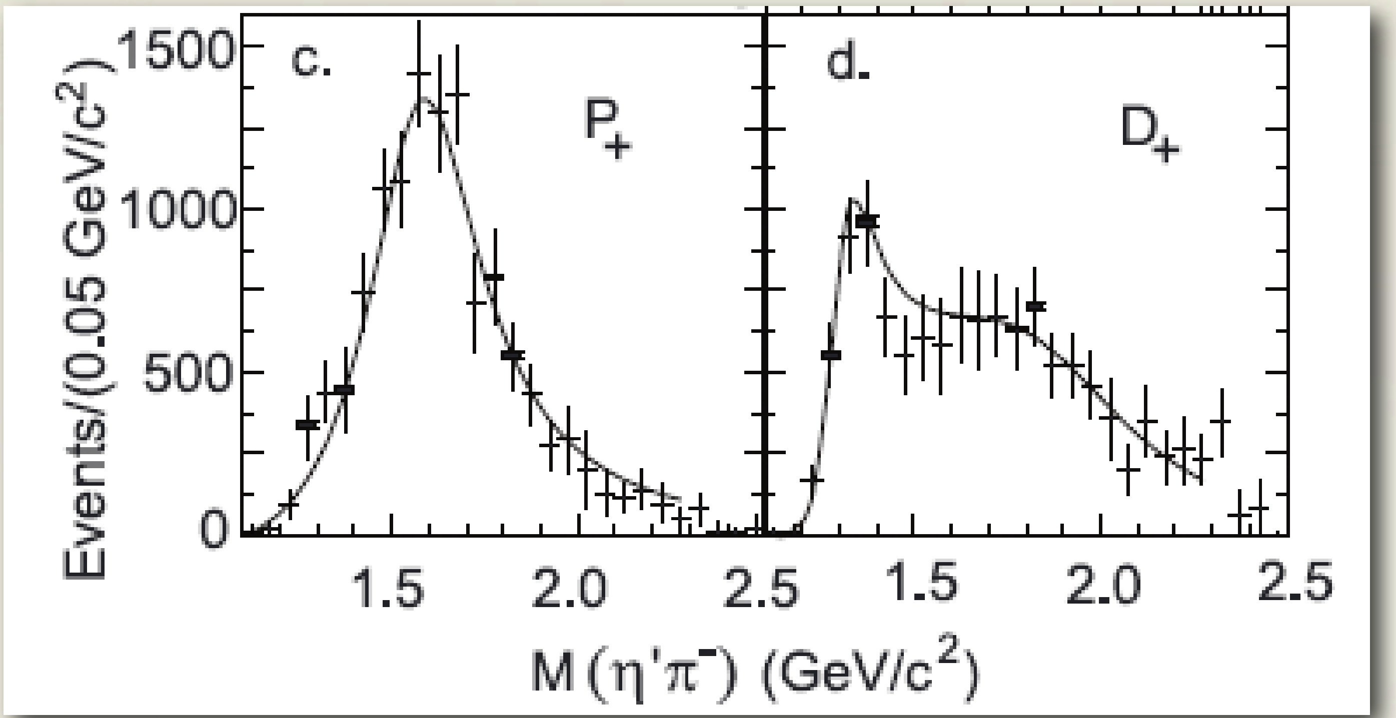
BNL (E852)
new analysis reduces the strength but COMPASS find the signal again

not every bump is a resonance
(and even if, it may not be a BW)

it is important to understand
production mechanisms

$J^{PC} = 1^{-+}$ exotic wave signals (E852 data)

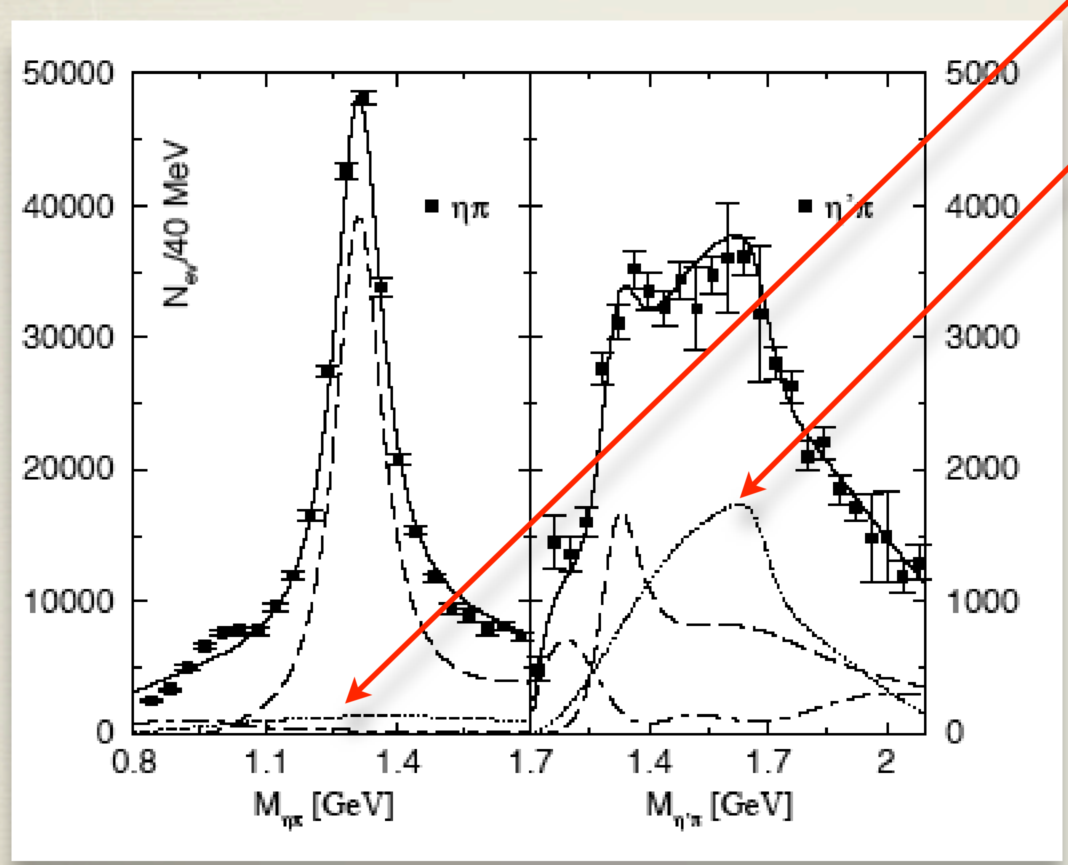
$\pi^- p \to \eta' \pi^- p$



(other signals identified by E852, CB,VES)

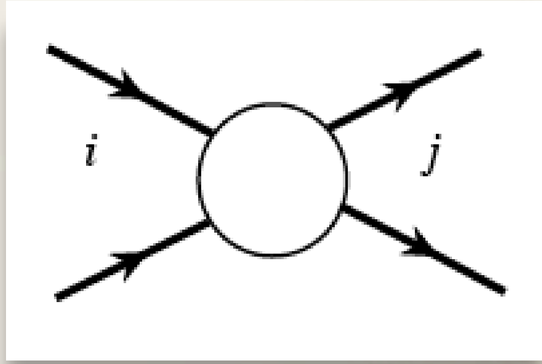
Fitting the E852 the ηπ and η' π spectra using eft give a good description of the exotic wave (APS et al.)

P-wave



P -wave ηπ, η'π
2 coupled channels

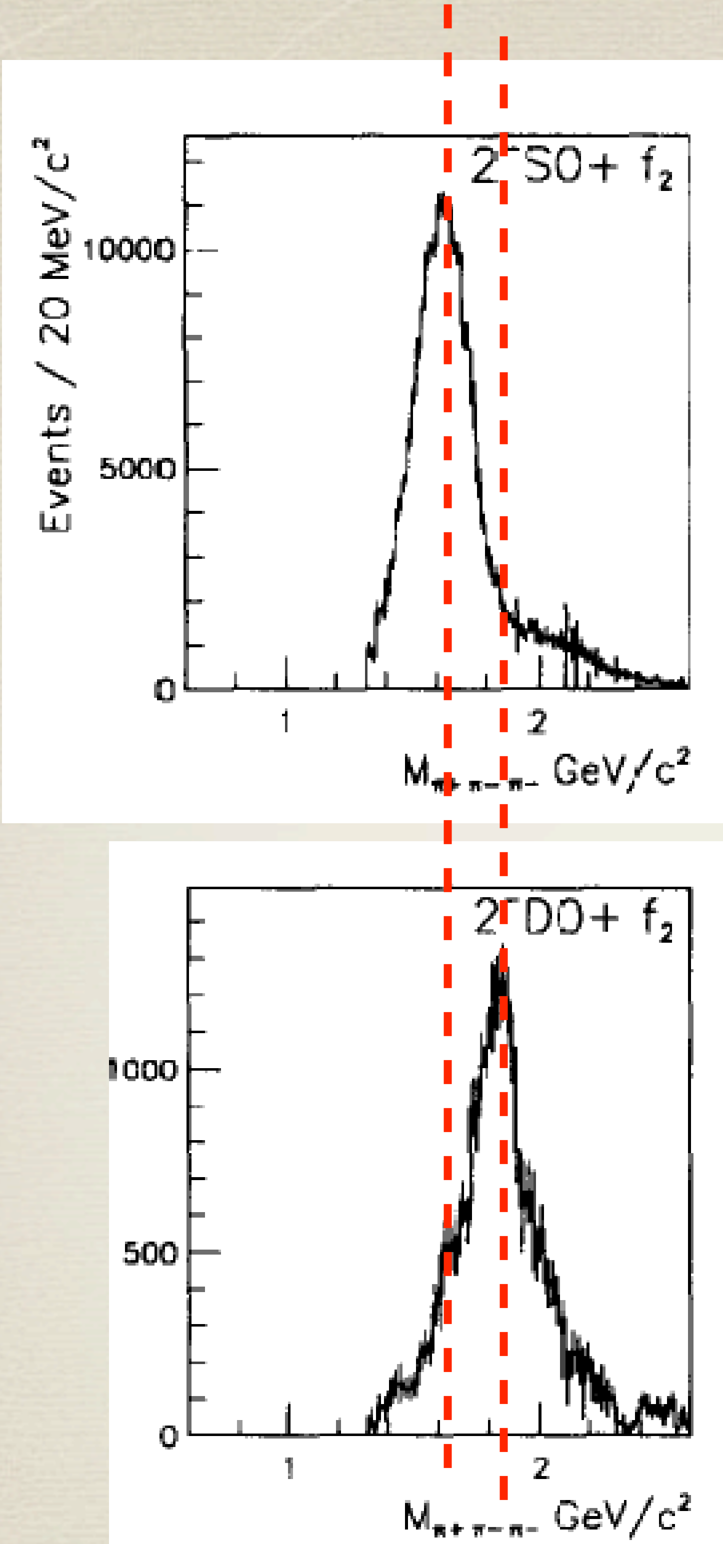
S, D -wave $K\bar{K}$, ηπ, η'π
3 coupled channels



$$t(s) = \frac{1}{\mathrm{Re}\, V^{-1} - i\rho}$$

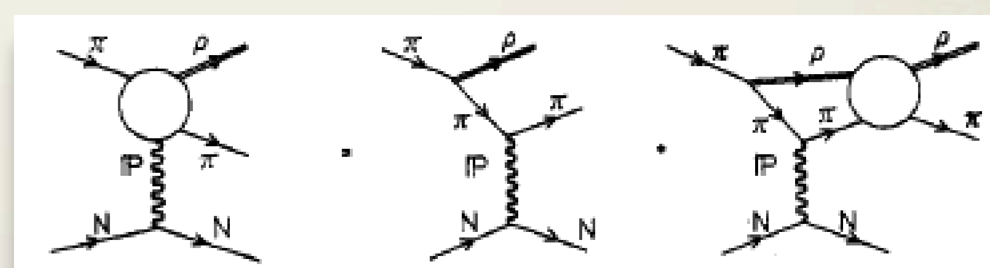
there are no long range forces in between η and π

to fit the data V needs to have short range interactions

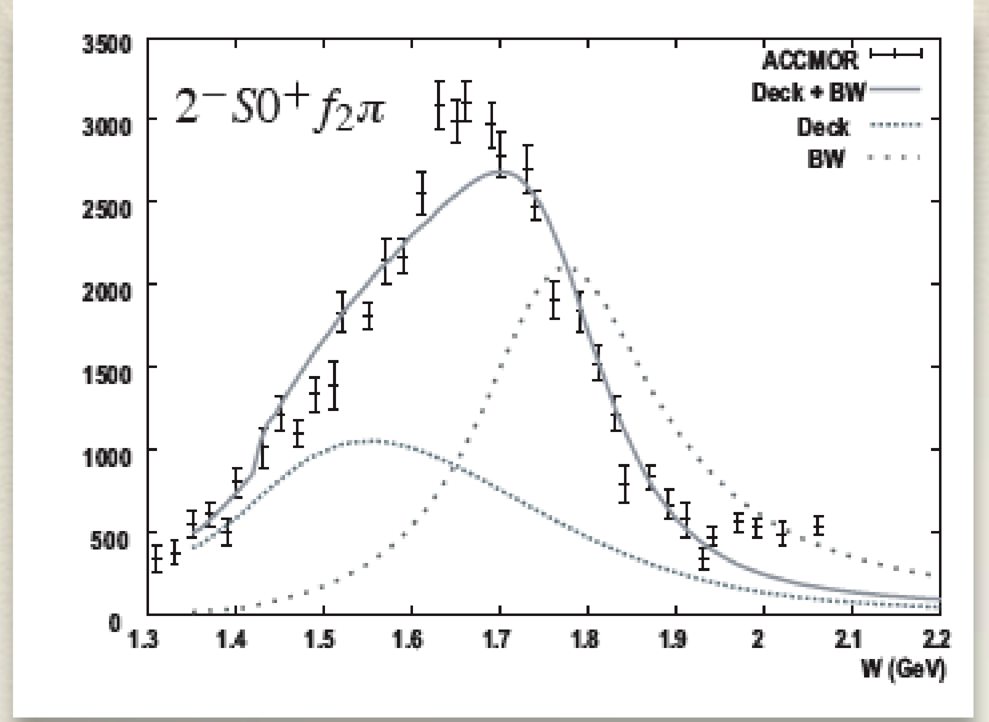


Moving $\pi_2(1670)$ peak

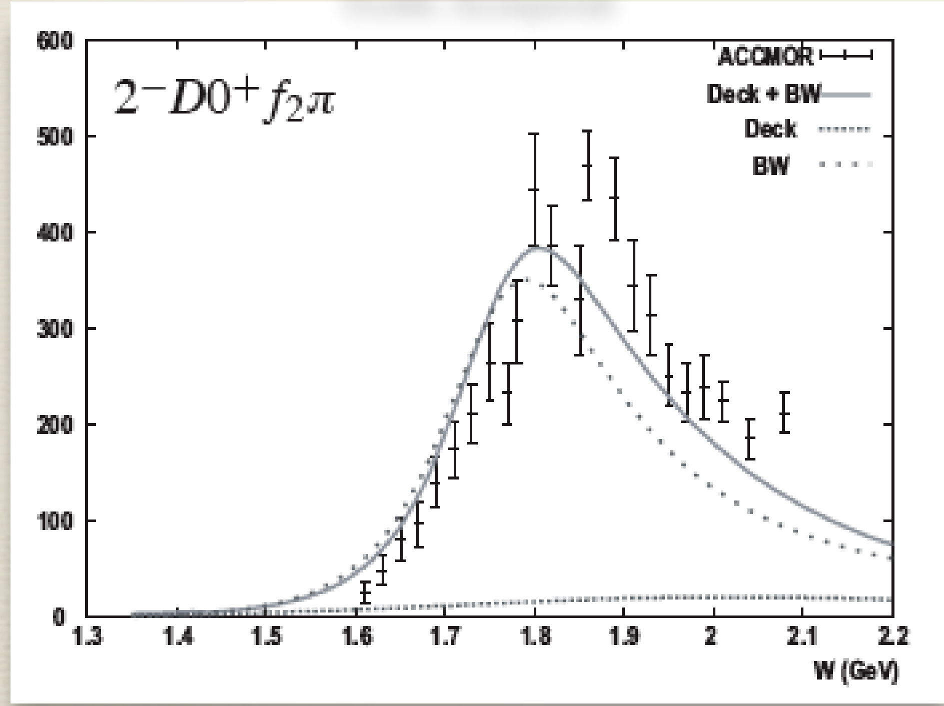
VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1672.4± 3.2 OUR AVERAGE	Error includes scale factor of 1.4. See the ideogram below.				
1749 ±10 ±100	145k	LU 05	E852		18 $\pi^- p \to \omega\pi^-\pi^0 p$
1676 ± 3 ± 8		[1] CHUNG 02	E852		18.3 $\pi^- p \to \pi^+\pi^-\pi^- p$
1685 ±10 ± 30		[2] BARBERIS 01			450 $pp \to p_f 3\pi^0 p_s$
1687 ± 9 ± 15		AMELIN 99	VES		37 $\pi^- A \to \omega\pi^-\pi^0 A^*$
1669 ± 4		BARBERIS 98B			450 $pp \to p_f \rho\pi p_s$
1670 ± 4		BARBERIS 98B			450 $pp \to p_f f_2(1270)\pi p_s$
1730 ±20		[3] AMELIN 95B	VES		36 $\pi^- A \to \pi^+\pi^-\pi^- A$
1690 ±14		[4] BERDNIKOV 94	VES		37 $\pi^- A \to K^+K^-\pi^- A$
1710 ±20	700	ANTIPOV 87	SIGM	−	50 π^- Cu $\to \mu^+\mu^-\pi^-$ Cu
1676 ± 6		[4] EVANGELISTA 81	OMEG	−	12 $\pi^- p \to 3\pi p$
1657 ±14		[4,5] DAUM 80D	SPEC	−	63–94 $\pi p \to 3\pi X$
1662 ±10	2000	[4] BALTAY 77	HBC	+	15 $\pi^+ p \to p 3\pi$
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1742 ±31 ± 49		ANTREASYAN 90	CBAL		$e^+e^- \to e^+e^-\pi^0\pi^0\pi^0$
1624 ±21		[1] BELLINI 85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1622 ±35		[6] BELLINI 85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1693 ±28		[7] BELLINI 85	SPEC		40 $\pi^- A \to \pi^-\pi^+\pi^- A$
1710 ±20		[8] DAUM 81B	SPEC	−	63,94 $\pi^- p$
1660 ±10		[4] ASCOLI 73	HBC	−	5–25 $\pi^- p \to p\pi_2$

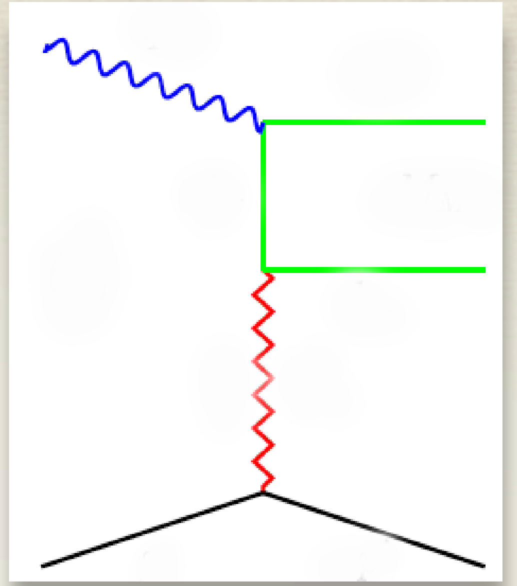


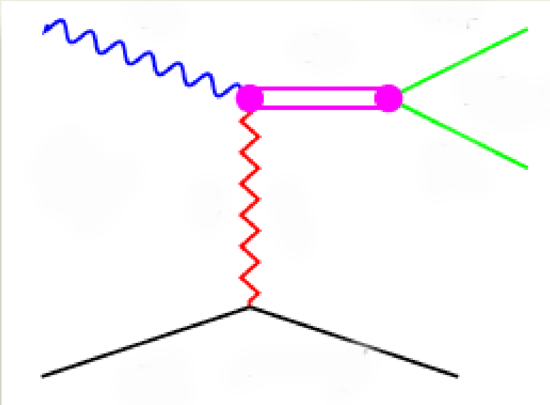
Duality @ work ?



Dudek, Szczepaniak





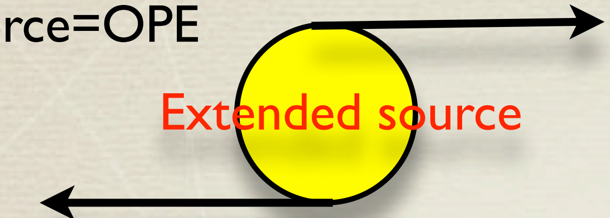


Isobar-type fits could involve spurious resonances

Resonances do not have to show up as peaks or can be skewed

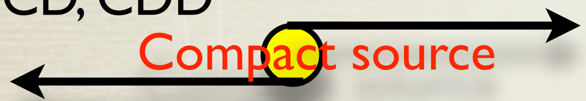
(S-wave)

force=OPE

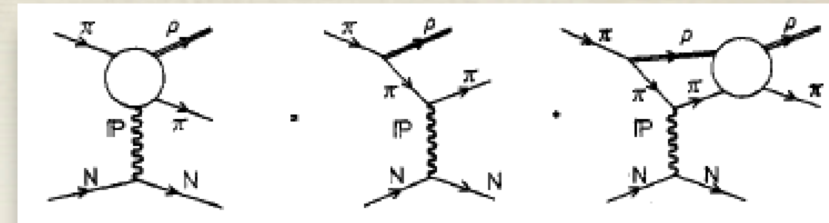


$$e^{i\delta(E)} \cos\delta(E)$$

QCD, CDD

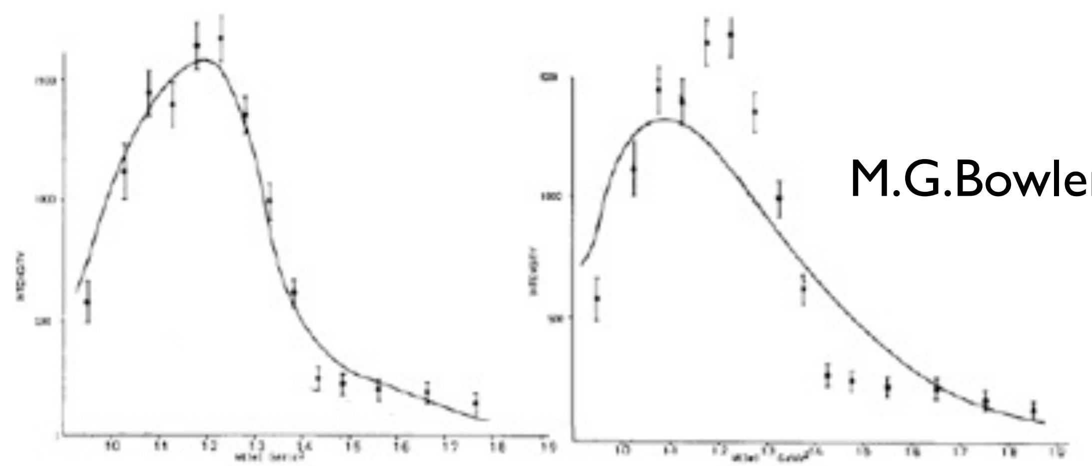


$$e^{i\delta(E)} \frac{\sin\delta(E)}{k}$$



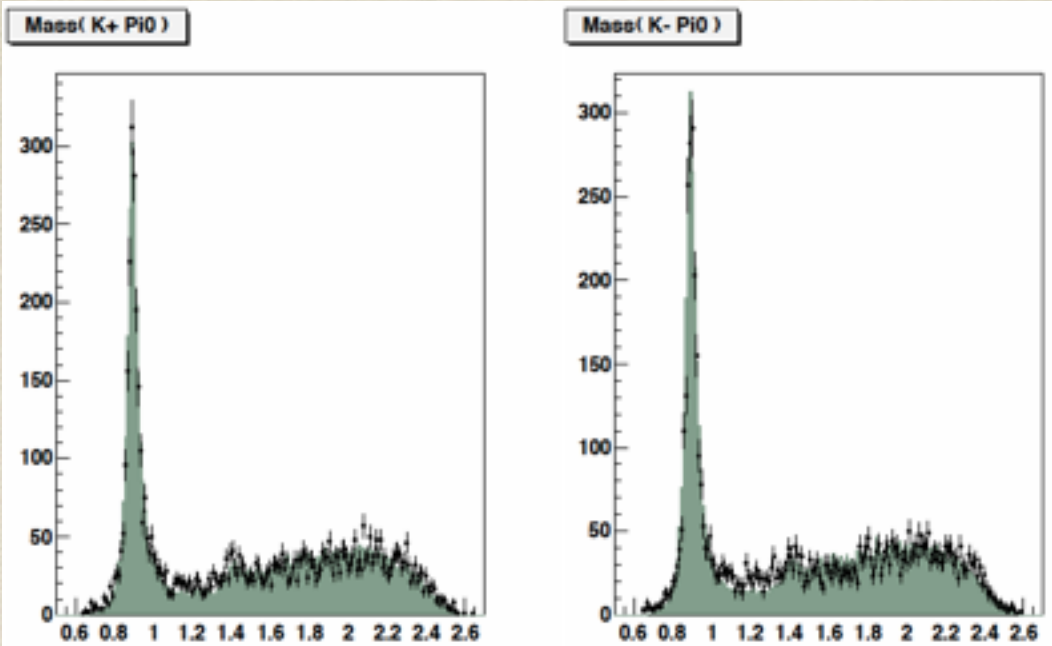
force=OPE+CDD

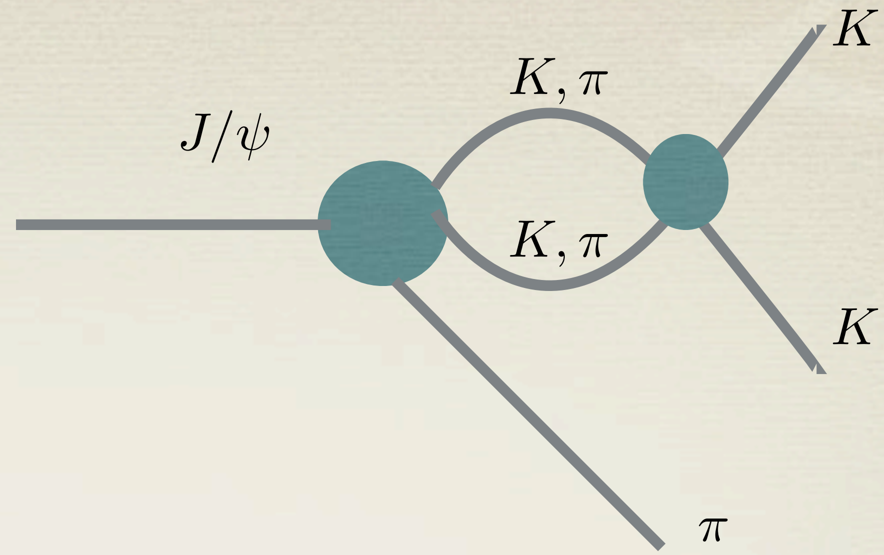
CDD

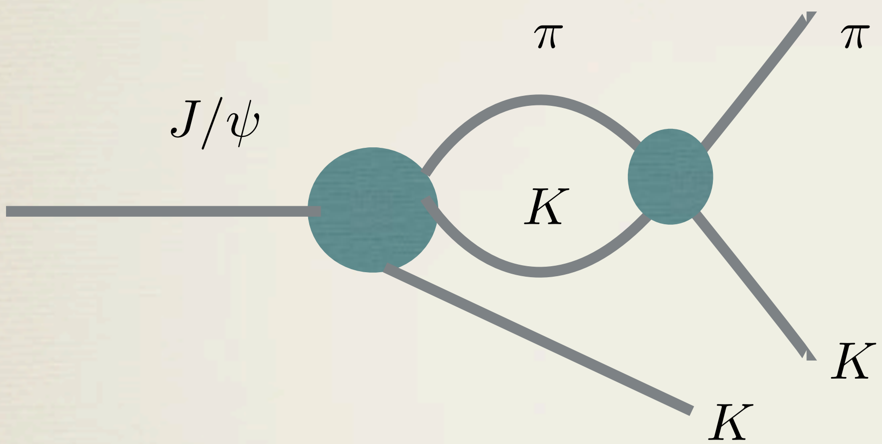


M.G.Bowler,(1975!)

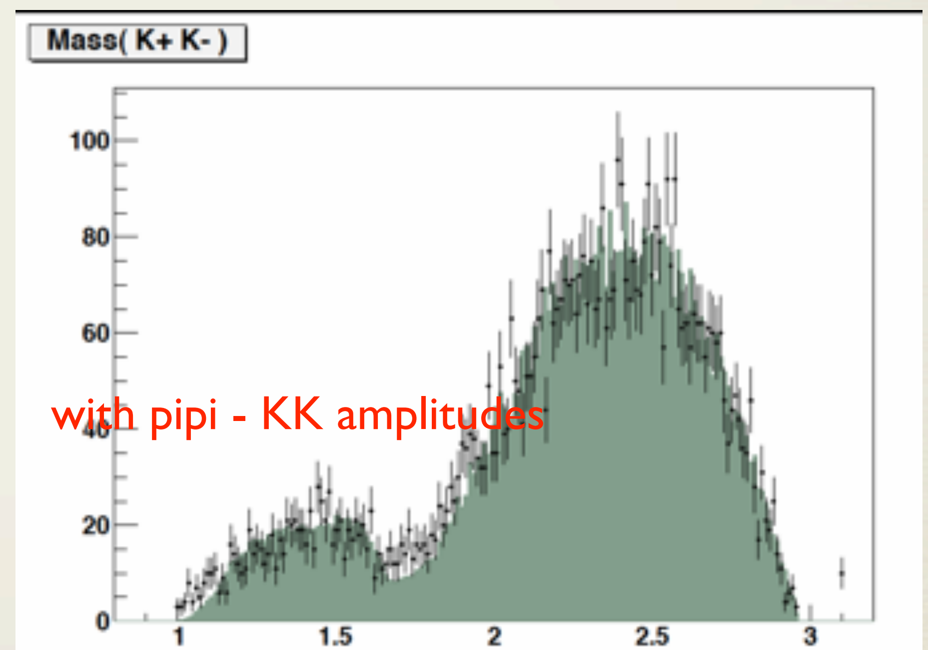
Figure 11: Fit to the 1^+ $\rho\pi$ intensity from $\pi^- p \to \pi^-\pi^-\pi^+ p$ at $E_\pi = 25$ and $E_\pi = 40$ GeV, CERN data [70], with (left) both long-range production from one pion exchange and short-range direct production and (right) short-range direct production only [63].

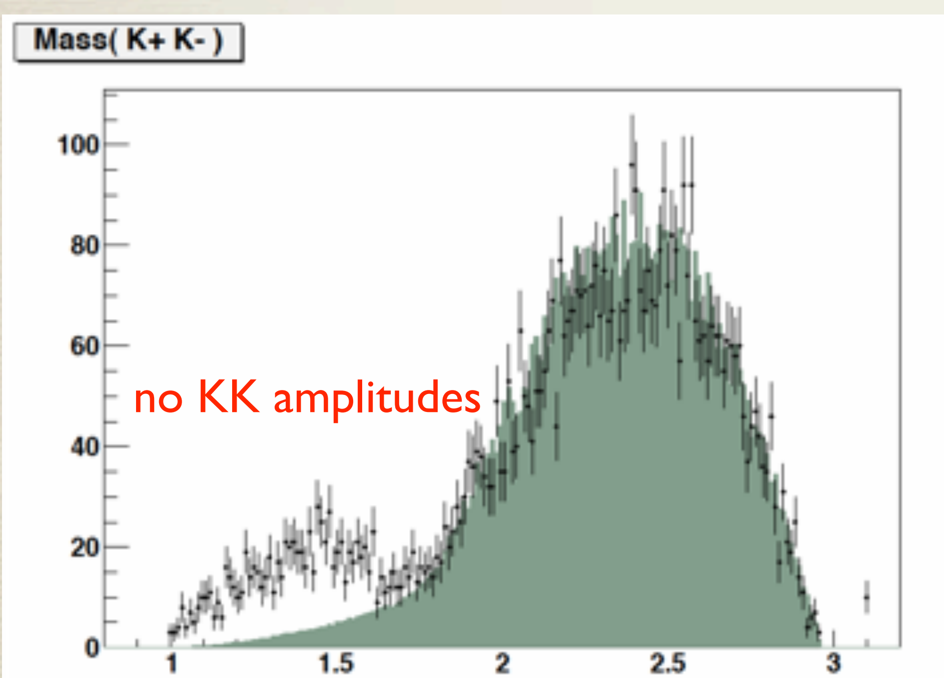






P.Guo,R.Mitchel,M.Shepherd,APS





PRELIMINARY

* General idea

$$ImA(s) = R(s)\rho(s)|A(s)|^2$$

$$A(s) = \frac{1}{\pi}\int_{-\infty}^{0} ds' \frac{ImA(s')}{s'-s} + \frac{1}{\pi}\int_{s_{th}}^{\infty} ds' \frac{ImA(s')}{s'-s}$$

integral equation for the amplitude

* output : through unitarity related to measured x-section

* input ("potential") : through crossing lhc is related to other physical amplitudes

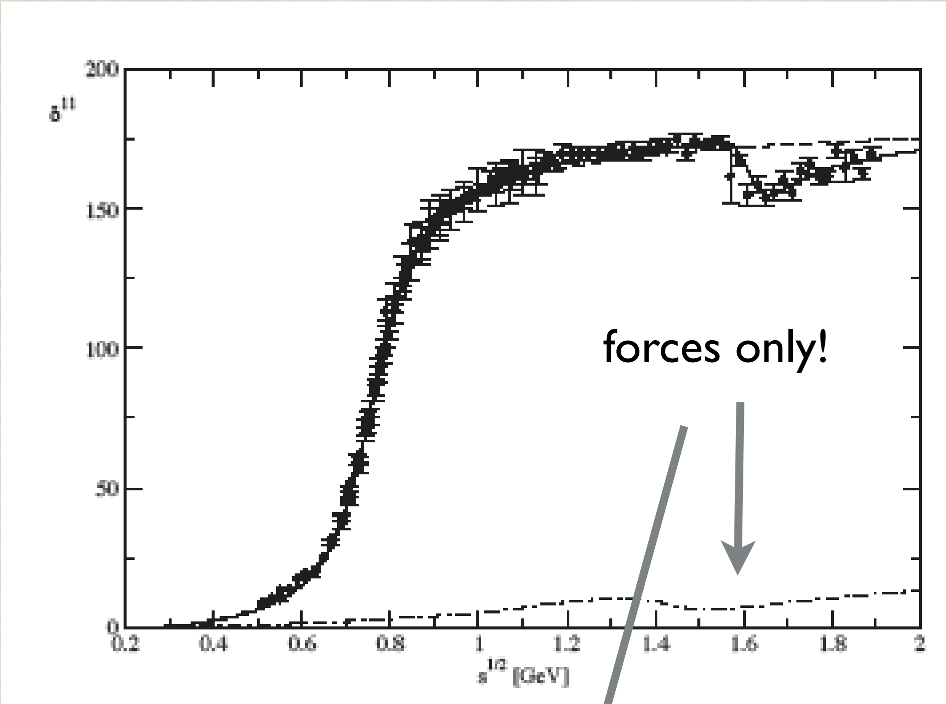
caveats

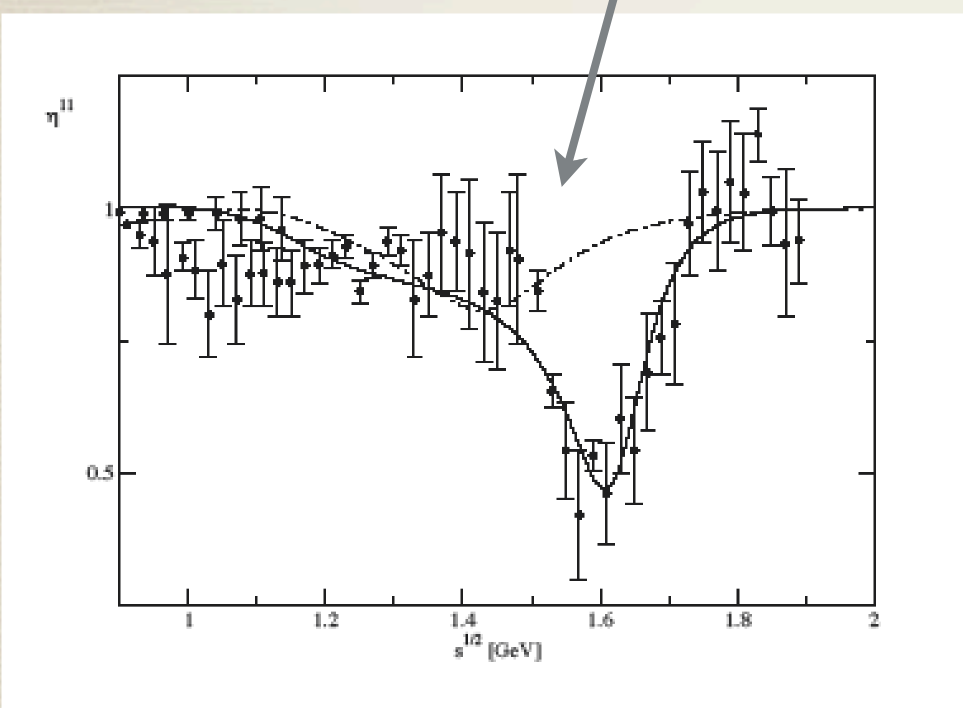
* potential not known everywhere
* in principle many (∞) channels contribute
* x-sections known over limited energy range
* solutions are not unique (CDD)

recent improvements and (1960's vs 2000)

* QCD: interpretation of the ambiguities
* chiral symmetry: low energy constraints

From dispersion relations





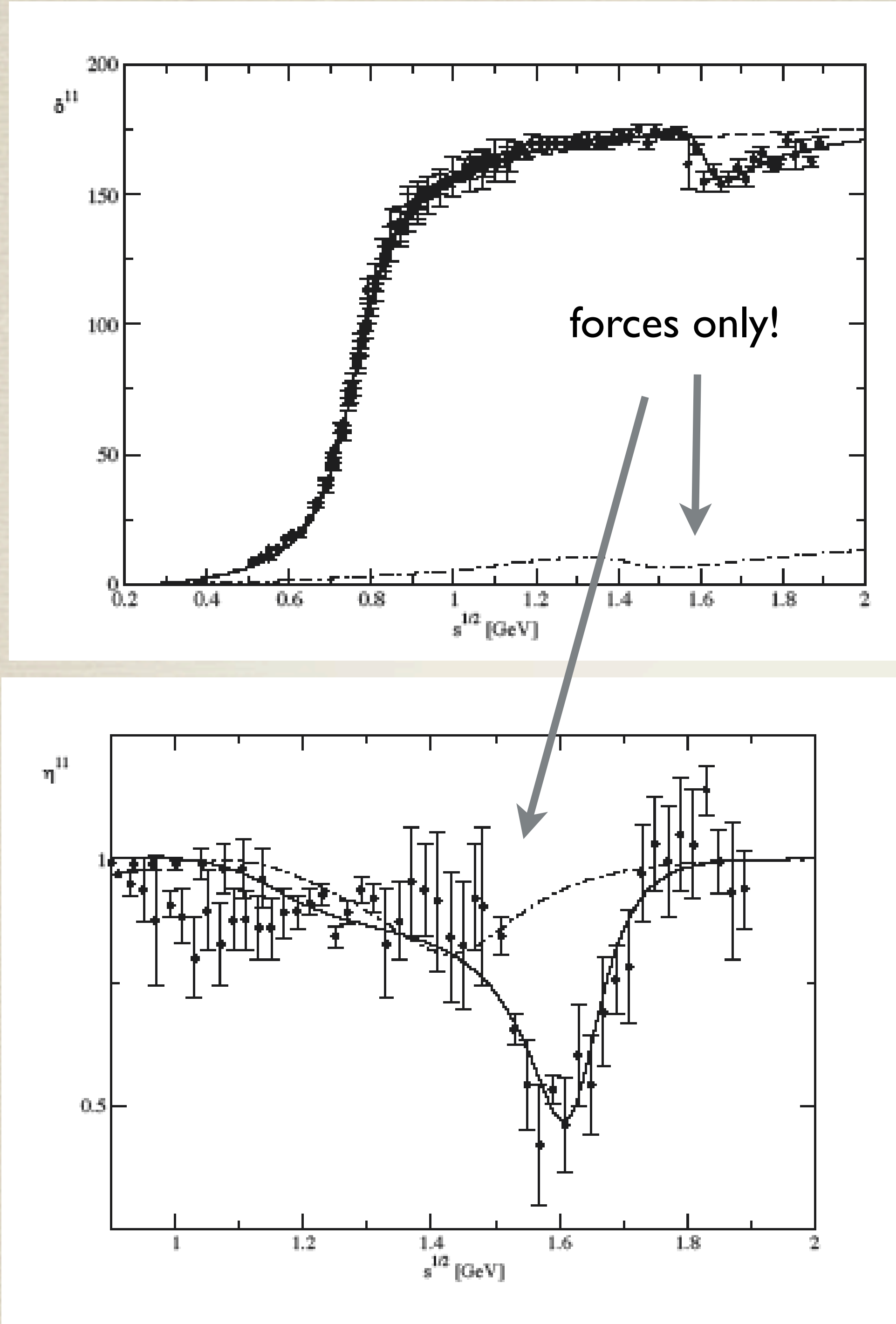
- CDD pole required

FIG. 1: *P*-wave phase shift (upper panel) and inelasticity (lower panel). Data from [34–36], dahsed-dotted (solid) line solution of dispersion relation without (with) a CDD pole. Dashed line is the fit of the quark model from Eq.(33).

M.Battaglieri,R.de Vita,P.Guo,AS

- bootstrap failed
- resonances are not generated dynamically from interactions between other resonances
- or as lattice suggests there are single hadron states in the spectrum

From dispersion relations



* CDD pole required

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M.Battaglieri,R.de Vita,P.Guo,AS

* bootstrap failed
* resonances are not generated dynamically from interactions between other resonances
* or as lattice suggests there are single hadron states in the spectrum
* how does it fit in with the success of dynamicaly generated resonance program from a unitarized chi-PT approach ?

do the Uch-PT poles move?

Summary

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* Lattice : solid evidence for single-hadron QCD states (CDD poles) including hybrids

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* solid evidence for Mandelstam, Nambu,t'Hooft,Polyakov superconductor model of QCD vacuum

"dressed" gluon exchange does not generate hadrons

but a correct phenomenology can be developed including hybrids

Summary

* Lattice : solid evidence for single-hadron QCD states (CDD poles) including hybrids

* solid evidence for Mandelstam, Nambu,t'Hooft,Polyakov superconductor model of QCD vacuum

"dressed" gluon exchange does not generate hadrons

but a correct phenomenology can be developed including hybrids

* bootstrap was abandoned because it discovered hadrons are not dynamically generated, S-matrix was abandoned because CDD poles could not be excluded

these, however, are based on model-independent constrains which should not be forgotten in modern amplitude analyses.