Nature of Exotic Mesons and Detection Methods

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for the JPAC collaborations

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LHCb meeting

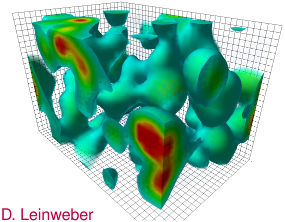
17.07.2017

Overview

1. Hadrons as laboratory for QCD
   - Effective gluons
2. Hybrids: expectations
   - Lattice results
   - Experimental results
3. How to identify them. Amplitude analysis
   - Resonance pole positions
   - Thresholds

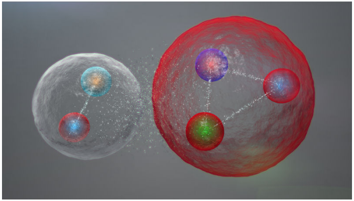
Why spectroscopy

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\Psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

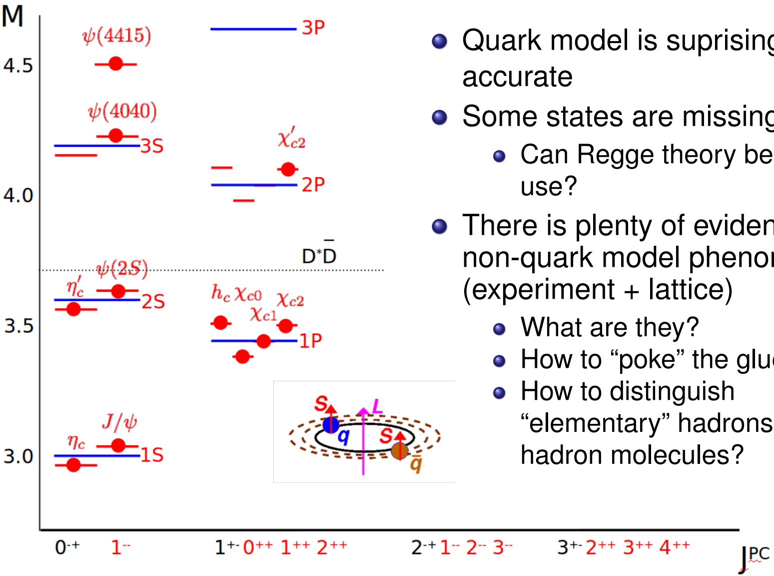


D. Leinweber

- Gluons are responsible for the mass generation and the color confinement
- States of matter dominated by radiation: glueballs, hybrids
- Quarks and gluons are not realized in the nature.
- Hadrons are the basic excitations of the QCD condensed matter (the vacuum)

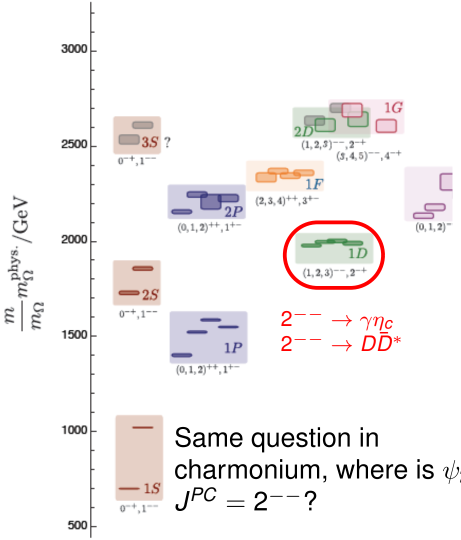


Quark model



- Quark model is suprisingly accurate
- Some states are missing
  - Can Regge theory be of use?
- There is plenty of evidence of non-quark model phenomenon (experiment + lattice)
  - What are they?
  - How to “poke” the glue?
  - How to distinguish “elementary” hadrons from hadron molecules?

Lattice results and Regge trajectories



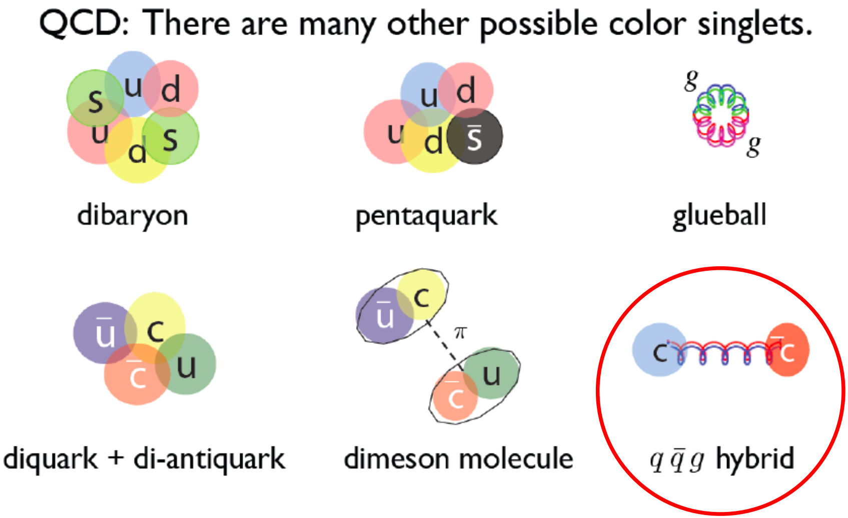
$2^{--} \to \gamma\eta_c$

$2^{--} \to D\bar{D}^*$

Same question in charmonium, where is ψ_2, $J^{PC} = 2^{--}$?

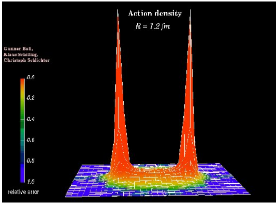
I^G	naturality $=P(-1)^J$	twist =+1 if J=0,2,.. =-1 if J=1,3...	name
0^+	+1	+1	f_0, f_2,...
0^+	+1	-1	$\eta/\eta'_1, \eta/\eta'_3$,... ($1^{-+}, 3^{-+}$,..)
0^+	-1	+1	$\eta/\eta'_0, \eta/\eta'_2$,...
0^+	-1	-1	f_1, f_3,...
0^-	+1	+1	h_0, h_2,.. ($0^{+-}, 2^{+-}$,..)
0^-	+1	-1	$\omega/\phi_1, \omega/\phi_3$,..
0^-	-1	+1	$\omega/\phi_0, \omega/\phi_2$,...($0^{--}, 2^{--}$,.. :not seen)
0^-	-1	-1	h_1, h_3,...
1^+	+1	+1	b_0, b_2,.. ($0^{+-}, 2^{+-}$,..)
1^+	+1	-1	ρ_1, ρ_3,..
1^+	-1	+1	ρ_0, ρ_2,... ($0^{--}, 2^{--}$,.. :not seen)
1^+	-1	-1	b_1, b_3,..
1^-	+1	+1	a_0, a_2,...
1^-	+1	-1	π_1, π_3,... ($1^{-+}, 3^{-+}$,..)
1^-	-1	+1	π, π_2,...
1^-	-1	-1	a_1, a_3,...

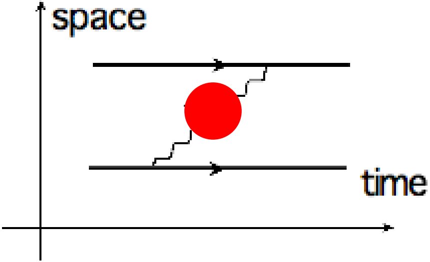
Hadrons beyond the quark model



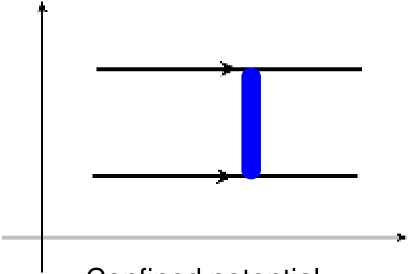
Confining and confined gluons

- provide confinement ⇒ long range correlations
- are confined ⇒ short range correlations





Constituent gluon of large effective mass



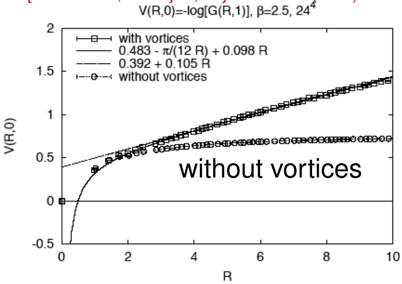
Confined potential between external sources

Some hints from the classical theory

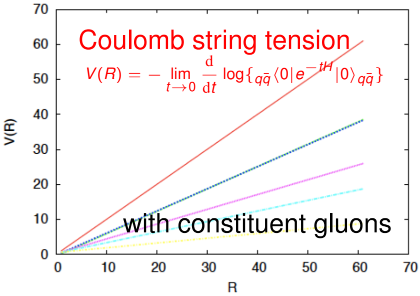
QCD hamiltonian approach,

- slope of the confining potential

[J. Greensite, S. Olejnik, Phys.Rev. D67 (2003) 094503]

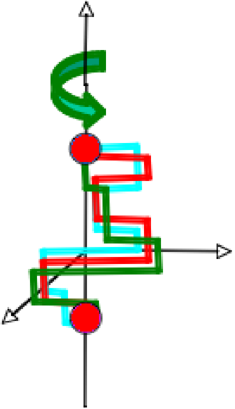


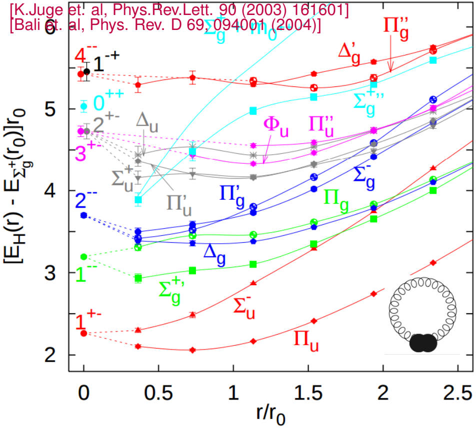
[J.Greensite, A.Szczepaniak, Phys.Rev. D91 034503]



- Physical quarks appear to move in a gluon mean field
- The condensate can be excited leading to effective (constituent) gluons

Static $q\bar{q}$ pair as a diatomic molecule

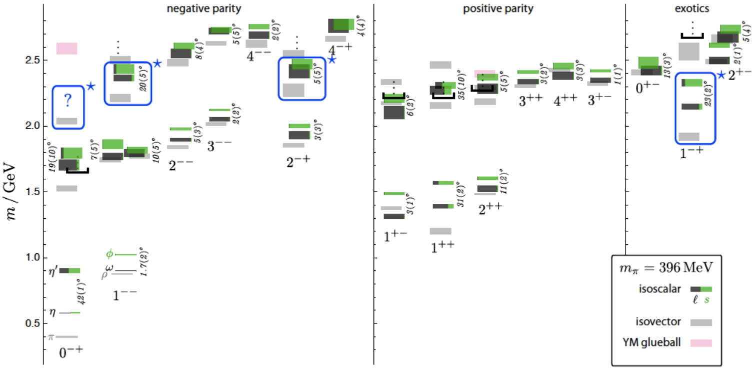




- Three-body forces are responsible for the energy level inversion
- Gluons behave as quasiparticles with $J^{PC} = 1^{+-}$

[P.Krupinski, A.Szczepaniak, Phys.Rev. D73 (2006) 116002]

Constituent gluons lead to the hybrid multiples

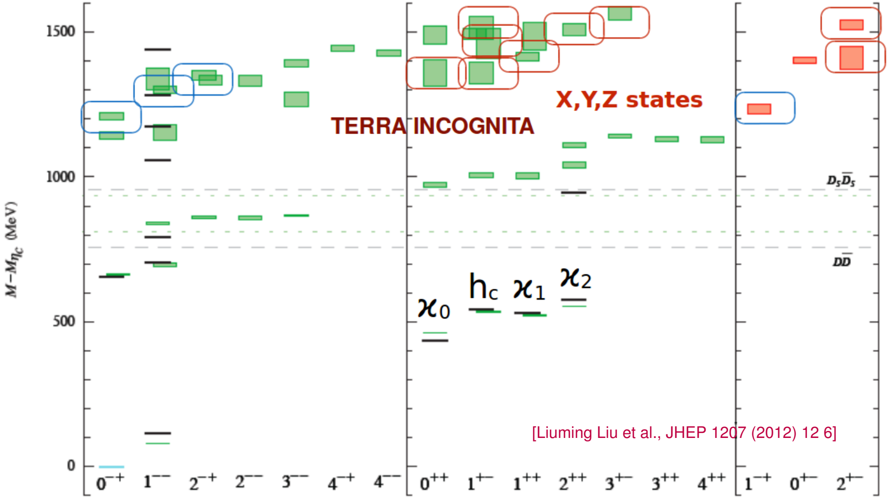


[Dudek et. al, Phys.Rev. D83 (2011) 111502]

- Four lowest multiplets in the hybrid super-multiplet:
  - $1^{+-} \otimes 0^{-+} = 1^{--}$,
    $1^{+-} \otimes 1^{-+} = 0^{-+}, 1^{-+}, 2^{-+}$.
- 10 multiplets of 1$^{\text{st}}$ orbital excitation.

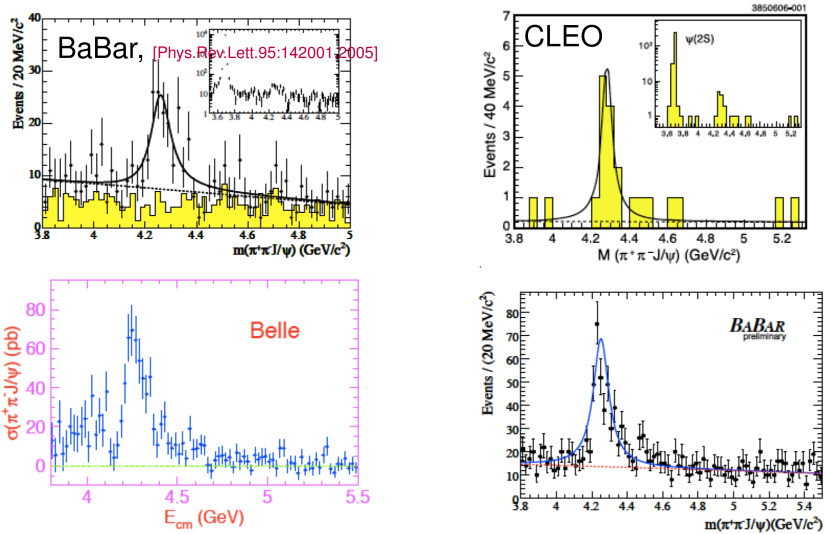
Charmonium spectrum form lattice

Expected hybrids: 0^{-+}, 1^{-+}, 2^{-+}, 1^{--}, 0^{++}, 1^{++}, 2^{++}, 0^{+-}, 1^{+-}, 1^{+-}, 1^{+-}, 2^{+-}, 2^{+-}, 3^{+-}



$Y(4260)$ is a hybrid candidate

Discovered by Babar in $J/\psi\pi^+\pi^-$, confirmed by CLEO, Belle



Exotics 1^{-+} in the experiment, [from A.Szczepaniak]

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

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

$\pi^- p \to \eta \pi^0 n$

No consistent B-W inter
possible but a weak ηπ
exists and can reproduce the exotic w

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

$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

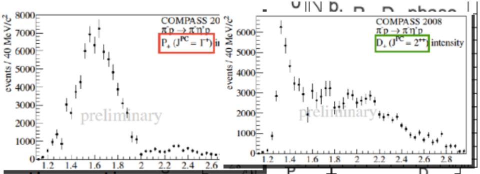
$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2

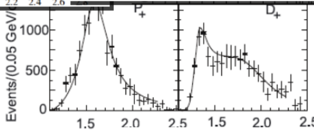
$\pi^- p \to \rho^0 \pi^- p$

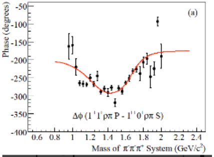
$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2

$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV / c^2

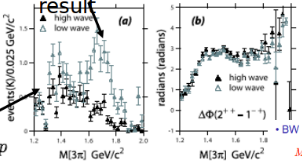
BNL (E852) yes/no
COMPASS yes





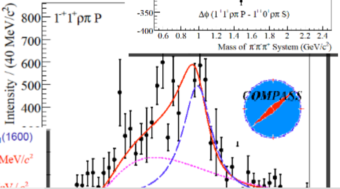


E852 result



$\pi^- p \to \pi_2^-(1600) p$

$\pi_2^- \to \rho^0 \pi^-$



• BW parameters for $\pi_1(1600)$

$M = \left(1660 \pm 10^{+0}_{-64}\right)$ MeV/c^2

Exotics 1^{-+} in the experiment, [from A.Szczepaniak]

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

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

$\pi^- p \to \eta \pi^0 n$

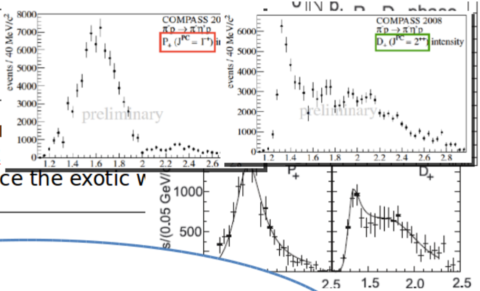
No consistent B-W inte
possible but a weak $\eta\pi$
exists and can reproduce the exotic w

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

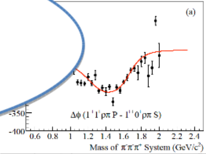
$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

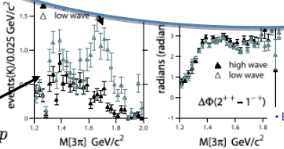
$\Gamma = 34$

$\pi^- p \to \rho^0$



Need to be confirmed

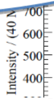




$\pi^- p \to \pi_2^-(1600) p$

$\pi_2^- \to \rho^0 \pi^-$

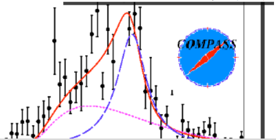
FIG. 25: (a) The $1^{-+}1^+$ P-wave $\rho\pi$ partial wave



• BW parameters for $\pi_1(1600)$

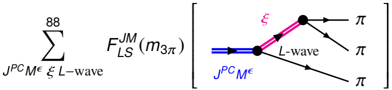
$M = \left(1660 \pm 10 ^{+0}_{-64}\right)$ MeV/c^2

$\Gamma = \left(269 \pm 21 ^{+42}\right.$ MeV / c^2



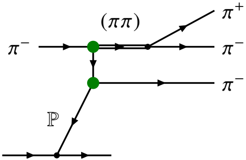
$1^{-+}\rho\pi$ *P*-wave at the 3π

PWA at COMPASS



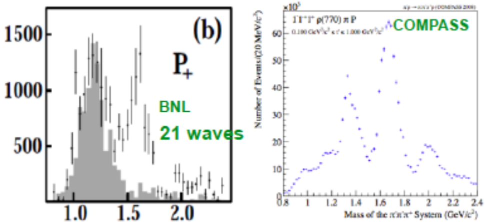
Isobars: ρ, ρ_3, f_2, $f_0(980)$, $f_0(600)$

Exchange process ("force") is decomposed to an infinite number of partial waves

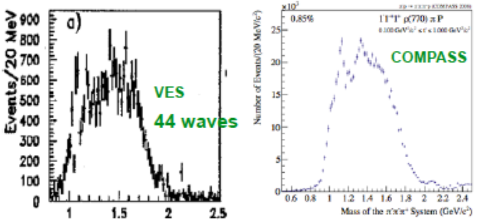


Interpretation ambiguous without implementing force-resonance duality

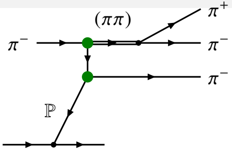
$\pi^- p \to \pi^-\pi^+\pi^- p : 1^{-+}\rho\pi P$



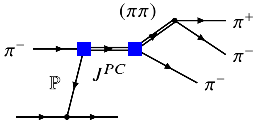
F. Haas, PhD thesis

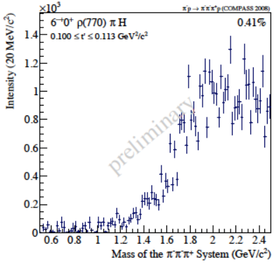


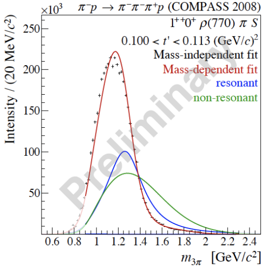
Forces-resonances duality

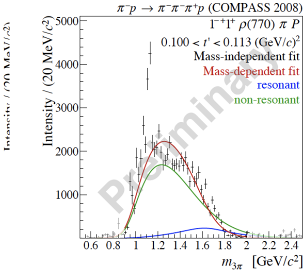


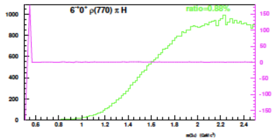
Exchange-processes are backgrounds to the resonances. It is not clear how to implement them in the mass-independent fit.

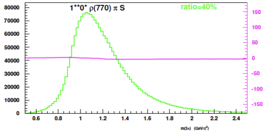


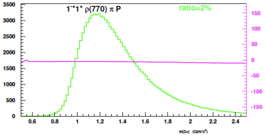










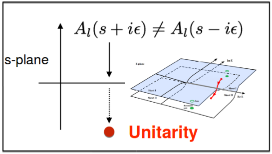


[D. Ryabchikov, PWA9/ATHOS4 meeting]

S-matrix principles

Crossing, Analyticity, Unitarity

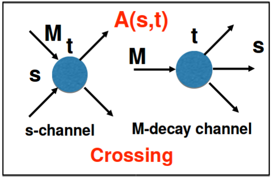
To test a hypothesis about the nature of a "peak" (e.g. resonance, etc.) one needs to construct an amplitude consistent with S-matrix principles (otherwise false singularities appear).



$$A(s,t) = \sum_l A_l(s) P_l(z_s)$$

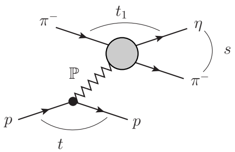
Analyticity

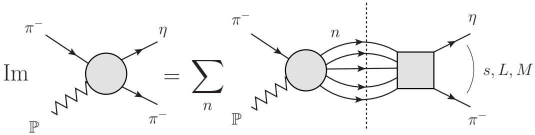
$$A_l(s) = \lim_{\epsilon \to 0} A_l(s+i\epsilon)$$



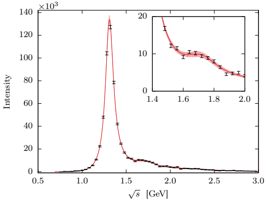
2^{++} states

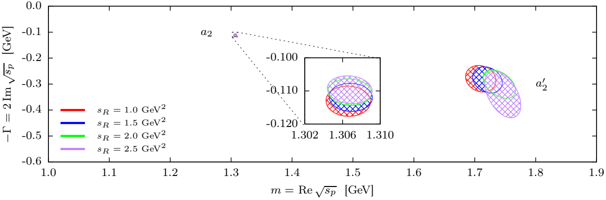
Amplitude analysis of $\eta\pi$ system [A.Jackura(JPAC), arXiv:1707.02848]





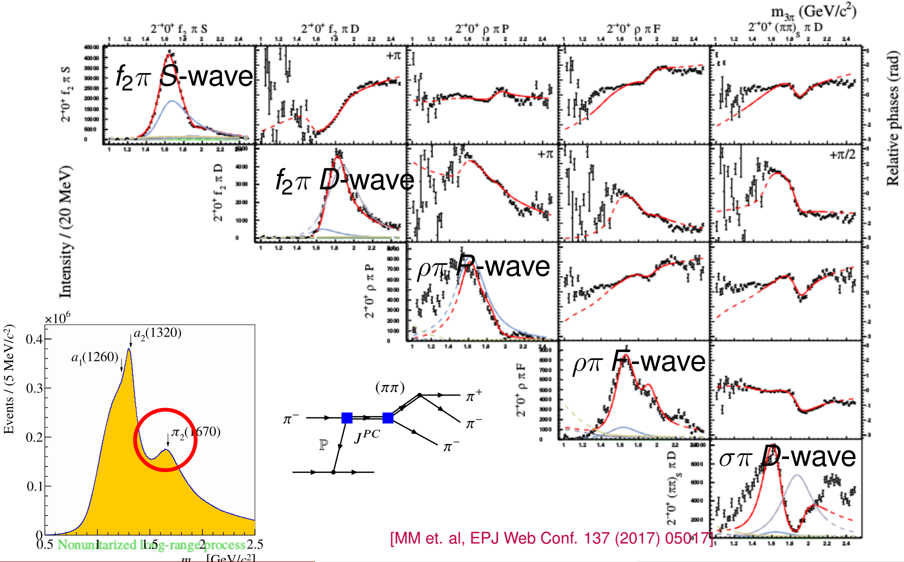
- Reaction is constrained by unitarity $\mathrm{Im}\, f(s) = f(s)\,\rho(s)\, a^{\star}_{\eta\pi}(s)$
- Amplitude = Production $\times$ $\eta\pi$-interaction
- N-over-D parametrization of $\eta\pi$-amplitude. $D = D_0(s) - \frac{s}{\pi}\int \mathrm{d}s' \frac{\rho(s')N(s')}{s'-s}$.
- Analytic amplitude $\rightarrow$ second sheet $\Rightarrow$ particles poles





2^{-+} states

Amplitude analysis of 3π system

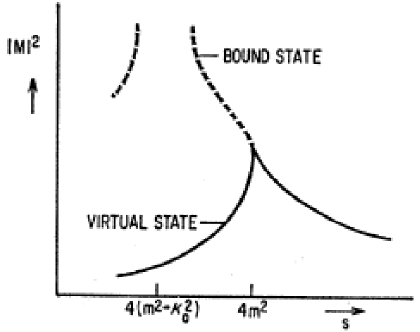


[MM et. al, EPJ Web Conf. 137 (2017) 05017]

Importance of thresholds

Molecules candidates: $f_0(980)$, $a_0(980)$, $a_1(1420)$, $\Lambda(1405)$, XYZ, ...

Deutron is *np*-molecule bound by meson-exchange forces.



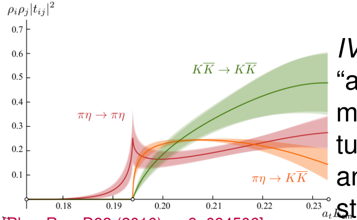
- Thresholds are "windows" to singularities (particles, visual states, forces") located on the nearby unphysical sheet.
- Singularities appear as cusps (if below threshold) or bumps (if above)

- Bound state: pole at the physical energy plane
- Virtual state: pole at the "unphysical sheet" closest to physical region.

Lattice resutls on $a_0(980)$

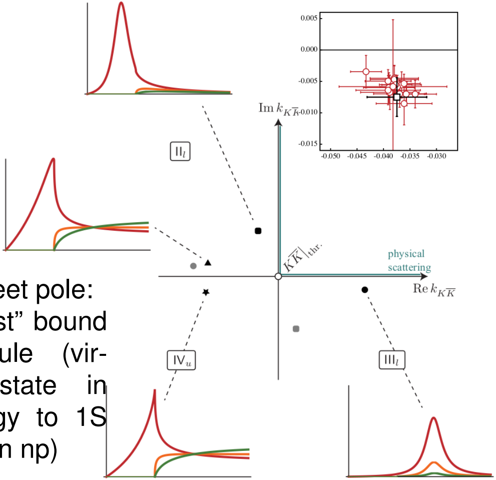
Scattering phase shifts

- Coupled-channel analysis of the $K\bar{K} - \eta\pi$ operators
- $a_0(980)$ is in the scalar isovector channel

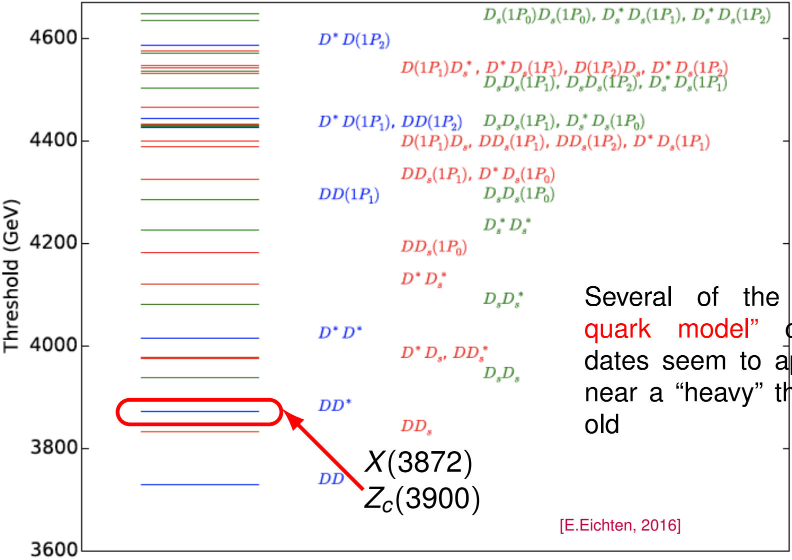


[Phys.Rev. D93 (2016) no.9, 094506]

IV sheet pole: “almost” bound molecule (virtual state in analogy to 1S state in np)



Thresholds in the charmonium sector



Several of the "non quark model" candidates seem to appear near a "heavy" threshold

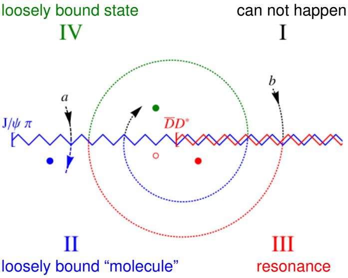
[E.Eichten, 2016]

Amplitude analysis of $Z_c(3900)$, [Pilloni et. al, Phys.Lett. B772 (2017) 200-209]

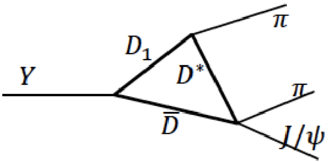
Different singularities $\rightarrow$ different natures

- reactions $Y(4260) \rightarrow J/\psi\pi\pi$ and $Y(4260) \rightarrow D^{\star}\bar{D}$
- Amplitude is analytic function of $J/\psi\pi$ mass s.
- Coupled channel analysis $\rightarrow$ 4 Riemann sheets of $A(s)$

Complex s-plane



Triangle singularity from the graph



incorporated in the amplitude

The fit, [Pilloni et. al, Phys.Lett. B772 (2017) 200-209]

Triangle + pole at the III-sheet of $J/\psi\pi$ amplitude

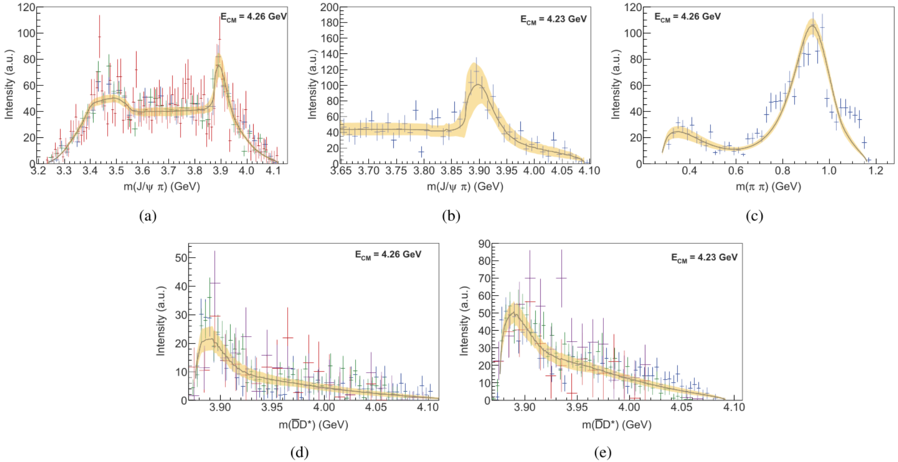
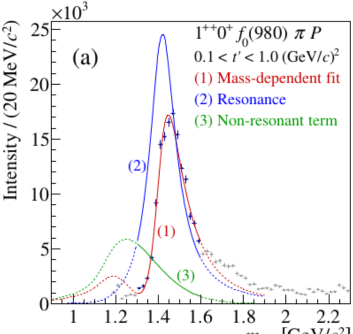


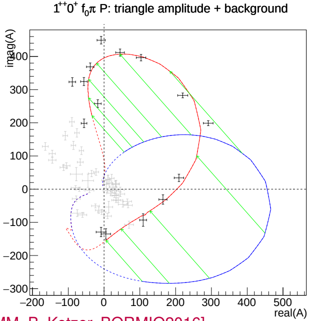
Fig. 4. Result of the fit for the scenario III + tr. (Flatté K-matrix, with triangle singularity). The plot legend and the comments on the fit are given in the caption of Fig. 3. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

COMPASS $a_1(1420)$ and the triangle singularity

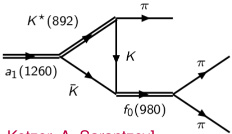
Unexpected peak in the $1^{++} f_0 \pi$ P-wave



[COMPASS 2015]



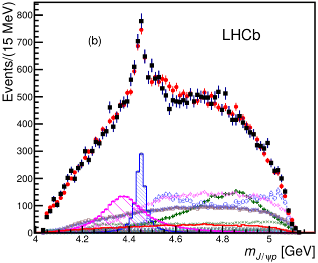
[MM, B. Ketzer, BORMIO2016]

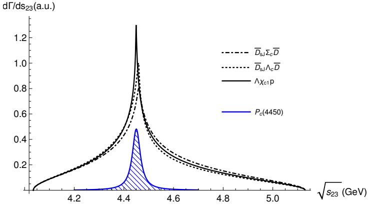


[MM, B. Ketzer, A. Sarantzev]

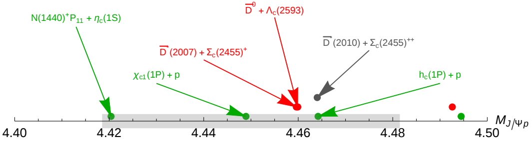
- Amplitude with the tr. diagram describes the data without free parameters
- Rescattering vs resonance – three body unitarity is required

Pentaquark, $P_c(4450)$

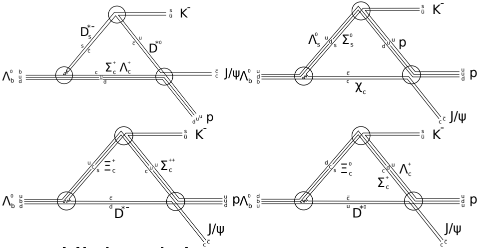




- Many thresholds nearby



- Difficult to find out the relevant channels



- High spin!

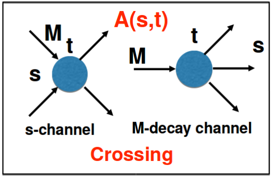
Determination of resonances quantum numbers

Spin formalism, [T. Skwarnicki & JPAC]

- What do we know about kinematics? $\Leftarrow$ Reps. of Rotation Group
- How can we constraint the dynamics? $\Leftarrow$ Unitarity

Formalisms on the market:

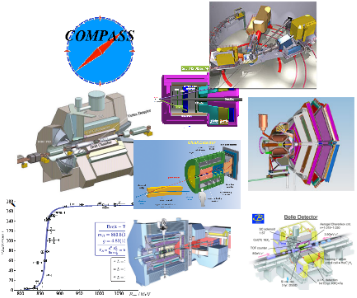
- Helicity, Spin-Orbit, Zemach tensors, Chung's relativistic corrections, Covariant LS by Fillipini, ...

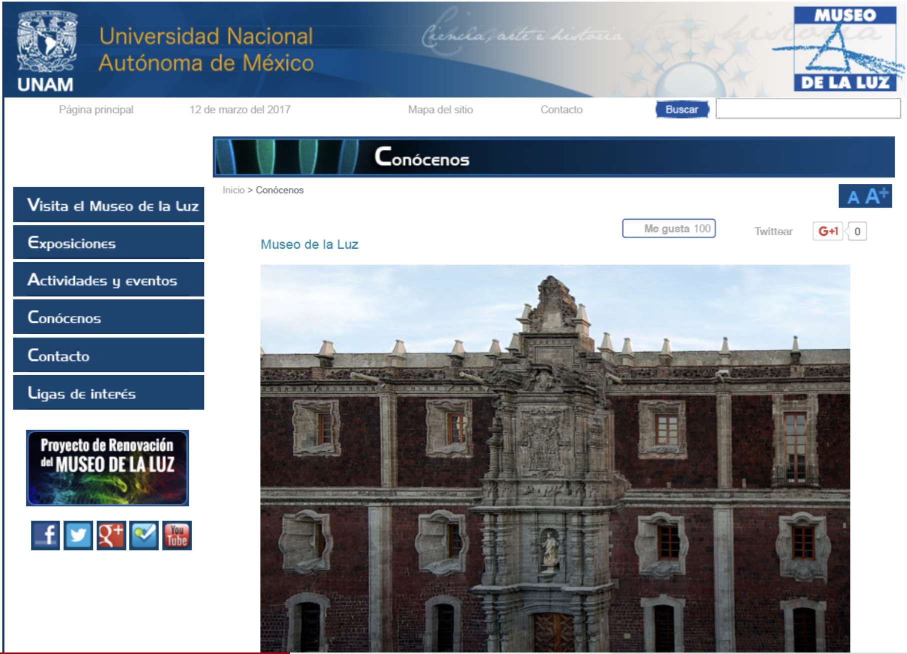


- Models have different energy dependence,
  In general unknown, coupling `const` is a model
- Some introduce spurious singularities
- Some do not satisfy crossing

Joint Physics Analysis Center(JPAC)

- Started in the Fall of 2013 to support the extraction of physics results from analysis of experimental data from JLab12 and other accelerator laboratories.
- Work is on theoretical, phenomenological and data analysis tools in close collaboration with theorists and experimentalists worldwide.
- Contribute to education of new generation of practitioners in physics of strong interactions.

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Thank you for the attention

I thank Bernhard Ketzer, Adam Szczepaniak for the help