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Overview of Light Meson Spectroscopy: Results and Perspectives

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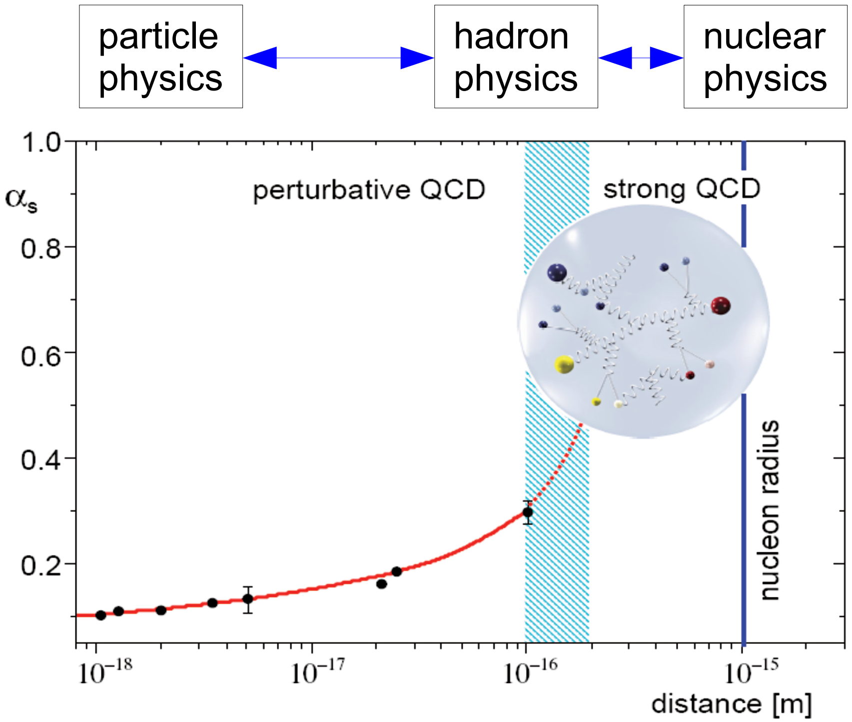
Outline

- Introduction
- Results in the past
  - scalar, pseudo-scalar and tensor resonances
- Recent results
  - spin-exotic 1^{-+} hybrid candidate $\pi_1(1600)$
  - coupled channel analysis with $\bar{p}p$ and $\pi\pi$-scattering data
- Perspectives
  - new data and experiments

Introduction

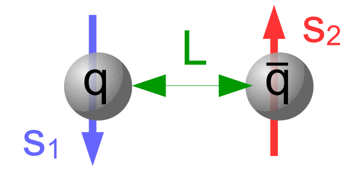
- Light mesons are bound states consisting of u-, d- and s-quarks
- Cover the non-perturbative QCD regime
- Description very challenging
  - lattice QCD
  - phenomenological models
- Observation and measurements of the resonance properties very challenging
  - many overlapping resonances with same quantum numbers
  - decays in different channels

energy dependence of α_s

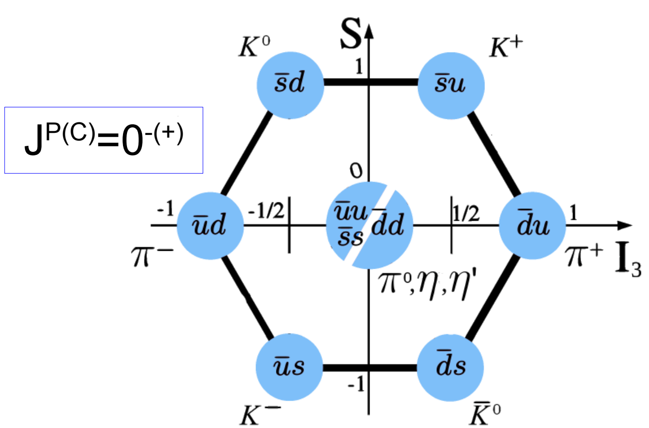


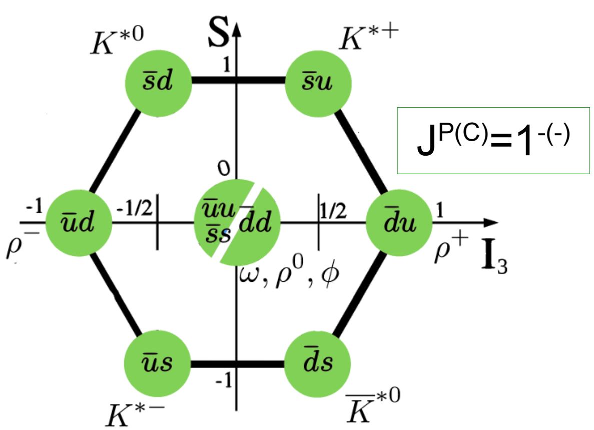
Quark Model

- Quark model successful for the classification of mesons
- q$\bar{q}$-mesons: $I^G J^{PC}$ determined by the isospin, the orientation of the quark spins and the orbital angular momentum
  - $P = (-1)^{L+1}$ $C = (-1)^{L+S}$ $G = (-1)^{I+L+S}$
  - possible: $J^{PC} = 0^{-+}, 0^{++}, 1^{+-}, 1^{--}, 1^{++}, 2^{-+}, 2^{++}, \ldots$
  - forbidden: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$



- Provides a scheme to group q$\bar{q}$-mesons in SU(3) nonets
- Many predicted states were found and classified
  - example: nonets of ground state pseudo scalar and vector mesons

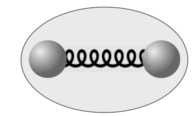




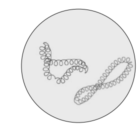
Exotic States

- QCD predicts also exotic states which can be grouped in 3 categories

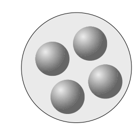
- Hybrids
  - $q\bar{q}$ states with excited gluonic degrees of freedom

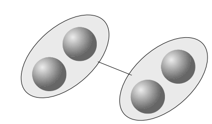


- Glueballs
  - hadrons without any valence quark content



- Multiquark states
  - tetraquark: tightly bound $(q\bar{q})$ $(q\bar{q})$ states
  - molecule: loosely bound pair of mesons

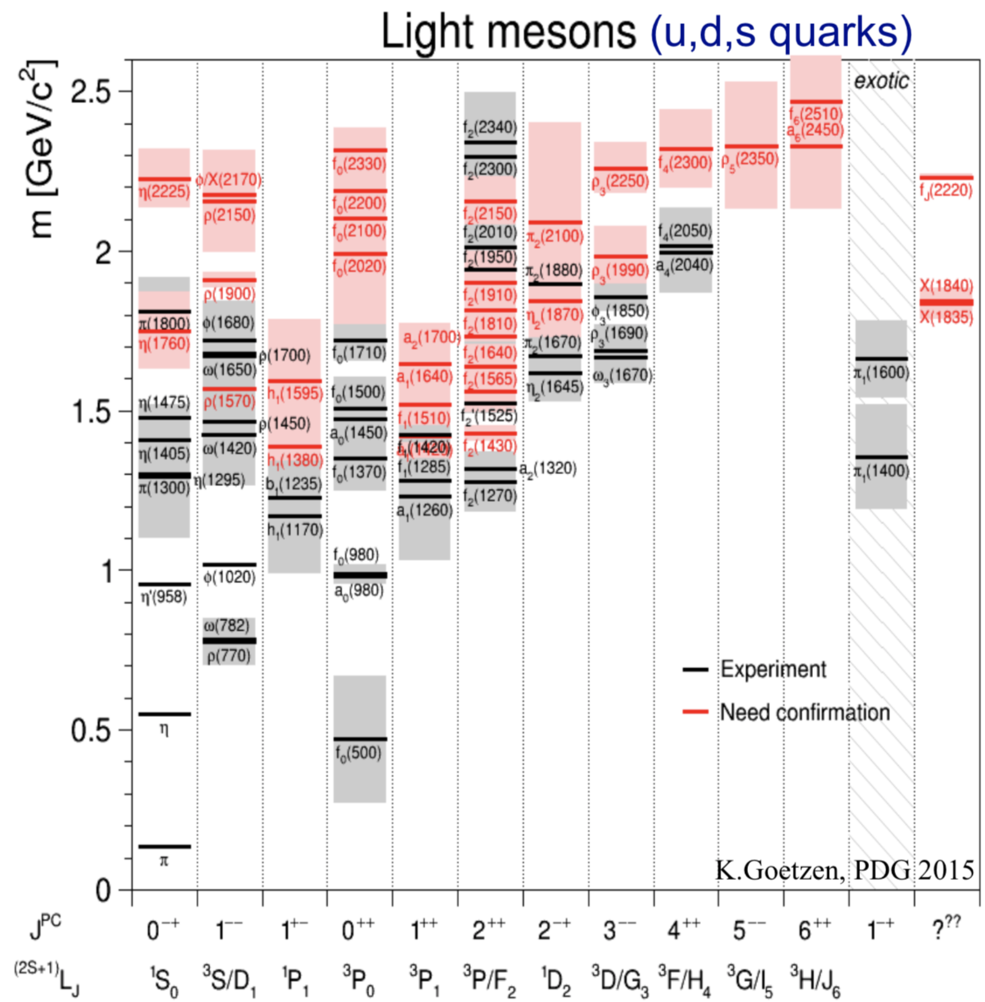




- For exotic states also quantum numbers are possible which are forbidden for conventional $q\bar{q}$ states: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, \ldots$

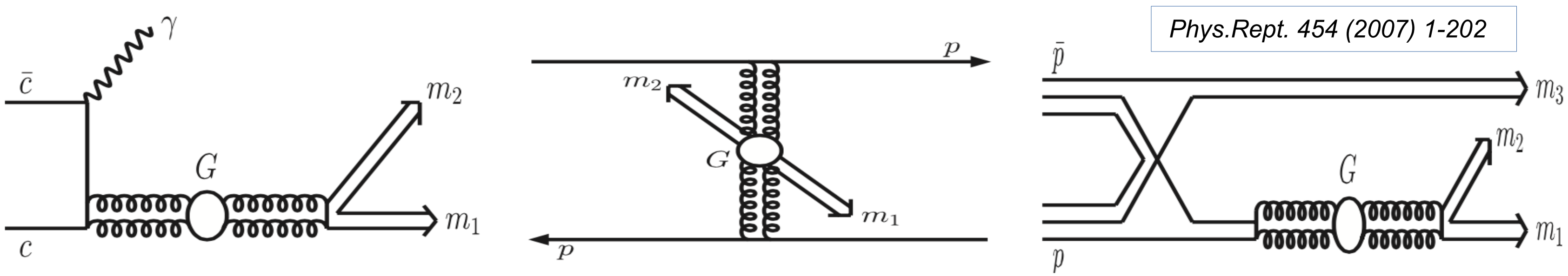
Light Meson Spectrum

- Rich spectrum
- Many states need confirmation
- Candidates with exotic quantum numbers observed
- Challenges
  - many overlapping resonances with same quantum numbers
  - distinction between conventional $q\bar{q}$ mesons and exotics difficult
  - proper access to resonance parameters



Access to the Inner Structure

- Characteristics of the production
  - γ induced processes include QED effects
  - exotics with gluonic content should
    - ➔ be mainly produced in gluon rich environments like radiative J/ψ decays, central production, or $\bar{p}p$ annihilation
    - ➔ couple weakly to γ induced processes like $\gamma\gamma$ fusion



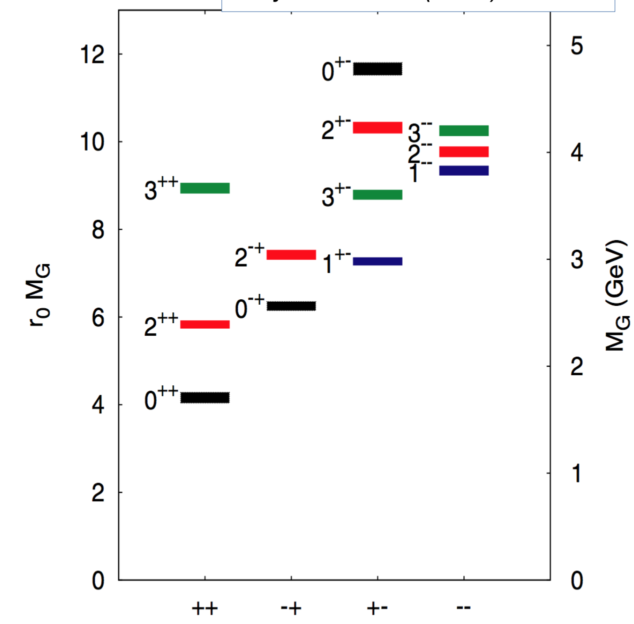
Phys.Rept. 454 (2007) 1-202

- Characteristics of the decay pattern
  - glueballs: flavour blind decay with a rather narrow width
  - molecules: decay into a meson pair close to threshold

 Glueballs and Hybrids

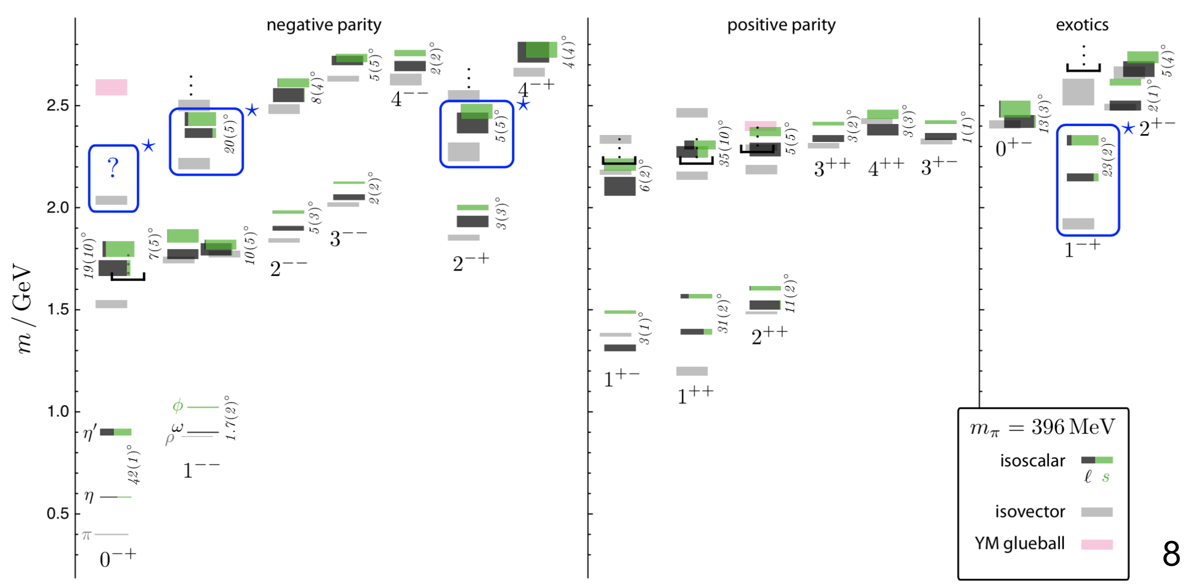
- LQCD: lightest glueballs with exotic quantum numbers above 4 GeV/c^2
- Glueballs in the light meson mass range only with non exotic quantum numbers $J^{PC}= 0^{++}, 0^{-+}, 2^{++}$ predicted

Phys.Rev. D73 (2006) 014516



- Lightest hybrid expected just below 2 GeV with exotic quantum numbers $J^{PC}=1^{-+}$

Phys.Rev. D84 (2011) 074023



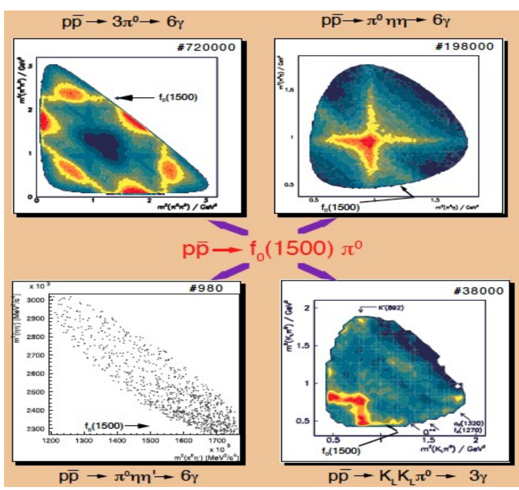
0^{+} (0^{++}) States

- Lots of scalar resonances observed in the light meson mass region
- Too many to fit in the ground state nonet: σ, $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$, ...

possible explanation

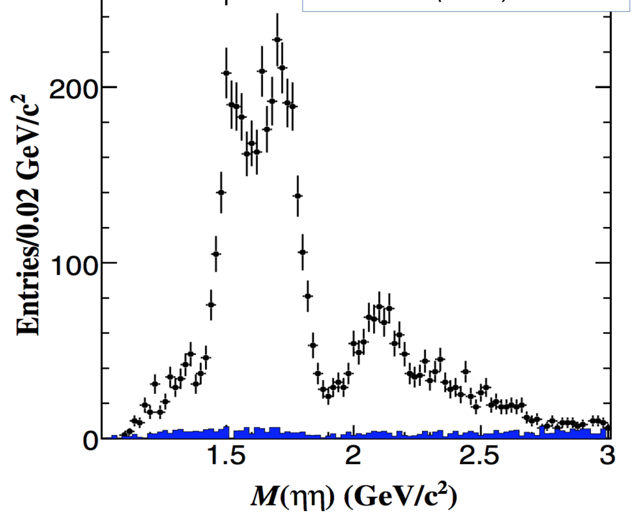
- $f_0(1370)$, $f_0(1500)$, $f_0(1710)$ are mixtures between $q\bar{q}$ states and glueball
- $f_0(1500)$ and $f_0(1710)$ are candidates with large gluonic content
  - strongly produced in gluon rich processes and suppressed in $\gamma\gamma$ fusion

Crystal Barrel @ LEAR



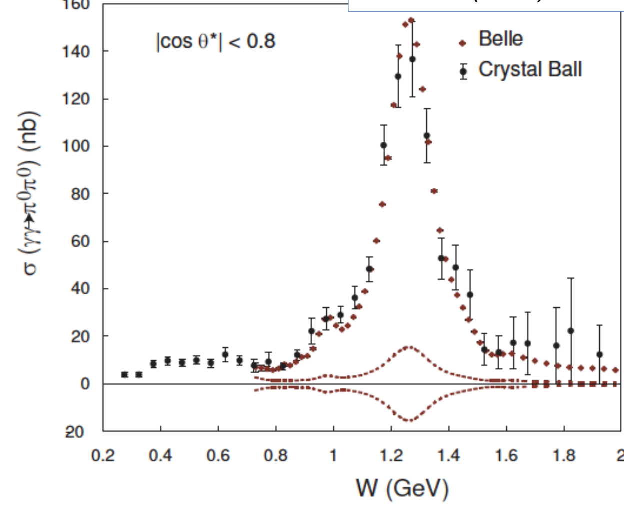
J/ψ → γηη @ BESIII

PRL 108 (2012) 182001



γγ → ππ @ Belle and Crystal Ball

PRD 78 (2008) 052004

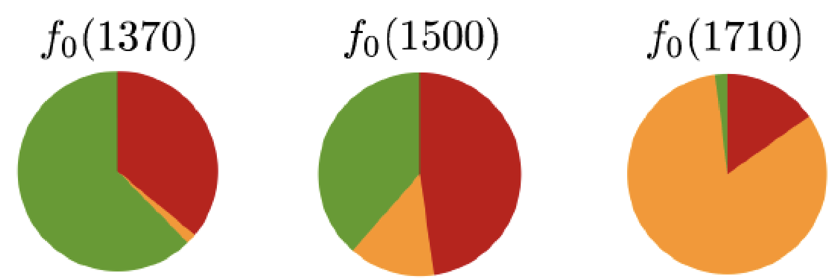


0^+ (0^{++}) States

- Various scenarios are existing for the mixing of ($u\bar{u}$+$d\bar{d}$), ($s\bar{s}$) and (gg) states based on the observed production and decay strengths
- Challenge: proper description of the dynamics above the $K\bar{K}$ threshold due to several contributing decay channels

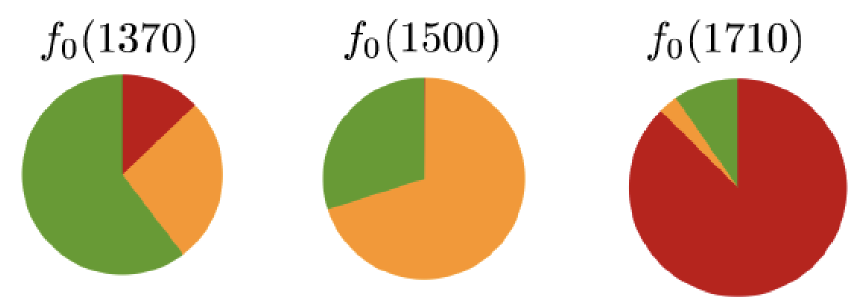
$$\begin{pmatrix} |f_0(1370)\rangle \\ |f_0(1500)\rangle \\ |f_0(1710)\rangle \end{pmatrix} = U \cdot \begin{pmatrix} |u\bar{u} + d\bar{d}\rangle \\ |s\bar{s}\rangle \\ |gg\rangle \end{pmatrix}$$

Close, Kirk: Phys. Lett. B483, 345 (2000)



More accurate measurements and sophisticated analyses in particular for the region above the $K\bar{K}$ threshold are needed

Cheng et al: Phys. Rev. D92, 094006 (2015)

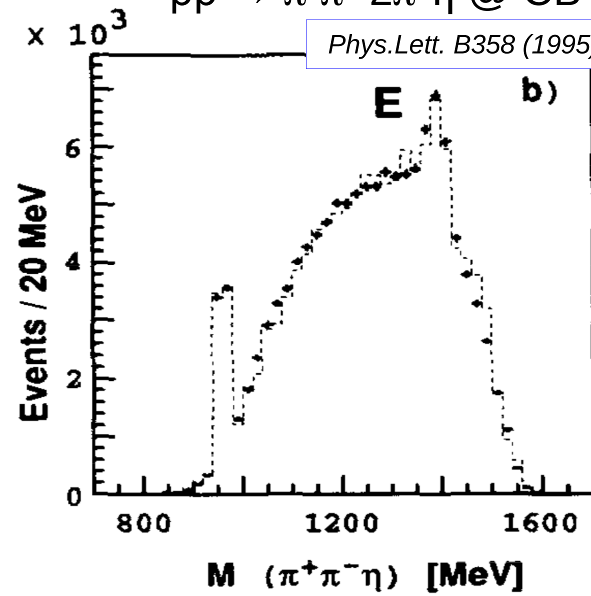


0^{+} (0^{-+}) States

- Many pseudo-scalar resonances observed
  - η, η', $\eta(1295)$, $\eta(1405)$, $\eta(1475)$, $\eta(1760)$, . . .
- $\eta(1405)$ is favored to be the 0^{-+} glueball
  - strongly produced in radiative J/ψ decays and also seen in $\bar{p}p$ annihilation
  - weak coupling to $\gamma\gamma$
  - $\eta(1295)$ and $\eta(1475)$ radial excitations of ground state members η and η'
- But
  - $\eta(1405)$ not seen in central production
  - LQCD predictions: $M_g(0^{-+}) > 2$ GeV
  - does the $\eta(1295)$ exist at all?
  - are $\eta(1405)$ and $\eta(1475)$ two different states?

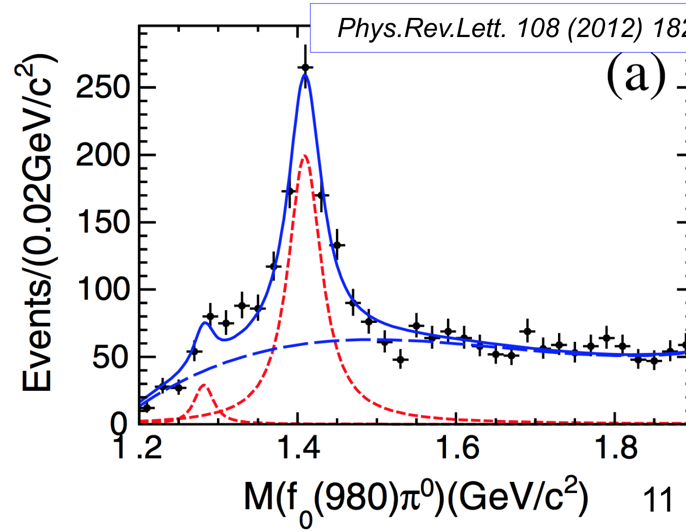
$\bar{p}p \rightarrow \pi^+\pi^- 2\pi^0\eta$ @ CB

Phys.Lett. B358 (1995) 389



$J/\psi \rightarrow \gamma f_0(980) \pi^0$ @ BESIII

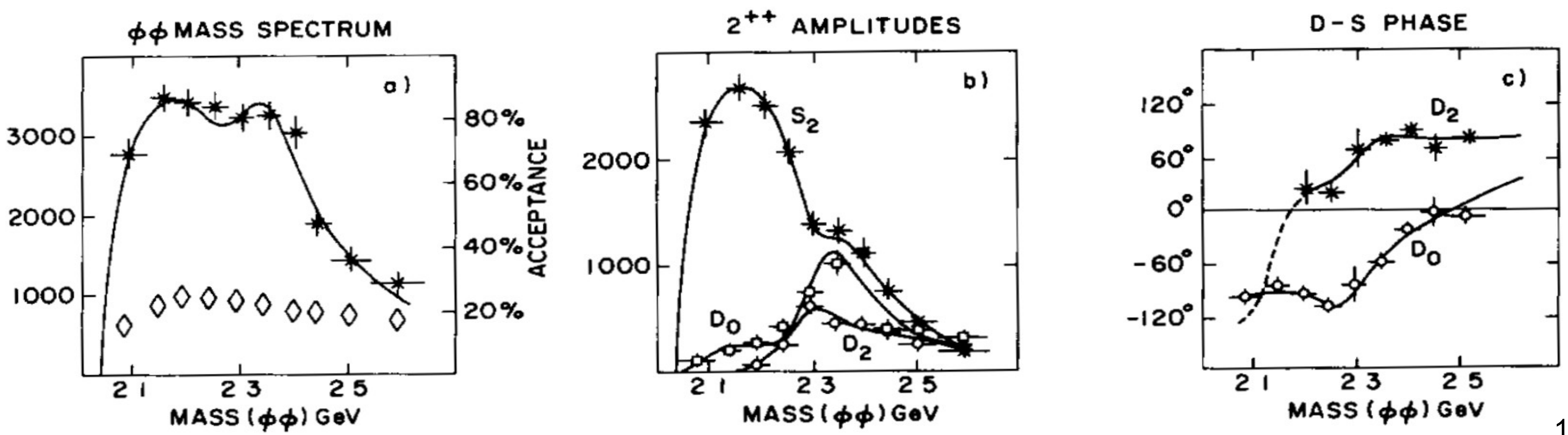
Phys.Rev.Lett. 108 (2012) 182001



0^{+} (2^{++}) States

- 2 isoscalar nonets result from the quark model: $^{(2S+1)}L_J = {}^3P_2$ and $^3F_2$
- More than 10 conventional $q\bar{q}$ states should exist in the light meson sector
- Poor knowledge in the mass region above the $\bar{p}p$ threshold so far
- Lightest tensor glueball predicted between 2 - 2.4 GeV
- Hints in $\pi p \rightarrow \phi\phi n$ at BNL with unexpected large cross section for 3 tensor mesons between 2 - 2.4 GeV

Phys.Lett. B201 (1988) 568-572



Status: Light Meson Spectroscopy

- Over the last 30 years significant amount of data analyzed, but still many unresolved questions
- Lots of broad and overlapping resonances
- Mixtures between conventional $q\bar{q}$ and exotic states possible
- Complete and unambiguous knowledge of all $q\bar{q}$ multiplets is needed
- Many resonance properties obtained from single channel analyses with Breit-Wigner parametrization
- Multi channel analyses with sophisticated approaches (unitarity, analyticity) by combining data with different decay and production modes are needed

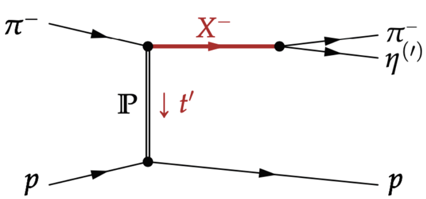
Dynamical Functions

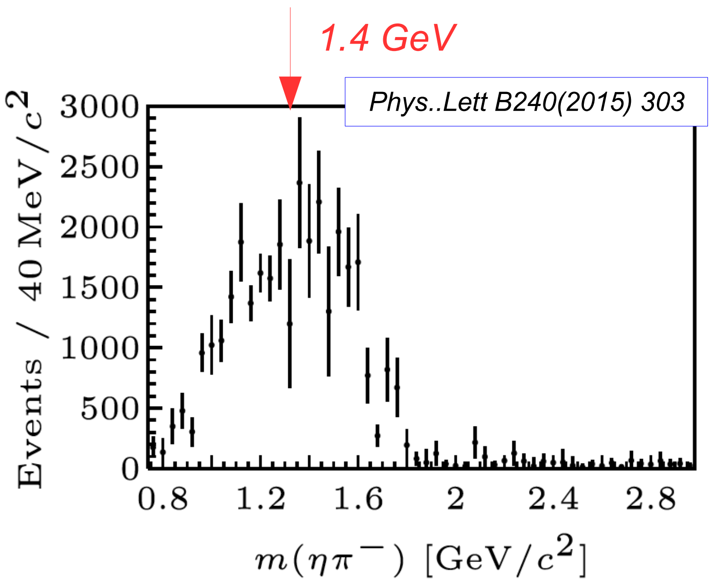
- Breit-Wigner functions widely used
  - good approximation for isolated resonances appearing in a single channel
  - resonance parameters depend on the production mechanism
- More sophisticated descriptions needed for
  - resonances decaying into multiple channels
  - several resonances appearing in the same channel
  - resonances located at thresholds → distortion of the line shape

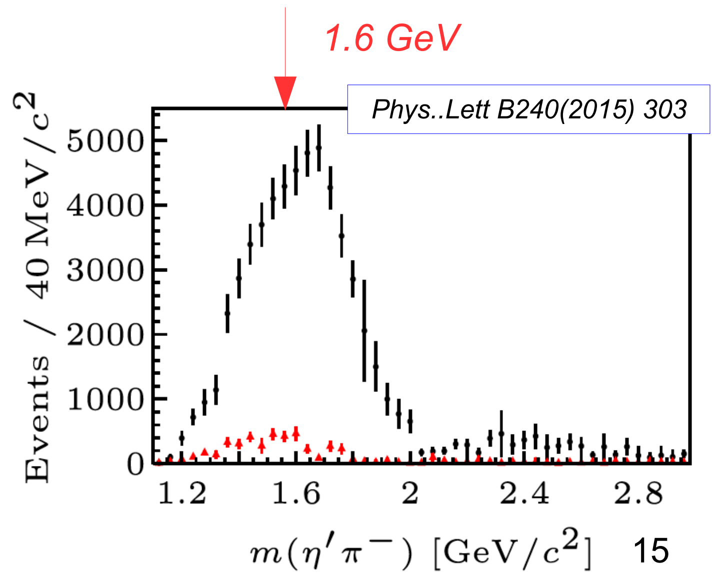
Approaches with an adequate consideration
of unitarity and analyticity needed
(K-matrix, N/D-method, Two-potential decomposition)

JPAC Analysis of COMPASS Data

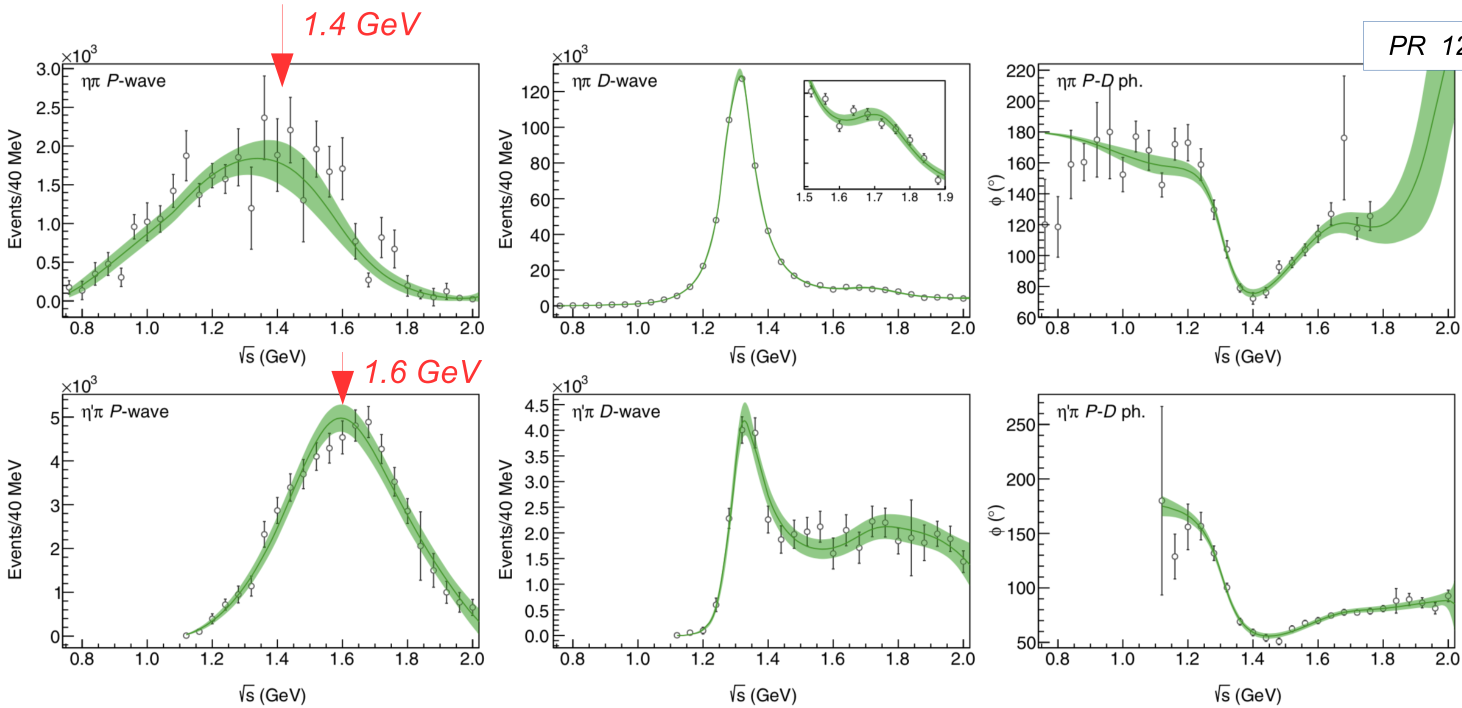
- Coupled channel analysis of the 1^{-+} and 2^{++} wave in $\pi^- p \rightarrow \pi^- \eta^{(\prime)} p$
- 2 hybrid candidates
  - at around 1.4 GeV only seen in $\pi\,\eta$
  - at around 1.6 GeV seen in $\pi\,\eta'$ but not in $\pi\,\eta$
- Enforcing analyticity and unitarity utilizing N/D method
- Mass shapes and phase shifts between 1^{-+} and 2^{++} are considered
- Decay channels to $\rho\,\pi$, $b_1\,\pi$ or $f_1\,\pi$ not considered



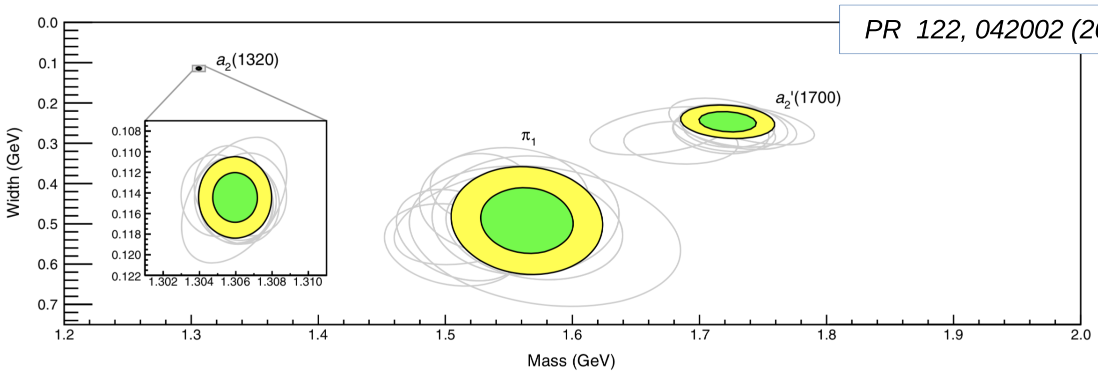




Only one 1^{-+} pole is needed to describe the peaks at 1.4 GeV in $\pi\,\eta$ and at 1.6 GeV in $\pi\,\eta'$



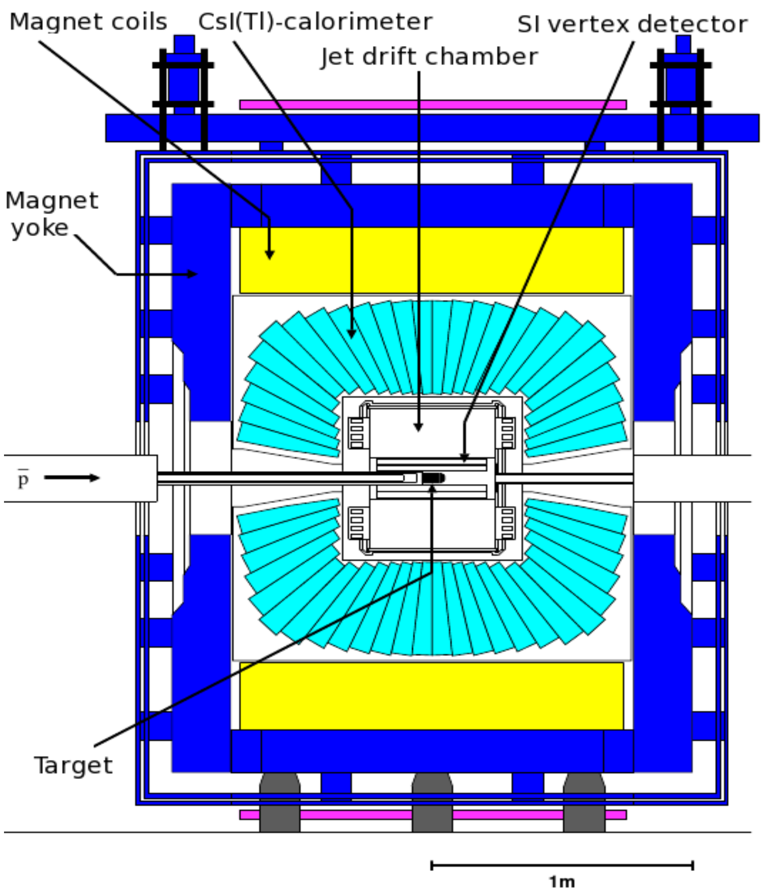
PR 122, 042002 (2019)



PR 122, 042002 (2019)

PWA with p̄p Data from Crystal Barrel at LEAR

- Fixed target experiment at CERN
- In operation between 1989 and 1996
  - leading p̄p-experiment in the field of light meson spectroscopy
- p̄p annihilation at rest and in flight
  - highest beam momentum 1.94 GeV/c



Eur. Phys. J. C (2020) 80:453

Coupled channel analysis of $\bar{p}p \rightarrow \pi^0\pi^0\eta, \pi^0\eta\eta$ and $K^+K^-\pi^0$ at 900 MeV/c and of $\pi\pi$-scattering data

The Crystal Barrel Collaboration

M. Albrecht[1], C. Amsler[4,5], W. Dünnweber[3], M. A. Faessler[3], F. H. Heinsius[1], H. Koch[1], B. Kopf[1,a], U. Kurilla[1,6], C. A. Meyer[2], K. Peters[1,6], J. Pychy[1], X. Qin[1], M. Steinke[1], U. Wiedner[1]

Motivation: $\bar{p}p \rightarrow K^+ K^- \pi^0, \pi^0 \pi^0 \eta, \pi^0 \eta \eta$

Why $\bar{p}p \rightarrow K^+ K^- \pi^0, \pi^0 \pi^0 \eta, \pi^0 \eta \eta$?

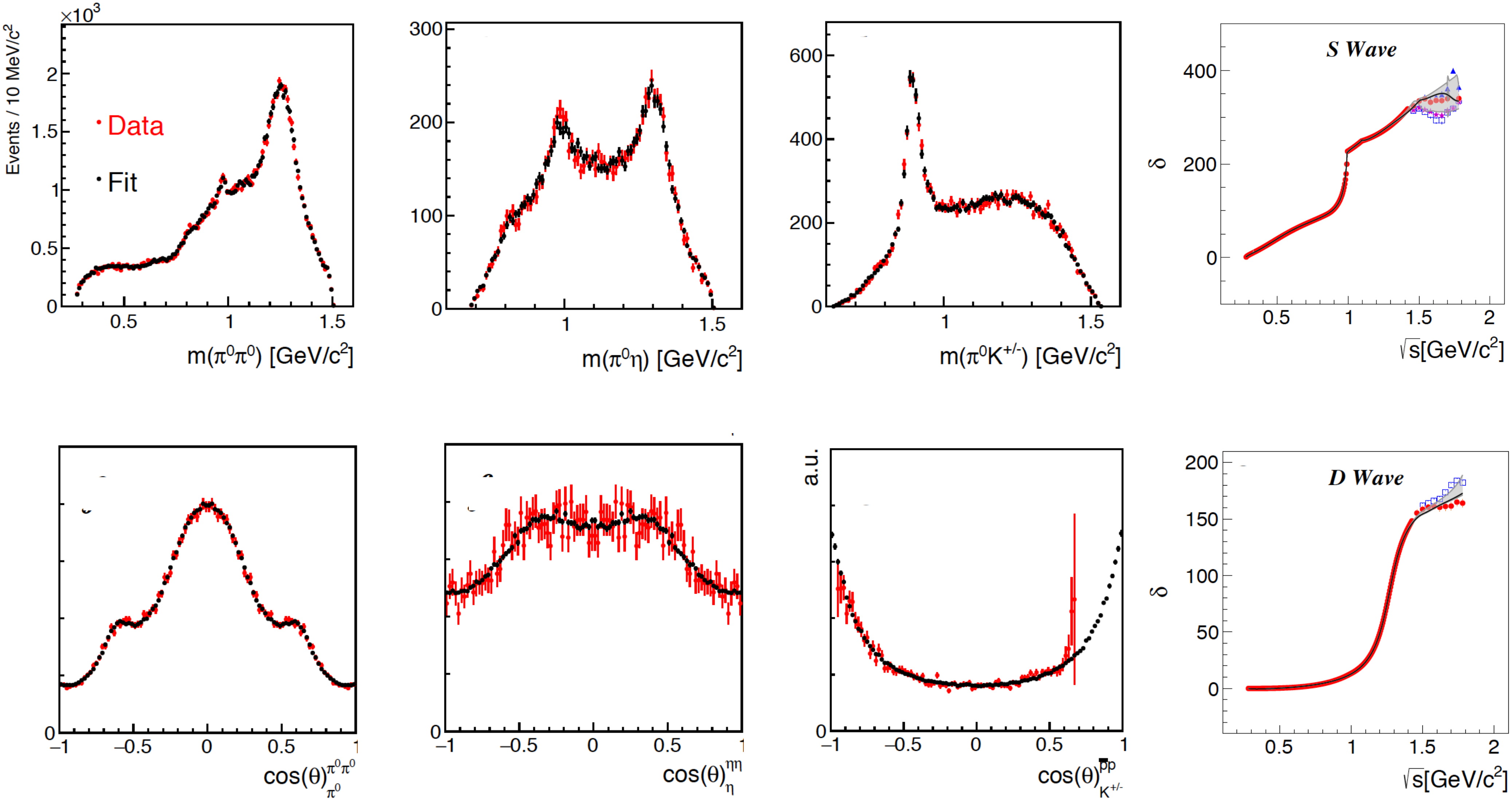
- Many a_0, a_2, f_0 and f_2 resonances appear in two or all three channels
  - constraints due to common production amplitudes
  - description of the dynamics via K-matrix (unitarity and analyticity)
- Exotic spin wave $\pi_1(1400) \rightarrow \pi\,\eta$ so far only seen in $\bar{p}p$ data at rest
  - also visible in $\bar{p}p$ data in flight @ 900 MeV/c beam momentum?

Why scattering data?

- Processes only characterized by elasticity and phase motion
  $\rightarrow$ good and easy access to resonance properties
- Considered for I=0 S- and D-wave and I=1 P-wave
- Good constraints for f_0, f_2 and ρ resonances

Some Fit Results

$\pi^0 \pi^0 \eta$ | $\pi^0 \eta \eta$ | $K^+ K^- \pi^0$ | $\pi\pi$ scattering data



Extracted Resonance Properties

name	relevant data	Breit-Wigner mass [MeV/c^2]	Breit-Wigner width Γ [MeV]
$K^*(892)$	$\bar{p}p$	$892.2 \pm 0.5 \pm 1.7$	$54.4 \pm 0.9 \pm 1.7$
$\phi(1020)$	$\bar{p}p$	$1018.4 \pm 0.5 \pm 0.1$	4.2 (fixed)

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]
π_1	$\bar{p}p$	$1404.7 \pm 3.5\,^{+15.1}_{-17.7}$	$628.3 \pm 27.1\,^{+35.8}_{-138.2}$
$f_0(500)$	scat	$857.0 \pm 5.7 \pm 366.4$	$771.6 \pm 8.3 \pm 291.1$
$f_0(980)^{---++}$	scat	$977.8 \pm 0.6 \pm 1.6$	$97.8 \pm 1.2 \pm 5.4$
$f_0(980)^{--+++}$	scat	$992.8 \pm 0.8 \pm 1.0$	$61.3 \pm 1.3 \pm 4.4$
$f_0(1370)$	scat	$1280.6 \pm 1.6 \pm 47.4$	$410.5 \pm 3.5 \pm 41.5$
$f_0(1500)$	$\bar{p}p$ + scat	$1496.0 \pm 1.2\,^{+4.4}_{-26.4}$	$80.8 \pm 0.6\,^{+20.0}_{-5.0}$
$f_0(1710)$	$\bar{p}p$ + scat	$1803.5 \pm 3.5\,^{+45.5}_{-10.4}$	$289.7 \pm 5.0\,^{+32.6}_{-19.3}$
$f_2(1810)$	scat	$1845.0 \pm 2.2\,^{+1.6}_{-7.2}$	$260.9 \pm 3.9\,^{+199.9}_{-38.2}$
$f_2(1950)$	scat	$1978.2 \pm 1.8\,^{+28.4}_{-16.9}$	$237.6 \pm 1.6\,^{+41.6}_{-15.5}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\eta\pi^0}$ [%]
$a_0(980)^{--}$	$\bar{p}p$	$1002.4 \pm 1.4 \pm 6.6$	$127.0 \pm 2.3 \pm 6.7$	$14.9 \pm 0.1 \pm 3.9$
$a_0(980)^{-+}$	$\bar{p}p$	$1004.1 \pm 1.5 \pm 6.5$	$97.2 \pm 1.9 \pm 5.7$	$13.8 \pm 0.1 \pm 3.5$
$a_0(1450)$	$\bar{p}p$	$1302.1 \pm 1.1 \pm 3.9$	$112.4 \pm 1.4 \pm 3.4$	$188.7 \pm 4.1 \pm 97.0$
$a_2(1320)$	$\bar{p}p$	$1312.5 \pm 0.7 \pm 2.6$	$106.9 \pm 1.2 \pm 3.7$	$35.2 \pm 1.1 \pm 17.5$
$a_2(1700)$	$\bar{p}p$	$1638.9 \pm 2.3\,^{+57.4}_{-0.1}$	$224.0 \pm 2.5\,^{+1.8}_{-48.3}$	$413.4 \pm 10.6\,^{+490.9}_{-298.8}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{\pi\pi}/\Gamma$ [%]	Γ_{KK}/Γ [%]	$\Gamma_{\eta\eta}/\Gamma$ [%]
$f_2(1270)$	$\bar{p}p$ + scat	$1263.3 \pm 0.2 \pm 1.5$	$193.7 \pm 0.4 \pm 1.6$	$85.6 \pm 0.1 \pm 5.0$	$3.3 \pm 0.1 \pm 0.5$	$0.4 \pm 0.1 \pm 0.2$
$f_2'(1525)$	$\bar{p}p$ + scat	$1495.0 \pm 1.1 \pm 8.1$	$104.8 \pm 0.9 \pm 9.8$	$3.4 \pm 1.5 \pm 1.0$	$74.6 \pm 0.2 \pm 16.6$	$5.9 \pm 0.3 \pm 2.6$
$\rho(770)$	scat	$766.8 \pm 0.2 \pm 0.2$	$126.2 \pm 0.3 \pm 0.4$	$100.5 \pm 0.1 \pm 6.7$	$0.5 \pm 0.1 \pm 0.1$	-
$\rho(1700)$	$\bar{p}p$ + scat	$1688.7 \pm 3.1\,^{+141.1}_{-1.3}$	$150.9 \pm 2.5\,^{+60.0}_{-10.6}$	$10.8 \pm 1.7\,^{+16.2}_{-0.4}$	$0.7 \pm 0.6\,^{+4.1}_{-0.2}$	-

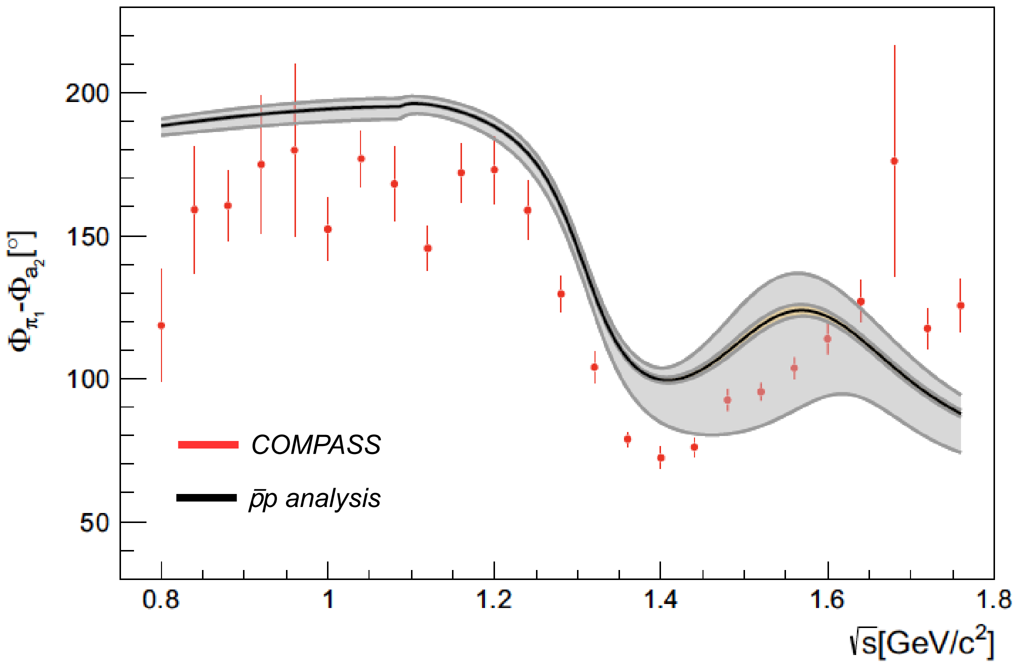
More than 50 different resonance properties extracted on the relevant Riemann-sheets

All obtained properties are within the ballpark of other measurements

1^{-+} Wave in $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$

- 1^{-+} wave seen in the decay $\pi^0\eta$
- Phase difference between the π_1 and a_2 wave from $T_{\pi\eta\rightarrow\pi\eta}$ in good agreement with COMPASS measurement
- Pole position of the π_1: $M = (1404.7 \pm 3.5\ (\text{stat.})\ ^{+9.0}_{-17.3}\ (\text{sys.}))\ \text{MeV}/c^2$

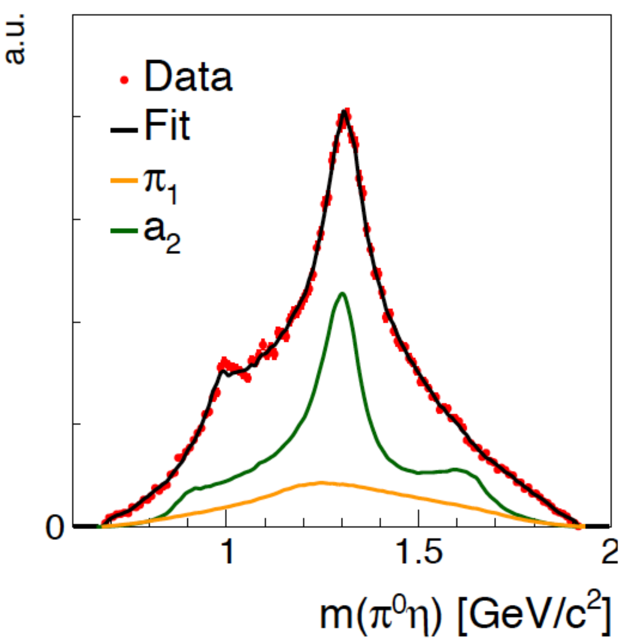
  $\Gamma = (628.3 \pm 27.1\ (\text{stat.})\ ^{+35.8}_{-138.2}\ (\text{sys.}))\ \text{MeV}$



Coupled Channel Analysis with $\bar{p}p$ and COMPASS Data

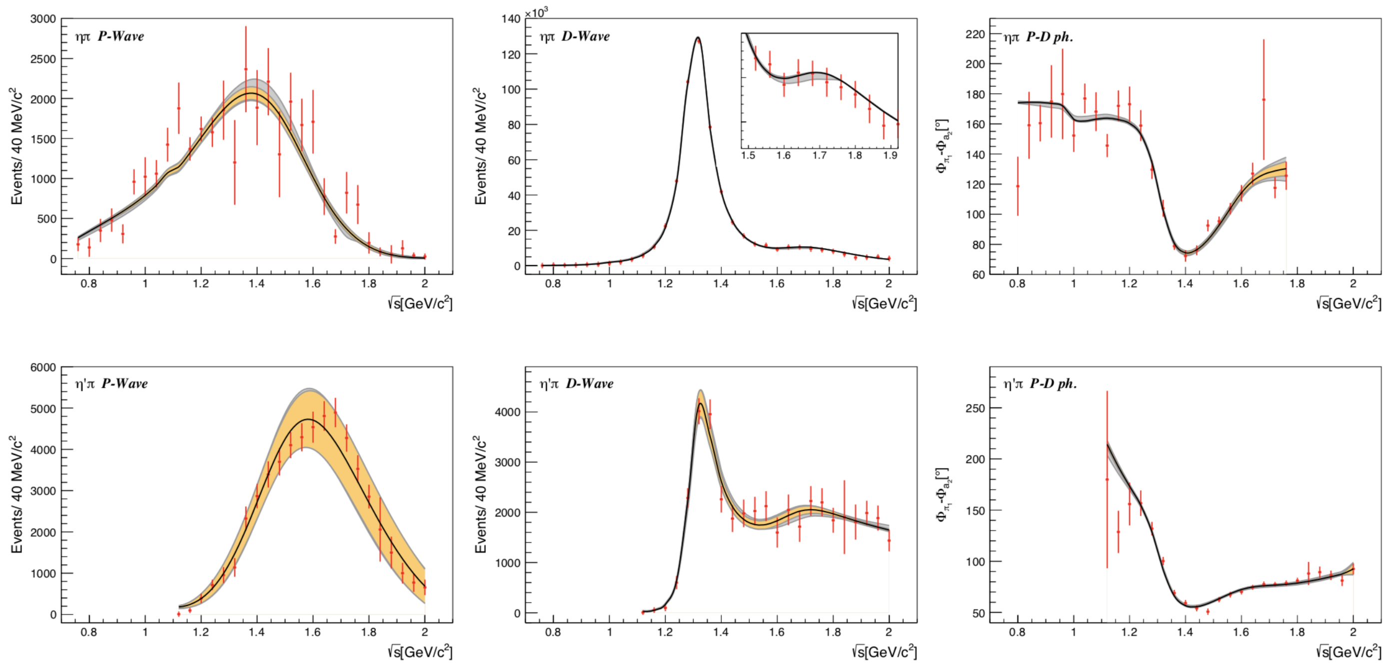
- Extension: simultaneous fit of $\pi\pi$-scattering data, $\bar{p}p \to K^+ K^- \pi^0$, $\pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $\pi^- p \to \pi^- \eta^{(\prime)} p$
- Good description with one pole scenario for the 1^{-+} wave
- Still under investigation

$\bar{p}p \to \pi^0 \pi^0 \eta$



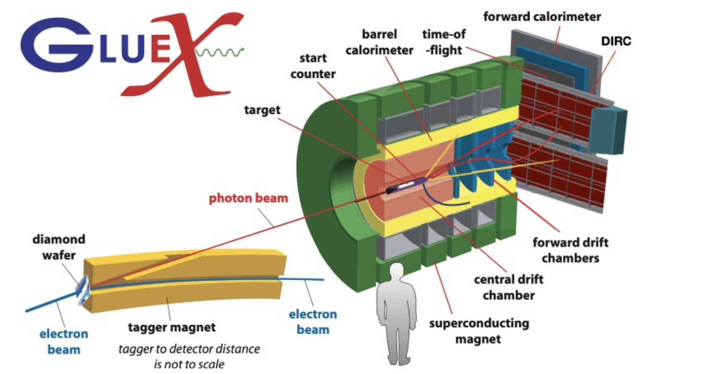
$\pi^- p \to \pi^- \eta^{(\prime)} p$

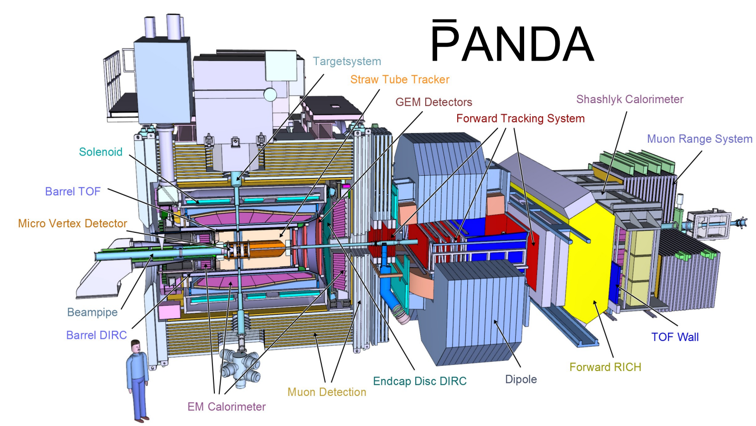
arXiv: 2008.11566 [hep-ph]



Perspectives

- GlueX
  - study of light mesons up to 3 GeV in photoproduction
  - search for hybrid states
- BELLE II
  - high statistics $\gamma\gamma$ data
- New J/ψ data at BESIII
  - ~ 10 billion decays have been recorded
  - new insight in particular for radiative decays
- LHCb
  - $B_{(s)}$ decays
- $\bar{P}$ANDA at FAIR
  - $\bar{p}p$ annihilations from 1.5 - 15 GeV/c
  - cover lack of data close to and above the $\bar{p}p$ threshold
- $\bar{p}$ physics with COMPASS++ / AMBER
- K_L facility at Jefferson Lab





Summary

- Many new insights have been gained in the last decades
- Still many unresolved questions in the light meson region
- Many broad and overlapping resonances with the same quantum numbers
- Mixtures between conventional $q\bar{q}$ and exotic states possible
- Access to the inner structure by investigating the different production processes and decay modes
- Sophisticated analysis methods are needed for the proper extraction of resonance properties e.g.
  - JPAC analysis of the spin exotic 1^{-+} wave: peak at 1.4 GeV in $\pi\eta$ and at 1.6 GeV in $\pi\eta'$ can be described by one pole
  - coupled channels analysis with $\bar{p}p$ annihilation and $\pi\pi$ scattering data
- New experiments and high statistics data important to shed more light on the still unresolved questions in the light meson region