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RUB

The light meson regime from coupled-channel analyses

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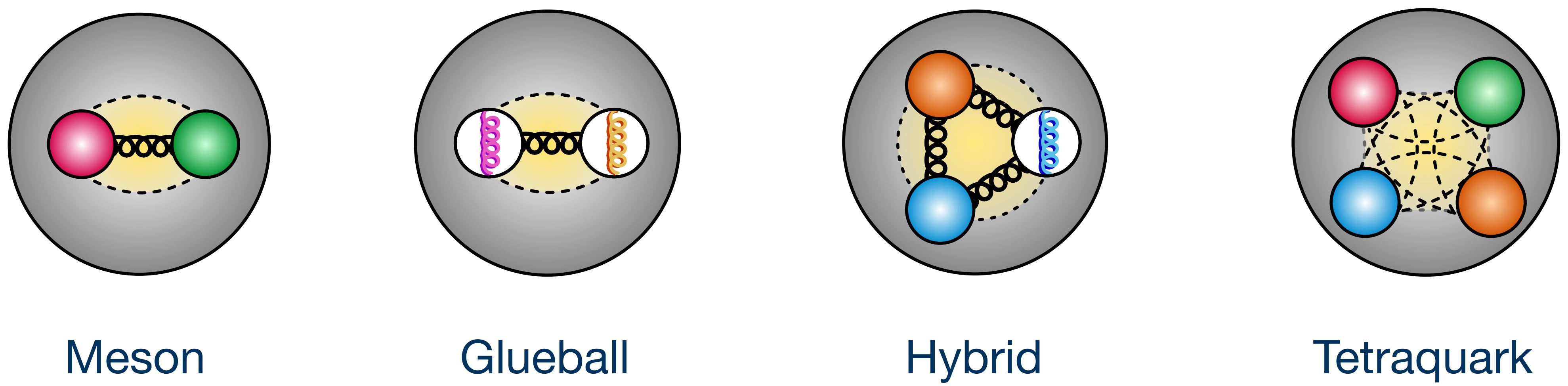
On behalf of the BESIII collaboration

Light Meson Regime

- Light mesons are tricky to tackle for both theory and experiment
- Highly populated spectrum: many overlapping, interfering, mixing or distorted states
- Some of the light mesons most likely have a more complex inner structure
- Easy identification through exotic q.n. but this rarely the case



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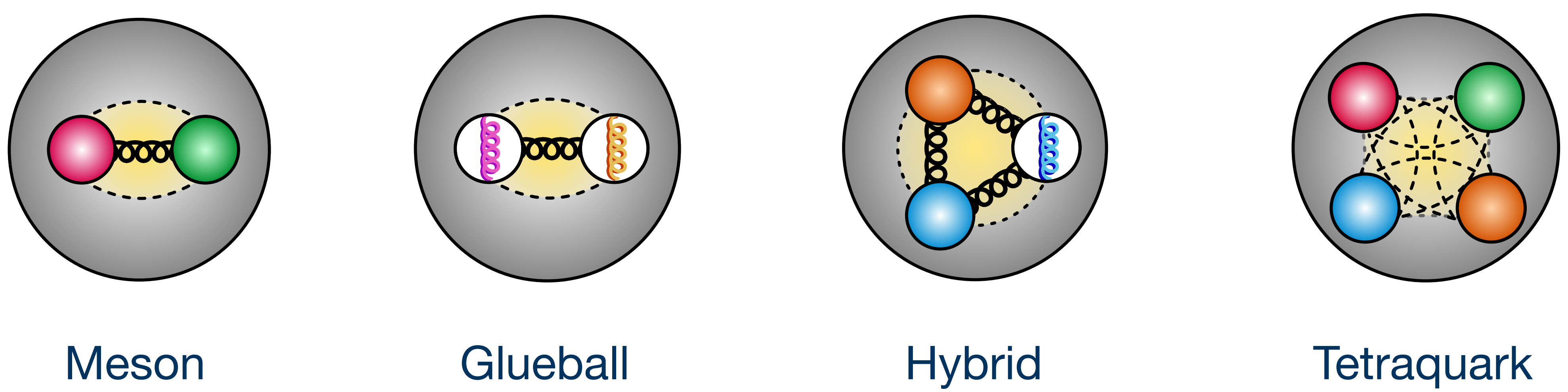


Combine different production mechanisms and decay channels to reveal a particle's nature

Experimental Possibilities

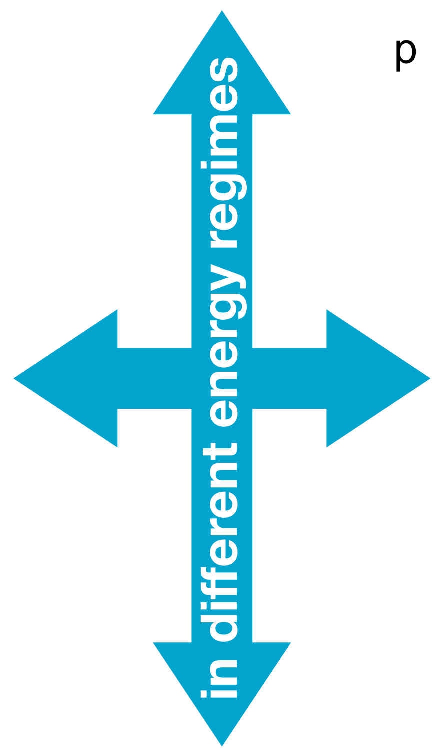
- Each experiment, detector and process has its own advantages
- To tackle these challenges ➡ combine forces!

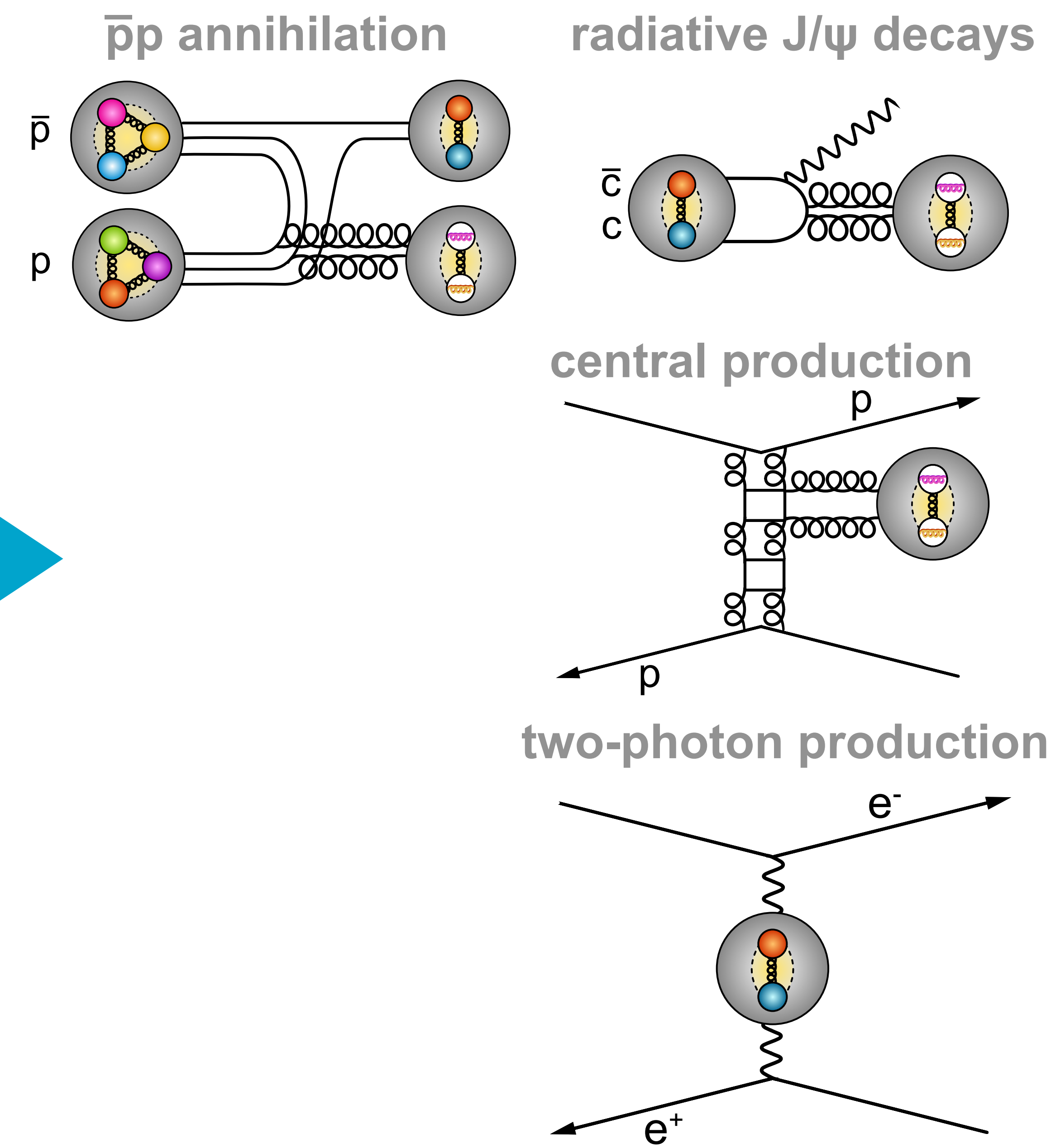
Gluon rich processes

- Radiative charmonium decays
- p̄p annihilation
- pp central production
- …

QED mediated process

- Two-photon production

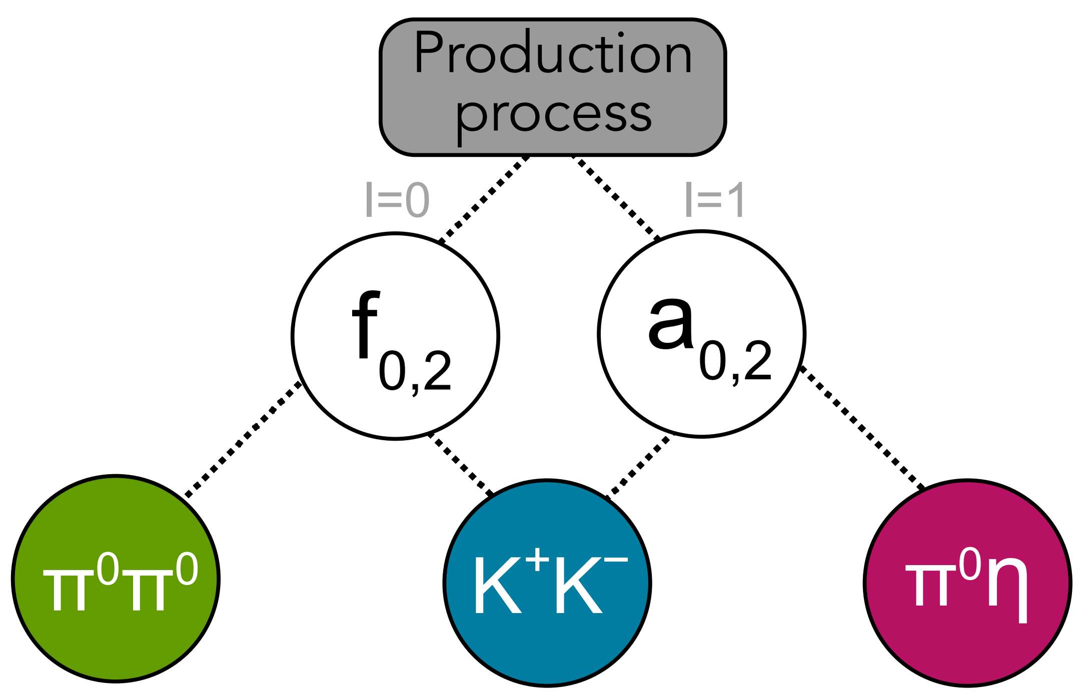




Why Coupled Channel Approach?

Advantages compared to single channel fits:

- More constraints due to common amplitudes and shared parameters
- Conservation of unitarity by using sophisticated models as e.g. K-matrix, N/D, …
- Better description of threshold effects
- Multiple resonances directly measurable in one analysis
- Proper determination of pole parameters and coupling strengths



One Prominent Example: The Lightest Hybrid Candidate

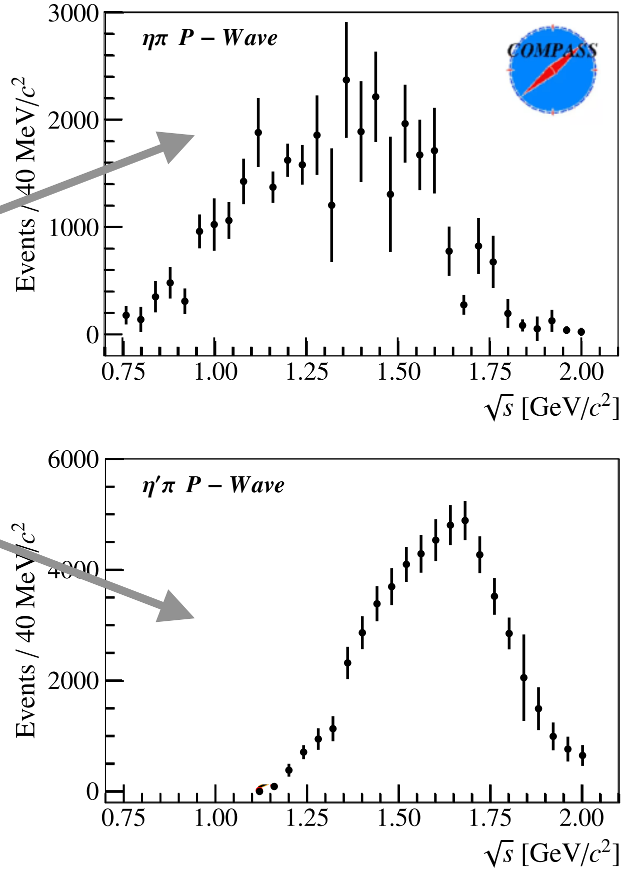
Two π_1 hybrid candidates below 2 GeV are listed in PDG

- one at around 1.4 GeV only seen in $\pi\eta$
- the other at around 1.6 GeV seen in $\pi\eta'$ but not in $\pi\eta$

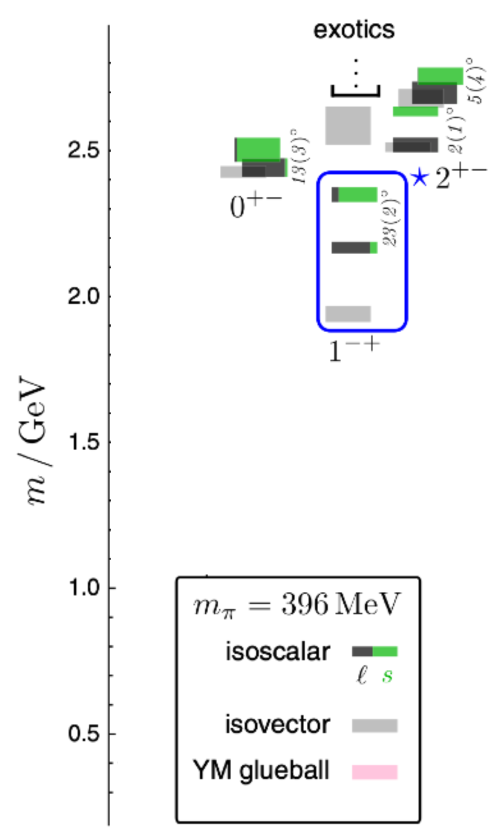
➡ Parameters obtained by Breit-Wigner fits!

➡ Theory: Only one π_1 state predicted slightly below 2 GeV

200 MeV apart!

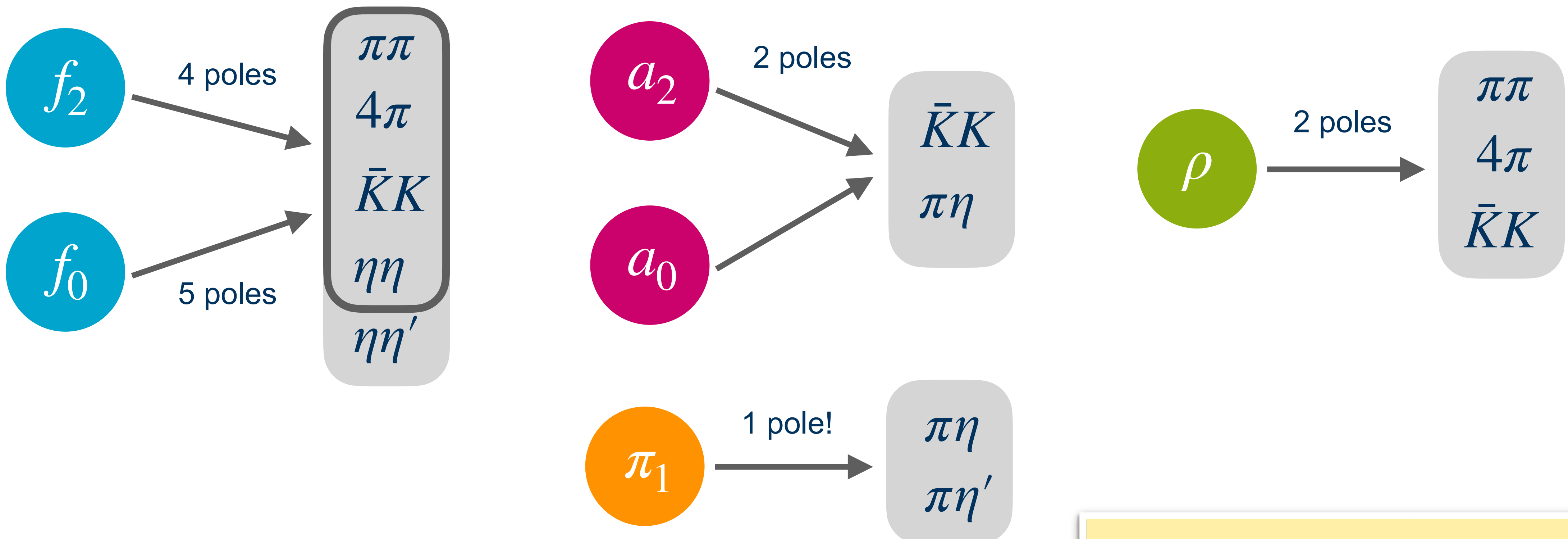


Phys.Rev. D84 (2011) 074023



Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

- Combining data from different experiments:
- $\bar{p}p \rightarrow \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$ data in flight form Crystal Barrel at LEAR
- COMPASS data of P- and D-waves in the $\pi\eta$ and $\pi\eta'$ systems
- 11 different $\pi\pi$ scattering data samples
- Simultaneously described using the K-Matrix formalism in the P-vector approach
- The whole process from the initial to the final state is described in all phase space dimensions



Eur. Phys. J. C (2021) 81, 1056

Why scattering data?

- Scattering processes only characterized by inelasticities and phase motions
  ➡ „Easy" access to resonance parameters
- Quite pure and simple reaction
- Known well from experiments from 80s and theory!!
  Phys. Rep. 969 (2022) 1–126, Phys. Rev. D 83, 074004 (2011)

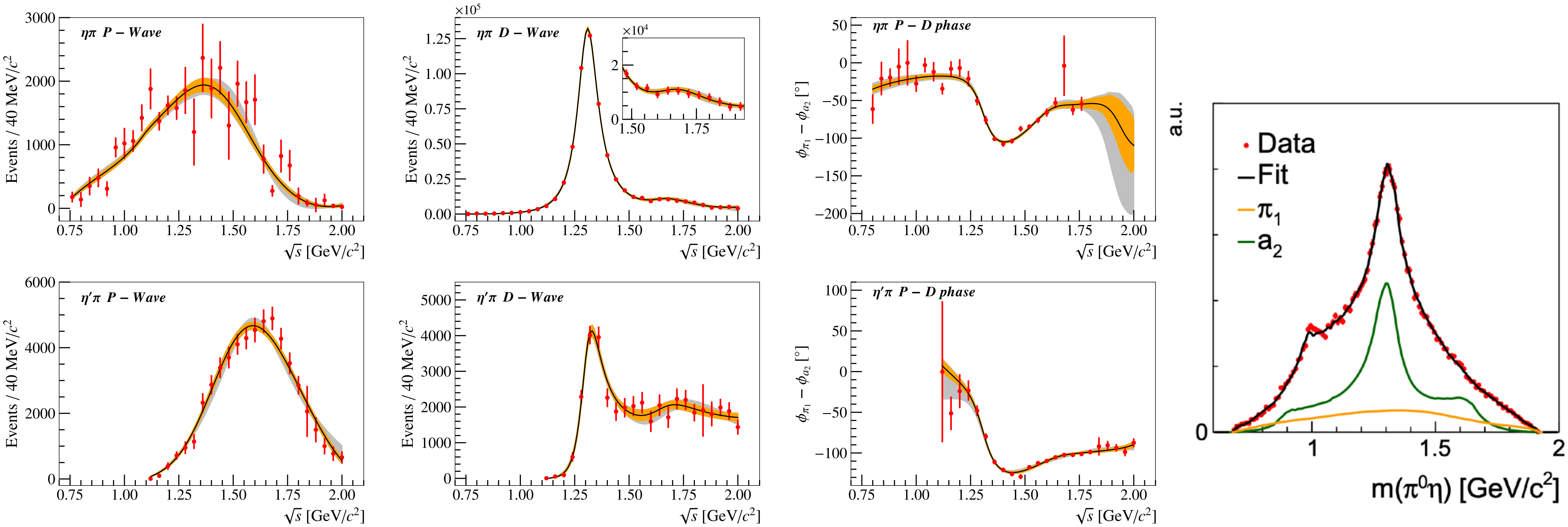
- Good constraints for f_0, f_2 and ρ resonances
- All dispersive relations are fulfilled automatically!

But: All this relies on data from $KN \rightarrow K\pi N'$ reactions from 70s and 80s!
Would be nice to have some new data on this

Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

Eur. Phys. J. C (2021) 81, 1056

- Exotic π_1 wave significantly contributing in the $\pi^0\eta$ system!
- Description with one pole possible!
- ➡ Confirmation of the JPAC analysis based on N/D-method Phys. Rev. Lett. 122 (2019) 4, 042002

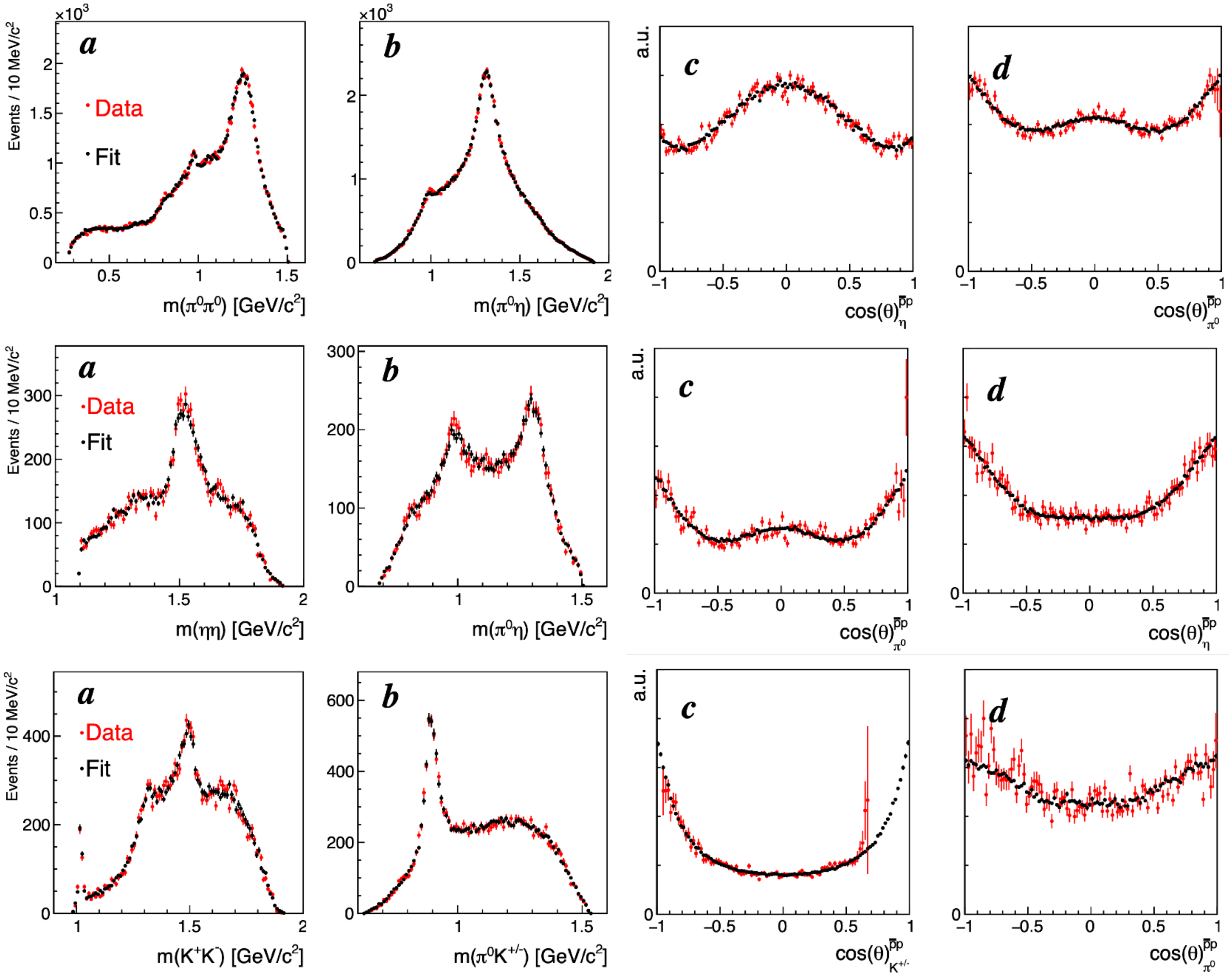


Obtained pole position:

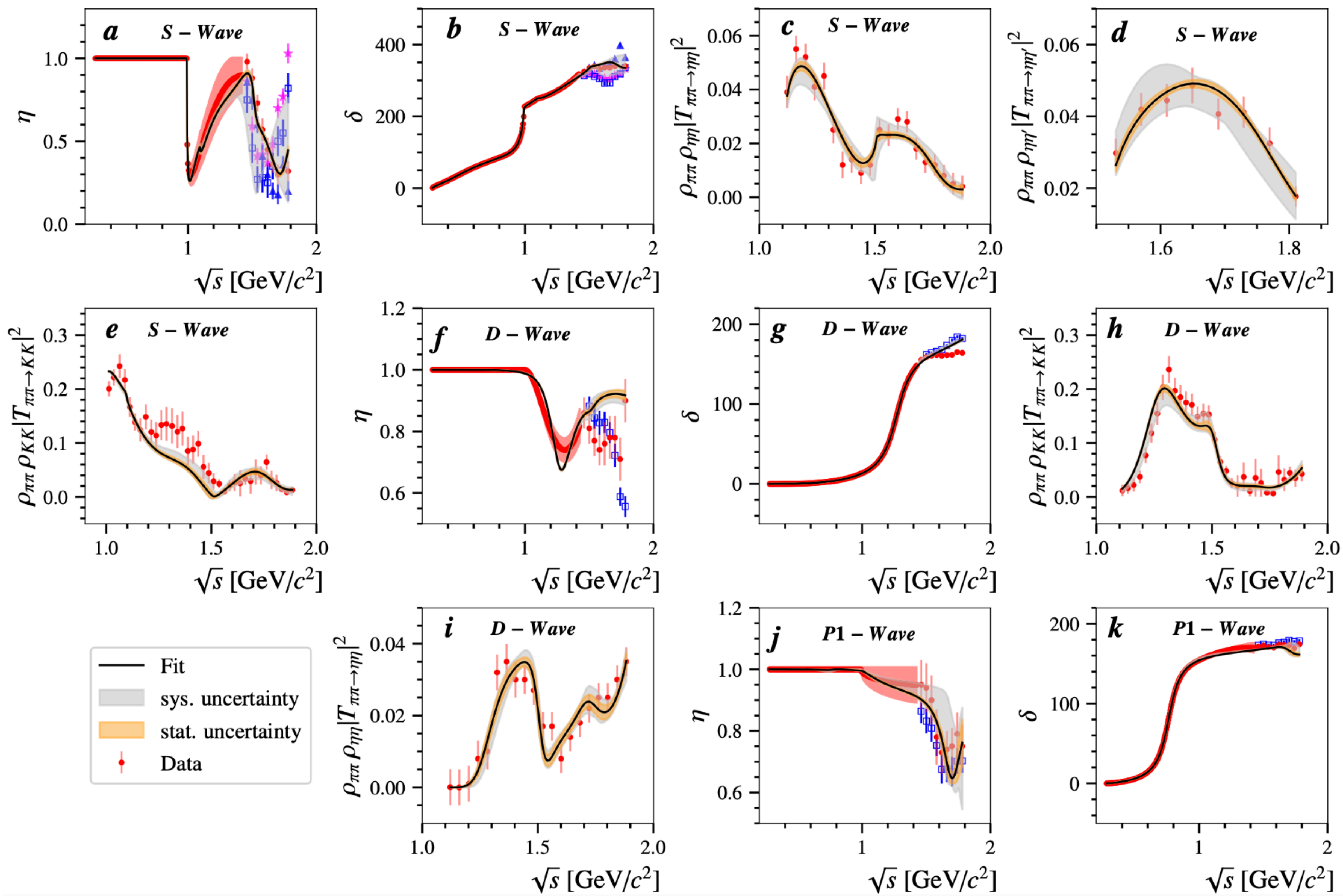
$$M = 1623 \pm 47^{+24}_{-75}\ \mathrm{MeV}/c^2$$
$$\Gamma = 455 \pm 88^{+144}_{-175}\ \mathrm{MeV}$$

$$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta} = 5.54 \pm 1.10^{+1.80}_{-0.27}$$

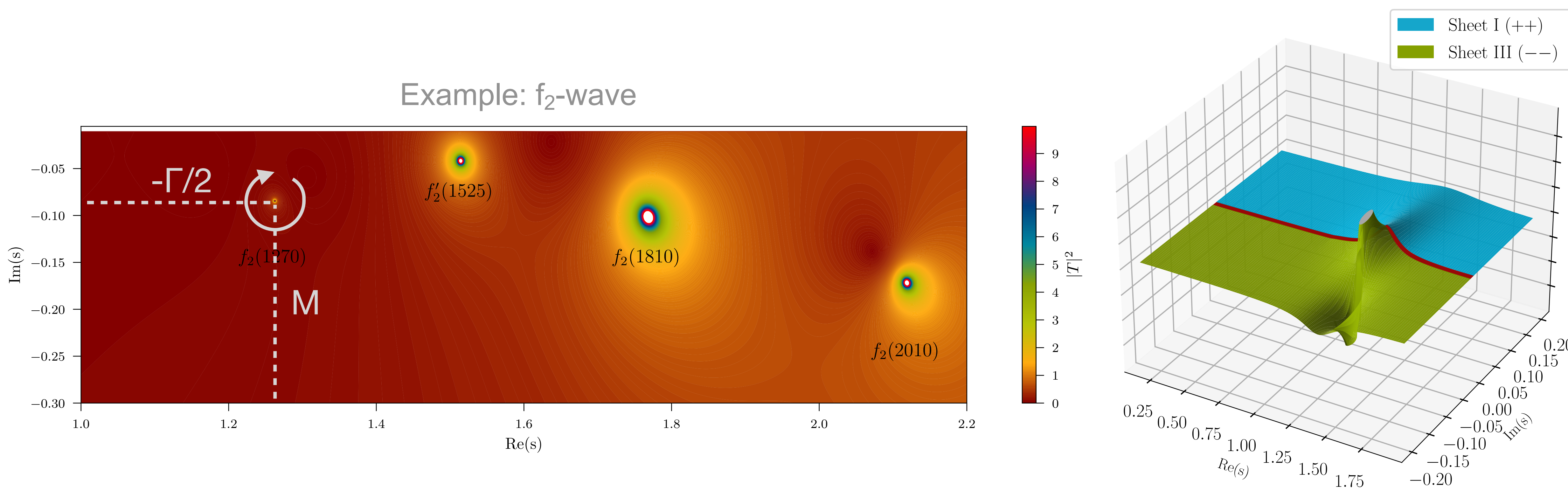
Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$



Simultaneous Description of Scattering Data



Extraction of Resonance Properties



- K-matrix and thus the pole itself contain all resonance properties
- Masses and widths defined by the pole position in the complex energy plane of the T-matrix sheet closest to the physical sheet

$$Res^{\alpha}_{k\to k} = \frac{1}{2\pi i}\oint_{C_{z_\alpha}} \sqrt{\rho_k}\cdot T_{k\to k}(z)\cdot\sqrt{\rho_k}\ \mathrm{d}z$$

Coupled Channel Analysis of p̄p and COMPASS Data

name	relevant data	Breit-Wigner mass [MeV/c^2]	Breit-Wigner width Γ [MeV]
$K^*(892)^\pm$	$\bar{p}p$	893.8 ± 1.0± 0.8	56.3 ± 2.0± 1.0
$\phi(1020)$	$\bar{p}p$	1018.4 ± 0.5± 0.2	4.2 (fixed)

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]
$f_0(980)^{---++}$	scat	977.8 ± 0.6± 1.4	98.8 ± 6.6± 11.2
$f_0(980)^{--+++}$	scat	992.6 ± 0.3± 0.5	61.2 ± 1.2± 1.7
$f_0(1370)$	scat	1281 ± 11 ± 26	410 ± 12± 50
$f_0(1500)$	$\bar{p}p$ + scat	$1511.0 \pm 8.5\,^{+3.5}_{-14.0}$	$81.1 \pm 4.5\,^{+26.9}_{-0.5}$
$f_0(1710)$	$\bar{p}p$ + scat	$1794.3 \pm 6.1\,^{+47.0}_{-61.2}$	$281 \pm 32\,^{+12}_{-80}$
$f_2(1810)$	scat	$1769 \pm 26\,^{+3}_{-26}$	$201 \pm 57\,^{+13}_{-87}$
$f_2(X)$	scat	$2119.9 \pm 6.4\,^{+25.7}_{-1.1}$	$343 \pm 11\,^{+32}_{-11}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ [%]
π_1	$\bar{p}p + \pi p$	$1623 \pm 47\,^{+24}_{-75}$	$455 \pm 88\,^{+144}_{-175}$	$554 \pm 110\,^{+180}_{-27}$

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\pi\eta}$ [%]
$a_0(980)^{--}$	$\bar{p}p$	1002.7 ± 8.8± 4.2	132 ± 11± 8	14.8 ± 7.1± 3.6
$a_0(980)^{-+}$	$\bar{p}p$	1003.3 ± 8.0± 3.7	101.1 ± 7.2± 3.0	13.5 ± 6.2± 3.1
$a_0(1450)$	$\bar{p}p$	1303.0 ± 3.8± 1.9	109.0 ± 5.0± 2.9	396 ± 72± 72

name	relevant data	pole mass [MeV/c^2]	pole width Γ [MeV]	$\Gamma_{KK}/\Gamma_{\pi\eta}$ [%]	$\Gamma_{\pi\eta'}/\Gamma_{\pi\eta}$ [%]
$a_2(1320)$	$\bar{p}p + \pi p$	$1318.7 \pm 1.9\,^{+1.3}_{-1.3}$	$107.5 \pm 4.6\,^{+3.3}_{-1.8}$	$31 \pm 22\,^{+9}_{-11}$	$4.6 \pm 1.5\,^{+7.0}_{-0.6}$
$a_2(1700)$	$\bar{p}p + \pi p$	$1686 \pm 22\,^{+19}_{-7}$	$412 \pm 75\,^{+64}_{-57}$	$2.9 \pm 4.0\,^{+1.1}_{-1.2}$	$3.5 \pm 4.4\,^{+6.9}_{-1.2}$

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	$1262.4 \pm 0.2\,^{+0.2}_{-0.3}$	$168.0 \pm 0.7\,^{+1.7}_{-0.1}$	$87.7 \pm 0.3\,^{+4.8}_{-4.4}$	$2.6 \pm 0.1\,^{+0.1}_{-0.2}$	$0.3 \pm 0.1\,^{+0.0}_{-0.1}$
$f_2'(1525)$	$\bar{p}p$ + scat	$1514.7 \pm 5.2\,^{+0.3}_{-7.4}$	$82.3 \pm 5.2\,^{+11.6}_{-4.5}$	$2.1 \pm 0.3\,^{+0.8}_{-0.0}$	$67.2 \pm 4.2\,^{+5.0}_{-3.8}$	$9.8 \pm 3.8\,^{+1.7}_{-3.3}$
$\rho(1700)$	$\bar{p}p$ + scat	$1700 \pm 27\,^{+13}_{-16}$	$181 \pm 25\,^{+0.0}_{-16}$	$13.6 \pm 1.2\,^{+0.9}_{-0.5}$	$0.8 \pm 0.1\,^{+0.0}_{-0.0}$	-

Several resonance properties measured simultaneously within one fit!

This parameterisation is universal - Can be used in other analyses!

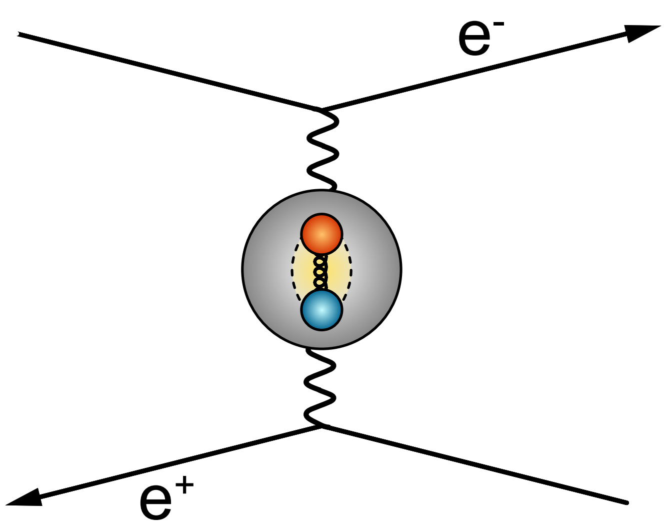
PArtial Wave Interactive ANalysis

Two-Photon Reactions

Idea: Learning More About the Inner Structure

- Clean e.m. process, only sensitive to charge
- Complementary information on glueball candidates!

- States with even C-parity $0^{\pm+}, (1^{\pm+}), 2^{\pm+}, \ldots$ can be directly produced

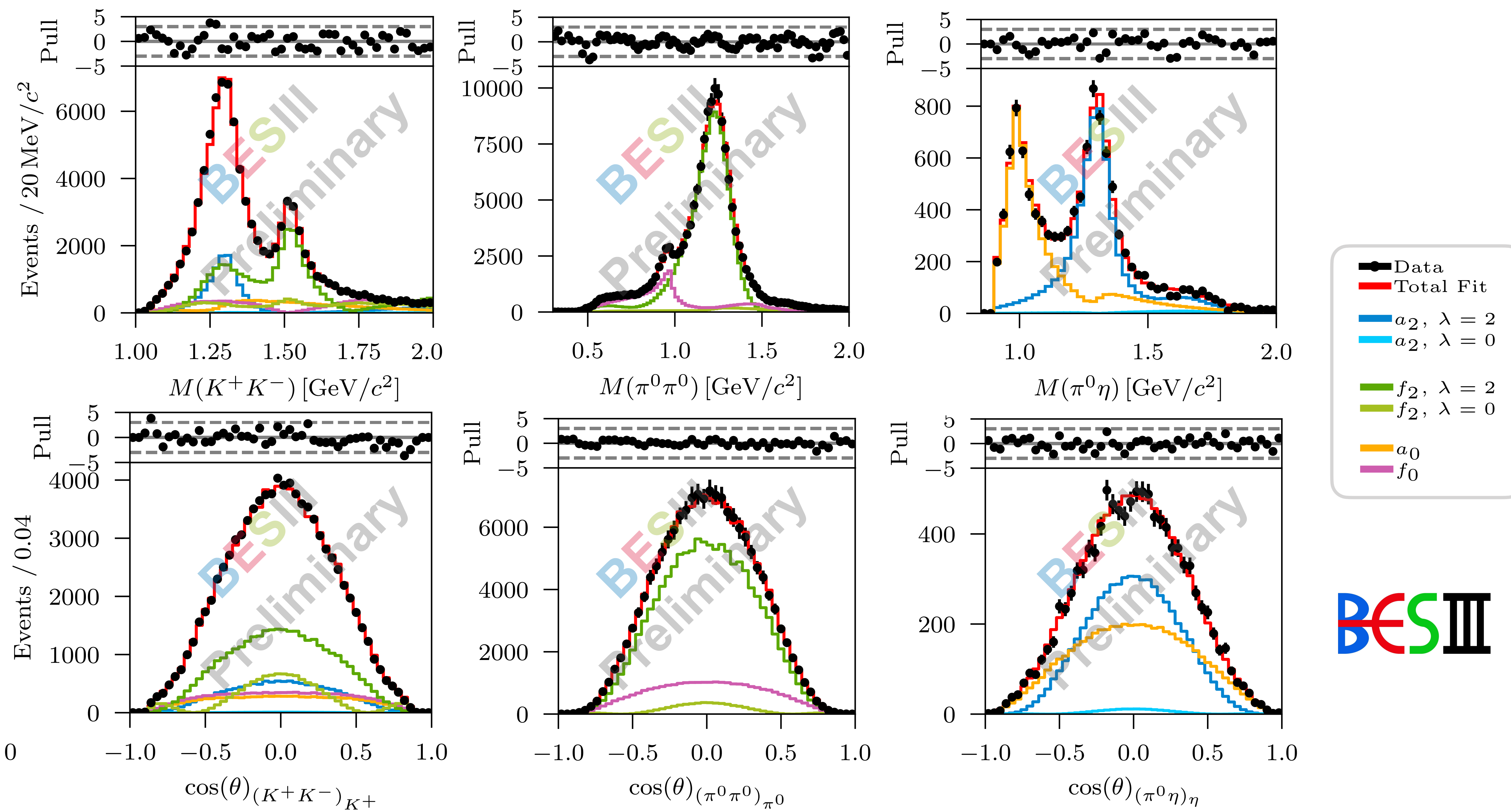


***Untagged reactions*:**

- Scattering angles of electron and positron are small and are not detectable
- Quasi real photons carrying small virtuality ➡ spin 1 strongly suppressed

Coupled Channel Analysis of Two-Photon Data

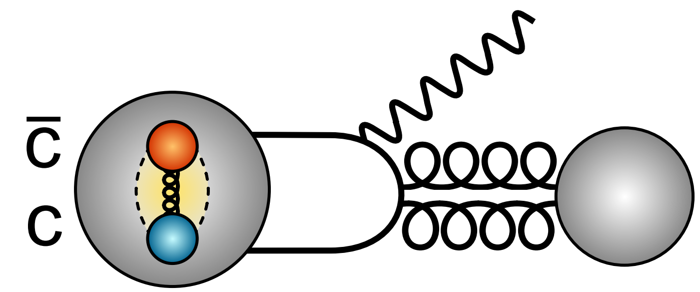
- Using obtained parameterization and fix all pole and decay parameters
- All structures can be well described
- Dominant contribution of $(J, \lambda) = (2{,}2), (0{,}0)$
- Best fit result using all 14 resonances and P-vector background terms: 1. order for f_2, a_2, a_0 -waves

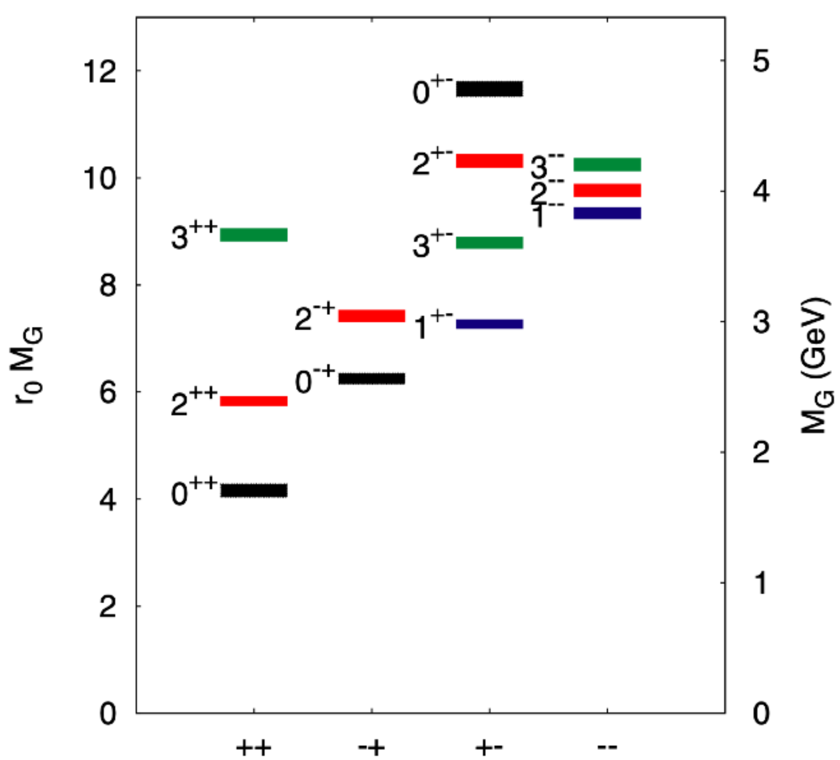


Radiative J/ψ decays

- Gluon-rich process ➡ production of glueballs and hybrids expected

- ***Glueballs Candidates:***
  - Lightest glueball 0^{++} is predicted below $2\,\mathrm{GeV}/c^2$
  - Observed states $f_0(1370), f_0(1500), f_0(1710)$ likely to be mixtures of pure glueball and quark component
  - BESIII has accumulated very high statistics at J/ψ
    - ➡ 50 times more than 10 years ago!
    - ➡ Great opportunities to search for the 0^{++}- and 2^{++} glueball candidates!



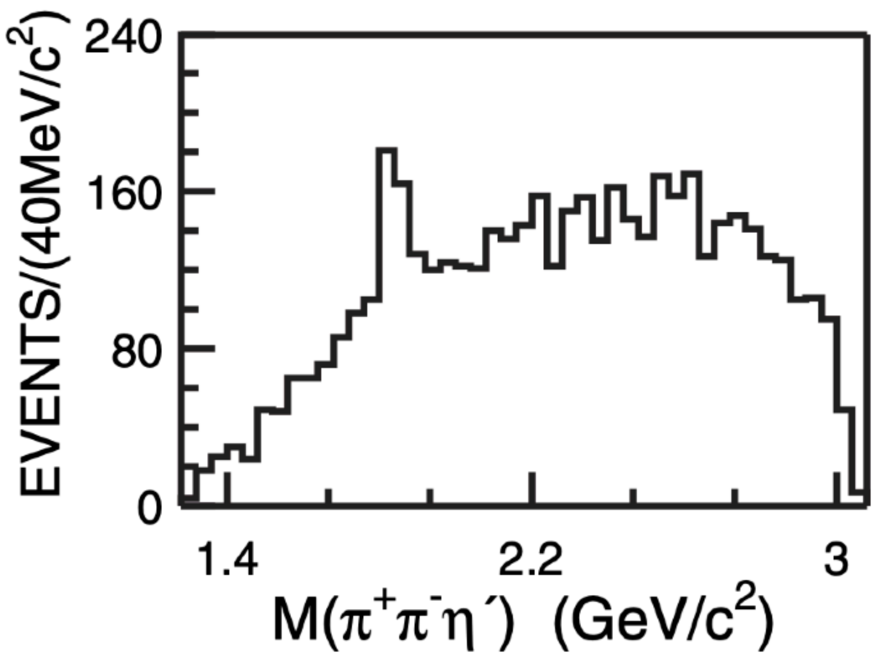


Phys. Rev. D 73, 014516 (2006)

$J/\psi \to \gamma\eta'\pi^+\pi^-$

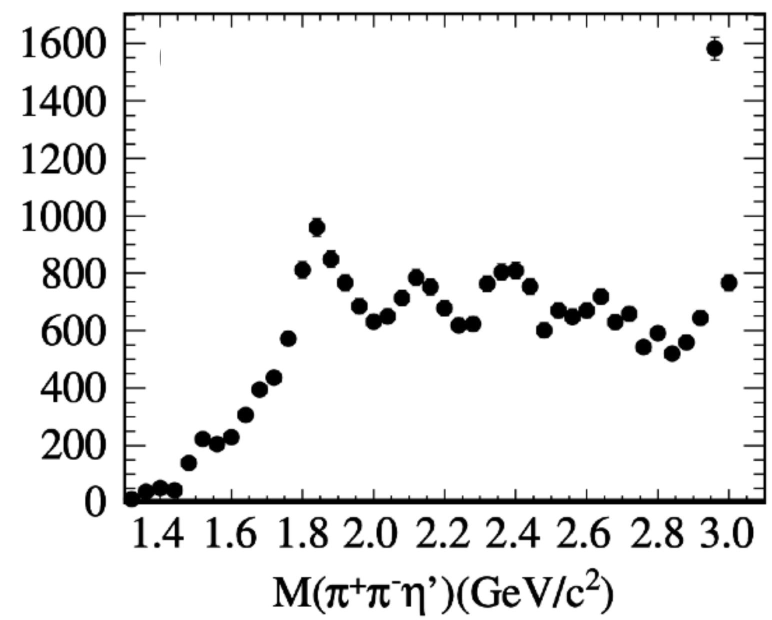
PRL 129, 042001 (2022)

58M J/ψ events



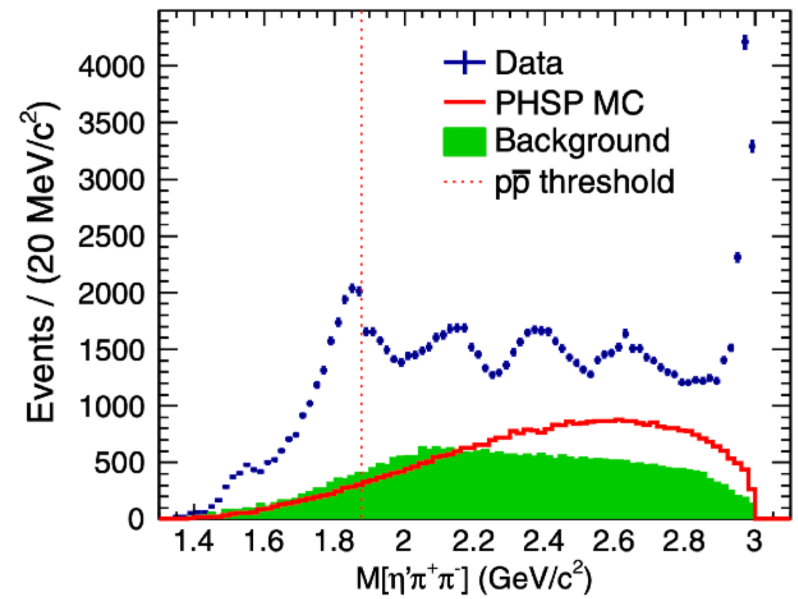
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

1090M J/ψ events



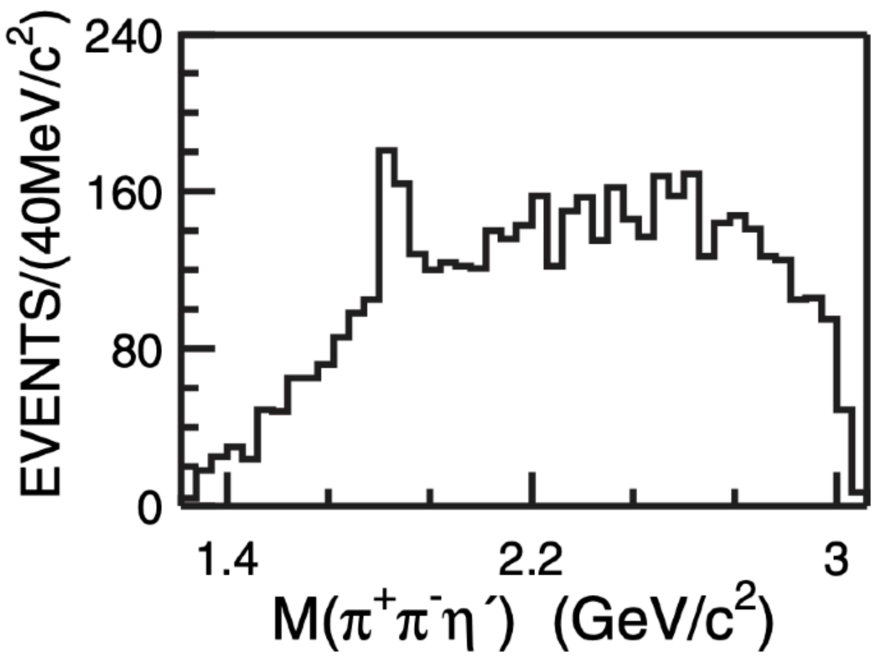
BESIII, PRL 117, 042002 (2016)

- Structure observed near $\bar{p}p$ threshold: $X(1835)$ and two additional states $X(2120)$ and $X(2370)$!
- $X(2370)$ more in the media recently, already seen in:
  - $J/\psi \to \gamma\eta' K\bar{K}$ BESIII, EPJ C80 746 (2020)
  - $J/\psi \to \gamma\eta'\pi^+\pi^-$ BESIII, PRL 106 072002 (2011)
  - Seem to indicate non-negligible $s\bar{s}$ component
  - ➡ Second radial excitation of η' ?

$J/\psi \to \gamma\eta'\pi^+\pi^-$

PRL 129, 042001 (2022)

58M J/ψ events



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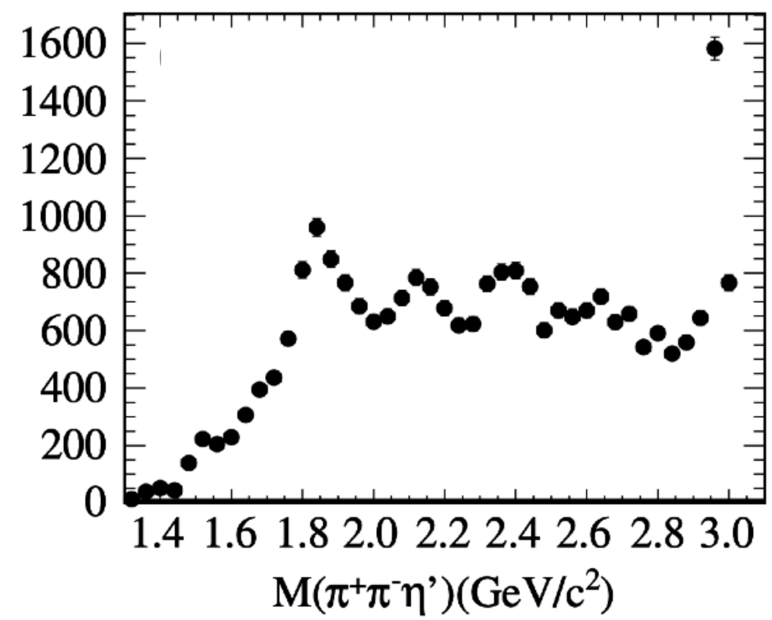

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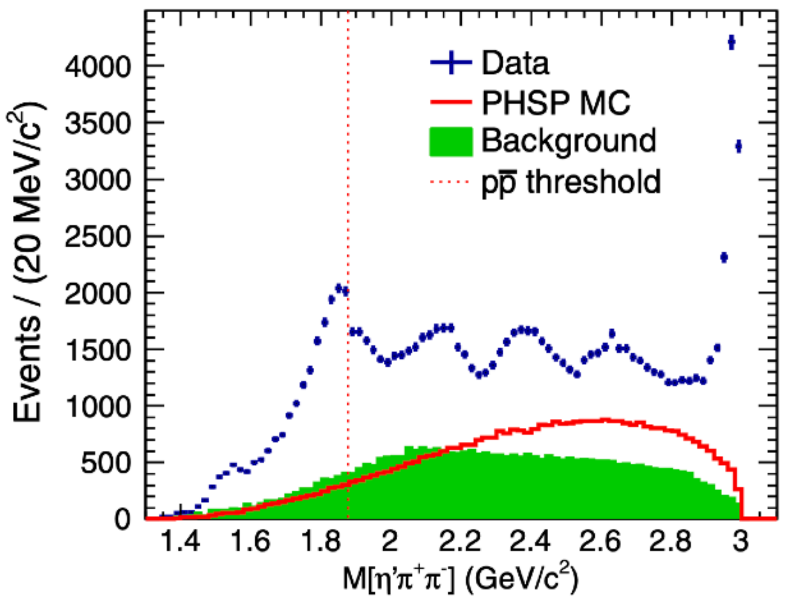
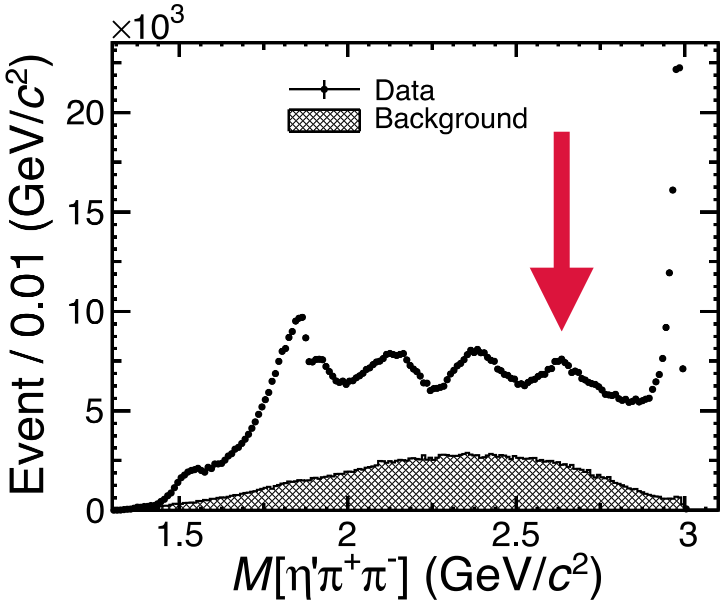


BESIII, PRL 117, 042002 (2016)

New Structure observed!

X(2600)



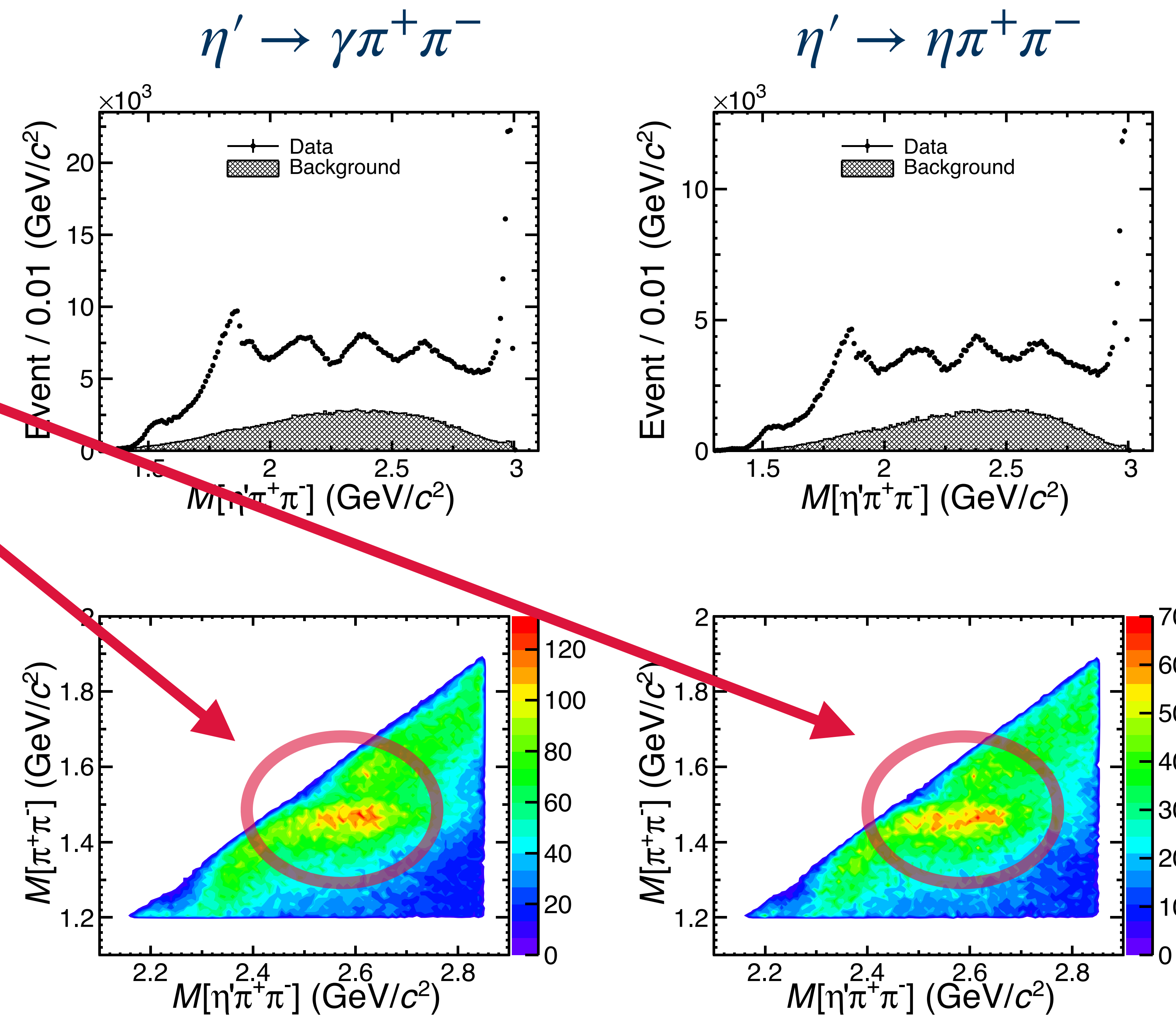
BESIII, PRL 129, 042001 (2022)

10B J/ψ events

$J/\psi \to \gamma\eta'\pi^+\pi^-$

PRL 129, 042001 (2022)

- Likely connected to a non trivial structure at $1500\,\mathrm{MeV}/c^2$ in $\pi^+\pi^-$ system



$J/\psi \to \gamma\eta'\pi^+\pi^-$

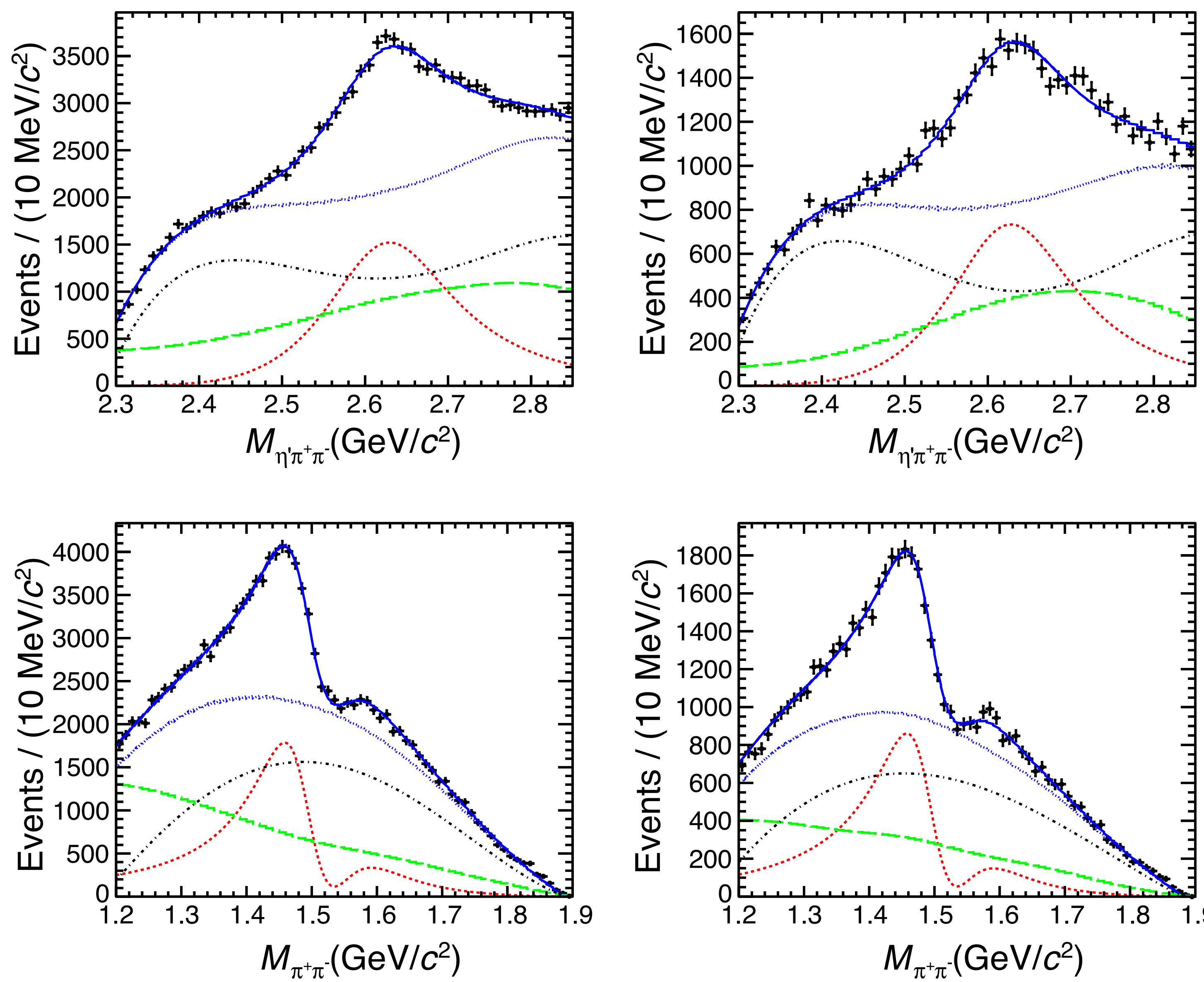
PRL 129, 042001 (2022)

- Likely connected to a non trivial structure at $1500\,\mathrm{MeV}/c^2$ in $\pi^+\pi^-$ system
- Simultaneous fit to $\pi^+\pi^-$ system and $\eta'\pi^+\pi^-$ systems performed
- $\pi^+\pi^-$ system described by $f_0(1500)$ and additional state $X(1540)$

Resonance	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

- Further studies ongoing, full PWA needed…

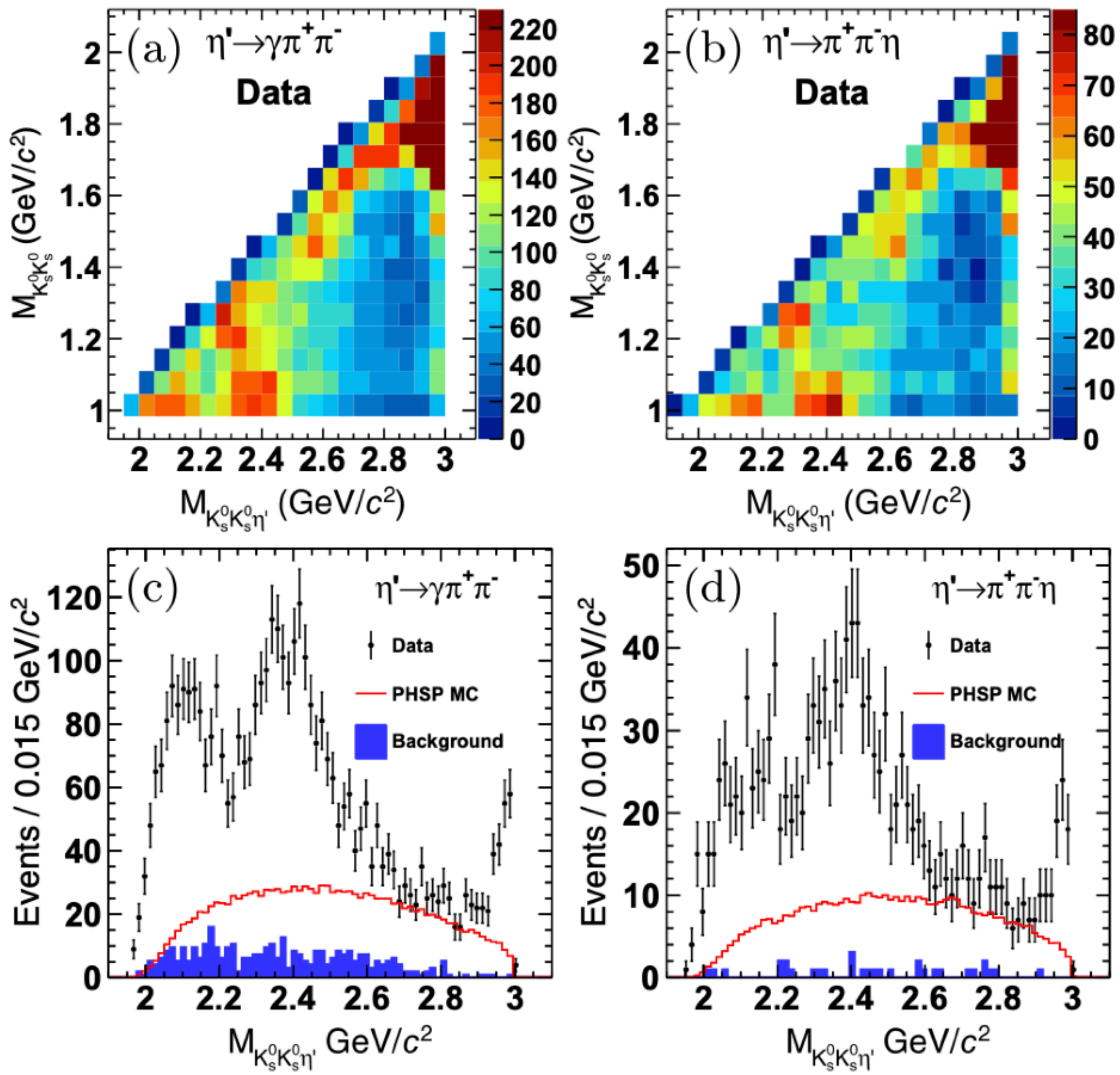
$\eta' \to \gamma\pi^+\pi^-$ $\eta' \to \eta\pi^+\pi^-$



$J/\psi \to \gamma\eta' K_S^0 K_S^0$

PRL 132 181901 (2024)

- Amplitude analysis using covariant tensor formalism including mostly Breit-Wigner line shapes + Flatté for $f_0(980)$
- Spin-parity of $X(2370)$ determined to be 0^{-+}!
- Could be a glueball candidate PRD 100 054511 (2019) but predictions vary strongly…
- Further analyses of other channels will help to learn about sub processes and interplay with $K\bar{K}$ and $\pi^+\pi^-$ system

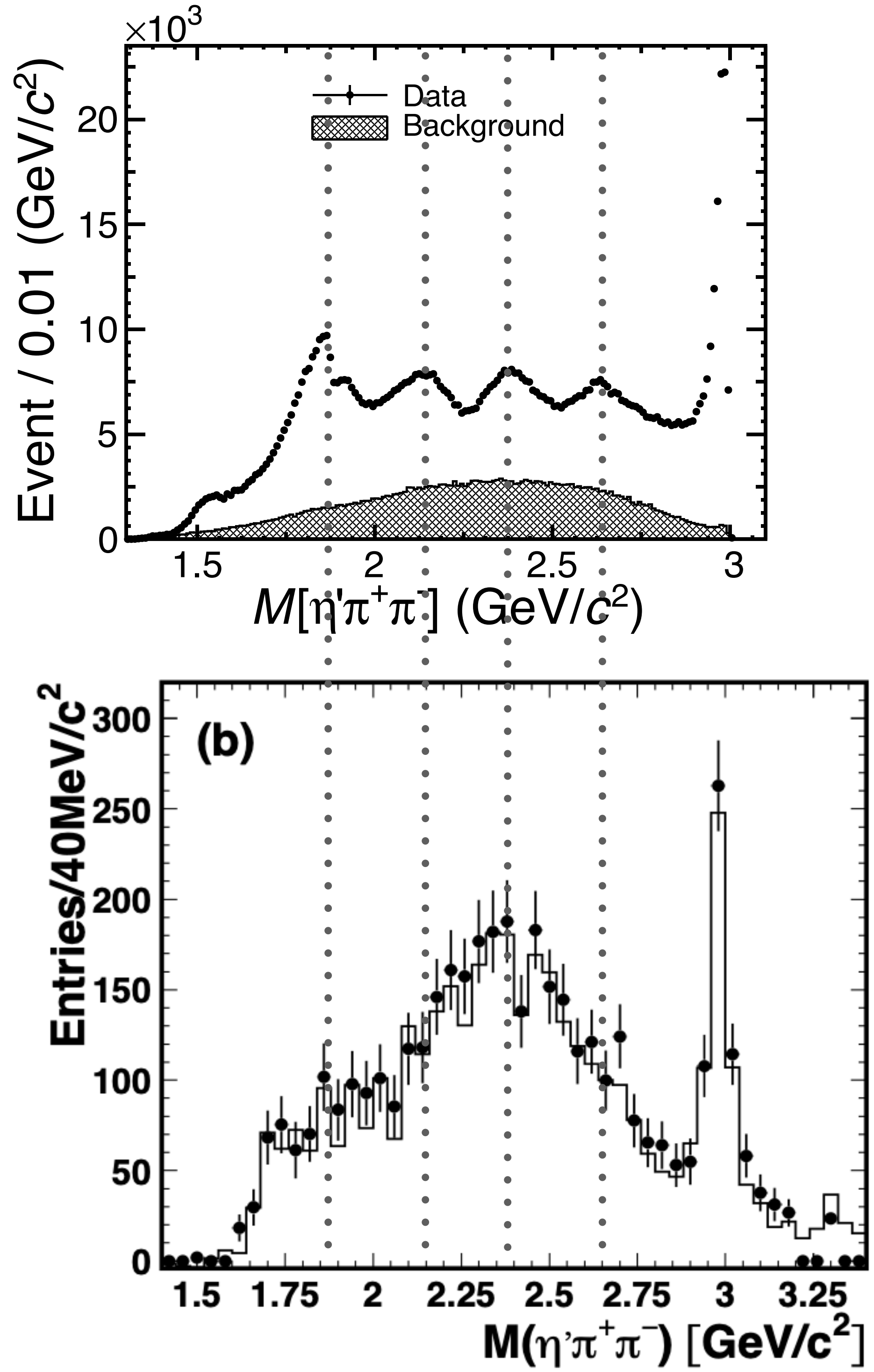


state	J^{PC}	Decay mode	Mass (MeV/c^2)	Width (MeV/c^2)	Significance
X(2370)	0^{-+}	$f_0(980)\eta'$	2395^{+11}_{-11}	188^{+18}_{-17}	14.9σ
X(1835)	0^{-+}	$f_0(980)\eta'$	1844	192	22.0σ
X(2800)	0^{-+}	$f_0(980)\eta'$	2799^{+52}_{-48}	660^{+180}_{-116}	16.4σ
η_c	0^{-+}	$f_0(980)\eta'$	2983.9	32.0	$> 20.0\sigma$
PHSP	0^{-+}	$\eta'(K_S^0K_S^0)_{S-wave}$	− − −	− − −	9.0σ
		$\eta'(K_S^0K_S^0)_{D-wave}$	− − −	− − −	16.3σ

- Would be interesting to search for X states in two-photon data…

$J/\psi \to \gamma\eta'\pi^+\pi^-$

$\gamma\gamma \to \eta'\pi^+\pi^-$



PRL 129, 042001 (2022)

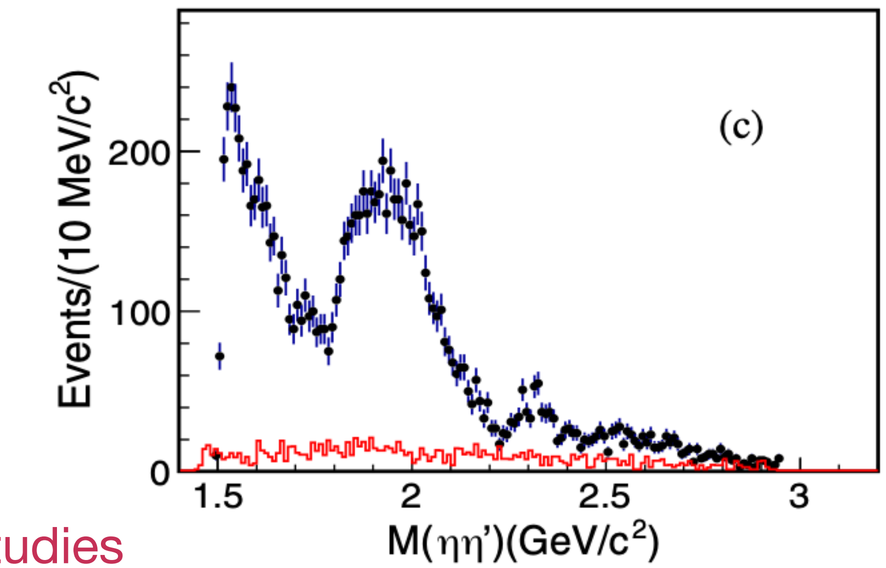
PRD 86 (2012) 052002

$J/\psi \to \gamma\eta'\eta$

PRL 129, 19, 192002 (2022)
PRD 106, 7, 072012 (2022)

- PWA of $J/\psi \to \gamma\eta\eta'$ using 10 Billion J/ψ events
- Veto ϕ in $\gamma\eta$ system
- 15000 signal events and $\sim$ 8-13% background events remaining
- All kinematically allowed resonances as listed in the PDG considered
  - $J^{PC} = 0^{++}, 2^{++}$ and 4^{++} ($\eta'\eta$ system)
  - $J^{PC} = 1^{+-}$ and 1^{--} ($\gamma\eta^{(\prime)}$ system)

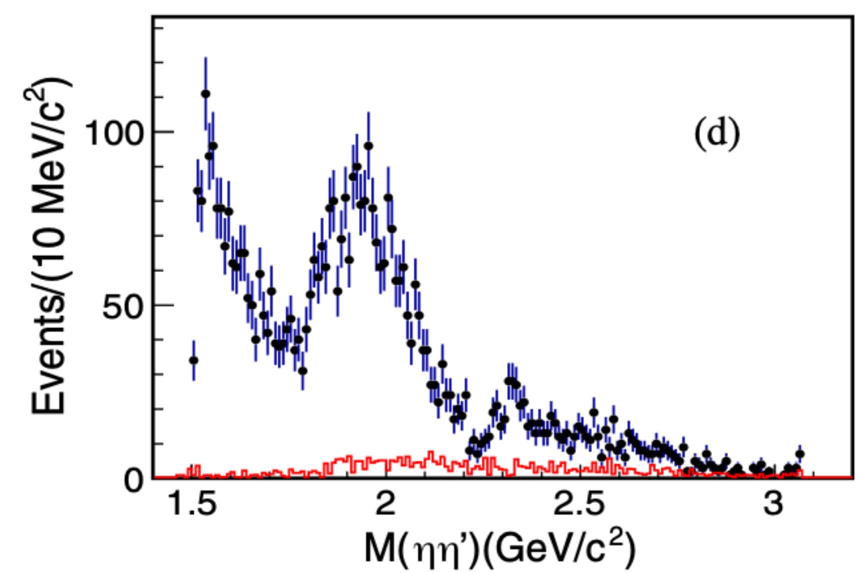
$\eta' \to \gamma\pi^+\pi^-$



fixed… floated for syst. studies

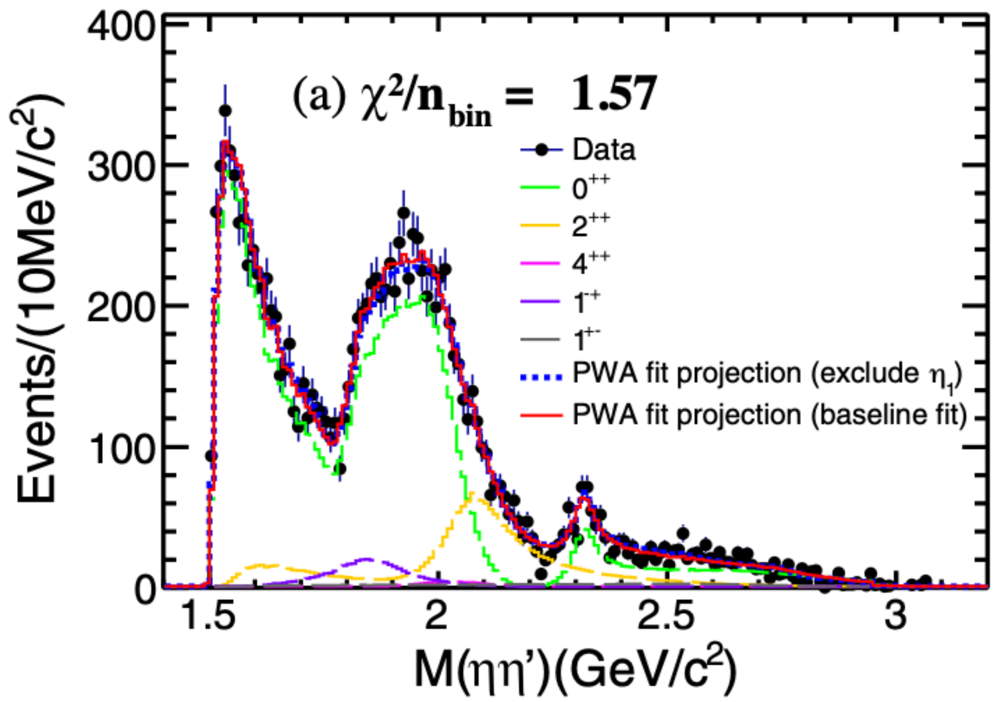
Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{PDG} (MeV)	B.F. ($\times 10^{-5}$)	Sig.
$J/\psi \to \gamma X \to \gamma\eta\eta'$	$f_0(1500)$	1506	112	1506	112	3.05 ± 0.07	$\gg 30\sigma$
	$f_0(1810)$	1795	95	1795	95	0.07 ± 0.01	7.6σ
	$f_0(2020)$	1935 ± 5	266 ± 9	1992	442	1.67 ± 0.07	11.0σ
	$f_0(2100)$	2109 ± 11	253 ± 21	2086	284	0.33 ± 0.03	5.2σ
	$f_0(2330)$	2327 ± 4	44 ± 5	2314	144	0.07 ± 0.01	8.5σ
	$f_2(1565)$	1542	122	1542	122	0.20 ± 0.03	6.2σ
	$f_2(1810)$	1815	197	1815	197	0.37 ± 0.03	7.0σ
	$f_2(2010)$	2022 ± 6	212 ± 8	2011	202	1.36 ± 0.10	8.8σ
	$f_2(2340)$	2345	322	2345	322	0.25 ± 0.04	6.5σ
	$f_4(2050)$	2018	234	2018	234	0.11 ± 0.02	5.6σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	0.14 ± 0.01	10.3σ
	$h_1(1595)$	1584	384	1584	384	0.41 ± 0.04	9.7σ
	$\phi(2170)$	2160	125	2160	125	0.24 ± 0.03	5.6σ
$J/\psi \to \eta X \to \gamma\eta\eta'$	$h_1(1595)$	1584	384	1584	384	0.50 ± 0.03	11.0σ
	$\rho(1700)$	1720	250	1720	250	0.22 ± 0.03	8.8σ

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

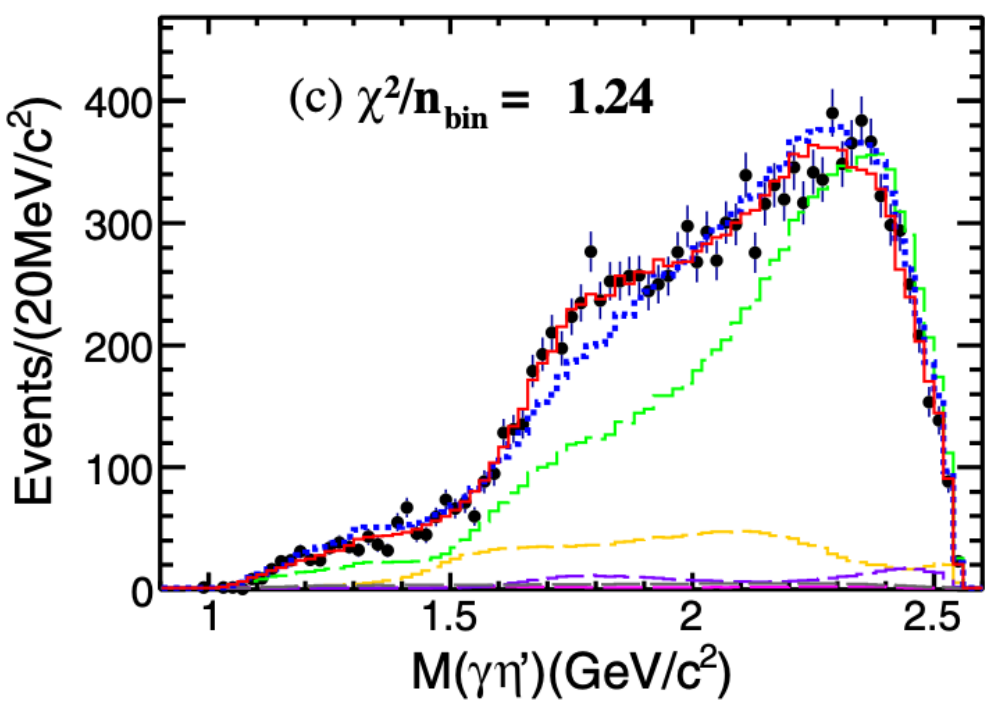


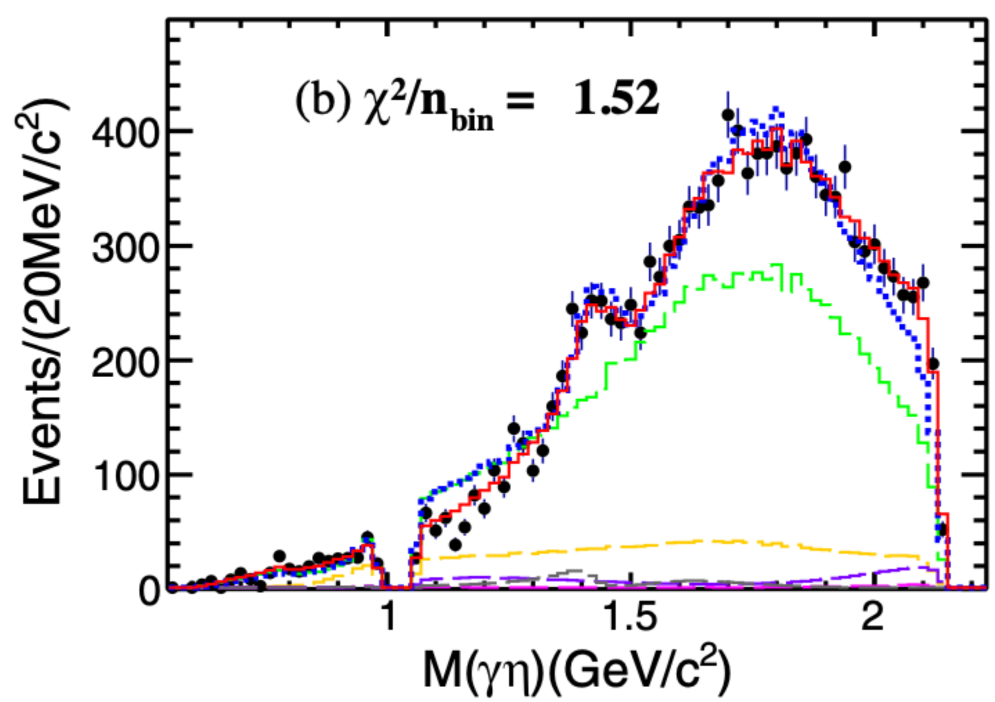
$J/\psi \to \gamma\eta'\eta$

PRL 129, 19, 192002 (2022)
PRD 106, 7, 072012 (2022)



- Additionally need of a spin exotic contribution found ➡ $\eta_1(1855)$
- $M = (1855 \pm 9^{+6}_{-1})\,\mathrm{MeV}/c^2, \Gamma = (199 \pm 18^{+3}_{-8})\,\mathrm{MeV}$
- May be the isoscalar partner of the $\pi_1(1600)$
- Further studies needed!
- Additional decay channels need to be investigated to improve the PWA model





$J/\psi \to \gamma\eta'\eta$

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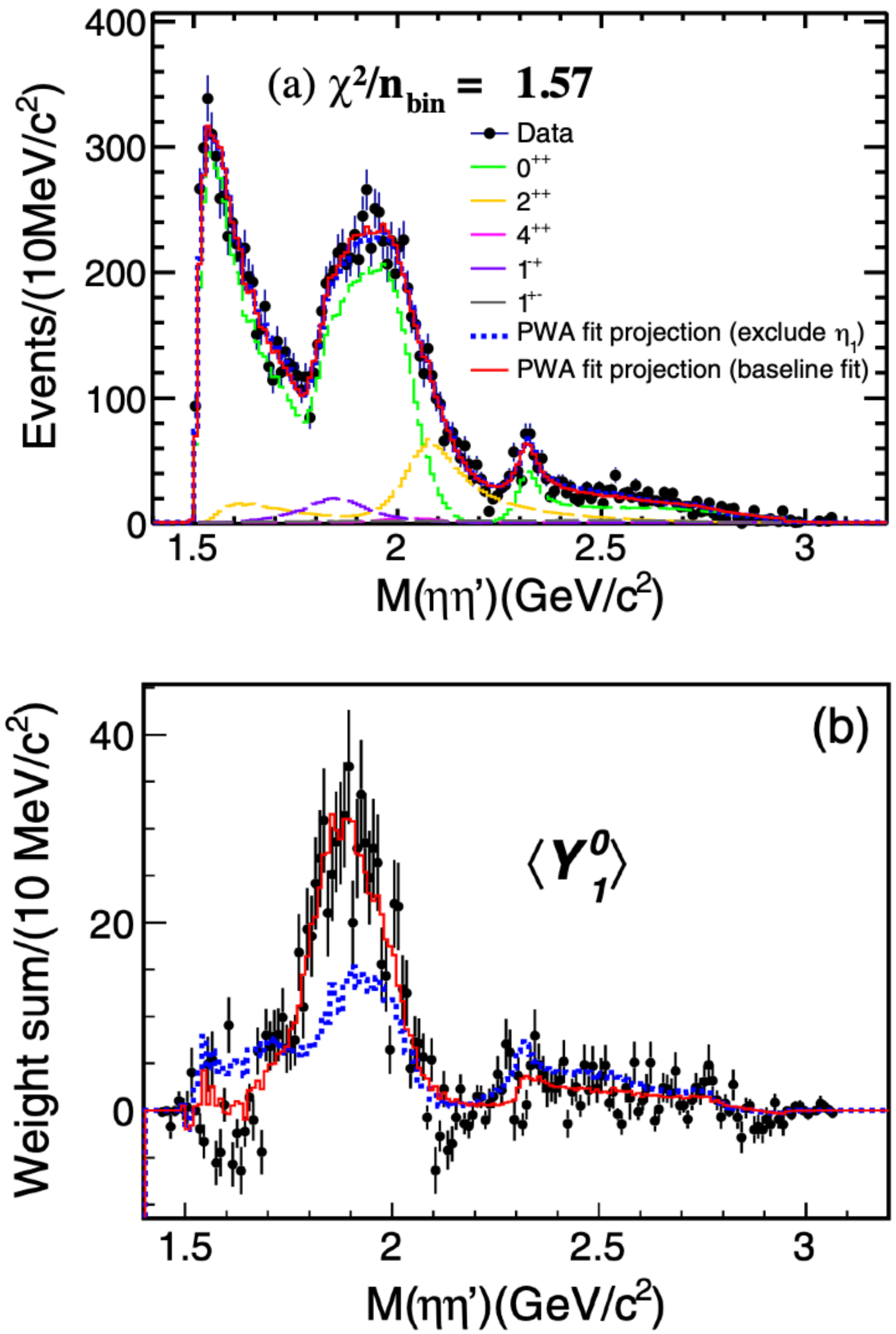

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Summary and Perspectives

- Although light mesons are studied for decades, there are still many open questions
- Coupled channel analyses seem to be a good tool to disentangle crowded spectra

- BESIII has accumulated world leading statistics in the charmonium region
- Especially J/ψ decays provide an excellent laboratory to study light hadron decays
- Recently many indications for new states
  - $\eta_1(1855)$ in $J/\psi \to \gamma\eta'\eta$
  - $X(2600)$ in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - Spin-parity determination of $X(2370)$ in $J/\psi \to \gamma\eta' K_S^0 K_S^0$
  - Coupled channel PWA of two-photon data is the first of its kind and adds hopefully infos to the inner structure of the light 0^{++} candidates

- Especially more sophisticated PWA analyses and additional decay channels needed
- Work closer together in the community - common effort is needed to answer fundamental questions!


Thank You!