How to understand the hadron spectrum

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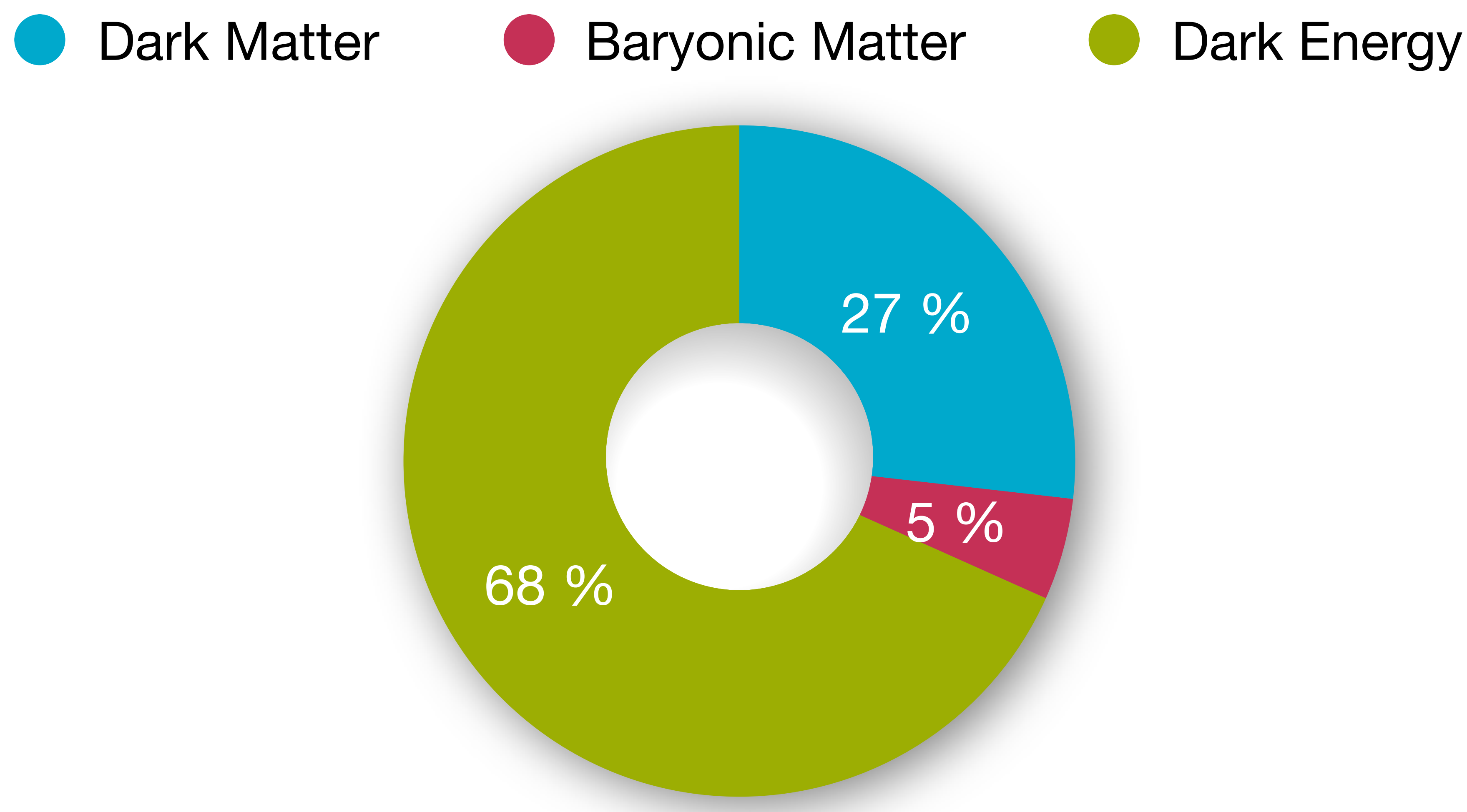
Fundamental Questions

The Higgs mechanism creates the mass of the fundamental particles, but this is not the end of the story!

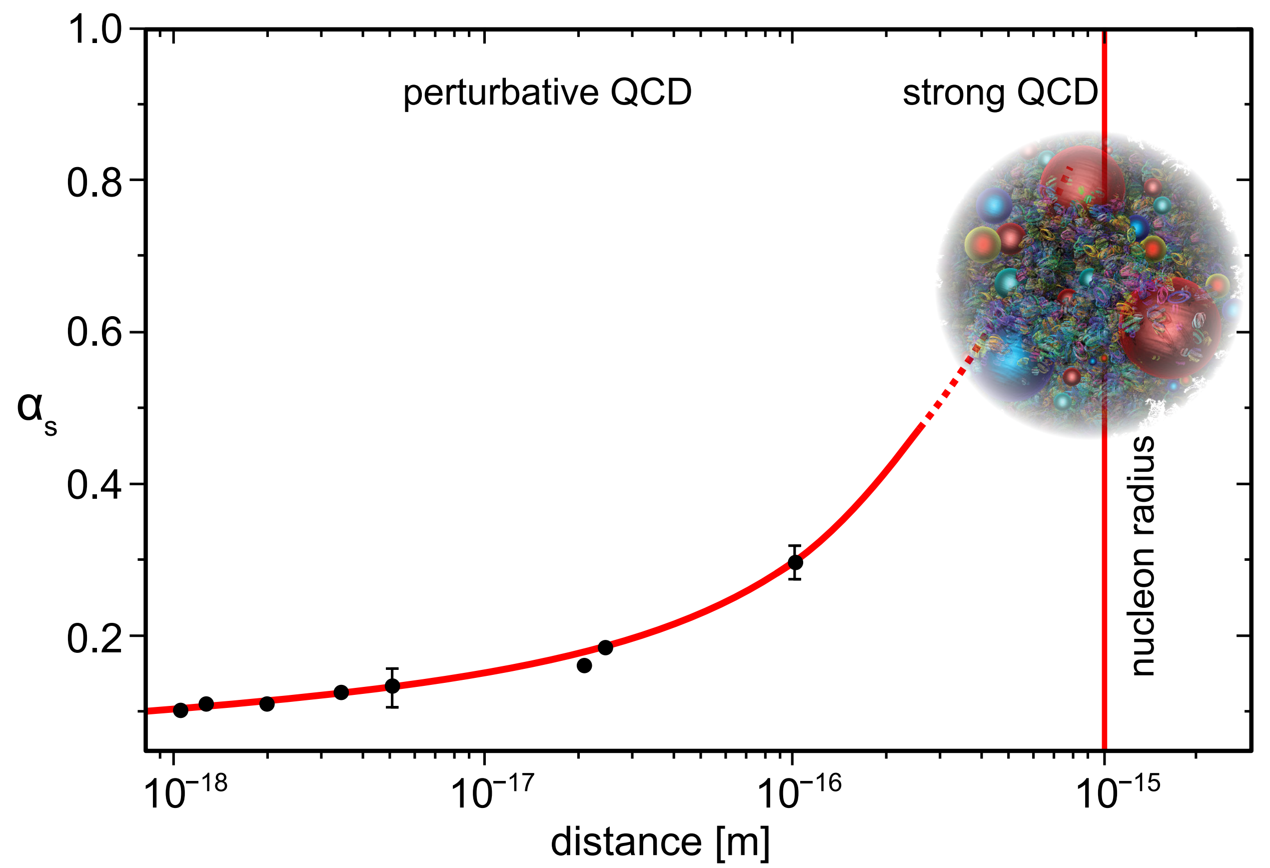


We even do not understand „conventional“ matter like the proton!

Open Questions of QCD

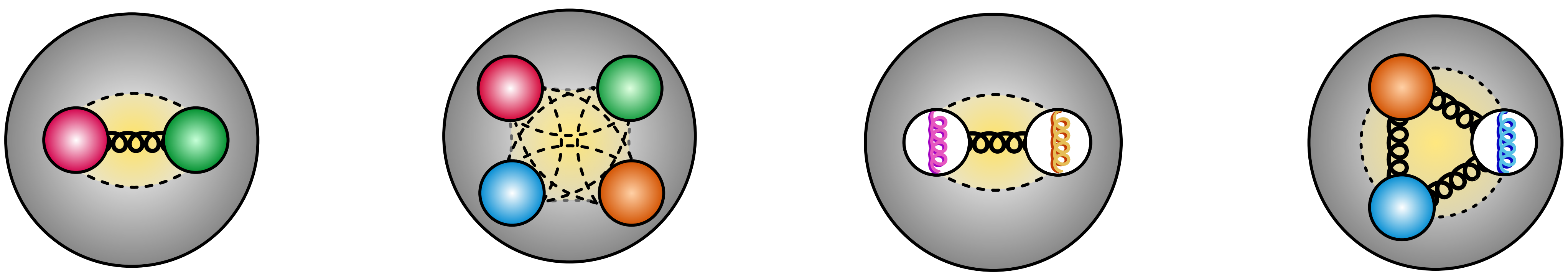
At a closer look, hadrons show a very complex inner structure!

- $\alpha_S \sim 1$, therefore processes are not suppressed anymore
- QCD becomes non-perturbative
- Theoretically very challenging since perturbative techniques fail
- Effective field theories are often model dependent and lattice calculations computational expensive



From the Perspective of Strong Interaction

- The mass of hadrons is predominantly generated by strong interaction (>90% in case of the proton)
- To understand how mass is generated we investigate other systems, e.g. with explicit gluonic degrees of freedom



Meson   Tetraquark   Glueball   Hybrid

- For a fermion-antifermion system not all quantum numbers can be formed

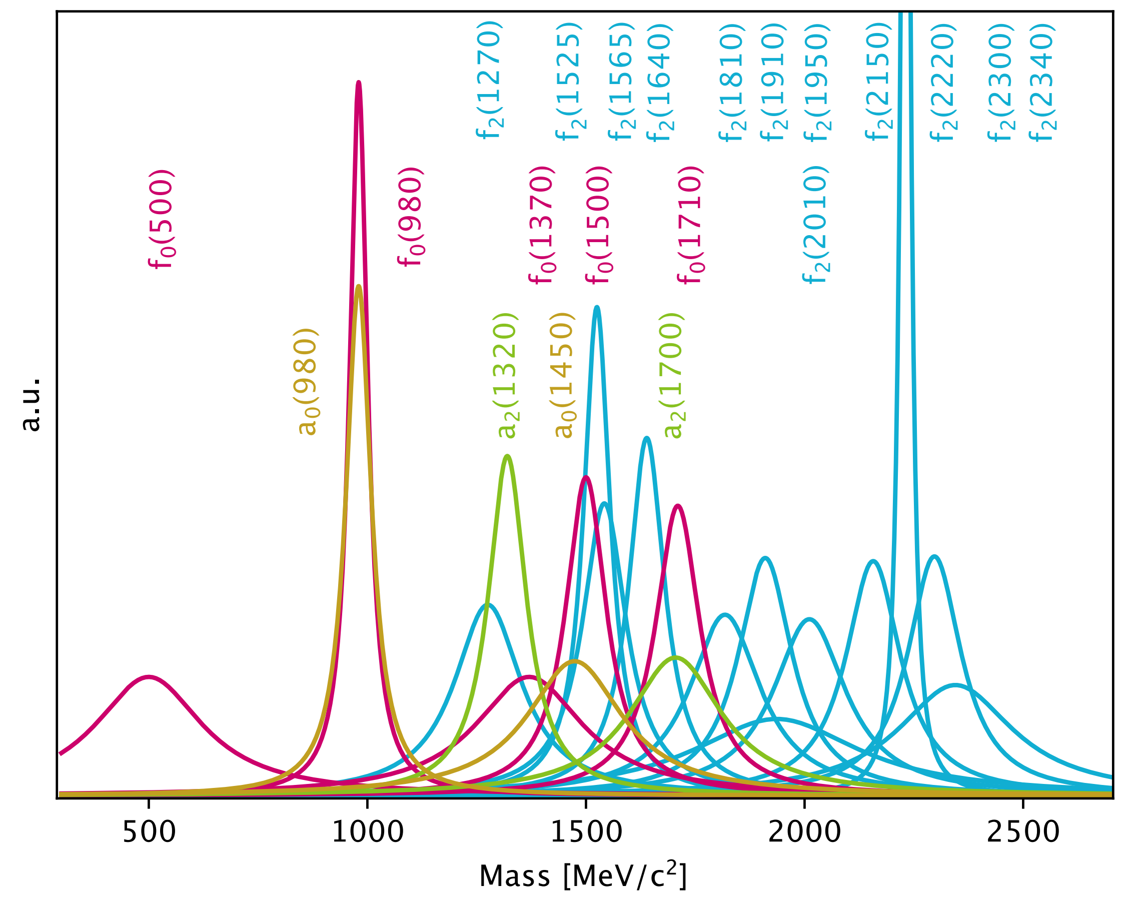
$$P = (-1)^{L+1}\,,\; C = (-1)^{L+S}$$

- Exotic quantum numbers: $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \ldots$
- But: Further states have been found which show odd properties or even exotic quantum numbers!

Light Meson Regime

- Light meson regime is extremely populated!
- Several (broad) interfering resonances of the same q.n.
- Various inelastic channels and thresholds opening
- Identifying and measuring resonance properties is not straight forward
- Resonances not always look like peaks
  ⬌ Peaks not necessarily caused by a resonance
- Analysing a single channel is not enough to disentangle states unambiguously
- More sophisticated tools and descriptions needed!

spectrum of well established states



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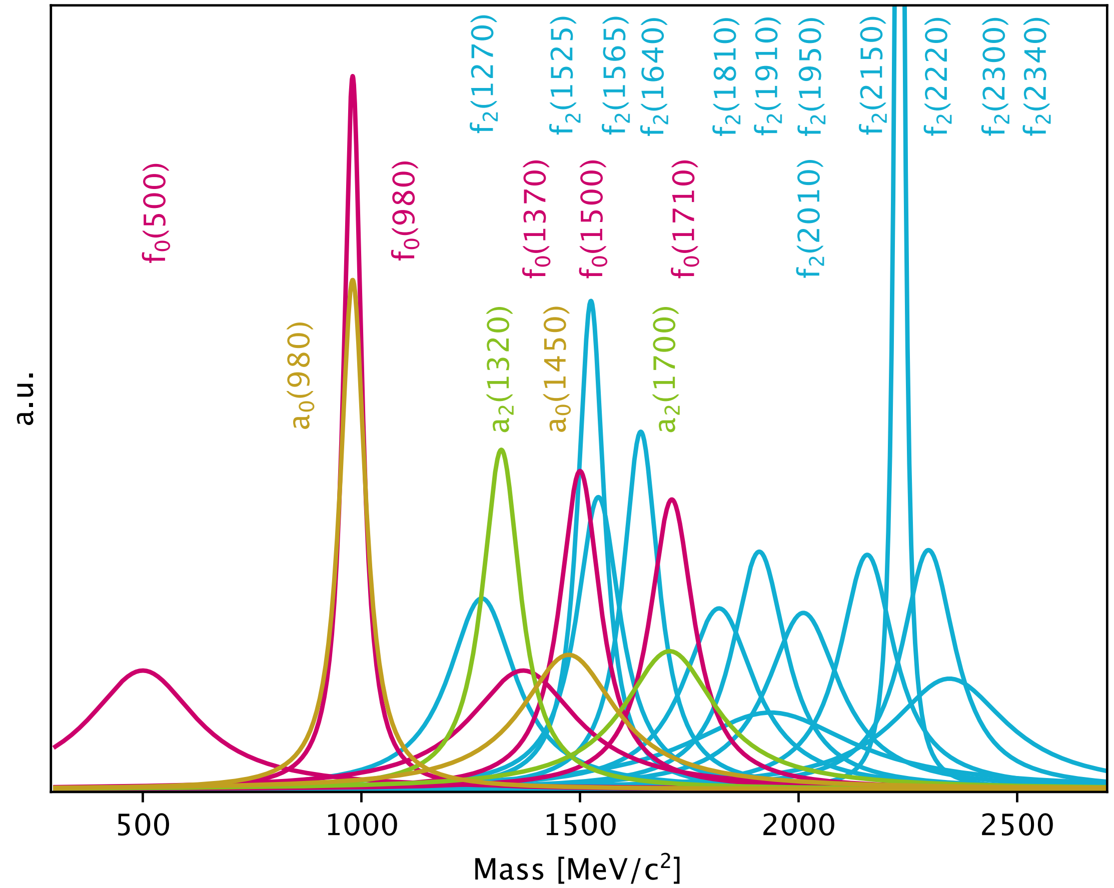


We should start thinking beyond experimental collaborations!

Experimental Possibilities

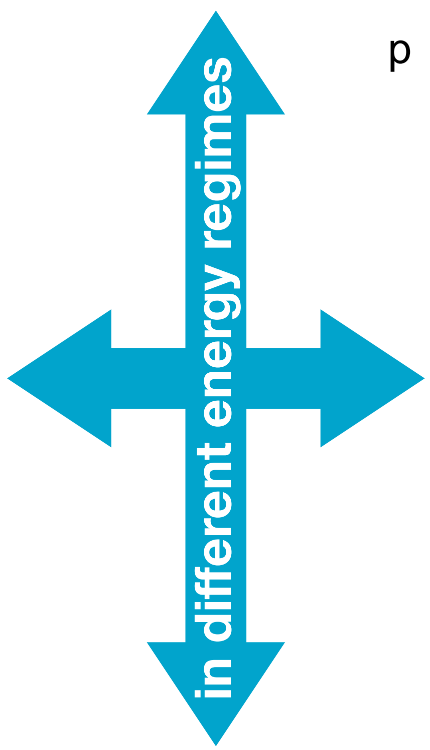
- Each experiment, detector and process has its own advantages
- To tackle these challenges, we need to combine forces

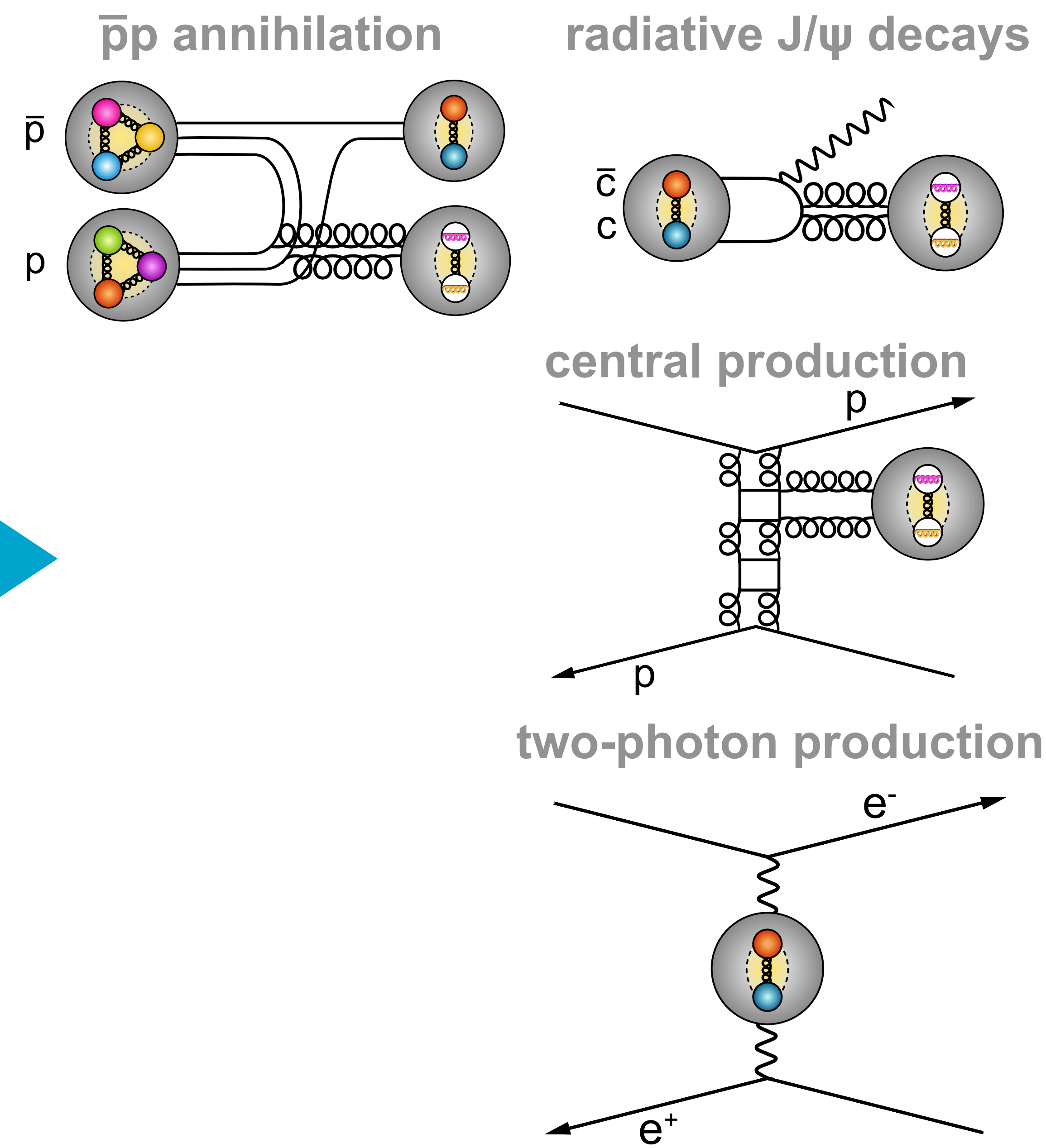
Gluon rich processes

- Radiative charmonium decays
- $\bar{p}p$ annihilation
- pp central production
- …

QED mediated process

- Two-photon production





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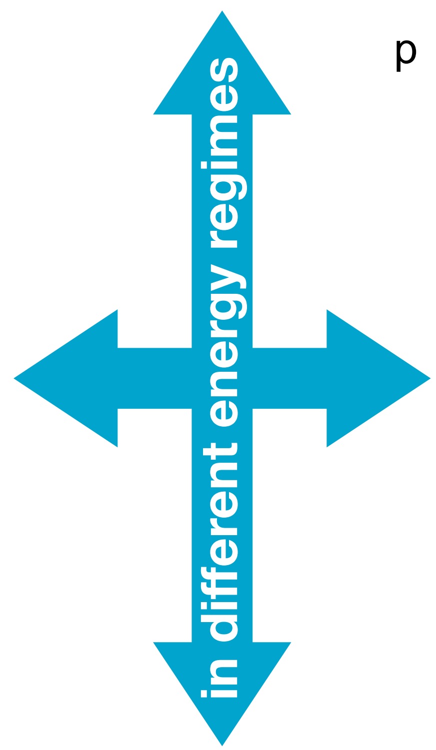
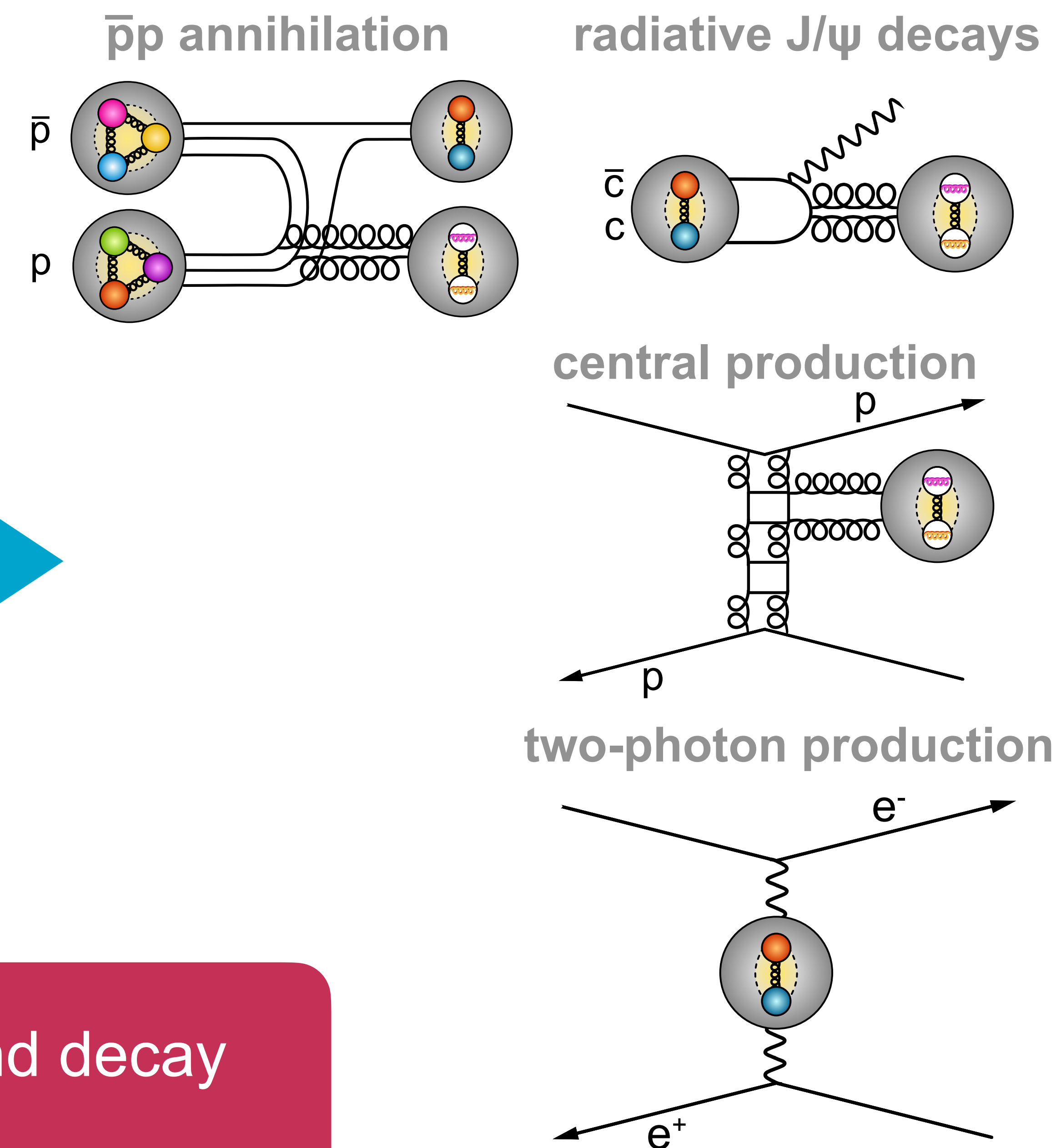




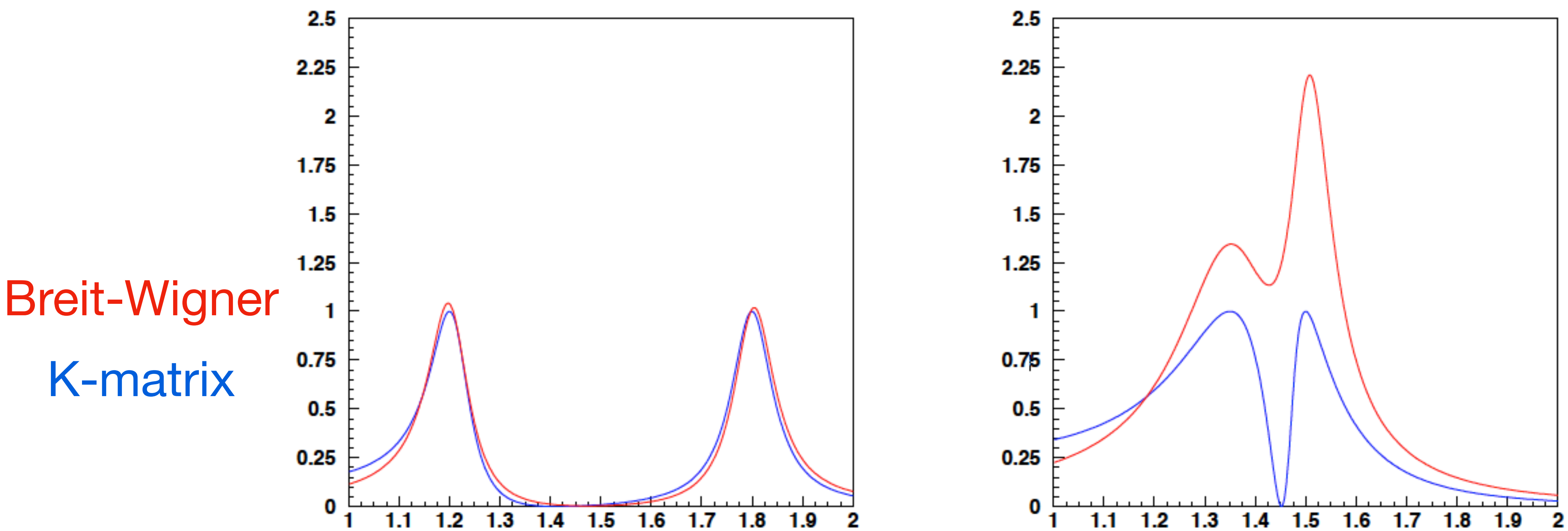
Combine different production mechanisms and decay channels to reveal a particle's nature

Why Coupled Channel Approach?

Breit-Wigner functions are widely used in single channel analyses which provides a good approximation for isolated resonances decaying to one channel

If this is not the case:

- there might be a violation of unitarity
- the extracted resonance parameters are not unique and depend on the process



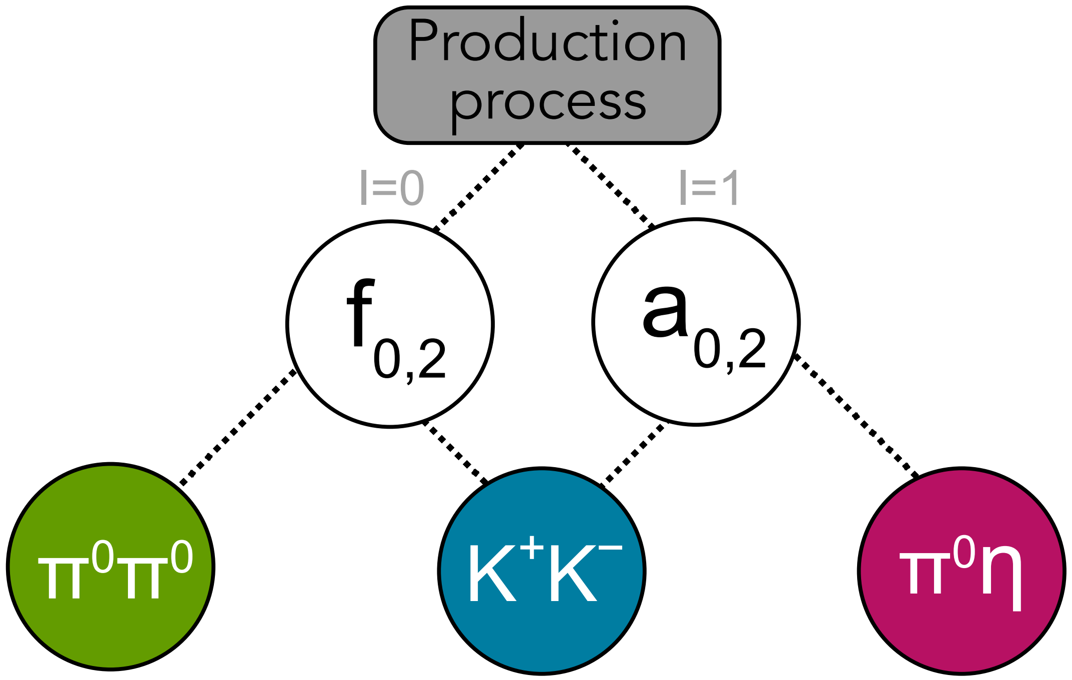
$1: M = 1200\,\mathrm{MeV},\ \Gamma = 100\,\mathrm{MeV}$
$2: M = 1800\,\mathrm{MeV},\ \Gamma = 100\,\mathrm{MeV}$

$1: M = 1300\,\mathrm{MeV},\ \Gamma = 300\,\mathrm{MeV}$
$2: M = 1500\,\mathrm{MeV},\ \Gamma = 100\,\mathrm{MeV}$

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

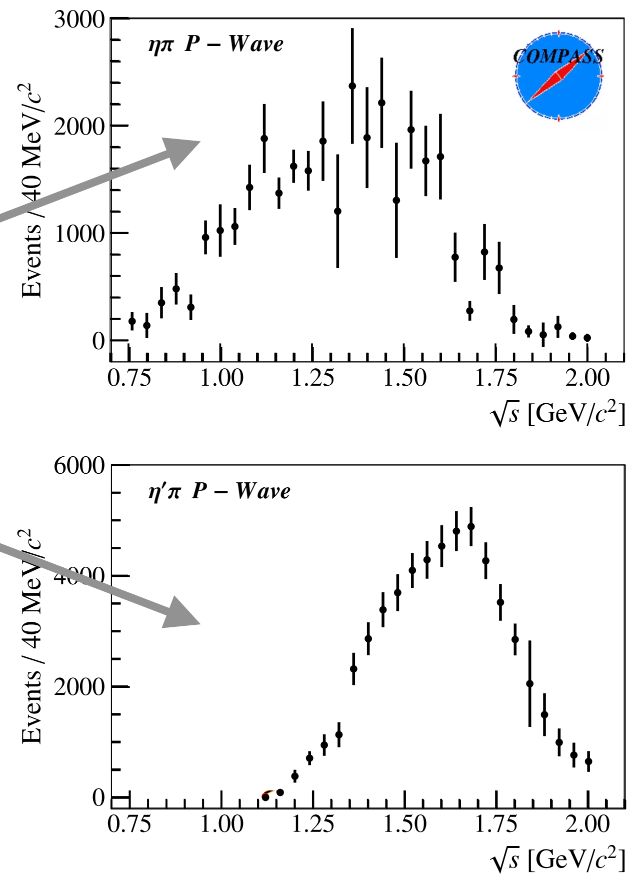
Two π_1 hybrid candidates below 2 GeV are listed in PDG

- one at around 1.4 GeV only seen in πη
- the other at around 1.6 GeV seen in πη’ but not in πη

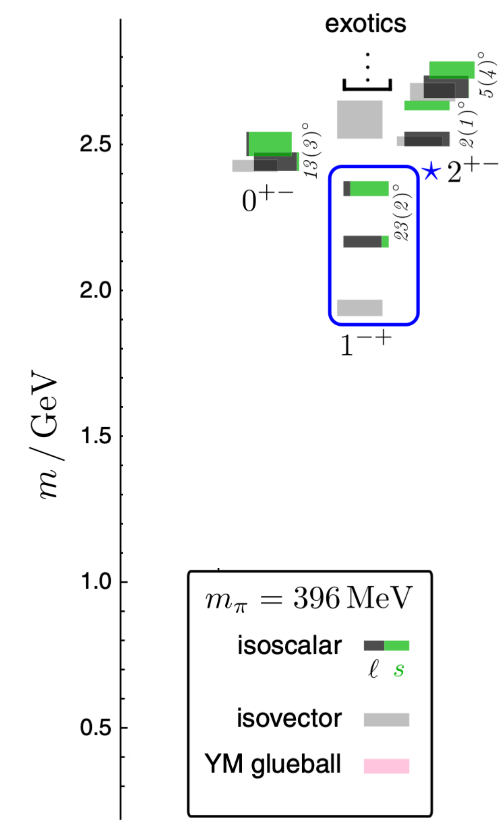
➡ Parameters obtained by Breit-Wigner fits!

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

200 MeV apart!

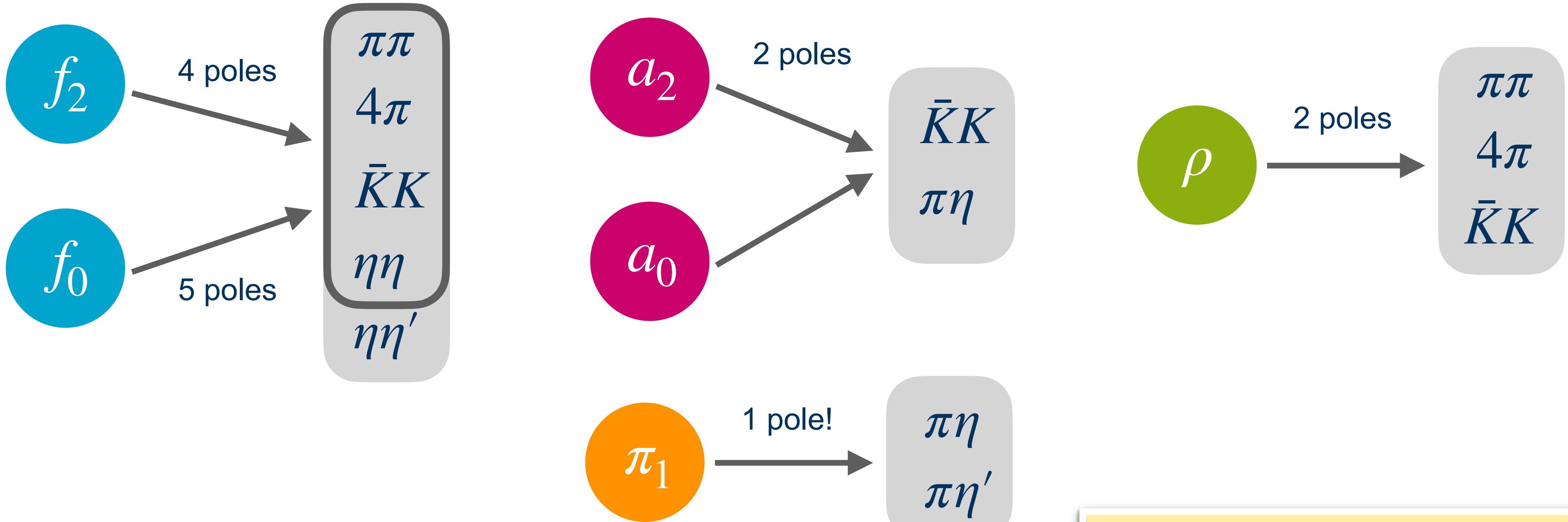


Phys.Rev. D84 (2011) 074023



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

- Combining data from different experiments:
- $\bar{p}p \to \pi^0\pi^0\eta$, $\pi^0\eta\eta$ 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

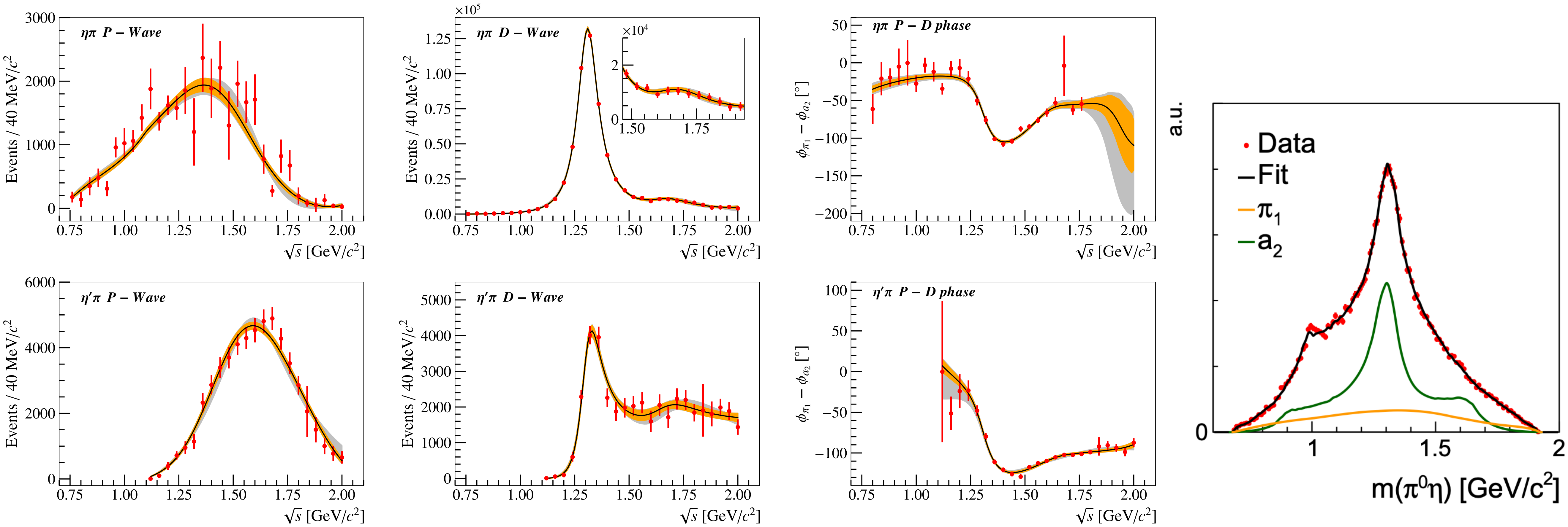


Eur. Phys. J. C (2021) 81, 1056

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:

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

Coupled Channel Analysis of $\bar{p}p$ 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 ± 8.5 $^{+3.5}_{-14.0}$	81.1 ± 4.5 $^{+26.9}_{-0.5}$
$f_0(1710)$	$\bar{p}p$ + scat	1794.3 ± 6.1 $^{+47.0}_{-61.2}$	281 ± 32 $^{+12}_{-80}$
$f_2(1810)$	scat	1769 ± 26 $^{+3}_{-26}$	201 ± 57 $^{+13}_{-87}$
$f_2(X)$	scat	2119.9 ± 6.4 $^{+25.7}_{-1.1}$	343 ± 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 ± 47 $^{+24}_{-75}$	455 ± 88 $^{+144}_{-175}$	554 ± 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 ± 1.9 $^{+1.3}_{-1.3}$	107.5 ± 4.6 $^{+3.3}_{-1.8}$	31 ± 22 $^{+9}_{-11}$	4.6 ± 1.5 $^{+7.0}_{-0.6}$
$a_2(1700)$	$\bar{p}p + \pi p$	1686 ± 22 $^{+19}_{-7}$	412 ± 75 $^{+64}_{-57}$	2.9 ± 4.0 $^{+1.1}_{-1.2}$	3.5 ± 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 ± 0.2 $^{+0.2}_{-0.3}$	168.0 ± 0.7 $^{+1.7}_{-0.1}$	87.7 ± 0.3 $^{+4.8}_{-4.4}$	2.6 ± 0.1 $^{+0.1}_{-0.2}$	0.3 ± 0.1 $^{+0.0}_{-0.1}$
$f_2'(1525)$	$\bar{p}p$ + scat	1514.7 ± 5.2 $^{+0.3}_{-7.4}$	82.3 ± 5.2 $^{+11.6}_{-4.5}$	2.1 ± 0.3 $^{+0.8}_{-0.0}$	67.2 ± 4.2 $^{+5.0}_{-3.8}$	9.8 ± 3.8 $^{+1.7}_{-3.3}$
$\rho(1700)$	$\bar{p}p$ + scat	1700 ± 27 $^{+13}_{-16}$	181 ± 25 $^{+0.0}_{-16}$	13.6 ± 1.2 $^{+0.9}_{-0.5}$	0.8 ± 0.1 $^{+0.0}_{-0.0}$	-

Several resonance properties measured simultaneously within one fit!

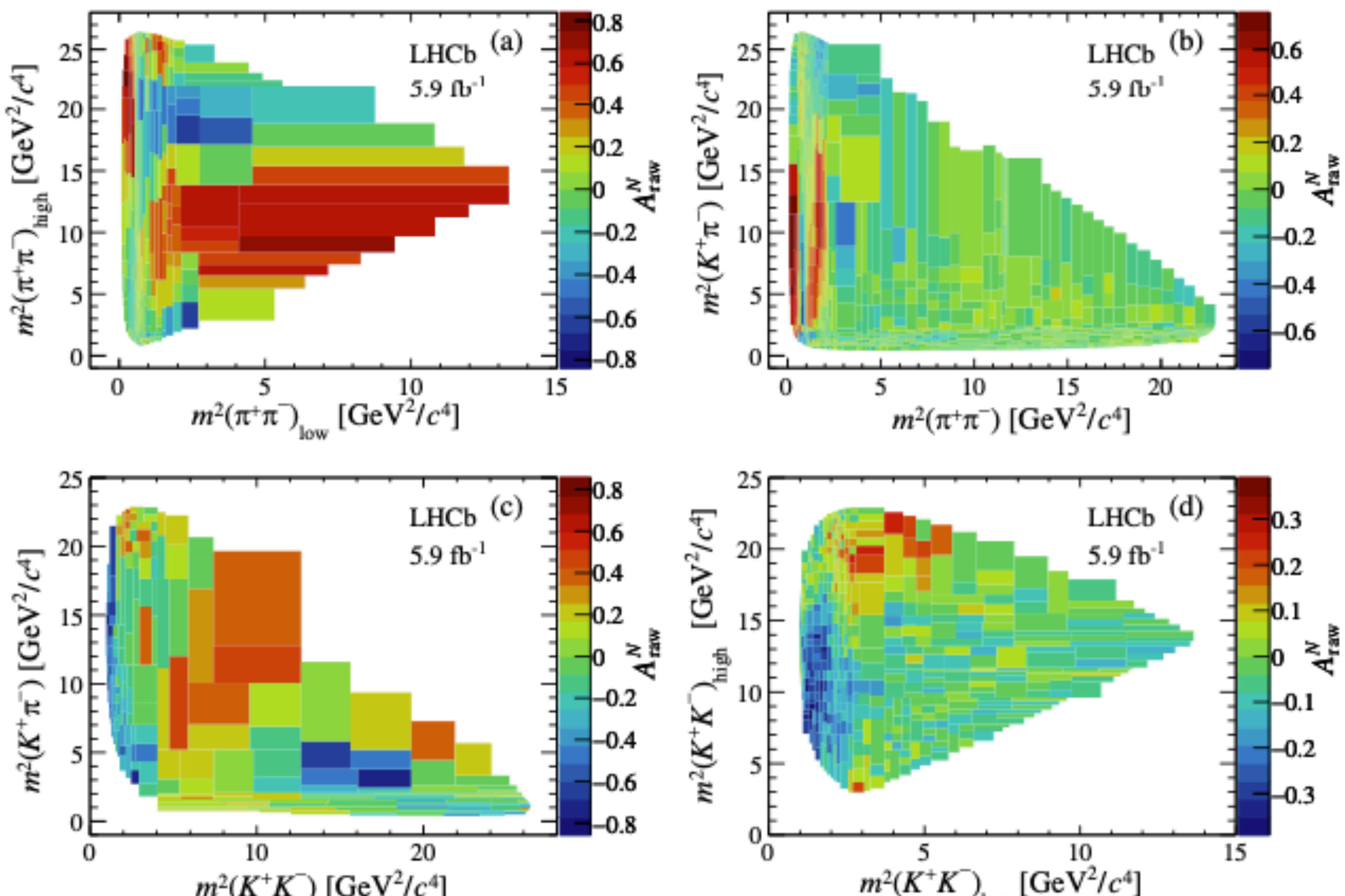
This parameterisation is universal - Can be used in other analyses!

Input for CP Violation Studies?

- CP violation in $B \to 3h$ is very much depending on intermediate resonances
- Strong and weak phase CPV contributions need to be separated

➡ Mechanisms from strong interaction as final state interaction assumed to play a big role!

- The Hadron spectroscopy community has the tools!
- Descriptions for $(\pi\pi)_{S/D}$ above $2\,\mathrm{GeV}/c^2$ needed - scattering data missing



PRD 108, 012008 (2023)

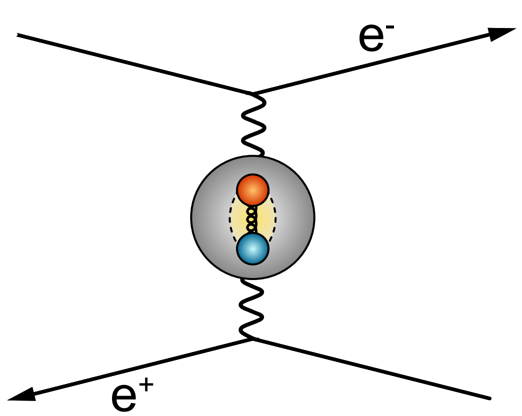
Learning More About the Inner Structure

Besides measuring resonance parameters as mass, width, …

Usually: Measure form factors!

Two photon physics

- Clean e.m. process, only sensitive to charge
- Complementary information on glueball candidates!
- States with even C-parity $0^{\pm+}, 2^{\pm+}, \ldots$ can be directly produced

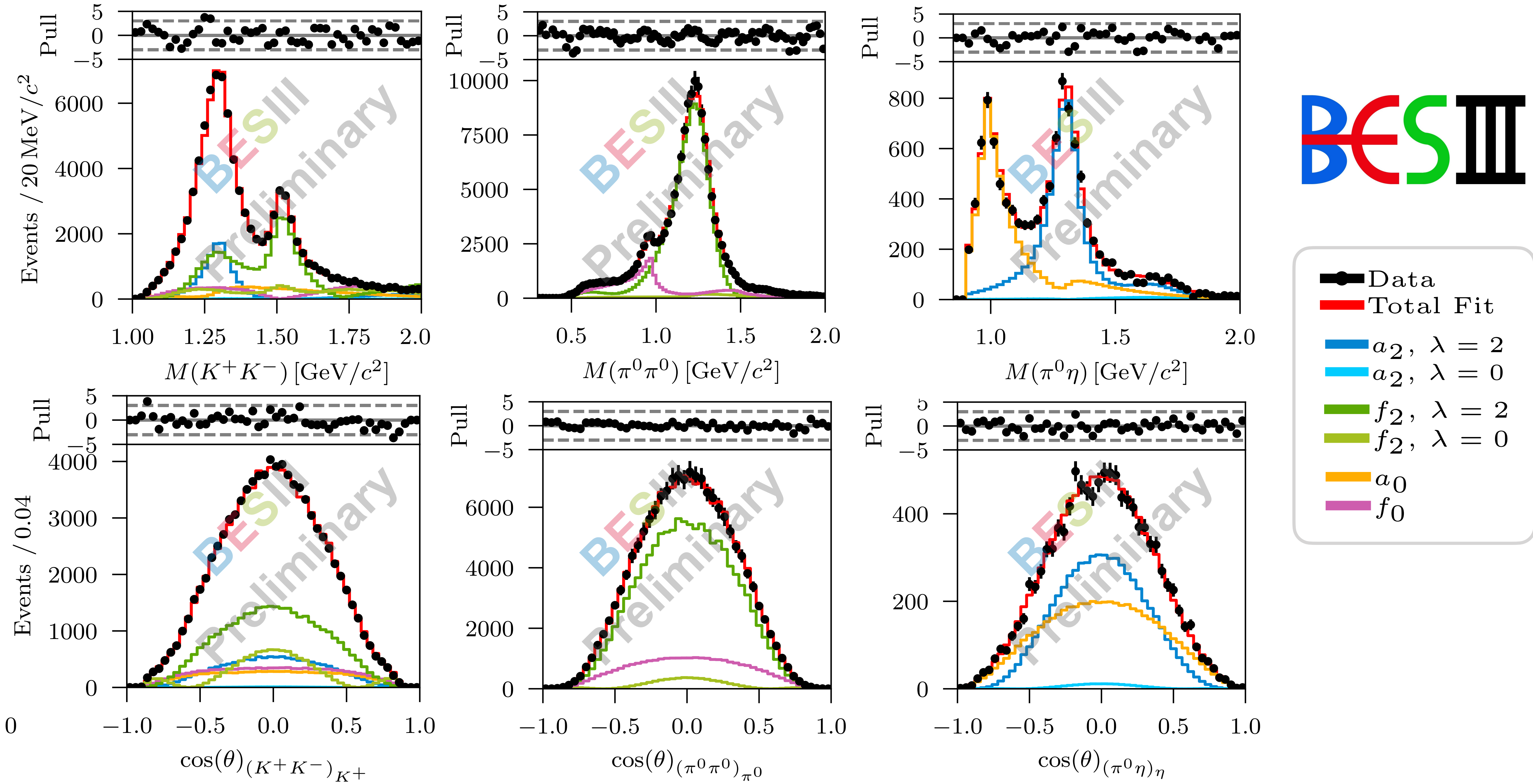


Untagged reactions:

- 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

- K-matrix parameterisation (*EPJ C* (2021) 81, 1056) fixing all pole parameters on decay side
- Determination of two-photon width based on pole residue (even for f_0 wave)



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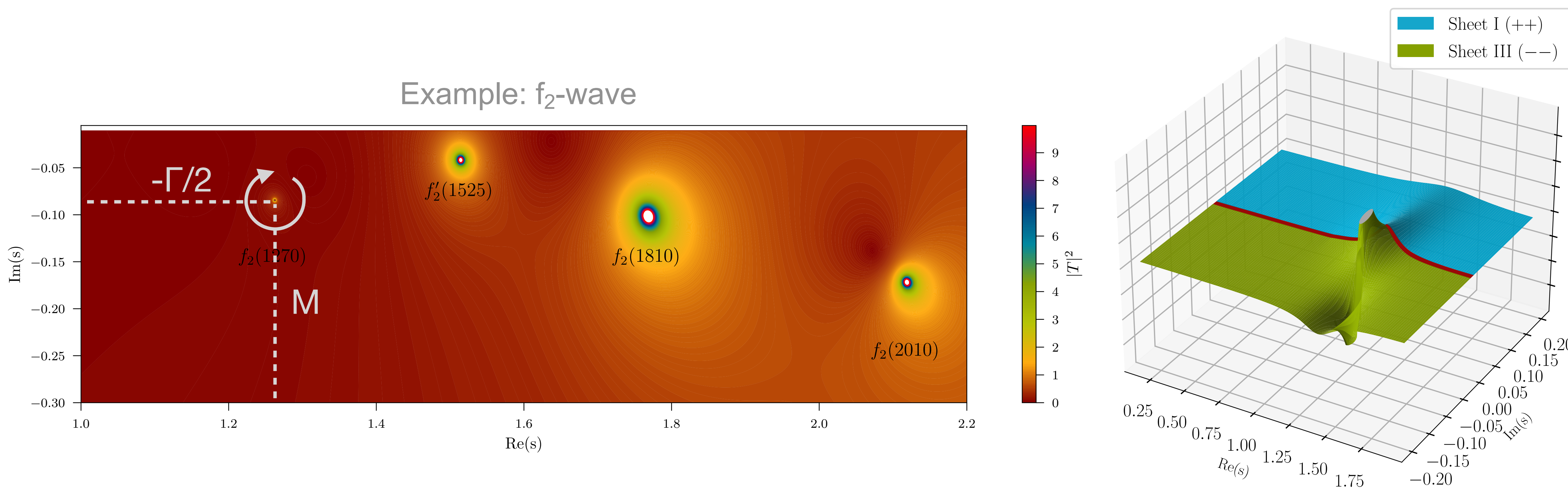


- K-matrix and thus the pole itself contain all resonance properties
- Masses and widths defined by the pole position in the complex energy plane of the T-matrix sheet closest to the physical sheet

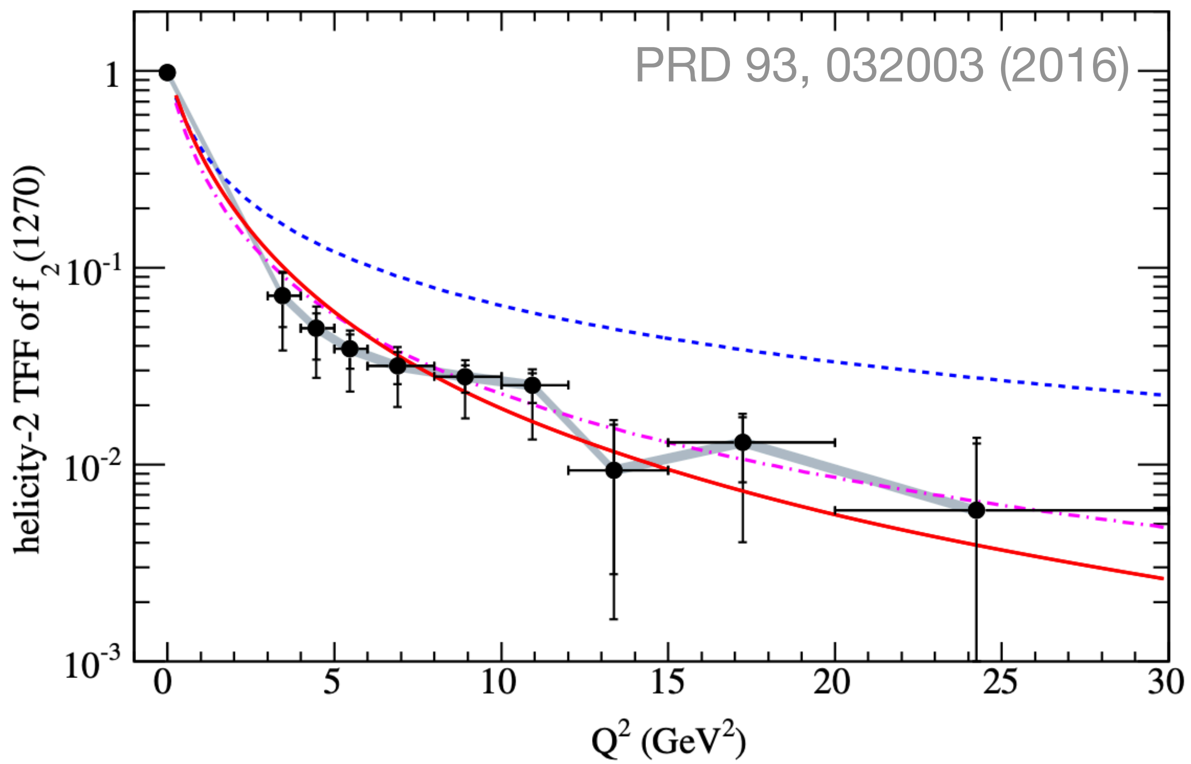
Benefits of Two-Photon Data

Tagged two-photon reactions:

- Measuring transition form factors of light mesons useful to cleanly determine gluonic admixtures!
- Momentum transfer of involved photons can be measured
- Formation of $J = 1$ states possible due to non negligible γ virtuality

- TFF measurements at BESIII especially powerful at $Q^2 = 0.3 - 1.5\ \mathrm{GeV}^2$
- Higher beam momenta needed to access higher Q^2 regime and states above $2\,\mathrm{GeV}$, ($\chi_{c1}(3872)$ …)
- BELLEII (?)

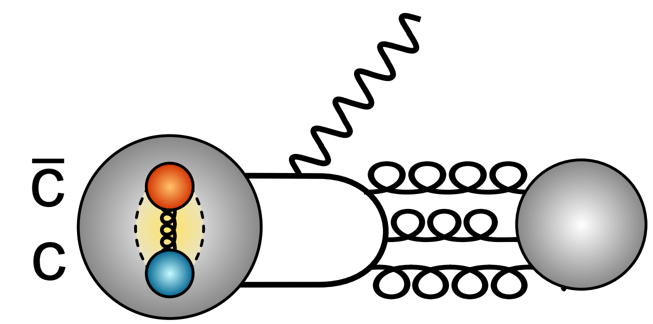
TFF of $f_2(1270)$ by BELLE

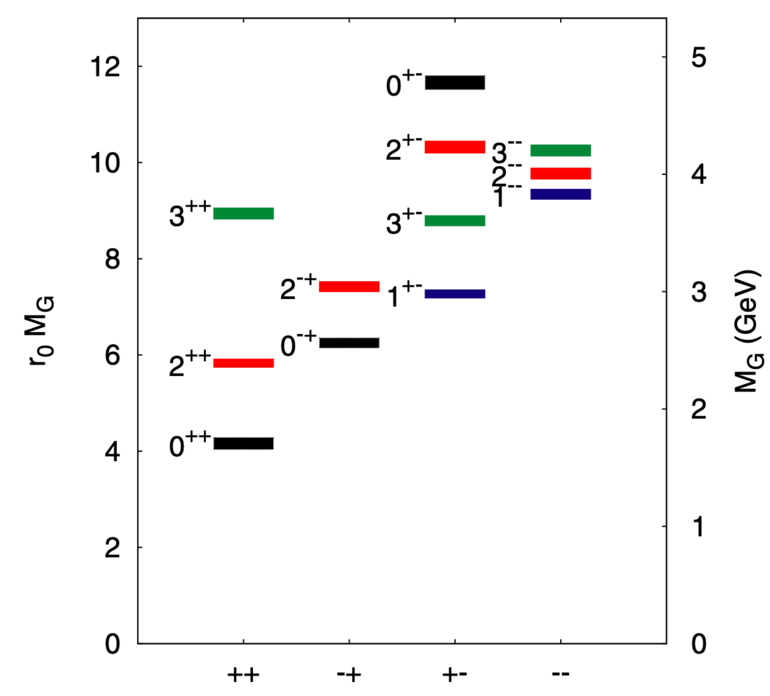


Unique Features of Radiative J/ψ decays

- Gluon-rich process ➡ production of glueballs expected
- 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!

Physics-, statistics- and phase space-wise great opportunities to search for glueball candidates!



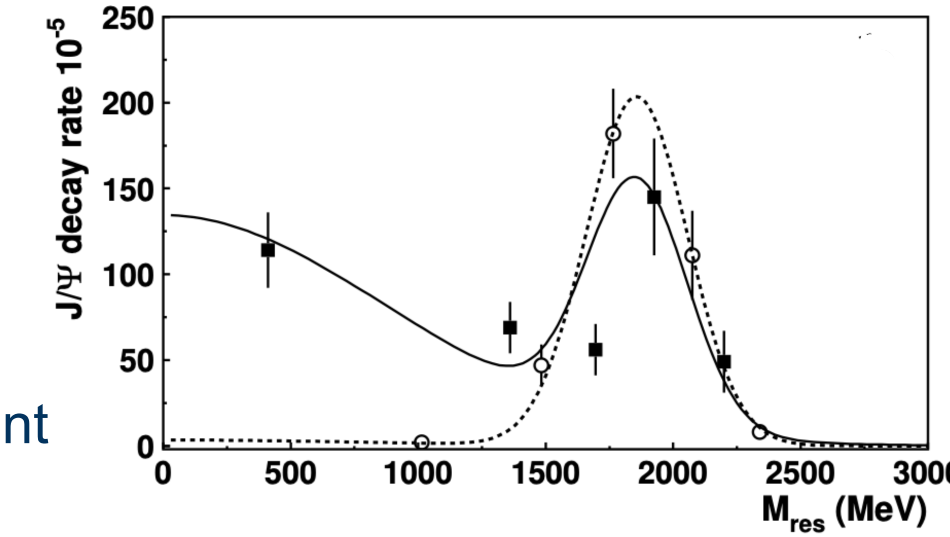


Phys. Rev. D 73, 014516 (2006)

Recent Analyses

Coupled channel fit by Sarantsev et. al.: *Phys. Lett. B 816* (2021), 136227

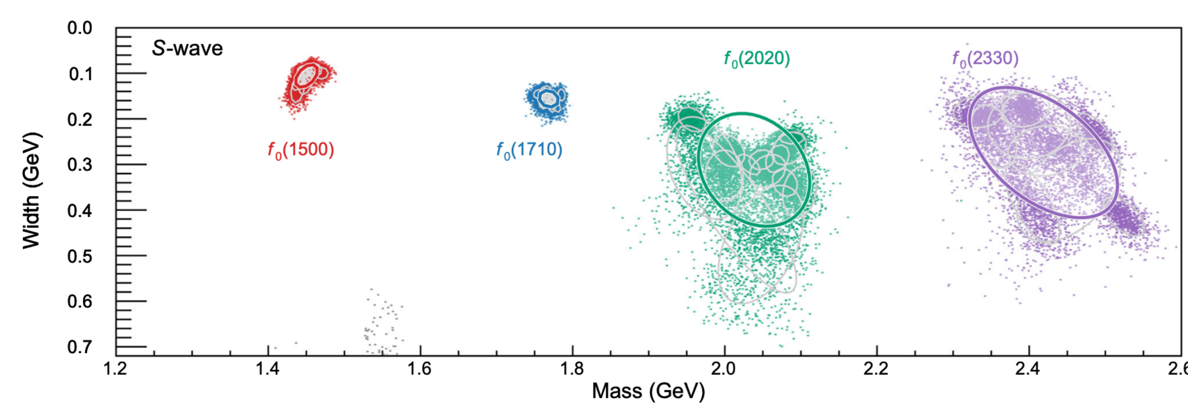
- $J/\psi \to \gamma + (\pi^0\pi^0, K^0_S K^0_S, \eta\eta, \omega\phi)$ (BESIII)
- $\pi^+\pi^-$- scattering data (CERN-Munich, GAMS, BNL)
- $\bar{p}N \to$ 3 mesons (CB-LEAR)



- Indirect hint for the light scalar glueball candidate by measuring production strengths of scalar states
- 0^{++} glueball mixing interpretation via coupling of the 10 different scalar singlet and octet states

Coupled channel fit by JPAC group: *EPJ C* ***82****, 80 (2022)*

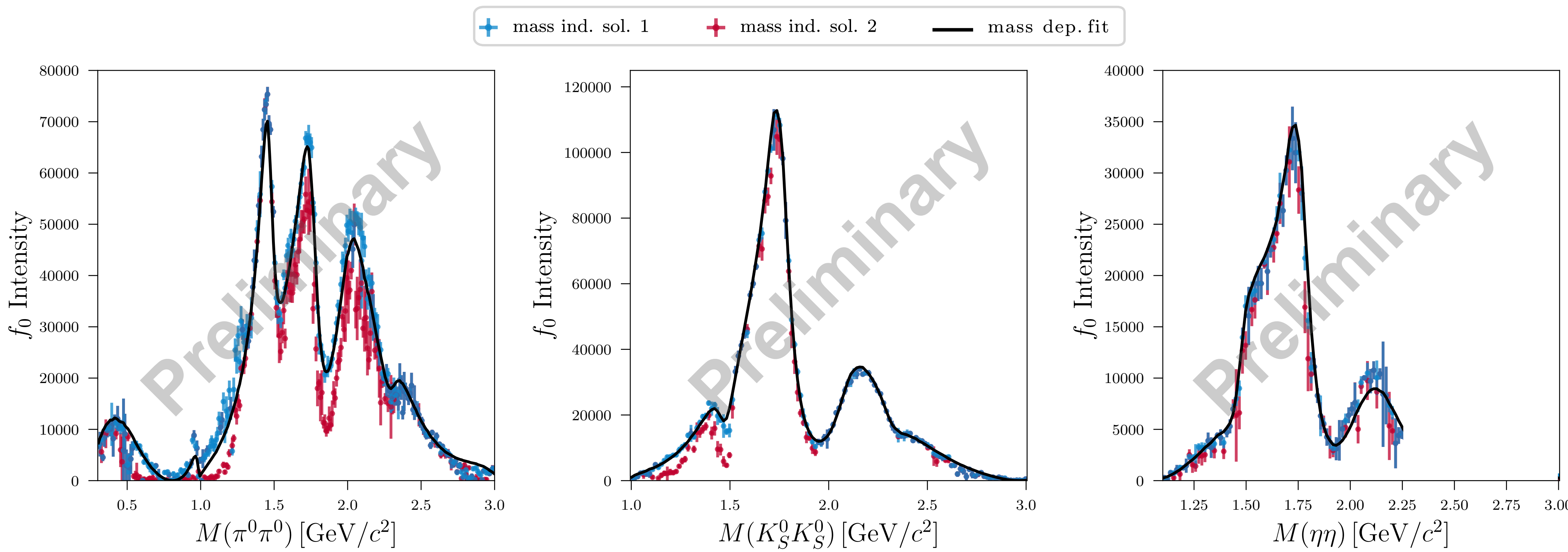
- Used $J/\psi \to \gamma\, \pi^0\pi^0, \gamma\, K^0_S K^0_S$ (BESIII) data
- Only 4 scalar poles needed - not as 10
- No statement towards glueball contributions
- But: Theory has only access to binned data based on older data samples



Recent Analyses

Much higher statistics available now - *50 times more!*

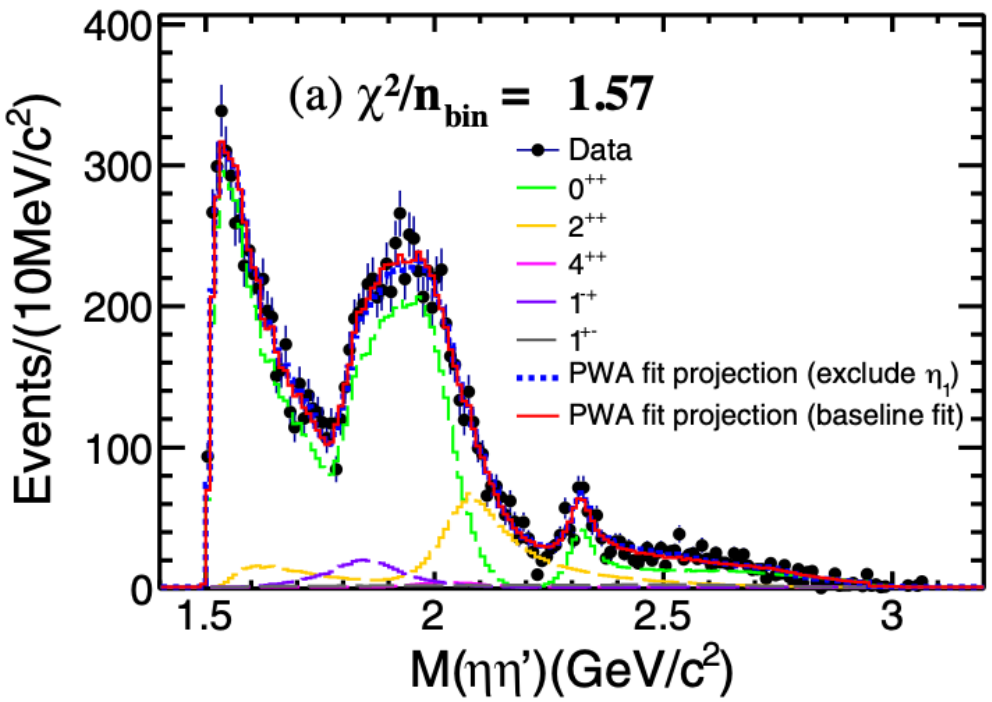
Event based mass-independent and coupled channel amplitude analyses in preparation for $J/\psi \rightarrow \gamma\pi^0\pi^0$, $\gamma K_S^0 K_S^0$ and $\gamma\eta\eta$!



Ultimate goal coupled channel analysis together with $\gamma\gamma$ data…

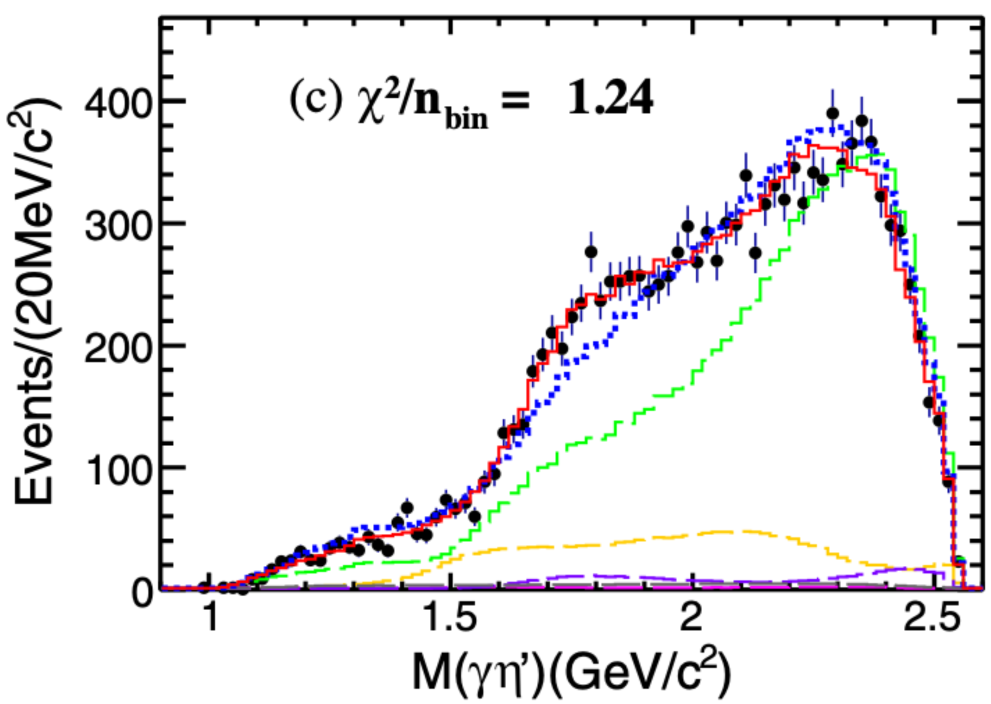
$J/\psi \rightarrow \gamma\eta'\eta$

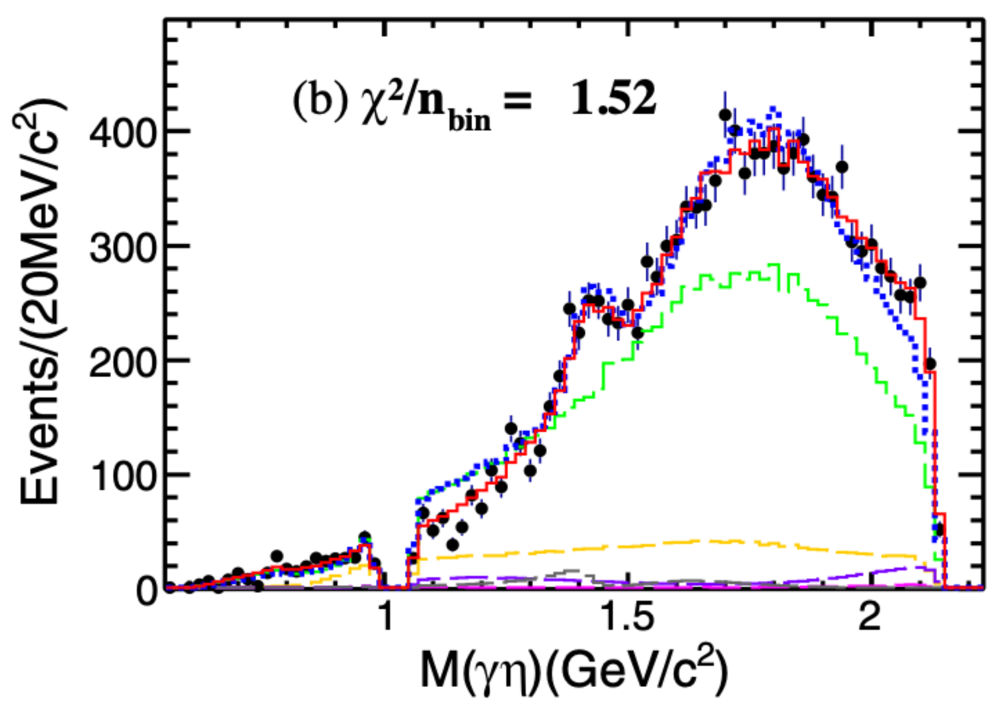
PRL 129, 19, 192002 (2022)
PRD 106, 7, 072012 (2022)



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





New Methods

NRW-FAIR Netzwerk

In order to perform such computational expensive coupled analyses with increasing statistics we need to get faster!

Development of faster algorithms required:

- Including AI techniques where helpful

but leads to a:

- More sustainable use of resources and data!

New network project working on techniques to accelerate PWA s

- Automated differentiation
- Improved gradient decent methods
- Pseudo event clustering

Future Experimental Prospects

$\bar{p}p$ annihilation

two-photon production

radiative J/ψ decays

πp- , pp scattering
photo production

• • •

- Several interesting research projects on the horizon!
- $\bar{p}p$ annihilations have unique discovery potential, several resonances were observed here
- Planned hadron programme of AMBER can contribute here
- Ultimately we will need a high statistics and precision, as possible with PANDA

Summary

- Although light mesons are studied for decades, there are still many open questions
- The non-perturbative regime of QCD challenges theory and experiment!
- This affects also other sectors as CP violation!
- Sophisticated line shape models should be used whenever possible
- Different experiments and theory need to collaborate to solve this
- Coupled channel analyses seem to be a good tool to disentangle crowded spectra
- Work closer together in the community - common effort is needed to answer fundamental questions!
- This strengthens the research field, especially in times when basic research is experiencing more headwinds

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Thank You!