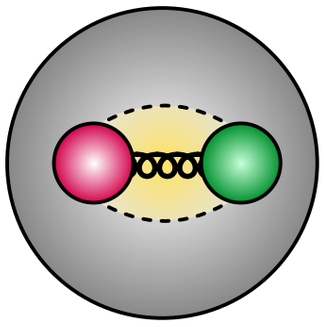
The Charm of Exotic Hadrons

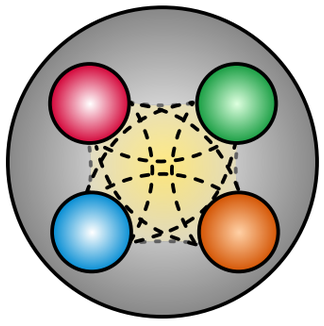
Meike Küßner - College of William and Mary

March 2nd - 2026

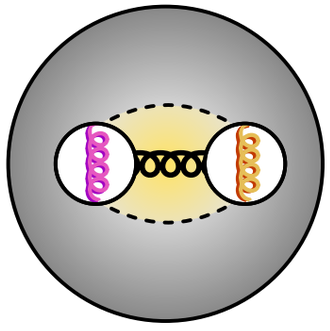
What is Exotic Matter?



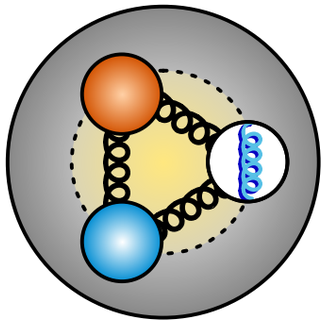
Meson



Tetraquark



Glueball



Hybrid

At least there are some characteristics that help to identify them:

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

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

- Exotic quantum numbers: $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \ldots$
- States with exotic quantum numbers have indeed been found!
- Other states show odd behavior and cannot be clearly classified (exotics?)

➡ Measure their resonance properties and occurrence in different production- and decay reactions

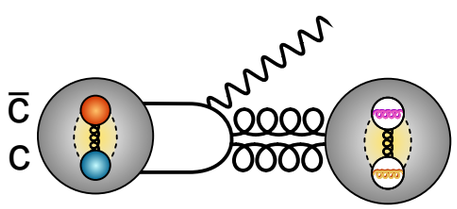
Coupled Channel Approach

- Combine data from different reactions and/or experiments to gain more constraints

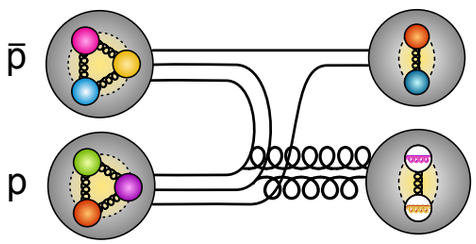
„Gluon rich“ processes

- Charmonium decays
- $\bar{p}p$ annihilation
- pp central production

radiative J/ψ decays

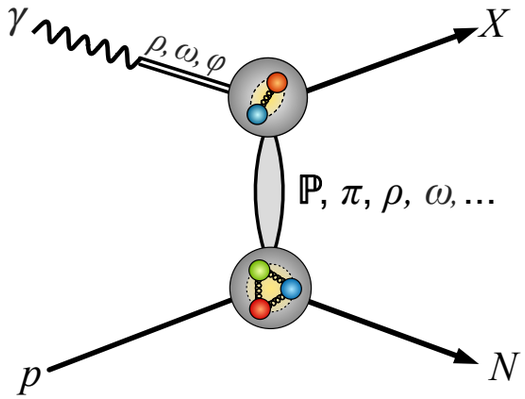


p̄p annihilation



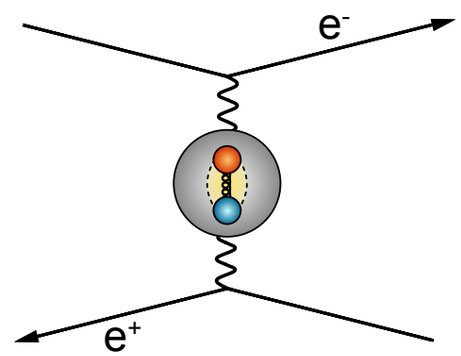
• • •

- Photo production



„Gluon poor“ processes

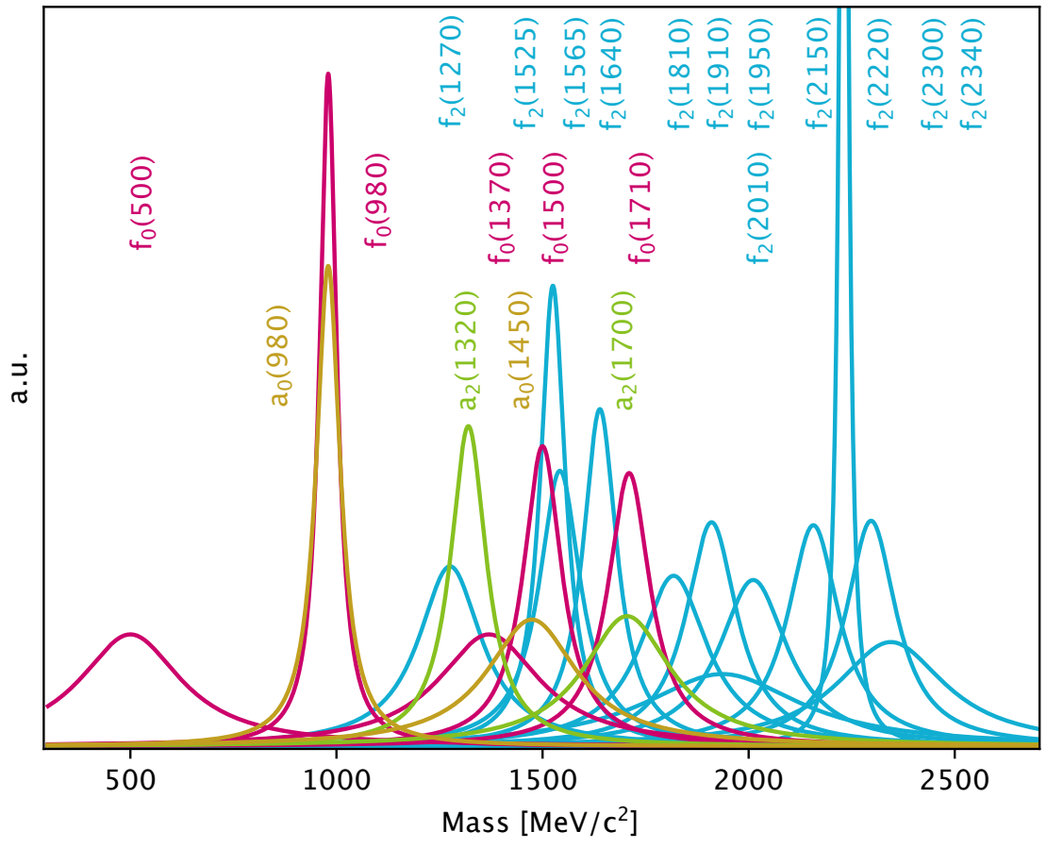
- Two-photon production



Light Meson Regime

- Spectrum is very populated!
- Several broad resonances of the same Q.N. overlap and interfere
- Inelastic channels and thresholds appear
- Determination of resonance properties is difficult
- Sometimes resonances appear not always as peaks ⇔ Peaks not necessarily caused by a resonance
- Analyzing a single reaction is not enough to disentangle states unambiguously
- More sophisticated tools and descriptions needed!

spectrum of well established states



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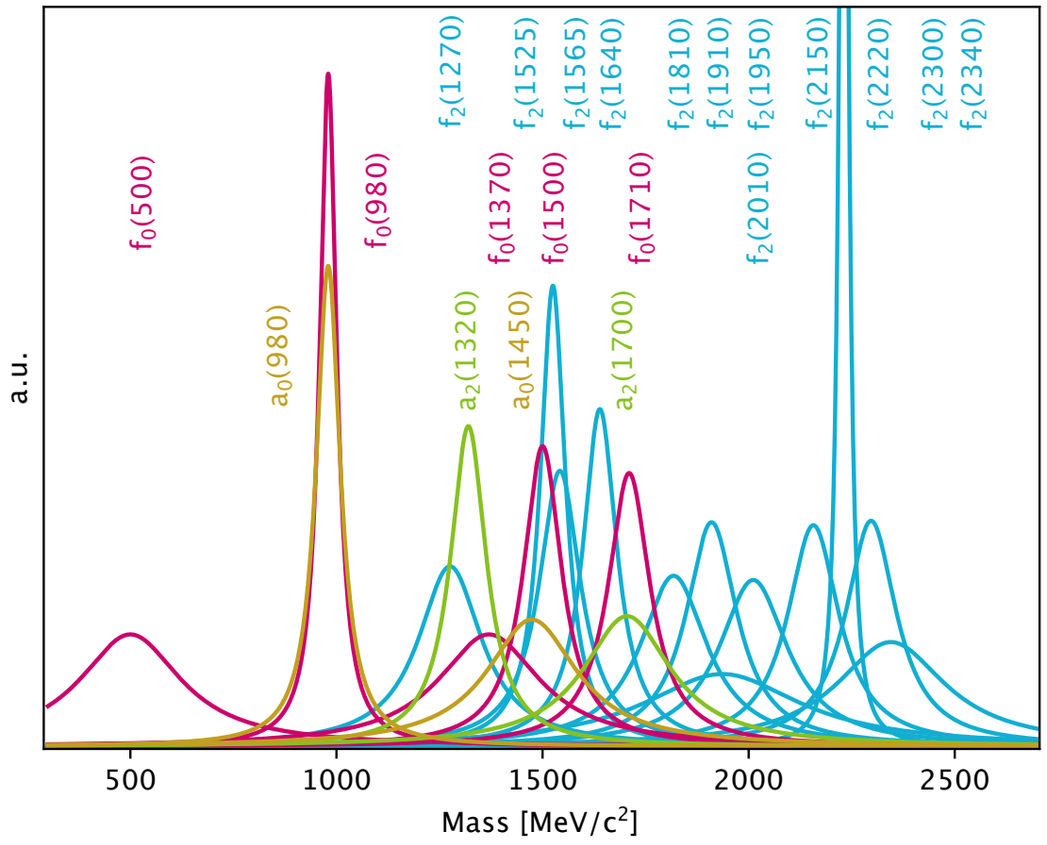
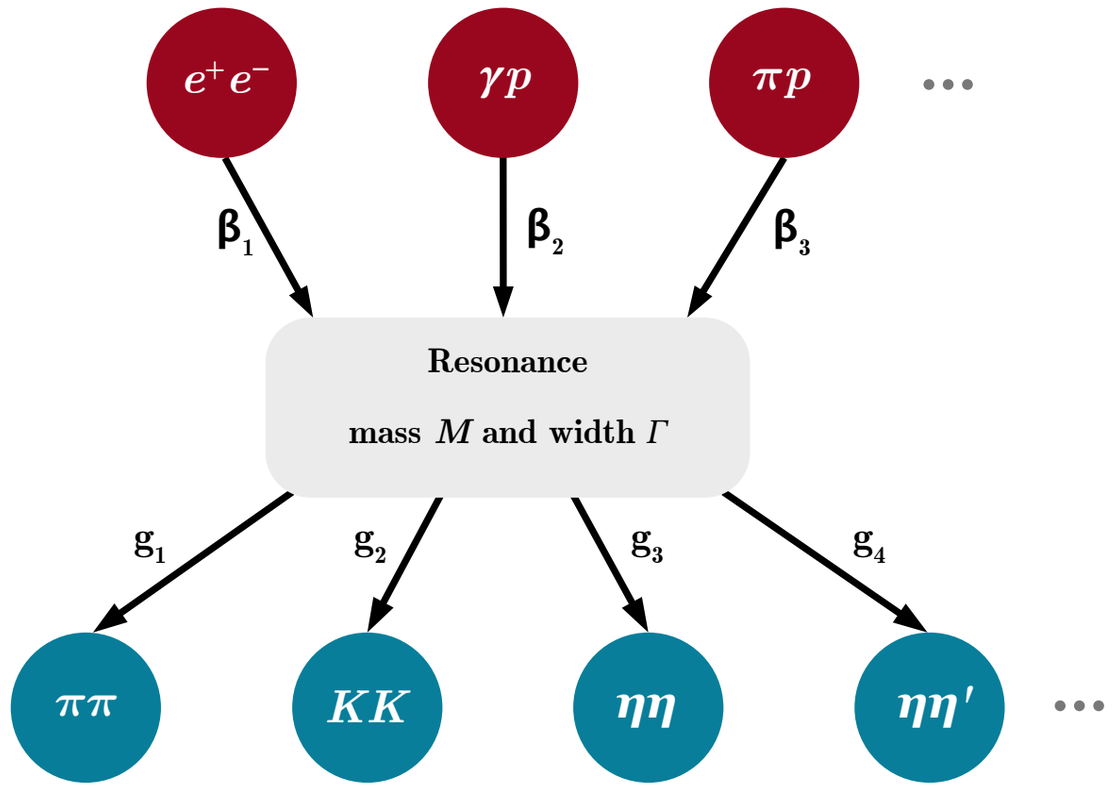
spectrum of well established states



We should start thinking beyond individual experimental collaborations!

Coupled Channel Approach

Compare different production mechanism and decay channels to learn about the inner structure of particles

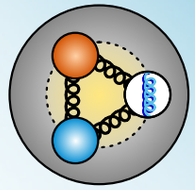


Many parameters can be shared and thus better determined

Better conservation of unitarity and description of threshold effects

Bringing all the pieces of the puzzle together

One Prominent Example: The Lightest Hybrid Candidate



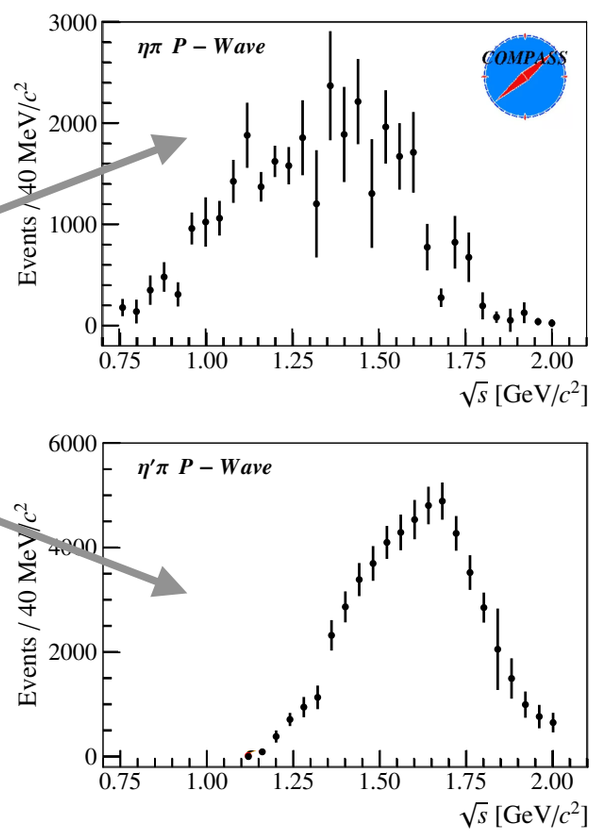
Two π_1 hybrid candidates below 2 GeV are listed in PDG

- 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 $\pi\eta$

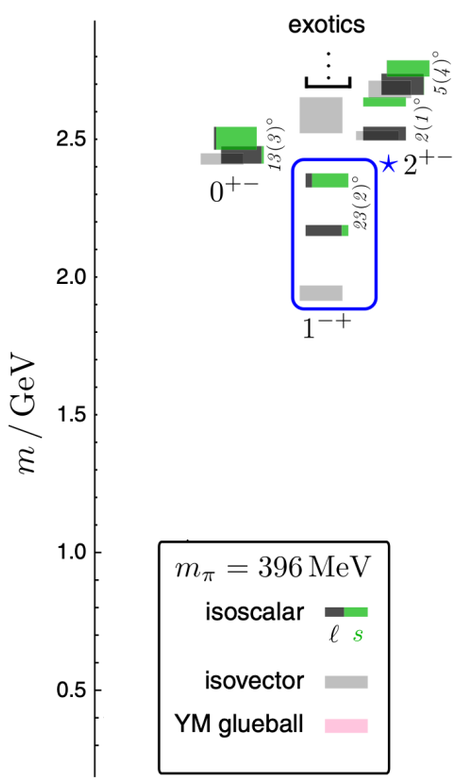
➡ Parameters obtained by Breit-Wigner fits!

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

200 MeV apart!

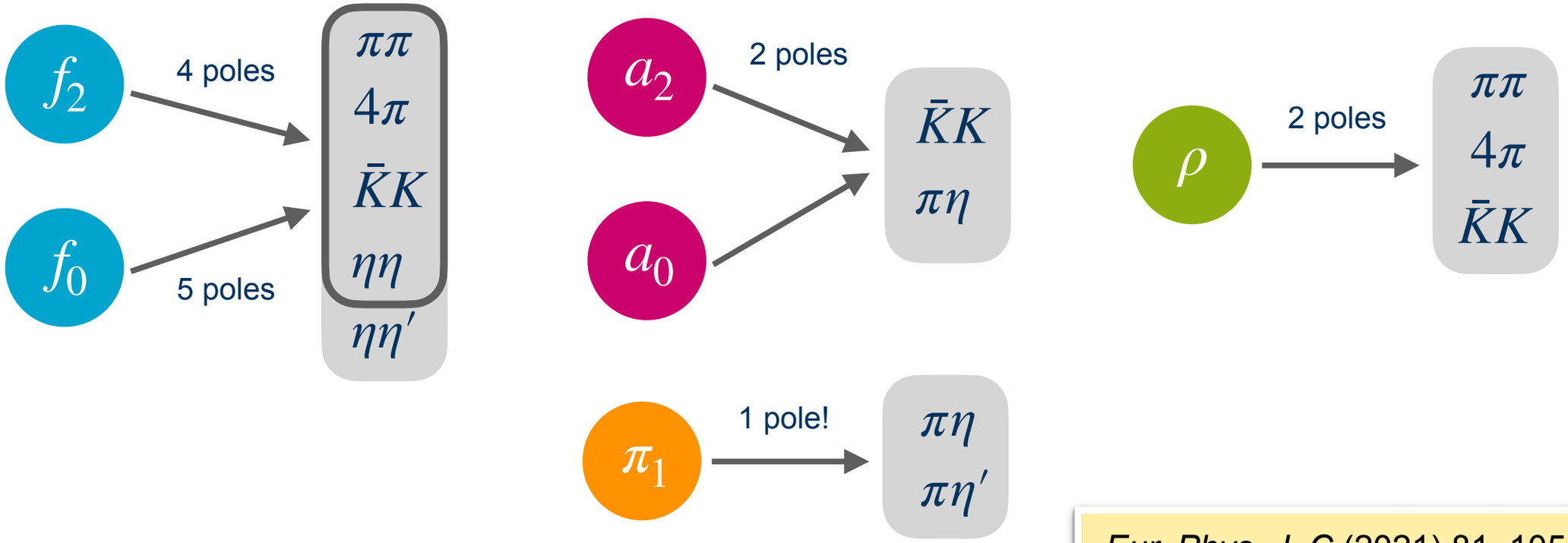


Phys.Rev. D84 (2011) 074023



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

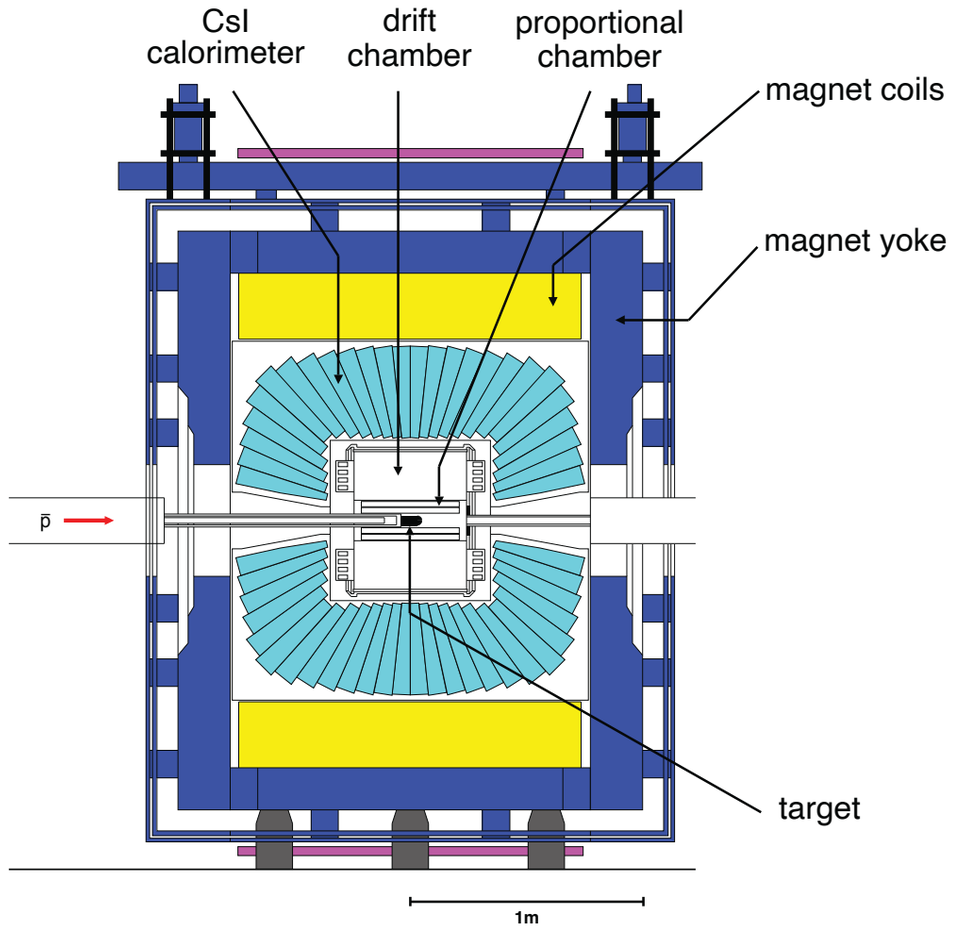
- Combining data from different experiments:
- $\bar{p}p \to \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$ data in flight form Crystal Barrel at LEAR
- COMPASS data of P- and D-waves in the $\pi\eta$ and $\pi\eta'$ systems
- 11 different $\pi\pi$ scattering data samples
- Simultaneously described 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

$\bar{p}p$ Data from Crystal Barrel at LEAR

- Crystal Barrel was in operation from 1989 - 1996
  - Fixed target experiment at LEAR
  - $\bar{p}p$ annihilation at rest and in flight ➡ fundamental studies in the light meson sector!
  - Highest beam momentum 1.94 GeV/c (overlap with $\bar{P}$ANDA 1.5-15 GeV/c)



$\bar{P}$ANDA will have a 100 times higher luminosity!

➡ 1 year data taking becomes 3.5 days!

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

- 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

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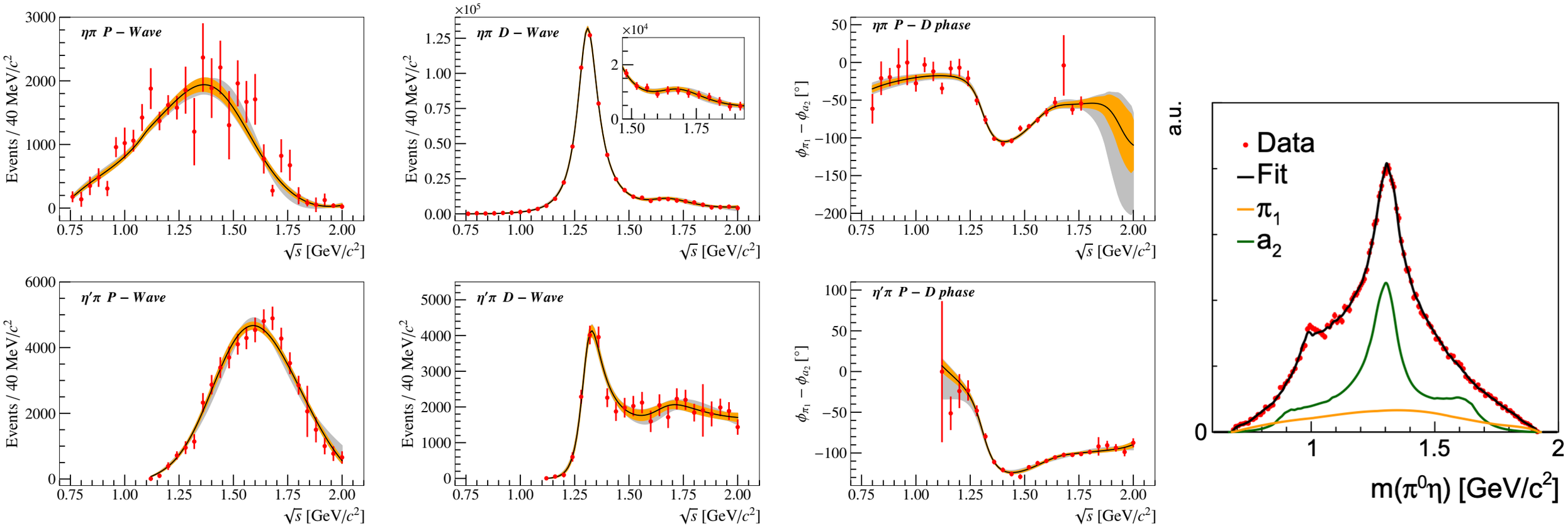
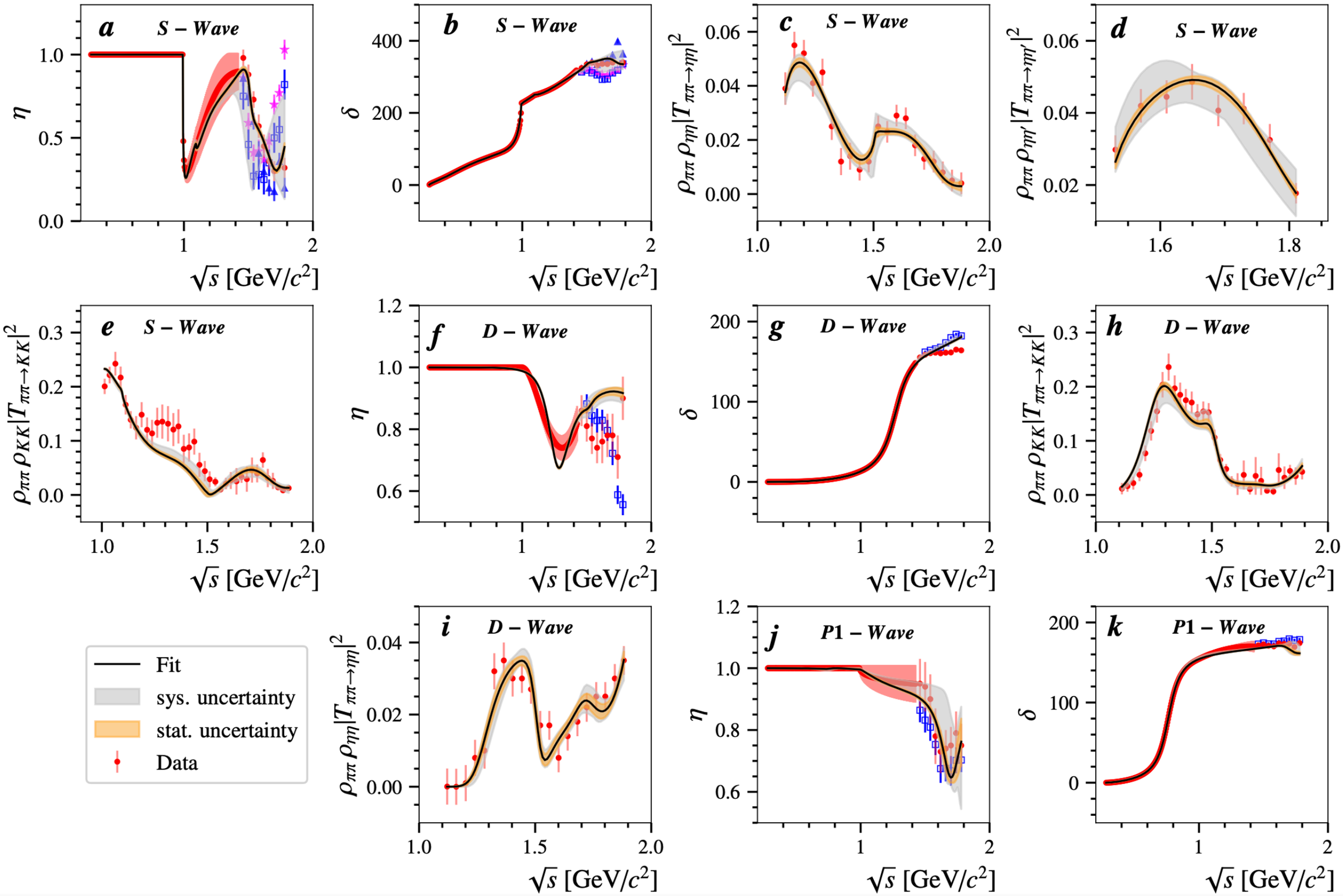


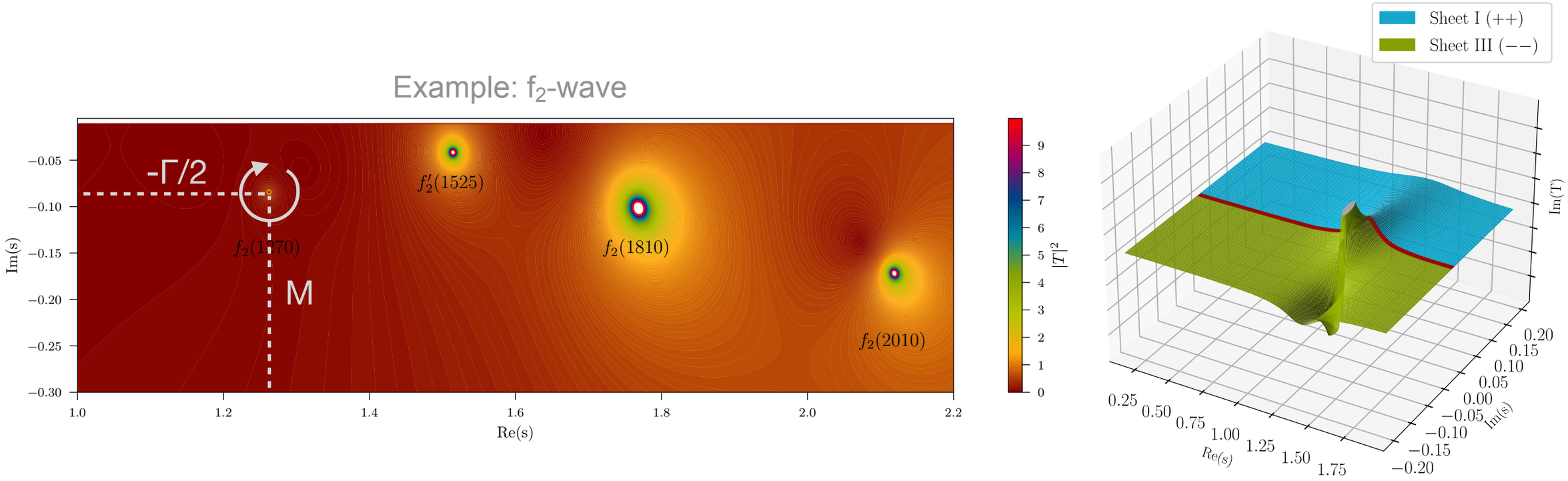
Obtained pole position:

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

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 $\bar{p}p$ 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	$1511.0 \pm 8.5\ ^{+3.5}_{-14.0}$	$81.1 \pm 4.5\ ^{+26.9}_{-0.5}$
$f_0(1710)$	$\bar{p}p$ + 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	$1700 \pm 27\ ^{+13}_{-16}$	$181 \pm 25\ ^{+0.0}_{-16}$	$13.6 \pm 1.2\ ^{+0.9}_{-0.5}$	$0.8 \pm 0.1\ ^{+0.0}_{-0.0}$	-

In our analysis several resonance properties measured simultaneously within a single fit!

(Although running 2 weeks on 200 CPUs)

Such parameterizations are universal and can be used in other analyses!

PAWIAN

PArtial Wave Interactive ANalysis

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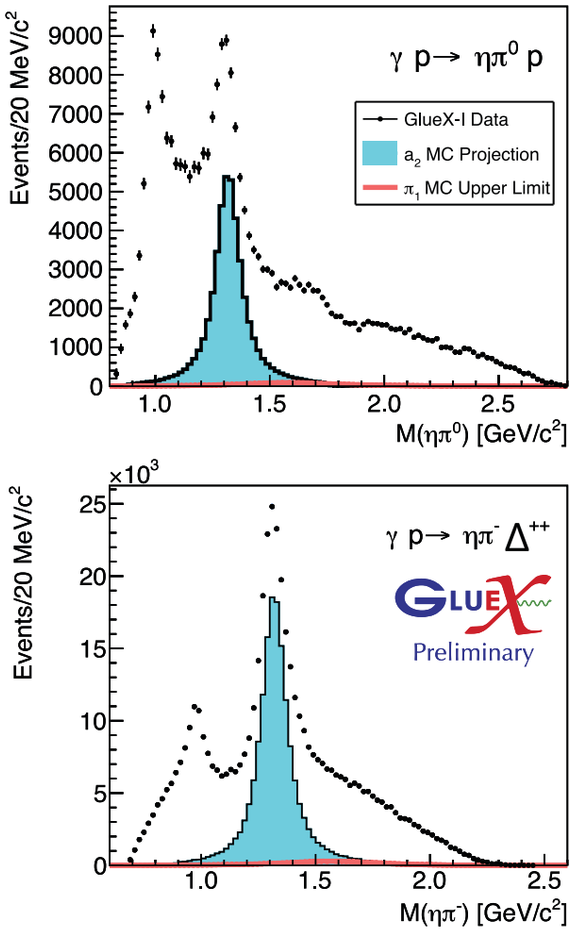
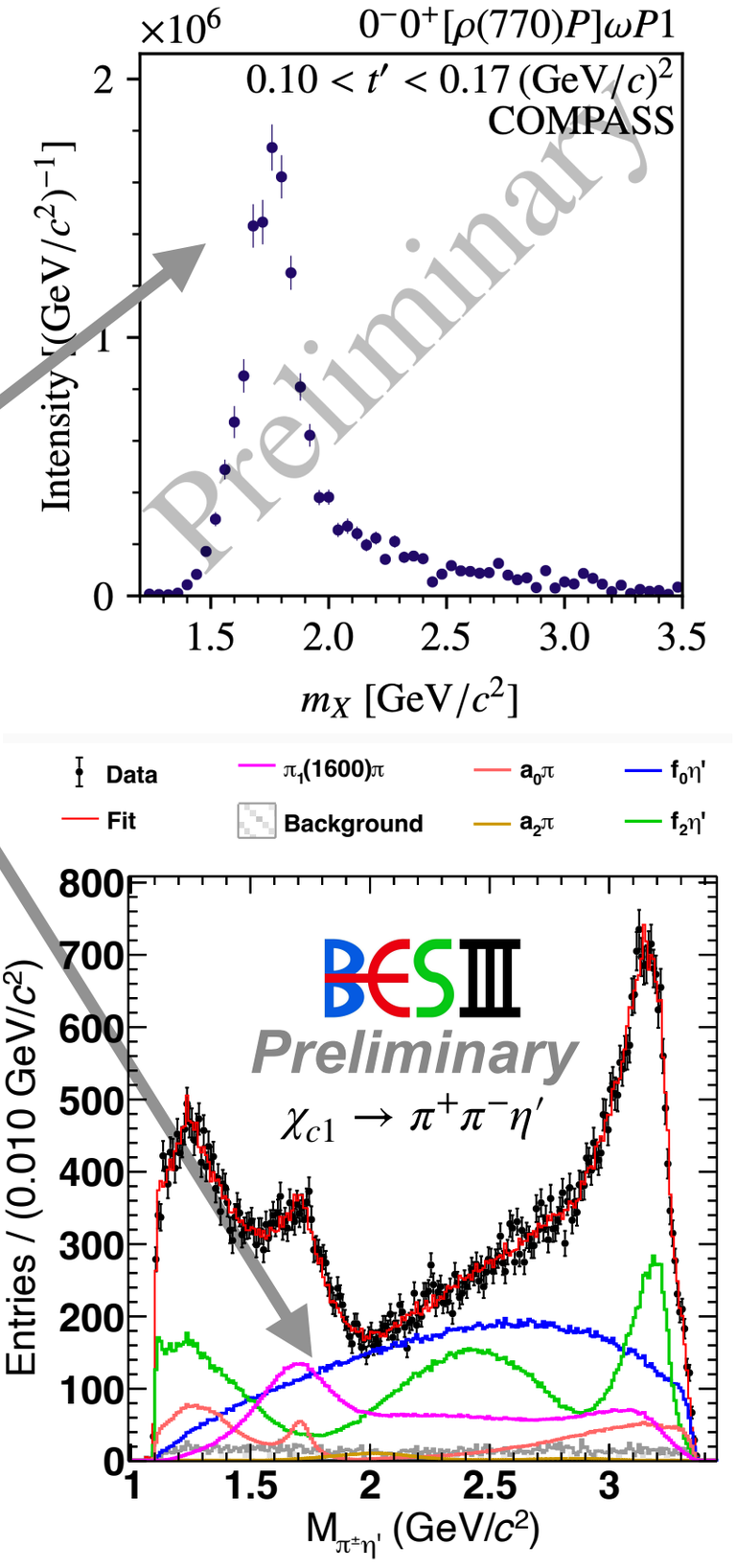
Future Prospects

- Study the π_1 in different production processes to learn about the inner structure
- Extend coupled fits to additional decay channels: e.g. $\rho\pi$ and $b_1\pi$

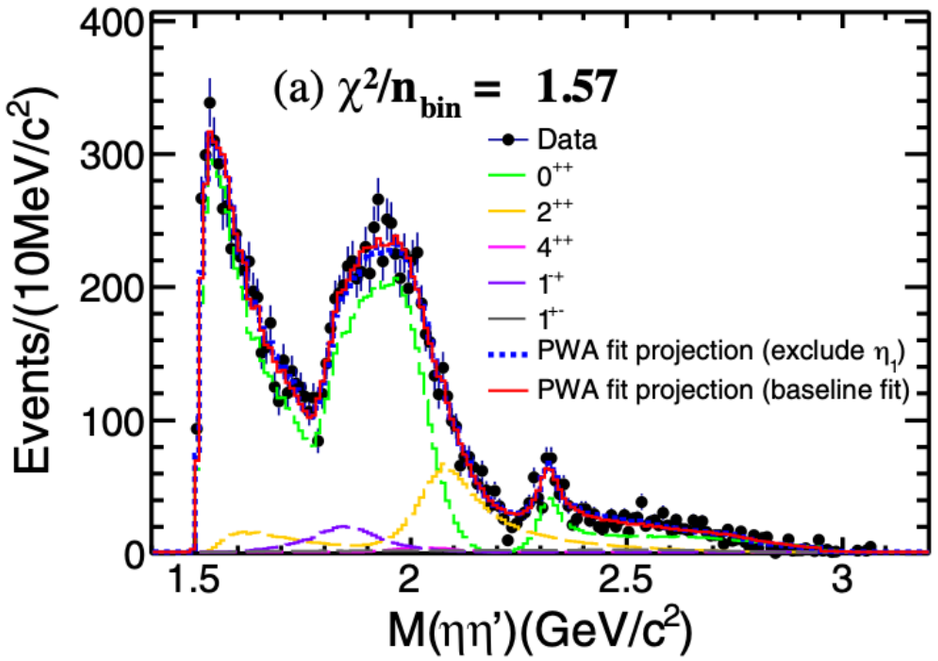
$\pi_1(1600)$!





BESIII: Exotic candidate $\eta_1(1855)$ seen in $J/\psi \to \gamma\eta'\eta$

- Additional 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 $\pi_1(1600)$
- But a quite simple model used here…



BESIII + GlueX

- Further studies needed!
- Unique opportunity to combine data from GlueX, BESIII, ($\bar{p}$p) to clarify this candidate
- Search for additional decay channels and improve the PWA model

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

New Software Tools

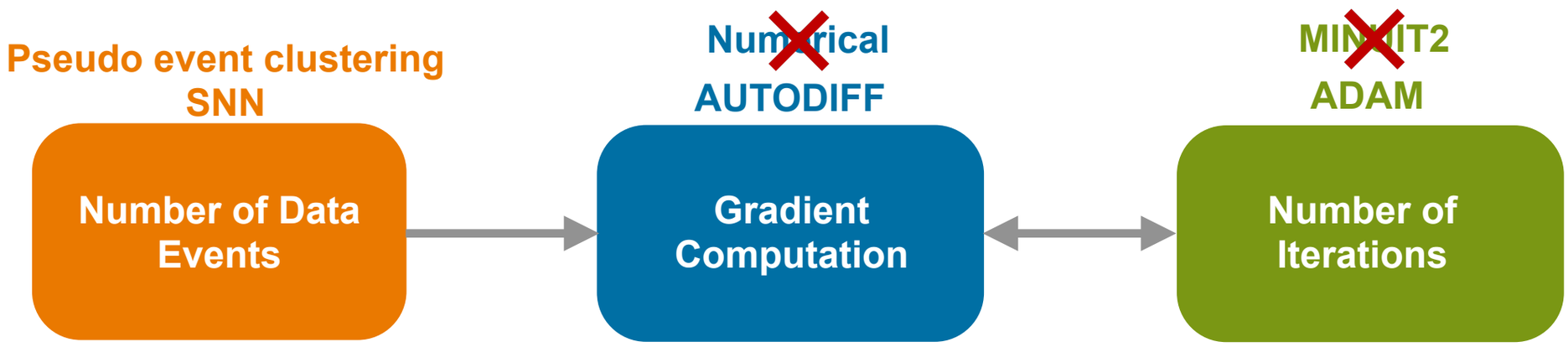
NRW-FAIR Netzwerk

To perform expensive analyses with increasing statistics we need to get faster and more efficient!

Development of faster algorithms required:

- Including AI techniques where helpful

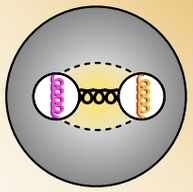
<u>Fit time depends mainly on:</u>

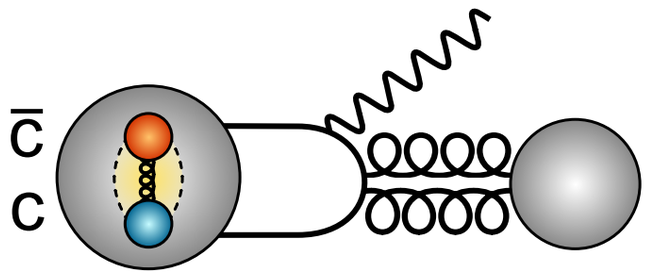


Preliminary results show speed-increase of up to 20!

Interesting for other experiments!

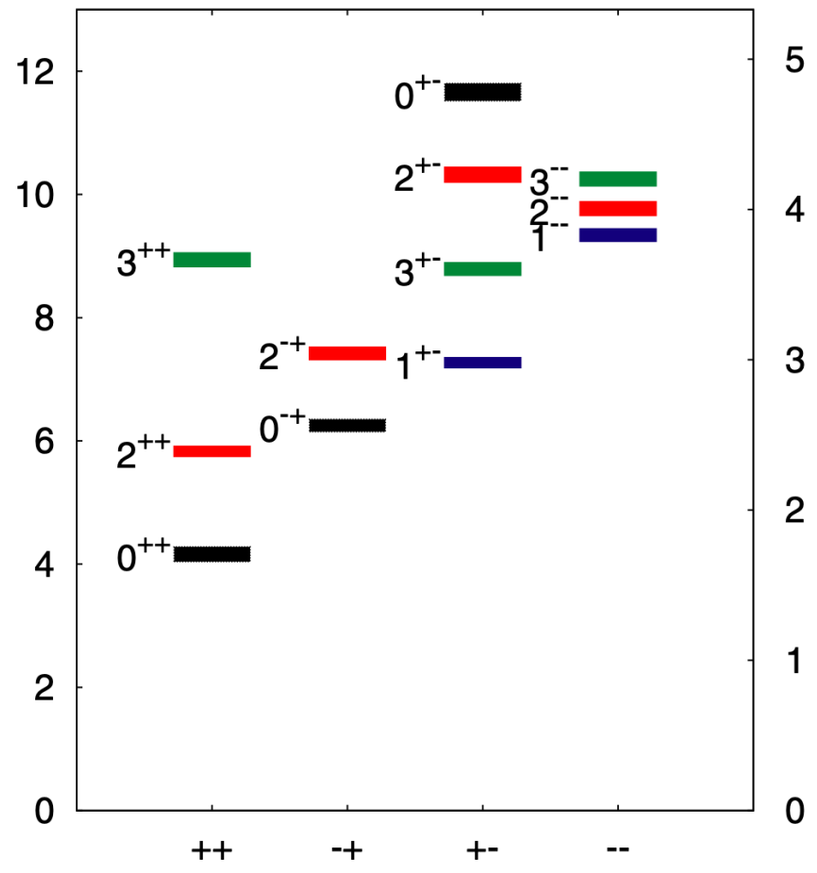
BESIII: Charmonium Decays





- 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 , ψ', …
  - ➡ 50 times more than 10 years ago!

Phys. Rev. D 73, 014516 (2006)



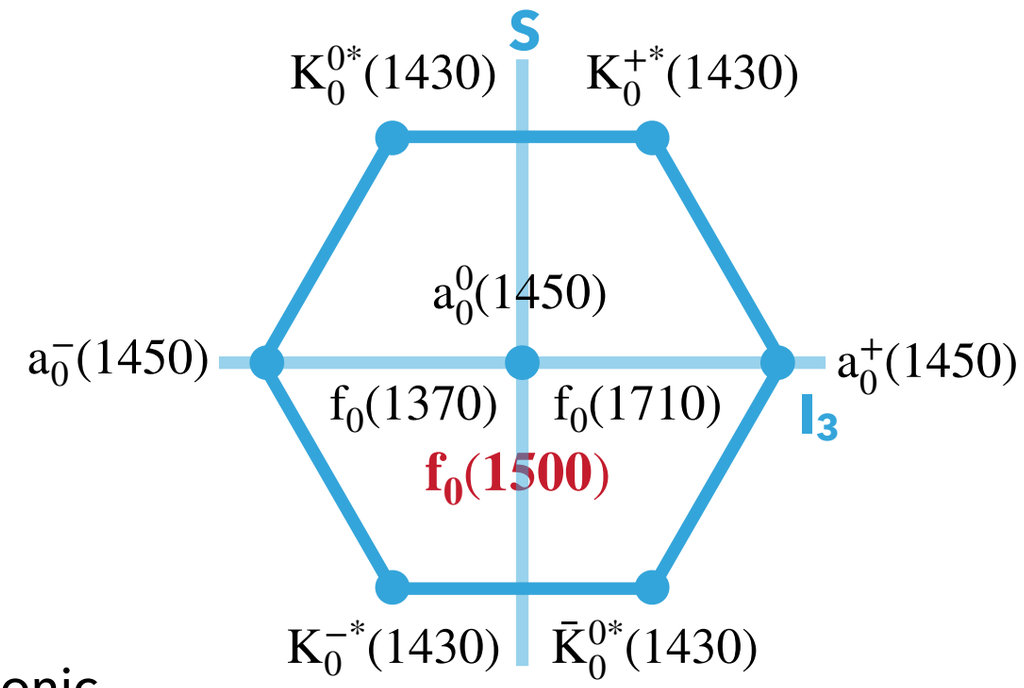
Candidates for the $J^{PC} = 0^{++}$ Glueball

- Lattice calculations predict for the ground-state $M = 1400 - 1700\,\mathrm{MeV}/c^2$:
- Scalar mesons below 1 GeV (e.g. $f_0(500), f_0(980)$) are widely assumed as tetra quarks

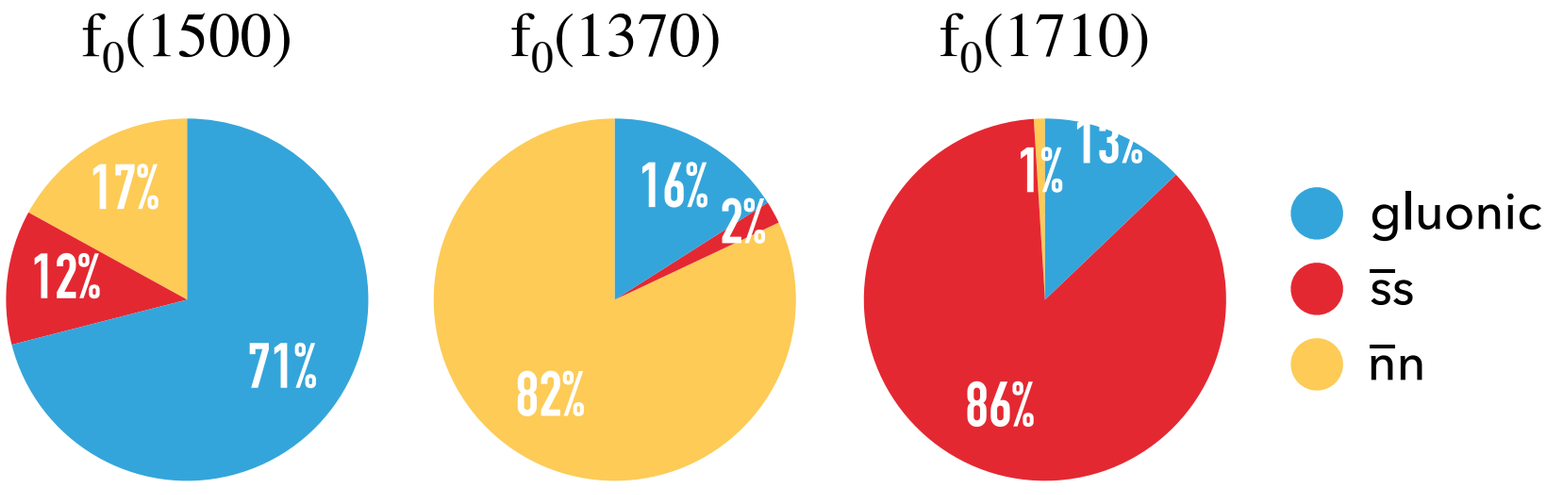
s. PRD 91 (2015) 114015

- Same quantum numbers as ordinary $q\bar{q}$ mesons
- Glueball can mix with states close by in mass

$$\begin{pmatrix} |\mathrm{f_0(1370)}\rangle \\ |\mathrm{f_0(1500)}\rangle \\ |\mathrm{f_0(1700)}\rangle \end{pmatrix} = \mathrm{U} \begin{pmatrix} |\mathrm{gg}\rangle \\ |\bar{\mathrm{s}}\mathrm{s}\rangle \\ |\bar{\mathrm{u}}\mathrm{u} + \bar{\mathrm{d}}\mathrm{d}\rangle / \sqrt{2} \end{pmatrix}$$



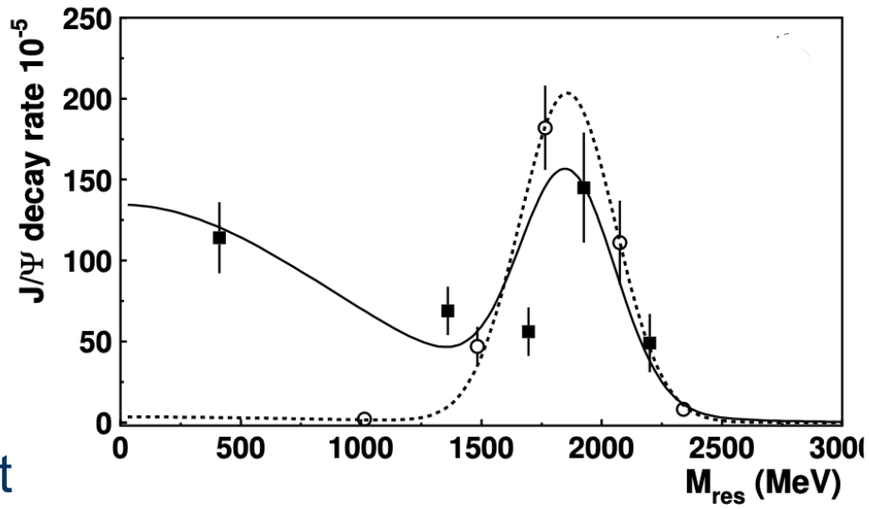
One is supernumerous!



based on C. Amsler, Lecture Notes in Physics

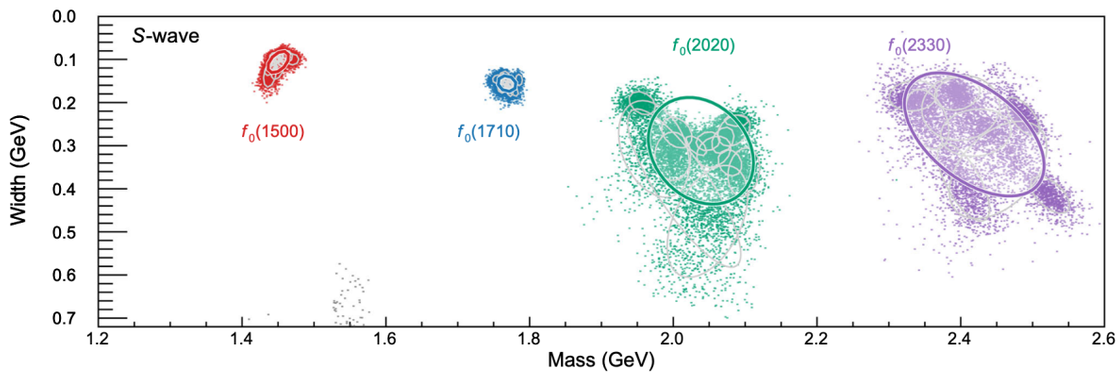
Recent Analyses for the 0^{++} Glueball

- ***Coupled channel fit by Sarantsev et. al.:*** *Phys. Lett. B 816* (2021), 136227
  - $J/\psi \rightarrow \gamma + (\pi^0\pi^0, K_S^0K_S^0, \eta\eta, \omega\phi)$ (BESIII)
  - $\pi^+\pi^-$- scattering data (CERN-Munich, GAMS, BNL)
  - $\bar{p}N \rightarrow$ 3 mesons (CB-LEAR)



- Indirect hint for the light scalar glueball candidate by measuring the production strengths of scalar states included in the PWA
- 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 only mass independent amplitudes for $J/\psi \rightarrow \gamma\,\pi^0\pi^0, \gamma\,K_S^0K_S^0$ (BESIII)
  - Only 4 scalar poles needed - in contrast to 10 needed by Sarantsev et. al.
  - No statement towards glueball contributions
  - But: Theory has only access to binned data based on older data samples

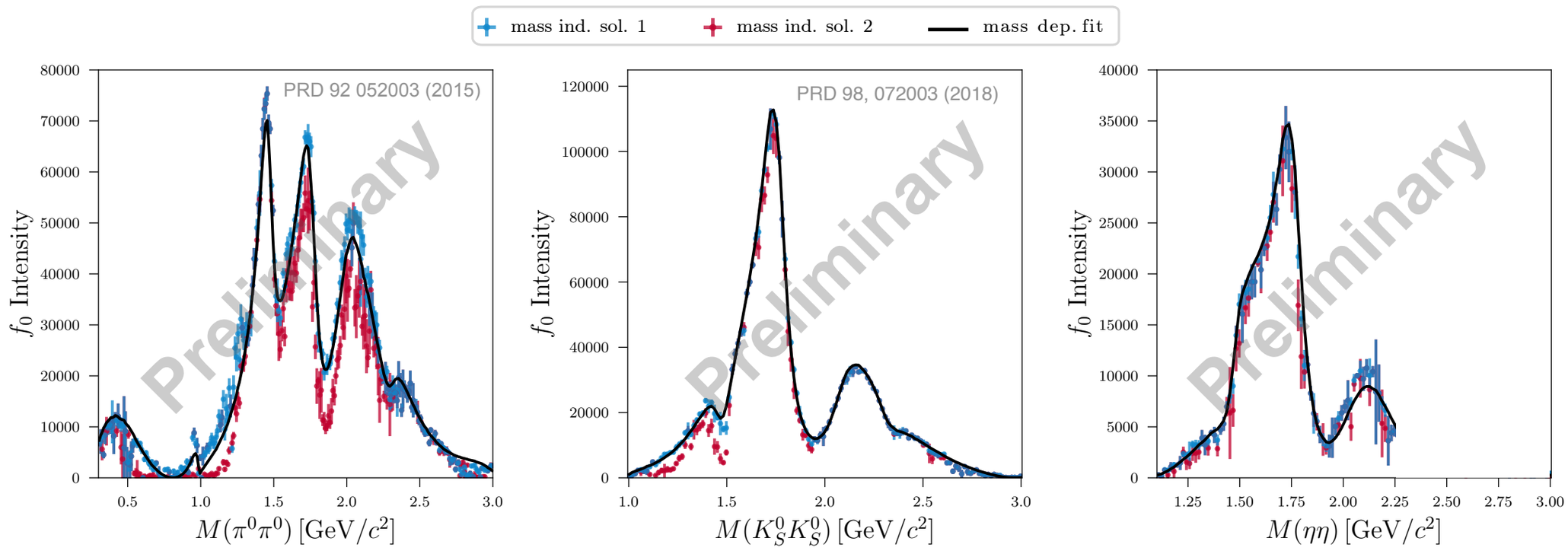


BESIII: Ongoing Analyses

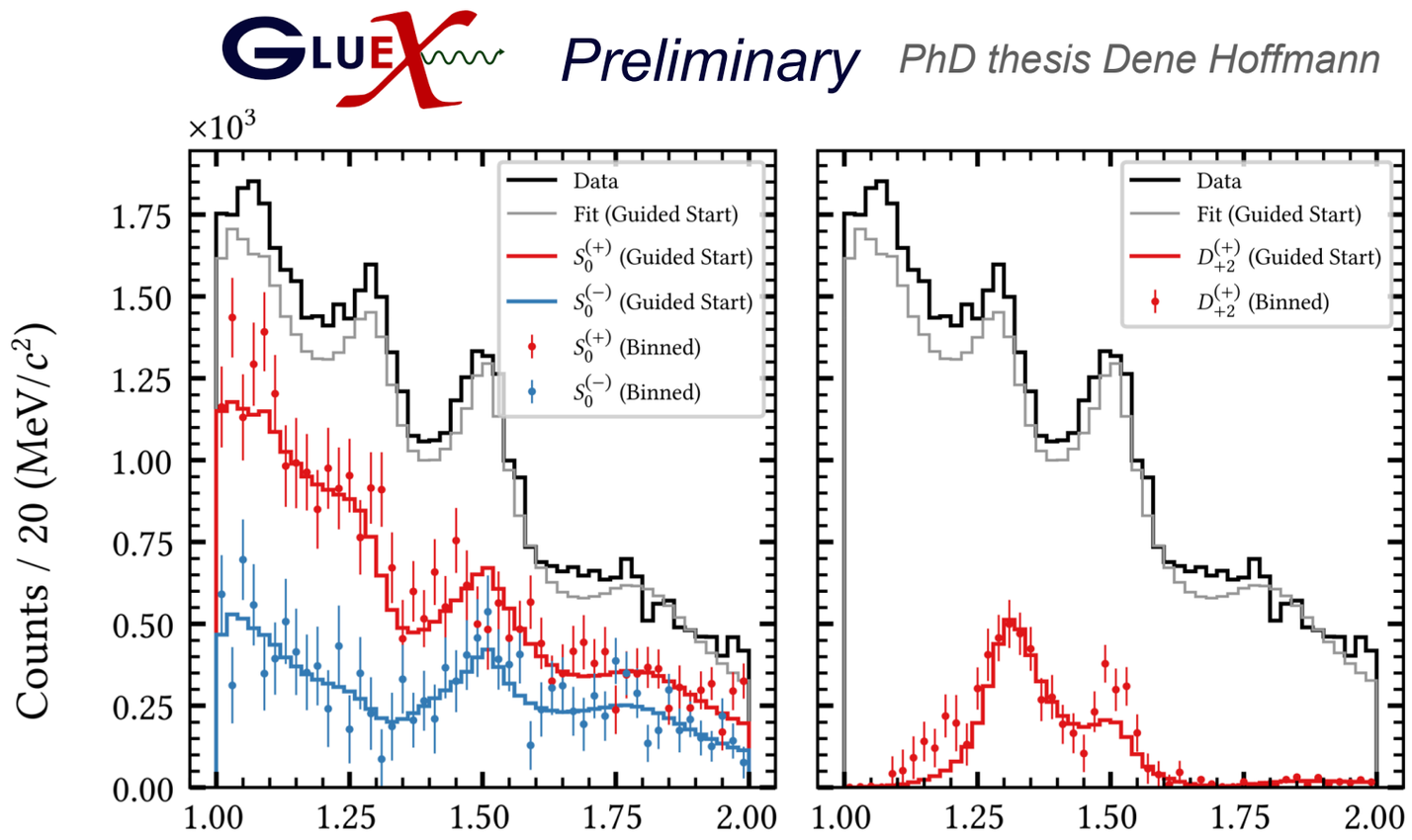
- Much higher statistics available (*50 times more now available!*)
- Mass-independent amplitude analysis in preparation for $J/\psi \to \gamma\pi^0\pi^0$, $\gamma K_S^0 K_S^0$ and $\gamma\eta\eta$

⊕ model-independent ⊖ ambiguous solutions

- Mass-dependent coupled channel fits - based on 4-vectors for all channels ongoing
  - ➡ Already promising results in good agreement with mass independent solution
  - ➡ Ambiguities from model-independent likely to be solved
  - ➡ Proper determination of production strength of 0^{++} and 2^{++} states possible!

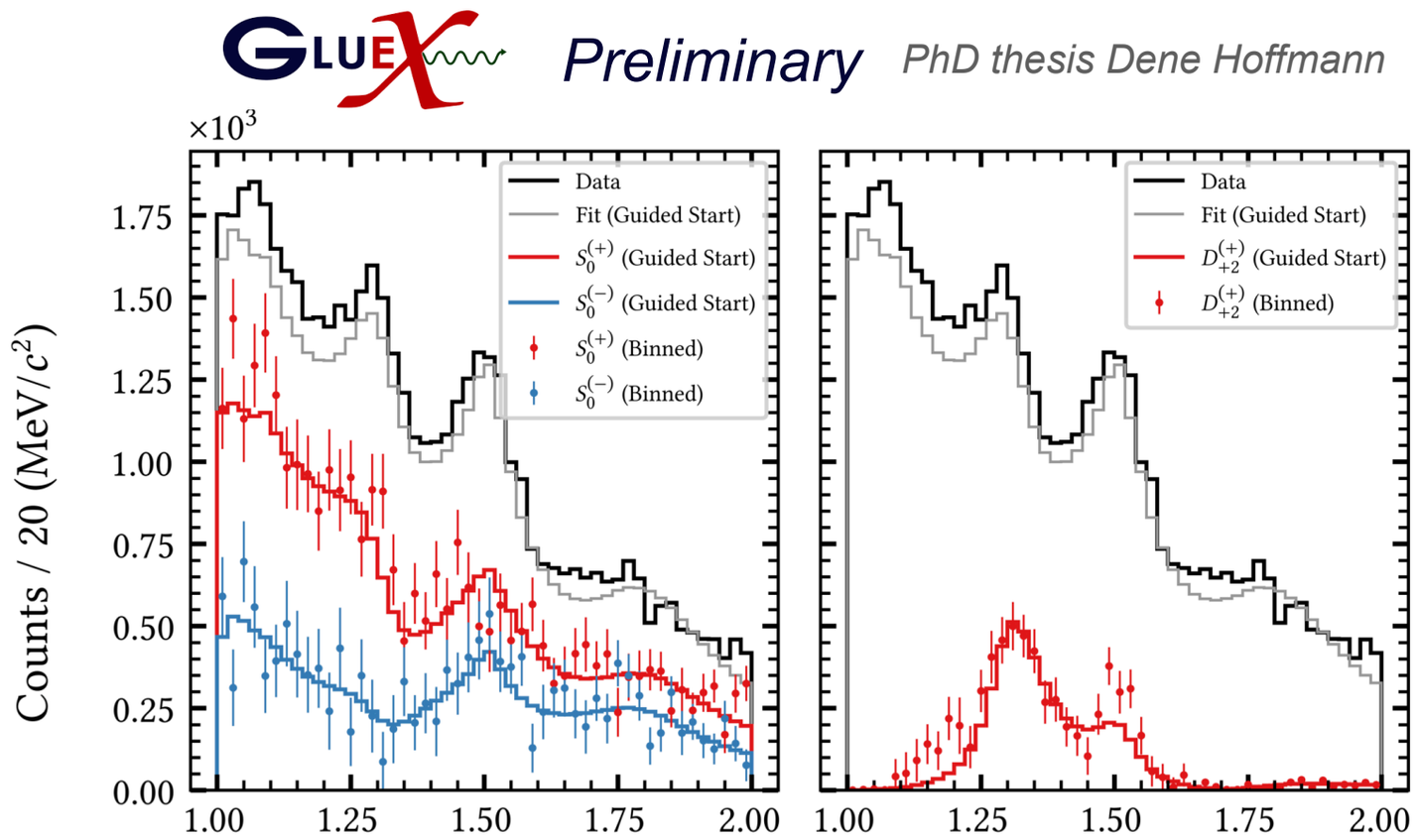


Future Prospects - $\gamma p \to K^0_S K^0_S p$



- Model independent analysis in good agreement with K-Matrix model from coupled channel result *Eur. Phys. J. C (2021) 81, 1056*
- Interesting feature in the S-wave 1500 region both in positive and negative reflectivity

Future Prospects - $\gamma p \to K^0_S K^0_S p$

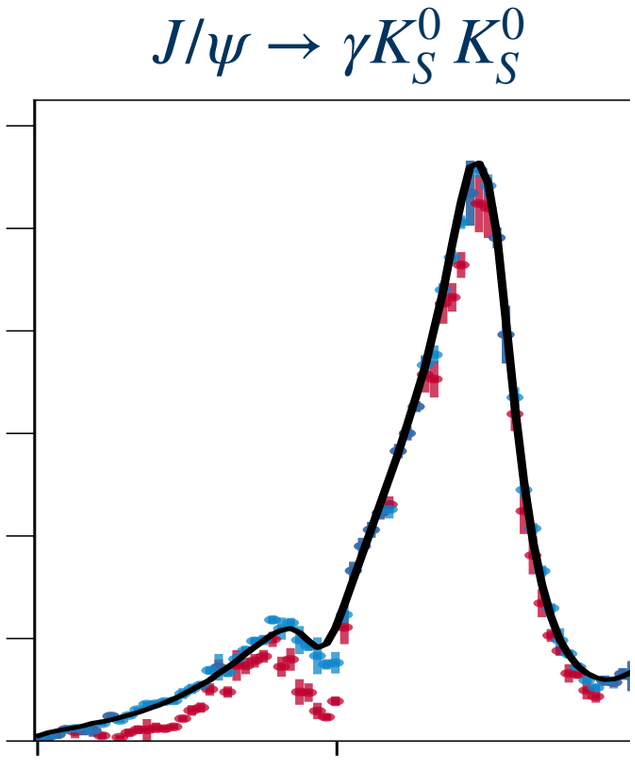


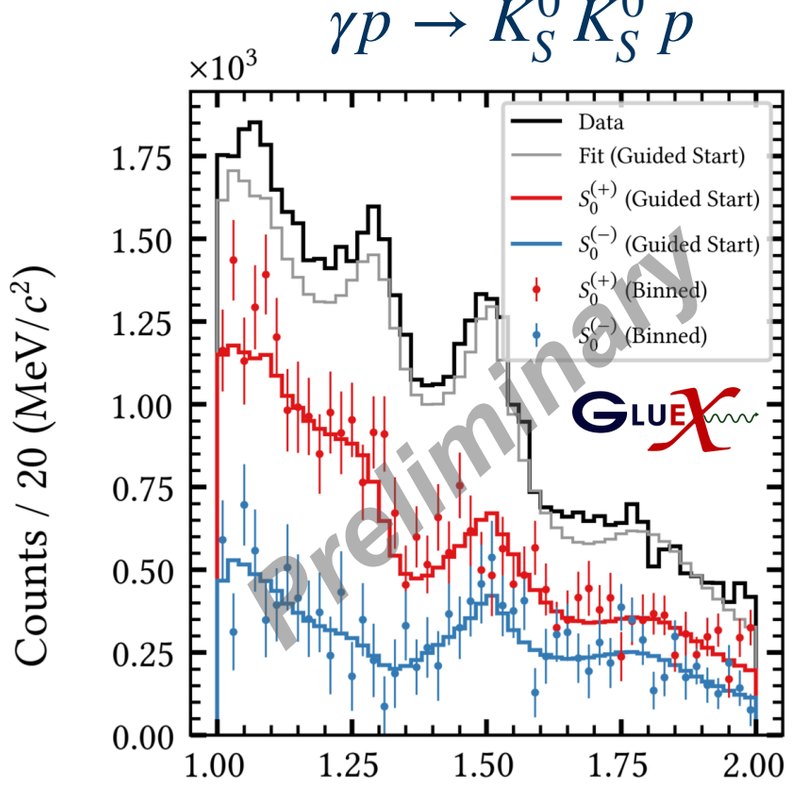
Start a coupled channel analysis project on GlueX data:

- Combine with $\pi^0\pi^0, \pi^0\eta, K^+K^-$ to disentangle states
- Get access to t-dependence

Comparison with Radiative J/ψ Data

- No contribution in $f_0(1700)$ region compared to J/ψ
- Different production mechanism for the $f_0(1500)$?
- What does it tell if it is produced in photo-production vs in rad J/ψ?



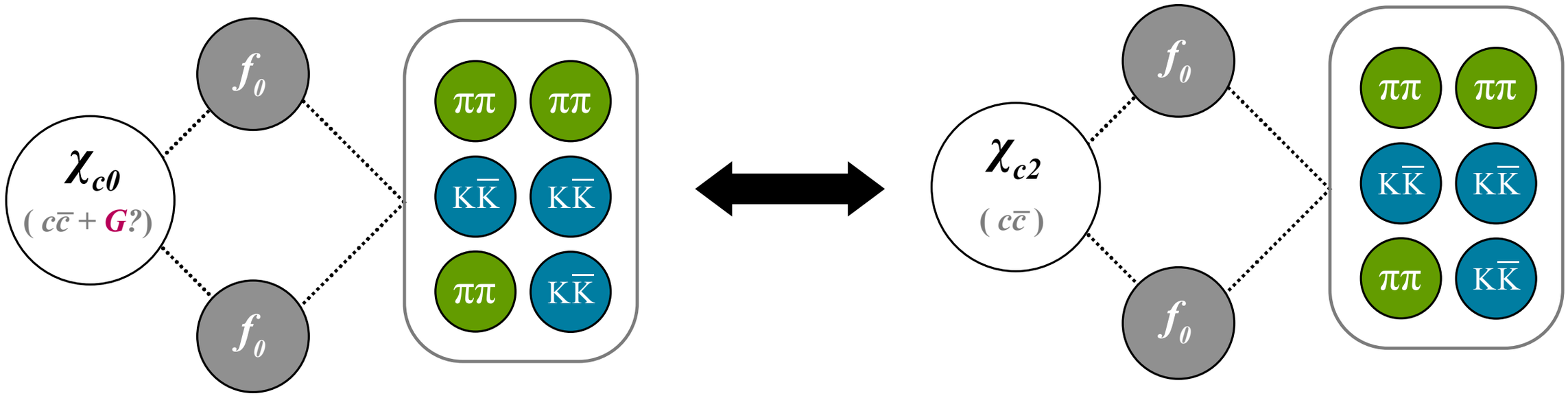


A New Approach to Search for Glueballs

- Excited 0^{++} glueball predicted around $3\,\mathrm{GeV}/c^2$, unquenched calculations even higher towards $3.7\,\mathrm{GeV}/c^2$

  JHEP **2012**, 170 (2012)

- χ_{c0} might contain a gluonic admixture due to the presence of a nearby glueball
- Glueballs are expected to decay also into lighter glueballs…
- Idea:
  - Measure the coupling of χ_{c0} to $f_0(X)f_0(Y)$, … and compare it to χ_{c2} couplings



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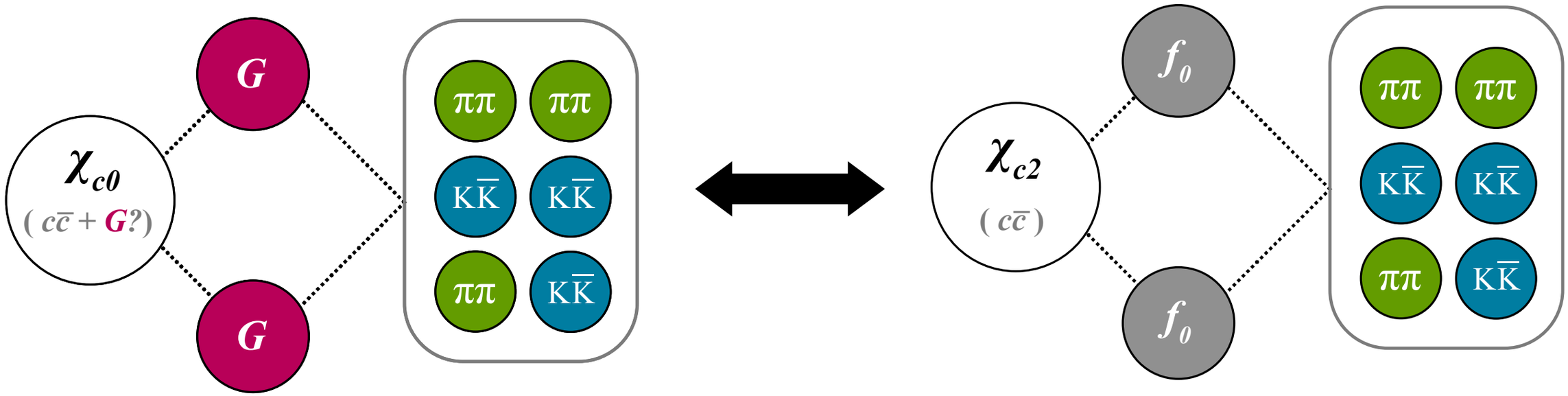


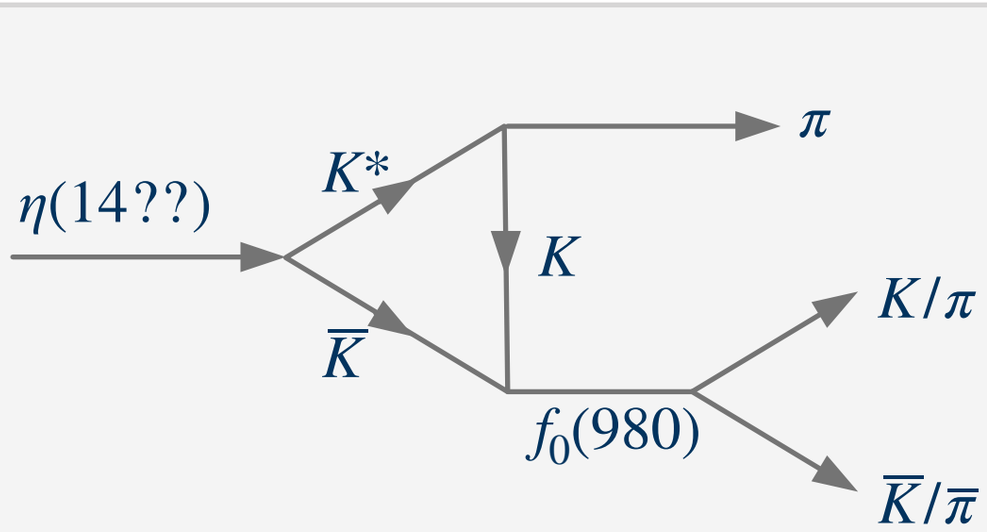
Thoughts on the 0^{-+} Glueball

From simple quark model arguments there should be radial excitations of the η, η'

- But three states have been seen in several reactions: $\eta(1295), \eta(1405), \eta(1475)\ldots$
- Most theory predictions expect the 0^{-+} glueball around $2.6\,\mathrm{GeV}/c^2$ although some others see it below $2\,\mathrm{GeV}/c^2$ …

PLB 309, 378 (1993), PRD 60, 034509 (1999), PRD 73, 014516 (2006), PRD 82, 034501 (2010), PRD70, 114033 (2004) PRD 79, 014024 (2009), …

- Are the $\eta(1405), \eta(1475)$ one or two states ➡ Triangle singularity…?



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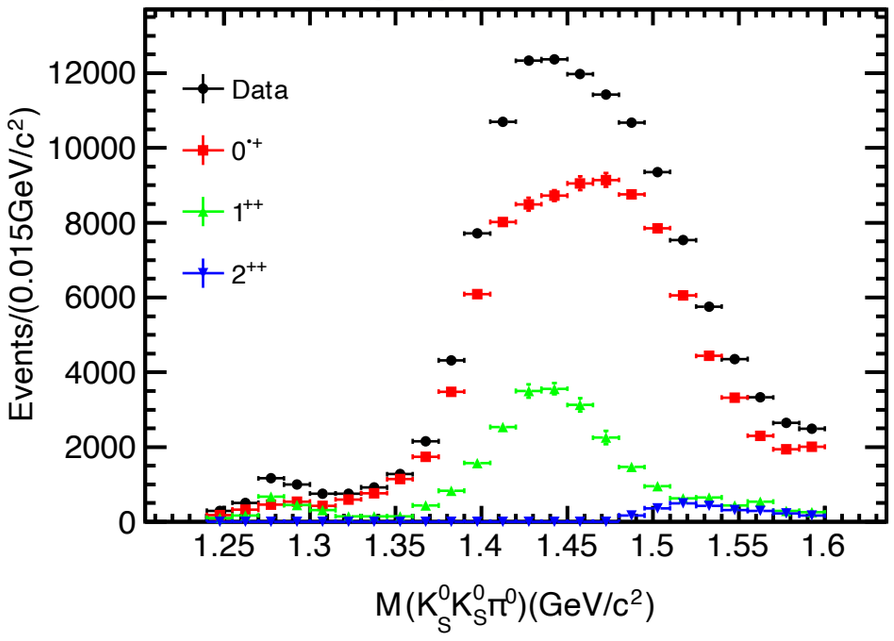
$J/\psi \to \gamma K_S^0 K_S^0 \pi^0$ JHEP 2023, 121 (2023)



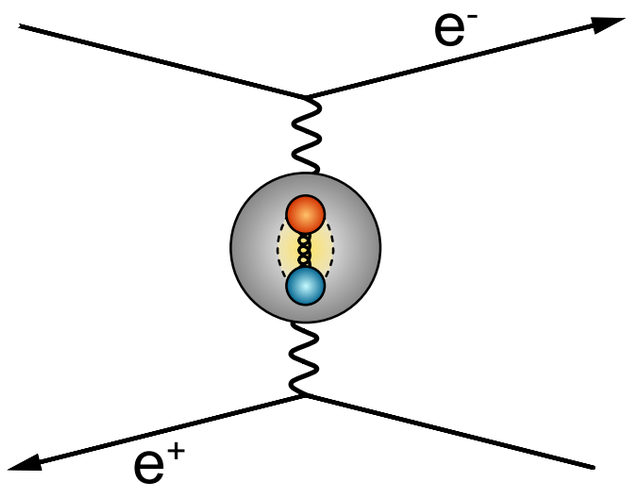
+

- Combine with GlueX data
- $\gamma p \to \eta(14??)p$
  - $KK\pi$
  - $\pi\pi\eta$

Two-Photon Reactions

- 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

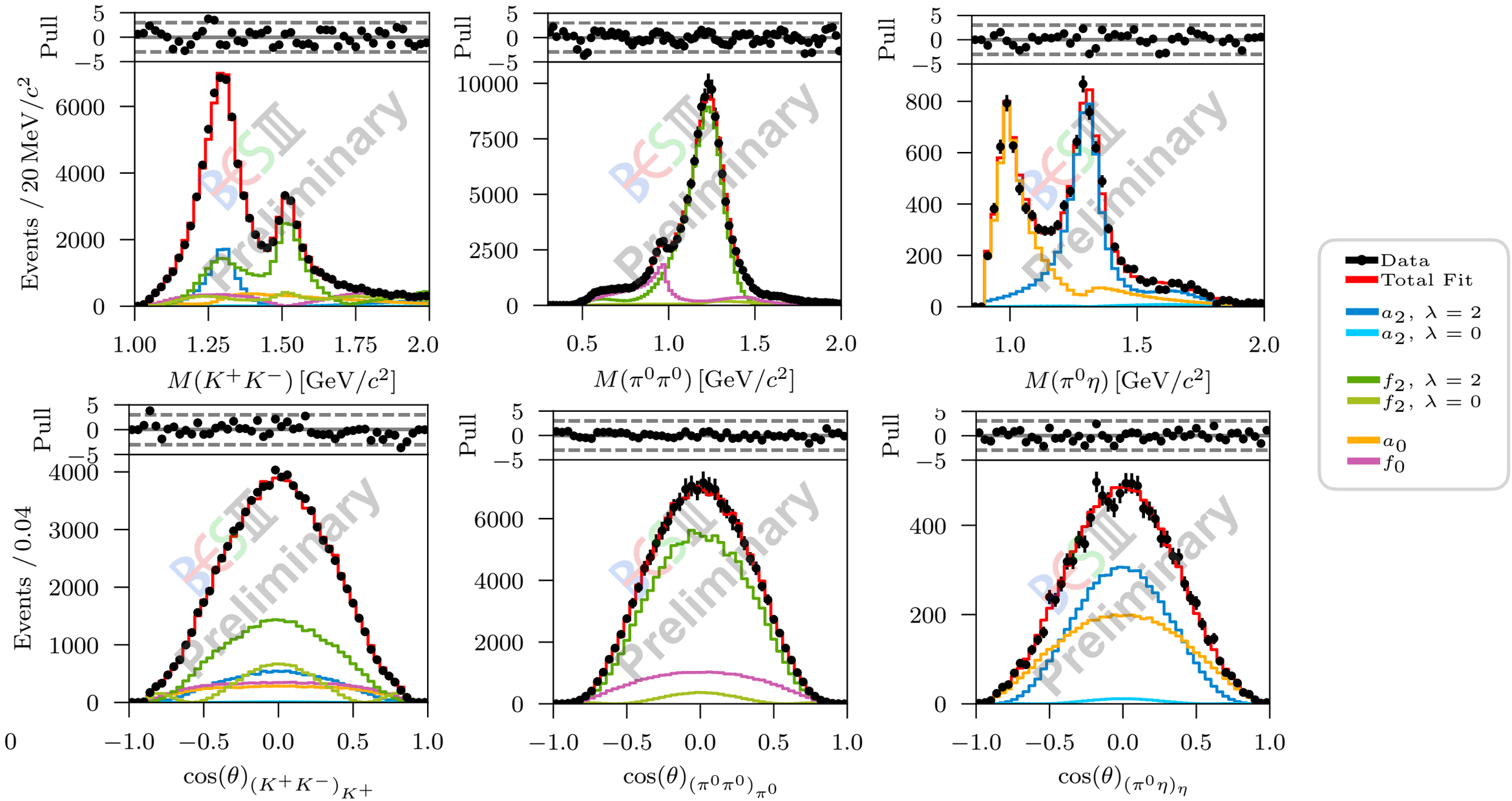


***Untagged reactions*:**

- Scattering angles of electron and positron are small and are not detectable

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

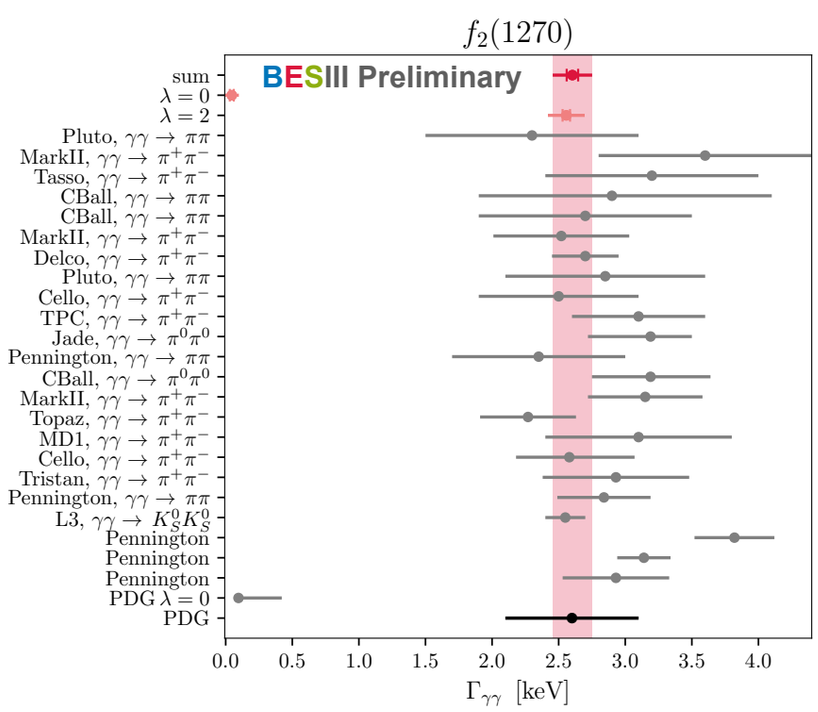


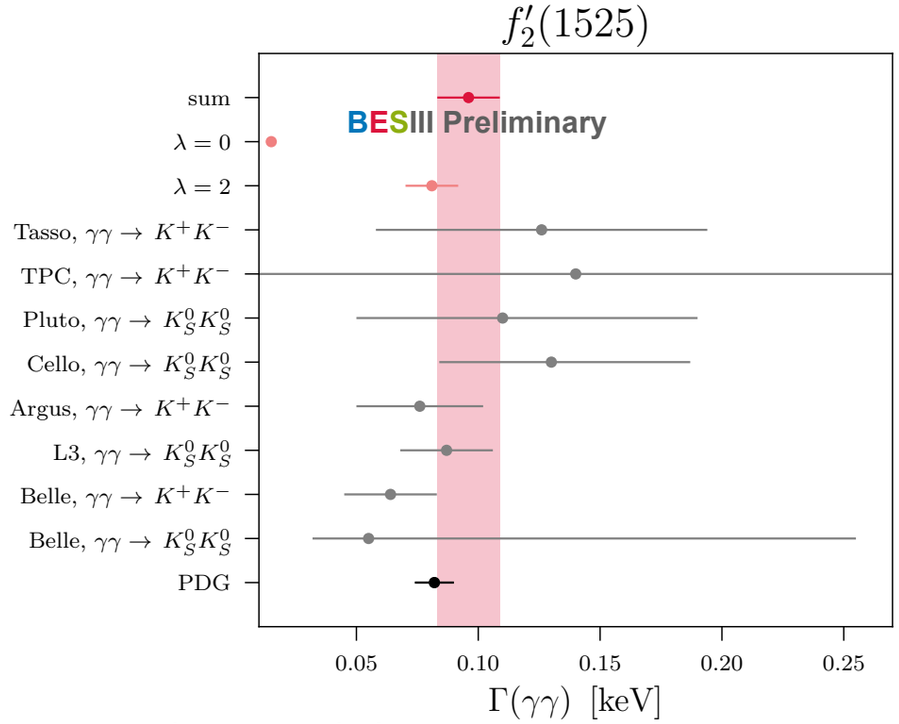
Determination of the Coupling Strength

- Determination of the two-photon width using the F-vector pole residue itself
- More accurate method than based on Breit-Wigner peak intensities
  - Also heavily interfering resonances can be separated…
  - Helicity contributions can be determined

$$\Gamma(X \to \gamma\gamma) = \frac{\alpha^2}{4\,(2J+1)\,M_R} \cdot \frac{Res_X(\gamma\gamma \to FS)}{\Gamma_{dec}}$$

Phys. Rev. D **90**, 036004





Error bars include systematic uncertainties

- Most accurate measurement for $f_2(1270)$ and $a_2(1320)$
- Scalar mesons $f_0(1370)$, $f_0(1500)$ und $f_0(1710)$ measured for the first time

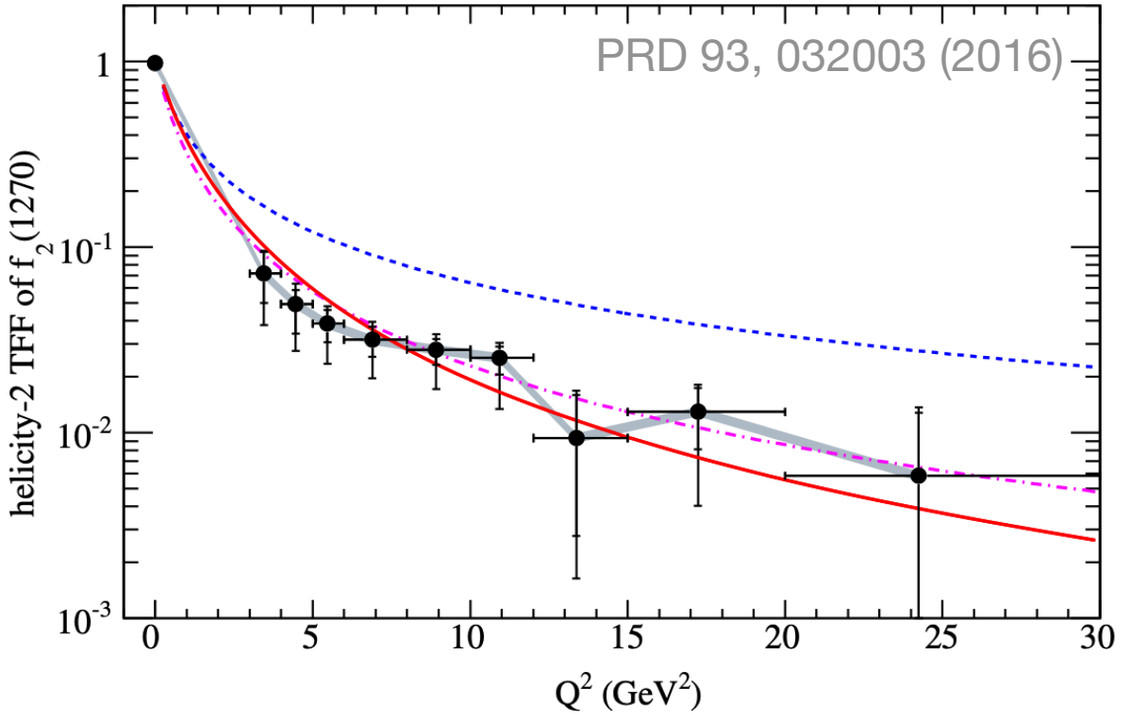
Other Benefits of Two-Photon Data

Tagged two-photon reactions:

- Measuring transition form factors of light mesons might be useful for a clean determination of 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 $2\,\mathrm{GeV}$, ($\chi_{c1}(3872)$ ...)
- Belle II (?)

TFF of $f_2(1270)$ by BELLE

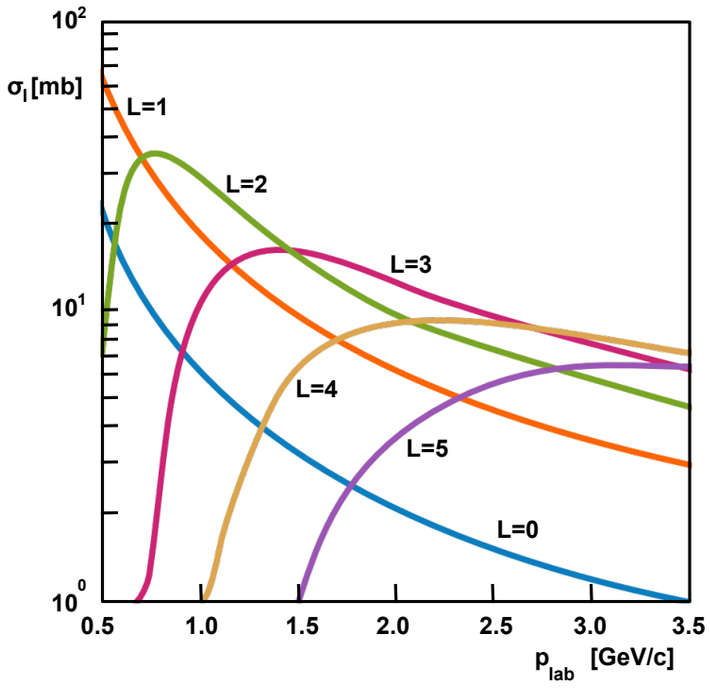


Resonance Production in $\bar{p}p$ Annihilations

- High-spin states possible without limitations on quantum numbers
- Cross section for glueball and light hybrid production similar to light hadrons

This is not speculation nor wishful thinking but measured fact based on Crystal Barrel at LEAR data!

based on Nucl. Phys. A523, 499 (1991)



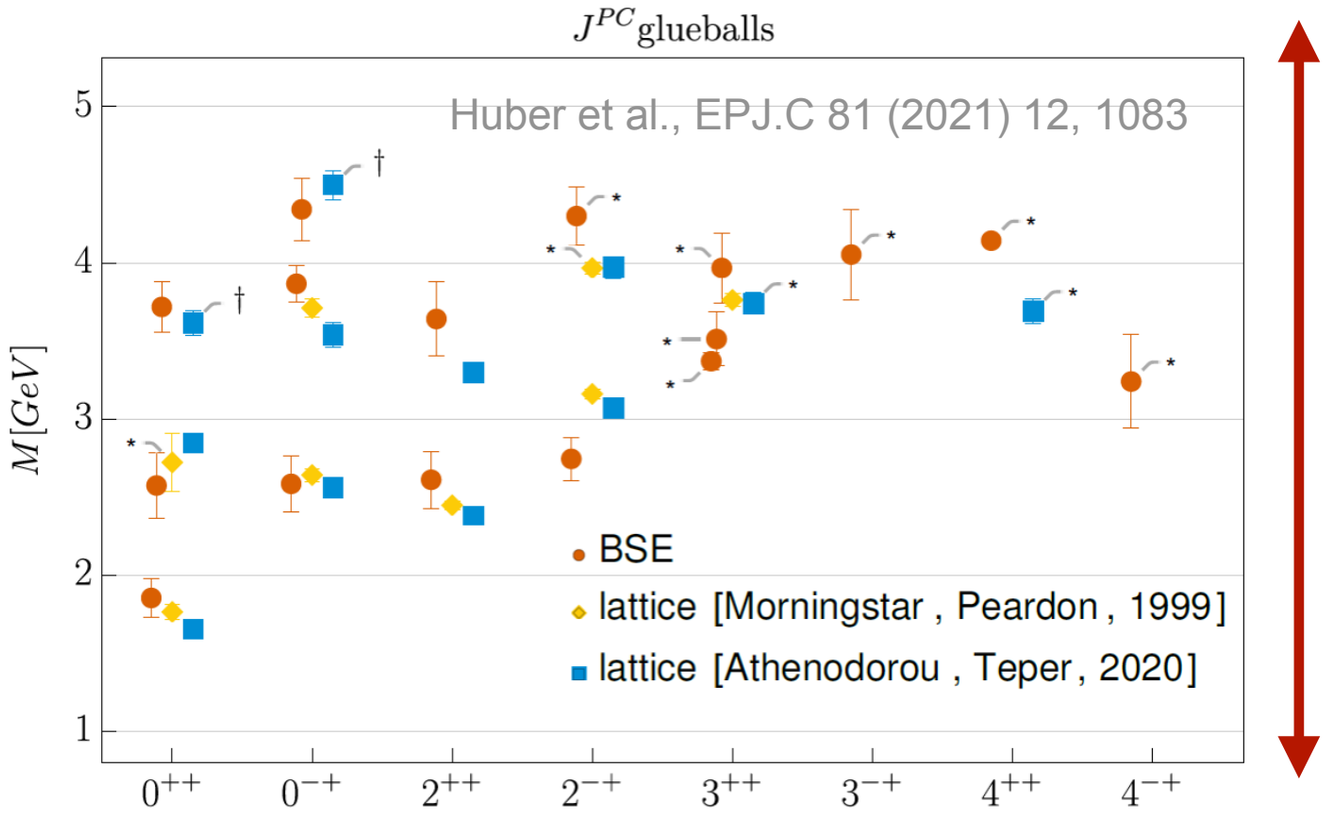
$\bar{p}p \to \omega\pi^0$

momentum [MeV/c]	$L_{\bar{p}p}^{max}$	significance of likelihood ratio $\frac{\ln L(L_{\bar{p}p}^{max})}{\ln L(L_{\bar{p}p}^{max}-1)}$	significance of likelihood ratio $\frac{\ln L(L_{\bar{p}p}^{max}+1)}{\ln L(L_{\bar{p}p}^{max})}$
600	2	>10 σ	1.05 σ
900	4	6.5 σ	0.22 σ
1050	4	>10 σ	0.01 σ
1350	5	5.6 σ	0.03 σ
1525	5	>10 σ	0.25 σ
1642	5	5.0 σ	$8 \cdot 10^{-3}$ σ
1800	5	>10 σ	0.55 σ
1940	5	>10 σ	0.69 σ

Eur. Phys. J. C75 (2015) 124

- In accordance to theory it was found that L_{max} increases from 2 to 5, even higher L to be expected at PANDA beam momenta…

PANDA as a Goldmine For Exotics



Whole spectrum accessible within the PANDA energy

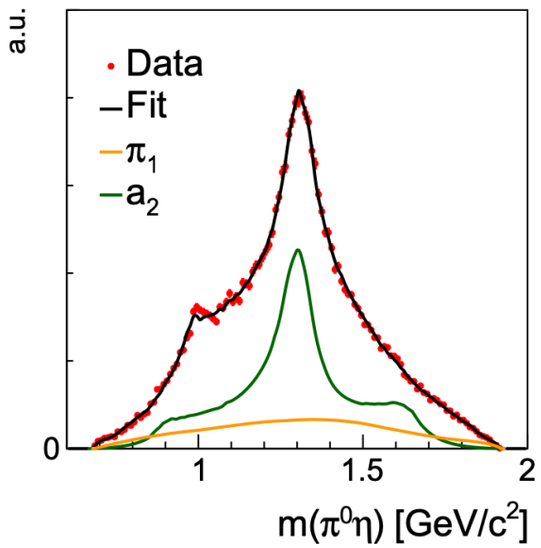
- High-spin states accessible by PANDA
  - Spectrum less populated, therefore less mixing + easier identification
  - Spare knowledge overall of higher spin states

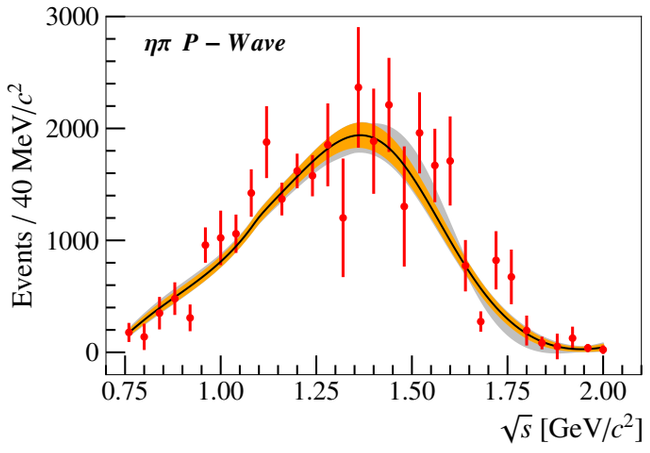
➡ **PANDA has unique discovery power!**

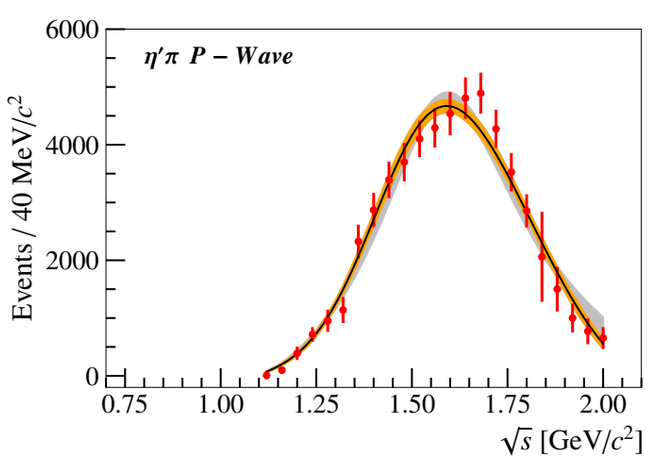
Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0\pi^0\eta$, $\pi^0\eta\eta$ and $K^+K^-\pi^0$

- Exotic π_1 wave contributing at the same level like „ordinary“ mesons!

process	cross section [μb]
$\bar{p}p \rightarrow K^*(892)^{\pm}K^{\mp}$	$396 \pm 29 \pm 19 \pm 42$
$\bar{p}p \rightarrow \phi(1020)\pi^0$	$20.2 \pm 3.6 \pm 1.4 \pm 2.1$
$\bar{p}p \rightarrow \pi_1\pi^0, \pi_1 \rightarrow \pi^0\eta$	$25.8 \pm 3.5 \pm 4.1 \pm 1.5$







$\bar{P}$ANDA will have a 100 times higher luminosity!

➡ 1 year data taking becomes 3.5 days!

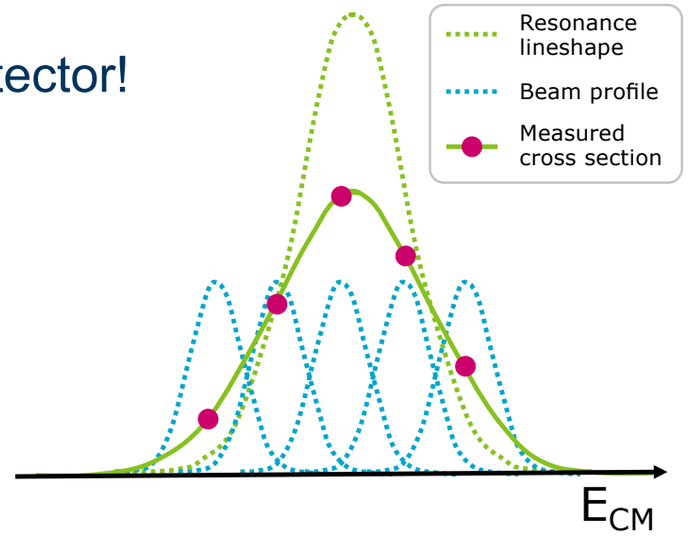
Formation Studies at $\bar{\text{P}}$ANDA

Powerful example: Measurement of the total width of the $\chi_{c1}(3872)$

- Compact (BW) or molecule (Flatté)?
- Molecule or virtual ← Flatté parameter E_f
- Best measurement so far:
  - Width assuming Breit-Wigner
    (for sure not a good model at threshold…):
    $\Gamma = (1.39 \pm 0.24 \pm 0.10)\,\text{MeV}$ (LHCb 2020)
  - Width assuming Flatté model:
    FWHM = $0.22^{+0.06+0.25}_{-0.08-0.17}\,\text{MeV}$ (LHCb 2020*))

- Not possible to distinguish scenarios, pole mass still not distinguishable from $D\bar{D}^*$ threshold
- LHCb and other experiments measuring in production have reached their sensitivity to probe the natural width of $\chi_{c1}(3872)$

- For PANDA resolution only limited by the beam resolution and not by the detector!
  - $\Delta p/p \sim \left(10^{-4} - 10^{-5}\right)$ ➡ sensitive to structures up to 30 keV width!



PANDA: Eur. Phys. J A55, 42 (2019)
PANDA: Eur. Phys. J A 57:184 (2021)
F. Nerling, PoS CHARM2020, 004 (2021).

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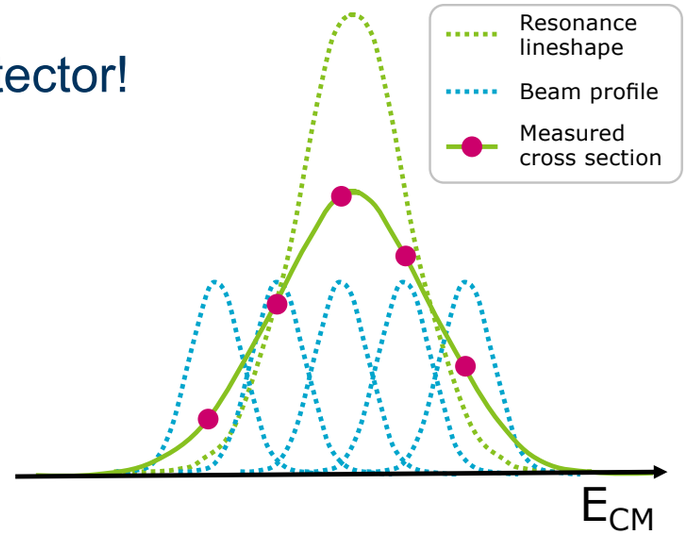
➡ Separation possible already in Phase One (~2 days per E-point)!
➡ Will establish its nature! And therefore most likely also for related states as T_{cc}
➡ Same applies to other states with $\bar{q}q$ quantum numbers!



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Future Experimental Prospects

$\bar{p}p$ annihilation



two-photon production





radiative Charmonium decays



πp- , photo-production







• • •

- Several interesting experiments on the horizon!
- $\bar{p}p$ annihilations have unique discovery potential, several resonances were observed here
- Coupled channel analyses proof to be powerful and are the necessary step towards a better understanding of QCD
- Sophisticated line shape models should be used whenever possible
- Although we study light mesons for decades, there are still many open questions
- Work closer together in the community - common effort is needed to answer fundamental questions!

Thank You!