Precision Hadron Spectroscopy of Light and Heavy Quarks

Meike Küßner

Ruhr-Universität Bochum and now University of Bonn

Present and future perspectives in Hadron Physics - Frascati

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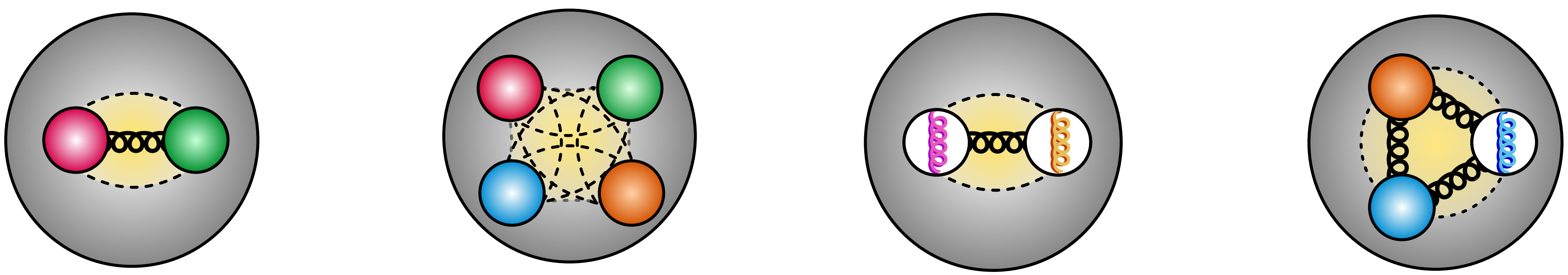
From the Perspective of Strong Interaction

- 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

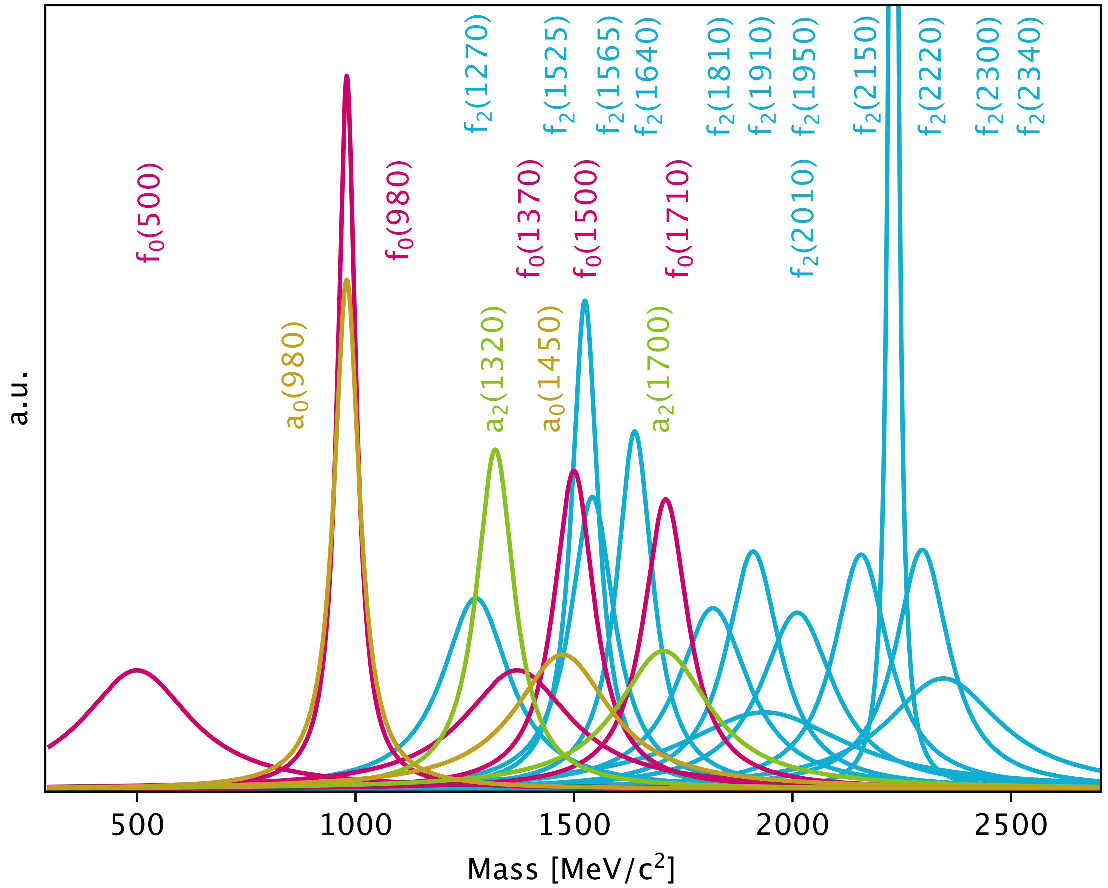
$$P = (-1)^{L+1}\,,\, C = (-1)^{L+S}$$

- 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



We should start thinking beyond experimental collaborations!

Experimental Possibilities

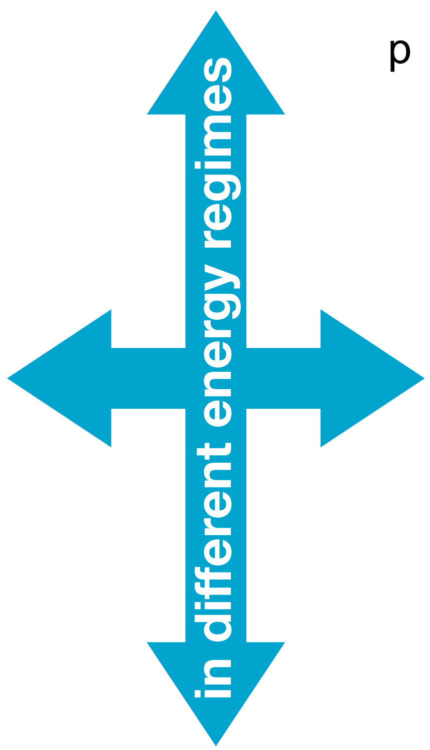
- Each experiment, detector and process has its own advantages
- To tackle these challenges, we need to combine forces

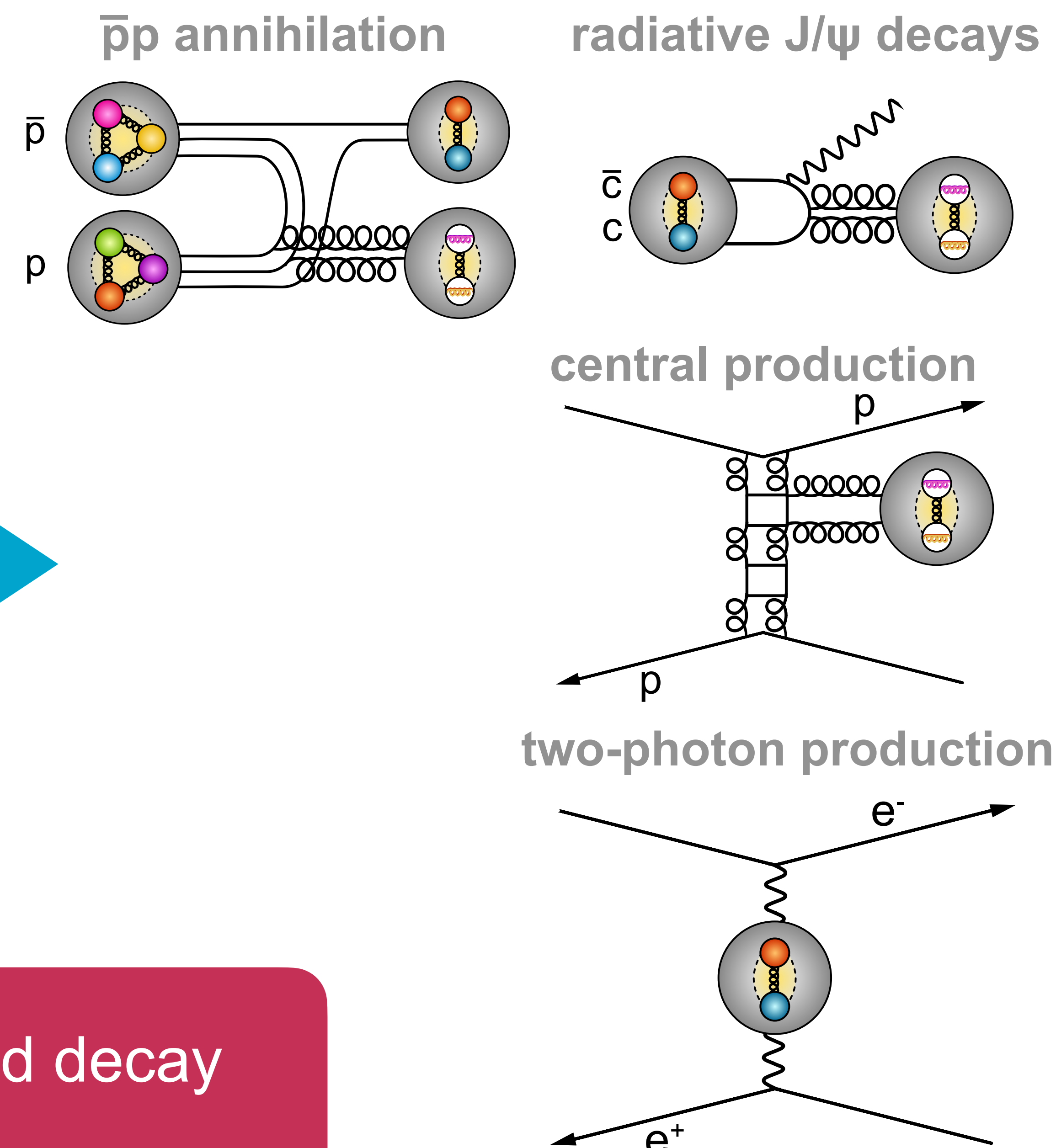
Gluon rich processes

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

QED mediated process

- Two-photon production



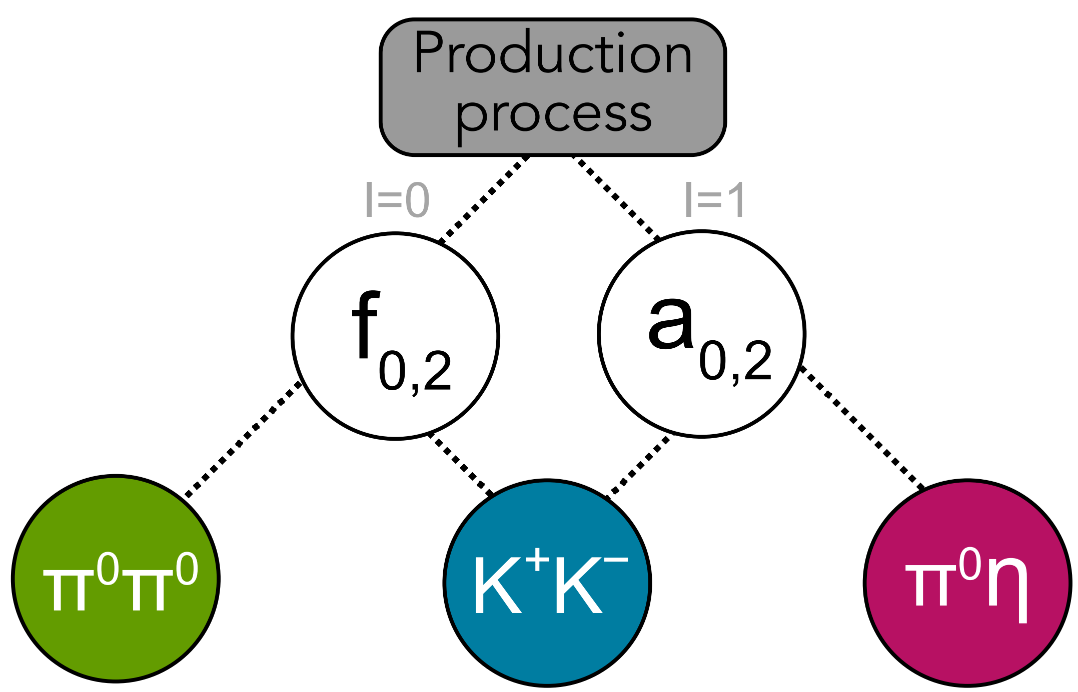


Combine different production mechanisms and decay channels to reveal a particle's nature

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

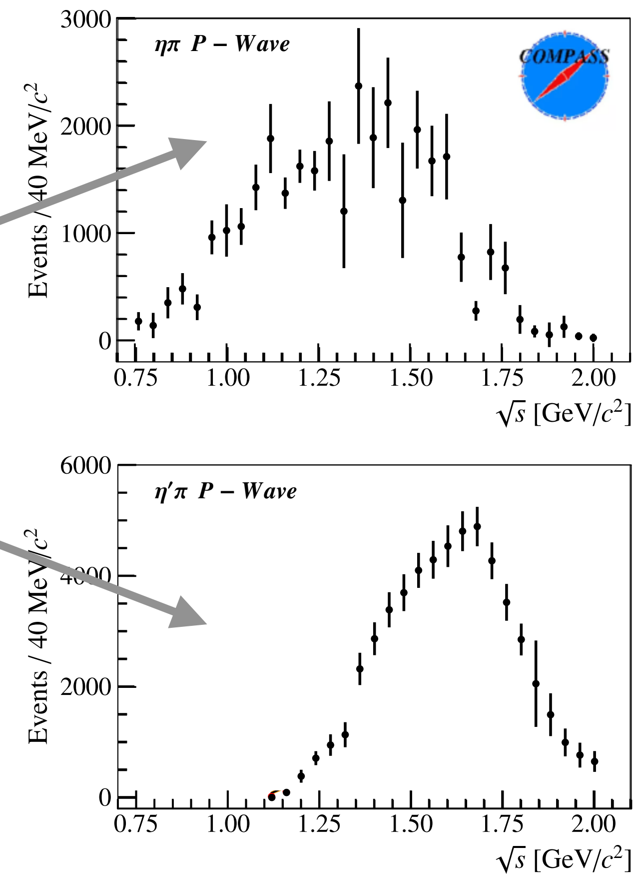
Two π_1 hybrid candidates below 2 GeV are listed in PDG

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

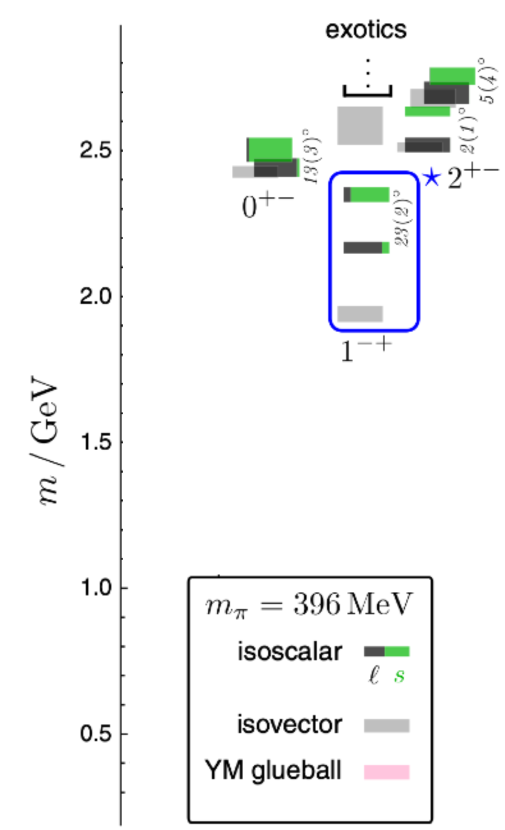
➡ Parameters obtained by Breit-Wigner fits!

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

200 MeV apart!

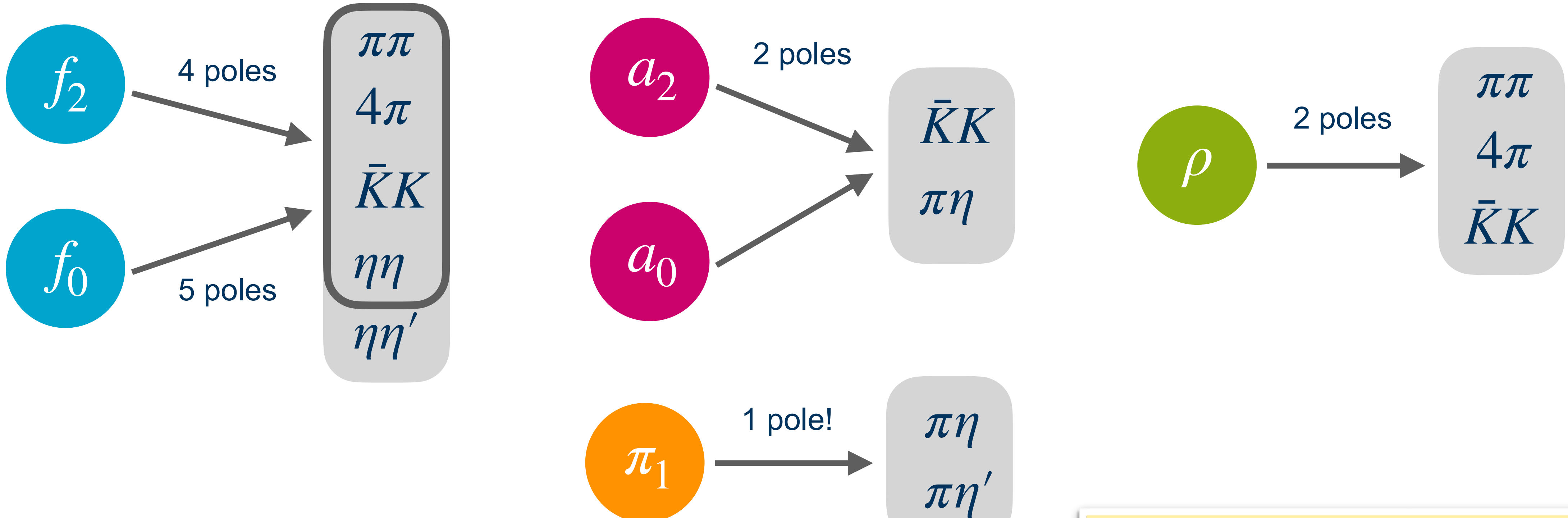


Phys.Rev. D84 (2011) 074023



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

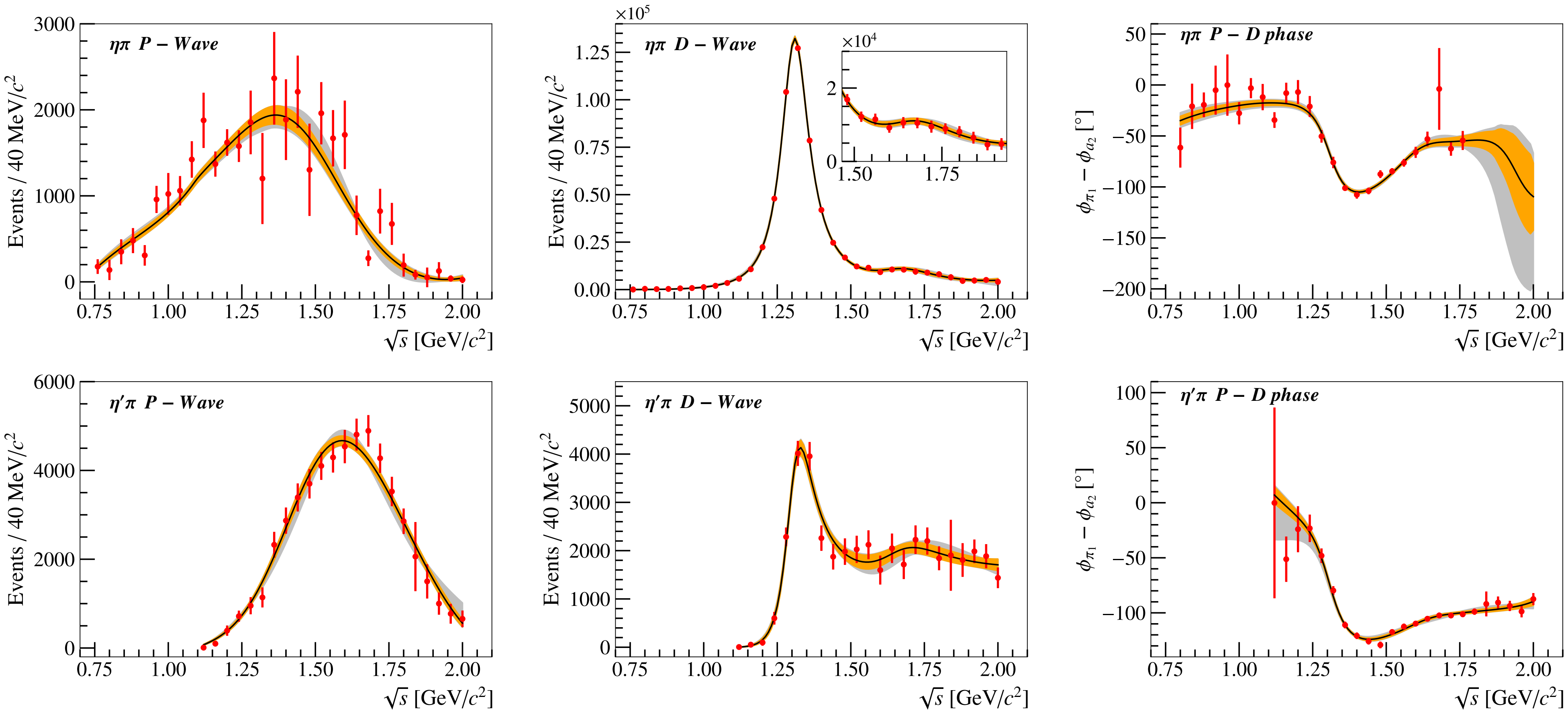


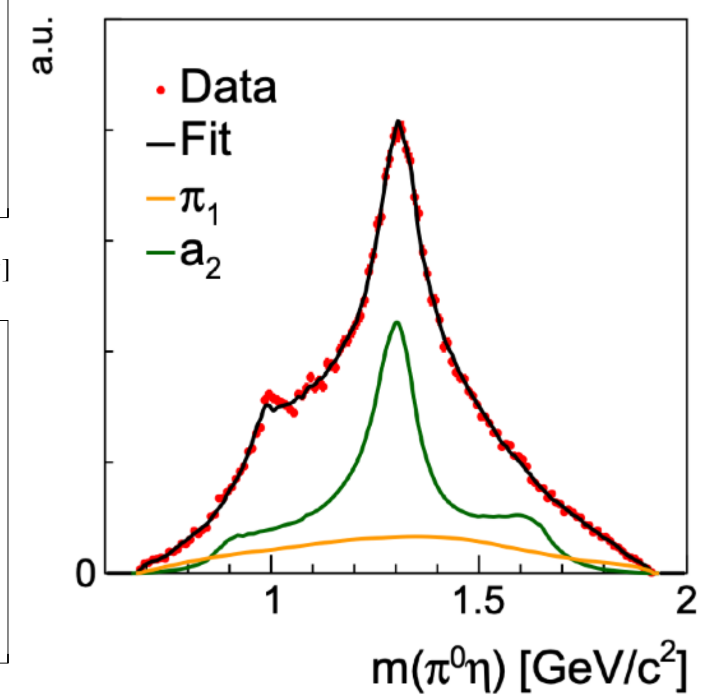
Eur. Phys. J. C (2021) 81, 1056

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



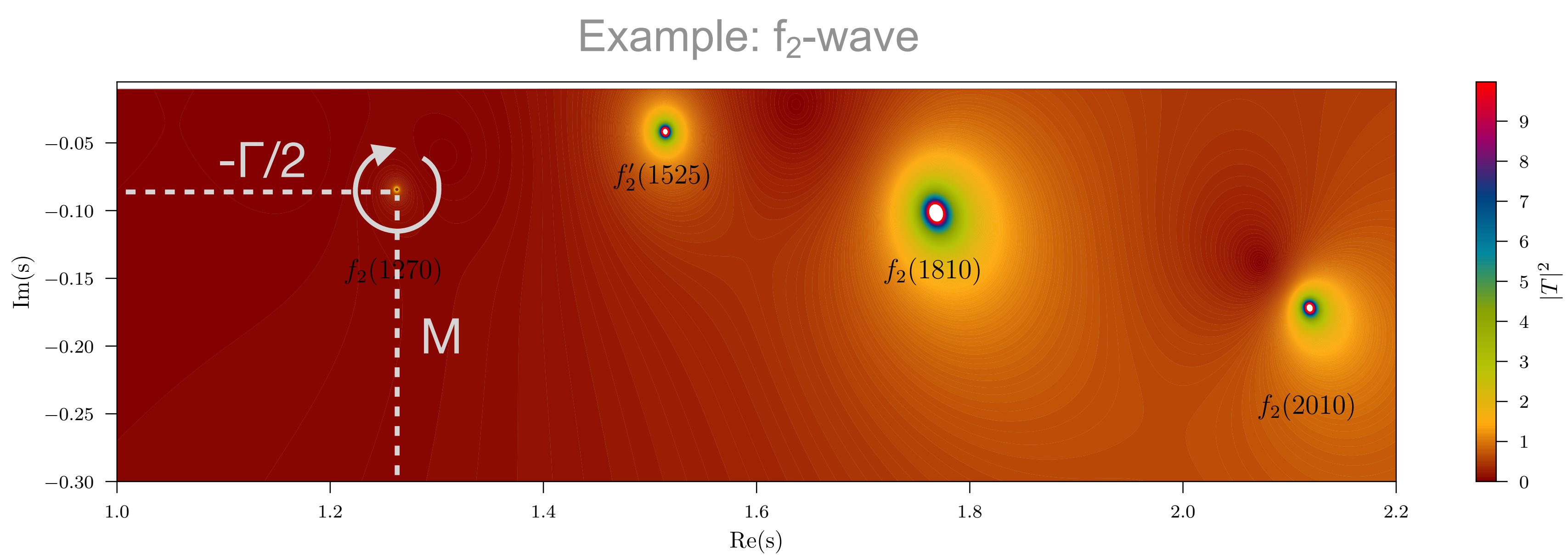


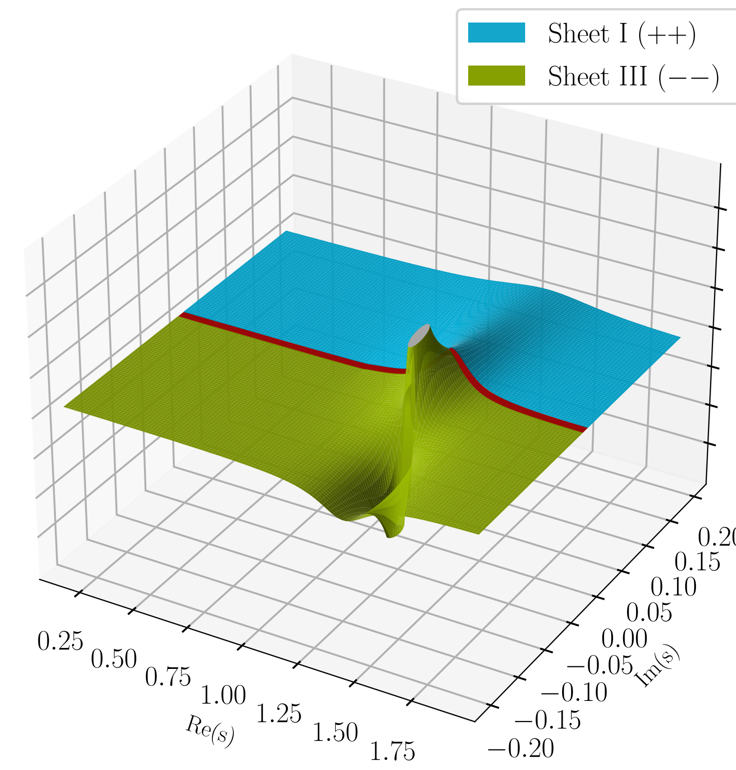
Obtained pole position:

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

$$\Gamma = 455 \pm 88^{+144}_{-175}\ \mathrm{MeV}$$

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	$1700 \pm 27\,^{+13}_{-16}$	$181 \pm 25\,^{+0.0}_{-16}$	$13.6 \pm 1.2\,^{+0.9}_{-0.5}$	$0.8 \pm 0.1\,^{+0.0}_{-0.0}$	-

Several resonance properties measured simultaneously within one fit!

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

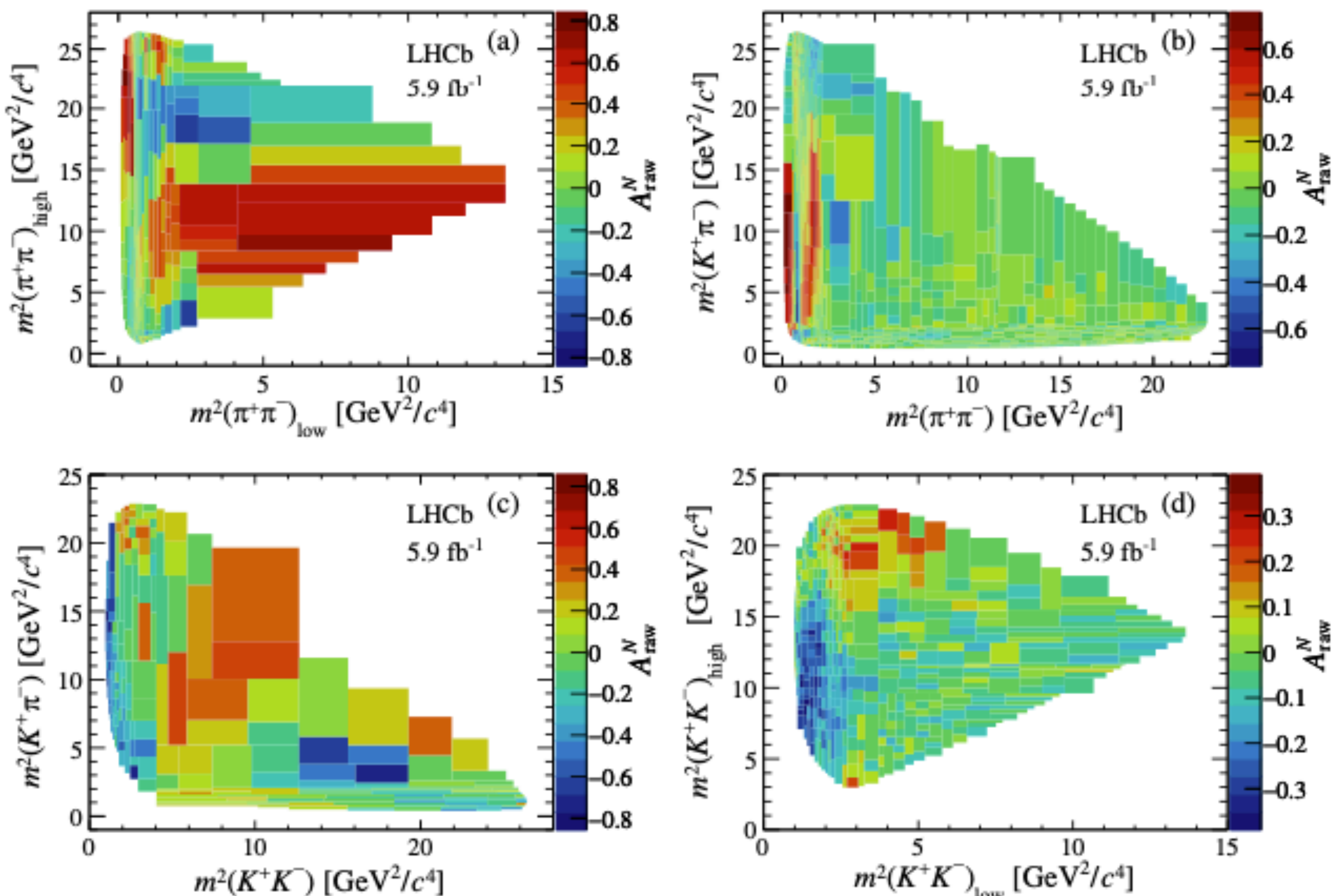
PArtial Wave Interactive ANalysis

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)

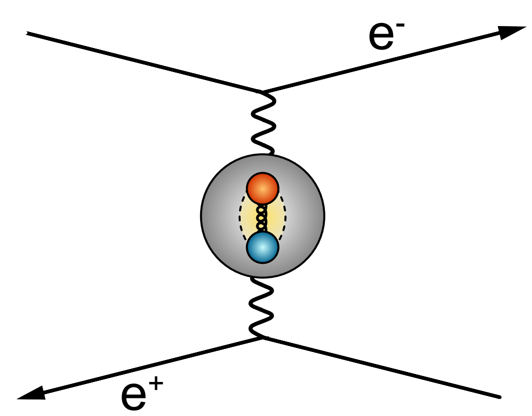
Learning More About the Inner Structure

Besides measuring resonance parameters as mass, width, …

Usually: Measure form factors!

Two photon physics

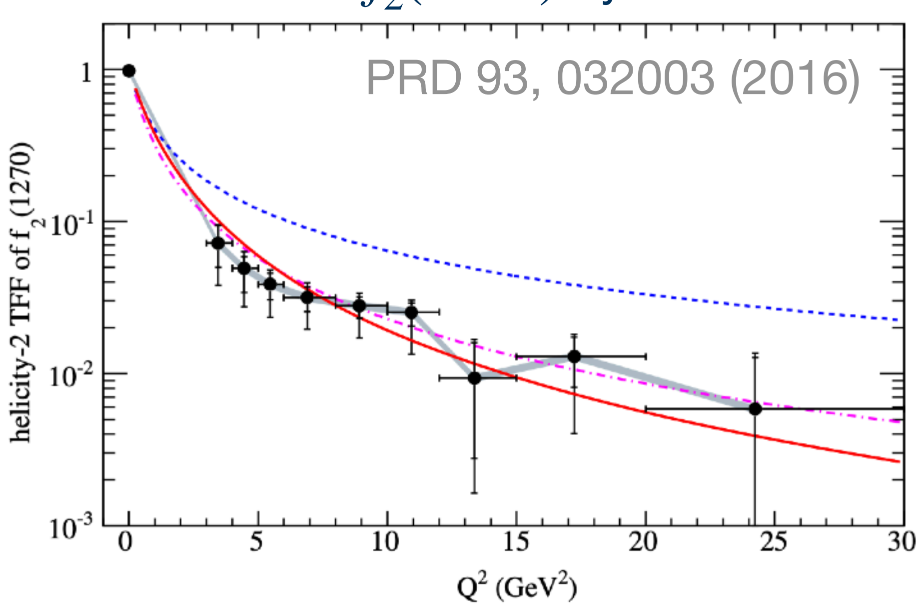
- Clean e.m. process, only sensitive to charge
- Complementary information on glueball candidates!
- States with even C-parity $0^{\pm +}, 2^{\pm +}, \ldots$ can be directly produced



Untagged reactions:

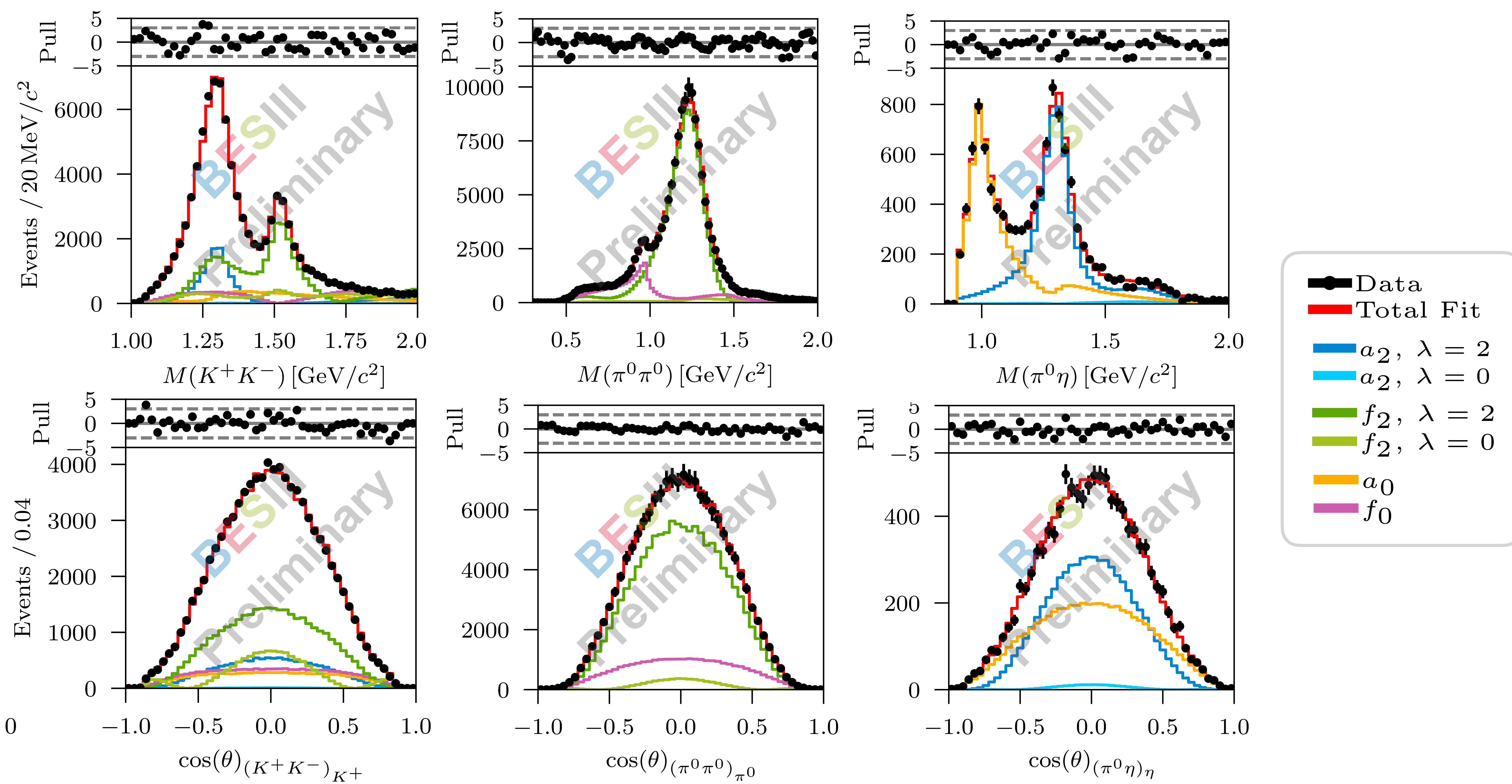
- Scattering angles of electron and positron are small and are not detectable
- Quasi real photons carrying small virtuality ➡ spin 1 strongly suppressed

TFF of $f_2(1270)$ by BELLE



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)

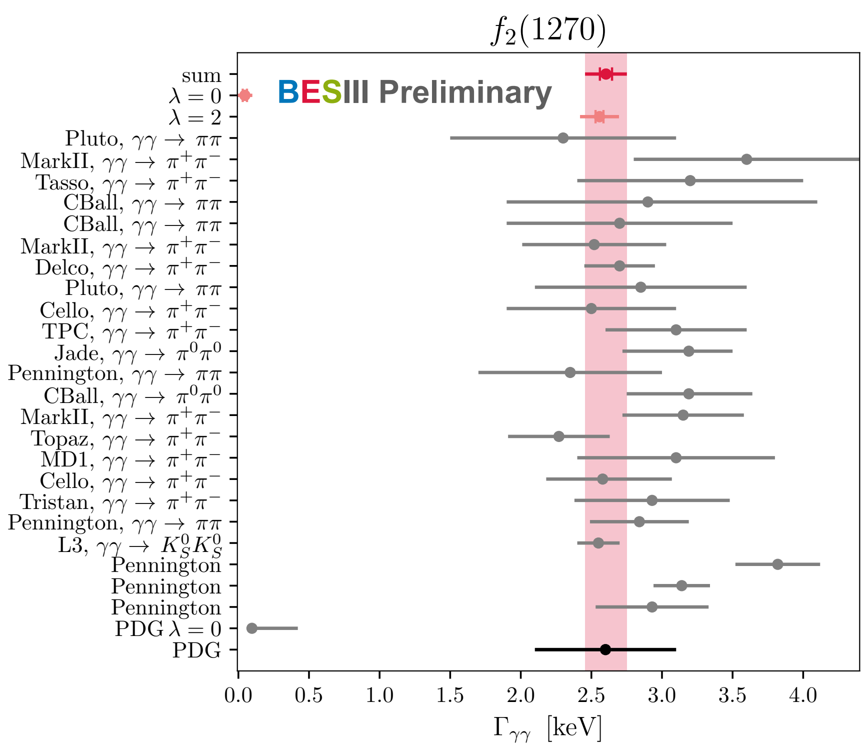


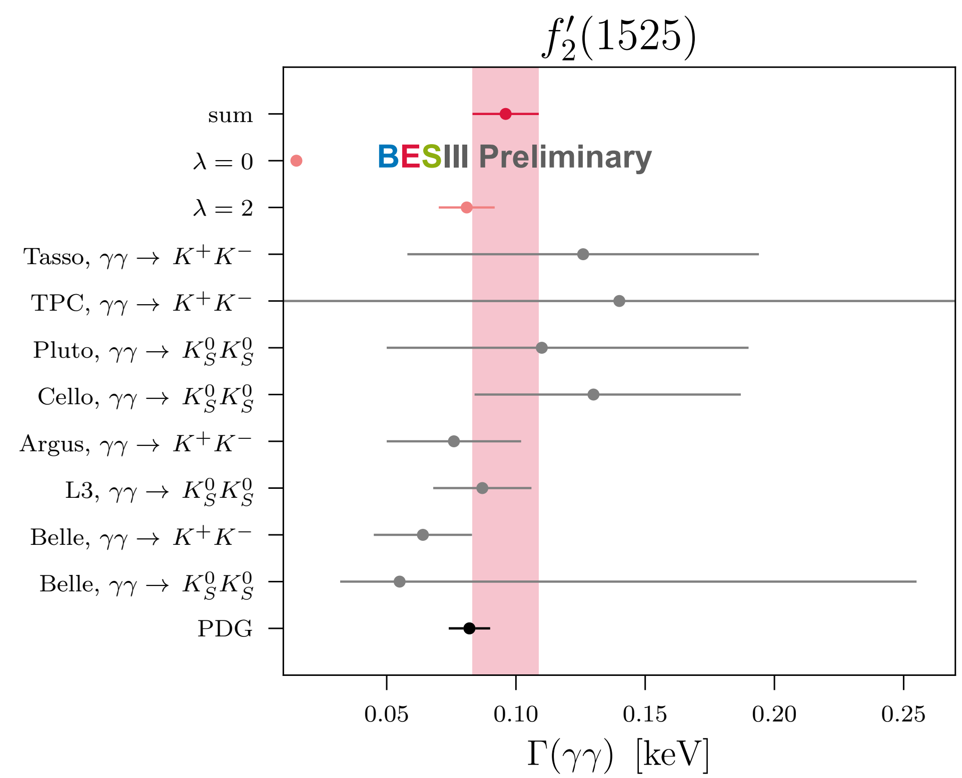
Determination of the Coupling Strength

- Determination of the two-photon width using the F-vector pole residue itself

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

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

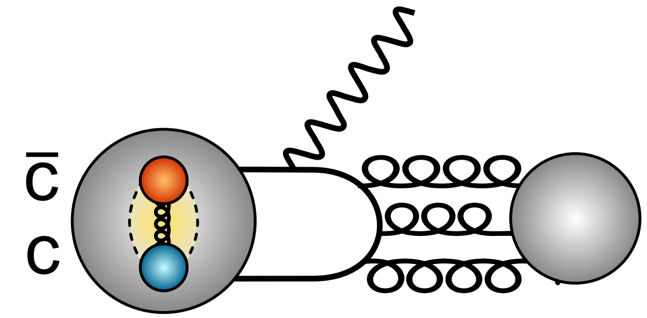


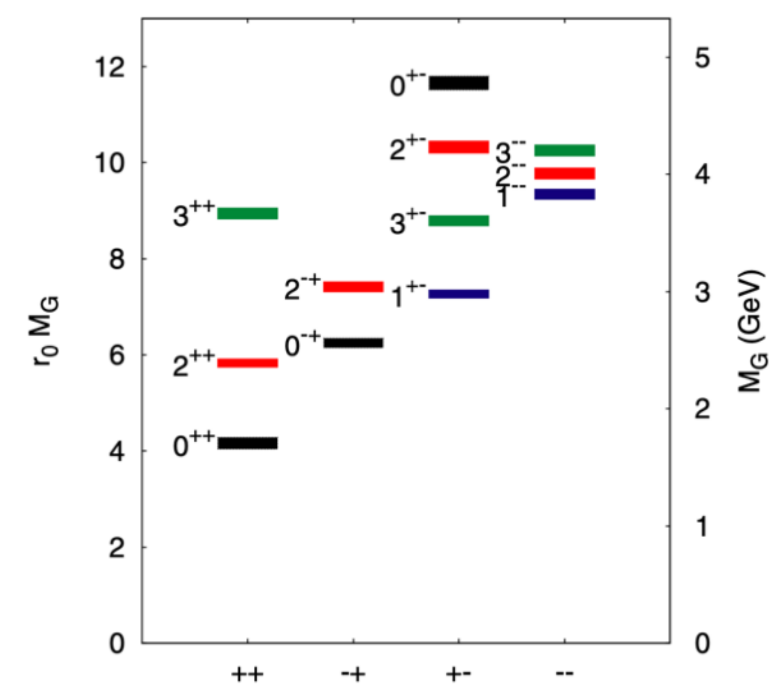


- First determination of the helicity contributions for the $f_2'(1525)$
- Most accurate measurement for $f_2(1270)$ and $a_2(1320)$
- Scalar mesons $f_0(1370)$, $f_0(1500)$ und $f_0(1710)$ measured for the first time

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!





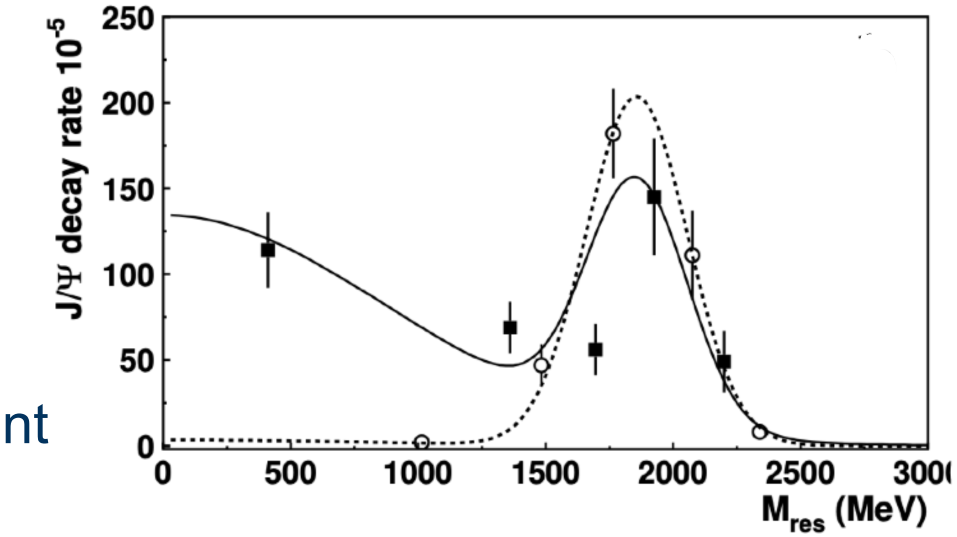
Phys. Rev. D 73, 014516 (2006)

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

Recent Analyses

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

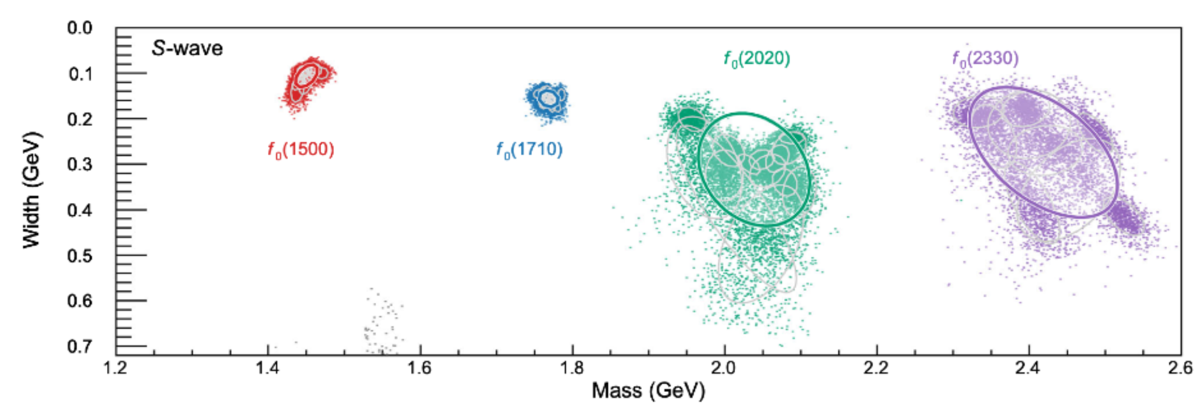
- $J/\psi \to \gamma + (\pi^0\pi^0, K_S^0K_S^0, \eta\eta, \omega\phi)$ (BESIII)
- $\pi^+\pi^-$- scattering data (CERN-Munich, GAMS, BNL)
- $\bar{p}N \to 3$ mesons (CB-LEAR)



- 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 $J/\psi \to \gamma\, \pi^0\pi^0, \gamma\, K_S^0K_S^0$ (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



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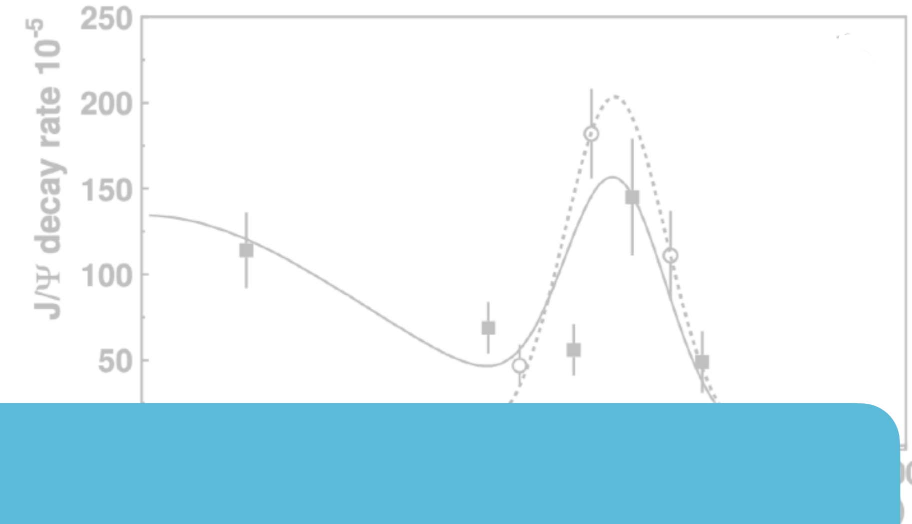

Much higher statistics available now - *50 times more!*

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

- Used $J/\psi \to \gamma\, \pi^0\pi^0, \gamma\, K_S^0K_S^0$ (BESIII) data
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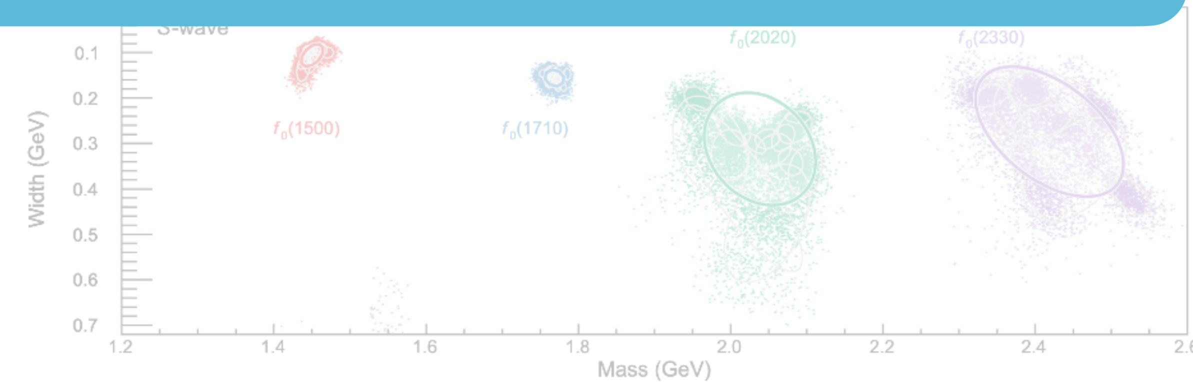
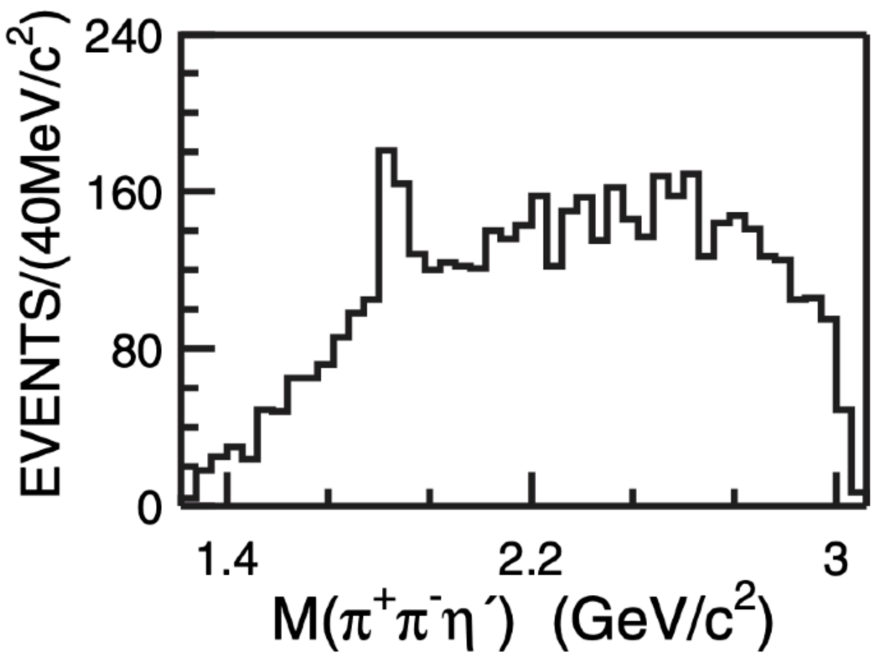


$J/\psi \to \gamma\eta'\pi^+\pi^-$

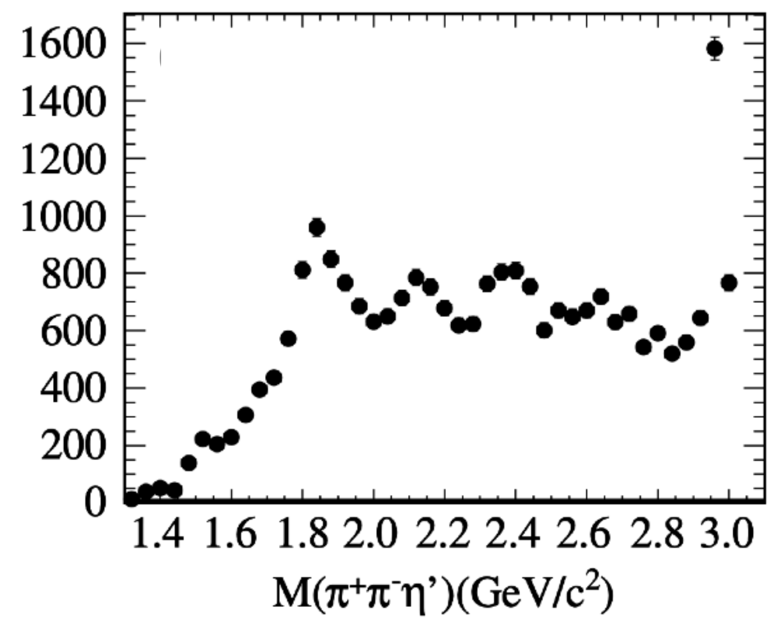
PRL 129, 042001 (2022)

58M J/ψ events



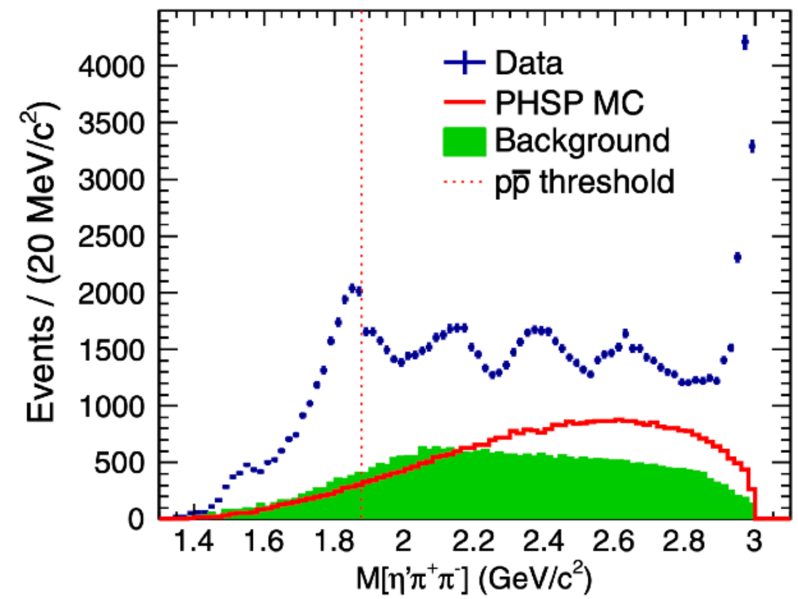
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

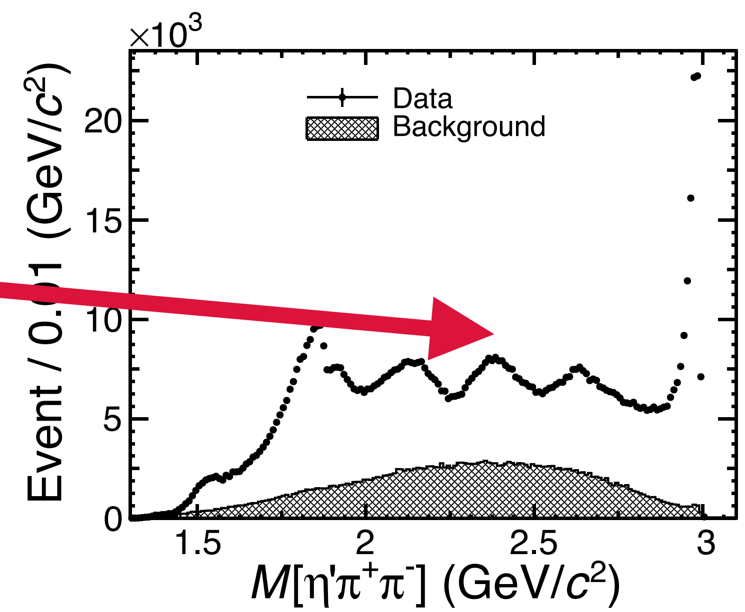
1090M J/ψ events



BESIII, PRL 117, 042002 (2016)

- Spin-parity of $X(2370)$ recently determined to be 0^{-+}!

PRL 132 181901 (2024)



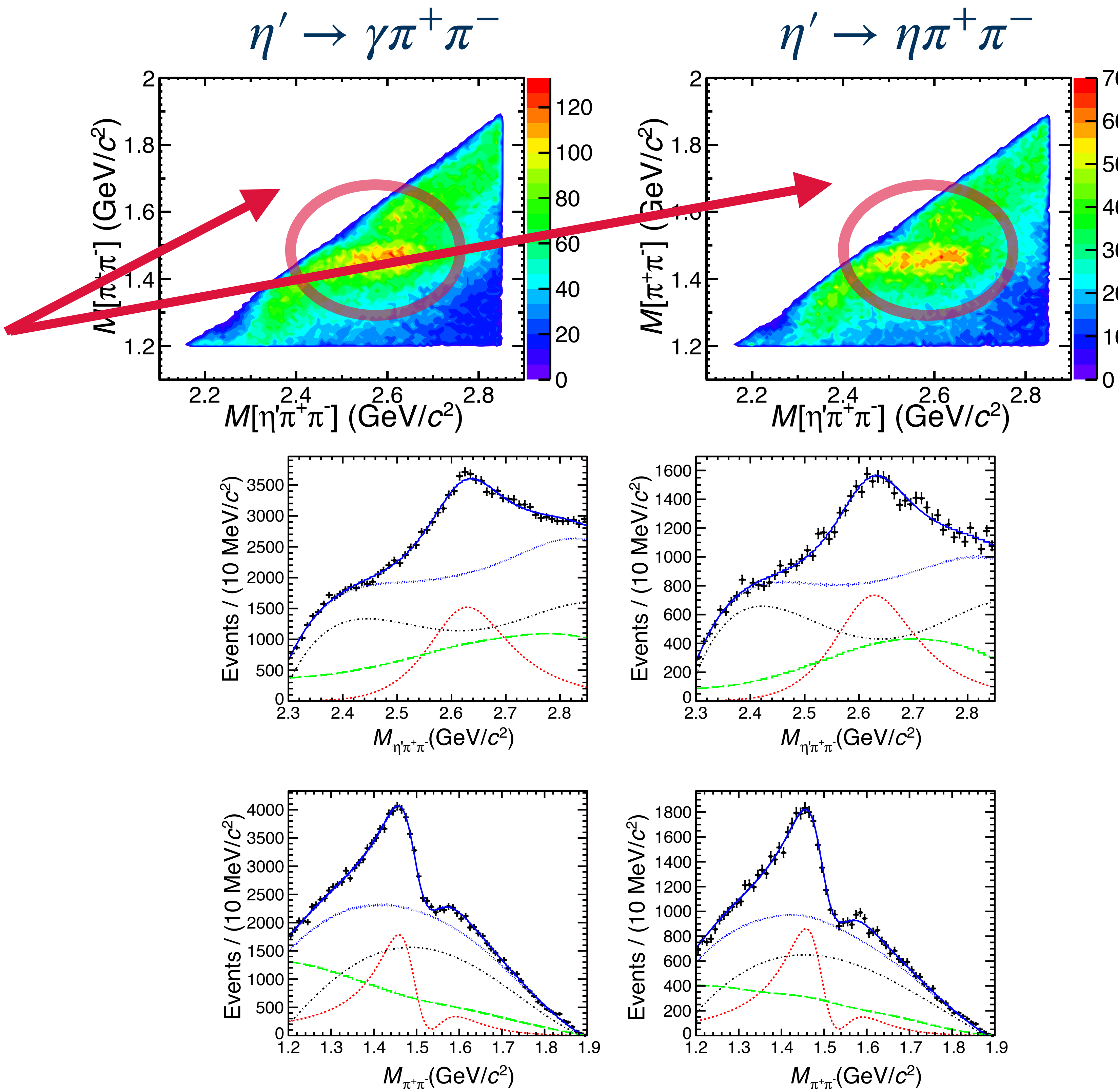
BESIII, PRL 129, 042001 (2022)

10B J/ψ events

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

PRL 129, 042001 (2022)

- Interesting structure at 2.6 GeV
- Likely connected to a non trivial structure at $1500\,\mathrm{MeV}/c^2$ in $\pi^+\pi^-$ system
- Further studies ongoing, full PWA needed…



Era of High Statistics

- One is suddenly sensitive to effects one could safely neglect in former times…
- (systematical errors > statistical errors…)
- The model is more important than ever!
- Such computational expensive coupled analyses demand us to get faster!

Development of faster algorithms required:

- Including AI methods where ever helpful

Leads also to:

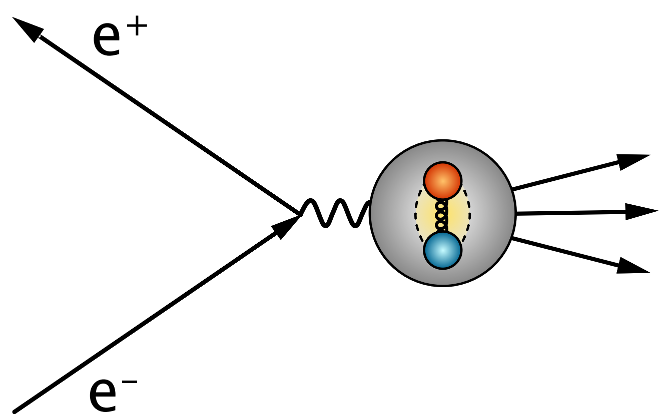
- More sustainable use of resources and data!

New network project working on techniques to accelerate PWA:

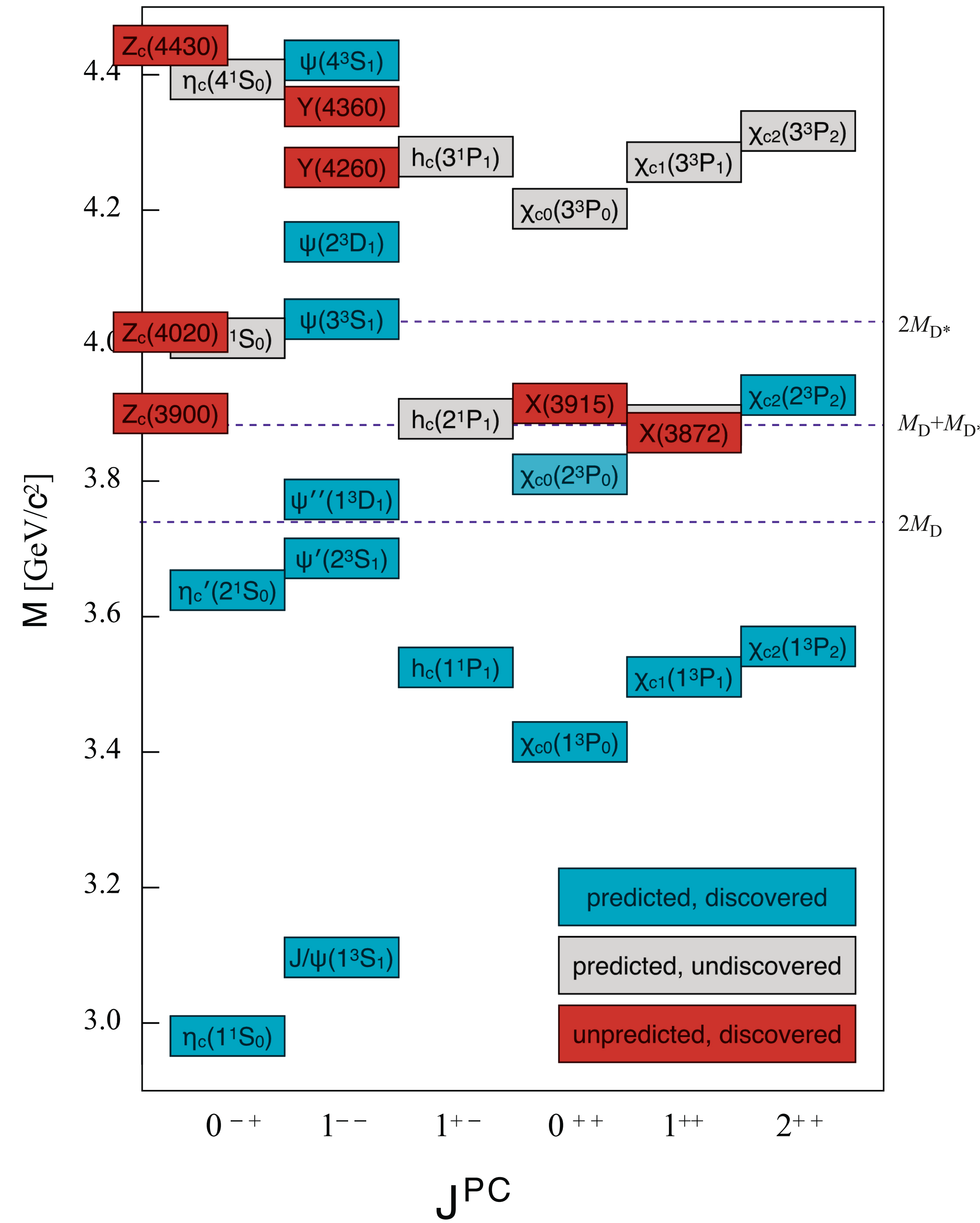
- Automated differentiation
- Improved gradient decent methods
- Pseudo event clustering

Charmonium Sector

- Charmonia with vector q.n. can be directly created at e^+e^-colliders

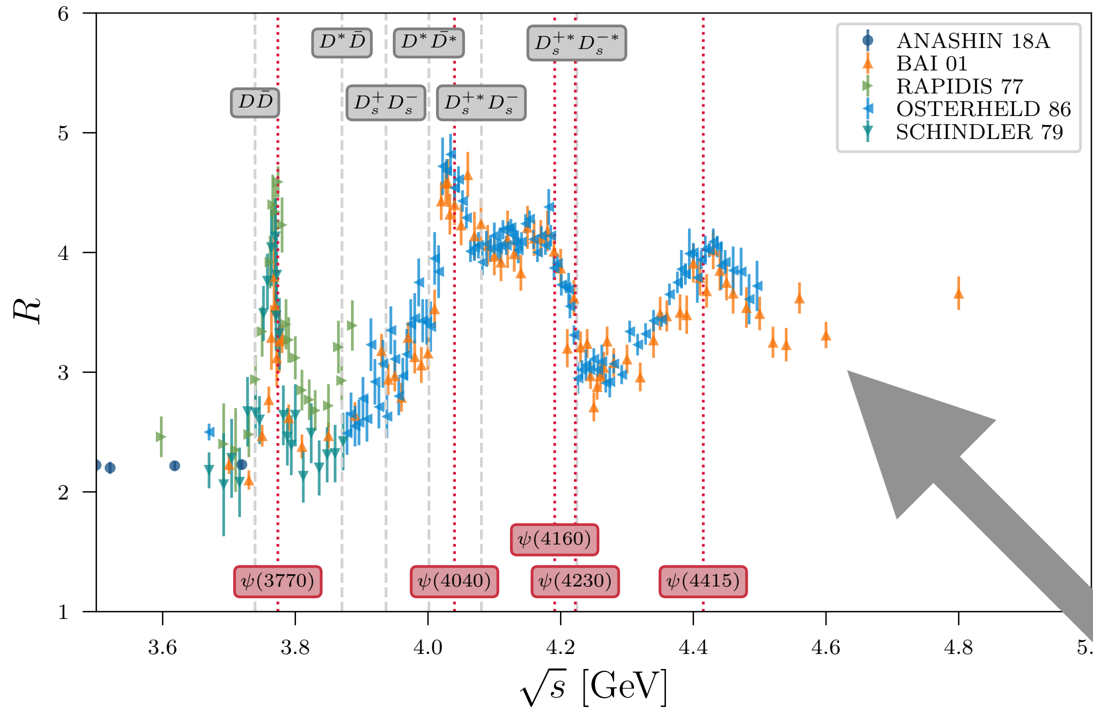


- Other q.n. can only be accessed by sequential decays which limits the statistics

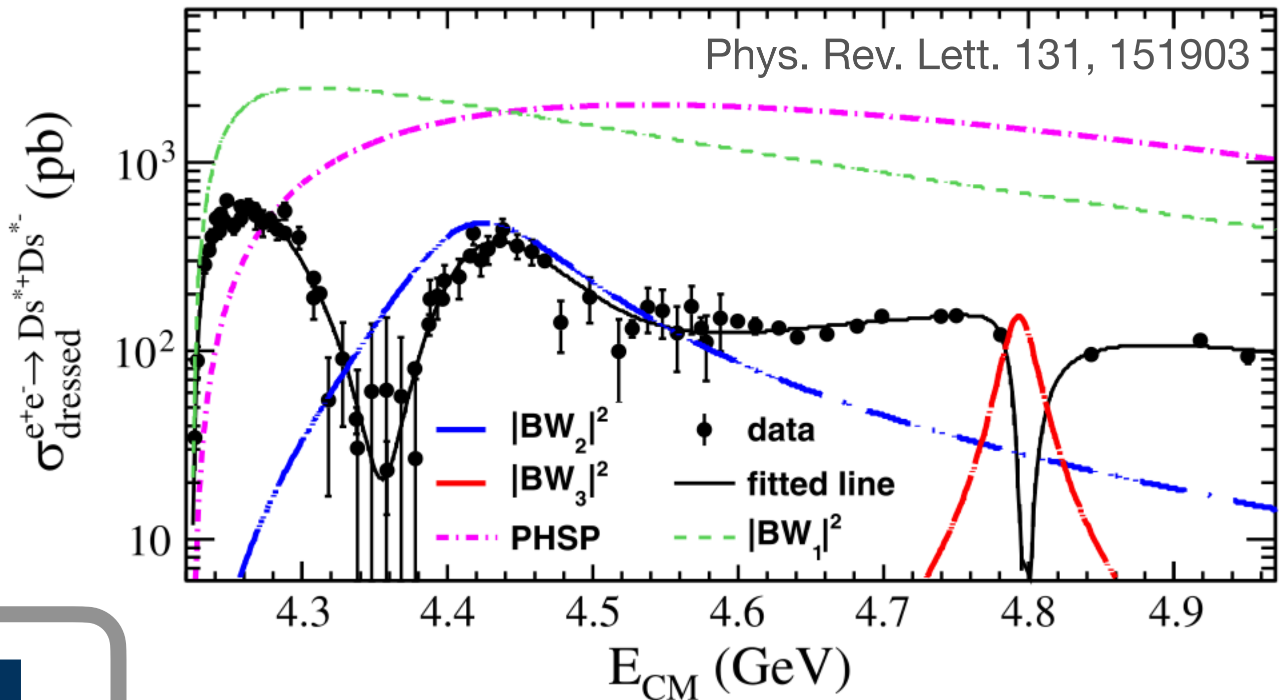


- Besides expected states, additional „unconventional“ states where observed!

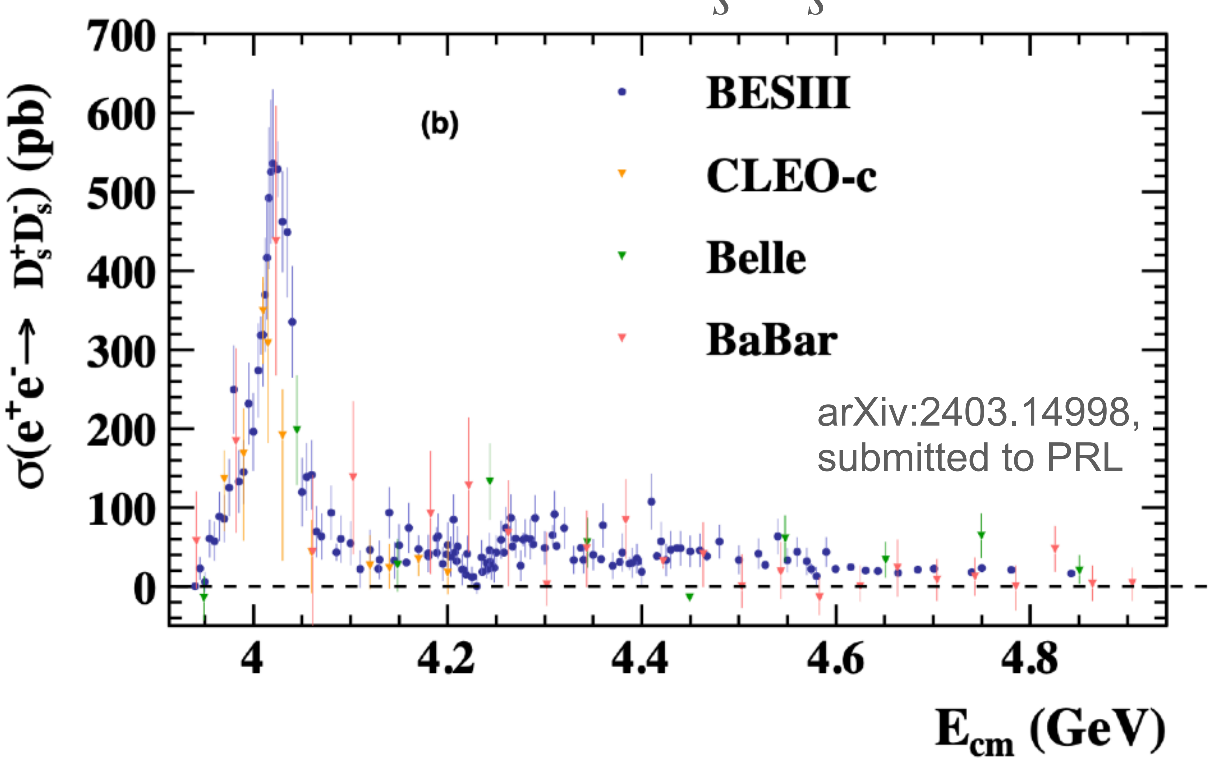
Vector Charmonia



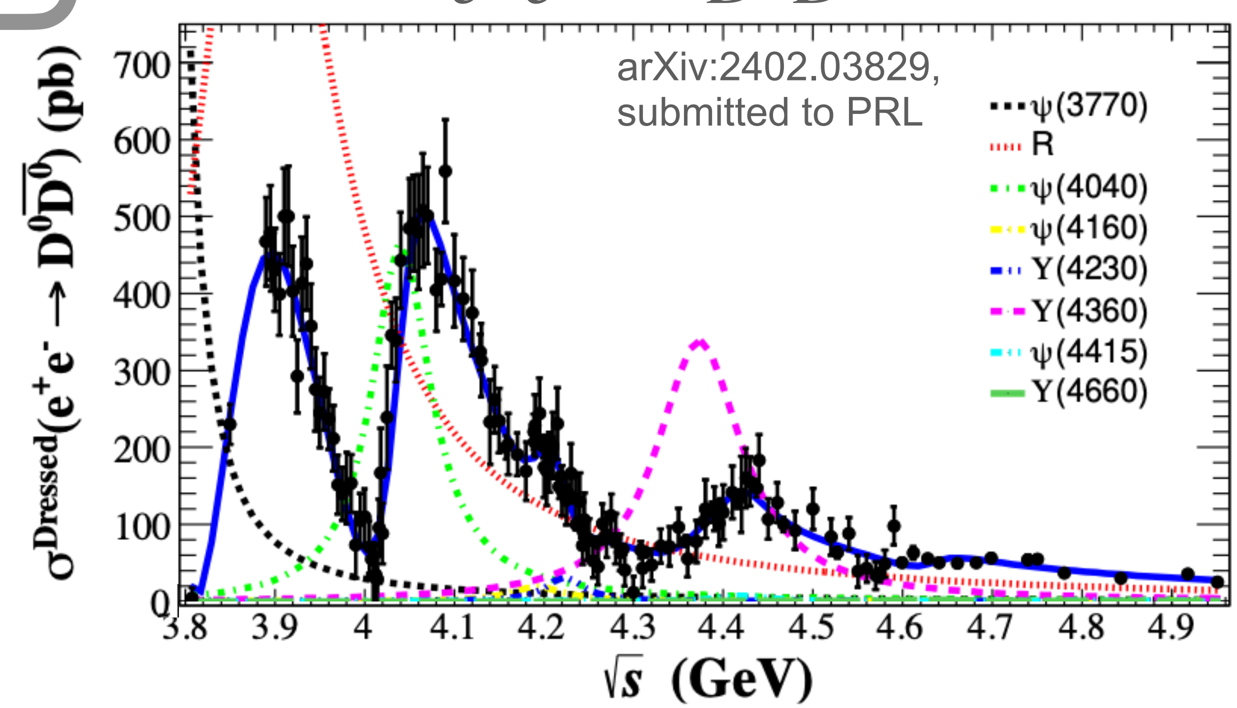
$e^+e^- \to D_s^{+*}D_s^{-*}$



$e^+e^- \to D_s^+D_s^-$



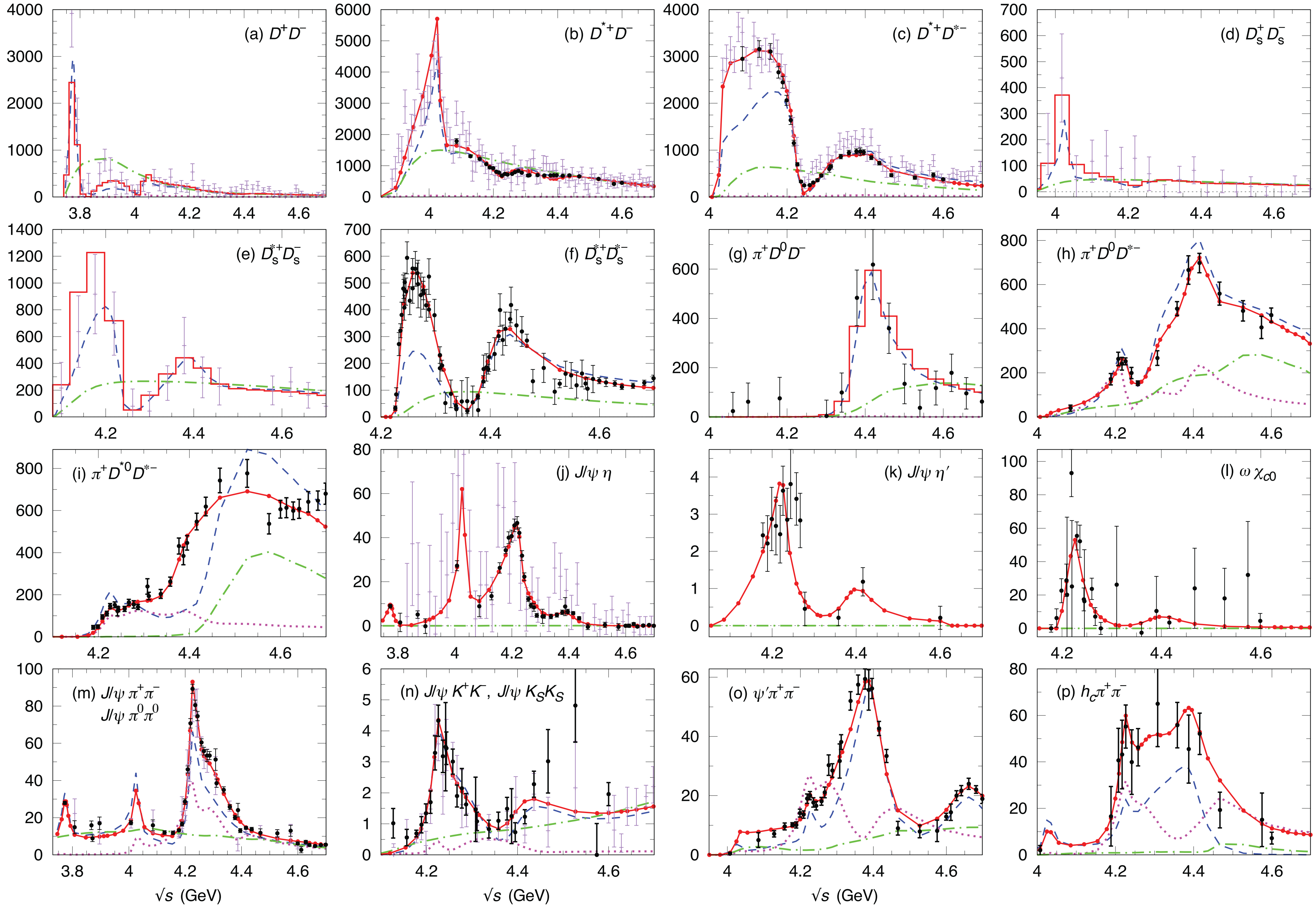
$e^+e^- \to D^0\overline{D^0}$



A first Step Towards a Global Description

arXiv:2312.17658

- Combined fit to 19 BESIII and Belle cross section results



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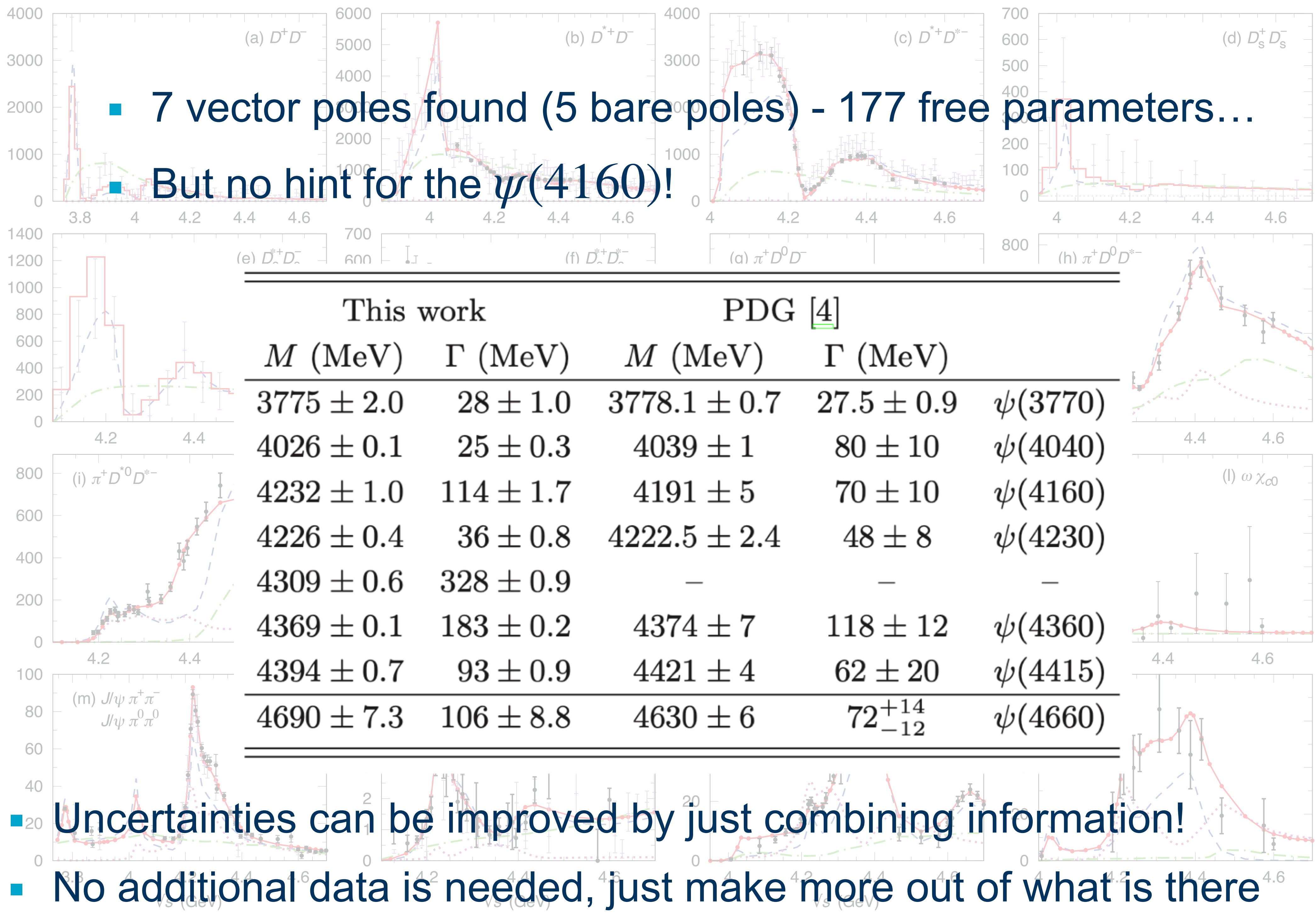
- Combined fit to 19 BESIII and Belle cross section results

arXiv:2312.17658



- 7 vector poles found (5 bare poles) - 177 free parameters…
- But no hint for the $\psi(4160)$!

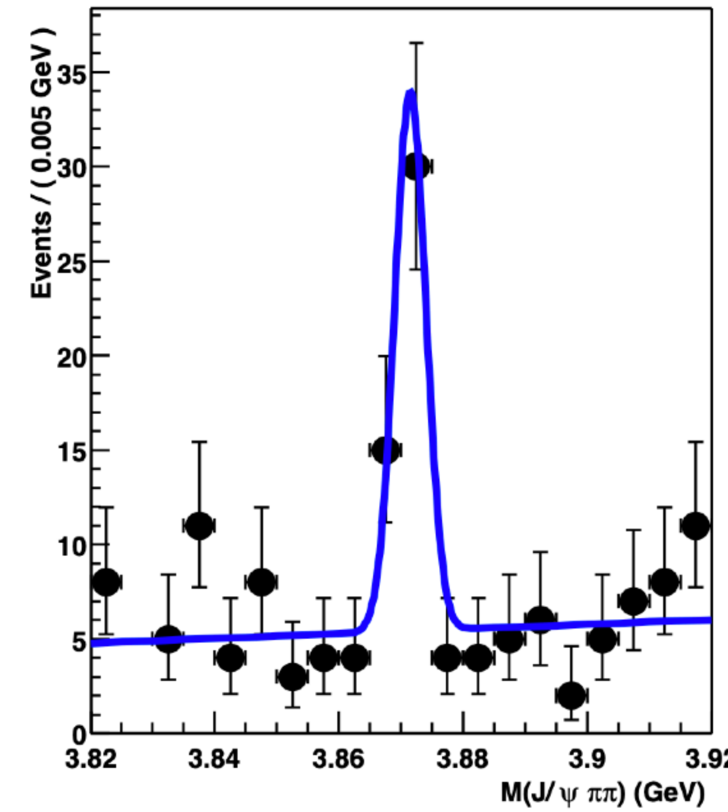
This work		PDG [4]		
M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)	
3775 ± 2.0	28 ± 1.0	3778.1 ± 0.7	27.5 ± 0.9	$\psi(3770)$
4026 ± 0.1	25 ± 0.3	4039 ± 1	80 ± 10	$\psi(4040)$
4232 ± 1.0	114 ± 1.7	4191 ± 5	70 ± 10	$\psi(4160)$
4226 ± 0.4	36 ± 0.8	4222.5 ± 2.4	48 ± 8	$\psi(4230)$
4309 ± 0.6	328 ± 0.9	–	–	–
4369 ± 0.1	183 ± 0.2	4374 ± 7	118 ± 12	$\psi(4360)$
4394 ± 0.7	93 ± 0.9	4421 ± 4	62 ± 20	$\psi(4415)$
4690 ± 7.3	106 ± 8.8	4630 ± 6	72^{+14}_{-12}	$\psi(4660)$

- Uncertainties can be improved by just combining information!
- No additional data is needed, just make more out of what is there

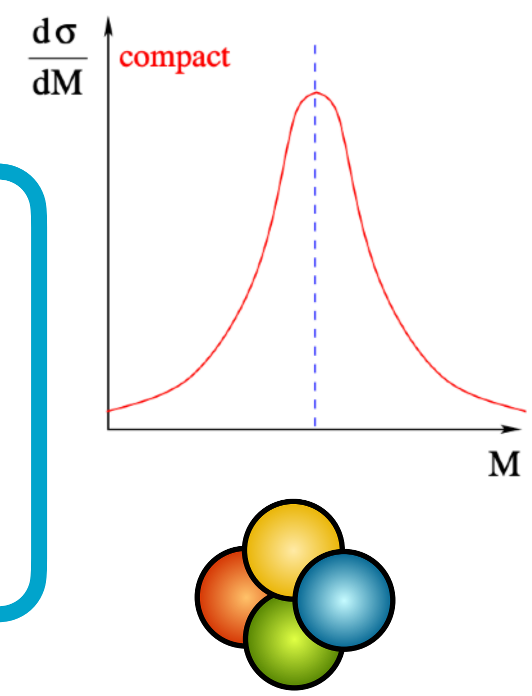
The Story of $\chi_{c1}(3872)$/X(3872)

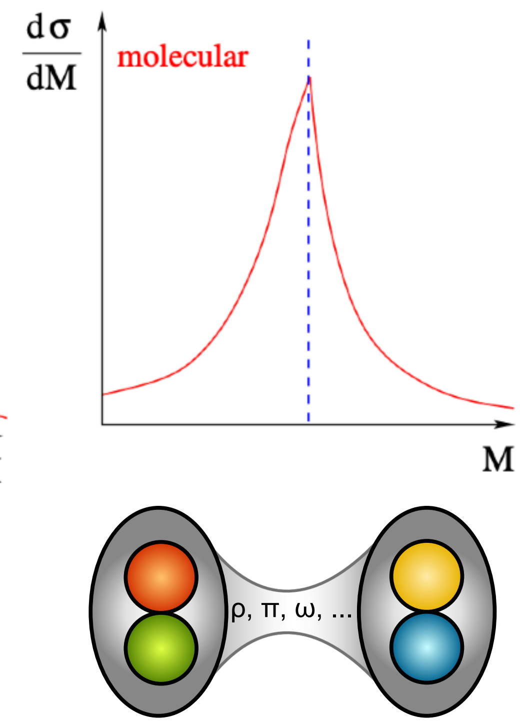
- First observed by Belle in 2003 in $X(3872) \to \pi^+\pi^- J/\psi$
- Very narrow 1^{++} state, sitting just at the $D^0\bar{D}^{*0}$ threshold
- Well established production channel: $\psi(4230) \to \gamma\chi_{c1}(3872)$
  - ➡ Precision studies possible!
- Seen in various production channels by now: B/Λ_b decays, pp, Pb Pb, e^+e^-
- ... and in various decay modes: $J/\psi(\pi^+\pi^-)\rho$, $D^0\bar{D}^{*0}$, $J/\psi\gamma$ $\psi(2S)\gamma$, $\chi_{c1}\pi^0$, …
- Isospin violating decay is enhanced by a factor of 5 compared to „ordinary“ charmonia

PRL 91, 262001 (2003)



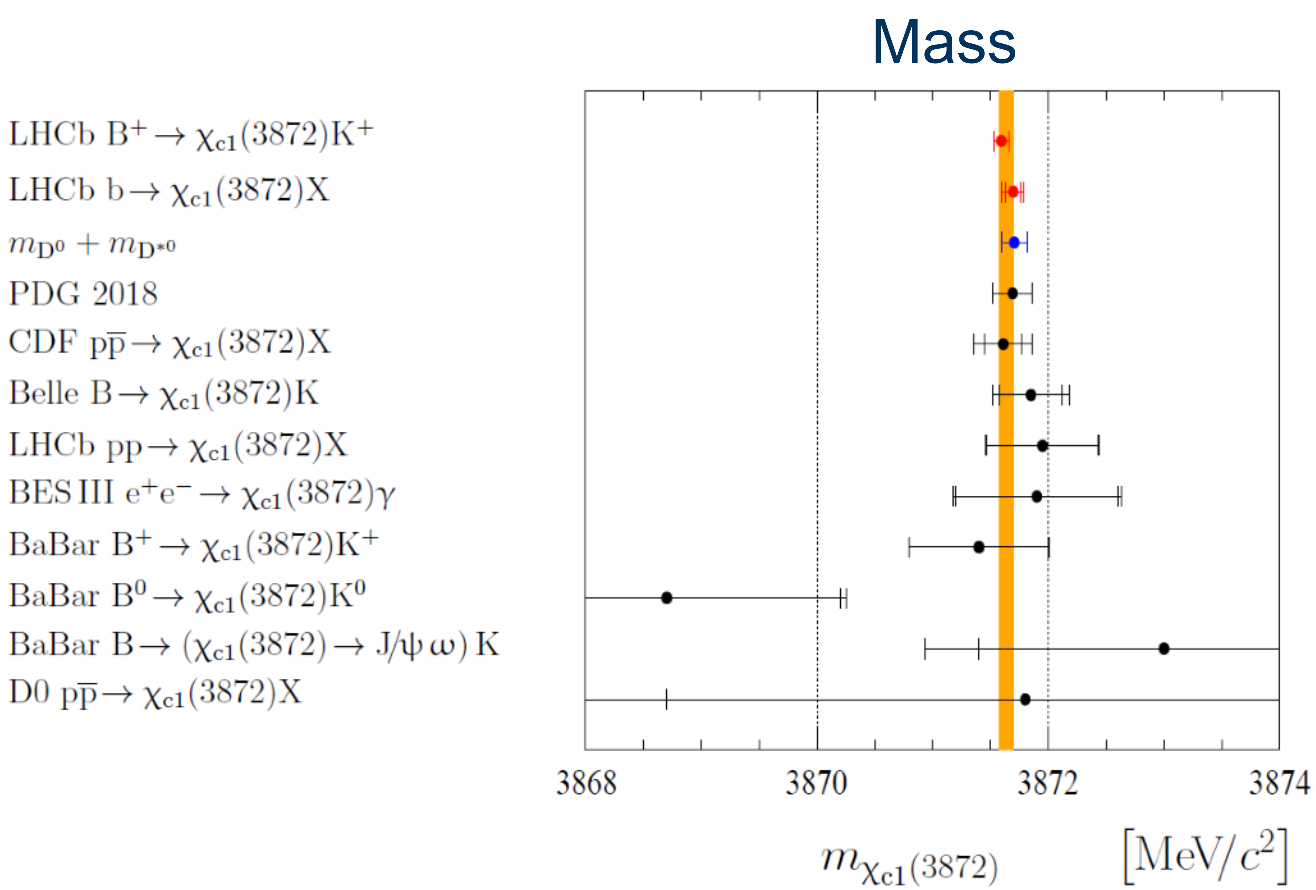
- Similar structures seen in $D^0D^0\pi^+$: $T_{cc}(3875)$
- How are they related? Is it the same underlying physics?
- Can we describe both with one model?

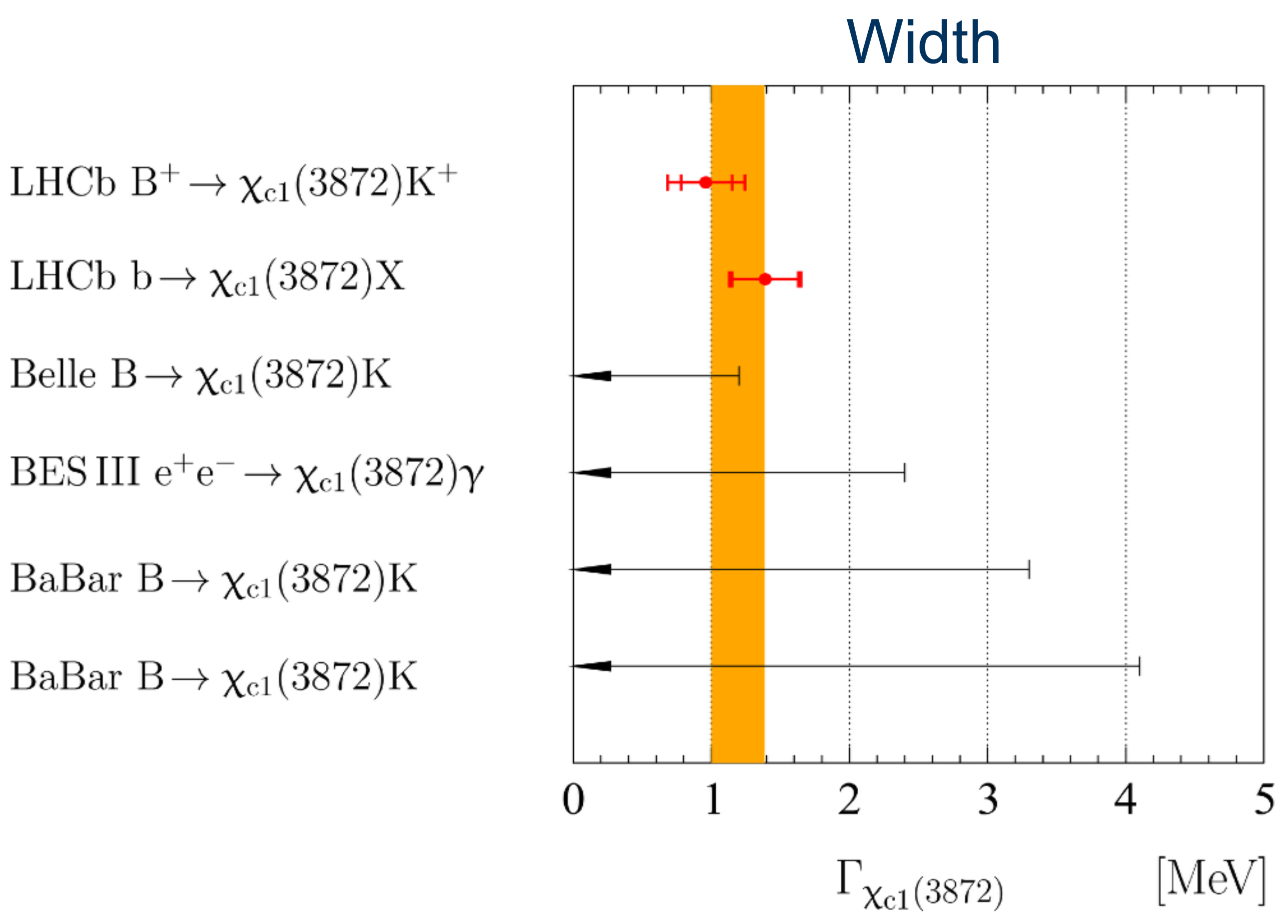




The Story of $\chi_{c1}(3872)$

- Precision has increased a lot
- First width and QN measurement by LHCb
- But: still the state is compatible with the $D^0\bar{D}^{*0}$ threshold!



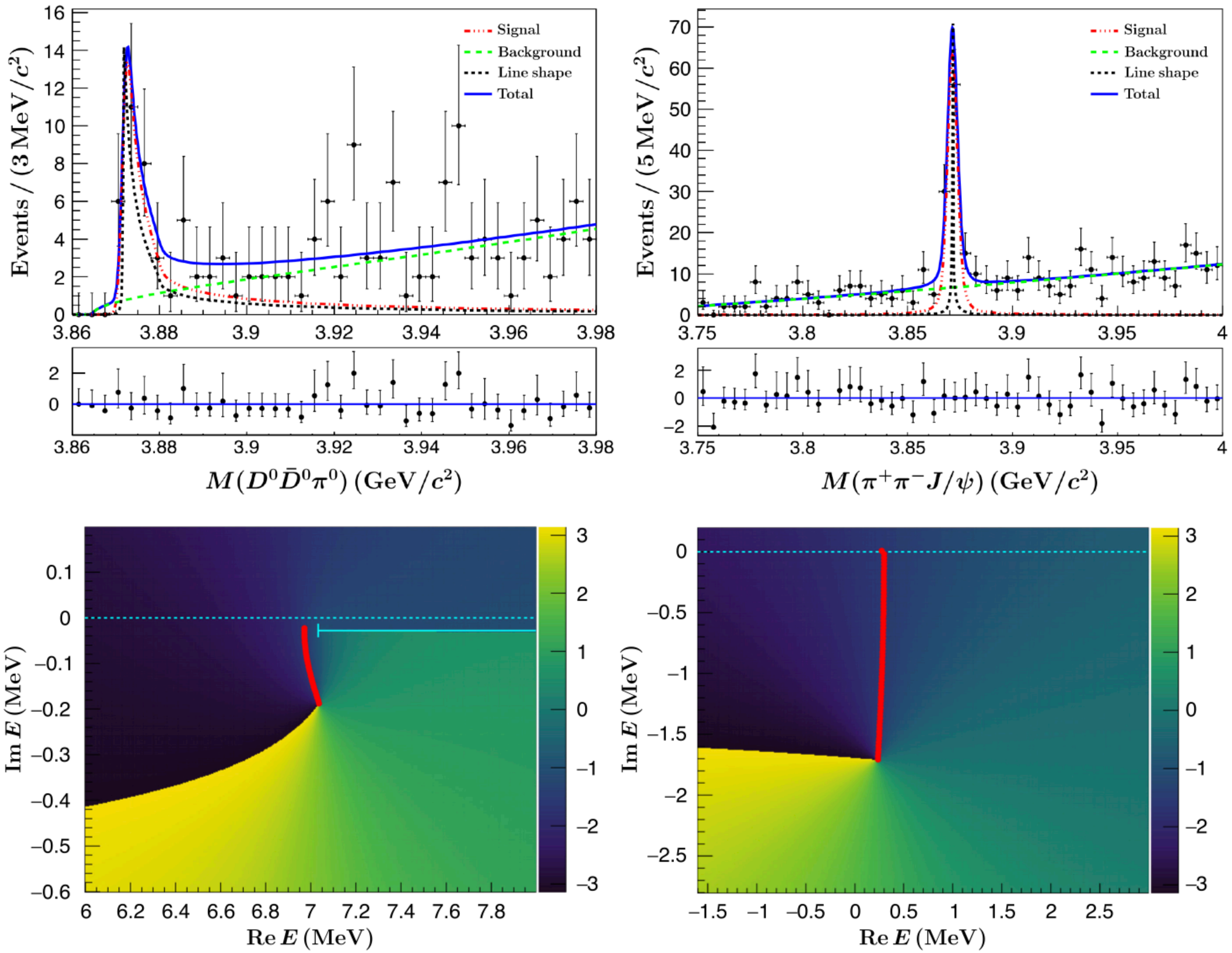


- Sensitivity to the underlying lineshape is washed out by the detector resolution
- If we want to clarify this we need << MeV resolution! No detector can do this.

Coupled Channel Fit to $\chi_{c1}(3872)$

PRL 132 (2024) 15, 151903

- Simultaneous fit to $D^0\bar{D}^0\pi^0$ and $\pi^+\pi^-J/\psi$



(a) Sheet I: $E_{\mathrm{I}} = 7.04 - 0.19i$ MeV

(b) Sheet II: $E_{\mathrm{II}} = 0.26 - 1.71i$ MeV

Coupled Channel Fit to $\chi_{c1}(3872)$

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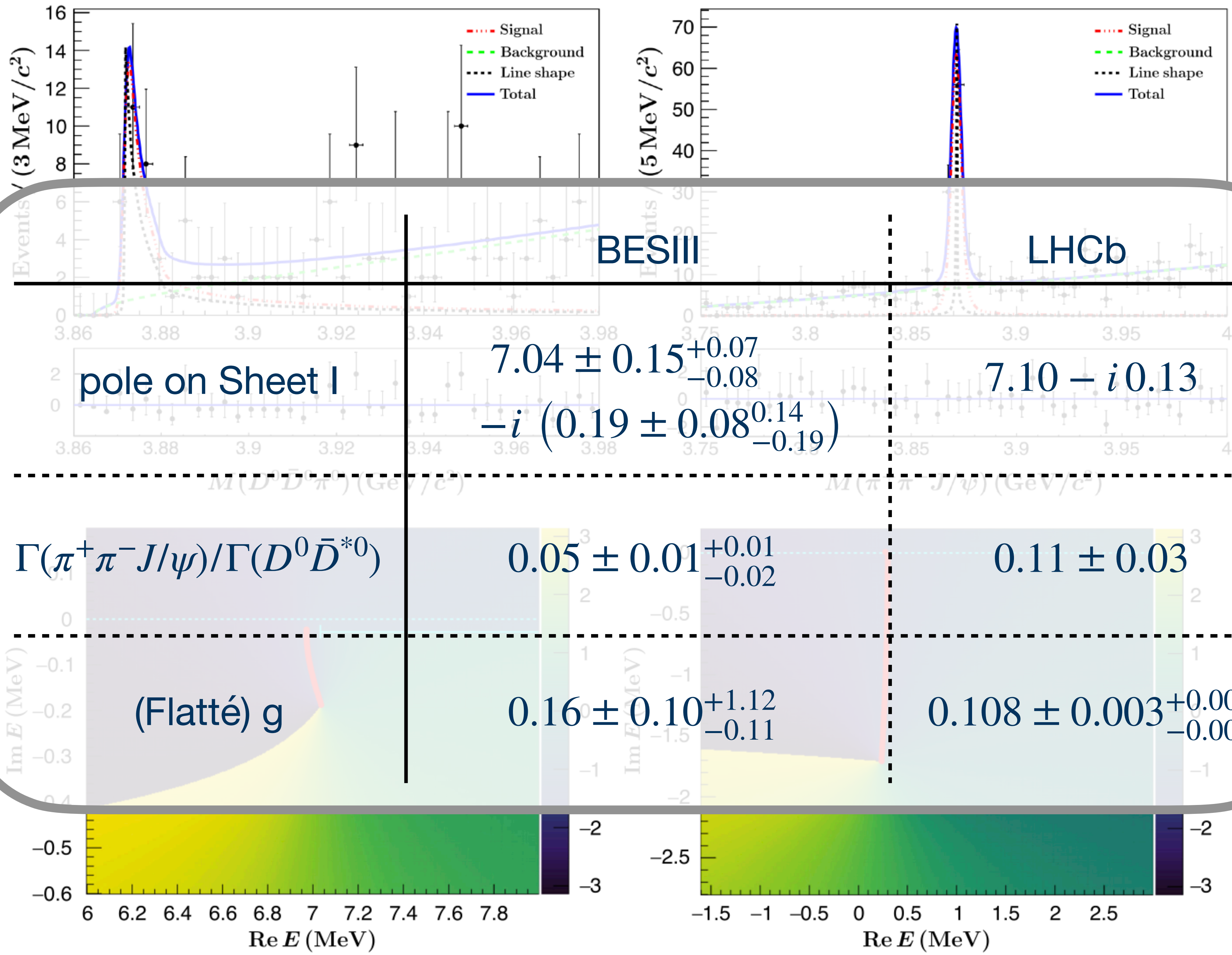


	BESIII	LHCb
pole on Sheet I	$7.04 \pm 0.15^{+0.07}_{-0.08}$ $-i\,(0.19 \pm 0.08^{0.14}_{-0.19})$	$7.10 - i\,0.13$
$\Gamma(\pi^+\pi^-J/\psi)/\Gamma(D^0\bar{D}^{*0})$	$0.05 \pm 0.01^{+0.01}_{-0.02}$	0.11 ± 0.03
(Flatté) g	$0.16 \pm 0.10^{+1.12}_{-0.11}$	$0.108 \pm 0.003^{+0.005}_{-0.006}$

(a) Sheet I: $E_{\mathrm{I}} = 7.04 - 0.19i$ MeV (b) Sheet II: $E_{\mathrm{II}} = 0.26 - 1.71i$ MeV

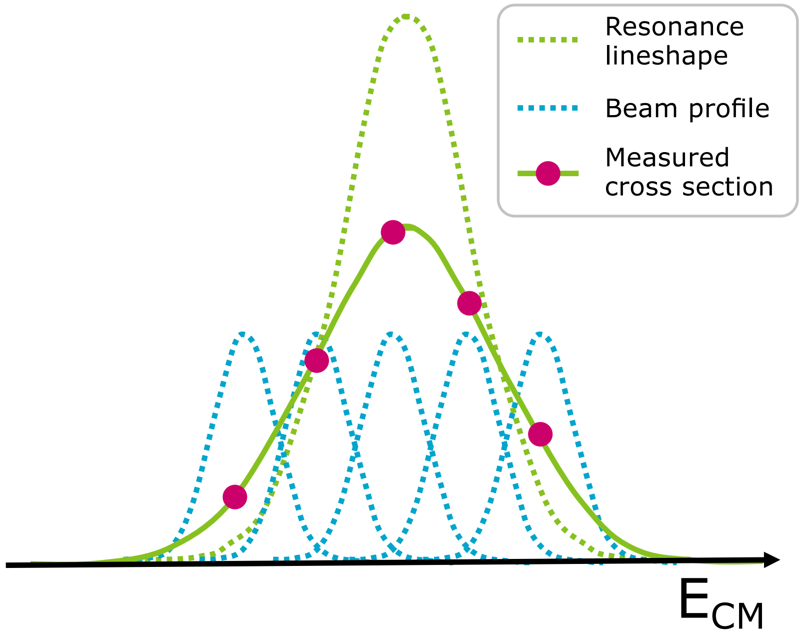
Line Shape Scans at $\bar{\text{P}}$ANDA

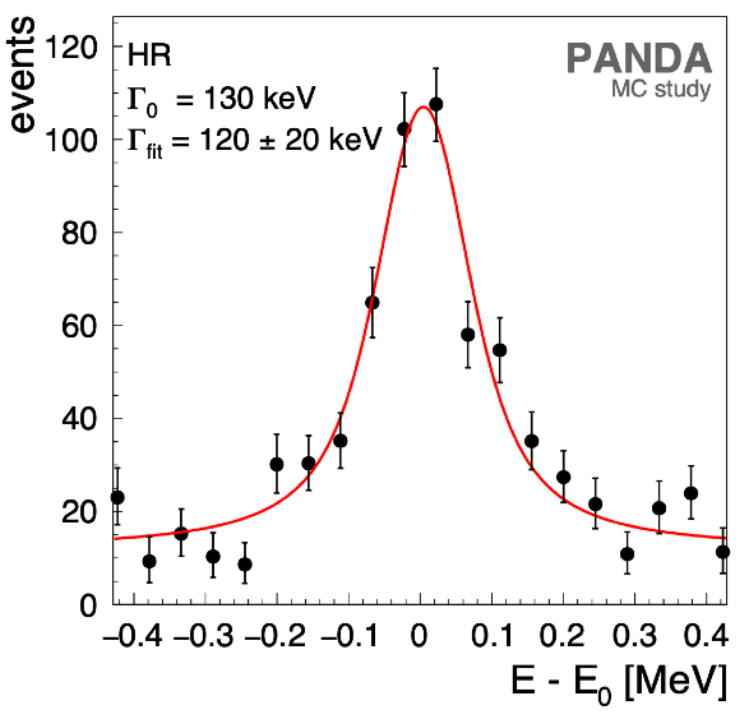
Eur. Phys. J. A (2019) **55**: 42

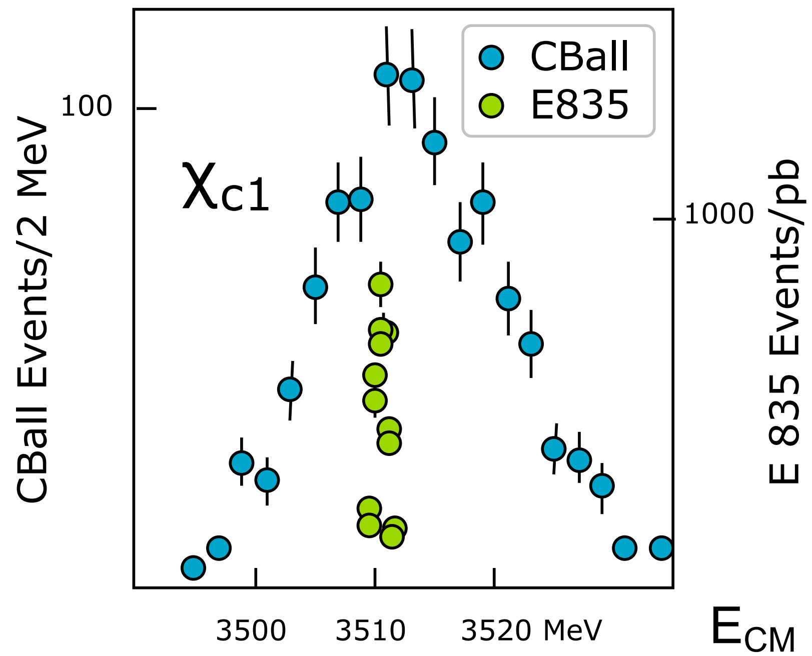
- Measure the lineshape with high precision by scanning the resonance in production
- **Line shape resolution is only limited by the beam resolution, not the detector resolution here!**
- Analysis performed for 20 energy points around nominal mass
- In sensitivity studies able to distinguish the two scenarios

➡ With the $\bar{\text{P}}$ANDA setup this corresponds to only about a month of data taking!

➡ In $\bar{p}p$ annihilation almost all Q.N. can be produced directly!





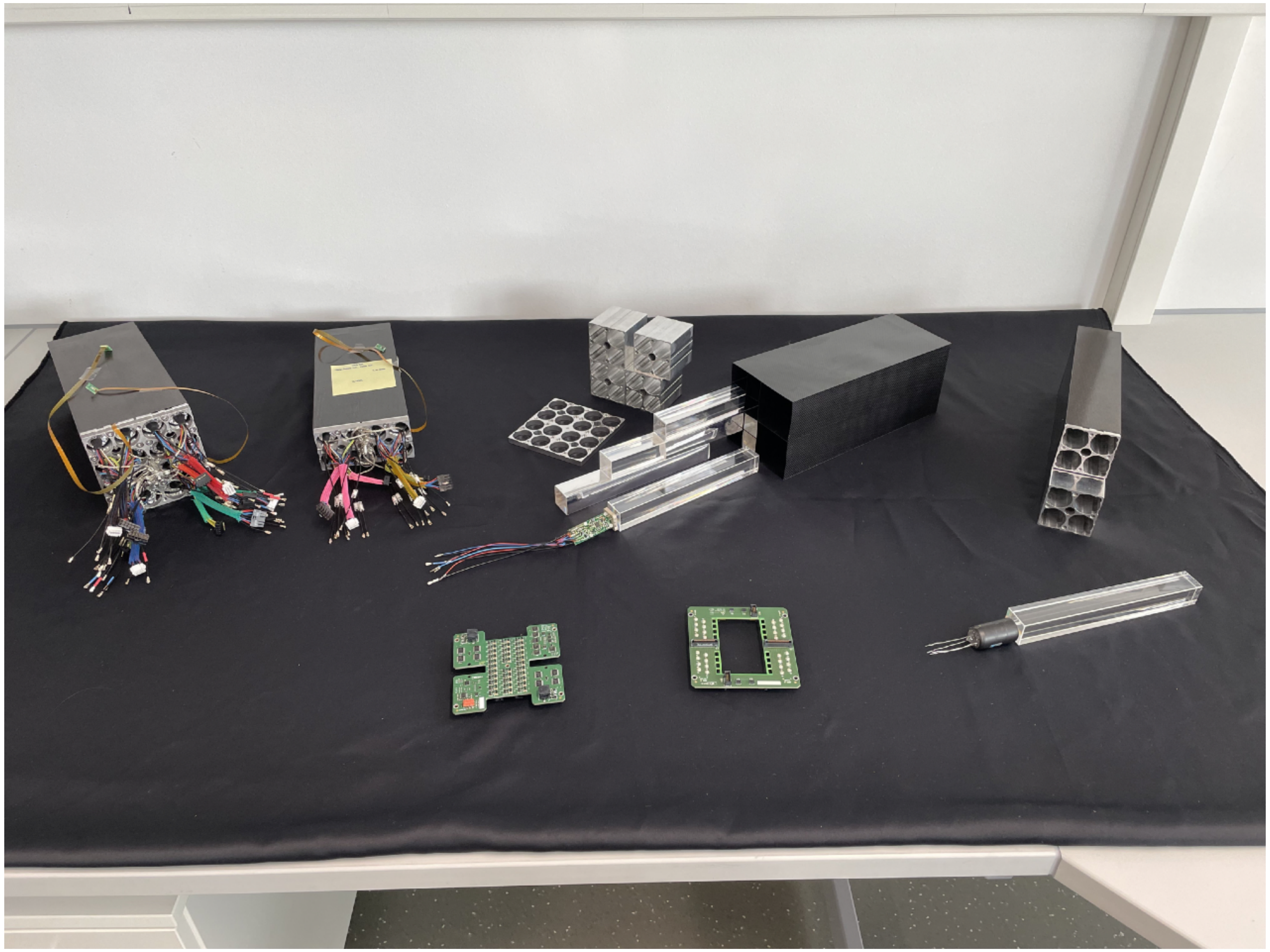


$\bar{\text{P}}$ANDA will be able to study all this!

Design beam resolution:

$\Delta p/p = 4 \cdot 10^{-5}$

$\overline{\text{P}}$ANDA Forward Endcap EMC Beam Test



- Consisting of 15604 $PbWO_4$ crystals
- Operated at -25 ± 0.1°C for best energy resolution
- Just recently successful test beam operation at COSY@FZJ with final detector design!
- Preliminary results show leading edge performance

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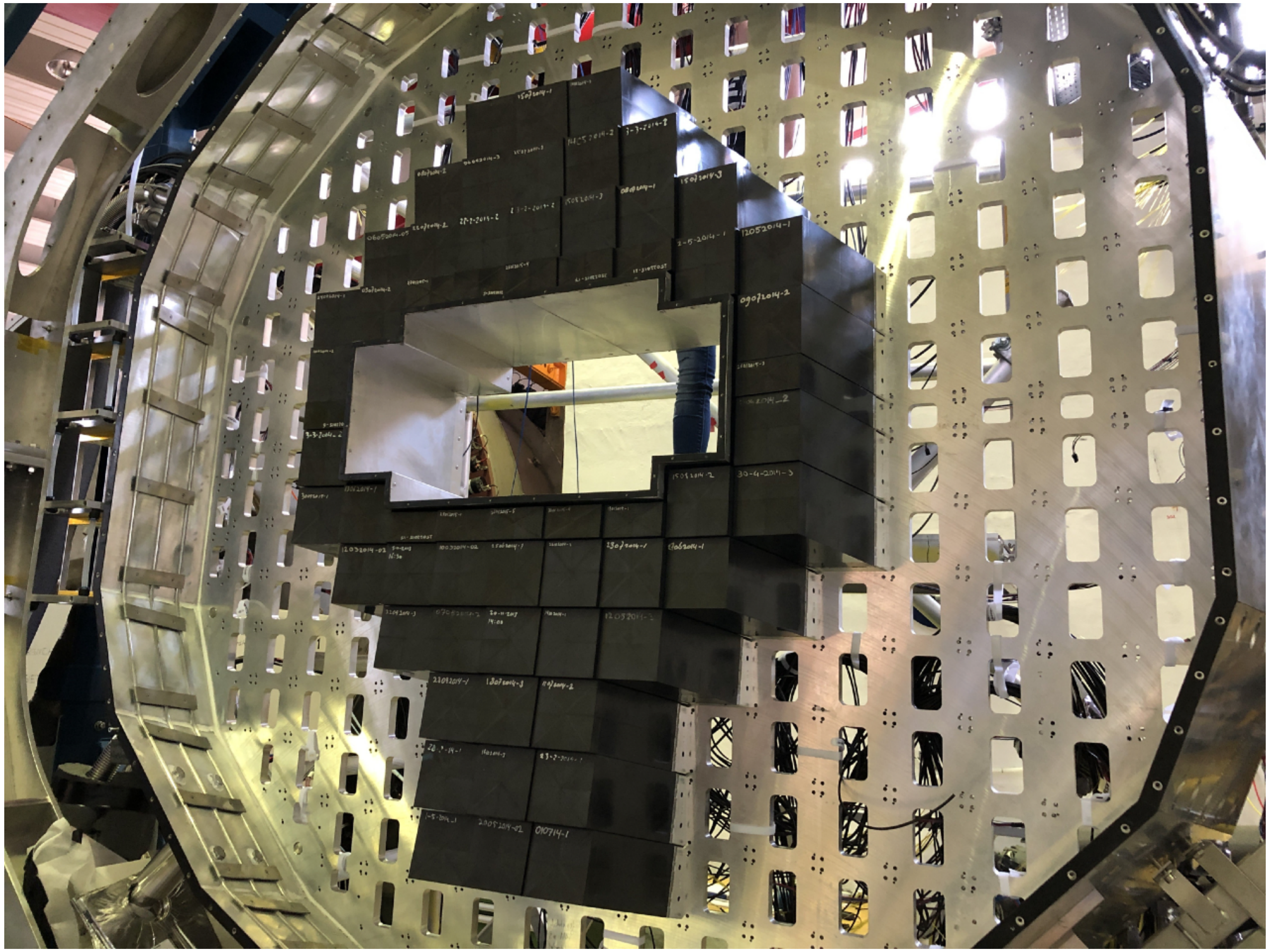

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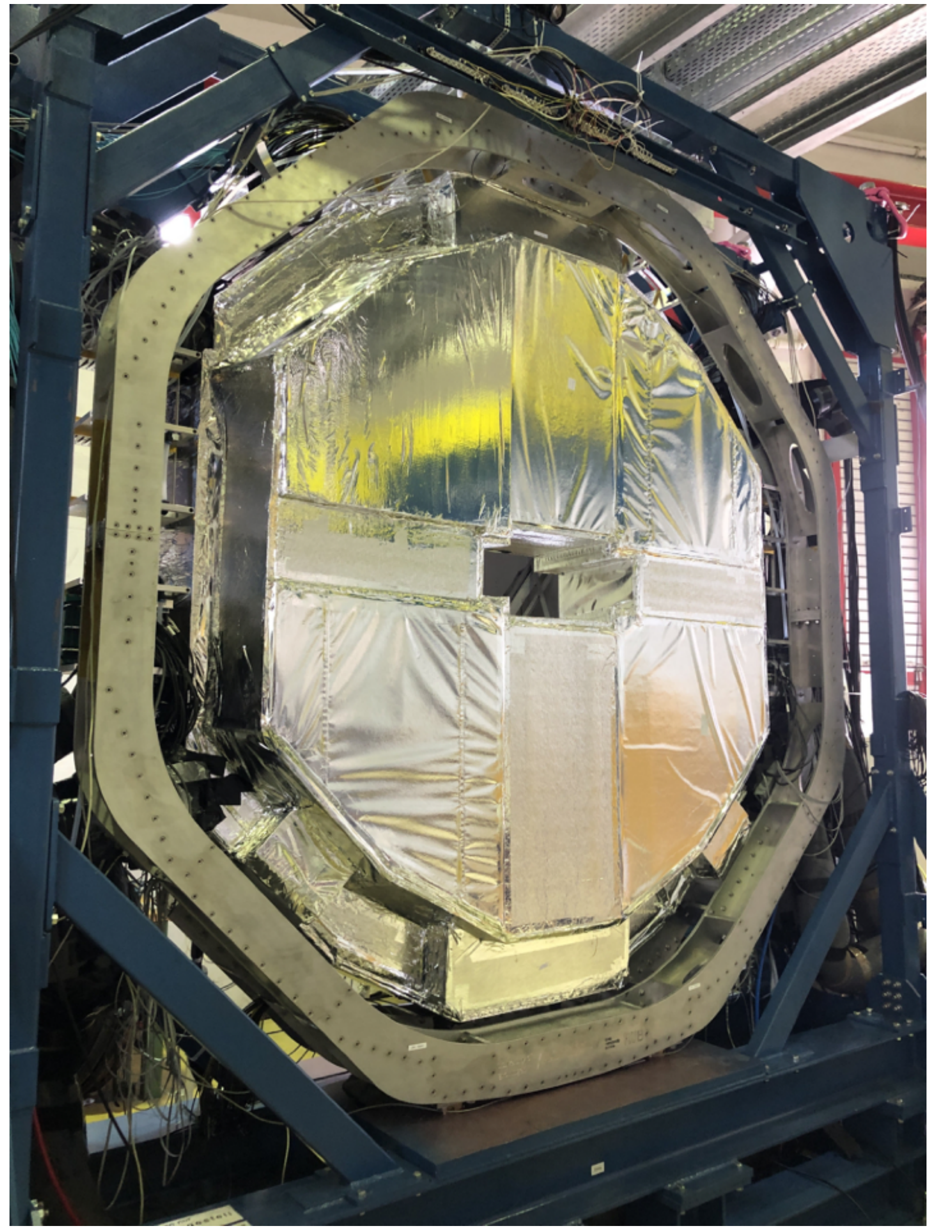

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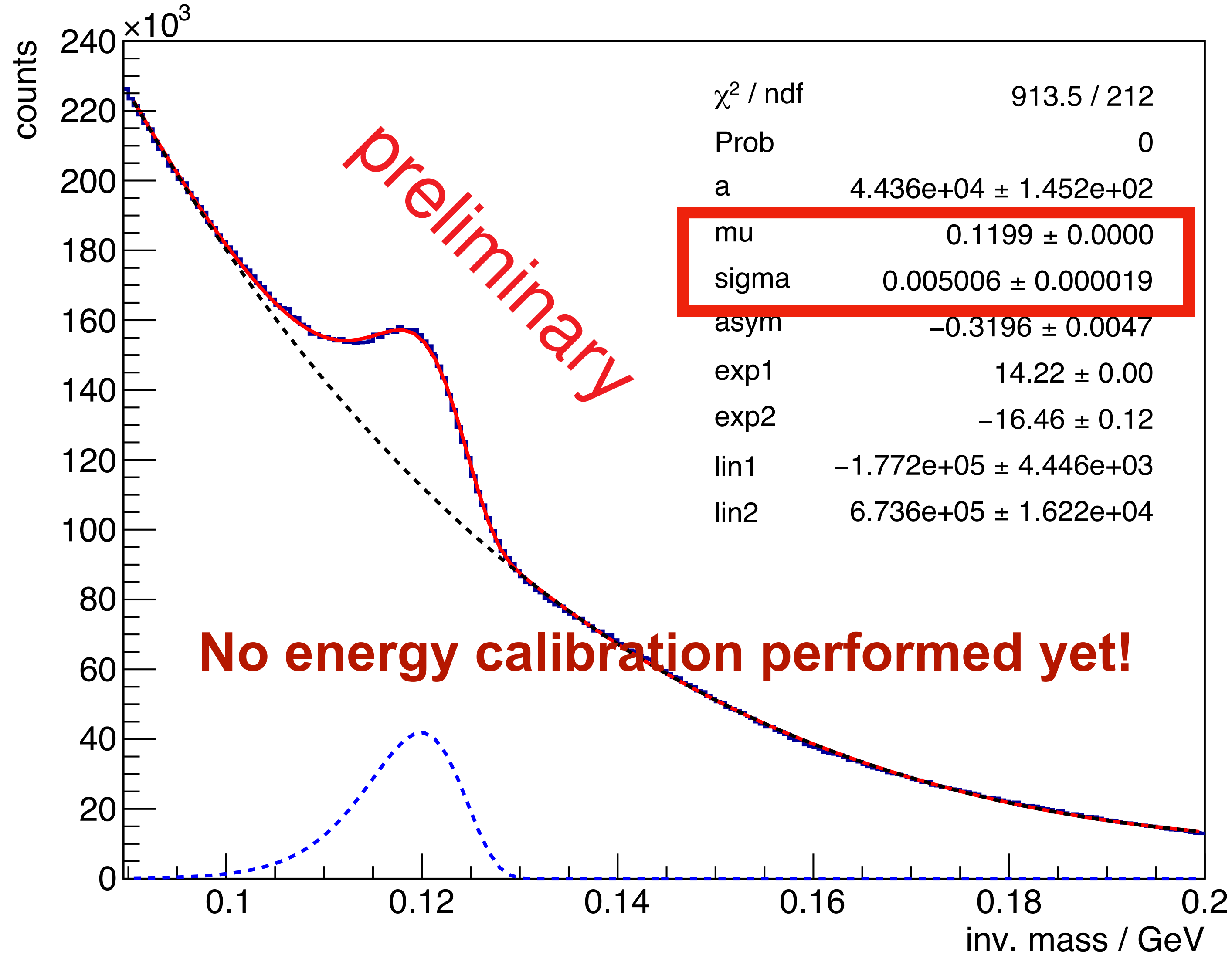

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Summary

- Although light mesons are studied for decades, there are still many open questions
- This affects also other sectors as CP violation!
- Different experiments and theory need to collaborate to solve this
- Coupled channel analyses seem to be a good tool to disentangle crowded spectra
- …and to even increase precision without additional data!
- Work closer together in the community - common effort is needed to answer fundamental questions
- And to prepare our toolsets in times of high statistic data awaiting us
- This strengthens the research field, especially in times when basic research is experiencing more headwinds


Thank You!