QCD Exotics and where to find them

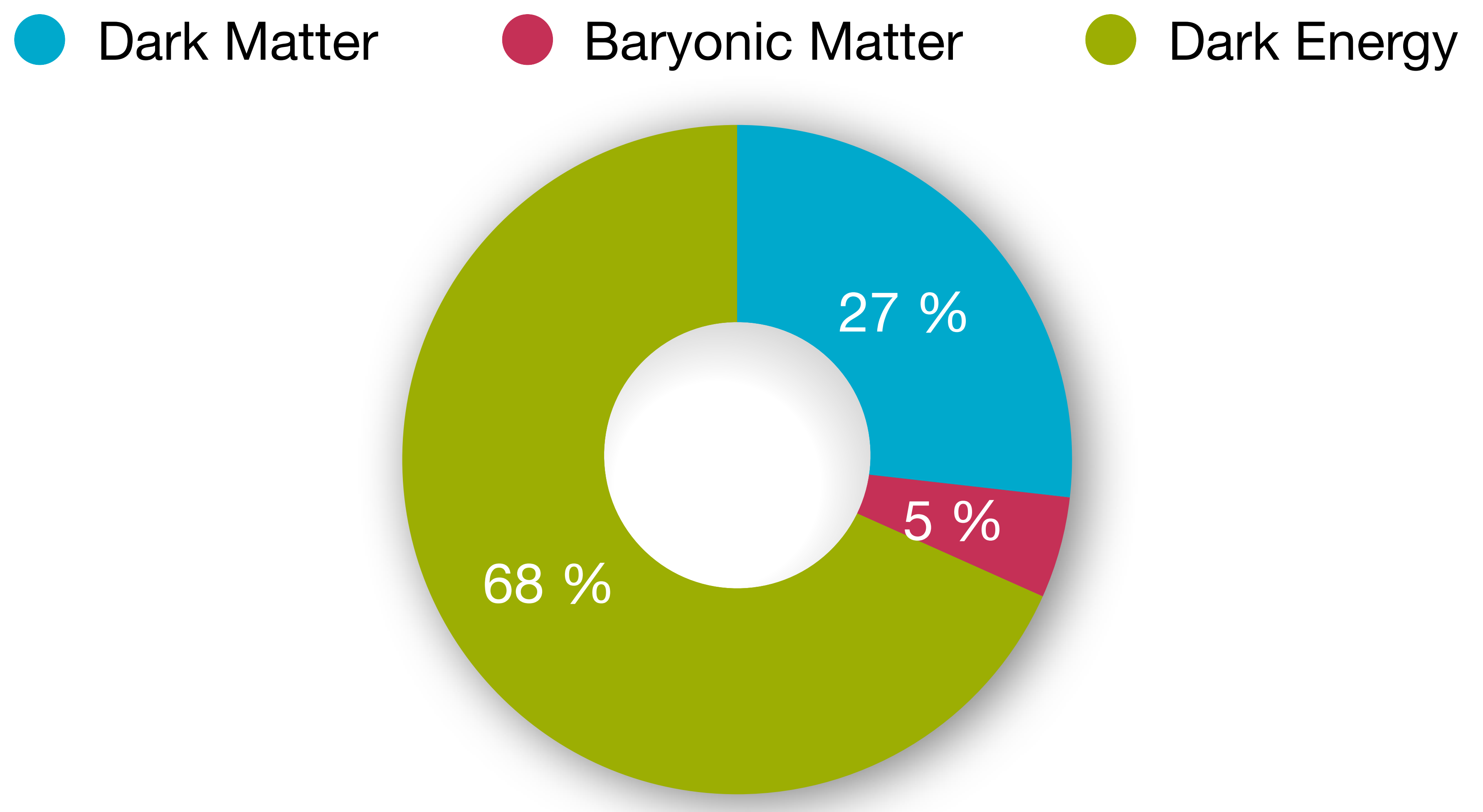
Meike Küßner

Exotic multi-quark states and baryon spectroscopy workshop Bonn

25th of June 2024

Fundamental Questions

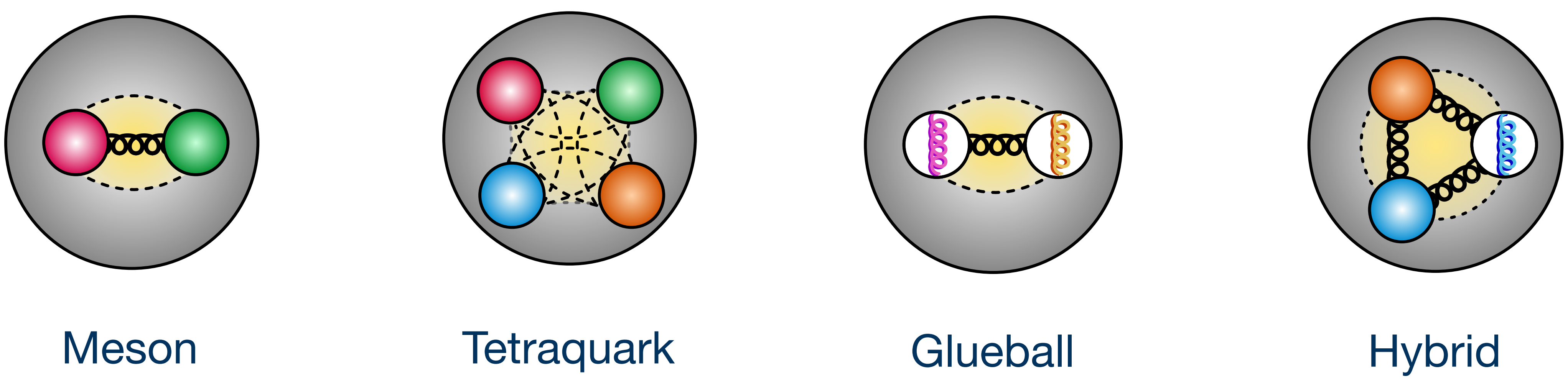
The Higgs mechanism creates the mass of the fundamental particles, but this is not the end of the story!



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

From the Perspective of Meson Spectroscopy

- 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



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

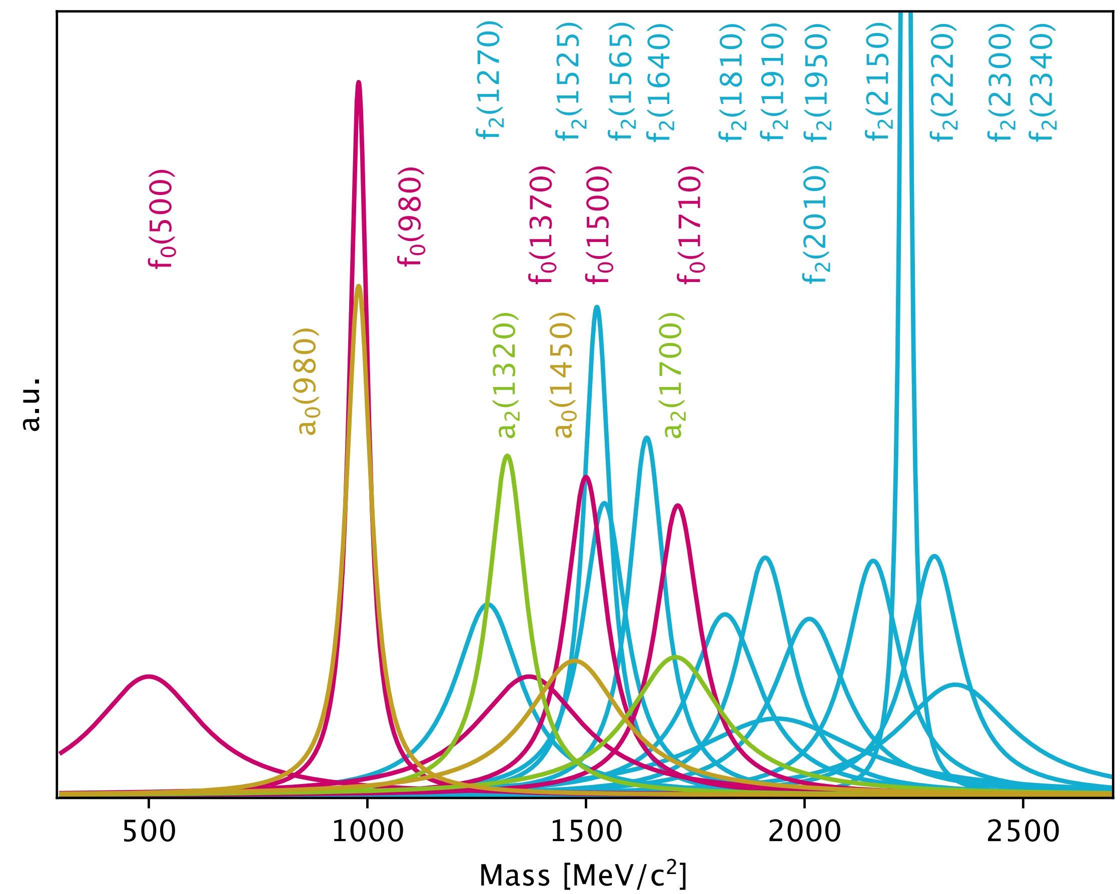
$$P = (-1)^{L+1}\, ,\, C = (-1)^{L+S}$$

- 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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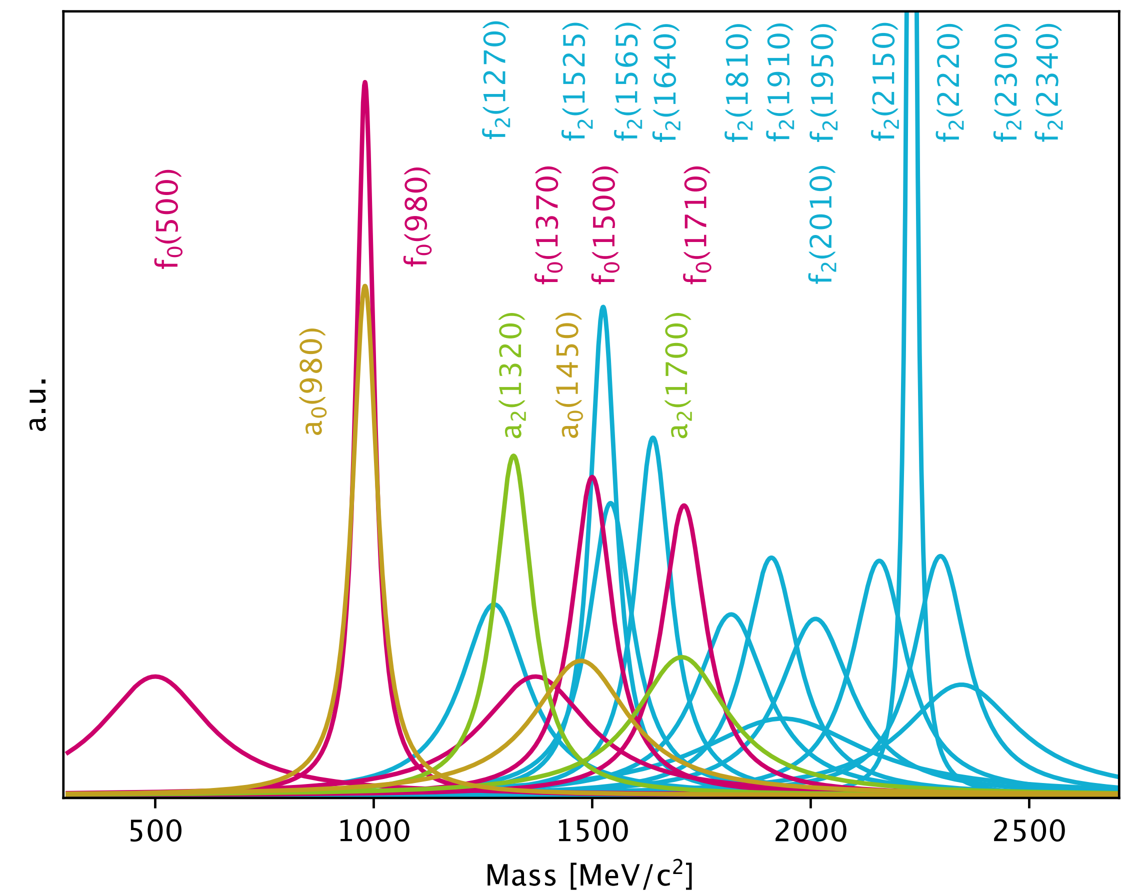


We should start thinking beyond experimental collaborations!

Experimental Possibilities

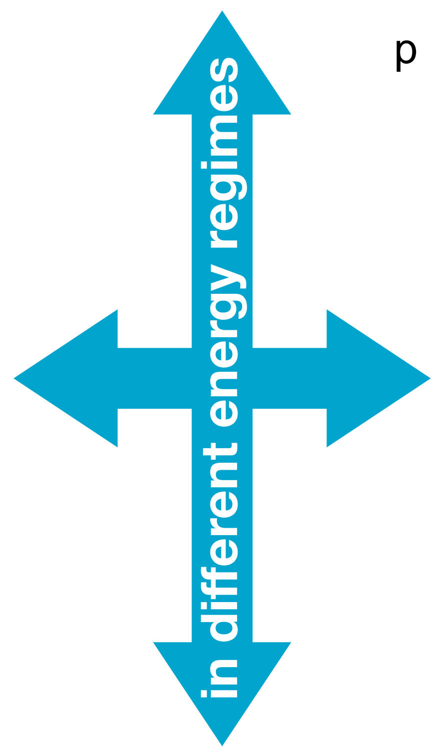
- Each experiment, detector and process has its own advantages
- To tackle these challenges, we need to combine forces

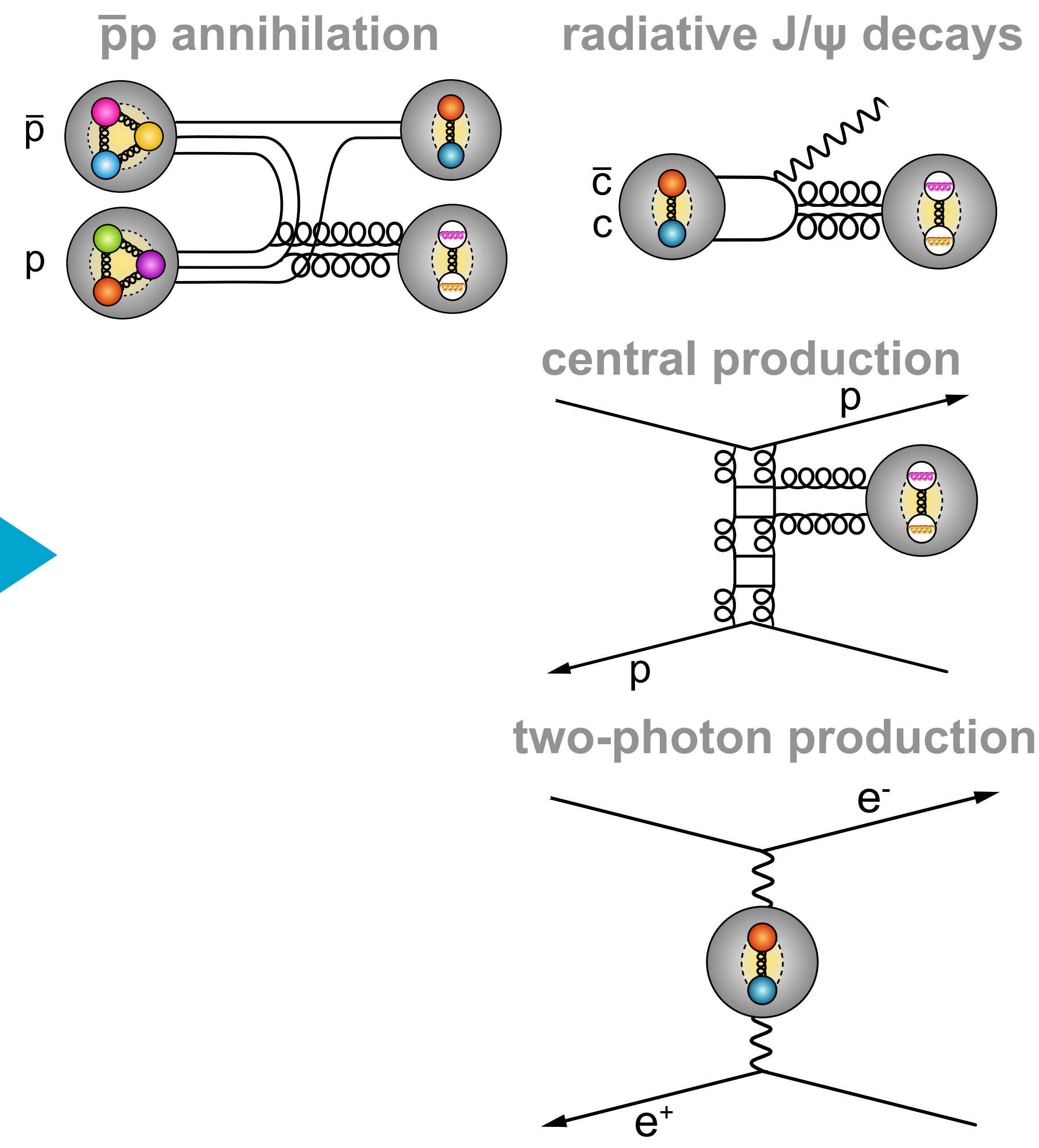
Gluon rich processes

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

QED mediated process

- Two-photon production





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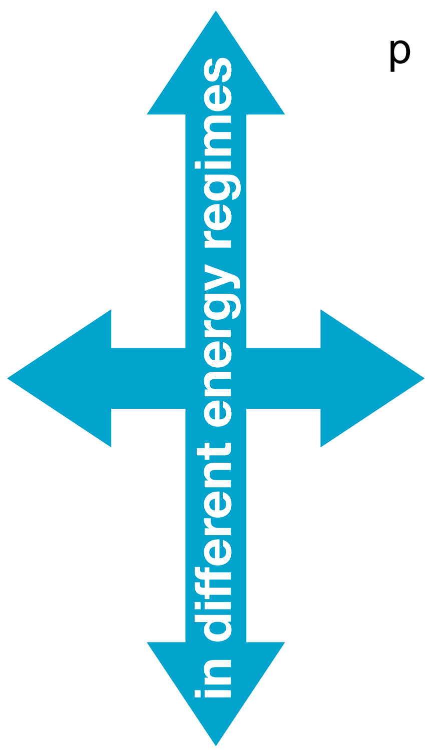
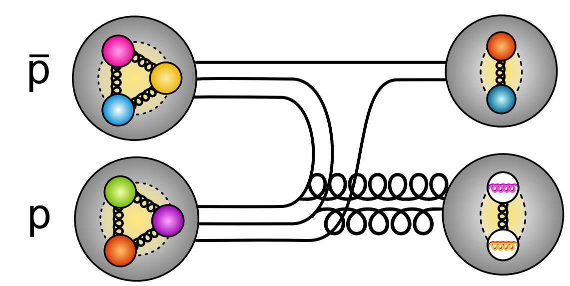
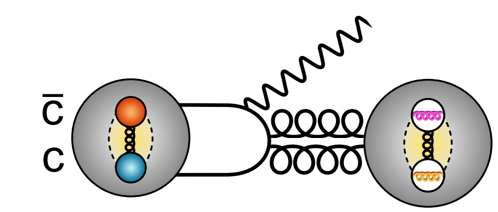


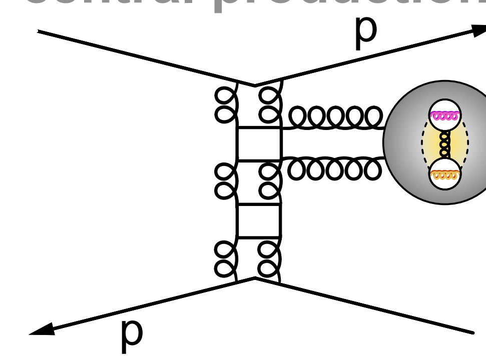
$\bar{p}p$ annihilation



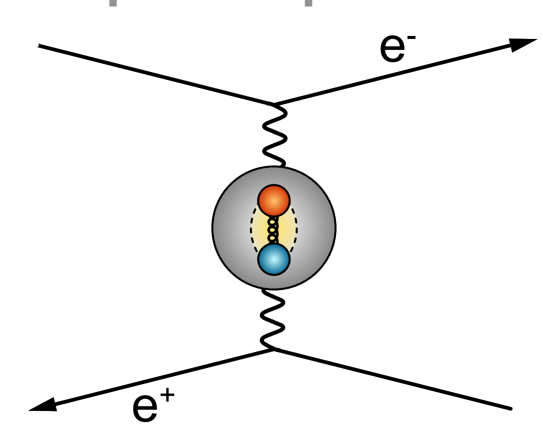
radiative J/ψ decays



central production



two-photon production

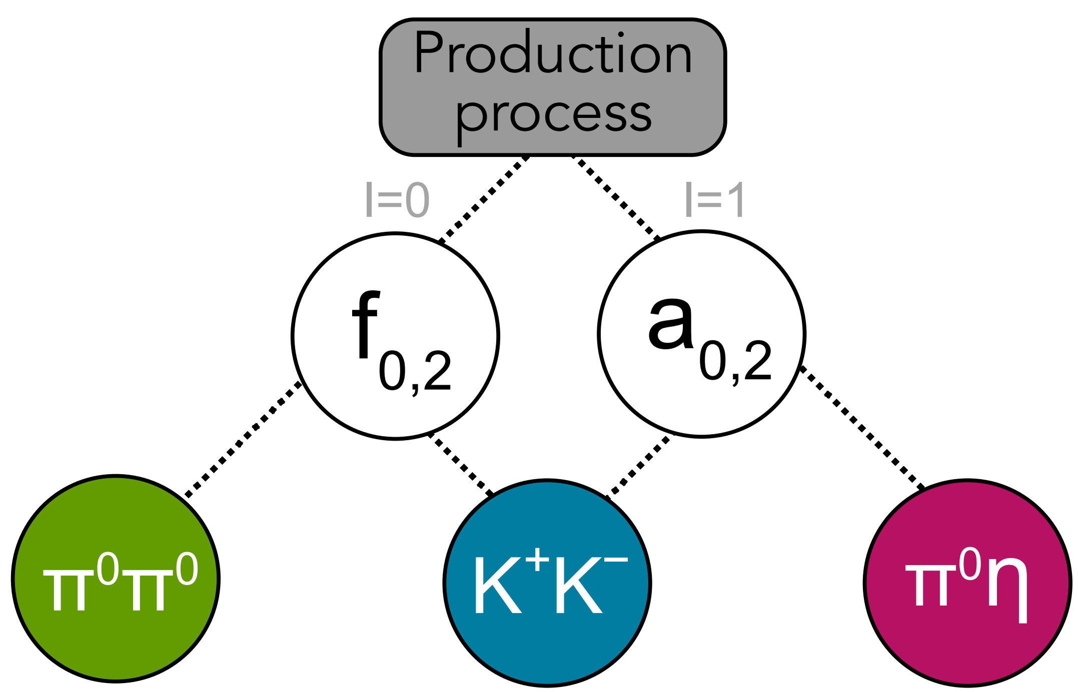


Combine different production mechanisms and decay channels to reveal a particle's nature

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

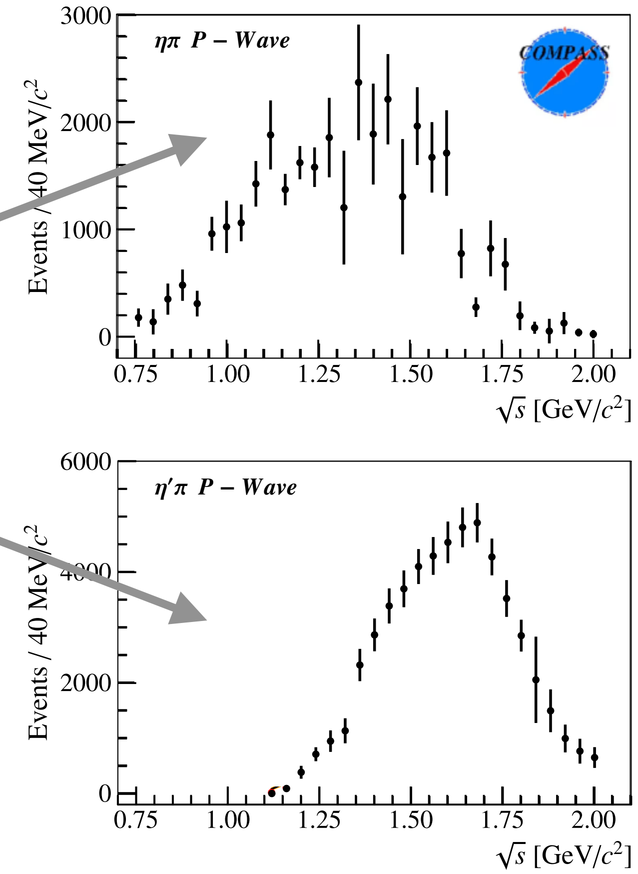
Two π_1 hybrid candidates below 2 GeV are listed in PDG

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

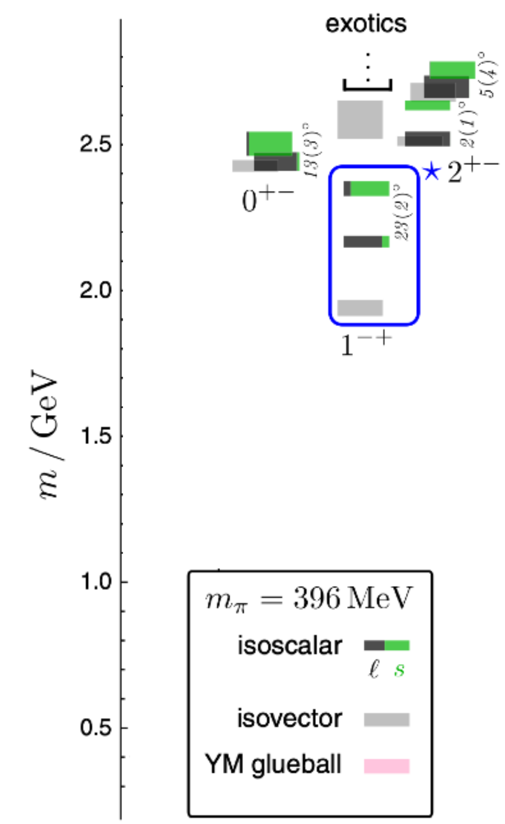
➡ Parameters obtained by Breit-Wigner fits!

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

200 MeV apart!

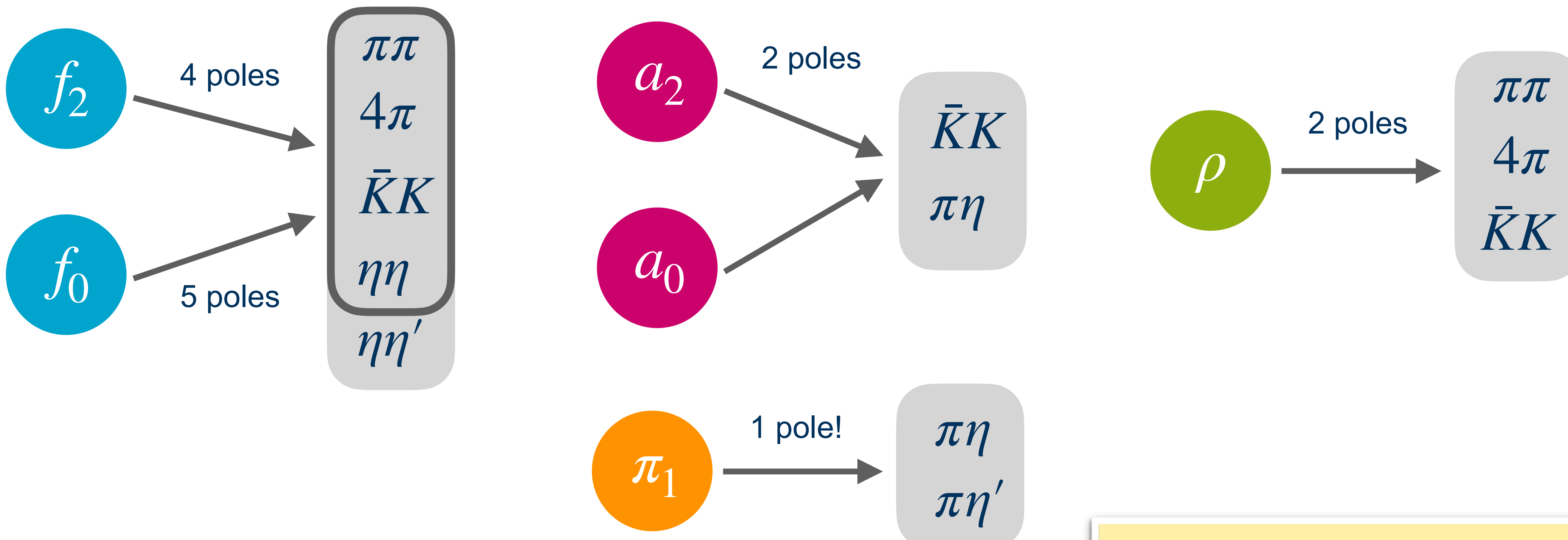


Phys.Rev. D84 (2011) 074023



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)

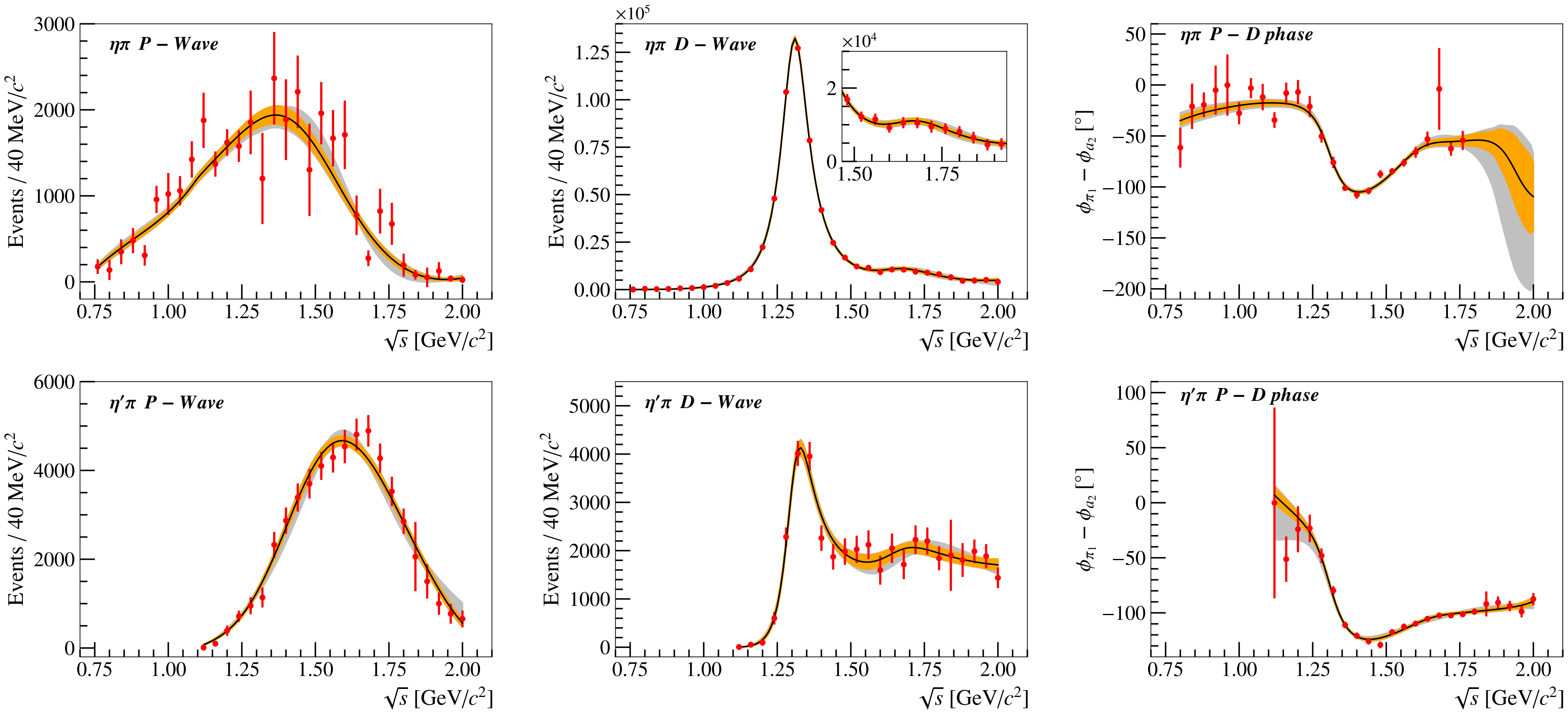
- Good constraints for f_0, f_2 and ρ resonances
- All dispersive relations are fulfilled automatically!

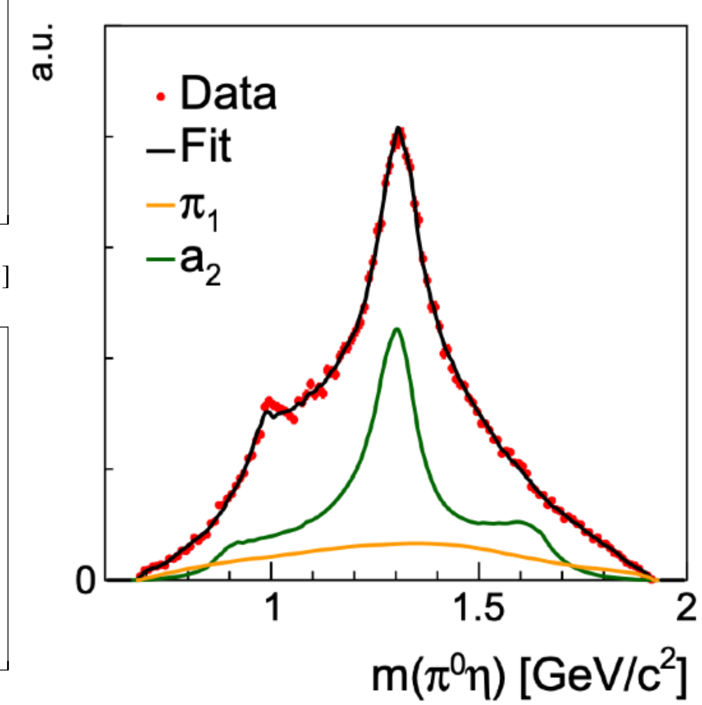
But: All this relies on data from $KN \to K\pi N'$ reactions from 70s and 80s!
Would be nice to have some new data on this

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:

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

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

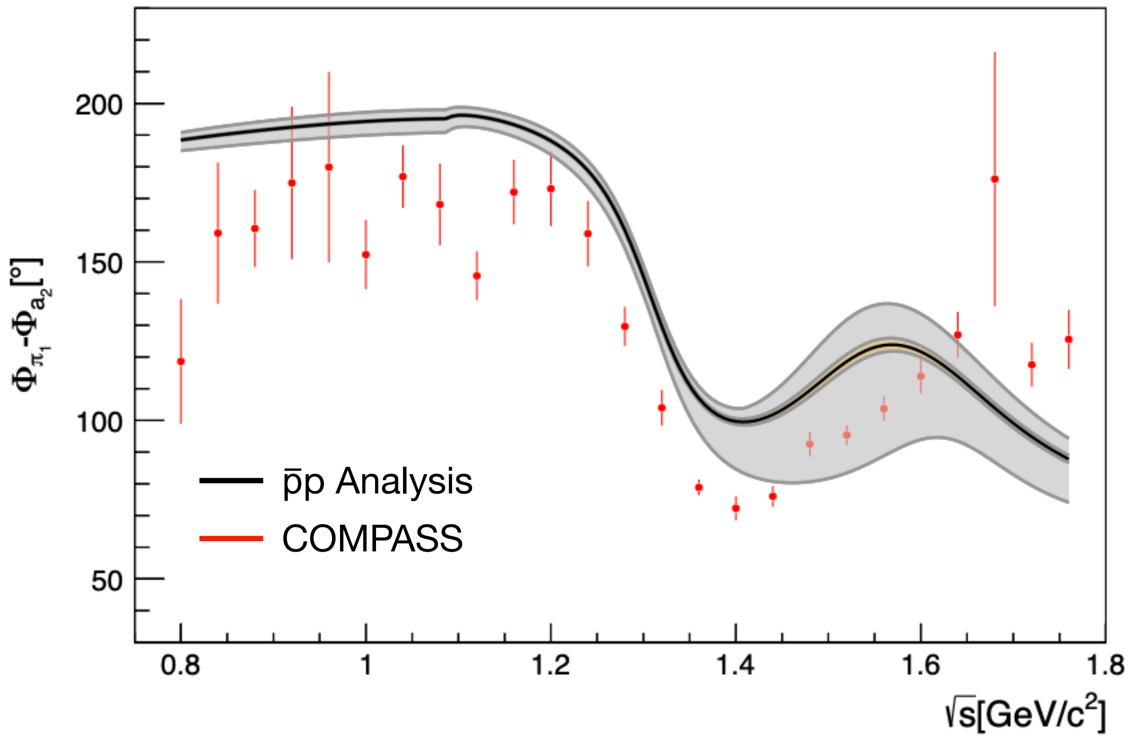
Coupled Channel Analysis of $\bar{p}p \rightarrow \pi^0 \pi^0 \eta$, $\pi^0 \eta \eta$ and $K^+ K^- \pi^0$

- Exotic π_1 wave significantly contributing in the $\pi^0\eta$ system!

Without COMPASS data

	contribution (in %) for channel $\pi^0\pi^0\eta$	$\pi^0\eta\eta$	$K^+K^-\pi^0$
$f_0\,\pi^0$		$23.7 \pm 1.2 \pm 2.3$	$7.4 \pm 0.3 \pm 4.1$
$f_0\,\eta$	$10.7 \pm 0.4 \pm 1.8$		
$f_2\,\pi^0$		$30.1 \pm 1.3 \pm 2.7$	$17.1 \pm 0.7 \pm 10.0$
$f_2\,\eta$	$52.3 \pm 0.8 \pm 5.0$		
$\rho\,\pi^0$			$17.2 \pm 1.0 \pm 4.0$
$a_0\,\pi^0$	$22.4 \pm 0.4 \pm 1.0$		$6.1 \pm 0.2 \pm 2.8$
$a_0\,\eta$		$28.6 \pm 1.1 \pm 7.5$	
$a_2\,\pi^0$	$33.0 \pm 0.6 \pm 2.9$		$6.4 \pm 0.2 \pm 2.9$
$a_2\,\eta$		$18.8 \pm 1.1 \pm 5.6$	
$K^*(892)^\pm K^\mp$			$45.0 \pm 1.3 \pm 11.0$
$(K\pi)_S^\pm K^\mp$			$6.1 \pm 0.4 \pm 4.9$
$\phi(1020)\,\pi^0$			$2.5 \pm 0.3 \pm 0.3$
$\pi_1\,\pi^0$	$16.7 \pm 0.5 \pm 3.0$		
Σ	$135.0 \pm 1.2 \pm 8.7$	$101.2 \pm 2.4 \pm 11.7$	$107.8 \pm 1.9 \pm 12.5$

T-Matrix phase difference in agreement!

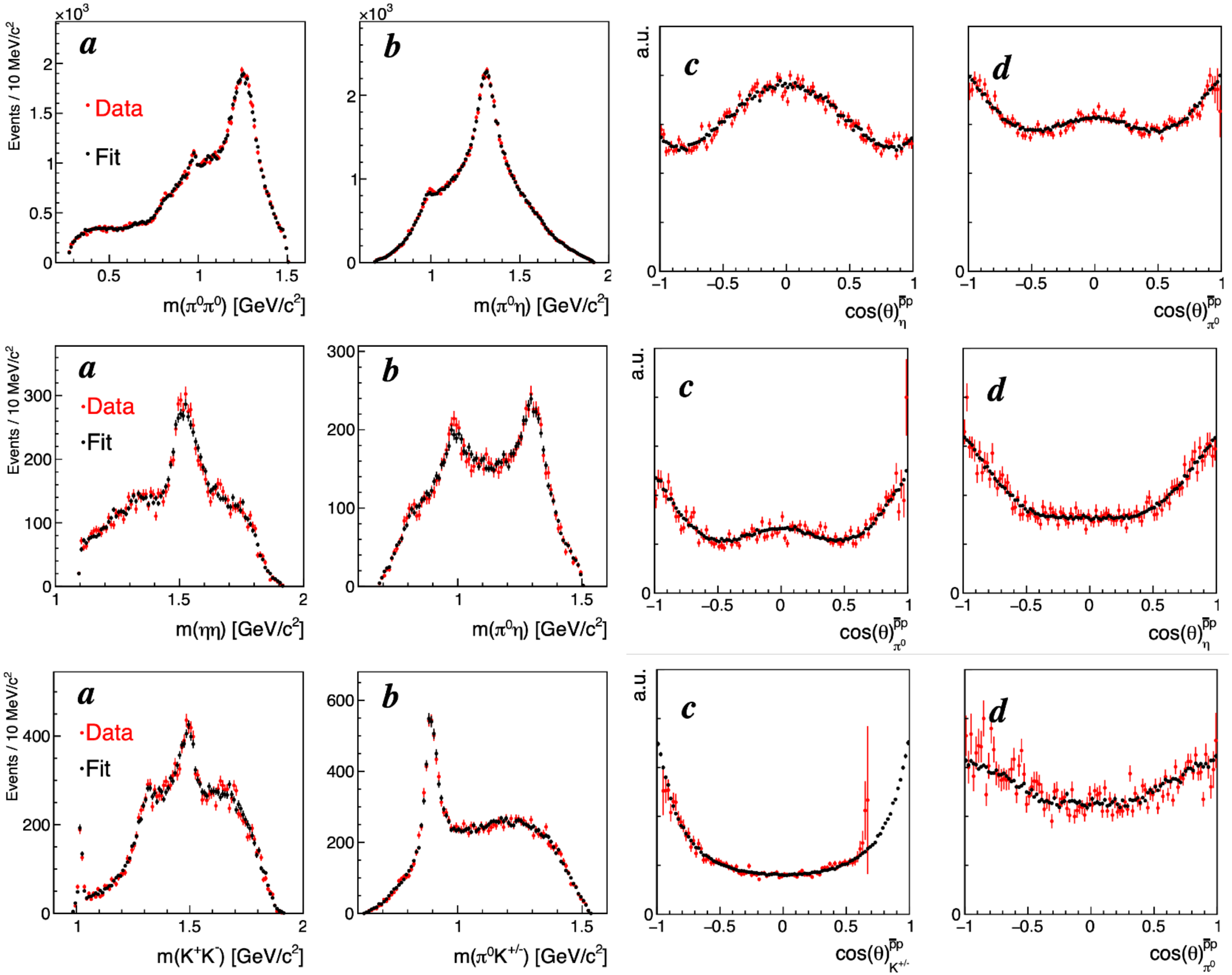


- K-matrix description with 1 pole and two channels πη and πη'
- Phase difference between the π_1 and a_2 wave from $T_{\pi\eta\rightarrow\pi\eta}$ in good agreement with COMPASS measurement Phys. Lett. B740 (2015) 303-311, Phys. Lett. B811 (2020) 135913 (erratum)
- Obtained pole position of the π_1: M = $(1404.7 \pm 3.5\ (stat.)\ ^{+9.0}_{-17.3}\ (sys.))\ \mathrm{MeV}/c^2$

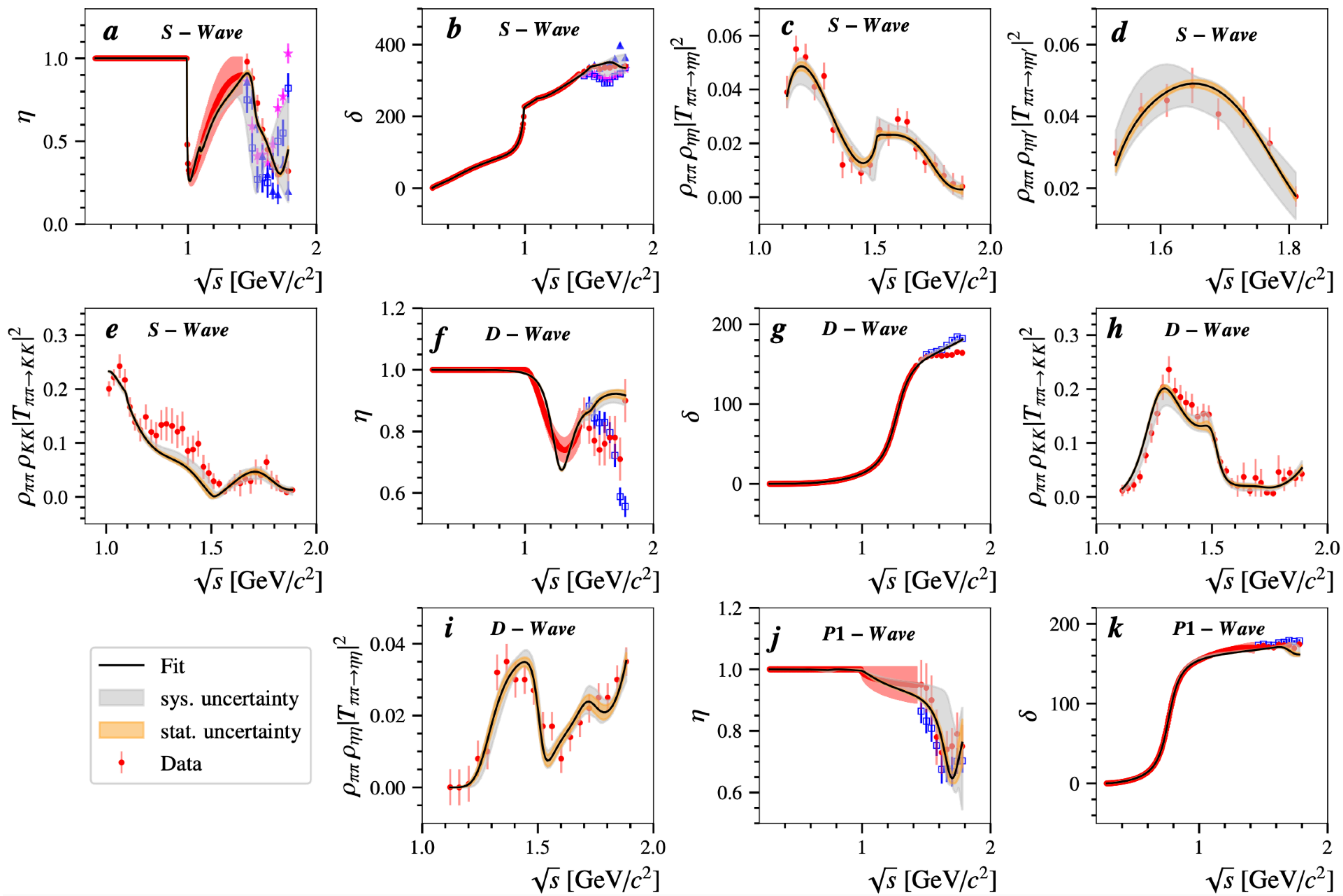
  Γ = $(628.3 \pm 27.1\ (stat.)\ ^{+35.8}_{-138.2}\ (sys.))\ \mathrm{MeV}$

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

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

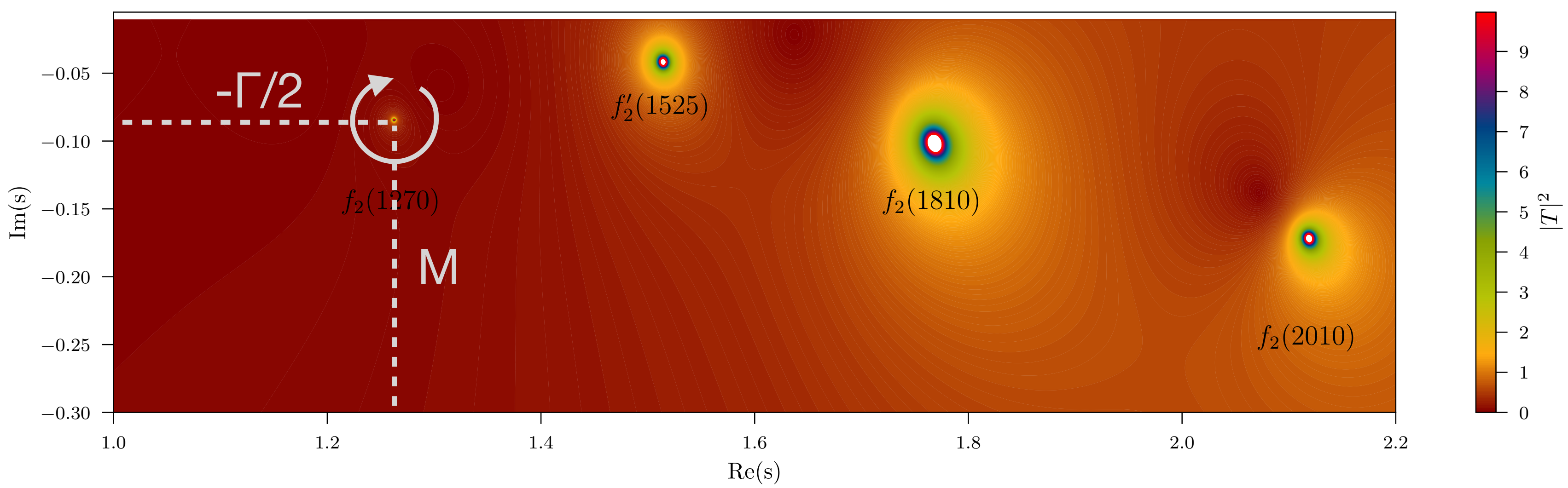


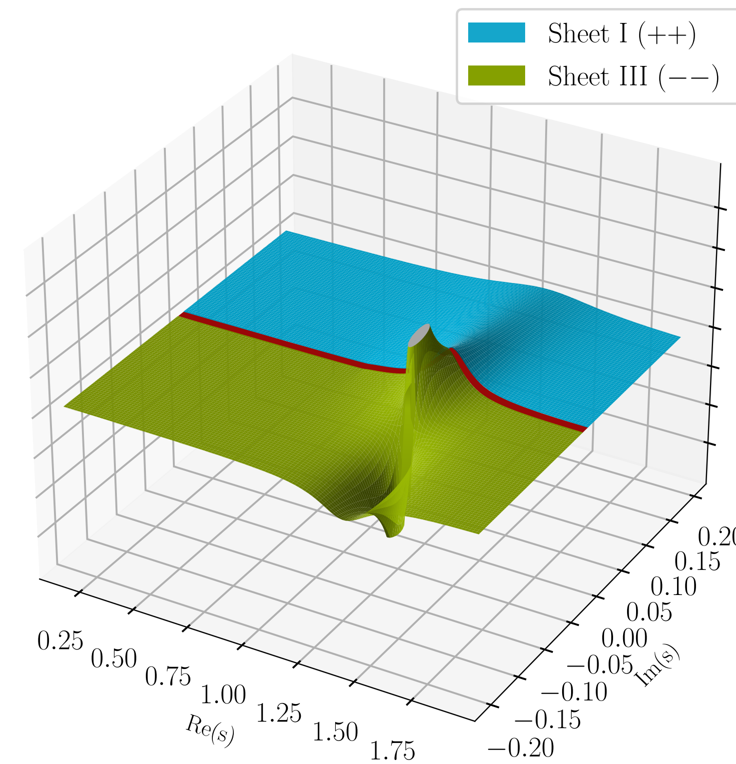
Simultaneous Description of Scattering Data



Extraction of Resonance Properties

Example: f_2-wave





- 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!

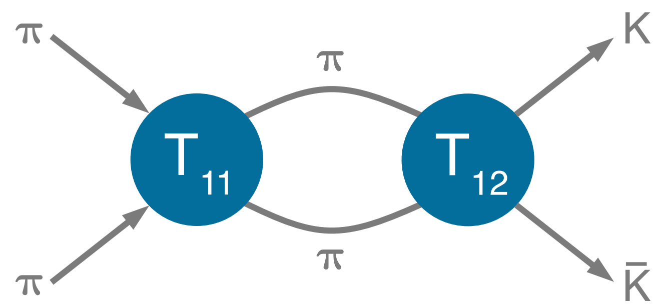
This parameterisation is universal - Can be used in other analyses!

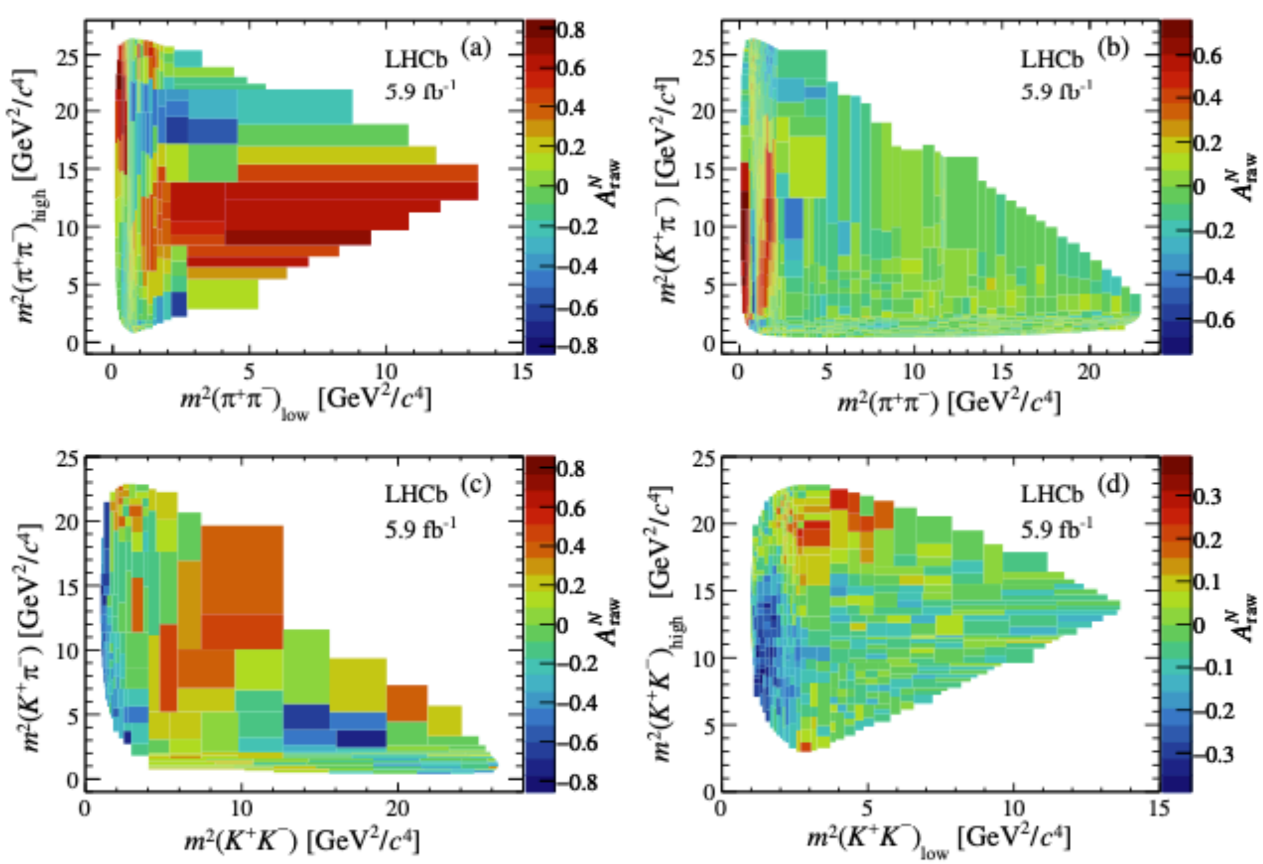
PArtial Wave Interactive ANalysis

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!





PRD 108, 012008 (2023)

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

PRL130, 201901 (2023)

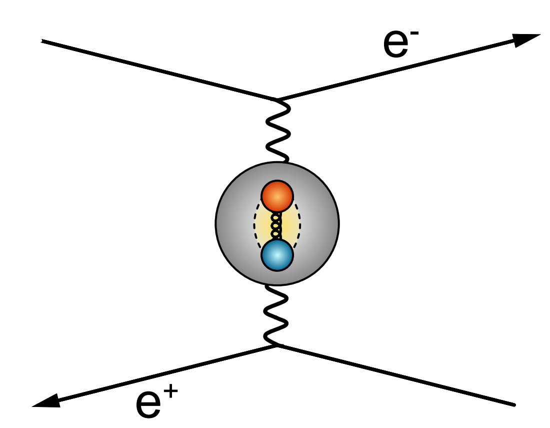
Learning More About the Inner Structure

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

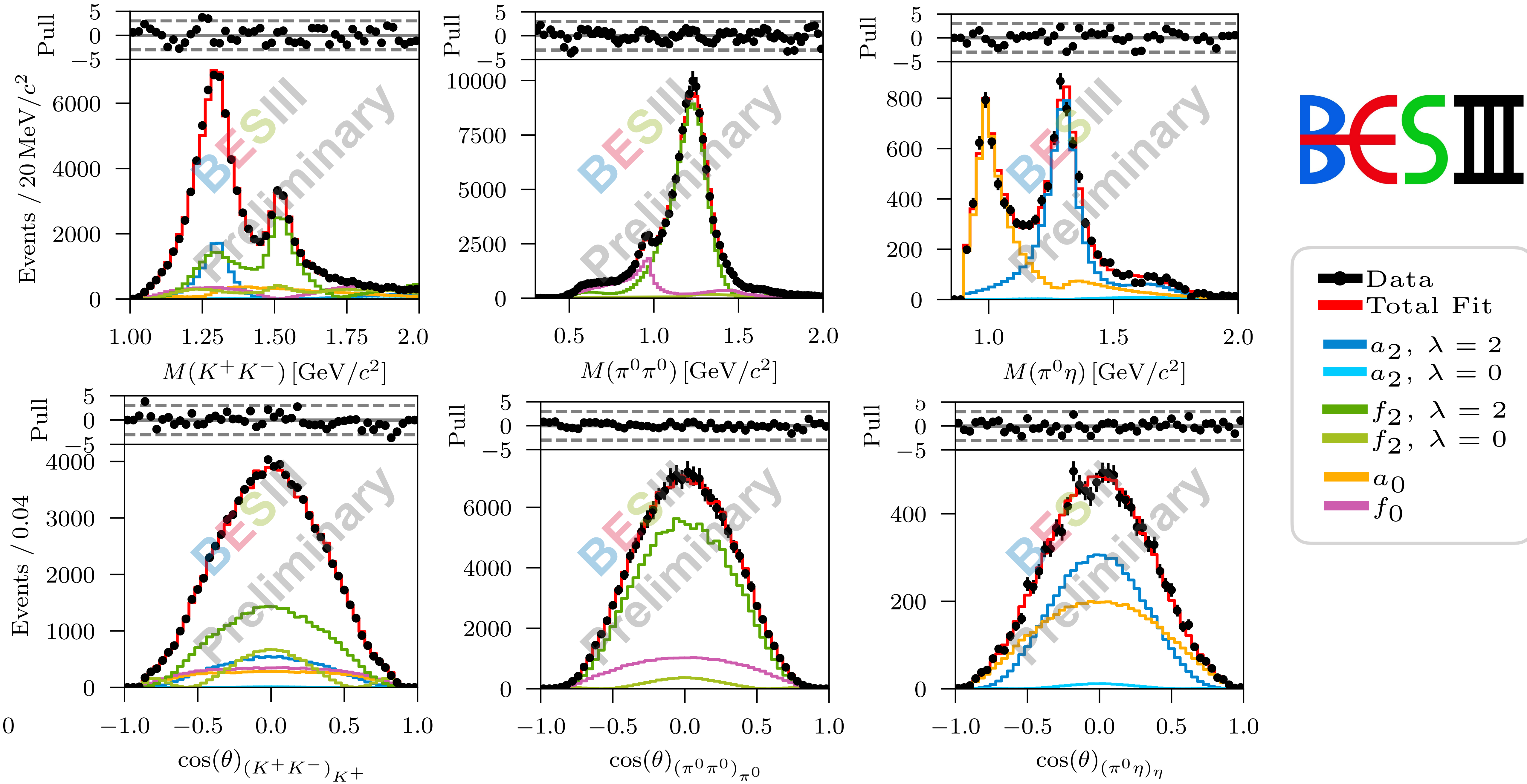


Untagged reactions:

- 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)

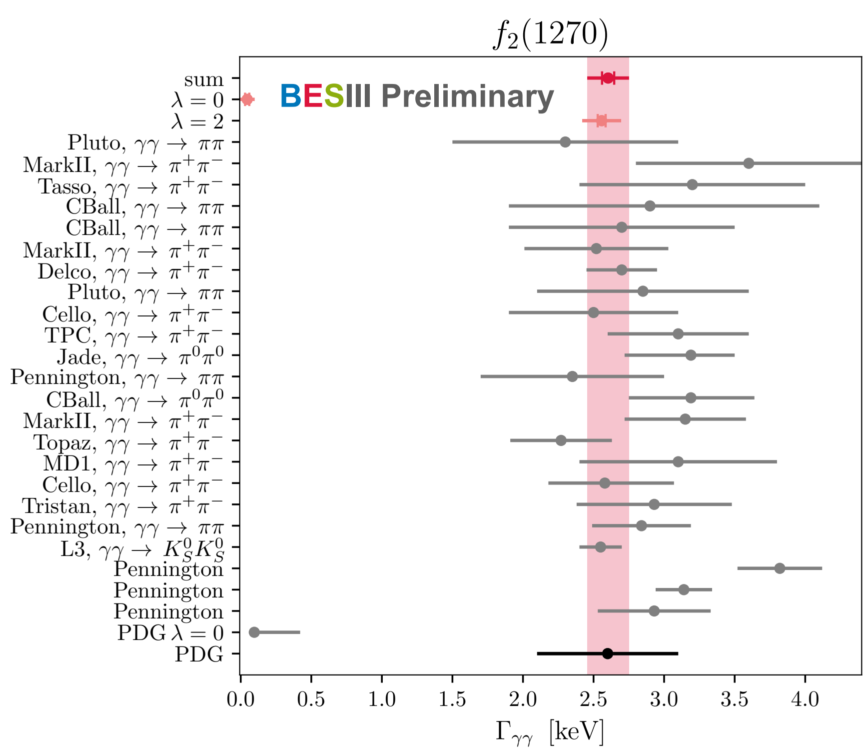


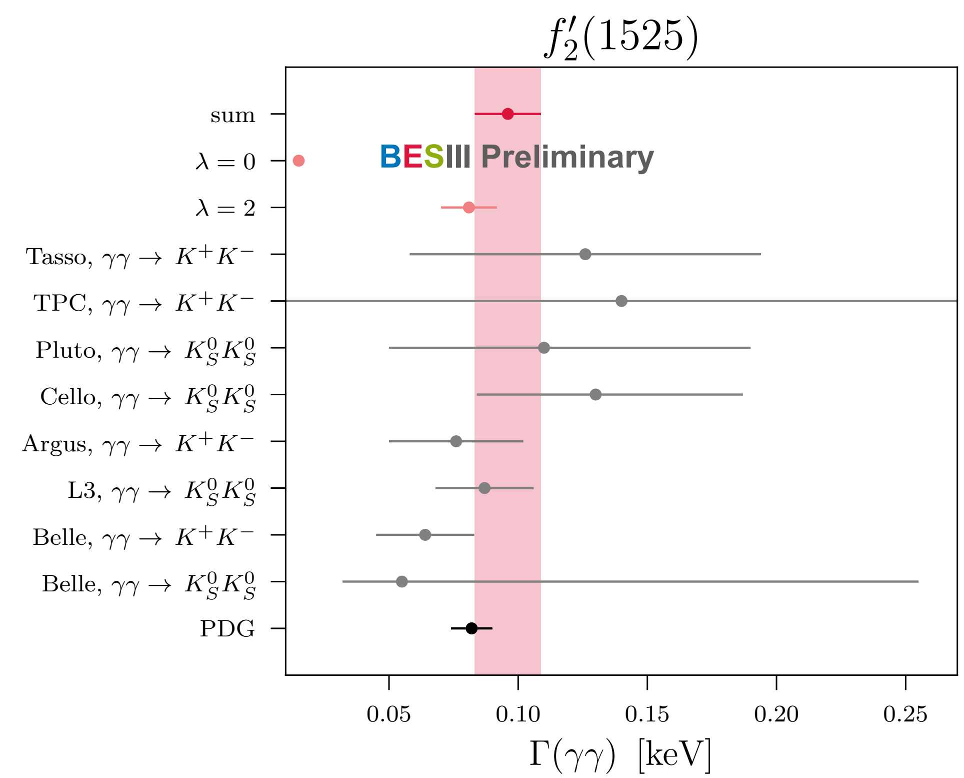
Determination of the Coupling Strength

- 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

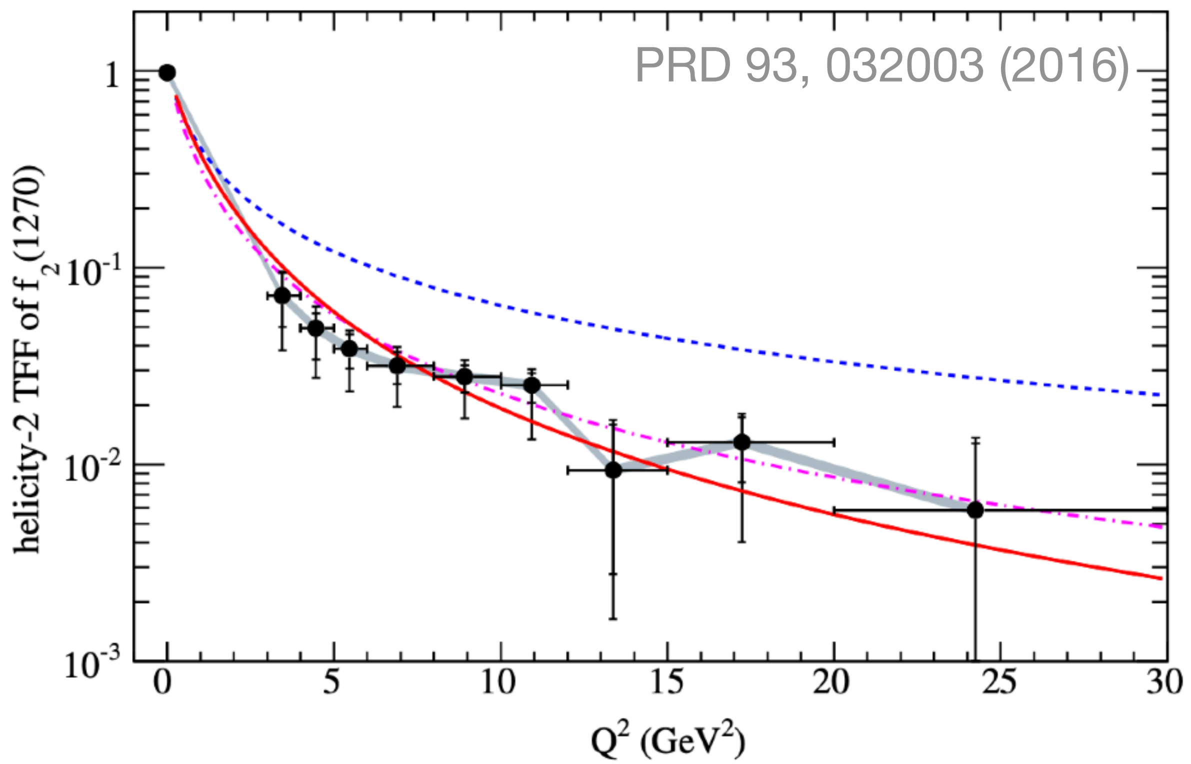
Benefits of Two-Photon Data

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

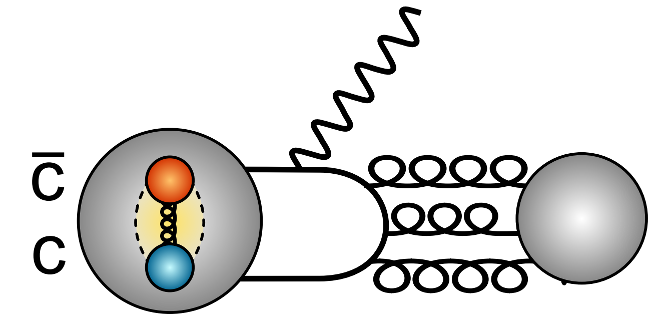
- TFF measurements at BESIII especially powerful at $Q^2 = 0.3 - 1.5\ \mathrm{GeV}^2$
- Higher beam momenta needed to access higher Q^2 regime and states above $2\,\mathrm{GeV}$, ($\chi_{c1}(3872)$ …)
- BELLEII (?)

TFF of $f_2(1270)$ by BELLE

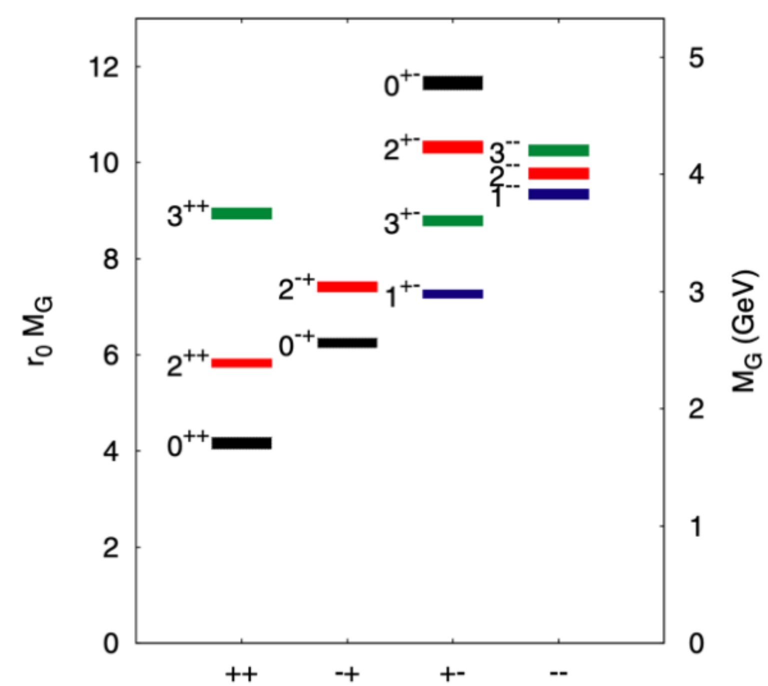


Unique Features of Radiative J/ψ decays

- 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!

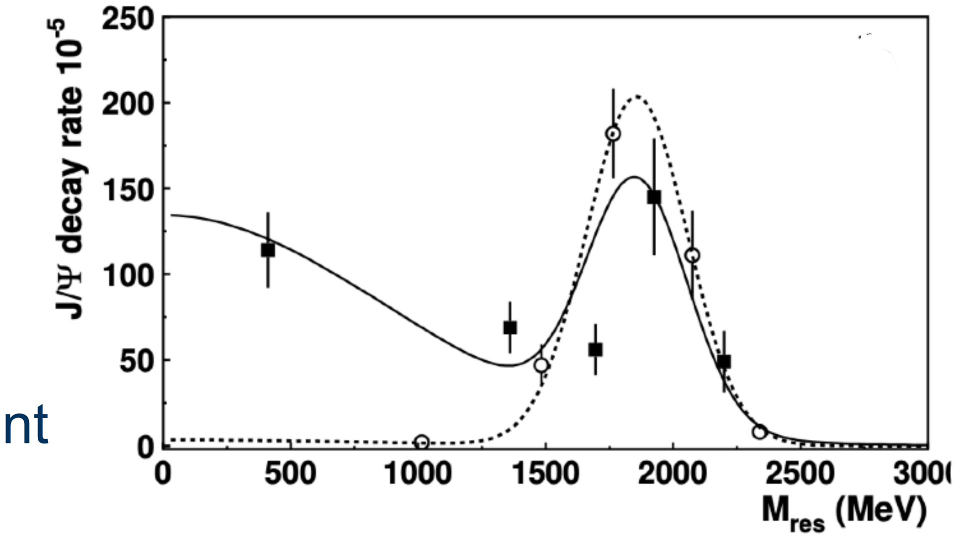


Phys. Rev. D 73, 014516 (2006)

Recent Analyses

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

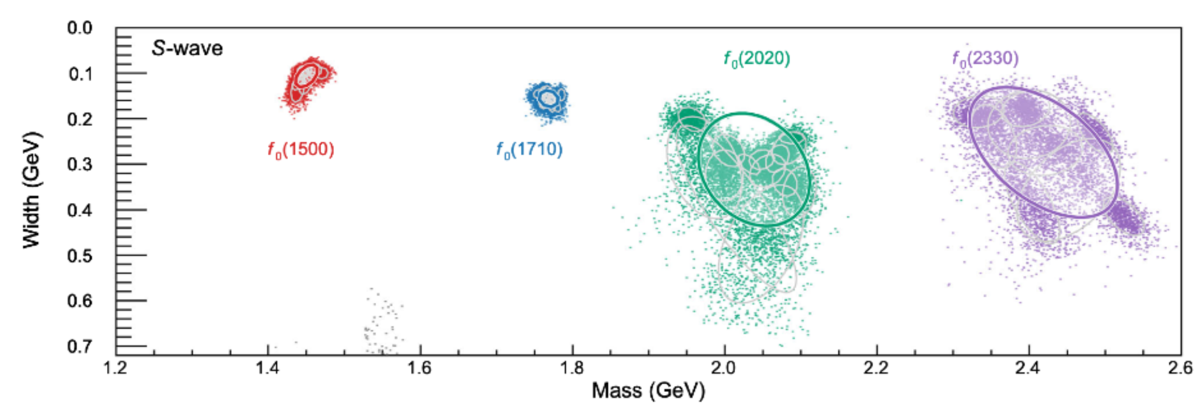
- $J/\psi \rightarrow \gamma + (\pi^0\pi^0, K^0_S K^0_S, \eta\eta, \omega\phi)$ (BESIII)
- $\pi^+\pi^-$- scattering data (CERN-Munich, GAMS, BNL)
- $\bar{p}N \rightarrow$ 3 mesons (CB-LEAR)



- 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)*

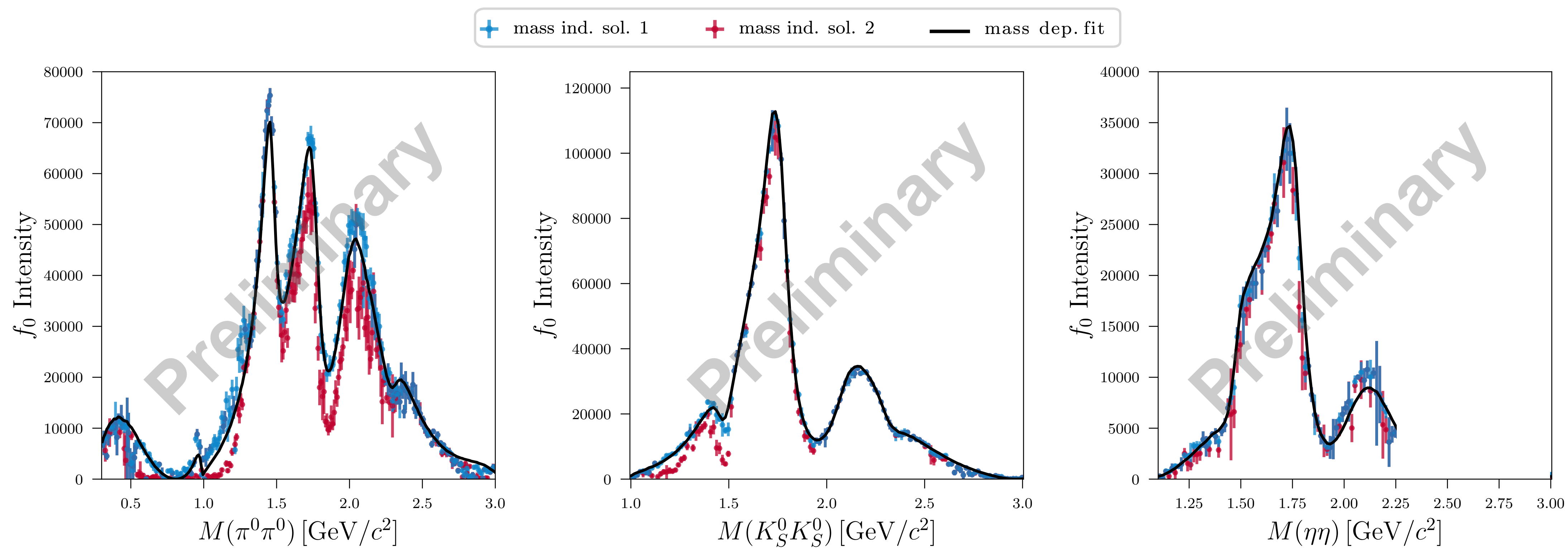
- Used $J/\psi \rightarrow \gamma\, \pi^0\pi^0, \gamma\, K^0_S K^0_S$ (BESIII) data
- Only 4 scalar poles needed - not as 10
- No statement towards glueball contributions
- But: Theory has only access to binned data based on older data samples



Recent Analyses

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

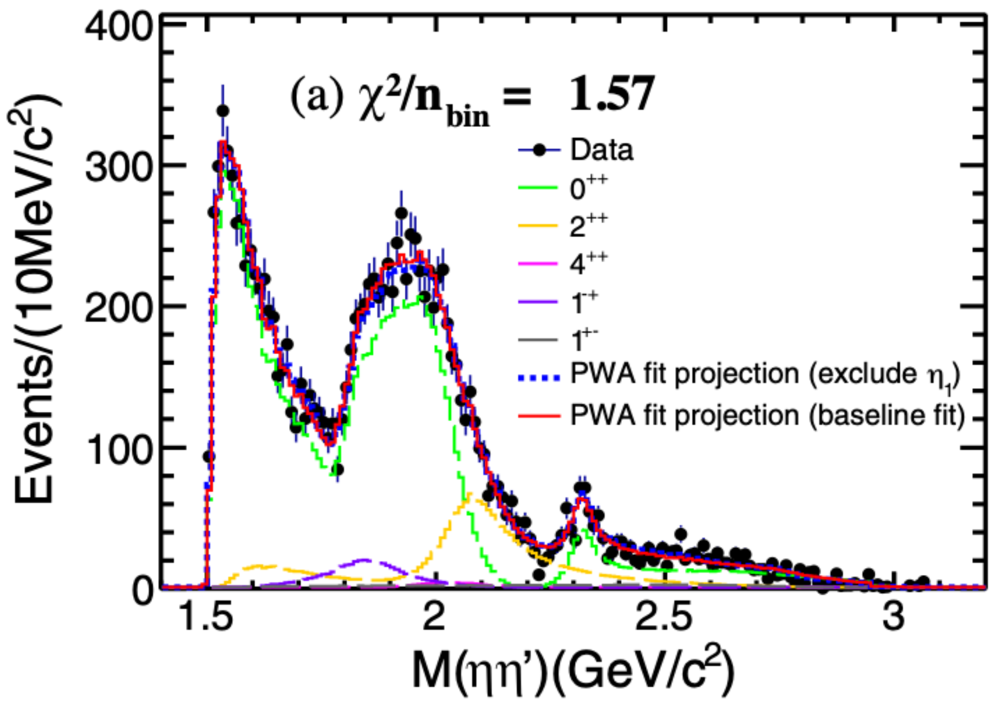
Event based mass-independent and coupled channel amplitude analyses in preparation for $J/\psi \rightarrow \gamma\pi^0\pi^0$, $\gamma K_S^0 K_S^0$ and $\gamma\eta\eta$!



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

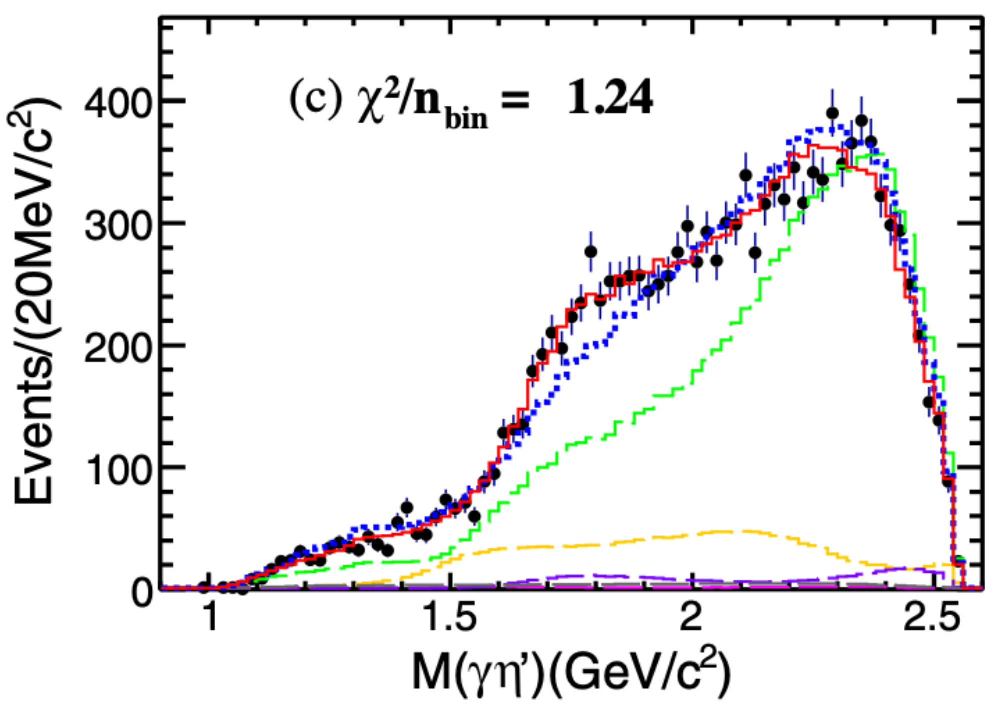
$J/\psi \rightarrow \gamma\eta'\eta$

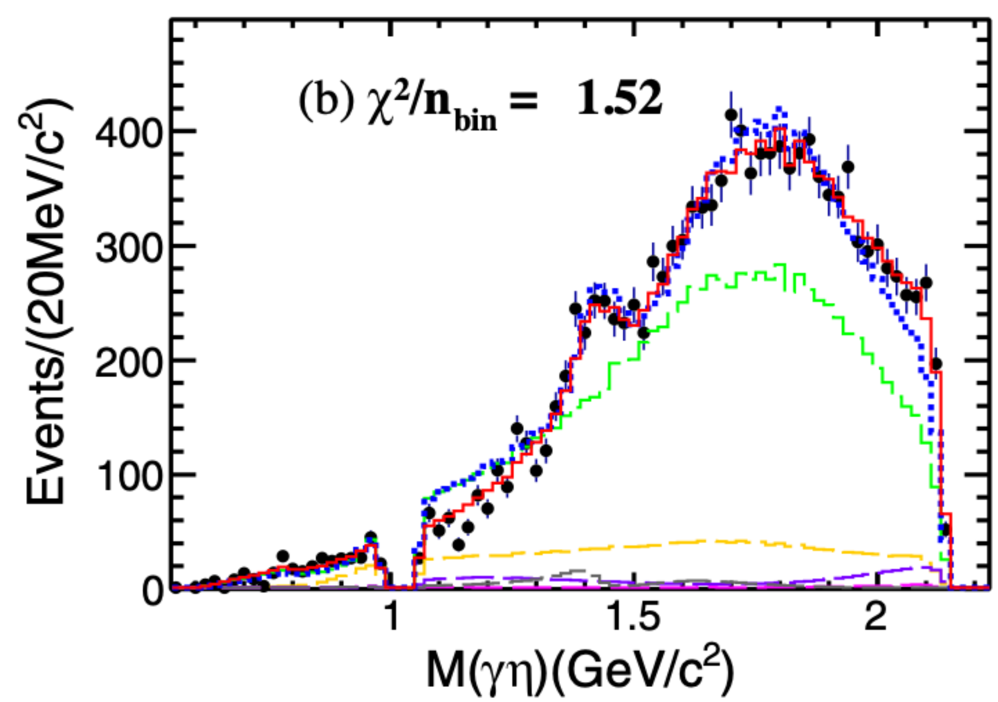
PRL 129, 19, 192002 (2022)
PRD 106, 7, 072012 (2022)



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

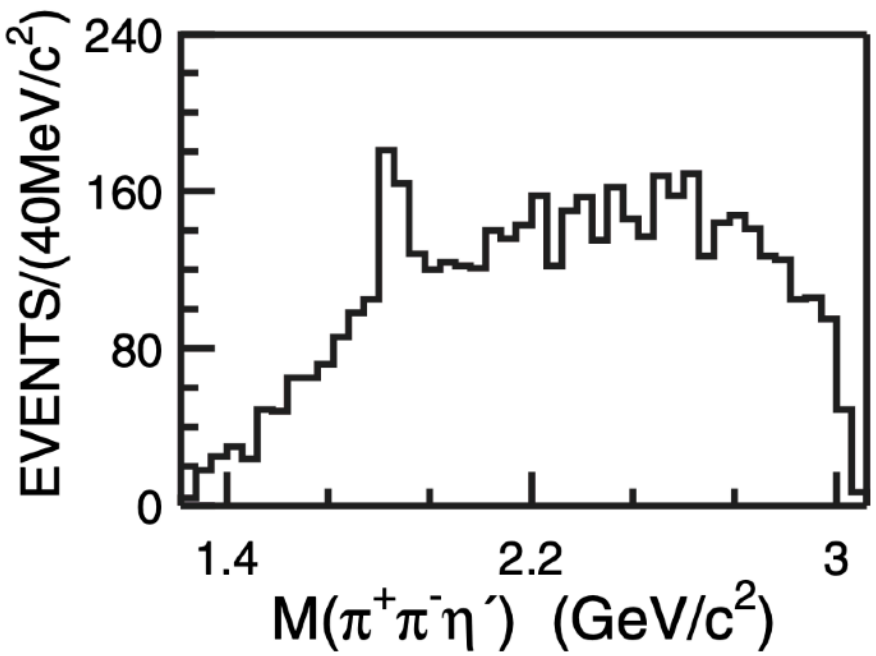




$J/\psi \to \gamma\eta'\pi^+\pi^-$

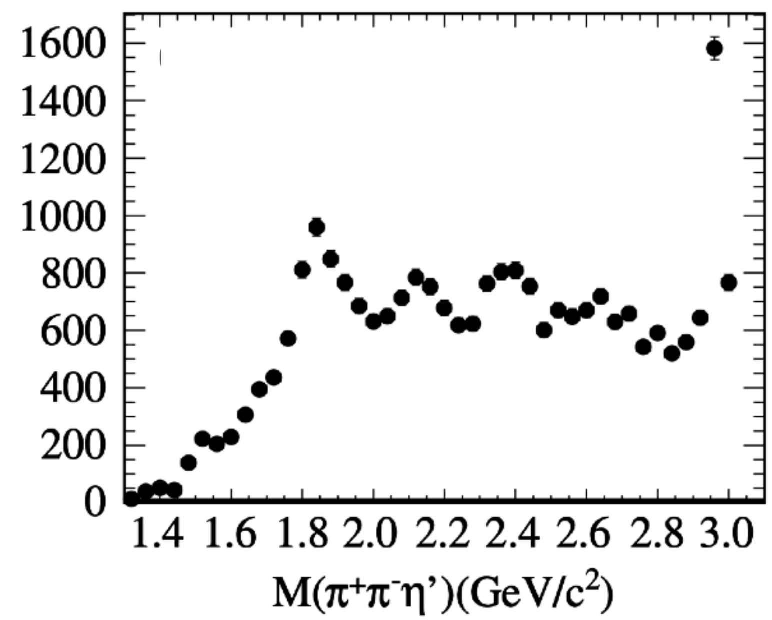
PRL 129, 042001 (2022)

58M J/ψ events



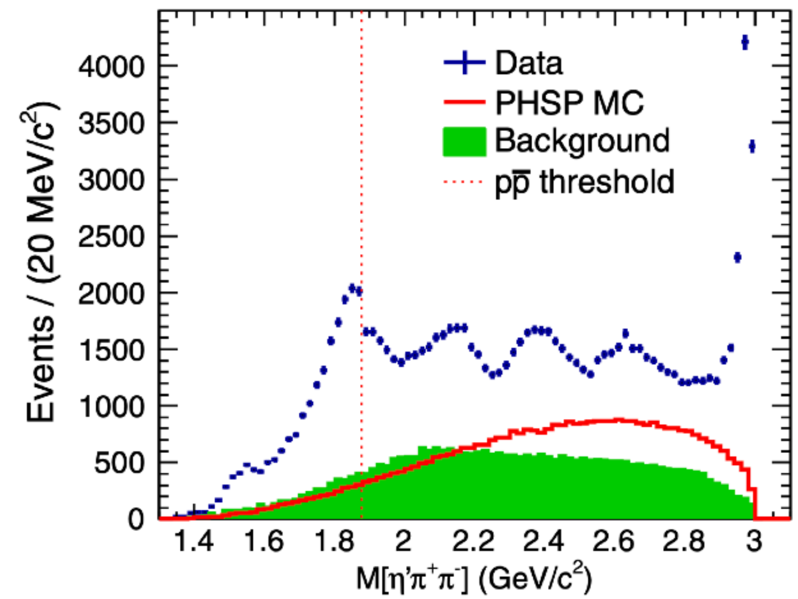
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

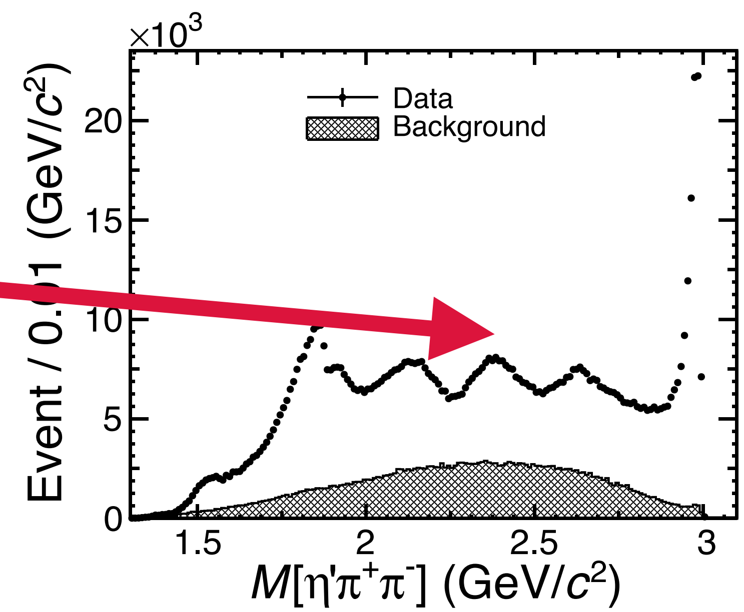
1090M J/ψ events



BESIII, PRL 117, 042002 (2016)

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

PRL 132 181901 (2024)



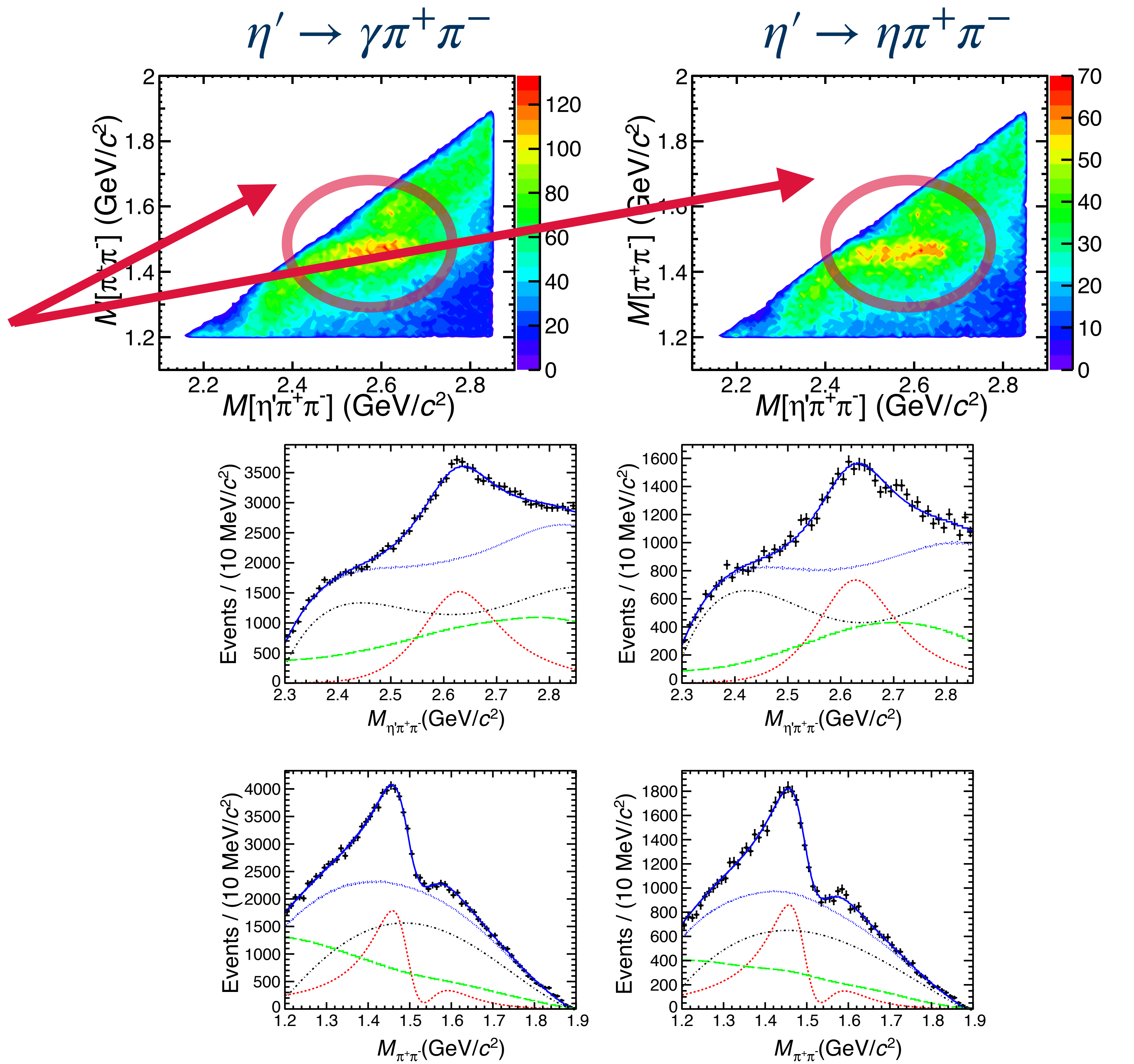
BESIII, PRL 129, 042001 (2022)

10B J/ψ events

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

PRL 129, 042001 (2022)

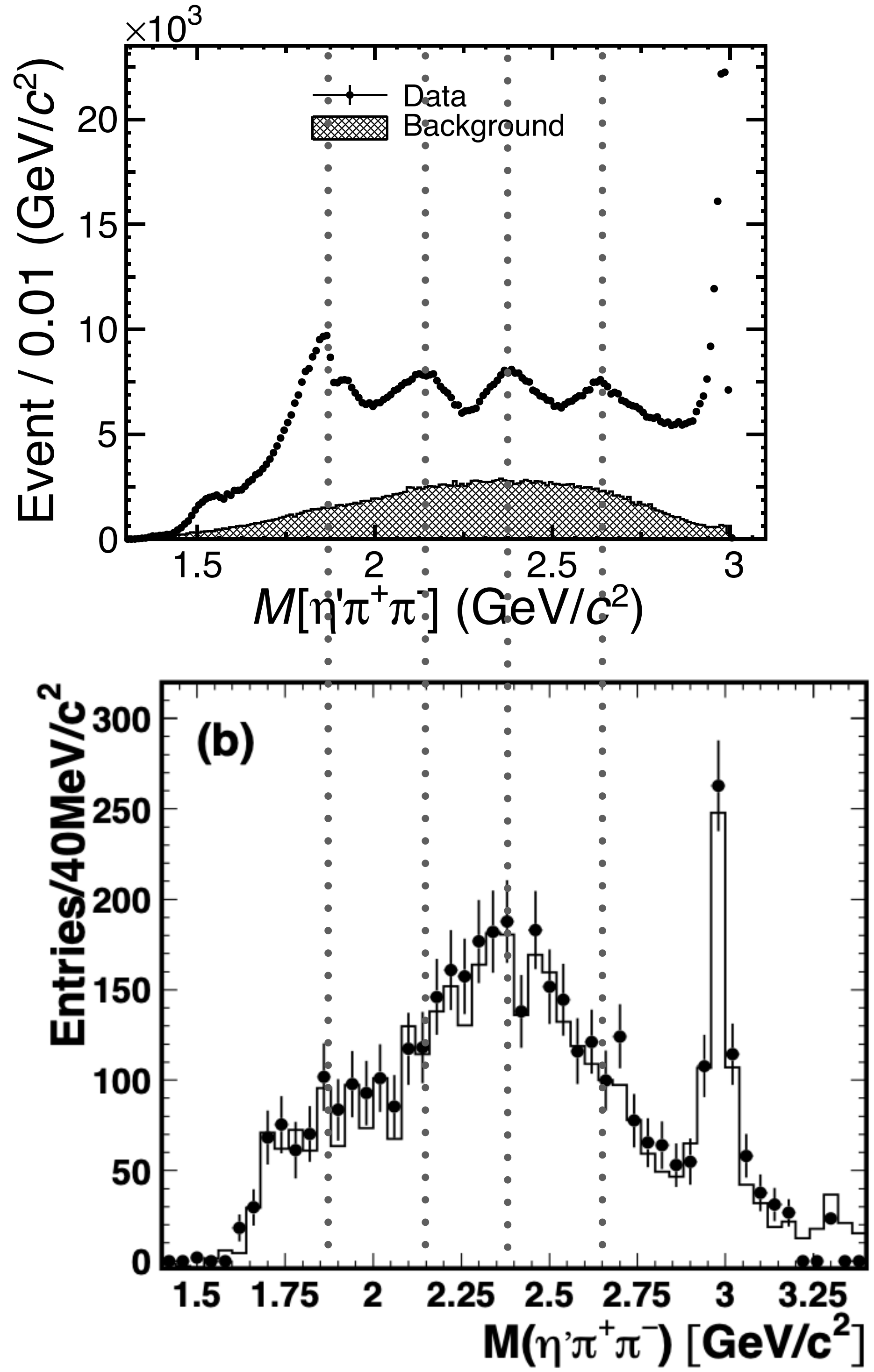
- Interesting structure at 2.6 GeV
- Likely connected to a non trivial structure at $1500\,\mathrm{MeV}/c^2$ in $\pi^+\pi^-$ system
- Further studies ongoing, full PWA needed…



- 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

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:

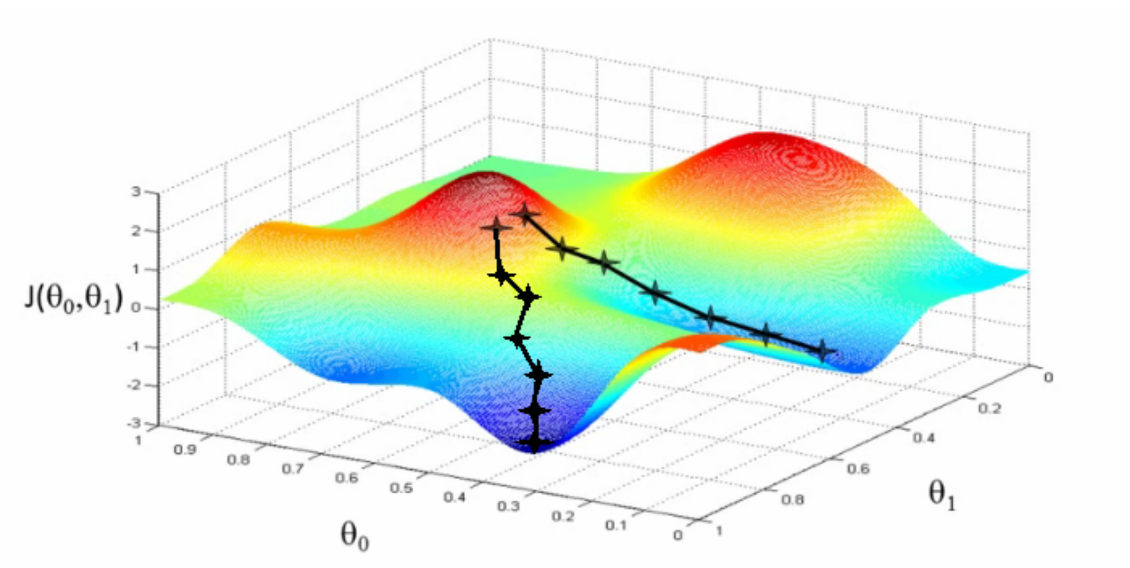
- Including AI methods where ever helpful

Leads also to:

- More sustainable use of resources and data!

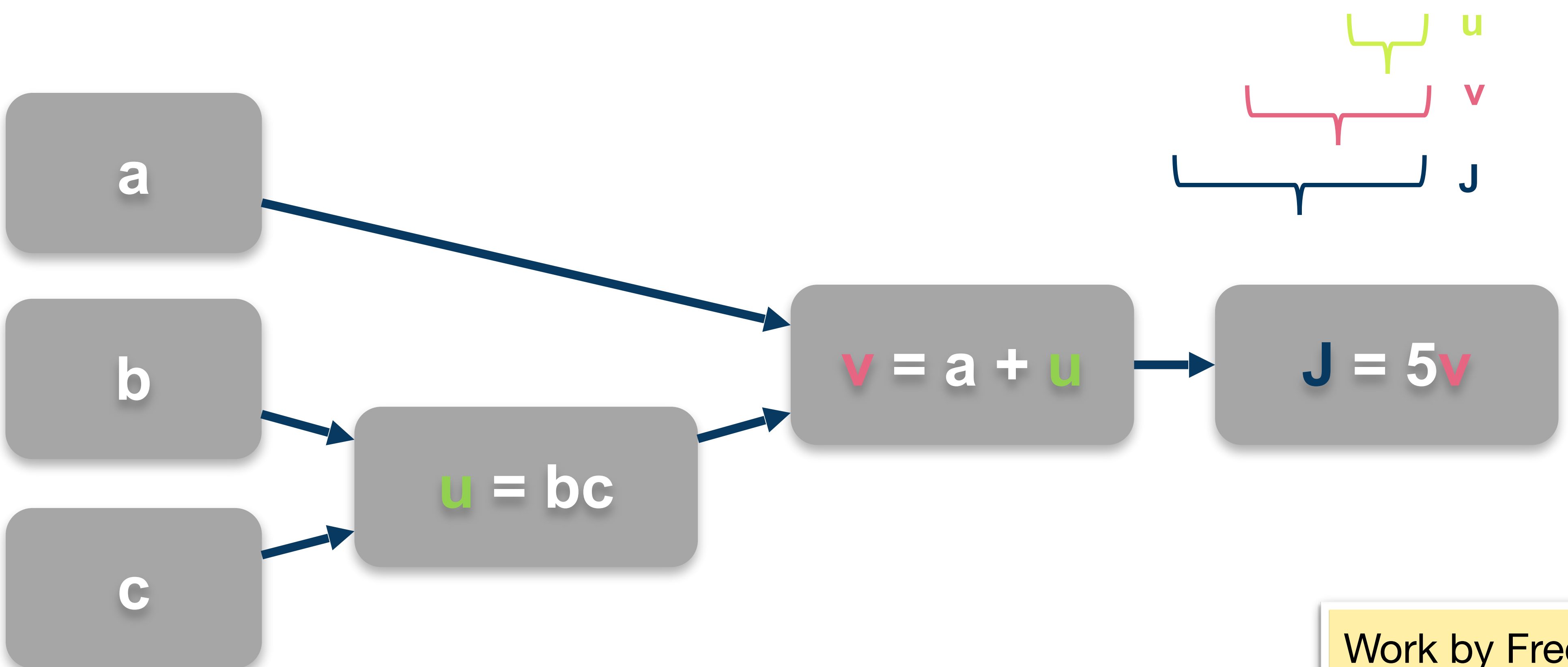
New network project working on techniques to accelerate PWA:

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



https://miro.medium.com/max/1100/1*ZfdJDpJ8prZVJVDb2gaqRA.png

Work by Frederike Hanisch

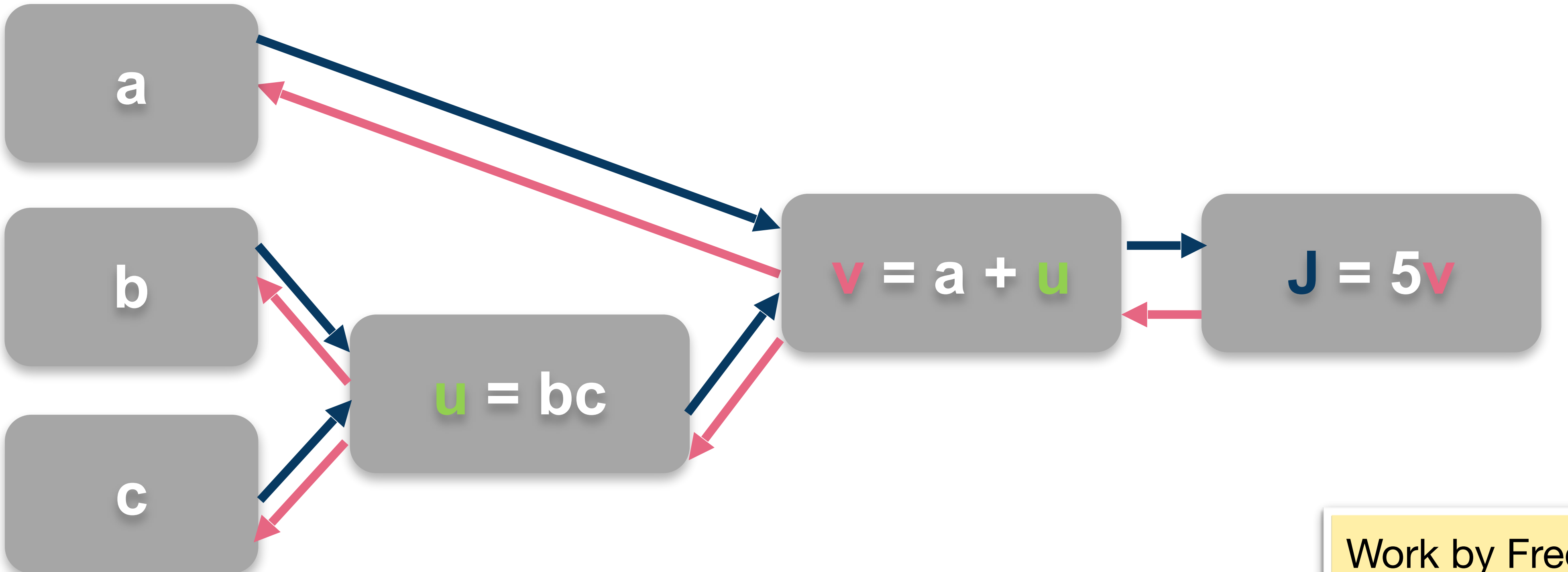


Computation Graph

Work by Frederike Hanisch

- **Forward mode**: Calculates the derivative of a function by successively applying the chain rule to the elementary function

- **Reverse mode**: Calculates the derivative of a function by applying the chain rule to the output of the function (backpropagation)
 → Suitable for PWA → a lot of free parameters

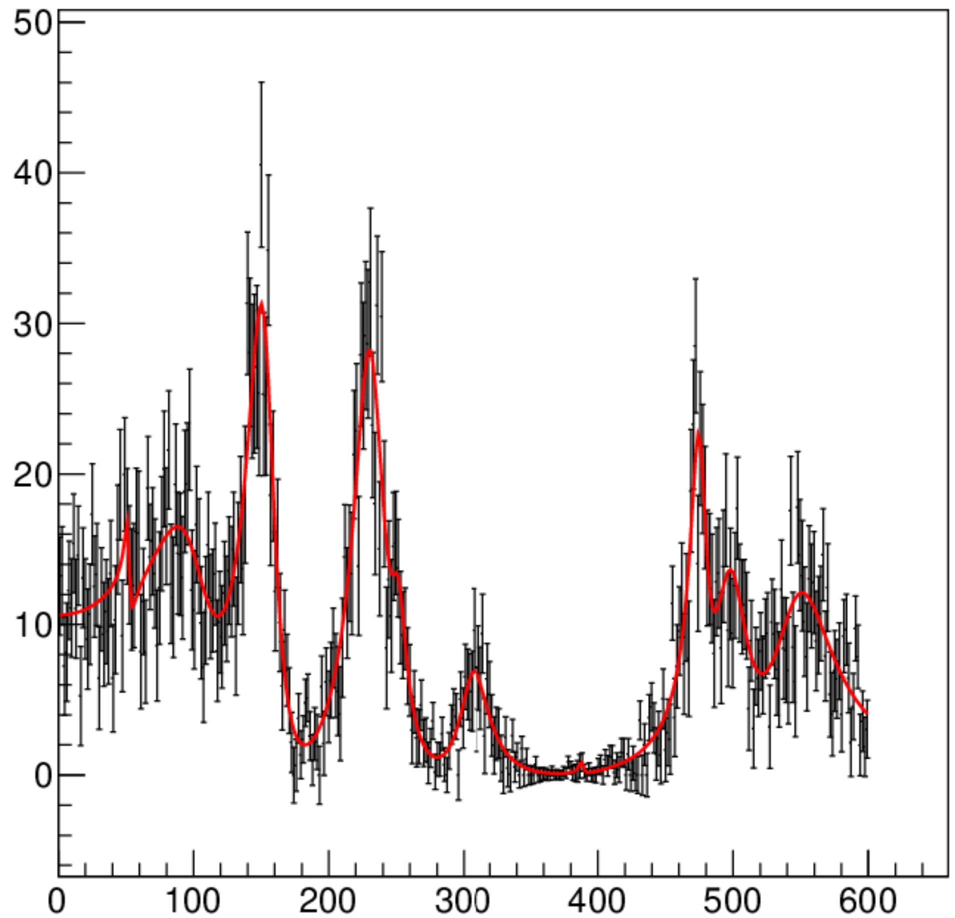


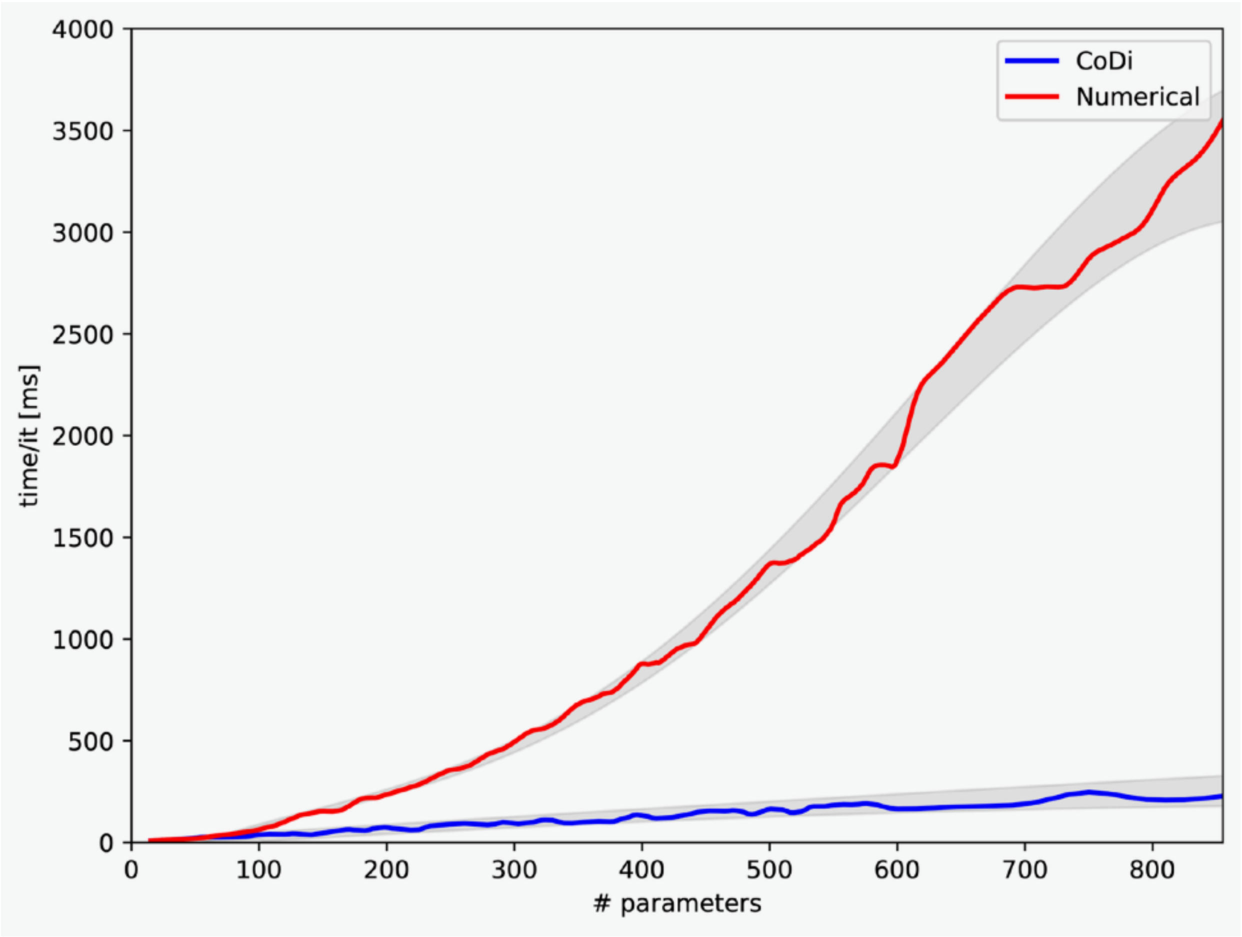
Computation Graph

Work by Frederike Hanisch

Work by Frederike Hanisch

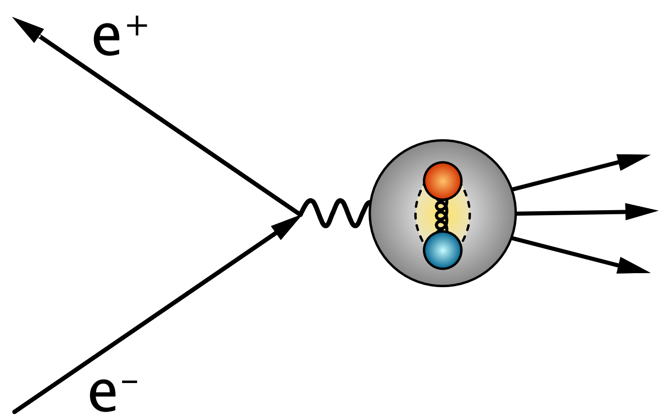
- PAWIAN test application
  - ~100k generated events
  - 10 – 300 Breit-Wigner functions (30 – 900 parameters)
  - Comparison between numerical and automatic differentiation (reverse mode)
  - **Autodiff is faster (up to 10 times!!!!) and more stable than numerical differentiation with a higher number of parameters**



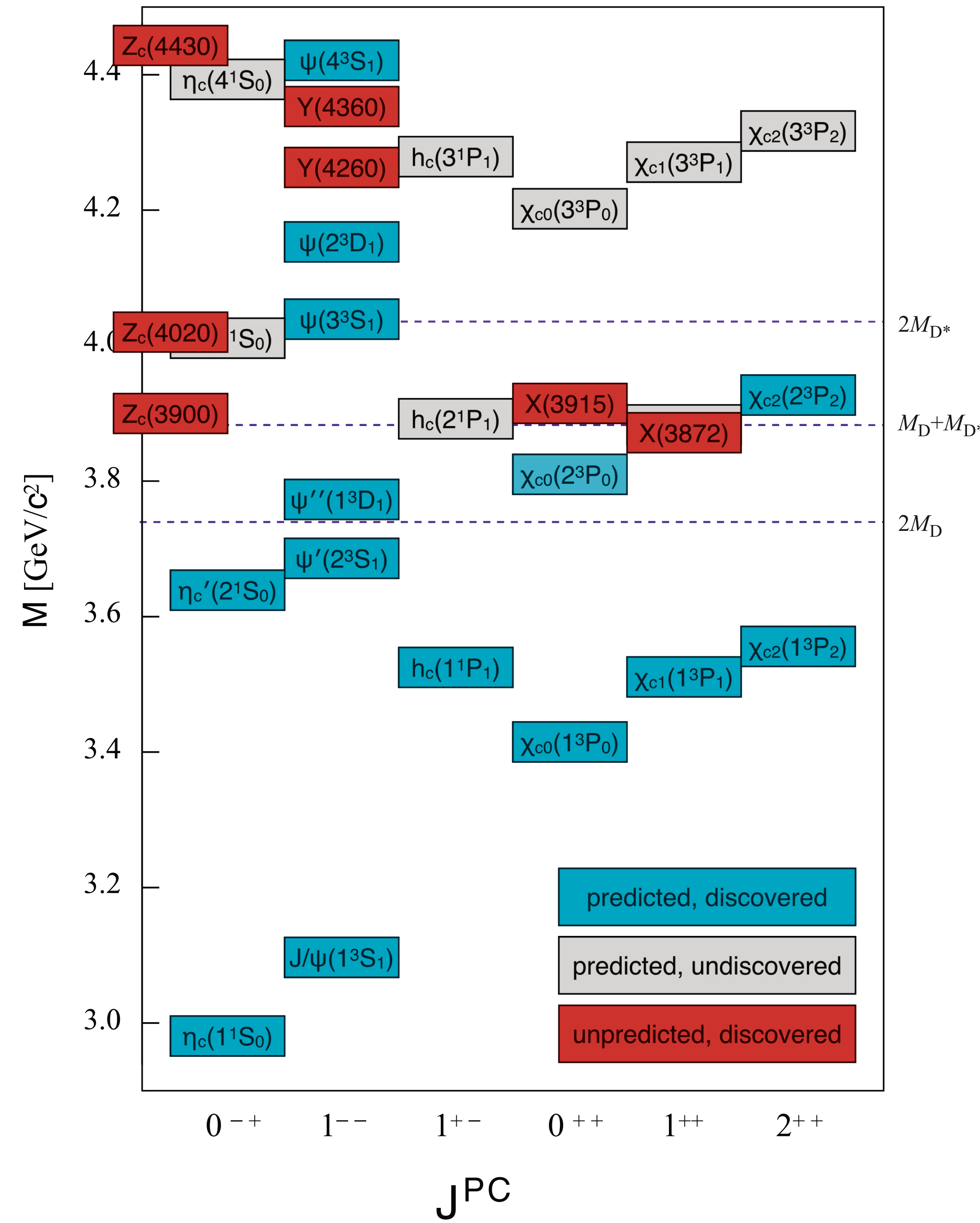


Charmonium Sector

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

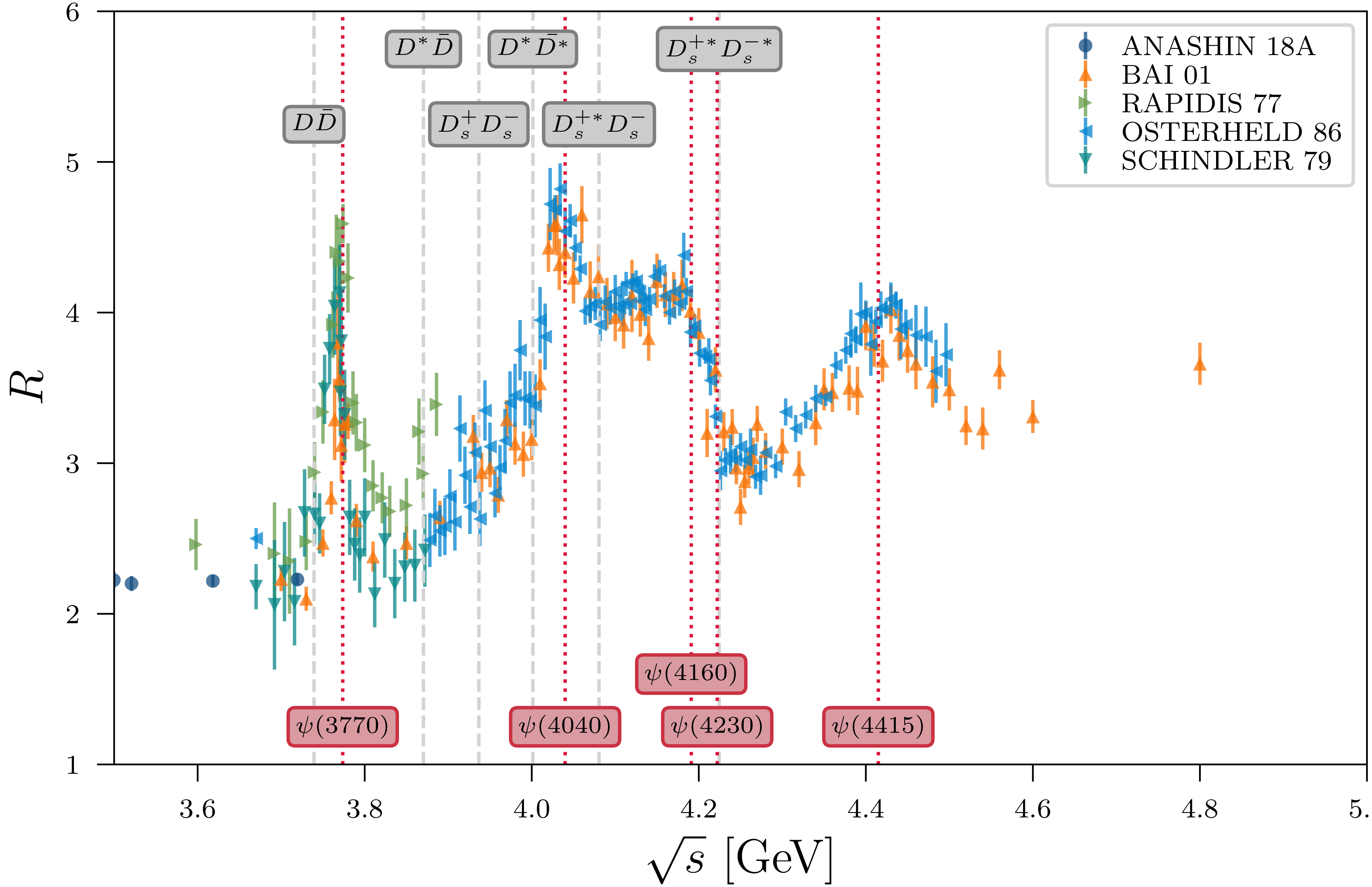


- Other q.n. can only be accessed by sequential decays which limits the statistics

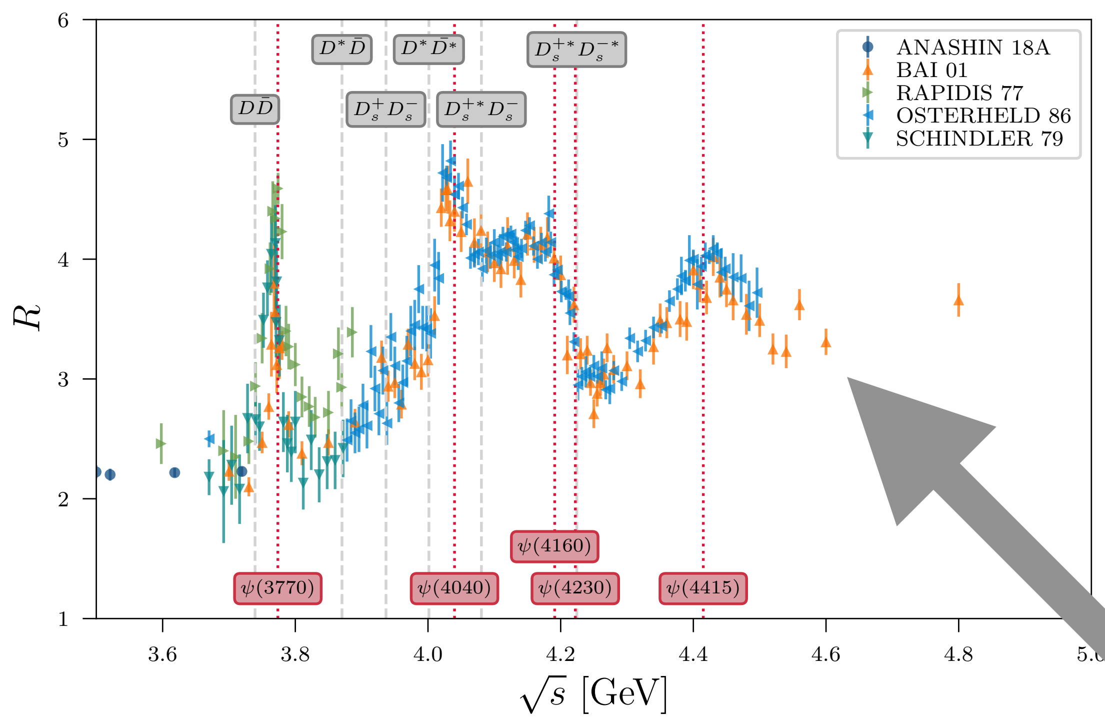


- Besides expected states, additional „unconventional“ states where observed!

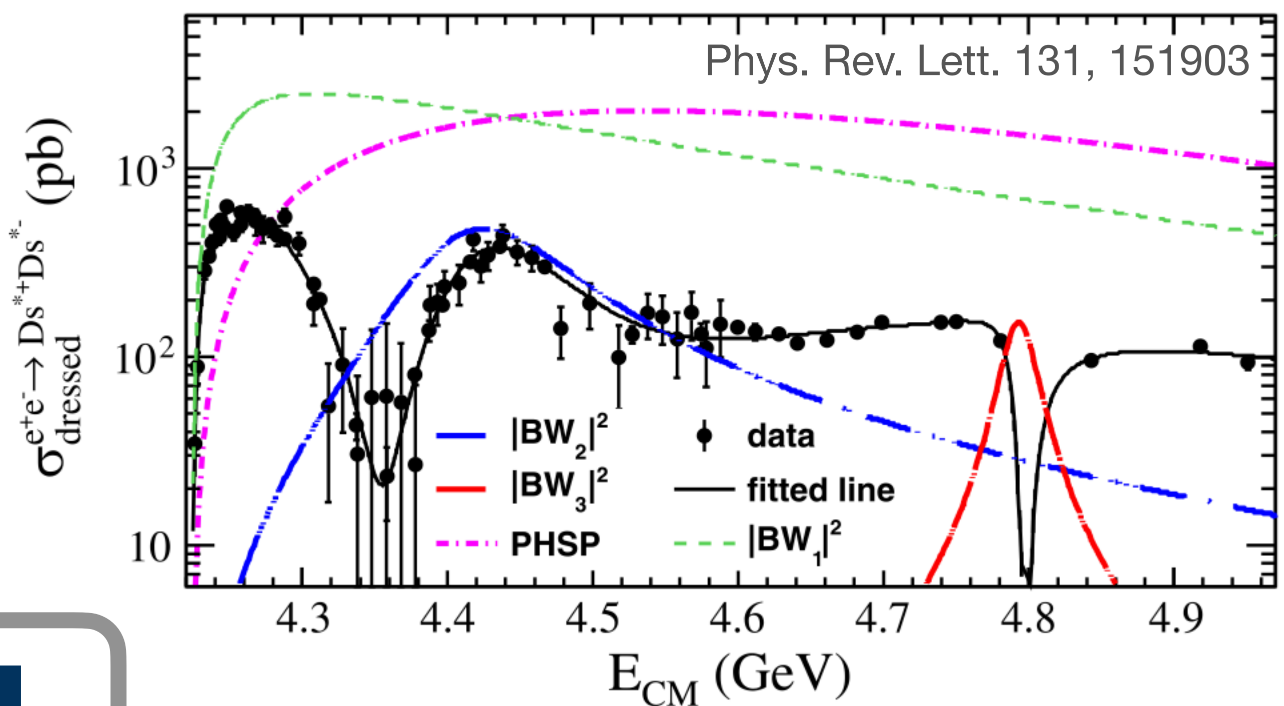
Vector Charmonia



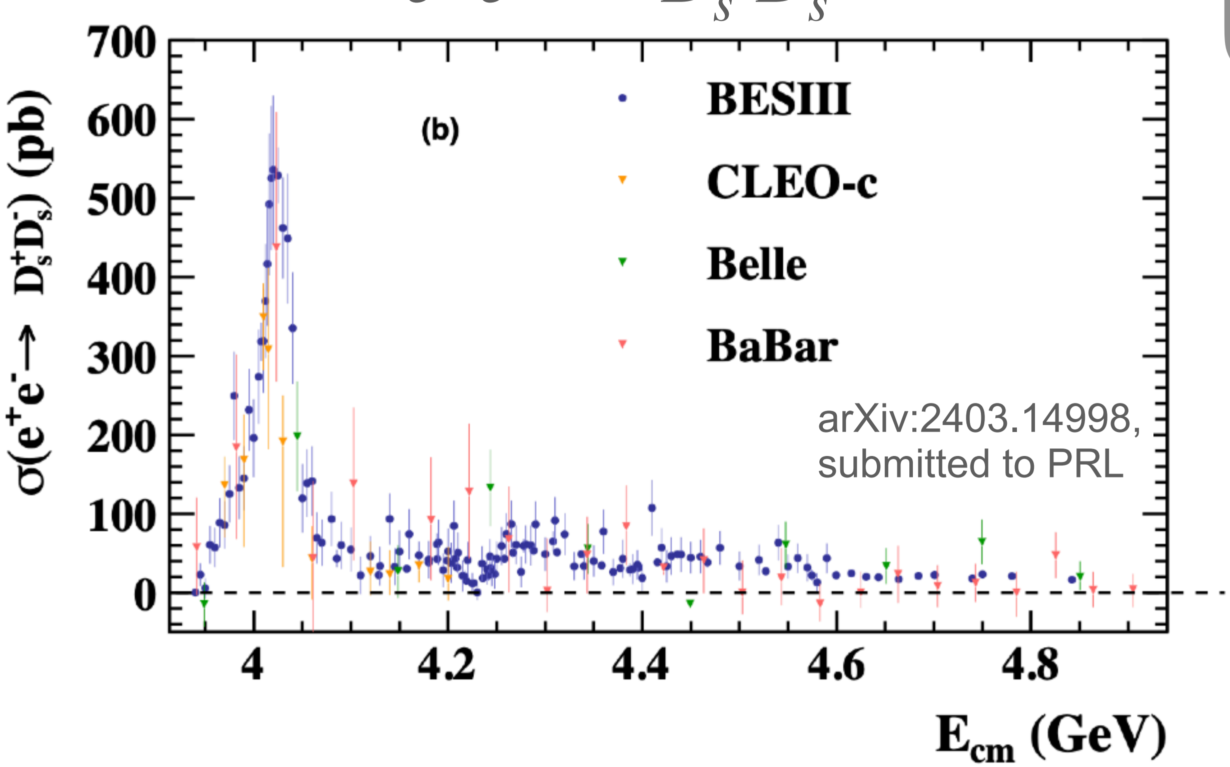
Vector Charmonia



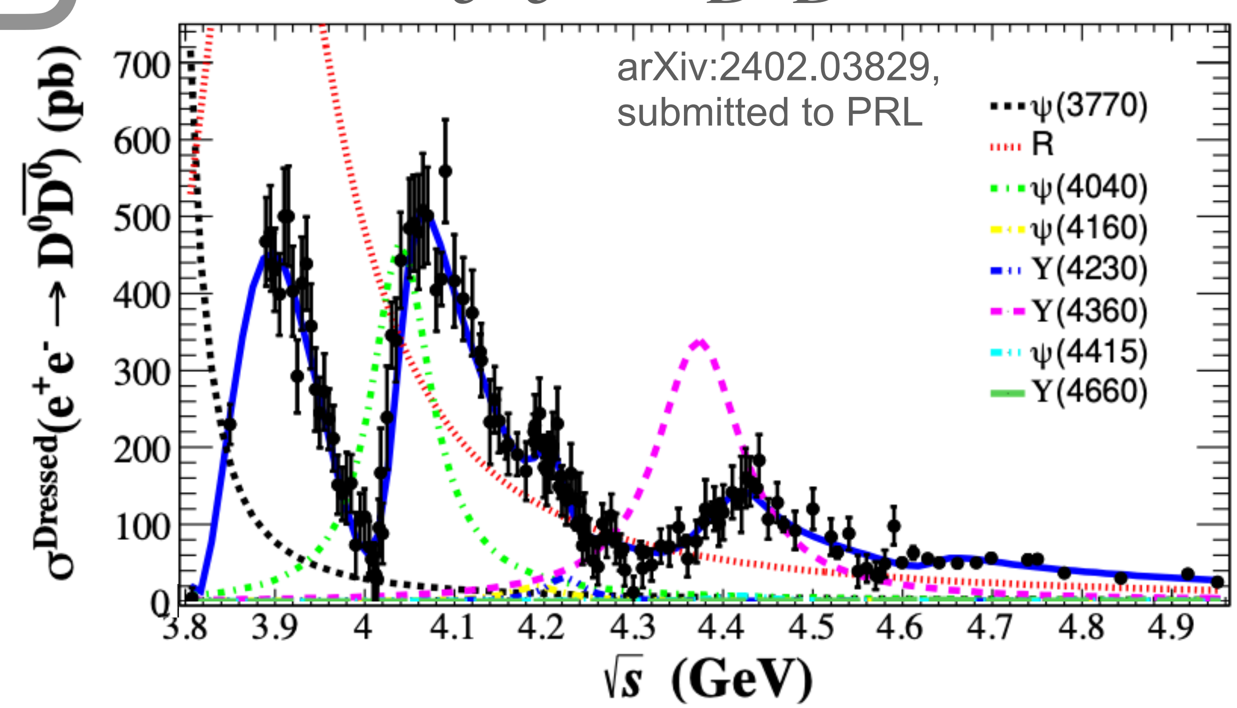
$e^+e^- \rightarrow D_s^{+*}D_s^{-*}$



$e^+e^- \rightarrow D_s^+D_s^-$



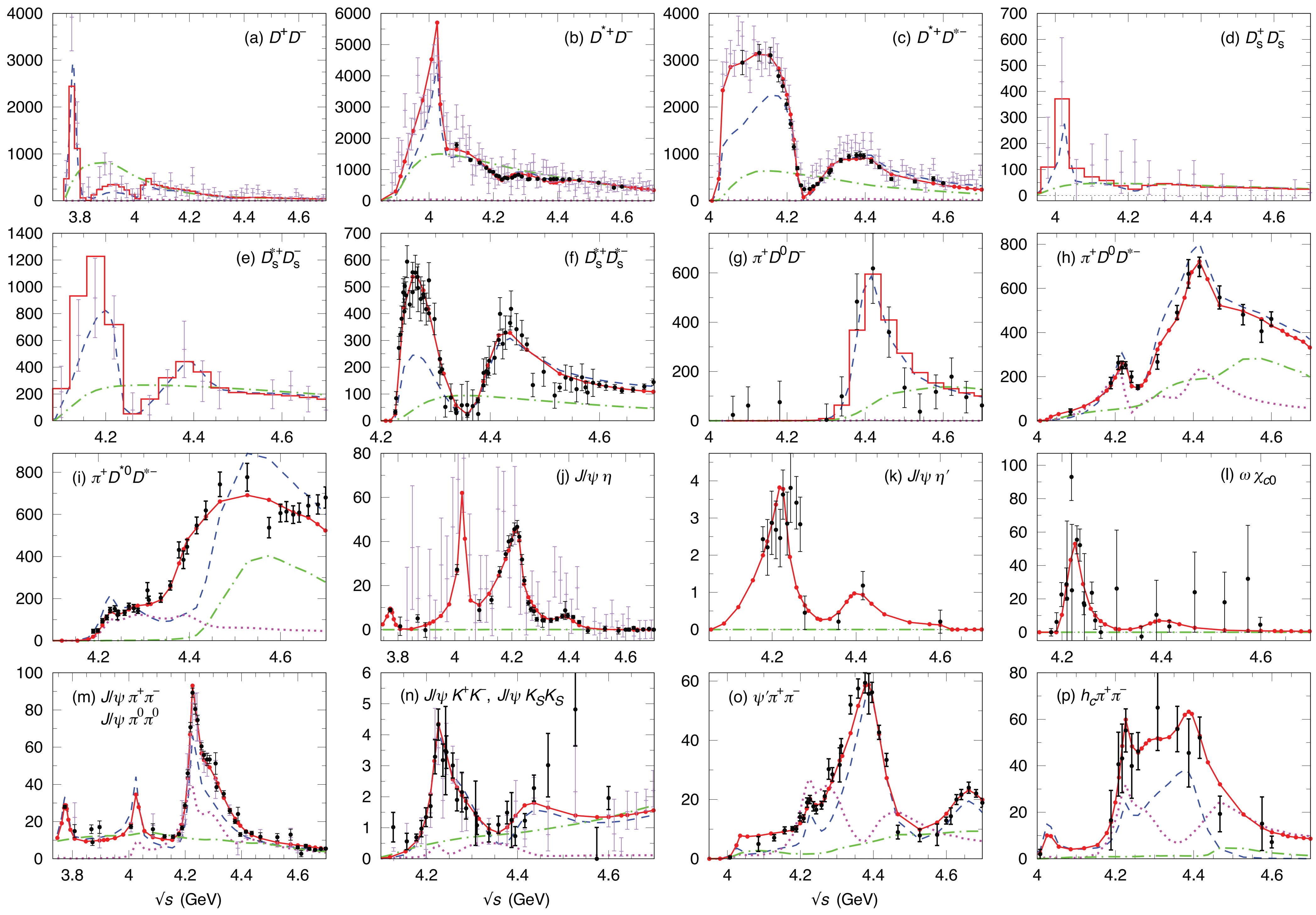
$e^+e^- \rightarrow D^0\overline{D^0}$



A first Step Towards a Global Description

arXiv:2312.17658

- Combined fit to 19 BESIII and Belle cross section results



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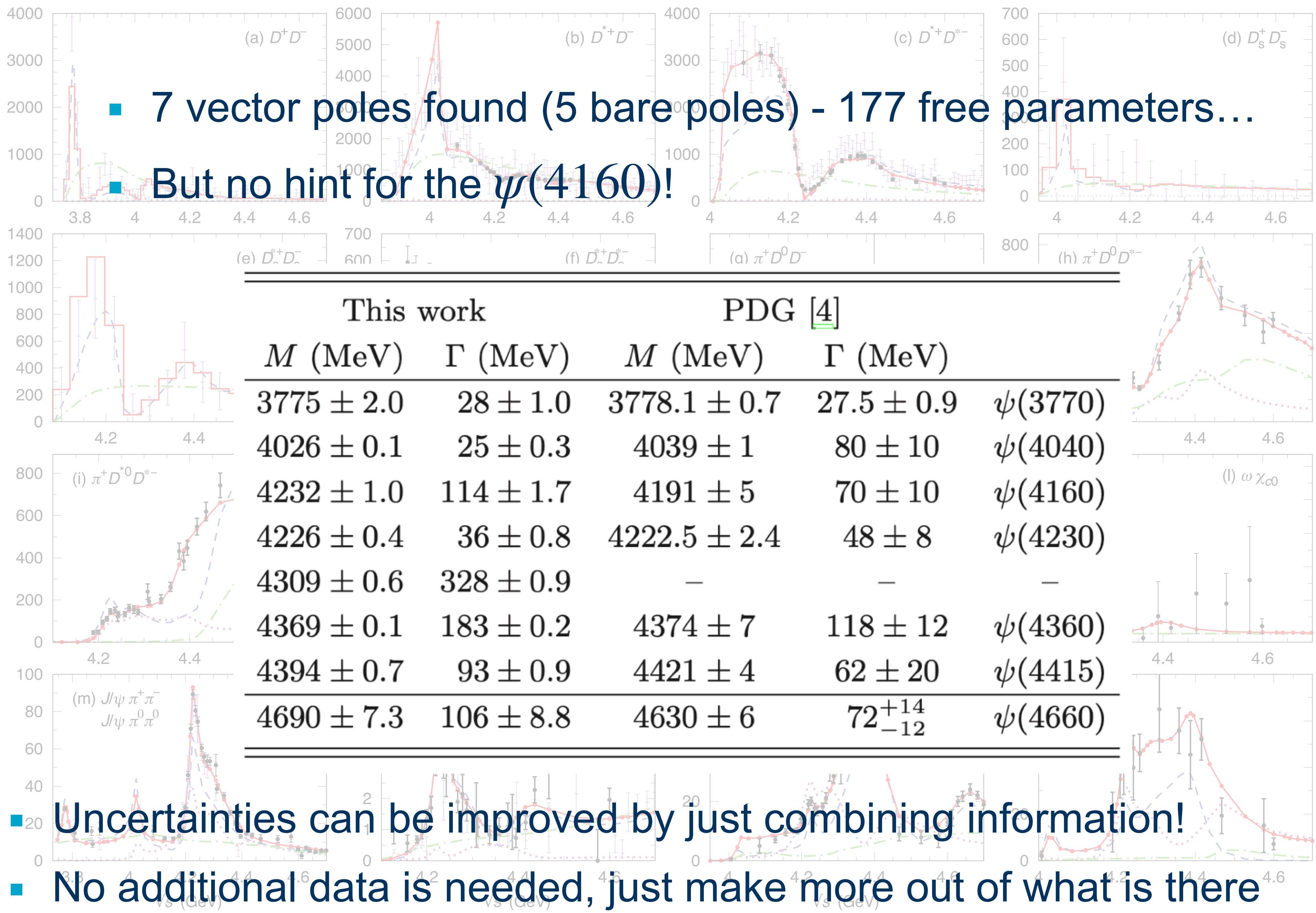


- 7 vector poles found (5 bare poles) - 177 free parameters…
- But no hint for the $\psi(4160)$!

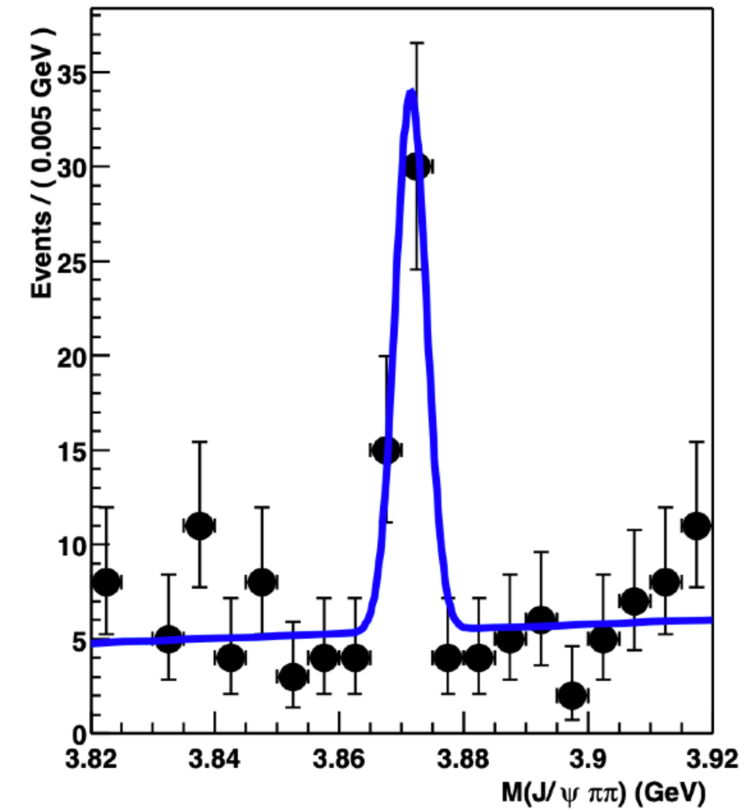
This work		PDG [4]		
M (MeV)	Γ (MeV)	M (MeV)	Γ (MeV)	
3775 ± 2.0	28 ± 1.0	3778.1 ± 0.7	27.5 ± 0.9	$\psi(3770)$
4026 ± 0.1	25 ± 0.3	4039 ± 1	80 ± 10	$\psi(4040)$
4232 ± 1.0	114 ± 1.7	4191 ± 5	70 ± 10	$\psi(4160)$
4226 ± 0.4	36 ± 0.8	4222.5 ± 2.4	48 ± 8	$\psi(4230)$
4309 ± 0.6	328 ± 0.9	–	–	–
4369 ± 0.1	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

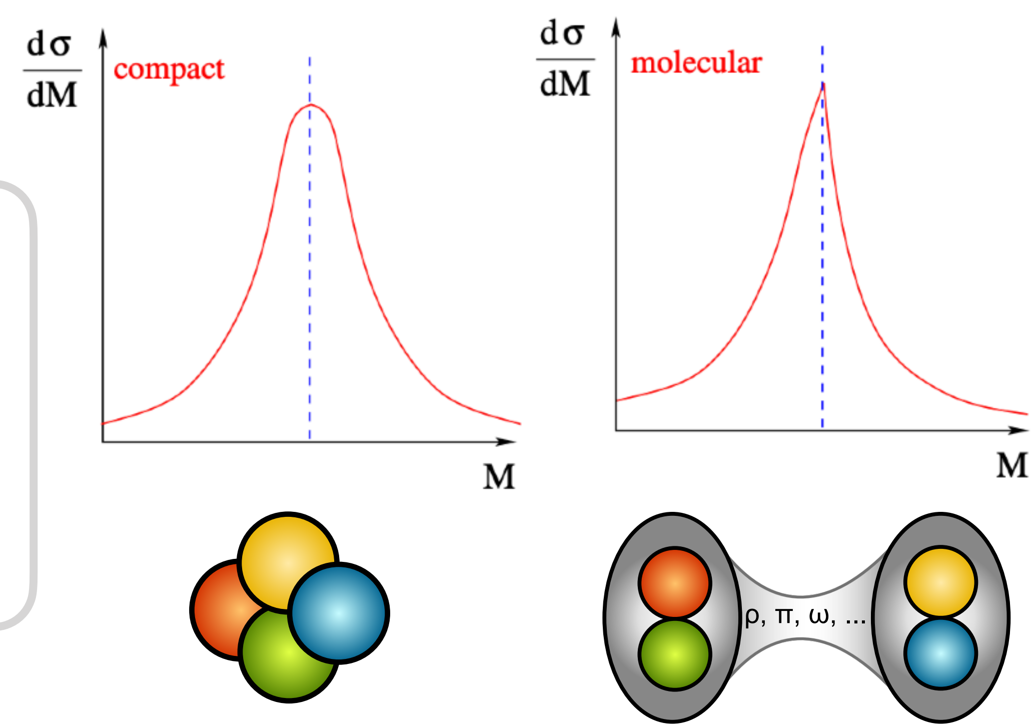
The Story of $\chi_{c1}(3872)/X(3872)$

- 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: $J/\psi(\pi^+\pi^-)\rho$, $D^0\bar{D}^{*0}$, $J/\psi\gamma$ $\psi(2S)\gamma$, $\chi_{c1}\pi^0$, …
- Ispospin violating decay is enhanced by a factor of 5 compared to „ordinary“ charmonia

PRL 91, 262001 (2003)



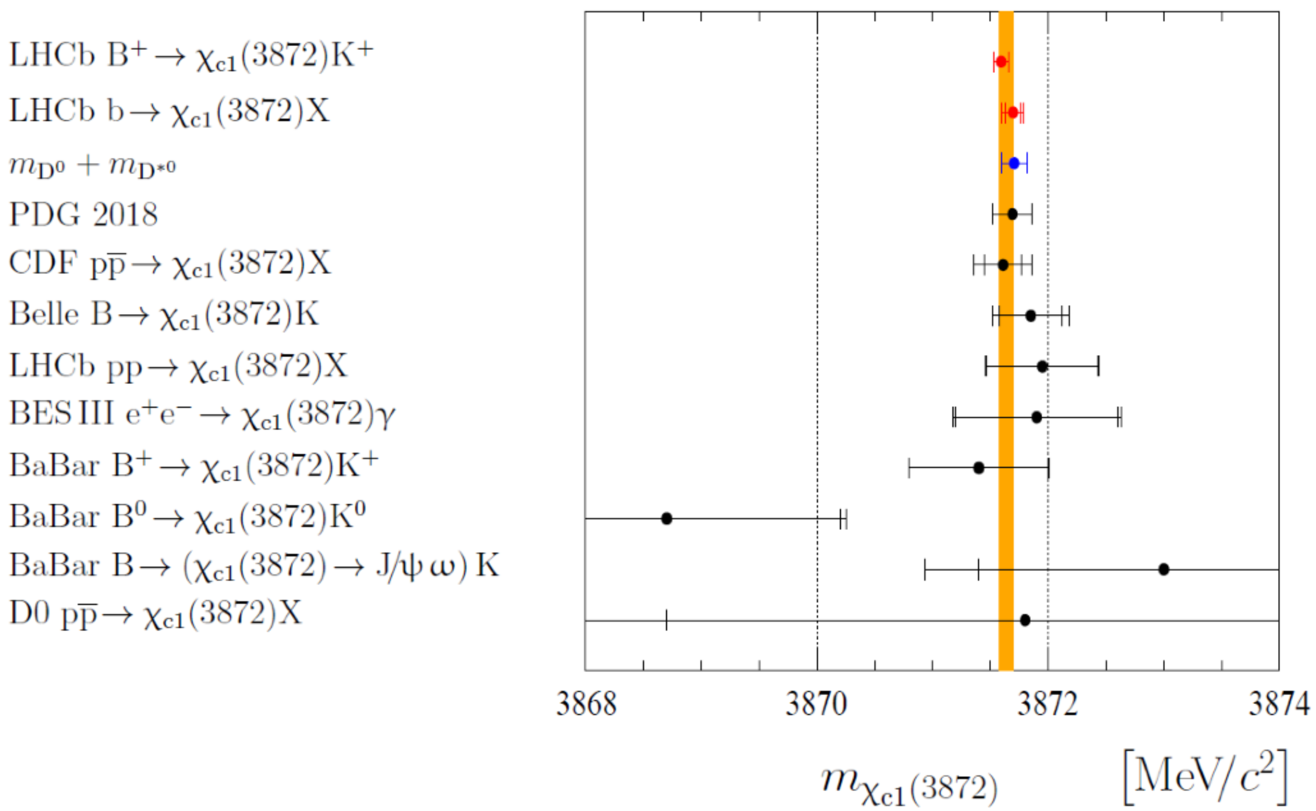
- Similar structures seen in $D^0D^0\pi^+$: $T_{cc}(3875)$
- How are they related? Is it the same underlying physics?
- Can we describe both with one model?



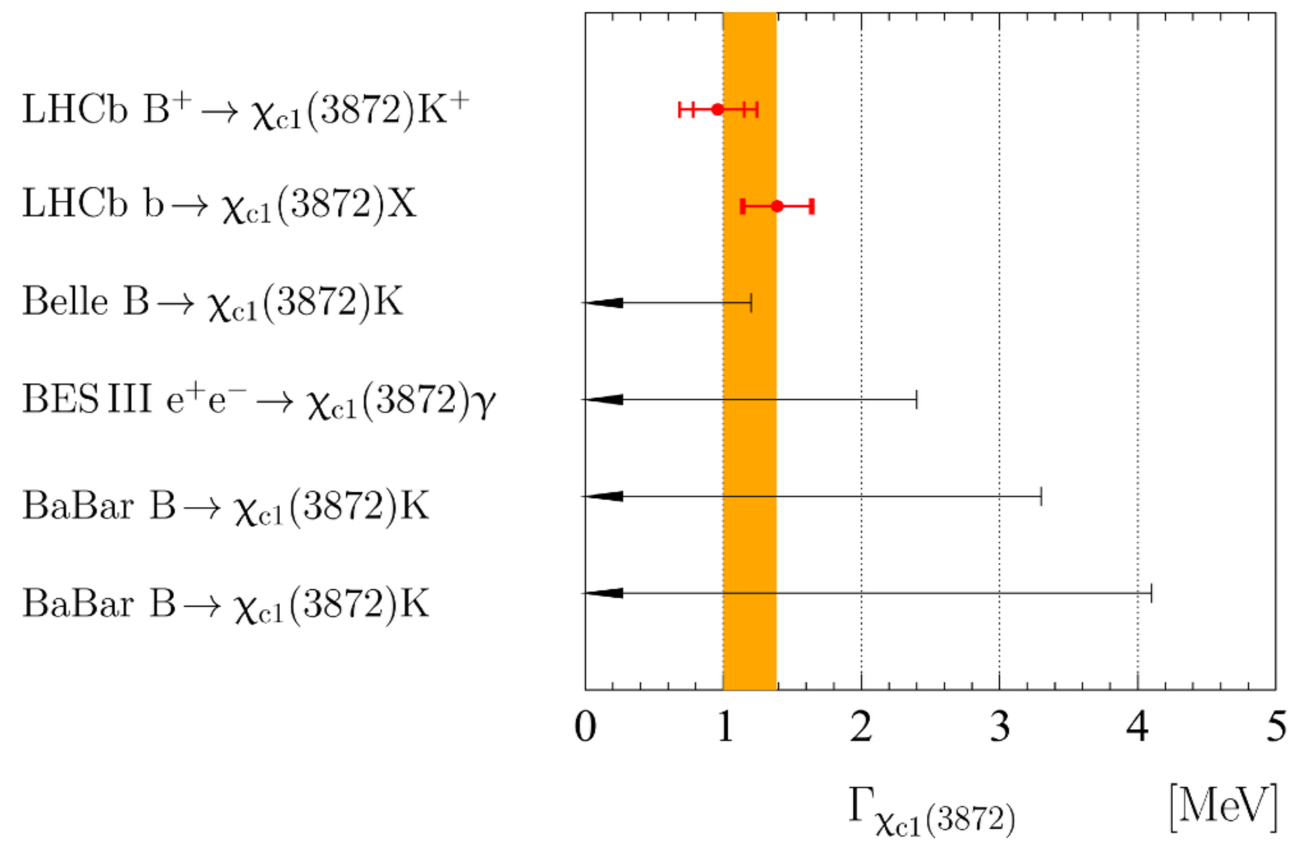
The Story of $\chi_{c1}(3872)$

- 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!

Mass



Width

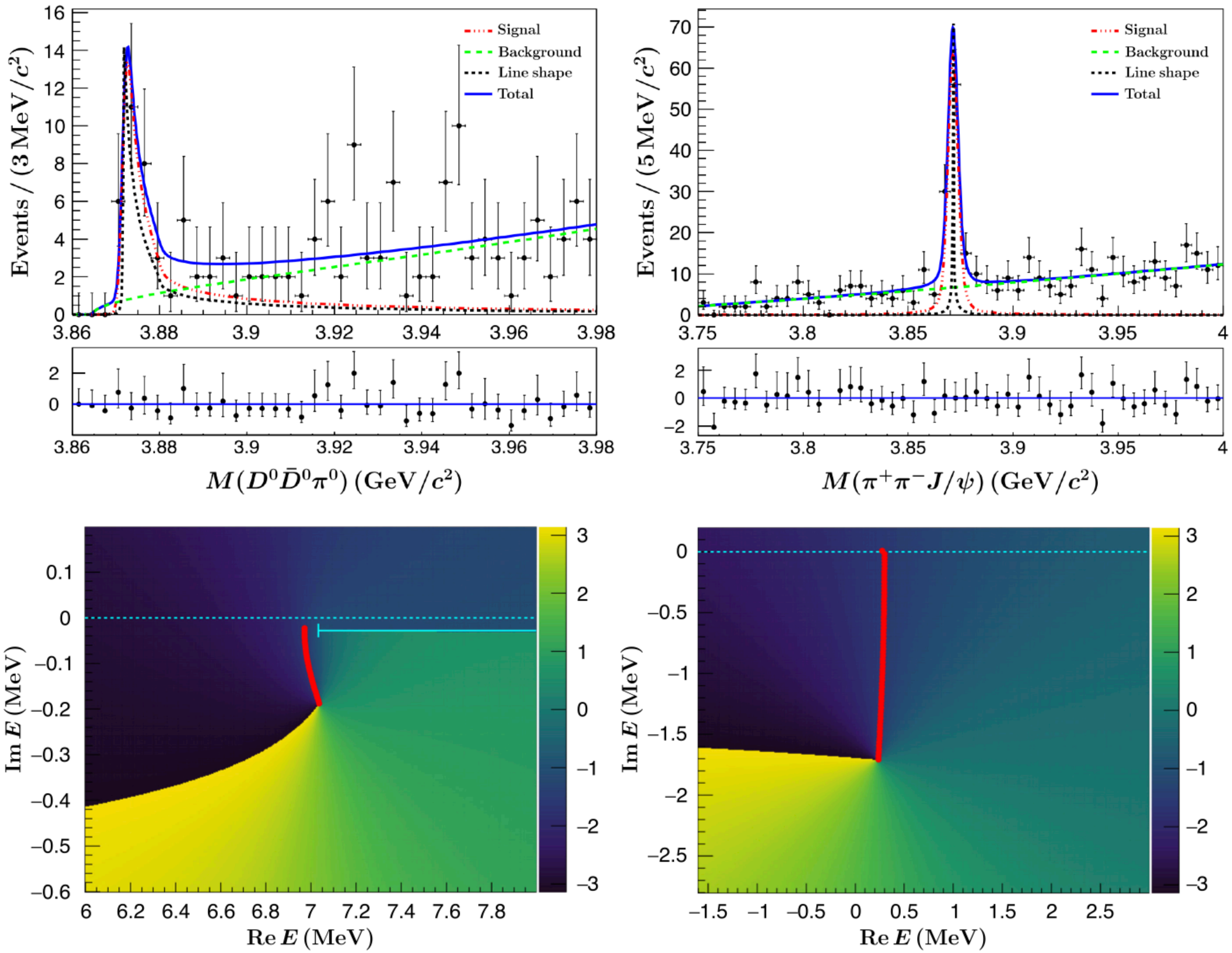


- Sensitivity to the underlying lineshape is washed out by the detector resolution
- If we want to clarify this we need << MeV resolution! No detector can do this.

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 $\chi_{c1}(3872)$

PRL 132 (2024) 15, 151903

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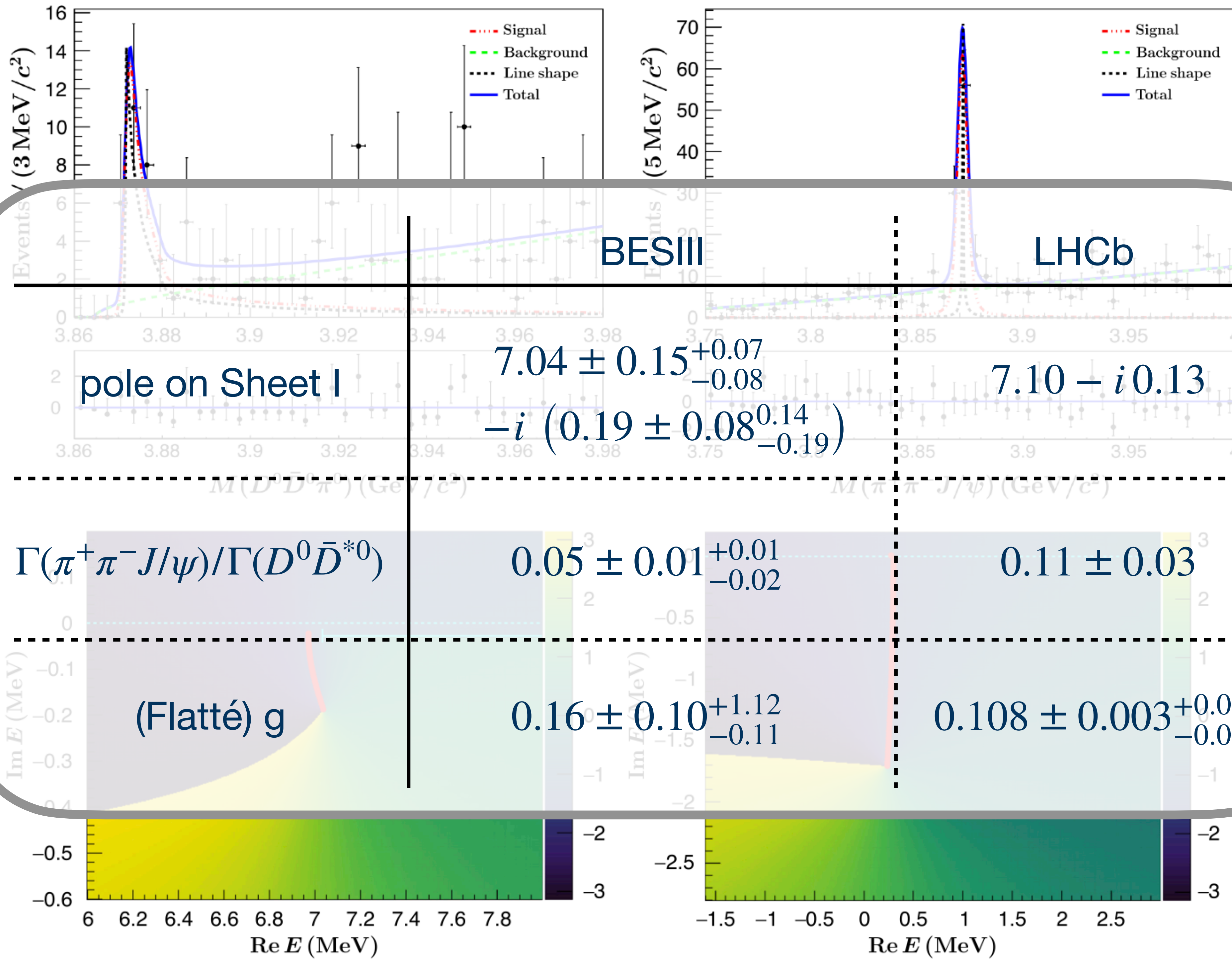


(a) Sheet I: $E_\mathrm{I} = 7.04 - 0.19i$ MeV
(b) Sheet II: $E_\mathrm{II} = 0.26 - 1.71i$ MeV

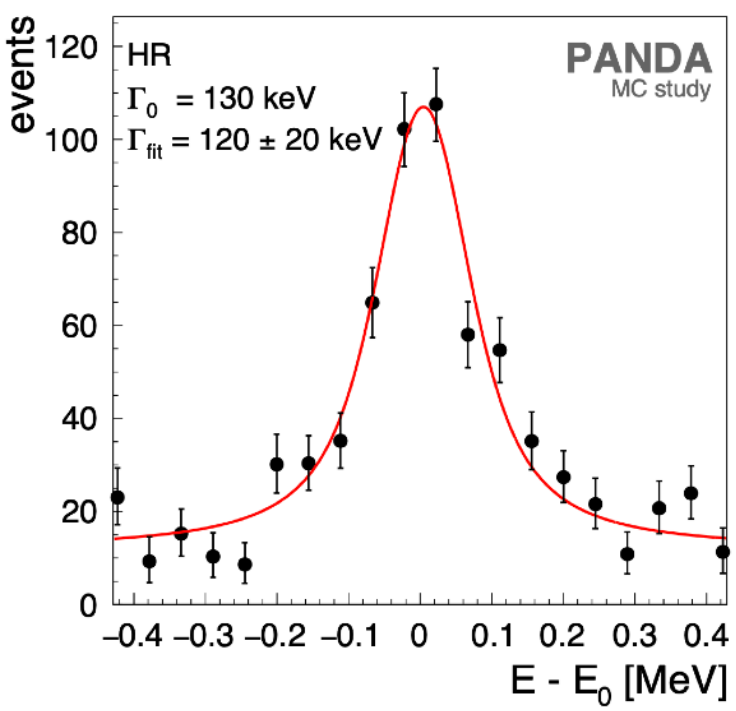
	BESIII	LHCb
pole on Sheet I	$7.04 \pm 0.15^{+0.07}_{-0.08}$ $-i\ (0.19 \pm 0.08^{0.14}_{-0.19})$	$7.10 - i\,0.13$
$\Gamma(\pi^+\pi^-J/\psi)/\Gamma(D^0\bar{D}^{*0})$	$0.05 \pm 0.01^{+0.01}_{-0.02}$	0.11 ± 0.03
(Flatté) g	$0.16 \pm 0.10^{+1.12}_{-0.11}$	$0.108 \pm 0.003^{+0.005}_{-0.006}$

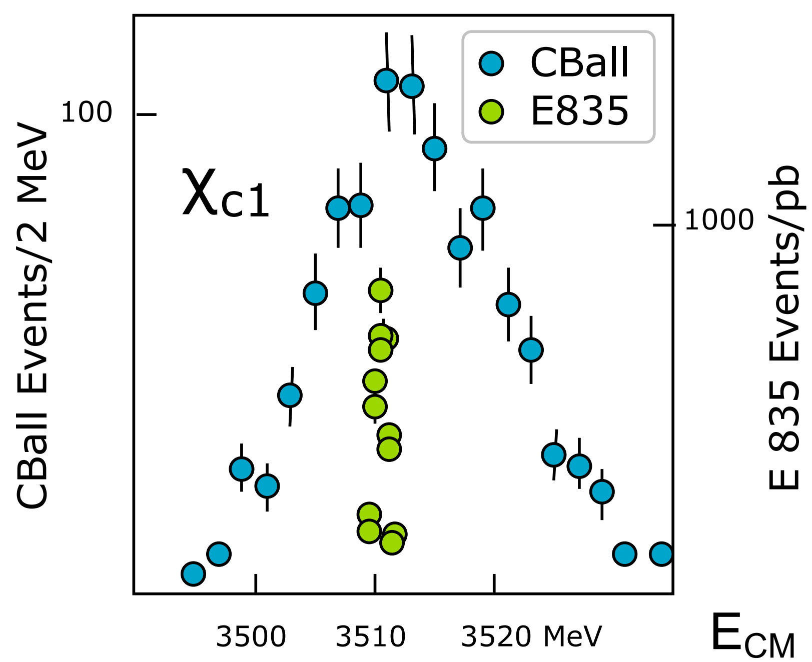
Line Shape Scans at $\overline{\text{P}}$ANDA

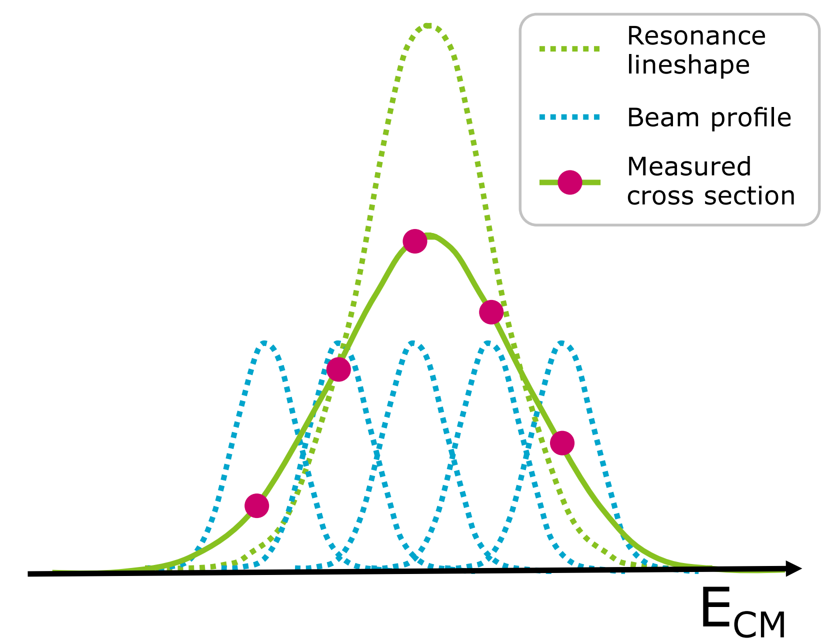
- Measure the lineshape with high precision by scanning the resonance in production
- **Line shape resolution is only limited by the beam resolution, not the detector resolution here!**
- Analysis performed for 20 energy points around nominal mass
- In sensitivity studies able to distinguish the two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

➡ With the $\overline{\text{P}}$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!







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
- Ultimately we will need high statistics and precision, as it is e.g. 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

Thank You!