25th of October

Meson Spectroscopy with BESIII

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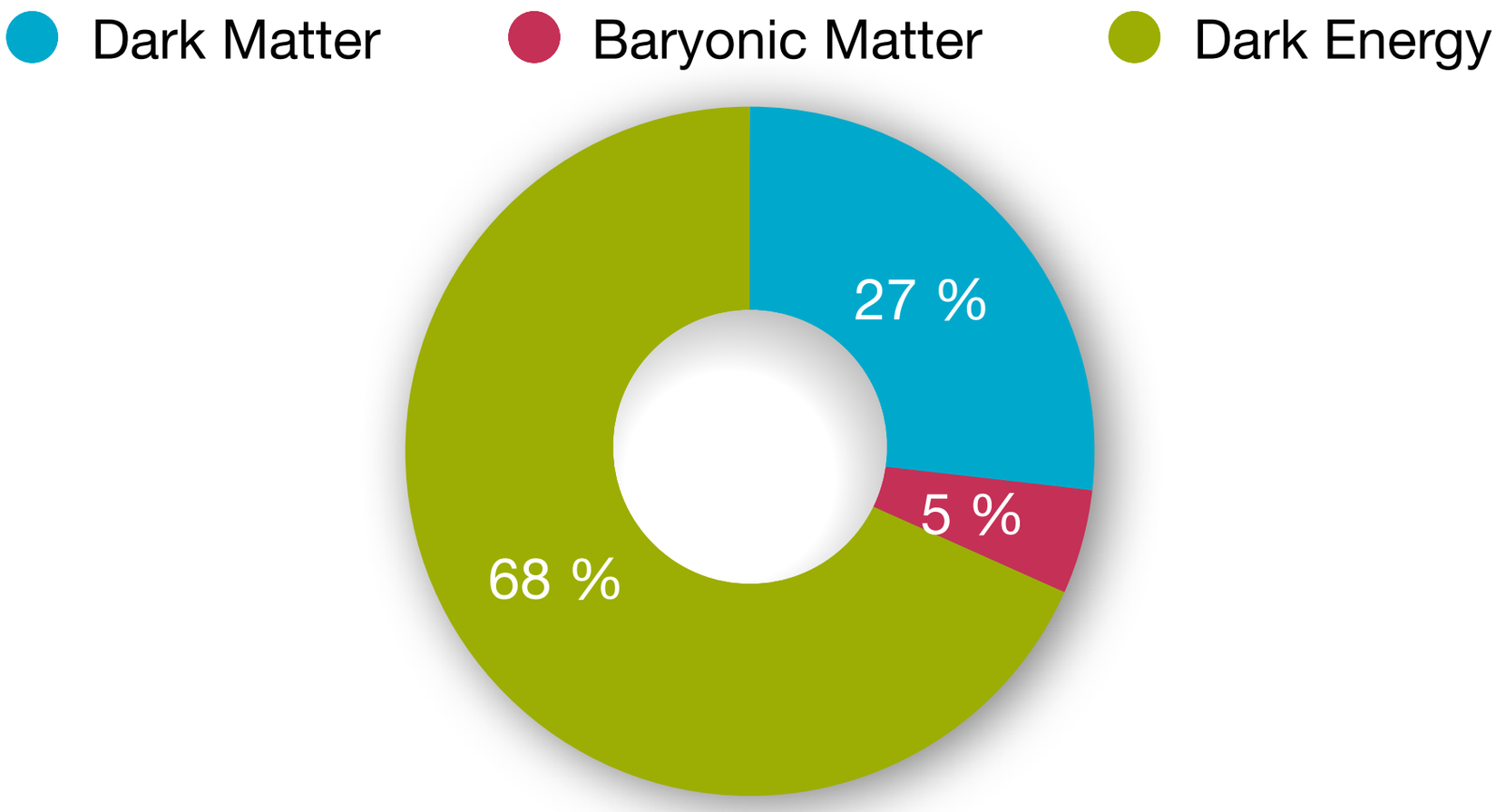
On behalf of the BESIII collaboration

Fundamental Questions in Physics

- What is matter?
- The more we learn about fundamental particles the more we ask what is actually mass?



- We even do not understand „conventional“ matter!

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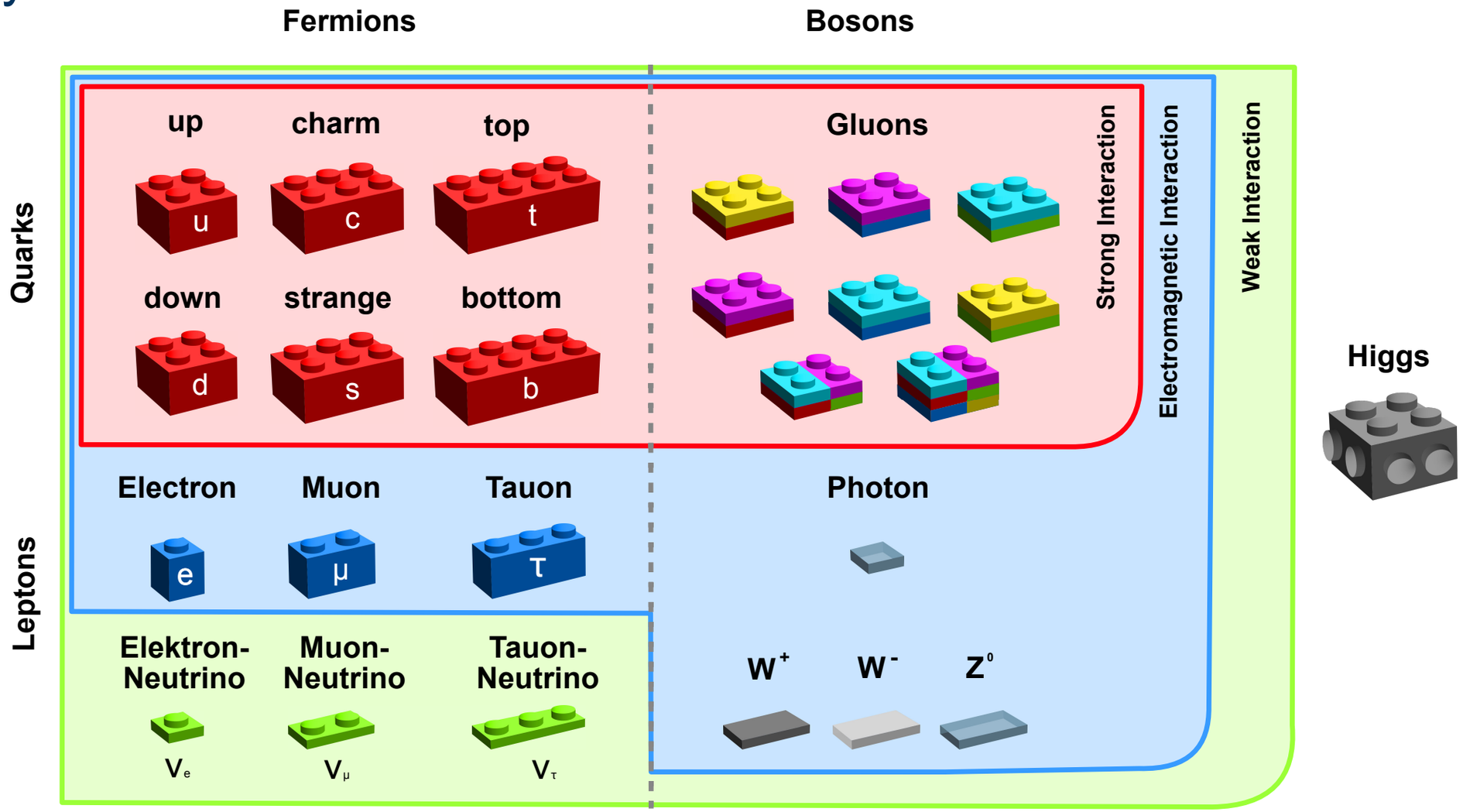
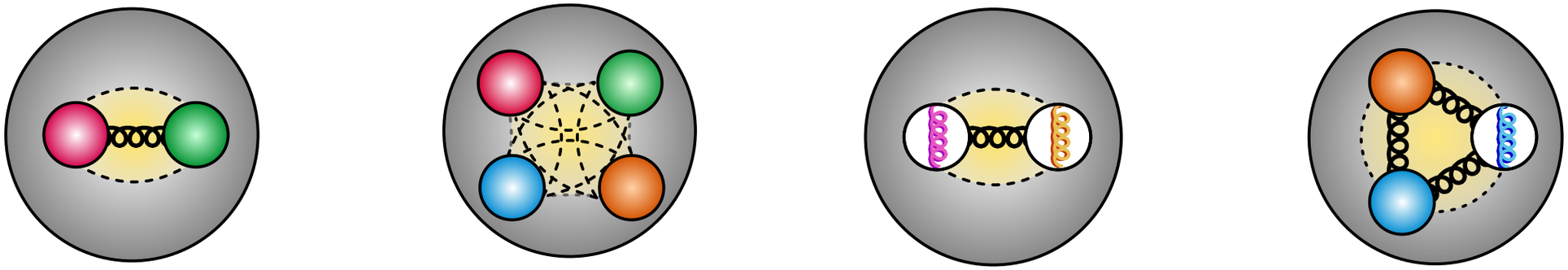


- We even do not understand „conventional“ matter!

From the Perspective of Strong Interaction

- The mass of hadrons is predominantly generated by strong interaction (>95% in case of the proton)
- To understand how mass is generated we investigate other systems, e.g. with explicit gluonic degrees of freedom

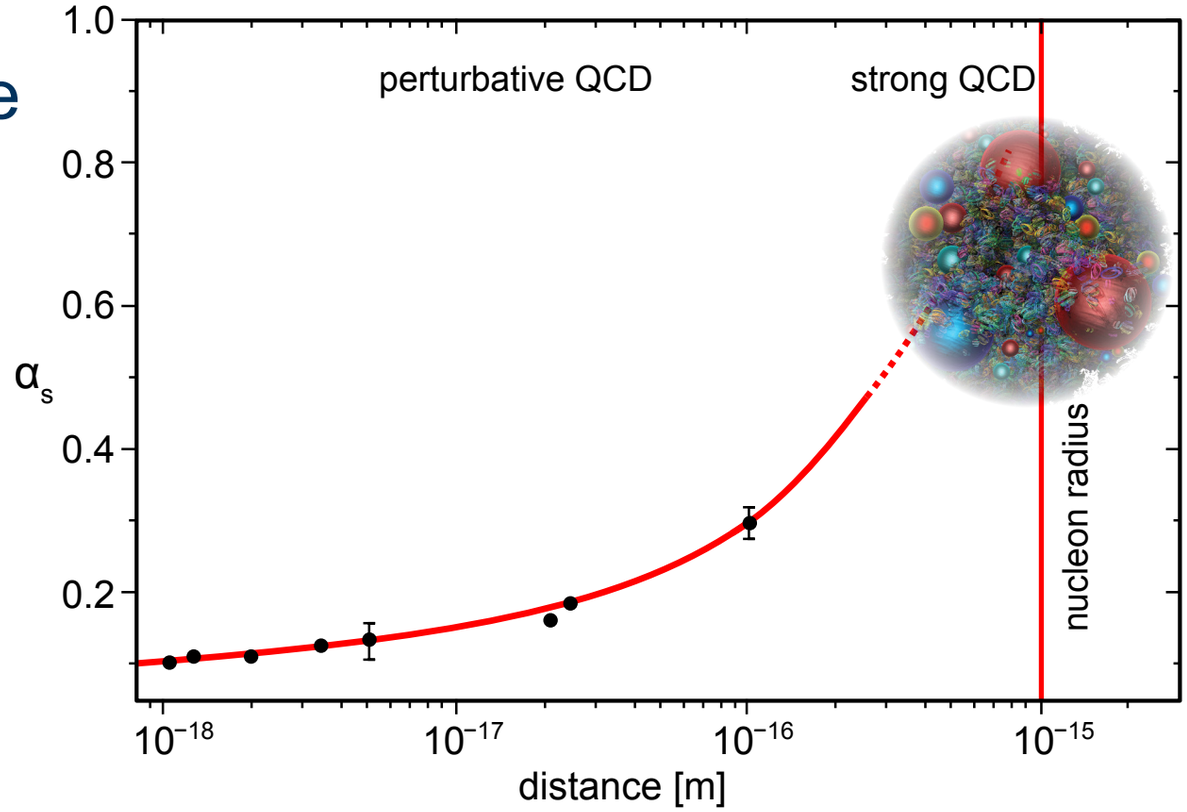


Meson | Tetraquark | Glueball | Hybrid

- Theoretically very challenging since perturbative techniques fail in this energy regime
- State of the art calculations as lattice are very costly and not good in predicting decay strengths

Open Questions of QCD

- When getting closer, hadrons show a very complex inner structure
- Hadrons occur in the non-perturbative regime of QCD
- Theoretically very challenging since perturbative techniques fail
- Since $\alpha_s \sim 1$, higher order processes are not suppressed anymore to be ignored
- Alternative theoretical tools are often model dependent or very computational expensive

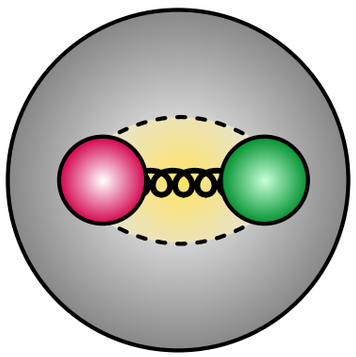


Exotic Hadrons

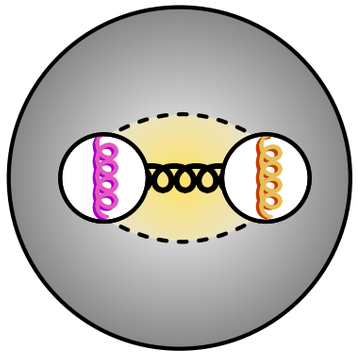
- For a fermion-antifermion system not all quantum numbers can be formed

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

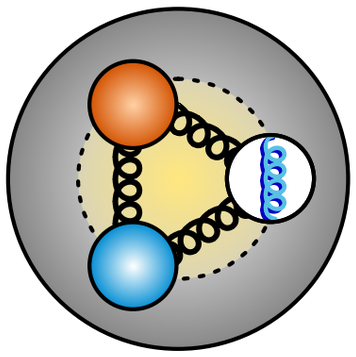
- Exotic quantum numbers: $J^{PC} = 0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \ldots$
- But: Further states have been found which show odd properties or even exotic quantum numbers!



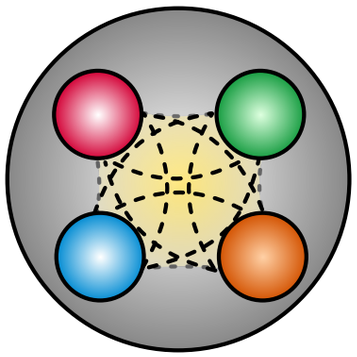
Meson



Glueball



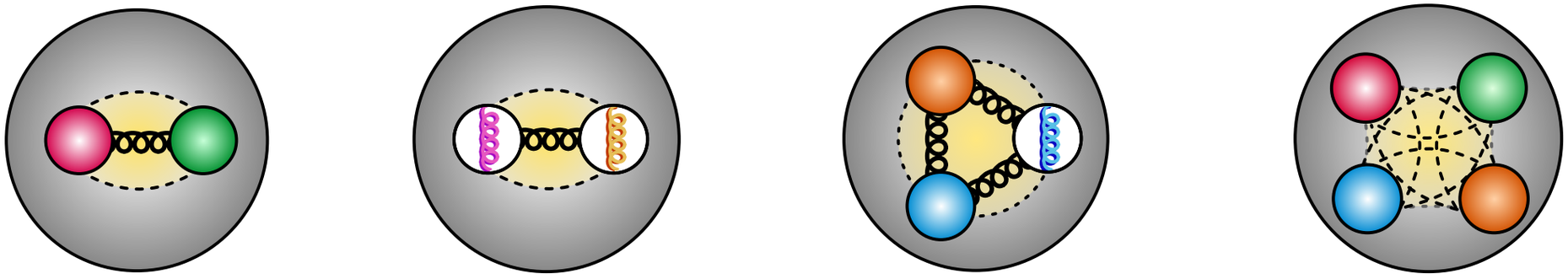
Hybrid



Tetraquark

Experimental Approaches

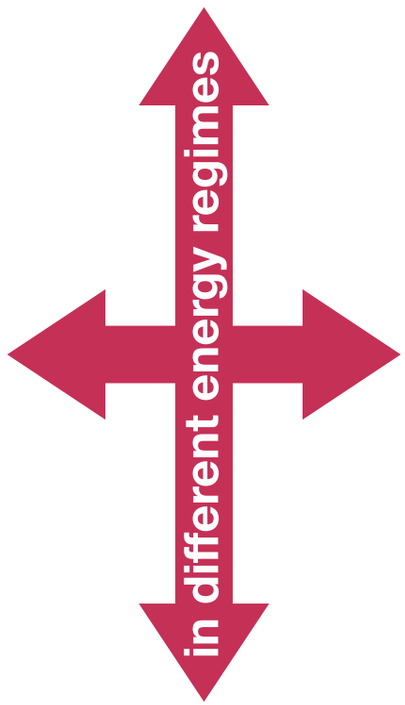
- Some of the light mesons most likely have a more complex inner structure



Meson | Glueball | Hybrid | Tetraquark

Gluon rich processes

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

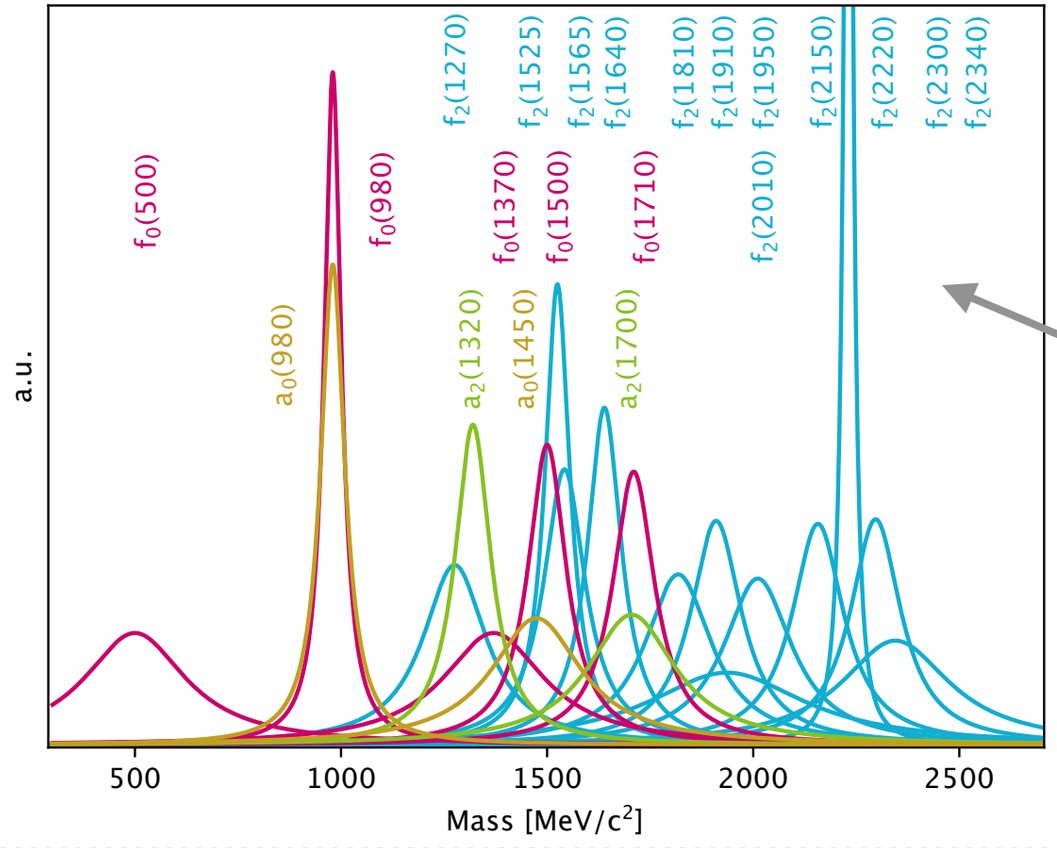


QED mediated process

- Two-photon production

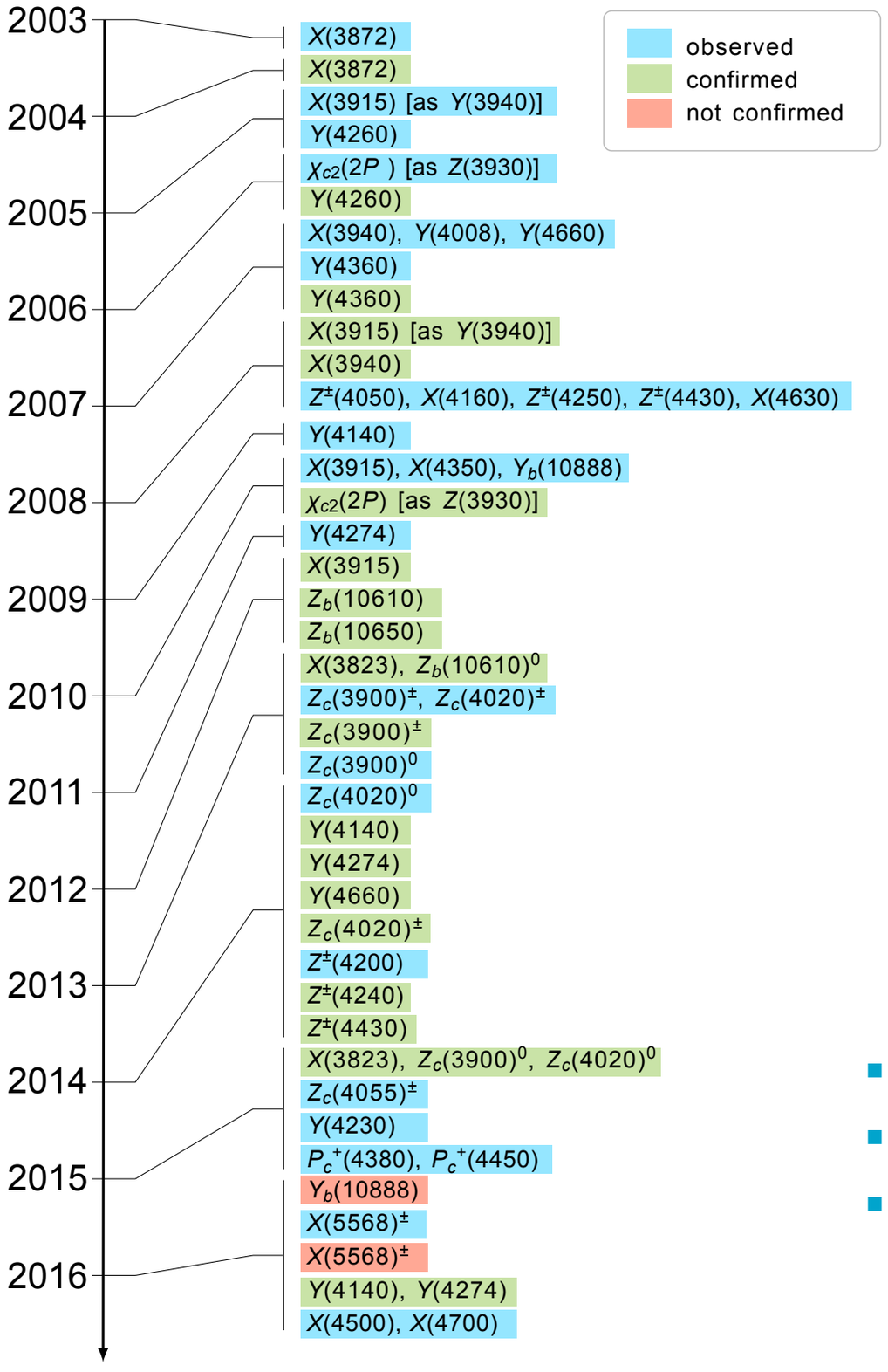
Light Meson Regime

- Light meson regime is extremely populated due to several resonances
- Identifying and measuring resonance properties is not straight forward
- Several (broad) interfering resonances of the same q.n., which often couple to different channels
- Analysing a single channel is not enough to disentangle the interference unambiguously
- More sophisticated tools and descriptions needed!
- Resonances not always look like peaks ⟷ Peaks not necessarily caused by a resonance



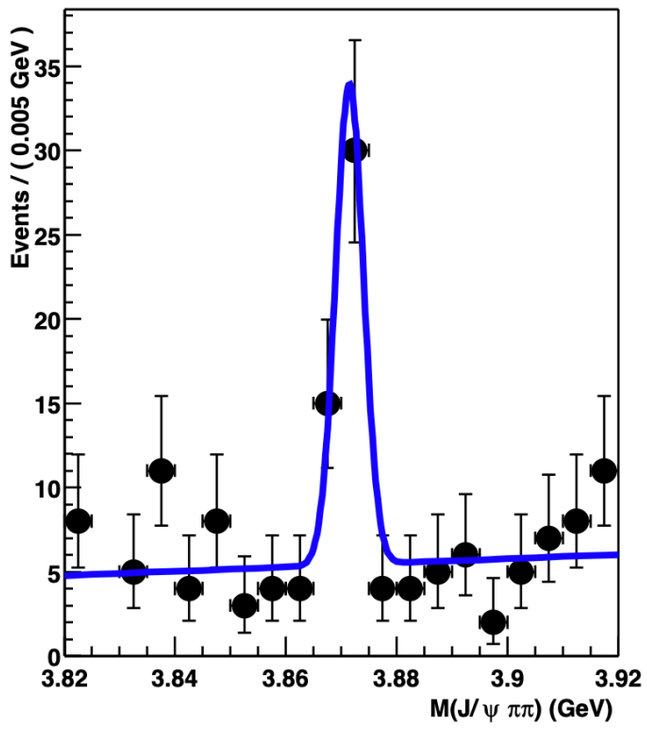
Only well established states with q.n. 0^{++} and 2^{++} shown

Heavy Quark QCD Exotica



- All began 2003 with the observation of the X(3872)

PRL 91, 262001 (2003)

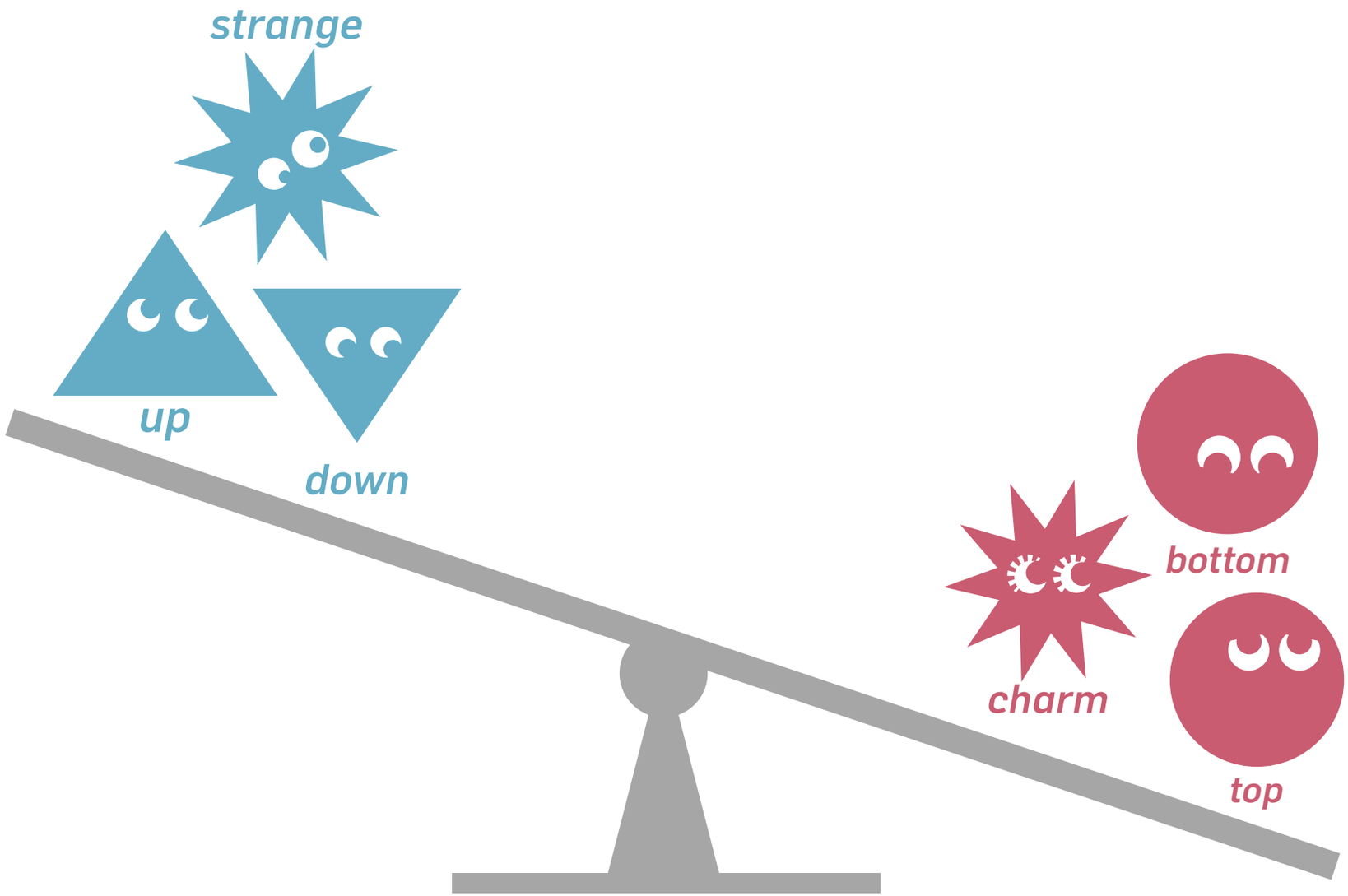


- Unexpected, very narrow resonance just above the D*D threshold not fitting in any prediction for $c\bar{c}$ states

- Since then many exotic states have been observed
- Some have clear exotic characteristics (e.g. $Z_c^{\pm}$)
- Others have unusual properties as small width, close to thresholds, unexpected decays

Charmonium Sector

- u-, d- and s-quarks have a rather small mass ➡ can be treated as massless in chiral limit ➡ underlying symmetry group SU(3)
- The heavier c quark ($\sim 1.3\,\mathrm{GeV}/c^2$) enables to use non relativistic potential models
- non-relativistic models + relativistic corrections + perturbative QCD (pQCD)



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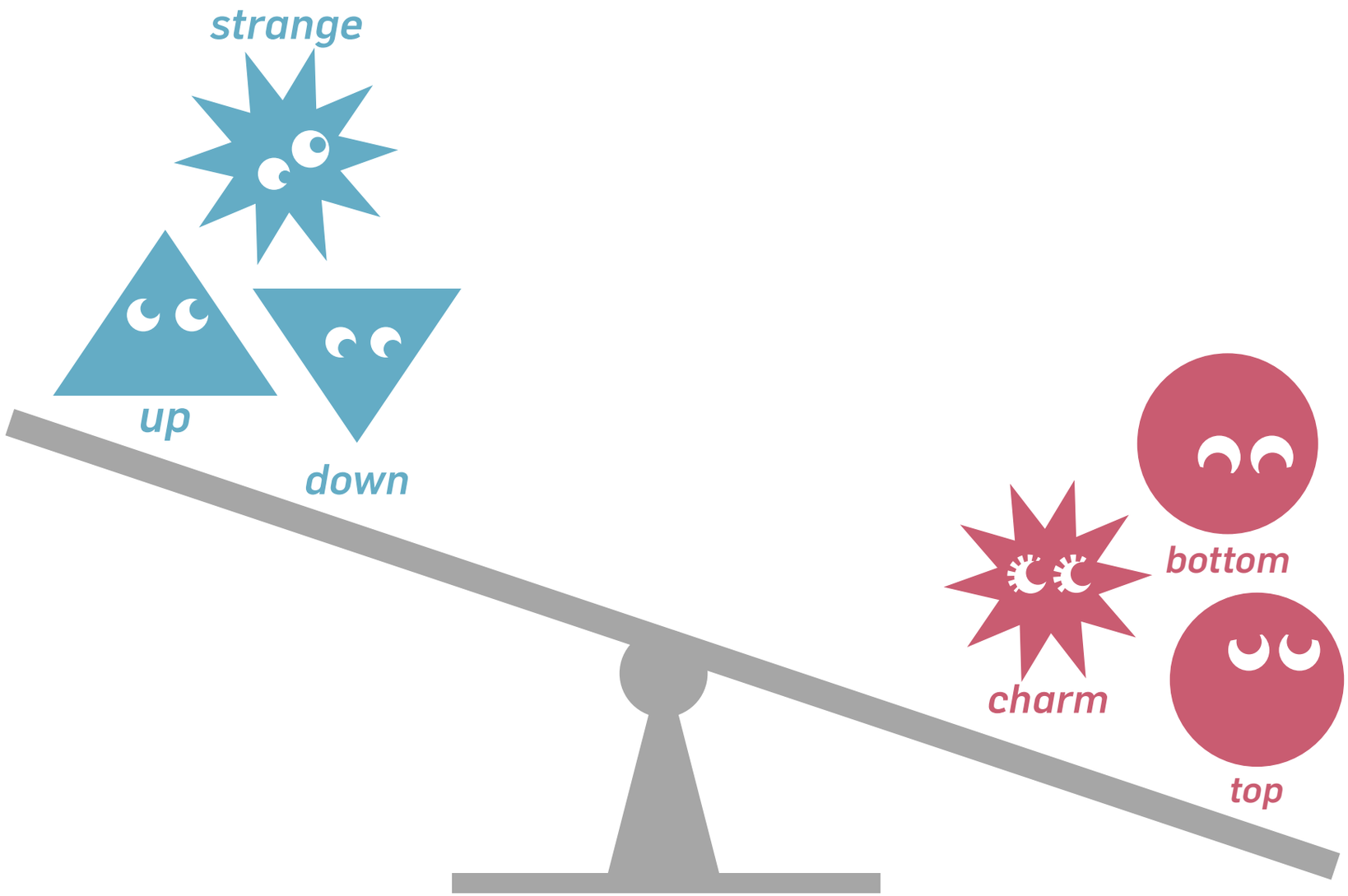
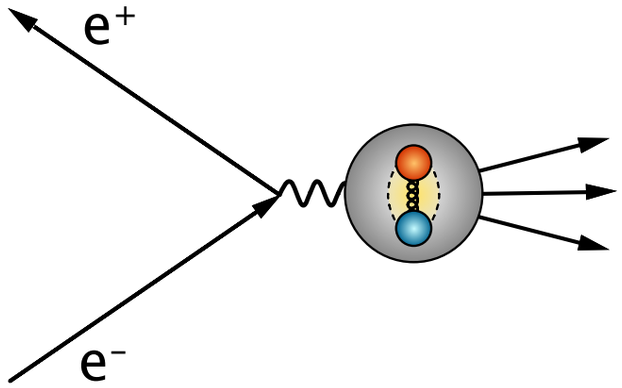
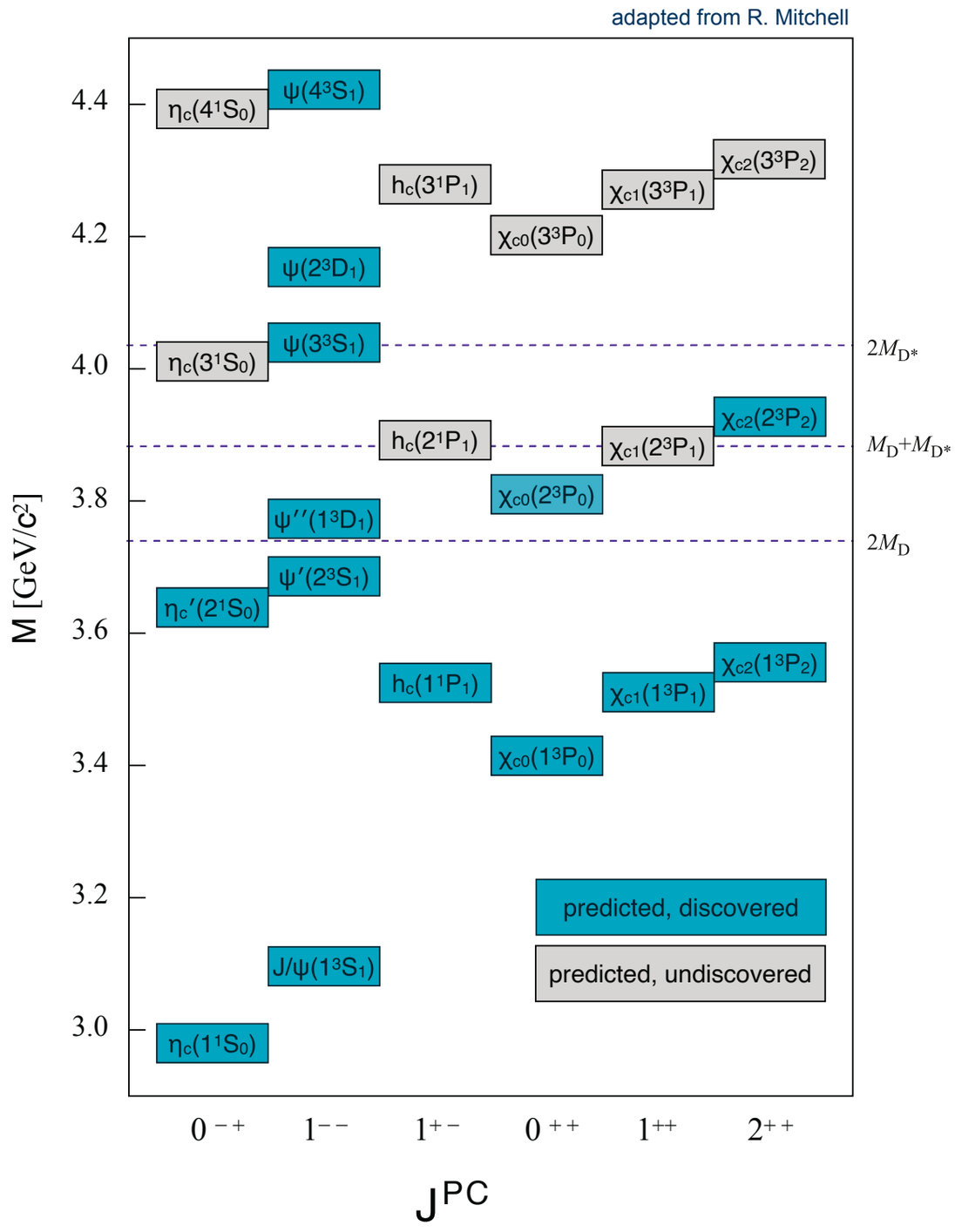


Charmonium Sector

- 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
- Traditional nomenclature:
  - Y: neutral vector states
  - Z: charged multi quark state
  - X: neutral non-vector states



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

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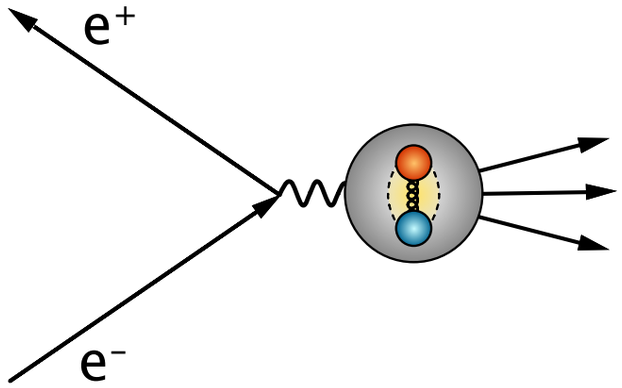

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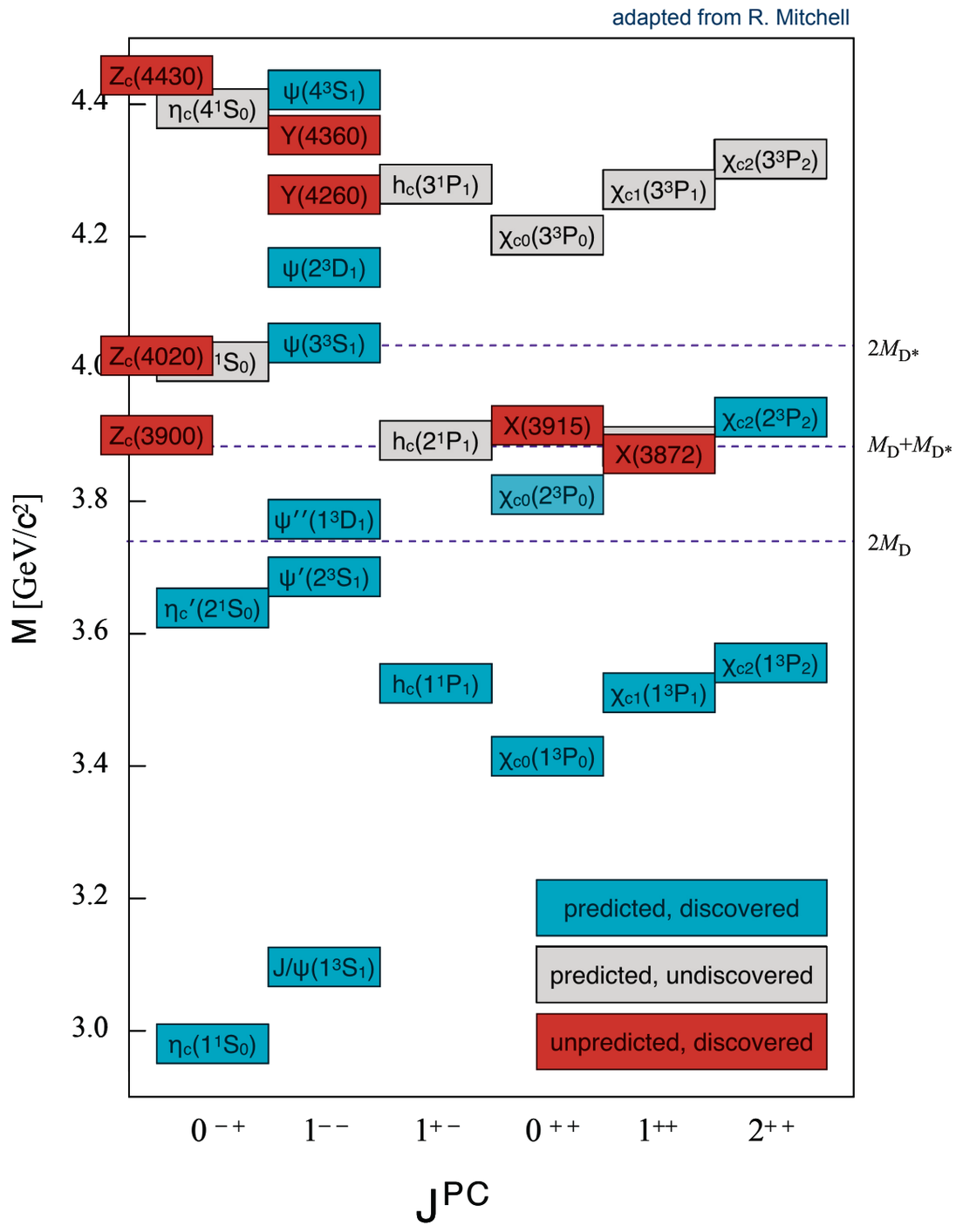

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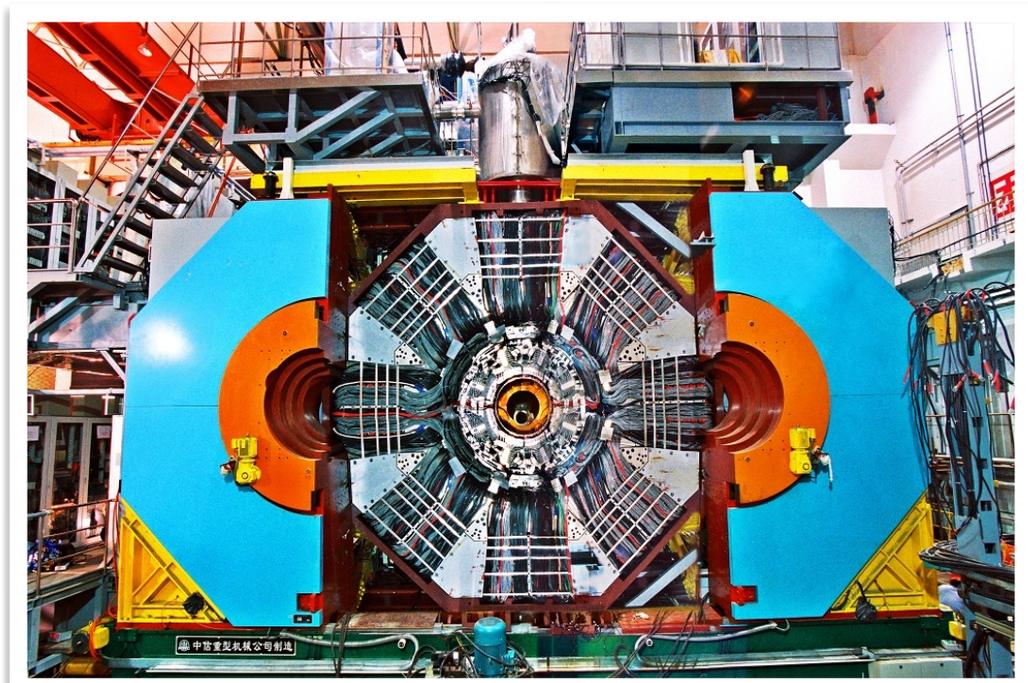
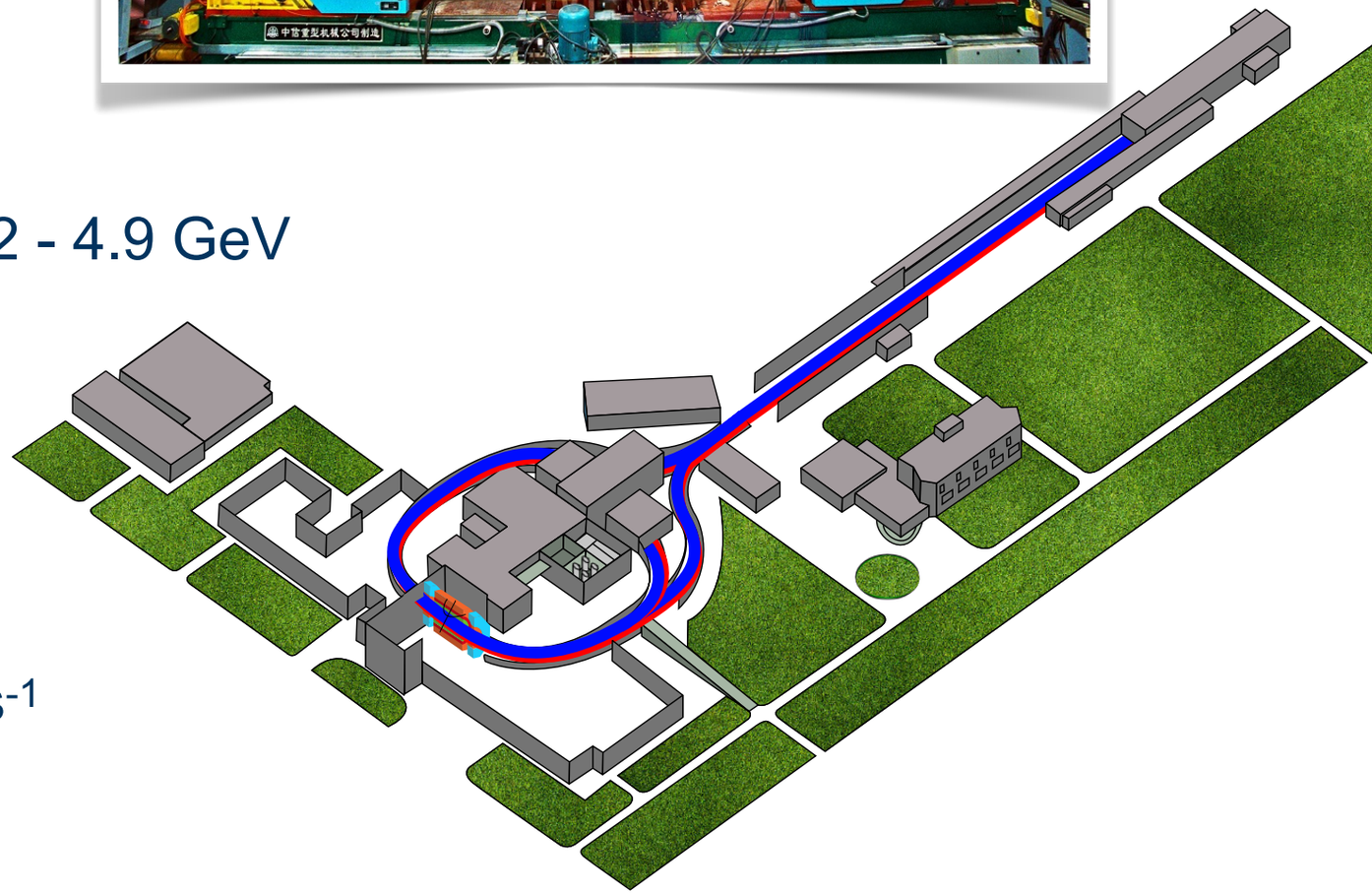
BESIII at BEPCII

- Symmetric e^+e^- collider in Beijing
- Update of BEPC accelerator
  - 2004: construction started
  - 2008: first collisions
  - 2009-today: BESIII physic runs
- Center of mass energy range: $\sqrt{s}$ = 2 - 4.9 GeV
- Single beam current: 0.91 A
- Crossing angle: 11 mrad
- Design luminosity: $1 \cdot 10^{33}$ cm^{-2} s^{-1}
- Achieved luminosity: $1.01 \cdot 10^{33}$ cm^{-2} s^{-1}





BESIII Detector

Nucl. Instr. Meth. A614, 345 (2010)

MDC (Drift Chamber):

- Spatial resolution $\sigma(\mathrm{r}\phi) = 130\ \mu\mathrm{m}$ (single wire)
- Momentum resolution: 0.5% at 1 GeV

TOF:

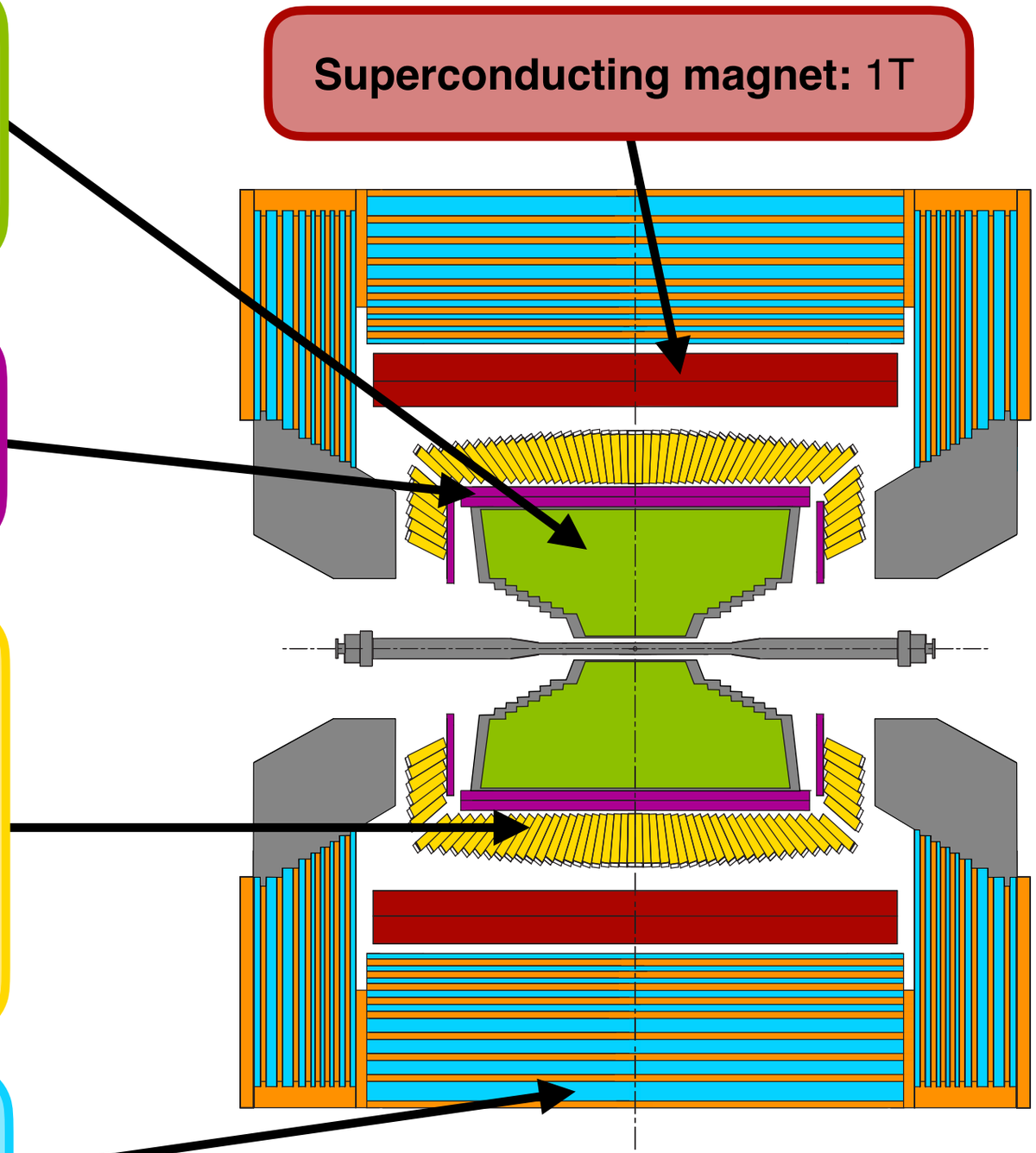
- Time resolution: $\sigma(\mathrm{t})$ = 90 ps (barrel)
  $\sigma(\mathrm{t})$= 120 ps (end caps)

EMC:

- 6240 CsI(Tl) crystals
- Energy resolution: < 2.5% at 1GeV (barrel)
  < 5% at 1GeV (end caps)
- Spatial resolution $\sigma(\mathrm{xy})$ = 6 mm at 1GeV

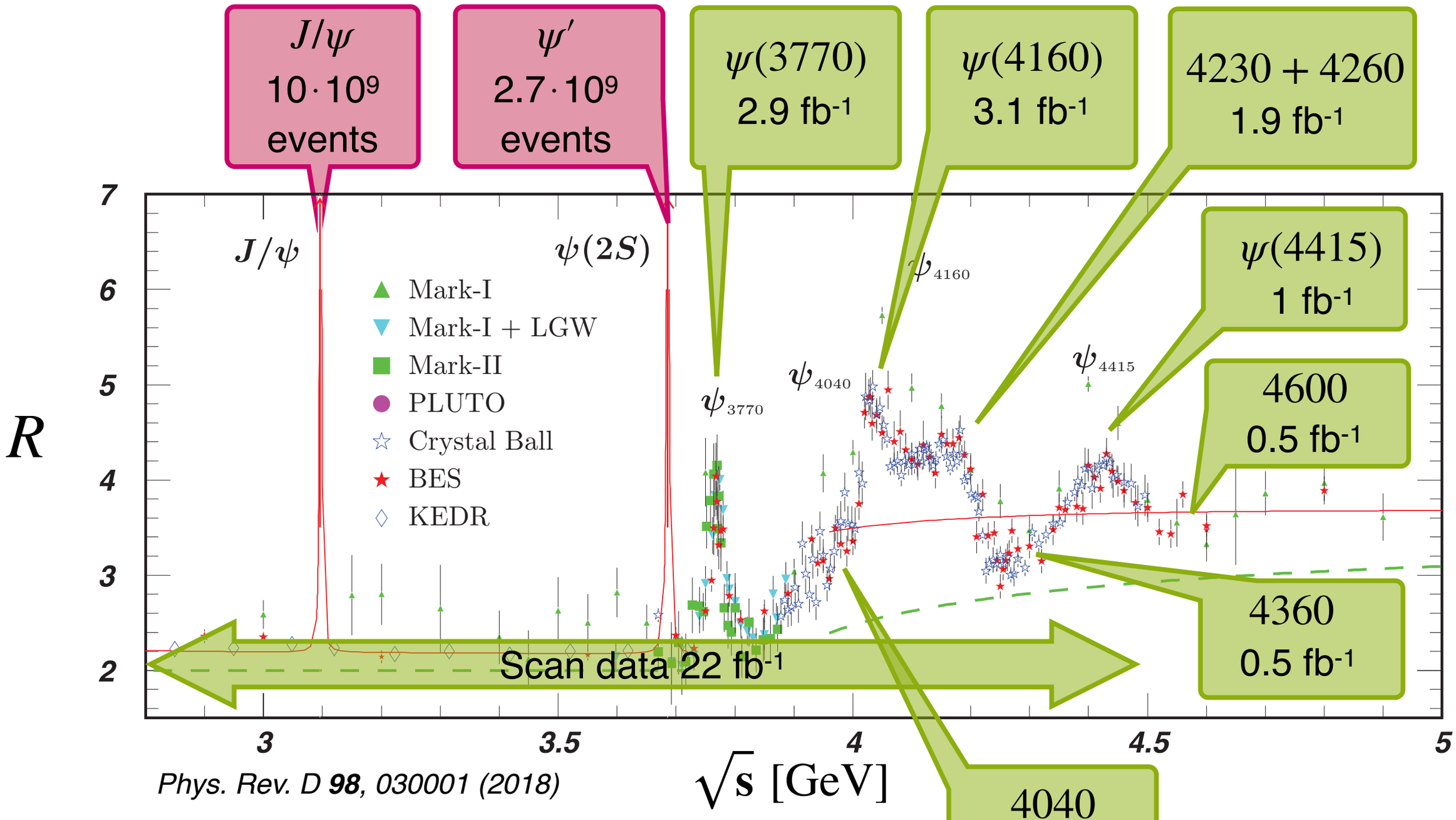
Muon ID (RPC):

- 9 layers barrel and 8 layers end caps



Spatial Coverage: 93% $\Delta\Omega/4\pi$

Data Samples



Phys. Rev. D ***98****, 030001 (2018)*

World largest J/ψ, ψ(3686), ψ(3770), ... data samples on resonance

Y States at BESIII

- Y-states are usually studied in exclusive e^+e^- cross-section measurements
- First Y state - $Y(4260)$ - was observed by BaBar

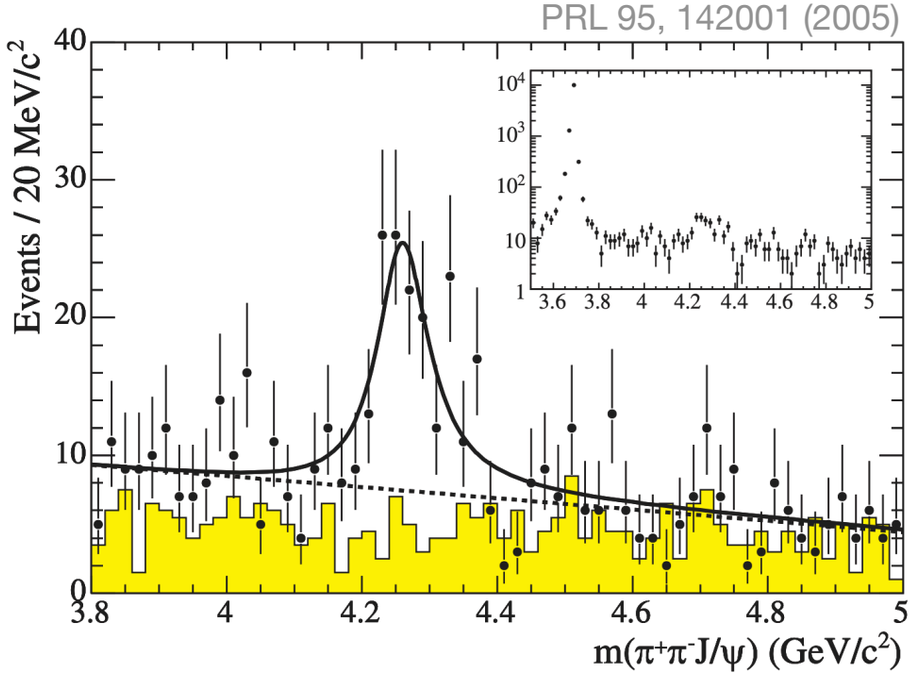
  PRL95 (2005) 142001
- PDG suggests to name them ψ states…

Old but New - The $\pi\pi J/\psi$ Spectrum

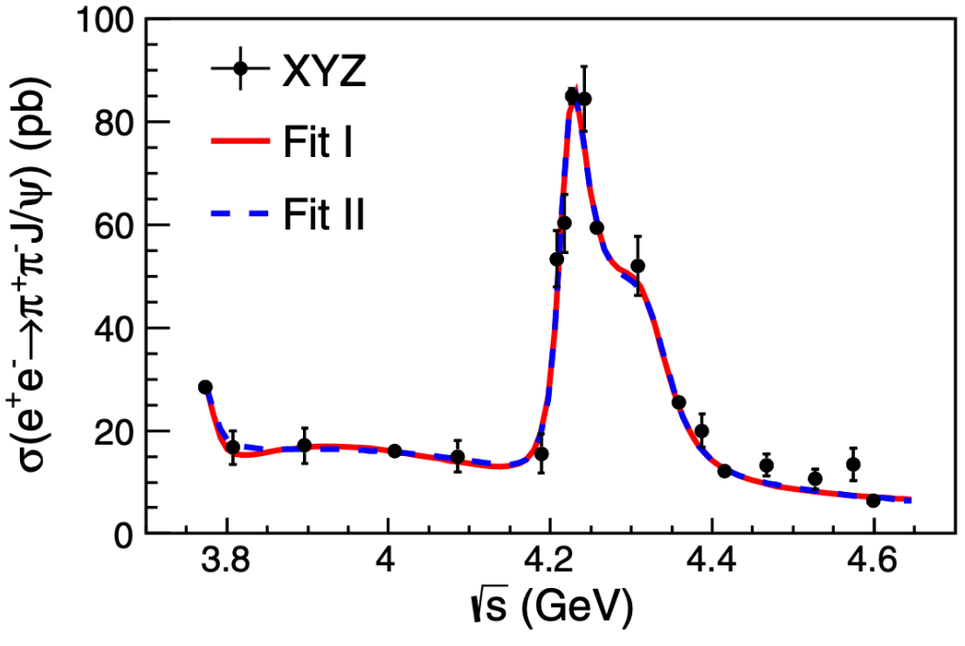
- The $Y(4260)$ was observed in ISR production by BaBar in 2005
- BESIII measured the cross section more precisely in exclusive e^+e^- production
- Two states where needed to describe the data!
- $Y(4230)$ and $Y(4360)$ (so far only seen in $e^+e^- \to \pi^+\pi^-\psi(2S)$ at BELLE and BaBar)

PRL 99, 142002 (2007)
PRL 98, 212001 (2007)

PRL 95, 142001 (2005)



PRL 118, 092001 (2017)



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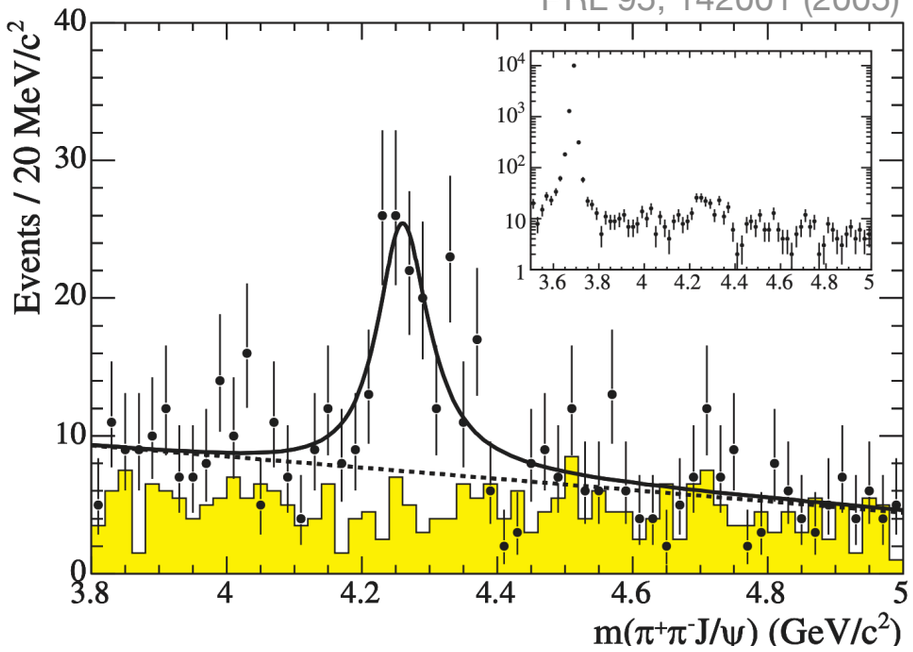
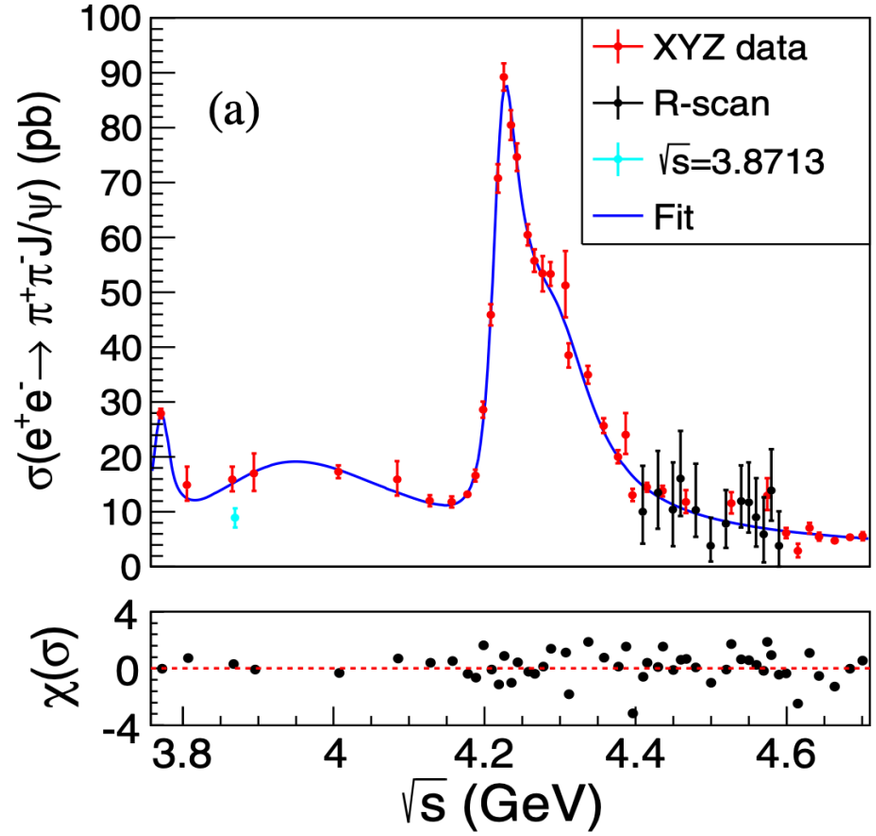
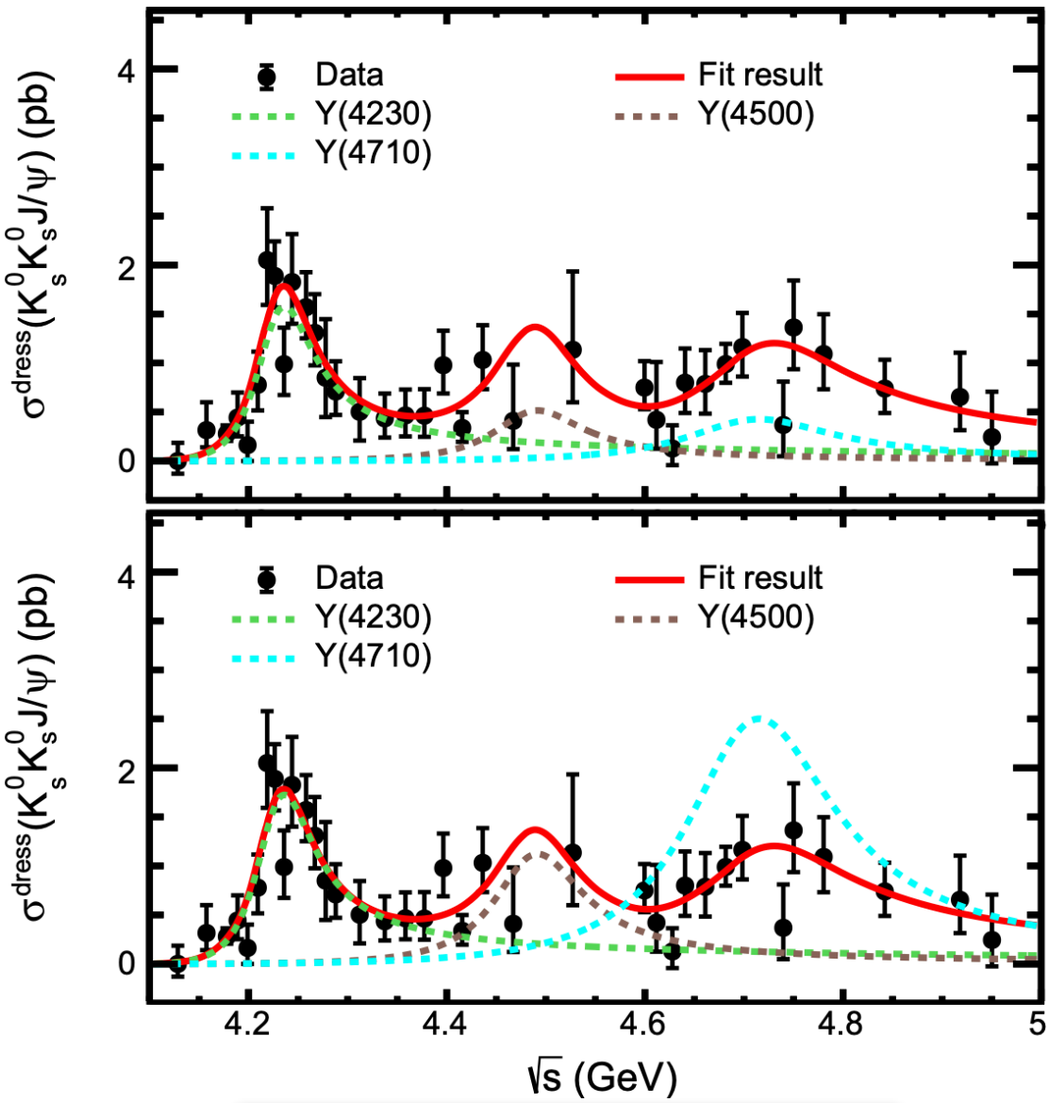


- Recent more precise data settles the two structure interpretation Phys. Rev. D 106, 072001 (2022)



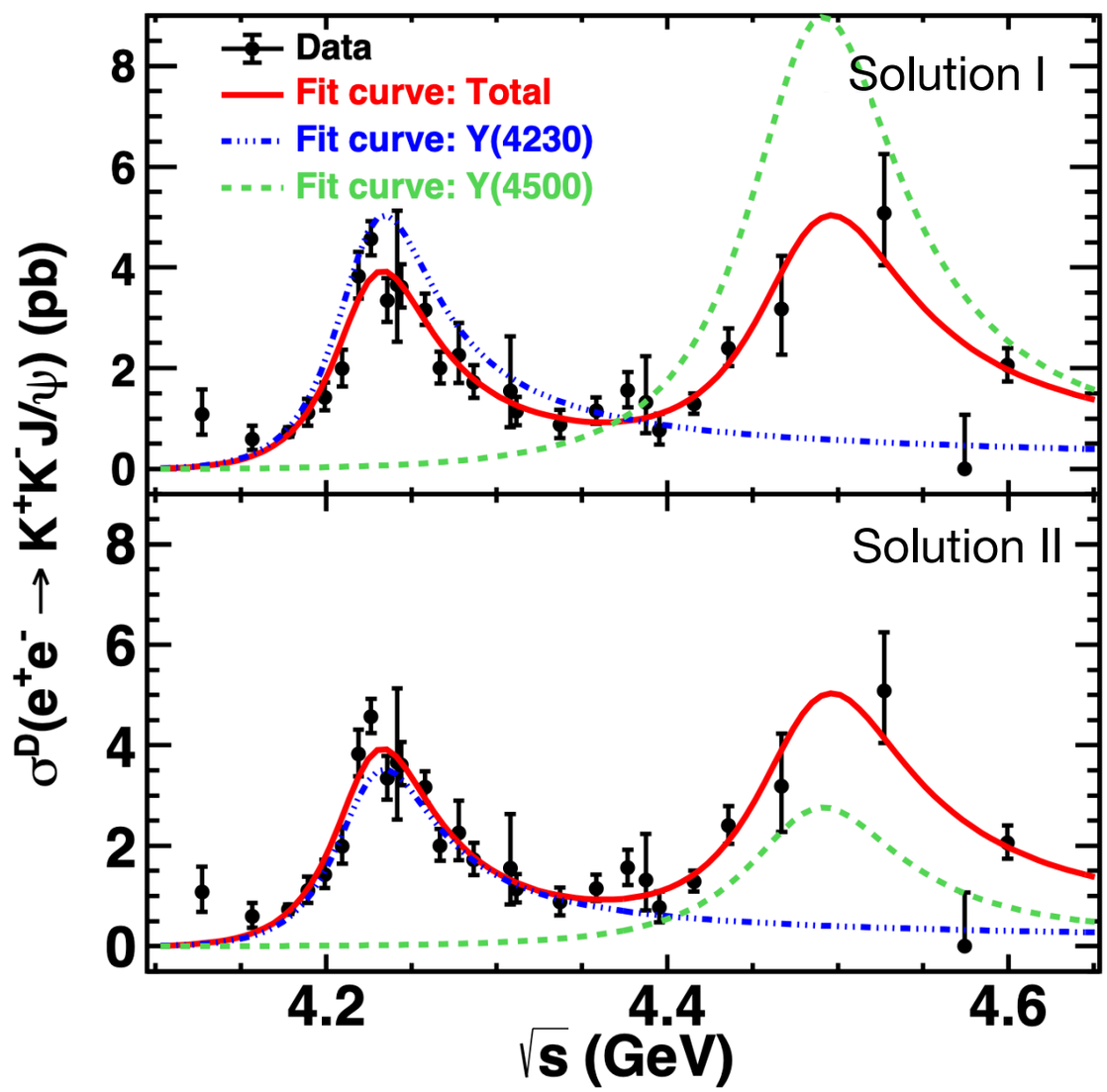
A new structure in $e^+e^- \to K\bar{K}\,J/\psi$

$e^+e^- \to K^0_S K^0_S\, J/\psi$



Phys. Rev. D 107, 092005 (2023)

$e^+e^- \to K^+K^-\, J/\psi$



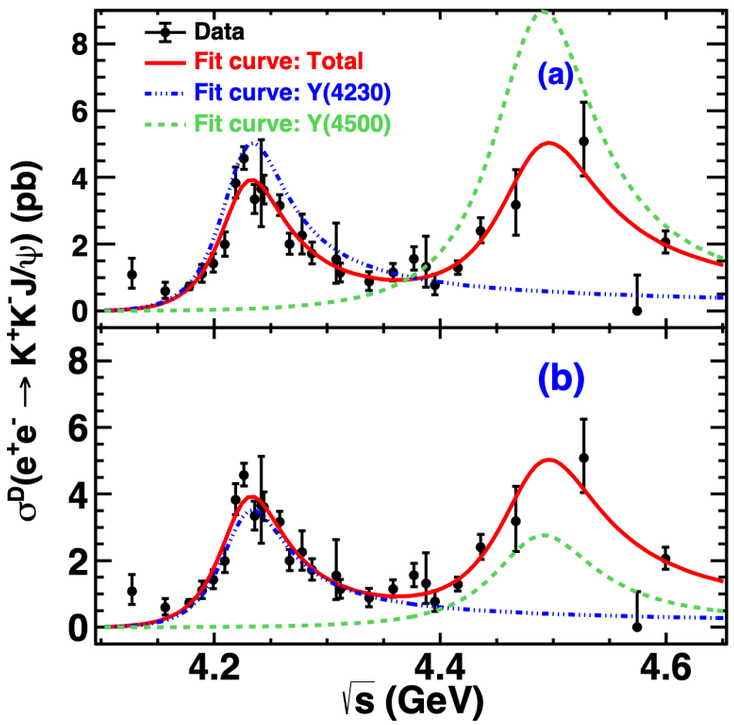
Chin. Phys. C, 46, 111002 (2022)

A new structure in $e^+e^- \to K\bar{K}J/\psi$

- Structure around 4.5 GeV - $Y(4500)$ - observed for first time!

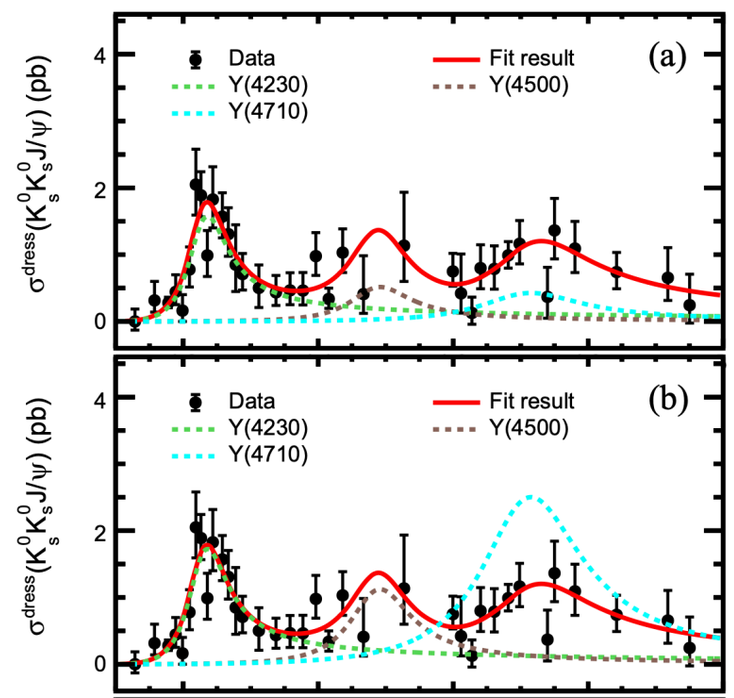
$$M = 4487.7 \pm 13.3 \pm 24.1\,\mathrm{MeV}/c^2$$
$$\Gamma = 111.1 \pm 30.1 \pm 15.2\,\mathrm{MeV}$$

Chin. Phys. C, 46, 111002 (2022)



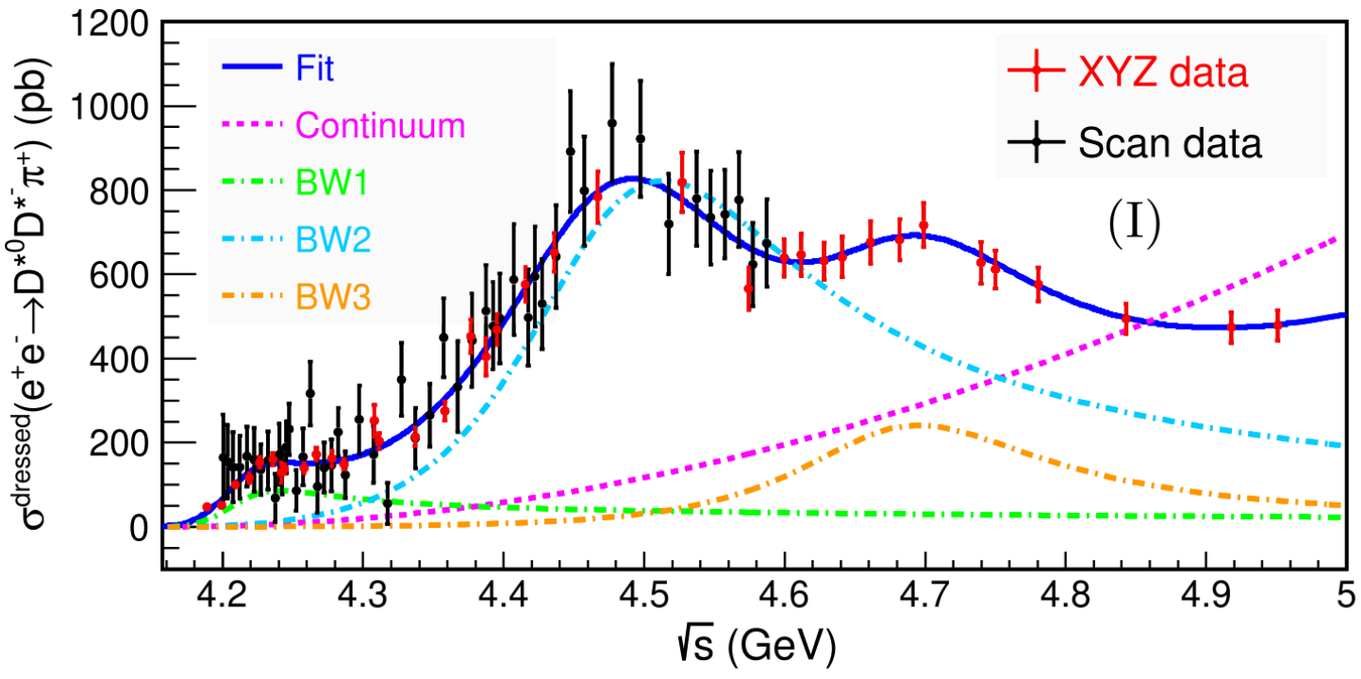
- Inner structure unclear several different interpretations possible:
  - Hadronic molecule Phys. Rev. D 73, 094510 (2006)
  - Lattice results for a $(cs\bar{c}\bar{s})$ state Phys. Rev. D 73, 094510 (2006)
- Evidence for another vector state $Y(4710)$
- $Y(4230)$ seen for the first time in this reaction

Phys. Rev. D 107, 092005 (2023)



Analysis of $e^+e^- \to D^{*0}D^{*-}\pi^+$

PRL 130, 121901 (2023)

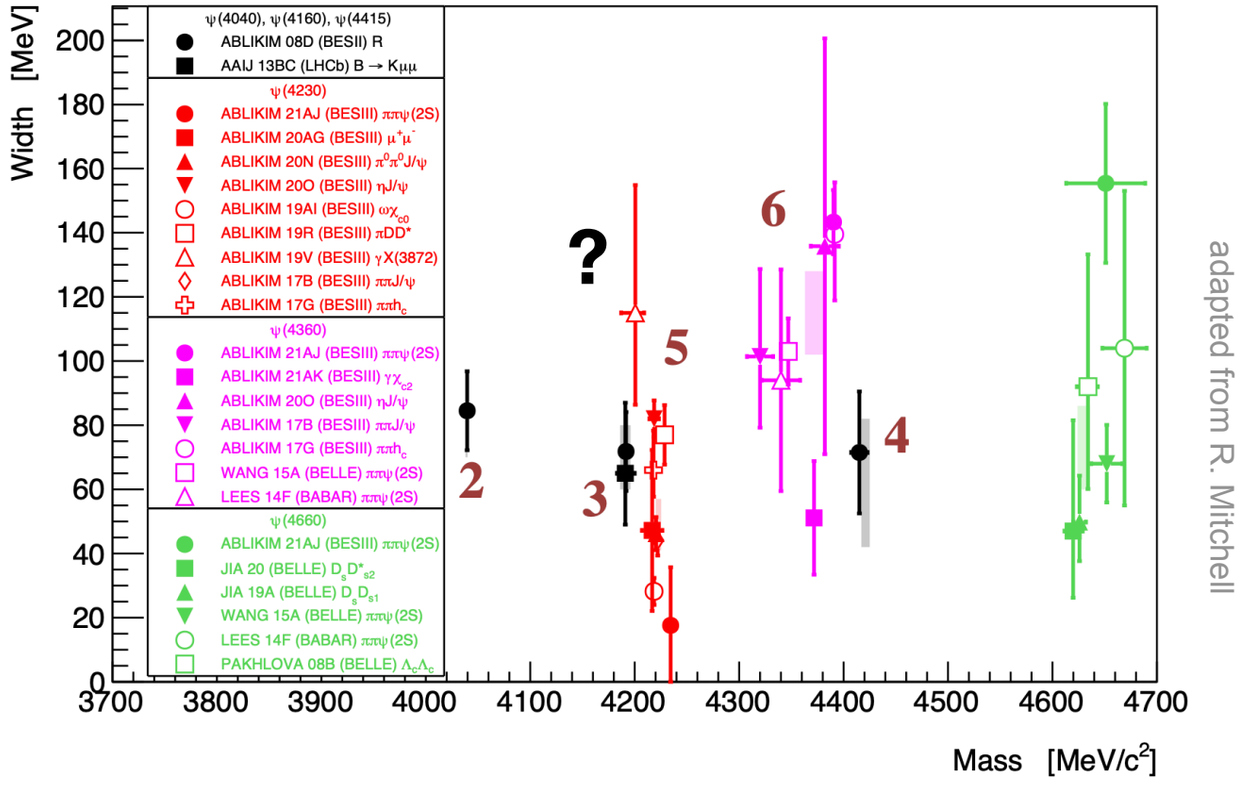


- Born cross section measured at 86 energy points from 4.189 to 4.951 GeV
- Data described with 3 Breit-Wigner shapes and a continuum contribution
- In total 8 equally good solutions where found with different relative phases…
- BW1: In agreement with $\psi(4230)$, seen in
- BW2: In agreement with $\psi(4500)$
  - Tetraquark interpretation unlikely due to: $\frac{BF(\psi \to D^*\bar{D}^*\pi)}{BF(\psi \to K\bar{K}J/\psi)} > 10^2$
- BW3: In agreement with $\psi(4660)$

What to do with all these states?

$Y(4260)$ $Y(4360)$ $Y(4500)$ $Y(4660)$ $Y(4710)$?

All listed Y states in the PDG 2022



- One dimensional fits suffer from multiple ambiguities!
- Perform a coupled channel analysis to constrain all data sets and hopefully get a global picture

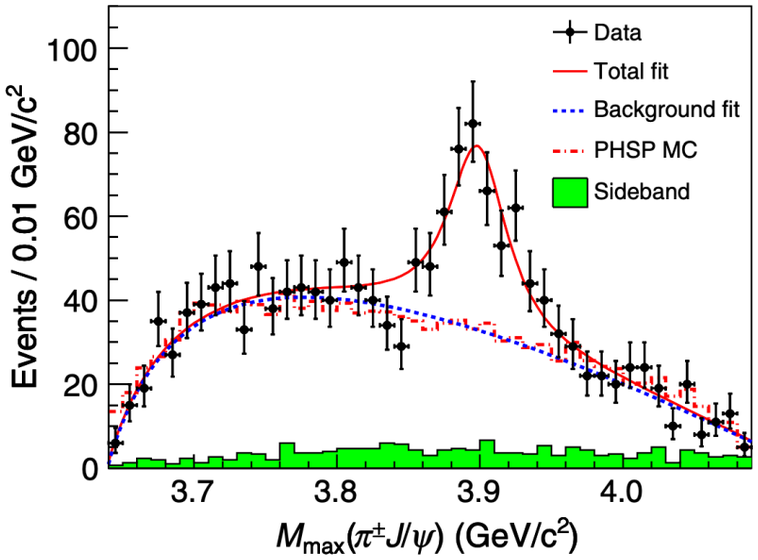
Z States at BESIII

- States in the charmonium region seen in $c\bar{c} + LH$
- Obviously unconventional due to charge
- Must have a more complex structure than $c\bar{c}$

History of the Z_c States

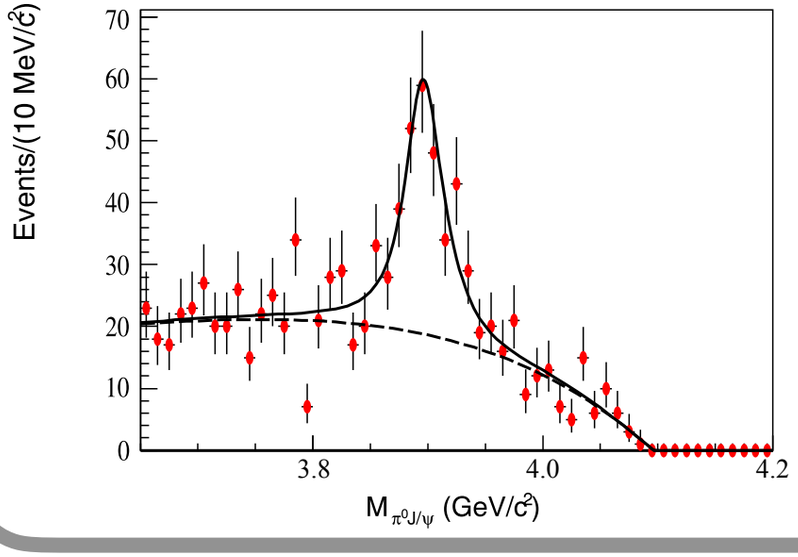
$Z_c(3900)^{\pm,0}$

$e^+e^- \to \pi^+\pi^- J/\psi$



PRL 110 (2013) 252001

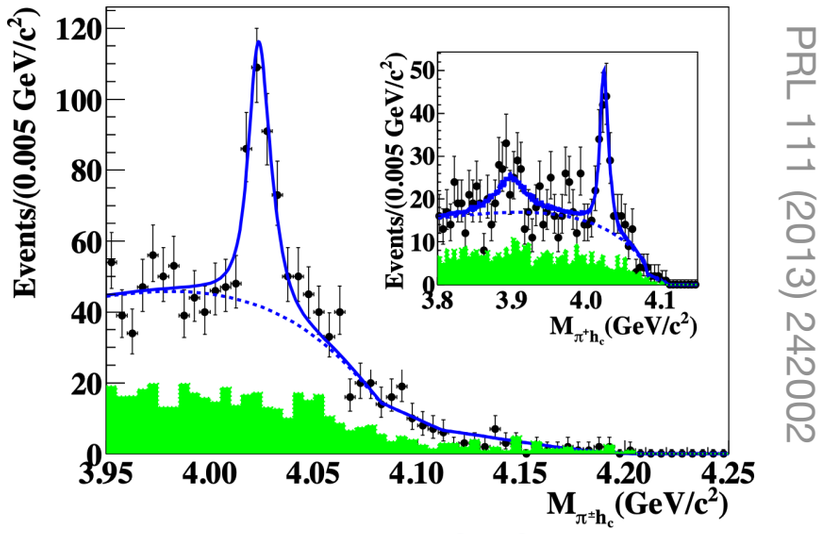
$e^+e^- \to \pi^0\pi^0 J/\psi$



PRL 115 (2015) 112003

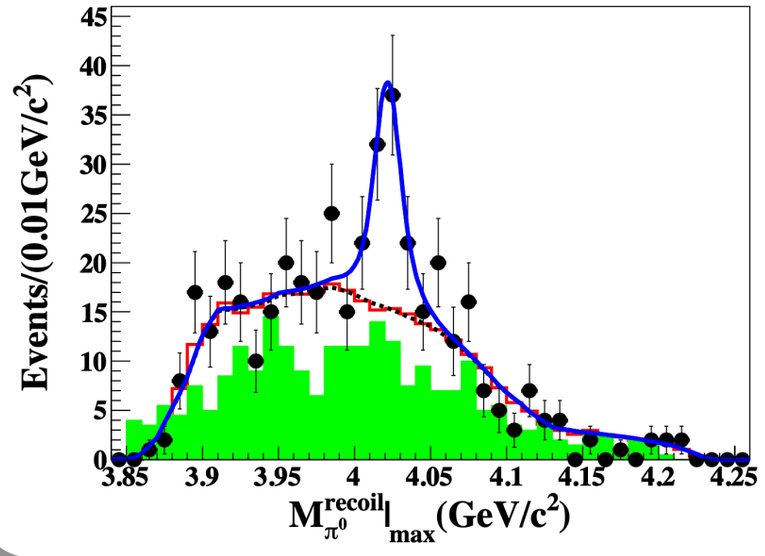
$Z_c(4020)^{\pm,0}$

$e^+e^- \to \pi^+\pi^- h_c$



PRL 111 (2013) 242002

$e^+e^- \to \pi^0\pi^0 h_c$



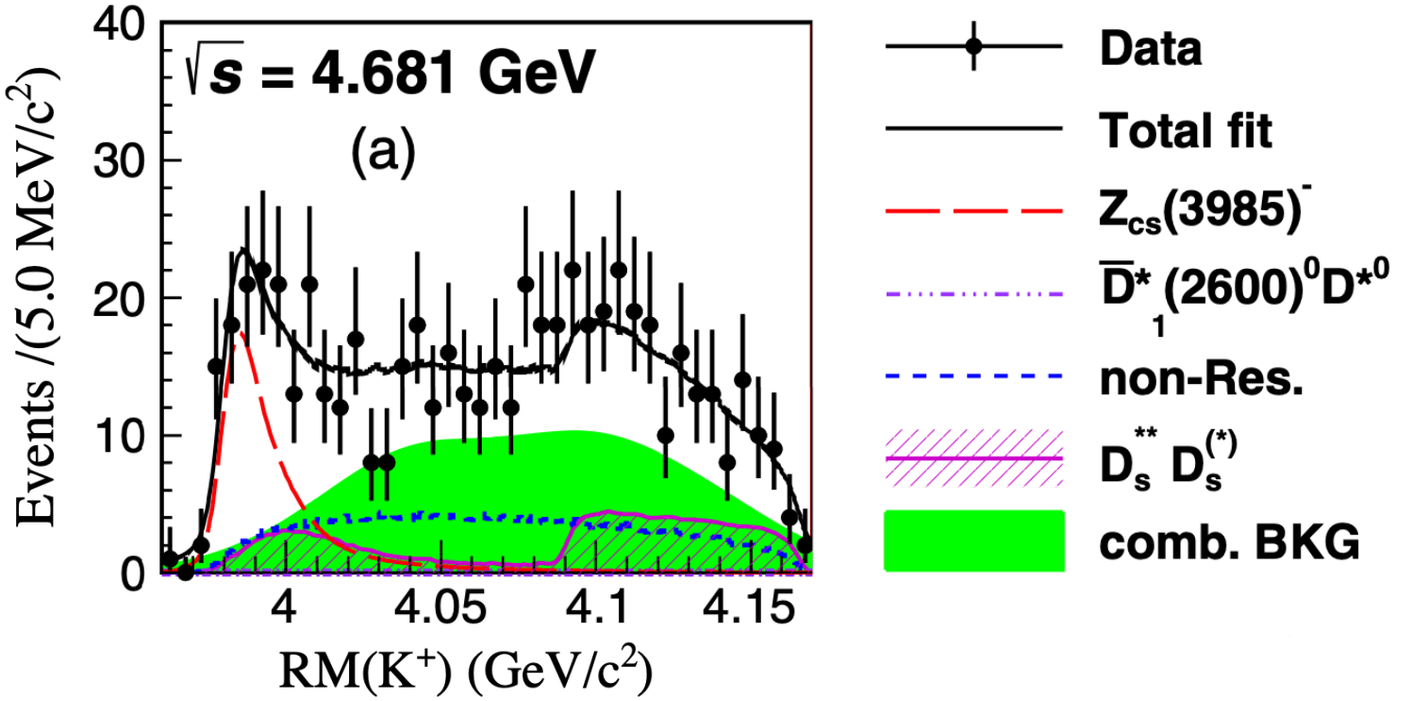
PRL 113 (2014) 212002

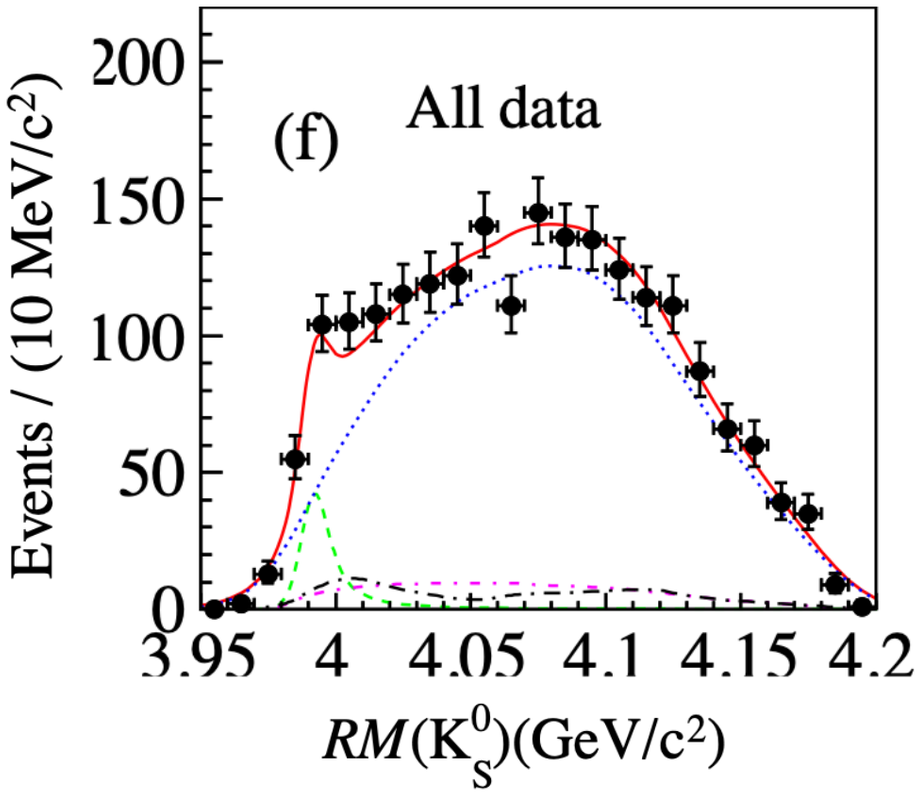
- BESIII observed two exotic Z_c triplets together with Belle

Observation of $Z_{cs}(3985)$

PRL 126, 102001 (2021)

- A near threshold enhancement was observed in $e^+e^- \to K^+(D_S^- D^{*0} + D_S^{*-} D^0)$ at $\sqrt{s} = 4.681\,\text{GeV}$
- $M = (3982.5^{+1.8}_{-2.6} \pm 2.1)\,\text{MeV}/c^2$, $\Gamma = (12.8^{+5.3}_{-4.4} \pm 3.0)\,\text{MeV}$





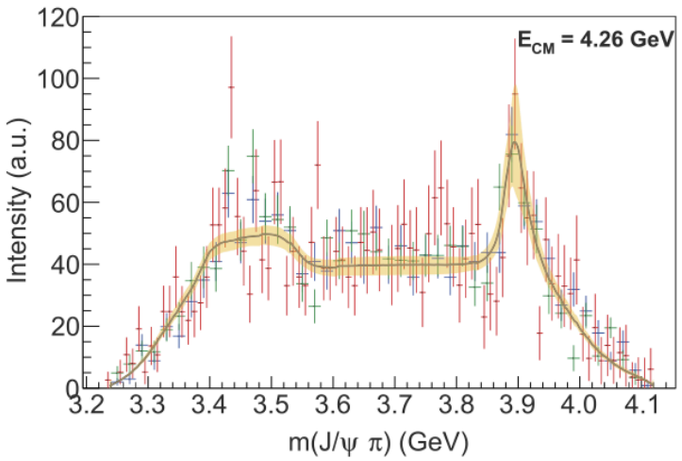
- Evidence for a similar structure was also seen in the neutral channel!
- Minimal quark content should be $c\bar{c}s\bar{q}$
- LHCb reports a $Z_{cs}(4000)$ in $B \to \phi(J/\psi K^+)$, but 10 times broader…
- Same state in two decays?

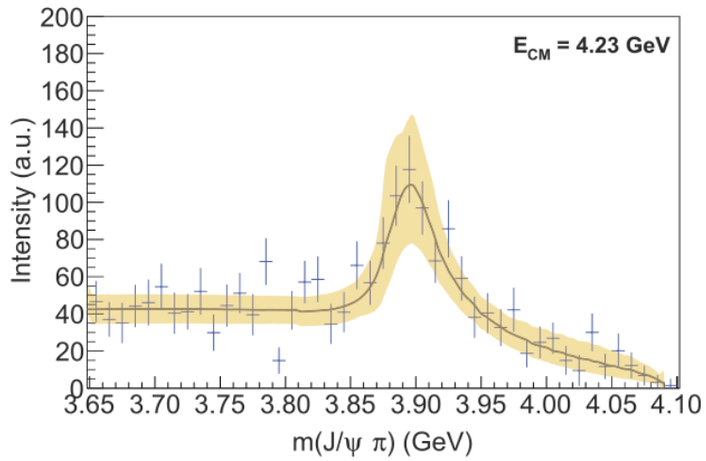
PRL 129, 112003 (2022)

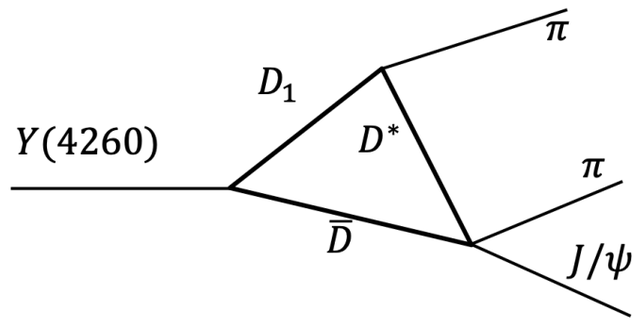
Data Driven Approaches

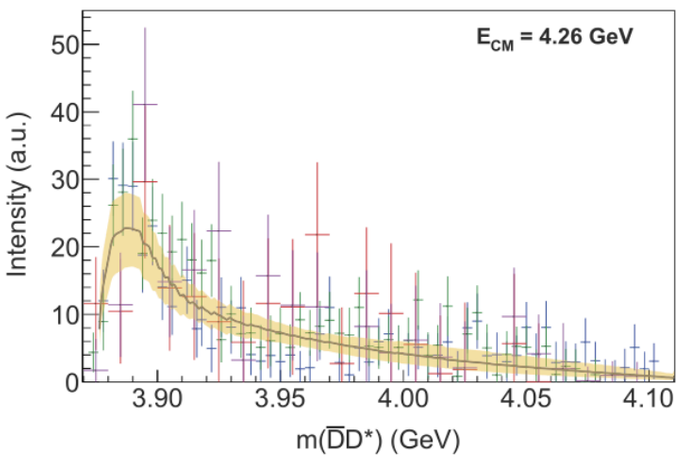
PLB 772, 200 (2017)

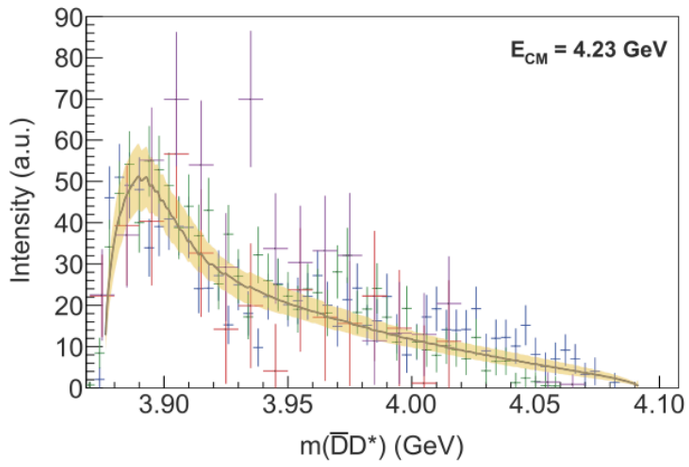
- Approach to interpret the collected spectra in a consistent way using sophisticated line shape descriptions
- Tried to describe the $Z_c(3900)$ either by a K-Matrix with one pole an two decay channels and/or a triangle singularity contribution











- Theory can not tell a signifikant difference with the current available data!
- Mass projections are not enough!
- Experiment and theory should work closer together!

X States at BESIII

- Neutral states that can not have $J^{PC} = 1^{--}$
- Usually seen close to open charm thresholds

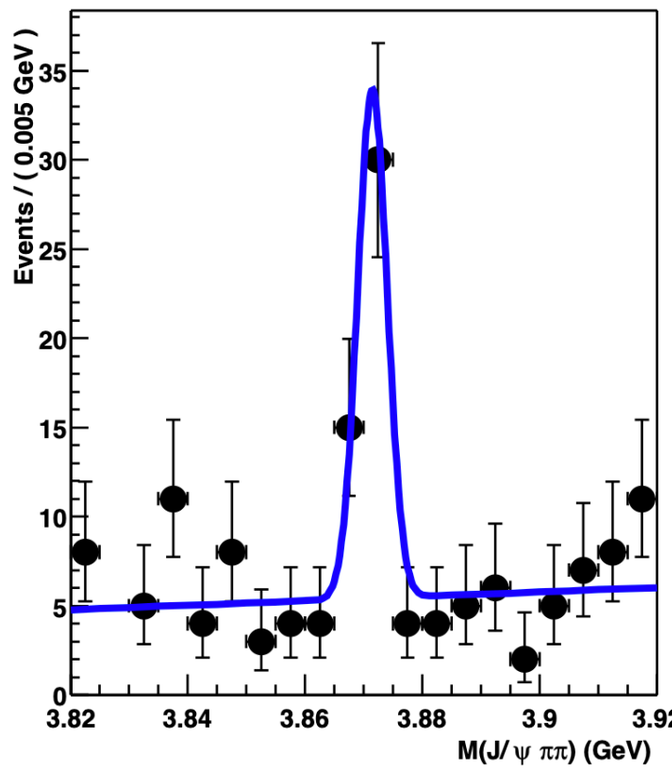
Historical review of the X(3872)

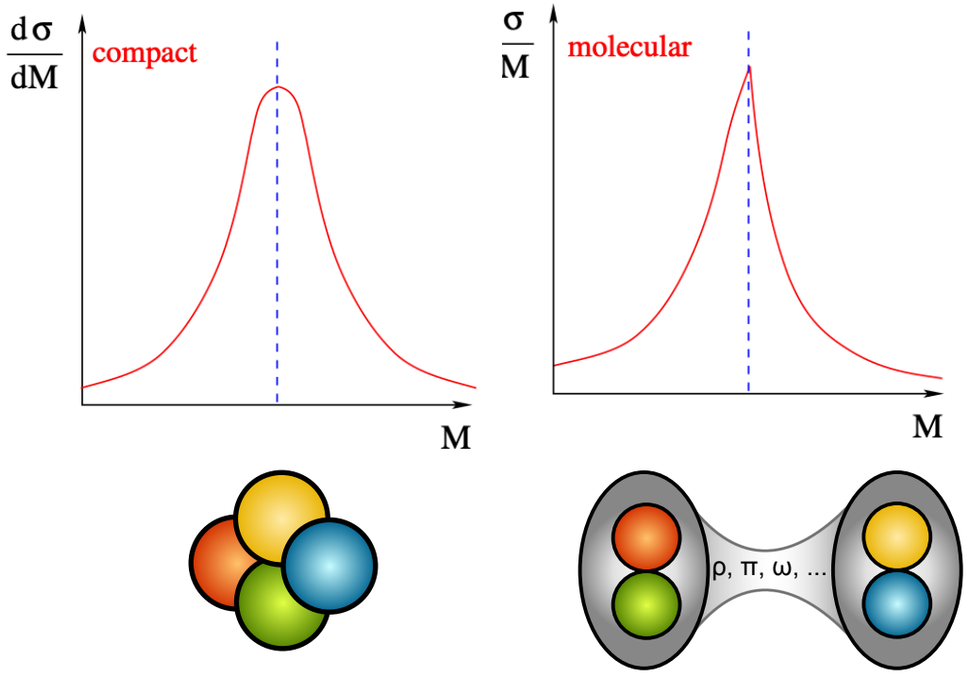
- First observed by Belle in 2003 in $X(3872) \to \pi^+\pi^- J/\psi$
- Very narrow, sitting just at the $D^0\bar{D}^{*0}$ threshold
- Quantum numbers determined to be $J^{PC} = 1^{++}$
  - ➡ now called $\chi_{c1}(3872)$
- Seen in various production channels by now: B/Λ_b decays, pp, PbPb, e^+e^-
- ... 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 PRD 108 (2023) 011103

$$\frac{g_{\chi_{c1}(3872)\to\rho^0 J/\psi}}{g_{\chi_{c1}(3872)\to\omega J/\psi}} = 0.29 \pm 0.04 \qquad \frac{g_{\psi(2S)\to\pi^0 J/\psi}}{g_{\psi(2S)\to\eta J/\psi}} = 0.045 \pm 0.001$$

- Large isospin violation is naturally expected in models with a significant $D\bar{D}^*$ component (either molecular or generated dynamically)

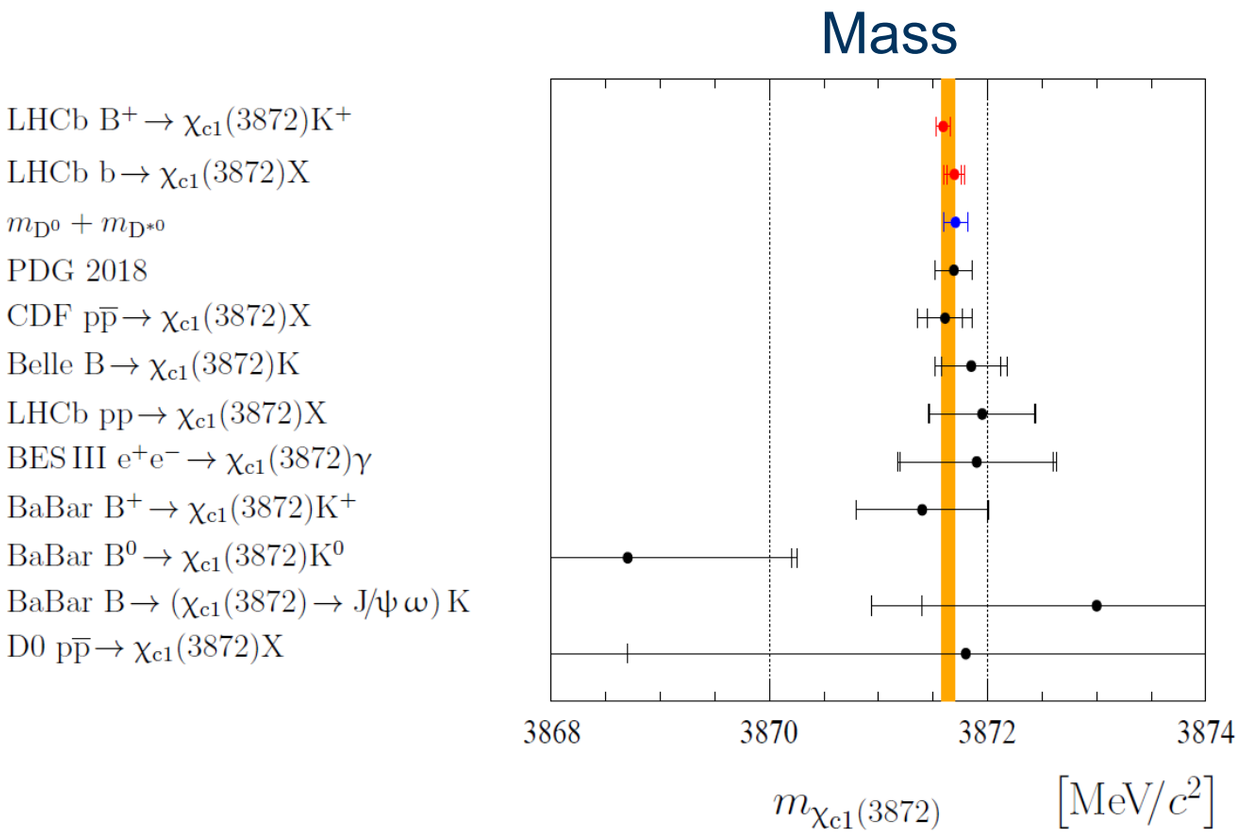
PRL 91, 262001 (2003)

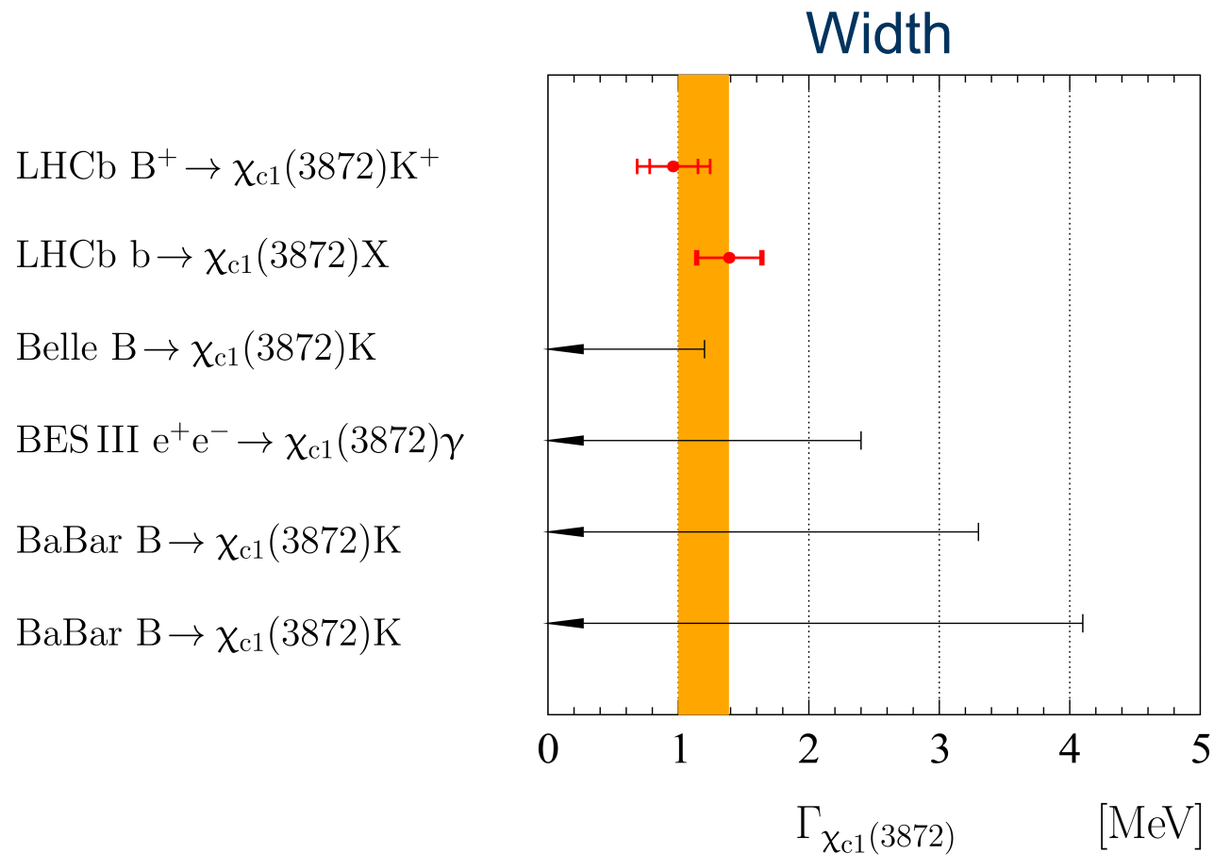




Historical review of the X(3872)

- Precision has increased a lot meanwhile
- But: still the state is compatible with the $D^0\bar{D}^{*0}$ threshold!



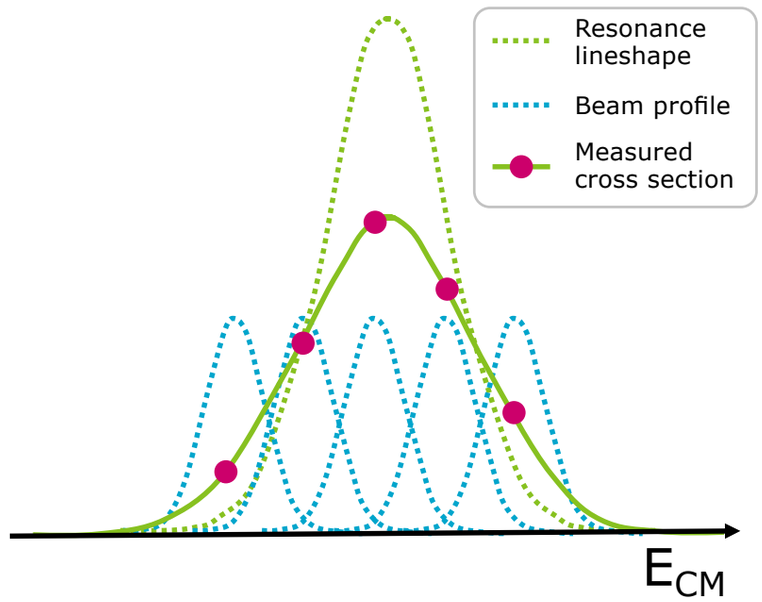


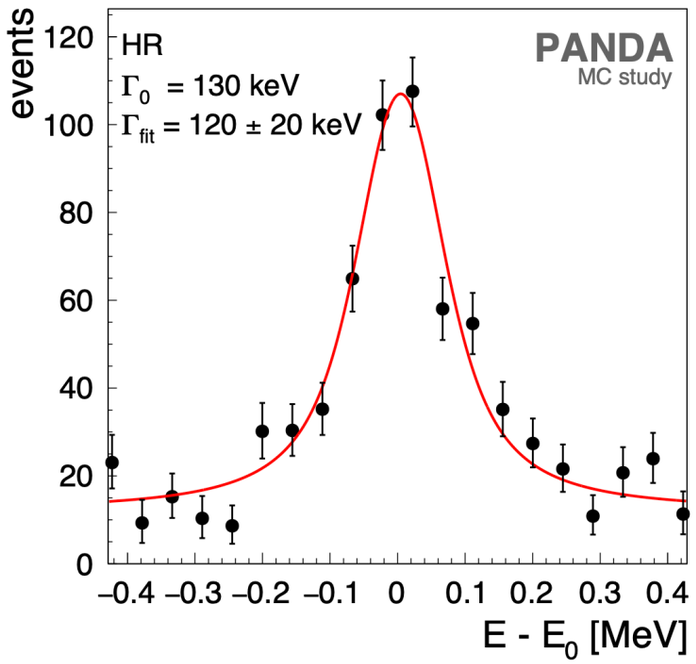
- If we want to clarify this we need << MeV resolution!

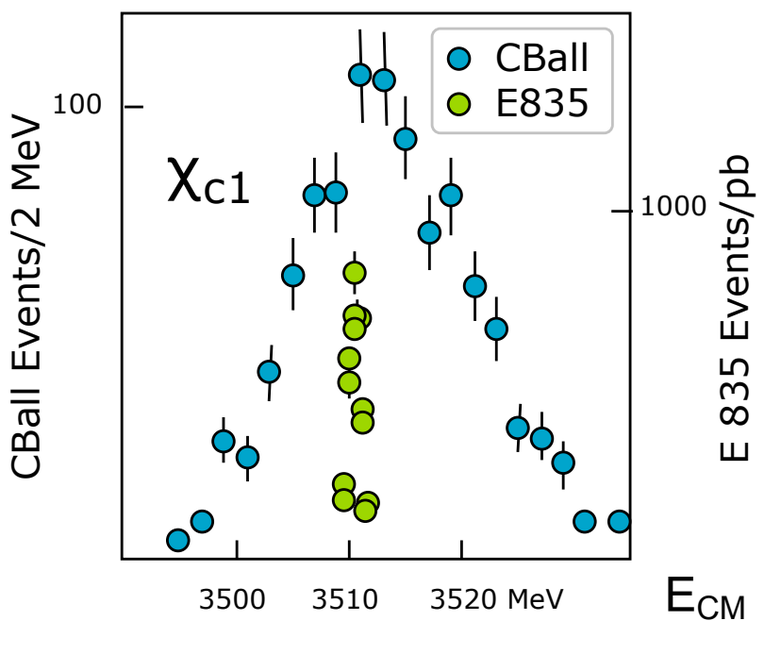
Line Shape Scans at $\bar{P}$ANDA

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

- Main idea: 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!
- Analysis performed for 20 energy points around nominal mass
- Sensitivity studies to distinguish the two scenarios
- ➡ It is possible to distinguish with more than 90% confidence for sizeable Flatté energies $\Delta E_f := |E_{f,0} - E_{f,th}| > 700$ keV
- ➡ With the $\bar{P}$ANDA setup this corresponds to only about a month of data taking!







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

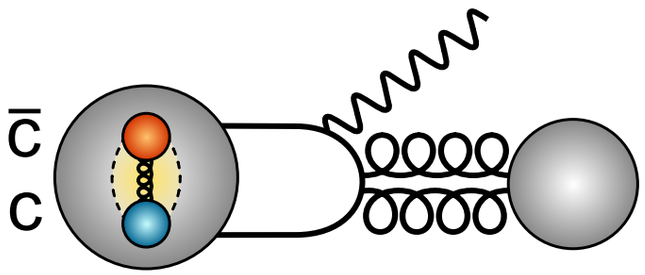
Design beam resolution:

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

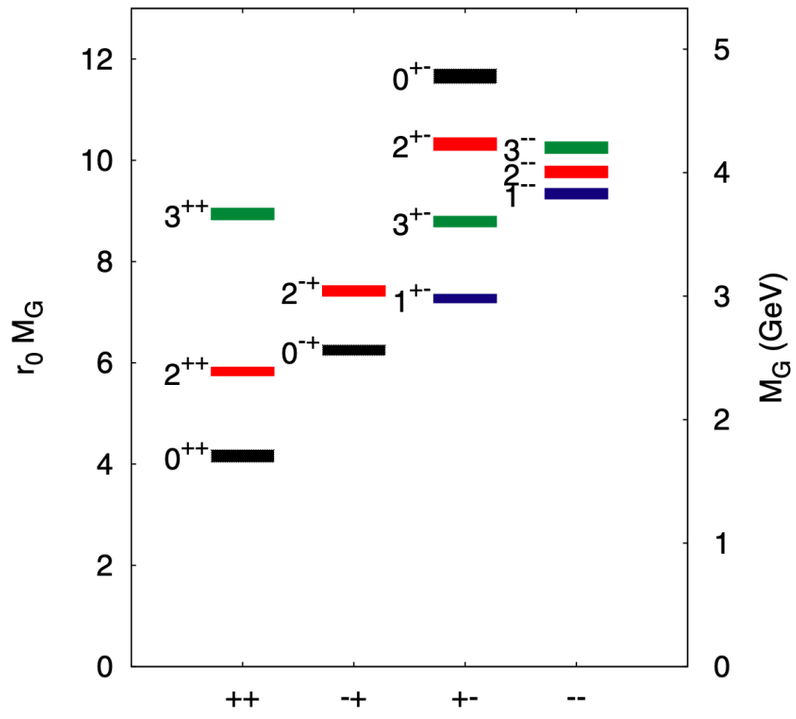
Light Meson Spectroscopy

Radiative J/ψ decays

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



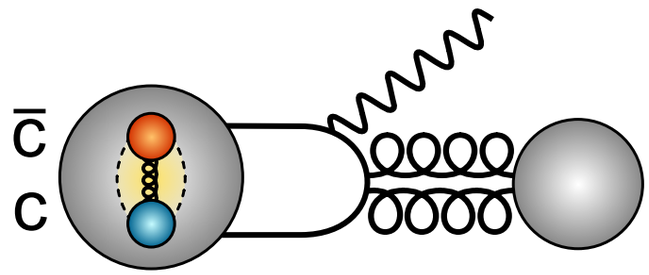
- ***Glueballs Candidates:***
  - Lightest glueball 0^{++} is predicted below $2\,\mathrm{GeV}/c^2$
  - Observed states $f_0(1370), f_0(1500), f_0(1710)$ likely to be mixtures of pure glueball and quark component
  - BESIII has accumulated very high statistics at J/ψ
    - ➡ 50 times more than 10 years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



Phys. Rev. D 73, 014516 (2006)

Radiative J/ψ decays

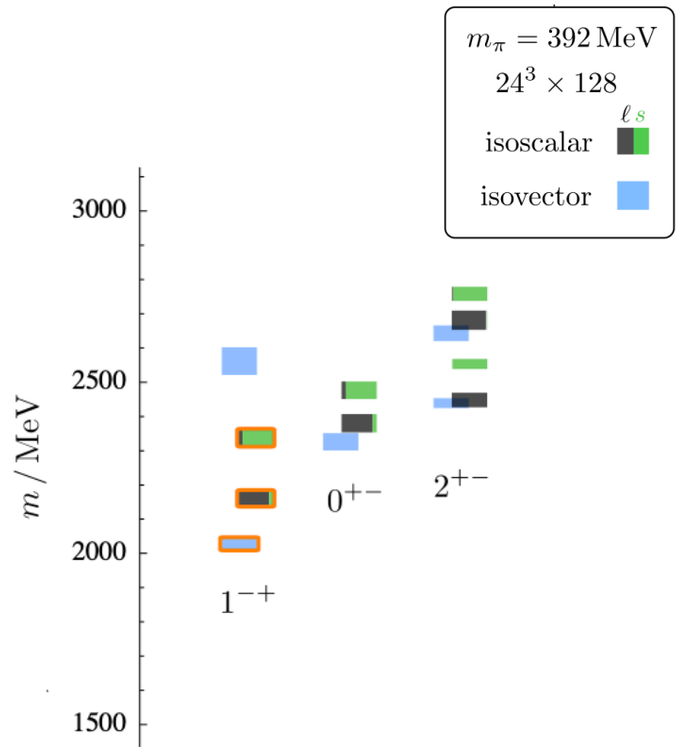
- Gluon-rich process ➡ production of glueballs and hybrids expected



- ***Hybrid Candidates:***
  - Lightest spin-exotic: predicted 1^{-+} around $2\,\mathrm{GeV}/c^2$
  - $\pi_1(1400)$ and $\pi_1(1600)$ recently described by 1 K-matrix pole

JPAC, PRL 122, 042002 (2019)
B. Kopf et. al., EPJC81, 1056 (2021)

  - More expected…

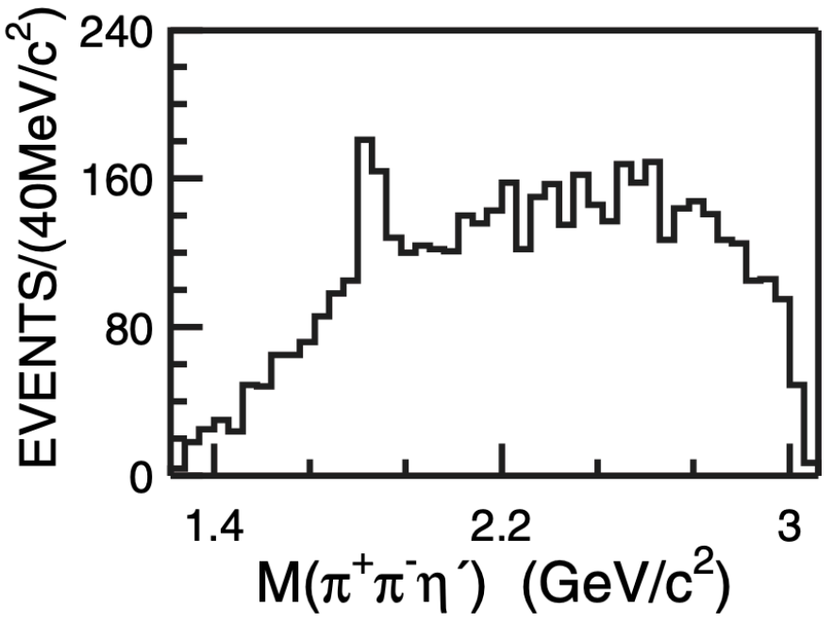


Phys. Rev. D 88, 094505 (2013)

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

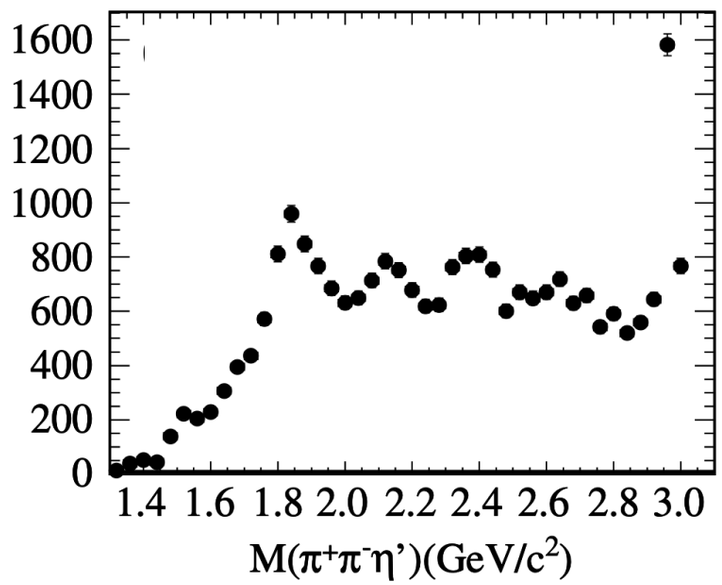
PRL 129, 042001 (2022)

58M J/ψ events



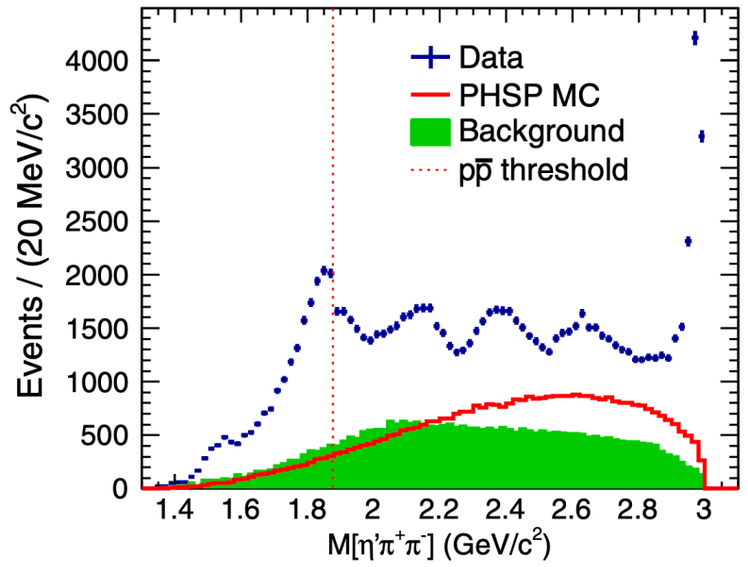
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

1090M J/ψ events

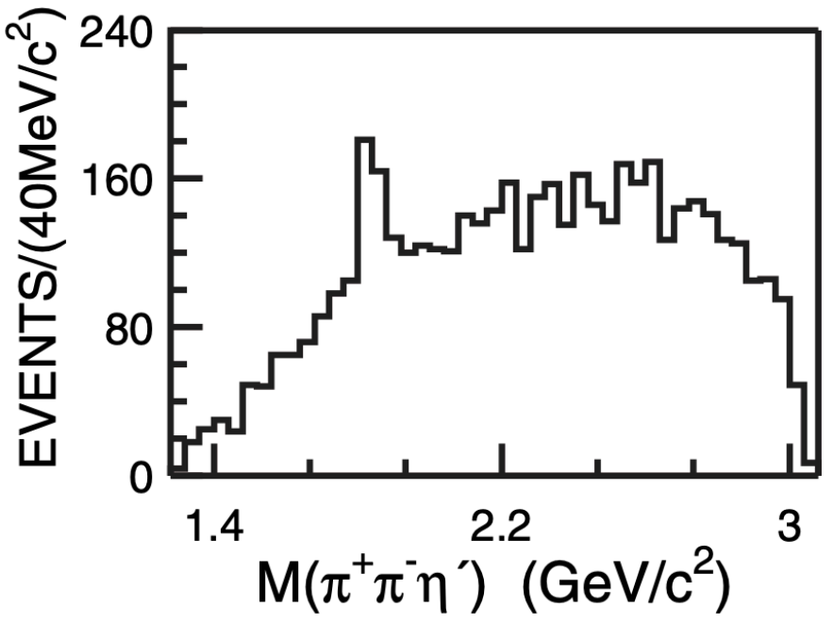


BESIII, PRL 117, 042002 (2016)

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

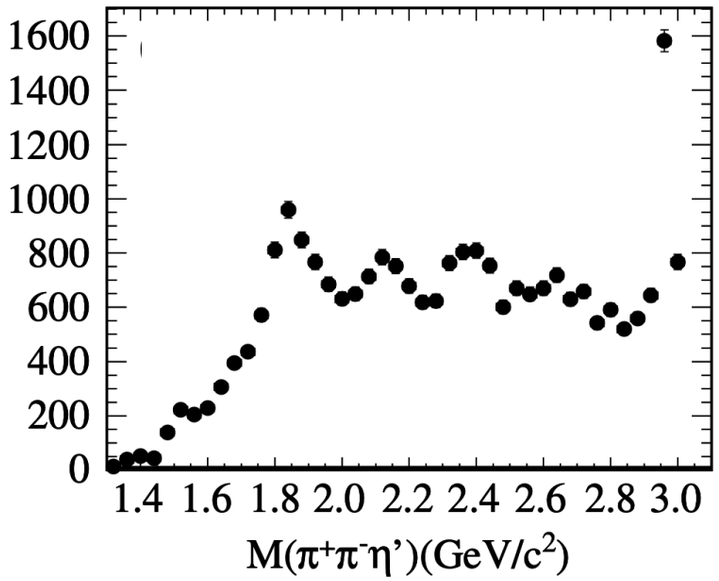
PRL 129, 042001 (2022)

58M J/ψ events



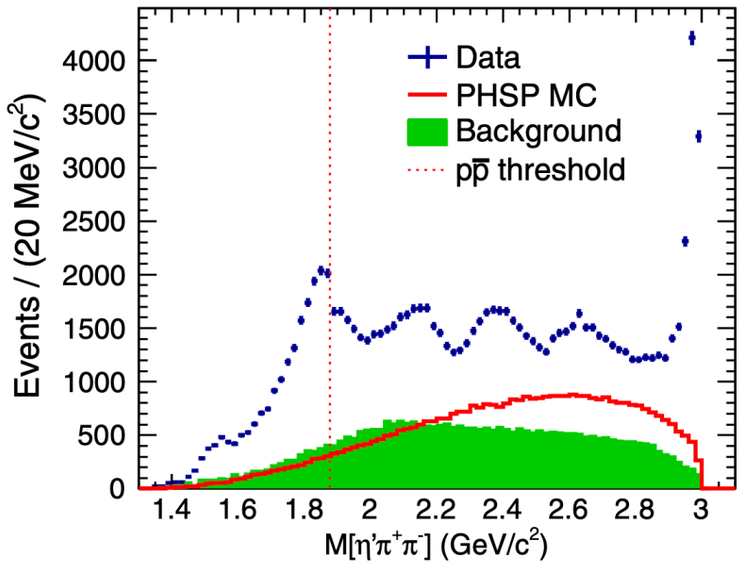
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

1090M J/ψ events



BESIII, PRL 117, 042002 (2016)

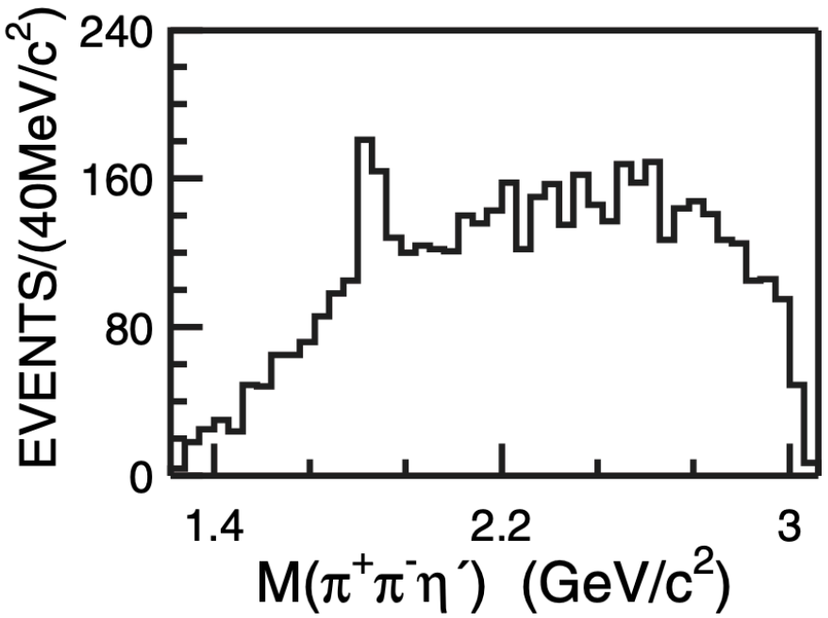
- Structure observed near $\bar{p}p$ threshold: $X(1835)$ and two additional states $X(2120)$ and $X(2370)$
- Line shape analysis finds equally good descriptions for Flatté and BW scenario…
  - Either a narrow state below threshold - bound state
  - Or a broad state with strong coupling above threshold - molecular structure
- Also seen in Dalitz decay $J/\psi \to e^+e^-\eta'\pi^+\pi^-$ and other decay modes:
  - $J/\psi \to \gamma 3(\pi^+\pi^-)$ BESIII, PRD 88 (2013) 091502
  - $J/\psi \to \gamma\eta K_S^0 K_S^0$ BESIII, PRL 115 (2015) 091803
  - $J/\psi \to \gamma\gamma\phi$ BESIII, PRD 97 (2018) 051101

- Seem to indicate non-negligible $s\bar{s}$ component
- ➡ Second radial excitation of η' ?

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

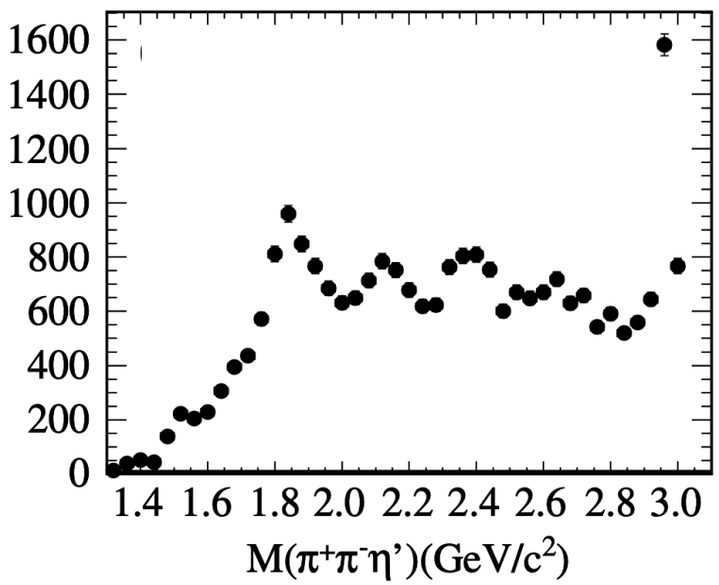
PRL 129, 042001 (2022)

58M J/ψ events



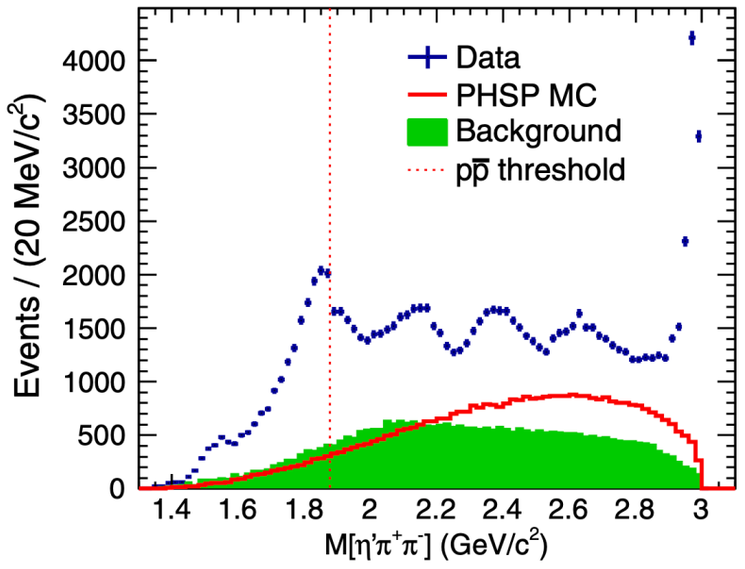
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

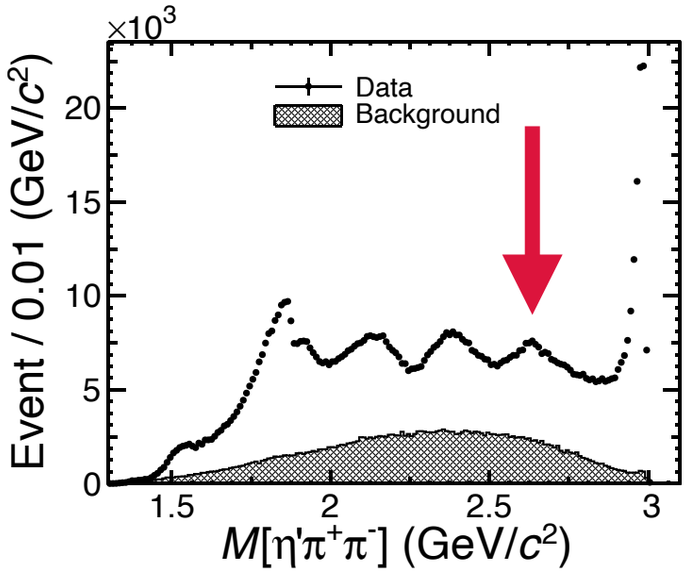
1090M J/ψ events



BESIII, PRL 117, 042002 (2016)

New Structure observed!

X(2600)



BESIII, PRL 129, 042001 (2022)

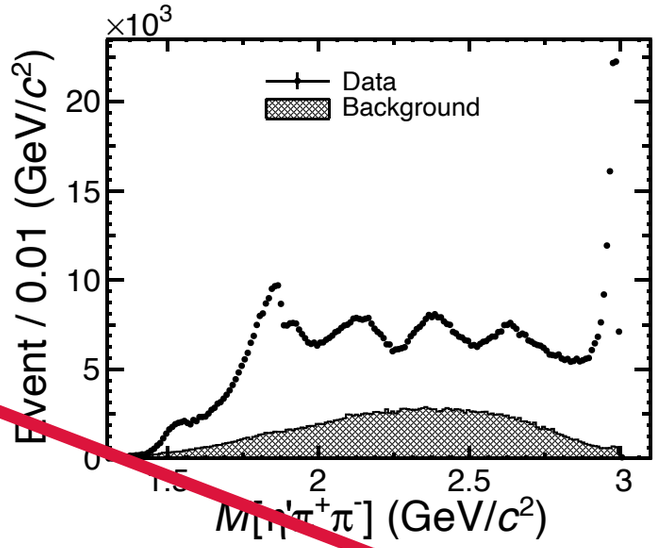
10B J/ψ events

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

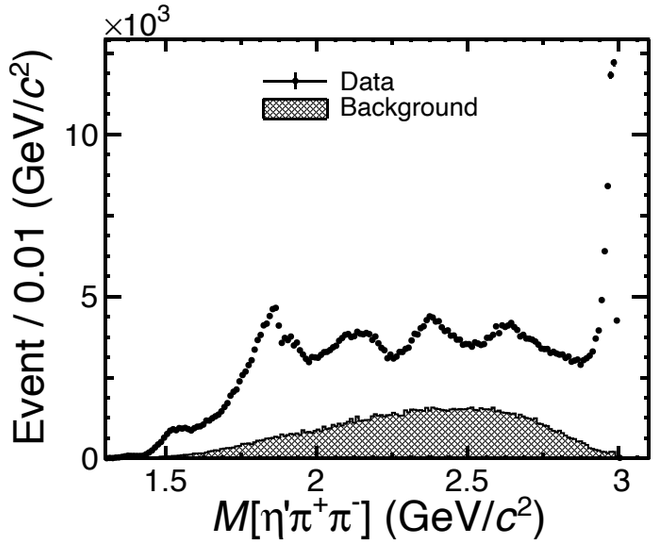
PRL 129, 042001 (2022)

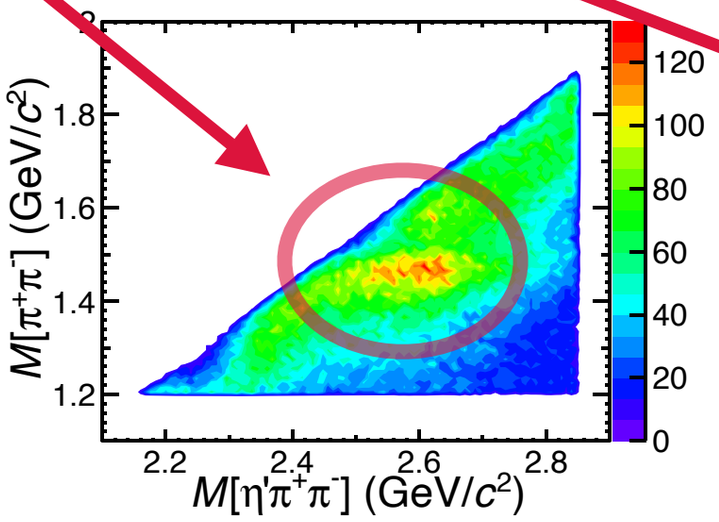
- Likely connected to a non trivial structure at $1500\,\mathrm{MeV}/c^2$ in $\pi^+\pi^-$ system

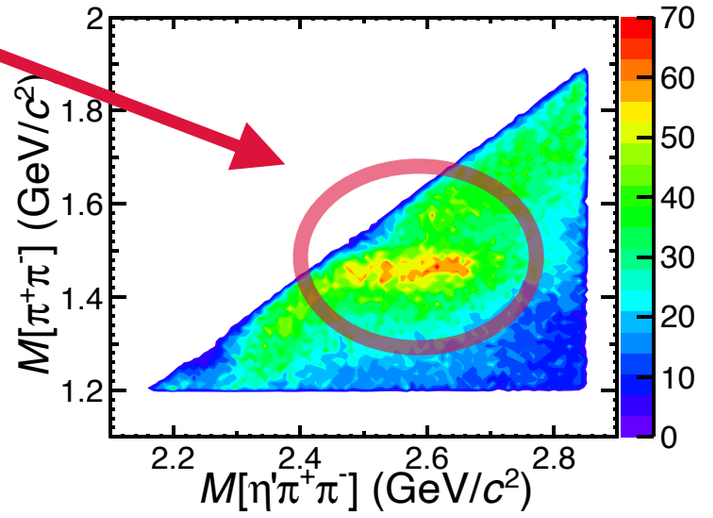
$\eta' \to \gamma\pi^+\pi^-$



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







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

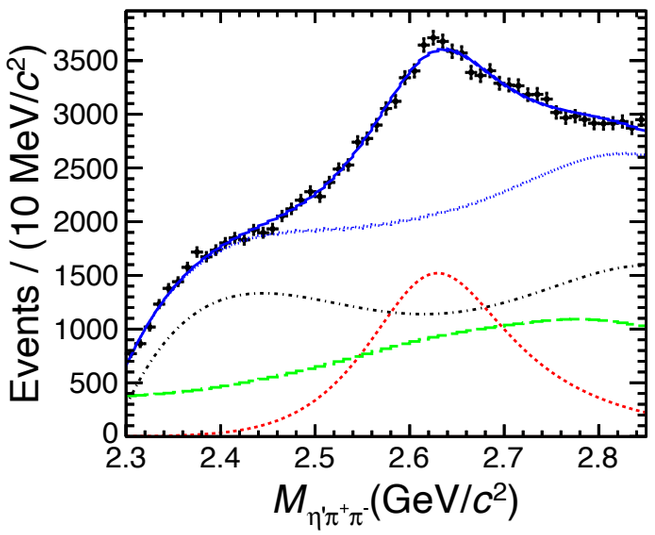
PRL 129, 042001 (2022)

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

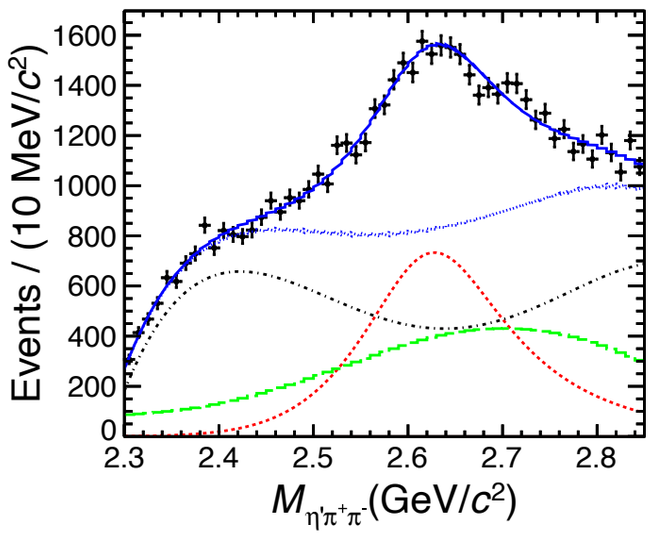
Resonance	Mass (MeV/c^2)	Width (MeV)
$f_0(1500)$	$1492.5 \pm 3.6^{+2.4}_{-20.5}$	$107 \pm 9^{+21}_{-7}$
$X(1540)$	$1540.2 \pm 7.0^{+36.3}_{-6.1}$	$157 \pm 19^{+11}_{-77}$
$X(2600)$	$2618.3 \pm 2.0^{+16.3}_{-1.4}$	$195 \pm 5^{+26}_{-17}$

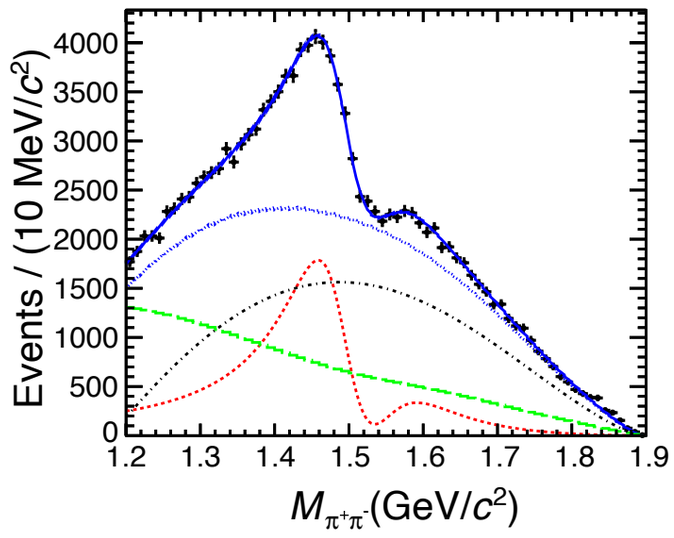
- Further studies ongoing
- Full PWA needed to determine QN and disentangle states

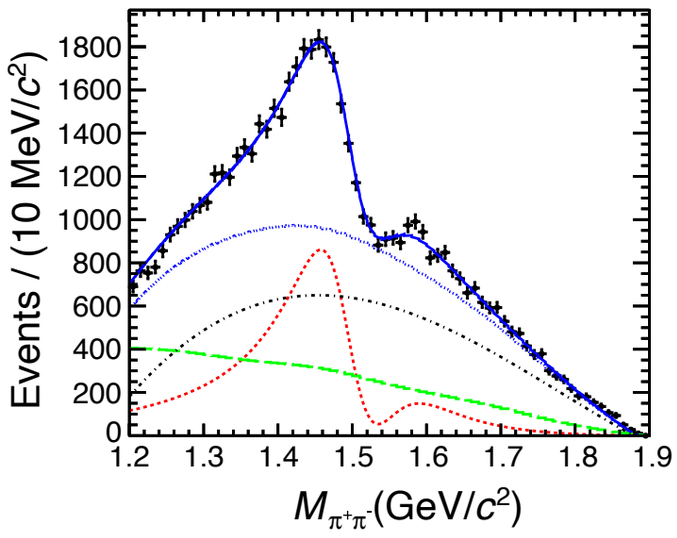
$\eta' \to \gamma\pi^+\pi^-$



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







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

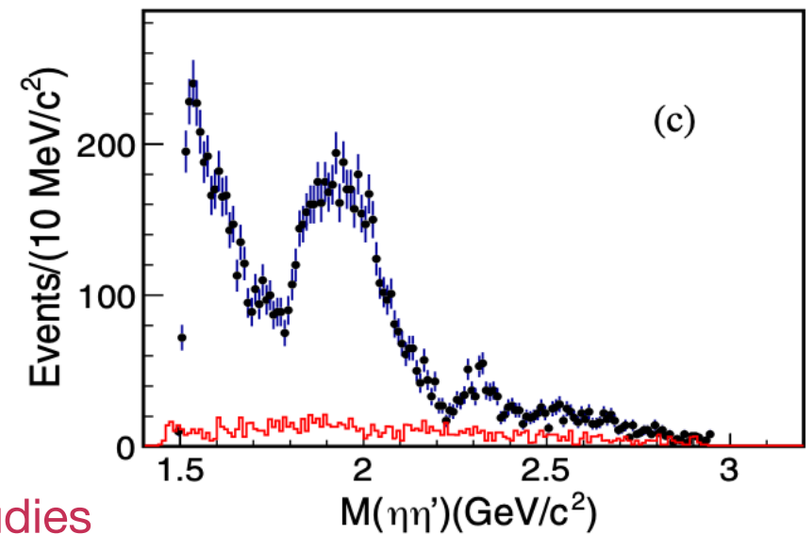
PRL 129, 19, 192002 (2022)
PRD 106, 7, 072012 (2022)

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

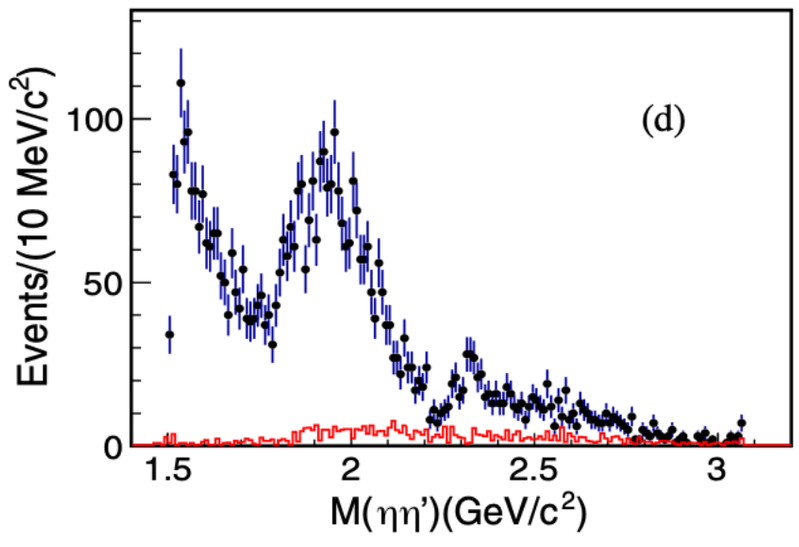
fixed… floated for syst. studies

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

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

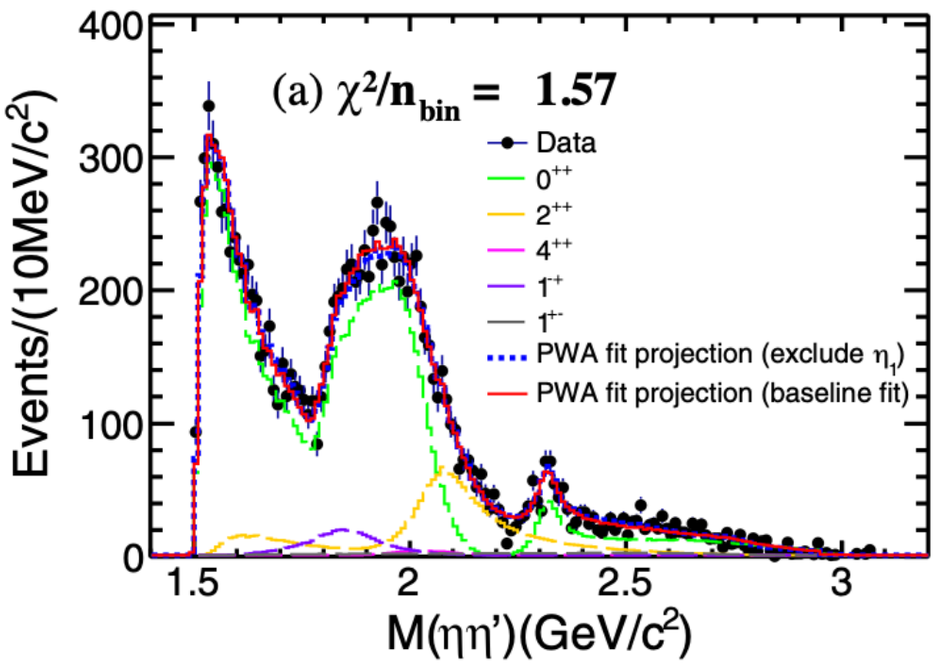


$\eta' \to \eta\pi^+\pi^-$

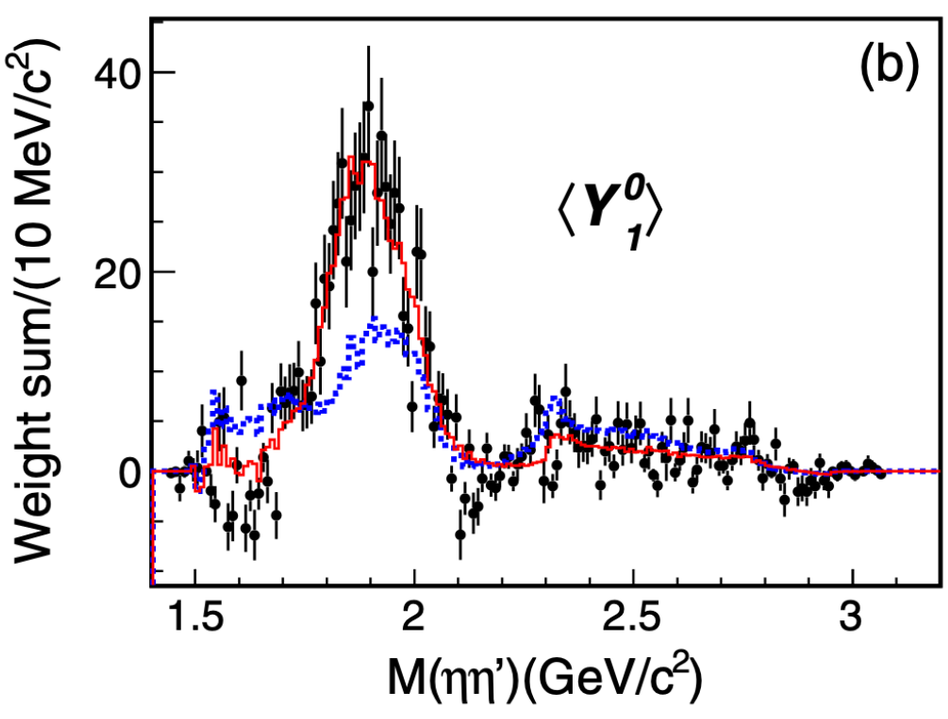


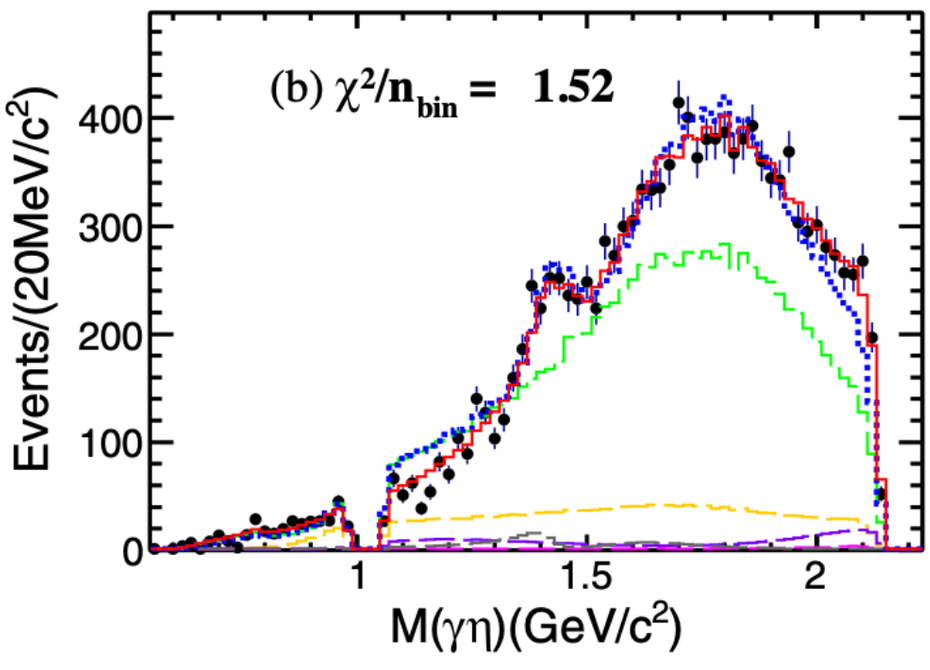
$J/\psi \to \gamma\eta'\eta$

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



- Additionally need of a spin exotic contribution found!
  ➡ $\eta_1(1855)$
- $M = (1855 \pm 9^{+6}_{-1})\,\mathrm{MeV}/c^2, \Gamma = (199 \pm 18^{+3}_{-8})\,\mathrm{MeV}$
- May be the isoscalar partner of the $\pi_1(1600)$
- Further studies needed!
- Additional decay channels need to be investigated to improve the PWA model
- Theory predicts a strong coupling to K_1K, the final state $J/\psi \to \gamma\pi\pi KK$ was not investigated since 2000



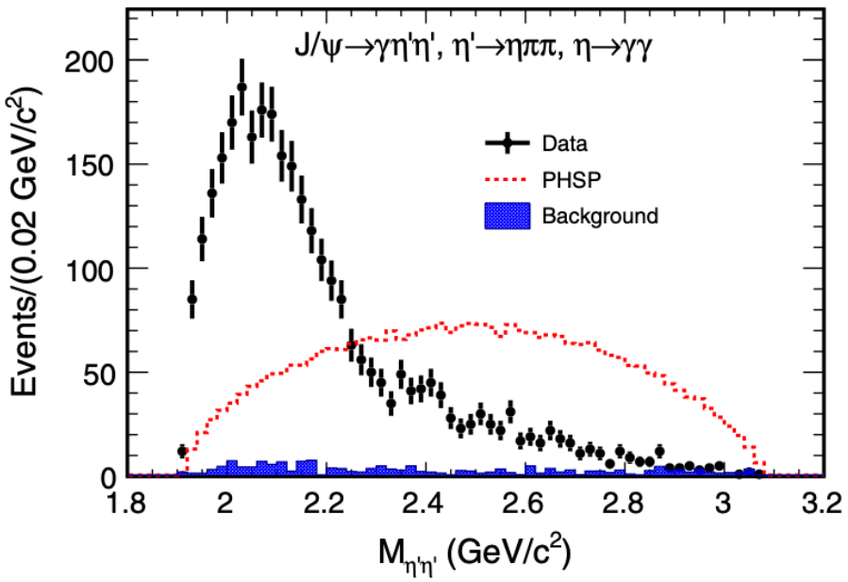


$J/\psi \to \gamma\eta'\eta'$

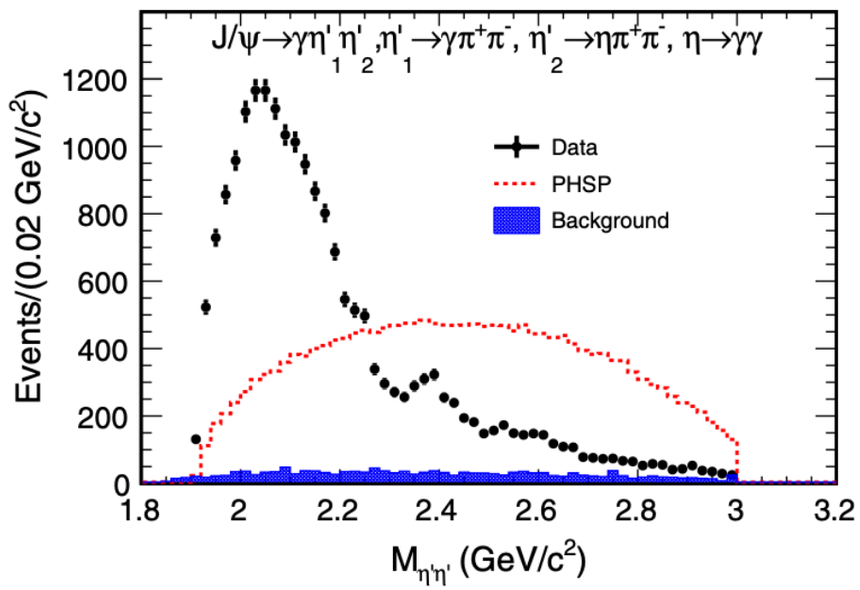
PRD 105, 072002 (2022)

- PWA of $J/\psi \to \gamma\eta'\eta'$ using 10 Billion J/ψ events
- All kinematically allowed resonances as listed in the PDG considered
  - $J^{PC} = 0^{++}, 2^{++}$ and 4^{++} ($\eta'\eta'$ system)
  - $J^{PC} = 1^{+-}$ and 1^{--} ($\gamma\eta'$ system)
  - $f_0(2020)$ described with Flatté, all others with BW…

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



$\eta_1' \to \gamma\pi^+\pi^- \quad \eta_2' \to \eta\pi^+\pi^-$



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

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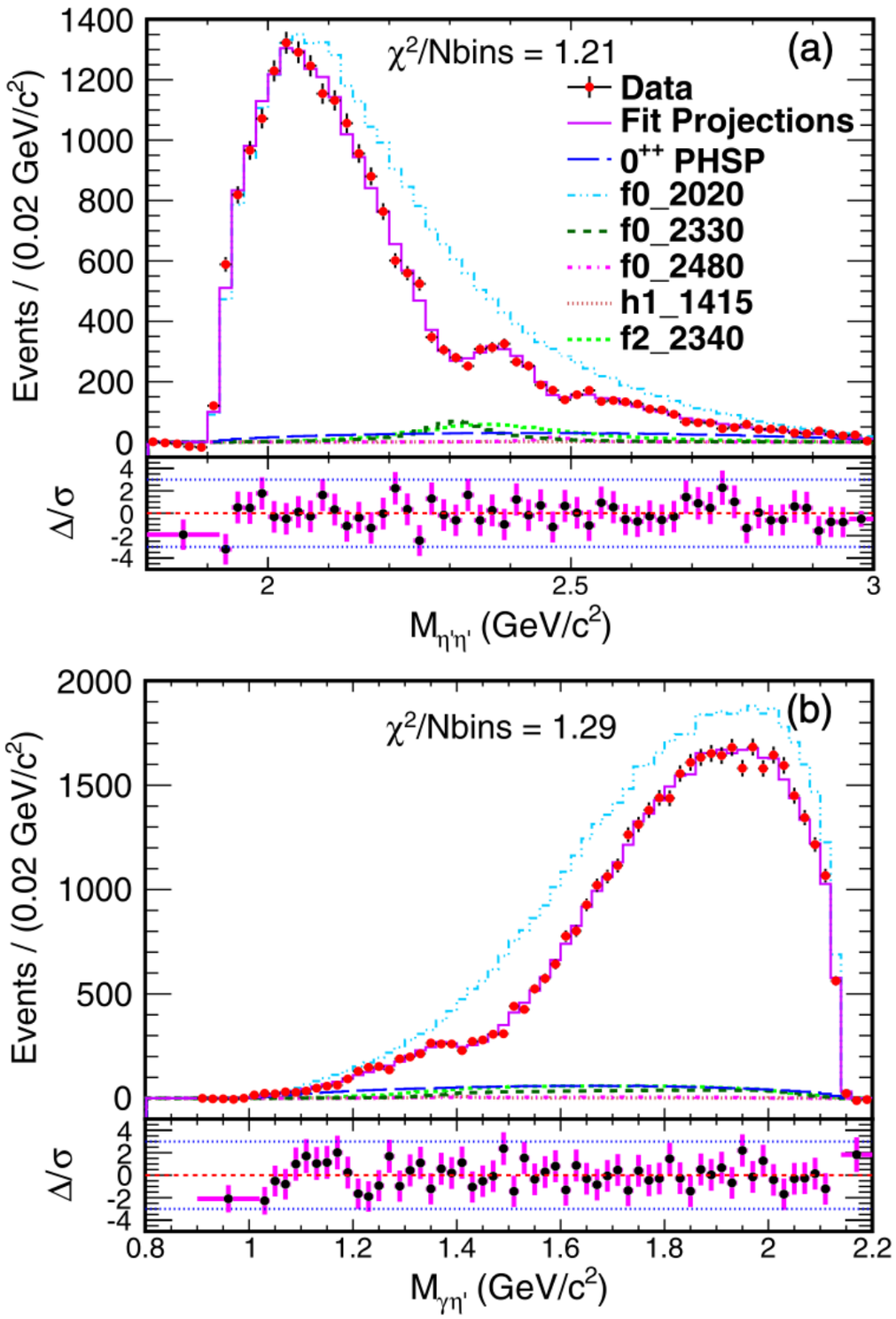
- PWA of $J/\psi \to \gamma\eta'\eta'$ using 10 Billion J/ψ events
- All kinematically allowed resonances as listed in the PDG considered
  - $J^{PC} = 0^{++}, 2^{++}$ and 4^{++} ($\eta'\eta'$ system)
  - $J^{PC} = 1^{+-}$ and 1^{--} ($\gamma\eta'$ system)
  - $f_0(2020)$ described with Flatté, all others with BW…

Resonance	M(MeV/c^2)	Γ(MeV)	B.F.
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$	$(8.18 \pm 1.77^{+3.73}_{-2.23}) \times 10^{-7}$
$h_1(1415)$	$1384 \pm 6^{+9}_{-0}$	$66 \pm 10^{+12}_{-10}$	$(4.69 \pm 0.80^{+0.74}_{-1.82}) \times 10^{-7}$
$f_2(2340)$	$2346 \pm 8^{+22}_{-6}$	$332 \pm 14^{+26}_{-12}$	$(8.67 \pm 0.70^{+0.61}_{-1.67}) \times 10^{-6}$
0^{++} PHSP	···	···	$(1.17 \pm 0.23^{+4.09}_{-0.70}) \times 10^{-5}$

- $f_0(2020), f_0(2330)$ and $f_2(2340)$ observed in the $\eta'\eta'$ decay mode for the first time
- Possible new 0^{++} state $f_0(2480)$ with:

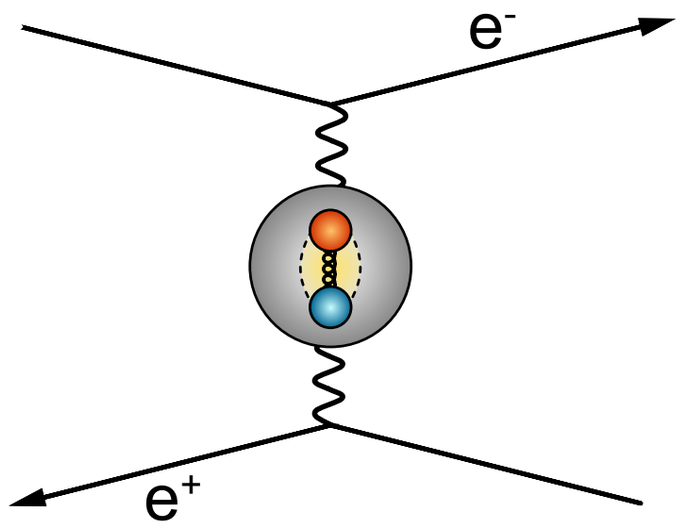
$M = 2470 \pm 4^{+4}_{-6}\,\mathrm{MeV}/c^2$ and $\Gamma = (75 \pm 9^{+11}_{-8})\,\mathrm{MeV}$

needed to describe the data



Two-Photon Reactions

- Two photon widths ➡ information about inner structure of resonances!
- Complementary information on glueball candidates!



***Untagged reactions*:**

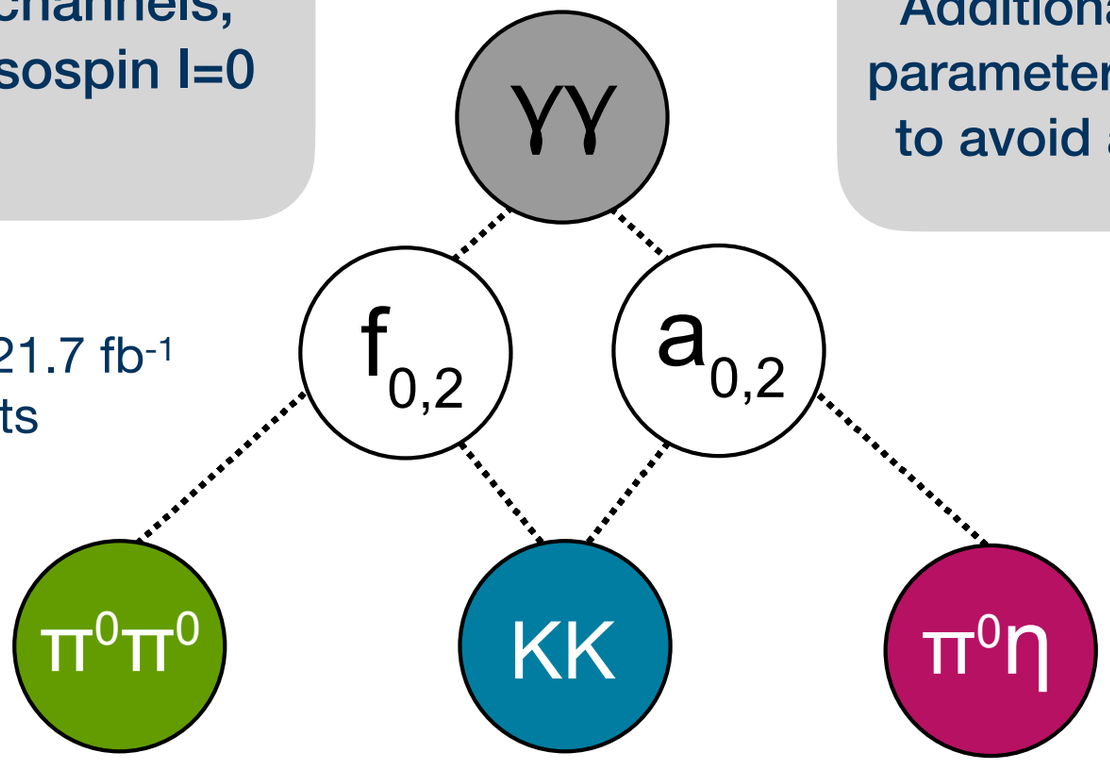
- Scattering angles of electron and positron are small and are not detectable
- Quasi real photons carrying small virtuality ➡ spin 1 strongly suppressed
- All resonances with quantum numbers $0^{\pm+}, 2^{\pm+}, \ldots$ can be directly produced

Coupled Channel Analysis of Two-Photon Data

By combining these channels, one can disentangle Isospin I=0 and I=1

Additional constraints by shared parameters between channels help to avoid ambiguous descriptions

Using data samples of 21.7 fb^{-1} at 28 energy points



- Described using the K-Matrix formalism in the P-vector approach
- Sophisticated Parametereization used for the decay side based on analysis of:
  - $\bar{p}p \to \pi^0\pi^0\eta, \pi^0\eta\eta$ and $K^+K^-\pi^0$ data from Crystal Barrel
  - $\pi\pi$ scattering data and $\pi^- p \to \pi^-\eta^{(\prime)}\pi$ data

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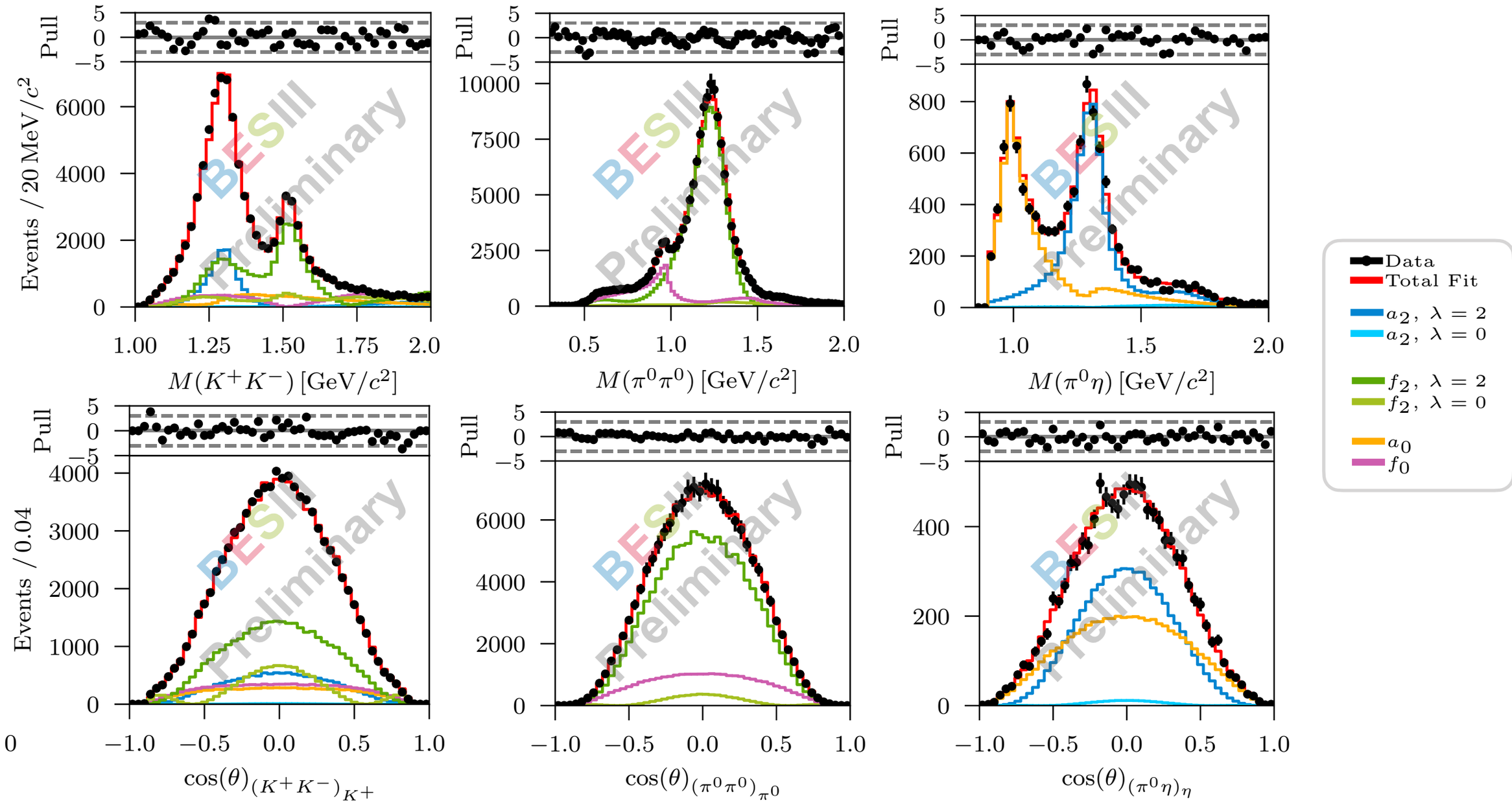
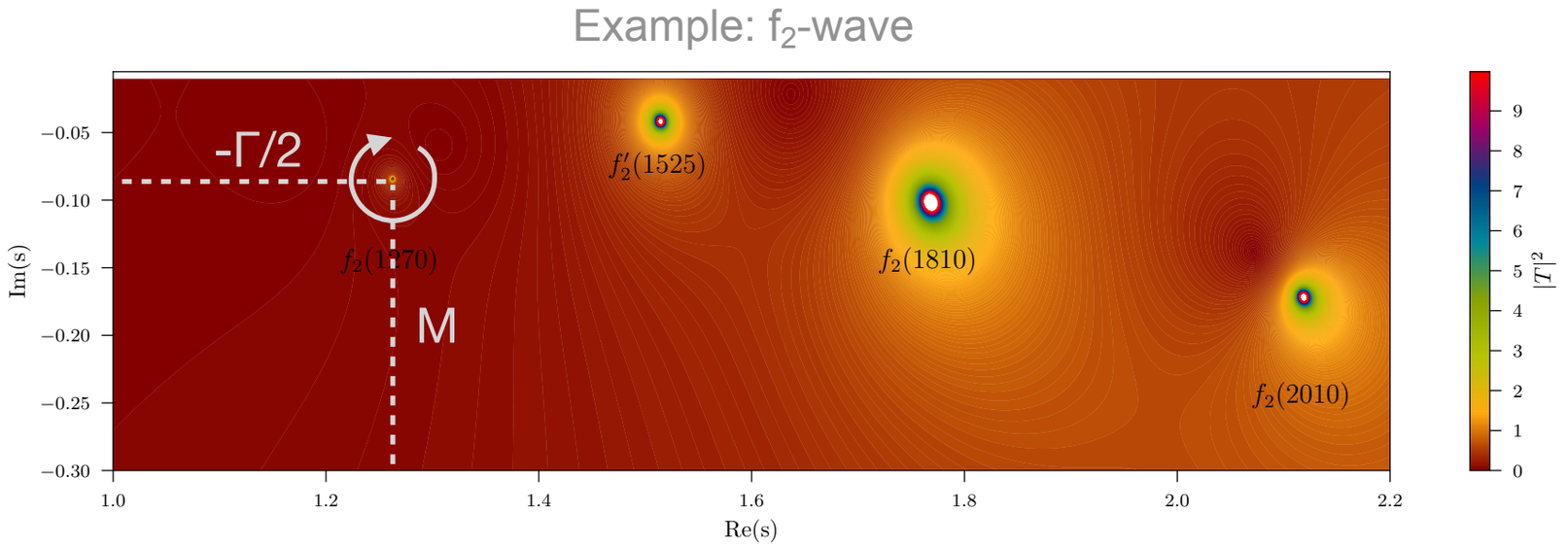
Coupled Channel Analysis of Two-Photon Data

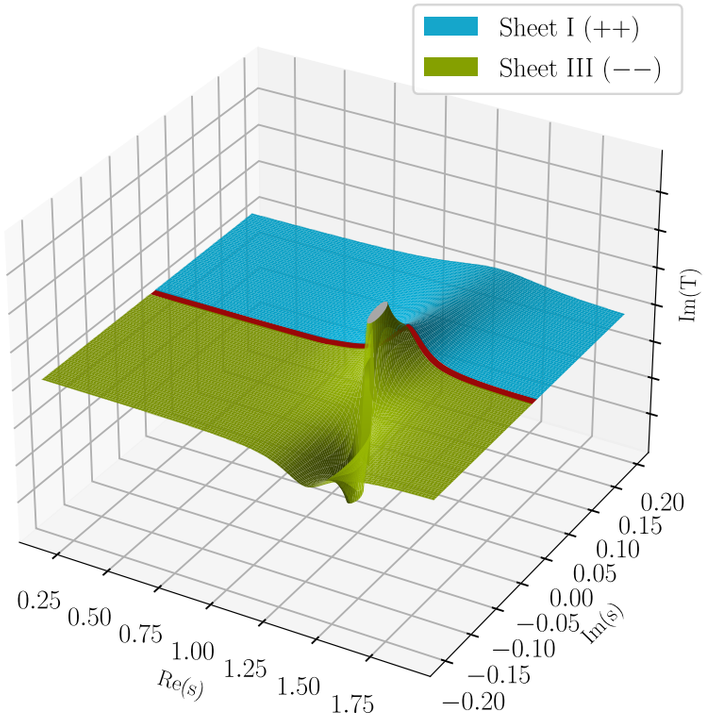
- Using obtained parameterization and fix all pole and decay parameters
- All structures can be well described
- Dominant contribution of $(J,\lambda) = (2,2), (0,0)$
- Best fit result using all 14 resonances and P-vector background terms: 1. order for f_2, a_2, a_0 -waves



Extraction of Resonance Properties

- K-matrix and thus the pole itself contains 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





example for 2 channel case

- Partial decay widths can be extracted via the residues:

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

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

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

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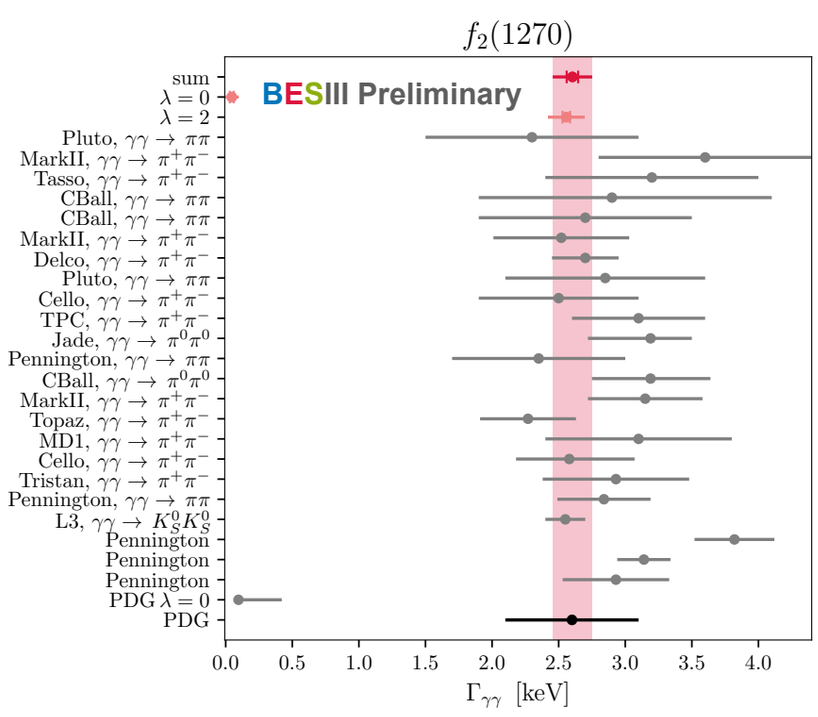
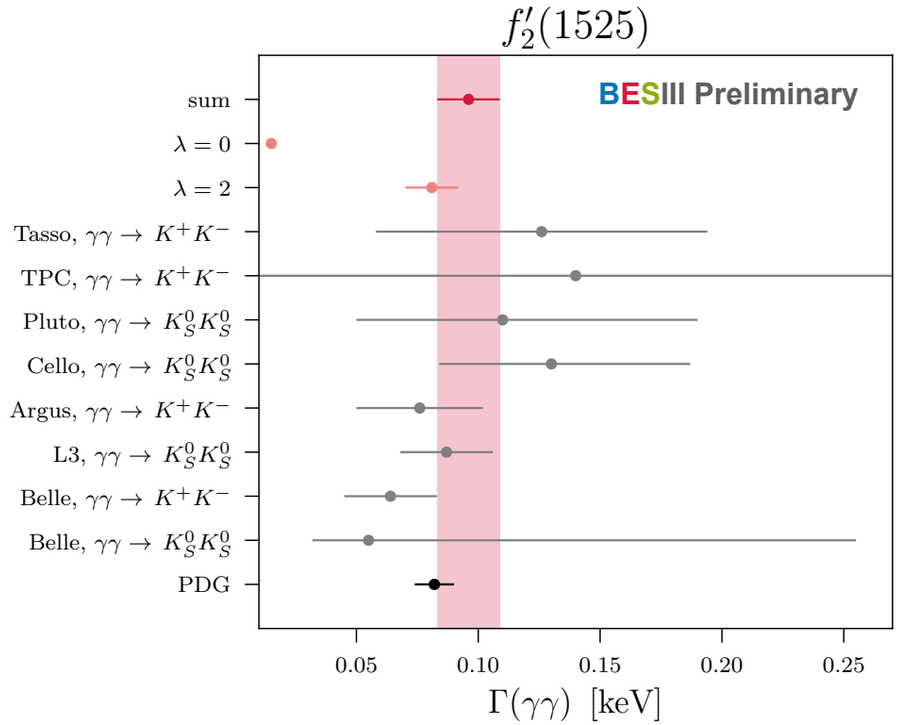
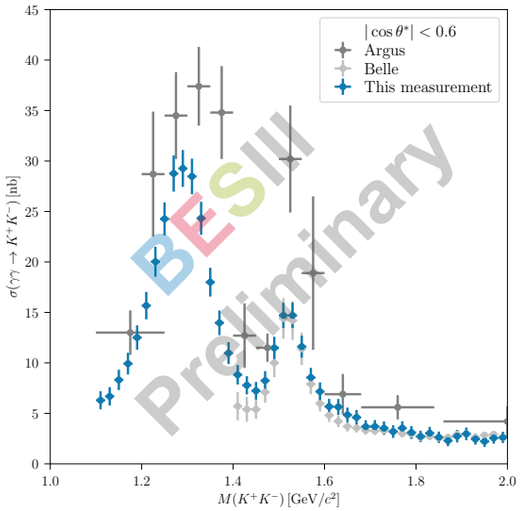


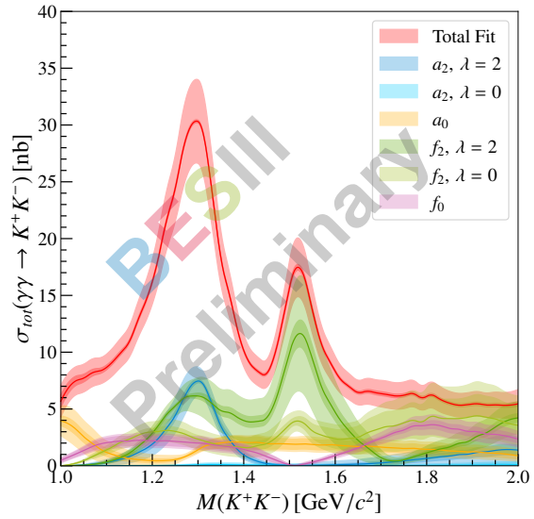


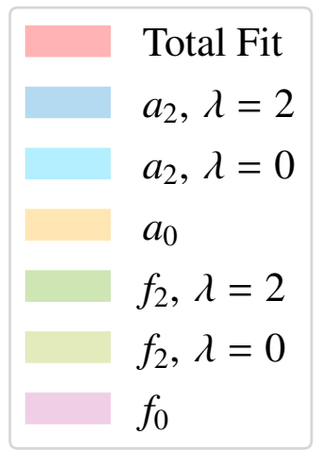
- First determination of the helicity contributions for the $f_2'(1525)$
- Most accurate measurement for $f_2(1270)$ and $a_2(1320)$
- Scalar mesons $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ measured for the first time

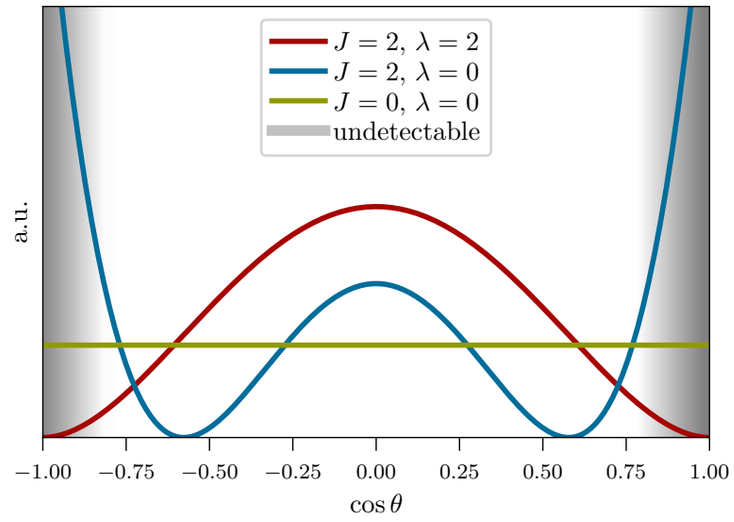
Determination of the Total Cross Section

K^+K^-



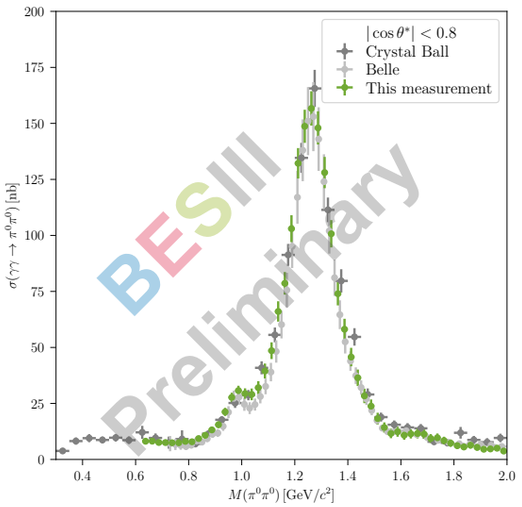


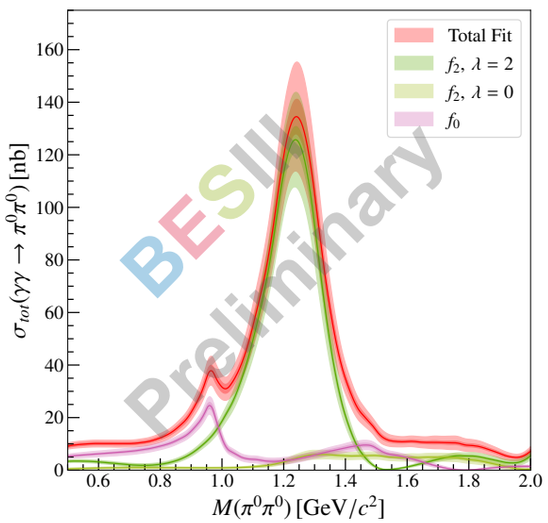




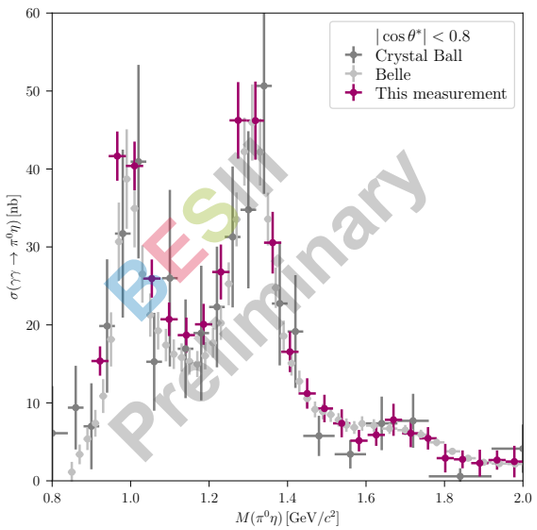
inner band statistical uncertainty, outer systematical

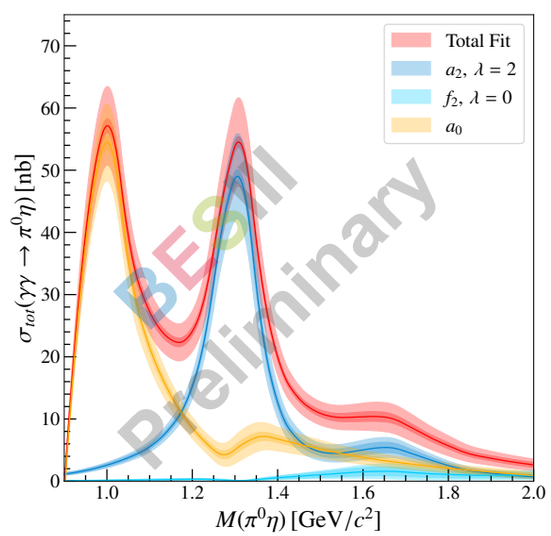
$\pi^0\pi^0$





$\pi^0\eta$





- Cross section in good agreement with previous measurements, where comparable
- First measurement of the lower K^+K^-mass region
- ➡ Furthermore: Extrapolation to the full angular range using the PWA result

Summary and Perspectives

- BESIII has accumulated world leading statistics in the charmonium region
- Especially J/ψ decays provide an excellent laboratory to study light hadron decays
- Recently many indications for new states
  - $\eta_1(1855)$ in $J/\psi \to \gamma\eta'\eta$
  - $X(2600)$ in $J/\psi \to \gamma\eta'\pi^+\pi^-$
  - $f_0(2480)$ in $J/\psi \to \gamma\eta'\eta'$
  - $Z_{cs}(3985)$
  - $Y(4660)$
  - $Y(4710)$
  - $Y(4500)$
  - Of course more investigations necessary
  - Especially more sophisticated PWA analyses and additional decay channels needed to pin down the QN and properties
- Coupled channel PWA of two-photon data is the first of its kind and adds hopefully infos to the inner structure of the light 0^{++} candidates

Further promising analyses ongoing!

- Further upgrades planned:
  - $\sqrt{s} = 4.9 \Rightarrow 5.6\,\mathrm{GeV}$
  - Luminosity increase of factor 3 ➡ BEPCII-U planned for the next year
  - Inner MDC exchanged by CGEM

May 9, 2023:
500th paper submitted!

79 during 2022 (record!) already 60+ during this year

Thank you!

Taken from Symmetry Magazine