17th of October

Recent Results on Hadron Spectroscopy at BESIII

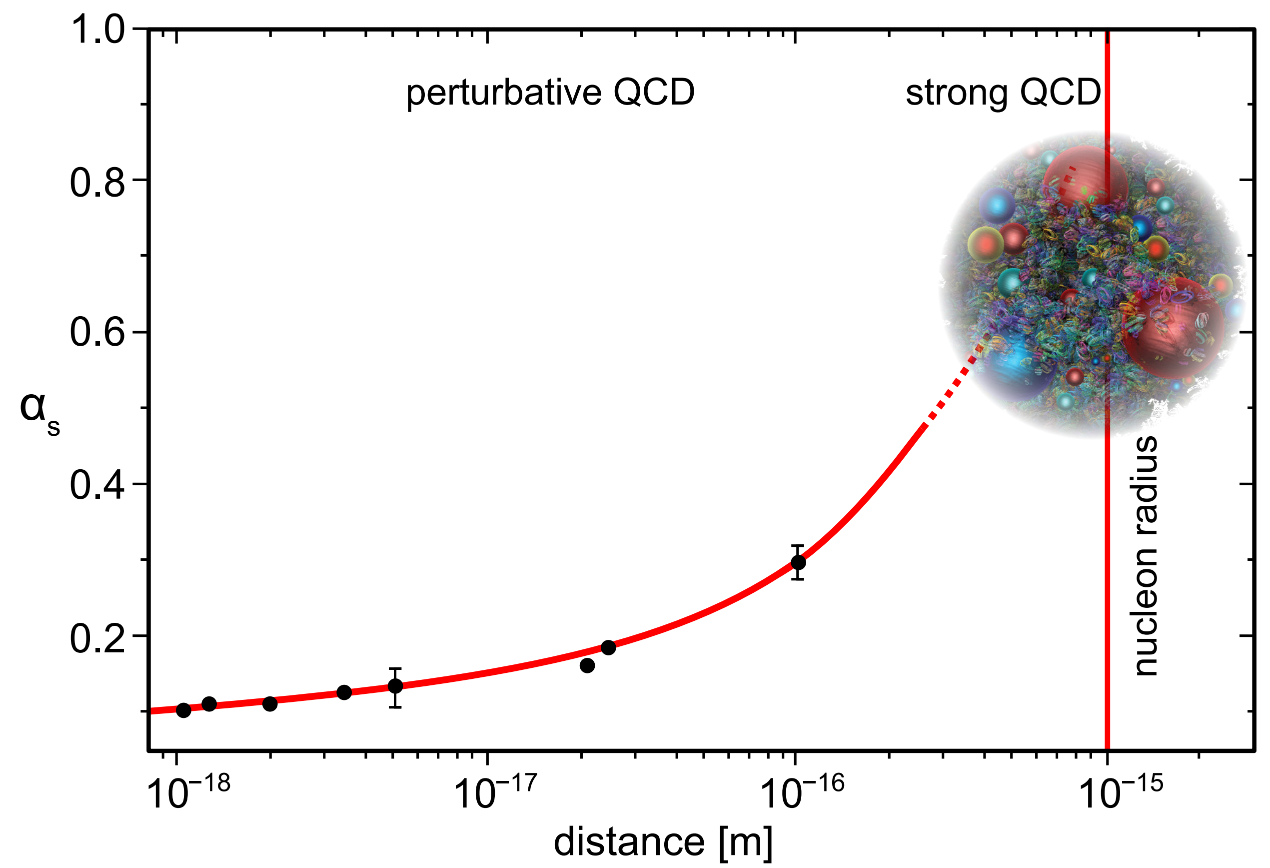
Meike Küßner

Institut für Experimental Physik I – Ruhr-Universität Bochum

On behalf of the BESIII collaboration

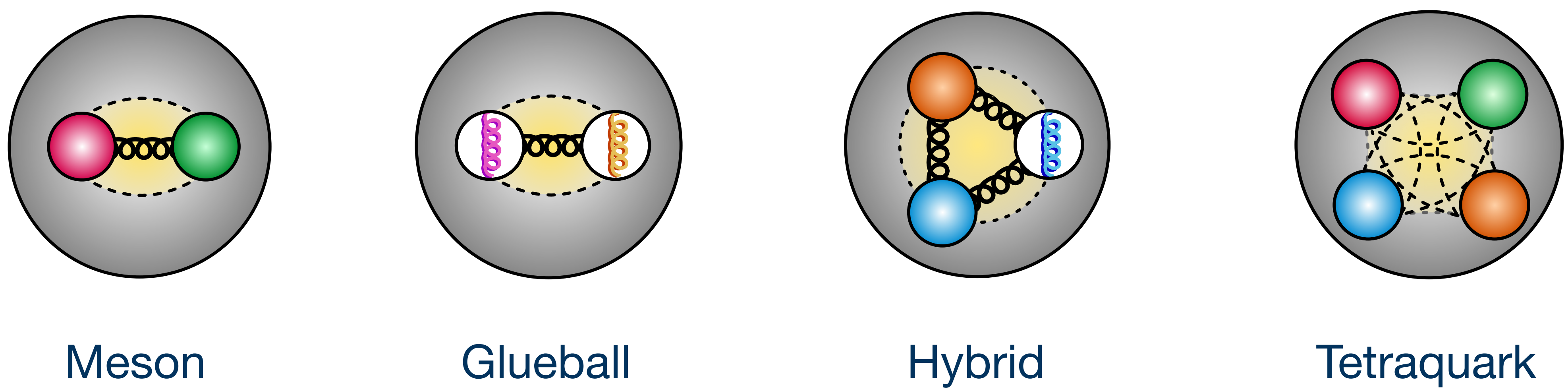
Light Meson Regime

- Light mesons are tricky to tackle for both theory and experiment
- Since $\alpha_s \sim 1$, higher order processes are not suppressed anymore
- Occurring in the non-perturbative regime of QCD ➡ perturbative techniques fail
- Alternative theoretical tools often model dependent or very computational expensive
- Highly populated spectrum: many overlapping, interfering, mixing or distorted states



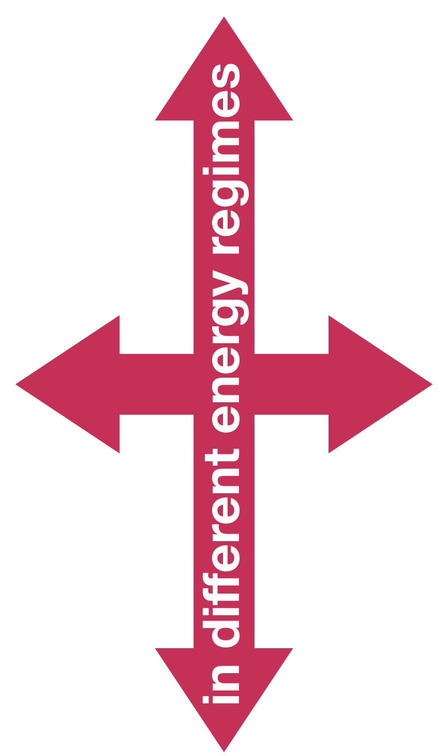
Light Meson Regime

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



Gluon rich processes

- Charmonium decays
- p̄p annihilation
- pp central production
- …



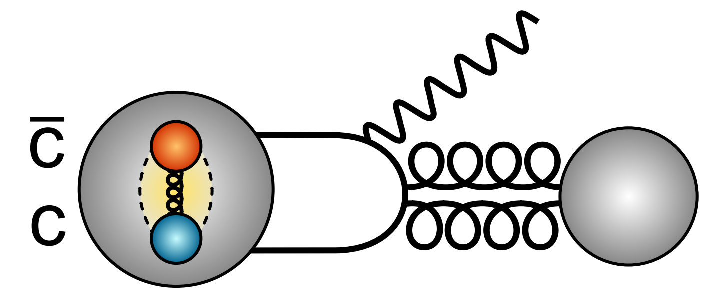
QED mediated process

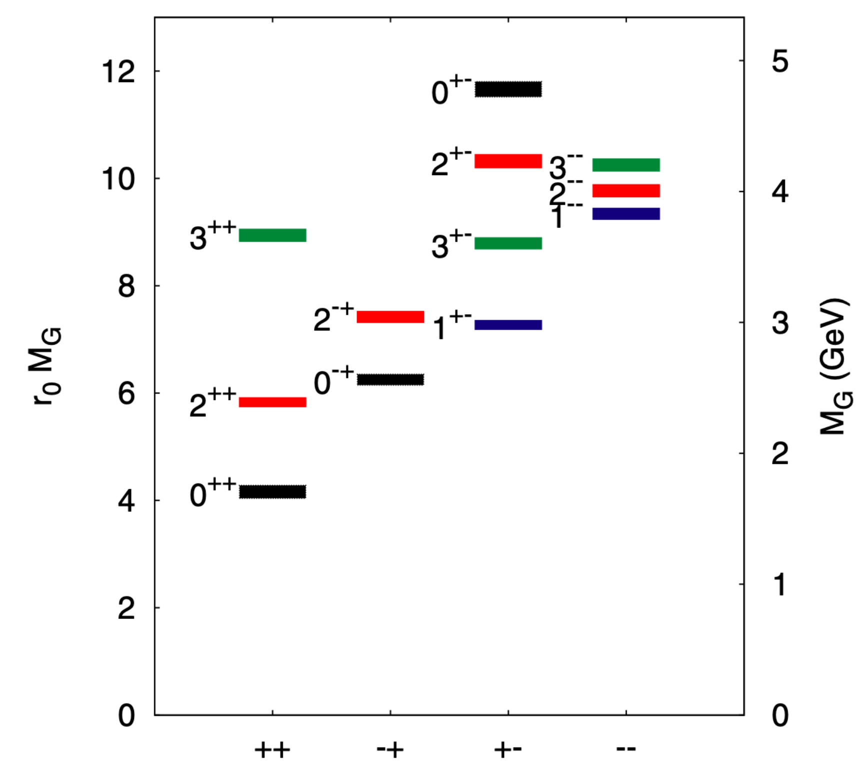
- Two-photon production

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!

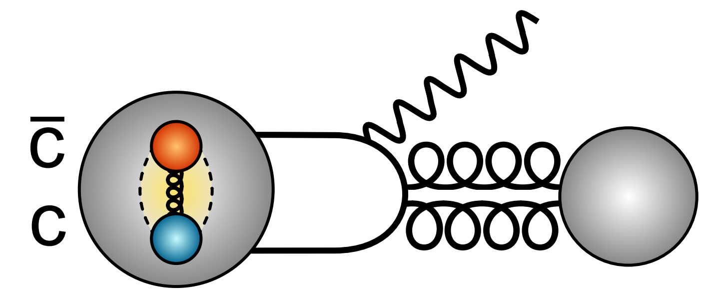




Phys. Rev. D 73, 014516 (2006)

Radiative J/ψ decays

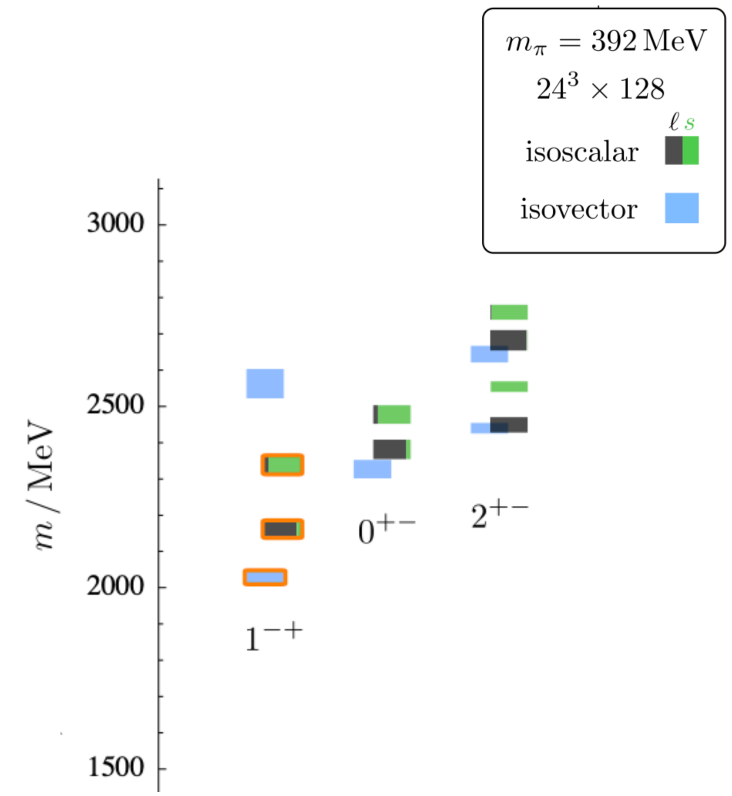
- Gluon-rich process ➡ production of glueballs and hybrids expected



- ***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)

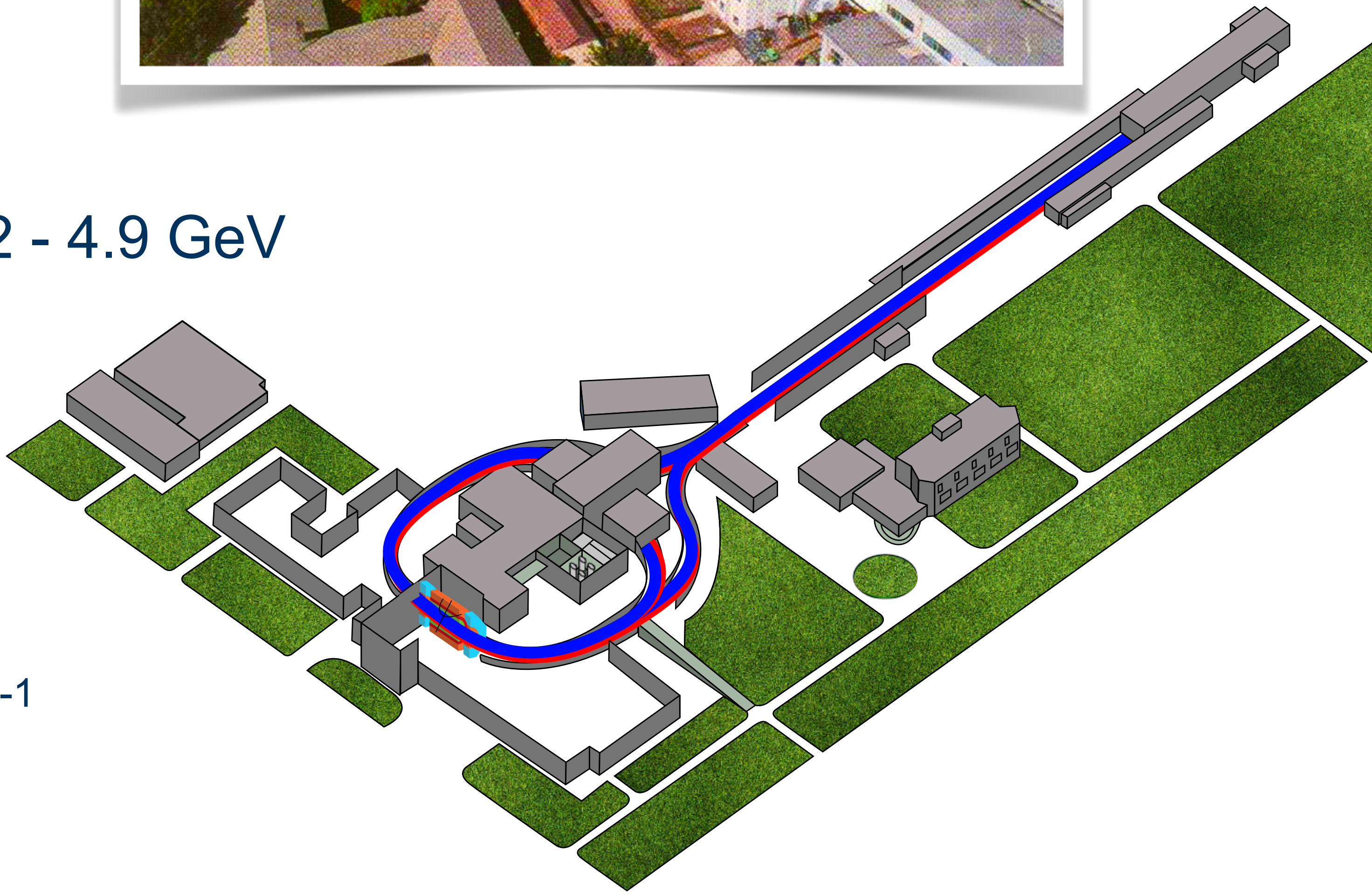
  - More expected…



Phys. Rev. D 88, 094505 (2013)

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}



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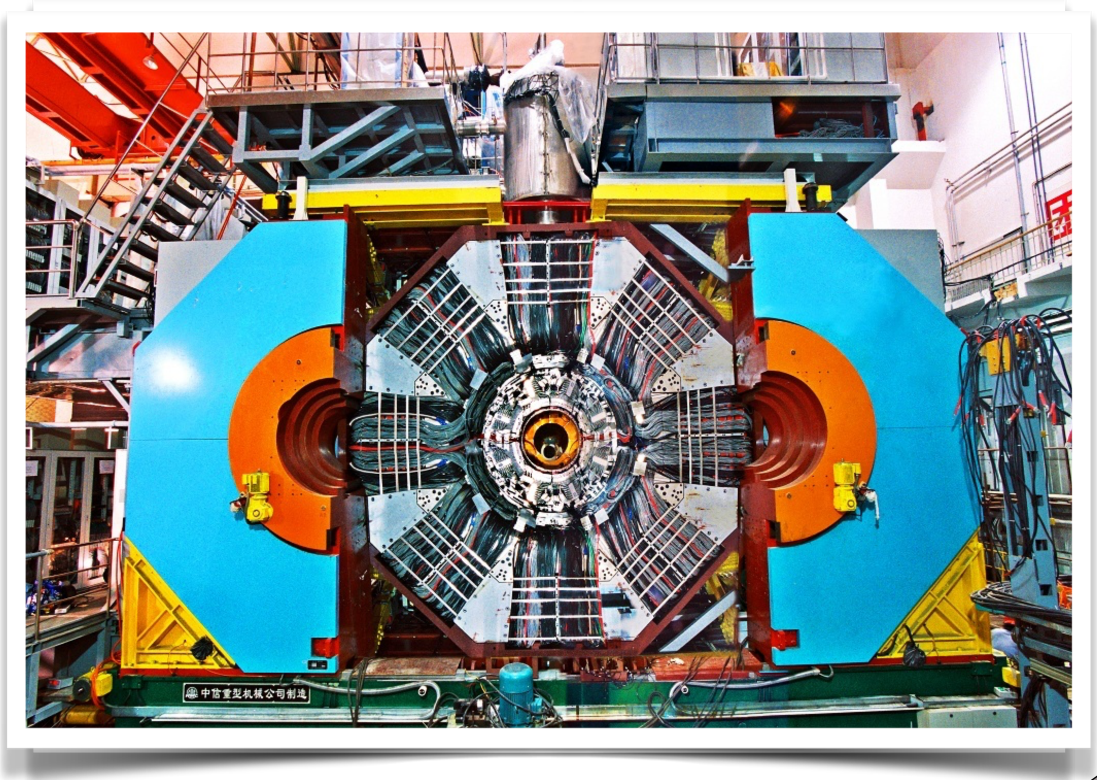
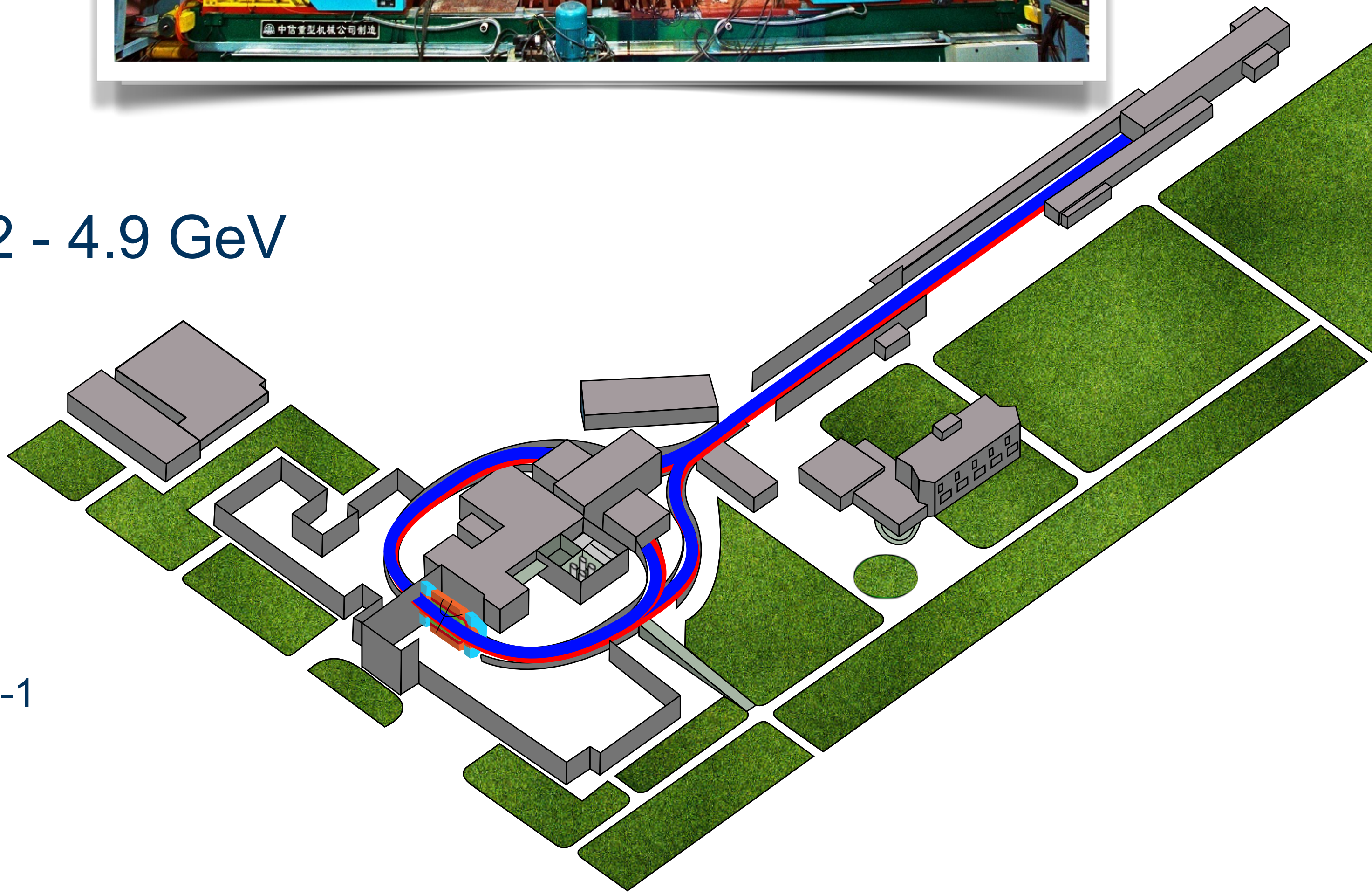




BESIII Detector

MDC (Drift Chamber):
- Spatial resolution $\sigma(r\phi)$ = 130 μm (single wire)
- Momentum resolution: 0.5% at 1 GeV

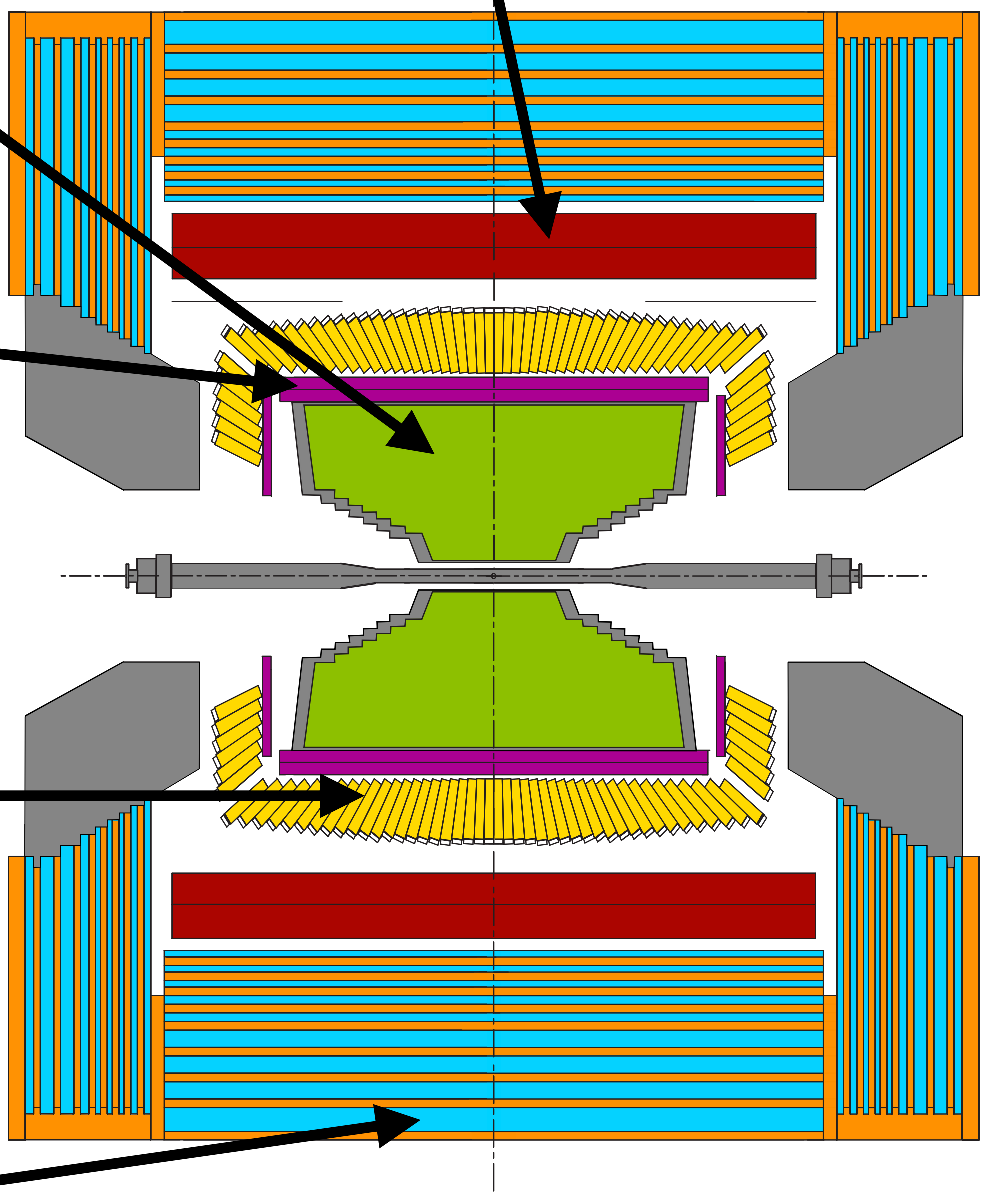
TOF:
- Time resolution: $\sigma(t)$ = 90 ps (barrel)
  $\sigma(t)$ = 120 ps (end caps)

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

Muon ID (RPC):
- 9 layers barrel and 8 layers end caps

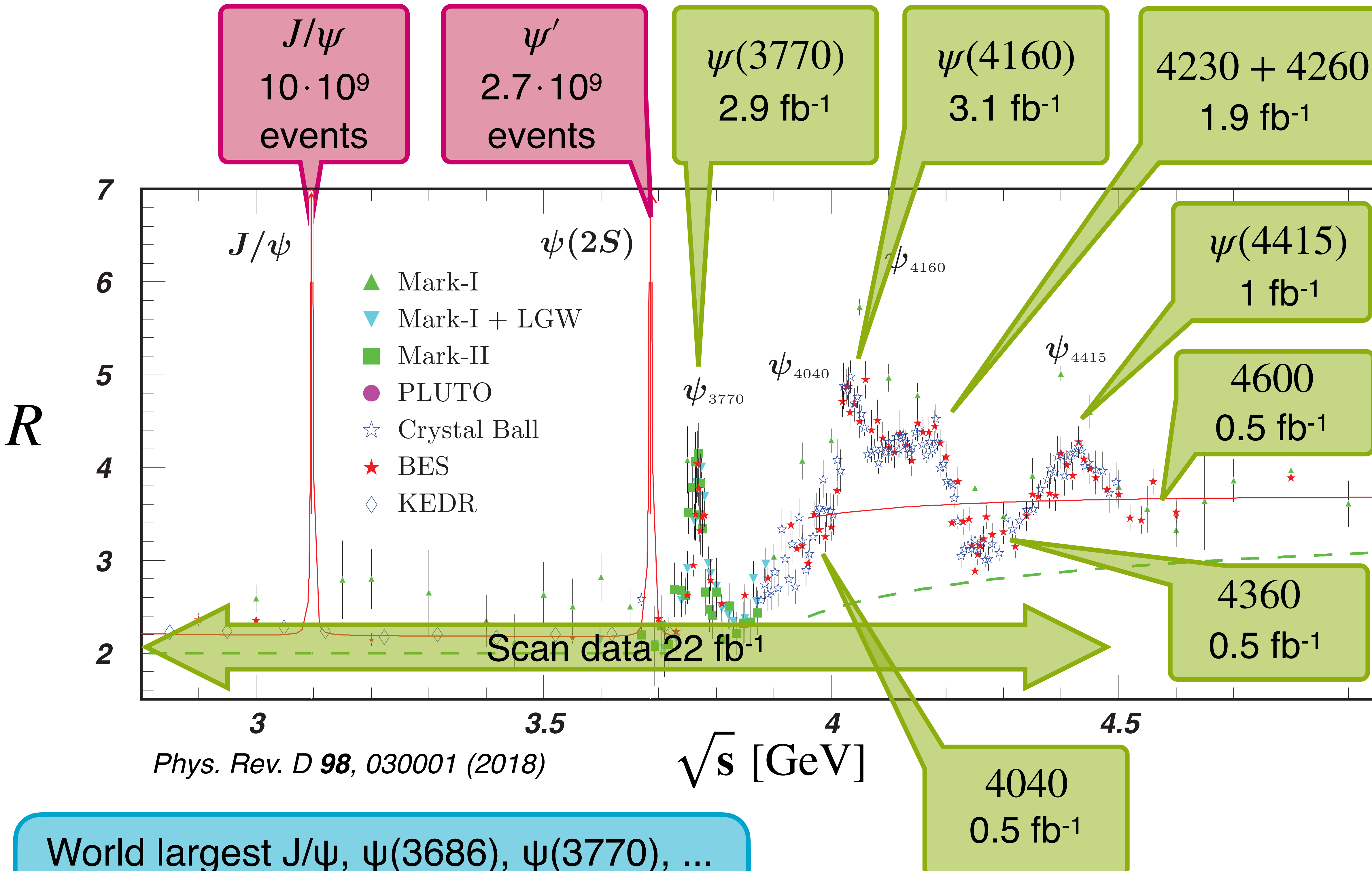
Nucl. Instr. Meth. A614, 345 (2010)

Superconducting magnet: 1T



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

Data Samples



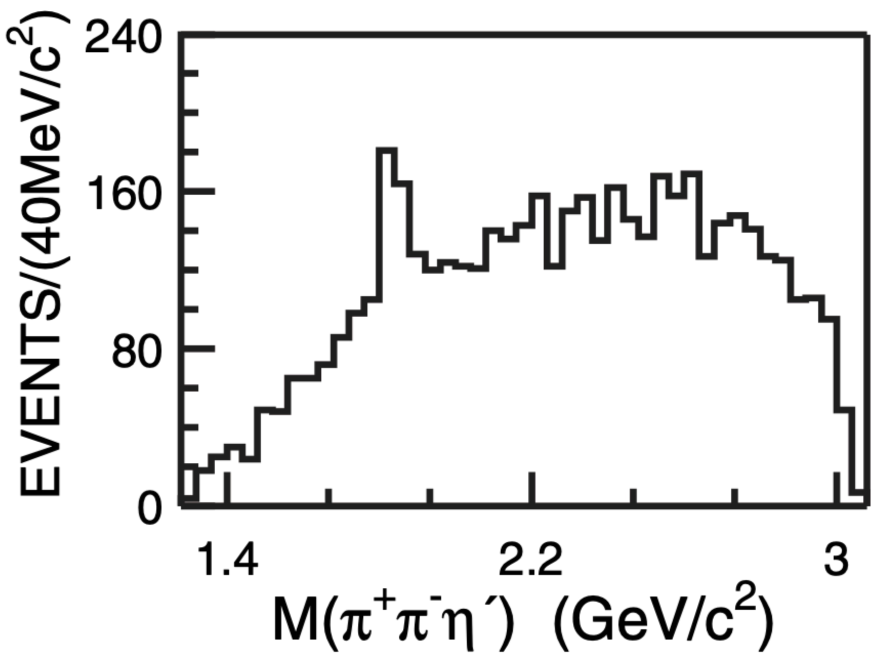
Phys. Rev. D ***98****, 030001 (2018)*

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

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

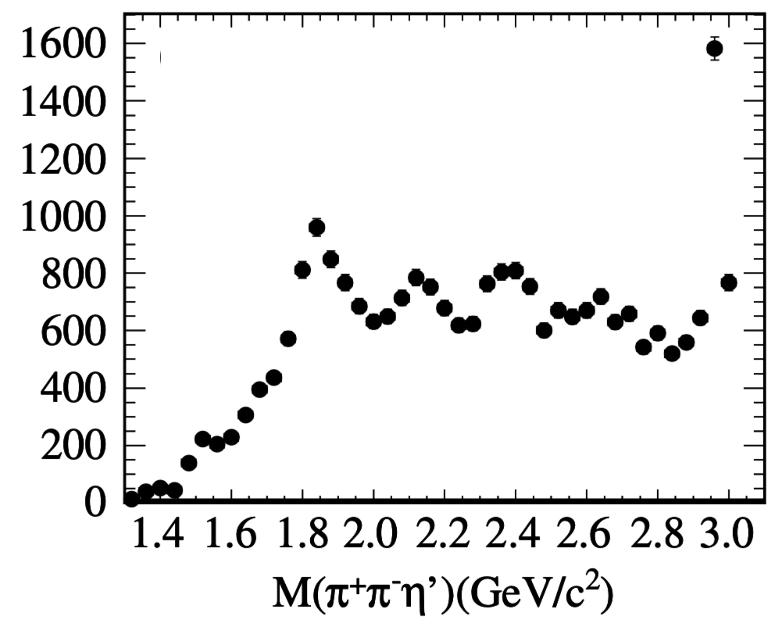
PRL 129, 042001 (2022)

58M J/ψ events



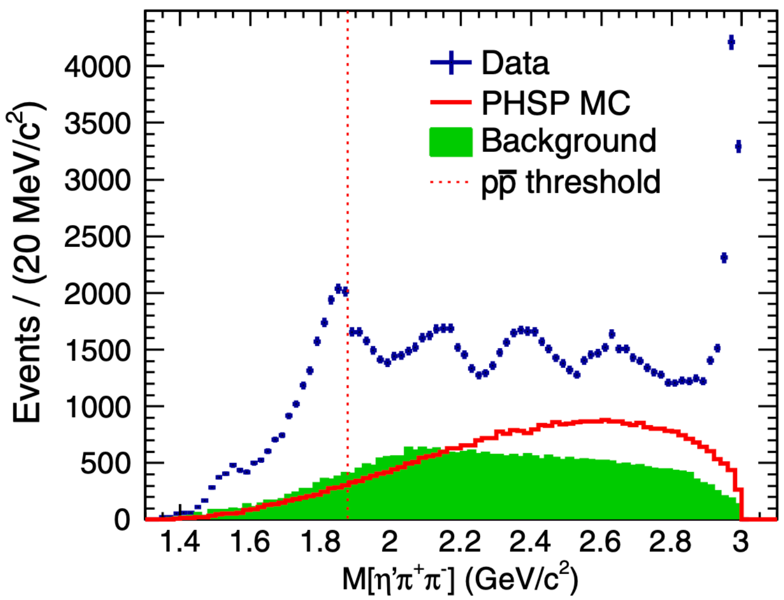
BES, PRL 95, 262001 (2005)

225M J/ψ events



BESIII, PRL 106, 072002 (2011)

1090M J/ψ events



BESIII, PRL 117, 042002 (2016)

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

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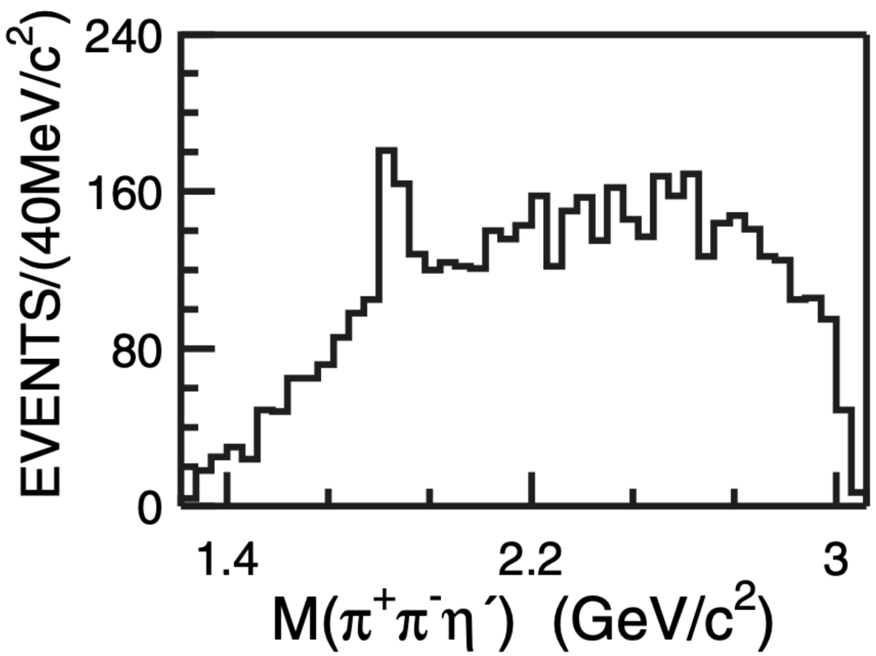

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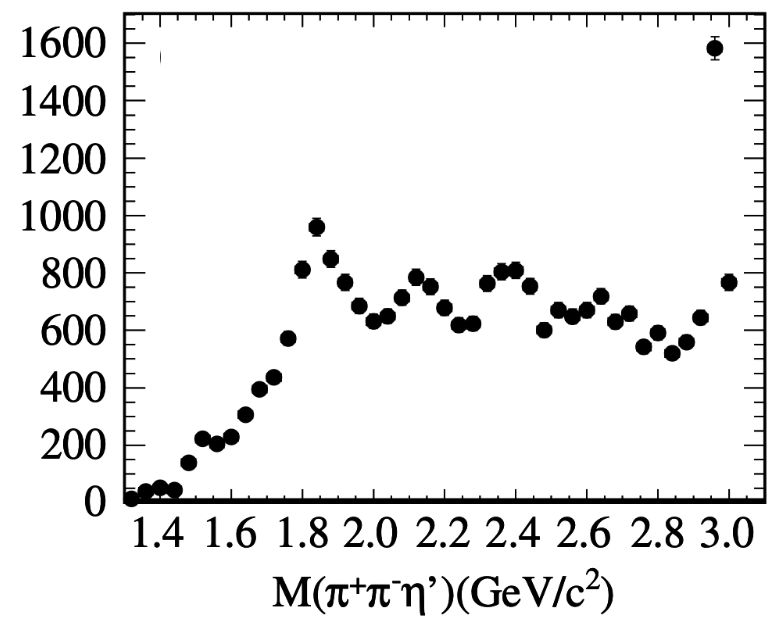

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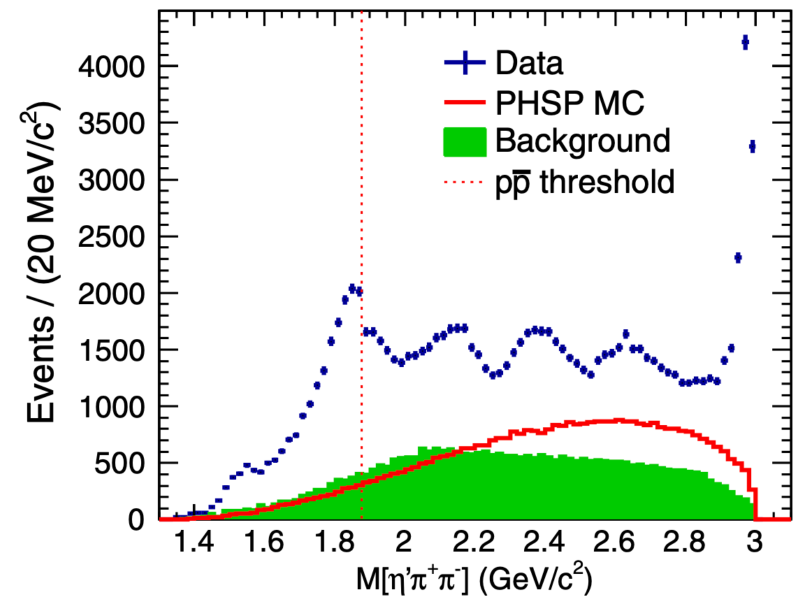


BESIII, PRL 117, 042002 (2016)

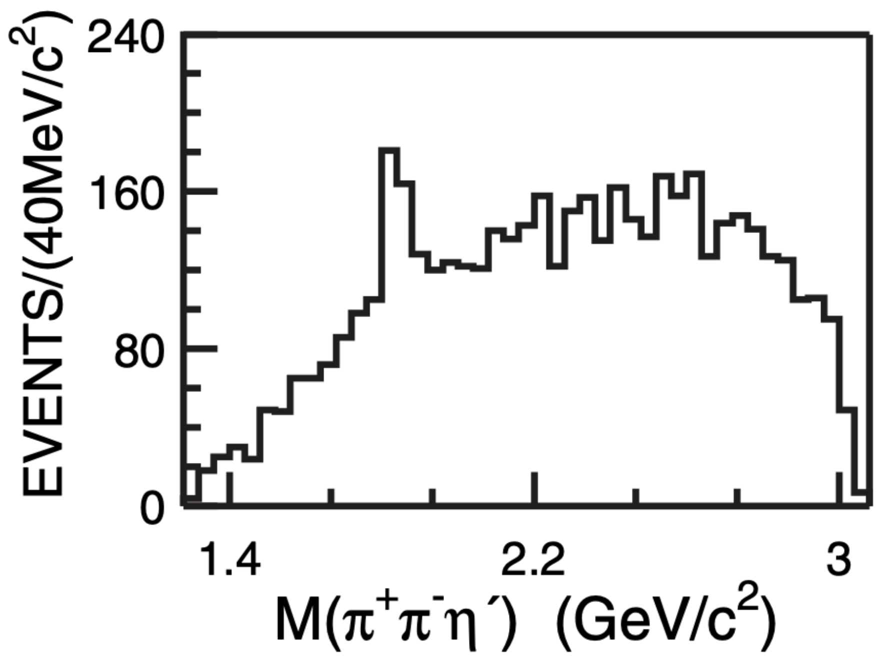
- Structure observed near $\bar{p}p$ threshold: $X(1835)$ and two additional states $X(2120)$ and $X(2370)$
- Line shape analysis finds equally good descriptions for Flatté and BW scenario…
  - Either a narrow state below threshold - bound state
  - Or a broad state with strong coupling above threshold - 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)

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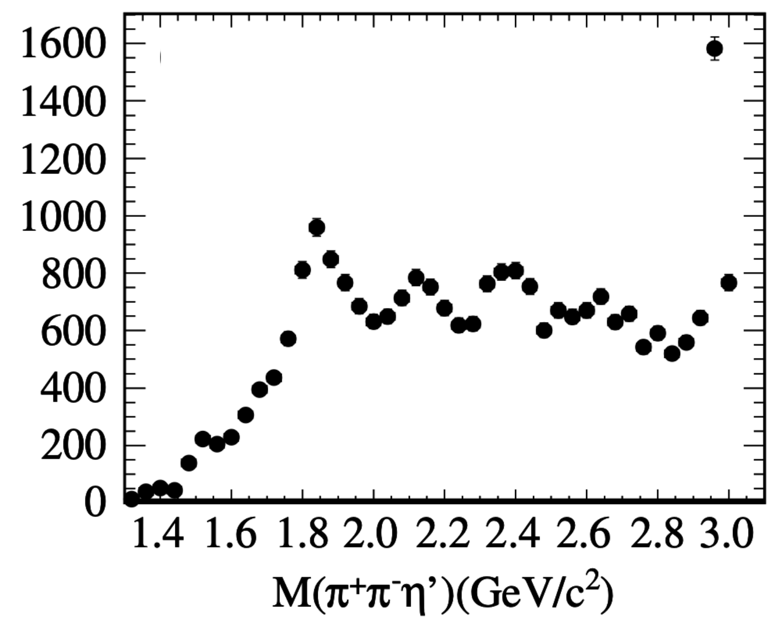

BESIII, PRL 106, 072002 (2011)

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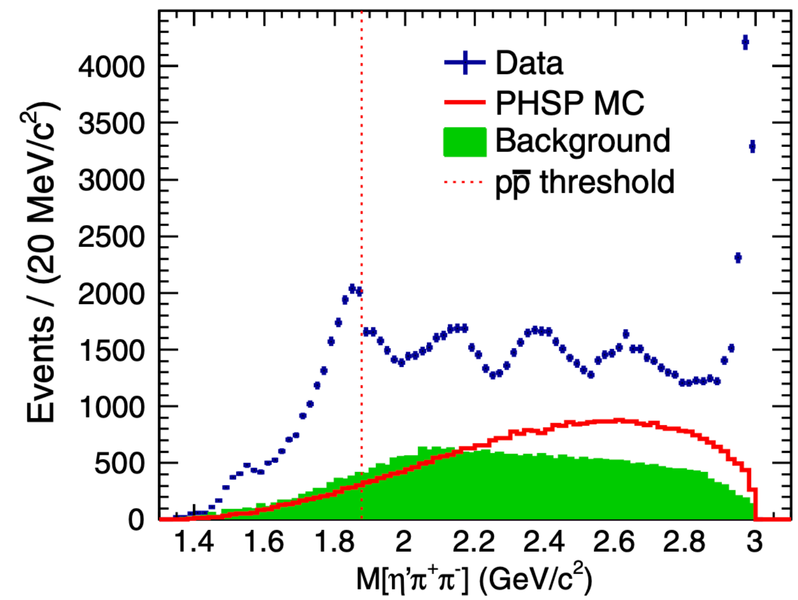
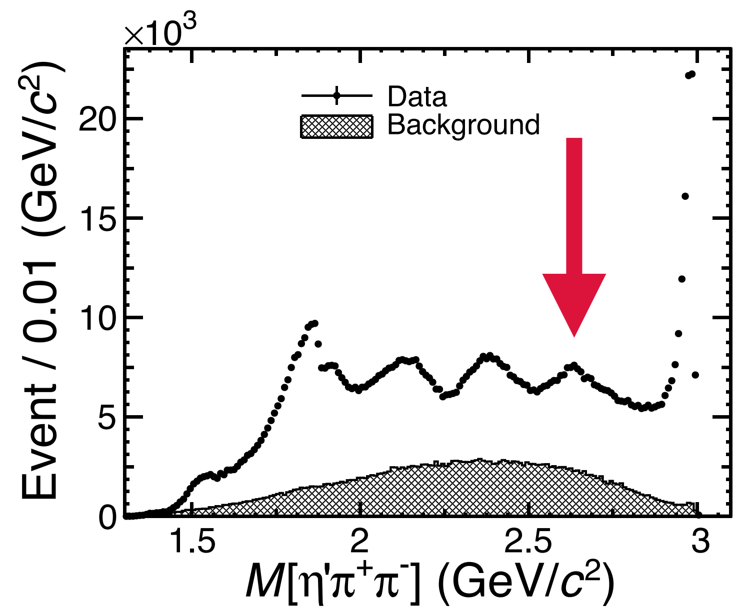


BESIII, PRL 117, 042002 (2016)

New Structure observed!

X(2600)



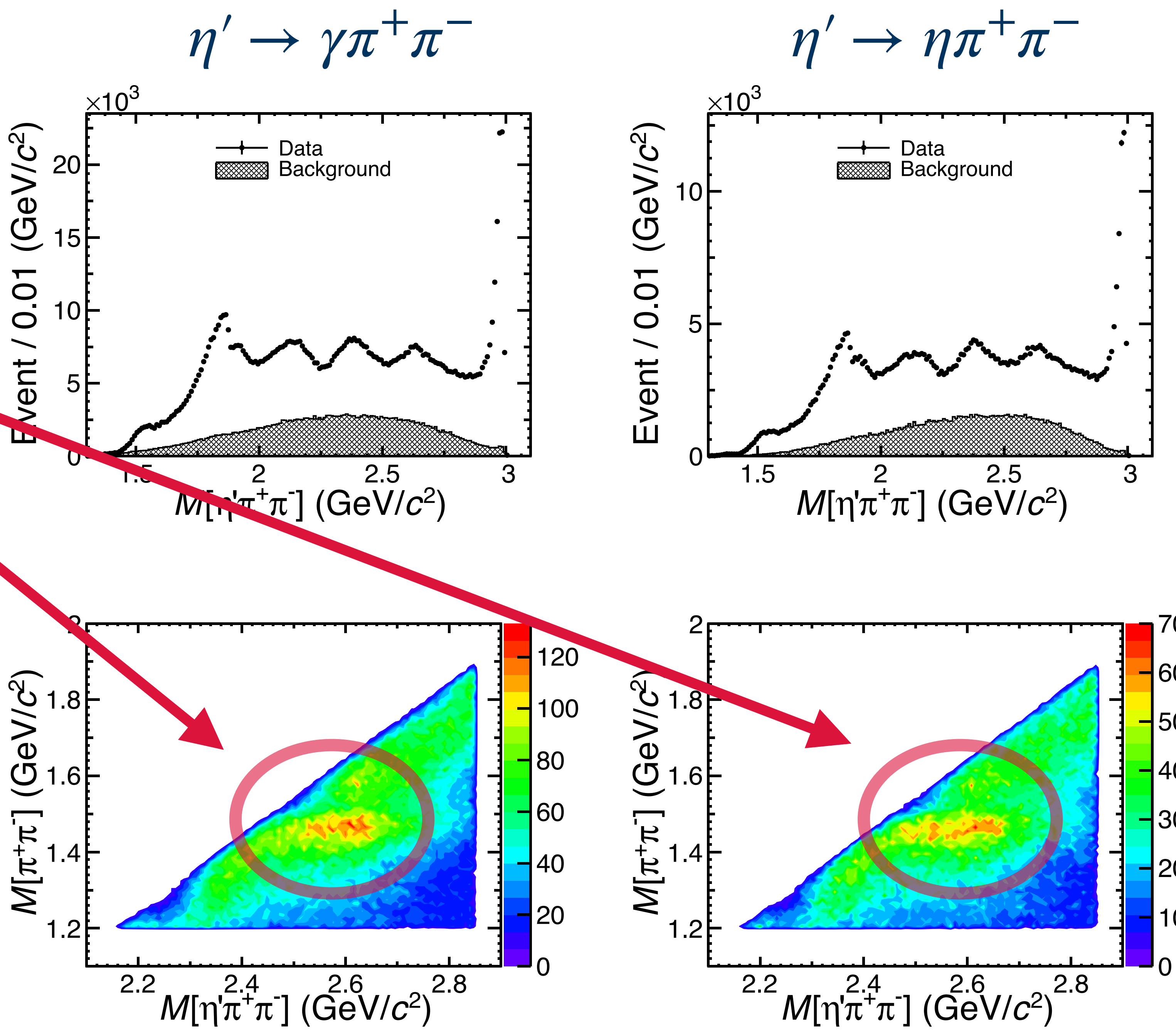
BESIII, PRL 129, 042001 (2022)

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



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

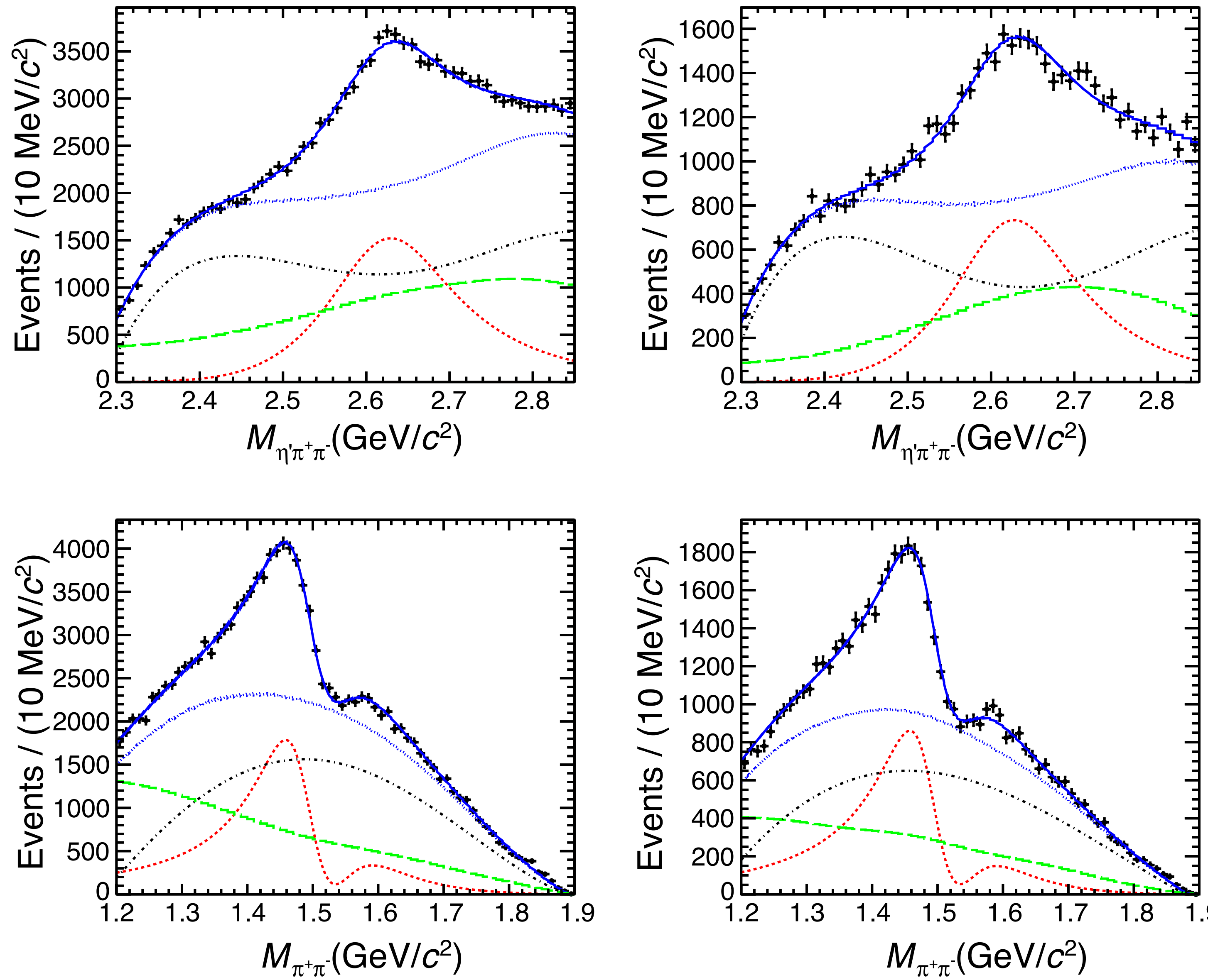
PRL 129, 042001 (2022)

- 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

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



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

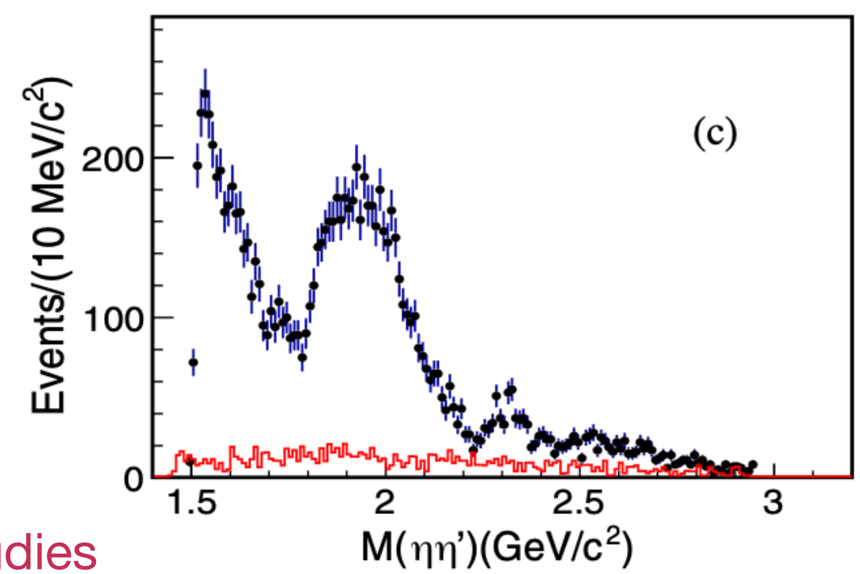
PRL 129, 19, 192002 (2022)
PRD 106, 7, 072012 (2022)

- 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)

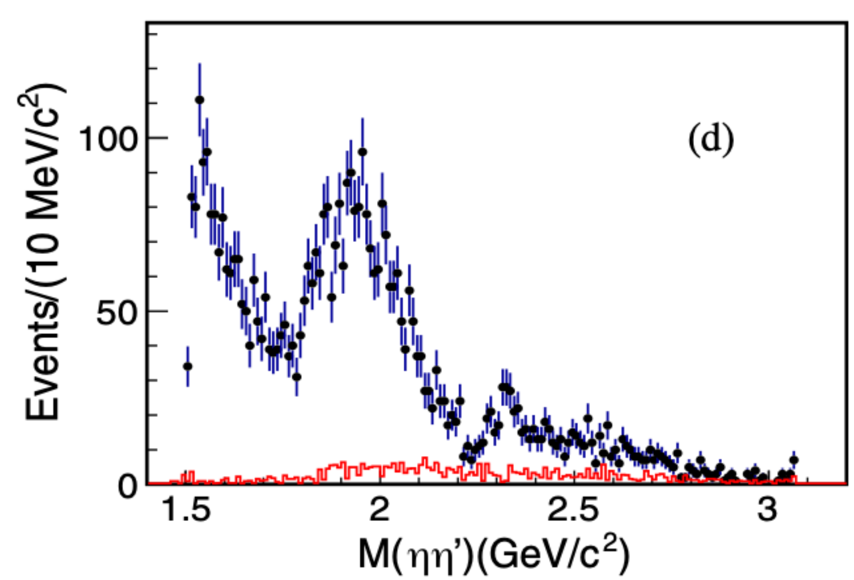
fixed… floated for syst. studies

Decay mode	Resonance	M (MeV/c^2)	Γ (MeV)	M_{PDG} (MeV/c^2)	Γ_{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

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

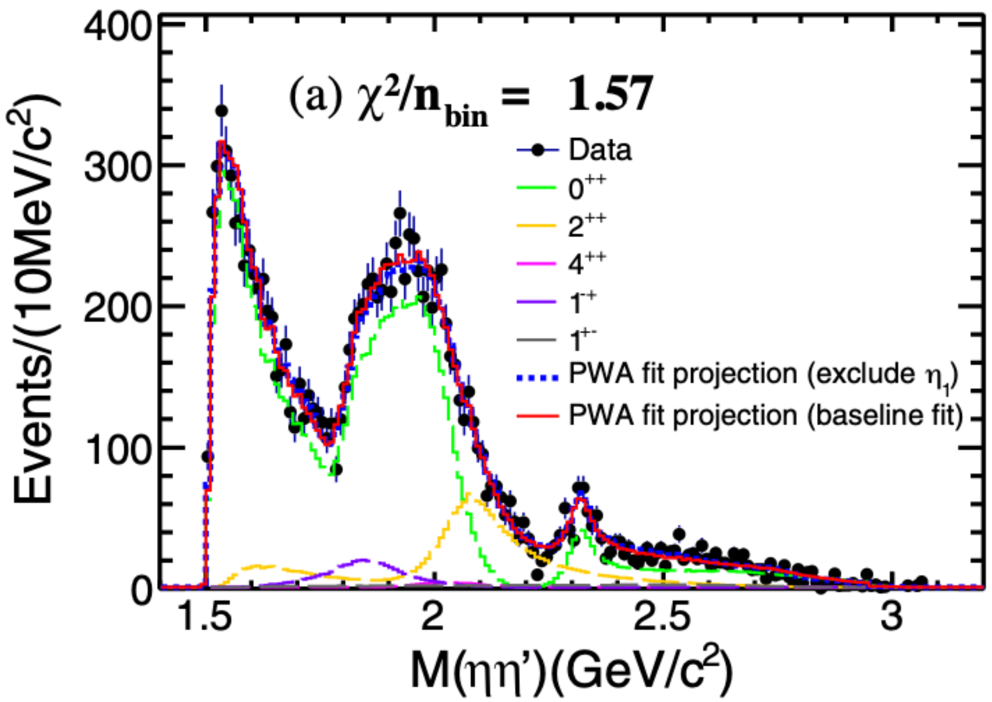


$\eta' \to \eta\pi^+\pi^-$

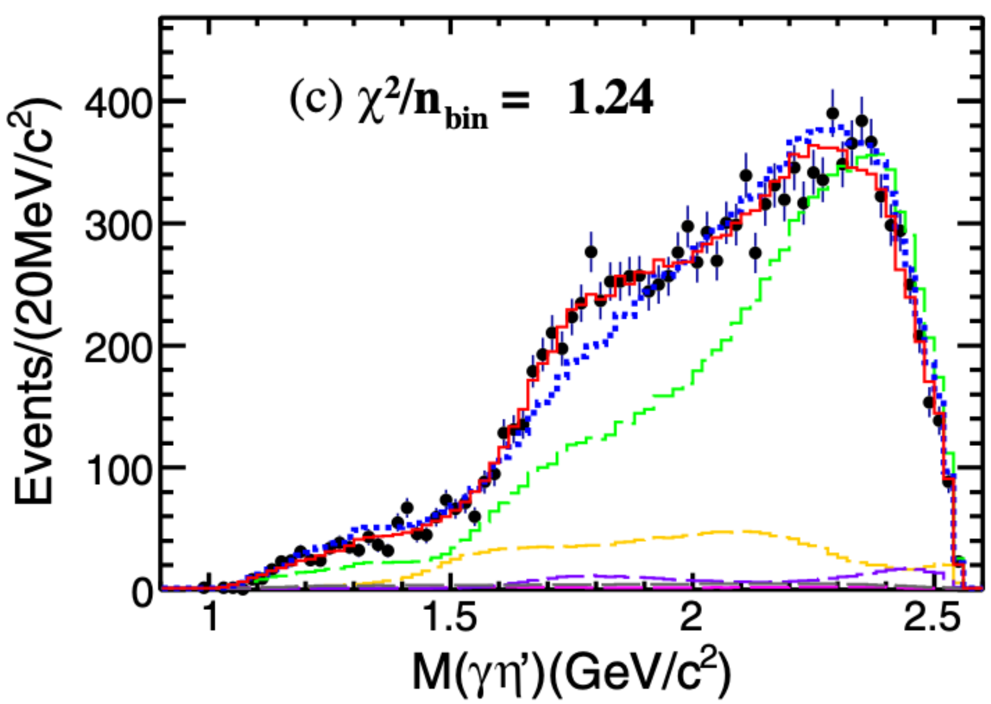


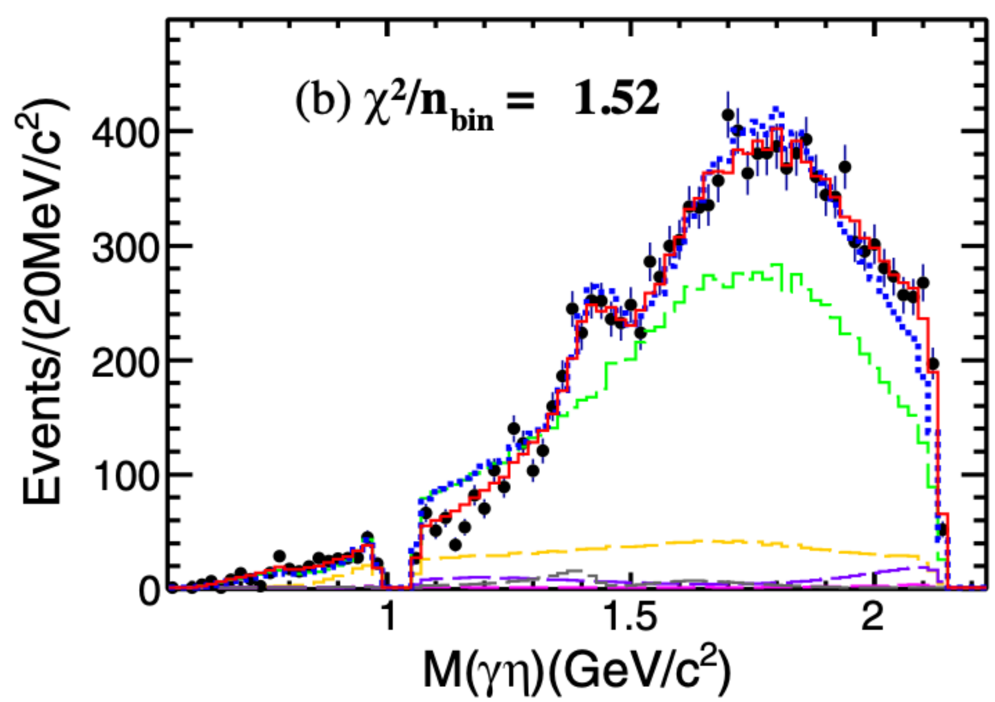
$J/\psi \rightarrow \gamma\eta'\eta$

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





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

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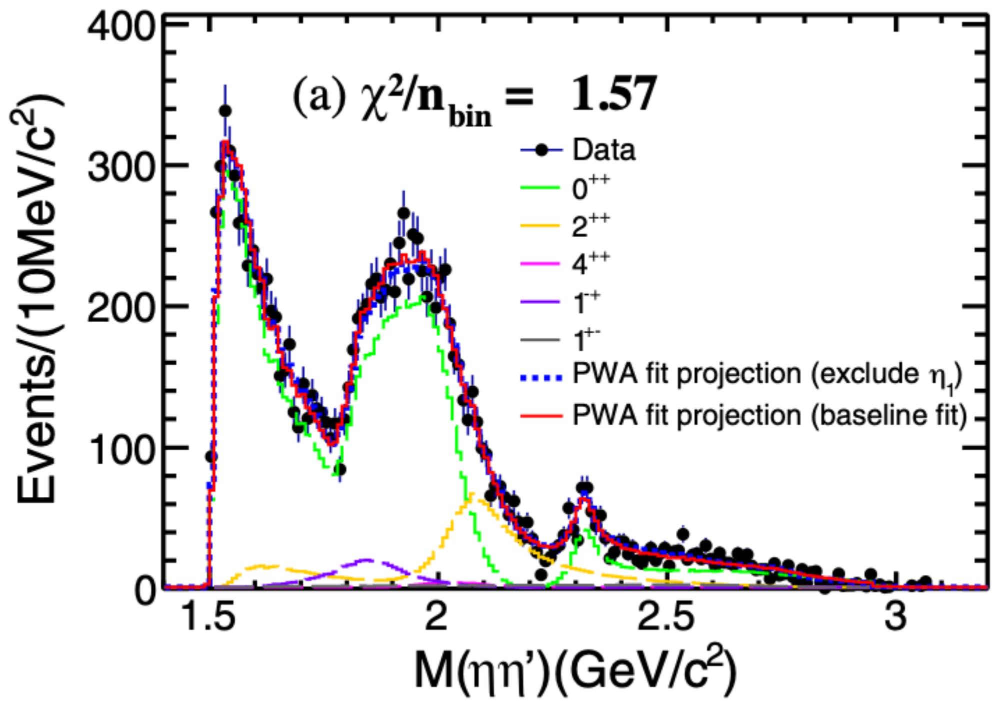

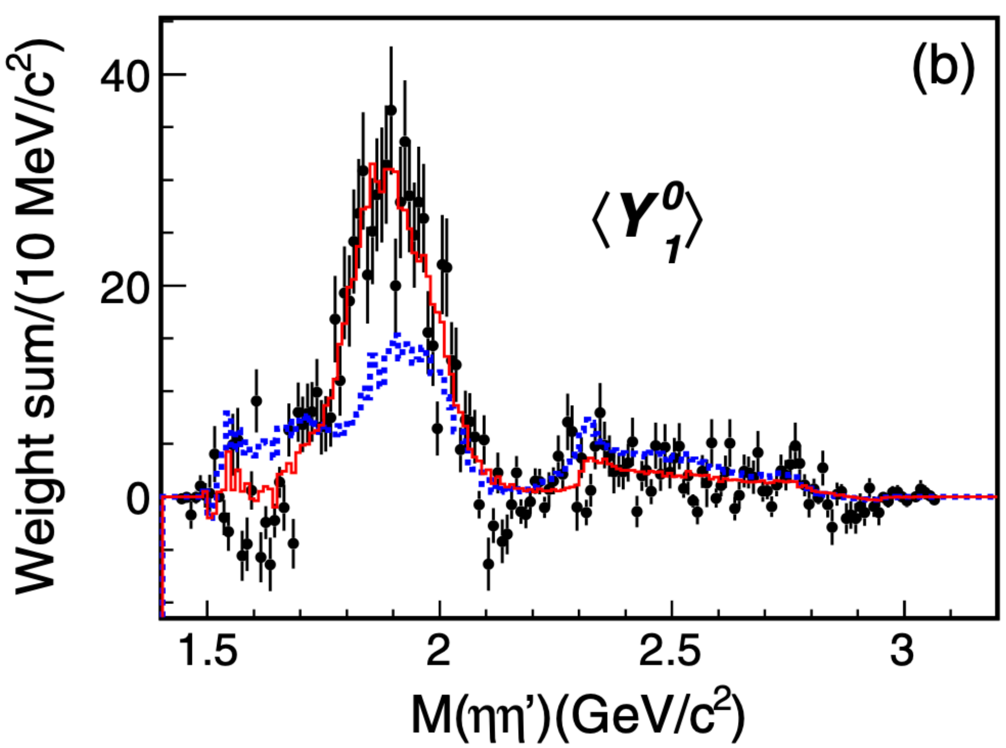

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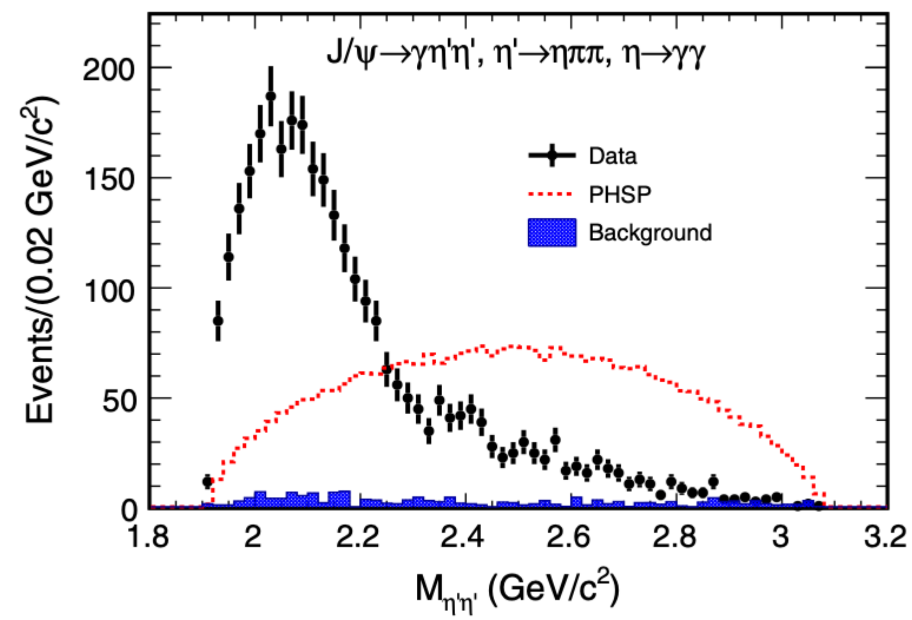
$J/\psi \to \gamma\eta'\eta'$

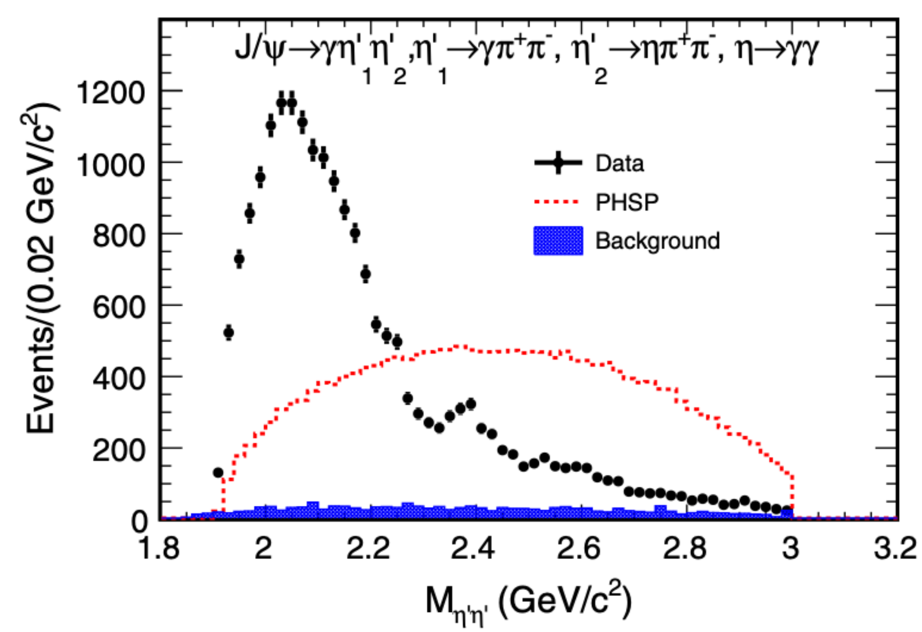
PRD 105, 072002 (2022)

- 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…

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



$\eta'_1 \to \gamma\pi^+\pi^-$ $\eta'_2 \to \eta\pi^+\pi^-$



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

PRD 105, 072002 (2022)

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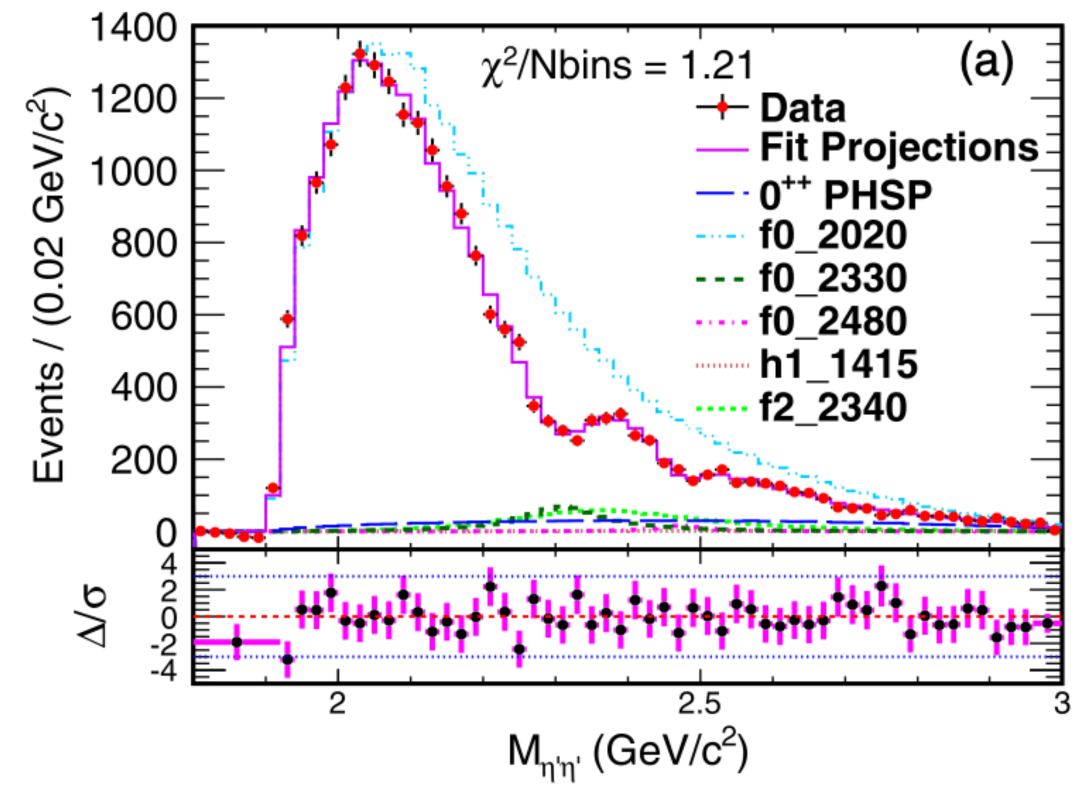
  - $J^{PC} = 1^{+-}$ and 1^{--} ($\gamma\eta'$ system)
  - $f_0(2020)$ described with Flatté, all others with BW…

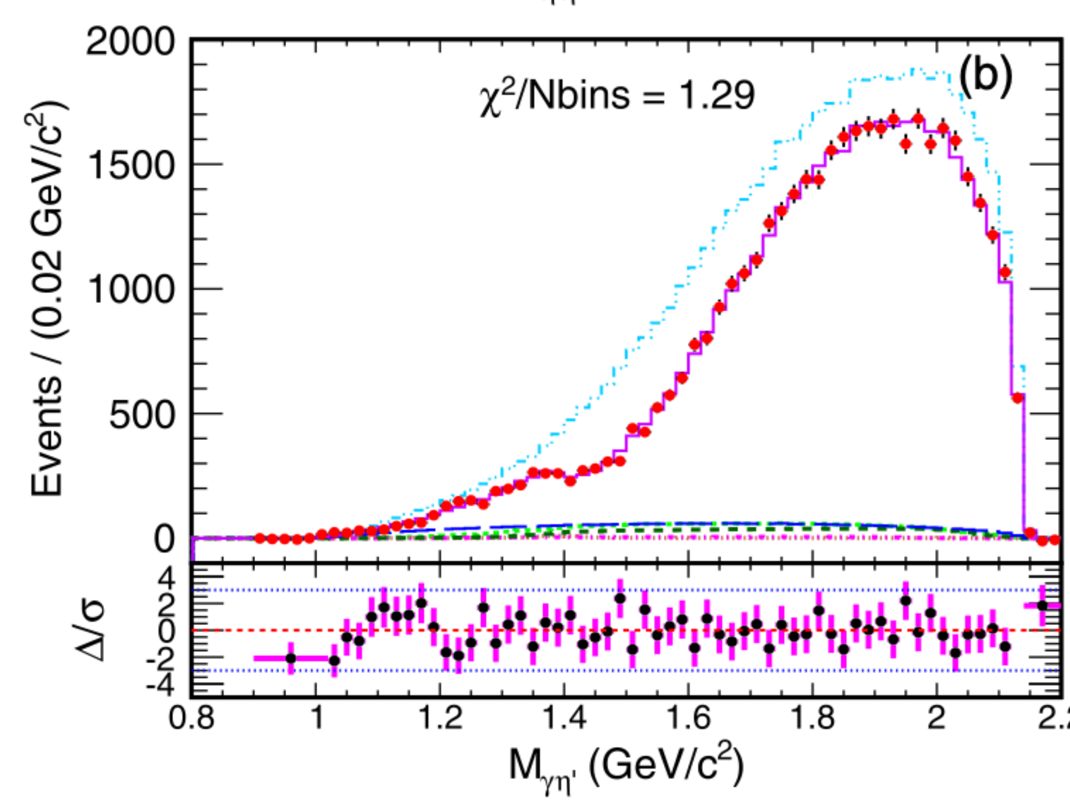
Resonance	M(MeV/c^2)	Γ(MeV)	B.F.
$f_0(2020)$	$1982 \pm 3^{+54}_{-0}$	$436 \pm 4^{+46}_{-49}$	$(2.63 \pm 0.06^{+0.31}_{-0.46}) \times 10^{-4}$
$f_0(2330)$	$2312 \pm 2^{+10}_{-0}$	$134 \pm 5^{+30}_{-9}$	$(6.09 \pm 0.64^{+4.00}_{-1.68}) \times 10^{-6}$
$f_0(2480)$	$2470 \pm 4^{+4}_{-6}$	$75 \pm 9^{+11}_{-8}$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

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

needed to describe the data



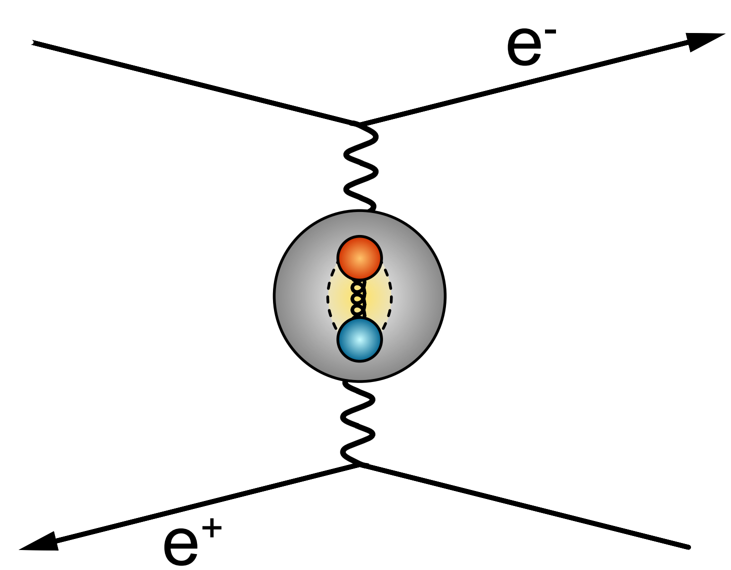


Two-Photon Reactions

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

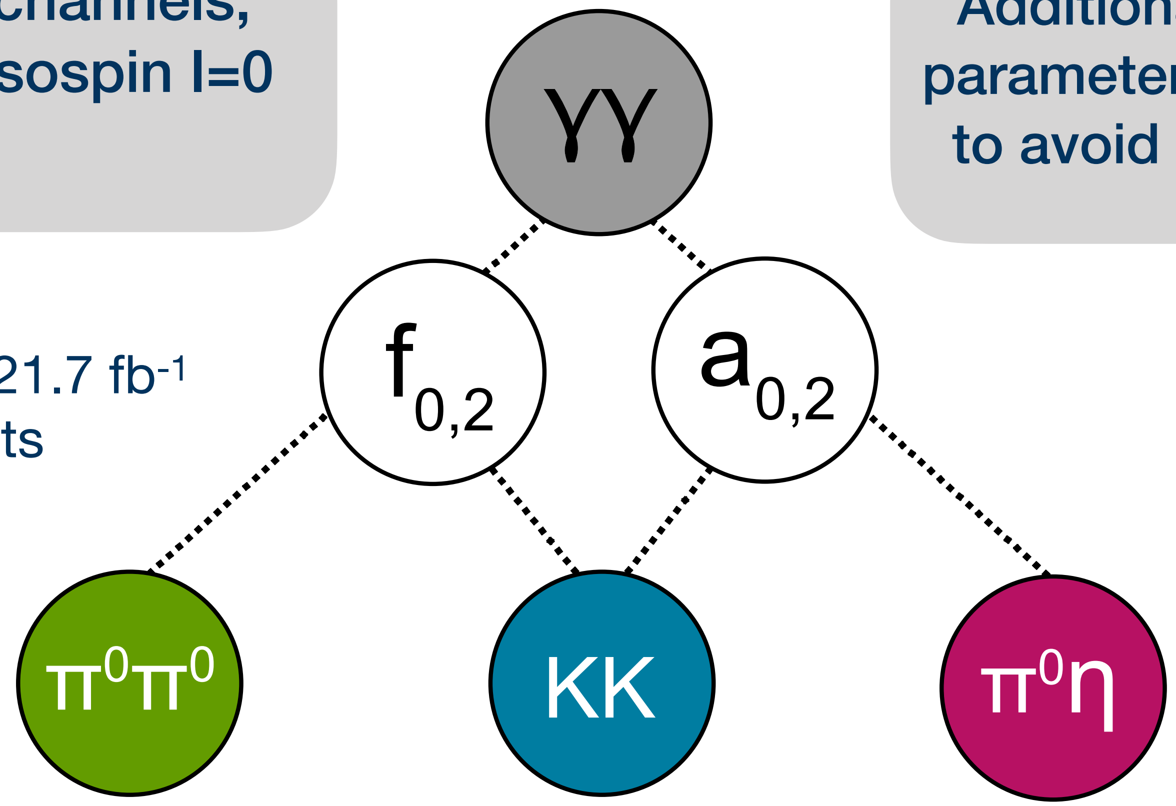
***Untagged reactions*:**

- 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

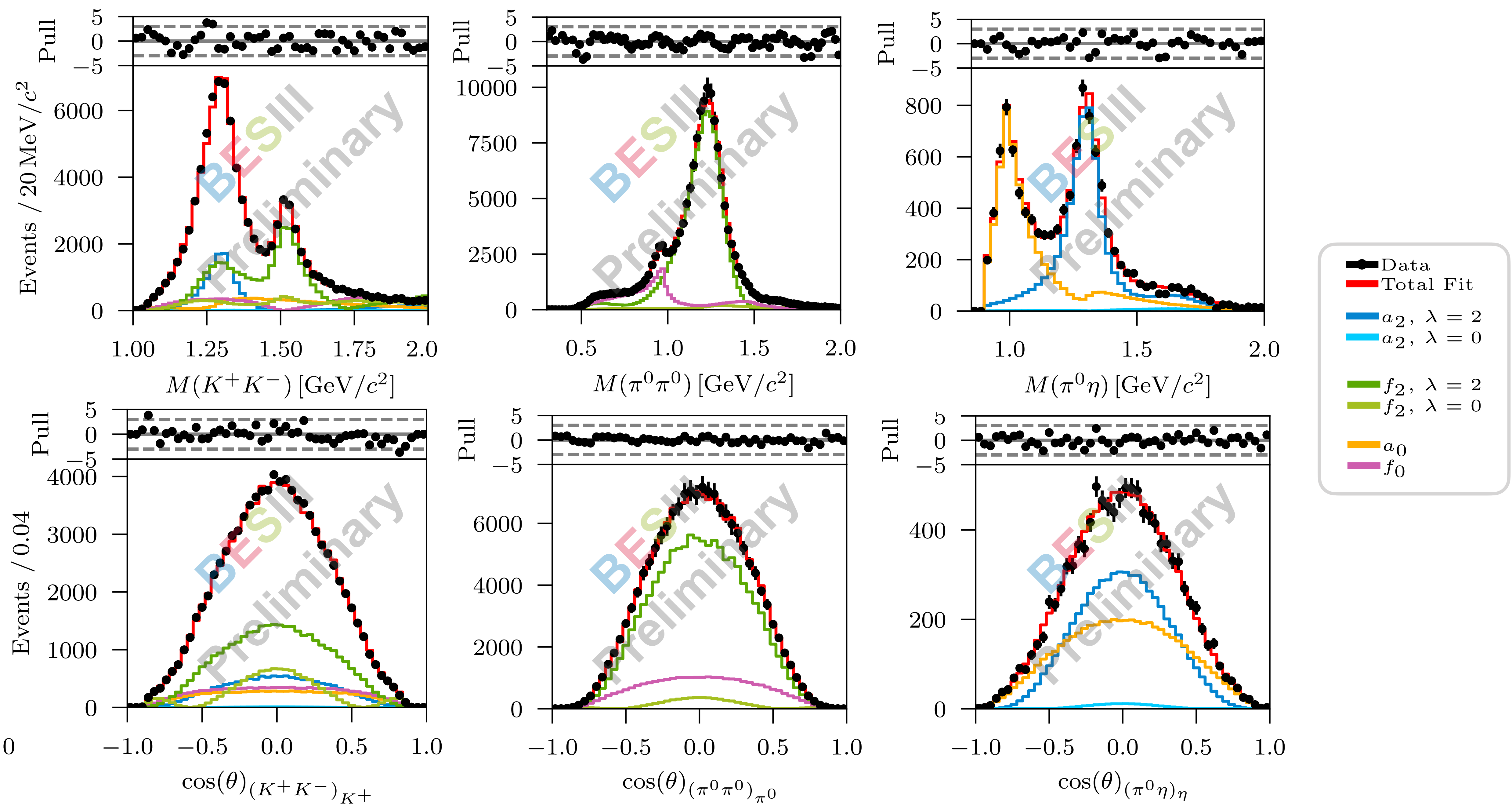
Using data samples of 21.7 fb^{-1} at 28 energy points

- 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

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

Coupled Channel Analysis of Two-Photon Data

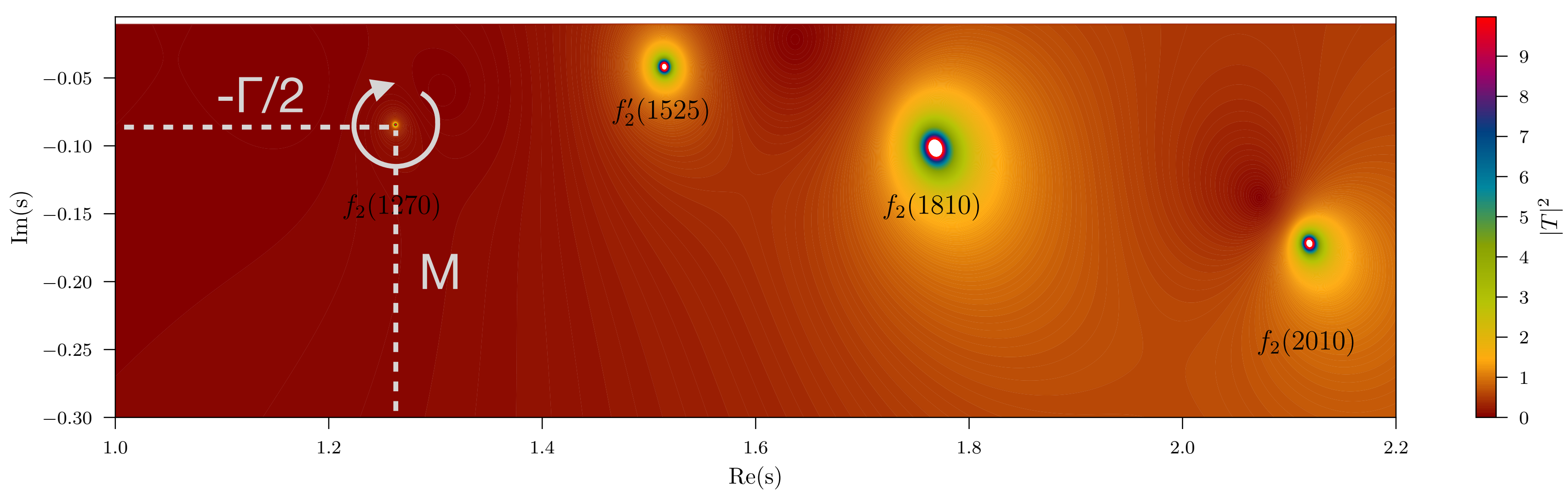
- Using obtained parameterization and fix all pole and decay parameters
- All structures can be well described
- Dominant contribution of $(J,\lambda) = (2{,}2), (0{,}0)$
- Best fit result using all 14 resonances and P-vector background terms: 1. order for f_2, a_2, a_0 -waves

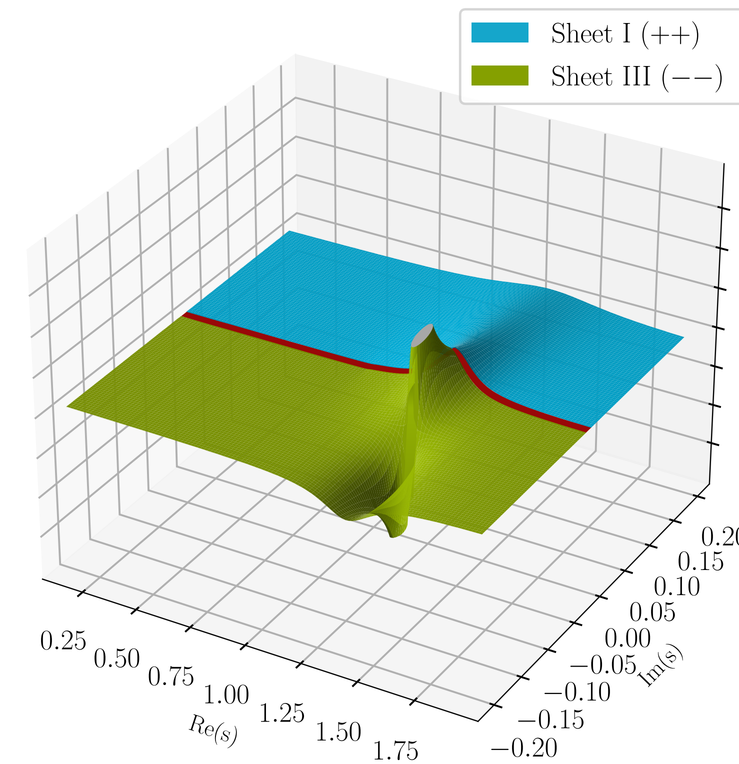


Extraction of Resonance Properties

- 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: f_2-wave





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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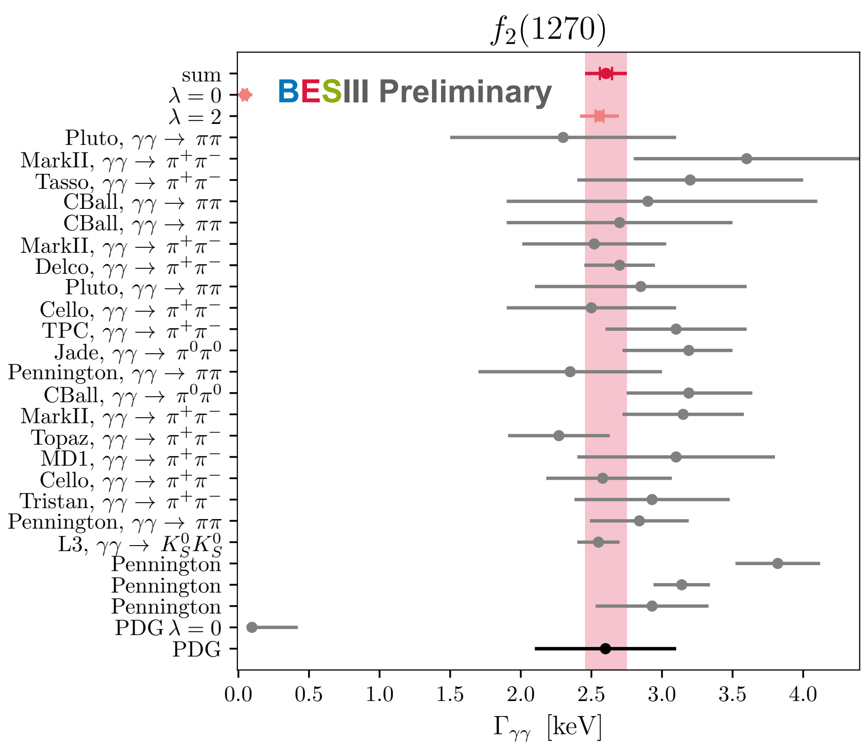

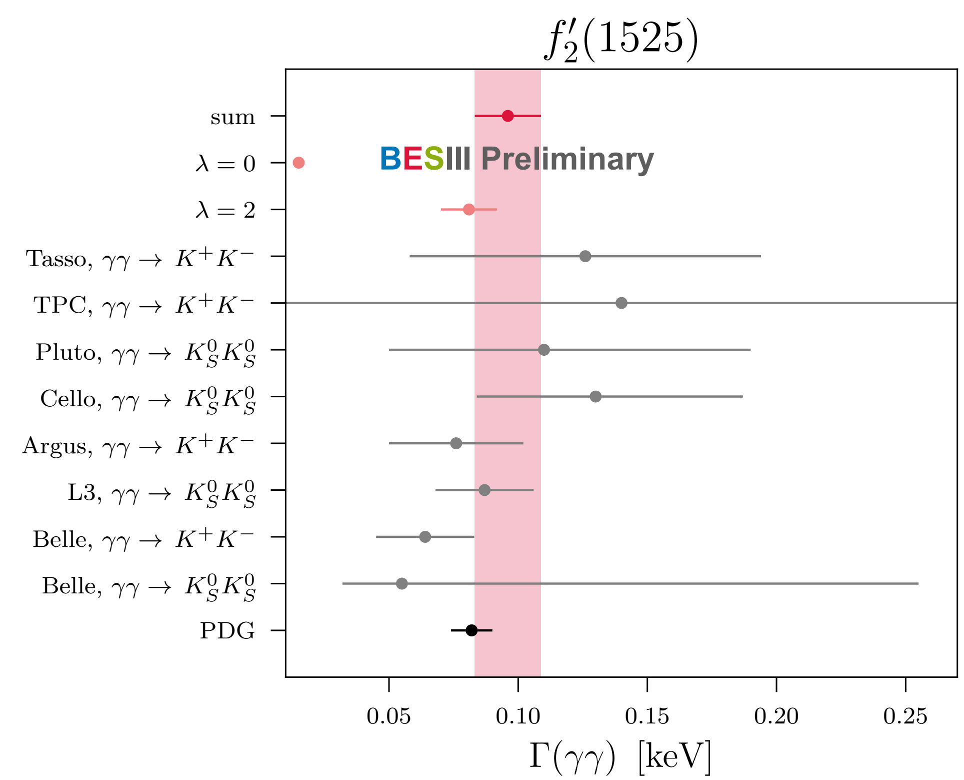

- First determination of the helicity contributions for the $f_2'(1525)$
- Most accurate measurement for $f_2(1270)$ and $a_2(1320)$
- Scalar mesons $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ measured for the first time

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 $J/\psi \to \gamma\eta'\eta'$
  - 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:
  - $\sqrt{s} = 4.9$ ➡ $5.6\,\mathrm{GeV}$
  - 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