



JINR

Searches for glueballs at BESIII

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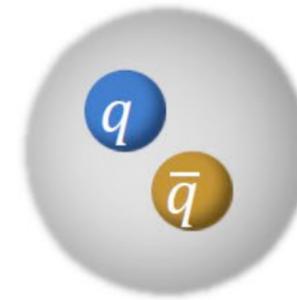
on behalf of BESIII Collaboration

Conference on High Energy Physics

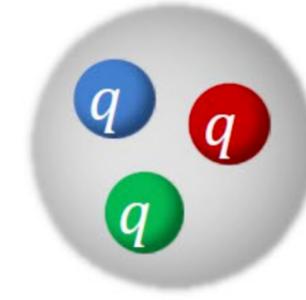
29 September – 03 October 2025, AANL, Yerevan

What is a glueball?

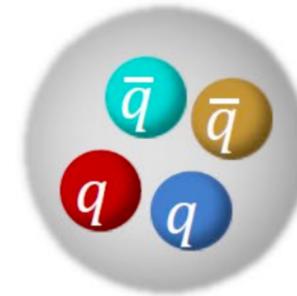
- Conventional hadrons — 2 or 3 valence quarks/antiquarks
- QCD allows for additional forms of hadrons:
 - Multi-quark states, $N_q \geq 4$
 - Hybrids: qqg , $qq\bar{q}g$, etc.
 - Glueballs: gg , ggg — colorless bound states of multiple gluons, **possible due to the non-Abelian nature of QCD and gluon self-interaction!**



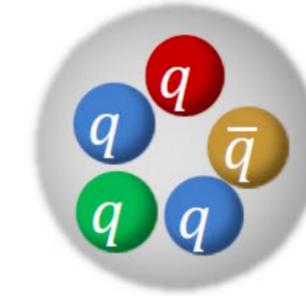
Meson



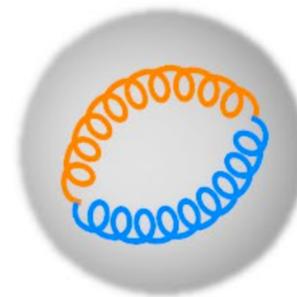
Baryon



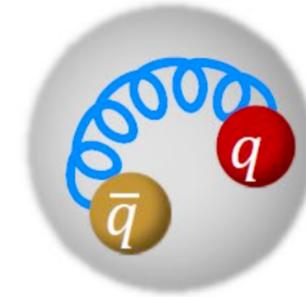
Tetraquark



Pentaquark



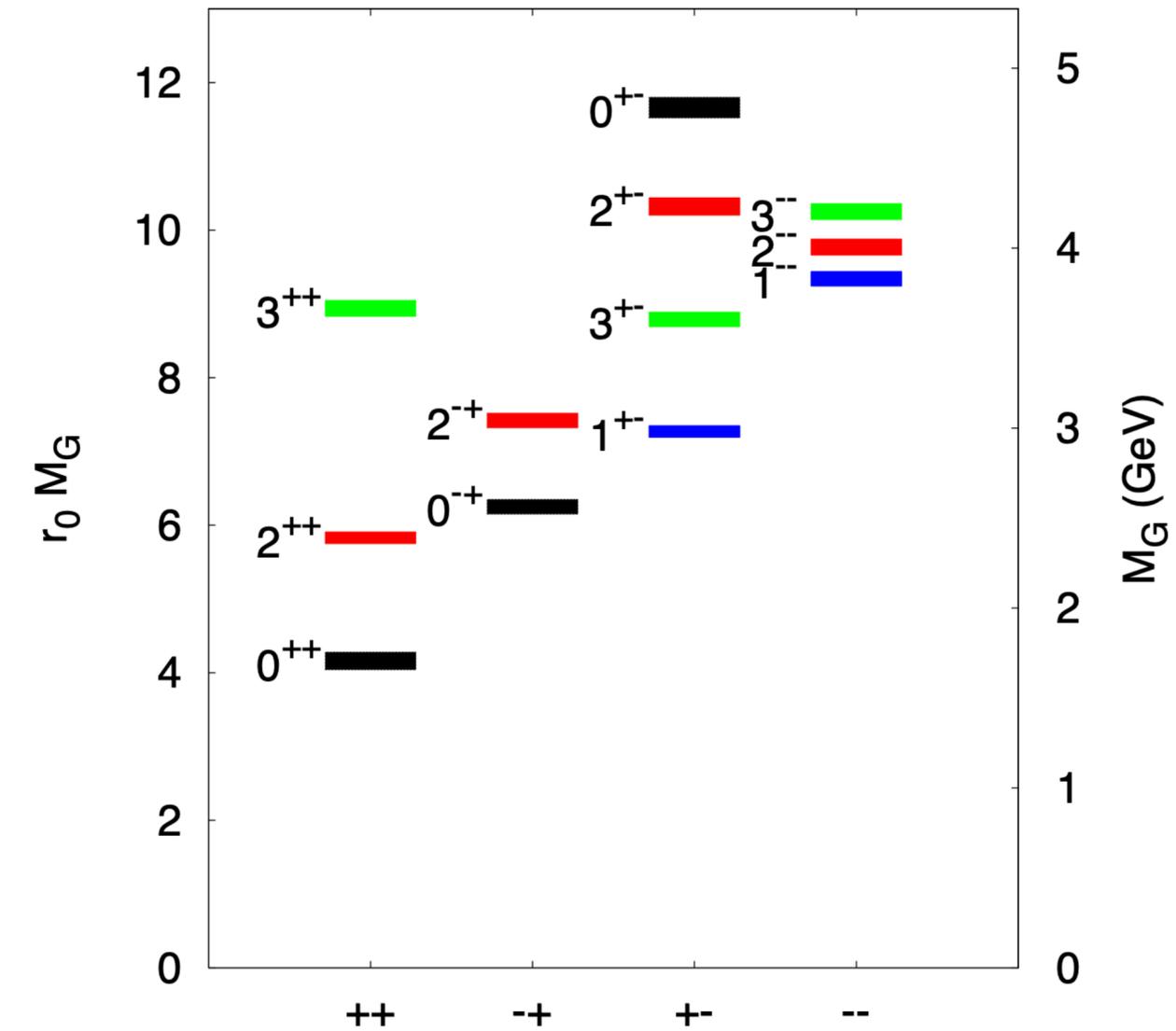
Glueball



Hybrid

Glueball spectrum predictions

- Glueball mass spectrum is predicted in a wide array of non-perturbative approaches (details on the next slide)
- Predictions range for the three lightest glueball states:
 - 0^{++} ground state: $1.5 - 2.0 \text{ GeV}/c^2$
 - 2^{++} ground state: $1.8 - 2.7 \text{ GeV}/c^2$
 - 0^{-+} ground state: $2.1 - 2.6 \text{ GeV}/c^2$
- Glueball widths are much less defined, ranging in predictions from $15 \text{ MeV}/c^2$ to more than $390 \text{ MeV}/c^2$
- LQCD predictions for radiative yields of glueballs:
 - PRL110, 021601 (2013): $Br(J/\psi \rightarrow \gamma G_{0^{++}}) = (3.8 \pm 0.9) \times 10^{-3}$
 - PRL111, 091601 (2013): $Br(J/\psi \rightarrow \gamma G_{2^{++}}) = (11 \pm 2) \times 10^{-3}$
 - PRD100, 054511 (2019): $Br(J/\psi \rightarrow \gamma G_{0^{-+}}) = (0.231 \pm 0.080) \times 10^{-3}$



Unquenched lattice QCD prediction for
glueball mass

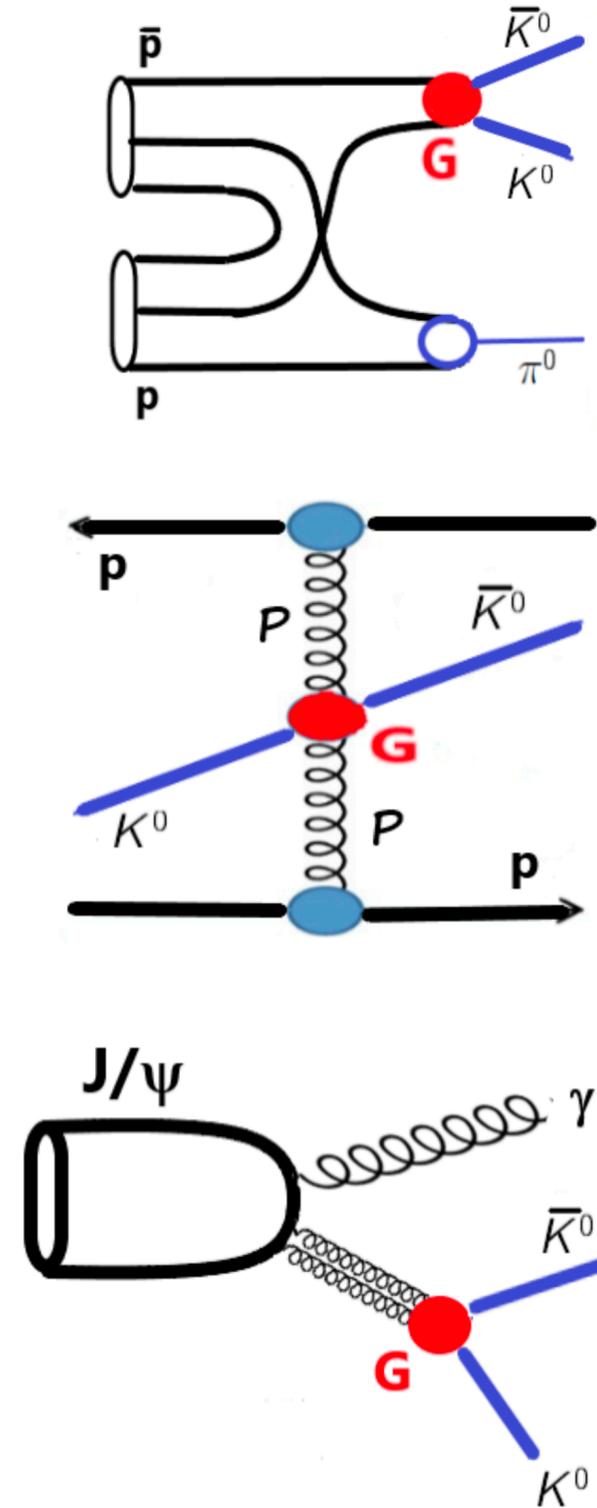
(Phys.Rev.D73 (2006) 014516)

Glueball spectrum predictions

Model	Link to paper	Glueball mass prediction, MeV/c^2		
		$J^{PC} = 0^{++}$	$J^{PC} = 2^{++}$	$J^{PC} = 0^{-+}$
Quenched LQCD	PRD73, 014516(2006) JHEP11, 172(2020)	$1710 \pm 50 \pm 80$ 1653 ± 26	$2390 \pm 30 \pm 120$ 2376 ± 32	$2560 \pm 40 \pm 120$ 2561 ± 40
Unquenched LQCD	JHEP10, 170(2012)	1795 ± 60	2620 ± 50	–
Instanton calculations	PLB577, 61(2003)	~ 1980	~ 2420	~ 2220
Dyson-Schwinger equations	EPJC80, 1077(2020), EPJC81, 1083(2021)	1850 ± 130	2610 ± 180	2580 ± 180
AdS/QCD	PRD104.3, 034016(2021)	~ 1920	~ 2371	–
QCD sum rule	PRD104.9, 094050(2021)	1780^{+140}_{-170}	1860^{+140}_{-170}	2170 ± 110

Glueball production search channels

- $p\bar{p}$ -annihilation
- Central production (Pomeron-Pomeron fusion)
- **Radiative charmonia decays**



EPJCG83, 1125 (2023)

Radiative decays of J/ψ and $\psi(3686)$

Main advantages of these decays specifically:

- Gluon rich environment (due to the $c\bar{c}$ -annihilation)
- Isospin filter: final state is dominated by processes with $I = 0$
- Spin-parity filter: positive C parity is required, allowing for $J^{PC} = 0^{++}, 0^{-+}, 1^{++}, 2^{++}, 2^{-+}, \dots$
- Clean environment for experiments on e^+e^- colliders

As a result, charmonia decays provide amazing environment for the glueball search!

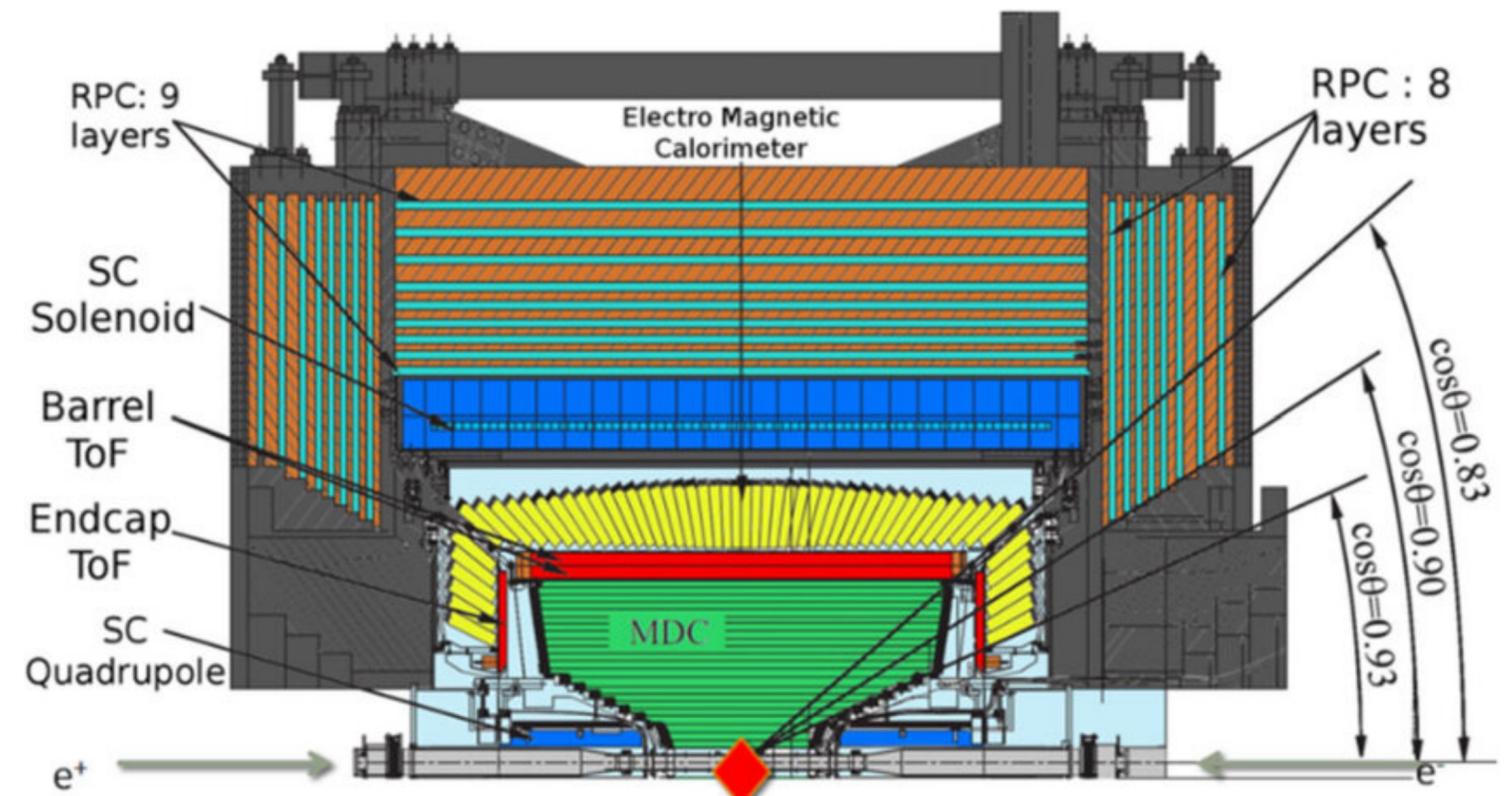
BESIII @ BEPCII — τ -charm factory

BEPCII — e^+e^- collider in Beijing, China:

- Center-of-mass energy range:
 $\sqrt{s} = 1.84 - 4.95 \text{ GeV}/c^2$
- Peak luminosity: $L_{\text{peak}} = 1.1 \times 10^{33} \text{ cm}^{-2}$

BESIII – multi-purpose detector at the interaction point of BEPCII:

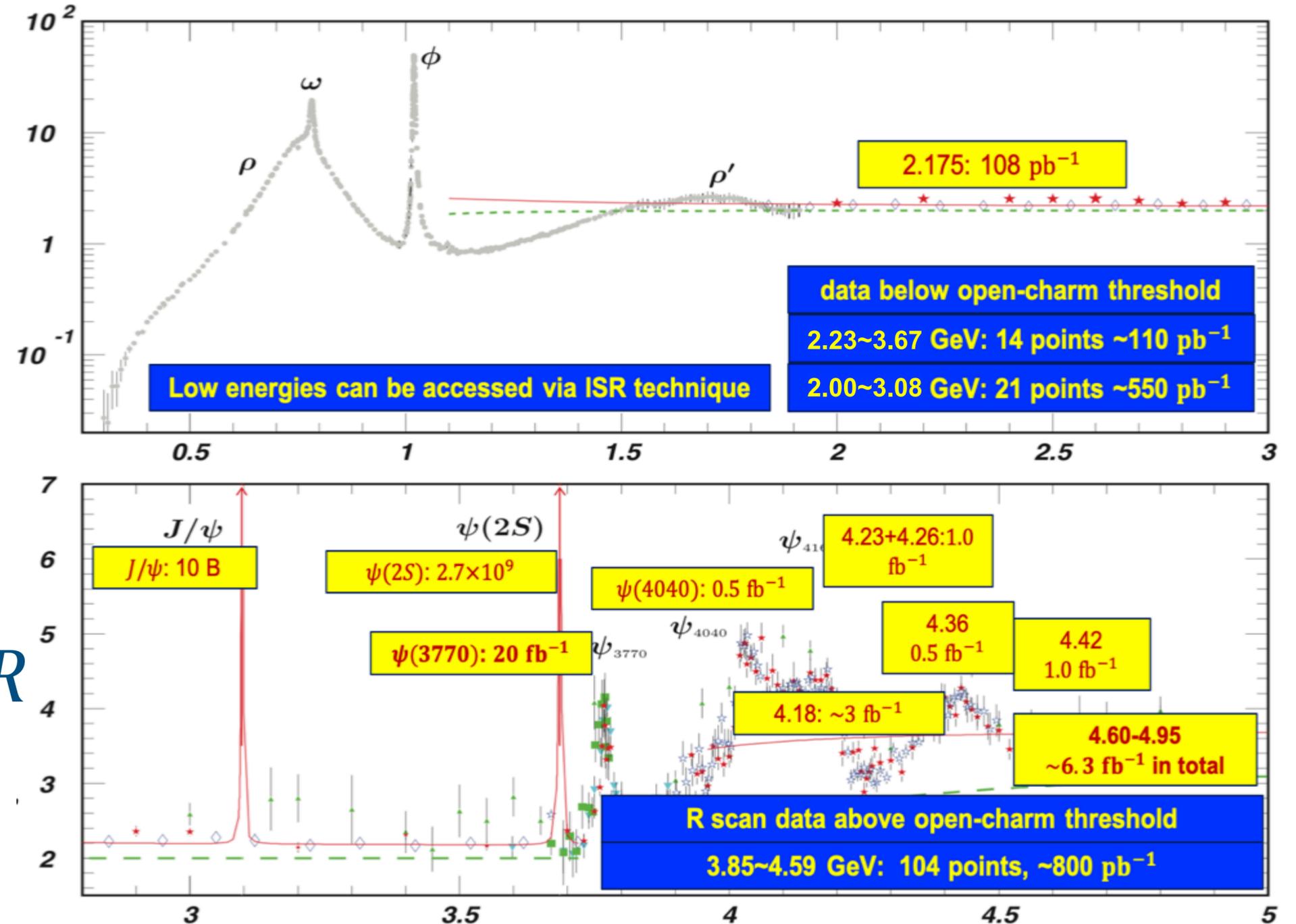
- Charged particle momentum resolution @ 1 GeV/c: 0.5 %
- EMC resolution for photon energies:
 2.5 % @ 1 GeV for barrel region,
 5 % @ 1 GeV for endcap region
- ToF resolution: 68 ps/60 ps, barrel/endcap



BESII data

Collected data sets so far:

- 10×10^9 J/ψ events
- 2.7×10^9 $\psi(3686)$ events
- 20 fb^{-1} $\psi(3770)$
- Scan data:
 $2.00 - 3.08 \text{ GeV}/c^2$ and
 $2.23 - 3.67 \text{ GeV}/c^2$
- Large datasets for XYZ studies above open-charm threshold



Glueball mixing

- One of the main issues in the experimental glueball observation is a mixing of the final states from glueballs and conventional mesons decays
- This is further exasperated by many possible interpretations of the scalar meson spectrum
- Precise determination of meson spectra, their production and decay properties is crucial for identification of glueballs
 - In particular, combined analyses of different production processes and final states can provide the strongest evidence of their existence
- PWA is a must!

Partial wave analysis formalism

- Main idea – decompose decay amplitude into a sum of partial waves with specific angular dependencies

Example – amplitude for radiative decays of J/ψ into the pair of pseudoscalars:

$$U^{M,\lambda_\gamma}(\vec{x}, s) = \sum_{j,J_\gamma} V_{j,J_\gamma}(s) A_{j,J_\gamma}^{M,\lambda_\gamma}(\vec{x})$$

- Likelihood function is constructed based on the specific model and fitted to the data
- Free parameters of the model are obtained as a result of the fit
- Decay amplitude is usually factorised into an angular part and a dynamic part
- Dynamic part of the amplitude contains information about resonance production and decay, as well as interaction dynamics

Dynamic part parametrisation: two approaches

Model-dependent (MD)

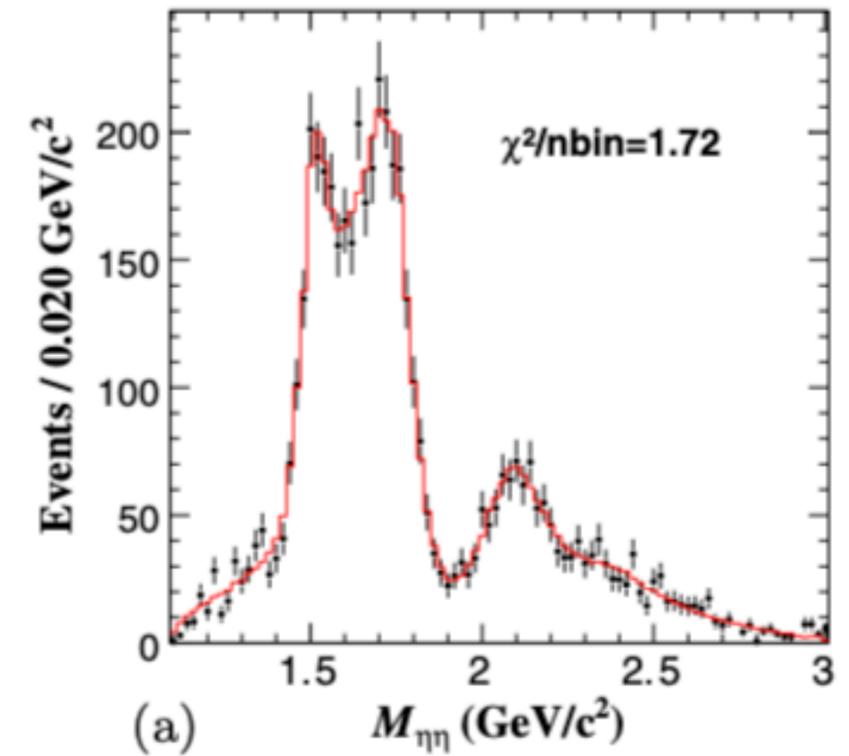
- Dynamic part is described via selected model
- Examples: coherent sum of resonances parameterised via Breit-Wigner functions or K-matrix parameterisation
- **PRO:** Model parameters are tied directly to properties of the scattering amplitude
- **CONTRA:** Limited usability outside of chosen model assumptions

Model-independent (MI)

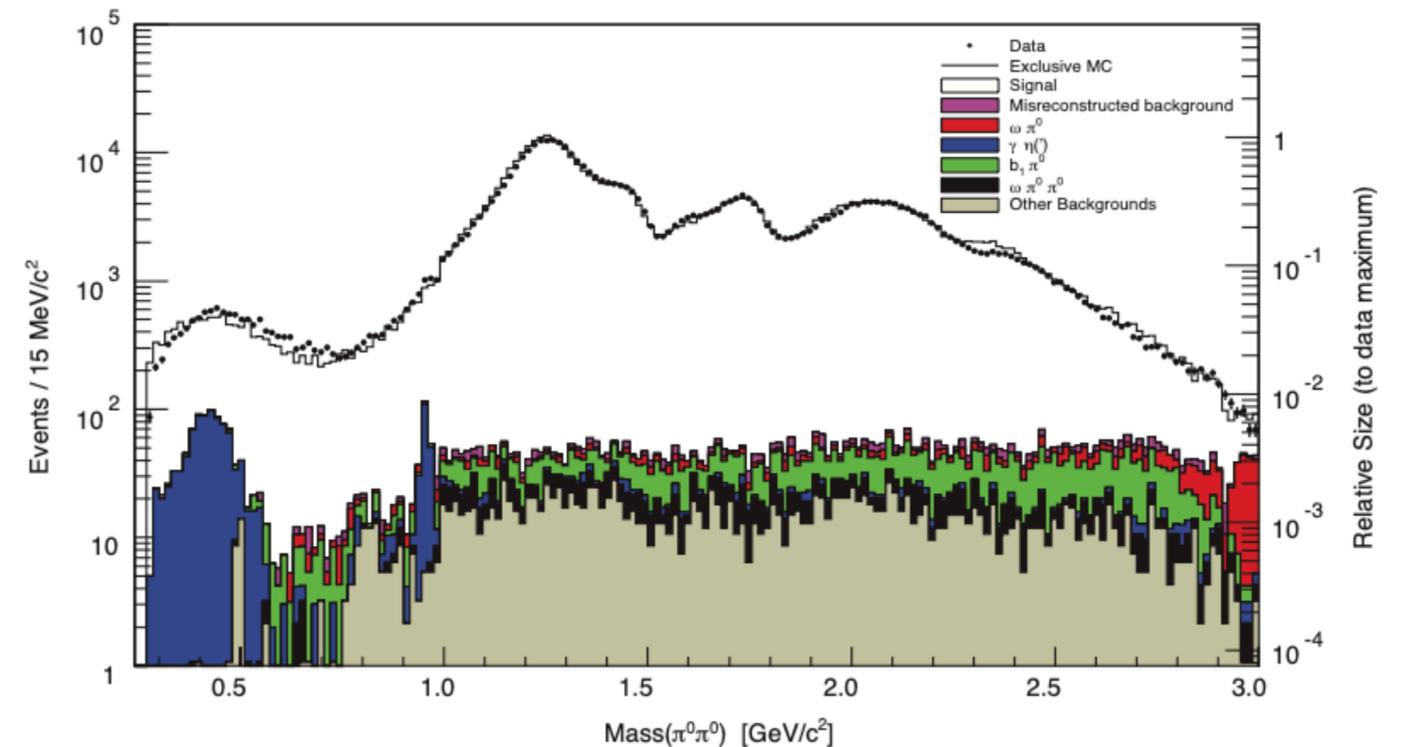
- Dynamic part of the amplitude is measured as a function of the invariant mass of resonance's decay products
- Dynamic part is taken as a constant for each partial wave in each invariant mass bin
- **PRO:** Results could be included in subsequent analyses of multiple channels
- **CONTRA:** Difficult to interpret fit parameters directly

Scalar glueball search

- $J/\psi \rightarrow \gamma X \rightarrow \gamma \eta \eta$, PRD87, 092009 (2013): MD,
 $f_0(1500)$ and $f_0(1710)$ are observed
 $Br(J/\psi \rightarrow \gamma f_0(1500) \rightarrow \gamma \eta \eta) = (1.01 \pm 0.34) \times 10^{-5}$
 $Br(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma \eta \eta) = (4.01 \pm 1.0) \times 10^{-4}$



- $J/\psi \rightarrow \gamma X \rightarrow \gamma \pi^0 \pi^0$, PRD92, 052003 (2015): MI,
 used extensively in subsequent coupled-channel
 analyses



Scalar glueball search

- $J/\psi \rightarrow \gamma X \rightarrow \gamma K_S K_S$, PRD98, 072003 (2018): both MD and MI approaches were used, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ are observed among other resonances

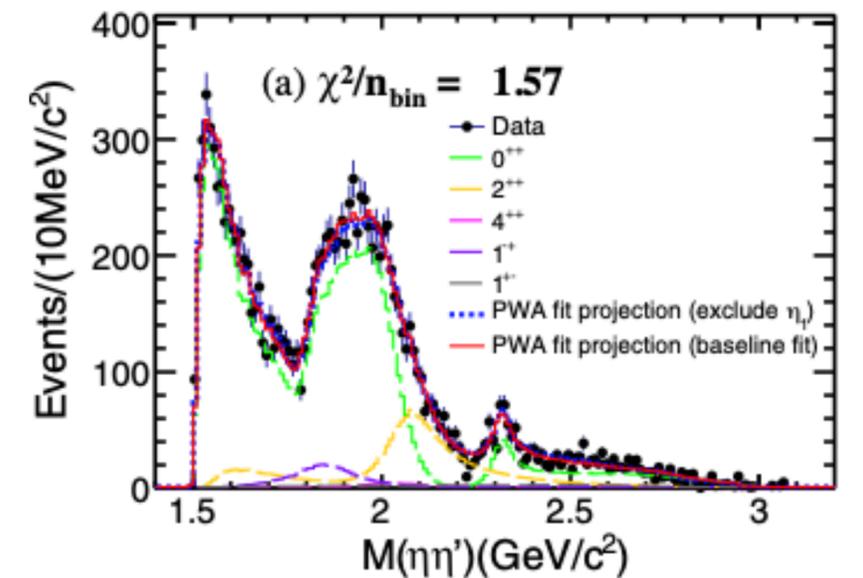
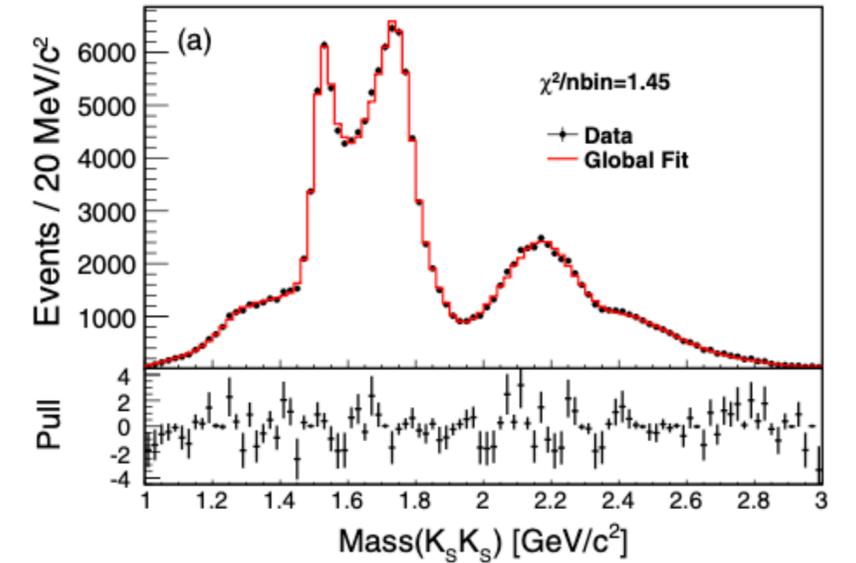
$$Br(J/\psi \rightarrow \gamma f_0(1370) \rightarrow \gamma K_S K_S) = (1.07^{+0.08+0.36}_{-0.07-0.34}) \times 10^{-5}$$

$$Br(J/\psi \rightarrow \gamma f_0(1500) \rightarrow \gamma K_S K_S) = (1.59^{+0.16+0.18}_{-0.16-0.56}) \times 10^{-5}$$

$$Br(J/\psi \rightarrow \gamma f_0(1710) \rightarrow \gamma K_S K_S) = (2.00^{+0.03+0.31}_{-0.02-0.10}) \times 10^{-4}$$

- $J/\psi \rightarrow \gamma \eta \eta'$, PRD106, 072012 (2022), PRL129, 192002 (2022): MD analysis, ratio of branchings points to $f_0(1710)$ having large scalar glueball contribution

$$\frac{Br(f_0(1710) \rightarrow \eta \eta')}{Br(f_0(1710) \rightarrow \pi \pi)} < 1.61 \times 10^{-3} \text{ @ } 90 \% C.L.$$



Scalar glueball search

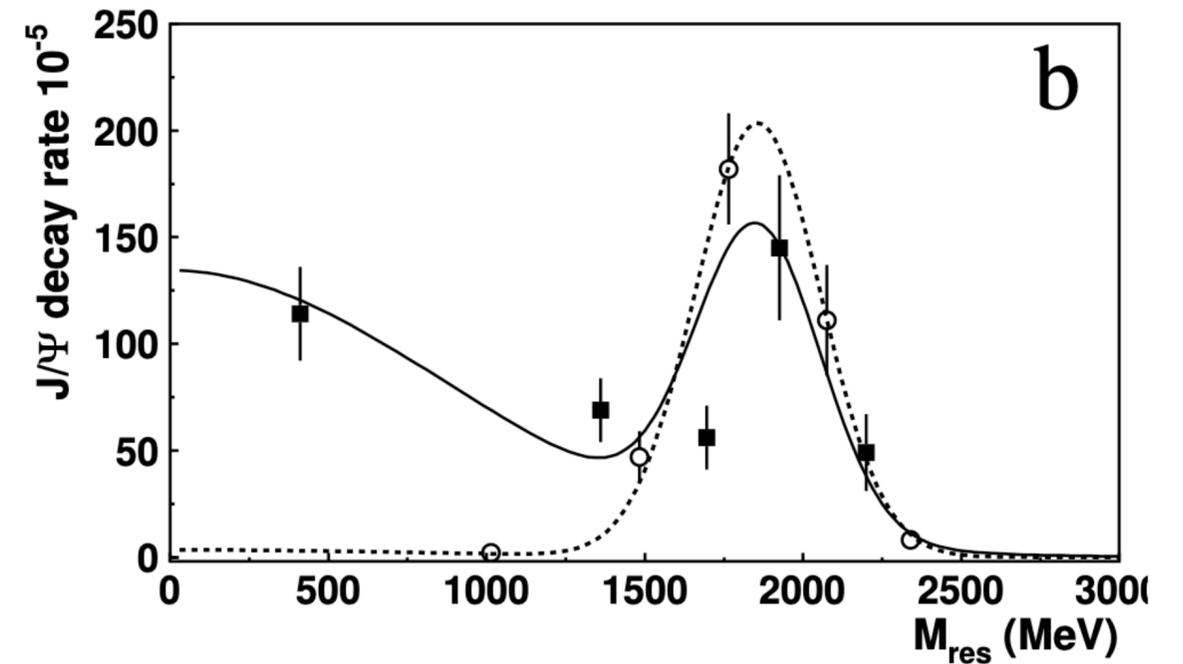
Coupled channel analyses:

- $J/\psi \rightarrow \gamma X; X \rightarrow \eta\eta', \pi\pi, K\bar{K}, \eta\eta, \omega\phi + \pi\pi$ collision data + $\bar{p}N$ annihilation at rest, PLB 816, 136227 (2021), PLB 826, 136906 (2022): MD analysis, K-matrix + Breit-Wigner amplitudes + final state rescattering. Peak structure is observed:

$$M_G = (1865 \pm 25_{-30}^{+10}) \text{ MeV}/c^2, \Gamma_G = (370 \pm 50_{-20}^{+30}) \text{ MeV}/c^2$$

— interpreted as scalar glueball mixing with multiple scalar mesons

- $J/\psi \rightarrow \gamma X; X \rightarrow \pi\pi, K_S K_S$, EPJC 82, 80 (2022): MD analysis, N/D formalism, no restriction for two-meson rescattering amplitudes. No enhancement was observed, $f_0(1710)$ is proposed to have sizeable glueball component



Tensor glueball search

- Tensor glueball candidates were studied in multiple MD analyses:

- $J/\psi \rightarrow \gamma X \rightarrow \gamma\eta\eta$, PRD87, 092009 (2013): $f_2(2340)$ state is observed

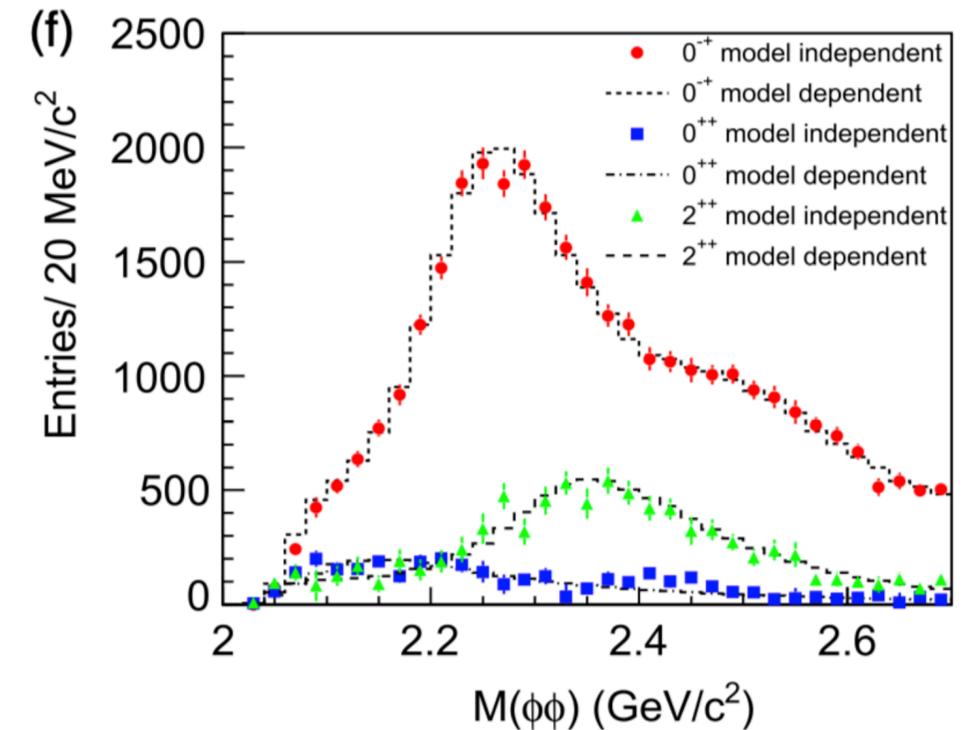
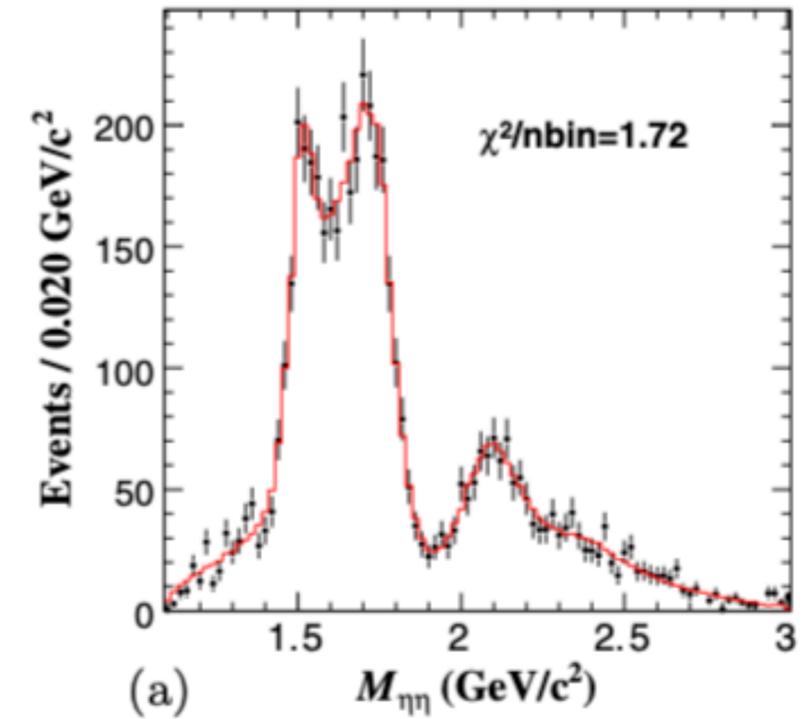
$$Br(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\eta\eta) = (5.60^{+0.62+2.37}_{-0.65-2.07}) \times 10^{-5}$$

- $J/\psi \rightarrow \gamma X \rightarrow \gamma\phi\phi$, PRD93, 112011 (2016): three tensor states with mass above 2 GeV/c^2 are observed

$$Br(J/\psi \rightarrow \gamma f_2(2010) \rightarrow \gamma\phi\phi) = (3.5 \pm 0.5^{+2.8}_{-1.5}) \times 10^{-5}$$

$$Br(J/\psi \rightarrow \gamma f_2(2300) \rightarrow \gamma\phi\phi) = (4.4 \pm 0.7^{+0.9}_{-1.5}) \times 10^{-5}$$

$$Br(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma\phi\phi) = (19.1 \pm 1.4^{+7.2}_{-7.3}) \times 10^{-5}$$



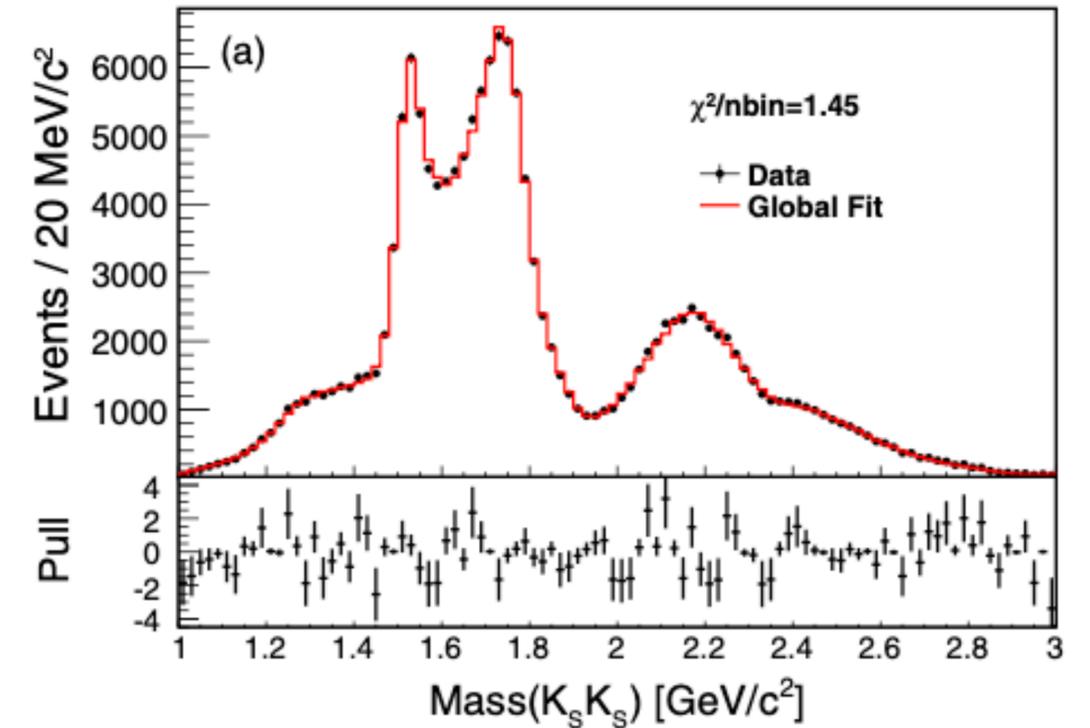
Tensor glueball search

- $J/\psi \rightarrow \gamma X \rightarrow \gamma K_S K_S$, PRD98, 072003 (2018):

$f_2(2340)$ state is observed

$$Br(J/\psi \rightarrow \gamma f_2(2340) \rightarrow \gamma K_S K_S) = (5.54^{+0.34+3.82}_{-0.40-1.49}) \times 10^{-5}$$

- $f_2(2340)$ is a tensor state with mass consistent with a LQCD predictions for the tensor glueball and a substantial yield observed in $\eta\eta$, $\phi\phi$ and $K_S K_S$ final states



Pseudoscalar glueball search

- **Main candidate at the moment — $X(2370)$ state**
- $J/\psi \rightarrow \gamma X \rightarrow \gamma \pi^+ \pi^- \eta'$, PRL106, 072002 (2011): first observation of $X(2370)$

$$M_{X(2370)} = (2376.3 \pm 8.7^{+3.2}_{-4.3}) \text{ MeV}/c^2,$$

$$\Gamma_{X(2370)} = (83 \pm 17^{+44}_{-6}) \text{ MeV}/c^2$$

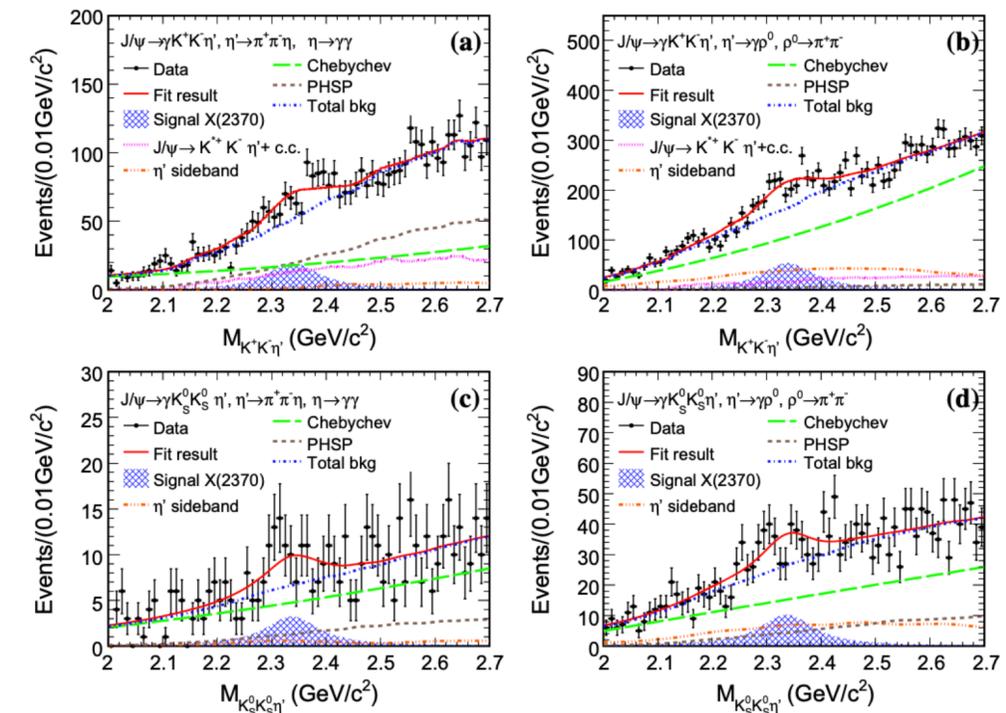
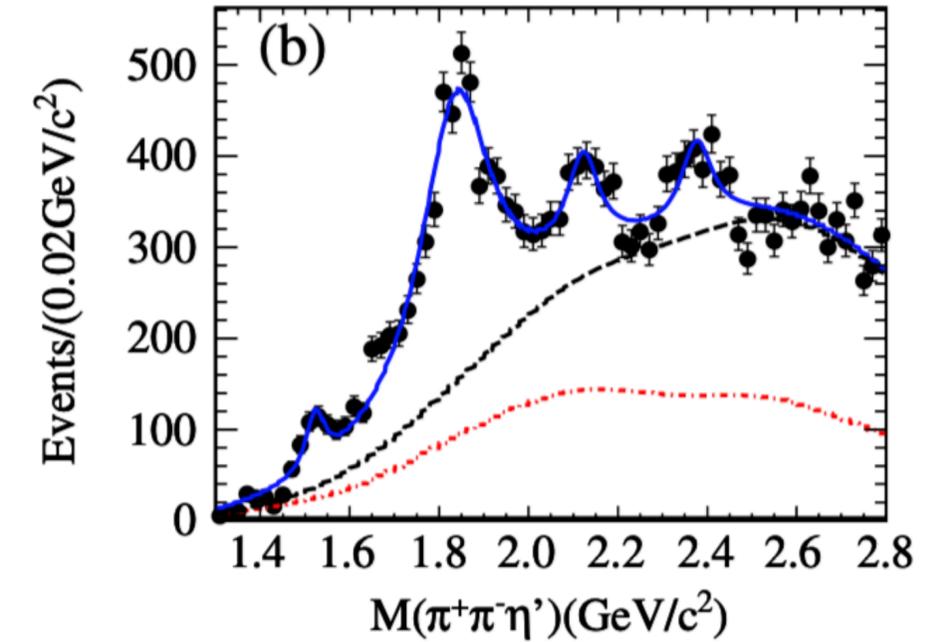
- $J/\psi \rightarrow \gamma X \rightarrow \gamma K \bar{K} \eta'$, EPJC80, 746 (2020): confirmation of $X(2370)$ and branching measurement (mass spectra fit instead of PWA)

$$M_{X(2370)} = (2341.6 \pm 6.5 \pm 5.7) \text{ MeV}/c^2,$$

$$\Gamma_{X(2370)} = (117 \pm 10 \pm 8) \text{ MeV}/c^2,$$

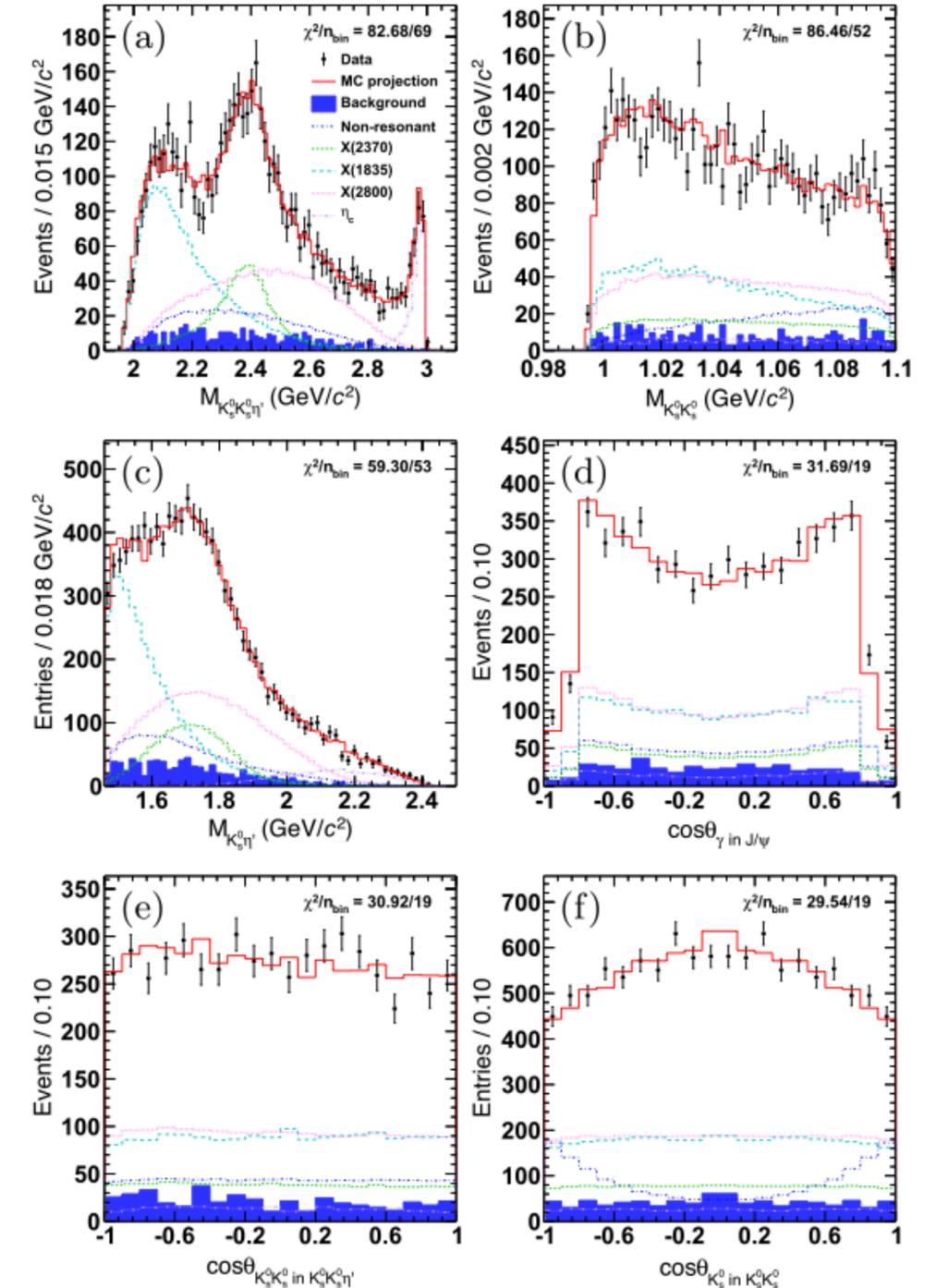
$$Br(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma K^+ K^- \eta') = (1.79 \pm 0.23 \pm 0.65) \times 10^{-5}$$

$$Br(J/\psi \rightarrow \gamma X(2370) \rightarrow \gamma K_S^0 K_S^0 \eta') = (1.18 \pm 0.32 \pm 0.39) \times 10^{-5}$$



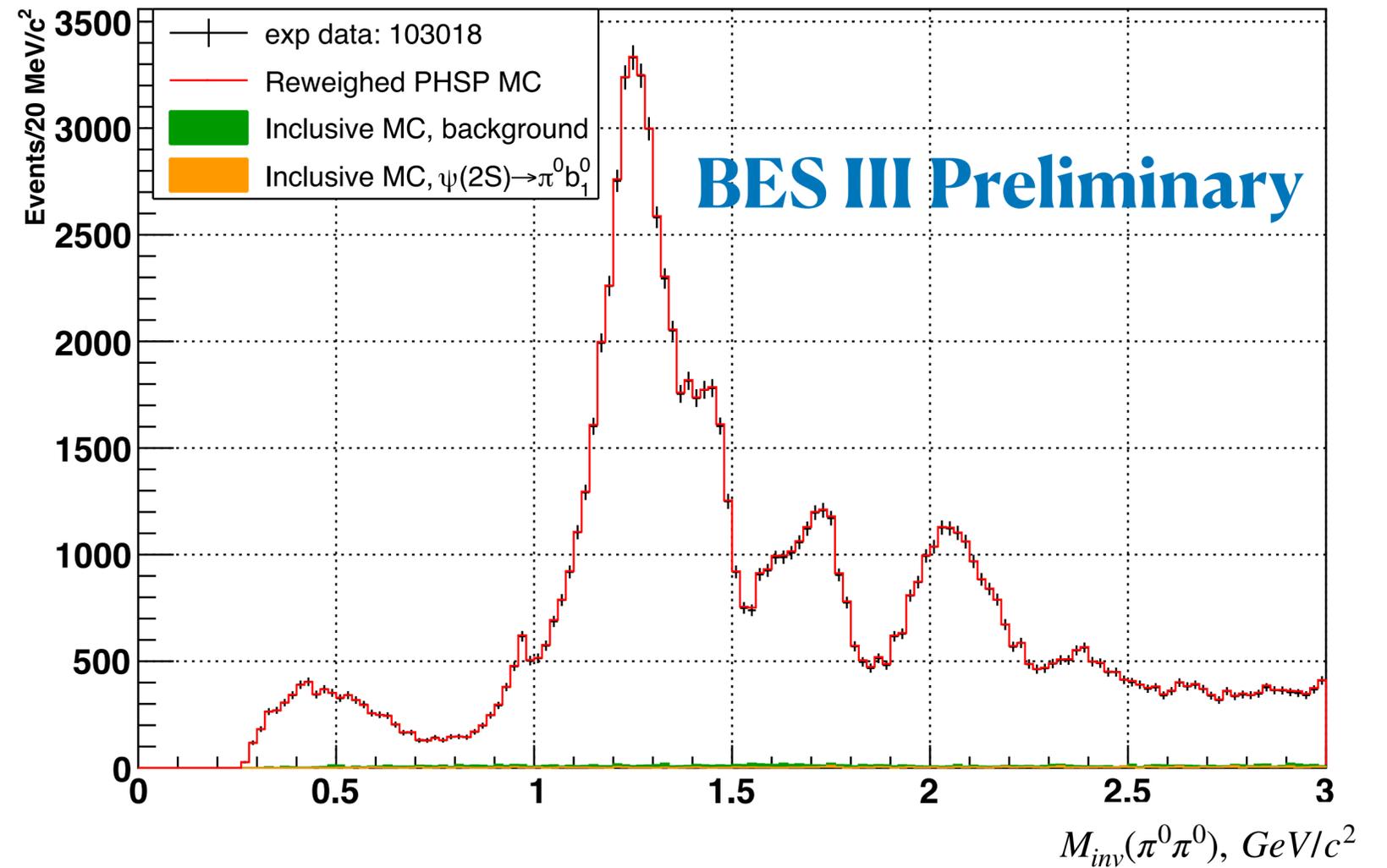
Pseudoscalar glueball search

- $J/\psi \rightarrow \gamma X \rightarrow \gamma K_S^0 K_S^0 \eta'$, PRL132, 181901 (2024): used updated J/ψ dataset, determined quantum numbers of $X(2370)$ to be 0^{-+}
 $M_{X(2370)} = (2395 \pm 11^{+26}_{-94}) \text{ MeV}/c^2$,
 $\Gamma_{X(2370)} = (188^{+18+124}_{-17-33}) \text{ MeV}/c^2$
- Currently, there are no observations which contradict the hypothesis of $X(2370)$ state being a pseudoscalar glueball



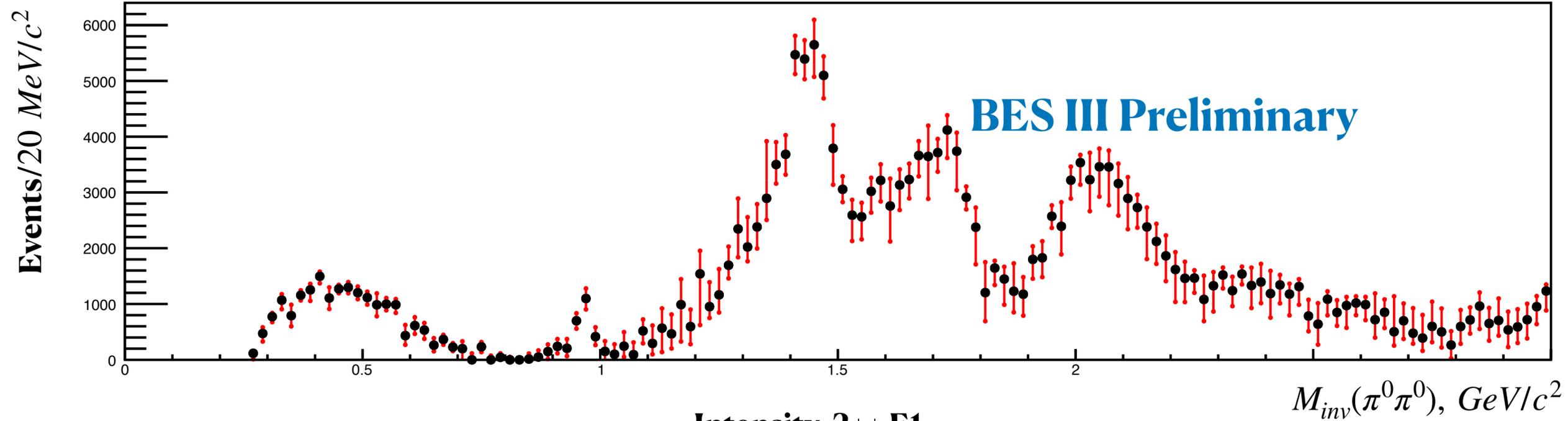
Study of radiative $\psi(3686)$ decays (Preliminary)

- 2.7×10^9 $\psi(3686)$ decays now allow for precise amplitude analyses
- Benefits of $\psi(3686)$ decays:
 - Availability of higher invariant mass region
 - Less restrictions due to the available phase space volume in comparison to J/ψ , especially in energy region 2.0 – 3.0 GeV
- MI approach is being used



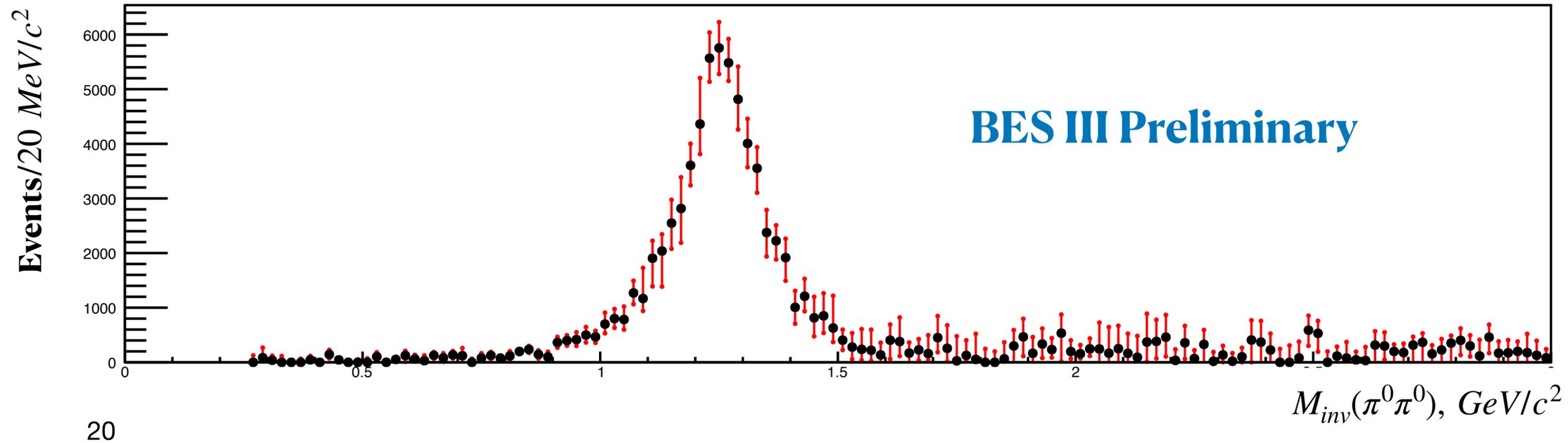
PWA Results

Intensity, 0^{++} E1



**Black dots — PWA results,
red bars — 1σ confidence
intervals**

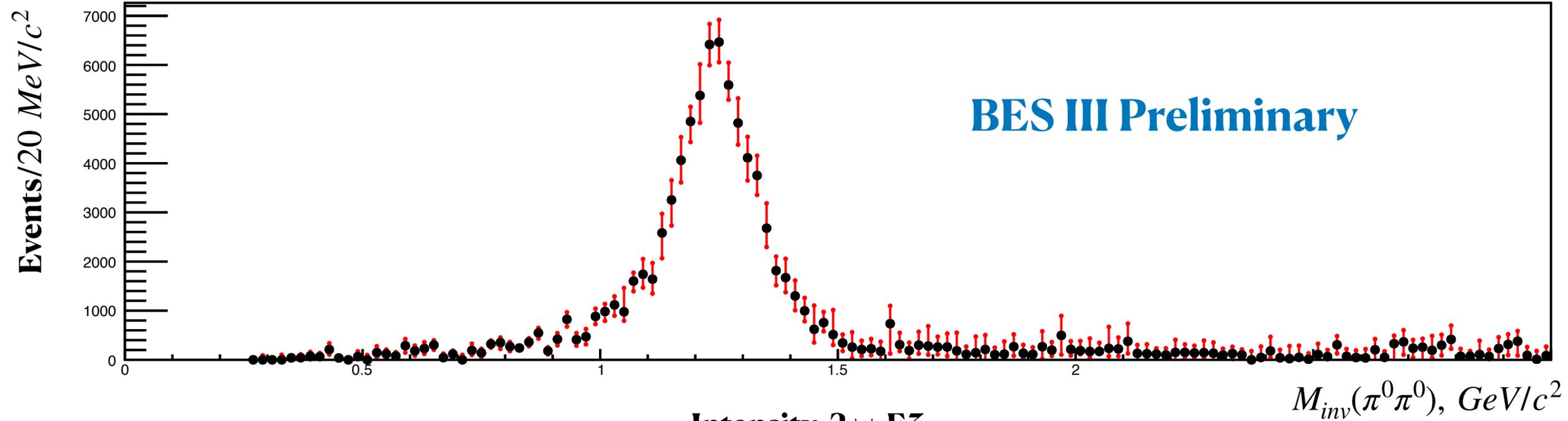
Intensity, 2^{++} E1



**Tensor waves above 2.0
GeV are consistent with
zero, no evidence for
tensor glueball is
observed in MI results**

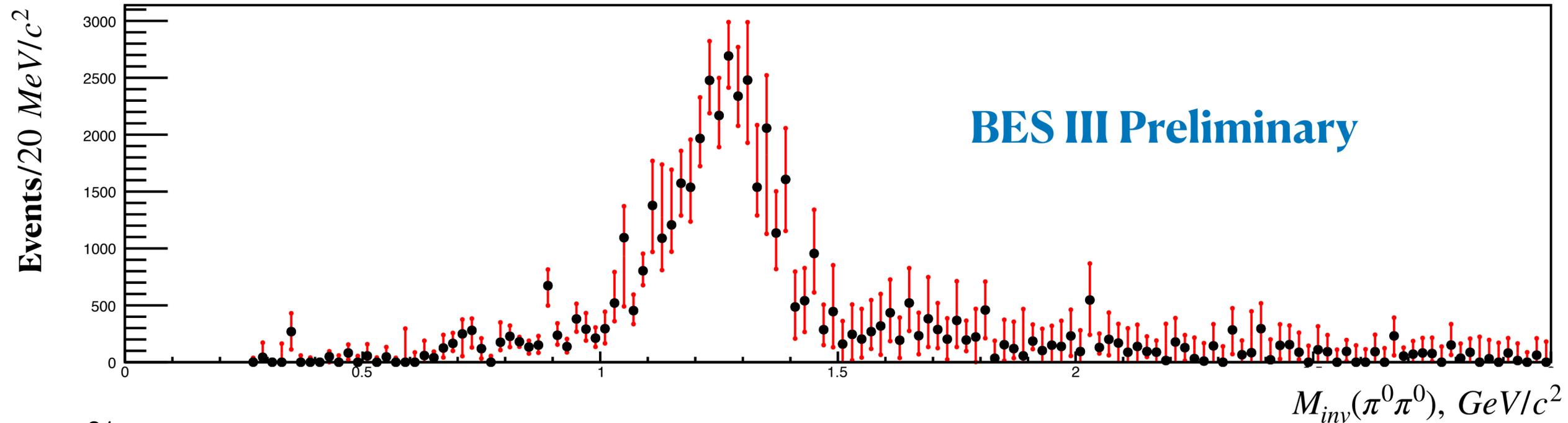
PWA Results

Intensity, 2^{++} M2



**Black dots — PWA results,
red bars — 1σ confidence
intervals**

Intensity, 2^{++} E3



**Tensor waves above 2.0
GeV are consistent with
zero, no evidence for
tensor glueball is
observed in MI results**

Summary

- The existence of glueballs is predicted by QCD and their properties are predicted in wide array of non-perturbative approaches to QCD
- The BESIII collaboration has acquired unprecedented datasets of both J/ψ and $\psi(3686)$ decays
- BESIII studies of radiative J/ψ decays yielded precise measurements of light scalar mesons spectrum, indicating the scalar glueball mixing with multiple scalar states
- In the tensor meson spectrum, there are candidates observed with masses consistent with the predictions for tensor glueball mass and substantial yields
- In the pseudoscalar meson spectrum, the $X(2370)$ state is the primary glueball candidate
- Subsequent studies of the $\psi(3686)$ decays dataset would be of great interest for further searches for glueball states, especially for tensor and pseudoscalar ones



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Thank you for your attention!