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Light QCD exotics at BESIII

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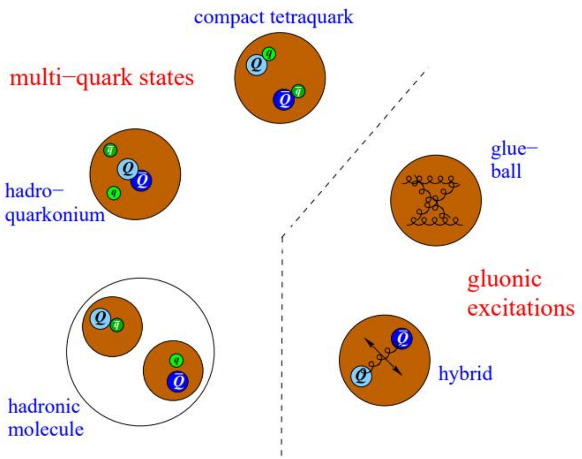
第二十一届全国重味物理和CP破坏研讨会，衡阳

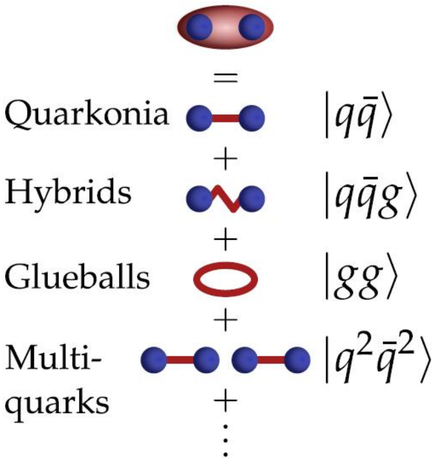
light QCD physics

- Well-known classes of hadrons: meson($q\bar{q}$), baryon(qqq)
- Key things to search for: additional degree of freedom
  - **•Multi-quark states ; Hybrids ; Glueballs**
  - •Strong evidences for multi-quark in heavy quark sector
    - A new "particle zoo": https://qwg.ph.nat.tum.de/exoticshub/
  - •Evidence for gluonic excitations remains sparse

Phys.Rept. 873 (2020) 1



- **Light meson spectroscopy**
  - •Key tool to study/develop QCD in non-perturbative region



Identification is challenging

Manifestly exotic: with forbidden QN

Flavor exotic : $Z_c, T_{cc}, T_{\psi\psi}....$

Spin exotic: $J^{PC} = 0^{--}, even^{+-}, odd^{-+}$

Crypto exotic : with QN as $q\bar{q}$

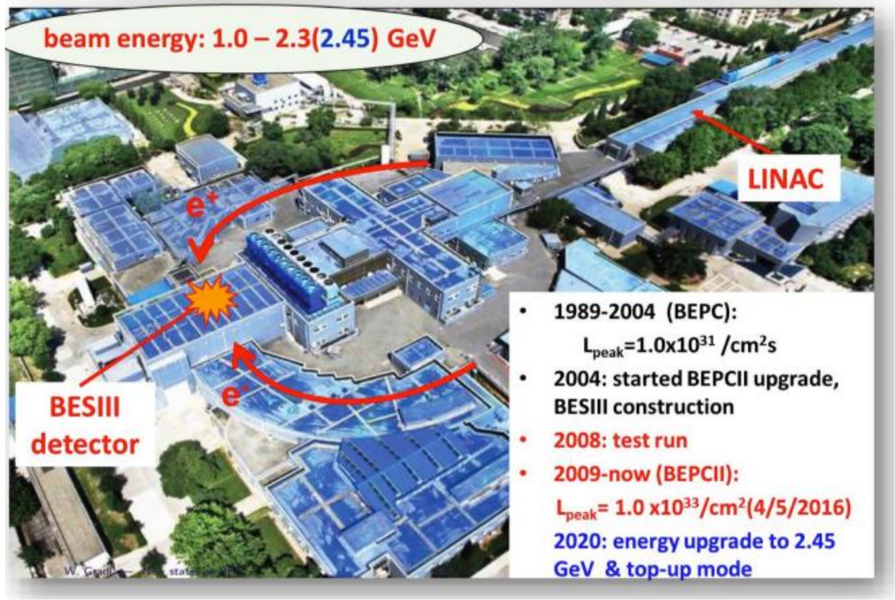
Supernumerary states

Abnormal properties

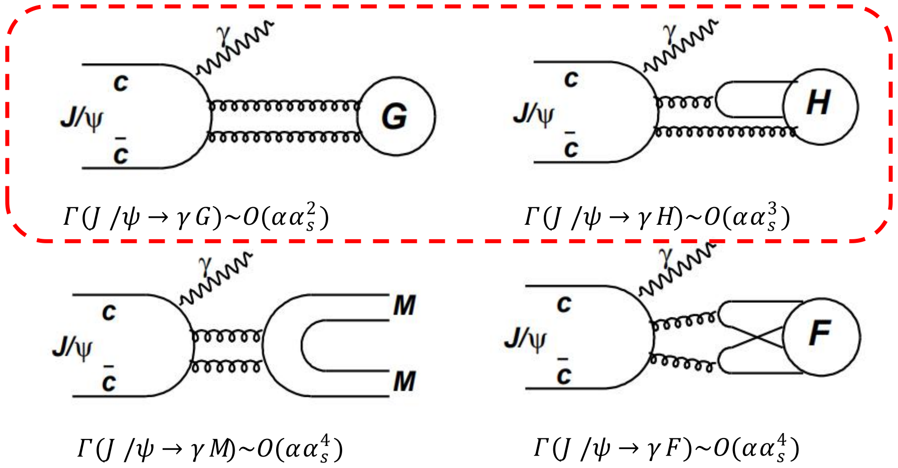
+ Kinematic effects

World's Largest τ –charm Data Sets in e^+e^- Annihilation

Beijing Electron Positron Collider (BEPCII)



$$\Gamma(J/\psi \to \gamma G) > \Gamma(J/\psi \to \gamma H) > \Gamma(J/\psi \to \gamma M) \geq \Gamma(J/\psi \to \gamma F)$$



Glueballs and hybrids are expected to have a larger yield compared to mesons.

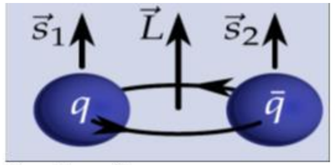
Charmonium radiative decays provide an ideal laboratory for gluonic states

- Gluon-rich process
- Well defined initial and final states
  - Kinematic constraints
  - I (J^{PC}) filter : final states dominated by I=0 processes and C parity must be +
- Clean high statistics data sample : 10×10^9 J/ψ and 2.9×10^9 $\psi(2S)$ @BESIII

Light hadrons with exotic quantum numbers

- **Unambiguous signature for exotics**
  - ✓ Light Flavor-exotic hard to establish
  - ✓ Efforts concentrate on Spin-exotic
    - Forbidden for for $(q\bar{q})$: 0^{--}, $even^{+-}$, odd^{-+}

Detailed reviews: PRC 82, 025208 (2010)，PPNP 82, 21 (2015)



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

Allowed J^{PC}: $0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 2^{++}, \ldots$

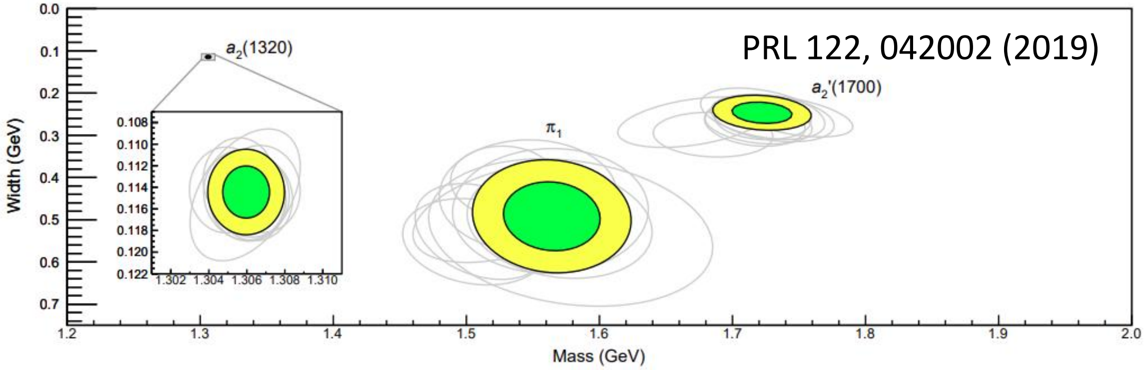
- **Only 3 spin exotic candidate so far ⇒ all 1^{-+} isovectors :**

$\pi_1(1400)$: seen in $\eta\pi$

$\pi_1(1600)$: seen in $\rho\pi, \eta'\pi, b_1\pi, f_1\pi$

$\pi_1(2015)$: seen in $b_1\pi, f_1\pi$ ⇒ needs confirmation

✓ $\pi_1(1400), \pi_1(1600)$ can be one pole



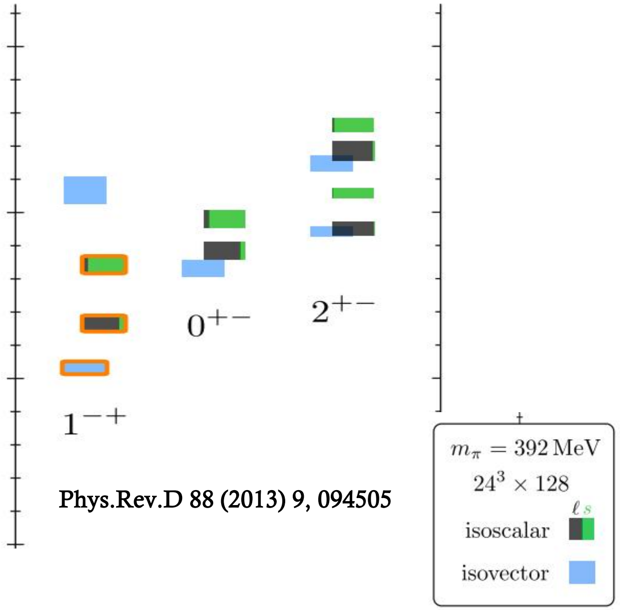
	Decay mode	Reaction	Experiment
$\pi_1(1400)$	$\eta\pi$	$\pi^- p \to \pi^- \eta p$ $\pi^- p \to \pi^0 \eta n$ $\pi^- p \to \pi^- \eta p$ $\pi^- p \to \pi^0 \eta n$ $\bar{p}n \to \pi^- \pi^0 \eta$ $\bar{p}p \to \pi^0 \pi^0 \eta$	GAMS KEK E852 E852 CBAR CBAR
	$\rho\pi$	$\bar{p}p \to 2\pi^+ 2\pi^-$	Obelix
$\pi_1(1600)$	$\eta'\pi$	$\pi^- Be \to \eta' \pi^- \pi^0 Be$ $\pi^- p \to \pi^- \eta' p$	VES E852
	$b_1\pi$	$\pi^- Be \to \omega \pi^- \pi^0 Be$ $\bar{p}p \to \omega \pi^+ \pi^- \pi^0$ $\pi^- p \to \omega \pi^- \pi^0 p$	VES CBAR E852
	$\rho\pi$	$\pi^- Pb \to \pi^+ \pi^- \pi^- X$ $\pi^- p \to \pi^+ \pi^- \pi^- p$	COMPASS E852
	$f_1\pi$	$\pi^- p \to p \eta \pi^+ \pi^- \pi^-$ $\pi^- A \to \eta \pi^+ \pi^- \pi^- A$	E852 VES
$\pi_1(2015)$	$f_1\pi$	$\pi^- p \to \omega \pi^- \pi^0 p$	E852
	$b_1\pi$	$\pi^- p \to p \eta \pi^+ \pi^- \pi^-$	

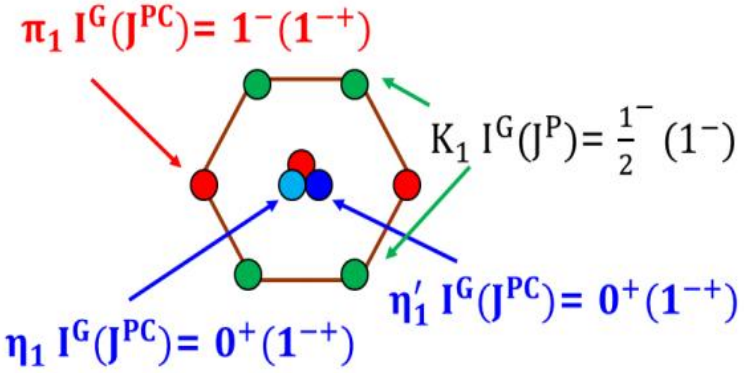
Light hadrons with exotic quantum numbers

- Lightest spin-exotic: 1^{-+} **hybrid** $\Longrightarrow$ $1.7 \sim 2.1 GeV/c^2$
- Isoscalar 1^{-+} is critical to establish the hybrid nonet
  - Can be produced in the gluon-rich charmonium decays
  - Can decay to $\eta\eta'$ in P-wave

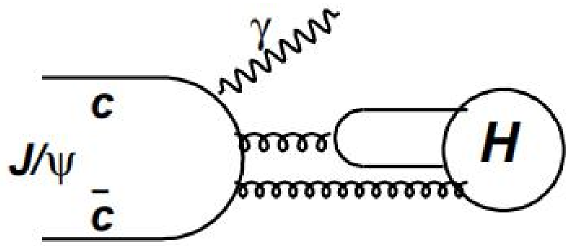
[PRD 83,014021 (2011), PRD 83,014006 (2011), EP.J.P 135, 945(2020)]

LQCD prediction for Exotic Hybrids





Search for $\eta_1(1^{-+})$ in $J/\psi \to \gamma\eta\eta'$



$\Gamma(J/\psi \to \gamma H) \sim O(\alpha\alpha_s^3)$

Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi \to \gamma\eta\eta'$

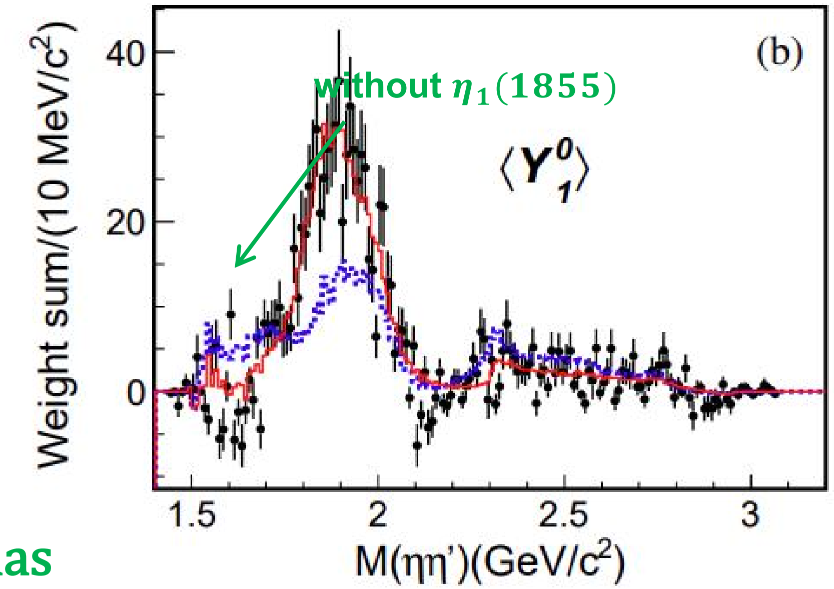
- An isoscalar 1^{-+} state, $\eta_1(1855)$, has been observed with statistical significance larger than 19σ

PRL 129, 192002 (2022) ; PRL 130, 159901 (2023) (erratum)
PRD 106,072012 (2022) ; PRD 107,079901 (2023) (erratum)

$$M = (1855 \pm 9^{+6}_{-1})\ MeV/c^2;\quad \Gamma = (188 \pm 18 \pm^{+3}_{-8})\ MeV$$

$$B(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$

- Mass is consistent with hybrid on LQCD



- Inspired many interpretations:
  - Hybrid? Molecule? Tetraquark?

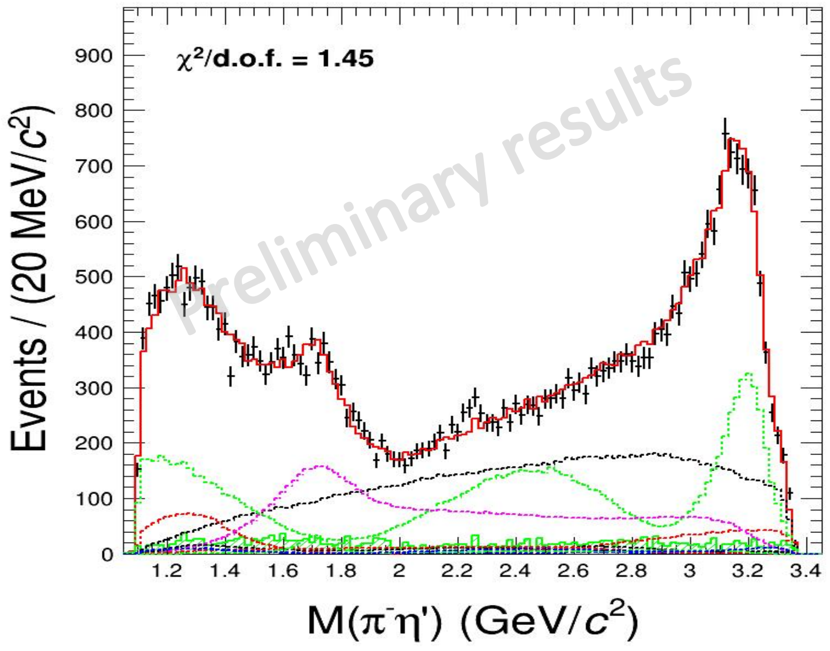
- Further more, suppression of $f_0(1710) \to \eta\eta'$ supports it has a large overlap with glueball

$$\frac{Br(f_0(1500) \to \eta\eta')}{Br(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1} \qquad \frac{Br(f_0(1710) \to \eta\eta')}{Br(f_0(1710) \to \pi\pi)} < 2.7 \times 10^{-3} @90\% C.L$$

Opens a new direction to completing the picture of spin-exotics

Observation of $\pi_1(1600)$ in $\chi_{c1} \to \eta'\pi^+\pi^-$

2.7×10^9 $\psi(3686)$ @BESIII [preliminary]



- **Amplitude analysis of $\chi_{c1} \to \eta'\pi^+\pi^-$ is performed**
- **$\pi_1(1600)$ is observed with significances > 17σ**
- **The J^{PC} of $\pi_1(1600)$ is measured to be exotic 1^{-+}**
  - ✓ better than other assignments
- **With significant Breit-Wigner phase motion**
  - ✓ Evidence of $\pi_1(1600) \to \eta'\pi$ at CLEO-c is confirmed

[PR D84 112009 (2011)]

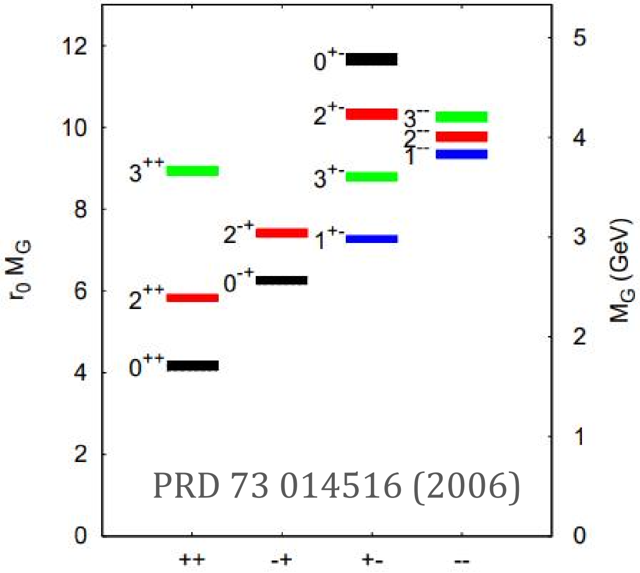
source	M (MeV/c^2)	Γ (MeV)	$\mathcal{B}[\chi_{c1} \to \pi_1^{\pm}\pi^{\mp}] \times \mathcal{B}[(\pi_1^{\pm} \to \eta'\pi^{\pm}]$ ($\times 10^{-4}$)
CLEO-c [2]	$1670 \pm 30 \pm 20$	$240 \pm 50 \pm 60$	$2.9 \pm 0.5 \pm 0.6 \pm 0.1$
Our	$1711 \pm 10(\text{stat})^{+113}_{-6}(\text{syst})$	$404 \pm 16(\text{stat})^{+104}_{-11}(\text{syst})$	$4.10 \pm 0.12(\text{stat})^{+0.39}_{-0.29}(\text{syst})$

Observations of π_1 and η_1 in charmonium decays provide a new path to study 1^{-+}

Glueball

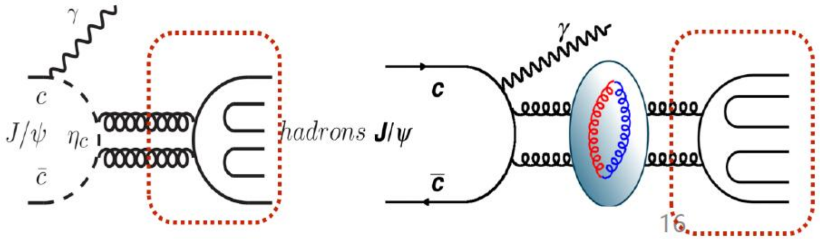
- **Glueballs: the most direct prediction of QCD**
  - Color singlets emerge as a consequence of the gluon self interactions
- **Low-lying glueballs with ordinary J^{PC} $(0^{++}, 2^{++}, 0^{-+})$**
  - gluon is flavor-blind⇨No dominate decay mode⇨mixing with nearby $q\bar{q}$
  - Could be analogy to OZI suppressed decays of charmoniums

  [PLB 380 189(1996), Commu. Theor. Phys. 24.373(1995)]

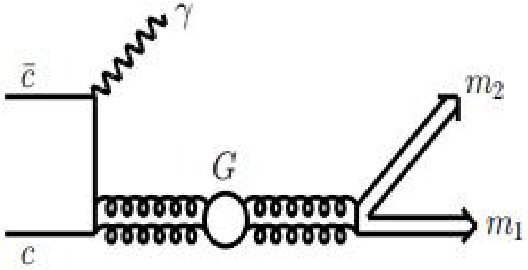


Light Yang-Mills glueballs on lattice (quenched and unquenched results)

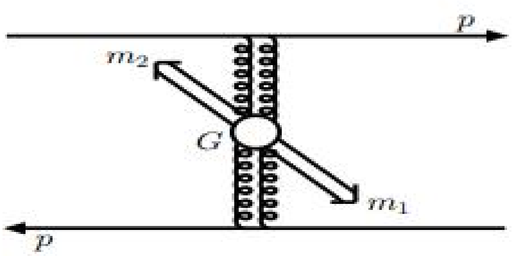
- **Non $q\bar{q}$ nature difficult to be established**
  - ✓ Overpopulation, but QM assignment is difficult
  - ✓ Identification is model-dependent
  - ⇒**Systematical study is needed in the identification**



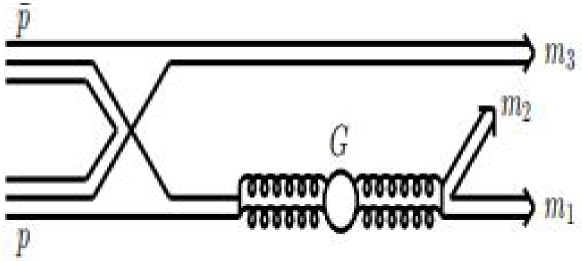
[PLB 380 189(1996),Commu. Theor. Phys. 24.373(1995)]



Charmonium decays: BESIII，MARKIII.....



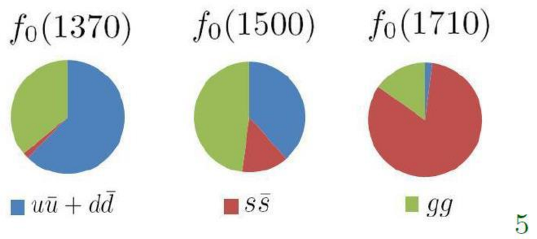
pp double-Pomeron exchange: WA102, GAMS…

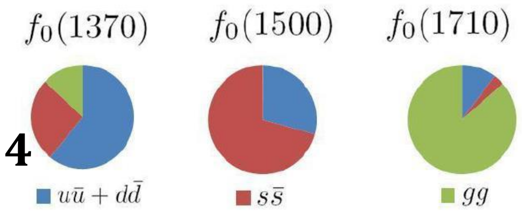


$p\bar{p}$ annihilation: Crystal barrel, OBELIX…

Scalar Glueball

Close and Kirk, PLB483 (2000) 345





- **Observed $f_0(1370)$, $f_0(1500)$, $f_0(1710)$**
  - ✓ Supernumerary scalars suggest additional degrees of freedom
  - ✓ However, mixing scenarios are controversial
- **Flavor-blindness of glueball decays**

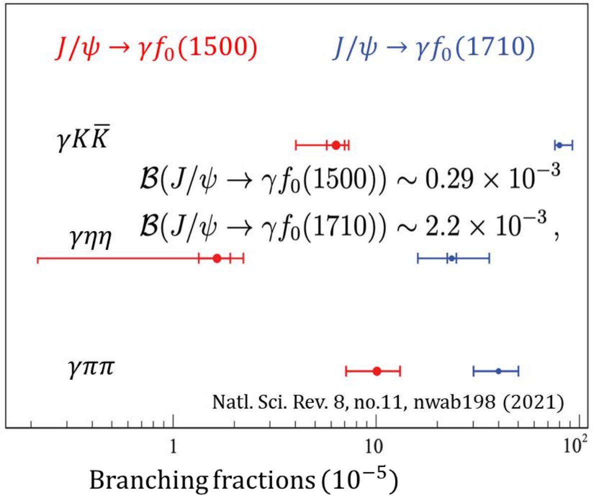
  $\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta') = 3:4:1:0:1$

  - $G \to \eta\eta'$ decay is expected to be suppressed
  - Scalar glueball expected to be suppressed $\Gamma(G \to \eta\eta')/\Gamma(G \to \pi\pi) < 0.04$

    [PR D 92, 121902; PR D 92, 114035]

- **$f_0(1710)$: mass consistent with LQCD**
  - Measured $B(J/\psi \to \gamma f_0(1710))$ is x10 larger than $f_0(1500)$

    BESIII [PRD 87 092009, PRD 92 052003, PRD 98 072003]



- **New inputs from $J/\psi \to \gamma\eta\eta'$**
- **Significant $f_0(1500)$**

$$\frac{Br(f_0(1500) \to \eta\eta')}{Br(f_0(1500) \to \pi\pi)} = (1.66^{+0.42}_{-0.40}) \times 10^{-1}$$

PRL 129, 192002 (2022) ; PRL 130, 159901 (2023) (erratum)
PRD 106,072012 (2022) ; PRD 107,079901 (2023) (erratum)

- **Absence of $f_0(1710)$**

$$\frac{Br(f_0(1710) \to \eta\eta')}{Br(f_0(1710) \to \pi\pi)} < 2.7 \times 10^{-3} @90\%C.L$$

Supports to the hypothesis that $f_0(1710)$ overlaps with the ground state scalar glueball

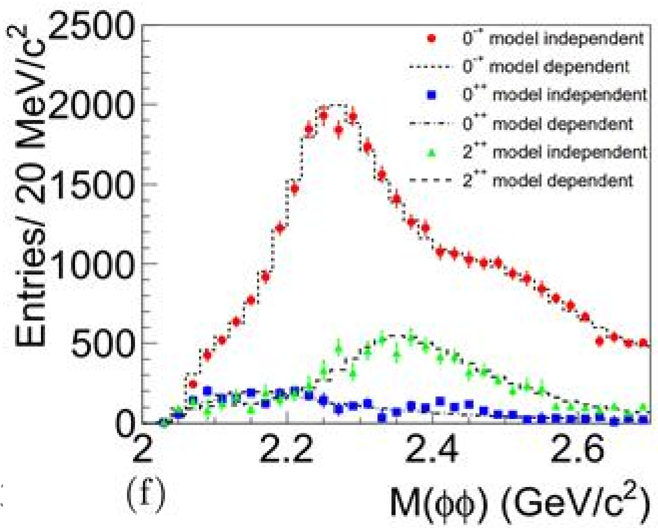
Tensor Glueball

$$\Gamma(J/\psi \to \gamma G_{2+}) = 1.01(22)keV$$

$$\Gamma(J/\psi \to \gamma G_{2+})/\Gamma_{tot} = 1.1 \times 10^{-2}$$

CLQCD, Phys. Rev. Lett. 111, 091601 (2013)

BESIII $J/\psi \to \gamma\phi\phi$ with 1.3B J/ψ



- $f_2(2340)$: consistent with LQCD's calculation for the mass of a tensor glueball

- Experimental results

$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta\eta) = (3.8^{+0.62}_{-0.65}{}^{+2.37}_{-2.07}) \times 10^{-5}$ BESIII PRD 87,092009 (201:

$Br(J/\psi \to \gamma f_2(2340) \to \gamma\phi\phi) = (1.91 \pm 0.14^{+0.72}_{-0.75}) \times 10^{-4}$ BESIII PRD 93, 112011 (2016)

$Br(J/\psi \to \gamma f_2(2340) \to \gamma K_s^0 K_s^0) = (5.54^{+0.34}_{-0.40}{}^{+3.82}_{-1.49}) \times 10^{-5}$ BESIII PRD 98,072003 (2018)

$Br(J/\psi \to \gamma f_2(2340) \to \gamma\eta'\eta') = (8.67 \pm 0.7^{+0.16}_{-1.67}) \times 10^{-6}$ BESIII PRD 105,072002 (2022)

Resonance	M(MeV/c^2)	Γ(MeV/c^2)	B.F.($\times 10^{-4}$)	Sig.
$\eta(2225)$	$2216^{+4}_{-5}{}^{+21}_{-11}$	$185^{+12}_{-14}{}^{+43}_{-17}$	$(2.40 \pm 0.10^{+2.47}_{-0.18})$	28 σ
$\eta(2100)$	$2050^{+30}_{-24}{}^{+75}_{-26}$	$250^{+36}_{-30}{}^{+181}_{-164}$	$(3.30 \pm 0.09^{+0.18}_{-3.04})$	22 σ
$X(2500)$	$2470^{+15}_{-19}{}^{+101}_{-23}$	$230^{+64}_{-35}{}^{+56}_{-33}$	$(0.17 \pm 0.02^{+0.02}_{-0.08})$	8.8 σ
$f_0(2100)$	2101	224	$(0.43 \pm 0.04^{+0.24}_{-0.03})$	24 σ
$f_2(2010)$	2011	202	$(0.35 \pm 0.05^{+0.28}_{-0.15})$	9.5 σ
$f_2(2300)$	2297	149	$(0.44 \pm 0.07^{+0.09}_{-0.15})$	6.4 σ
$f_2(2340)$	2339	319	$(1.91 \pm 0.14^{+0.72}_{-0.73})$	11 σ
0^{-+} PHSP			$(2.74 \pm 0.15^{+0.16}_{-1.48})$	6.8 σ

- More complicated due to the large number of tensor states in the mass region of 2.3GeV
  - More decay modes and coupled-channel analysesare desired

Pseudoscalar Glueball

- **Pseudoscalar meson spectrum**
  - ✓ Only η and η' (& radial excitations) from quark model
  - ✓ A promising place to search for extra states

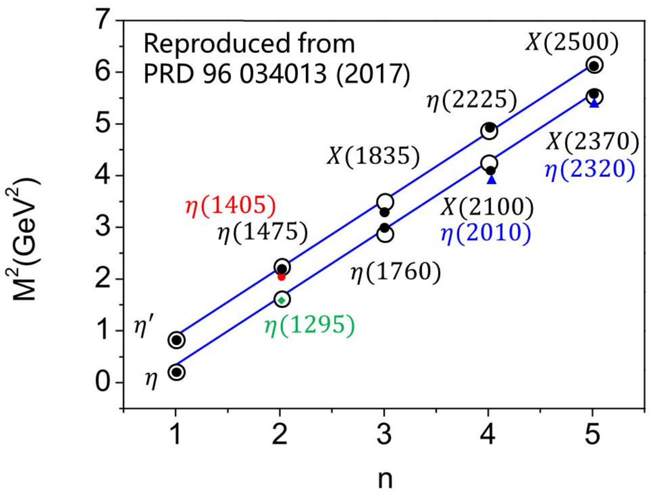
- **LQCD predicts: 0^{-+} glusball (2.3~2.6 GeV)**
  - ✓ The first glueball candidate: ι (1440) (Split into $\eta(1405)$ and $\eta(1475)$)
    - Quark model predicts : only one pseudoscalar meson near 1.4 GeV
    - Theoretical interpretations :

      $\eta(1475)$⇨ the first radial excitation of η'

      $\eta(1405)$ ⇨ the glueball candidate &&Mass incompatible with LQCD
  - ✓Little experimental information above 2 GeV
    - A glueball-like state **X(2370)**

- **Production**
  - $\Gamma(J/\psi \to \gamma G_{0^{-+}})/\Gamma_{total} = 2.31(80)\times 10^{-4}$, at the same level as 0^{-+} meson

- **Decays**
  - **Possible guidance: OZI suppressed decays of η_c**
  - **3 pseudoscalar final state is a good place to look for Pseudoscalar glueball ($0^{-+} \to 2P$ is forbidden)**



$\eta_c \to 3P$ in PDG

Decays involving hadronic resonances

$\eta'(958)\pi\pi$	(2.0 ± 0.4) %
$\eta'(958)K\bar{K}$	(1.73 ± 0.35) %

Decays into stable hadrons

$K\bar{K}\pi$	(7.1 ± 0.4) %
$K\bar{K}\eta$	(1.32 ± 0.15) %
$\eta\pi^+\pi^-$	(1.6 ± 0.4) %

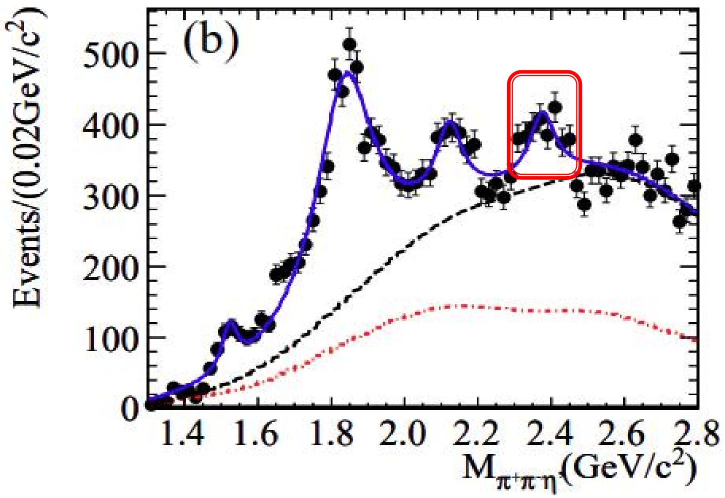
No dominant decay
Flavor symmetric

A glueball-like state X(2370)

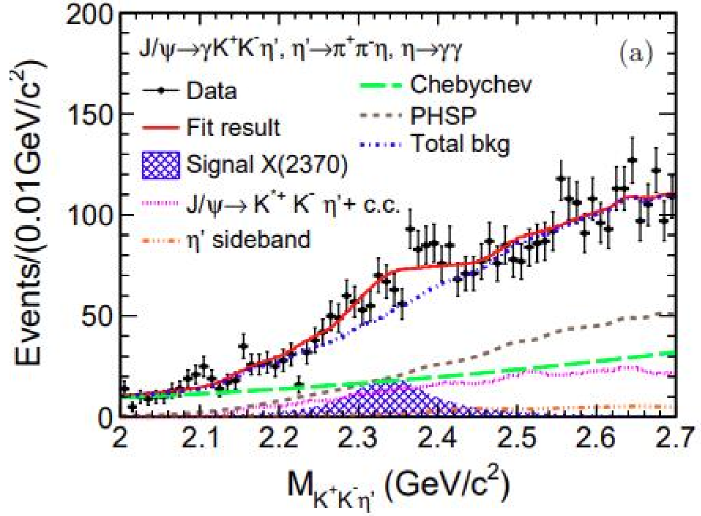
- Discovered by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ decay in 2011
- Confirmed by BESIII in $J/\psi \to \gamma\pi^+\pi^-\eta'$ and $J/\psi \to \gamma KK\eta'$
  - Not seen in $J/\psi \to \gamma\eta\eta\eta'$ [BESIII PRD 103 012009 (2021)], $J/\psi \to \gamma\gamma\phi$ [BESIII arXiv: 2401.00918]. Upper limits of BF are well consistent with predictions of 0^{-+}glueball
- Mass consistent with LQCD prediction for 0^{-+}glueball
- Spin-parity determined to be 0^{-+} by $J/\psi \to \gamma K_S^0 K_S^0 \eta'$ [BESIII PRL 132, 181901(2024)]

PRL 117, 042002 (2016)

PRL 106, 072002(2011)



EPJC 80 746(2020)

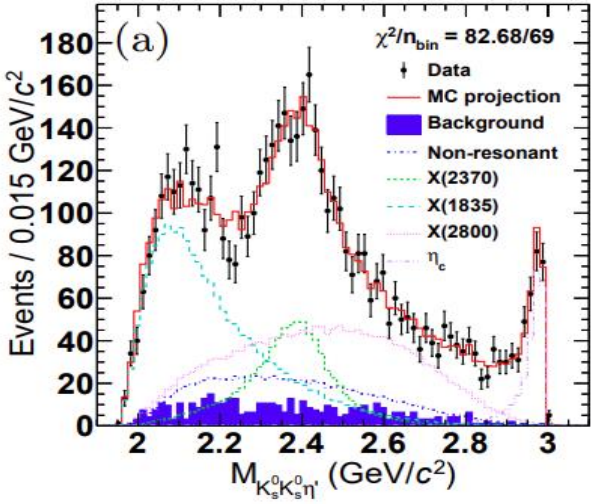


X(2370) : $J^{PC} = 0^{-+}$ with significance >9.8σ

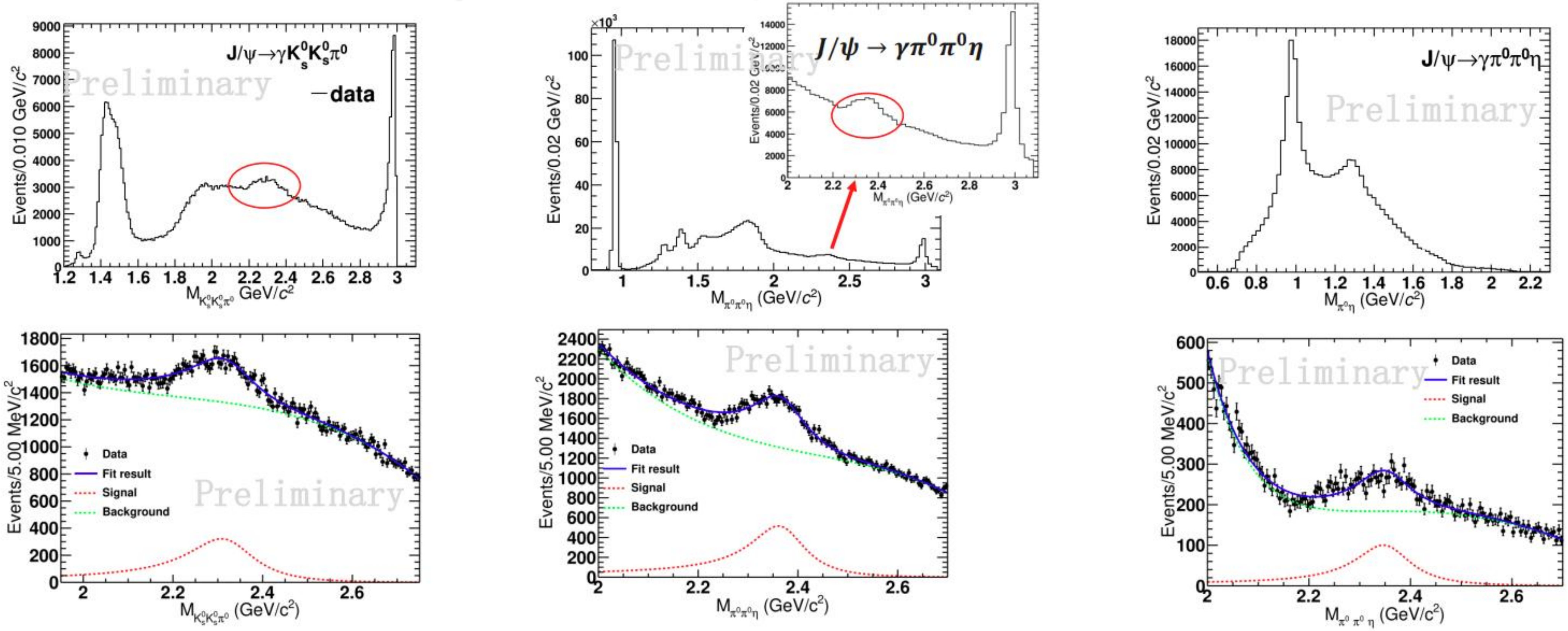
$M = 2395 \pm 11^{+26}_{-94}\ MeV$

$\Gamma = 188^{+18+124}_{-17-33}\ MeV$

$B(J/\psi \to \gamma X(2370) \to f_0(980)\eta' \to K_0^s K_0^s \eta') = 1.32 \pm 0.22^{+2.85}_{-0.84}$



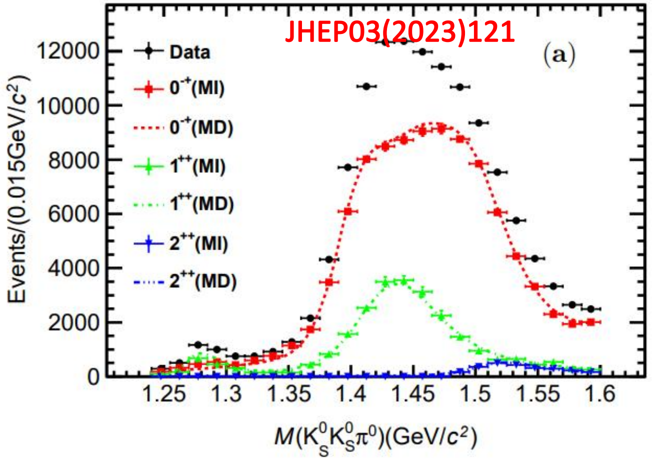
New (preliminary) results on X(2370)

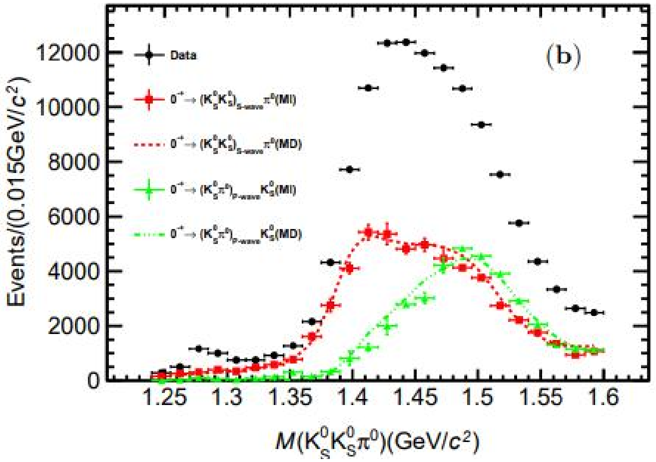


- $X(2370)$ observed in the gluon-rich J/ψ radiative decays
- Mass and production rate are consistent with LQCD
- Decay modes $X(2370) \rightarrow \pi\pi\eta', KK\eta', K_s^0K_s^0\pi^0, \pi^0\pi^0\eta, a_0(980)\pi^0$ observed, in analog to $\boldsymbol{\eta_c}$

Such high similarity between the X(2370) and η_c decay modes strongly supports the glueball interpretation of the X(2370)

Partial Wave Analysis of $J/\psi \to \gamma K_s^0 K_s^0 \pi^0$





Resonance	M(MeV/c^2)	Γ(MeV)
$\eta(1405)$	$1391.7 \pm 0.7^{+11.3}_{-0.3}$	$60.8 \pm 1.2^{+5.5}_{-12.0}$
$\eta(1475)$	$1507.6 \pm 1.6^{+15.5}_{-32.2}$	$115.8 \pm 2.4^{+14.8}_{-10.9}$
$f_1(1285)$	$1280.2 \pm 0.6^{+1.2}_{-1.5}$	$28.2 \pm 1.1^{+5.5}_{-2.9}$
$f_1(1420)$	$1433.5 \pm 1.1^{+27.9}_{-0.7}$	$95.9 \pm 2.3^{+13.6}_{-10.9}$
$f_2(1525)$	$1515.4 \pm 2.5^{+3.2}_{-7.6}$	$64.0 \pm 4.3^{+2.0}_{-6.1}$

- **Mass Independent PWA : Disentangle J^{PC} in each bin**
  - **Valuable inputs to develop models**
  - Two 0^{-+} around 1.4 GeV/c^2 in $(K_s^0 K_s^0)_{s-wave}\pi^0$ and $(K_s^0\pi^0)_{p-wave}K_s^0$ partial waves
- **Mass Dependent PWA with BW to extract resonances**
  - Dominated by 0^{-+}
  - Two BWs $\eta(1405)$ and $\eta(1475)$ around 1.4 GeV is needed
- **Consistency between MI and MD results**
- **Theorists attempt to reveal $\eta(1405)/\eta(1475)$ pole structure**
  - further study are needed

Phys.Rev.D 107 , L091505 (2023)
Phys.Rev.D 109 , 014021 (2024)

Partial Wave Analysis of $J/\psi \to \gamma\gamma\phi$

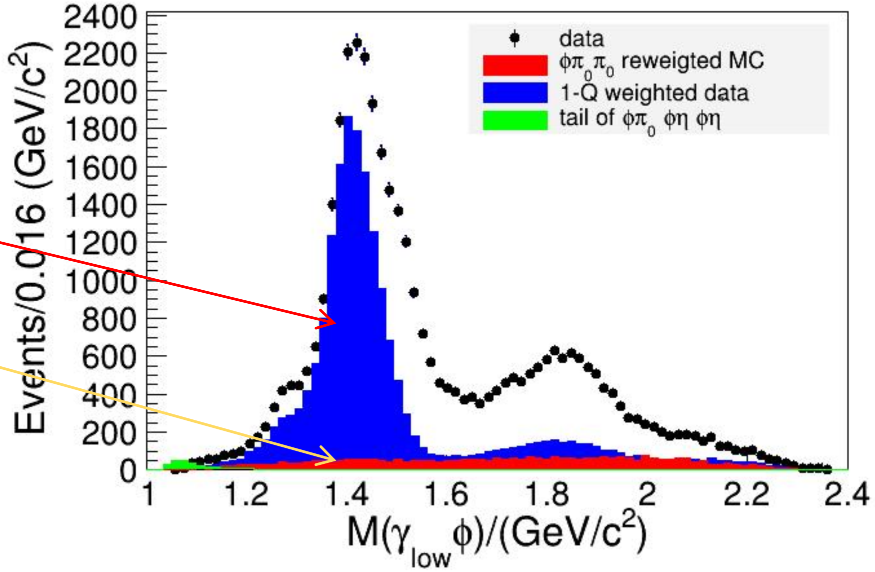
The decays $J/\psi \to \gamma X, X \to \gamma V\ (V = \rho, \omega, \phi)$ serve as flavor filter

arXiv: 2401.00918

•unravelling quark contents of the intermediate resonances

■ Main challenges

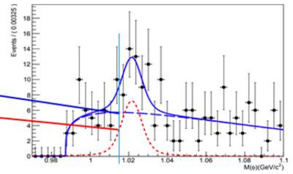
- high background level (55%)
  - non-ϕ background (46.7%)
  - ϕ background (8.2%)



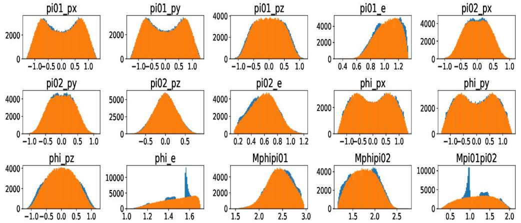
■ Innovative point

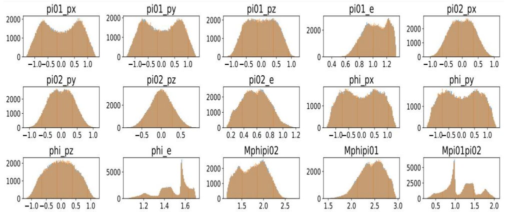
- non-ϕ background (Q factor method，CLAS)

$$Q_i = \frac{F_s(\vec{\xi}_r, \hat{\alpha}_i)}{F_s(\vec{\xi}_r, \hat{\alpha}_i) + F_b(\vec{\xi}_r, \hat{\alpha}_i)}$$



- ϕ background (ML based multi-dimensional reweighting method, BESIII)





Partial Wave Analysis of $J/\psi \to \gamma\gamma\phi$

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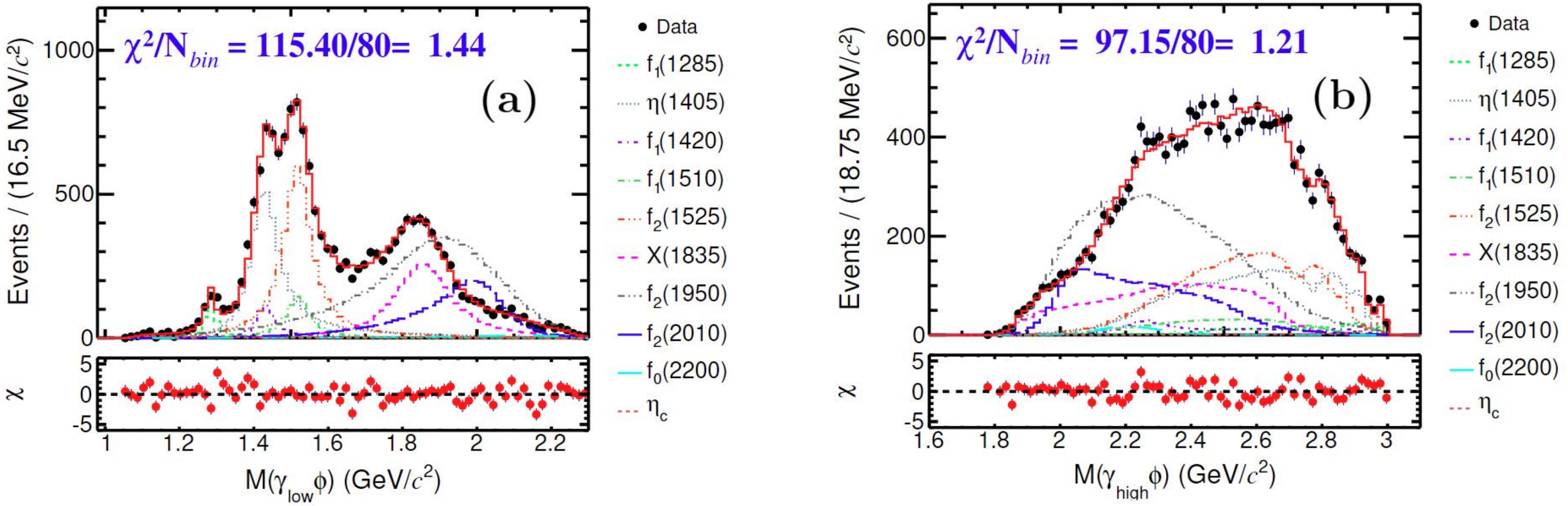


- $\eta(1405)$ is observed, while $\eta(1475)$ can not be excluded
- $X(1835) \to \gamma\phi$ suggests its assignment of second η' excitation
- $\eta_c \to \gamma\phi$ is observed for the first time, the first radiative decay mode of η_c
- Observation of $f_2(1950)$ and $f_0(2200) \to \gamma\phi$ unfavored their glueball interpretations.

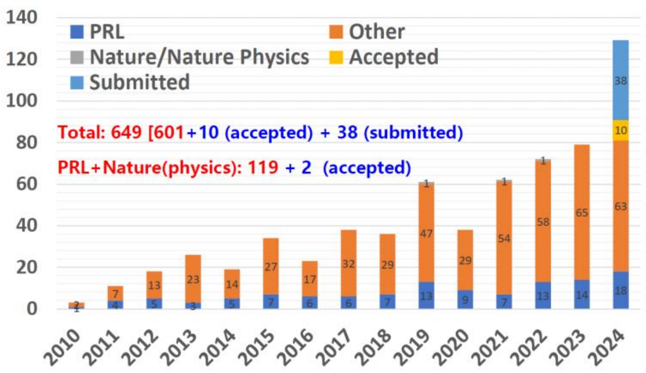
  [PRD 108, 014023 (2013); arXiv: 2404.01564]
- No evidence of $\eta_1(1855)$ and X(2370), well consistent with the predictions for hybrid/glueball。

  [PRD 107, 114020(2023); NPA 1037, 122683]

Summary and outlook

BESIII experiment is an excellent laboratory to study light meson physics and search for light QCD exotic states

Publications as of Oct. 8, 2024



Exciting results from new J/ψ and ψ' data are presented

- pesudoscalar state : $\eta(1405)$, X(2370)
- 1^{-+}spin exotics state: $\eta_1(1855)$, $\pi_1(1600)$

BESIII is taking data since 2008. It will continue to run ~2030

- BEPCII-U: 3x upgrade on luminosity; Ecms expanded to 5.6 GeV (2024-2028)

High statistics data bring us more opportunities and challenges！！

Back Up

Prospects of spin-exotics at BESIII

Uniqueness, enrichment and complementary

- **High statistics gluon-rich environment: 10 B J/ψ, 2.7 B ψ', a lot of χ_{cJ}**

Isoscalar: $\eta_1(1855)$

- **Decay properties**
  - $J/\psi \to \gamma + \pi a_1, \eta f_1, K_1\overline{K}, VV,$ ......
- **Production properties**
  - $J/\psi \to \omega\eta\eta', \phi\eta\eta'$, ...
  - $\chi_{c1} \to \eta + \eta\eta'$, ...
- **Where is $\eta_1^{(\prime)}$**
- **Other partners: 2^{+-}, ...**
- **Analog in $\bar{c}c$**

Isovector: $\pi_1(1600)$

- $J/\psi \to \rho\eta'\pi$, ...
- $\chi_{c1} \to \pi + \pi b_1, \pi f_1, \pi\eta'$, ...
  - LQCD predicted major decay modes

- **Lattice QCD predictions for glueball masses and BR:**
  - 0^{++} ground state: 1.5-1.7 GeV/c^2 ; $B(J/\psi \to \gamma G_{0^{++}}) = 3.8(9)\times 10^{-3}$
  - 0^{-+} ground state: 2.3-2.4 GeV/c^2 ; $B(J/\psi \to \gamma G_{0^{-+}}) = 2.31(80)\times 10^{-4}$
  - 2^{++} ground state: 2.3-2.6 GeV/c^2 ; $B(J/\psi \to \gamma G_{2^{++}}) = 1.1(2)\times 10^{-2}$

- For 5 golden PPP decay modes: similar number of events under the X(2370) peak — No dominant decay modes, similar to η_c!
- Naïve estimation on the BR of each mode ~ 5-10%, i.e., partial width of each decay mode is ~ 10MeV!
- This would be very hard to be explained if there were quark content (qqbar, qqg, or multiquark) in X(2370) for OZI allowed decays:
  - Typical OZI allowed decay partial width ~100MeV (see all PDG mesons)
  - OZI allowed decays usually have dominant decay modes
- X(2370) decay should be OZI suppressed decays as η_c, i.e., via gluons!

Observation of **An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$**

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

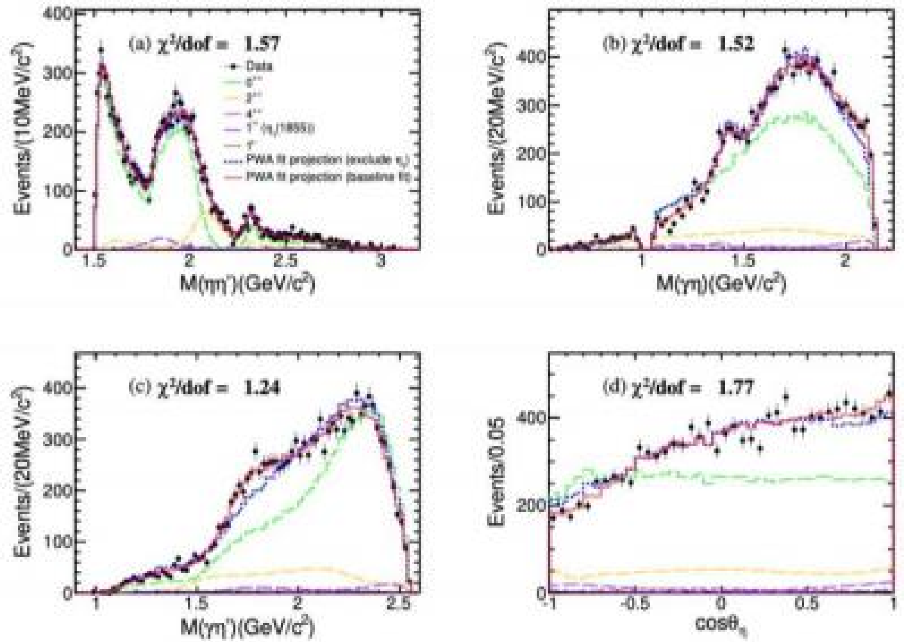
- The η' is reconstructed from $\gamma\pi^+\pi^-$ & $\eta\pi^+\pi^-$, η from $\gamma\gamma$
- Partial wave analysis of $J/\psi \to \gamma\eta\eta'$
  - Quasi two-body decay amplitudes in the sequential decay processes $J/\psi \to \gamma X, X \to \eta\eta'$ and $J/\psi \to \eta X, X \to \gamma\eta'$ and $J/\psi \to \eta' X, X \to \gamma\eta$ are constructed using the covariant tensor formalism[Eur. Phys. J. A 16, 537] and GPUPWA [J. Phys. Conf. Ser. 219, 042031(2010)] *

**World's first PWA framework with GPU acceleration*

- **An isoscalar 1^{-+} , $\eta_1(1855)$, has been observed in $J/\psi \to \gamma\eta\eta'$ (>19σ)**

$$\mathbf{M} = (1855 \pm 9^{+6}_{-1})\ \mathrm{MeV}/c^2, \Gamma = (188 \pm 18^{+3}_{-8})\ \mathrm{MeV}/c^2$$

$$\mathrm{B}(J/\psi \to \gamma\eta_1(1855) \to \gamma\eta\eta') = (2.70 \pm 0.41^{+0.16}_{-0.35}) \times 10^{-6}$$



- **Mass is consistent with LQCD calculation for the 1^{-+} hybrid ($1.7 \sim 2.1\ \mathrm{GeV}/c^2$)**

Observation of An Exotic 1^{-+} Isoscalar State $\eta_1(1855)$

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

- Angular distribution as a function of $M(\eta\eta')$ expressed **model-independently**

$$\langle Y_l^0 \rangle \equiv \sum_{i=1}^{N_k} W_i Y_l^0(cos\theta_\eta^i)$$

- Related to the spin-0(S), spin-1(P), spin-2(D) amplitudes in $\eta\eta'$ by:

$$\sqrt{4\pi}\langle Y_0^0\rangle = S_0^2 + P_0^2 + P_1^2 + D_0^2 + D_1^2 + D_2^2,$$

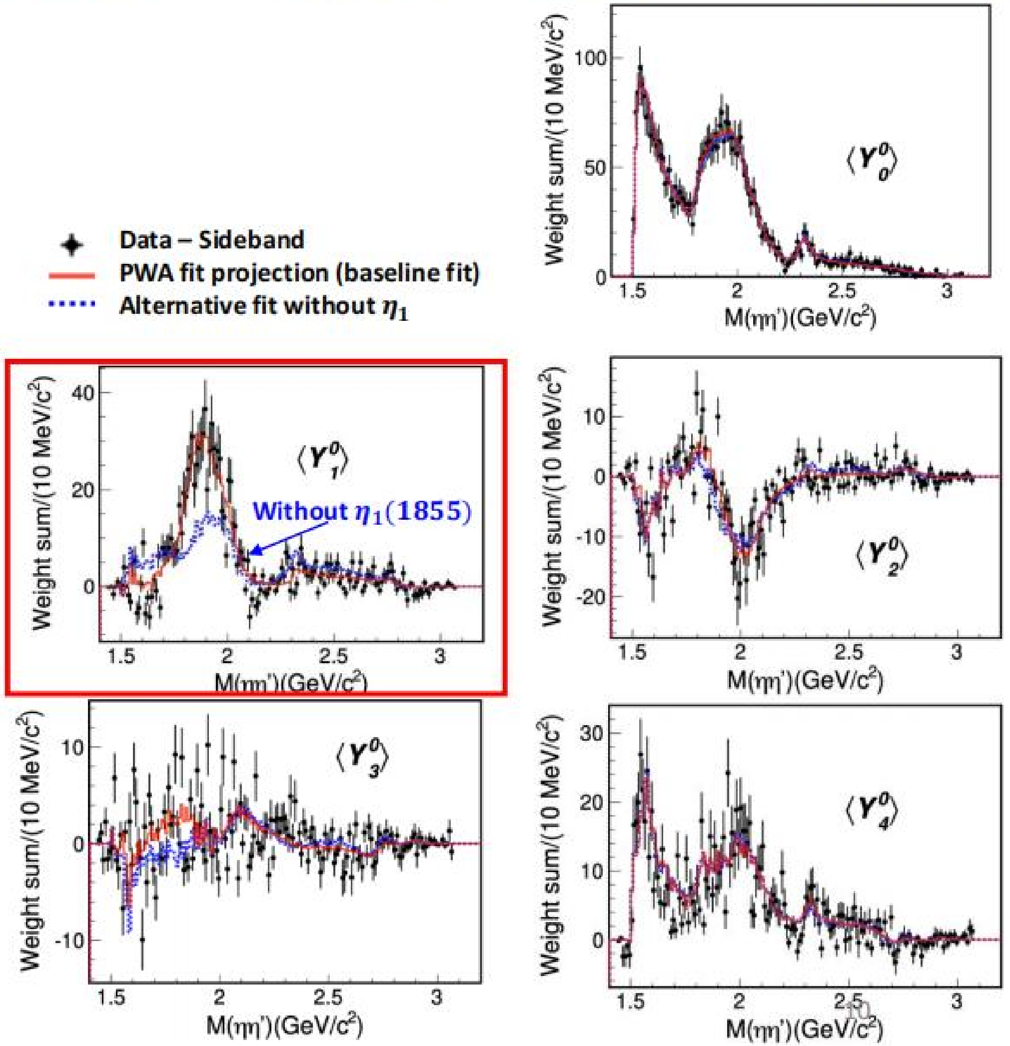
$$\sqrt{4\pi}\langle Y_1^0\rangle = 2S_0P_0\cos\phi_{P_0} + \frac{2}{\sqrt{5}}(2P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) + \sqrt{3}P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_2^0\rangle = \frac{1}{7\sqrt{5}}(14P_0^2 - 7P_1^2 + 10D_0^2 + 5D_1^2 - 10D_2^2) + 2S_0D_0\cos\phi_{D_0},$$

$$\sqrt{4\pi}\langle Y_3^0\rangle = \frac{6}{\sqrt{35}}(\sqrt{3}P_0D_0\cos(\phi_{P_0}-\phi_{D_0}) - P_1D_1\cos(\phi_{P_1}-\phi_{D_1})),$$

$$\sqrt{4\pi}\langle Y_4^0\rangle = \frac{1}{7}(6D_0^2 - 4D_1^2 + D_2^2).$$

- **Narrow structure** in $\langle Y_1^0\rangle$
  - ➢ **Cannot be described by resonances in $\gamma\eta(\eta')$**
  - **$\eta_1(1855) \to \eta\eta'$ needed**

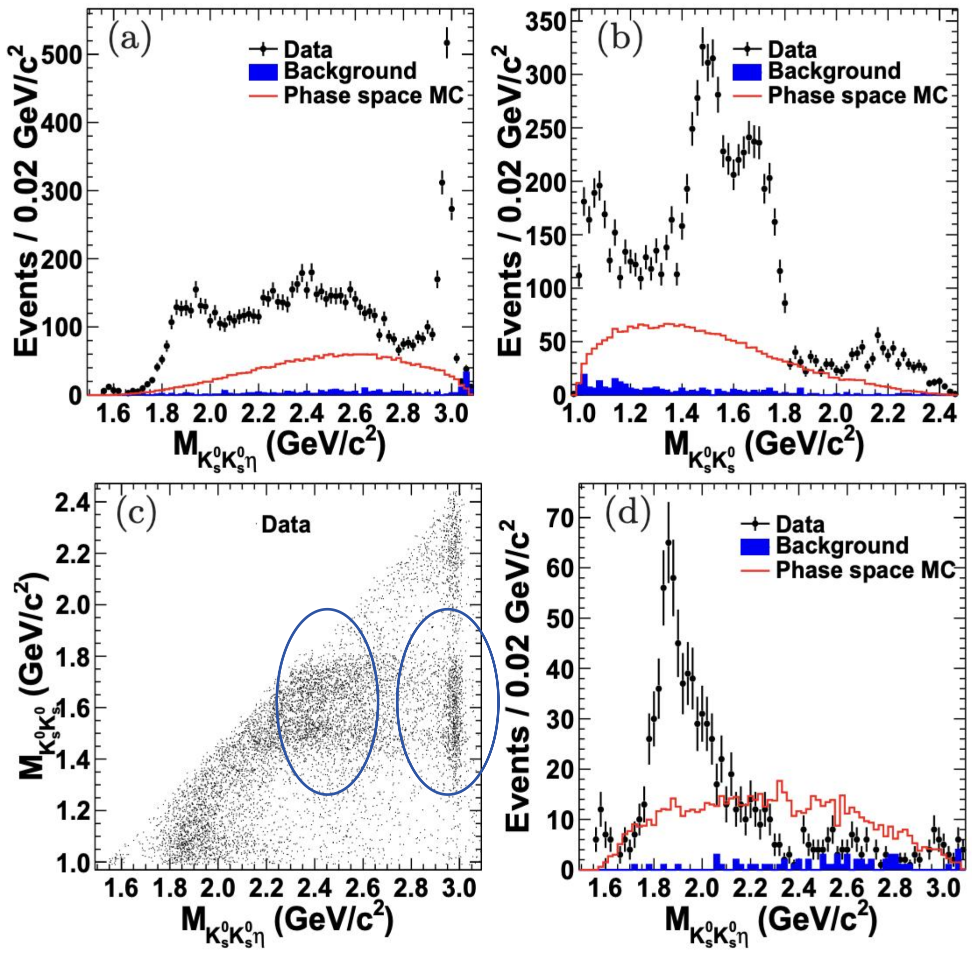


Study of $J/\psi \to \gamma K_s^0 K_s^0 \eta$

In the 2D mass plot of M_{KK} vs $M_{KK\eta}$ in the BESIII paper on the spin-parity determination of the X(1835), qualitatively, we can clearly observe:

- In the upper M_{KK} mass band of 1.5-1.7GeV range, clear signals of both X(2370) and η_c.

- In the lower M_{KK} mass band of f0(980), no X(2370), nor η_c.

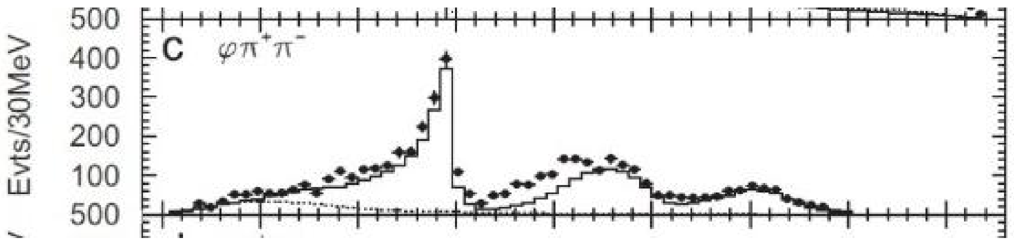


Background treatment

The remaining background can be divided into two categories

- **ϕ background**

Dominated by $J/\psi \to \phi\pi^0\pi^0$, which has rich structures. Difficult to be modeled with MC.



- **non-ϕ background**

ϕ sideband is tricky:

$e.g.\ J/\psi \to \gamma\eta(1405), \eta(1405) \to \pi_0 K^+K^-, \pi_0 \to \gamma\gamma$

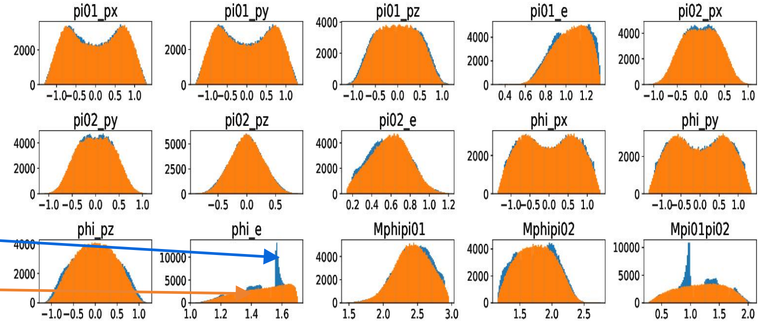
(1) If one of the photons $\gamma_2\ \gamma_3$ from the π_0 decay is soft (say, γ_3), the γ_2 will be energetic and M($\gamma_2 K^+K^-$) will be at the $\eta(1405)$ mass.

(2)The K^+K^- mass distribution from $\eta(1405) \to \pi_0 K^+K^-$ peaks nears K^+K^- threshold, which is very close to ϕ mass.

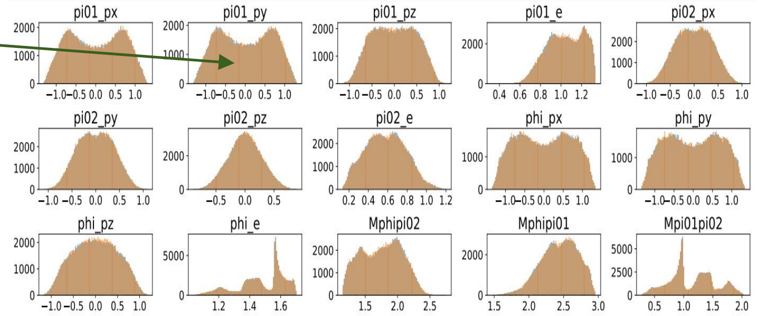
Background treatment

➢ ϕ background

Using a Machine learning based multi-dimensional reweighting method to get "data-like" MC of J/$\psi \rightarrow \phi\pi^0\pi^0$



- Select J/$\psi \rightarrow \phi\pi_0\pi_0$events from data
- Generate J/$\psi \rightarrow \phi\pi_0\pi_0$PHSP MC
- Perform multi-dimensional reweighting (ML)
- The distributions of weighted MC are well consistent with data



- The weighted J/$\psi \rightarrow \phi\pi_0\pi_0$ MC after $\boldsymbol{J/\psi \rightarrow \gamma\gamma\phi}$ event selection will be used for background estimation

* Beijiang. Liu, Xian Xiong, Guoyi Hou, Shiming Song, and Lin Shen. PoS ICHEP2018, 160 (2019). http://doi.org/10.5281/zenodo.1451985

Background treatment

- **Q-factor method: multi-dimensional sideband subtraction** [JINST 4 P10003 (2009)

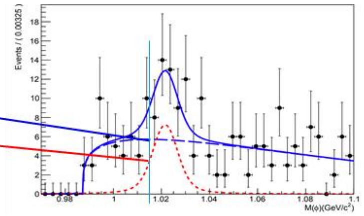
Generalize the 'sideband' subtraction method to higher dimensions without requiring the data to be divided into bins, successfully used in BAM-00221, Phys. Rev. D 100, 052012, by Malte Albrecht et al.

- In multi-dimensional phase space of $J/\psi \to \gamma\gamma\phi$, a so called Q-weight is given event-by-event , representing the probability of signal.
- A set of coordinates $\vec{\xi}$ must be defined($\cos\theta(\gamma_{rad})$,$\cos\theta(\phi)$, $\cos\theta(K^+)$, $M^2(\gamma_{high}\phi)$, $M^2(\gamma_{low}\phi)$). For event i , we find 200 of its nearest neighboring events in PHSP. The normalization Δ_k by default is set to the largest possible distance between two events in the coordinate ξ_k, and fit the reference coordinate $\vec{\xi}_r = M(K^+K^-)$.

$$d_{i,j}^2 = \sum_{k \neq r} \left[\frac{\xi_k^i - \xi_k^j}{\Delta_k} \right]^2$$

- Q-factor for event i , is determined by the fitting results and its $M(K^+K^-)$.

$$Q_i = \frac{F_s(\vec{\xi}_r, \hat{\alpha}_i)}{F_s(\vec{\xi}_r, \hat{\alpha}_i) + F_b(\vec{\xi}_r, \hat{\alpha}_i)}$$



CLAS experiment: Journal of Instrumentation, 4(10):P10003, 2009.
CB/LEAR experiment: The European Physical Journal C, 75(3), 2015.