BESIII Highlights

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Outline

BESIII introduction

LH spectroscopy:

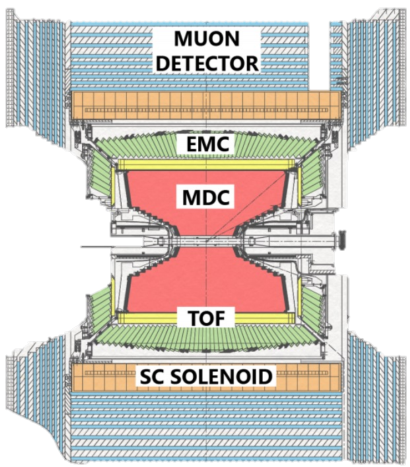
- ***The η_1(1855) exotic isoscalar state***
- ***η(1405)/η(1475) and $J/\psi \to K^0_S K^0_S \pi^0$ Mass Independent PWA***
- ***PWA of $J/\psi \to \gamma\gamma\phi$***
- ***X(2370): glueball-like particle in $J/\psi \to \gamma K^0_S K^0_S \eta$***
- ***X(1880): a new state observed in $J/\psi \to \gamma(3\pi^+\pi^-)$***
- ***Observation of a narrow structure near the $p\bar{\Lambda}$ threshold***

Fragmentation function at BESIII:

- ***Normalized differential cross section of inclusive $\pi^0/K^0_S/\eta$ production***

Summary and Conclusions

The BESIII experiment @ BEPCII



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

中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

BESIII

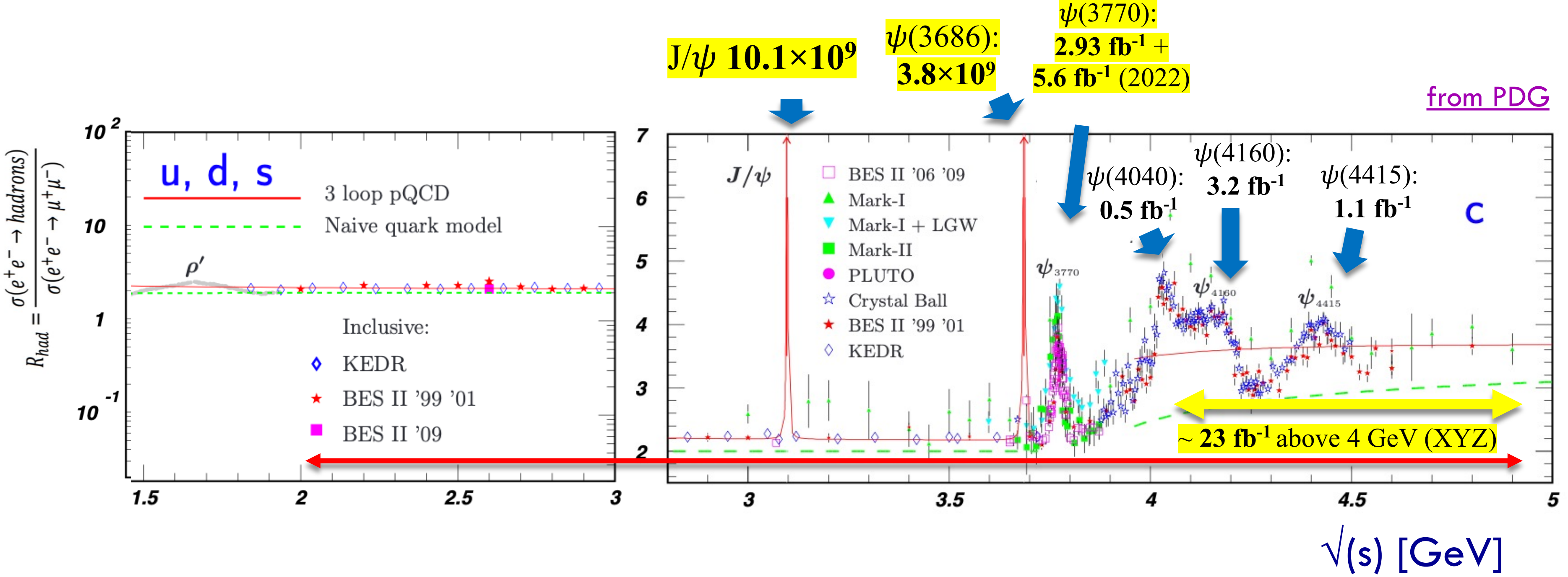
2004: started Beijing Electron Positron Collider II/BESIII construction

- ✓ Double rings
- ✓ Beam energy: 1 - 2.45 GeV
- ✓ Peak luminosity: 1.05×10^{33} cm^{-2}s^{-1} @ $\psi(3770)$, achieved in January 7th, 2023

2009 – today: BESIII physics runs

BESIII dataset and physics program

Optimised for flavour physics in the τ-charm region



- 130 points between 2 and 4.6 GeV (~715 pb^{-1} up to 3.08 GeV for ρ*, ω*, ϕ*,… studies)

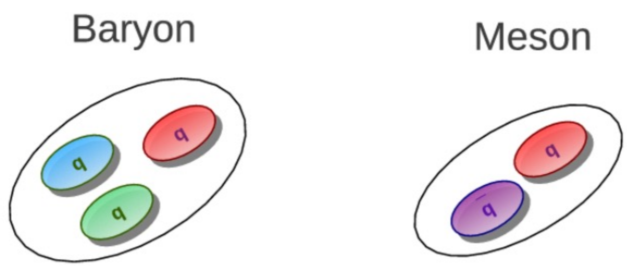
- Light hadron spectroscopy
- η/η' decays
- Hyperon physics
- Charmonium transitions

- D^0D^0pairs
- $D_{(S)}$ meson decays
- $D^*_{(s)}$
- …

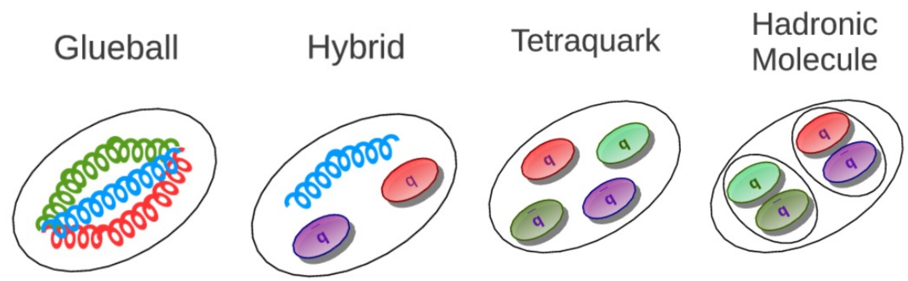
- XYZ decays and spectroscopy
- Open charm production
- Charmed baryons
- ...

Hadron Spectrum

Hadron spectroscopy: establish the spectrum and study the exotic hadrons properties



Naïve Quark Model:
conventional hadrons
contain two or three quarks



… ***but*** QCD allows also different combinations of quarks and gluons: ***EXOTIC*** hadrons

A lot of exotic states observed experimentally, but their nature is still far from being understood!!!

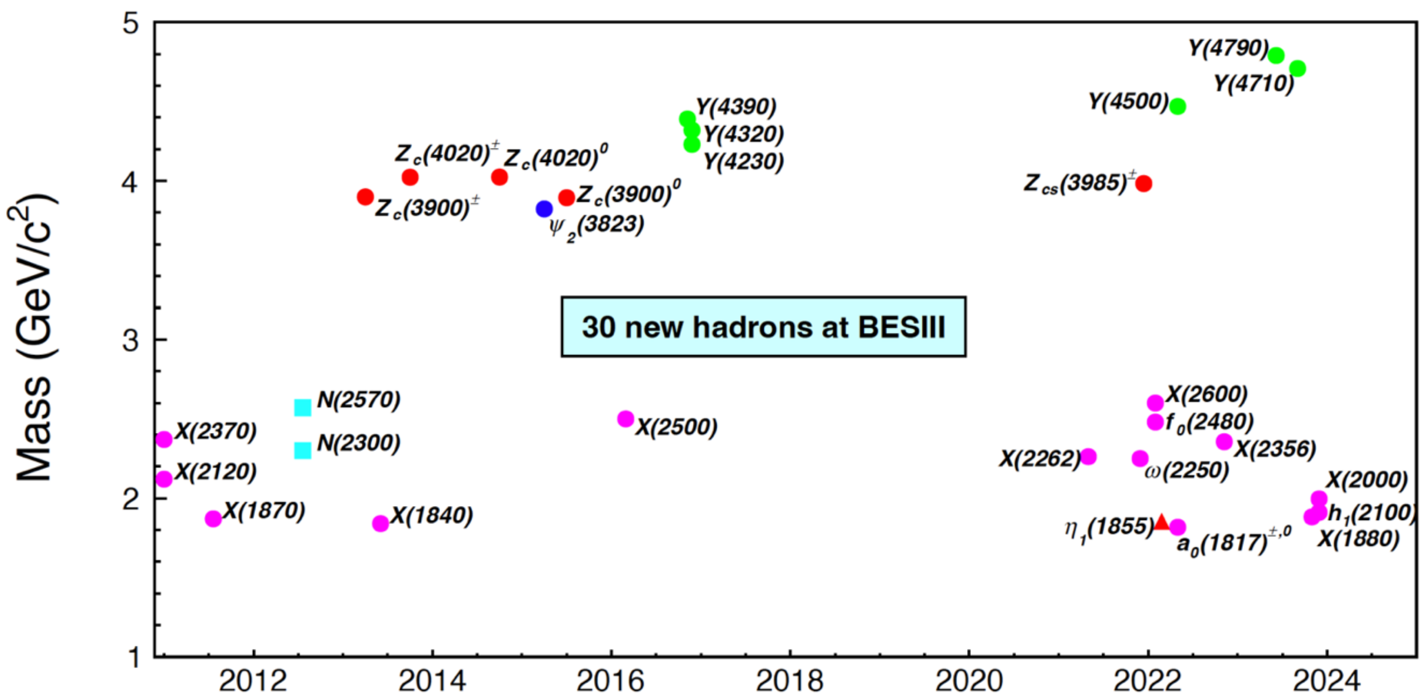
@ BESIII J/ψ **10.1×10⁹**

Light hadron physics

- Meson and baryon spectroscopy
- Glueballs and hybrids
- ….

New discoveries at BESIII

New particles @ BESIII



Manifestly exotic

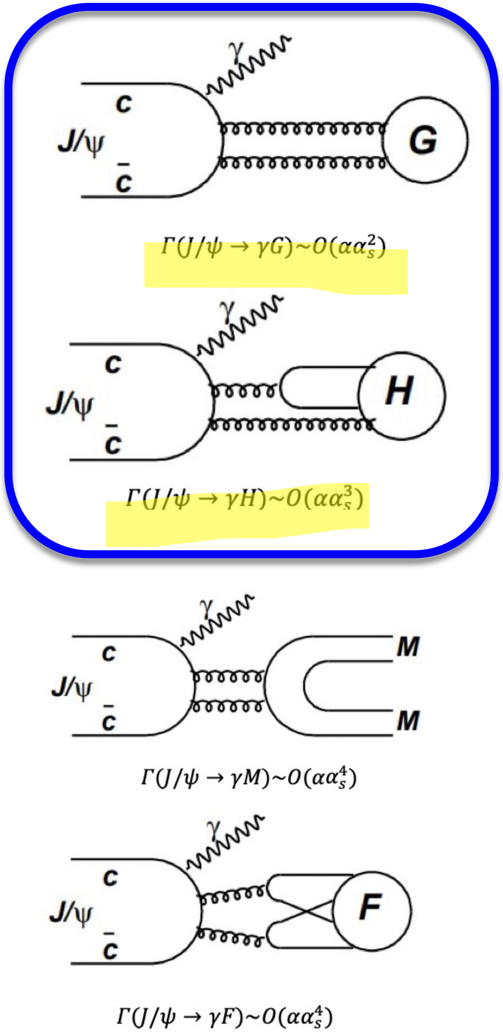
- *Quark contents more than $q\bar{q}$ or qqq*
- *Quantum number J^{PC} not reachable for ordinary mesons or baryons*

'Cryptoexotic' exotic

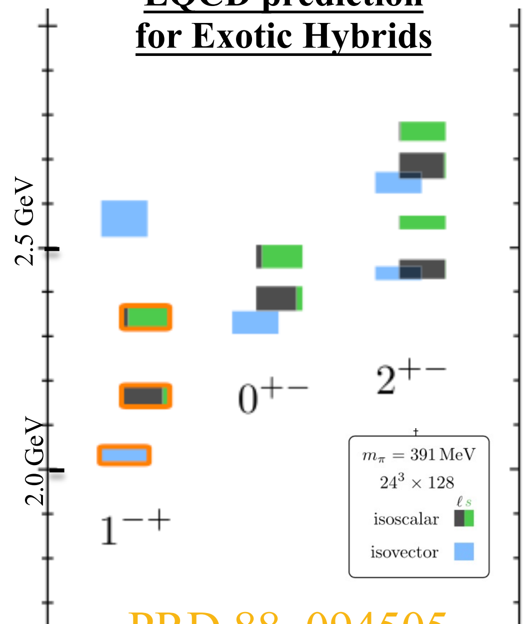
- *overpopulation of states*
- *mass/width not fitting in spectra*
- *production and/or decay patterns incompatible with standard mesons/baryons*

Hunting for glueballs and new form of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies (clean, high statistics and gluon-rich process)

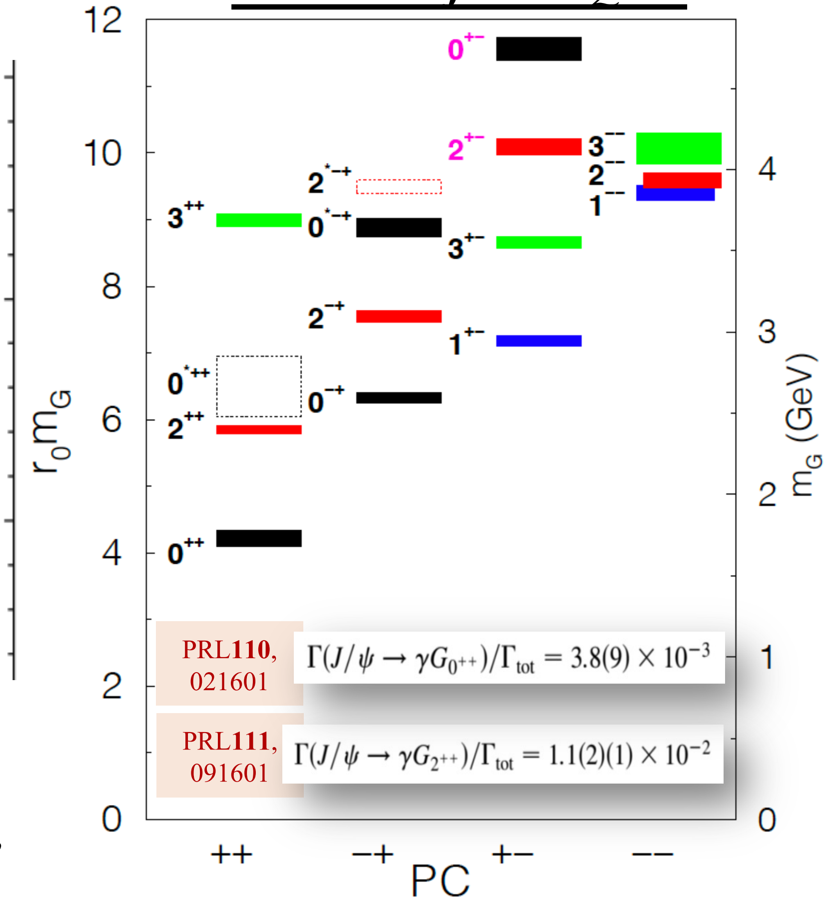


LQCD prediction for Exotic Hybrids



PRD 88, 094505

Prediction from LQCD



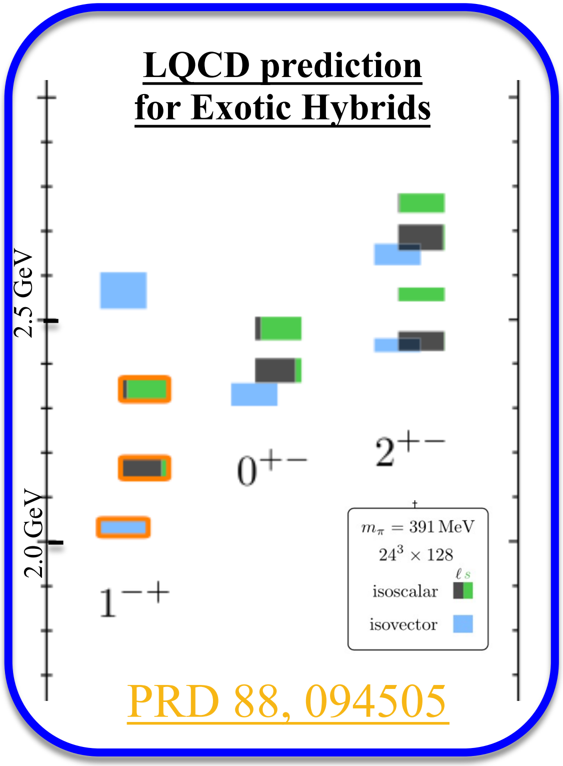
Glueballs and hybrids are expected to have a larger yield compared to mesons

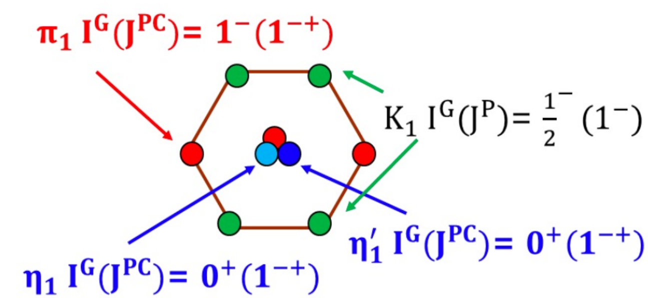
https://doi.org/10.1142/S0218301309012124

Hunting for glueballs and new form of hadrons

- Charmonium radiative decays is the ideal laboratory for light glueballs and hybrids hadron studies (clean, high statistics and gluon-rich process)

- **Exotic Hybrids**: $J^{PC} = 0^{+-}, 1^{-+}, 2^{+-}$ (forbidden in the conventional QCD scheme)
- The exotic $J^{PC} = 1^{-+}$ nonet of hybrids is predicted to be the lightest
- Only isovector candidate observed yet: $\pi_1(1400)$, $\pi_1(1600)$ [the most extensively studied], $\pi_1(2015)$





BESIII experiment offers the ideal environment for this search $J/\psi \rightarrow \gamma\eta\eta'$

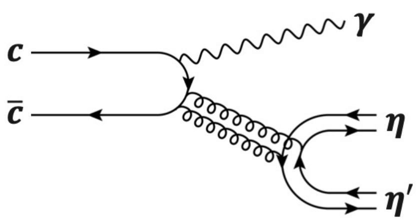
- Isoscalar 1^{-+} hybrids is important to establish the hybrid nonet
  - Can be produced in J/ψ radiative decays
  - Can decay to $\eta\eta'$ in P-wave (PRD 83,014021, PRD 83, 014006, Eur.Phys.J.Plus 135, 945)

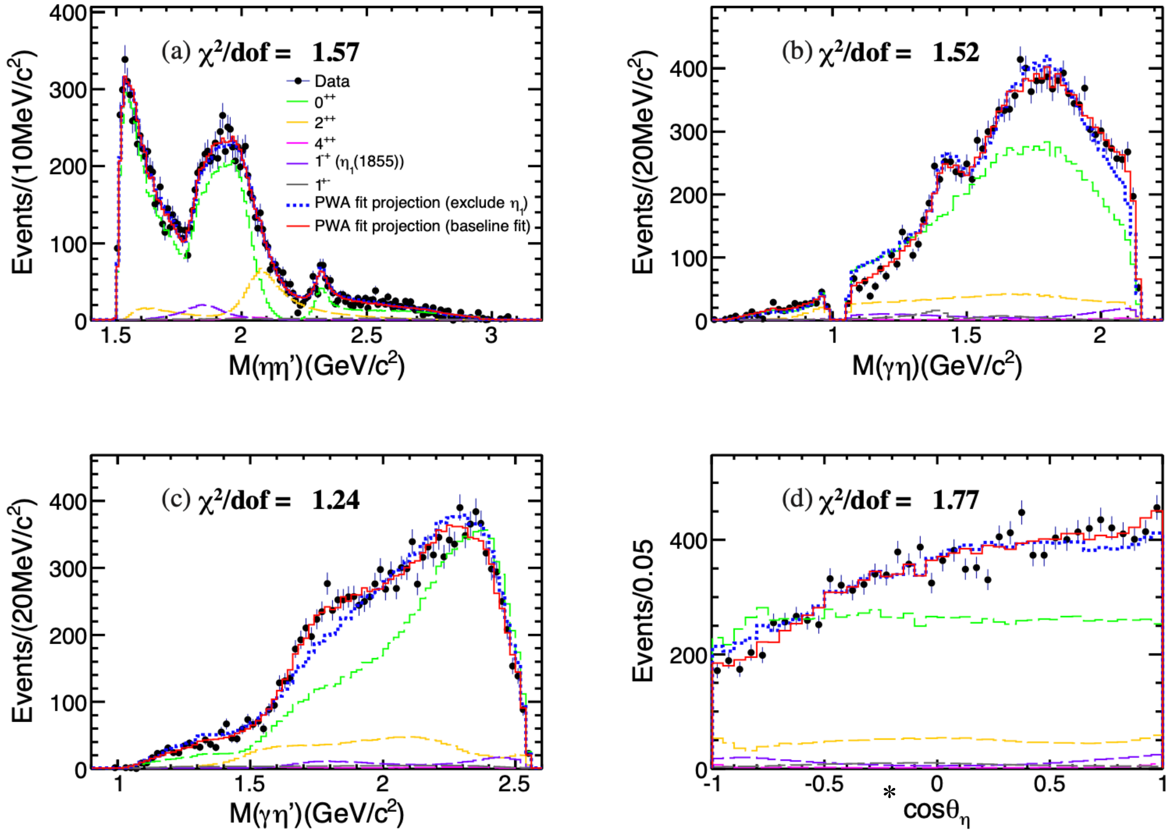
Observation of Exotic Isoscalar State $\eta_1(1855)$ in $J/\psi\to\gamma\eta\eta'$

PRL **129**, 192002 (2022)
PRD **106**,072012 (2022)
PRD **107**,079901 (2023)

PWA of $J/\psi\to\gamma\eta\eta'$ using 10 Billion of J/ψ data @ BESIII

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





*spin information

- An isoscalar 1^{-+} state, $\eta_1(1855)$, has been observed with statistical significance larger than 19σ
- Mass is consistent with LQCD calculation for the 1^{-+} hybrid (1.7 – 2.1 GeV/c^2)

$$M=(1855\pm9^{+6}_{-1})\ \mathrm{MeV}/c^2;\quad \Gamma=(188\pm18^{+3}_{-8})\ \mathrm{MeV}$$

$$\mathcal{B}(J/\psi\to\gamma\eta_1(1855)\to\gamma\eta\eta')=(2.70\pm0.41^{+0.16}_{-0.35})\times10^{-6}$$

J/ψ radiative decay: PWA status in a nutshell

<table>
<tr><th></th><th>0+</th><th>2+</th><th>0−</th></tr>
<tr><td>$J/\psi \to \gamma PP$</td><td colspan="2">$J/\psi \to \gamma\eta\eta$ (PRD87,092009)
$J/\psi \to \gamma\pi^0\pi^0$ (PRD92,052003)
$J/\psi \to \gamma K_S K_S$ (PRD98,072003)
$J/\psi \to \gamma\eta\eta'$ (PRL129,192002)
$J/\psi \to \gamma\eta'\eta'$ (PRD105,072002)</td><td></td></tr>
<tr><td>$J/\psi \to \gamma VV$</td><td></td><td colspan="2">$J/\psi \to \gamma\omega\phi$ (PRD87,032008)
$J/\psi \to \gamma\phi\phi$ (PRD93,112011)
$J/\psi \to \gamma\omega\omega$ (PRD100,052012)</td></tr>
<tr><td>$J/\psi \to \gamma PPP$</td><td></td><td></td><td>$J/\psi \to \gamma\eta'\pi\pi$ (PRL106,072002, noPWA)
$J/\psi \to \gamma K_S K_S \eta$ (PRL115,091803)
$J/\psi \to \gamma K_S K_S \pi^0$ (JHEP 03,121)</td></tr>
</table>

- **$J/\psi \to \gamma PP$: 0^{++}, 2^{++}, …**
- **$J/\psi \to \gamma PPP$, γVV: 0^{-+}**
- Neutral channel is much cleaner than the charged ones

Amplitude Analysis: toll to extract the complex amplitudes from experimental data

- Models with free parameters
- Consider the kinematic of final states particles
- Vary the parameters to maximize the likelihood

- **Mass Dependent (MD) PWA**: model the dynamics of particle interactions as coherent sum of resonances
- **Mass Independent (MI) PWA**: make minimal model assumptions and measure the dynamical amplitudes independently in small regions of two-meson invariant mass (JHEP 03,121 (2023))

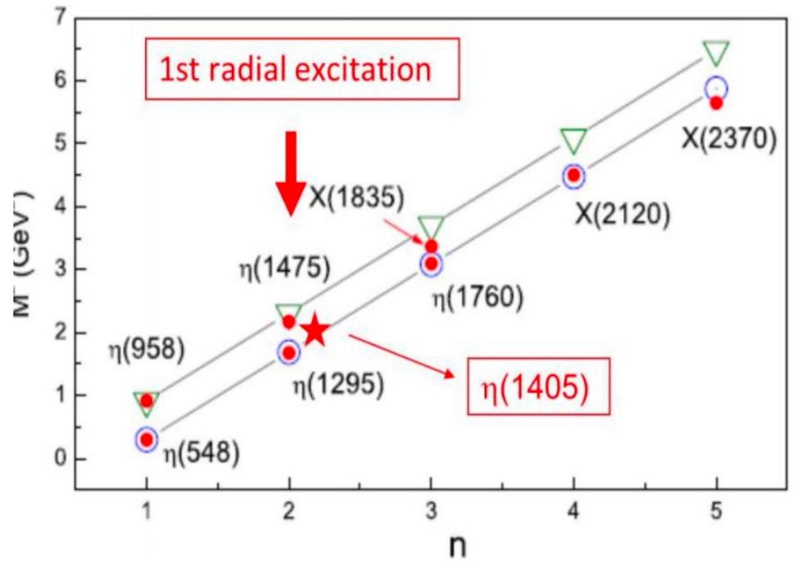
Toward the η(1405)/η(1475) puzzle solving

JHEP03(2023)121

What's the nature of pseudoscalar structure with a mass around 1.4 GeV/c^2 (the so called "ι" state) ?

- Observed first in the J/ψ radiative decay to the $K\bar{K}\pi$ final state in the early 1980s by the Crystal Barrel [PHL 97, 328] and Mark II [PRL 49, 259]

- Quark model predicts only one pseudoscalar meson near 1.4 GeV
- Theoretical interpretation:
  - η(1475): first radial excitation of η'
  - η(1405): glueball candidate
- LQCD prediction for the 0^{-+} lightest glueball candidate: [2.3-2.6] GeV



η(1405) and η(1475) are two separate states or just one pseudoscalar state, namely η(1440), in different decay mode?

What's the nature of the outnumbered η(1405)?

$J/\psi \to \gamma K^0_S K^0_S \pi^0$ - Mass Independent PWA

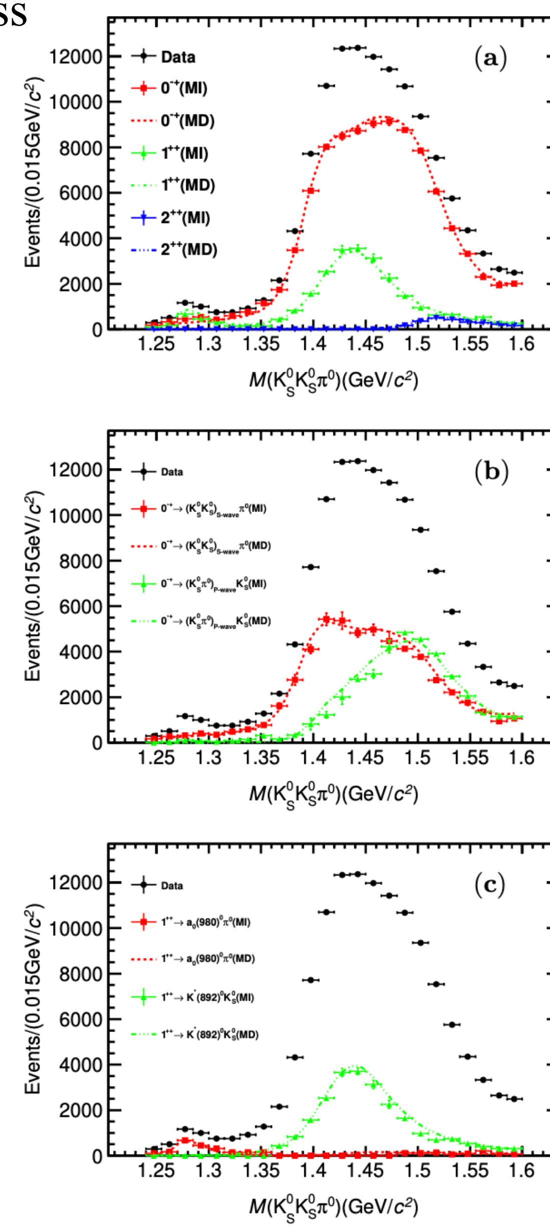
JHEP03(2023)121

- Mass independent fit by scanning the invariant $K^0_S K^0_S \pi^0$ mass
  - identification of the strongest waves
- The pseudoscalar component is the dominant contribution
  - relatively constant around 1.4 GeV/c^2
  - $(K^0_S K^0_S)_{S\text{-wave}}\pi^0$ and $(K^0_S \pi^0)_{P\text{-wave}} K^0_S$ partial waves are of comparable magnitude, but with different line shapes and peaks
  - two resonances parameterization needed
- Axial vector component peaking at 1.28 GeV/c^2 and 1.42 GeV/c^2; Tensor component around 1.52 GeV/c^2 decaying into $K^*(892)^0 K^0_S$ observed for the first time

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

Consistency between MI and MD results

Theorists attempt to reveal the η(1405)/η(1475) pole structure [PRD107, L091505]



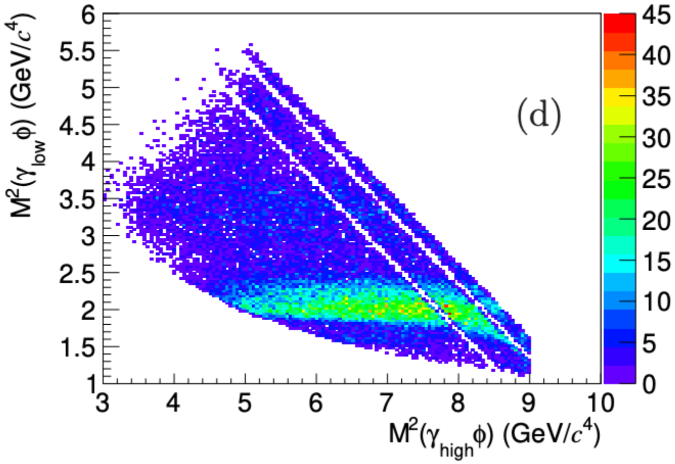
PWA of $J/\psi \to \gamma\gamma\phi$

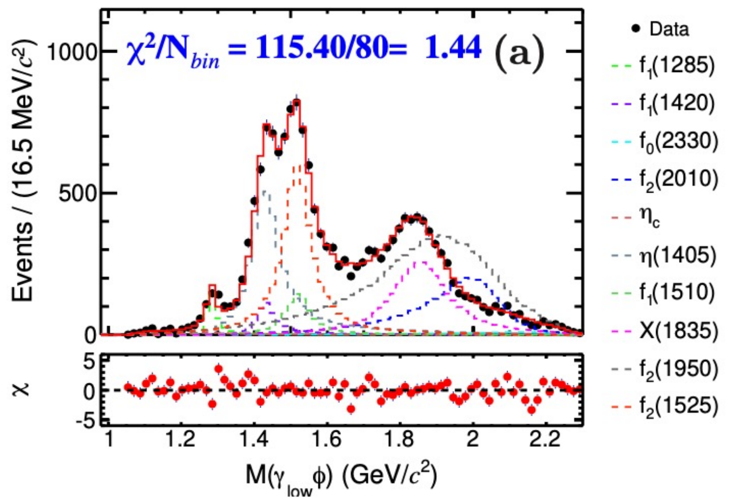
arXiv:2401.00918

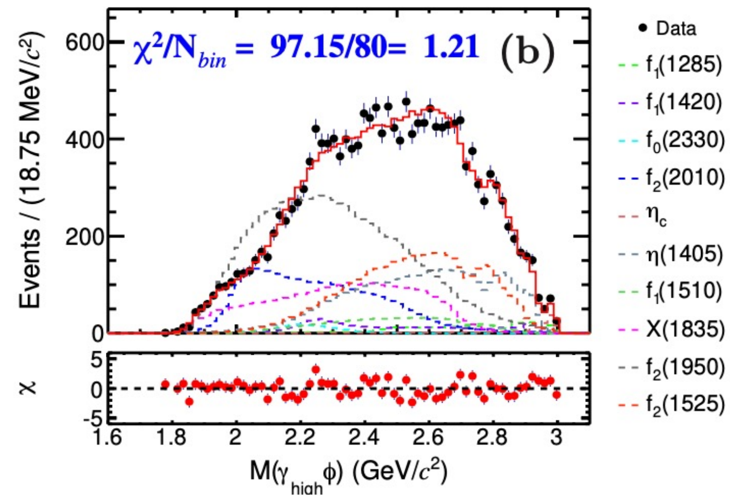
The decays $J/\psi \to \gamma X$, $X \to \gamma V$ ($V = \rho, \omega, \phi$) serve as flavor filter

- unravelling quark contents of the intermediate resonances

GPUPWA framework used to disentangle the structures in the Dalitz plot







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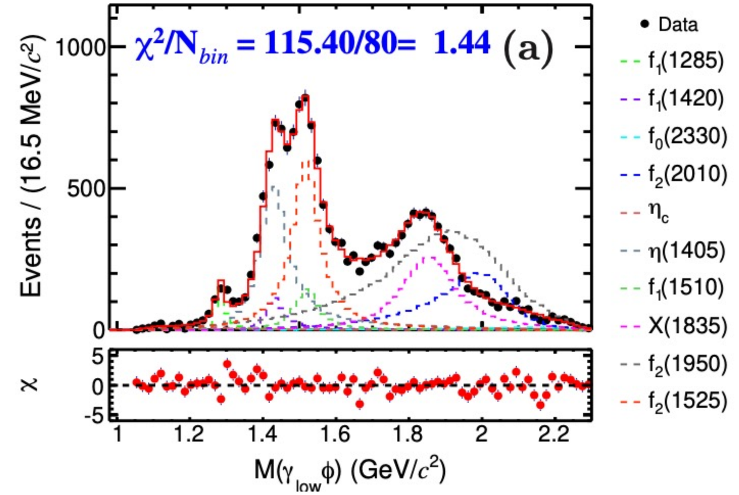
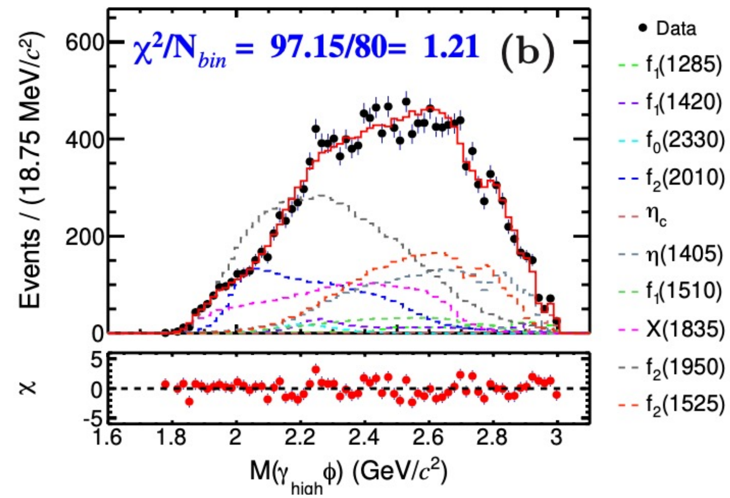
The decays $J/\psi \to \gamma X$, $X \to \gamma V$ ($V = \rho, \omega, \phi$) serve as flavor filter

- unravelling quark contents of the intermediate resonances

Resonance	M (MeV/c^2)	Γ (MeV)	$\mathcal{B}(\times 10^{-6})$	Significance
$f_1(1285)$	1281.9	22.7	$0.29\pm0.03^{+0.11}_{-0.09}$	17.3σ
$f_1(1420)$	1426.3	54.5	$0.55\pm0.07^{+0.18}_{-0.17}$	9.0σ
$\eta(1405)$	$1422.0 \pm 2.1^{+5.9}_{-7.8}$	$86.3 \pm 2.7^{+6.6}_{-17.4}$	$3.57\pm0.18^{+0.59}_{-0.61}$	18.9σ
$f_1(1510)$	1518.0	73.0	$0.78\pm0.09^{+0.34}_{-0.30}$	5.3σ
$f_2(1525)$	1517.4	86.0	$2.76\pm0.18^{+0.90}_{-0.61}$	16.4σ
$X(1835)$	$1849.3 \pm 3.0^{+7.6}_{-10.0}$	$179.6 \pm 8.7^{+22.5}_{-27.9}$	$3.37\pm0.19^{+0.78}_{-1.10}$	15.3σ
$f_2(1950)$	1936.0	464.0	$9.96\pm0.60^{+3.44}_{-2.13}$	13.1σ
$f_2(2010)$	2011.0	202.0	$4.63\pm0.43^{+1.42}_{-1.46}$	11.3σ
$f_0(2200)$	2187.0	207.0	$0.20\pm0.04^{+0.05}_{-0.07}$	6.3σ
η_c	2983.9	32.0	$0.21\pm0.03^{+0.05}_{-0.07}$	12.9σ

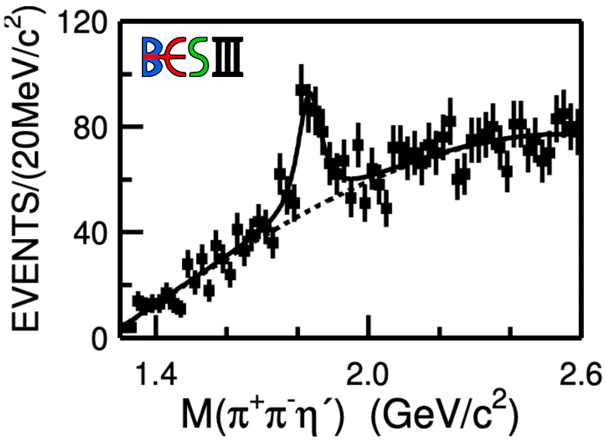


- $\eta(1405)$ and $f_1(1420)$ are needed to describe the structure with mass around 1.4 GeV
- X(1835) is confirmed to be 0^{-+} with a sizable ss component
- $\eta_c \to \gamma\phi$ observed for the first time
- No significant signals are observed for η(1295), η(1475), $\eta_1(1855)$ and X(2370)



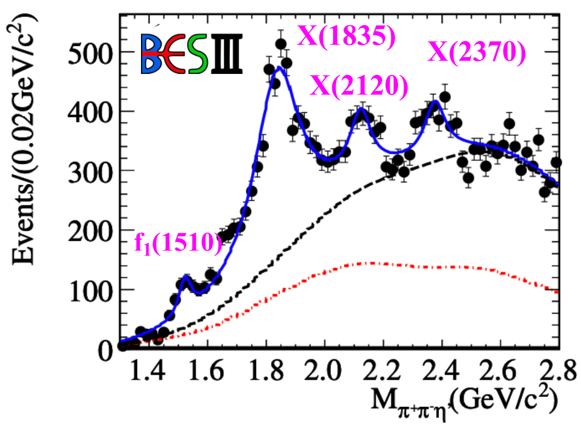
X states observed in the $J/\psi\to\gamma\pi^+\pi^-\eta'$ decay

PRL 95, 262001 (2005)



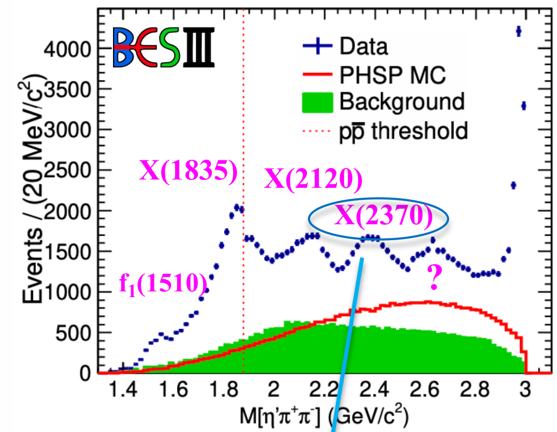
58×10^6 J/ψ events

PRL 106, 072002 (2011)



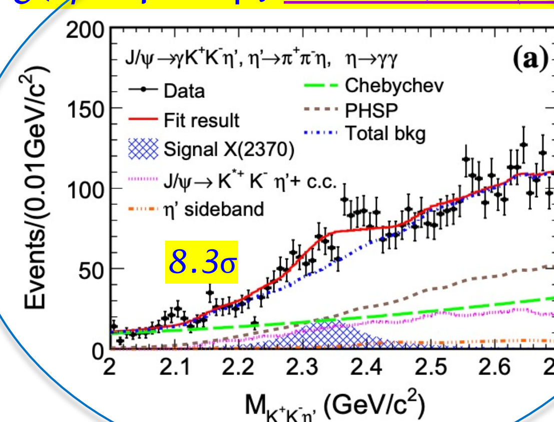
225.2×10^6 J/ψ events

PRL 117, 042002 (2016)



1090×10^6 J/ψ events

$J/\psi\to\gamma KK\eta'$, EPJC80, 746(2020)



- Structure just at or below $p\bar{p}$ threshold: X(1835)
  - Non-trivial line shape: try to fit with Flatté or sum of interfering BWs
- Additional structures: X(2120), X(2370), ?

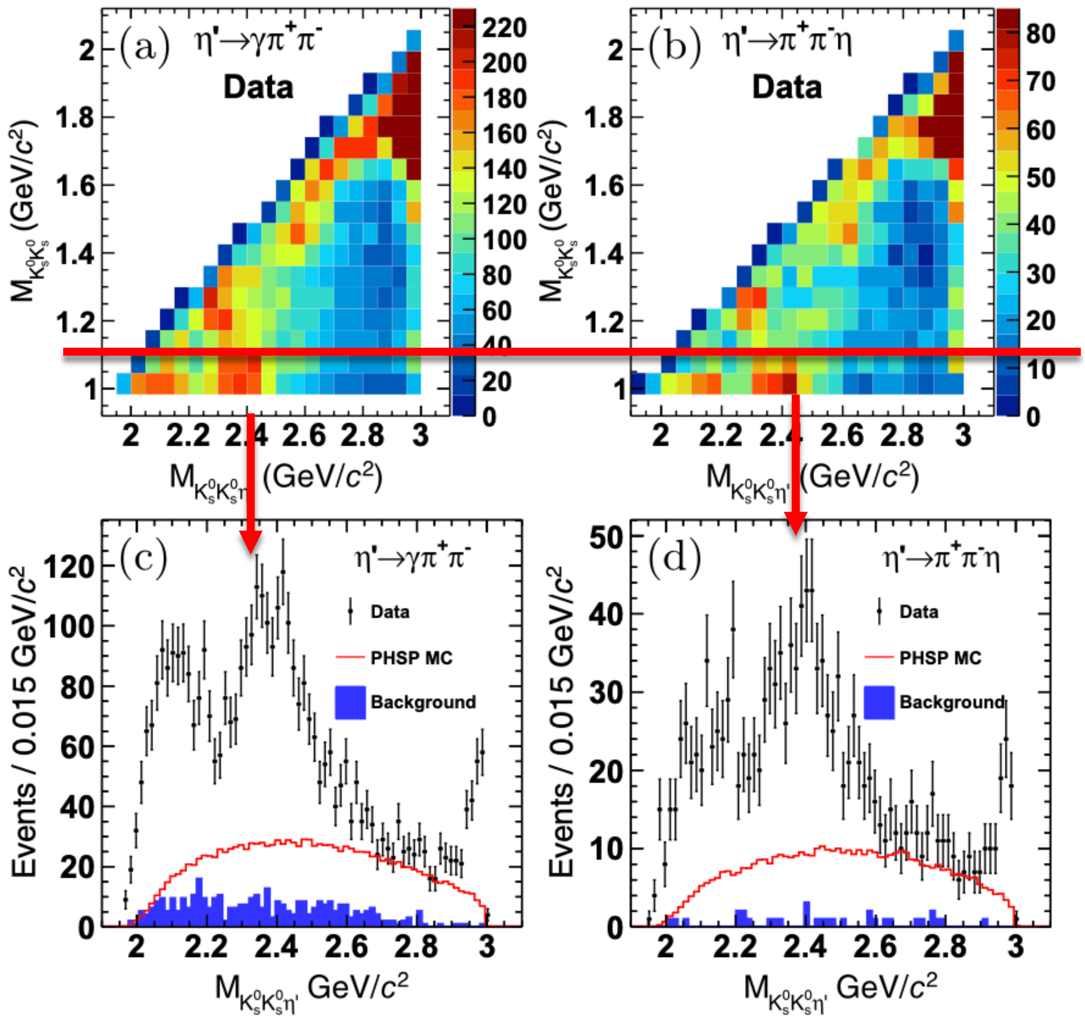
NEW BESIII Highlight!!!

X(2370): Glueball-like particle in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

PRL 132, 181901 (2024)

PWA using 10 Billion of J/ψ data @ BESIII

- Minimal background contribution: $J/\psi \to \pi^0 K_S^0 K_S^0 \eta'$ and $J/\psi \to K_S^0 K_S^0 \eta'$ since they are forbidden by exchange symmetry and CP conservation
- $\eta' \to \gamma\pi^+\pi^- / \eta\pi^+\pi^-$; $K_S^0 \to \pi^+\pi^-$



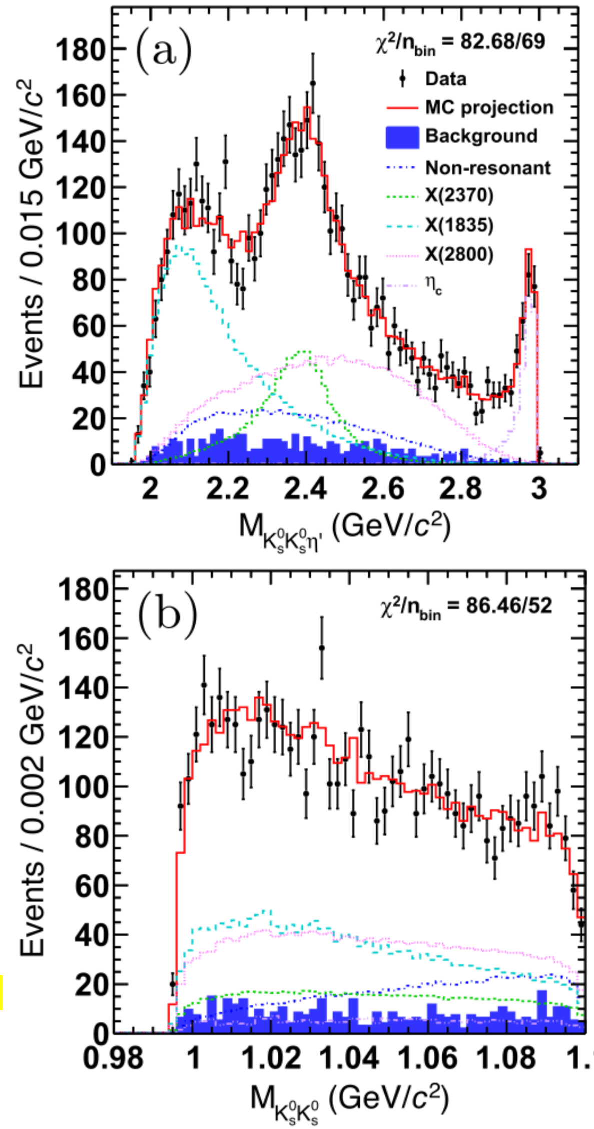
- Strong enhancement near $K^0_S K^0_S$ mass threshold from $f_0(980)$
- Clear connection between $f_0(980)$ and the structure around 2.4 GeV
- $M(K^0_S K^0_S)$ <1.1GeV to select the $f_0(980)$

NEW BESIII Highlight!!!

X(2370): Glueball-like particle in $J/\psi \to \gamma K_S^0 K_S^0 \eta'$

PRL 132, 181901 (2024)

state	J^{PC}	Decay mode	Mass (MeV/c^2)	Width (MeV/c^2)	Significance
X(2370)	0^{-+}	$f_0(980)\eta'$	2395^{+11}_{-11}	188^{+18}_{-17}	14.9σ
X(1835)	0^{-+}	$f_0(980)\eta'$	1844	192	22.0σ
X(2800)	0^{-+}	$f_0(980)\eta'$	2799^{+52}_{-48}	660^{+180}_{-116}	16.4σ
η_c	0^{-+}	$f_0(980)\eta'$	2983.9	32.0	$> 20.0\sigma$
PHSP	0^{-+}	$\eta'(K_S^0 K_S^0)_{S-wave}$	− − −	− − −	9.0σ
		$\eta'(K_S^0 K_S^0)_{D-wave}$	− − −	− − −	16.3σ

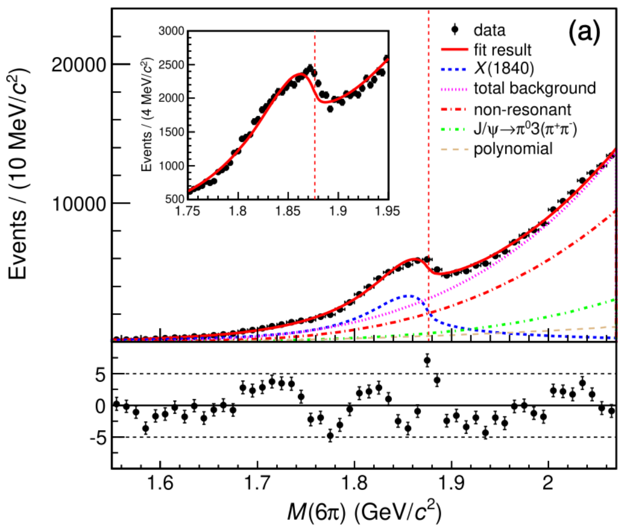


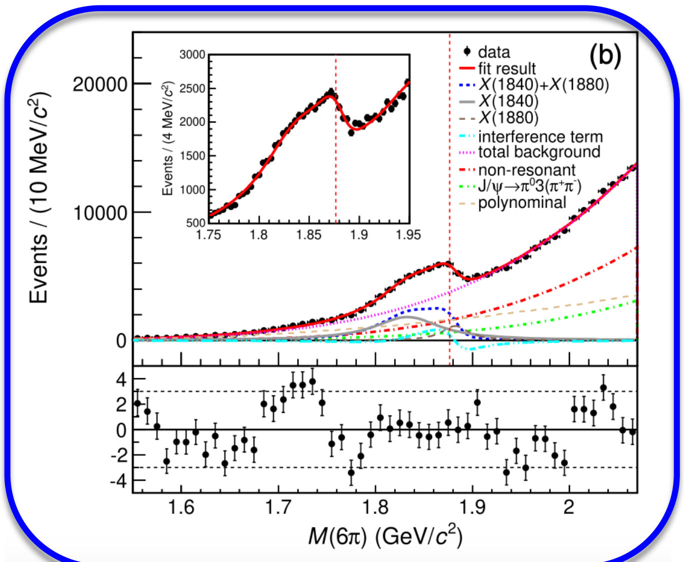
- Best fit can well describe the data including resonances X(1835), X(2370), X(2800), η_c
- Spin parity of X(2370) is determined to be 0^{-+} for the first time with significance greater than 10σ
- X(2800): broad structure to describe the effective contributions from possible high mass resonances (X(2600)) and the tail of the η_c line shape

$$M(X(2370)) = 2395 \pm 11^{+26}_{-94}\ \ \mathrm{MeV/c^2}$$
$$\Gamma(X(2370)) = 118^{+18}_{-17}(\mathrm{stat})^{+124}_{-33}(\mathrm{sist})\ \ \mathrm{MeV}$$

Good agreement with LQCD prediction of lightest pseudoscalar glueball

X(1880): A New State Observed in $J/\psi\to\gamma(3\pi^+\pi^-)$





PRL132,151901 (2024)

10 Billion of J/ψ data @ BESIII

(45 times larger than the sample previously analyzed)

- Study the line shape around the $p\bar{p}$ threshold
- Understand the nature of the X(1840) previously observed in the $J/\psi\to\gamma3(\pi^+\pi^-)$ [PRD88,091502]
- An anomalous line shape near the pp mass threshold is clearly observed
- Two models:
  1. opening of the $X(1840)\to p\bar{p}$ decay
  2. **interference between two resonances**

Parameters	Solution I	Solution II
$M_{X(1840)}$ (MeV$/c^2$)	$1832.5 \pm 3.1 \pm 2.5$	
$\Gamma_{X(1840)}$ (MeV)	$80.7 \pm 5.2 \pm 7.7$	
$\mathcal{B}_{X(1840)} (\times 10^{-5})$	$1.19 \pm 0.30 \pm 0.15$	$2.07 \pm 0.50 \pm 0.36$
$M_{X(1880)}$ (MeV$/c^2$)	$1882.1 \pm 1.7 \pm 0.7$	
$\Gamma_{X(1880)}$ (MeV)	$30.7 \pm 5.5 \pm 2.4$	
$\mathcal{B}_{X(1880)} (\times 10^{-5})$	$0.29 \pm 0.20 \pm 0.09$	$1.19 \pm 0.31 \pm 0.18$

much narrower than X(1835)

Observed line shape consistent with two overlapping resonant structure: X(1840) and X(1880) (10σ)

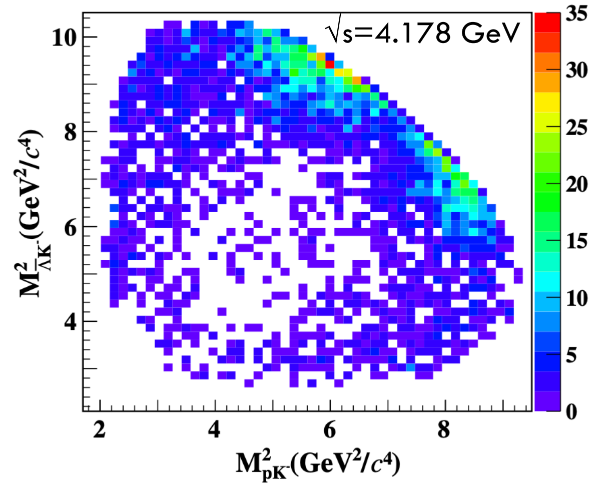
→ complex resonant structures near the $p\bar{p}$ threshold

Observation of a narrow structure near the $p\bar{\Lambda}$ threshold

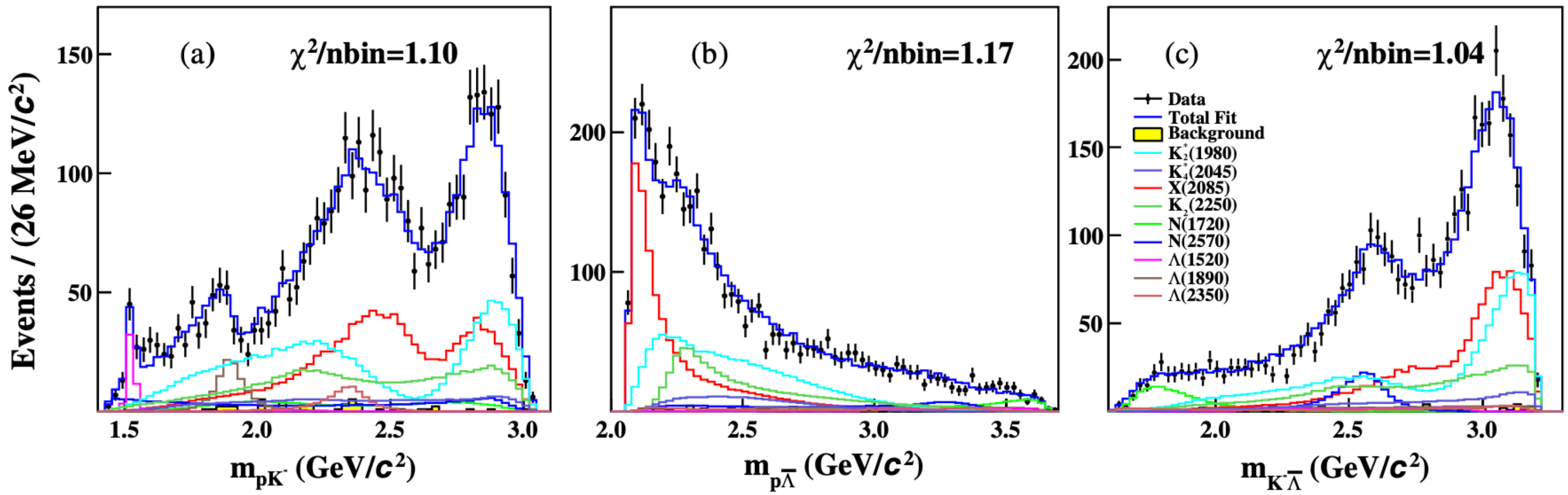
PRL131, 151901 (2023)

Evidence of a structure in $p\bar{\Lambda}$ was reported in several decays of B mesons and charmonium states (PRL90,201802; PRL93,112002; PRD79,1129)

- $e^+e^-\to pK^-\bar{\Lambda}$: anomalous enhancement near $p\bar{\Lambda}$ threshold (named X(2085)) with stat significance greater than 20σ
  - amplitude analysis for spin parity determination: **1+** with stat significance greater than 5σ
- No matching with the prediction from potential model and the narrow width → **exotic properties of X(2085)**



$$M_{pole} = (2086^{+4}_{-2} \pm 9)\ \text{MeV} \quad \text{and} \quad \Gamma_{pole} = (56^{+4}_{-3} \pm 25)\ \text{MeV}$$

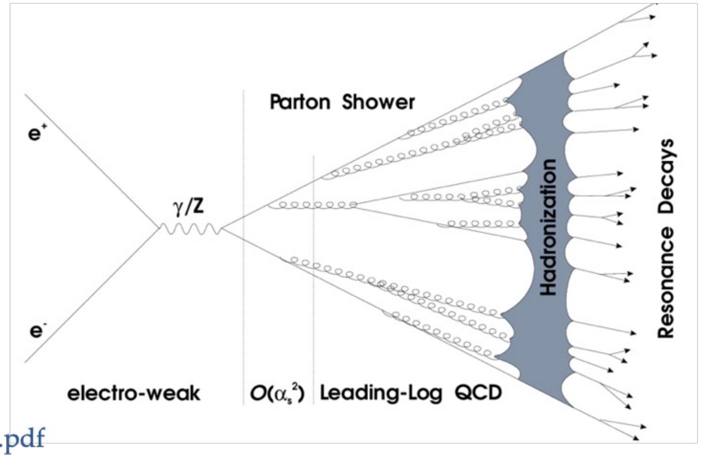


Unpolarized Fragmentation Function at BESIII

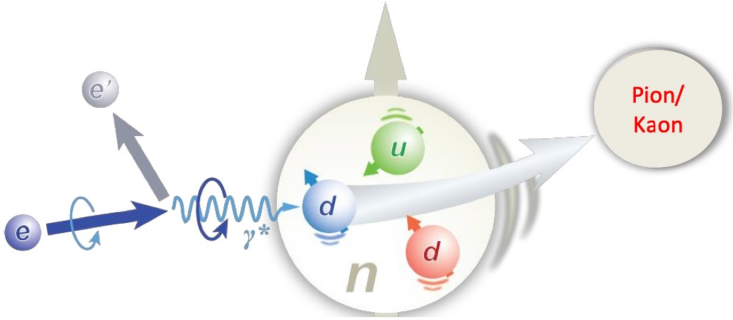
Hadron formation

- How many particles and how many jets created?
- What fraction of the initial parton momenta do they carry?

https://pdg.lbl.gov/2019/reviews/rpp2019-rev-frag-functions.pdf



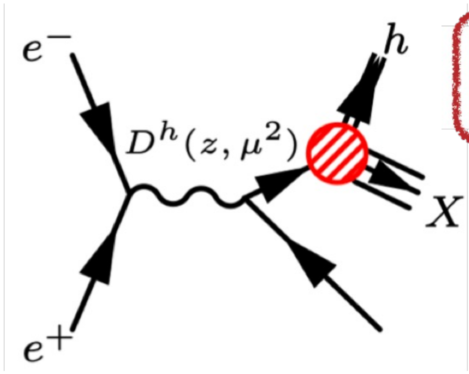
Fragmentation Functions (FFs)



$$\sigma^{\ell N \to \ell h X} = \hat{\sigma} \otimes PDF \otimes FF$$

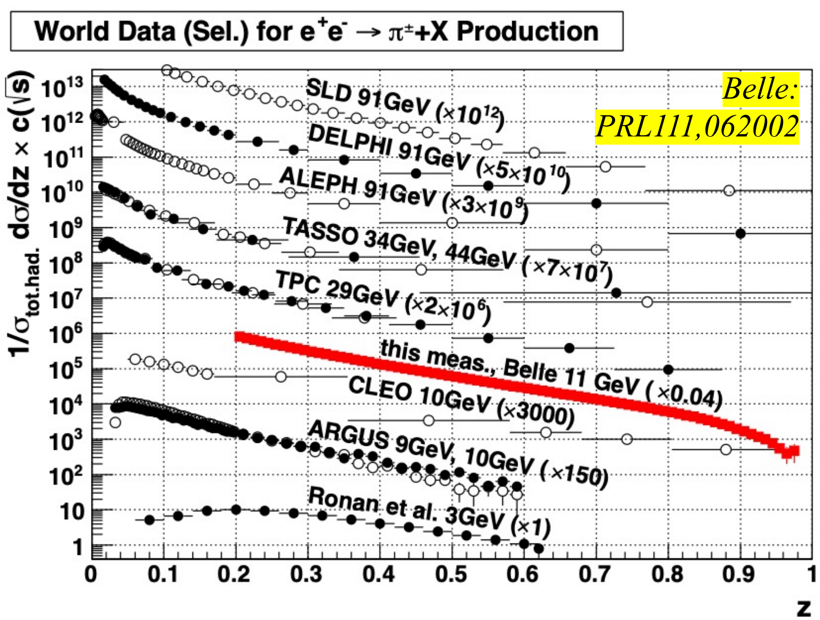
To accurately extract the Parton Distribution Functions (PDFs) more precise FFs are needed

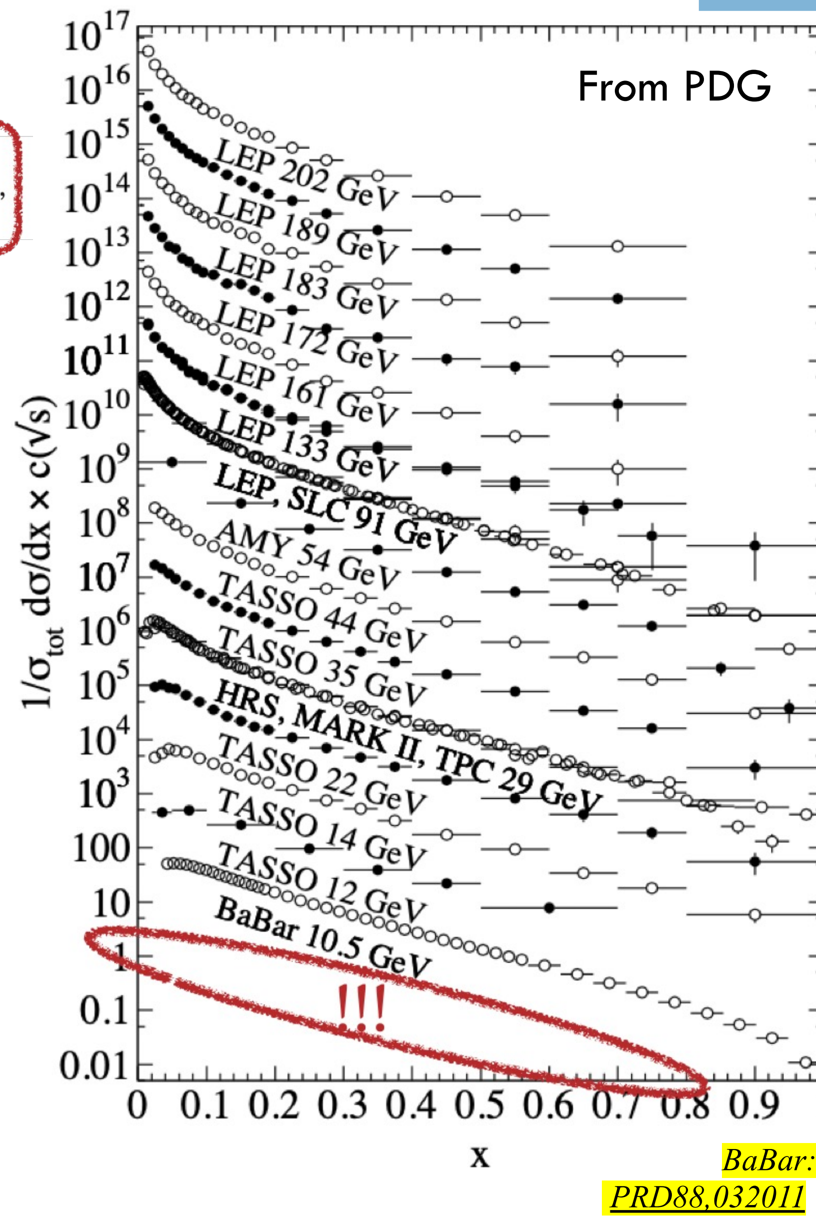
Unpolarized Fragmentation Functions



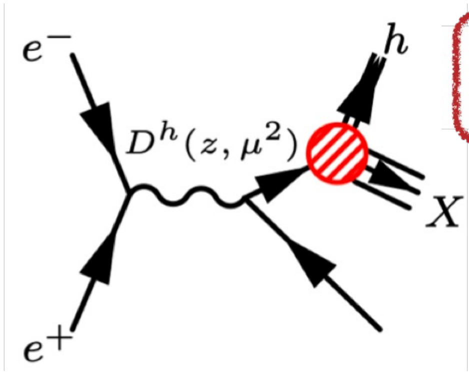
$$\frac{1}{\sigma(e^+e^- \to \text{hadrons})}\,\frac{d\sigma(e^+e^- \to h+X)}{dp_h},$$

D: unpolarized FF





Unpolarized Fragmentation Functions

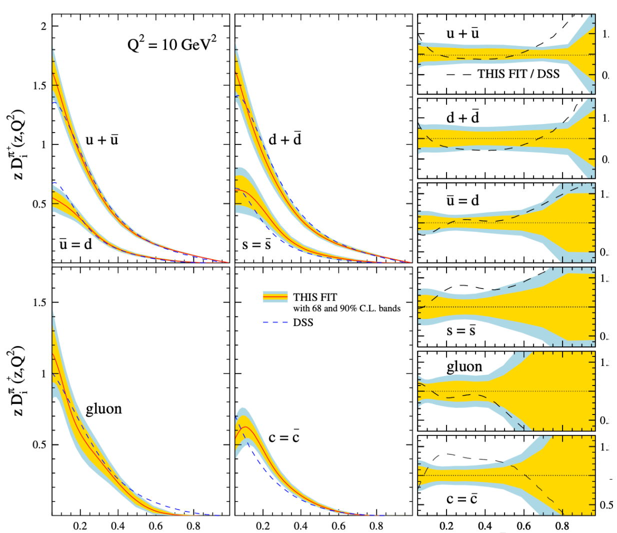


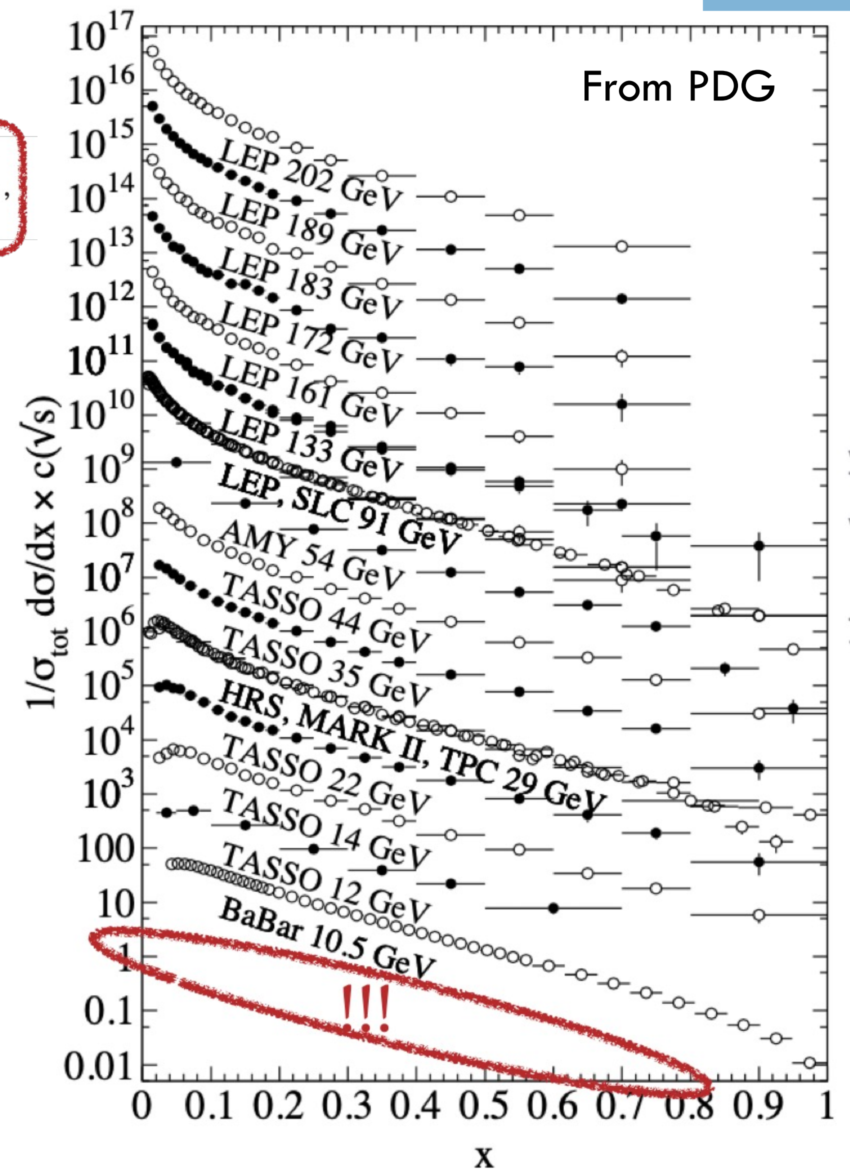
$$\frac{1}{\sigma(e^+e^- \to \text{hadrons})} \frac{d\sigma(e^+e^- \to h + X)}{dp_h},$$

D: unpolarized FF

Global fit analysis (e+e-, SIDIS and pp data) performed in order to extract the FFs for gluons and different quark flavours

DSS fit:
PRD 91, 014035
(it includes Belle and BaBar data)



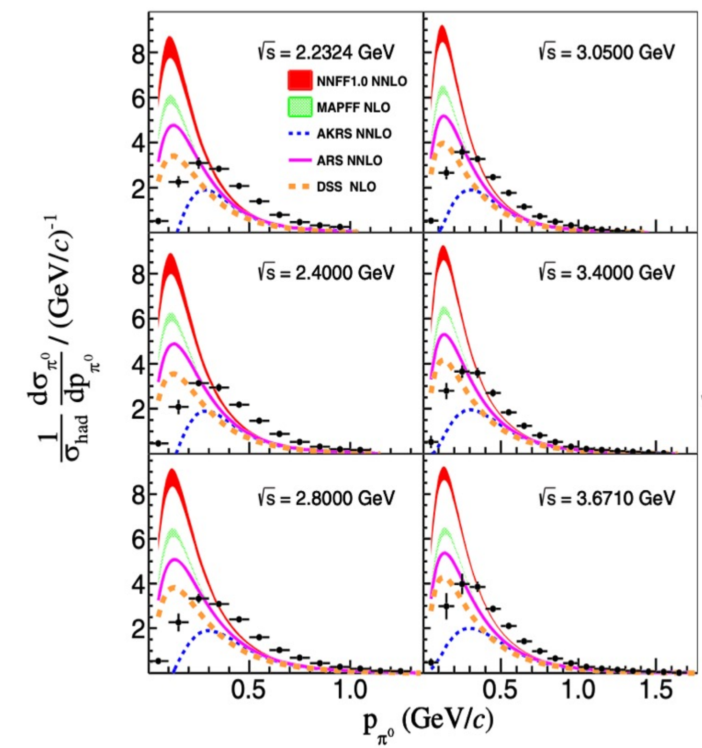


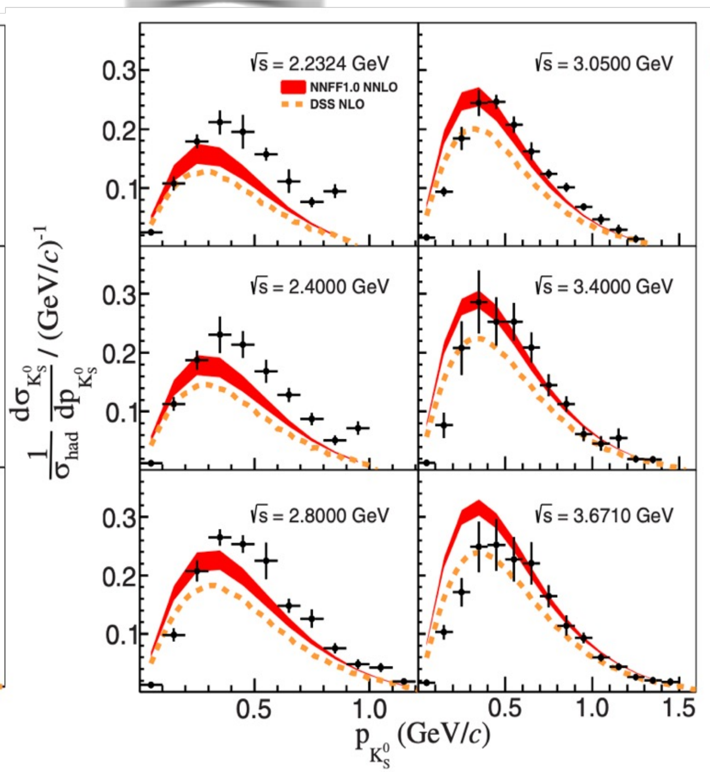
Inclusive π^0 and K^0_S production @ BESIII

PRL 130, 231901 (2023)
Suppl. Material

$e^+e^- \rightarrow \pi^0/K^0_S+X$ studied at six c.m. energies from 2.2324 to 3.6710 GeV

- $M(\gamma\gamma)$ and $M(\pi^+\pi^-)$ spectra divided into $\Delta p_{\pi/K}$=0.1 GeV/c intervals in order to extract the corresponding number of signal events
- Normalized differential cross section: $$\frac{N_h^{\rm obs}}{N_{\rm had}^{\rm obs}} \frac{1}{\Delta p_h} f_h$$





NNFF1.0, ARS, AKRS: inclusive e+e- data at NNLO accuracy

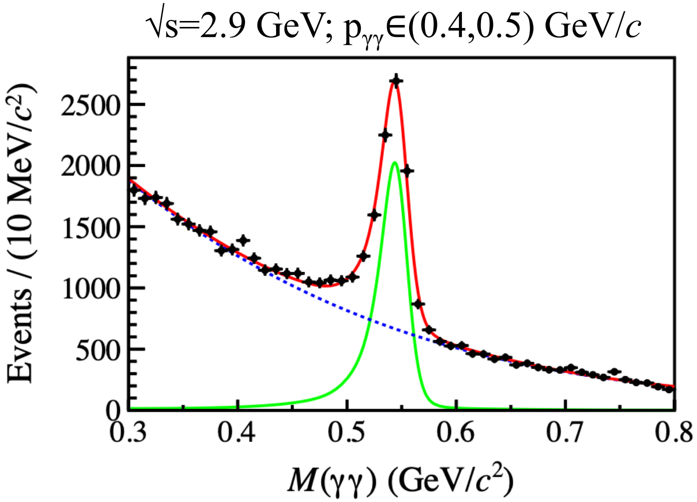
MAPFF: + Lepton-proton fixed target

DSS: + Lepton-proton fixed target and proton-proton collision

Disagreement observed to depend on both c.m energy and hadron momentum

Leading twist calculation not sufficient at BESIII energy scale? Consider quark mass and hadron mass correction effects? small-z resummation effects? problem in the extrapolation of FFs from high energy data to low-energy scale?

Inclusive η production @ BESIII



arXiv:2401.17873

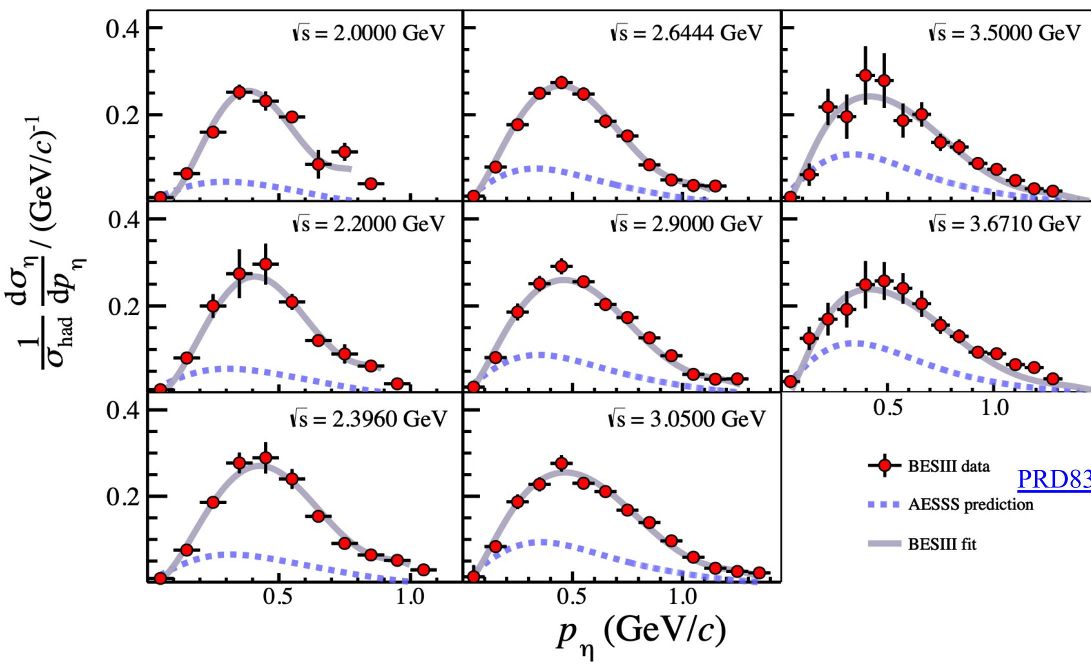
Normalized cross section of the inclusive process $e^+e^-\to\eta+X$ measured at 8 c.m. energies from 2.000 GeV to 3.6710 GeV

- more info on the hadronization process since the η wave function contains all light quarks and antiquarks

Experimental observation:

$$\frac{N_h^{\rm obs}}{N_{\rm had}^{\rm obs}}\frac{1}{\Delta p_h}f_h$$

- AESSS prediction: NLO, pp data and e^+e^- data from √s>10 GeV
  Huge tension with BESIII data
- BESIII fit: e^+e^- data from √s>10 GeV (except unpublished BaBar data) + BESIII data + NNLO + higher twist effects + hadron mass corrections



PRD83,034002

Conclusions

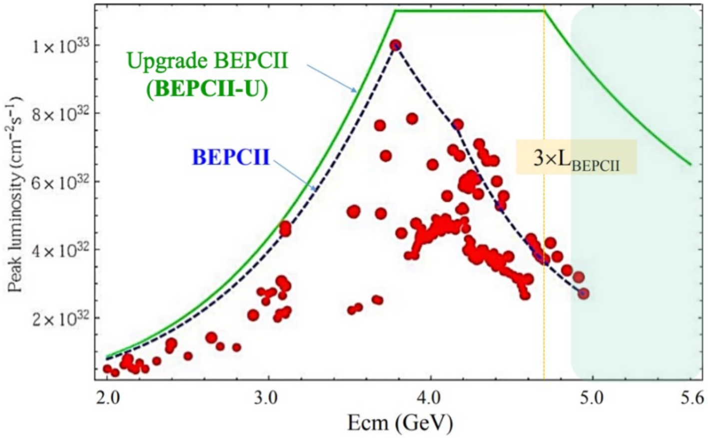
BESIII experiment is an excellent laboratory to study light hadron physics, search for light QCD exotic states, study the nature of XYZ mesons, as well as study charmonium and charm physics and QCD features

- Exciting results from new J/ψ data are presented:
  - $\eta(1405)$ and glueball candidate X(2370)
  - $\eta_1(1855)$: isoscalar 1^{-+} spin exotic state
  - X(1880) a new state observed in $J/\psi\to\gamma 3(\pi^+\pi^-)$
  - $p\Lambda$ structure
- Unpolarized Fragmentation Functions
  - The normalized differential cross section of inclusive $\pi^0/K^0_S/\eta$ production are measured using BESIII data
  - Charged $K/\pi/\phi/K^*(892)$ analyses in progress
  - Analysis in progress also for the polarized FFs

From July 1 to December 31:
Machine shutdown for the upgrade

Upgrade in energy (5.6 GeV) and luminosity (BEPCII-U, 3x)

- Opportunities to study other charmed baryons (Σ_c, Ξ_c, Ω_c) in the BEPCII-U
- Remove the inner MDC and replace it with CGEM

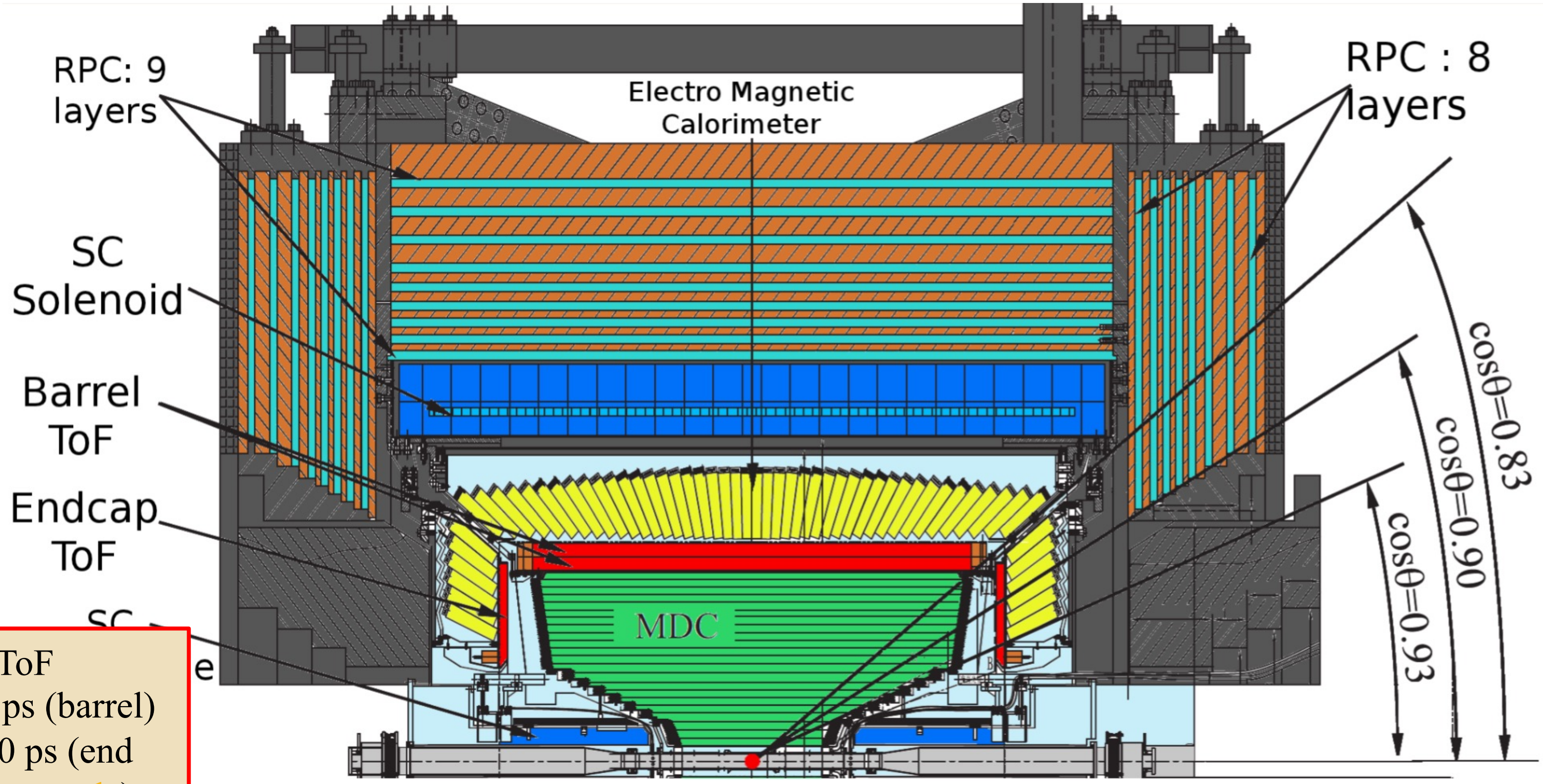


Thank you for your attention

Back-up slides

The BESIII Detector

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



ToF
$\sigma_t \sim 68$ ps (barrel)
$\sigma_t \sim 60$ ps (end caps, upgrade)

Drift Chamber
$\sigma_{r\phi} \sim 130$ μm (single wire)
$\sigma_{pt}/p_t \sim 0.5$ % @ 1 GeV

Electromagnetic CsI(Tl) Calorimeter
$\sigma_E/E < 2.5\%$ @ 1 GeV (barrel)
$\sigma_E/E < 5\%$ @ 1 GeV (end caps)
$\sigma_{xy} \sim (6\ \text{mm})/E^{1/2}$ @ 1 GeV

RPC Muon Detector
$\Delta\Omega/4\pi = 93\%$

X(2370)

X(2370) measurements:

$J^{PC} = 0^{-+}$ with significance >9.8σ

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

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

$B(J/\psi \to \gamma X(2370)) B(X(2370) \to f_0(980)\eta') B(f_0(980) \to K^0_S K^0_S)$
$= 1.31 \pm 0.22^{+2.85}_{-0.84} \times 10^{-5}$

PRL 132 (2024) 181901

LQCD prediction on lightest pseudoscalar glueball:

$J^{PC} = 0^{-+}$

$M = 2395 \pm 14$ MeV

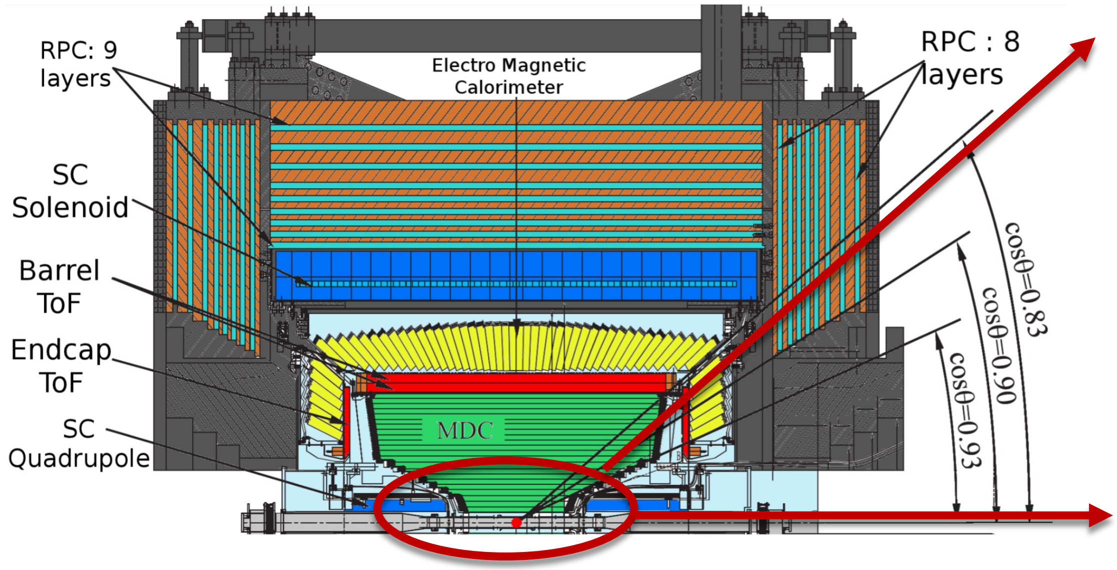
$B(J/\psi \to \gamma G_{0^{-+}}) = 2.31 \pm 0.80 \times 10^{-4}$

PRD 100 (2019) 054511

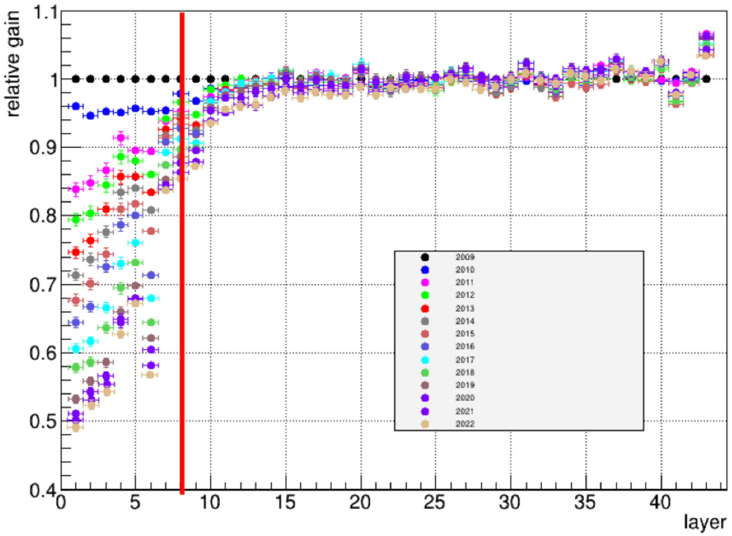
- The measurements are in a agreement with the predictions on lightest pseudoscalar glueball
  - **The spin-parity of the X(2370) is determined to be 0^{-+} for the first time**
  - **Mass is in a agreement with LQCD predictions**
  - The estimation on $B(J/\psi \to \gamma X(2370))$ and prediction on $B(J/\psi \to \gamma G_{0^{-+}})$ are consistent within errors (assuming ~5% decay rate, $B(J/\psi \to \gamma X(2370)) = 10.7^{+22.8}_{-7} \times 10^{-4}$)

Courtesy of **Yanping Huang**

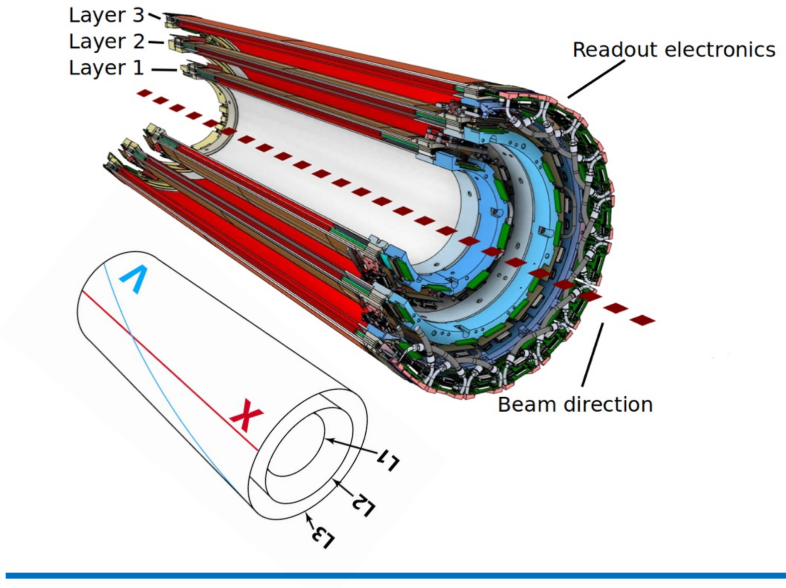
Why CGEM-IT ?



Gain loss of the inner MDC



Gain loss per year ~ 4 %

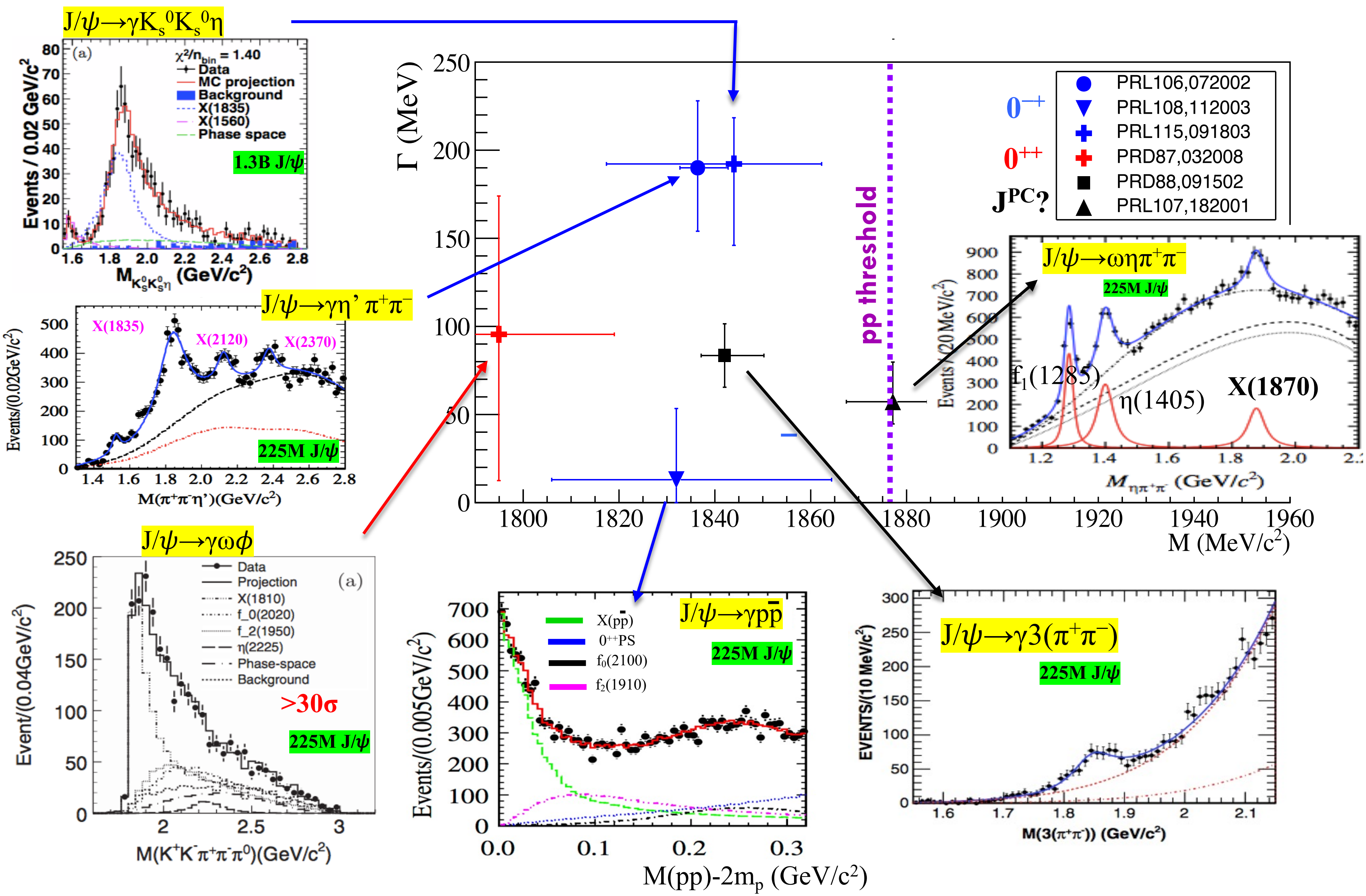


- Replace the inner MDC with 3 layers of cylindrical triple-GEM detectors
- Improve rate capability, aging and secondary vertex reconstruction, while retaining the current momentum and tracking performance

Main system requirements:

- Low Material budget ~1.5% of X_0 in total
- Spatial resolution of 130-150 μm with charge and time readout

Structures between 1.8-1.9 GeV



Further Checks on the $\eta_1(1855)$

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

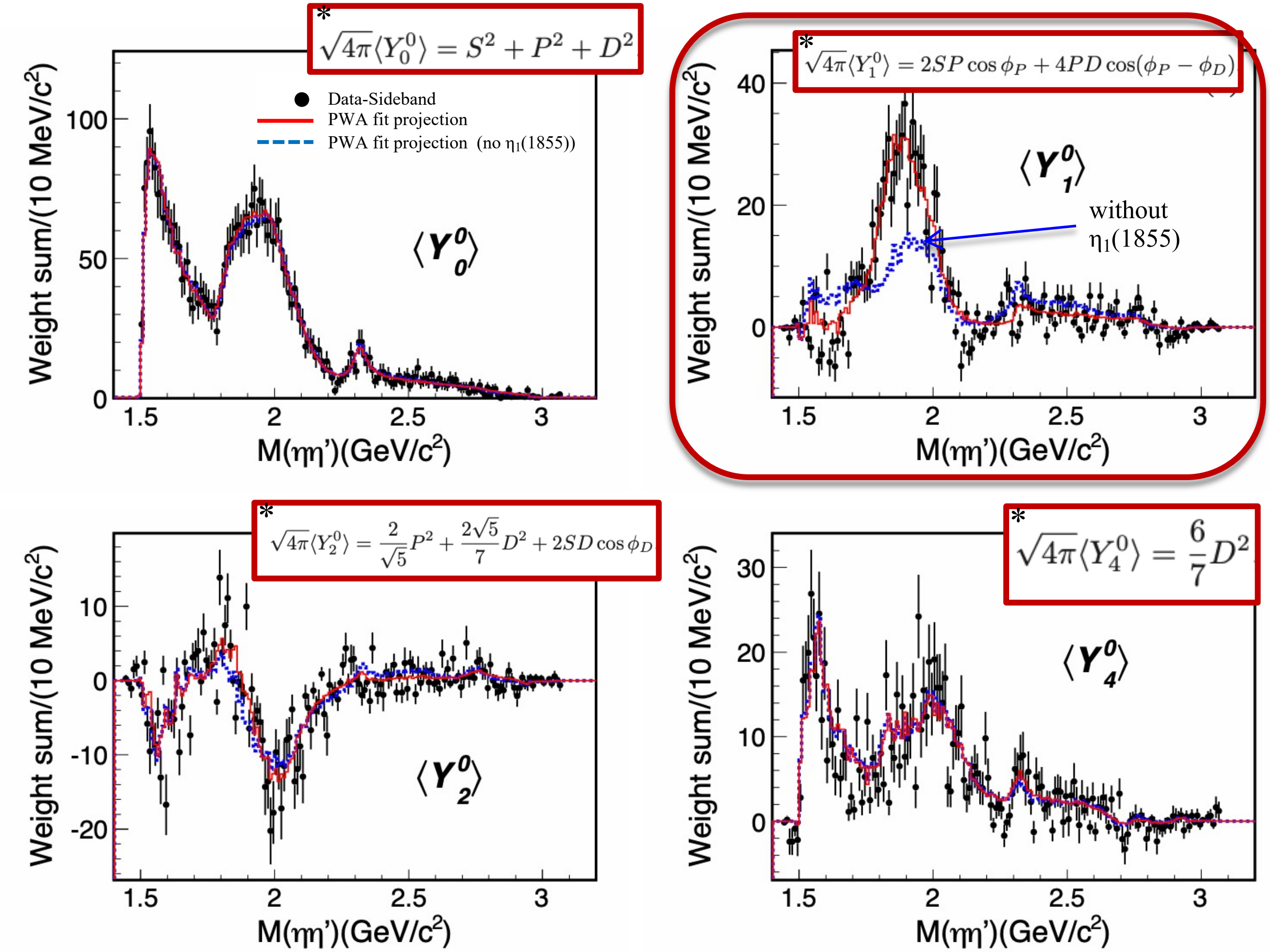
The $\cos(\theta_\eta)$ distribution can be expressed as an expansion in terms of Legendre polynomials; the coefficients (unnormalized moments of expansion) characterize the spin of the ηη' resonances

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

- Neglecting resonance contributions in the γη(') subsystem and amplitude with spin greater than 2, the moments are related to the spin-0 (S), spin-1 (P) and spin-2 (D) amplitudes

- Good data/PWA consistency
- Narrow structure in $\langle Y^0_1 \rangle$: $\eta_1(1855)$ P-wave component is needed

*Assuming ηη' system has zero helicity



Discussion about $f_0(1500)$ and $f_0(1710)$

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

The dominant contributions in the baseline PWA are from scalar resonance:

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	$1.81\pm0.11^{+0.19}_{-0.13}$	$\gg30\sigma$
	$f_0(1810)$	1795	95	1795	95	$0.11\pm0.01^{+0.04}_{-0.03}$	11.1σ
	$f_0(2020)$	$2010\pm6^{+6}_{-4}$	$203\pm9^{+13}_{-11}$	1992	442	$2.28\pm0.12^{+0.29}_{-0.20}$	24.6σ
	$f_0(2330)$	$2312\pm7^{+7}_{-3}$	$65\pm10^{+3}_{-12}$	2314	144	$0.10\pm0.02^{+0.01}_{-0.02}$	13.2σ
	$\eta_1(1855)$	$1855\pm9^{+6}_{-1}$	$188\pm18^{+3}_{-8}$	-	-	$0.27\pm0.04^{+0.02}_{-0.04}$	21.4σ
	$f_2(1565)$	1542	122	1542	122	$0.32\pm0.05^{+0.12}_{-0.02}$	8.7σ
	$f_2(2010)$	$2062\pm6^{+10}_{-7}$	$165\pm17^{+10}_{-5}$	2011	202	$0.71\pm0.06^{+0.10}_{-0.06}$	13.4σ
	$f_4(2050)$	2018	237	2018	237	$0.06\pm0.01^{+0.03}_{-0.01}$	4.6σ
	0^{++} PHSP	-	-	-	-	$1.44\pm0.15^{+0.10}_{-0.20}$	15.7σ
$J/\psi \to \eta' X \to \gamma\eta\eta'$	$h_1(1415)$	1416	90	1416	90	$0.08\pm0.01^{+0.01}_{-0.02}$	10.2σ
	$h_1(1595)$	1584	384	1584	384	$0.16\pm0.02^{+0.03}_{-0.01}$	9.9σ

$$\frac{\mathcal{B}(f_0(1500)\to\eta\eta')}{\mathcal{B}(f_0(1500)\to\pi\pi)} = \frac{~~(8.96^{+2.95}_{-2.87}\times10^{-2})~~}{(1.66^{+0.42}_{-0.40}\times10^{-1})} \;*$$

Consistent with PDG

$$\frac{\mathcal{B}(f_0(1710)\to\eta\eta')}{\mathcal{B}(f_0(1710)\to\pi\pi)} < \frac{~~1.61\times10^{-3}~~}{2.87\times10^{-3}} \;*$$

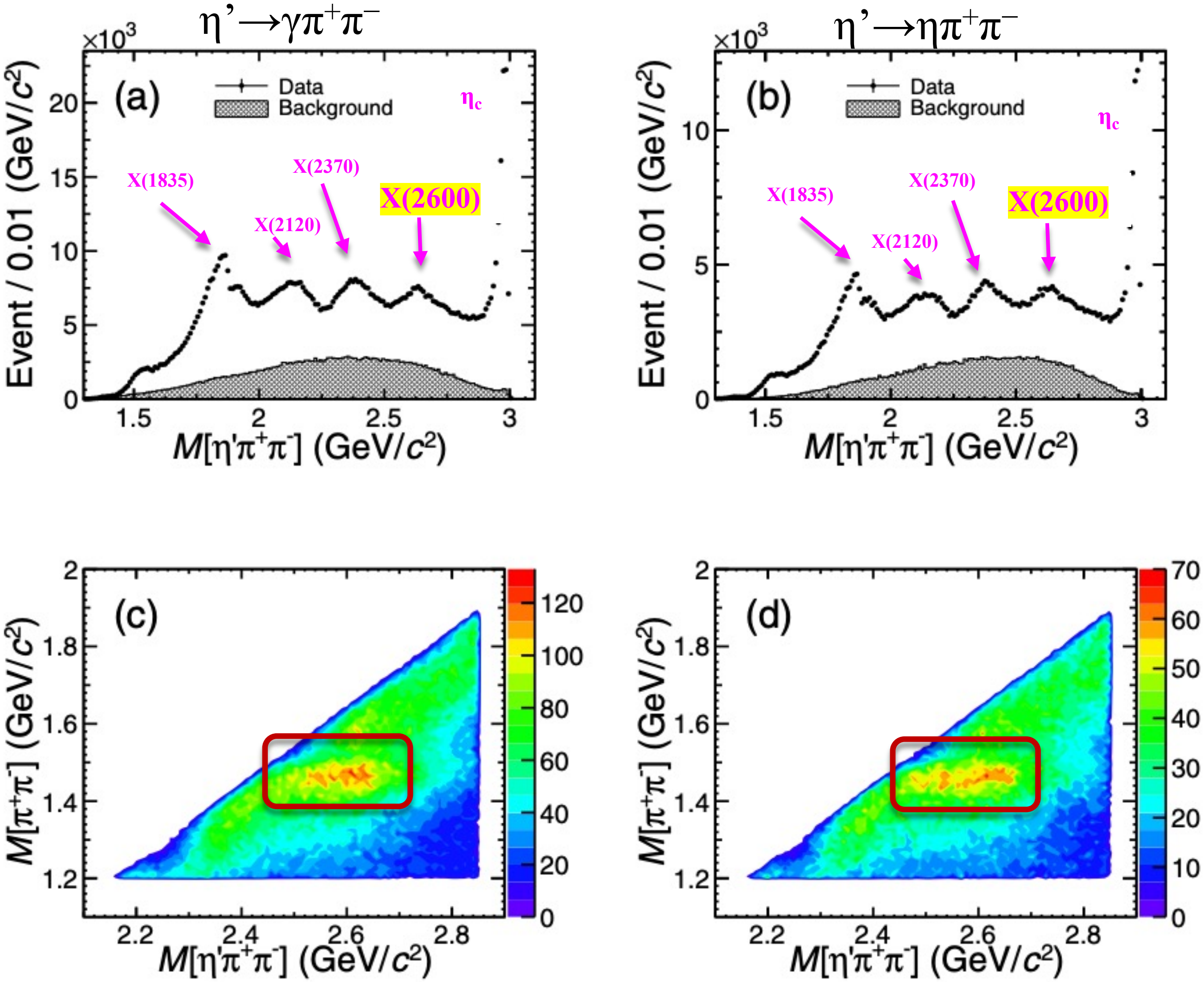
@90% C.L.

This suppressed decay rate supports the hypothesis that the $f_0(1710)$ has a large overlap with the ground state scalar glueball (PRD 92,121902)

X(2600): A New State Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

10 Billion of J/ψ data @ BESIII ($\eta' \to \gamma\pi^+\pi^-/\eta\pi^+\pi^-$)

PRL 129, 042001 (2022)



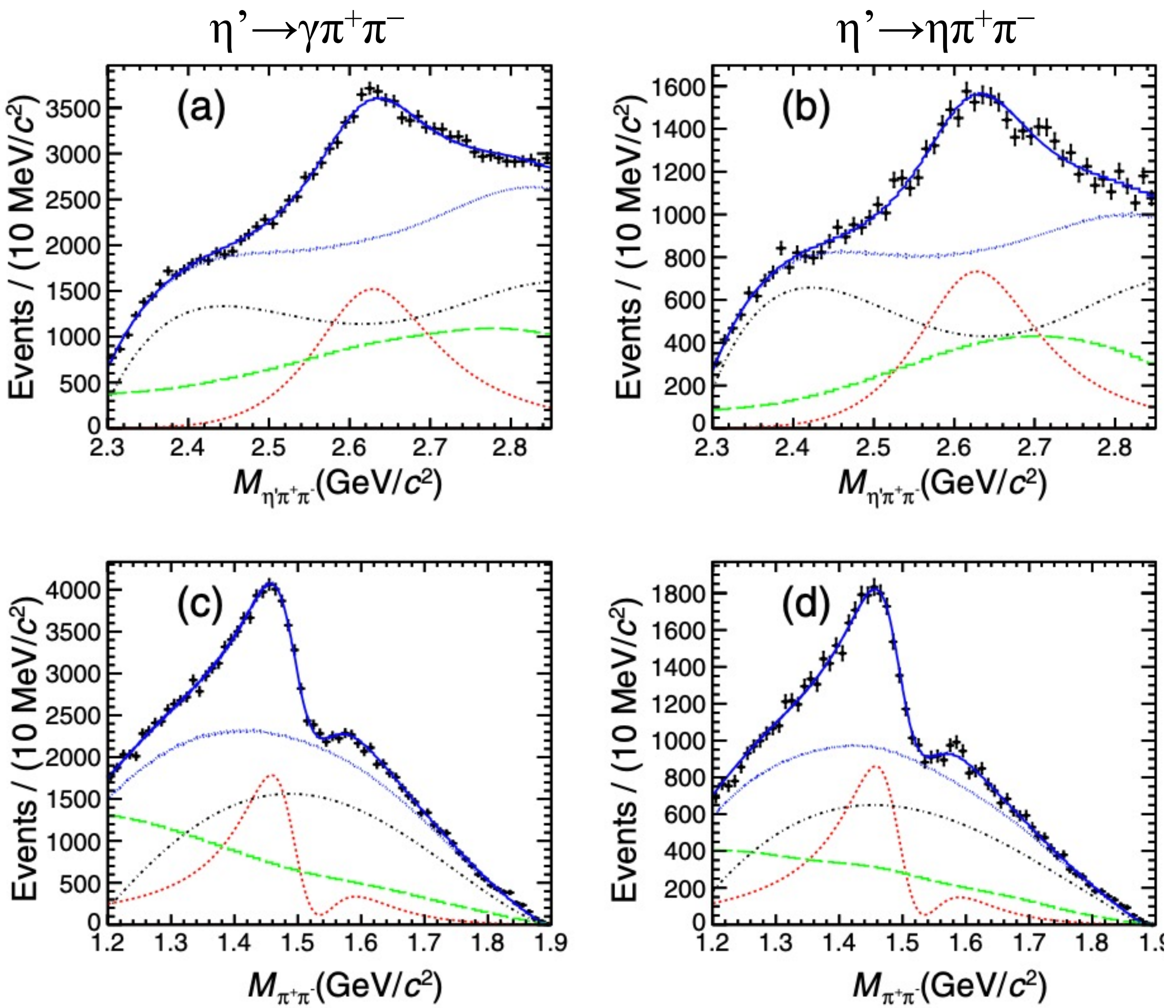
A new state in $M(\eta'\pi^+\pi^-)$ invariant mass is observed around 2.6 GeV/c^2, which is correlated to a structure in $M(\pi^+\pi^-)$ @ 1.5 GeV/c^2

$X(2600)$: A New State Observed in $J/\psi \to \gamma\pi^+\pi^-\eta'$

PRL 129, 042001 (2022)

- Simultaneous fit to $\eta'\pi^+\pi^-$ and $\pi^+\pi^-$ mass spectra is performed

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

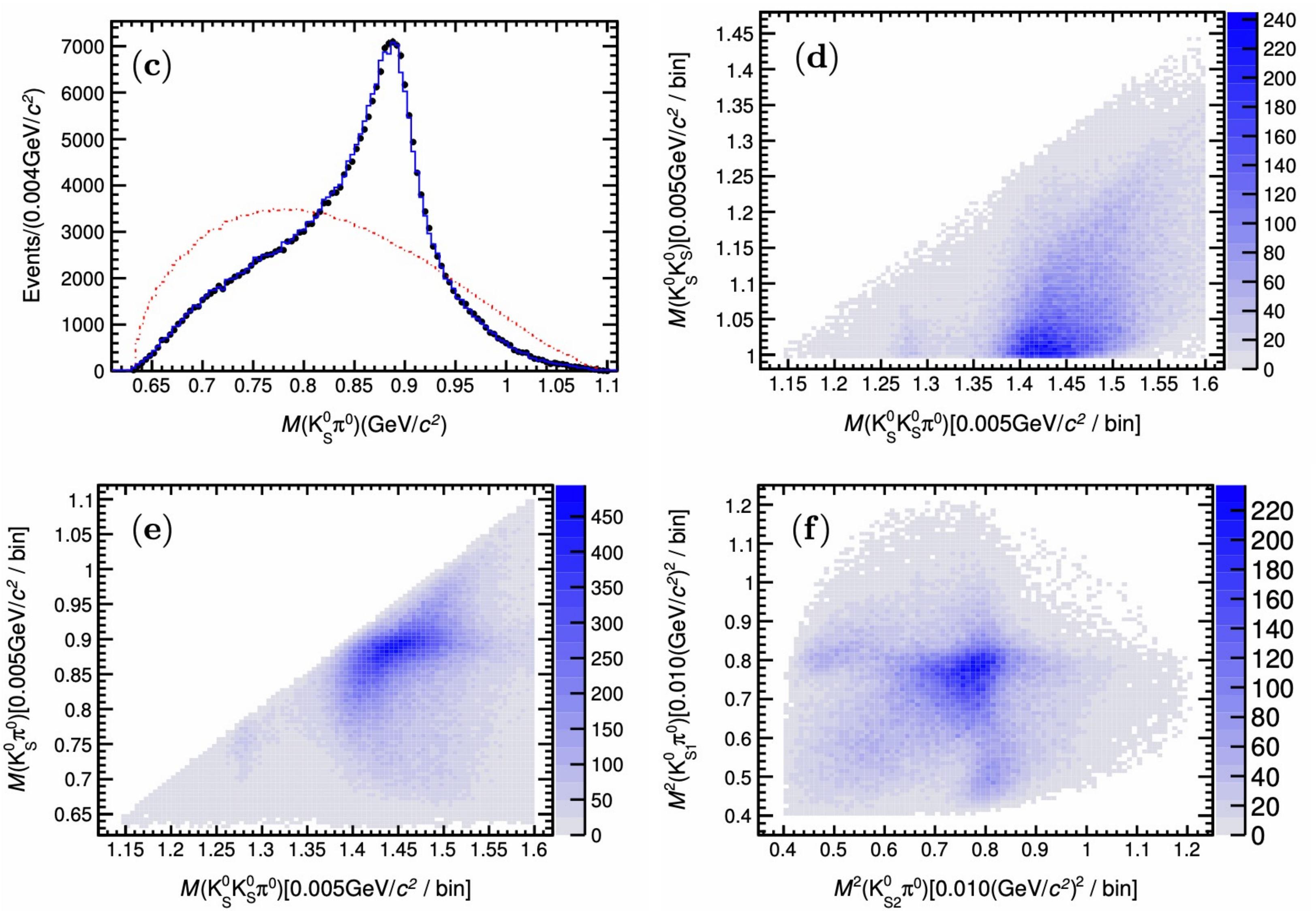


- X(2600) resonance observed for the first time with a statistical significance greater than 20σ

- The structure in $M(\pi^+\pi^-)$ around 1.5 GeV/c^2 can be well described with the interference between $f_0(1500)$ and the X(1540) resonances

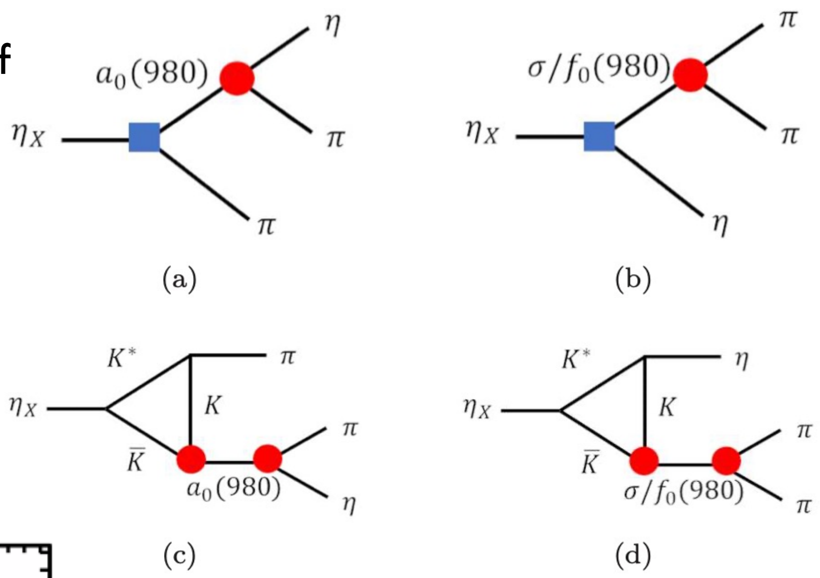
Dalitz Plot - $J/\psi \to \gamma K^0_S K^0_S \pi^0$

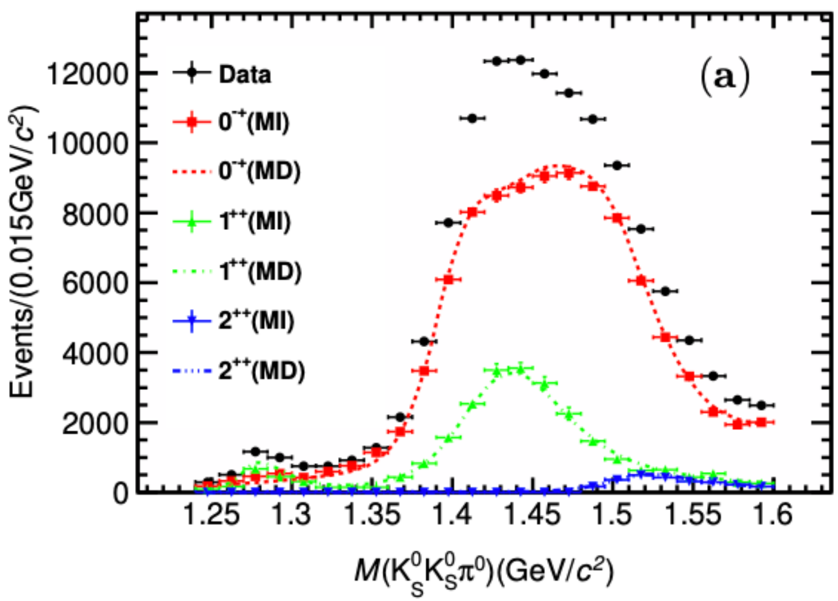
JHEP03(2023)121



Dalitz Plot - $J/\psi \to \gamma K^0_S K^0_S \pi^0$

https://arxiv.org/pdf/2302.01210.pdf

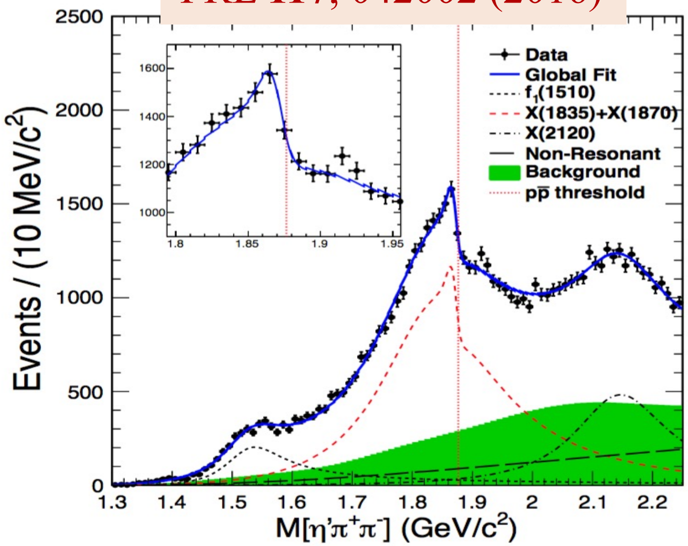




JHEP03(2023)121

Other Results on X(1835)

PRL **117**, 042002 (2016)



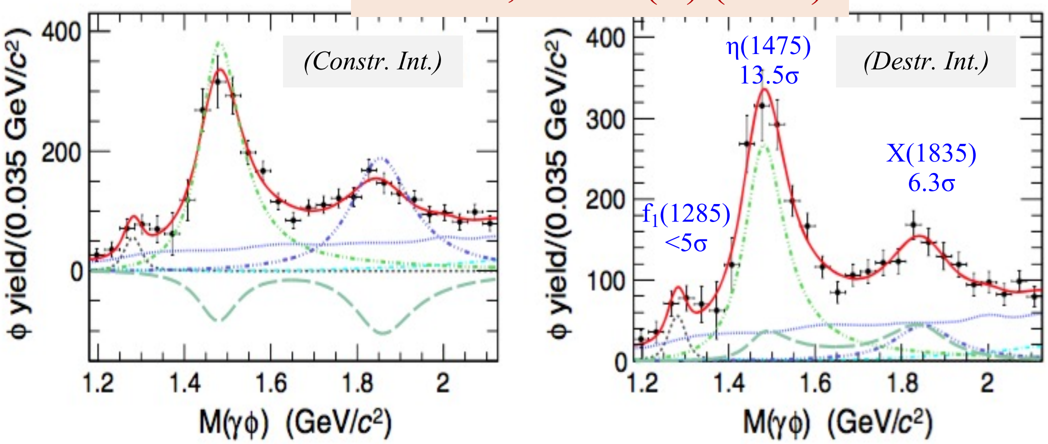
1.09×10^9 J/ψ @ BESIII

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

Significant distortion of the $\eta' \pi^- \pi^+$ line shape near the ppbar mass threshold

Two fit models are taken into account and both support the existence of a $p\bar{p}$ moleculelike or bound state

PRD **97**,051101(R) (2018)



1.3×10^9 J/ψ @ BESIII

$J/\psi \to \gamma\gamma\phi$: two structures corresponding to η(1475) and X(1835) are observed

- X(1835) and η(1475): $J^{PC} = 0^{-+}$ assignment favored
- Sizable $s\bar{s}$ component in X(1835)
  - more complicated than a pure $N\bar{N}$ state

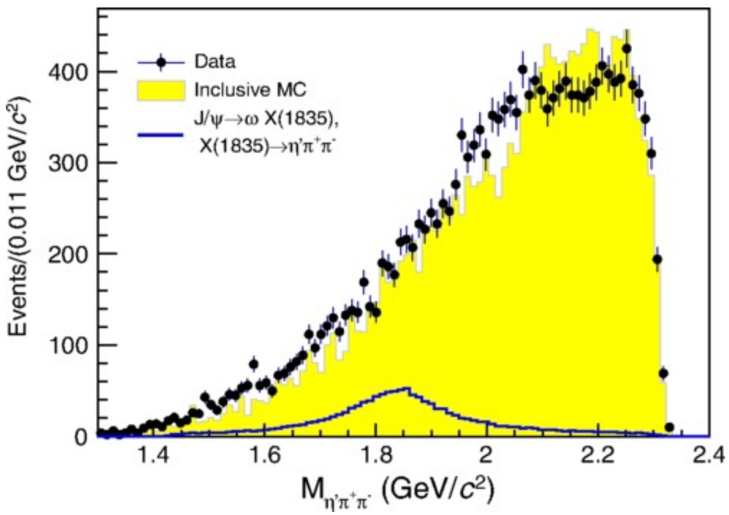
Solution	Resonance	m_R (MeV/c^2)	Γ (MeV)
I (*Destr. Int.*)	$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$
II (*Constr. Int.*)	$\eta(1475)$	$1477 \pm 7 \pm 13$	$118 \pm 22 \pm 17$
	$X(1835)$	$1839 \pm 26 \pm 26$	$175 \pm 57 \pm 25$

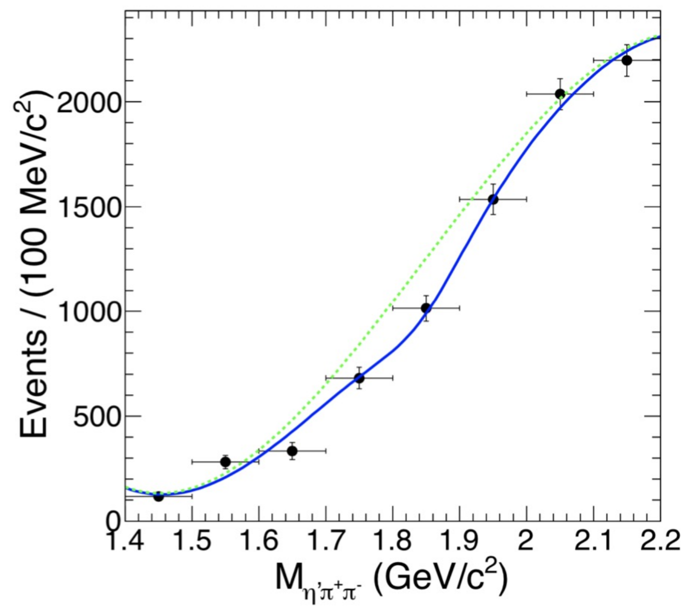
Search for X(1835) in other decay modes

- $J/\psi \to \omega\eta'\pi^+\pi^-$ hadronic decay and search for $X(1835) \to \eta'\pi^+\pi^-$

PRD **99**, 071101 (R) (2019)

1.3×10^9 J/ψ @ BESIII





- No obvious sign of X(1835)'s existence
- Large gluon component? [PRD74,034019]

$$\mathcal{B}(J/\psi \to \omega\eta'\pi^+\pi^-) = (1.12 \pm 0.02 \pm 0.13) \times 10^{-3}$$
$$\mathcal{B}(J/\psi \to \omega X(1835),\ X(1835) \to \eta'\pi^+\pi^-) < 6.2 \times 10^{-5}$$

@ 90% C.L.

The puzzle is still not complete ….

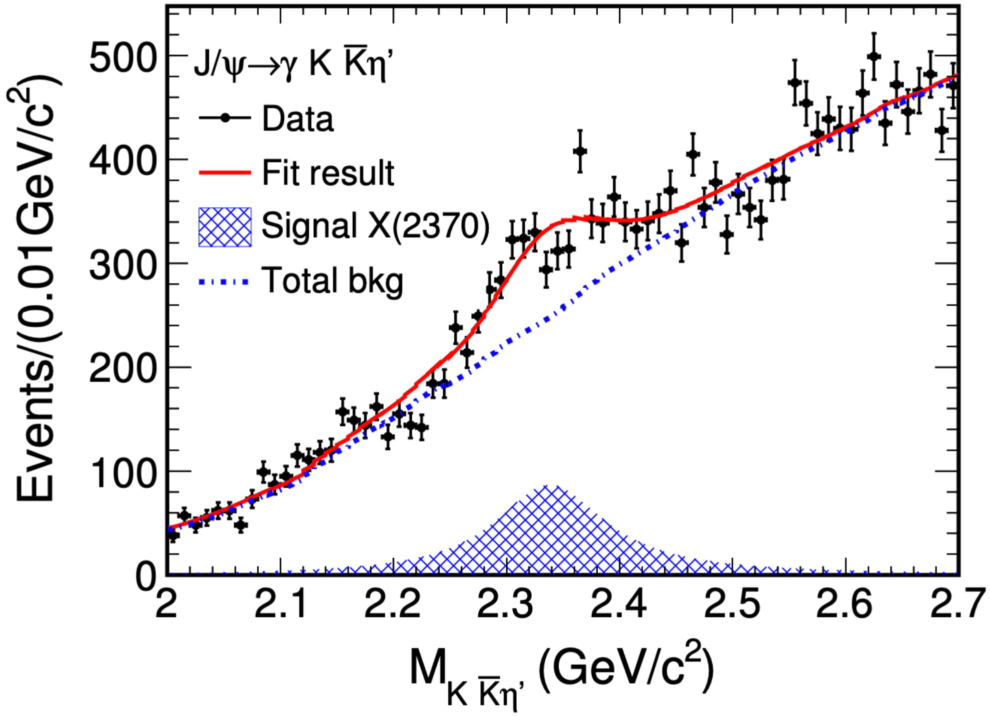
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)

- X(2120) and X(2370) states observed in the $\pi^-\pi^+\eta'$ invariant mass spectra (PRL**106**,072002)
- The **X(2370)** measured mass is consistent with the pseudoscalar glueball candidate predicted by LQCD calculation (PRD**73**,014516)

➢ Simulataneus fit performed for two decay η’ modes



➢ **No evidence of X(2120) is found**

$$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^+K^-\eta') < 1.49 \times 10^{-5}$$

$$\mathcal{B}(J/\psi \to \gamma X(2120) \to \gamma K^0_S K^0_S \eta') < 6.38 \times 10^{-6}$$

➢ **Clear X(2370) signal observed with significance of about 8.3σ**

$$M_{X(2370)} = 2341.6 \pm 6.5 \pm 5.7\ \mathrm{MeV}/c^2 \quad \Gamma_{X(2370)} = 117 \pm 10 \pm 8\ \mathrm{MeV}$$

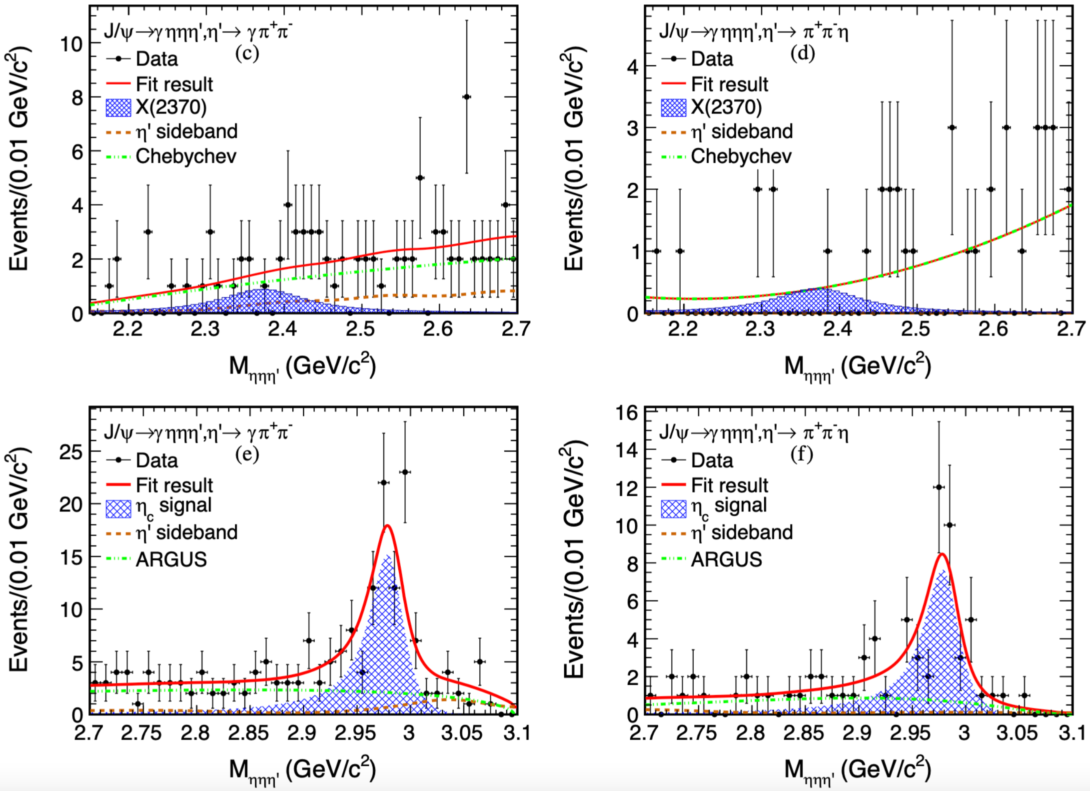
$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^+K^-\eta') = (1.79 \pm 0.23 \pm 0.65) \times 10^{-5}$$

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma K^0_S K^0_S \eta') = (1.18 \pm 0.32 \pm 0.39) \times 10^{-5}$$

Search for X(2370) in $J/\psi \to \gamma\eta\eta\eta'$

PRD **103**, 012009 (2021)

1.3×10^9 J/ψ @ BESIII



Branching ratios prediction for the decay of pseudoscalar glueball with M~2.37 GeV into three pseudoscalar mesons (PRD **87**,054036 (2013))

$$\Gamma_{G\to\eta\eta\eta'}/\Gamma_G^{tot} = 0.00082$$

$$\Gamma_{G\to KK\eta'}/\Gamma_G^{tot} = 0.011$$

$$\Gamma_{G\to\pi\pi\eta'}/\Gamma_G^{tot} = 0.090$$

- **No obvious signal of X(2370)**

Simultaneous unbinned maximum likelihood fit to the ηηη' is performed and the 90% C.L. upper limit is calculated

$$\mathcal{B}(J/\psi \to \gamma X(2370) \to \gamma\eta\eta\eta') < 9.2\times10^{-6}$$

(it does not contradict PRD **87**,054036)

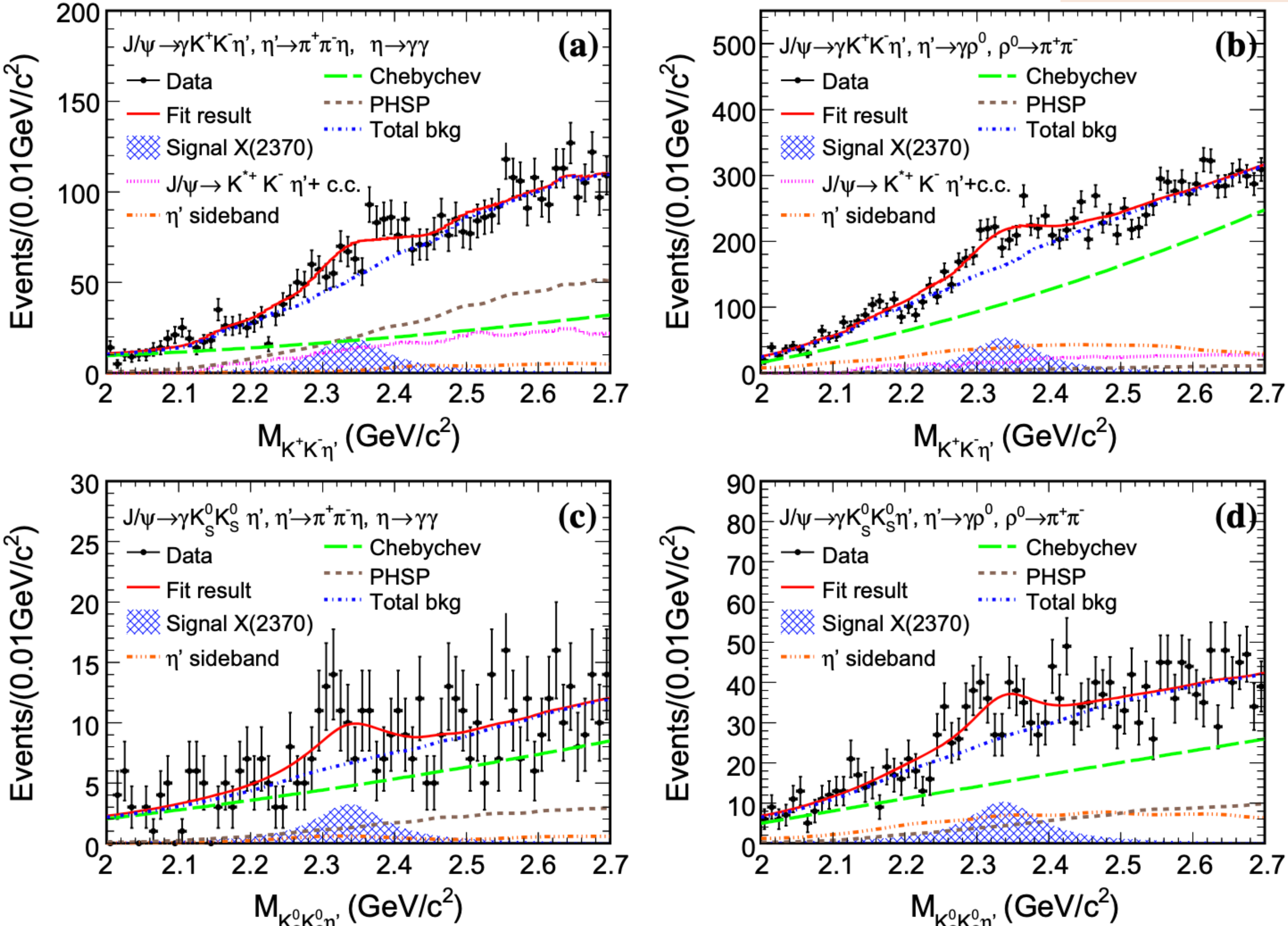
$$\mathcal{B}(J/\psi \to \gamma\eta_c)\cdot\mathcal{B}(\eta_c \to \eta\eta\eta') = (4.86\pm0.62\pm0.45)\times10^{-5}$$

FIRST OBSERVATION in the ηηη' invariant mass spectra

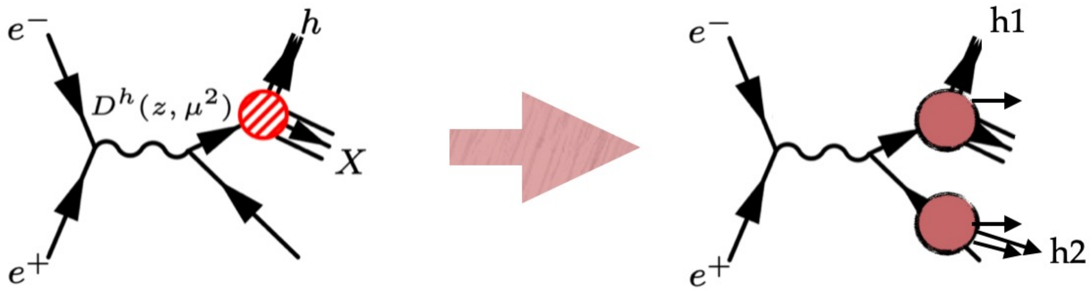
First Observation of X(2370) in $J/\psi \to \gamma K\bar{K}\eta'$

1.3×10^9 J/ψ @ BESIII

EPJC **80**, 746 (2020)



Polarised FF: the Collins effect



q↑→hX: $$D_1^{q\uparrow}(z, \mathbf{P}_\perp; s_q) = D_1^q(z, P_\perp) + \frac{P_\perp}{zM_h} H_1^{\perp q}(z, P_\perp)\, \mathbf{s}_q \cdot (\mathbf{k}_q \times \mathbf{P}_\perp)$$

Unpolarized FF

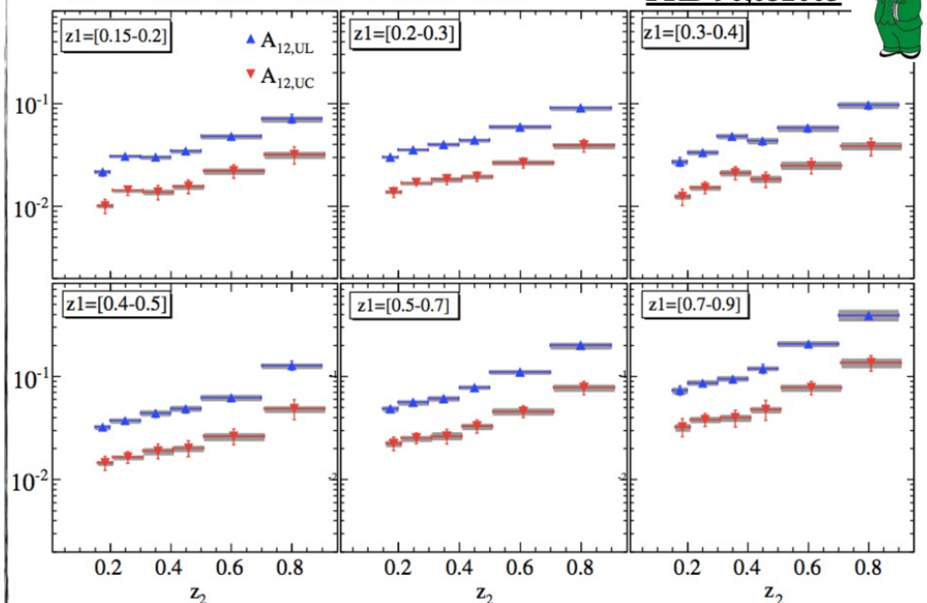
Collins FF [NP**B 396**, 161 (1993)]: related to the probability that a transversely polarized quark (q↑) fragments into a spinless hadron

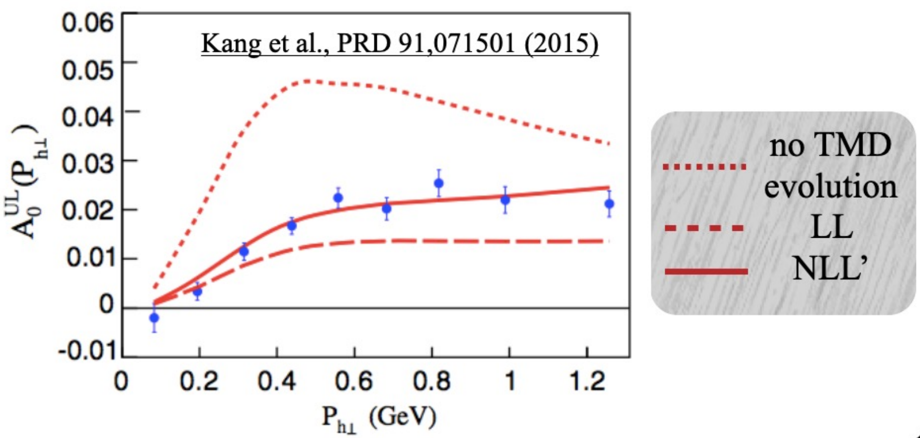
- Evolution of TMD objects
- Global analysis (PRD 78,032011 (2007); PRD 87,094019 (2013), PRD 91,014034 (2015)):
  - combines Semi Inclusive Deep Inelastic Scattering (SIDIS) and e^+e^- data
  - extraction of $H^\perp_1$ and transversity parton distributions h_1 for the “u” and “d” quarks

Collins FFs Results

$\mathcal{L}$ ~ 468 fb^{-1} at ~10.58 GeV

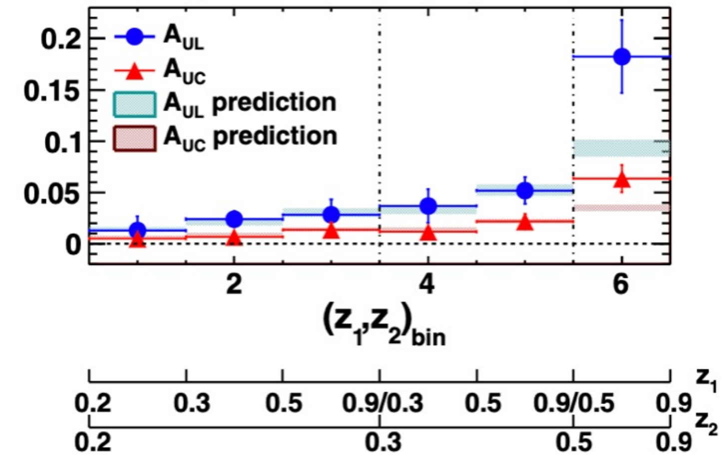
PRD 90,052003

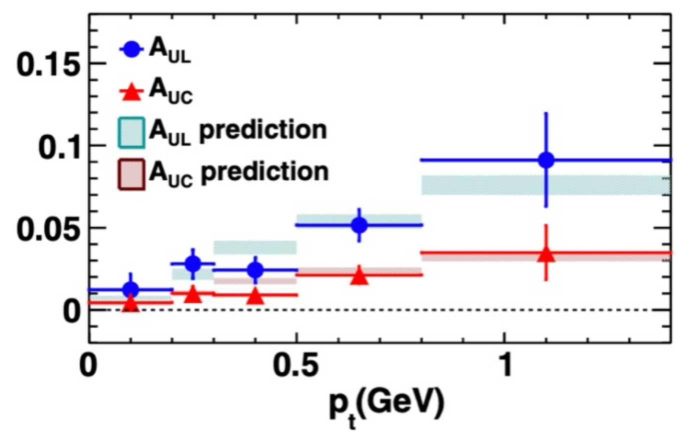




$\mathcal{L}$ ~ 62 pb^{-1} at ~3.65 GeV

PRL116, 042[illegible]1



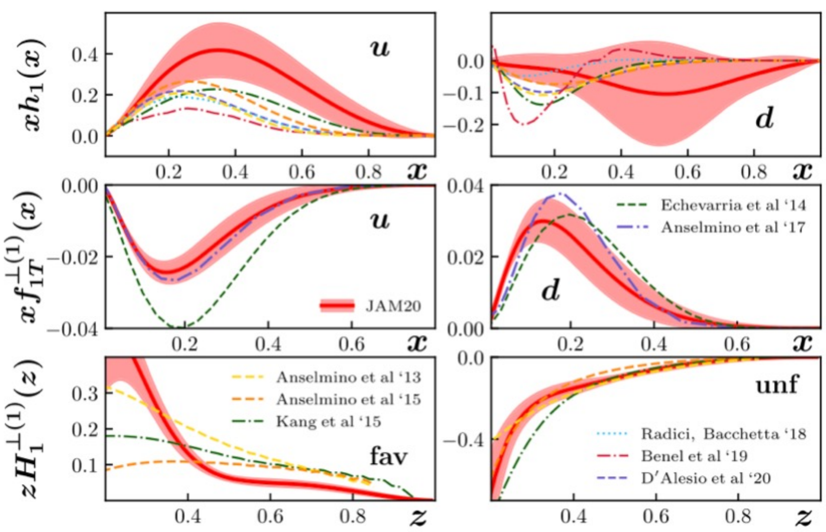


First Global Analysis

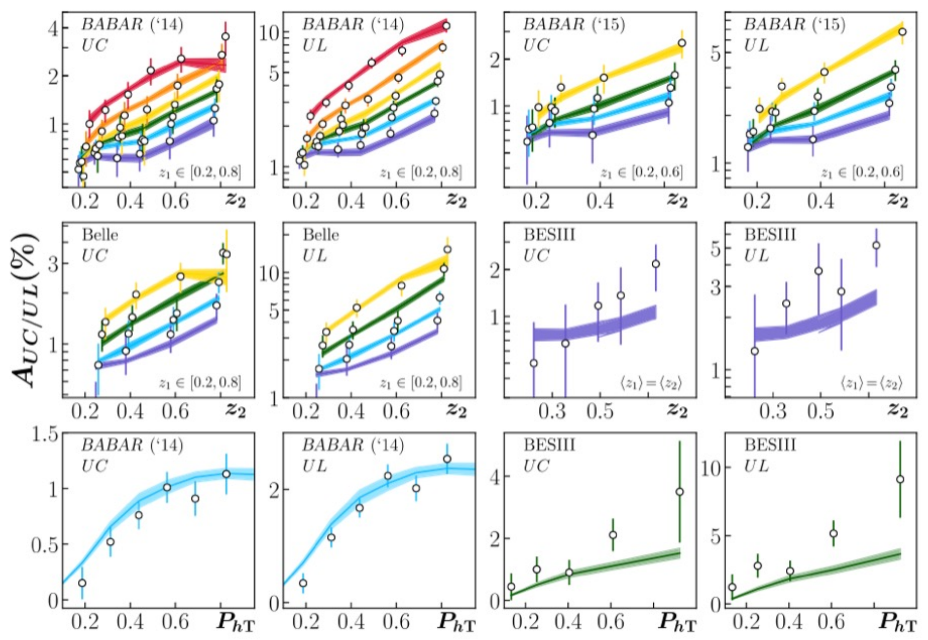
PRD 102, 054002 (2020)

First simultaneous QCD global analysis with SIDIS, e+e- annihilation, DY and proton-proton collisions

- Test of universality
- Indication that transverse-spin asymmetries in high-energy collisions have a common origin
- Extracted quark tensor charges are in excellent agreement with lattice QCD



Anselmino'13, Anselmino'15, Anselmino'17, Benel'19, D'Alessio'20, Echevarria'14, Kang'15, Radici-Bacchetta'18



Comparison between theory and data
(BaBar, Belle, BESIII)