Search for hexaquark/di-baryon state at BESIII

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On behalf of the BESIII Collaboration

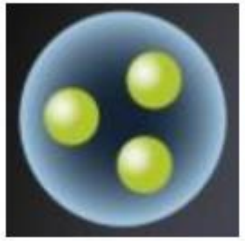
2023/06/05 HADRON2023, Genova, Italy

Outline

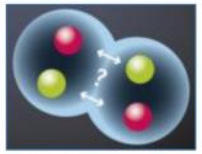
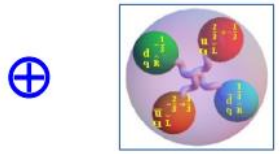
- **Introduction**
- **Brief history of $d^*(2380)$**
- **BESIII detector**
- **Study of $e^+e^- \to 2(p\bar{p})$@4.0-4.6 GeV** PRD 103 (2021) 052003
- **Observation of $e^+e^- \to pp\bar{p}\bar{p}\pi^- + c.c.$** CPC 47 (2023) 043001
- **Prospects**
- **Summary**

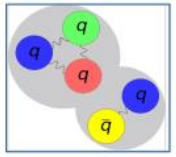
Introduction

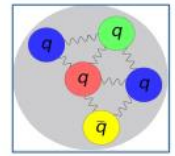
- **Naïve Quark Model has made great success in particle physics**
  - ✓ **Meson with two quarks**
  - ✓ **Baryon with three quarks**

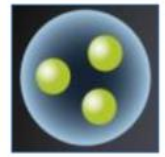



- **Any particle beyond it? Not forbidden by QCD!**
  - **Multi-quark/exotic states**

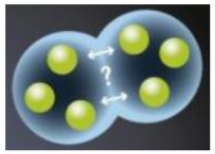







Glueball Hybrid Four quarks Five quarks

- **The world was once simple, until 2003($X(3872)$)**
- **Story on hexa-quark/di-baryon state…**




Six quarks

Brief history of $d^*(2380)$

- **Deuteron is so far the only confirmed six-quark state (*p-n* molecule)**
- **Any other baryon-baryon molecule? Does hexa-quark state really exist?**
- **Many di-baryon states predicted by theory from 1960s, the ABC effect**
  - **ΔΔ bound state in 1964, Dyson and Xuong based on SU(6)**

$Y = 2$ STATES IN SU(6) THEORY*

Freeman J. Dyson† and Nguyen-Huu Xuong
Department of Physics, University of California, San Diego, La Jolla, California
(Received 30 November 1964)

Table I. $Y = 2$ states with zero strangeness predicted by the 490 multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass
D_{01}	0	1	10*	Deuteron	A
D_{10}	1	0	27	Deuteron singlet state	A
D_{12}	1	2	27	S-wave N-N^* resonance	$A+6B$
D_{21}	2	1	35	Charge-3 resonance	$A+6B$
D_{03}	0	3	10*	S-wave N^*-N^* resonance	$A+10B$
D_{30}	3	0	28	Charge-4 resonance	$A+10B$

Brief history of $d^*(2380)$

Professor Marek Karliner

M. Karliner and J. L. Rosner,
Phys. Rev. Lett. **115**, no. 12, 122001 (2015)

doubly-heavy hadronic molecules:
most likely candidates with $Q\bar{Q}'$, $Q = c, b$, $\bar{Q}' = \bar{c}, \bar{b}$:

$D\bar{D}^*$, $D^*\bar{D}^*$, D^*B^*, $\bar{B}B^*$, $\bar{B}^*B^*$,

$\Sigma_c\bar{D}^*$, Σ_cB^*, $\Sigma_b\bar{D}^*$, Σ_bB^*, the lightest of new kind

$\Sigma_c\bar{\Sigma}_c$, $\Sigma_c\bar{\Lambda}_c$, $\Sigma_c\bar{\Lambda}_b$, $\Sigma_b\bar{\Sigma}_b$, $\Sigma_b\bar{\Lambda}_b$, and $\Sigma_b\bar{\Lambda}_c$.

$c\bar{c}$ and $b\bar{b}$ states decay strongly to $\bar{c}c$ or $\bar{b}b$ and π-(s)
$b\bar{c}$ and $c\bar{b}$ states decay strongly to $B_c^{\pm}$ and π-(s)

QQ' candidates – dibaryons

$\Sigma_c\Sigma_c$, $\Sigma_c\Lambda_c$, $\Sigma_c\Lambda_b$, $\Sigma_b\Sigma_b$, $\Sigma_b\Lambda_b$, and $\Sigma_b\Lambda_c$.

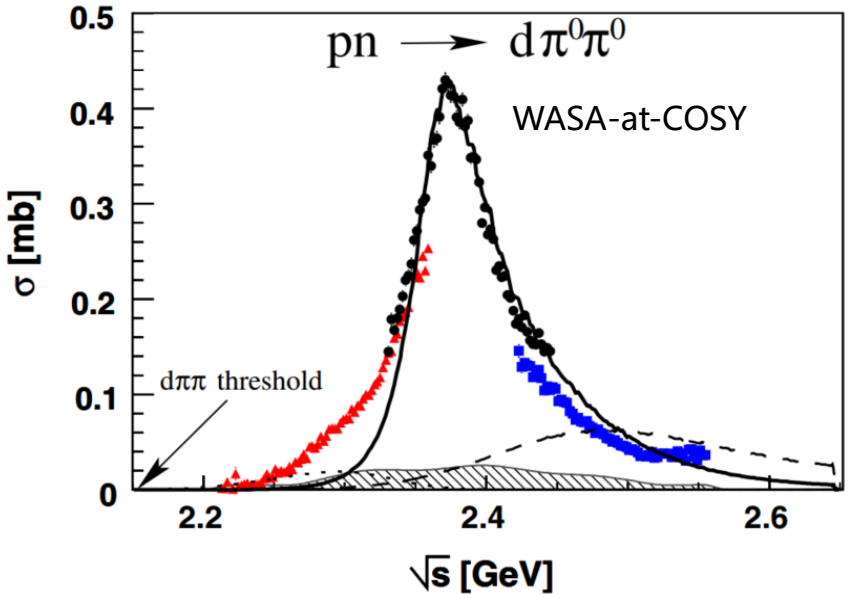
like a whole new periodic table

M. Karliner, New Heavy Exotics PKU 2 Jun 2023 52

Brief history of $d^*(2380)$

- **Several experiments performed the search**
  - ✓ $pn/\bar{p}\bar{n}$ scattering experiments
  - ✓ Until 2011, WASA-at-COSY firstly observe $d^*(2380)$ in $pn \to d\pi^0\pi^0$
  - ✓ Confirmed by $pn \to d\pi^+\pi^-$
  - ✓ Further evidence from $pn \to pp\pi^0\pi^-$, $pn \to pn\pi^0\pi^0$…

PRL 106 (2011) 242302

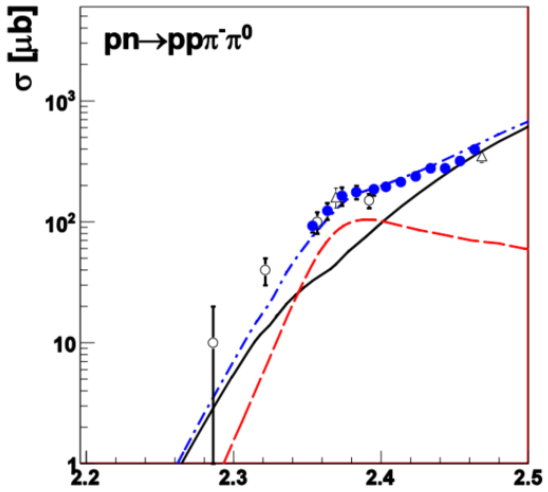


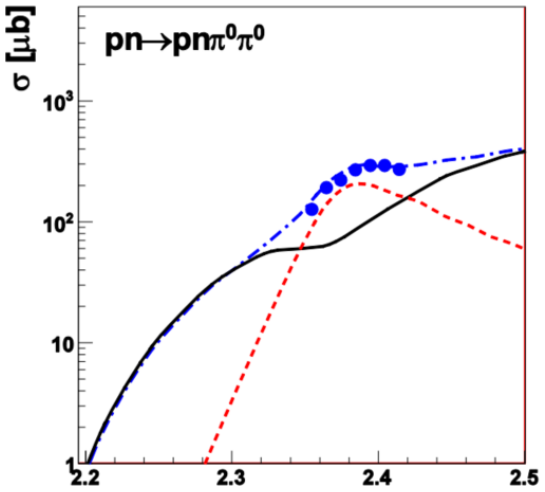
$$m \approx 2.37\ \mathrm{GeV}/c^2, \Gamma \approx 70\ \mathrm{MeV}$$
$$I(J^P) = 0(3^+)$$

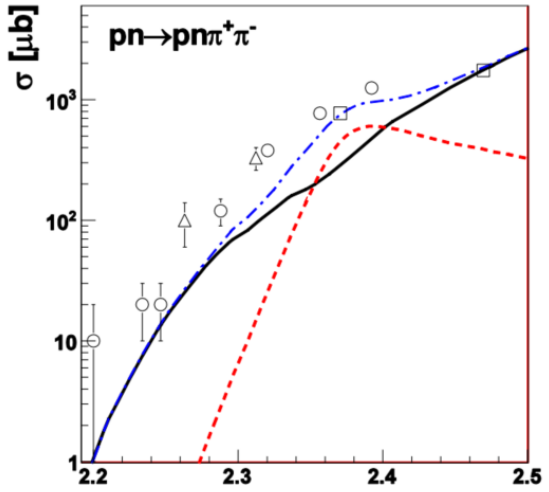
Other proofs

✓ **Non-fusion reactions @COSY**

WASA-at-COSY, PLB 743 (2015) 325

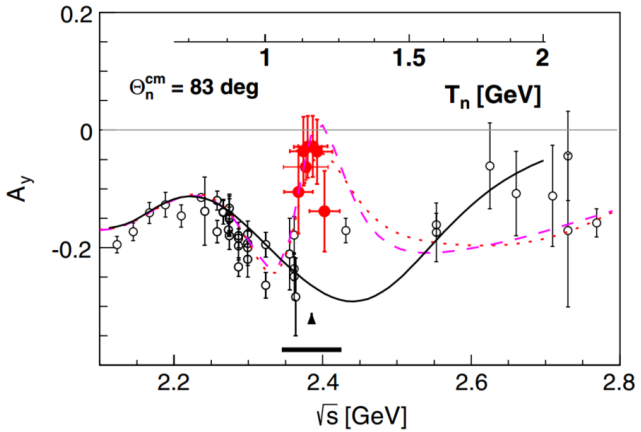






✓ **From $\vec{n}p$ scattering @COSY &SAID DAC**

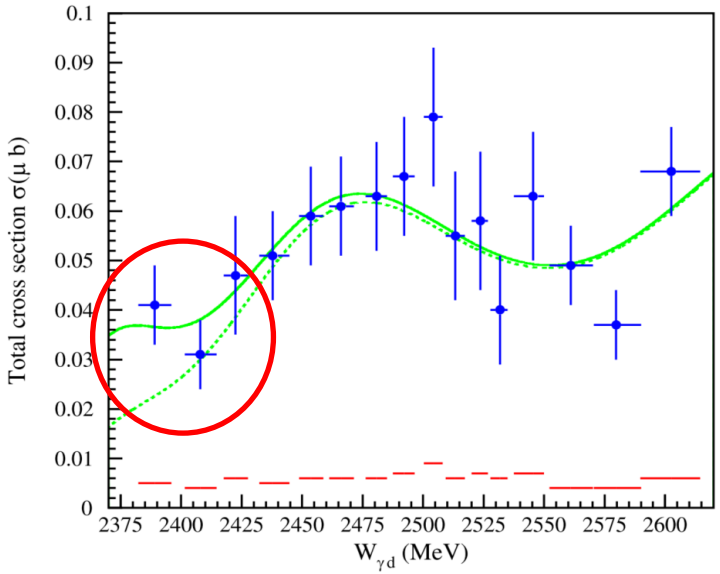
WASA-at-COSY & SAID DAC, PRL 112 (2014) 202301

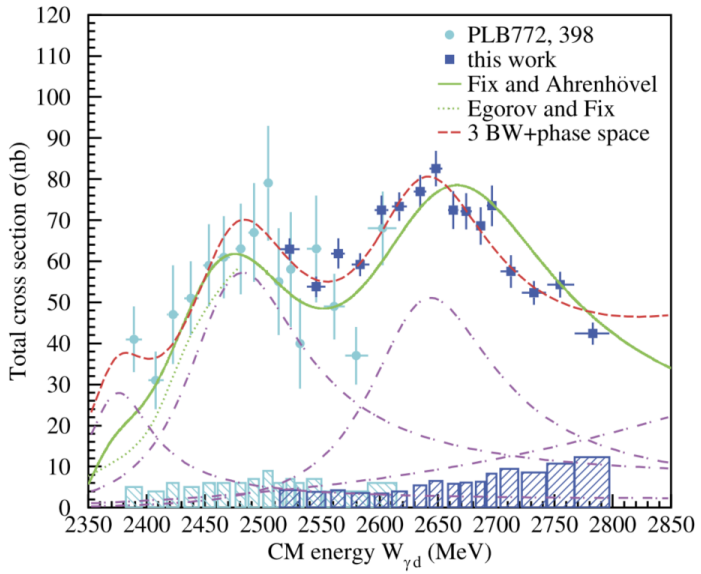


✓ **Also in fusion reactions to helium isotopes**

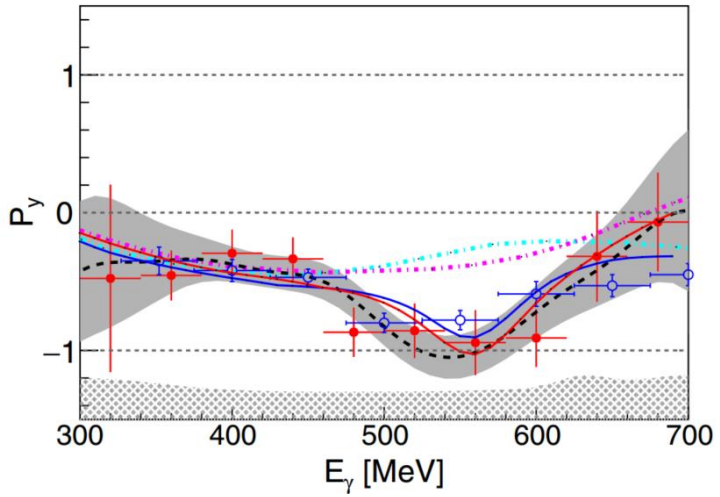
Other evidence

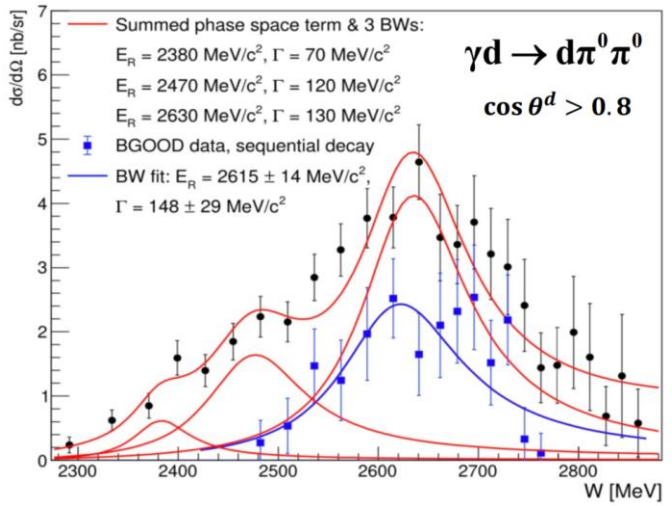
✓ **Experiments @ELPH2017/ELPH2019/MAMI/ELSA**





[FOREST-at-ELPH, PLB 772 (2017) 398]
[FOREST-at-ELPH, PLB 789 (2019) 413]



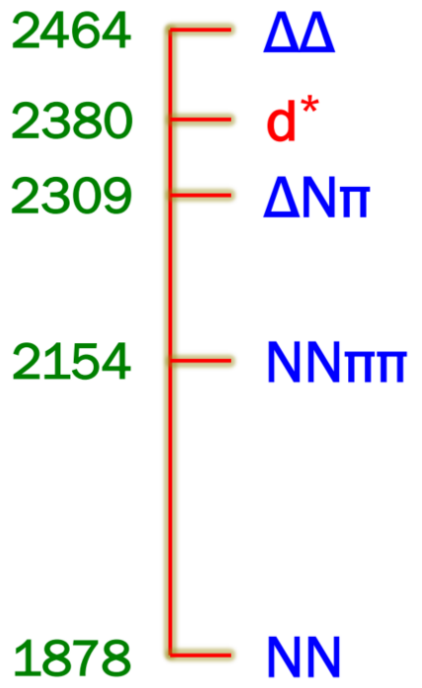


[A2-at-MAMI, PRL 124 (2020) 132001]

[BGOOD-at-ELSA, PLB 832 (2022) 137277]

$d^*(2380)$ at BESIII

- **Why $d^*(2380)$ exceptional?**
  - ✓ Exotic state, nature is not known
  - ✓ Different with other exotic states, unusual narrow width, far from $\Delta\Delta$ mass threshold and highest known spin
  - ✓ $d^*(2380)$ could be a candidate of dark matter?
- **Why BESIII?**
  - ✓ Unique at $\tau - \mathrm{Charm}$ region and large data within 4-4.95 GeV
  - ✓ Very clean environment
  - ✓ Unique advantage in $\bar{d}^*(2380)$, which could not be achieved by p-n scattering experiment



$\Gamma_{d*} \approx 70\ \mathrm{MeV}$
$< 1/3 \times 2\Gamma_{\Delta}$

Decays of $d^*(2380)$

- The observation and measurement are all from nuclear reactions

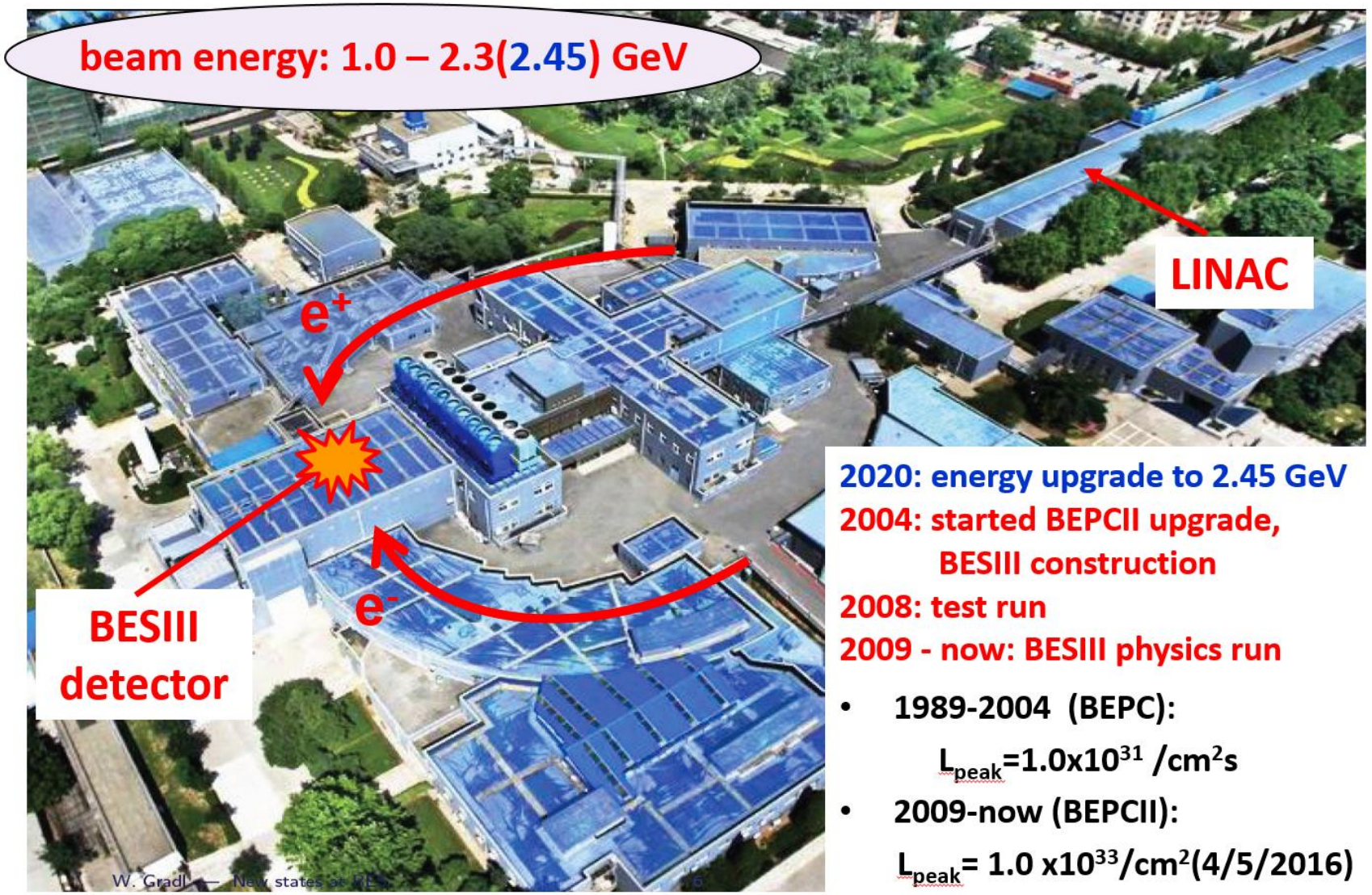
- $\bar{d}^*(2380)$ has never been searched at e^+e^- collision experiment, it's necessary to have a cross check, especially the *NN* mass spectra

- Any other potential hexaquark/ dibaryon candidate?

Eur. Phys. J. A 51 (2015) 87

Channels	Branching ratio(%)
$d\pi^0\pi^0$	$14(1)$
$d\pi^+\pi^-$	$23(2)$
$pn\pi^0\pi^0$	$12(2)$
$pn\pi^+\pi^-$	$30(5)$
$pp\pi^-\pi^0$	$6(1)$
$nn\pi^+\pi^0$	$6(1)$
$NN\pi$	–
np	$12(3)$
Total	$103(15)$

BEPCII and BESIII detector



2020: energy upgrade to 2.45 GeV

2004: started BEPCII upgrade,
BESIII construction

2008: test run

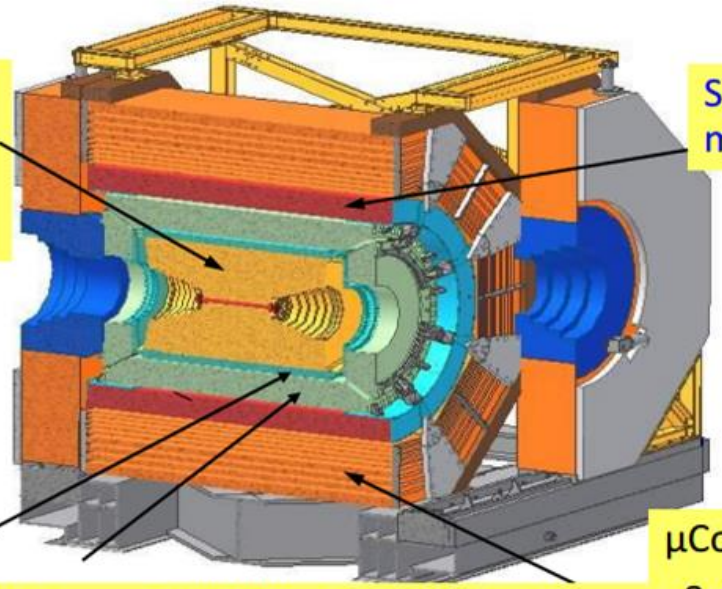
2009 - now: BESIII physics run

- 1989-2004 (BEPC):
  L_{peak}=1.0x10^{31} /cm^{2}s
- 2009-now (BEPCII):
  L_{peak}= 1.0 x10^{33}/cm^2(4/5/2016)

BEPCII and BESIII detector

NIM A614, 345 (2010)

The BESIII Detector



Drift Chamber (MDC)
$\sigma P/P\ (^0/_0) = 0.5\%(1GeV)$
$\sigma_{dE/dx}\ (^0/_0) = 6\%$

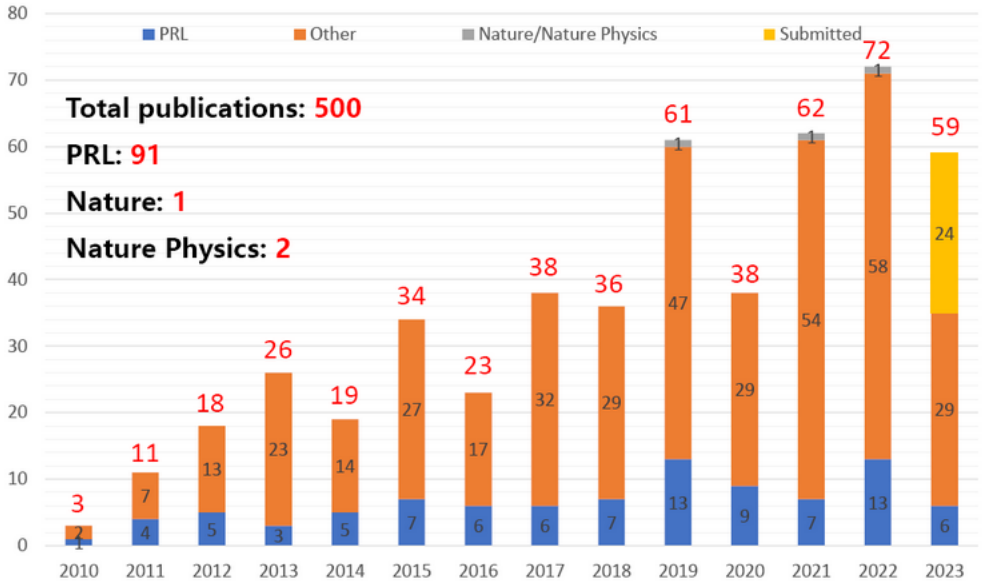
Super-conducting magnet (1.0 tesla)

Time Of Flight (TOF)
σ_T: 90 ps Barrel
110 ps endcap

EMC: $\sigma E/\sqrt{E}(^0/_0) = 2.5\ \%\ (1\ GeV)$
(CsI) $\sigma_{z,\phi}(cm) = 0.5 - 0.7\ cm/\sqrt{E}$

μCounter
8- 9 layers RPC
$\delta R\Phi$=1.4 cm~1.7 cm

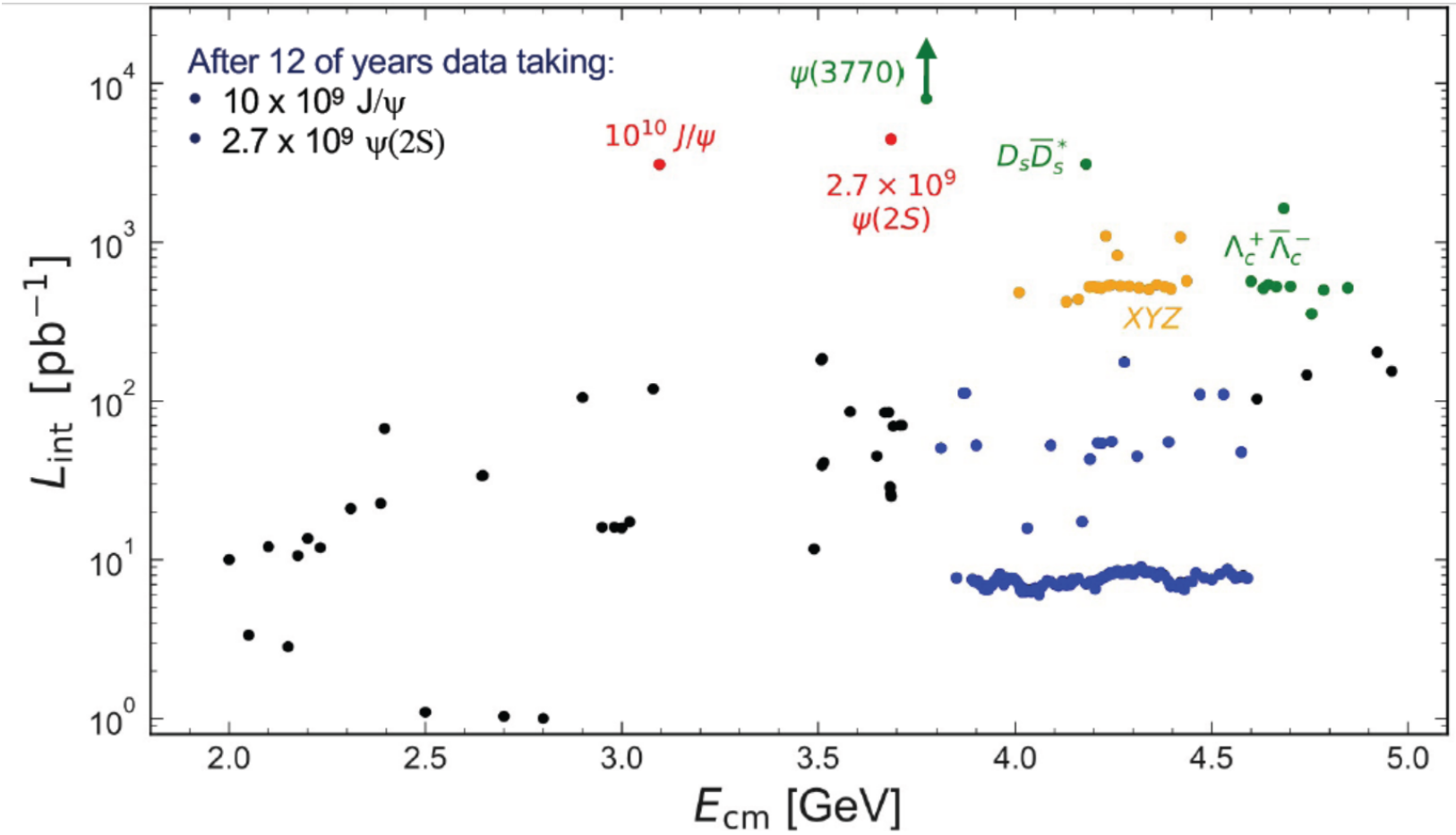
BESIII publications (May 9, 2023)



http://english.ihep.cas.cn/bes/re/pu/pjp/

BESIII data

From W. Gradl



- Total integrated luminosity $> \mathbf{30\ fb^{-1}}$
- Reach to 4.95 GeV
- Large data samples taken from 4.0-4.94 GeV

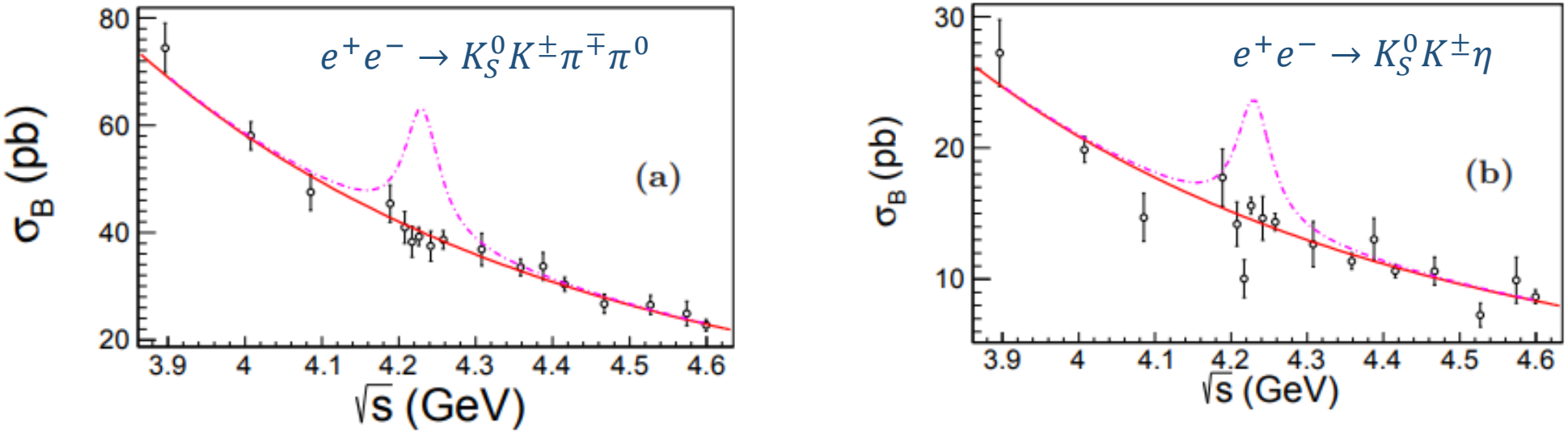
Measurement of $e^+e^- \to p\bar{p}p\bar{p}$

PRD 103 (2021) 052003

Motivation of $e^+e^- \to p\bar{p}\bar{p}$

- Motivated by studying $Y(4220)$, observed only in many open or hidden charm processes, never in light hadrons

- Nature of $Y(4260)$ remains an open question



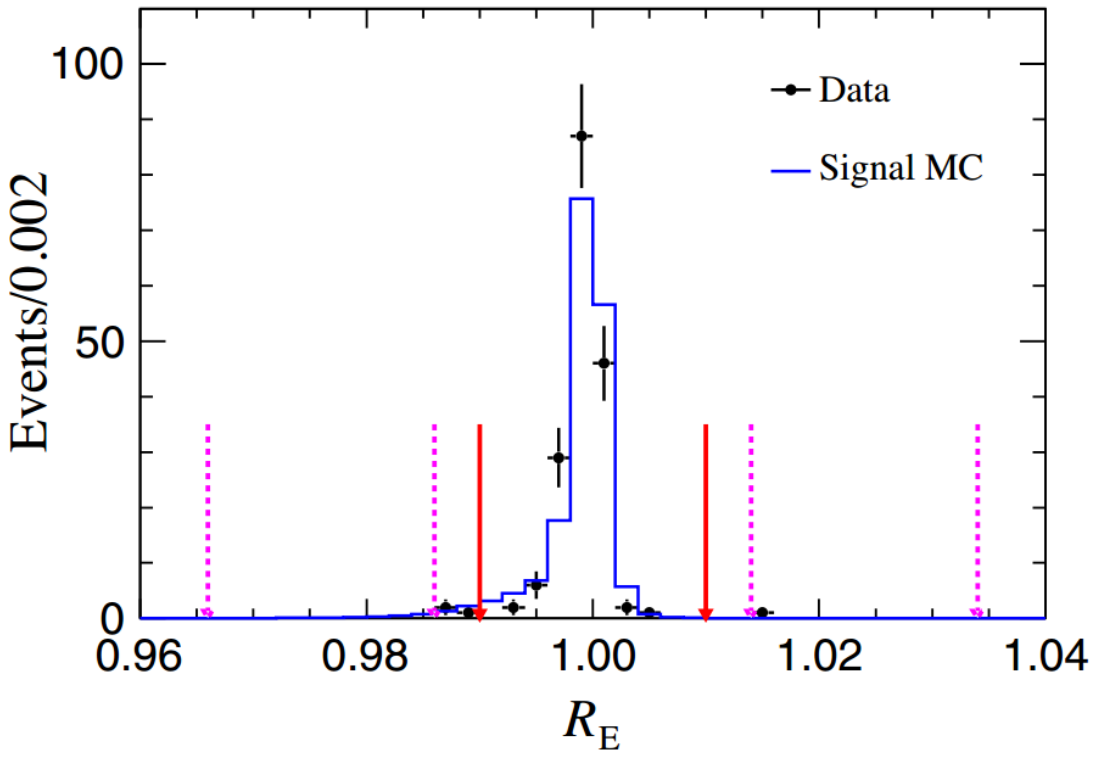
- Baryon pair mass spectra could be checked for di-baryon searches

Data and signals

- Data taken at 23 c.m. energies, $\sqrt{s}$=4.0-4.6 GeV
- Signal is extracted with R_E

$$R_E = E_{measure}/E_{cm}$$

- Almost background free



Cross section results

- Cross section results

$$\sigma^{Born} = \frac{N^{net}}{\mathcal{L} \times \epsilon \times (1+\delta^{\gamma}) \times (\frac{1}{|1-\Pi|^2})}$$

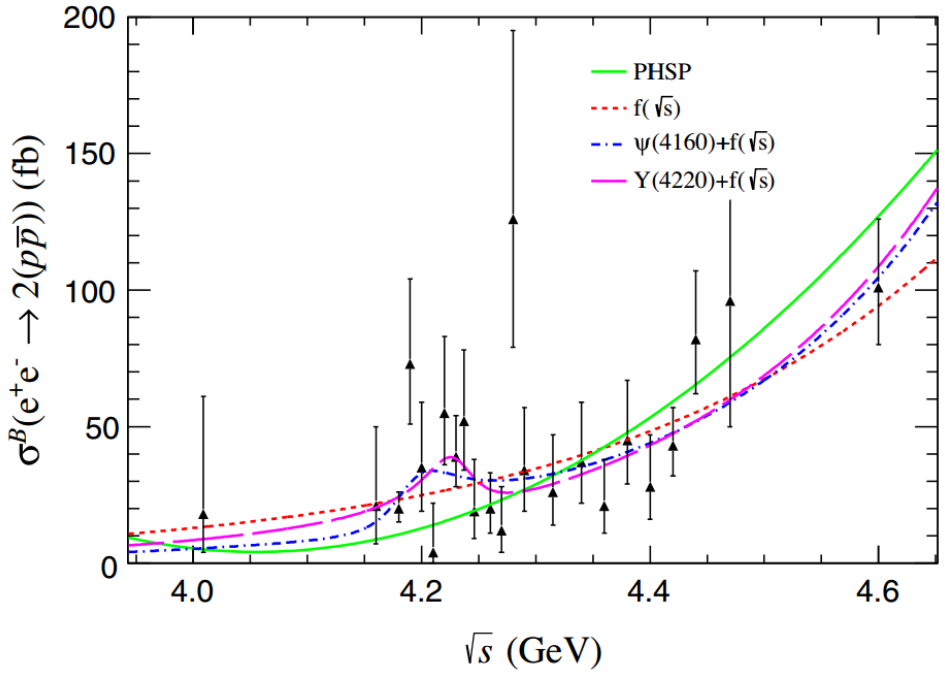
- Fit with four assumptions
  - a) Purely continuum production(4 body PHSP)
  - b) Exponential function

$$\sigma^{Born}(s) = \frac{1}{s} \times e^{-p_0(\sqrt{s}-M_{th})} \times p_1$$

  - c) b)+$\psi(4160)$

$$\sigma^{Born}(s) = |BW(\sqrt{s})e^{i\phi} + \sqrt{f(\sqrt{s})}|^2$$

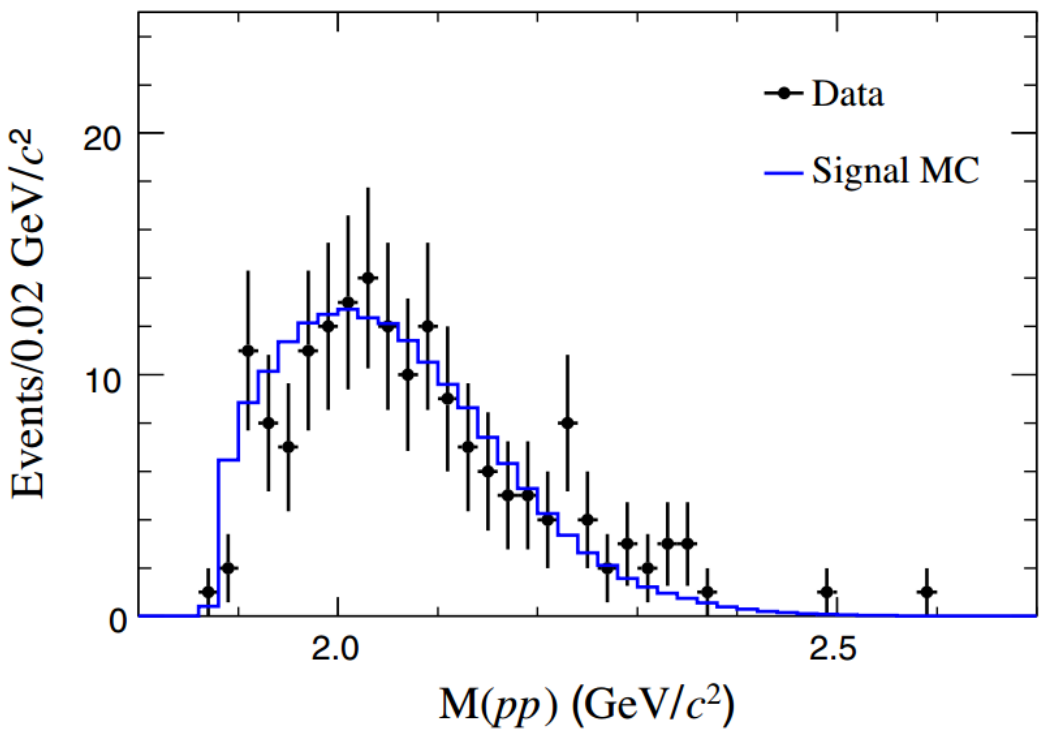
  - d) b)+$Y(4220)$

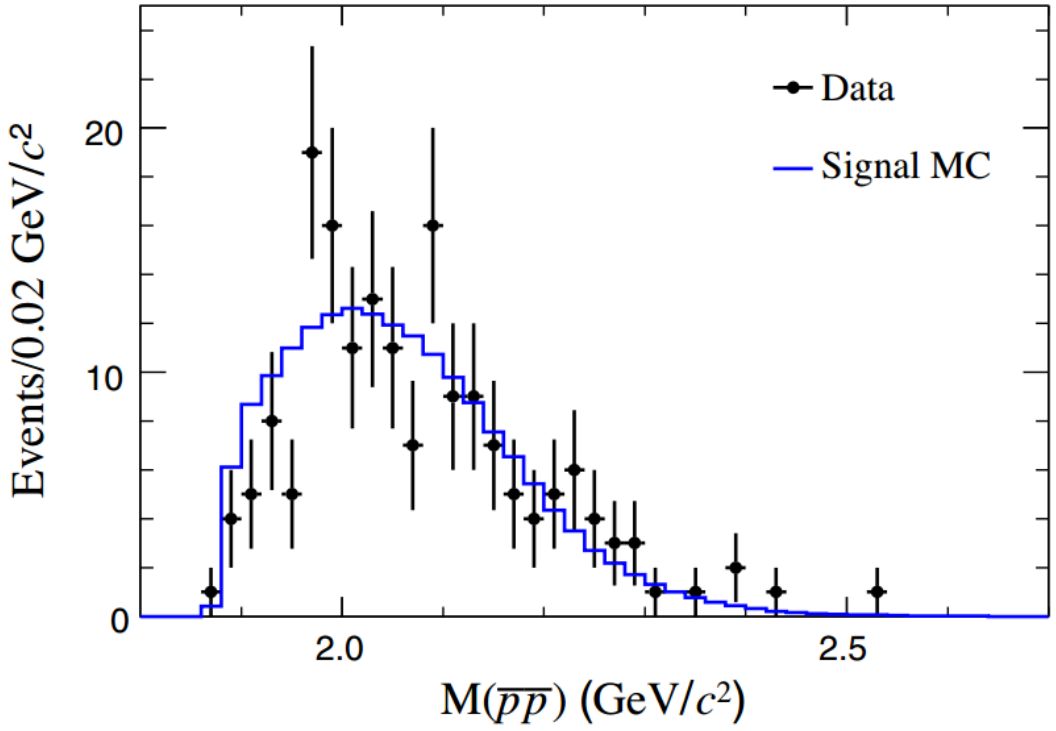


- $0.83\,\sigma$ for $\psi(4160)$, $1.69\,\sigma$ for $Y(4220)$
- Disfavor to $2(p\bar{p})$

Baryon-pair spectra

- Baryon-pair mass spectra





- No hexa-quark or di-baryon state evidence within current statistics

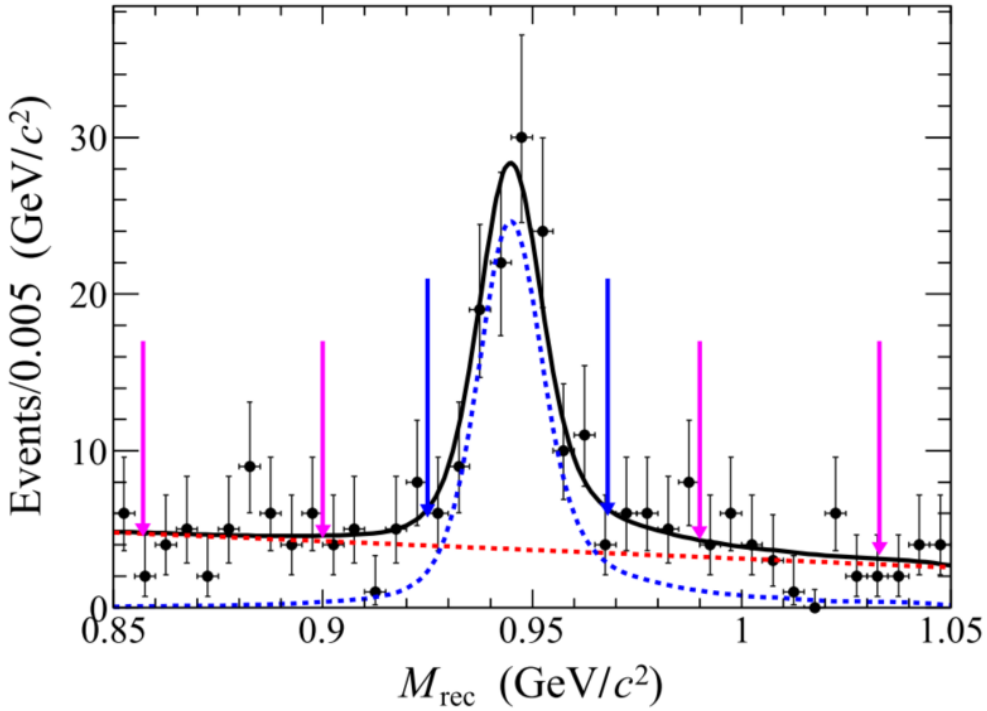
Observation of $e^+e^- \to pp\bar{p}\bar{n}\pi^- + c.c.$

CPC 47 (2023) 043001

Data and signals

- Data with 29 energy points, $\sqrt{s}$=4.160-4.700 GeV
- Signal is fitted with recoil mass of reconstructed charged particles

$$M_{rec}c^2 = \sqrt{(E_{e^+e^-} - E_{pp\bar{p}\pi^-})^2 - (\vec{P}_{e^+e^-} - \vec{P}_{pp\bar{p}\pi^-})^2 \cdot c^2}$$



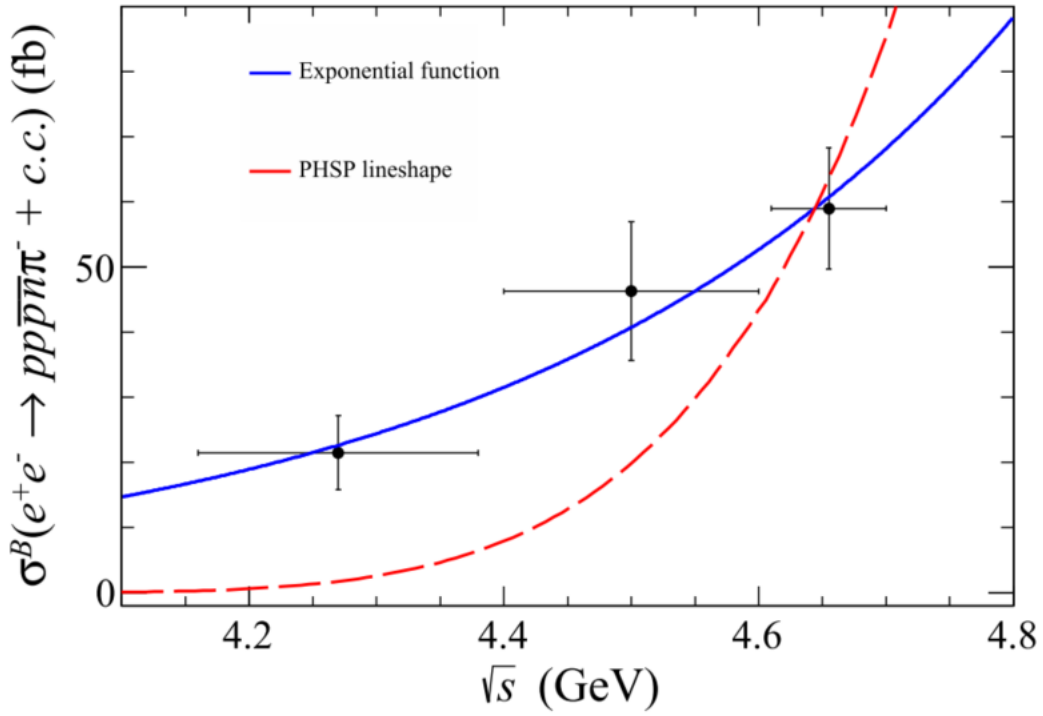
- Statistical significance of 11.5 σ
- Average observed and Born cross section are determined

$$\bar{\sigma}_j^{obs} = \frac{N_j^{sig}}{(\Sigma_i \varepsilon_i \cdot \mathcal{L}_i) \cdot f_{PID} \cdot f_{trk}}$$

$$\bar{\sigma}_j^{Born} = \frac{\bar{\sigma}_j^{obs}}{(1+\delta^{\gamma})_j \cdot (\frac{1}{|1-\Pi|^2})_j}$$

Cross section results

- Cross section results

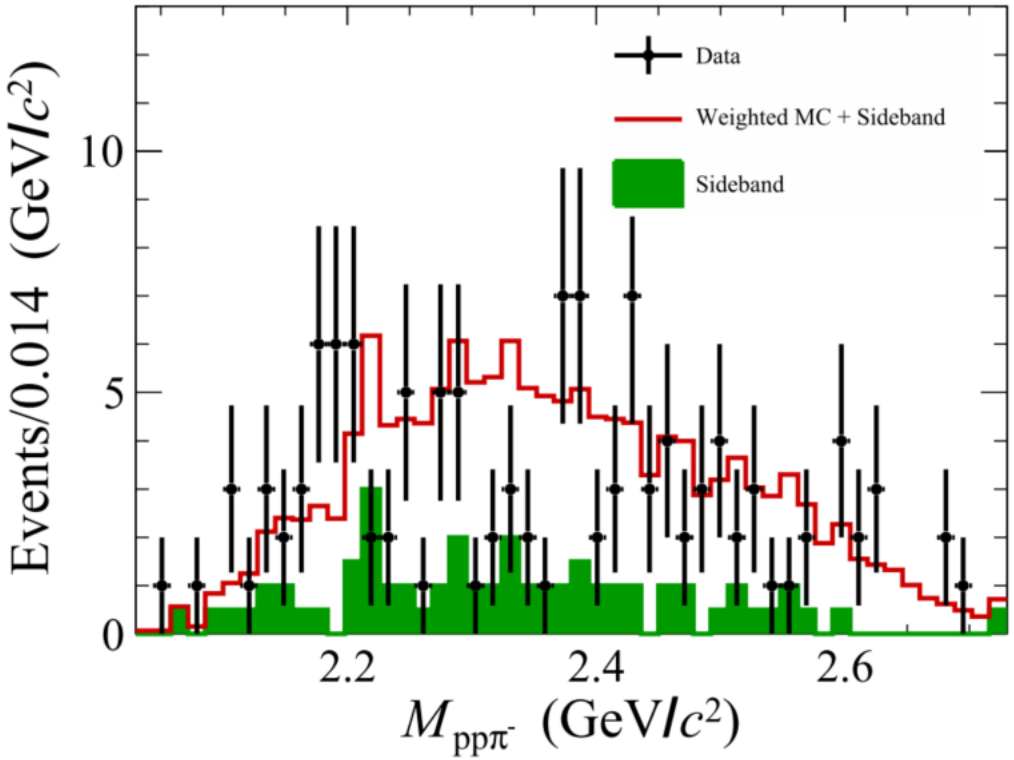


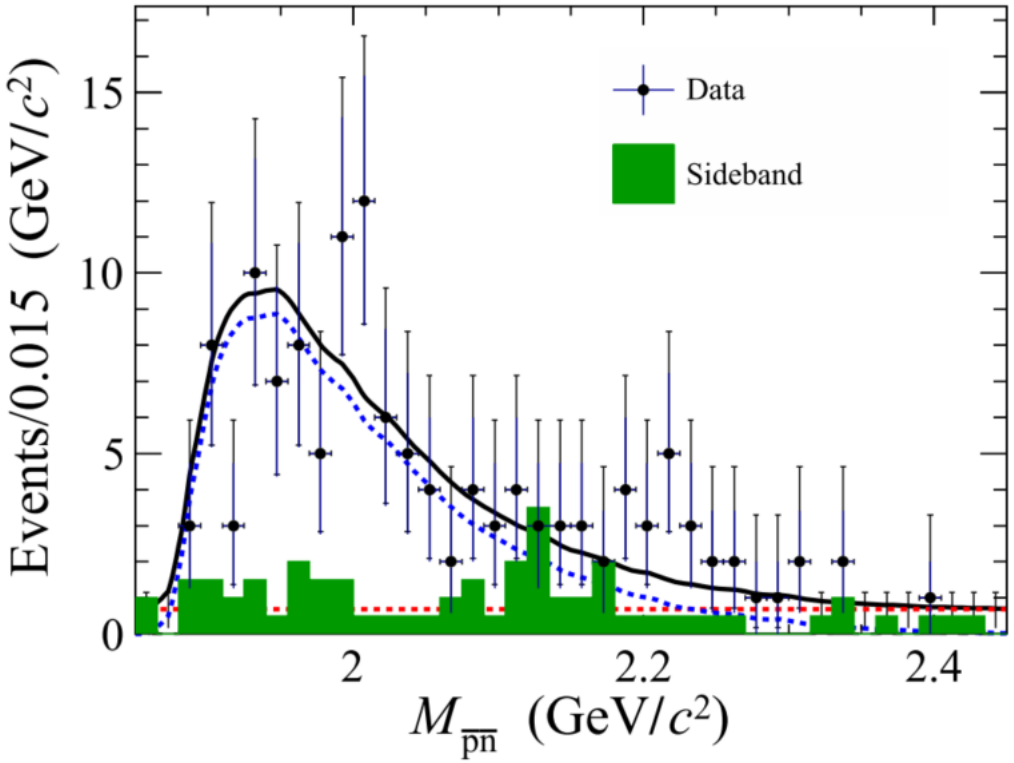
- $\sigma^{Born}(s) = \frac{1}{s} \times e^{p_0(\sqrt{s}-M_{th})} \times p_1$

- Seems favor the exponential function curve, but need more precision measurement

Mass spectra

- Mass spectra of $pp\pi^-$ and $\bar{p}\bar{n}$

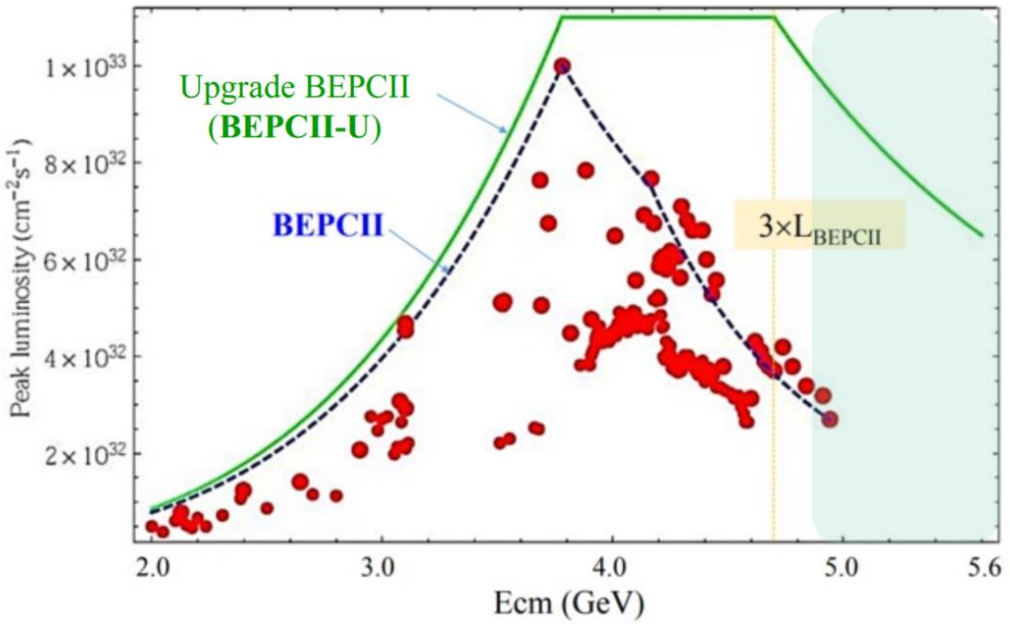




- Consistent with PHSP MC and no significant structure

Prospects of BESIII

- More data taking proposals in 2024--
  - ✓ BEPCII upgrade scheduled in July, 2024
  - ✓ To 5.6 GeV
  - ✓ 3 times more luminosity



- More channels with multi-baryon process could be achieved

Summary

- Interesting di-baryon state, $d^*(2380)$, never confirmed within e^+e^- colliders
- With the BESIII data in 4.0-4.7 GeV, cross section of two multi-baryon processes are measured, $e^+e^- \to pp\bar{p}\bar{p}$ and $pp\bar{p}\bar{n}\pi^- + c.c.$
- No evidence of hexaquark or di-baryon state found
- More searches in the future, with upgrade of BESIII

Thanks for your attention!