Recent BESIII results and perspectives for the PANDA experiment on exotic XYZ states

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Frankfurt University & GSI Darmstadt,
on behalf of the BESIII and PANDA Collaborations

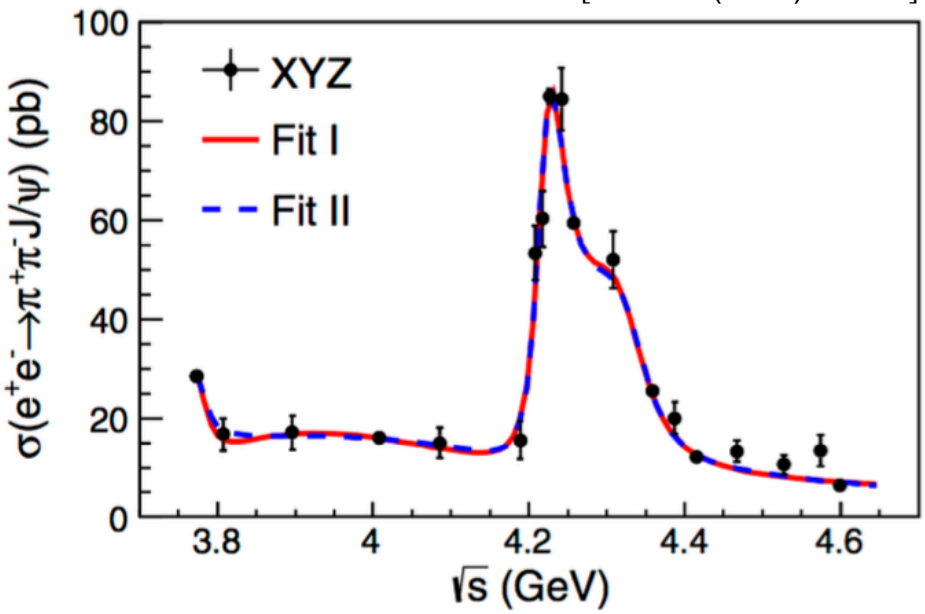
3rd EMMI Workshop:
Anti-matter, hyper-matter and exotica production at the LHC,
University of Wroclaw, Dec 4th 2019

Outline

- **Introduction**
  - Motivation
- **Selected BESIII results**
  - Experiment and data sets
  - Recent XYZ results at BESIII
- **Uniqueness of PANDA for XYZ states**
  - FAIR facility and experiment
  - Precision spectroscopy at PANDA
- **Summary & outlook**

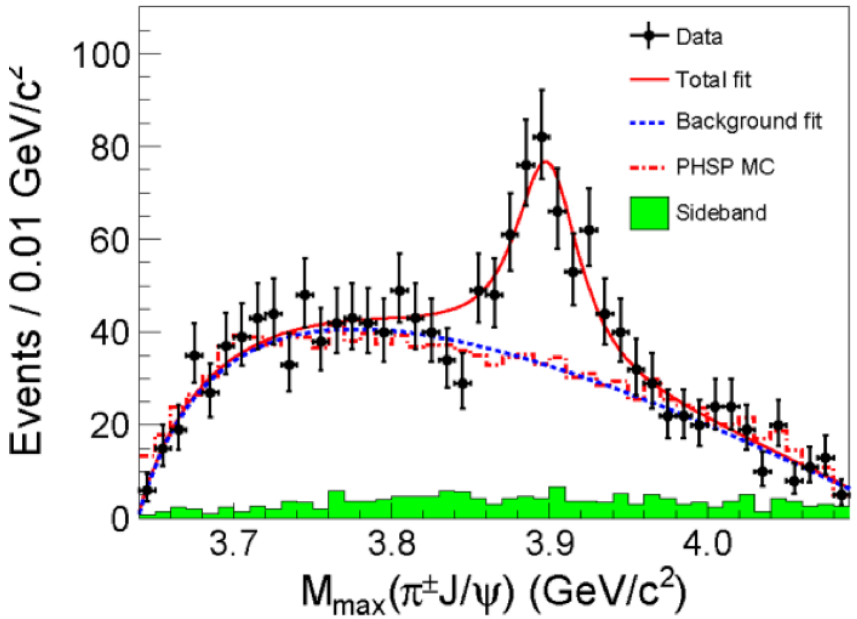
Famous exotic (?) XYZ states

[PRL 118 (2017) 092001]



$Y(4260) \to J/\psi\pi\pi$

[PRL 110 (2013) 252001]

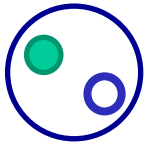


$Z_c(3900) \to J/\psi\pi$

Mesons and (spin) exotic states

Quark model

- Mesons: Color neutral $q\bar{q}$ systems



Conventional $(q\bar{q})_1$

QCD: Meson states beyond $q\bar{q}$

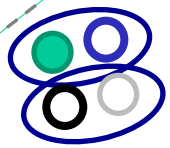
- Nowadays definition: Meson = Hadron with B = 0
- In contrast to simple $q\bar{q}$ allows for **=> huge variety of states:**

Hybrid $(q\bar{q})_8 g$

Tetraquark $(q\bar{q}q\bar{q})_1$

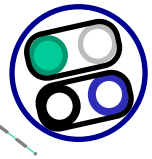
Glue-ball $(gg)_1$ or $(ggg)_1$

Further 4-quark-configurations:



Molecule $(q\bar{q})_1(q\bar{q})_1$

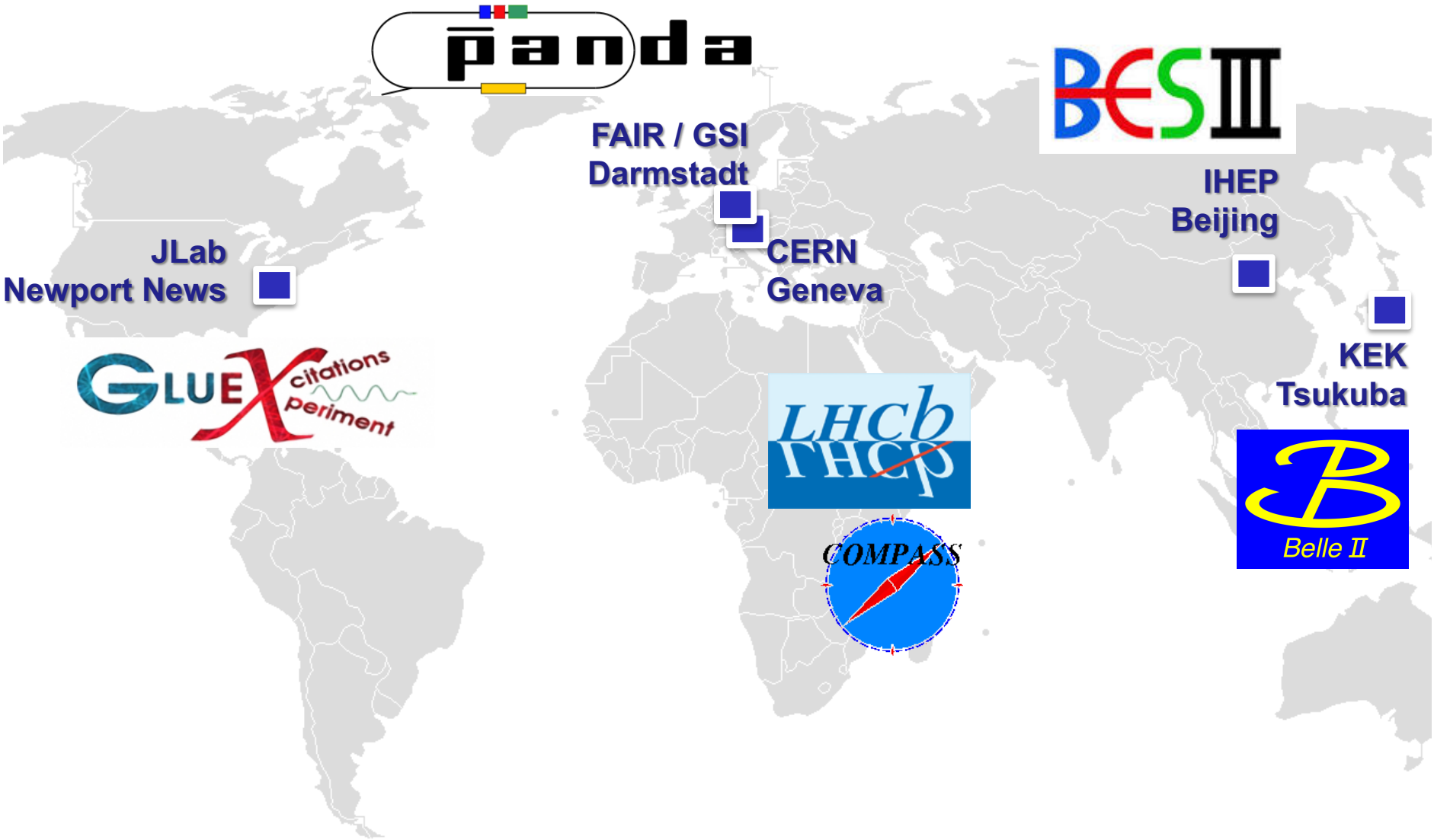
Hadro-quarkonium $(Q\bar{Q})_1(q\bar{q})_1$



Di-quarkonium $(qq)_{\bar{3}}(\bar{q}\bar{q})_3$

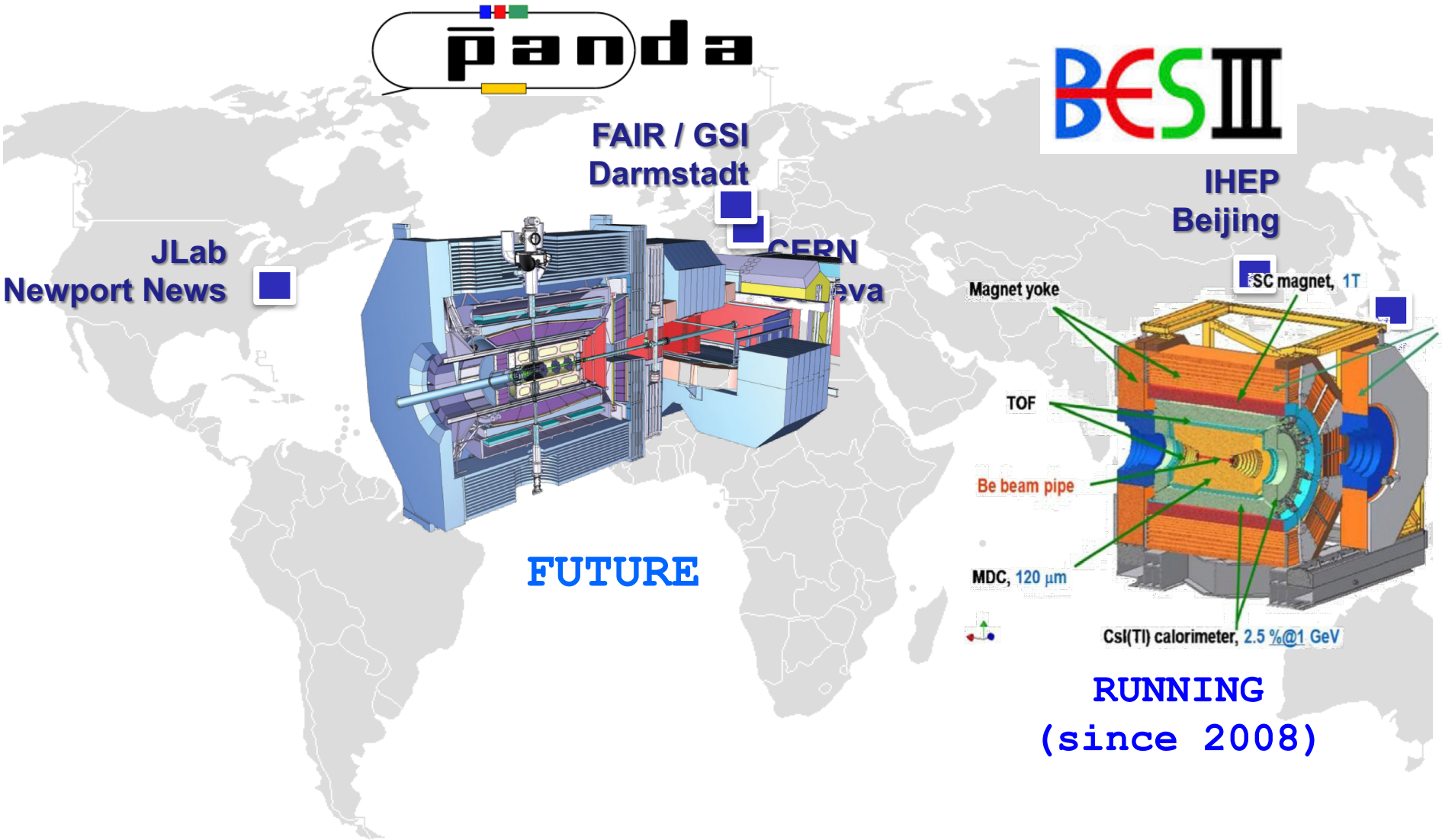
[e.g. Braaten, PRD 90 (2014) 014044]

Hadron Physics – Major labs & experiments



Hadron Physics – Major labs & experiments

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

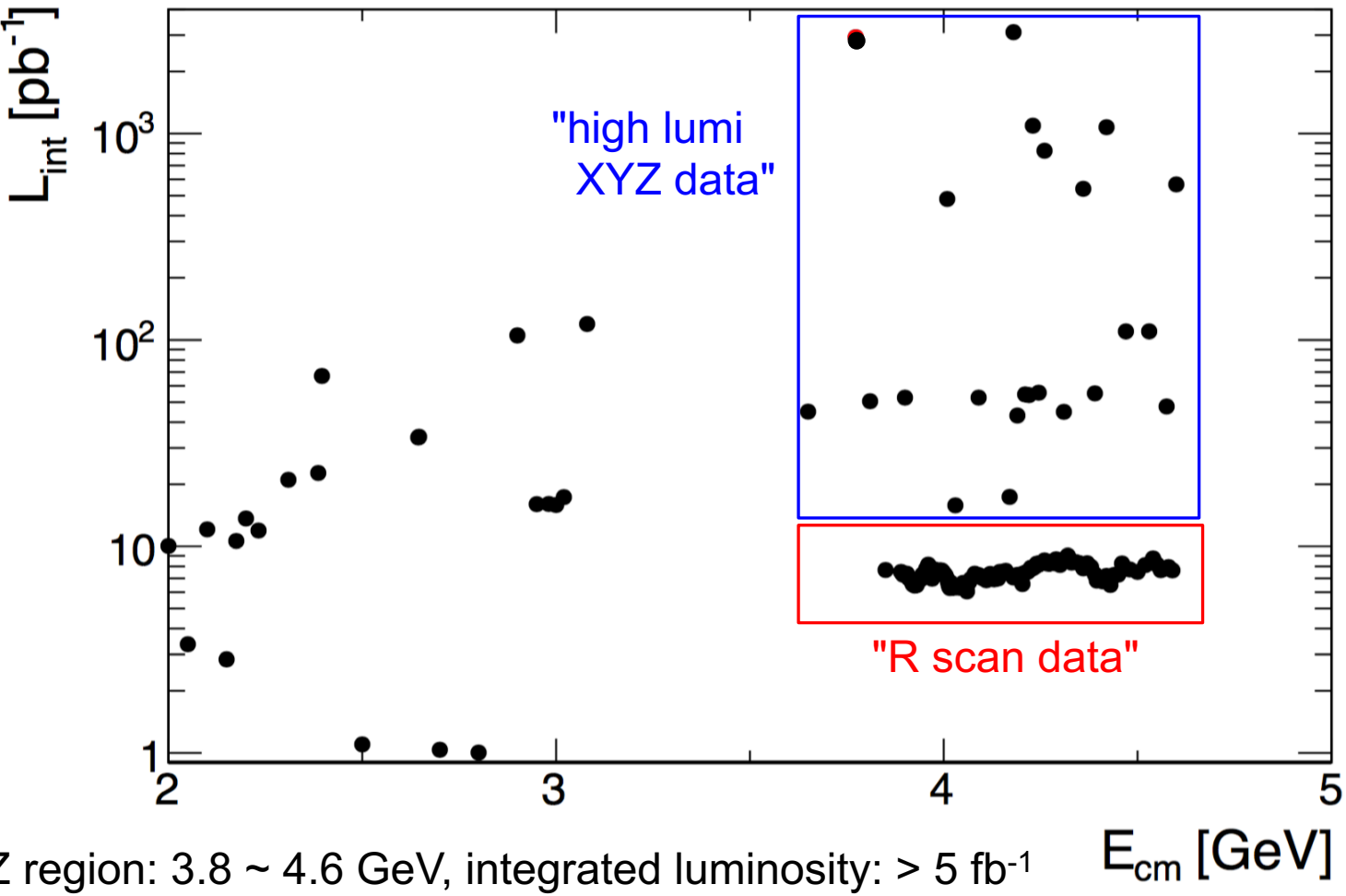


BESIII at BEPCII

- Symmetric e^+e^- collider:
  - $\sqrt{s}$ = 2.0 - 4.6 GeV
- Design luminosity:
  - 1×10^{33} $cm^{-2}s^{-1}$ (at $\psi(3770)$, achieved in 04/2016)

- Multi-purpose 4π detector with
  - good tracking
  - calorimetry
  - PID and muon detection
- Operating since March 2008

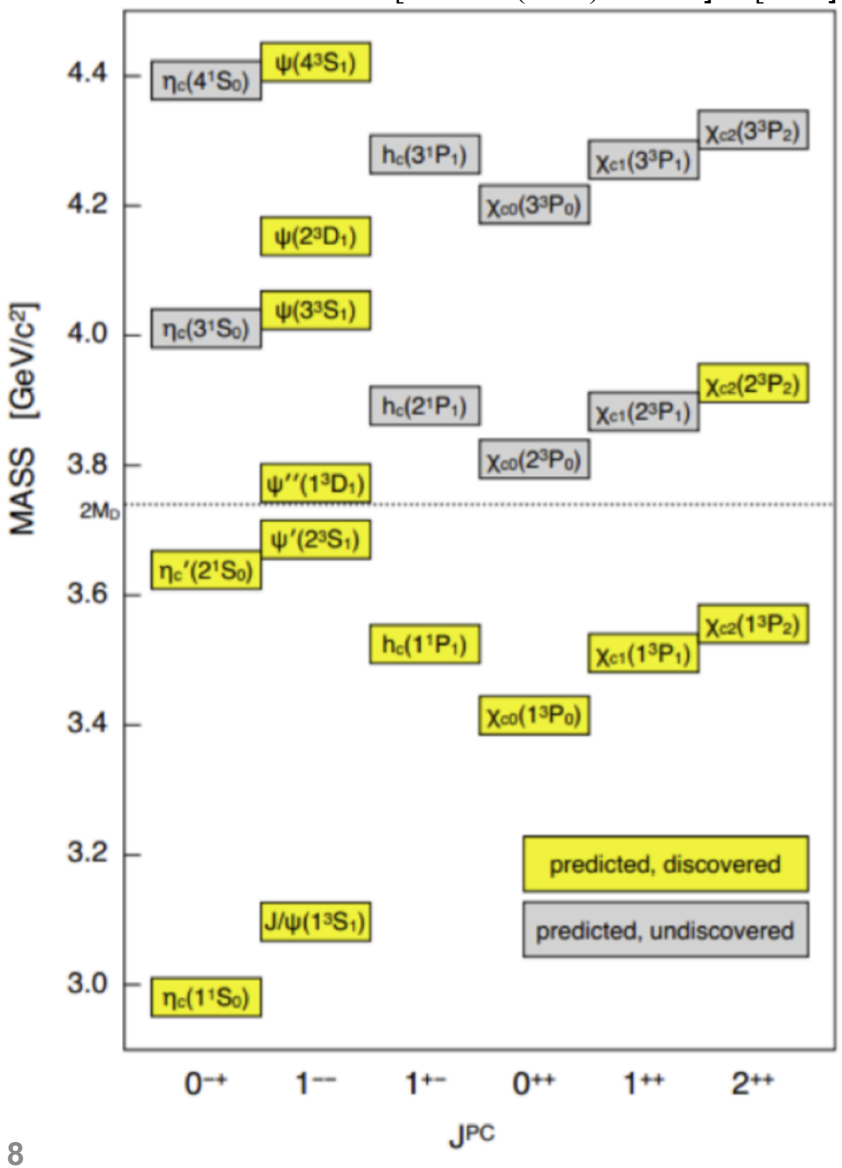
Unique BESIII data set
(collected so far ...)



- XYZ region: 3.8 ~ 4.6 GeV, integrated luminosity: > 5 fb^{-1}
- 104 energy points between 3.85 and 4.59 GeV *(R scan)*
- ~20 energy points between 2.0 and 3.1 GeV

The puzzle of XYZ states

[PRD 72 (2005) 054026] & [PDG]



- Below open charm threshold:
  - Good agreement theory vs. experiment
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  - Many predicted states not discovered
  - Many unexpected states observed

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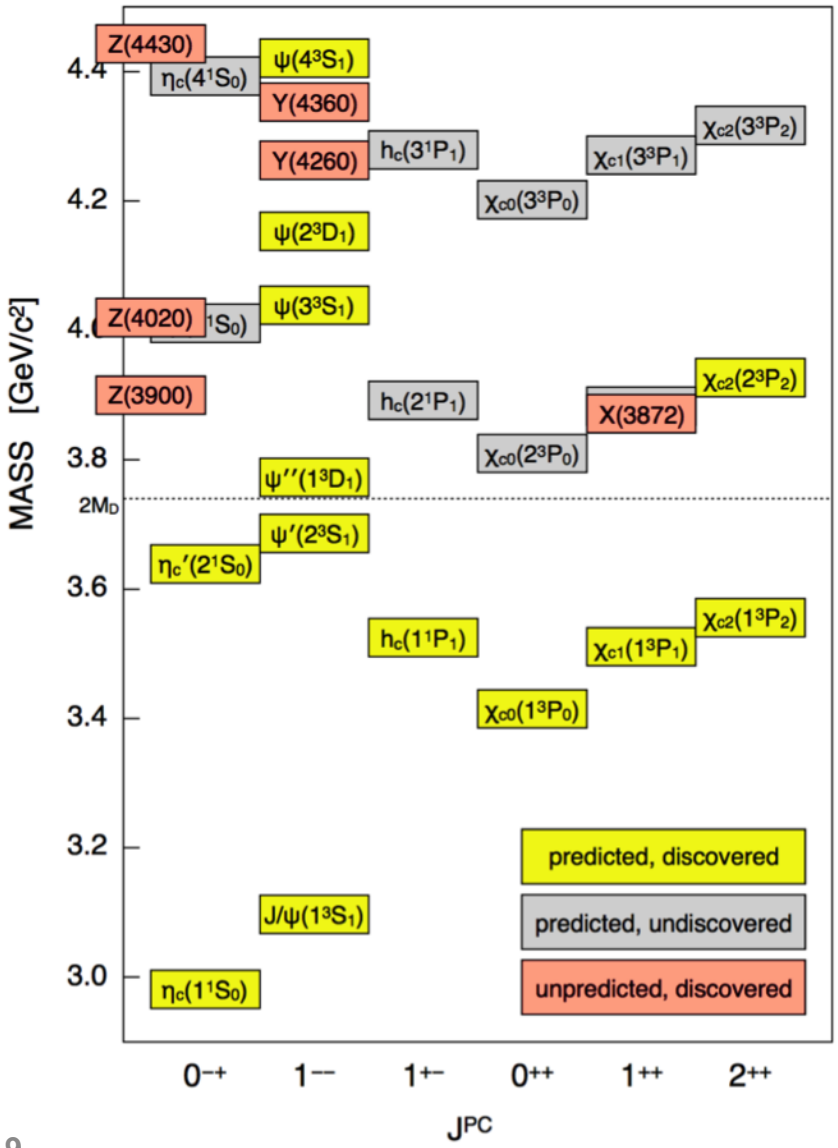

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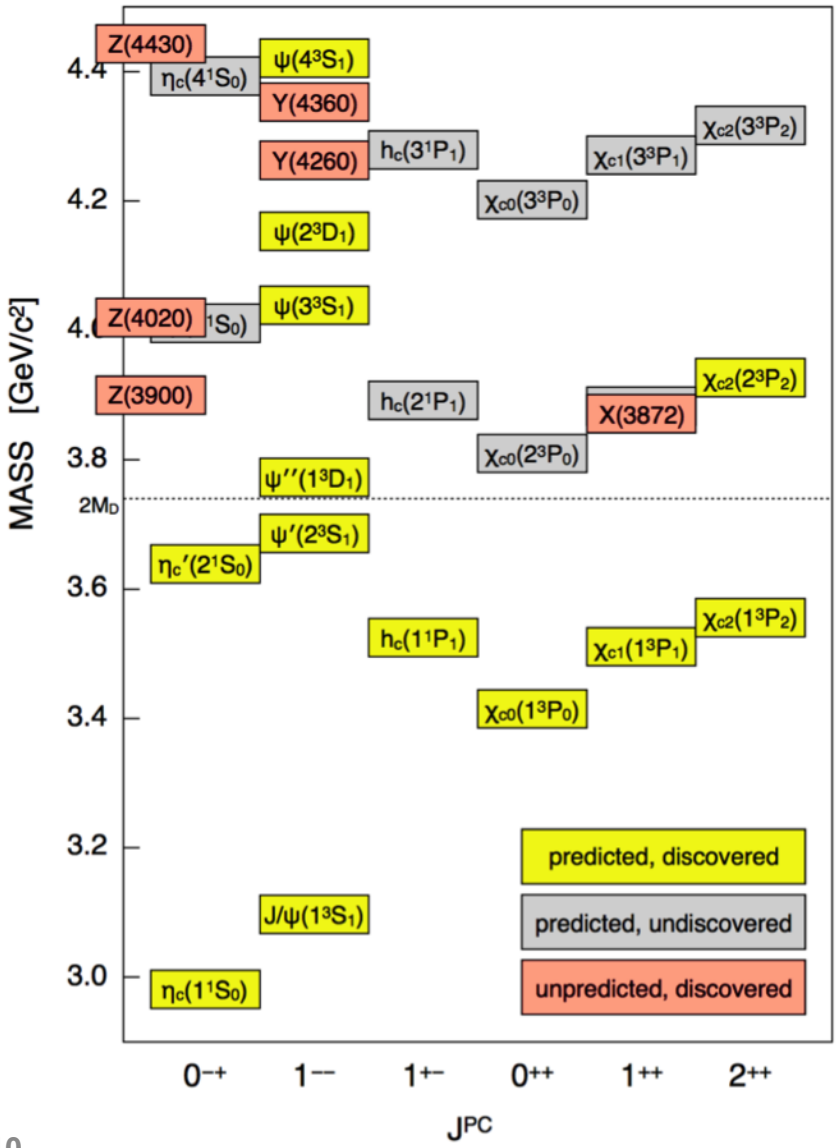

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BESIII: Study conventional as well as charmonium-like (exotic) XYZ states

- Direct access to Y states (1^{--}) in direct formation (e^+e^- annihilation)
- Study (charged & neutral) Z states
- Study X states in radiative decays

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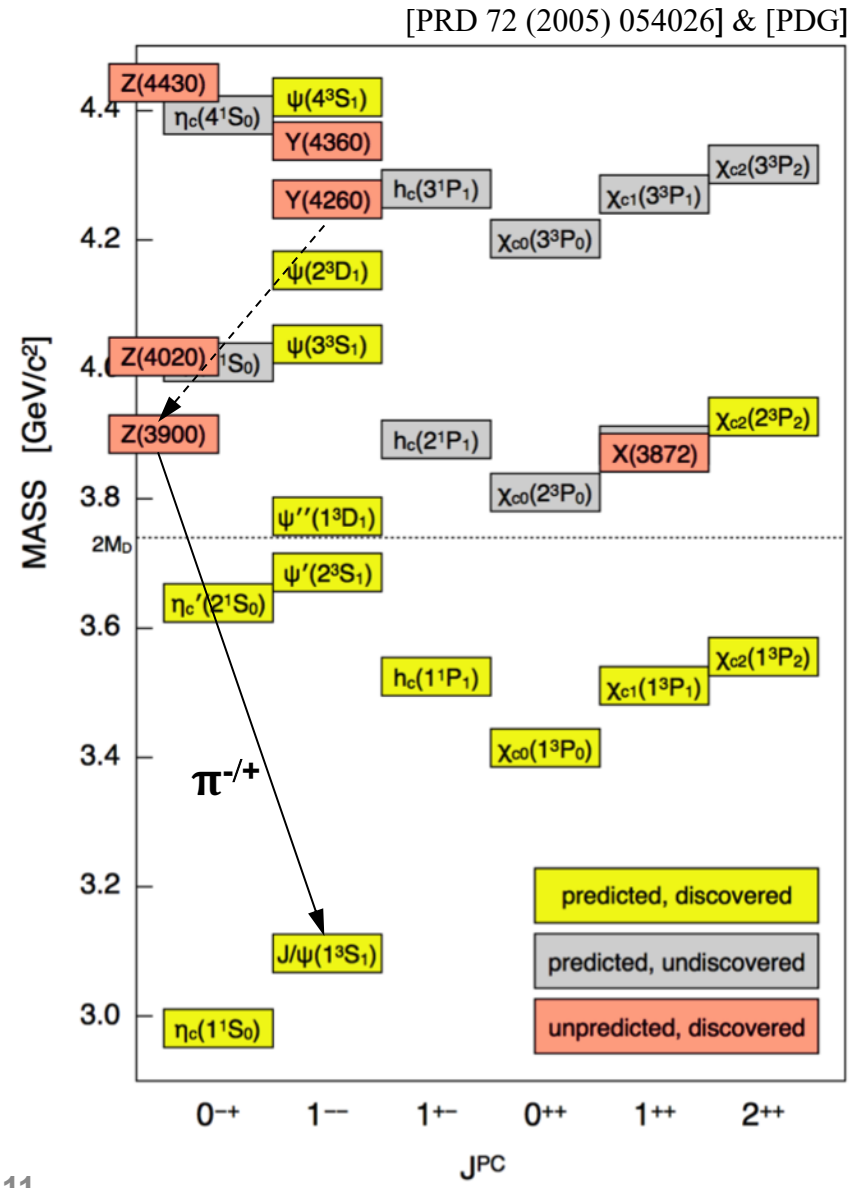

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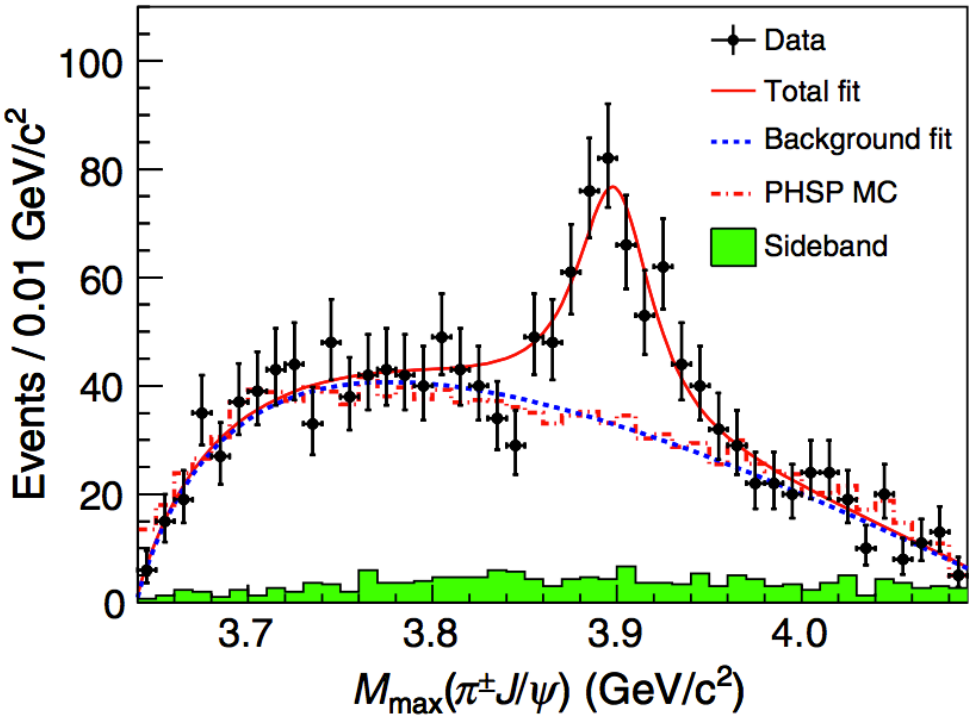
The charged $Z_c(3900)$

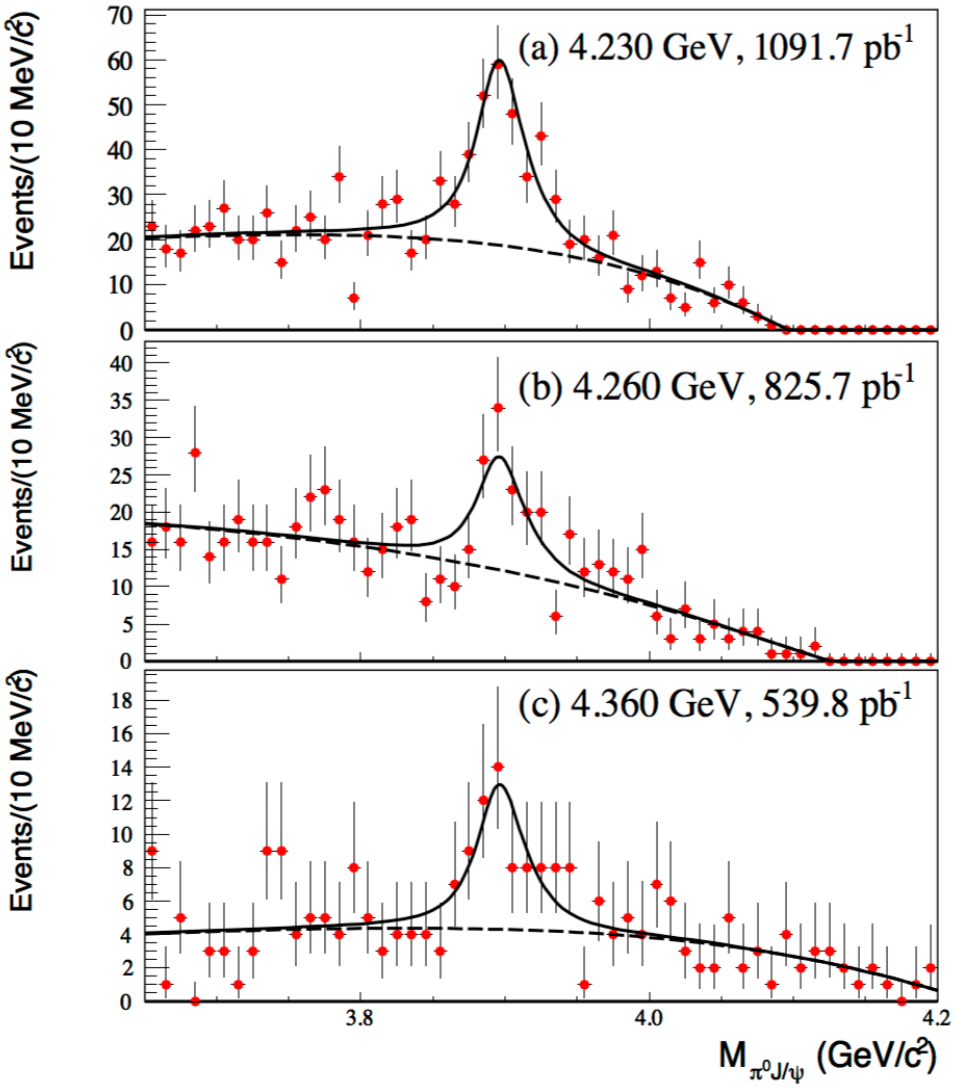


- Discovery of $Z_c(3900)^{\pm} \rightarrow J/\psi\pi^{\pm}$
  - $e^+e^- \rightarrow J/\psi\pi^+\pi^-$
  - at $\sqrt{s}$ = 4.26 GeV (525 pb^{-1}, >8σ)
- Mass close to $D\bar{D}^*$ threshold
- $m = (3899.0 \pm 3.6 \pm 4.9)\,\mathrm{MeV}/c^2$
  $\Gamma = (46 \pm 10 \pm 20)\,\mathrm{MeV}$
- Manifestly exotic:
  - decays to *J/ψ* => contains $c\bar{c}$
  - electrical charged => contains $u\bar{d}$

  => First 4-quark state observation (?!)
- Confirmed by Belle and CLEO-c

[PRL 110 (2013) 252001]

The neutral partner of the $Z_c(3900)$



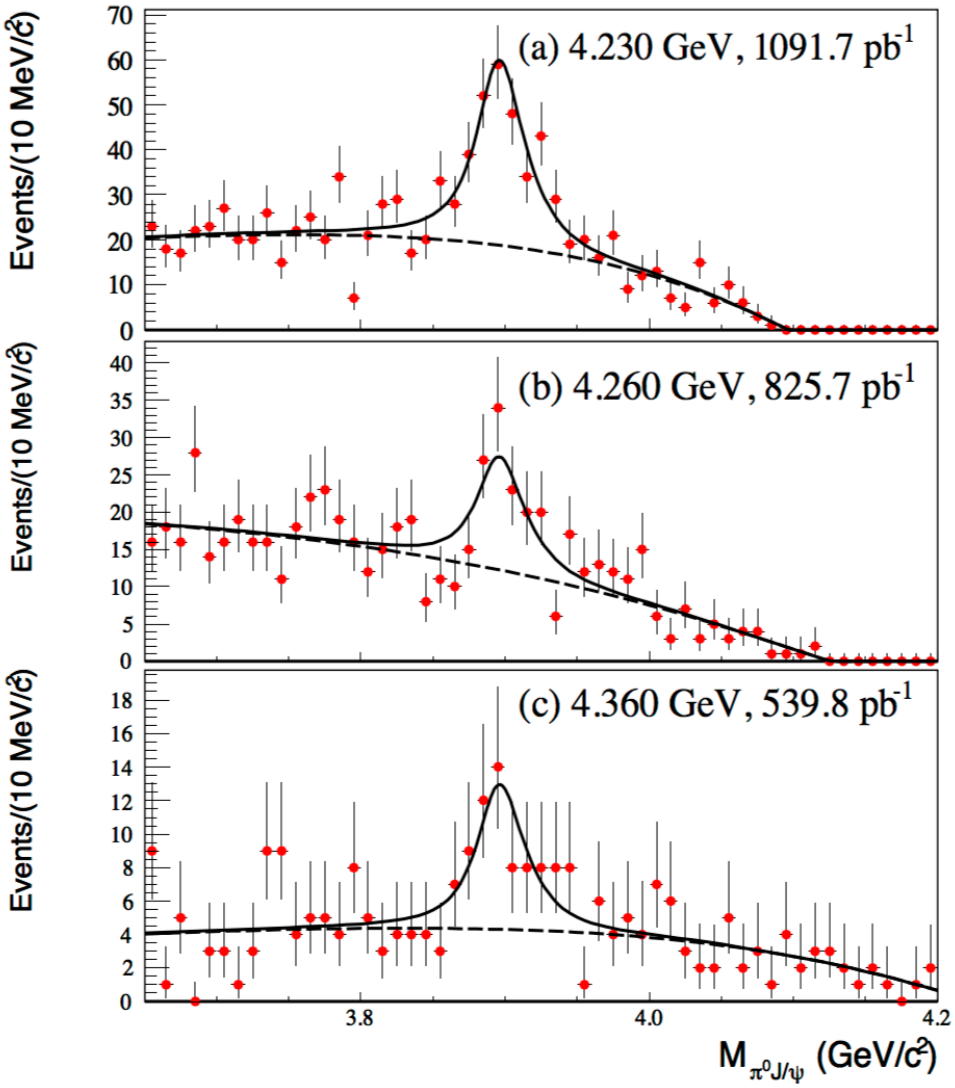
- Observation of $Z_c(3900)^0 \to J/\psi\pi^0$
  - in $e^+e^- \to J/\psi\pi^0\pi^0$ GeV (2.8 fb^{-1}, 10.4σ)
  - confirms earlier evidence in CLEO-c data
- Parameters consistent with those of $Z_c(3900)^{\pm}$
- $m = 3894.8 \pm 2.3 \pm 2.7\,\mathrm{MeV}/c^2$

  $\Gamma = 29.6 \pm 8.2 \pm 8.2\,\mathrm{MeV}$

  => Establishes an isospin triplet $Z_c(3900)$
- Confirmed by Belle and consistent with CLEO-c data

[PRL 115 (2015) 112003]

The neutral partner of the $Z_c(3900)$



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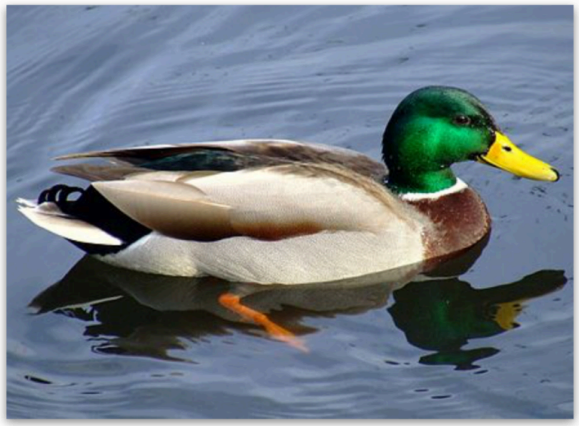
"When I see a bird that walks like a duck and swims like a duck and quacks like a duck, I call that bird a duck."

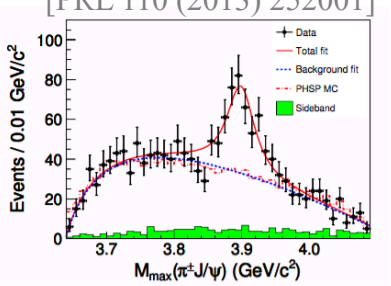
— James Whitcomb Riley
Indiana Poet



[Taken over from M.Sheppard, different context, Hadron'17]

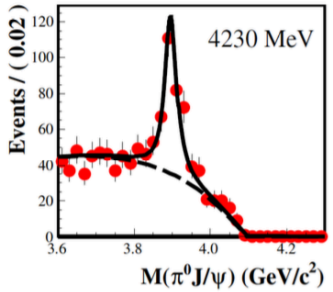
Two Z_c triplets established

[PRL 110 (2013) 252001]



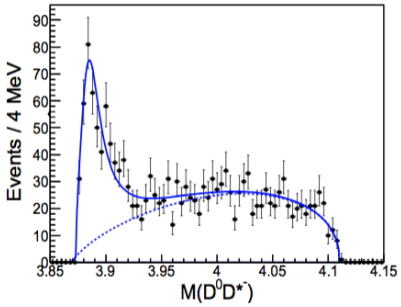
$e^+e^- \to \pi^-\pi^+ J/\psi$

[PRL 115 (2015) 112003]

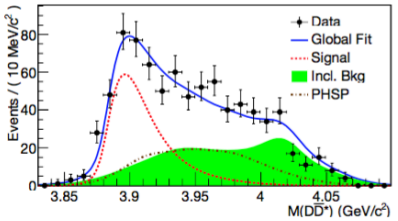


$e^+e^- \to \pi^0\pi^0 J/\psi$

[PRL 112 (2014) 022001]



[PRL 115 (2015) 222002]



$e^+e^- \to \pi^- (D\bar{D}^*)^+$

$Z_c(3900)^{\pm,0}$ → $J^P = 1^+$

- Nature of these states?
  - ➢ two isospin triplets of charmonium-like exotic states established
- Different decay modes *(hidden vs. open charm)* of same state observed?
  - ➢ further decay channels?

Two Z_c triplets established

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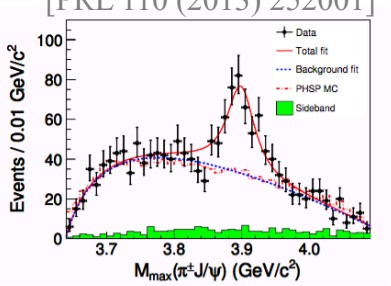
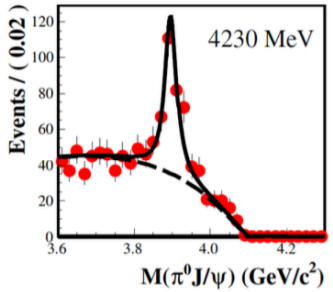


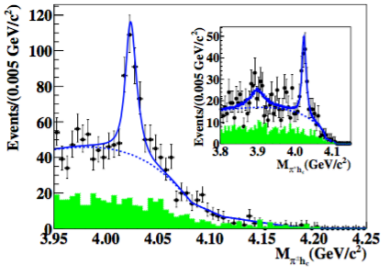
$e^+e^- \to \pi^-\pi^+ J/\psi$

[PRL 115 (2015) 112003]



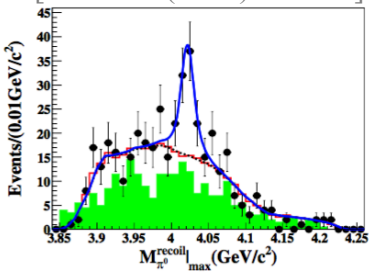
$e^+e^- \to \pi^0\pi^0 J/\psi$

[PRL 111 (2013) 242002]



$e^+e^- \to \pi^-\pi^+ h_c$

[PRL 113 (2014) 212002]



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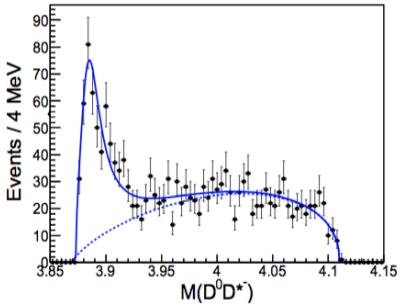
[PRL 112 (2014) 022001]



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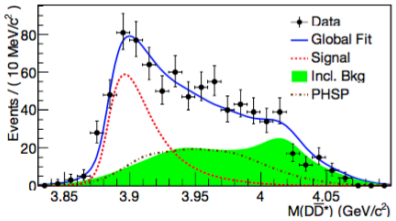
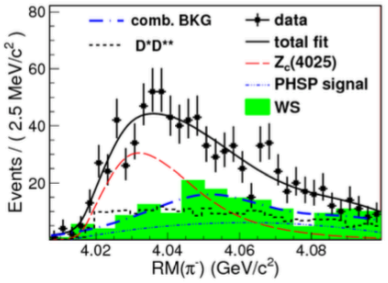
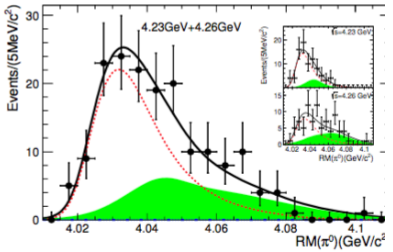


$e^+e^- \to \pi^-(D\bar{D}^*)^+$

[PRL 112 (2013) 132001]



[PRL 115 (2015) 182002]



$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Z_c(3900)^{\pm,0}$ → $J^P = 1^+$

$Z_c(4020)^{\pm,0}$?

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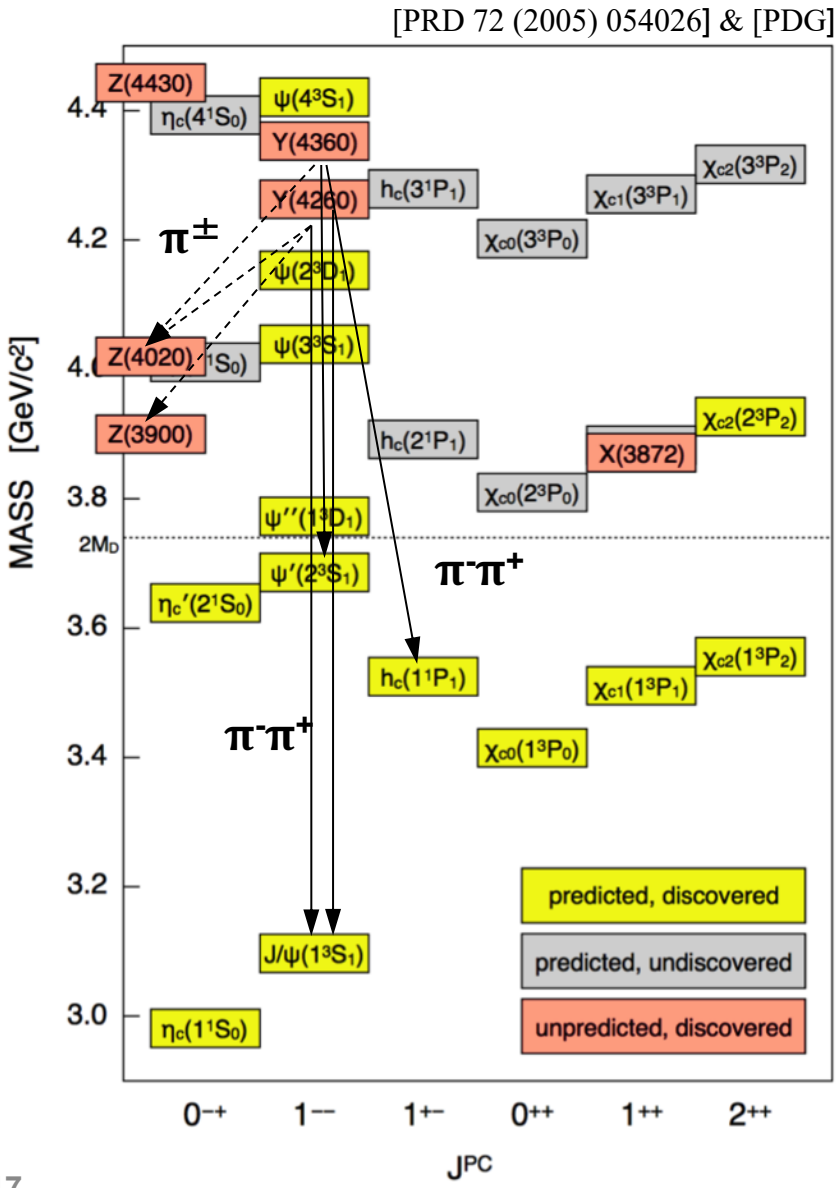
The puzzle of XYZ states



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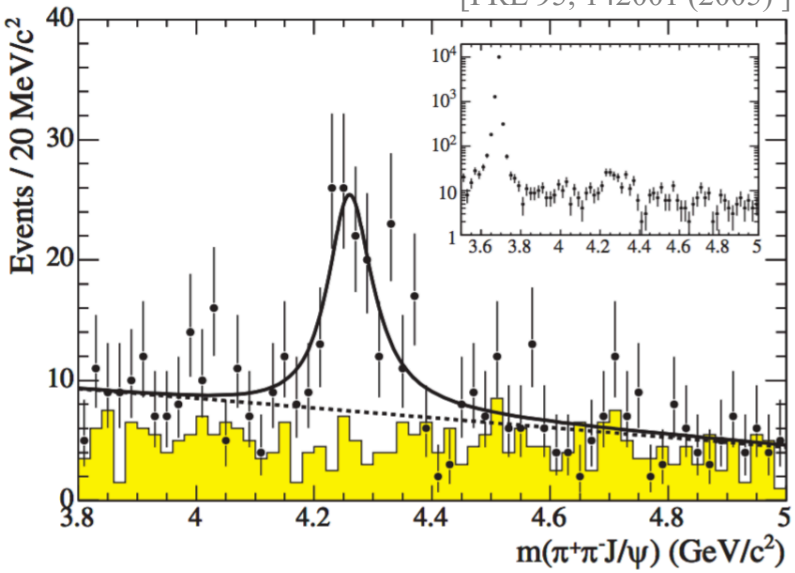
The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

Some history:

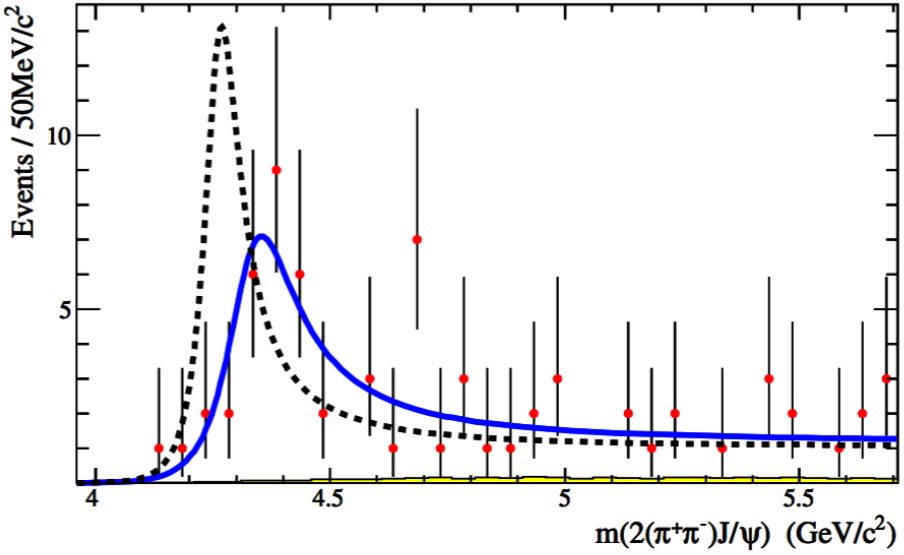
$e^+e^- \to J/\psi\pi^+\pi^-$

[PRL 95, 142001 (2005)]



$e^+e^- \to \psi(2S)\,\pi^+\pi^-$

[PRL 98, 212001 (2007)]



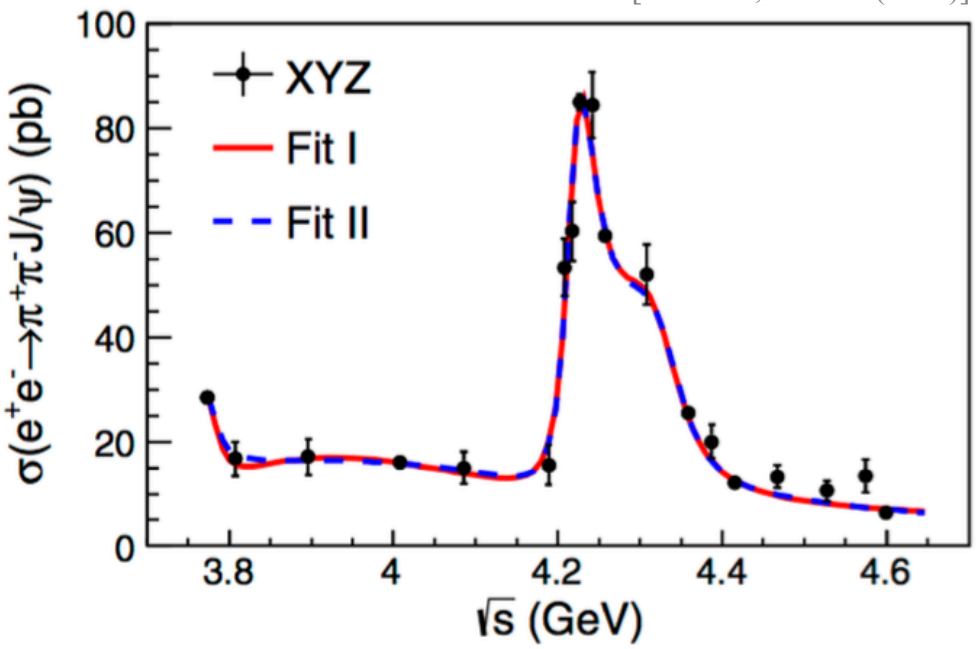
- Discovery of the Y(4260) using ISR by BaBar in $J/\psi\pi^+\pi^-$
- Discovery of the Y(4360) using ISR by BaBar in $\psi(2S)\pi^-\pi^+$

The Y states, e^+e^- production of $J/\psi\pi\pi$, $h_c\pi\pi$ and $\psi(2S)\pi\pi$

BESIII result, published

$e^+e^- \to J/\psi\,\pi^+\pi^-$ at BESIII (direct)

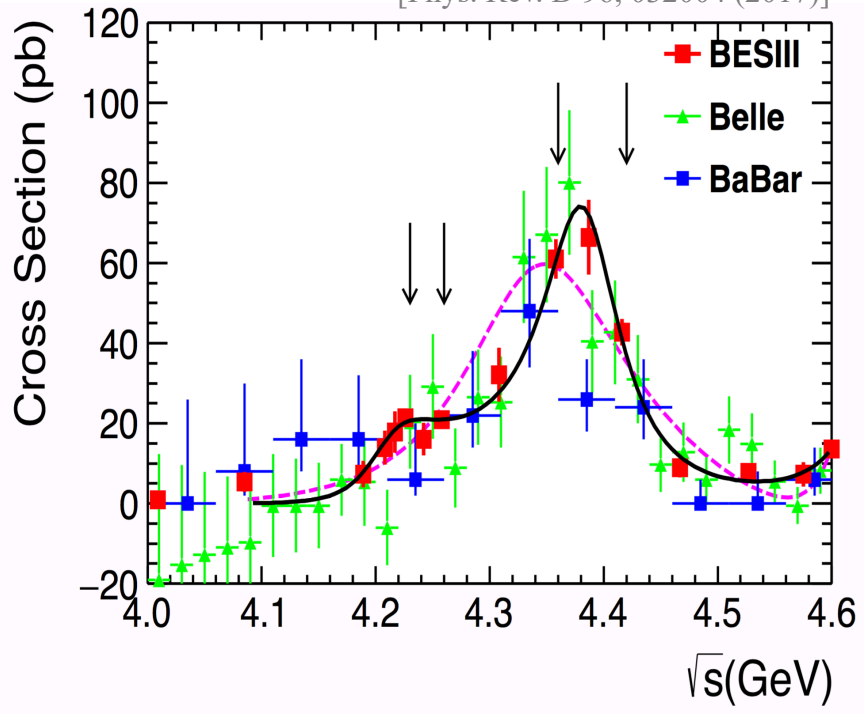
[PRL 118, 092001 (2017)]



- Cross-section in-consistent with a single peak for the Y(4260) !
  - ➢ two peaks favoured over one by >7σ

$e^+e^- \to \psi(2S)\;\pi^+\pi^-$ at BESIII (direct)

[Phys. Rev. D 96, 032004 (2017)]



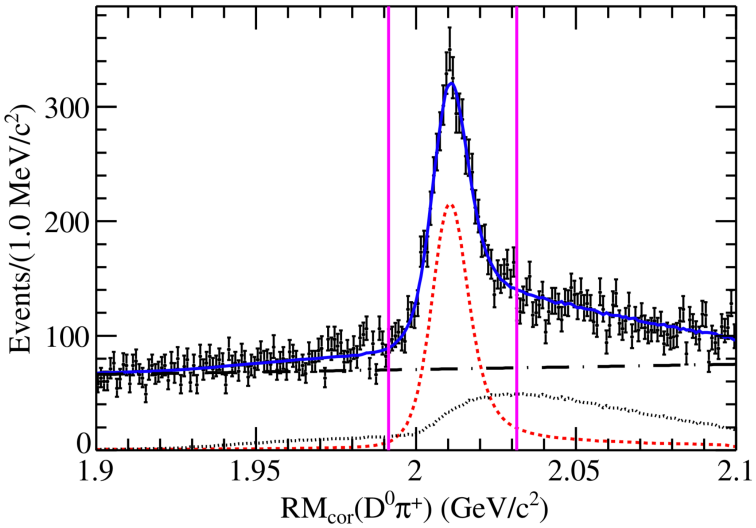
- BESIII much higher precision (5.8σ)
- 3 coherent BW fit: Y(4220) and Y(4390)

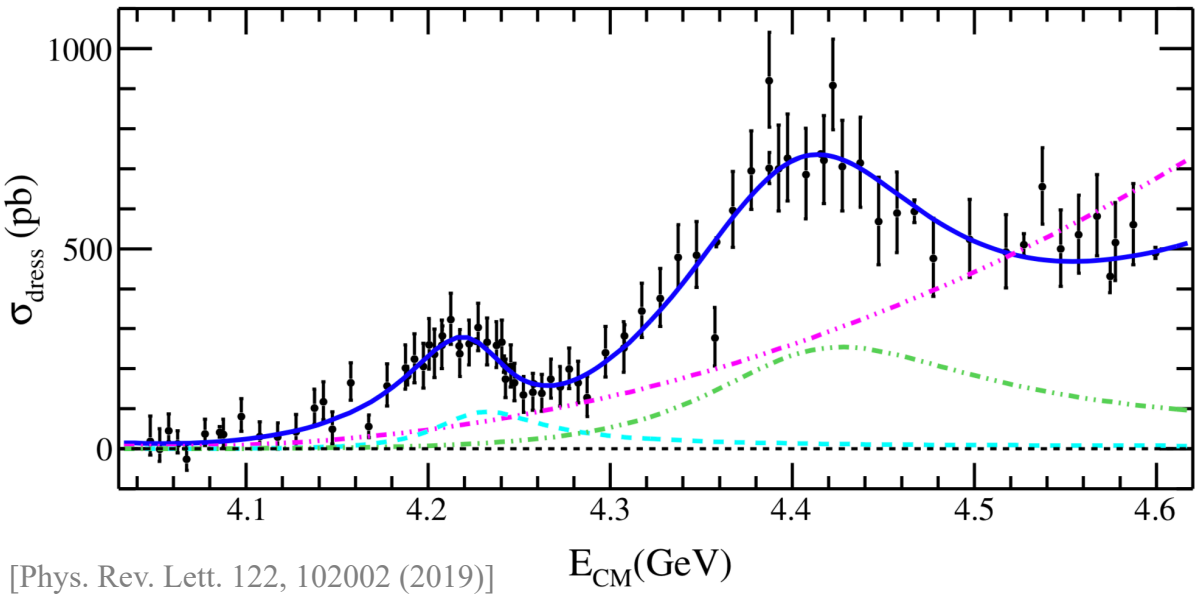
Open charm: $e^+e^- \to D^0D^{*-}\pi^+$

- Based on data samples from E_{cms} = 4.05 to 4.6 GeV
- Reconstructed: $D^0 \to K^-\pi^+$

- Using $RM(D^0\pi^+) + M(D^0) - m(D^0)$ to select D^{*-} signal
- Peaking bkgd from isospin partner $e^+e^- \to D^{*0}D^-\pi^+$

- Fit of coherent sum of 3-body PHSP and 2 BW fctns.
- Significance of two over one structure: **>10σ**





[Phys. Rev. Lett. 122, 102002 (2019)]

Y(4220):
- M = (4224.8 ± 5.6 ±4.0) MeV/c²
- Γ = (72.3 ± 9.1 ±0.9) MeV/c²

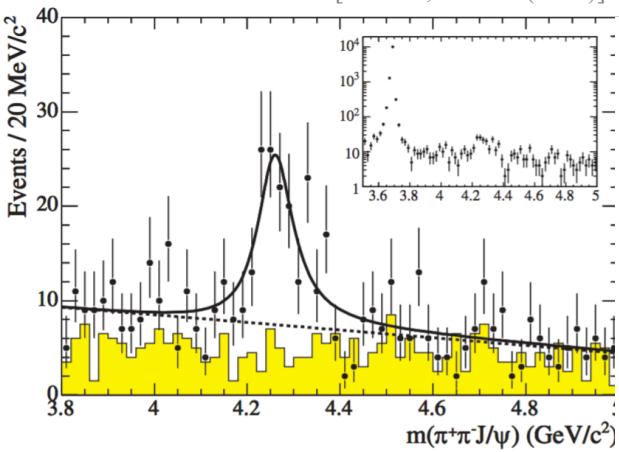
Y(4390):
- M = (4400.1 ± 9.3 ±2.1) MeV/c²
- Γ = (181.7 ± 16.9 ±7.4) MeV/c²

=> Consistent with structures observed in $h_c\pi\pi$, $\psi(2S)\pi\pi$

What happened to the Y states?

$e^+e^- \to J/\psi\pi^+\pi^-$

[PRL 95, 142001 (2005)]



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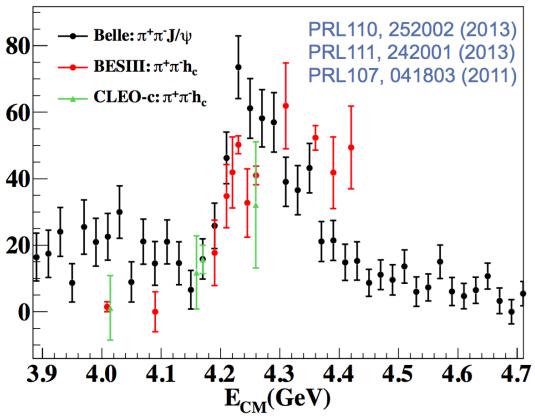

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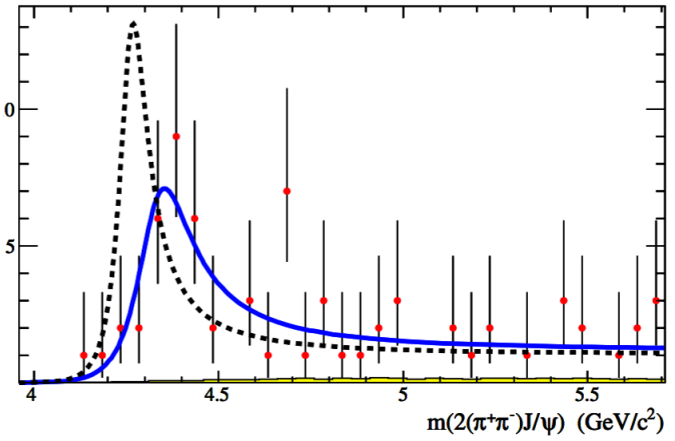
[PRL 98, 212001 (2007)]



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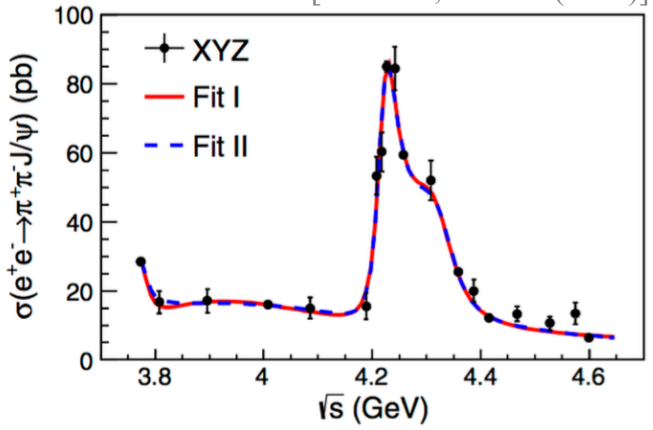
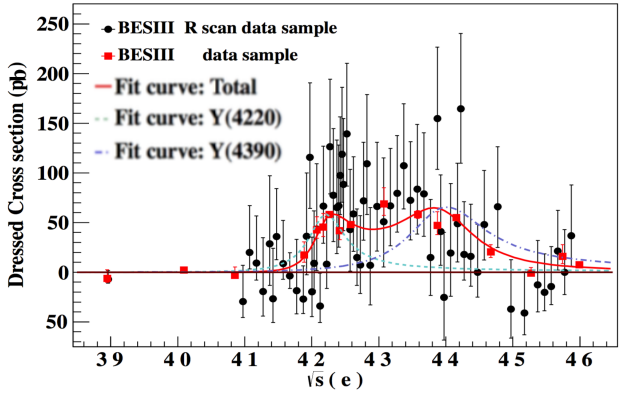
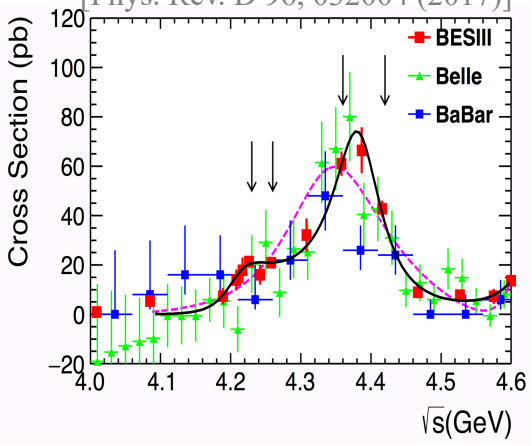


[Phys. Rev. Lett. 118 092002 (2017)]



[Phys. Rev. D 96, 032004 (2017)]

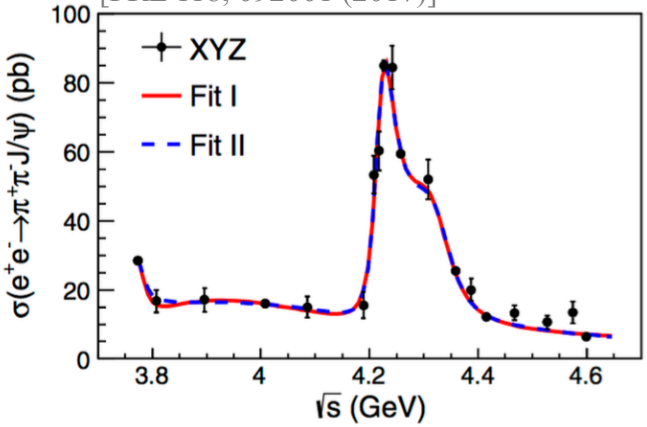


Two structures now observed/resolved in all three cases
=> Y(4260) → Y(4220) , Y(4360) → Y(4390) ?

What happened to the Y states?

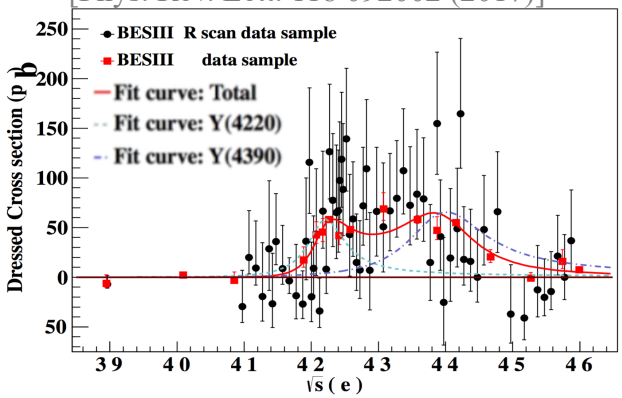
$e^+e^- \to J/\psi\pi^+\pi^-$

[PRL 118, 092001 (2017)]



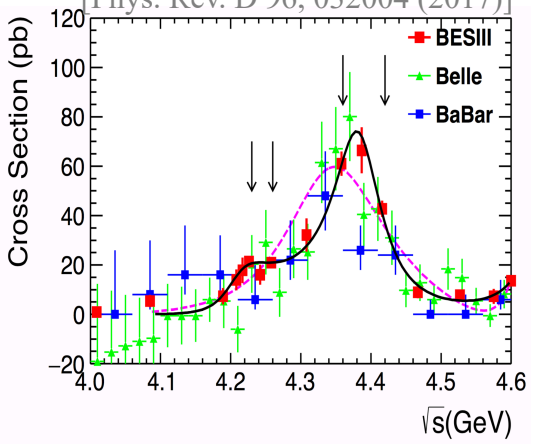
$e^+e^- \to h_c\,\pi^+\pi^-$

[Phys. Rev. Lett. 118 092002 (2017)]

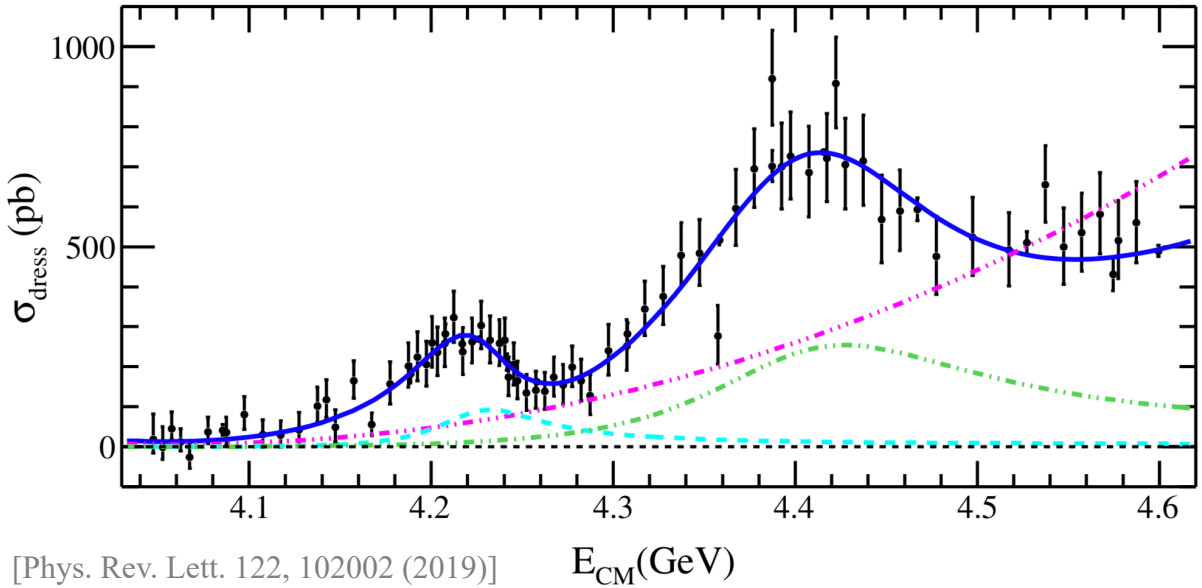


$e^+e^- \to \psi(2S)\,\pi^+\pi^-$

[Phys. Rev. D 96, 032004 (2017)]



$e^+e^- \to D^0D^{*-}\pi^+$

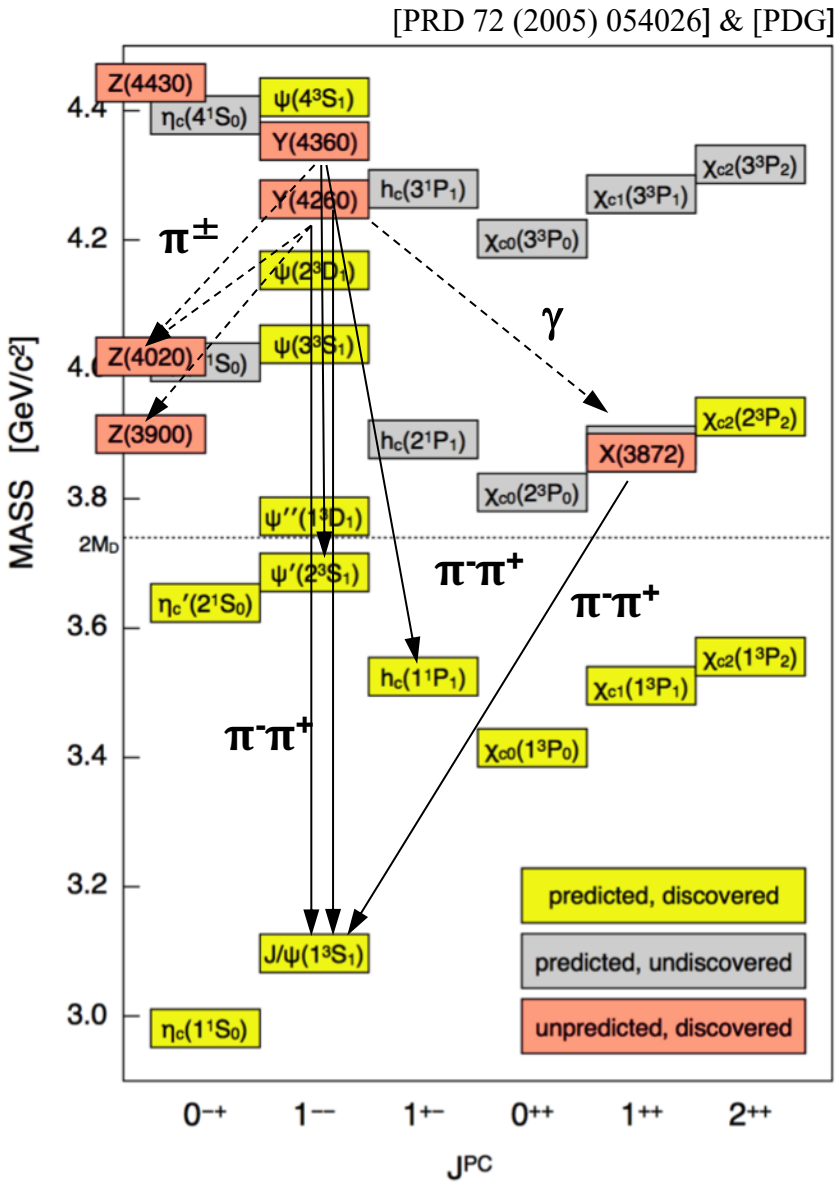


[Phys. Rev. Lett. 122, 102002 (2019)]

Two structures consistently observed: Y(4220) & Y(4390)

=> Y(4260) → Y(4220) ?

The puzzle of XYZ states



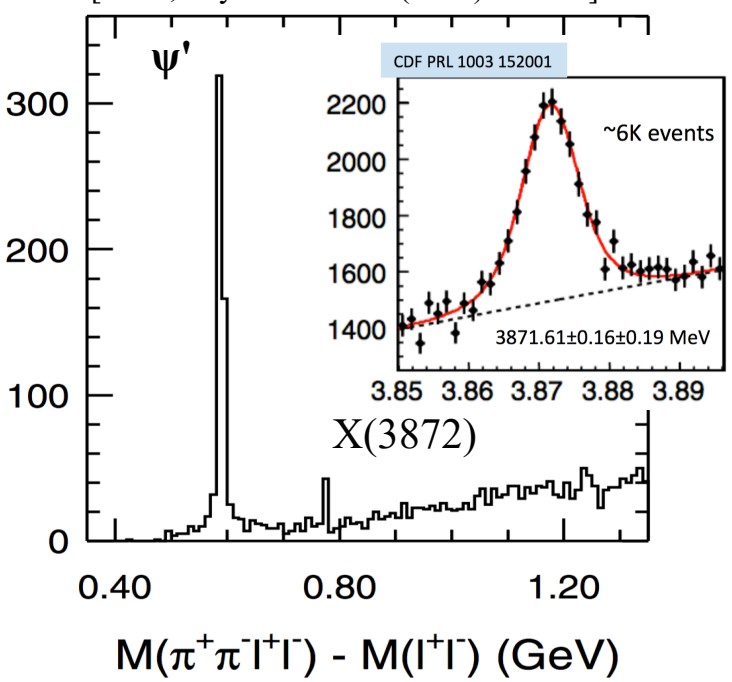
- Below open charm threshold:
  - Good agreement theory vs. experiment
- Above open charm threshold:
  - Many predicted states not discovered
  - Many unexpected states observed

BESIII: Study conventional as well as charmonium-like (exotic) XYZ states

- Direct access to Y states (1^{--}) in direct formation (e^+e^- annihilation)
- Study (charged & neutral) Z states
- Study X states in radiative decays

Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



- The first unexpected states
  - and the most intriguing one
- First observed by Belle in 2003
  - $X(3872) \rightarrow J/\psi\,\pi\pi$
  - very narrow state with $J^{P\,C} = 1^{++}$
- Both, Belle & BaBar report signal in
  - $X(3872) \rightarrow D^0\bar{D}^{*0}$ ($D^0D^0\pi^0$ and $D^0D^0\gamma$)

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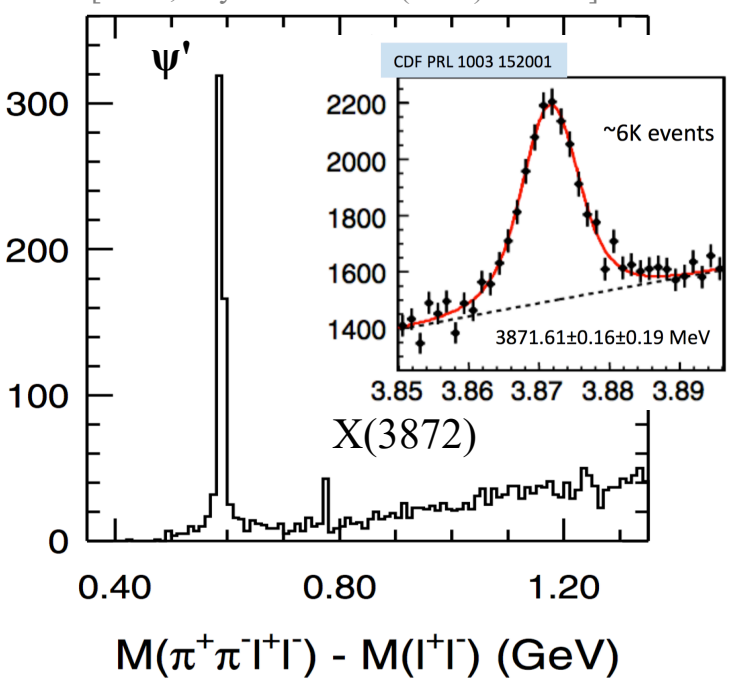

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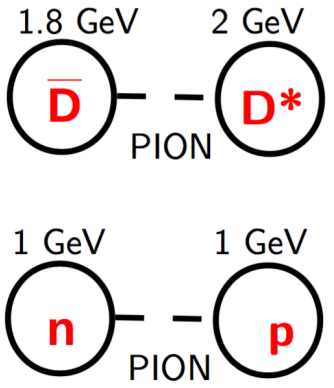
- Mass: $m(X) - m(\bar{D}^{*0}) - m(D^0) =$
  $= -0.12 \pm 0.19\ \text{MeV}/c^2$
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2$ MeV (90% c.l., 2011)

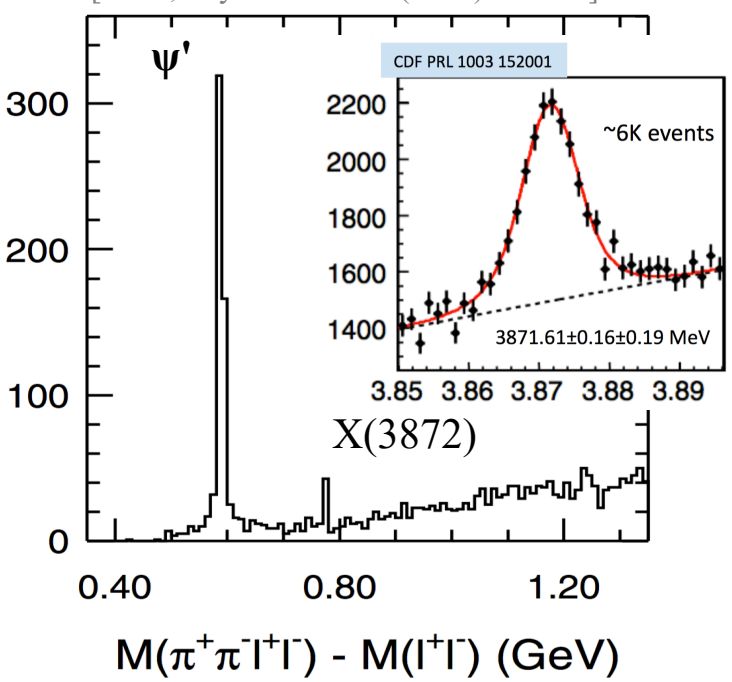
"binding energy" of
-0.12+-0.19 MeV ?

Intriguing Analogon



Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



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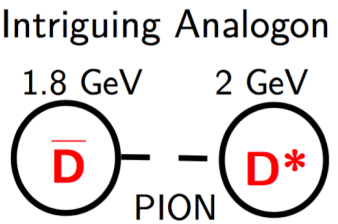
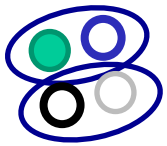




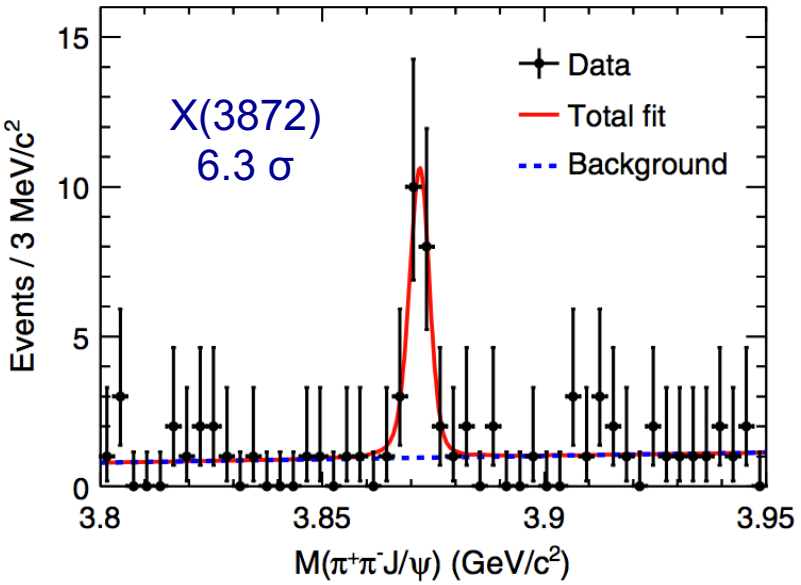
Molecule ?
$(q\bar{q})_1(q\bar{q})_1$

For clarification: Precision measurement of $\Gamma_{X(3872)}$ in the sub-MeV range needed!

First observation of $e^+e^- \to \gamma X(3872)$

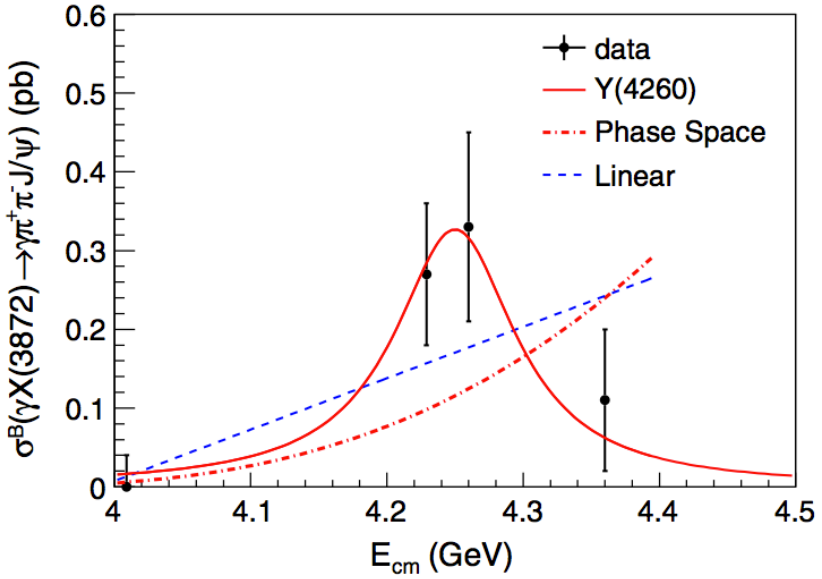
- X(3872) is the first-discovered and best-studied of the XYZ states
- BESIII: First observation of $e^+e^- \to \gamma X(3872) \to \gamma\pi^+\pi^- J/\psi$
  - Analysed at $\sqrt{s}$ = 4009, 4229, 4260, 4360 MeV

[Phys. Rev. Lett. 112 (2014) 092001]



- $m = (3871.9 \pm 0.7 \pm 0.2)\,\mathrm{MeV}/c^2$
- $\Gamma < 2.4\,\mathrm{MeV}$ (90% CL)

cross section



- Cross-section shape hints to production via a Y state – more data needed!

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- X(3872) is the first-discovered and best-studied of the XYZ states
- BESIII: First observation of $e^+e^- \to \gamma X(3872) \to \gamma\omega J/\psi$
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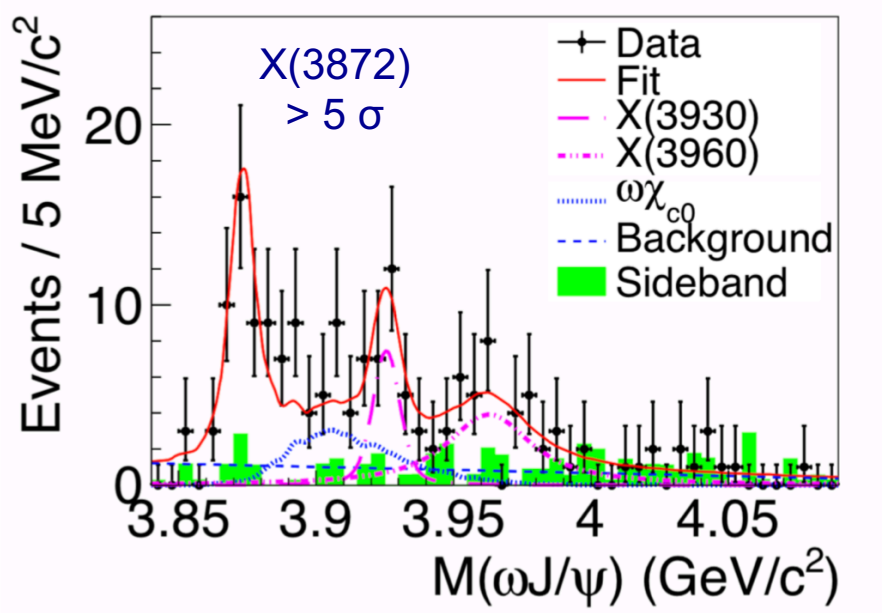

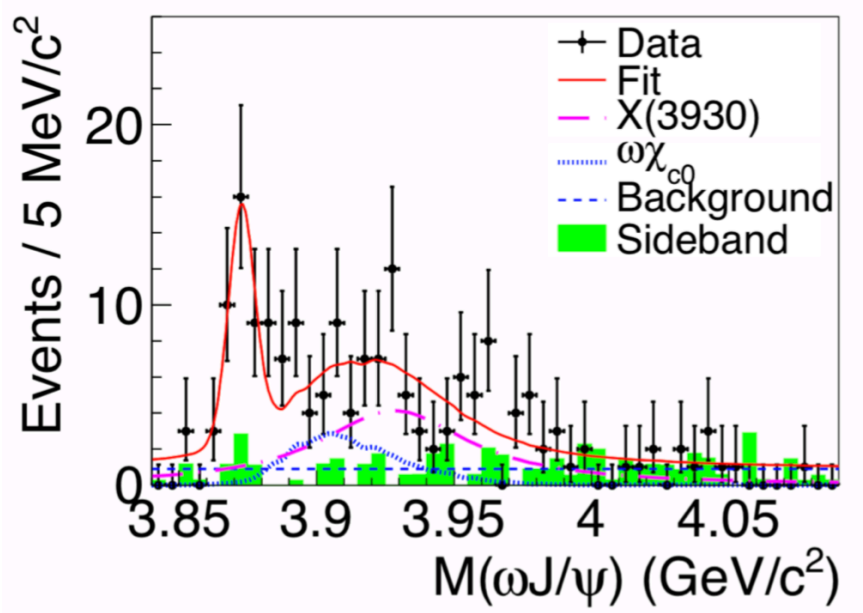

- Applying a fit including three (left) and two (right) Breit-Wigner resonances

=> *Evidence for two more structures*

[Phys. Rev. Lett., 122, 232002 (2019)]

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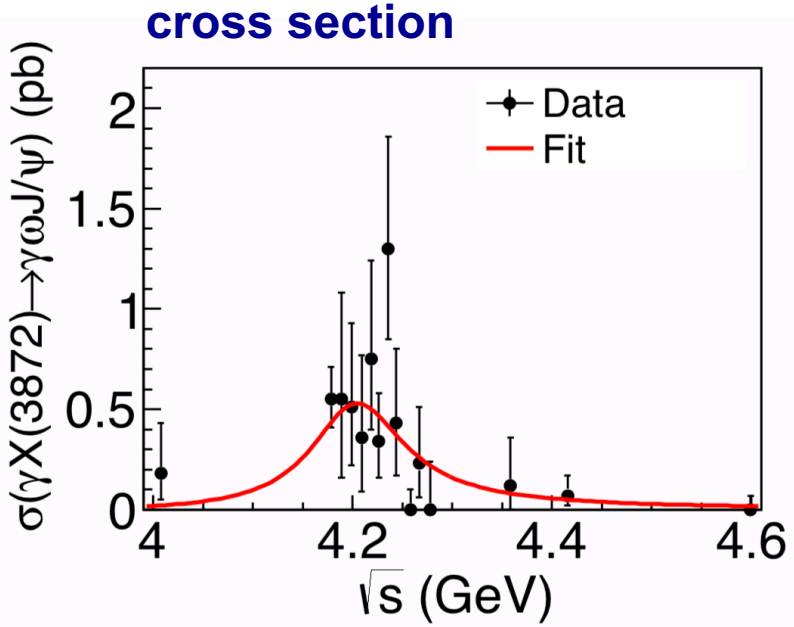

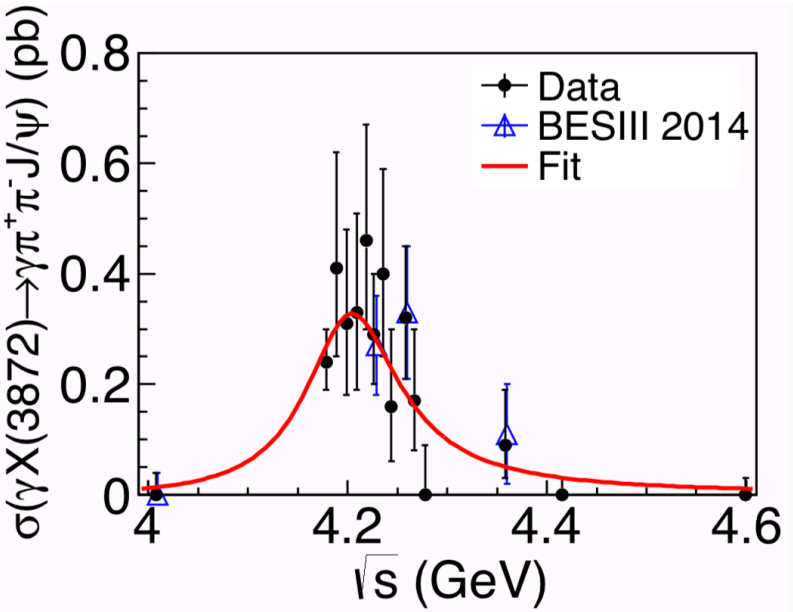

- $m = (4200.6^{+7.9}_{-13.3} \pm 3.0\ \mathrm{MeV}/c^2$
- $\Gamma = (115^{+38}_{-26} \pm 12\ \mathrm{MeV}/c^2$

- Cross-section shape consistent with production via a Y state

[Phys. Rev. Lett., 122, 232002 (2019)]

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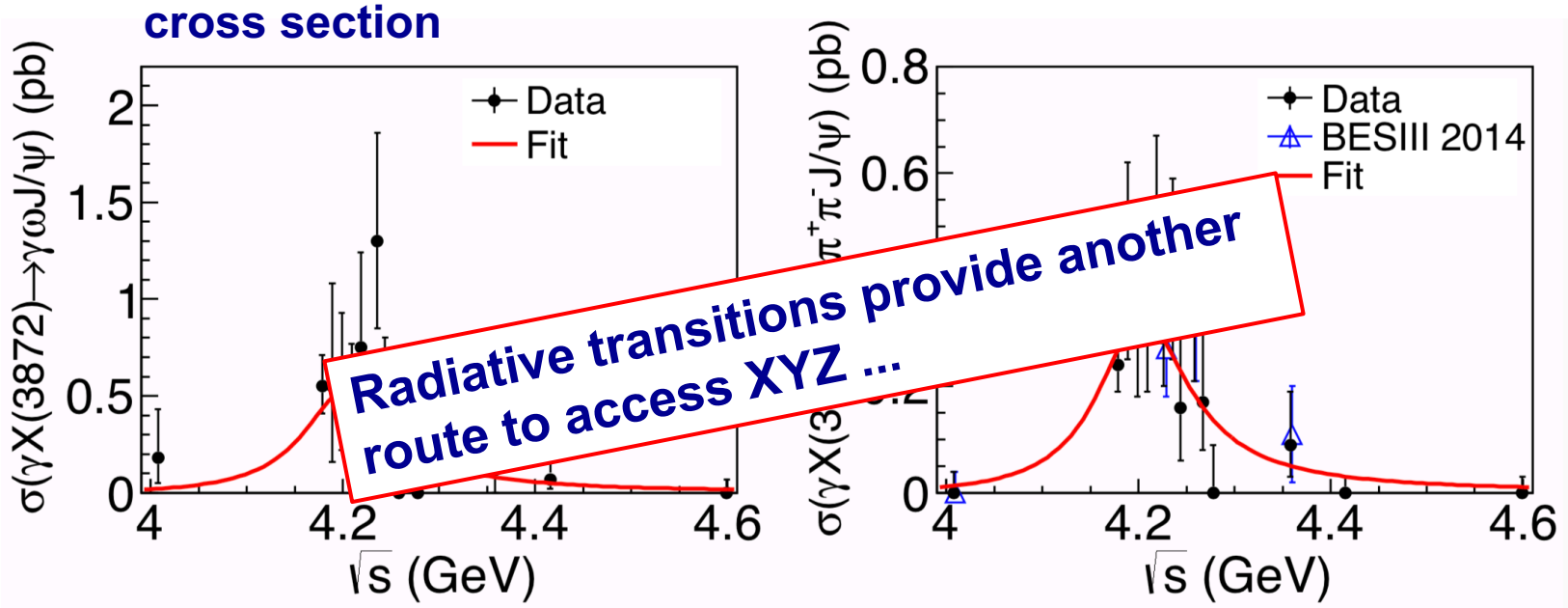

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[Phys. Rev. Lett., 122, 232002 (2019)]

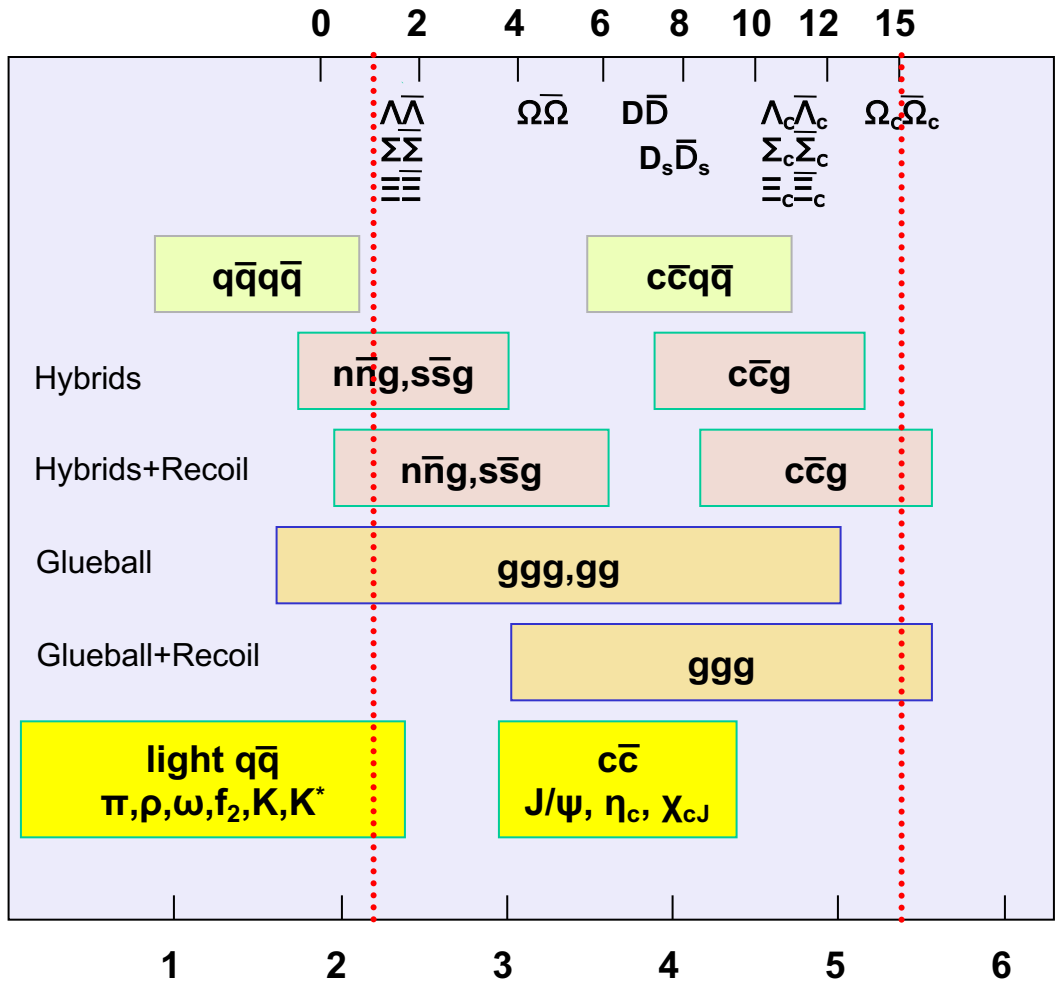
PANDA Physics Programme

Anti-Proton ANnihilation in DArmstadt

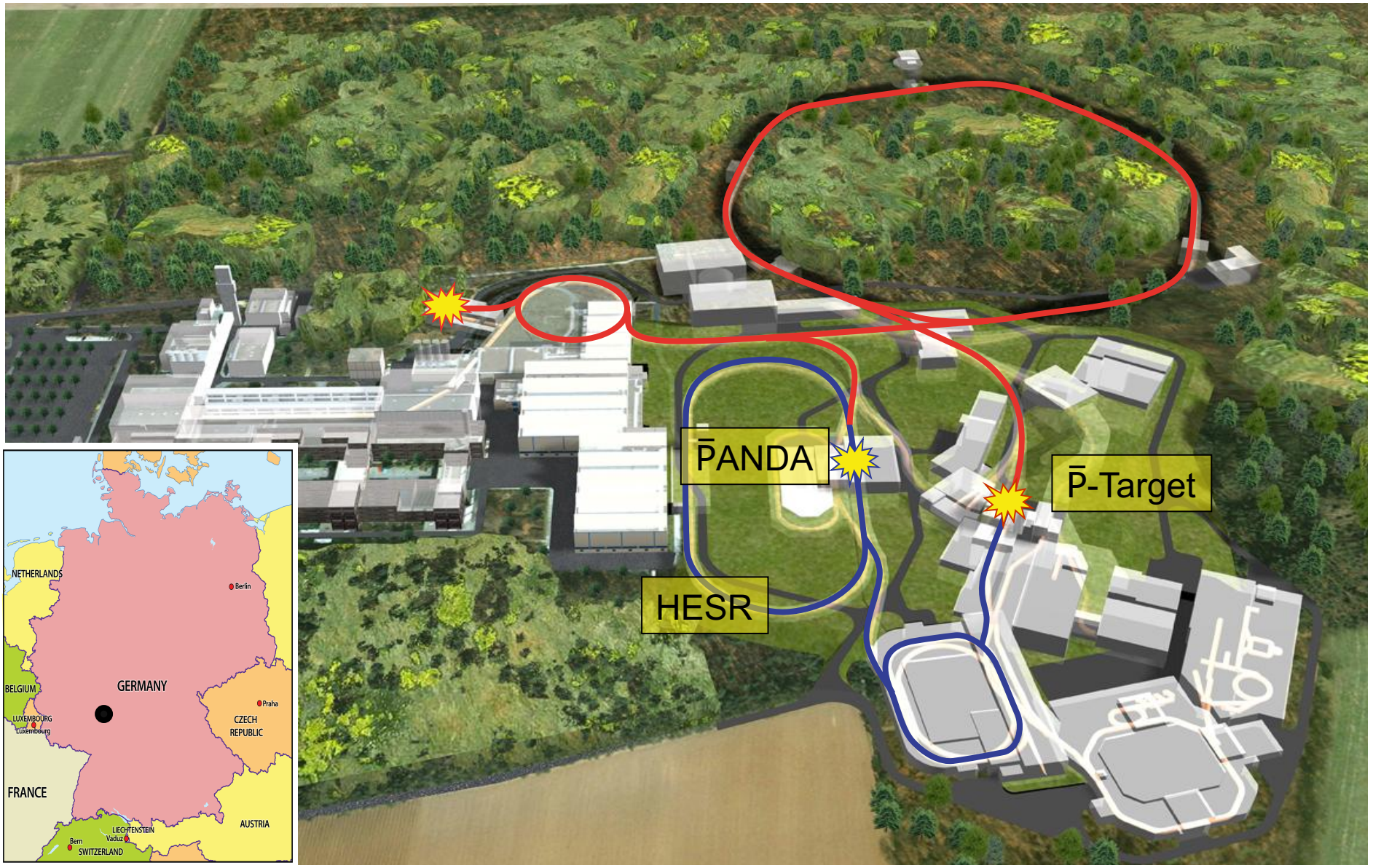
- **Hadron spectroscopy**
  - Light mesons
  - Charmonium
  - Exotic states:

    glue-balls, hybrids,

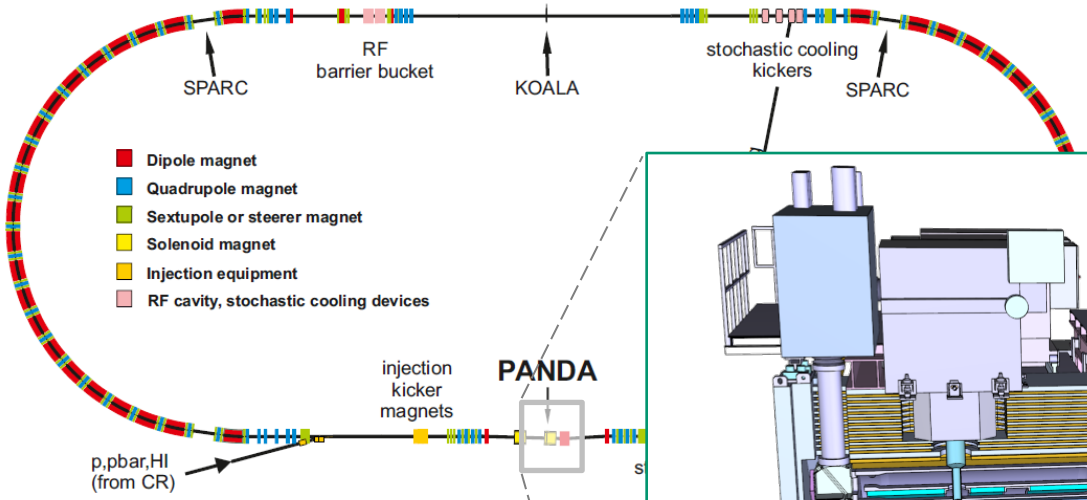
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - hypernuclei
  - S = -2 nuclear system



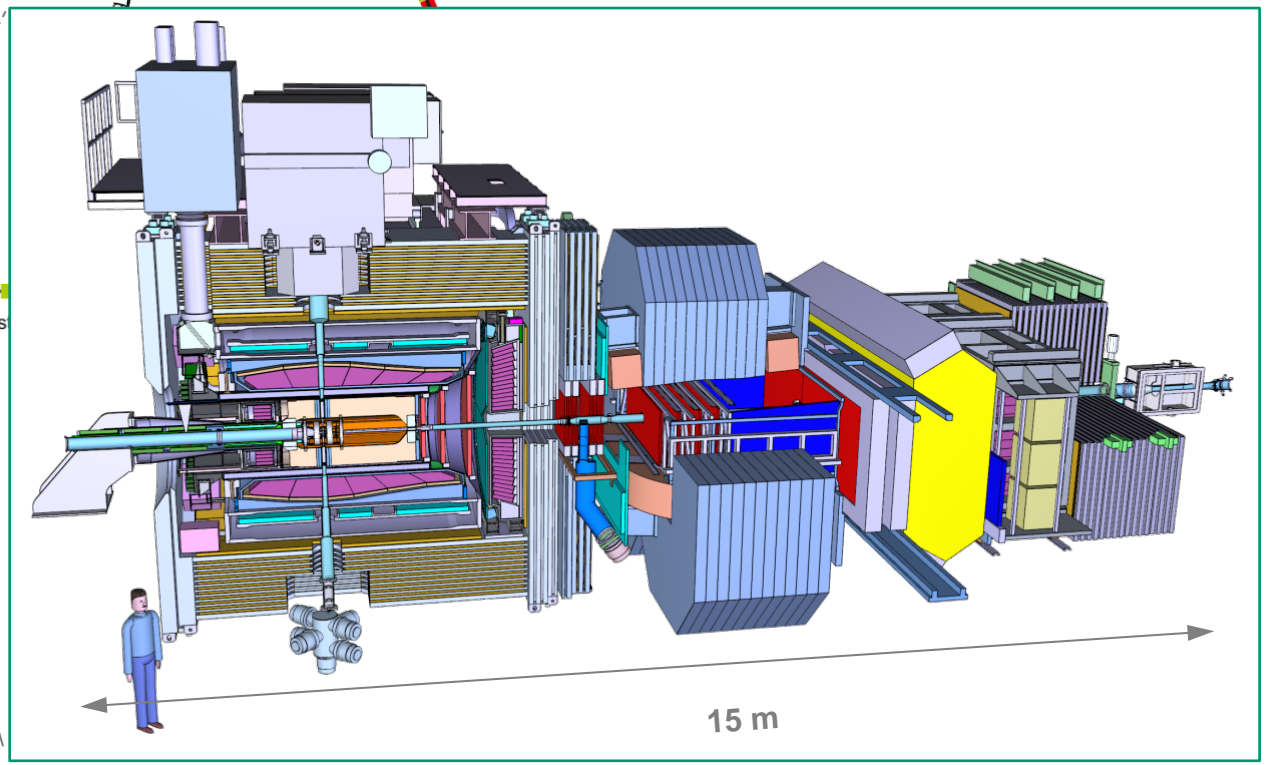
Facility for Antiproton and Ion Research



High Energy Storage Ring – HESR



PANDA Experiment, Detector



XYZ region:

- p = 1.5 – 15 GeV/c

=> $\sqrt{s}$ = 2.2 – 5.5 GeV

High Resolution (HR) mode:

- Luminosity up to 2 x 10^{31} cm^{-2} s^{-1}
- $\Delta p/p = 2 \times 10^{-5}$

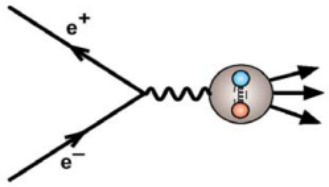
High Luminosity (HL) mode:

- Luminosity up to 2 x 10^{32} cm^{-2} s^{-1}
- $\Delta p/p = 1 \times 10^{-4}$

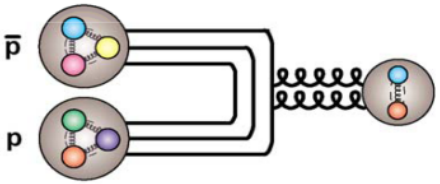
Some Advantages of Anti-Protons

- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*
- Access to states of high spin J

Formation:



only $J^{PC} = 1^{--}$



all $q\bar{q}$ J^{PC}

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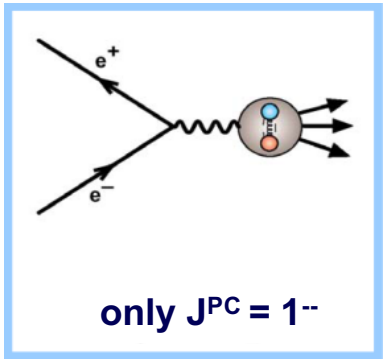

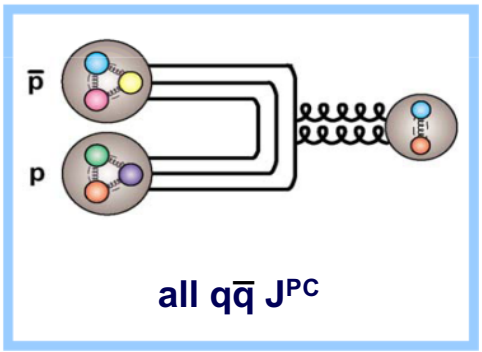

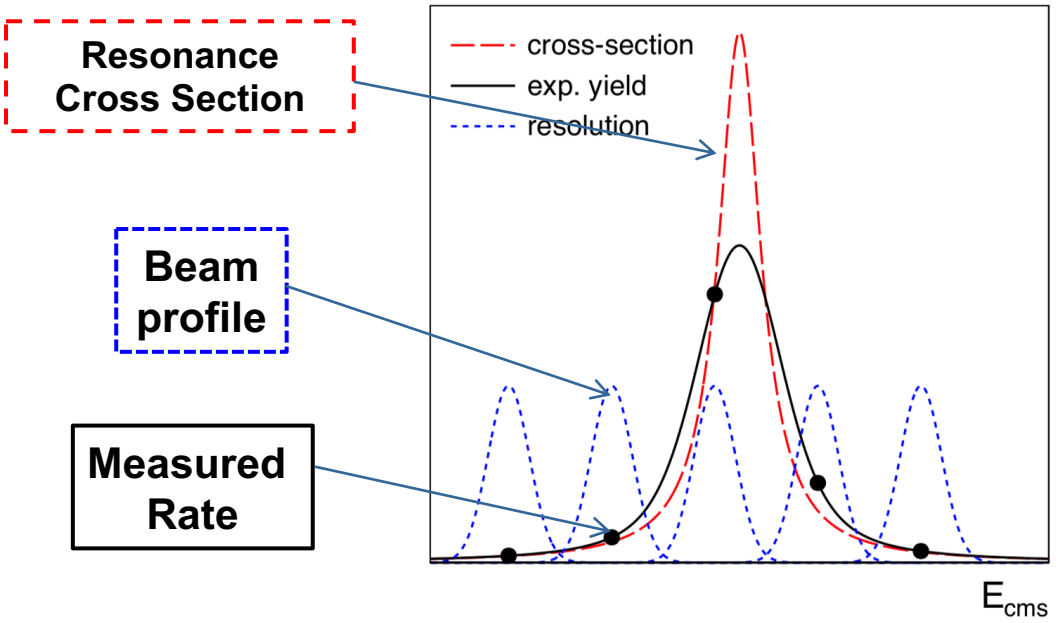

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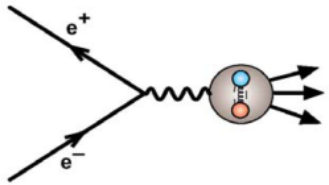

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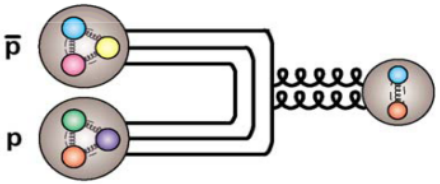
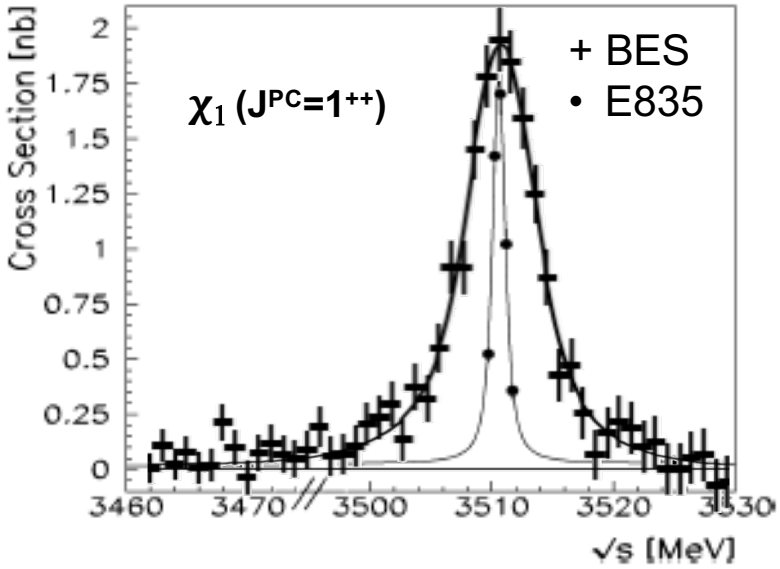


all $q\bar{q}$ J^{PC}



E760/835@Fermilab ≈ 240 keV

PANDA@FAIR ≈ 50 keV

Ablikim et al., Phys. Rev. D71 (2005) 092002: *BES (IHEP):* 3510.3 ± 0.2 MeV/c^2

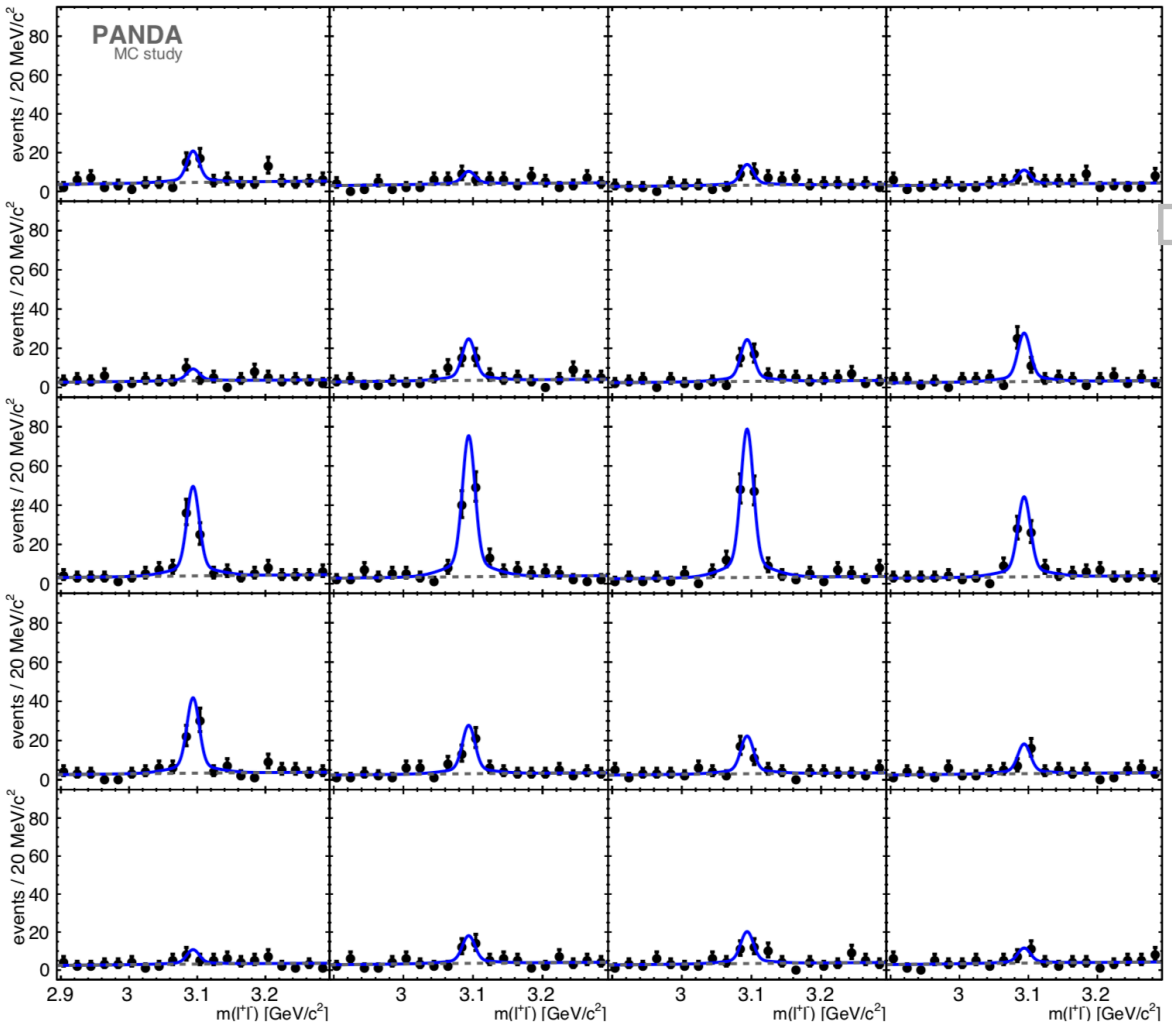
Andreotti et al., Nucl. Phys. B717 (2005) 34: E835 (Fermilab): 3510.641 ± 0.074 MeV/c^2

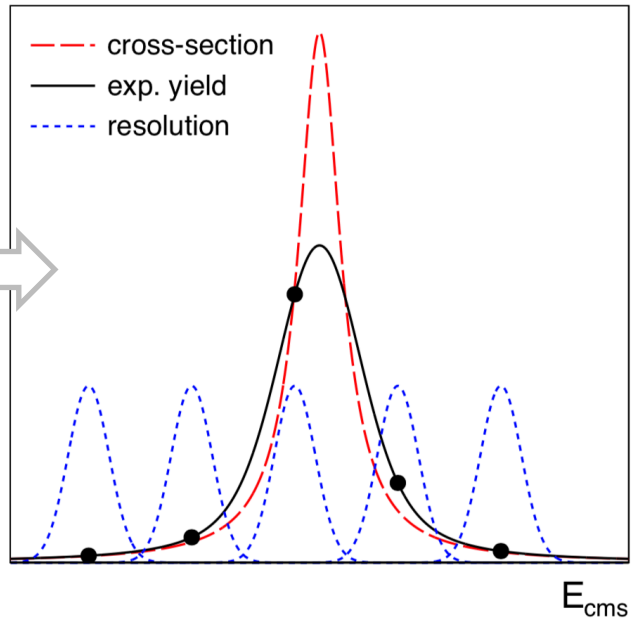
Perfomance Study for energy resonance scans of narrow resonances, like the X(3872)

Reminder:
Sub-MeV resolution needed to clarify nature
=> PANDA

Scan Procedure Principle (Example)

20 E_{cms} scan point within ±0.4 MeV window around nominal mass





[PANDA, arXiv:1812.05132, hep-ex]

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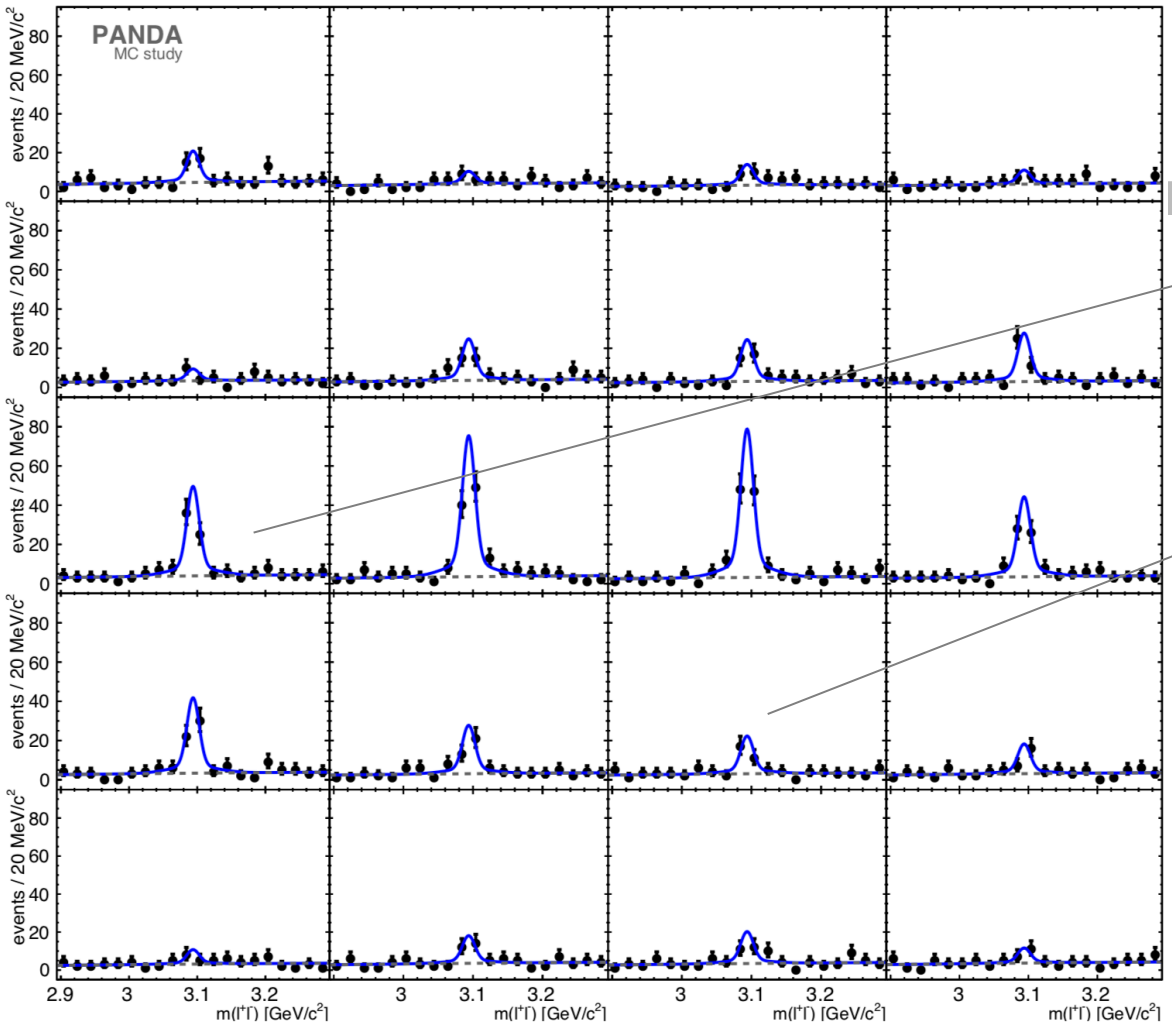

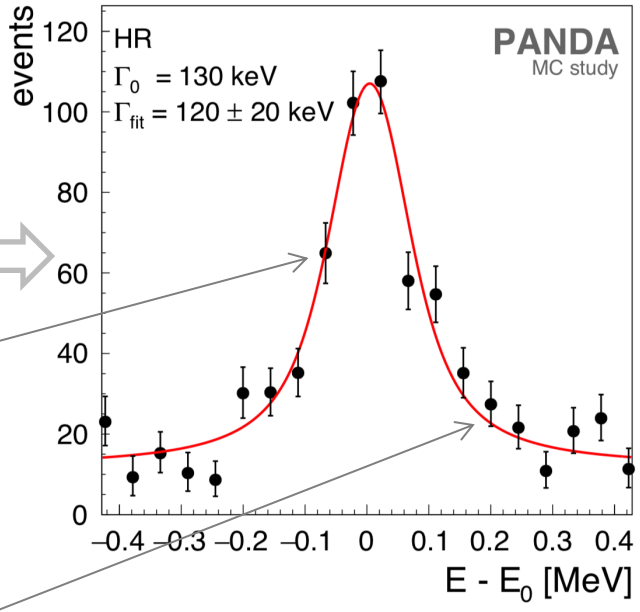

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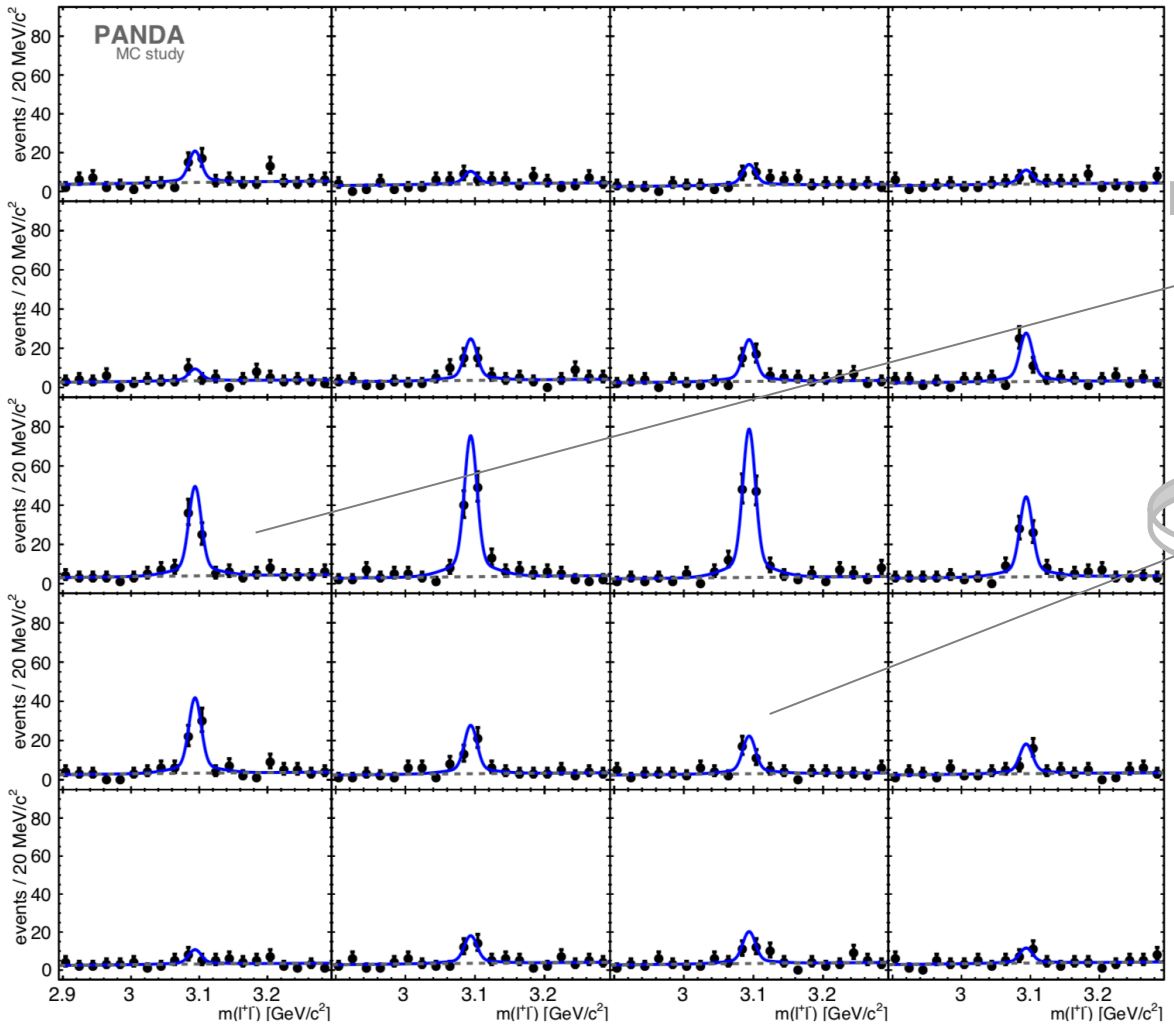
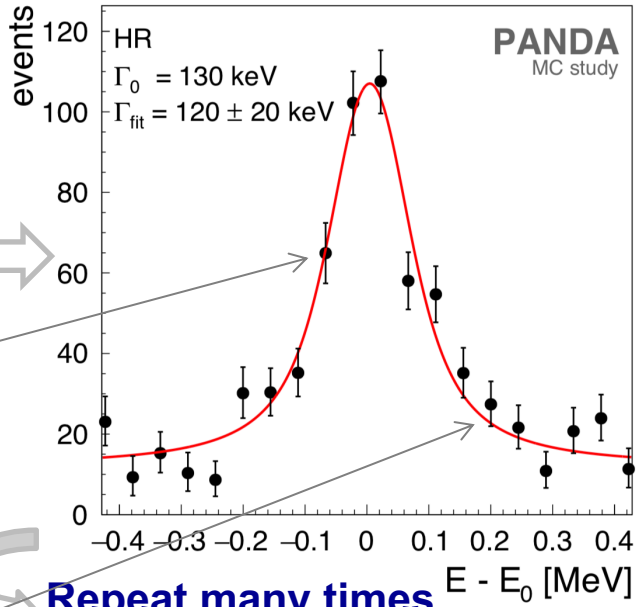
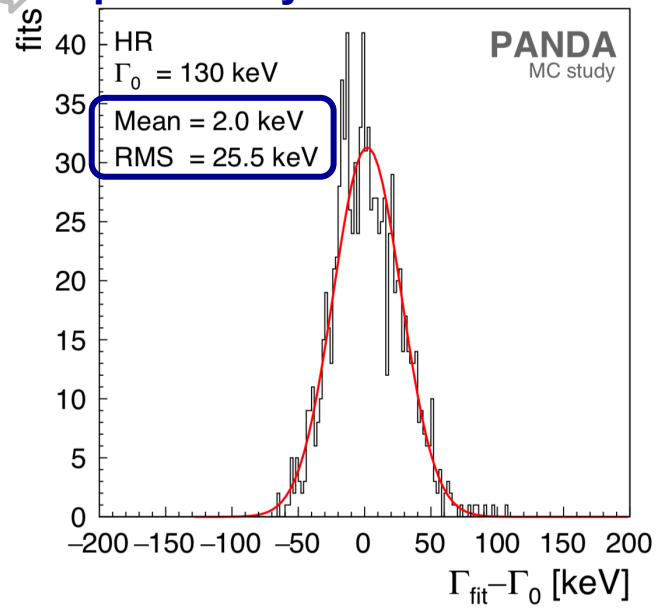




Repeat many times ...



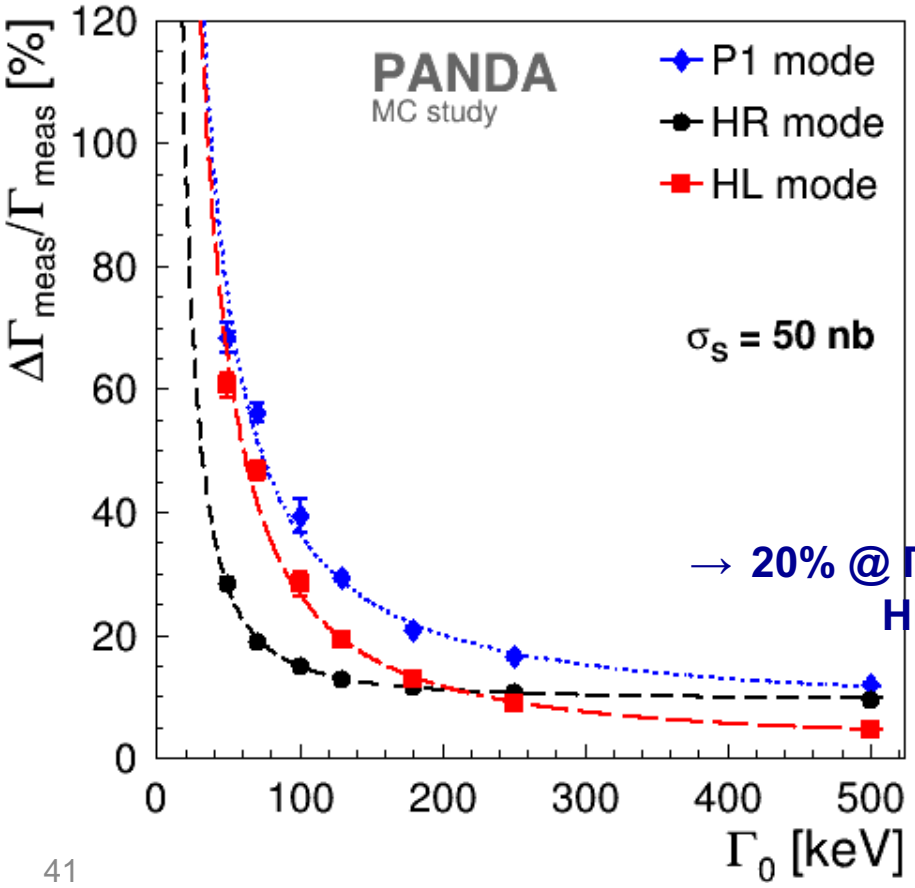
[PANDA, arXiv:1812.05132, hep-ex]

Sensitivities Breit-Wigner Γ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $rms_{fit}/\bar{\Gamma}_{fit}$ in [%]

Sensitivity

$$\frac{\Delta\Gamma_{meas}}{\Gamma_{meas}} = \frac{RMS}{Mean + \Gamma_0} \qquad \text{(Breit-Wigner case)}$$



→ **20% @ Γ= 50 ... 120 keV**
HR HL

[PANDA, arXiv:1812.05132, hep-ex]

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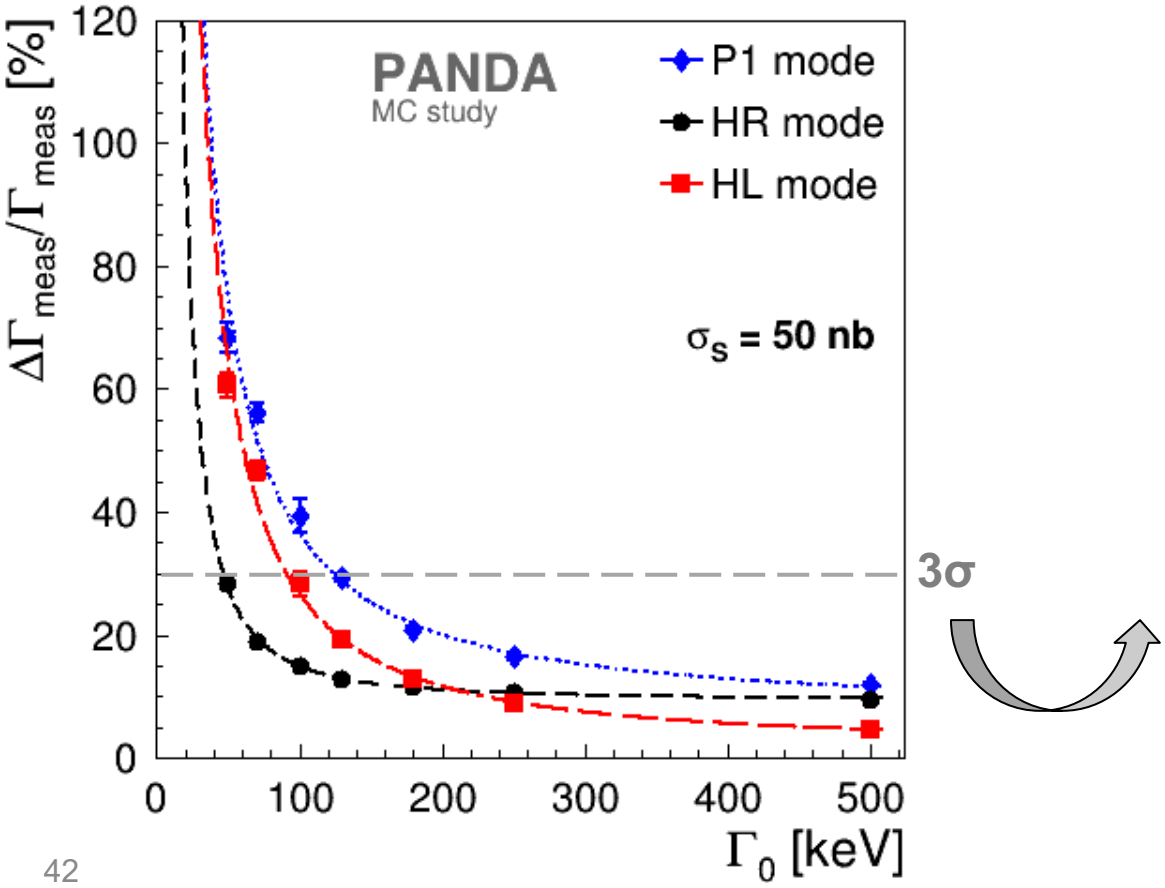

[PANDA, arXiv:1812.05132, hep-ex]

Sensitivities Breit-Wigner Γ (40 x 2d)

- Extract standard deviation from toy MC fits
- Show relative error $rms_{fit}/\bar{\Gamma}_{fit}$ in [%]

Sensitivity

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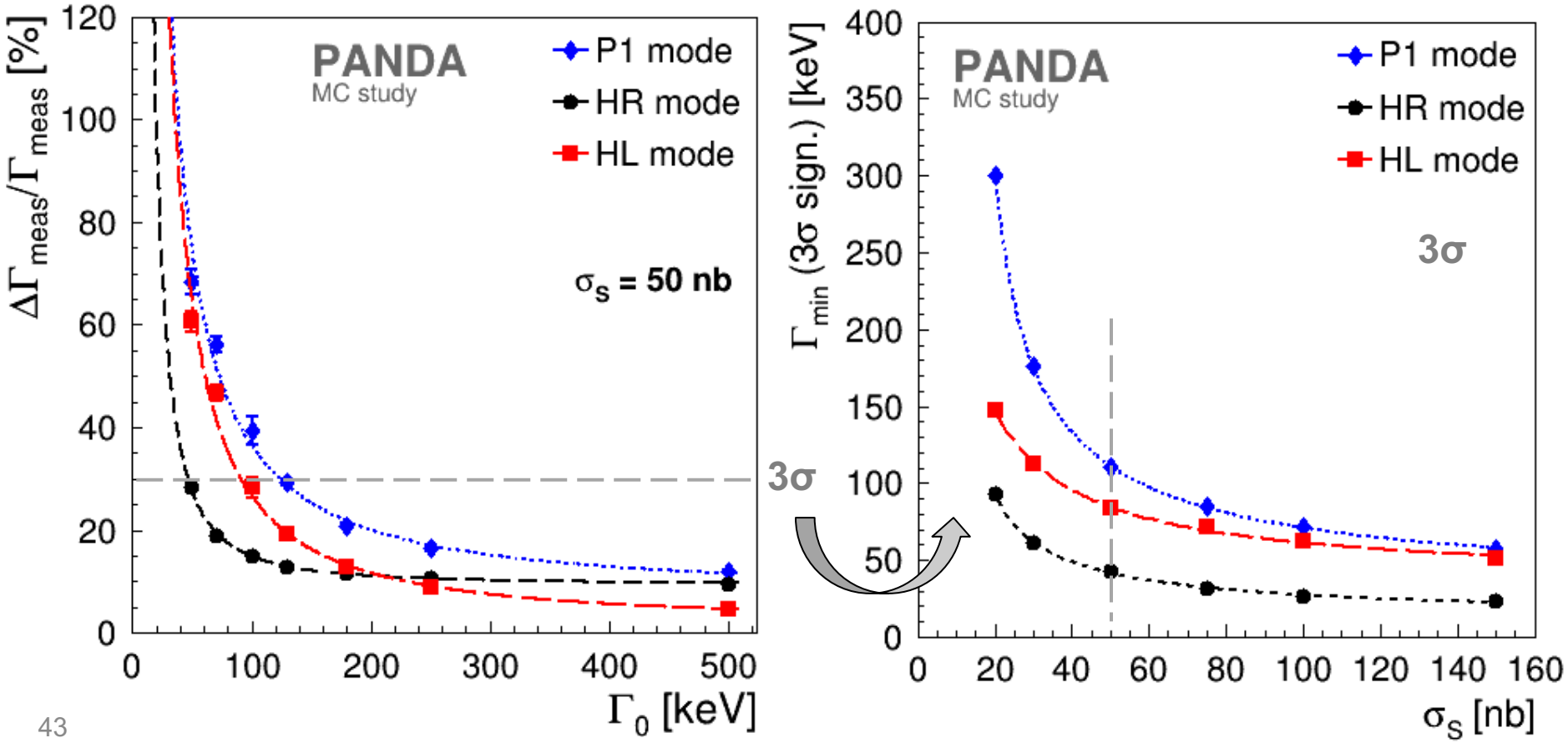
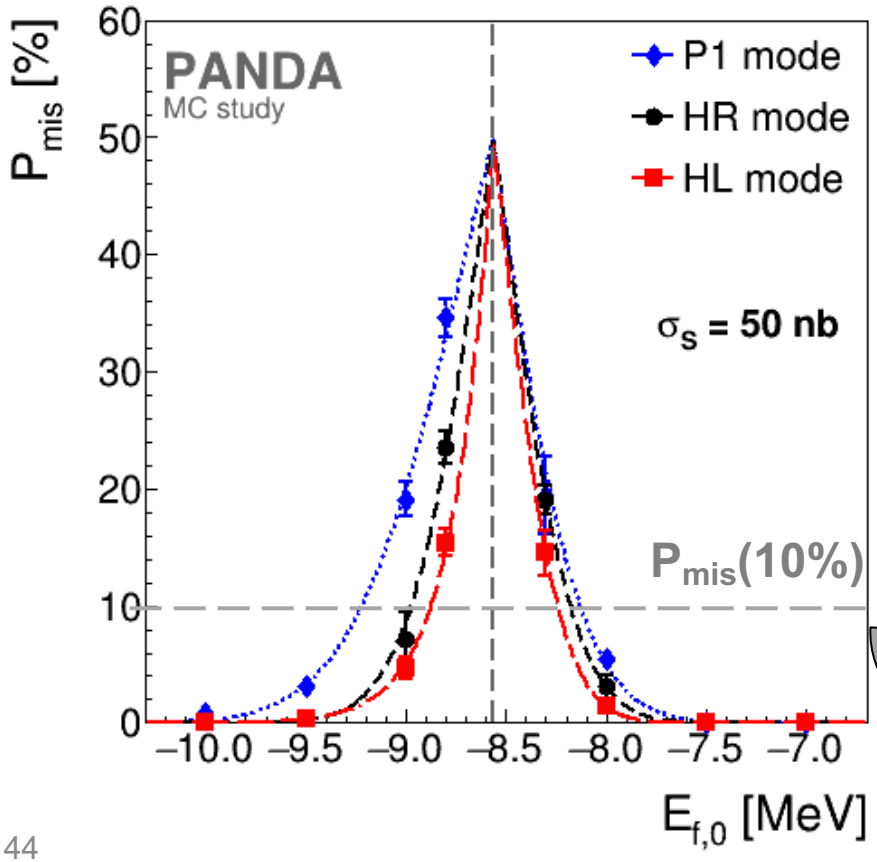


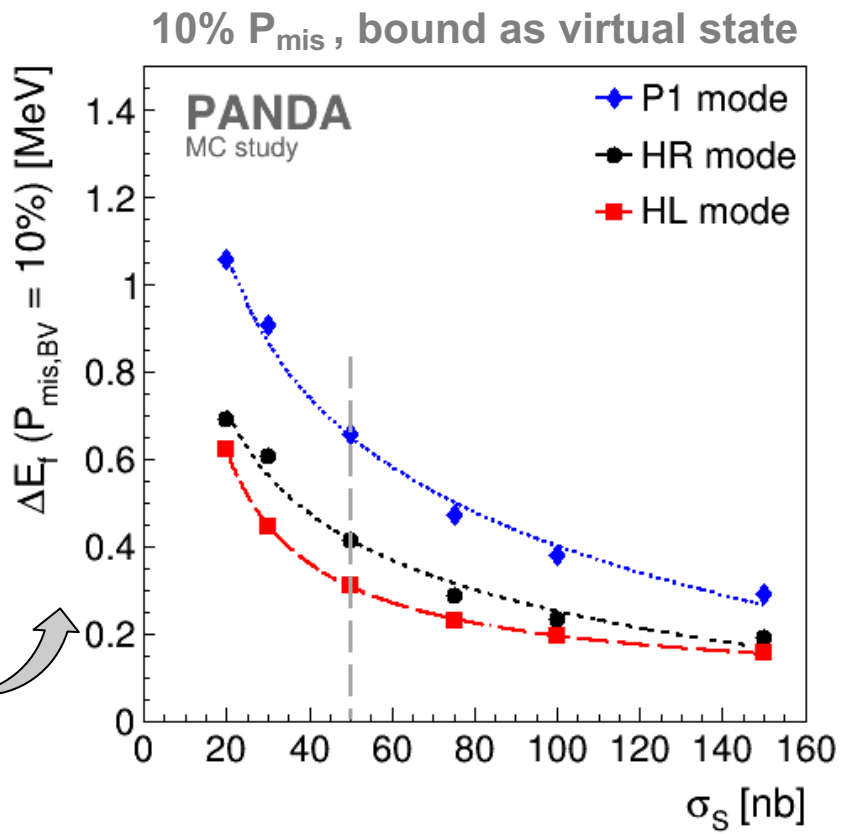
Distinction of Lineshapes (40 x 2d)

- Extract standard deviation from toy MC fits
- How well can virtual vs bound state be distinguished? → *integrate mismatch region:*

Sensitivity

$$P_{\mathrm{mis}} = N_{\mathrm{mis-id}}/N_{\mathrm{MC}} \quad \text{(Molecule case)}$$





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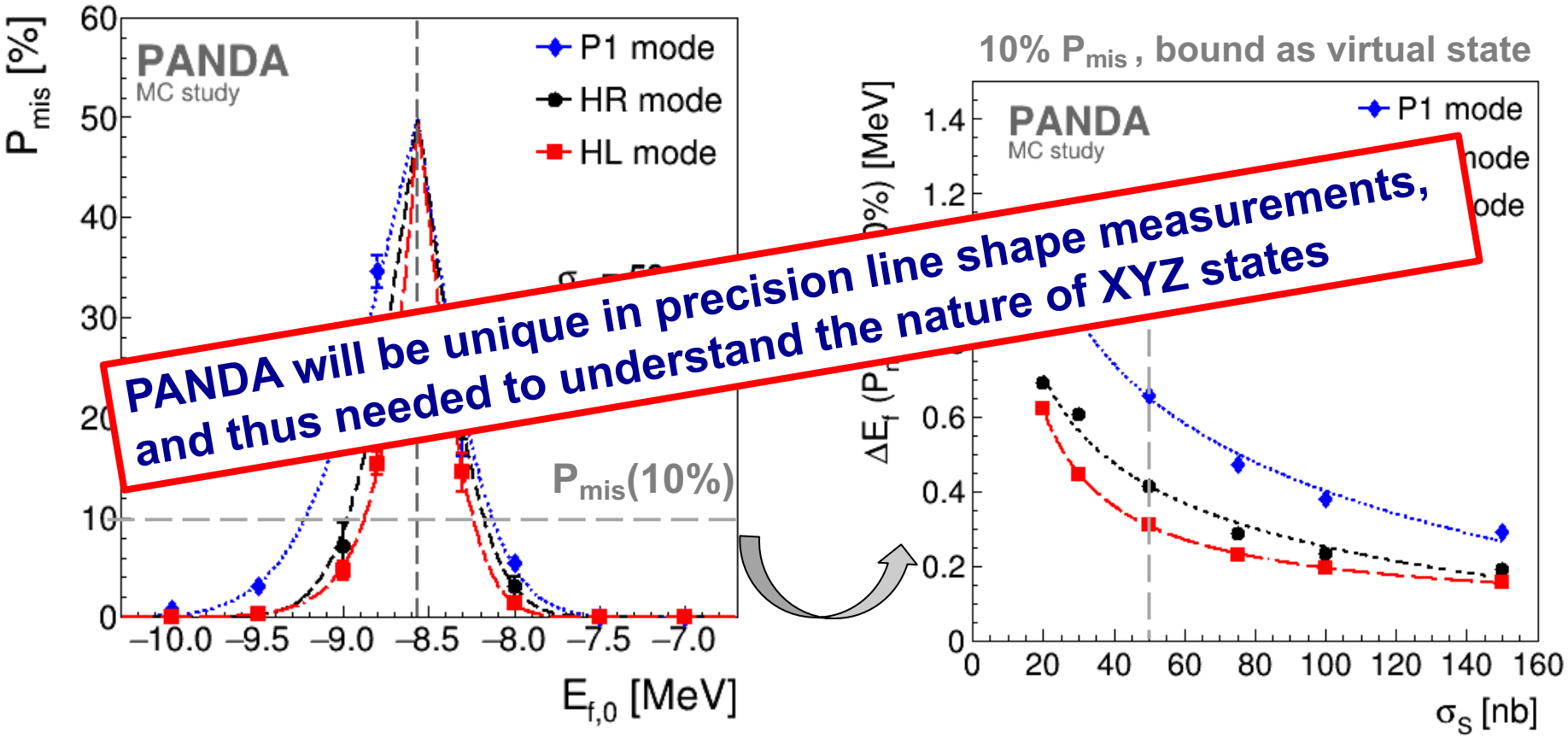
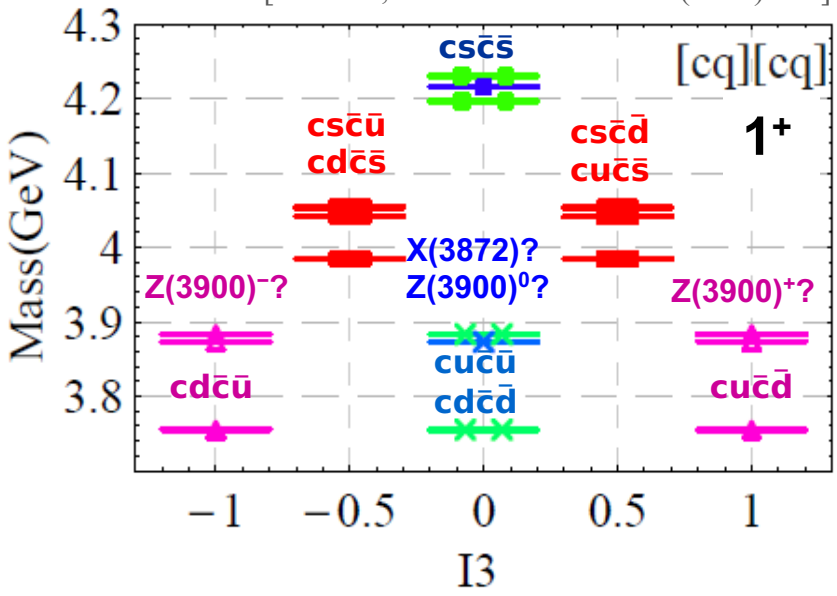


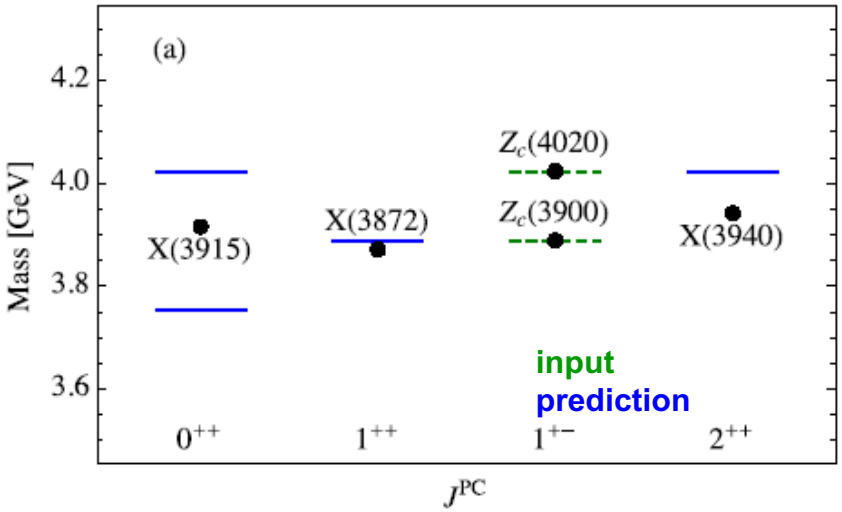
Models and Multiplets for XYZ

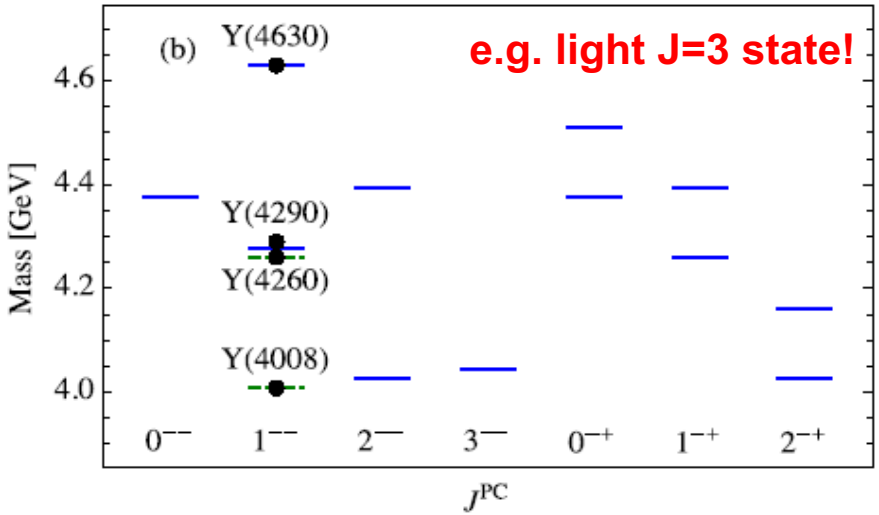
- Need to measure complete multiplets
  → *to really understand XYZ nature*
- e.g. di-quarkonium [cq][c̄q̄] models provide predictions
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

[Drenska, Riv. Nuovo Cim. 033 (2010) 633]



[Cleven et al., arXiv:1505.01771]





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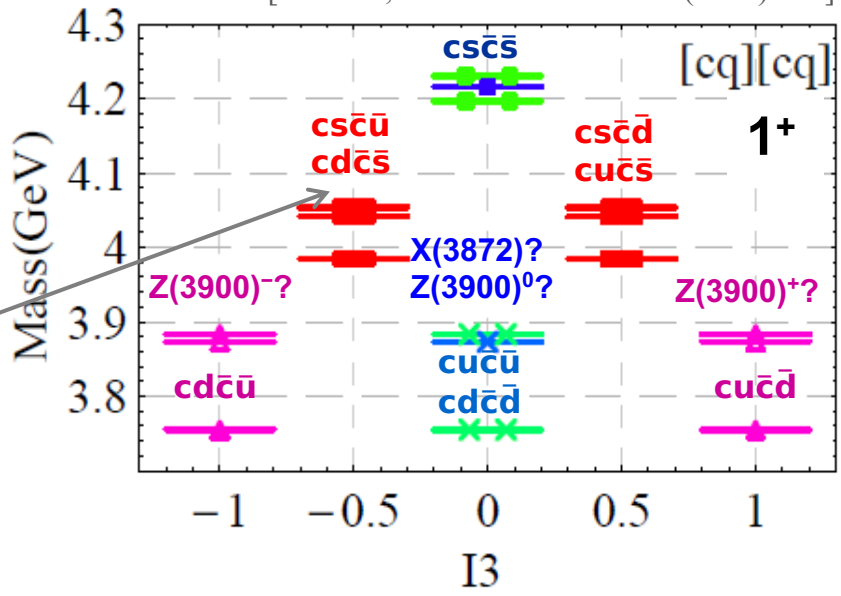

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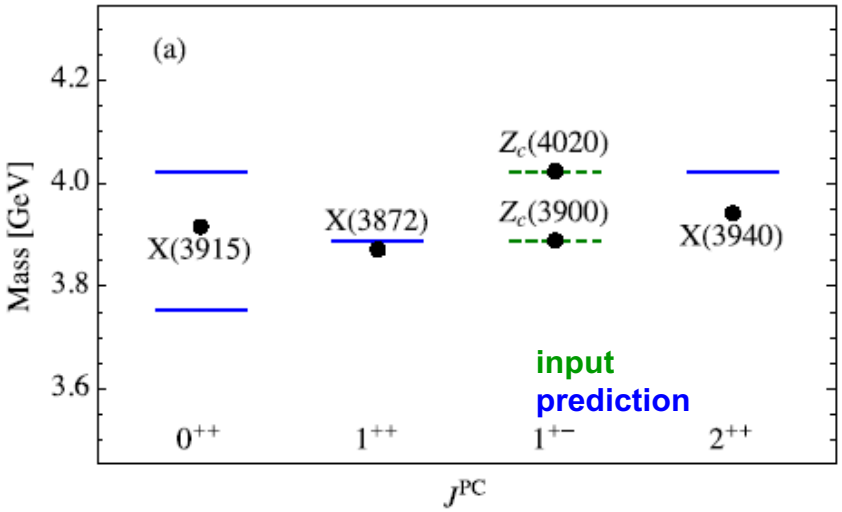

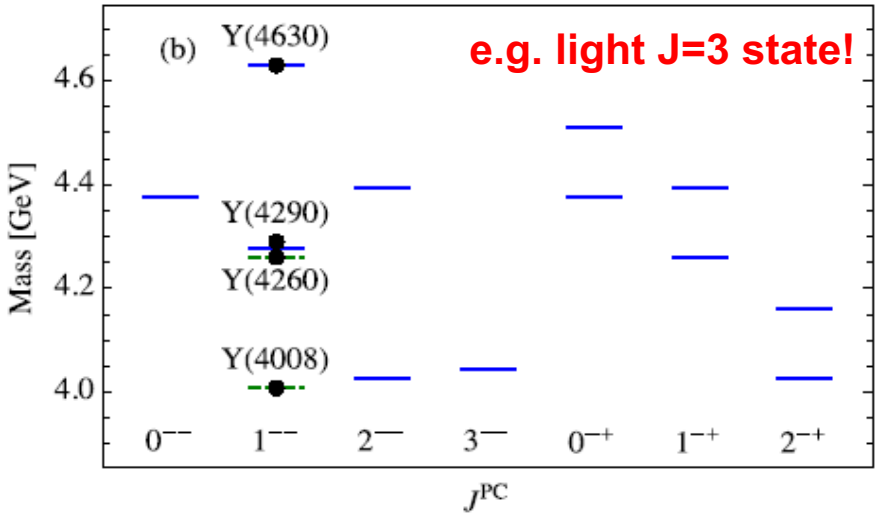

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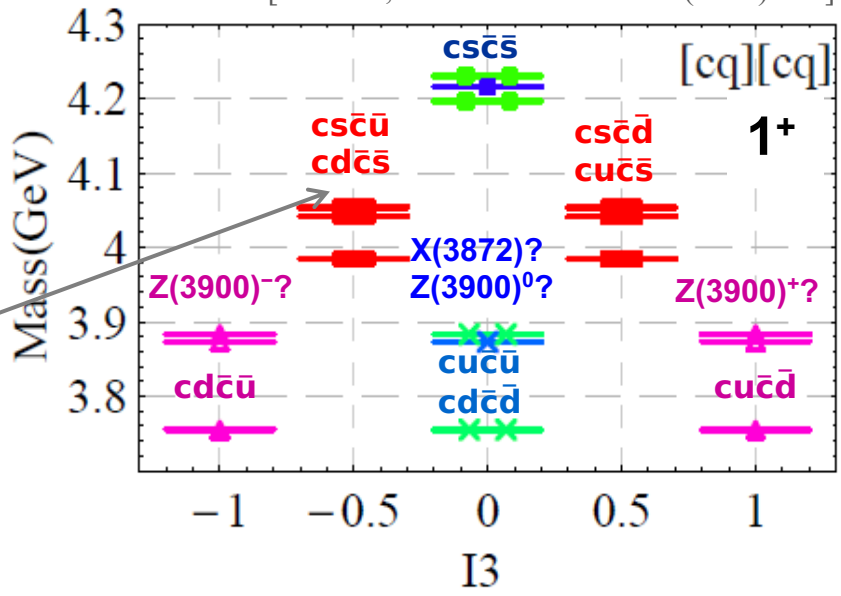

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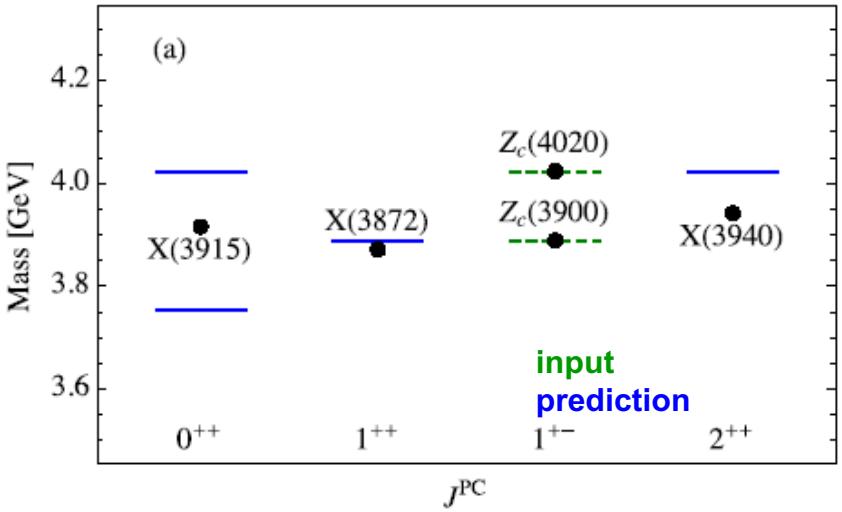

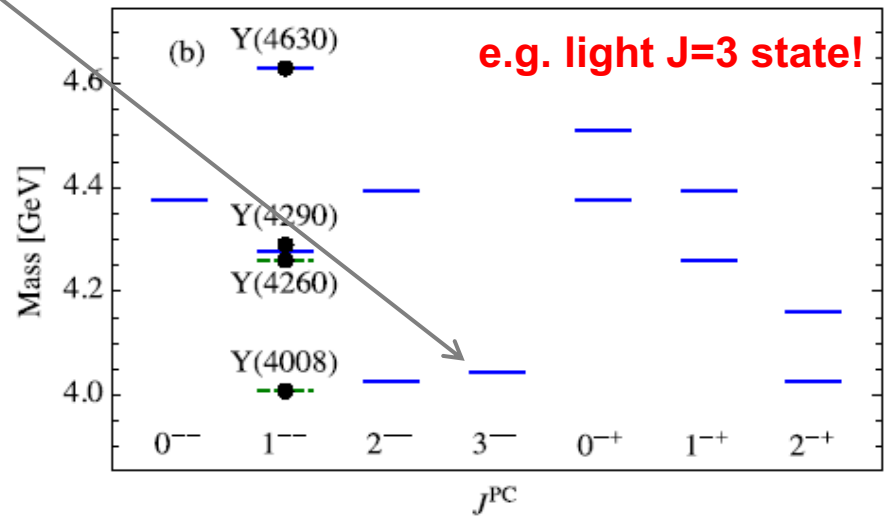

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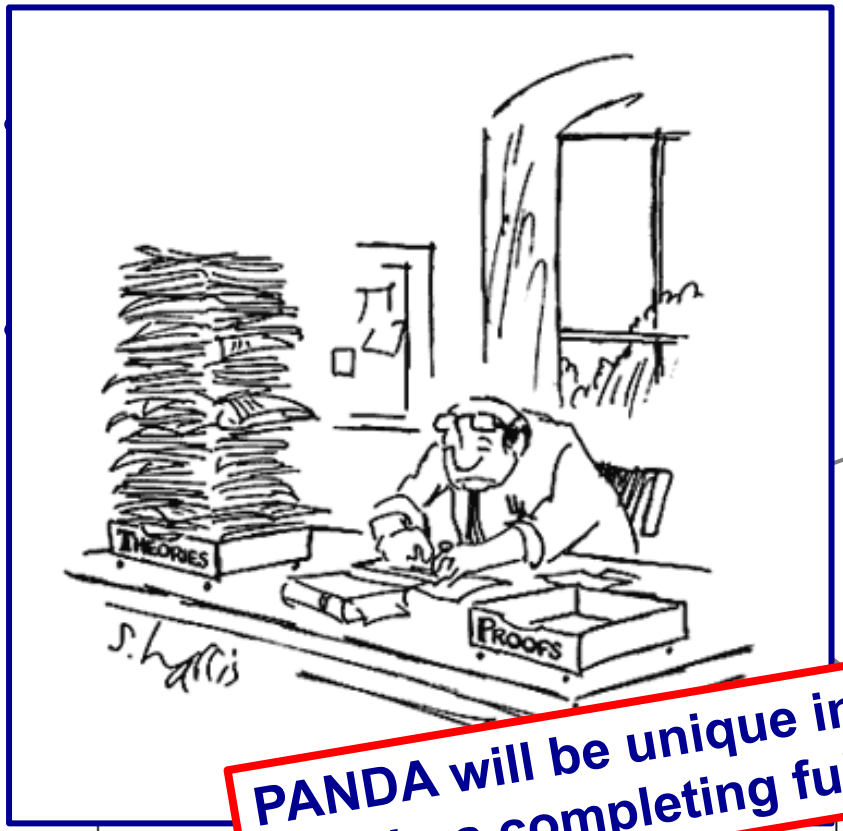

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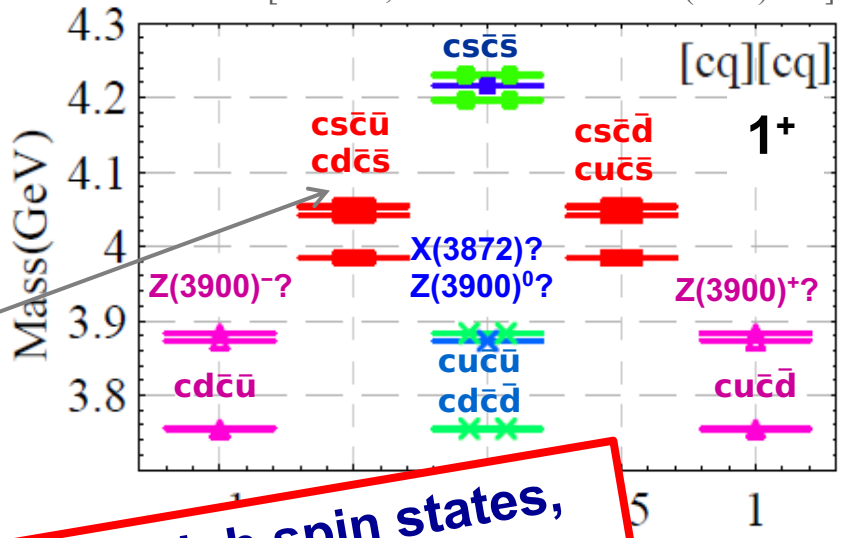
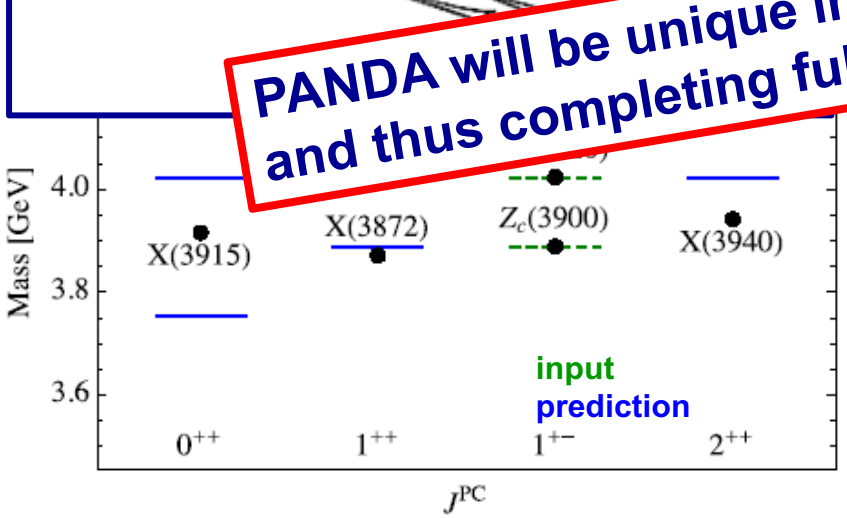
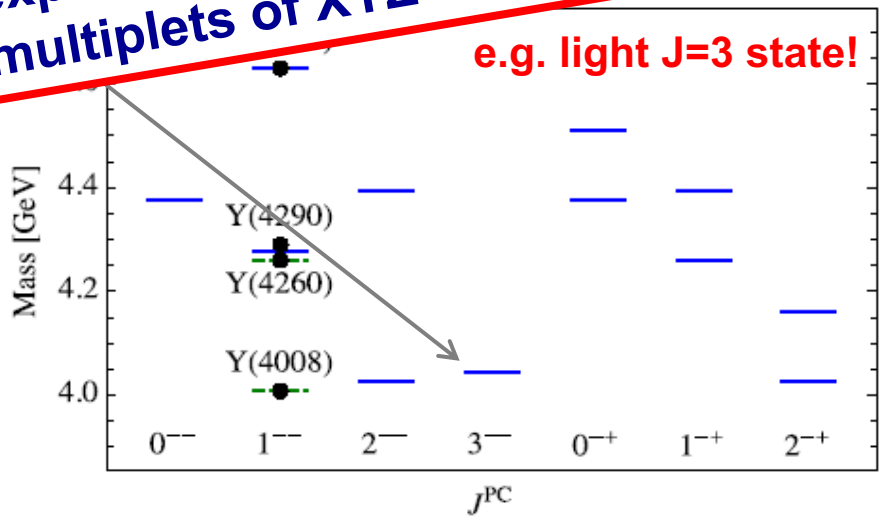


PANDA will be unique in exploring high spin states, and thus completing full multiplets of XYZ states.



e.g. light J=3 state!



Summary and Prospectives

- **BESIII/BEPCII successfully operating since 2008**
  - World largest data sets in tau-charm mass region, unique XYZ data
  - Ideally suited to explore transitions and decays of Y states
    → *Y(4220) & Y(4390) observed in J/ψππ, h_cππ and ψ(2S)ππ*
  - First two isospin triplet states $Z_c(3900)$, $Z_c(4020)$ established
    → *Charged states manifestly exotic matter*

- **Upcoming PANDA experiment at FAIR**
  - Complementary production mechanisms and measurements needed
  - Precise knowledge of decay width and line shape essential
  - Complete the exotic multiplets
    → *Unique: High statistics + precision resonance scans + high spin states*

Outlook

- More XYZ (energy scan) data (4.2-4.3 GeV), extension to > 4.6 GeV
- Further data taking for 10 more years approved for BESIII ...
- PANDA coming soon ...

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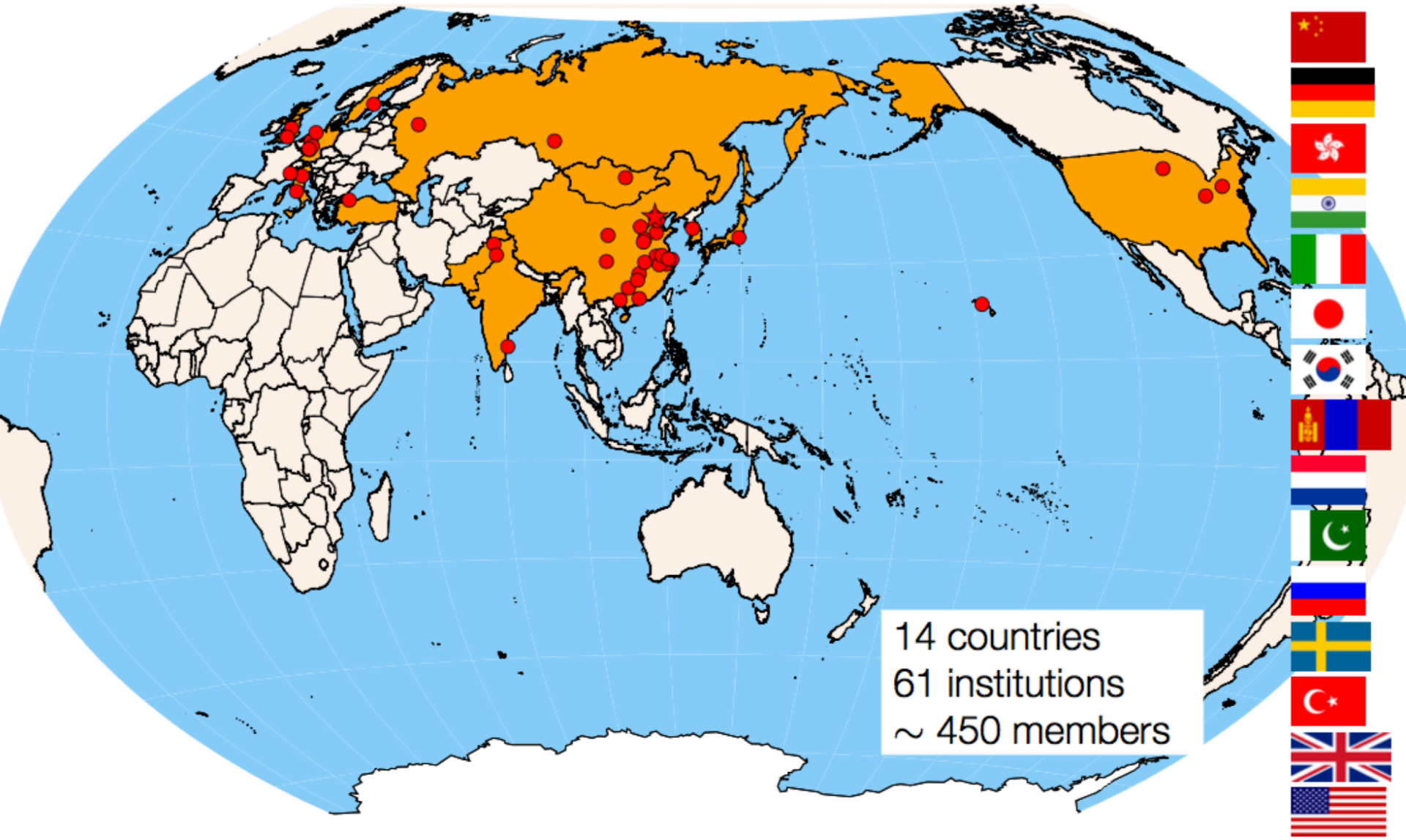
BESIII is and PANDA will be the facility to study QCD – hadron structure & spectroscopy

The BESIII Collaboration



The PANDA Collaboration

UniVPM Anconca
U Basel
IHEP Beijing
U Bochum
U Bonn
U Brescia
IFIN-HH Bucharest
AGH UST Cracow
IFJ PAN Cracow
JU Cracow
U Cracow
FAIR Darmstadt
GSI Darmstadt
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston

U & INFN Ferrara
FIAS Frankfurt
U Frankfurt
LNF-INFN Frascati
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BITS Pilani KKBGC, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
FH Iserlohn
FZ Jülich
IMP Lanzhou
INFN Legnaro
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HI Mainz

U Mainz
INP Minsk
ITEP Moscow
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BARC Mumbai
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BINP Novosibirsk
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18 countries
> 65 institutes
> 420 members