The charm of XYZ -- Hadron spectroscopy and exotica in the charmonium region

Frank Nerling
Frankfurt University & GSI Darmstadt

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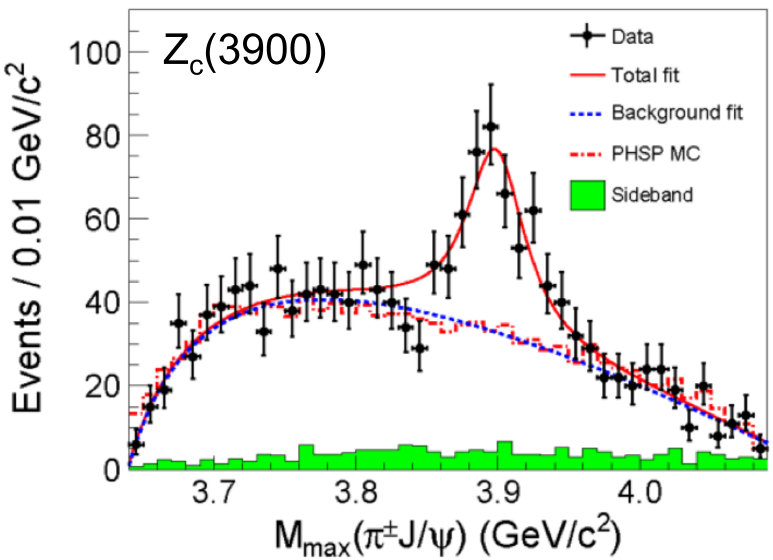
Outline

- **Introduction**
  - Motivation
- **Recent results**
  - Overview dedicated experiments
  - Recent XYZ results at BESIII
  - Prospects for precision spectroscopy at PANDA
- **Summary & outlook**

Hadron Spectroscopy -- Recent Highlights

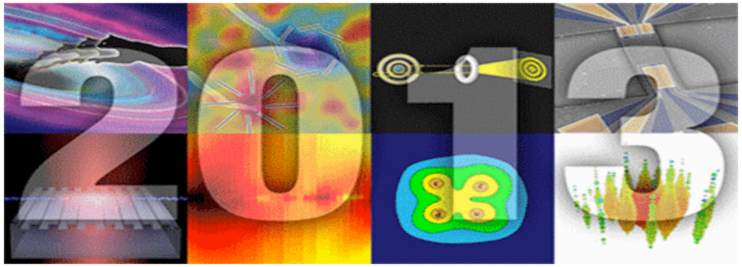
Meson Spectroscopy

BESIII, arXiv:1303.5949

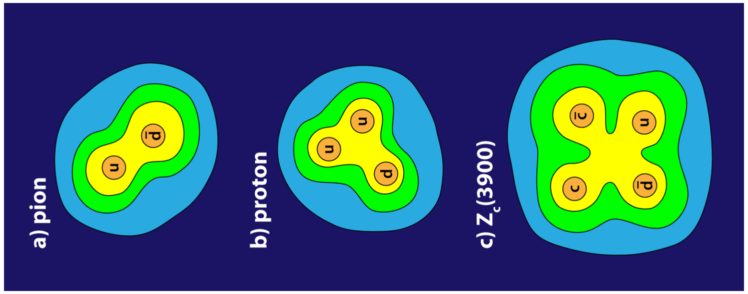


unexpected,
manifestly exotic!

American Physical Society:



pion: proton: $Z_c(3900)$:



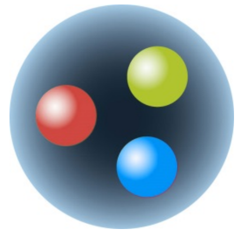
Viewpoint: New Particle Hints at Four-Quark Matter → *Highlight 2013!*

[http://physics.aps.org/articles/v6/139]

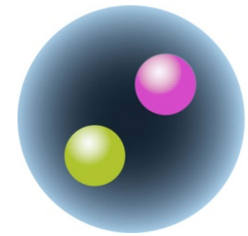
What are Hadrons?

- Hadrons = bound states of strong interaction, QCD (quarks/gluons)
- Well known are

Baryons: qqq
Anti-Baryons: $\bar{q}\bar{q}\bar{q}$



Mesons: $q\bar{q}$



Focus in this talk

- Some examples are:

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ — Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$ — Mesons are bosonic hadrons. These are a few of the many types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

Quarks spin =1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

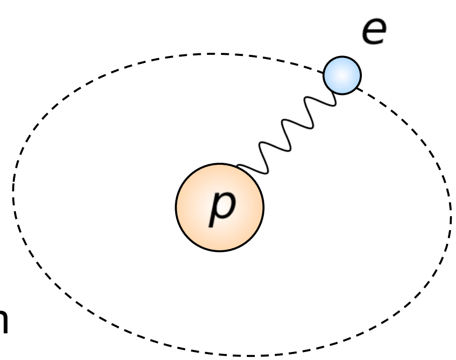
Exotics: And there should be other configurations ...

NB: gluons are (colour) charged

Comparison QED vs QCD

- How do they compare to QED bound states?

QED



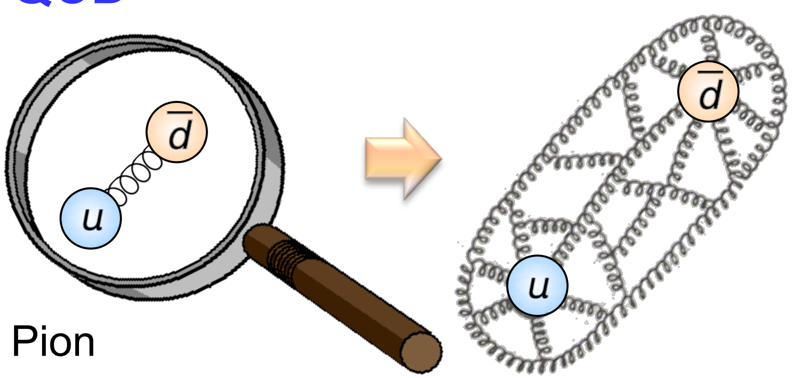
H-Atom

m_e = 0.5 MeV
m_p = 938 MeV
m_H = 938.5 MeV
E_B = -13 eV

Field bosons basically do not influence the mass

$m_H < m_e + m_p$

QCD



Pion

m_u = 2 MeV
m_d = 5 MeV
m_π = 139 MeV
E_B = +132 MeV

Field bosons ‚are' the mass!

$m_\pi >> m_u + m_d$

Non-relativistic Potential

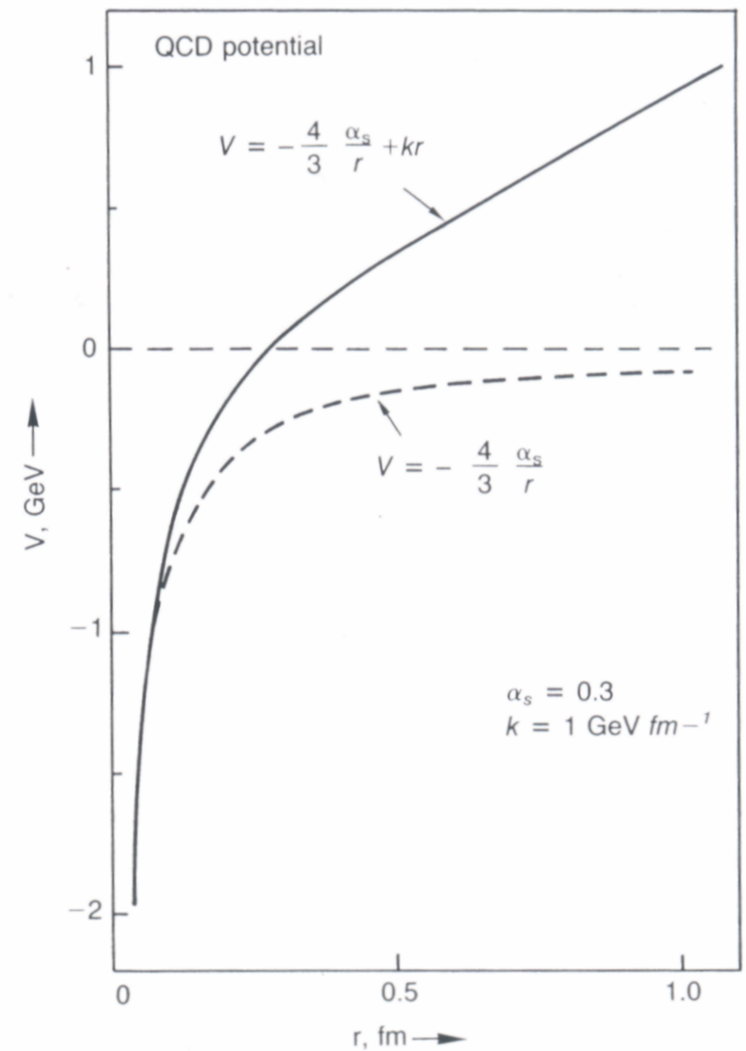
- Reproduce the asymptotic behaviour of strong interaction

- Coulomb like at small distances
  ➥ Asymptotic freedom

$$V(r) \xrightarrow{r \to 0} -\frac{4}{3}\frac{\alpha_S(r)}{r}$$

- Linear at large distances
  ➥ Confinement

$$V(r) \xrightarrow{r \to \infty} k \cdot r$$



[Godfrey & Isgur, PRD 32 (1985) 189]

Charmonium spectrum ($c\bar{c}$)

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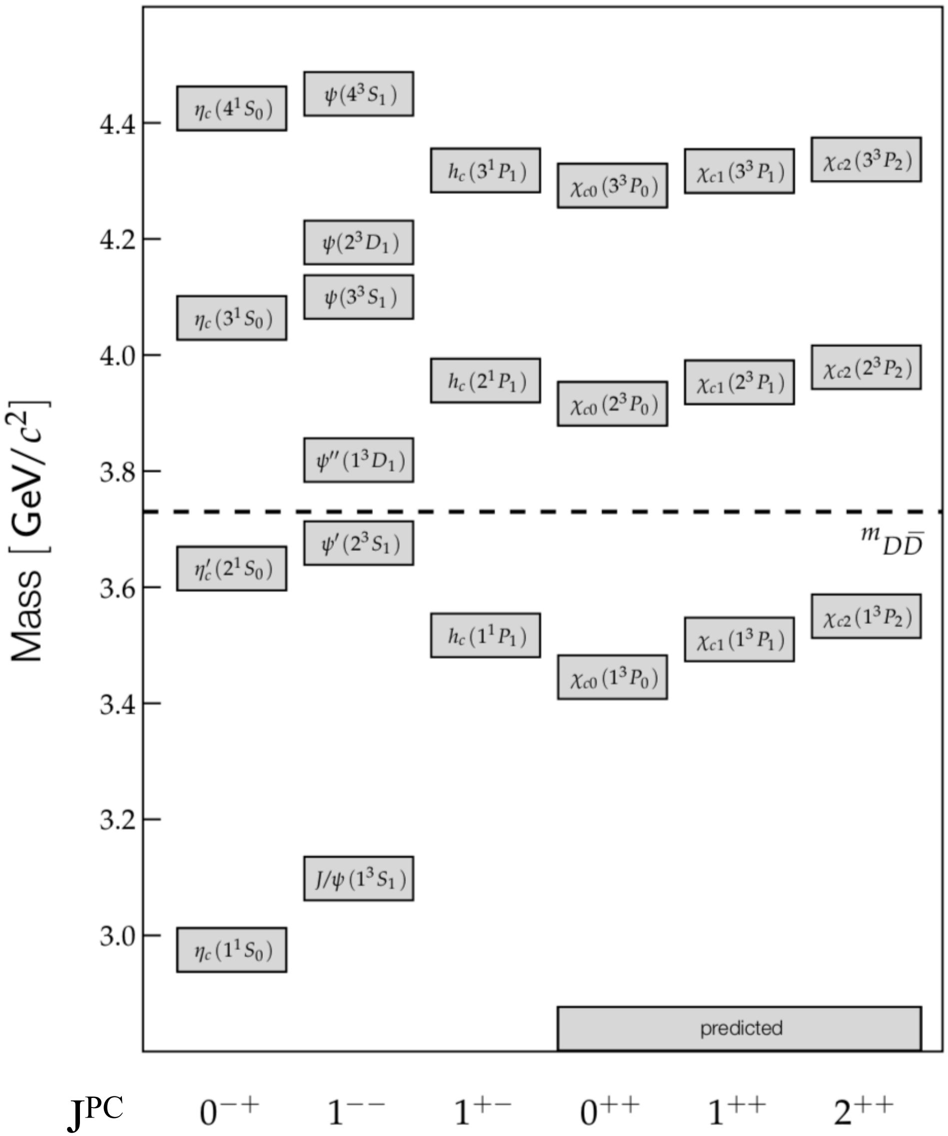
[PRD 72 (2005) 054026] & [PDG]



- Below open charm threshold:
  - Good agreement theory vs. experiment

$$V_0^{c\bar{c}} = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\delta(r)\vec{S}_c\vec{S}_{\bar{c}}$$

$$V_{\text{spin-dep.}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

+ relativistic corrections!

[Godfrey & Isgur, PRD 32 (1985) 189]
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

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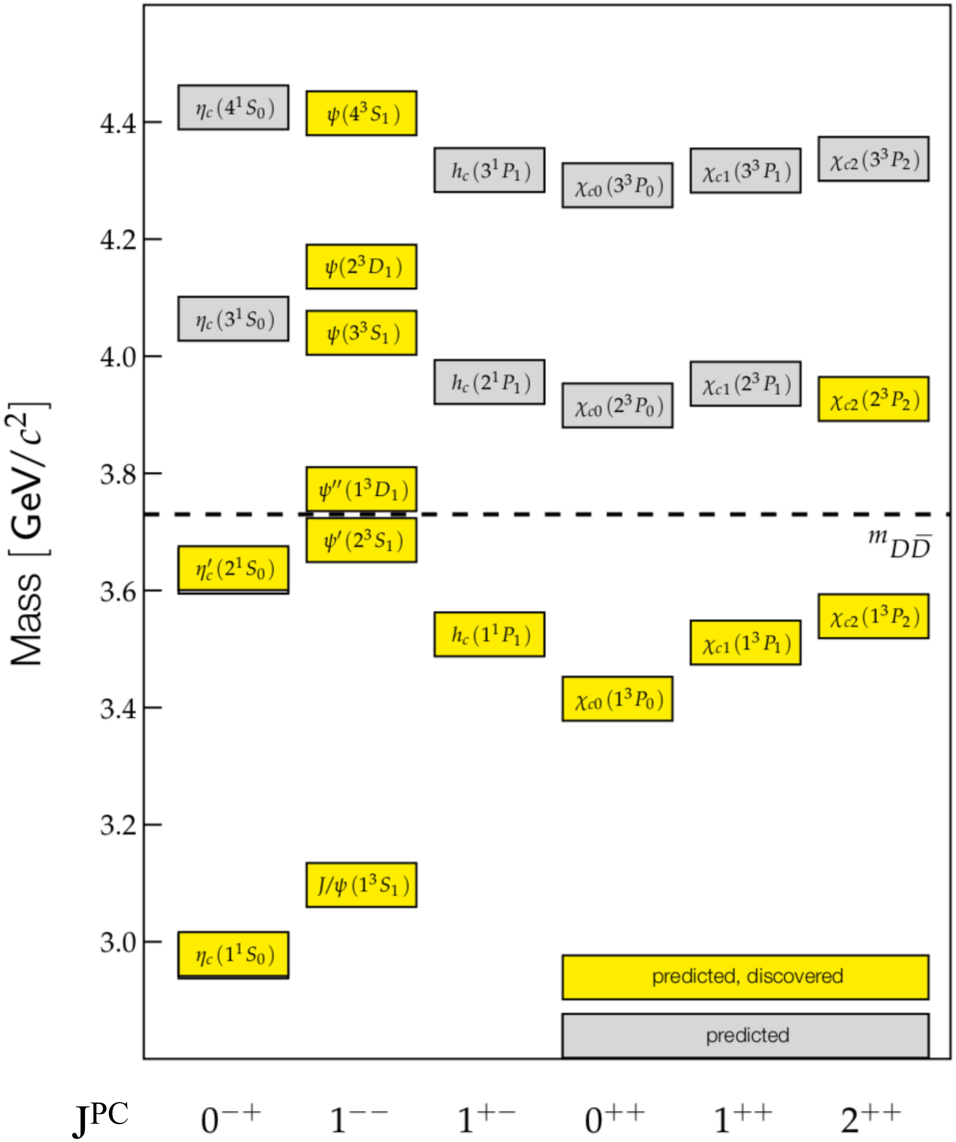

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The puzzle of XYZ states

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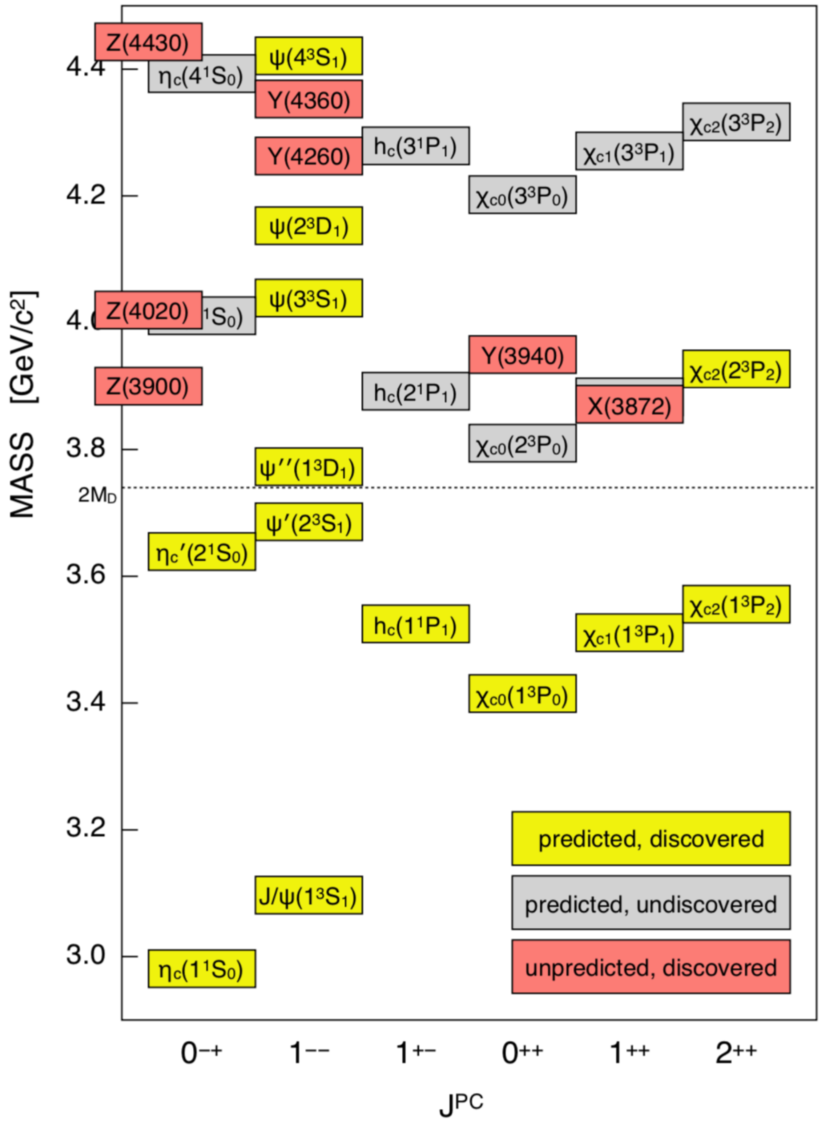

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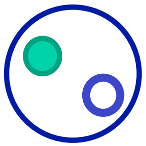
[Barnes, Godfrey & Swanson, PRD 72 (2005) 054026]

Mesons and (spin) exotic states

Quark model

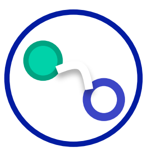
- Mesons: Color neutral $q\bar{q}$ systems



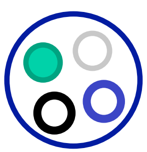
Conventional $(q\bar{q})_1$

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

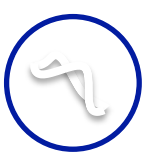
- Nowadays definition: Meson = Hadron with B = 0
- In contrast to simple $q\bar{q}$ allows for **=> huge variety of states:**



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

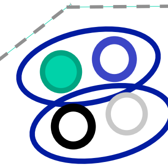


Tetraquark $(q\bar{q}q\bar{q})_1$

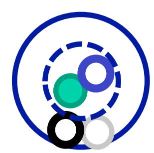


Glue-ball $(gg)_1$ or $(ggg)_1$

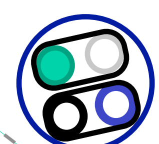
Further 4-quark-configurations:



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



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

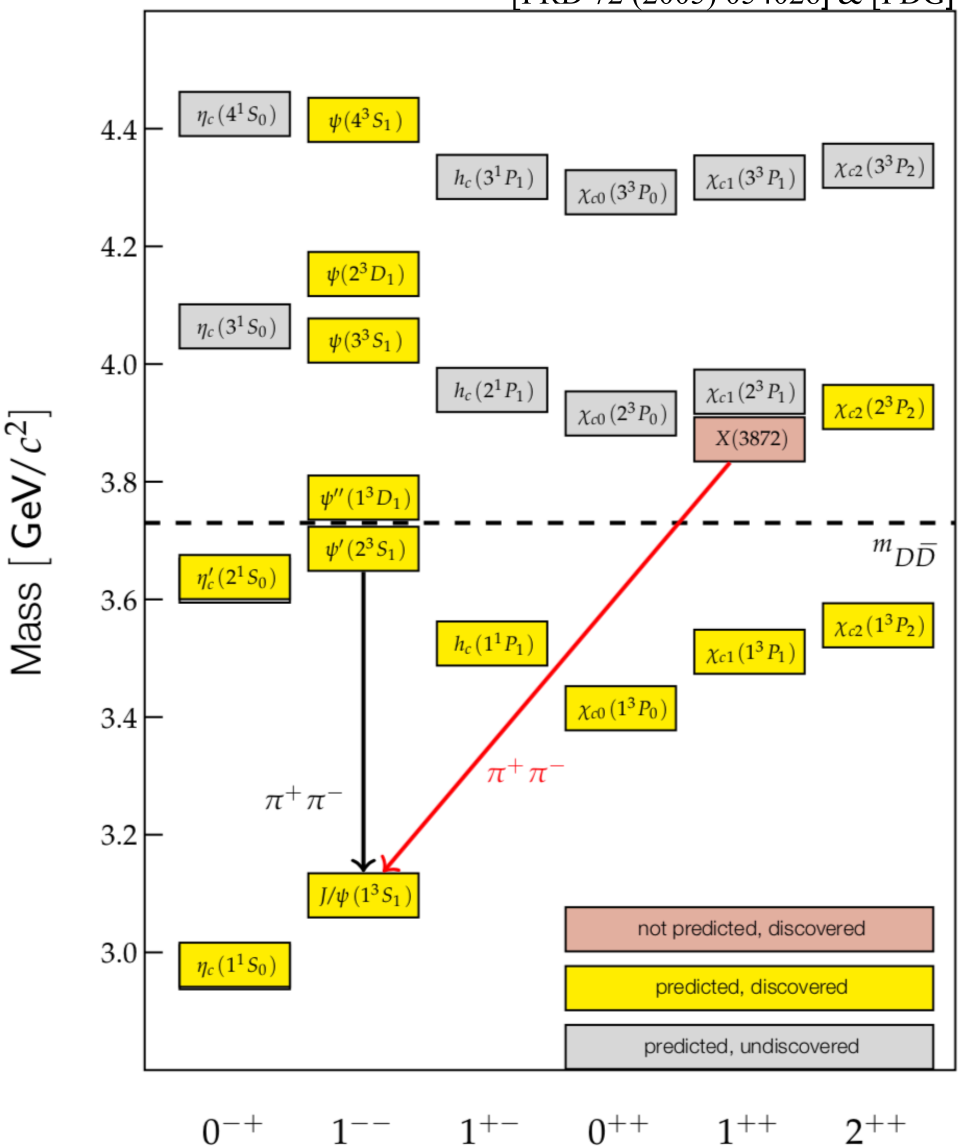


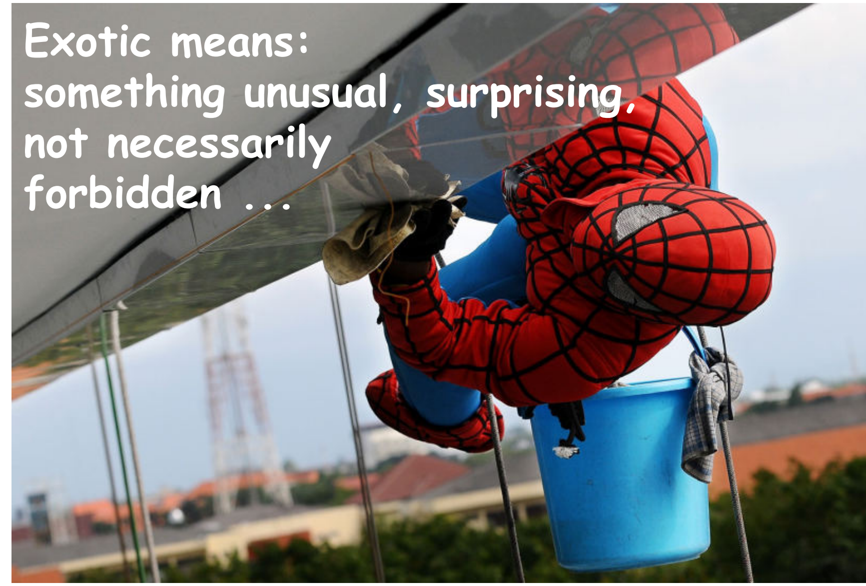
Di-quarkonium $(qq)_{\bar{3}}(\bar{q}\bar{q})_3$

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

The puzzle of XYZ states

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



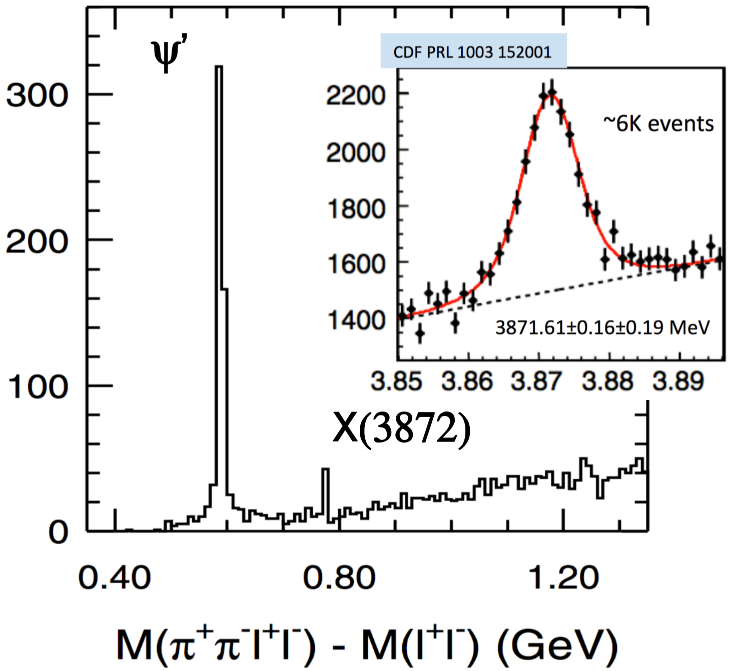


„Bilder des Tages“, [stern.de]

The X(3872) is one of the first unexpected and most prominent examples, observed already in 2003 !

Experimental Review of the X(3872)

[Belle, PhysRevLett.91 (2003) 262001]



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

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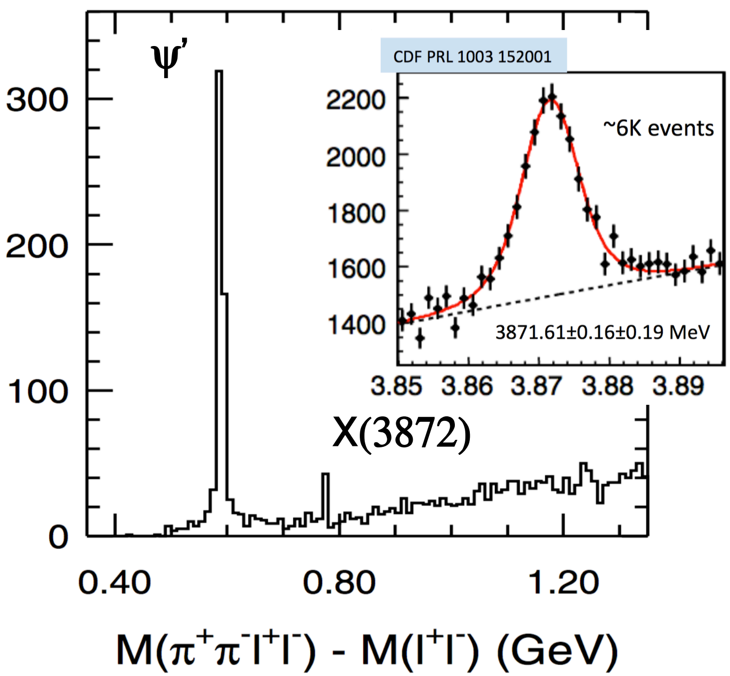

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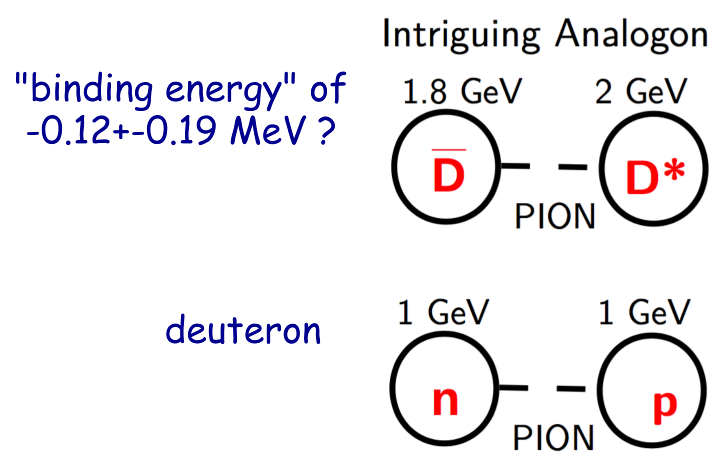
- Mass: $m(X) - m(\bar{D}^{*0}) - m(D^0) =$
  $= -0.12 \pm 0.19$ MeV/c^2
- Width: Upper limit by Belle
  - $\Gamma_{X(3872)} < 1.2\,\text{MeV}$ (90% c.l., 2011)



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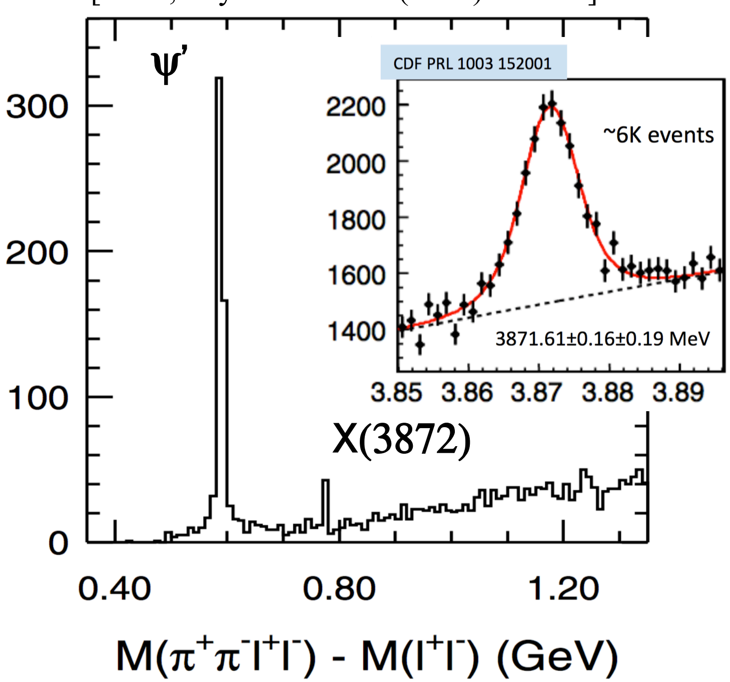

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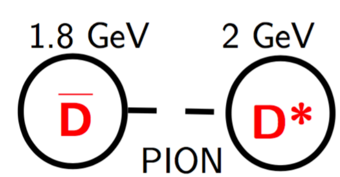
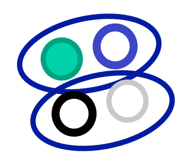
"binding energy" of -0.12+-0.19 MeV ?

Intriguing Analogon





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

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

Hadron Physics – Major labs & experiments

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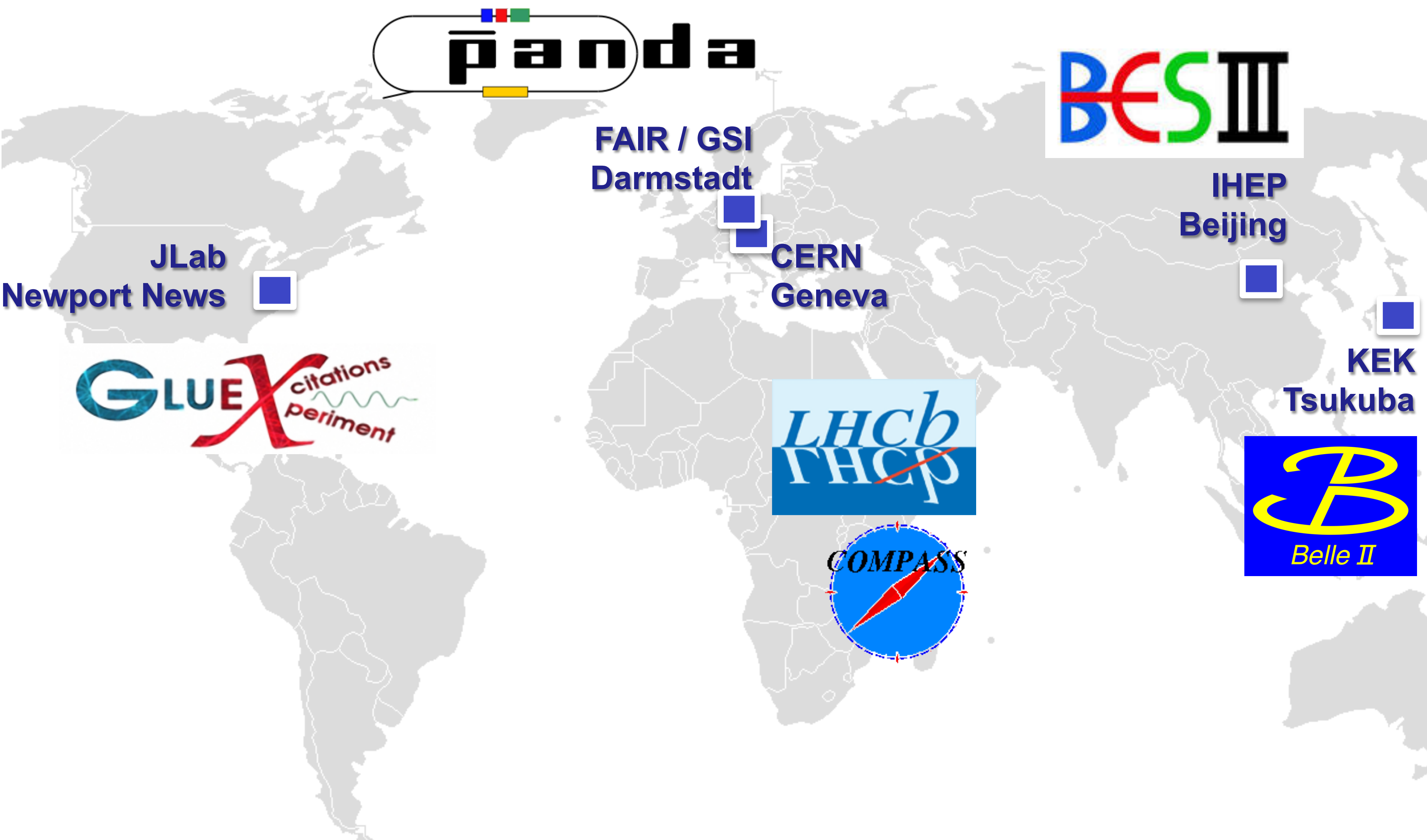

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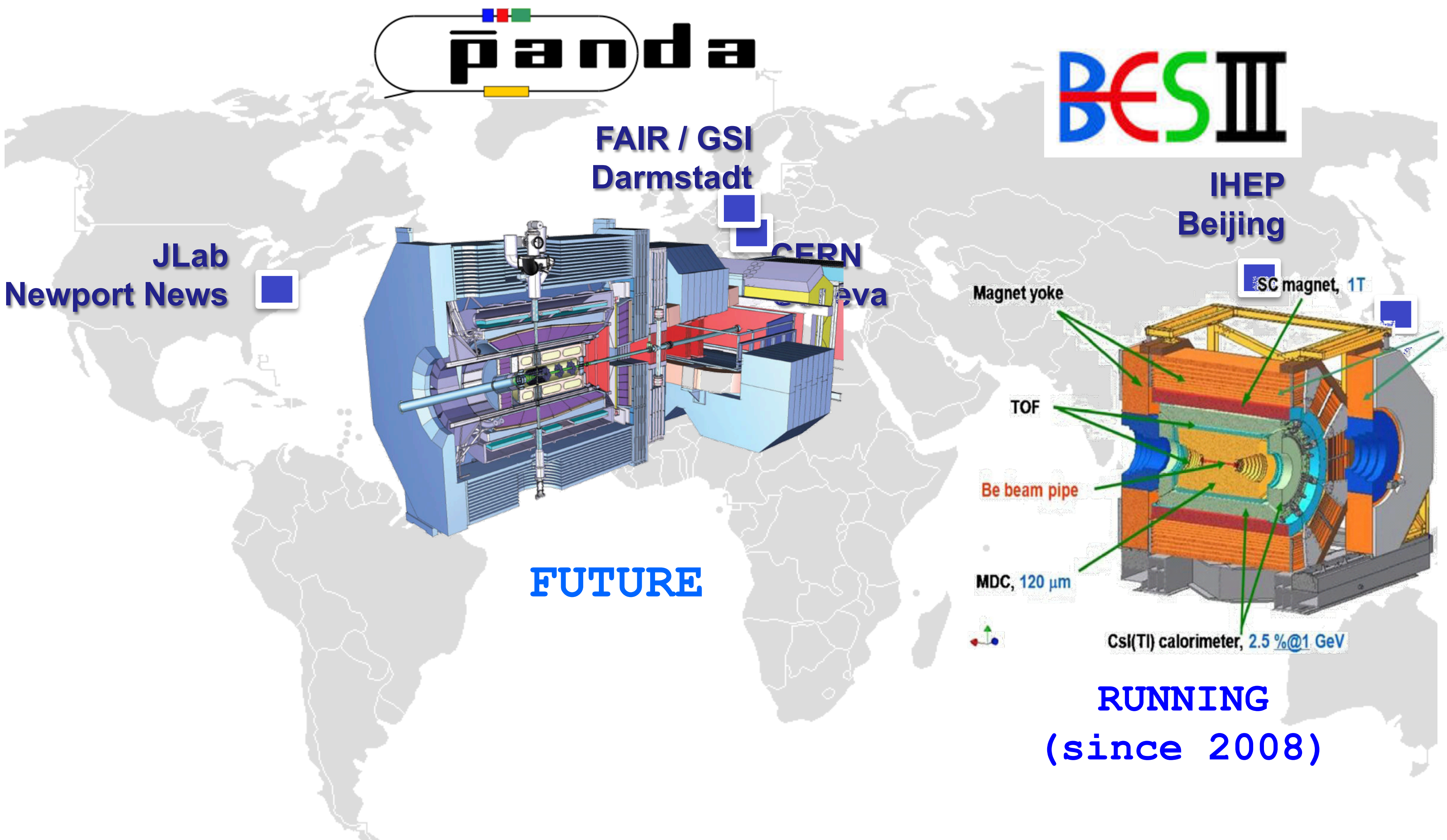


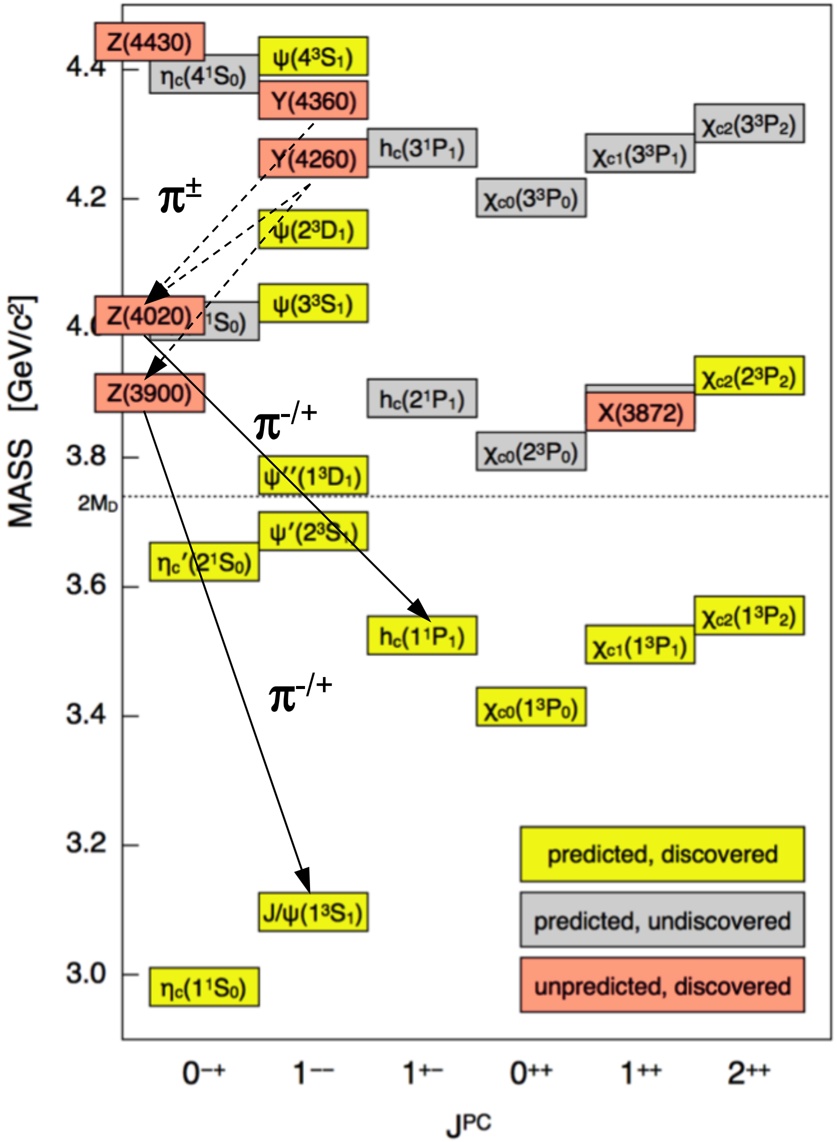
BESIII at BEPCII

- 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

The puzzle of XYZ states

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



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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

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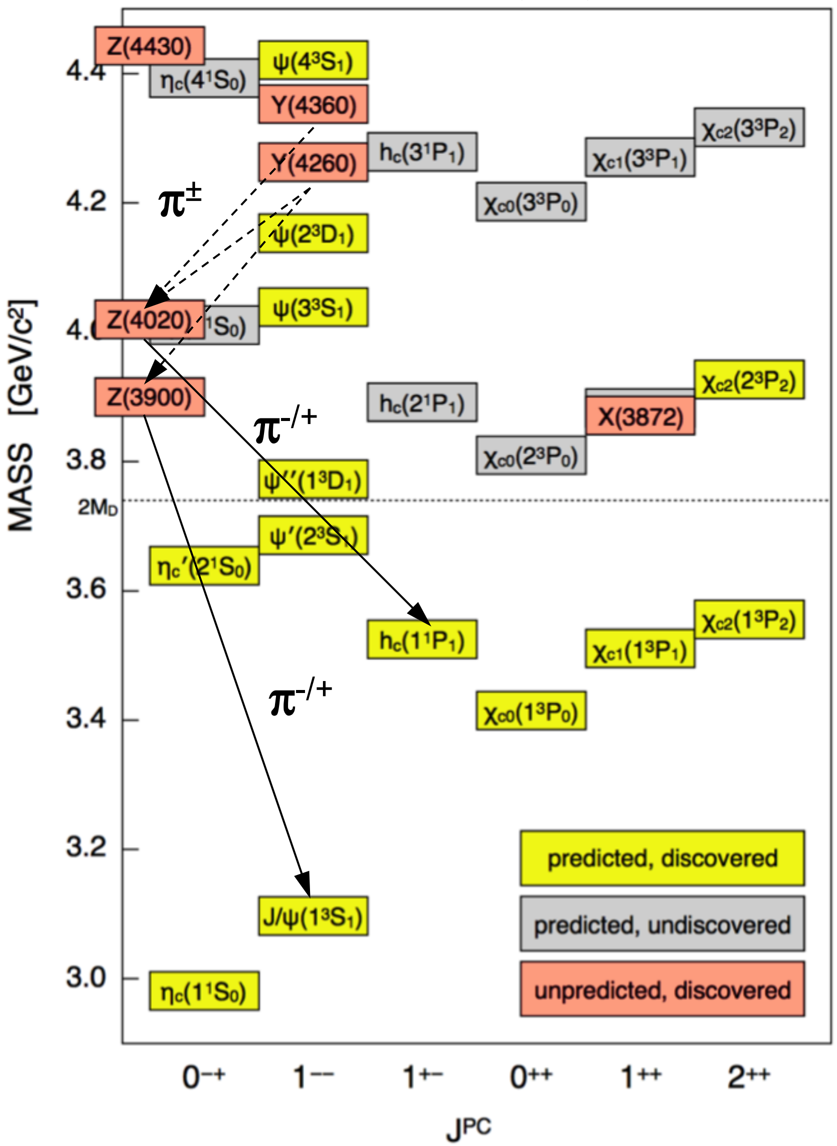

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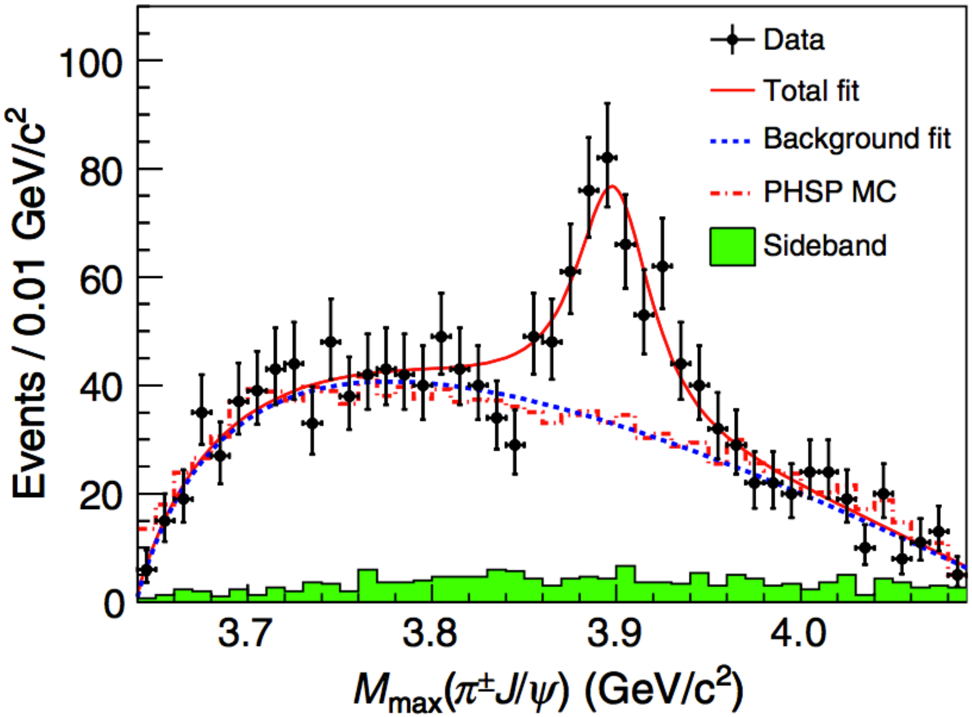
The charged $Z_c(3900)$

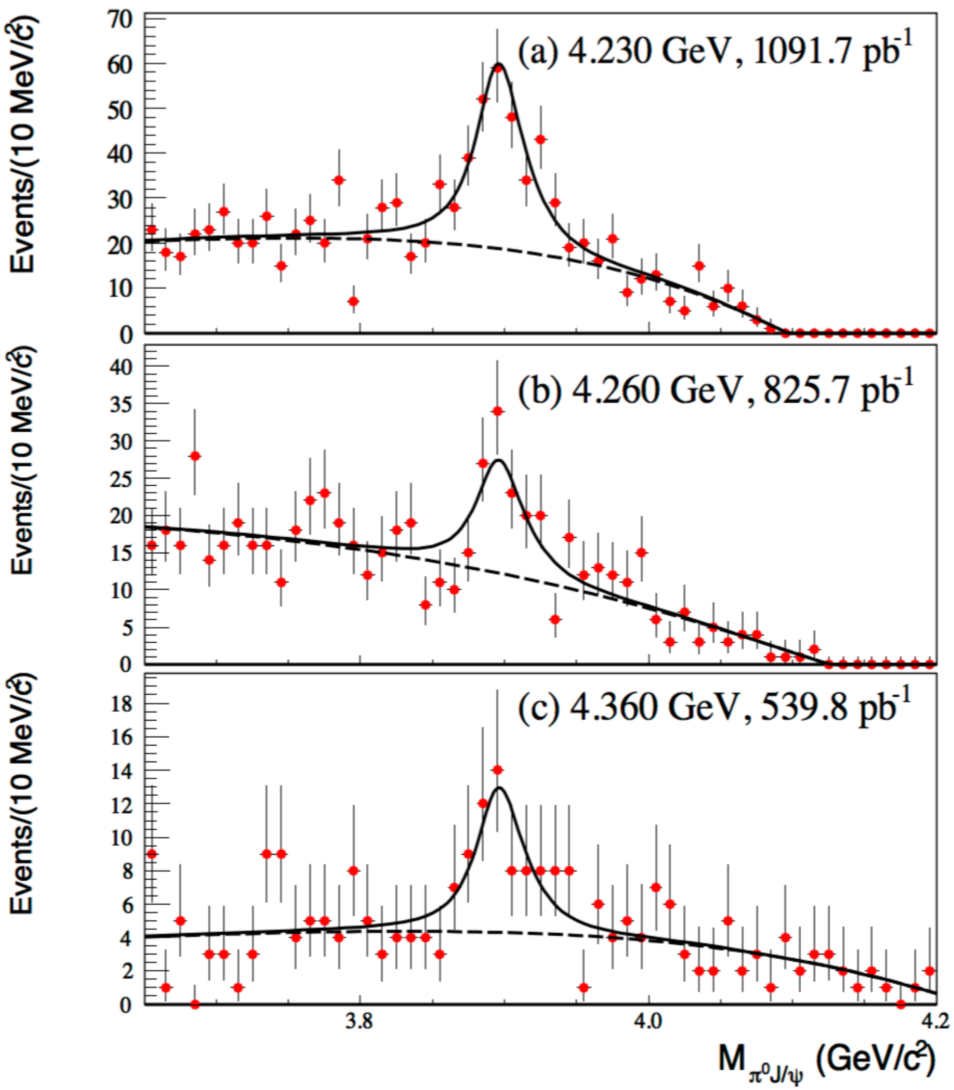


- Discovery of $Z_c(3900)^{\pm} \rightarrow J/\psi\pi^{\pm}$
  - $e^+e^- \rightarrow J/\psi\pi^+\pi^-$
  - at $\sqrt{s}$ = 4.26 GeV (525 pb^{-1}, >8σ)
- Mass close to $D\bar{D}^*$ threshold
- $m = (3899.0 \pm 3.6 \pm 4.9)\ \mathrm{MeV}/c^2$
  $\Gamma = (46 \pm 10 \pm 20)\ \mathrm{MeV}$
- Manifestly exotic:
  - 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 $Z_c(3900)^0 \rightarrow J/\psi\pi^0$
  - in $e^+e^- \rightarrow J/\psi\pi^0\pi^0$ GeV (2.8 fb^{-1}, 10.4σ)
  - confirms earlier evidence in CLEO-c data

- Parameters consistent with those of $Z_c(3900)^{\pm}$

- $m = 3894.8 \pm 2.3 \pm 2.7\,\mathrm{MeV}/c^2$

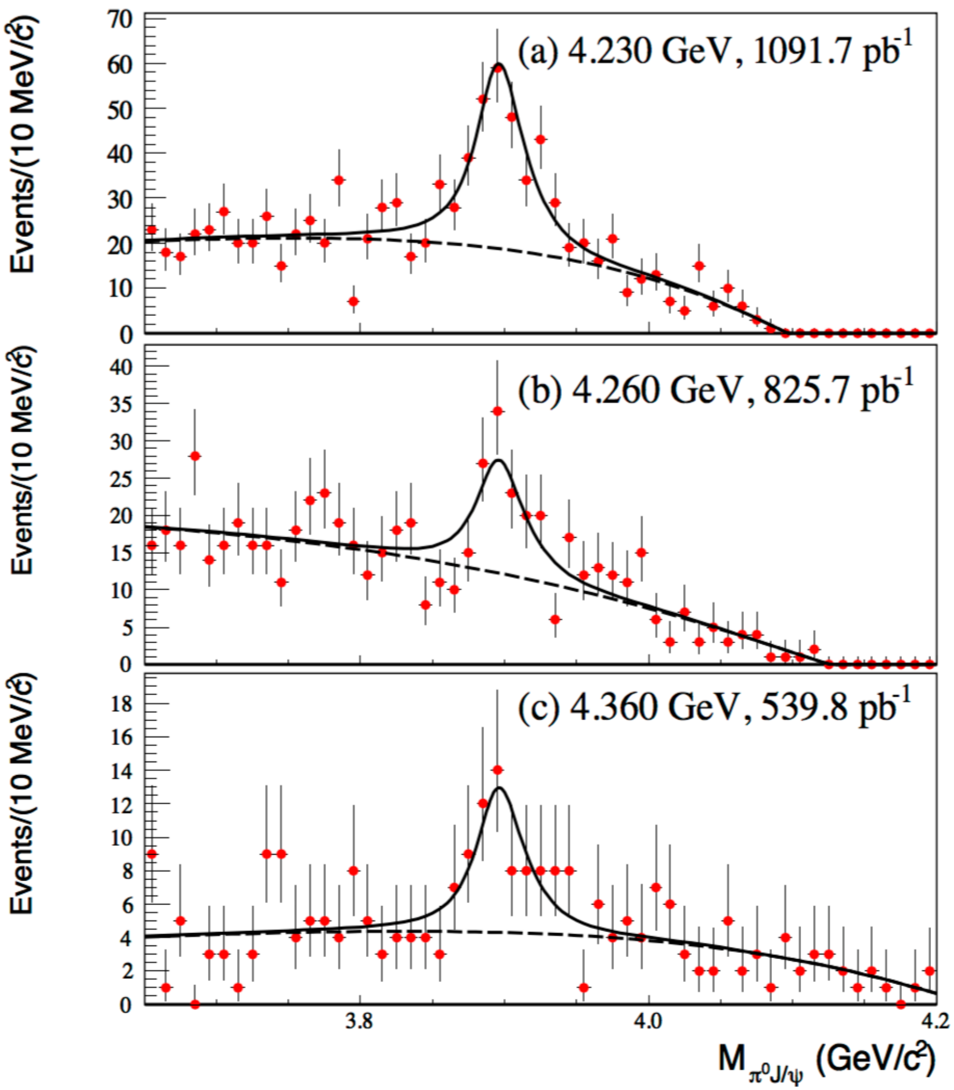
  $\Gamma = 29.6 \pm 8.2 \pm 8.2\,\mathrm{MeV}$

=> 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 $Z_c(3900)$



[PRL 115 (2015) 112003]

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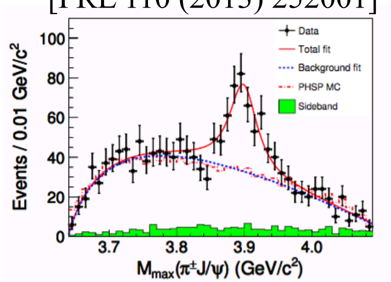
> *"When I see a bird that walks like a duck and swims like a duck and quacks like a duck, I call that bird a duck."*
>
> — James Whitcomb Riley
> Indiana Poet

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

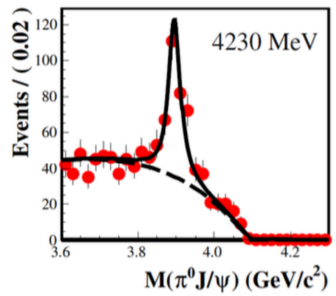
Two Z_c triplets established

[PRL 110 (2013) 252001]



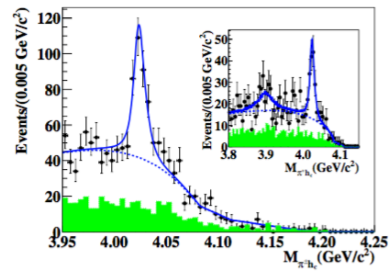
$e^+e^- \to \pi^-\pi^+J/\psi$

[PRL 115 (2015) 112003]



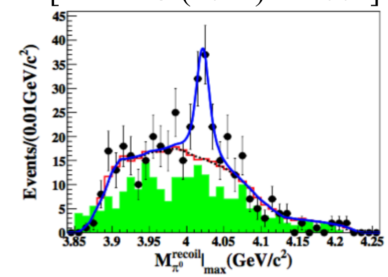
$e^+e^- \to \pi^0\pi^0J/\psi$

[PRL 111 (2013) 242002]



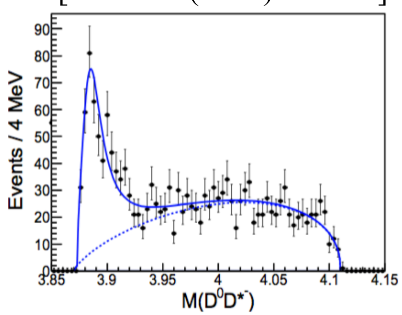
$e^+e^- \to \pi^-\pi^+h_c$

[PRL 113 (2014) 212002]

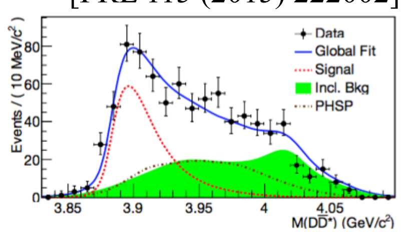


$e^+e^- \to \pi^0\pi^0h_c$

[PRL 112 (2014) 022001]

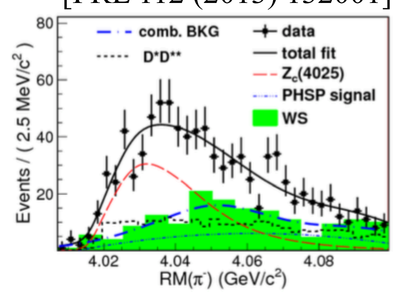


[PRL 115 (2015) 222002]

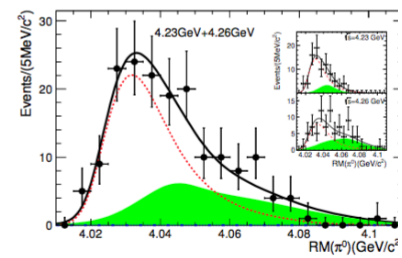


$e^+e^- \to \pi^-(D\bar{D}^*)^+$

[PRL 112 (2013) 132001]



[PRL 115 (2015) 182002]



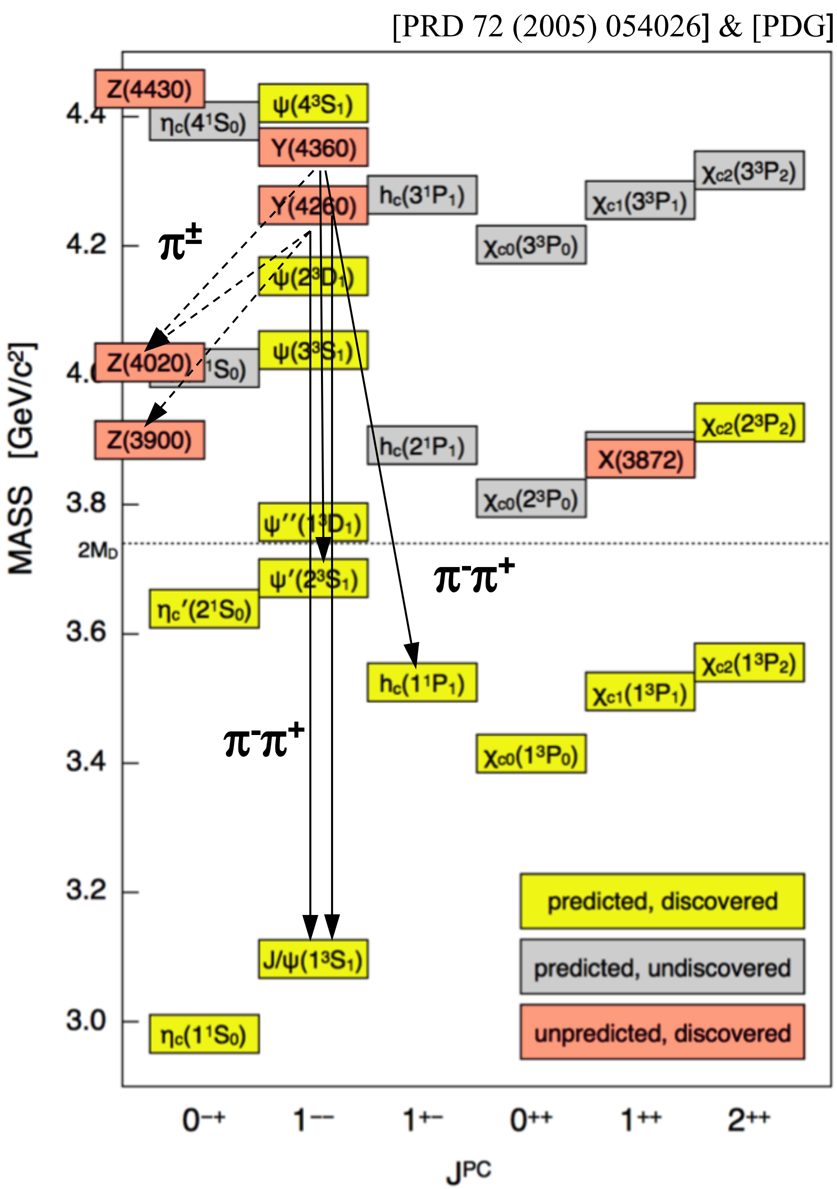
$e^+e^- \to \pi^-(D^*\bar{D}^*)^+$

$Z_c(3900)^{\pm,0}$ → $J^P = 1^+$

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

- 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?

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)

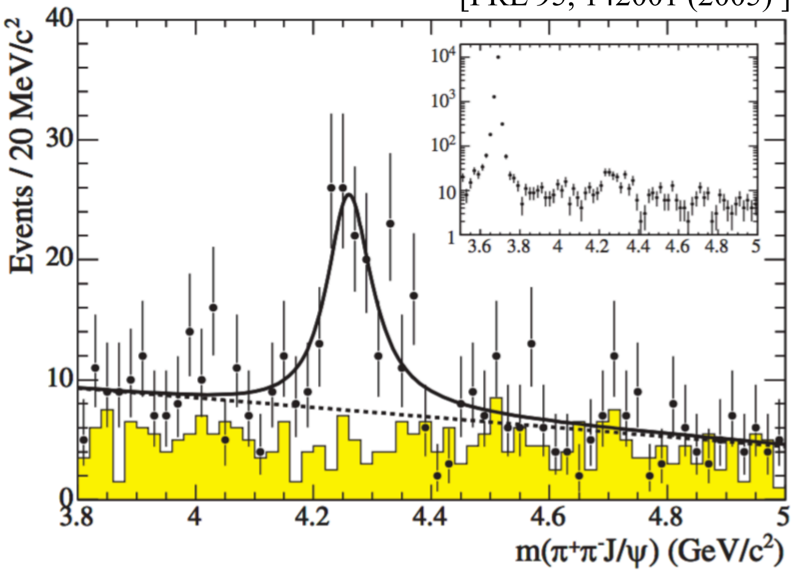
- Study (charged & neutral) Z states

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

Some history:

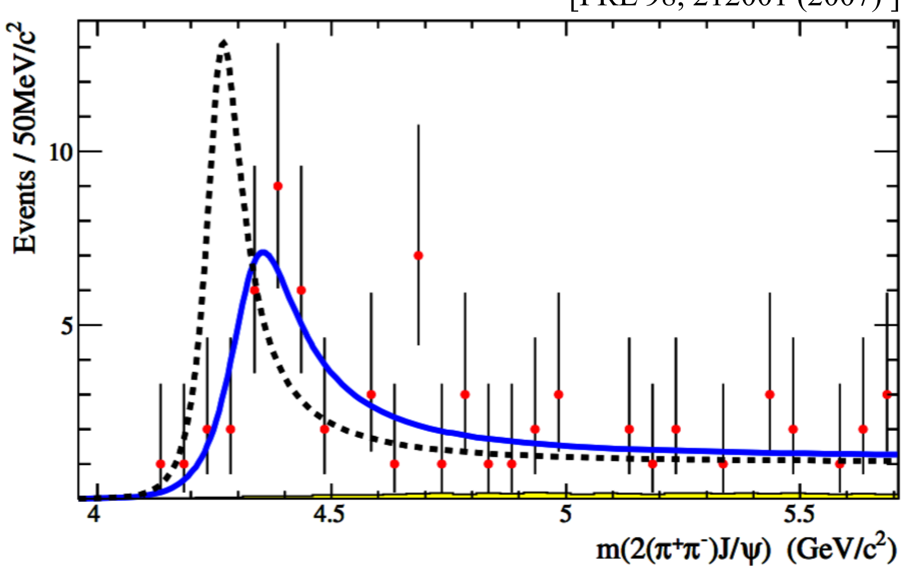
$e^+e^- \to J/\psi\pi^+\pi^-$

[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 $J/\psi\pi^+\pi^-$

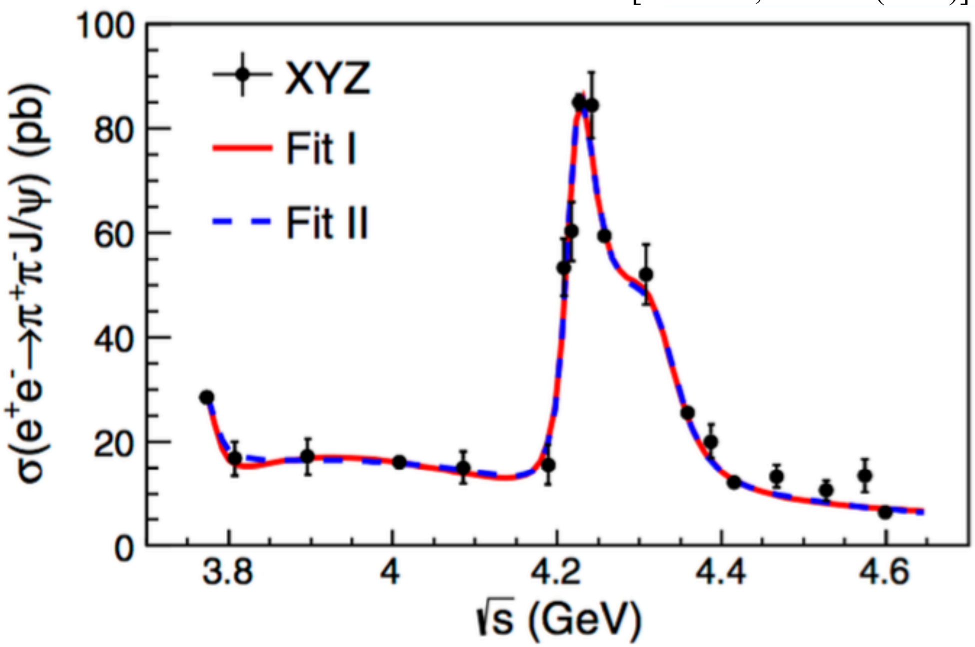
- Discovery of the Y(4360) using ISR by BaBar in $\psi(2S)\pi^-\pi^+$

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

BESIII result, published

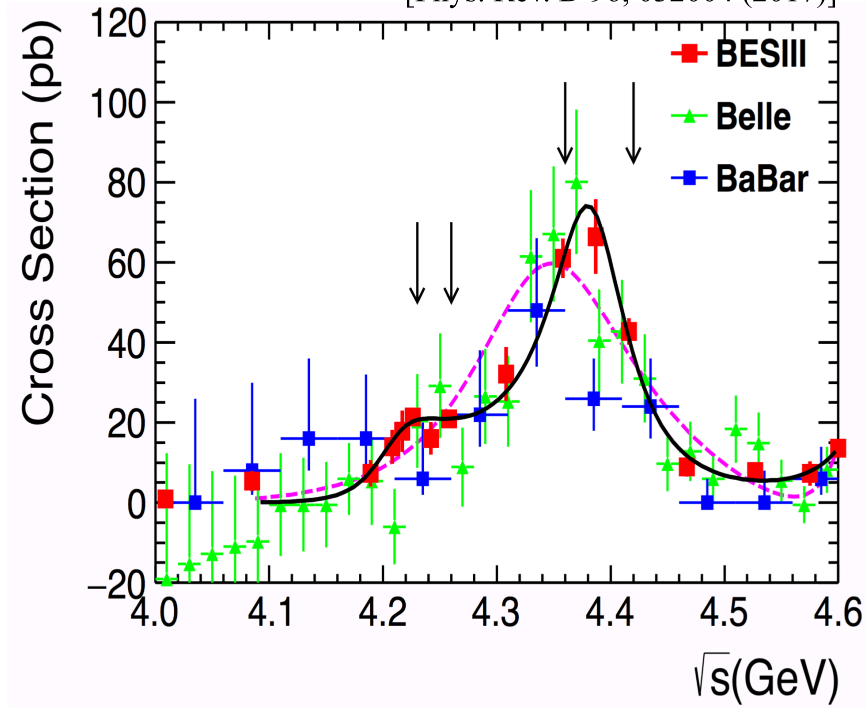
$e^+e^- \to J/\psi\pi^+\pi^-$ at BESIII (direct)

[PRL 118, 092001 (2017)]



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

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

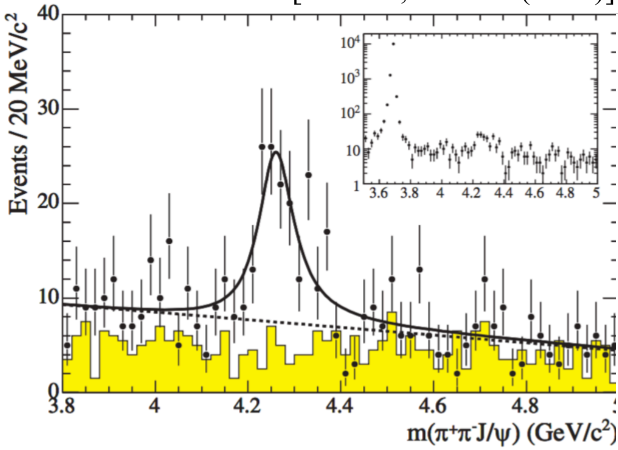


- Cross-section in-consistent with a single peak for the Y(4260) !
  - ➢ two peaks favoured over one by >7σ

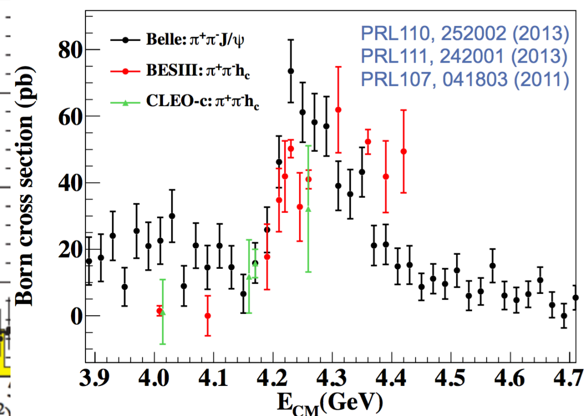
- BESIII much higher precision (5.8σ)
- 3 coherent BW fit: Y(4220) and Y(4390)

What happened to the Y states?

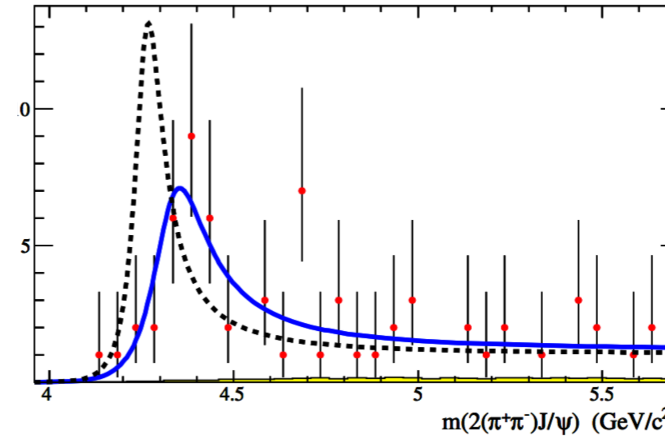
$e^+e^- \to J/\psi\pi^+\pi^-$ [PRL 95, 142001 (2005)]



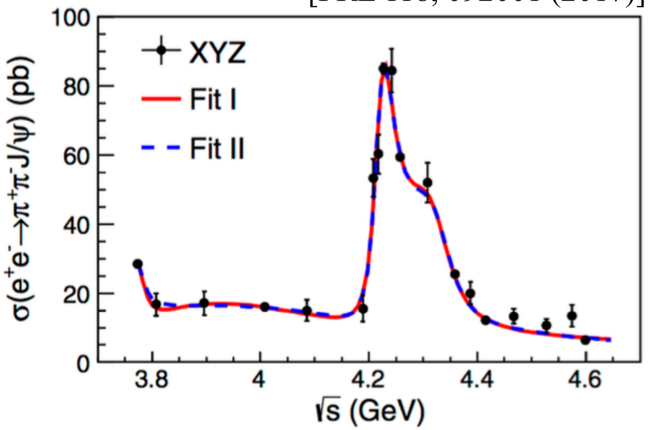
$e^+e^- \to h_c\pi^+\pi^-$



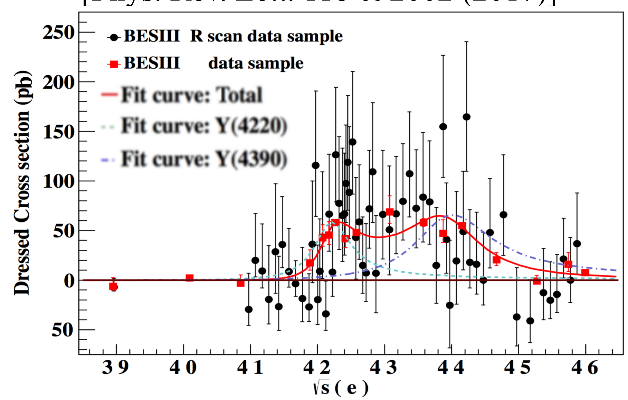
$e^+e^- \to \psi(2S)\pi^+\pi^-$ [PRL 98, 212001 (2007)]



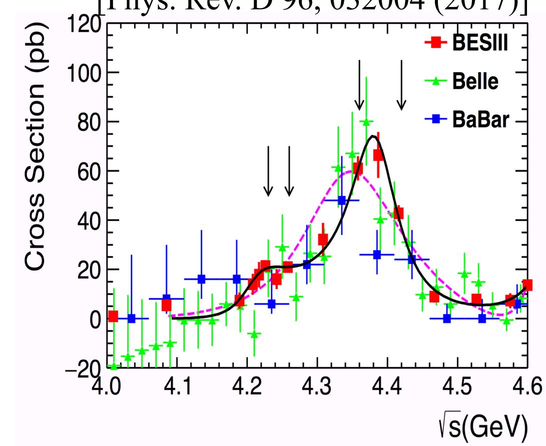
[PRL 118, 092001 (2017)]



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



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

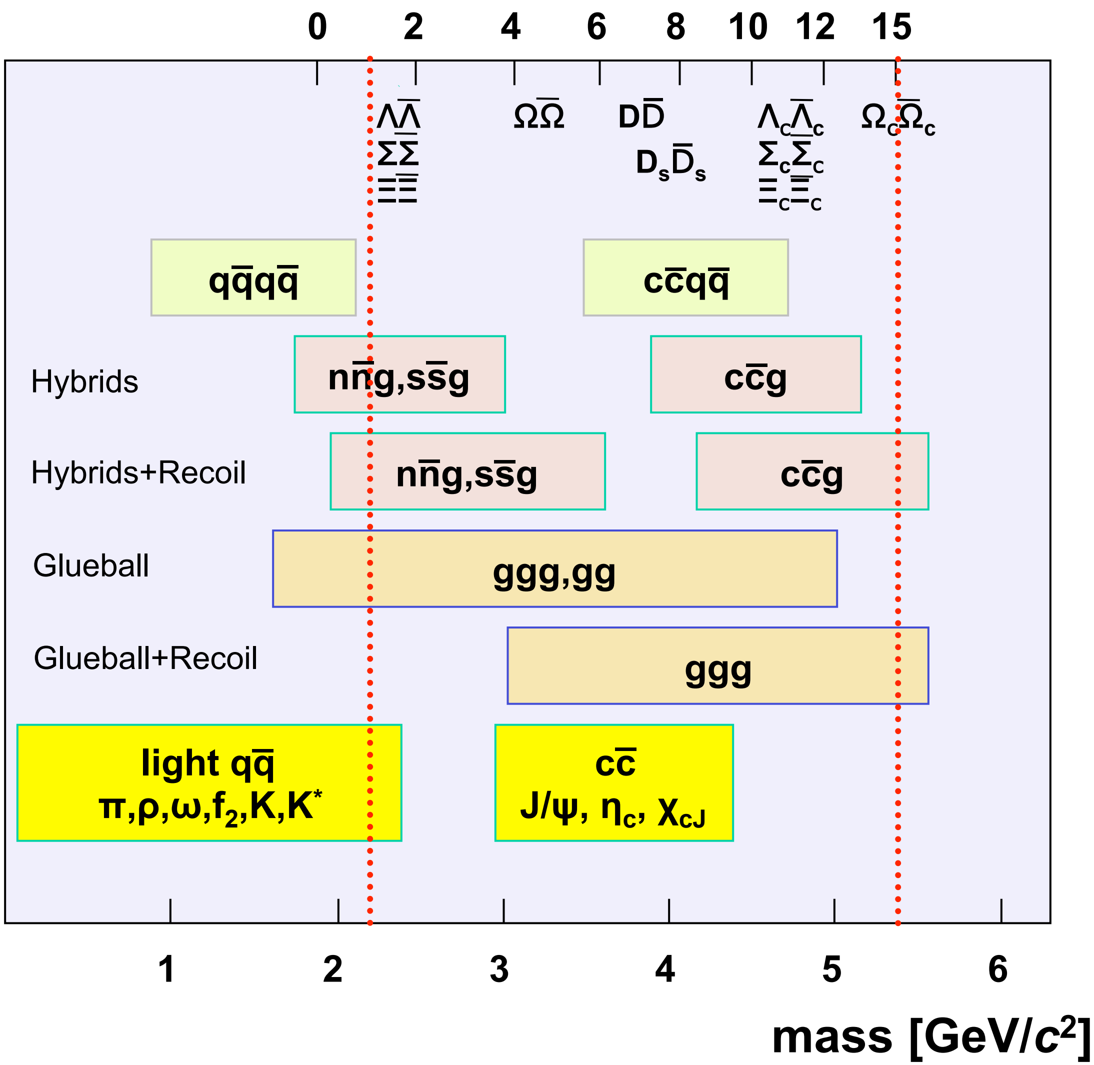


Two structures now observed/resolved in all three cases
=> Y(4260) → Y(4220) , Y(4360) → Y(4390) ?

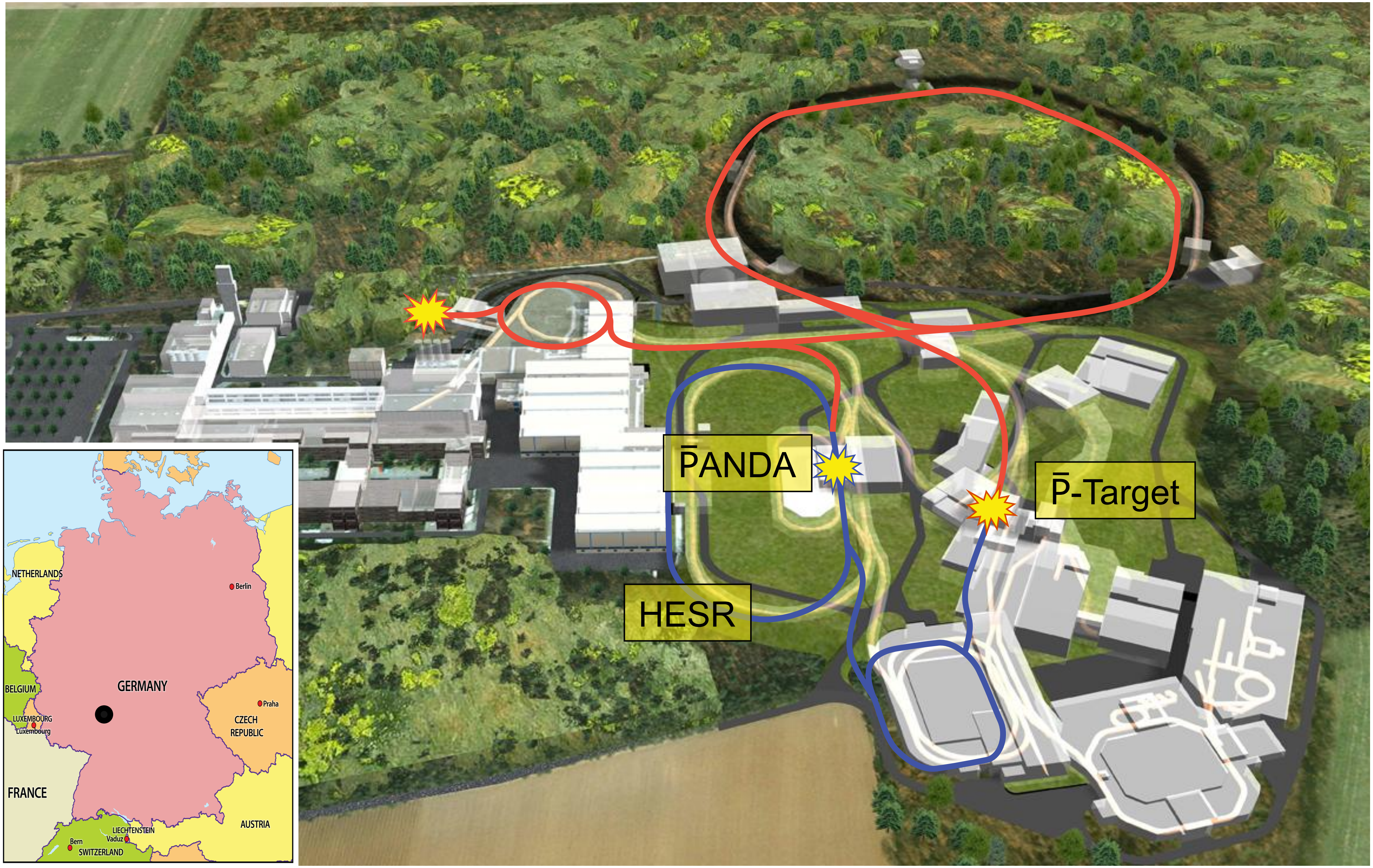
PANDA Physics Programme

Anti-Proton ANnihilation in DArmstadt

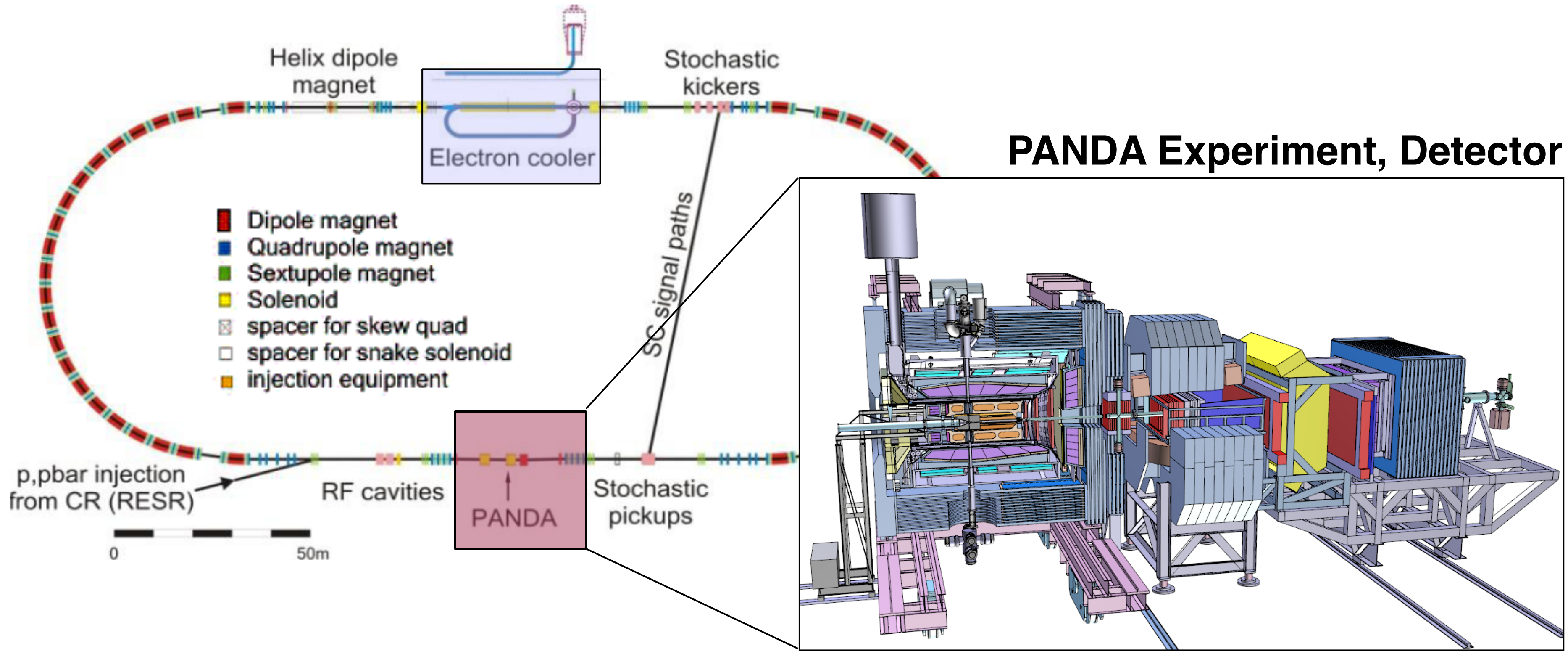
- **Hadron spectroscopy**
  - Light mesons
  - Charmonium
  - Exotic states:
    glue-balls, hybrids,
    molecules / multi-quarks
- **(Anti-) Baryon production**
- **Nucleon structure**
- **Charm in nuclei**
- **Strangeness physics**
  - hypernuclei
  - S = -2 nuclear system



Facility for Antiproton and Ion Research



High Energy Storage Ring -- HESR



High Resolution (HR) mode:

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

High Luminosity (HL) mode:

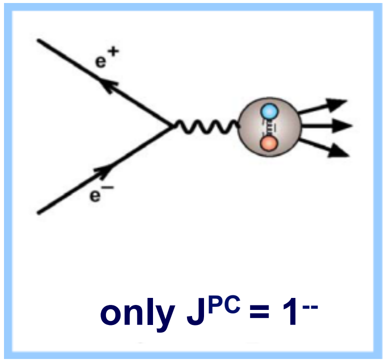
- Luminosity up to 2 x 10^{32} cm^{-2} s^{-1}
- $\Delta p/p$ = 1 x 10^{-4}

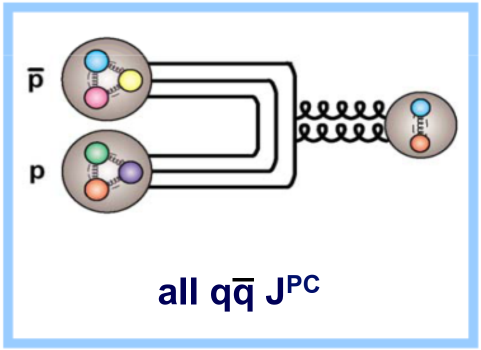
Some Advantages of Anti-Protons

- Access to all fermion-antifermion quantum numbers *(not in e^+e^-)*

- Access to states of high spin J

Formation:





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- Precise mass resolution in formation reactions

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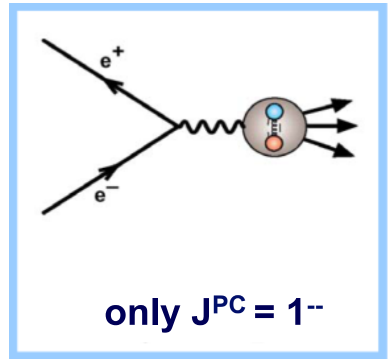

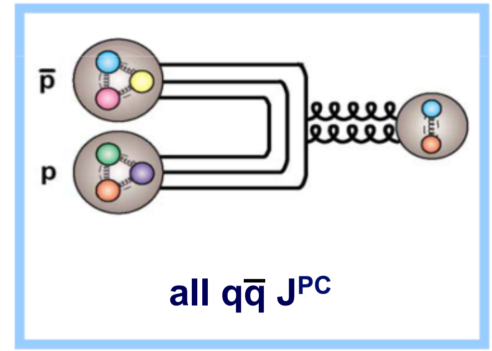

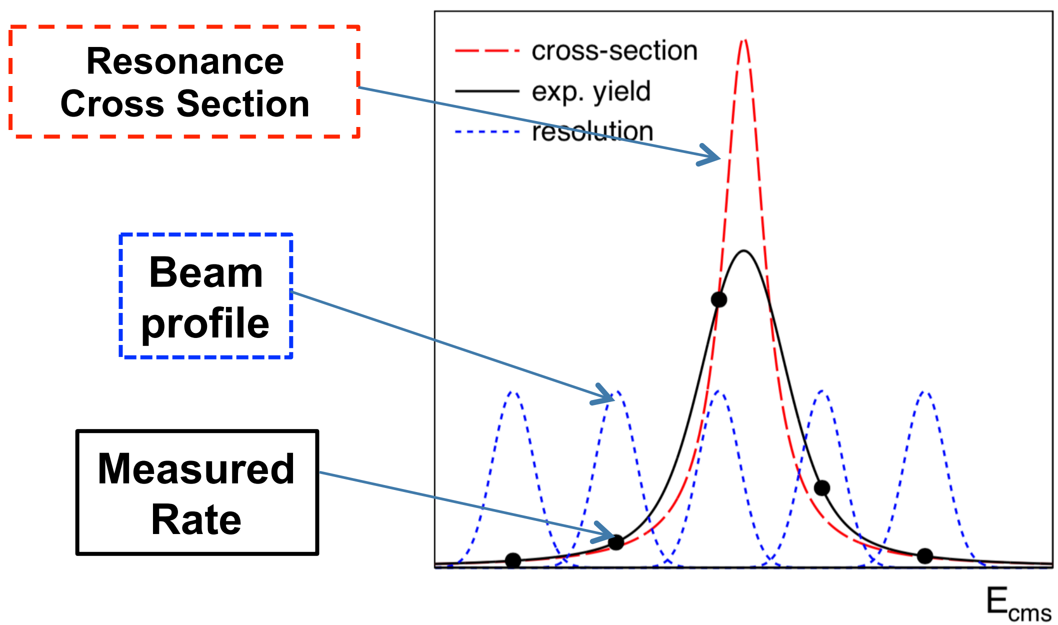

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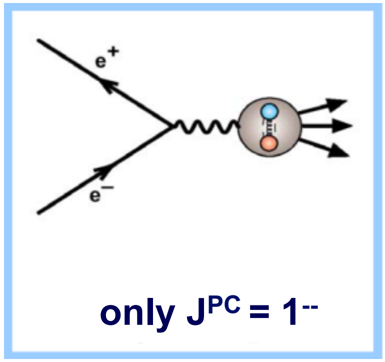
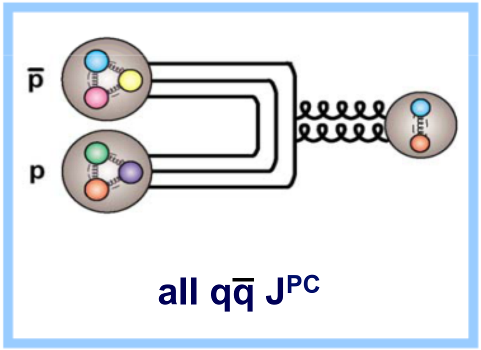
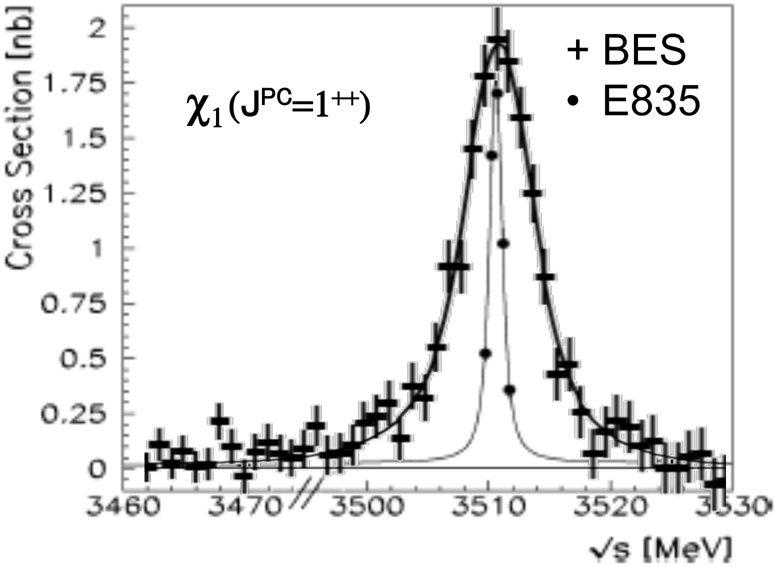
E760/835@Fermilab ≈ 240 keV
PANDA@FAIR ≈ 50 keV

Formation:







Ablikim et al., Phys. Rev. D71 (2005) 092002:
BES (IHEP): 3510.3 ± 0.2 MeV/c²

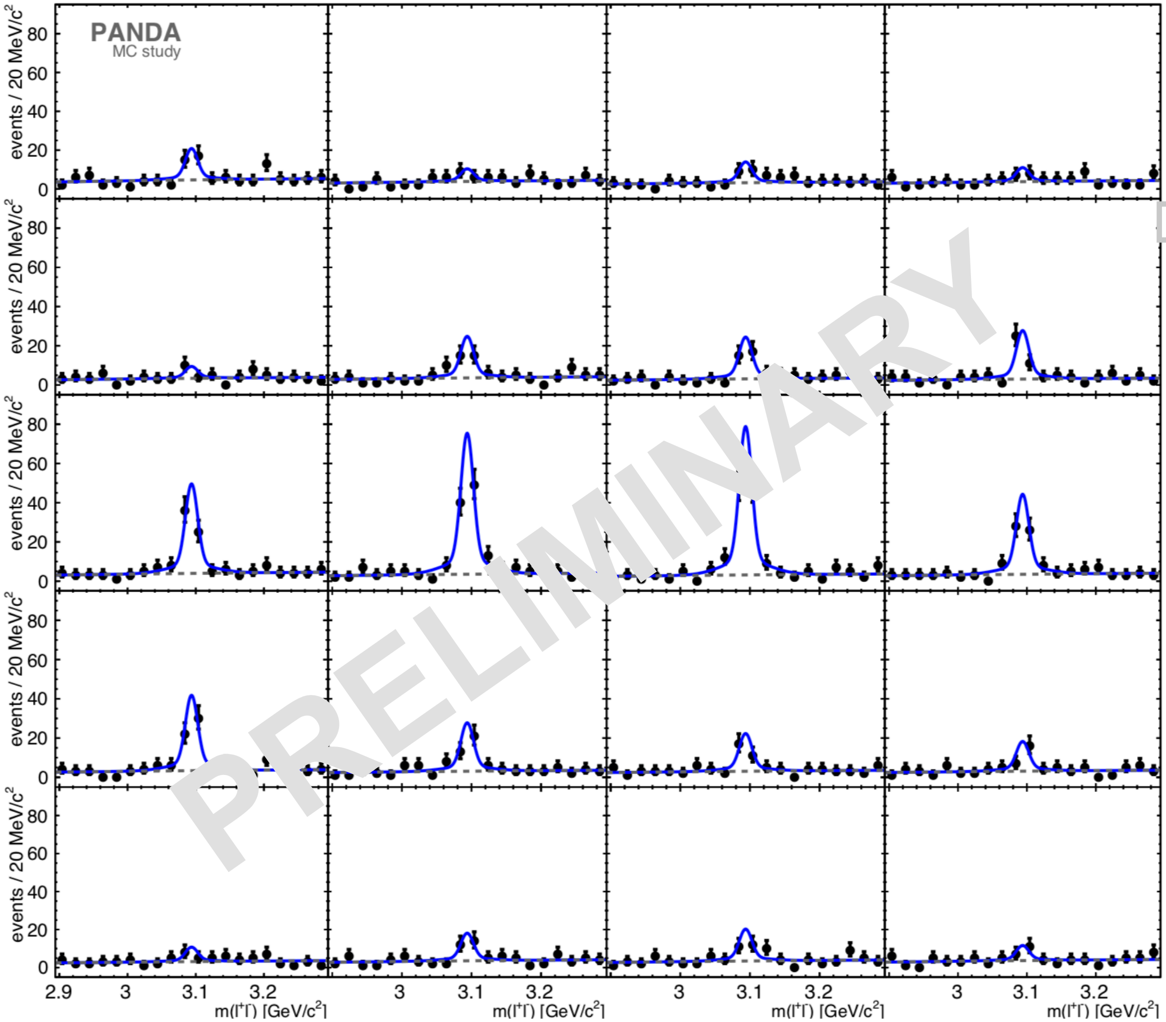
Andreotti et al., Nucl. Phys. B717 (2005) 34:
E835 (Fermilab): 3510.641 ± 0.074 MeV/c²

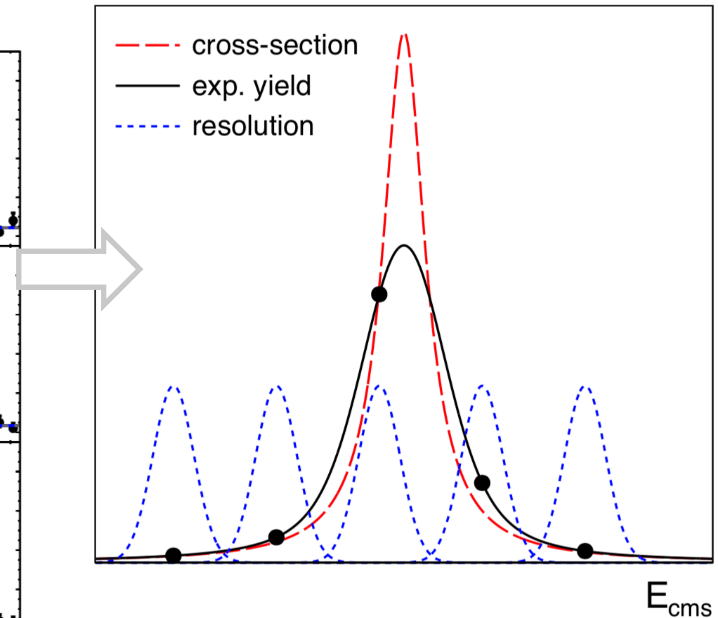
Perfomance Study for energy resonance scans of narrow resonances, like the X(3872)

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





[FN et al. for the PANDA Collab., Confinment Conf. Aug 2018]

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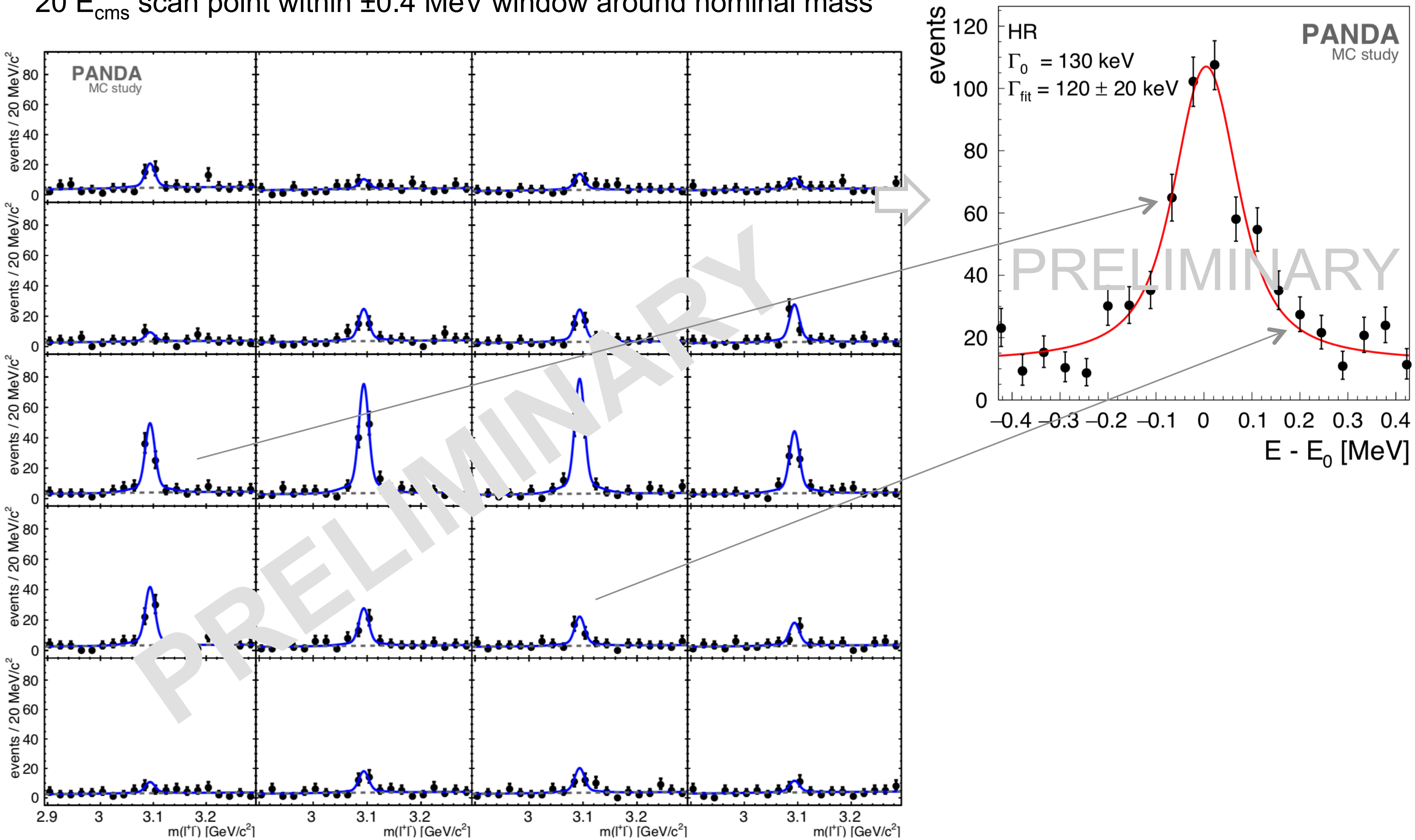

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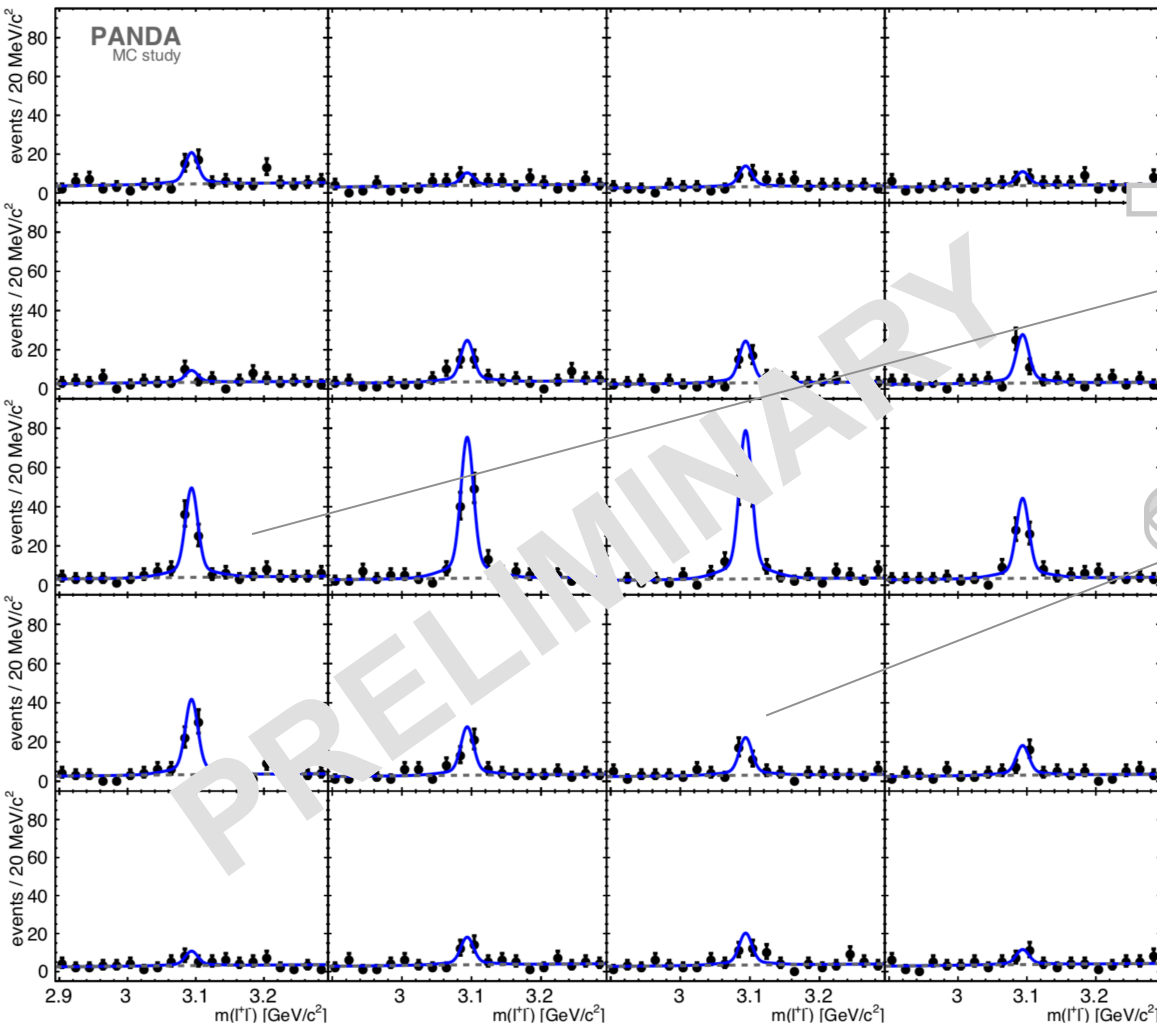
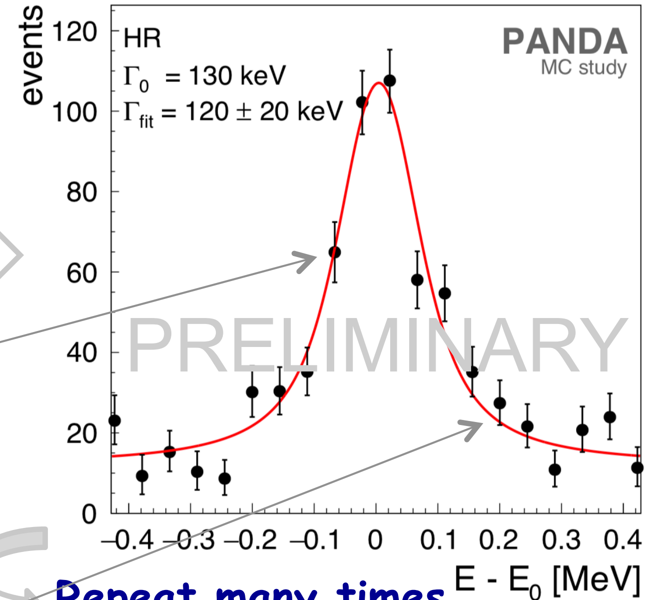
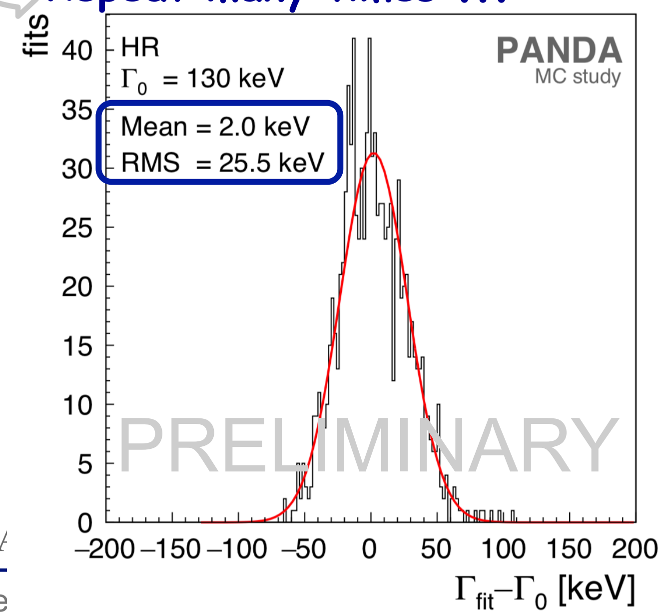




Repeat many times ...



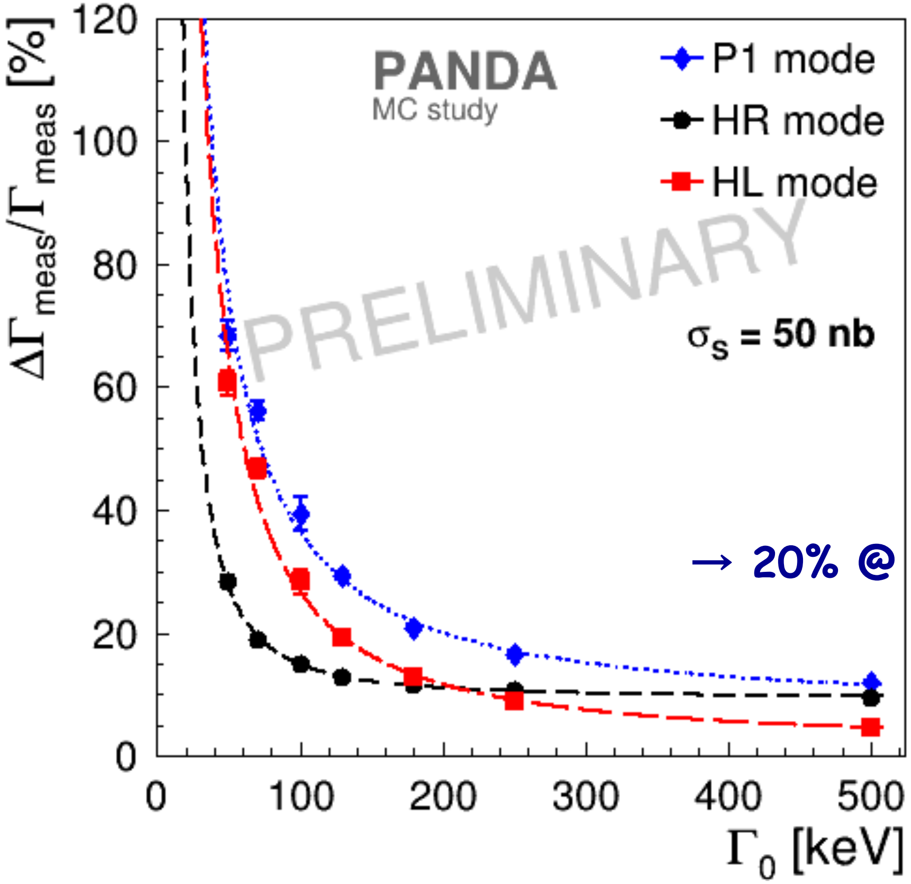
[FN et al. for the PA

Here: Sensitivities Breit-Wigner Γ (40 x 2d)

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

Sensitivity

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



→ 20% @ Γ= 50 ... 120 keV
HR HL

[FN et al. for the PANDA Collab., Confinment Conf. Aug 2018]

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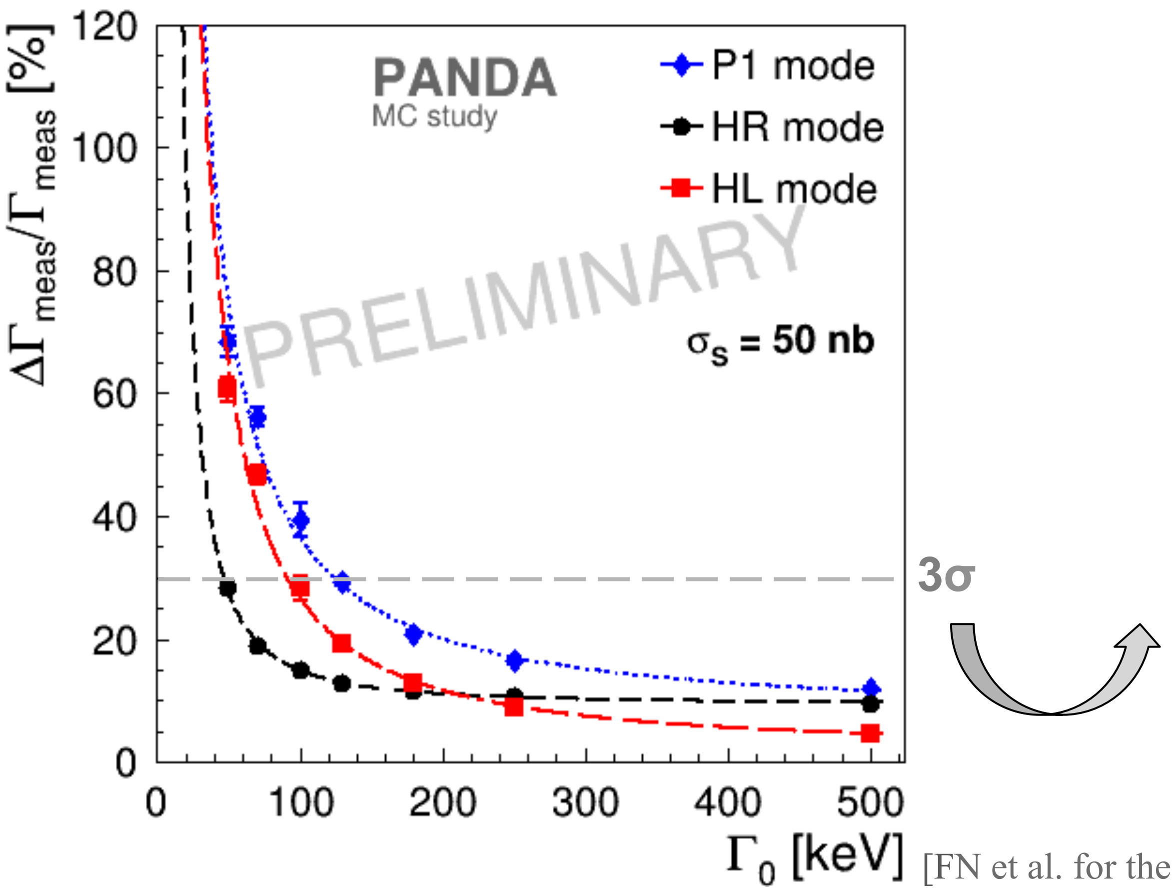

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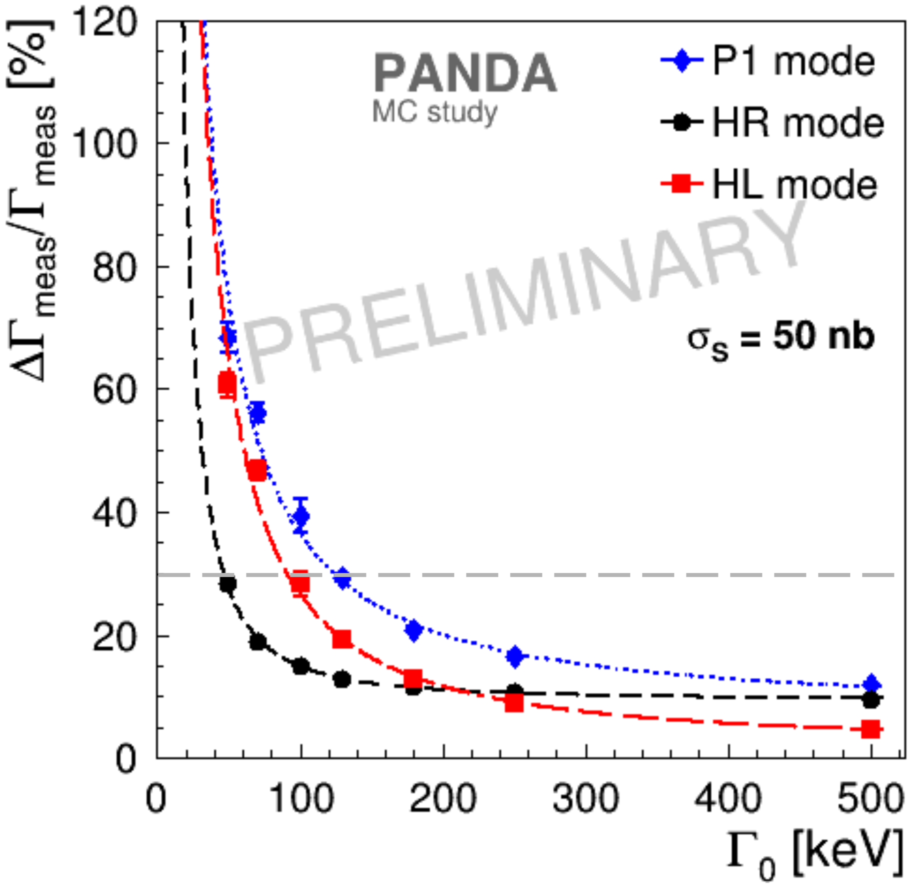
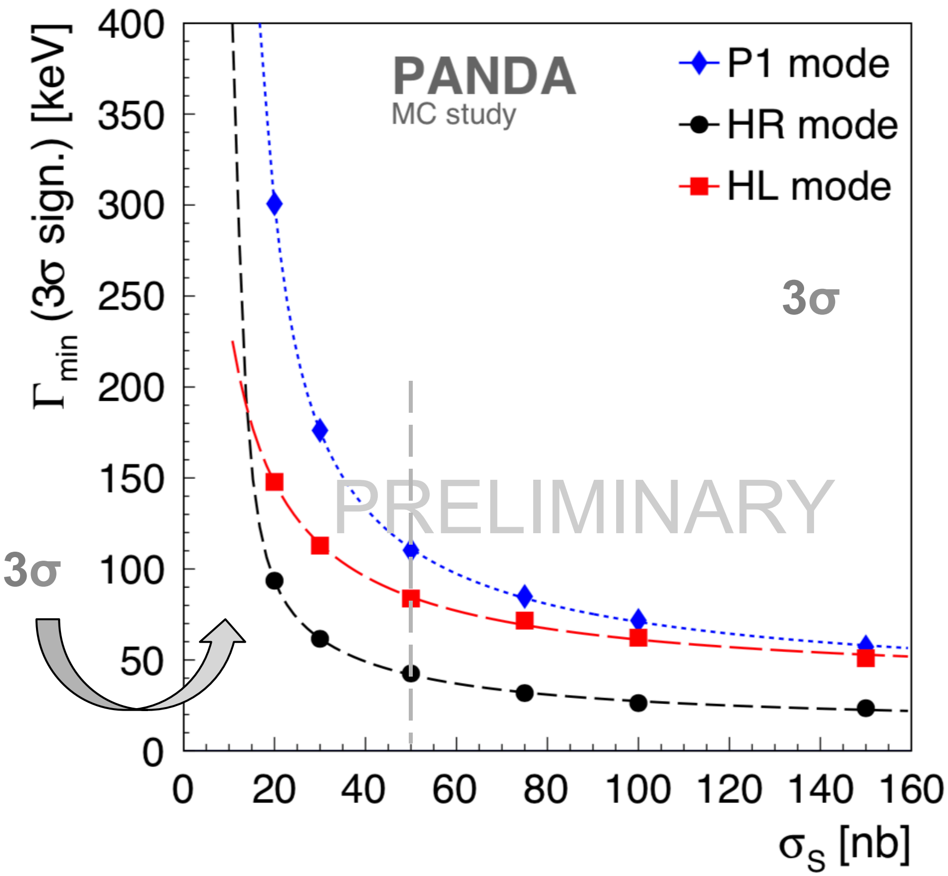
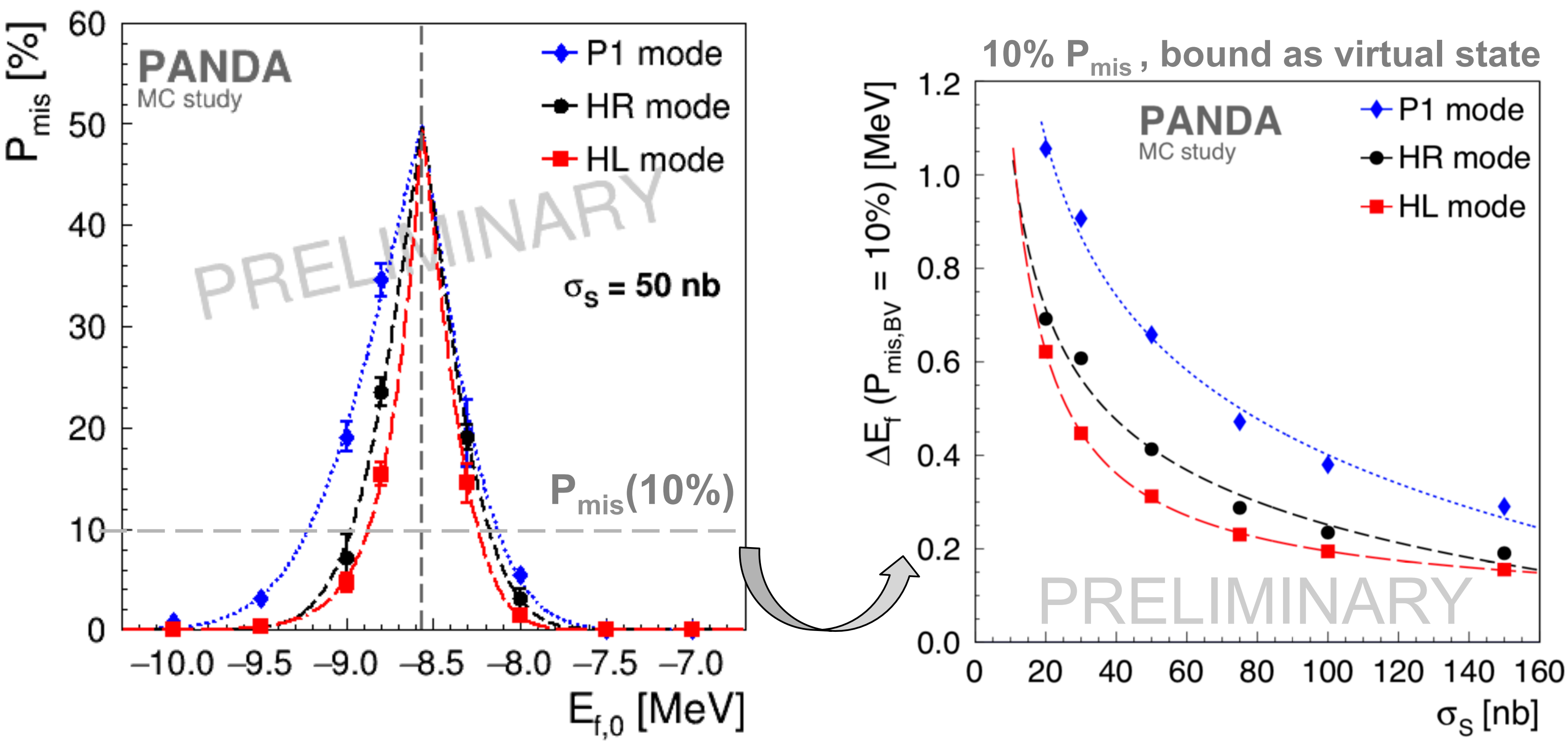




And: Distinction of Lineshapes (40 x 2d)

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

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



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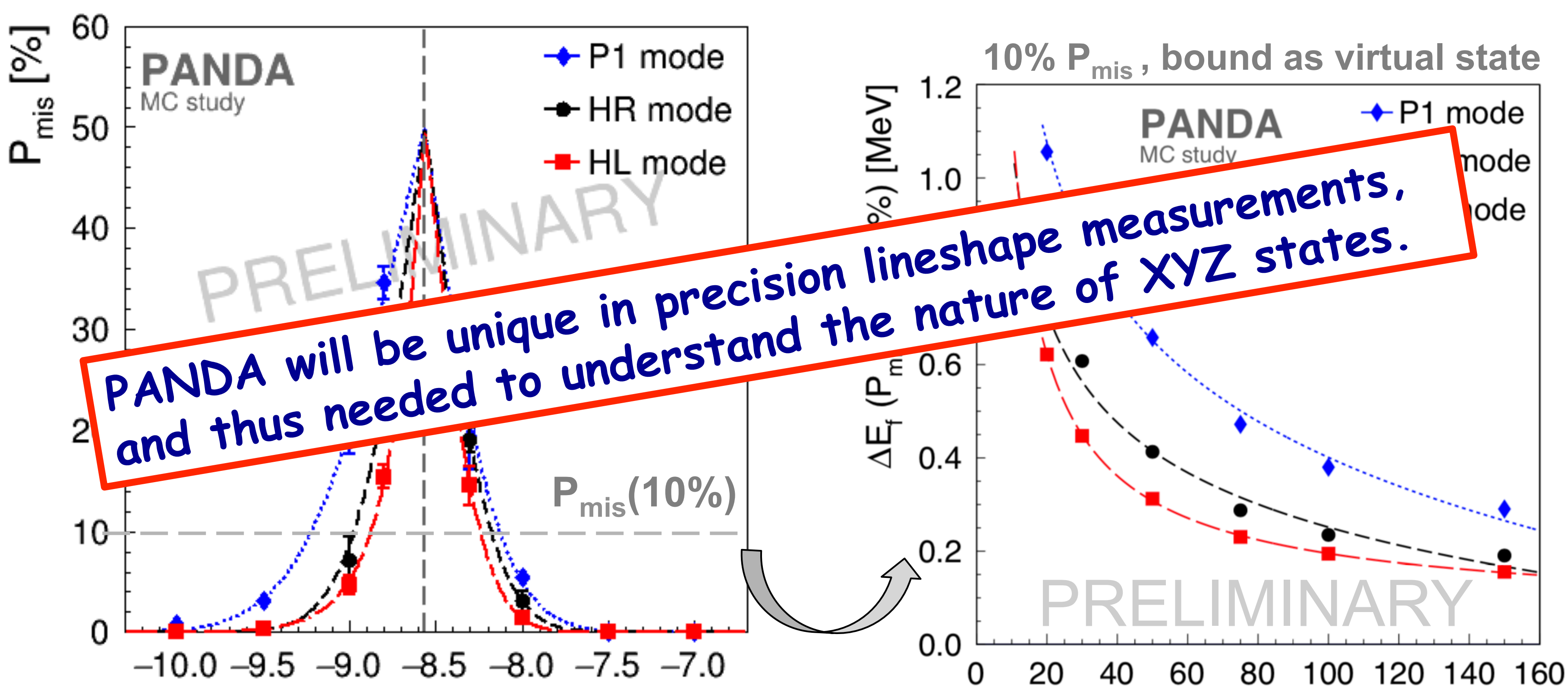


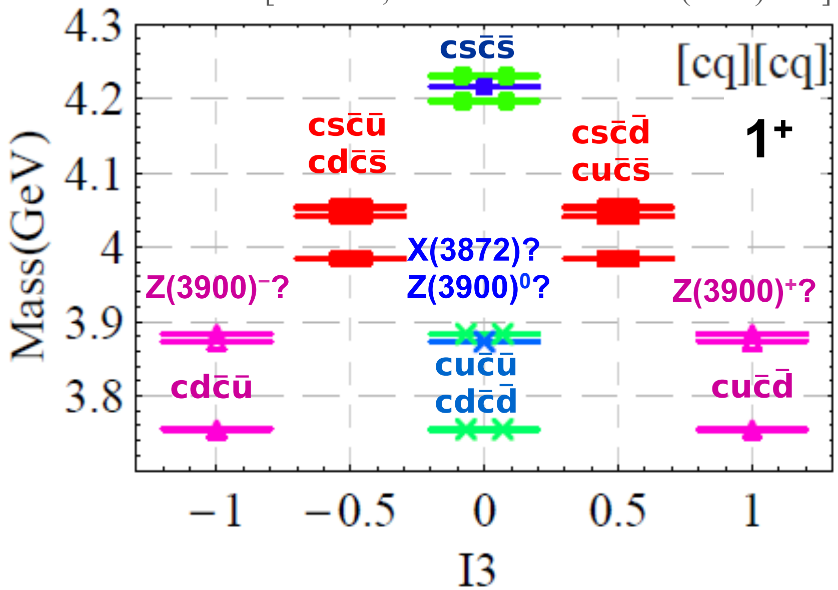
... about to be submitted to EPJ A

Models and Multiplets for XYZ

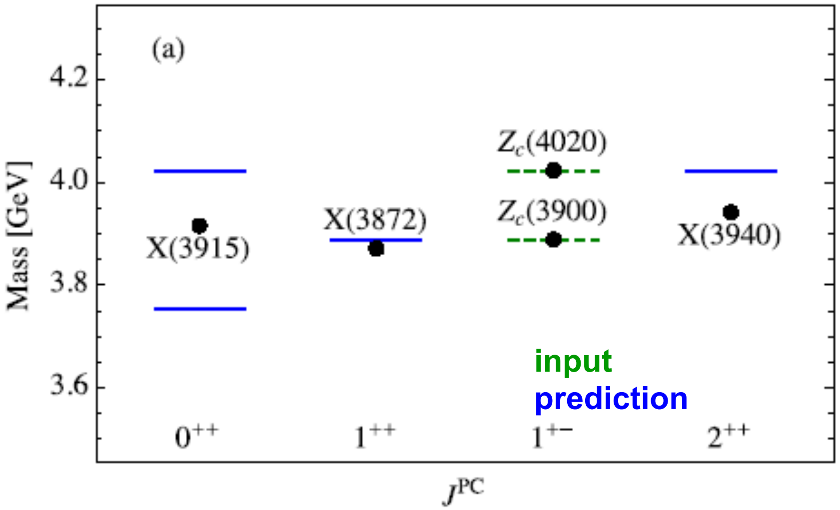
- Need to measure complete multiplets
  → *to really understand XYZ nature*

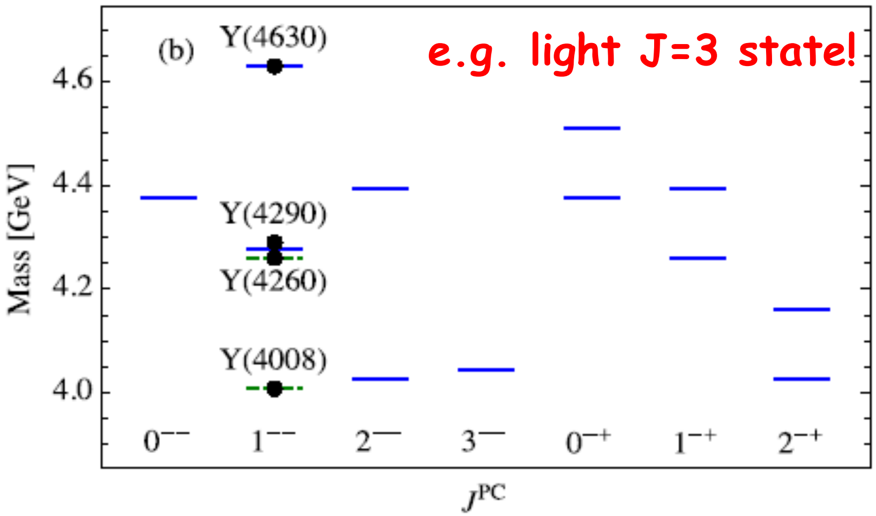
- e.g. di-quarkonium $[cq][\bar{c}\bar{q}]$ models provide predictions
  - ➢ Look for stranged partners
  - ➢ Look for light high spin states

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



[Cleven et al., arXiv:1505.01771]





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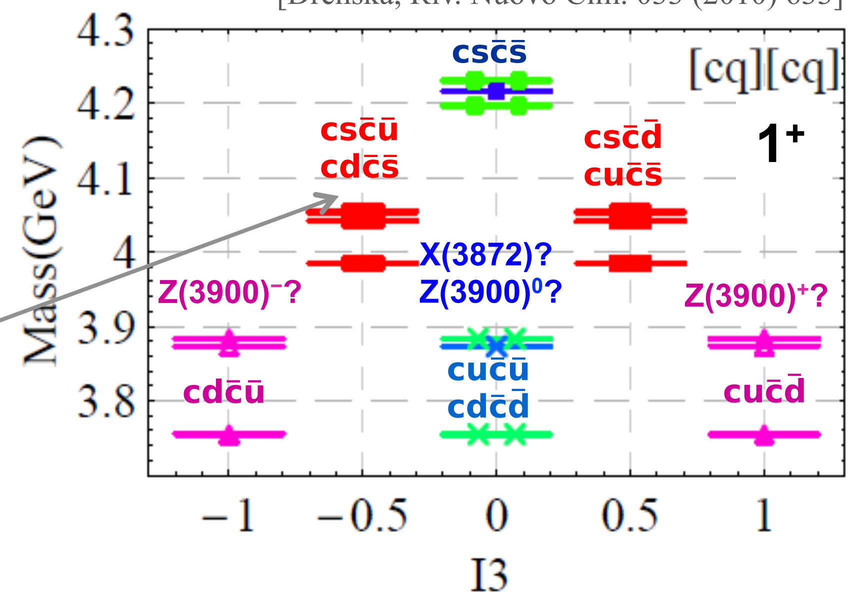

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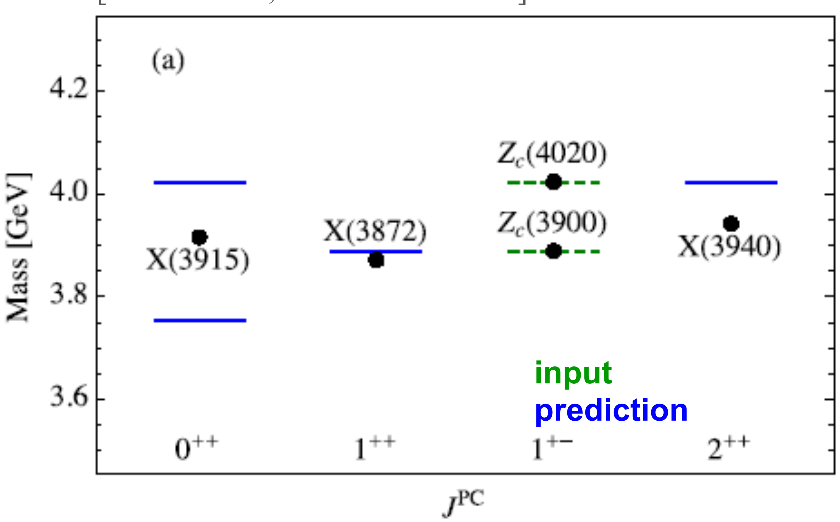

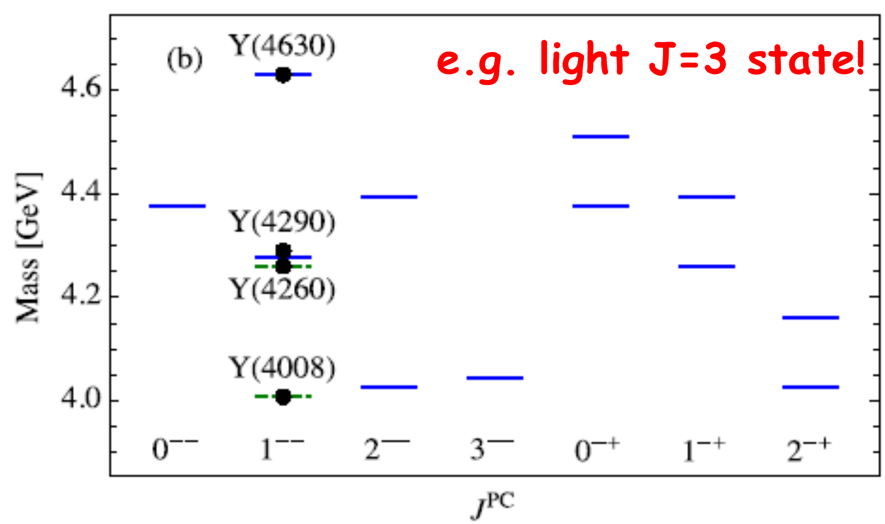

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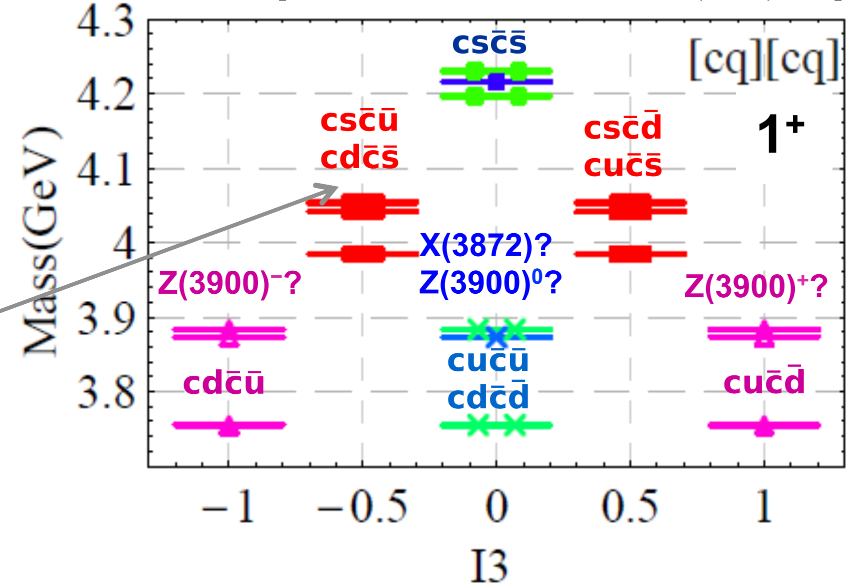

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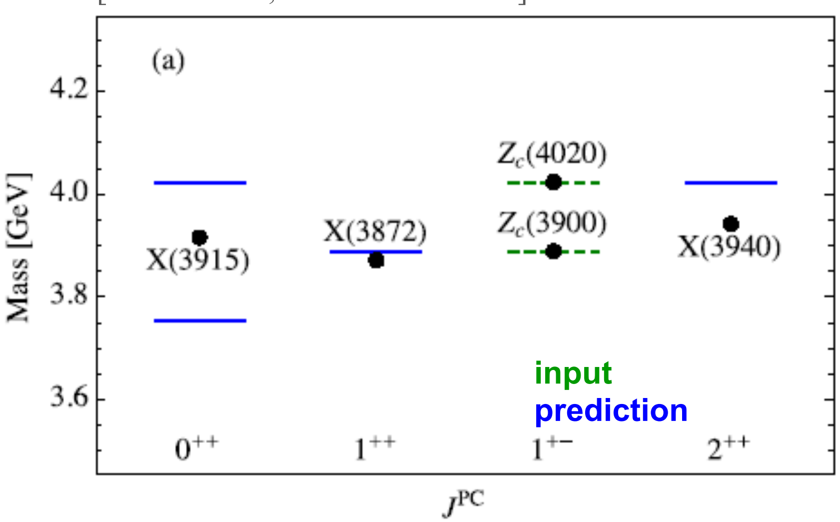

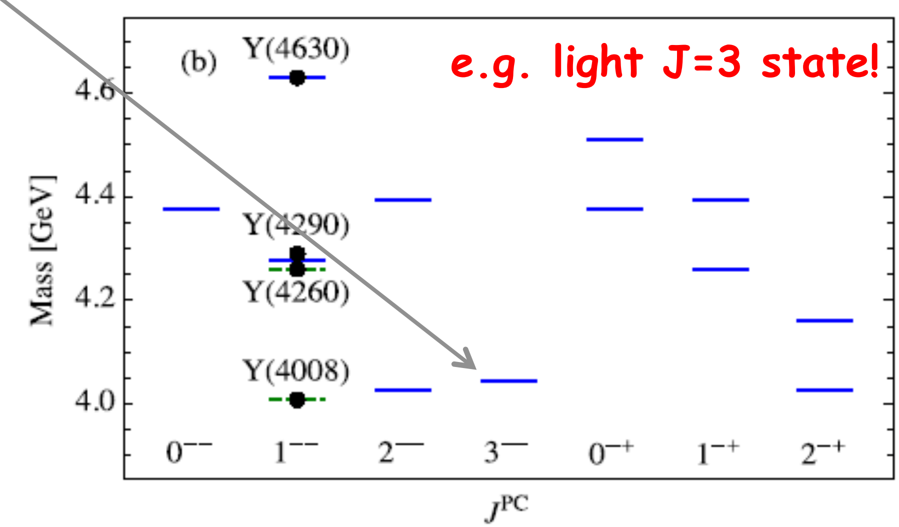

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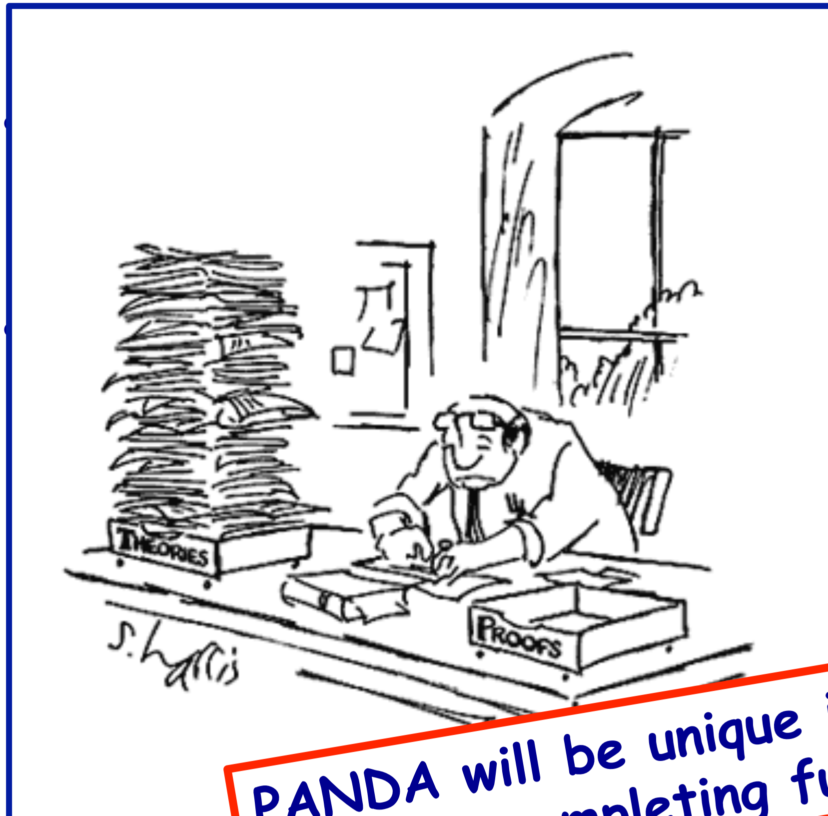

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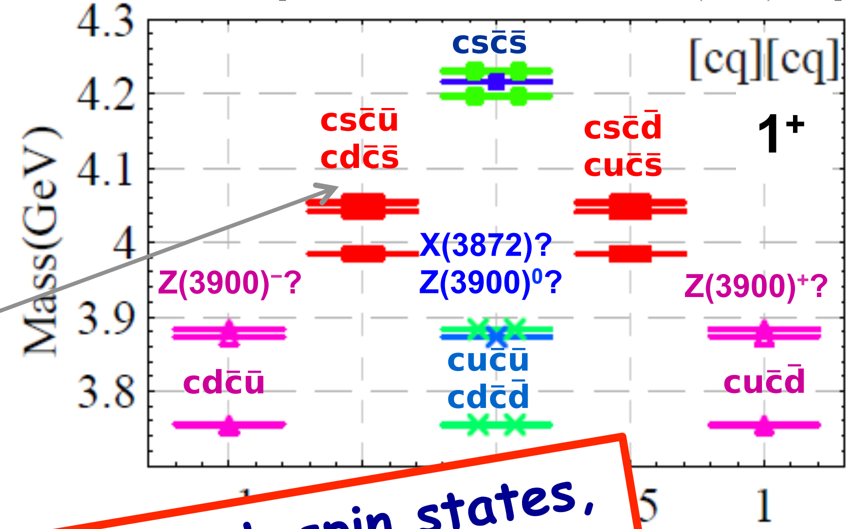
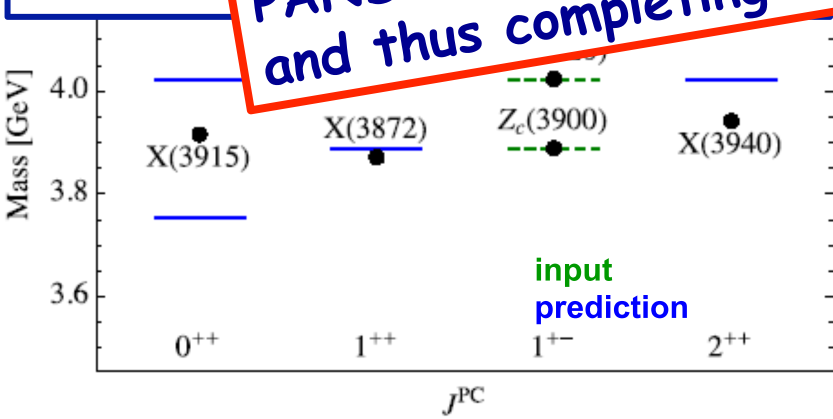
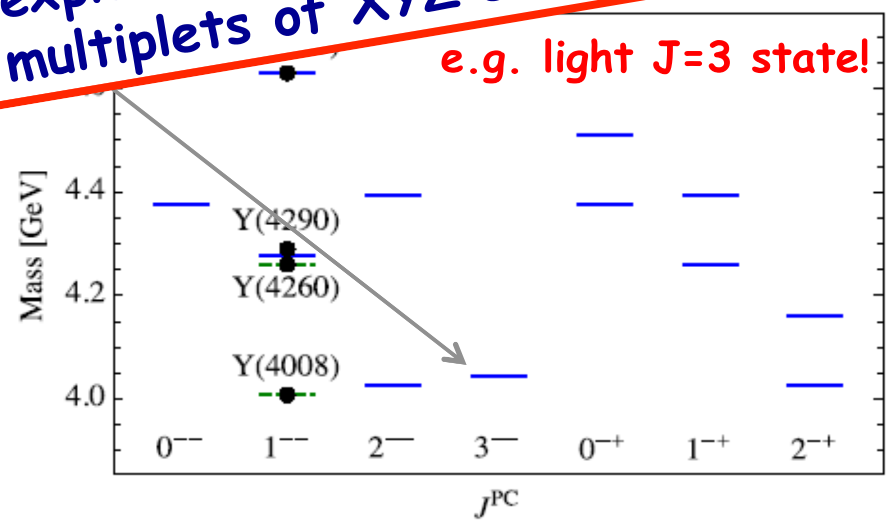




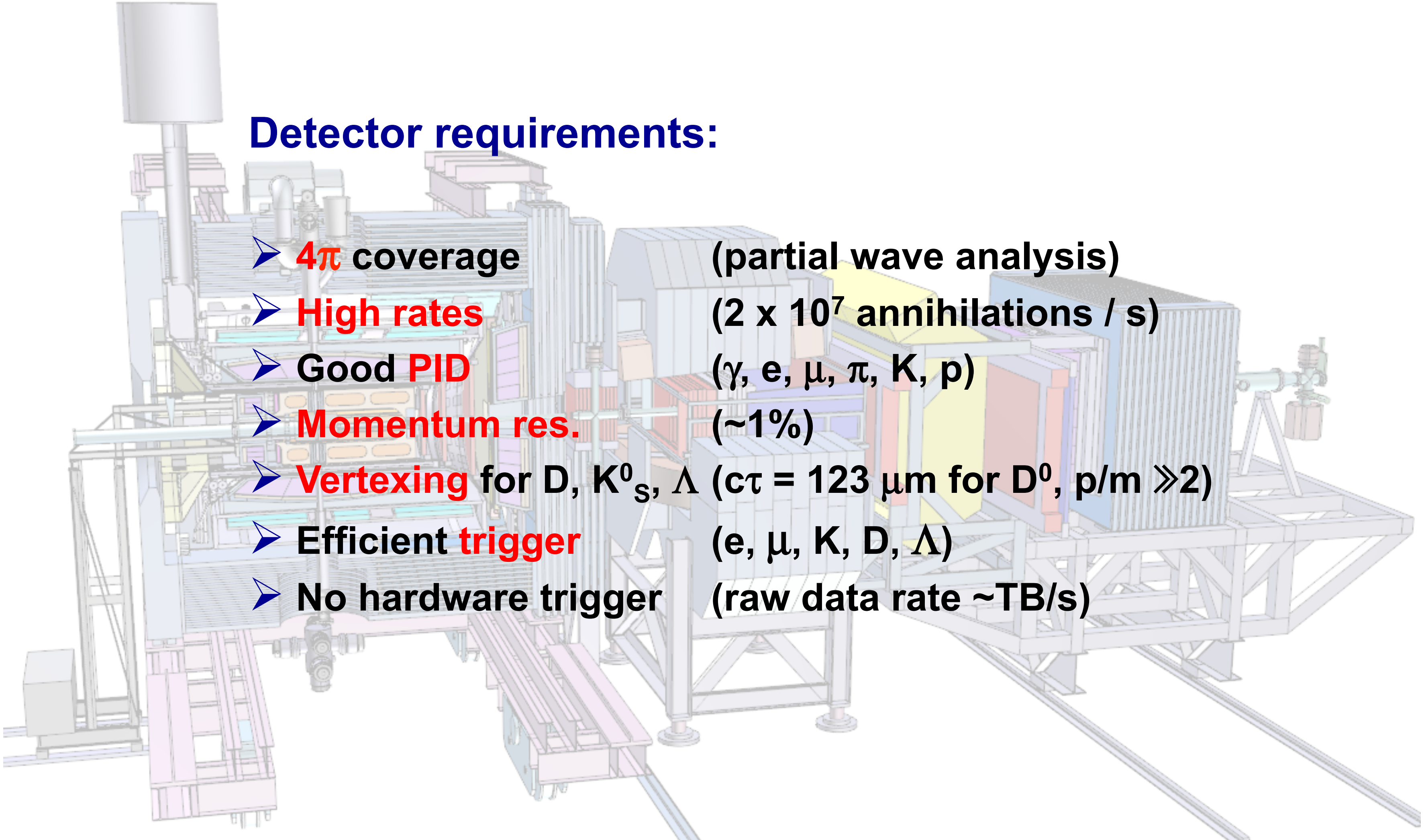


PANDA will be unique in exploring high spin states, and thus completing full multiplets of XYZ states.

e.g. light J=3 state!

AntiProton Annihilation at Darmstadt

AntiProton Annihilation at Darmstadt



Detector requirements:

- **4π coverage** (partial wave analysis)
- **High rates** (2 x 10^7 annihilations / s)
- **Good PID** (γ, e, μ, π, K, p)
- **Momentum res.** (~1%)
- **Vertexing for D, K^0_S, Λ** (cτ = 123 μm for D^0, $p/m \gg 2$)
- **Efficient trigger** (e, μ, K, D, Λ)
- **No hardware trigger** (raw data rate ~TB/s)

Summary and Prospectives

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

- **Hadron physics -- Spectroscopy**
  - Recent hot discoveries in (baryon and) meson spectroscopy
  - New exotic states observed during last decade
  - Proof validity of fundamental QCD principles
  - Charmonium-like exotics:

    → *Charged states manifestly exotic matter*

- **Running & new experiments**
  - Complementary production mechanisms and measurements needed
  - Precise knowledge of decay width and line shape essential
  - Complete the exotic multiplets

    → *PANDA unique:*

    High statistics + precision resonance scans + high spin states

- **Quite some way still to go ...**

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  - Complete the exotic multiplets
    → *PANDA unique:*
    High statistics + precision resonance scans + high spin states

- **Quite some way still to go ...**

... stay tuned for further exciting discoveries!

Summary and Prospectives

- **Hadron physics -- Spectroscopy**
  - Recent hot discoveries in (baryon and) meson spectroscopy
  - New exotic states observed during last decade
  - Proof validity of fundamental QCD principles
  - Charmonium-like exotics:
    → *Charged states manifestly exotic matter*

- **Running & new experiments**
  - Complementary production r
  - Precise knowledge of decay
  - Complete the exotic multiple
    → *PANDA unique:*
    High statistics + precision r

PANDA will be the facility to study QCD -- hadron structure and spectroscopy ...

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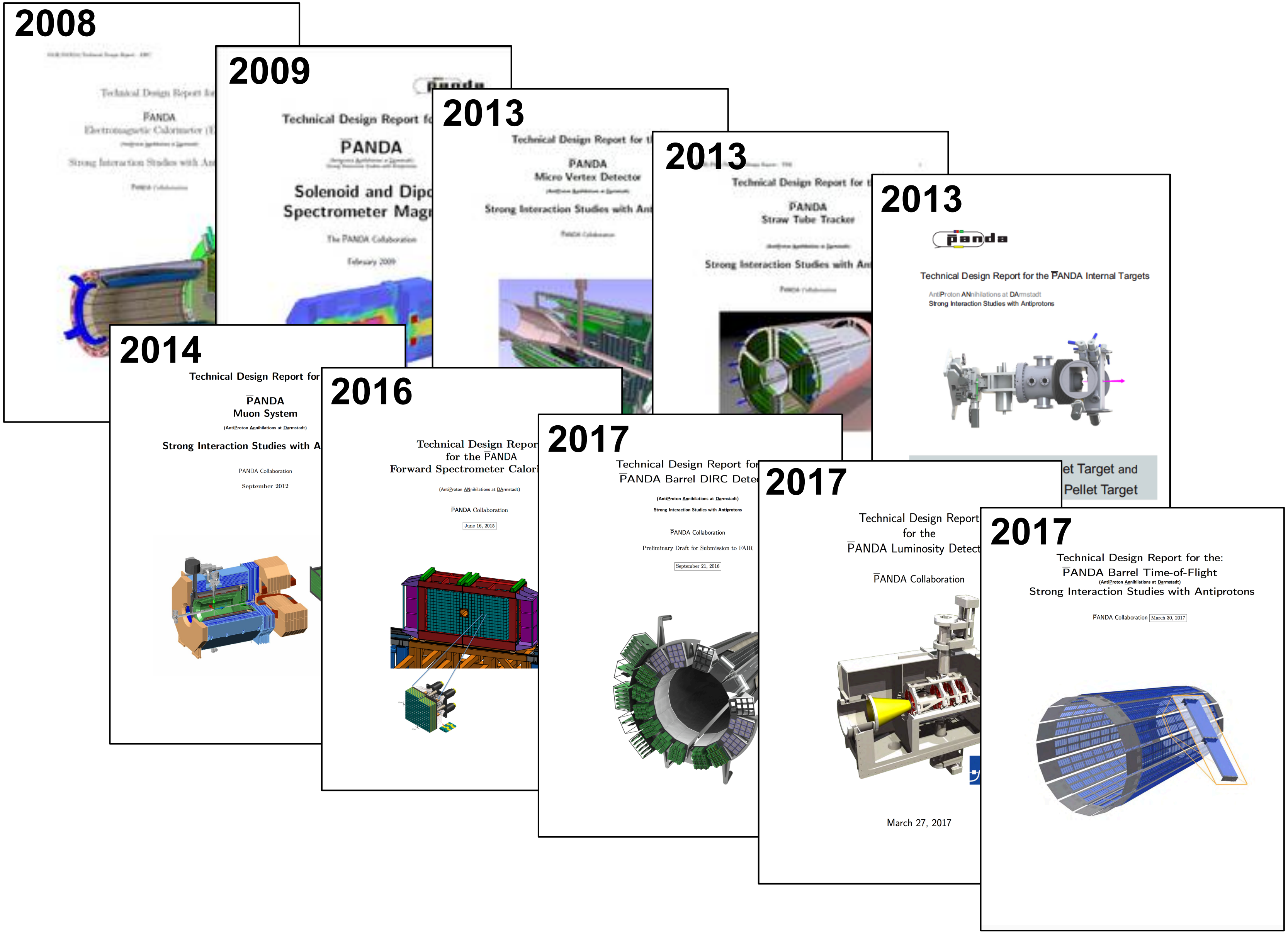
Thank you for your attention!

The PANDA collaboration:
~ 500 Members, 72 Institutes, 20 Countries

Austria, Australia, Belarus, China, France, Germany, India, Italy, Poland, Romania, Russia, Spain, Sweden, Switzerland, Thailand, Netherlands, USA, UK, ... (to be updated/completed)

Status of TDRs and Construction



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
U & INFN Genova
U Gießen
U Glasgow
BITS Pilani KKBGC, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
FH Iserlohn
FZ Jülich
IMP Lanzhou
INFN Legnaro
U Lund
HI Mainz

U Mainz
INP Minsk
ITEP Moscow
MPEI Moscow
BARC Mumbai
U Münster
BINP Novosibirsk
Novosibirsk State U
Novosibirsk STU
IPN Orsay
U & INFN Pavia
Charles U, Prague
Czech TU, Prague
IHEP Protvino
Irfu Saclay
U of Sidney

PNPI St. Petersburg
KTH Stockholm
U Stockholm
Suranaree University
SVNIT Surat-Gujarat
South Gukarat U, Surat-Gujarat
FSU Tallahassee
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Uppsala
U Valencia
SMI Vienna
U Visva-Bharati
SINS Warsaw