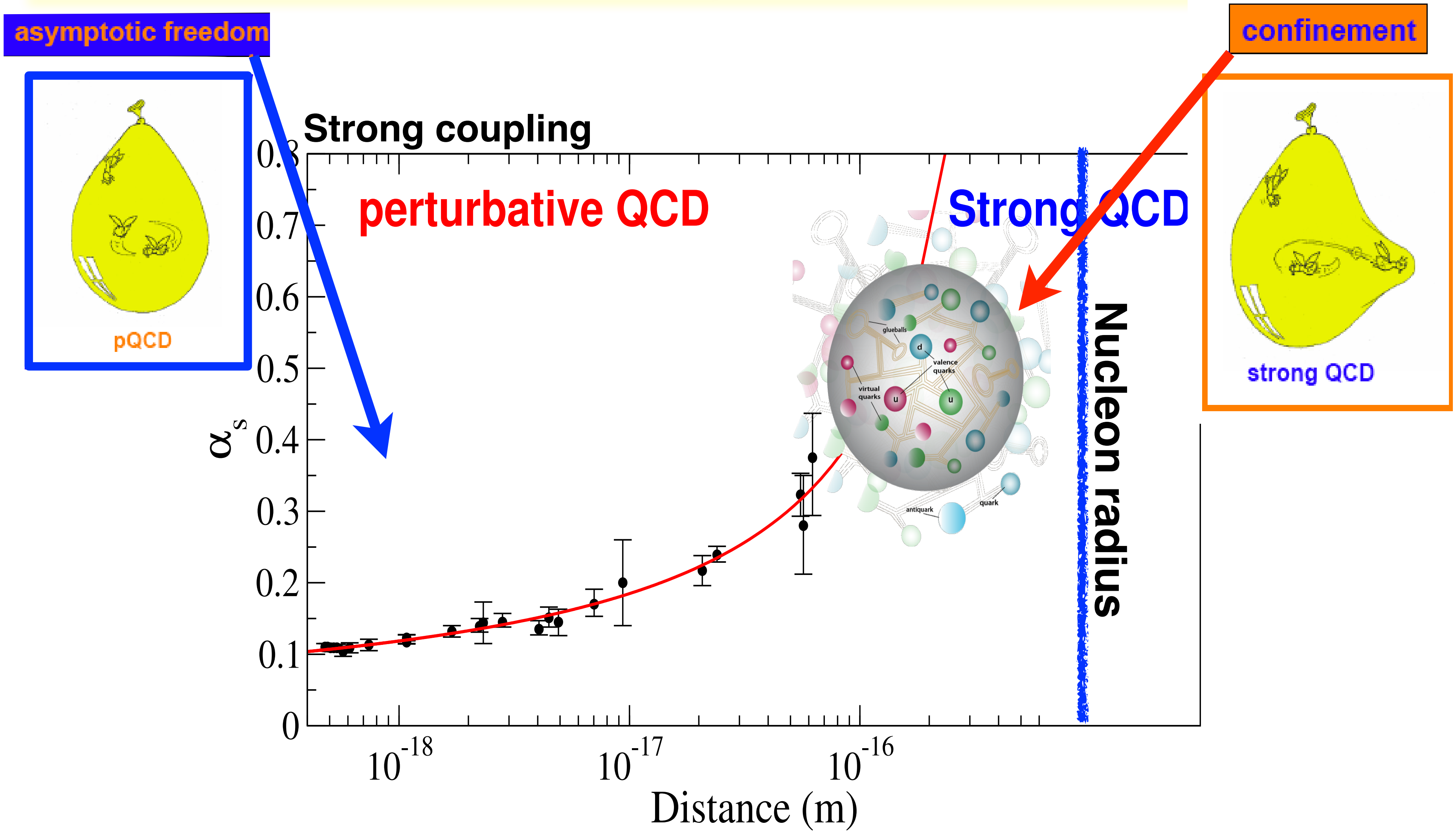
university of groningen
kvi - center for advanced radiation technology

Charming Discoveries in Matter-Antimatter Annihilations

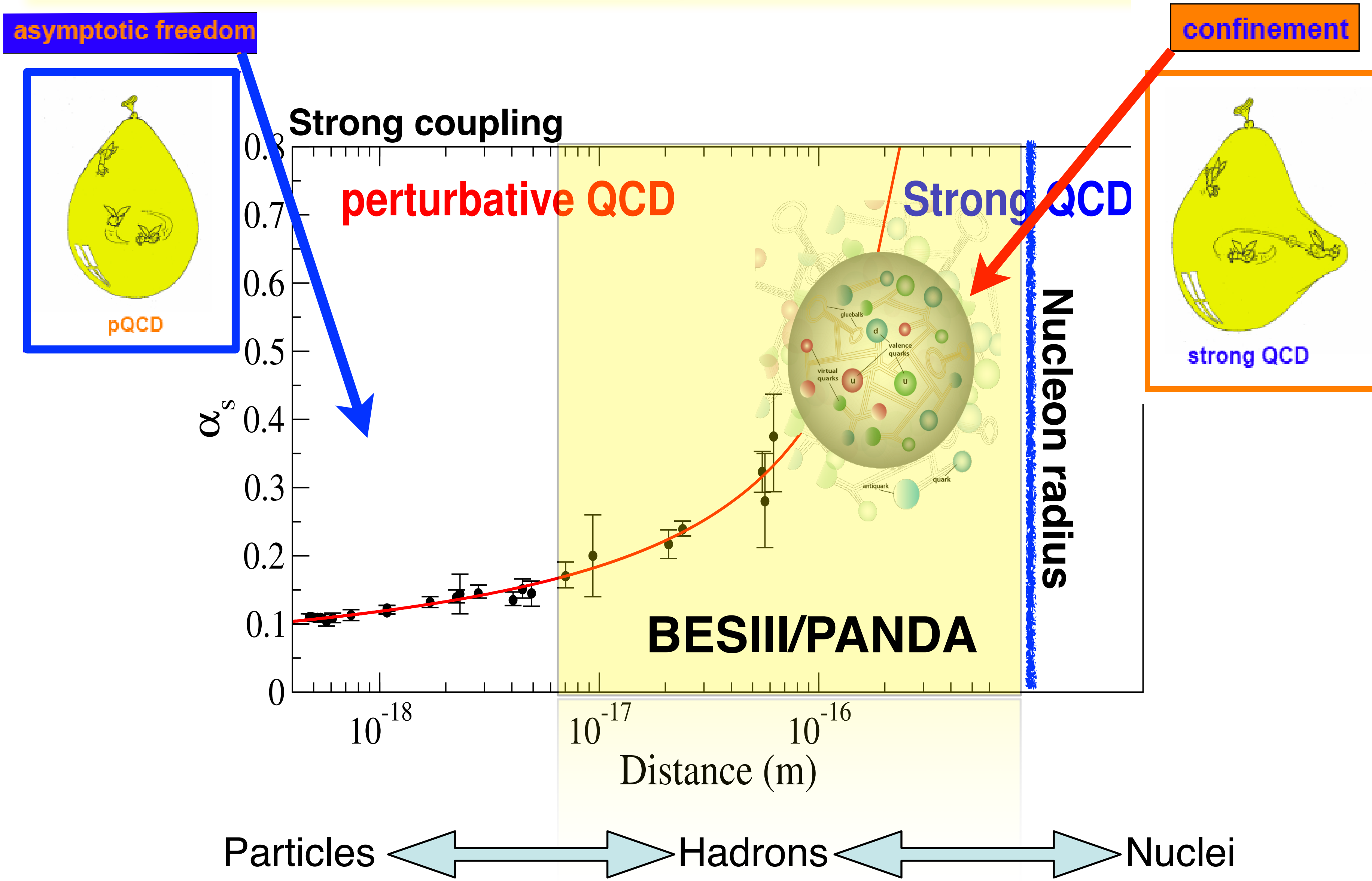
Johan Messchendorp (University of Groningen)

The dynamics of QCD!



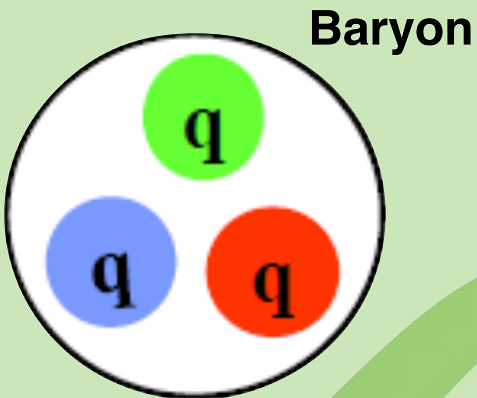
Particles ⟷ Hadrons ⟷ Nuclei

The dynamics of QCD!

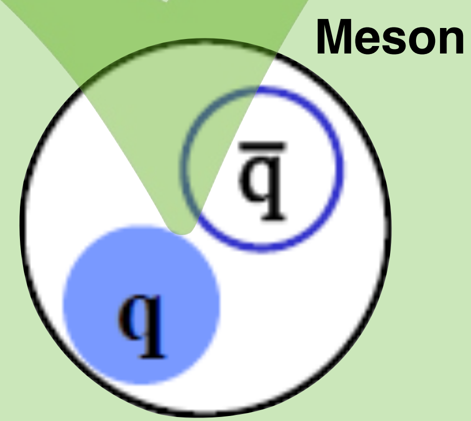


Ordinary versus “exotic” matter

Ordinary versus "exotic" matter

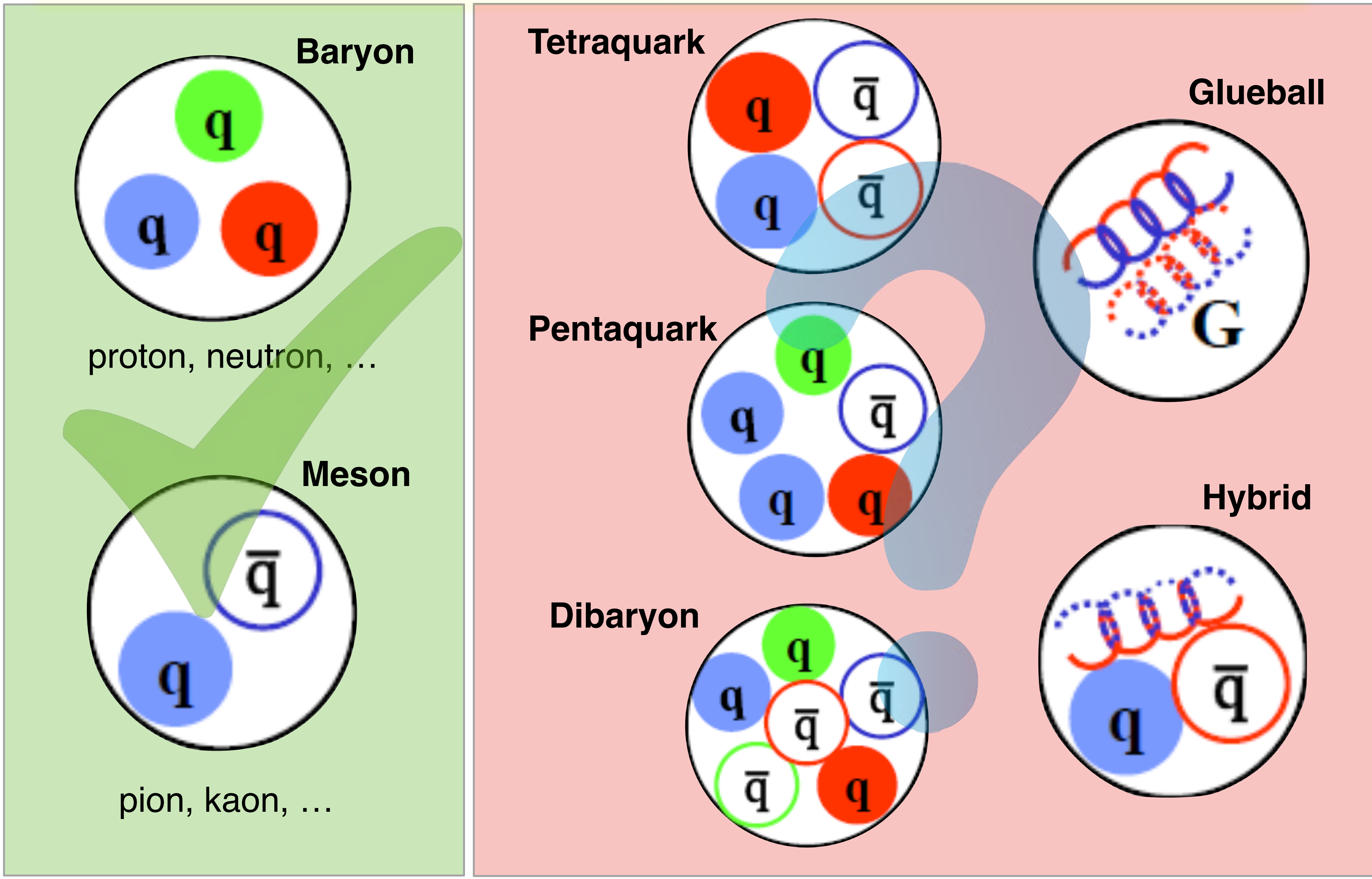


proton, neutron, …



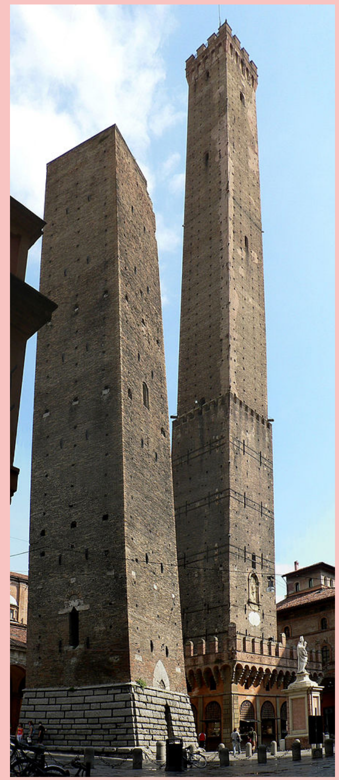
pion, kaon, …

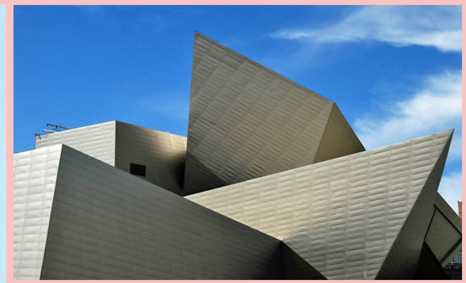
Ordinary versus “exotic” matter



Ordinary versus "exotic" matter

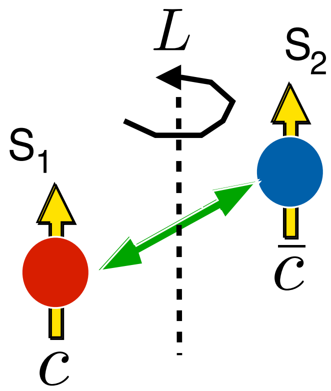
"ordinary matter"





"matter at extremes"

Charmonium - the “positronium” of QCD



$S = S_1 + S_2$

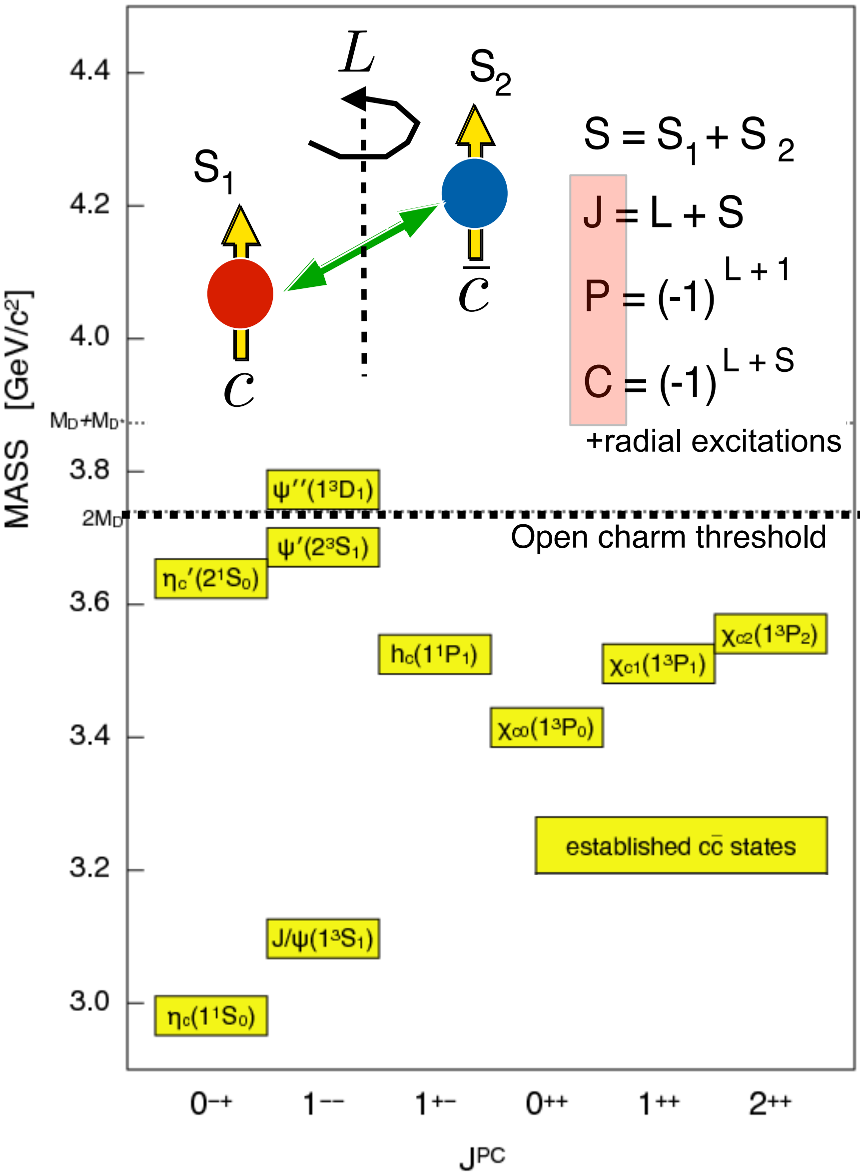
$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

+radial excitations

Charmonium - the “positronium” of QCD



Example from Barnes, Godfrey, Swanson:

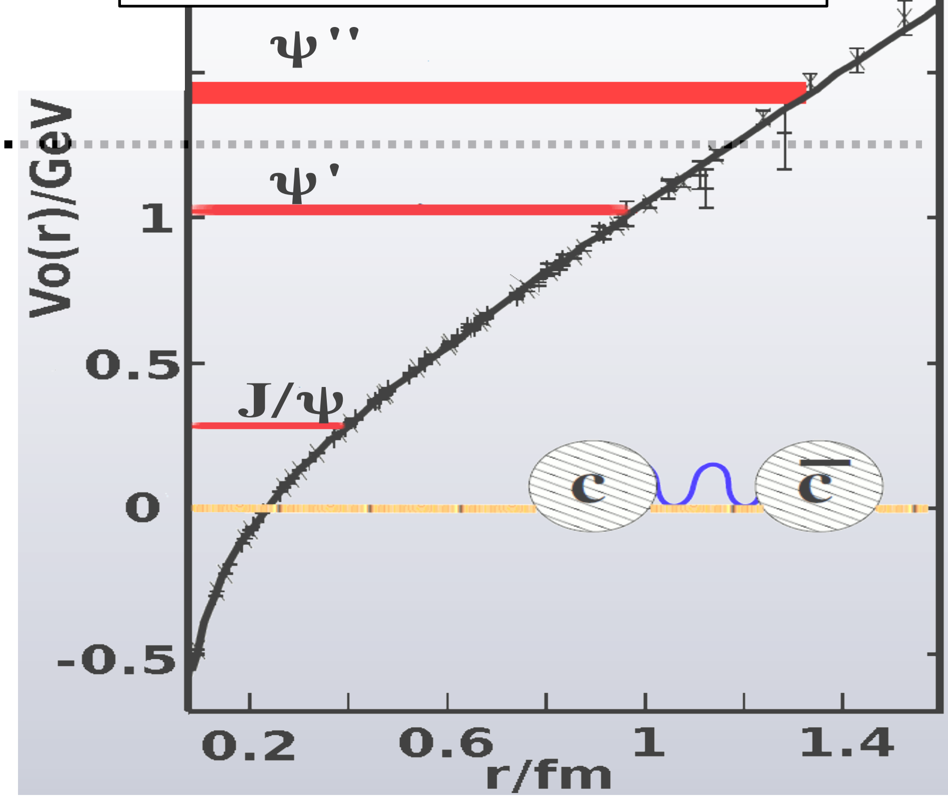
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{\mathrm{S}}_c\cdot\vec{\mathrm{S}}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

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

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)



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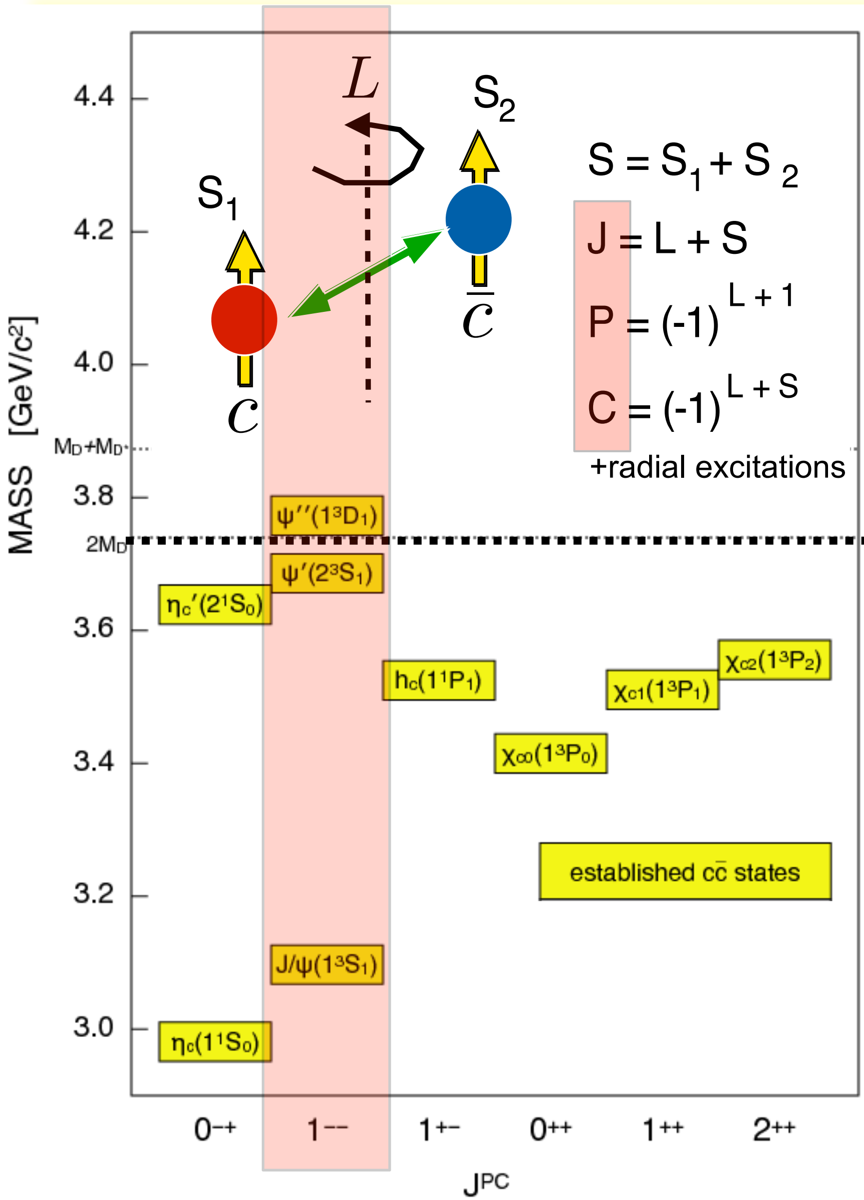

- Symmetric e^+e^- collider:
  - $\sqrt{s}$ = 2.0 - 4.6 GeV
- Design luminosity:
  - 1×10^{33} $cm^{-2}s^{-1}$ (at $\psi(3770)$, achieved in 04/2016)
- Data taking started in 2009

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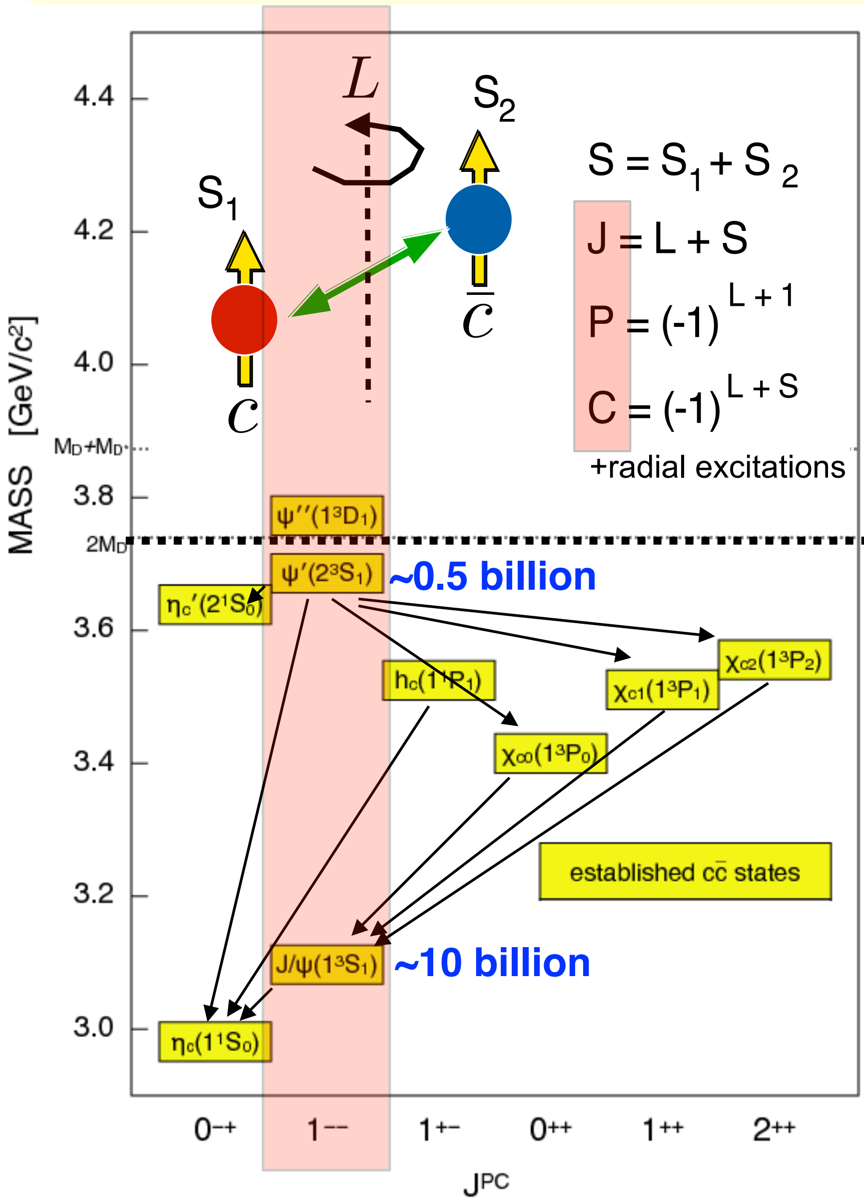

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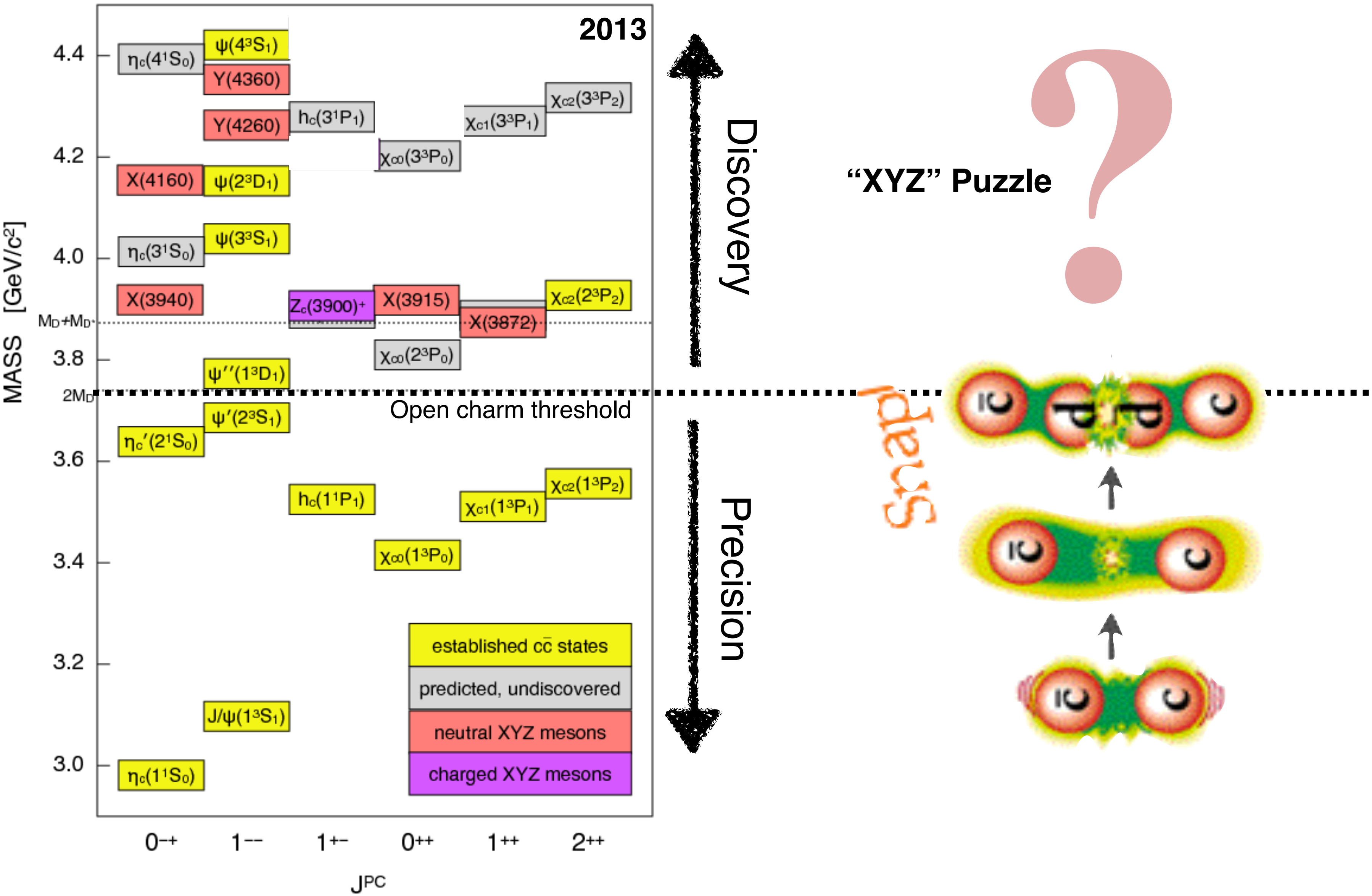
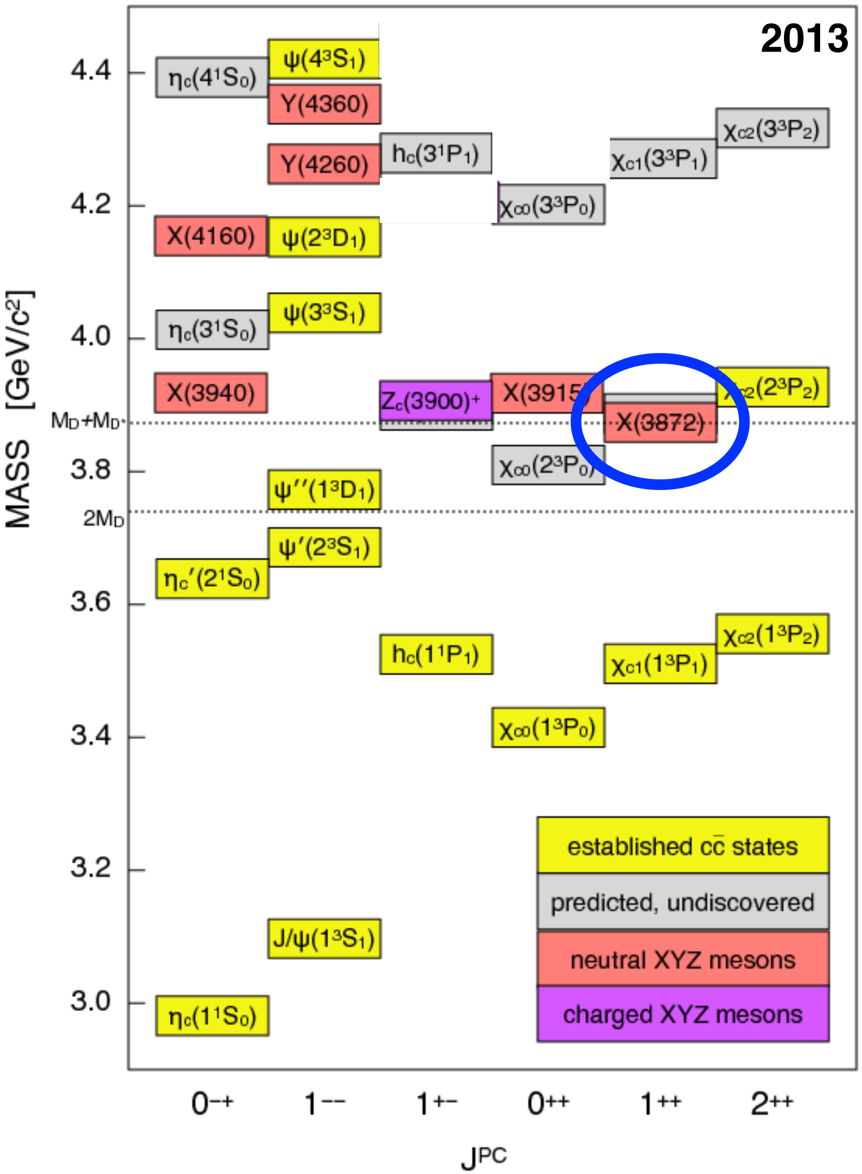
Charmonium-like particles - terra incognita



X(3872) - “Poster Boy” of a new era!



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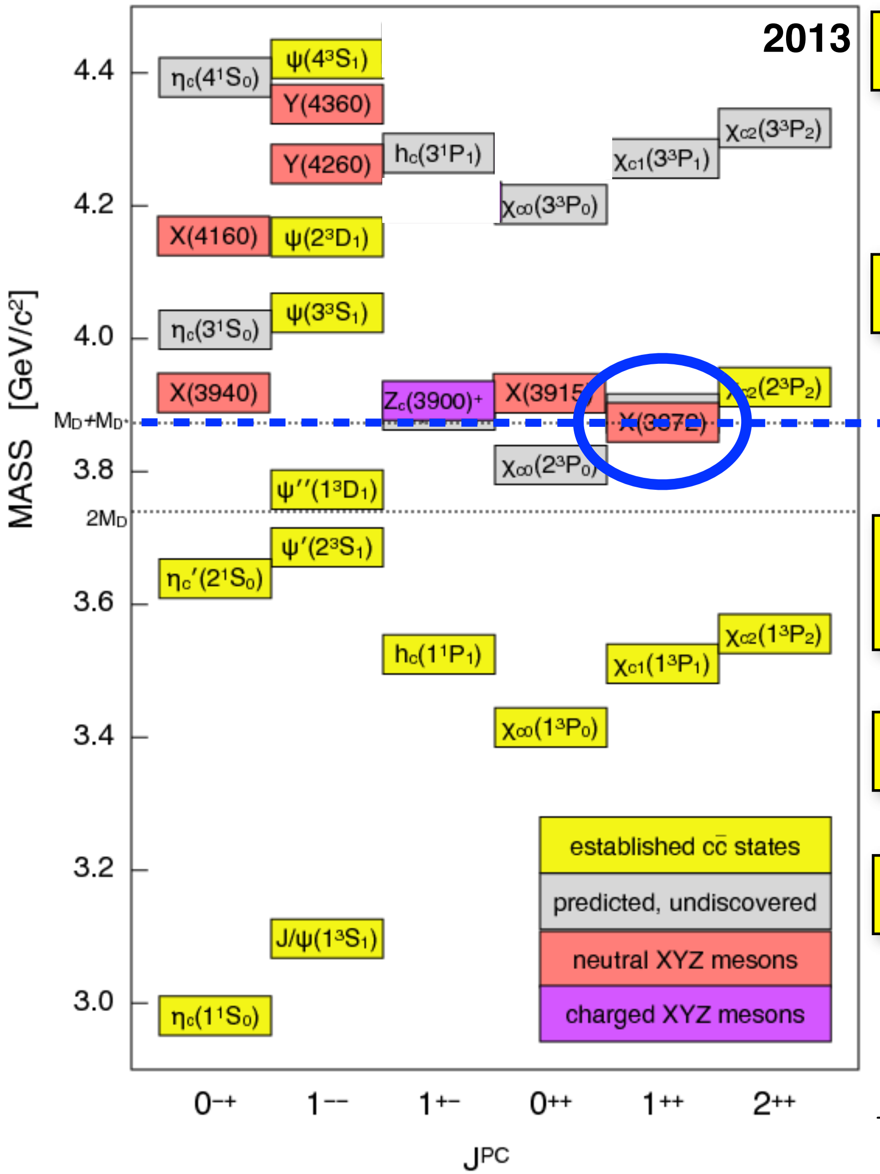


Surprisingly narrow $J^{PC}=1^{++}$ state:

$$\Gamma < 1.2\,\mathrm{MeV} \quad (\Gamma(\psi'') = 27\,\mathrm{MeV})$$

Suspiciously close to DD* threshold:

$$\Delta E = 0.01 \pm 0.18\ \mathrm{MeV}$$

Particle seen by *many* experiments, including BESIII!

No isospin partners found (yet)

… but hints towards isospin breaking:

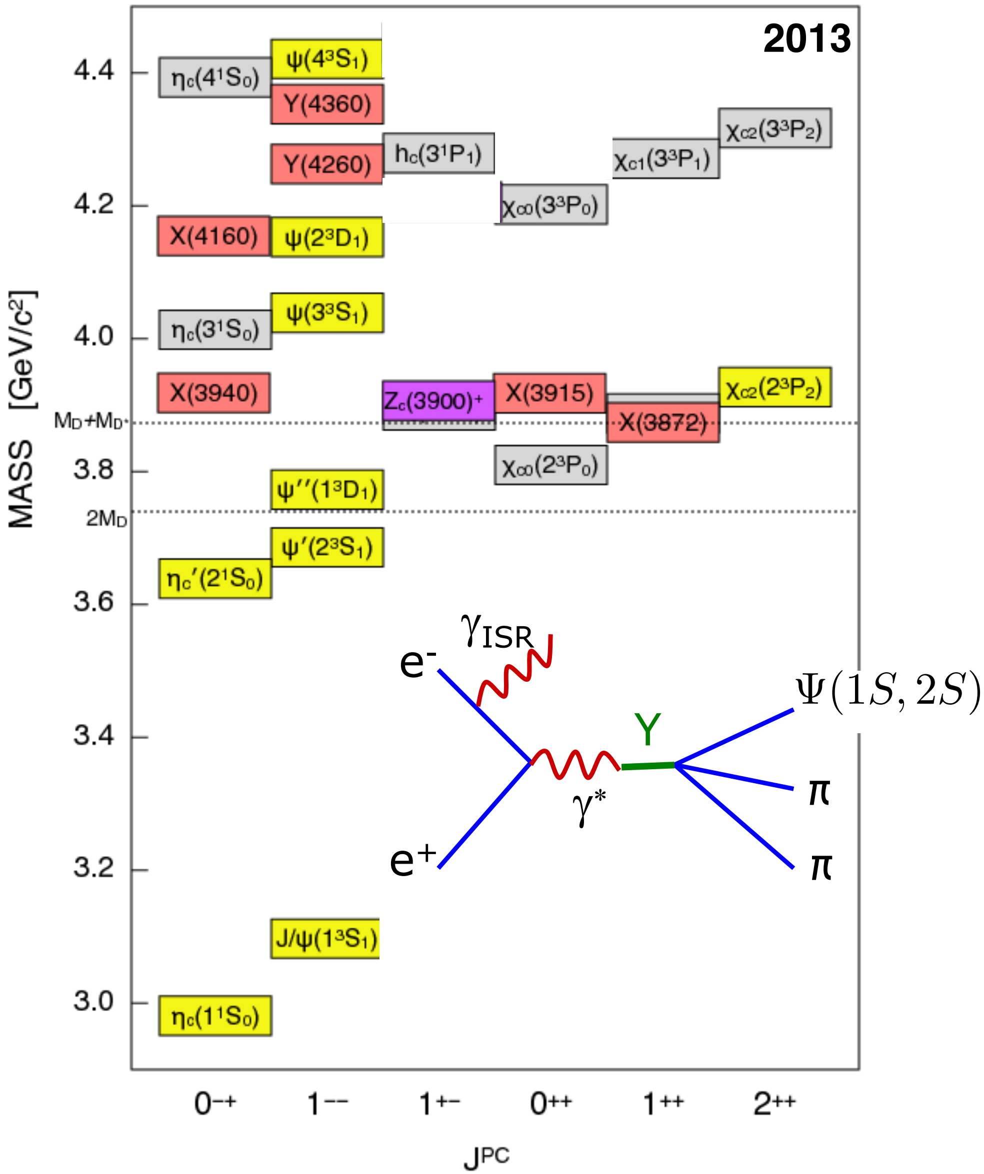
$$B(X \to \rho J/\Psi) \approx B(X \to \omega J/\Psi)$$

$$B(X \to \pi^0 \chi_{c1}) \approx B(X \to \pi\pi J/\Psi)$$

NEW!

BESIII: arXiv:1901.03992

The mysterious "Y" states: Y(4260, 4360, 4660)



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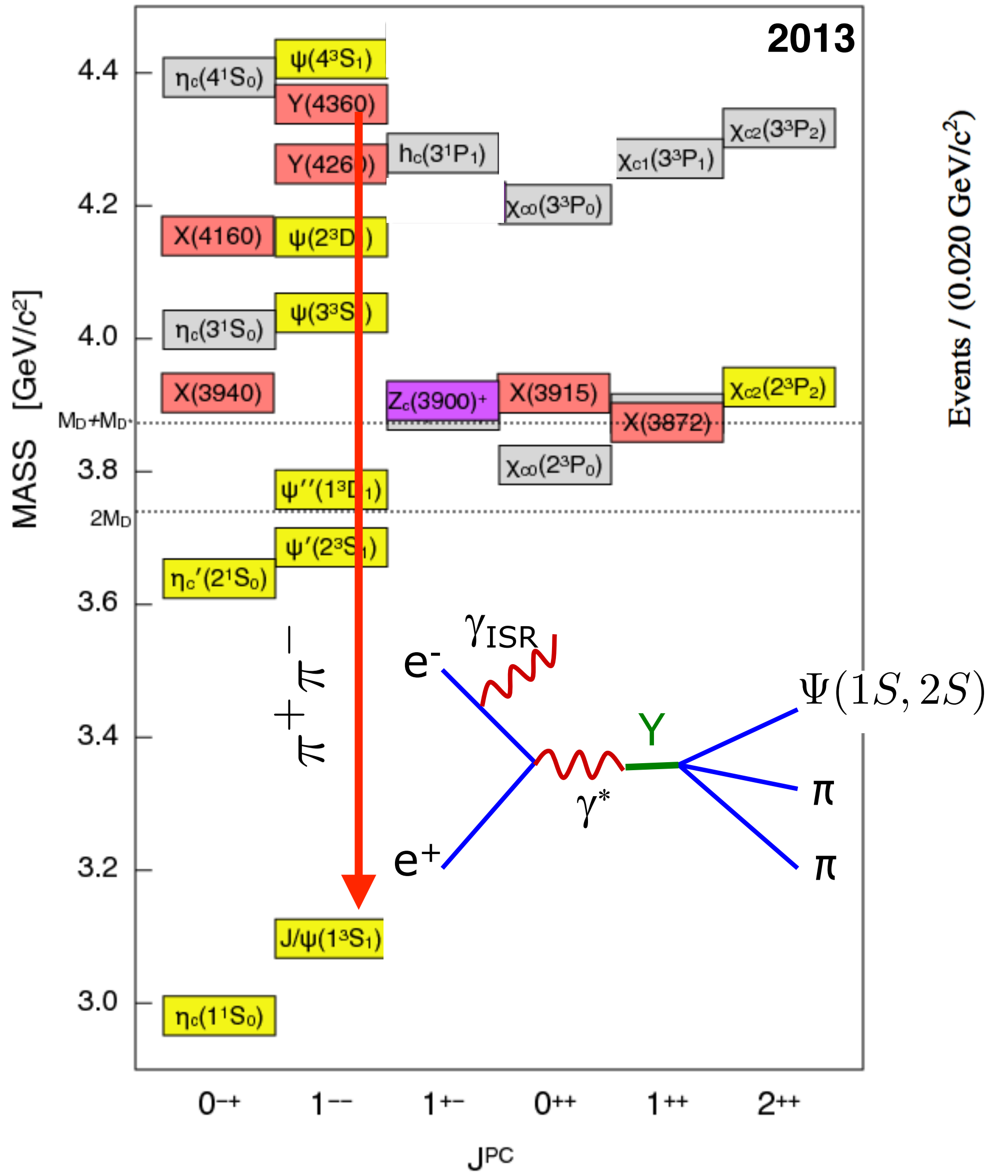
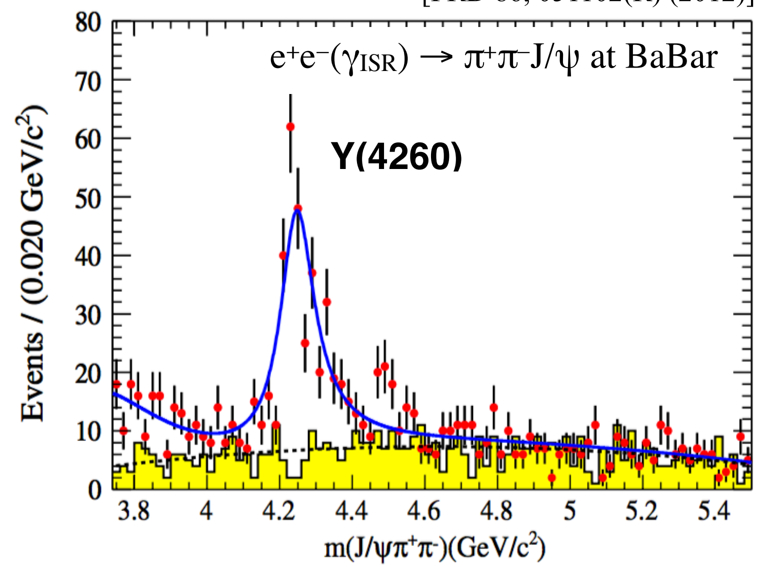


[PRD 86, 051102(R) (2012)]



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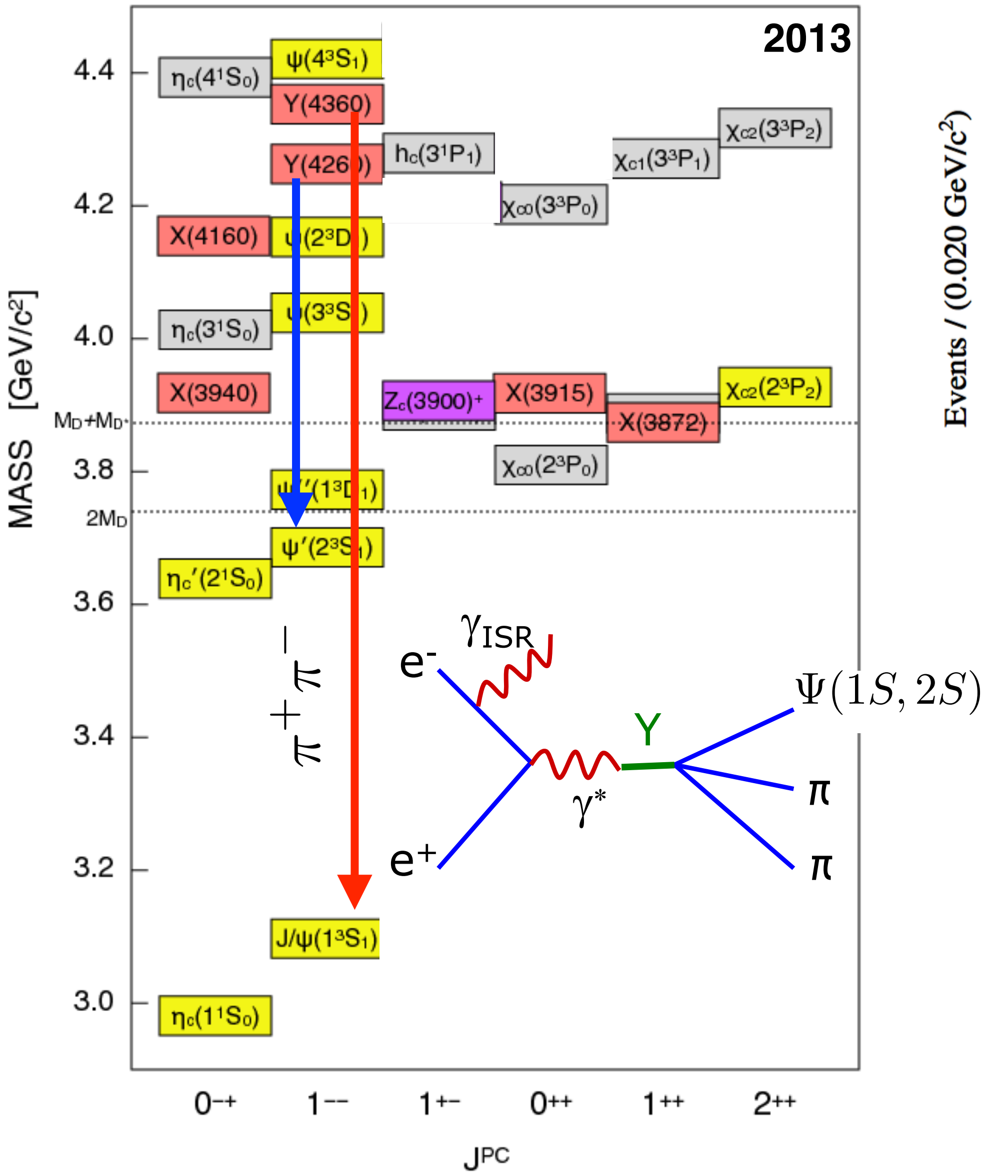
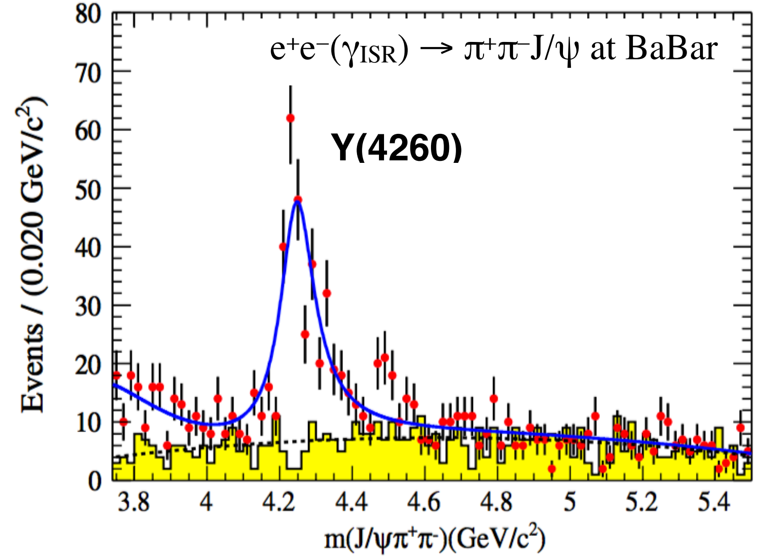
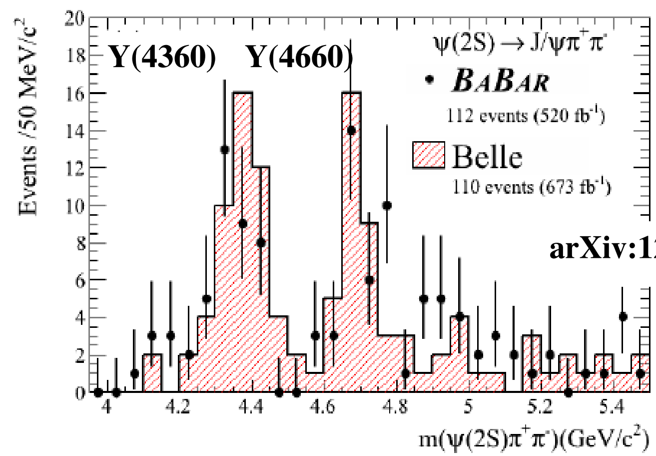


[PRD 86, 051102(R) (2012)]



$e^+e^-(\gamma_{ISR}) \to \pi^+\pi^-\psi(2S)$ at BaBar and Belle



arXiv:1211.62?1

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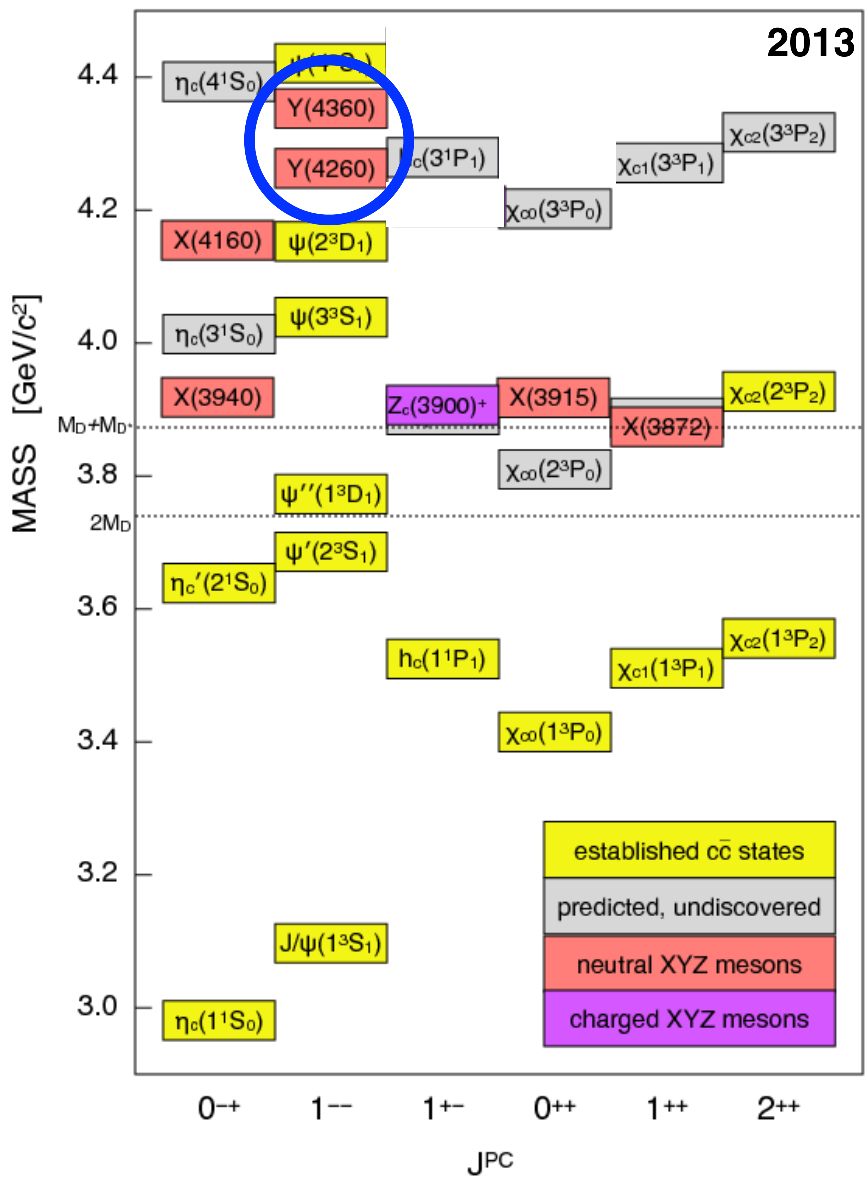
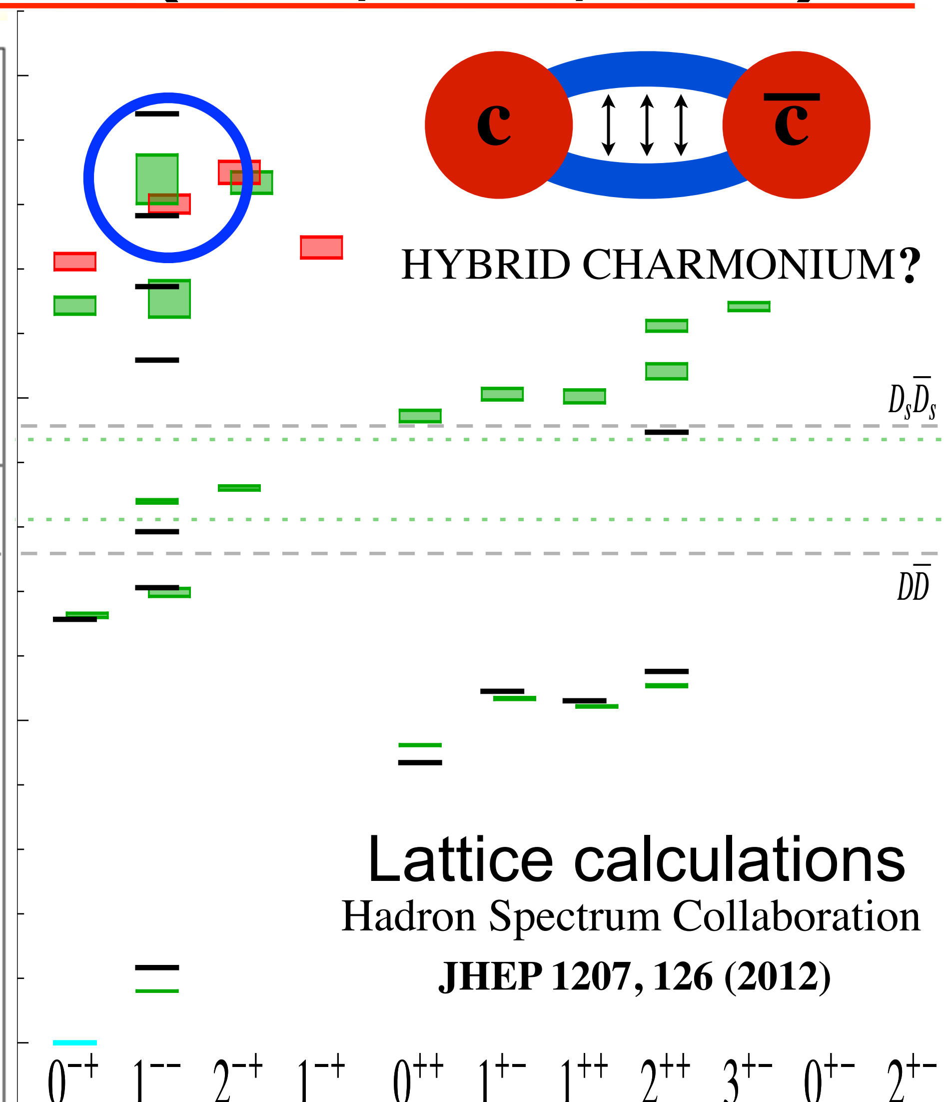
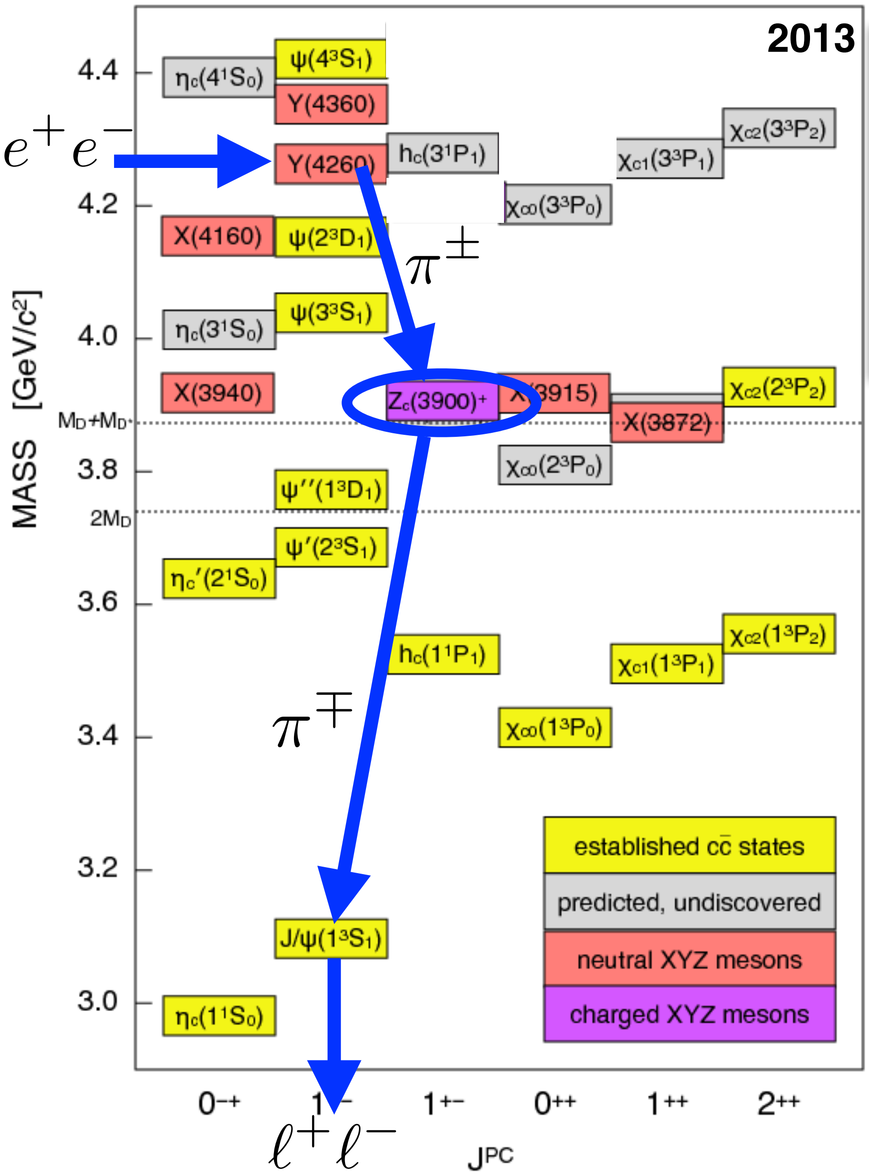
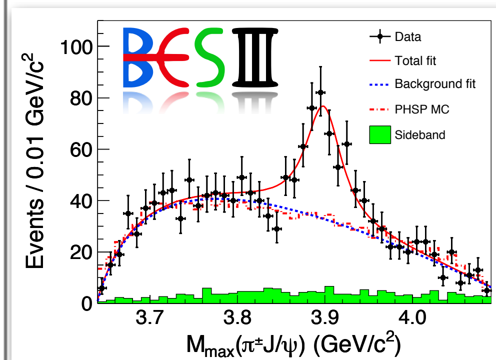


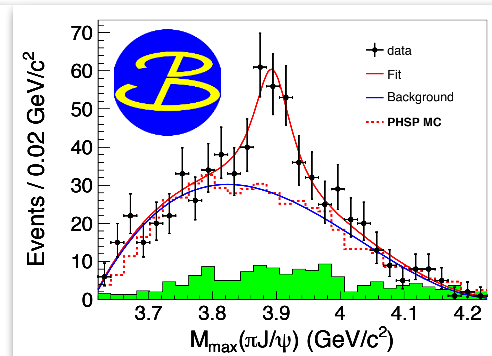


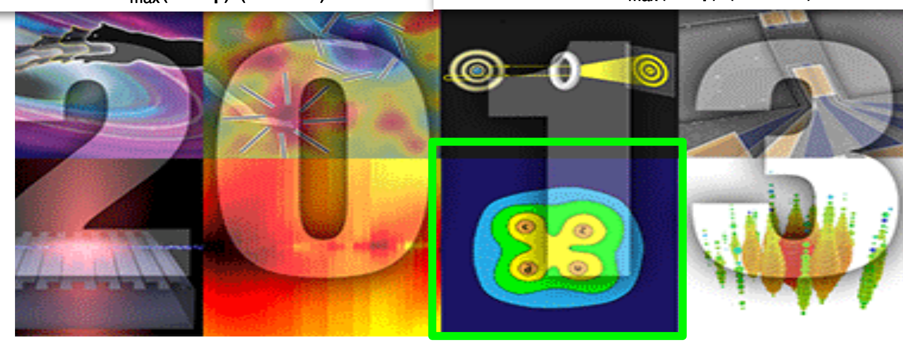
Z(3900) - APS highlight of 2013!

PRL110, 252001, 252001, 252002 (2013)









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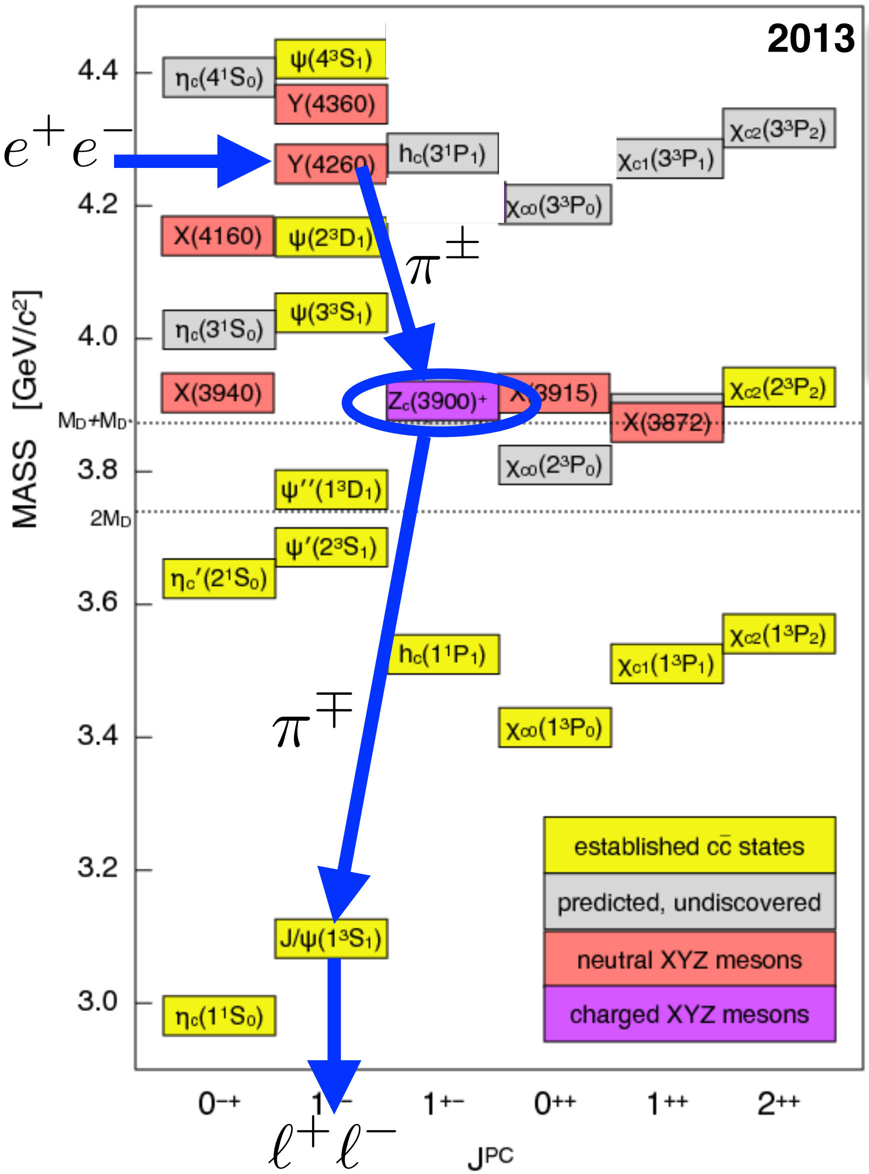
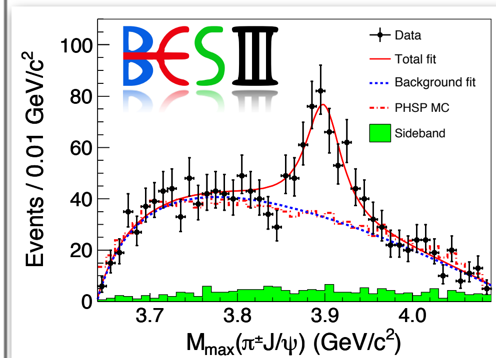
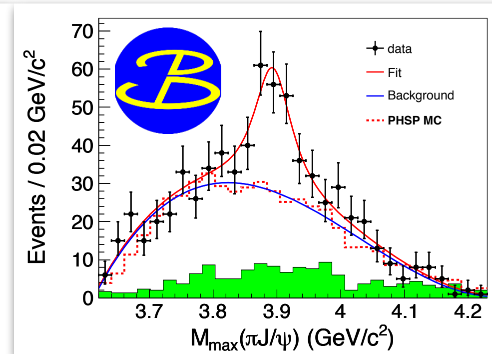
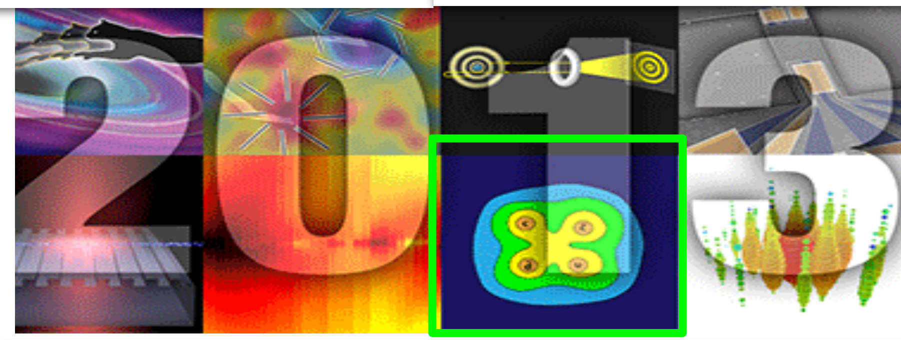








A charged and charmonium-rich state

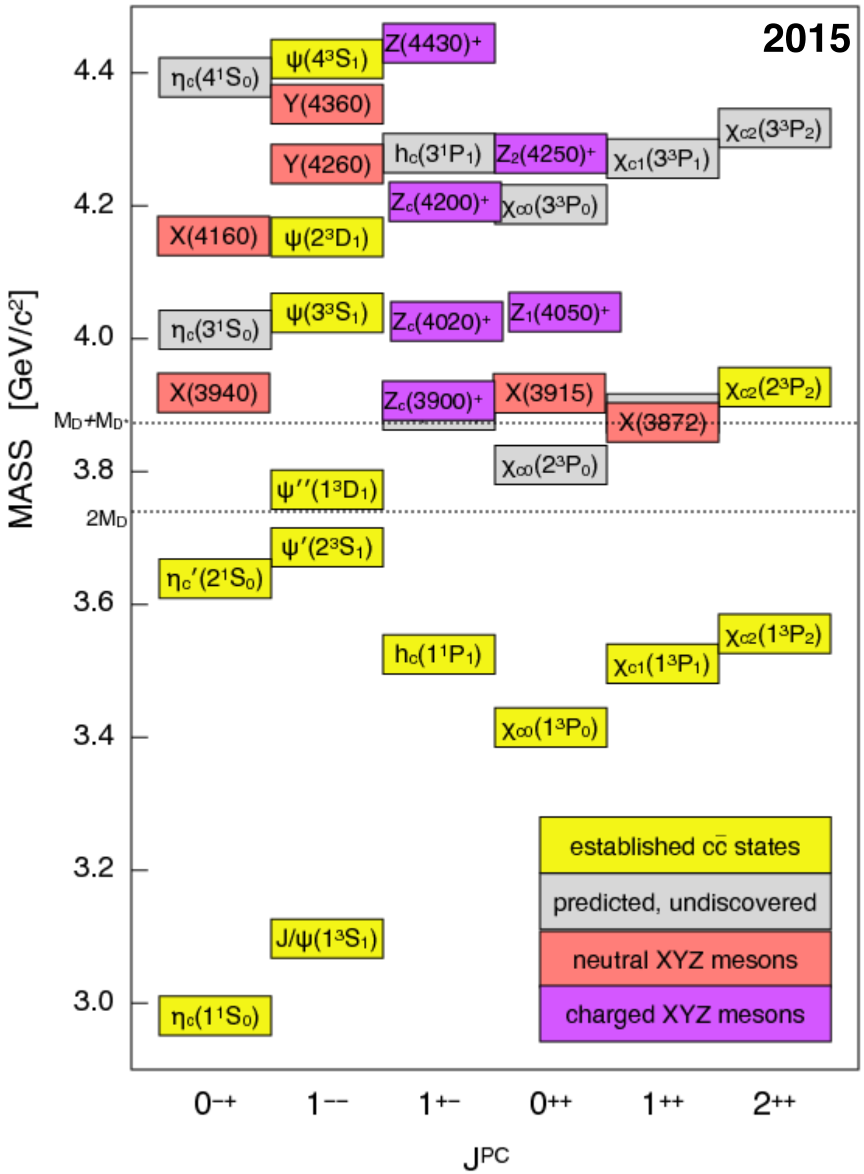
At least 4 quarks involved

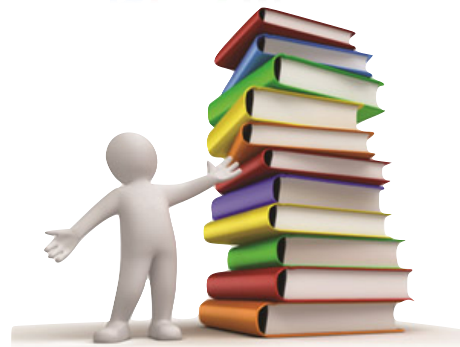
Confirmed by CLEO-c data

Spin-parity 1⁺: [BESIII, PRL119, 072001 (2017)]

More Z states discovered afterwards!

Z(3900) and beyond...





$Z_c(3900)$: PRL110, 252001 (2013)

$Z_c(4040)$: PRL112, 132001 (2014)

$Z_c(3885)$: PRL112, 022001 (2014)

$X(3872)$: PRL112, 092001 (2014)

$Z_c(4020)^0$: PRL113, 212002 (2014)

$X(3823)$: PRL115, 011803 (2015)

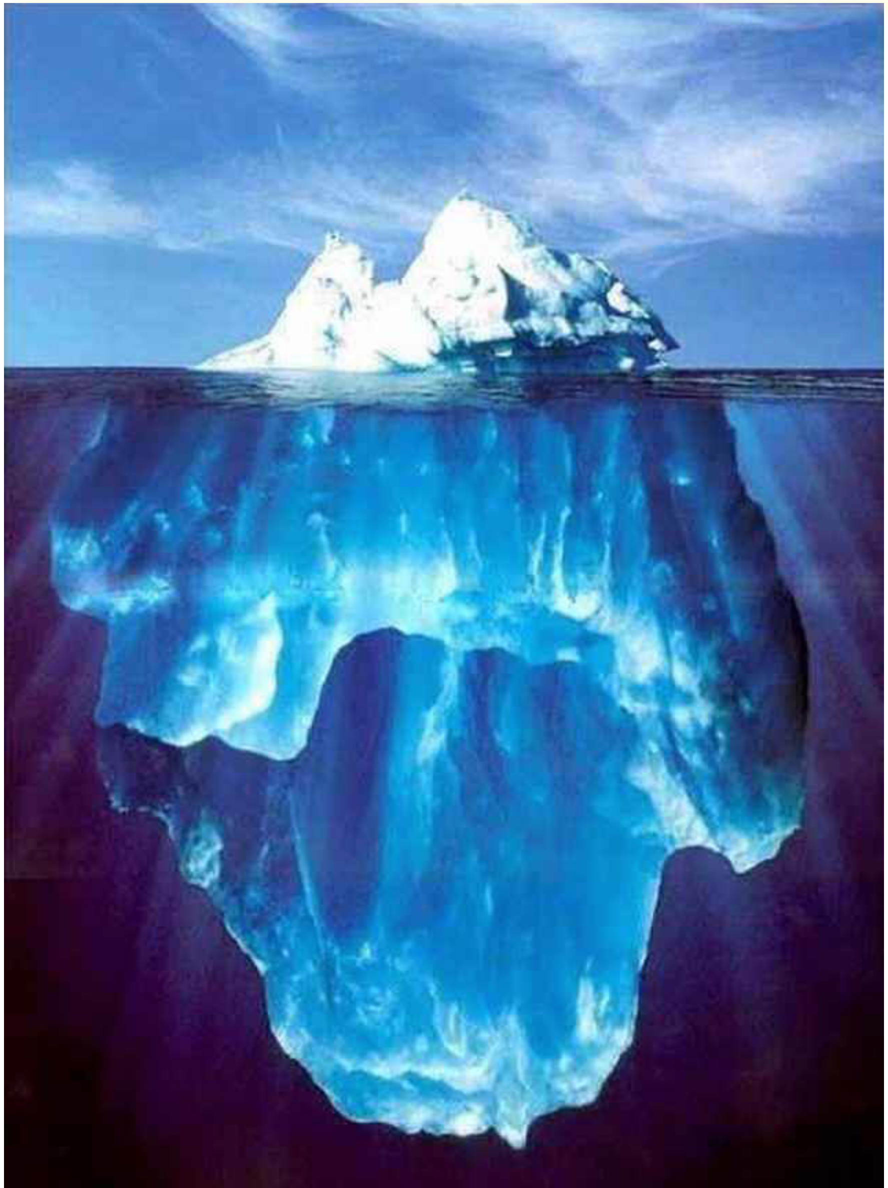
$Z_c(3900)^0$: PRL115, 112003 (2015)

$Z_c(4025)^0$: PRL115, 182002 (2015)

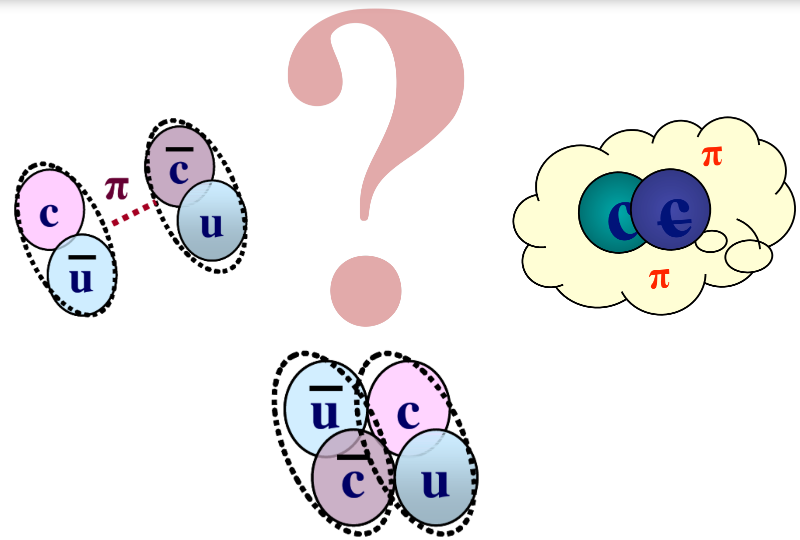
$Z_c(3885)^0$: PRL115, 222002 (2015)

Multiplet(s) of new matter discovered!

Break-through! It is just the beginning…



XYZ particles: tip of the iceberg?



Internal structure?

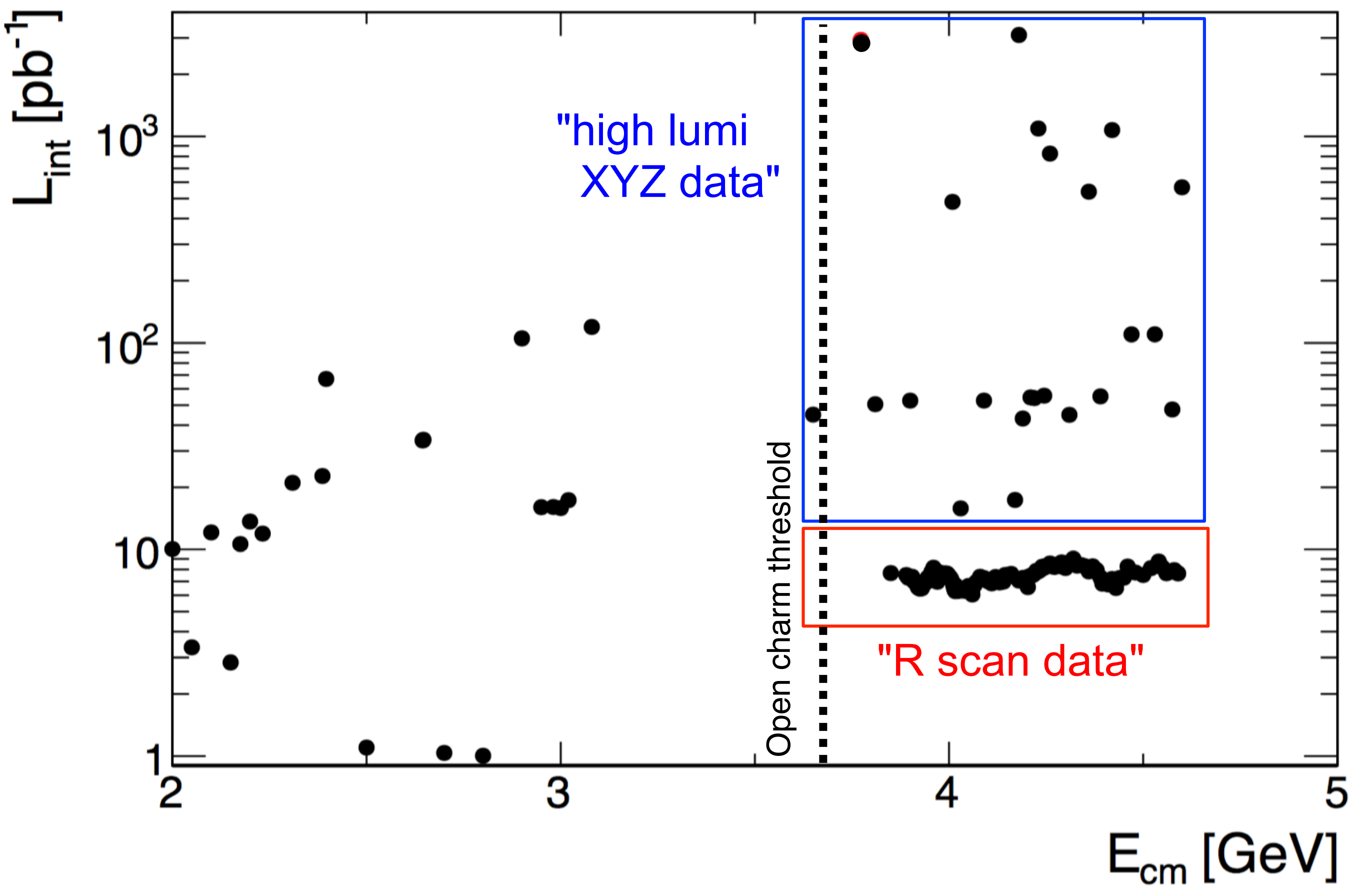
Level scheme?

Spin-parity J^{PC}?

Width/lifetime?

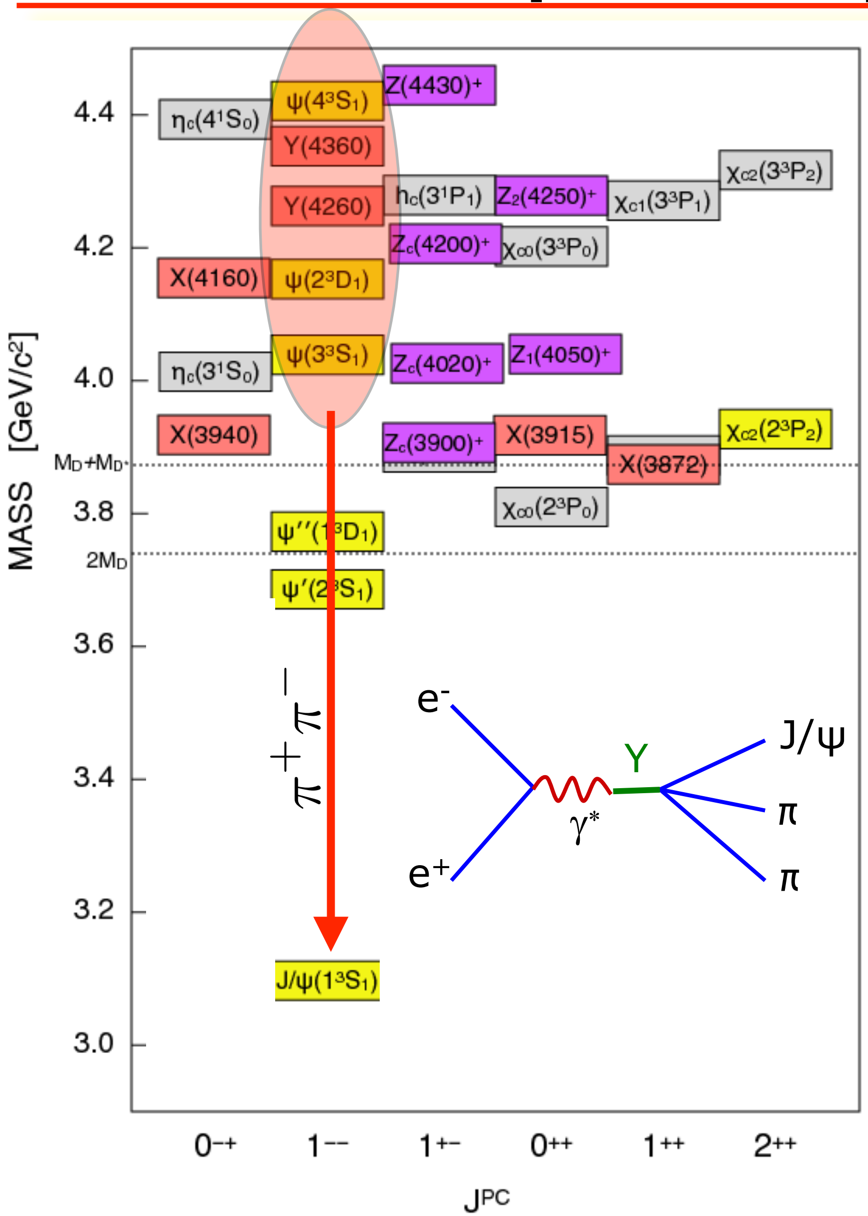
Production and decay?

From discovery towards precision



- XYZ region: 3.8 ~ 4.6 GeV, integrated luminosity: **12 fb^{-1}**
- 104 energy points between 3.85 and 4.59 GeV *(R scan)*
- ~20 energy points between 2.0 and 3.1 GeV

Precision "Y" spectroscopy at BESIII



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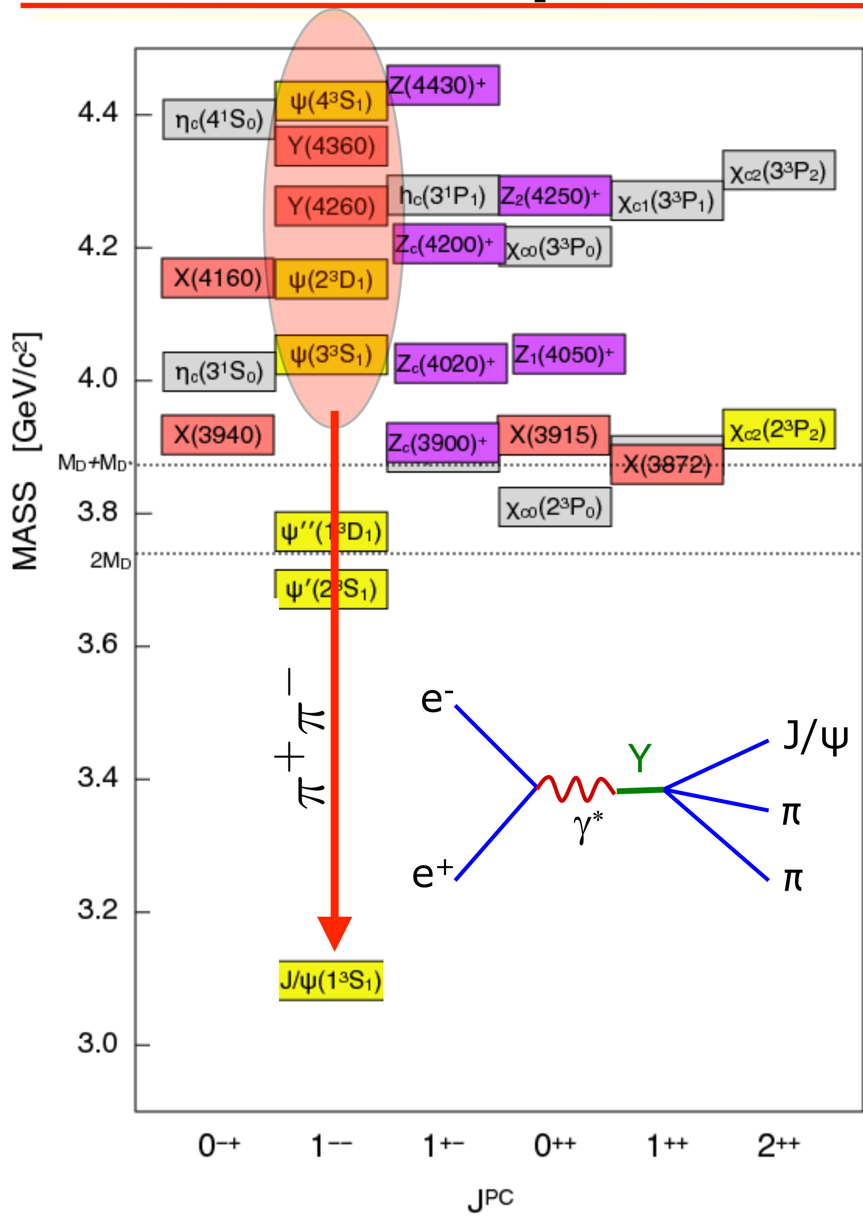
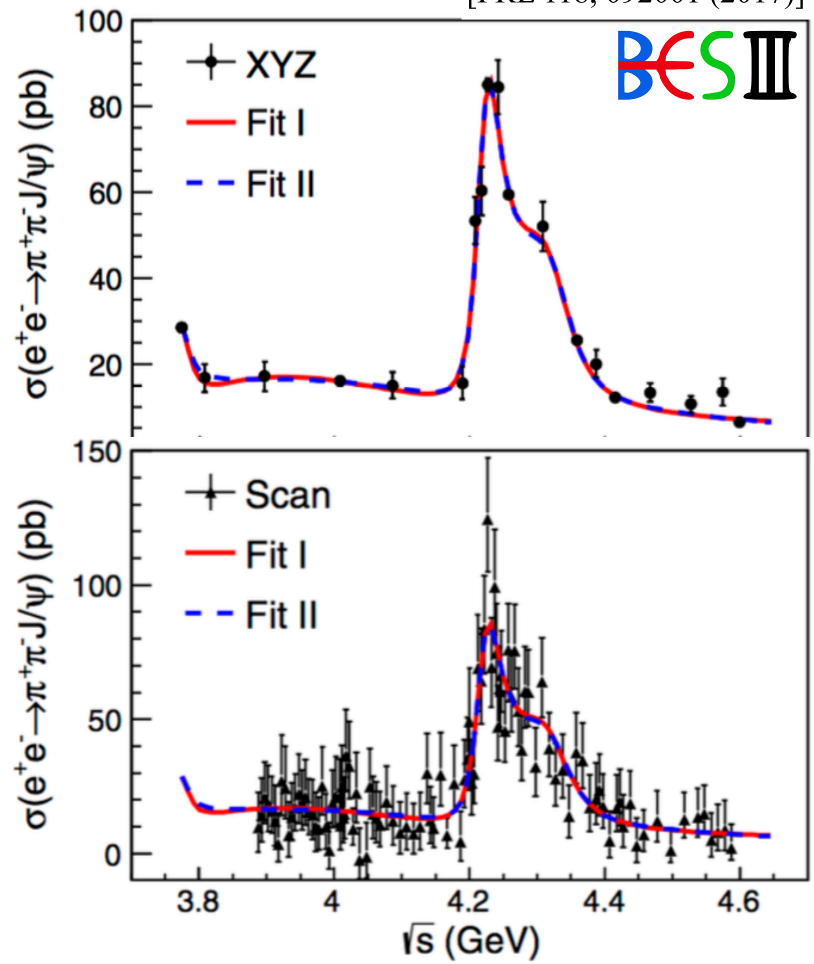


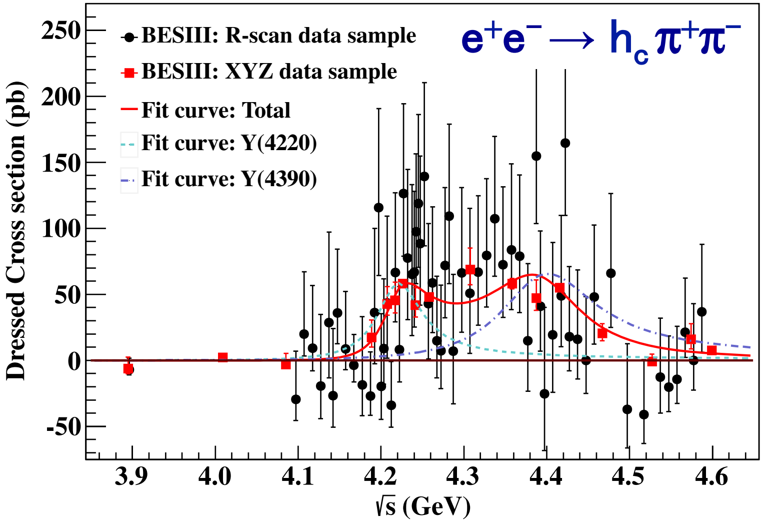
[PRL 118, 092001 (2017)]



Two resonances!

Precision “Y” spectroscopy at BESIII

[PRL 118, 092002 (2017)]



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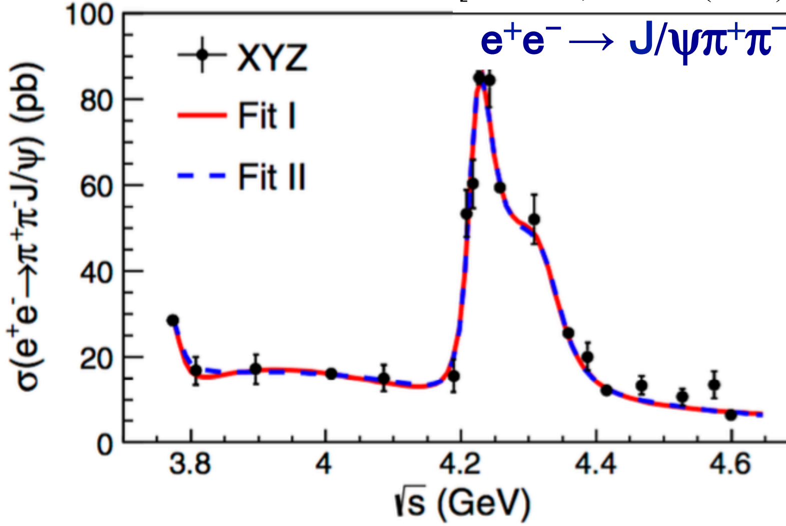
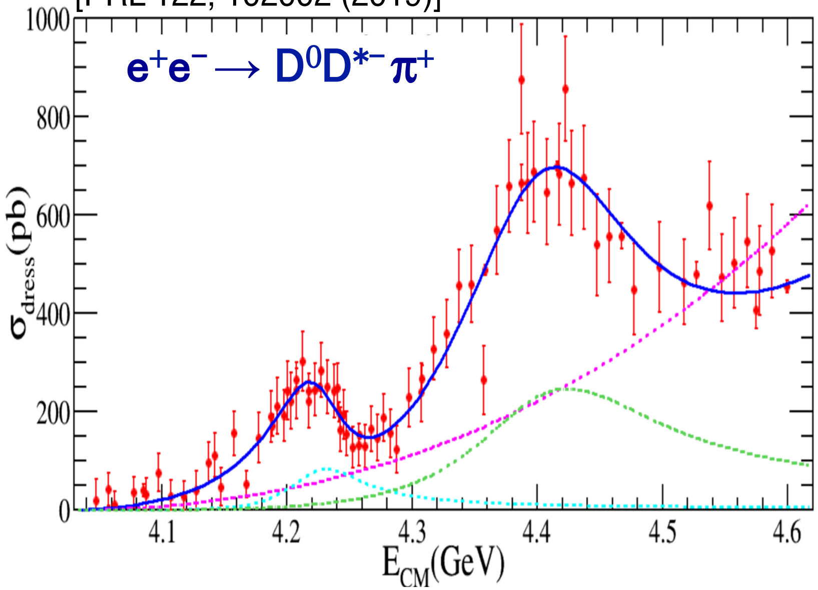
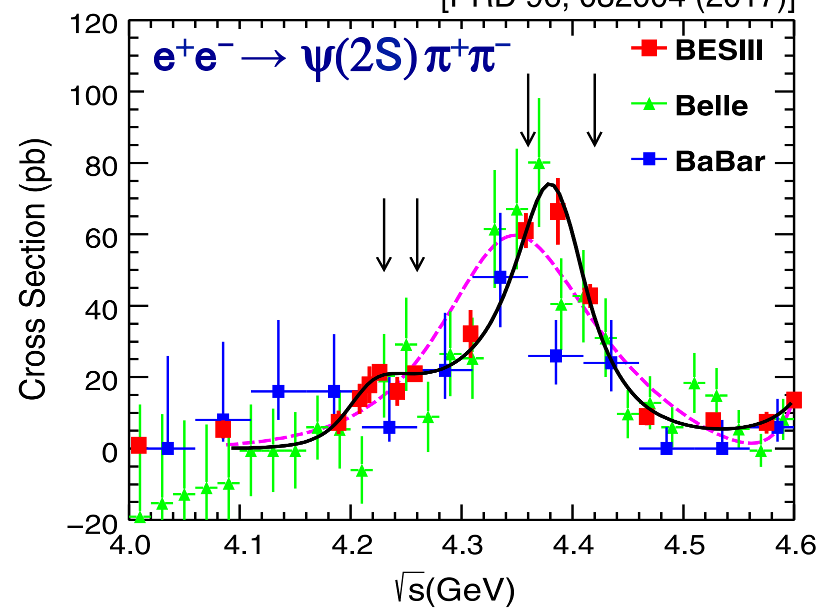


[PRL 122, 102002 (2019)]



[PRD 96, 032004 (2017)]



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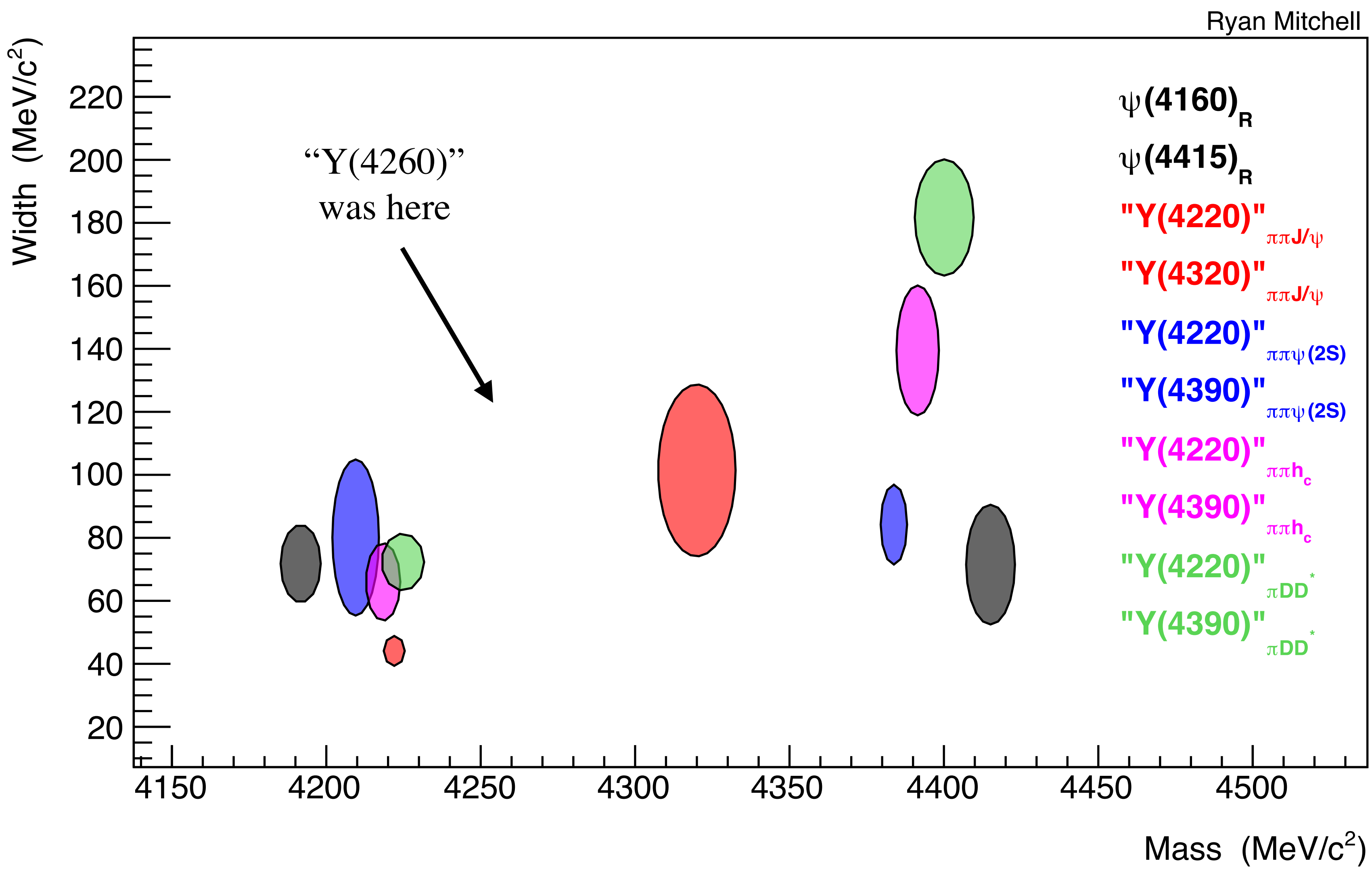

The next generation...

BESIII at IHEP, China

> electron+positron, upgrade foreseen

> couples to $J^{PC}=1^{--}$ states

> clean environment

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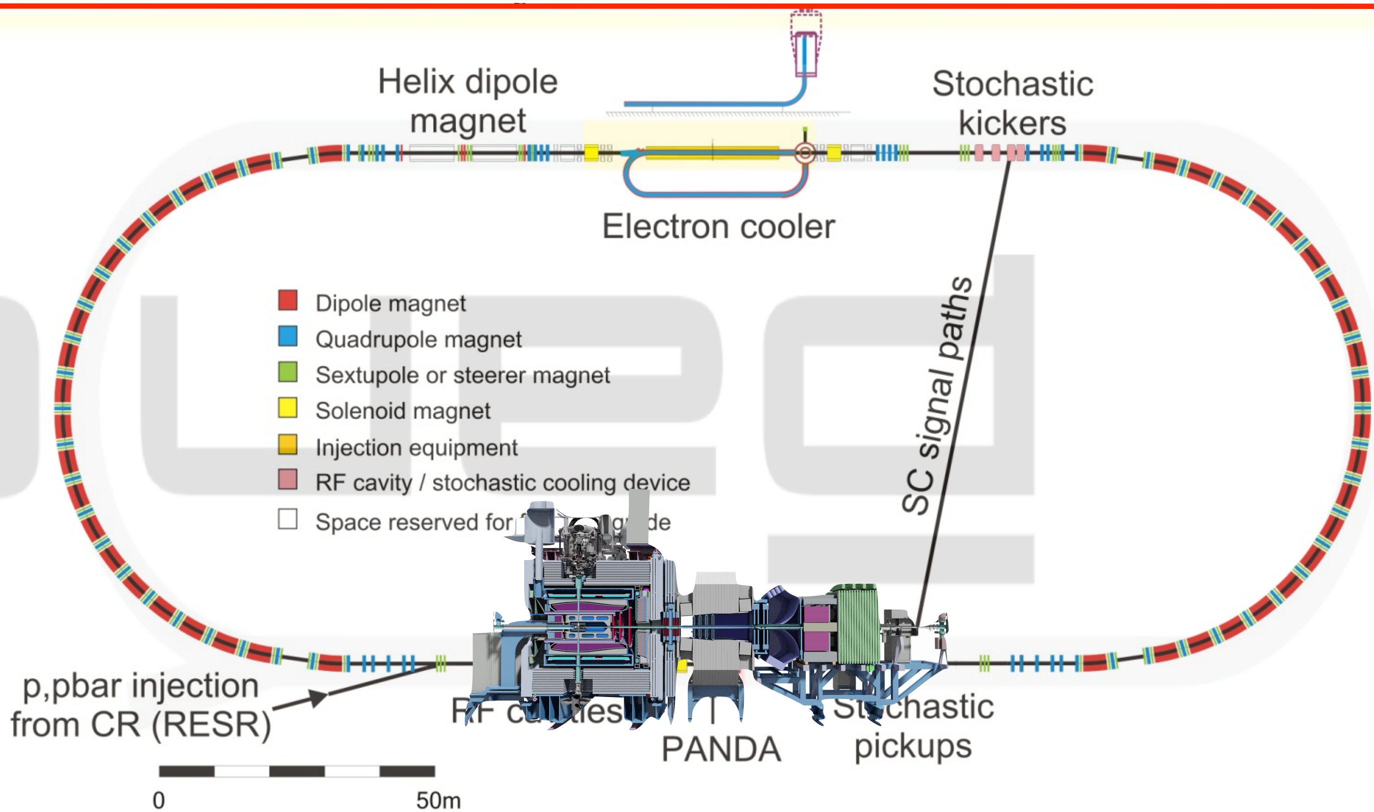
PANDA at FAIR, Germany

> **anti-proton**+proton or light nuclei

> couples to **all** conventional J^{PC} states

> hadronic environment, background

High **E**nergy **S**torage **R**ing - *precision* antiprotons



High resolution mode:

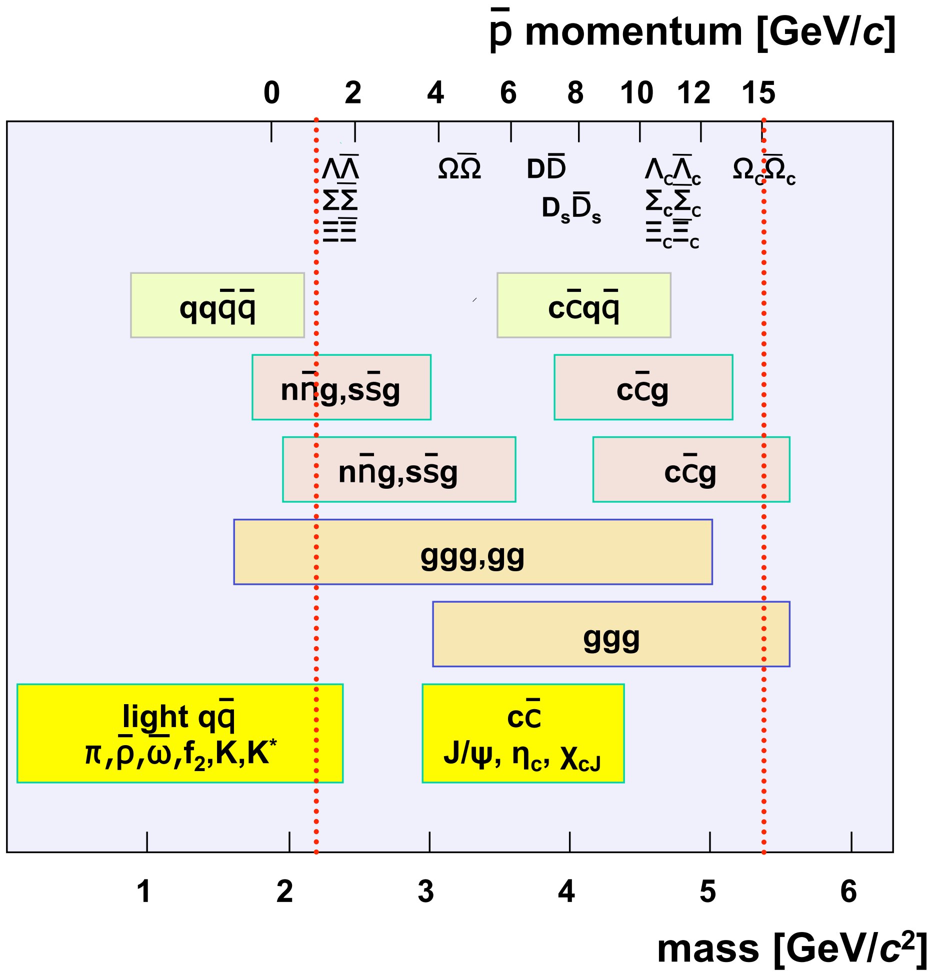
- e^- cooling : p<8.9 GeV/c
- 10^{10} antiprotons stored
- Luminosity up to $2\text{x}10^{31}$ $cm^{-2}s^{-1}$
- dp/p = $4\text{x}10^{-5}$

High intensity mode:

- Stochastic cooling
- 10^{11} antiprotons stored
- Luminosity up to $2\text{x}10^{32}$ $cm^{-2}s^{-1}$
- dp/p = $2\text{x}10^{-4}$

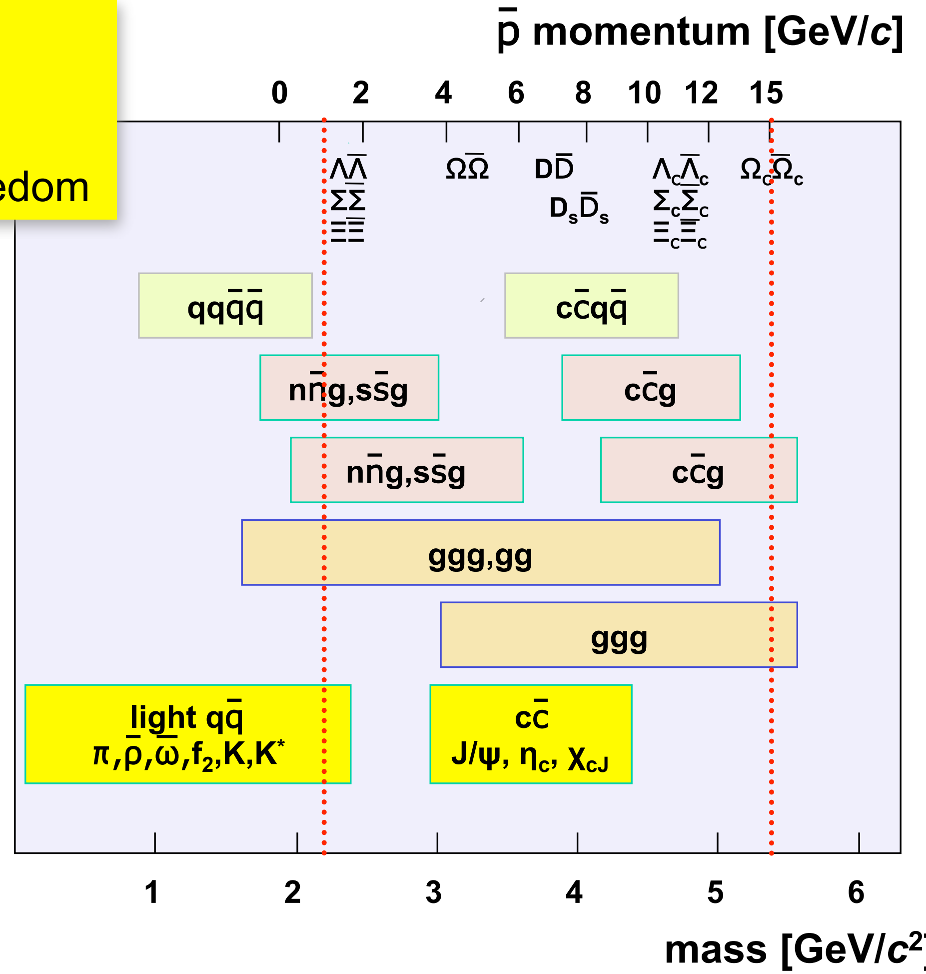
Phase 1+2: max. 10^{10} antiprotons stored

Versatility of antiprotons



Versatility of antiprotons

Large mass-scale coverage
- center-of-mass energies from 2 to 5.5 GeV
- from light, strange, to charm-rich hadrons
- from quark/gluons to hadronic degrees of freedom



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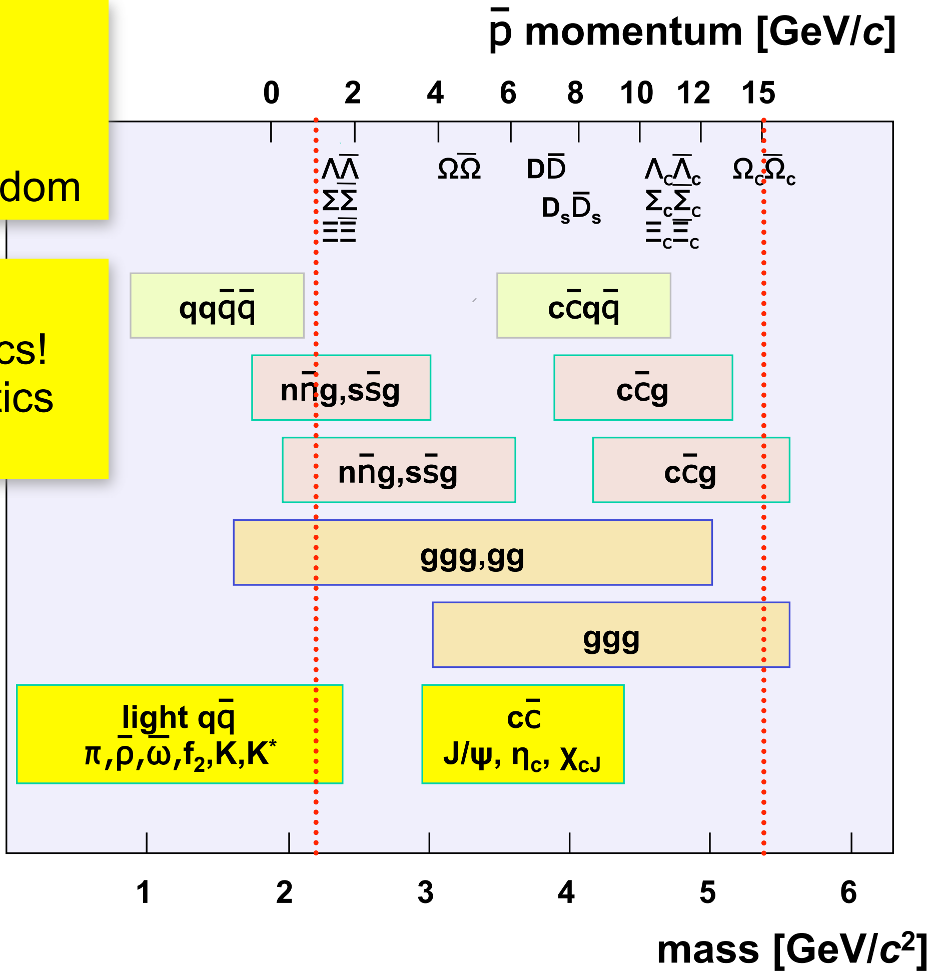
High hadronic production rates
- charm+strange factory -> discovery by statistics!
- gluon-rich production -> potential for new exotics
- good perspectives already at “Day-One"!



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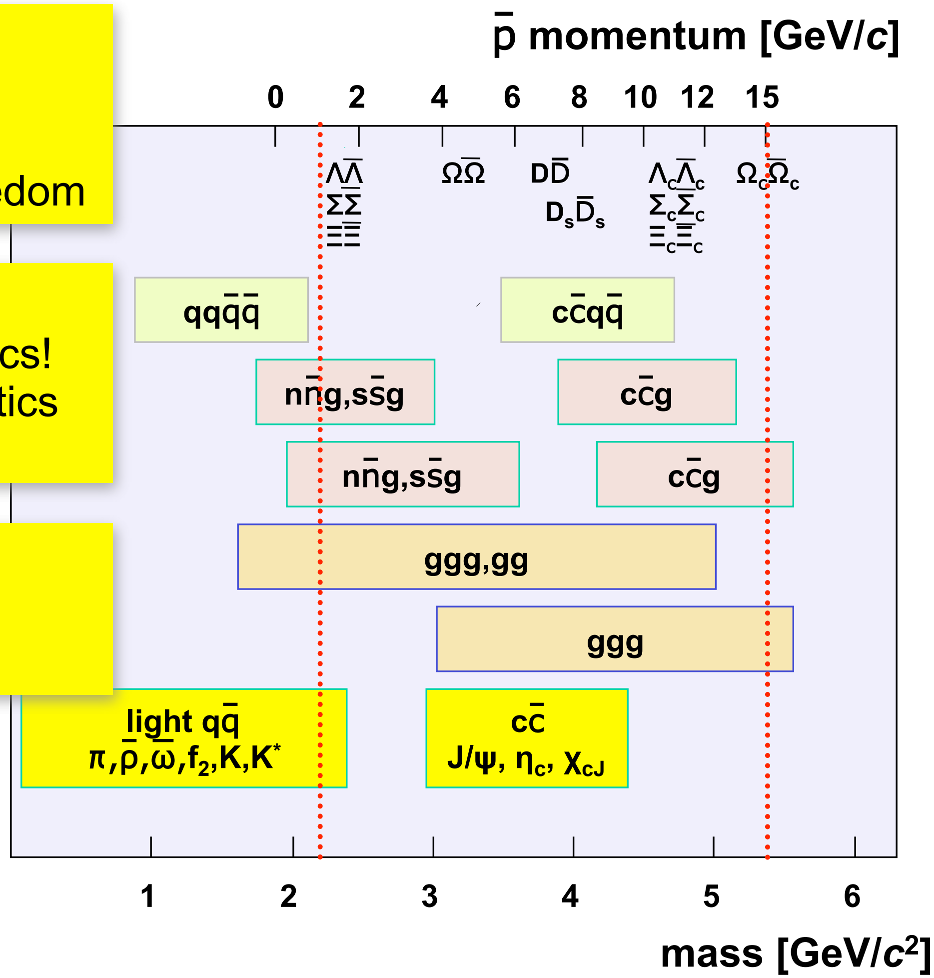
Access to large spectrum of J^{PC} states
- direct formation of *all* conventional J^{PC} states
- large sensitivity to high spin states



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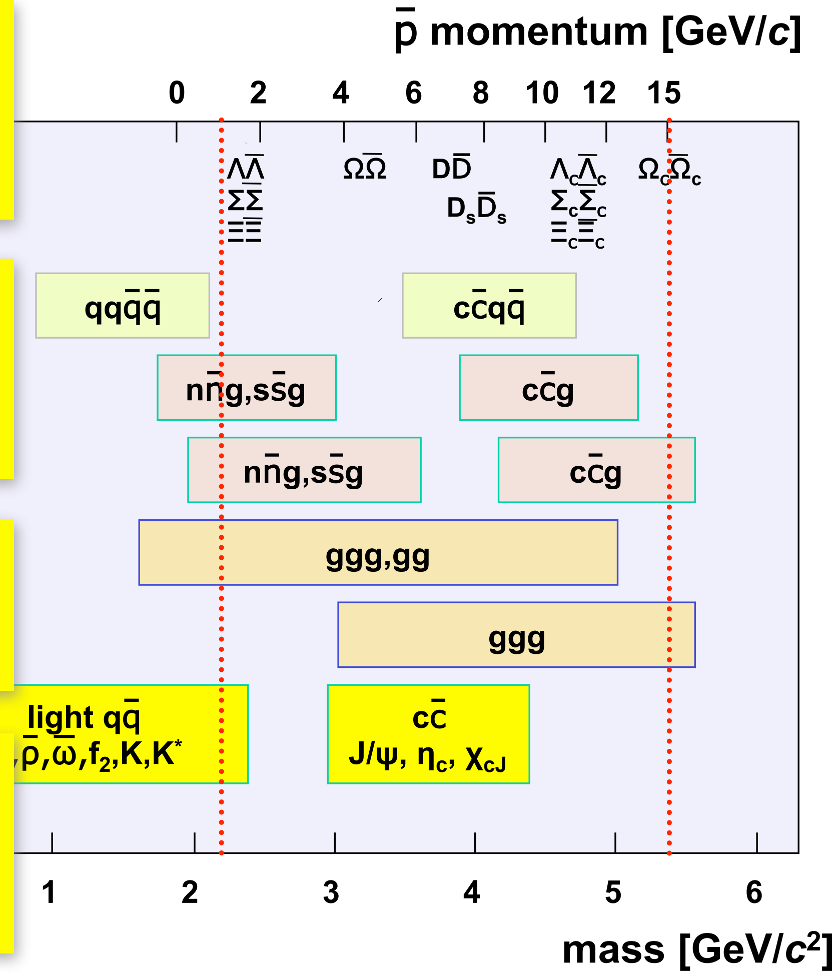
Associated hadron-pair production
- access to hidden-strange/charm hadrons
- tagging possibilities
- near thresh.: good resolution and low background



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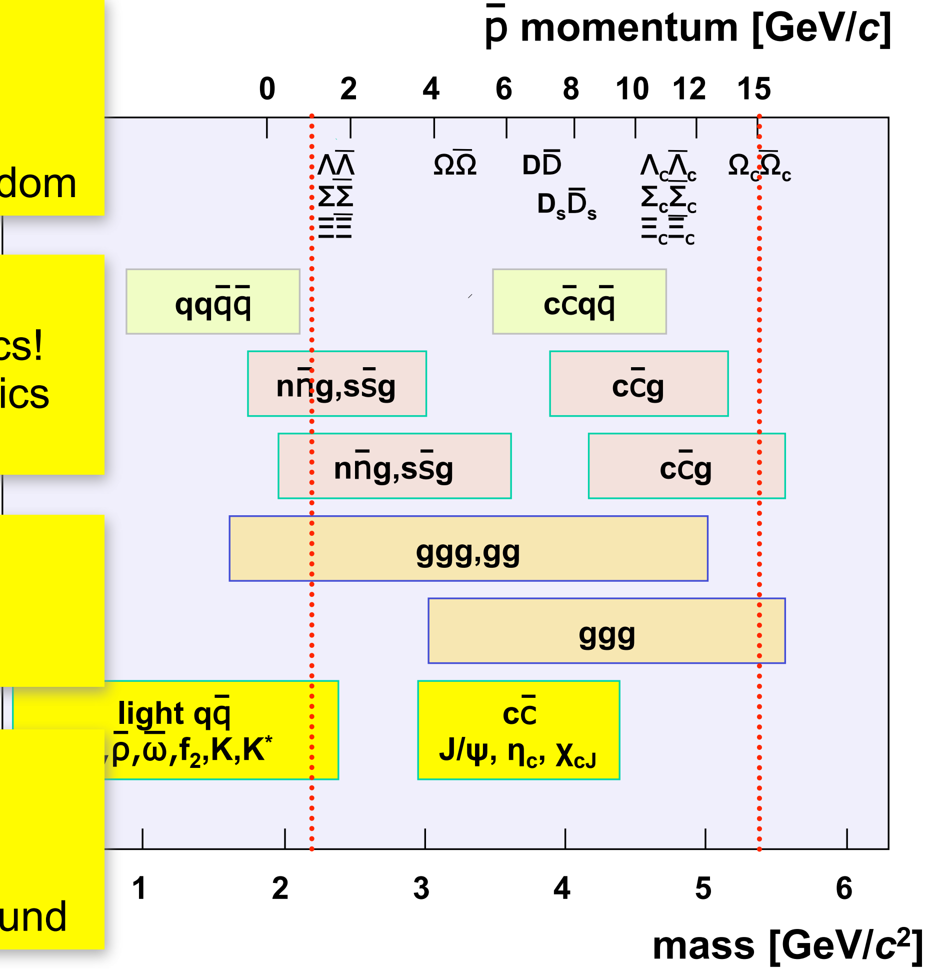


Systematic and precise tool to rigorously study the dynamics of QCD

PANDA physics: interdisciplinary

HEP underlying elementary processes

Spectroscopy

New narrow XYZ:
Search for partner states

Production of exotic QCD states:
Glueballs & hybrids

HEP interference of coupled channels

Nucleon Structure

Generalized parton distributions:
Orbital angular momentum

Drell Yan process:
Transverse structure, valence anti-quarks

Time-like form factors:
Low and high E, e and μ pairs

Bound States of Strong Interaction

astrophysics strange n-stars

Strangeness

Strange baryons:
Spectroscopy
Polarization

nuclear physics hyper-nuclear spectroscopy

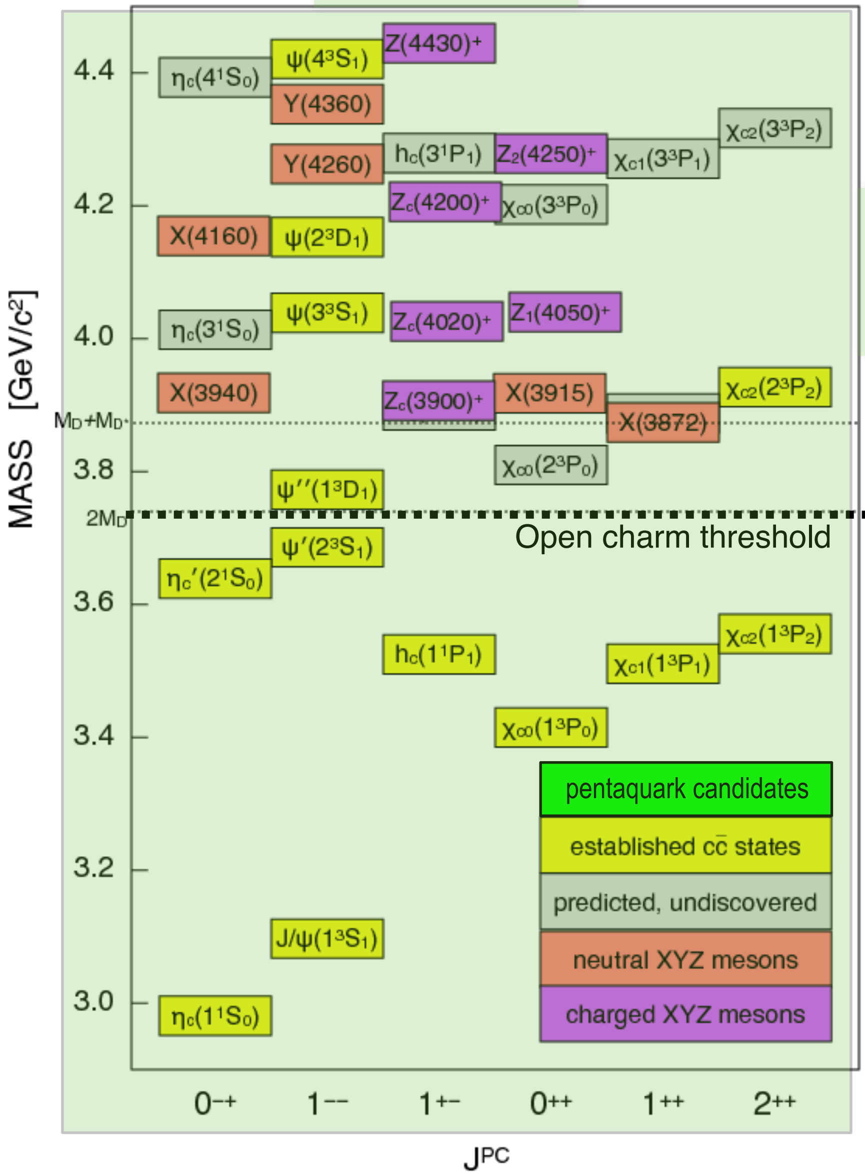
Nuclear Physics

Hypernuclear physics:
Double Λ hypernuclei
Hyperon interaction

Hadrons in nuclei:
Charm and strangeness in the medium

HI collisions comparing QGP to elementary reactions

Charmonium-like particles - PANDA opportunities

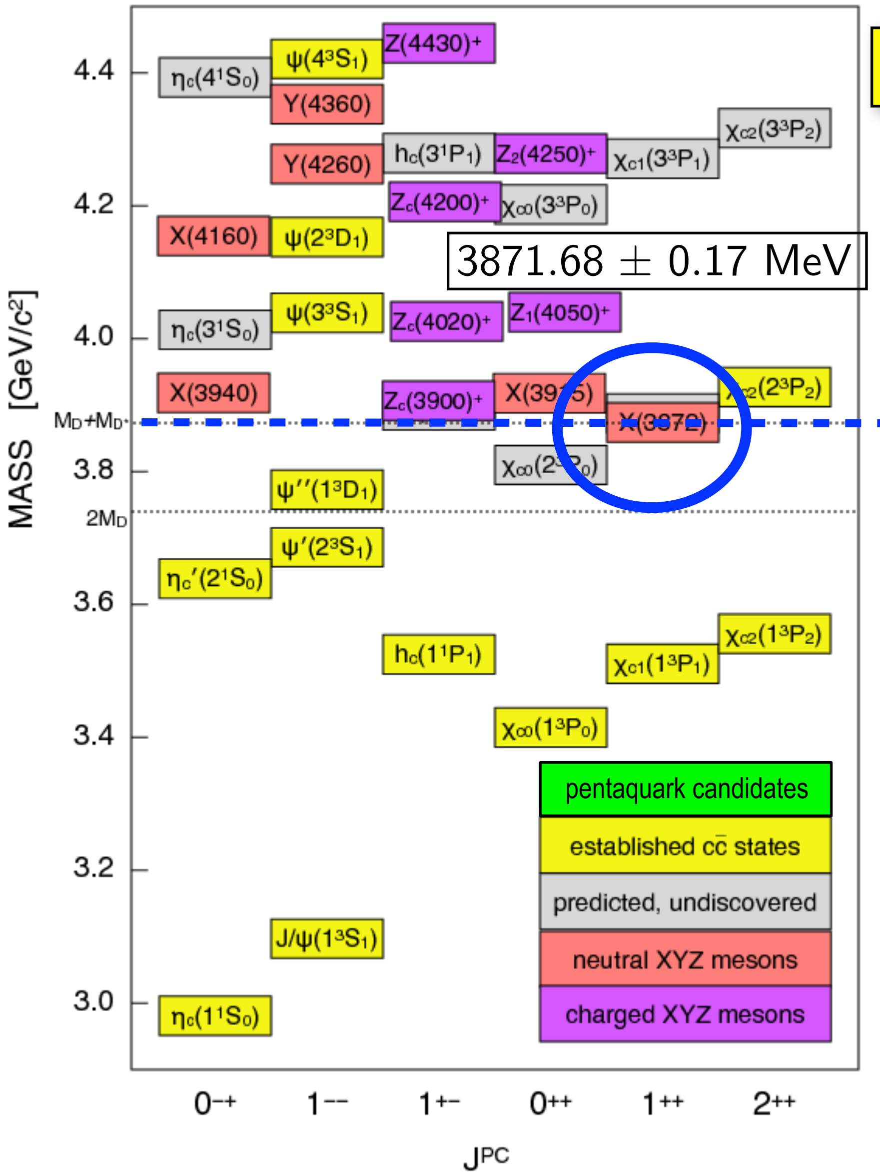


- line shape of X(3872)
- neutral+charged Z-states
- X,Y,Z decays
- search for h_c', $^3F_4$, …
- spin-parity/mass&width of $^3D_2$

- line shape/width of the h_c
- radiative transitions
- hadronic transitions
- light-quark spectroscopy

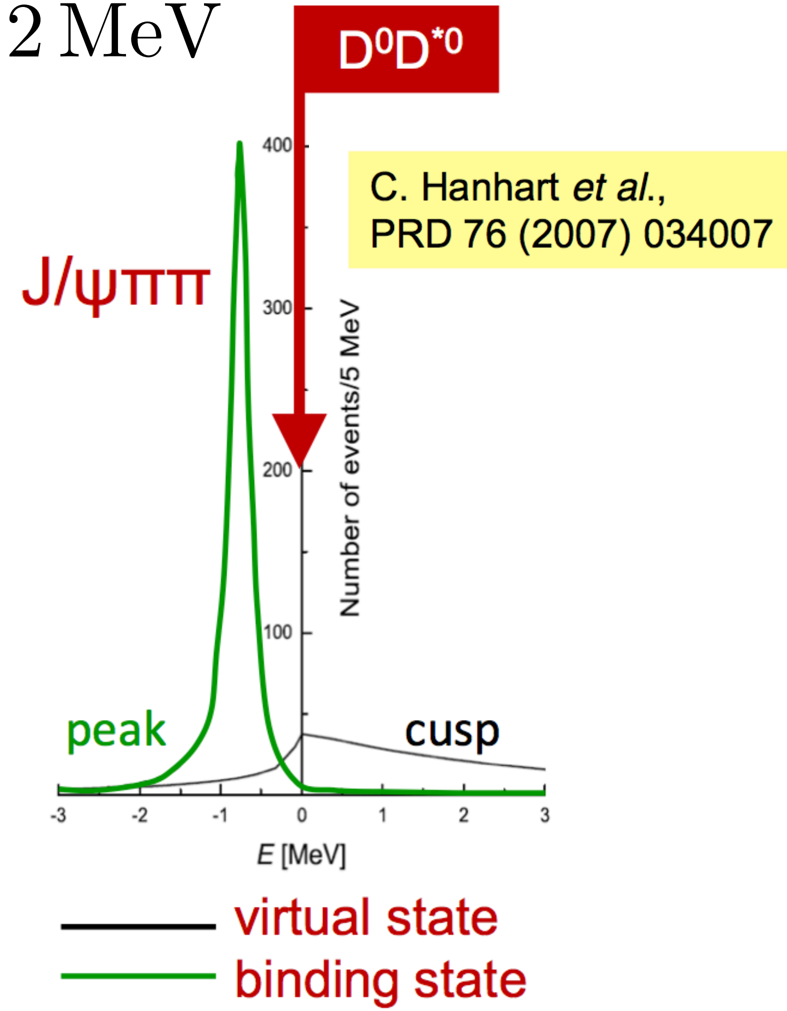
Note: LHCb discovery of $^3D_3$ candidate: [arXiv:1903.12240]

Line-shape study of the X(3872)

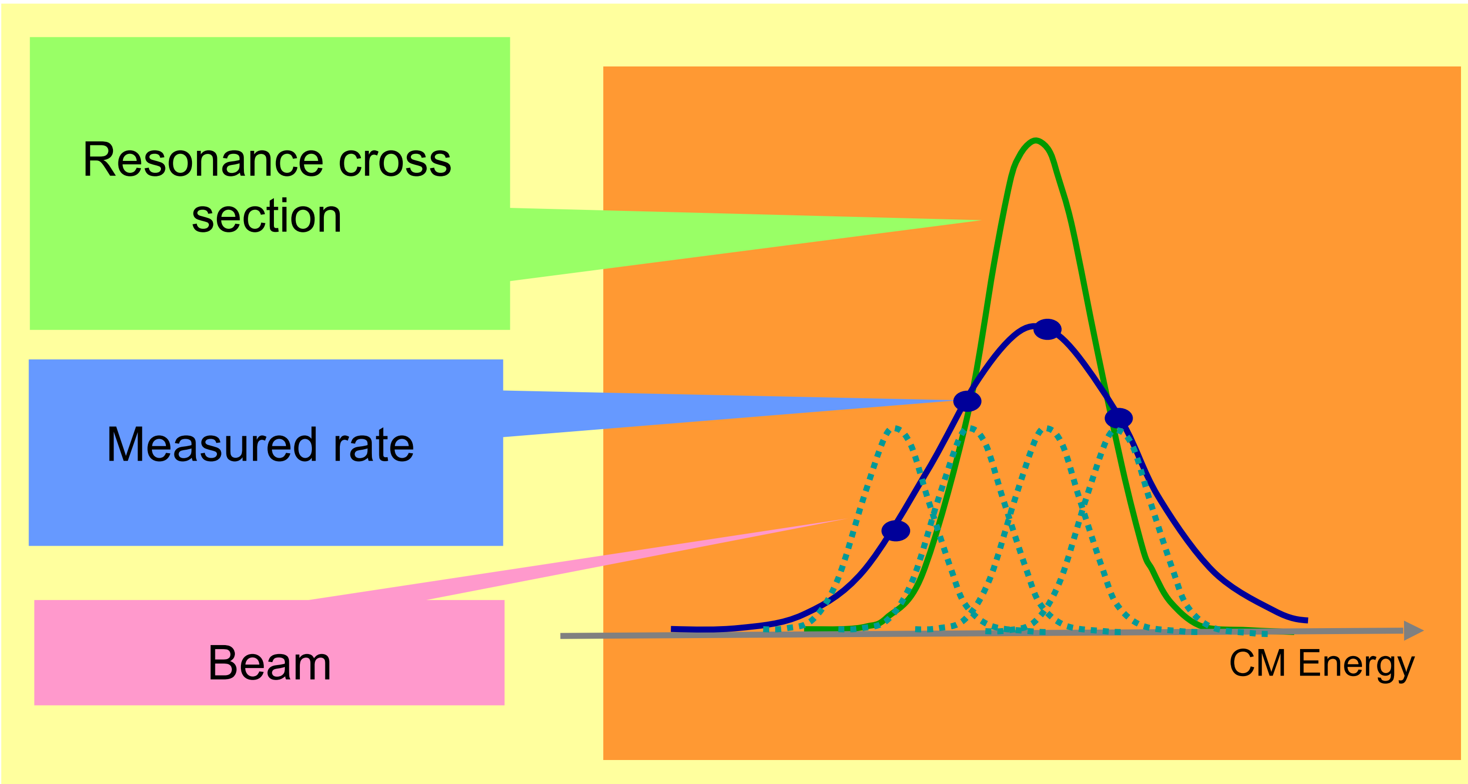


Strikingly narrow:

$$\Gamma < 1.2\,\mathrm{MeV}$$



Resonance scanning



Energy scan with e^+e^-:	energy resolution	1-2 MeV (primarily J^{PC}=1- -)
Energy scan with $p\bar{p}$:	energy resolution	240 keV (E760/835@Fermilab)
		≈50 keV (PANDA@FAIR)

arXiv:1812.05132

Resonance scanning, case study

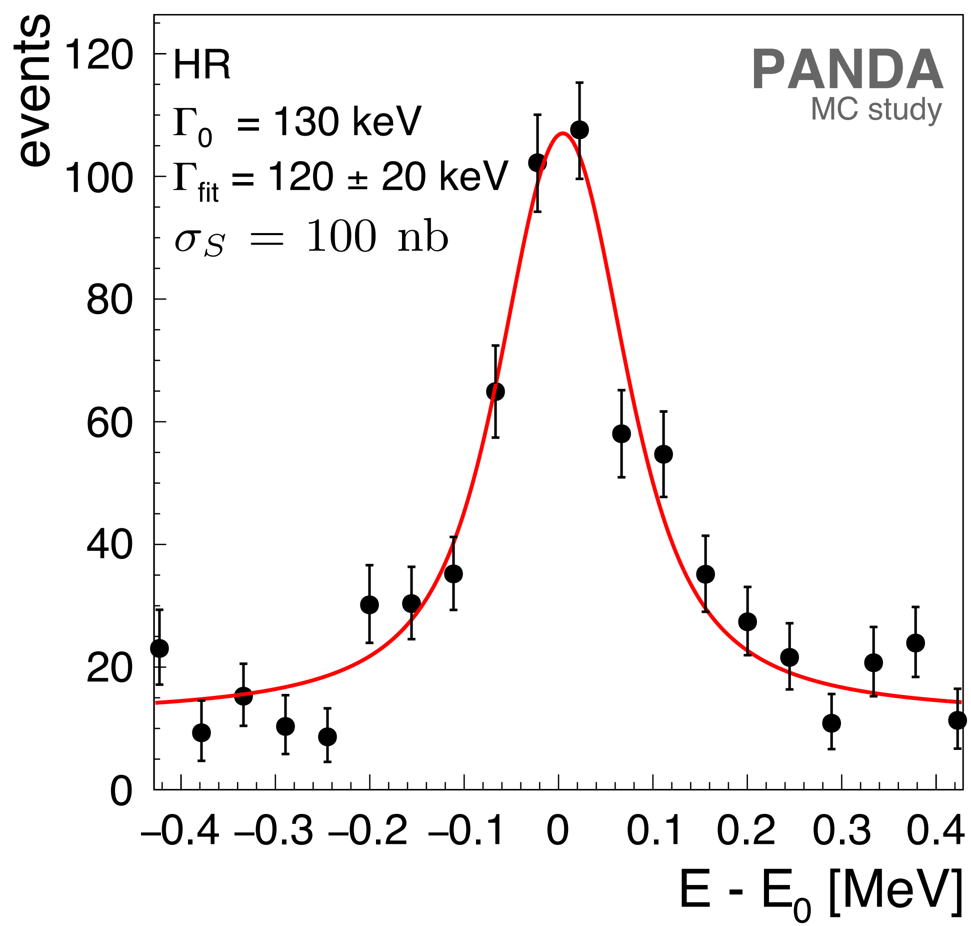
$$\bar{p}p \to X(3872) \to J/\psi\pi^+\pi^-$$

Detailed Monte Carlo study

Taking into account ~50 mb background channels

Systematic study for various input xsections, widths, phases, …

20 points each 2 days data taking!



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Resonance scanning, case study

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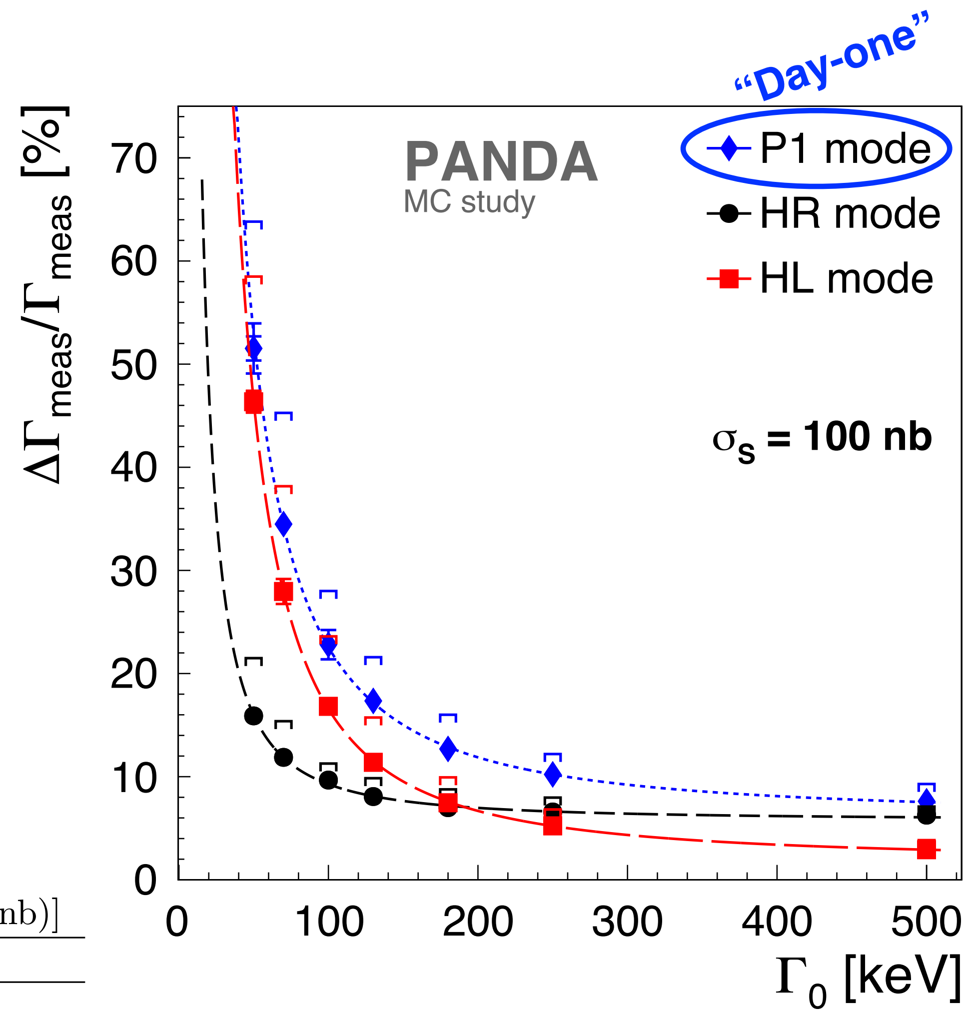

HESR mode	dp/p	dE_{cms} [keV]	$\mathcal{L}$ [1/(day · nb)]
HL	$1 \cdot 10^{-4}$	167.8	13680
HR	$2 \cdot 10^{-5}$	33.6	1368
P1	$5 \cdot 10^{-5}$	83.9	1170

Resonance scanning, case study

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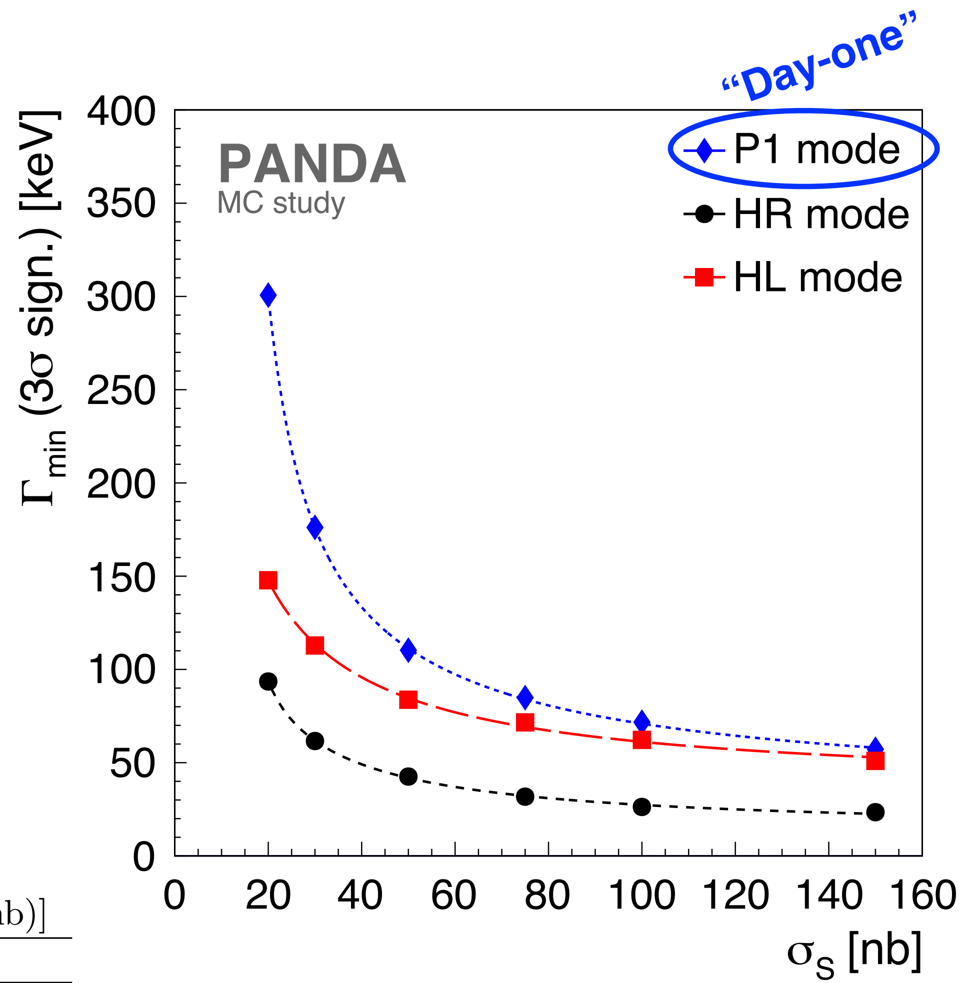

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Charming discoveries in antimatter-matter annihilations

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Charming discoveries in antimatter-matter annihilations

The charm sector is hot…

- New multiplet of "exotic" charmonium-like states found.
- Hidden-charm hadrons advantageous as probes!

The charm sector is challenging…

- Nature of XYZ particles remains unclear.
- Opportunity: precision study of the properties of hidden-charm *above* and *below* the open-charm threshold.

The future is bright…

- *BESIII*: lots of data for vector meson states, intensity and energy increase foreseen.
- *PANDA*: complementary probe with a data challenge!
- lets not forget: B-factories (BelleII, LHCb), tagged-photon facilities (Glue-X),…

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