International Workshop on Heavy Quarkonium
17-20 Oct. 2007, DESY Hamburg

Prospects for Panda

Charmonium Spectroscopy

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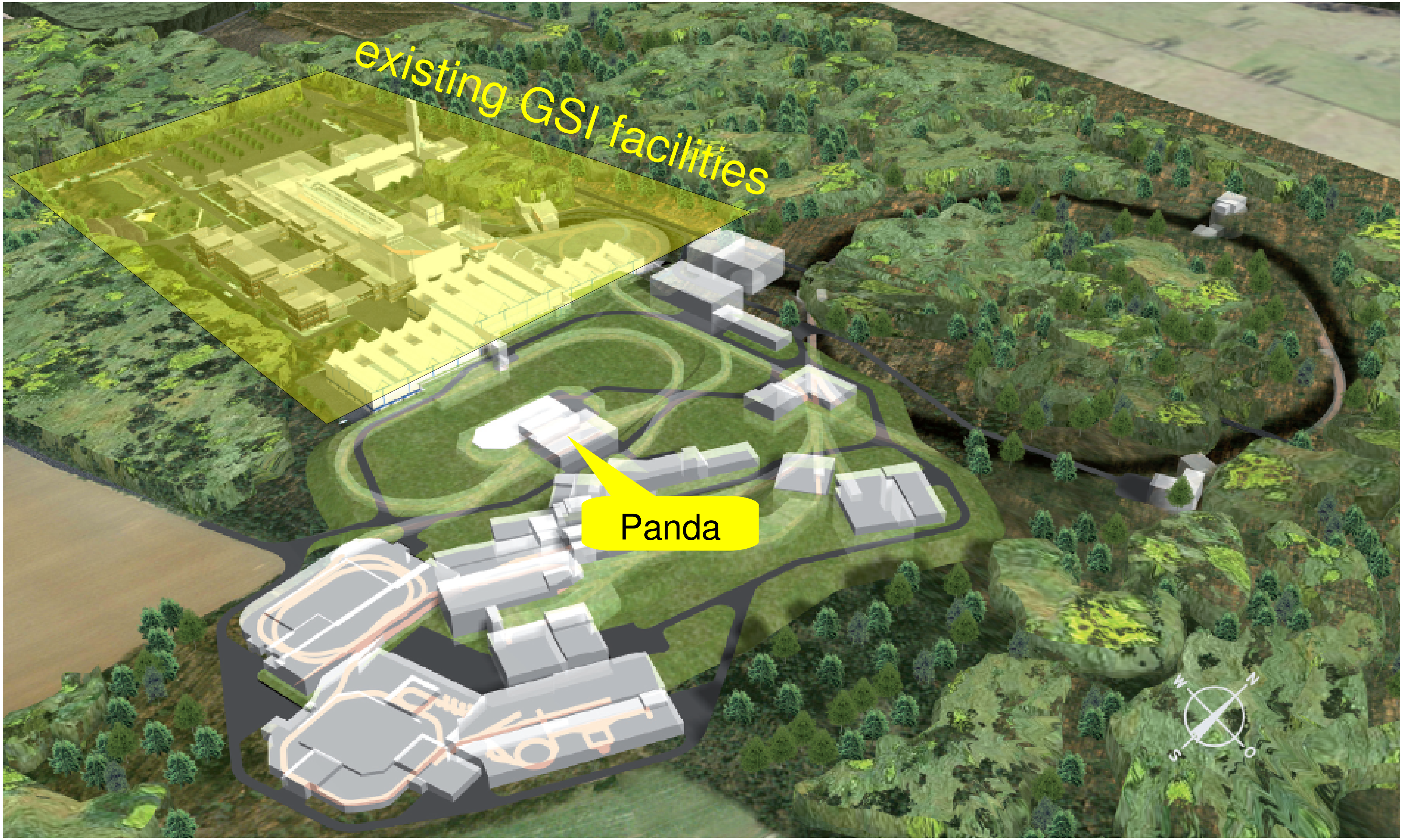
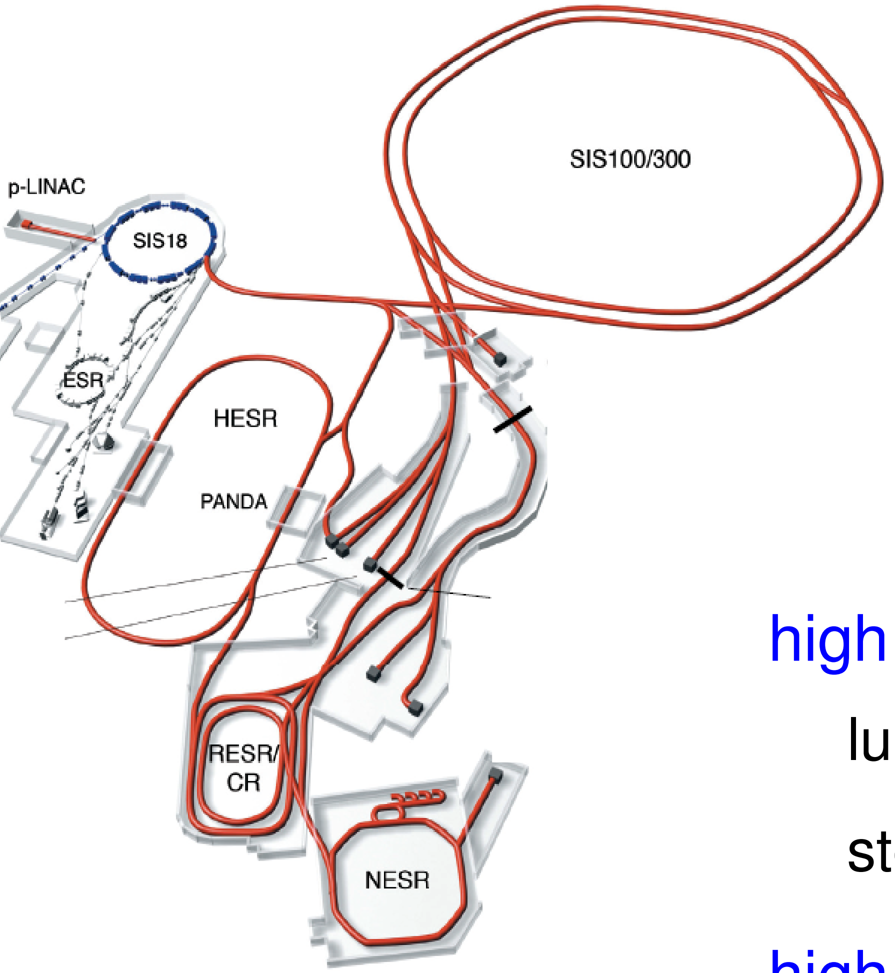
on behalf of the Panda Collaboration

FAIR accelerator complex

Facility of Antiproton and Ion Research (Darmstadt, Germany)





High Energy Storage Ring (HESR)

p(p̄)=1.5-15 GeV/c

high density target (p̄p / p̄A collisions)

pellet / cluster jet (10^{14}–$10^{15}/cm^3$)

wire

high luminosity mode

luminosity $L=10^{32}cm^{-2}s^{-1}$

stochastic cooling: $\Delta p/p=10^{-4}$

high resolution mode, p(p̄)<8GeV

luminosity $L=10^{31}cm^{-2}s^{-1}$

electron cooling: $\Delta p/p=10^{-5}$

Physics program

meson spectroscopy

- light mesons
- charmonium
- exotic matter
  - (charmed) molecules
  - (charmed) hybrids
  - glueballs
- open charm

baryon anti-baryon production

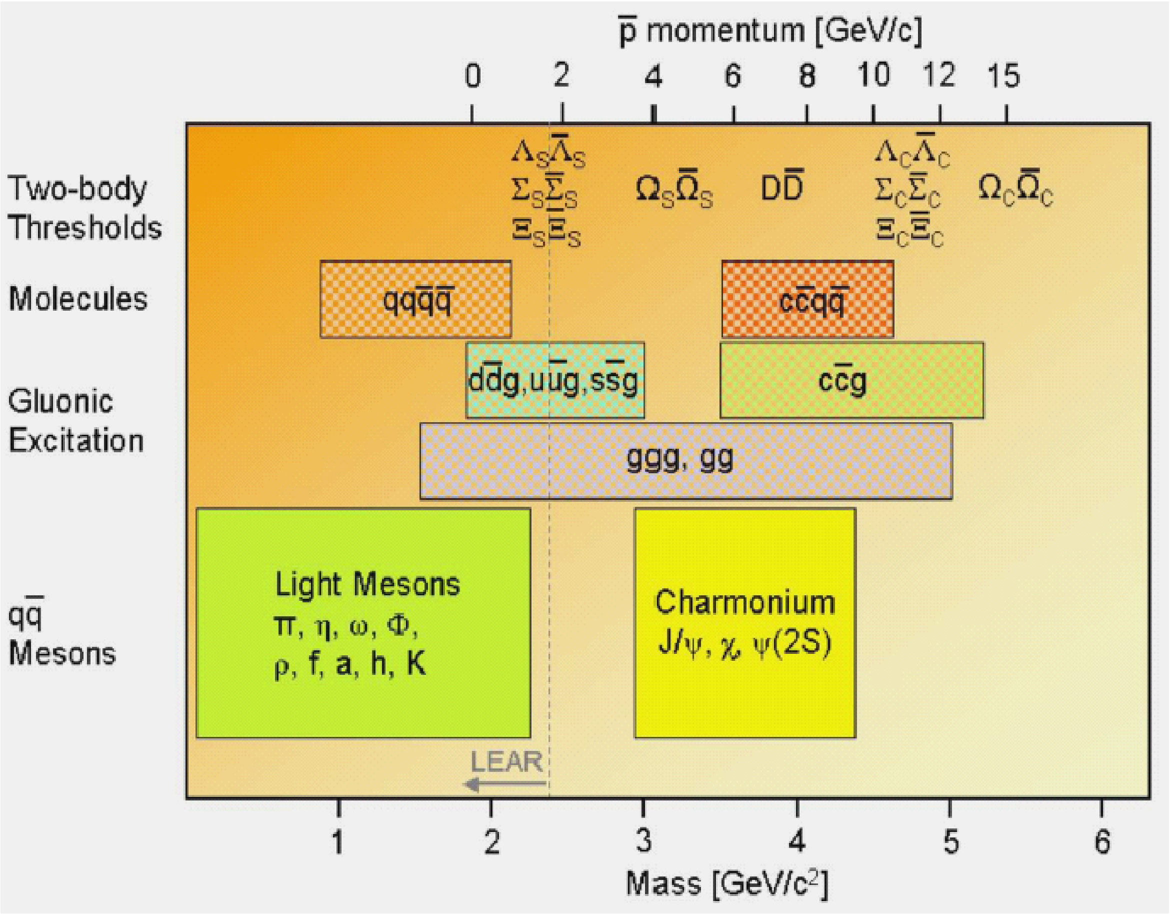
charm in nuclei

hypernuclei

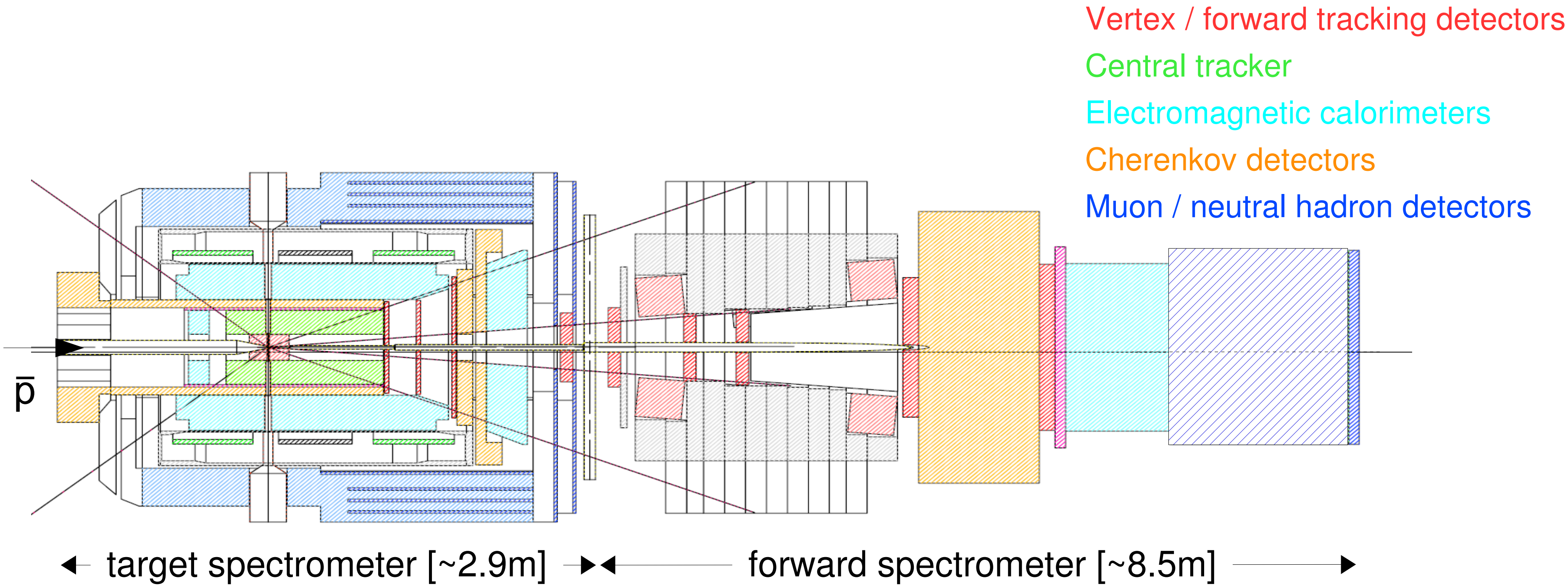
many further options, e.g.

time-like electromagnetic form factors of the proton

transverse quark distributions



Detector design



exclusive measurements

- almost 4π coverage
- target / forward spectrometer

high event rates [$10^7 s^{-1}$]

sophisticated online processing

- detection of rare decay modes

charged particle tracking [p<10 GeV/c]

- good momentum / vertex resolution
- PID: $e^\pm$, $\mu^\pm$,$\pi^\pm$,$K^\pm$,p

photon detection [E=0.02-10 GeV]

- excellent energy / angular resolution
- detection of low energetic photons

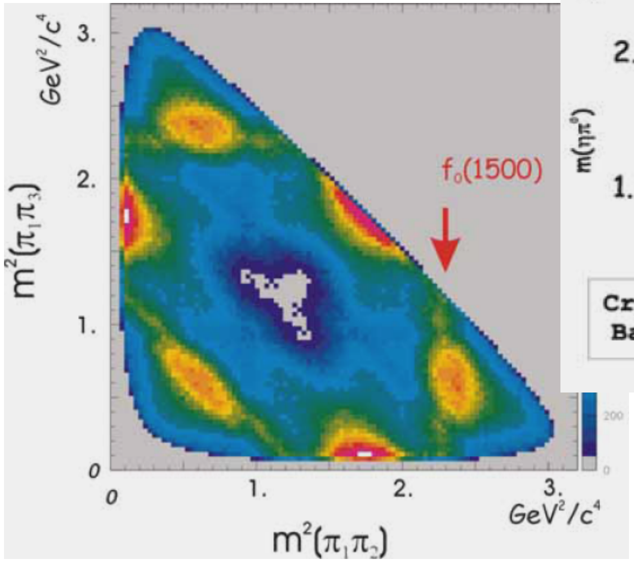
$N\ ^{2S+1}L_J$	J^{PC}	$u\bar{d}$, $u\bar{u}$, $d\bar{d}$ $I=1$	$u\bar{u}$, $d\bar{d}$, $s\bar{s}$ $I=0$	$\bar{s}u$, $\bar{s}d$ $I=1/2$
$1\ ^1S_0$	0^{-+}	π	η, η'	K
$1\ ^3S_1$	1^{--}	ρ	ω, φ	K*(892)
$1\ ^1P_1$	1^{+-}	$b_1(1235)$	$h_1(1170)$, $h_1(1380)$	K_{1B}†
$1\ ^3P_0$	0^{++}	$a_0(1450)$*	$f_0(1370)$*, $f_0(1710)$*	K_0*(1430)
$1\ ^3P_1$	1^{++}	$a_1(1260)$	$f_1(1285)$, $f_1(1420)$	K_{1A}†
$1\ ^3P_2$	2^{++}	$a_2(1320)$	$f_2(1270)$, $f_2'(1525)$	K_2*(1430)
$1\ ^1D_2$	2^{-+}	$\pi_2(1670)$	$\eta_2(1645)$, $\eta_2(1870)$	$K_2(1770)$
$1\ ^3D_1$	1^{--}	ρ(1700)	ω(1650)	K*(1680)‡
$1\ ^3D_2$	2^{--}			$K_2(1820)$
$1\ ^3D_3$	3^{--}	$\rho_3(1690)$	$\omega_3(1670)$, $\phi_3(1850)$	K_3*(1780)
$1\ ^3F_4$	4^{++}	$a_4(2040)$	$f_4(2050)$, $f_4(2220)$	K_4*(2045)
$2\ ^1S_0$	0^{-+}	π(1300)	η(1295), η(1440)	K(1460)
$2\ ^3S_1$	1^{--}	ρ(1450)	ω(1420), φ(1680)	K*(1410)‡
$2\ ^3P_2$	2^{++}		$f_2(1810)$, $f_2(2010)$	K_2*(1980)
$3\ ^1S_0$	0^{-+}	π(1800)	η(1760)	K(1830)

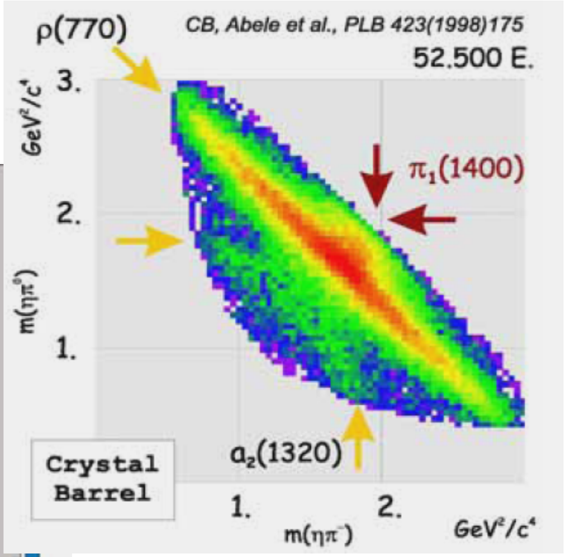
LEAR contributions

LEAR p̄p experiments

- numerous contributions to light meson spectroscopy
- often analyses with high statistics required (i.e Dalitz plot analyses)

p̄p collisions: very fertile outcome

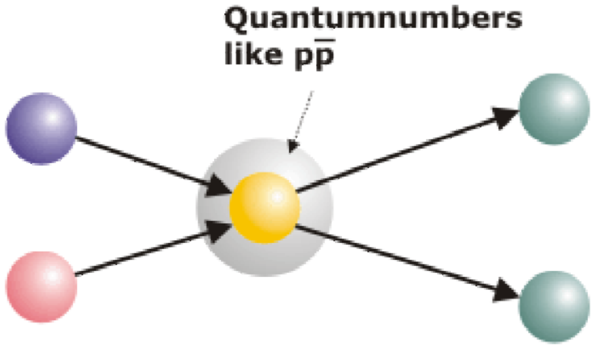




Charmonium in $\bar{p}p$ annihilation

formation in $\bar{p}p$ collisions

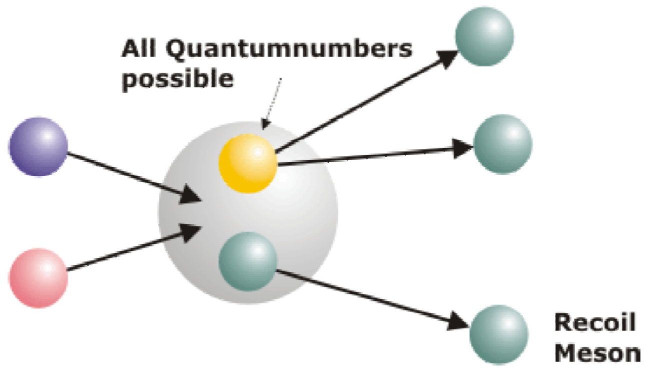
all J^{PC} allowed for $q\bar{q}$ can be generated



production in $\bar{p}p$ collisions

states with all J^{PC} accessible

(i.e. spin-exotic states)



Charmonium in p̄p annihilation

- formation in p̄p collisions
  - direct access to all charmonium states
  - scan resonances with high beam momentum resolution
  - precision mass and width measurements
    (not limited by detector resolution)

- in contrast to e^+e^- processes
  - only 1^{--} states directly accessible
  - access to other states via higher order processes, e.g.
    - $\psi(2S) \rightarrow \chi_{cJ}\gamma$
    - $B \rightarrow (c\bar{c})K$
    - $e^+e^- \rightarrow (c\bar{c})(c\bar{c})$
    - $e^+e^- \rightarrow e^+e^-(\gamma\gamma) \rightarrow e^+e^-(c\bar{c})$

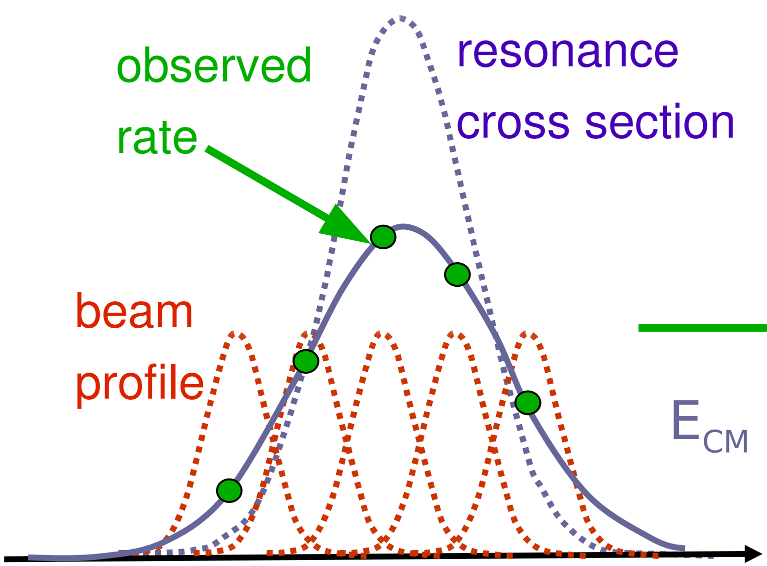
    } small branching ratios / cross sections
  - signal resolution determined by detector resolution

Example: Observation of χ_{c1}

E835 (formation)

$$\bar{p}p \to \chi_{c1} \hookrightarrow J/\psi\gamma \hookrightarrow e^+e^-$$

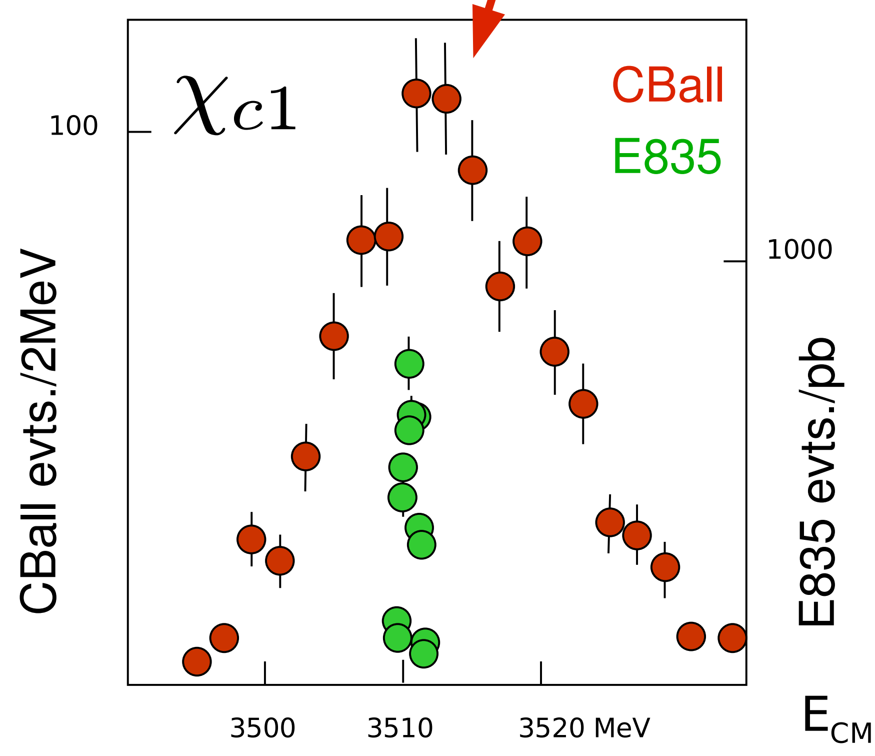
scan across resonance



Crystal Ball (production)

$$e^+e^- \to \psi(2S) \hookrightarrow \chi_{c1}\gamma \hookrightarrow J/\psi\gamma \hookrightarrow e^+e^-$$

invariant mass



Charmonium in p̄p annihilation

Expected: $\mathcal{L} = 1 - 2fb^{-1}/y$

Reaction	Peak Cross Section $\sigma(M) \times \mathcal{B}[\,\mathrm{nb}\,]$	events/d $(\sigma(M) \times \mathcal{B} \times \mathcal{L})$
$\overline{p}p \rightarrow \eta_c(\rightarrow \gamma\gamma)$	0.1	10^3
$\overline{p}p \rightarrow \eta_c(\rightarrow K^+K_S^0\pi^-)$	10	10^5
$\overline{p}p \rightarrow J/\psi\,(\rightarrow e^+e^-, \mu^+\mu^-)$	630	10^6
$\overline{p}p \rightarrow \chi_{c2}(\rightarrow J/\psi\,\gamma)$	3.7	10^4

p̄p collisions: rich source for charmonium

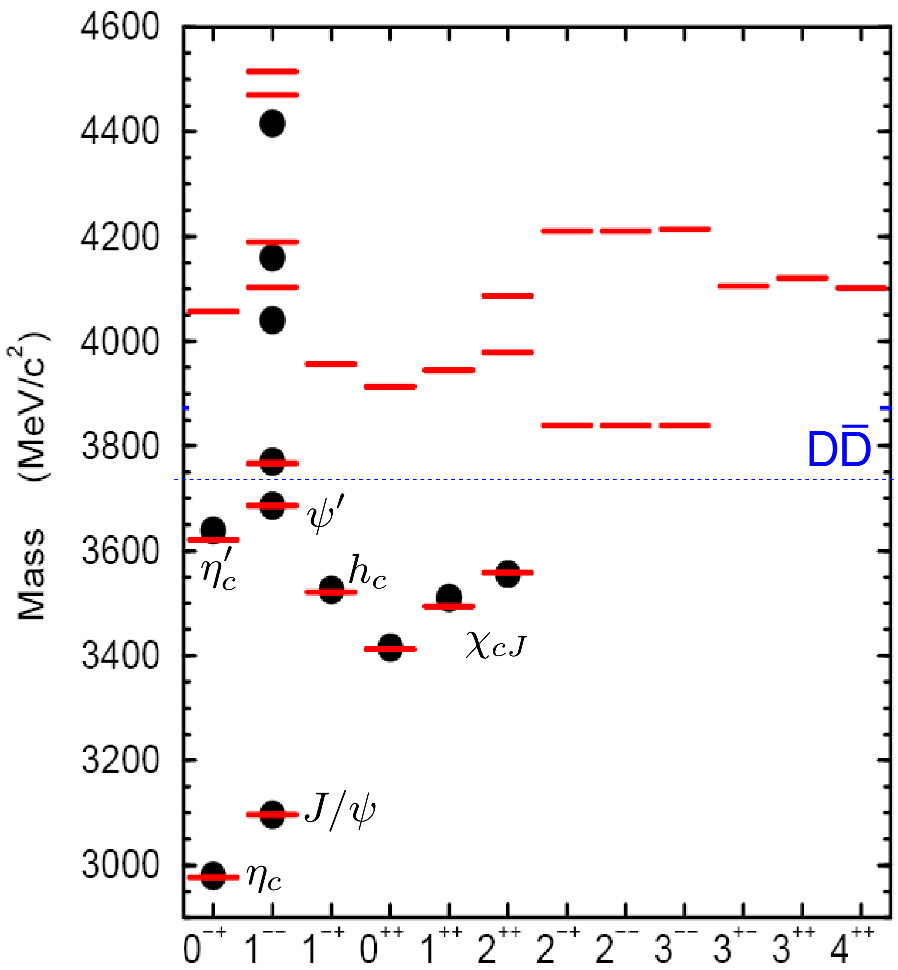
Charmonium: Open questions

- below $D\bar{D}$ threshold
  - all predicted states detected, but
  - lack of precise measurement of mass, width and branching ratios

    (i.e. $\eta_c,\ \eta_c(2S),\ h_c$)

- above $D\bar{D}$ threshold
  - only 4 vector states detected

    (not all unambiguously confirmed)
  - diagnostic of long range spin-dependend $q\bar{q}$ potential (i.e. 2P and 1D states)
  - appearance of several new resonances in this region (nature still unclear)



how will Panda contribute?

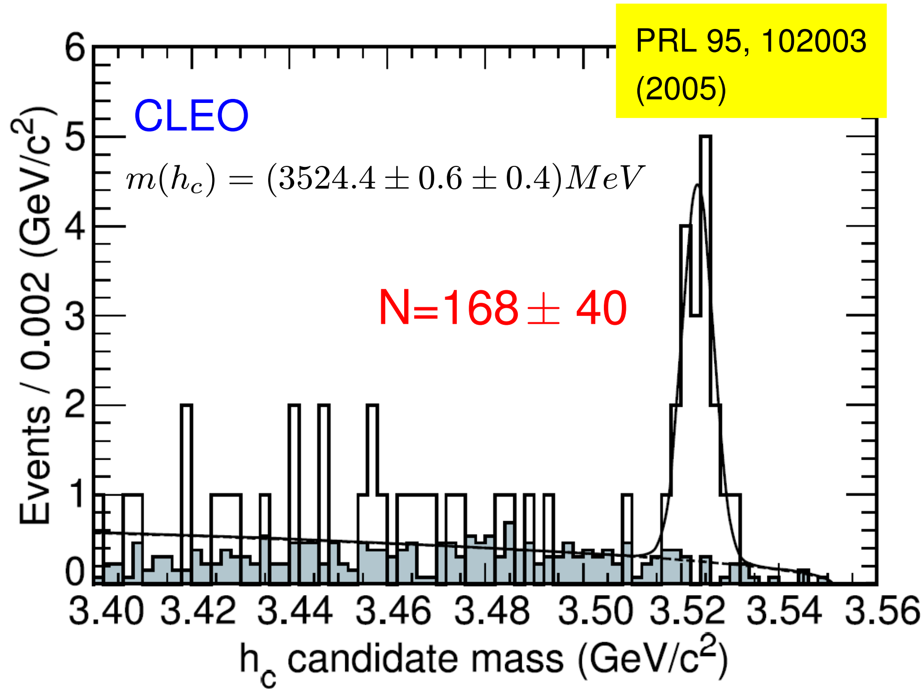
Charmonium below D$\bar{\text{D}}$ threshold: h_c

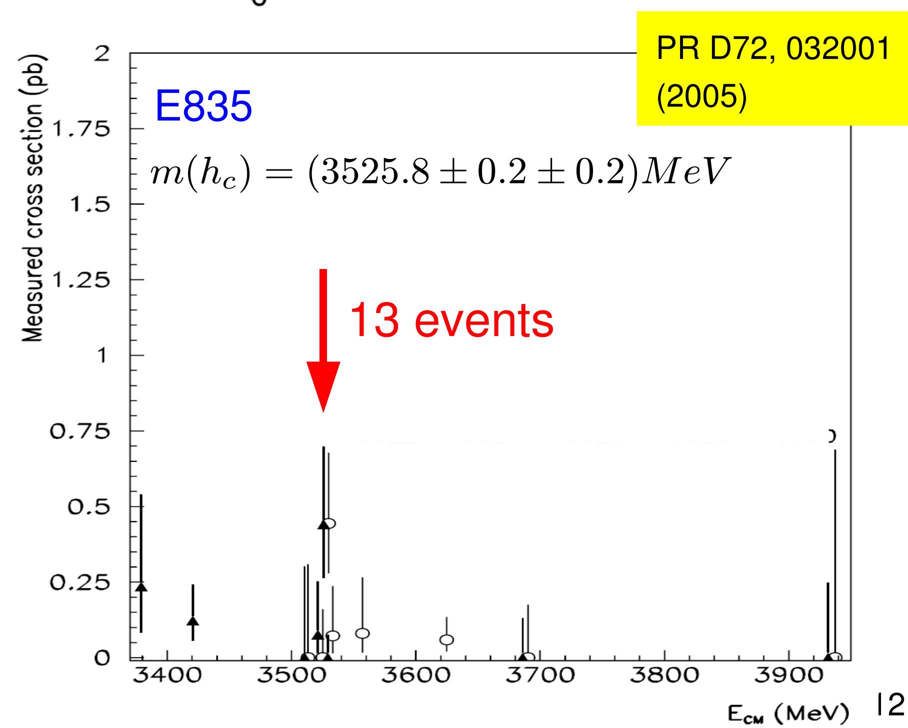
- determine spin contributions of confinement potential from
  $$m(h_c) - \frac{1}{9}(m(\chi_{c0}) + 3m(\chi_{c1}) + 5m(\chi_{c2}))$$
  - precise mass measurement required
- two recent measurements

  CLEO: $e^+e^- \to \psi(2S) \to h_c\pi^0$
  $$h_c \to \eta_c\gamma$$
  $$\eta_c \to hadrons$$

  E835: $\bar{p}p \to h_c, h_c \to \eta_c\gamma$
  $$\eta_c \to \gamma\gamma$$

- Panda
  - scan with high luminosity / precision
  - detect hadronic decay modes (charged hadron reco. / PID)





Charmonium: Open questions

- below $D\bar{D}$ threshold
  - all predicted states detected, but
  - lack of precise measurement of mass, width and branching ratios (i.e. η_c, $\eta_c(2S)$, h_c)

- above $D\bar{D}$ threshold
  - only 4 vector states detected (not all unambiguously confirmed)
  - diagnostic of long range spin-dependend $q\bar{q}$ potential (i.e. 2P and 1D states)
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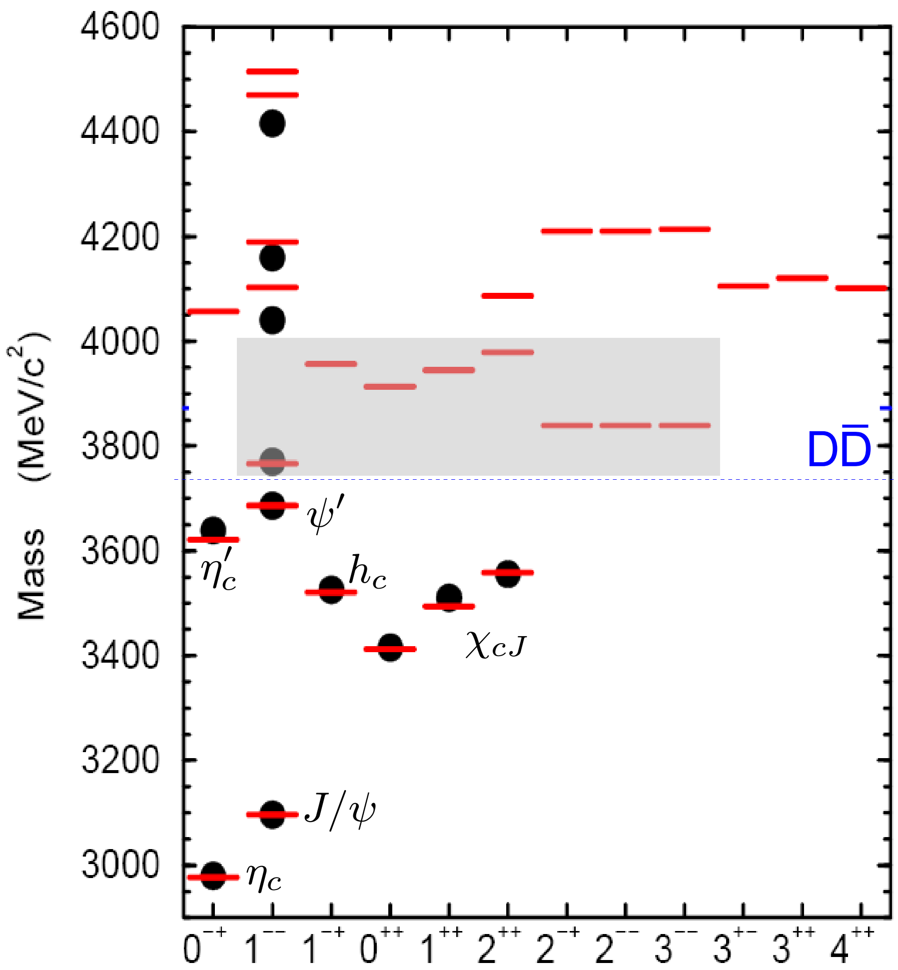
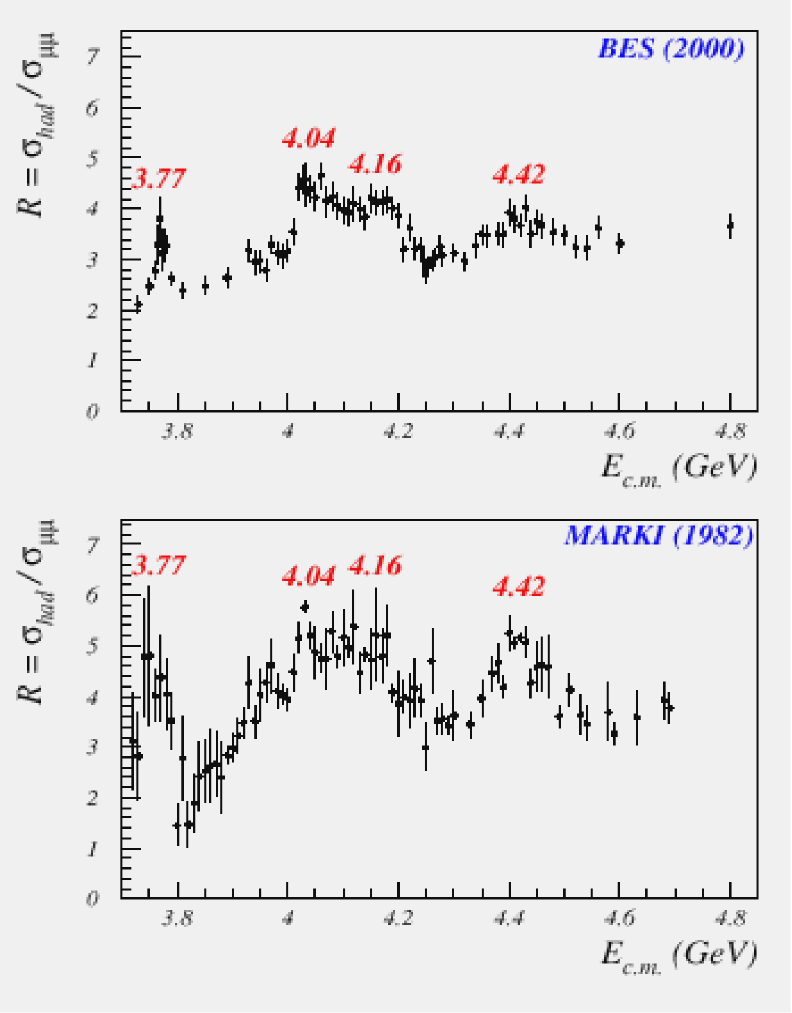


how will Panda contribute?

Charmonium above D$\bar{D}$ threshold

- $\psi(4040), \psi(4160), \psi(4415)$
  - broad structures observed in R measurements by e^+e^- experiments
  - lack unambiguous confirmation
- 1D states
  - only $\psi(3770)$ observed [large D contrib.?]
  - 1 broad (J=3) / 2 narrow (J=2) states exp.
- 2P states
  - possibly Y(3940), Z(3930)?



- Panda
  - perform search for undetected states (production)
  - scan regions of particular interrest with high precision / luminosity
  - establish quantum numbers (high statistics required)

New resonances above $D\bar{D}$ threshold

X(3872) ($\rightarrow J/\psi\pi^+\pi^-, D^0\bar{D}^0\pi^0, J/\psi\gamma$) $J^{PC}=1^{++}$ preferred

Belle, Babar, CDF II, D0

X(3940) ($\rightarrow D^*\bar{D}, \not\rightarrow D\bar{D}$), $J^{PC}=0^{-+}$ (?)

Belle

Y(3940) ($\rightarrow J/\psi\omega, \not\rightarrow D^{(*)}\bar{D}$), $J^{PC}=J^{P+}$

Belle, Babar

Z(3930) ($\rightarrow D\bar{D}$), $J^{PC}=2^{++}$ favored

Belle

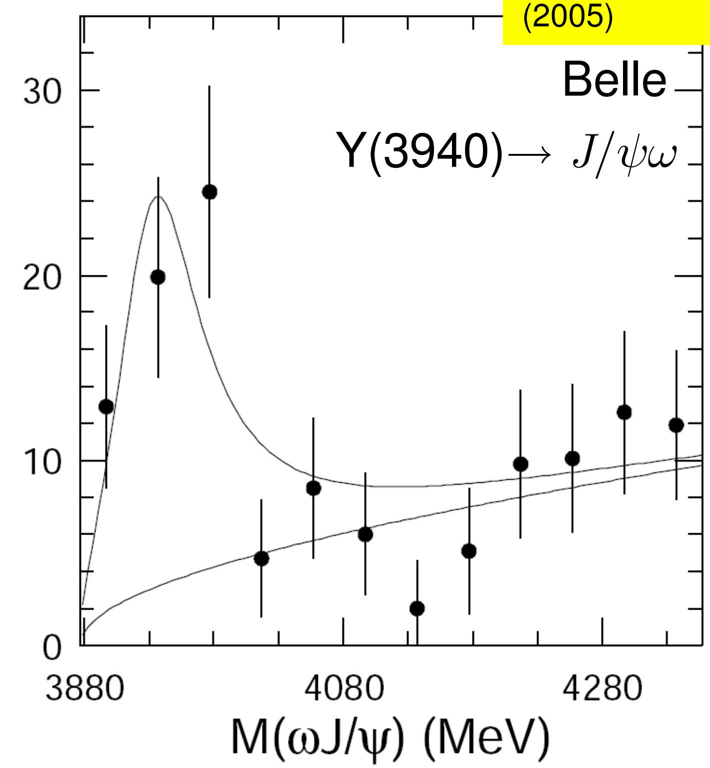
Y(4260) ($\rightarrow J/\psi\pi\pi$), $J^{PC}=1^{--}$

Babar, CLEO, Belle

Y(4350) ($\rightarrow\psi'\pi^+\pi^-$), $J^{PC}=1^{--}$

Babar, Belle

PRL 94, 182002 (2005)

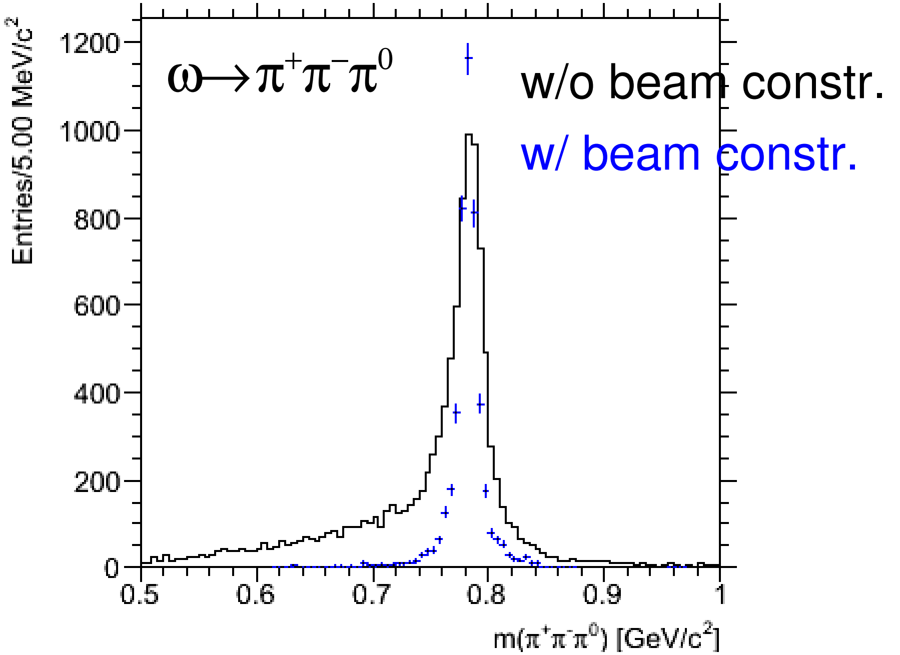


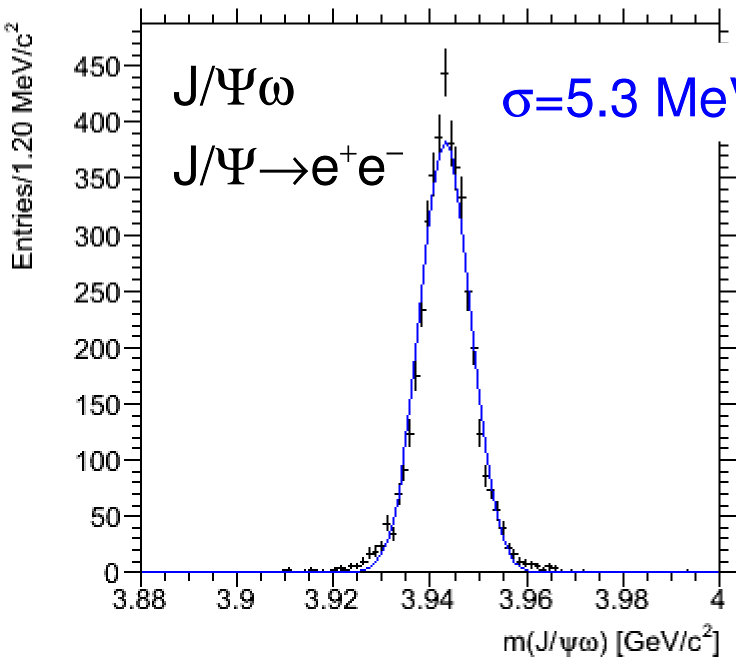
- for most states J^{PC} not well established
- nature unclear (conventional $c\bar{c}$ or exotic)

most resonances are currently investigated in MC studies for further detector optimization, e.g. Y(3940)

MC study of Y(3940) in formation

- detailed simulation / reconstruction, e.g.
  - PID exploiting EMC, Cherenkov and muon detectors information
  - kinematic fit with beam constraint
- yields good efficiency of ~20%
  - integrated luminosity: 1-2 fb^{-1}/y
  - assume formation cross section of 10nb
  - expected:
    BR(Y(3940)→J/Ψω)x 900 reco. events/d
- low background expected
  - $J/\Psi \to e^+e^-$ provides clean tag



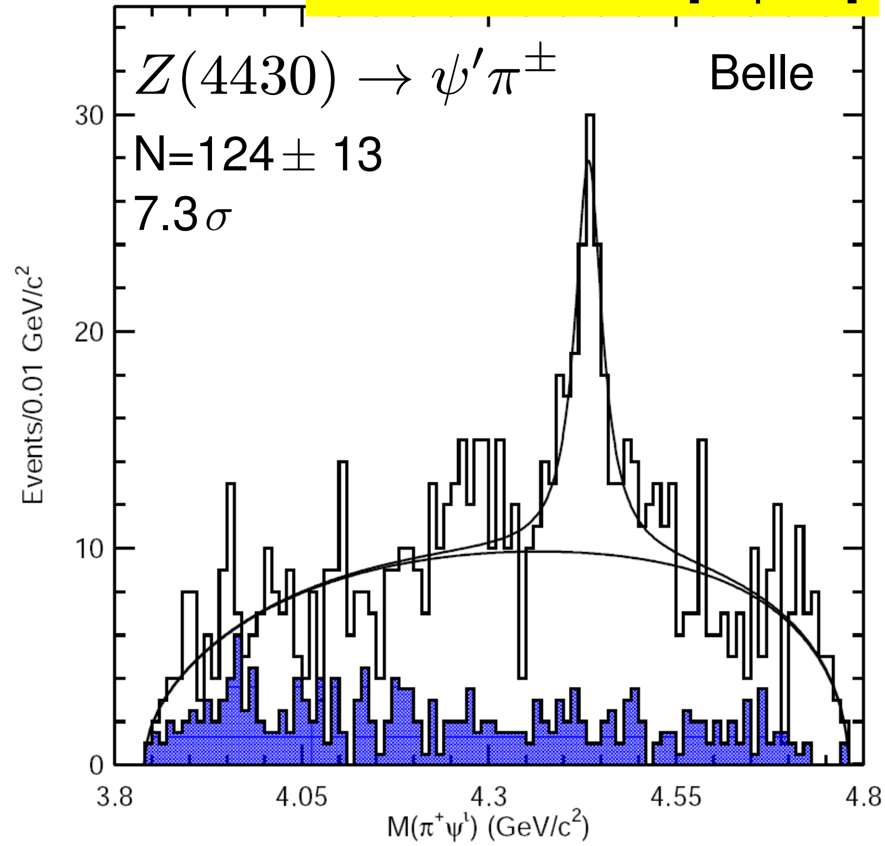


Recent observation by Belle

- evidence for an resonance-like structure at 4.43 GeV decaying to $\psi(2S)\pi^{\pm}$

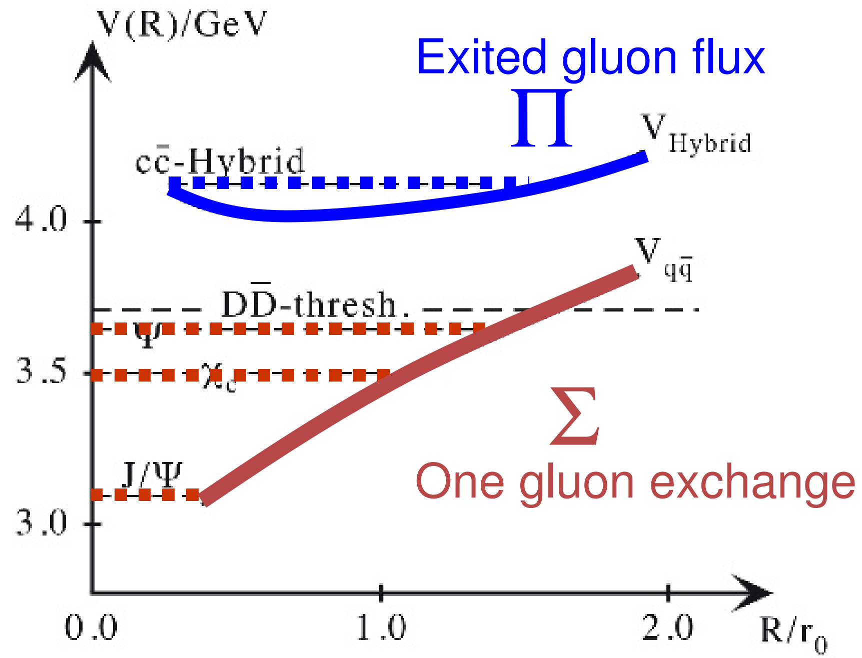
- interesting options for Panda
  - production $\bar{p}p \to Z(4430)\pi^{\pm}$
  - formation (deuteron target) $\bar{p}n \to Z(4430) \to \psi'\pi^{-}$

arXiv:0708.1790 [hep-ex]

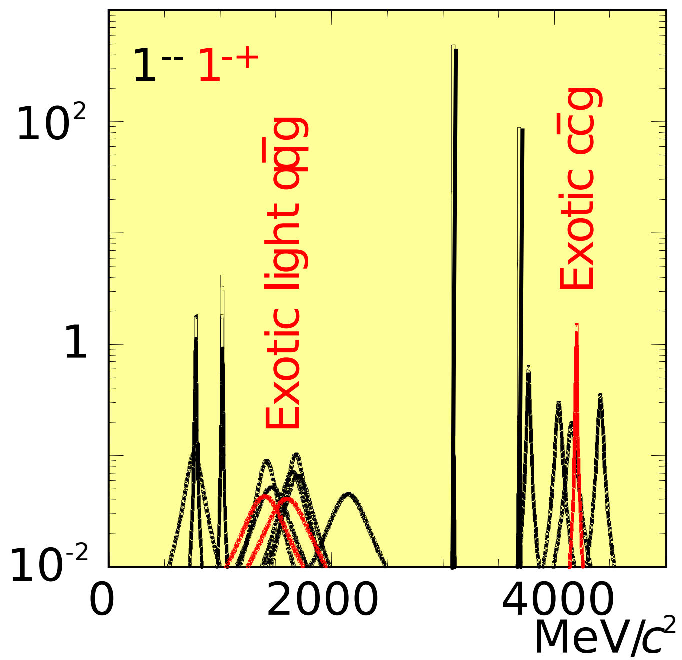


Charmonium hybrids

- gluonic excitations in $q\bar{q}$ potential can lead to bound states
- LQCD / flux tube model predictions for lightest state
  - m = 4.1-4.4 GeV
    exotic $J^{PC}=1^{-+}$



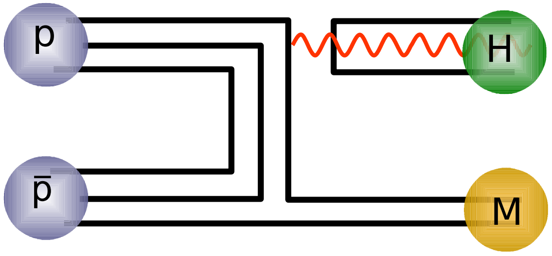
- decays to open charm forbidden or suppressed for some states
  - states could be very narrow
- also in contrast to light quark sector
  - lower state density
  - less overlap with conventional states
  - exotics should be easier to identify



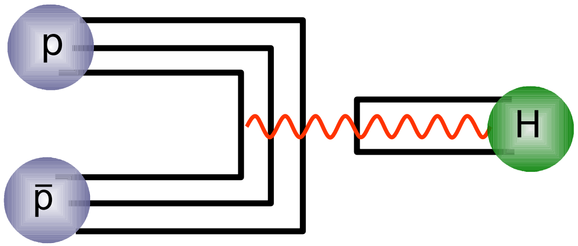
p̄p annihilations

- gluon rich processes
- good conditions to generate hybrids
- for $c\bar{c}$ hybrids: initial quarks must annihilate
- similar production cross section as for charmonium expected

Production



Formation



Summary

- Panda at FAIR
  - $\bar{p}p$ / $\bar{p}A$ collisions at $p(\bar{p})$=1.5-15 GeV
  - rich physics program
  - multi-purpose detector providing
    - large solid angle coverage
    - good momentum and precise vertex resolution
    - excellent photon detection
    - very good particle identification

- prospects for charmonium spectroscopy
  - high precision / luminosity measurements
    - mass, width, quantum numbers and branching ratios
  - all states below / above $D\bar{D}$ threshold directly accessible
  - charmonium hybrids
    - gluon rich $\bar{p}p$ annihilations expected to be a fertile source