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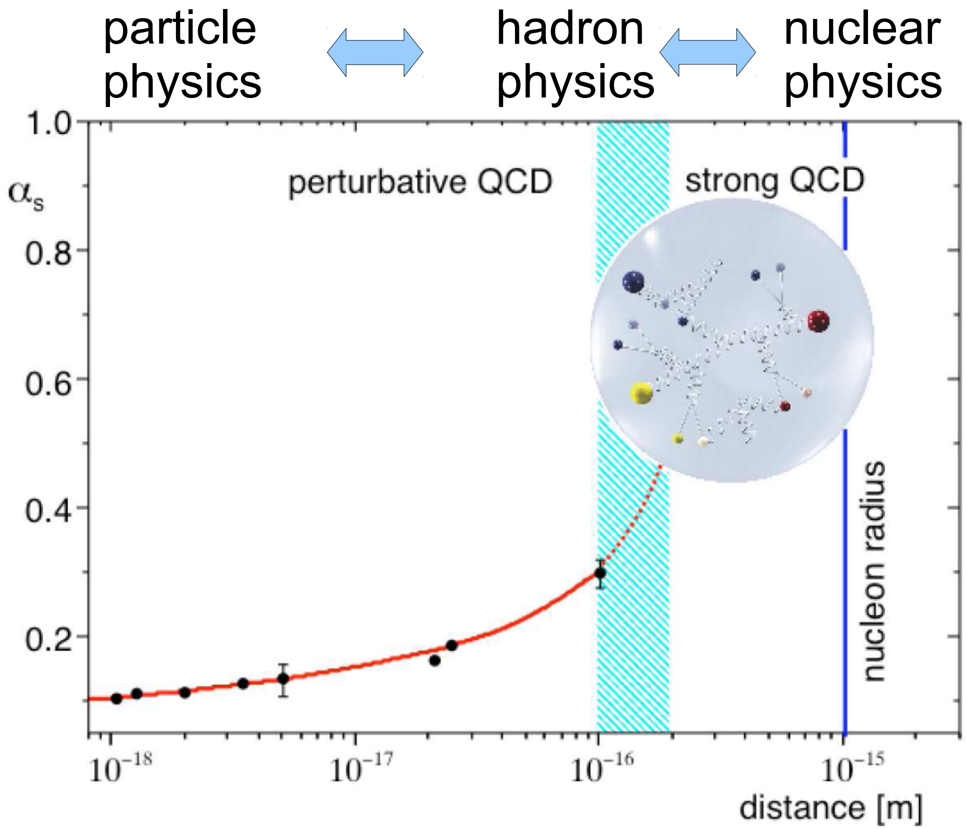
HIC for FAIR Workshop: Heavy Flavor Physics with CBM
May 26-28, Frankfurt, Germany

Charm Spectroscopy at the $\bar{\text{P}}$ANDA Experiment

Hadron Physics at PANDA

Study of the strong interaction in the transition region between perturbative QCD and nuclear phenomena.

Energy dependence of α_s



Related questions:

- Confinement: Why do we not observe free quarks?
- Origin of the hadron mass
- Are there (color neutral) bound states other than mesons and baryons?
- Structure of the nucleon?
- Spin degrees of freedom?

Physics Program

Hadron spectroscopy
- light mesons
- charmonium
- open charm mesons
- search for exotics
- baryons
  (double strange, charmed)

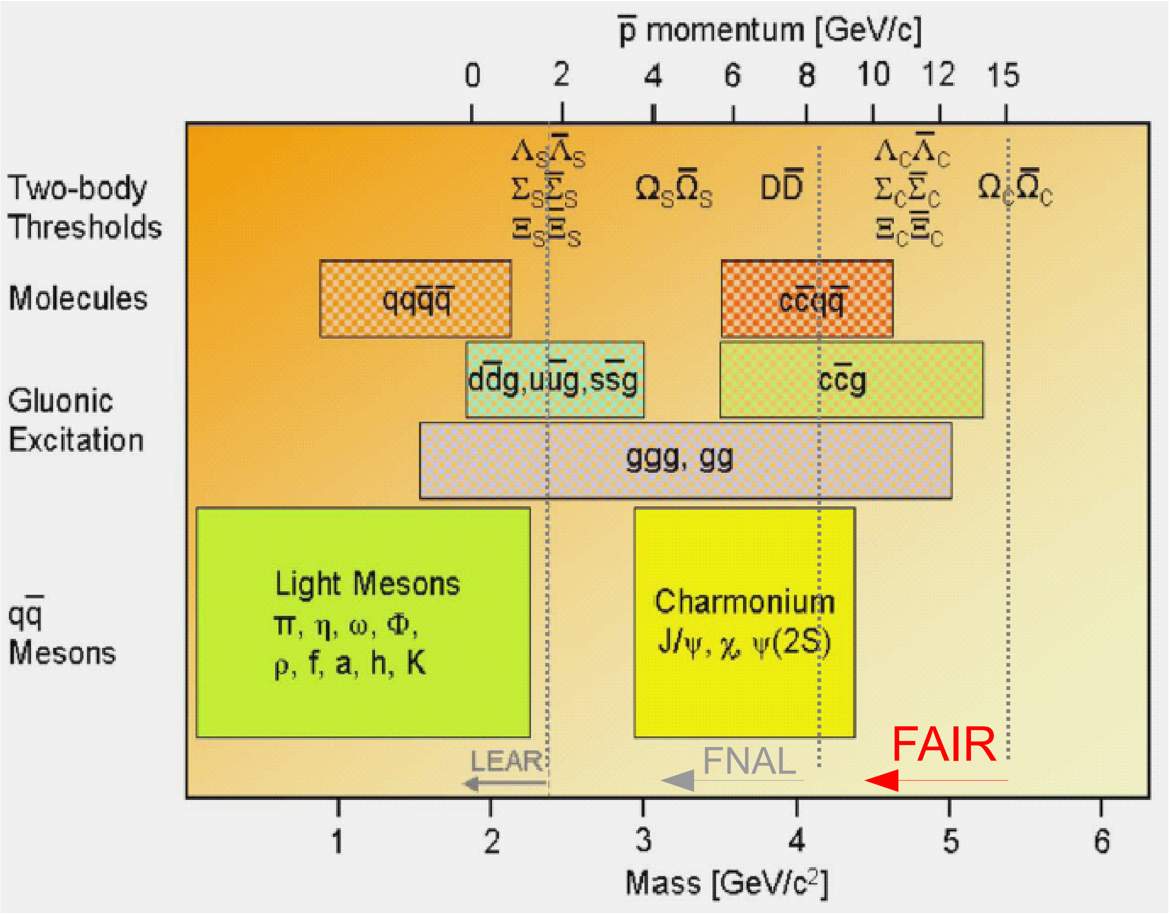
Baryon anti-baryon production

Mesons in nuclei

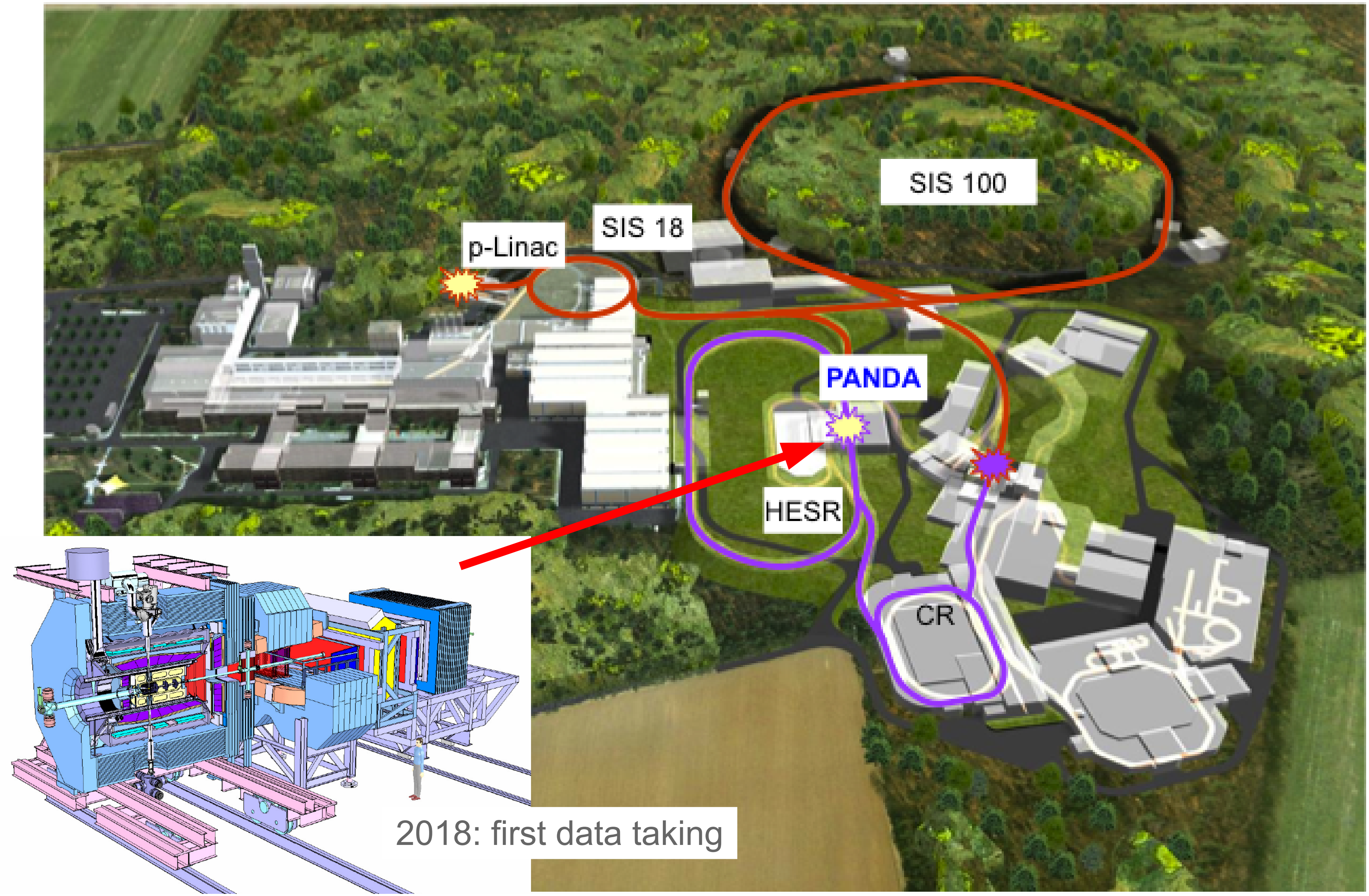
Hypernuclei

Many further options, e.g.

time-like electromagnetic form factors of the proton,
transverse quark distributions



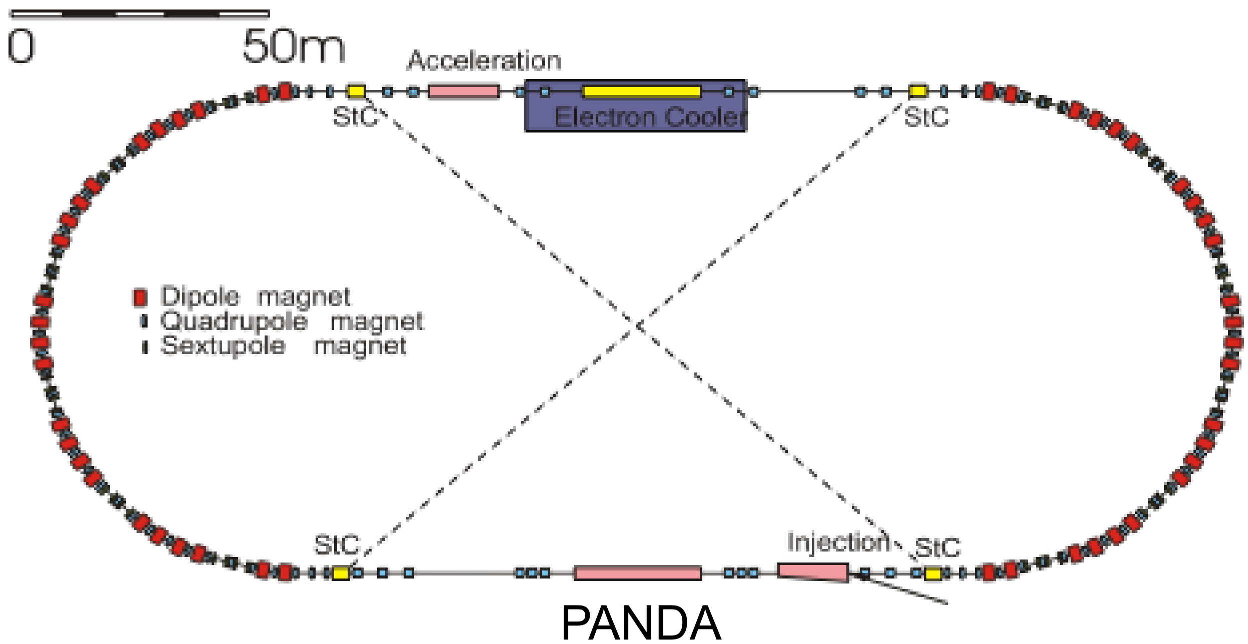
PANDA at FAIR



Antiprotons at FAIR

High Energy Storage Ring (HESR)

$p(\bar{p}) = 1.5 - 15\,\mathrm{GeV}/c$



Internal target (p̄p / p̄A)

high density $10^{14} - 10^{15}/\mathrm{cm}^2$

High luminosity mode

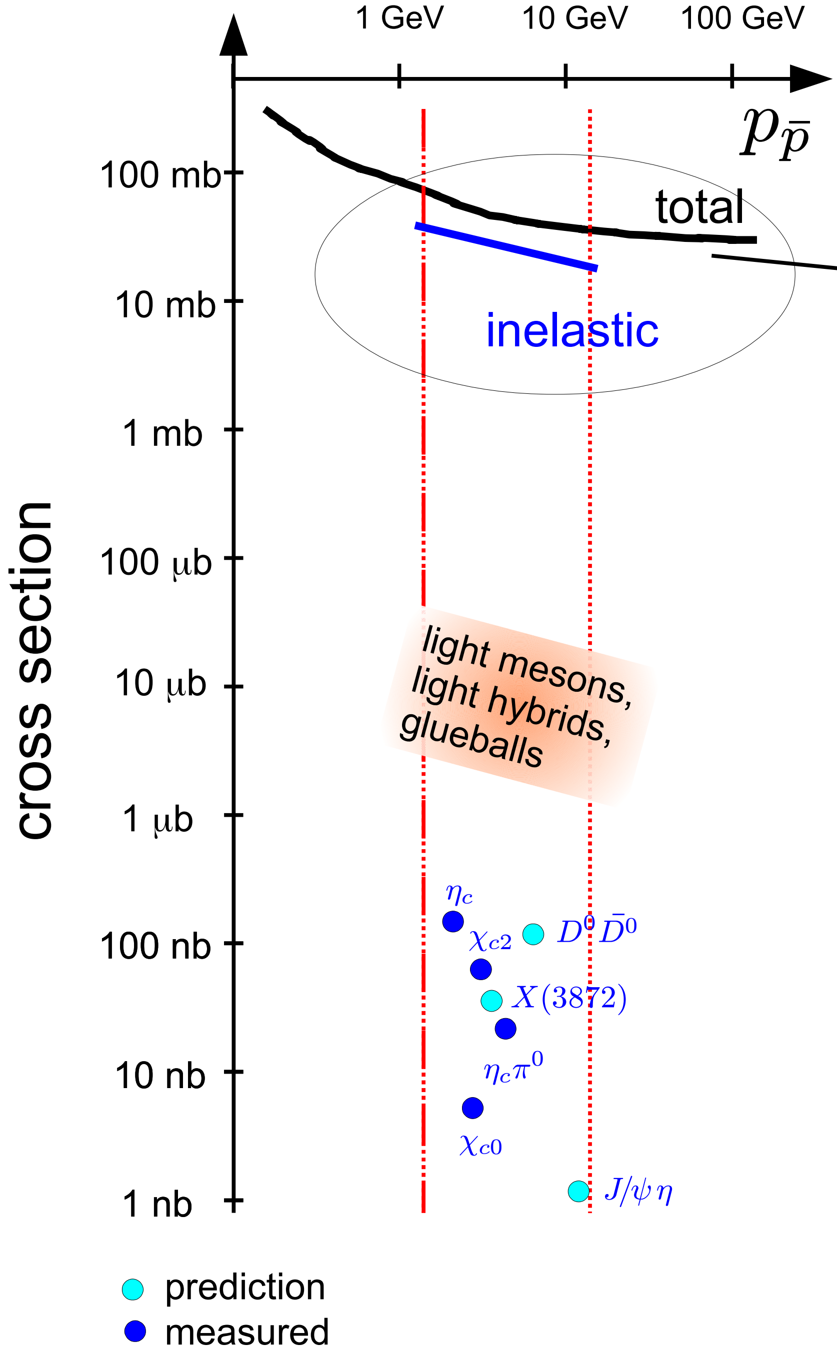
luminosity $L = 2 \cdot 10^{32} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
stochastic cooling: $\delta p/p < 10^{-4}$

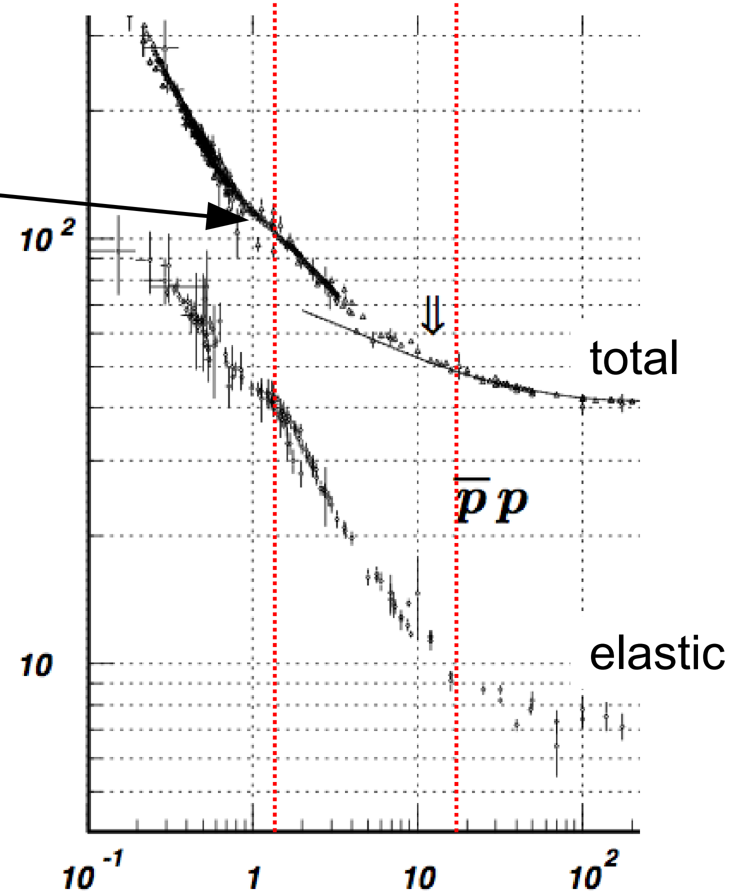
High resolution mode, p(p̄)<9 GeV

luminosity $L = 2 \cdot 10^{31} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
additional electron cooling: $\delta p/p < 4 \cdot 10^{-5}$

Cross Sections

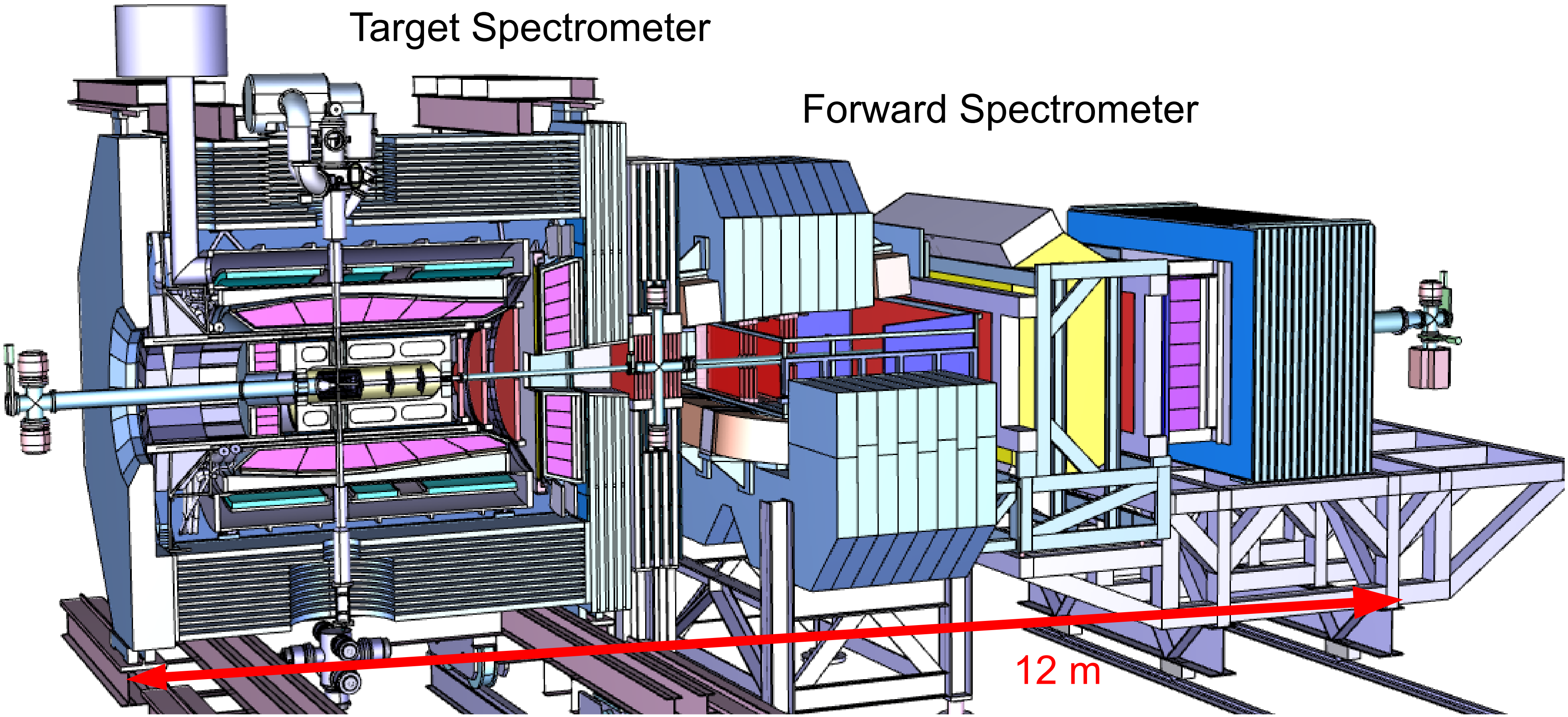
K. Nakamura *et al.* (PDG), J. Phys. G 37, 075021 (2010)





need high luminosity and effective background suppression

The PANDA Detector



exclusive measurements
- almost 4π coverage
- target / forward spectrometer

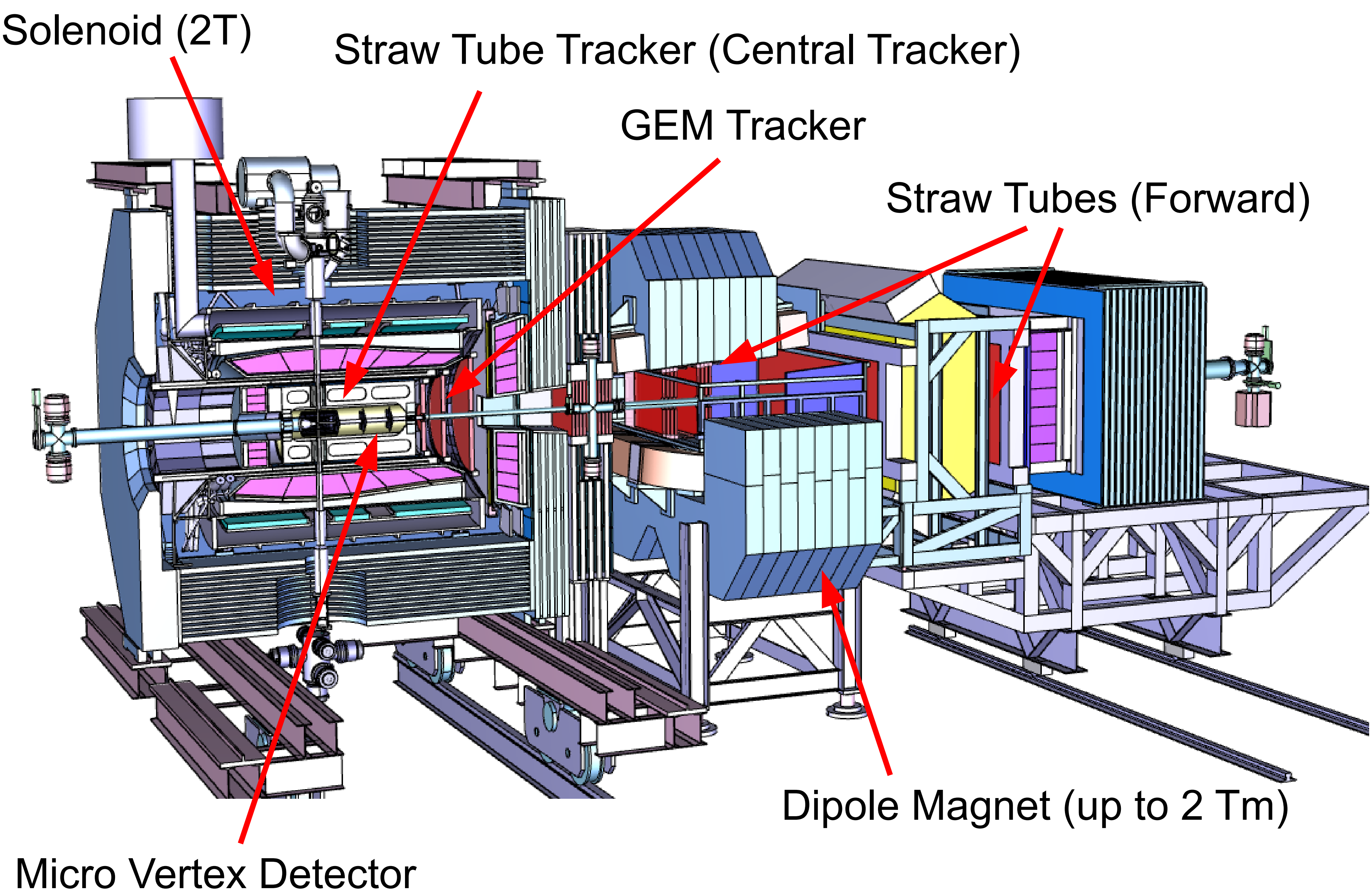
high event rates [10^7/s]

sophisticated online processing
- detection of rare decay modes

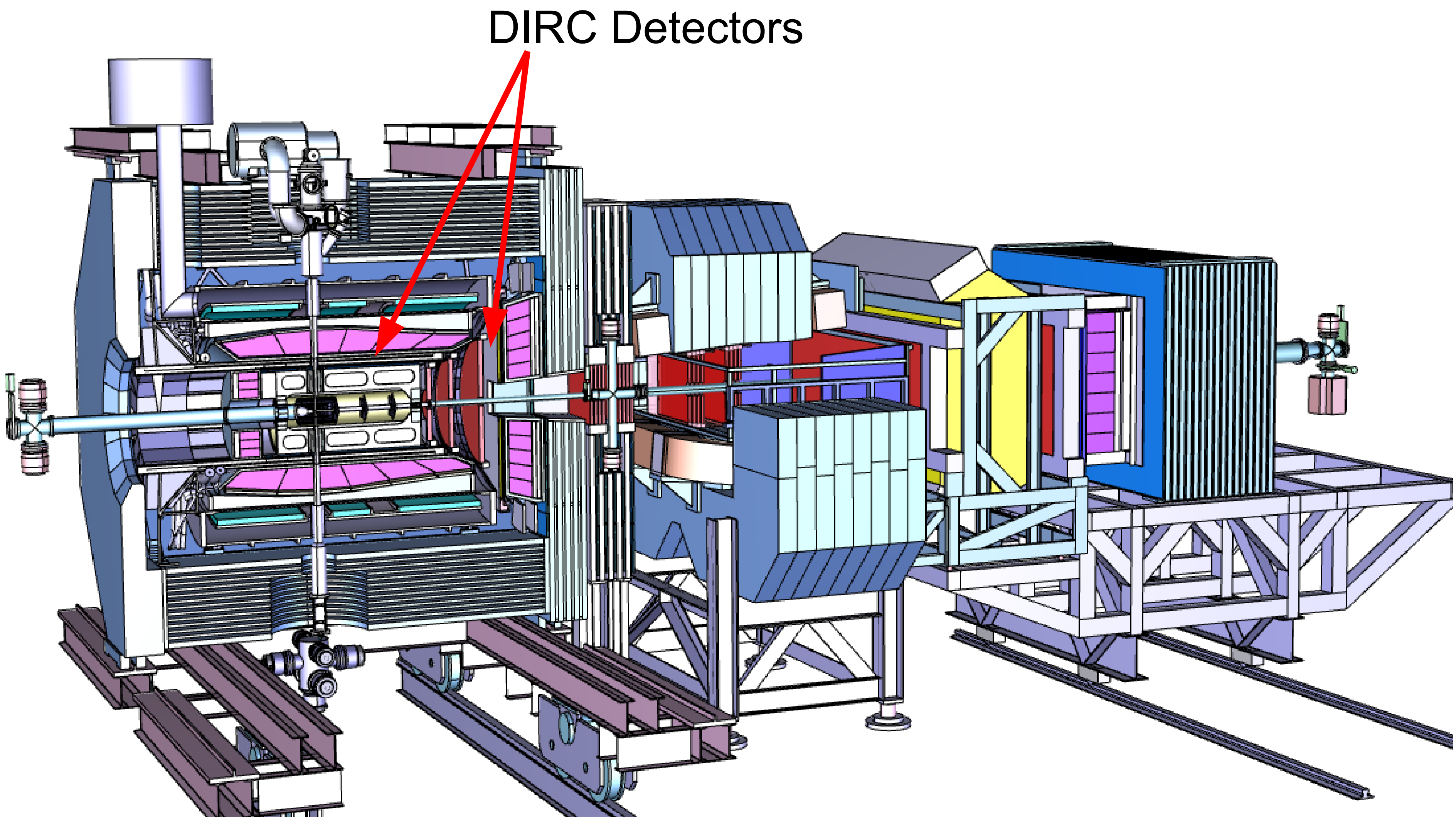
charged particle tracking
- good momentum / vertex resolution
- PID: $e^\pm \mu^\pm, \pi^\pm, K^\pm, p$

photon detection [E=0.02-15 GeV]
- excellent energy / angular resolution
- detection of low energetic photons

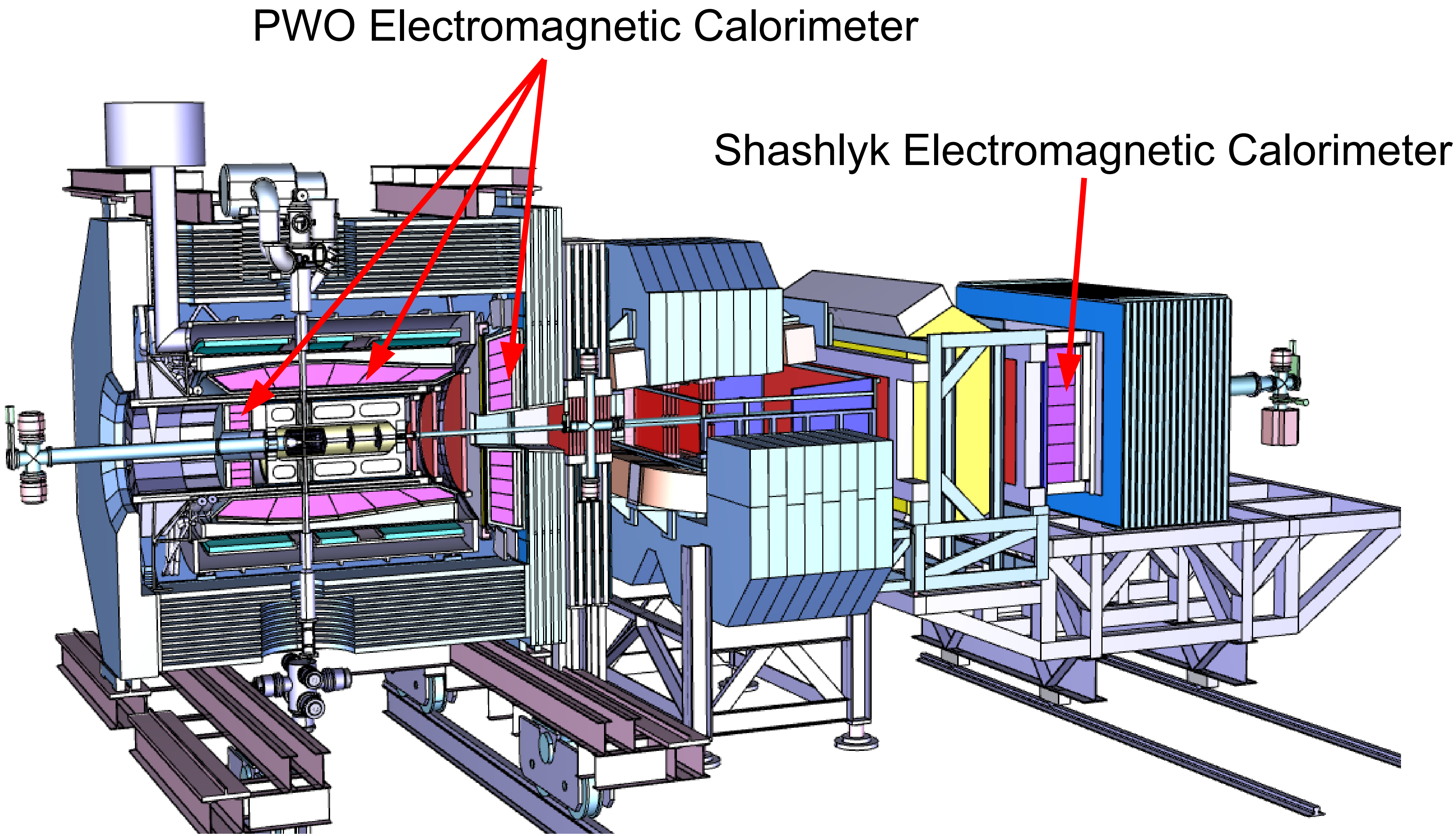
The PANDA Detector



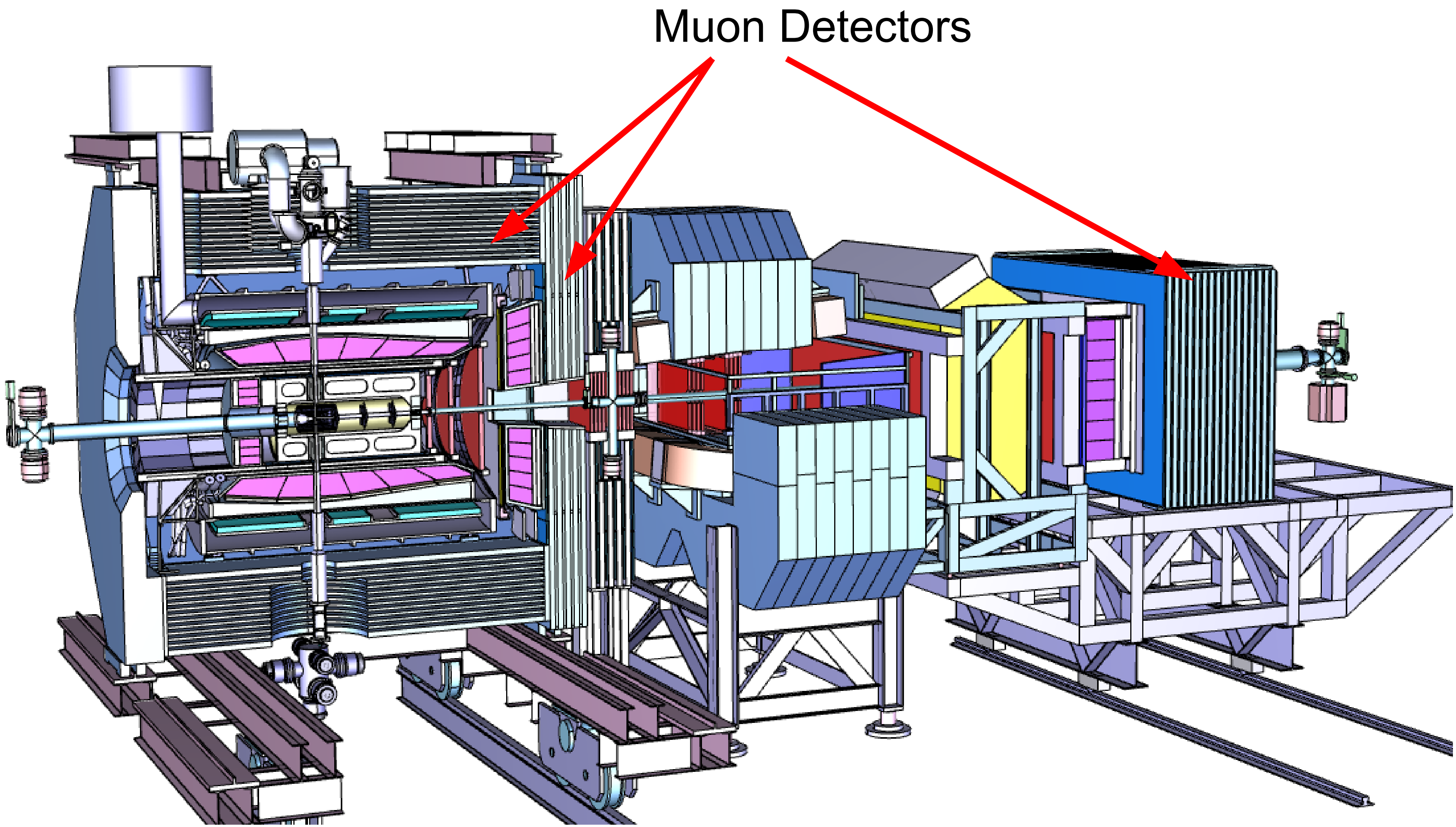
The PANDA Detector



The PANDA Detector

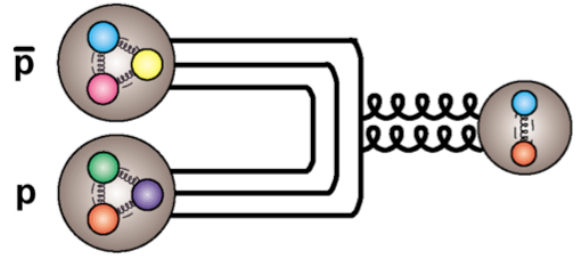


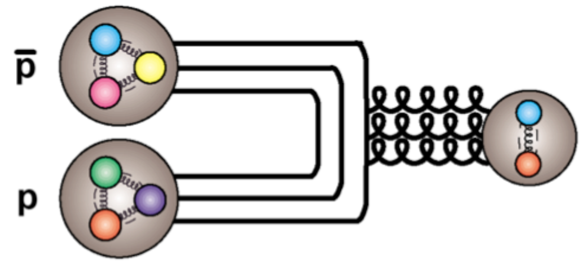
The PANDA Detector



Why Antiprotons?

- All quantum numbers allowed for a $q\bar{q}$ system directly accessible (compared to JPC=1^{--} for e^+e^-)
- Formation of resonances: Excellent mass resolution
- States with higher angular momenta accessible
- Annihilation: Gluon rich processes
  - hybrids and glueballs





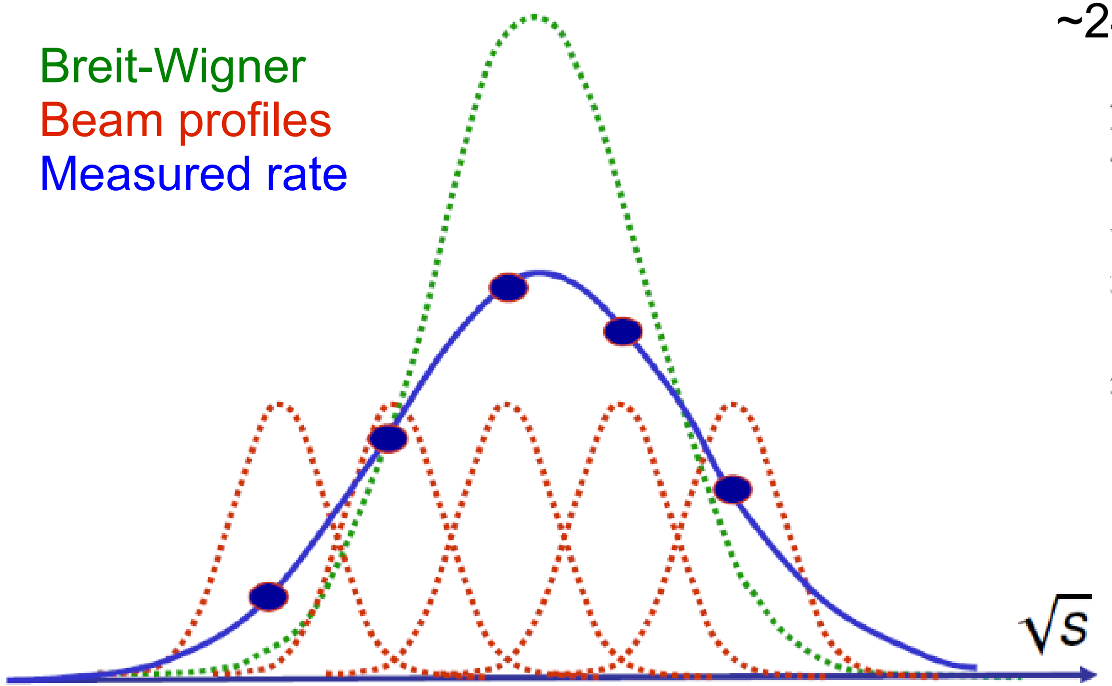
Non-exotic quantum numbers:

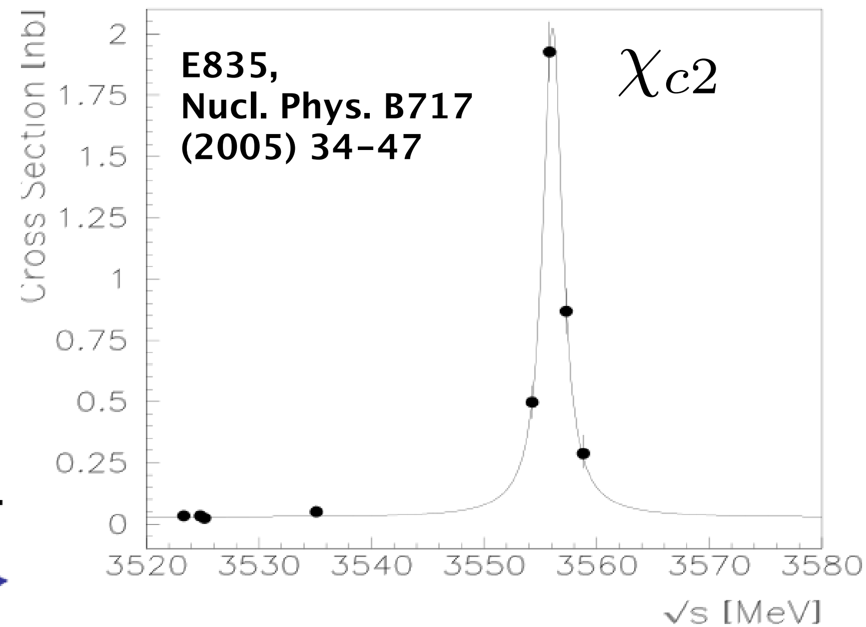
$$J^{PC} = 0^{-+}, 0^{++}, 1^{++}, 1^{+-}, 2^{++}, \ldots$$

Resonance Scans

$\bar{p}p \rightarrow \chi_c \rightarrow \gamma J/\psi \rightarrow \gamma e^+e^-$

resolution depends only on beam resolution
~240 keV for E835 and ~30 keV for PANDA

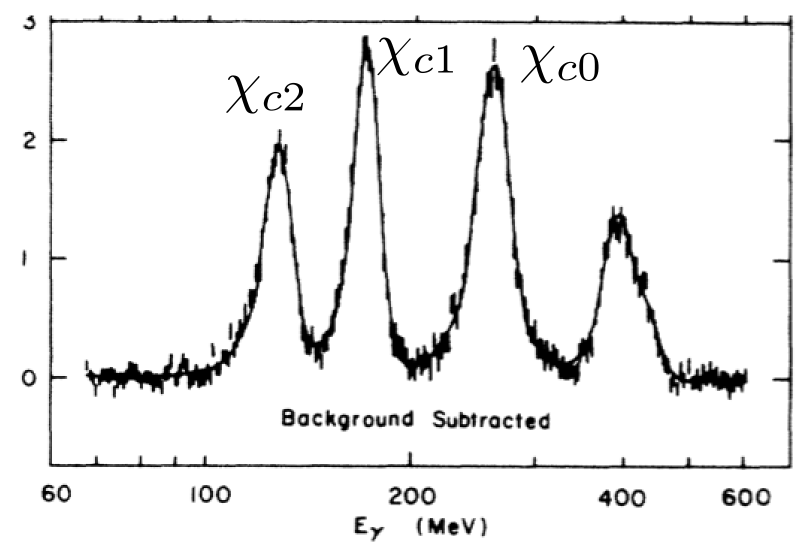




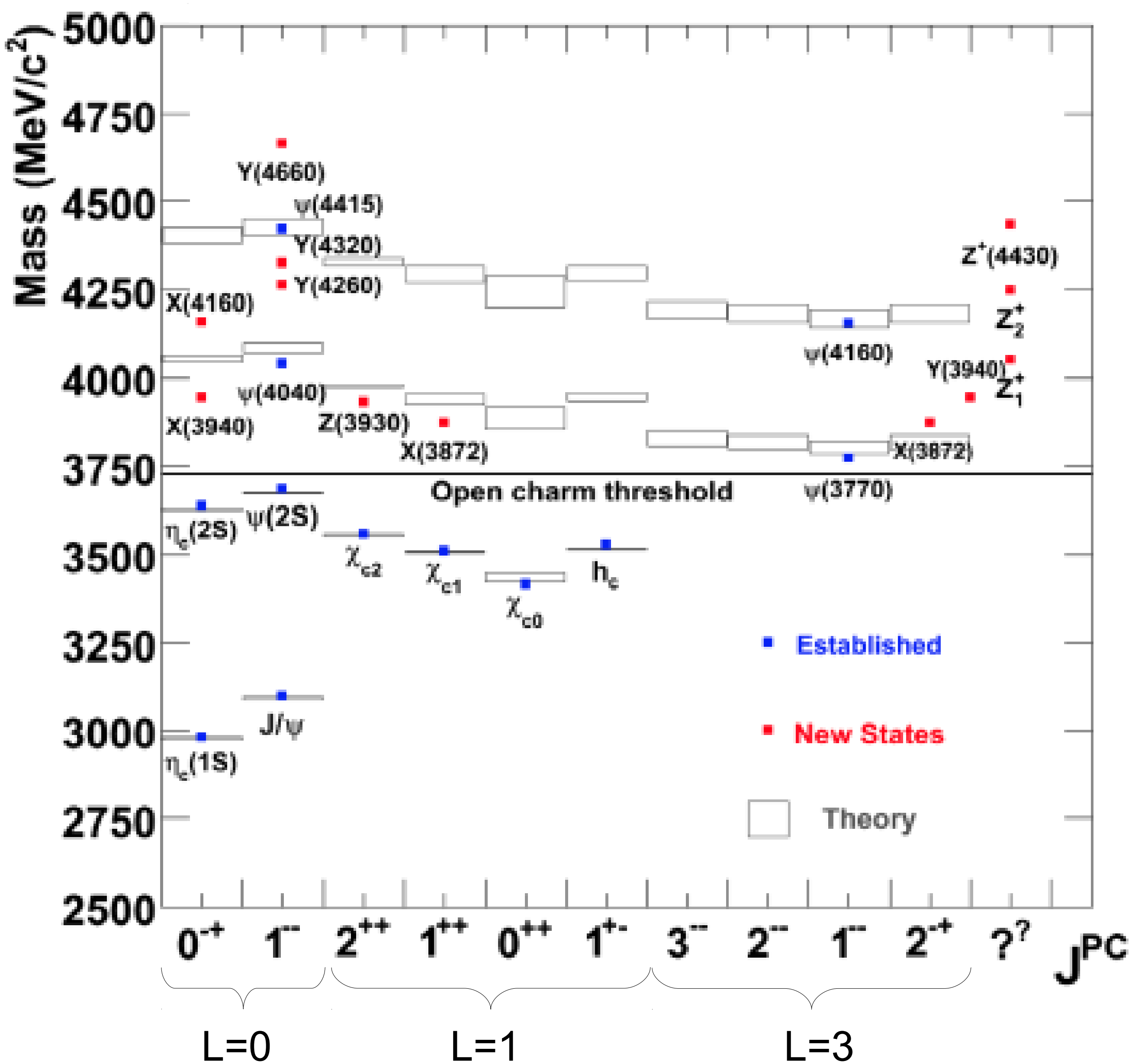
$e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_c \rightarrow \gamma(\gamma J/\psi) \rightarrow \gamma\gamma e^+e^-$

resolution limited by detector resolution
typically ~5-10 MeV

Crystal Ball, Phys. Rev. D34 (1986) 711



Charmonium Spectroscopy

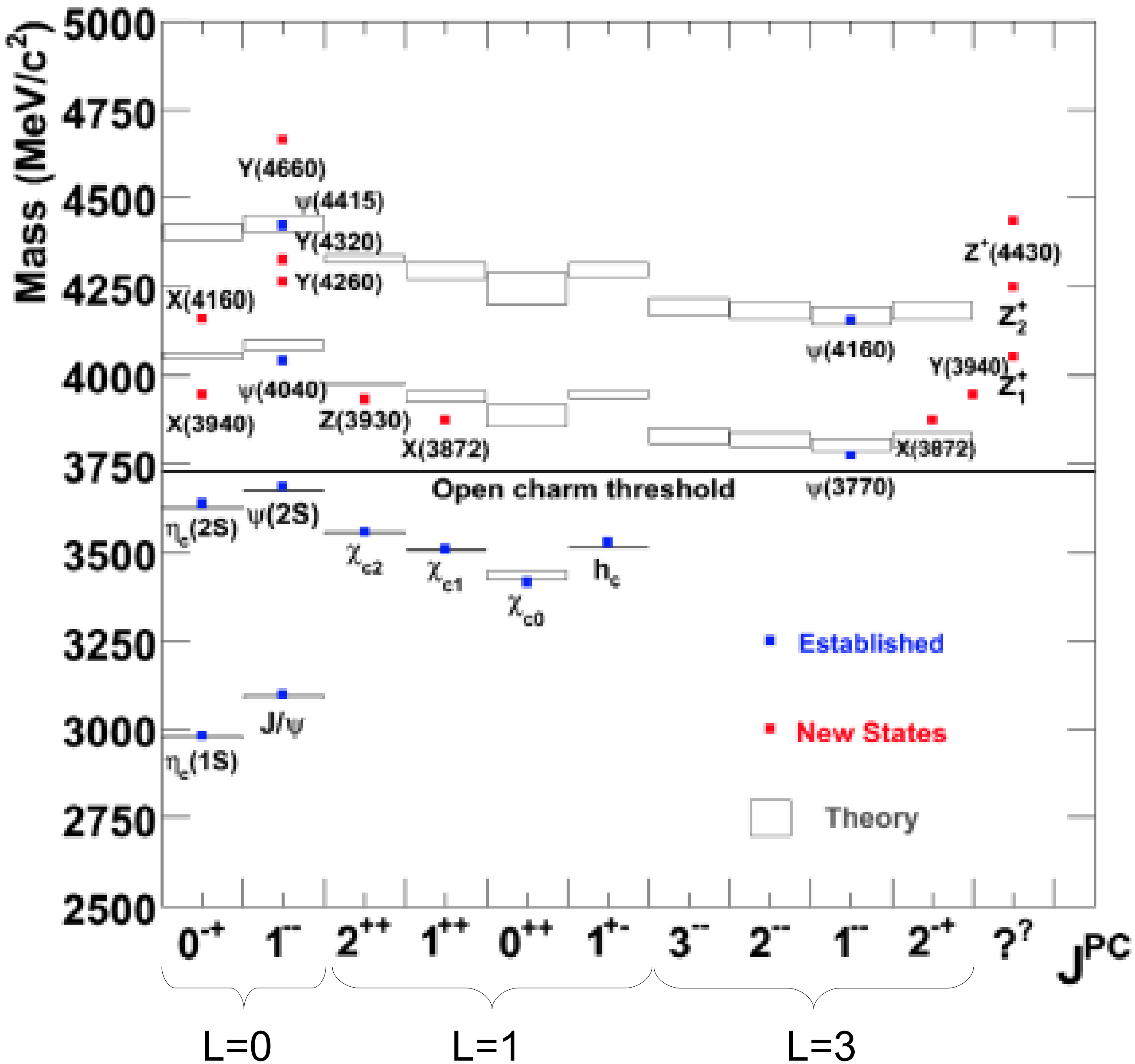


- Below the $D\bar{D}$ threshold: Precision measurements of
  - masses
  - widths
  - partial decay widths
- Above $D\bar{D}$ threshold: Search for
  - missing states with high angular momentum (limited access in e^+e^-, accessible in $\bar{p}p$)
  - excited states of S and P wave states

Charmonium Spectroscopy

New observed X, Y and Z states

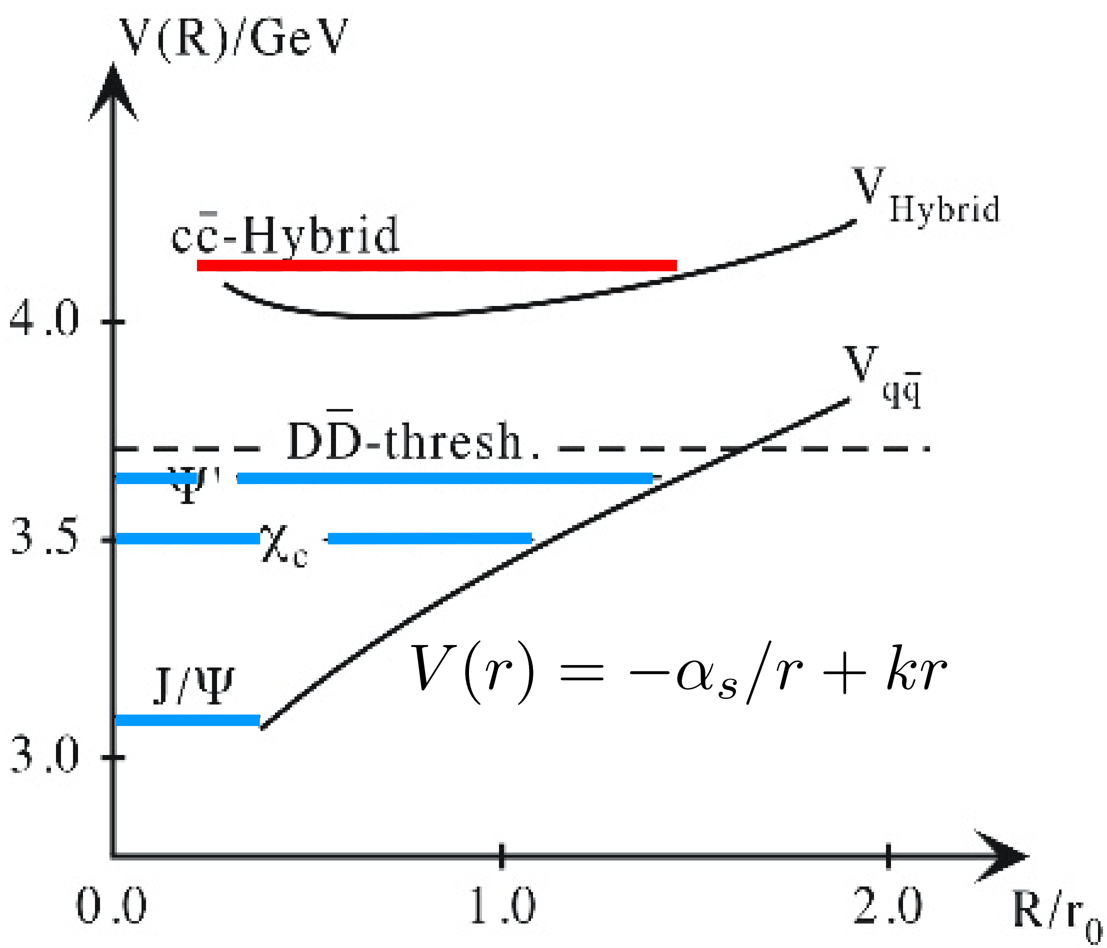
Babar, Belle, BESIII, CLEO, CDF, D0, LHCb



- Masses are poorly known
- Often only upper limits on widths
- Only few decay modes known
- Quantum numbers only known for a few states
- Some resonances lack confirmation
- What is the exact nature of the new states?
- New degrees of freedom?

Charmonium Hybrids

- formation and excitation of a flux tube
  - additional, gluonic degrees of freedom

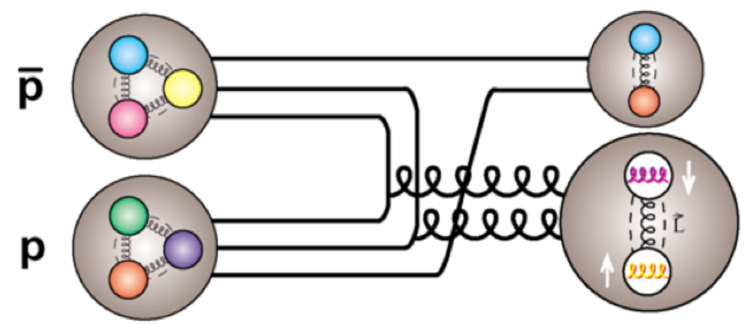


K. Juge, J. Kuti, C. Morningstar, Phys. Rev. Lett. 90, 161601 (2003)

$c\bar{c}$	gluonic 1^-		gluonic 1^+	
$^1S_0, 0^{-+}$	1^{++}		1^{--}	
$^3S_1, 1^{--}$	0^{+-}	← exotic	0^{-+}	
	1^{+-}		1^{-+}	← exotic
	2^{+-}	← exotic	2^{-+}	

J^{PC} not allowed for conventional charmonium

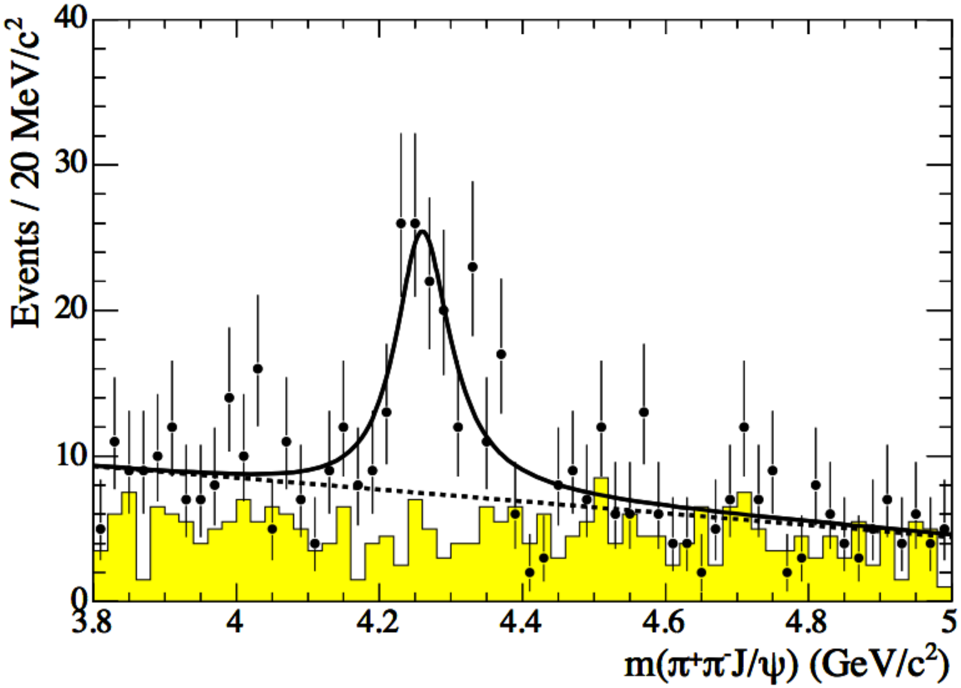
Access to states with exotic quantum numbers in $\bar{p}p$ production:



Y(4260) – A Charmonium Hybrid with $J^{PC}=1^{--}$?

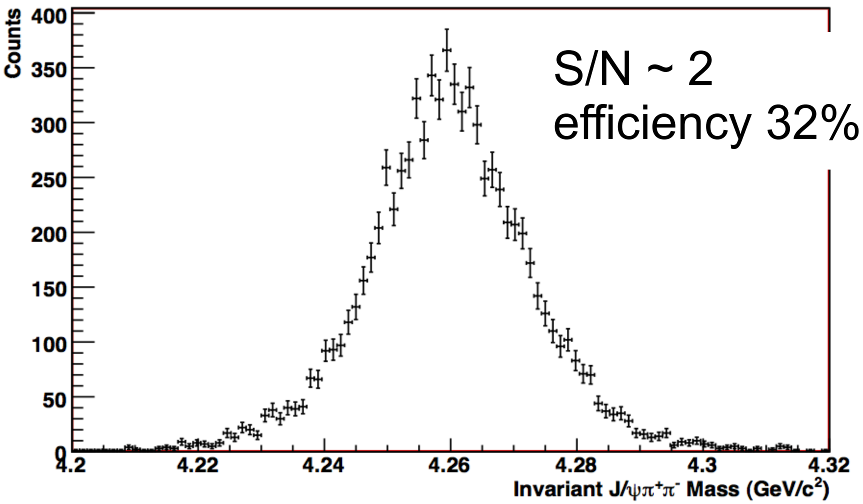
$$e^+e^- \to \gamma_{ISR} Y(4260) \to J/\psi\,\pi^+\pi^-$$

Babar, Phys. Rev. Lett. 95, 42001 (2005)



MC simulation studies for PANDA

$$\bar{p}p \to Y(4260) \to J/\psi\,\pi^+\pi^-$$



$$m = 4263^{+8}_{-9}\,\mathrm{MeV}/c^2$$

$$\Gamma = 95 \pm 14\,\mathrm{MeV}$$

not observed in open charm decays
→ charmonium hybrid?

Production of an Exotic Charmonium Hybrid

- exotic 1^{-+} state with mass ~4.3 GeV/c^2
  - expected to be narrow (10 MeV)

requires good PID, excellent calorimetry and good momentum resolution for kinematic fits for efficient background rejection

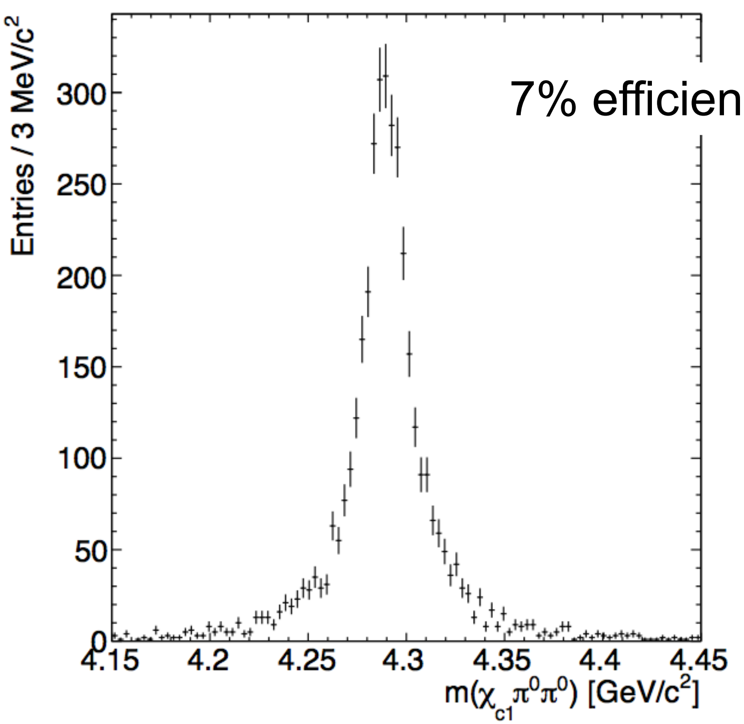
$$\bar{p}p \to \tilde{\eta}_{c1}\eta \to \chi_{c1}\pi^0\pi^0\eta$$

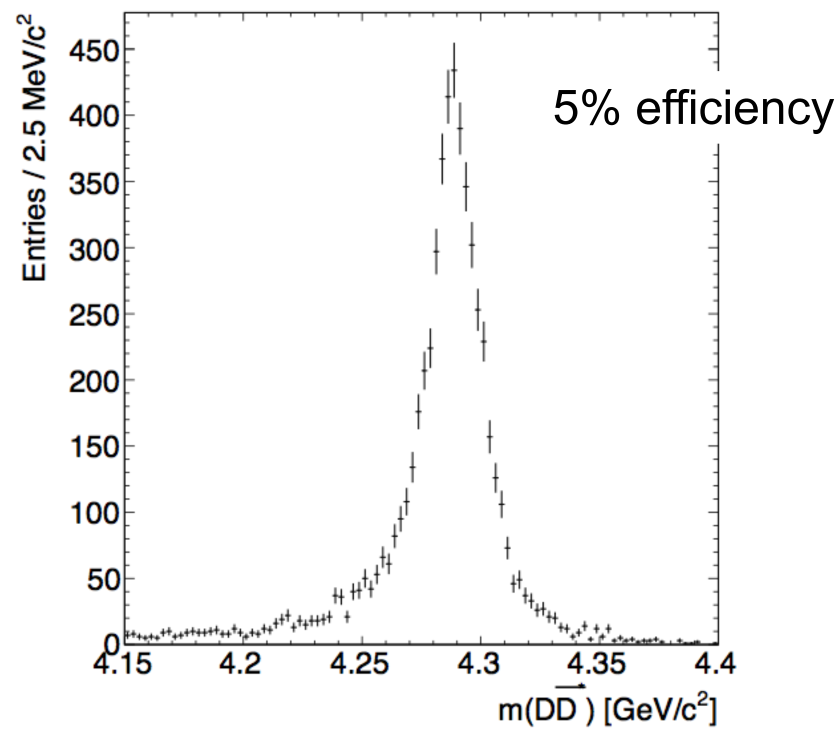
$$\chi_{c1} \to J/\psi\,\gamma$$

$$\bar{p}p \to \tilde{\eta}_{c1}\eta \to D^0\overline{D}^{*0}\eta$$

$$D^{*0} \to D^0\pi^0$$

$$D^0 \to K^-\pi^+\pi^0$$

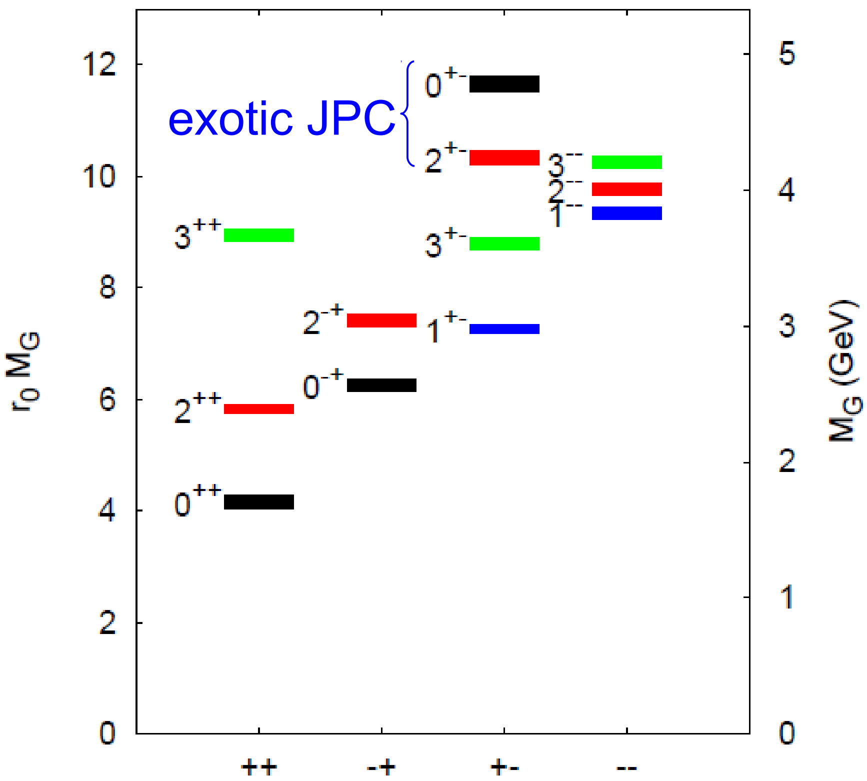




Glueballs

- LQCD calculations predict excited glueballs (gg, ggg) in the charmonium mass region
- Can have same quantum numbers as $q\bar{q}$ bound states
- Identification by decay pattern
  - couplings to final states independent of the flavor content
  - no coupling to photons
- Best candidate for the ground state $f_0(1500)$

Glueball Spectrum (LQCD)

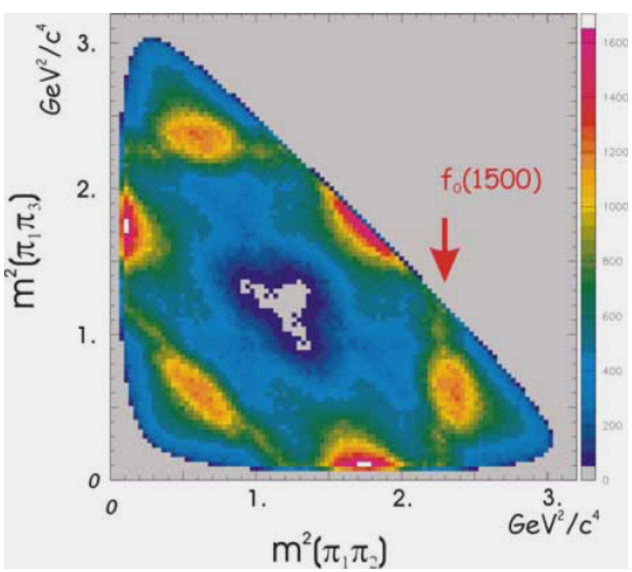


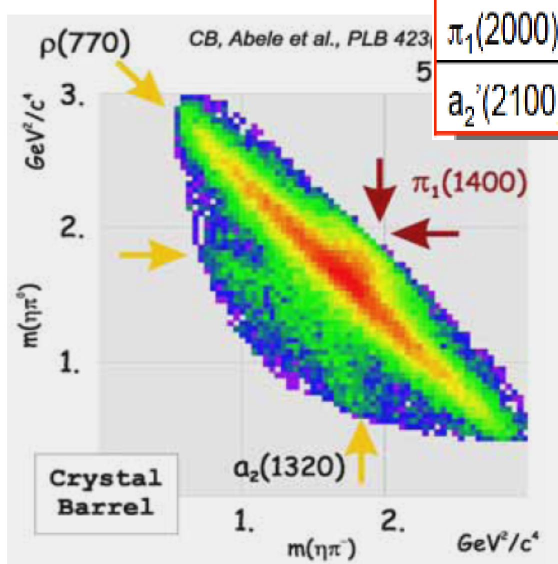
C. Morningstar, M. Peardon, Phys. Rev. D60, 34509 (1999)
C. Morningstar, M. Peardon, Phys. Rev. D56, 4043 (1997)

Light Exotics

- Many states in the light quark sector do not fit expectations for $q\bar{q}$
- Some have exotic J^{PC}
- Almost all exotic candidates observed in $\bar{p}p$ annihilation
  - with rates comparable to conventional hadrons (~1-100 μb)
- High discovery potential for PANDA also in the charmonium mass region

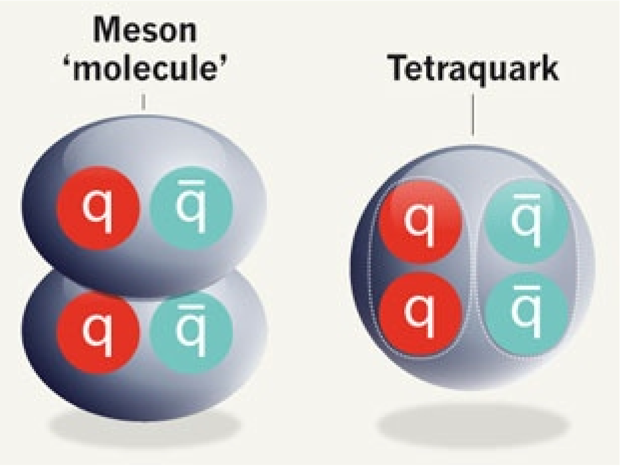
Main non-$q\bar{q}$ candidates	
$f_0(980)$	4q state - molecule
$f_0(1500)$	0^{++} glueball candidate
$f_0(1370)$	0^{++} glueball candidate
$f_0(1710)$	0^{++} glueball candidate
$\eta(1410)$; $\eta(1460)$	0^{-+} glueball candidate
$f_1(1420)$	hybrid, 4q state
$\pi_1(1400)$	hybrid candidate 1^{-+}
$\pi_1(1600)$	hybrid candidate 1^{-+}
π (1800)	hybrid candidate 0^{-+}
$\pi_2(1900)$	hybrid candidate 2^{-+}
$\pi_1(2000)$	hybrid candidate 1^{-+}
$a_2'(2100)$	hybrid candidate 1^{++}





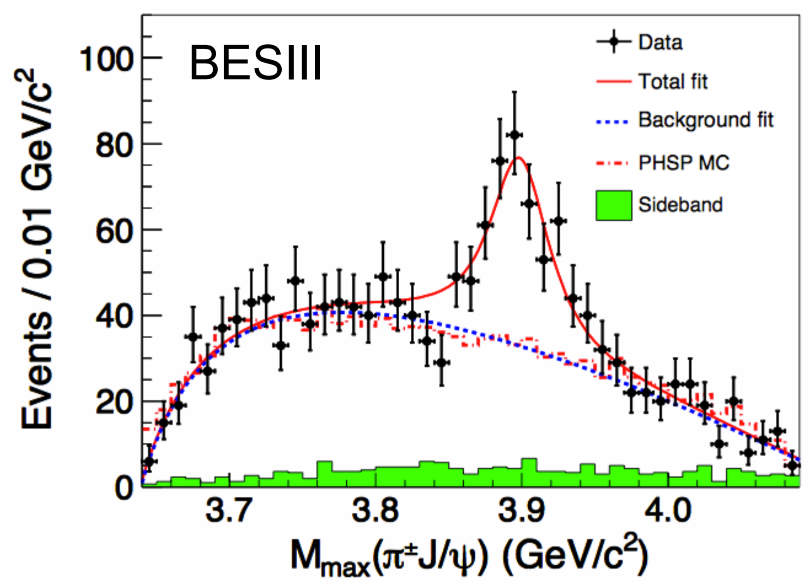
Charged Z States

- $Z_c(4430)^+$ observed by Belle and LHCb
- $Z_c(4050)^+$ and $Z_c(4250)^+$ only observed by Belle
- $Z_c(3900)^+$ observed by BESIII, Belle and CLEO



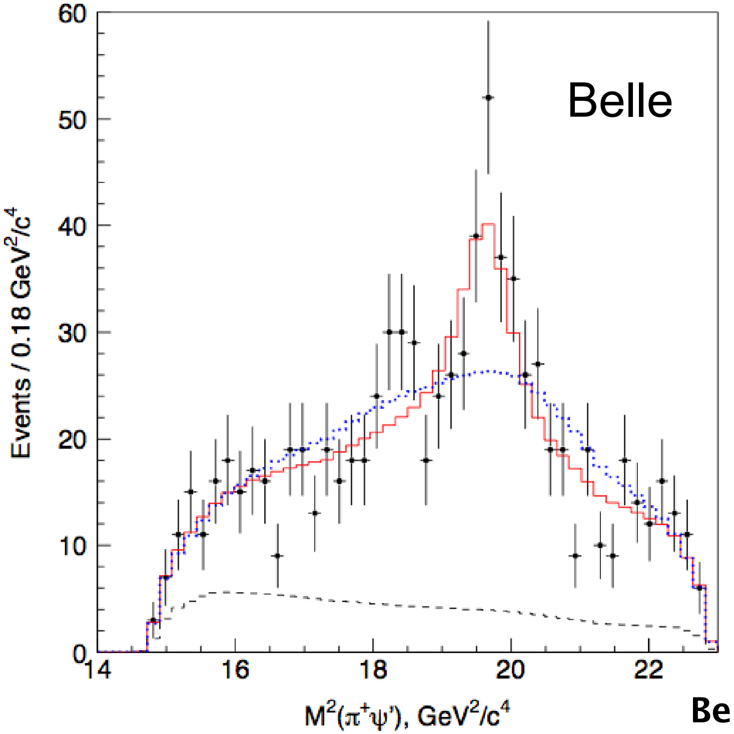
- Exotic matter: Minimal flavor content $c\bar{c}\ u\bar{d}$
  - nature: tetraquarks, molecules, ...?

$Z_c(3900)^+ \to J/\psi\,\pi^+$



BESIII, Phys. Rev. Lett. 110, 252002 (2013)

$Z_c(4430)^+ \to \psi'\pi^+$



Belle, Phys.Rev. D80, 031104, 2009

Charged Z_c States

- Planned studies at PANDA

in production $\bar{p}p \to Z_c(4430)^+\pi^- \to \psi'\pi^+\pi^-$

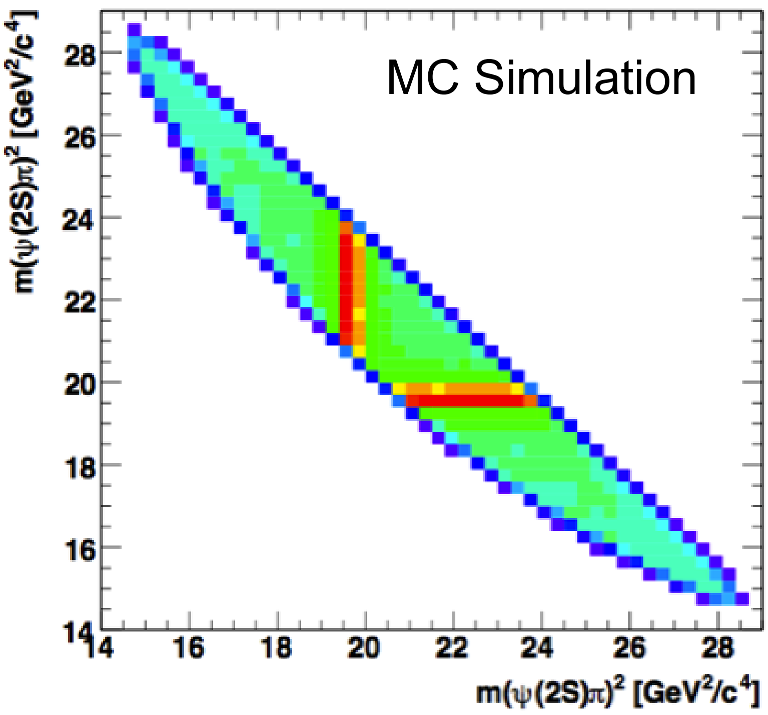
in formation (deuteron target):

$\bar{p}d \to Z_c(4430)^- p_{\rm spect} \to \psi'\pi^- p_{\rm spect}$

including other Z_c states in different decay modes and searches for new states in production

$\bar{p}p \to Z_c(4430)^+\pi^-$

$(p_{\bar{p}} = 15\,\mathrm{GeV}/c)$



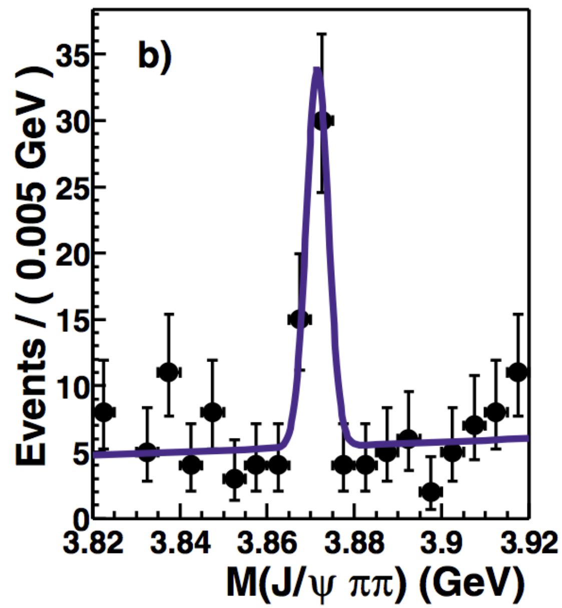
X(3872)

Discovered in 2003 by Belle

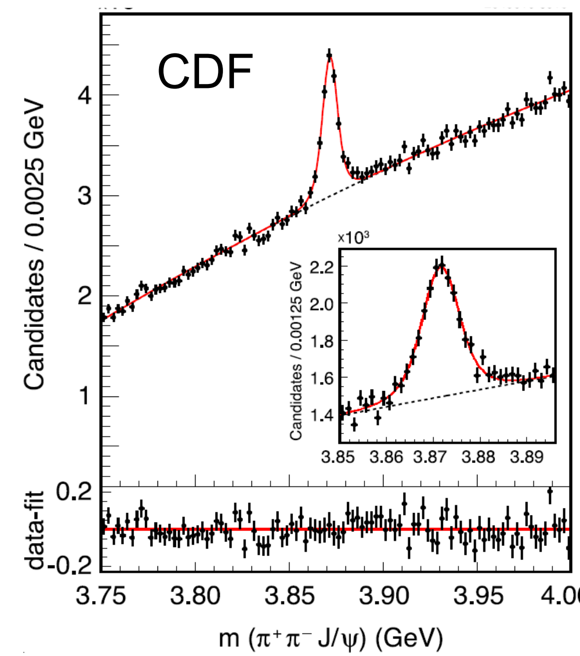
$$B \to X(3872)K \to J/\psi\,\pi^+\pi^- K$$

Since then confirmed by several experiments in various production mechanisms and observed in further decay modes.

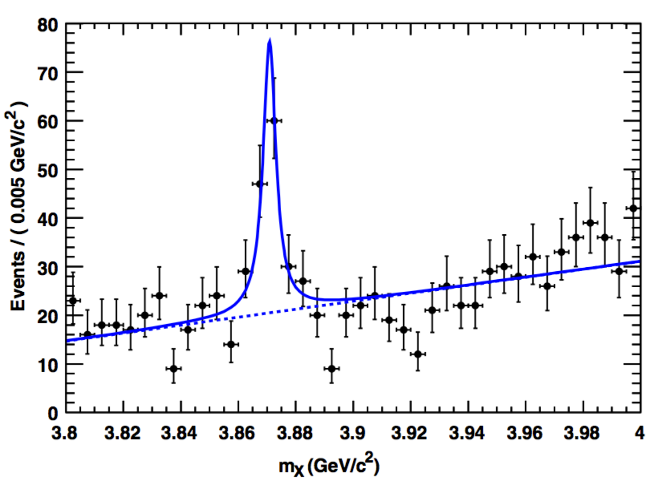
Belle, Phys. Rev. Let. 91 262001 (2003)



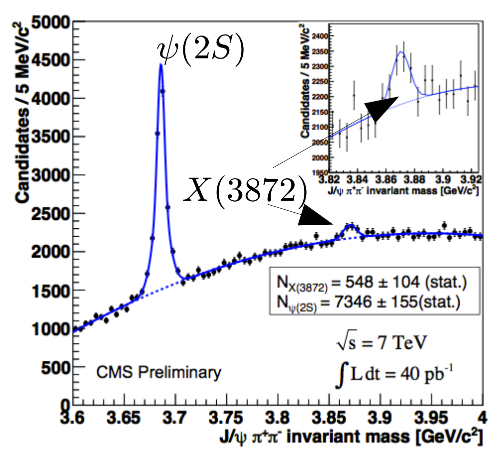
CDF, Phys. Rev. Lett. 103, 152001 (2009)



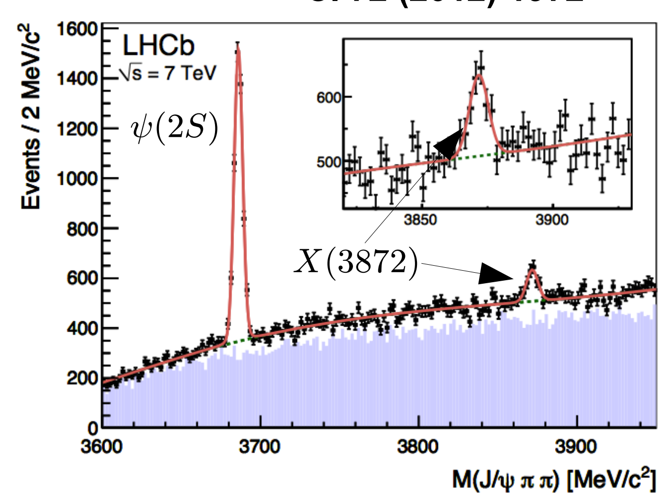
Babar, Phys. Rev. D77 011102R (2008)



CMS, CMS-PAS-BPH-10-018



LHCb, Eur. Phys. J. C. 72 (2012) 1972

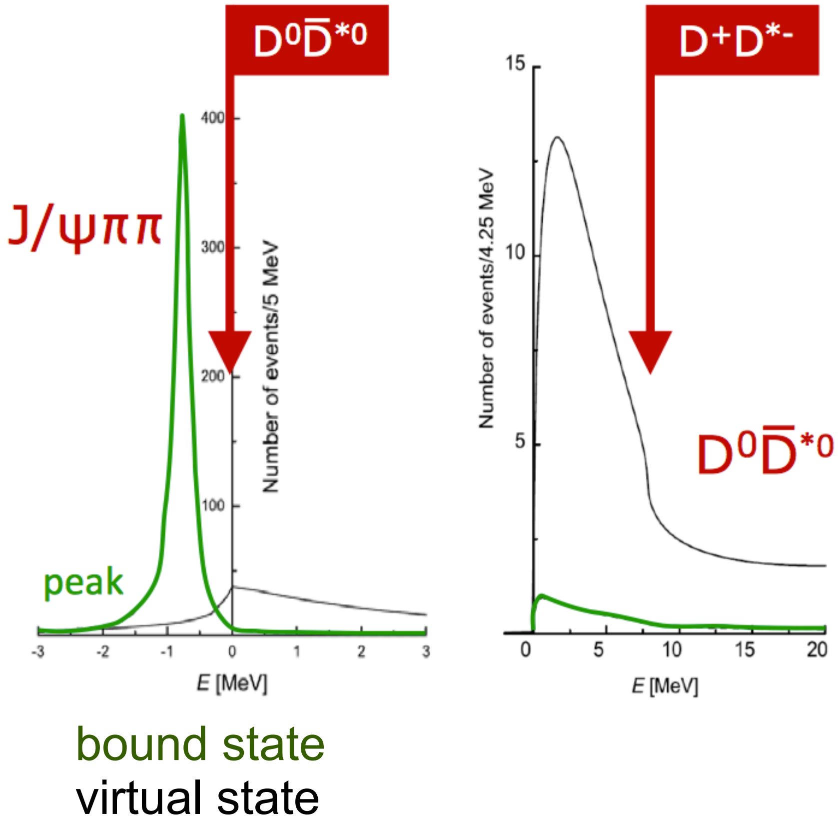


X(3872) Scan

- Mass very close to D̄D* threshold $\Delta m = (-420 \pm 390)\mathrm{keV}$
- Narrow width <1.2 MeV (90% CL)
- $J^{PC}=1^{++}$
- Observed decay modes:

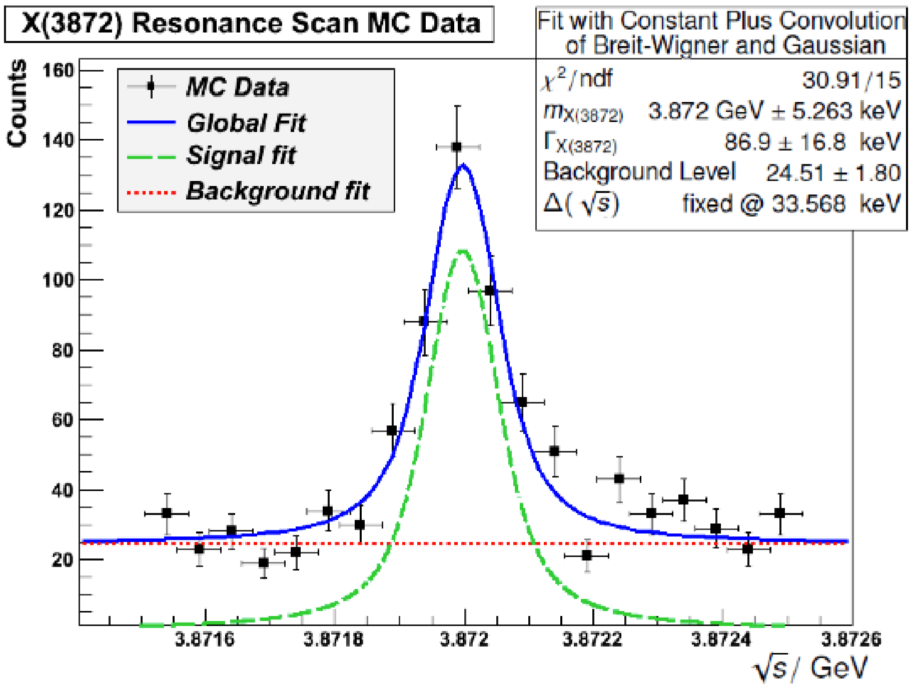
  $J/\psi\,(\pi^+\pi^-, \pi^+\pi^-\pi^0, \gamma), \psi'\gamma, D^{*0}\bar{D}^0$

- Possible interpretations include loosely bound S-wave molecule
- Lineshape measurement needed
  - Scan in different decay modes essential



X(3872) Scan at PANDA

- Simulation of a scan in $J/\psi\,\pi^+\pi^-$ decay mode
  - simultaneous measurement of other decay channels
- High resolution mode of HESR
- Assumed cross section: 50 nb (E. Braaten)
- 20 scan points with 2 days of data taking each (subsequent branching fractions and 50% duty efficiency included)



Sensitivity for width of all known states in the charmonium region:

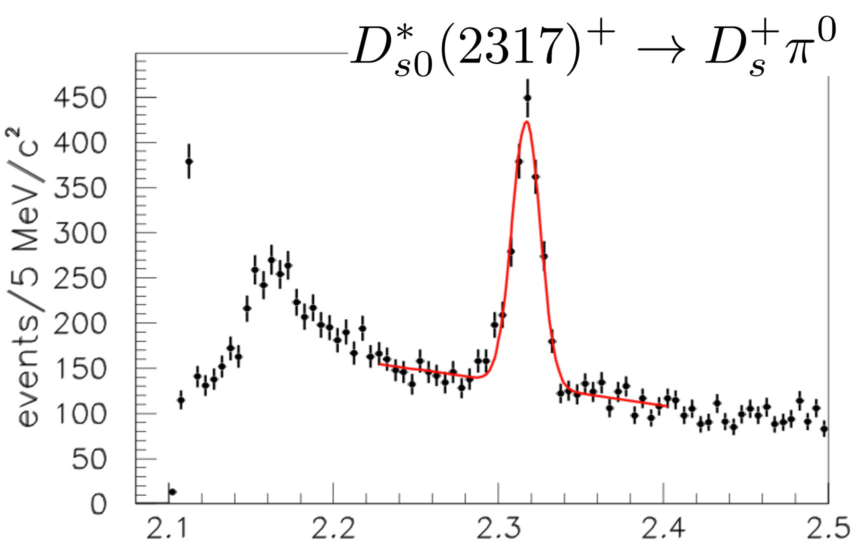
$$\delta p/p = 10^{-5} \quad \rightarrow \quad 10\,\mathrm{keV}$$
$$\delta p/p = 10^{-4} \quad \rightarrow \quad 100\,\mathrm{keV}$$

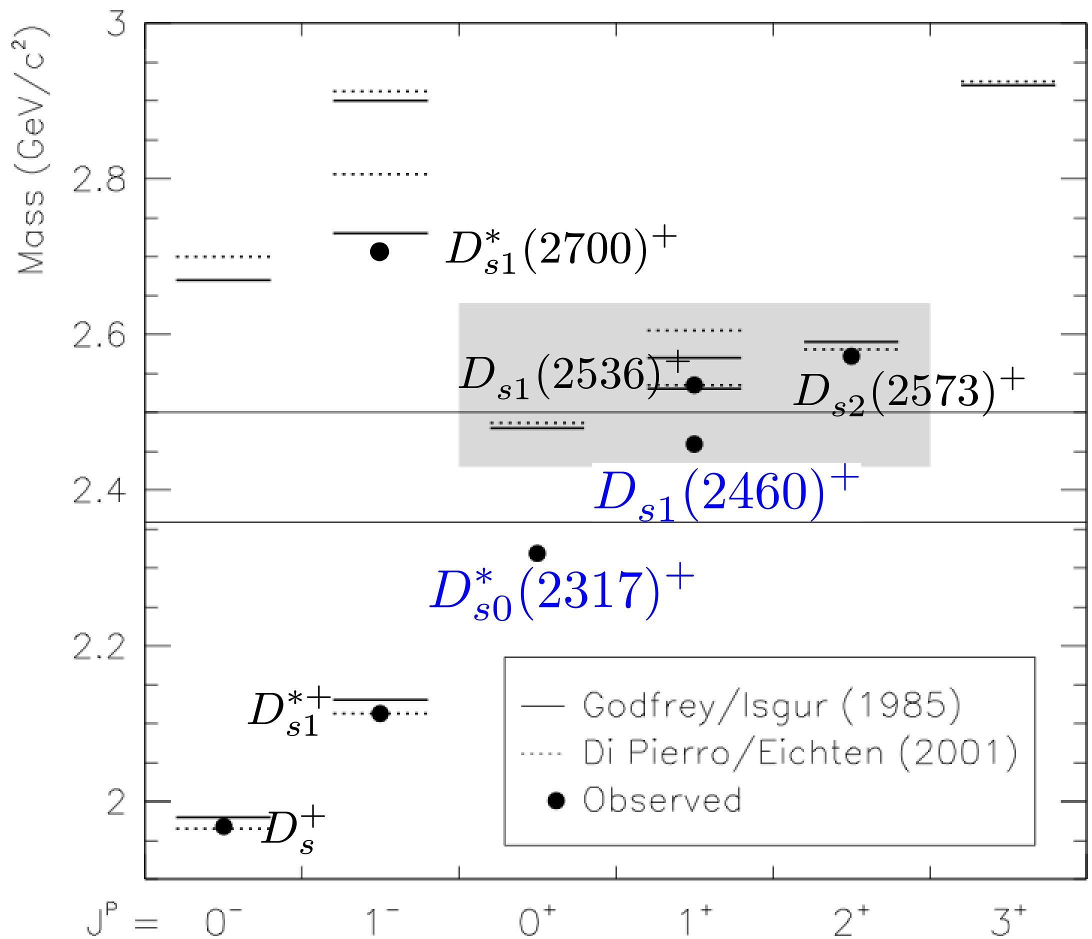
Open Charm

- Qualitative agreement between theory and experiment, except for $D^*_{s0}(2317)^+$ and $D_{s1}(2460)^+$
- Masses substantially lower than expected and close to D$^{(*)}$K threshold

- Nature of the two states unclear, interpretations include conventional $c\bar{s}$, D$^{(*)}\bar{K}$ molecules, tetraquarks, ...
  → sensitive to widths

Babar, Phys. Rev. Lett. 90, 242001 (2003)

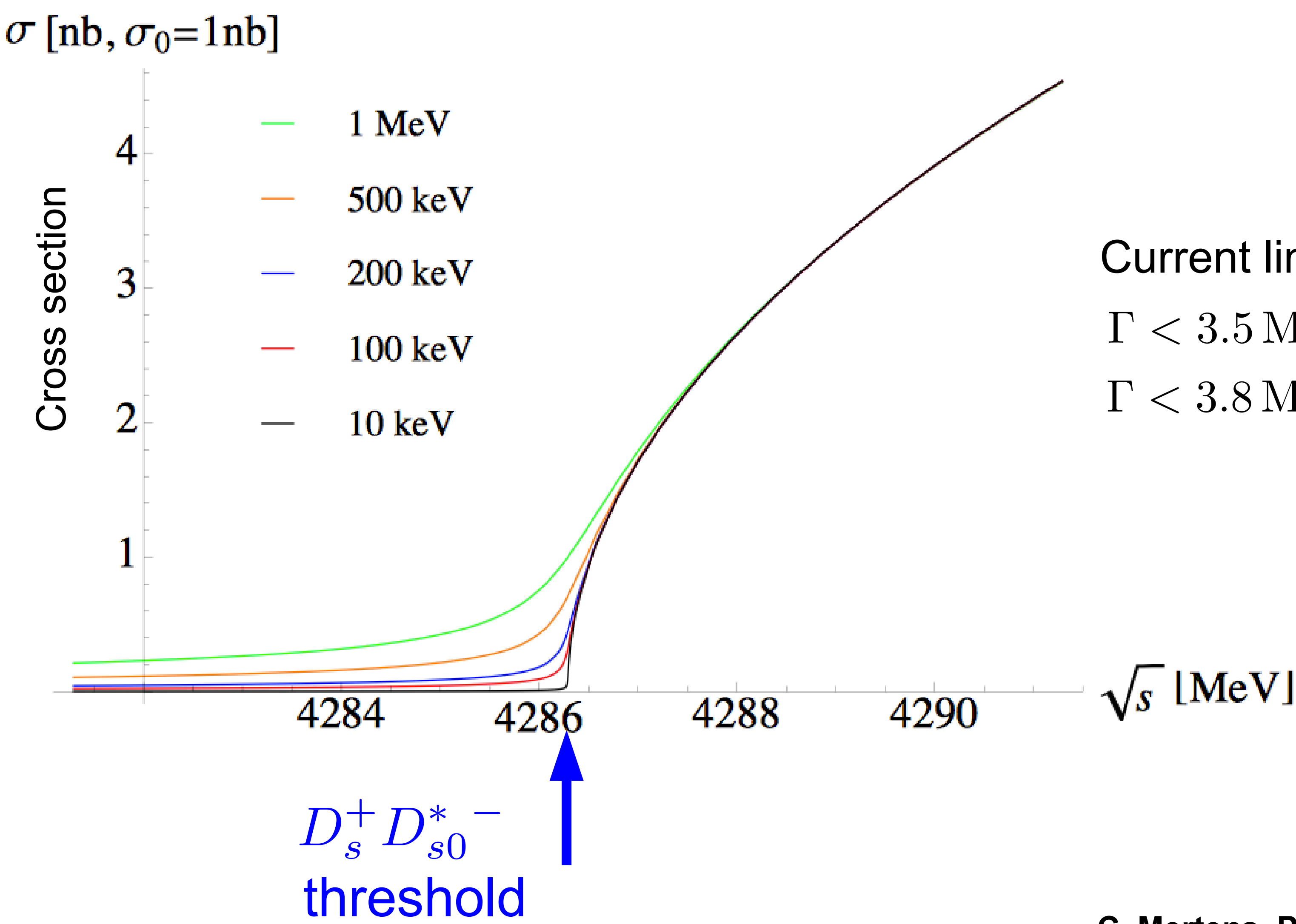




further states (J^{PC} undetermined):
$D^*_{sJ}(2860)^+$ and $D_{sJ}(3060)^+$

Determination of D_{sJ} widths at PANDA

- Determine widths from excitation function of $\bar{p}p \to D_s^+ D_{s0}^*(2317)^-$
  - energy scan around the production threshold



Current limits:

$\Gamma < 3.5\,\mathrm{MeV}$ $(D_{s0}^*(2317)^+)$

$\Gamma < 3.8\,\mathrm{MeV}$ $(D_{s1}(2460)^+)$

C. Mertens, PhD thesis, Bochum (2010)

Conclusion and Outlook

- Hadron physics at PANDA with antiprotons
  - address key questions for QCD
  - high precision
  - high statistics
  - high discovery potential

- Charmonium and open charm mesons
  - new observations confront simple quark model
  - new degrees of freedom?
    - Y(4260): A charmonium hybrid?
    - X(3872) and Z_c: Molecules or tetraquarks?
  - PANDA is designed for studies in this mass region with direct access to all states with non-exotic quantum numbers

- Accelerator and detector are on track

520 members from 69 institutions in 18 countries

http://www-panda.gsi.de/

Thank you!