News with Charm

- Introduction
- Open Charm States
- States with hidden Charm
- Future: PANDA-Detector at FAIR
- Conclusions

Introduction (1)

Present activities in Hadron Spectroscopy

BaBar; BES; BELLE; CLEO; CDF; D∅, FOCUS, E 835 (Fermilab)

BaBar/BELLE/CLEO: Fixed CM-energy (Υ(4s))

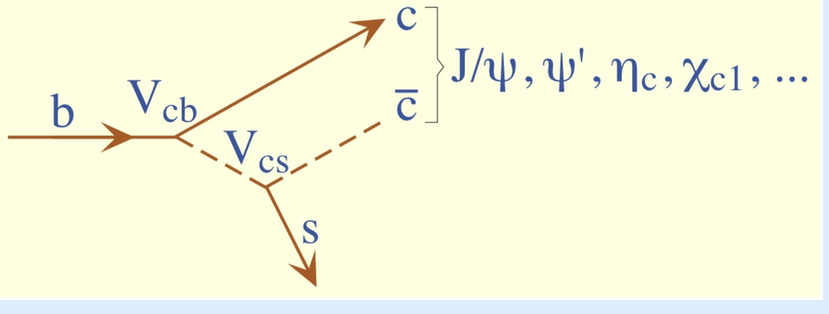
Non resonant $q\bar{q}$ production

$e^+e^- \to$	σ[nb]
$c\bar{c}$	1.30
$s\bar{s}$	0.35
$d\bar{d}$	0.35
$u\bar{u}$	1.39

Resonant $b\bar{b}$ production

$e^+e^- \to b\bar{b}$	1.05

Additionally: $\gamma\gamma$ – Fusion, ISR



B-mesons good source for charm

BR ≈ 10^{-2} (incl.)

$\int L dt \approx 400 (fb)^{-1}$ (BaBar/BELLE))

Introduction (2)

BES, CLEO-c: Discrete Energies: J/ψ, ψ', ψ'', ...

$e^+e^- \rightarrow \psi''' \rightarrow D\bar{D}$

$e^+e^- \rightarrow \psi' \rightarrow \gamma\chi_c$

$e^+e^- \rightarrow \psi' \rightarrow \gamma q\bar{q}$

CDF, D∅ : $\bar{p}p$ (E_{CM} = 2TeV) $\rightarrow B\bar{B}$

↳ Charm

Focus : γ(200GeV) Be $\rightarrow$ B + X

↳ Charm

E 791 : π^-(500GeV)Pt(C) $\rightarrow$ B + X

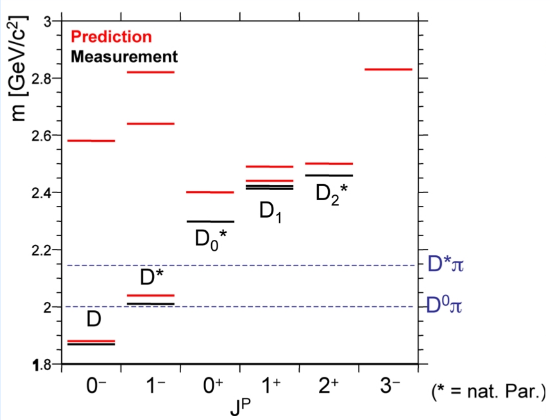
↳ Charm

E 835 : $\bar{p}p$ (Scan mode) $\rightarrow J/\psi$, ψ', χ_c, η_c, ...

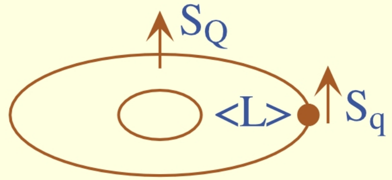
Open Charm States (1)

$D(c\bar{q}, \bar{c}q)$ (q = u, d)-states (BELLE, FOCUS, CDF)

Expectation:



Heavy Quark limit



Conserved: S_Q, $j_q = L + S_q$

$j_q = {}^1/_2$ = Broad

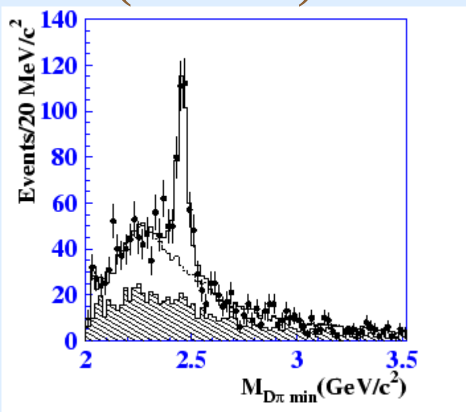
$j_q = {}^3/_2$ = Narrow

Two newly discovered broad states: Dπ, D*π-modes

M = (2352 ± 50)MeV ; Γ = (261 ± 50)MeV $D_0^*(2400)$?

M = (2427 ± 36)MeV ; Γ = (384 ± 117)MeV $D_1(2430)$?

Evidence (BELLE) : B → Dππ



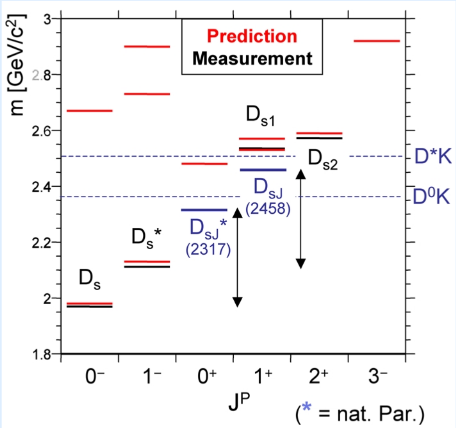
J^P: Compatible with 0^+, 1^+

Interpretation: Missing $c\bar{q}$-states

Open Charm States (2)

$D_s(c\bar{s}, \bar{c}s)$-states (BaBar, CLEO, BELLE, CDF)

Expectation:

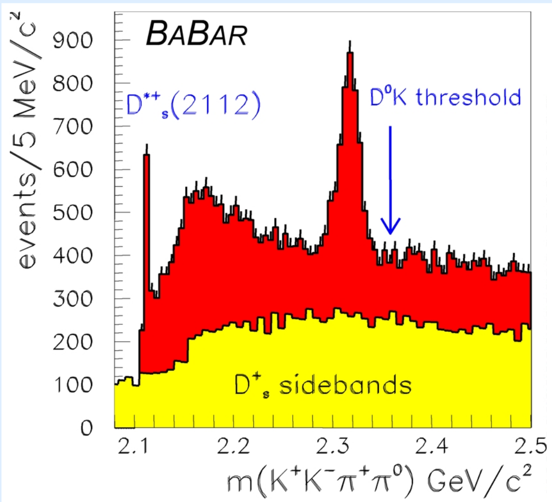


Two newly discovered narrow states

1) $M = (2319.6 \pm 0.2 \pm 1.4)\text{MeV}$; $\Gamma < 3.8\text{MeV}$!

$(M_{Model} \approx 2480\text{MeV})$

Evidence (BaBar). $D_{sJ}^{*}(2317)^{\pm} \rightarrow D_s^{\pm}\pi^0$



Decays:

$\rightarrow D_s^{\pm}\pi^0$ (I − violation)

$\not\rightarrow D_s^{+}\gamma$ (Forbidden, $J^P = 0^+$)

$\not\rightarrow D_s^{*}(2112)^{+}\pi^0$ (Forbidden, $J^P = 0^+$)

$\not\rightarrow D_s^{+}\pi^0\pi^0$ (Forbidden, $J^P = 0^+$)

$\not\rightarrow D_s^{*}(2112)^{+}\gamma$ (Allowed)

$\not\rightarrow D_s^{+}\pi^+\pi^-$ (Forbidden, $J^P = 0^+$)

Consistent with $J^P = 0^+$

Open Charm States (3)

Quantum numbers:

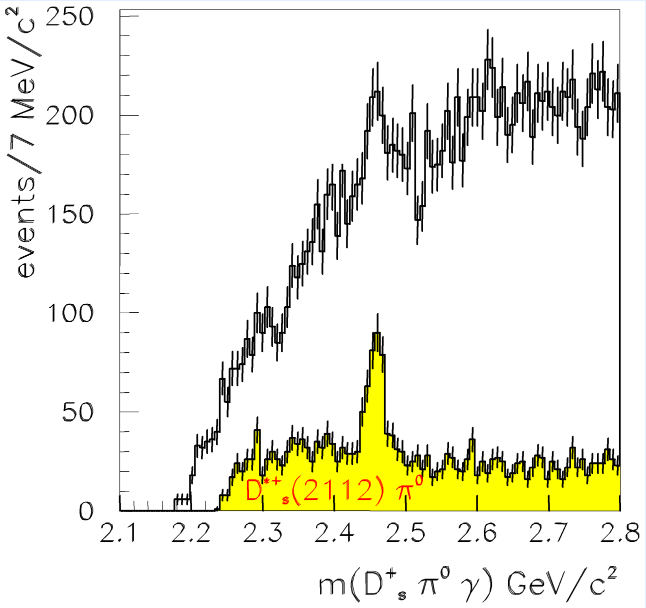
$J^P = 0^+$ from $B \to \bar{D} D^*_{sJ}(2317)$ (BELLE, Angular Distr.)

I = 0 ?   No evidence for $D_s^+\pi^-$-, $D_s^+\pi^+$-states

2) $M = (2460.2 \pm 0.2 \pm 0.8)$MeV ; $\Gamma < 3.5$MeV

($M_{Model} \approx 2560$MeV)

Evidence (BaBar). $D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma$



Decays:

$\to D_s^+\pi^0\gamma\left(D_s^*(2120)\pi^0\right)$

$\to D_s^+\pi^+\pi^-$

$\to D_s^+\gamma(\to J \neq 0)$

$\not\to D_s^+\pi^0$ (Forbidden, $J^P = 1^+$)

$\not\to D_{sJ}^*(2317)^+\gamma$ (Allowed)

$\not\to D_s^+\pi^0\pi^0$ (Allowed)

$\not\to D_s^*(2112)^+\gamma$ (Allowed)

Consistent with $J^P = 1^+$

Quantum numbers:

$J^P = 1^+$ from $B \to \bar{D} D_{sJ}(2460)$ (BELLE, Angular Distr.)

$\hookrightarrow D_s\gamma$

I = 0 ?   No evidence for $D_s^+\pi^-$

Open Charm States (4)

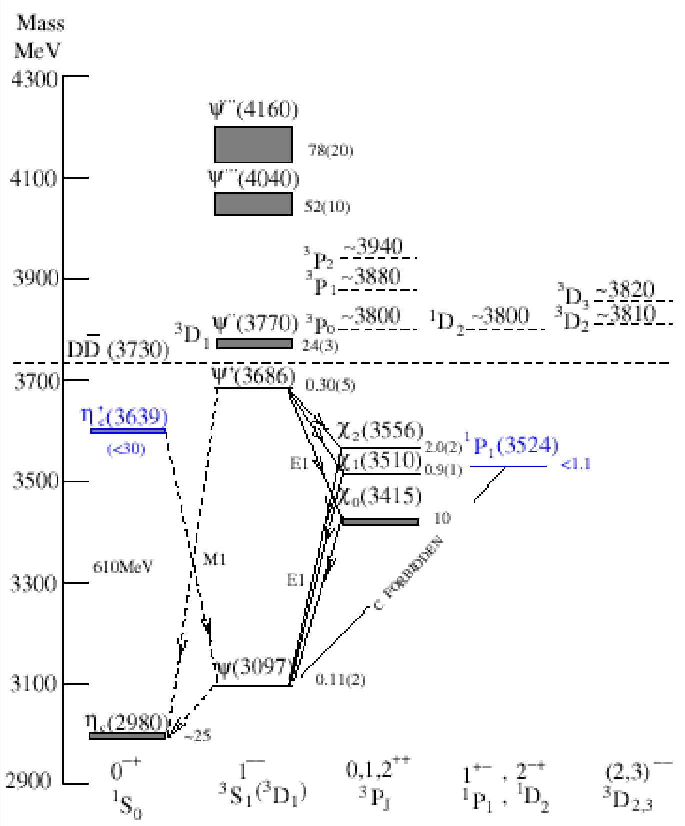
Interpretation of $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$

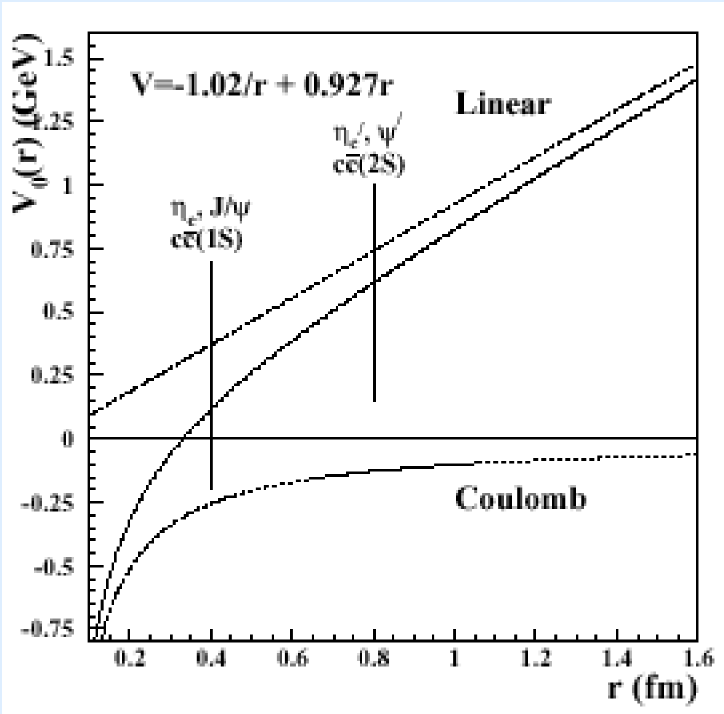
- 0^+, 1^+-$c\bar{q}$-states: Problem: Masses
- DK-Molecules
- Charmed Four Quark States
- Chiral Multiplets of Heavy-Light Mesons (Eichten, ..., Novak, Lutz, ...)

  Prediction: $M\left(D^*_{s0^+}(2317)\right) - M(D_s) \approx M\left(D_{s1^+}(2460)\right) - M(D^*_s) \approx m_{N}/3$

States with Hidden Charm (1)

Expectation:





States below DD̄-threshold:

Much information about J/ψ, ψ′, $\chi_{0,1,2}$

Very little known about η_c, η_c', h_c (Spin-Singletts), Important for spin-spin-interaction

States above DD̄-threshold:

Many are undetected, lots to do

(Heavy Quarkonium Physics, N. Brambilla et al., CERN Yellow Report; hep-ph/0412158)

States with Hidden Charm (2)

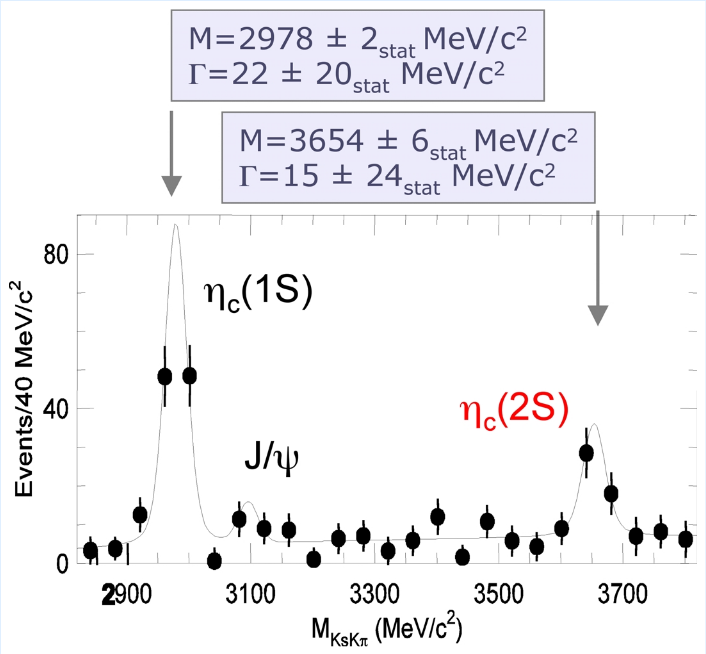
$\eta_c'(2\,^1S_0)$: Rediscovery (BELLE, CLEO, BaBar)

BELLE: $B \to K(K_sK^+\pi^-)$ and $e^+e^- \to J/\psi\ (c\bar{c})$

CLEO/BaBar: $\gamma\gamma$-Fusion ($\gamma\gamma \to K_sK\pi$)

M = (3642.9 ± 3.4)MeV ; Γ < 30MeV   (Crystal Ball: (3594 ± 5)MeV)

Evidence:



Decay modes:
$\to K_sK^+\pi^-$
$\to$?

Quantum numbers:

J^P : Probably 0^-

I : Probably 0

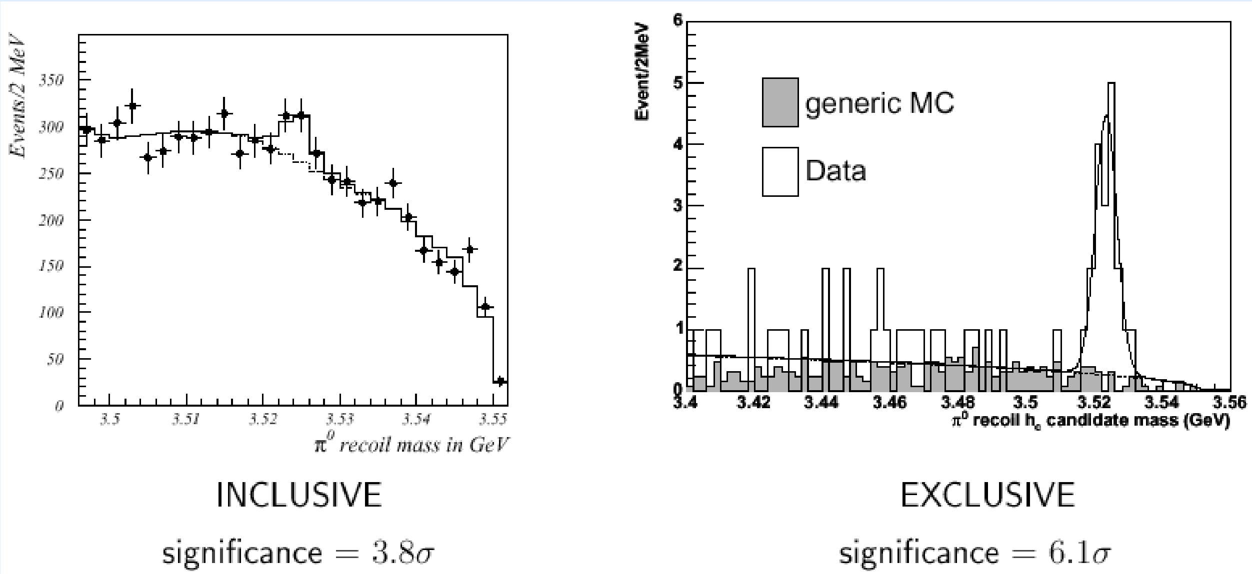
$\Delta M_{hf}(2s)$ = (47 ± 4)MeV, while $\Delta M_{hf}(1s)$ = (117 ± 1)MeV ?

States with Hidden Charm (3)

h_c ($1\,^1P_1$)

CLEO: $\psi(2s) \rightarrow \pi^0 h_c \rightarrow \pi^0(\gamma\eta_c)$
M = (3524.4 ± 0.6 ± 0.4)MeV ; Γ < 10MeV

Evidence (CLEO):



Decays:
→ $\gamma\eta_c$
→ ?

Quantum numbers:

J^P : Probably 1^+
I : Probably 0

$\Delta M_{hf}(1P) = \langle M(\chi_{cJ})\rangle - M_{h_c} = (1.0 \pm 0.6 \pm 0.4)$MeV

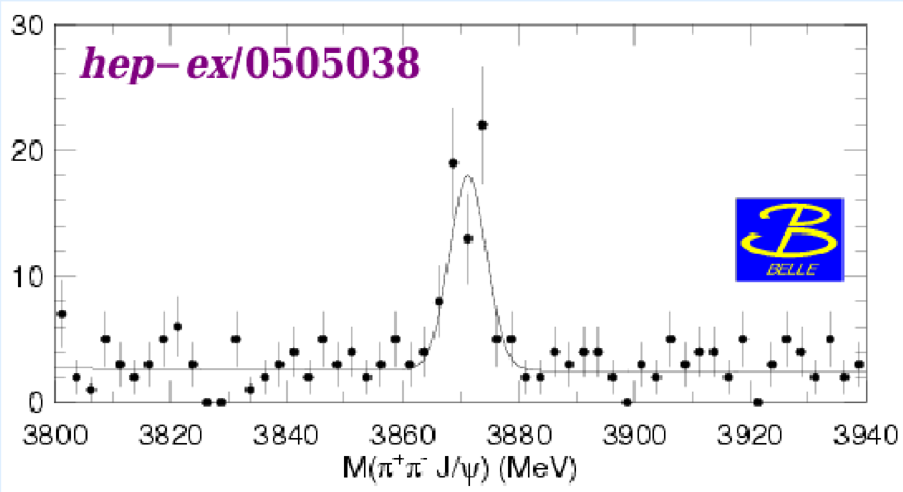
In agreement with the confinement potential being a Lorentz scalar

States with Hidden Charm (4)

X(3872) (BELLE, CDF, D∅; BaBar, BES)

$M = (3871.5 \pm 0.4)$MeV ; $\Gamma < 2.3$MeV!!

Evidence (BELLE): $B^{\pm} \rightarrow K^{\pm}(J/\psi\pi^{+}\pi^{-})$



Decays:

- $\rightarrow J/\psi\pi^{+}\pi^{-}$ (dominant) ($J/\psi\rho$?)
- $\rightarrow \gamma J/\psi$ (1 bin effect) $\rightarrow C = +1$
- $\rightarrow J/\psi\pi^{+}\pi^{-}\pi^{0}$ ($J/\psi\omega$?)
- $\rightarrow D^{0}D^{0}\pi^{0}$
- $\not\rightarrow \gamma\chi_{cJ}$

Production:

$$0.15 < R\left(\frac{B^{0} \rightarrow X \ldots}{B^{+} \rightarrow X \ldots}\right) < 1.34 \ \ (90\%\,\mathrm{CL})$$

Quantum numbers:

$J^{PC} = ?$

BELLE: Angular distributions of $J/\psi\rho \rightarrow$ Preference for $J^{PC} = 1^{++}$

$I = 0$?

BaBar: Search for $B^{-} \rightarrow K^{0}X^{-} \rightarrow K^{0}(J/\psi\rho^{-})$; $B^{0} \rightarrow K^{\pm}X^{\mp}$ ($B < 5 \times 10^{-4}$)

States with Hidden Charm (5)

X(3872) (contin.)

Nature of X(3872):

➢ Ordinary charmonium

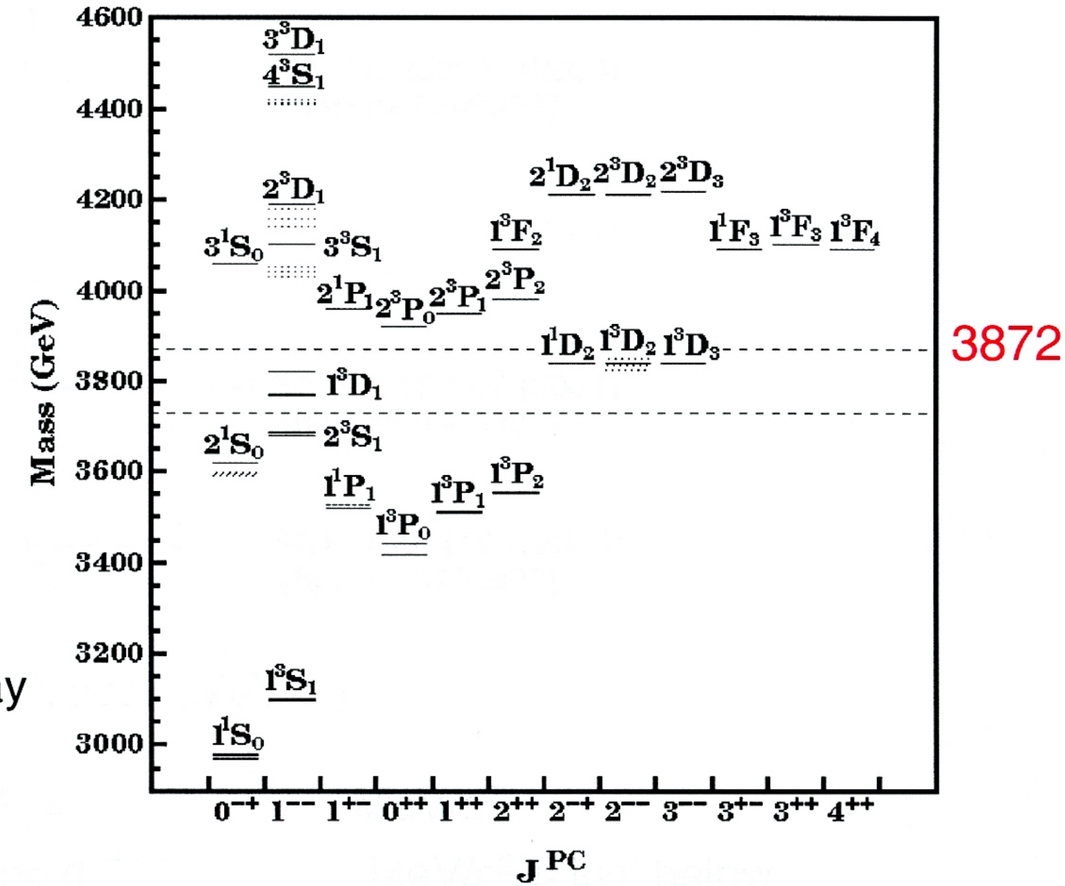
Many assignments eliminated by the small width of the *X*

1^3D_2 or 1^1D_2 ?

- ☺ narrow (~ 1 MeV)
- ☹ maybe slightly lighter than *X*
- ☹ expected to have radiative decay (*X* decay into $\chi_{c1}\ \gamma$ not observed

2^3P_1 or 2^1P_1 ?

- ☺ not expected to have radiative decay
- ☺ narrow (1-2 MeV)
- ☹ ~100 MeV heavier than *X*
- ☹ not expected to decay into $J/\psi\ \pi\pi$



States with Hidden Charm (6)

- Diquark - Antidiquark (Maiani et al.)

$$2 \text{ neutral states} \quad X_u = [cu][\bar{c}\bar{u}] \quad X_d = [cd][\bar{c}\bar{d}] \quad \Delta M = (7 \pm 2)\text{MeV}$$

$$2 \text{ charged states} \quad X^+ = [cu][\bar{c}\bar{d}] \quad X^- = [cd][\bar{c}\bar{u}]$$

Neutral states produced in B^0, B^+-decays have different masses and rates.
Slight experimental evidence. No evidence for charged states

- s-Wave D^0 D^{*0} molecule (Braaten, Kusunoki, Swanson, Tornquist)

$m_{D0} + m_{D^*0} = (3870.3 \pm 2.0)\text{MeV}$ $\Delta M = (+1.2 \pm 2.0)\text{MeV}$

Model predictions:

$B^0 \to K^0X$ suppressed by one order of magnitude wrt $B^+ \to K^+X$

$J^{PC} = 1^{++}$ is favored

$\Gamma(X \to \gamma J/\psi) < \Gamma(X \to \pi\pi J/\psi)$

States with Hidden Charm (7)

X(3940) (BELLE, BaBar)

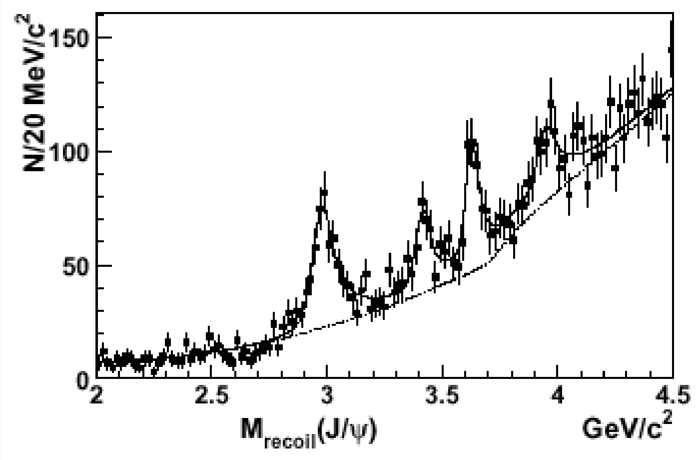
$M = (3943 \pm 6 \pm 6)\text{MeV}$; $\Gamma < 52\text{MeV}$

Evidence (BELLE): $e^+e^- \to J/\psi(c\bar{c})$

Quantum numbers:

$I, J^{PC} = ?$

Nature: ?



Decays:

$\to D^*\bar{D}$ (96%)

$\not\to J/\psi\omega$ (< 26%)

$\not\to D\bar{D}$ (< 41%)

Y(3940) (BELLE, BaBar)

$M = (3943 \pm 11 \pm 13)\text{MeV}$; $\Gamma = (87 \pm 22)\text{MeV}$

Evidence (BELLE): $B \to K(\omega J/\psi)$

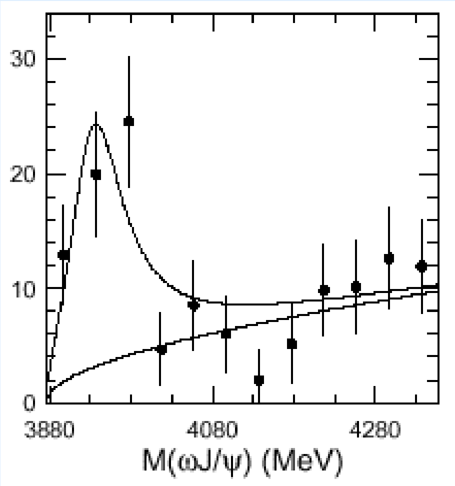
Quantum numbers:

$J^{PC} = ?$

$I = 0$

Nature:

$(\bar{c}cg)$-Hybrid?



Decays:

$\to \omega J/\psi$

$\not\to D^*\bar{D}$

States with Hidden Charm (8)

Z(3940) (BELLE, BaBar)

$M = (3931 \pm 4 \pm 2)$MeV ; $\Gamma = (20 \pm 8 \pm 3)$MeV

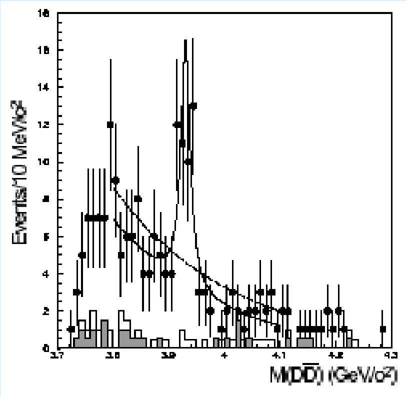
Evidence (BELLE): $e^+e^- \to e^+e^-(\gamma\gamma)$; $\gamma\gamma \to D\bar{D}$

Quantum numbers:

$J^{PC} = ?$

Nature:

$\chi'_{c2}(2\ ^3P_2)$?



Decays:
$\to D\bar{D}$
$\to$?

Y (4260) (BaBar)

$M = (4259 \pm 8^{+2}_{-6})$MeV ; $\Gamma = (88 \pm 23^{+6}_{-4})$MeV

Evidence (BaBar): $e^+e^- \to \gamma(e^+e^-)$; $e^+e^- \to \pi^+\pi^- J/\psi$ (ISR)

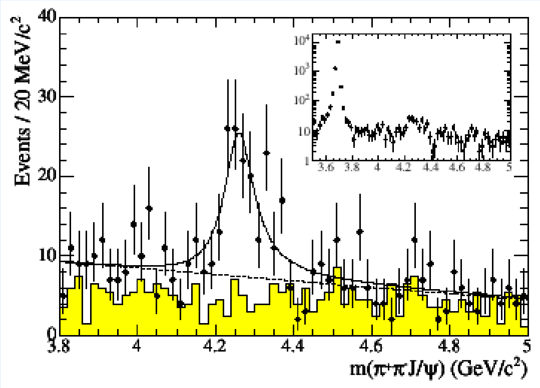
Quantum numbers:

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

$I = ?$

Nature:

1^{--}- $c\bar{c}$-resonance?



Decays:
$\to J/\psi\pi^+\pi^-$
$\to$?

Future Perspectives (1)

BaBar: $(\Upsilon(4s); \rightarrow 2008)$

BELLE: $(\Upsilon(4s); \rightarrow \; ? \;)$

CLEO: $(\psi(2s), \; \psi(3s), \; J/\psi \; ?; \; \rightarrow \geq 2 \; \text{years})$

BES: $(\psi(2s), \; J/\psi; \; \rightarrow \; ? \;)$

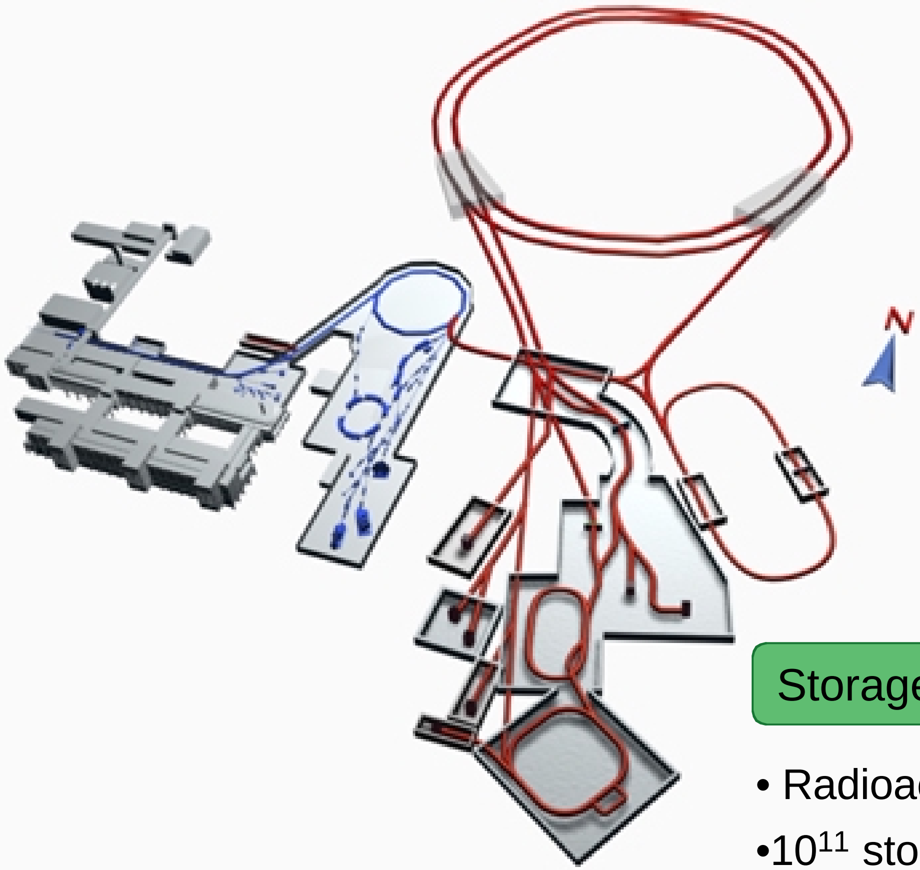
COMPASS: $(\text{Hadron} - \text{Program}; \; \rightarrow \; ? \;)$

PANDA: $(1.5 \leq \bar{p} \leq 15\text{GeV}; \; \text{From } 2013)$

Super B-Factory: $(\Upsilon(4s); \rightarrow \; ? \;)$

Future Perspectives (2)

FAIR-Project at GSI



Primary Beams

- 10^{12}/s; 1.5 GeV/u; $^{238}U^{28+}$
- 10^{10}/s $^{238}U^{73+}$ up to 35 GeV/u
- $3x10^{13}$/s 30 GeV protons

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
- Antiprotons 3 (0) - 30 GeV

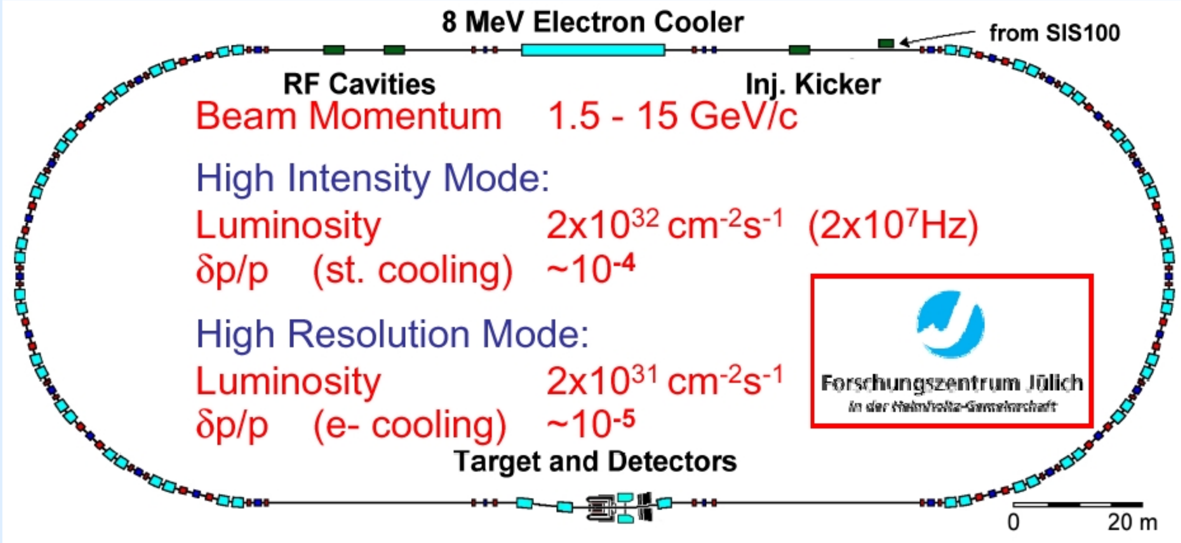
Storage and Cooler Rings

- Radioactive beams
- 10^{11} stored and cooled 1 - 15 GeV/c antiprotons

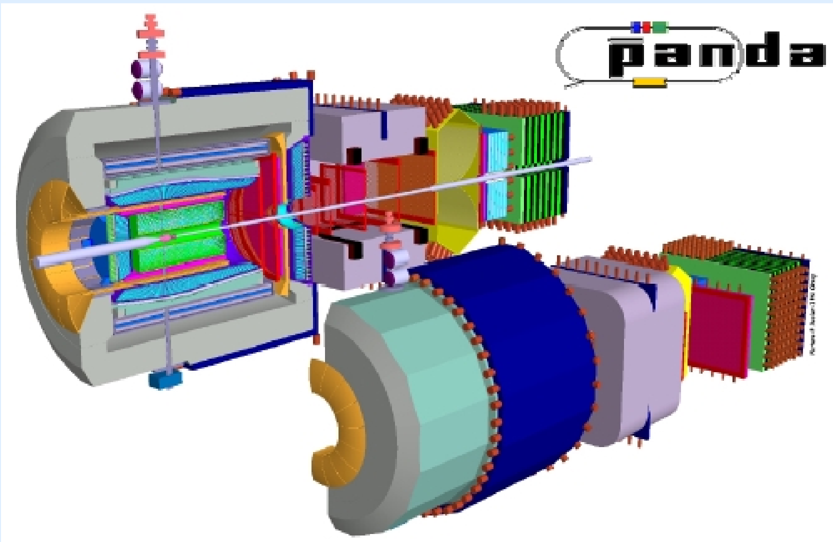
Future Perspectives (3)

Antiprotons at FAIR

HESR:



General Purpose Detector: PANDA



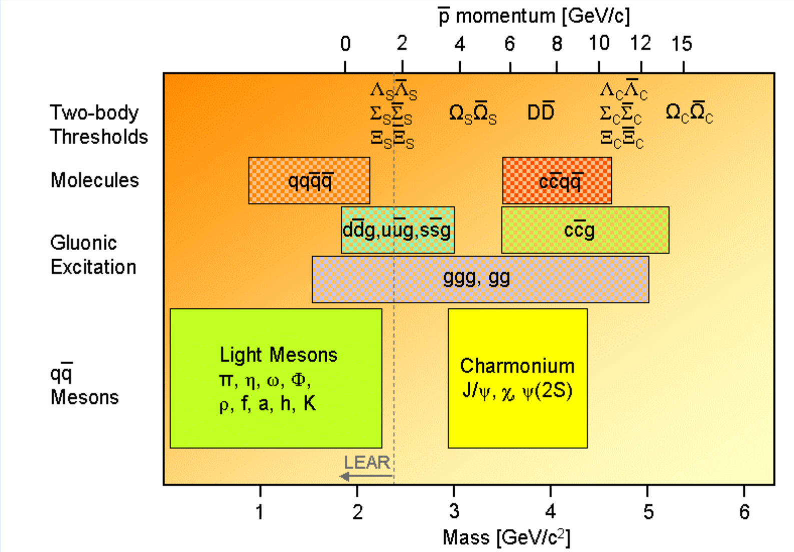
Formation: $\bar{p}$(scan)p → X → ...
Production: $\bar{p}$(fixed)p → X + nπ + ...

PANDA-Collaboration:

370 scientists from 8 countries
and 30 institutions

Future Perspectives (4)

QCD systems to be studied with PANDA



Rates

Production Rates (1-2 (fb)$^{-1}$/y)

Final State	**cross section**	**# reconstr. events/y**
Meson resonance + anything	100μb	10^{10}
$\Lambda\bar{\Lambda}$	50μb	10^{10}
$\Xi\bar{\Xi}$ ($\rightarrow_{\Lambda\Lambda}$ A)	2μb	10^{8} (10^{5})
$D\bar{D}$	250nb	10^{7}
J/ψ ($\rightarrow e^+e^-, \mu^+\mu^-$)	630nb	10^{9}
χ_2 ($\rightarrow J/\psi + \gamma$)	3.7nb	10^{7}
$\Lambda_c\bar{\Lambda}_c$	20nb	10^{7}
$\Omega_c\bar{\Omega}_c$	0.1nb	10^{5}

Common Feature : Low multiplicity events
Moderate particle energies

For Pairs : Charge symmetric conditions
Trigger on one, investigate the other

Future Perspectives (5)

Physics Program

Charmonium

Search for new states above $D\bar{D}$-threshold

Precision determination of masses and widths

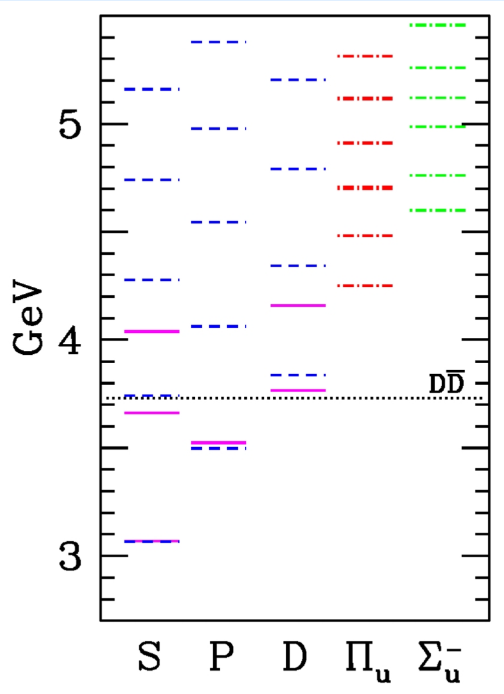
(Extremly high masses resolution → 20keV)

Production cross sections

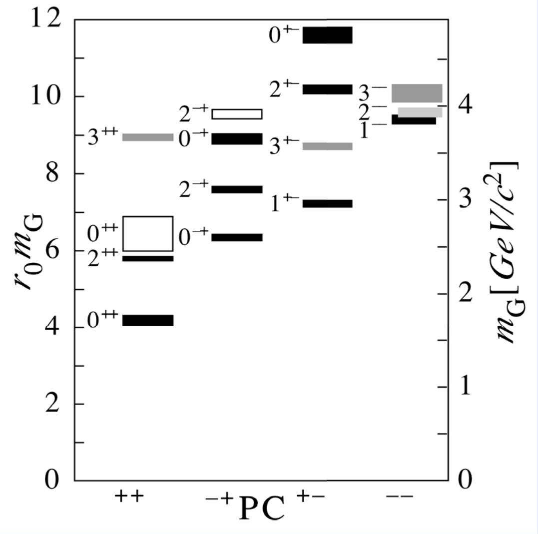
Decay branching ratios

Exotica

Glueballs, Charmed Hybrids, Multiquark states



Predictions for Glueballs



Prediction for Charmed Hybrids

Lowest energy states: 3.9 - 4.5GeV

Ground state: $J^{PC} = 1^{-+}$ (Spin exotic!)

Widths: Could by narrow in some cases (≈ MeV)

Future Perspectives (6)

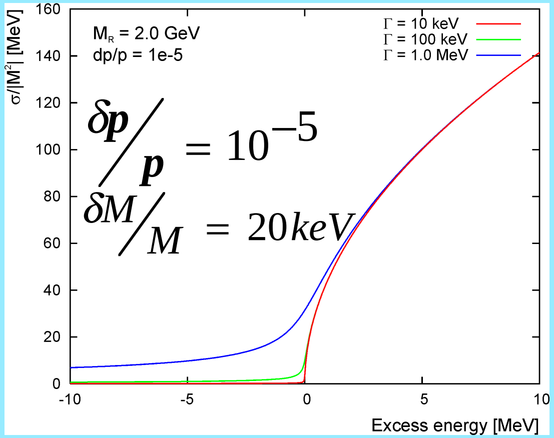
Open Charm Physics

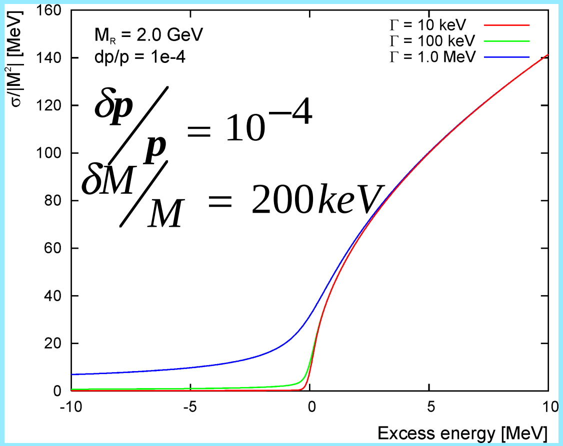
Widths of states

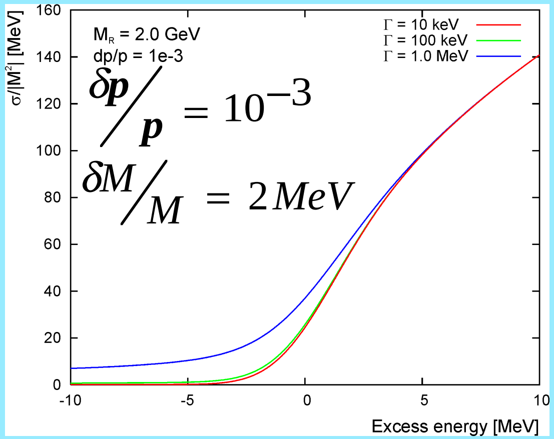
e.g.: $\bar{p}p \rightarrow D^{*}_{sJ}(2317)\ \overline{D^{*}_{sJ}(2317)}$

Depend on internal structure
the width of D_{sJ}* can be different:

_ Current limit ~ 4.9 MeV
_ χ-doubling ~ 10 keV
_ Phenomenological ~ 130 keV
_ D_sK – molecules ~ 200 keV

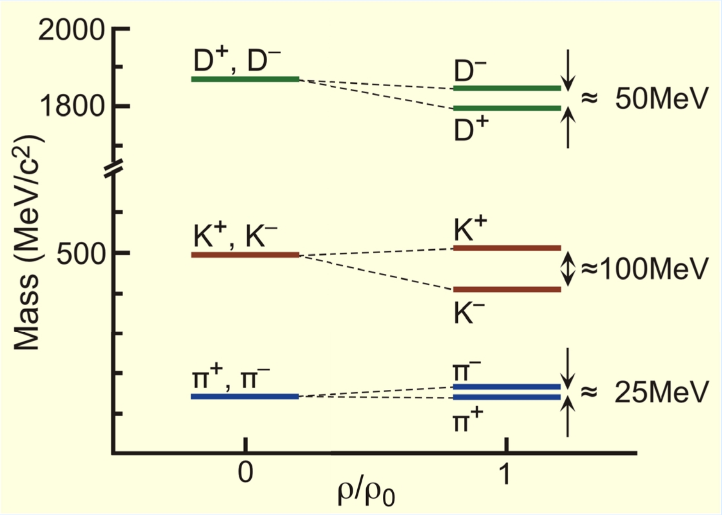






Future Perspectives (7)

Hadrons in matter



Hypernuclear Physics

$\bar{p}$(3GeV/c)p → Ξ^- (slow) $\overline{\Xi^-}$ (fast)

↳ Ξ^- p → ΛΛ (inside nucleus)

Further Options

Baryon Spectroscopy

CP-Violation in D-decays

Deeply Virtual Compton Scattering (DVCS)

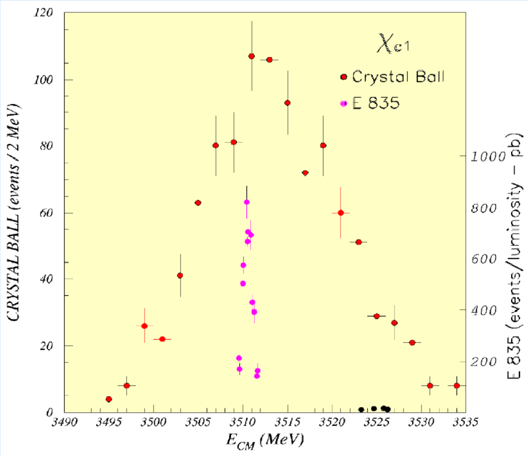
Proton FF in time-like region

Not discussed: Low energy $\bar{p}$-physics:
$\bar{H}$, Antiprotonic Atoms, $\bar{p}$ ^{4}He

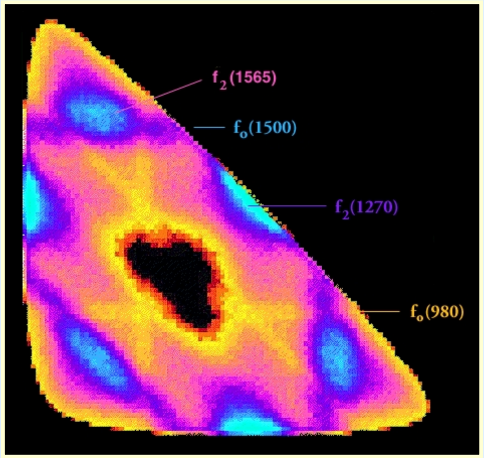
Future Perspectives (8)

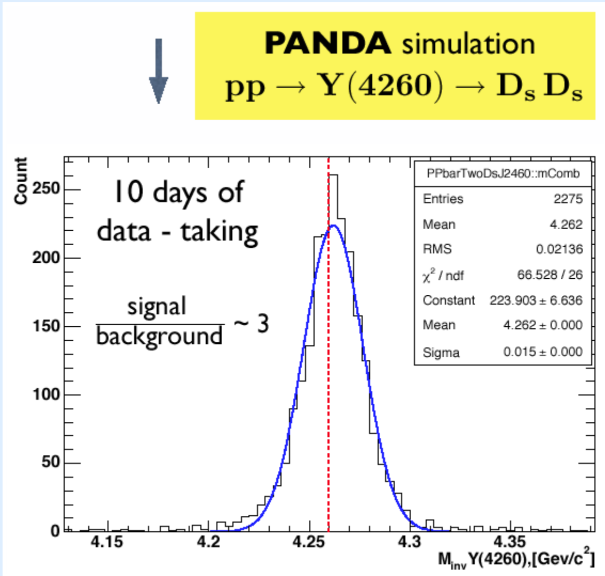
Merits of Antiprotons

- In $\bar{p}p$-annihilation all $q\bar{q}$-states can be formed directly (not only $J^{PC} = 1^{--}$)
  - ↳ High mass resolution for all states (≈ 20keV)



- $\bar{p}p$ cross sections high
  - ↳ Data with very high statistics





Future Perspectives (9)

- High probability for production of exotic states
  Example: Crystal Barrel @ LEAR; Spin exotic states ($J^{PC} = 1^{-+}$) at 1400/1600MeV

- Low final state multiplicities
  ↳ Clean spectra, good for PWA analyses

Conclusions

- Hadron Spectroscopy is in the focus of interest again

- Experimental developments
  Lots to be expected from further running of BaBar, BELLE, CLEO, BES, COMPASS, ...
  New and very precise data to be expected from PANDA/GSI

- Theoretical developments
  Lattice QCD
  Effective Field Theories
  Chiral calculations