# Physics with the PANDA Detector at GSI

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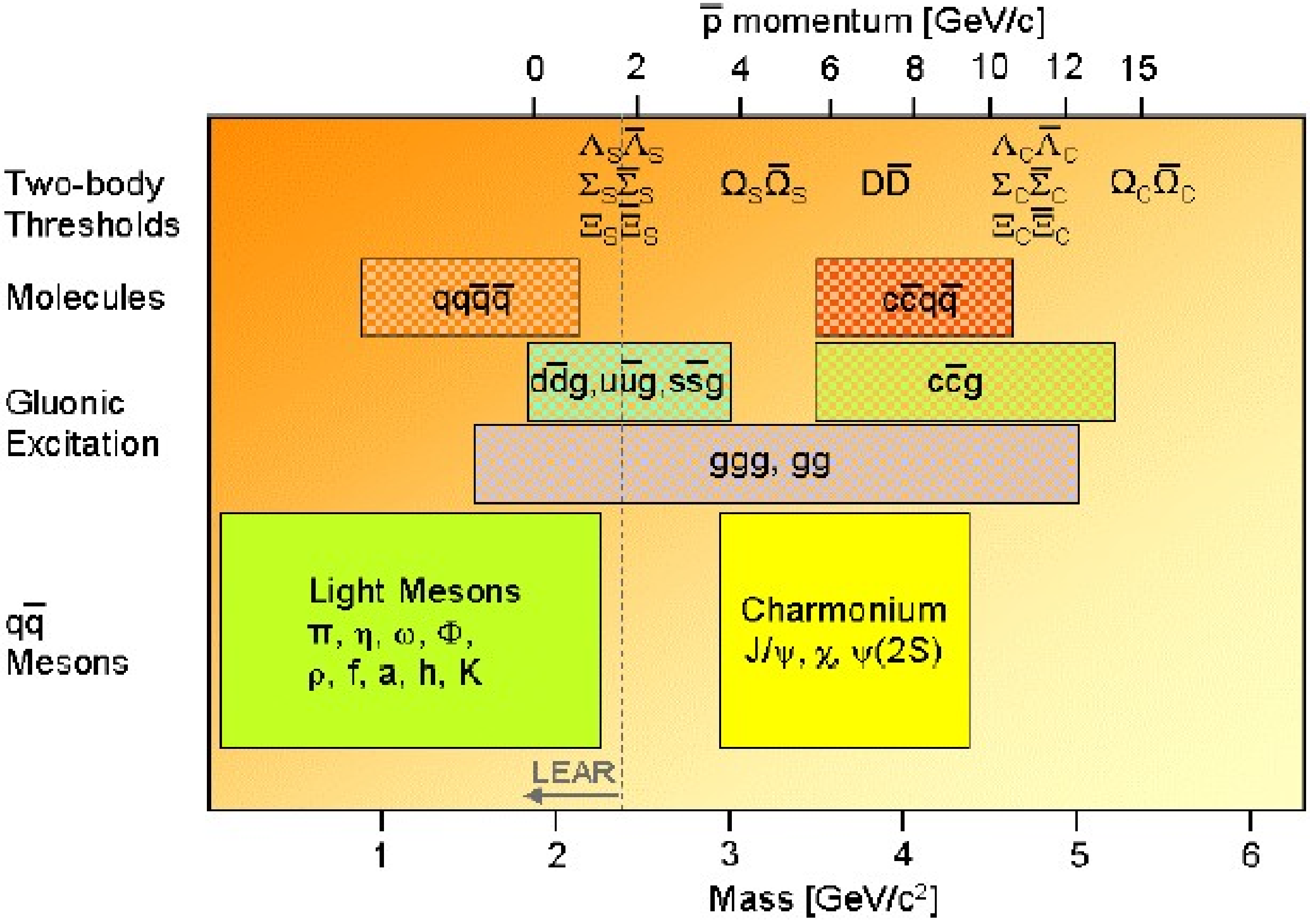
# Outline

- PANDA Physics Program
  - Charmonium Spectroscopy
  - Hybrids and Glueballs
  - Hadrons in Nuclear Matter
  - Hypernuclear Physics
  - Timelike Electromagnetic Form Factors of the Proton
- Overview of FAIR
- HESR
- The PANDA Detector
- Conclusions

# Antiproton Physics Program

- Charmonium Spectroscopy. Precision measurement of masses, widths and branching ratios of all ($c\bar{c}$) states (hydrogen atom of QCD).
- Search for gluonic excitations (hybrids, glueballs) in the charmonium mass range (3-5 GeV/$c^2$).
- Search for modifications of meson properties in the nuclear medium, and their possible relation to the partial restoration of chiral symmetry for light quarks.
- Precision $\gamma$-ray spectroscopy of single and double hypernuclei, to extract information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.
- Electromagnetic processes (DVCS, D-Y, FF ...) , open charm physics

# QCD Systems to be studied in Panda

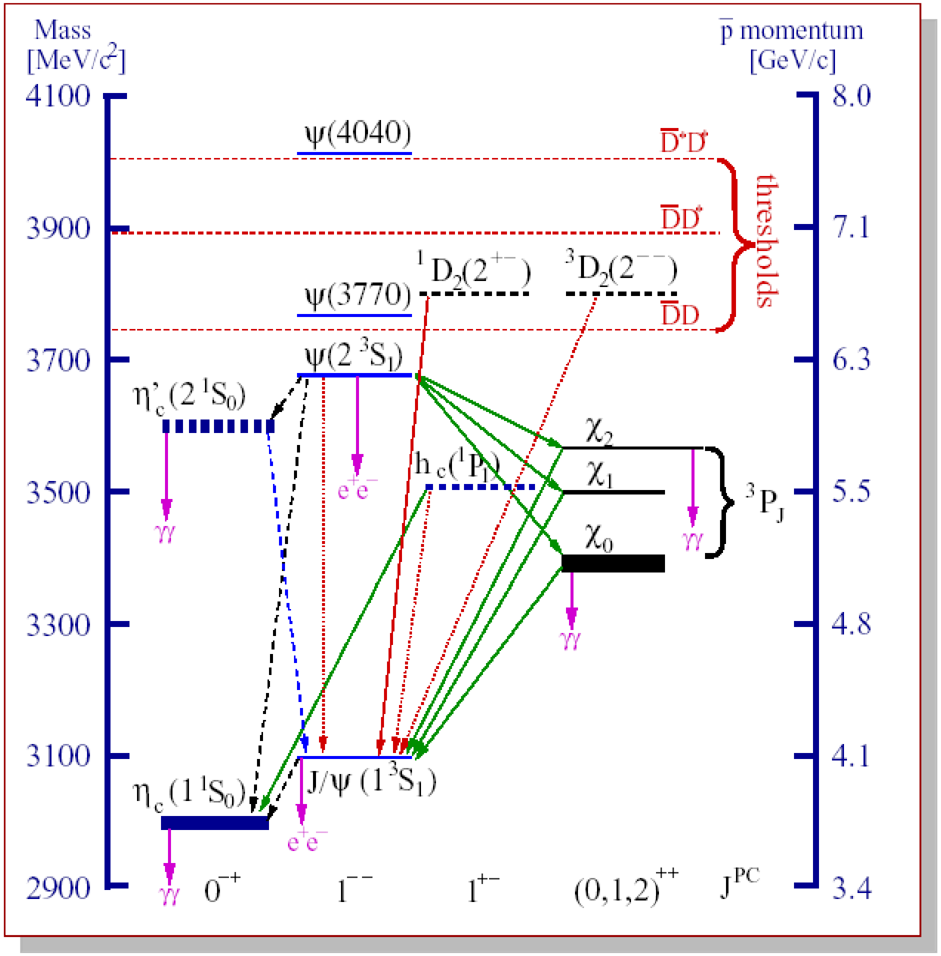


# Charmonium Spectroscopy

Charmonium is a powerful tool for the understanding of the strong interaction. The high mass of the c quark ($m_c$ ~ 1.5 GeV/$c^2$) makes it plausible to attempt a description of the dynamical properties of the ($c\bar{c}$) system in terms of non relativistic potential models, in which the functional form of the potential is chosen to reproduce the known asymptotic properties of the strong interaction. The free parameters in these models are determined from a comparison with experimental data.

$$\beta^2 \approx 0.2 \quad \alpha_s \approx 0.3$$

Non-relativistic potential models + Relativistic corrections + PQCD + LQCD



# Experimental Study of Charmonium

## $e^+e^-$ annihilation

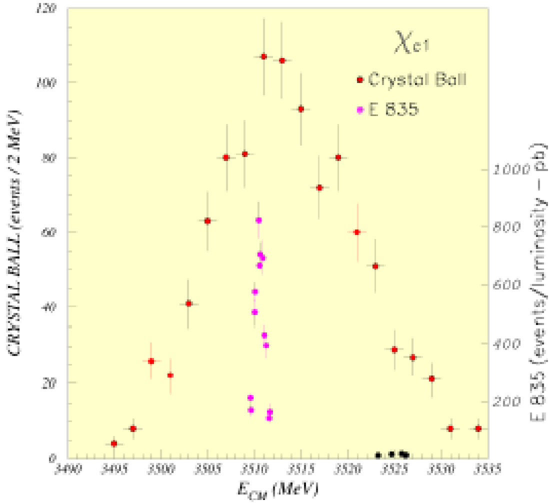
- Direct formation only possible for $J^{PC} = 1^{--}$ states.
- All other states must be produced via radiative decays of the vector states, or via two-photon processes, ISR, B-decay, double charmonium.

Good mass and width resolution for the vector states. For the other states modest resolutions (detector-limited).

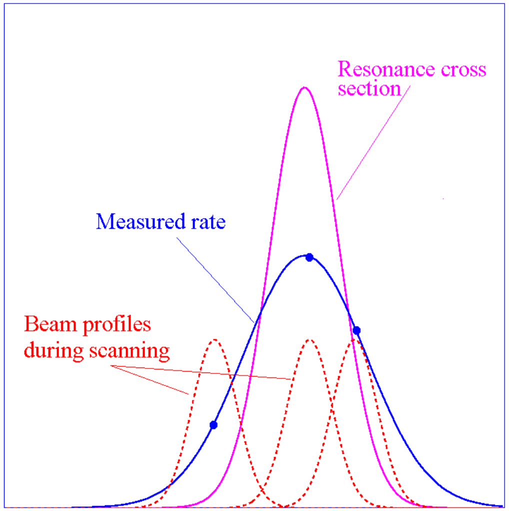
**In general, the measurement of sub-MeV widths not possible in $e^+e^-$.**

## $\bar{p}p$ annihilation

- Direct formation possible for all quantum numbers.
- **Excellent measurement of masses and widths for all states, given by beam energy resolution and not detector-limited.**



# Experimental Method in $\bar{p}p$ Annihilation



The cross section for the process:

$$\bar{p}p \rightarrow \bar{c}c \rightarrow \text{final state}$$

is given by the Breit-Wigner formula:

$$\sigma_{BW} = \frac{2J+1}{4}\frac{\pi}{k^2}\frac{B_{in}B_{out}\Gamma_R^2}{(E-M_R)^2+\Gamma_R^2/4}$$

The production rate ν is a convolution of the BW cross section and the beam energy distribution function $f(E,\Delta E)$:

$$\nu = L_0\{\varepsilon \int dE f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\}$$

The resonance mass $M_R$, total width $\Gamma_R$ and product of branching ratios into the initial and final state $B_{in}B_{out}$ can be extracted by measuring the formation rate for that resonance as a function of the cm energy $E$.

# Hot Topics in Charmonium Spectroscopy

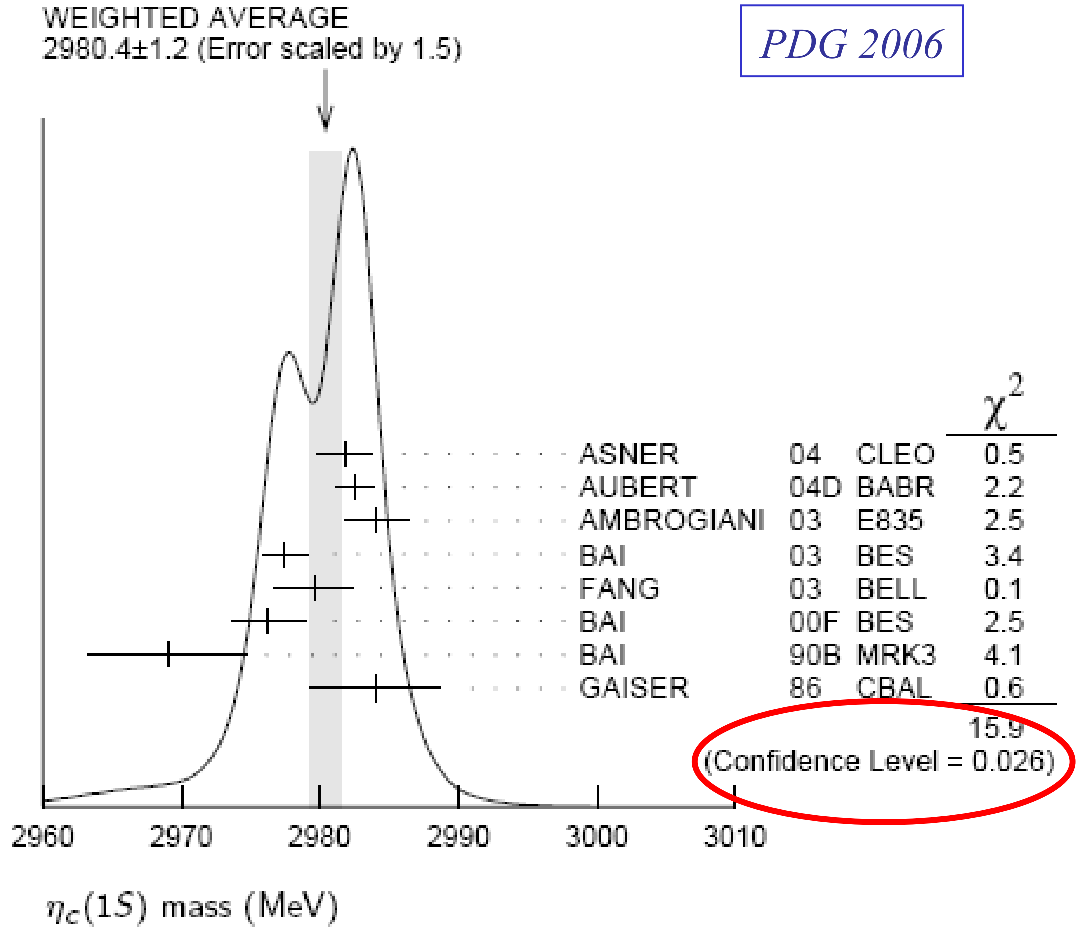
# The $\eta_c(1^1S_0)$

- It is the ground state of charmonium, with quantum numbers $J^{PC}=0^{-+}$.
- Knowledge of its parameters is crucial. Potential models rely heavily on the mass difference $M(J/\psi)-M(\eta_c)$ to fit the charmonium spectrum.
- The $\eta_c$ cannot be formed directly in $e^+e^-$ annihilations:
  - Can be formed directly in $\bar{p}p$ annihilations.
  - Can be produced in M1 radiative decays from the $J/\psi$ and $\psi'$ (small BR).
  - Can be produced in photon-photon fusion.
  - Can be produced in B-meson decay.
- Many measurements of mass and $\eta_c$ width (6 new measurements in the last 2 years). However errors are still relatively large and internal consistency of measurements is rather poor.
- Large value of $\eta_c$ width difficult to explain in simple quark models.
- Decay to two photons provides estimate of $\alpha_s$.

# The $\eta_c(1^1S_0)$ Mass

| Experiment | Mass (MeV/c²) |
|---|---|
| **CLEO** | **2981.8 ± 1.3 ± 1.5** |
| **BaBar** | **2982.5 ± 1.1 ± 0.9** |
| **E835** | **2984.1 ± 2.1 ± 1.0** |
| **BES** | **2977.5 ± 1.0 ± 1.2** |
| **Belle** | **2979.6 ± 2.3 ± 1.6** |
| **BES** | **2976.3 ± 2.3 ± 1.2** |
| **Mark III** | **2969 ± 4 ± 4** |
| **Crystal Ball** | **2984± 2.3 ± 4** |

*PDG 2006*

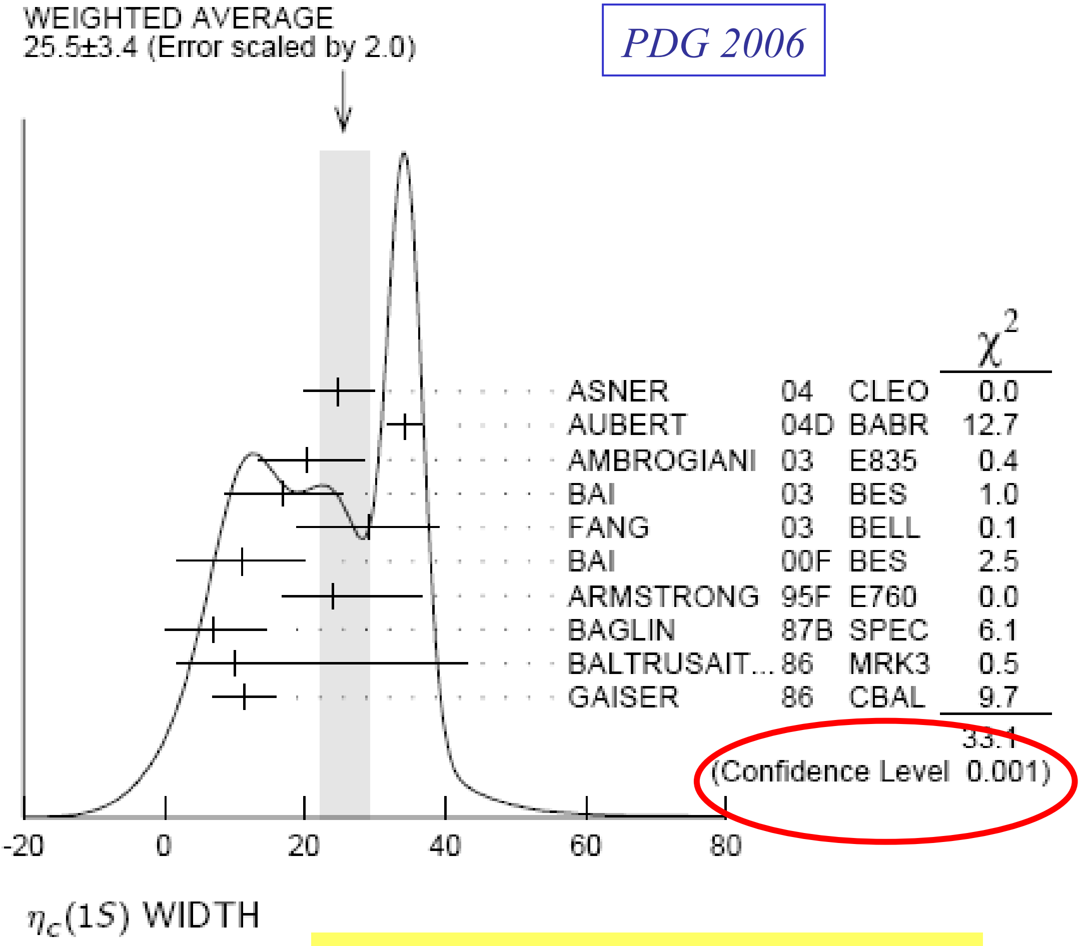


$$M(\eta_c) = 2980.4 \pm 1.2\ \mathrm{MeV}/c^2$$

# The $\eta_c(1^1S_0)$ Total Width

| Experiment | Width (MeV) |
|---|---|
| **CLEO** | **24.8 ± 3.4 ± 3.5** |
| **BaBar** | **34.3 ± 2.3 ± 0.9** |
| **E835** | **$20.4^{+7.7}_{-6-7} \pm 2.0$** |
| **BES** | **17.0 ± 3.7 ± 7.4** |
| **Belle** | **29 ± 8 ± 6** |
| **BES** | **11.0 ± 8.1 ± 4.1** |
| **E760** | **$23.9^{+12.6}_{-7.1}$** |
| **R704** | **$7.0^{+7.5}_{-7.0}$** |
| **Mark III** | **$10.1^{+33.0}_{-8.2}$** |
| **Crystal Ball** | **11.5 ± 4.5** |

*PDG 2006*



$\Gamma(\eta_c) = 25.5 \pm 3.4$ MeV

# $\eta_c \rightarrow \gamma\gamma$

In PQCD the $\gamma\gamma$ BR can be used to calculate $\alpha_s$:

$$B(\eta_c \rightarrow \gamma\gamma) = \frac{\Gamma_{\gamma\gamma}}{\Gamma(\eta_c)} \approx \frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}$$

$$\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}} \approx \frac{8}{9}\frac{\alpha^2}{\alpha_s^2}\left(\frac{1-3.4\alpha_s/\pi}{1+4.8\alpha_s/\pi}\right)$$

Using $\alpha_s$=0.32 (PDG) and the measured values for the widths:

$$\left.\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}\right|_{th} \approx 2.4\times10^{-4} \qquad \left.\frac{\Gamma_{\gamma\gamma}}{\Gamma_{gg}}\right|_{\exp} = (4.3\pm1.1)\times10^{-4}$$

| Experiment | Mass (MeV/$c^2$) |
|---|---|
| **Belle** | **5.5 ± 1.2 ± 1.8** |
| **CLEO** | **7.4 ± 0.4 ± 2.3** |
| **Delphi** | **13.9 ± 2.0 ± 3.0** |
| **E835** | **$3.8\,^{+1.1}_{-1.0}\,^{1.9}_{-1.0}$** |
| **L3** | **6.9 ± 1.7 ± 2.1** |
| **E760** | **$6.7\,^{2.4}_{-1.7} \pm 2.3$** |
| **ARGUS** | **11.3 ± 4.2** |
| **CLEO** | **$5.9^{2.1}_{-1.8} \pm 1.9$** |
| **TPC** | **$6.4\,^{5.0}_{-3.4}$** |
| **BaBar** | **5.2 ± 1.2** |
| **CLEO2** | **7.6 ± 0.8 ± 2.3** |

$$\Gamma_{\gamma\gamma}(\eta_c) = 6.7^{+0.9}_{-0.8}$$

# Expected properties of the $\eta_c(2^1S_0)$

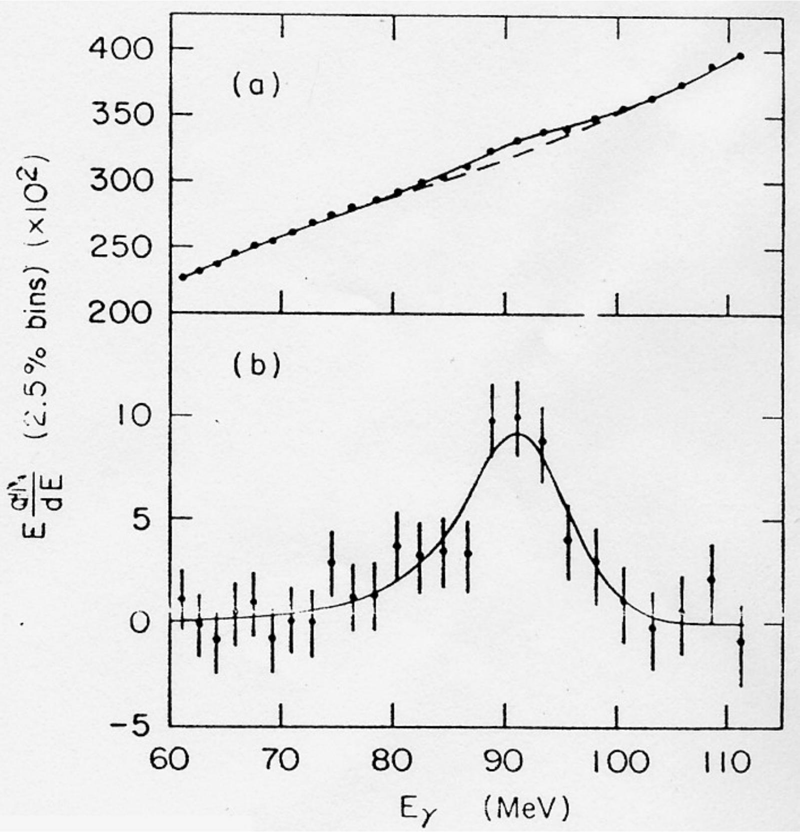
- The mass difference $\Delta'$ between the $\eta'_c$ and the $\psi'$ can be related to the mass difference $\Delta$ between the $\eta_c$ and the $J/\psi$ :

$$\Delta' = \frac{\alpha_s(M_{\psi'})}{\alpha_s(M_{J/\psi})} \frac{M^2_{\psi'}}{M^2_{J/\psi}} \frac{\Gamma(\psi' \to e^+e^-)}{\Gamma(J/\psi \to e^+e^-)} \Delta \approx 67\ MeV$$

- Various theoretical predictions of the $\eta'_c$ mass have been reported:
  - $M(\eta'_c)$ = 3.57 GeV/c2 [Bhaduri, Cohler, Nogami, Nuovo Cimento A, 65(1981)376].
  - $M(\eta'_c)$ = 3.62 GeV/c2 [Godfrey and Isgur, Phys. Rev. D 32(1985)189].
  - $M(\eta'_c)$ = 3.67 GeV/c2 [Resag and Münz, Nucl. Phys. A 590(1995)735].
- Total width ranging from a few MeV to a few tens of MeV:

  $\Gamma(\eta'_c) \approx 5 \div 25$ MeV
- Decay channels similar to $\eta_c$.

# The $\eta_c(2^1S_0)$ Crystal Ball Candidate



The first $\eta'_c$ candidate was observed by the Crystal Ball experiment:

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

By measuring the recoil $\gamma$ they found:

$$M(\eta'_c) = (3594 \pm 5)\ \mathrm{MeV}/c^2$$

$$\Gamma(\eta'_c) \leq 8\ \mathrm{MeV}\ (95\ \%\ \mathrm{C.L.})$$

# The $\eta_c(2^1S_0)$
# E760/E835 search

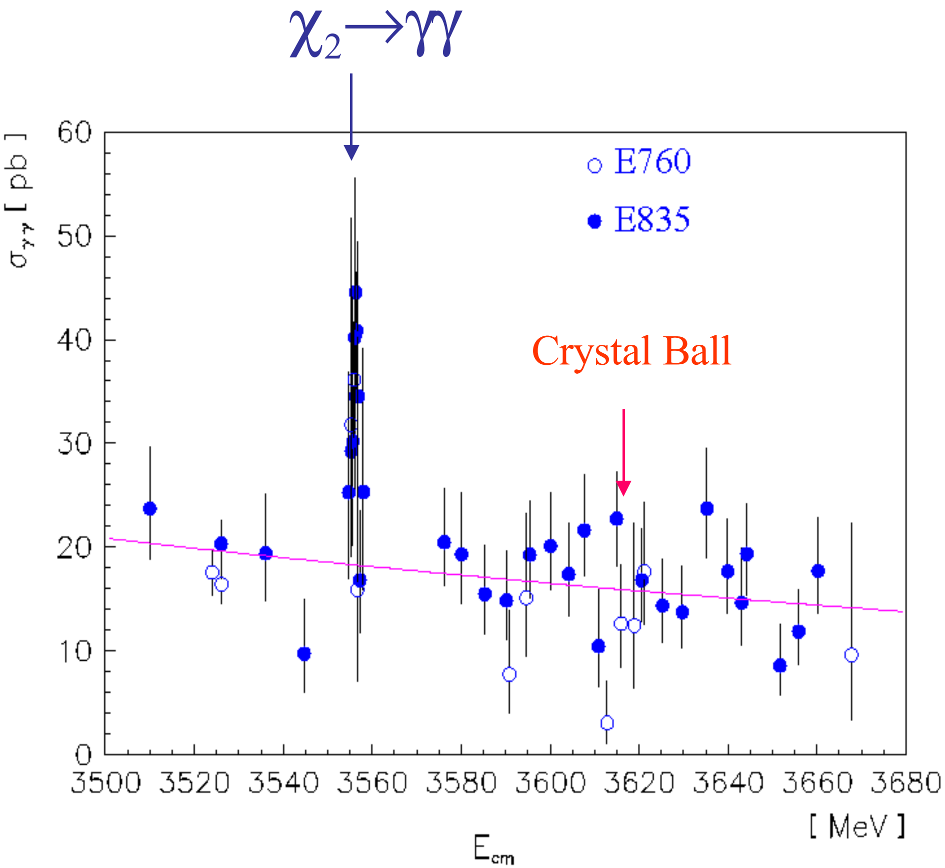
Both E760 and E835 searched for the $\eta'_c$ in the energy region:

$$E_{cm} = (3570 \div 3660)\ \mathrm{MeV}$$

using the process:

$$\bar{p} + p \rightarrow \eta'_c \rightarrow \gamma + \gamma$$

but no evidence of a signal was found.



# $\eta_c(2^1S_0)$ search in $\gamma\gamma$ collisions at LEP

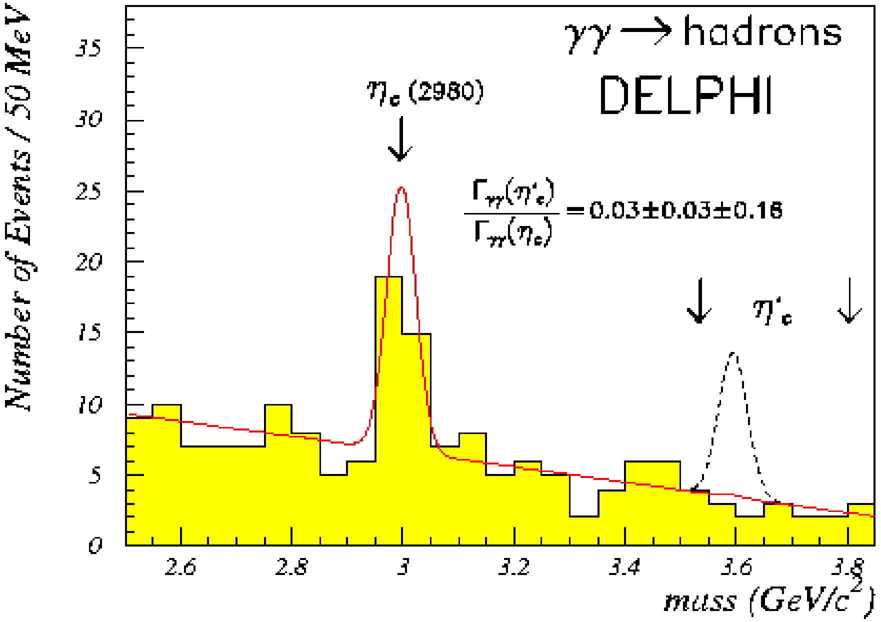
The $\eta'_c$ has been looked for by the LEP experiments via the process:

$$e^+e^- \rightarrow e^+e^- + (\gamma\gamma)_{\eta_c}$$

L3 sets a limit of 2 KeV (95 %C.L.) for the partial width $\Gamma(\eta'_c \rightarrow \gamma\gamma)$.

DELPHI data (shown on the right) yield:

$$\frac{\Gamma(\eta'_c \rightarrow \gamma\gamma)}{\Gamma(\eta_c \rightarrow \gamma\gamma)} \leq 0.34 \text{ (90\% C.L.)}$$



# The $\eta_c(2^1S_0)$ discovery by BELLE

The Belle collaboration has recently presented a 6σ signal for $B \rightarrow KK_sK\pi$ which they interpret as evidence for $\eta'_c$ production and decay via the process:

$$B \rightarrow K\eta'_c; \quad \eta'_c \rightarrow K_S K^+ \pi^-$$

with:

$$M(\eta'_c) = 3654 \pm 6 \pm 8 \text{ MeV}/c^2$$

$$\Gamma(\eta'_c) < 55 \text{ MeV}/c^2$$

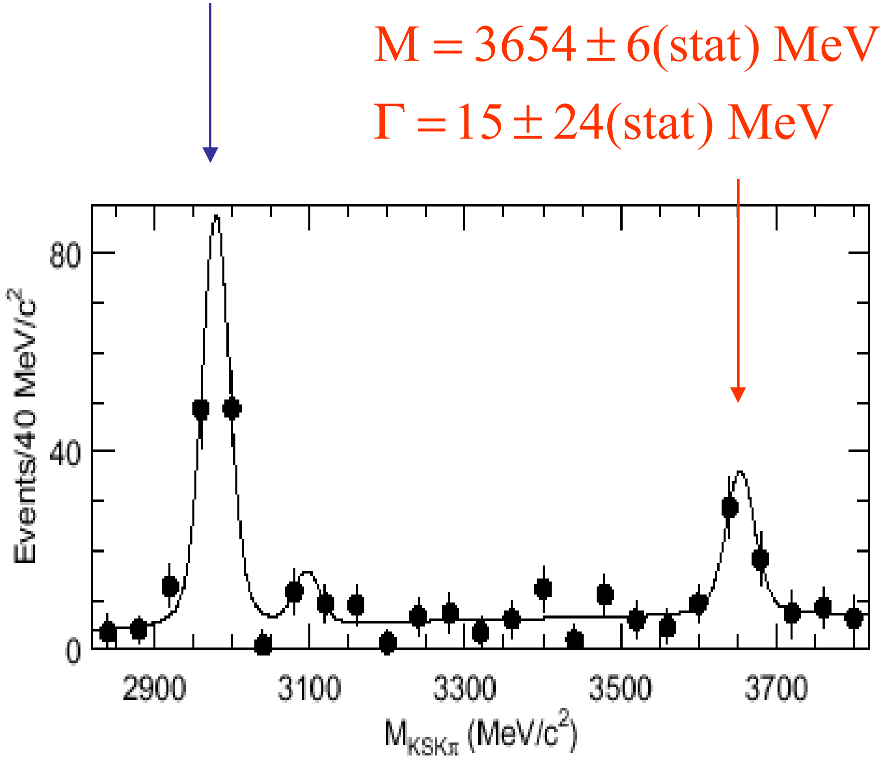
in disagreement with the Crystal Ball result.

$$M = 2978 \pm 2(\text{stat}) \text{ MeV}$$

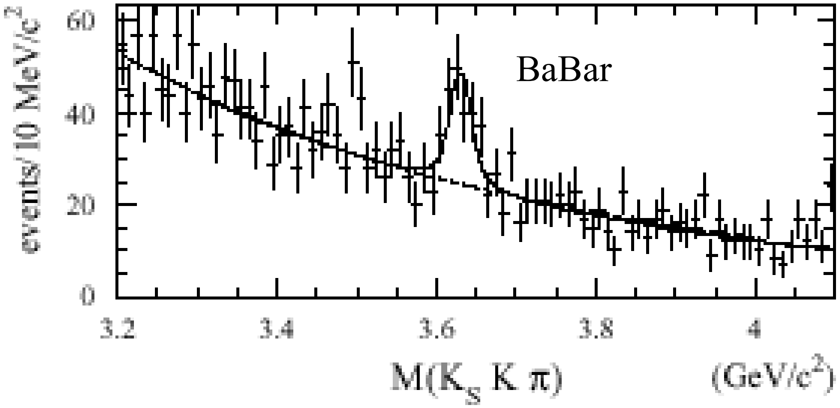
$$\Gamma = 22 \pm 20(\text{stat}) \text{ MeV}$$

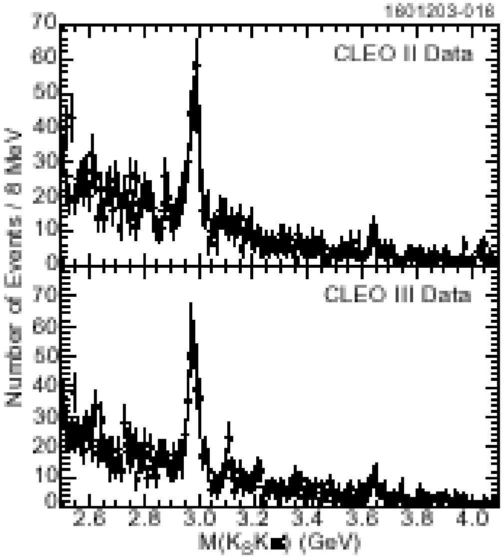
$$M = 3654 \pm 6(\text{stat}) \text{ MeV}$$

$$\Gamma = 15 \pm 24(\text{stat}) \text{ MeV}$$



# $\gamma\gamma \to \eta_c(2^1S_0)$





BaBar: $\Gamma(\eta'_c) = 17.0 \pm 8.3 \pm 2.5$ MeV

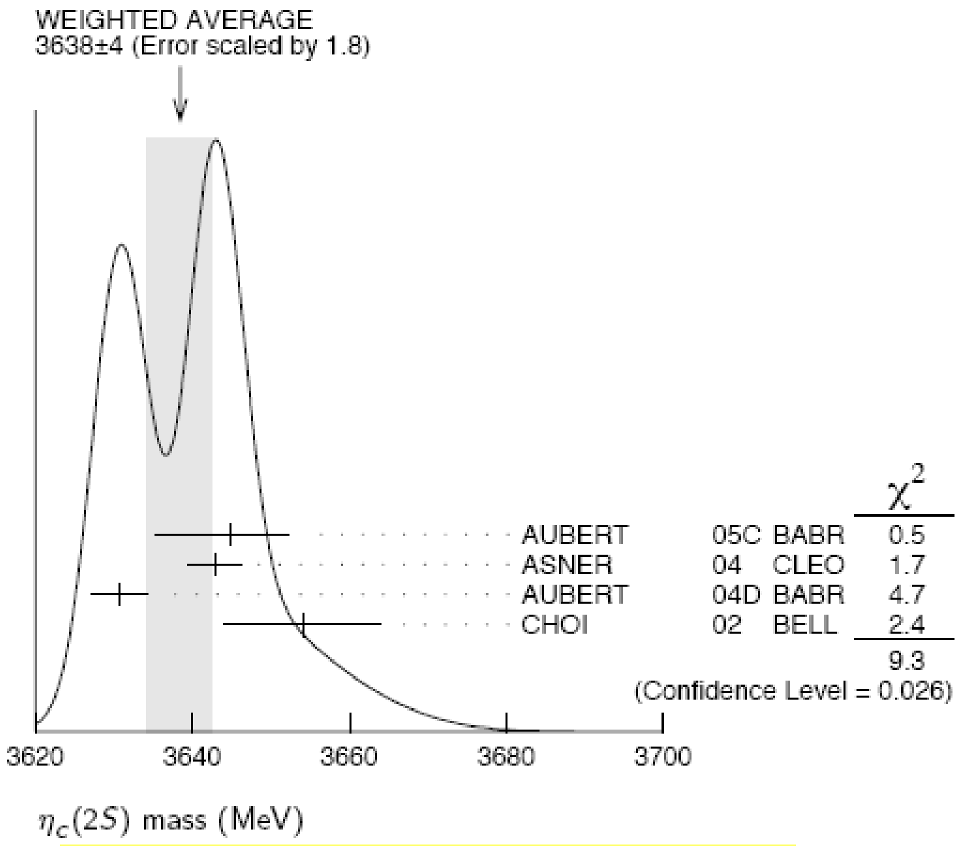
CLEO: $\Gamma(\eta'_c) = 6.3 \pm 12.4 \pm 4.0$ MeV

PDG 2006: $\Gamma(\eta'_c) = 14 \pm 7$ MeV

# The $\eta_c(2^1S_0)$ Mass

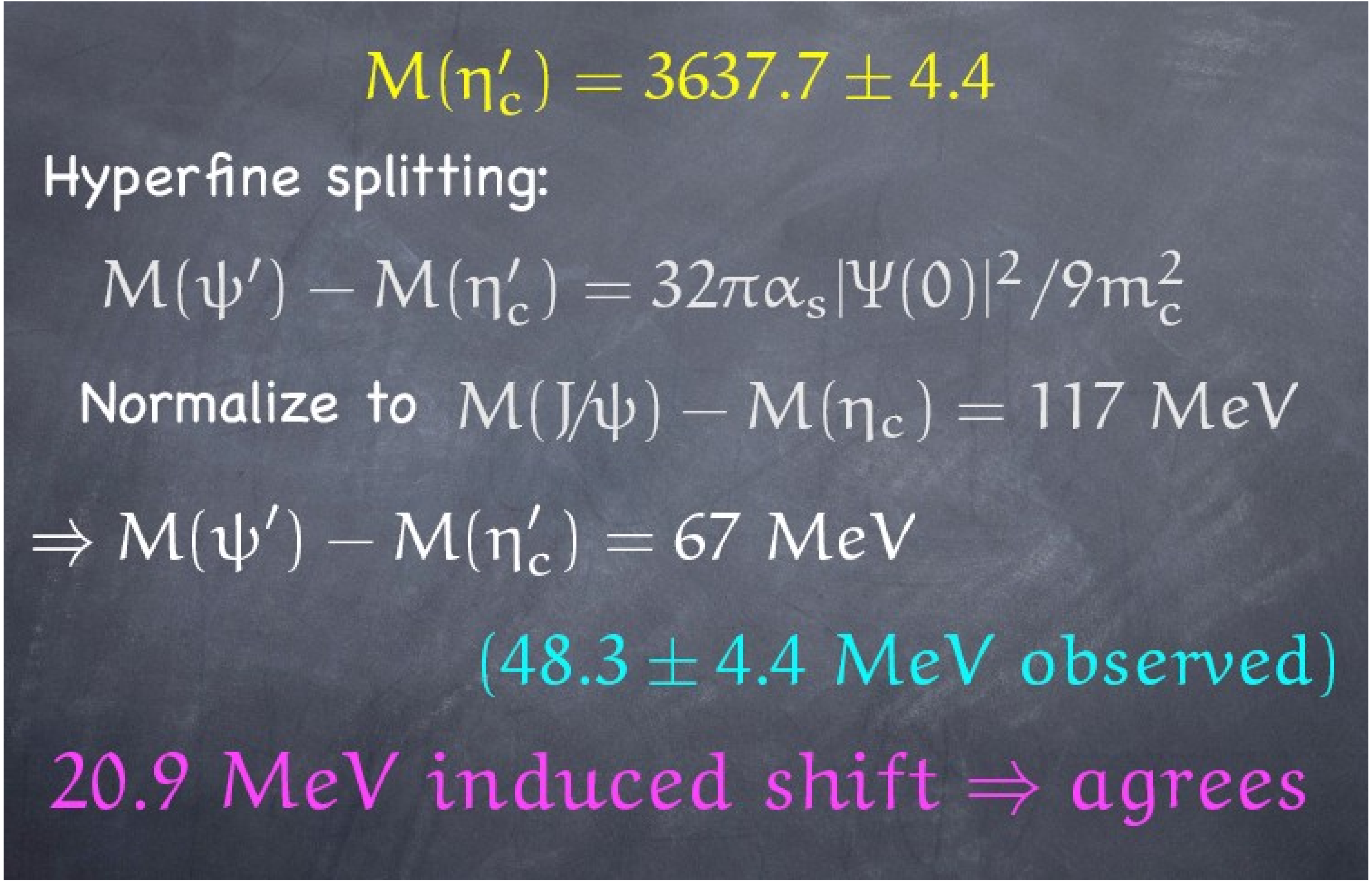
*PDG 2006*

| Experiment | Mass (MeV/c²) |
|---|---|
| **BaBar** | **$3645.0 \pm 5.5\,^{+4.9}_{-7.8}$** |
| **CLEO** | **3642.9 ± 3.1 ± 1.5** |
| **BaBar** | **3630.8 ± 3.4 ± 1.0** |
| **Belle** | **3654 ± 6 ± 8** |
| **BaBar** | **3639 ± 7** |
| **Belle** | **3630 ± 8** |
| **Belle** | **3622 ± 12** |
| **Crystal Ball** | **3594 ± 5** |



$M(\eta_c') = 3638 \pm 4$ MeV/c²

# Effect of Coupled Channel on the Mass Spectrum



$$M(\eta_c') = 3637.7 \pm 4.4$$

Hyperfine splitting:

$$M(\psi') - M(\eta_c') = 32\pi\alpha_s|\Psi(0)|^2/9m_c^2$$

Normalize to $M(J/\psi) - M(\eta_c) = 117\ \mathrm{MeV}$

$$\Rightarrow M(\psi') - M(\eta_c') = 67\ \mathrm{MeV}$$

(48.3 ± 4.4 MeV observed)

20.9 MeV induced shift ⇒ agrees

Estia Eichten – BaBar workshop on heavy quark and exotic spectroscopy

# The $h_c(1^1P_1)$

Precise measurements of the parameters of the $h_c$ give extremely important information on the spin-dependent component of the $q\bar{q}$ confinement potential. The splitting between triplet and singlet is given by the spin-spin interaction (hyperfine structure).

$$V_{SS} = \frac{2(S_1 \cdot S_2)}{3m_c^2} \nabla^2 V_V(r)$$

If the vector potential is 1/r (one gluon exchange) than the expectation value of the spin-spin interaction for P states (whose wave function vanishes at the origin) should be zero. In this case the $h_c$ should be degenerate in mass with the center-of-gravity of the $\chi_{cJ}$ states. A comparison of the $h_c$ mass with the masses of the triplet P states measures the deviation of the vector part of the $q\bar{q}$ interaction from pure one-gluon exchange.

Total width and partial width to $\eta_c+\gamma$ will provide an estimate of the partial width to gluons.

# Expected properties of the $h_c(^1P_1)$

- Quantum numbers $J^{PC}=1^{+-}$.
- The mass is predicted to be within a few MeV of the center of gravity of the $\chi_c(^3P_{0,1,2})$ states

$$M_{cog} = \frac{M(\chi_0) + 3M(\chi_1) + 5M(\chi_2)}{9}$$

- The width is expected to be small $\Gamma(h_c) \leq 1$ MeV.
- The dominant decay mode is expected to be $\eta_c+\gamma$, which should account for ≈ 50 % of the total width.
- It can also decay to $J/\psi$:

| | |
|---|---|
| $J/\psi + \pi^0$ | violates isospin |
| $J/\psi + \pi^+\pi^-$ | suppressed by phase space and angular momentum barrier |

# The $h_c(^1P_1)$ E760 observation

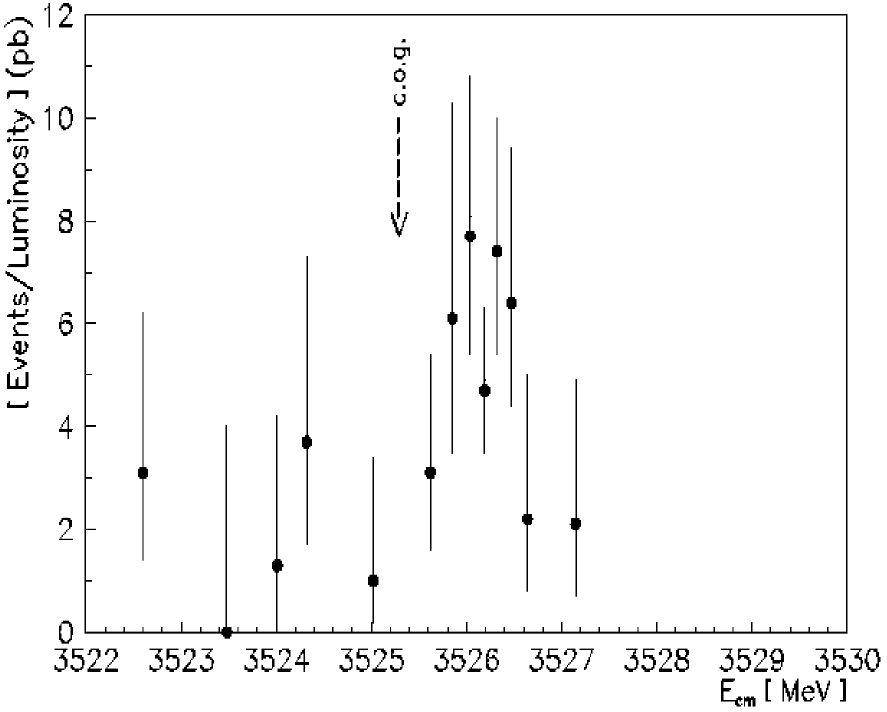
A signal in the $h_c$ region was seen by E760 in the process:

$$\bar{p}p \to h_c \to J/\psi + \pi^0$$

Due to the limited statistics E760 was only able to determine the mass of this structure and to put an upper limit on the width:

$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2\ MeV/c^2$$

$$\Gamma(h_c) < 1.1\ MeV\ (90\%CL)$$



$$\frac{B(J/\psi\pi\pi)}{B(J/\psi\pi^0)} \leq 0.18 \quad (90\%C.L.)$$

$$(1.8 \pm 0.4) \times 10^{-7} < B(p\bar{p})B(J/\psi\pi^0) < (2.5 \pm 0.6) \times 10^{-7}$$

# E835 Results for $h_c \to \eta_c\gamma$

Observe excess of events in $\eta_c\gamma$ mode.
Background hypothesis rejected with
P = 0.001.

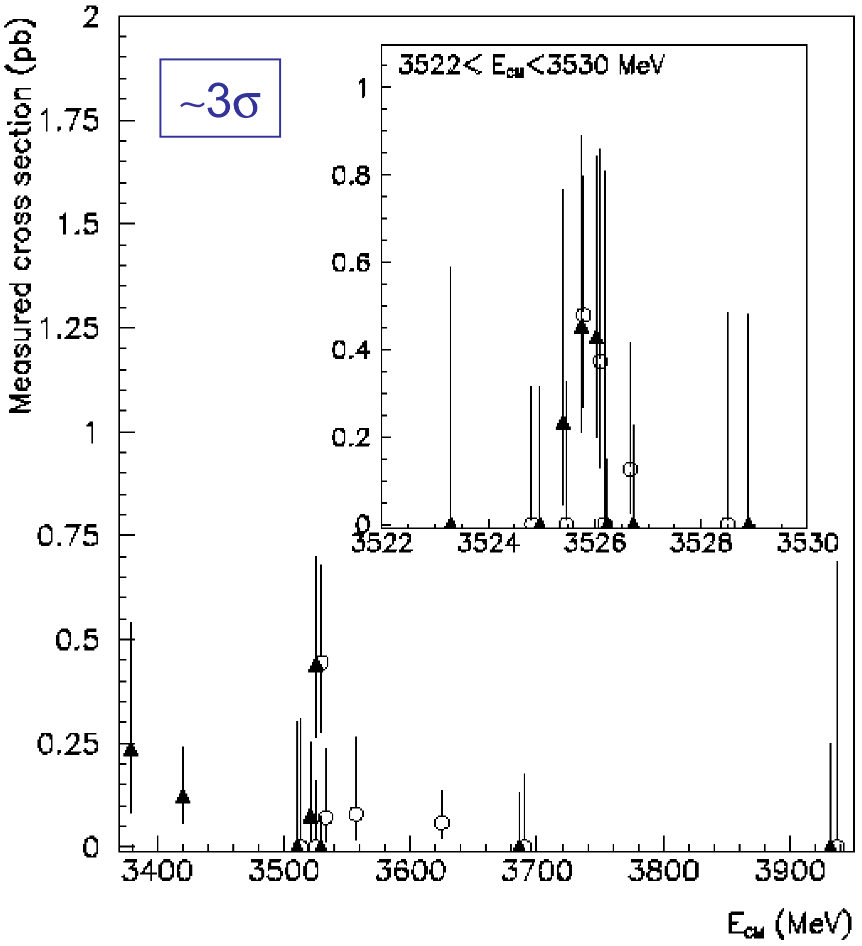
$$M(h_c) = 3525.8 \pm 0.2 \pm 0.2\ MeV/c^2$$

$$\Gamma(h_c) \leq 1\ MeV$$

$$\Gamma(p\bar{p})B(\eta_c\gamma) \leq 12.0 \pm 4.5\ eV$$

cfr E760 value:

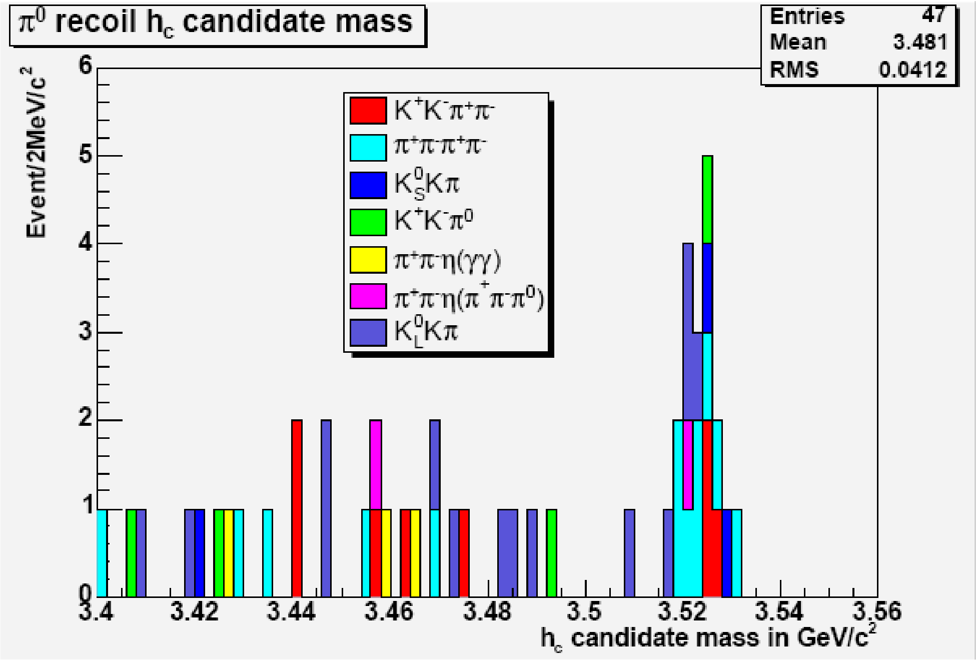
$$M(h_c) = 3526.2 \pm 0.15 \pm 0.2\ MeV/c^2$$



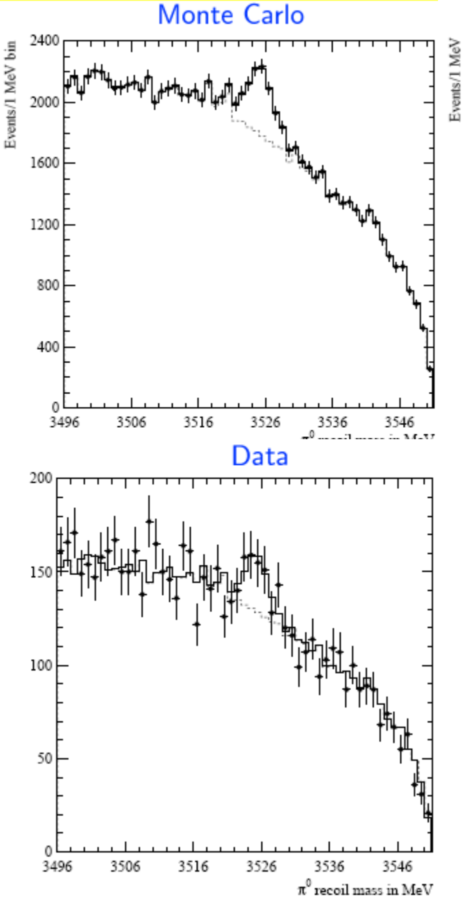
# $h_c$ Observation at CLEO

$e^+e^- \to \psi' \to \pi^0 h_c$     $h_c \to \eta_c \gamma$   $\eta_c \to$ hadrons

Inclusive analysis



exclusive analysis

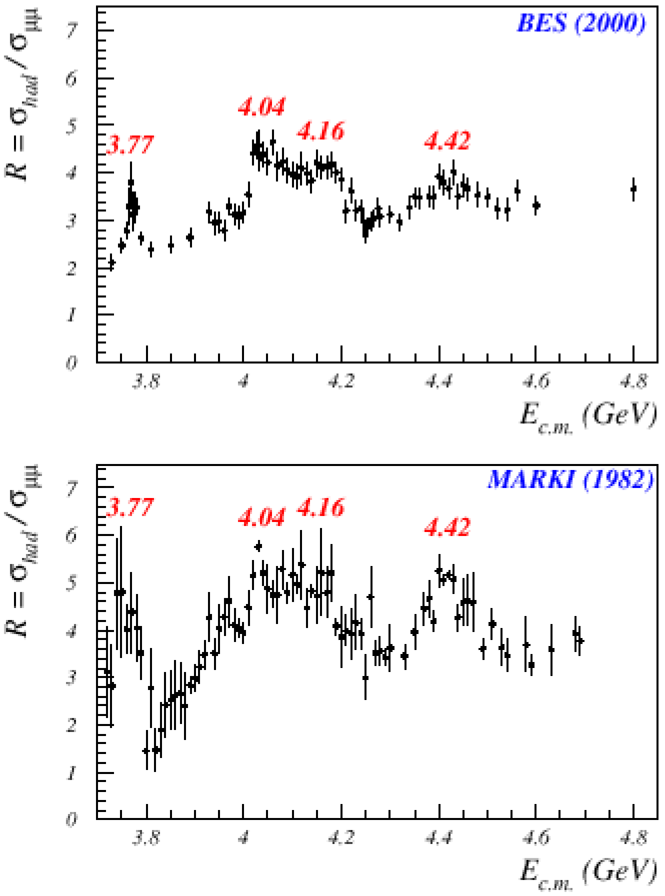


$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4\ MeV/c^2$$

# Charmonium States above the $D\bar{D}$ threshold

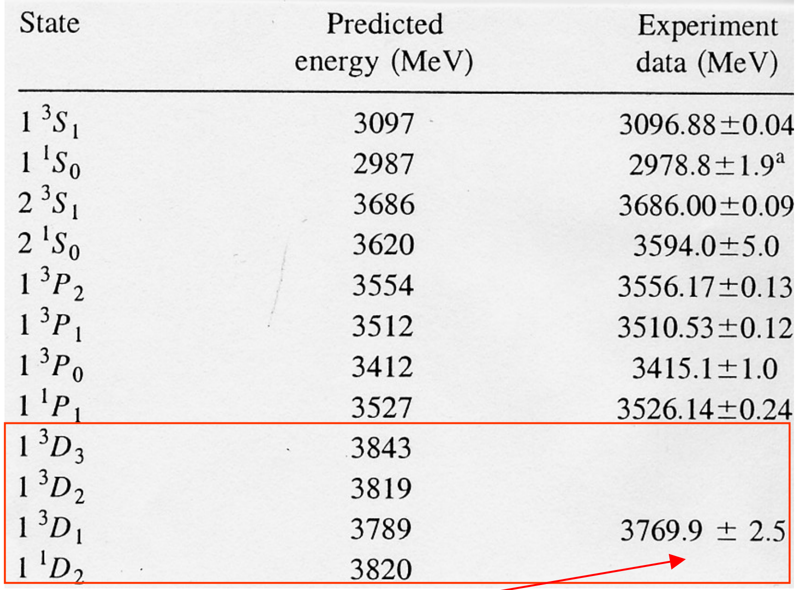
The energy region above the $D\bar{D}$ threshold at 3.73 GeV is very poorly known. Yet this region is rich in new physics.

- The structures and the higher vector states (ψ(3S), ψ(4S), ψ(5S) ...) observed by the early e+e- experiments have not all been confirmed by the latest, much more accurate measurements by BES.
- This is the region where the first radial excitations of the singlet and triplet P states are expected to exist.
- It is in this region that the narrow D-states occur.



# The D wave states

- The charmonium "D states" are above the open charm threshold (3730 MeV ) but the widths of the J= 2 states ${}^3D_2$ and ${}^1D_2$ are expected to be small:



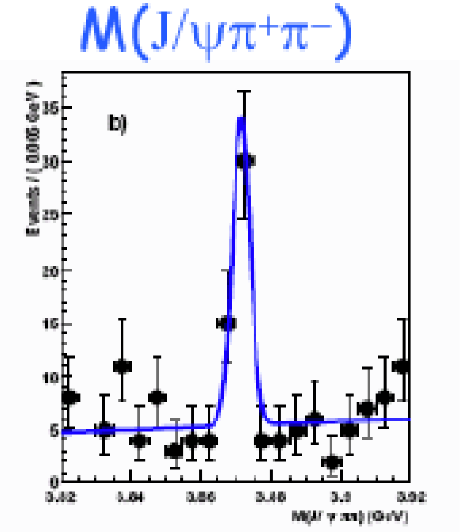
| State | Predicted energy (MeV) | Experiment data (MeV) |
|---|---|---|
| $1\,{}^3S_1$ | 3097 | 3096.88±0.04 |
| $1\,{}^1S_0$ | 2987 | 2978.8±1.9[a] |
| $2\,{}^3S_1$ | 3686 | 3686.00±0.09 |
| $2\,{}^1S_0$ | 3620 | 3594.0±5.0 |
| $1\,{}^3P_2$ | 3554 | 3556.17±0.13 |
| $1\,{}^3P_1$ | 3512 | 3510.53±0.12 |
| $1\,{}^3P_0$ | 3412 | 3415.1±1.0 |
| $1\,{}^1P_1$ | 3527 | 3526.14±0.24 |
| $1\,{}^3D_3$ | 3843 | |
| $1\,{}^3D_2$ | 3819 | |
| $1\,{}^3D_1$ | 3789 | 3769.9 ± 2.5 |
| $1\,{}^1D_2$ | 3820 | |

${}^{1,3}D_2 \not\to D\bar{D}$ forbidden by parity conservation

${}^{1,3}D_2 \not\to D\bar{D}^*$ forbidden by energy conservation

Only the ψ(3770), considered to be largely ${}^3D_1$ state, has been clearly observed. It is a wide resonance ($\Gamma(\psi(3770)) = 25.3 \pm 2.9$ MeV) decaying predominantly to $D\,\bar{D}$. The $J/\psi\pi^+\pi^-$ decay mode was recently observed by BES and by CLEO-c.

# Discovery of New States above the $D\bar{D}$ threshold - I



## **X(3872)**

New state discovered by Belle (BaBar, CDF, D0) in the hadronic decays of the B-meson:

$B^{\pm} \rightarrow K^{\pm} (J/\psi\pi^{+}\pi^{-})$, $J/\psi \rightarrow \mu^{+}\mu^{-}$ or $e^{+}e^{-}$

$M = 3872.0 \pm 0.6 \pm 0.5$ MeV
$\Gamma < 2.3$ MeV (90 % C.L.)

$D^{0}D^{0*}$ molecule ?

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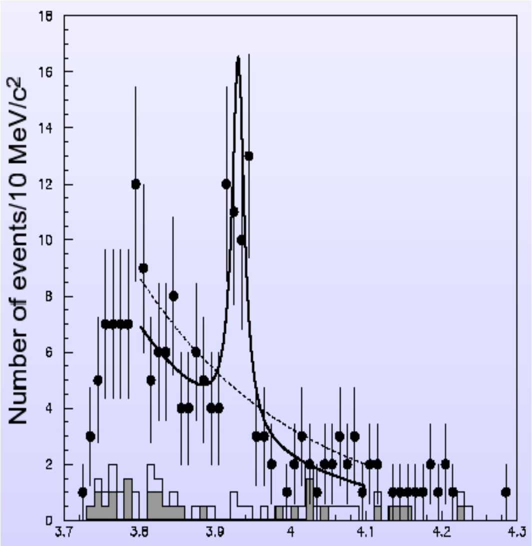


## **Z(3931)**

New state observed by Belle in

$\gamma\gamma \rightarrow Z(3931) \rightarrow D\bar{D}$

41± 11 evts (5.5σ)
$M = 3929 \pm 5 \pm 2$ MeV/c²
$\Gamma = 29 \pm 10 \pm 2$ MeV

$\chi_{c2}(2P)$ ?

# Discovery of New States above the $D\bar{D}$ threshold - II

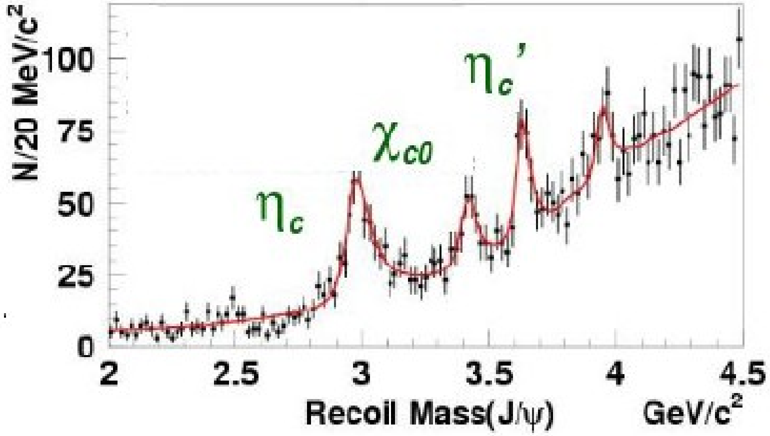
## X(3940)

$e^+ e^- \rightarrow J/\psi + X$ (double $c\bar{c}$)

$$M = 3943 \pm 6 \pm 6\ MeV/c^2$$

$$\Gamma = 15.4 \pm 10.1\ MeV$$

$\eta_c(3S)$ ?



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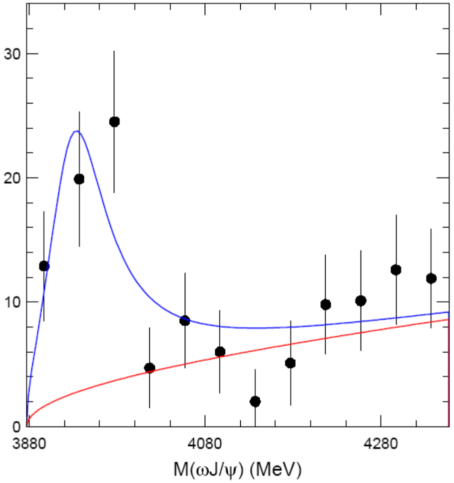


## Y(3940)

New state observed by Belle in

**$M=3943 \pm 11 \pm 13\ MeV/c^2$**

**$\Gamma = 87 \pm 22\ MeV$**

What can the X(3940) be ?

- charmonium ($\chi_{c1}$(2P)).
- threshold enhancement.
- charmonium hybrid.
- ...

# Discovery of New States above the D $\bar{D}$ threshold - III

## Y(4260)

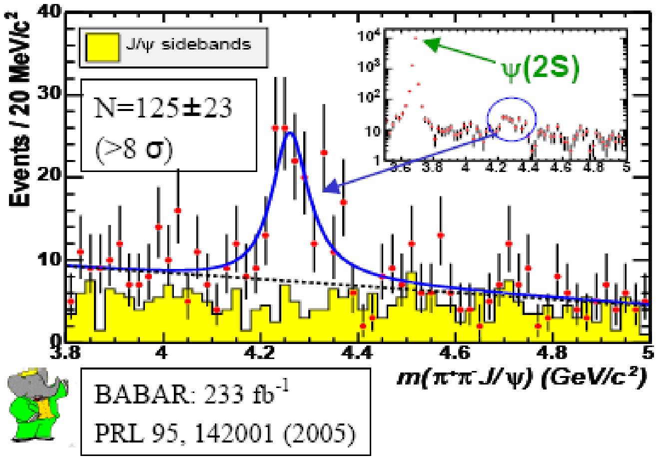
New state discovered by BaBar in ISR events:

$e^+e^- \to \gamma_{ISR}\pi^+\pi^- J/\psi$

$$M = 4259 \pm 8^{+2}_{-6}\ MeV/c^2$$

$$\Gamma = 88 \pm 23^{+6}_{-4}\ MeV$$

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



N=125±23 (>8 σ)

BABAR: 233 $fb^{-1}$
PRL 95, 142001 (2005)

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## Y(4320)

New state discovered by BaBar in ISR events:

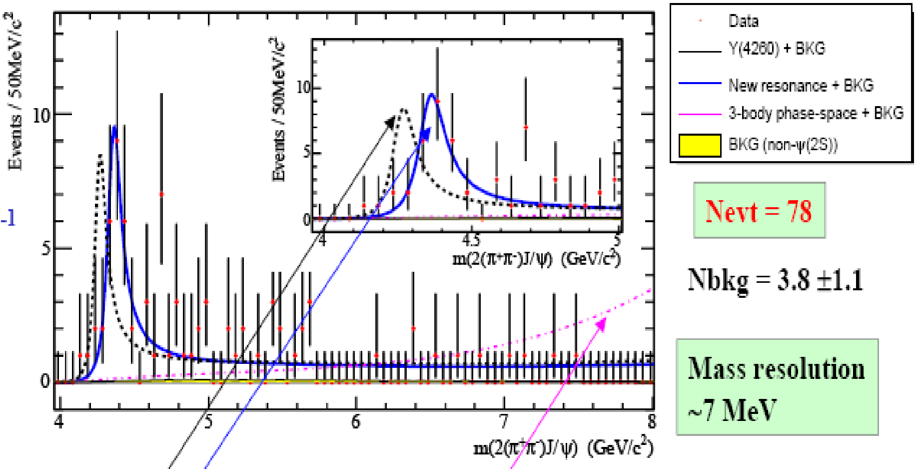
$e^+e^- \to \gamma_{ISR}\pi^+\pi^-\psi(2S)$

$$M = 4324 \pm 24\ MeV/c^2$$

$$\Gamma = 172 \pm 33\ MeV$$

298 $fb^{-1}$

BABAR preliminary



Nevt = 78

Nbkg = 3.8 ±1.1

Mass resolution ~7 MeV

# Open Issues in Charmonium Spectroscopy

- All 8 states below threshold have been observed: $h_c$ evidence stronger (E835, CLEO), its properties need to be measured accurately.
- The agreement between the various measurements of the $\eta_c$ mass and width is not satisfactory. New, high-precision measurments are needed. The large value of the total width needs to be understood.
- The study of the $\eta'_c$ has just started. Small splitting from the $\psi'$ must be understood. Width and decay modes must be measured.
- The angular distributions in the radiative decay of the triplet P states must be measured with higher accuracy.
- The entire region above open charm threshold must be explored in great detail, in particular the missing D states must be found.
- Decay modes of all charmonium states must be studied in greater detail: new modes must be found, existing puzzles must be solved (e.g. $\rho$-$\pi$), radiative decays must be measured with higher precision.

# Charmonium at PANDA

- At $2\times10^{32}$cm$^{-2}$s$^{-1}$ accumulate 8 pb$^{-1}$/day (assuming 50 % overall efficiency) ⇒ $10^{4}\div10^{7}$ ($c\bar{c}$) states/day.
- Total integrated luminosity 1.5 fb$^{-1}$/year (at $2\times10^{32}$cm$^{-2}$s$^{-1}$, assuming 6 months/year data taking).
- Improvements with respect to Fermilab E760/E835:
  - Up to ten times higher instantaneous luminosity.
  - Better beam momentum resolution $\Delta p/p = 10^{-5}$ (GSI) vs $2\times10^{-4}$ (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).

# Hybrids and Glueballs

The QCD spectrum is much richer than that of the quark model as the gluons can also act as hadron components.

Glueballs states of pure glue

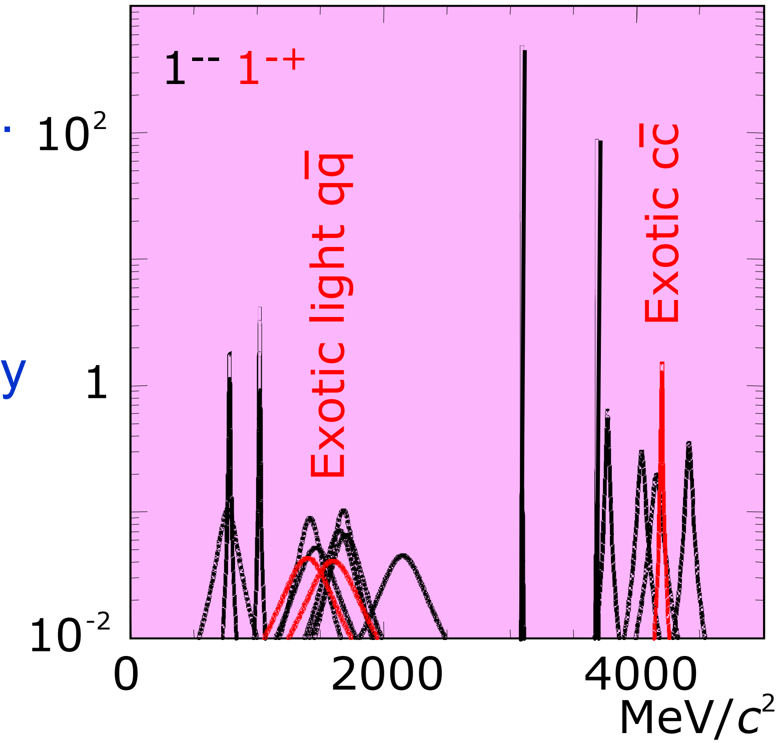
Hybrids $q\bar{q}g$

- Spin-exotic quantum numbers $J^{PC}$ are powerful signature of gluonic hadrons.
- In the light meson spectrum exotic states overlap with conventional states.
- In the $c\bar{c}$ meson spectrum the density of states is lower and the exotics can be resolved unambiguously.

∀$\pi_1(1400)$ and $\pi_1(1600)$ with $J^{PC}=1^{-+}$.

∀$\pi_1(2000)$ and $h_2(1950)$

- Narrow state at 1500 MeV/$c^2$ seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).

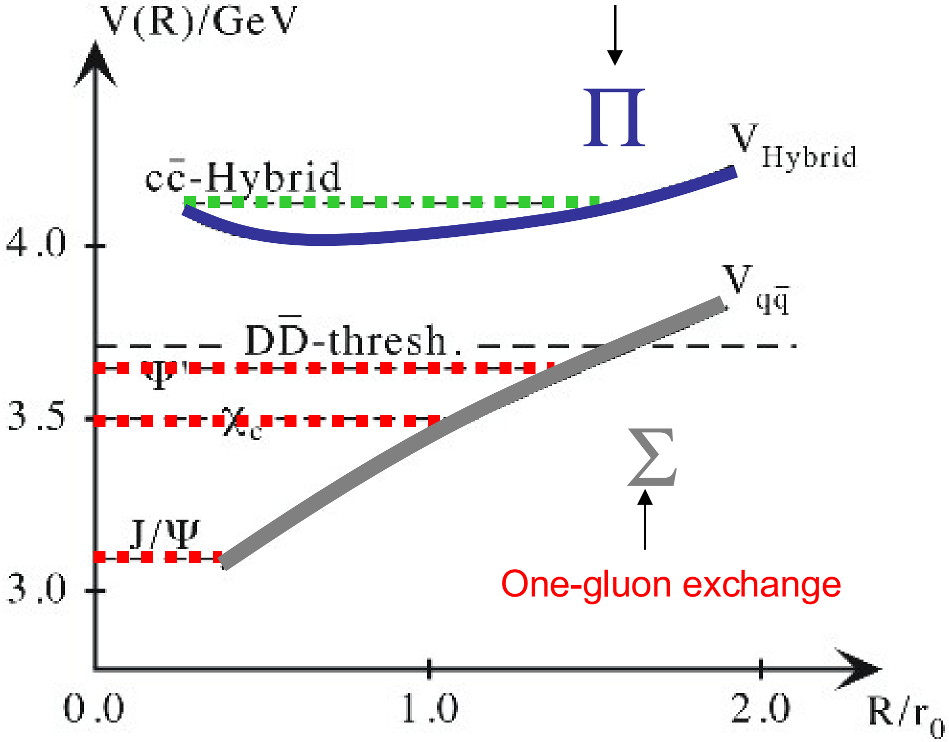


# Charmonium Hybrids

- Bag model, flux tube model constituent gluon model and LQCD.
- Three of the lowest lying $c\bar{c}$ hybrids have exotic $J^{PC}$ ($0^{+-}$, $1^{-+}$, $2^{+-}$)

  ⇒ no mixing with nearby $c\bar{c}$ states
- Mass 4.2 – 4.5 GeV/$c^2$.
- Charmonium hybrids expected to be much narrower than light hybrids (open charm decays forbidden or suppressed below DD** threshold).
- Cross sections for formation and production of charmonium hybrids similar to normal $c\bar{c}$ states

  (~ 100 – 150 pb).



Excited gluon flux

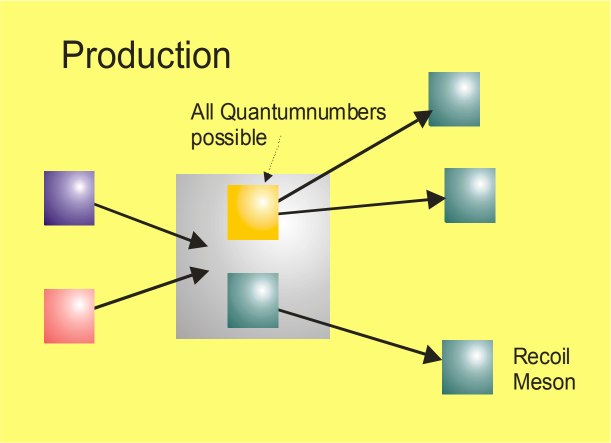
One-gluon exchange

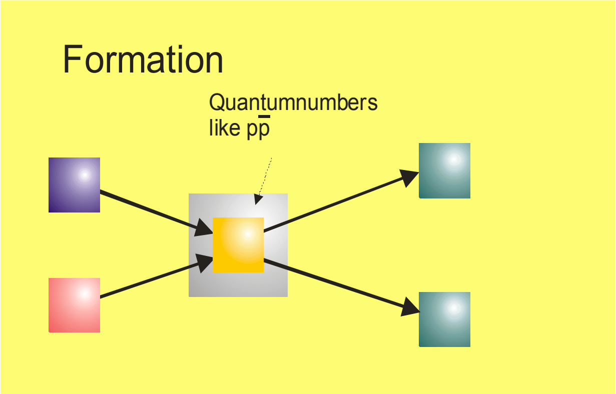
# Charmonium Hybrids

- Gluon rich process creates gluonic excitation in a direct way
  - ccbar requires the quarks to annihilate (no rearrangement)
  - yield comparable to charmonium production

- 2 complementary techniques
  - Production (Fixed-Momentum)
  - Formation (Broad- and Fine-Scans)

- Momentum range for a survey
  - p → ~15 GeV





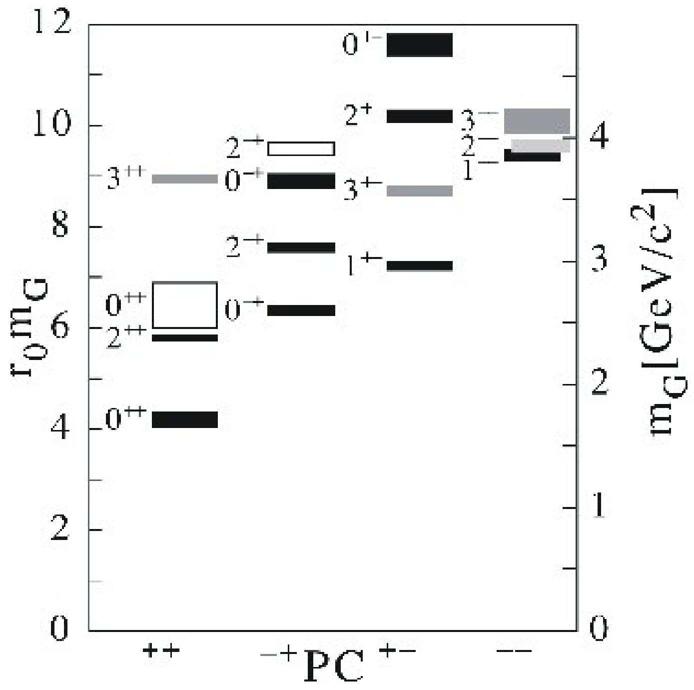
# Glueballs

Detailed predictions of mass spectrum from quenched LQCD.

- Width of ground state ~ 100 MeV
- Several states predicted below 5 GeV/$c^2$, some exotic (oddballs)
- Exotic heavy glueballs:
    - m($0^{+-}$) = 4140(50)(200) MeV
    - m($2^{+-}$) = 4740(70)(230) MeV
    - predicted narrow width

Can be either formed directly or produced in $\bar{p}p$ annihilation.

Some predicted decay modes $\phi\phi$, $\phi\eta$, $J/\psi\eta$, $J/\psi\phi$ ...

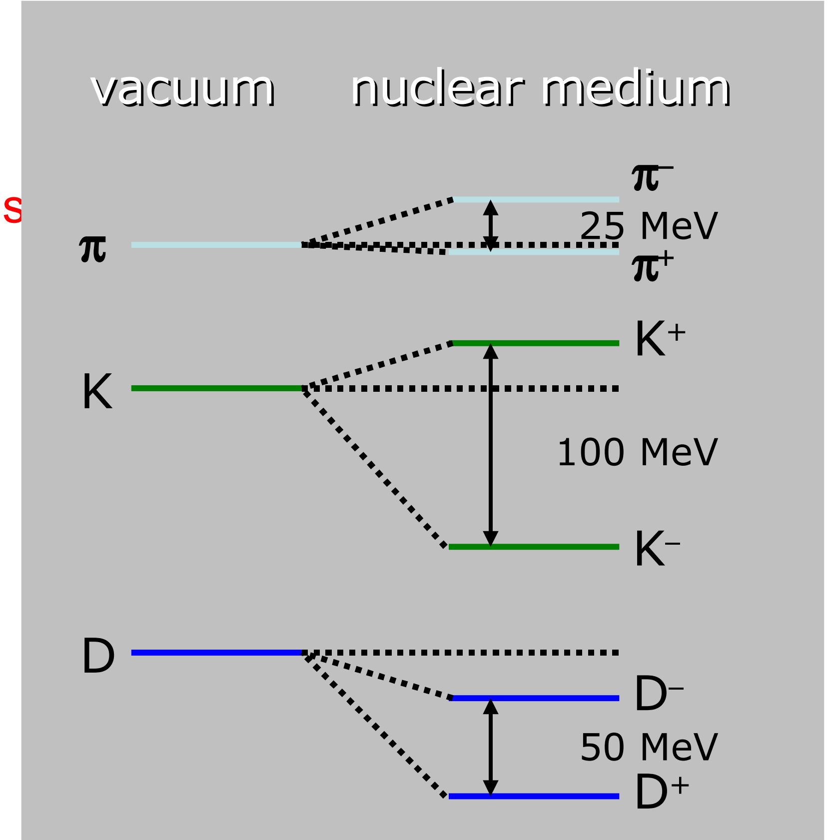


*Morningstar und Peardon, PRD60 (1999) 034509*
*Morningstar und Peardon, PRD56 (1997) 4043*

The detection of non-exotic glueballs is not trivial, as these states mix with the nearby q $\bar{q}$ states with the same quantum numbers, thus modifying the expected decay pattern.

# Hadrons in Nuclear Matter

- Partial restoration of chiral symmetry in nuclear matter
  - Light quarks are sensitive to quark condensate
- Evidence for mass changes of pions and kaons has been deduced previously:
  - deeply bound pionic atoms
  - (anti)kaon yield and phase space distribution
- $(c\bar{c})$ states are sensitive to gluon condensate
  - small (5-10 MeV/$c^2$) in medium modifications for low-lying $(c\bar{c})$ ($J/\psi$, $\eta_c$)
  - significant mass shifts for excited states: 40, 100, 140 MeV/$c^2$ for $\chi_{cJ}$, $\psi'$, $\psi(3770)$ resp.
- D mesons are the QCD analog of the H-atom.
  - chiral symmetry to be studied on a single light quark
  - theoretical calculations disagree in size and sign of mass shift (50 MeV/$c^2$ attractive – 160 MeV/$c^2$ repulsive)



*Hayaski, PLB 487 (2000) 96*
*Morath, Lee, Weise, priv. Comm.*

# Charmonium in Nuclei

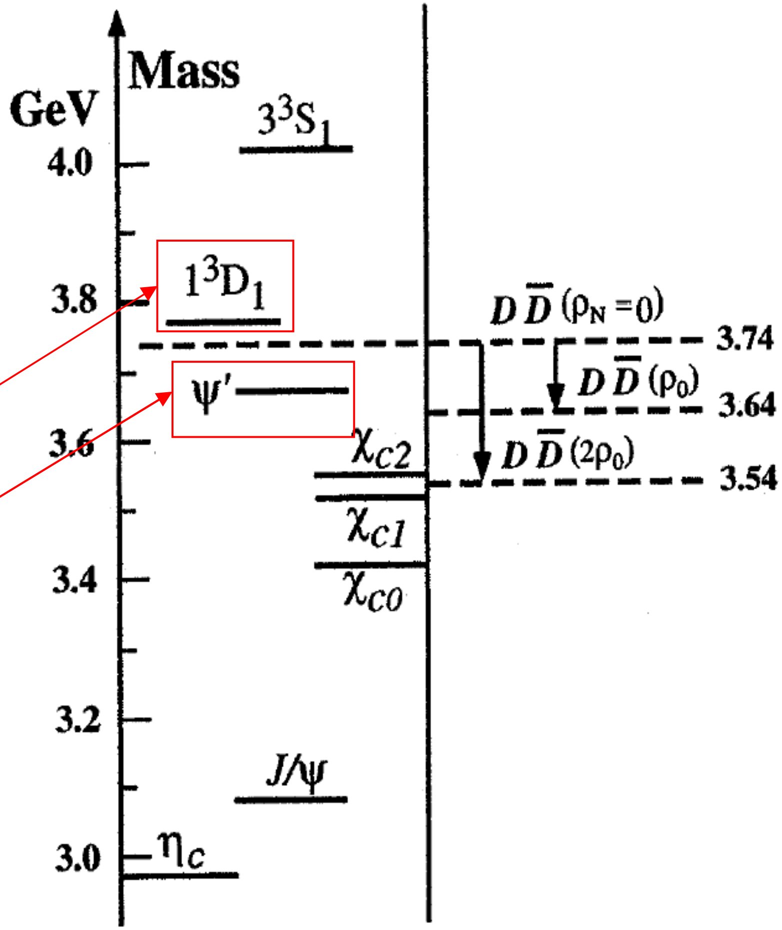
- Measure J/ψ and D production cross section in $\bar{p}$ annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the $D^+D^-$ mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

ψ(1D) 20 MeV → 40 MeV

ψ(2S) .28 MeV → 2.7 MeV

⇒Study relative changes of yield and width of the charmonium states.

- In medium mass reconstructed from dilepton (c $\bar{c}$) or hadronic decays (D)

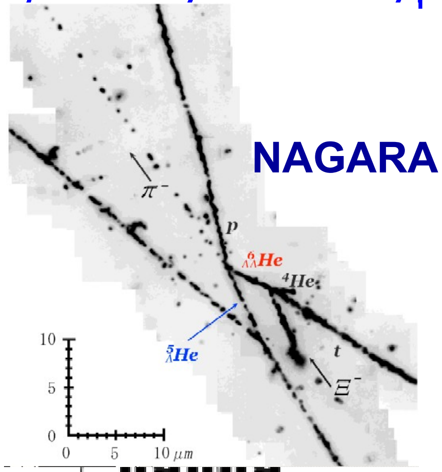


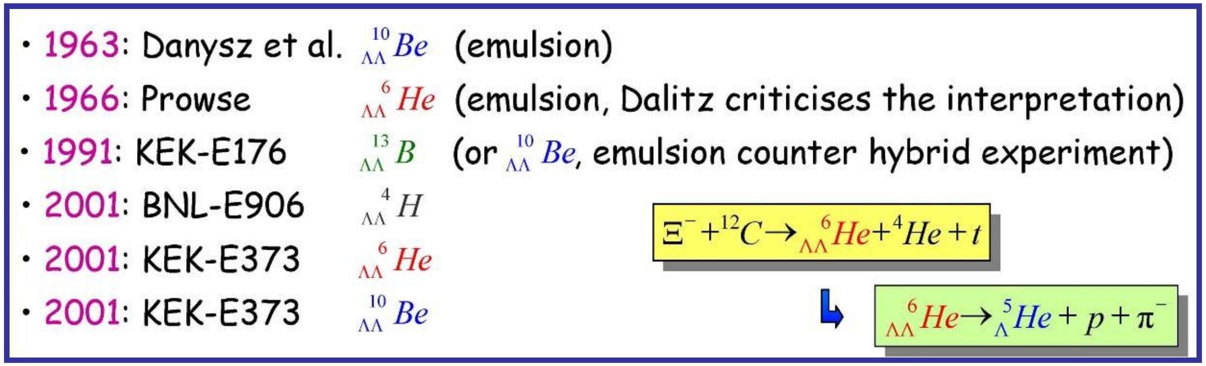
# Multi-Strangeness Systems

Hypernuclei, systems where one (or more) nucleon is substituted by one (or more) hyperon, allow access to a whole set of nuclear states containing an extra degree of freedom: strangeness

The lighter single strangeness Λ-hypernuclei have been studied since 50 years allowing to test and define shell model parameters and ΛN interaction. ΛΛ-hypernuclei, Ξ-atoms Ω-atoms are described by more complicated approaches, but allows to have an inset to more complex nuclear systems containing strangeness (hyperon-star, strange-quark star,...)

Experimental situation : ~35 Λ-hypernuclei established since 50 years ago. Only 6 ΛΛ-hypernuclei





- 1963: Danysz et al. $^{10}_{\Lambda\Lambda}Be$ (emulsion)
- 1966: Prowse $^{6}_{\Lambda\Lambda}He$ (emulsion, Dalitz criticises the interpretation)
- 1991: KEK-E176 $^{13}_{\Lambda\Lambda}B$ (or $^{10}_{\Lambda\Lambda}Be$, emulsion counter hybrid experiment)
- 2001: BNL-E906 $^{4}_{\Lambda\Lambda}H$
- 2001: KEK-E373 $^{6}_{\Lambda\Lambda}He$
- 2001: KEK-E373 $^{10}_{\Lambda\Lambda}Be$

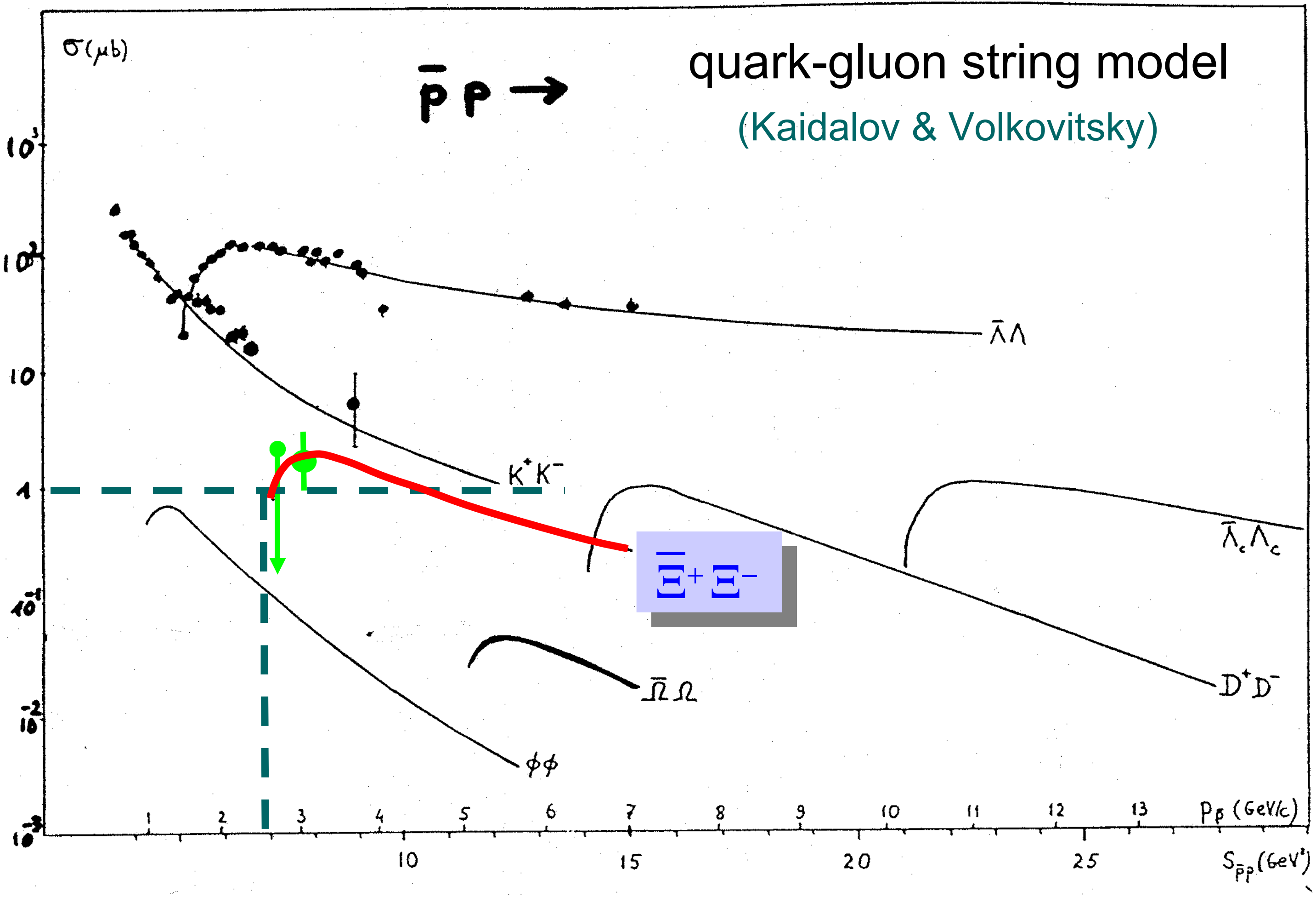
$\Xi^- + {}^{12}C \rightarrow {}^{6}_{\Lambda\Lambda}He + {}^{4}He + t$

↳ $^{6}_{\Lambda\Lambda}He \rightarrow {}^{5}_{\Lambda}He + p + \pi^-$

H. Takahashi *et al.*, PRL 87, 212502-1 (2001)

# Double-Lambda Hypernuclei

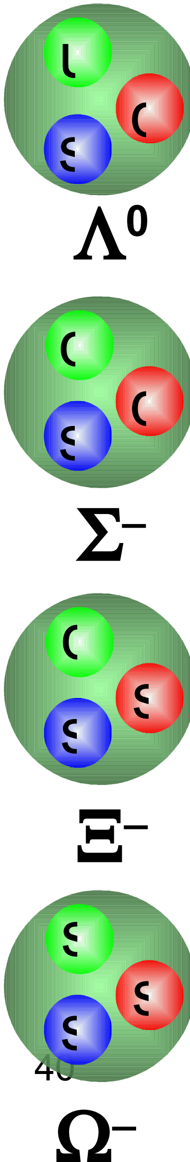
- Use $\bar{p}p$ Interaction to produce a hyperon "beam" ($t \sim 10^{-10}$ s) which is tagged by the antihyperon or its decay products



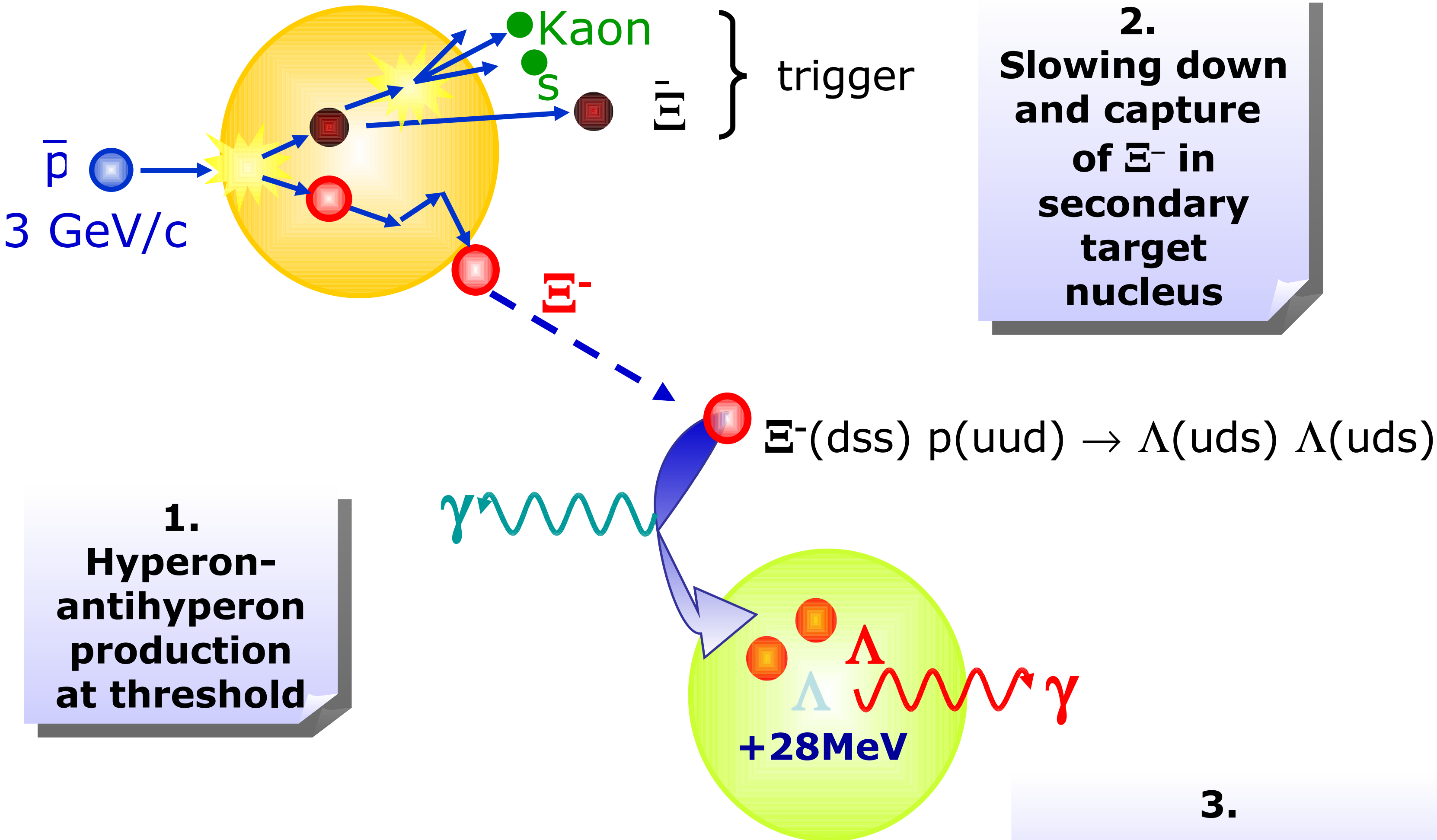
quark-gluon string model

(Kaidalov & Volkovitsky)

$\bar{\Xi}^{+}\Xi^{-}$



# Production of Double Hypernuclei



**1.**
**Hyperon-antihyperon production at threshold**

**2.**
**Slowing down and capture of $\Xi^-$ in secondary target nucleus**

**3.**
**$\gamma$-spectroscopy with Ge-detectors**

# Proton Electromagnetic Form Factors in the Timelike Region

The electromagnetic form factors of the proton in the time-like region can be extracted from the cross section for the process:

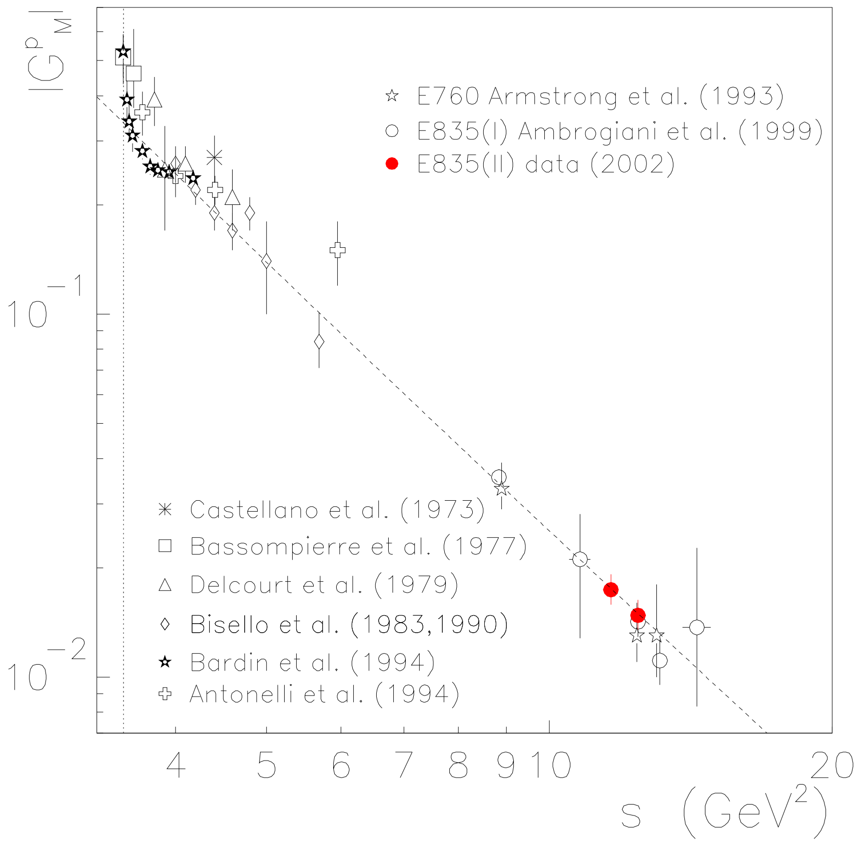
$\bar{p}p \rightarrow e^+e^-$

First order QED predicts:

$$\frac{d\sigma}{d\left(\cos\theta^*\right)} = \frac{\pi\alpha^2 \; {}^2 c^2}{2xs}\left[\left|G_M\right|^2\left(1+\cos^2\theta^*\right)+\frac{4m_p^2}{s}\left|G_E\right|^2\left(1-\cos^2\theta^*\right)\right]$$

Data at high $Q^2$ are crucial to test the QCD predictions for the asymptotic behavior of the form factors and the spacelike-timelike equality at corresponding values of $Q^2$.

# E835 Form Factor Measurement



The dashed line is the PQCD fit:

$$\frac{|G_M|}{\mu_p} = \frac{C}{s^2 \ln^2\left(\frac{s}{\Lambda^2}\right)}$$

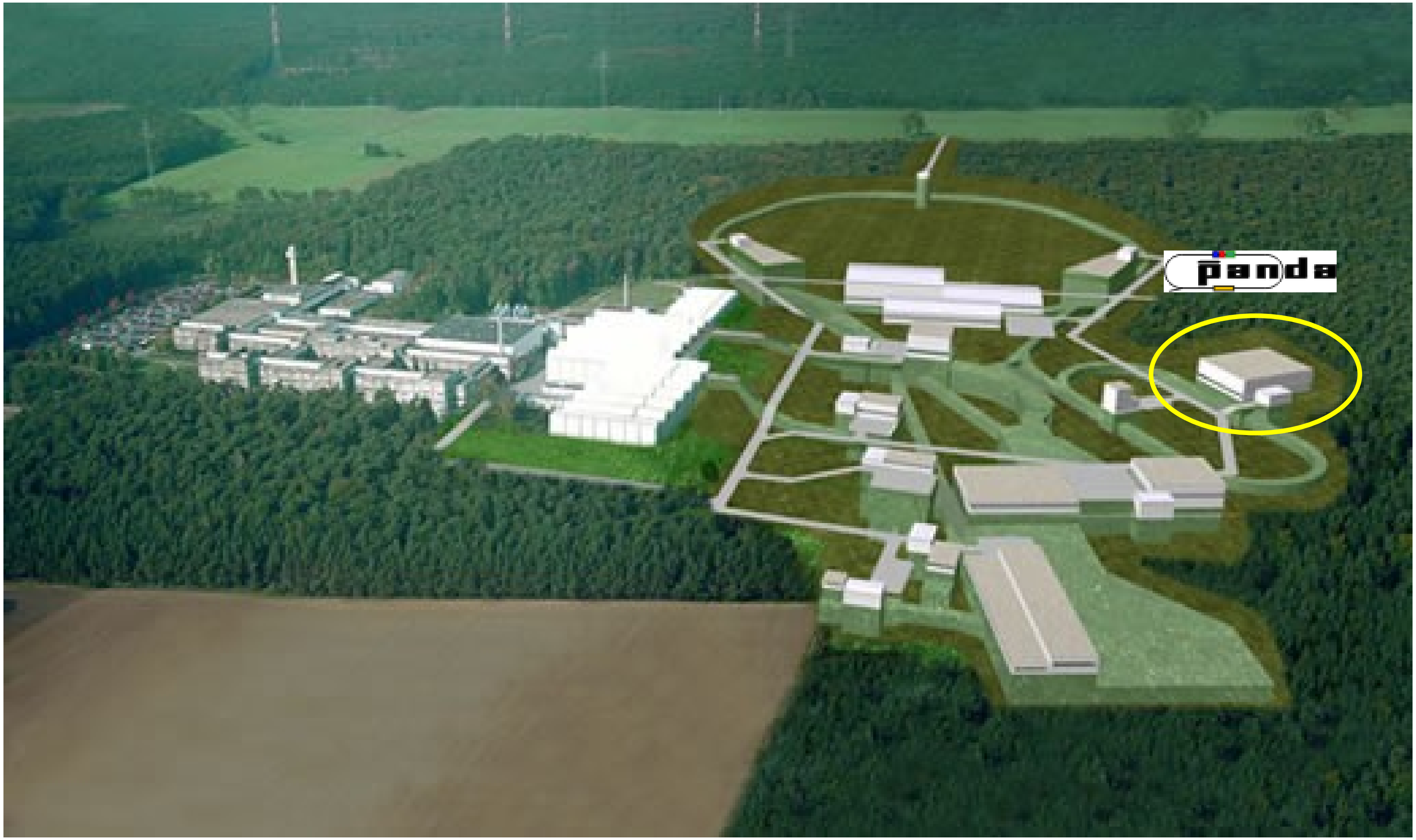
| s<br>(GeV²) | 10²×\|G$_M$\|<br>(a) | 10²× \|G$_M$\|<br>(b) |
|---|---|---|
| 11.63 | $1.74^{+0.18+0.11}_{-0.16-0.07}$ | $1.94^{+0.20+0.12}_{-0.17-0.08}$ |
| 12.43 | $1.48^{+0.15+0.08}_{-0.13-0.05}$ | $1.63^{+0.17+0.09}_{-0.14-0.05}$ |

# Form Factor Measurement in Panda

In Panda we will be able to measure the proton timelike form factors over the widest $q^2$ range ever covered by a single experiment, from threshold up to $q^2=30\ \mathrm{GeV}^2$, and reach the highest $q^2$.

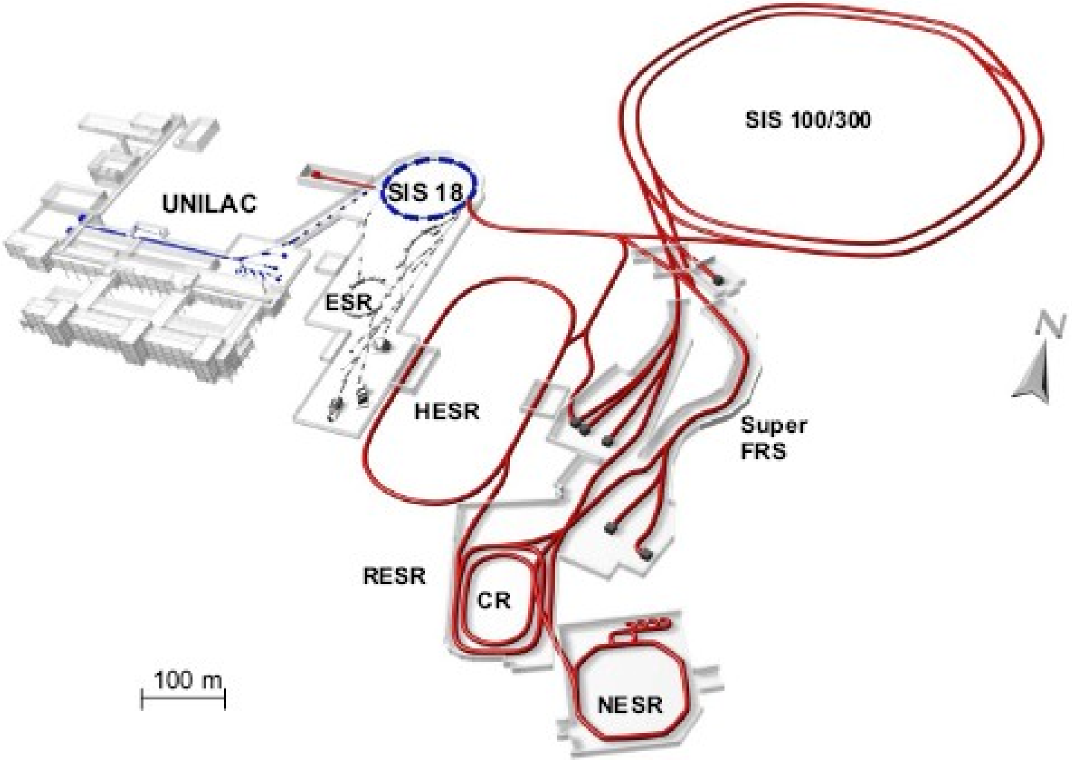
- At low $q^2$ (near threshold) we will be able to measure the form factors with high statistics, measure the angular distribution (and thus $G_M$ and $G_E$ separately) and confirm the sharp rise of the FF.
- At the other end of our energy region we will be able to measure the FF at the highest values of $q^2$ ever reached, $\leq 30\ \mathrm{GeV}^2$, which is 2.5 larger than the maximum value measured by E835. Since the cross sections decrease $\sim 1/s^5$, to get comparable precision to E835 we will need ~82 times more data.
- In the E835 region we need to gain a factor of at least 10-20 in data size to be able to measure the electric and magnetic FF separately.

# The GSI FAIR Facility



# FAIR : the GSI future facility

## Facility for Antiproton and Ion Research



### Primary Beams

- $10^{12}$/s; 1.5 GeV/u; $^{238}U^{28+}$
- Factor 100-1000 present in intensity
- 2(4)x$10^{13}$/s 30 GeV protons
- $10^{10}$/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

### 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
- e – A collider
- $10^{11}$ stored and cooled 0.8 - 14.5 GeV antiprotons

### Key Technical Features

- Cooled beams
- Rapidly cycling superconducting magnets

# HESR - High Energy Storage Ring

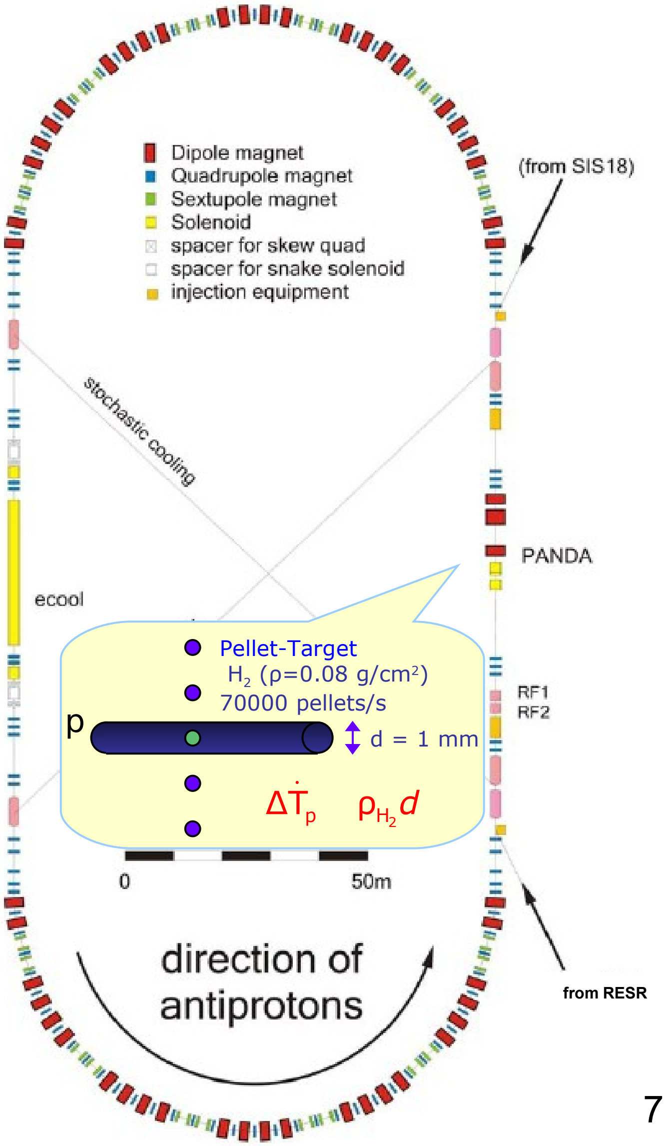
- Production rate $2\text{x}10^{7}$/sec
- $P_{beam}$ = 1 - 15 GeV/c
- $N_{stored}$ = $5\text{x}10^{10}\ \bar{p}$
- Internal Target

**High resolution mode**

- $\delta p/p \sim 10^{-5}$ (electron cooling)
- Lumin. = $10^{31}$ cm$^{-2}$ s$^{-1}$

**High luminosity mode**

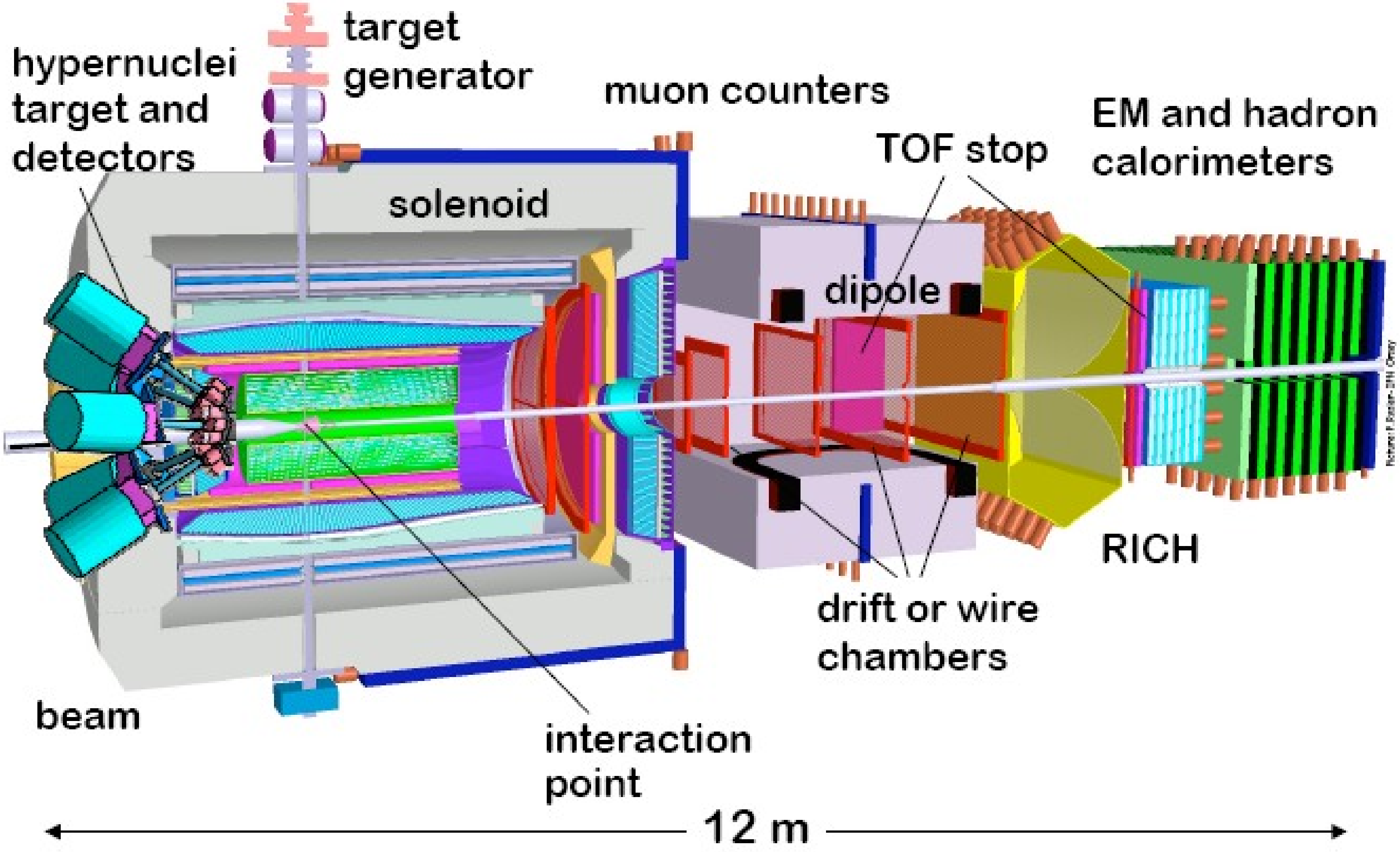
- Lumin. = 2 x $10^{32}$ cm$^{-2}$ s$^{-1}$
- $\delta p/p \sim 10^{-4}$ (stochastic cooling)



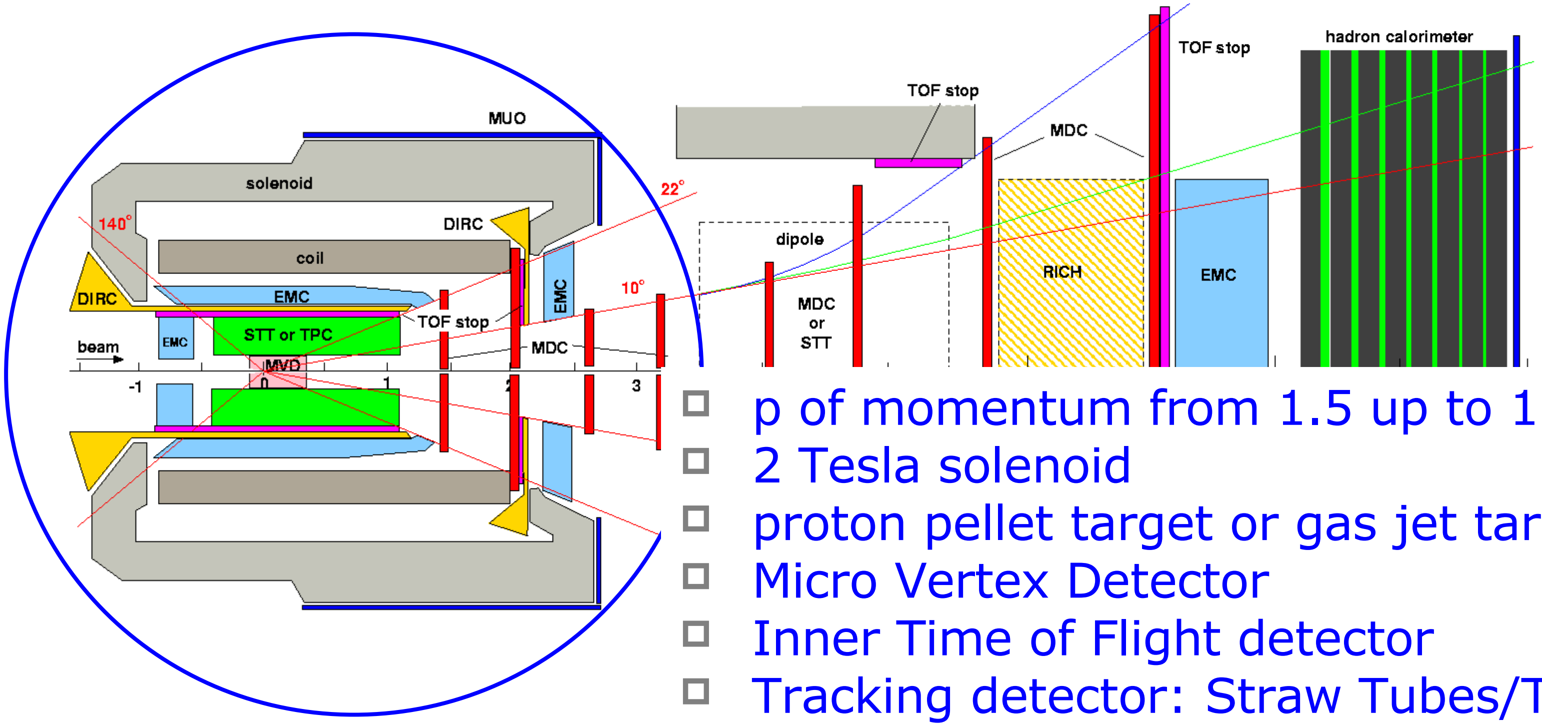
# The Detector

- Detector Requirements:
  - (Nearly) 4π solid angle coverage (partial wave analysis)
  - High-rate capability (2×$10^7$ annihilations/s)
  - Good PID (γ, e, μ, π, K, p)
  - Momentum resolution (≈ 1 %)
  - Vertex reconstruction for D, $K^0_s$, Λ
  - Efficient trigger
  - Modular design
- For Charmonium:
  - Pointlike interaction region
  - Lepton identification
  - Excellent calorimetry
    - Energy resolution
    - Sensitivity to low-energy photons

# Panda Detector

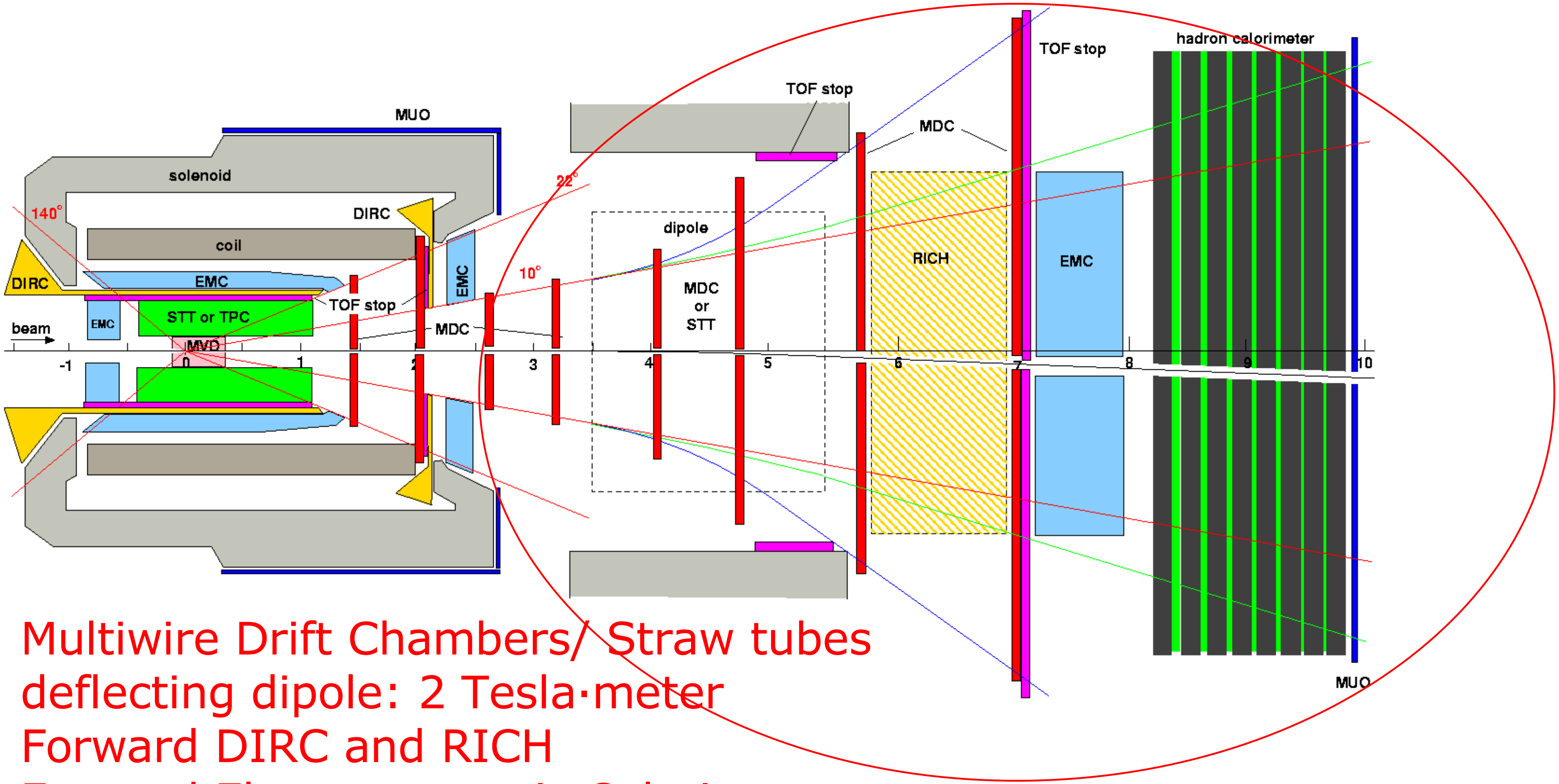


# Target Spectrometer



- p of momentum from 1.5 up to 15 GeV/c
- 2 Tesla solenoid
- proton pellet target or gas jet target
- Micro Vertex Detector
- Inner Time of Flight detector
- Tracking detector: Straw Tubes/TPC
- DIRC
- Electromagnetic Calorimeter
- Muon counters
- Multiwire Drift Chambers

# Forward Spectrometer



- Multiwire Drift Chambers/ Straw tubes
- deflecting dipole: 2 Tesla·meter
- Forward DIRC and RICH
- Forward Electromagnetic Calorimeters
- Time of Flight counters
- Hadron Calorimeter

# panda Collaboration

- At present a group of **350 physicists** from 47 institutions of 15 countries

**Austria – Belaruz - China - Finland - France - Germany – Italy – Poland – Romania - Russia – Spain - Sweden – Switzerland - U.K. – U.S.A..**

Basel, Beijing, Bochum, Bonn, IFIN Bucharest, Catania, Cracow, Dresden, Edinburg, Erlangen, Ferrara, Frankfurt, Genova, Giessen, Glasgow, GSI, Inst. of Physics Helsinki, FZ Jülich, JINR Dubna, Katowice, Lanzhou, LNF, Mainz, Milano, Minsk, TU München, Münster, Northwestern, BINP Novosibirsk, Pavia, Piemonte Orientale, IPN Orsay, IHEP Protvino, PNPI St. Petersburg, Stockholm, Dep. A. Avogadro Torino, Dep. Fis. Sperimentale Torino, Torino Politecnico, Trieste, TSL Uppsala, Tübingen, Uppsala, Valencia, SINS Warsaw, TU Warsaw, AAS Wien

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

# Conclusions

The HESR at the GSI FAIR facility will deliver high-quality $\bar{p}$ beams with momenta up to 15 GeV/c ($\sqrt{s} \approx 5.5$ GeV).

This will allow Panda to carry out the following measurements:

- High resolution charmonium spectroscopy in formation experiments
- Study of gluonic excitations (glueballs, hybrids)
- Study of hadrons in nuclear matter
- Hypernuclear physics
- Deeply Virtual Compton Scattering and Drell-Yan