The PANDA experiment at FAIR

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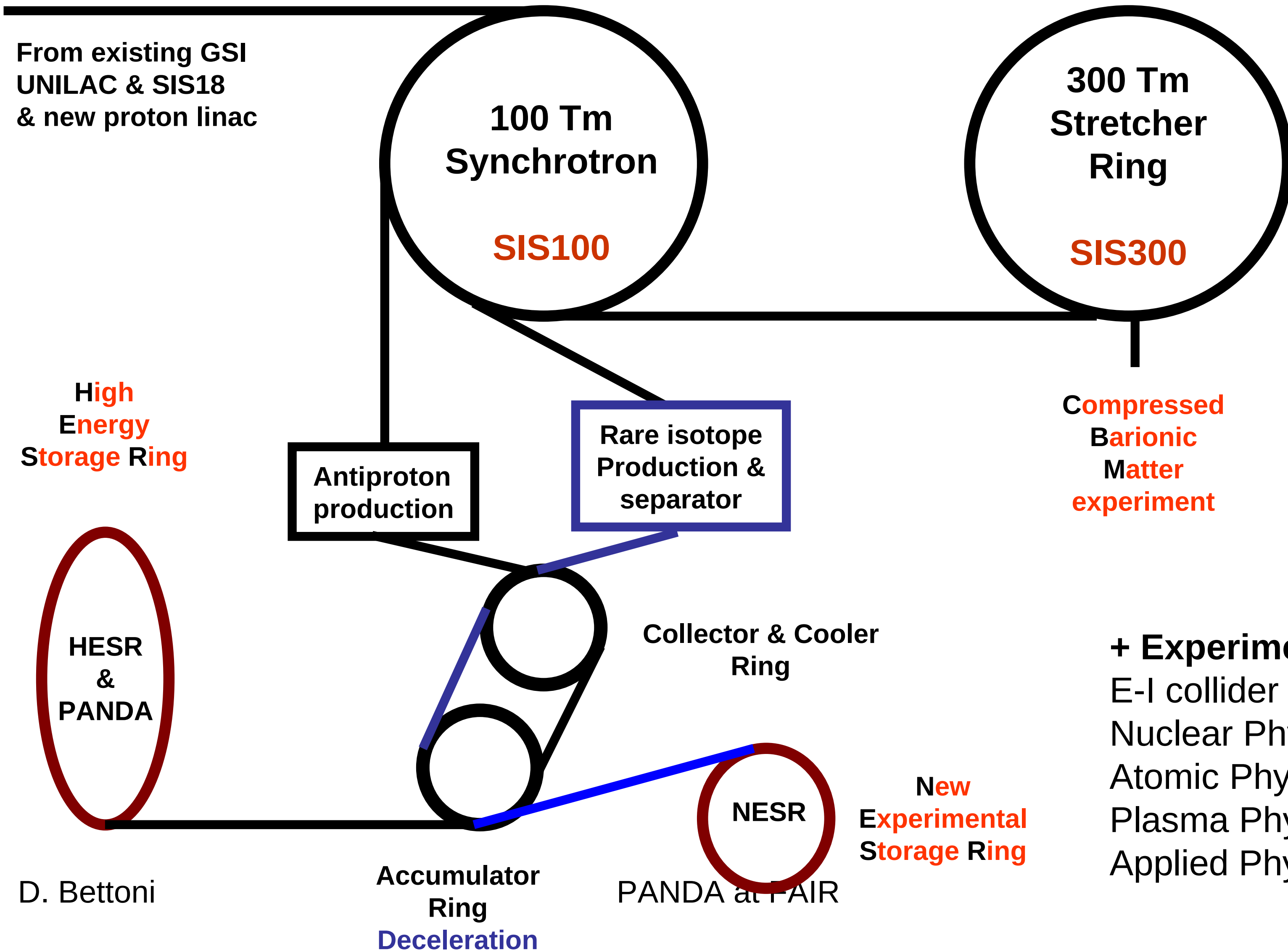
Outline

- FAIR
- HESR
- PANDA Physics Program
  - Charmonium Spectroscopy
  - Hybrids and Glueballs
  - Hadrons in Nuclear Matter
  - Open charm physics
- The PANDA Detector
- Conclusions

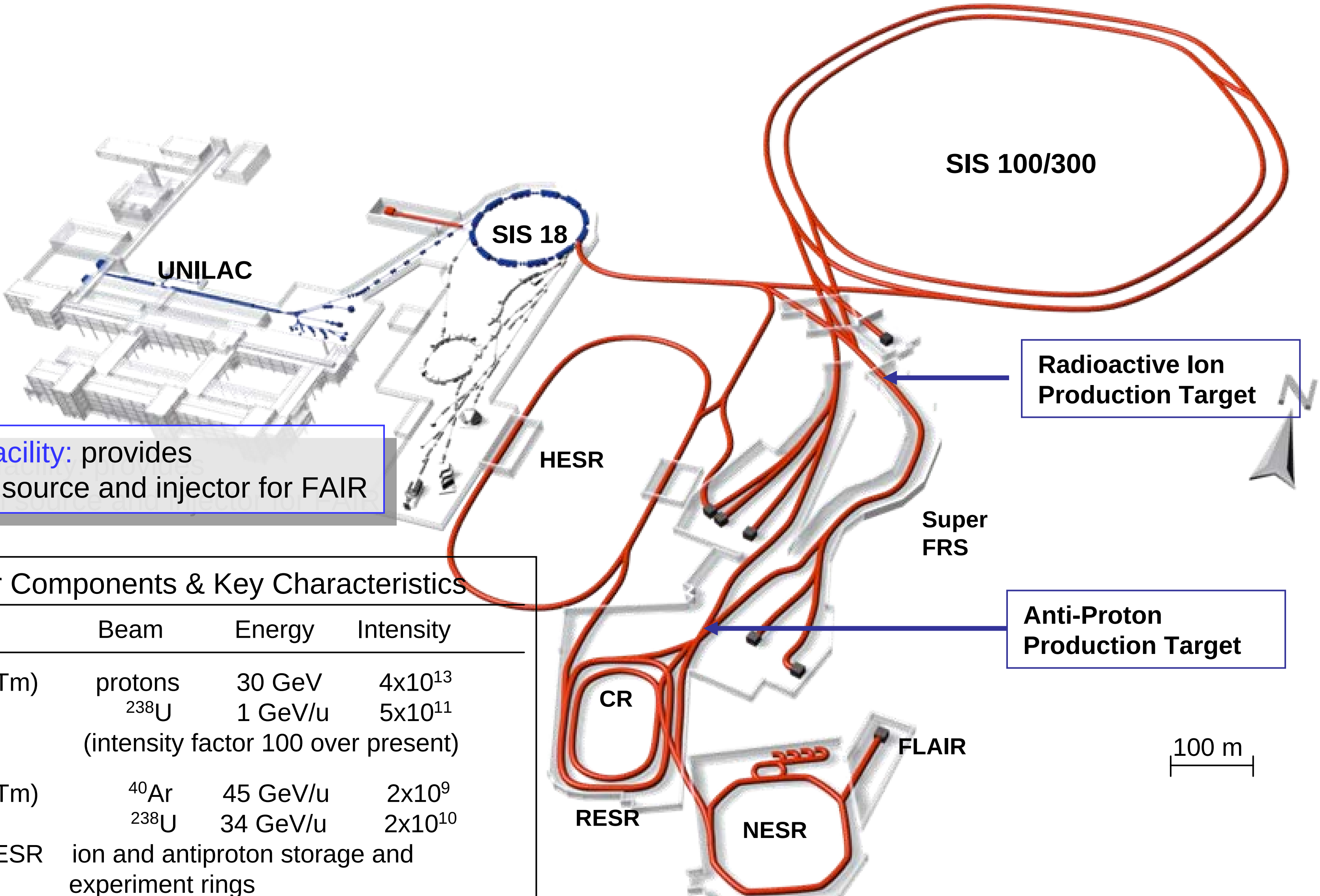

FAIR at a glance

The FAIR Complex



+ Experiments:
E-I collider
Nuclear Physics
Atomic Physics
Plasma Physics
Applied Physics

Technical Realization of FAIR



Existing facility: provides ion-beam source and injector for FAIR

Accelerator Components & Key Characteristics

Ring/Device	Beam	Energy	Intensity
SIS100 (100Tm)	protons	30 GeV	4×10^{13}
	^{238}U	1 GeV/u	5×10^{11}
	(intensity factor 100 over present)		
SIS300 (300Tm)	^{40}Ar	45 GeV/u	2×10^{9}
	^{238}U	34 GeV/u	2×10^{10}
CR/RESR/NESR	ion and antiproton storage and experiment rings		
HESR	antiprotons	14 GeV	$\sim10^{11}$
Super-FRS	rare-isotope beams	1 GeV/u	$<10^{9}$

New future facility: provides ion and anti-matter beams of highest-intensity and up to high energies

Unprecedented System Parameters at FAIR

Beam Intensity:
- primary heavy-ion beam intensity increases by x 100 – x 1000
- secondary beam intensity increases by up to x 10000

Beam Energy:
- heavy-ion energy : x 30

Beam Variety:
- antiprotons
- protons to uranium & radioactive ion beams

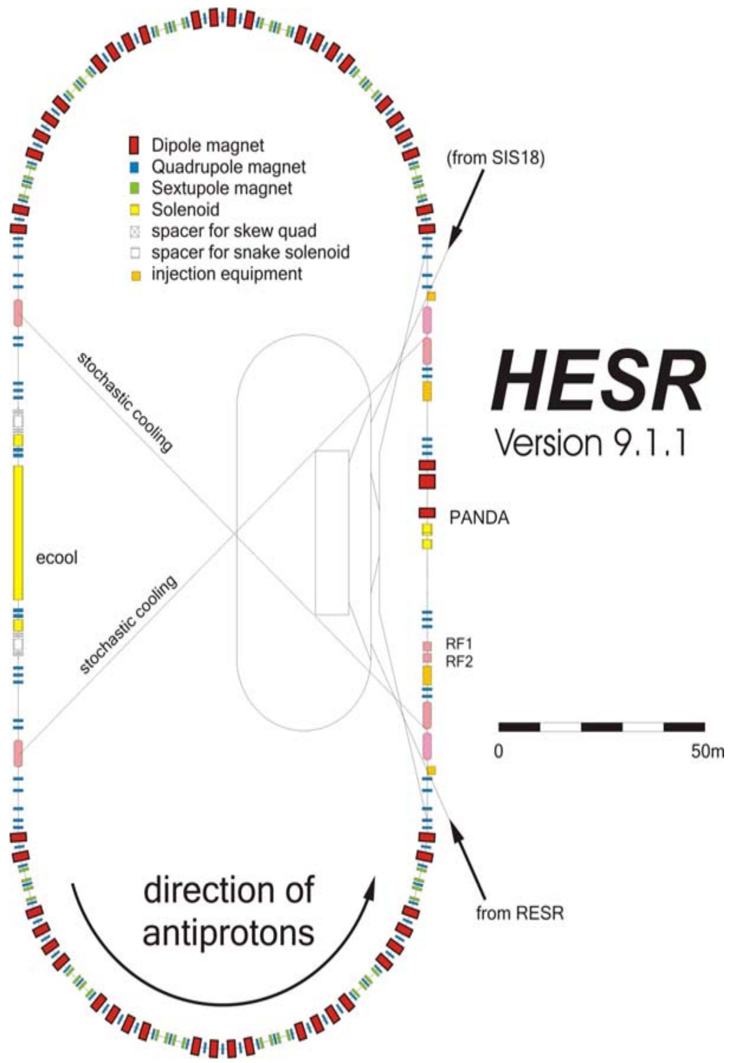
Beam Precision:
- cooled antiproton beams
- intense cooled radioactive ion beams

Beam Pulse structure:
- optimized for experiments: from dc to 50 ns

Parallel Operation:
- full accelerator performance for up to four different and independent experiments and experimental programs

High-Energy Storage Ring

- Production rate $2x10^7$/sec
- P_{beam} = 1 - 15 GeV/c
- N_{stored} = $5x10^{10}$ $\bar{p}$
- Internal Target



High resolution mode

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

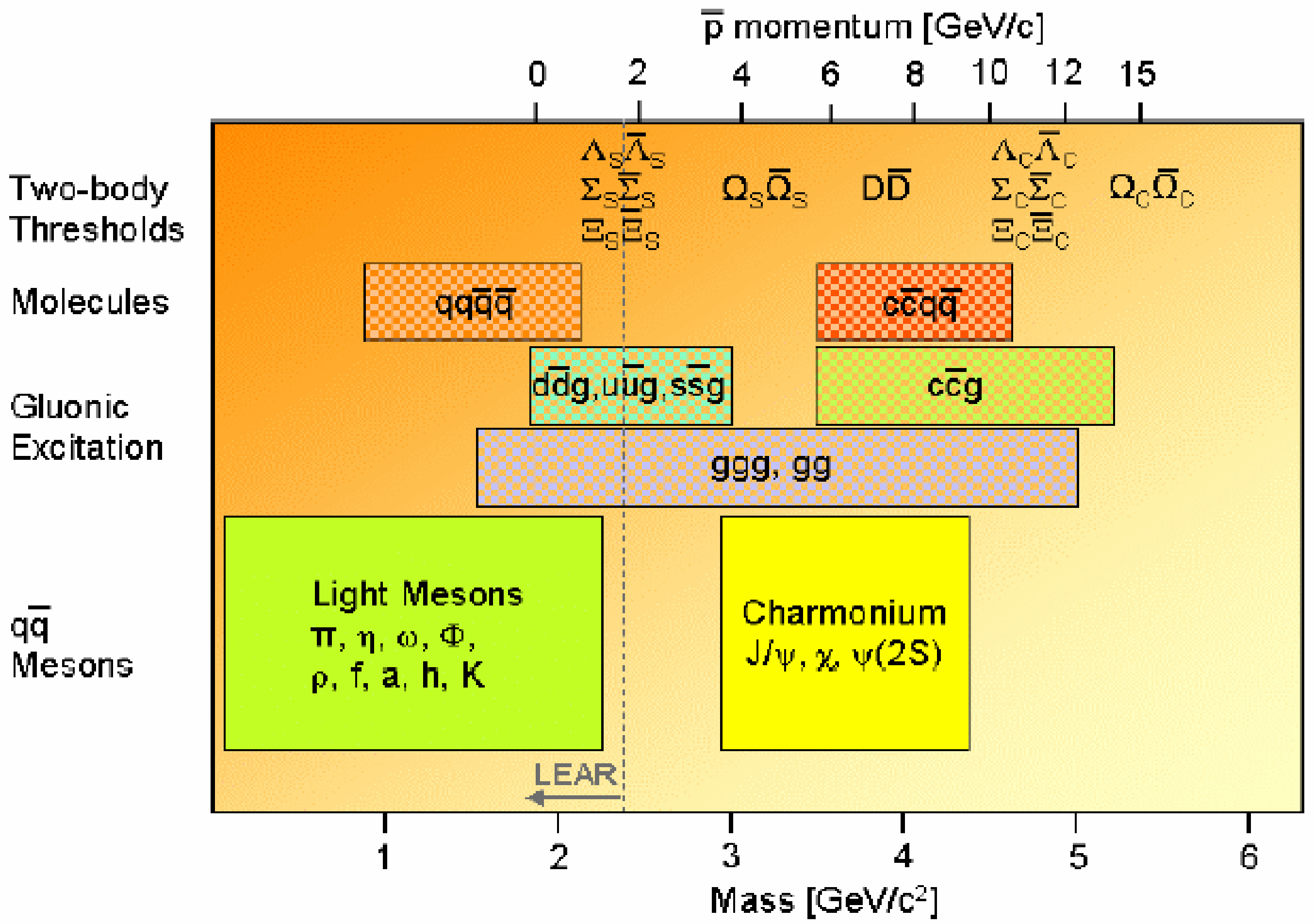
High luminosity mode

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

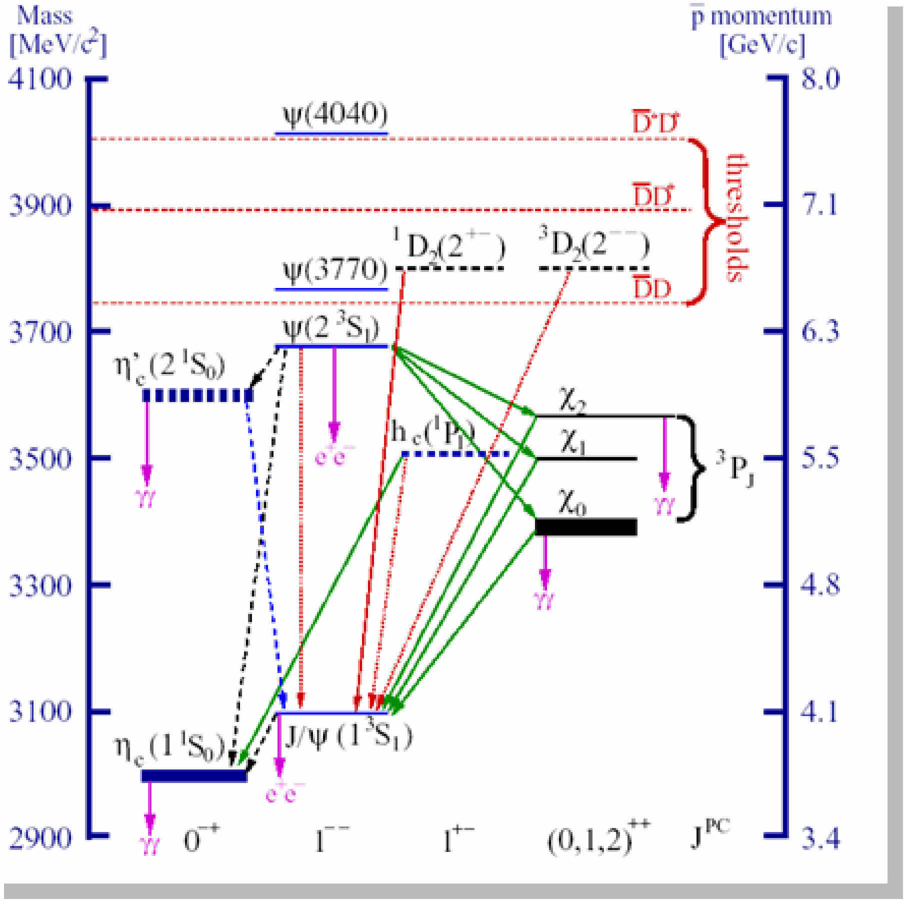
PANDA Physics Program

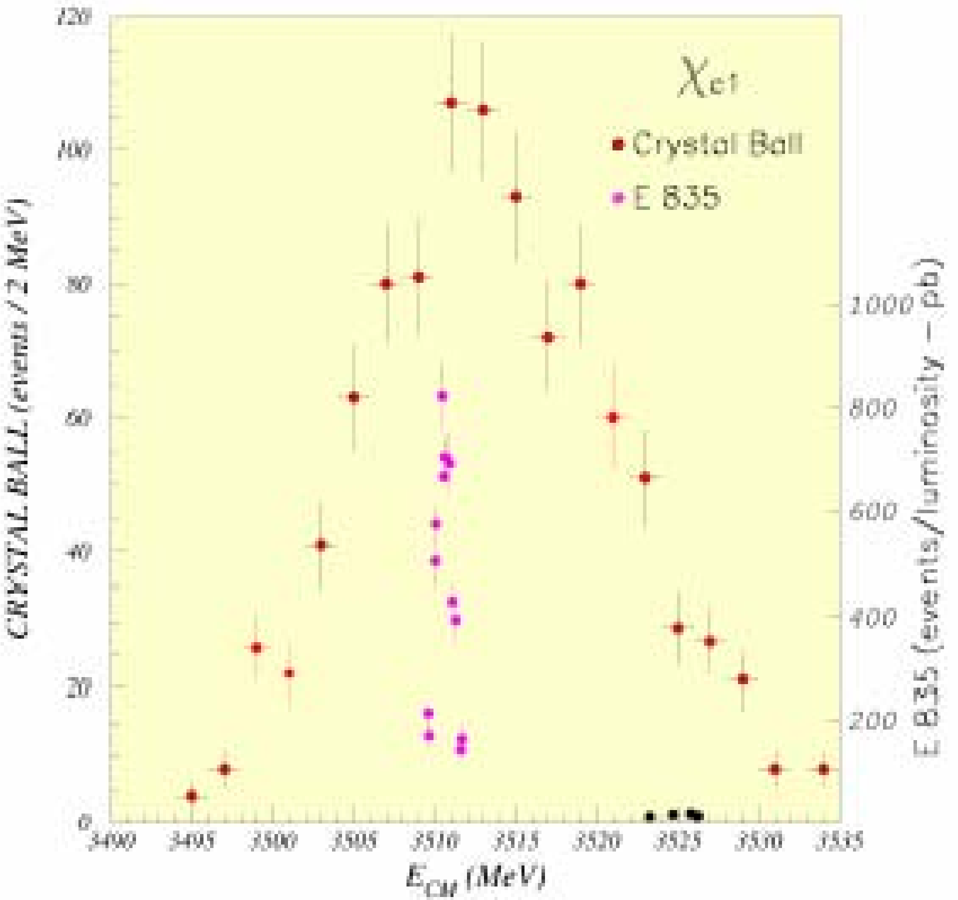
- Charmonium Spectroscopy. Precision measurement of masses, widths and branching ratios of all ($c\bar{c}$) states (hydrogen atom of QCD).
- Search for gluonic excitations (hybrids, glueballs) in the charmonium mass range (3-5 GeV/c^2).
- Search for modifications of meson properties in the nuclear medium, and their possible relation to the partial restoration of chiral symmetry for light quarks.
- Precision γ-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





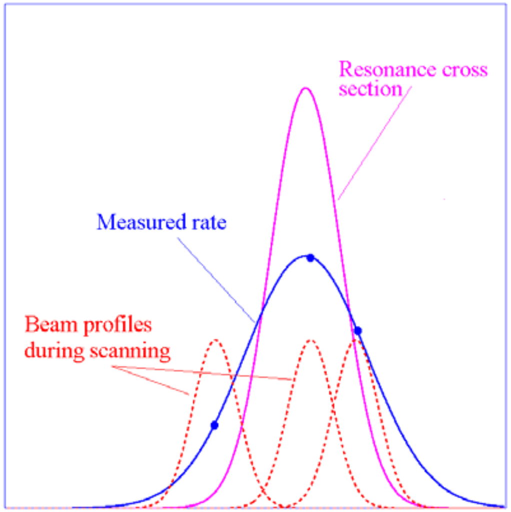
Experimental Method in $\bar{p}p$ Annihilation

The cross section for the process:

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

is given by the Breit-Wigner formula:

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

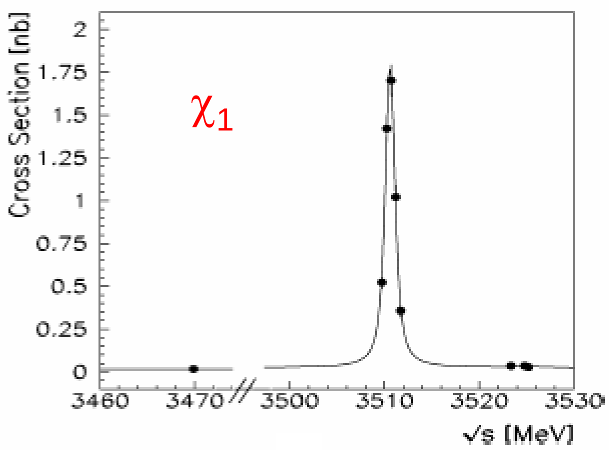


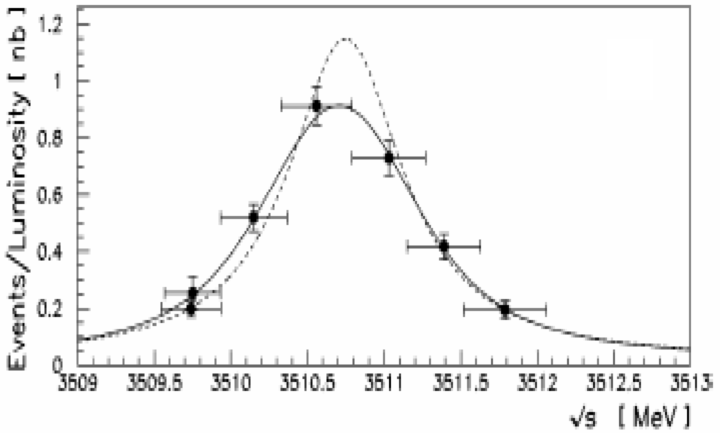
The production rate ν is a convolution of the BW cross section and the beam energy distribution function *f(E,ΔE)*:

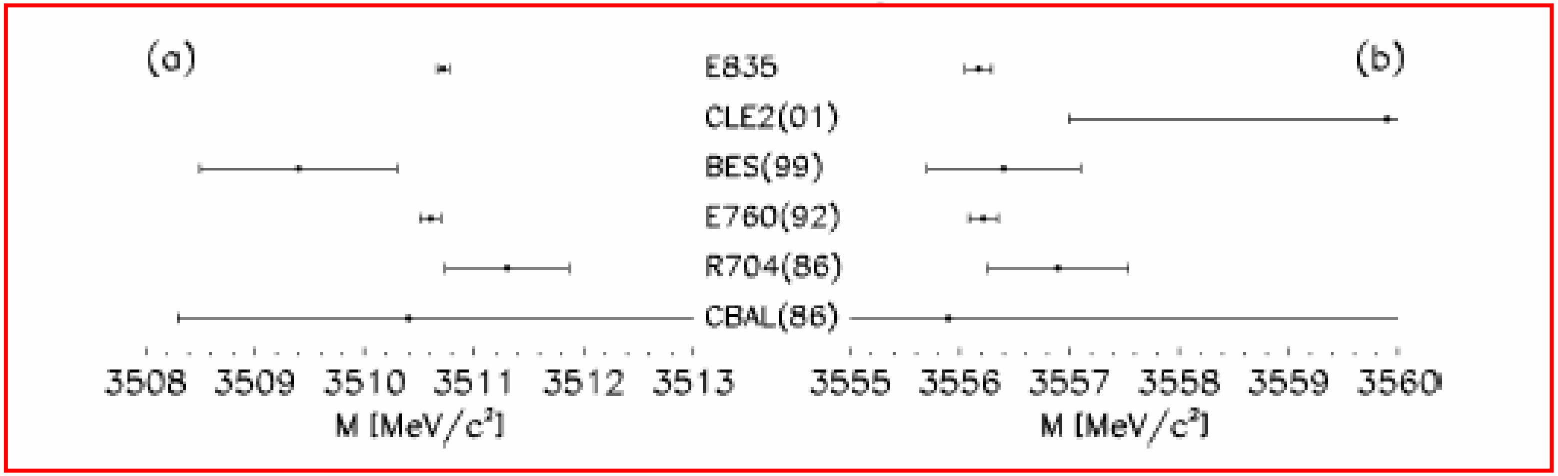
$$\nu = L_0\left\{\varepsilon\int dE f(E,\Delta E)\sigma_{BW}(E)+\sigma_b\right\}$$

The resonance mass M_R, total width Γ_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.

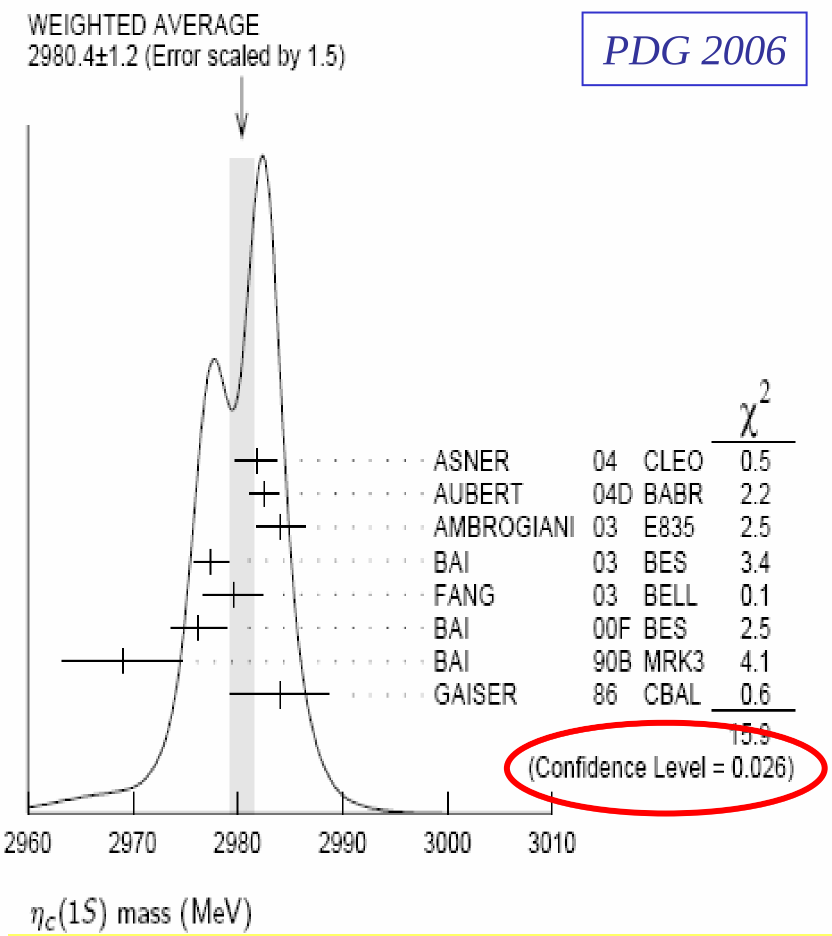
Example: χ_{c1} and χ_{c2} scans in Fermilab E835

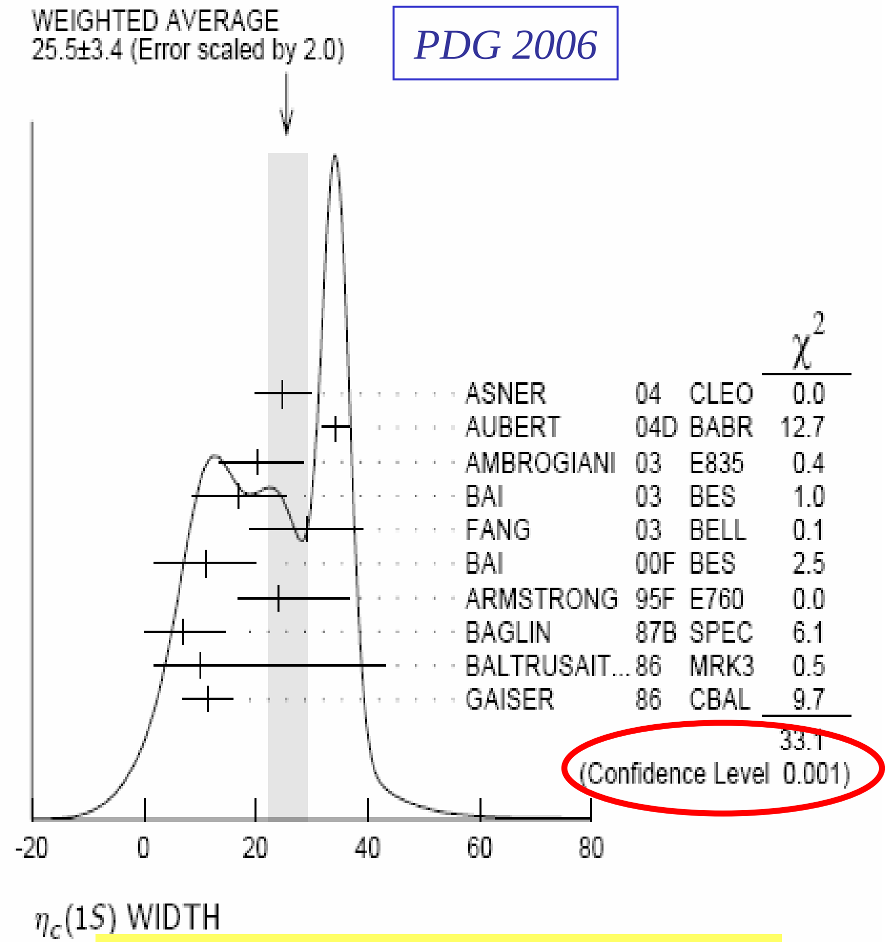






The $\eta_c(1^1S_0)$ Mass and Total Width

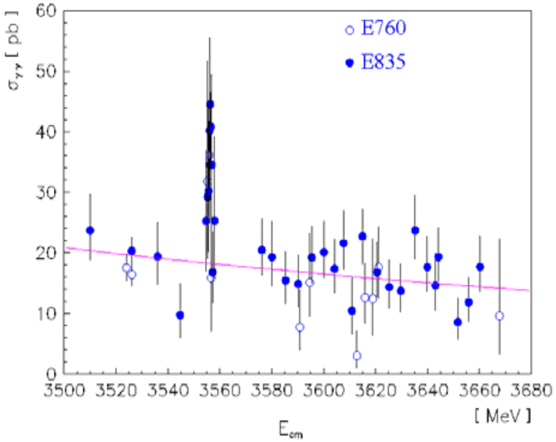


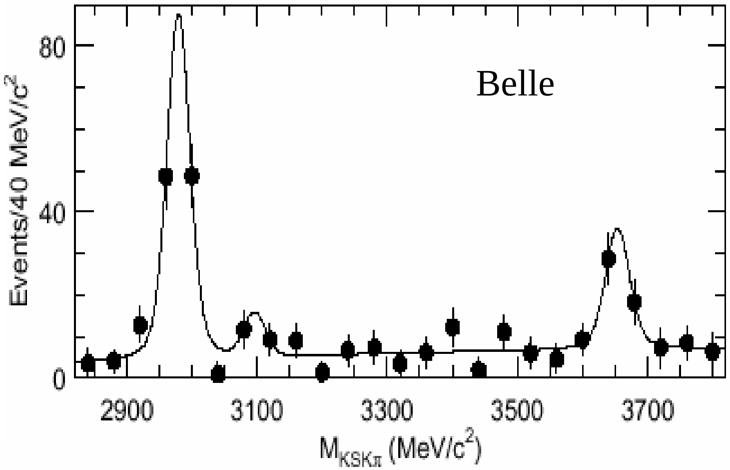


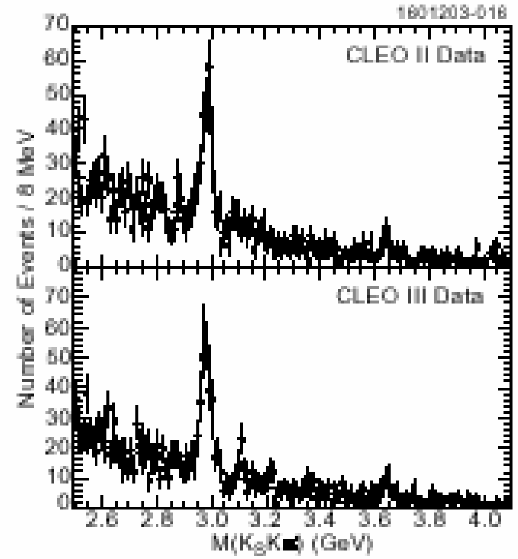
$M(\eta_c) = 2980.4 \pm 1.2$ MeV/c^2

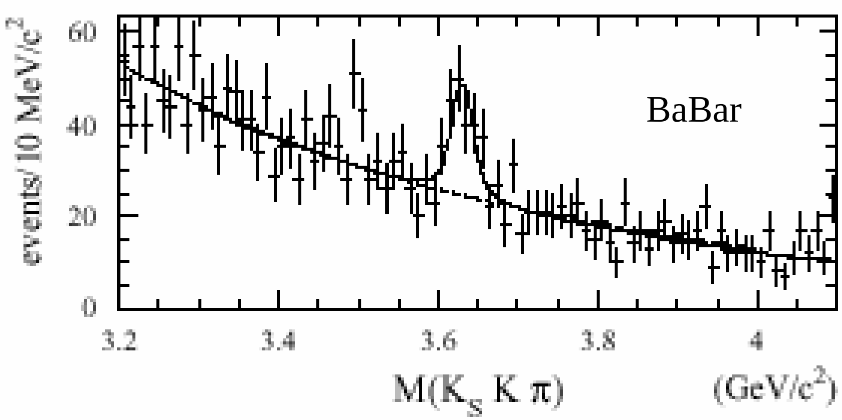
$\Gamma(\eta_c) = 25.5 \pm 3.4$ MeV

The $\eta_c(2^1S_0)$









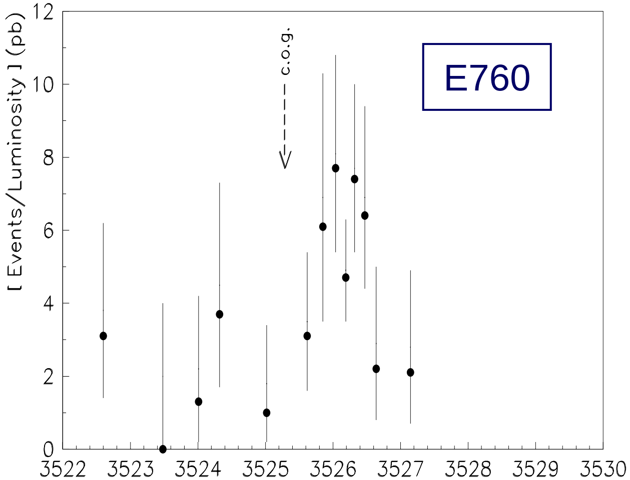
PDG 2006

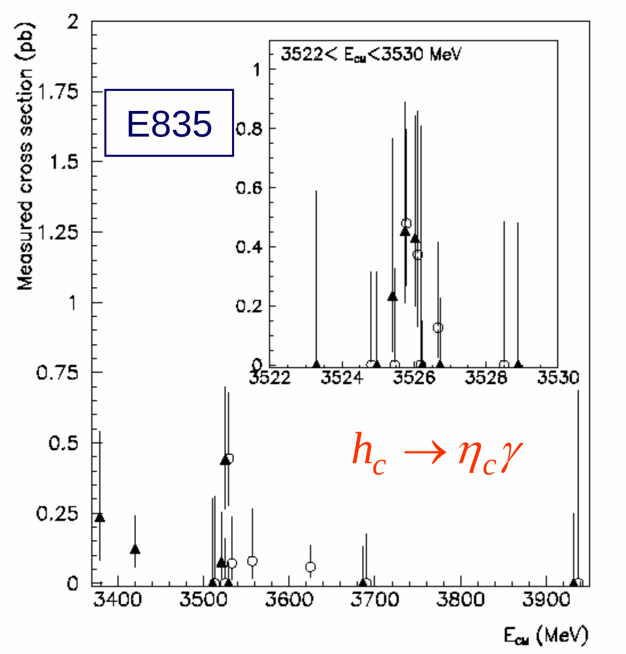
$M(\eta_c') = 3638 \pm 4$ MeV/c^2

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

The $h_c(1^1P_1)$

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

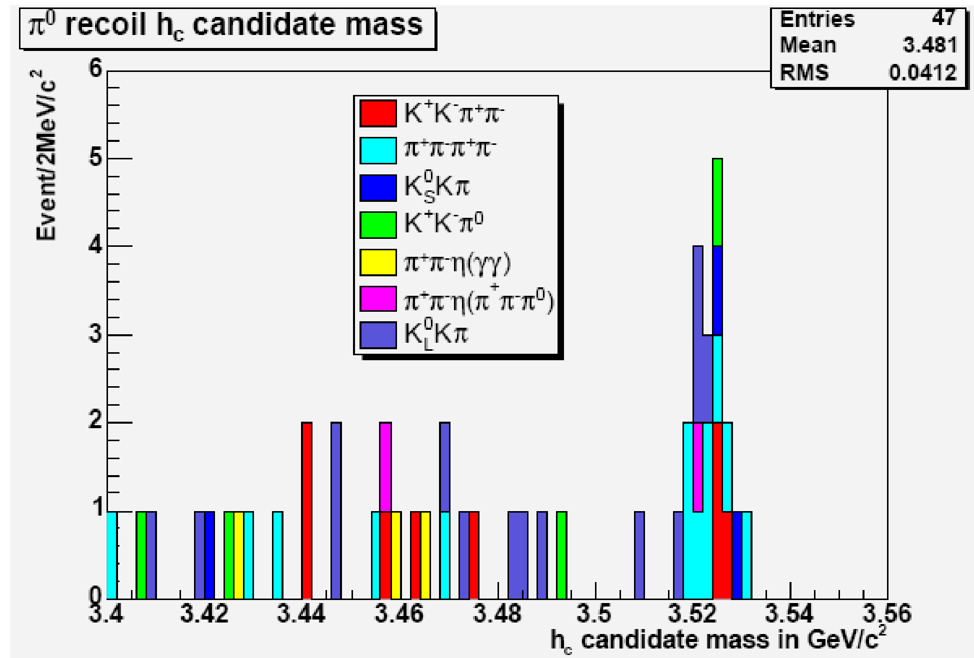




CLEO

$e^+e^- \rightarrow \psi' \rightarrow \pi^0 h_c$

$h_c \rightarrow \eta_c \gamma \quad \eta_c \rightarrow \text{hadrons}$



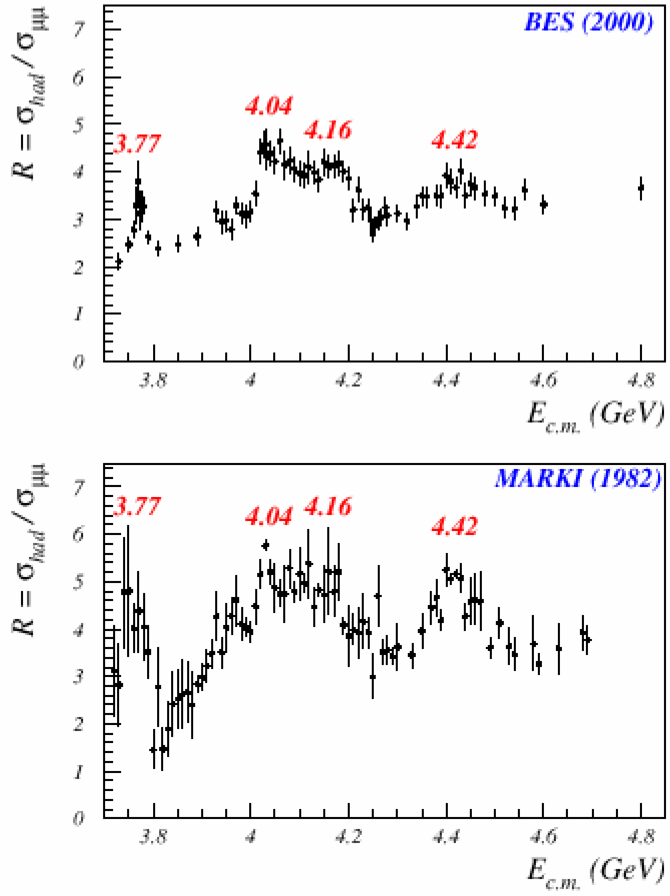
$$M(h_c) = 3524.4 \pm 0.6 \pm 0.4\ MeV/c^2$$

M(E835) = 3525.8±0.2±0.2 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:

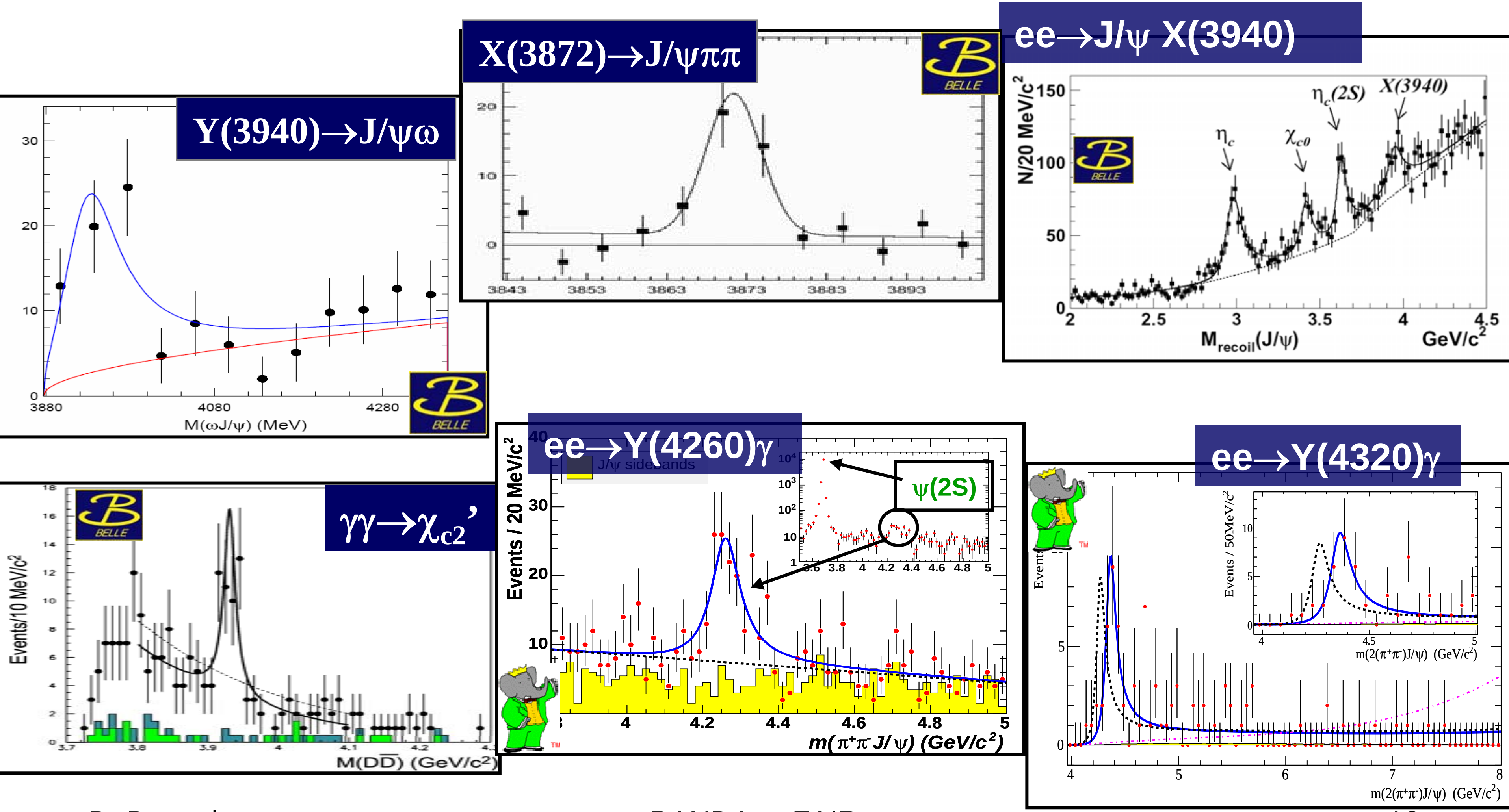
State	Predicted energy (MeV)	Experiment data (MeV)
$1\,^3S_1$	3097	3096.88 ± 0.04
$1\,^1S_0$	2987	2978.8 ± 1.9^a
$2\,^3S_1$	3686	3686.00 ± 0.09
$2\,^1S_0$	3620	3594.0 ± 5.0
$1\,^3P_2$	3554	3556.17 ± 0.13
$1\,^3P_1$	3512	3510.53 ± 0.12
$1\,^3P_0$	3412	3415.1 ± 1.0
$1\,^1P_1$	3527	3526.14 ± 0.24
$1\,^3D_3$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

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

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

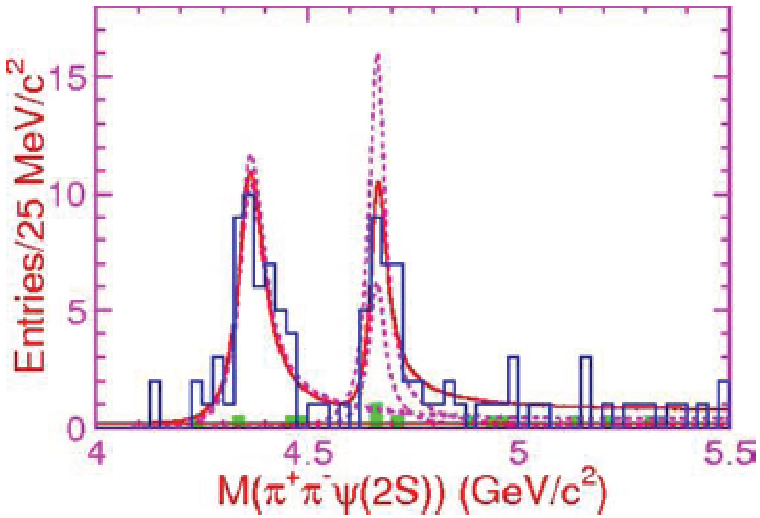
Only the $\psi(3770)$, considered to be largely $^3D_1$ state, has been clearly observed. It is a wide resonance ($\Gamma(\psi(3770)) = 25.3 \pm 2.9$ MeV) decaying predominantly to D $\overline{\text{D}}$. A recent observation by BES of the $J/\psi\pi^+\pi^-$ decay mode was not confirmed by CLEO-c.

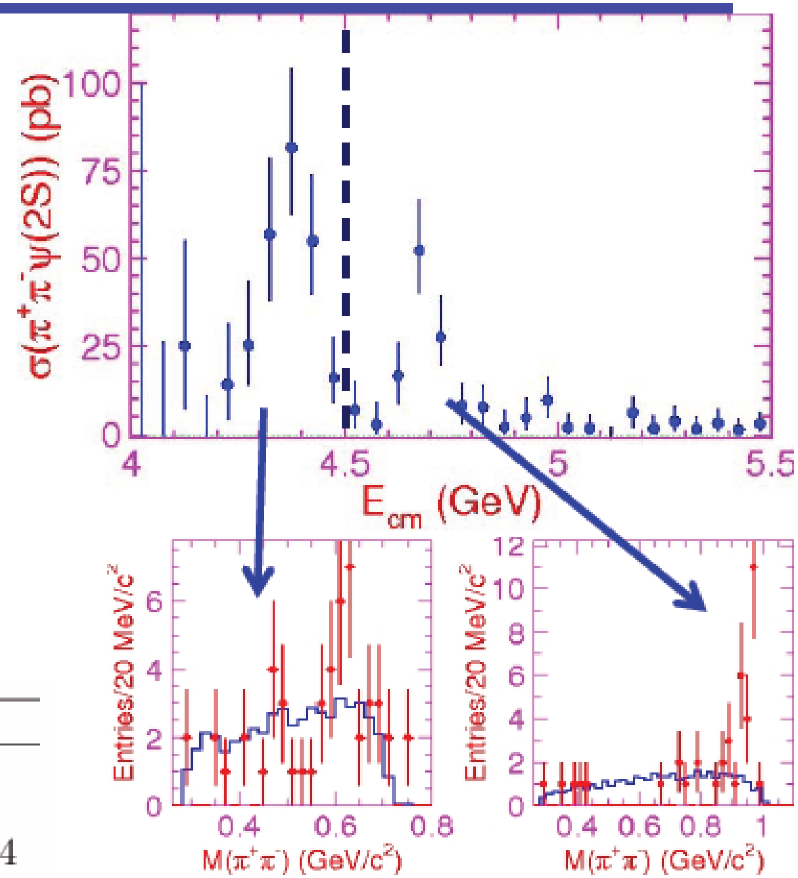
New States above D $\bar{D}$ threshold



Cross section and interpretation

- **Bg subtracted M(J/ψππ) corrected for efficiency and differential luminosity**





Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

Y(4360) – consistent with BaBar
Y(4660) – NEW (5.8σ)

EPS-HEP 2007, Manchester, July 2007

P.Pakhlov

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 η_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 η'_c has just started. Small splitting from the ψ' 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
  - the newly discovered states understood ($c\bar{c}$, exotics, multiquark, ...)
  - Confirm vector states observed in R

Charmonium at PANDA

- At $2\times10^{32}cm^{-2}s^{-1}$ accumulate 8 pb^{-1}/day (assuming 50 % overall efficiency) $\Rightarrow$ $10^4\div10^7$ ($c\bar{c}$) 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 2×10^{-4} (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).
- Fine scans to measure masses to ≈ 100 KeV, widths to ≈ 10 %.
- Explore entire region below and above open charm threshold.
- Decay channels
  - $J/\psi+X$, $J/\psi \rightarrow e^+e^-$, $J/\psi \rightarrow \mu^+\mu^-$
  - $\gamma\gamma$
  - hadrons
  - $D\bar{D}$

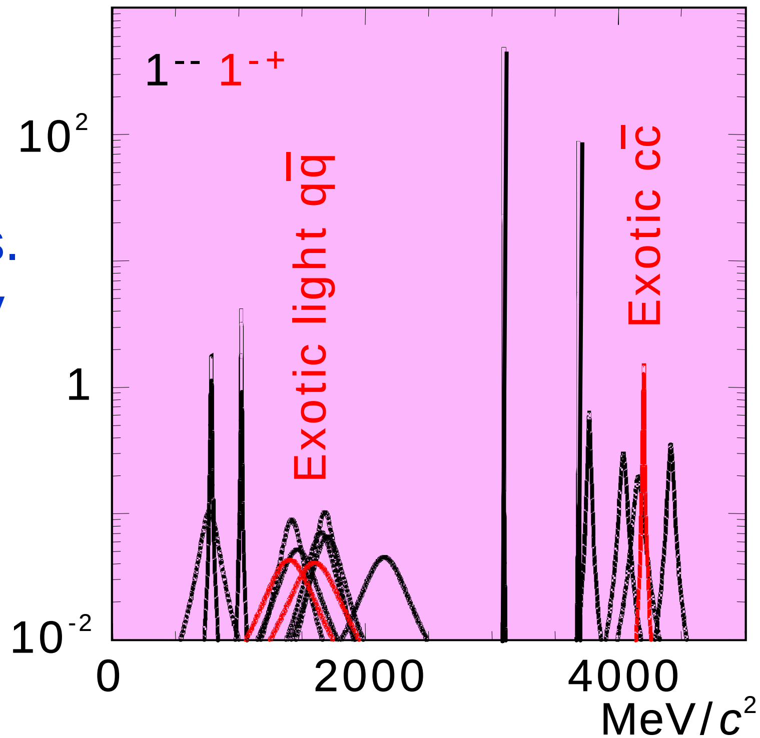
Hybrids and Glueballs

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.
- π_1(1400) and π_1(1600) with $J^{PC}=1^{-+}$.
- π_1(2000) and h_2(1950)
- Narrow state at 1500 MeV/c^2 seen by Crystal Barrel best candidate for glueball ground state ($J^{PC}=0^{++}$).

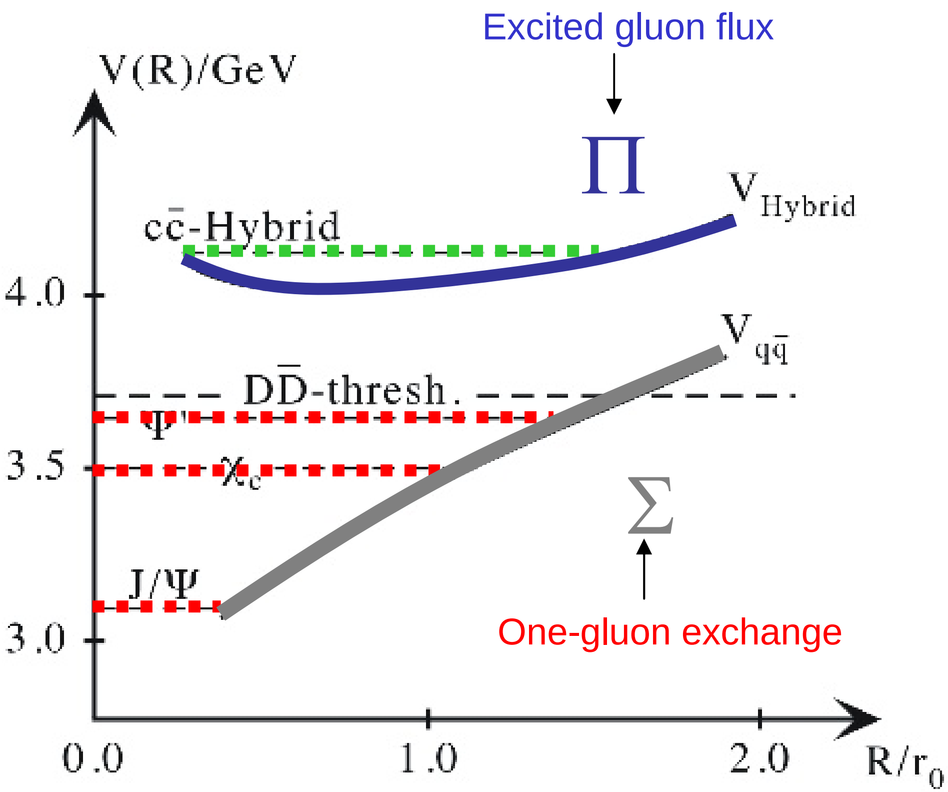


Charmonium Hybrids

- 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^{+-})

  $\Rightarrow$ 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).

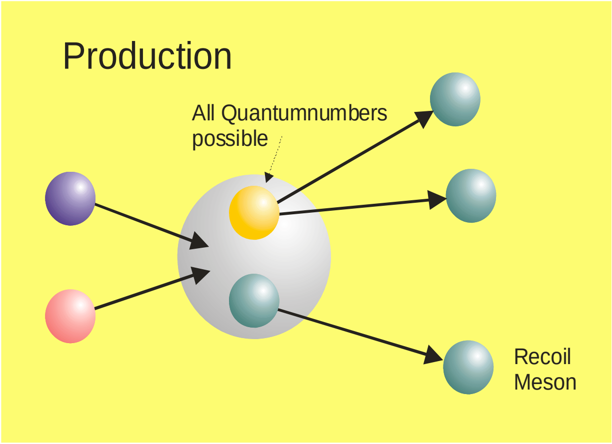


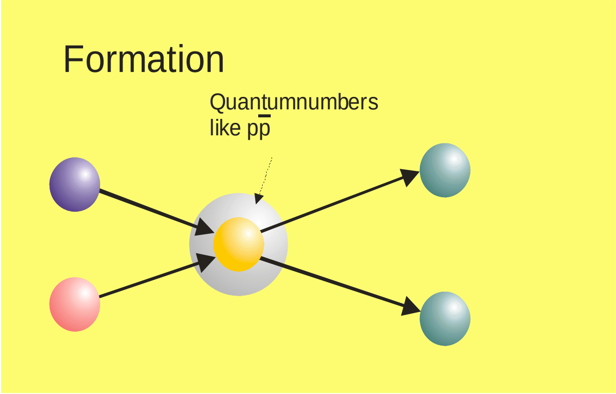
Charmonium Hybrids

- •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 $\rightarrow$ ~15 GeV





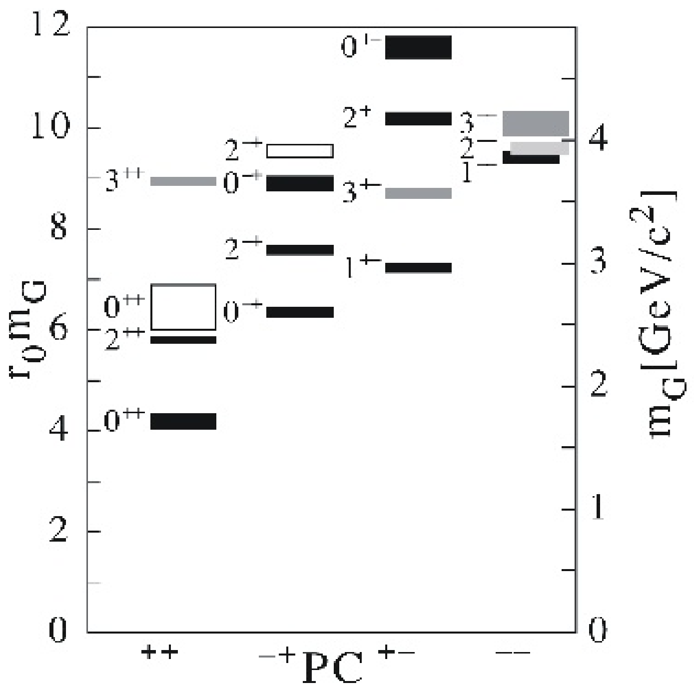
Glueballs

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 $\phi\phi$, $\phi\eta$, $J/\psi\eta$, $J/\psi\phi$ ...

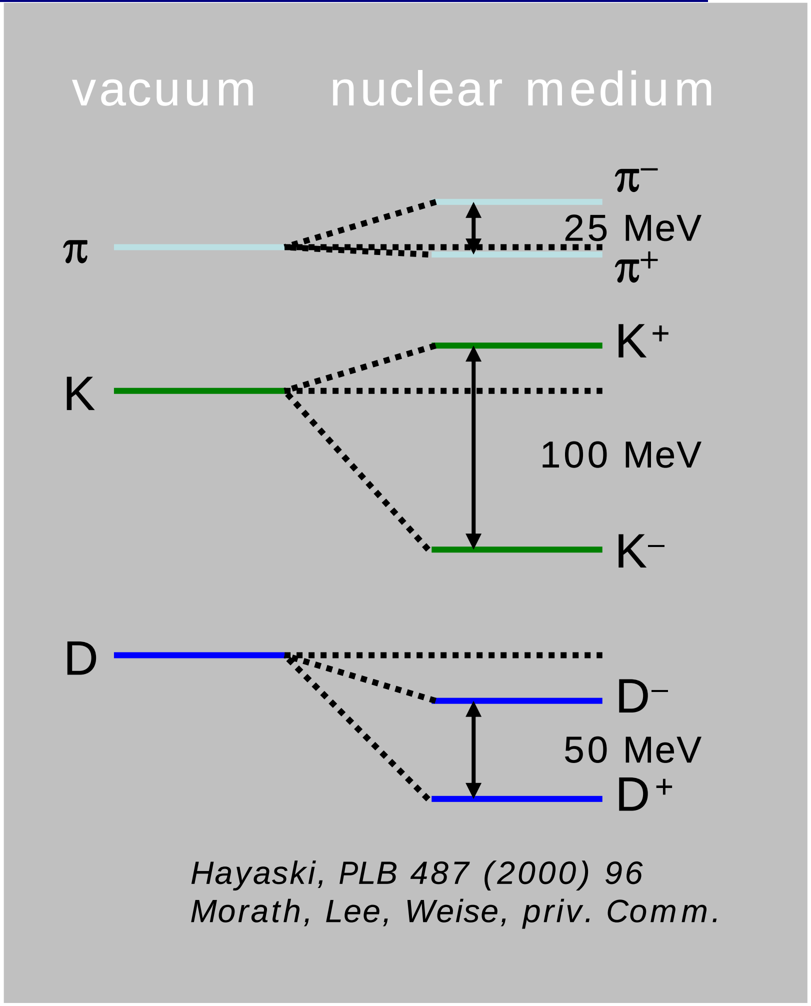


Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043

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/ψ, η_c)
  - significant mass shifts for excited states: 40, 100, 140 MeV/c^2 for χ_{cJ}, ψ', $\psi(3770)$ 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)



Charmonium in Nuclei

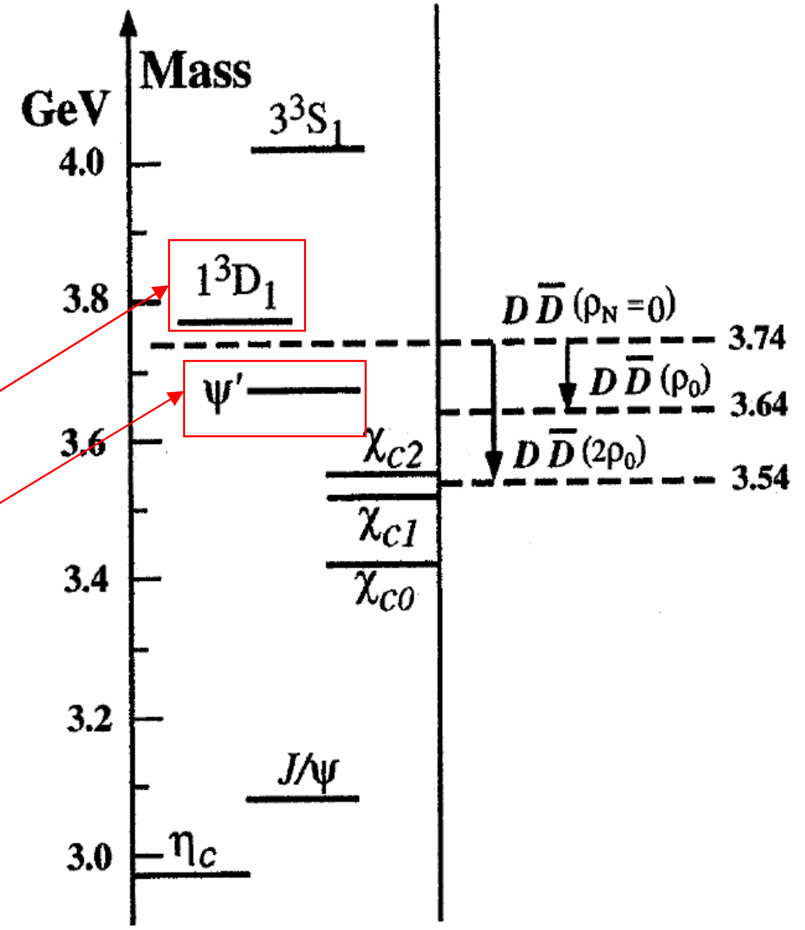
- Measure J/ψ and D production cross section in p̄ annihilation on a series of nuclear targets.
- J/ψ nucleus dissociation cross section
- Lowering of the D^+D^- mass would allow charmonium states to decay into this channel, thus resulting in a dramatic increase of width

ψ(1D) 20 MeV → 40 MeV

ψ(2S) .28 MeV → 2.7 MeV

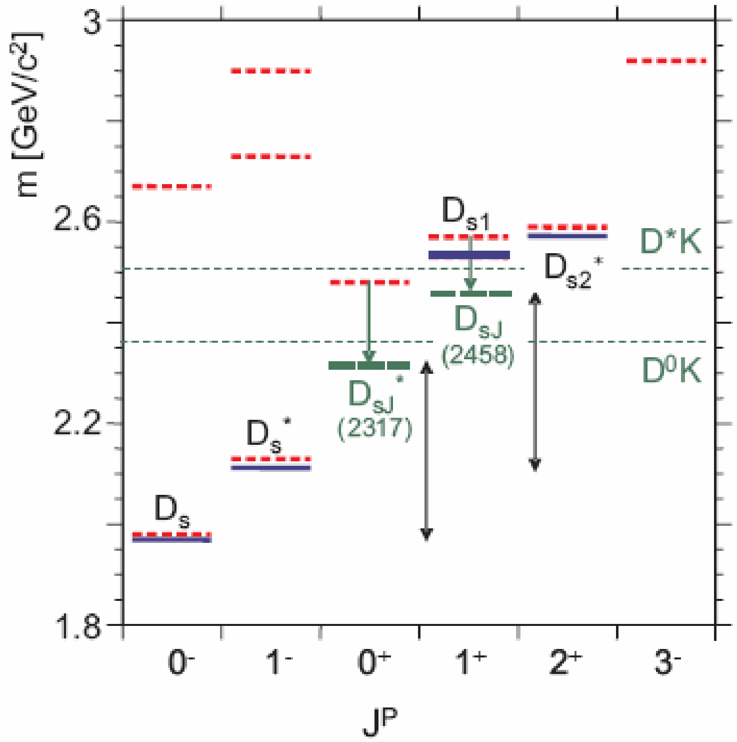
⇒Study relative changes of yield and width of the charmonium states.

- In medium mass reconstructed from dilepton (c c̄) or hadronic decays (D)



Open Charm Physics

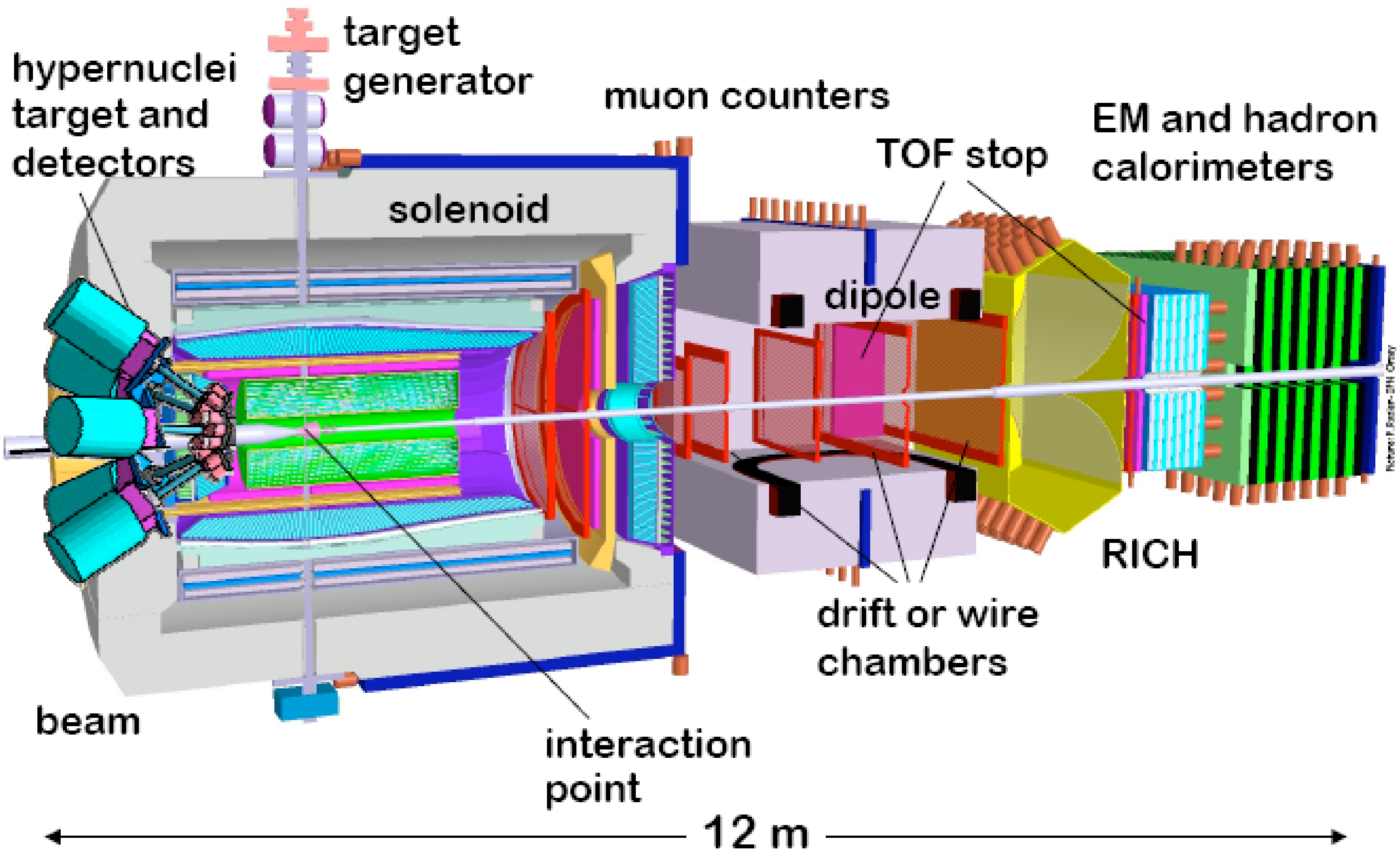
- New narrow states D_{sJ} recently discovered at B factories do not fit theoretical calculations.
- At full luminosity at $\bar{p}$ momenta larger than 6.4 GeV/c PANDA will produce large numbers of $D\bar{D}$ pairs.
- Despite small signal/background ratio (5×10^{-6}) background situation favourable because of limited phase space for additional hadrons in the same process.



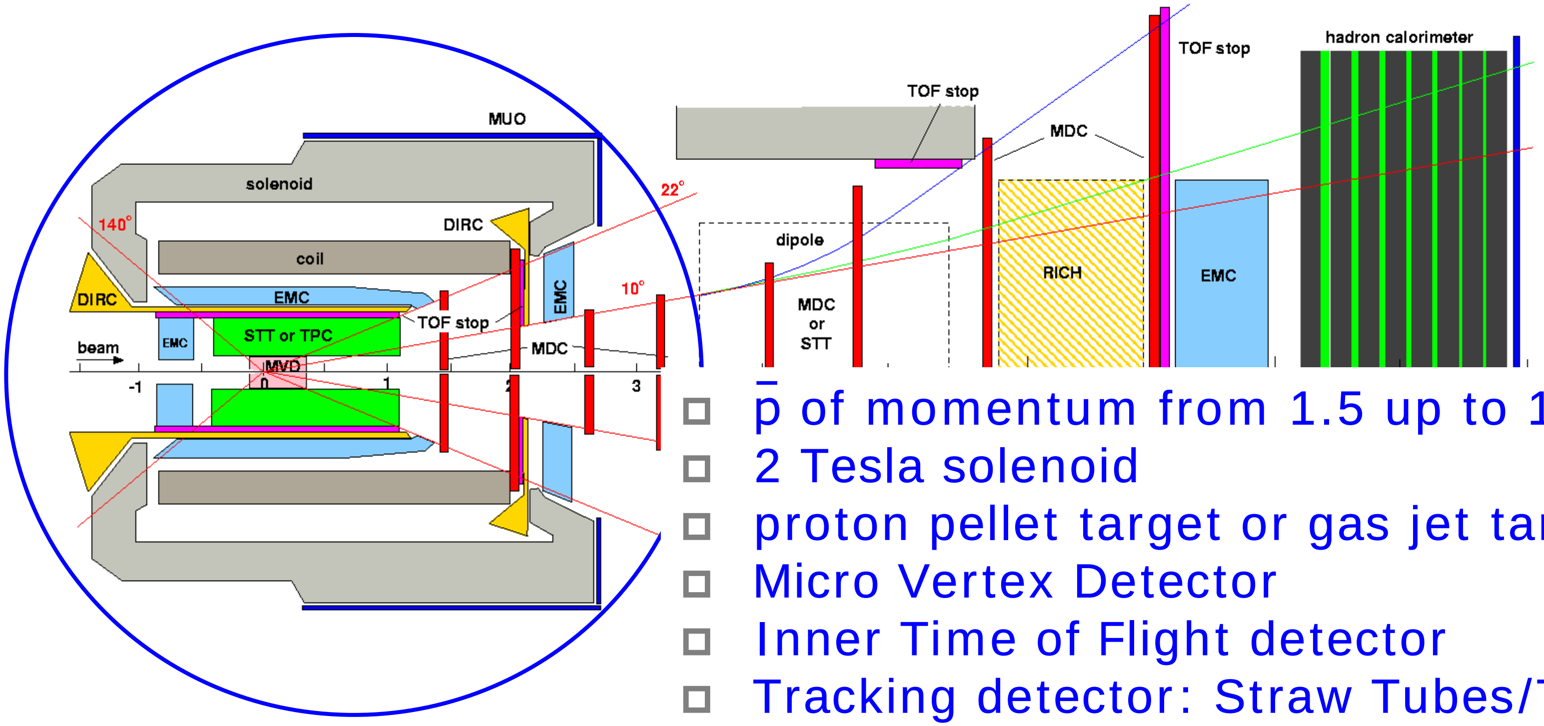
The Detector

- 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

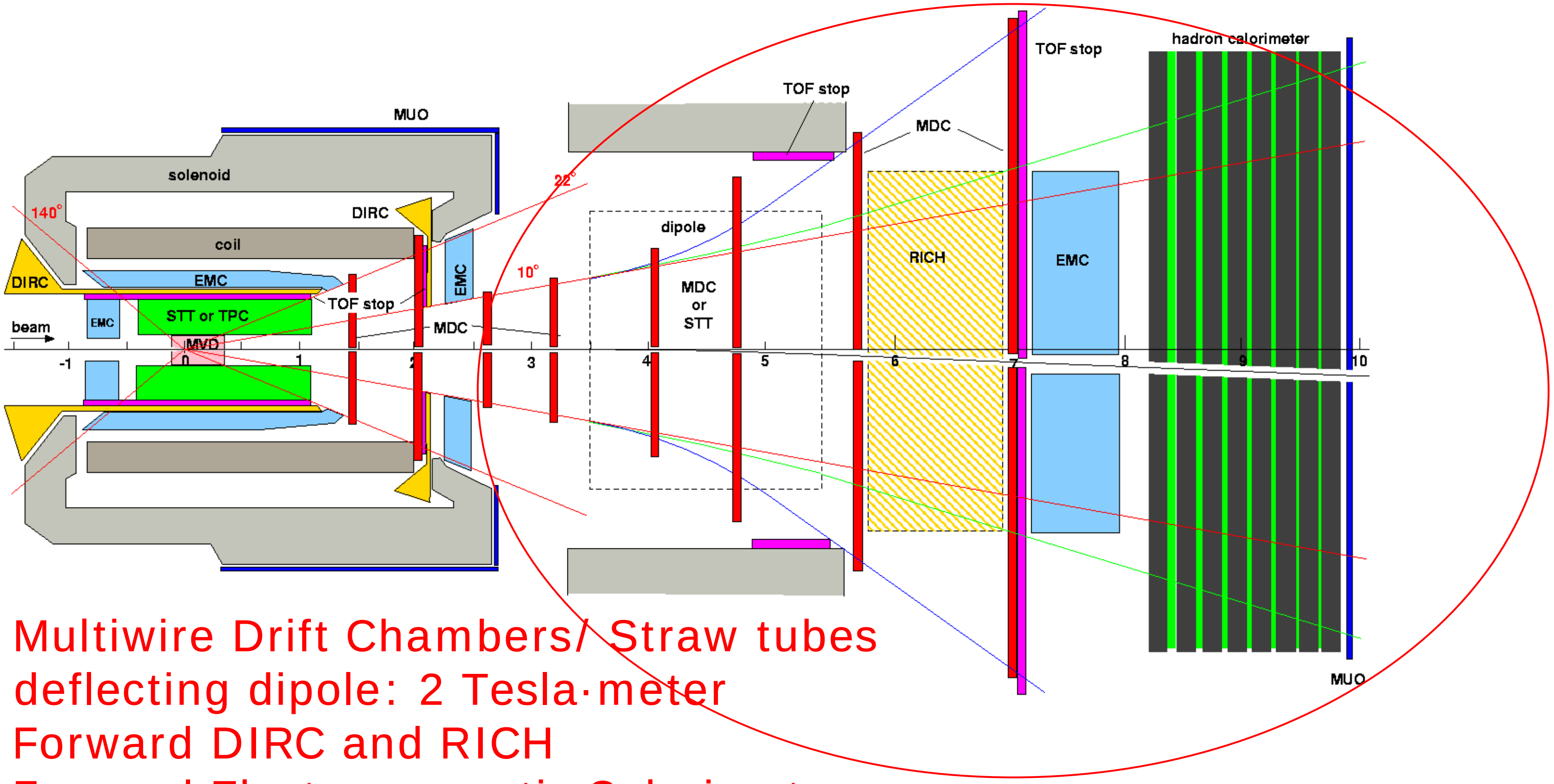


Target Spectrometer



- $\bar{p}$ 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
- Open charm physics
- *Hypernuclear physics*
- *Proton timelike form factors*
- *Deeply Virtual Compton Scattering and Drell-Yan*

Recent decision by German Minister Ms. Schavan:

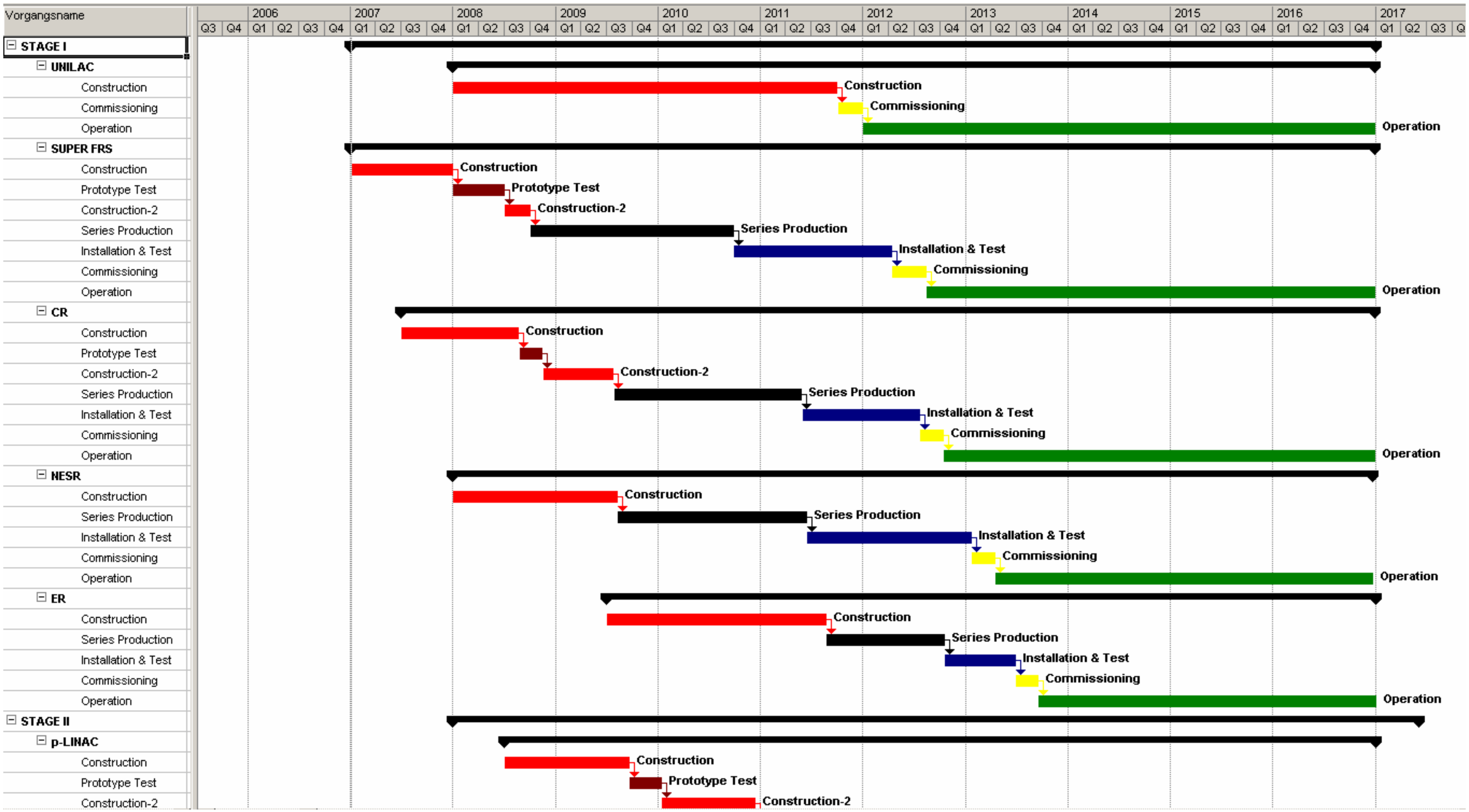
Start of the International FAIR Project

on November 7, 2007

together with all partners that have expressed their commitment on FAIR.

Backup Slides

FAIR Schedule



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:

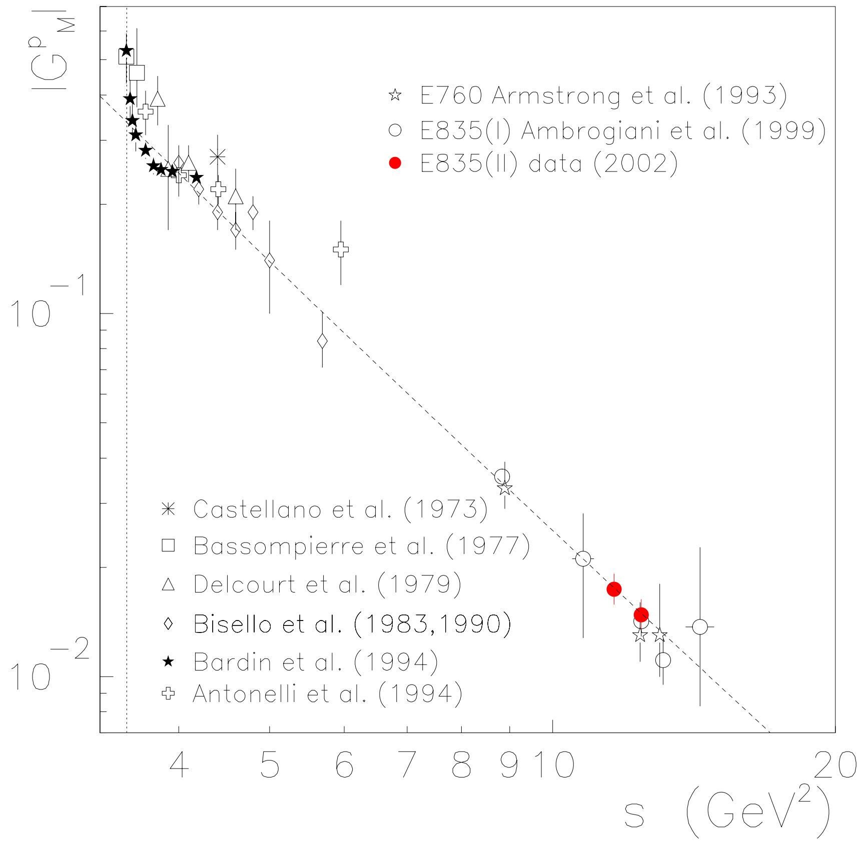
$$\bar{p}p \rightarrow e^+e^-$$

First order QED predicts:

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

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

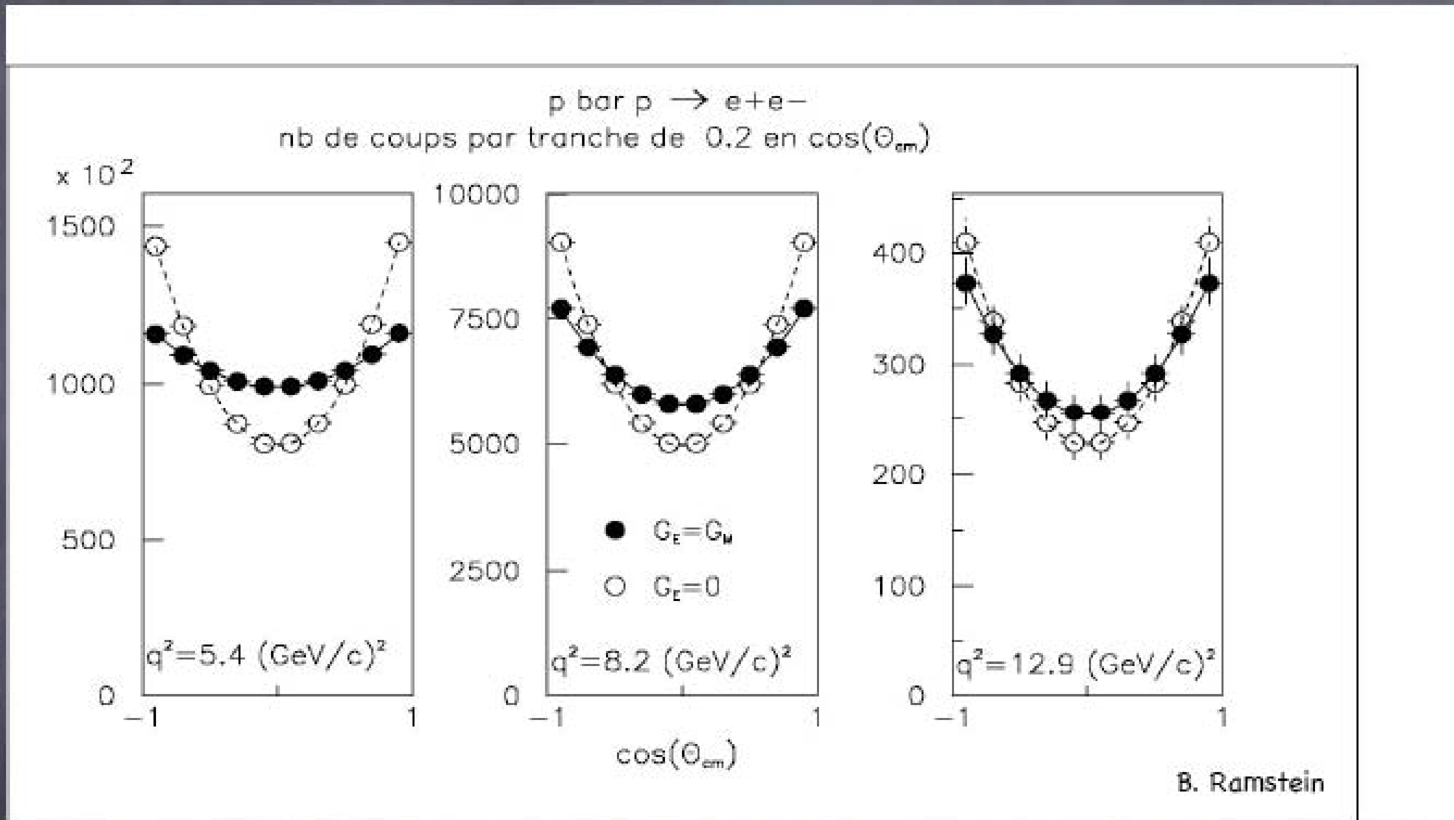


The dashed line is the PQCD fit:

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

s (GeV^2)	$10^2\times|G_M|$ (a)	$10^2\times|G_M|$ (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	$1.48^{+0.15+0.08}_{-0.13-0.05}$	$1.63^{+0.17+0.09}_{-0.14-0.05}$

Physics: Counting Rates and |G_E|/|G_M|separation



T=1 GeV | T=5GeV | T=10GeV

q^2=5.4(GeV^2/c) | q^2=12.9(GeV^2/c) | q^2=22.3(GeV^2/c)

100 days, L=2 10^{32} $cm^{-2}s^{-1}$, 2 fb^{-1}

N_{tot} = 10^6 | N_{tot} = 2750 | N_{tot} = 82

Fermilab: 14 evts at 13 $(GeV/c)^2$

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 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, $\leq$ 25-30 GeV^2, which is 2.5 larger than the maximum value measured by E835. Since the cross sections decrease ~$1/s^5$, 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.