Experimental Study of the Strong Interaction at FAIR

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Outline

• FAIR
• HESR
• PANDA Physics Program
  – Charmonium Spectroscopy
  – Hybrids and Glueballs
  – Hadrons in Nuclear Matter
  – Hypernuclear Physics
  – Timelike Proton Form Factors
• The PANDA Detector
• PAX Physics Program
  – Transversity in Polarized Deep Inelastic Scattering
  – Single Spin Asymmetries
  – Timelike Proton Form Factors
• The PAX Detector Concept
• Conclusions
The FAIR Complex

From existing GSI UNILAC & SIS18 & new proton linac

100 Tm Synchrotron
SIS100

300 Tm Stretcher Ring
SIS300

Antiproton production

Rare isotope Production & separator

Collector & Cooler Ring

Compressed Barionic Matter experiment

High Energy Storage Ring

HESR & PANDA

Accumulator Ring Deceleration

NESR

New Experimental Storage Ring

Physics at FAIR

+ Experiments:
E-I collider
Nuclear Physics
Atomic Physics
Plasma Physics
Applied Physics
**Technical Realization of FAIR**

### Accelerator Components & Key Characteristics

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

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

**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 $2 \times 10^7$/sec

• $P_{\text{beam}} = 1 - 15$ GeV/c

• $N_{\text{stored}} = 5 \times 10^{10}$ \(\bar{p}\)

• Internal Target

  High resolution mode

• $\delta p/p \sim 10^{-5}$ (electron cooling)

• Lumin. = $10^{31}$ cm$^{-2}$ s$^{-1}$

High luminosity mode

• Lumin. = $2 \times 10^{32}$ cm$^{-2}$ s$^{-1}$

• $\delta p/p \sim 10^{-4}$ (stochastic cooling)
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/c²).
- 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 is a powerful tool for the understanding of the strong interaction. The high mass of the $c$ quark ($m_c \sim 1.5$ 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.
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 $\nu$ is a convolution of the BW cross section and the beam energy distribution function $f(E, \Delta E)$:

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

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 $E$. 
Example: $\chi_{c_1}$ and $\chi_{c_2}$ scans in Fermilab E835

$\chi_1$

$\chi_2$
$\chi_{c1}$ and $\chi_{c2}$ masses and widths

|          | $\chi_{c1}$ | E835                | E760                |
|----------|-------------|----------------------|----------------------|
| M(MeV/c²)|             | $3510.719 \pm 0.051 \pm 0.019$ | $3510.60 \pm 0.09 \pm 0.02$ |
| $\Gamma$(MeV) | $0.876 \pm 0.045 \pm 0.026$ | $0.87 \pm 0.11 \pm 0.08$ |
| $B(p \rightarrow p)\Gamma(J/\psi\gamma)$(eV) | $21.5 \pm 0.5 \pm 0.6 \pm 0.6$ | $21.4 \pm 1.5 \pm 2.2$ |

|          | $\chi_{c2}$ | E835                | E760                |
|----------|-------------|----------------------|----------------------|
| M(MeV/c²)|             | $3556.173 \pm 0.123 \pm 0.020$ | $3556.22 \pm 0.13 \pm 0.02$ |
| $\Gamma$(MeV) | $1.915 \pm 0.188 \pm 0.013$ | $1.96 \pm 0.17 \pm 0.07$ |
| $B(p \rightarrow p)\Gamma(J/\psi\gamma)$(eV) | $27.0 \pm 1.5 \pm 0.8 \pm 0.7$ | $27.7 \pm 1.5 \pm 2.0$ |
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                 |

$M(\eta_c) = 2980.4 \pm 1.2$ MeV/c²

PDG 2006
The $\eta_c(1^1S_0)$ Total Width

| Experiment | Width (MeV) |
|------------|-------------|
| CLEO       | $24.8 \pm 3.4 \pm 3.5$ |
| BaBar      | $34.3 \pm 2.3 \pm 0.9$ |
| E835       | $20.4^{+7.7}_{-6.7} \pm 2.0$ |
| BES        | $17.0 \pm 3.7 \pm 7.4$ |
| Belle      | $29 \pm 8 \pm 6$ |
| BES        | $11.0 \pm 8.1 \pm 4.1$ |
| E760       | $23.9^{+12.6}_{-7.1}$ |
| R704       | $7.0^{+7.5}_{-7.0}$ |
| Mark III   | $10.1^{+33.0}_{-8.2}$ |
| Crystal Ball | $11.5 \pm 4.5$ |

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

PDG 2006
The $\eta_c(2^1S_0)$

PDG 2006

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

$\Gamma(\eta_c') = 14 \pm 7 \text{ MeV}$
The $h_c(1^1P_1)$

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

CLEO

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

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

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

$M(E835) = 3525.8 \pm 0.2 \pm 0.2 \text{ MeV} / c^2$

Physics at FAIR
Charmonium States above the D ¯D threshold

The energy region above the D ¯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 ($\psi(3S)$, $\psi(4S)$, $\psi(5S)$ ...) 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:

\[ ^1,^3D_2 \not\to \bar{D}D \quad \text{forbidden by parity conservation} \]

\[ ^1,^3D_2 \not\to \bar{D}D^* \quad \text{forbidden by energy conservation} \]

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 $D \bar{D}$. A recent observation by BES of the $J/\psi \pi^+\pi^-$ decay mode was not confirmed by CLEO-c.
New States above D̅D threshold

\[ \text{ee} \rightarrow J/\psi X(3940) \]

\[ \text{ee} \rightarrow Y(4260)\gamma \]

\[ \text{ee} \rightarrow Y(4320)\gamma \]

\[ \gamma \gamma \rightarrow \chi_{c2}' \]

\[ \text{X}(3872) \rightarrow J/\psi \pi \pi \]

\[ \text{Y}(3940) \rightarrow J/\psi \omega \]
Cross section and interpretation

- Bg subtracted $M(J/\psi \pi \pi)$ corrected for efficiency and differential luminosity

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

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

EPS-HEP 2007, Manchester, July 2007

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Physics at FAIR
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 measurements 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
  - the newly discovered states understood ($c\bar{c}$, exotics, multiquark, ...)
  - Confirm vector states observed in R
Charmonium at PANDA

- At $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ accumulate 8 pb$^{-1}$/day (assuming 50 % overall efficiency) $\Rightarrow 10^4 \div 10^7$ (c $\bar{c}$) states/day.

- Total integrated luminosity 1.5 fb$^{-1}$/year (at $2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$, 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 $2 \times 10^{-4}$ (FNAL)
  - Better detector (higher angular coverage, magnetic field, ability to detect hadronic decay modes).

- Fine scans to measure masses to $\approx 100$ KeV, widths to $\approx 10$ %.
- 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.
- $\pi_1(1400)$ 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 ($J^{PC}=0^{++}$).
\( \pi_1(1400) \) – Proof of Exotic Wave (CB)

Positive \( \chi^2 \) (Fit - Data)

No \( \pi_1 \) in Fit

Negative \( \chi^2 \) (Fit - Data)

\( \rho \)

\( a_2 \)

\( m^2(\eta\pi^0) \) [GeV\(^2/c^4\)]

\( m^2(\eta\pi^-) \) [GeV\(^2/c^4\)]

Crystal Barrel

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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 ($\sim 100 – 150$ pb).
Charmonium Hybrids

• Gluon rich process creates gluonic excitation in a direct way
  – $c\bar{c}$bar 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
  – $p \rightarrow \sim 15$ GeV
Glueballs

Detailed predictions of mass spectrum from quenched LQCD.

- Width of ground state $\sim$ 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 $\phi\phi$, $\phi\eta$, $J/\psi\eta$, $J/\psi\phi$ ...

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.

Morningstar und Peardon, PRD60 (1999) 034509
Morningstar und Peardon, PRD56 (1997) 4043
The $f_0(1500)$

Observed in $\bar{p}p$ annihilations by Crystal Barrel ($\pi^0\eta\eta$, $\pi^0\pi^0\eta$ and $3\pi^0$) and Obelix ($\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $KK^0_S\pi$).

$f_0(1450)$ and $a_0(1370)$ also observed in same channels.

Mixing between conventional scalar mesons ($0^{++}$) and glueball state.

Evidence for tensor glueball at 2 GeV contradictory.

$$m_G = 1440 \pm 16 \text{ MeV} / c^2$$
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 $J/\psi$ and D production cross section in $p$ annihilation on a series of nuclear targets.
- $J/\psi$ 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
  \[ \psi(1D) \quad 20 \text{ MeV} \rightarrow 40 \text{ MeV} \]
  \[ \psi(2S) \quad .28 \text{ MeV} \rightarrow 2.7 \text{ MeV} \]
⇒ 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 $\Lambda$-hypernuclei have been studied since 50 years allowing to test and define shell model parameters and $\Lambda N$ interaction. $\Lambda\Lambda$-hypernuclei, $\Xi$-atoms $\Omega$-atoms are described by more complicated approaches, but allows to have an insight to more complex nuclear systems containing strangeness (hyperon-star, strange-quark star,...)

Experimental situation: $\sim 35 \ \Lambda$-hypernuclei established since 50 years ago. Only 6 $\Lambda\Lambda$-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 $^{10}_\Lambda\Lambda Be$

H. Takahashi et al., PRL 87, 212502-1 (2001)
Production of Double Hypernuclei

1. Hyperon-antihyperon production at threshold

\[ \bar{p} \rightarrow \Xi^- \] 

2. Slowing down and capture of \( \Xi^- \) in secondary target nucleus

\[ \Xi^- \text{(dss)} p(uud) \rightarrow \Lambda(uds) \Lambda(uds) + 28 \text{ MeV} \]

3. \( \gamma \)-spectroscopy with Ge-detectors
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:

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

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:

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

| s (GeV^2) | 10^2×|G_M| \ (a) | 10^2× |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

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

$nb$ de coups par tranche de 0.2 en $\cos(\theta_{em})$

$q^2 = 5.4 \text{ (GeV}/c)^2$
$q^2 = 8.2 \text{ (GeV}/c)^2$
$q^2 = 12.9 \text{ (GeV}/c)^2$

$T=1 \text{ GeV}$
$q^2=5.4(\text{GeV}^2/c)$
100 days, $L=2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, 2 fb$^{-1}$
$N_{\text{tot}} = 10^6$

$T=5 \text{ GeV}$
$q^2=12.9(\text{GeV}^2/c)$

$T=10 \text{ GeV}$
$q^2=22.3(\text{GeV}^2/c)$
$N_{\text{tot}} = 2750$

B. Ramstein

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

$N_{\text{tot}} = 82$
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 $q^2=30 \text{ GeV}^2$, 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, $\leq 25-30 \text{ GeV}^2$, 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 $\sim 82$ 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.
Crossed-Channel Compton Scattering

Wide angle Compton scattering
factorisation into hard amplitude
(calculable in perturbative QCD)
and soft amplitude
(information on parton distributions)

Reversed Deeply Virtual
Compton Scattering

\[ \bar{p}p \to \gamma\gamma \]

clear experimental signature
both baryons in ground state

\[ \sigma \approx 2.5\text{pb} @ s \approx 10 \text{ GeV}^2 \]

\[ L = 2 \cdot 10^{32} \text{ cm}^{-2} \text{s}^{-1} \to 10^3 \text{ events per month} \]
The Detector

- **Detector Requirements:**
  - (Nearly) $4\pi$ solid angle coverage (partial wave analysis)
  - High-rate capability ($2 \times 10^7$ annihilations/s)
  - Good PID ($\gamma$, e, $\mu$, $\pi$, K, p)
  - Momentum resolution ($\approx 1\%$)
  - Vertex reconstruction for D, $K^0_s$, $\Lambda$
  - Efficient trigger
  - Modular design

- **For Charmonium:**
  - Pointlike interaction region
  - Lepton identification
  - Excellent calorimetry
    - Energy resolution
    - Sensitivity to low-energy photons
Target Spectrometer

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

Nucleon structure: polarized reactions

Proton EFFs

Fixed target experiment ($\sqrt{s}<2$ GeV):
- pol./unpol. pbar beam ($p<4$ GeV/c)
- internal H polarized target

Asymmetric collider ($\sqrt{s}=15$ GeV):
- polarized antiprotons in HESR ($p=15$ GeV/c)
- polarized protons in CSR ($p=3.5$ GeV/c)

PAX Detector

Parton distribution: transversity

Drel-I-Yan

SSA

Charmonium

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

$\bar{p}p^+\rightarrow DX, l^+l^-X$

$p^+\bar{p}^+\rightarrow J/\psi X$
Nucleon Structure and Transverse Spin Effects

\[ f_1^q = \quad \begin{array}{c} \text{unpolarised quarks} \\ \text{and nucleons} \end{array} \quad g_1^q = \quad \begin{array}{c} \text{longitudinally polarised} \\ \text{quarks and nucleons} \end{array} \quad h_1^q = \quad \begin{array}{c} \text{transversely polarised} \\ \text{quarks and nucleons} \end{array} \]

\[ h_1(x): \text{helicity flip} \quad \begin{array}{c} \text{chiral-odd} \\ \rightarrow \text{needs a chiral odd partner} \end{array} \]

Inclusive DIS \quad Semi-inclusive DIS \quad Drell-Yan

\[ h_1 \times H_1^1 \quad h_1 \times h_1 \]
Drell-Yan

\[ q\bar{q} \rightarrow \gamma^* \rightarrow l^+l^- \]

\[
\frac{d^2\sigma}{dM^2dx_F} = \frac{4\pi\alpha^2}{9M^2s} \frac{1}{x_1 + x_2} \sum_q e_q^2[q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)]
\]

\[
x_F = x_1 - x_2 \quad x_1x_2 = M^2 / s \equiv \tau \quad x_F = 2Q_L / \sqrt{s}
\]

\( q = u, \bar{u}, d, \bar{d}, \ldots \)

M invariant Mass of lepton pair

\( M^2 > 4 \text{ GeV}^2 \)
\[ A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \sum_q e_q^2 [h_{1q}(x_1)h_{1q}(x_2) + h_{1\bar{q}}(x_1)h_{1\bar{q}}(x_2)] \\
\sum_q e_q^2 [q(x_1)q(x_2) + \bar{q}(x_1)\bar{q}(x_2)] \]

- u-dominance
- \( |h_{1u}| > |h_{1d}| \)

\[ A_{TT} \approx \hat{a}_{TT} \frac{h_{1u}(x_1)h_{1u}(x_2)}{u(x_1)u(x_2)} \]

PAX: \( M^2/s = x_1x_2 \sim 0.02 - 0.3 \)
valence quarks
\( (A_{TT} \text{ large } \sim 0.2 - 0.3) \)

1 year run: 10% precision on the \( h_{1u}(x) \) in the valence region

Anselmino et al.
PLB 594, 97 (2004)

Similar predictions by Efremov et al.,
Eur. Phys. J. C35, 207 (2004)
**h$_1$ from pp Drell-Yan**

$$A_{TT} = \hat{a}_{TT} \frac{\sum_q e_q^2 [h_{1q}(x_1)h_{1\bar{q}}(x_2) + h_{1\bar{q}}(x_1)h_{1q}(x_2)]}{\sum_q e_q^2 [q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2)]} \approx \hat{a}_{TT} \frac{h_{1u}(x_1)h_{1\bar{u}}(x_2)}{u(x_1)\bar{u}(x_2)}$$

$h_{1\bar{q}}(x, Q^2) \neq h_{1q}(x, Q^2)$

$h_{1q}(x, Q^2)$ small and with much slower evolution than $\Delta q(x, Q^2)$ and $q(x, Q^2)$ at small $x$

- **RHIC**: $M^2/s = x_1 x_2 \sim 10^{-3} \rightarrow$ sea quarks ($A_{TT} \sim 0.01$)
- **JPARC/U70**: $M^2/s = x_1 x_2 \sim 10^{-1} - 10^{-2} \rightarrow$ valence and sea ($A_{TT} \sim 0.1$)
- **PAX**: $M^2/s = x_1 x_2 \sim 10^{-1} - 10^{-2} \rightarrow$ valence and sea ($A_{TT} \sim 0.1$)
DY Event Distribution

\[ M^2/s = x_1x_2 \sim 0.02-0.3 \]

At \( x_1=x_2 \), \( A_{TT} \sim h_{1u}^2 \)
Direct measurement of \( h_{1u} \)
for \( 0.05<x<0.5 \)

Extraction of \( h_{1d}, h_{1q} \)
for \( x<0.2 \)

\( \bar{p}^\uparrow p^\uparrow, p^\uparrow p^\uparrow, \bar{p}^\uparrow d^\uparrow \): complete mapping of transversity
Single Spin Asymmetries

Sivers effect = number of partons in polarized proton depends on $\mathbf{P} \cdot (\mathbf{p} \times \mathbf{k}_\perp)$
Chiral-Even

Boer-Mulders effect = polarization of partons in unpolarized proton depends on $\mathbf{P}_q \cdot (\mathbf{p} \times \mathbf{k}_\perp)$
Chiral-Odd

Collins effect = fragmentation of polarized quark depends on $\mathbf{P}_q \cdot (\mathbf{p}_q \times \mathbf{k}_\perp)$
Chiral-Odd

Polarizing FF = polarization of hadrons from unpolarized partons depends on $\mathbf{P}_\Lambda \cdot (\mathbf{p}_q \times \mathbf{k}_\perp)$

These effects may generate SSA

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}$$
BNL-AGS $\sqrt{s} = 6.6$ GeV
$0.6 < p_T < 1.2$ \text{ p}$^+\text{p}$

E704 $\sqrt{s} = 20$ GeV
$0.7 < p_T < 2.0$ \text{ p}$^+\text{p}$

STAR-RHIC $\sqrt{s} = 200$ GeV
$1.1 < p_T < 2.5$ \text{ p}$^+\text{p}$

SSA, pp $\rightarrow \pi X$
The Sivers Function

Test of Universality

\[ f_{1T}^\perp(x, p_T^2)_{SIDIS} = -f_{1T}^\perp(x, p_T^2)_{DY} \]

\[ PAX: p^\uparrow \bar{p} \rightarrow e^+ e^- X \]

\[ A_{UT}^{sin(\phi_{T} - \phi_{N})/M_N} \]

\[ x_{1/2} = \sqrt{M^2/s} \ e^\pm y \]

\[ SIDIS: ep^\uparrow \rightarrow e\pi X \]

\[ E704: p^\uparrow p \rightarrow \pi X \]
The Sivers Function

\[ p^+ p \rightarrow DX \]

No Collins effect

\[ q \bar{q} \rightarrow c\bar{c} \]

No fragmentation process

\[ p^+ \bar{p} \rightarrow DX \]

\[ p^+ \bar{p} \rightarrow \gamma X \]

U.D'Alesio and F. Murgia
hep-ph/0612208
Proton Electromagnetic Form Factors

Comparison between Rosenbluth separation and polarization transfer techniques.

Two different methods.

Two different results.

**Figure 1.** (Color online) Ratio of electric to magnetic form factor as extracted by Rosenbluth measurements (hollow squares) and from the JLab measurements of recoil polarization (solid circles). The dashed line is the fit to the polarization transfer data.

*(Phys. Rev. C 68 (2003) 034325)*
Proton Timelike Form Factors

- Double-spin asymmetry in $pp \rightarrow e^+e^-$
  - independent $G_E - G_m$ separation
  - test of Rosenbluth separation in the time-like region

- Single-spin asymmetry in $\bar{p}p \rightarrow e^+e^-$
  Measurement of relative phases of magnetic and electric FF in the time-like region

\[
A_y = \frac{\sin(2\theta) \cdot \text{Im}(G_E^* \cdot G_M)}{\sqrt{\left(1 + \cos^2(\theta)\right) |G_M|^2 + \sin^2(\theta)|G_E|^2 / \tau}}
\]

\[
\tau = \frac{q^2}{4m_p^2}
\]

S. Brodsky et al., Phys. Rev. D69 (2004)
pp, pd, pp beams are possible

- **APR**: Antiproton Polarizer Ring ($P_{\bar{p}} > 0.2$)
- **CSR**: Cooled Synchrotron Ring ($p < 3.5$ GeV/c)
- **HESR**: High Energy Synchrotron Ring ($p < 15$ GeV/c)

Asymmetric collider Luminosity up to $5 \times 10^{31}$ cm$^{-2}$s$^{-1}$
PAX Detector Concept

Designed for Collider but compatible with fixed target

Forward detector
Scintillation hodoscope
Drift chambers (200 \( \mu \)m)
Silicon detector (20 \( \mu \)m)
EM calorimeter
Vacuum pipe
Magnet coils

P 3.5 GeV/c
\( \bar{P} \) 15 GeV/c

GEANT simulation

1 m.

PAX Detector

Designed for Collider but compatible with fixed target
Polarized Antiproton Experiments

**Phase I:** Proton time-like FFs
Hard pbar-p elastic scatt.

- Fixed target experiment \( (\sqrt{s} < 2 \text{ GeV}) \):
  - pol./unpol. pbar beam \( (p < 4 \text{ GeV/c}) \)
  - internal H polarized target

**Phase II:** Transversity Distribution
Asymmetric collider \( (\sqrt{s} = 15 \text{ GeV}) \):
- polarized antiprotons in HESR \( (p = 15 \text{ GeV/c}) \)
- polarized protons in CSR \( (p = 3.5 \text{ GeV/c}) \)
Antiproton Polarization

The polarization of antiprotons is based on the Spin Filtering method (interaction of unpolarized antiprotons with a polarized hydrogen target). This technique has been experimentally tested in 1992 (Filtex experiment) and it works, but:

1. Controversial interpretations of FILTEX experiment
   - Further experimental tests necessary
   - How does spin-filtering works?
   - Which role do electrons play?
   → Tests with protons at COSY

2. No data to predict polarization from filtering with antiprotons.
   → Measurements with antiprotons at AD/CERN

| Year       | Description                                                                 |
|------------|-----------------------------------------------------------------------------|
| Fall 2007  | Technical proposal to COSY-PAC for spin filtering                           |
|            | Technical proposal to SPSC for spin filtering at AD                         |
| 2007-2008  | Depolarization studies                                                      |
| 2008-2009  | Design and construction phase                                               |
| 2009-2010  | Spin-filtering studies at COSY                                              |
|            | Commissioning of AD experiment                                              |
| 2010       | Installation at AD                                                          |
| 2010-2011  | Spin-filtering studies at AD                                                |
Summary and Outlook: Spectroscopy at FAIR

**PANDA**

High-intensity cooled antiproton beams

High precision spectroscopy from $\sqrt{s}$ 2.25 GeV to 5.5 GeV:

- charmonium
- hybrids and glueballs
- multiquark
- mesons and hadrons
- open charm
Summary and Outlook: Nucleon Structure at FAIR

**PANDA**
- Proton Timelike Form Factors
  - Very high-statistics measurement near threshold
  - Measure angular distribution \( |G_E|/|G_M| \)
  - Extend \( q^2 \) range to 20-25 GeV²

**PAX**
- Transversity in polarized \( \bar{p}p \) DY
- Single Spin Asymmetries and Sivers Function
- Proton Timelike Form Factors
  - Measurement with polarized beams
  - Single- and double-spin observables
  - Moduli and phases of TL form factors
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
Transversity and Tensor Charges

Transversity

\[ x \Delta_T u(x) \]

\[ x \Delta_T d(x) \]

Tensor charges

\[
\begin{array}{|c|c|c|c|c|c|c|c|c|c|}
\hline
\text{Model [Ref.]} & \Delta u & \Delta d & \Delta \Sigma & \delta u & \delta d & |\delta u/\delta d| & Q_0[\text{GeV}] & \delta u(Q^2) & \delta d(Q^2) \\
\hline
\text{NRQM} * & 1.33 & -0.33 & 1 & 1.33 & -0.33 & 4.03 & 0.28 & 0.97 & -0.24 \\
\text{MIT [14]} & 0.87 & -0.22 & 0.65 & 1.09 & -0.27 & 4.04 & 0.87 & 0.99 & -0.25 \\
\text{CDM [92]} & 1.08 & -0.29 & 0.79 & 1.22 & -0.31 & 3.94 & 0.40 & 0.99 & -0.25 \\
\text{CQSM1 [223]} & 0.90 & -0.48 & 0.37 & 1.12 & -0.42 & 2.67 & 0.60 & 0.97 & -0.37 \\
\text{CQSM2 [226]} & 0.88 & -0.53 & 0.35 & 0.89 & -0.33 & 2.70 & 0.60 & 0.77 & -0.29 \\
\text{CQM [231]} & 0.65 & -0.22 & 0.43 & 0.80 & -0.15 & 5.33 & 0.80 & 0.72 & -0.13 \\
\text{LC [86]} & 1.00 & -0.25 & 0.75 & 1.17 & -0.29 & 4.03 & 0.28 & 0.85 & -0.21 \\
\text{Spect. [252]} & 1.10 & -0.18 & 0.92 & 1.22 & -0.25 & 4.88 & 0.25 & 0.83 & -0.17 \\
\text{Lattice [260]} & 0.64 & -0.35 & 0.29 & 0.84 & -0.23 & 3.65 & 1.40 & 0.80 & -0.22 \\
\hline
\end{array}
\]

\[ \delta u \approx 0.39, \quad \delta d \approx -0.16 \]

Soffer inequality

\[ f(x) + \Delta f(x) \geq 2|\Delta_T f(x)| \]

M. Anselmino et al.

hep-ph/0008186

Physics at FAIR

M. Wakamatsu

arXiv: 0705.2917
Elastic Scattering

Low-\( E \) pp, \( \bar{p}d \) at AD

Polarization build-up studies

High-\( t \) pp from ZGS, AGS

Spin-dependence at large-\( P_\perp \) (90°\(_{\text{cm}}\)): Hard scattering takes place only with spins \( \uparrow \uparrow \).

Similar studies in \( \bar{p}p \) elastic scattering

D.G. Crabb et al., PRL 41, 1257 (1978)

T=10.85 GeV

D. Bettoni

Physics at FAIR
Principle of spin filter method

\[ \sigma_{\text{tot}} = \sigma_0 + \sigma_\perp \cdot \vec{P} \cdot \vec{Q} + \sigma_\parallel \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k}) \]

- P beam polarization
- Q target polarization
- k \parallel beam direction

For initially equally populated spin states: \( \uparrow (m=+\frac{1}{2}) \) and \( \downarrow (m=-\frac{1}{2}) \)

| Transverse case: \( \sigma_{\text{tot} \pm} = \sigma_0 \pm \sigma_\perp \cdot Q \) |
| Longitudinal case: \( \sigma_{\text{tot} \pm} = \sigma_0 \pm (\sigma_\perp + \sigma_\parallel) \cdot Q \) |

Unpolarized anti-\( p \) beam

Polarized \( H \) target