PAX

Polarized Antiproton eXperiments

M. Contalbrigo

INFN - Università di Ferarra

PAX Collaboration

178 physicists (121 in August 2004)
35 institutions (15 EU, 20 NON-EU)

TIMELINE

Jan. 04	Letter of Intent
May 04	QCD-PAC meeting at GSI
Aug. 04	Workshop on polarized antiprotons at GSI
Jan. 05	Technical Report
Mar. 05	QCD-PAC meeting at GSI

Evaluation by QCD-PAC (March 2005)

… the PAC would like to stress again the uniqueness of the program with polarized anti-protons and polarized protons that could become available at GSI.

…the PAC considers it is essential for the FAIR project to commit to polarized antiproton capability at this time and include polarized transport and acceleration capability in the HESR, space for installation of the APR and CSR and associated hardware, and the APR in the core project

We request the PAX collaboration to:
1) Commit to the construction and testing of the APR
2) Explore all options to increase the luminosity to the value of 10^{31} cm^{-2}s^{-1}
3) Prepare a more detailed physics proposal and detector design for each of the proposed stages. These stages may include:
    a) 3.5 GeV/c polarized antiprotons on a polarized proton target
    b) 15 GeV/c polarized antiprotons with the PANDA detector (for single spin asymmetries)
    c) 15 GeV/c polarized antiprotons on a polarized proton target in a dedicated detector
    d) Collisions of 15 GeV/c antiprotons with 3.5 GeV/c polarized protons.

Outline

- Introduction
  - Physics Case
  - The FAIR project

- PAX Accelerator Setup
  - Staging
  - Antiproton Polarizer Ring
  - Asymmetric Antiproton-Proton Collider

- Experiment
  - Conceptual Detector Design
  - Preliminary Results for Drell-Yan Studies
  - Rate estimates

Physics with polarized antiprotons at GSI-PAX

High Energy

Transversity via Drell-Yan processes

A_{TT} → direct access to transversity

Transverse Single Spin Asymmetries

A_N → QCD "theorem": $(\text{Sivers})_{\text{D-Y}} = -\,(\text{Sivers})_{\text{DIS}}$

Elastic processes

$A_N\,,\ A_{NN}\,,\ A_{LL}\,,\ A_{SS}\,,\ A_{SL}$ → spin mysteries like in pp ?

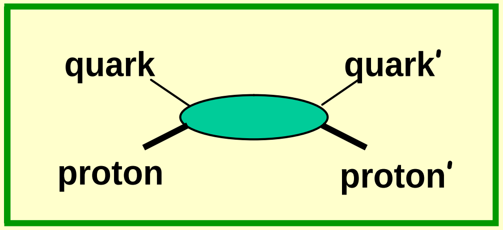
Time-like e.l.m. form factors

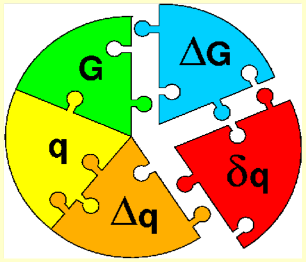
$p\bar{p} \to l^+ l^-$ → form factors

Low Energy

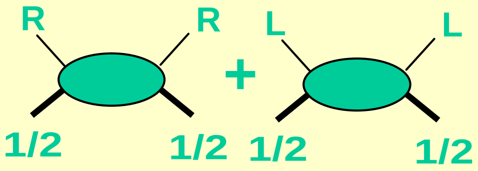
Leading Twist Distribution Functions

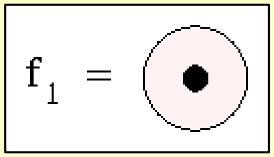
Probabilistic interpretation
in helicity base:





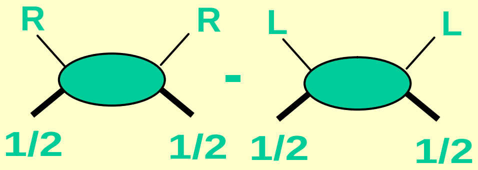
$f_1(x)$

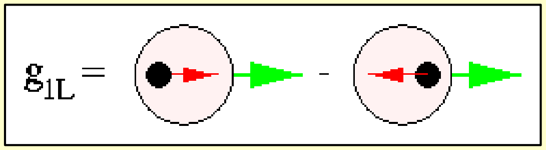




q(x) spin averaged
(well known)

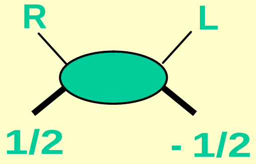
$g_1(x)$





Δq(x) helicity diff.
(known)

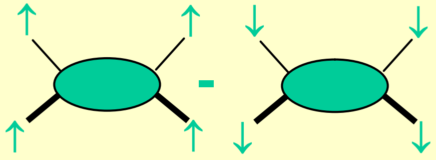
$h_1(x)$

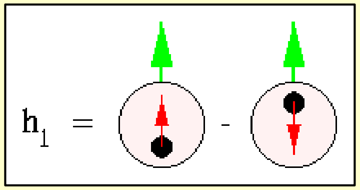


No probabilistic interpretation in the helicity base (off diagonal)

Transversity base $u_\uparrow = 1/\sqrt{2}(u_R + u_L)$

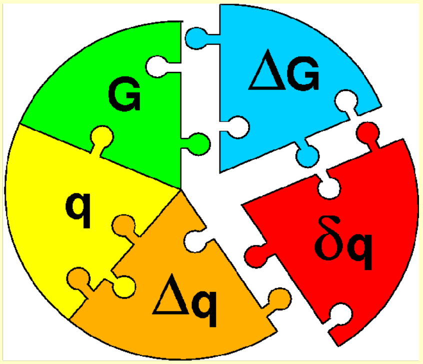
$u_\downarrow = 1/\sqrt{2}(u_R - u_L)$





δq(x) helicity flip
(unknown)

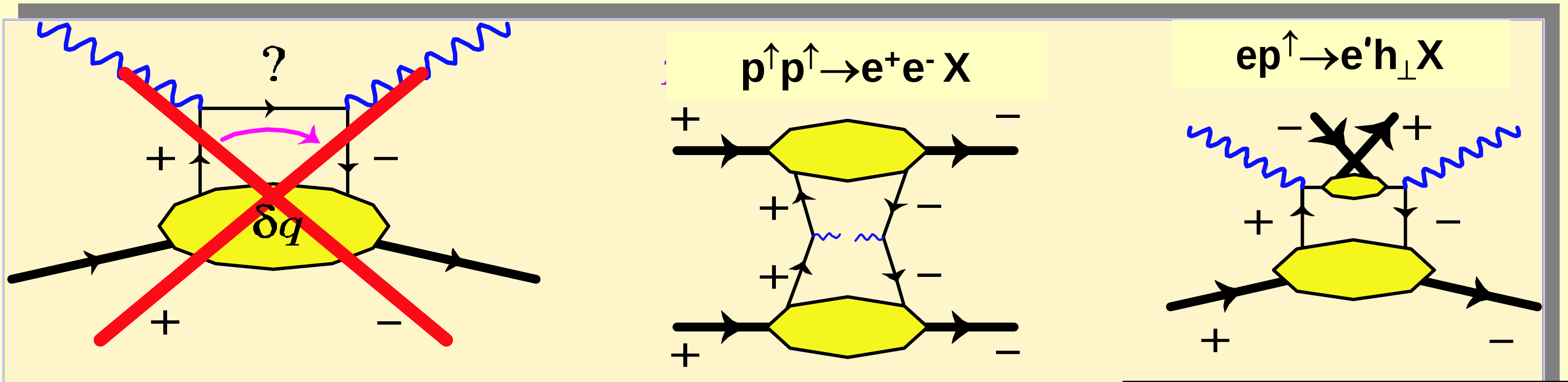
Transversity



Properties:

- Probes relativistic nature of quarks
- No gluon analog for spin-1/2 nucleon
- Different Q^2 evolution than Δq
- Sensitive to valence quark polarization

Chiral-odd: requires another chiral-odd partner



Impossible in DIS

Direct Measurement

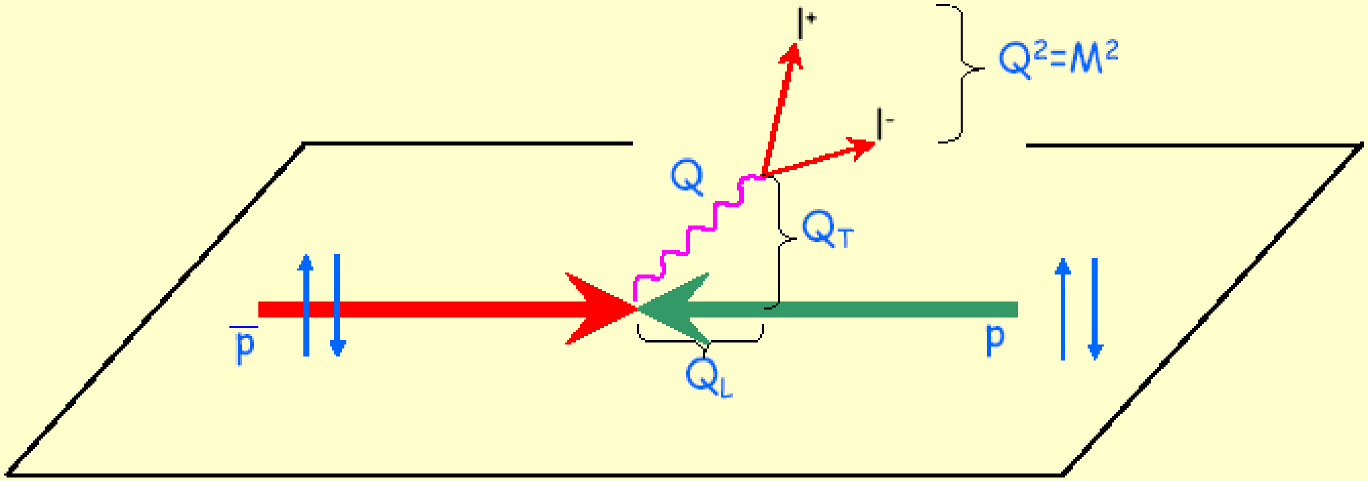
Indirect Measurement: Convolution of with unknown fragment. fct.

h_1 must couple to another chiral-odd function

h_1 x h_1

h_1 x Collins function

Drell- Yan process



Elementary LO interaction:

$$q\bar{q} \to \gamma^* \to l^+ l^-$$

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

$\mathrm{q} = \mathrm{u}, \bar{\mathrm{u}}, \mathrm{d}, \bar{\mathrm{d}}, \ldots$

M invariant Mass of lepton pair

$$x_F = x_1 - x_2 \qquad x_1 x_2 = M^2 / s \equiv \tau \qquad x_F = 2Q_L / \sqrt{s}$$

h_1 from p-p Drell-Yan at RICH

RICH energies : $\sqrt{s} = 200\,\mathrm{GeV} \quad M^2 \leq 100\ \mathrm{GeV}^2 \quad \tau \leq 2 \cdot 10^{-3}$

$$A_{TT} = \frac{\mathrm{d}\sigma^{\uparrow\uparrow} - \mathrm{d}\sigma^{\uparrow\downarrow}}{\mathrm{d}\sigma^{\uparrow\uparrow} + \mathrm{d}\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[h_{1q}(x_1) h_{1\bar{q}}(x_2) + h_{1\bar{q}}(x_1) h_{1q}(x_2)\right]}{\sum_q e_q^2 \left[q(x_1)\bar{q}(x_2) + \bar{q}(x_1) q(x_2)\right]}$$

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

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

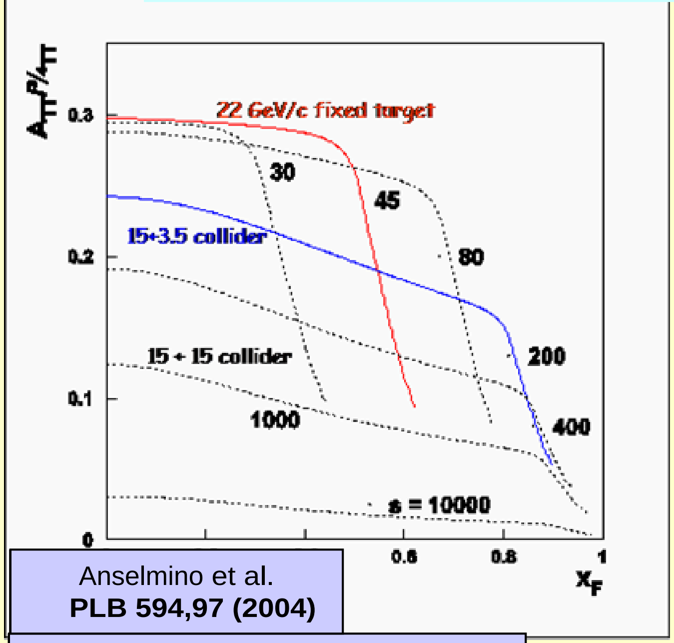
RHIC: **$\tau = x_1 x_2 \sim 10^{-3}$ → sea quarks** **(A_{TT} very small ~ 0.01)**

Barone, Calarco, Drago
Martin, Schäfer, Stratmann, Vogelsang

h_1 from pbar-p Drell-Yan at GSI

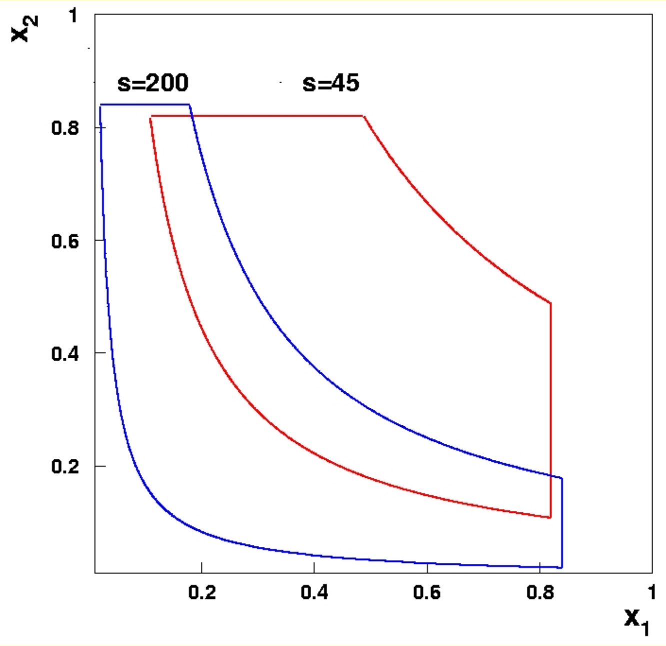
GSI energies: $s = 30 - 210\ \mathrm{GeV}^2 \qquad M \geq 2\ \mathrm{GeV}^2$

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



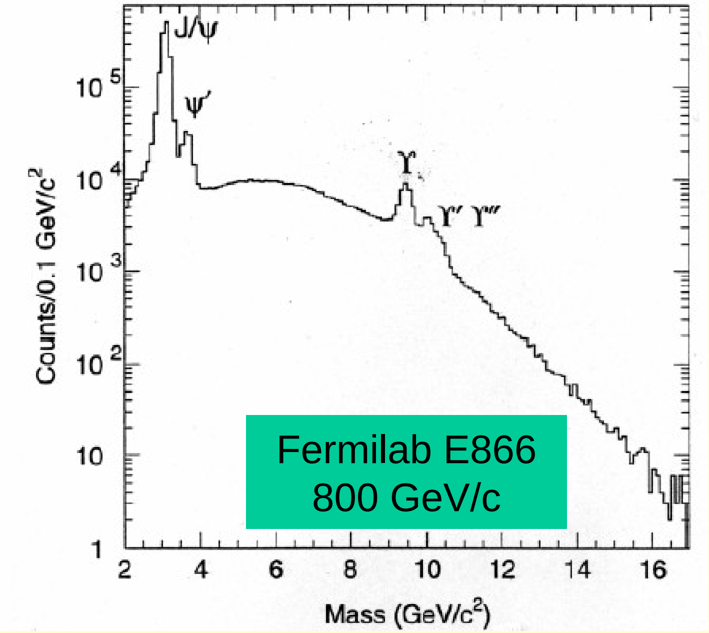
Anselmino et al.
PLB 594,97 (2004)

Similar predictions by Efremov et al.,
Eur. Phys. J. C35, 207 (2004)

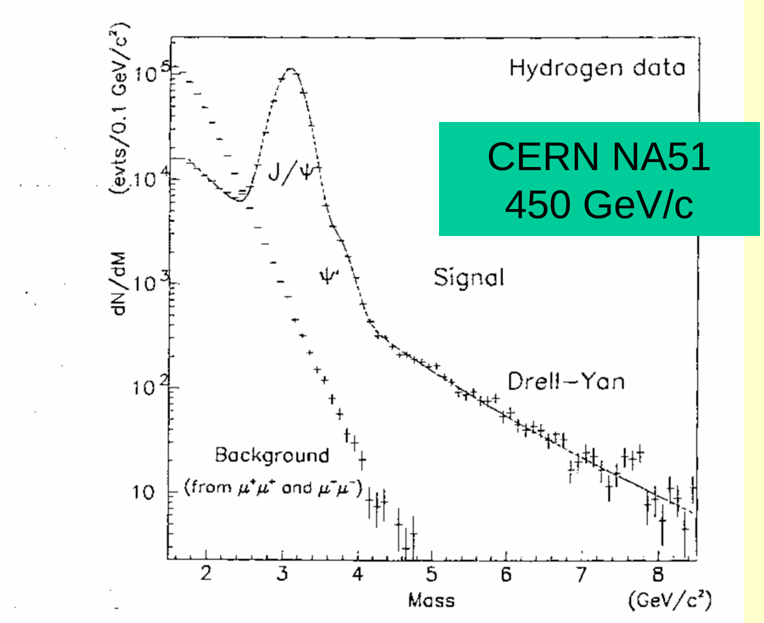


PAX : $M^2/s = x_1 x_2 \sim 0.1 - 0.3$ → **valence quarks** **(A_{TT} large ~ 0.2-0.4)**

Kinematics for Drell-Yan processes



Fermilab E866
800 GeV/c



CERN NA51
450 GeV/c

$$M \geq M_{J/\Psi}$$

Usually taken as "safe region"

➡ $$\tau \geq \frac{M^2_{J/\Psi}}{s}$$

QCD corrections might be very large at smaller values of *M*:

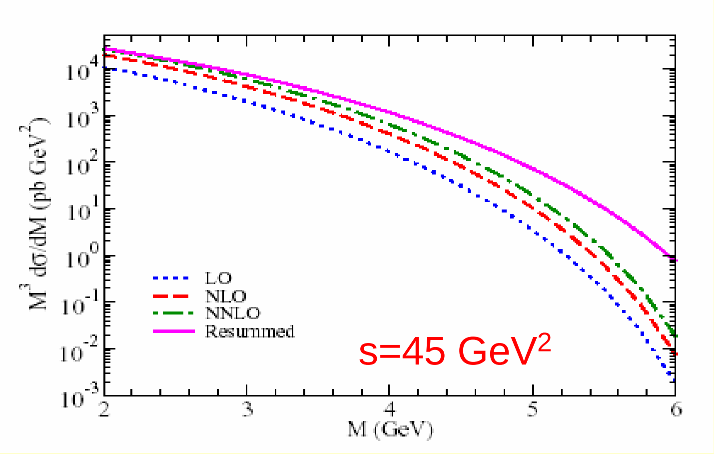
yes, for cross-sections, not for A_{TT}

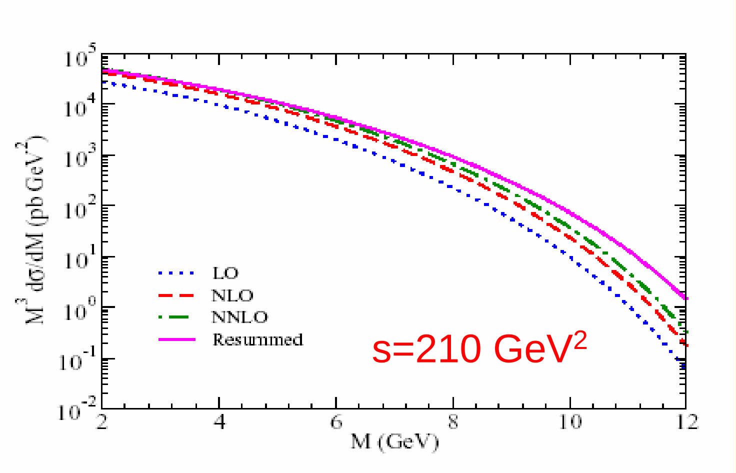
K-factor almost spin-independent

H. Shimizu, G. Sterman, W. Vogelsang and H. Yokoya, hep-ph/0503270

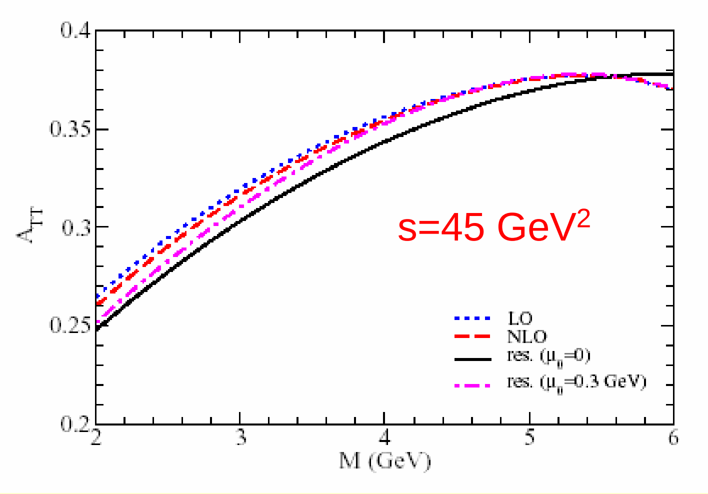
V. Barone et al., in preparation

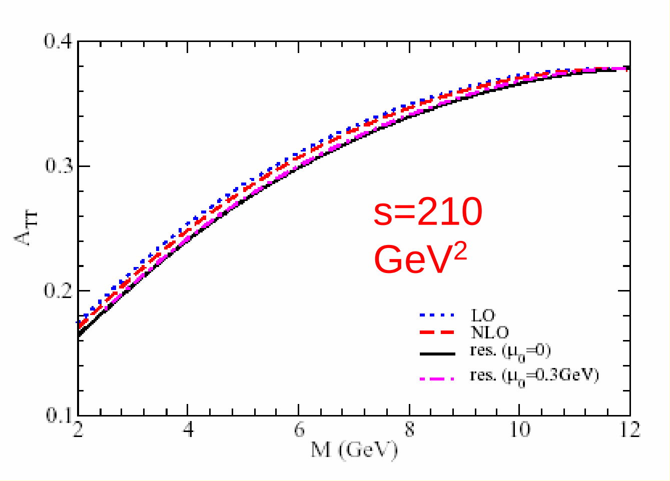
Cross-section





Asymmetry





Physics with polarized antiprotons at GSI-PAX

High Energy

↑

Low Energy

Transversity via Drell-Yan processes

A_{TT} → direct access to transversity

Transverse Single Spin Asymmetries

A_N → QCD "theorem": (Sivers)$_{\text{D-Y}}$ = − (Sivers)$_{\text{DIS}}$

Elastic processes

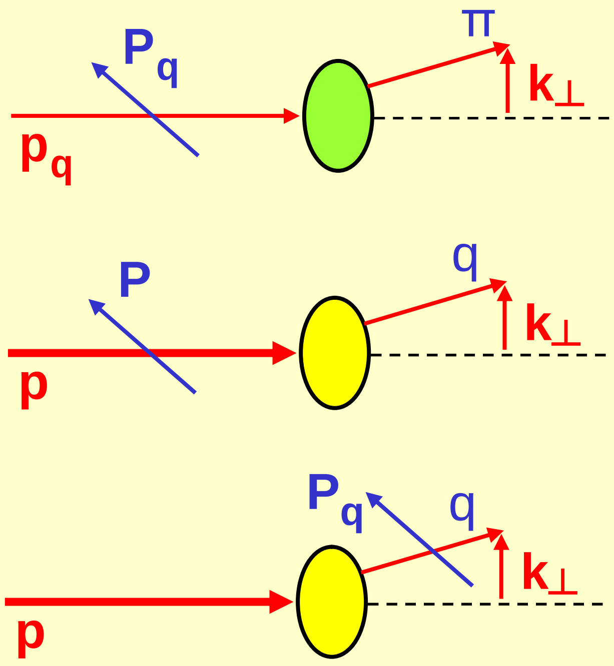
$A_N\,,\ A_{NN}\,,\ A_{LL}\,,\ A_{SS}\,,\ A_{SL}$ → spin mysteries like in pp ?

Time-like e.l.m. form factors

$p\bar{p} \rightarrow l^+ l^-$ → form factors

Single Spin Asymmetries

(and their partonic origin)



Collins effect = fragmentation of polarized quark depends on $\mathbf{P_q} \cdot (\mathbf{p_q} \times \mathbf{k_\perp})$

Sivers effect = number of partons in polarized proton depends on $\mathbf{P} \cdot (\mathbf{p} \times \mathbf{k_\perp})$

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

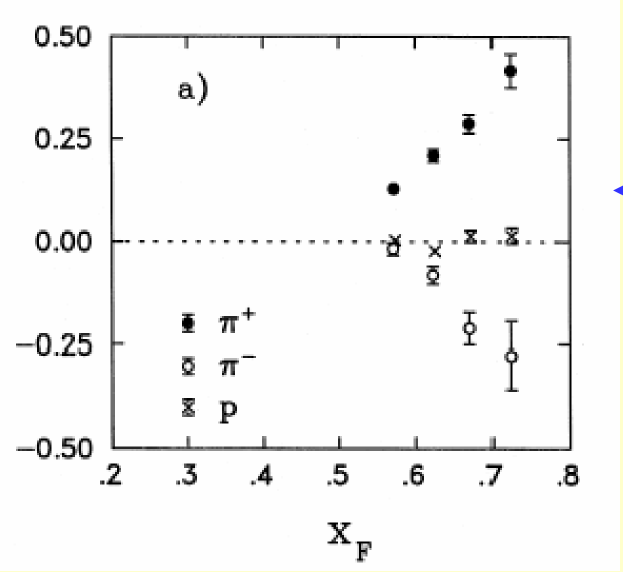
Collins: chiral-odd

Sivers: chiral-even

Boer-Mulders: chiral-odd

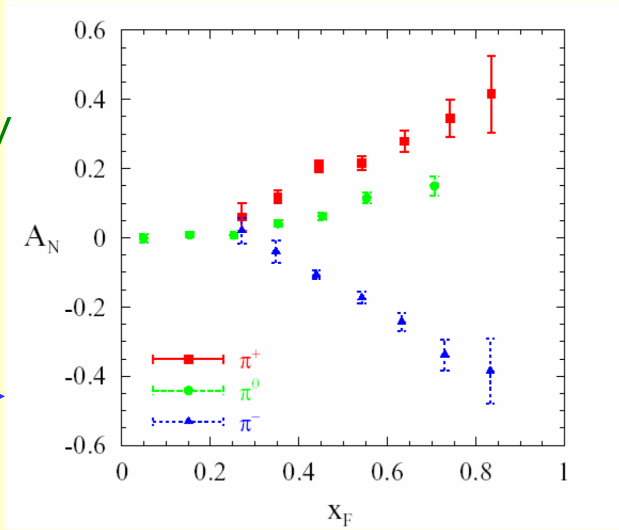
These effects may generate SSA

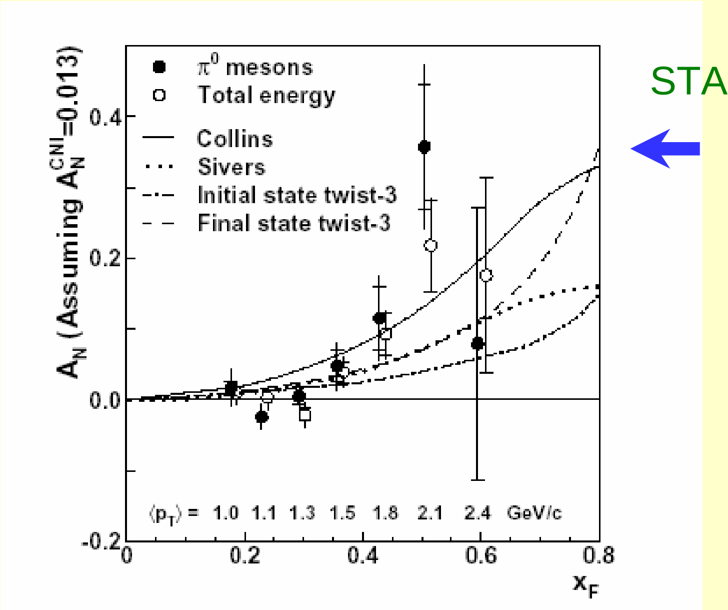
$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$$



BNL-AGS $\sqrt{s} = 6.6$ GeV
$0.6 < p_T < 1.2$ $p^{\uparrow}p$

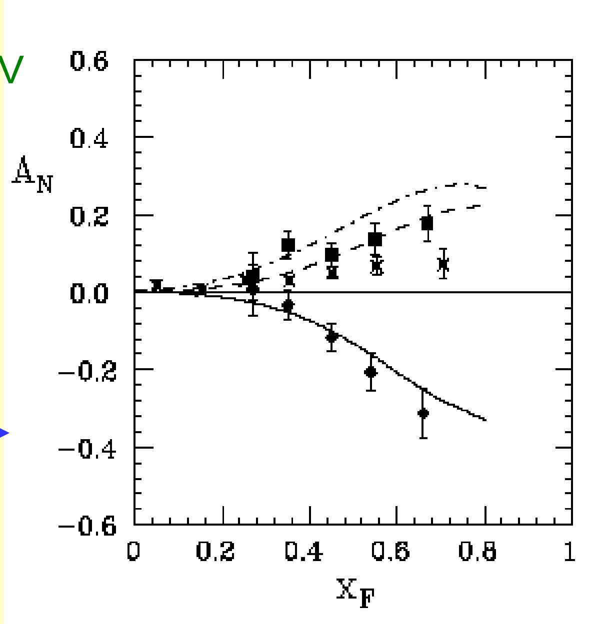
E704 $\sqrt{s} = 20$ GeV
$0.7 < p_T < 2.0$ $p^{\uparrow}p$





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

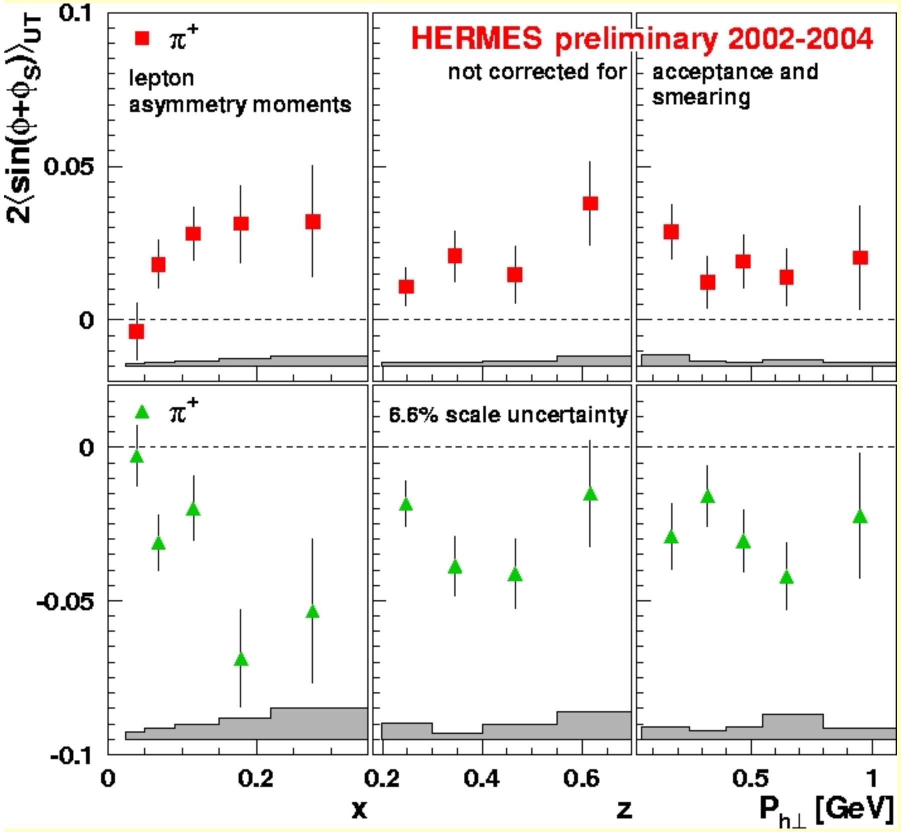
E704 $\sqrt{s} = 20$ GeV
$0.7 < p_T < 2.0$ $\bar{p}^{\uparrow}p$



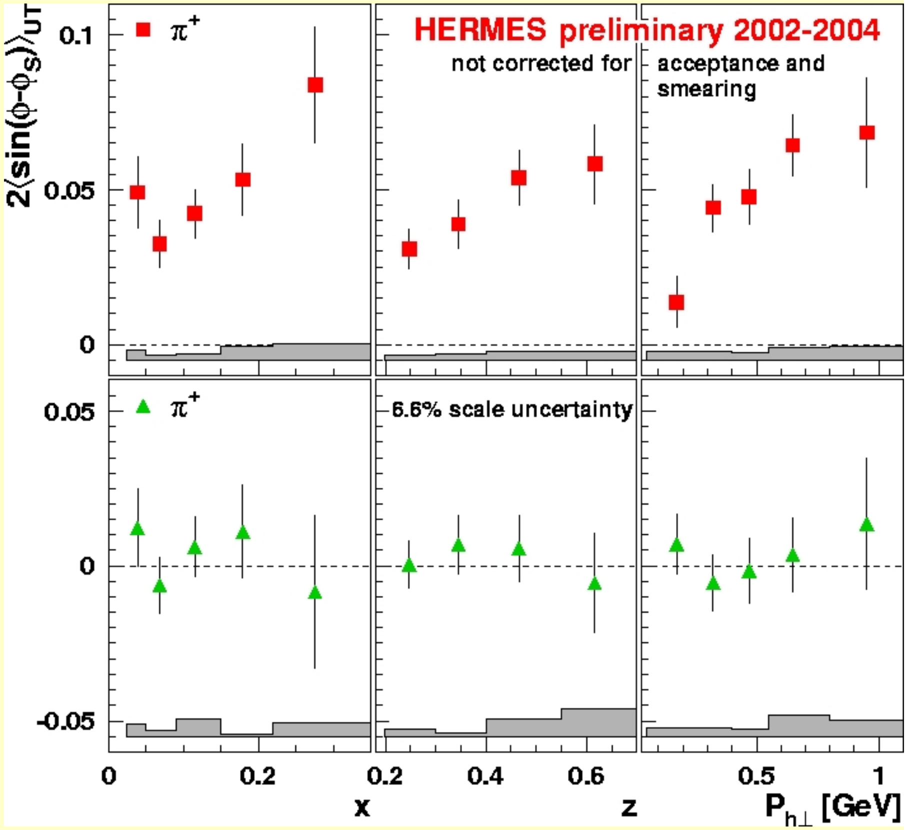
SSA, pp → πX

HERMES

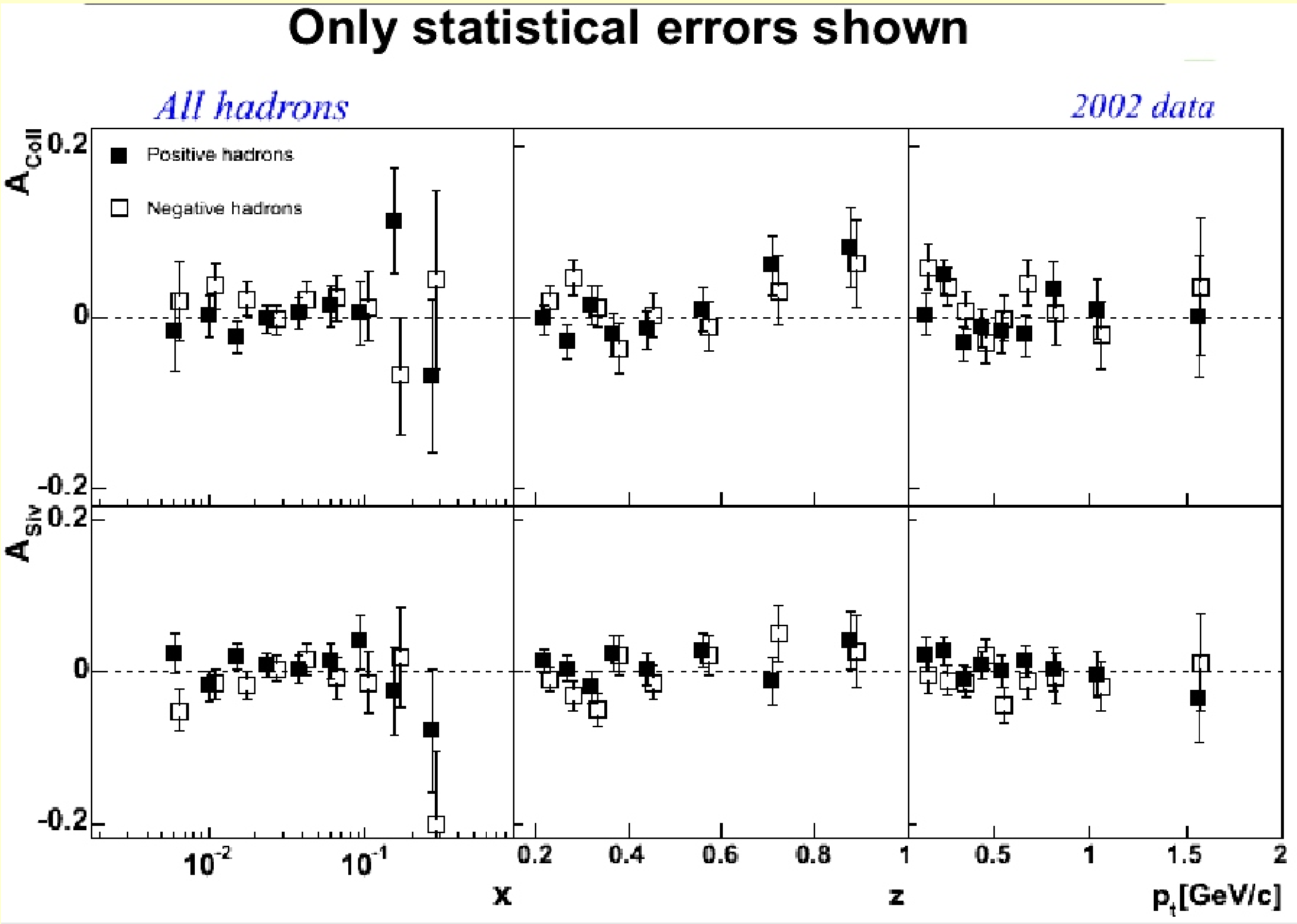
Collins



Sivers



COMPASS



SSA, SIDIS

Physics with polarized antiprotons at GSI-PAX

Transversity via Drell-Yan processes

A_{TT} ➡ direct access to transversity

Transverse Single Spin Asymmetries

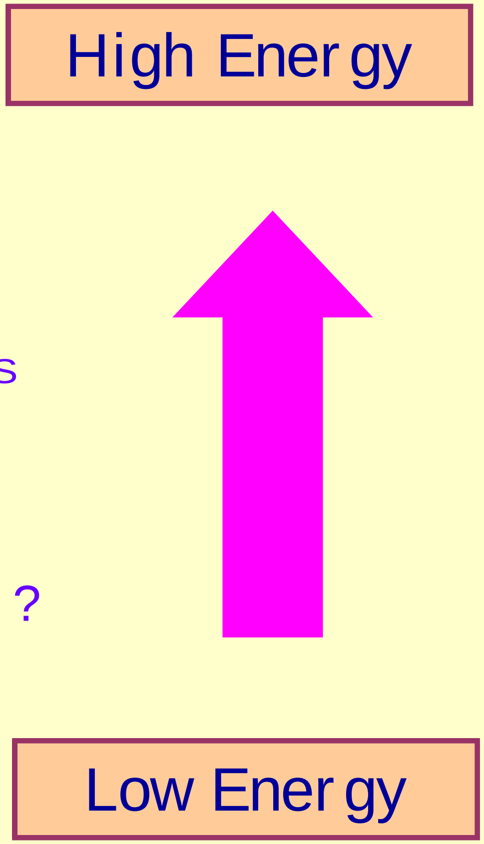
A_N ➡ QCD "theorem": $(\text{Sivers})_{\text{D-Y}} = - (\text{Sivers})_{\text{DIS}}$

Elastic processes

$A_N, A_{NN}, A_{LL}, A_{SS}, A_{SL}$ ➡ spin mysteries like in pp ?

Time-like e.l.m. form factors

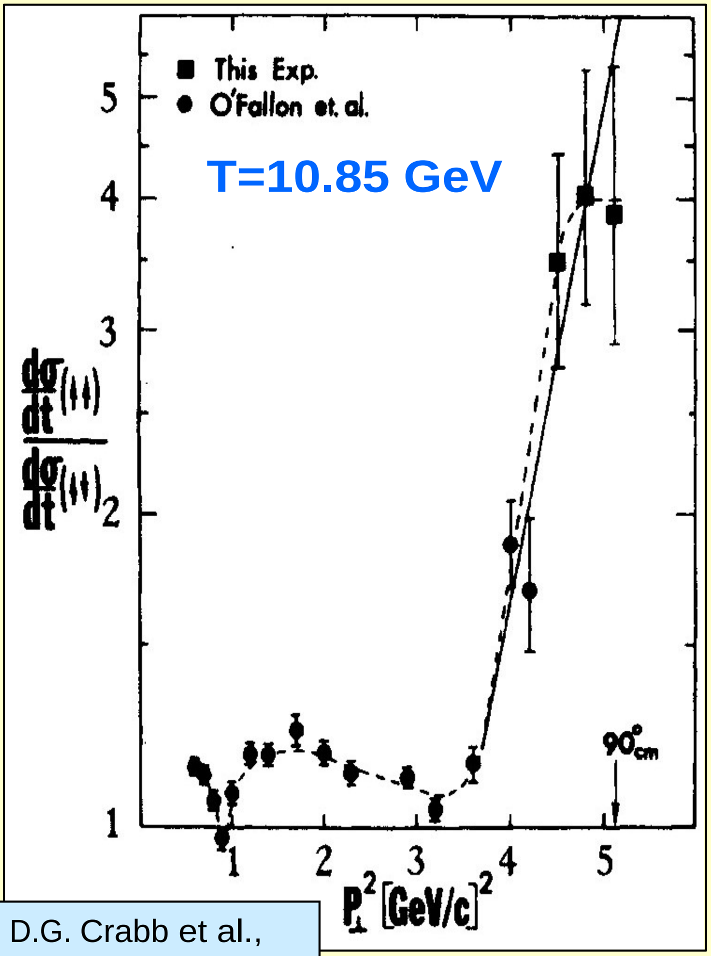
$p\bar{p} \rightarrow l^+ l^-$ ➡ form factors



pp Elastic Scattering from ZGS

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

Similar studies in $\bar{p}p$ elastic scattering



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

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Low Energy

$p\bar{p} \to l^+ l^-$ → form factors

Proton Electromagnetic Formfactors

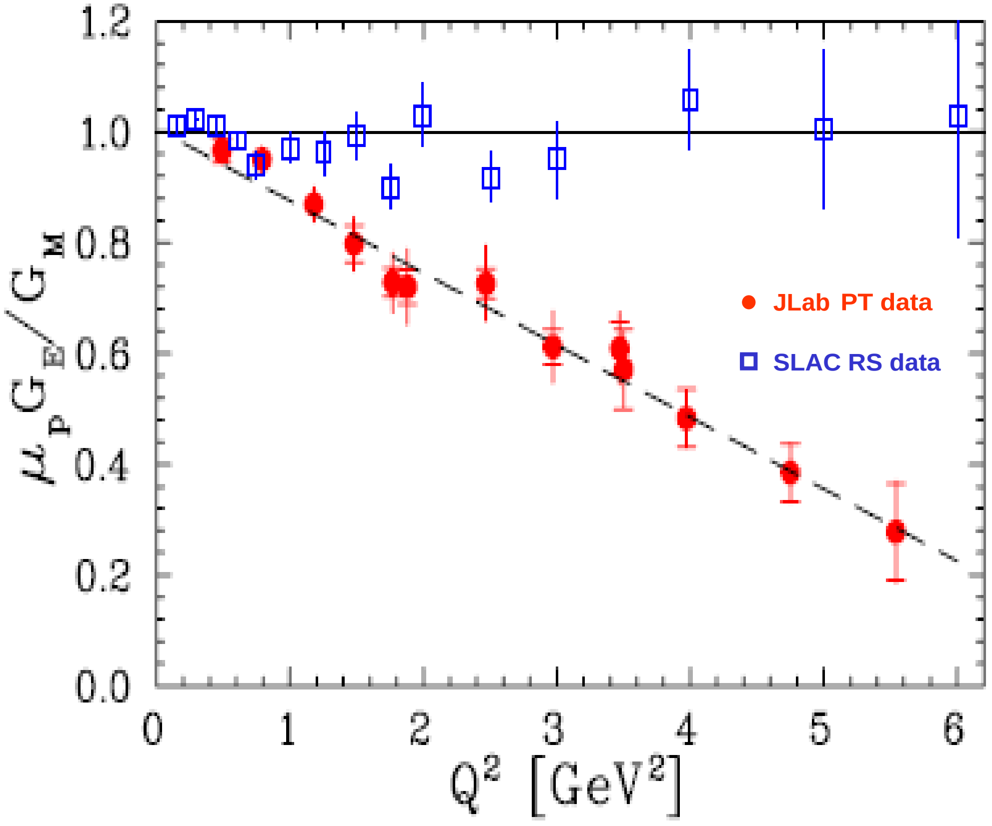


FIG. 1. (Color online) Ratio of electric to magnetic form factor as extracted by Rosenbluth measurements (hollow squares) and from the JLab measurements of recoil polarization (solid circles). The dashed line is the fit to the polarization transfer data.

(Phys. Rev.C 68 (2003) 034325)

COMPARISON BETWEEN

ROSENBLUTH SEPARATION AND

POLARIZATION TRANSFER TECNIQUES

TWO DIFFERENTS METHODS

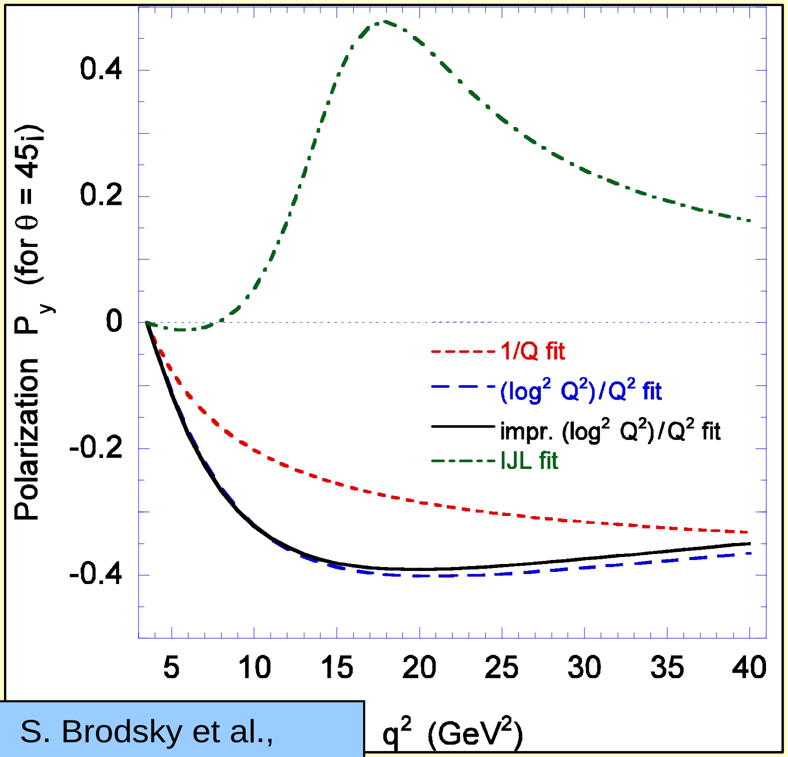
TWO DIFFERENTS RESULTS

Proton Electromagnetic Formfactors

- Single-spin asymmetry in pp → e^+e^-
  - Measurement of relative phases of magnetic and electric FF in the time-like region

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

$$\tau = q^2/4m_p^{\;2}$$



S. Brodsky et al.,
Phys. Rev. D69 (2004)

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

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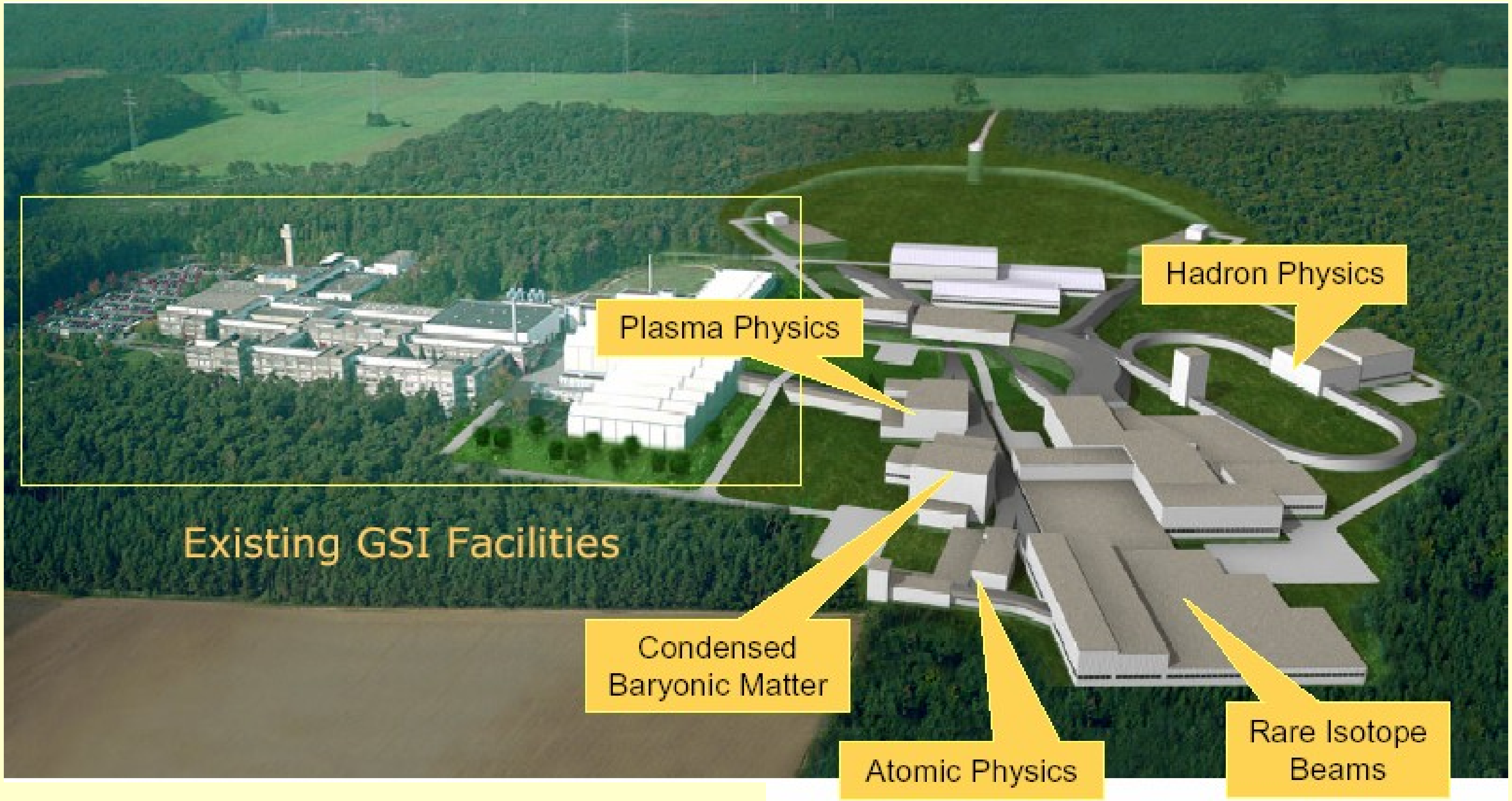
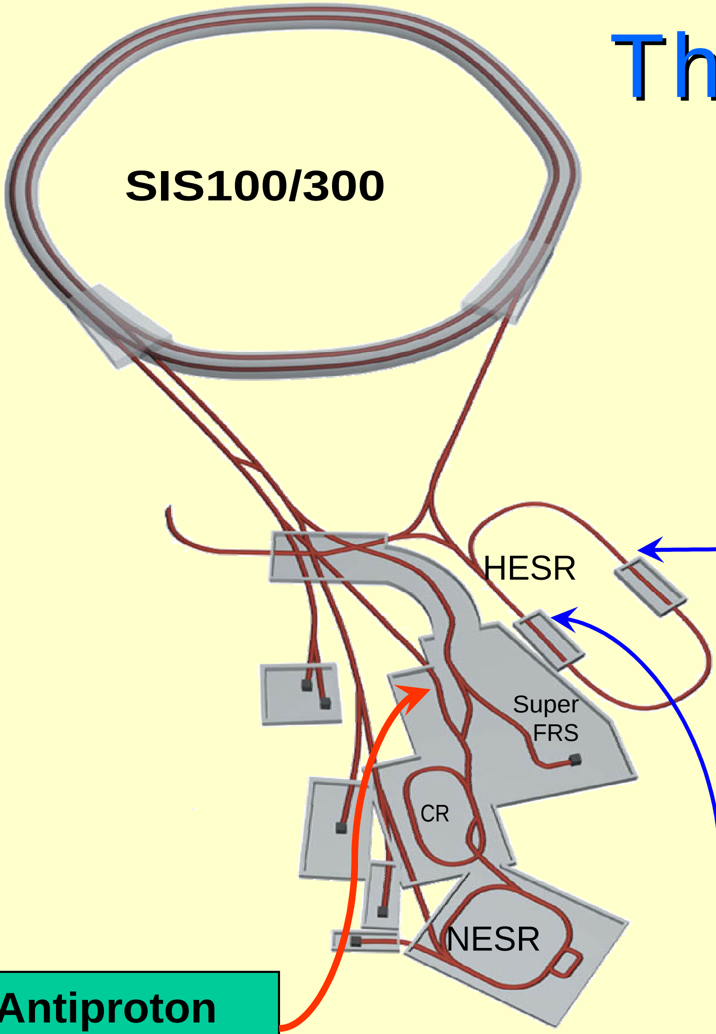
Facilty for Antiproton and Ion Research
(GSI, Darmstadt, Germany)



- Proton linac (injector)
- 2 synchrotons (30 GeV p)
- A number of storage rings

→ Parallel beams operation

The Antiproton Facility



HESR (High Energy Storage Ring)

p = 1.5 - 15 GeV/c (22 GeV/c)

(Length 442 m $B\rho$ = 50 Tm)

PANDA: storage ring **(N=5 x 10^{10} pbar)**

High luminosity mode ($\Delta p/p \sim 10^{-4}$)

Luminosity = 2 x 10^{32} $cm^{-2}s^{-1}$

High resolution mode ($\Delta p/p \sim 10^{-5}$)

Luminosity = 10^{31} $cm^{-2}s^{-1}$

PAX : synchroton **(N=3 x 10^{11} pbar)**

Preserve polarization

Luminosity = 2 x 10^{30} $cm^{-2}s^{-1}$

Beam Cooling:

e^- and/or stochastic

Antiproton
Production Target

- **Antiproton production similar to CERN**
- **Production rate 10^7/sec at 30 GeV**

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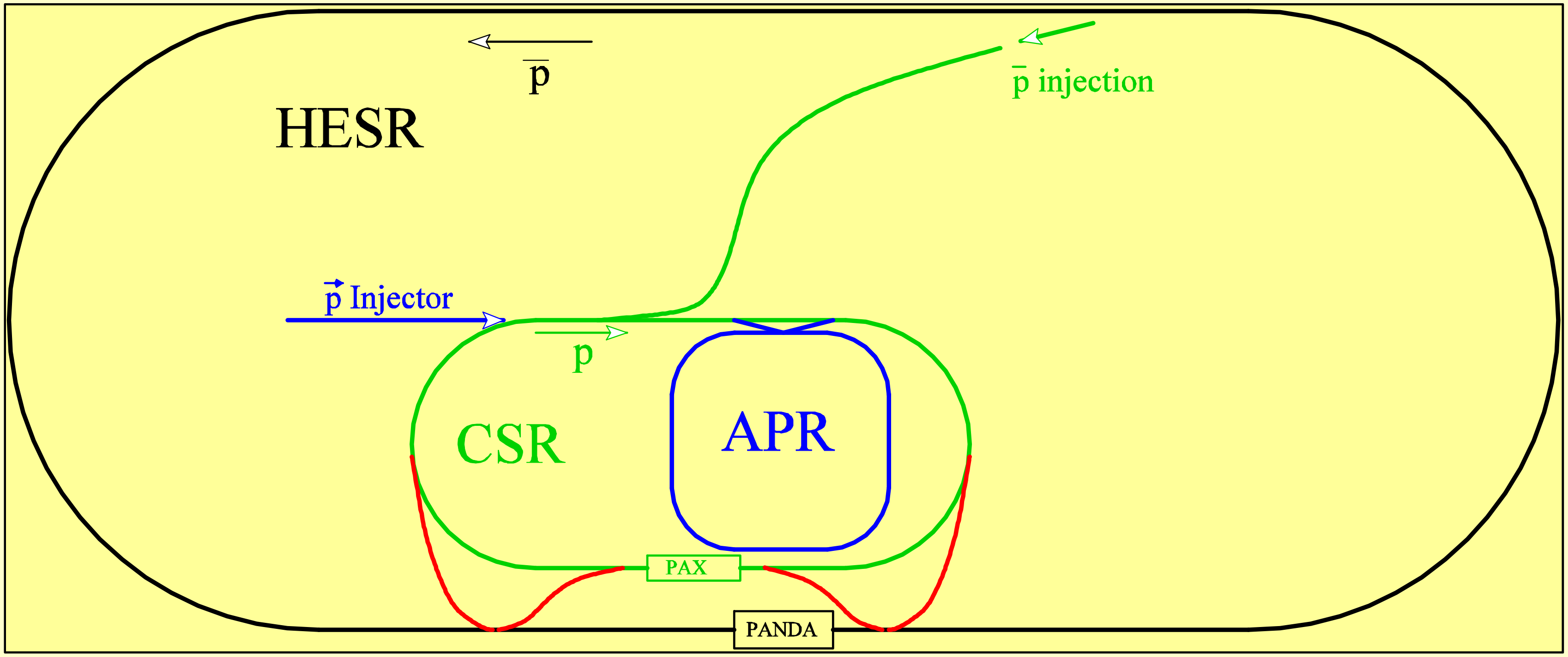
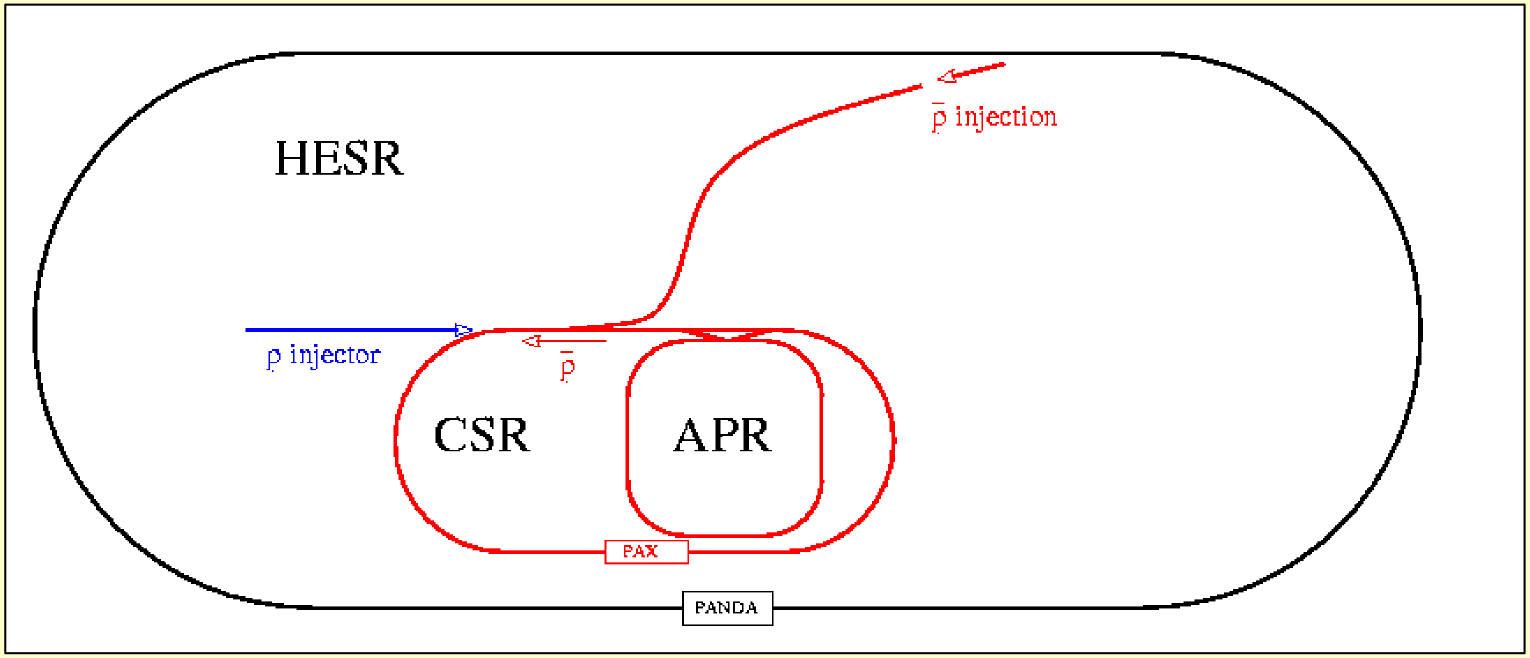
PAX Accelerator Setup



In the following, focus on two issues:

- Antiproton Polarizer Ring (APR)
- Asymmetric Antiproton-Proton Collider

Staging: Phase I (PAX@CSR)

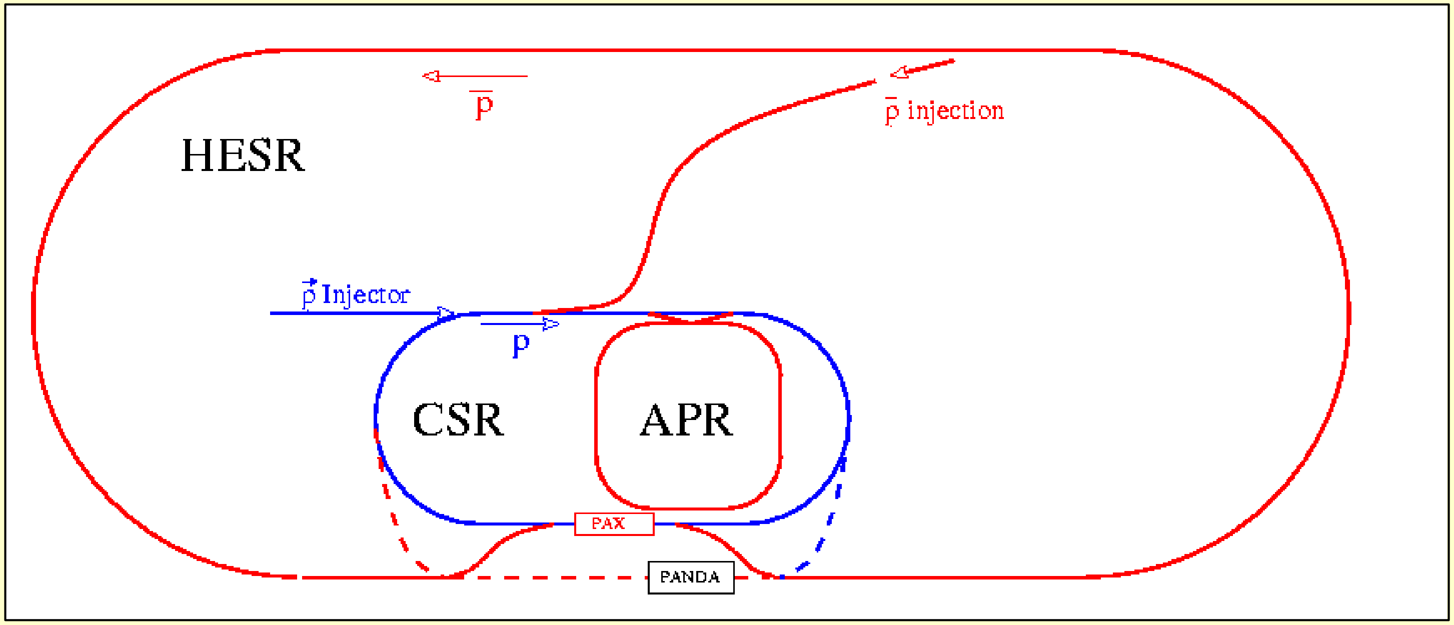


Physics: **EMFF**
pbar- p elastic

Experiment: **pol./unpol. pbar on internal polarized target**

Independent from HESR running

Staging: Phase II (PAX@HESR)



Physics: Transversity

EXPERIMENT:

1. **Asymmetric collider**:

polarized antiprotons in HESR (p=15 GeV/c)

polarized protons in CSR (p=3.5 GeV/c)

2. Internal polarized target with 22 GeV/c polarized antiproton beam.

Second IP with minor interference with PANDA

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Principle of spin filter method

$$\sigma_{tot} = \sigma_0 + \sigma_\perp \cdot \vec{P} \cdot \vec{Q} + \sigma_{||} \cdot (\vec{P} \cdot \vec{k})(\vec{Q} \cdot \vec{k})$$

P beam polarization
Q target polarization
k || beam direction

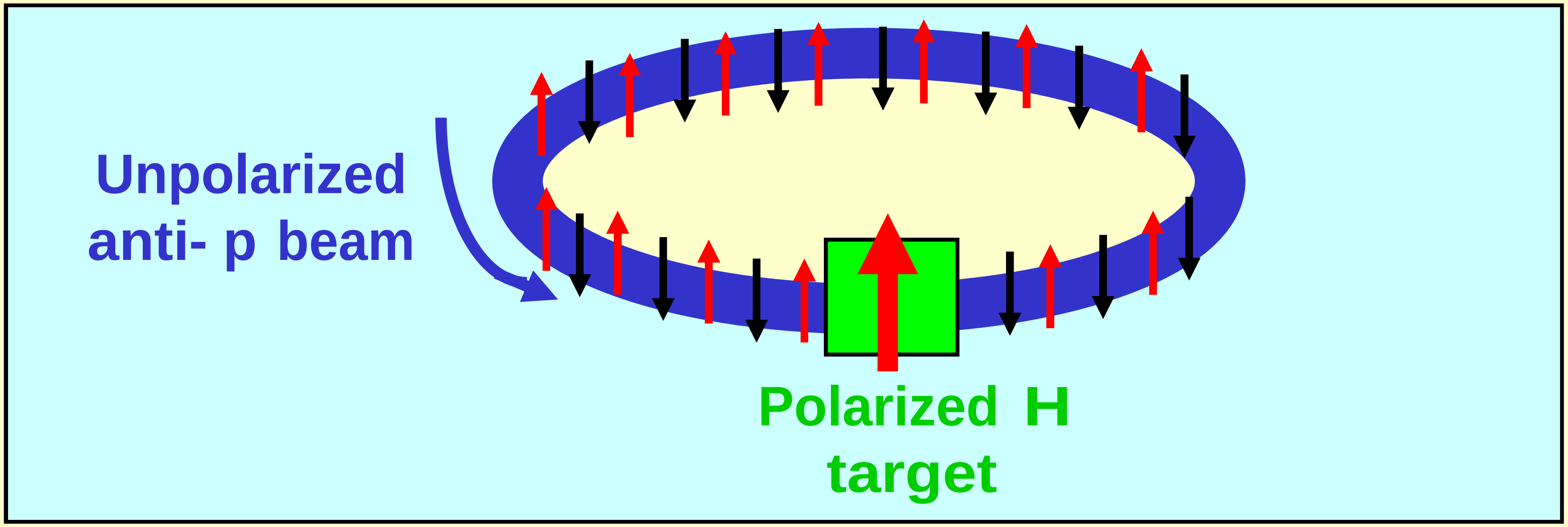
For initially equally populated spin states: ↑ (m=+½) and ↓ (m=-½)

transverse case:

$$\sigma_{tot\pm} = \sigma_0 \pm \sigma_\perp \cdot Q$$

longitudinal case:

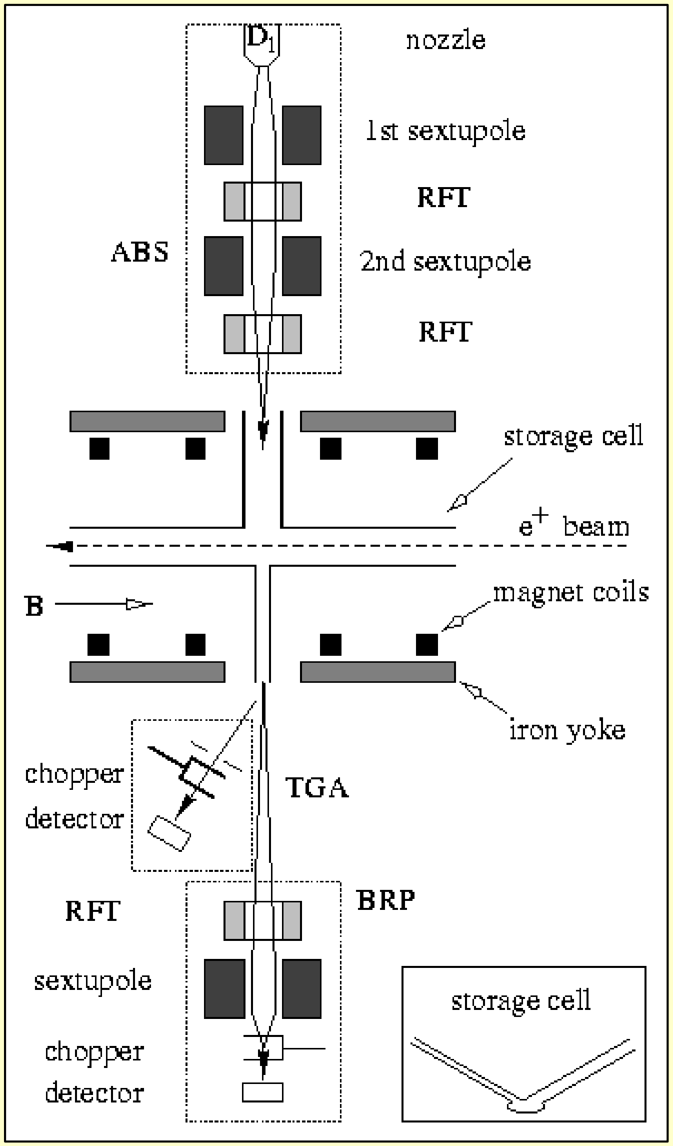
$$\sigma_{tot\pm} = \sigma_0 \pm (\sigma_\perp + \sigma_{||}) \cdot Q$$



Unpolarized anti- p beam

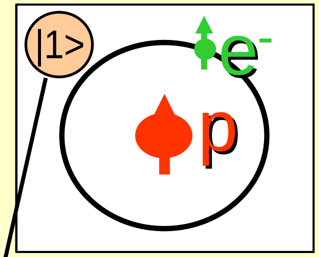
Polarized H target

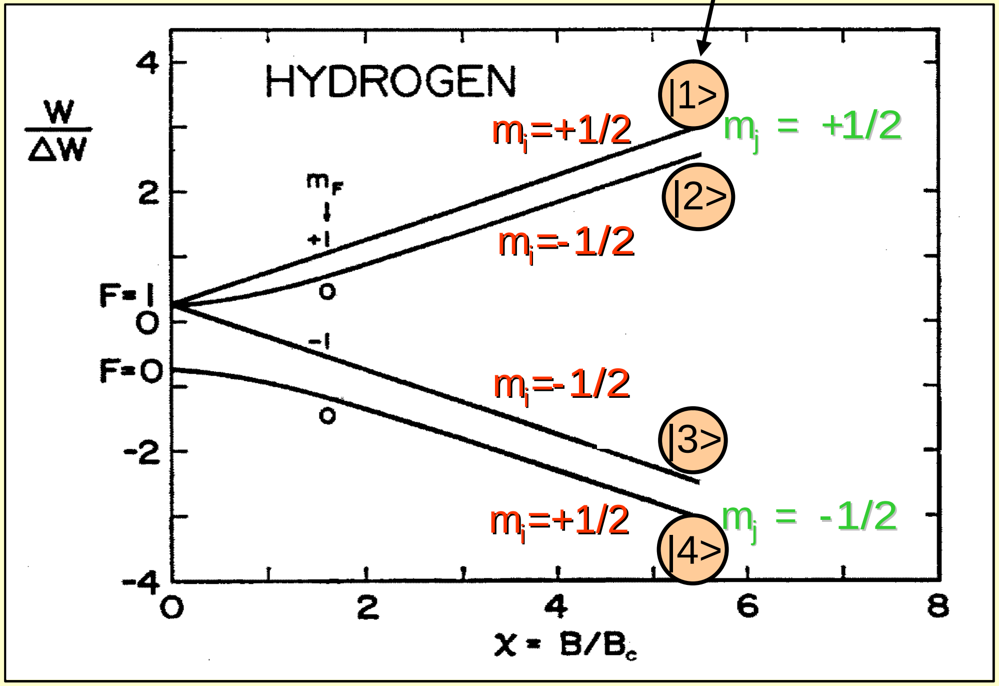
The HERMES target



Atomic Beam Source

NIM A 505, (2003) 633



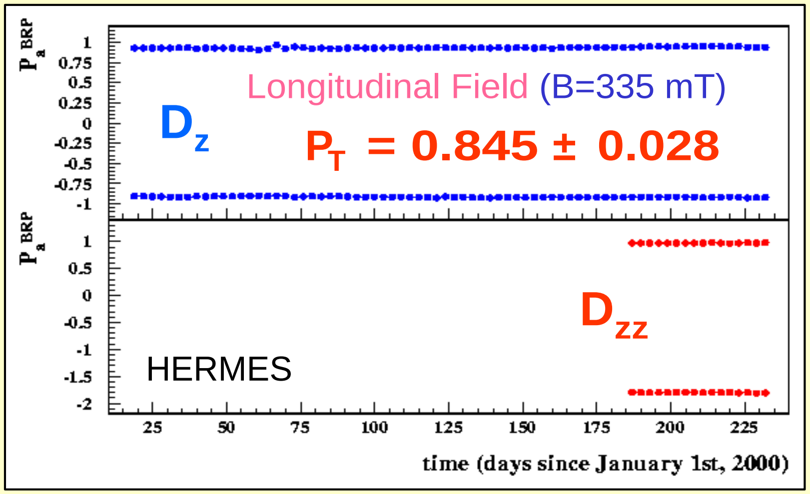


$$P_{z+} = |1> + |4>$$

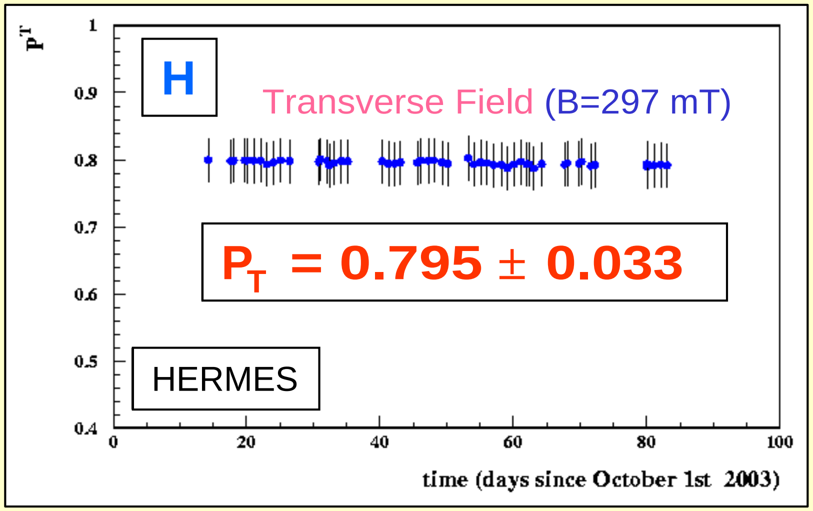
$$P_{z-} = |2> + |3>$$

Performance of Polarized Internal Targets

HERMES: Stored Positrons

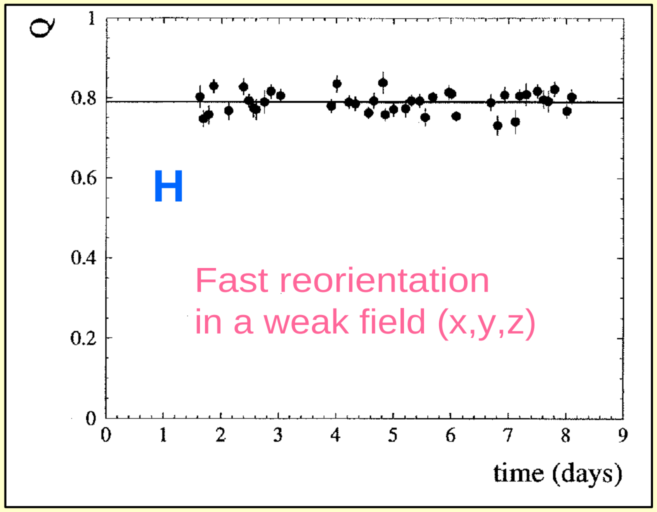

Longitudinal Field (B=335 mT)

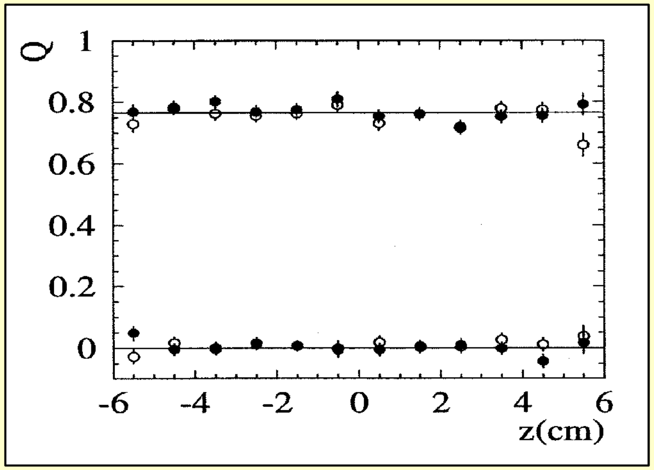
$P_T = 0.845 \pm 0.028$


Transverse Field (B=297 mT)

$P_T = 0.795 \pm 0.033$

PINTEX: Stored Protons

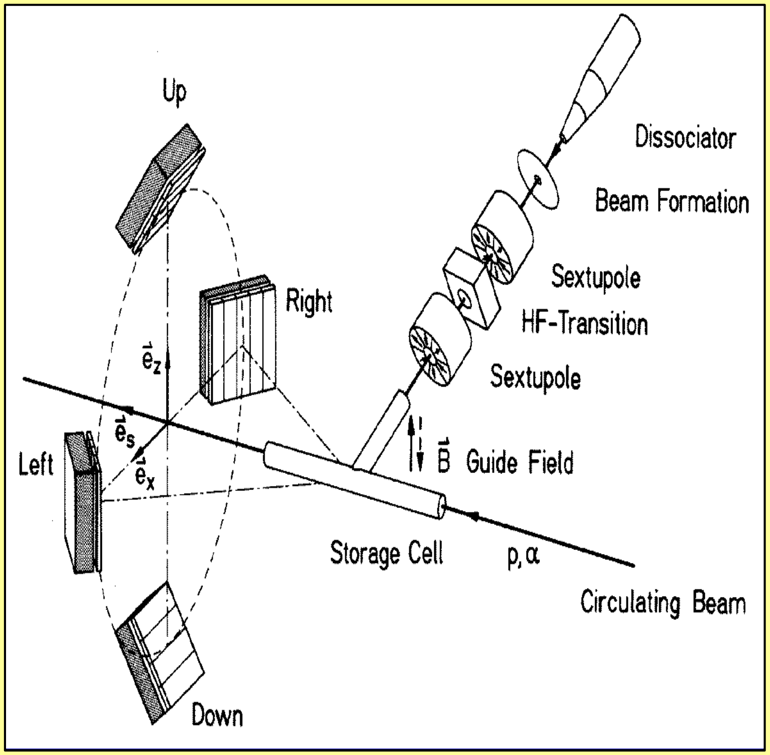

Fast reorientation
in a weak field (x,y,z)



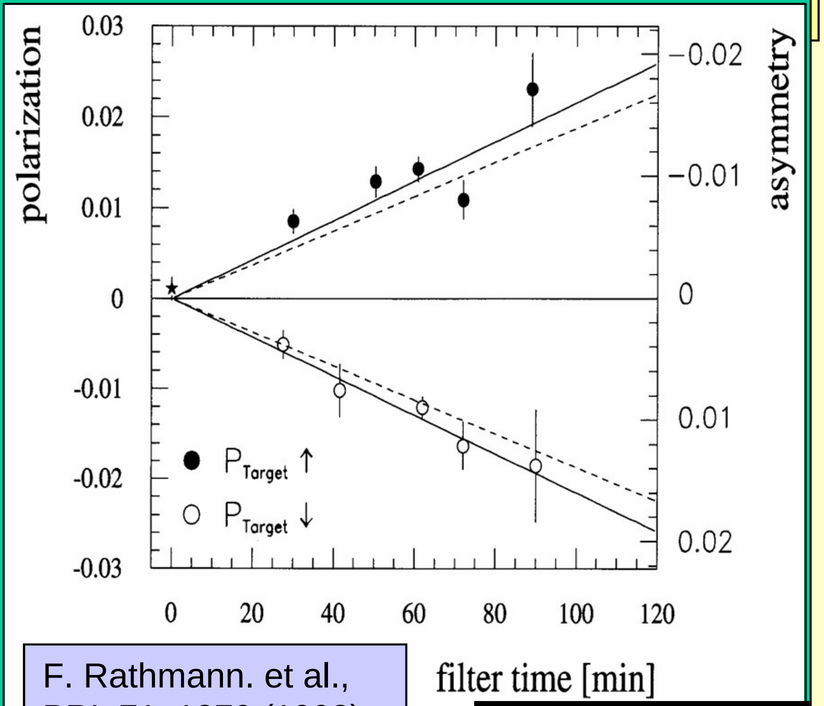
Targets work very reliably (months of stable operation)

Exploitation of Spin Transfer

PAX will employ spin-filter from internal polarized hydrogen target to antiprotons



FILTEX Results



F. Rathmann. et al., PRL 71, 1379 (1993)

Low energy pp scattering
$\sigma_1 < 0 \Rightarrow \sigma_{tot+} < \sigma_{tot-}$

Expectation	
Target	Beam
↑	↑
↓	↓

Puzzle from FILTEX Test

Observed polarization build-up: $dP/dt = \pm(\mathbf{1.24 \pm 0.06}) \times 10^{-2}\ h^{-1}$

Expected build-up: $P(t)=\tanh(t/\tau_{pol})$,

$1/\tau_{pol}=\sigma_1 Q d_t f$ $\mathbf{=2.4x10^{-2}\ h^{-1}}$

⇒ **about factor 2 larger!**

σ_1 = 122 mb (pp phase shifts)

Q = 0.83 ± 0.03

d_t = (5.6 ± 0.3) x 10^{13} cm^{-2}

f = 1.177 MHz

Three distinct effects (measured σ_1=65 mb):

1. **Selective removal through scattering beyond Ψ_{acc}=4.4 mrad**

   $\sigma_{R\perp}$=83 mb

2. **Small angle scattering of target protons into ring acceptance**

   $\sigma_{S\perp}$=52 mb

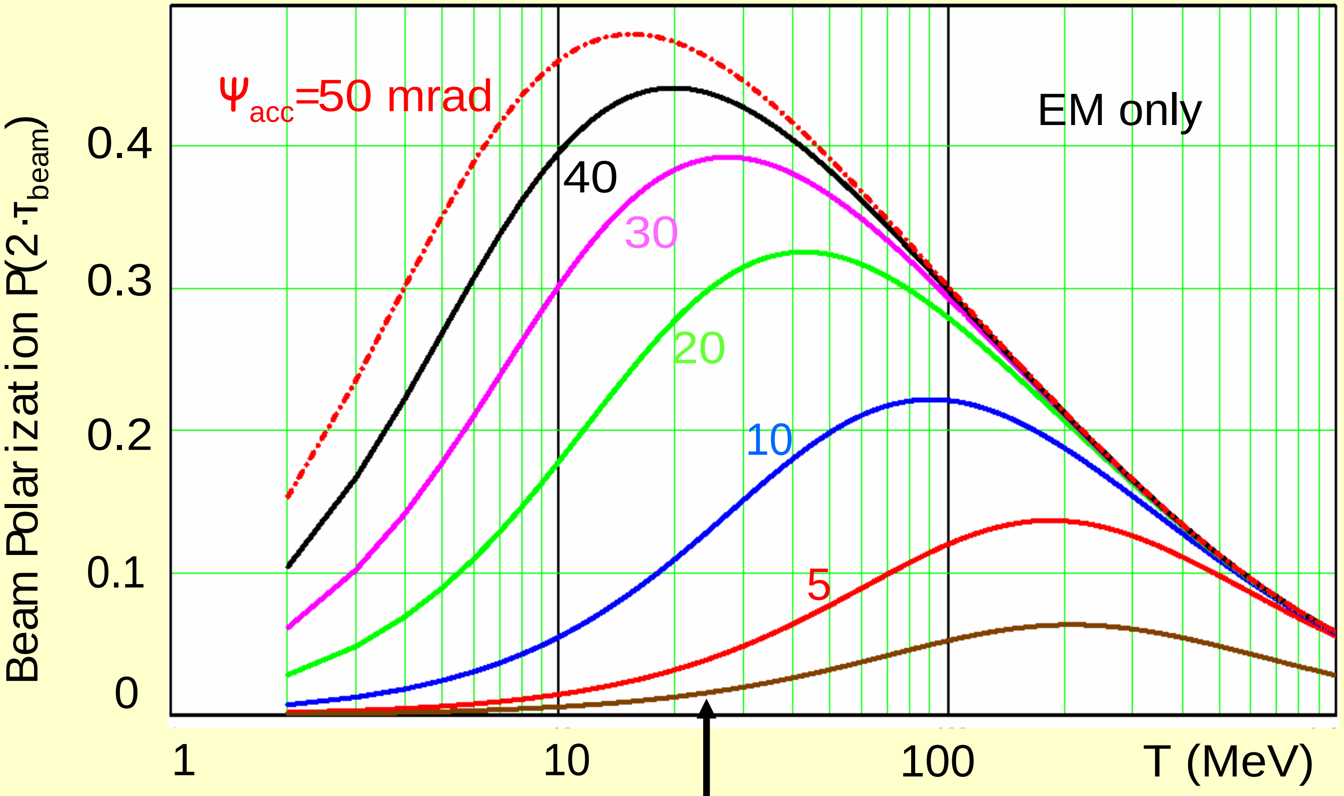
3. **Spin transfer from polarized electrons of the target atoms to the stored protons**

   $\sigma_{EM\perp}$=70 mb (-)

Horowitz & Meyer, PRL 72, 3981 (1994)
H.O. Meyer, PRE 50, 1485 (1994)

Beam Polarization

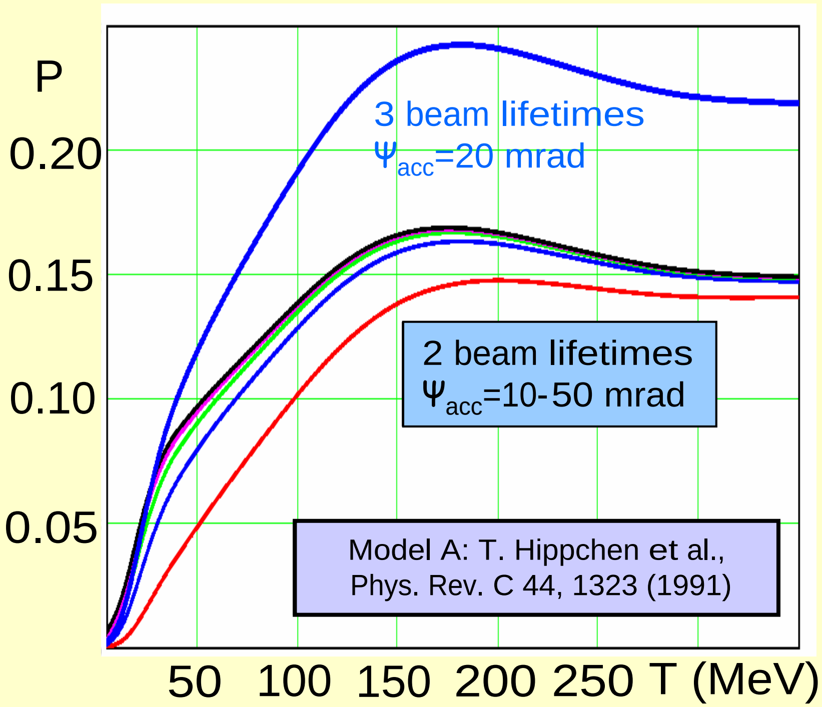
(Electromagnetic Interaction)



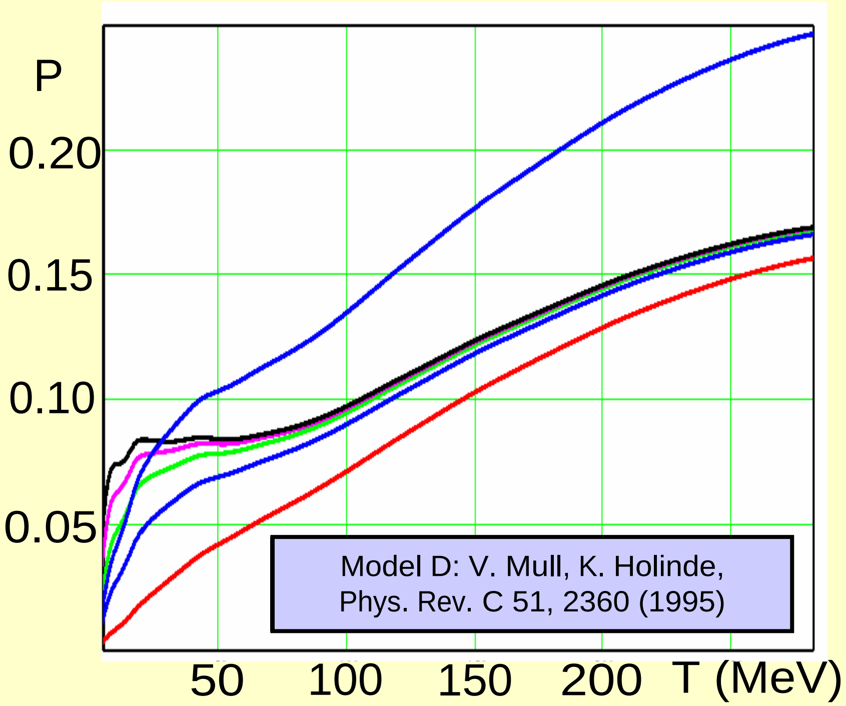
Filter Test: T = 23 MeV
Ψ_{acc}= 4.4 mrad

Beam Polarization

(Hadronic Interaction: Longitudinal Case)



Model A: T. Hippchen et al., Phys. Rev. C 44, 1323 (1991)



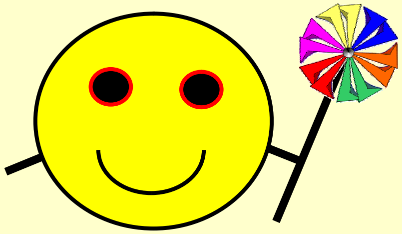
Model D: V. Mull, K. Holinde, Phys. Rev. C 51, 2360 (1995)

Experimental Tests required:

- **EM effect needs protons only (COSY)**
- **Final Design of APR: Filter test with p at AD (CERN)**

From COSY to FAIR...

- Study of spin-filtering process.
- **Electromagnetic interaction:** unpolarized protons on polarized internal target at COSY
- **Hadronic interaction:** unpolarized antiprotons on polarized internal target at AD (CERN).



SMILE:
Spin Measurements
in Interactions at Low Energy

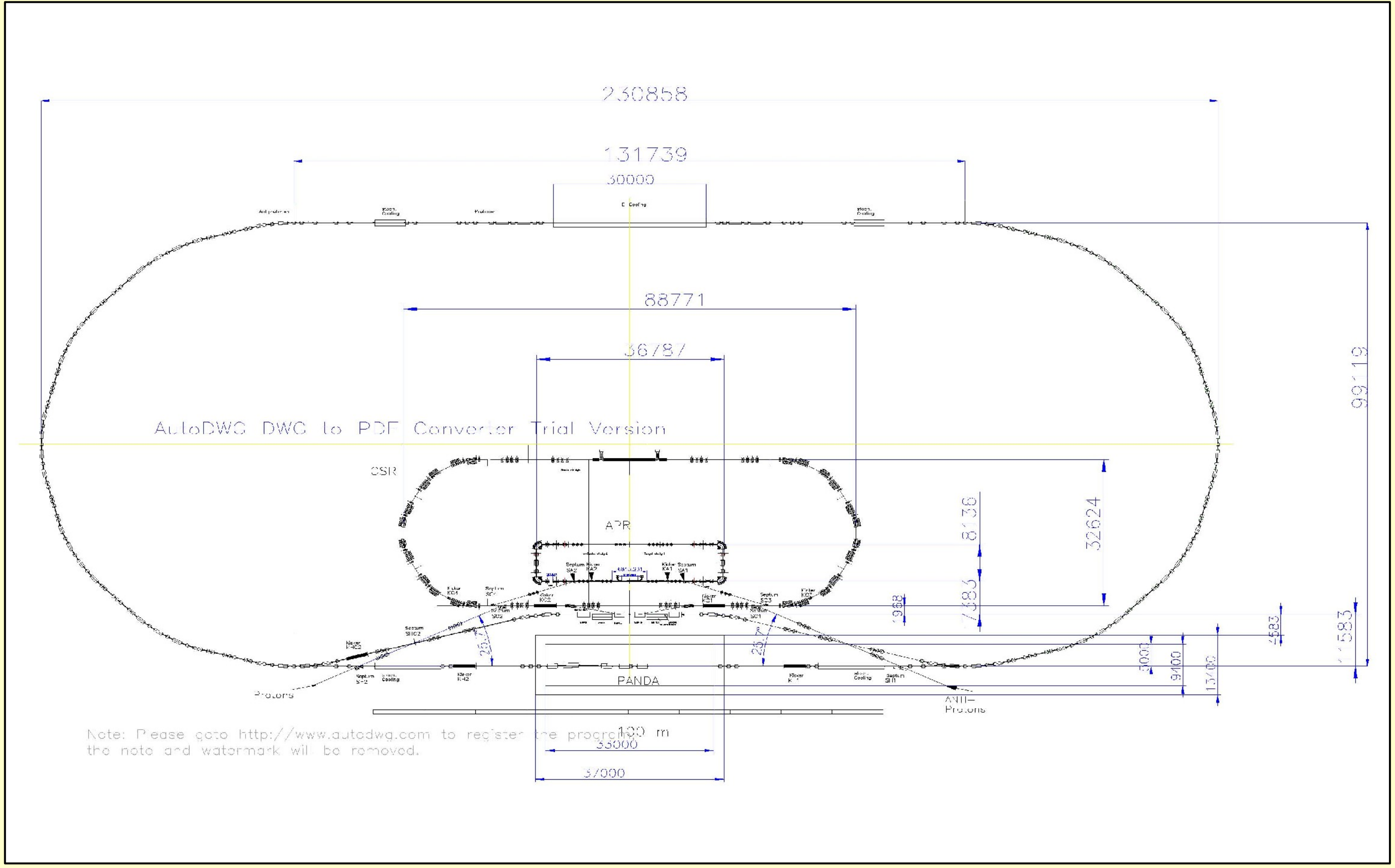
Outline

- Introduction
  - Physics Case
  - The FAIR project

- PAX Accelerator Setup
  - Staging
  - Antiproton Polarizer Ring
  - Asymmetric Antiproton-Proton Collider

- Experiment
  - Conceptual Detector Design
  - Preliminary Results for Drell-Yan Studies
  - Rate estimates

RINGS SETUP



asymmetric collider $L = 2 \cdot 10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

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PAX Detector Concept

Physics: h_1 distribution $\sin^2\theta$
EMFF $\sin 2\theta$
pbar-p elastic high |t|

→ Azimuthally Symmetric:
BARREL GEOMETRY
LARGE ANGLES

Experiment: Flexible Facility

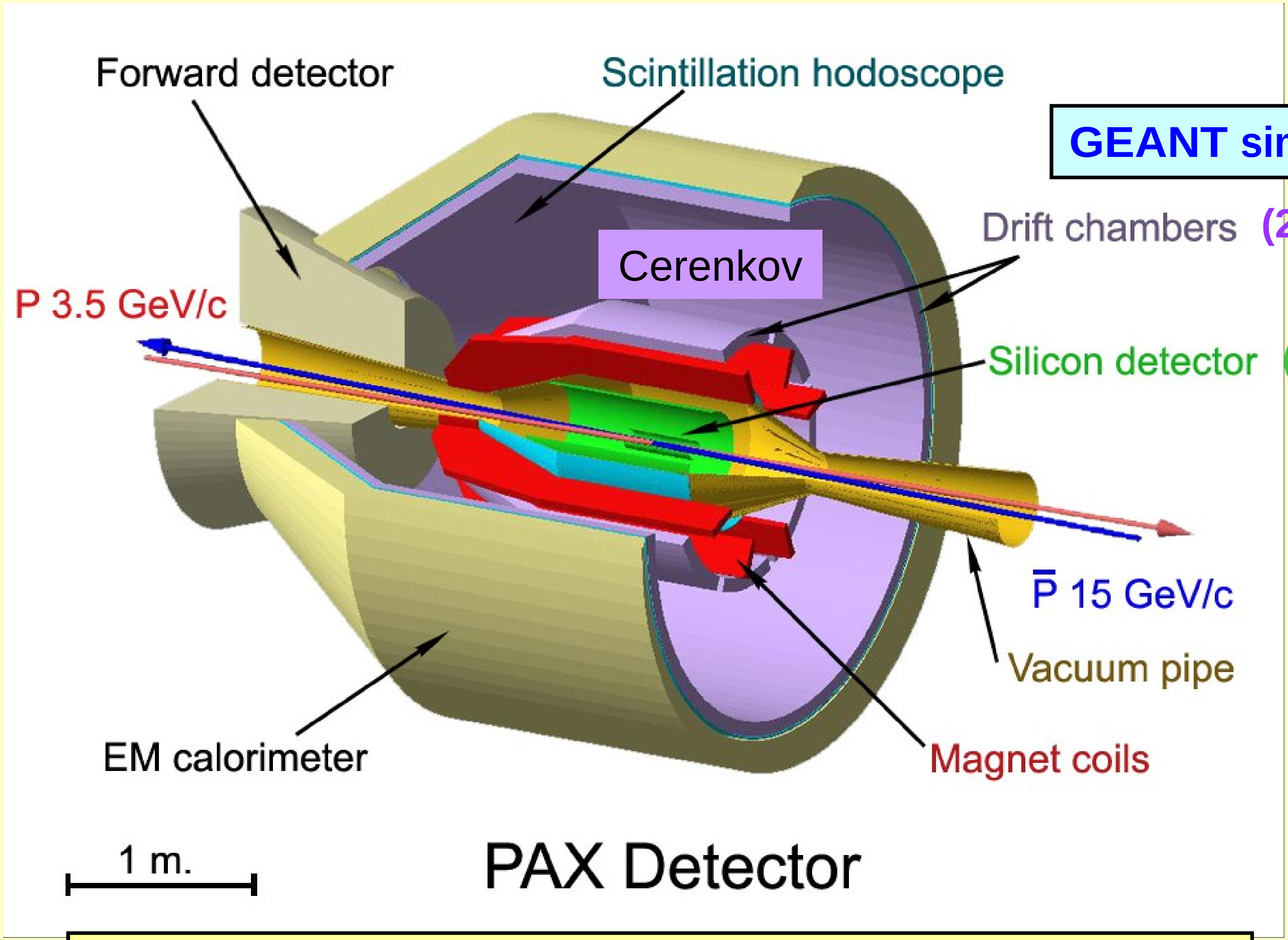
Detector: Extremely rare DY signal (10^{-7} p-pbar)
Maximum Bjorken-x coverage (M interval)
Excellent PID (hadron/e rejection ~ 10^4)
High mass resolution ($\lesssim$2 %)
Moderate lepton energies (0.5-5 GeV)

→ e^+e^-

Magnet: Keeps beam polarization vertical
Compatible with Cerenkov
Compatible with polarized target

→ TOROID
NO FRINGE FIELD

PAX Detector Concept



GEANT simulation

Designed for Collider but compatible with fixed target

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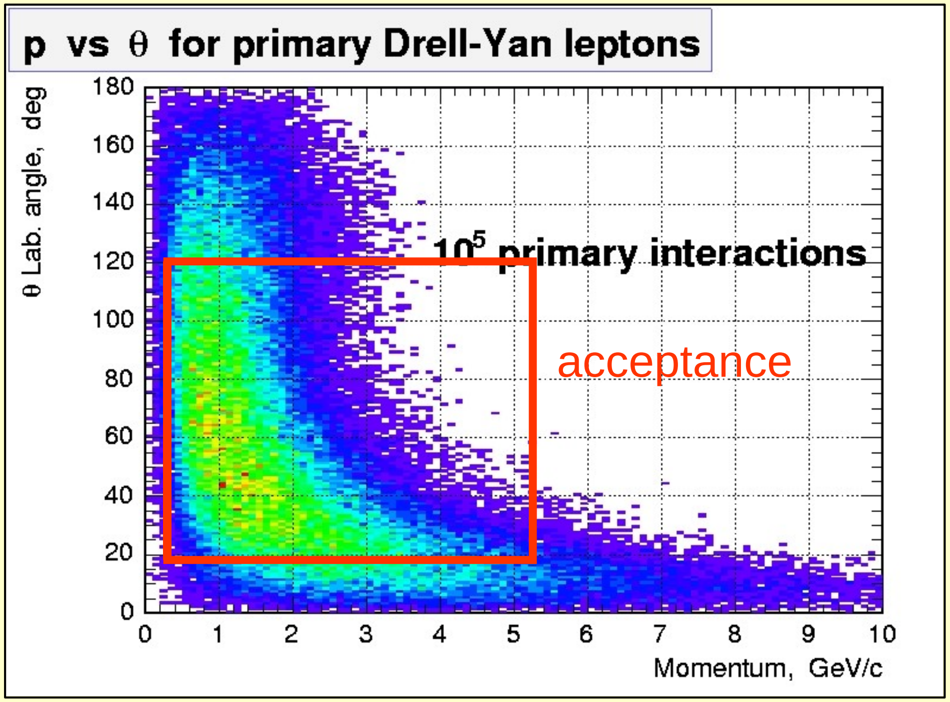
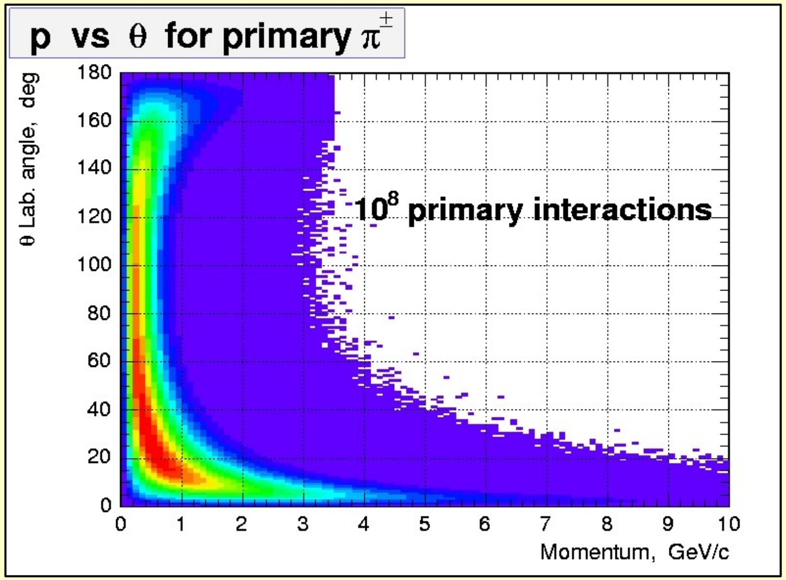
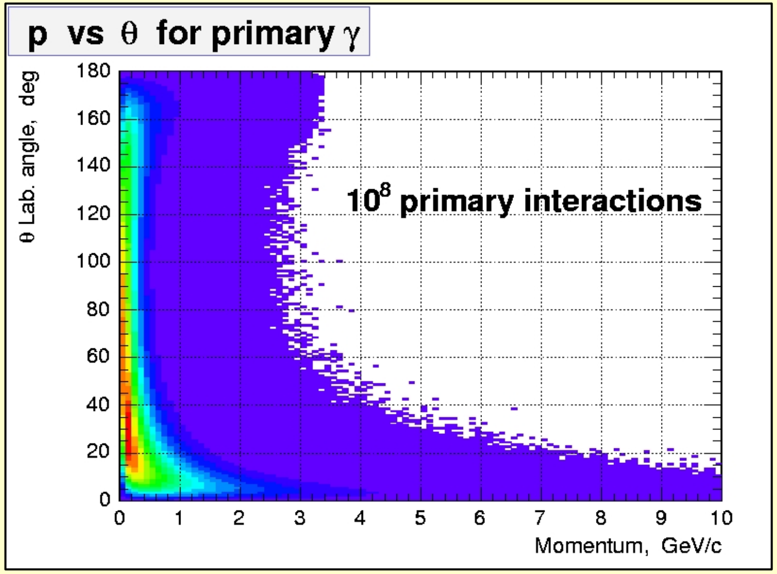
θ- p Phase Space



p vs θ for primary Drell-Yan leptons



p vs θ for primary $\pi^{\pm}$



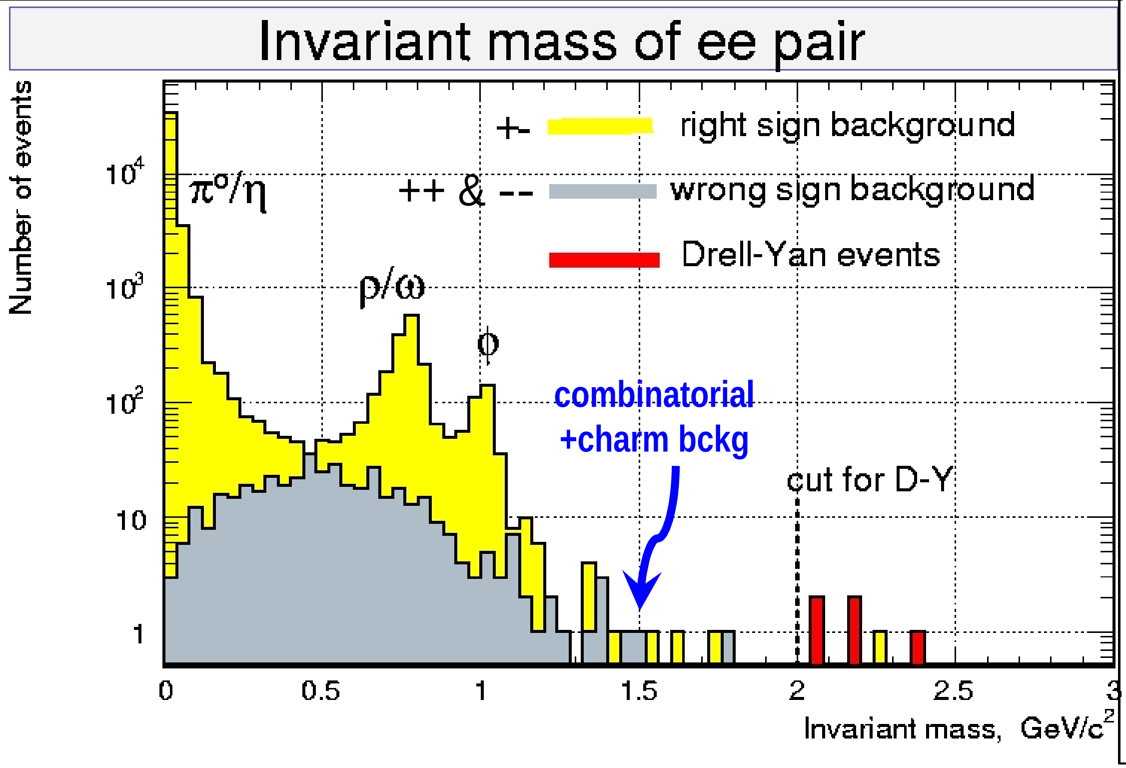
p vs θ for primary γ

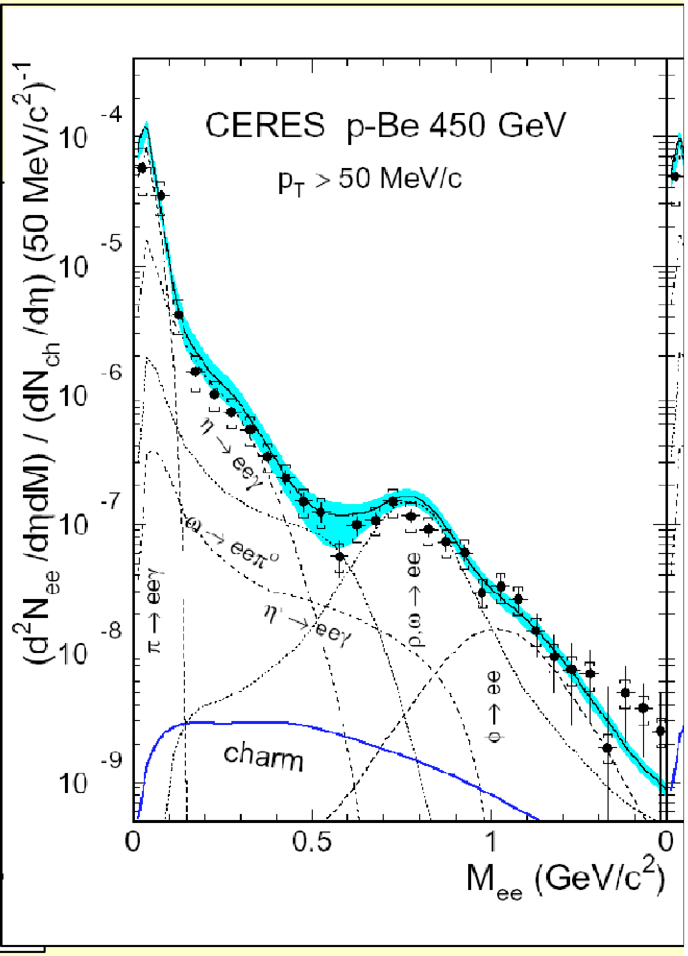
Background peaks at

- * low energy
- * forward direction

Background to Drell- Yan e^+e^-

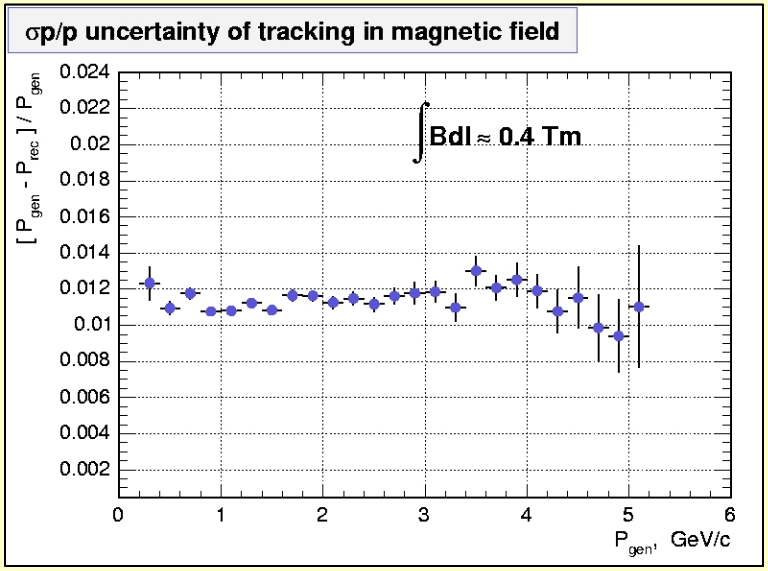
½ hour experiment: $2 \cdot 10^8$ p- pbar interactions
several DY events

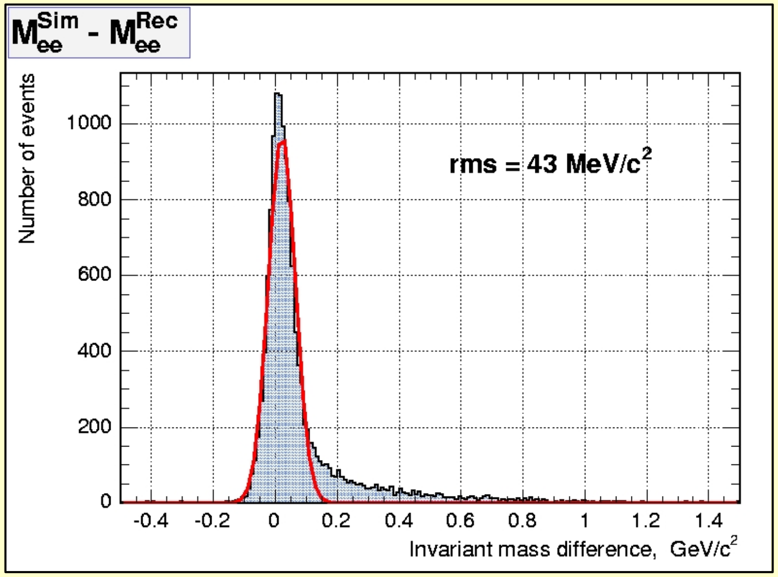


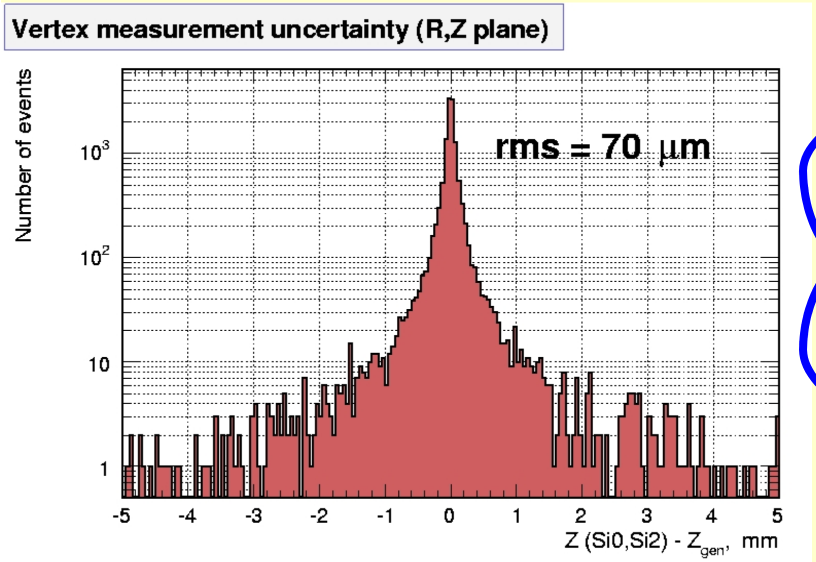


Background 1:1 to signal after PID, E>300 MeV, conversion veto, mass cut
* the combinatorial component can be subtracted (wrong- sign control sample)
* the charm can be reduced (vertex decay)

θ- p Phase Space


σp/p uncertainty of tracking in magnetic field


$M_{ee}^{Sim} - M_{ee}^{Rec}$


Vertex measurement uncertainty (R,Z plane)

Better than 2% mass resol
*** x dependence of h_1**
*** resonance vs continuum**

Mandatory to study M below J/ψ mass

Vertex resolution high enough
to study charm background

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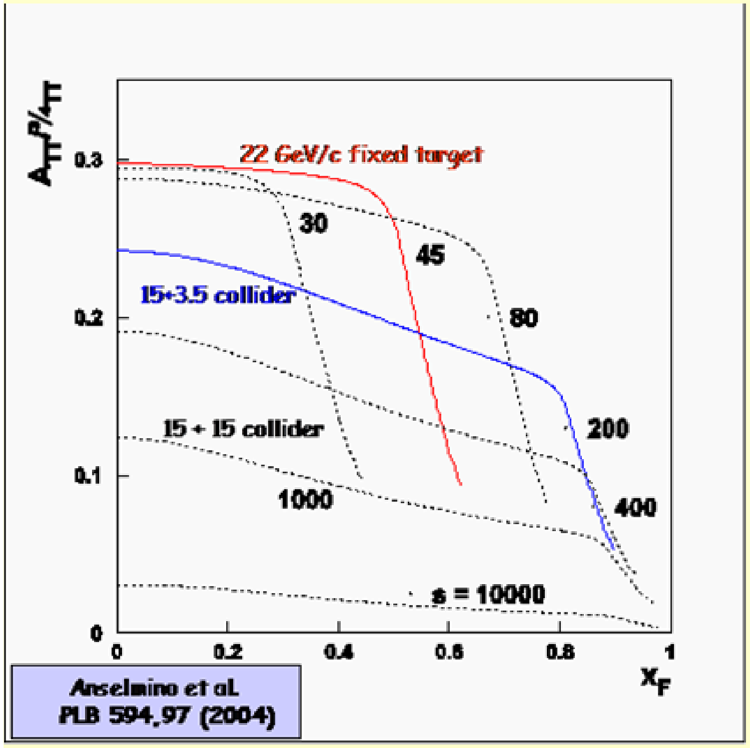
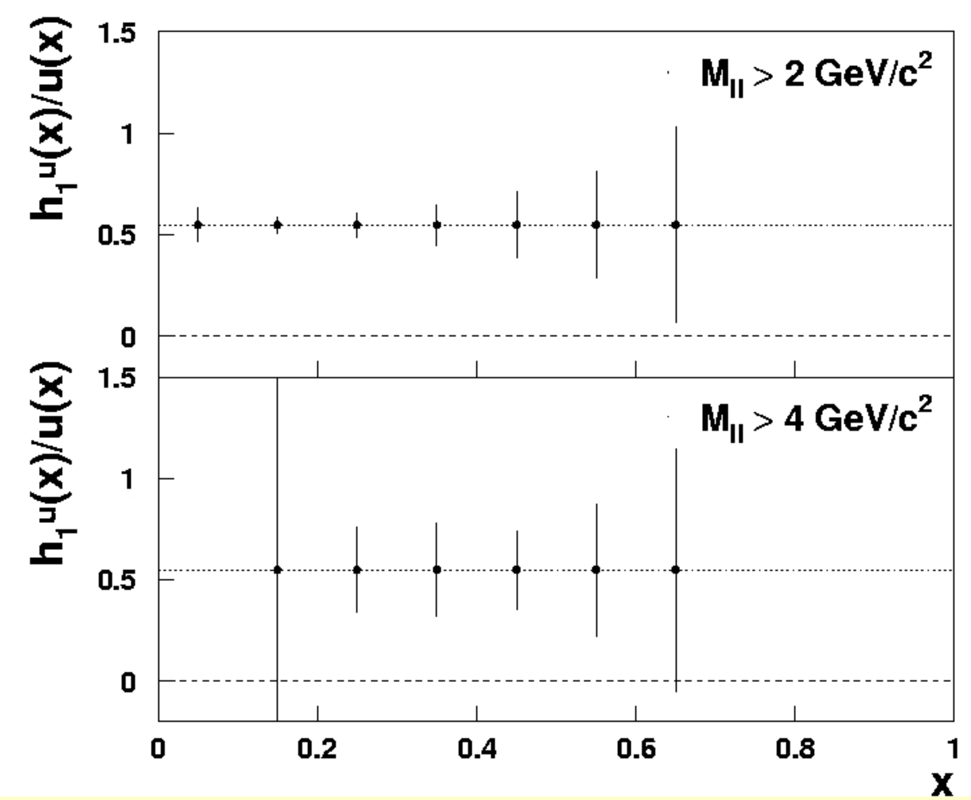
Precision in h_1 measurement

1 year of data taking at 15+3.5 GeV collider $L = 2 \cdot 10^{30}\ cm^{-2}s^{-1}$



Anselmino et al.
PLB 594,97 (2004)



10 % precision on the h_1^u (x) in the valence region

Summary

- PAX project has an innovative spin physics program
  - * transversity
  - * SSA
  - * EMFF
  - * hard p-pbar scatterings

- A method to obtain an antiproton beam with high degree of polarization has to be optimized (APR)

- PAX viable accelerator setup provides fexible 2nd IP really matched to the physics items
  - * lots of interesting QCD physics in PAX Phase-I
  - * asymmetric collider ideal to map transversity (Phase-**II)**