Possible future experiments on hadron structure at FAIR

Study of the proton structure with (polarized) interactions at FAIR

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Hirshegg.18.01.11

Outline

- Polarized proton-antiproton interactions
- Polarized DIS
- Status of polarized antiprotons studies

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- Polarized DIS
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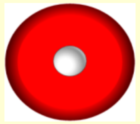
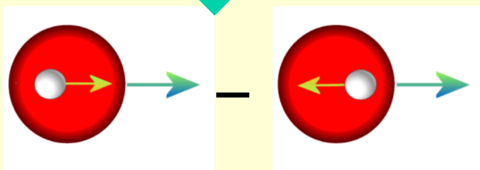
Quark structure of the nucleon

$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ \boxed{q(x)} + S_L \boxed{\Delta q(x)}\gamma_5 + \boxed{\delta q(x)}\gamma_5\gamma^1 S_T \right\} n^+$$

q = 

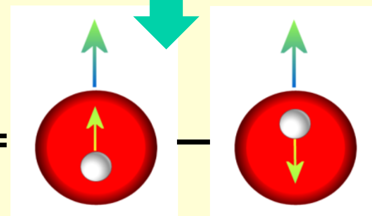
unpolarised quarks and nucleons

Well known

Δq= 

longitudinally polarised quarks and nucleons

Known

δq= 

transversely polarised quarks and nucleons

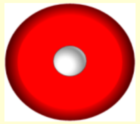
Less known

Peculiarities of δq

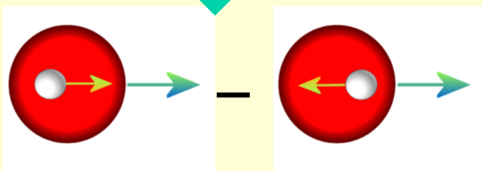
- probes relativistic nature of quarks
  →otherwise $\delta q = \Delta q$
- no gluon analog for spin-1/2 nucleon
  →different Q^2 evolution than Δq
- sensitive to *valence* quark polarisation
- only known way to obtain tensor charge

Quark structure of the nucleon

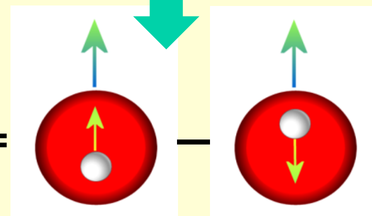
$$\Phi^{\mathrm{Tw2}}_{\mathrm{Corr}}(x) = \frac{1}{2}\left\{ \boxed{q(x)} + S_L \boxed{\Delta q(x)}\gamma_5 + \boxed{\delta q(x)}\gamma_5 \gamma^1 S_T \right\} n^+$$

$q =$ 

unpolarised quarks and nucleons

$\Delta q =$ 

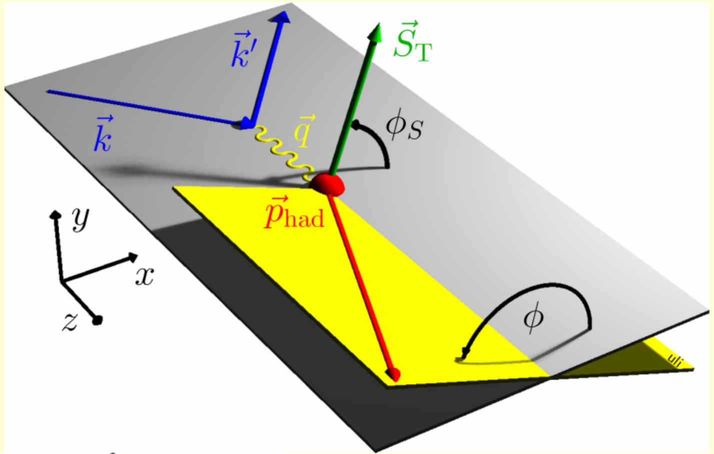
longitudinally polarised quarks and nucleons

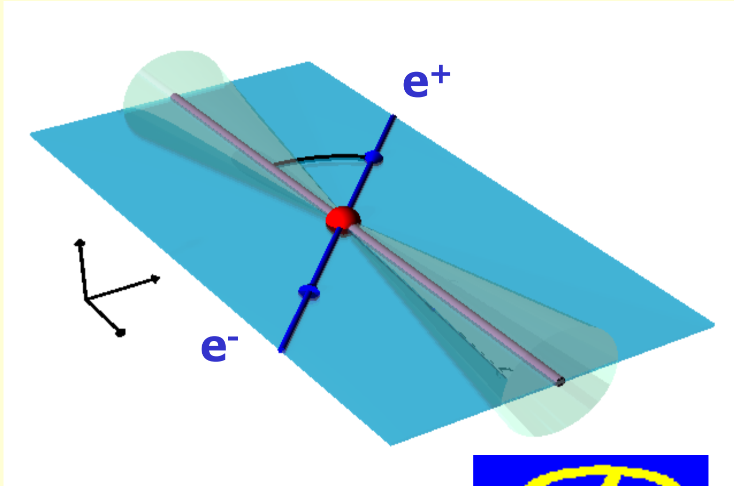
$\delta q =$ 

transversely polarised quarks and nucleons

Transversity with SIDIS

$$\boxed{A_{UT}^{\sin(\phi+\phi_S)}} \propto \delta q(x) \otimes \boxed{H_1^{\perp q}(z)}$$

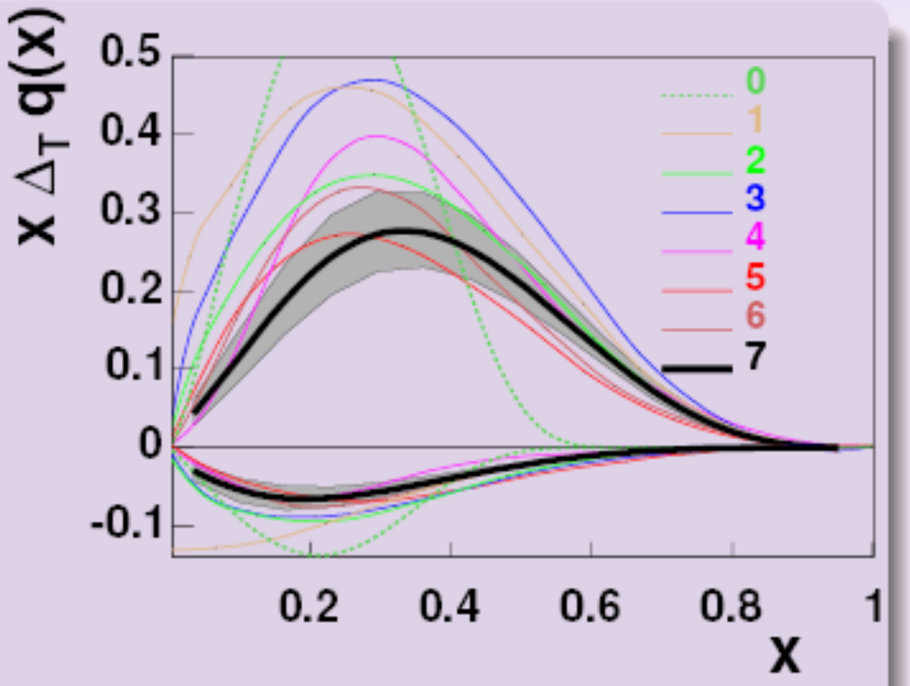




$e\,p^{\uparrow} \rightarrow e'\,\pi\,X$ $\quad e\,d^{\uparrow} \rightarrow e'\,h\,X$

$$e^+e^- \rightarrow \pi^+_{jet1}\,\pi^-_{jet2}\,X$$

New extraction (2008): close to most models



0. Barone, Calarco, Drago PLB 390 287 (97)
1. Soffer et al. PRD 65 (02)
2. Korotkov et al. EPJC 18 (01)
3. Schweitzer et al. PRD 64 (01)
4. Wakamatsu, PLB B653 (07)
5. Pasquini et al., PRD 72 (05)
6. Cloet, Bentz and Thomas PLB 659 (08)
7. This analysis.

A. Prokudin, Ferrara 2008

Can we claimed to have measured transversity? Well ...

SIDIS and BELLE at different scales: $\langle Q^2 \rangle = 2.4\ GeV^2$ vs $Q^2 = 110\ GeV^2$

Both azimuthal asymmetries involve TMDs beyond tree level

Anselmino et al. use:

$$H_1^{\perp}(z,k^2_{\perp}) = D_1(z)F(z,k^2_{\perp})$$

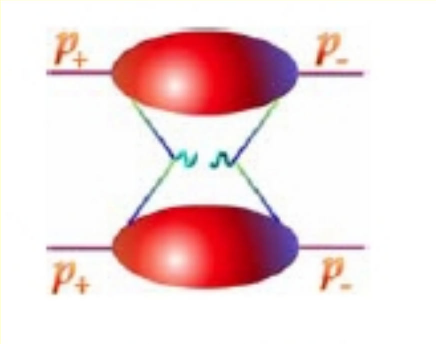
Evolution is taken to be the one of $D_1(z)$

Modification of the $k_{\perp}$ dependence is also important

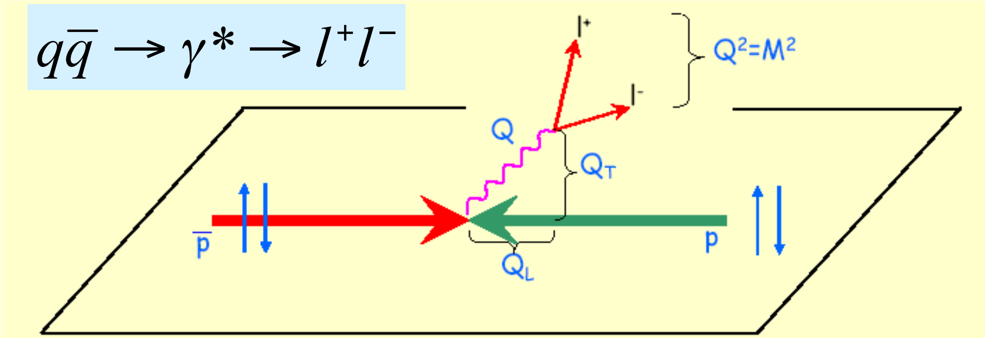
Extraction from SIDIS remains a hard theoretical challenge

New (possibly) direct measurements needed:

The "golden-gate" to transversity: h_1 from $\bar{p}\uparrow$-p $\uparrow$ Drell-Yan



Drell-Yan



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

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

M invariant Mass of lepton pair

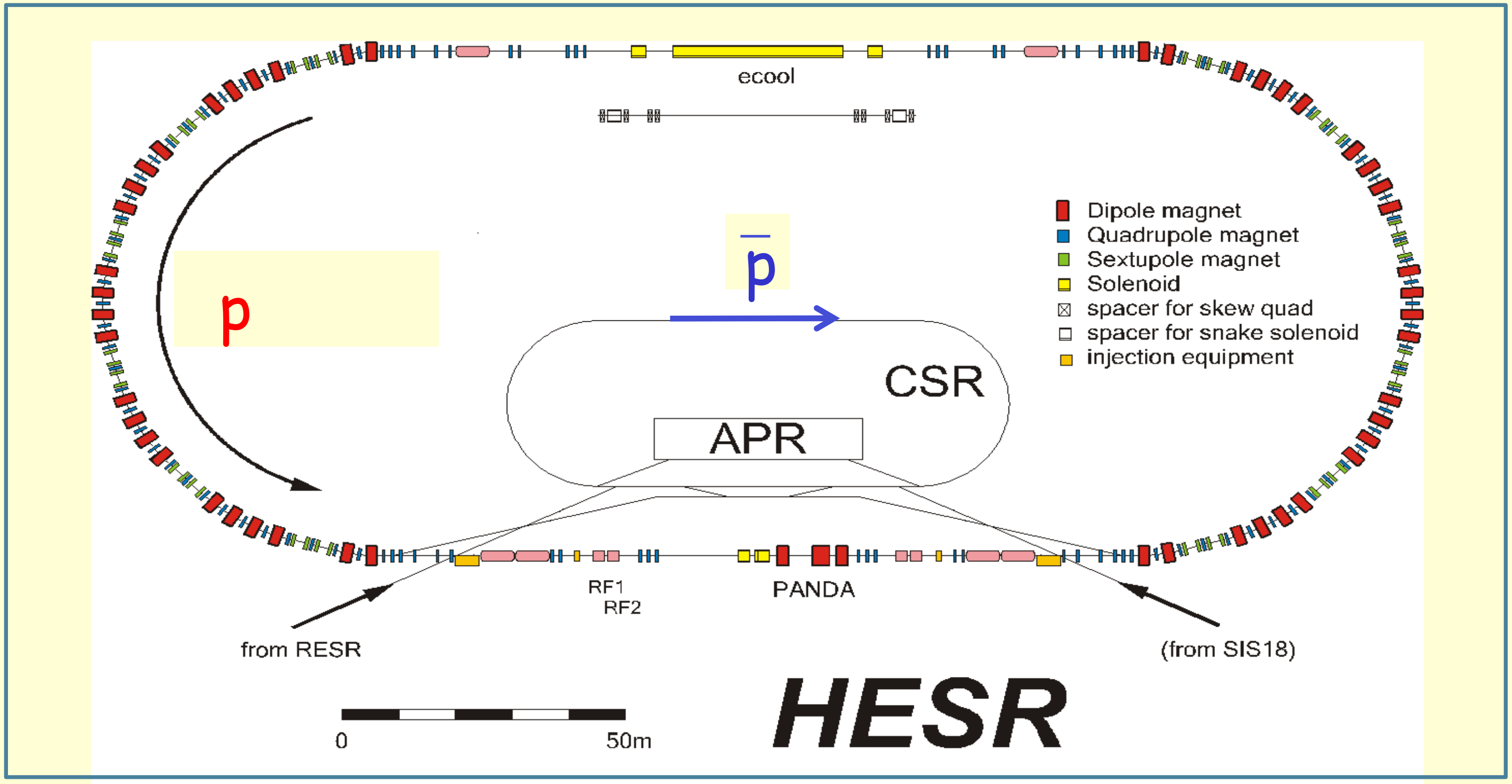
$$x_F = x_1 - x_2 \qquad x_1 x_2 = M^2/s \equiv \tau \qquad x_F = 2Q_L/\sqrt{s}$$

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

A double polarized pbar-p collider for FAIR

Asymmetric (double-polarized)

proton (15 GeV/c) - antiproton (3.5 GeV/c) collider



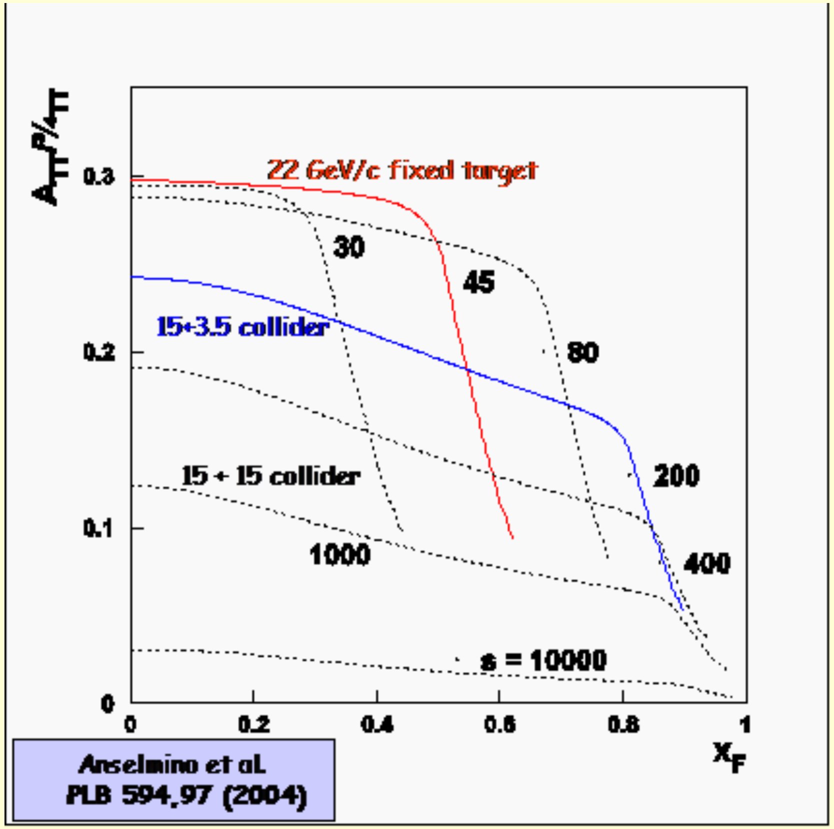
h_{1u} from $\bar{p}\uparrow$-$p\uparrow$ Drell-Yan at PAX

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

- **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 : $M^2/s = x_1 x_2 \sim 0.02-0.3$
valence quarks
(A_{TT} large ~ 0.2-0.3)



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

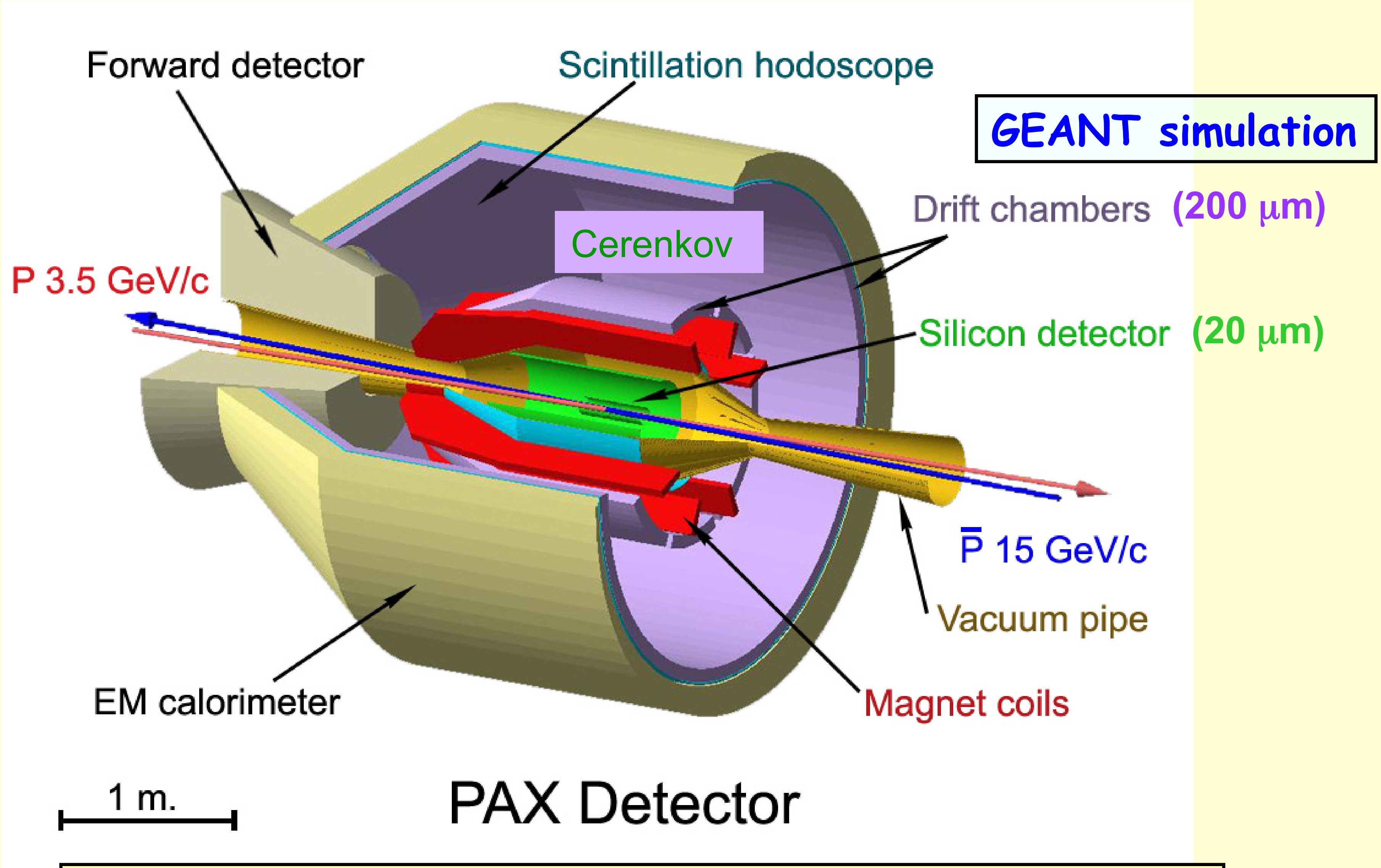
⇒ e^+e^-

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)

Magnet:
Keeps beam polarization vertical
Compatible with Cerenkov
Compatible with pol. target

⇒ TOROID
NO FRINGE FIELD

PAX Detector Concept

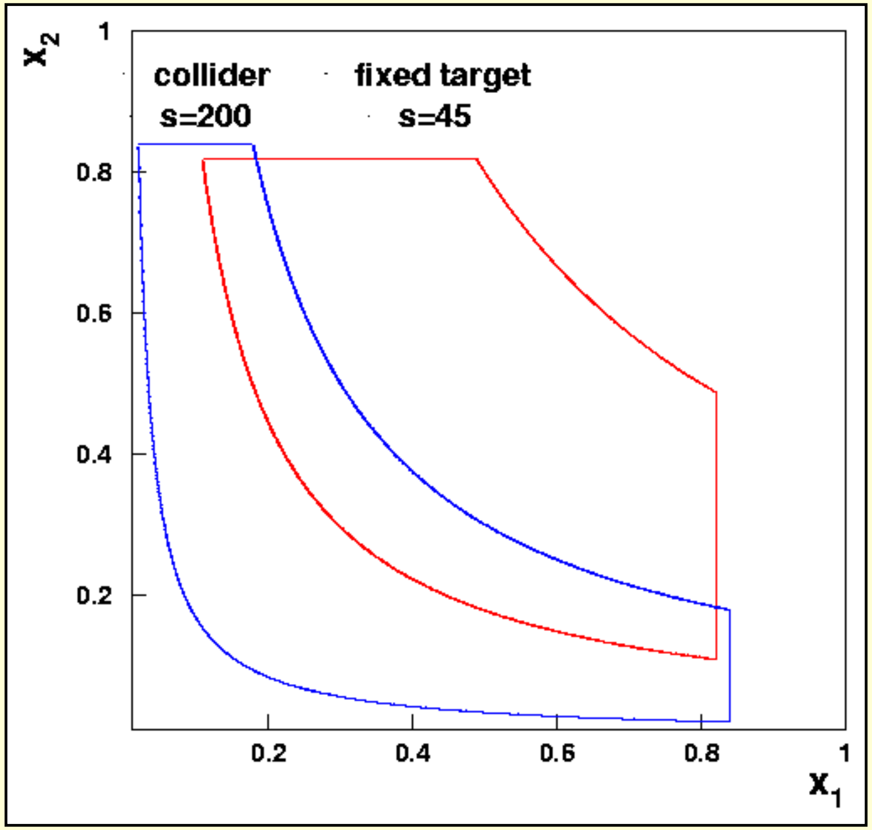


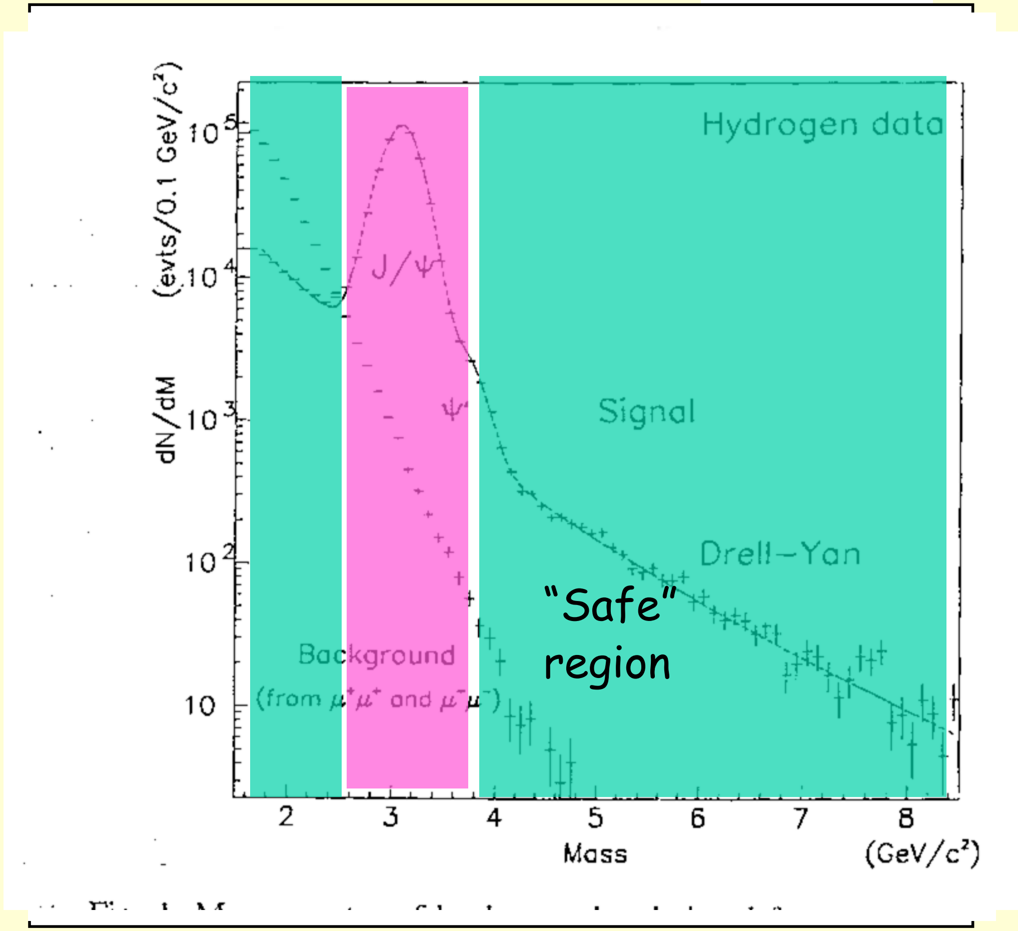
Designed for Collider but compatible with fixed target

Kinematics for Drell-Yan process

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

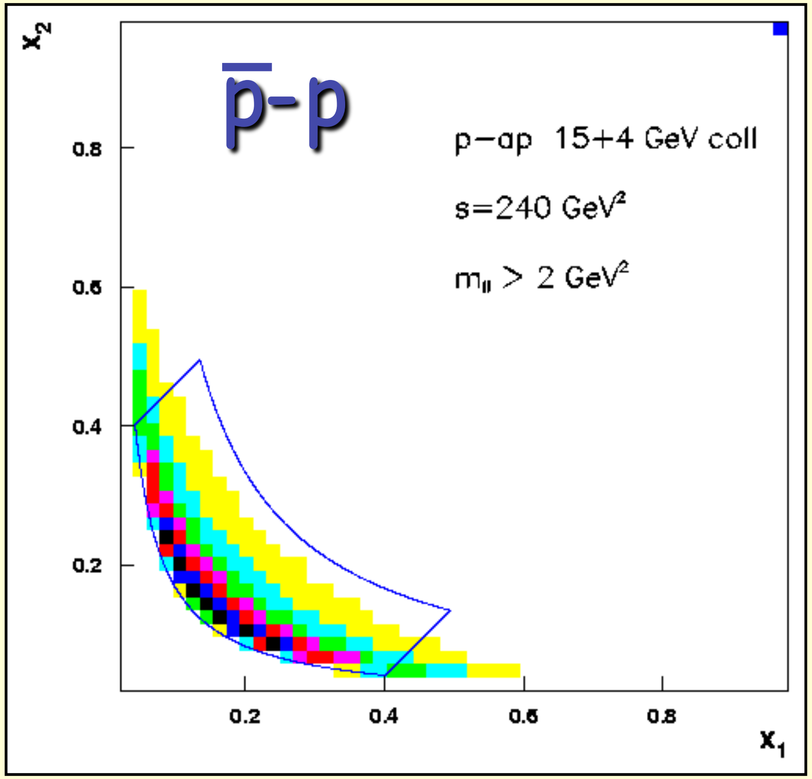
- $M^2 = s\, x_1 x_2$
- $x_F = 2Q_L/\sqrt{s} = x_1 - x_2$

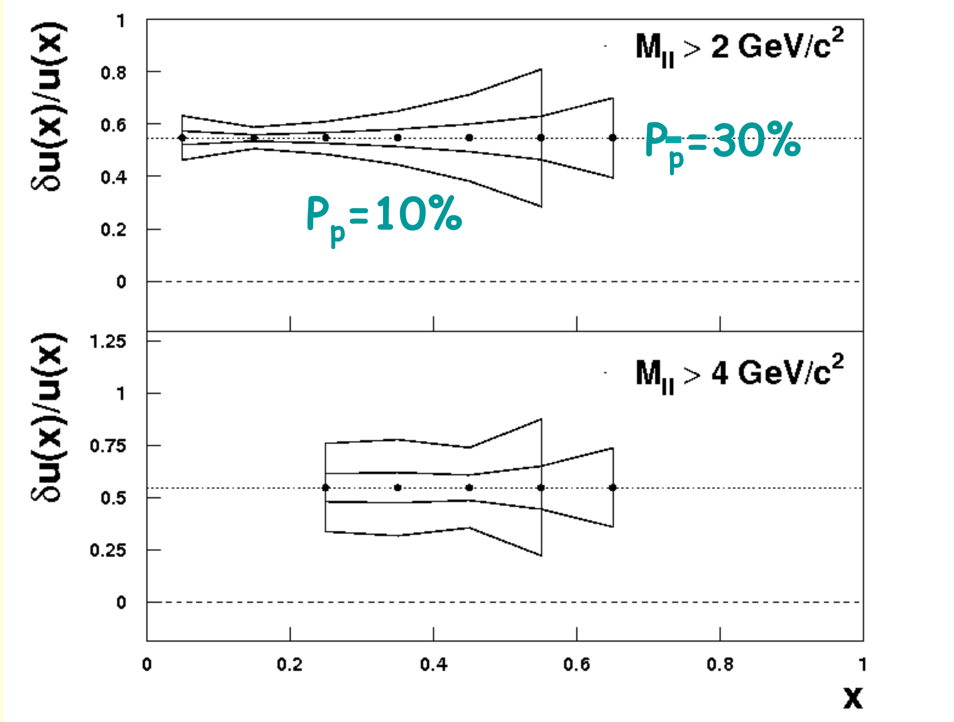




Precision in h_1 measurement

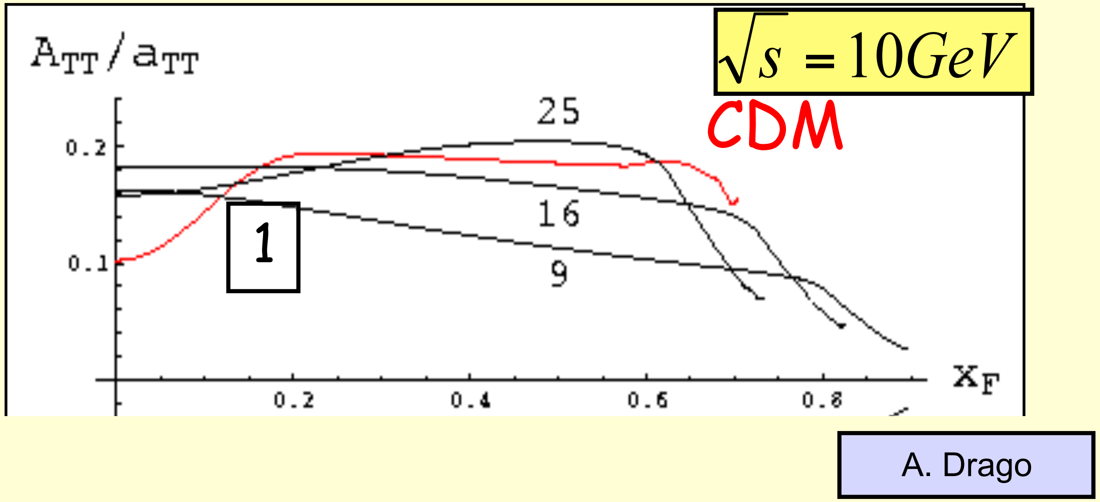
1 year of data taking at 15+3.5 GeV collider $L = 1.5 \cdot 10^{31}$ $cm^{-2}s^{-1}$





1 year run -> 10 % precision on the h_1^u (x) in the valence region

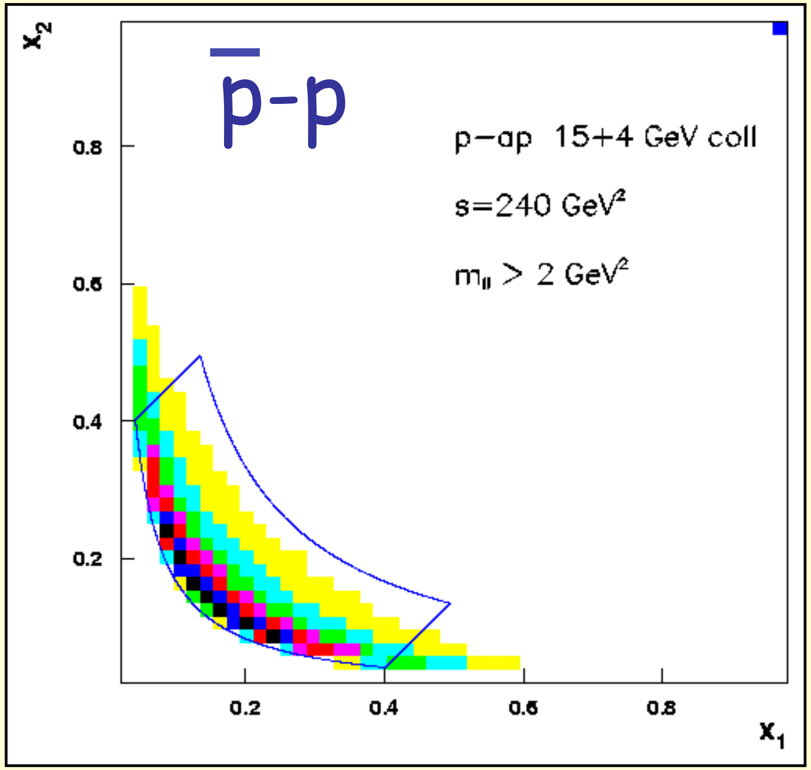
Another option: DY from p↑-p↑

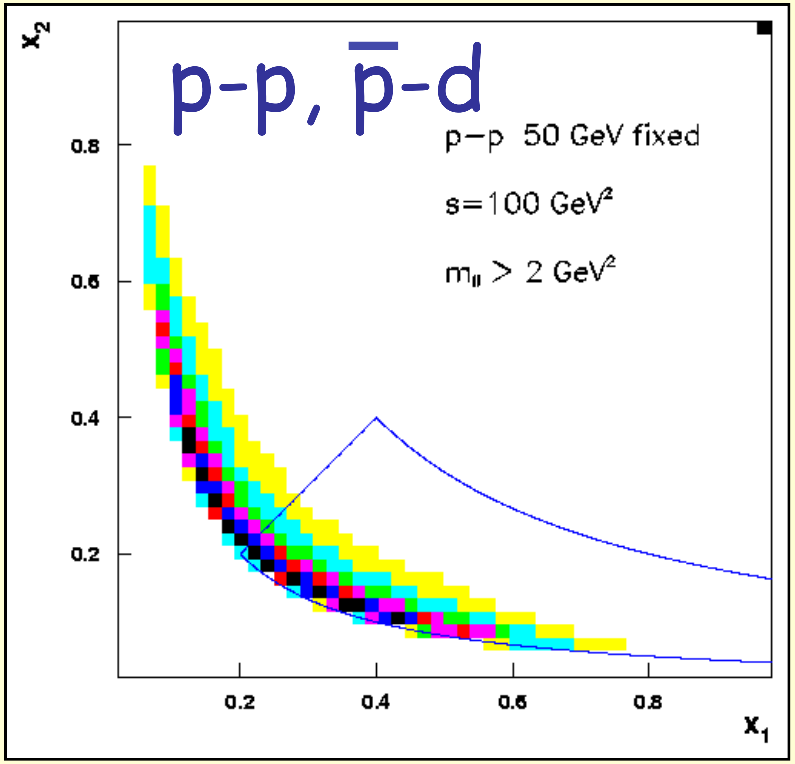


Asymmetries are estimated to be large at PAX energies -> access to $h_{1\bar{u}}(x)$

RHIC:	$\tau=x_1x_2\sim10^{-3}$ →	sea quarks	(A_{TT} ~ 0.01)
JPARC/U70:	$\tau=x_1x_2\sim10^{-1}$ →	valence and sea	(A_{TT} ~ 0.1)
PAX:	$\tau=x_1x_2\sim10^{-1}$ →	valence and sea	(A_{TT} ~ 0.1)

DY events distribution ($p\uparrow\bar{p}\uparrow$, $p\uparrow p\uparrow$ and $\bar{p}\uparrow d\uparrow$)





$M^2/s = x_1x_2 \sim 0.02\text{-}0.3$

At $x_1=x_2$ $A_{TT} \sim h_{1u}^2$ → Extraction of h_{1d}, $h_{1\bar{q}}$ for x<0.2

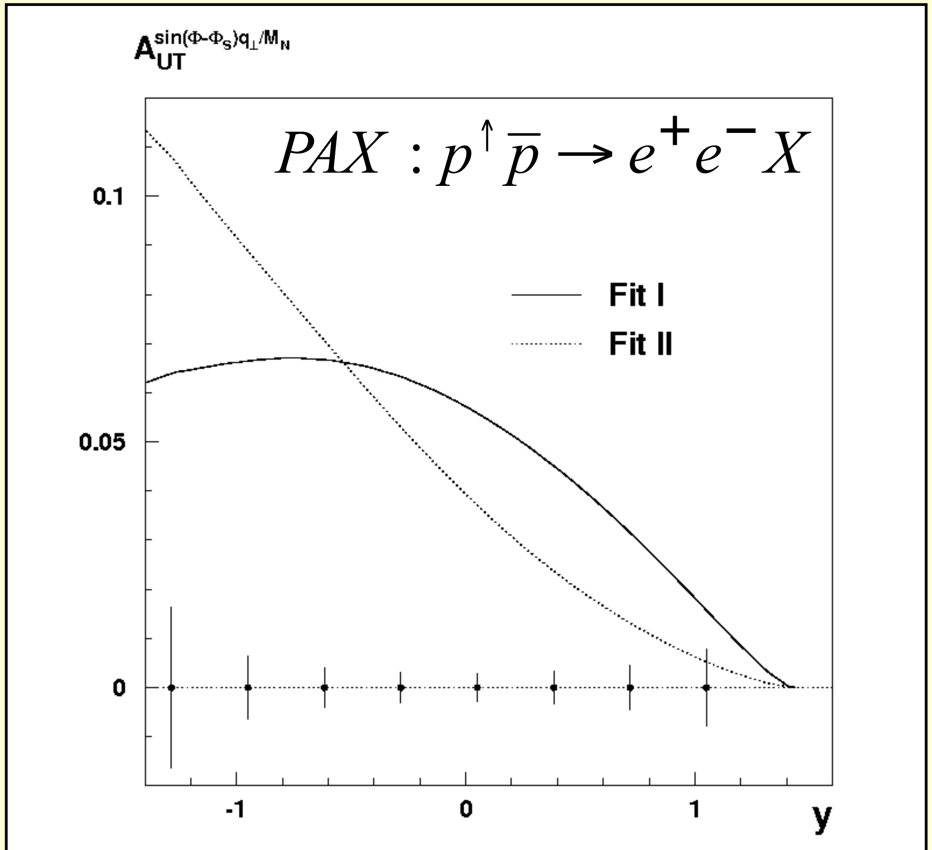
Direct measurement of h_{1u} for 0.05<x<0.5

$\bar{p}\uparrow p\uparrow$: Any combination of polarization possible: A_{LT}, A_{LL}

Sivers function from $\bar{p}\uparrow p$ or $\bar{p}p\uparrow$ Drell-Yan @ PAX

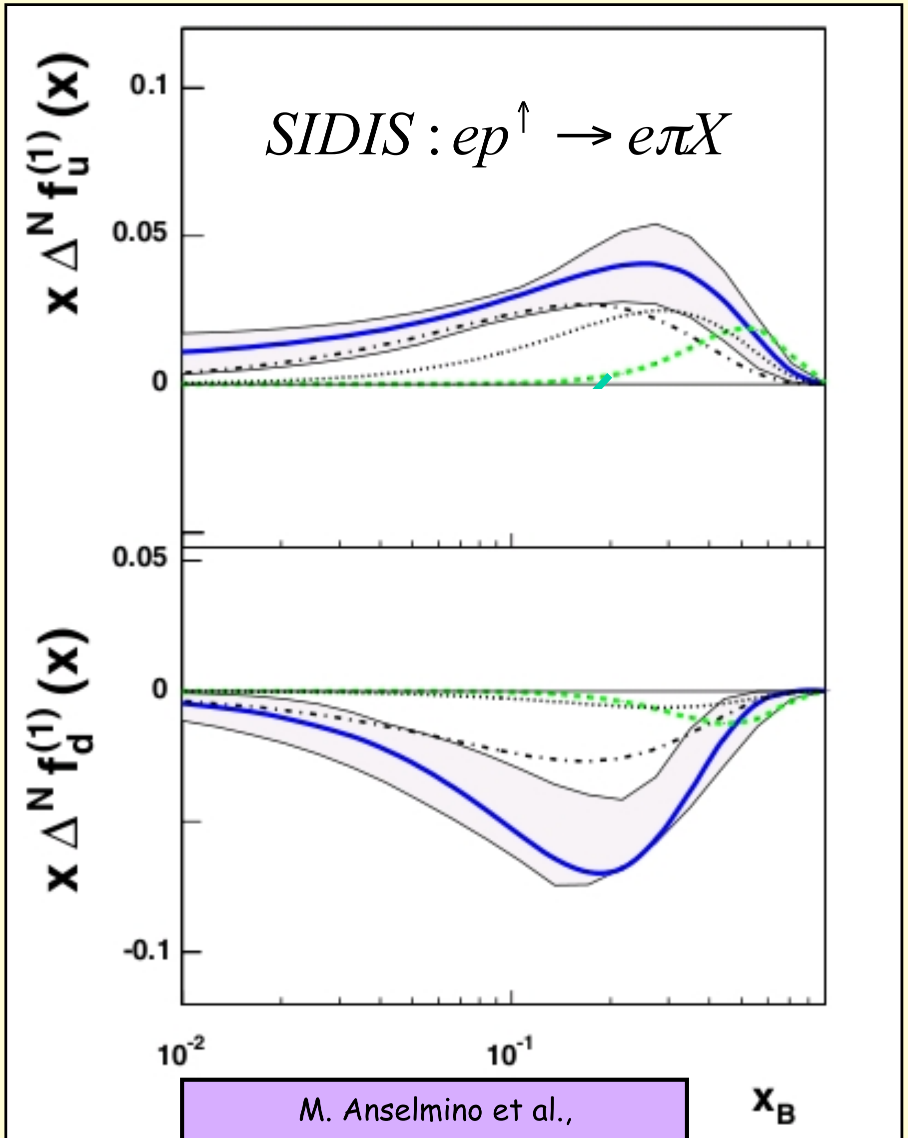
Test of Universality

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



A.V. Efremov et al.,
Phys. Lett. B 612, 233 (2005)

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



M. Anselmino et al.,
Phys. Rev. D72, 094007 (2005)

Transversity @ PANDA?

Measurement of Transversity

	non-TMD	TMD
self-sufficient	$\bar{p}^{\uparrow} p^{\uparrow} \to \ell \bar{\ell} X$ $p^{\uparrow} p^{\uparrow} \to (\text{high-}p_T \text{ jet}) X$	$\boxed{\begin{array}{l} p\,\bar{p}^{\uparrow} \to \ell \bar{\ell} X \\ \bar{p}\,p^{\uparrow} \to \ell \bar{\ell} X \end{array}}$
needs e^+e^-	$p\,p^{\uparrow} \to \Lambda^{\uparrow} X$ $e\,p^{\uparrow} \to e'\,\Lambda^{\uparrow} X$ $p\,p^{\uparrow} \to (\pi^+ \pi^-) X$ $e\,p^{\uparrow} \to e'\,(\pi^+ \pi^-) X$	$e\,p^{\uparrow} \to e'\,\pi\,X$

- There is only a single self-sufficient process with a single polarized beam
  - Single spin-asymmetry in $\bar{p}^{\uparrow}p$ or $p\bar{p}^{\uparrow}$ Drell-Yan

A “window” to transversity: pbar - p↑ → l^+l^- X

Only self-sufficient single spin-asymmetry (involves TMDs)

Unpolarized DY production cross-section

$$d\sigma^{DY} \propto \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1^{\perp}(x_2, k_{T2}^2) \cos 2\phi$$

↑ Boer-Mulders ↑

→ analogue of BELLE cos2φ asymmetry

Single-polarized DY production cross-section

$$d\sigma^{DY} \propto \bar{f}_1(x_1, k_{T1}^2) \otimes f_{1T}^{\perp}(x_2, k_{T2}^2) \sin(\phi - \phi_{S2}) +$$

↑ Sivers

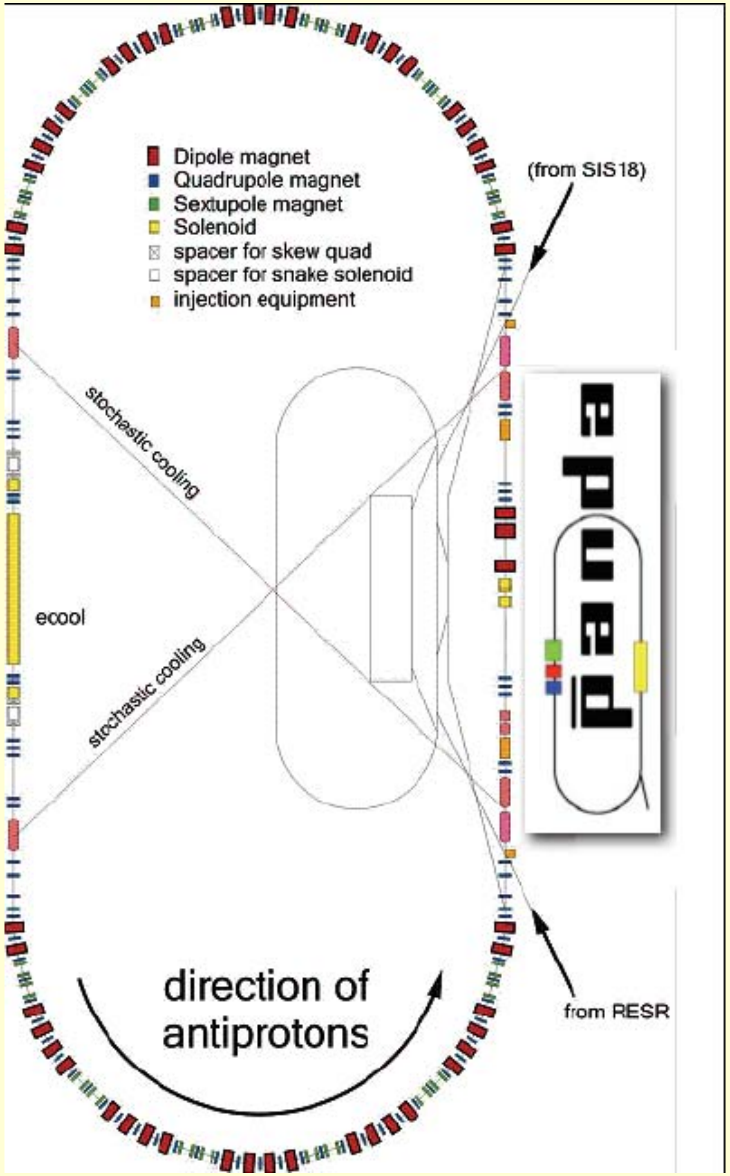
$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1(x_2, k_{T2}^2) \sin(\phi + \phi_{S2}) +$$

↑ Boer-Mulders ↑ Transversity

→ analogue of SIDIS Collins asymmetry

DY measurements @ PANDA

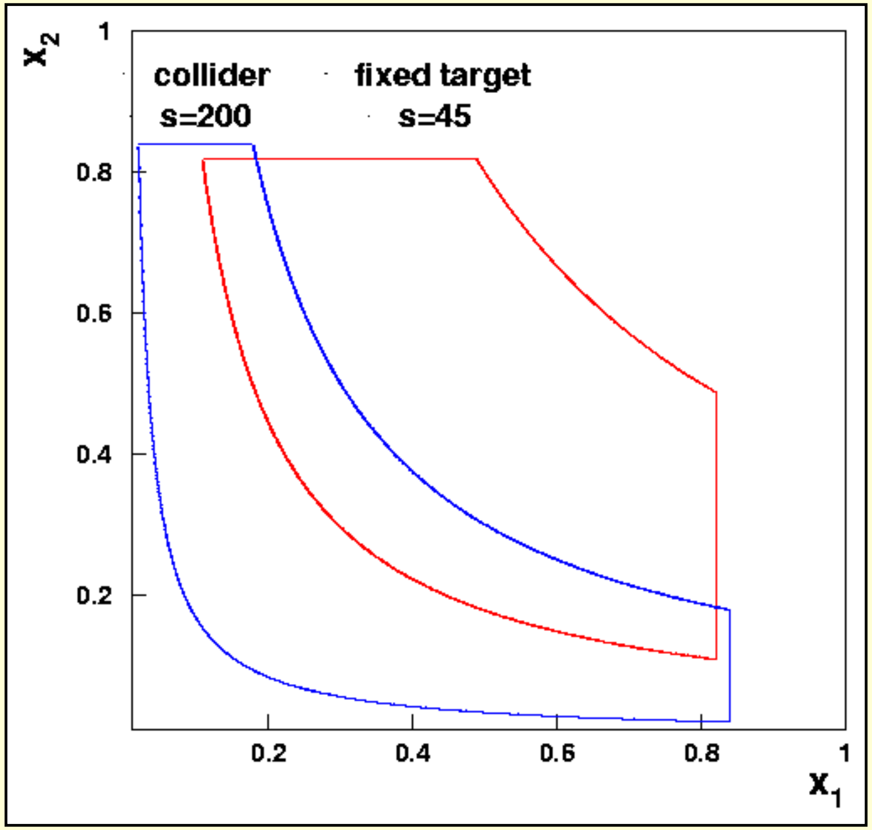
- antiproton momentum
  1.5 GeV/c < p < 15 GeV/c
- Stochastic and electron cooling: $\Delta p/p < 10^{-5}$
- Luminosity > $10^{31}cm^{-2}s^{-1}$
- Hydrogen pellet or jet target, polarised Hydrogen under study
- Variety of nuclear targets

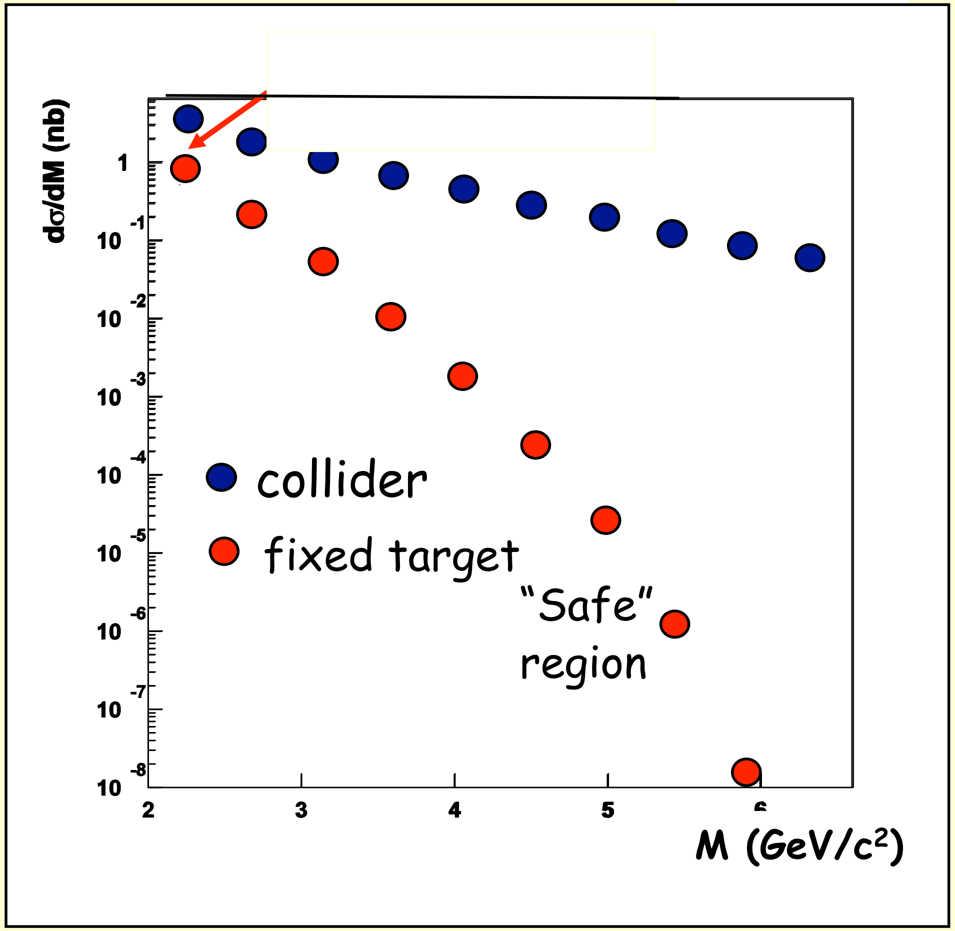


Kinematics and cross section

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

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



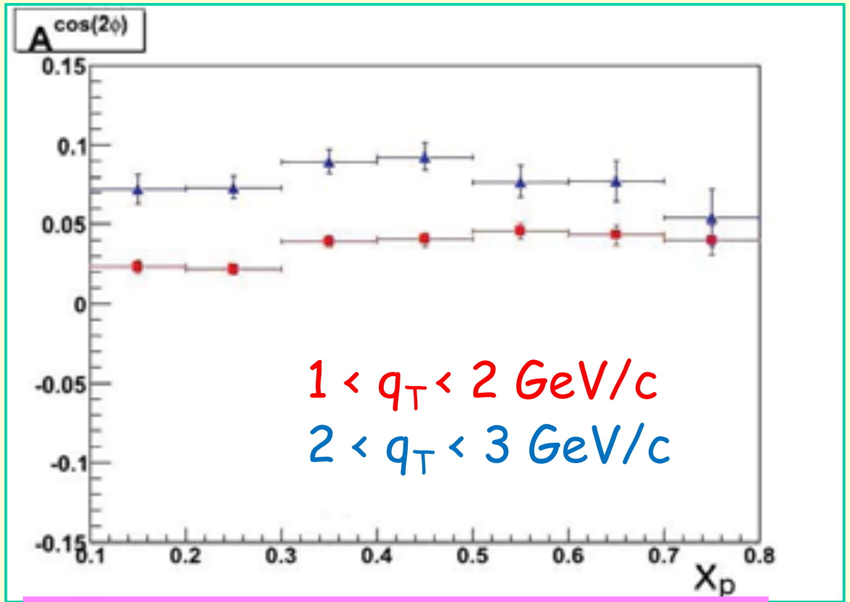


Use of region M<3 GeV/c² mandatory

DY@PANDA: MC – Simulations I

A. Bianconi NIM A593, 562 (2008)

Unpolarized case: $\bar{p}\,p \rightarrow \mu^+\mu^- X$



M. Maggiora Univ. Torino and INFN (I)

5×10^5 events

$1.5 < M^2_{l^+l^-} < 2.5$ GeV^2
$q_T > 1$ GeV/c
$60° < \theta^{CS}_{\mu+} < 120°$

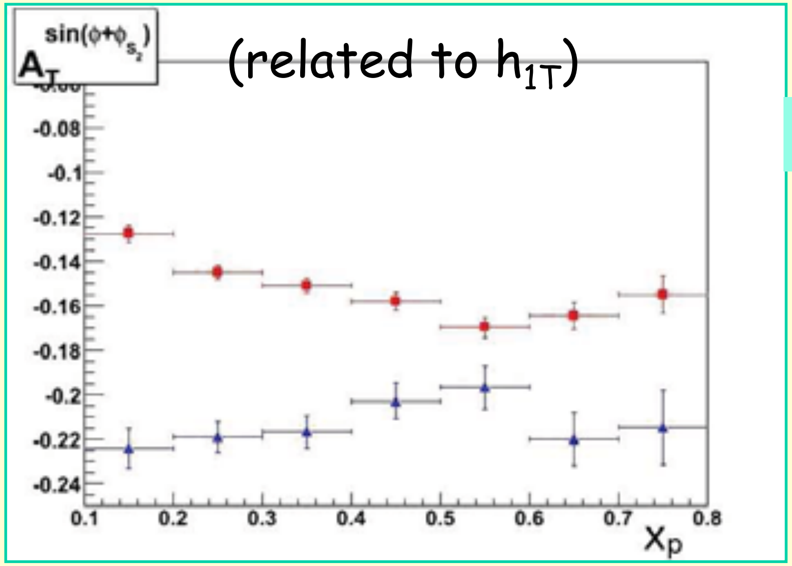
Luminosity = 2×10^{32} cm^{-2}s^{-1}
σ = 0.8 nb
Rate = 0.16 s^{-1}

- Cos2ϕ asymmetry (related to $h_1^\perp$) not negligible and measurable
- Study of the dependence from q_T possible

DY@PANDA: MC - Simulations II

A. Bianconi, M. Radici Phys. Rev. D71, 074014 (2005)

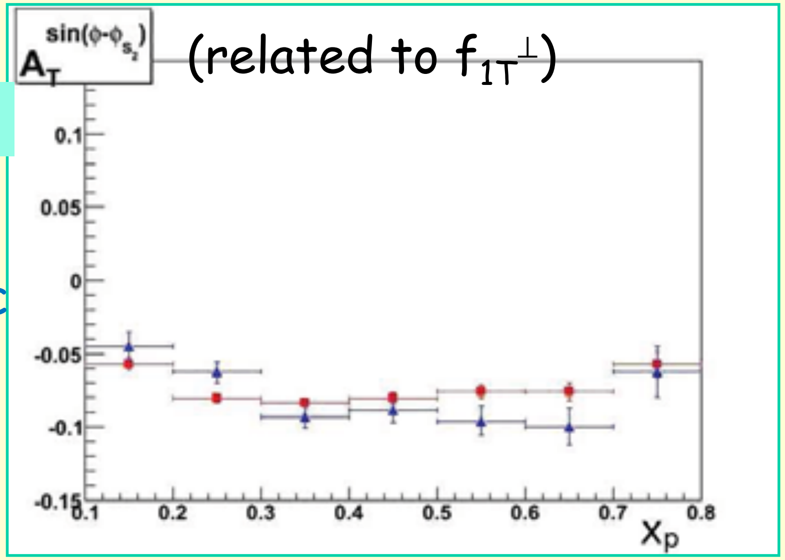
Single-spin asymmetry: $\bar{p}\, p\uparrow \rightarrow \mu^+\mu^- X$



5x10^5 events

$1 < q_T < 2$ GeV/c

$2 < q_T < 3$ GeV/c



- Sin($\phi+\phi_s$) asymmetry (related to h_{1T}) not negligible and measurable
  - Study of the dependence from q_T possible
- Sin($\phi-\phi_s$) asymmetry (related to $f_{1T}^{\perp}$) very small
  - Weak q_T dependence

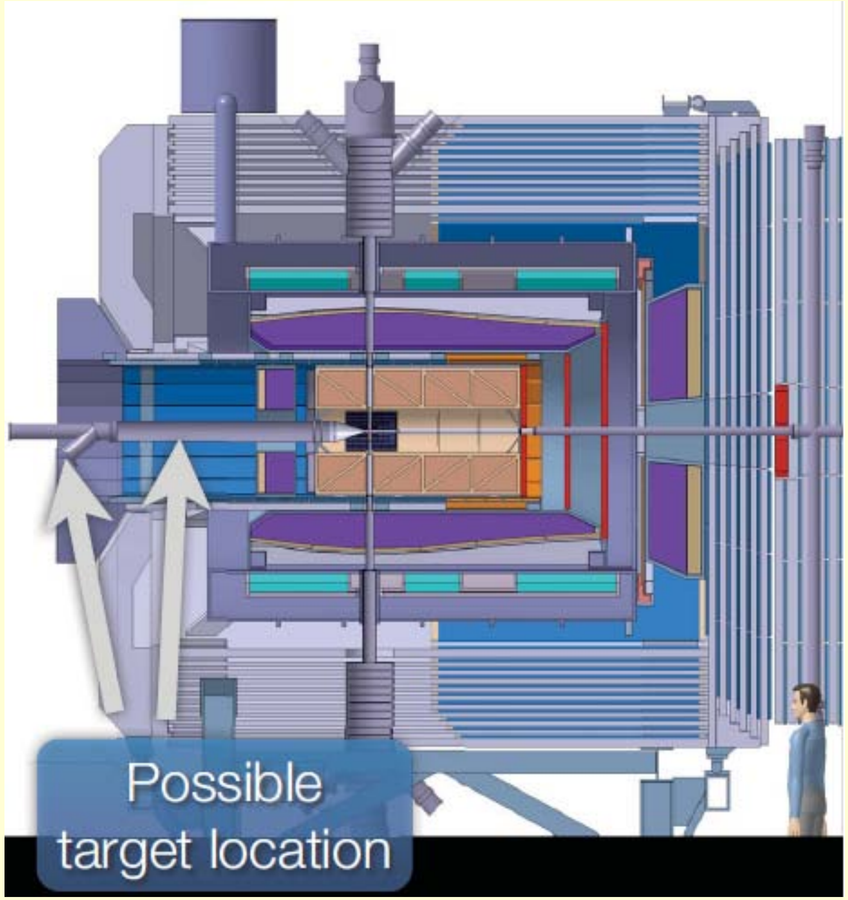
DY with e^+/e^- @ PANDA? Pion-rejection

T_{p_bar} (GeV)	Q^2 $(GeV/c)^2$	θ_{CM}	θ_{lab}	p_{lab} (GeV/c)	one π Misident. Probability ECAL×DIRC×dE/dx	$\pi^+\pi^-$ Misident. Probability
1.	5.4	20°	13°	2.2	0.001 × 0.5 ×0.05 = 2.5 10^{-5}	0.1 10^{-9}
		160°	132°	0.57	0.033 × 0.003 ×0.03 = 3.0 10^{-6}	
		90°	54°	1.43	0.001 × 0.3 ×0.03 = 9. 10^{-6}	0.1 10^{-9}
		90°	54°	1.43	0.001 × 0.3 × 0.03 = 9. 10^{-6}	
2.5	8.2	20°	10°	3.7	0.001 × 1. ×0.05 = 5. 10^{-5}	0.3 10^{-9}
		160°	117°	0.7	0.014 × 0.014 × 0.03 = 6. 10^{-6}	
		90°	41°	2.2	0.001 × 1. × 0.03 = 3. 10^{-5}	0.9 10^{-9}
		90°	41°	2.2	0.001 × 1. × 0.03 = 3. 10^{-5}	
5.	12.9	20°	7.4°	6.1	0.001 × 1. × 0.1 = 10^{-4}	0.6 10^{-9}
		160°	102°	0.8	0.014 × 0.014 × 0.03 = 6. 10^{-6}	
		90°	32°	3.4	0.001 × 1. × 0.05 = 5. 10^{-5}	2.5 10^{-9}
		90°	32°	3.4	0.001 × 1. × 0.05 = 5. 10^{-5}	
10.	22.3	20°	5.4°	10.9	0.001 × 1. × 0.3 = 3. 10^{-4}	5.4 10^{-9}
		160°	85°	1.0	0.005 × 0.12 × 0.03 = 1.8 10^{-5}	
		90°	24°	5.95	0.001 × 1. × 0.1 = 1. 10^{-4}	10. 10^{-9}
		90°	24°	5.95	0.001 × 1. × 0.1 = 1. 10^{-4}	

F. Maas Univ. of Mainz – GSI (D)

A polarized target in PANDA?

A (very) difficult task!



Positioning:

- Keep good PID for EM physics
- No parasitic run possible

Technical issues:

- Transport of polarized gas
- Compensation of solenoidal field
- Pumping of polarized gas

Other options:

- new detector with thoroidal field?
- additional IP in HESR?
- Asymmetric pbar-p collider

Proton Electromagnetic Form Factors

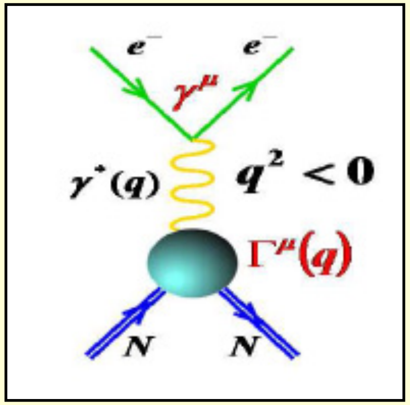
Space-like and Time-like regions

- FFs are analytical functions.
- One photon exchange: functions of $t = q^2 = -Q^2$.

$t=q^2<0$ (spacelike)
real function

Scattering

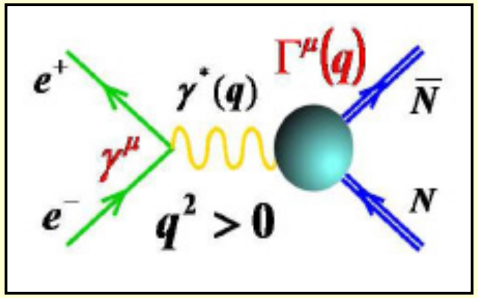
$e^- + h \Rightarrow e^- + h$



$t=q^2>0$ (timelike)
complex function

Annihilation

$e^+ + e^- \Rightarrow \bar{h} + h$

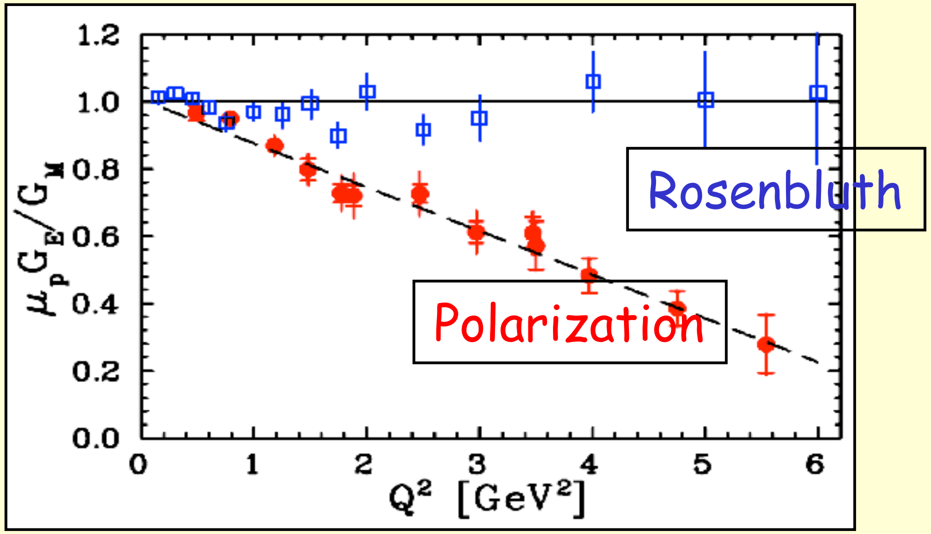


$$\lim_{q^2 \to -\infty} F^{SL}(q^2) = \lim_{q^2 \to +\infty} F^{TL}(q^2)$$

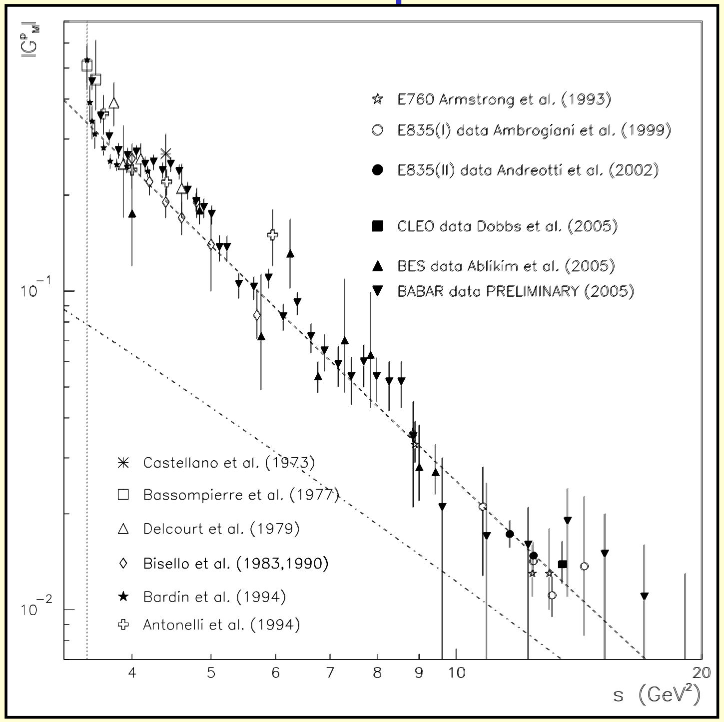
(Different from pQCD predictions)

Study of the Proton Electromagnetic Form-Factors

Space-Like FFs: proton data



Time-Like FFs: proton data



JLab results dramatically changed picture of the Nucleon:
- G_E^p/G_M^p decreases with Q^2
- data suggest G_E^p crosses 0 at $Q^2 \approx 8$ GeV^2

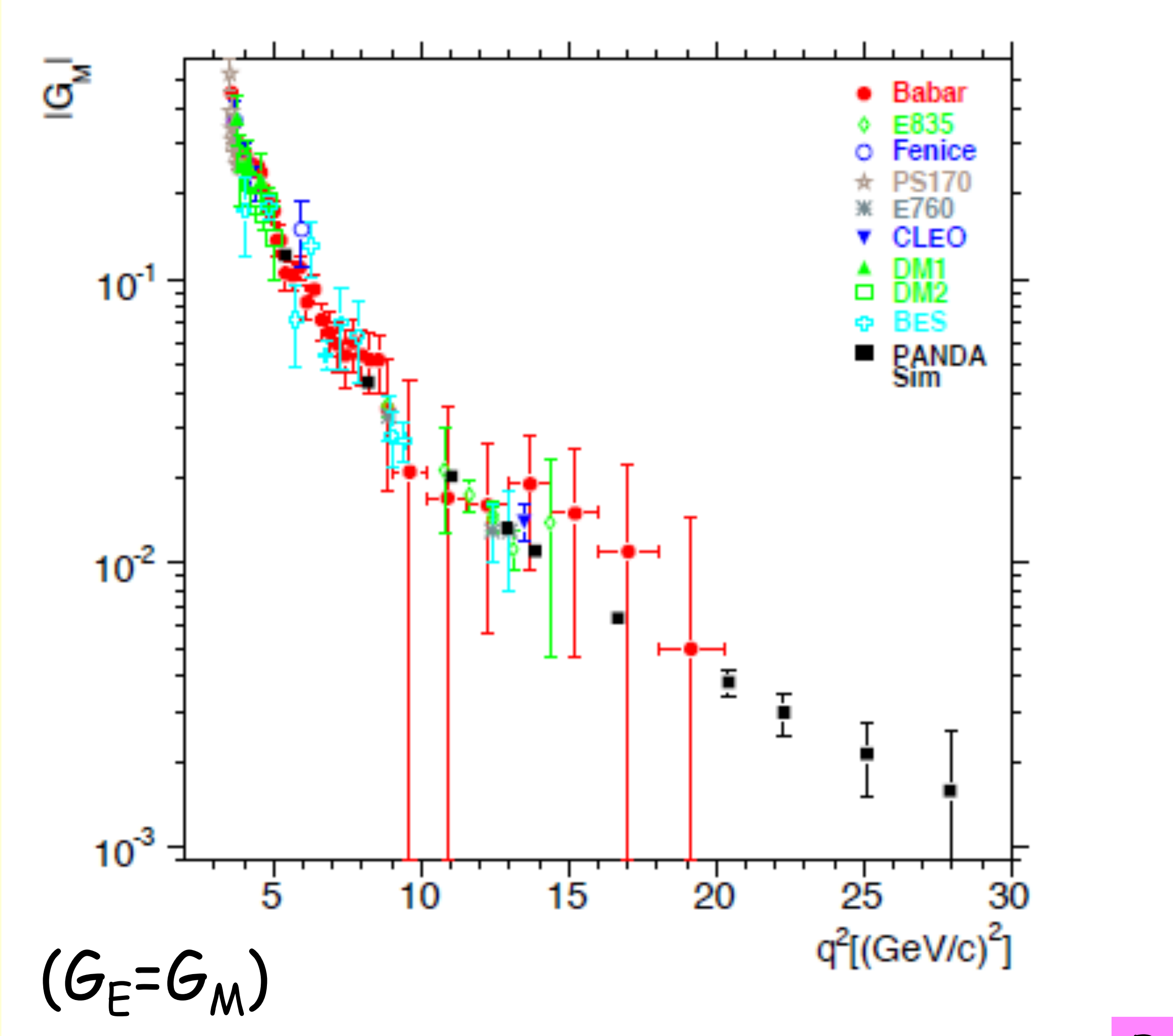
Expected Q^2 behaviour reached quite early, however ...
... there is still a factor of 2 between timelike and spacelike.

Additional and more precise measurements needed

Time-like form factor measurement @ PANDA

T_{p_bar} (GeV)	Q^2 (GeV/c)^2	θ_{CM}	θ_{lab}	p_{lab} (GeV/c)	one π Misident. Probability ECAL×DIRC×dE/dx	$\pi^+\pi^-$ Misident. Probability
1.	5.4	20°	13°	2.2	$0.001 \times 0.5 \times 0.05 = 2.5\ 10^{-5}$	$0.1\ 10^{-9}$
		160°	132°	0.57	$0.033 \times 0.003 \times 0.03 = 3.0\ 10^{-6}$	
		90°	54°	1.43	$0.001 \times 0.3 \times 0.03 = 9.\ 10^{-6}$	$0.1\ 10^{-9}$
		90°	54°	1.43	$0.001 \times 0.3 \times 0.03 = 9.\ 10^{-6}$	
2.5	8.2	20°	10°	3.7	$0.001 \times 1. \times 0.05 = 5.\ 10^{-5}$	$0.3\ 10^{-9}$
		160°	117°	0.7	$0.014 \times 0.014 \times 0.03 = 6.\ 10^{-6}$	
		90°	41°	2.2	$0.001 \times 1. \times 0.03 = 3.\ 10^{-5}$	$0.9\ 10^{-9}$
		90°	41°	2.2	$0.001 \times 1. \times 0.03 = 3.\ 10^{-5}$	
5.	12.9	20°	7.4°	6.1	$0.001 \times 1. \times 0.1 = 10^{-4}$	$0.6\ 10^{-9}$
		160°	102°	0.8	$0.014 \times 0.014 \times 0.03 = 6.\ 10^{-6}$	
		90°	32°	3.4	$0.001 \times 1. \times 0.05 = 5.\ 10^{-5}$	$2.5\ 10^{-9}$
		90°	32°	3.4	$0.001 \times 1. \times 0.05 = 5.\ 10^{-5}$	
10.	22.3	20°	5.4°	10.9	$0.001 \times 1. \times 0.3 = 3.\ 10^{-4}$	$5.4\ 10^{-9}$
		160°	85°	1.0	$0.005 \times 0.12 \times 0.03 = 1.8\ 10^{-5}$	
		90°	24°	5.95	$0.001 \times 1. \times 0.1 = 1.\ 10^{-4}$	$10.\ 10^{-9}$
		90°	24°	5.95	$0.001 \times 1. \times 0.1 = 1.\ 10^{-4}$	

Expected count-rates and statistical projection

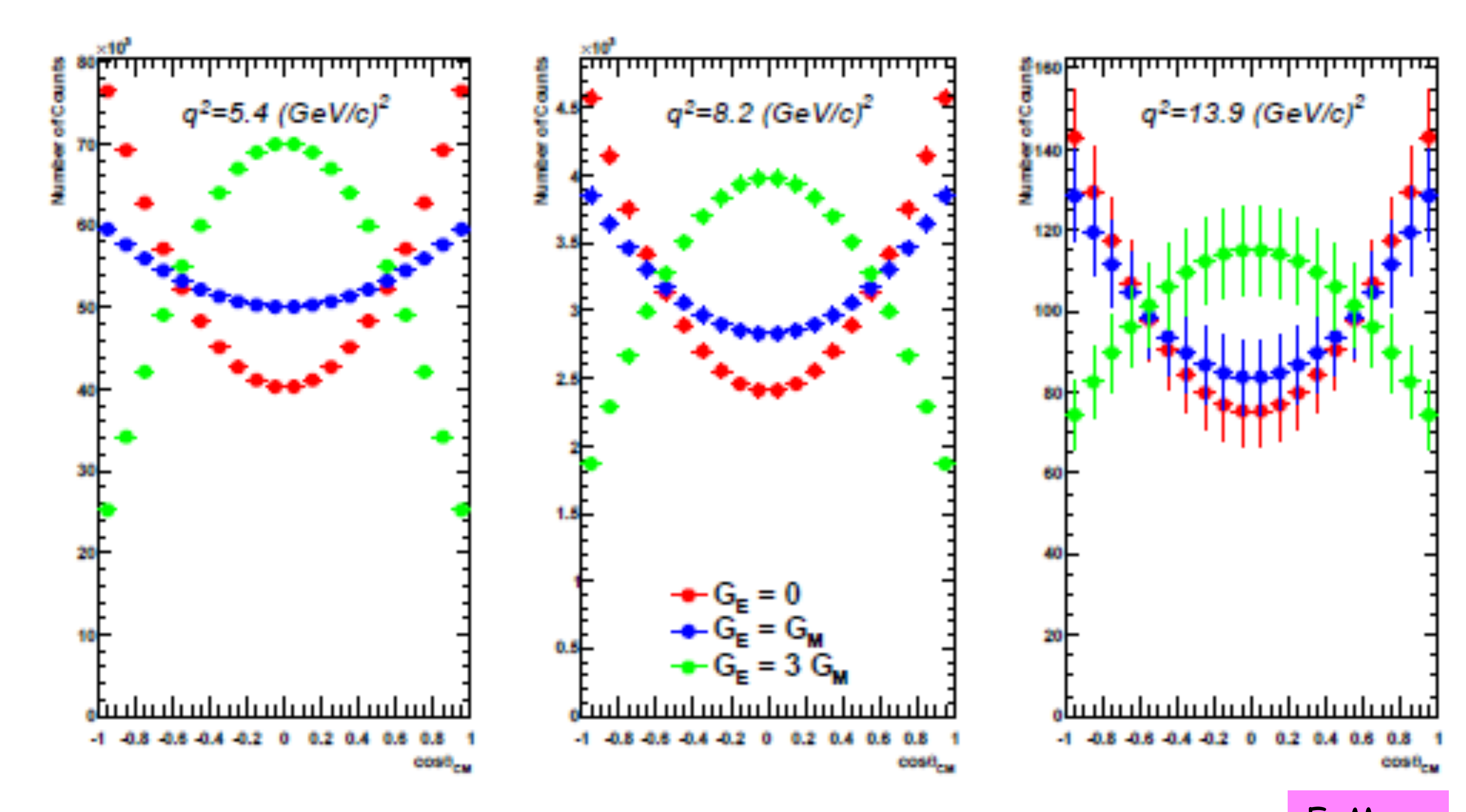


F. Maas

$2fb^{-1}$ (4 months @ $2 \times 10^{32} cm^{-2} s^{-1}$)

Measurement of G_E and G_M moduli @ PANDA

- Use of different angular dependence for G_E and G_M

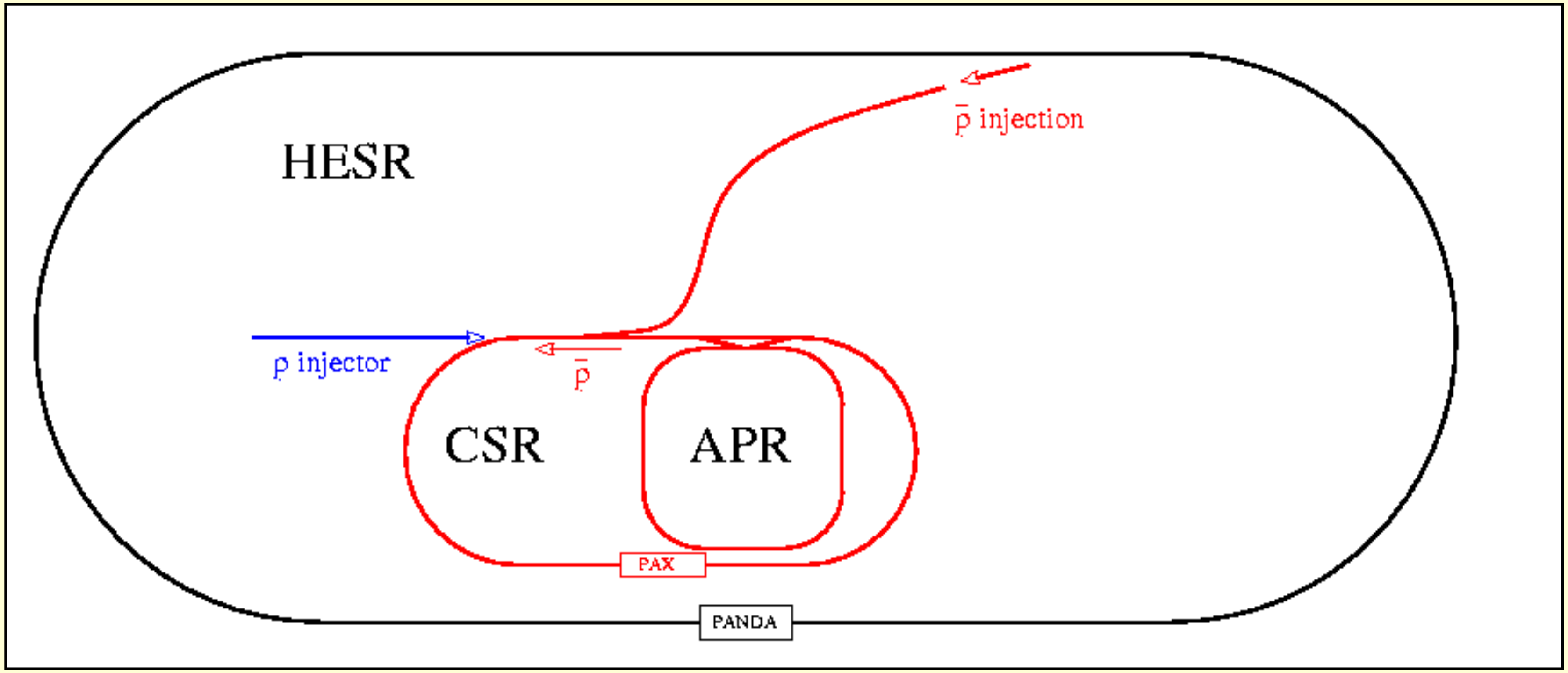


F. Maas

-Generated events: 2fb^{-1} (4 months @ 2x10^{32}cm^{-2}s^{-1})

Polarized antiprotons on fixed target

(PAX-Phase I)

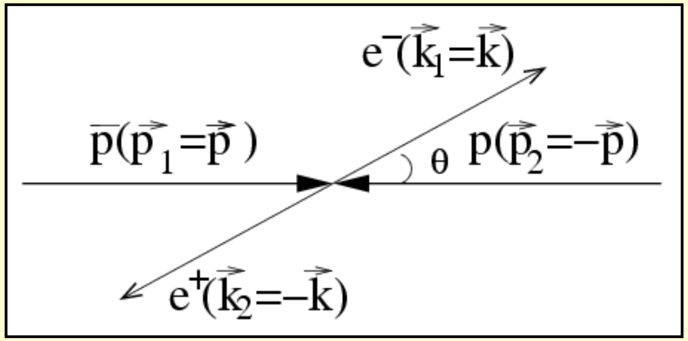


EXPERIMENT:

Fixed target experiment:

- **polarized antiprotons protons in CSR (p>200 MeV/c)**
- **fixed polarized protons target**

Double polarized pbar-p annihilation:



$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xx} = \sin^2\theta\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{yy} = -\sin^2\theta\left(|G_M|^2 - \frac{1}{\tau}|G_E|^2\right)\mathcal{N},$$

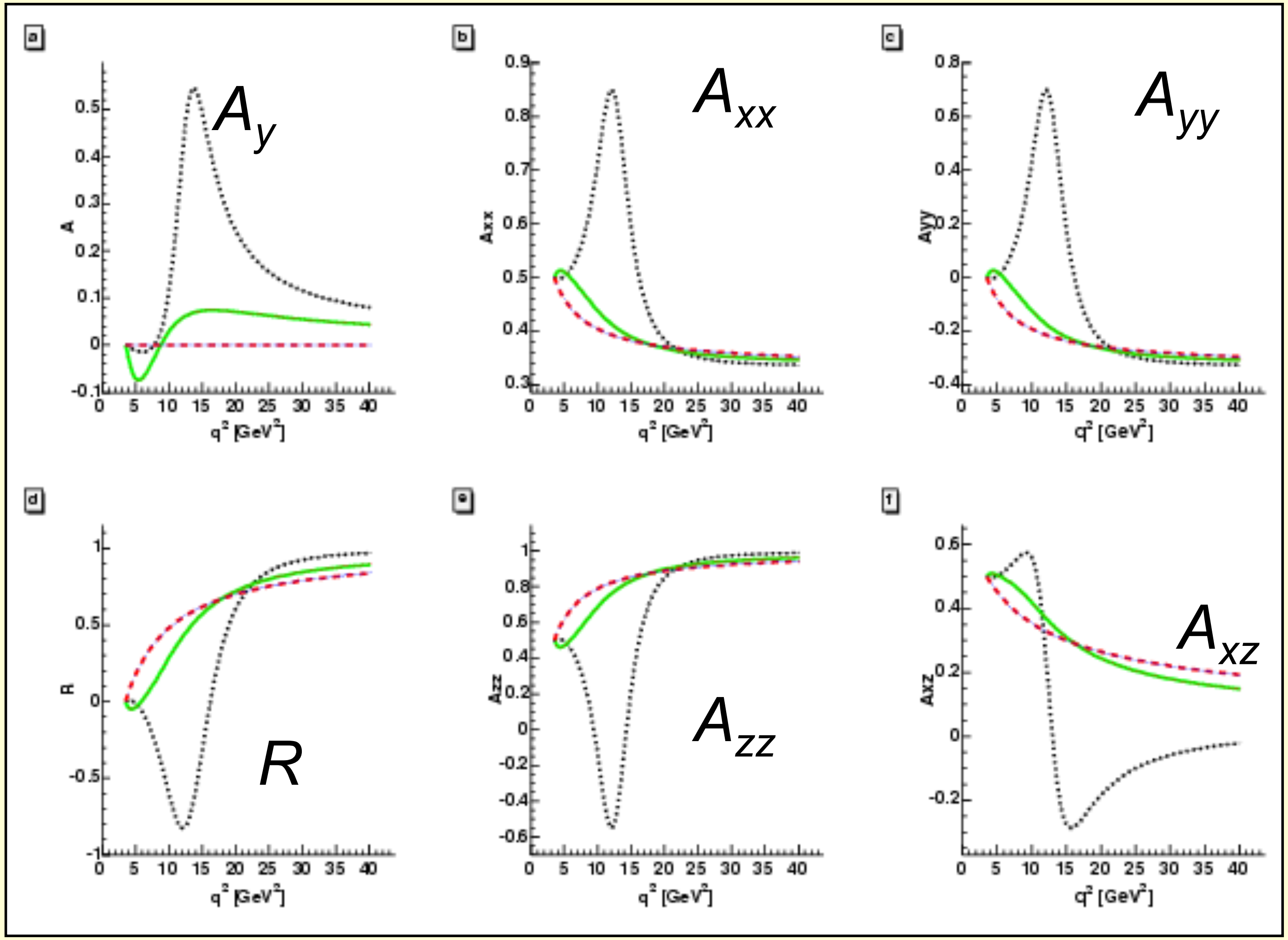
$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{zz} = \left[(1+\cos^2\theta)|G_M|^2 - \frac{1}{\tau}\sin^2\theta|G_E|^2\right]\mathcal{N},$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{xz} = \left(\frac{d\sigma}{d\Omega}\right)_0 A_{zx} = \frac{1}{\sqrt{\tau}}\sin 2\theta Re G_E G_M^* \mathcal{N}.$$

E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)

- Most contain moduli G_E, G_M
  - Independent G_E-G_M separation
  - Test of Rosenbluth separation in the time-like region
- Access to G_E-G_M phase
- Very sensitive to different models (next transparencies)

Polarization and Models in T.L. Region



VDM : IJL

Ext. VDM

'QCD inspired'

E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)

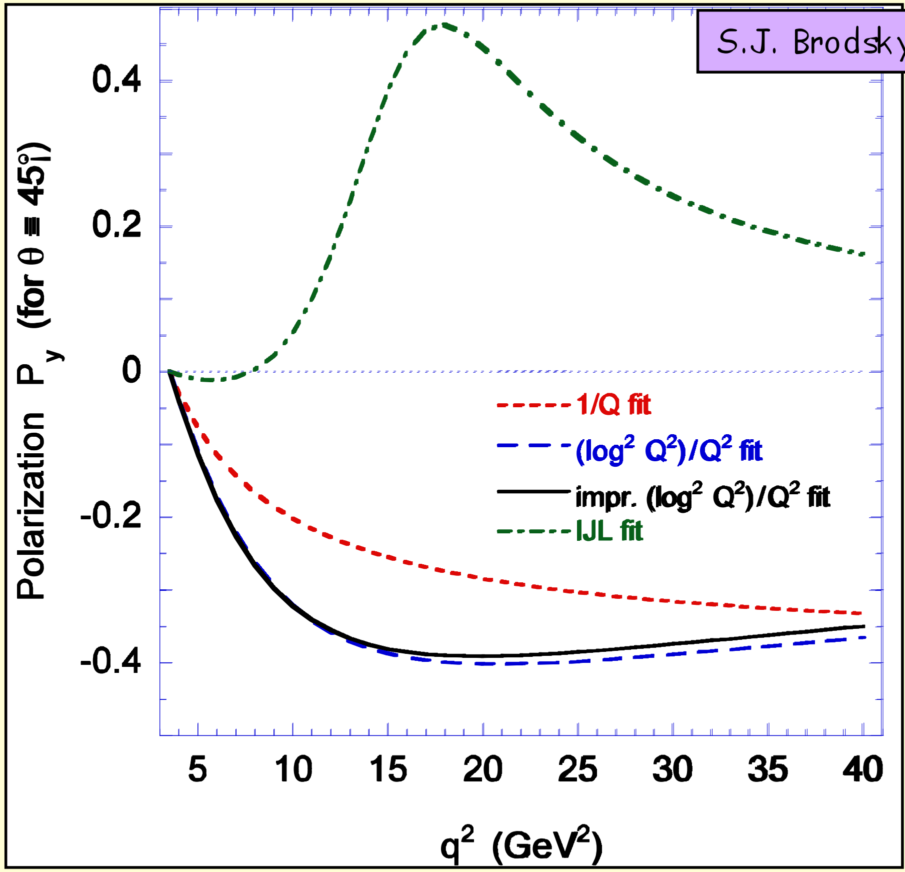
Single Spin Observables

$$\frac{d\sigma}{d\Omega}(P_y) = \left(\frac{d\sigma}{d\Omega}\right)_0 [1 + \mathcal{A}P_y],$$

$$\mathcal{A} = \frac{\sin 2\theta \, Im G_E^* G_M}{D\sqrt{\tau}}, \quad D = |G_M|^2(1+\cos^2\theta) + \frac{1}{\tau}|G_E|^2 \sin^2\theta$$

A. Z. Dubnickova, S. Dubnicka, M.P. Rekalo Nuovo Cimento A109, 241 (1996)

S.J. Brodsky, C.E. Carlson, J.R. Hiller, D.S. Hwang PRD 69, 054022 (2004)



- Contains imaginary part
  - Access relative phase
- Very sensitive to different models

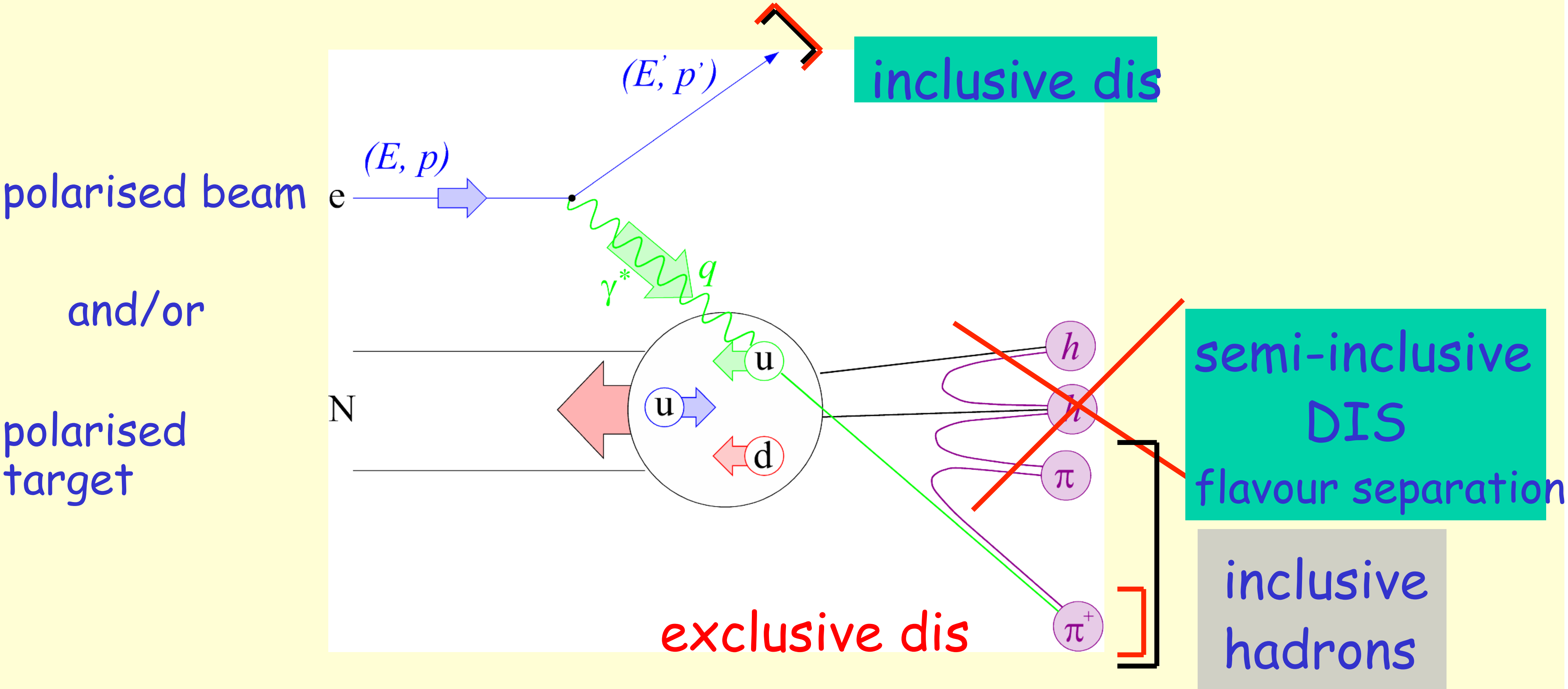
- Additional options:
  - •Polarized target in PANDA
  - •Asymmetric pbar-p collider

Outline

- Polarized proton-antiproton interactions
- Polarized DIS
- Status of polarized antiprotons studies

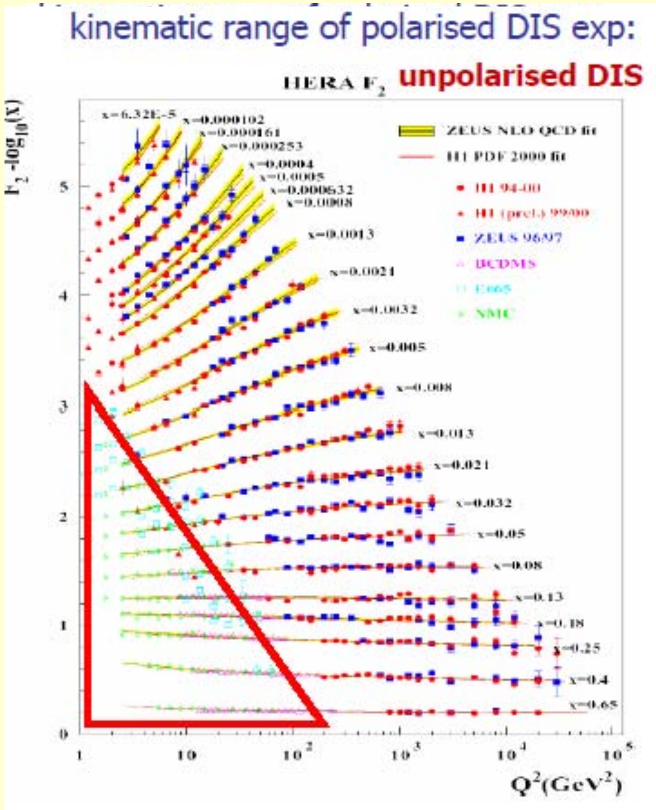
Polarized deep inelastic scattering

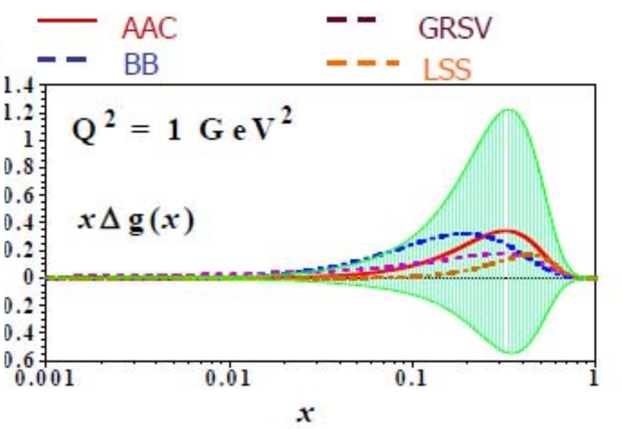
$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g \quad \boxed{= J_q + J_g}$$



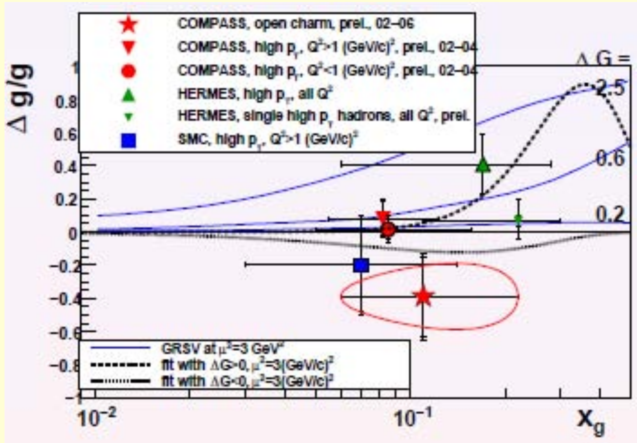
Gluon polarization: present status

•DGLAP evolution





•Measurements

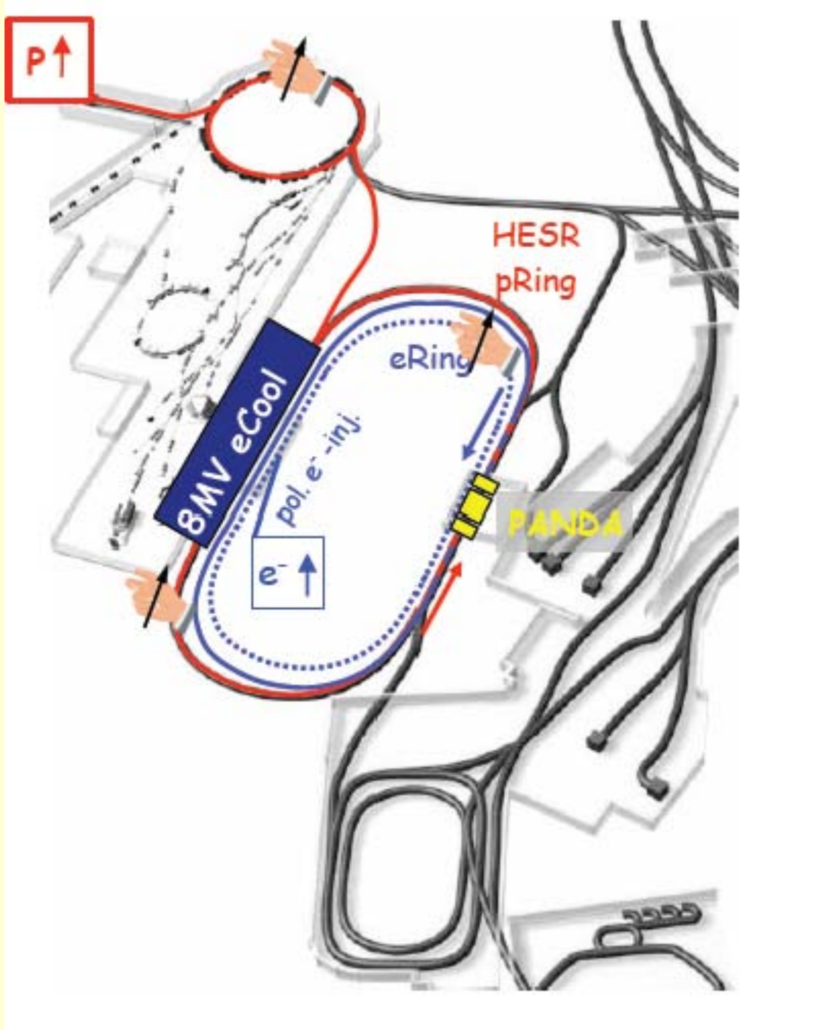


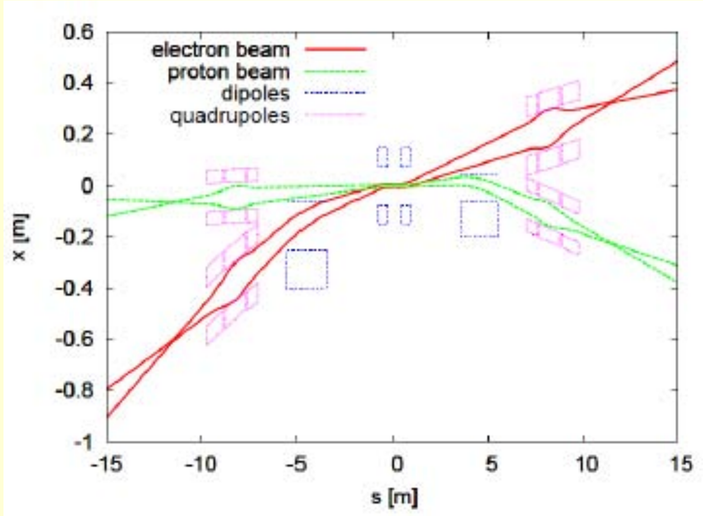
COMPASS point obtained with the least model dependent open charm method

- Data show small values of $\Delta g/g$ at x_g~0.1
- Confirmed by indirect measurements
  - Scaling violations of g_1
  - p↑p↑ scattering at RHIC
- All measurements concentrated around x_g=0.1
- Little known about $\Delta g(x_g)$

- Need polarized collider to extend kinematic range (USA-projects)
- Need more direct probes (ENC)

A double polarized e-p/d collider for FAIR





- $L \approx 1(4) \times 10^{32}$ $1/cm^2s$
- $\sqrt{s} > 10$ GeV: 3.3 GeV $e^- \leftrightarrow$ 15 GeV p
- Polarized e- (>80 %)
- Polarized p/d (> 80 %)
  - transversal + longitudinal
- Use PANDA detector

Performance and comparison

- Energy and luminosity

Experiment	JLAB(12 GeV)	HERMES	ENC	COMPASS
s $(GeV)^2$	23	50	180	300
L $(cm^{-2}s^{-1})$	$\approx 10^{38}$	$\approx 10^{31}$	$\approx 10^{32}$	$\approx 10^{32}$

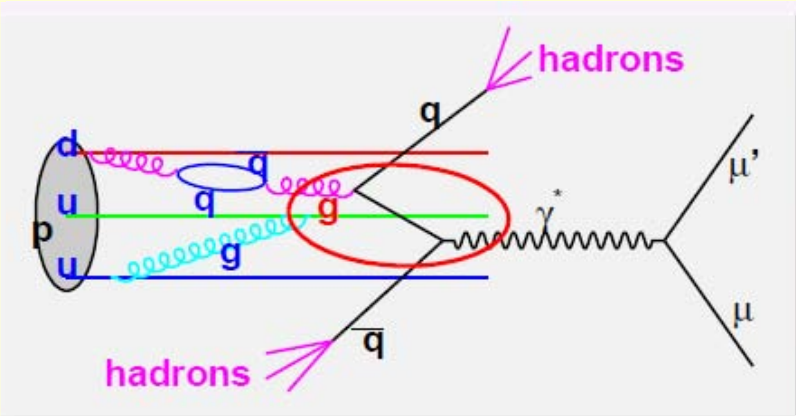
- Factor of merit

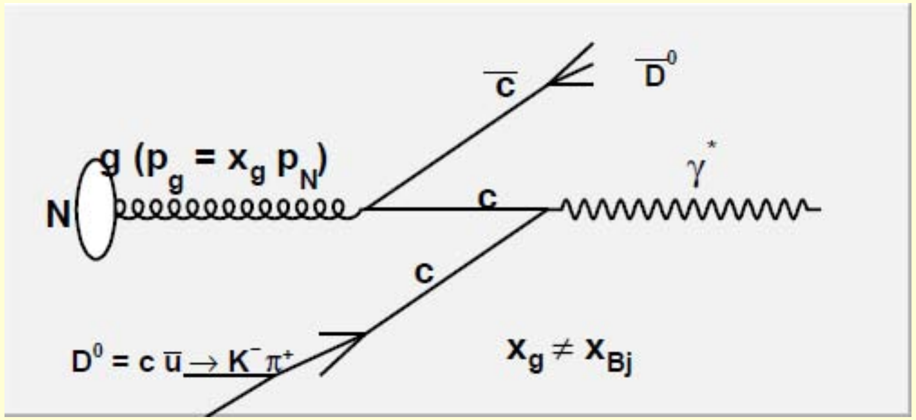
$$\delta\sigma \propto \frac{1}{P_b P_t f} \cdot \frac{1}{\sqrt{N}}$$

	Diluting factor		ratio
	COMPASS*	ENC	
unpolarized	1	1	1
Single spin $(P_t f)^2$	0.02	0.64	32
Double spin $(P_b P_t f)^2$	0.013	0.41	32
Rec. hadr. final state		√	

*NH_3 target

Measurement of ΔG: Photon-gluon fusion





- Golden channel: Charm production
  - Theoretically very clean
  - Experimentally very challenging
    - (low statistics)

Double spin-asymmetries to access ΔG:

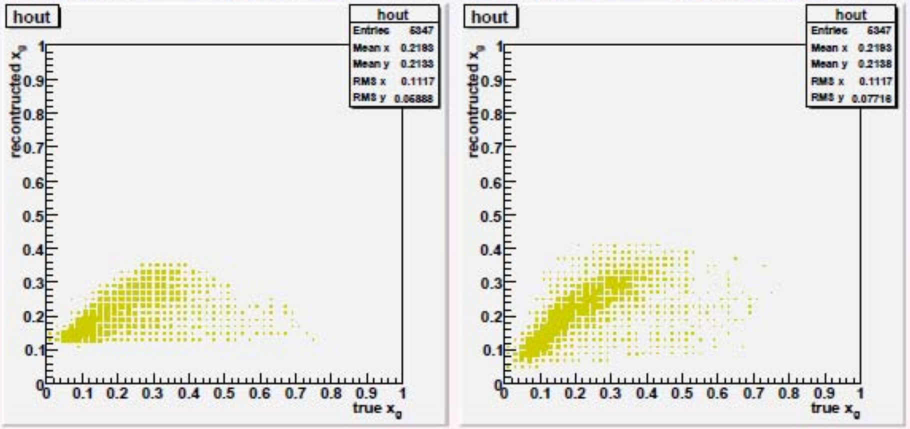
$$A^{raw} = \frac{N^{\uparrow\downarrow} - N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + N^{\uparrow\uparrow}} \propto \frac{\Delta G}{G}$$

ENC vs COMPASS

- COMPASS: only one of the D mesons reconstructed
  - →x_g cannot be reconstructed
- ENC: both D mesons reconstructed
  - →Better access to x_g
  - → Measurement of $\Delta G/G$ (x_g) possible not only $\langle\Delta G/G\rangle x_g$

using information of . . .

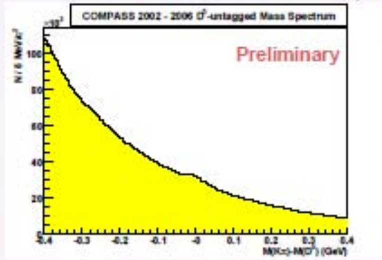
. . . one D^0 (52% corr.) . . . both D^0 (70% corr.)



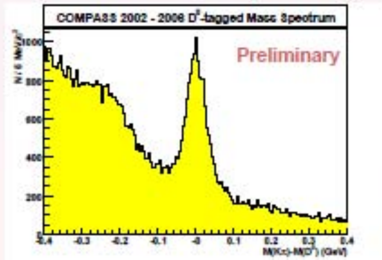
(From J. Pretz)

COMPASS

$D^0 \to K^-\pi^+ + c.c$ (37k D^0)



D^0 from $D^{*+} \to D^0 + \pi^+$
$\to K^-\pi^+\pi^+$ (9k D^0)

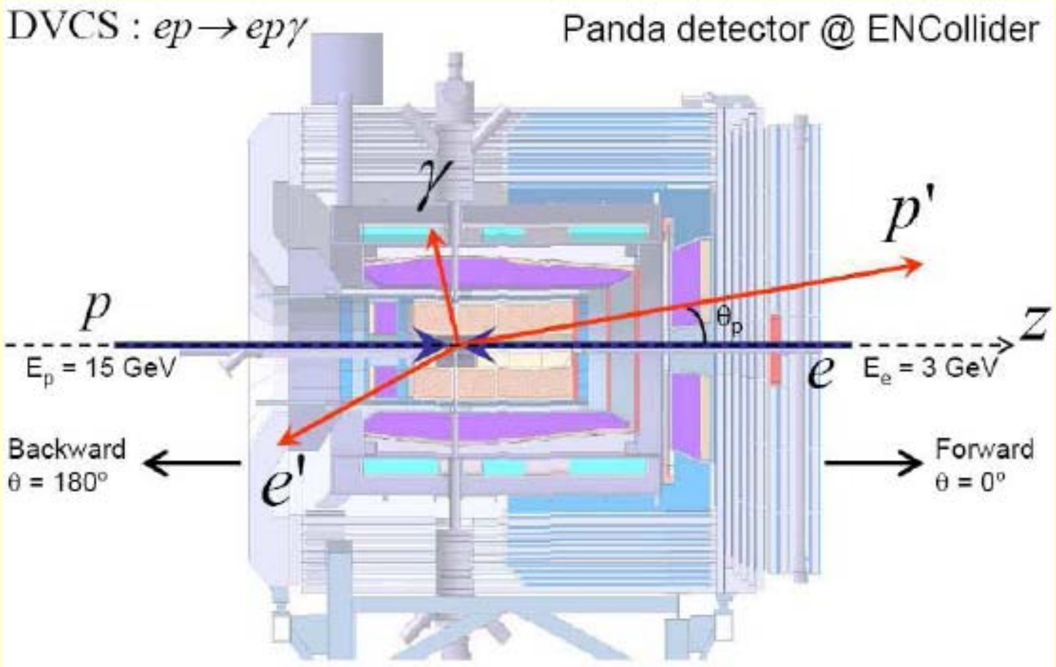


collider

S:B = 4:1
(expected for PANDA)

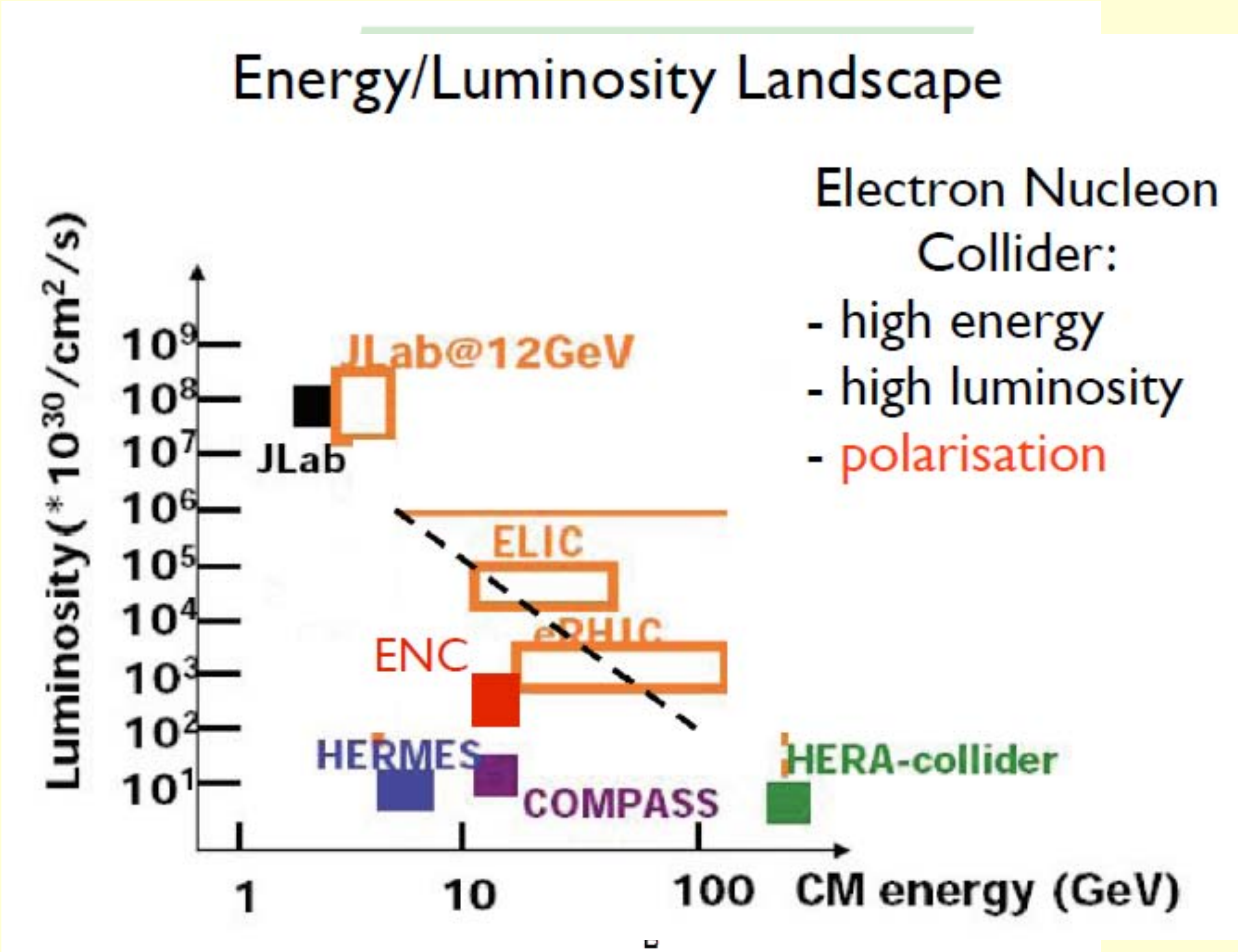
assume B=0

Other issues …



- Deep Virtual Compton Scattering
  - Orbital Angular Momentum
- Semi-inclusive DIS
  - Transversity and TMD
- Spin dependence of fragmentation process

ENC and the others...

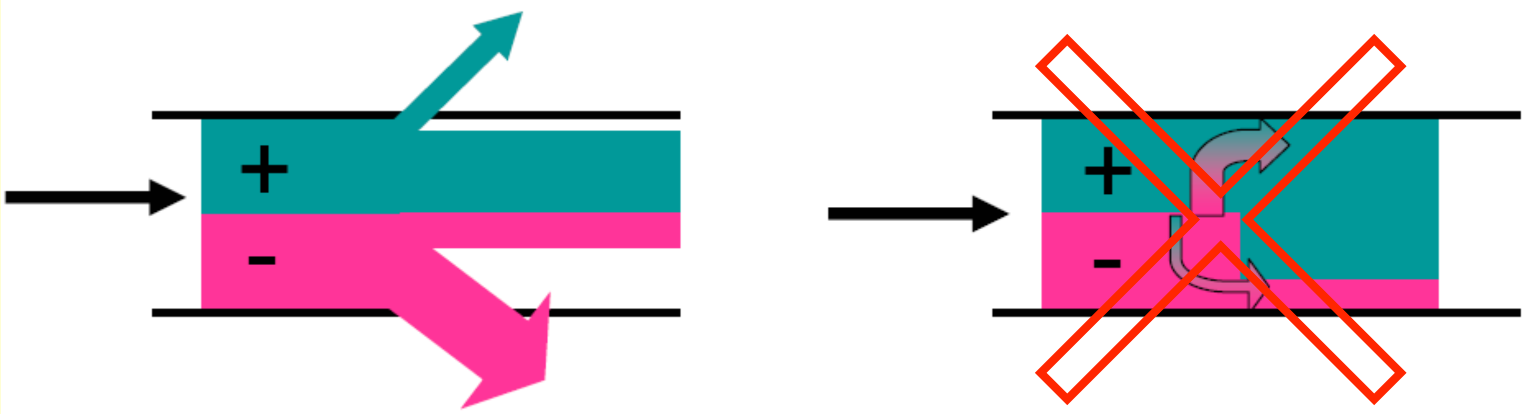


Outline

- Polarized proton-antiproton interactions
- Polarized DIS
- Status of polarized antiprotons studies

Production of polarization in a stored beam
Two Methods: Loss versus spin flip

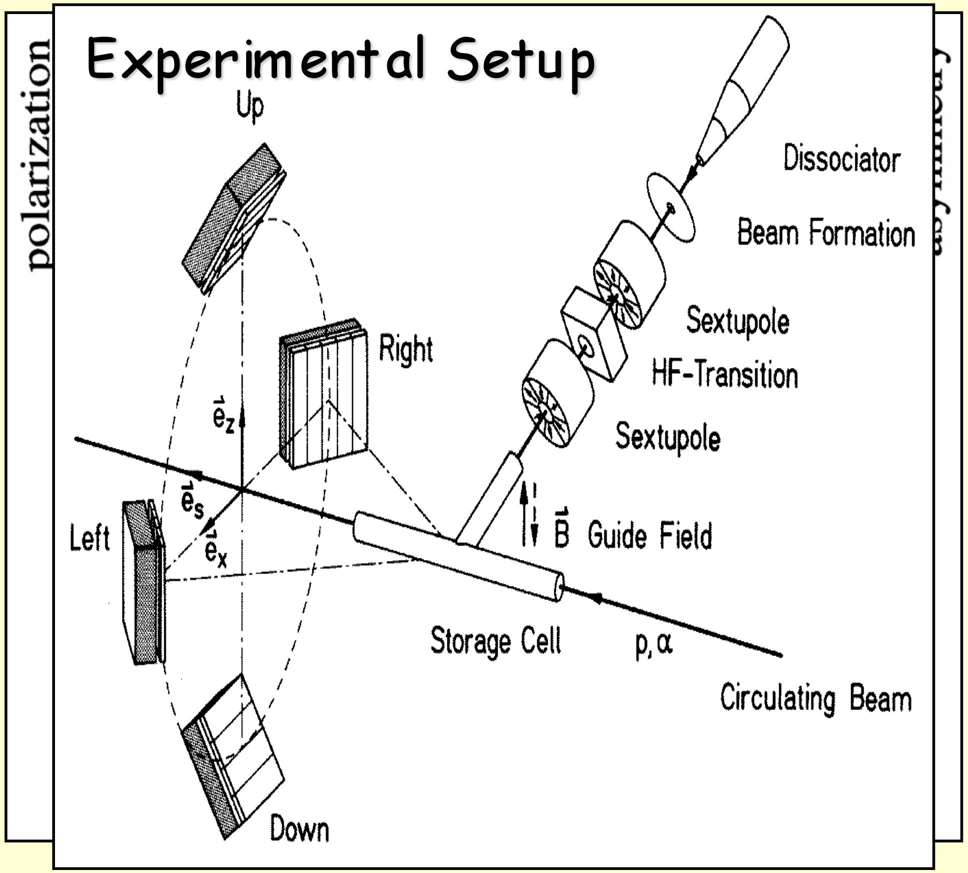
For an ensemble of spin ½ particles with projections + (↑) and – (↓)



discard (one) substate
(more than the other)

reverse (one) substate
(more than the other)

Spin-filtering at TSR: „FILTEX“ - proof-of-principle



Spin filtering works for protons

PAX submitted new proposal to find out **how well does spin filtering work for antiprotons:**

Measurement of the Spin-Dependence of the $p\bar{p}$ Interaction at the AD Ring

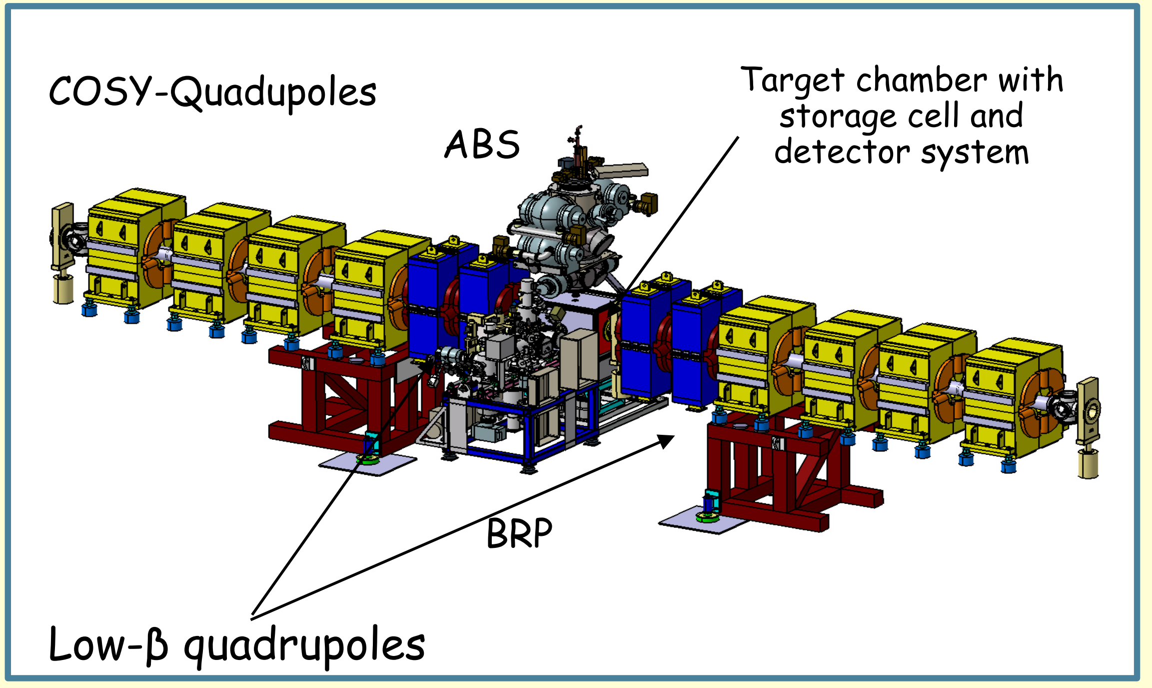
(CERN-SPSC-2009-012 / SPSC-P-337)

Spin-filtering studies at COSY

Main purpose:
1. Commissioning of the experimental setup for AD
2. Quantitative understanding of the machine parameters

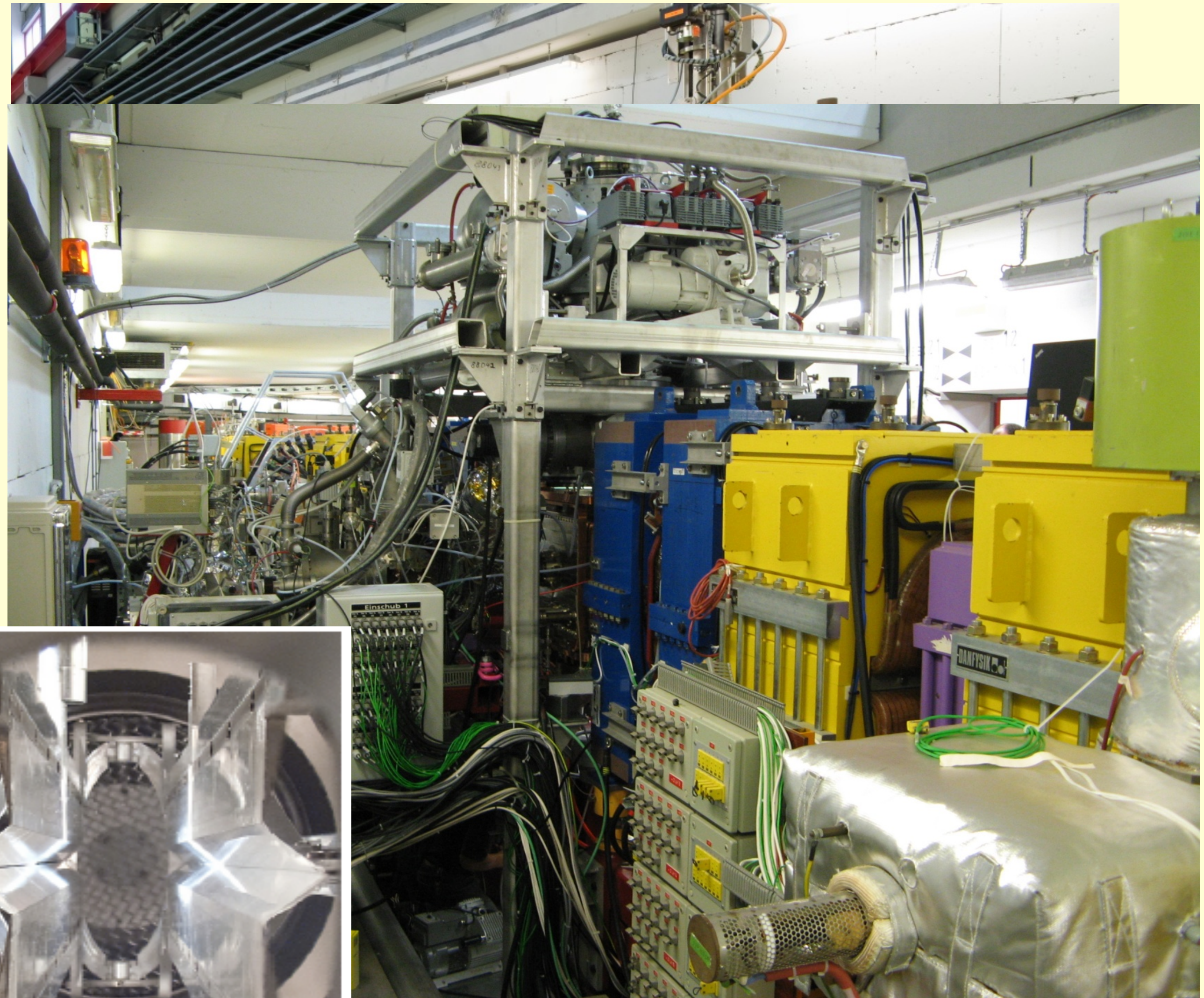
Phases of COSY installation:

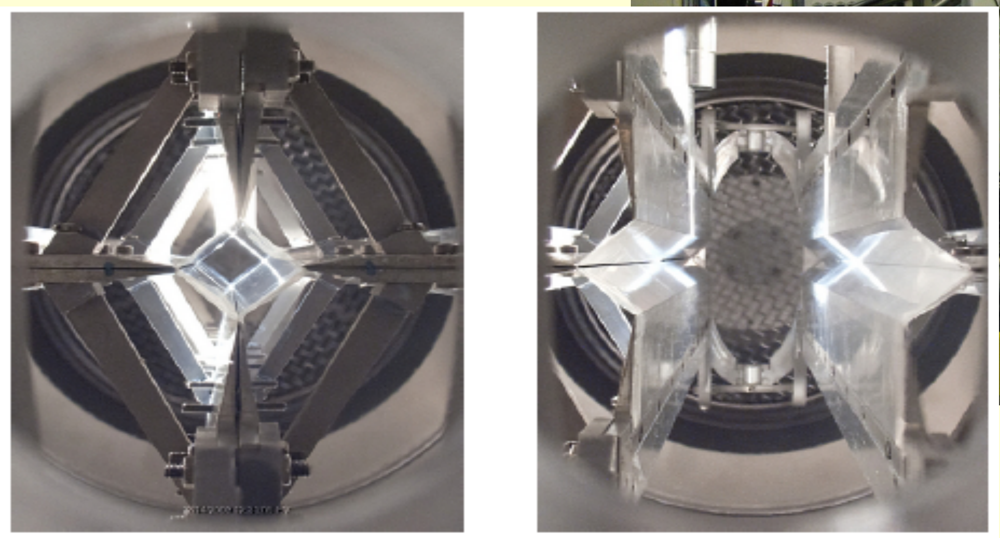
1.	July 2009:	Installation of quadrupole magnets (✓)
2.	July 2010:	Installation of rest of equipment (✓)
3.	October 2010:	Commissioning of equipment (✓)
4.	September 2011	Spin-filtering studies



Experimental setup at COSY (commissioning Oct. 2010)

- Low-ß section
- Atomic Beam Source
- Breit-Rabi polarimeter
- Openable storage cell



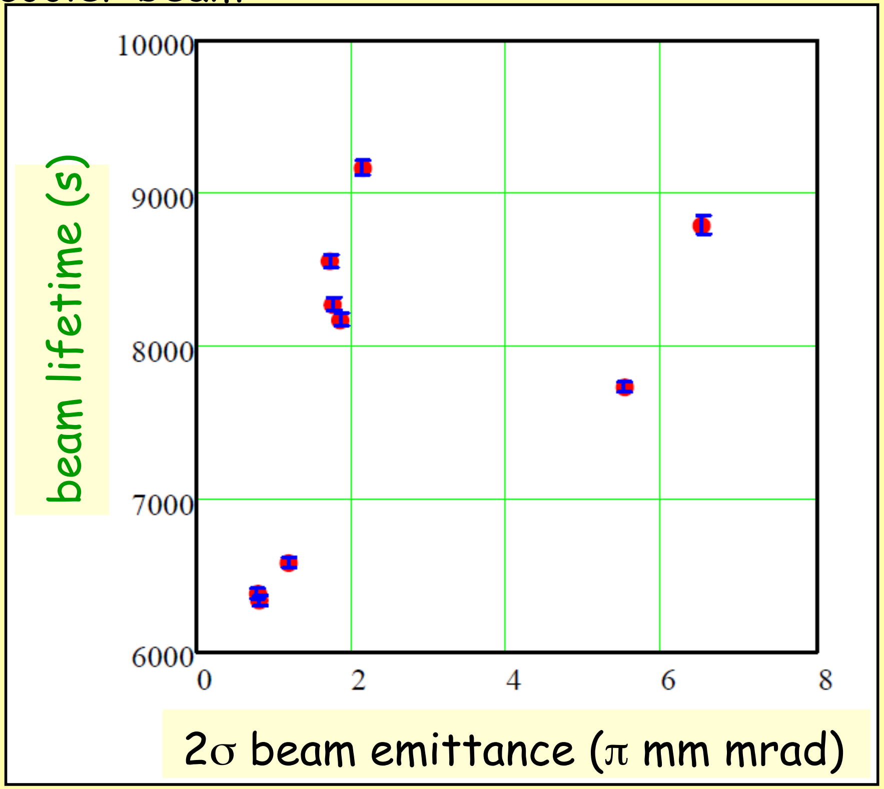


Commissioning I: Beam lifetime optimization

High beam lifetimes require:
- optimized closed orbit
- low residual gas in machine
- optimized electron cooler setup

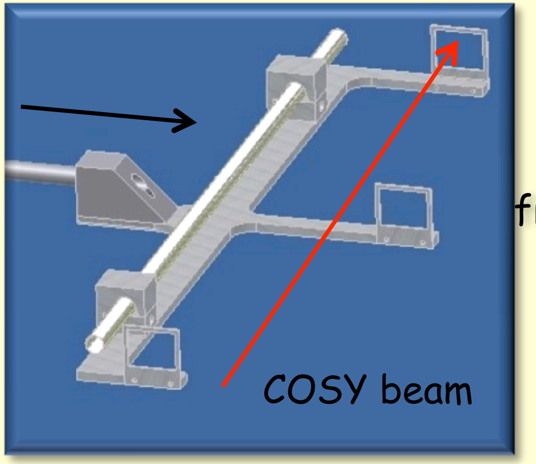
In case intra-beam scattering poses a limitation, increase of beam emittance should increase lifetime!

Recent result: Increase of beam emittance achieved by tilting of electron cooler beam

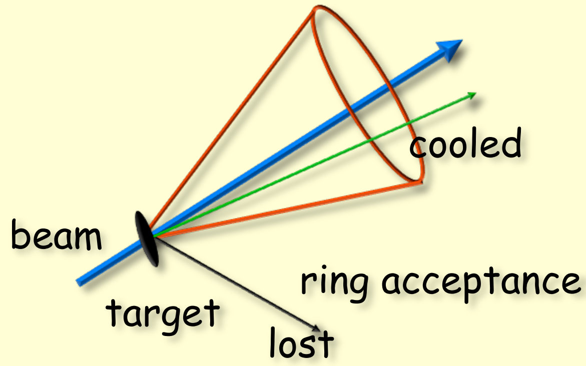


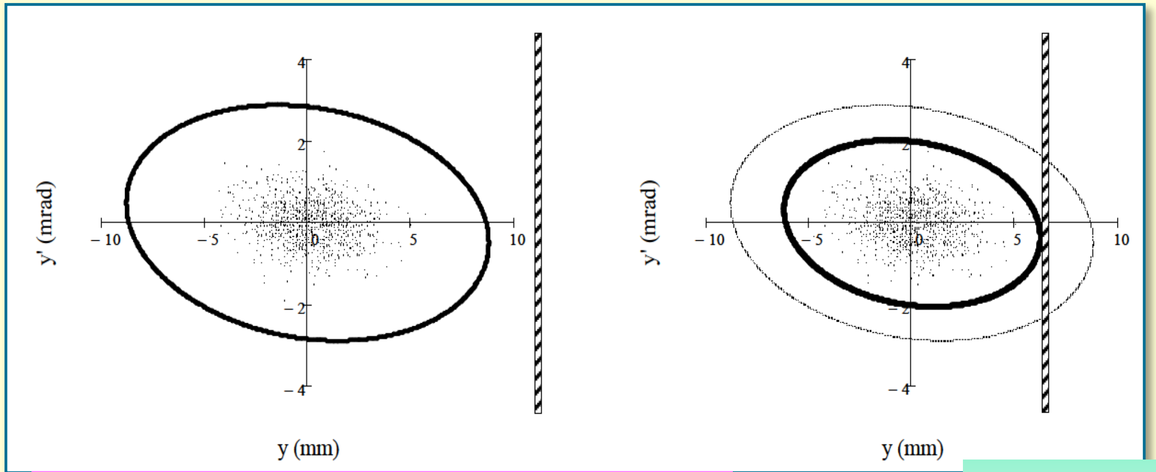
Commissioning II: Acceptance measurement

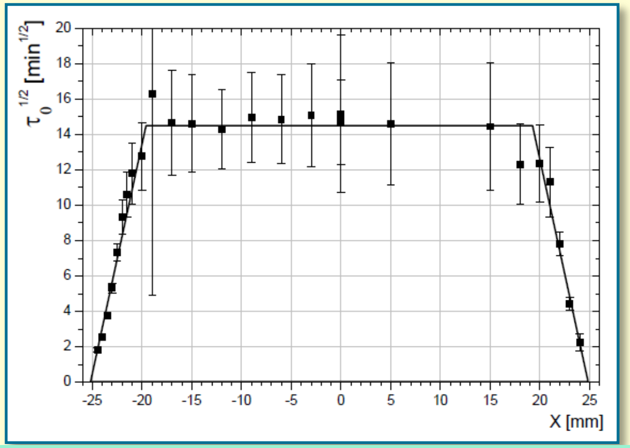
In an ideal machine Single-Coulomb scattering at the target dominates beam loss



movable frame system



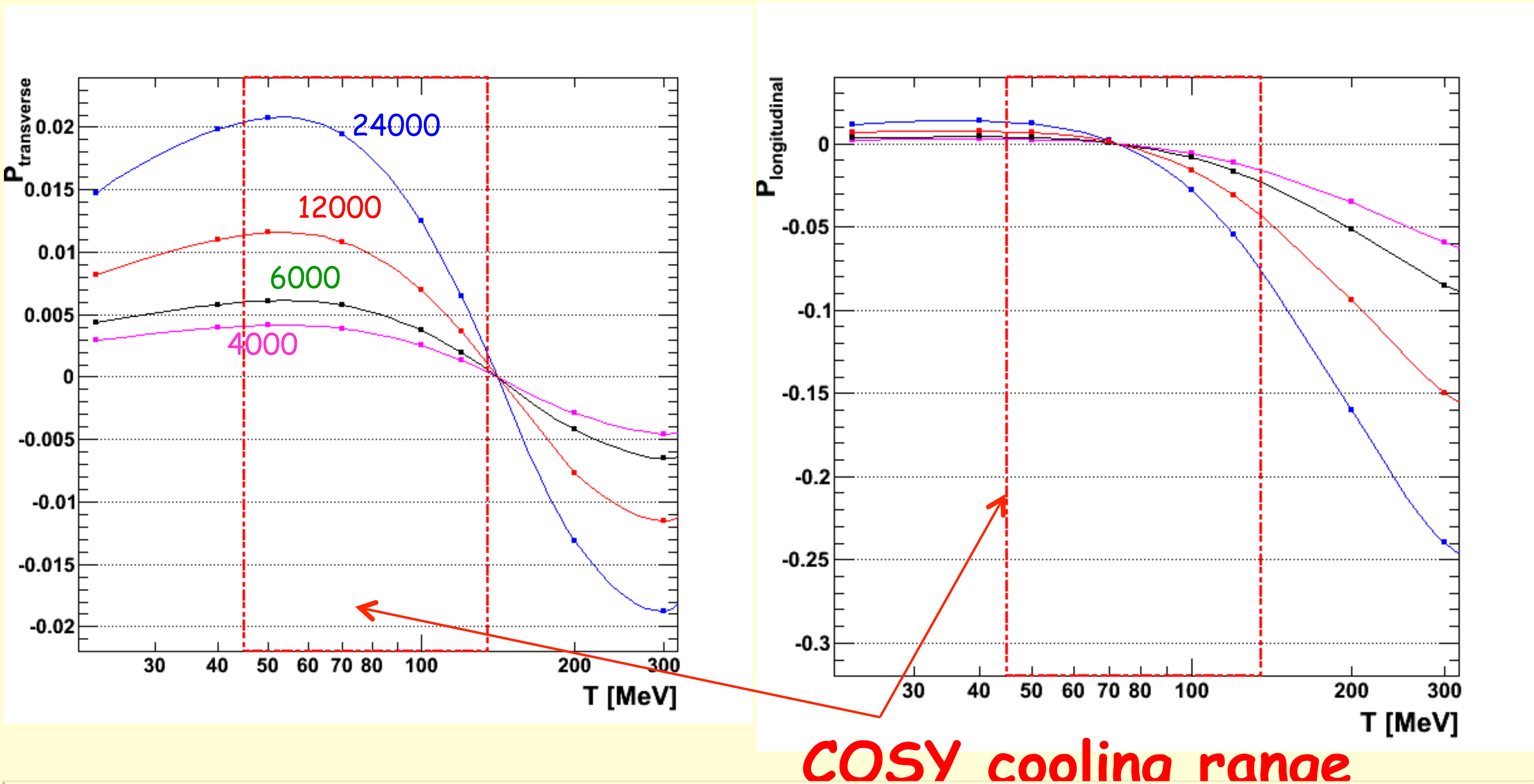




K. Grigoriev et al., NIMA 599,130 (2009)

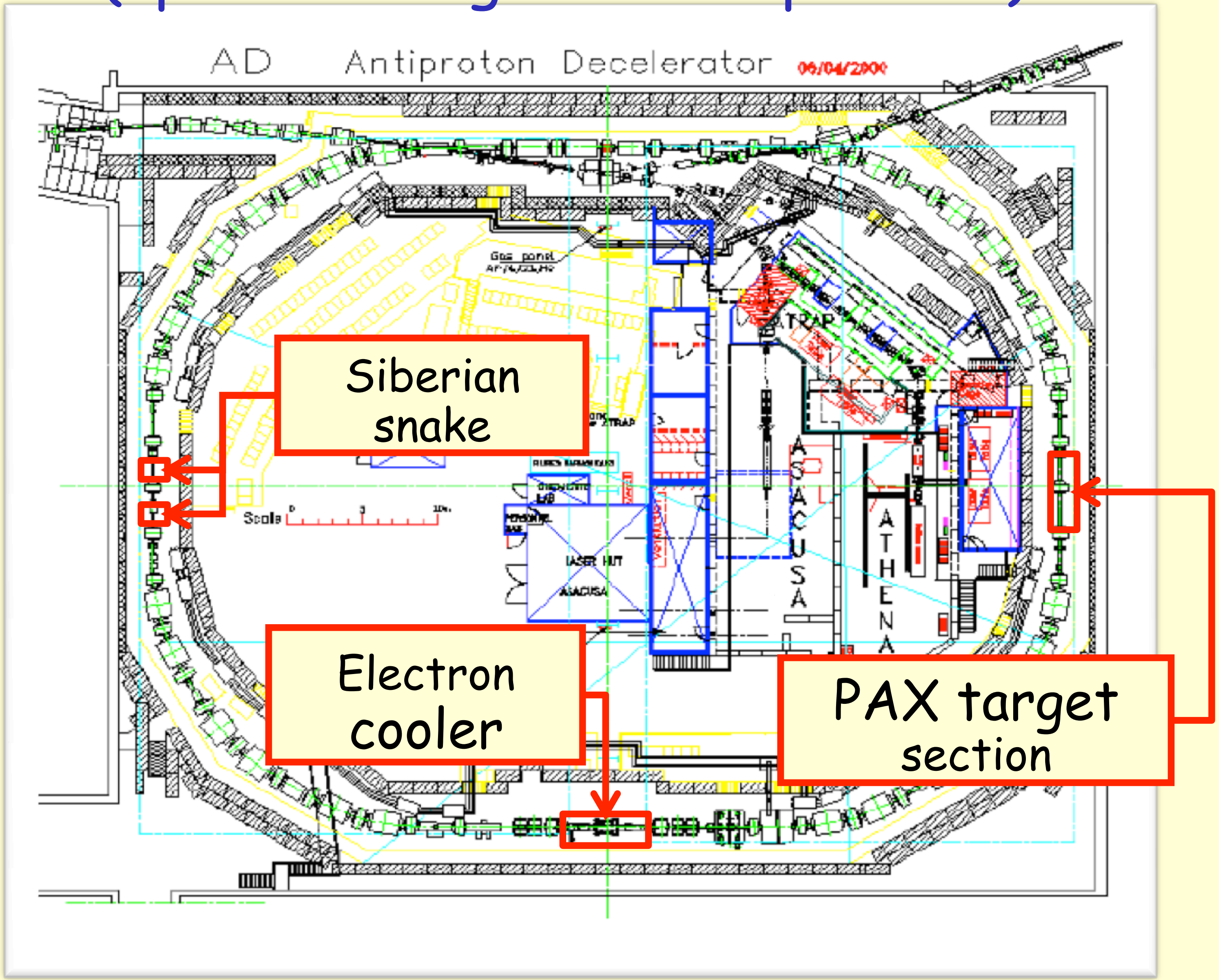
- Commissioning completed: Oct. 2010
- Measurements: Sept. 2011

Polarization build-up at COSY:projections



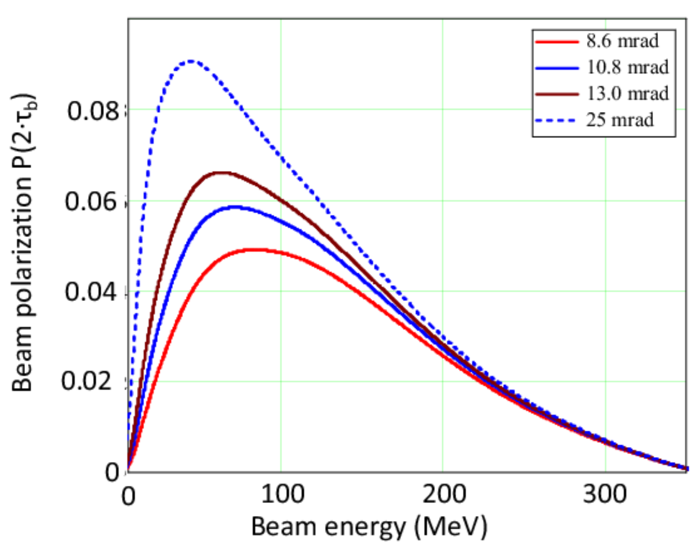
calculated beam polarization after 2 beam lifetimes (T_P = 49.3 MeV; Q = 0.8; dt = $5 \cdot 10^{13} cm^{-2}$)

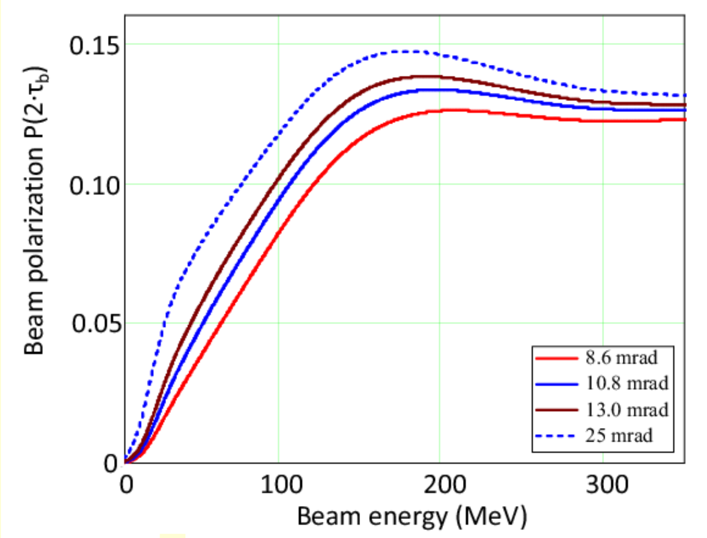
PAX at the CERN-AD
(spin filtering with antiprotons)



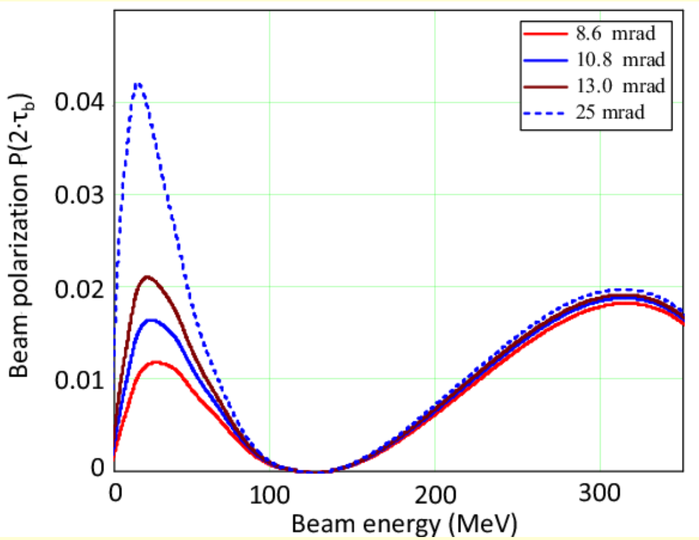
Expected polarizations after filtering for two lifetimes

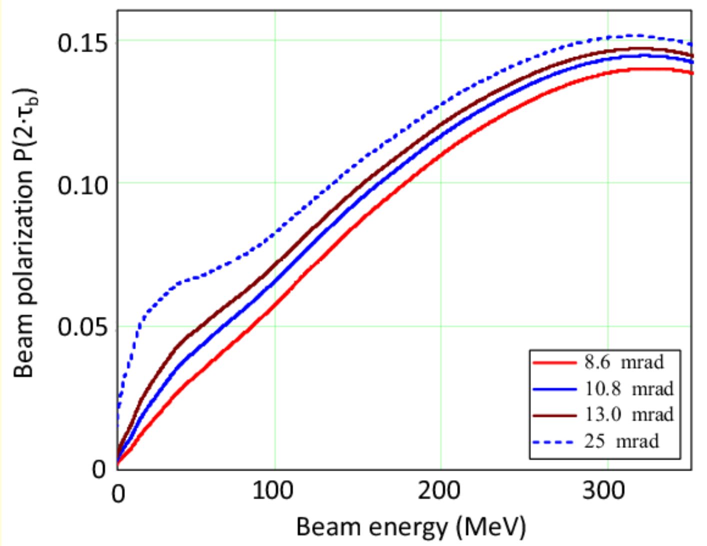
transverse | longitudinal





A





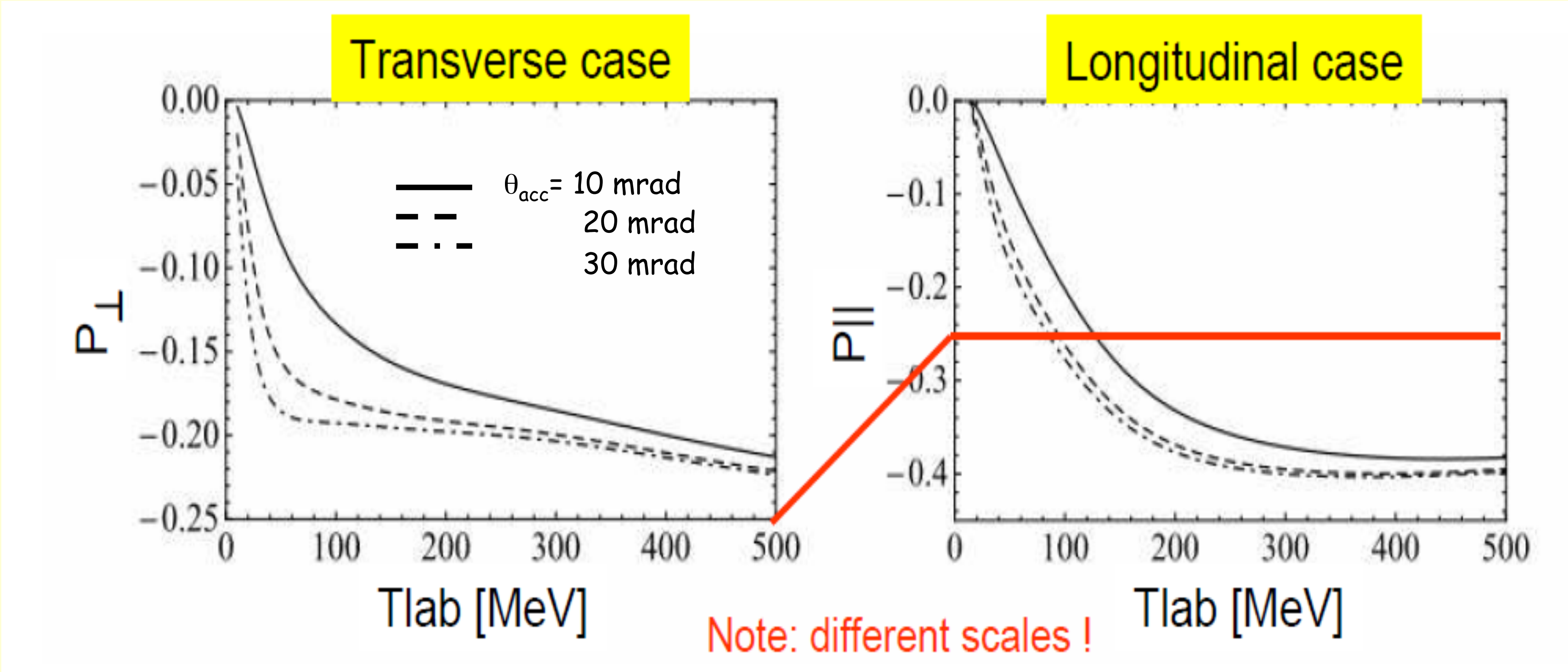
D

New calculation of expected polarizations

Spin-dependent part of $p\bar{p}$ interaction cross section and Nijmegen potential

V.F. Dmitriev [a,b], A.I. Milstein [a,b], S.G. Salnikov [a,b,*]

PLB 690 (2010)



Conclusions

- e-p collider: 3rd generation polarized DIS experiment
  - Systematic studies towards the (still unsolved) proton-spin puzzle
  - Complementary to USA projects
- Appealing perspectives for pbar-p single-spin asymmetries
  - Polarized target in PANDA?
  - Asymmetric collider (pbar-p↑,d↑)
- Double polarized pbar-p: worldwide unique facility
  - Asymmetric collider (pbar↑-p↑,d↑)
  - Polarized pbar studies under way

Polarization is missing tool that will be an added value to FAIR!

Beyond Collinear Approximation: Transverse Momentum Dependent DFs

LO quark distribution functions

Mulders and Tangerman, Nucl. Phys. B 461 (1996) 197

A. Bacchetta et al., JHEP 0702 (2007)

		quark		
		U	L	T
nucleon	U	f_1		$h_1^\perp$
	L		g_1	$h_{1L}^\perp$
	T	$f_{1T}^\perp$	$g_{1T}^\perp$	h_1 $h_{1T}^\perp$

Boer-Mulders DF *#

'worm-gear 1' DF #

Transversity DF #

Prezelosity DF #

Sivers DF *

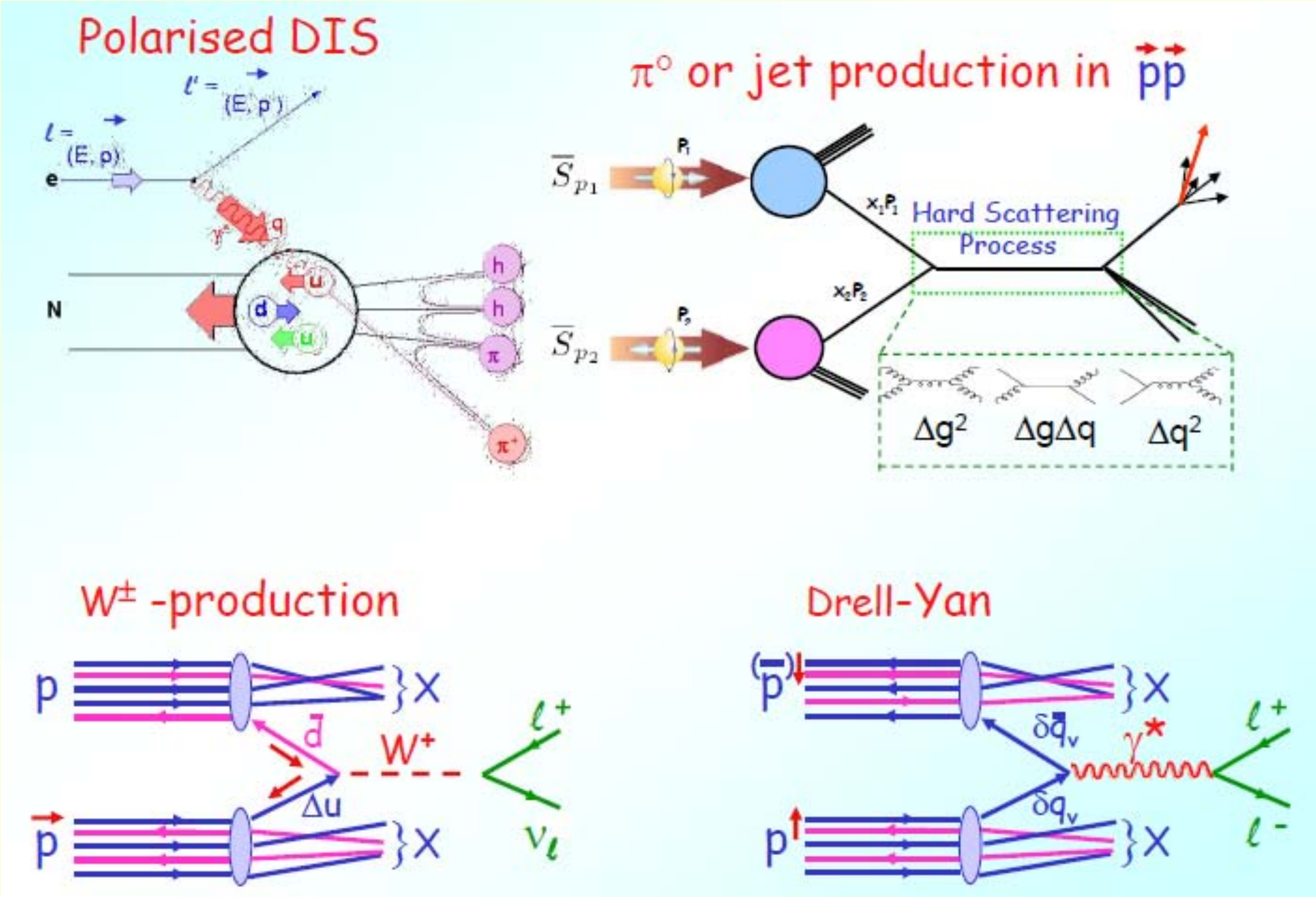
'worm-gear 2' DF

Only f_1 and g_1 measurable in inclusive DIS, all others in SIDIS

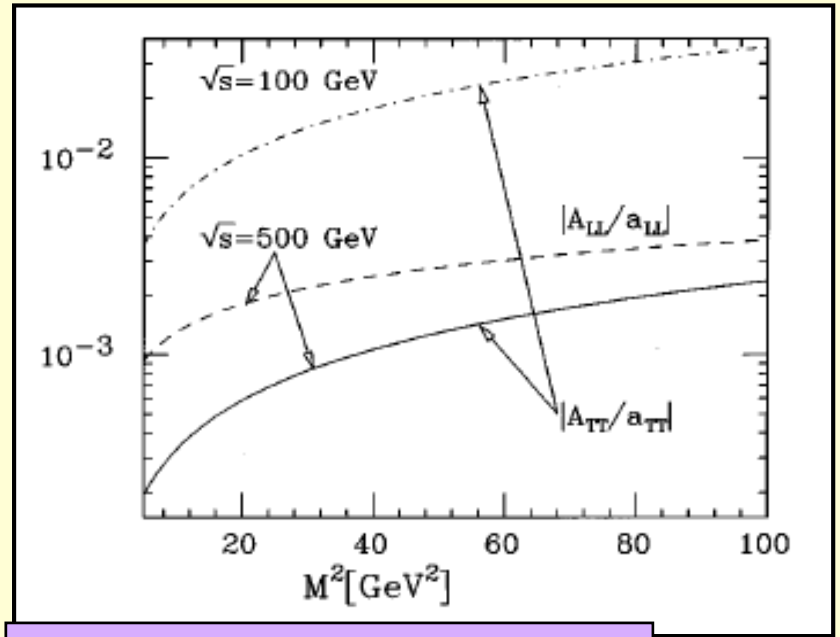
$D_1 \equiv D_q^h$ = ‚normal' FF,

$H_1^\perp$ = spin-dependent Collins FF

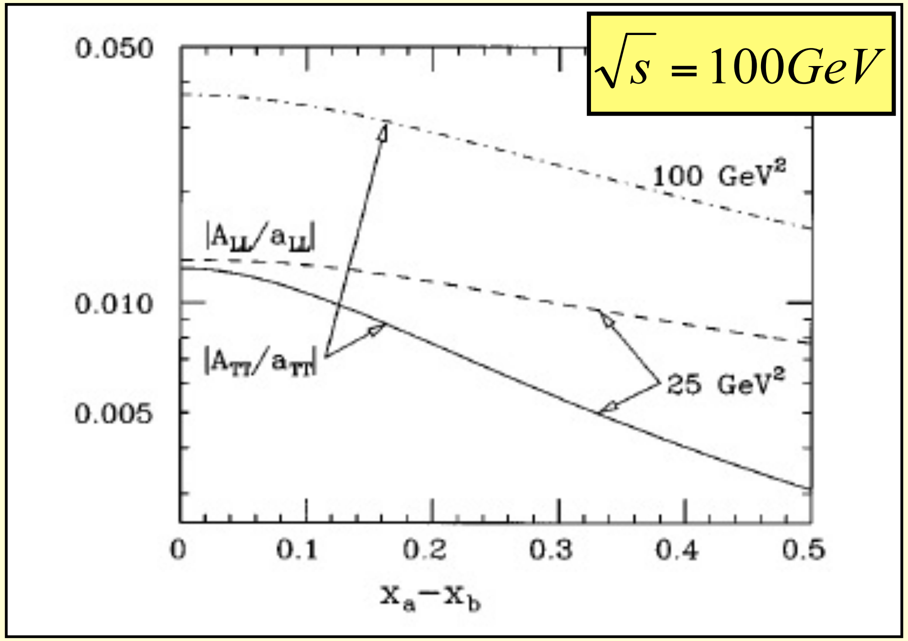
Experimental tools for spin-physics

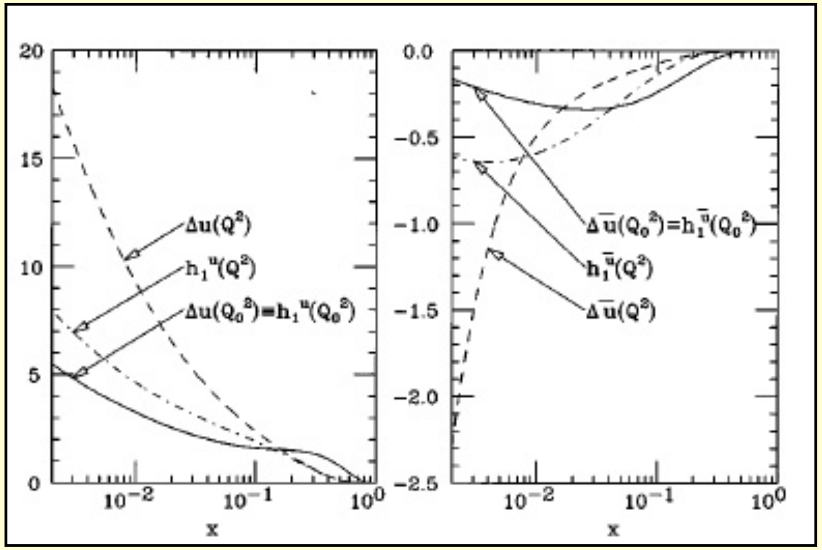


Higher energy p-p machine



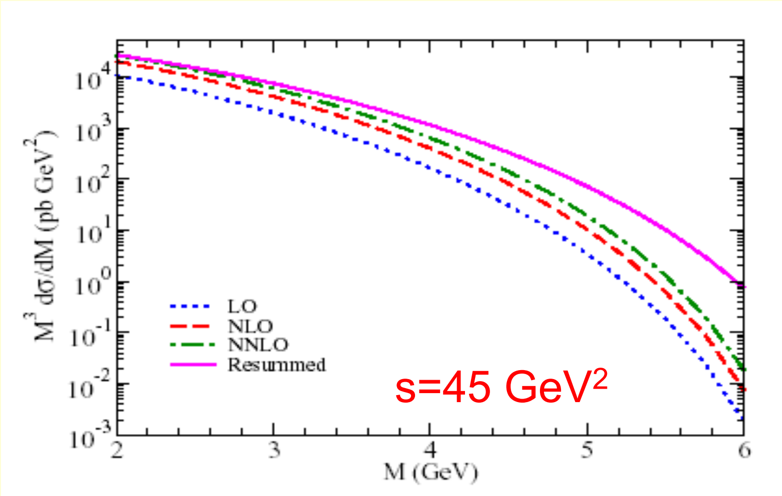
V. Barone, T. Calarco and A. Drago
Phys. Rev. D 56 (1997) 527

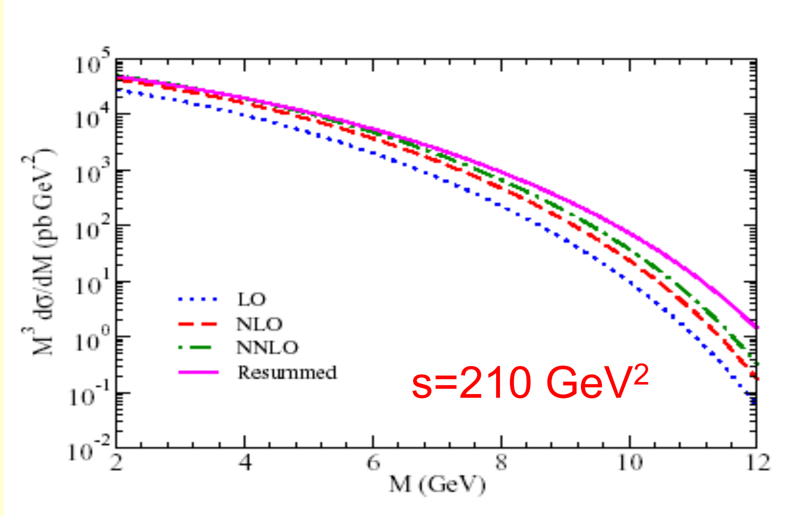




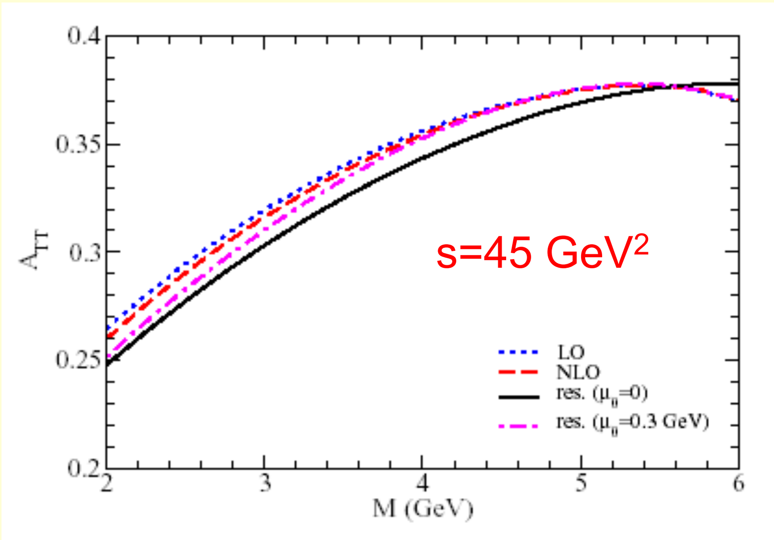
- s ↑
  - Asymmetry ↓
- $A_{LL} > A_{TT}$
- s_{JPARC} ideal

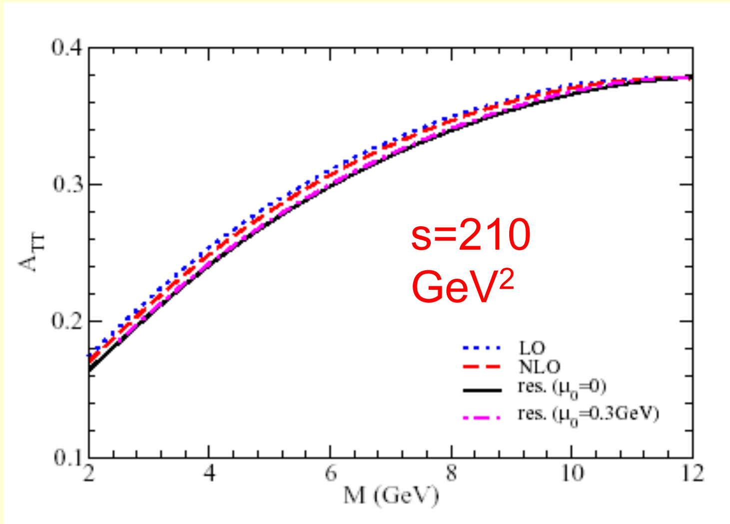
Cross-section



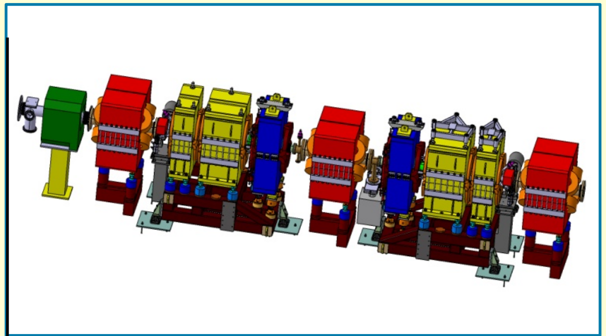


Asymmetry

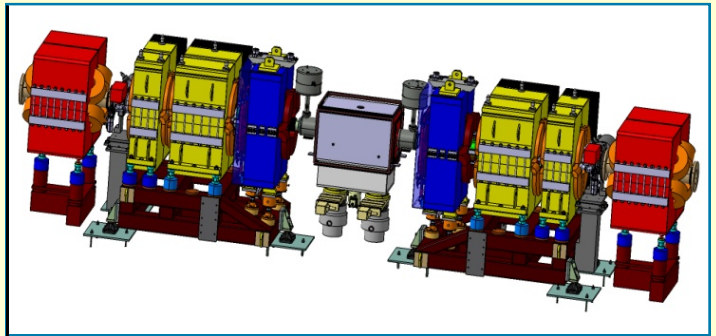




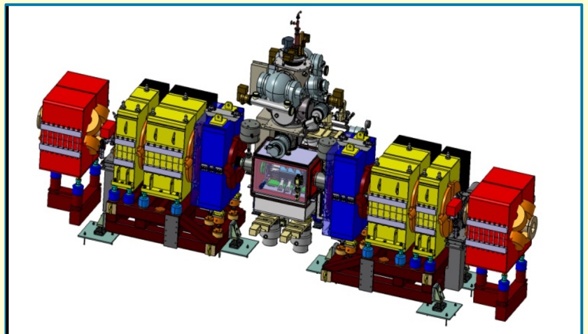
Main phases of installation at AD



Central quadrupole
magnet remains in place



Installation of
target chamber

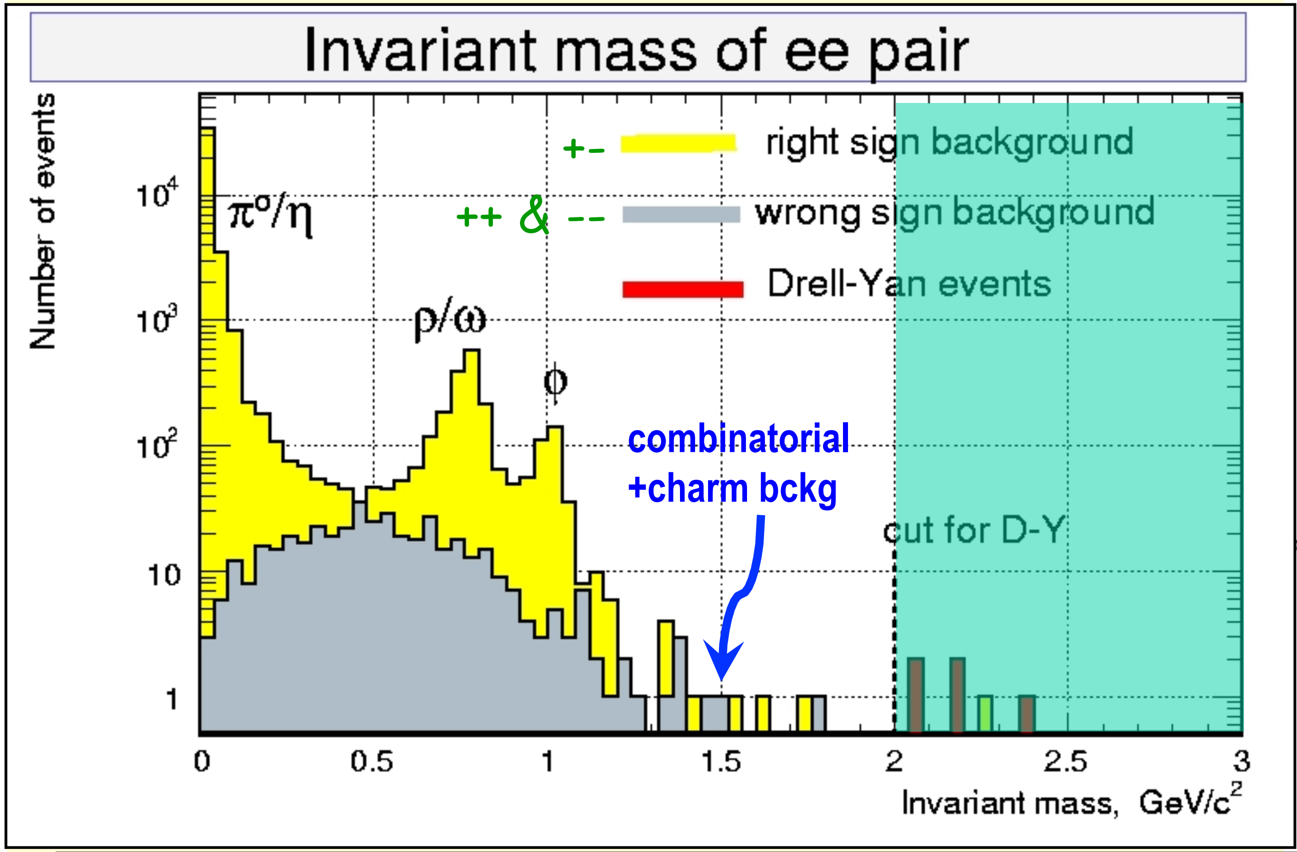


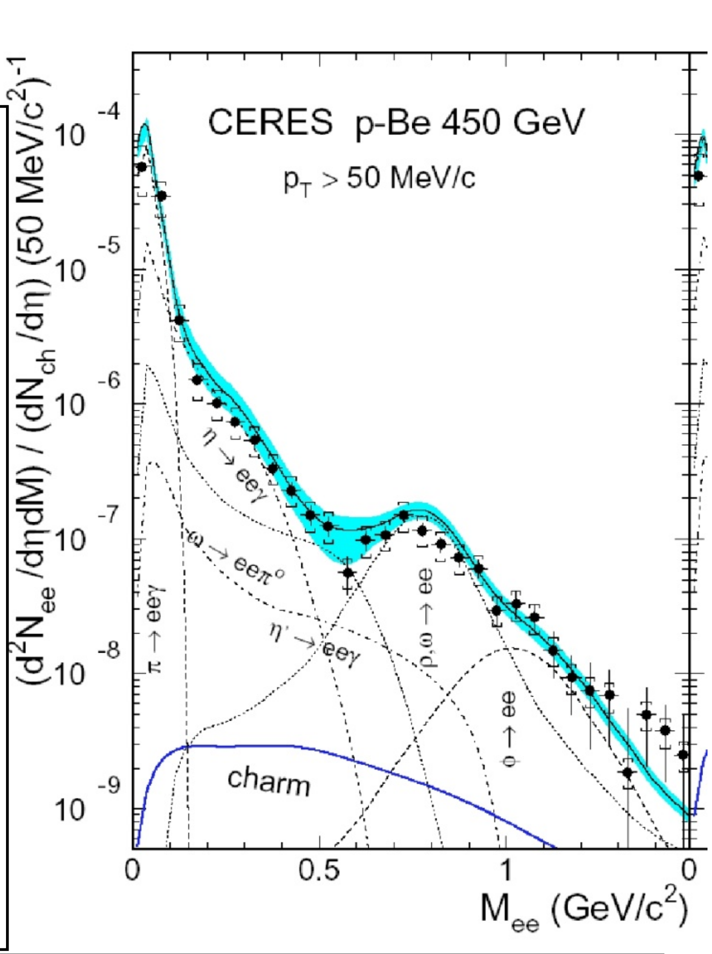
Installation of
ABS, BRP and
Detector

2011 **2012** **2013**

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)

Theoretical models

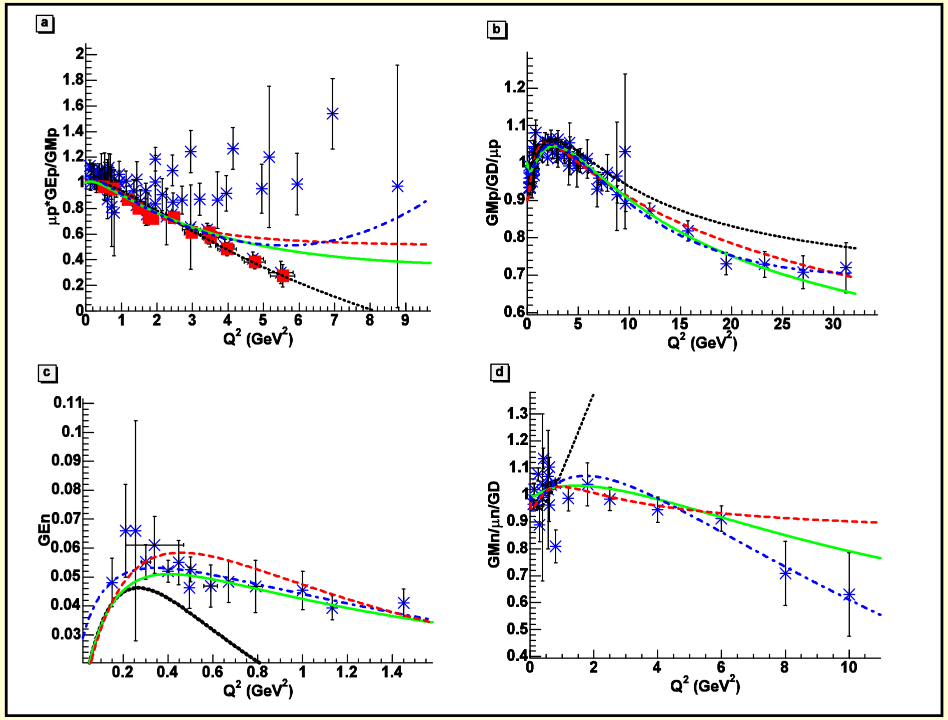
Spacelike

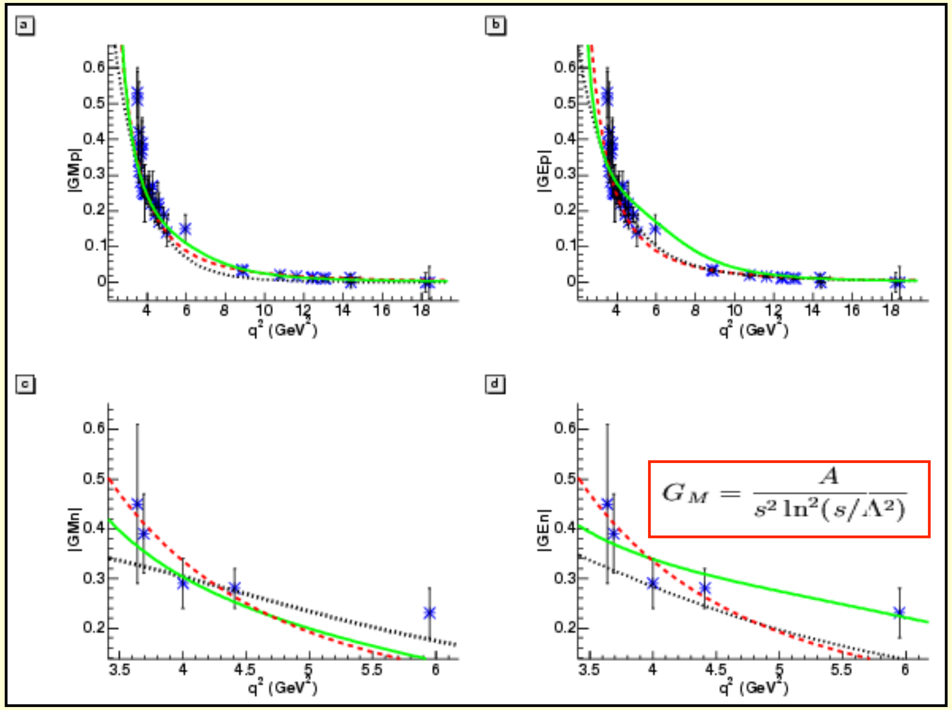
Timelike

Electric **Magnetic** **Electric** **Magnetic**

proton

neutron





QCD inspired
Bosted **PRC 51, 409 (1995)**

Extended VDM
E.L.Lomon PRC 66, 045501 2002)

VDM : IJL
F. Iachello..PLB 43, 191 (1973)

Hohler
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E. Tomasi, F. Lacroix, C. Duterte, G.I. Gakh, EPJA 24, 419(2005)