13 August 2010
FERMILAB

HARD COLLISIONS of SPINNING PROTONS: PAST, PRESENT & FUTURE

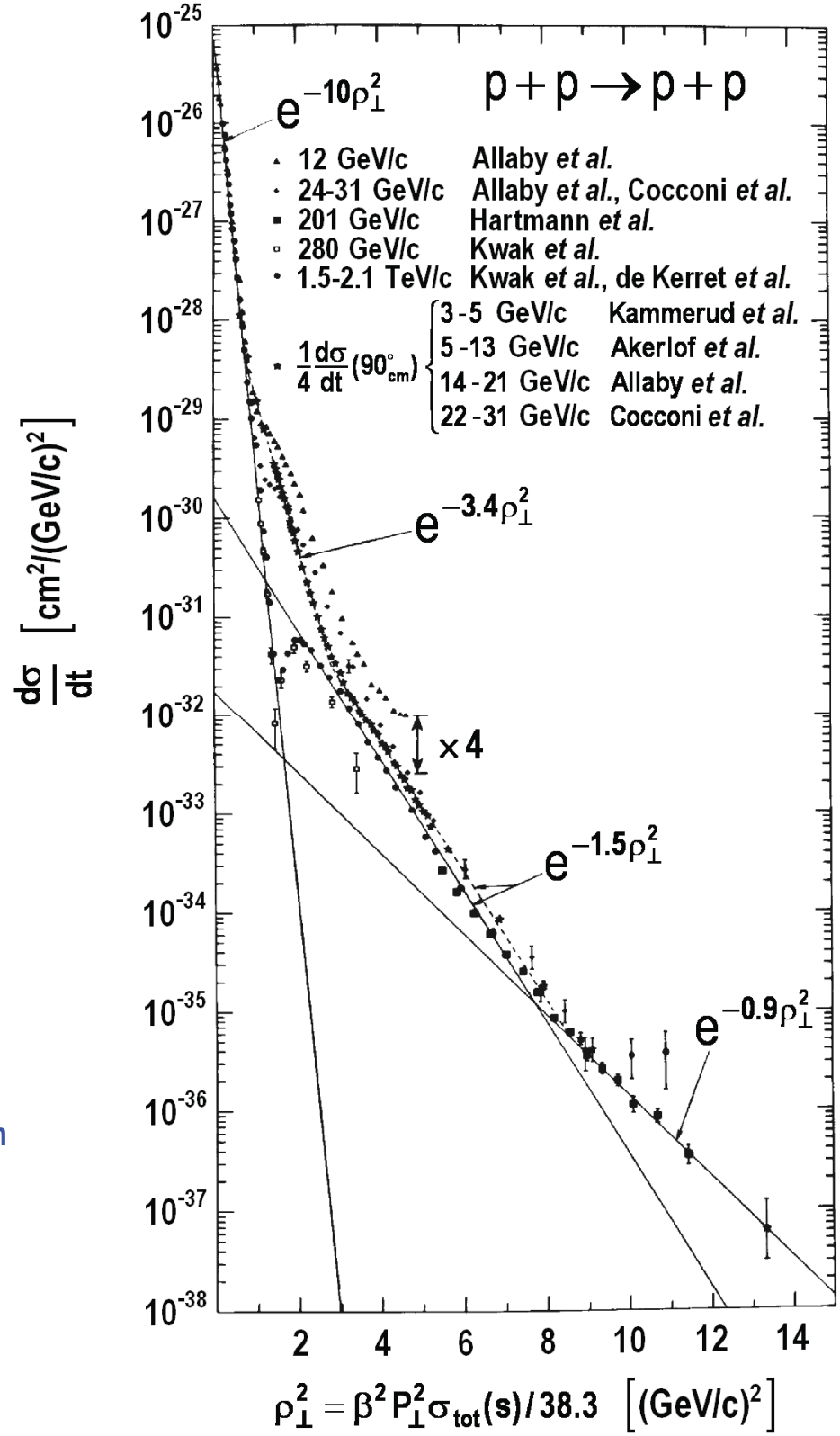
A. D. KRISCH
UNIVERSITY of MICHIGAN

PROTON-PROTON ELASTIC CROSS-SECTION

UNPOLARIZED $d\sigma/dt$ for all
$p + p \rightarrow p + p$ data above 3 GeV
PLOTTED vs. SCALED $P_\perp^2$ VARIABLE

NOTE 4 DIFFERENT SLOPES
FIRST EVIDENCE for STRUCTURE inside PROTON (Akerlof *et al.* 1966)

1968 Comment by Prof. Serber on x4 at 90°_{cm}
led to interest in spin & polarized beams



UNPOLARIZED BEAM and TARGET

$$\left\langle d\sigma / dt \right\rangle \propto \left(N_{\uparrow\uparrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow} + N_{\downarrow\downarrow}\right)$$

EITHER BEAM or TARGET POLARIZED (ONE-SPIN)

$$A_n = \frac{A_{meas}}{P_i} = \frac{\left(N_{\uparrow} - N_{\downarrow}\right)}{P_i\left(N_{\uparrow} + N_{\downarrow}\right)}$$

BOTH BEAM and TARGET POLARIZED (TWO-SPIN)

$$A_{nn} = \frac{A_{meas}}{P_T P_B} = \frac{\left(N_{\uparrow\uparrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow} + N_{\downarrow\downarrow}\right)}{P_T P_B\left(N_{\uparrow\uparrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow} + N_{\downarrow\downarrow}\right)}$$

A_{meas} = MEASURED ASYMMETRY

P_T and P_B = TARGET and BEAM POLARIZATIONS

N_i and N_{ij} = NORMALIZED ELASTIC EVENT RATES

ARGONNE 12 GeV ZGS WORLD'S FIRST HIGH ENERGY POLARIZED PROTON BEAM

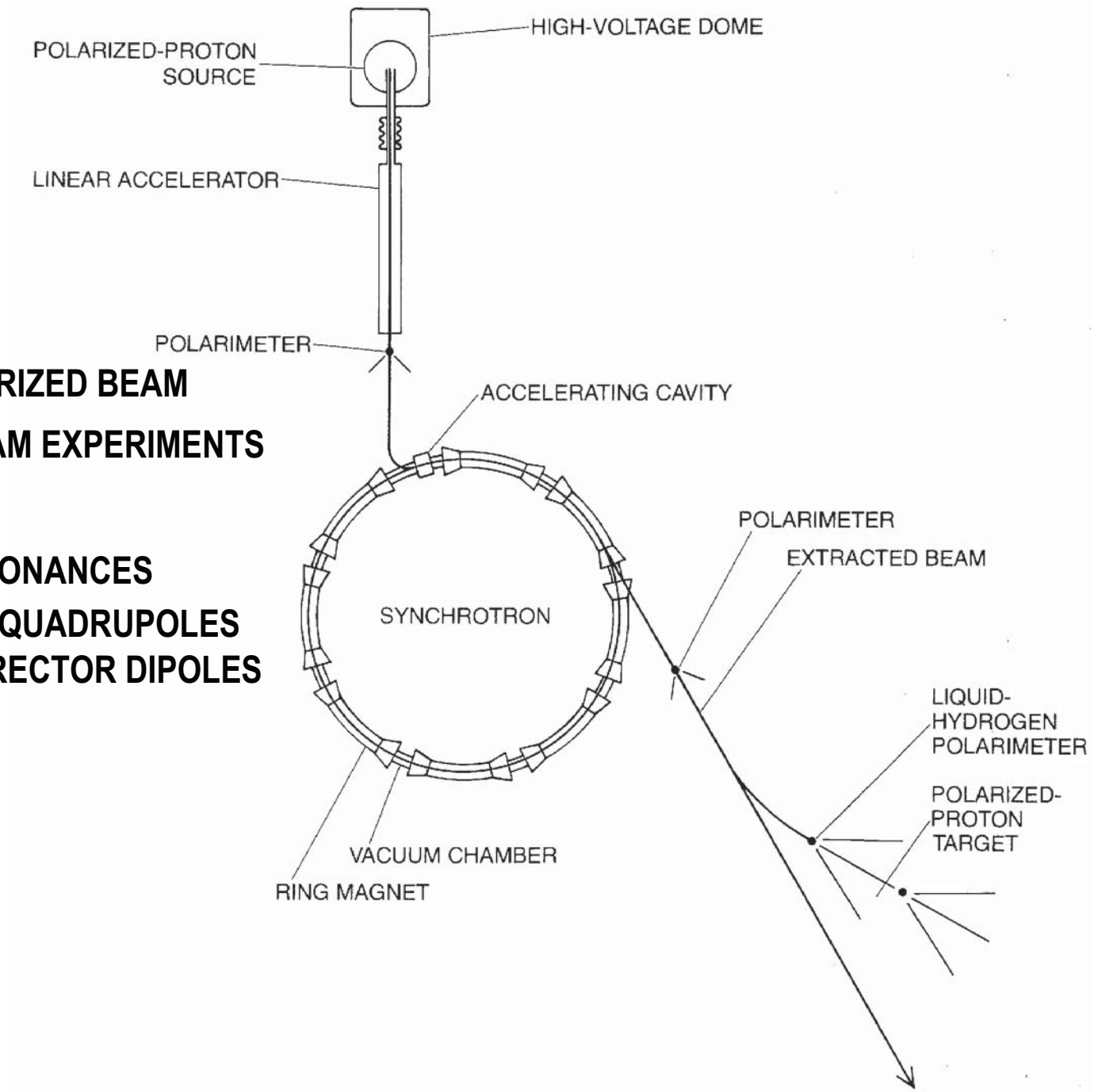
1969-1973 DEVELOP POLARIZED BEAM

1973-1979 POLARIZED BEAM EXPERIMENTS

DEPOLARIZING RESONANCES

INTRINSIC: PULSED QUADRUPOLES

IMPERFECTION: CORRECTOR DIPOLES



2-SPIN PROTON-PROTON ELASTIC CROSS SECTIONS

12 GeV ZGS

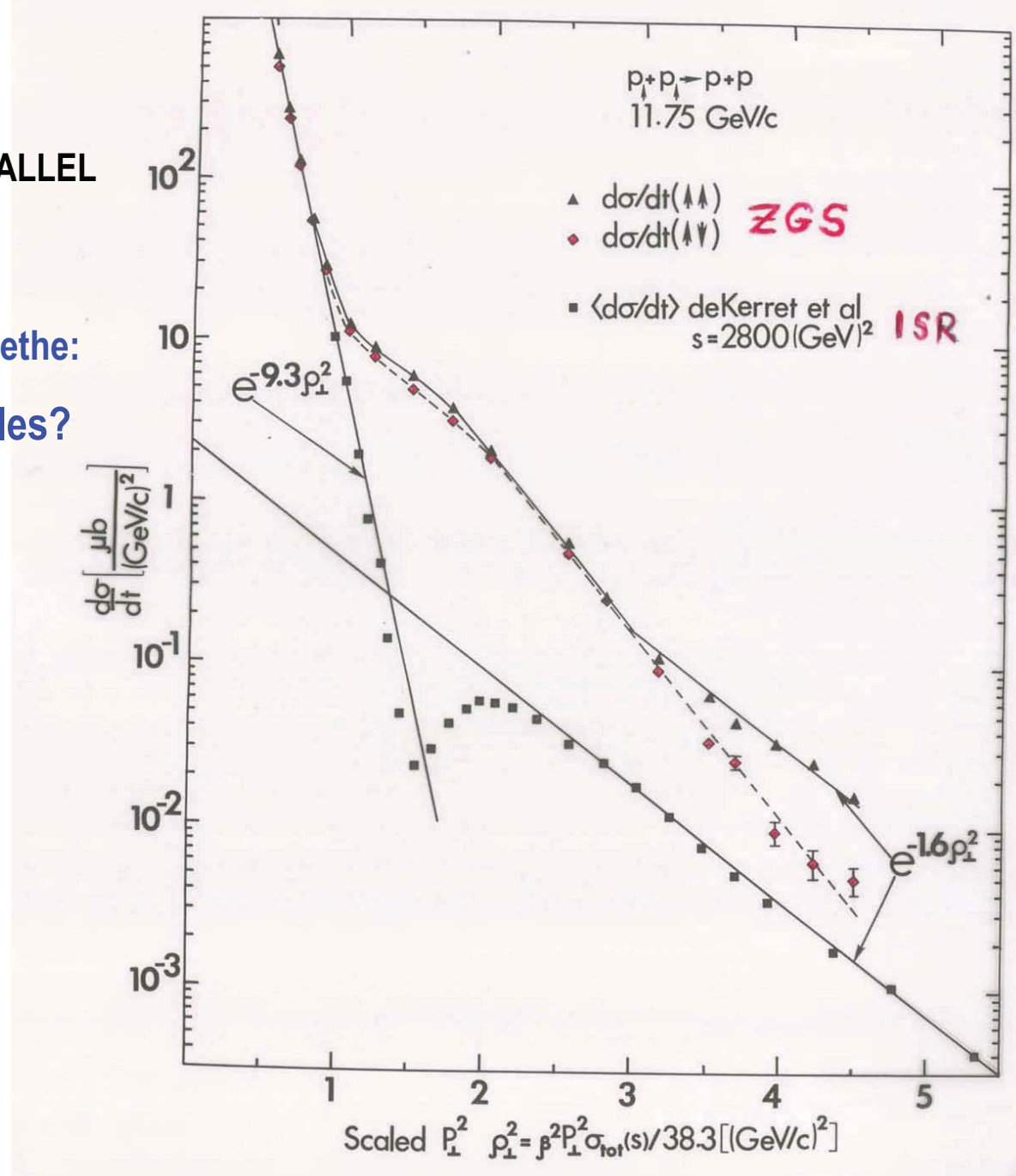
1977-1978

SPINS PARALLEL 4x SPINS ANTIPARALLEL

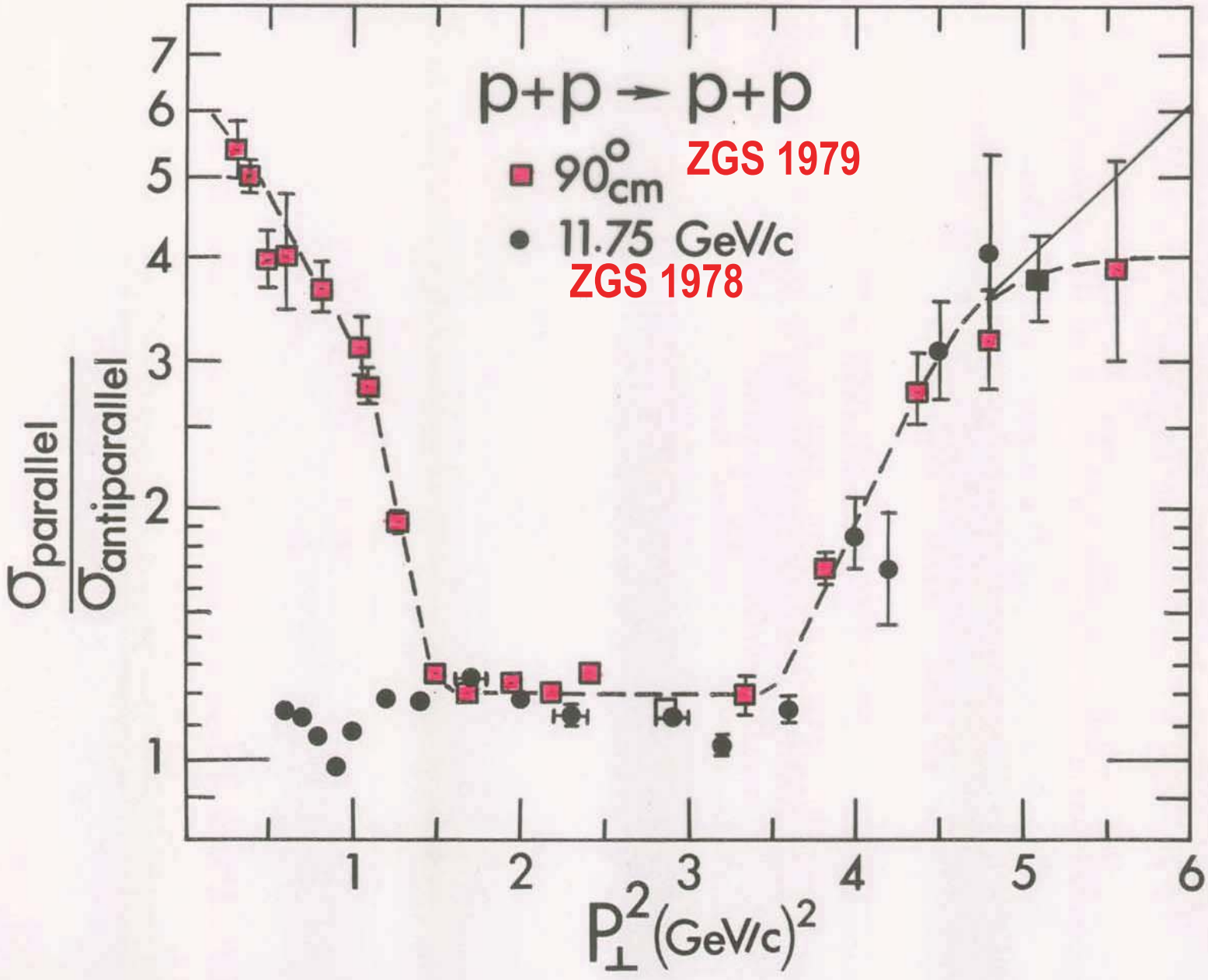
TOTALLY UNEXPECTED

Questions by Profs. Weisskopf & Bethe:

High P_T or 90°_{cm} Identical Particles?



Answer to Questions by Profs. Weisskopf & Bethe



BNL AGS: First Strong Focusing Polarized Proton Beam

1977- 84 Polarized Beam Development
1984-now Experiments & RHIC Injector

VERY DIFFICULT PROJECT

Hardware: $10 Million 1980$

45 Depol. Resonances:

INTRINSIC	IMPERFECTION
12 Pulsed Quads	96 Correction Dipoles

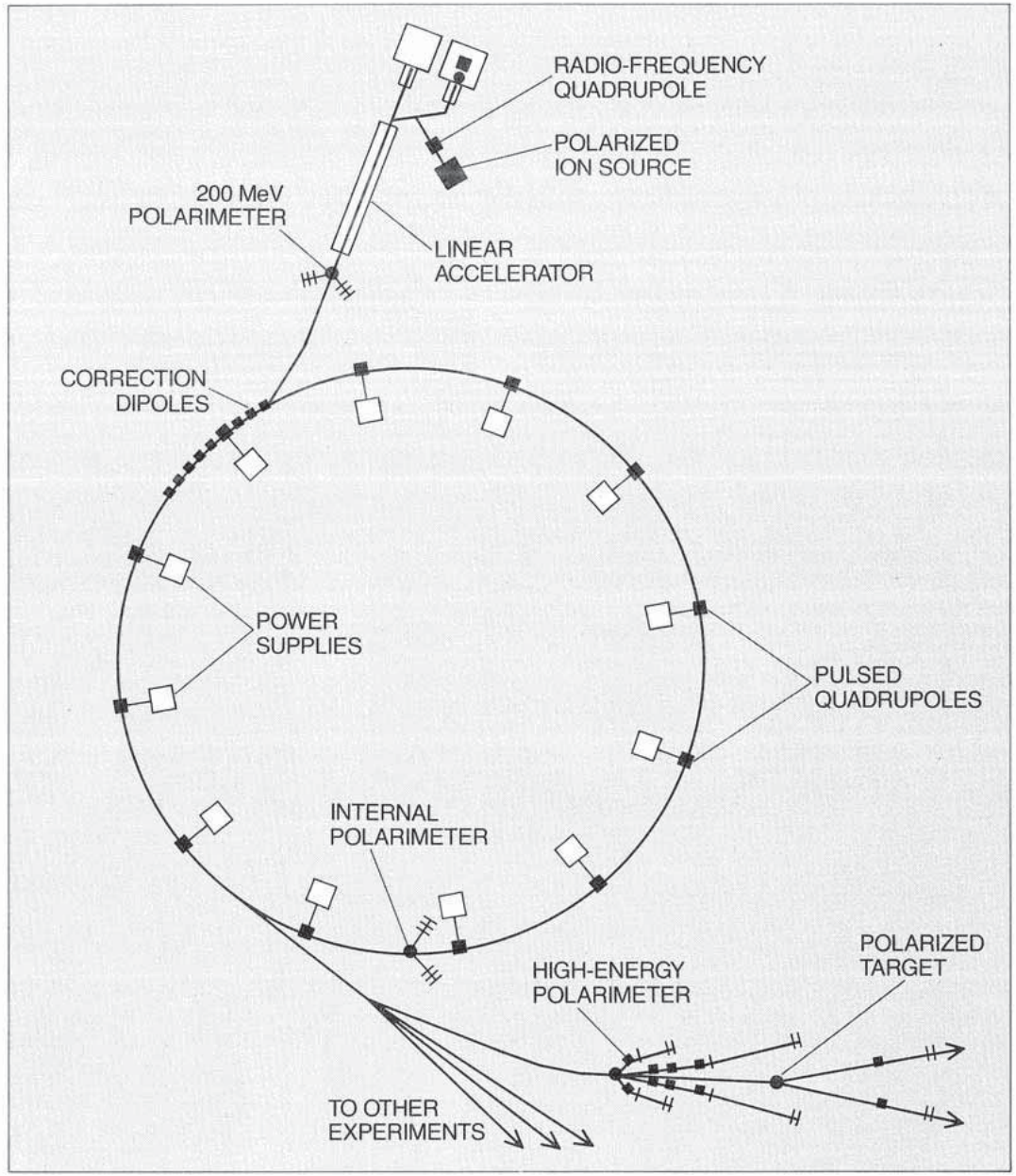
AGS Tune-up Time:

1984-88: 3-7 weeks each year

1988: 22 GeV/c Polarization 42%

2000-now: Better with new ideas; but still hard

IMPORTANT LESSON



AGS 1985-1990 A_n

PERTURBATIVE QCD $\Rightarrow$

$A_n = 0$ at HIGH $P_\perp^2$ and HIGH ENERGY

$A_n \neq 0 \Rightarrow$

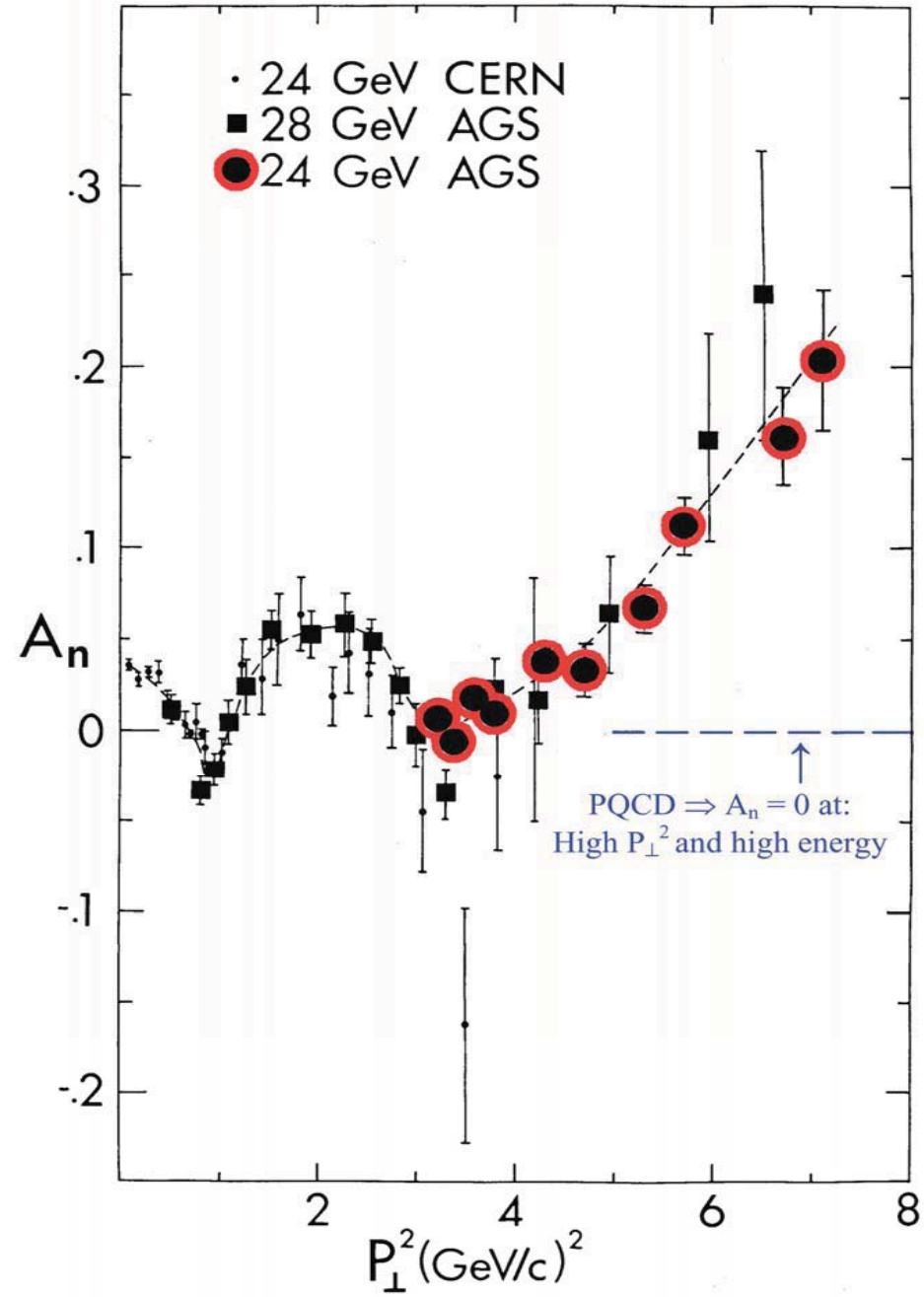
PROBLEM with PQCD?

NO MODEL can EXPLAIN ALL HIGH-$P_\perp^2$ SPIN EFFECTS (A_n & A_{nn})

GOAL

MEASURE A_n (and A_{nn})

up to $P_\perp^2 = 12\ (\mathrm{GeV/c})^2$



INCLUSIVE HYPERON POLARIZATION (P)

Devlin, Pondrum, Bunce, Heller *et al.* 1976-80 FermiLab

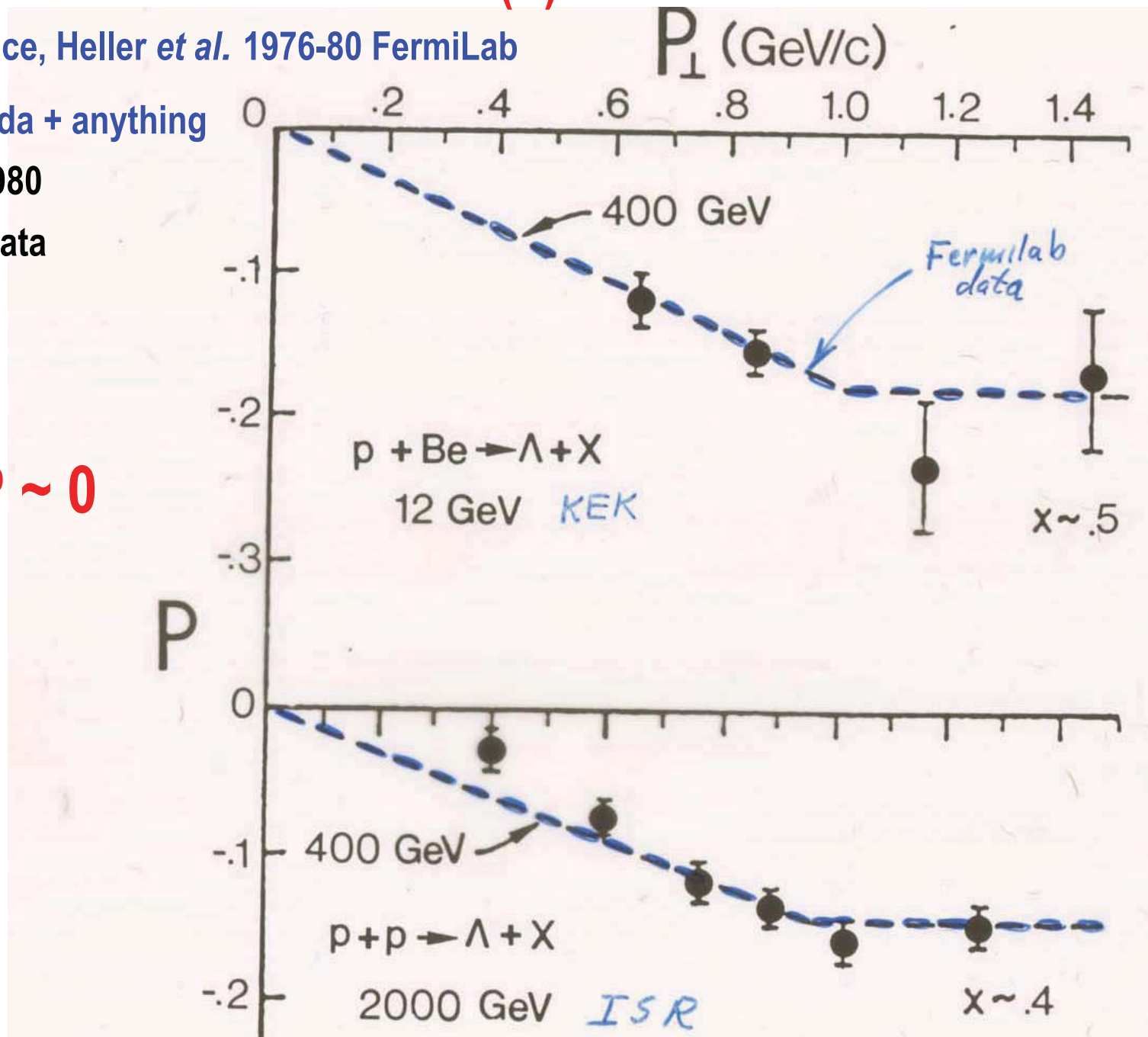
400 GeV p+p -> Lambda + anything

Plot by Heller ~1980

with KEK & ISR data

P ~ 15-20 %

PQCD says P ~ 0



INCLUSIVE PION PRODUCTION

200 GeV Polarized Proton Beam

from Polarized Hyperon Decay

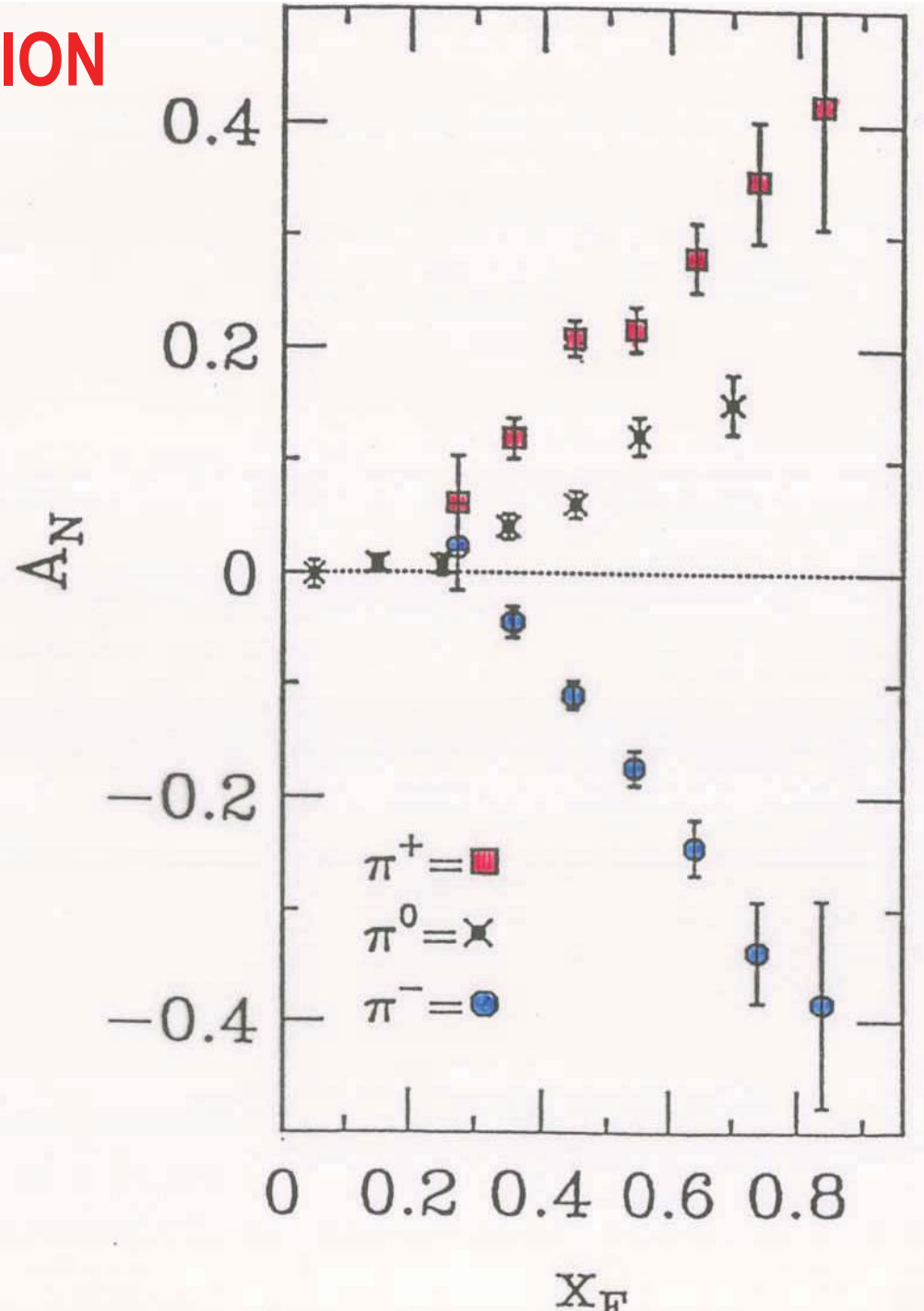
1990s Fermilab E-704

Yokosawa *et al.*

Phys Lett B264, 462 (1991)

$A_n \sim 40\%$

PQCD said $A_n \sim 0$



SSC 1984

POLARIZED PROTONS at 20-20 TeV

INDIVIDUALLY OVERCOME EACH RESONANCE

- Worked very well at 12 GeV Weak Focusing ZGS
- Worked painfully at 28 GeV Strong Focusing AGS
- Impossible at 20 TeV Strong Focusing SSC

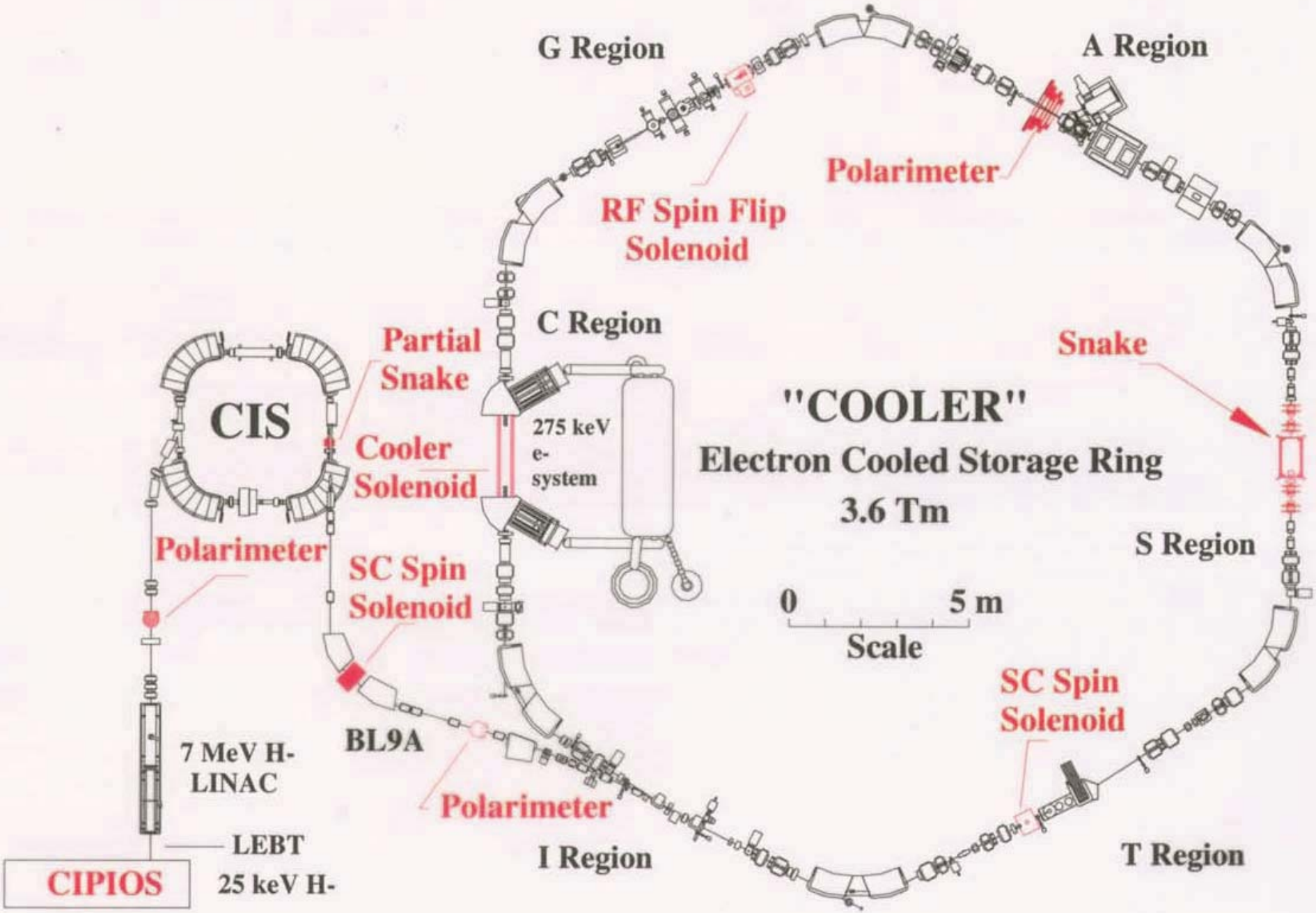
SIBERIAN SNAKES DERBENEV & KONDRATENKO ~1977

CHAMBERLAIN, COURANT, TERWILLIGER, ADK
1985 ANN ARBOR WORKSHOP on PPB in SSC:
CONCLUSIONS:

1. 20 TeV PPB POSSIBLE with 26 SNAKES / RING
   BUT SEEMS: "TOO GOOD TO BE TRUE"

2. MUST TEST SIBERIAN SNAKE EXPERIMENTALLY

TEST SIBERIAN SNAKE IUCF COOLER RING: 1985-2002



FIRST SIBERIAN SNAKE TEST 1989

ROTATES SPIN by 180° per TURN

SIBERIAN SNAKE TEST

PRL 1989

VOLUME 63, NUMBER 11 PHYSICAL REVIEW LETTERS 11 SEPTEMBER 1989

First Test of the Siberian Snake Magnet Arrangement to Overcome Depolarizing Resonances in a Circular Accelerator

A. D. Krisch, S. R. Mane,[a] R. S. Raymond, T. Roser, J. A. Stewart, K. M. Terwilliger,[b] and B. Vuaridel
Randall Laboratory of Physics, The University of Michigan, Ann Arbor, Michigan 48109

J. E. Goodwin, H-O. Meyer, M. G. Minty, P. V. Pancella, R. E. Pollock, T. Rinckel, M. A. Ross, F. Sperisen, and E. J. Stephenson
Indiana University Cyclotron Facility, Bloomington, Indiana 47408

E. D. Courant, S. Y. Lee, and L. G. Ratner
Brookhaven National Laboratory, Upton, New York 11973
(Received 25 July 1989)

We studied the $G\gamma=2$ imperfection depolarizing resonance at 108 MeV, both with and without a Siberian snake, by varying the resonance strength while storing beams of 104- and 120-MeV polarized protons at the Indiana University Cooler Ring. We used a cylindrically symmetric polarimeter to simultaneously study the effect of a depolarizing resonance on both the vertical and radial components of the polarization. At 104 MeV we found that the Siberian snake eliminated the effect of the nearby $G\gamma=2$ depolarizing resonance.

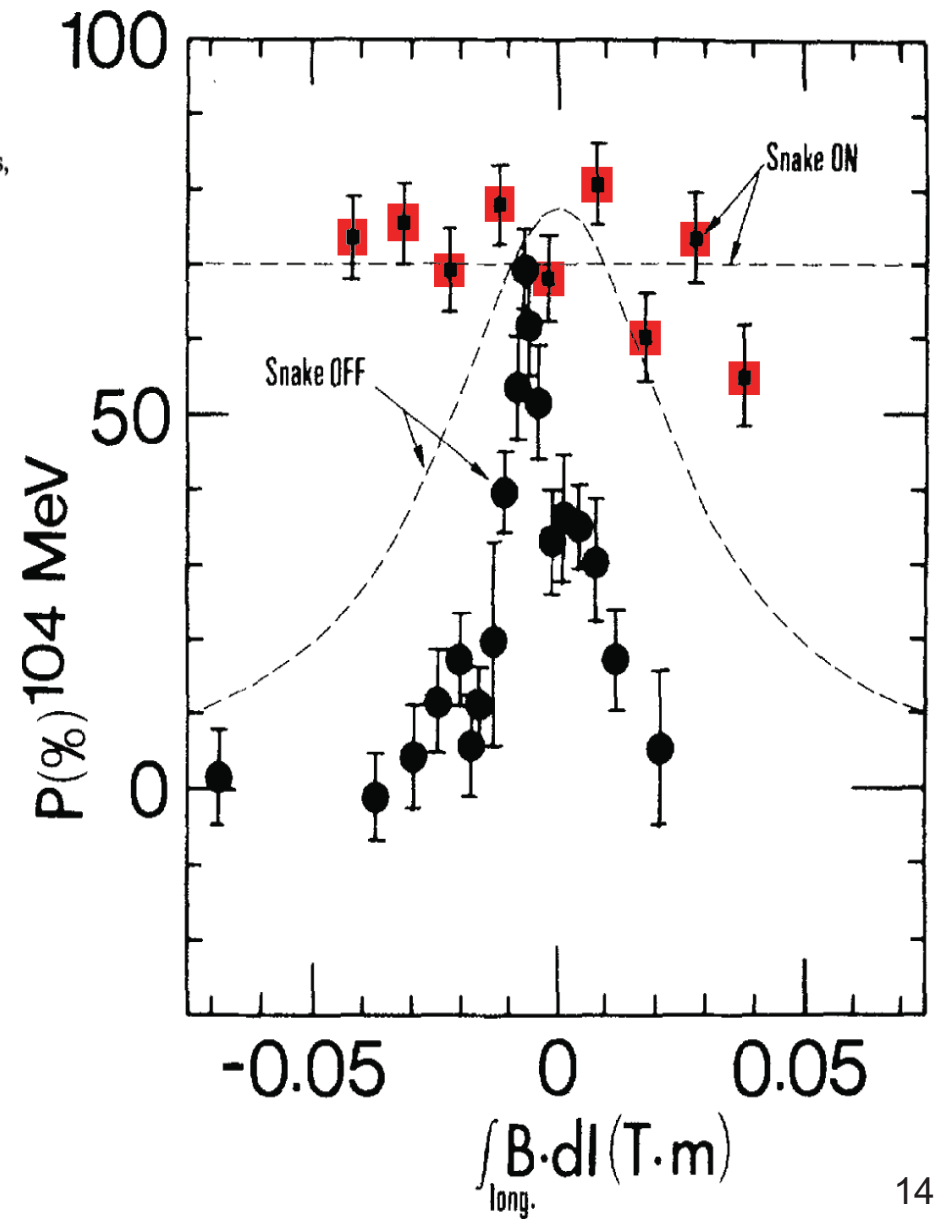


FIG. 4. The beam polarization in each stable polarization direction at 104 MeV is plotted against the longitudinal magnetic field integral in the Cooler Ring solenoids. The circles are the vertical polarization with the snake off and the injection of vertically polarized protons. The squares are the radial polarization with the snake on and the injection of horizontally polarized protons. We combined all data into bins of width 0.00115 Tm. There is a systematic normalization uncertainty of about $\pm 5\%$. The dashed curve is the predicted behavior. The straight dashed line is a fit.

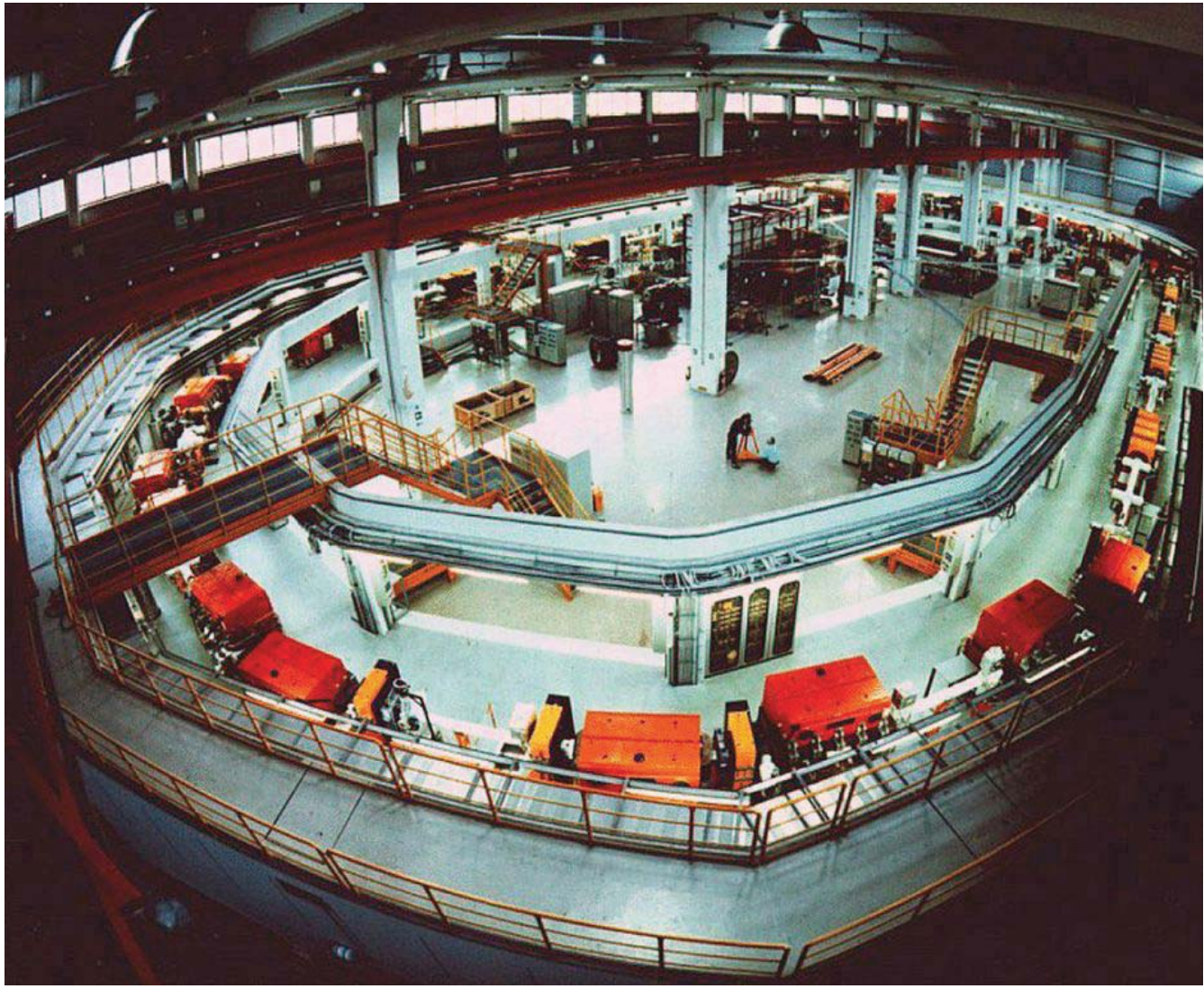
SPIN@COSY 2002-2009

CERN COURIER

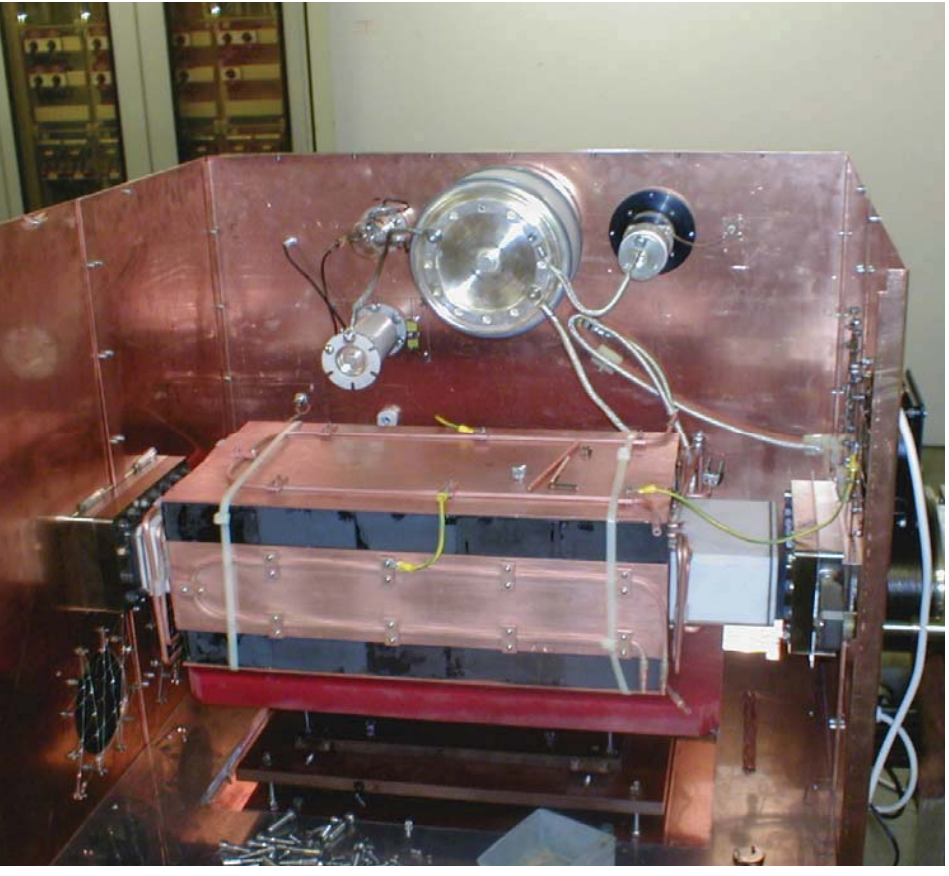
Nov 24, 2004

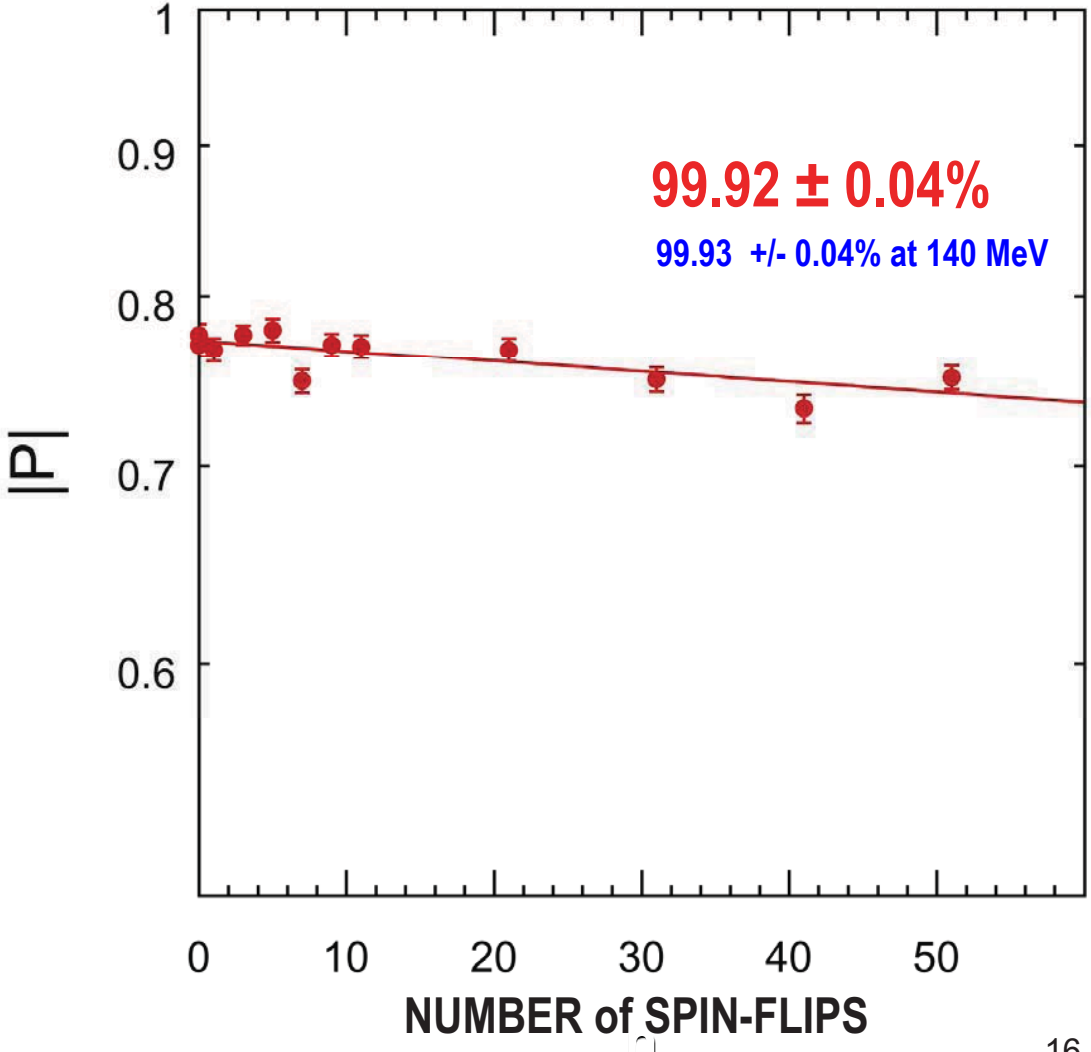
Spin-flipping crosses the Atlantic

After the venerable Cooler Ring at the Indiana University Cyclotron Facility (IUCF) passed on to accelerator heaven in autumn 2002, the polarized beam team, led by Alan Krisch, crossed the Atlantic to continue their spin-manipulation work at COSY, the cooler synchrotron at the Forschungszentrum in Jülich (figure 1). As part of the SPIN@COSY collaboration, they have been improving the polarization capabilities of the 3.5 GeV/c proton and deuteron storage ring. Recently, the collaboration - from Michigan and Brookhaven in America, COSY, Bonn and Hamburg in Germany, and KEK and J-PARC in Japan - has used a new ferrite RF-dipole magnet to flip the spins of stored 2.1 GeV/c protons with almost no polarization loss.



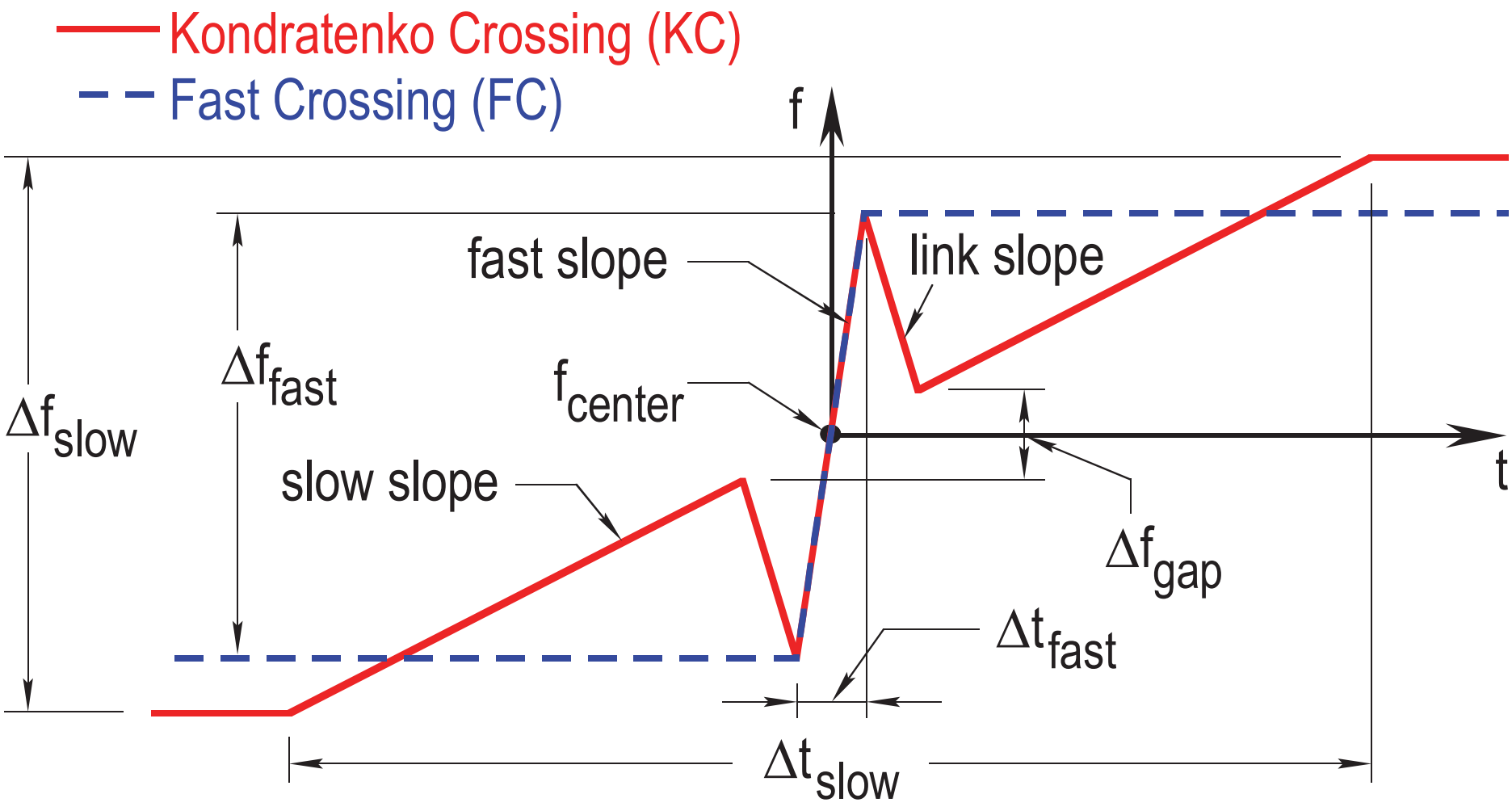
VERY HIGH SPIN-FLIP EFFICIENCY with SMALL RF DIPOLE





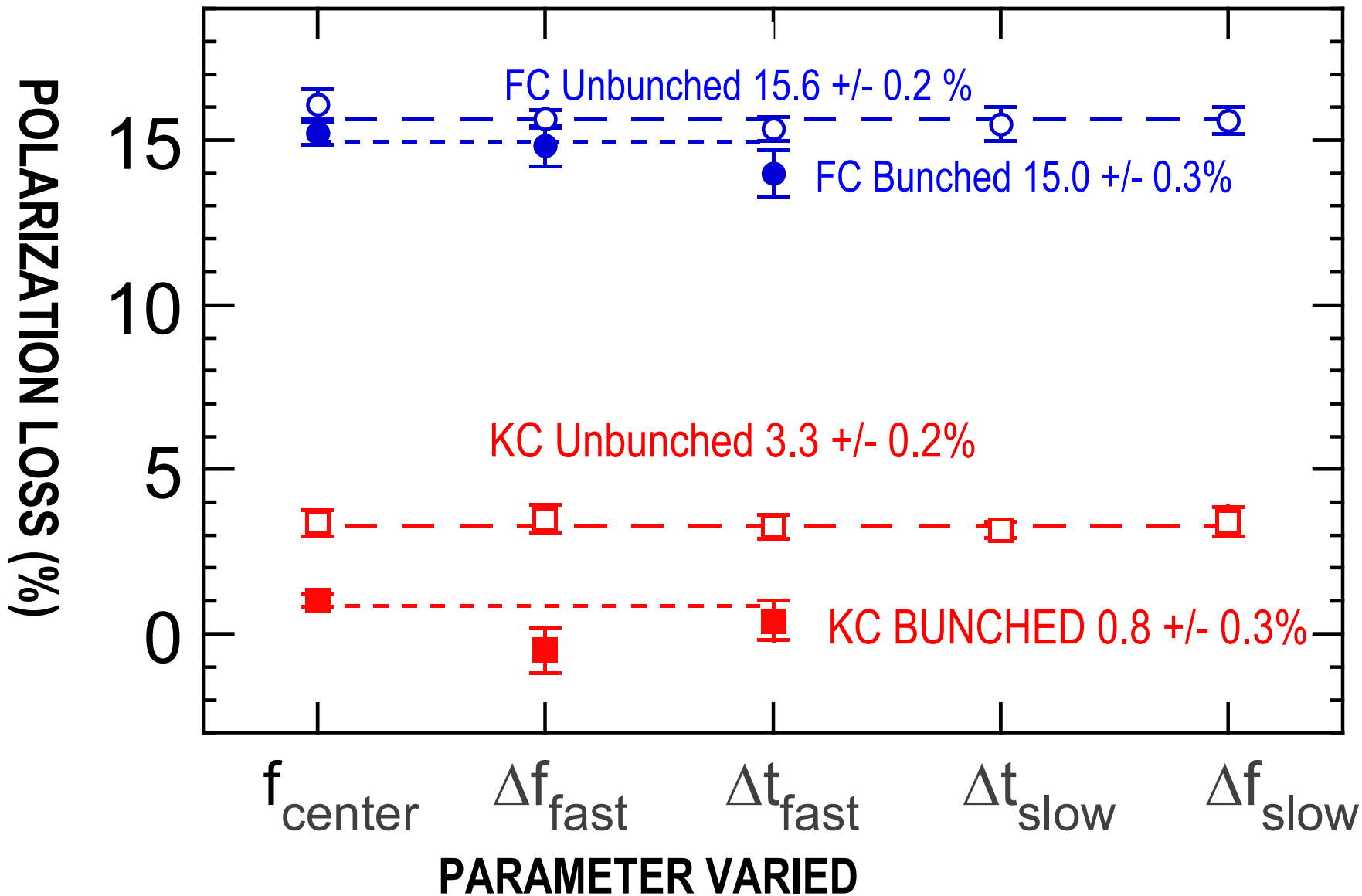
$\int B_{rms} \cdot dl$ = 0.54 T·mm at ~917 kHz

KONDRATENKO CROSSING SHAPE



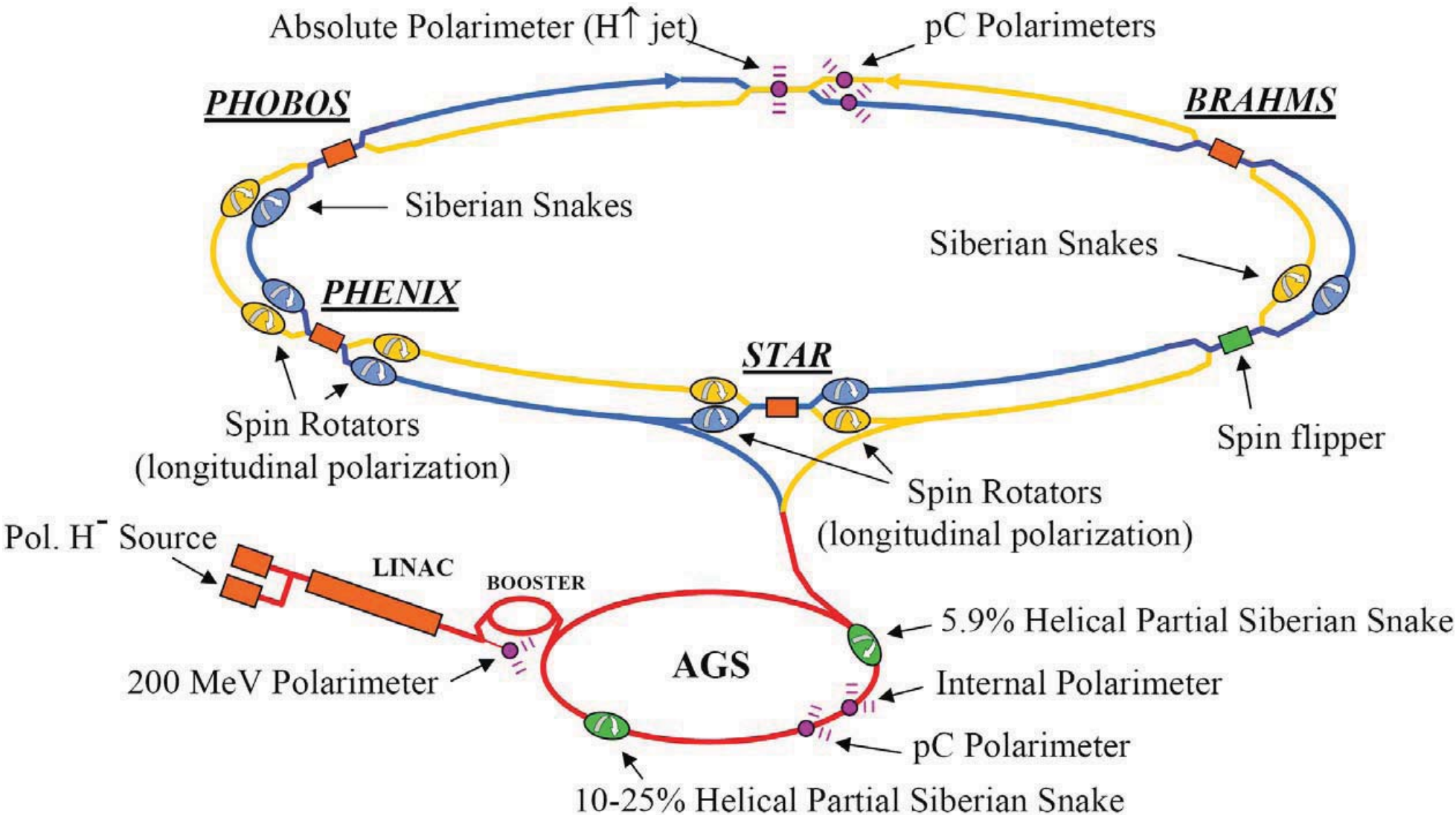
KONDRATENKO CROSSING (KC) vs. FAST CROSSING (FC)

At KC Polarization Peak **At EQUAL KC and FC Crossing Speeds** **MAY 2008 COSY**



V.S. Morozov *et al.* PRL **102**, 244801 (2009)

RHIC POLARIZED BEAM COMPLEX



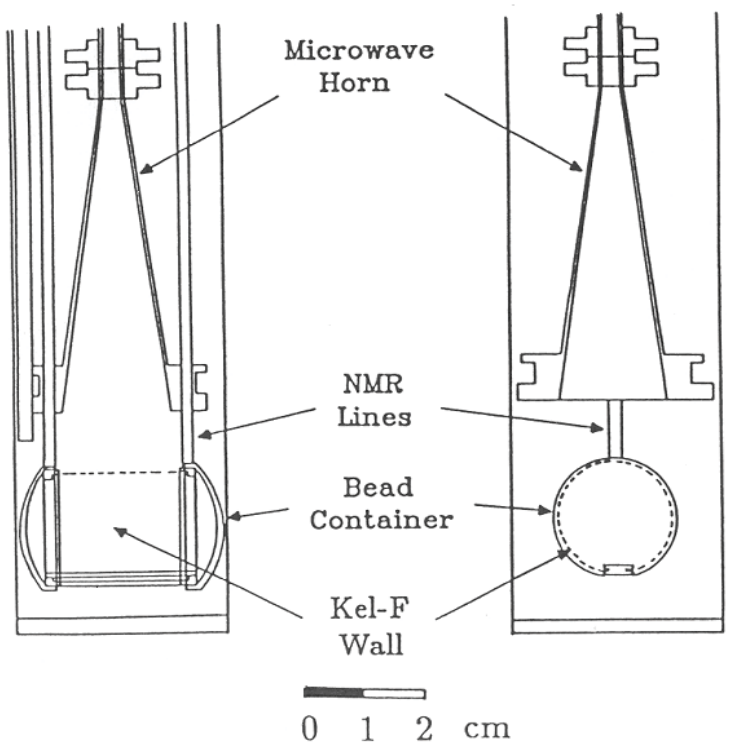
SPIN@FERMI

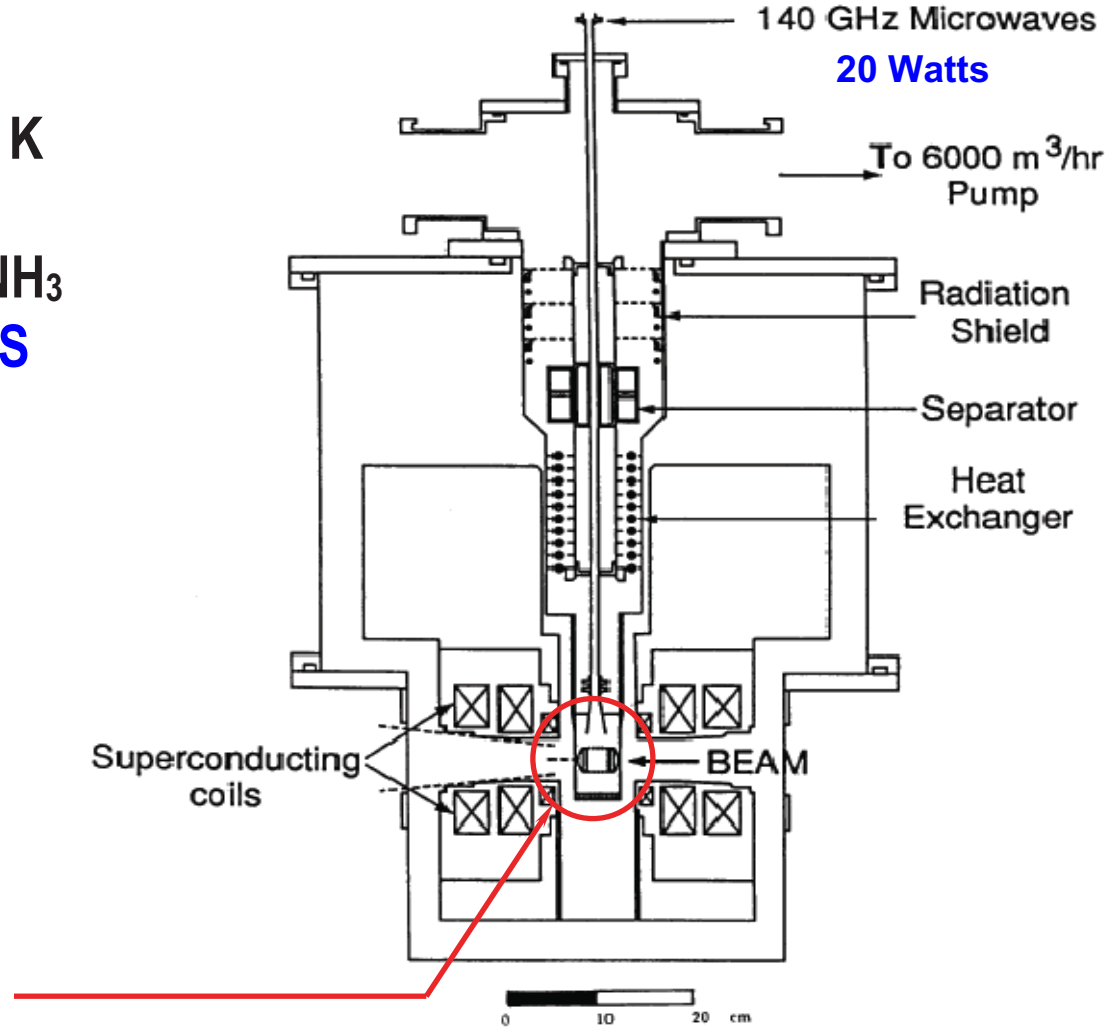
MICHIGAN SOLID POLARIZED PROTON TARGET

USED at AGS 1990 NOW on LOAN to KEK

- Highly uniform 5 T field
- 0.9 W of cooling power at 1 K
- Target cavity filled with NH_3
- 96% proton polarization in NH_3
- 85% average 3-month at AGS

@ 10^{11} protons/sec

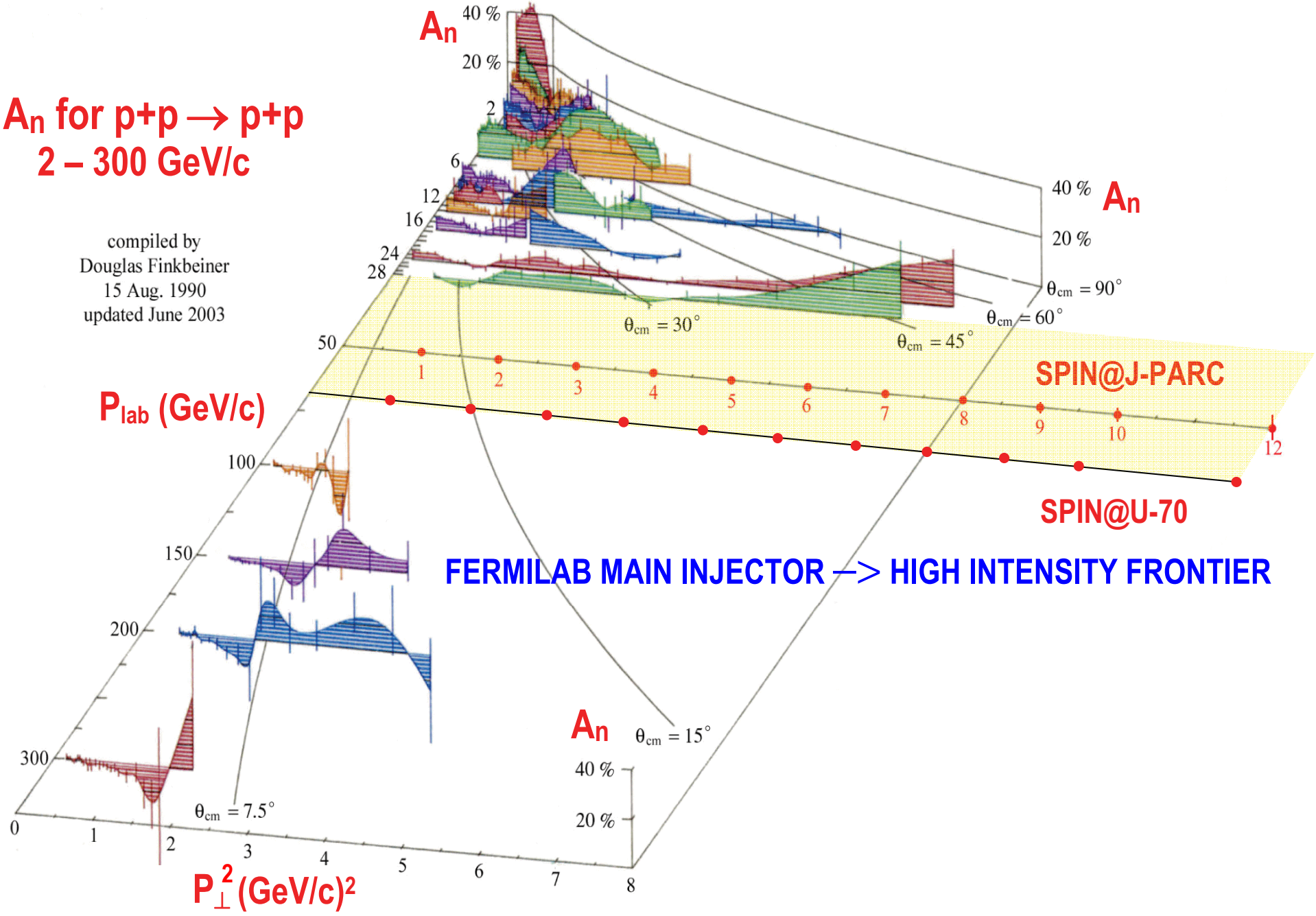




SPIN@U-70 SPECTROMETER
JANUARY 2002
M1
APRIL 2002 TEST RUN
RECOIL SPECTROMETER ALONE
80:1 ELASTIC/INELASTIC

A_n for p+p → p+p
2 – 300 GeV/c

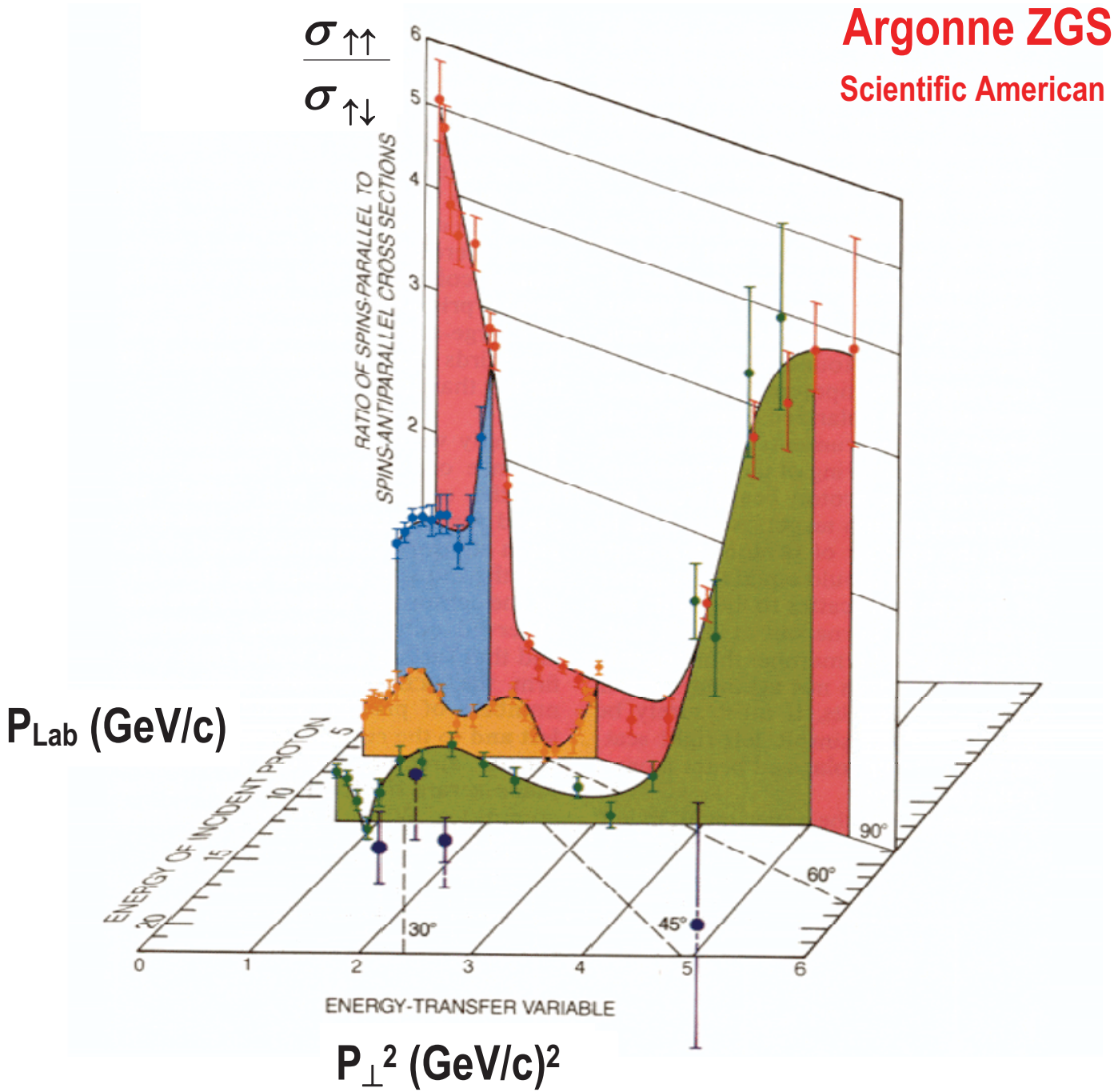
compiled by
Douglas Finkbeiner
15 Aug. 1990
updated June 2003



Ratio Spin-Parallel: Spin-Antiparallel p-p Elastic Cross-Sections

Argonne ZGS 1977-79

Scientific American 1979 & 1987

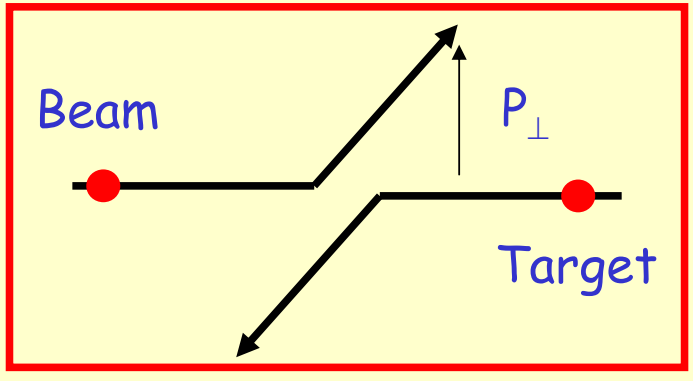


Why are Spin Effects in Hard p-p Elastic Sattering Important?

Answers by: Profs. Lenisa (pp 24-25), Glashow (25), Brodsky (25), Sivers (26) & Salam (27)

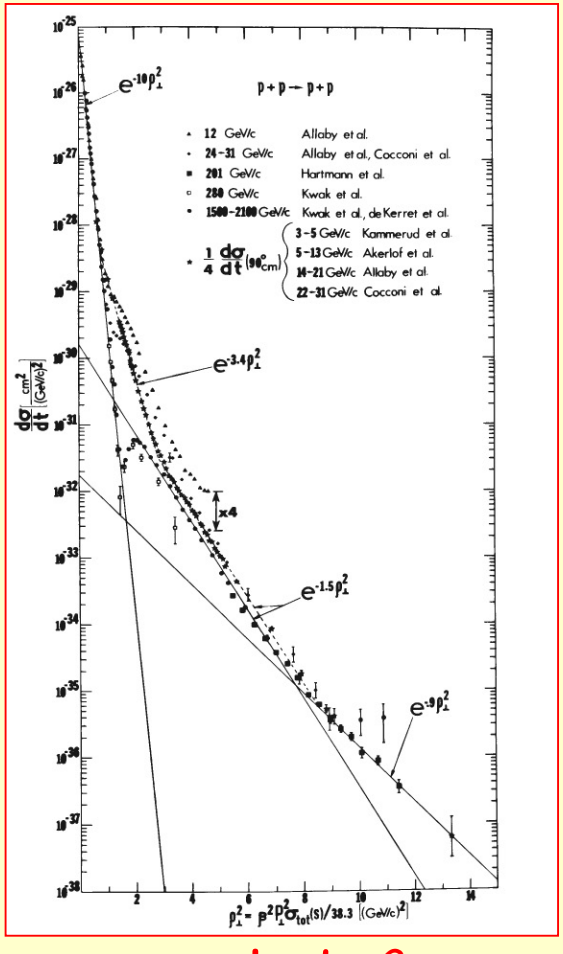
Notes shown in this Blue font

Hard polarized scattering



Unpolarized p-p elastic cross section

$d\sigma/dt$



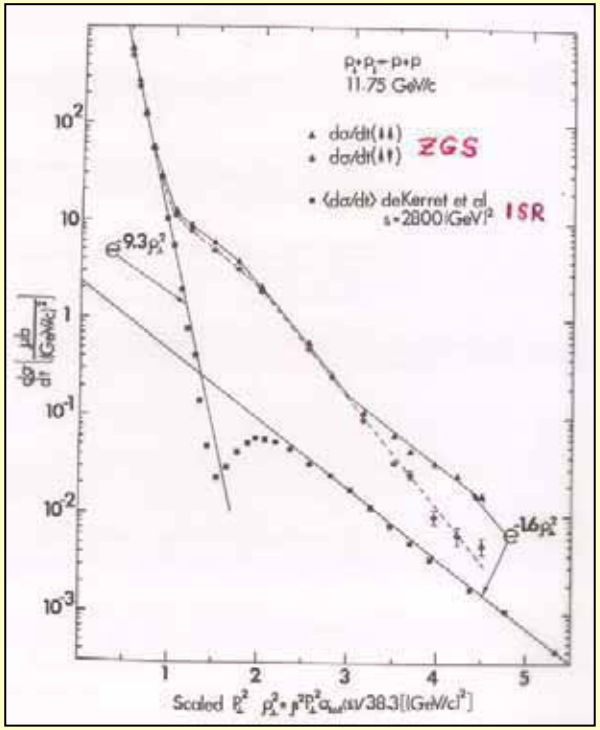
scaled $p^2_\perp$

Dividing $d\sigma/dt$ at 90° c.m by 4 made all p-p elastic data fit on a single curve …

P. LENISA Ferrara University

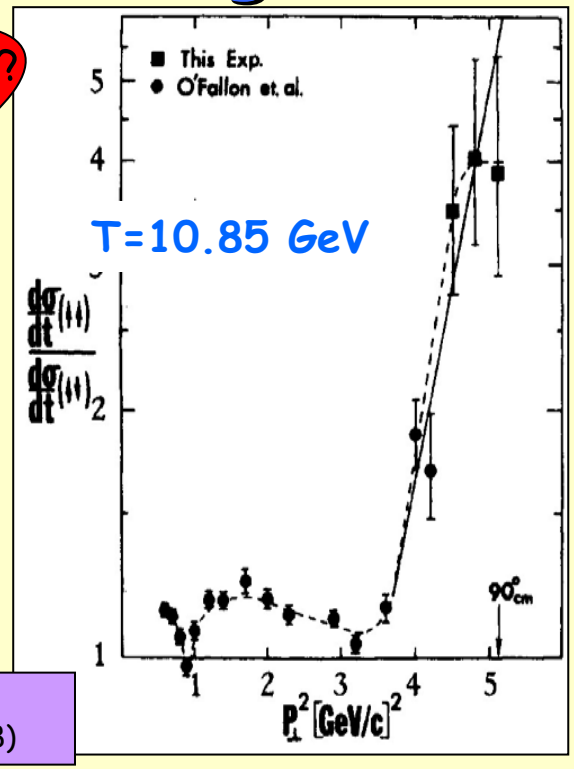
Medium Energy antiproton-proton Experimenter

Hard p-p polarized scattering



Spin Crisis "ante litteram"?

"The graeatest asymmetries in hadron physics ever seen by a human being" (Brodsky)



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

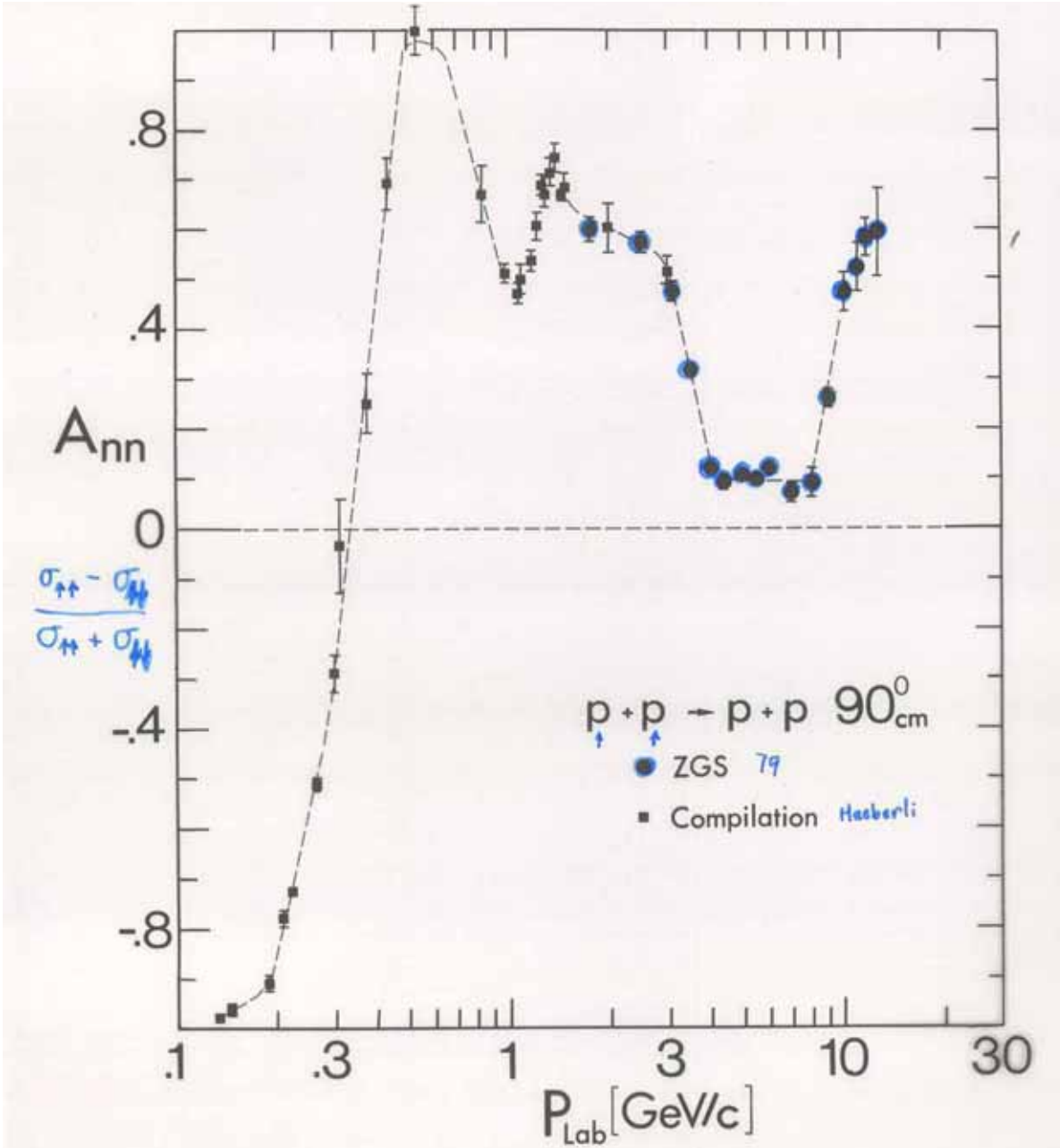
"The results challenge the prevailing theory that describes the proton's structure and forces" (Krish, 1987)

"One of the unsolved mysteries of hadron physics"(Brodsky, 2005)

"… the thorn in the side of QCD" (Glashow)

It would be very interesting to performe this measurements with polarized antiprotons.

Compilation: Proton-Proton Elastic A_{nn} at 90°_{cm} (10 MeV to 12 GeV)



A. SALAM
Particle physics today

Annales de l' I.H.P., section A, tome 49, n° 3 (1988), p. 369-385
<http://www.numdam .org/item?id=AIH PA_1988_49_3_369_0>

●●●

11. THREE TYPES OF IDEAS

We shall divide our remarks into three topics:

A) Ideas which have been tested or will soon be tested with accelerators which are in existence or presently being constructed;

B) Theoretical ideas whose time has not yet come (so far as the availability of accelerators to test them goes), but hopefully the situation may change before the year 2000 AD; and

C) Passive, non-accelerator experiments which have tested-but not conclusively so far - some of the theories of the 1970's. To give a brief summary, consider each of these three topics in turn.

●●●

B) Theoretical ideas whose time has not yet come (from supersymmetry to the Theory of everything); basically because accelerators to test them are not yet commissioned. These ideas include:

●●●

vi.) Superstrings. (The axial colour gluons interfering with vector gluons may give the simplest explanation of the spin dependence of scattering of polarised protons as well as of the left-right asymmetry observed by Krisch and collaborators in pp scattering up to 30 GeV.)

Searchable reconstructed version with a few typos corrected
M.A. Leonova June 23, 2010

UM HE 95-09
July 24, 1995

Acceleration of Polarized Protons to 120 GeV and 1 TeV at Fermilab

SPIN Collaboration

Michigan, Indiana, Fermilab,

IHEP-Protvino, JINR-Dubna, Moscow, INR-Moscow, BINP-Novosibirsk

KEK

TRIUMF

The SPIN collaboration has studied the acceleration of a polarized proton beam in the Fermilab Main Injector and Tevatron. The first section of this Report summarizes some physics goals for a polarized proton beam near 120 GeV and 1 TeV; it also contains a schedule and budget for the Polarized Main Injector and Polarized Tevatron-Collider projects. The rest of the Report describes the detailed plan to accelerate polarized protons and to perform polarized proton experiments in the Main Injector, the Tevatron and the Tevatron-Collider. Some highlights are:

- Nine Siberian snakes and some other minor hardware should allow 75% polarization to be maintained and manipulated in the Booster, Main Injector, and Tevatron.
- Recent progress in ABS and OPPIS polarized ion sources (0.6 mA and 1.6 mA) should allow a polarized Collider luminosity of about $7 \cdot 10^{31}$ cm^{-2}s^{-1}. We are supporting R & D for both source types to reach an even higher polarized luminosity.
- The source's 30-month preparation time makes it a critical-path item. A decision is required by *mid-August 1995* to allow installation of a polarized source and other polarized hardware during the 1998 Main Injector installation shutdown.
- To make empty spaces in the Tevatron for six Siberian snakes and four Collider-detector spin rotators, twenty new 6 T superconducting dipoles would replace thirty-six existing 4.4 T Tevatron ring dipoles. Since an *immediate* decision on the 6 T dipoles would be needed to install them and the Tevatron snakes during the 1998 Main Injector installation shutdown, we instead recommend a *phased* commissioning of the Polarized Main Injector and Polarized Tevatron.

1.2 SPIN collaboration list

July 20, 1995

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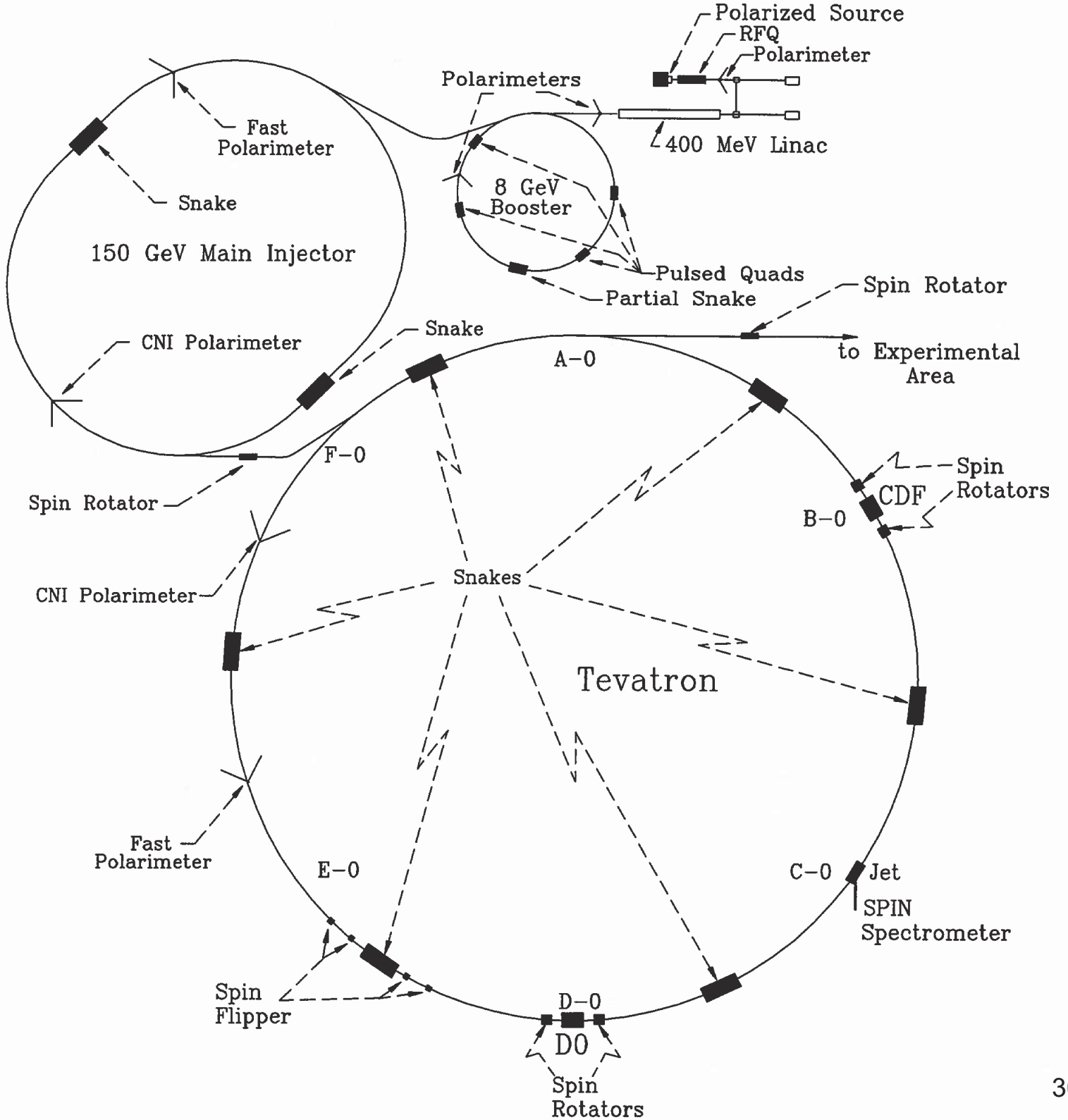
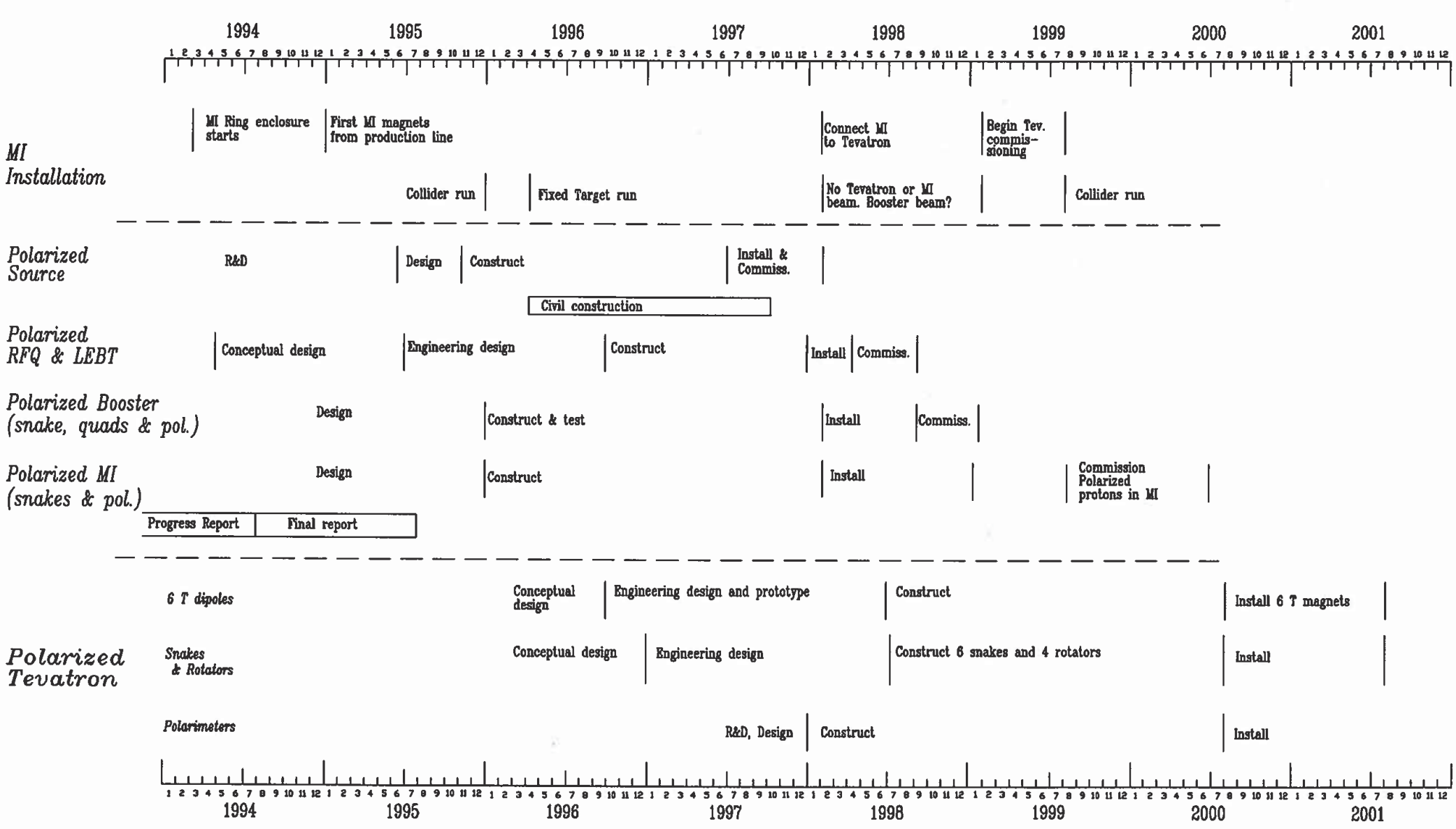
c National Center Univ. -Taiwan	*f* King Fahd Univ.	*i* SLAC	*l* Kyushu Univ.
			m INR-Moscow


Polarized Source
RFQ
Polarimeter
Polarimeters
400 MeV Linac
Fast Polarimeter
Snake
150 GeV Main Injector
8 GeV Booster
Pulsed Quads
Partial Snake
Spin Rotator
to Experimental Area
CNI Polarimeter
Snake
A-0
F-0
Spin Rotator
Spin Rotators
CDF
B-0
CNI Polarimeter
Snakes
Tevatron
Fast Polarimeter
E-0
C-0
Jet
SPIN Spectrometer
Spin Flipper
D-0
D0
Spin Rotators

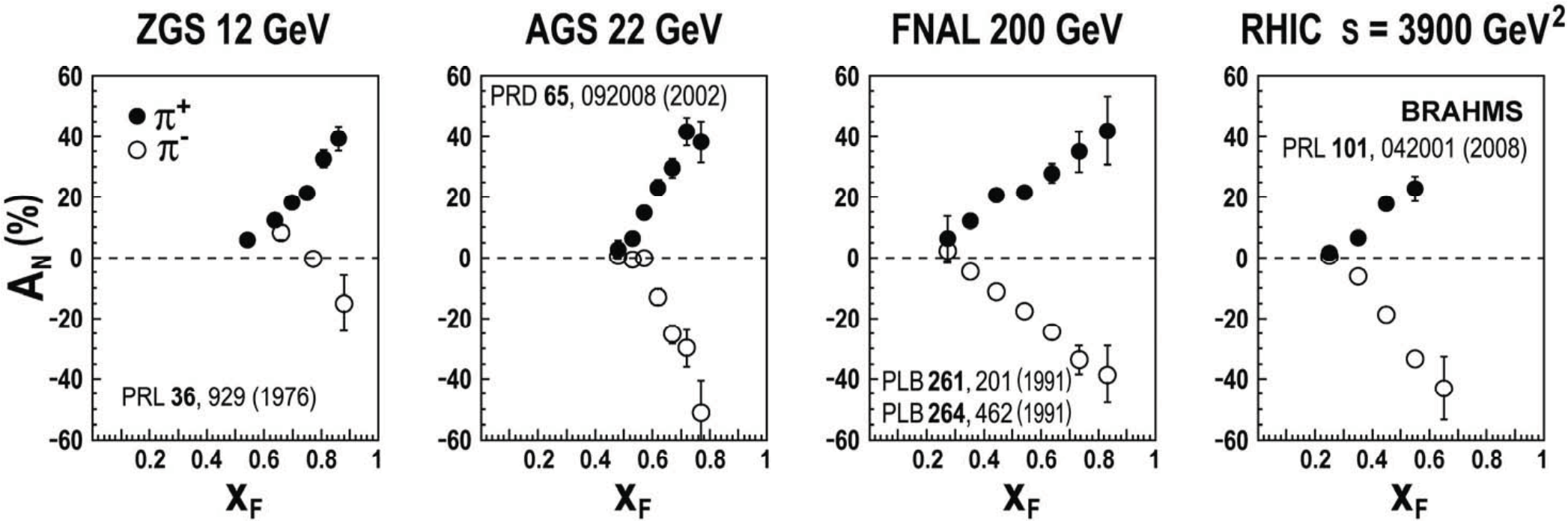

Calendar Years
1994
1995
1996
1997
1998
1999
2000
2001
MI Installation
MI Ring enclosure starts
First MI magnets from production line
Connect MI to Tevatron
Begin Tev. commis-sioning
Collider run
Fixed Target run
No Tevatron or MI beam. Booster beam?
Collider run
Polarized Source
R&D
Design
Construct
Install & Commiss.
Civil construction
Polarized RFQ & LEBT
Conceptual design
Engineering design
Construct
Install
Commiss.
Polarized Booster (snake, quads & pol.)
Design
Construct & test
Install
Commiss.
Polarized MI (snakes & pol.)
Design
Construct
Install
Commission Polarized protons in MI
Progress Report
Final report
Polarized Tevatron
6 T dipoles
Conceptual design
Engineering design and prototype
Construct
Install 6 T magnets
Snakes & Rotators
Conceptual design
Engineering design
Construct 6 snakes and 4 rotators
Install
Polarimeters
R&D, Design
Construct
Install
Calendar Years

1.8 Budget

Preaccelerator		$3.7M
Polarized H^- ion source	$1.8M	
RFQ and power supply (20 keV to 750 KeV)	$0.4M	
Low energy beam transport, switching magnets, and vacuum system	$0.4M	
Building Extension	$1.0M	
750 keV polarimeter	$0.1M	
400 MeV LINAC		$0.1M
400 MeV polarimeter (p-Carbon)	$0.1M	
8 GeV Booster		$0.4M
Solenoid partial Siberian snake (ramped warm)	$0.1M	
Four 3 μsec pulsed quadrupoles with power supplies	$0.2M	
8 GeV polarimeter (p-Carbon)	$0.1M	
Main Injector		$1.5M
Two Helical Siberian snakes	$0.8M	
Power supplies for snakes	$0.2M	
150 GeV polarimeters (CNI and Inclusive)	$0.5M	
Miscellaneous		$1.0M
120 to 150 GeV transfer line spin rotator	$0.2M	
Computers, control modules, cables, and interface	$0.8M	
Main Injector subtotal		$6.7M
Contingency (25%)		$1.7M
MAIN INJECTOR TOTAL		**$8.4M ($7.0M)***
Twelve 9-meter-long and eight 6-meter-long 6 T dipoles	$5→10M	
Six 5-meter-long 6 T Siberian snakes	$1.5M	
Four 4-meter-long 6 T Spin Rotators	$1.0M	
Power supplies for snakes and rotators	$0.4M	
1 TeV polarimeters (CNI, Inclusive, plus third)	$1.0M	
Spin Flippers	$0.2M	
TeV transfer line spin rotator	$0.2M	
Tevatron Subtotal		$9.3→14.3M
Contingency (25%)		$2.3→3.6M
TEVATRON TOTAL		**$11.6→17.9M**
120 GeV Extracted Polarized Beam Experiments	$1.2M	
Modify p-West cave;		
Install Michigan solid PPT and 2 spectrometers		
Tevatron Internal Target Experiments	$1.0M	
Modify C0;		
Install Mark-III polarized Jet and 2 spectrometers		
Spin Experiments subtotal		$2.2M
Contingency (25%)		$0.6M
SPIN EXPERIMENTS TOTAL		**$2.8M**
GRAND TOTAL		**$22.8→29.1M**

INCLUSIVE PION ASYMMETRY IN PROTON-PROTON COLLISIONS

C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009



Planned Polarized Drell-Yan Experiments

Yuji Goto
April 27, 2010
DY workshop
CERN

experiment	particles	energy	x1 or x2	luminosity
COMPASS	$\pi\pm + p\uparrow$	160 GeV $\sqrt{s}$ = 17.4 GeV	x2 = 0.2 – 0.3	2×10^{33} cm^{-2}s^{-1}
COMPASS (low mass)	$\pi\pm + p\uparrow$	160 GeV $\sqrt{s}$ = 17.4 GeV	x2 ~ 0.05	2×10^{33} cm^{-2}s^{-1}
PAX	$p\uparrow$ + pbar	collider $\sqrt{s}$ = 14 GeV	x1 = 0.1 – 0.9	2×10^{30} cm^{-2}s^{-1}
PANDA (low mass)	pbar + $p\uparrow$	15 GeV $\sqrt{s}$ = 5.5 GeV	x2 = 0.2 – 0.4	2×10^{32} cm^{-2}s^{-1}
J-PARC	$p\uparrow$ + p	50 GeV $\sqrt{s}$ = 10 GeV	x1 = 0.5 – 0.9	10^{35} cm^{-2}s^{-1}
NICA	$p\uparrow$ + p	collider $\sqrt{s}$ = 20 GeV	x1 = 0.1 – 0.8	10^{30} cm^{-2}s^{-1}
SPASCHARM (low mass)	p + $p\uparrow$	60 GeV $\sqrt{s}$ = 11 GeV	x2 = 0.05 – 0.2	
SPASCHARM (low mass)	$\pi\pm + p\uparrow$	34 GeV $\sqrt{s}$ = 8 GeV	x2 = 0.1 – 0.3	
RHIC PHENIX Muon	$p\uparrow$ + p	collider $\sqrt{s}$ = 500 GeV	x1 = 0.05 – 0.1	2×10^{32} cm^{-2}s^{-1}
RHIC Internal Target phase-1	$p\uparrow$ + p	250 GeV $\sqrt{s}$ = 22 GeV	x1 = 0.25 – 0.4	2×10^{33} cm^{-2}s^{-1}
RHIC Internal Target phase-2	$p\uparrow$ + p	250 GeV $\sqrt{s}$ = 22 GeV	x1 = 0.25 – 0.4	6×10^{34} cm^{-2}s^{-1}
Fermilab Main Injector polarized	$p^{\uparrow}$ + p	120 GeV $\sqrt{s}$ = 15 GeV	x1 = 0.3 – 0.9	~1 x 10^{36} cm^{-2} s^{-1}

Polarized M.I. beam intensity: 2.3 x 10^{12} p/pulse (w/ 2.8 s/pulse) on SeaQuest target (60% delivered to NM4)
-> L = 1 x 10^{36} /cm^2/s (SeaQuest lH_2 target limited)

W. Lorenzon, Michigan

SUMMARY

For 30+ years QCD-based calculations have not explained some large spin effects:

- **ZGS 2-spin & AGS 1-spin p-p elastic data;**
- **Fermilab discovery of large hyperon polarization;**
- **ZGS, AGS, Fermilab & RHIC p-p inclusive spin data.**

Elastic scattering: only exclusive process large enough to measure above 100 GeV because:

- **p+p→p+p dominated by Diffraction due to 10^5+ inelastic channels all competing for σ_{TOT}; σ_{TOT} < 100 mb σ_{EL}~ 20% even at TeV energies. See simple optical-geometrical model.***

** R. Serber, PRL 10, 357 (1963); RMP 36, 649 (1964); ADK, PRL 11, 217 (1963); PR 135, B1456 (1964); PRL 19, 1149 (1967)*

★ **Large spin effects do not go to zero at high-energy or high-$P_\perp$ as was earlier predicted.**

★ **Resulted in some needed modifications of Standard Model**

BASIC PRINCIPLE OF SCIENCE:

If theory does not agree with reproducible experimental data:

Then theory must be modified

HIGH INTENSITY POLARIZED MAIN INJECTOR WOULD ALLOW:

Precise Spin Experiments ➔ Guidance: How to Modify Standard Model

- High-$P_\perp$ Elastic $d\sigma/dt$, A_n & A_{nn} data;
- High-$P_\perp$ Inclusive A_n data;
- Polarized Drell-Yan A_n data.

Unpolarized Experiments can not show the need for these Modifications

POLARIZED MAIN INJECTOR ➔ HIGH INTENSITY & HIGH PRECISION FRONTIERS

CONFERENCE INTERSECTIONS between PARTICLE AND NUCLEAR PHYSICS

CIPANP 1986 LAKE LOUISE ***AIP Conf Proc 150, vii (1986)***

INTRODUCTION (ADK with thanks to LOUIS ROSEN for much advice)

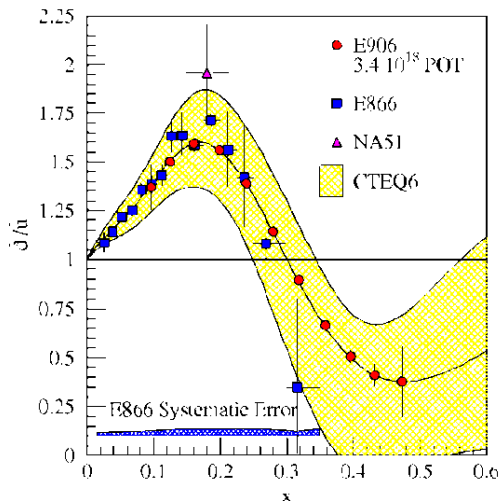
"To maximize the probability of scientific progress, I believe that we must maintain active and exciting research on as many frontiers as we possibly can. …
The SSC is aimed toward the fascinating high energy frontier.
This conference is focused toward the exciting high intensity and high precision frontiers in the GeV range."

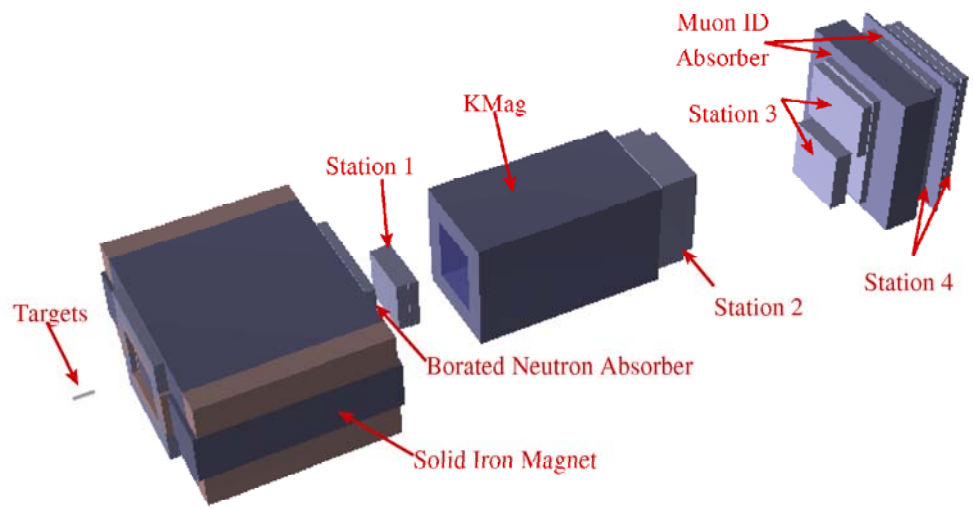
Drell-Yan at Fermilab

Unpolarized Drell-Yan experiment (at 120 GeV Main Injector):

Fermilab E906: SeaQuest -> Anti-quark distribution in nucleon sea

beam intensity: 1 x 10^{13} p/spill (w/ 5 s slow extraction spill / min) on 20" lH_2 (2.1 x 10^{24} /cm^2) -> L = 3.4 x 10^{35} /cm^2/s





Polarized Drell-Yan experiment:

Not yet done!

Measure Sivers function in single-transverse spin asymmetries (with same spectrometer)

➡ check sign-change: $$f_{1T}^{\perp q}\Big|_{DIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

➡ fundamental prediction of QCD (goes to heart of gauge formulation of field theory)

Polarized M.I. beam intensity: 2.3 x 10^{12} p/pulse (w/ 2.8 s/pulse) on SeaQuest target (60% delivered to NM4)
-> L = 1 x 10^{36} /cm^2/s (SeaQuest lH_2 target limited)

Single Transverse Spin Asymmetry

Sivers effect:

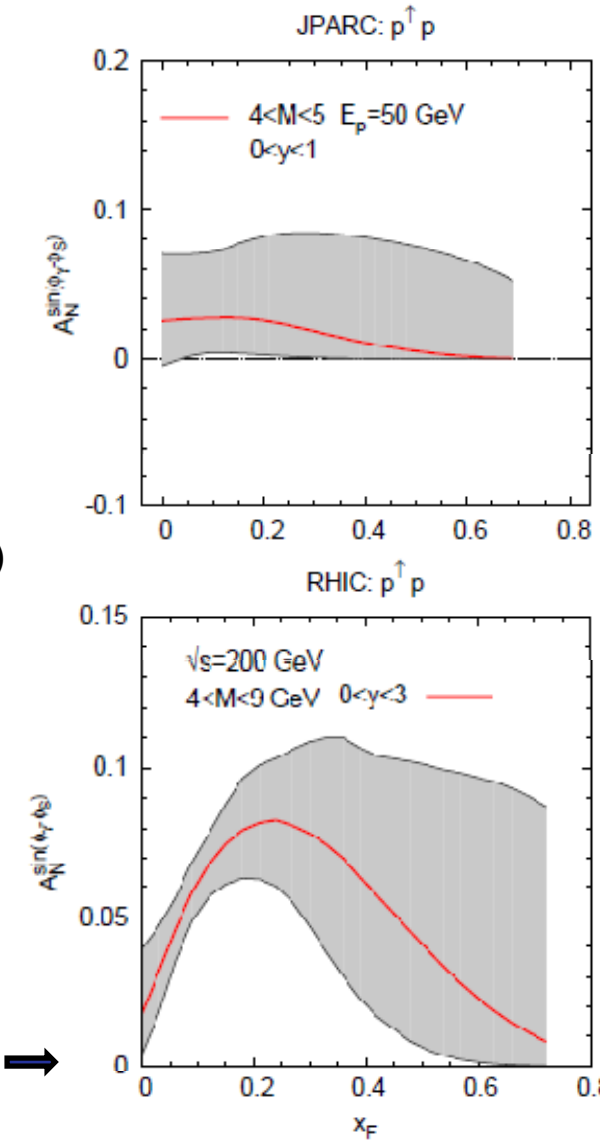
- described by transverse-momentum dependent distribution function
- captures non-perturbative spin-orbit coupling effects inside a polarized proton
- leads to a sin $(\phi - \phi_S)$ asymmetry in SIDIS and Drell-Yan
- done in SIDIS (HERMES, COMPASS)
- Sivers function is time-reversal odd

➡ leads to sign change

$$f_{1T}^{\perp q}\Big|_{DIS} = -f_{1T}^{\perp q}\Big|_{D-Y}$$

➡ crucial test of TMD factorization approach

Predictions based on fit to SIDIS data ➡



J-PARC
50-GeV
polarized beam
$\sqrt{s}$ ~ 10 GeV

RHIC
collider
$\sqrt{s}$ = 200 GeV

Anselmino et al. PRD79, 054010 (2009)