Outline

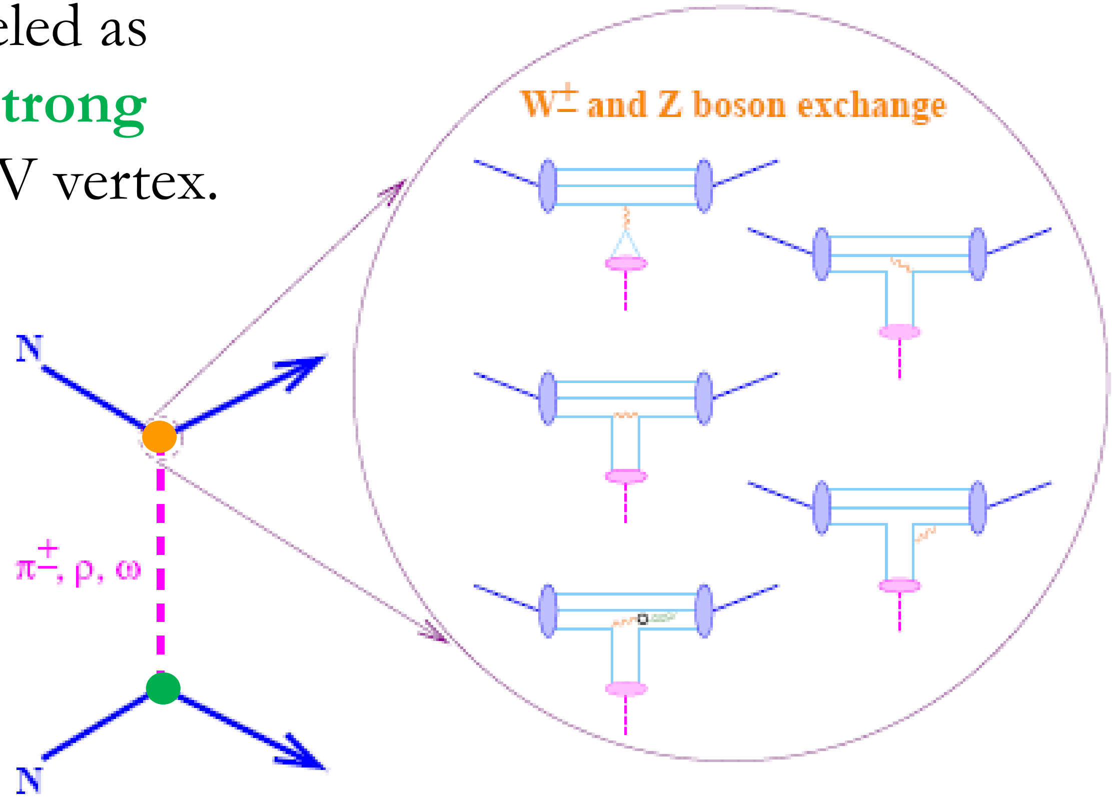
- What can we learn from $\vec{p} - p$ parity violation experiments ?
- Defining the Goal for TRIC
- The Experimental Set-up
- Final State Interaction
- Principal Error Analysis
- Some Experimental Details
- Summary

S.L. Glashow:

> „Since there are too many high-energy physicists for too few high-energy accelerators, they must learn to do high precision experiments at low-energy machines“

The Time-Reversal Invariance Test at COSY (TRIC)
Parity Violation

N-N weak interaction modeled as Meson exchange with one **strong** PC vertex, and one **weak** PV vertex.



The weak PV couplings-

$$H_\pi^1, H_\rho^0, H_\rho^1, H_\rho^{1'}, H_\rho^2, H_\omega^0, H_\omega^1$$

-measured in various combinations by a variety of observables

Parity Violation

How to study the hadronic weak interaction ?

The ratio of weak and strong amplitudes is:

$$4\pi G_F m_\pi^2 / g_{\pi NN}^2 \sim 10^{-7}$$

In order to verify this very small effect a powerful technique is to be used: **Parity Violation**.

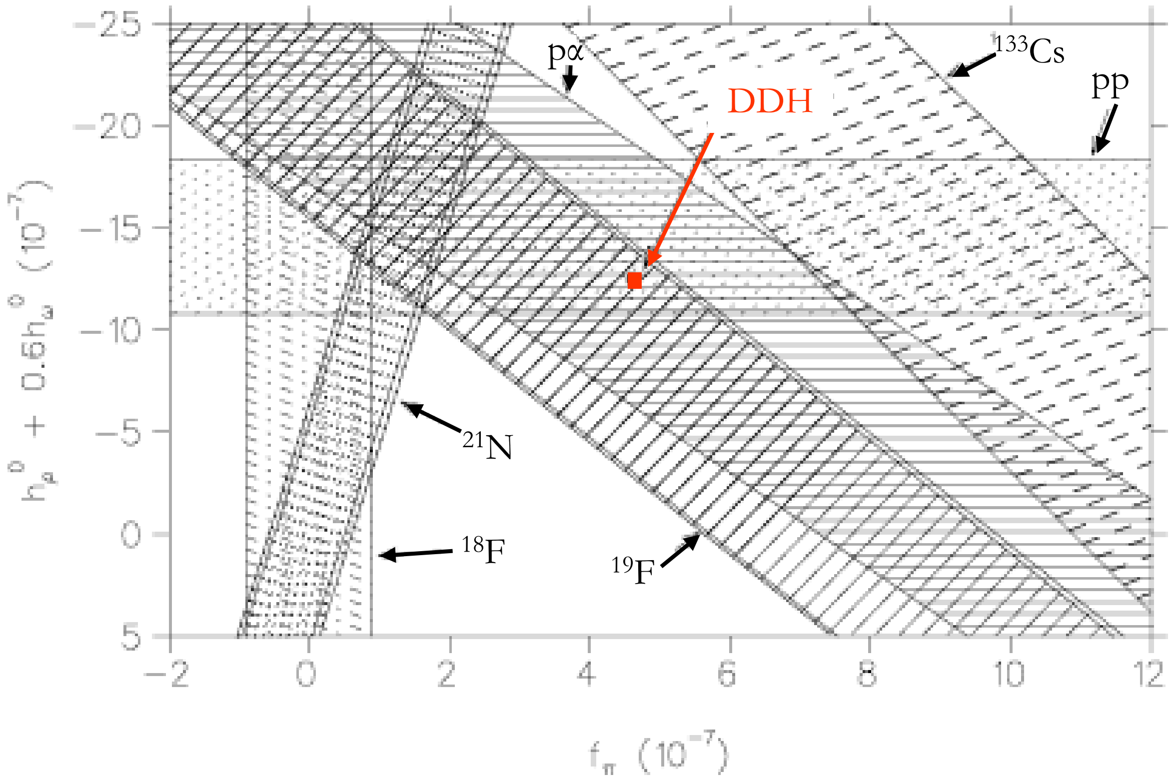
The Time-Reversal Invariance Test at COSY (TRIC)
Parity Violation

- The range of Z, W+, W- bosons is 0,002 fm
- But nucleon interactions take place on a scale of 1 fm (short range repulsion)

: **weak force** interaction between nucleons and hadrons is **mediated by meson exchange**

- At low energies (< 300 MeV)
  Mesons are the appropriate degree of freedom
- The meson exchange model is a successful picture of strong interactions between nucleons
  (describes to a few % n-p/p-p scattering σ´s)

Experimental Constrains on Weak N-N Couplings



N.B. $f_\pi = \frac{\sqrt{32}}{g_{\pi NN}} \cdot H_\pi^1$

[W. van Oers, Nucl. Phys. **A684** (2001) 266]

Parity Violation

Why can A_z be measured to the 10^{-7} level ?

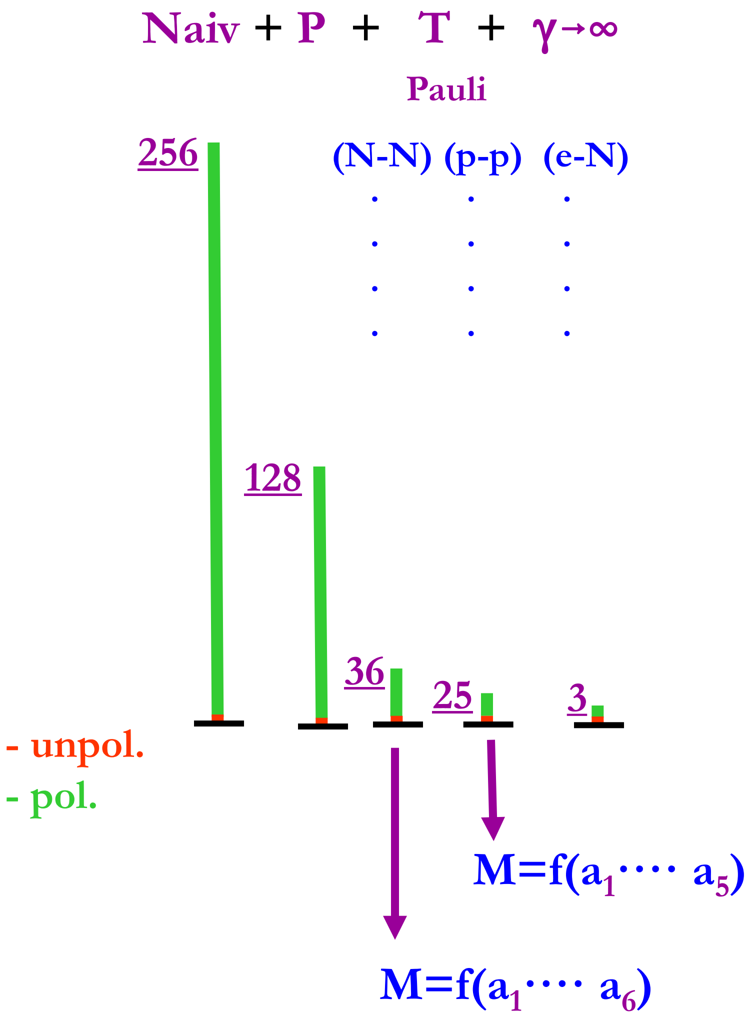
- A_z measurement is a **Null-Experiment.**
- **Signature** of A_z is **unique** compared to other observables.
- As A_z is a polarization observable, it is a **relative measurement**.

In addition:

- **Reduce sensitivities** to errors by proper set-up/alignment.
- Reduce „error amplitudes“ by **feedback control**.
- **Correct** for remaining errors.
- Convince yourself by measurement, that error contributions thought to be negligible, are negligible.
- Is the reduced χ^2 after all corrections close to **1** ?

Parity Violation

Number of Spin½ + Spin½ Observables

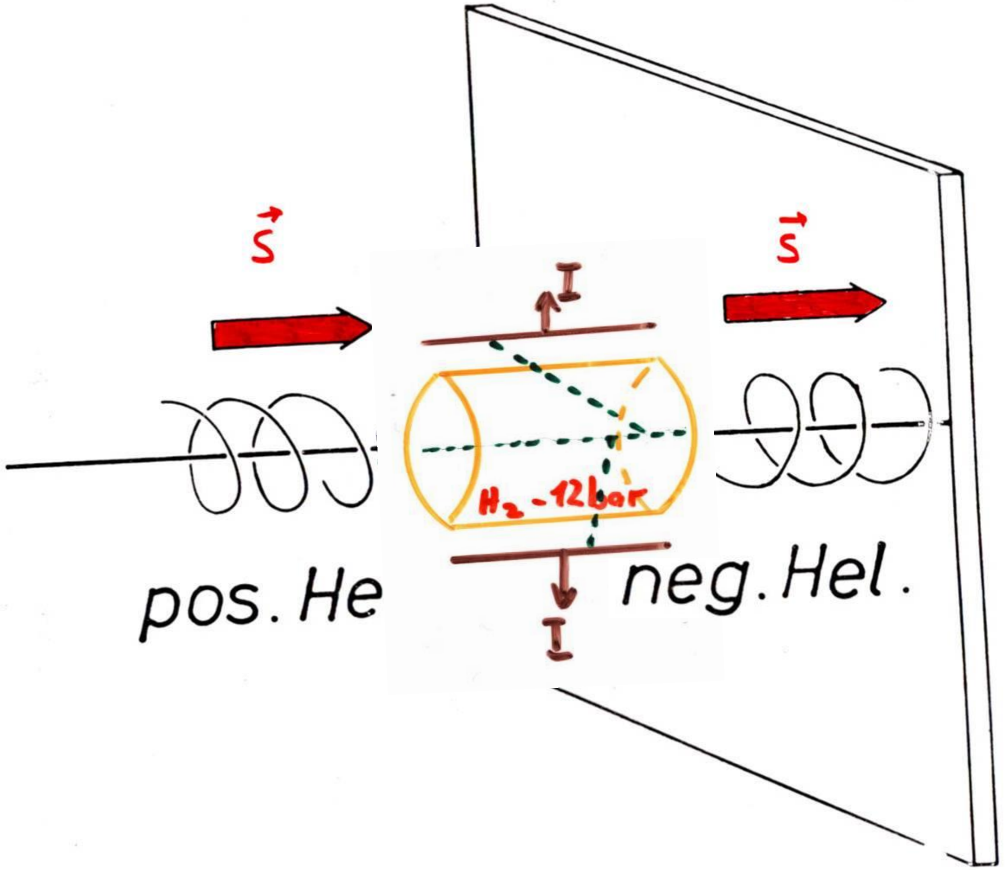


Example:

$$\sigma_0 = \sum_i a_i a_i^*$$

$$\sigma_{pol} = \sum_{i,j} \pm a_i a_j^*$$

The Principle of the Experiment

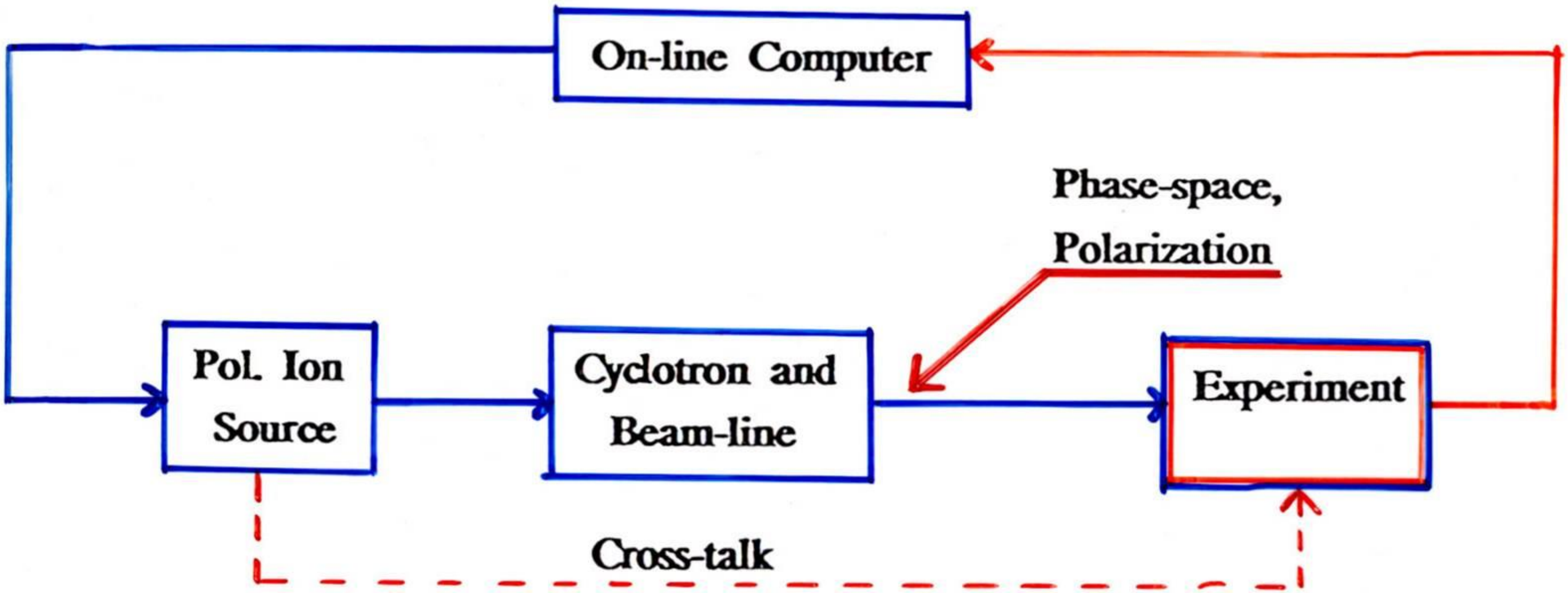


Parity Violation

Error Path

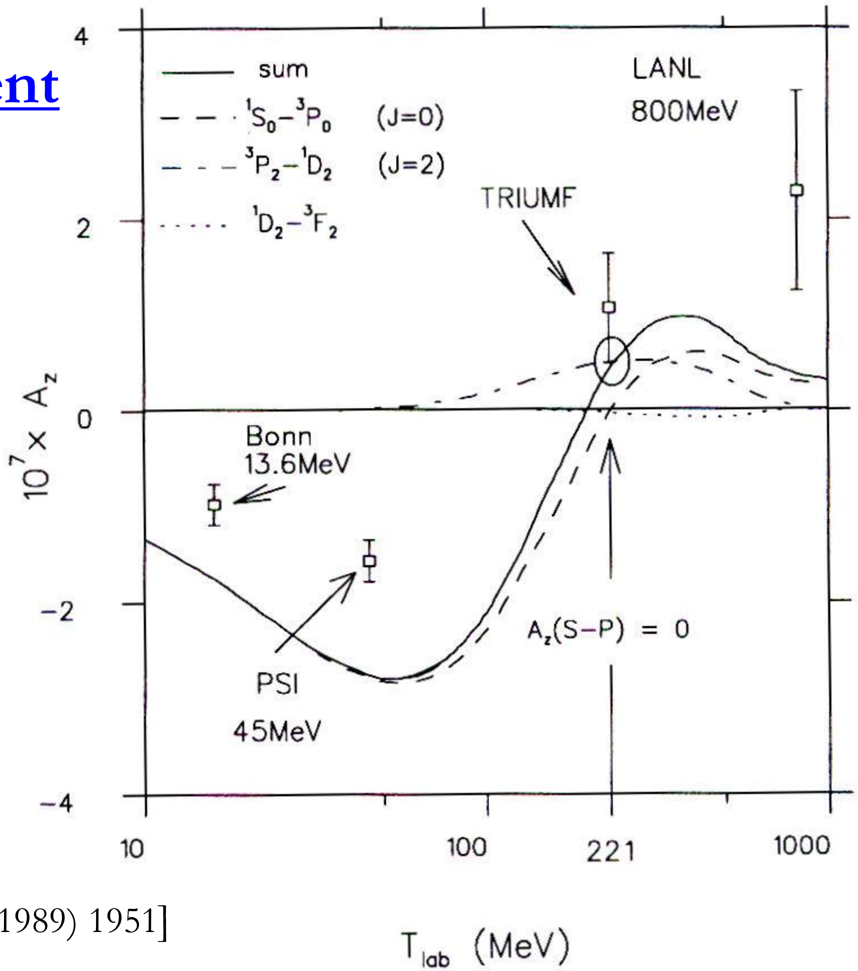
$$A_L = A_L^{true} + A_L^{false}$$

$$A_L^{false} = \sum_i \frac{\partial A_L}{\partial m_i} \cdot \delta m_i$$



The Time-Reversal Invariance Test at COSY (TRIC)
Parity Violation

Prediction and Experiment
(Phase Shifts)

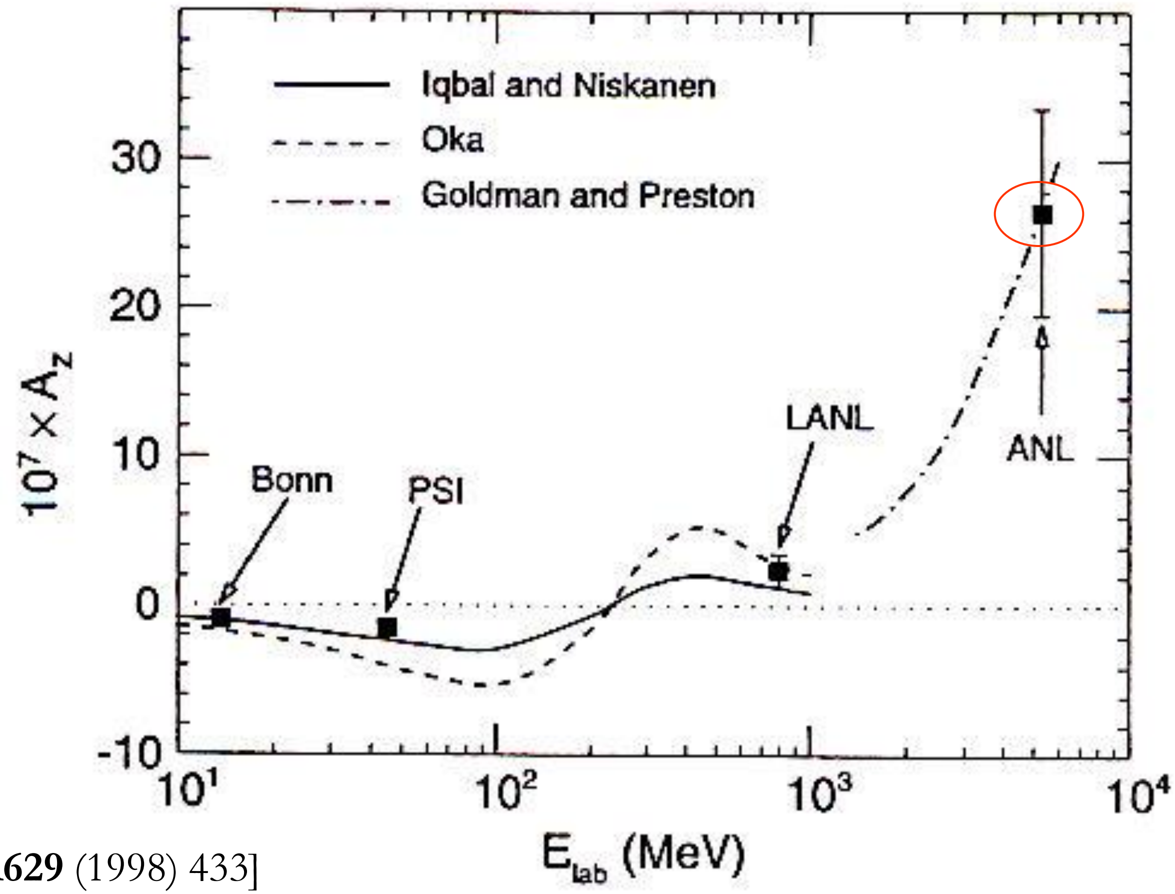


[D.E. Driscoll and G.A. Miller, Phys. Rev. C39, (1989) 1951]

Parity Violation

Prediction and Experiment

(Controversy)



[A.R. Berdoz et al., Nucl. Phys. **A629** (1998) 433]

The Time-Reversal Invariance Test at COSY (TRIC)
Lessons to be learned

- Have a **model** to get an idea about the **size** of the effect.
- Choose a **simple system** (that can be easily analysed).
- Identify an **observable** with a **clear signature**.
- Design the **experimental set-up**.
- Consider the **principal error contributions**.

The Time-Reversal Invariance Test at COSY (TRIC)
Defining the Goal for TRIC

TRIC

- (Most) accurately test TRI (T-odd, P-even) in nuclear matter
- Dynamics independent;
  especially: Not sensitive to final state interaction
- Only dependent on the structure of the reaction matrix as determined by general conservation laws „True test of TRI“
- Simple reaction (Two particles in → two particles out)

True TRI Null-Test

Defining the Goal for TRIC

But:

There is no such TRI Null-Test for any reaction in atomic nuclear or elementary physics

*F.Arash, M.J. Moravcsik and G.R. Goldstein, Phys.Rev.Lett. **54** (1985) 2649*
*M.Simonius, Phys. Lett. **B58** (1975) 147*

Loophole: **Proof holds for bilinear observables only.**

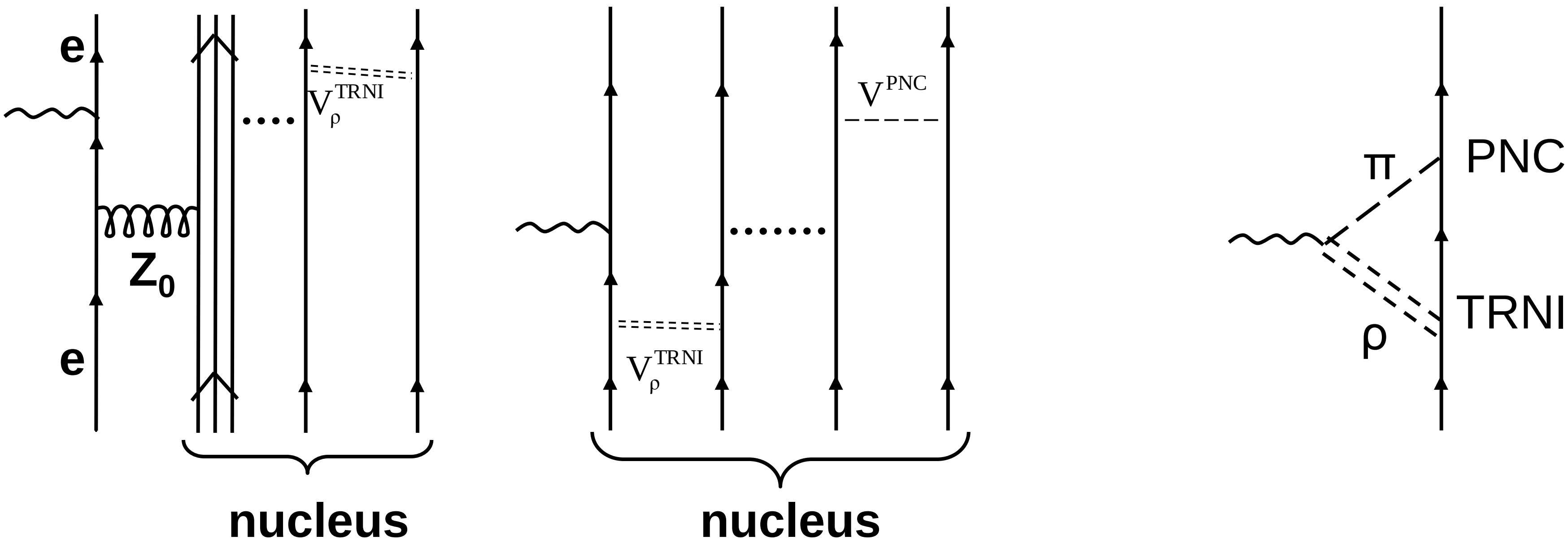
H.E. Conzett, „7th Int. Conf. on „Pol. Phen. Nucl. Phys.", Paris (1990) 2D

→ **Measure forward scattering amplitude and thus total cross sections via the Optical Theorem**

→ **Measure total $A_{y,xz}$ in $\vec{p}-\vec{d}$ scattering**

Defining the Goal for TRIC

The atomic EDM | The nuclear EDM | The nucleon EDM



W.C.Haxton. Antje Höring and M.J. Musolf, Phys.Rev. ***D50*** *(1994) 3422*

Defining the Goal for TRIC

EDM of an elementary particle :

Observable : $\vec{\sigma} \cdot \vec{E}$

→ **P-odd/T-odd** experiment

Upper limit from n-EDM

↓

Prediction: Deduced Strength for **P-even/T-odd** : $\bar{g}_{\rho T\!\!\!/} < 1.5 \cdot 10^{-3}$

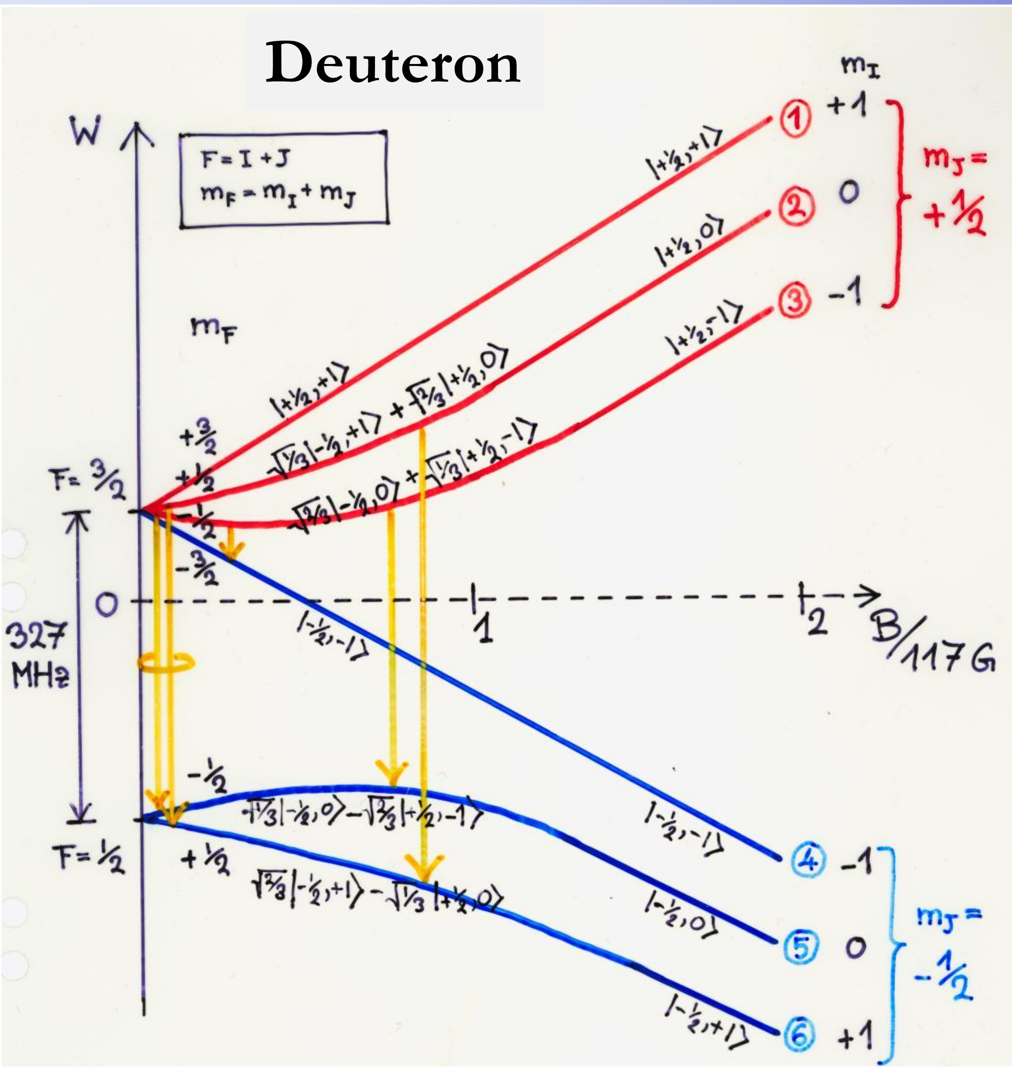
W.C.Haxton. Antje Höring and M.J. Musolf, Phys.Rev. ***D50*** *(1994) 3422*

Experiment: From $A_5 = 8.6 \pm 7.7 \cdot 10^{-6}$ gives: $\bar{g}_{\rho T\!\!\!/} : 2.3 \pm 2.1 \cdot 10^{-2}$

P.R. Huffmann et al., Phys.Rev. ***C55*** *(1997) 2684*

The Time-Reversal Invariance Test at COSY (TRIC)

Defining the Goal for TRIC



- **It makes no sense to talk about polarization without having defined a quantisation axis.**
- An **unpolarized beam** has all states populated equally .
- **Vector polarization:**

$$P_V = \frac{1}{A_V} \cdot \frac{N^+ - N^-}{N^+ + N^- + N^0}$$

- **Tensor polarization:**

$$P_T = \frac{1}{A_T} \cdot \frac{(N^+ - N^0) + (N^- - N^0)}{N^+ + N^- + N^0}$$

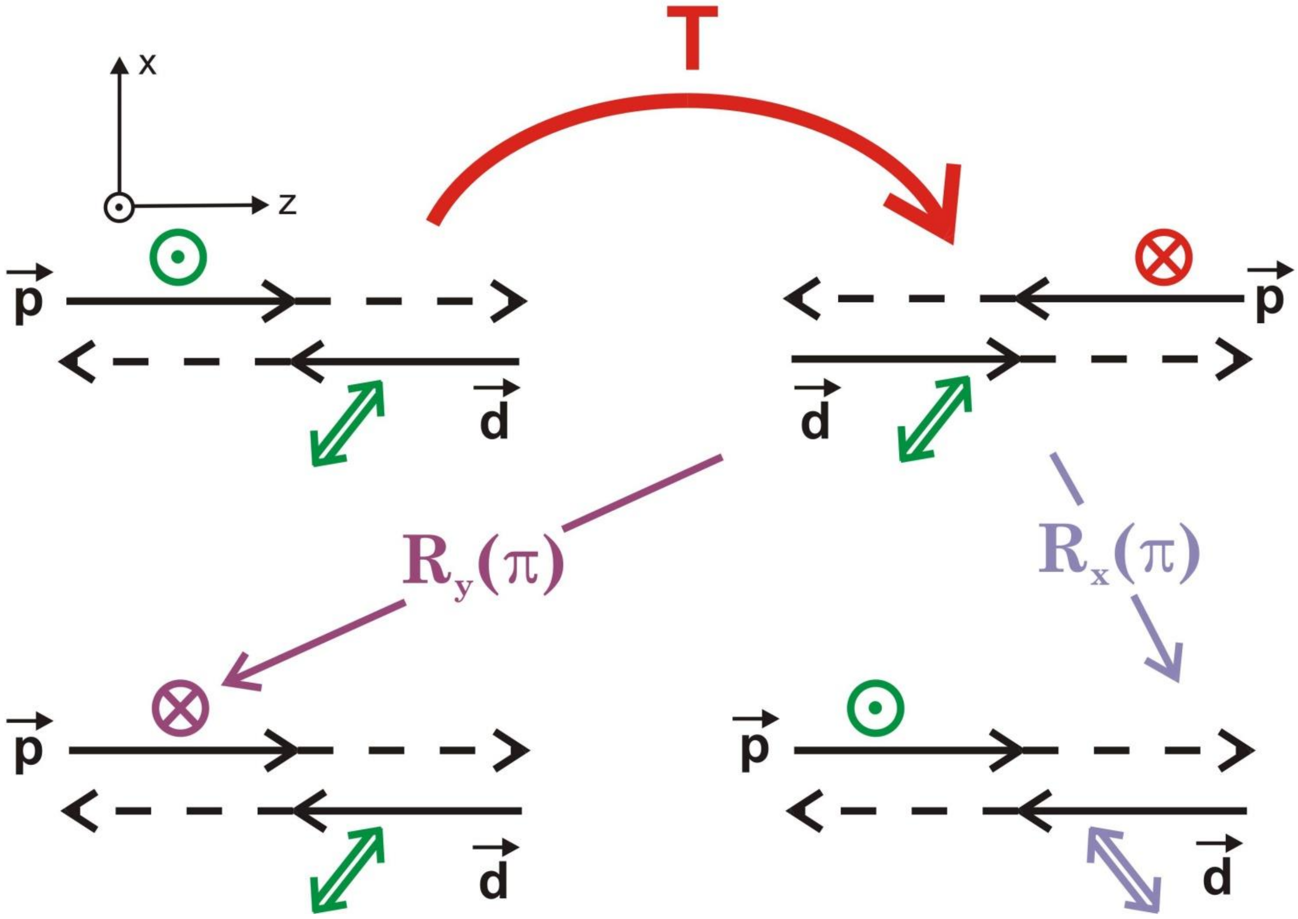
$$=: \frac{1}{A_T} \cdot \frac{N^+ + N^- - 2N^0}{\Sigma}$$

for $\Sigma = 1 \Rightarrow$

$$P_T = \frac{1}{A_T} \cdot (1 - 3N^0)$$

The Time-Reversal Invariance Test at COSY (TRIC)
The Principle Idea of the Experimental Setup

The Principle of the Time Reversal Invariance test at COSY (TRIC)

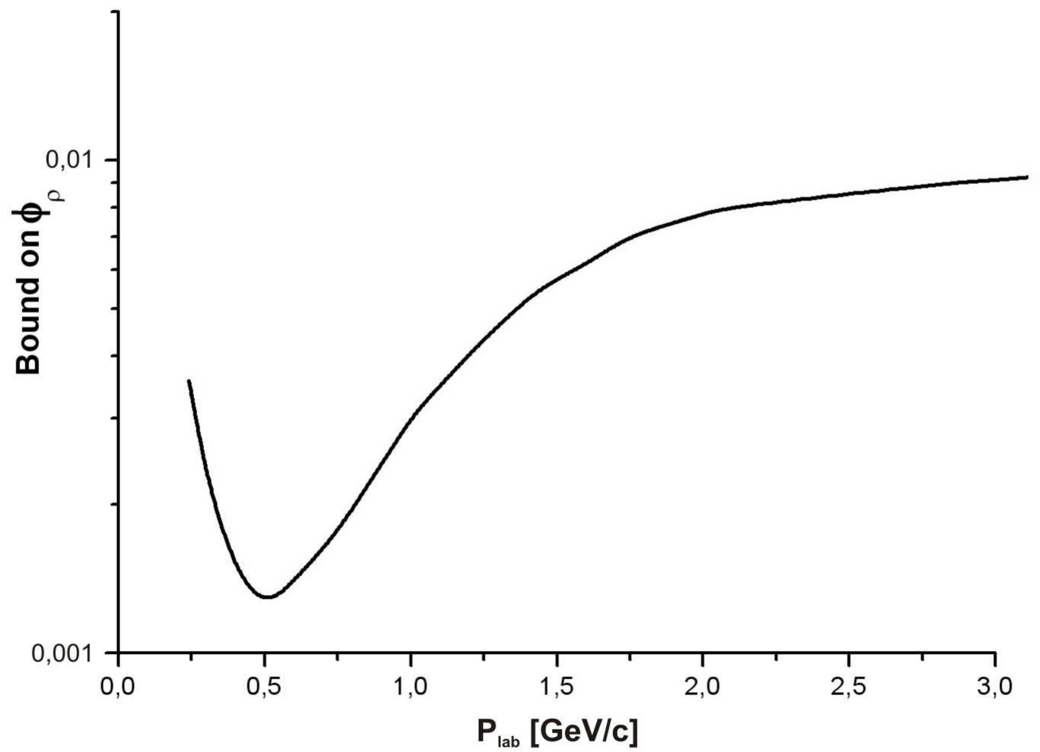


The Time-Reversal Invariance Test at COSY (TRIC)
What is the Proper Energy to Measure at ?

TRIC

Theoretical bound on TRV by ρ exchange

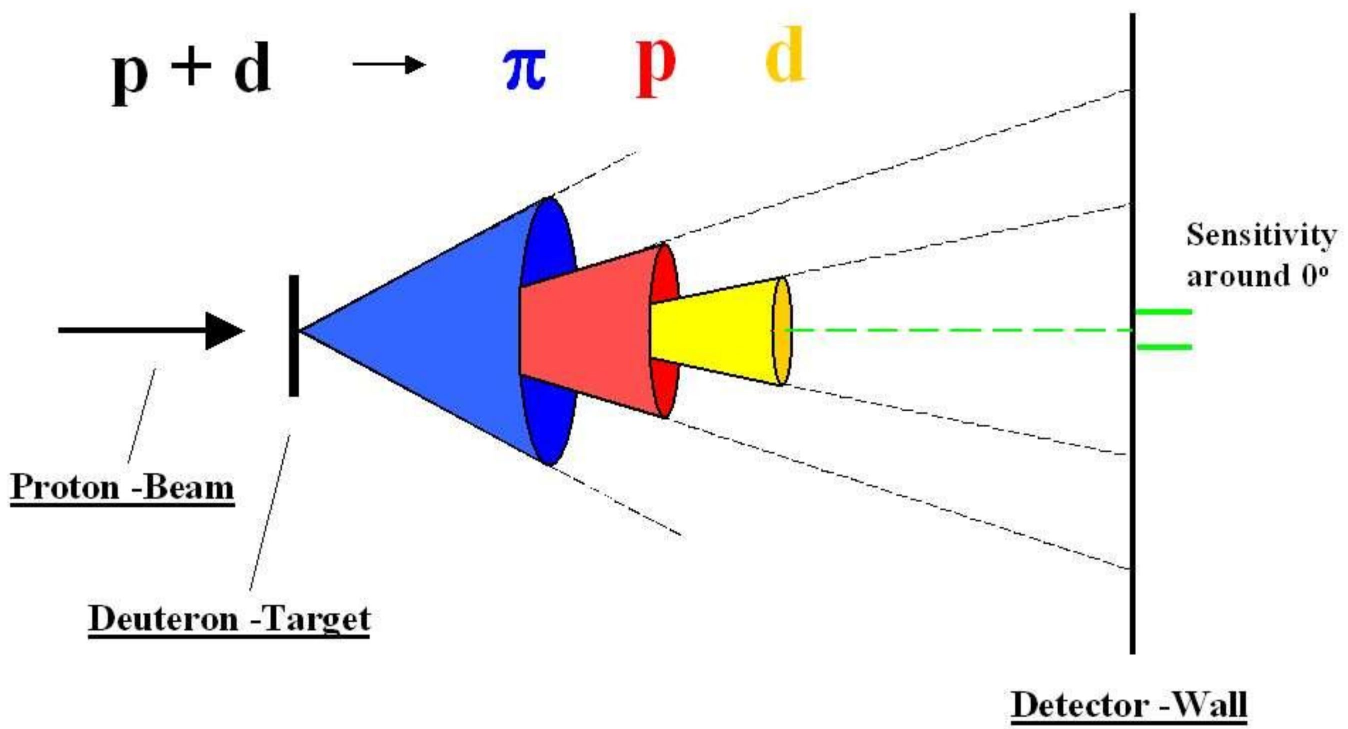
M. Beyer, Nucl. Phys. ***A560*** *(1993) 895*



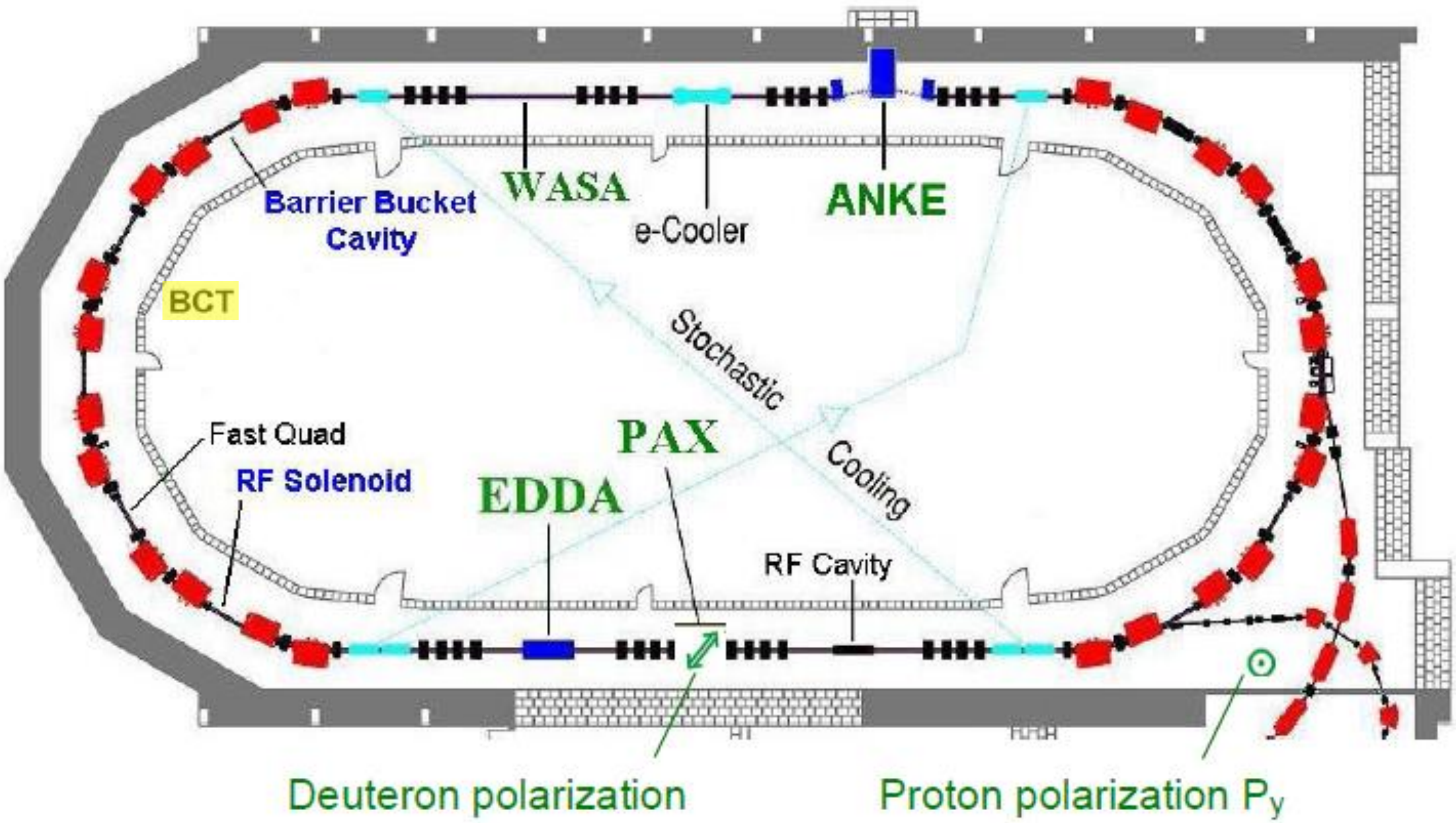
The Experimental Setup

External Fixed Target

Scattering-Cones and Detector-Sensitivity



The Time-Reversal Invariance Test at COSY (TRIC)
The Experimental Setup



The Time-Reversal Invariance Test at COSY (TRIC)

The Experimental Setup

TRIC

The total pol. correlation $A_{y,\,xz}$ is measured via the forward scatt. amplitude $\mathcal{F}(0)$

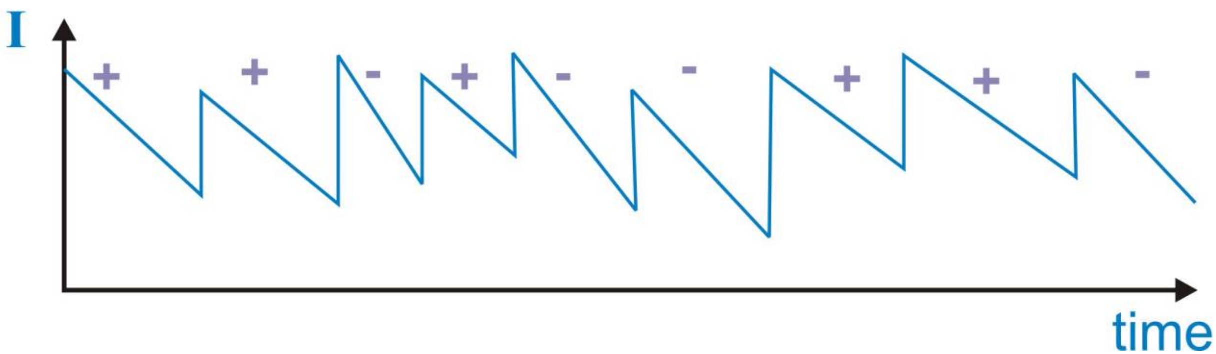
$$\sigma_{tot} = \frac{4\pi}{k}\, Im\, F(0) \;\rightarrow\; \frac{4\pi}{k}\, Im\, tr\,(\, \rho\, \mathcal{F}(0)\,)$$

$F(0)$ - Forward scatt. amplitude for unpolarized particles

ρ - Density matrix

$\mathcal{F}(0)$ - Forward scatt. amplitude (matrix) for polarized particles

$A_{y,\,xz}$ is proportional to the relative difference of the current slopes of the circulating proton beam with respect to the chosen polarization configuration (+/-) of the proton beam and deuteron target.



Final State Interaction

Concerning FSI :

Reading the Optical Theorem carefully: $$\frac{4\pi}{k}\,\mathrm{Im}\,F^{el}(0°) = \sigma_{tot}^{el} + \sigma_{tot}^{inel}$$

Has been proven by R.M. Ryndin

(proceeding of 3rd LNPI Winter School, *Test of T-invariance in strong interactions*),

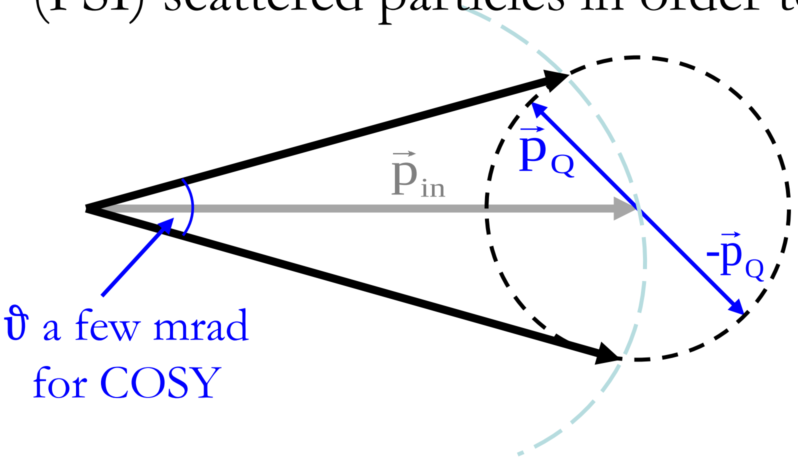
the idea of the proof can be found in: *V. Gudkov and Young-Ho Song, arXiv:1110.1279vl [nucl-th] 6Oct 2011*

Unitarity ⟶ Optical Theorem ⟶ $F_i(0°) = F_f(0°)$ ⟶ Unitarity

Final State Interaction

$$\frac{4\pi}{k}\,\mathrm{Im}\,F^{el}(0°) = \sigma_{tot}^{el} + \sigma_{tot}^{inel}$$

For all inelastic processes the following conditions have to be fulfilled by the (FSI) scattered particles in order to be transported by COSY:



i) The e/m has to be that of a proton to 10^{-4}

ii) The momentum p has to match to at least 10^{-4}

iii) The scattering angle ϑ must not exceed a few mrad

The phase space is considered to be virtually Zero

The Time-Reversal Invariance Test at COSY (TRIC)
Principal Error Analysis

TRIC

Involved Spins: ½ + 1 → ½ + 1

$I_{0,0}$	$A_{0,X}$	$A_{0,Y}$	$A_{0,Z}$
$A_{X,0}$	$A_{X,X}$	$A_{X,Y}$	$A_{X,Z}$
$A_{Y,0}$	$A_{Y,X}$	$A_{Y,Y}$	$A_{Y,Z}$
$A_{Z,0}$	$A_{Z,X}$	$A_{Z,Y}$	$A_{Z,Z}$

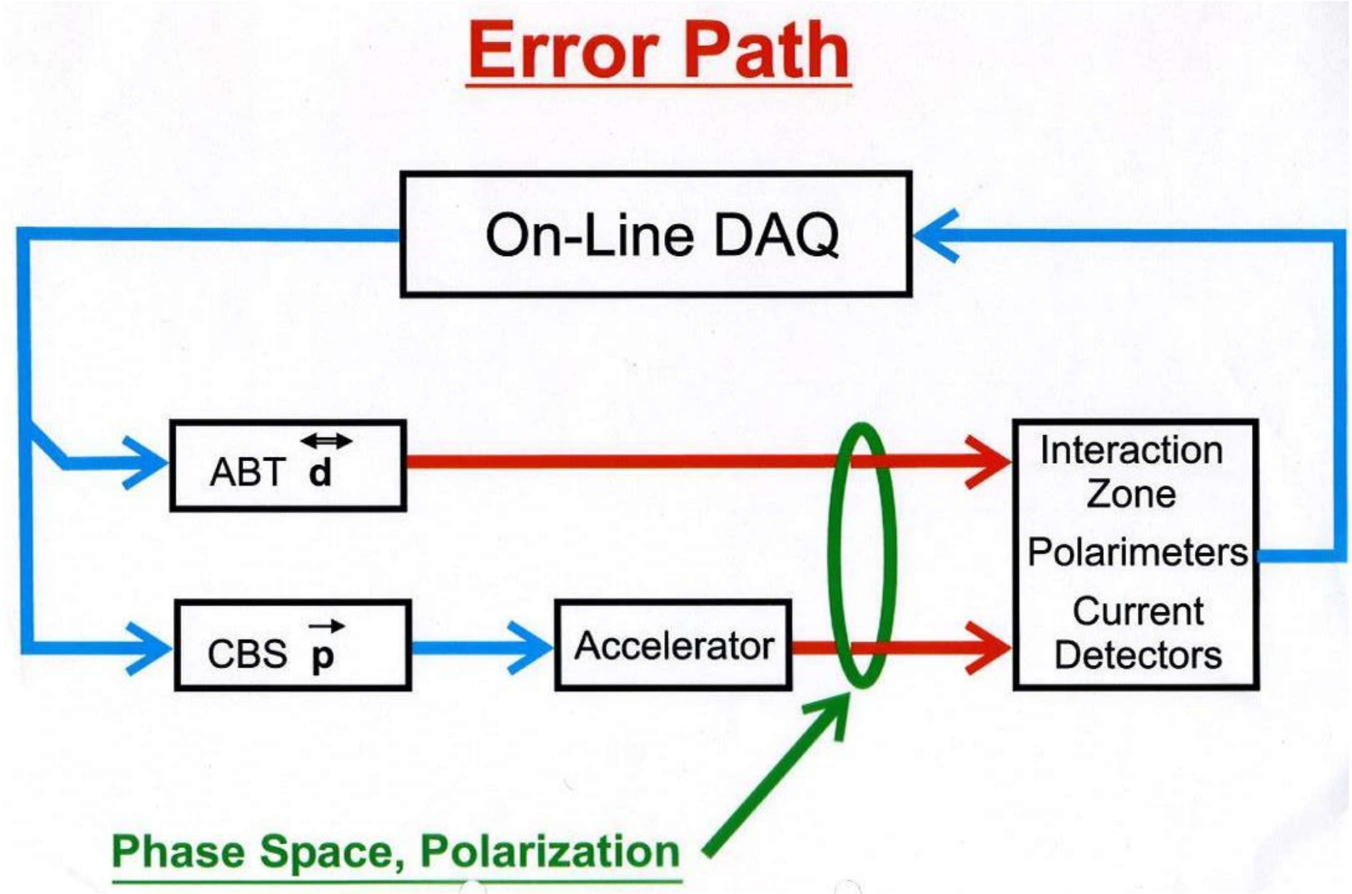
$A_{0,XX}$	$A_{0,YY}$	$A_{0,ZZ}$	$A_{0,XY}$	$A_{0,YZ}$	$A_{0,XZ}$
$A_{X,XX}$	$A_{X,YY}$	$A_{X,ZZ}$	$A_{X,XY}$	$A_{X,YZ}$	$A_{X,XZ}$
$A_{Y,XX}$	$A_{Y,YY}$	$A_{Y,ZZ}$	$A_{Y,XY}$	$A_{Y,YZ}$	$A_{Y,XZ}$
$A_{Z,XX}$	$A_{Z,YY}$	$A_{Z,ZZ}$	$A_{Z,XY}$	$A_{Z,YZ}$	$A_{Z,XZ}$

Line cancels because of : Protonspinflip
p_x, p_z negligible for protons

Quantity cancels because of : $\not{R}$, $\not{P}$

The Time-Reversal Invariance Test at COSY (TRIC)
Pincipal Error Analysis

TRIC



Some Experimental Details

- The error in the TRI sensitive observable $A_{y,xz}$ depends on :
  - i) The accuracy with which the current of circulating protons are measured
  - ii) The number of turns of the proton beam through the target

$$\Delta T_{y,xz} = \frac{T^+ - T^-}{T^+ + T^-} = \frac{\exp\text{-}(\chi^+) - \exp\text{-}(\chi^-)}{\exp\text{-}(\chi^+) + \exp\text{-}(\chi^-)}$$

with:

T^+ -Transmission factor for the proton-deuteron spin-configuration with $P_y \cdot P_{xz} > 0$

T^- -Transmission factor for the time reversed situation, i.e. $P_y \cdot P_{xz} < 0$

$\chi^{+/-}$ -Is the product of the factors $(\sigma_{tot} \cdot \varrho d \cdot n)$ with respect to the proton-deuteron spin-alignment

$$\Delta T_{y,xz} = -\sigma_o \varrho d \, n \, P_y \, P_{xz} \, A_{y,xz} =: - S \, A_{y,xz}$$

with:

S - Is the sensitivity of the experiment with respect to $A_{y,xz}$

n - Number of turns the beam takes through the target

The Time-Reversal Invariance Test at COSY (TRIC)

Some Experimental Details

$$\delta A^{meas}_{y,xz} = \frac{8 \cdot 10^{-6}}{I_0\, \sigma_0\, \rho d\, \nu\, P_y\, P_{xz}} \frac{\sqrt{\Delta t}}{h\sqrt{H}} \delta I$$

with: I_0	is the initial circulating proton current in COSY at the start of a slope measurement [A]
σ_0	is the total unpolarized cross-section [cm^2]
ρd	is the areal target density [atoms/cm^2]
ν	is the revolving frequency of the COSY beam [Hz]
P_y and P_{xz}	are the polarizations of beam and target, respectively
Δt	is the time interval between two consecutive current measurements on a slope [s]
h	is the spin flip period of the target [h]
H	is the total measuring time [h]
δI	is the error of the current measurement in the interval Δt [A]

Some Experimental Details

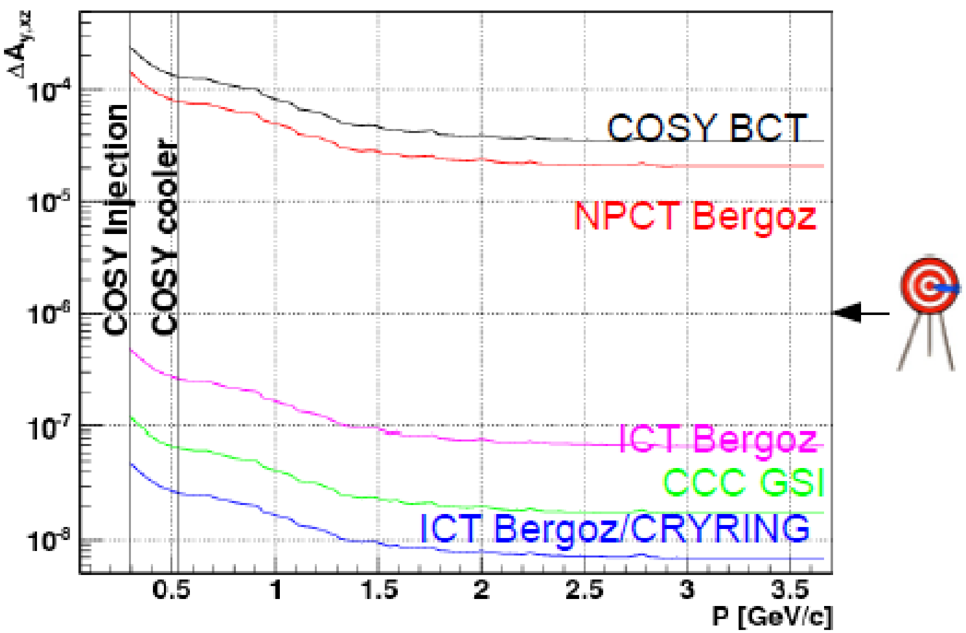
Beam time estimation

$$\delta A_{y,xz} = \frac{8*10^{-6}}{\rho d p_y p_{xz} \sigma_{tot}} \times \frac{\sqrt{t}}{h\sqrt{H}} \times \frac{\sigma_I}{\nu I_0}$$

Five options for σ_I :

1) COSY BCT σ_I=0.5μA/√Hz
2) NPCT Bergoz σ_I=0.3μA/√Hz
3) CCC GSI σ_I=0.25nA/√Hz
4) ICT Bergoz σ_I=1nA/√Hz
5) ICT Bergoz σ_I=0.1nA/√Hz

Precission after 30 days of beam-time



Some Experimental Details

When are these accuracies equal ? $\delta A_{y,xz}^{meas} = \delta A_{y,xz}^{shot}$

$$h_{min} = \frac{1.1 \cdot 10^{19}}{\nu^{3/2} \cdot \sqrt{\sigma_0\, \rho d\, N_0}} \cdot \frac{1}{P_y P_{xz}} \cdot \delta I$$

Given:		
	H	- 720 h (30 days)
	h	- 1/6 h
	σ_0	- 80 mb
	ρd	- $8 \cdot 10^{13}$ atoms/cm^2 (PAX target with openable cell)
	ν	- $8 \cdot 10^5$ Hz (@ 135 MeV)
	N_0	- $3 \cdot 10^9$ protons
	P_y, P_{xz}	- 0.8
	Δt	- 1 s

The Time-Reversal Invariance Test at COSY (TRIC)

Summary

- **The TRIC experiment at COSY constitutes a T-odd, P-even True TRI Null-Test**

- **The TRIC experiment has the ability to probe the lower bound of a T-odd, P-even test of TRI as derived from n-EDM**

- **For the TRIC experiment COSY serves as accelerator, ideal foreward spectrometer and detector**

"Go right to the frontiers of science
and you will learn soon what is missing"

Georg Christoph Lichtenberg (1742-1799)

Thank You