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Test of Time-Reversal Invariance at COSY

3rd of December 2012 | Yury Valdau

Status of T symmetry tests

- CP violation observed in decays of K^0 (1964) and B (2001) mesons can be linked to T-invariance via CPT theorem
- Amount of CP violation in SM is not sufficient to explain baryon-antibaryon asymmetry of the universe
- Time-Reversal violation observed recently in B0 system can not be explained by SM (PRL 109 (2012) 211801
- In order to compare different observables, testing fundamental symmetry, they are usually recalculated in to the strength of T-odd potential

Strength of T-odd potential

Reaction	Result	Symmetry	Reference	
EDM of n	$g_{PT}<10^{-11}$	PT	PR43(1978)409	
	$g_T<10^{-4}$	T	PRD63(2001) 076007	
γ-γ in ^{57}Fe	$\alpha_T<10^{-4}$	T	PRC53(1996)2546	
P-A in pp	$g_T<10^{-2}$	T	PR119(1960)352	
$p^{27}Al\rightarrow{}^{4}He+{}^{24}Mg$	$\alpha_T\approx g_T<10^{-3}$	T	PRL51(1983)355	
A_5 in $n^{165}Ho$	$\alpha_T<7.1*10^{-4}$	T	PRC55(1997)2684	Current upper limit
	$A_5=8.6*10^{-5}$			
$\vec{p}\vec{d}$ $A_{y,xz}(\Delta\sim10^{-6})$	$\alpha_T<10^{-6}$	T	This experiment	This experiment

g-strength of T-odd NN potential

α-strength of an effective T-odd N-core potential

Null test of Time-Reversal Invariance

Theorem:
"It is impossible to construct, in any reaction in atomic, nuclear, or particle physics, a null experiment that would unambiguously test the validity of time-reversal invariance independently of dynamic assumptions"

F. Arash, M. J. Moravcsik, and G. R. Goldstein PRL 54 (1985) 2649

This means:
There is no Null-Experiment for a reaction with two particles in and two particles out.

Alternative:
Since the total cross section asymmetry is non-bilinearly related to a T-odd amplitude in forward scattering, a measurements of the total cross section allows to perform a null test of TRI

Method:
In the forward direction total cross section can be measure via the optical theorem

$$\sigma_{tot}=4\pi/k\cdot Im(F(0))$$

H. E. Conzett, PRC 48 (1993) 423

Observable selection

$$\vec{\tfrac{1}{2}}+\vec{1}\rightarrow\vec{\tfrac{1}{2}}+\vec{1}$$

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

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

Line cancels because of: Proton spin flip

p_x,p_z negligible for protons

D. Eversheim, B. Lorentz and Yu. Valdau, COSY-Proposal #215

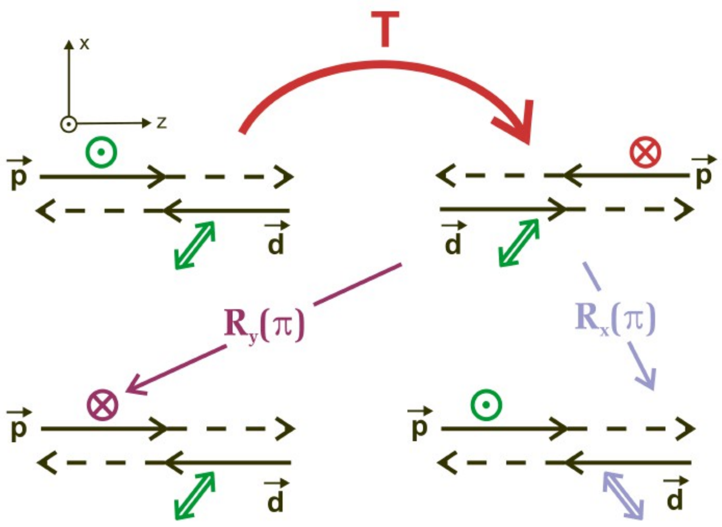
Quantity cancels because of: ~~R~~ ~~P~~

Thus: $A_{y,xz}$ is true null observable

$A_{y,y}$ is probably small, but has to be determined

Time Reversal Invariance test

$$\vec{\tfrac{1}{2}}+\vec{1}\rightarrow\vec{\tfrac{1}{2}}+\vec{1}$$



$\sigma_{tot}=\sigma(1+A_{y,xz}p_y p_{xz})+\sigma_{rest\ gas}$

Since:

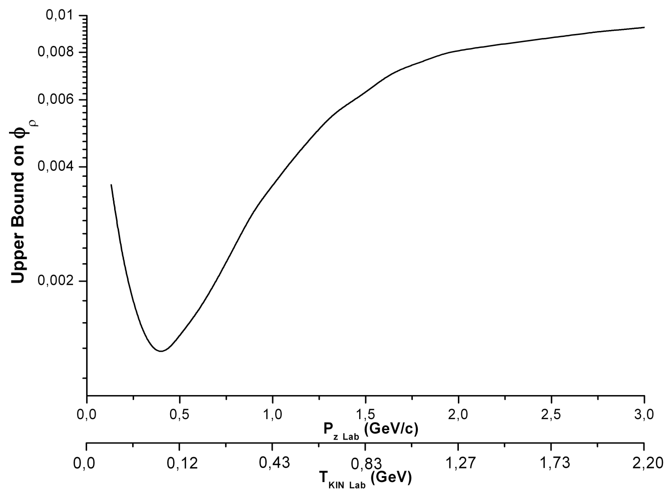
$A_{y,x}$ and $A_{y,yz}<10^{-7}$(from P violation)

$\sigma_{rest\ gas}$ does not depend on beam polarisation

Thus:

Total cross section measurement at ~150 MeV/c in pd scattering in this combination of beam and target polarisations is true T-odd null observable

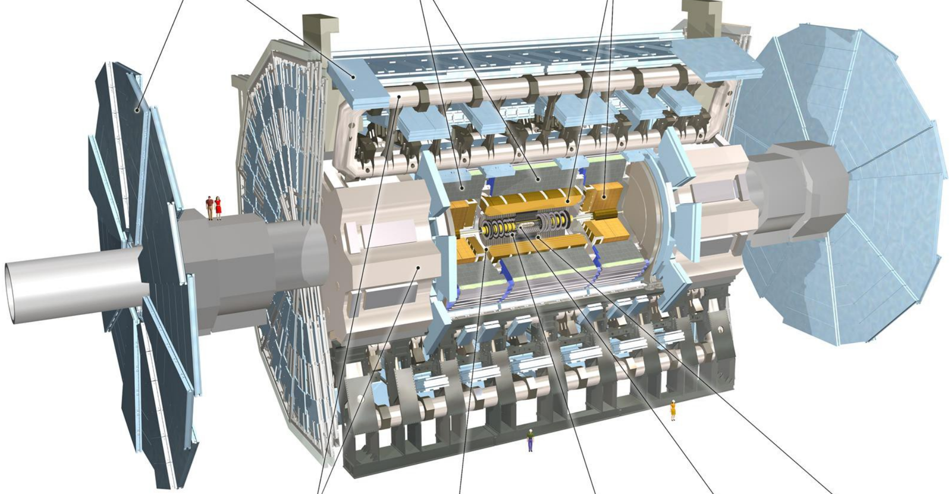
But how to measure total cross section?



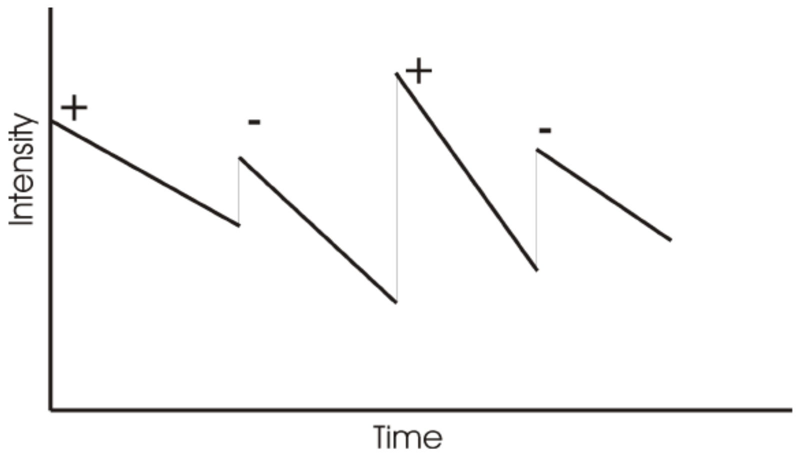
M. Beyer NPA 560 (1993) 895

Method to measure total cross section

One can either:
Build a complicated detector system to **detect all the particle scattered from the beam**, and still use approximation for zero degree



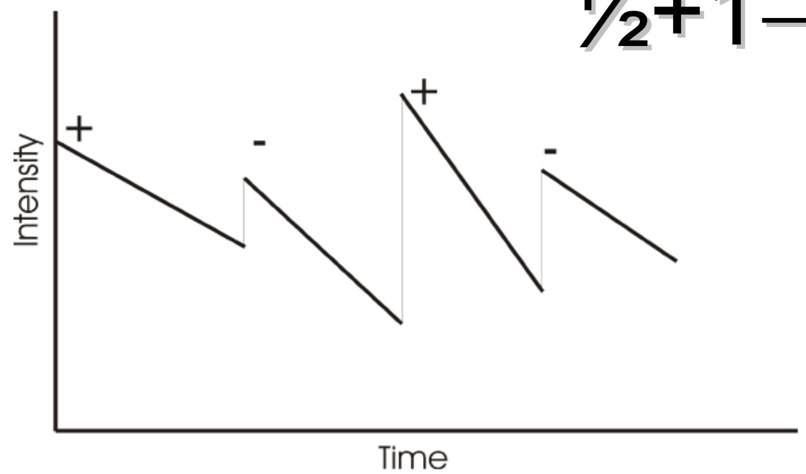
Or:
Perform a transmission experiment – detect particles **which remain in the beam after interaction with the target**

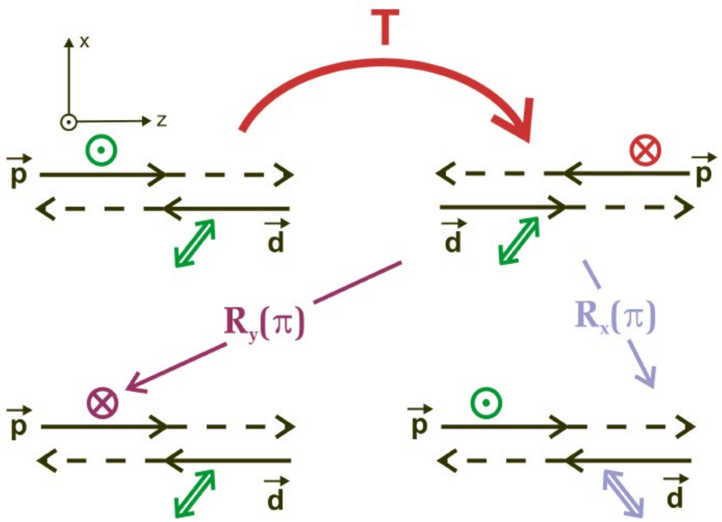


Optical theorem:
$\sigma_{tot} = 4\pi/k \cdot Im(F(0))$

Advantages of proposed method

$$\vec{\tfrac{1}{2}}+\vec{1}\rightarrow\vec{\tfrac{1}{2}}+\vec{1}$$





- Model independent analysis due to use of deuteron – simplest spin 1 particle
- This kind of experiment is not sensitive to final state interaction
- Possibility to flip beam and target polarisation allows to check systematic errors

Four tasks for TRI experiment

■ Beam (high polarisation; life time, polarisation life time, low betta, e-cooler, …)	?
■ Target (high thickness deuterium target with openable storage cell and holding field system)	?
■ Polarimetry of the beam and target (detector?, polarimeter for the target, …)	?
■ Beam current measurement (precission, stability, DAQ, …)	?

COSY

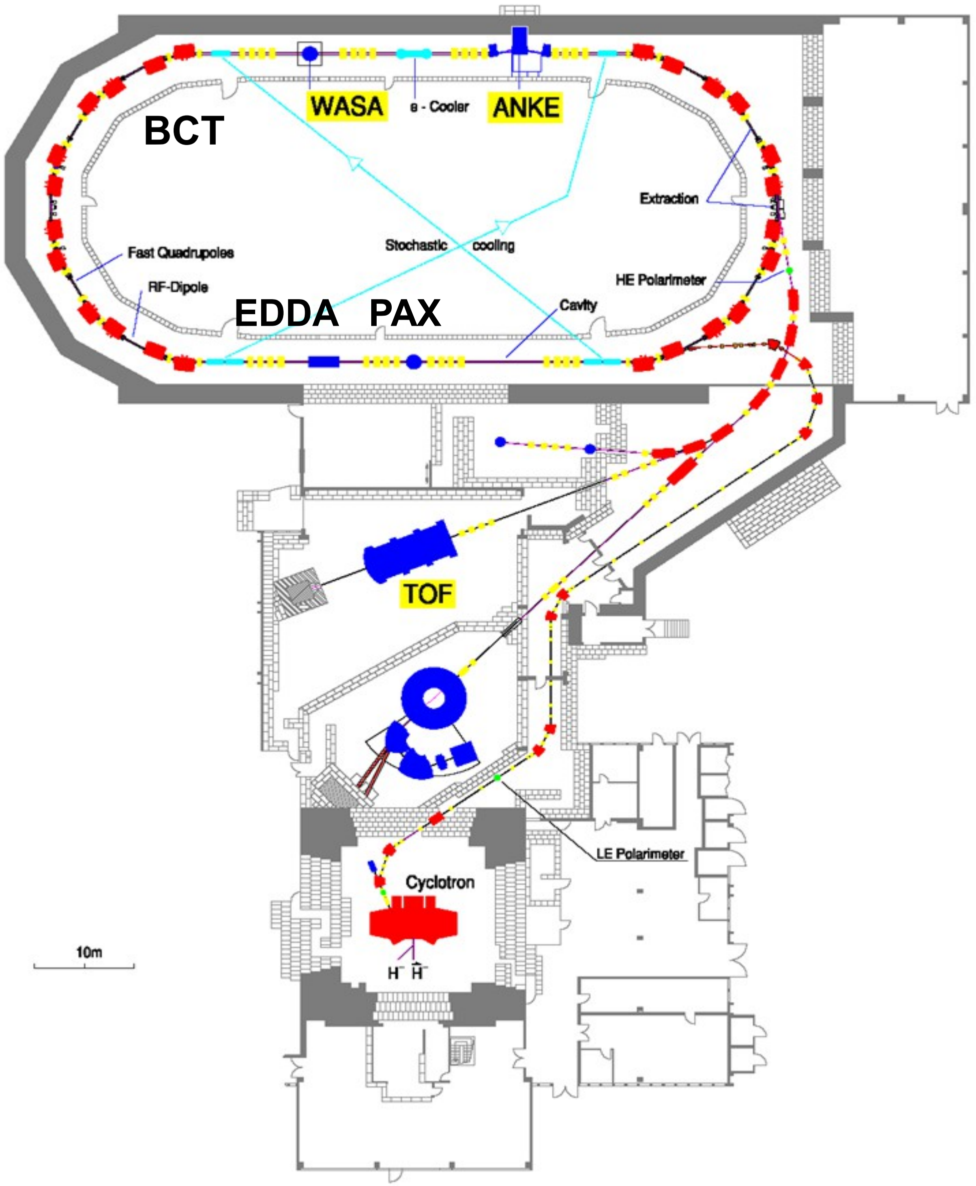
Polarised and unpolarised beams: p,d

Maximal particle momentum: 3.7 GeV/c

Stochastic and electron cooling

Internal and external target positions

Internal and external beam polarimeters



TRI beam-development in September 2012

- COSY can provide stable e-cooled proton beam accelerated to 135 MeV/c through the low beta section and storage cell of 8 mm
- Beam life time of >10000 s was observed for both bunched and unbunched beams
- Two different methods of bunching was tested: beam bunched with Barrier Backet has longer beam life time then bunched with COSY RF
- Beam intensity and target thickness is sufficient to perform the experiment

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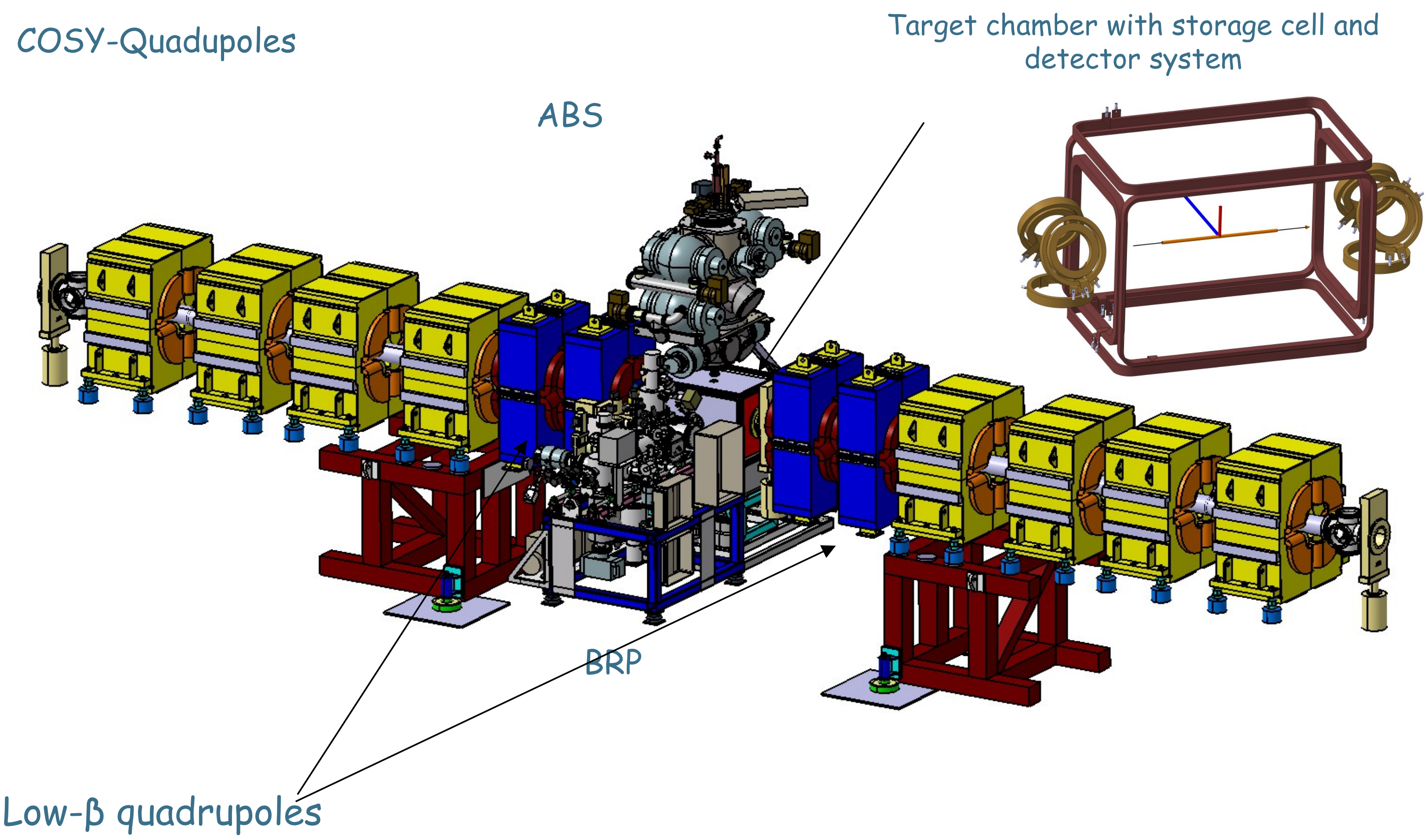
Four tasks for TRI experiment

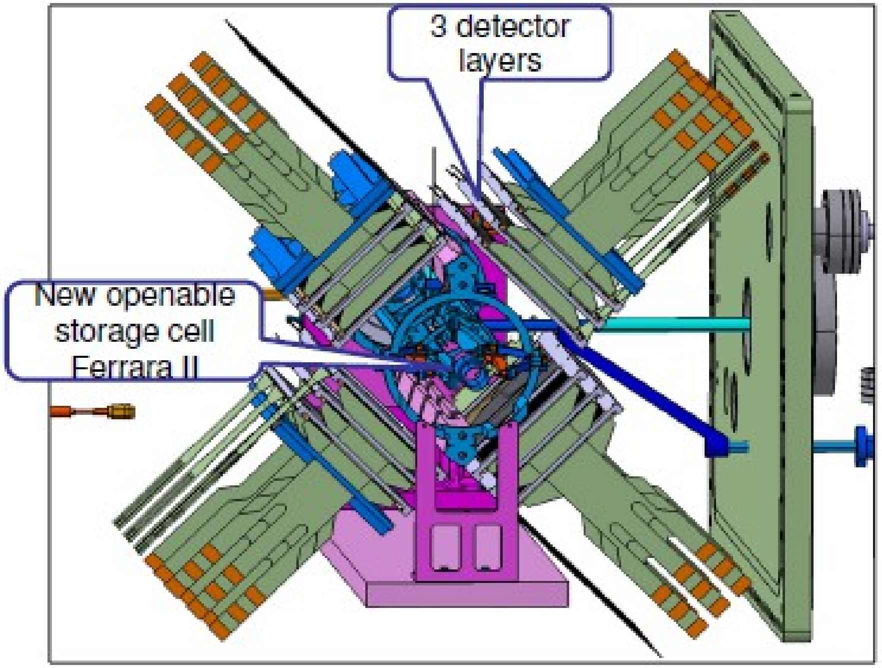
■ Beam (high polarisation; life time, polarisation life time, low beta, e-cooler, …)	COSY
■ Target (high thickness deuterium target with opennable storage cell and holding field system)	?
■ Polarimetry of the beam and target (detector?, polarimeter for the target, …)	?
■ Beam current measurement (precission, stability, DAQ, …)	?

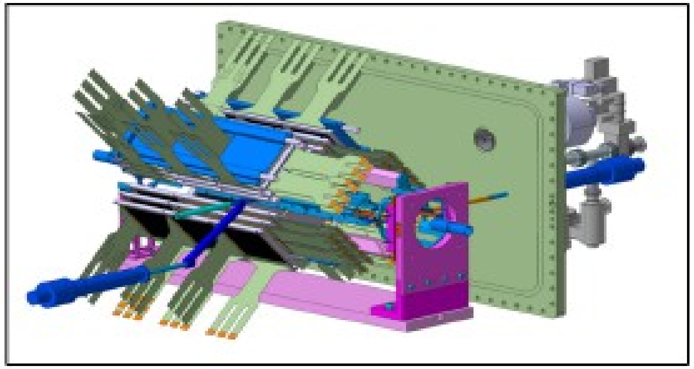
PAX installation



P. Lenisa and F. Rathmann CERN-SPSC-2012-013/SPSC-SR-099

PAX detector





In 2014 at the PAX target place will be available:

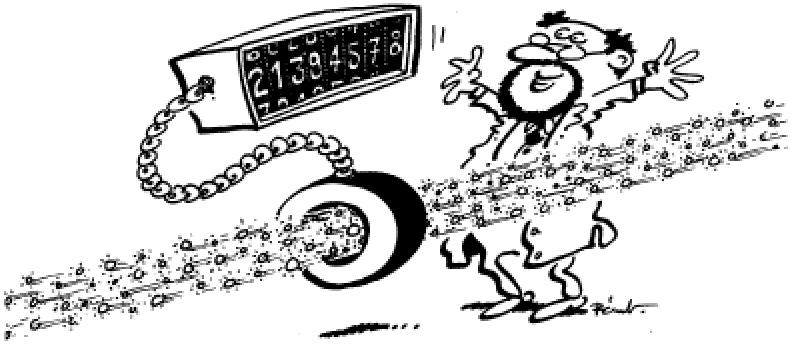
- Atomic Beam Source and Breit-Rabi Polarimeter will be capable to operate with deuterium
- Opennable storage-cell for high polarised target density
- Holding field system to preserve and flip target polarisation during measurement cycle
- φ - symmetric multipurpose PAX detector for beam and target polarimetry

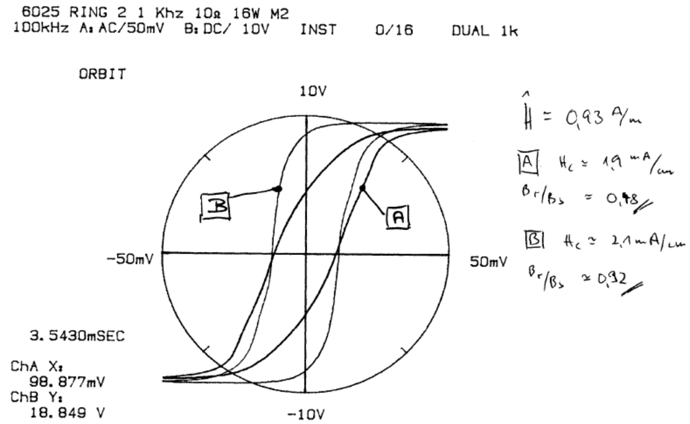
Four tasks for TRI experiment

▪ Beam (high polarisation; life time, polarisation life time, low betta, e-cooler, …)	**COSY**
▪ Target (high thickness deuterium target with openable storage cell and holding field system)	**PAX**
▪ Polarimetry of the beam and target (detector?, polarimeter for the target, …)	**PAX**
▪ Beam current measurement (precission, stability, DAQ, …)	**?**

Beam current measurement in storage ring

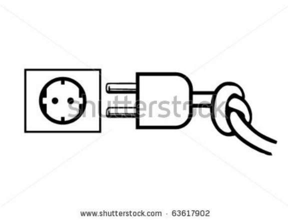
DC current

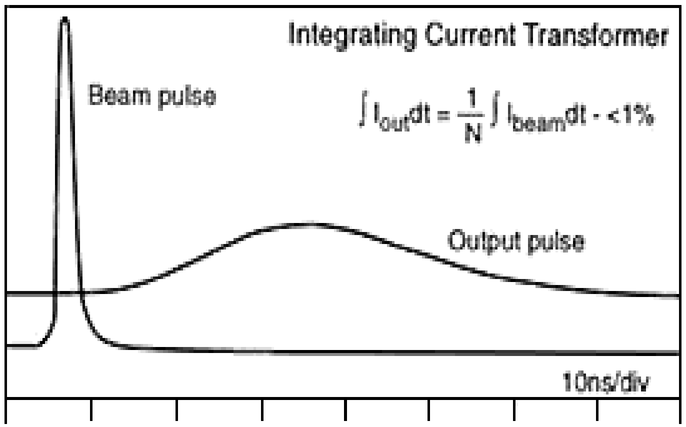




H. G. Reeg: B-H measurements, Vitrovac 6025F

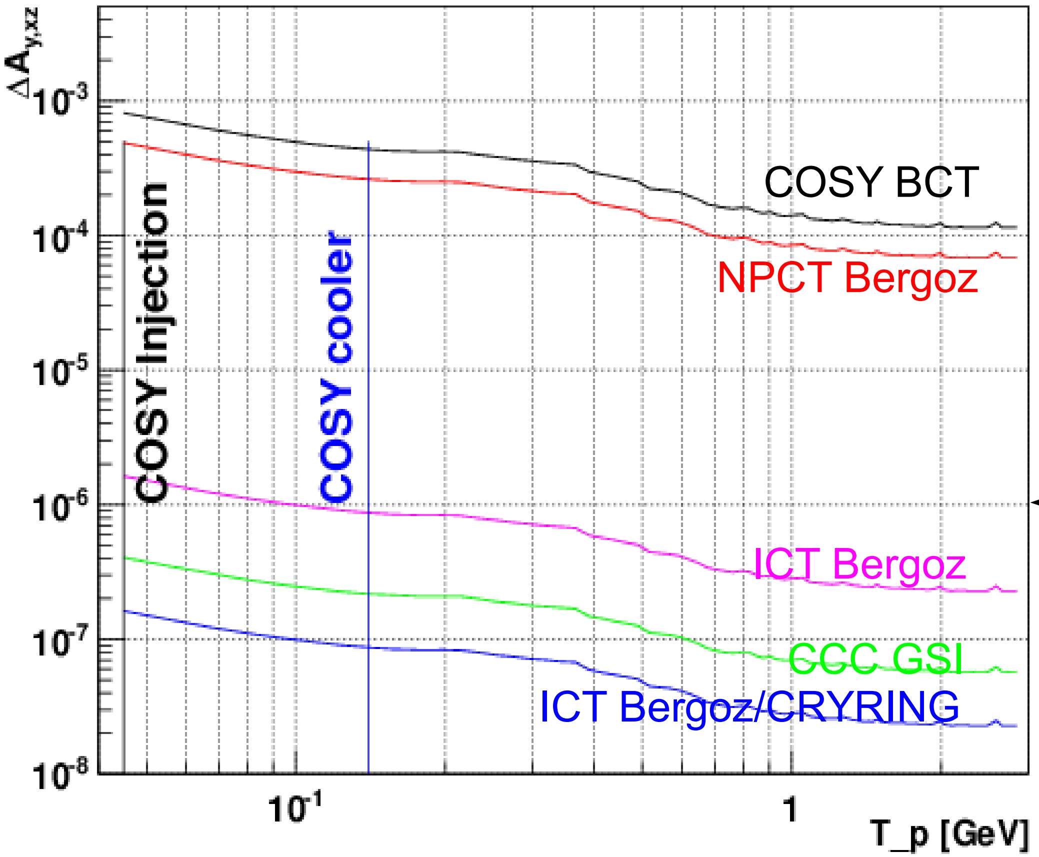
AC current

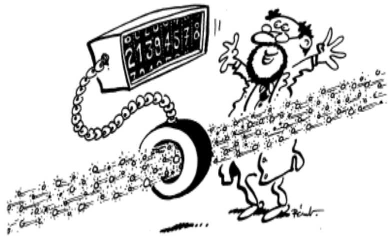


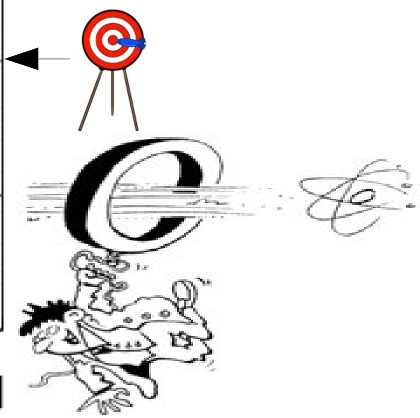


BCT sensitivities

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







Assuming:

- N_p =3*10^9 protons in the ring
- ρd – target density (8*10^{13} atoms/cm^2)
- $p_y p_{xz}$ – target and beam polarisation
- h – spin flip time (10 min)
- t – measurement integration time (1 s)
- H – total measurement time (30 days)

Four tasks for TRI experiment

Task	
Beam (high polarisation; life time, polarisation life time, low betta, e-cooler, …)	**COSY**
Target (high thickness deuterium target with openable storage cell and holding field system)	**PAX**
Polarimetry of the beam and target (detector?, polarimeter for the target, …)	**PAX**
Beam current measurement (precission, stability, DAQ, …)	**possible**

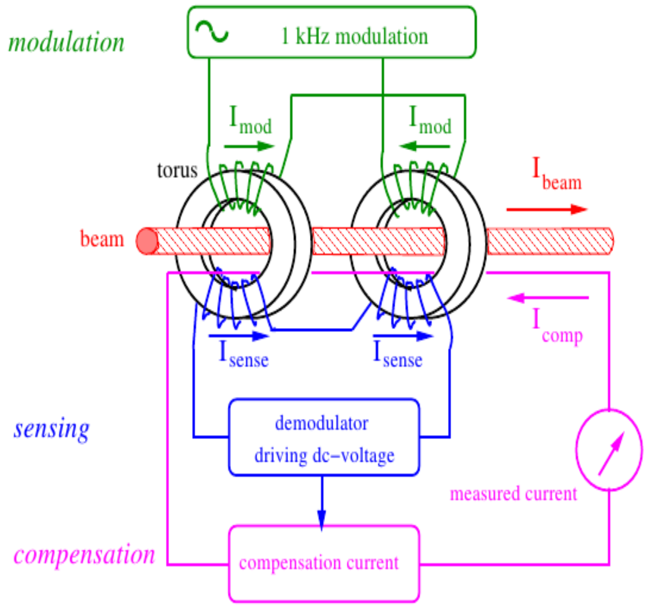
Conclusions&Outlook

- Using proposed method it is possible to improve limit on T-odd P-even interaction by an order of magnitude
- COSY and PAX installation are very well suited for such an experiment
- First beam time in September 2012 have shown that COSY can provide beam for the TRI experiment
- High precision beam current measurement system must be developed and installed at COSY in 2014

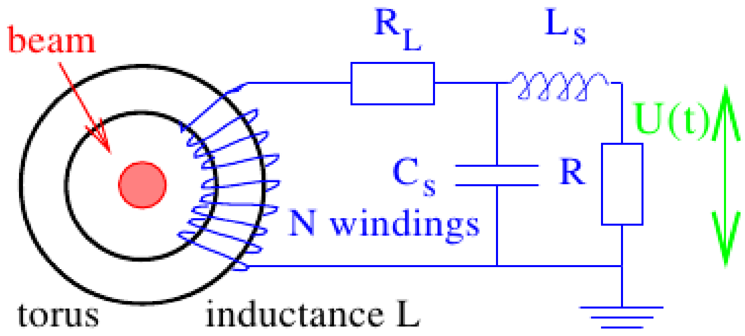
Thank you!

Types of BCTs

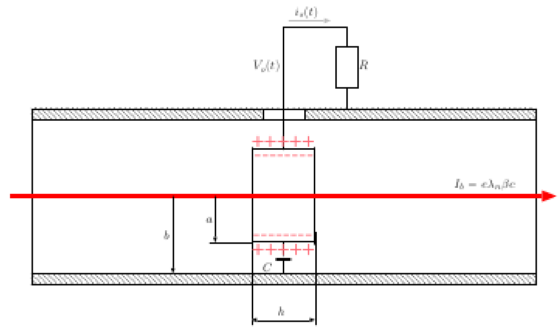
DC transformer



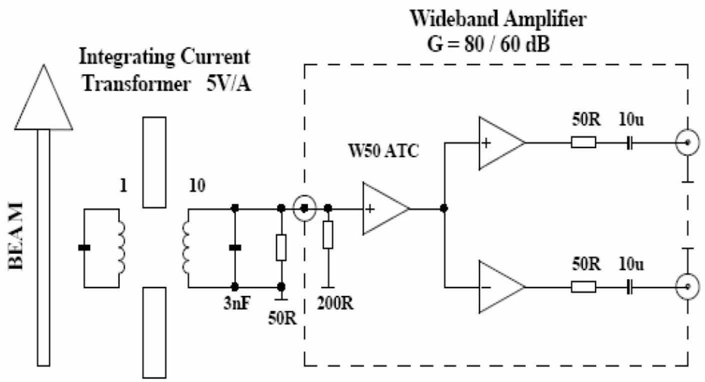
AC transformer



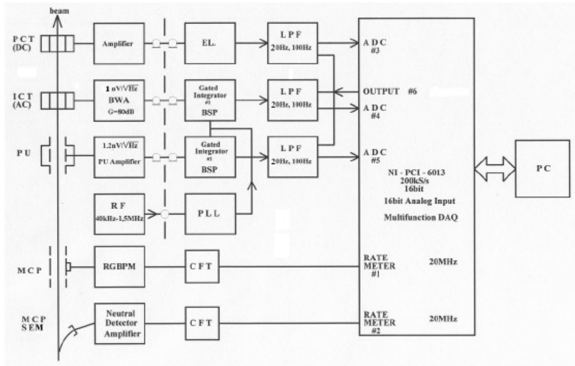
Capacitive pick up



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/CRYRING σ_I=0.1nA/√Hz

DC or bunched beams

Bunched beam only

Summary of beam current measurements

- Sensitivity of conventional DC beam measurements systems is not sufficient to perform TRI test
- It is possible to reach the desired precision using the ICT and a bunched COSY beam
  - Dedicated beam development is needed (long life time for bunched beam, ...)
  - Readout scheme for ICT must be developed
  - ICT must be impemented to COSY
- Using capacitive pick-up (BPM) it is possible improve sensitivity even further (CRYRING method)

Final State Interaction

Concerning FSI :

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

Has been proven by R.M. Ryndin

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

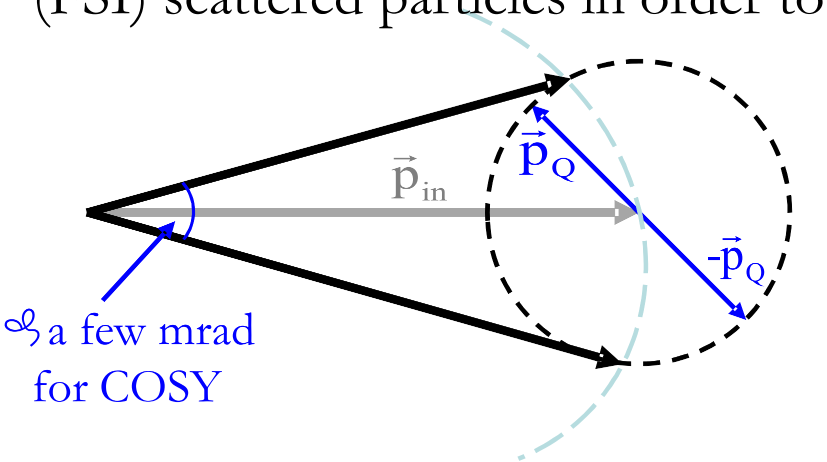
the idea of the proof can be found in: *V. Gudkov and Young-Ho Song, arXiv:1110.1279vl [nucl-th] 6Oct 2011*

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

Final State Interaction

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

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



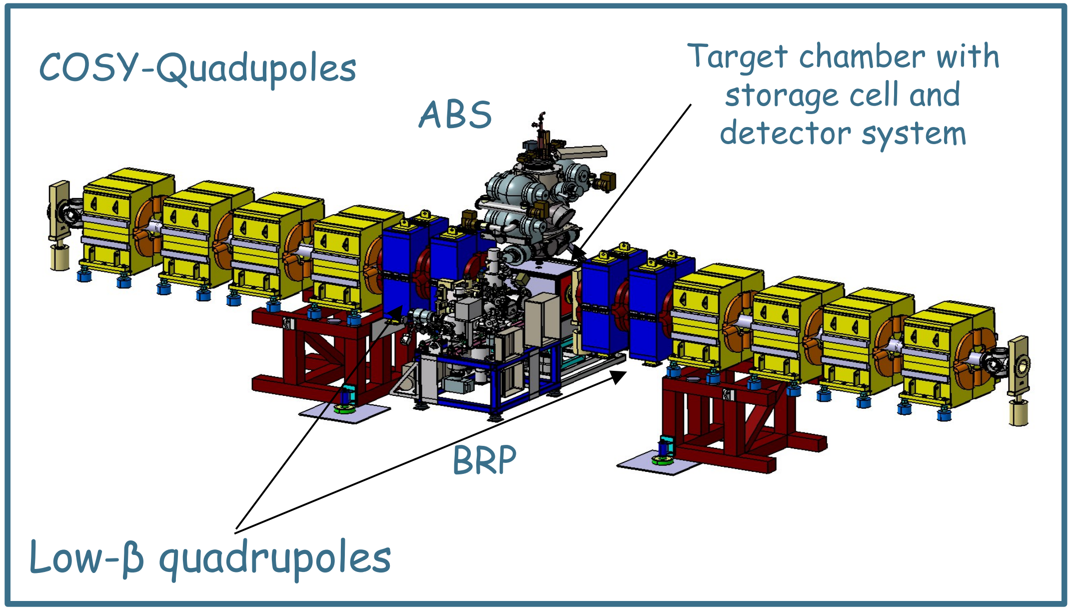
i) The e/m has to be that of a proton to 10^{-4}

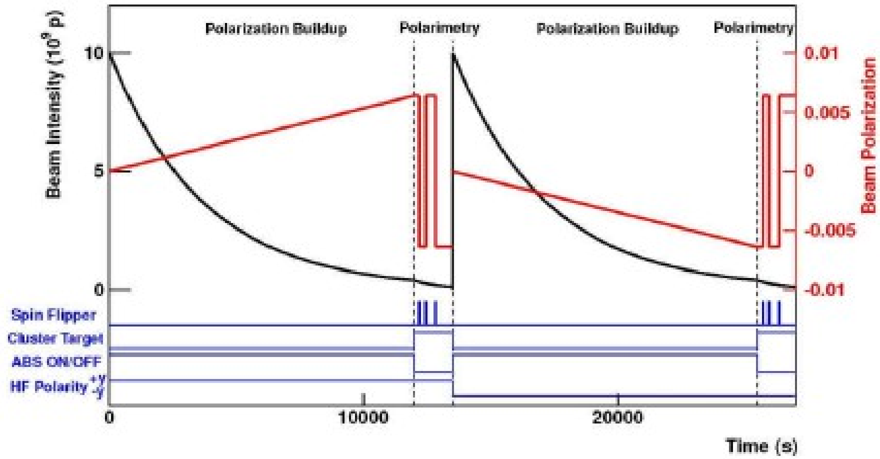
ii) The momentum p has to match to at least 10^{-4}

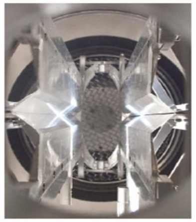
iii) The scattering angle ϑ must not exceed a few mrad

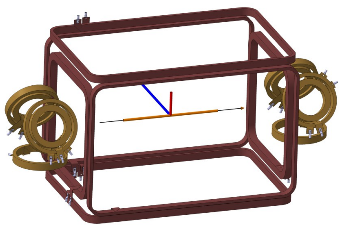
The phase space is considered to be virtually Zero

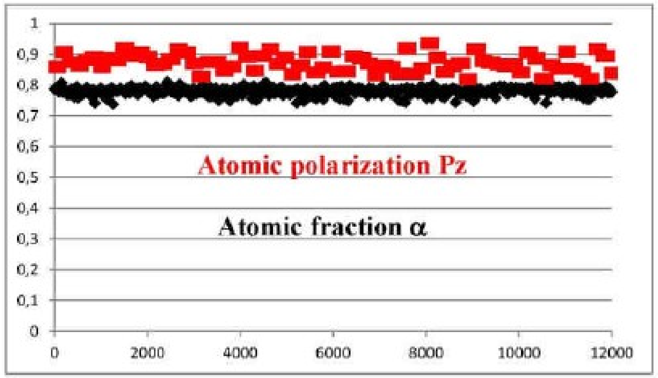
PAX installation











P. Lenisa and F. Rathmann CERN SPS reports

- ✔ Beam life time of ~8000s at injection energy
- ✔ Polarisation life time of >10^5 s at injection energy
- ✔ ABS with polarised H^0 gas
- ✔ Breit-Rabi polarimeter
- ✔ Openable storage cell
- ✔ Holding field system

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Symmetries in physics

The Noether theorem:

For every continuous symmetry of the laws of physics there exists a conservation law and vice versa. (1915)

Symmetry = Conservation Law

Emmi Noether (1882-1932)

Laws of physics are independent of:

- Origin of time axis → Energy conservation
- Origin of spacial axis → Momentum conservation
- Orientation of spacial axis → Angular momentum conservation

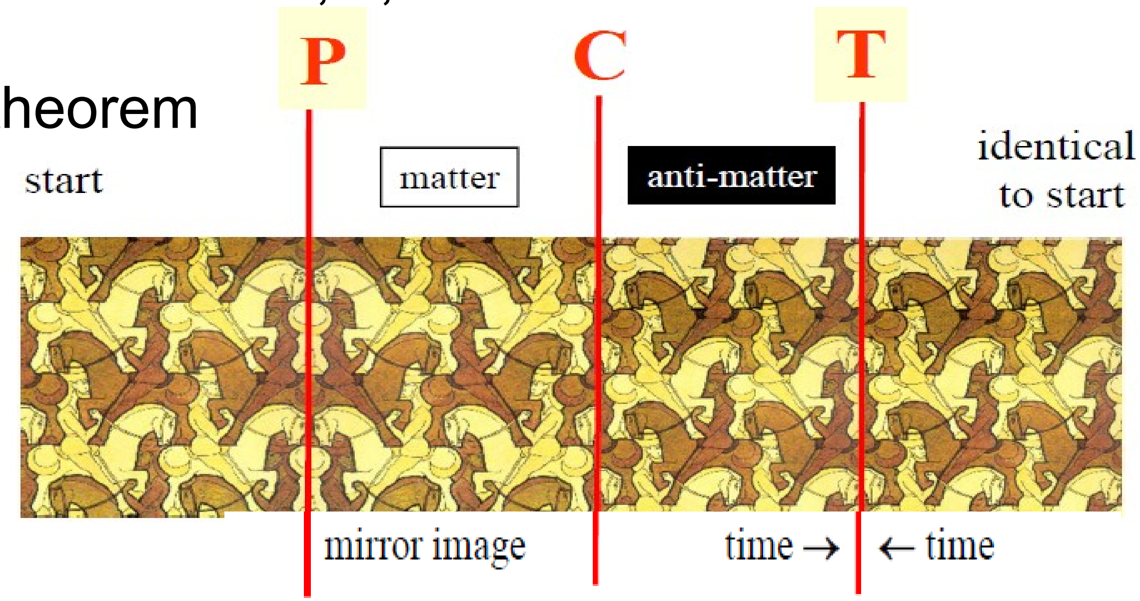
What is symmetry?

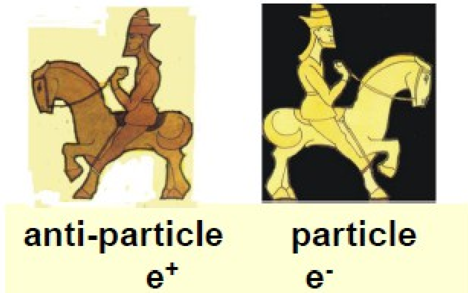
"An object is called *symmetric*, if one can do something with it, without, at the end, when one is finished with the procedure, having changed it."

R.P. Feynman:
(1918-1988)

Three discrete symmetries are fundamental in the standard model C, P, and T

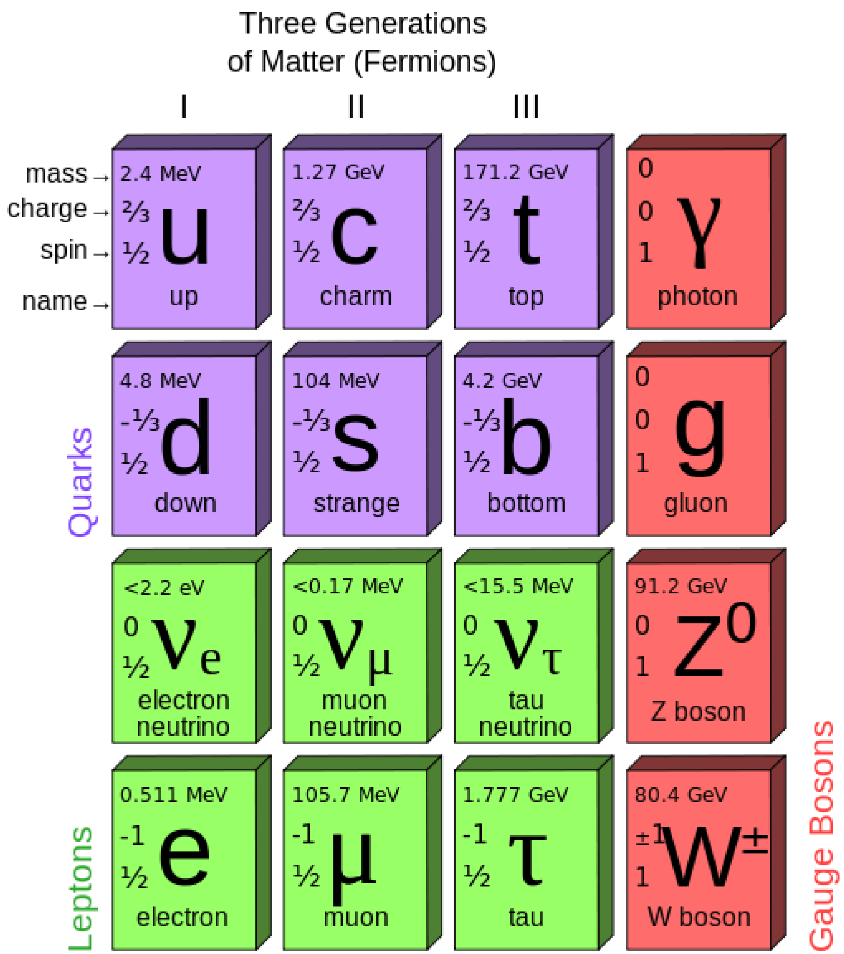
CPT theorem

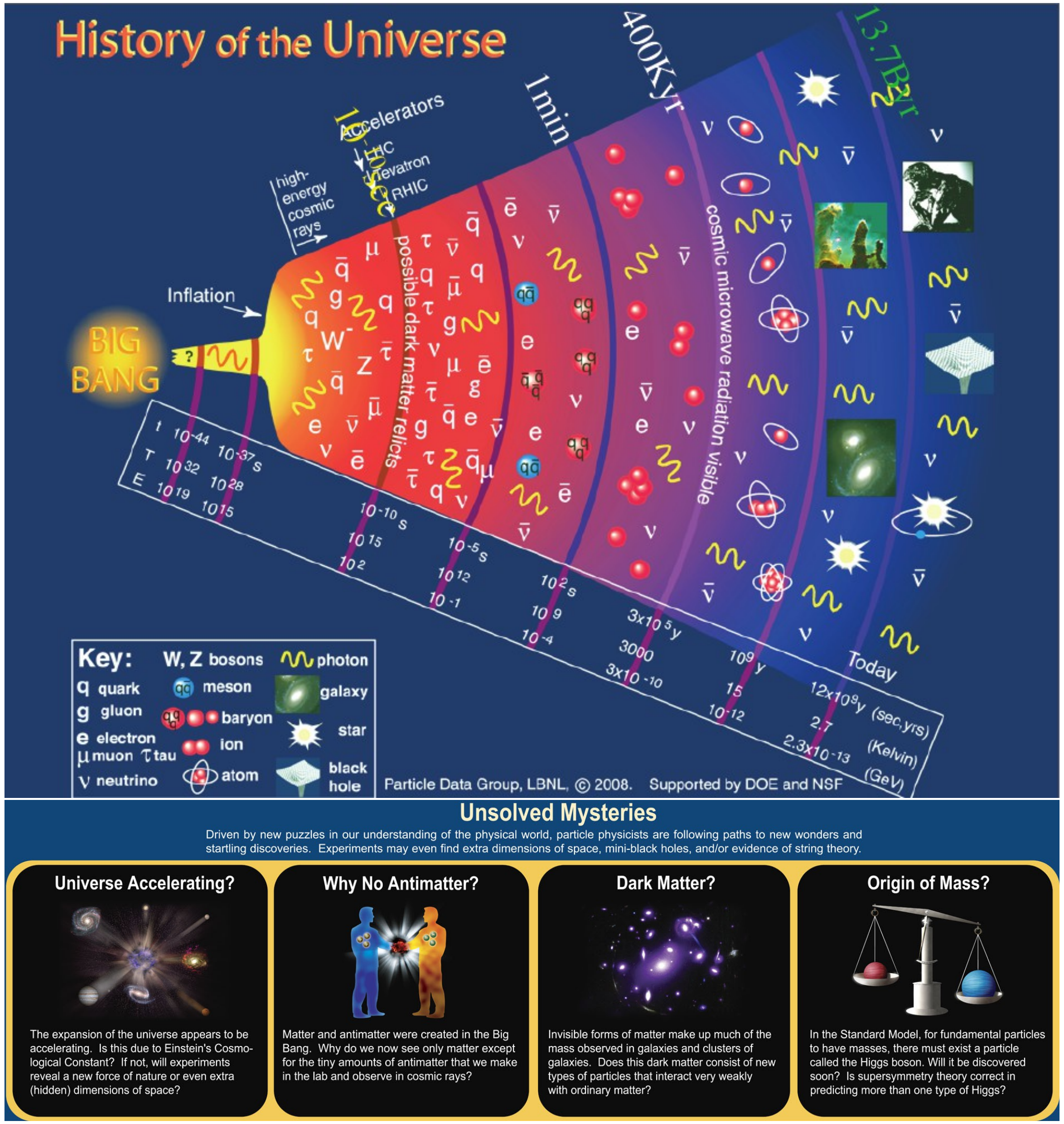




Picture from M.C. Escher

Standard Model





http://pdg.lbl.gov