STORI'14: 9th International Conference on Nuclear Physics at Storage Rings

September 28th – October 3rd, 2014
St. Goar (Germany)

SPIN COHERENCE TIME studies of a POLARIZED DEUTERON beam @ COSY

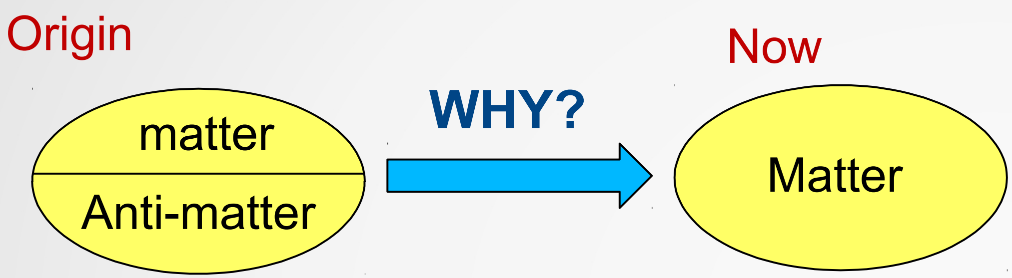
On behalf of the JEDI Collaboration

G. Guidoboni
University of Ferrara and INFN

PHYSICAL MOTIVATIONS

See “Electrice Dipole Moment measurements at storage rings” by J. Pretz

Electric Dipole Moment of fundamental particles



BARYOGENESIS

Sakharov's conditions (1967):

- $B = n_b - n_{\bar{b}}$ violation
- ***C*** and ***CP*** violation
- Far from thermal equilibrium

Standard Model (SM):

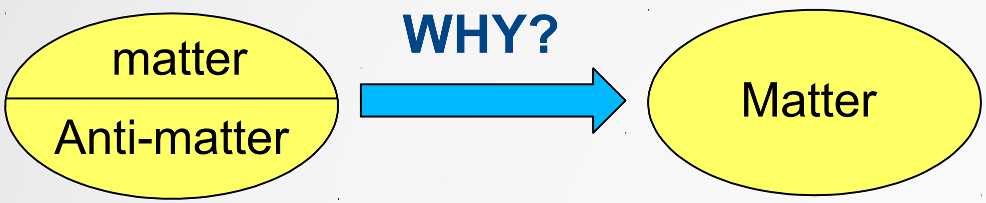
- Not enough to explain *Baryon Asymmetry*
- **Too small CP violation**

PHYSICAL MOTIVATIONS

Electric Dipole Moment of fundamental particles

Origin

Now



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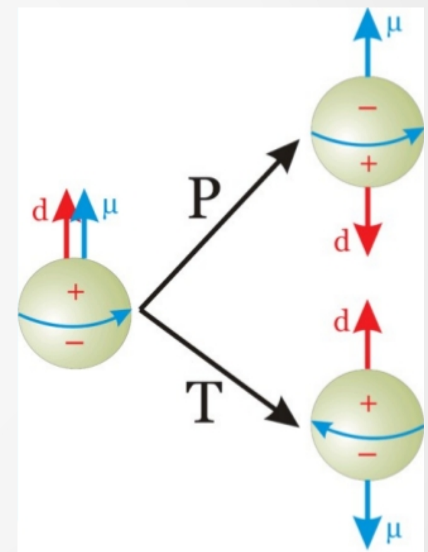
Def: permanent charge displacement within the particle volume

d=EDM
μ=spin



Assuming CPT symmetry

T violation = **CP violation**

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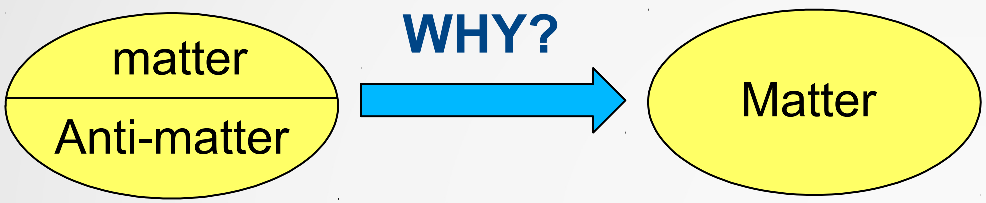

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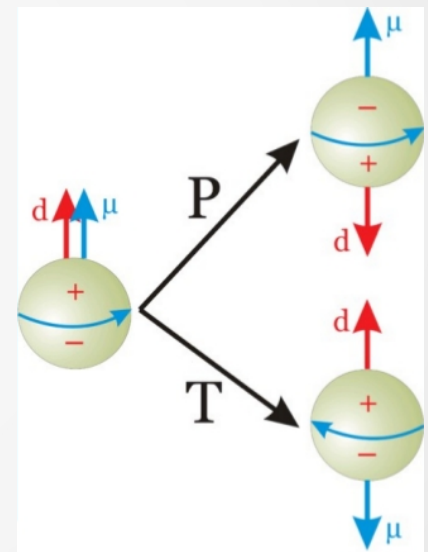

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EDM$_{SM}$ too small to be observed

EDM$_{bSM}$ within exp. limits

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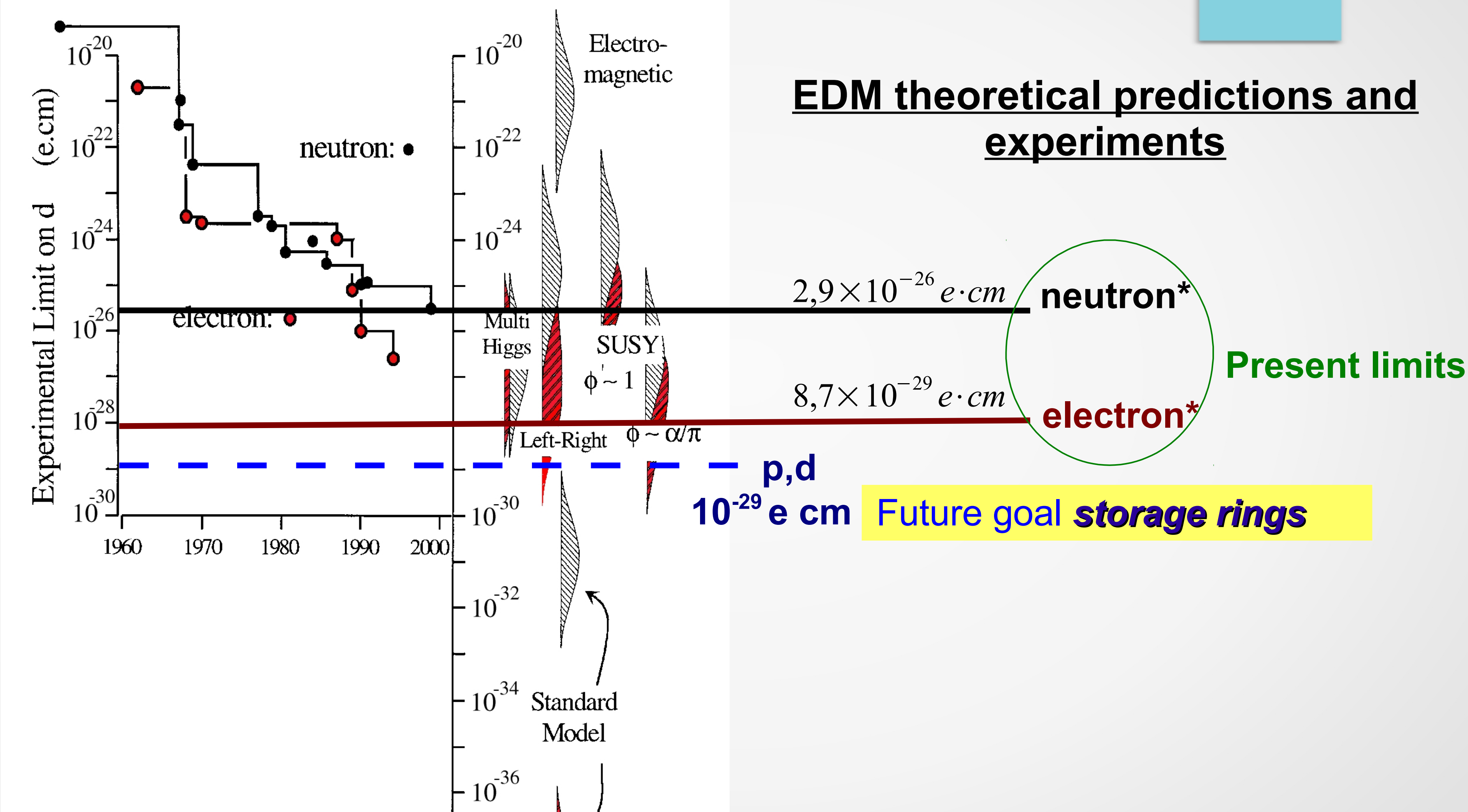
PHYSICAL MOTIVATIONS

* C.A. Baker et al.,
Phys. Rev. Lett. 97, 131801 (2006)

* The ACME collaboration
Science 343, p. 269-272 (2014)

EDM theoretical predictions and experiments



J.M. Pendlebury and E.A. Hinds
NIM A **440** (2000) 471

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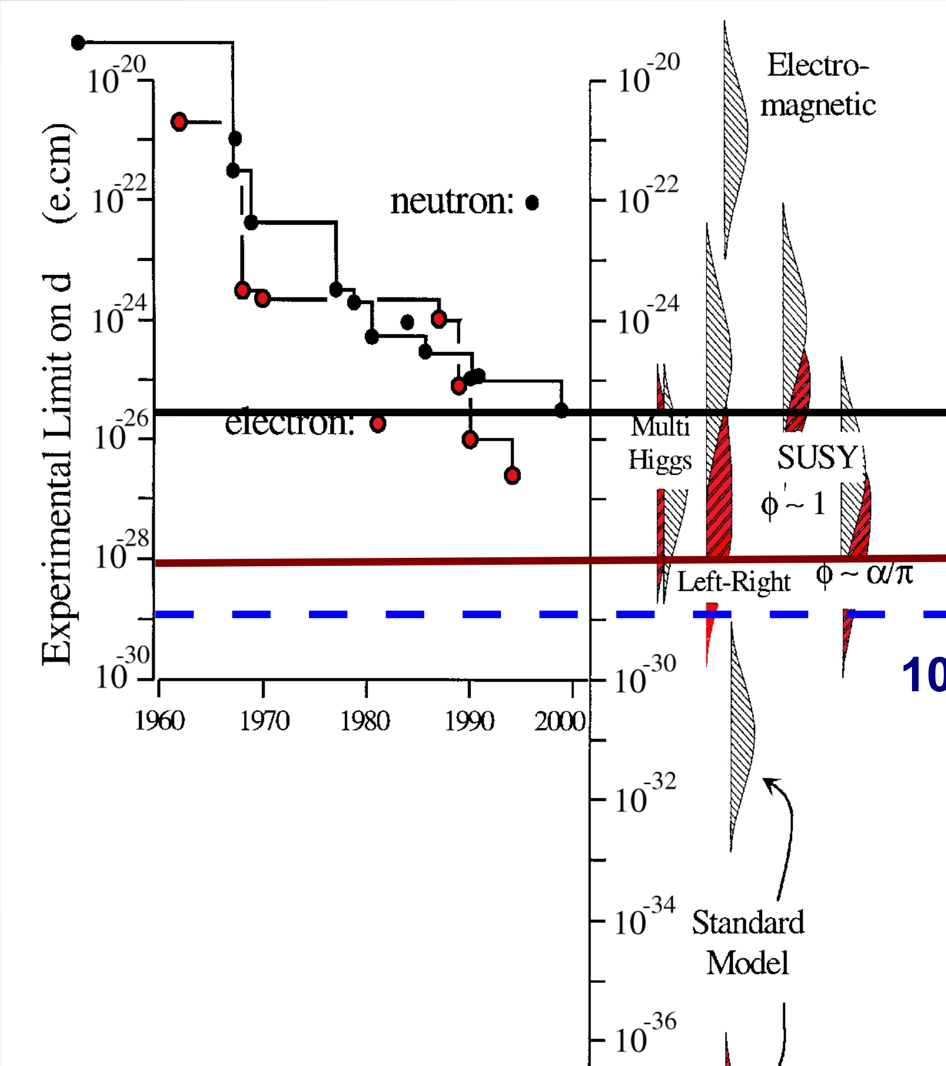

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EDM theoretical predictions and experiments

$2{,}9 \times 10^{-26}\, e \cdot cm$ **neutron***

$8{,}7 \times 10^{-29}\, e \cdot cm$ **electron***

Present limits

p,d

10^{-29} e cm Future goal ***storage rings***

No EDM has been observed yet

Because SM contributions are small
EDMs are an excellent place to search for NEW PHYSICS.

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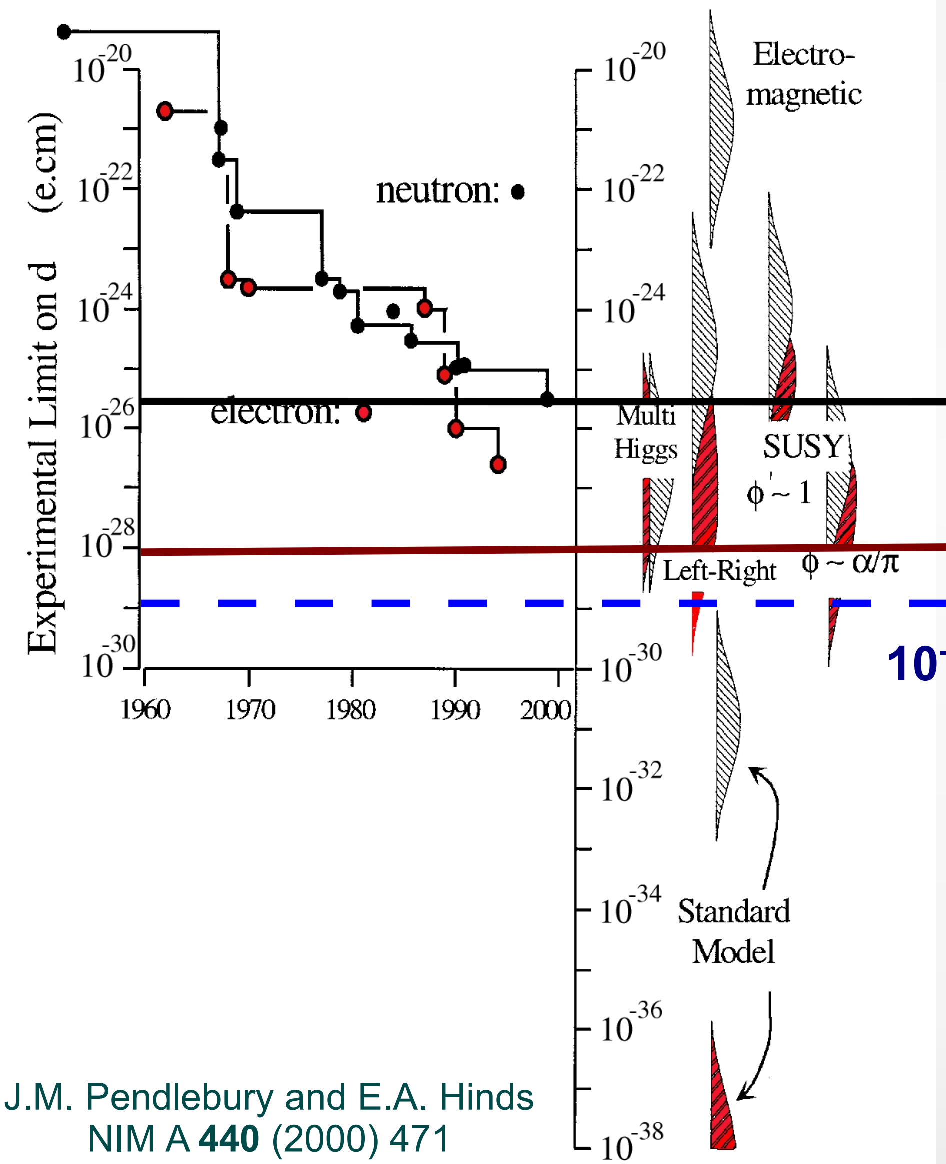

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New CP violation sources!

EDM EXPERIMENTS

<u>**Neutral systems**</u>

1951 Purcell and Ramsey:

parity violation in neutron scattering from nuclei

heavy atoms, molecules and neutrons

<u>Method</u>: apply electric field $\vec{\boldsymbol{E}}$

measure energy shift $\vec{\boldsymbol{d}} \cdot \vec{\boldsymbol{E}}$

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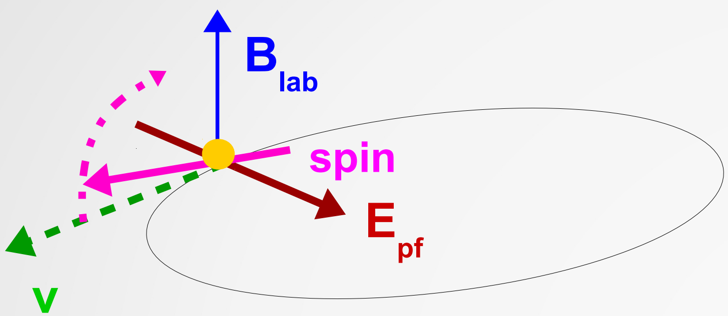
Charged particles

New method:

STORAGE RING as trap for POLARIZED charged particles beams

HOW TO: charged particle EDM

Storage ring



All rings have <u>inward</u> electric field in particle frame

$$\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}$$

EDM signal = spin precession in the vertical plane

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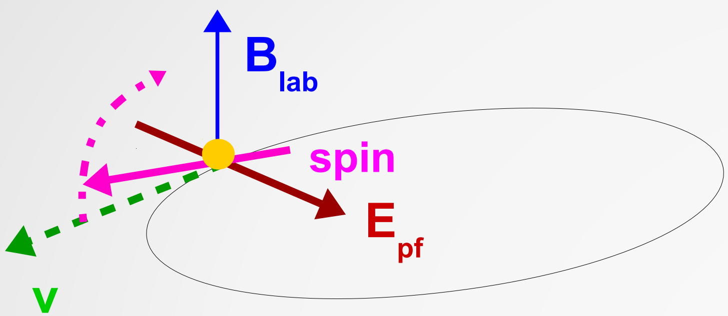

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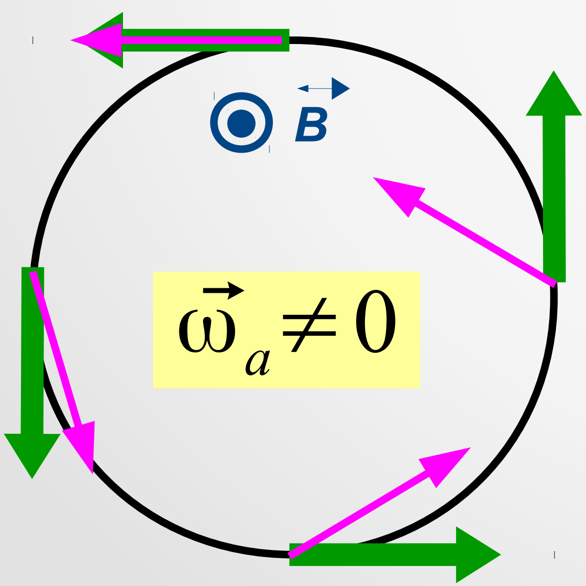
<u>TO DO:</u> FREEZE the spin along the velocity



From the Thomas-BMT equation:

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_r = \frac{-q}{m} \left\{ G\vec{B} + \left[G - \left(\frac{m}{p} \right)^2 \right] \frac{\vec{\beta} \times \vec{E}}{c} \right\}$$

$\vec{\omega}_s$ Spin precession in the horizontal plane

$\vec{\omega}_r$ Particle revolution frequency

$G = \frac{g-2}{2}$ Anomalous magnetic moment

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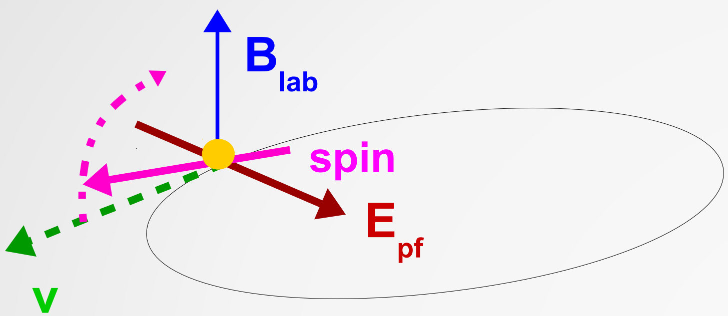

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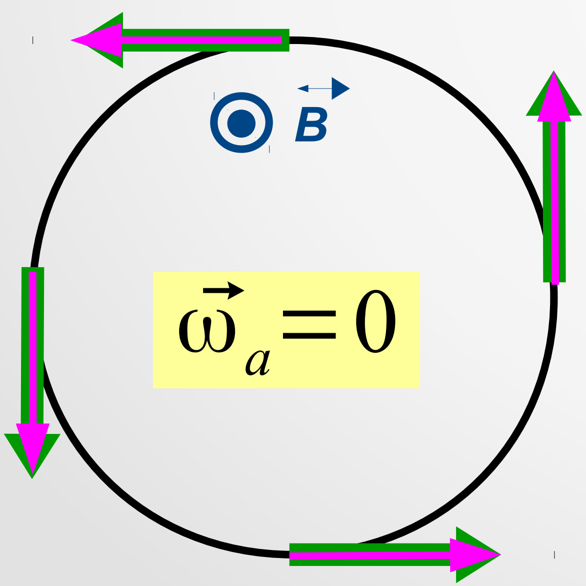

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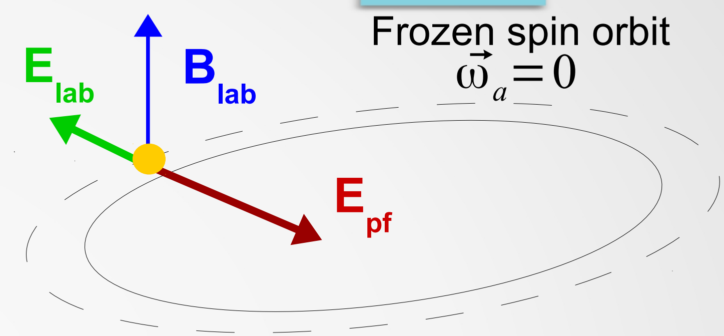
Find E (radial) and B fields combination!

HOW TO: charged particle EDM

DEUTERON CASE



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HOW TO: charged particle EDM

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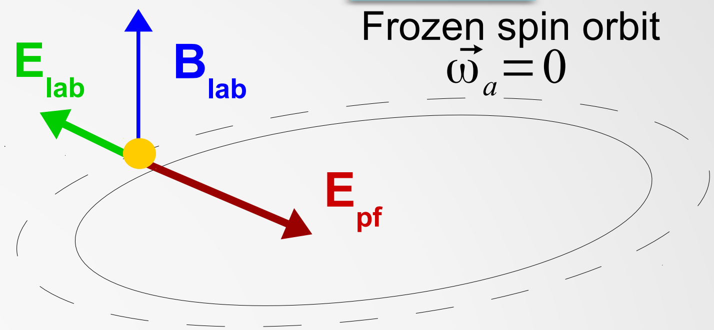

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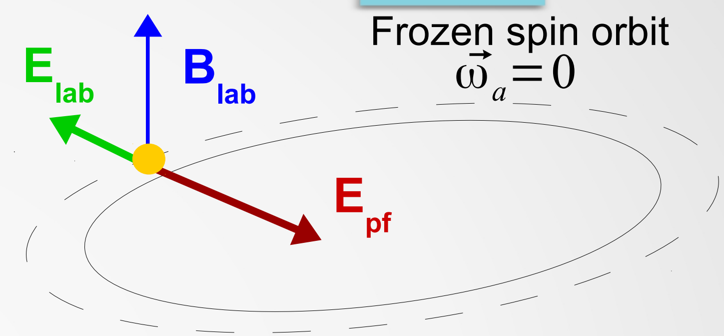

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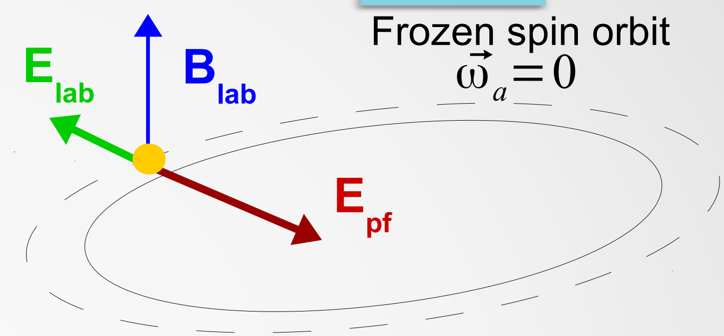

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- 10^9 turns needed to detect EDM signal
- **Spin aligned with velocity for t>1000 s** → **Is this an issue? YES!**

  (see spin coherence time later)

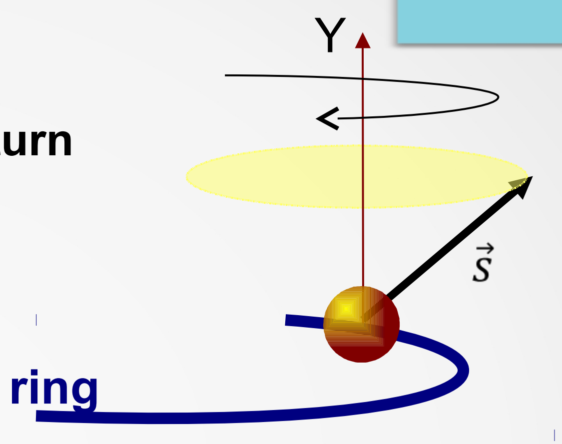
SPIN COHERENCE TIME (SCT)

Vertical direction (Y axis) $\longrightarrow$ stable spin direction

Spin tune $\nu_S = G\gamma$ **number of spin precession per turn**

Anomalous magnetic moment

Relativistic gamma



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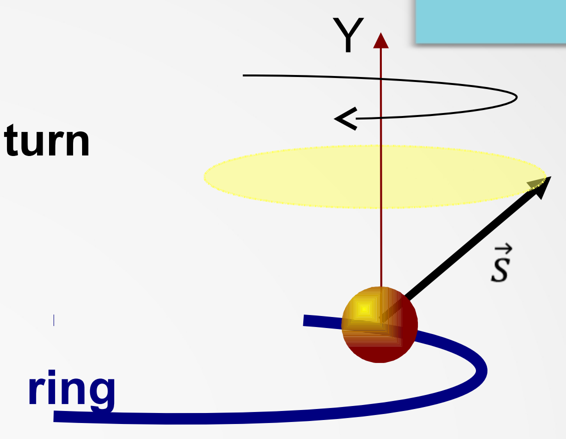

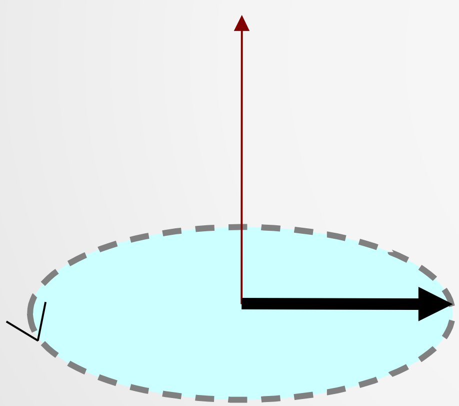

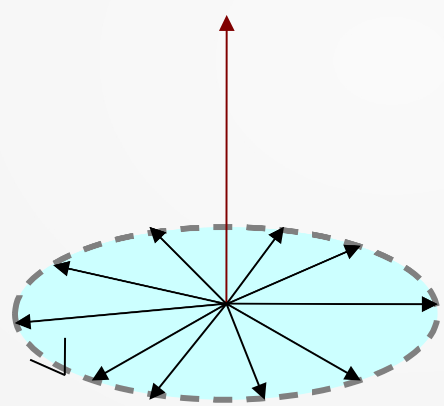

At injection:

all the spins are aligned

After some time:

Particles have different velocities and trajectories
Spins out of phase in the horizontal plane → Horizontal polarization vanishes!

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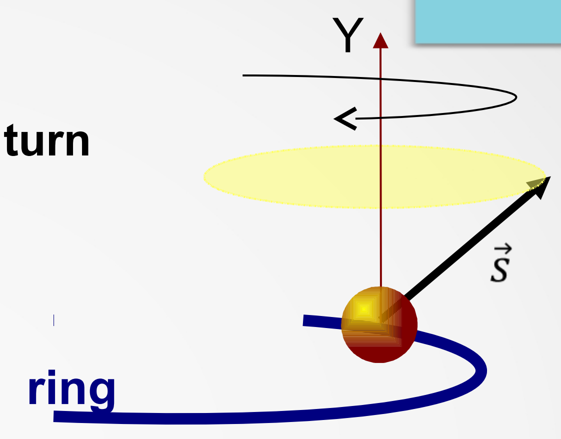

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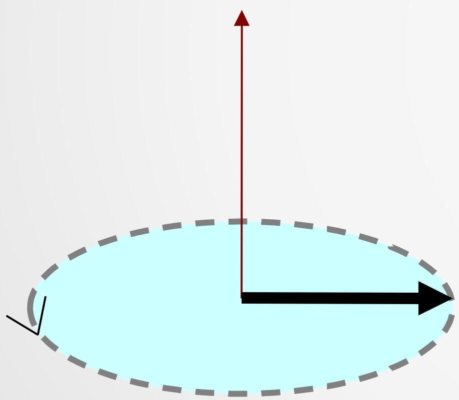

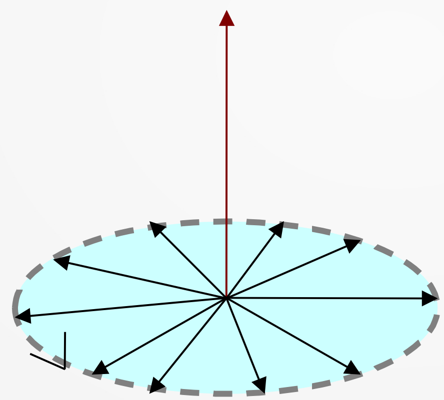

SCT
Horizontal pol. Lifetime
=
Observation time

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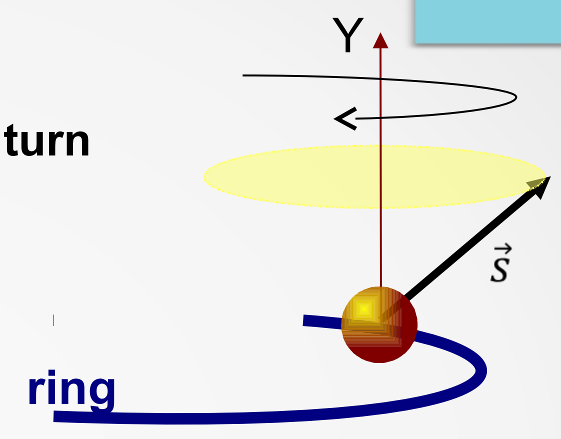

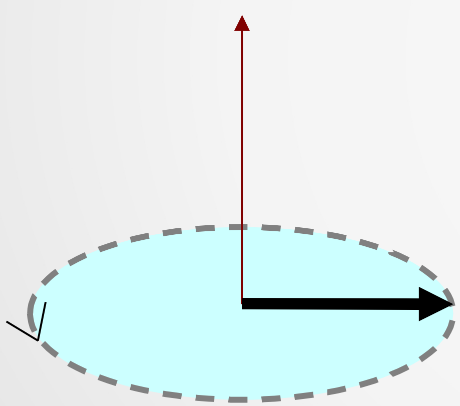

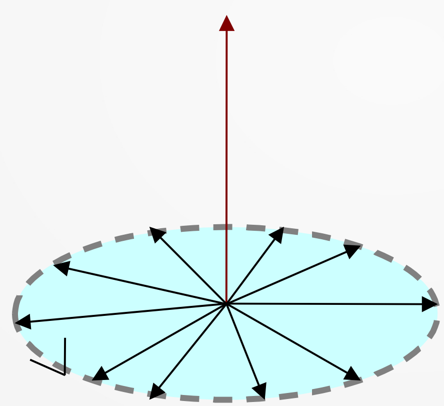

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SCT
Horizontal pol.
Lifetime

Feasibility studies @ COSY!!

SCT STUDIES @ COSY

AIM

Demonstrate **sextupole fields** can counteract the spread of spin tunes associated with **emittance** and **$(\Delta p/p)^2$** of a **deuteron** beam.

Second order effects!

In combination with beam preparation based on

- **eCooling** to shrink transverse and longitudinal beam size
- **Bunching** to <u>remove first order Δp/p contribution</u>

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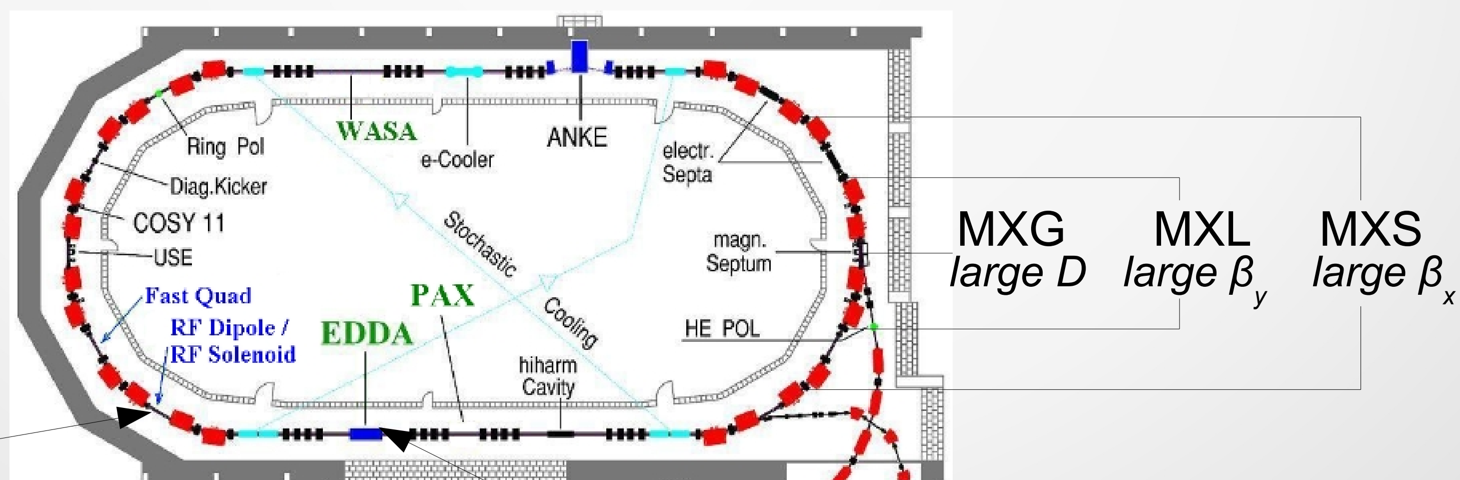


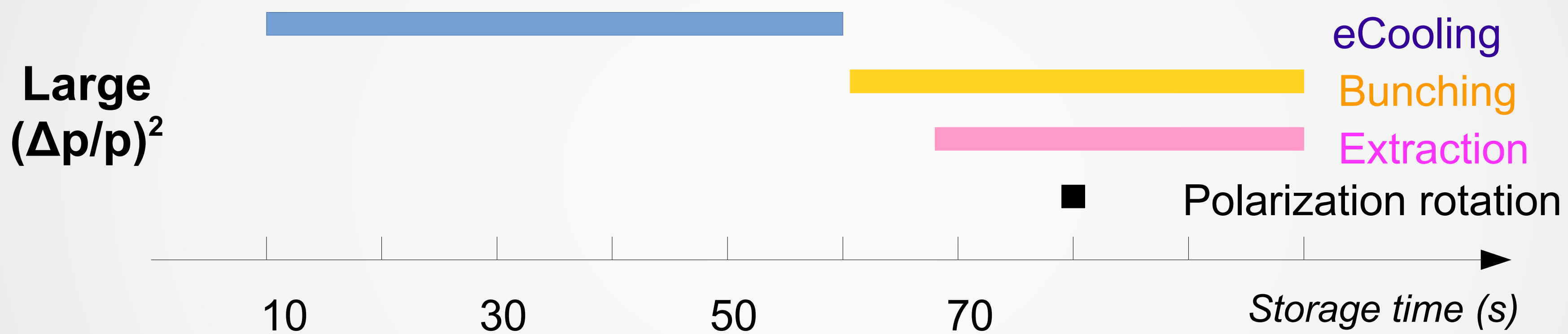
RF Solenoid
to move the polarization into the horizontal plane

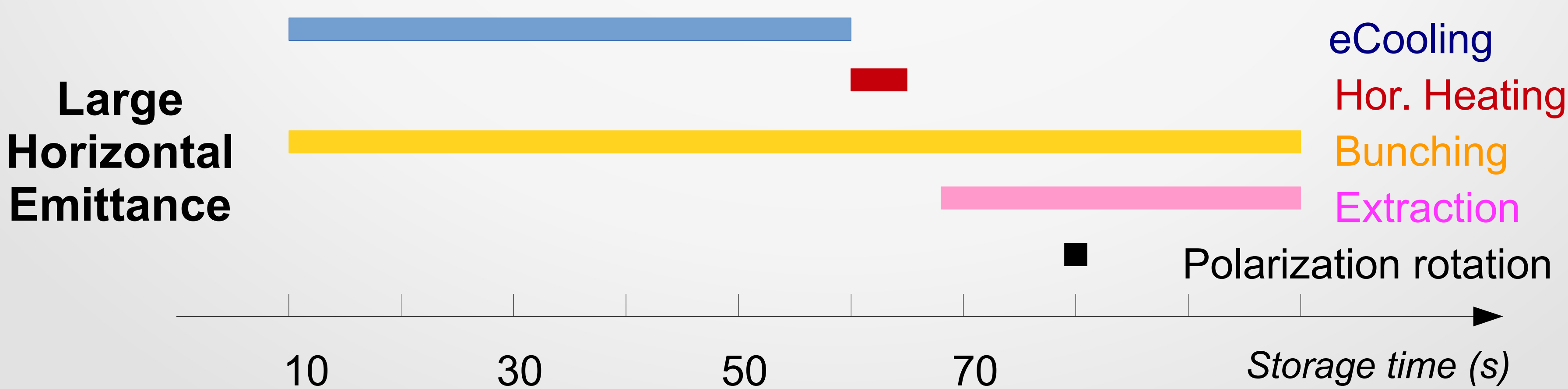
EDDA is the **polarimeter**

Sextupole families
located in the arcs

Beam preparation

Polarized deuterons at p=0,97 GeV/c
Bunched beam
Horizontal polarization with RF solenoid

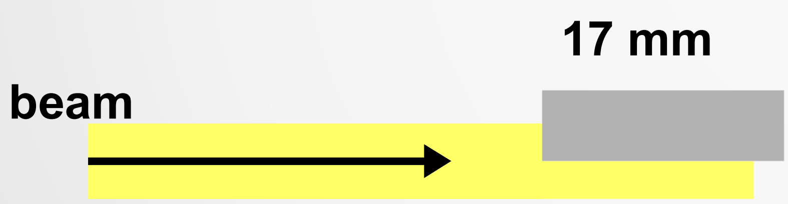




Experimental setup

Beam extraction

continuous extraction with **white noise** applied to electric field plates (vertical direction, y axis)

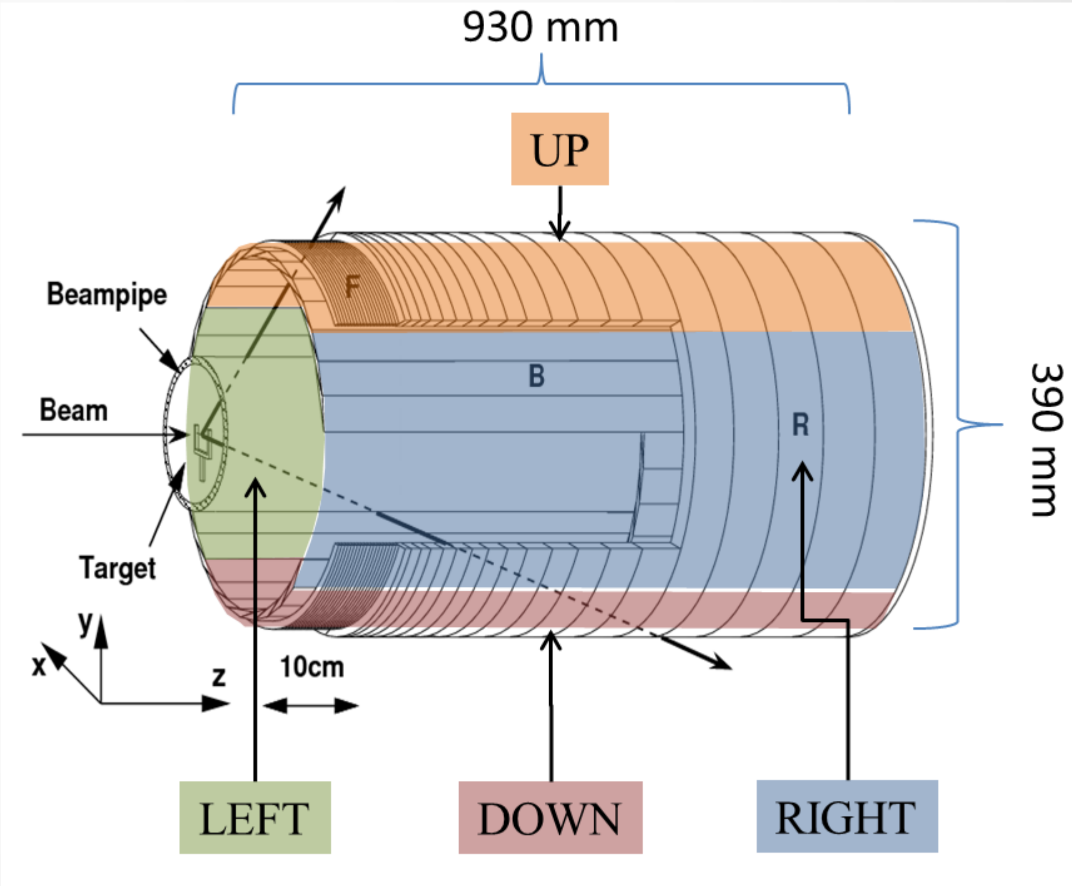


Carbon target

Elastic scattering events (high spin sensitivity)

Polarimeter: EDDA

Asymmetries L/R -->$\mathbf{p}_v$ and U/D -->$\mathbf{p}_h$



Data Acquisition (DAQ)

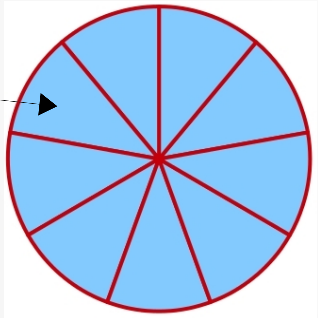
*Z. Bagdasarian et al., Phys. Rev. ST Accel. Beams 17, 052803 (2014)

- Timing → Count turn number **n** (bunched beam)
- Compute total spin precession angle

$$\theta_s = 2\pi G \gamma n$$

- Bin by phase φ the spin precession angle circle
- Compute asymmetry in each bin

$$\boxed{\epsilon_h = \frac{U - D}{U + D}}$$



As the polarization rotates
The ε_h reflects the sideways projection of the polarization.

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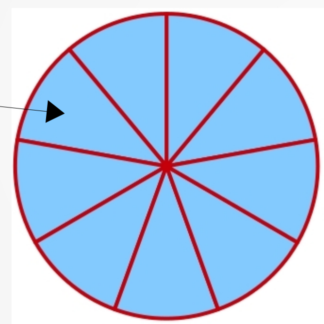

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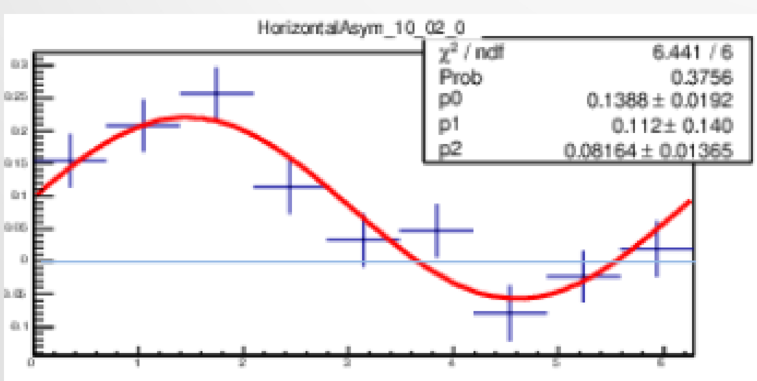

φ

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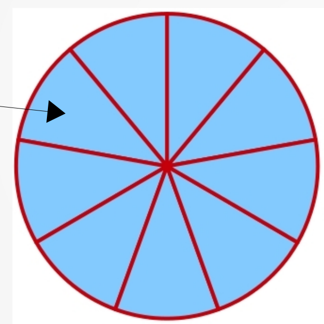

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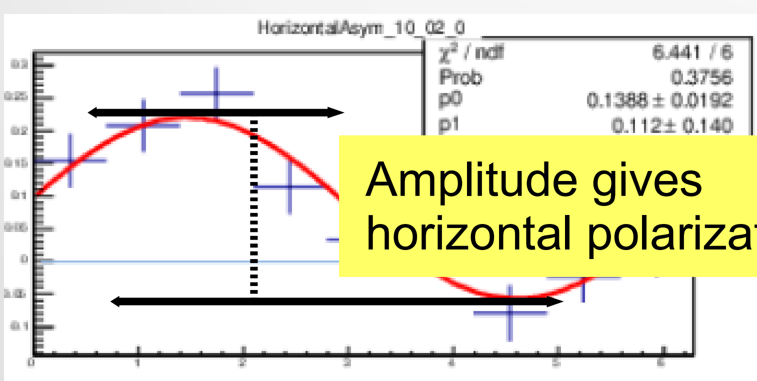

Amplitude gives horizontal polarization

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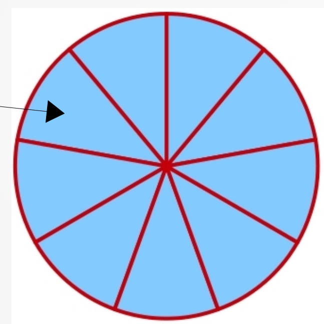

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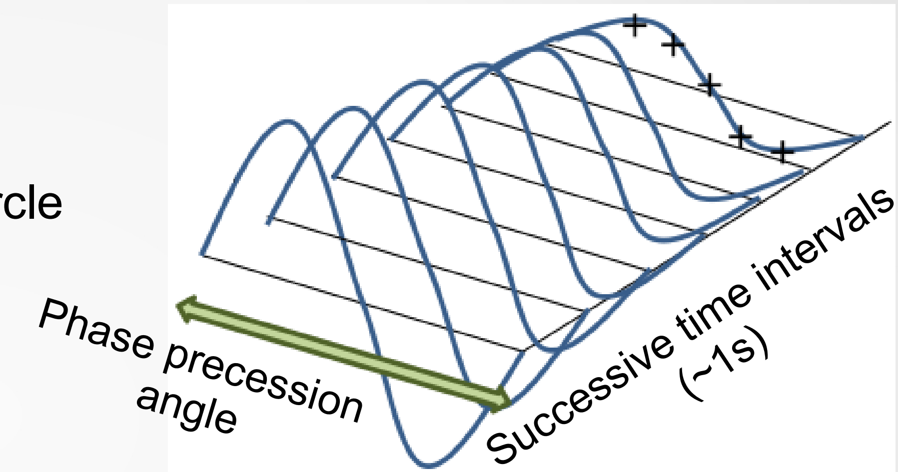

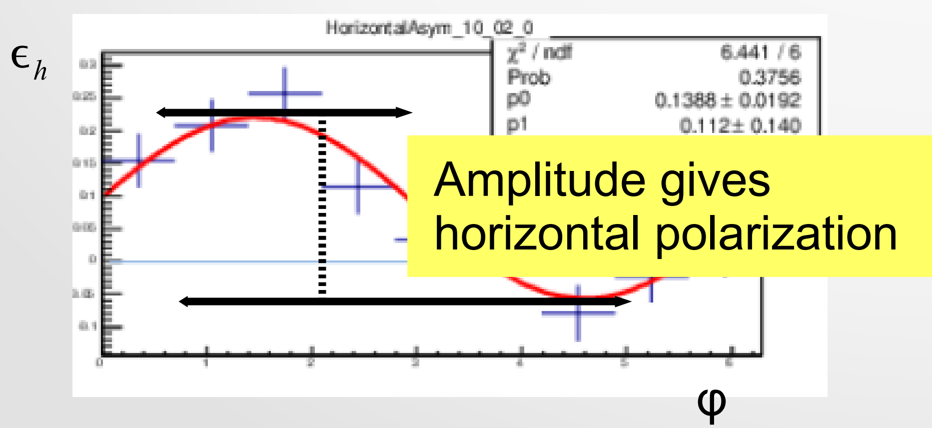

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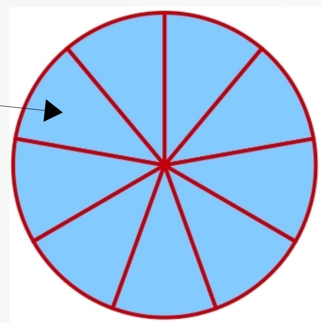
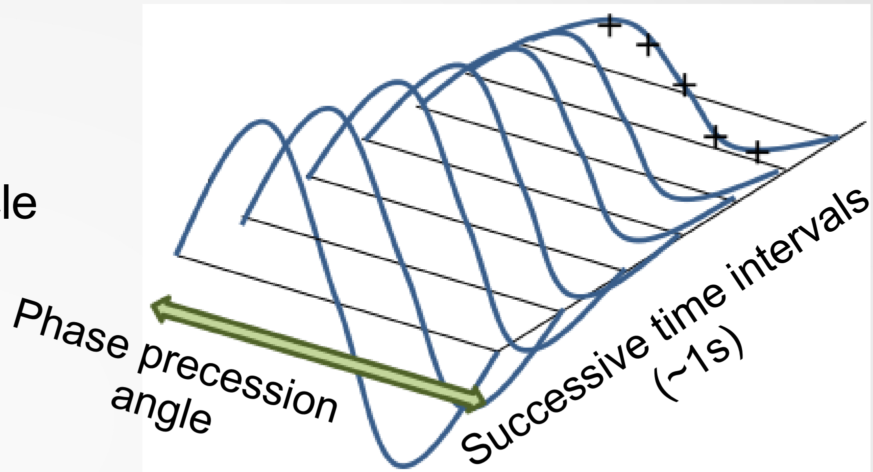
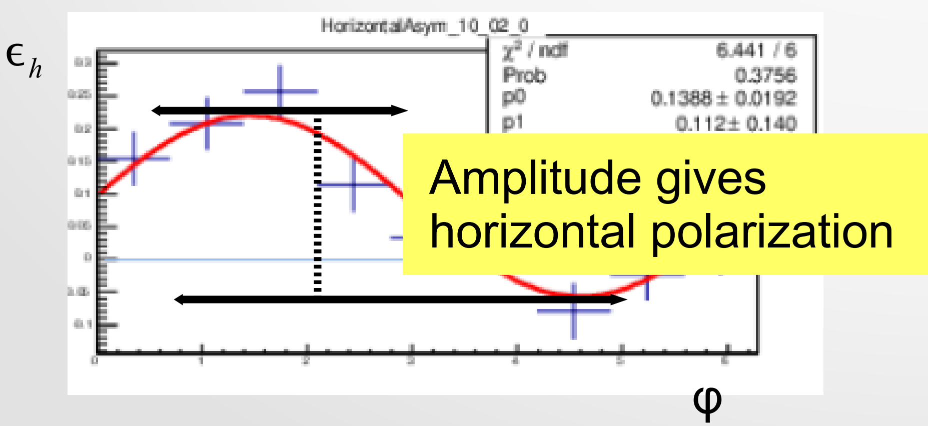
$$\boxed{\epsilon_h = \frac{U-D}{U+D}}$$

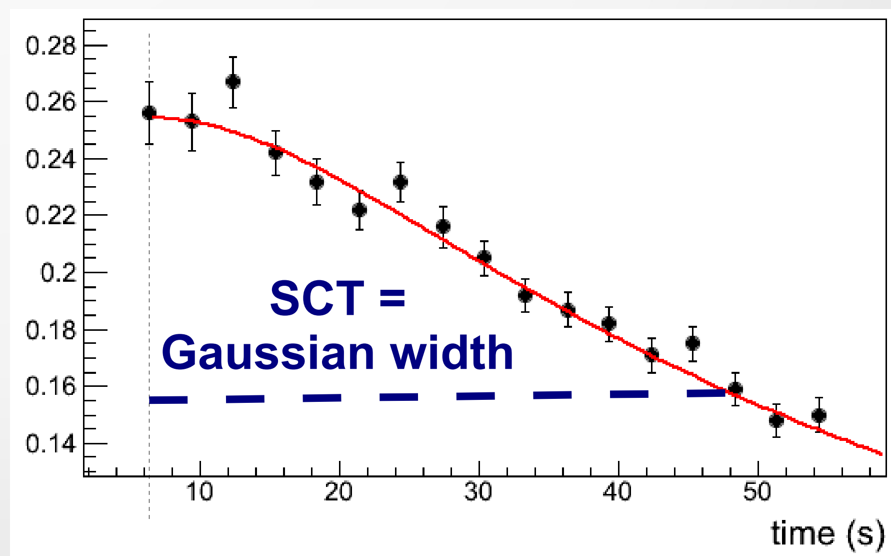




As the polarization rotates
The ε_h reflects the sideways projection of the polarization.



Amplitude vs time



Sextupole effect

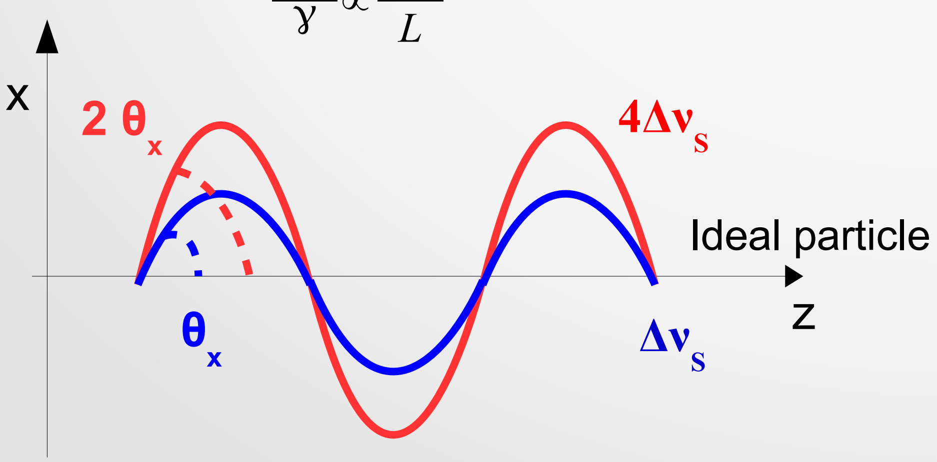
Decoherence sources

Spin Tune spread: $\Delta\nu_s = G\,\Delta\gamma$

Betatron oscillations increase particle **path length**

$$\frac{\Delta L}{L} \propto \frac{\theta_x^2 + \theta_y^2}{4}$$

Bunching freezes the revolution frequency $\frac{\Delta\gamma}{\gamma} \propto \frac{\Delta L}{L}$

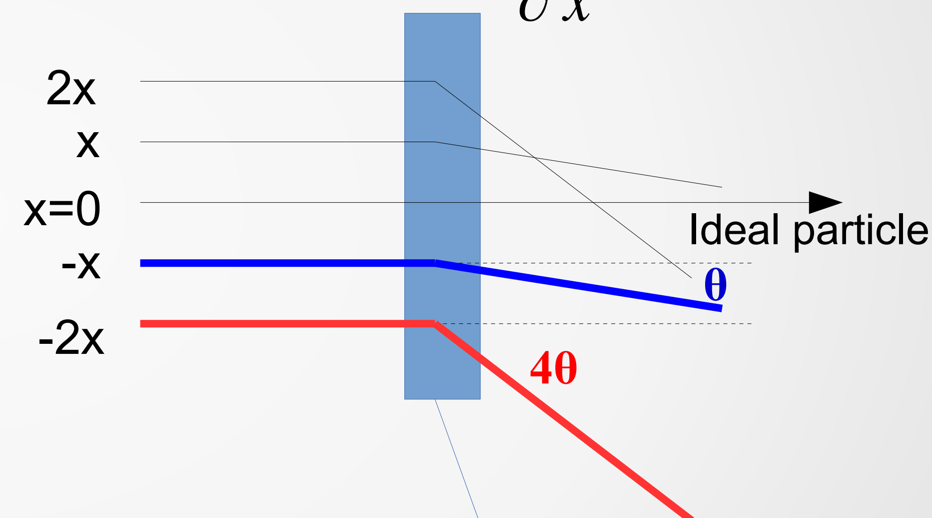


Sextupole effect

Decoherence sources —— to be corrected with ——► **Sextupole magnets**

Spin Tune spread: $\Delta \nu_s = G \Delta \gamma$

$$B \propto x^2 \qquad \frac{\partial B}{\partial x} \propto x$$



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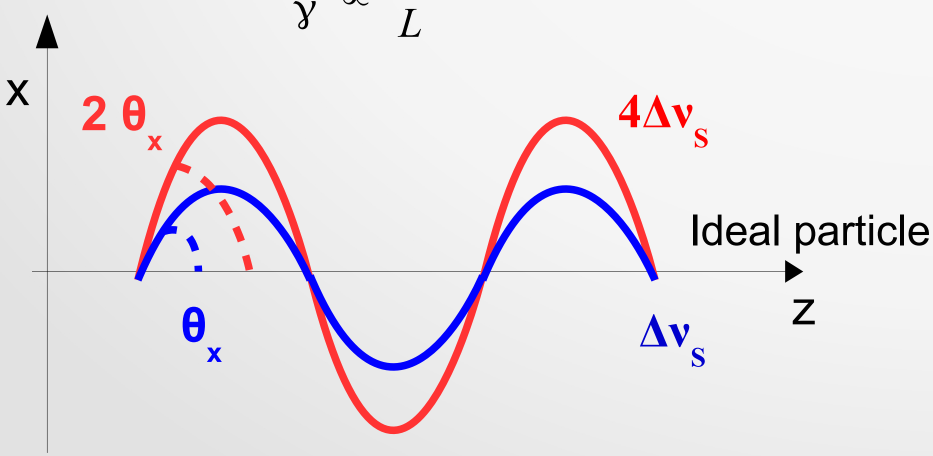
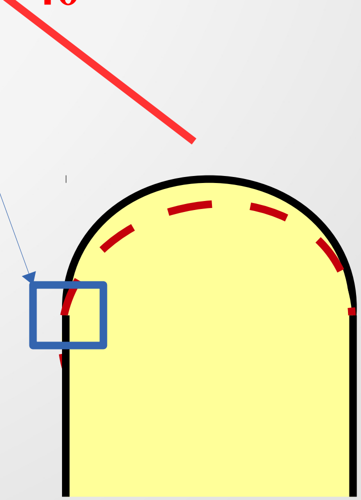


Compensation of path lengthening



Sextupole effects

SCT dependence on sextupoles

$$\frac{1}{SCT} = |A + a_1 S + a_2 L + a_3 G| \; \theta_x^2$$
$$+ |B + b_1 S + b_2 L + b_3 G| \; \theta_y^2$$
$$+ |C + c_1 S + c_2 L + c_3 G| \left(\frac{\Delta p}{p} \right)^2$$

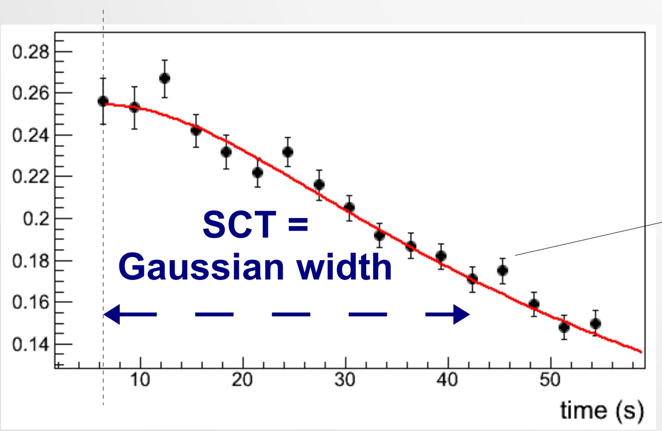
Drivers:
- beam widths
- 2nd order mom. spread

Sextupole fields
MXS, MXL, MXG

Sextupole effects

SCT dependence on sextupoles

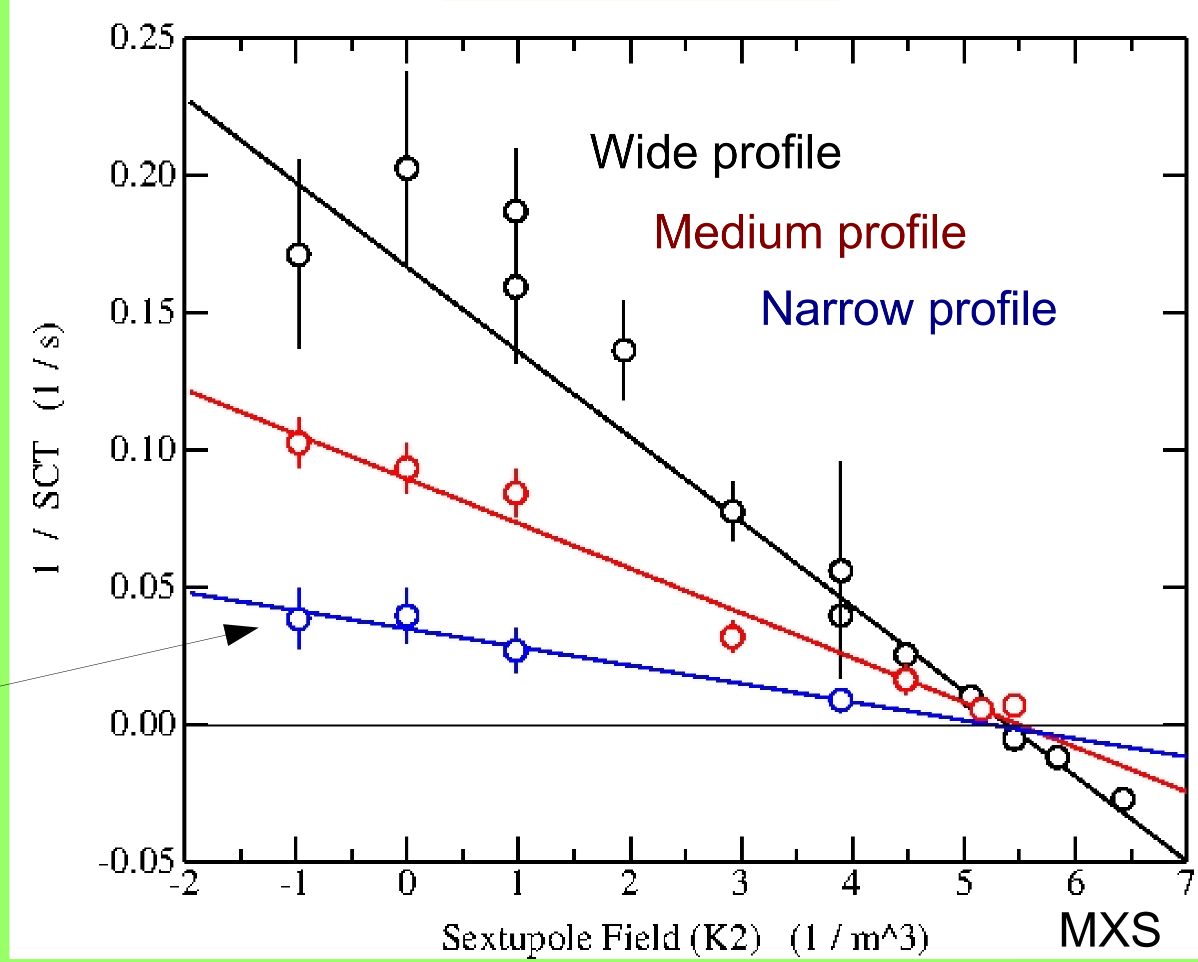
$$\frac{1}{SCT} = |A + a_1 S + a_2 \cancel{L} + a_3 \cancel{G}| \; \theta_x^2 + |B + b_1 S + b_2 L + b_3 G| \; \theta_y^2 + |C + c_1 S + c_2 L + c_3 G| \left(\frac{\Delta p}{p}\right)^2$$



2012 DATA

HORIZONTALLY (x) wide beam

$MXL = MXG = 0$



Sextupole effect

SCT dependence on sextupoles

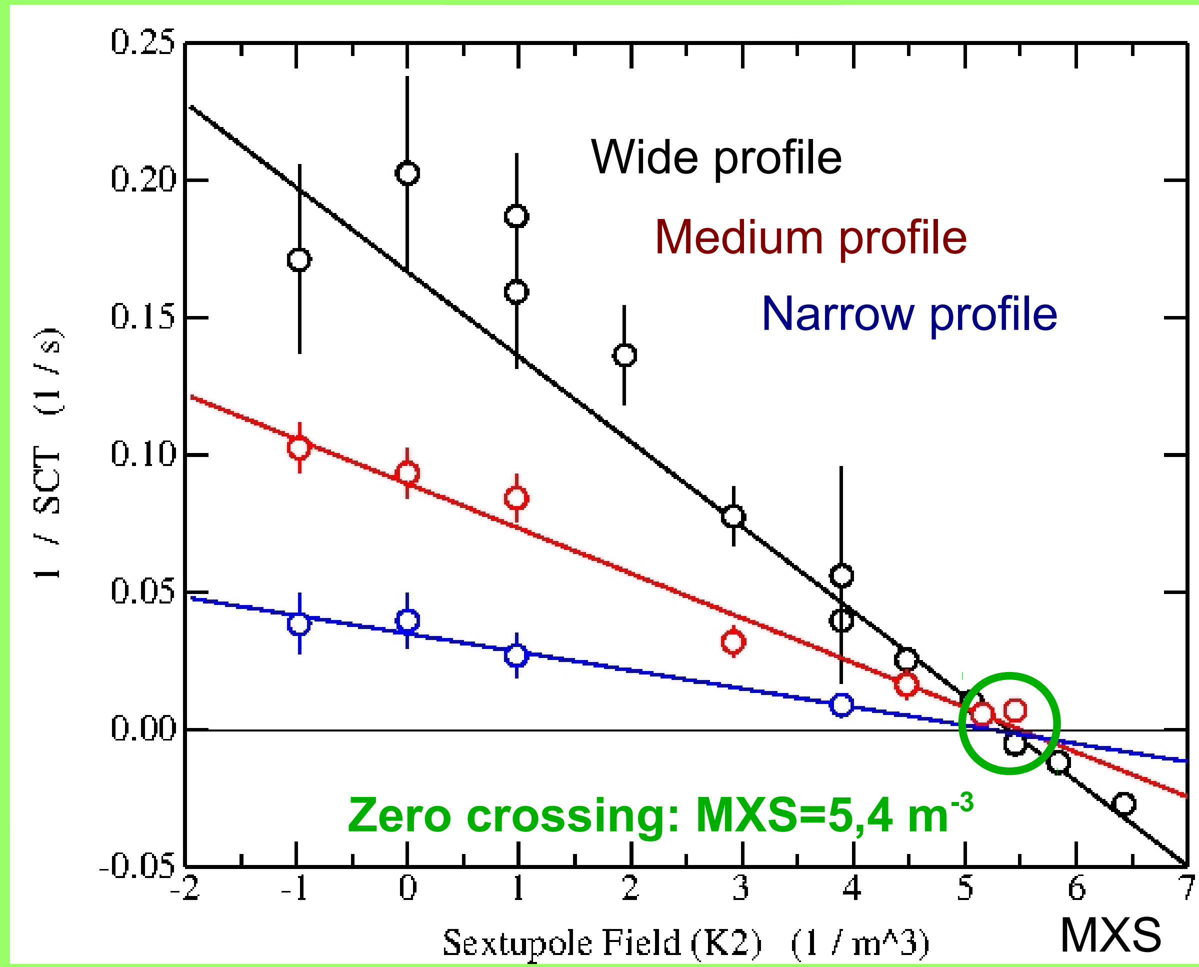
$$\frac{1}{SCT} = |A + a_1 S| \theta_x^2$$

- Flip **1/SCT** sign above zero crossing
- Different slopes
- **SCT** does not go to infinity.
  Point near zero may be above or below the line due to other contributions.
- The **same zero crossing**, independent of horizontal width

2012 DATA

HORIZONTALLY (x) wide beam

$$MXL = MXG = 0$$



Chromaticity = ZERO

Cromaticity ξ

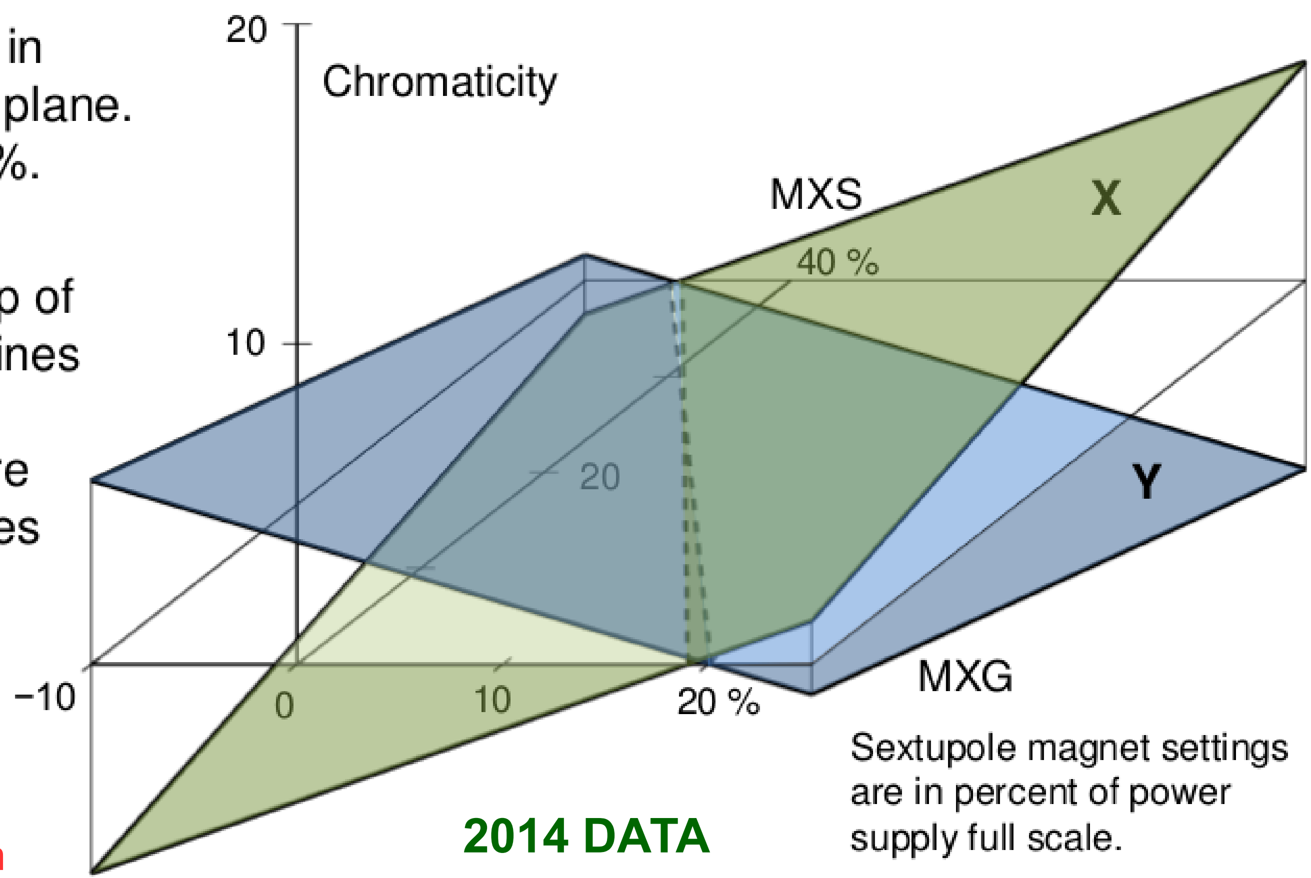
$$\frac{\Delta Q_{x,y}}{Q_{x,y}} = \xi_{x,y} \frac{\Delta p}{p}$$

Q = tune, number of betatron socillation per turn

A unique combination of MXG, MXS and MXL $\xi = 0$ $\Rightarrow \frac{\Delta L}{L} = 0 \Rightarrow \frac{\Delta \gamma}{\gamma} = 0$ $\Rightarrow \frac{\Delta \nu_s}{\nu_s} = 0$

Chromaticity in MXG x MXS plane. MXL = −2.0 %.

Note the overlap of the two dotted lines that represent the places where the chromaticities vanish.



Picture from Ed. J. Stephenson

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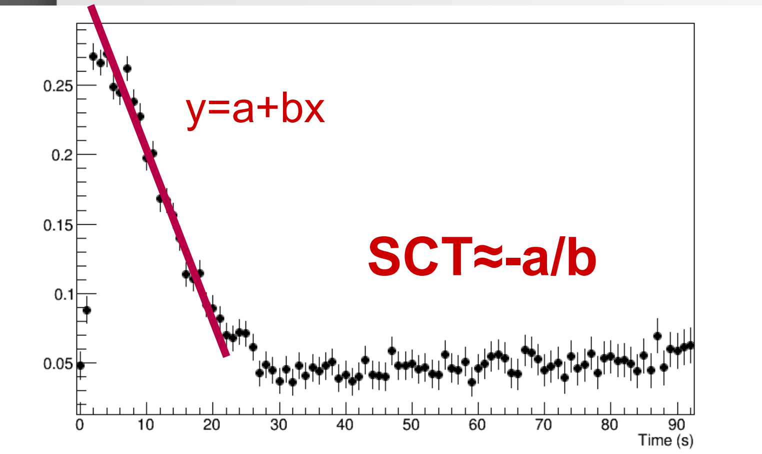
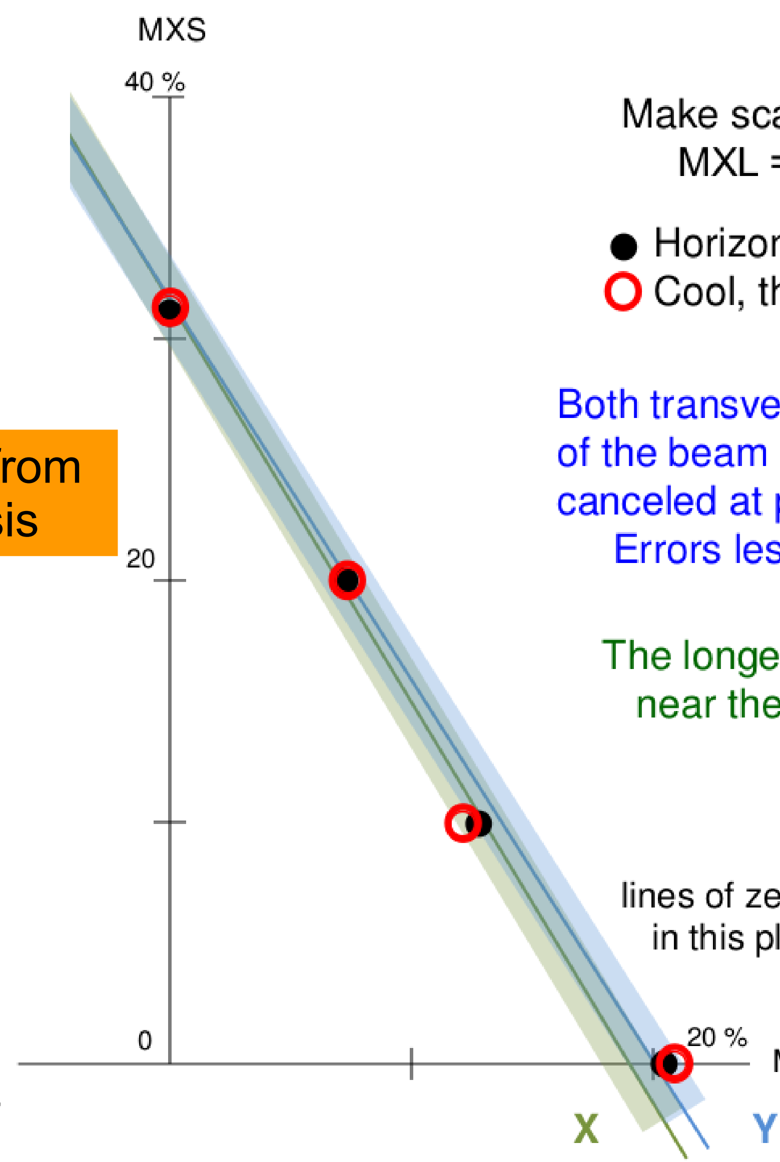


2014 DATA

PRELIMINARY from the online analysis



Make scans in 2D MXS x MXG space with MXL = −1.45%

● Horizontal heating (large X emittance)

○ Cool, then bunch (large synchrotron orbits)

Both transverse (X) and longitudinal spreads of the beam produce decoherence; both are canceled at places of zero chromaticity.
Errors less than the size of the symbols.

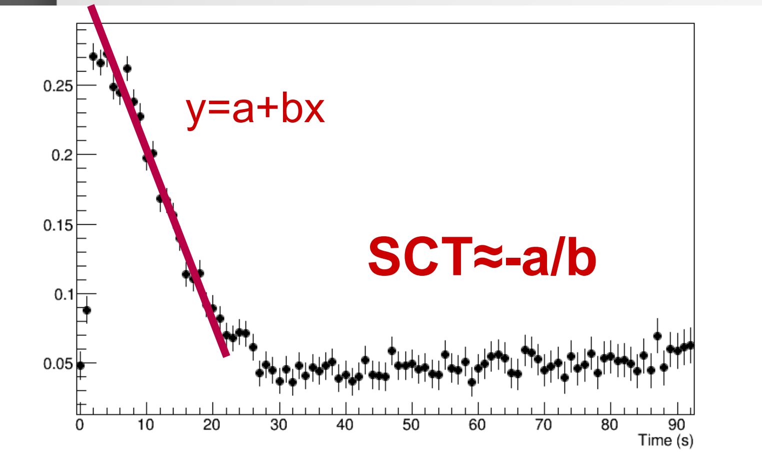
The longest polarization lifetimes are found near the middle of this range.

lines of zero chromaticity (X or Y) in this plane – errors ~ 1 %

Scales are in percent of power supply full range.

Picture from Ed. J. Stephenson

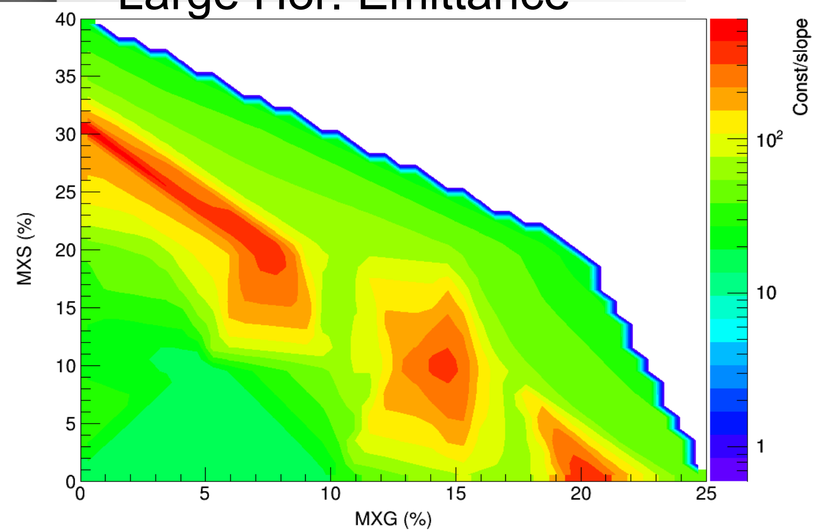
Chromaticity = ZERO

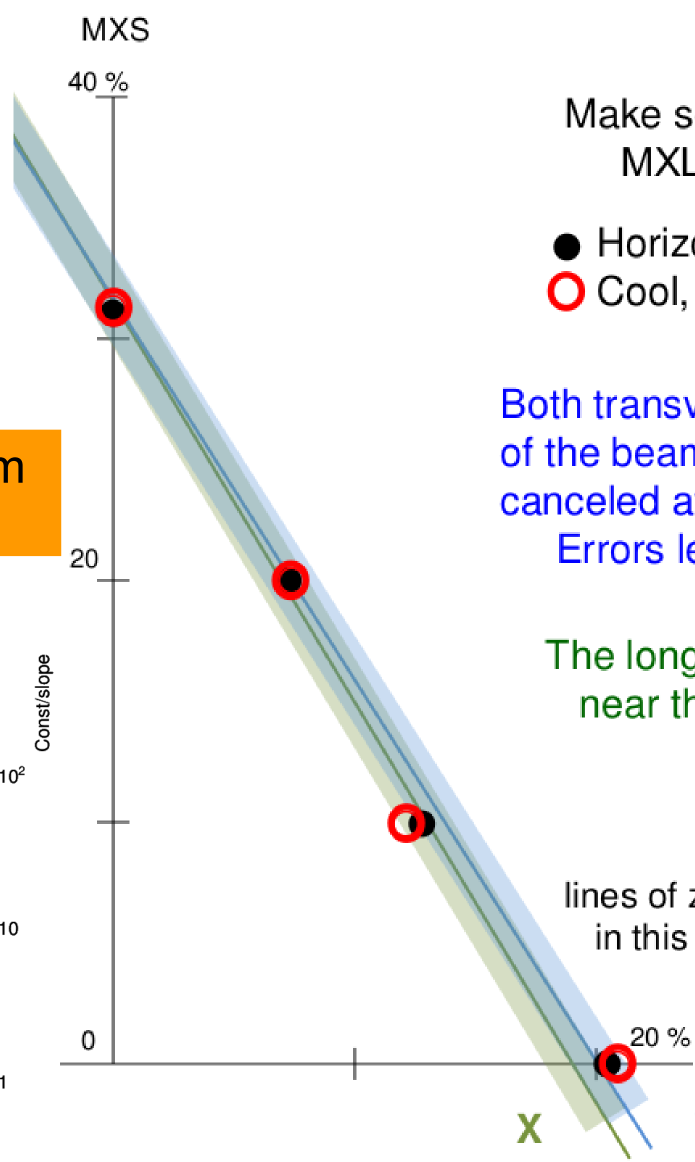


2014 DATA

PRELIMINARY from the online analysis

Large Hor. Emittance





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Conclusions

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Fundamental requirement for the EDM experiment on charged particles is 1000 s SCT

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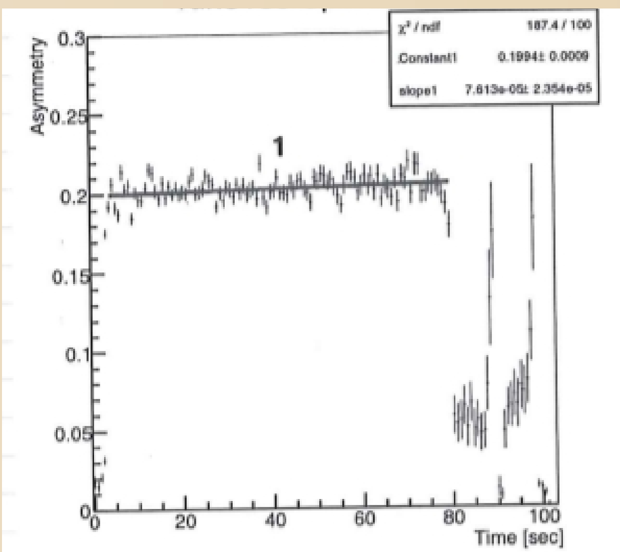
It has been demonstrated that the **lifetime of a horizontally polarized deuteron beam** may be substantially extended (**up to ~ 1000 s**) through a combination of:



- beam bunching on the first harmonic,
- electron cooling
- combination of SEXTUPOLE families
- both X and Y chromaticities are zero.

This meets the requirement for a storage ring to search for an EDM.

Conclusions

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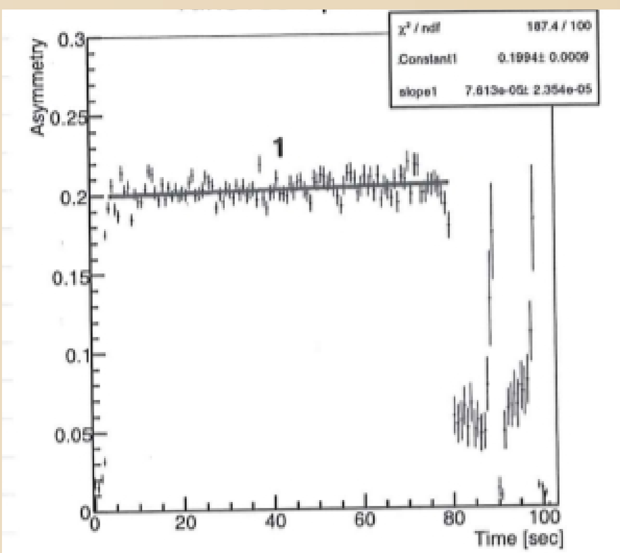

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FUTURE

- systematic error studies
- spin tracking simulations
- polarimeter
- development of a new ring

THANKS FOR YOUR ATTENTION

JEDI collaboration @ Juelich

PHYSICAL MOTIVATIONS

CP violating sources

STANDARD MODEL

- *Weak interaction:* complex phase **δ** in CKM quark mixing matrix
- *Strong interaction:* $\boldsymbol{\theta}_{QCD}$

$$|d_n| = |d_p| \simeq 4{,}5 \cdot 10^{-15}\,\theta_{QCD} \longrightarrow |d_n^{\exp}| \leqslant 10^{-26}\, e \cdot cm \quad \Rightarrow \quad \theta_{QCD} \leqslant 10^{-11}$$

Axion search

$$d_d = 0$$

SUSY

- quark-EDM $\quad \Delta = d_{down} - d_{up}/4$
- Chromo-EDM: EDM generated by a loop with SS-particle

$$\Delta^+ = d_{up}^c + d_{down}^c \qquad \Delta^- = d_{up}^c - d_{down}^c$$

If a **non-zero deuteron EDM** is measured, it would have a special sensitivity to the chromo-EDM due to the large coefficient of Δ^- .

$$d_n = 1{,}4\,\Delta + 0{,}83\,\Delta^+ - 0{,}27\,\Delta^-$$

$$d_p = 1{,}4\,\Delta + 0{,}83\,\Delta^+ + 0{,}27\,\Delta^-$$

$$d_d = d_{up} + d_{down} - 0{,}2\,\Delta^+ - 6\,\Delta^-$$

The EDM measurement of **several particles** is needed to determine the CP violating sources scenario.