May 3-8, 2015 Richmond, VA, USA

Topical meeting of Spin Tracking for Precision Measurements

Overview of Spin Coherence Time study results at COSY

Greta Guidoboni

University of Ferrara and INFN

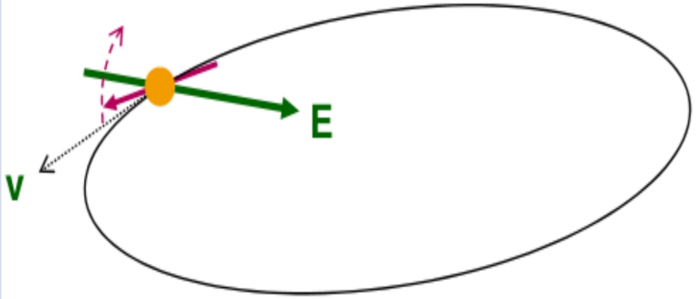
On behalf of the JEDI Collaboration

How to measure the EDM of a charged particle

Electric Dipole Moment (EDM)

- charge displacement within the particle volume
- Lies along the spin axis

Proposed solution: **- Storage ring**
- Keep spin aligned with velocity



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

EDM signal = spin precession in the vertical plane

Magnetic ring has <u>inward</u> electric field in particle frame

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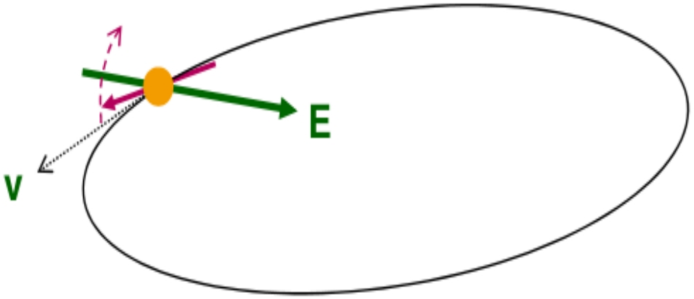

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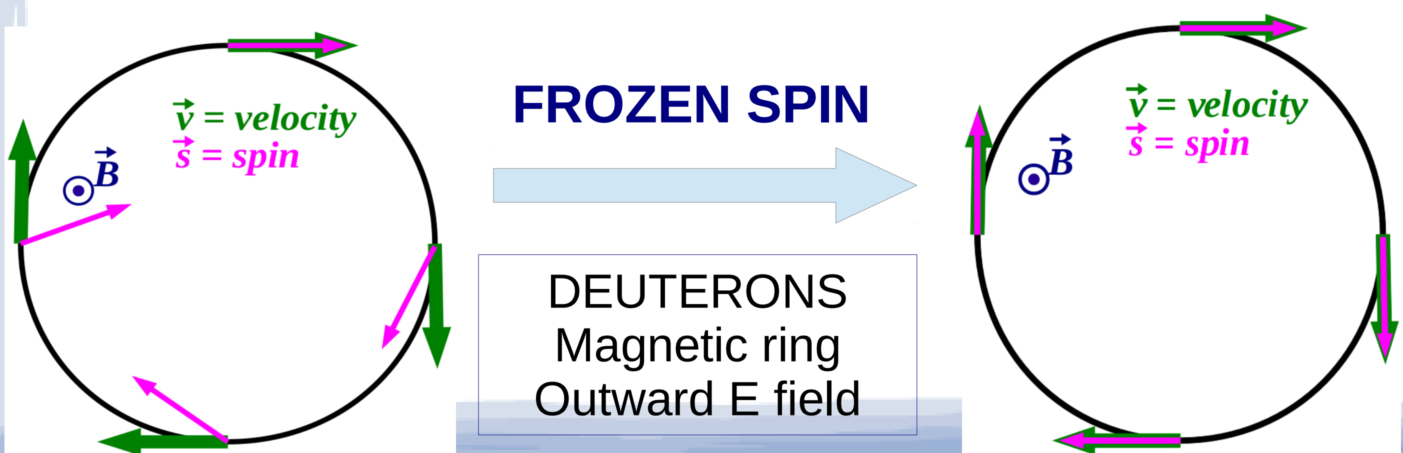
Magnetic ring has inward electric field in particle frame

Anomalous magnetic moment causes spin to precess different than velocity



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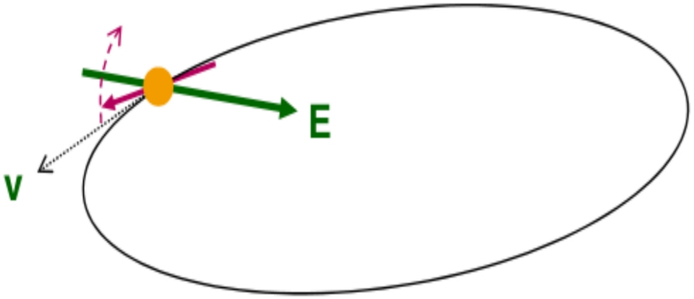

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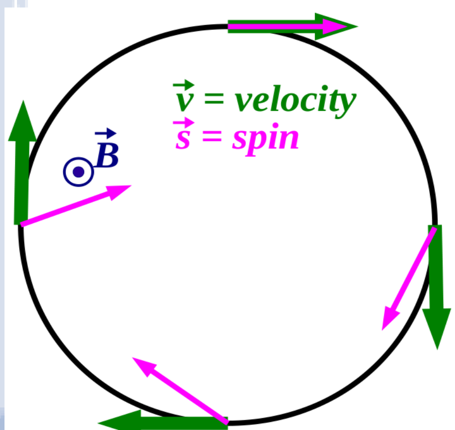
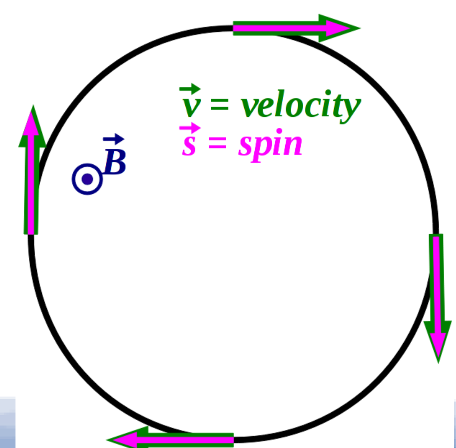


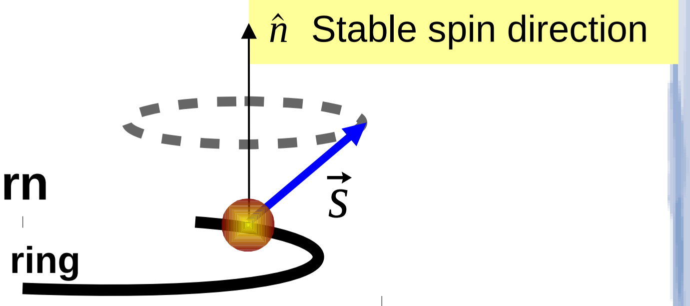
FROZEN SPIN

DEUTERONS
Magnetic ring
Outward E field



Horizontal pol. Lifetime
<u>Spin Coherence Time</u>
=
EDM observation time

Spin Coherence Time: DEFINITION

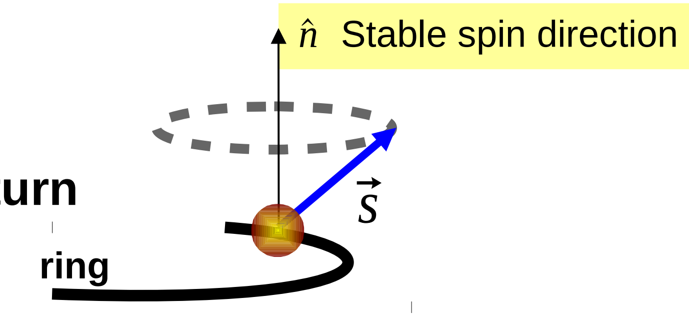


Spin tune $\nu_s = G\gamma$ **number of spin precessions per turn**

Anomalous magnetic moment (G)

Relativistic gamma (γ)

Spin Coherence Time: DEFINITION



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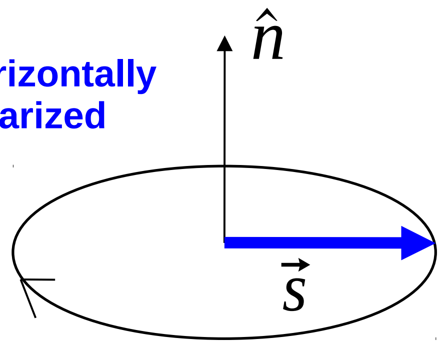
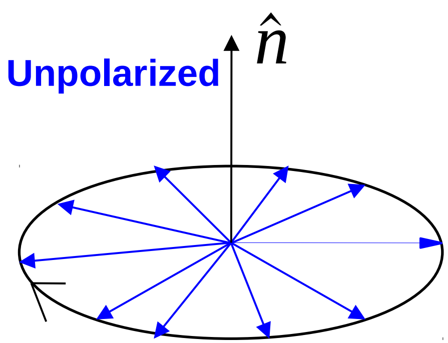
Horizontally polarized



At injection:
Spins aligned

Unpolarized



After some time:
Particles have different velocities
→ Spins out of phase in the horizontal plane

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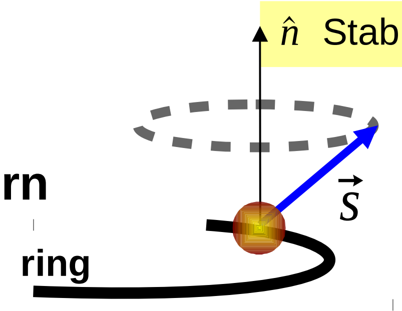

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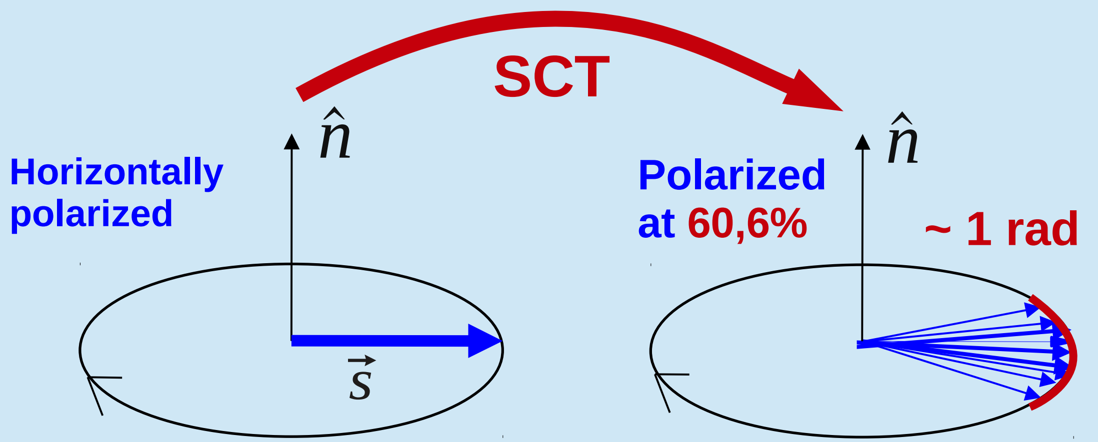

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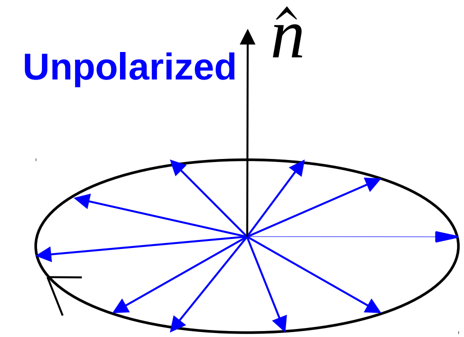
Gaussian width criterion



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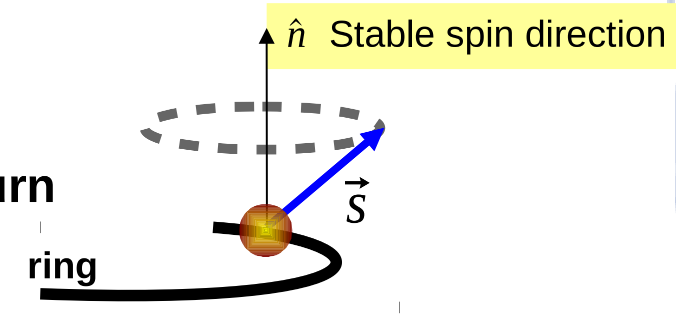

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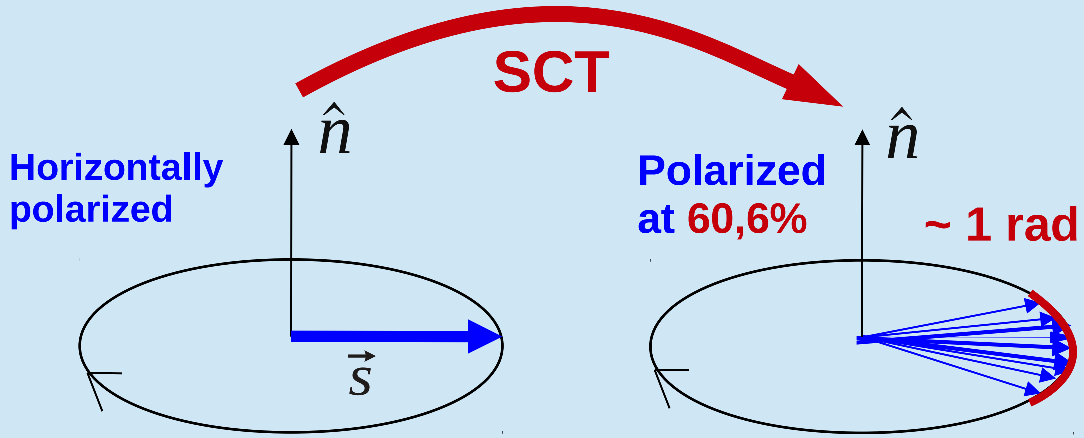

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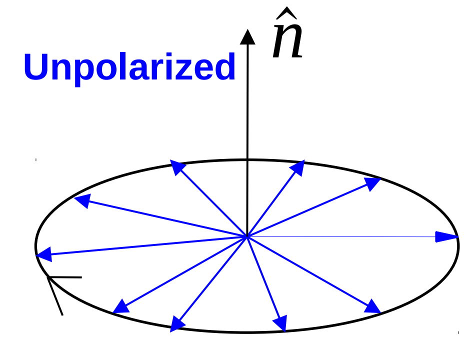

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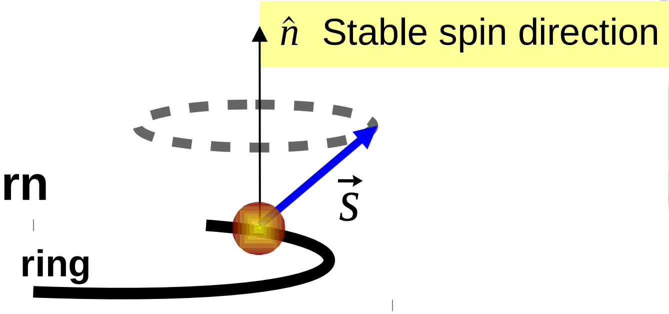
Minimum SCT?

Deuterons, assuming an EDM **d≈10^{-29} e·cm**

Possible ring: B_{lab}=0,42T E_{lab}=17MV/m p=1,5 GeV/c

Minimum detectable angle **θ≈10^{-6} rad**

Spin Coherence Time: DEFINITION



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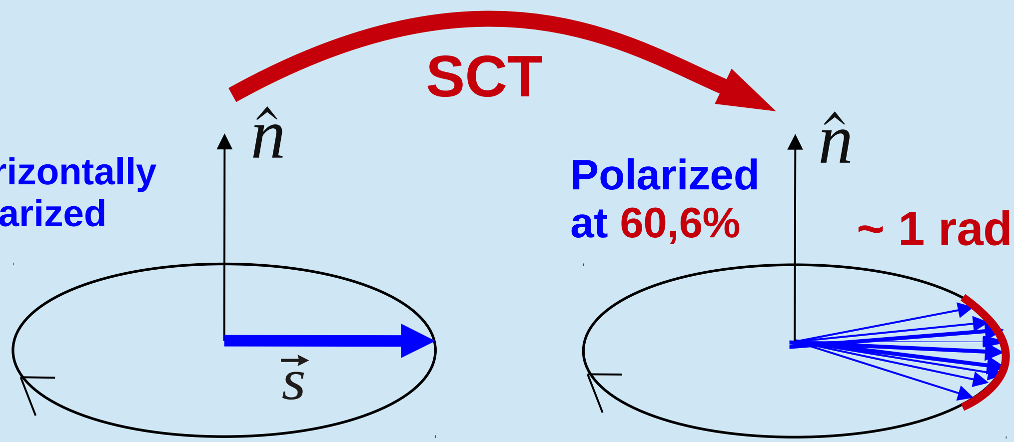

Horizontally polarized

Polarized at 60,6%

At injection:
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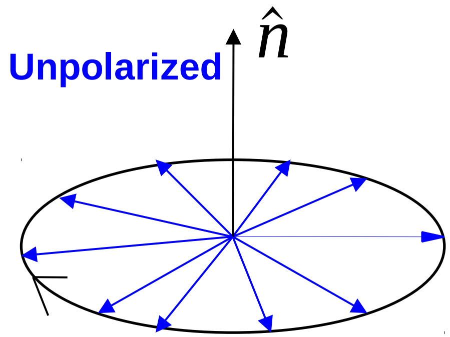
Gaussian width criterion



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1 year data taking for 10^{-29} e·cm precision

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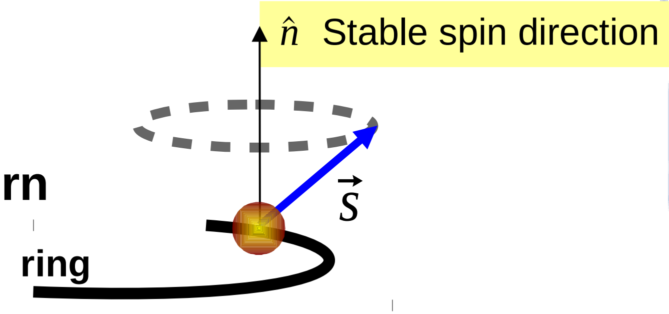

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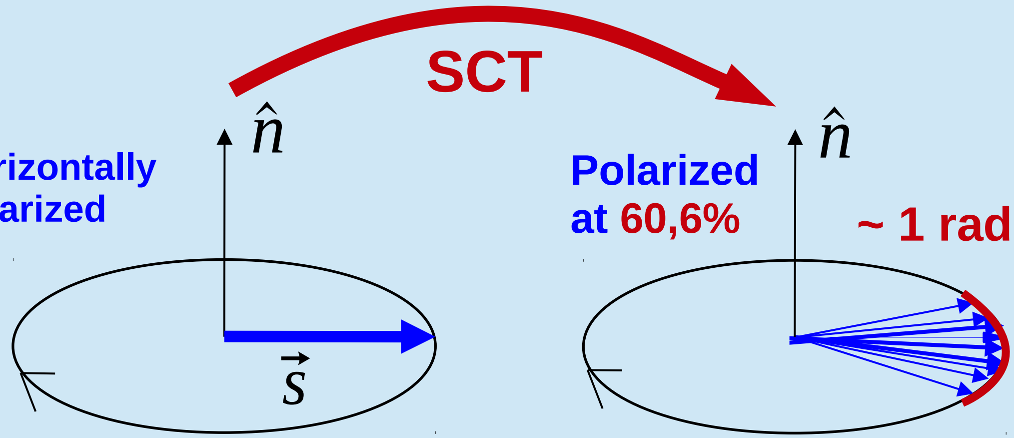

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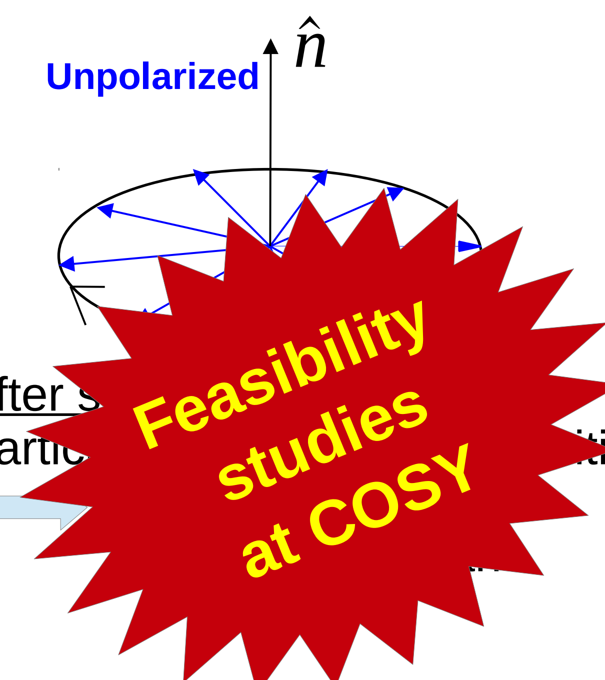

After s...
Partic... ...ities

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Spin Coherence Time: STUDIES

1) AIM

Demonstrate **sextupole fields** can counteract the spread of spin tunes associated with **emittance** and **(Δp/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 remove first order Δp/p contribution

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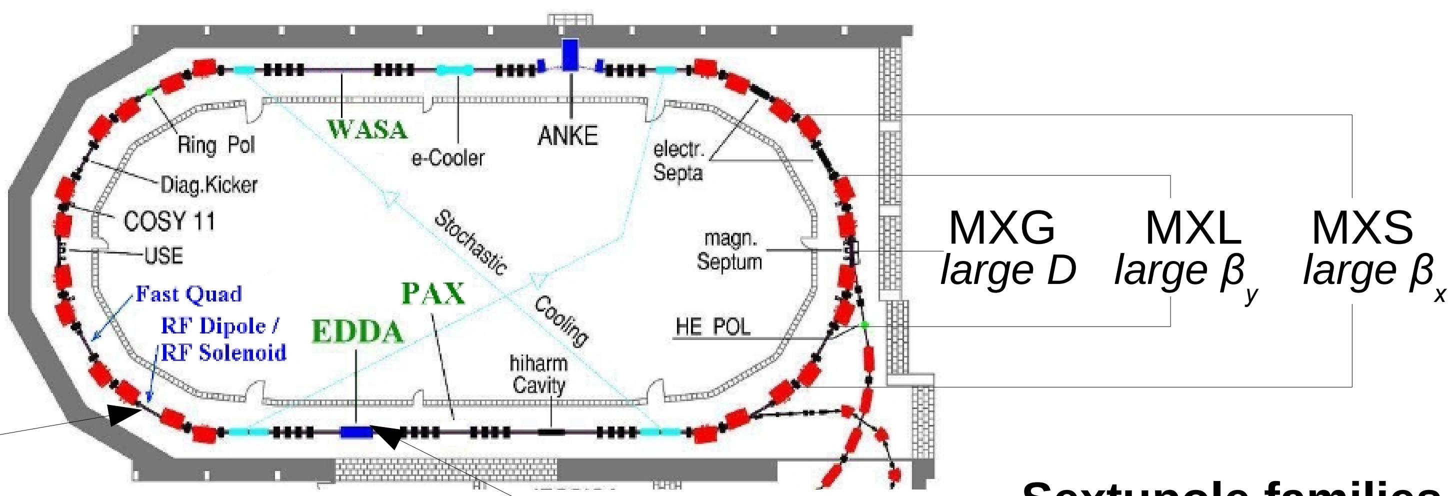
COoler SYnchrotron



RF Solenoid
to move the polarization into the horizontal plane

EDDA is the **polarimeter**

Sextupole families located in the arcs

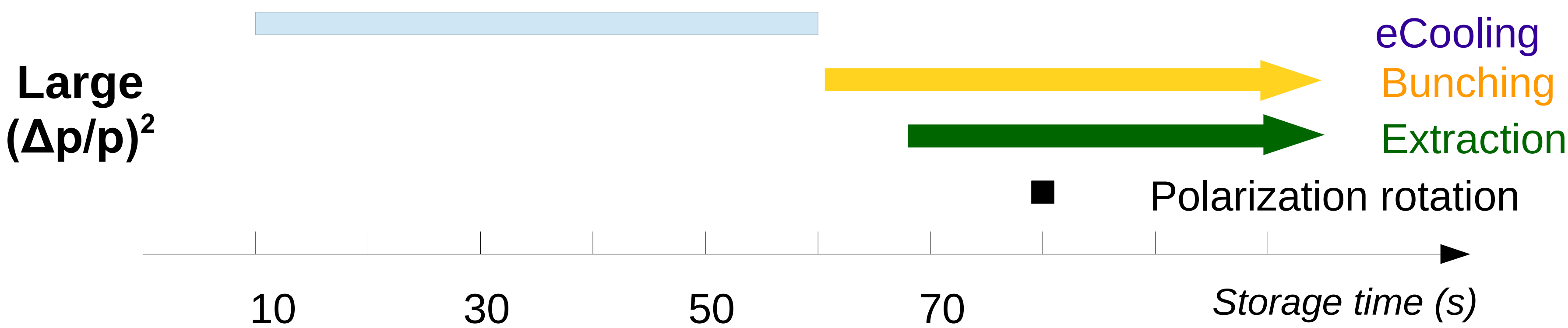
Spin Coherence Time: STUDIES

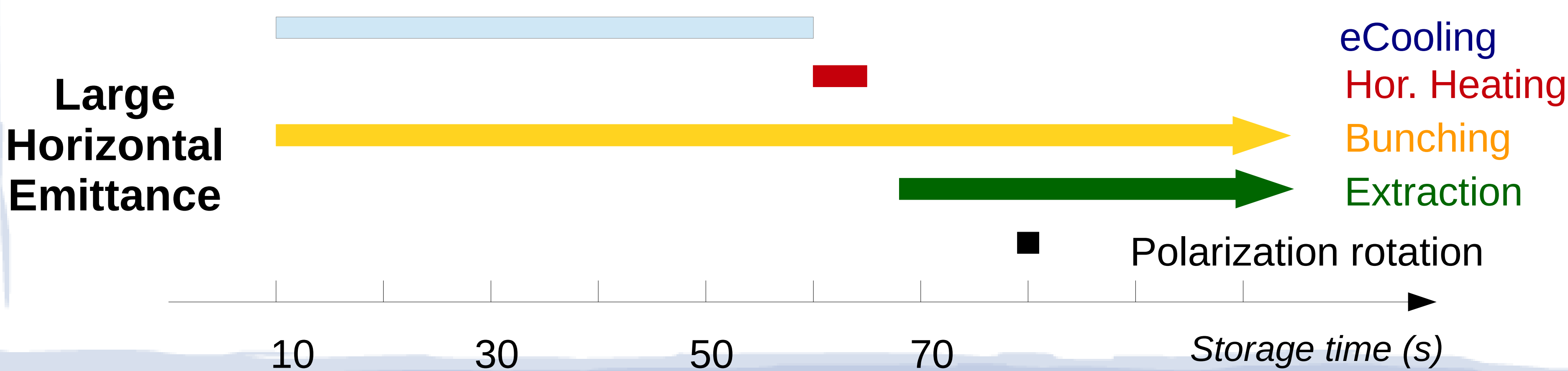
2) EXPERIMENTAL SETUP

Polarized DEUTERON beam with p=0.97 GeV/c
Bunched beam (h=1)
Beam extraction onto polarimeter target
Horizontal polarization with RF solenoid

<u>**Beam preparation**</u>

vertical emittance was not available for study due to limited acceptance





Spin Coherence Time: STUDIES

2) EXPERIMENTAL SETUP

Beam extractions

Continuous process during the storage

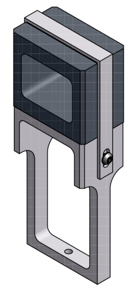
a) local bump (ramp)

b) white noise applied to electric field plates (vertical direction)

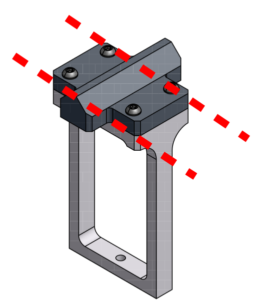
→ **beam**

Carbon targets

a) TUBE target



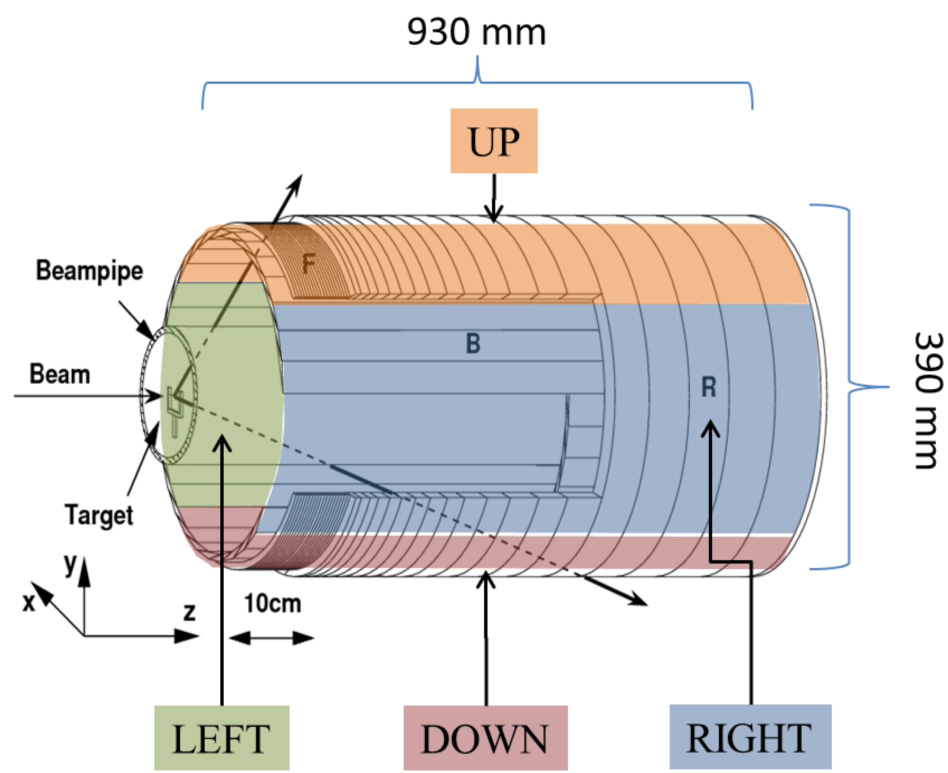
b) RIDGE target
Shaped to match tube target thickness



c) FLAT target

Polarimeter: EDDA

Elastic scattering events
(high spin sensitivity)



Asymmetries L/R ⟶ $\mathbf{p_v}$ and U/D ⟶ $\mathbf{p_h}$

Spin Coherence Time: STUDIES

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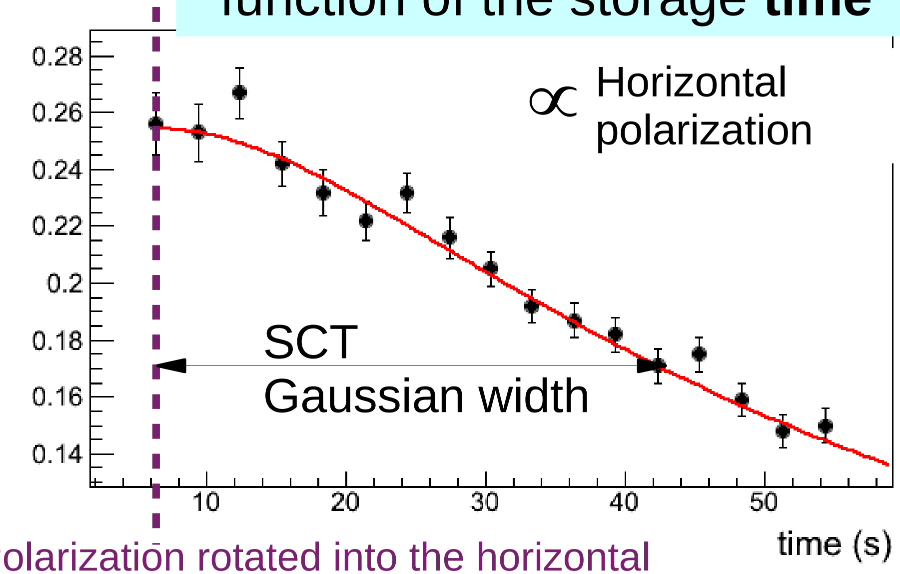
Up/Down asymmetry as a function of the storage **time**



Polarization rotated into the horizontal plane by the RF-solenoid

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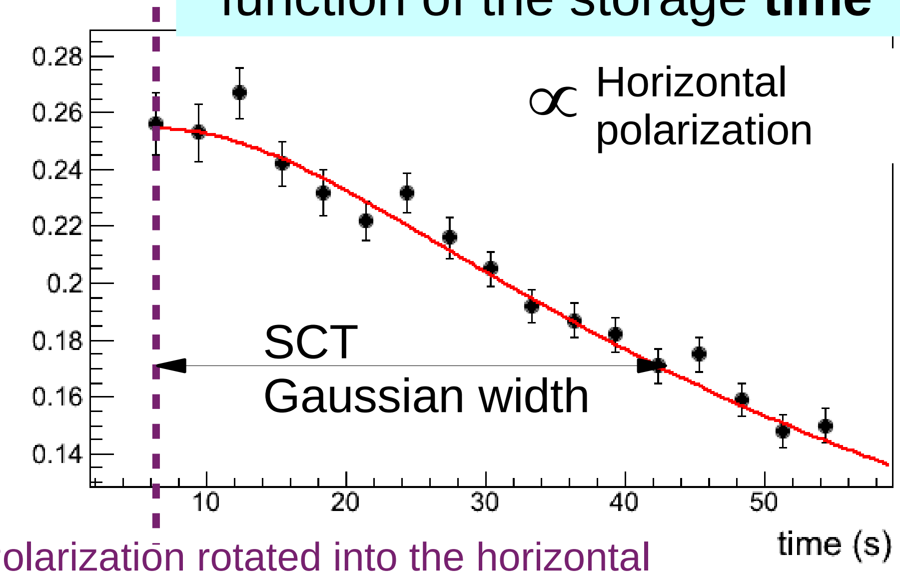
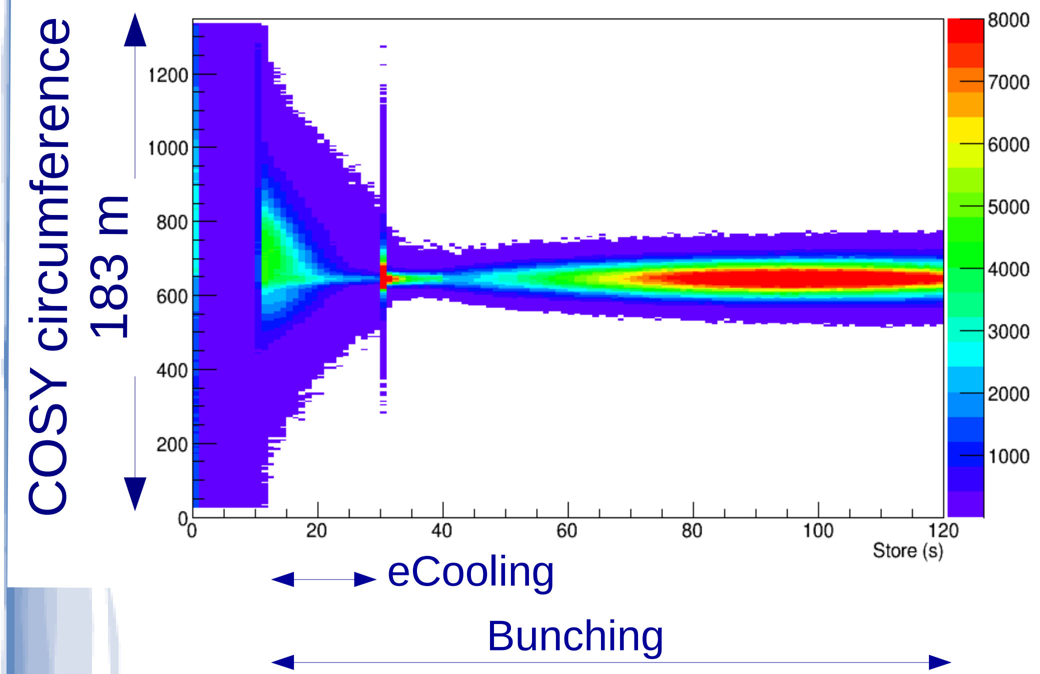


Polarization rotated into the horizontal plane by the RF-solenoid

Particle positions in the ring as a function of the storage time



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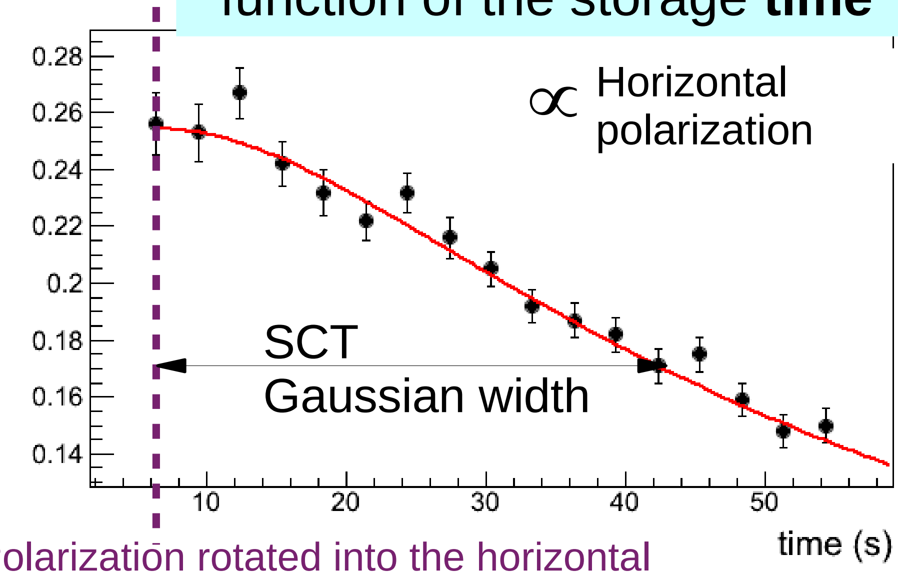

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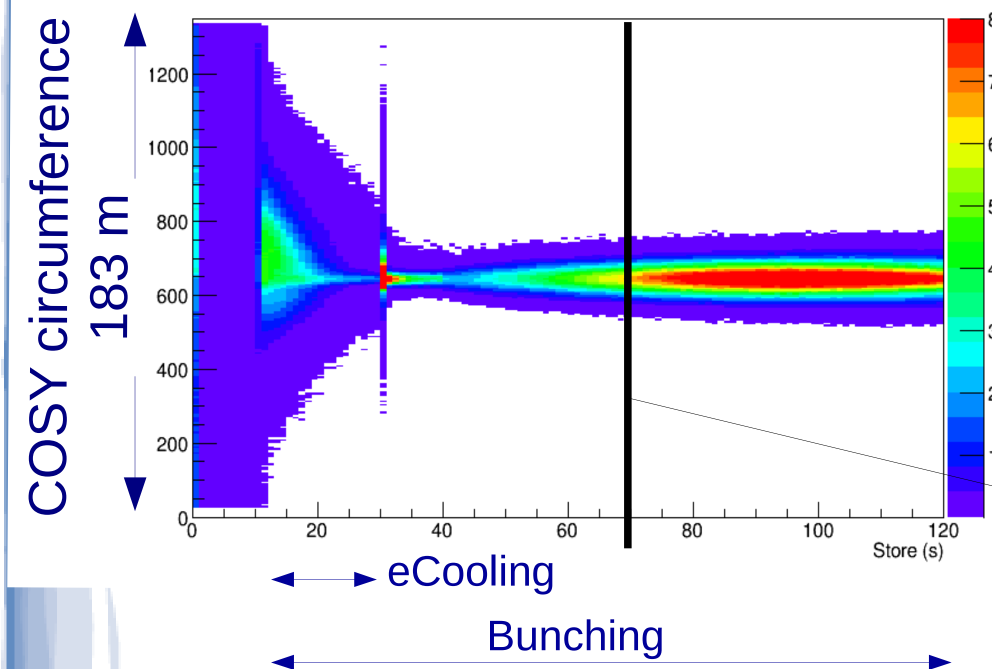
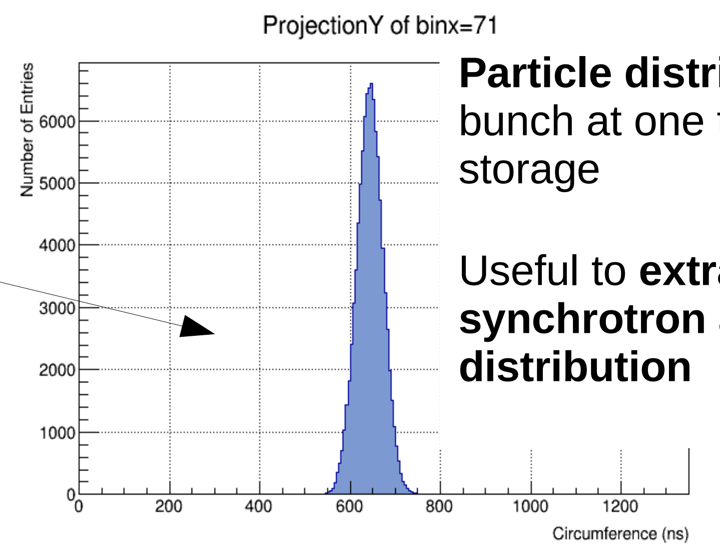




Particle distribution in the bunch at one time of the storage

Useful to **extract the synchrotron amplitude distribution**

Spin Coherence Time: STUDIES

4) Run Summaries

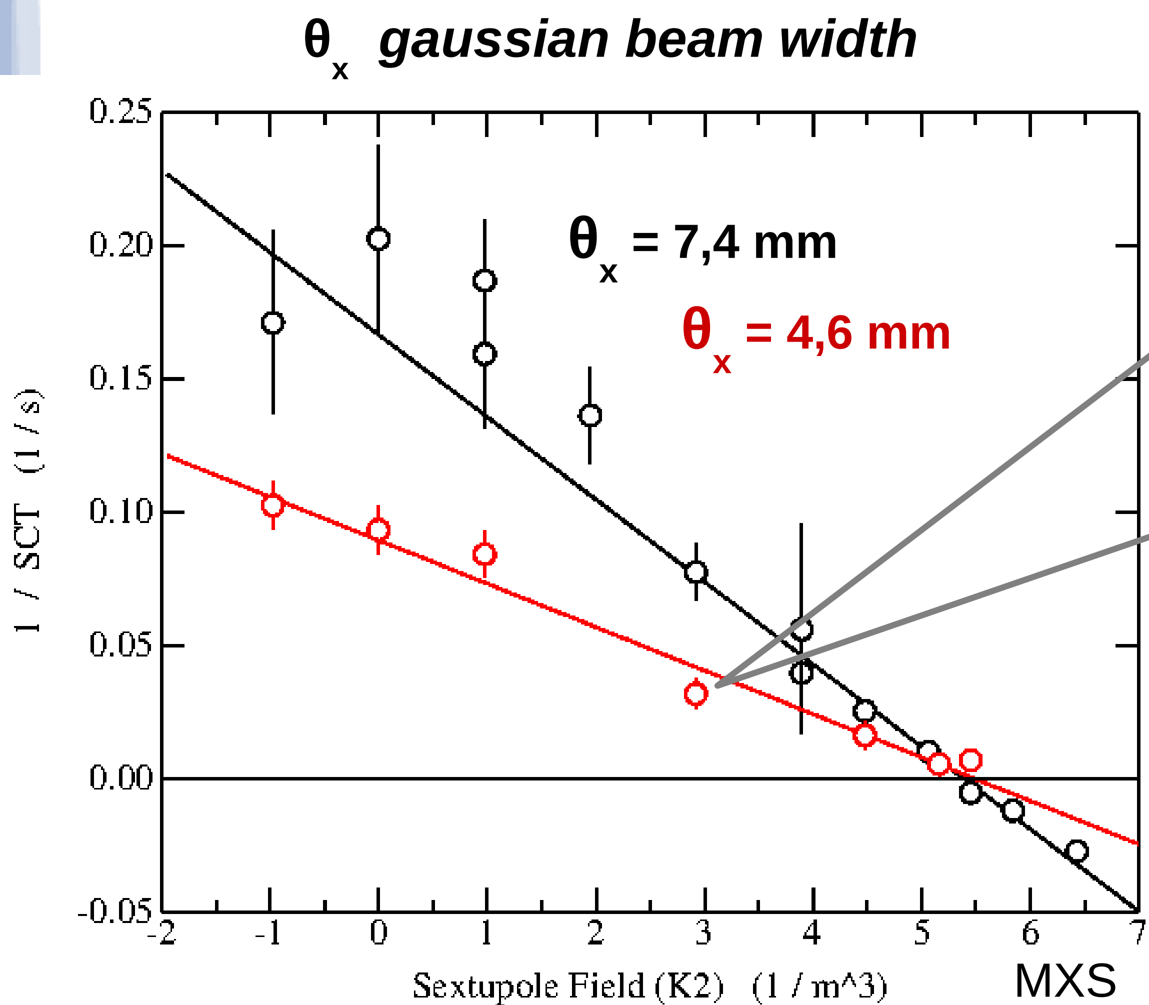
θ_x = horizontal emittance
ξ = chromaticity

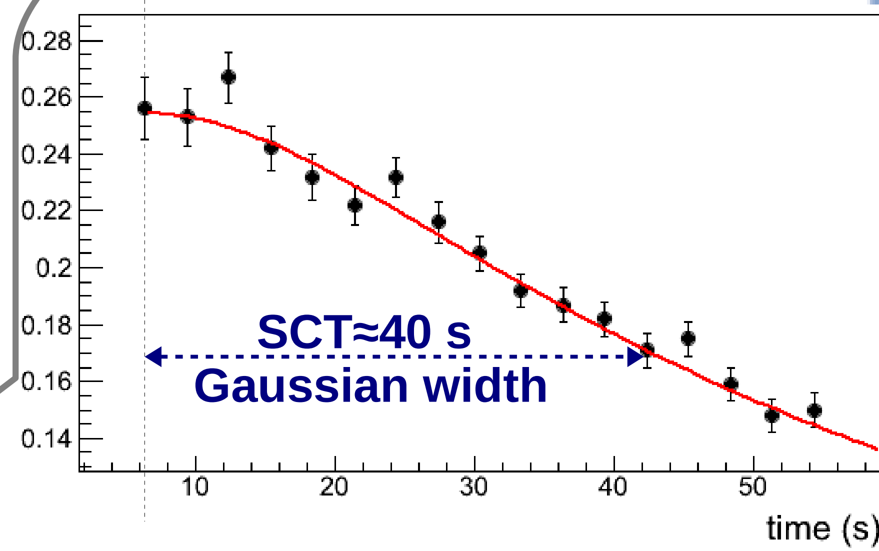
	May 2012	Feb 2013	Aug 13	Aug 14
BCT	$6 \cdot 10^8$	$2 \cdot 10^9$	$1 \cdot 10^9$	$1 \cdot 10^9$
Target	Tube	Tube	Ridge	Flat
Extraction	Ramped	Ramped	Ramped/ White noise	White noise
Large Hor. Emittance	Yes	Yes	Yes	Yes
Large DeltaP/P	No	No	Yes	Yes
Aim	Correction for $\boldsymbol{\theta_x}$ with sextupole (**MXS**)	- Correction for $\boldsymbol{\theta_x}$ - **ξ** measurements	- Correction for $\boldsymbol{\theta_x}$ and **(Δp/p)²** with sextupoles. (**2-D map** MXS-MXG) **- ξ=0 close to each other**	- Correction for $\boldsymbol{\theta_x}$ and **(Δp/p)²** with sextupoles. (**2-D map** MXS-MXG) **- ξ=0 overlap**
Comments	Proved!	50 Hz=Rate effect	Huge set of data	Huge set of data

ξ=0 sextupole settings changed

Results: MAY 2012

Sextupole field corrections for horizontal emittance





Spin Coherence Time: extracted from **template** based analysis

Model* of the time dependence based on different horizontal and vertical emittance distributions

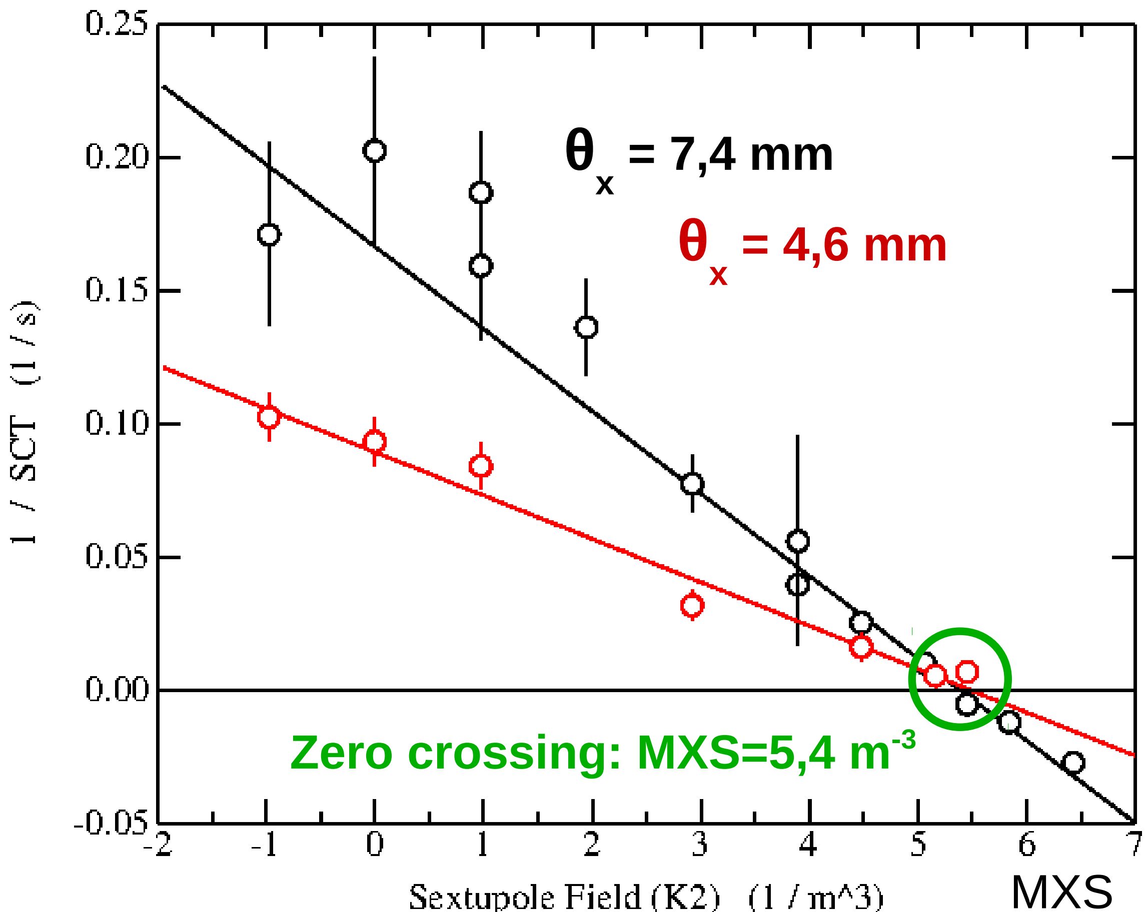
MXL=MXG=0 m^{-3}

*Z. Bagdasarian et al. , Phys. Rev. ST Accel. Beam 17, 052803 (2013)

Results: MAY 2012

Sextupole field corrections for horizontal emittance

θ_x *gaussian beam width*



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$$\frac{1}{SCT} = |A + a\,K_2|\,\theta_x$$

Sextupole field Beam profile width

Various horizontal profiles θ_x

- Flip **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 beam width

Results: MAY 2012

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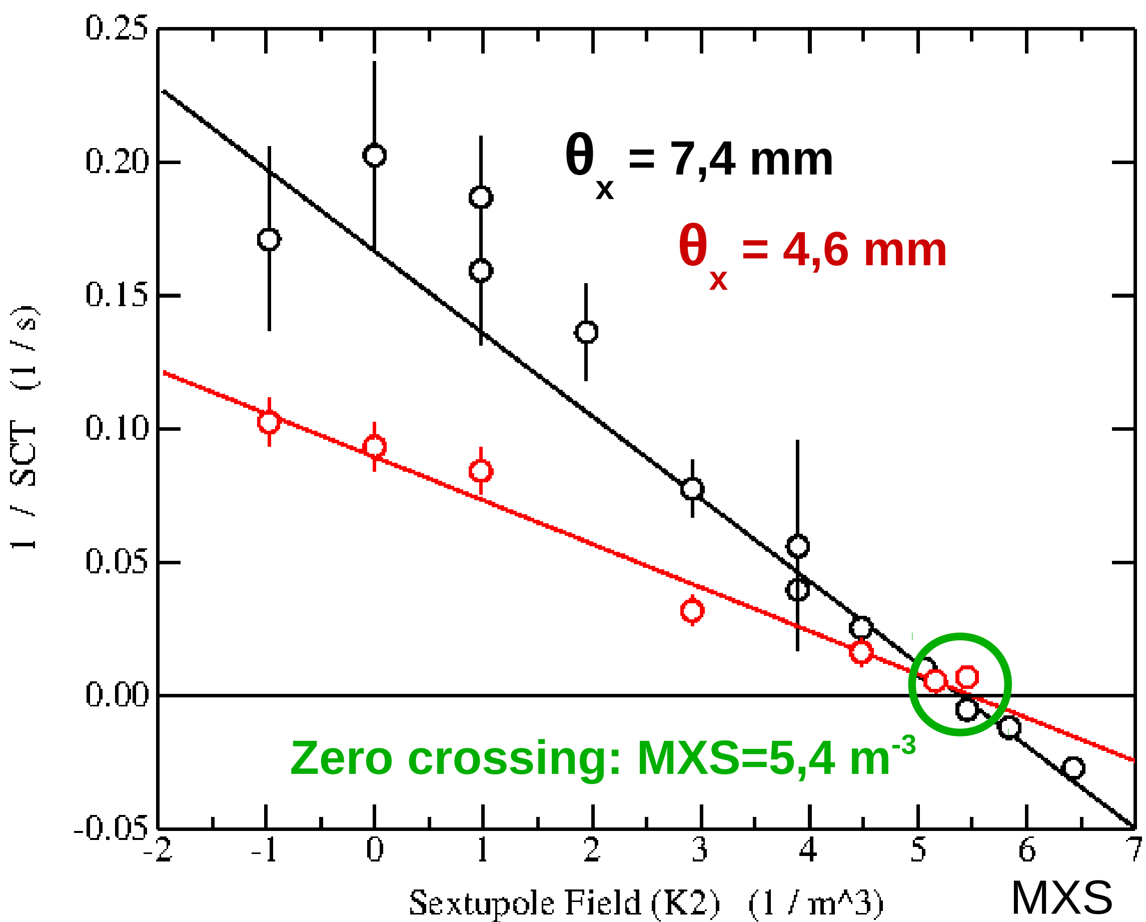
θ_x *gaussian beam width*



MXL=MXG=0 m^{-3}

$$\frac{1}{SCT} = |A + a K_2| \theta_x$$

Sextupole field (K_2) — Beam profile width (θ_x)

Various horizontal profiles θ_x

- Flip **SCT** sign above zero crossing
- Different slopes
- **SCT** does not go to infinity.

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- The **same zero crossing**, independent of beam width

Sextupole fields can be used to increase SCT

Results: AUGUST 2013

2D map of sextupole field corrections for horizontal emittance and $(\Delta p/p)^2$

MXS: 6-poles where β_x is large
MXG: 6-poles where D is large

MXL=-0,9% (-0,09 m^{-3})

Results: AUGUST 2013

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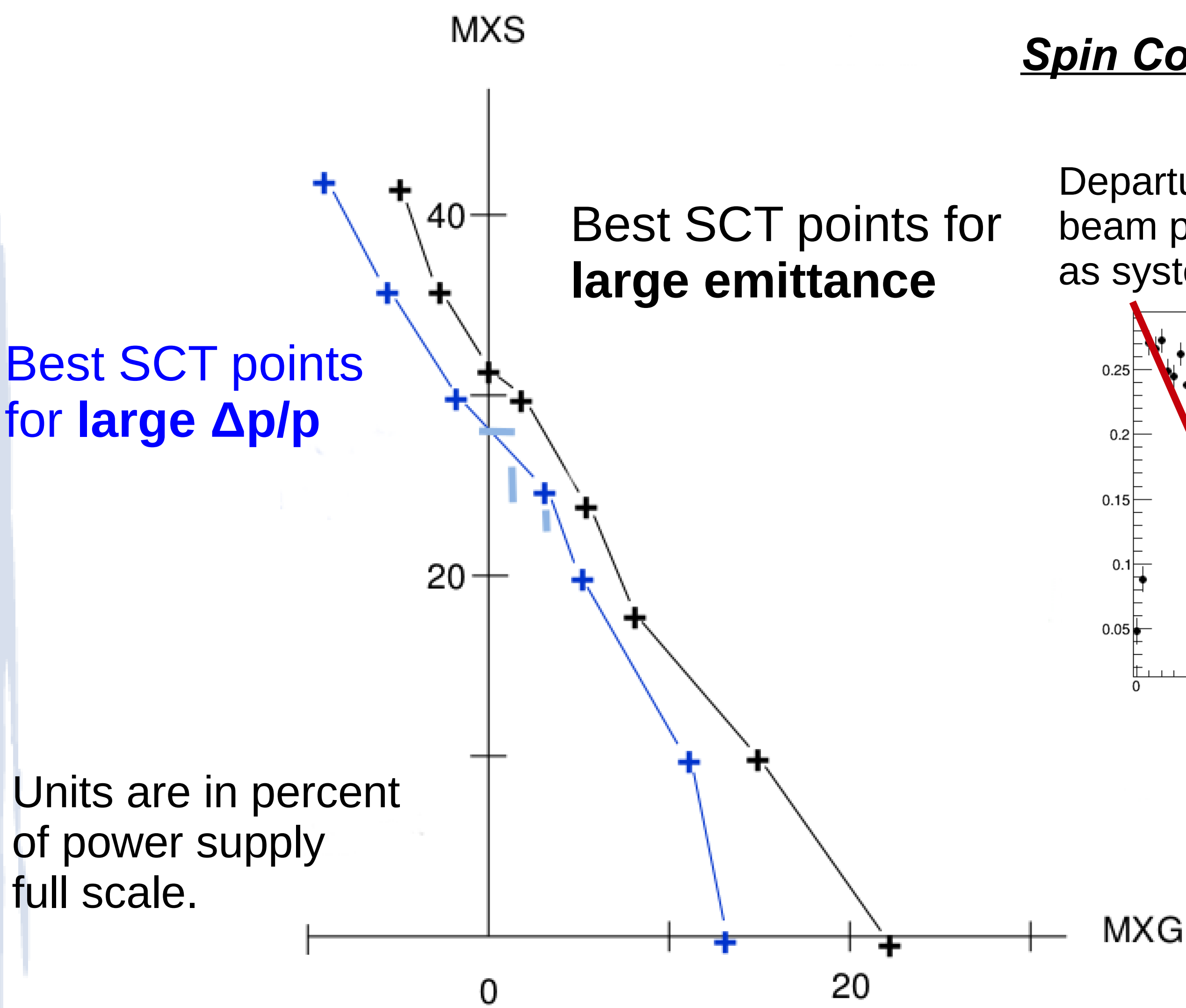
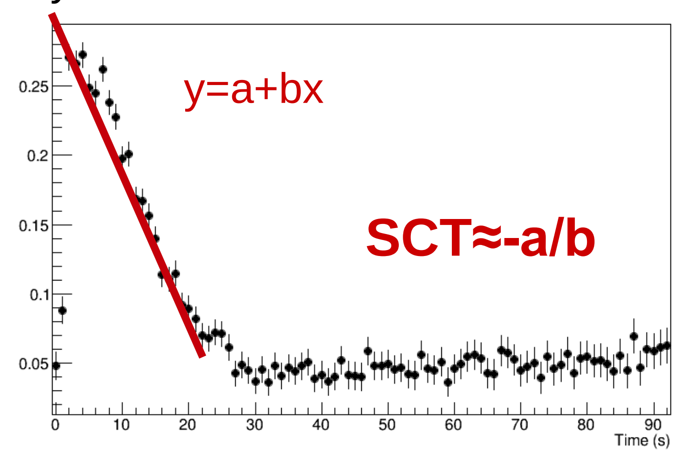


Units are in percent of power supply full scale.

Spin Coherence Time: extracted from INITIAL SLOPE

Departures from template shape reflect beam profile and extraction details as well as systematic effects in the measurement.



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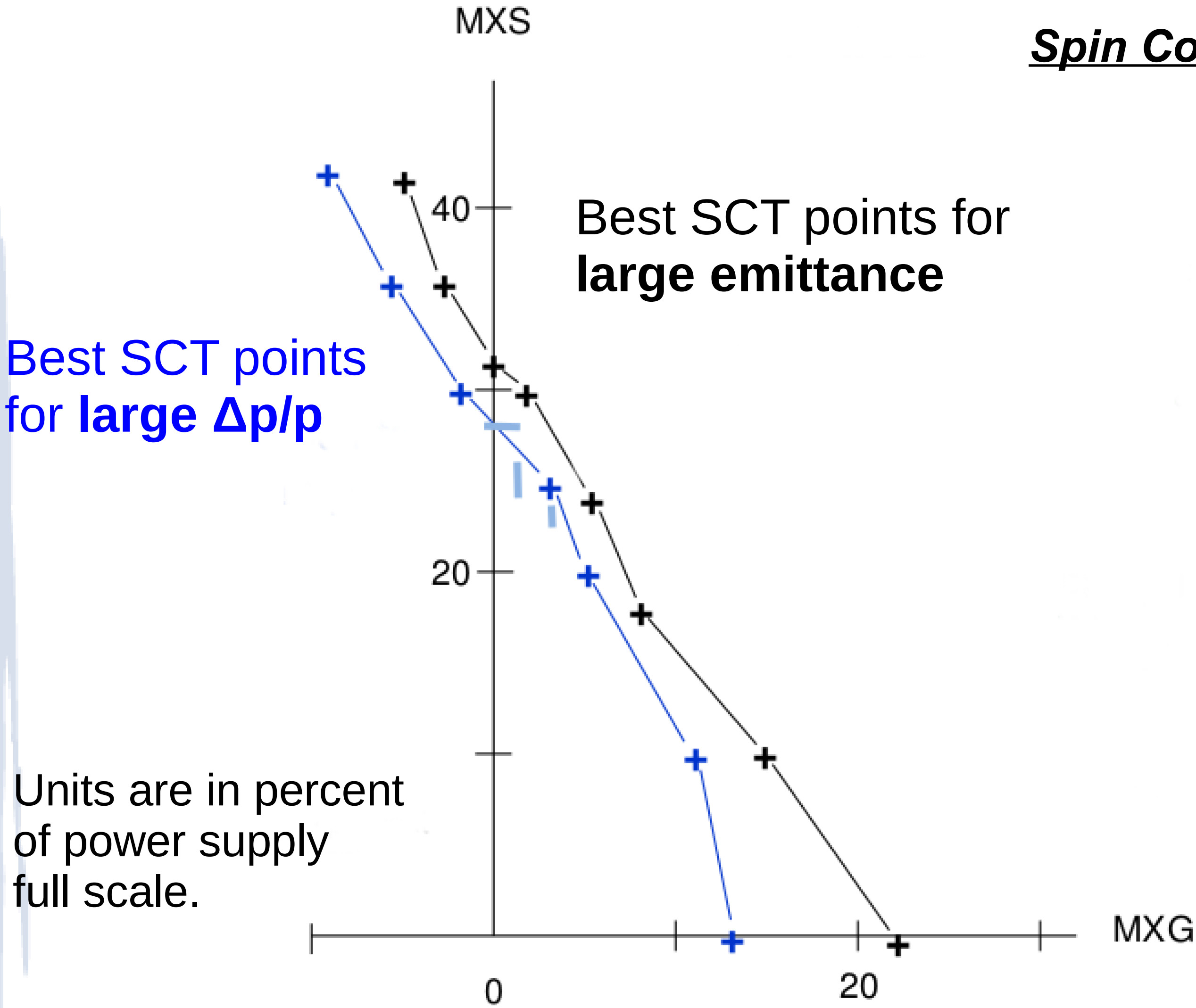

Each point represents the results of a scan across the locus.

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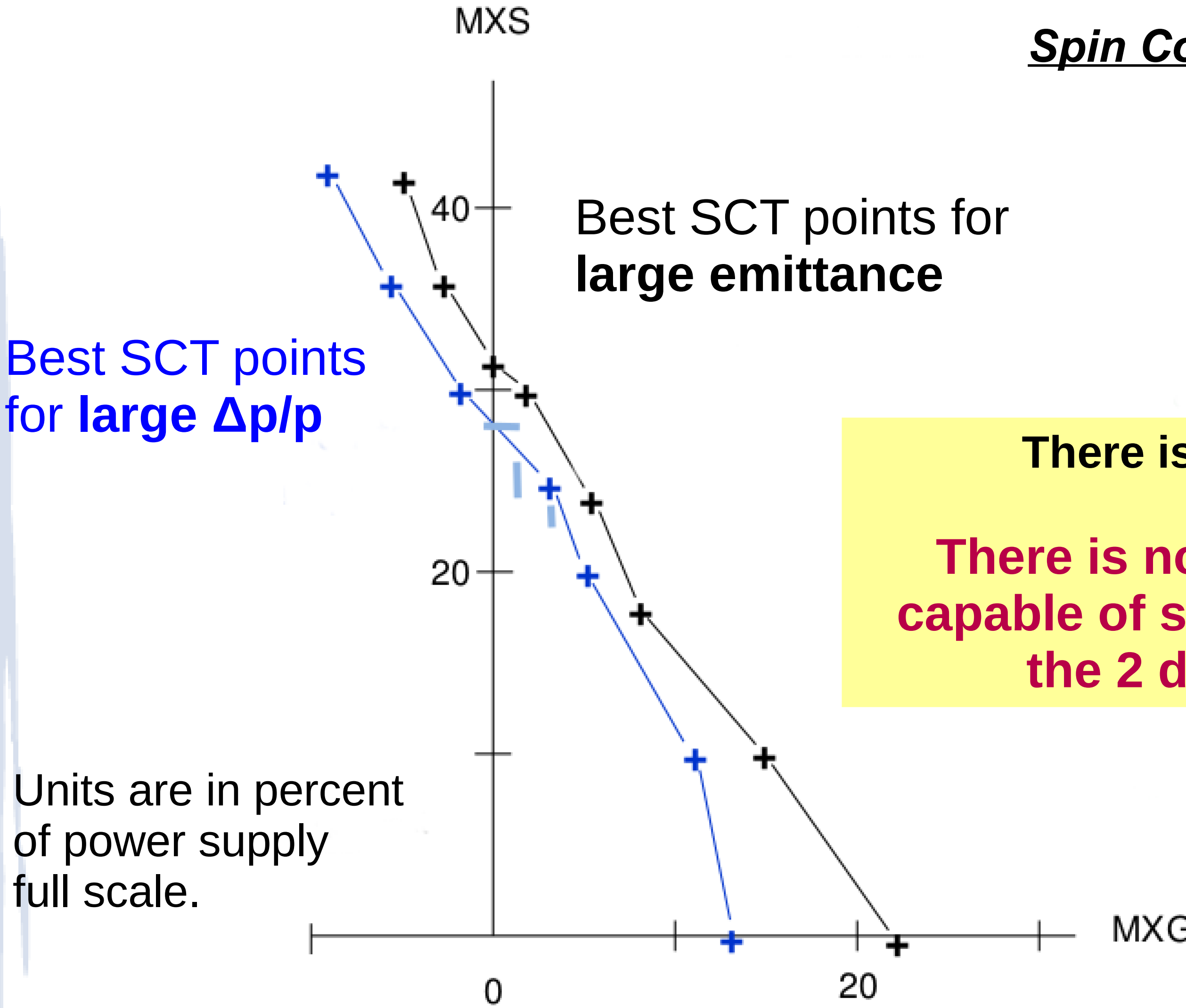

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Units are in percent of power supply full scale.

There is NO CROSSING POINT

There is no sextupole combination capable of simultaneous correction of the 2 decoherence sources

Results: AUGUST 2013

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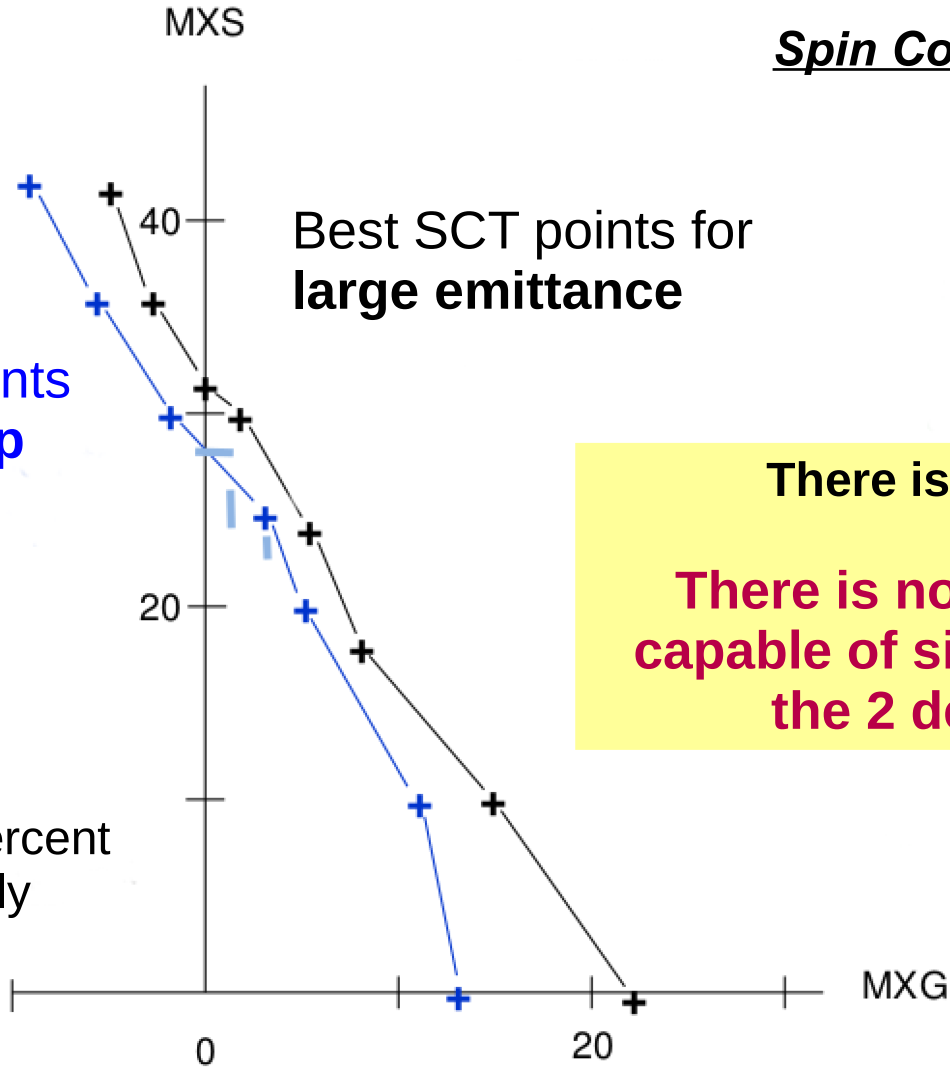

Best SCT points for **large emittance**

Best SCT points for **large Δp/p**

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But....

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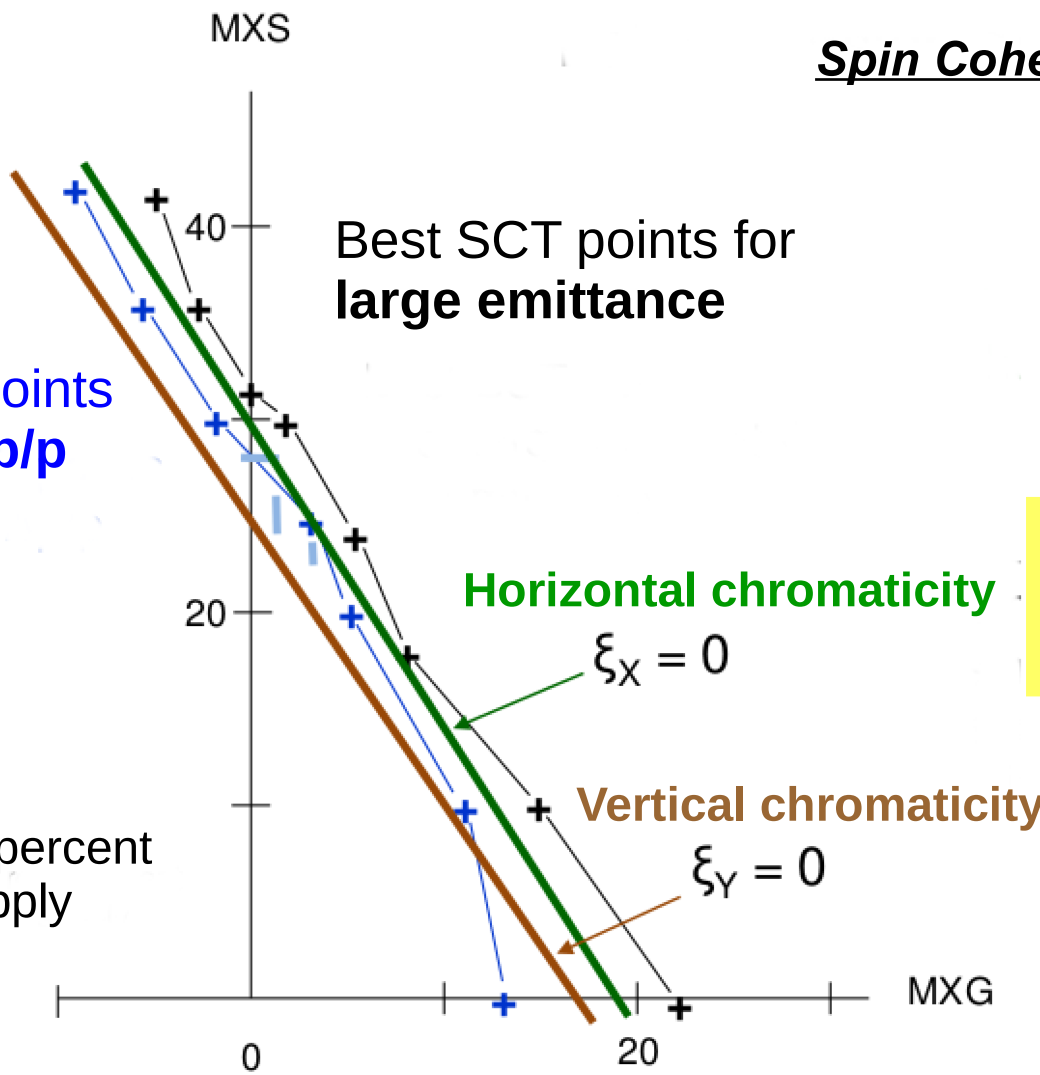

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Each point represents the results of a scan across the locus.

Large SCT and **ξ = 0** lines close to each other!

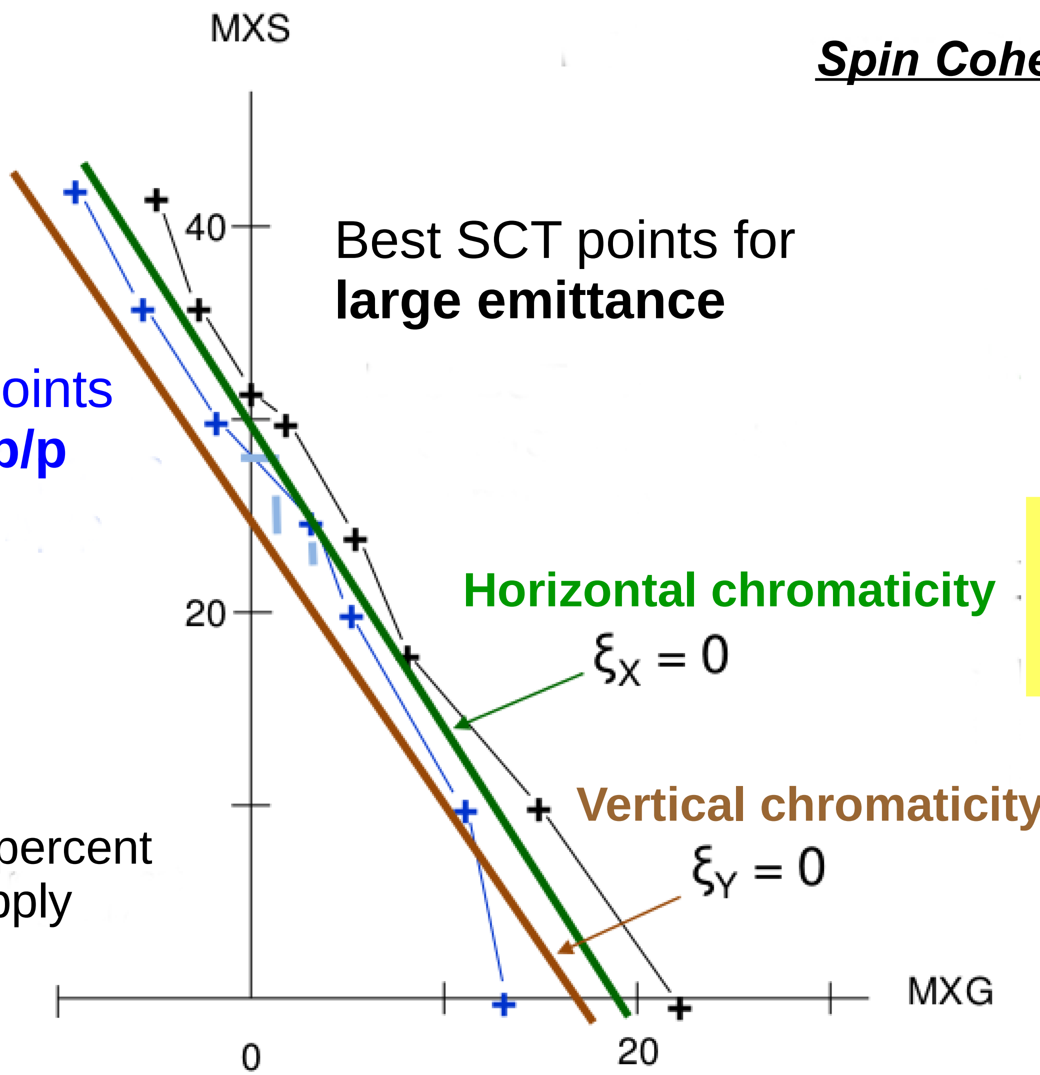
Results: AUGUST 2013

2D map of sextupole field corrections for <u>horizontal emittance</u> and <u>$(\Delta p/p)^2$</u>

- **MXS**: 6-poles where β_x is large
- **MXG**: 6-poles where D is large

MXL=-0,9% (-0,09 m^{-3})

<u>Spin Coherence Time:</u> extracted from INITIAL SLOPE



Best SCT points for **large Δp/p**

Units are in percent of power supply full scale.

Each point represents the results of a scan across the locus.

Large SCT and **ξ = 0** lines close to each other!

What's next?

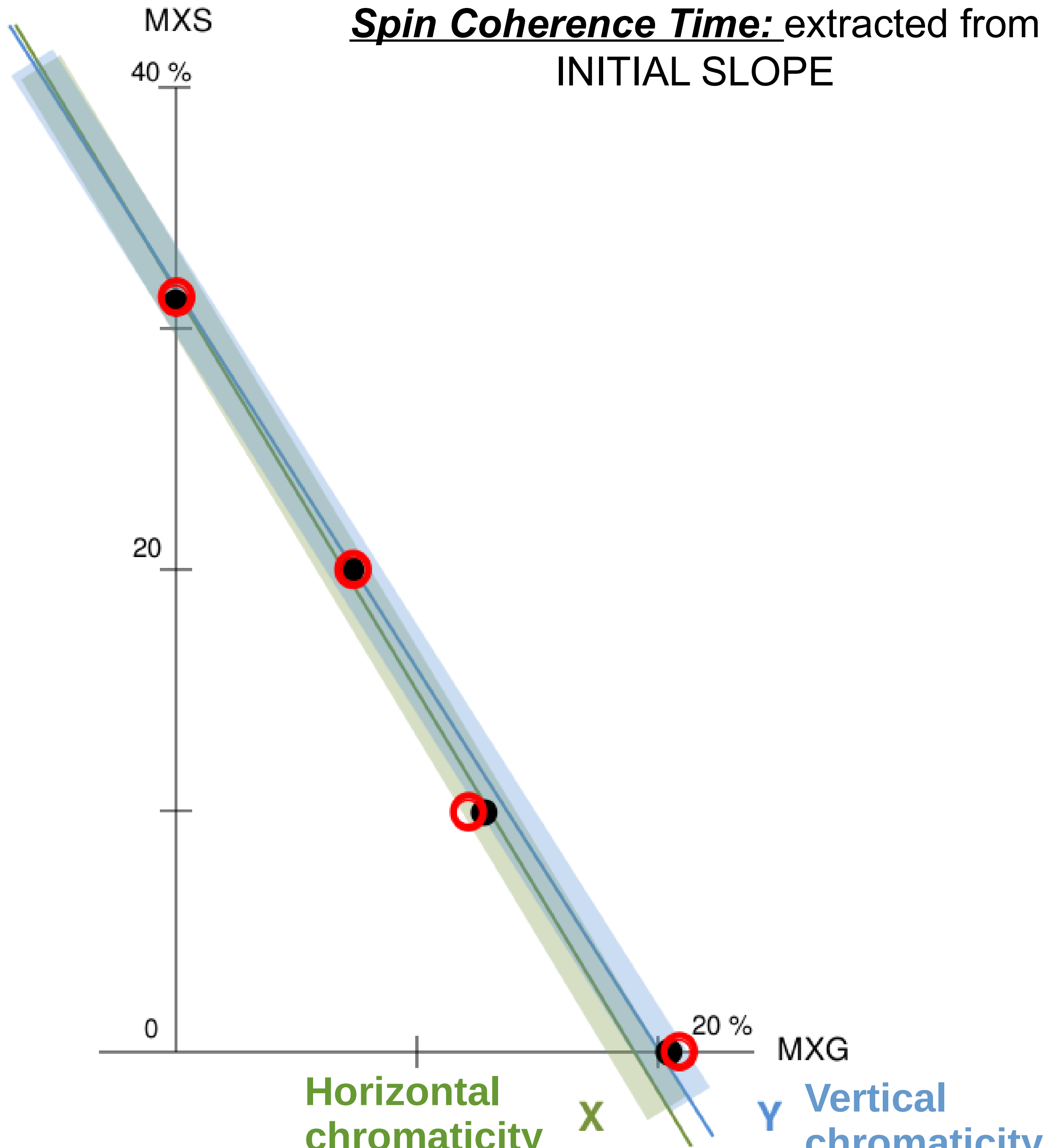
ξ=0 lines overlap changing MXL

Results: AUGUST 2014

Spin Coherence Time: extracted from INITIAL SLOPE

Change MXL in order get the chromaticity zero lines close to each other

MXL=-1,45% (-0,2 m^{-3})



Units are in percent of power supply full scale.

Results: AUGUST 2014

Spin Coherence Time: extracted from INITIAL SLOPE

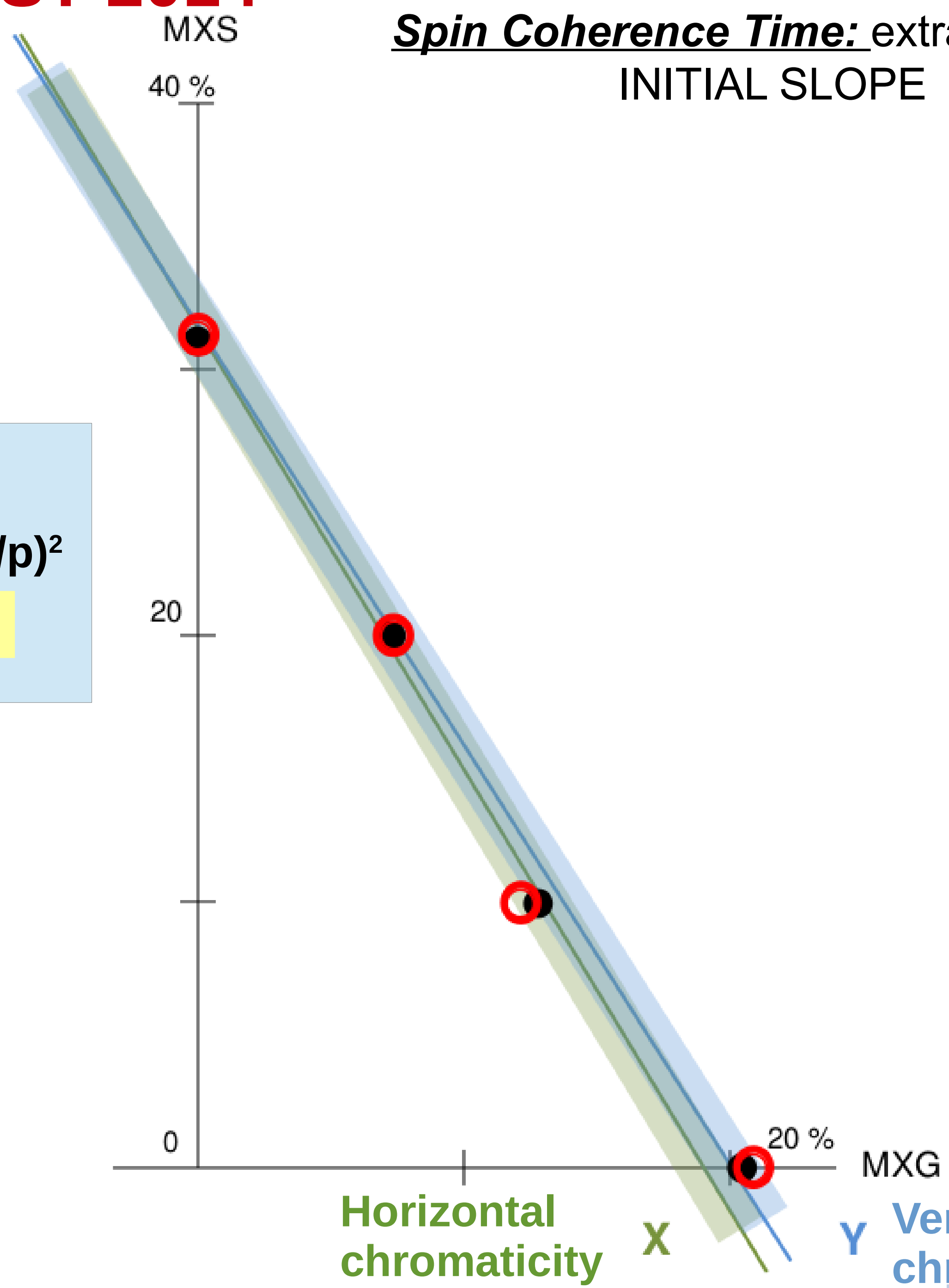
Change MXL in order get the chromaticity zero lines close to each other

MXL=-1,45% (-0,2 m^{-3})

Best SCT for **large θx**

Best SCT for **large $(\Delta p/p)^2$**

Along ξ=0 lines



Units are in percent of power supply full scale.

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Units are in percent of power supply full scale.

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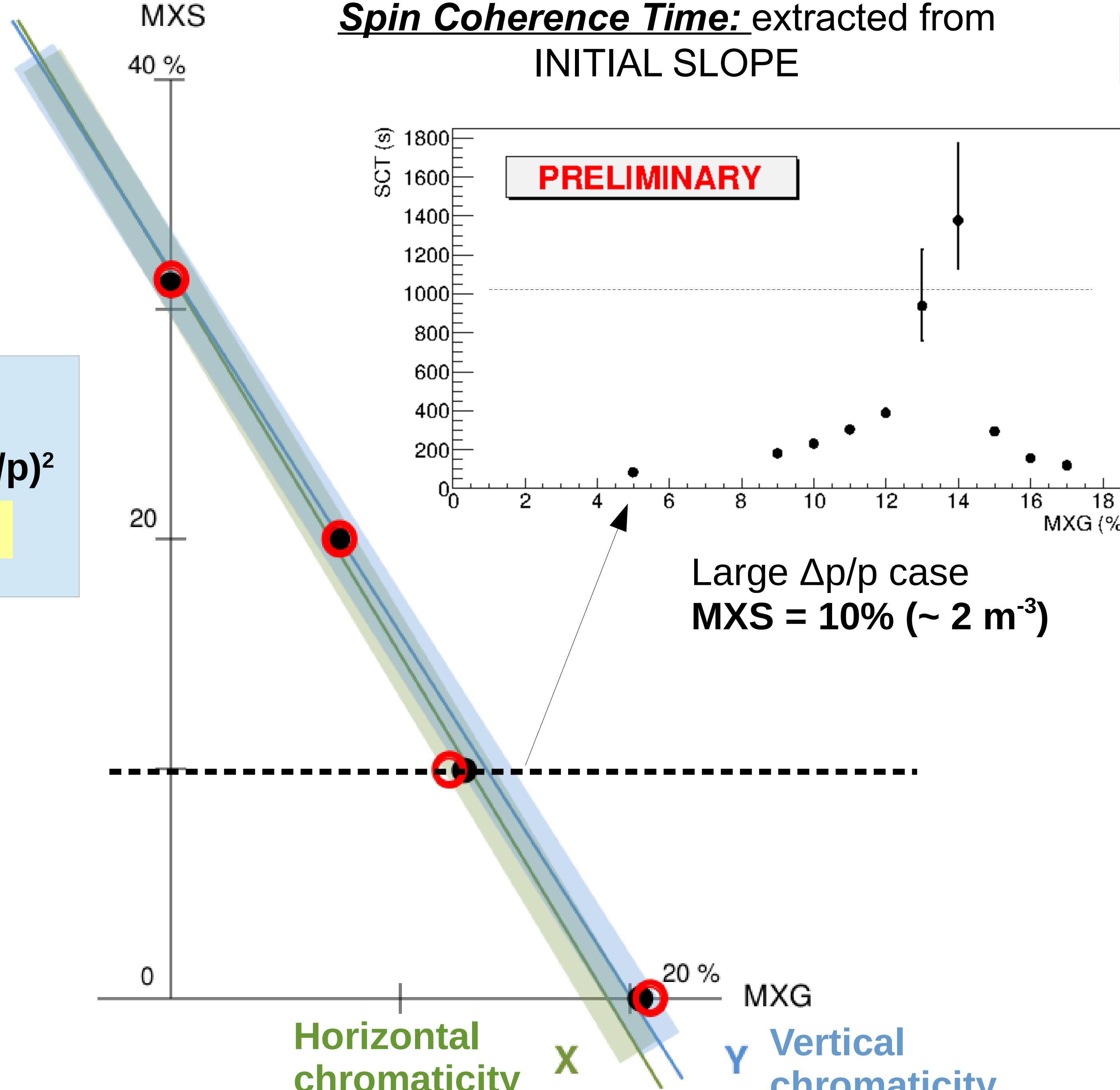


Large Δp/p case

MXS = 10% (~ 2 m^{-3})

Results: AUGUST 2014

Spin Coherence Time: extracted from INITIAL SLOPE

Change MXL in order get the chromaticity zero lines close to each other

MXL=-1,45% (-0,2 m^{-3})

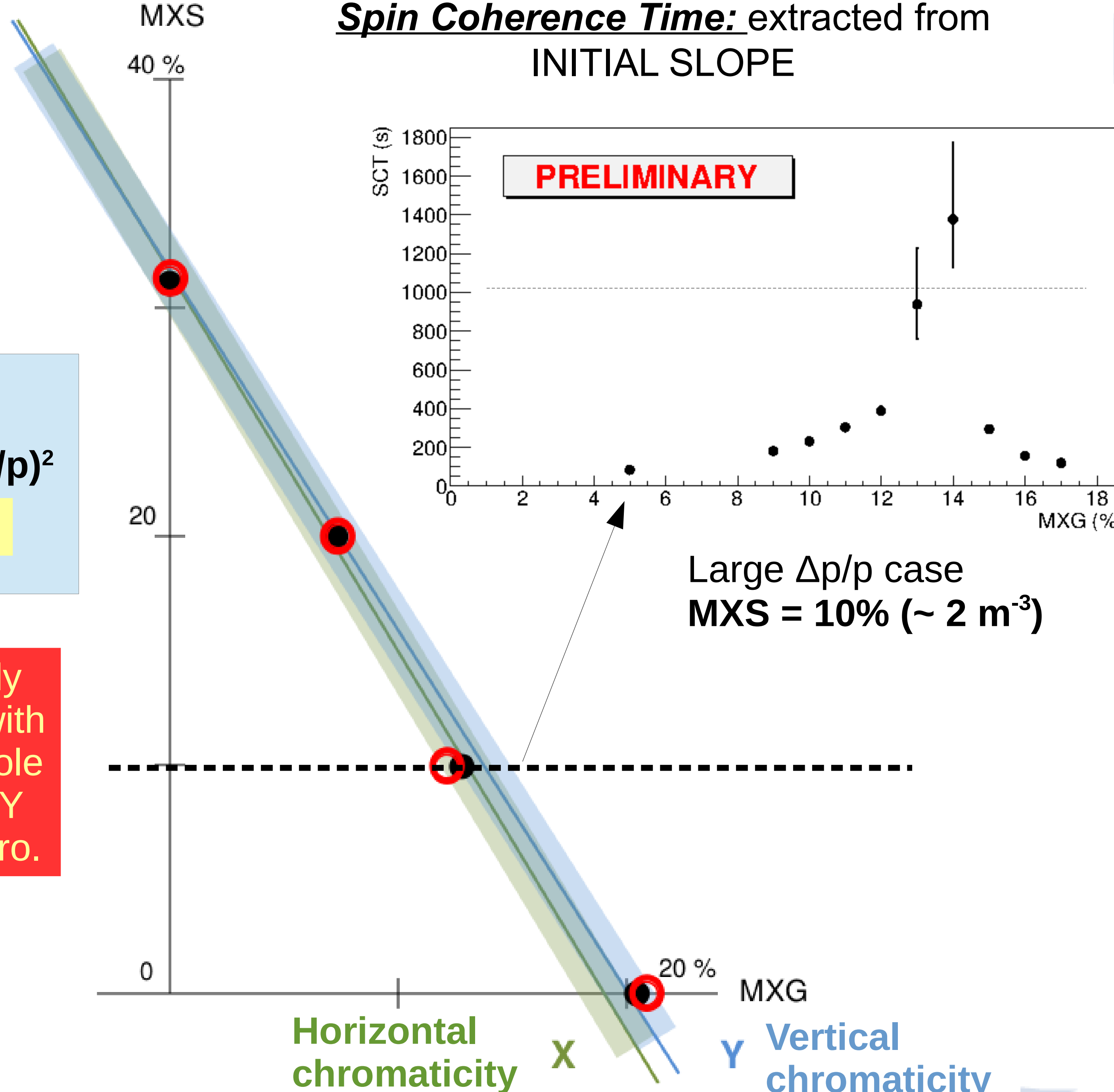
Best SCT for **large θx**

Best SCT for **large (Δp/p)^2**

Along ξ=0 lines

SCT may be substantially extended up to 1000 s with a combination of sextupole fields where both X and Y chromaticity are near zero.

Units are in percent of power supply full scale.



Large Δp/p case

MXS = 10% (~ 2 m^{-3})

Conclusions

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

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 fields where both X and Y chromaticities are near zero

Conclusions

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

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 fields where both X and Y chromaticities are near zero

This test was done for a **purely magnetic ring** and **meets the requirement for a storage ring to search for an EDM!**

Future work

- Feedback (for frozen spin)
- Polarimeter design database
- Polarimeter detector prototyping
- Crossed E,B field elements (deuteron)
- High precision beam control
- EDM ring design

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Thanks for your attention!

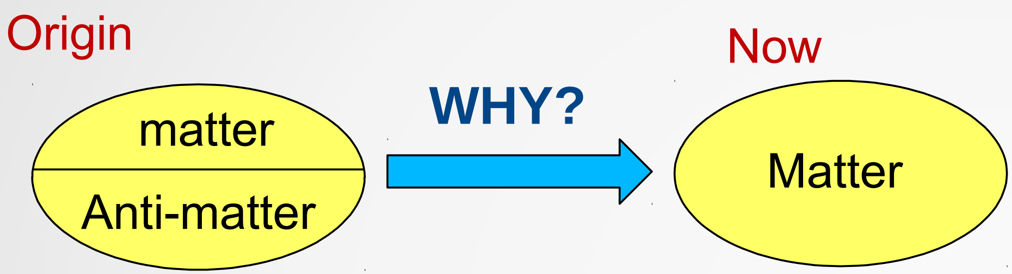
JEDI

Collaboration
(Jülich Electric Dipole Moment Investigations)

SPARE SLIDES

PHYSICAL MOTIVATIONS

<u>Electric Dipole Moment</u> of fundamental particles



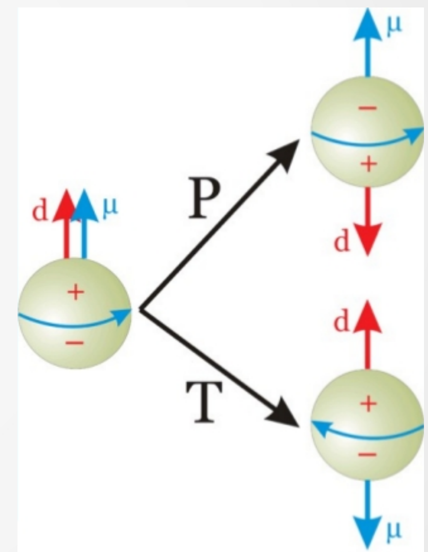
BARYOGENESIS

Sakharov's conditions (1967):

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

<u>Def:</u> permanent charge displacement within the particle volume

d=EDM
μ=spin



Assuming CPT symmetry

T violation = **CP violation**

EDM$_{SM}$ too small to be observed
EDM$_{bSM}$ within exp. limits

Standard Model (SM):

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

PHYSICAL MOTIVATIONS

CP violating sources

STANDARD MODEL

- *Weak interaction:* complex phase **δ** in CKM quark mixing matrix
- *Strong interaction:* **θ_{QCD}**

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

Axion search

$$d_d = 0$$

SUSY

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

$$\Delta^+ = d^c_{up} + d^c_{down} \qquad \Delta^- = d^c_{up} - d^c_{down}$$

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^- .

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

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

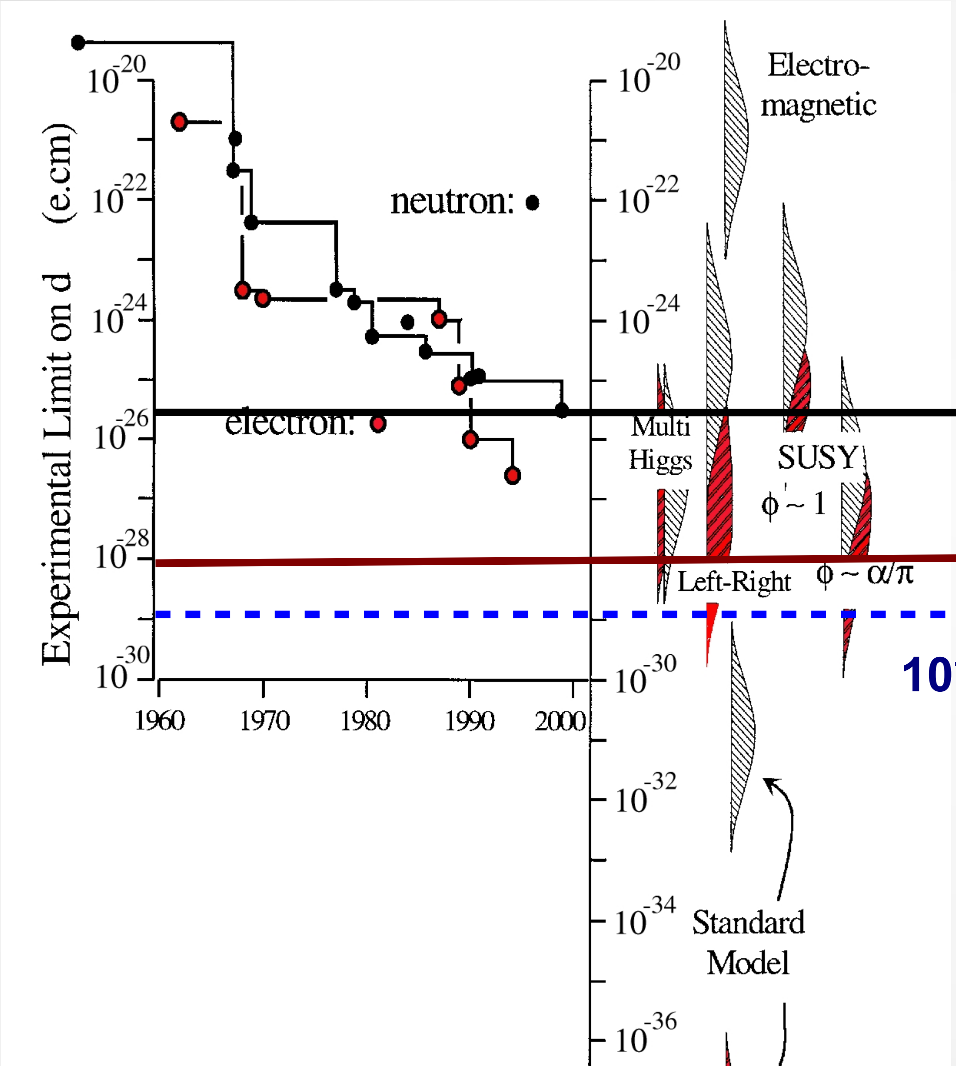
$$d_d = d_{up} + d_{down} - 0{,}2\,\Delta^+ - 6\,\Delta^-$$

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

PHYSICAL MOTIVATIONS

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

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



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

EDM theoretical predictions and experiments

$2,9\times10^{-26}\ e\cdot cm$ **neutron***

$8,7\times10^{-29}\ e\cdot cm$ **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.

New CP violation sources!

Data Acquisition (DAQ)

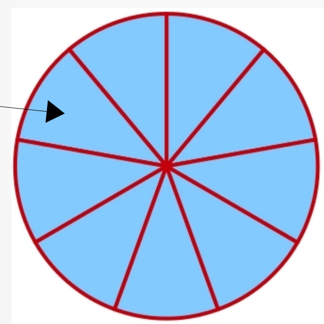
*Z. Bagdasarian et al., Phys. Rev. ST Accel. Beams 17, 052803 (2014)

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

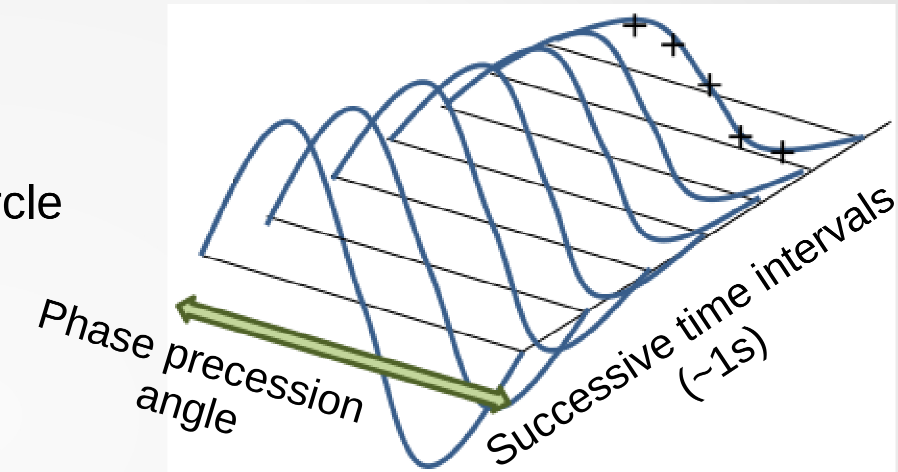
$$\theta_s = 2\pi G \gamma n$$

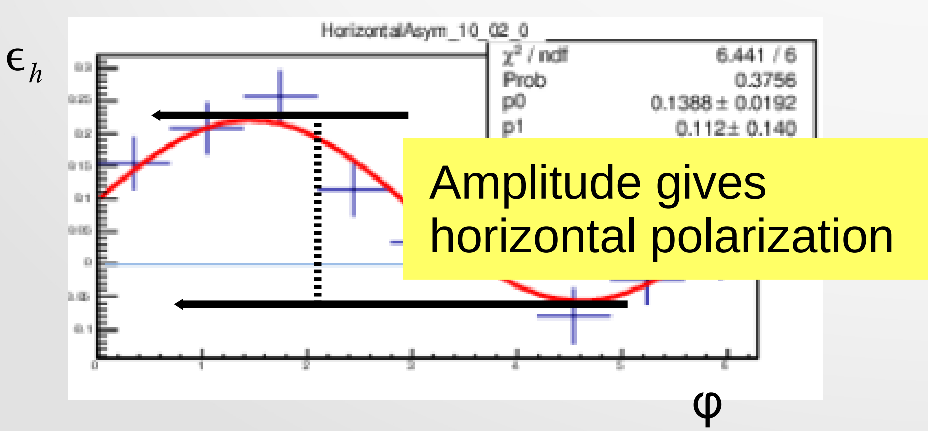
- Bin by phase φ the spin precession angle circle
- Compute asymmetry in each bin

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

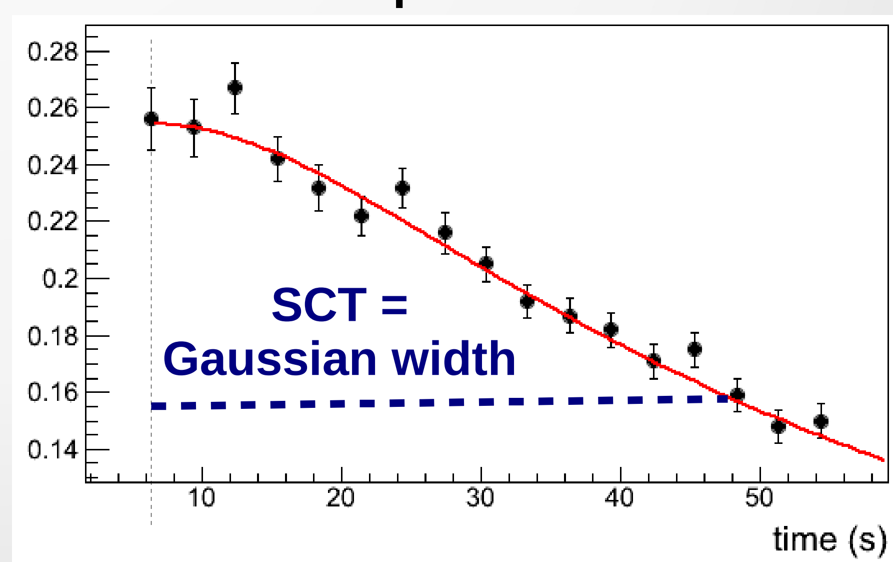


As the polarization rotates
The ε_h reflects the sideways projection of the polarization.





Amplitude vs time



Sextupole effect

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

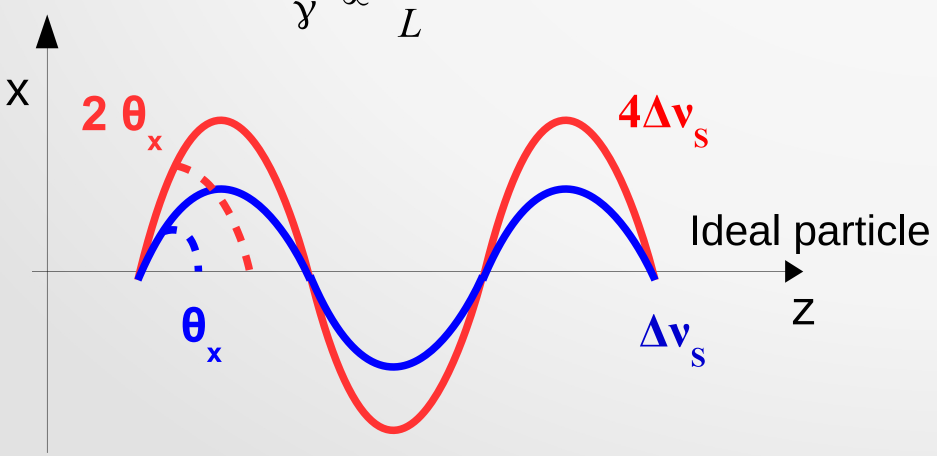
Spin Tune spread: $\Delta \nu_s = G \Delta \gamma$

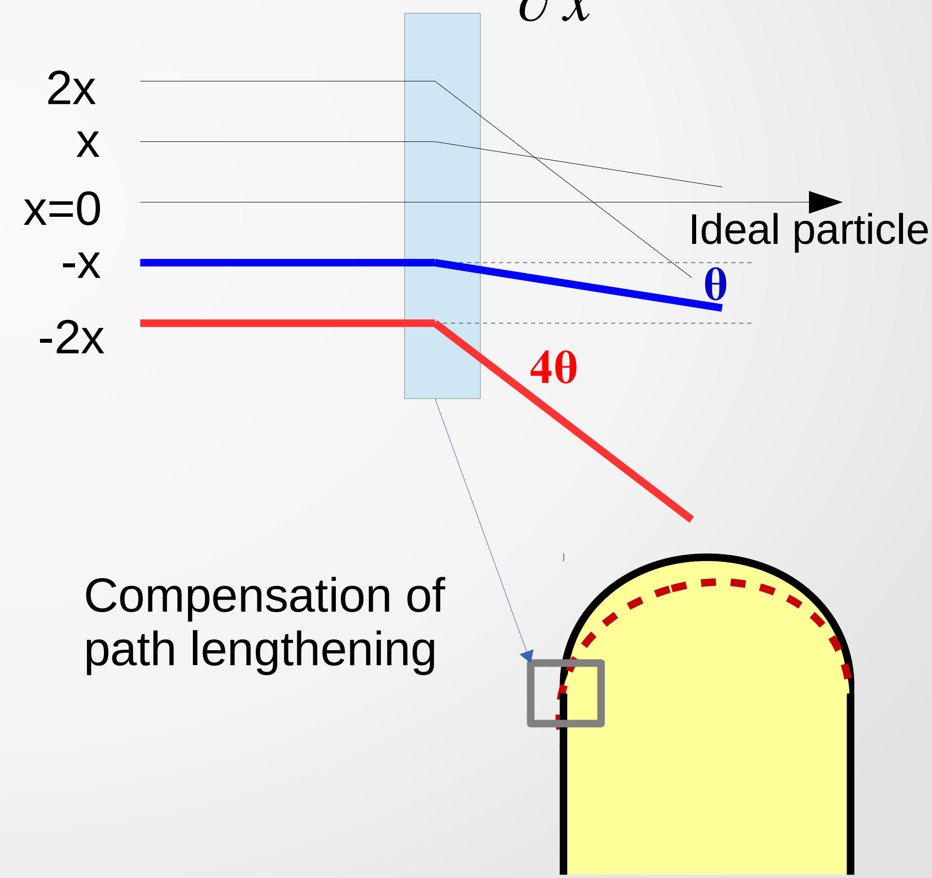
$$B \propto x^2 \qquad \frac{\partial B}{\partial x} \propto x$$

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 effects

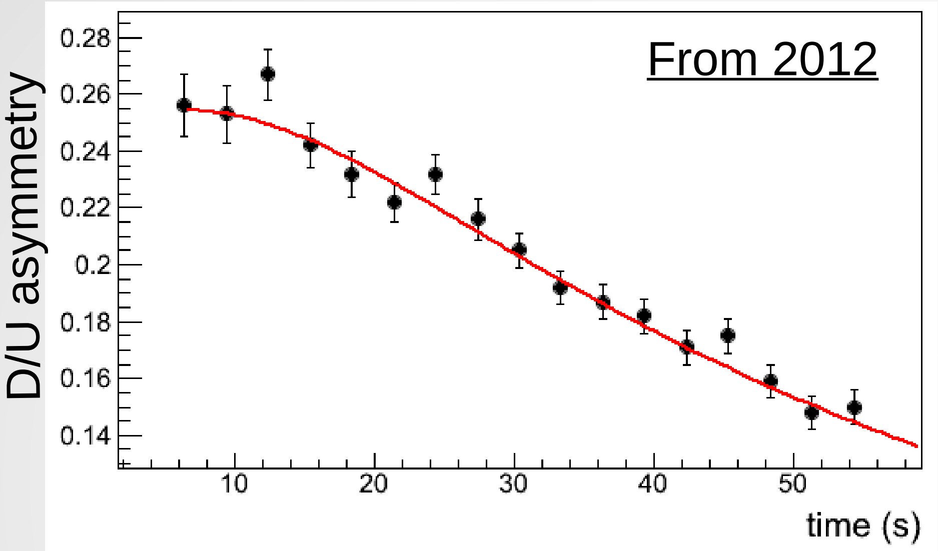
SCT dependence on sextupoles

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

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

Sextupole fields
MXS, MXL, MXG

Ago 2013: new issues



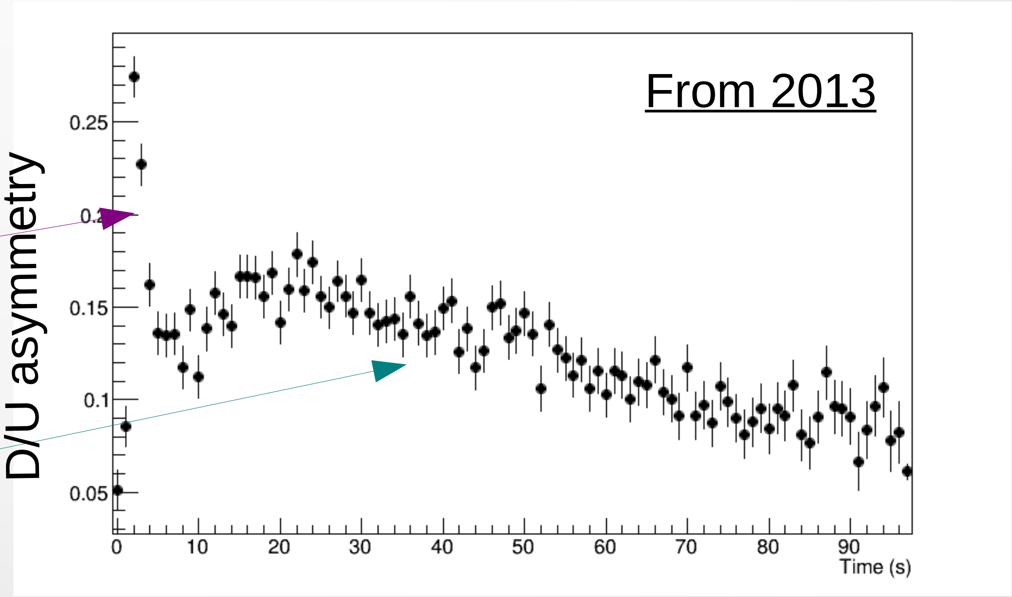
Wide horizontal profile

- **Balck dots**=data points
- **Red line**=template function based on **Gaussian spin distribution**

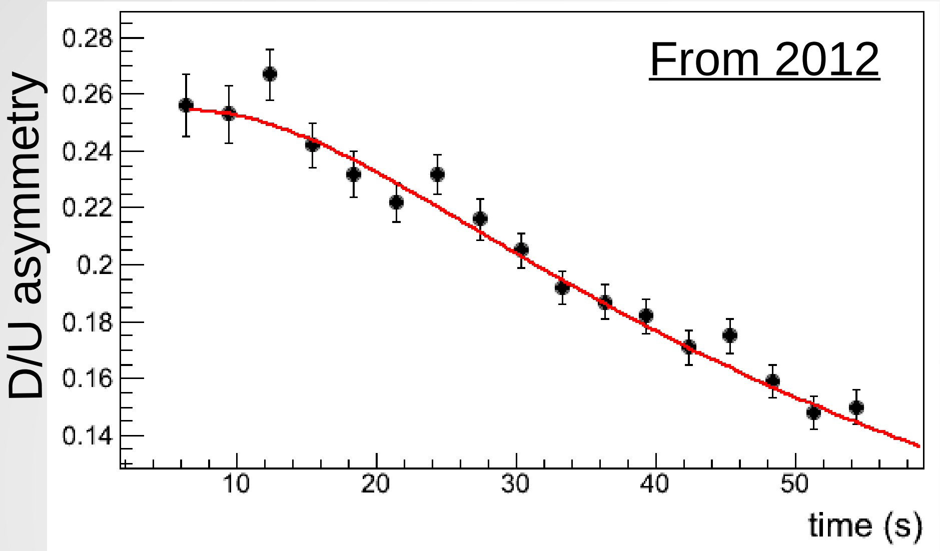
Wide horizontal profile
double slope

Early slope
Depends on:
Heating, tunes,
sextupole settings.

Late Slope
featureless



Ago 2013: new issues



Wide horizontal profile

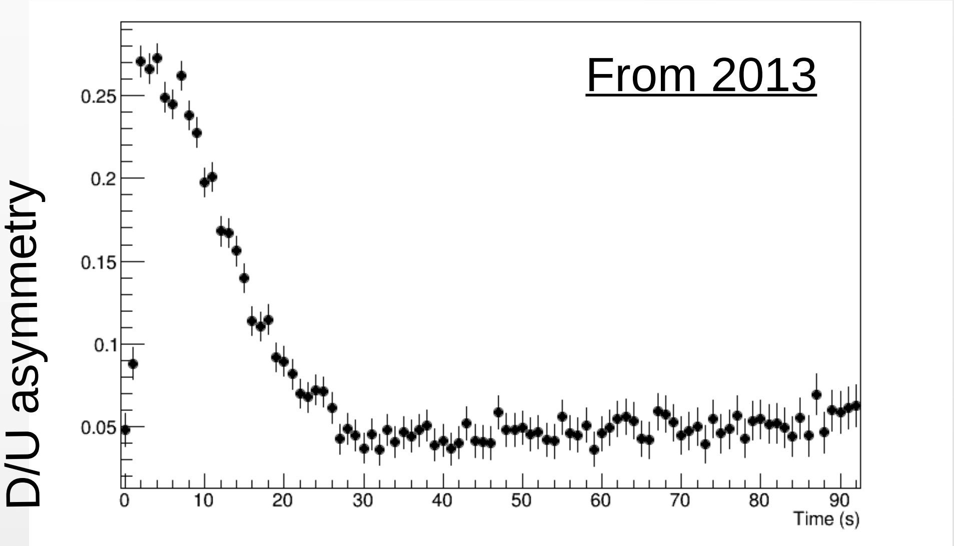
- **Balck dots**=data points
- **Red line**=template function based on **Gaussian spin distribution**

Wide Δp/p distribution

We probably need **new template curves**

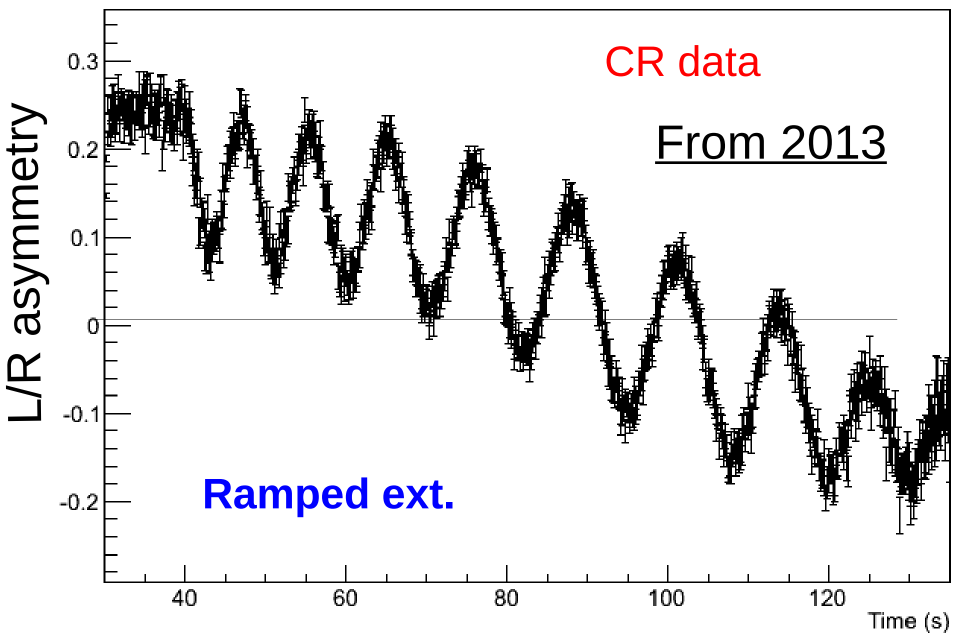
- the **distribution of synchrotron amplitudes is not gaussian**

- synchrotron oscillations are not simple harmonic solution (sinusoidal potential)

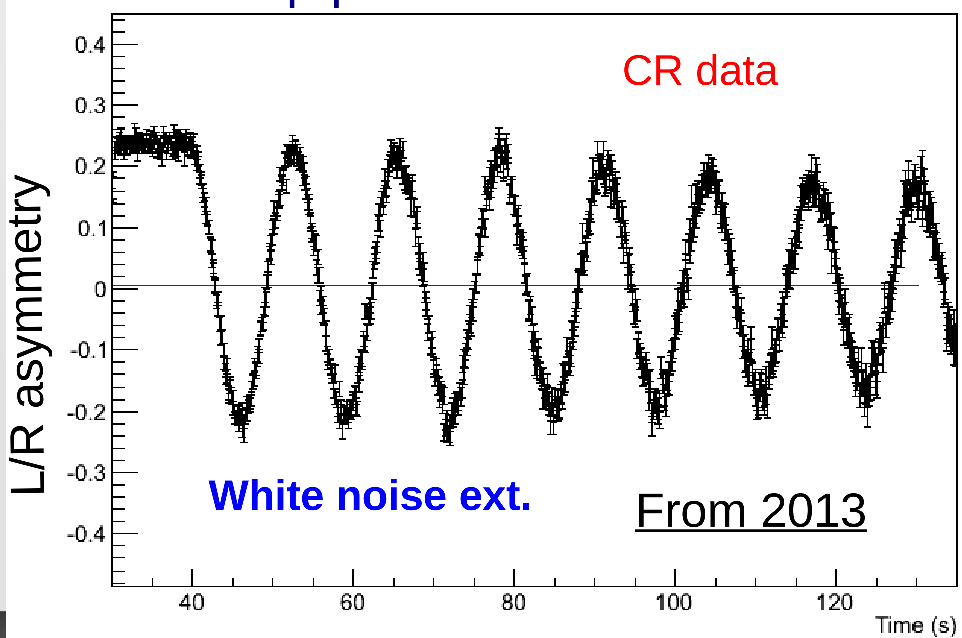


Ago 2013: new issues

Wide Δp/p distribution



Wide Δp/p distribution



Extraction method:
Ramping changes the spin tunes

↓

small Froissart-Stora scan that flips the polarization

It may be possible to reproduce the data with “no-lattice” model.