EXA2011

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Kernfysisch Versneller Instituut

Search for Electric Dipole Moments at Storage Rings

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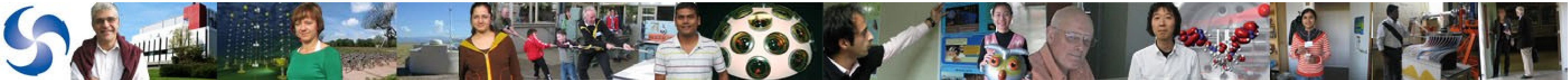
FOM

NWO



Outline

Motivation

Ring techniques

Experiments considered

R&D progress

Outlook

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Permanent EDMs violate T/CP and P

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

$$= -\left[\mu\,\vec{B} + d\,\vec{E}\right]\cdot\hat{S}$$

$$\vec{d} = \begin{cases} \cancel{\kappa\,\vec{E}} & \textit{induced} \\ d\,\hat{S} & \textit{permanent} \end{cases}$$

T **P**

$$= -\left[\mu\,\vec{B} + d\left(-\vec{E}\right)\right]\cdot\hat{S}$$

$$= -\left[\mu\left(-\vec{B}\right) + d\,\vec{E}\right]\cdot\left(-\hat{S}\right)$$

d ≠ 0 → **T** & **P** violation → **CP** violation

EDMs in the Standard Model : δ_{CP}

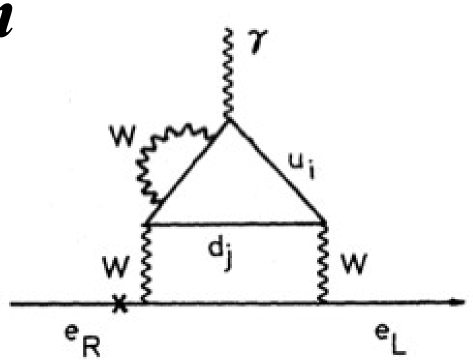
All CP-odd effects involve Jarlskog invariant:

$$J_{CP} = \sin^2\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta_{CP} \sim 3\times 10^{-5}$$

≠0 because of SM flavor structure (Nobel 2008)

$$d_n(SM) \sim (10^{-7})^2 \cdot J_{CP} \cdot \frac{e}{M_n} \sim 10^{-31}\, e\cdot cm$$

EDMs flavor-conserving → multi-loop (≥3)



SM Predictions:

Quarks	:	$\sim 10^{-33\cdots 34}$ $e\cdot$cm
Neutron	:	$\sim 10^{-31\cdots 32}$ $e\cdot$cm
^{199}Hg	:	$\sim 10^{-33\cdots 34}$ $e\cdot$cm
Electron	:	$<10^{-40}$ $e\cdot$cm

Standard Model CKM EDMs are (currently) unmeasurably small

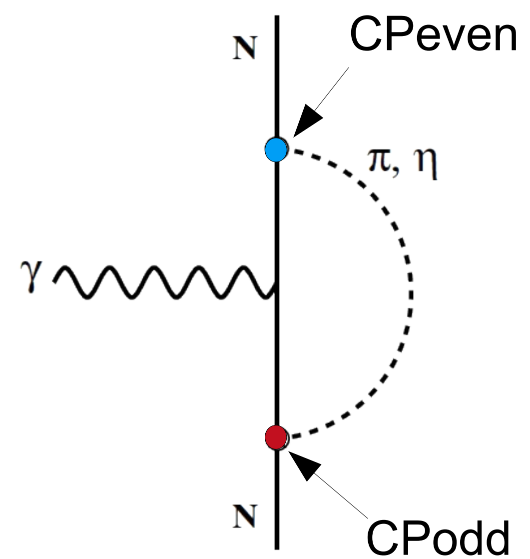
I.B. Khriplovich, S.K. Lamoreaux, *CP Violation Without Strangeness*, Springer, 1997

EDMs in the Standard Model : θ_{QCD}

QCD contains P- and T-odd term:

$$L_\theta = \theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}$$

$$\bar{g}_{\pi NN} \approx -0.027\,\bar{\theta} \qquad g_{\pi NN} \approx 13$$



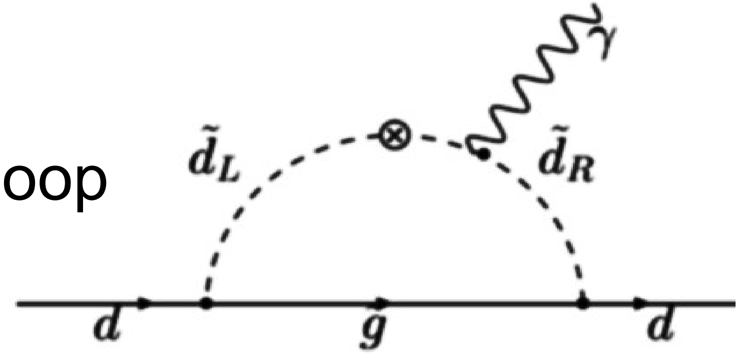
Naively, one would expect θ ~ O(1)

Experimentally, |θ| < 10^{-9} (from the neutron EDM)

Strong CP problem

e.g. M.E. Pospelov and A. Ritz, NP**B558** (1990) 243

EDMs from New Physics



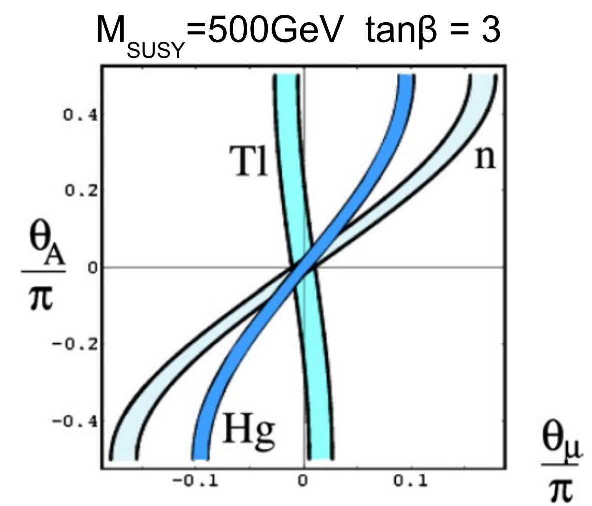
~ all “new physics” : extra CPV, often 1-loop

d(NP) >> d(SM)

e.g. SUSY :

$$d_n(NP) \sim \sin\delta_{CP}\left(\frac{1\ TeV}{M_{SUSY}}\right)^2 \times 10^{-25}\ e\cdot cm$$

SUSY CP Problem



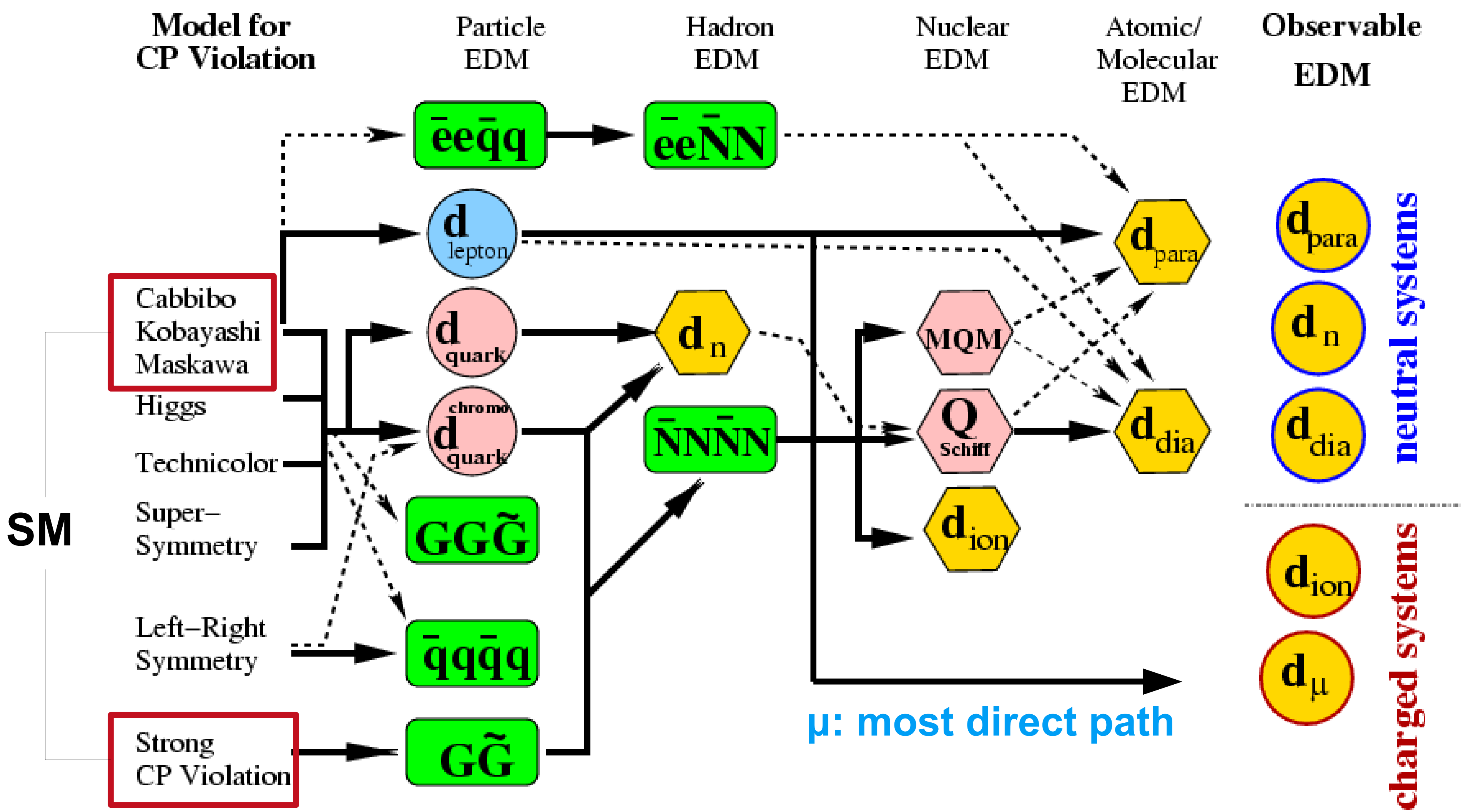
Fine-tuning of phases

- New physics expected at TeV scale (**LHC**)
- *current* EDM expt^s sensitive at few TeV scale
- BAU → additional sources of CPV?

Ultra-sensitive New Physics Probe

e.g. M.E. Pospelov and A. Ritz, **AP318** (2005) 119

From theory to observable … and back



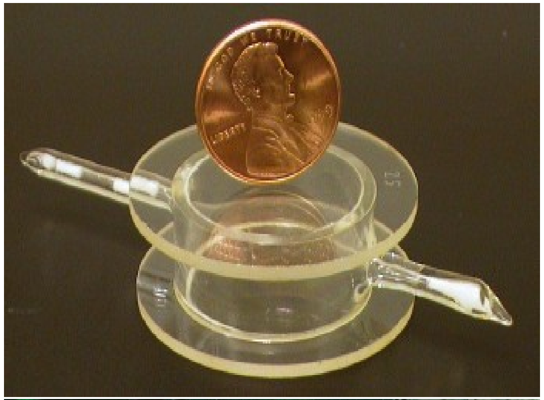
Need multiple experiments to unravel

e.g. J. de Vries et al., Phys. Rev. Lett. 107, 091804 (2011)

Interpretation of ^{199}Hg EDM

$|d_{Hg}| < 3.1\times10^{-29}$ e·cm (95% C.L.)

Parameter	^{199}Hg bound
$\tilde{d}_q$ (cm)	6×10^{-27}
d_p (e cm)	7.9×10^{-25}
C_S	5.2×10^{-8}
C_P	5.1×10^{-7}
C_T	1.5×10^{-9}
$\bar{\theta}_{QCD}$	3×10^{-10}
d_n (e cm)	5.8×10^{-26}
d_e (e cm)	3×10^{-27}



$\delta\nu_{stat} = 0.13$ nHz (7.5 ppt)

1 cycle per 244 years

W. C. Griffith,et al., Phys. Rev. Lett. 102, 101601 (2009)

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The challenge of an EDM search

$$H = -\vec{\mu}\cdot\vec{B} - \vec{d}\cdot\vec{E}$$

Corresponding energy shift

$$\Delta E = \hbar\omega = 2dE$$

SM value for neutron

$d = 10^{-31}\ e\cdot\text{cm}$, $E = 1$ MV/m

$\Delta E = 2 \cdot 10^{-25}$ eV (0.2 yeV)

ω = 0.3 nHz (~1/century)

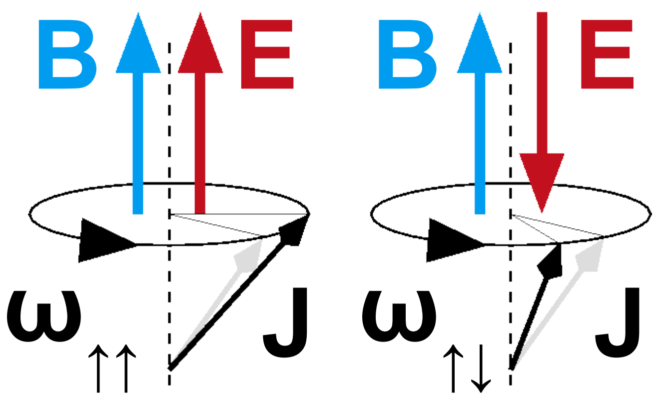
Equivalent to B ~ aT

EDM-induced spin precession

Prepare spin polarized ensemble

Interaction with electric field

Measure spin evolution



$$\frac{d\langle\vec{J}\rangle}{dt} = \big(\underbrace{\mu\vec{B} + d\vec{E}}_{\vec{\omega}}\big)\times\langle\hat{J}\rangle$$

$$\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow} = \frac{4dE}{\hbar}$$

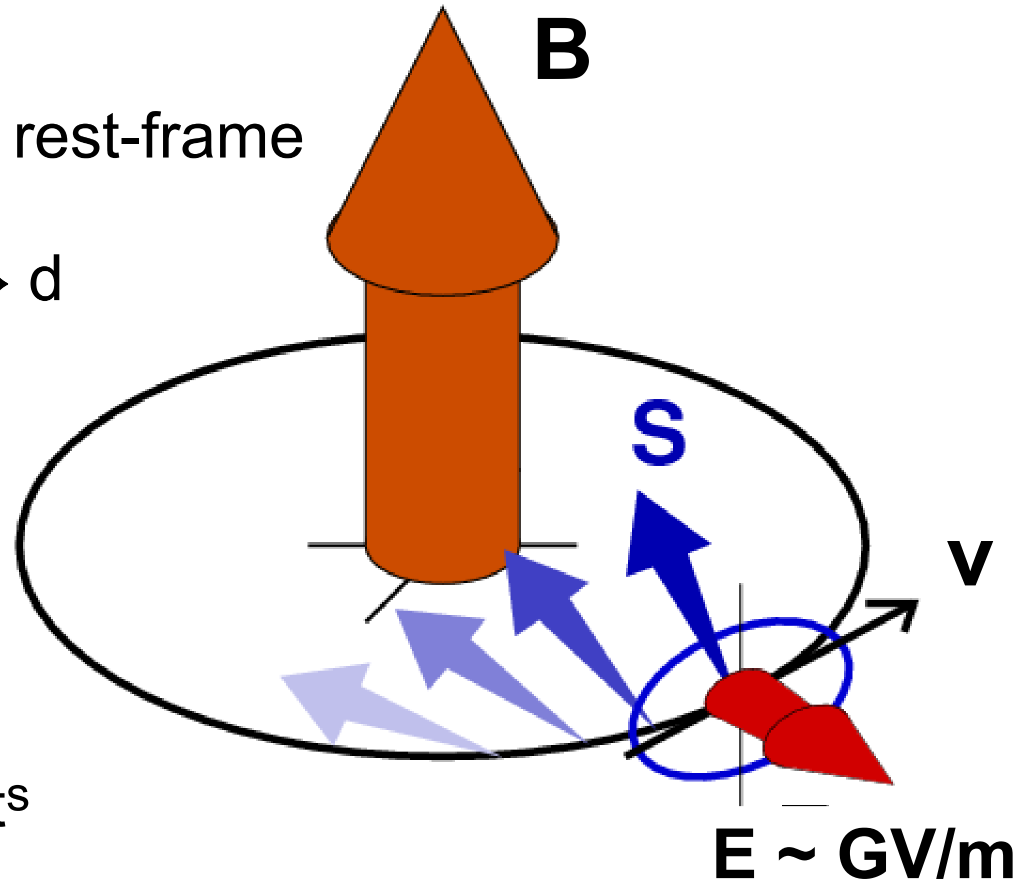
frequency measurement

Precision ~ Heisenberg

Magnetic Storage Ring

Use motional electric field in rest-frame

Track precession of S // B → d



Novel technique

Builds on experience from
- muon g-2 experiment
- nuclear physics expts
- “Conventional” EDM expts

Probe charged particles directly

F. Farley et al., Phys. Rev. Lett. 93, 052001 (2004)

EDM in an electromagnetic field

$$\vec{\Omega}=\frac{e}{m}\left[a\vec{B}+\left(a-\frac{1}{\gamma^2-1}\right)\vec{v}\times\vec{E}+\frac{\eta}{2}\left(\vec{E}+\vec{v}\times\vec{B}\right)\right]$$

magnetic moment anomaly

EDM

parasitic

$E=0$, $B=B_y$

(1) $\omega=\sqrt{a^2+(\eta\beta)^2/4}\,B$

(2) $\hat{\omega}\times\hat{B}=\eta\beta/2a$

electrostatic

$B=0$, E_r, $1/(\gamma^2-1)=a$

(1) $\langle\omega_\eta\rangle=\eta E/2$

(2) $\hat{\omega}_\eta=\hat{E}$

resonance

$E_z\approx E\cos(\Omega t)$

(1) $\langle\omega_\eta\rangle=\eta\Delta\beta B/4$

(2) $\langle\hat{\omega}_\eta\times\hat{B}\rangle=1$

frozens spin

$E_r\approx aBc\beta\gamma^2$

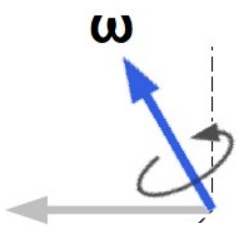
(1) $\omega=\eta\beta B/2$

(2) $\hat{\omega}\times\hat{B}=1$

C.J.G. Onderwater, Light ion EDM search in magnetic storage rings, Hyperfine Interactions **172** (2007) 35.

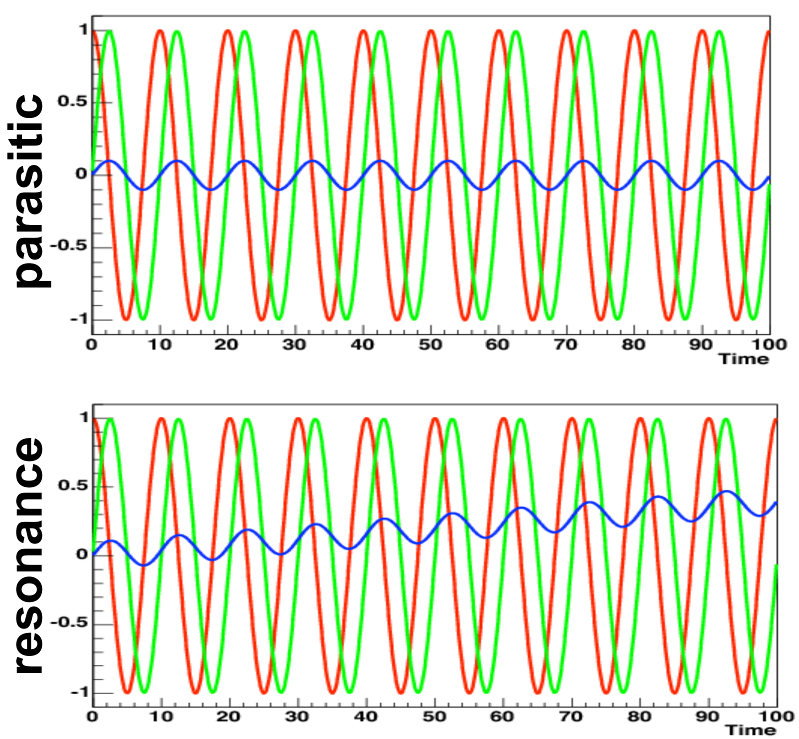
EDM in an electromagnetic field

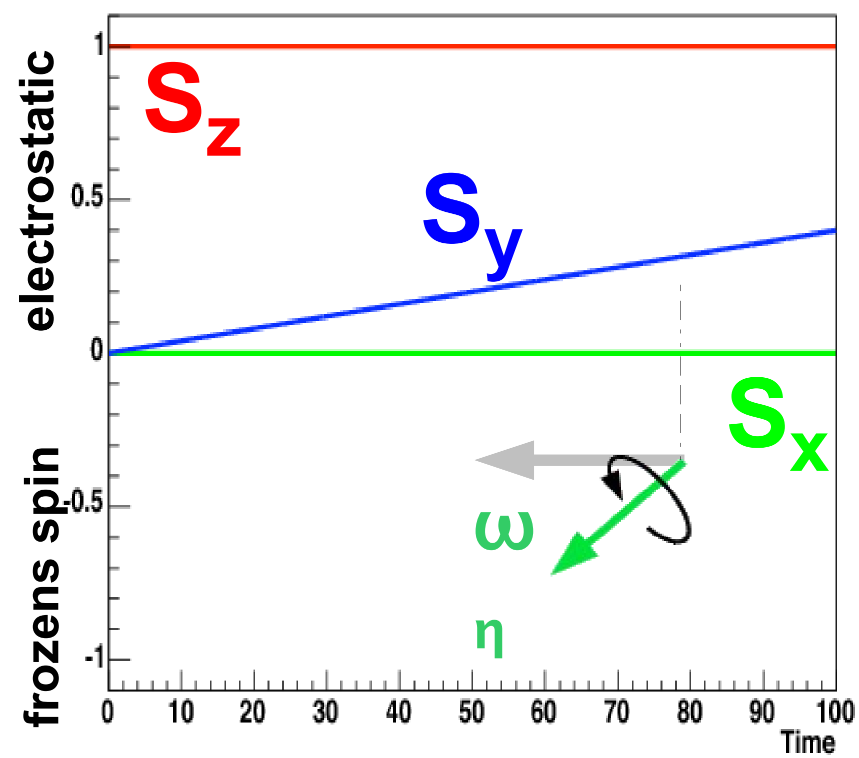
$$\vec{\Omega}=\frac{e}{m}\left[a\vec{B}+\left(a-\frac{1}{\gamma^2-1}\right)\vec{v}\times\vec{E}+\frac{\eta}{2}\left(\vec{E}+\vec{v}\times\vec{B}\right)\right]$$



magnetic moment anomaly

EDM





C.J.G. Onderwater, Light ion EDM search in magnetic storage rings, Hyperfine Interactions **172** (2007) 35.

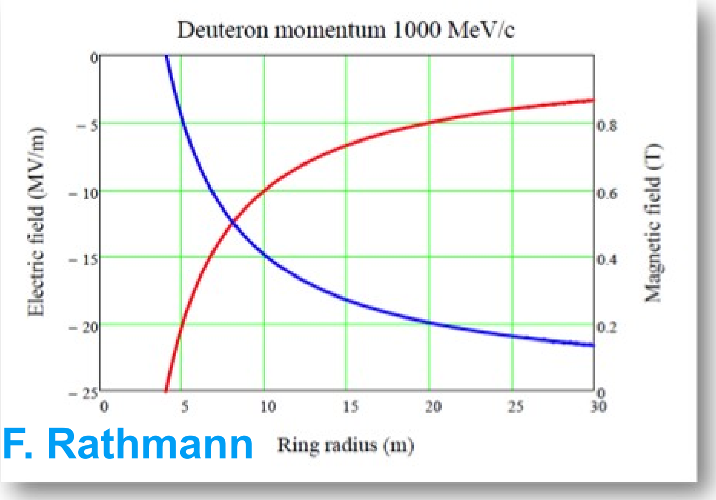
Candidate particles

β-Emitters with small *a*

$\mu^{\pm}$, ^{24}Na, ^{60}Co, ^{82}Br, ^{94}Rb, ^{110}Ag*, ^{118}In*, ^{121}Sn, ^{125}Sb, ^{131}I, ^{133}I, ^{133}Xe, ^{134}Cs, ^{136}s, ^{137}Cs, ^{139}Cs, ^{141}Cs, ^{143}Cs, ^{140}La, ^{160}Tb, ^{170}Tm, ^{177}Lu, ^{183}Ta, ^{196}Au, ^{198}Au, ^{203}Hg, ^{222}Fr, ^{223}Fr, ^{224}Fr, ^{242}Am

Suitable for ExB ring
Smaller a → lower E
Positive a → E reduces ring size

β emitter → self analyzing



F. Rathmann

Stable particles with small *a*

$e^{\pm}$, ^{2}**H**, ^{6}Li, ^{75}As, ^{123}Sb, ^{139}La, ^{171}Yb

Particles with large *a>0*

p, …

Suitable for electrostatic ring
Bigger a → lower momentum
Ring size ~ electric field strength

Khriplovich / Jungmann

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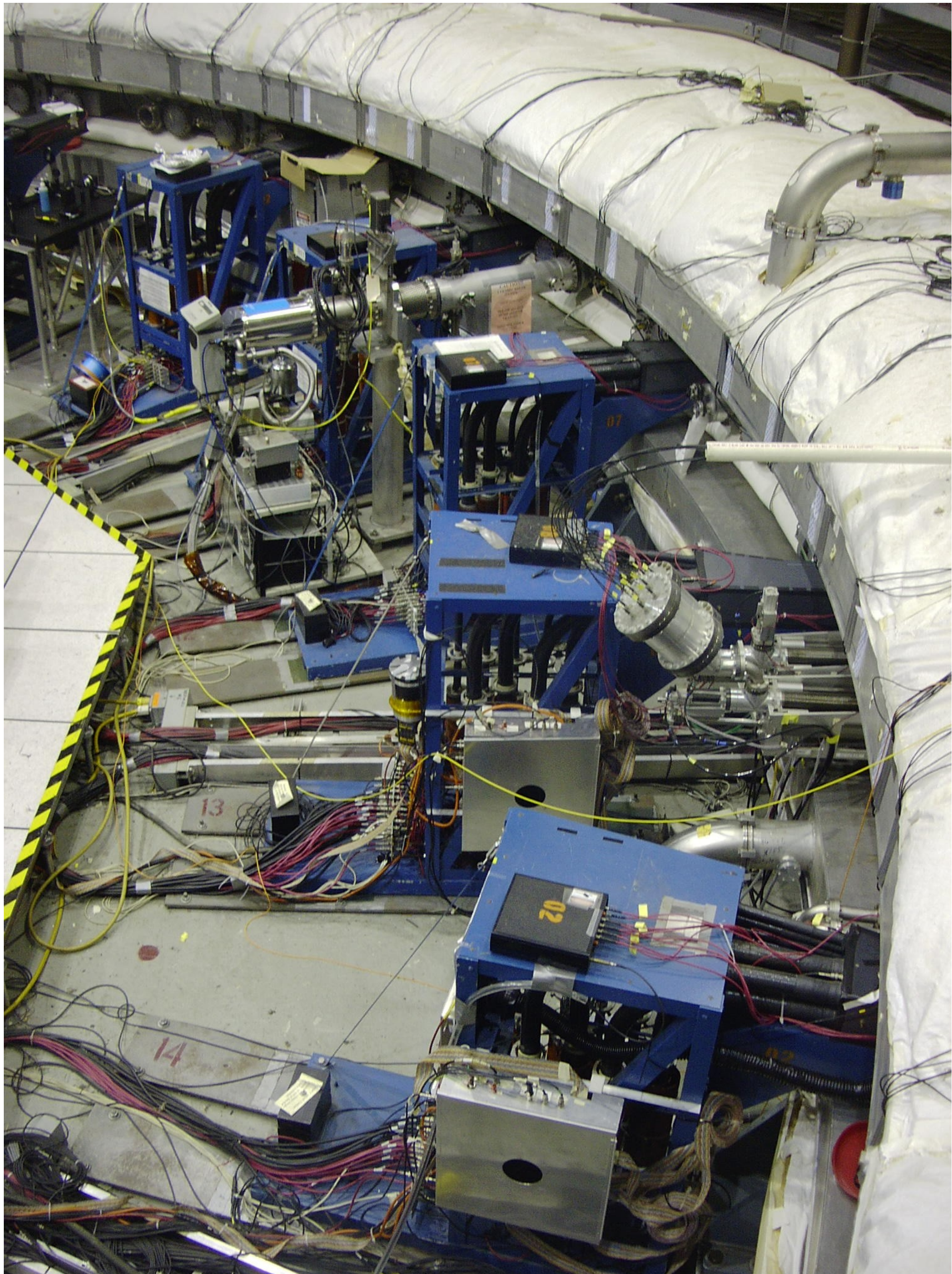
Parasitic : muon g-2 @ FNAL

R.M. Carey et al. (2009)
FNAL Proposal
"The New (g-2) Experiment: A Proposal to Measure the Muon Anomalous Magnetic Moment to 0.14 ppm Precision"



Design

- p = 3.1GeV/*c*
- B = 1.45T
- R = 7m

Estimated Sensitivity

around 10^{-21} e·cm
two orders below current limit

Frozen spin : muons @ J-PARC

A. Silenko et al. (2003)
J-PARC Letter of Intent
“Search for the Permanent Muon Electric Dipole Moment at the 10^{-24} e·cm Level”

Design

- p = 500MeV/*c*
- B = 0.25T,
- E = 2MV/m ← Defining
- R = 7m

Estimated Sensitivity
around 10^{-24} e·cm
five orders below current limit

Realization before 2015??

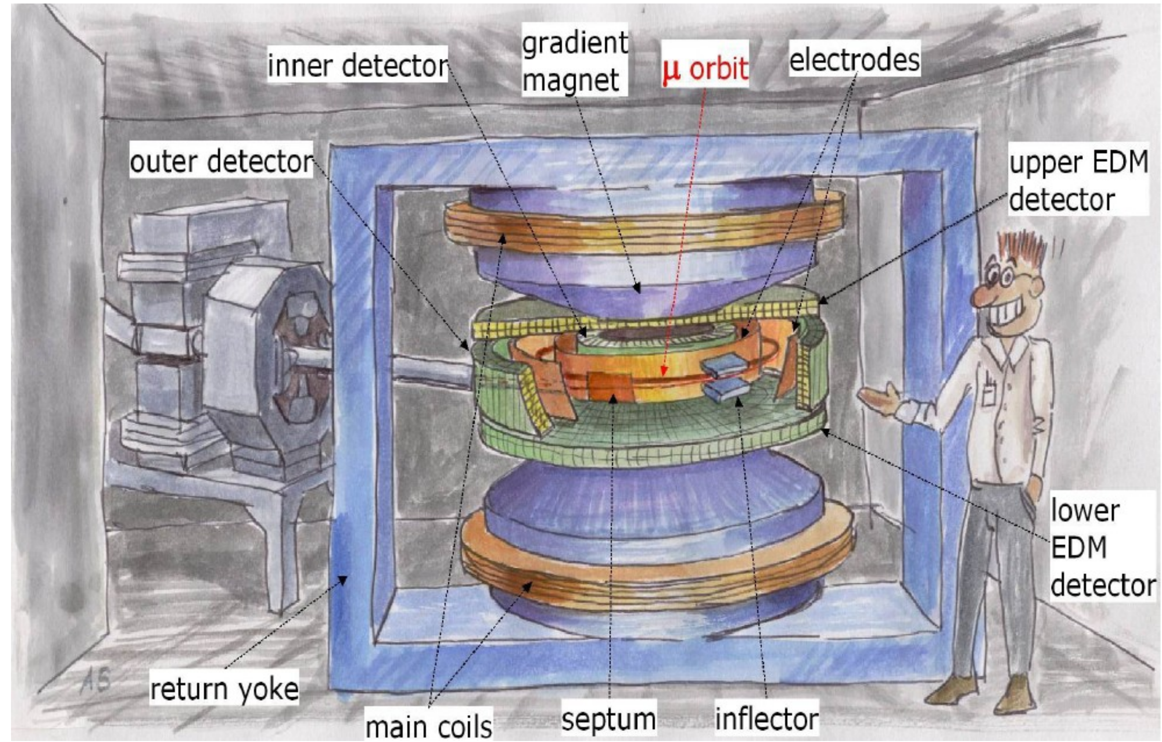
Post g-2 @ Project-X?

(B.L. Roberts *et al.)*

Frozen spin : muons @ PSI

Idea for PSI

- $p = 125\,\mathrm{MeV}/c$
- $N = 10^8/\mathrm{s}$
- $P = 92\%$
- $B = 1\mathrm{T}$ ← Defining
- $E = 0.64\,\mathrm{MV/m}$
- $R \sim 50\,\mathrm{cm}$



Reach: 5×10^{-23} e · cm / y

3-4 orders below current limit **@ 1 μ / shot → trivial upgrade**

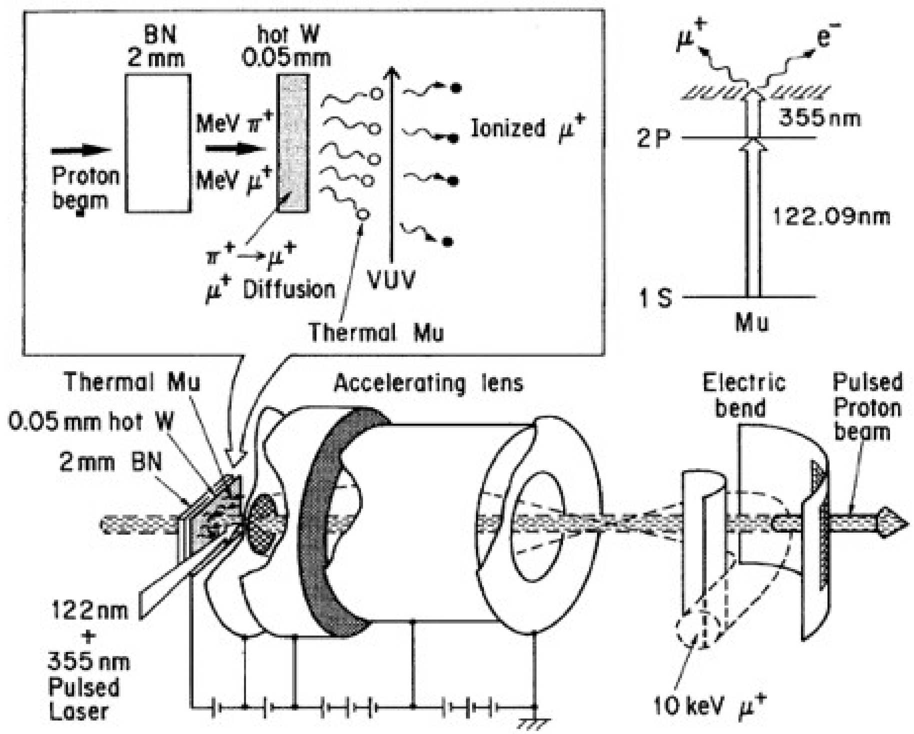
Adelmann, Kirch, Onderwater & Schietinger, J. Phys. G: Nucl. Part. Phys. 37 085001 (2010)

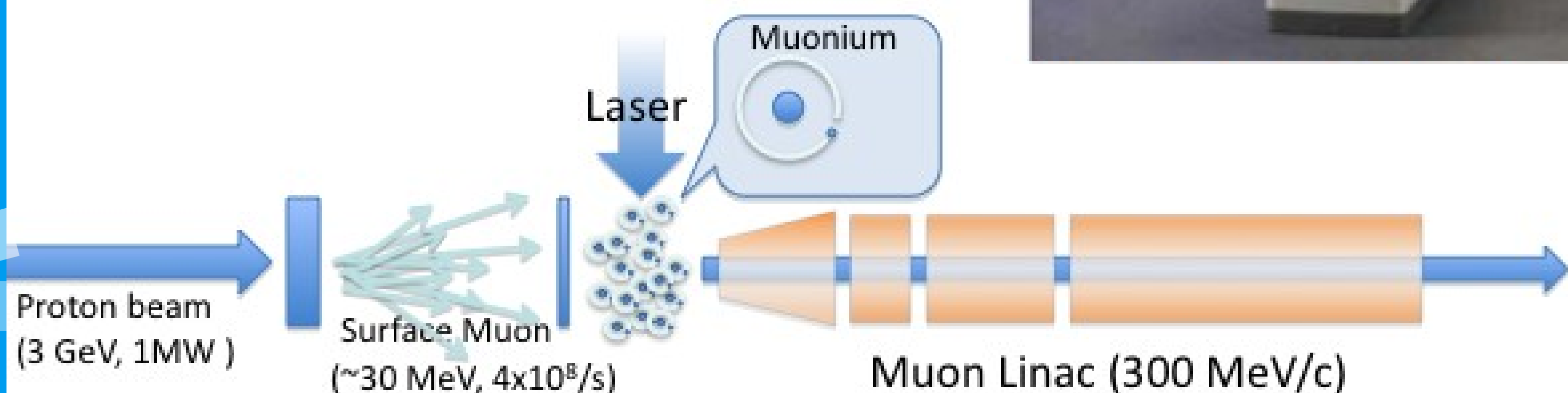
Table top experiment!

Ultra-cold muons @ J-PARC

K. Nagamine et al. PRL 74 (1995) 4811
Y. Matsuda et al. NPB(Proc) 155(2006) 346

LASER IONIZATION OF MUONIUM





N. Saito

Protons @ BNL

V. Anastassopoulos *et al.* (2011)
DOE CD0 proposal
"A Proposal to Measure the Proton Electric Dipole Moment with 10^{-29} e·cm Sensitivity"

Design

- p = 0.7GeV/c
- E = 10MV/m
- R = 40m

Estimated Sensitivity

around 10^{-29} e·cm
two orders below current **nEDM** limit

Y. Semertzidis, Bad Honnef, 2011

Light nuclei @ FZJ (JEDI)

EDM with E- and B-Fields

JÜLICH FORSCHUNGSZENTRUM

„all-in-one“ storage ring

Protons: p_p = 0.701 GeV/c
E_R = 16.8 MV/m, B_V = 0 T

Deuterons: p_d = 1.0 GeV/c
E_R = -4.0 MV/m, B_v = 0.16 T

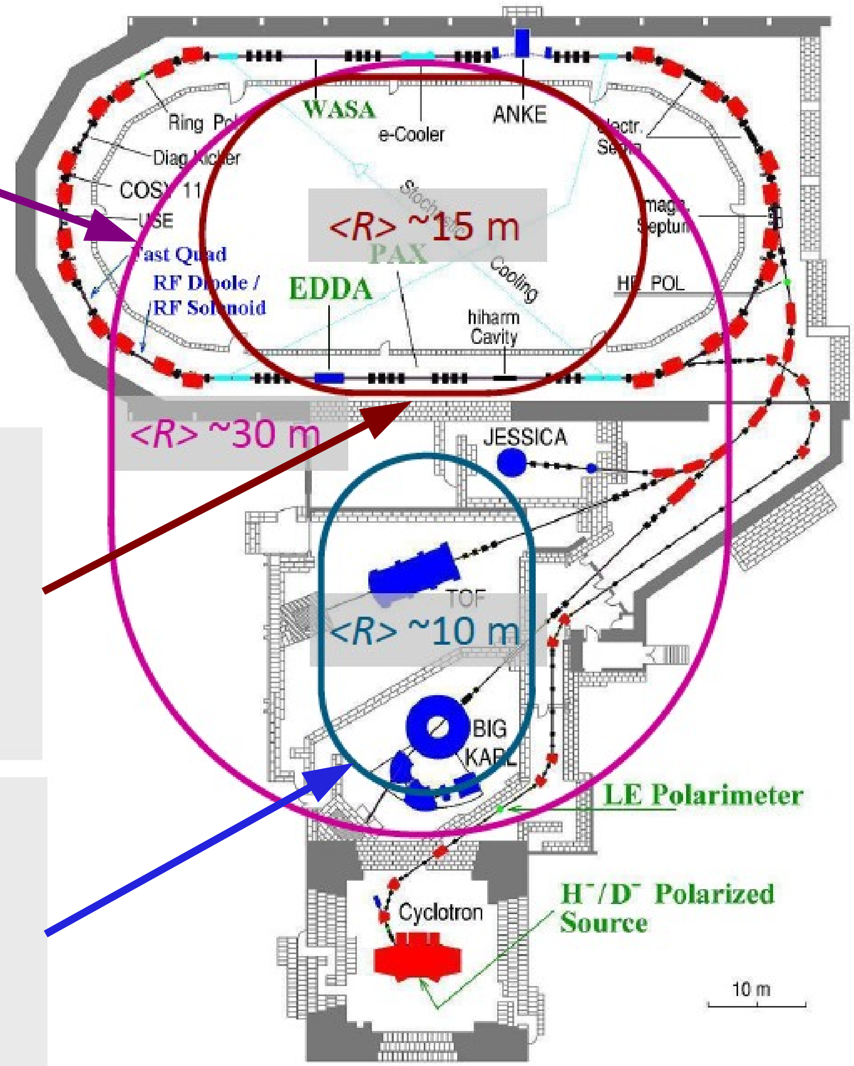
Helium-3: p_{3He} = 1.285 GeV/c
E_R = 17.0 MV/m, B_V = -0.05 T

„all-in-one“ storage ring

Protons: p_p = 0.527 GeV/c
Deuterons: p_d = 1.0 GeV/c
Helium-3: p_{3He} = 0.946 GeV/c
$E_R \leq$ 17 MV/m, $B_V \leq$ 0.31 T

„all-in-one“ storage ring

Protons: p_p = 0.435 GeV/c
Deuterons: p_d = 1.0 GeV/c
Helium-3: p_{3He} = 0.765 GeV/c
$E_R \leq$ 17 MV/m, B_V < 0.5 T



Mitglied in der Helmholtz-Gemeinschaft

A. Lehrach, Bad Honnef, 2011

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Sensitivity

General expression for the (statistical) uncertainty

$$\sigma_d \propto \frac{1}{P\,E\,\sqrt{N}\,T\,A}$$

N: number of particles in experiment

P: initial polarization of sample

A: analyzing power of polarimeter

E: electric field in particle rest frame

T: characteristic time

Pillars of a sensitive experiment

- Strong source
- High polarization
- Efficient polarimeter
- High electric field strength
- Spin coherence, efficient storage

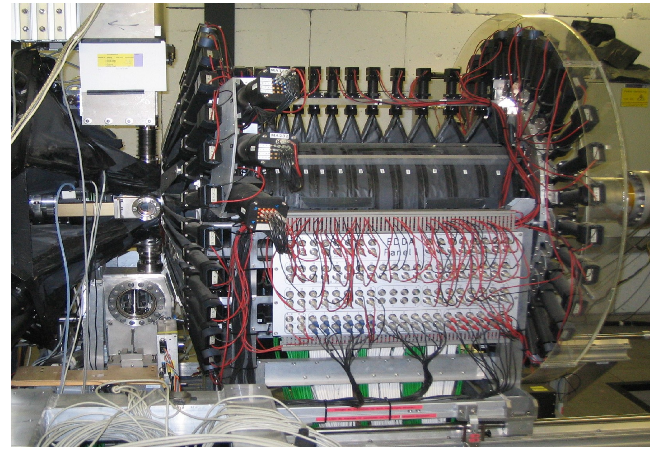
Work done
@ KVI / IBP
@ COSY / EDDA

Equally important: understand systematic effects

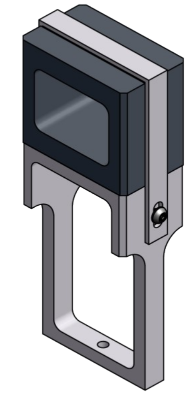
Polarimeter sensitivity

COSY/FZJ

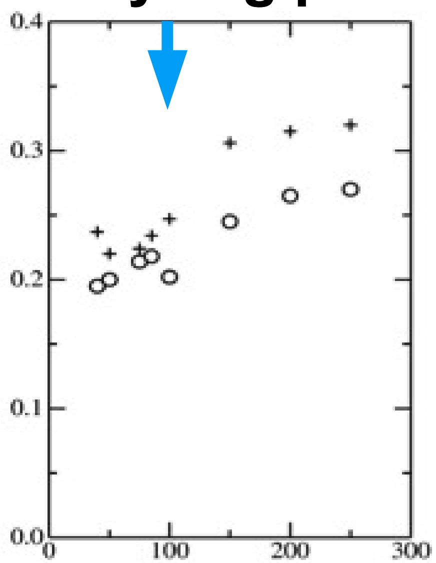
EDDA



Analyzer



Analyzing power



Efficiency

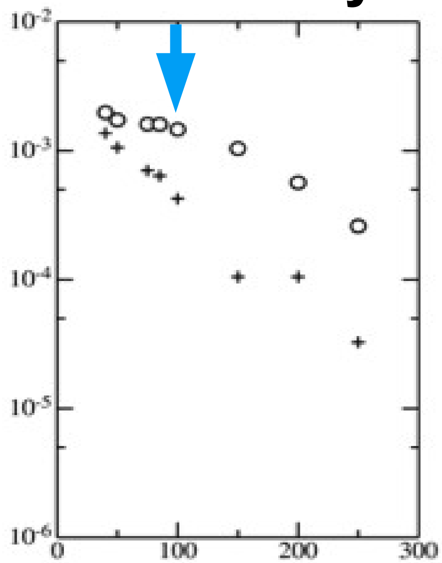
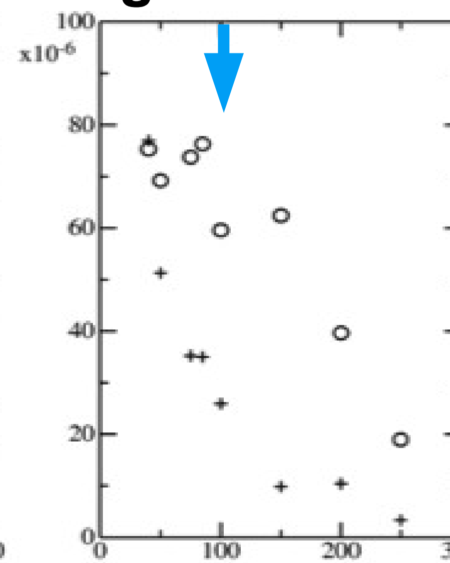


Figure-of-merit



Measured

No absorber

η = 1.5%
A = 0.05
F = 3.8×10^{-5}

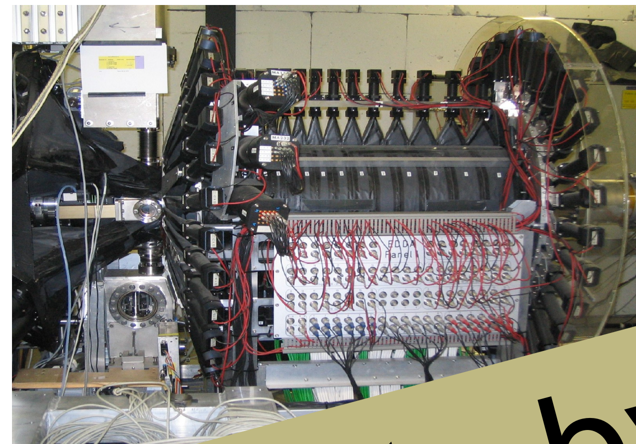
With absorber

η = 0.033%
A = 0.2
F = 1.3×10^{-5}

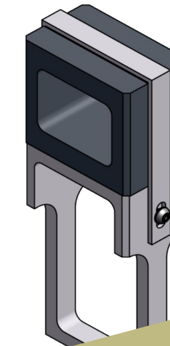
Polarimeter sensitivity

COSY/FZJ

EDDA

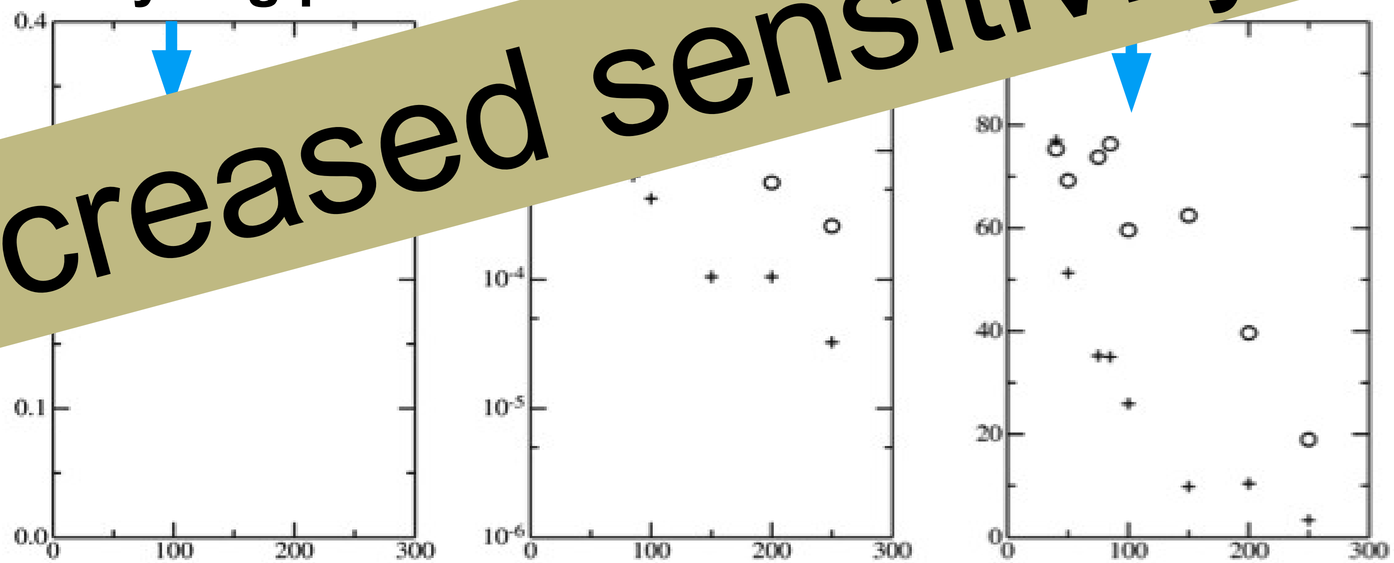


Analyzer



Increased sensitivity by ~10^4

Analyzing power



No absorber

η = 1.5%
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With absorber

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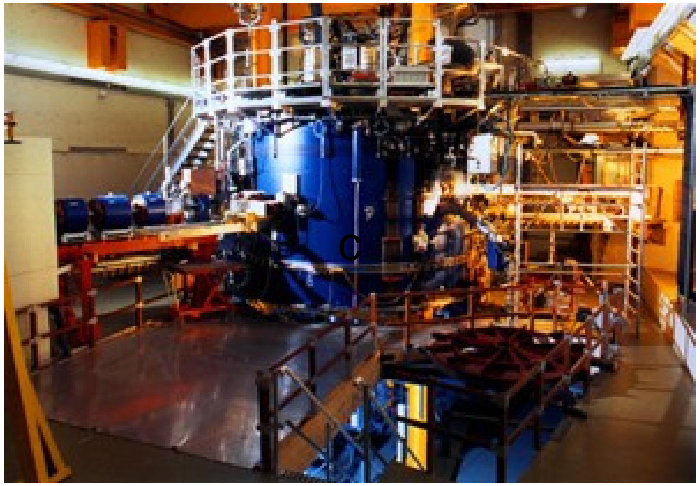
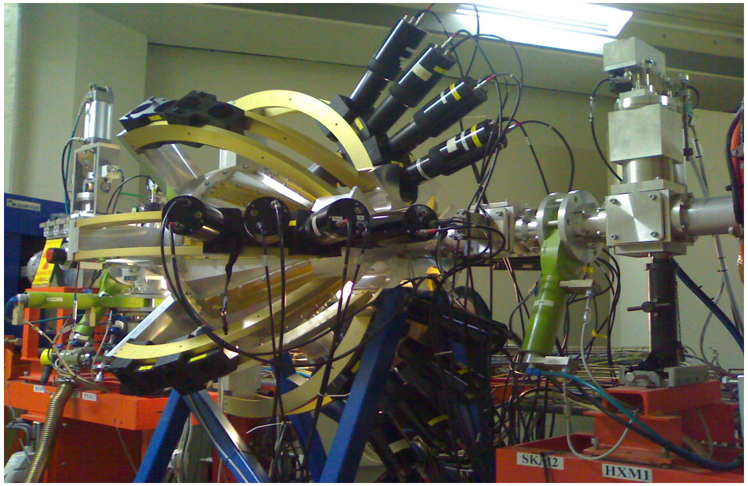
A = 0.2
F = 1.3×10^{-5}

Polarimeter systematics

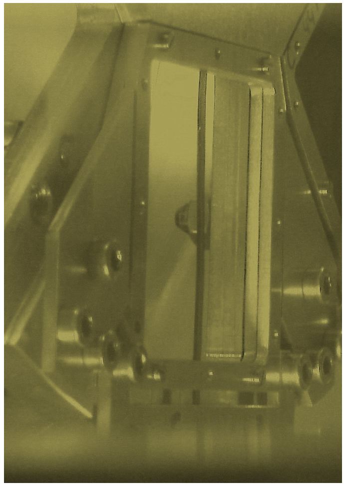
AGOR/KVI



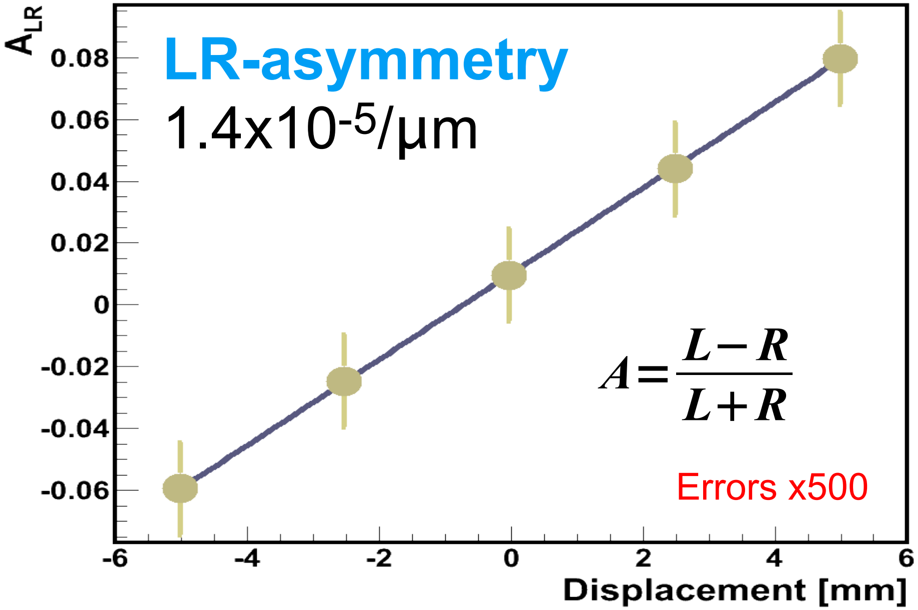
IBP

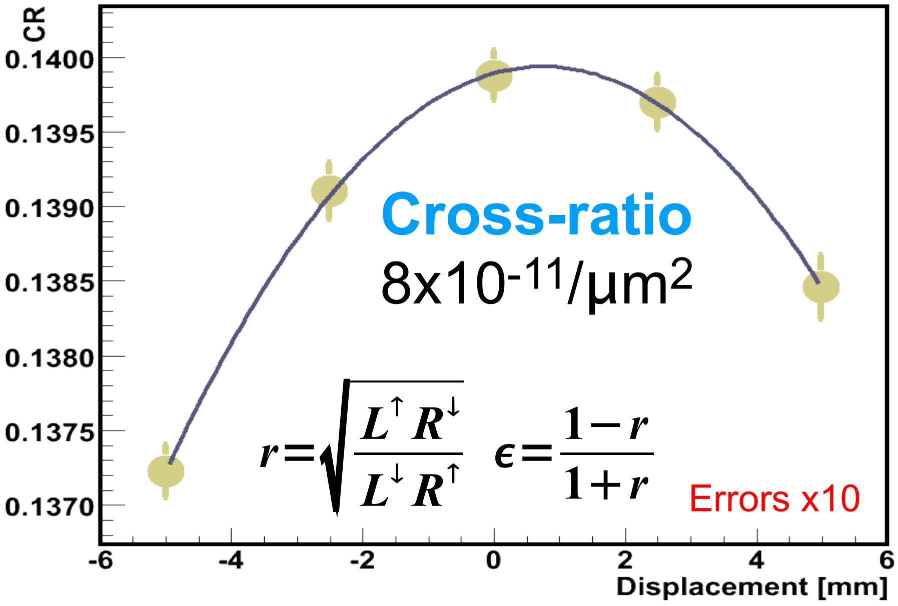


Strip



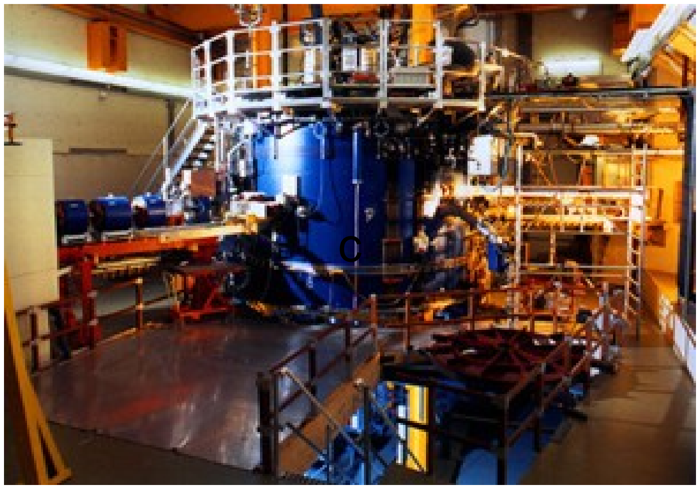
Example: systematic error due to beam displacement



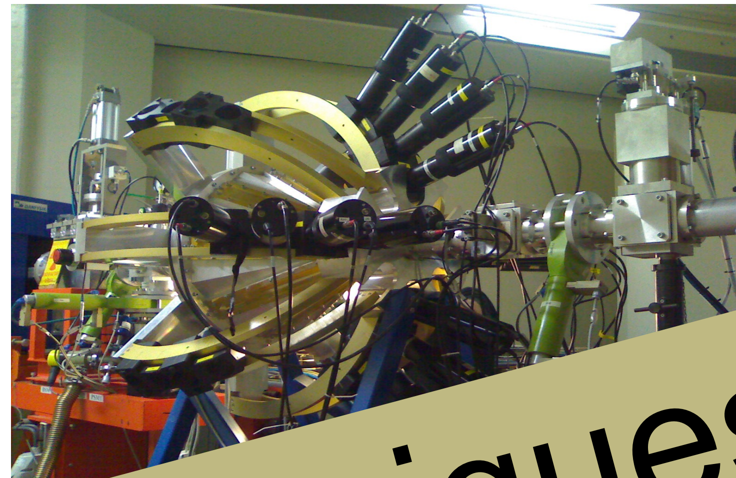


Polarimeter systematics

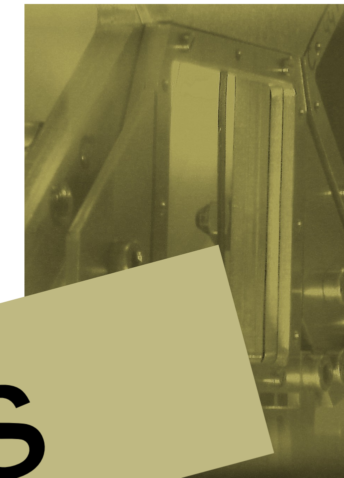
AGOR/KVI



IBP

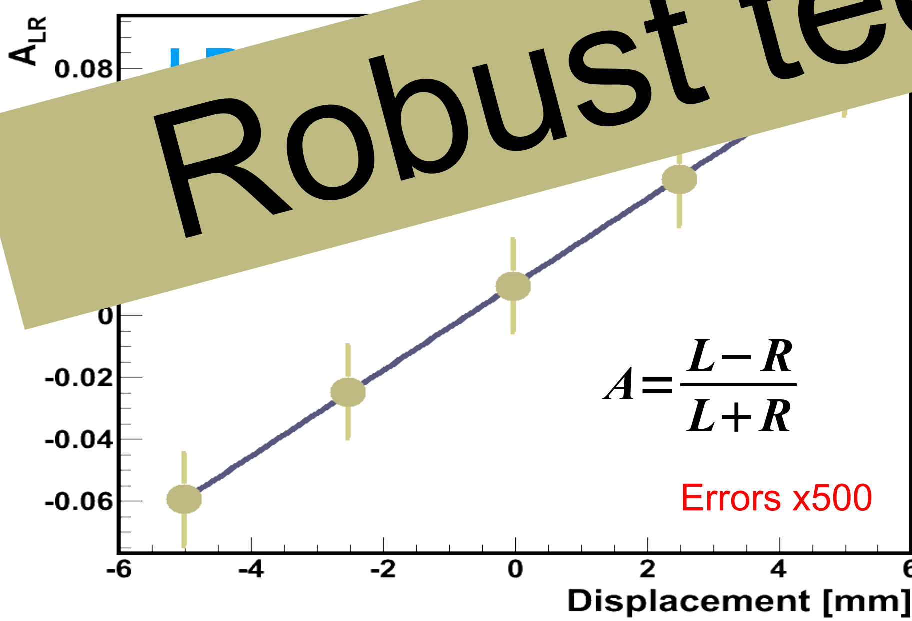


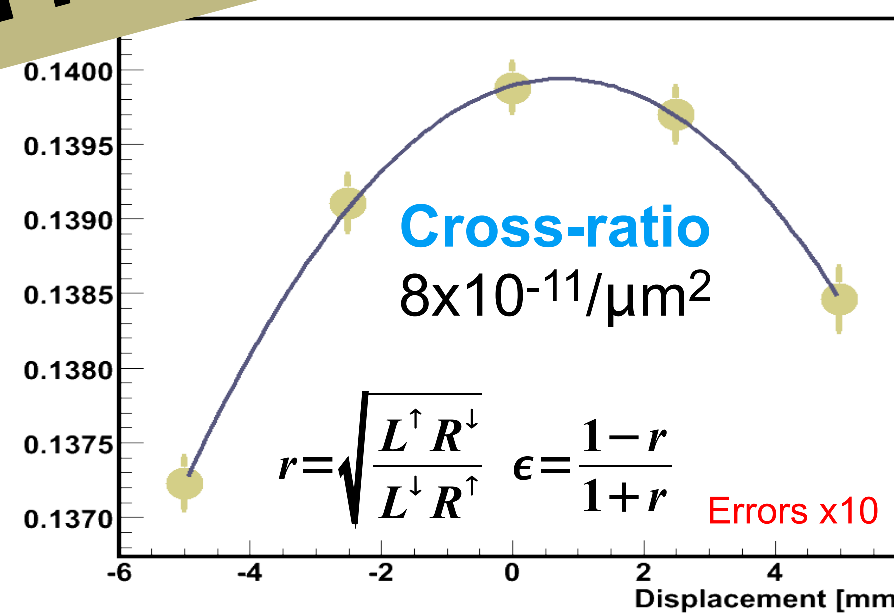
Strip



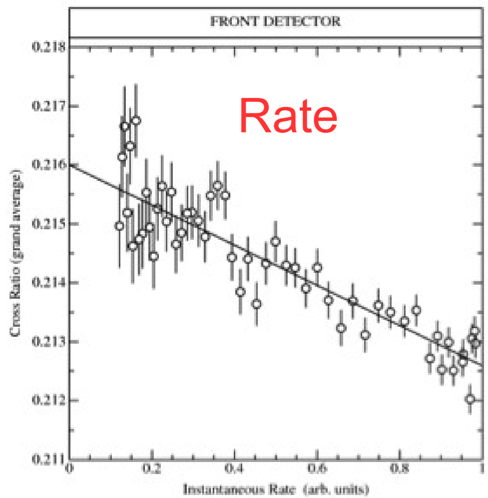
Robust techniques

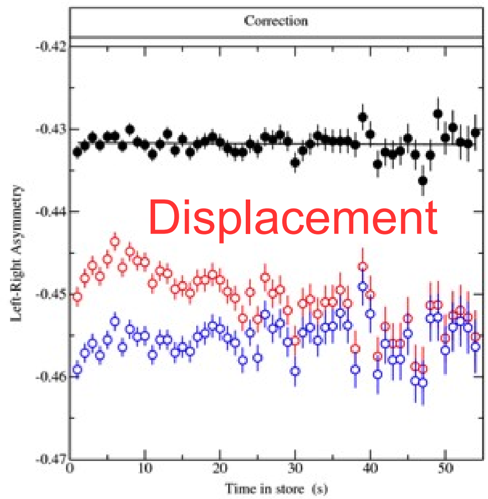
Example: sy… displacement

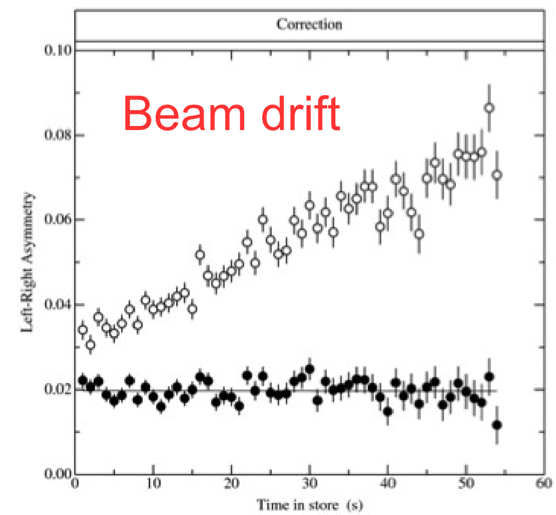


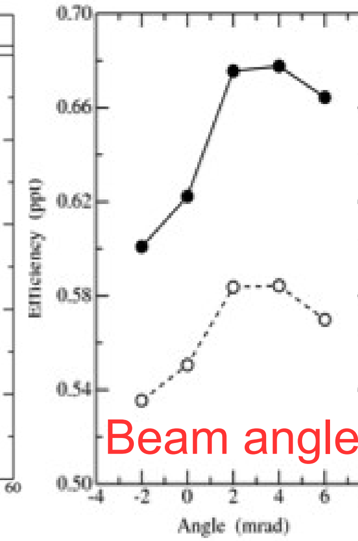


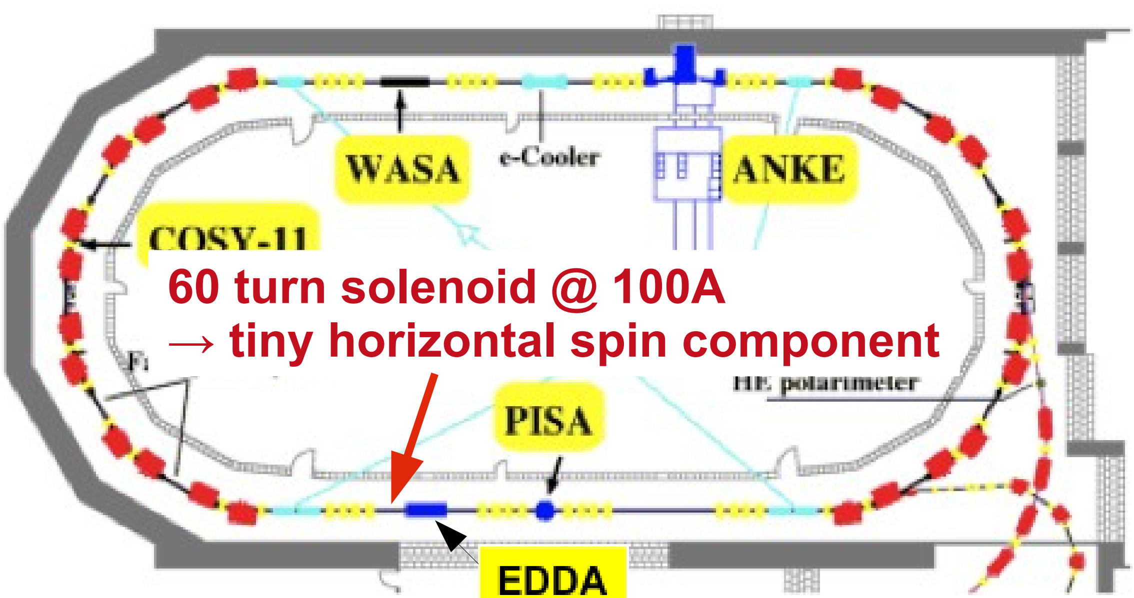
Correction Method & Blind Test

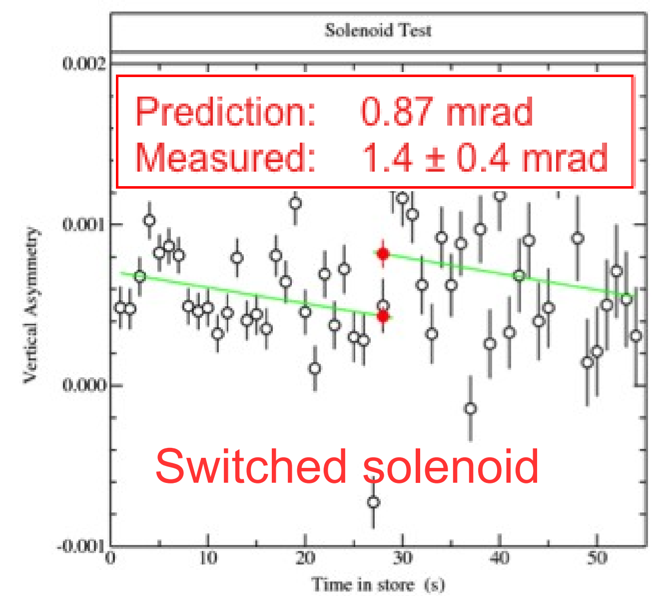




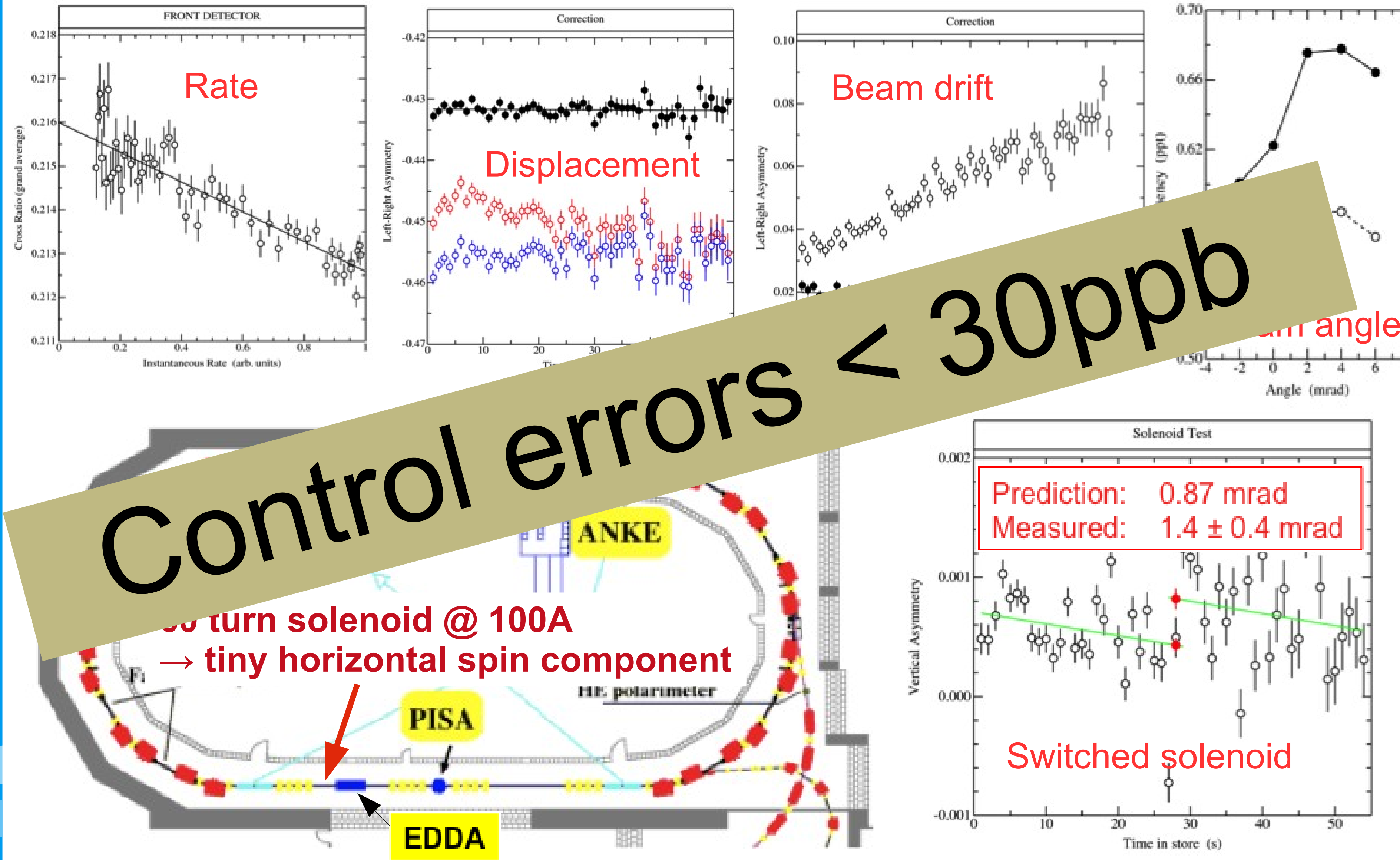






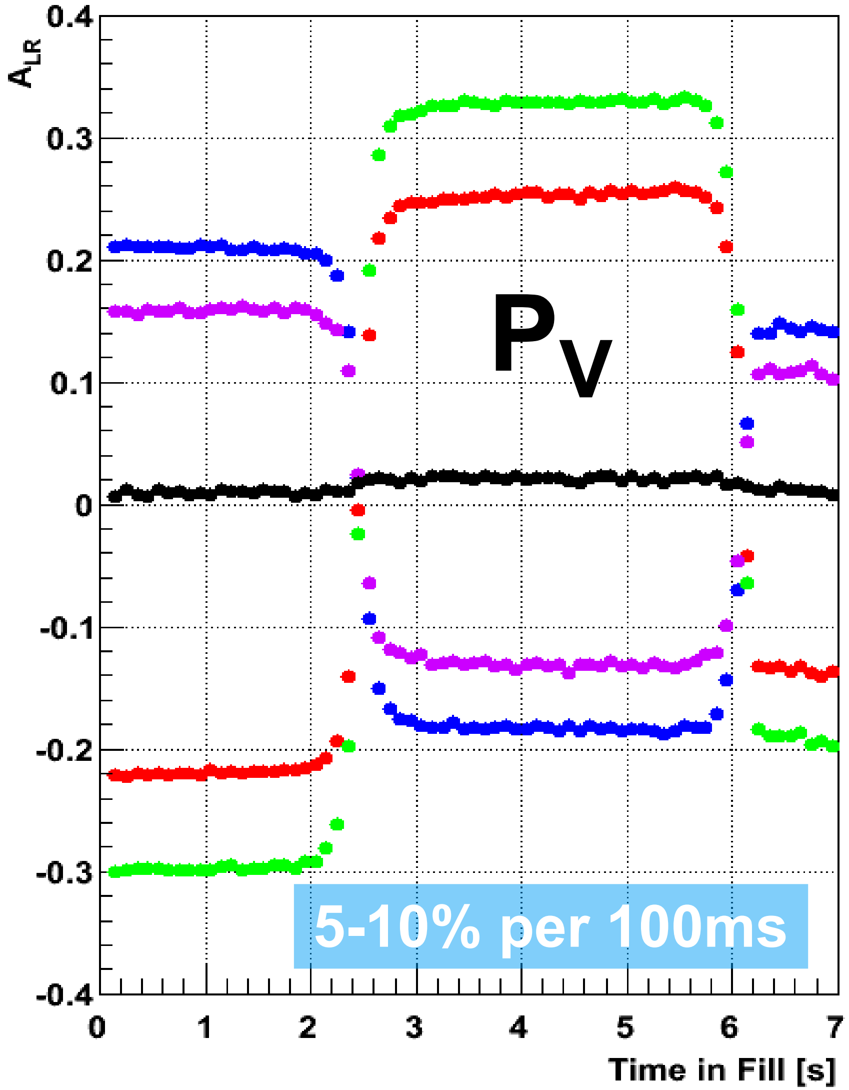


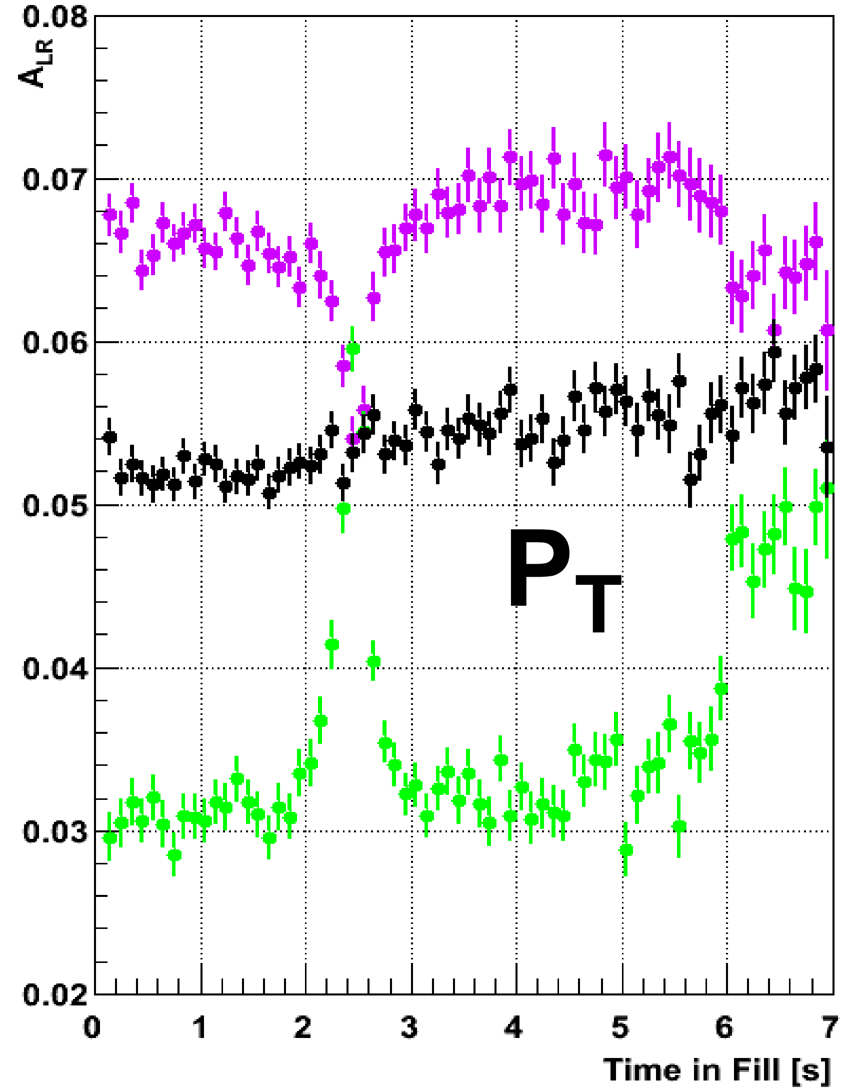
Correction Method & Blind Test



Control errors < 30ppb

Real-time polarimetry





10M particle & 1M spin revolutions

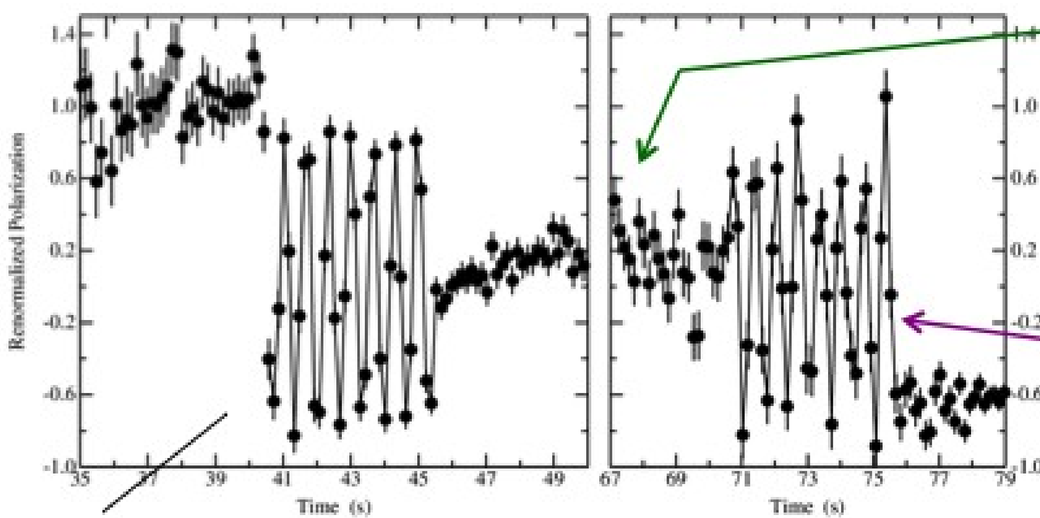
Use for feedback & spin coherence studies

Spin coherence studies

Lower limit on electron-cooled SCT from January run

RF-solenoid produces small polarization kicks about longitudinal direction.
(Kicks vary as cosine with maximum < 4 μrad.)
On (1–Gγ) resonance, this produces continuously reversing vertical P_Y.

Set process to turn RF-solenoid ON, OFF, then ON again.



During this time the polarization is in the ring plane and free to decohere.

If oscillation returns, (1) beam is still polarized, and (2) the RF-solenoid was still in phase (thus this is a lower limit).

Lines added to guide the eye.

5 s	25 s	5 s
reference oscillation	decoherence time	oscillation capture

E. Stephenson, Bad Honnef, 2011

Outline

Motivation

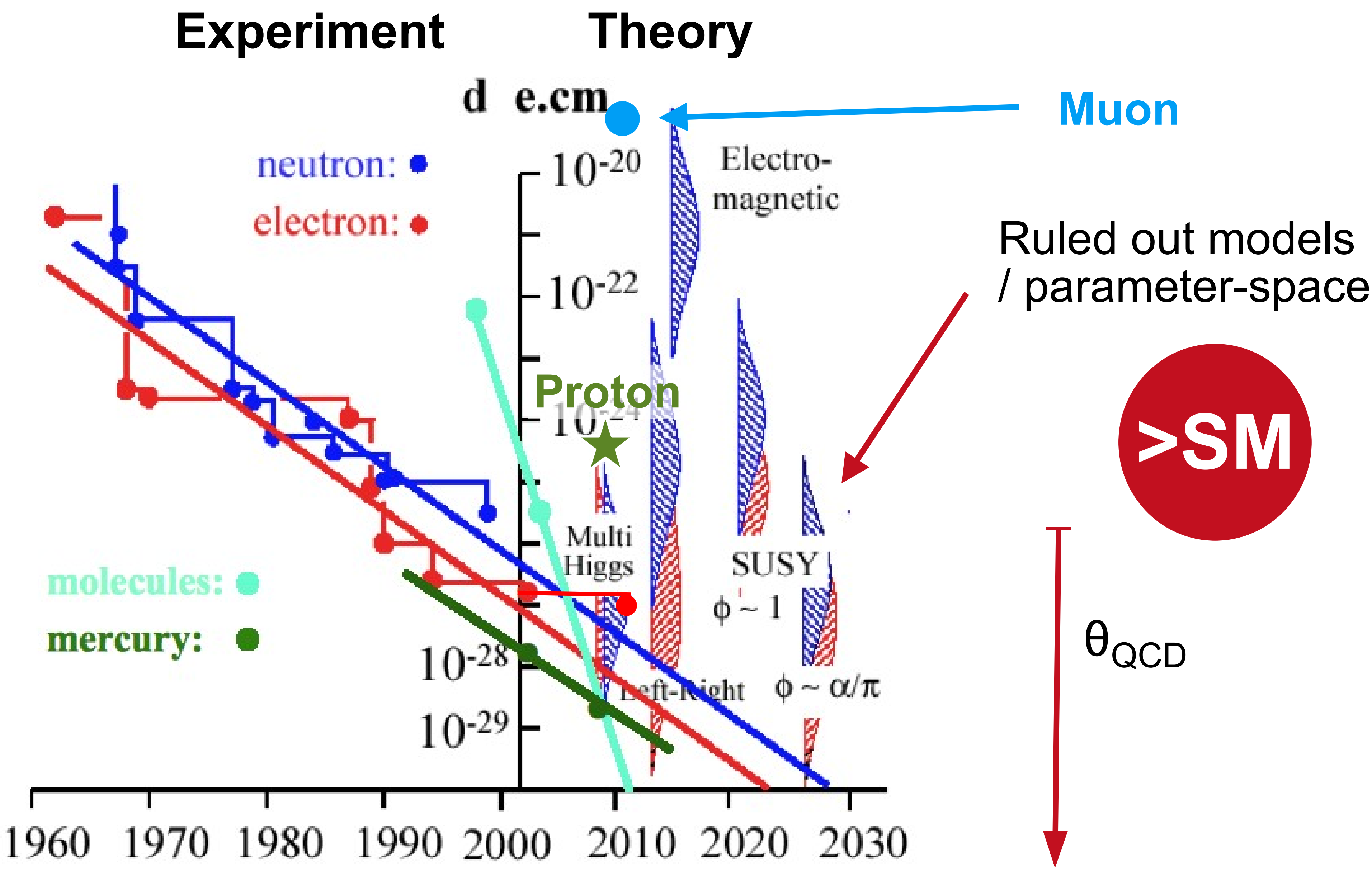
Ring techniques

Experiments considered

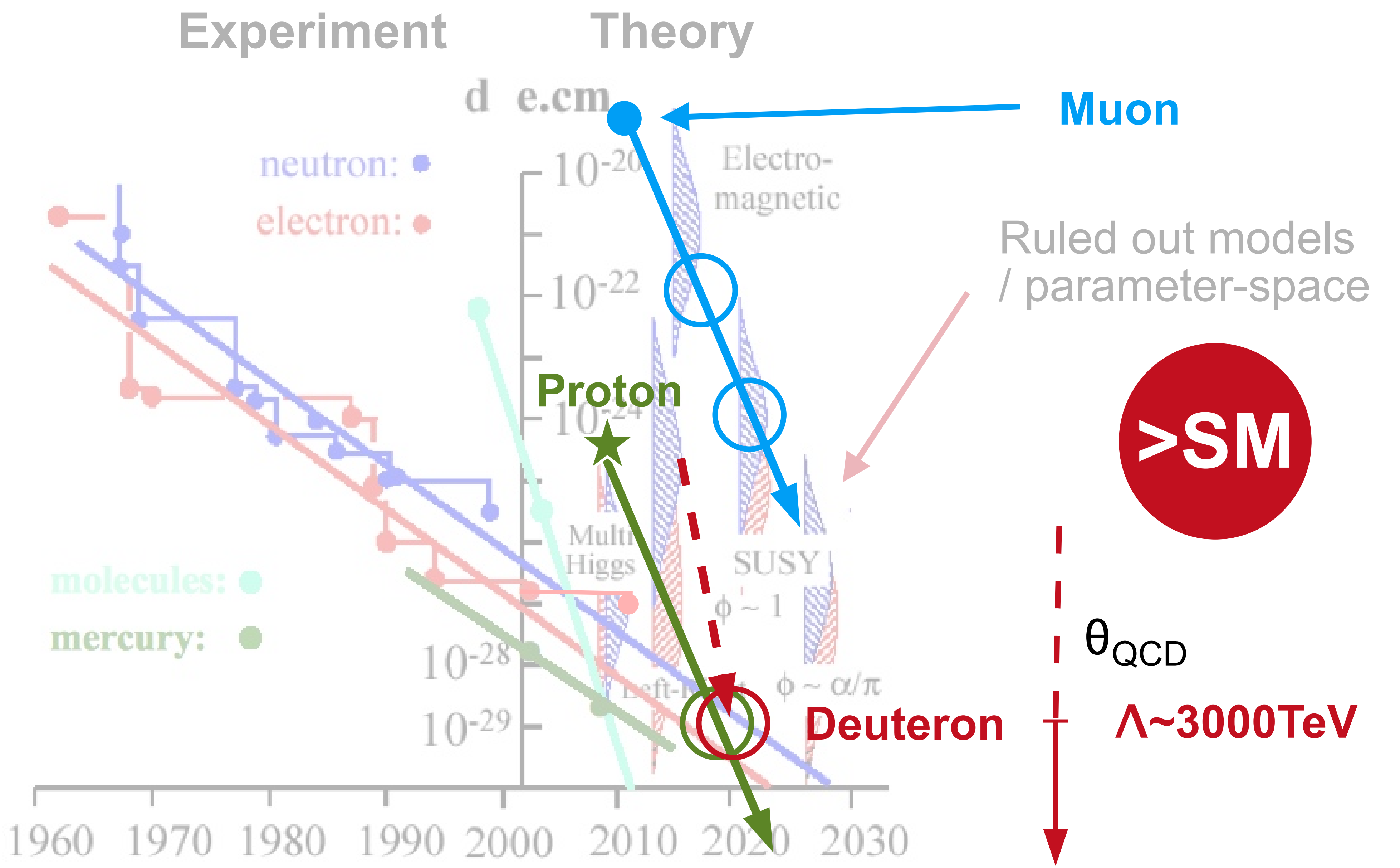
R&D progress

Outlook

Outlook

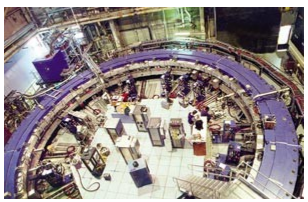

Experiment
Theory
d e.cm
Muon
neutron:
electron:
molecules:
mercury:
Proton
10^{-20}
10^{-22}
10^{-28}
10^{-29}
Electro-
magnetic
Multi
Higgs
SUSY
$\phi \sim 1$
Left-Right
$\phi \sim \alpha/\pi$
1960
1970
1980
1990
2000
2010
2020
2030
Ruled out models
/ parameter-space
>SM
θ_{QCD}

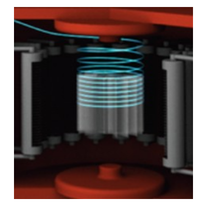
Outlook


Experiment
Theory
d e.cm
neutron:
electron:
molecules:
mercury:
10^{-20}
10^{-22}
10^{-24}
10^{-28}
10^{-29}
Electro-
magnetic
Multi
Higgs
SUSY
$\phi \sim 1$
$\phi \sim \alpha/\pi$
Muon
Proton
Deuteron
Ruled out models
/ parameter-space
>SM
θ_{QCD}
Λ~3000TeV
1960
1970
1980
1990
2000
2010
2020
2030

Many thanks to the people in the field ...

Thank you for your attention





485. Heraeus Seminar, Bad Honnef, 2011