POLARIMETRY FOR A STORAGE-RING ELECTRIC-DIPOLE-MOMENT MEASUREMENT

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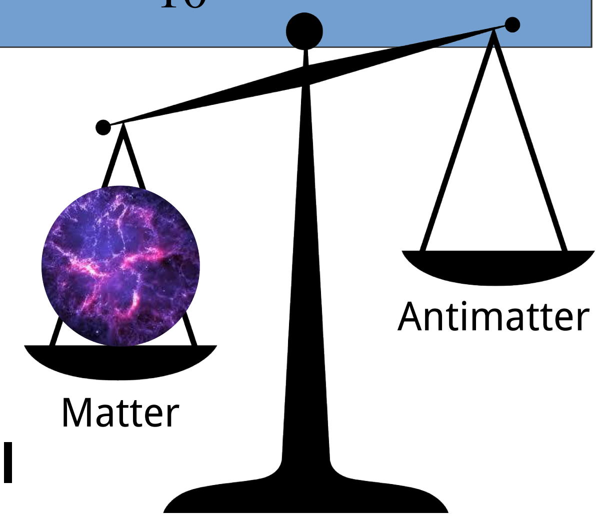
MOTIVATION

Barion Asymmetry Problem

Barion Asymmetry	Observation	Standard Cosmological Model
$(N_B - N_{\bar{B}}) / N_\gamma$	6×10^{-10}	$\sim 10^{-18}$

Preconditions needed to explain it (Sakharov):

- **$\mathcal{C}$ and $\mathcal{CP}$ violation**
- Baryon number violation
- Thermal non-equilibrium in the early Universe



$\mathcal{CP}$ violation in Standard Model

- **Electroweak sector** (CKM matrix well established)
- **Strong interactions** (θ-term, strong-$\mathcal{CP}$ puzzle)

Predictions orders of magnitude **too small** to explain the asymmetry!

New sources of $\mathcal{CP}$ violation can be seen in EDM of particles

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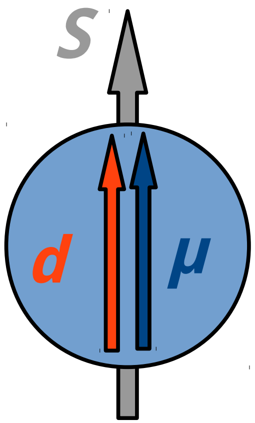
ELECTRIC DIPOLE MOMENT

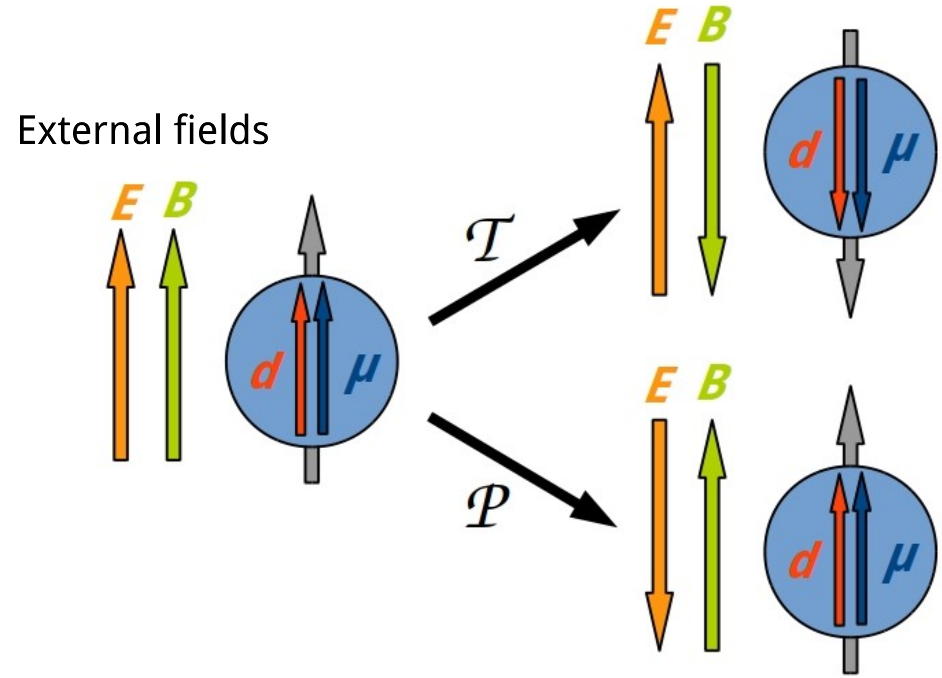
$\mathcal{CP}$-symmetry violation



$$\vec{d} = \eta \cdot \frac{q}{2mc}\vec{S}$$

$$\vec{\mu} = g \cdot \frac{q}{2m}\vec{S}$$

Pseudo vectors



The observable quantity - Energy:

- of electric dipole in electric field
- of magnetic dipole in magnetic field

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

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

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

H violates $\mathcal{T}$ and $\mathcal{P}$-symmetry if ***d≠0***

⇩

$\mathcal{T}$ violation

⇩

$\mathcal{CP}$ violation ($\mathcal{CPT}$ conserved)

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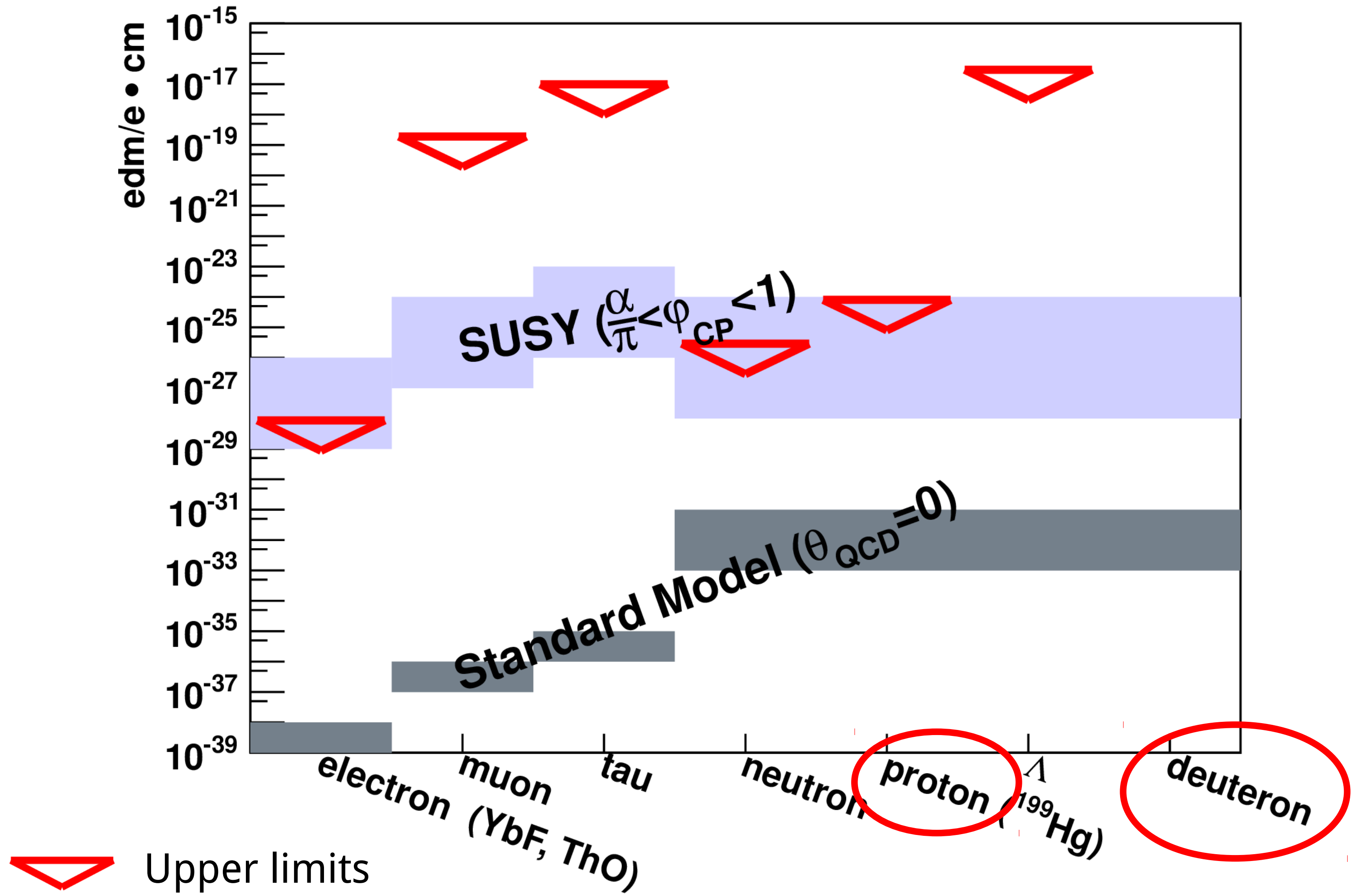
ELECTRIC DIPOLE MOMENT

Current limits



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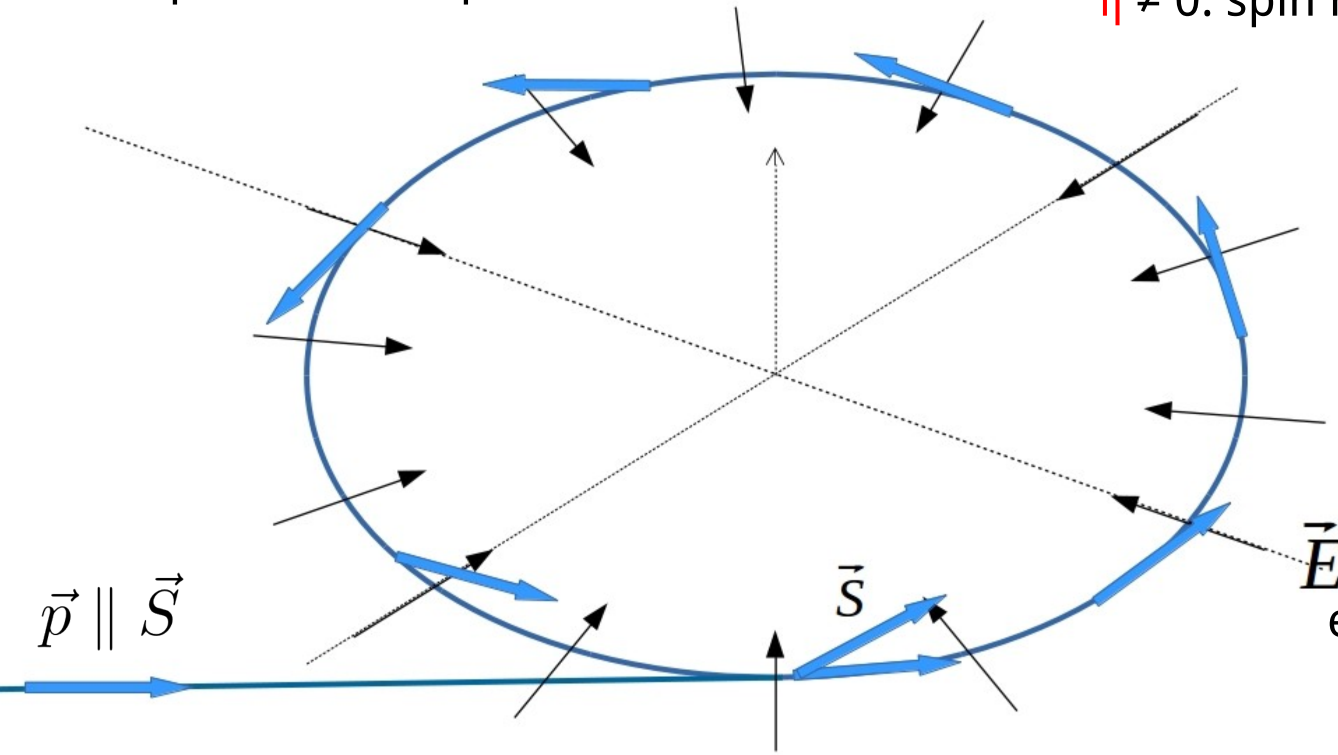
PRINCIPLE OF EDM MEASUREMENT

Charged Particles in a Storage Ring

General idea: Observation of **EDM** interaction with **electric field**

Simplified case – pure E field:



"Frozen spin" - Spin parallel to momentum

η ≠ 0: spin rotation out of horizontal plane

$$\frac{d\vec{S}}{dt} \sim \eta \vec{E} \times \vec{S}$$

Build-up of **vertical polarization**

η ∝ spin rotation angle

EDM ~ 10^{-29} e·cm

⇩

effect of the order of μdeg/hour

Extremely small effects!

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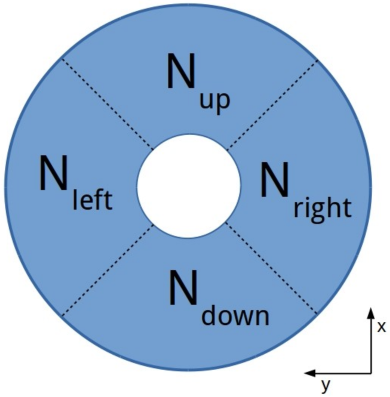
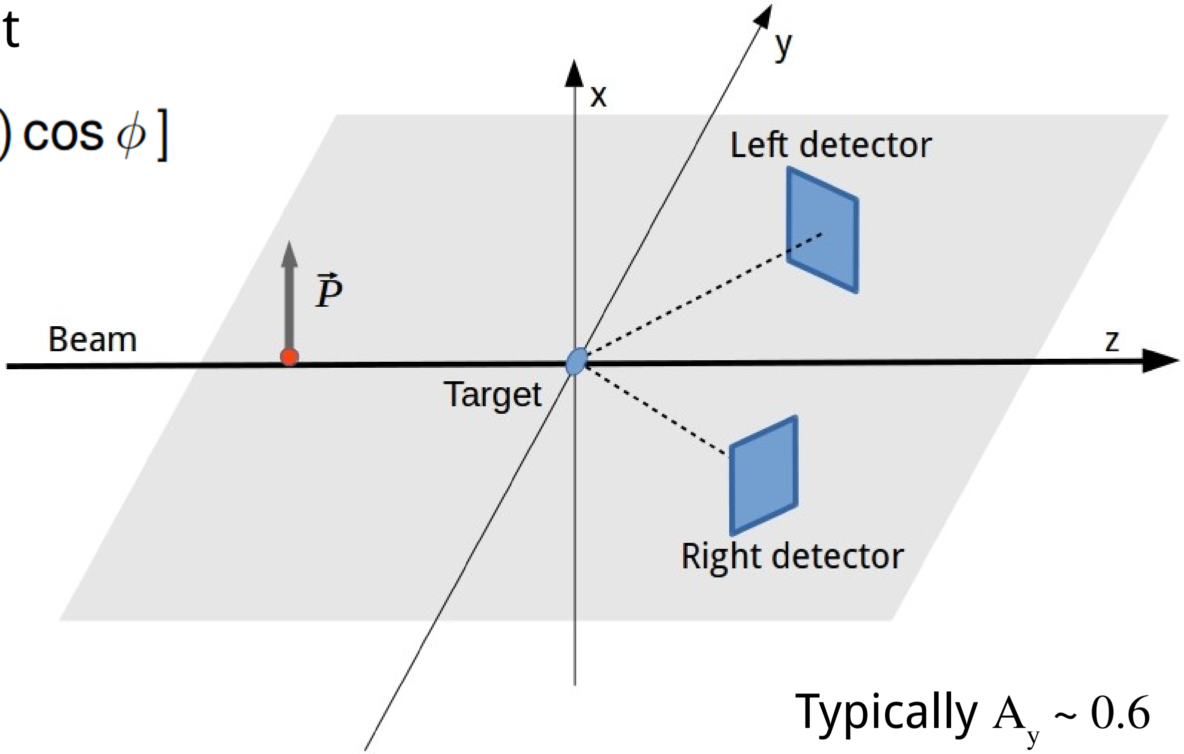
HOW TO MEASURE BEAM POLARIZATION?

Scattering from Carbon target

$$\sigma^{pol}(\theta,\phi) = \sigma_0(\theta)[1 + \tfrac{3}{2} P A_y(\theta) \cos\phi]$$



2π detector - “beam” view



Typically $A_y \sim 0.6$

Right/Left asymmetry ∝ vertical component of polarization P_y

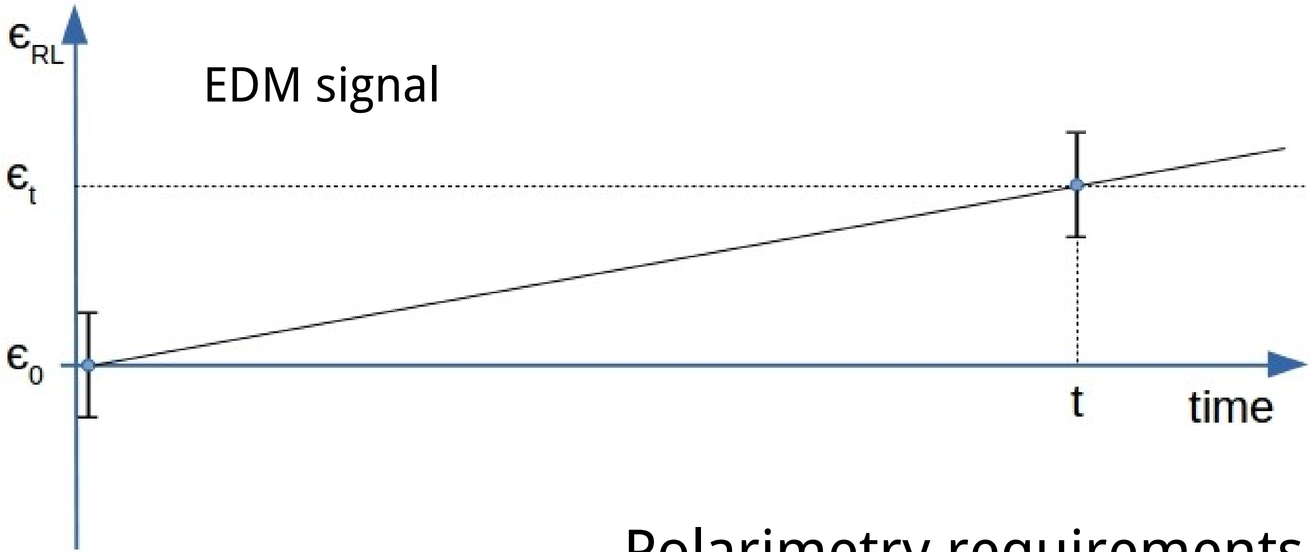
$$\epsilon_{LR} = \frac{N_L - N_R}{N_L + N_R} = P_y A_y$$ ⇒ EDM signal appears here

Up/Down asymmetry ∝ horizontal component of polarization P_x

$$\epsilon_{UD} = \frac{N_U - N_D}{N_U + N_D} = P_x A_y$$ ⇒ Needed to maintain “frozen spin” condition

POLARIMETRY FOR AN EDM EXPERIMENT

Challenge: measurement of **tiny polarization build-up**



For proton EDM ~ 10^{-29} e·cm and ~ 1year of measurement

$$\Delta\epsilon_{LR} = \epsilon_t - \epsilon_0$$
$$= \Delta P_y A_y \approx 10^{-6}$$

Systematics count!

Polarimetry requirements

Long term reproducibility:
→ Continuous measurement for a long time

$$\delta\epsilon_{LR}(\text{stat}) \propto \frac{1}{\sqrt{N}|A_y|} = \frac{1}{\sqrt{\text{FoM}}}$$

Minimization of asymmetry error:
→ Maximization of FoM

Figure of Merit

⇓ Efficiency ⇓ High A_y

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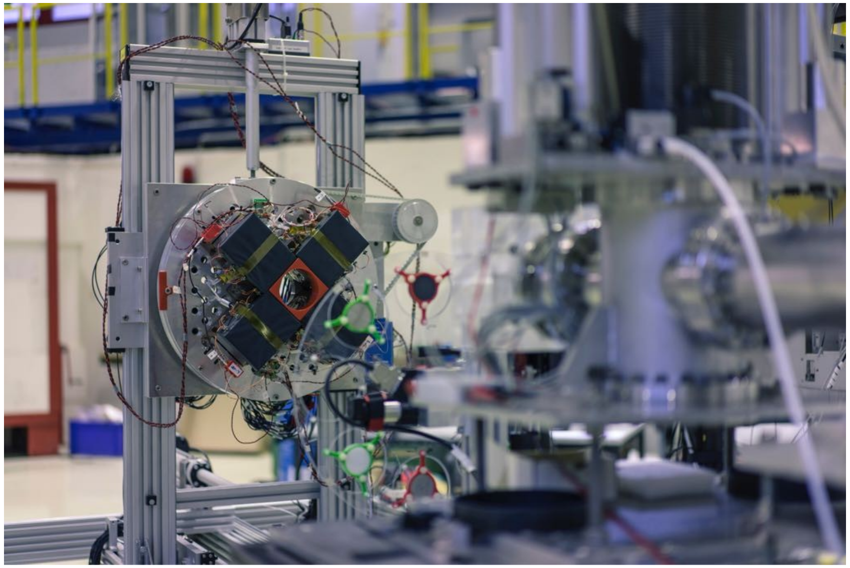
ACTIVITY AT COSY

Jülich Electric Dipole moment Investigations (JEDI)

R&D with towards first proof-of-principle EDM experiment for deuterons and protons

Polarimetry-group activity:
- Development of dedicated polarimeter based on LYSO crystals
- **Database experiment with WASA detector**



Motivation:
- Optimal configuration of the polarimeter

Goal: A_y, A_{yy}, $d\sigma/d\Omega$ for
- dC elastic scattering
- main background reactions (deuteron breakup)

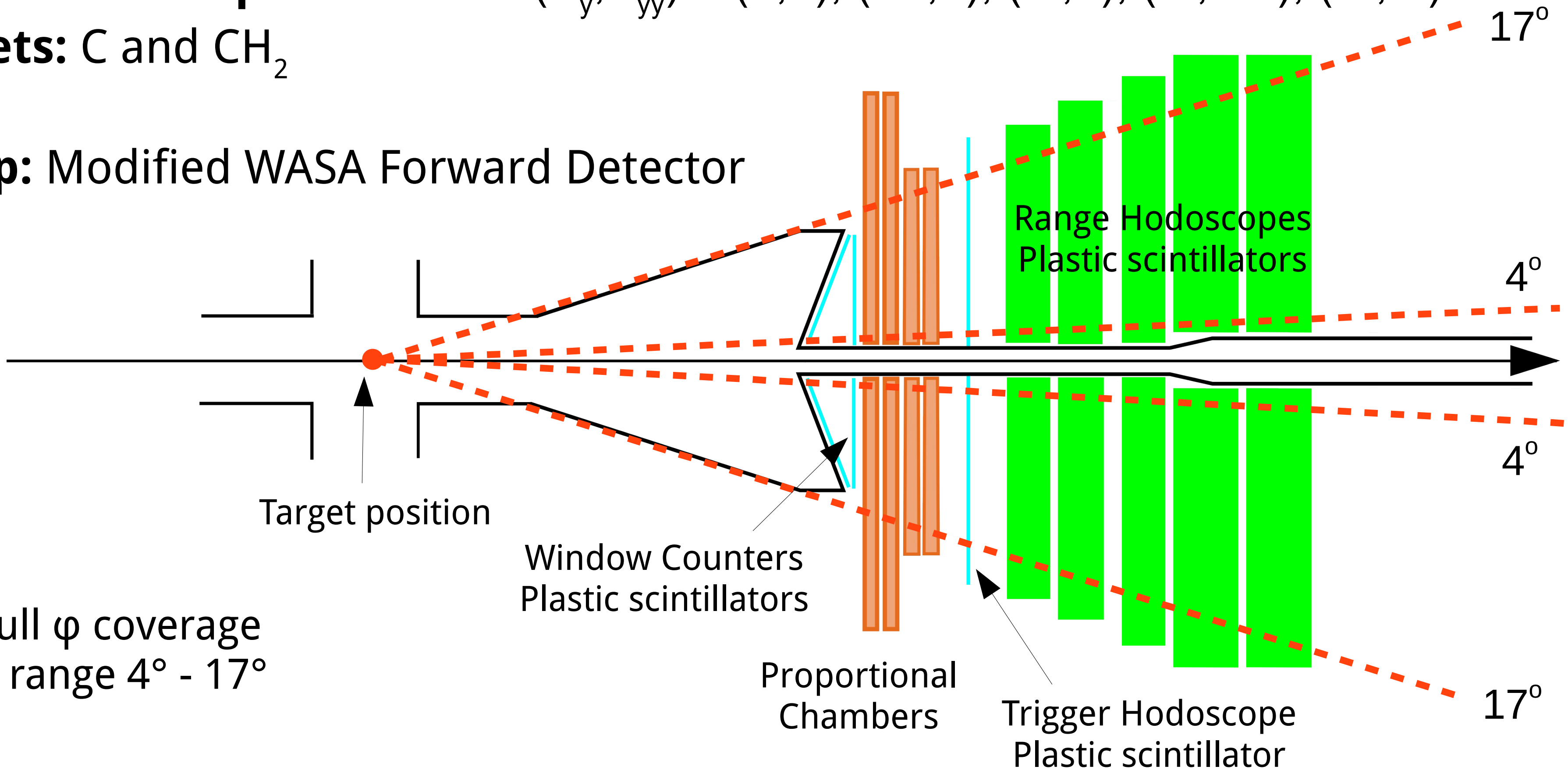
http://collaborations.fz-juelich.de/ikp/jedi/

DEUTERON DATABASE EXPERIMENT WITH WASA

Detector Setup

Beamtime in November 2016 (2 weeks)
Deuteron energies: 170, 200, 235, 270, 300, 340, 380 MeV
Nominal beam polarization: $(P_y, P_{yy}) = (0,0), (-⅔,0), (⅔,0), (½, -½), (-1, 1)$
Targets: C and CH_2

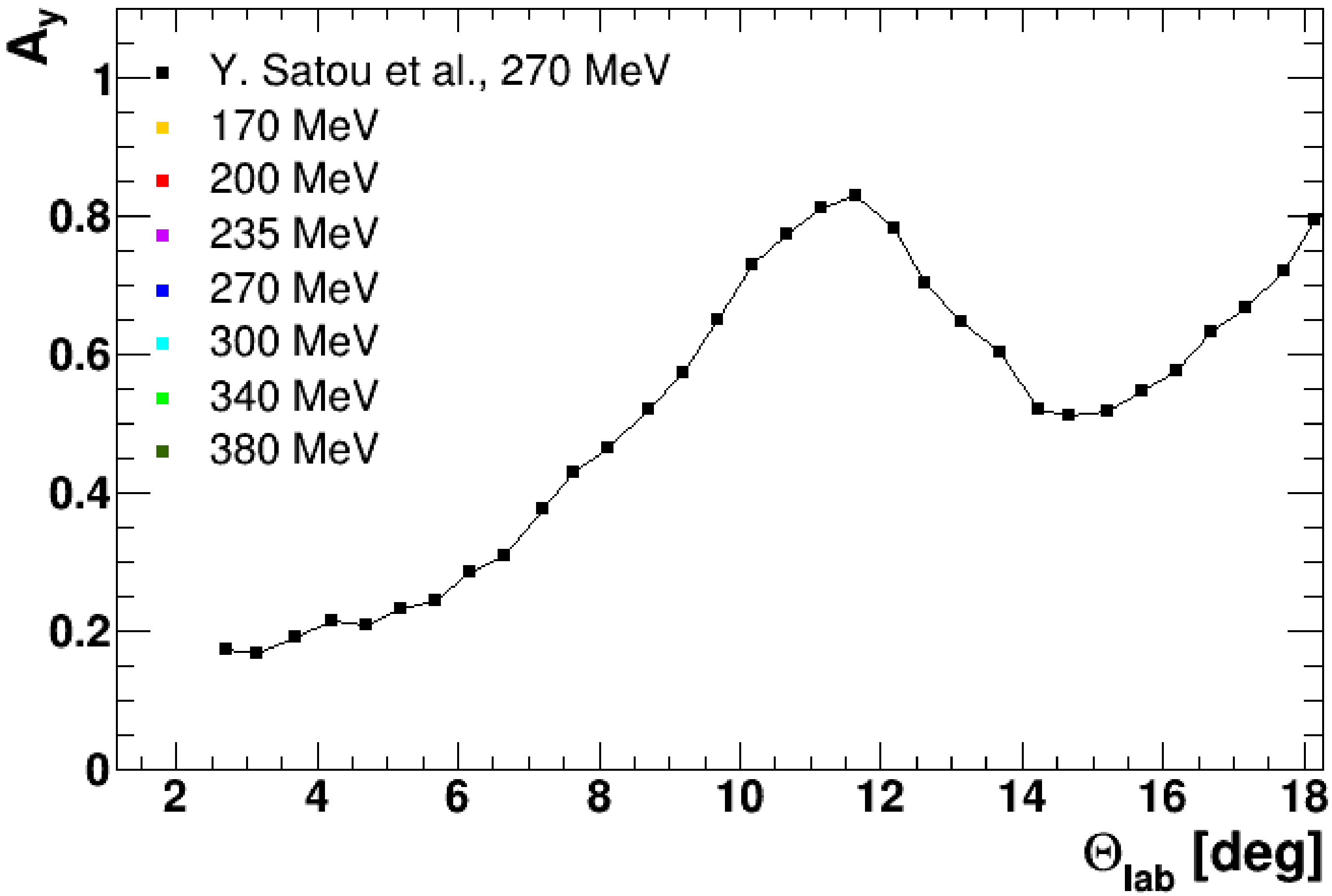
Setup: Modified WASA Forward Detector



- Full φ coverage
- θ range 4° - 17°

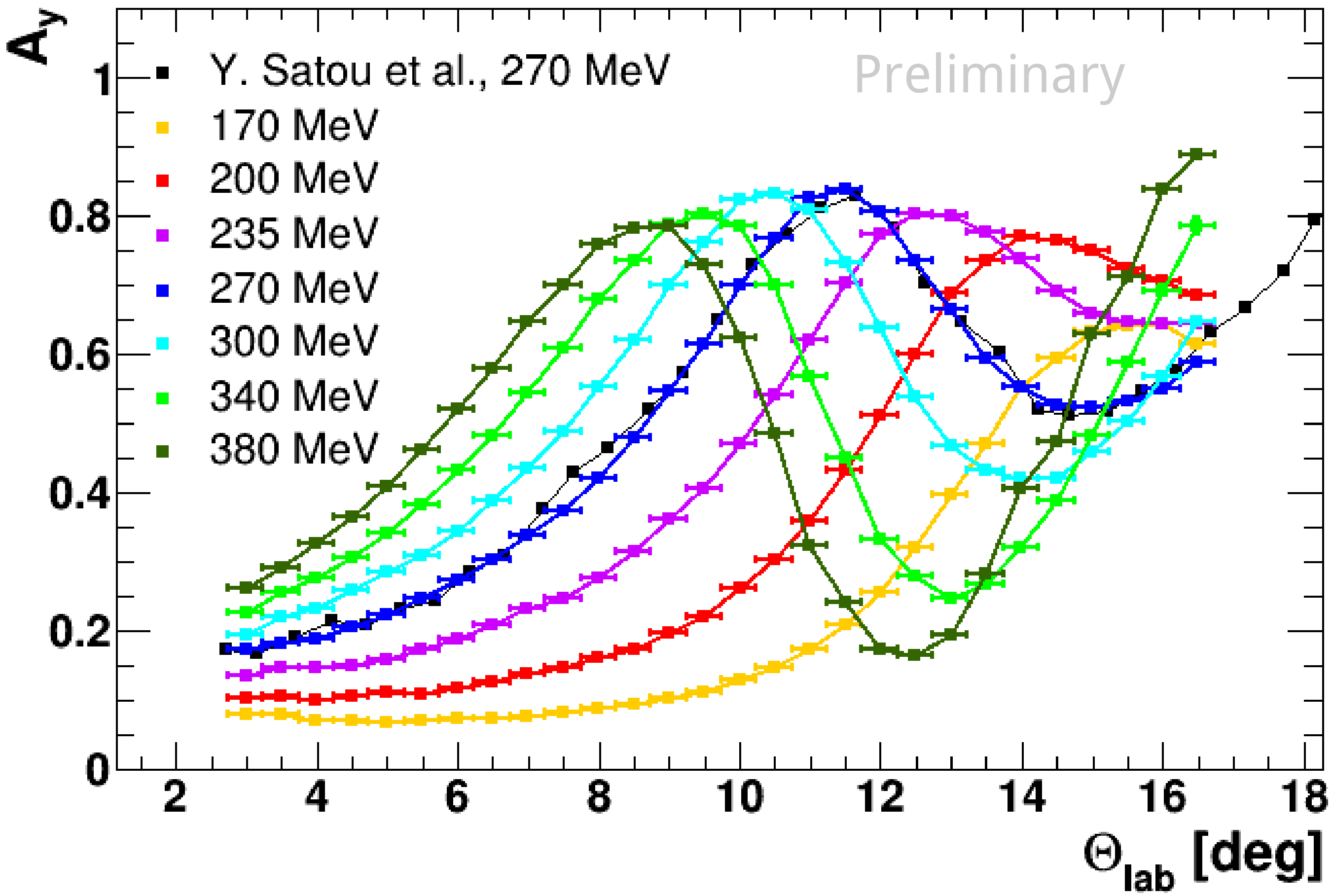
DATABASE EXPERIMENT WITH WASA

Analyzing power for elastic dC scattering



DATABASE EXPERIMENT WITH WASA

Analyzing power for elastic dC scattering



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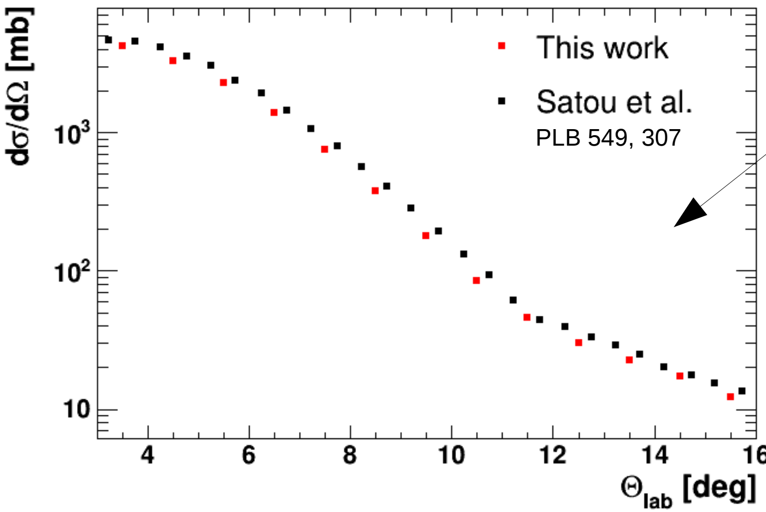
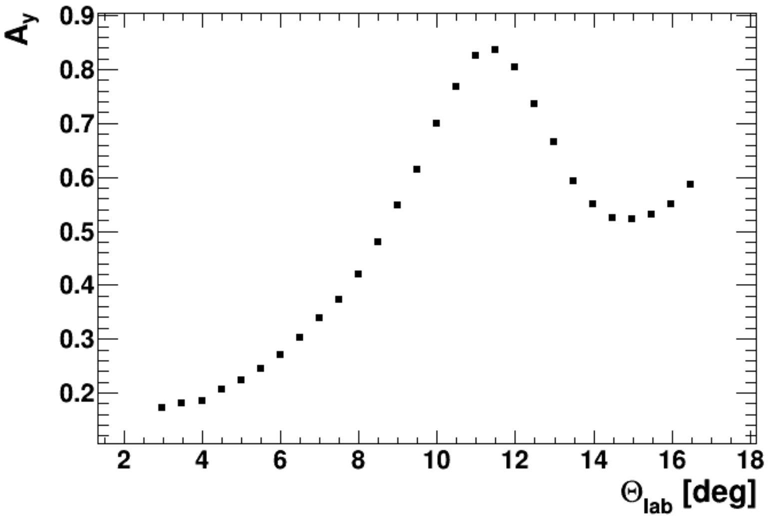
DATABASE EXPERIMENT WITH WASA

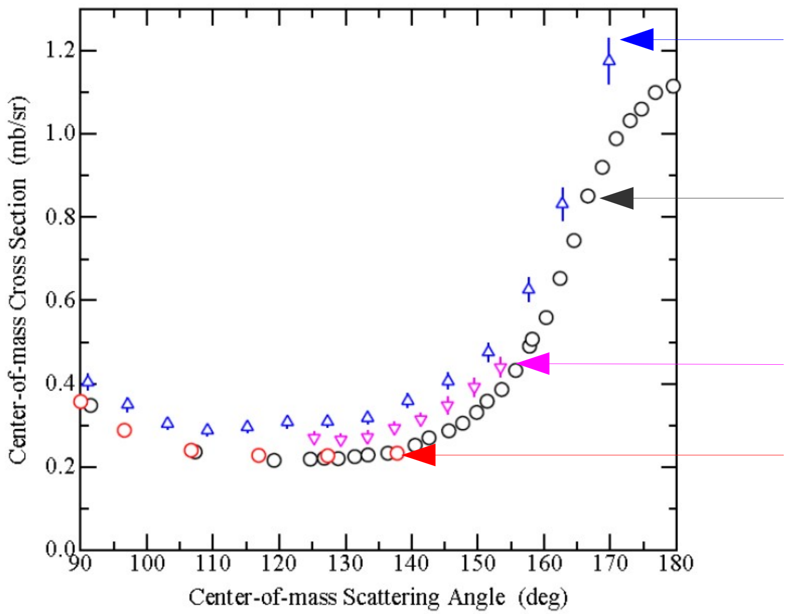
Cross section for E^{d}_{kin} = 270 MeV Preliminary





Elastic dC cross-section:

- Luminosity calculated using deuteron-proton elastic scattering registered with CH_2 target
- Discrepancy in available world data even 40%
- Statistical errors shown
- Additional systematic errors ~ 7%



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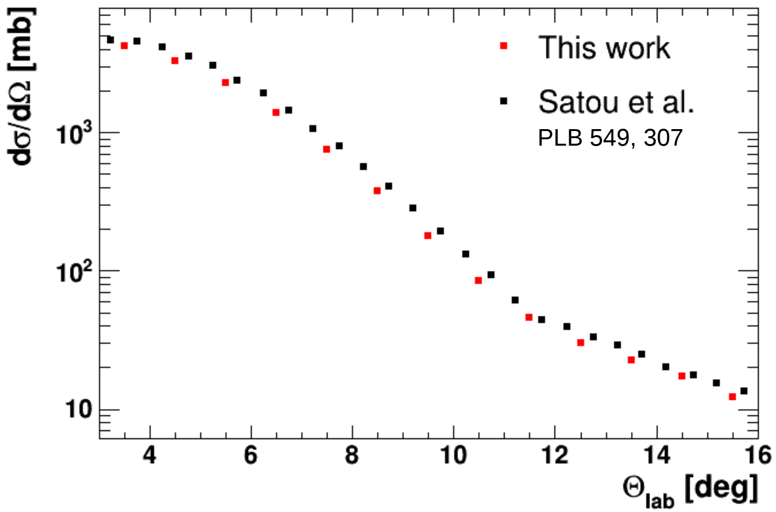
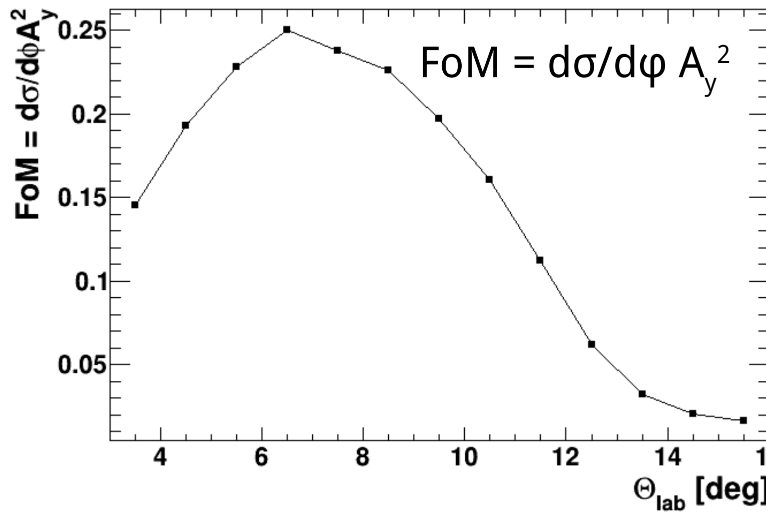
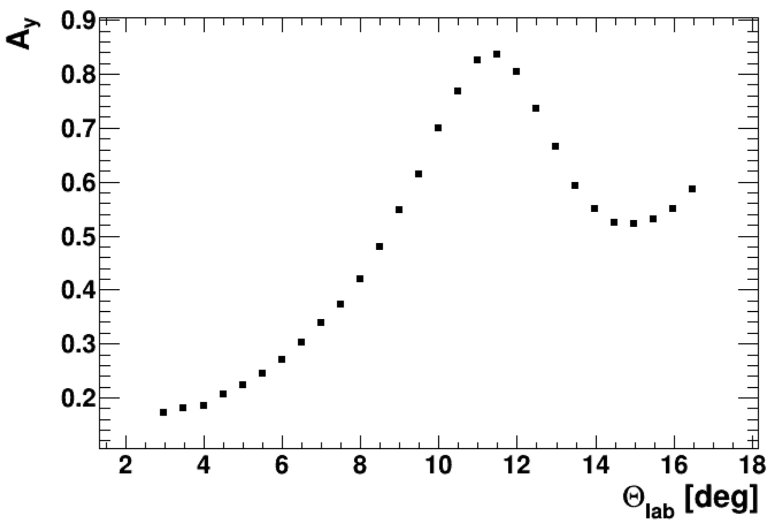
DATABASE EXPERIMENT WITH WASA

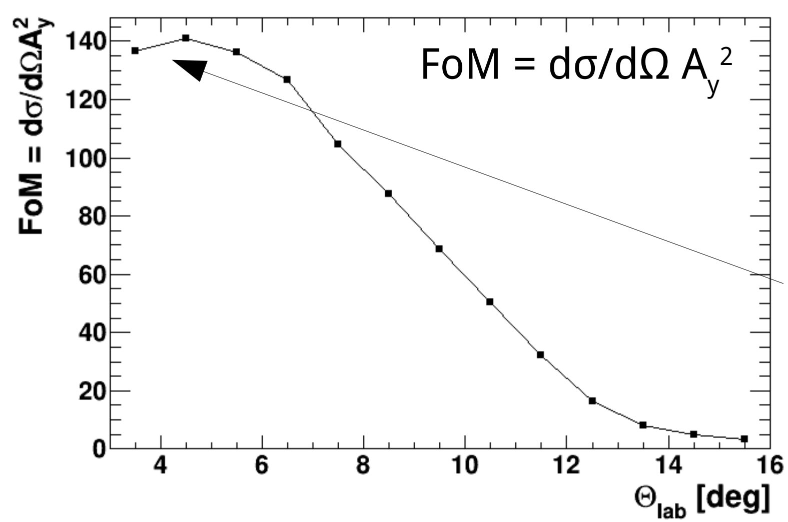
Figure of Merit for E^{d}_{kin} = 270 MeV Preliminary





Optimal working conditions for θ: 5-9°





Artificial enhancement by sinθ term

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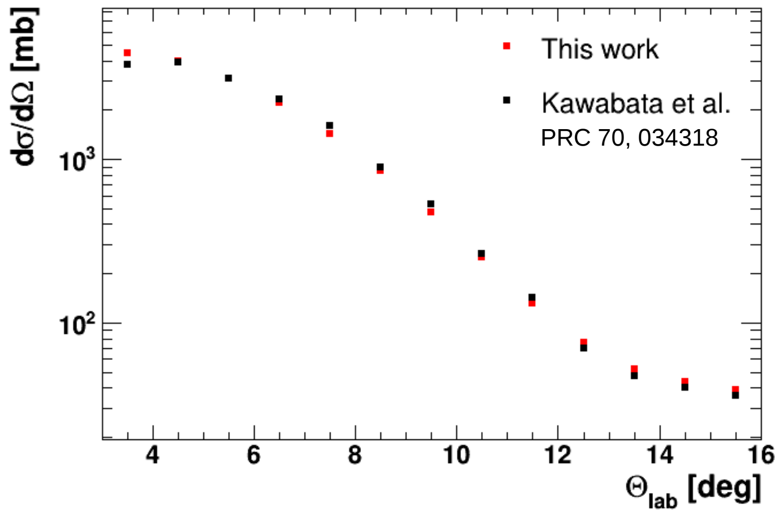
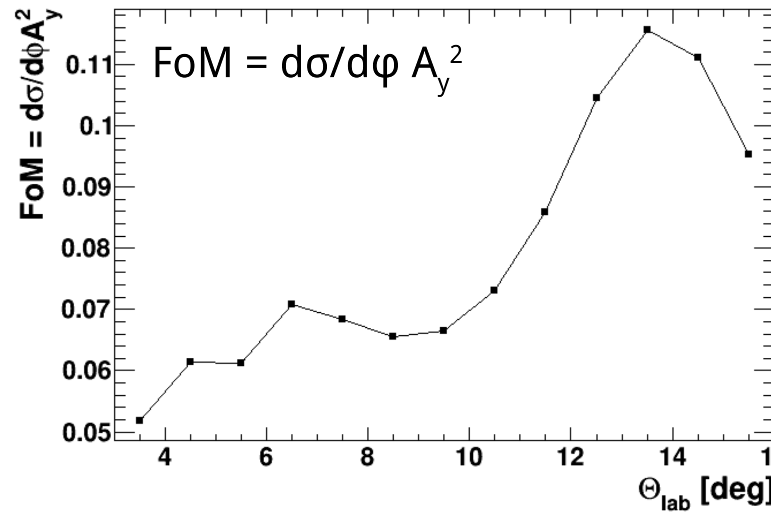
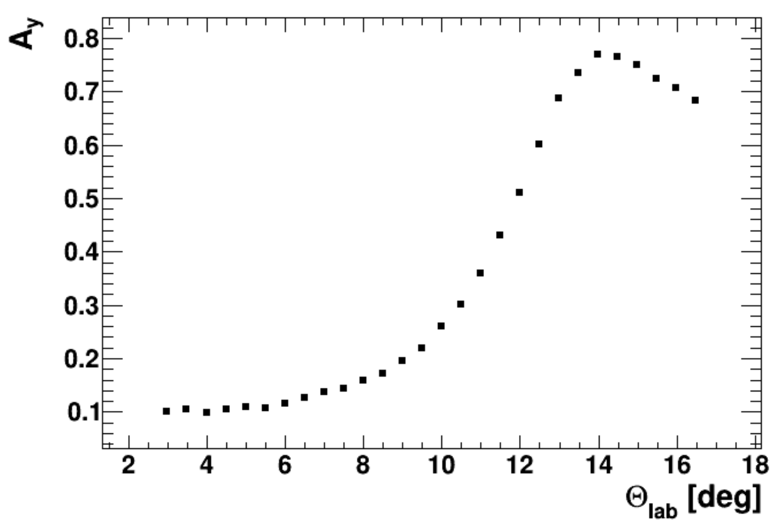
DATABASE EXPERIMENT WITH WASA

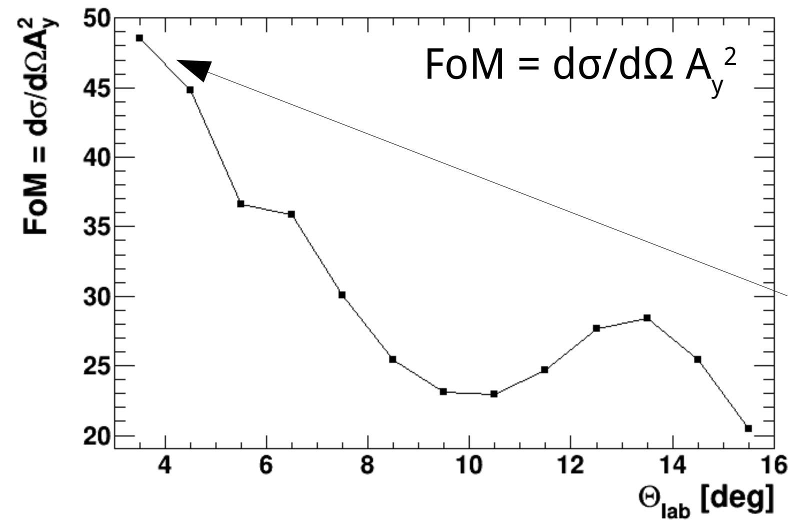
Figure of Merit for E^d_{kin} = 200 MeV Preliminary





Optimal working conditions for θ: 12-16°





Artificial enhancement by sinθ term

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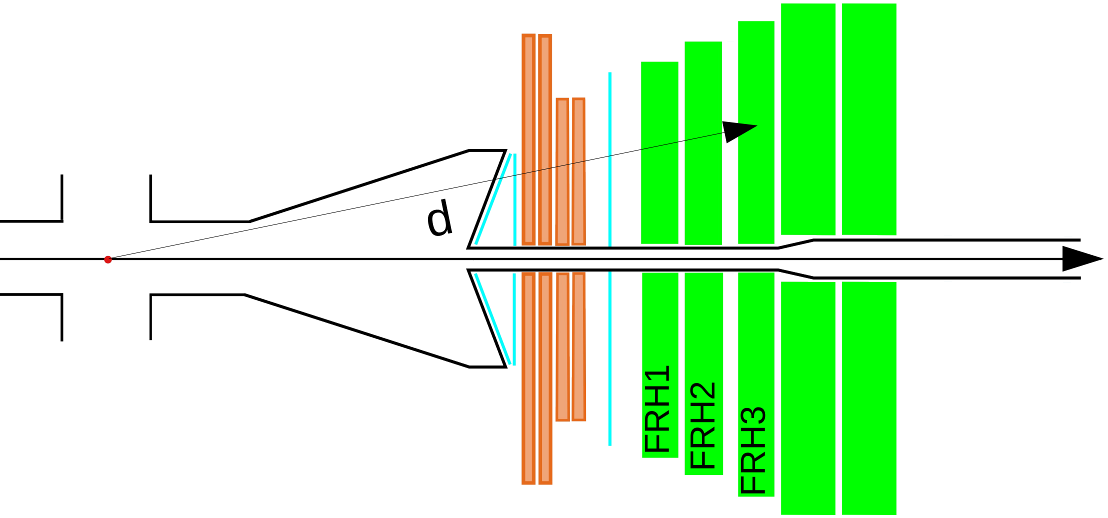
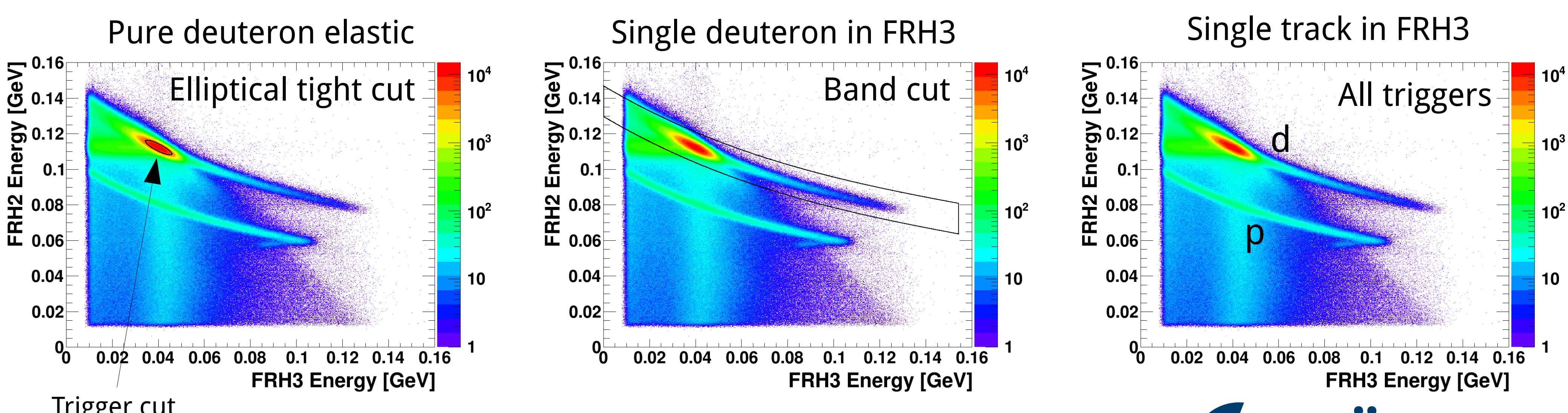
WASA AS A POLARIMETER



Possible energy acceptance:

1. Track reaching stopping layer
   - Pure elastic deuteron
   - Single deuteron
   - Single track
2. Single track in one layer before
3. Single track in two layers before etc.



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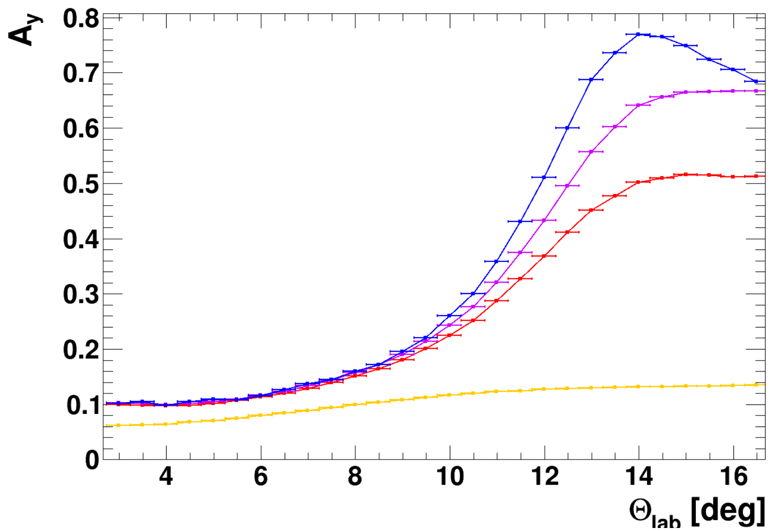
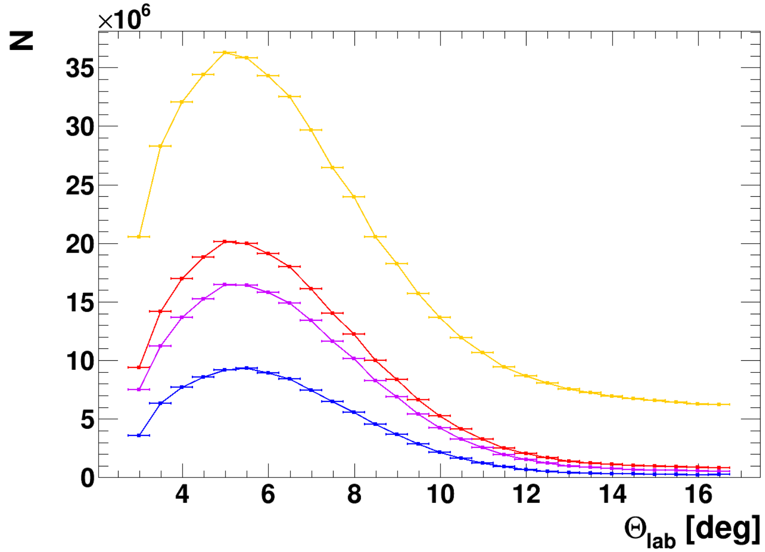
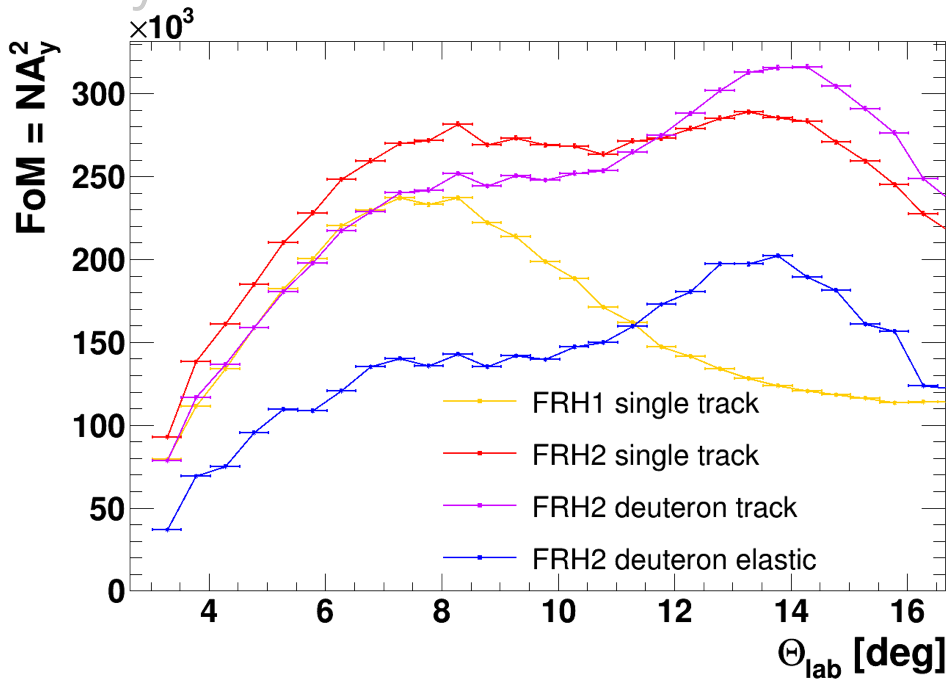
WASA AS A POLARIMETER

Figure of Merit for E^d_{kin} = 200 MeV Preliminary





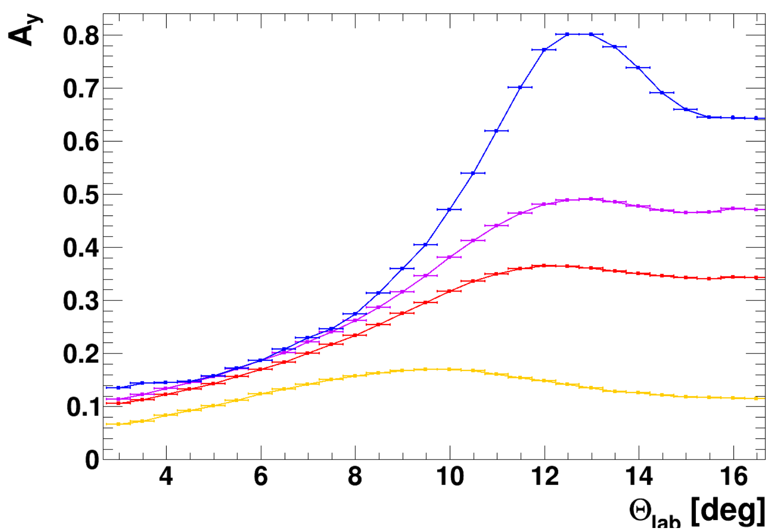


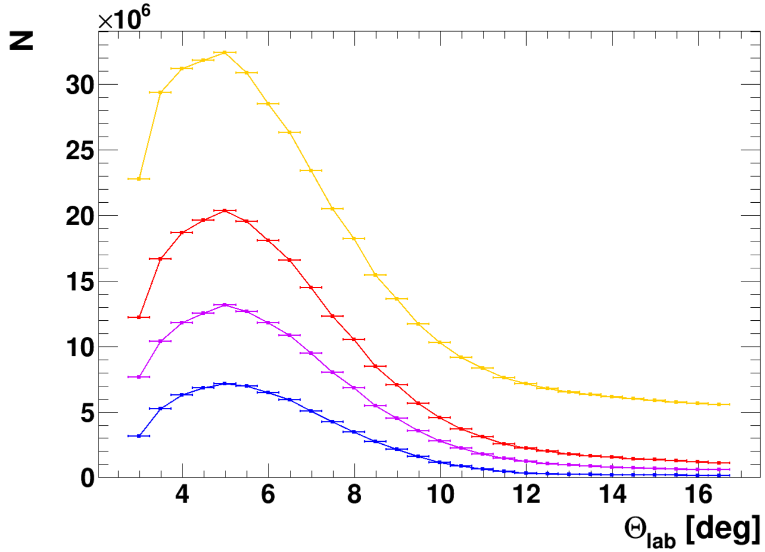
FoM = $NA_y^{\,2}$ – detector acceptance included

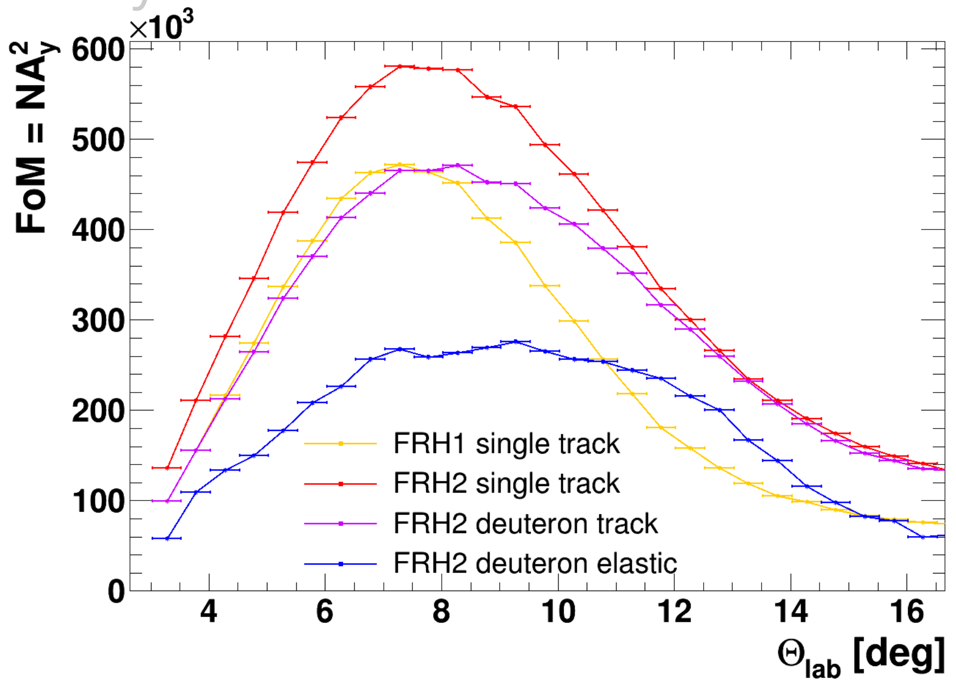
- Flat for 3-14° for single track in stopping layer (red line).
- Removing protons enhances FoM for higher angles because of larger A_y (magenta line).

WASA AS A POLARIMETER

Figure of Merit for E^{d}_{kin} = 235 MeV Preliminary







FoM = NA_y^2 – detector acceptance included

- Optimal for single track in stopping layer (red line).
- Distribution is peaking.
- Removing protons doesn't enhance FoM but enhances A_y (magenta line).

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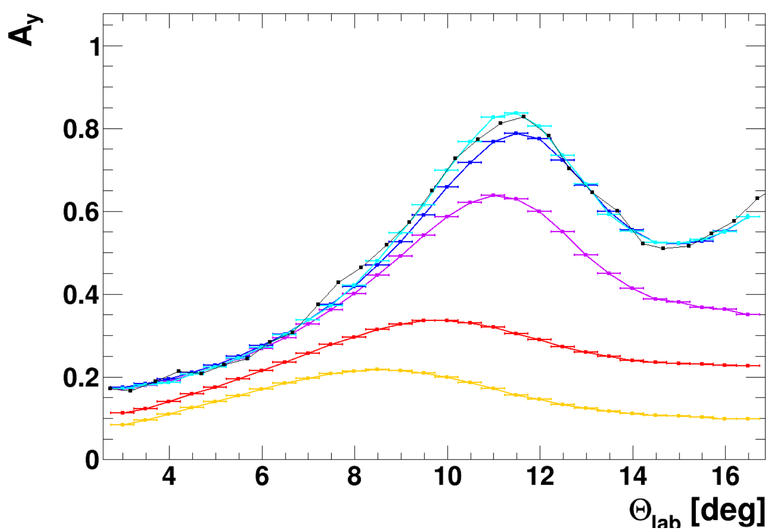
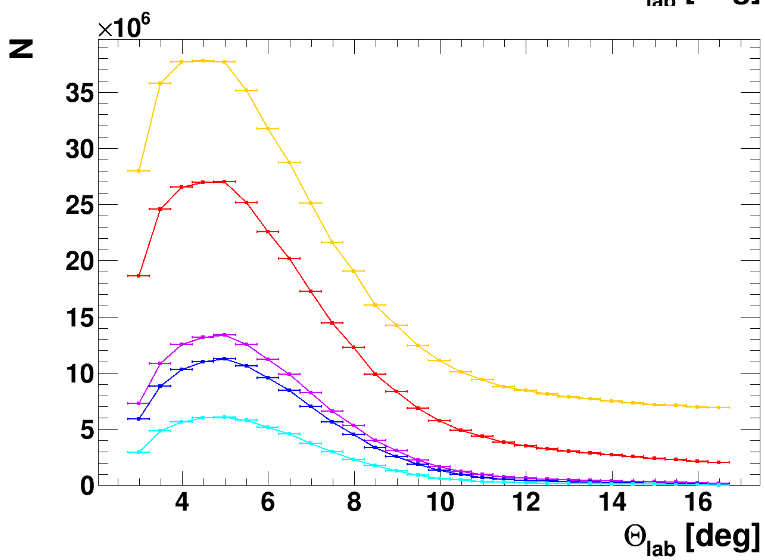
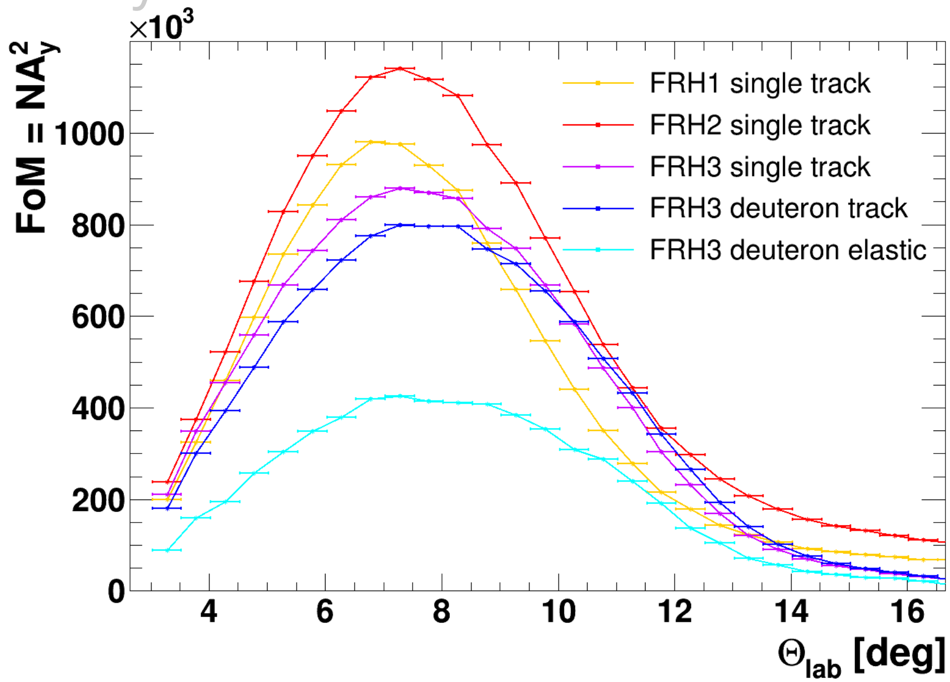
WASA AS A POLARIMETER

Figure of Merit for E^{d}_{kin} = 270 MeV Preliminary





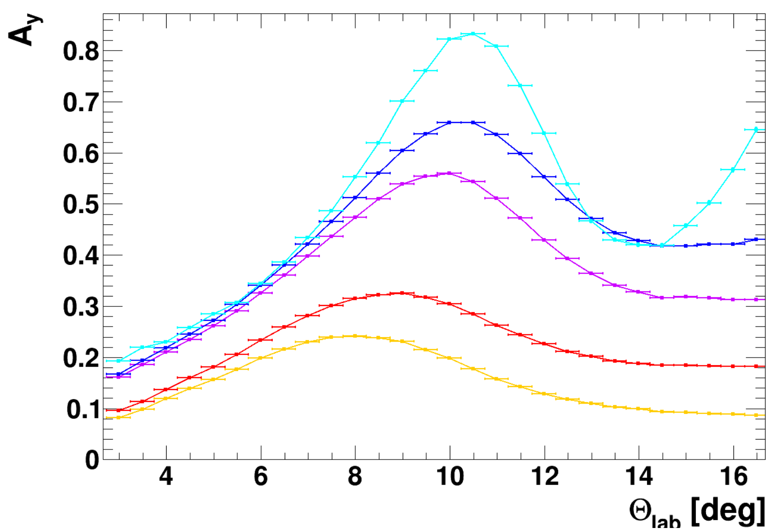


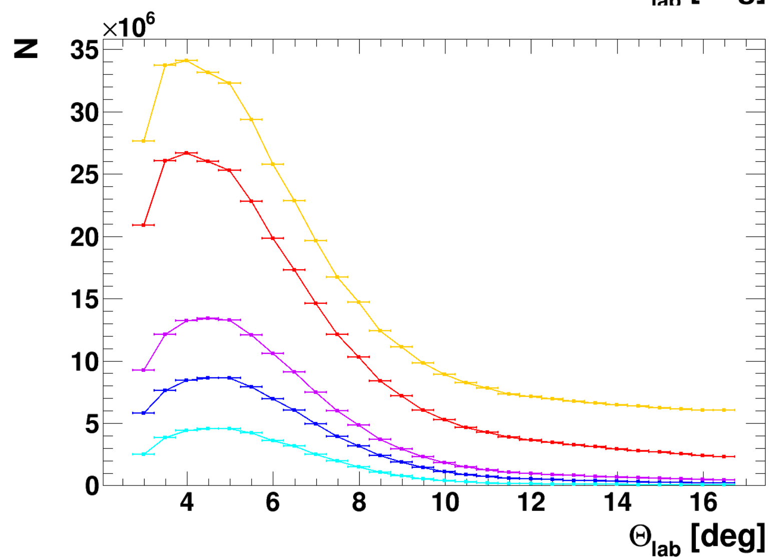
FoM = $NA_y^{\,2}$ – detector acceptance included

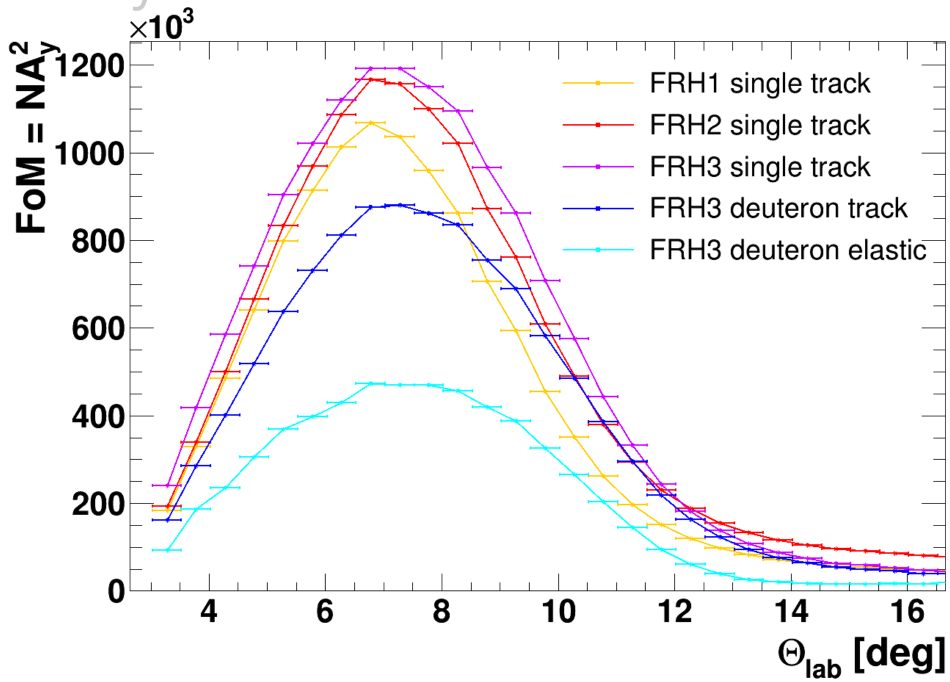
- Optimal single track in one before stopping layer (red line).
- Peak narrower then for 235 MeV.
- Removing protons doesn't enhance FoM but enhances A_y (magenta line and blue line).

WASA AS A POLARIMETER

Figure of Merit for E^d_{kin} = 300 MeV Preliminary







$FoM = NA_y^2$ – detector acceptance included

- Optimal for single track in stopping layer (red line).
- Peak is narrower then for 270 MeV.
- Removing protons doesn't enhance FoM but enhances A_y (magenta line and blue line).

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SUMMARY

- EDMs of elementary particles key for understanding sources of CP violation
  - → explanation of matter – antimatter imbalance
- Extremely ambitious measurement for charged particles
- Preparations for proof-of-principle experiment at COSY in progress for deuterons
- Polarimetry development to face the challenge of measurement of tiny polarization build-up
- Database measurement shows right direction to go

THANK YOU!

http://collaborations.fz-juelich.de/ikp/jedi/

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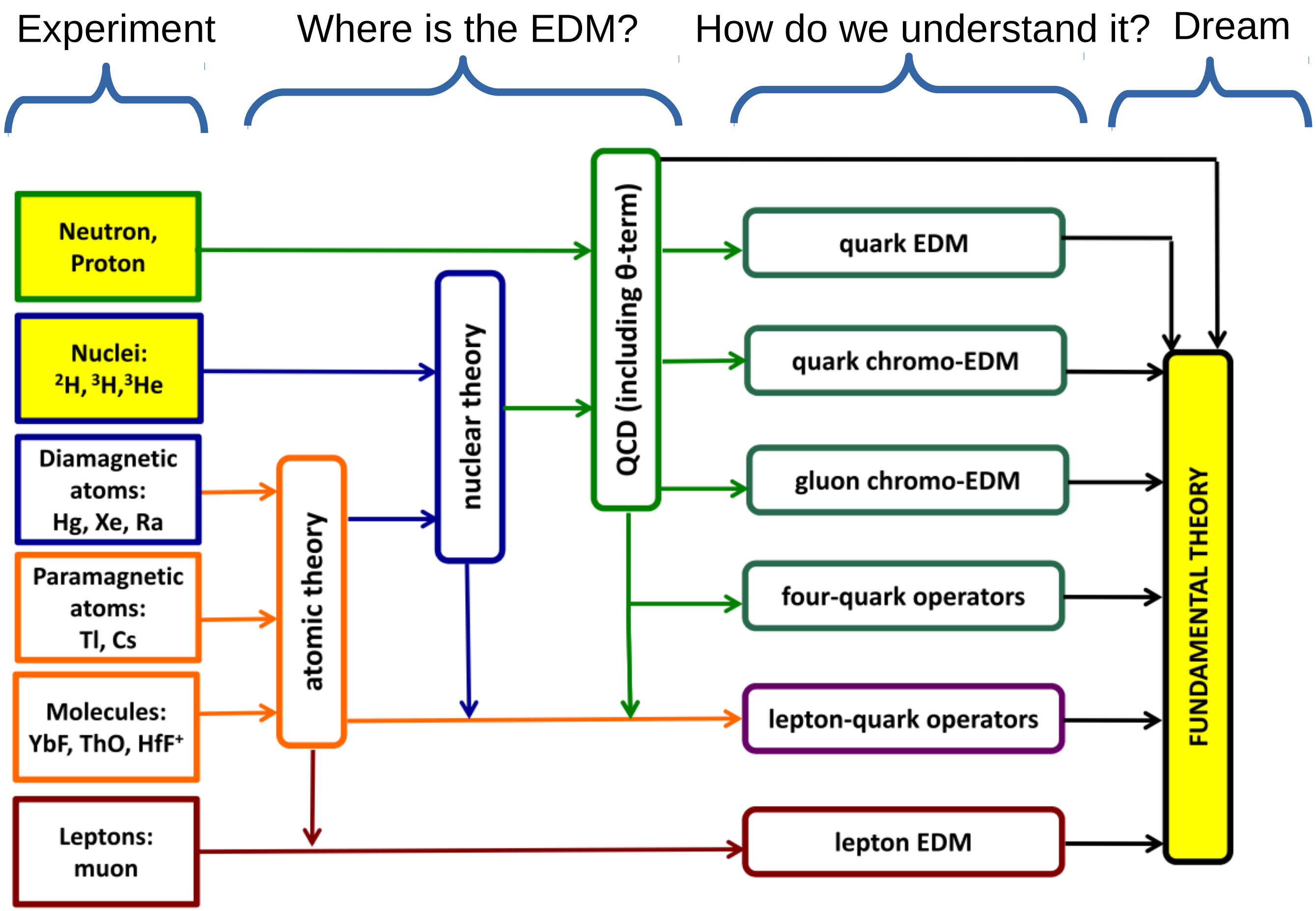
BACKUP

MOTIVATION

Electric Dipole Moment of proton and deuteron

Disentangle the fundamental source(s) of EDMs



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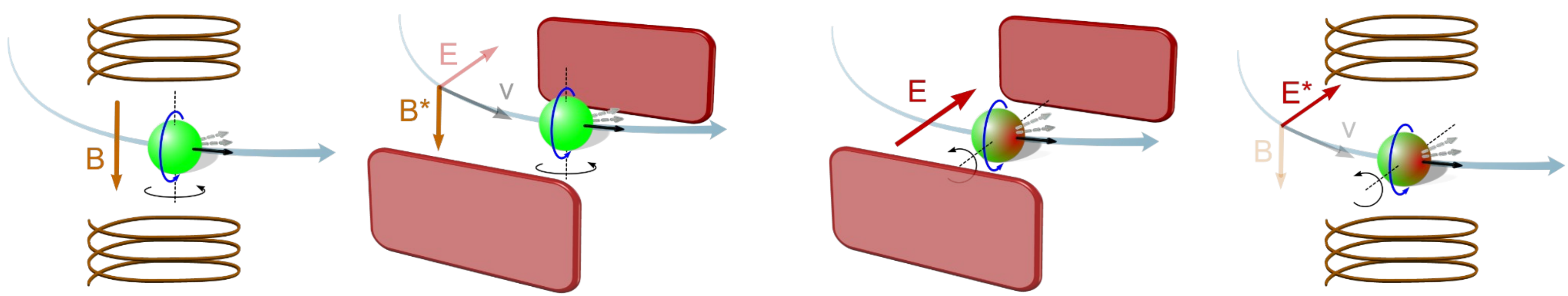
SPIN IN MAGNETIC AND ELECTRIC FIELD

Thomas-BMT equation:

In storage rings (magnetic field – vertical, electric field - radial)

magnetic moment EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{G\vec{B} + \left(\frac{1}{\gamma^2 - 1} - G\right)\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$



Magnetic moment causes fast spin precession in horizontal plane

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EXPERIMENTAL REQUIREMENTS

High precision storage ring	alignment, stability, field homogeneity
High intensity beams	N = 4 x 10^{10} per fill
Polarized hadron beams	P = 0.8
Large electric fields	E = 10 MV/m
Long spin coherence time	τ = 1000 s
Polarimetry	analyzing power A = 0.6, acc. f = 0.005

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf\tau PAE}} \Rightarrow \sigma_{\text{stat}}(1\text{ year}) \approx 10^{-29} e\text{cm}$$

Challenge: systematic uncertainties on the same level!

Even in Pure Electric Ring – lots of sources of syst. uncertainties
→ Very small radial B field can mimic an EDM effect

$$\mu B_r \sim dE_r$$

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R&D AT COSY

EDMs of charged hadrons: p, **d**

R&D with deuterons

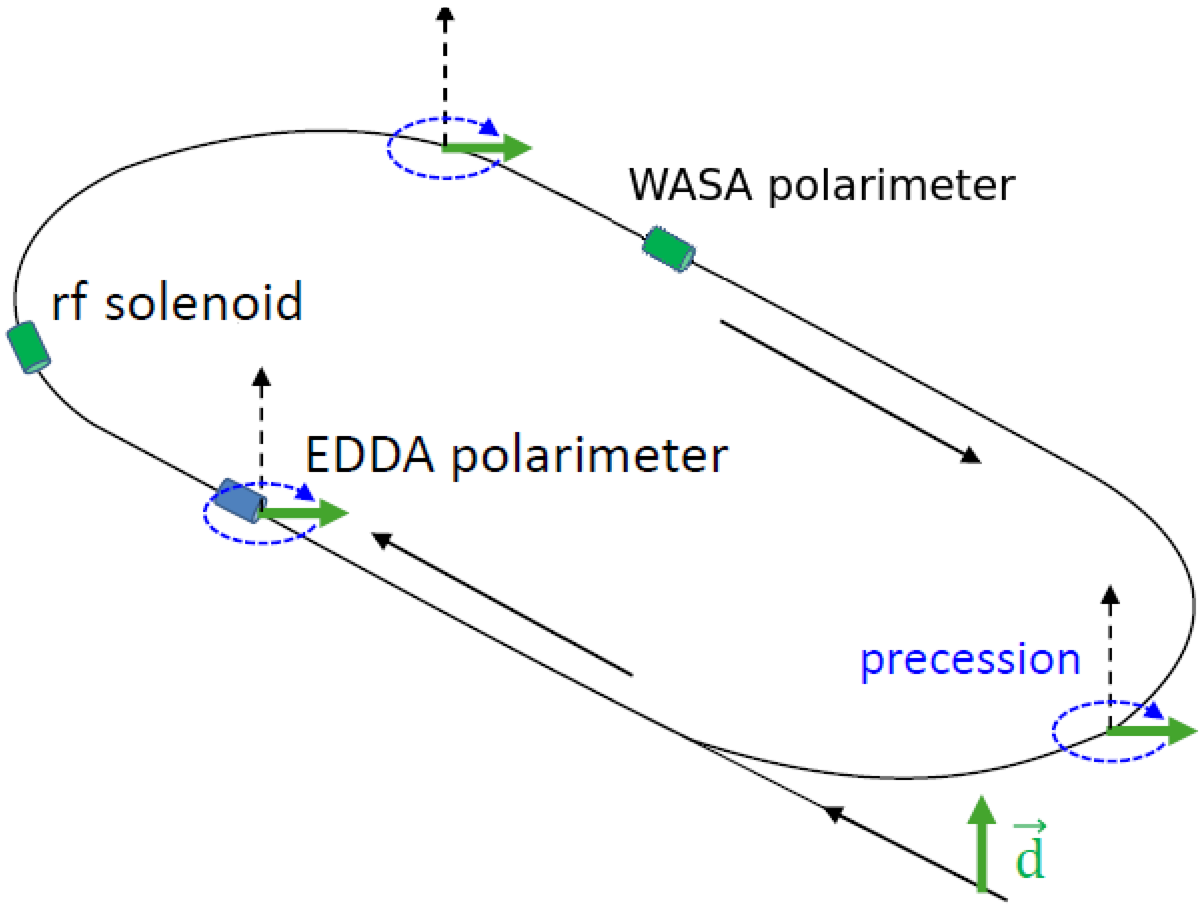
p = 1 GeV/c

G = -0.14256177(72)

ν_s ≈ -0.161 f ≈ 120 kHz

study spin tune $\upsilon_s = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\mathrm{cycl}}|} = \gamma G$

→ phase advance per turn



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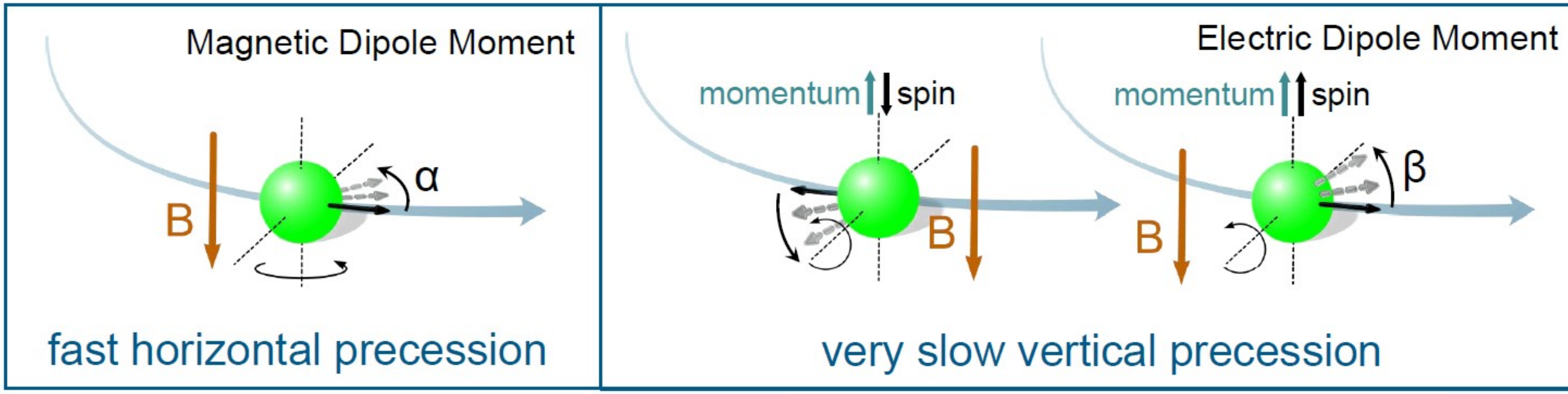
R&D AT COSY

- Measurement of fast precessing polarization
  Phys. Rev. ST Accel. Beams 17, 052803 (2014)
- Precise determination of spin tune
  Phys. Rev. Lett. 115, 094801 (2015)
- Spin coherence time
  Phys. Rev. Lett. 117, 054801 (2016)
- Phase lock of spin precession
  Phys. Rev. Lett. 119, 014801 (2017)

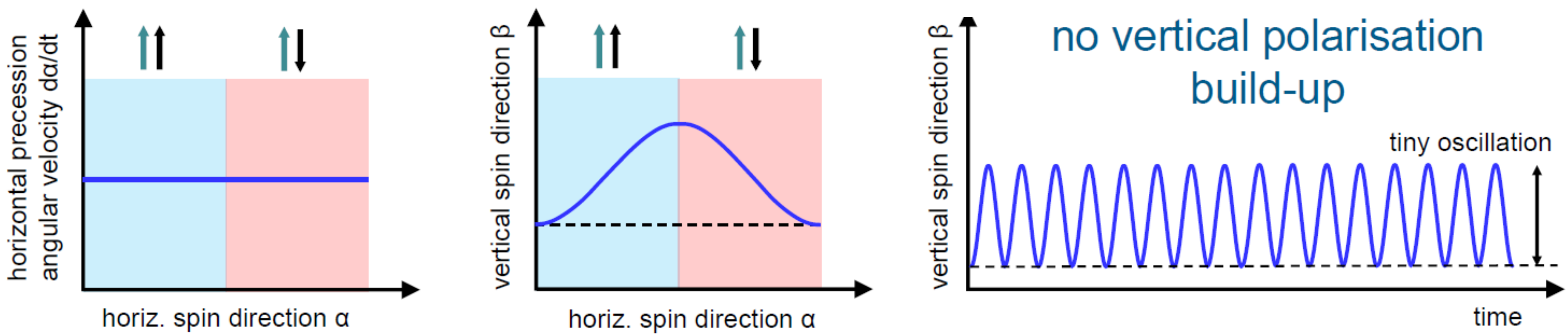
- Dedicated polarimetry & **Database for future polarimetry**
- Beam instrumentation
- Wien filter commissioning

WIEN FILTER METHOD



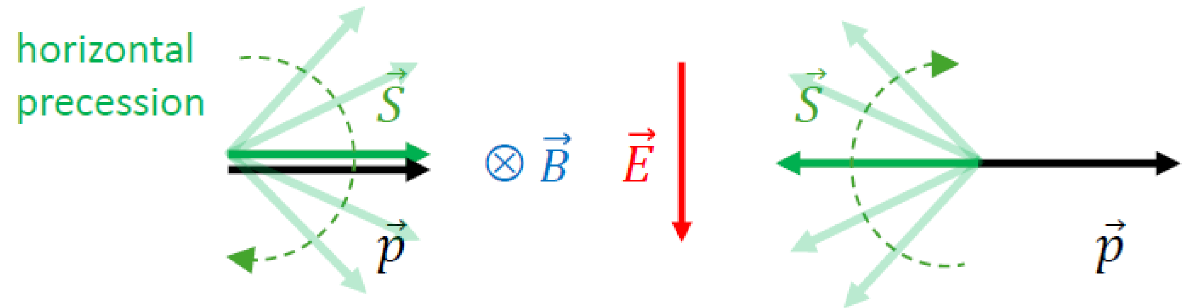
E* field tilts spin due to EDM
50% of time up
50% of time down

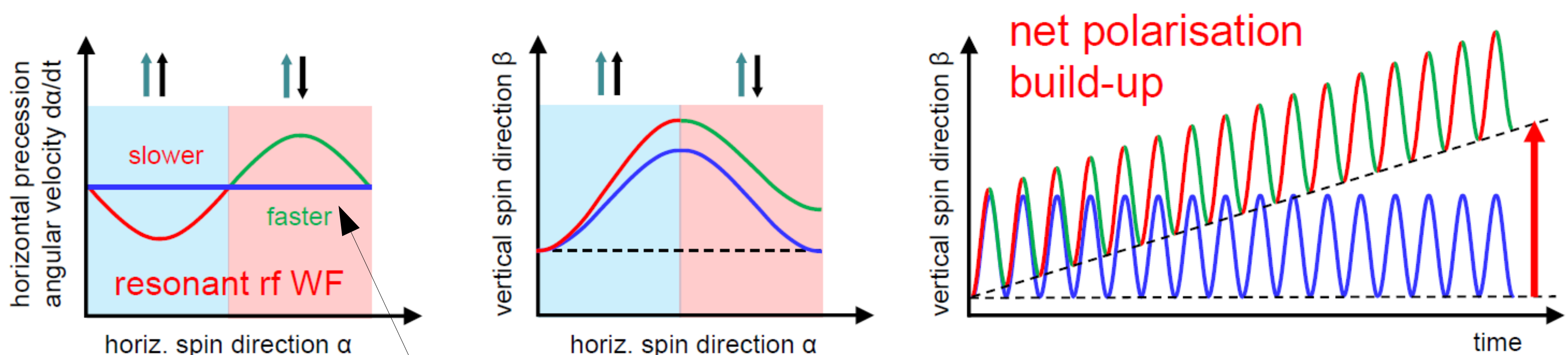
$$\frac{d\vec{S}}{dt} \propto \left(G\vec{B} + d\,\frac{m_0 c}{q\hbar S}\,\vec{\beta} \times \vec{B} \right) \times \vec{S}$$



WIEN FILTER METHOD

- Wien Filter: introduces B and E field oscillating with radio frequency
- Lorentz force vanishes: no effec on EDM rotation
- **Effect: Adds extra horizontal precession**

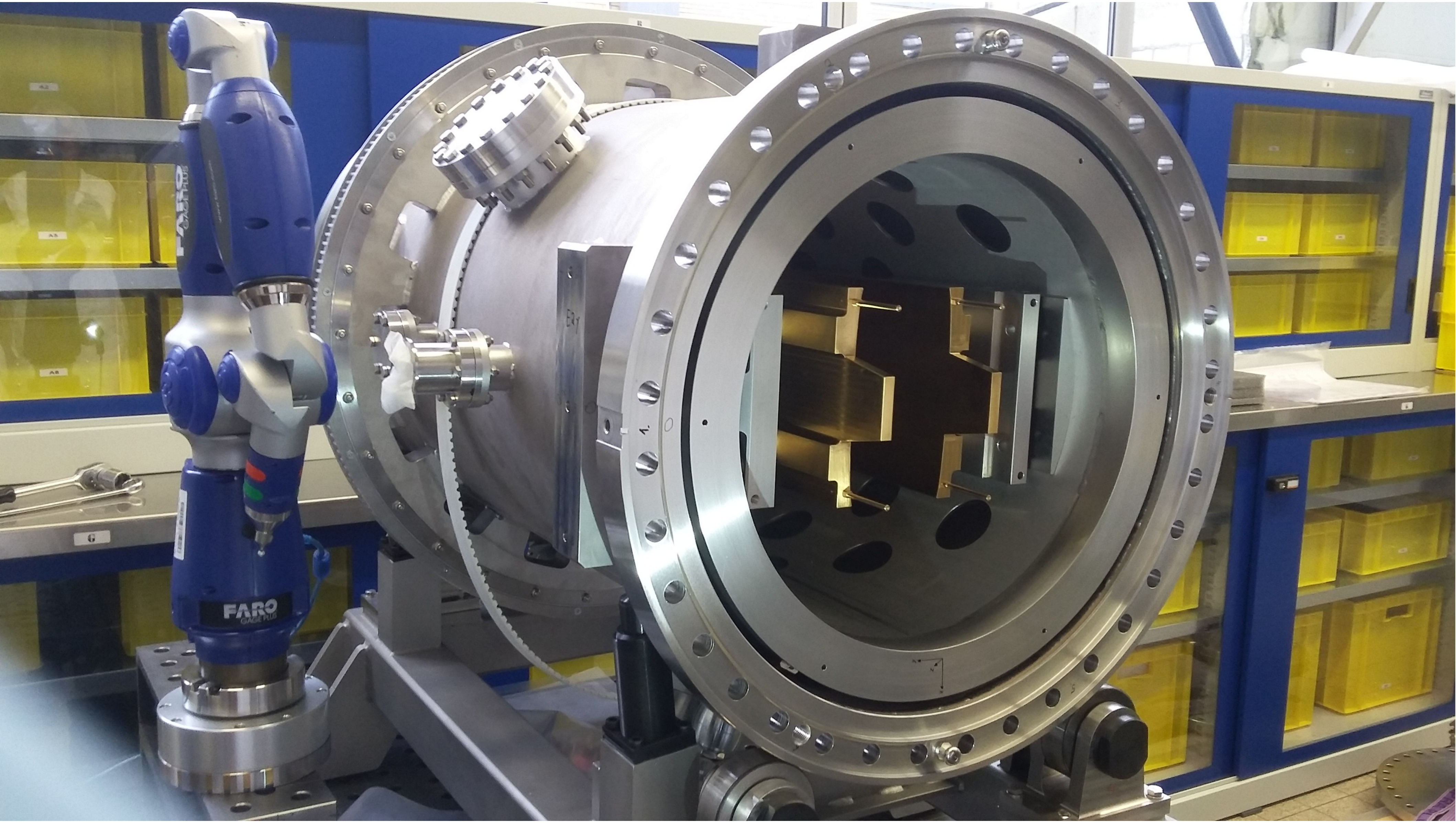




Wien Filter has to be always **in phase** with the horizontal spin precession!

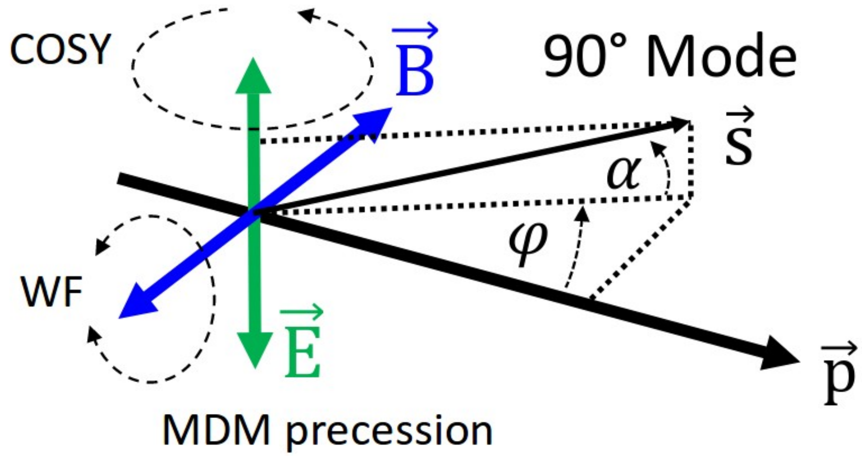
Feedback system developed and tested: Phys. Rev. Lett., 119, 014801 (2017)
Resonant frequency controlled, precession of spin phase locked

WIEN FILTER COMMISSIONING



WIEN FILTER COMMISSIONING – 90° MODE

SPIN ROTATIONS WITH PHASE LOCK

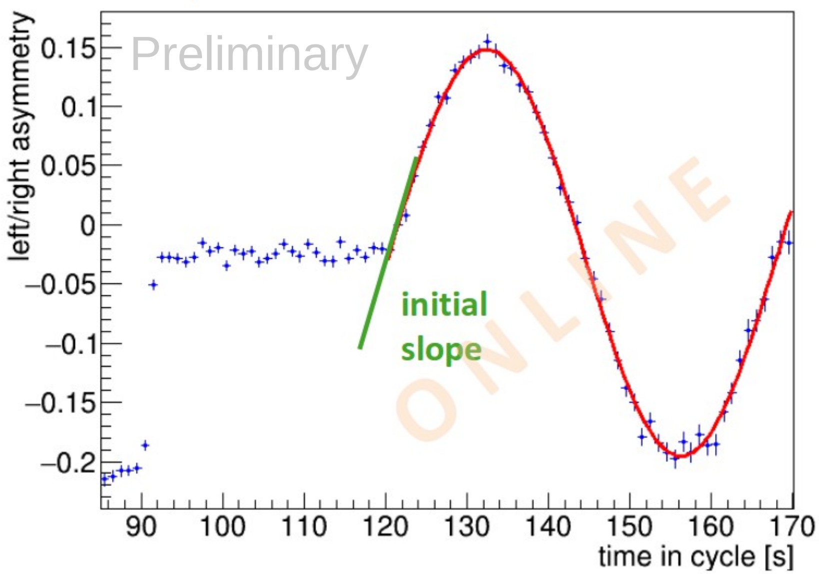


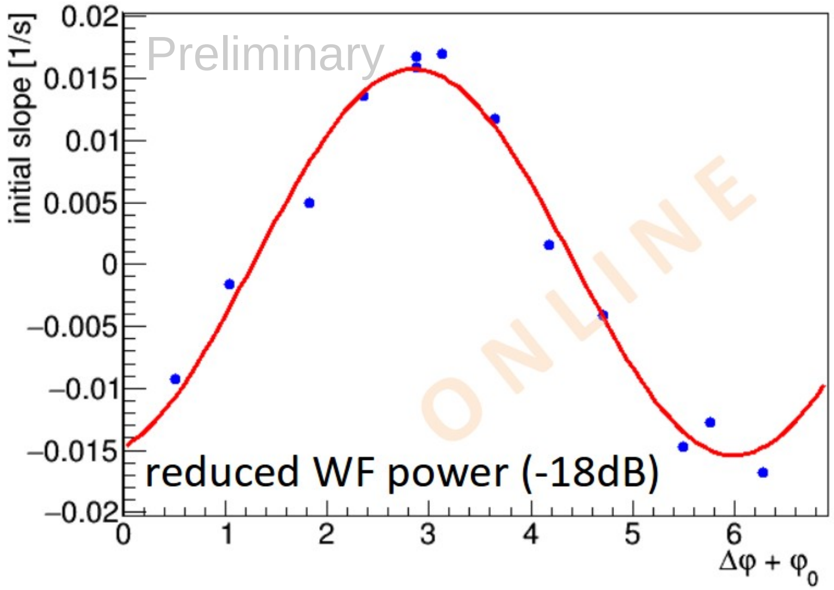
$$\varphi(t) = 2\pi\, \nu_s f_C t$$

$$B_{WF}(t) = B_0 \sin(\omega t + \Delta\varphi)$$

Task: maintain $\omega = 2\pi\,|k + \nu_s| f_C$ and fix $\Delta\varphi$

Controlled via WF frequency

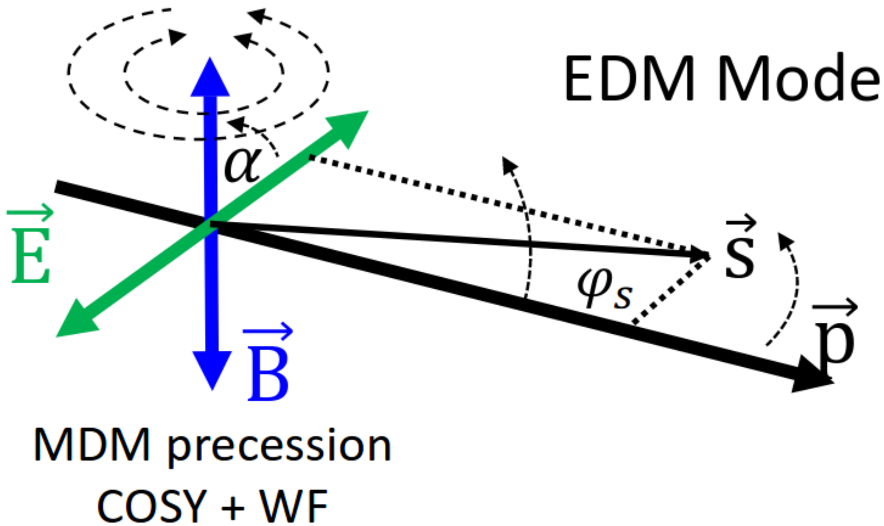


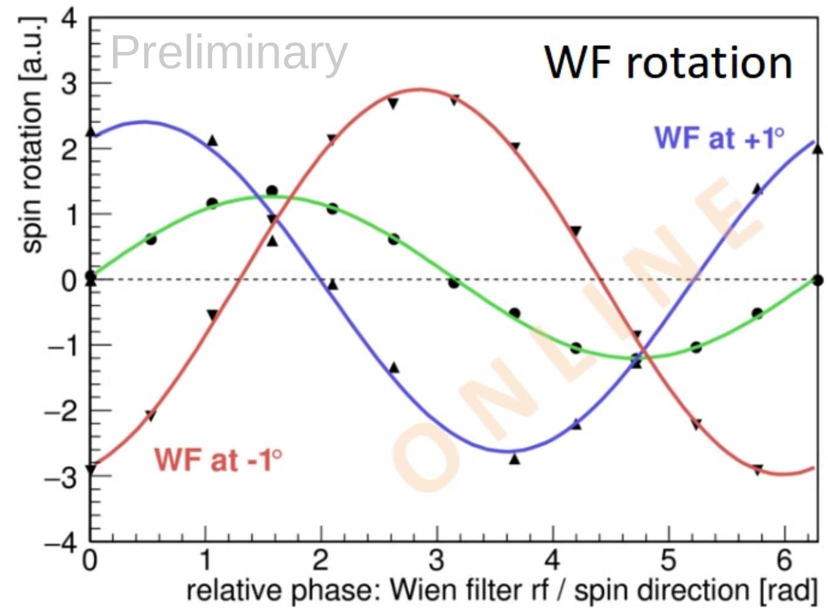


Spin build-up as a function of phase ~ sinΔφ → Feedback system works properly!

WIEN FILTER COMMISSIONING – 0^o MODE

SPIN ROTATIONS WITH PHASE LOCK





We see **vertical polarization buildup - EDM-like signal**

Two **systematic** contributions:

1. Residual, radial magnetic field from WF

- effect equivalent to WF rotation

2. Field imperfections in COSY

- transverse contribution: equivalent to WF rotation
- longitudinal contribution: equivalent to additional static solenoid field

The measurement shows the stability of COSY conditions within 24 hours

POLARIMETRY

Detector signal

$$N^{up,down} = 1 \pm PA \sin(2\pi \cdot f_{\text{prec}} t)$$
$$= 1 \pm PA \sin(2\pi \cdot \nu_s \, n_{\text{turns}})$$

P: polarisation, A: analysing power

Asymmetry

$$\varepsilon = \frac{N^{up} - N^{down}}{N^{up} + N^{down}} = PA \sin(2\pi \cdot \nu_s \, n_{\text{turns}})$$

Challenges

- precession frequency $f_{\text{prec}} \approx 120$ kHz
- $\nu_s \approx -0.16$ → 6 turns / precession
- event rate ≈ 5000 s^{-1} → 1 hit / 25 precessions

→ no direct fit of the rates

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POLARIMETRY

Detector signal

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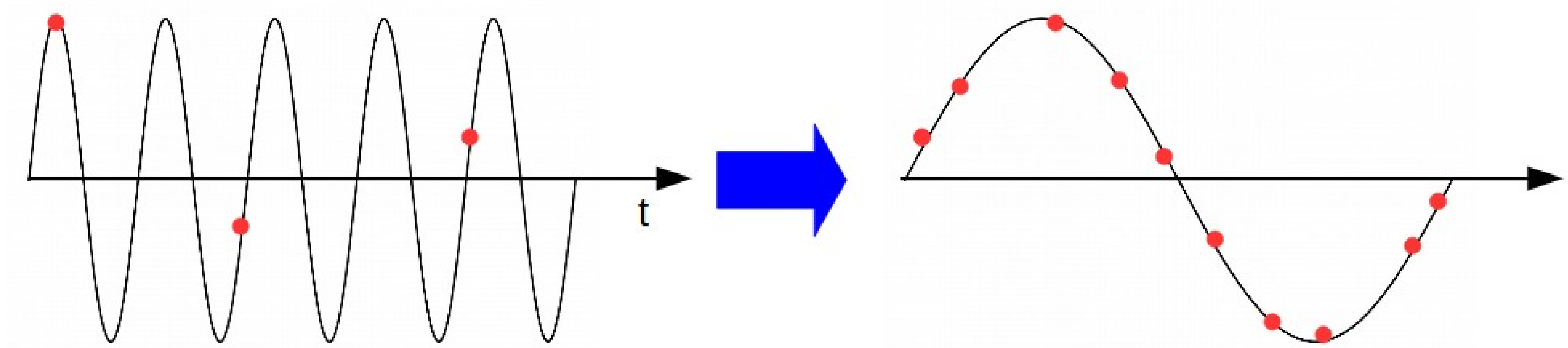


Too few polarimeter events to resolve oscillation directly!

Map many events to one cycle
Phys. Rev. ST Accel. Beams 17, 052803 (2014)

POLARIMETRY

beam revolutions: counting turn number n

↓

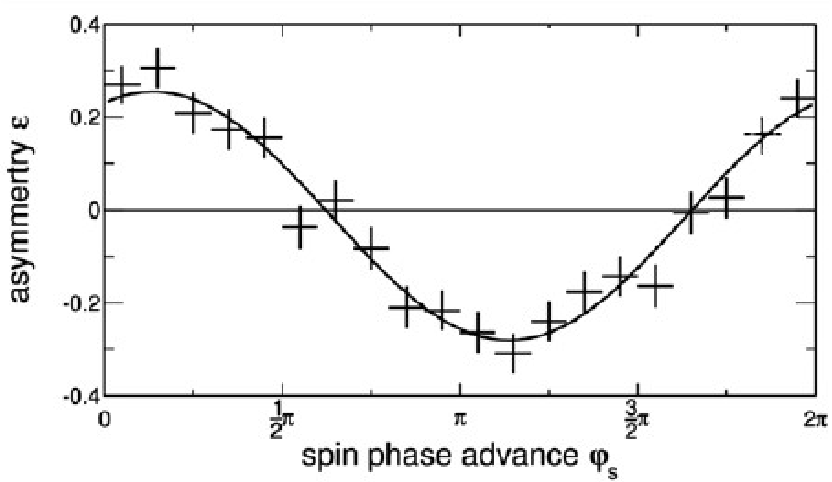
assign turn number n $\rightarrow$ phase advance $\varphi_s = 2\pi\nu_s n$

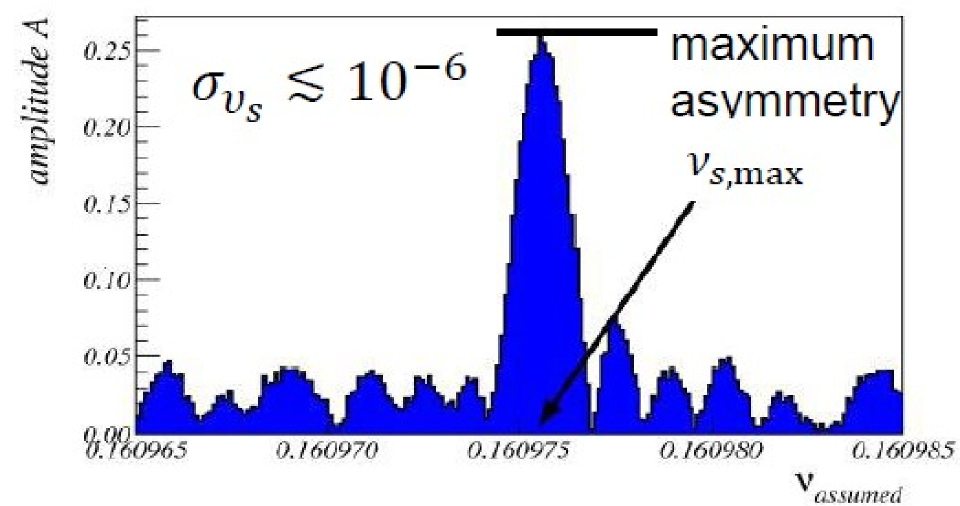
↓

for intervals of $\Delta n = 10^6$ turns: $\varphi_s \rightarrow \varphi_s \bmod 2\pi$

↓

scan ν_s in some interval around $\nu_s = \gamma G$





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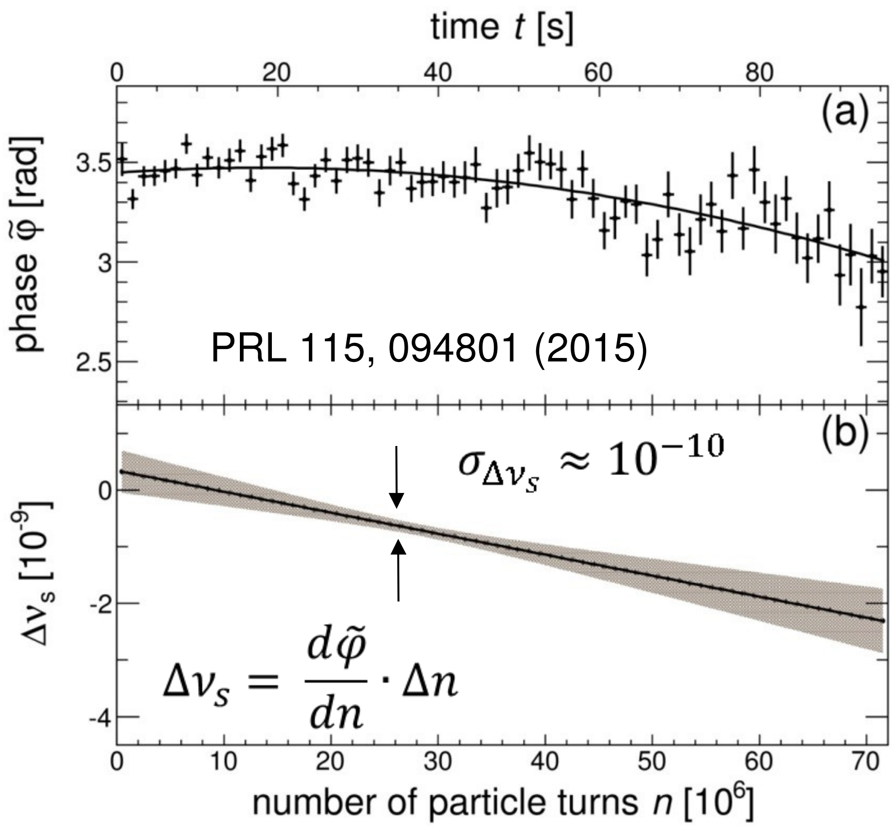
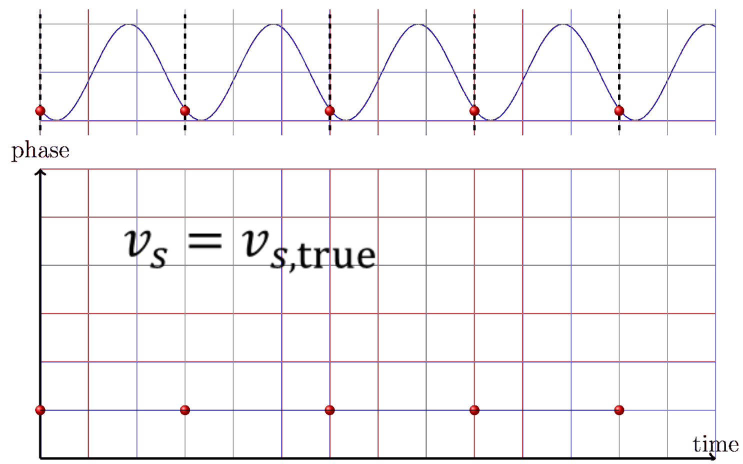
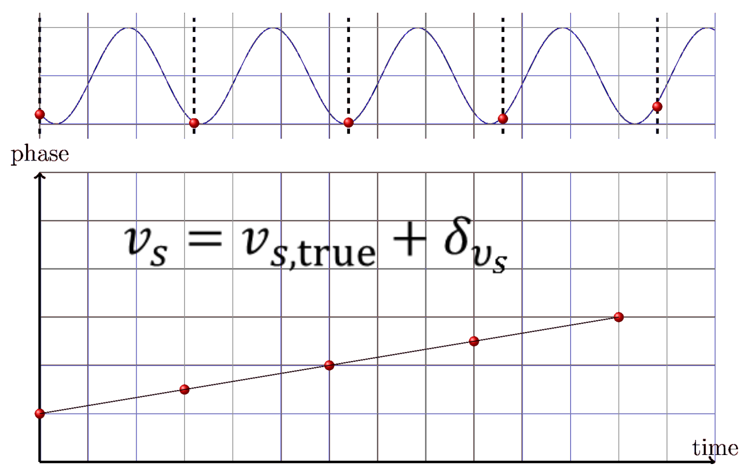
SPIN TUNE MEASUREMENT

Monitoring phase of asymmetry with fixed spin tune







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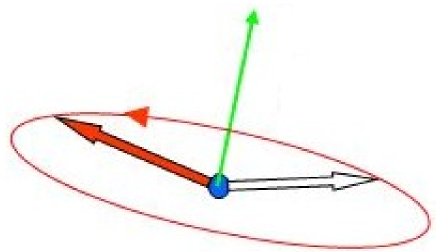
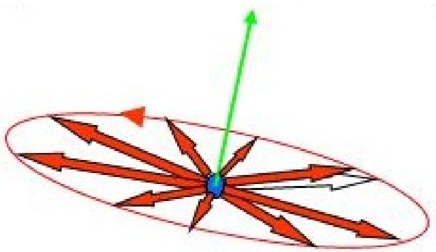
SPIN COHERENCE TIME



At the beginning all spin vectors aligned



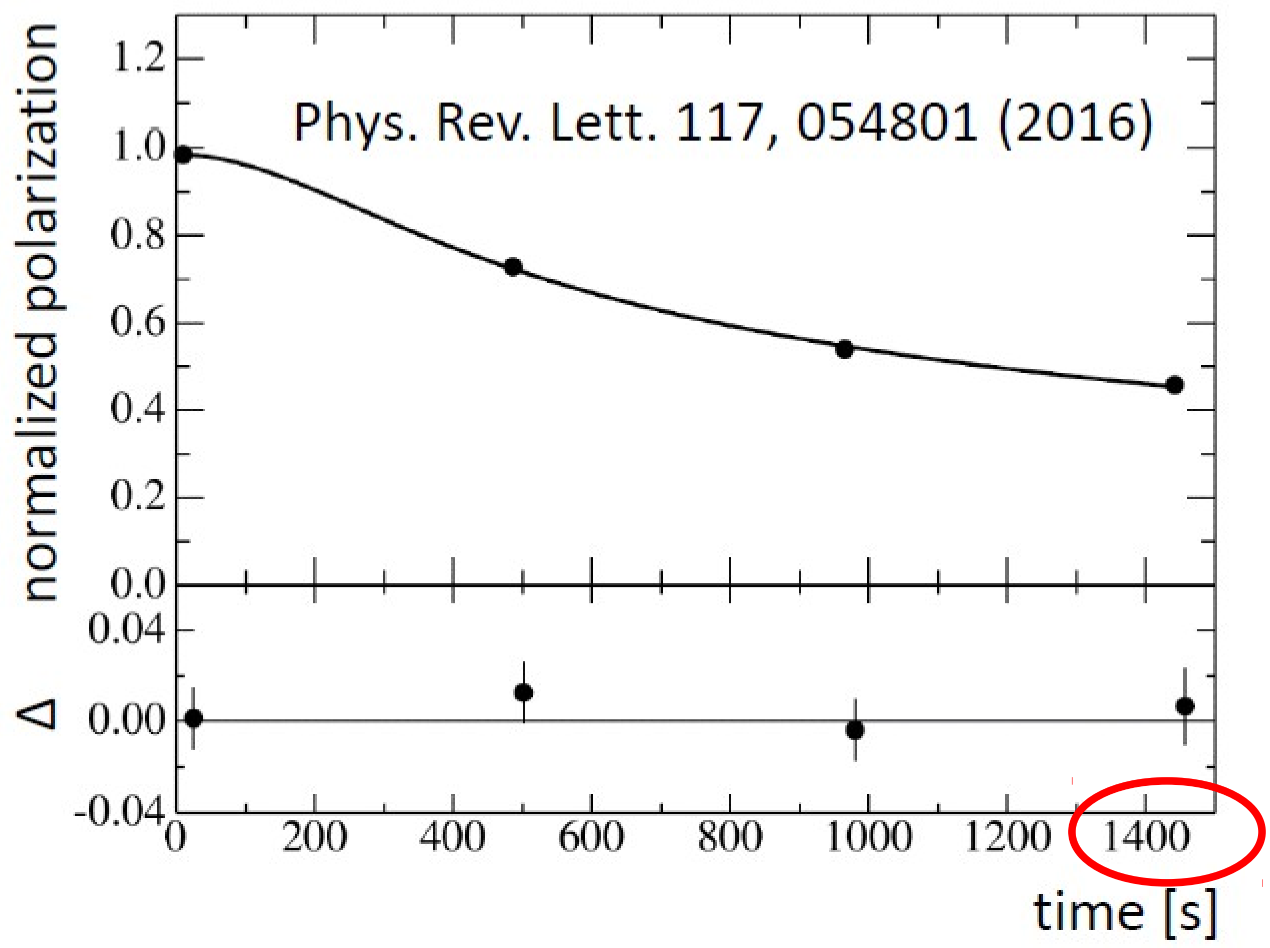
After some time spin vectors all out of phase

Polarization vanishes → measurement time limited

$$\frac{\Delta\gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta\nu}{\nu} \quad \Longrightarrow \quad \Delta\varphi \approx 60\ {}^{\mathrm{rad}}/_{\mathrm{s}}$$

- unbunched beam: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5} \Longrightarrow$ decoherence in < 1s
- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order → $\tau \approx 20$ s
- correcting higher order effects using sextupoles and (pre-) cooling → $\tau \approx 1000$ s

SPIN COHERENCE TIME



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CONTROLLING SPIN DIRECTION

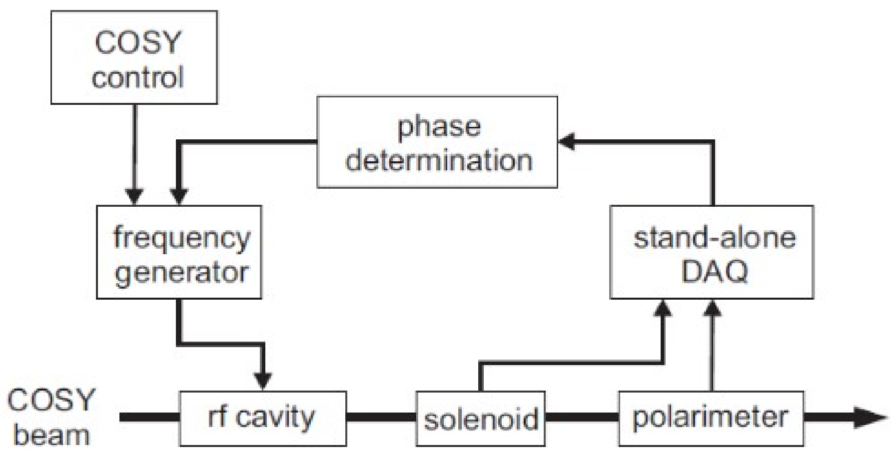
Feedback system

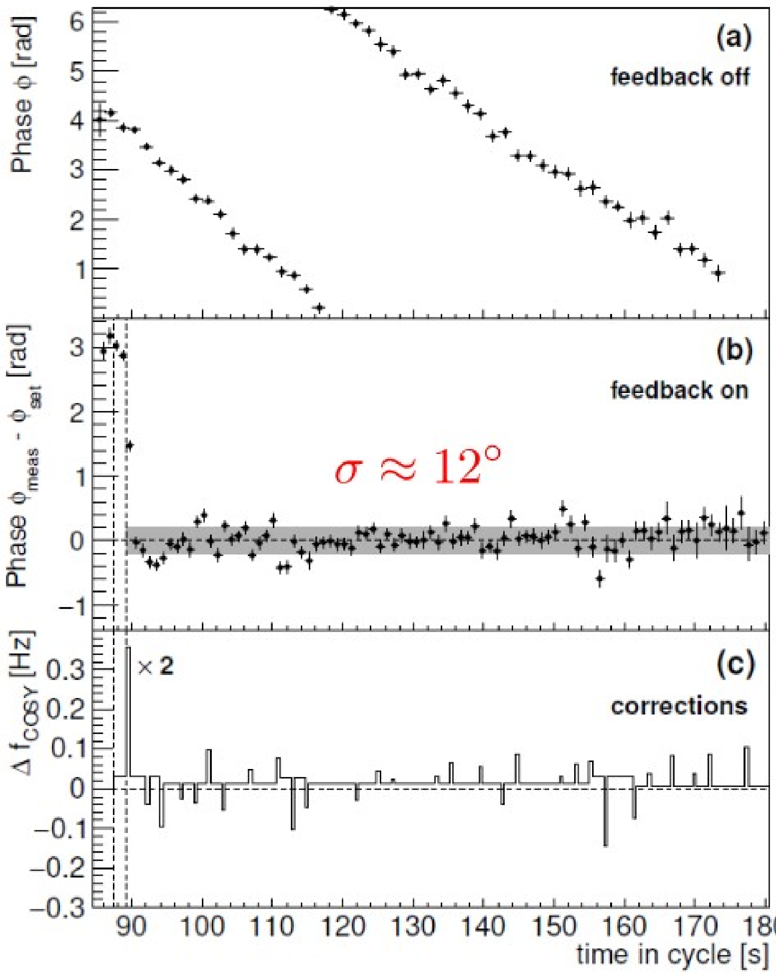
Goal: Maintain resonance frequency and phase between spin precession and Wien filter

- keep precession frequency stable
- match frequency and phase to Wien filter

Test at COSY:
control spin tune via COSY rf: $\nu_s = G\gamma$

control phase to external frequency
by accelerating/decelerating spin precession





PRL, 119, 014801 (2017)

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