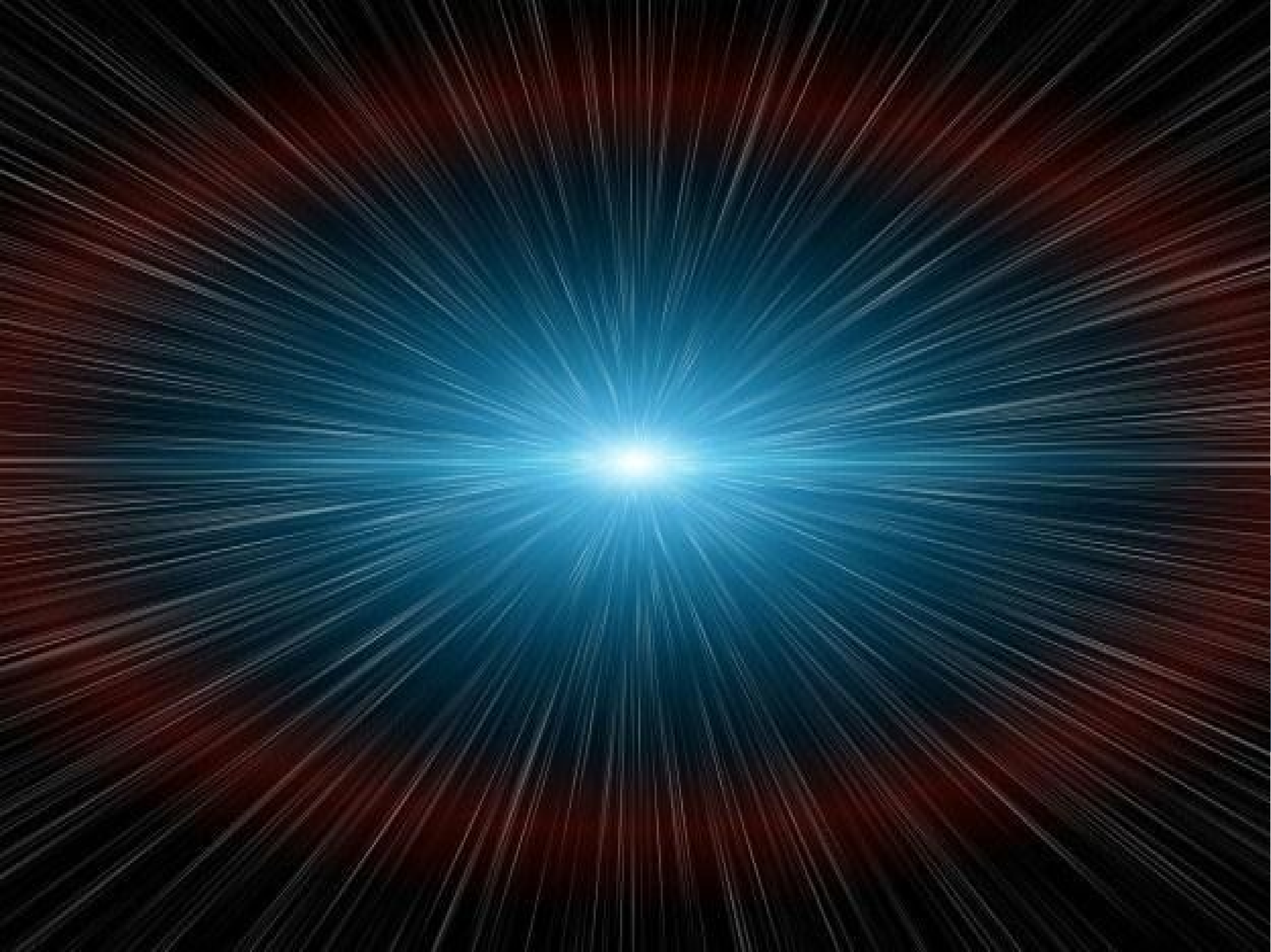
Probing symmetries in the world of hadrons with COSY

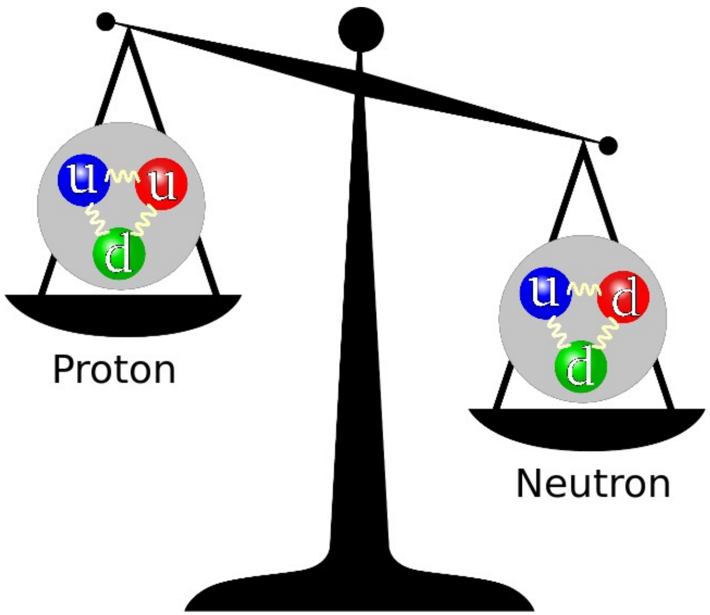
Maria Żurek I Research Center Jülich, Institute for Nuclear Physics

Lawrence Berkeley National Laboratory, HIT Seminar, 12.01.2018



Why does the Universe exist as it is?

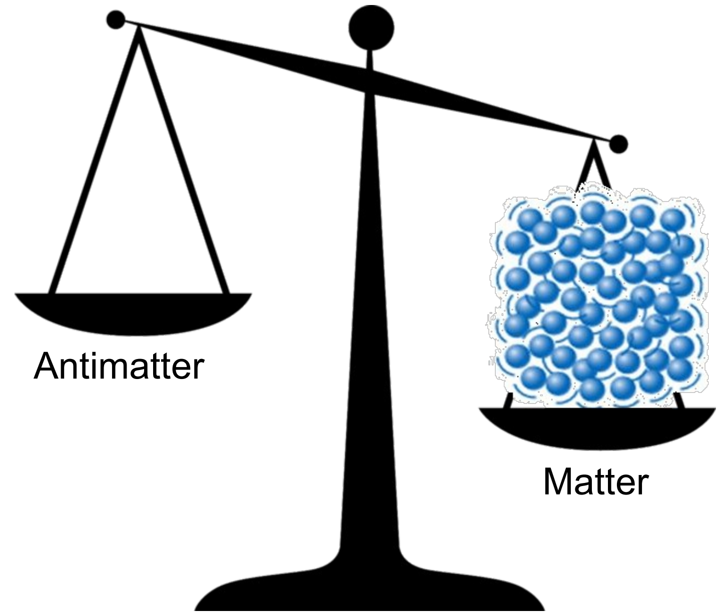
Stable hydrogen atom



Isospin symmetry breaking

***dd* $\rightarrow$ ^{4}Heπ^{0} reaction**

Matter-antimatter imbalance



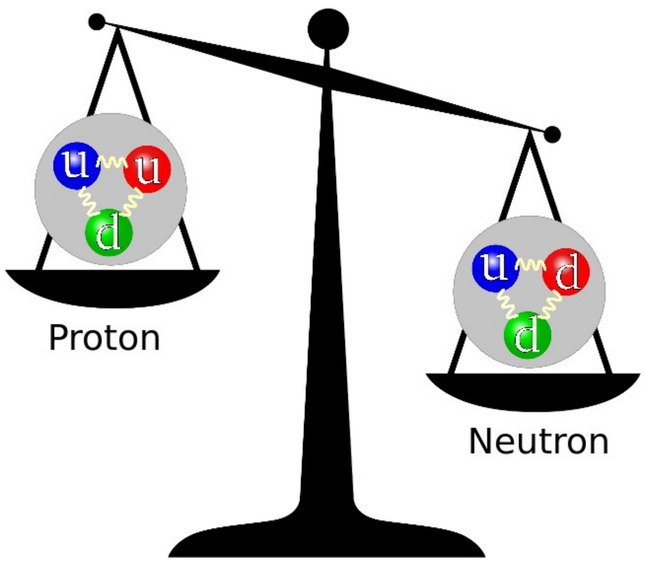
CP symmetry breaking

Electric dipole moment of p,d

Motivation

Isospin symmetry - two sources of violation:

- Electromagnetic interaction ($Q_u \neq Q_d$)
- Strong interaction ($M_u \neq M_d$) ↦ window for probing quark mass effects



Nucleon mass difference

$$\Delta M_{np} = \Delta M_{em} + \Delta M_{str}$$

-0.7 ± 0.3 MeV [1]

2.05 ± 0.3 MeV [1]

($\Delta M_{np} - \Delta M_{em}$)

[1] J. Gasser and H. Leutwyler, Phys. Rept. 87, 77–169 (1982)
[2] S.Weinberg, Trans. New York Acad. Sci. 38, 185–201 (1977)

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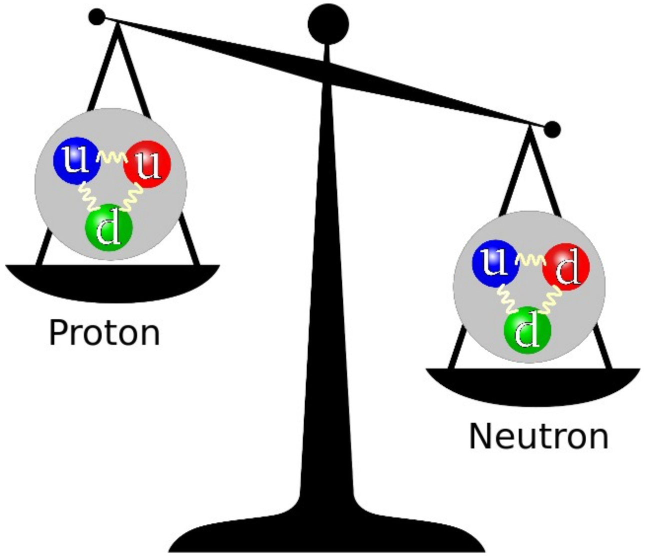

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Access to ΔM_{str} from dynamic ISB using Chiral Perturbation Theory

πN scattering length, $a(\pi^0 p) - a(\pi^0 n) = f(\Delta M_{str})$ [2]

However:

– No direct measurement of $\pi^0 N$

– Large electromagnetic corrections in $\pi^{\pm} N$

[1] J. Gasser and H. Leutwyler, Phys. Rept. 87, 77–169 (1982)
[2] S.Weinberg, Trans. New York Acad. Sci. 38, 185–201 (1977)

Motivation

Isospin Symmetry Breaking

Dominated by pion mass difference Δm_π – e.m. effect

↓

Charge Symmetry (CS) Breaking

Symmetry under the operation of $P_{CS} = e^{-i\tau_2\pi/2}$ – Δm_π does not contribute

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1. ***np→dπ*⁰ forward-backward asymmetry A_{fb}** [1]

   ΔM_{str} = (1.5 ± 0.8 (exp.) ± 0.5 (th.)) MeV (LO) [2]

2. ***dd*→^{4}He*π*⁰**

   CS ⇒ $\sigma = 0$ ~~CS~~ ⇒ $\sigma \neq 0$, $\sigma \propto |M_{CSB}|^2 = |M_1 + M_2 + \ldots|^2$

   σ_{tot} measured at treshold [3]

[1] Opper et al. PRL 91 (2003) 212302
[2] Filin et al. Phys. Lett. B681 (2009) 423
[3] Stephenson et al. PRL 91 (2003) 142302

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   σ_{tot} measured at treshold [3]

Result at threshold consistent with *s*-wave → Chiral Perturbation Theory → Parameter-free prediction of the *p*-wave contribution in $dd \rightarrow {}^4\mathrm{He}\pi^0$

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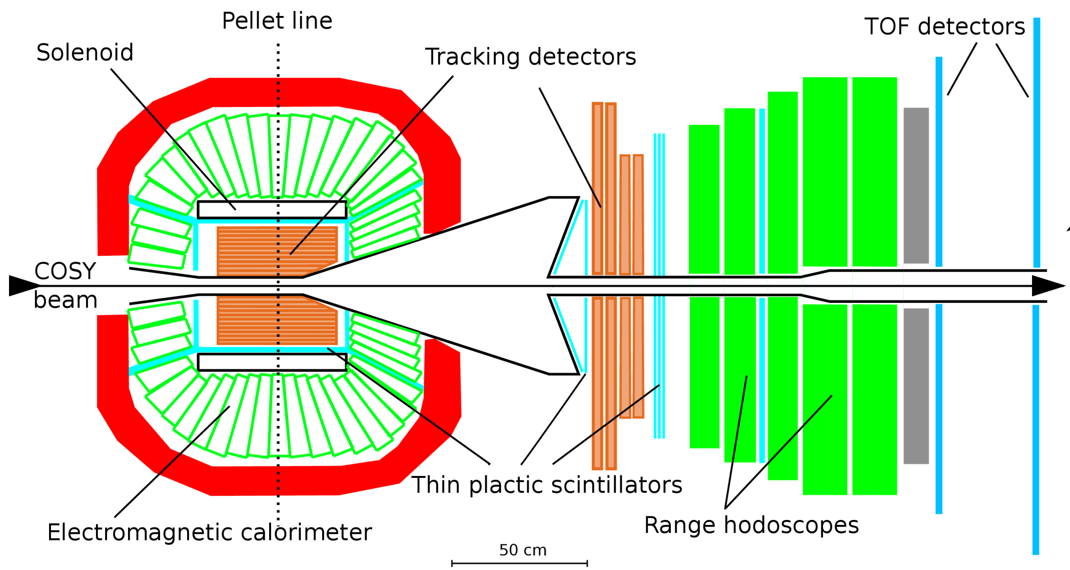
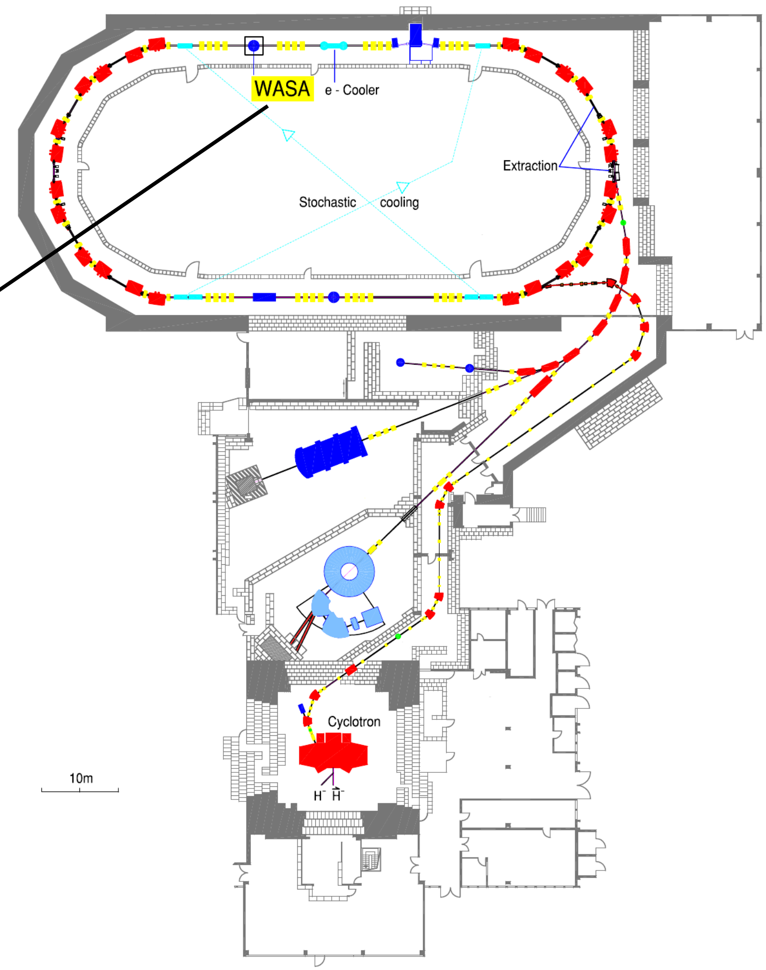
[3] Stephenson et al. PRL 91 (2003) 142302

WASA-at-COSY Experiment





CSB program with WASA-at-COSY:

2007: Measurement of $dd \to {}^3\mathrm{He}n\pi^0$

goal: description of main background, input for initial-state-interaction calculations

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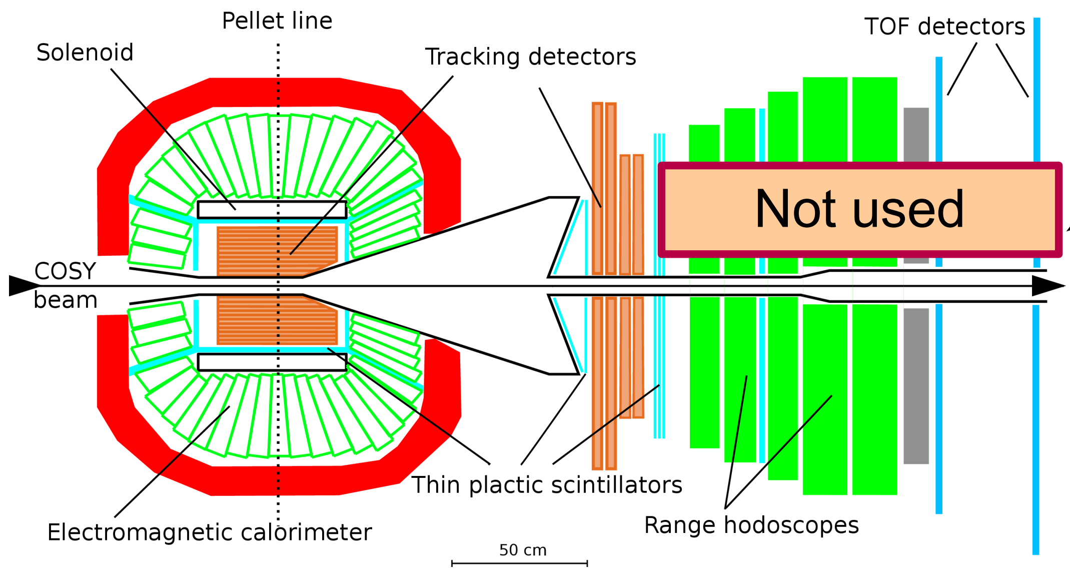

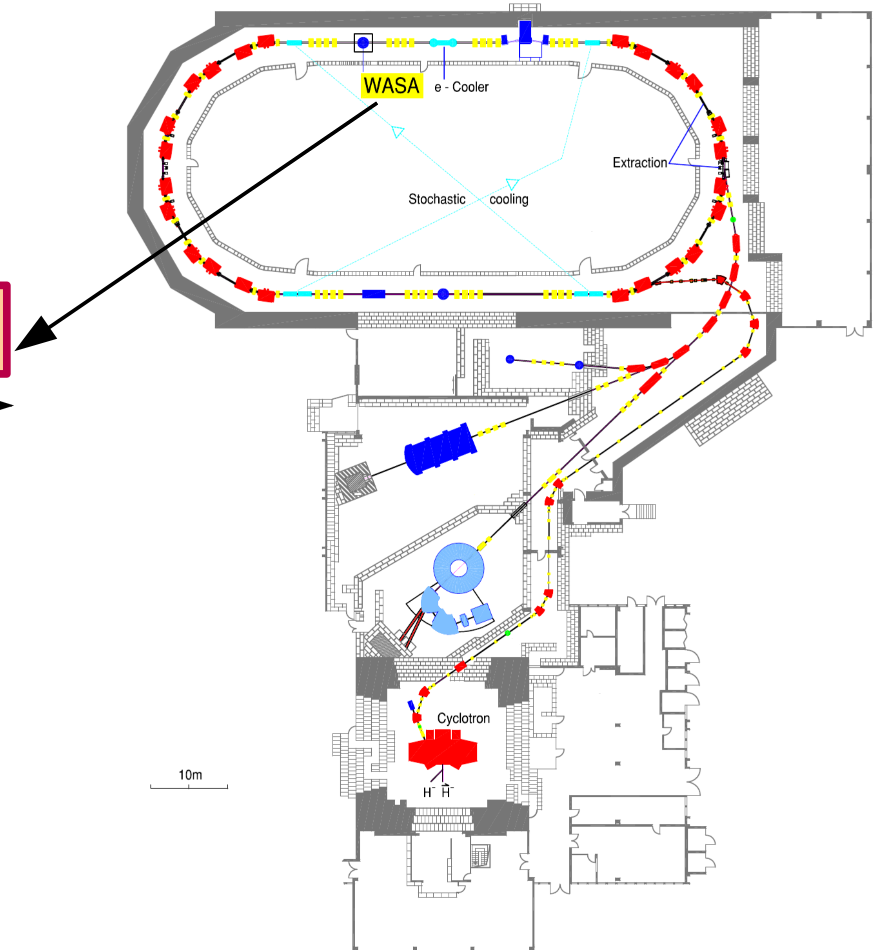

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goal: description of main background, input for initial-state-interaction calculations

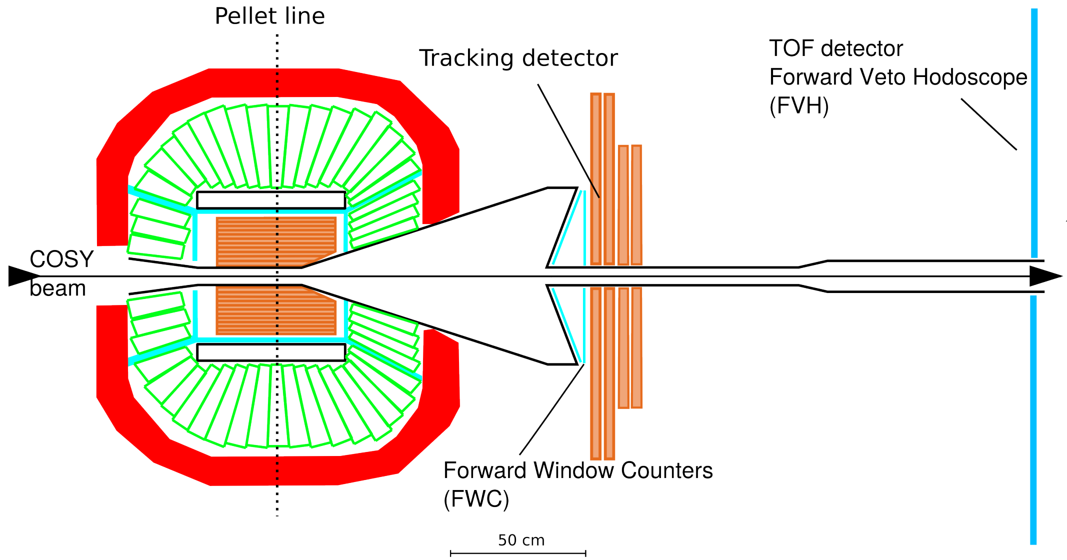
2008: First measurement of $dd \to {}^4\mathrm{He}\pi^0$ (2 weeks) @ Q = 60 MeV

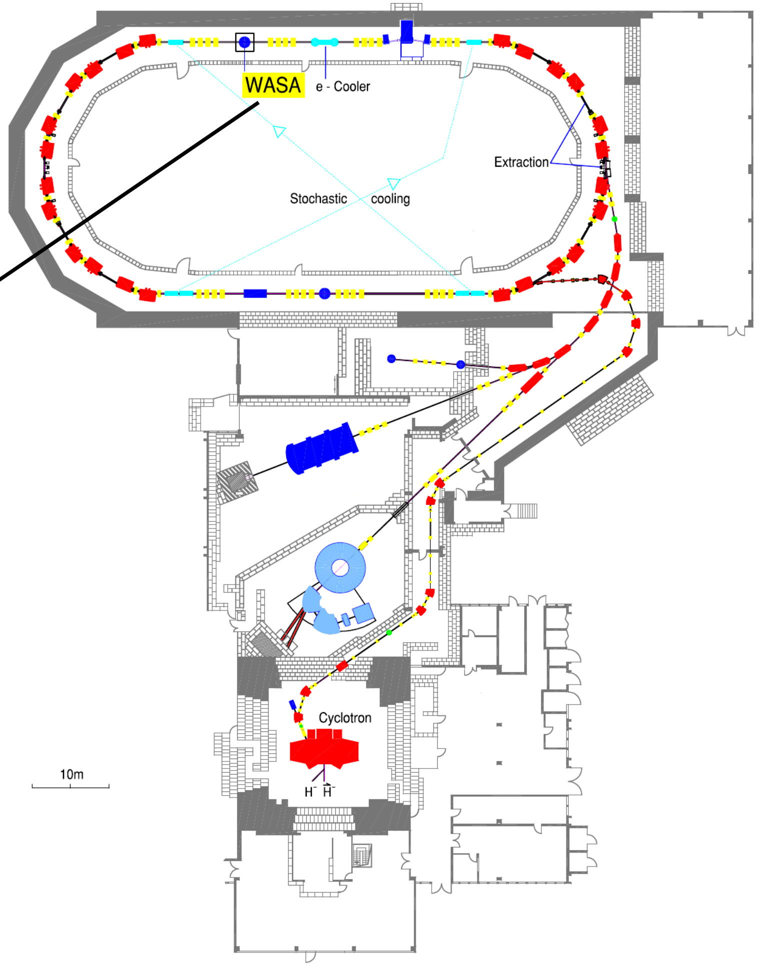
goal: σ_{total}

Result consistent with *s*-wave

Due to **limited statistics** not decisive to identify higher-wave contribution

WASA-at-COSY Experiment





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goal: description of main background, input for initial-state-interaction calculations

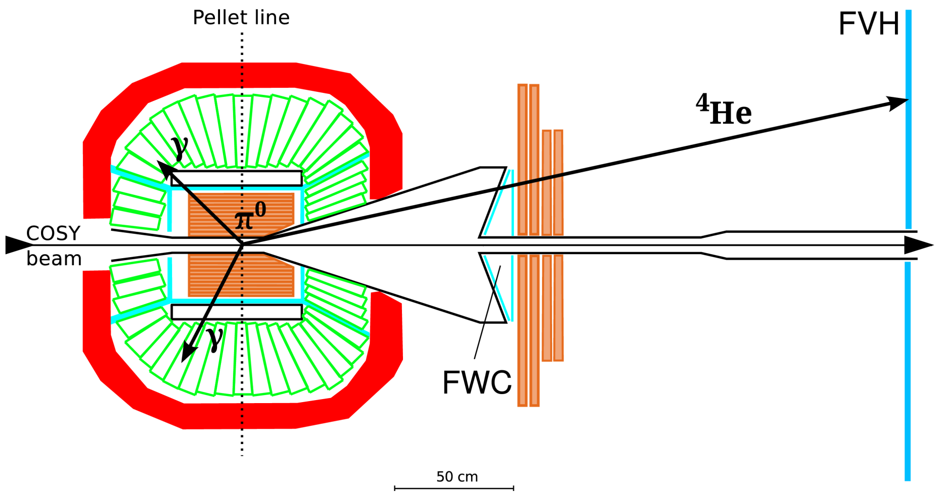
2008: First measurement of $dd \to {}^4\mathrm{He}\pi^0$ (2 weeks) @ Q = 60 MeV

goal: σ_{total}

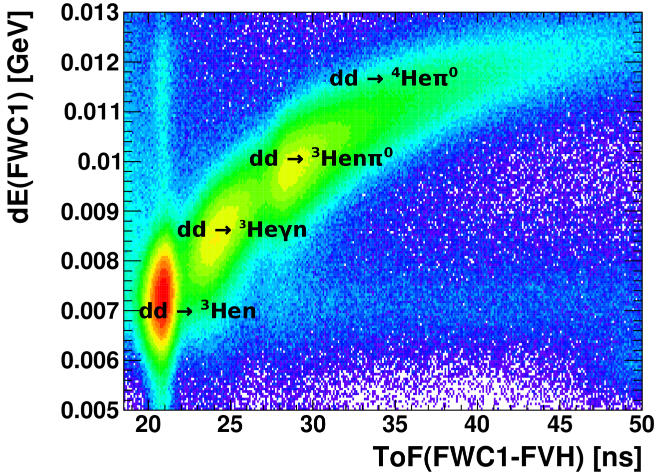
2014: New measurement of $dd \to {}^4\mathrm{He}\pi^0$ (10 weeks) @ Q = 60 MeV with modified detector

goal: angular distribution

New Experiment with Improved Setup

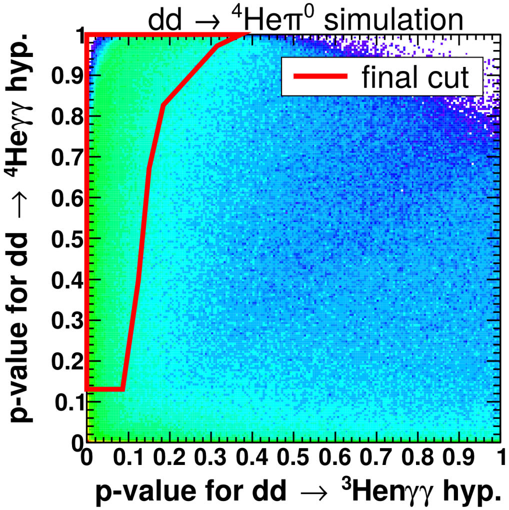


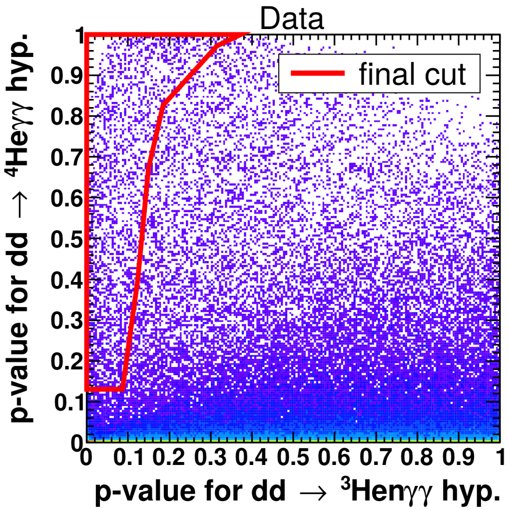
Status after calibration:



Background

- $dd \to (pnd, pnpn, tp) + \pi^0$
- $dd \to {}^3\mathrm{He}n\pi^0$ ($3 \cdot 10^5$ higher σ)
- $dd \to {}^4\mathrm{He}\gamma\gamma$ (physics bg)





Overall kinematic fit

→ 2 hypotheses fitted:

$dd \to {}^4\mathrm{He}\gamma\gamma$ and $dd \to {}^3\mathrm{He}n\gamma\gamma$

→ Optimized cuts on cumulated probability distribution (p-value)

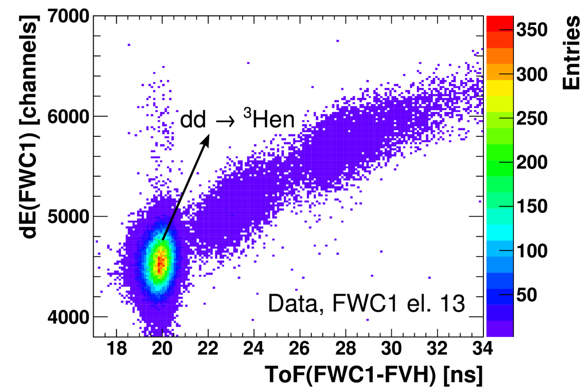
→ Suppresion of $dd \to {}^3\mathrm{He}n\pi^0$ about 10^4

Analysis

Detector Calibration

ToF Calibration

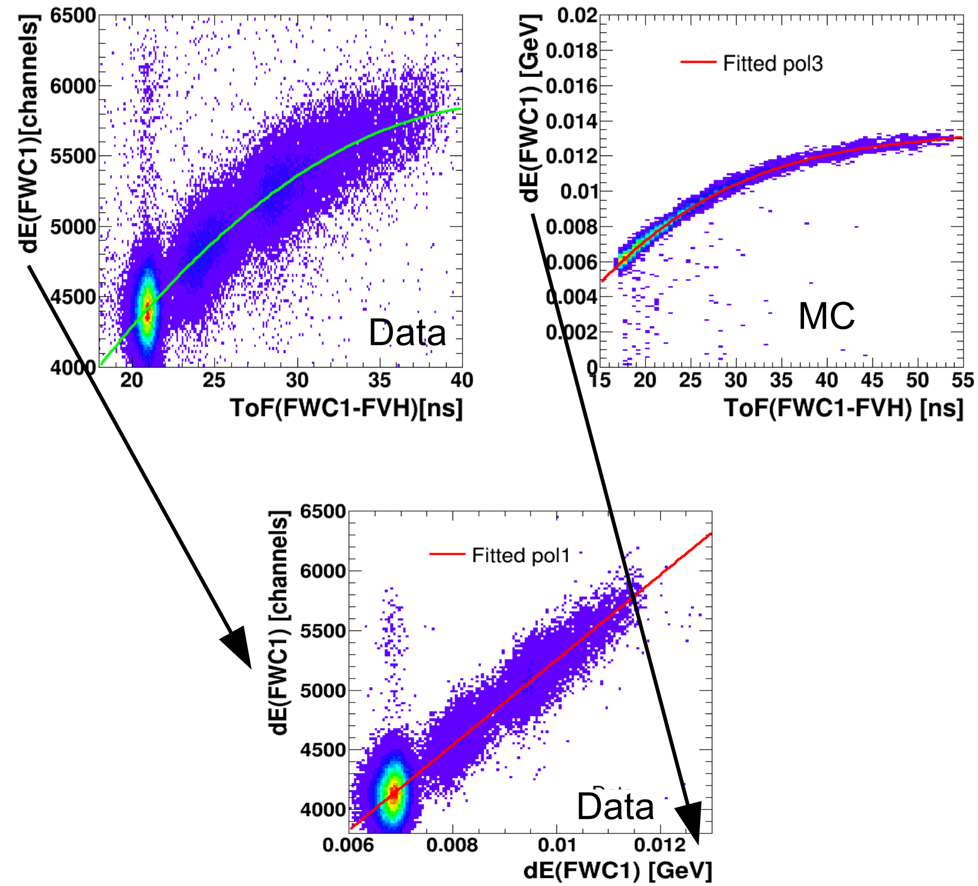
- Offset adjustment for every FWC and FVH element
- *dd* → ^{3}He*n* time peak position used
- Calibrate the data to the MC values for every detector element as a function of θ



dE Calibration

- Gain adjustment for every FWC element
- Based on ToF
  MC: dE [GeV] vs ToF [ns] → **dE_{GeV}(ToF)**
  Data: dE [channels] vs ToF [ns] → **dE_{ch}(ToF)**

→ θ-dependency correction



Kinetic Energy Reconstruction

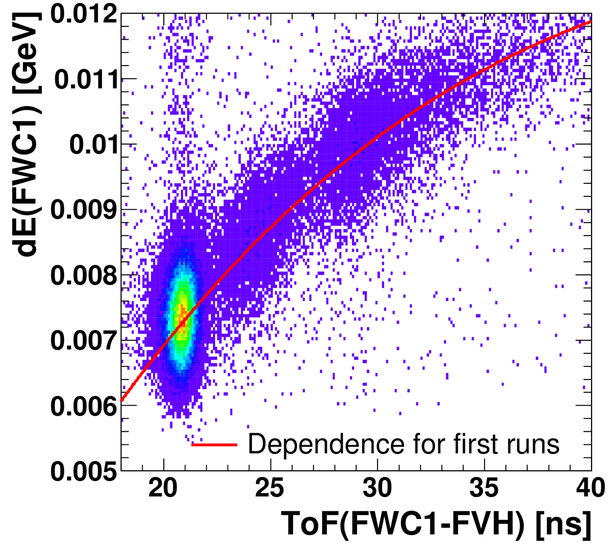
- Based on E_{kin}(ToF), E_{kin}(dE)
- χ^2 fit used to obtain the best matching E_{kin}

Analysis

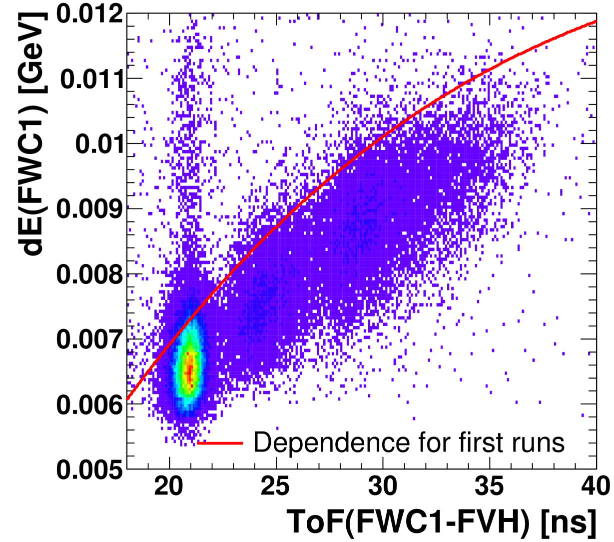
Detector Calibration

- Run-dependent correction for every FWC element
- Middle of the beamtime: → high voltage on photomultipliers raised
- Separate calibration for both datasets

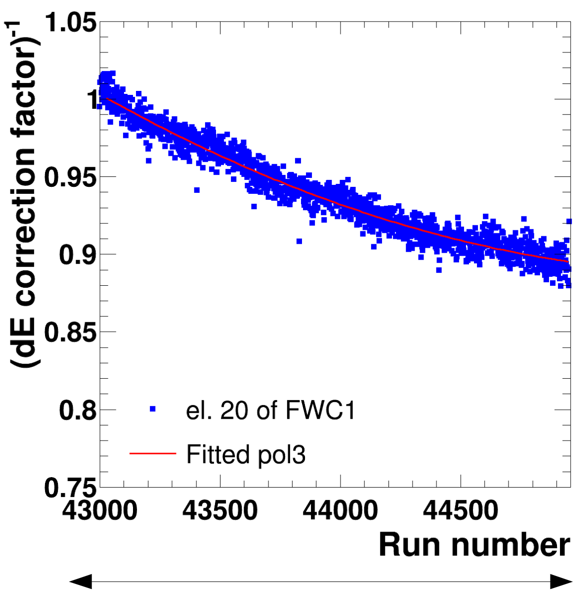
Beginning of the beamtime



3 weeks later

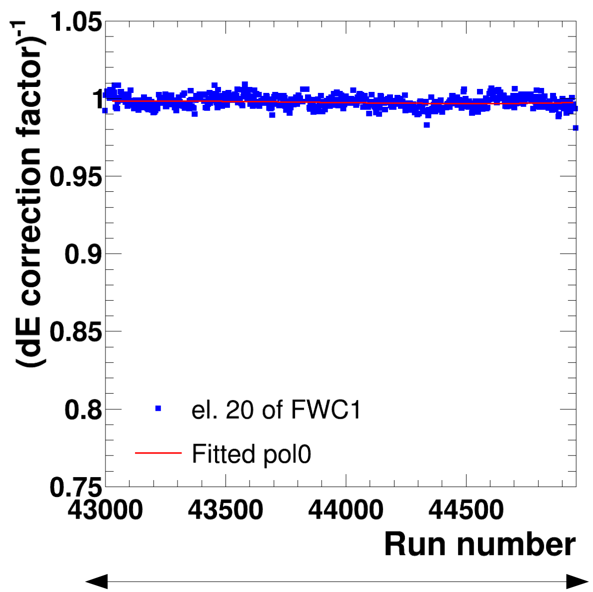


Before correction



4 weeks

After correction



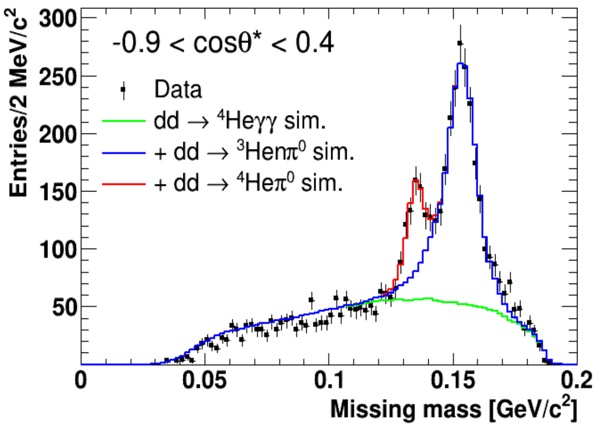
4 weeks

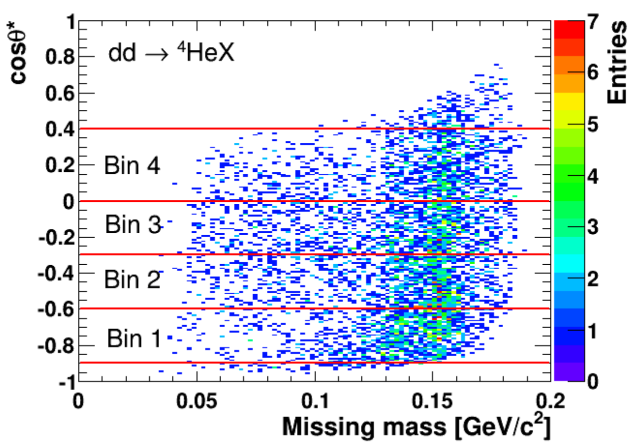
- Gain drop from 10% to 25% for different FWC elements
- Run-dependent correction for the ToF calibration also applied

Results

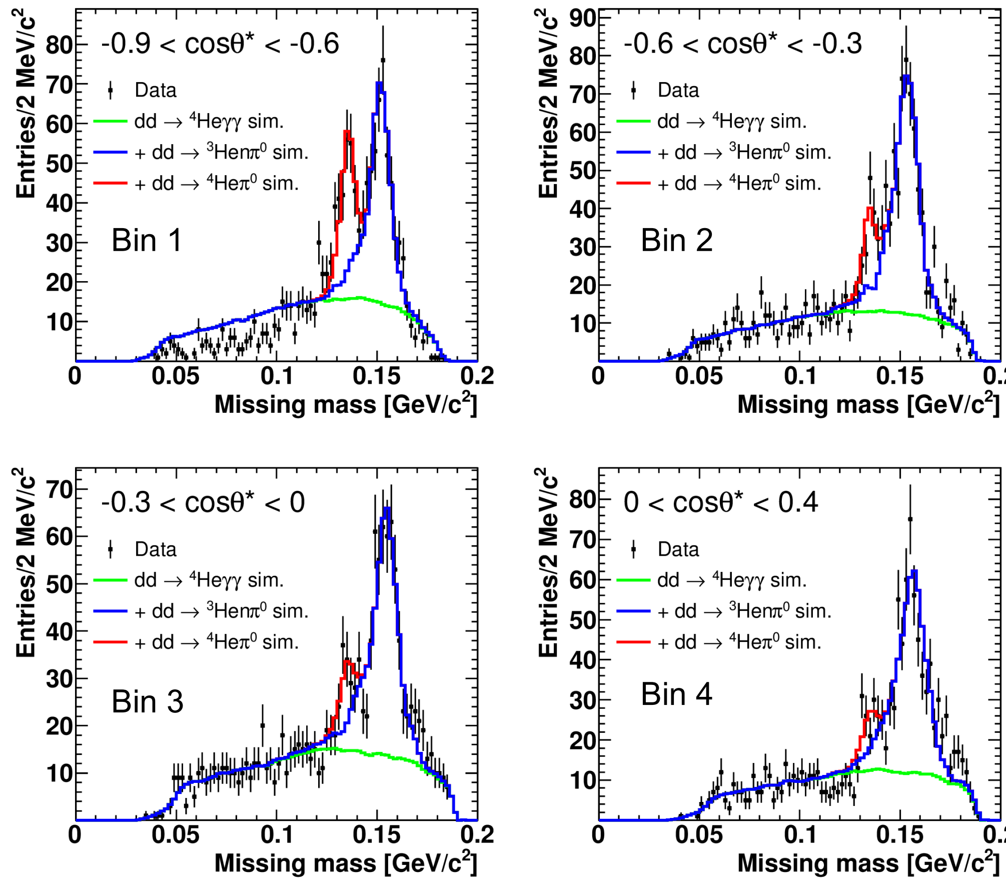
Missing mass of dd → ^{4}HeX

Full angular range
within detector acceptance





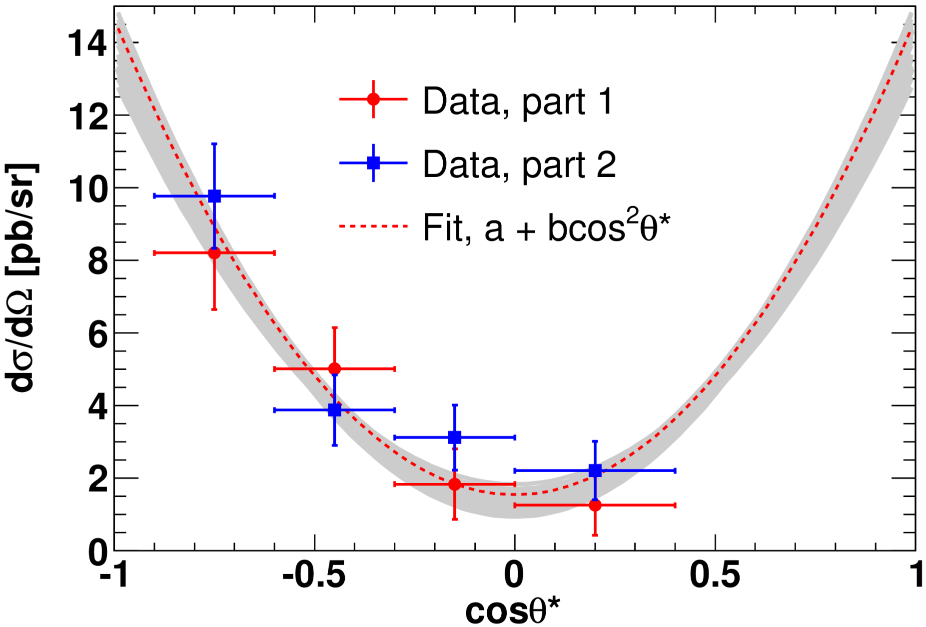
Four angular bins



- **Luminosity determination** using *dd→*^{3}He*nπ*^{0}, normalization to the σ from the previous measurement (Phys. Rev. C 88 (2013) 014004)
- **Acceptance correction**: 1st assuming uniform angular distribution for the signal, then using measured angular distribution

Results

Differential cross section



Identical particles in the initial state
→ forward-backward symmetric cross section
$\mathrm{d}\sigma/\mathrm{d}\Omega = a + b\cos^2\theta^*$ fit result:

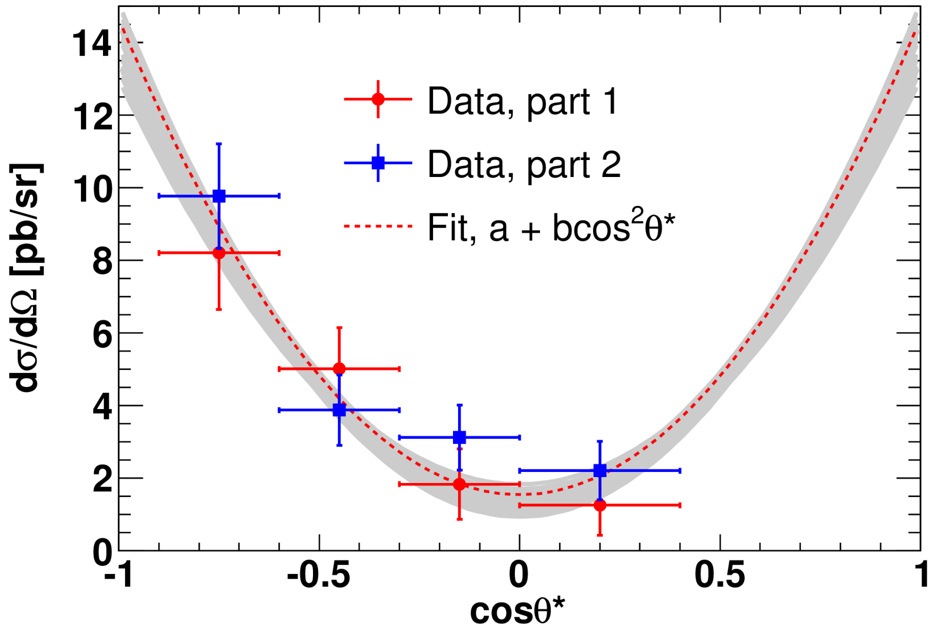
$$\mathrm{a} = \left(1.55 \pm 0.46(\mathrm{stat})^{+0.32}_{-0.8}(\mathrm{syst})\right)\ \mathrm{pb/sr}$$

$$\mathrm{b} = \left(13.1 \pm 2.1(\mathrm{stat})^{+1.0}_{-2.7}(\mathrm{syst})\right)\ \mathrm{pb/sr}$$

Common systematic uncertainty of 10% from external normalization

Results

Differential cross section



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Common systematic uncertainty of 10% from external normalization

Considering only ***s*- and *p*-waves** [1]: $b = -\frac{p_{\pi^0}}{p}\frac{2}{3}\boxed{|C|^2}p_{\pi^0}^2$ (*p*-wave)

- *p*-waves contribute with a **negative** sign → maximum at 90° in angular distribution
- **Observed minimum** at 90° → explained only with **d-waves** in the final state

Data establish for the first time presence of sizable contribution of d-waves

[1] A. Wronska et al., Eur. Phys. J. A26, 421 (2005).

Quantitative results

Including *d*-waves, terms up to fourth order in pion momentum has to be considered:

s-wave *s*-*d* interference *d*-wave *p*-wave

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{p_{\pi^0}}{p}\frac{2}{3}\Big(|A_0|^2 + 2\mathrm{Re}(A_0^* A_2)P_2(\cos\theta^*)p_{\pi^0}^2 + |A_2|^2 P_2^2(\cos\theta^*)p_{\pi^0}^4 + |C|^2 \sin^2\theta^* p_{\pi^0}^2$$

d-wave

$$+ |B|^2 \sin^2\theta^* \cos^2\theta^* p_{\pi^0}^4\Big)$$

Full fit with 4 amplitudes and 1 relative phase δ (between A_0 and A_2)

→ outside the scope of the presented data

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Including *d*-waves, terms up to fourth order in pion momentum has to be considered:

$$\frac{d\sigma}{d\Omega} = \frac{p_{\pi^0}}{p}\frac{2}{3}\Big(\underbrace{|A_0|^2}_{s\text{-wave}} + 2\underbrace{\mathrm{Re}(A_0^* A_2)}_{s\text{-}d\text{ interference}} P_2(\cos\theta^*) p_{\pi^0}^2 + \underbrace{|A_2|^2}_{d\text{-wave}} P_2^2(\cos\theta^*) p_{\pi^0}^4 + \underbrace{|C|^2}_{p\text{-wave}} \sin^2\theta^* p_{\pi^0}^2 + \underbrace{|B|^2}_{d\text{-wave}} \sin^2\theta^* \cos^2\theta^* p_{\pi^0}^4\Big)$$

Full fit with 4 amplitudes and 1 relative phase *δ* (between A_0 and A_2)

→ outside the scope of the presented data

Quantitative results - only using **additional constraints:**

1) Assuming that amplitudes do not carry any momentum dependence: $\boldsymbol{A_0 = A_{thr}}$ from [1]
2) Systematic check of the fit → ***B*** **– fixed to 0, phase** ***δ*** **– fixed to 0**

$$|A_2| = \left(258^{+50}_{-42}(\mathrm{stat})^{+45}_{-38}(\mathrm{syst})^{+37}_{-12}(\mathrm{norm})\right)\frac{(\mathrm{pb/sr})^{1/2}}{(\mathrm{GeV}/c)^2}$$

$$|C| = \left(6^{+9}_{-21}(\mathrm{stat})^{+3}_{-10}(\mathrm{syst})^{+10}_{-5}(\mathrm{norm})\right)\frac{(\mathrm{pb/sr})^{1/2}}{\mathrm{GeV}/c}$$

[1] Stephenson et al. PRL 91 (2003) 142302

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s-wave *s*-*d* interference *d*-wave *p*-wave *d*-wave

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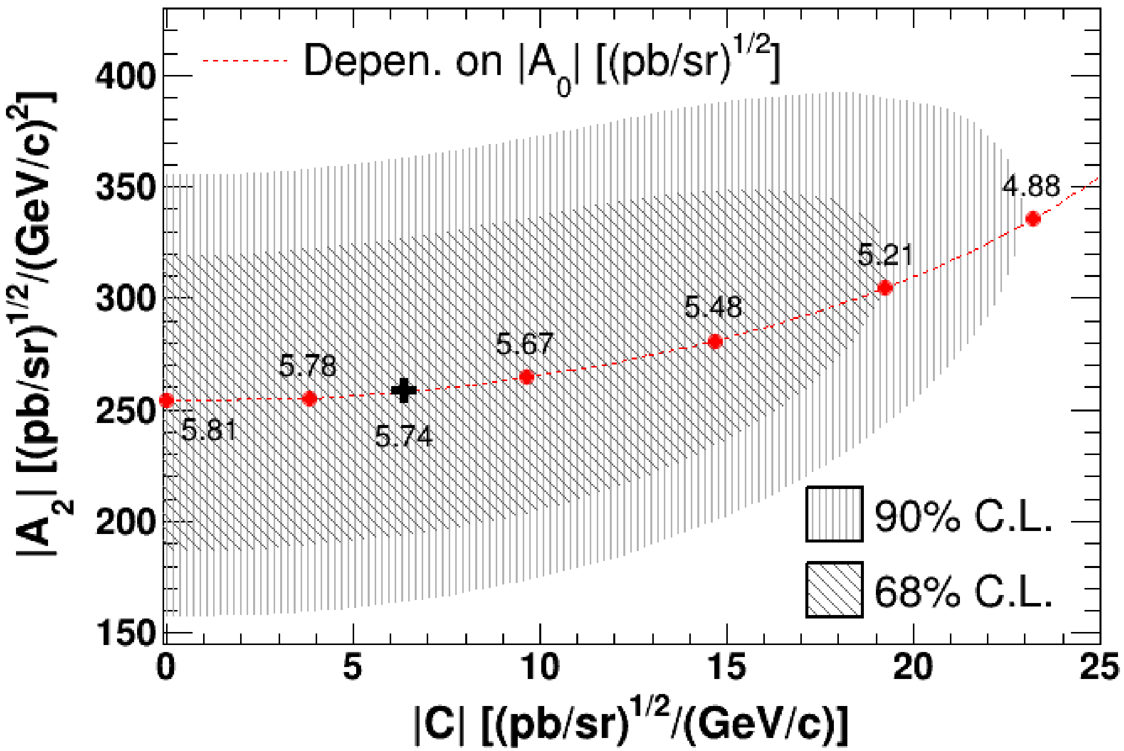
***A*$_0$ = *A*$_{thr}$** from [1], ***B* – fixed to 0, phase *δ* – fixed to 0**



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s-wave, *s*-*d* interference, *d*-wave, *p*-wave, *d*-wave

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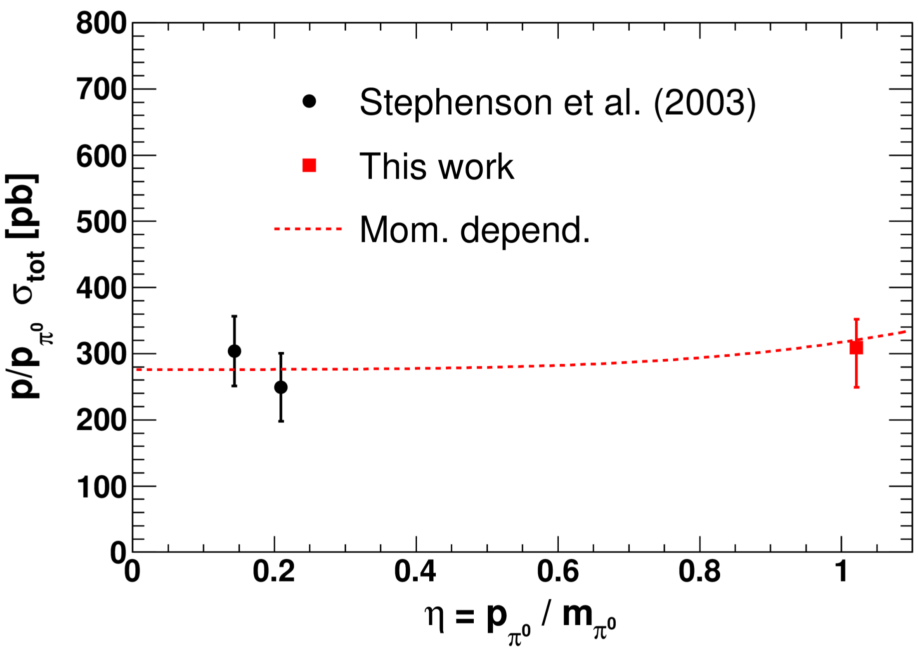


Obtained total cross section:

$$\sigma_{\mathrm{tot}} = (76.9 \pm 7.8(\mathrm{stat})^{+1.9}_{-8.8}(\mathrm{syst})^{+8.3}_{-5.7}(\mathrm{norm}))\ \mathrm{pb}.$$

Momentum dependence of total cross section

$$\sigma_{\mathrm{tot}} = \frac{p_{\pi^0}}{p}\frac{8\pi}{3}\Big(|A_0|^2 + \frac{2}{3}|C|^2 p_{\pi^0}^2 + \frac{1}{5}|A_2|^2 p_{\pi^0}^4 + \frac{2}{15}|B|^2 p_{\pi^0}^4\Big)$$

[1] Stephenson et al. PRL 91 (2003) 142302

What did we learn?

- **First measurement of contributions of higher partial waves** in the charge symmetry breaking reaction dd → $^{4}He\pi^{0}$
- Angular distribution with a minimum at $\theta^{*} = 90^{o}$ can be understood only by the presence of a **significant *d*-wave contribution** in the final state
- Data are consistent with **vanishing *p*-wave** contribution

⇩

Role of the Δ isobar ?

⇩

- Deep insights not only into the dynamics of the nucleon-nucleon interaction but also the role of **quark masses in hadron dynamic**

Motivation

Baryon Asymmetry Problem

	Standard Model	Observed
$\frac{n_B - n_{\bar{B}}}{n_\gamma}$	$\approx 10^{-18}$	6×10^{-10}

Preconditions needed to explain it:

- Baryon number violation
- **C and CP violation**
- Thermal non-equilibrium in the early Universe

Sakharov (1967)

Motivation

Baryon Asymmetry Problem

- **Electroweak sector** (CKM matrix well established)
  → First observation: 1964 - decay of the neutral K meson

- **Strong Interactions** (so called θ-term)
  → Not observed experimentally yet (it is very small)
  → Strong CP puzzle

↓

Predictions orders of magnitude too small to explain the observed matter-antimatter asymmetry!

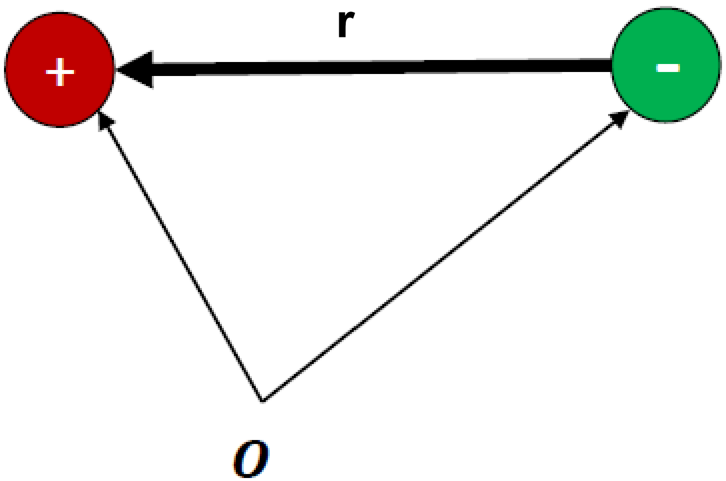
New sources of CP violation Beyond Standard Model needed!

They can manifest in **EDM** of particles

Motivation

Electric Dipole Moment

Classically



- Charge × displacement

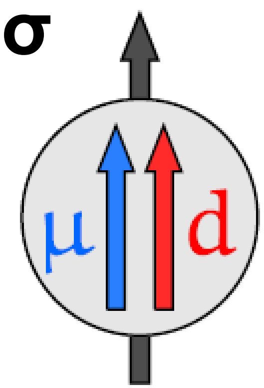
In Quantum Mechanics

Operator $\mathbf{d} = q\mathbf{r}$

Only available quantization axis is the spin $\mathbf{s} = s\boldsymbol{\sigma}$
(there can be only one vector in a quantum system)

$$\mathbf{d} = d\boldsymbol{\sigma}$$

- $\mathbf{d} \parallel \boldsymbol{\sigma}$ and $\boldsymbol{\mu} \parallel \boldsymbol{\sigma}$ (magnetic moment)

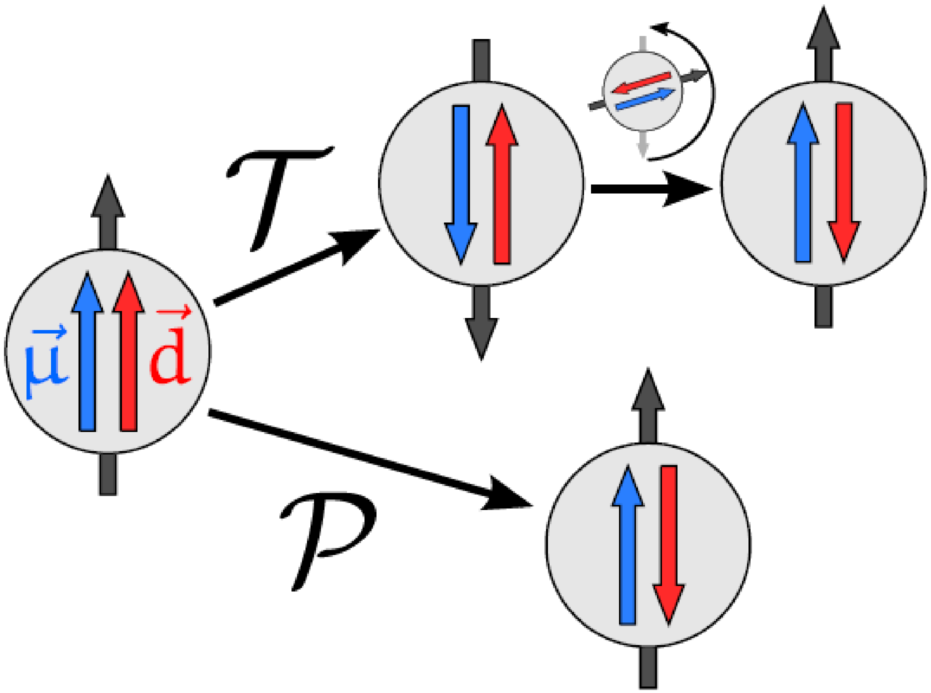


μ – magnetic dipole moment
d – electric dipole moment

Motivation

Electric Dipole Moment

T violation → CP violation
(since CPT conserved)



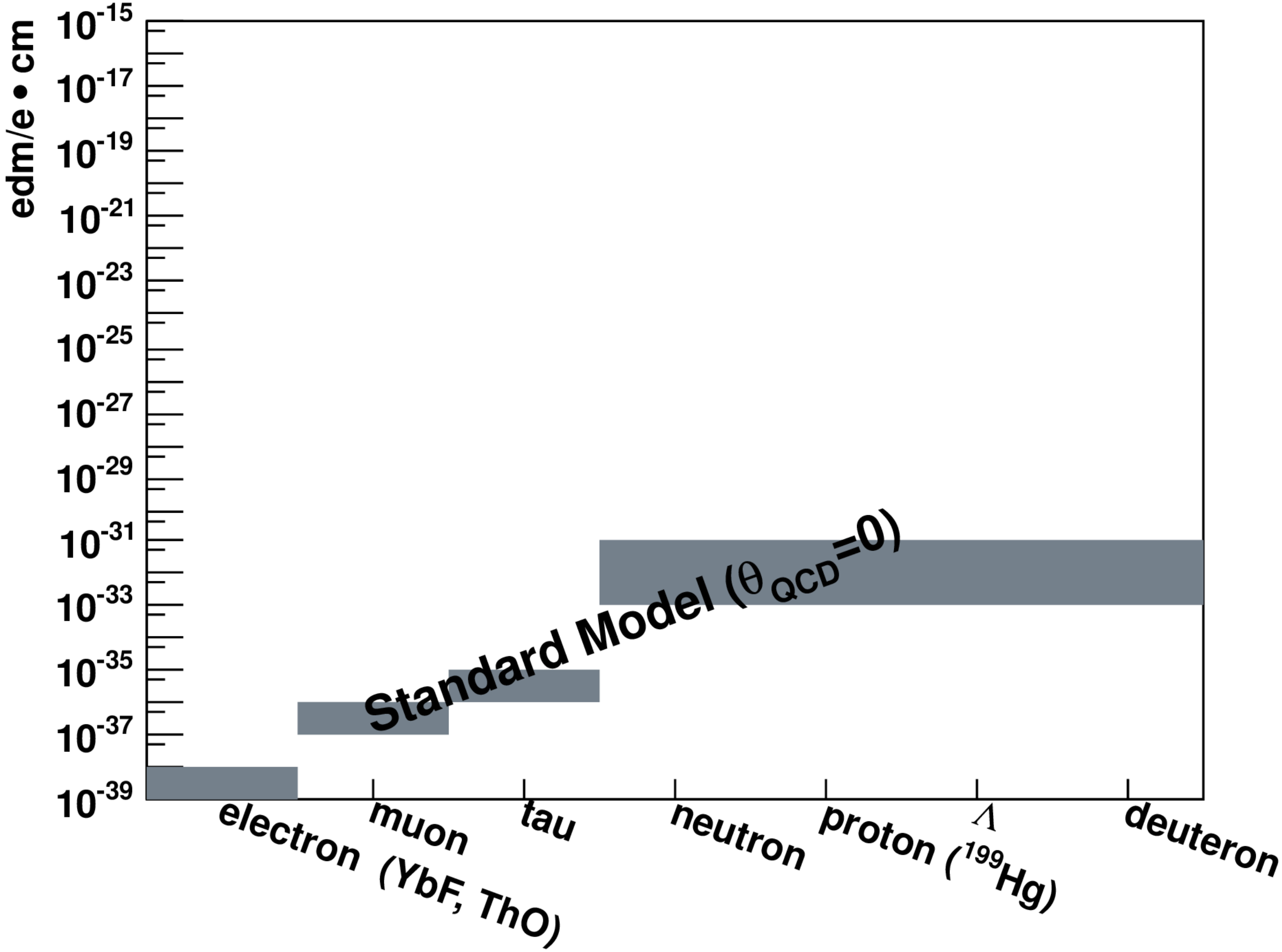
μ – magnetic dipole moment
d – electric dipole moment

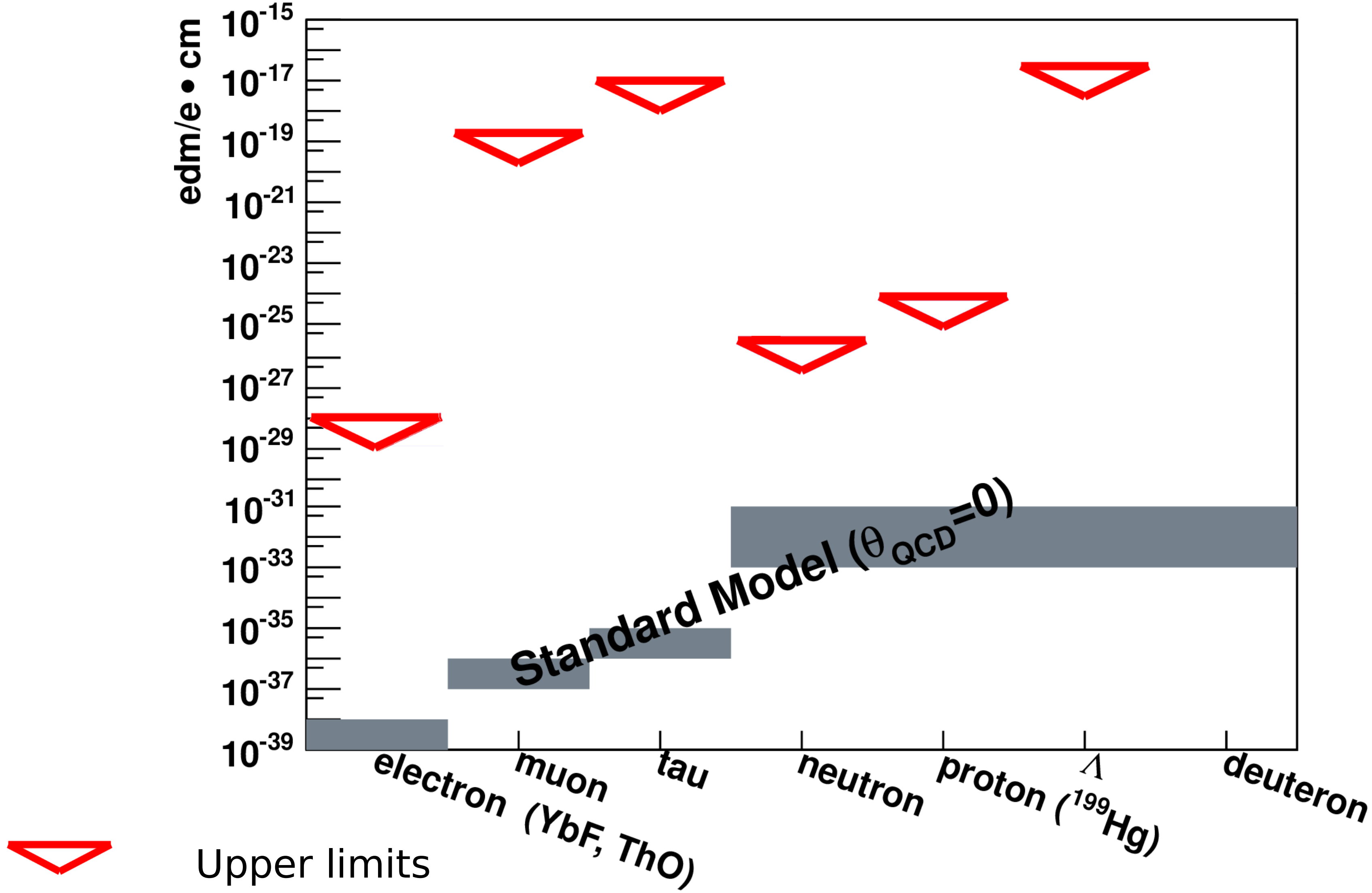
The observable quantity:

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

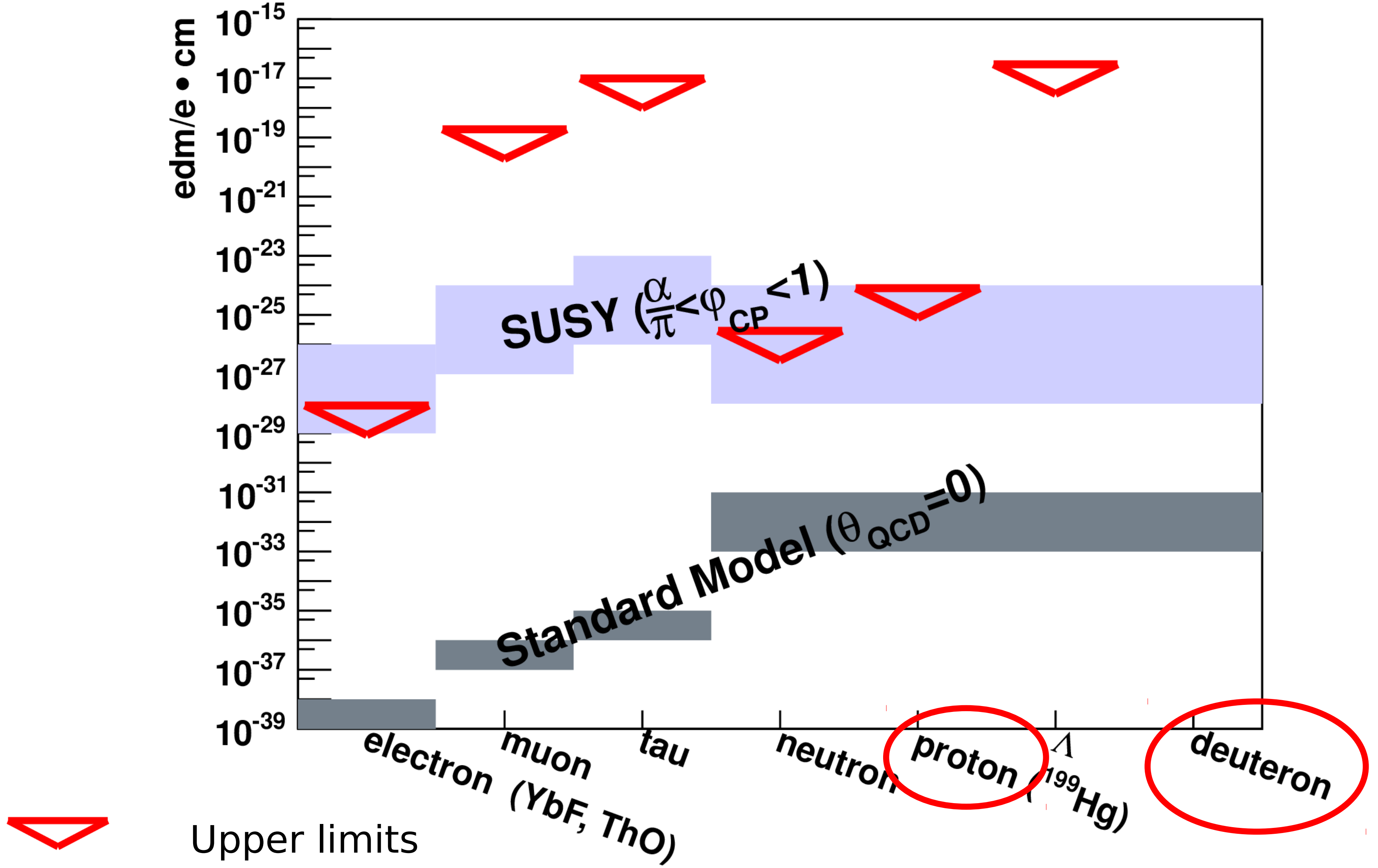
$$H = H_E + H_M = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} - d\boldsymbol{\sigma}\cdot\mathbf{E}$$

$$T: H = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} + d\boldsymbol{\sigma}\cdot\mathbf{E}$$
$$P: H = -\mu\boldsymbol{\sigma}\cdot\mathbf{B} + d\boldsymbol{\sigma}\cdot\mathbf{E}$$


edm/e • cm
10-15
10-17
10-19
10-21
10-23
10-25
10-27
10-29
10-31
10-33
10-35
10-37
10-39
Standard Model (θ QCD=0)
electron (YbF, ThO)
muon
tau
neutron
proton (199Hg)
Λ
deuteron



edm/e • cm
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-25}
10^{-27}
10^{-29}
10^{-31}
10^{-33}
10^{-35}
10^{-37}
10^{-39}
Standard Model (θ_{QCD}=0)
electron (YbF, ThO)
muon
tau
neutron
proton (^{199}Hg)
Λ
deuteron
Upper limits

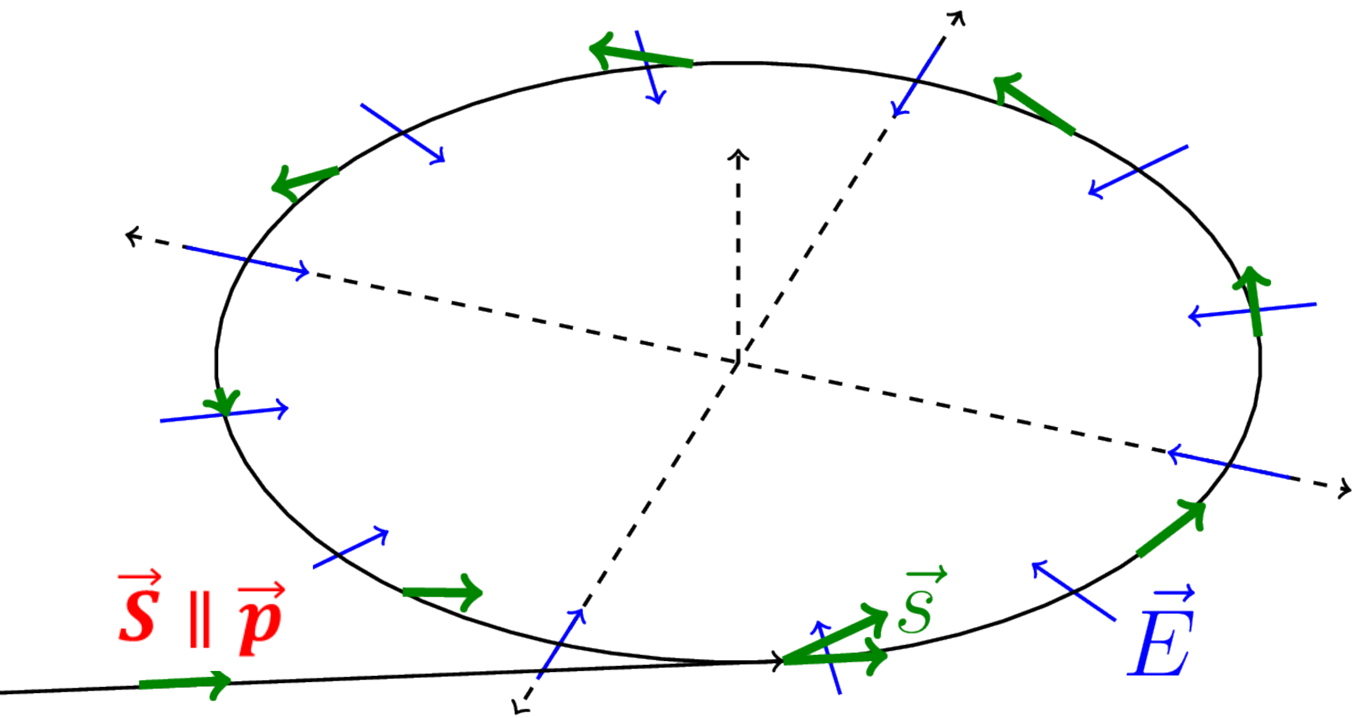

edm/e • cm
10-15
10-17
10-19
10-21
10-23
10-25
10-27
10-29
10-31
10-33
10-35
10-37
10-39
SUSY ($\frac{\alpha}{\pi} < \varphi_{CP} < 1$)
Standard Model ($\theta_{QCD}=0$)
electron (YbF, ThO)
muon
tau
neutron
proton
Λ
(199Hg)
deuteron
Upper limits

Measurement principle

For charged particles:

→ apply electric field in a storage ring

Simplified case:



"Frozen spin"

$$\frac{d\vec{S}}{dt} \propto d\vec{E} \times \vec{S}$$

⇓

Build-up of vertical polarization by slow precession

Extremely small effects!

With edm ~ 10^{-29} e·cm effect of the order of **μdeg/hour**

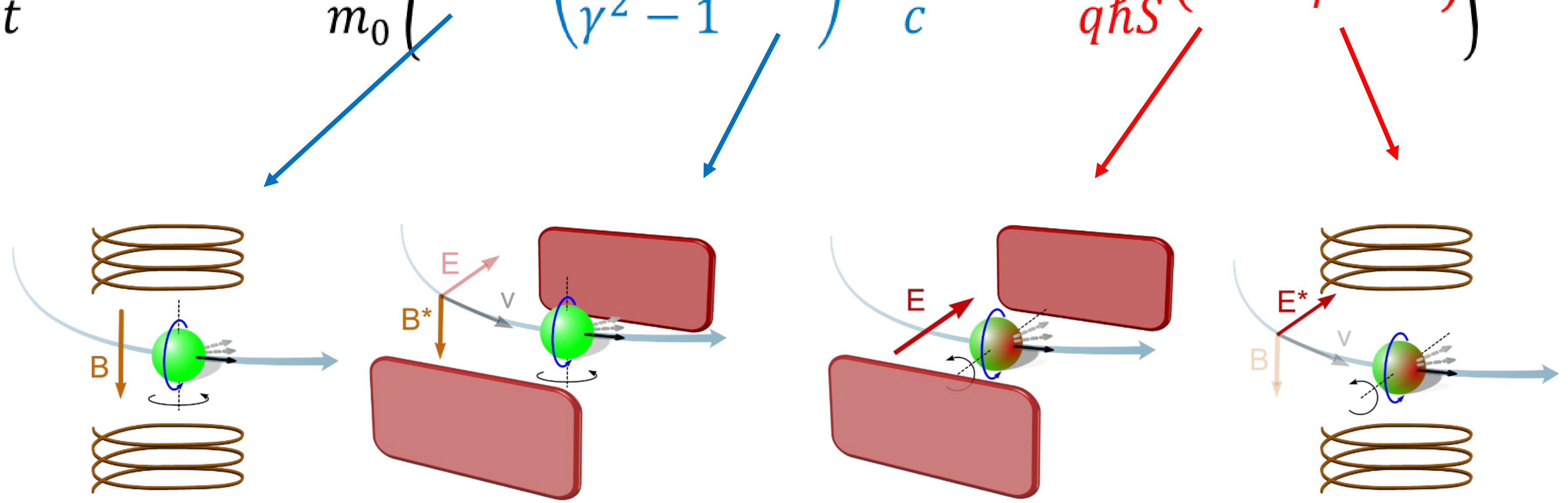
Measurement principle

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

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

γ: Lorentz factor

Measurement

Pure electric ring

magnetic moment EDM

$$\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0}\left\{ G\vec{B} + \underbrace{\left(\frac{1}{\gamma^2 - 1} - G\right)}_{\equiv 0!}\frac{\vec{\beta} \times \vec{E}}{c} + d\,\frac{m_0}{q\hbar S}\left(\vec{E} + c\vec{\beta} \times \vec{B}\right)\right\} \times \vec{S}$$

„frozen spin“ : precession vanishes at magic momentum

$$G = \frac{1}{\gamma^2 - 1} \Rightarrow p = \frac{m}{\sqrt{G}}$$

only possible for $G > 0$

Dedicated ring for protons

Measurement

Pure magnetic ring

magnetic moment EDM

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

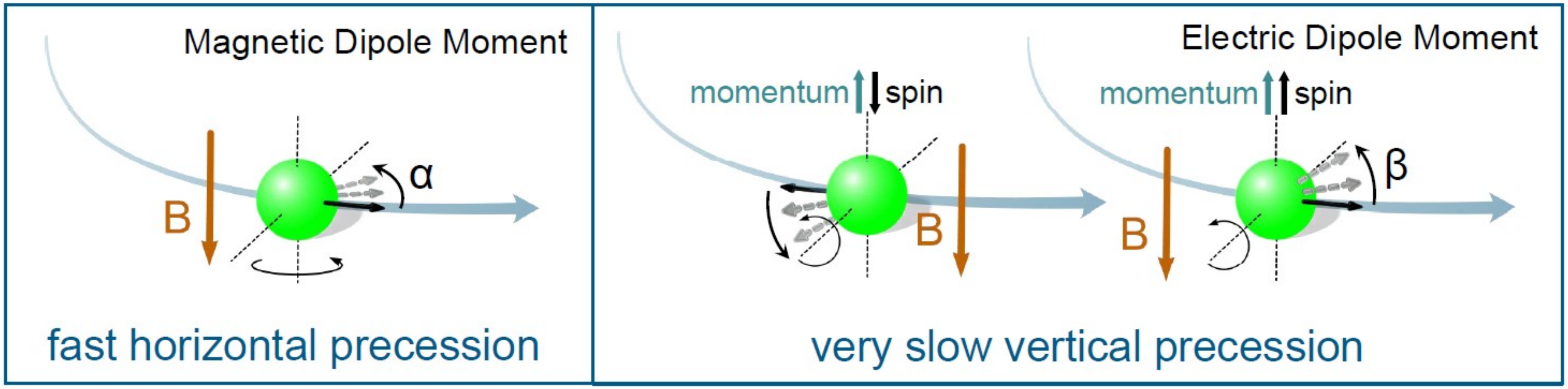
COSY: pure magnetic ring, polarized protons and deuterons

access to EDM via motional electric field $\vec{\beta} \times \vec{B}$

Starting point for a proof-of-principle experiment

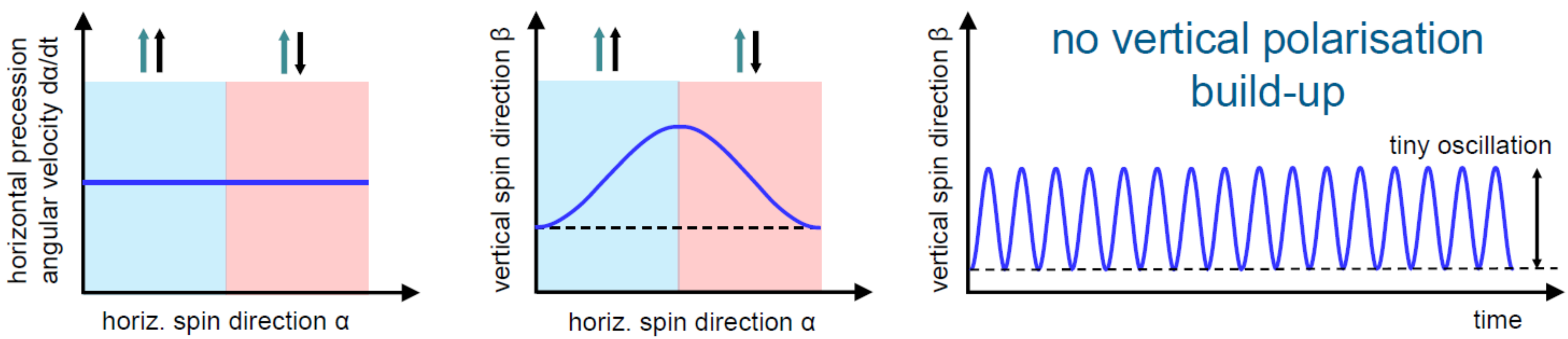
Measurement

Pure magnetic ring



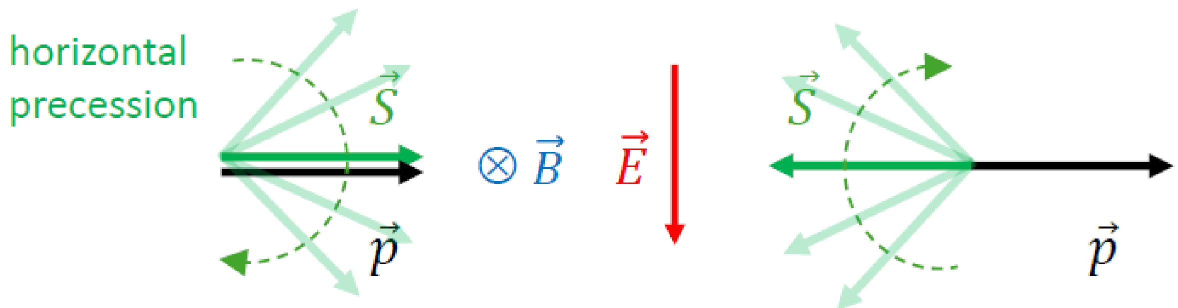
E* field tilts spin due to EDM
50% of time up and
50% of time down

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



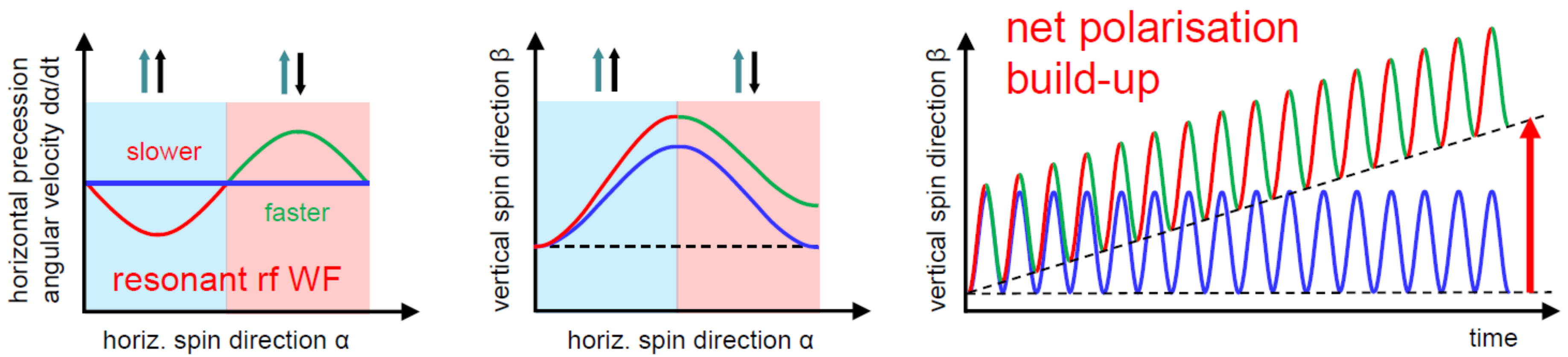
Measurement

RF Wien Filter method



Lorentz force vanishes: no effect on EDM rotation

Effect: Adds extra horizontal precession



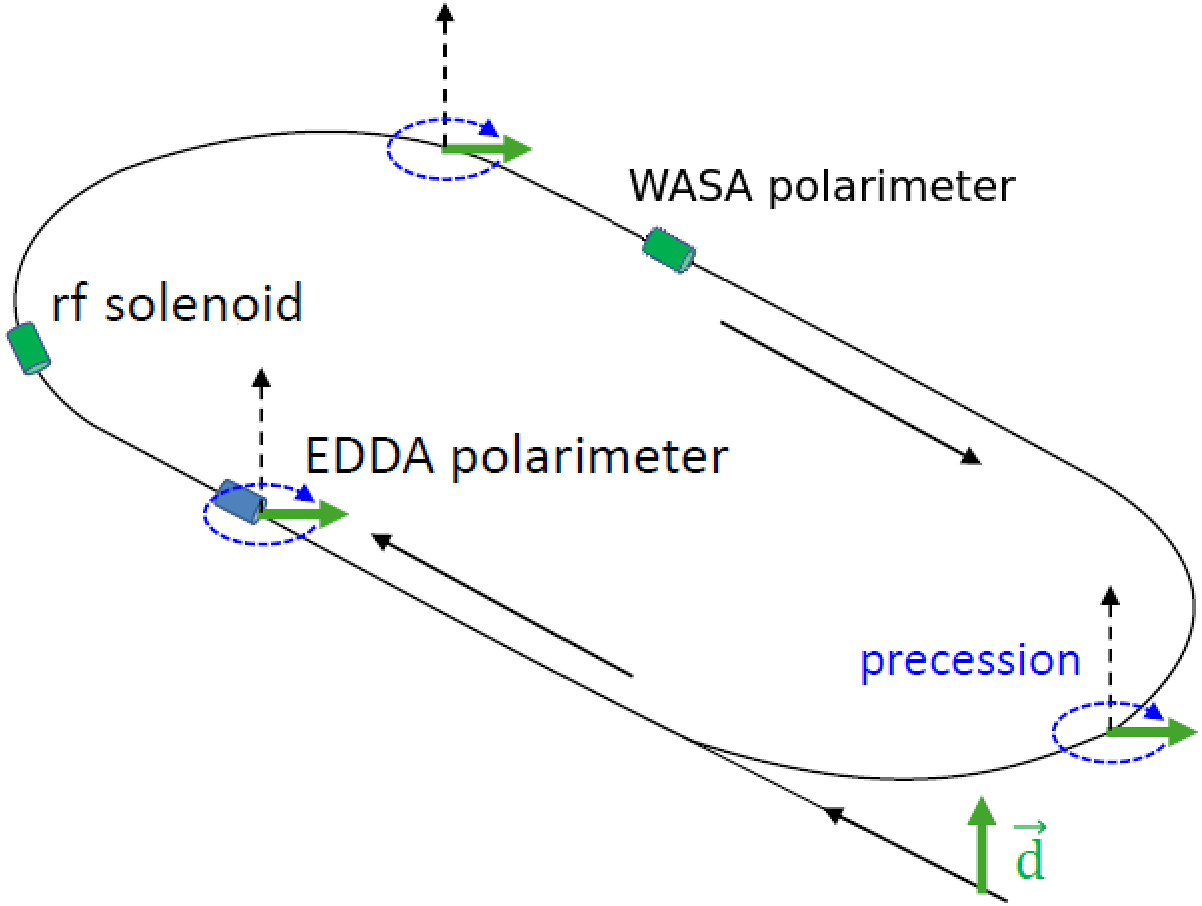
Research and Development at COSY

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

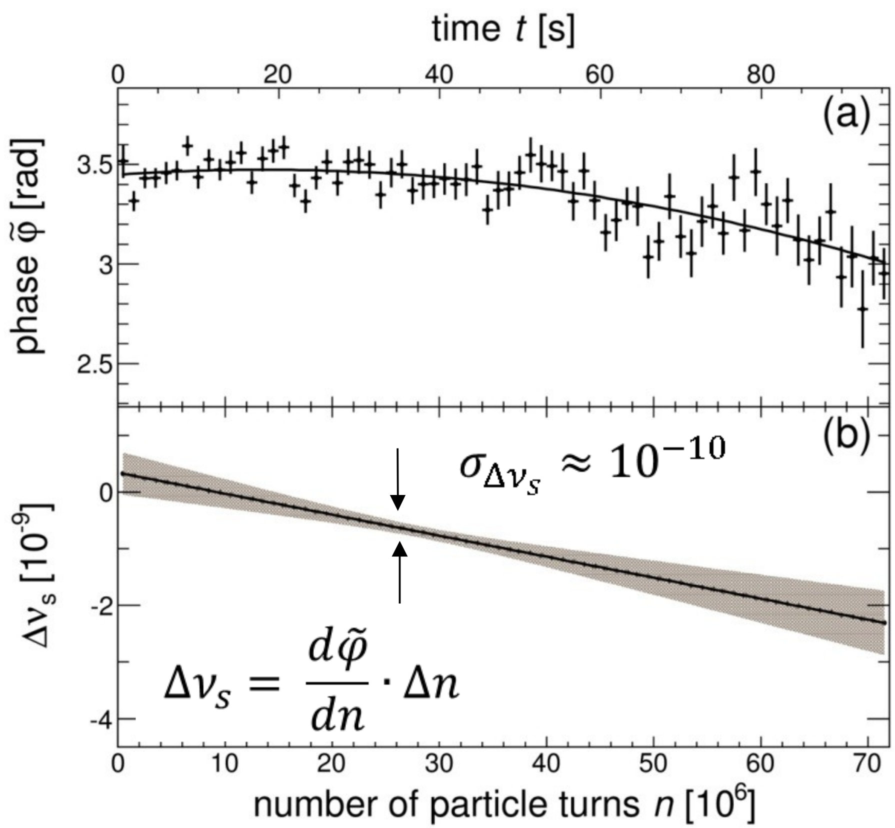
study spin tune $\nu_s = \frac{|\vec{\Omega}|}{|\vec{\omega}_{\text{cycl}}|} = \gamma G$

→ phase advance per turn



Research and Development at COSY

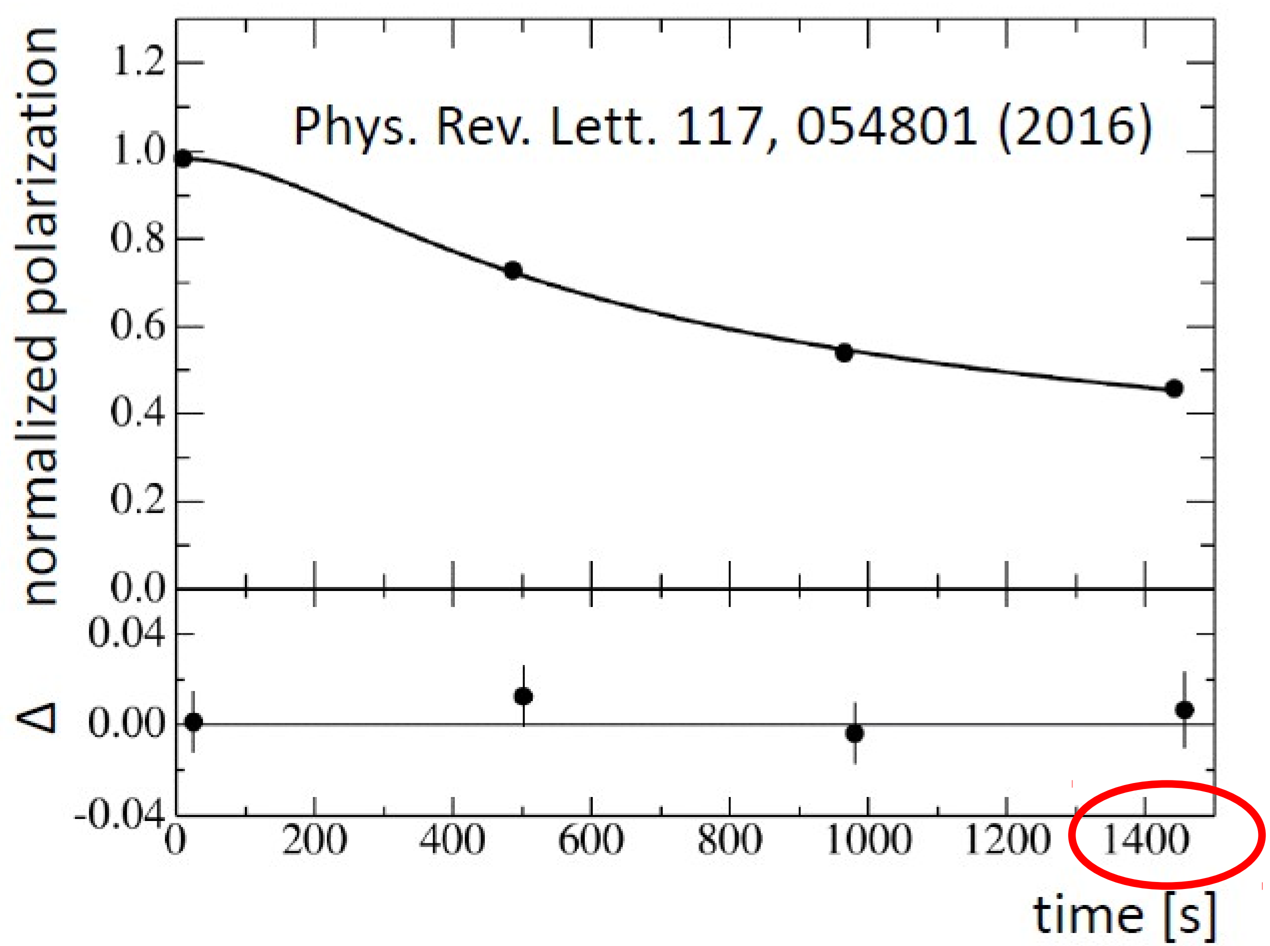
Precise measurement of the precession frequency (spin tune)
→ also time dependent within one cycle



Phys. Rev. Lett. 115, 094801 (2015)

Research and Development at COSY

Maximizing the spin coherence time (goal: ≈1000 s)

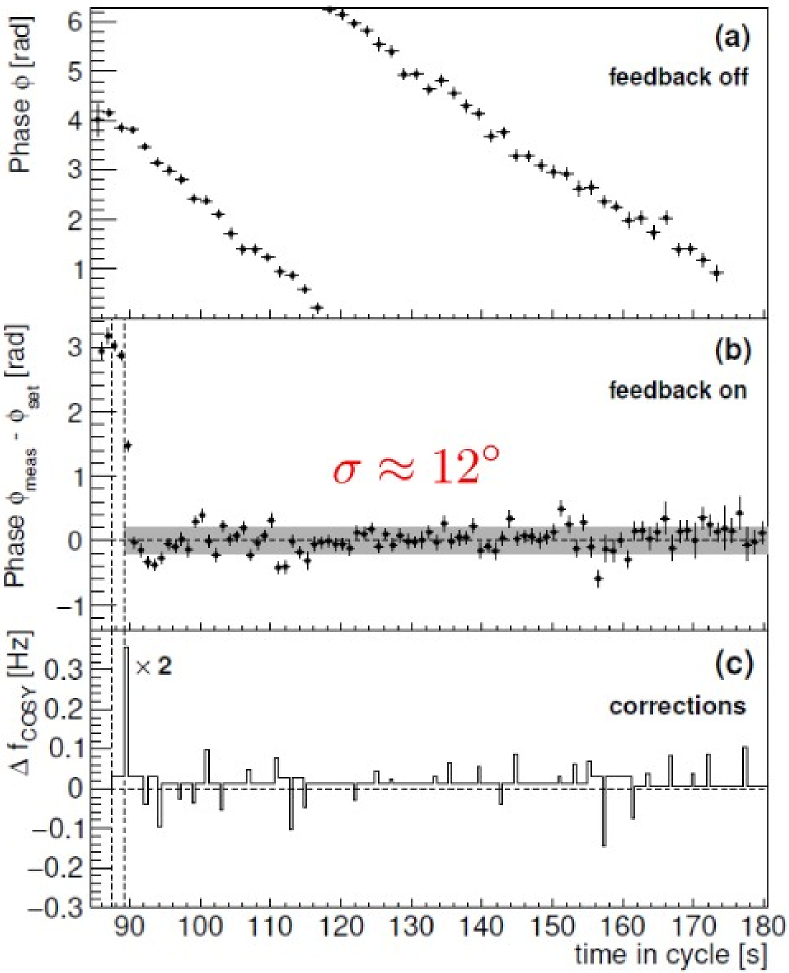


Research and Development at COSY

Maintaining the spin direction

→ keep precession frequency stable

→ match frequency and phase to Wien filter radio frequency

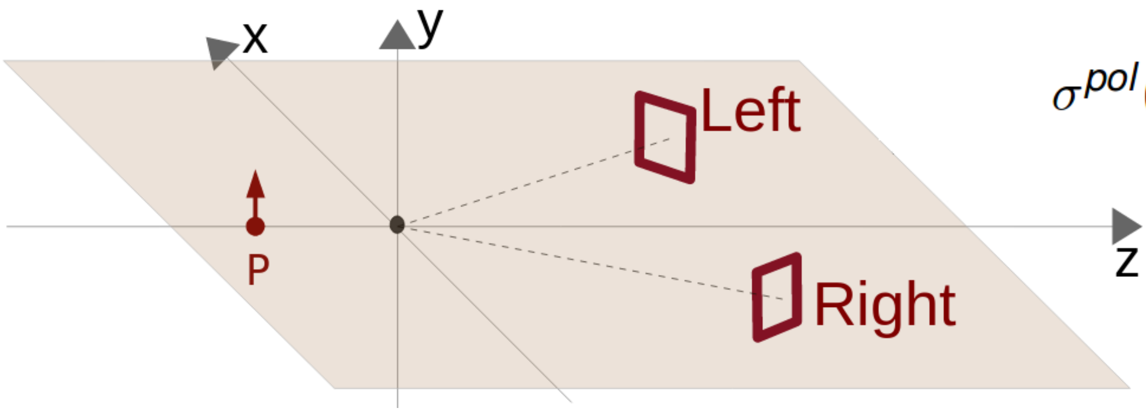


Polarimetry

Reaction: dC elastic scattering

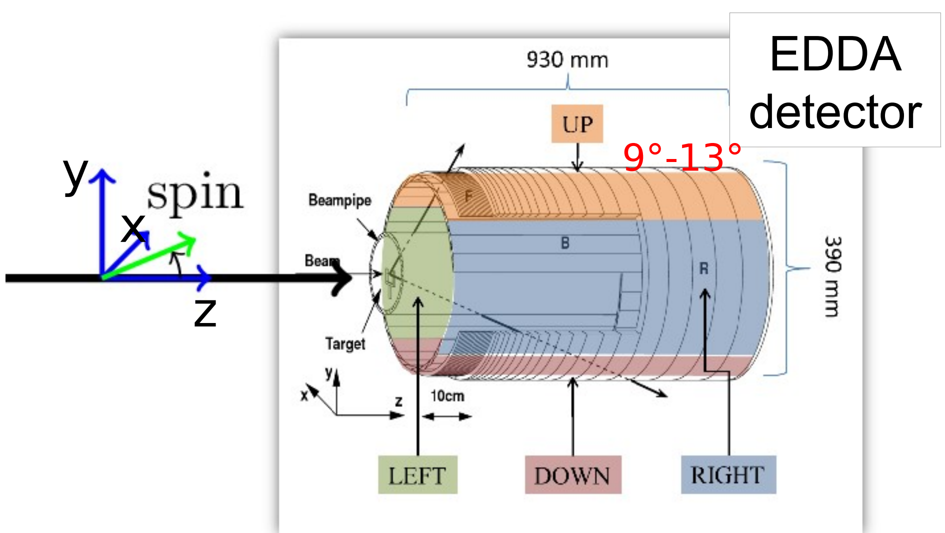
Up/Down asymmetry ∝ horizontal component of polarization P_x

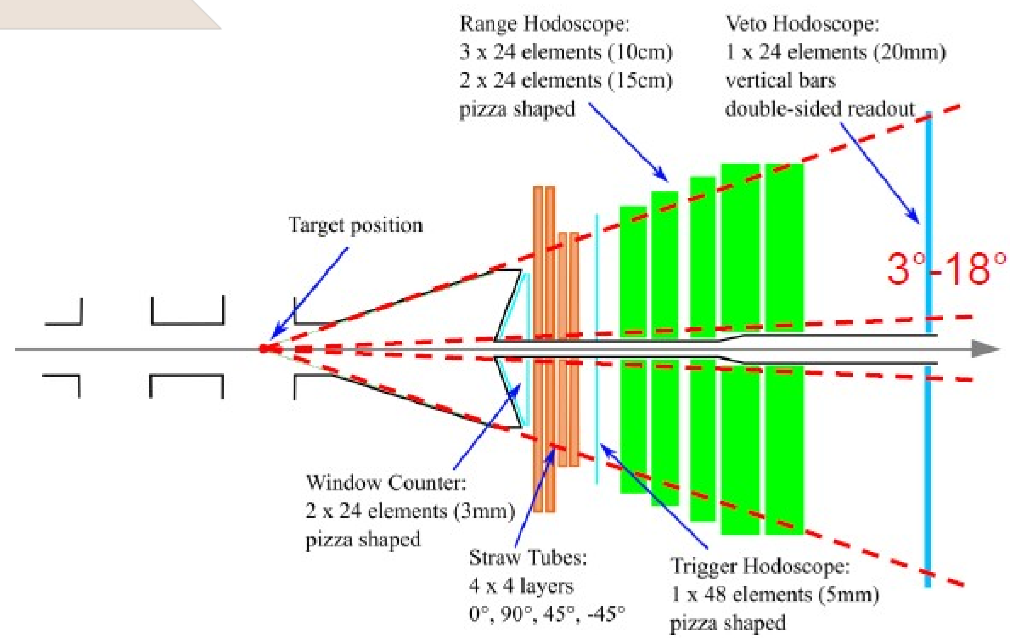
Right/Left asymmetry ∝ vertical component of polarization P_y



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

$$PA_y(\theta) = \frac{\sigma^L(\theta) - \sigma^R(\theta)}{\sigma^L(\theta) + \sigma^R(\theta)}$$





Polarimetry

Detector signal

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

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
- $\nu_s \approx -0.16$ $\longrightarrow$ 6 turns / precession
- event rate ≈ 5000 s^{-1} $\longrightarrow$ 1 hit / 25 precessions

$\longrightarrow$ no direct fit of the rates

Polarimetry

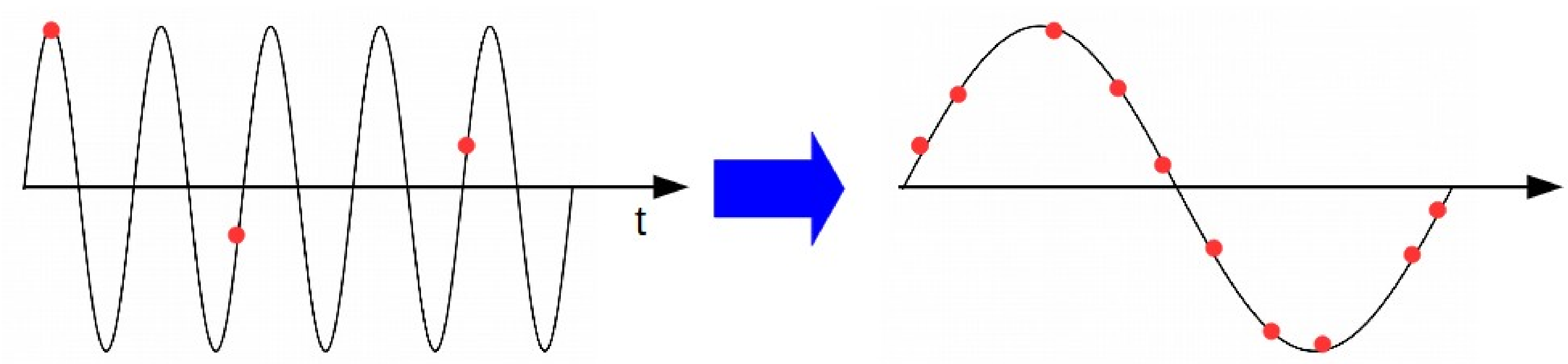
Detector signal

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

P: polarisation, A: analysing power

Asymmetry

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



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

↓

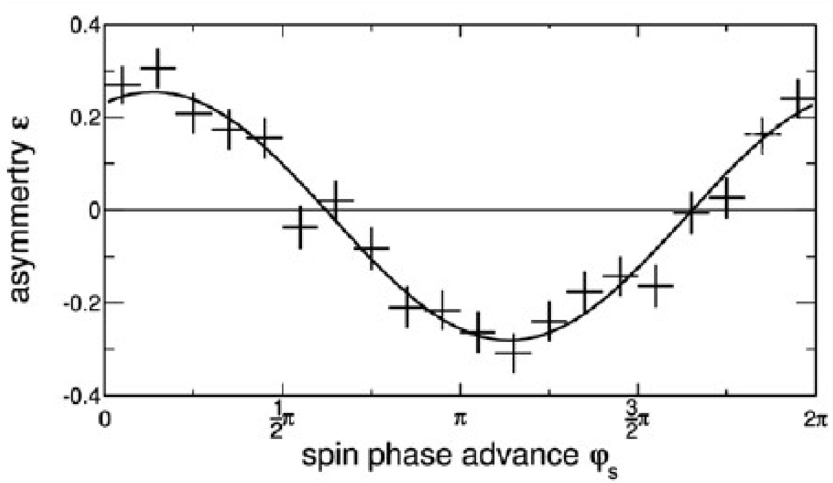
assign turn number n $\rightarrow$ phase advance $\varphi_s = 2\pi\nu_s n$

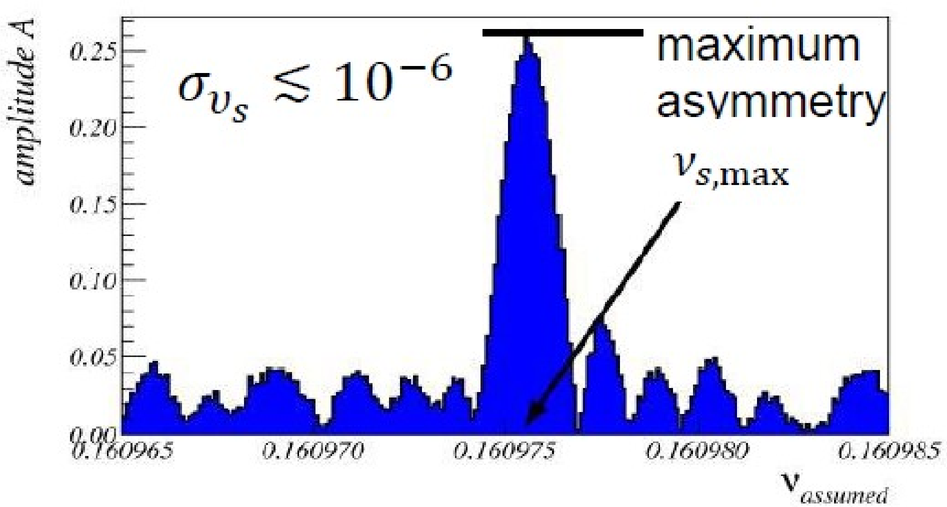
↓

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

↓

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

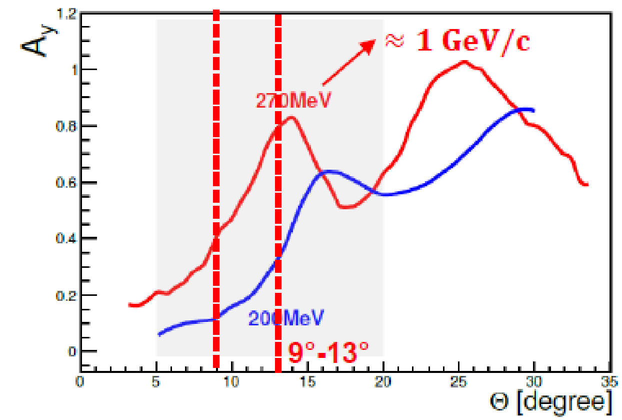




Polarimetry – database experiment

Motivation: database to produce realistic Monte Carlo simulations of detector responses for a polarimeter designed for EDM

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

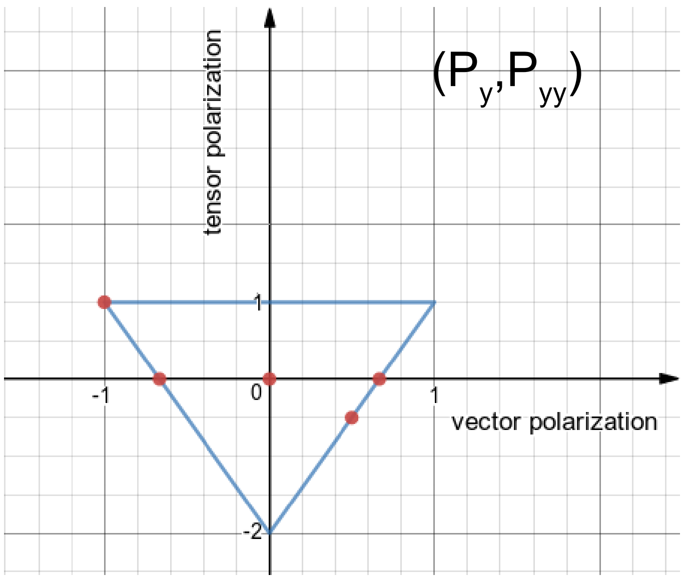


Beamtime in November 2016 (2 weeks)

d energies: 170, 200, 235, 270, 300, 340, 380 MeV
Targets: C and CH_2

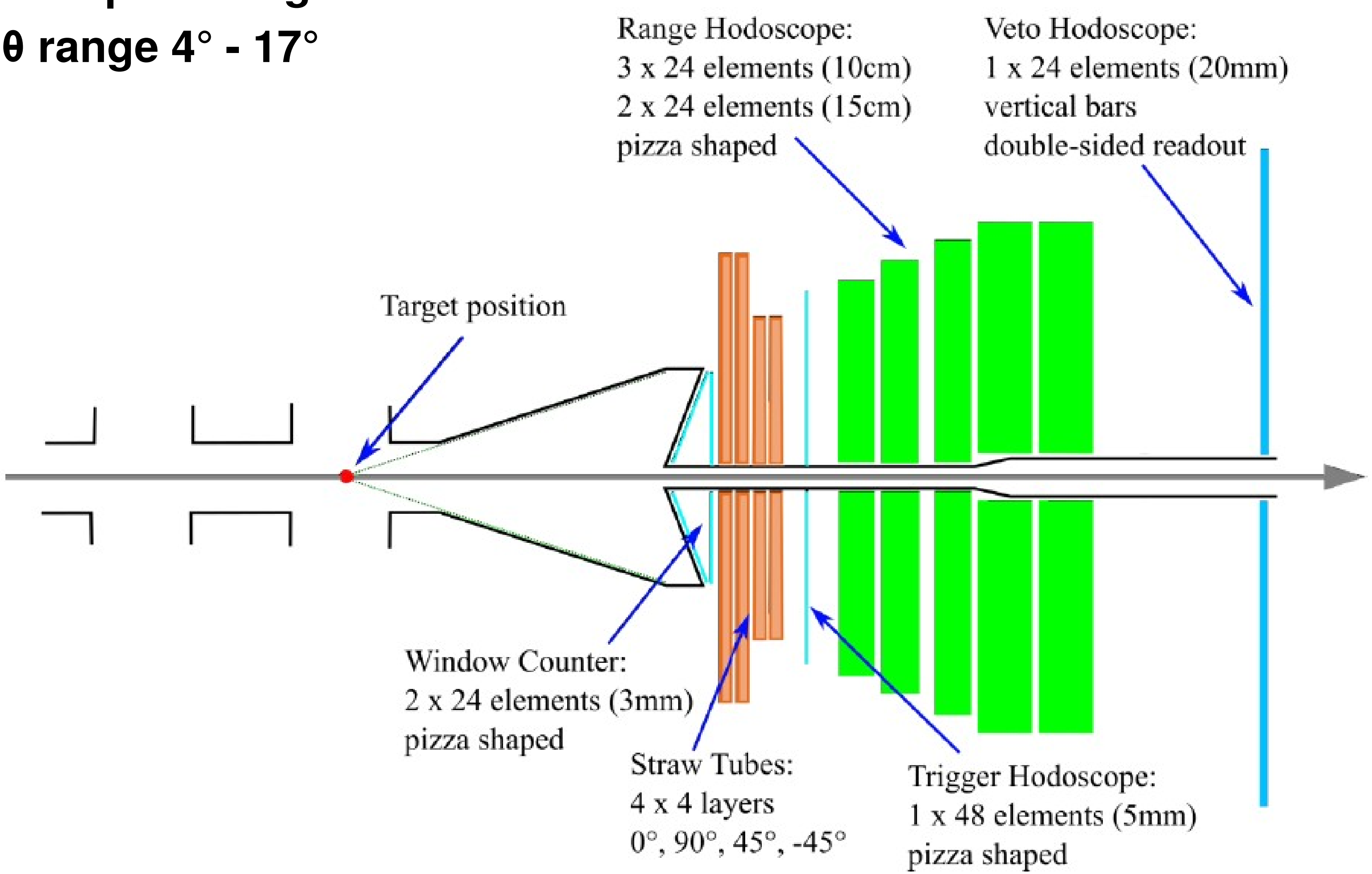
Beam polarization: 5 polarization states
(P_y,P_{yy}) = (0,0), (-⅔,0), (⅔,0), (½, -½), (-1, 1)

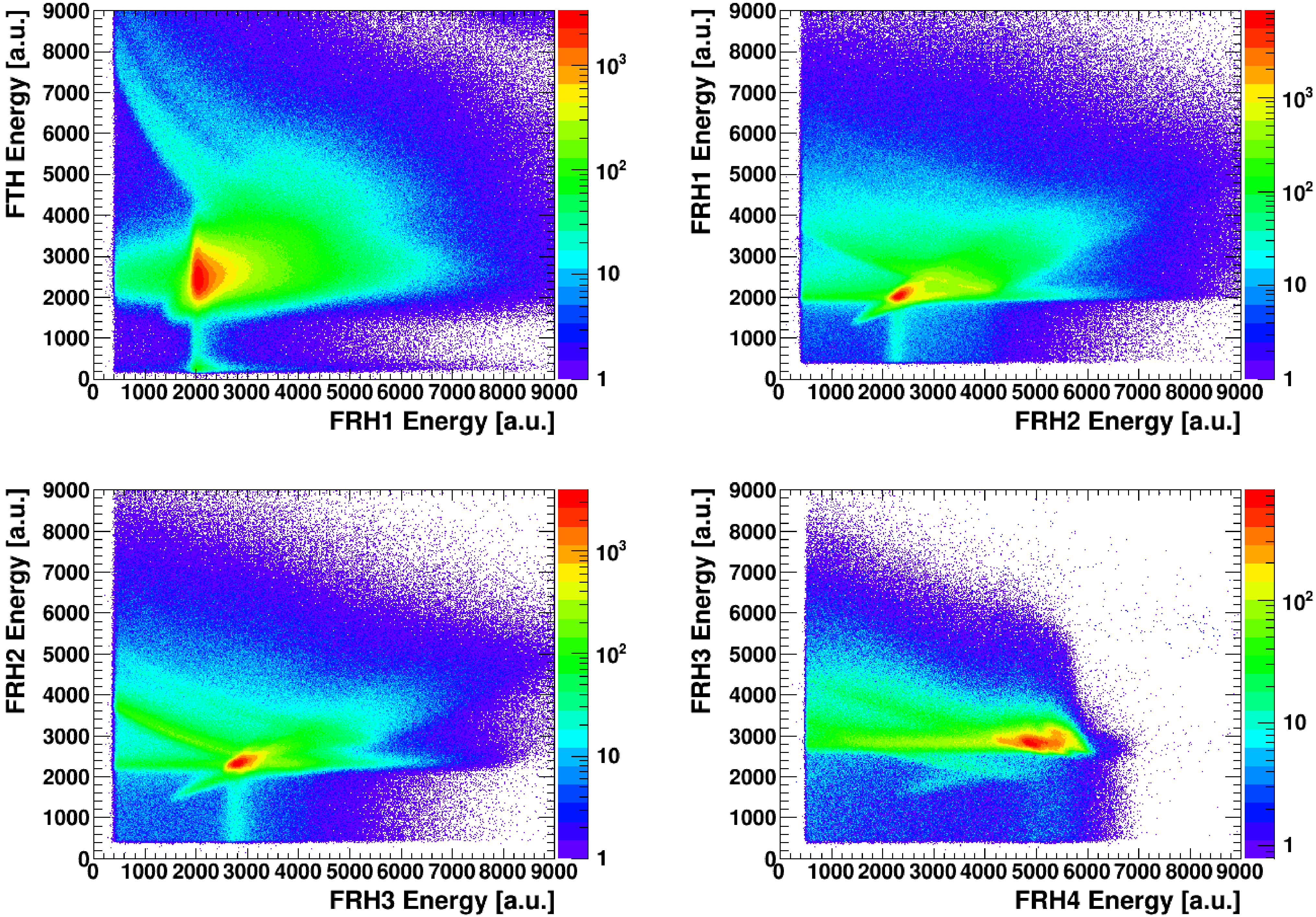
Setup: Modified WASA Forward Detector

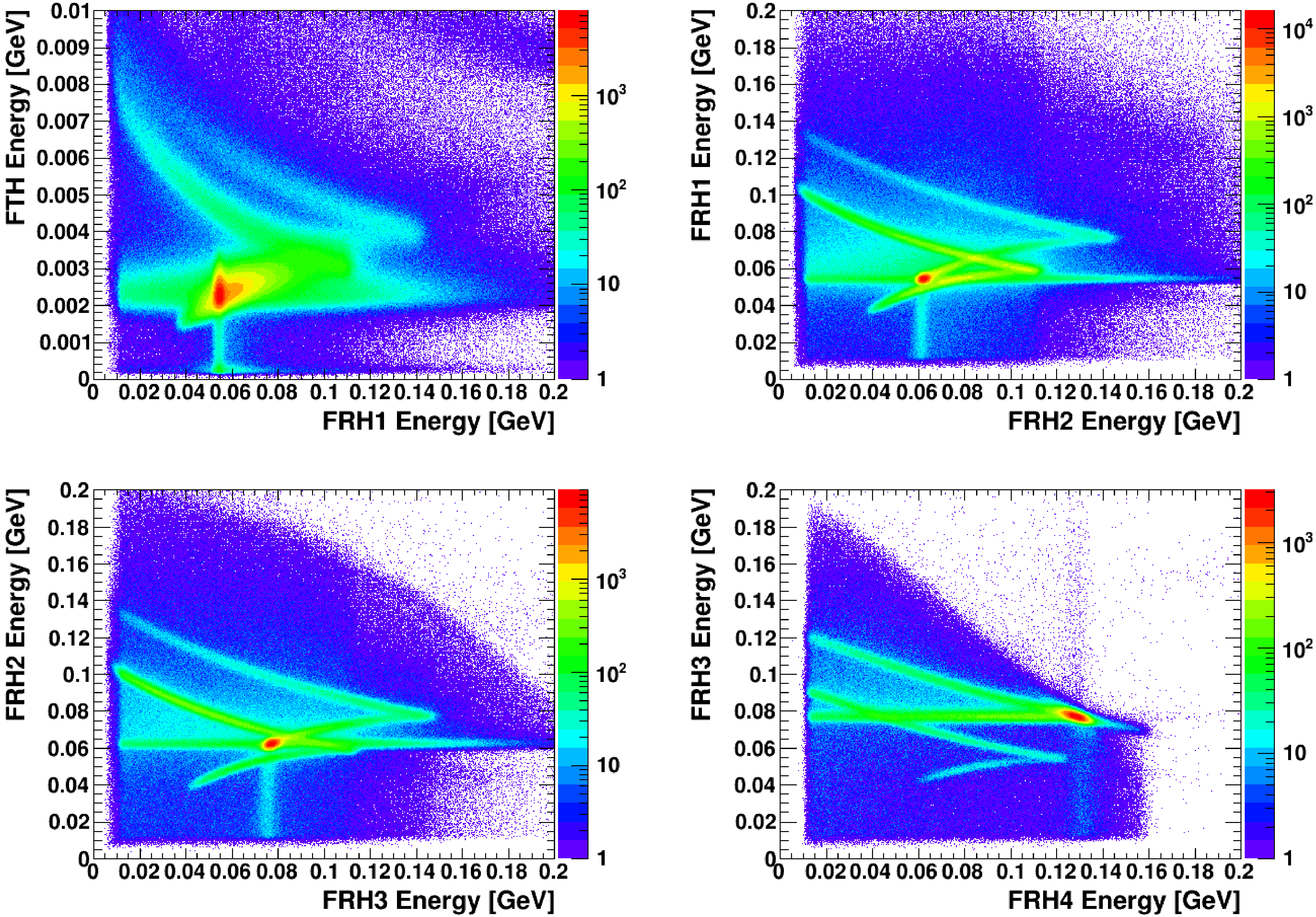


Polarimetry – database experiment

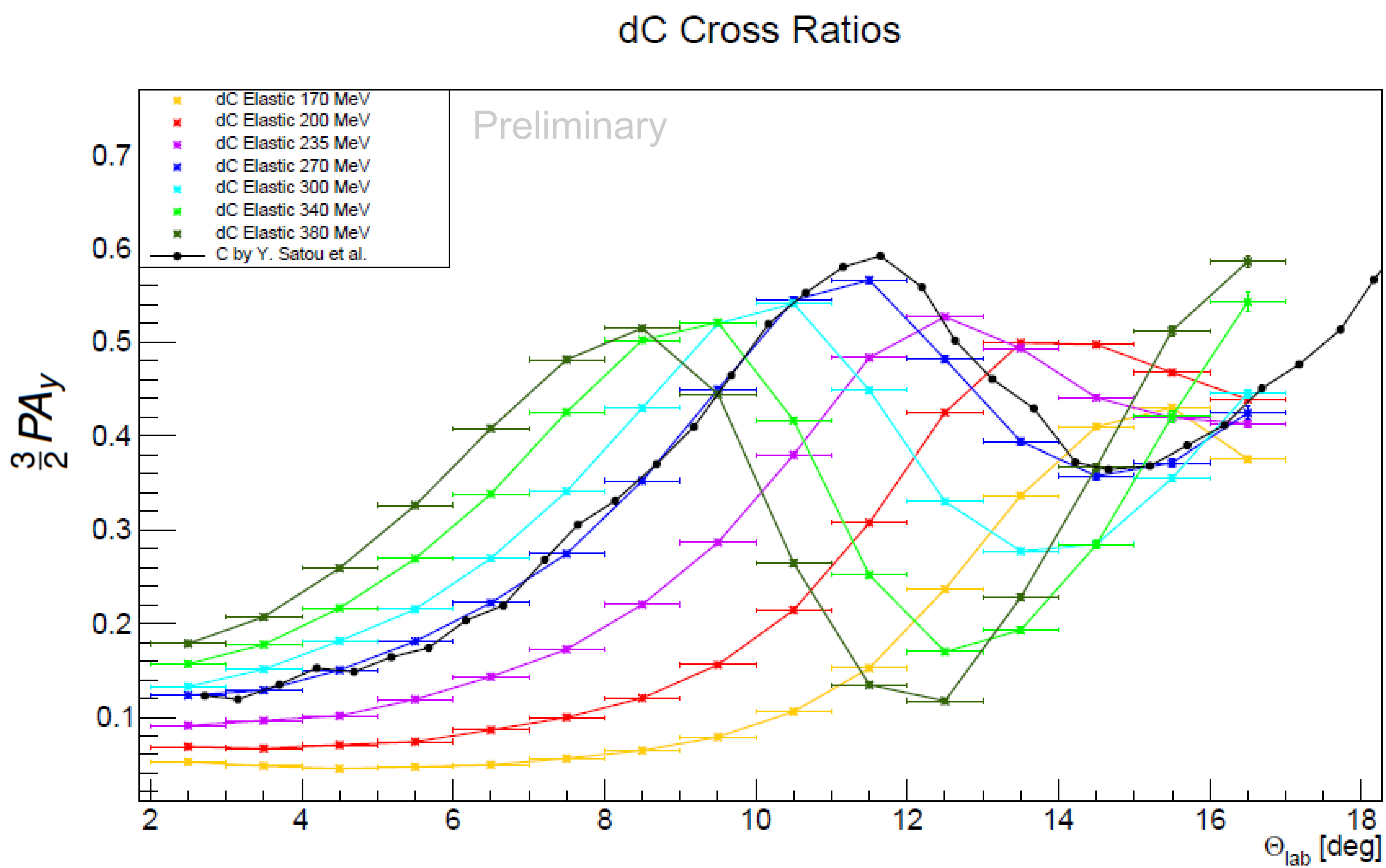
→ **Full φ coverage**
→ **θ range 4° - 17°**




FTH Energy [a.u.]
FRH1 Energy [a.u.]
FRH1 Energy [a.u.]
FRH2 Energy [a.u.]
FRH2 Energy [a.u.]
FRH3 Energy [a.u.]
FRH3 Energy [a.u.]
FRH4 Energy [a.u.]
0 1000 2000 3000 4000 5000 6000 7000 8000 9000
1 10 10^2 10^3


FTH Energy [GeV]
FRH1 Energy [GeV]
FRH1 Energy [GeV]
FRH2 Energy [GeV]
FRH2 Energy [GeV]
FRH3 Energy [GeV]
FRH3 Energy [GeV]
FRH4 Energy [GeV]

Polarimetry – database experiment



Cross rations for all energies and angles. Satou et al. data scaled for comparison.

What did we learn?

- EDMs of elementary particles key for understanding sources of CP violation
  $\rightarrow$ explanation of matter – antimatter imbalance

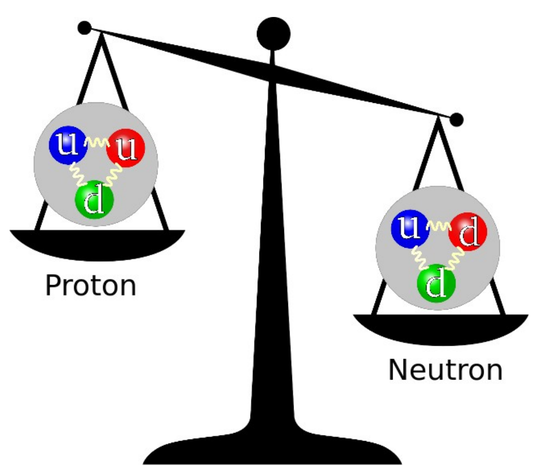
- Principle of experiments – measurements of spin precession in magnetic field
- EDM of charged particles measured in storage rings

- COSY: ideal starting point for R&D and a pre-cursor experiment with Wien Filter method

Conclusions

Symmetries:
Tool to address the most striking questions of modern science

Investigations at the Research Center Jülich:
From hadronic reactions to EDM with WASA



Antimatter

Matter

Backup

Fundamental Discrete Symmetries

A physical model is symmetric under a certain operation
$\rightarrow$ if its properties are invariant under this operation

- T-symmetry: t $\rightarrow$ -t
- P-symmetry: **r** $\rightarrow$ -**r**
- C-symmetry: particle-antiparticle interchange
- CPT conserved

	C	P	T	CP
Electric field **E**	**-E**	**-E**	**E**	**E**
Magnetic field **B**	**-B**	**B**	**-B**	**-B**
Momentum **p**	**p**	**-p**	**-p**	**-p**
Angular momentum **l**	**l**	**l**	**-l**	**l**
Charge density q	-q	q	q	-q

EDM – Orders of magnitude

Neutron (udd)	
Charge	e
$\| \mathbf{r}_1 - \mathbf{r}_2 \|$	1 fm = 10^{-13} cm
EDM	
Naive expectation	10^{-13} e · cm
Observed (upper limit)	< 3 · 10^{-26} e · cm
SM prediction - Parity violation - CP electroweak violation	~ 10^{-32} e · cm

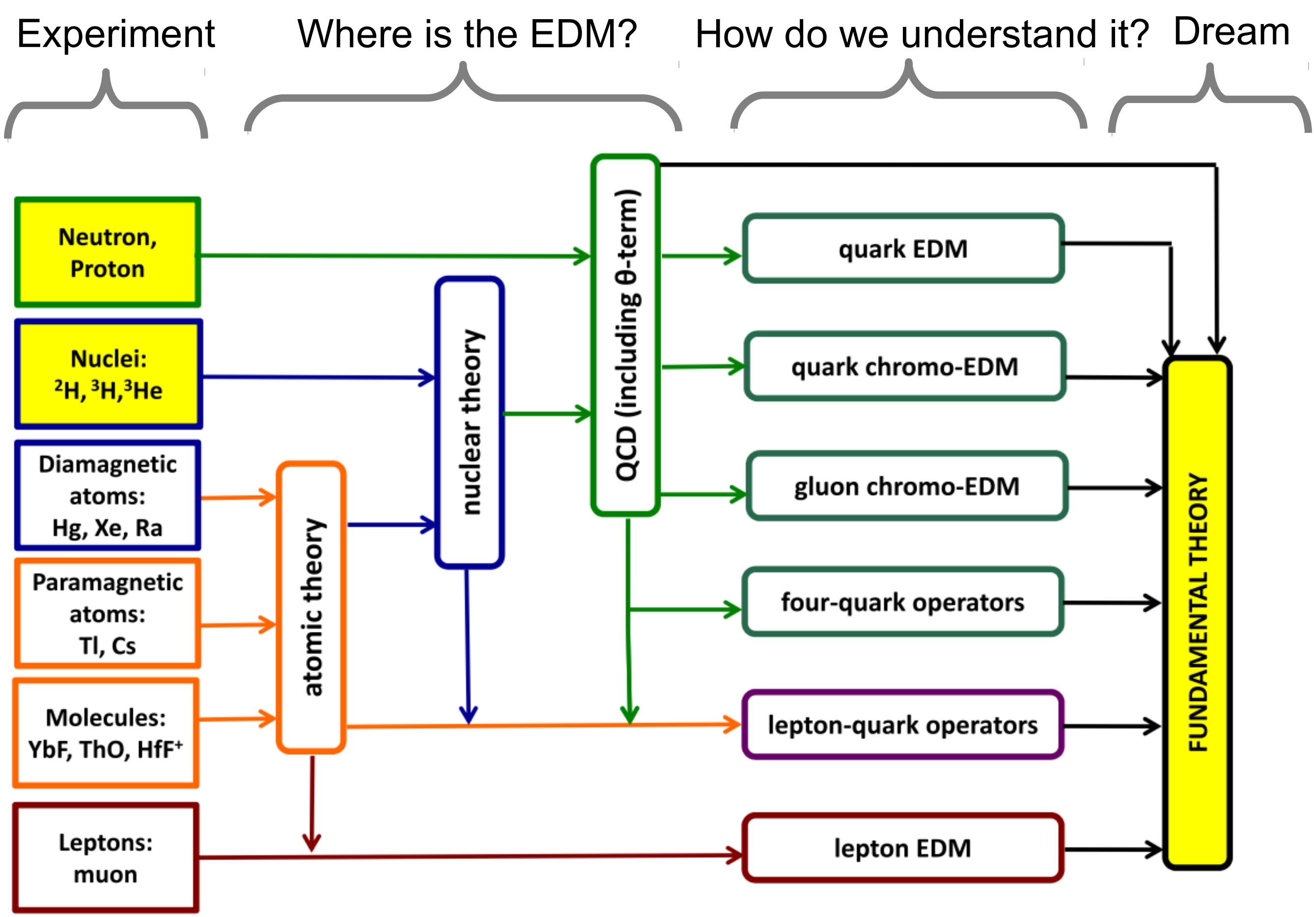
nEDM of 10^{-26} e · cm → separation of u from d quarks of ~ 5 · 10^{-26} cm

Motivation

Electric Dipole Moment of proton and deuteron

No direct measurement

Disentangle the fundamental source(s) of EDMs



Experimental requirements

High precision storage ring	alignment, stability, field homogeneity
High intensity beams	$N = 4 \times 10^{10}$ per fill
Polarized hadron beams	$P = 0.8$
Large electric fields	$E = 10$ MV/m
Long spin coherence time	$\tau = 1000$ 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

$$\mu B_r \sim dE_r$$

Storage rings: combined ring

magnetic moment EDM

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

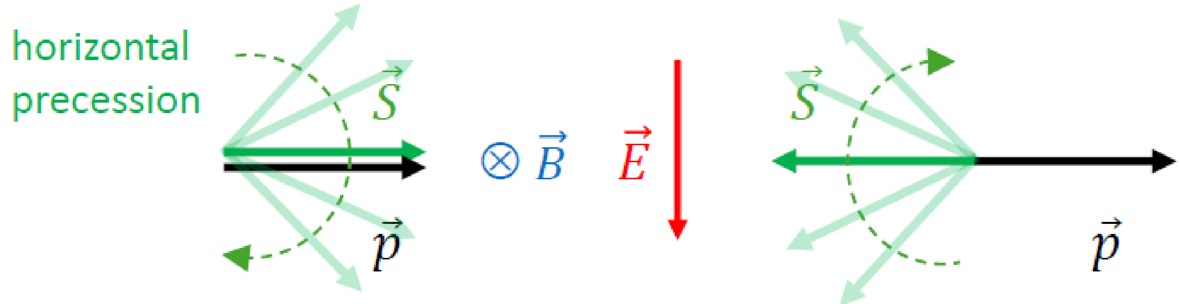
„frozen spin“: proper combination of $\vec{B}$, $\vec{E}$ and γ
also for $G < 0$ (i.e. deuterons, ^{3}He)

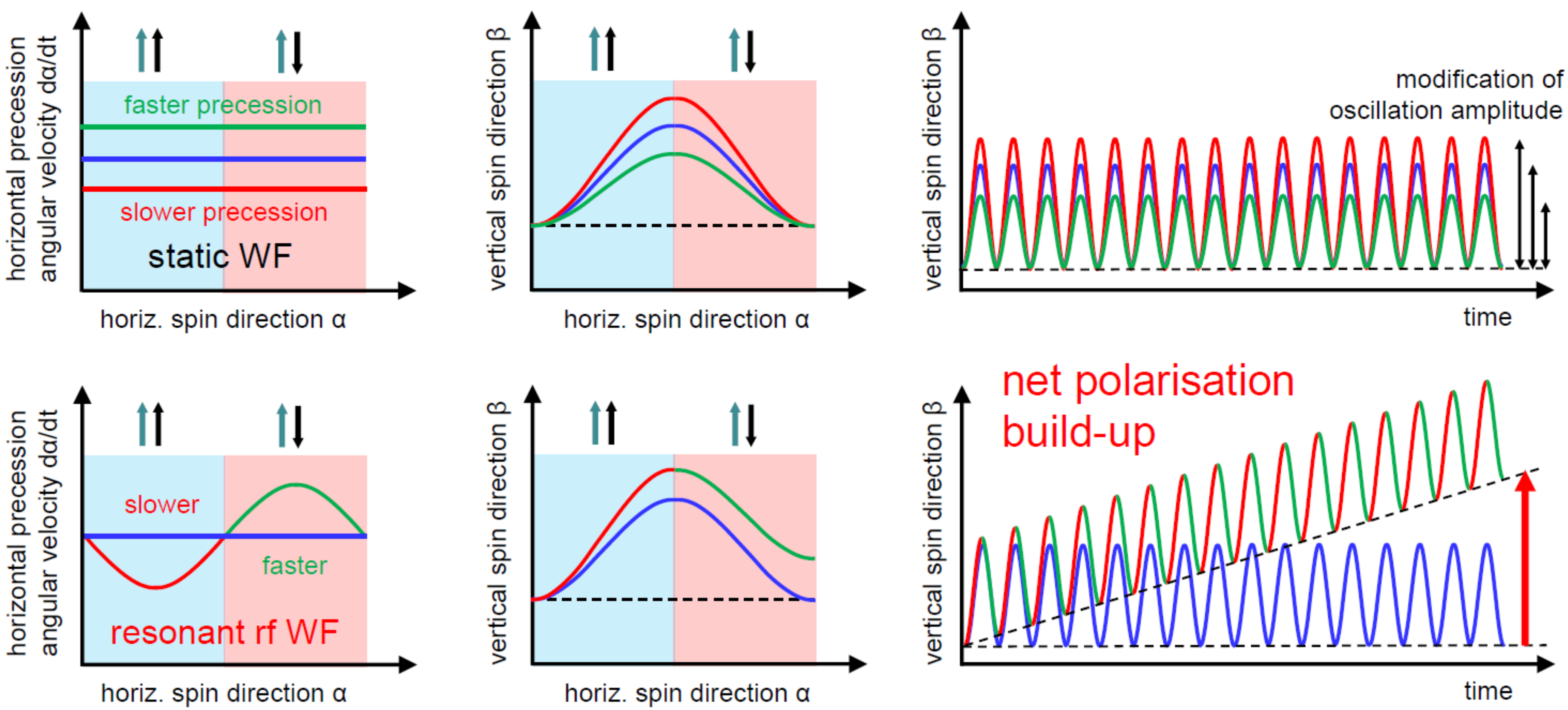
Combined ring both for protons and deuterons

Measurement

Wien Filter method

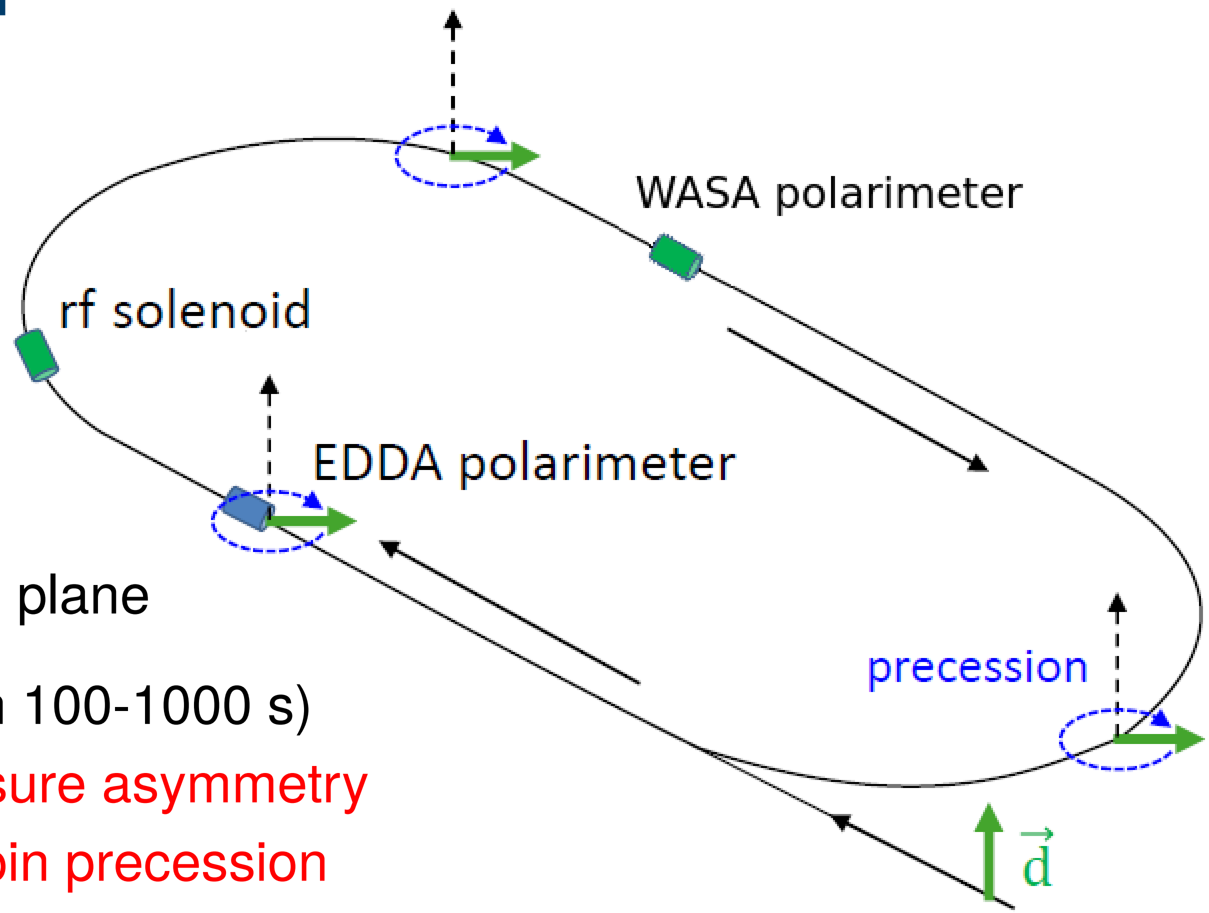
Lorentz force vanishes:
no effect on EDM rotation
Effect: Adds extra horizontal precession





Experimental setup

1. inject and accelerate vertically polarized deuterons to p=1GeV/c
2. bunch and (pre-)cool
3. turn spin by means of a RF solenoid into horizontal plane
4. extract beam slowly (within 100-1000 s) onto a carbon target, measure asymmetry and precisely determine spin precession

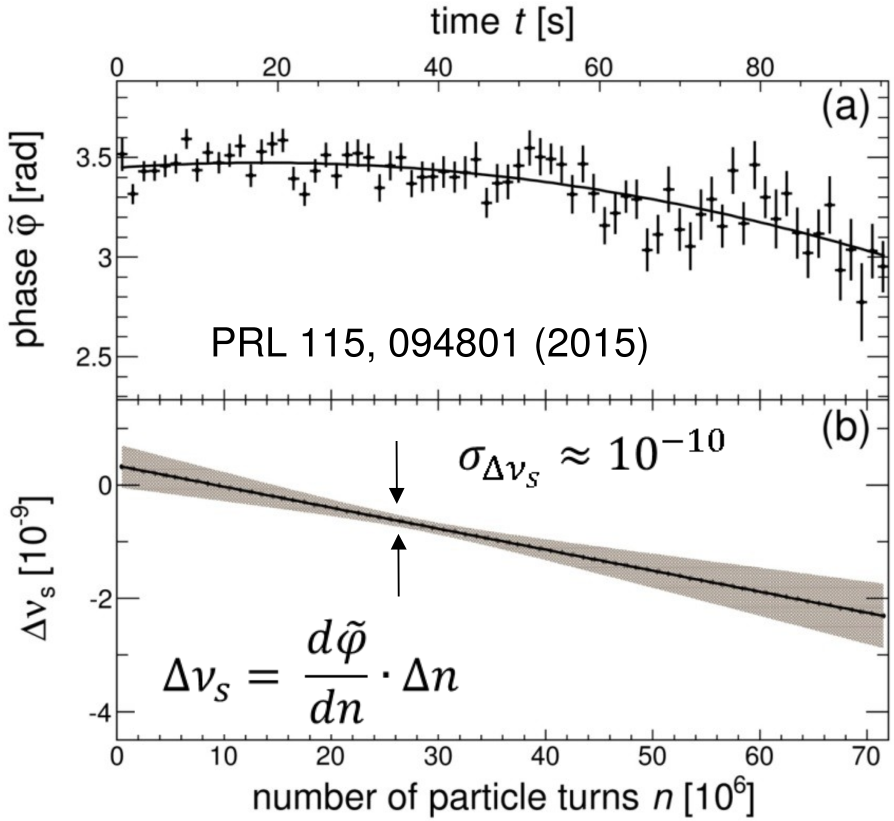


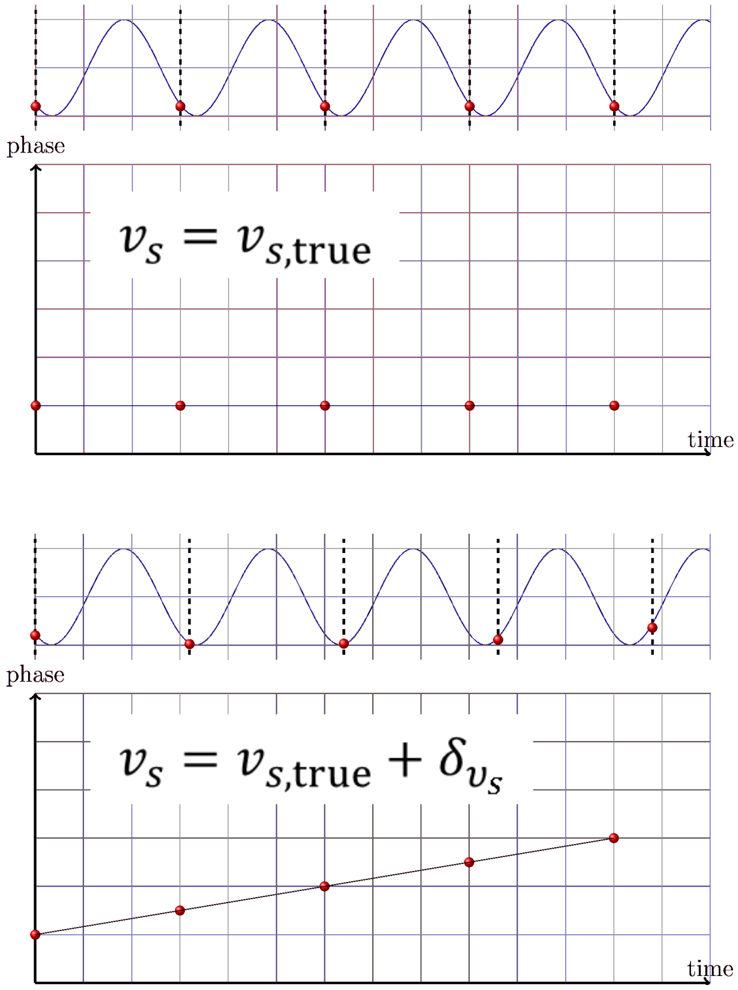
spin tune:

$$|\nu_s| = |\gamma G| = \frac{\text{spin precessions}}{\text{particle turn}} = \frac{f_{\text{prec}}}{f_{\text{rev}}} \approx \frac{120\text{ kHz}}{750\text{ kHz}} \approx 0.16$$

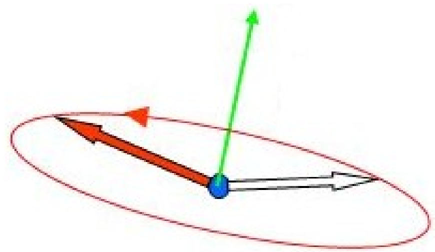
Precise spin tune measurement

Monitoring phase of asymmetry with fixed spin tune

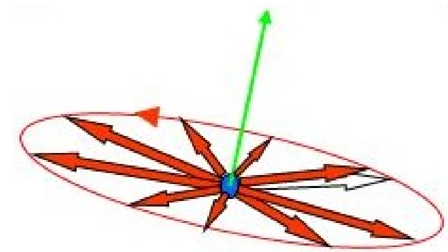




Spin coherence time



At the beginning all spin vectors aligned



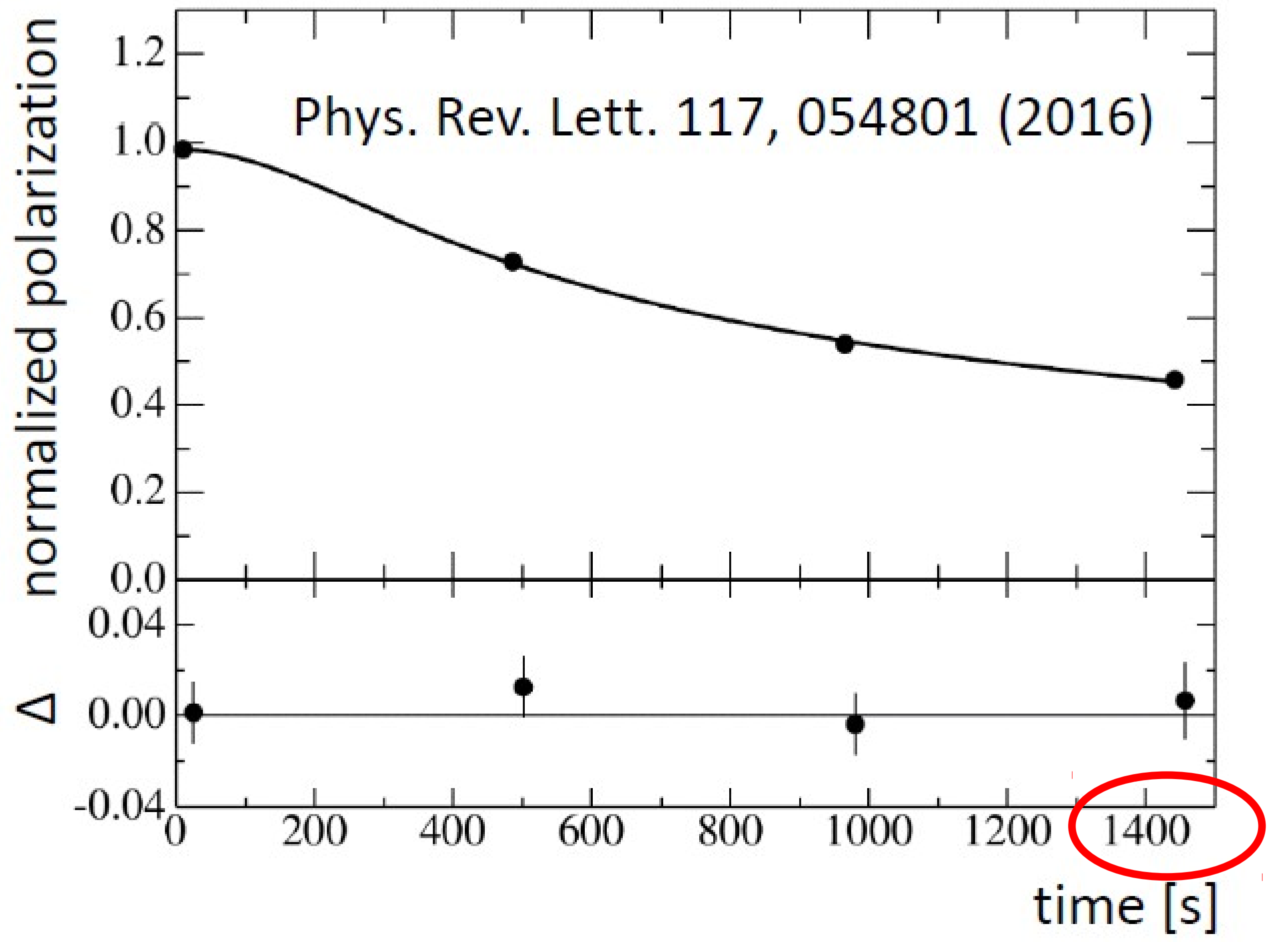
After some time spin vectors all out of phase

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: $\frac{\Delta\gamma}{\gamma} \approx 10^{-5} \quad \Longrightarrow$ 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



Controlling spin direction

Maintain resonance frequency and phase between spin precession and Wien filter

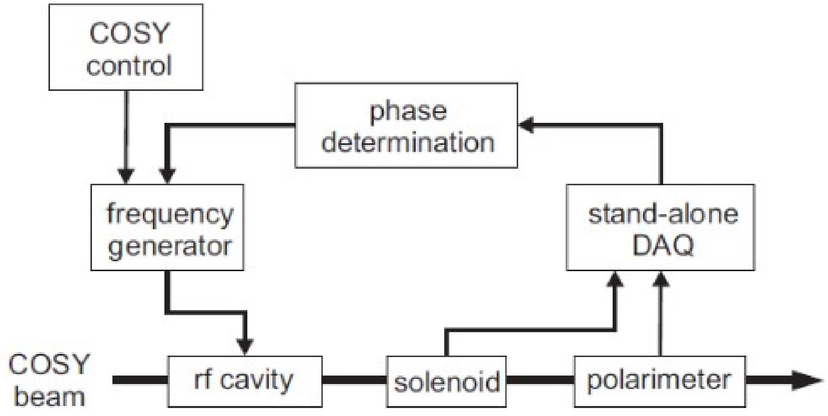
→ keep precession frequency stable
→ match frequency and phase to Wien filter

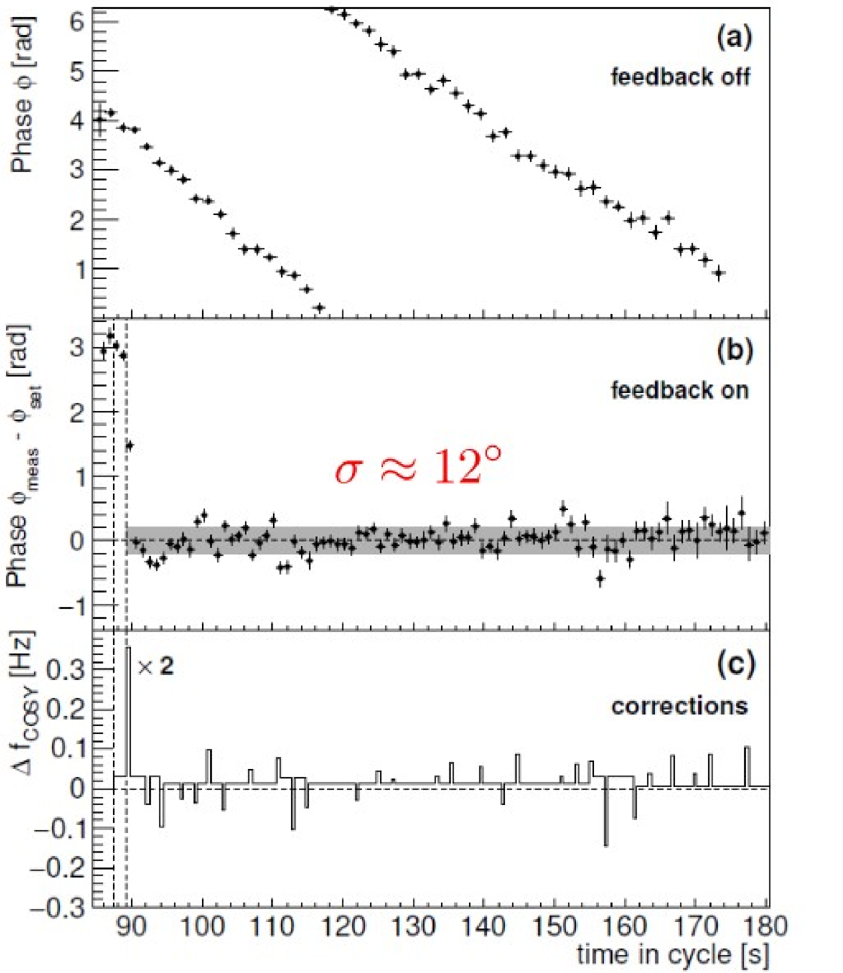
Test at COSY:

control spin tune via COSY rf:

$$\nu_s = G\gamma$$

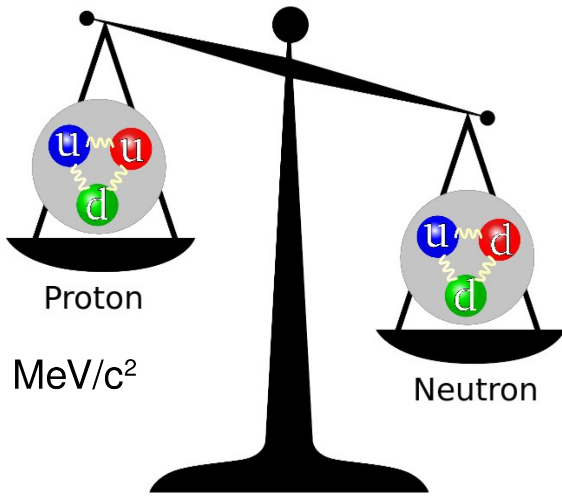
control phase to external frequency
by accelerating/decelerating spin precession





PRL, 119, 014801 (2017)

Proton-Neutron mass difference

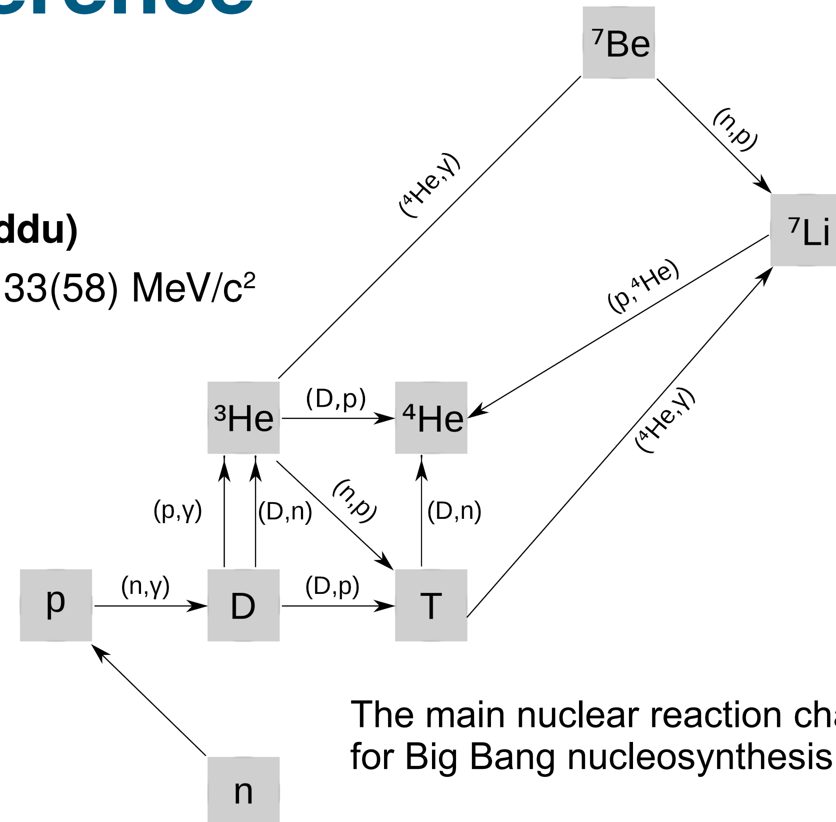


Proton (uud)

938.2720813(58) MeV/c²

Neutron (ddu)

939.5654133(58) MeV/c²



The main nuclear reaction chains for Big Bang nucleosynthesis [1]

$\mathbf{\Delta M_{np} = 1.29333217(42)\ MeV}$

$\mathbf{\Delta M_{np} / \langle M_{np} \rangle = 0.14\ \%}$

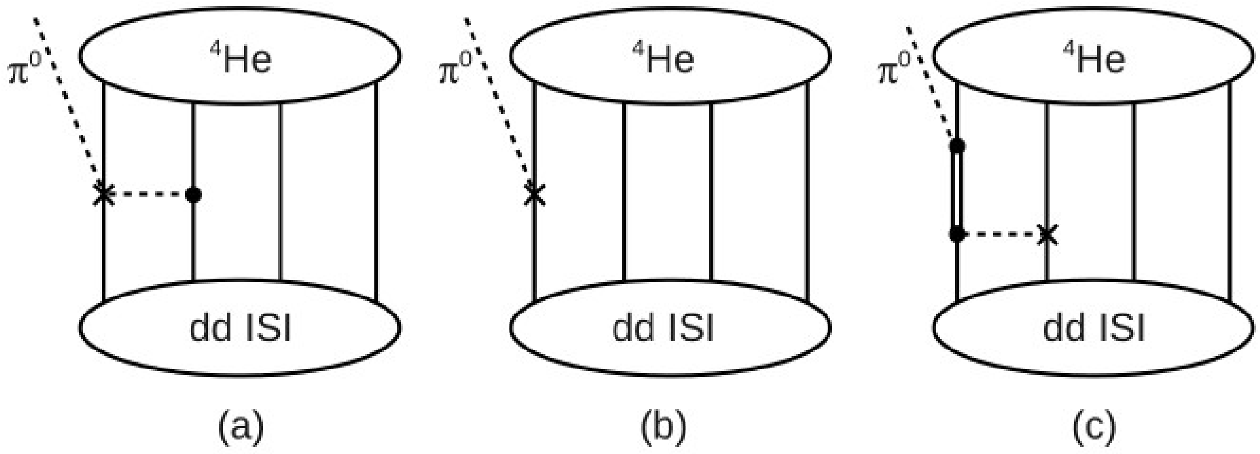
$\mathbf{\Delta M_{np} < 0}$: hydrogen atoms undergo inverse beta decay → predominantly neutrons

$\mathbf{0 < \Delta M_{np} / \langle M_{np} \rangle < 0.14\ \%}$: at the end of Big Bang Nucleosynthesis (BBN) much more He^4 and far less hydrogen than in our Universe (n/p ratio after nucleosynhtesis would be bigger than 1/7) → it would affect stars formation

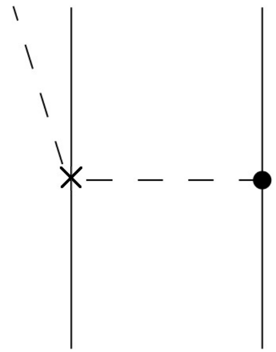
$\mathbf{\Delta M_{np} / \langle M_{np} \rangle >> 0.14\ \%}$**:** far fewer neutrons at the end of the BBN → the burning of hydrogen in stars and the synthesis of heavy elements more difficult

[1] https://en.wikipedia.org/wiki/Big_Bang_nucleosynthesis

Leading diagrams of CSB reactions



Formally leading operators for *p*-wave pion production in $dd \to {}^4\text{He}\pi^0$.



- cross – occurrence of CSB
- dot – leading order charge invariant vertex
- dashed line – pions
- single solid line – nucleons
- double solid line – Δ

Leading order diagram for the CSB *s*-wave amplitudes of the $np \to d\pi^0$ reaction

Differential cross section

Transition matrix *M*

- 2 identical particles in initial state
  → 3 scalar amplitudes to describe spin dependence: *A, B, C*
- p_d lie along z-direction → p_π in z-x plane

$$M = A(\epsilon_{1x}\epsilon_{2y} - \epsilon_{1y}\epsilon_{2x}) + Bp_{\pi^0}\sin\theta\cos\theta(\epsilon_{1y}\epsilon_{2z} - \epsilon_{1z}\epsilon_{2y}) - Cp_{\pi^0}\sin\theta(\epsilon_{1z}\epsilon_{2y} - \epsilon_{1y}\epsilon_{2z})$$

- 2nd deuteron – unpolarized

Remaining polarization information in density matrix

$$\rho = \sum_{m_2} M^\dagger M$$

- Trace of density matrix with vector and tensor projection operators and unity matrix

$$I = \frac{2}{3}(|A|^2 + |B|^2 p_{\pi^0}^4 \sin^2\theta\cos^2\theta + |C|^2 p_{\pi^0}^2 \sin^2\theta)$$

- C – odd waves, A,B – even waves (terms ~ C change sign under $p_\pi \rightarrow -p_\pi$)
- A – contains s-wave (survive at threshold)
- Partial wave expansion up to p_π^2: *B, C* – constant, $A = A_0 + A_2 p_\pi^2 P_2(\cos\theta)$

$$d\,d \rightarrow {}^4\mathrm{He}\,\pi^0$$

S^P: 1^+ 1^+ 0^+ 0^-

${}^{2S+1}L_{J+1}$:

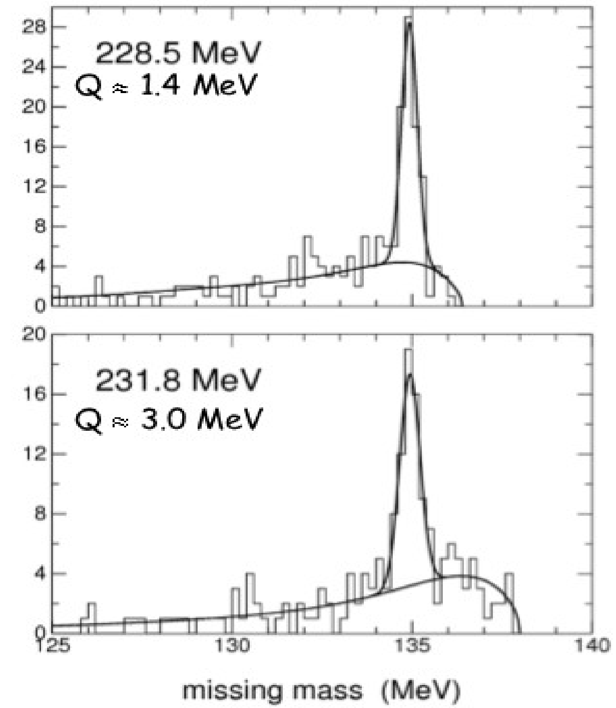
initial	final
$^3P_0$	$^1S_0$
$^5D_1$	$^1P_1$
$^3P_1/^3F_1$	$^1D_2$

$$\frac{d\sigma}{d\Omega} = \frac{2}{3}\frac{p_{\pi^0}}{p_d}\left(|A_0|^2 - p_{\pi^0}^2\Re\{A_0^* A_2\} + |C|^2 p_{\pi^0}^2\right) + \frac{p_{\pi^0}}{p_d}\left(2p_{\pi^0}^2\Re\{A_0^* A_2\} - \frac{2}{3}|C|^2 p_{\pi^0}^2\right)\cos^2\theta^*$$

Measurement close to treshold

Measurements of CSB observables

- **np→dπ⁰ forward-backward asymmetry A_{fb}**
  - leading CSB term: πN rescattering
  - Opper et al., A_{fb} = (17.2 ± 8.0 ± 5.5) $\cdot 10^{-3}$
    (PRL 91 (2003) 212302)



- **Pion production in dd→⁴He π⁰**

CSC ⇒ σ = 0

CSB ⇒ σ ≠ 0, $\sigma \propto |M_{CSB}|^2$

Complementary to np→dπ⁰:

- different strength of CSB terms
- dd initial state more demanding

Result: Stephenson et al.

(PRL 91 (142302) 2003)

σ_{tot} (Q=1.4 MeV) = 12.7 ± 2.2 pb

σ_{tot} (Q=3.0 MeV) = 15.1 ± 3.1 pb

Result consistent with s-wave production

$dd \to {}^3He n \pi^0$ reaction measurement

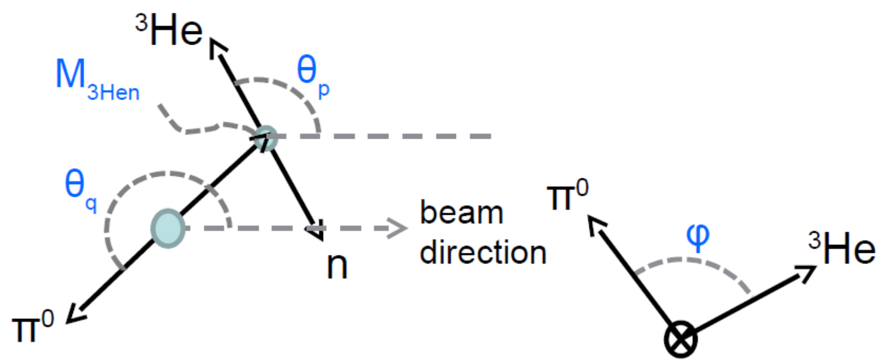
Two-fold model ansatz:

- Quasi-free contribution: $dd \to {}^3He\pi^0 + n_{spec}$
- Partial waves decomposition of the 3-body final state (limited to $L \leq 1$)

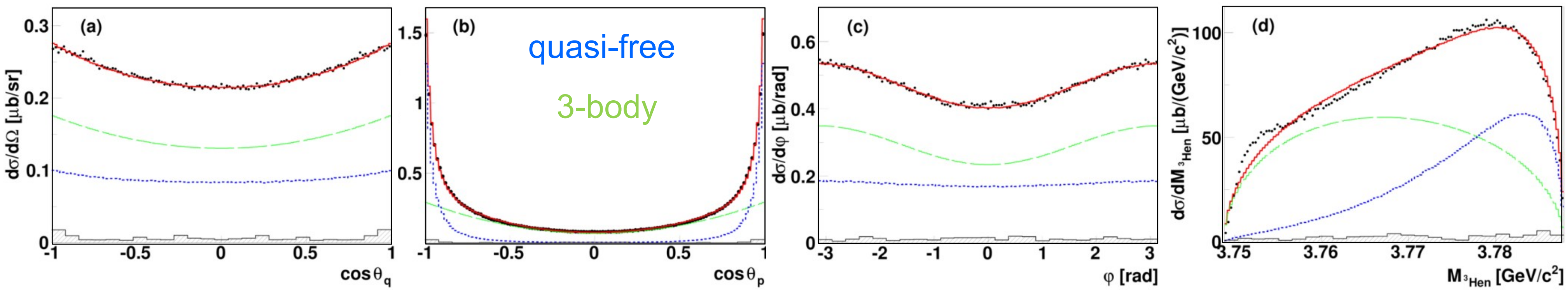
} full model incoherent sum

$\sigma_{tot} = (2.89 \pm 0.01_{stat} \pm 0.06_{sys} \pm 0.29_{norm})$ μb

Model used for **simulating** the $dd \to {}^3He n \pi^0$ background and for **normalization**



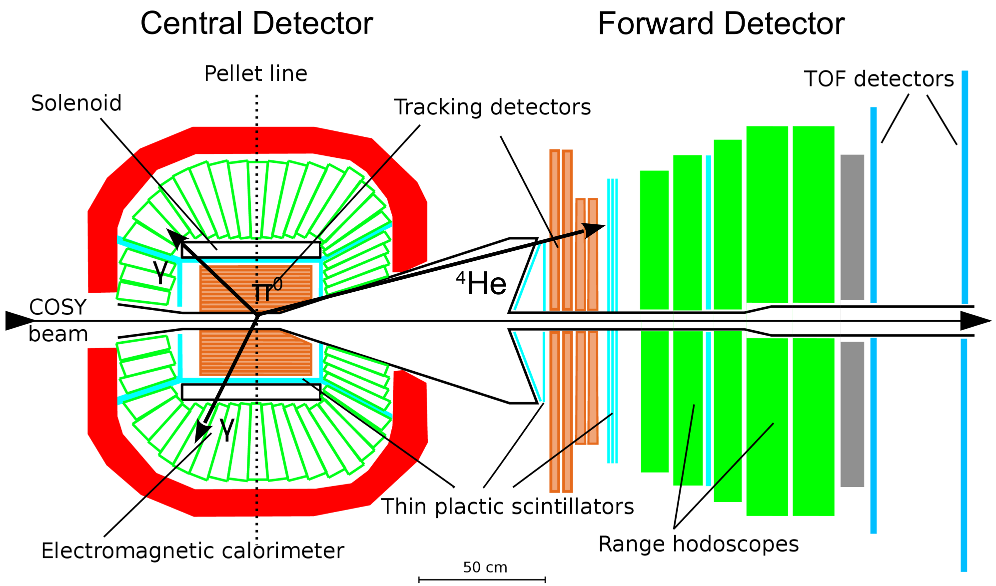
4 independent variables M_{3Hen}, θ_p, θ_q, φ



Phys. Rev. C 88 (2013) 014004

First measurement with WASA

2008: First measurement of $dd \rightarrow {}^4\mathrm{He}\pi^0$ (2 weeks) at Q = 60 MeV, **goal: total cross section**

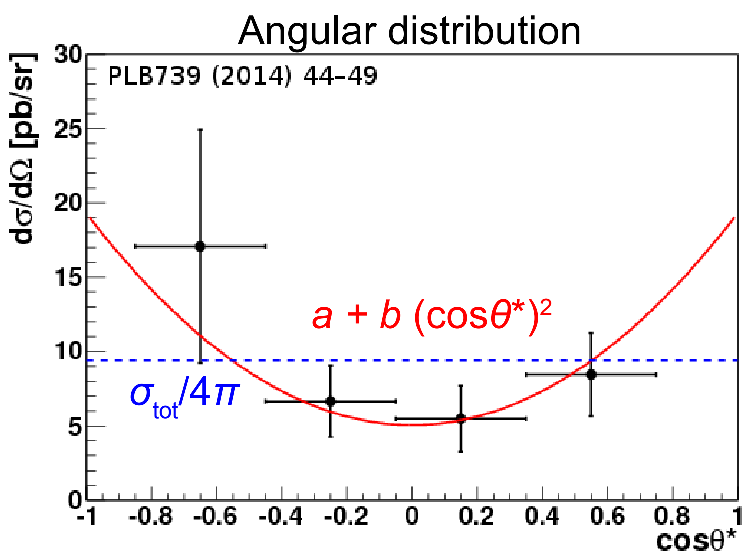


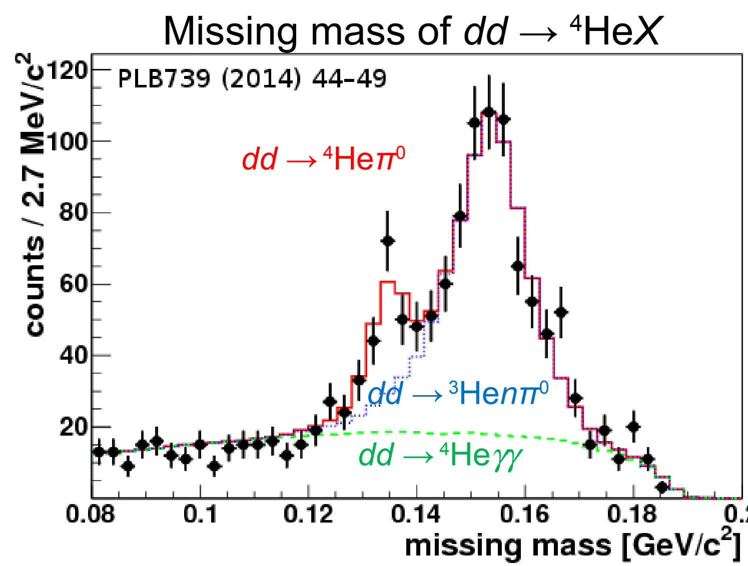
${}^4\mathrm{He}\pi^0$: $\sigma_{tot} = (118 \pm 18_{stat} \pm 13_{sys} \pm 8_{ext})$ pb

Result consistent with *s*-wave

Due to **limited statistics** not decisive to identify higher-wave contribution

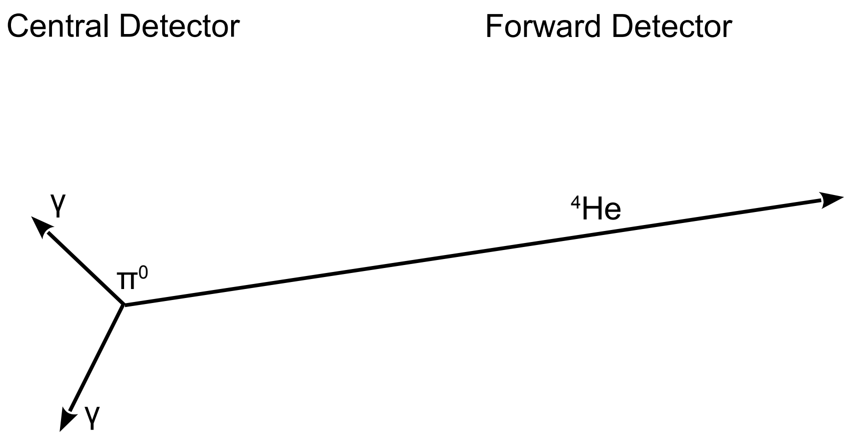
Parameter b of the $d\sigma/d\Omega$ fit $a + b\,(\cos\theta^*)^2$ consistent with 0





New Experiment with Improved Setup

2014: **10-week-long** beamtime dedicated to measurement of $dd \rightarrow {}^4He\pi^0$ at Q = 60 MeV with modified detector, **goal: angular distribution**



Background

- $dd \rightarrow (pnd, pnpn, tp) + \pi^0$
- $dd \rightarrow {}^3He n \pi^0$ ($3 \cdot 10^4$ higher σ)
- $dd \rightarrow {}^4He \gamma\gamma$ (physics bg)

Main challenge

$dd \rightarrow {}^3He n \pi^0$ suppression

↓

^{3}He/^{4}He separation in Forward Detector

Advantages

→ Access to Time-of-Flight (ToF)

- Better ^{3}He/^{4}He separation
- Independent energy reconstruction

Disadvantages

→ Smaller acceptance

- Slow ^{4}He stops in air before FVH

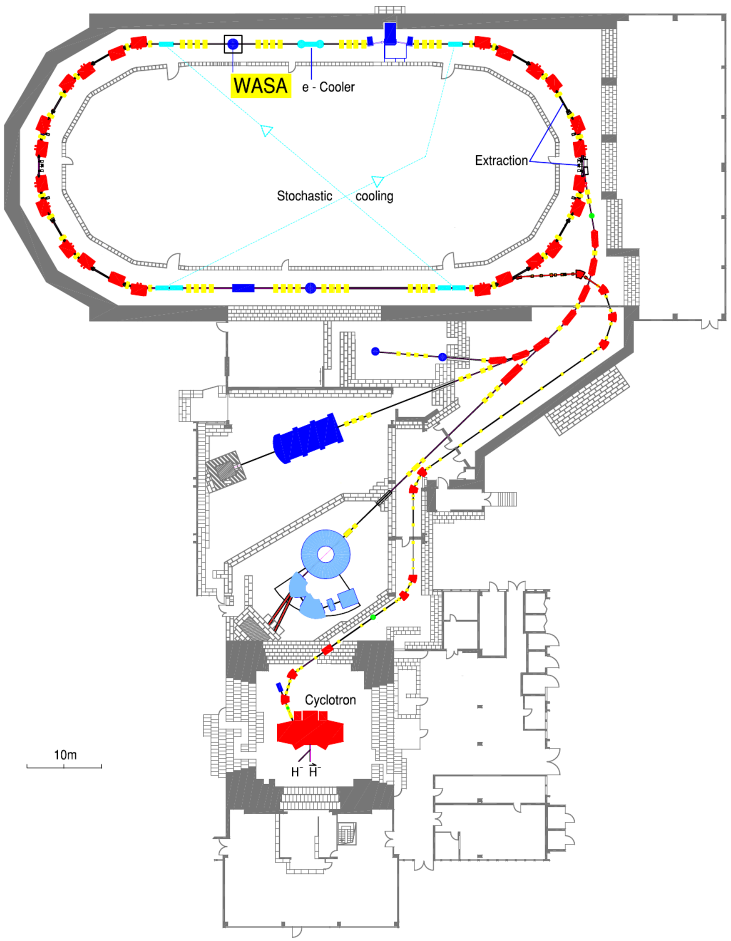
Challenges

- ToF calibration first time in WASA
- Dropping gain of FWC and FVH

Beamtime summary

- Beam momentum: 1.2 GeV/c^2
- Main trigger: high threshold in Forward Detector, ≥ 1 neutral candidate in Central Detector
- Integrated luminosity: (35.4 ± 3.7) pb^{-1}

Beamtime summary



Beamtime summary

- **Beam momentum:** 1.2 GeV/c^2
- **Beam kinetic energy:** 0.350 GeV
- **Pellet rate:** 1500 – 11000 Hz
- **Main trigger:** high threshold in Forward Detector, ≥1 neutral candidate in Central Detector
- **Integrated luminosity:** (35.4 ± 3.7) pb^{-1}
- **Average instantaneous luminosity:** ~ 6 x 10^{30} cm^{-2} s^{-1} (6 mb^{-1} s^{-1})
- **Deuterons in flat top:** 1.9 – 2.5 x 10^{10}
- **Typical rates in FWC:** 4 MHz
- **Effective time of measurement:** 41 days (989 hours)
- **Beamtime length:** 65 days

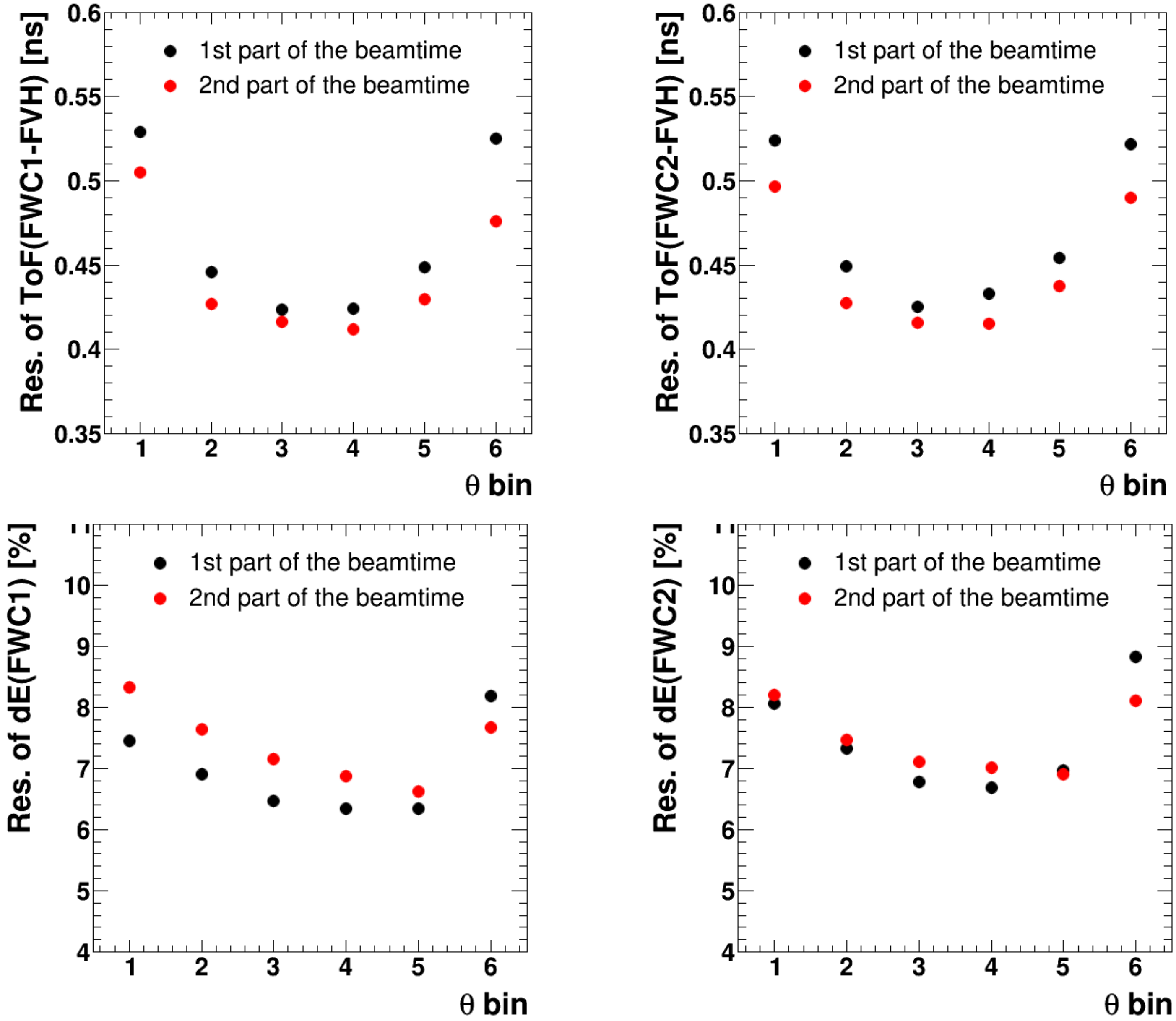
Challenges:

- Problem with blocked target nozzle
- Dropping gain of FWC and FVH

COoler SYnchrotron – General parameters

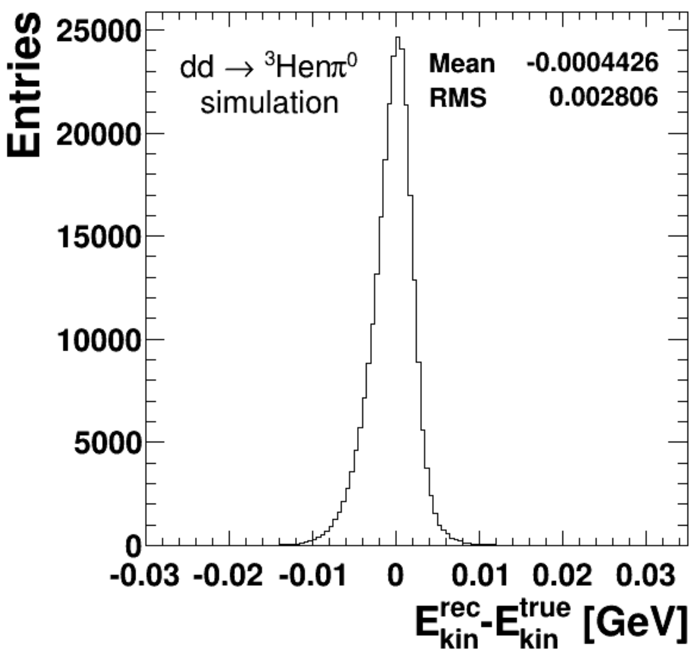
- Circumference: 183.5 m
- Ions: polarized/unpolarized protons and deuterons
- Momentum range 300 - 3700 MeV/c
- Polarization: up to 75%
- Cooling: stochastic and electron (above 1.5 GeV/c)
- Momentum resolution Δp/p: = 10^{-3} (uncooled), 10^{-4} (cooled)

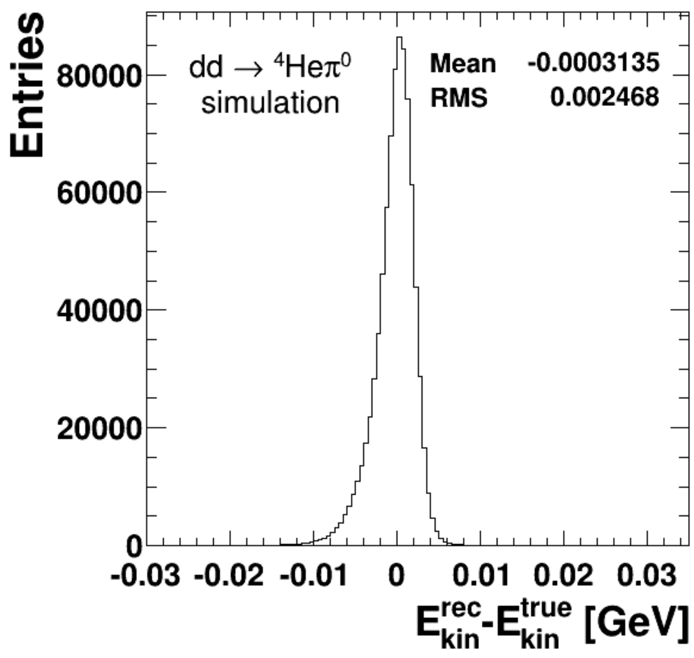
ToF and dE resolution



Kinetic energy calibration

- Minimization of χ^2: $\chi^2 = \sum_{i=1}^{n} \frac{(dE_i^{meas} - dE(E_{kin})_i)^2}{\sigma_i^2} + \sum_{j=1}^{m} \frac{(\mathrm{TOF}_j^{meas} - \mathrm{TOF}(E_{kin})_j)^2}{\sigma_j^2}$
- $E_{kin}(ToF_1)$, $E_{kin}(ToF_2)$, $E_{kin}(dE_{FWC1})$, $E_{kin}(dE_{FWC2})$ dependence from MC
- Uncertainties from data (*dd* → ^{3}He*n* used)



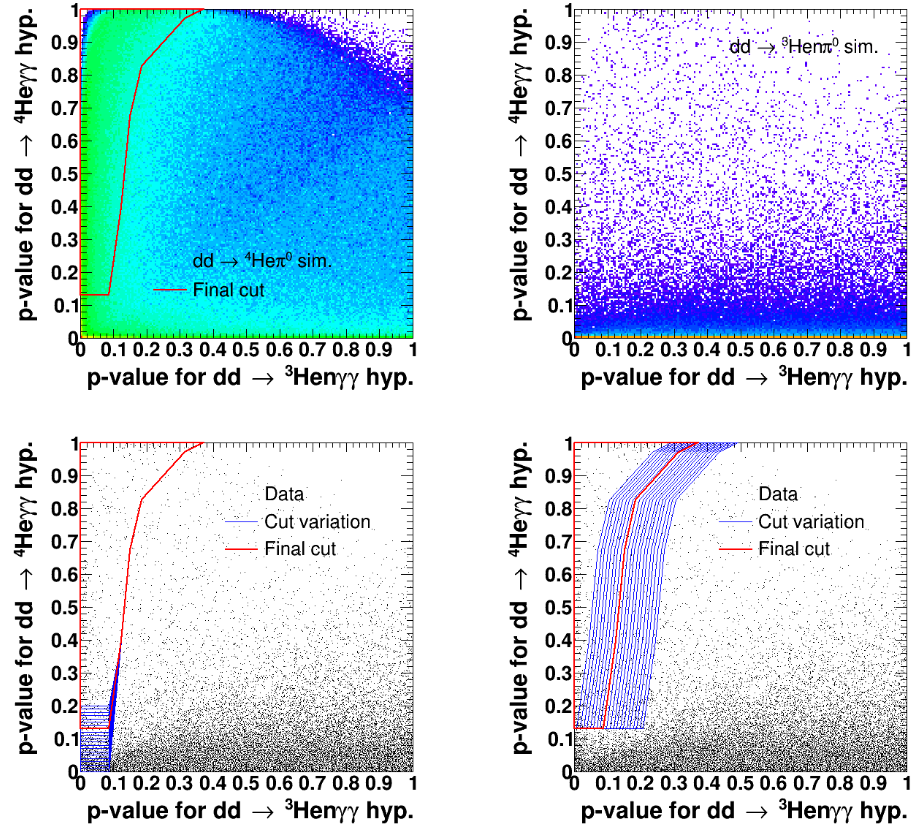


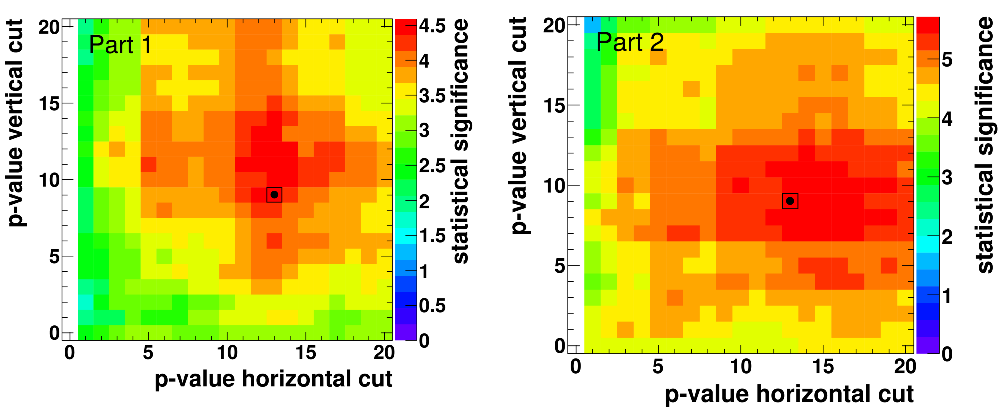
Cuts used in the analysis

Forward Detector:
- χ^2 from E_{kin} reconstruction: < 30
- $3^O < \theta(^4He) < 9^O$
- p-value cut

Central Detector:
- Type of clusters: neutral
- Number of clusters: 2
- Total energy in cluster: 20 MeV
- Time difference between clusters: 20 s
- Opening angle between clusters: 30^O

If there is more than 2 candidates in CD or 1 in FD: the combination with the best χ^2 from the kinematic fit of signal hypothesis taken

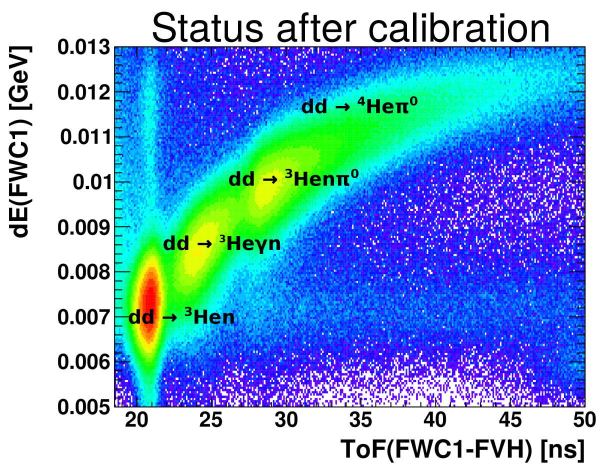




Optimization of the p-value cut:
Maximization of the statistical significance R

$$R = \frac{S}{\sqrt{S+B}}$$

Analysis
Signal Selection Cuts



- Cuts on ΔE-ΔE not enough for effective suppression of background
- **Overall kinematic fit used**

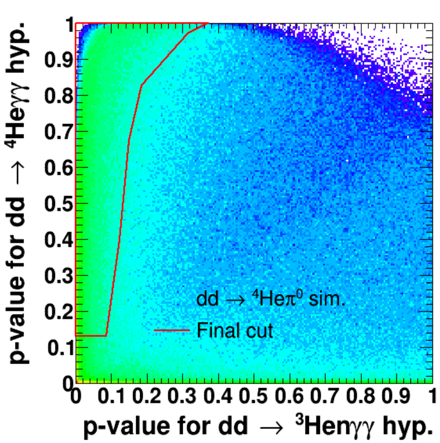
$$\chi^2 = \sum_{i=1}^{n} \left(\frac{v_i^{\mathrm{meas}} - v_i^{\mathrm{fit}}}{\sigma_i} \right)^2$$

- Constraint on energy and momentum conservation
- 2 hypotheses fitted: $dd \rightarrow {}^4\mathrm{He}\gamma\gamma$ and $dd \rightarrow {}^3\mathrm{He}n\gamma\gamma$

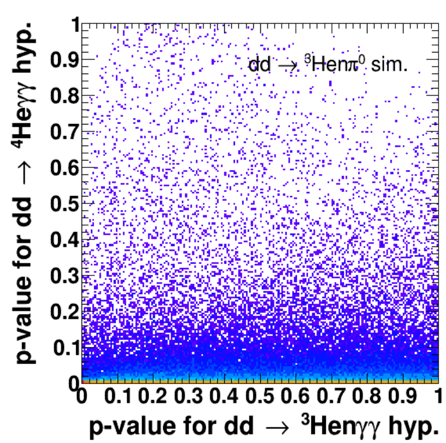
- Cut on cumulated probability distribution (p-value)
- Optimized to maximal statistical significance of signal peak
- **Suppression of $dd \rightarrow {}^3\mathrm{He}n\pi^0$ more than 10^3**

$$p(N, \chi^2_{\min}) = \frac{1}{2^{\frac{N}{2}} \Gamma\left(\frac{N}{2}\right)} \int_{\chi^2_{\min}}^{\infty} e^{-\frac{t}{2}} t^{\frac{N}{2}-1} \mathrm{d}t$$

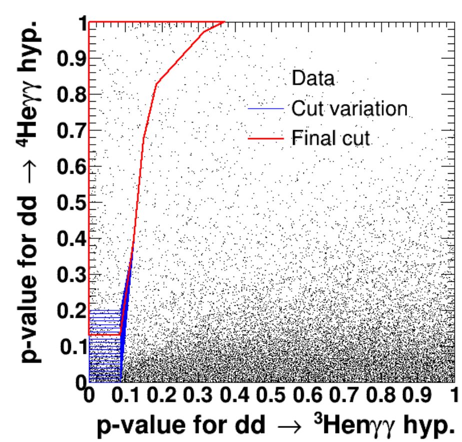
$dd \rightarrow {}^4\mathrm{He}\pi^0$ simulation



$dd \rightarrow {}^3\mathrm{He}n\pi^0$ simulation



data



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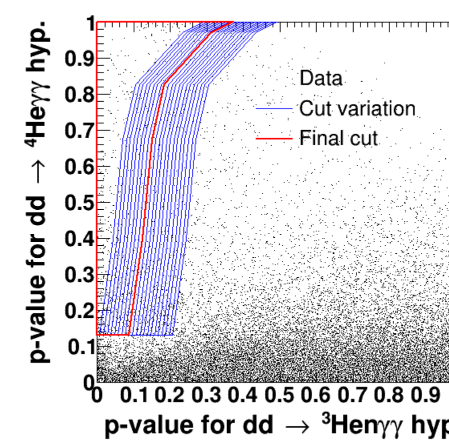


Luminosity calculation from $dd \to {}^3\text{He}n\pi^0$

Total cross section

$\sigma = (2.89 \pm 0.01_{stat} \pm 0.06_{sys} \pm 0.29_{norm})$ μb (Phys. Rev. C 88 (2013) 014004)

Number of events

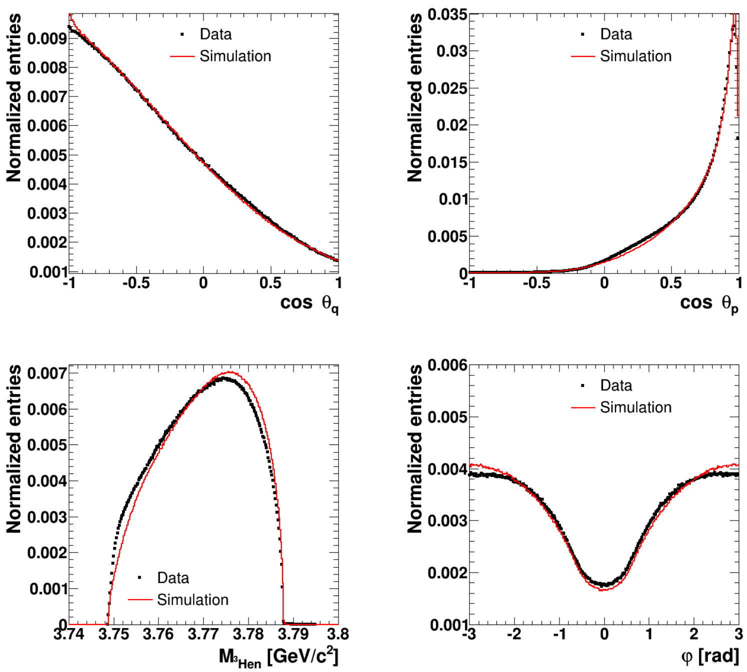
Cuts in the analysis:

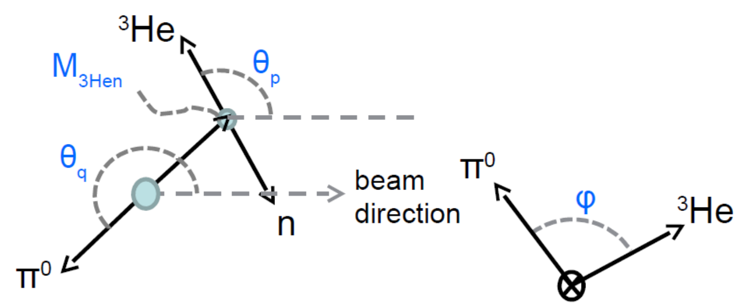
- Loose cut on χ^2 from E_{kin} reconstruction < 30
- Cut on p-value > 0.5 (see determination of systematic uncertainties)

$$L = \frac{N}{\epsilon \cdot \sigma}$$

Acceptance x cut efficiencies

MC generator obtained in Phys. Rev. C 88 (2013) 014004

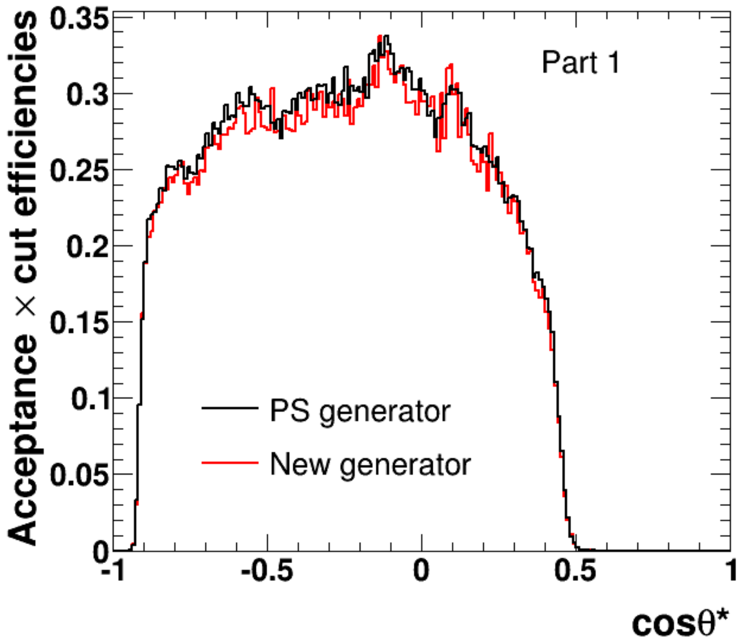


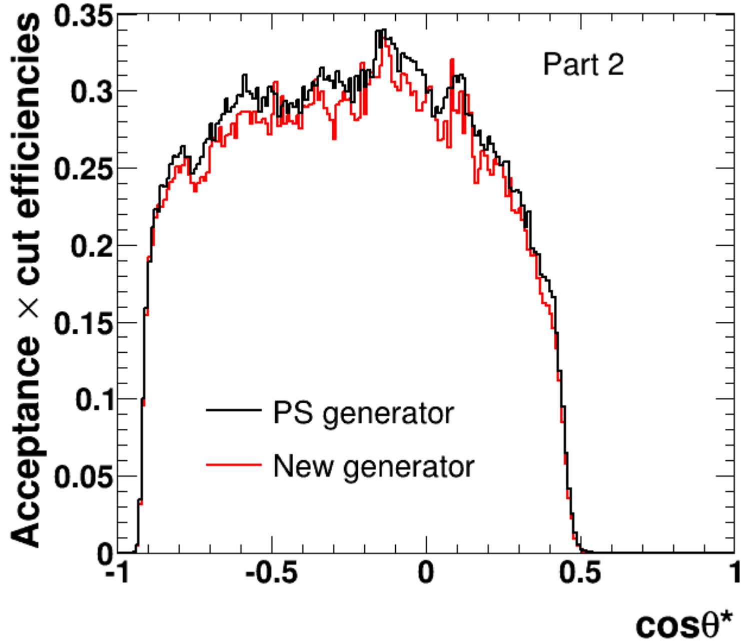


	1st part	2nd part
Number of $dd \to {}^3\text{He}n\pi^0$ ev.	5545240	6777114
Acceptance · Cut efficiency	12%	12%
Integrated luminosity	$(16.1 \pm 1.6(\text{norm.}))$ pb^{-1}	$(19.6 \pm 2.0(\text{norm.}))$ pb^{-1}

10^8 $dd \to {}^3\text{He}n\pi^0$ events generated

Acceptance





Bin number	Acceptance times cut eff. [%]	
	1st part	2nd part
1	24.3	24.4
2	28.5	28.6
3	30.2	30.1
4	24.3	24.0