Results from the NPDGamma n-p weak interaction experiment at SNS

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* for the NPDGamma collaboration

Instituto de Física
UNAM

A long way coming

First stage at the Los Alamos Neutron Science Center (LANL)

- Letter of intent in 1998
- Construction of FP12
- Data taking at Los Alamos in 2006-2007
- Statistically limited result: $A_\gamma = [-1.2 \pm 2.1(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-7}$

  Gericke et al. *Phys. Rev. C* 83, 015505 (2011)

Second stage at the Spallation Neutron Source (ORNL)

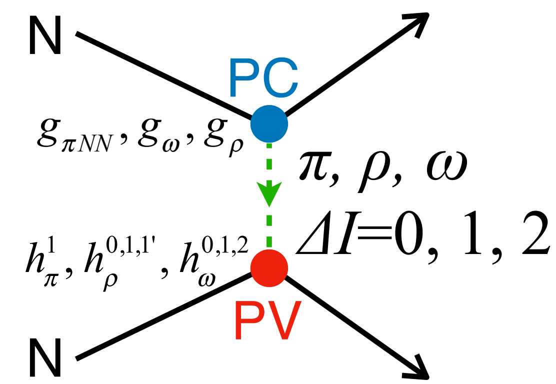
- More intense neutron flux available
- Modifications to some components, installation and commissioning (2008-2012)
- H_2 data taking at the SNS (November 2012 - March 2014)
- Apparatus decommissioned in the Summer of 2014 and partially reinstalled again in 2016 for background asymmetry measurement (aluminium inconsistencies)
- Final result: $A_\gamma = [-3.0 \pm 1.4(\text{stat.}) \pm 0.2\ (\text{syst.})] \times 10^{-8}$

  Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

Traditional theoretical description

Meson-exchange model

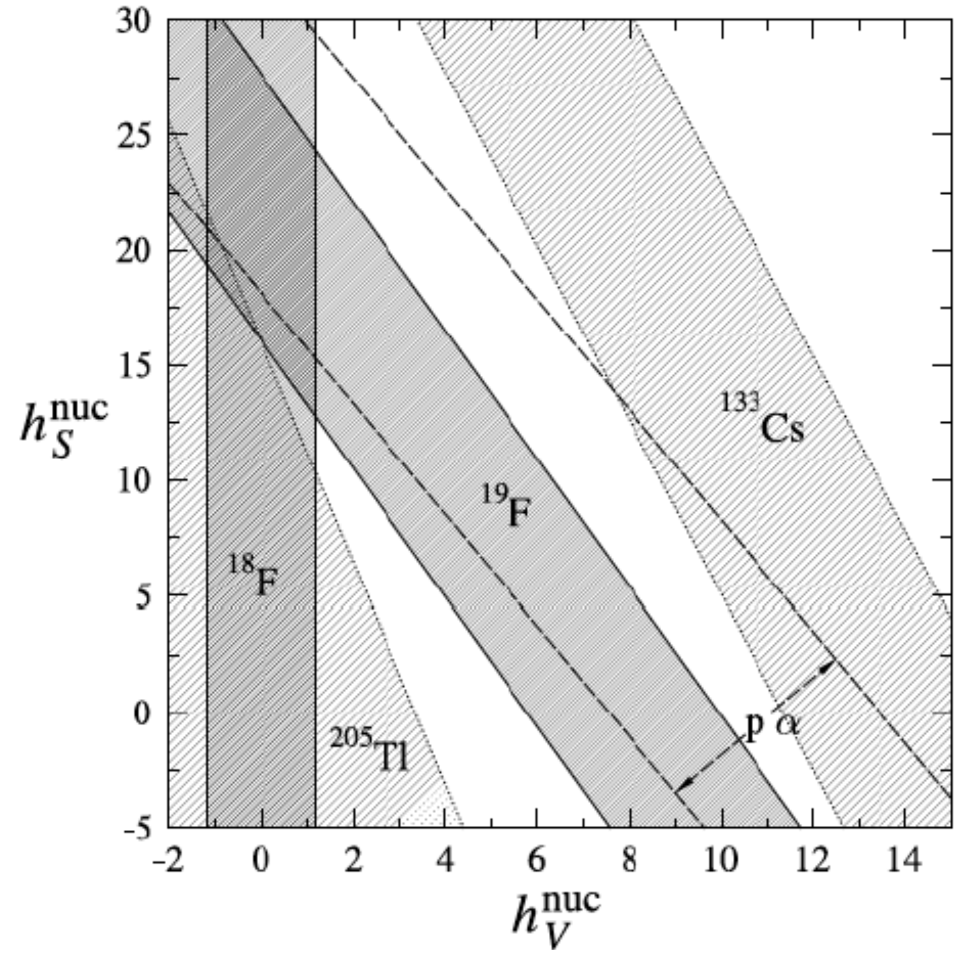
- One-meson-exchange potential
- Model dependent



Coupling	DDH reasonable range	DDH "best value"
h_π^1	0 → 11	+4.6
h_ρ^0	11 → -31	-11
h_ρ^1	-0.4 → 0	-0.2
h_ρ^2	-7.6 → -11	-9.5
h_ω^0	5.7 → -10.3	-1.9
h_ω^1	-1.9 → -0.8	-1.2

in units of ×10^{-7} $h_\rho^{1'}$ is set to zero

Desplanques, Donoghue, Holstein, *Annals of Physics* 124, 449 (1980)



$$h_V^{nuc} = h_\pi^1 - 0.12\, h_\rho^1 - 0.18\, h_\omega^1$$
$$h_S^{nuc} = -(h_\rho^0 + 0.7\, h_\omega^0)$$

Ramsey-Musolf, Page, *Annu. Rev. Nucl. Part. Sci.* 56, 1-52 (2006)

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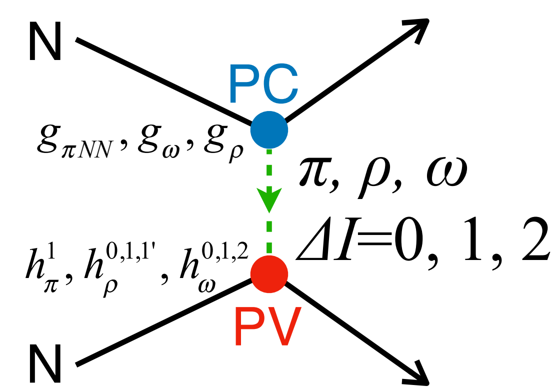

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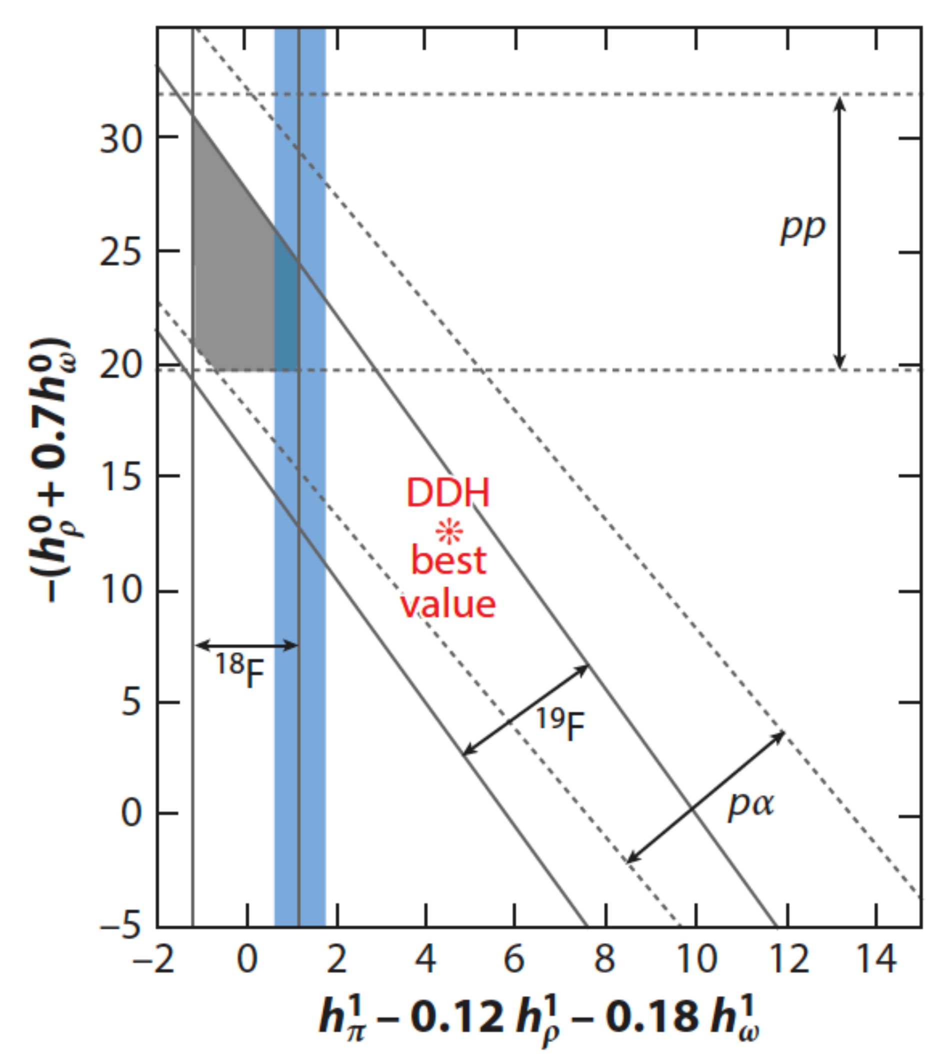

Haxton, Holstein, *Prog. Part. Nucl. Phys.* 71, 187 (2013)

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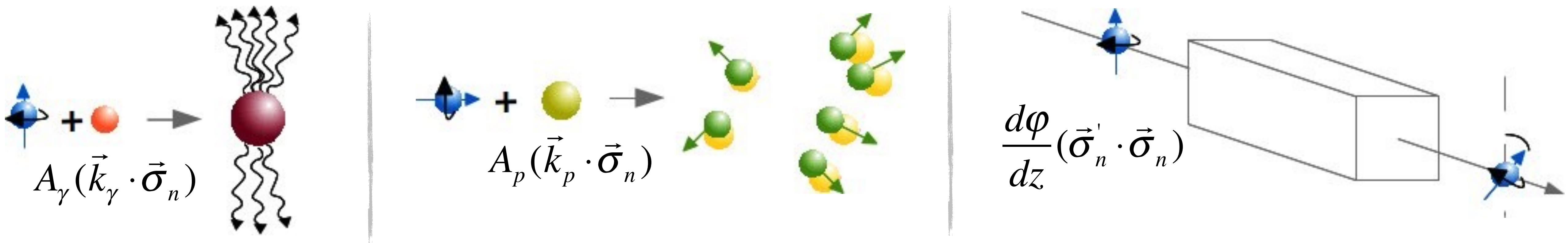
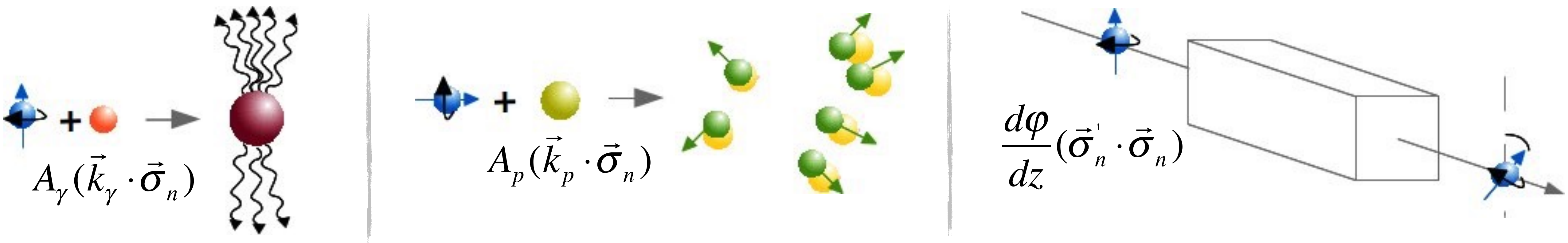
Motivation for NPDGamma and other few-nucleon experiments using neutrons



	$\vec{n}+p\to d+\gamma$ $A_\gamma(\times10^{-7})$	$\vec{n}+{}^3He\to{}^3H+p$ $A_p(\times10^{-7})$	$\vec{n}$-p $d\varphi/dz(\mu rad/m)$	$\vec{n}$-${}^4He$ $d\varphi/dz(\mu rad/m)$
h_π^1	-0.107	-0.185	-3.12	-0.97
h_ρ^0		-0.038	-0.23	-0.32
h_ρ^1	-0.001	0.023		0.11
h_ρ^2		0.001	-0.25	
h_ω^0		-0.05	-0.23	-0.22
h_ω^1	0.003	-0.023		0.22

Motivation for NPDGamma and other few-nucleon experiments using neutrons



NPDGamma

$\vec{n} + p \rightarrow d + \gamma$

- Exactly calculable two-body system (no nuclear structure uncertainty)
- Dominated by a $\Delta I=1$ $^3S_1$-$^3P_1$ parity-odd transition in the n-p system (π-exchange)
- h_π^1 coupling can be isolated (heavy meson contributions very small)
- $A_\gamma \approx -0.11\ h_\pi^1$ ($A_\gamma \approx -5\times10^{-8}$ using DDH "best value")
- Charged currents are suppressed for $\Delta I=1$, so potential to study neutral currents (not present in strangeness-changing HWI)

More recent theoretical developments

Effective Field Theory (EFT)

$$\Lambda_0^{^1S_0-^3P_0} = -g_\rho(2+\chi_\rho)h_\rho^0 - g_\omega(2+\chi_\omega)h_\omega^0$$

$$\Lambda_0^{^3S_1-^1P_1} = -3g_\rho\chi_\rho h_\rho^0 + g_\omega\chi_\omega h_\omega^0$$

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$$\Lambda_2^{^1S_0-^3P_0} = -g_\rho(2+\chi_\rho)h_\rho^2$$

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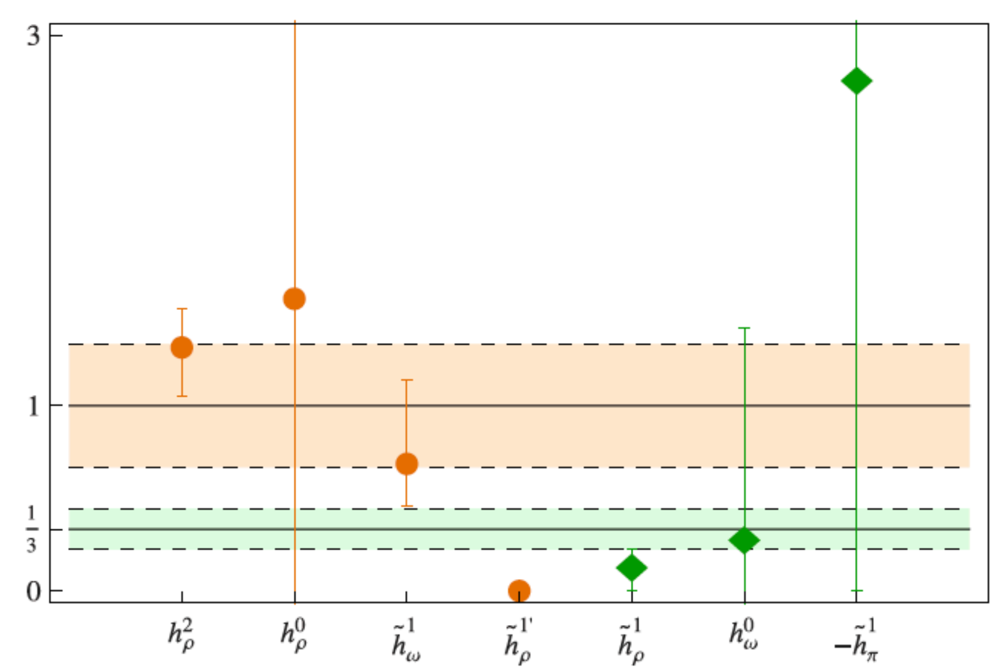
- Consistent with the symmetries and degrees of freedom of QCD

Haxton, Holstein, *Prog. Part. Nucl. Phys.* 71, 187 (2013)

Hierarchy of parameters in large-N_c expansion



Phillips, Samart, Schat, *Phys. Rev. Lett.* 114, 062301 (2015)

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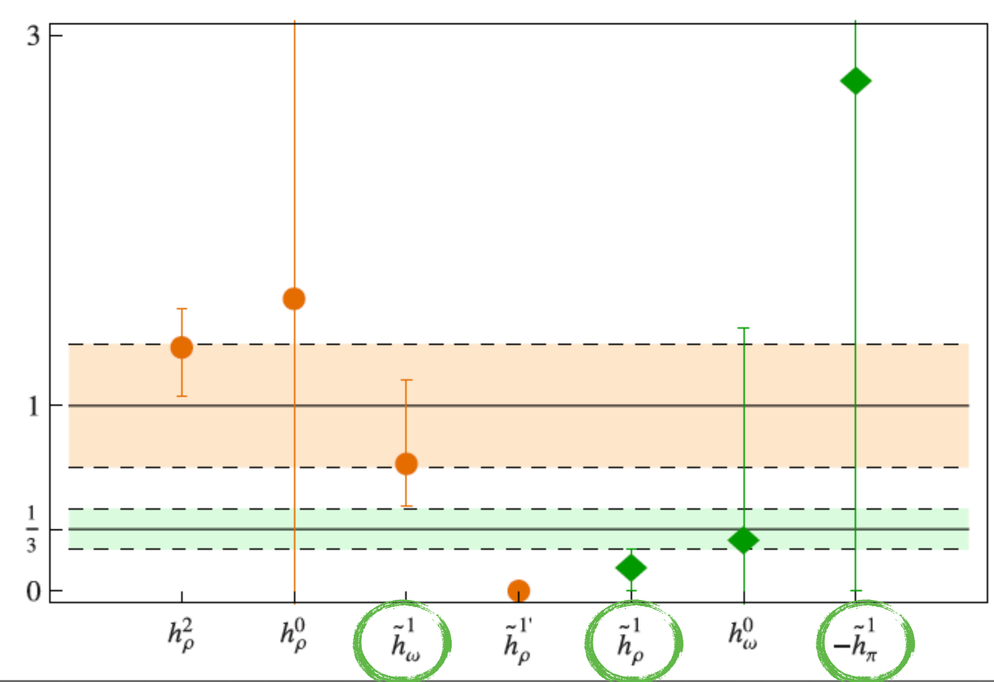

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Hierarchy of parameters in large-N_c expansion

LO and NLO

$$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{{}^3S_1-{}^1P_1} + \frac{1}{4}\Lambda_0^{{}^1S_0-{}^3P_0} \sim N_c$$
$$\Lambda_2^{{}^1S_0-{}^3P_0} \sim N_c$$

Three NNLO

$$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{{}^3S_1-{}^1P_1} - \frac{3}{4}\Lambda_0^{{}^1S_0-{}^3P_0} \sim 1/N_c$$
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Schindler, Springer, Vanasse, *Phys. Rev. C.* 93, 025502 (2016)
Gardner, Haxton, Holstein, *Annu. Rev. Nucl. Part. Sci.* 67, 69-95 (2017)

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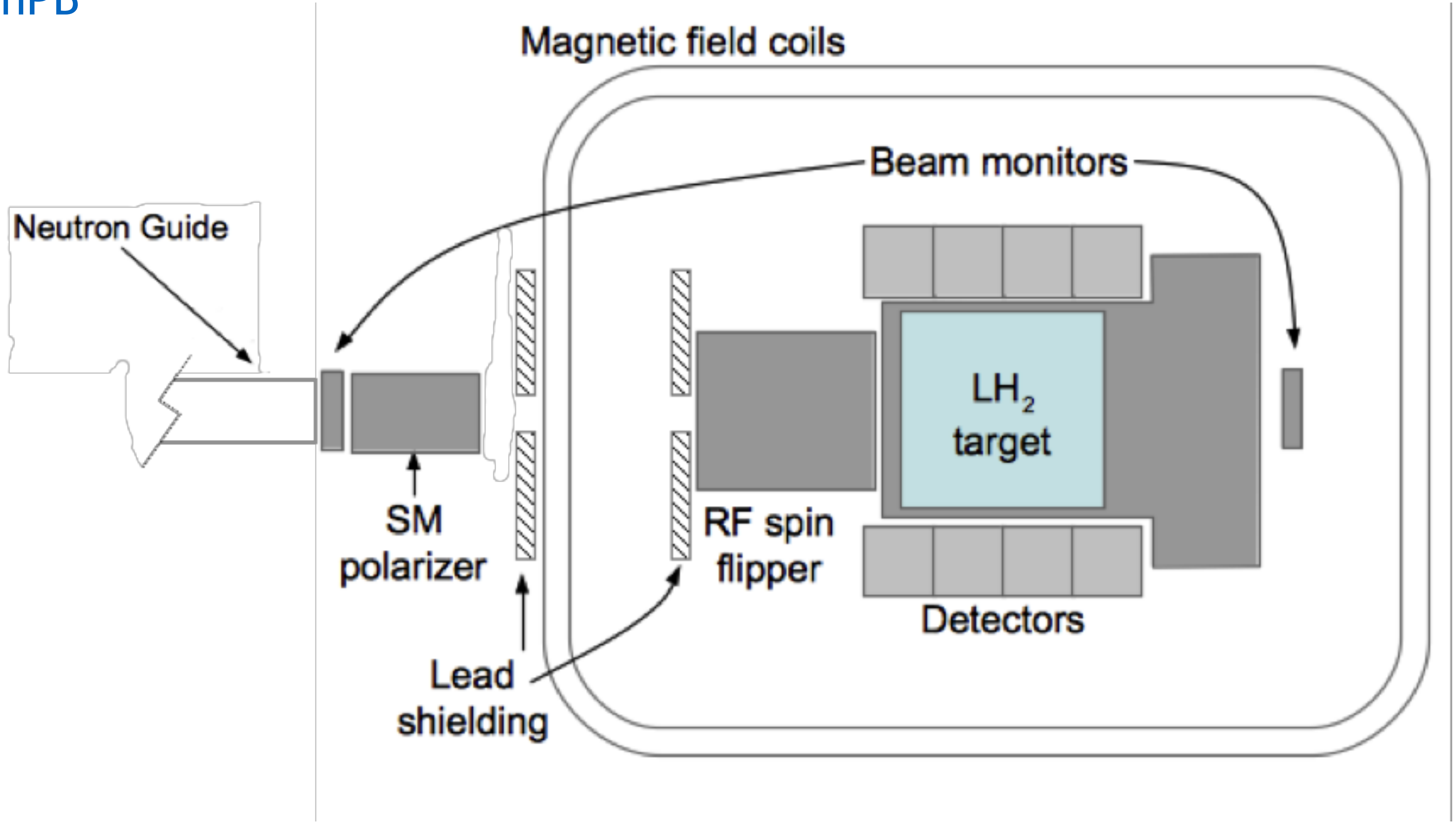
The experiment

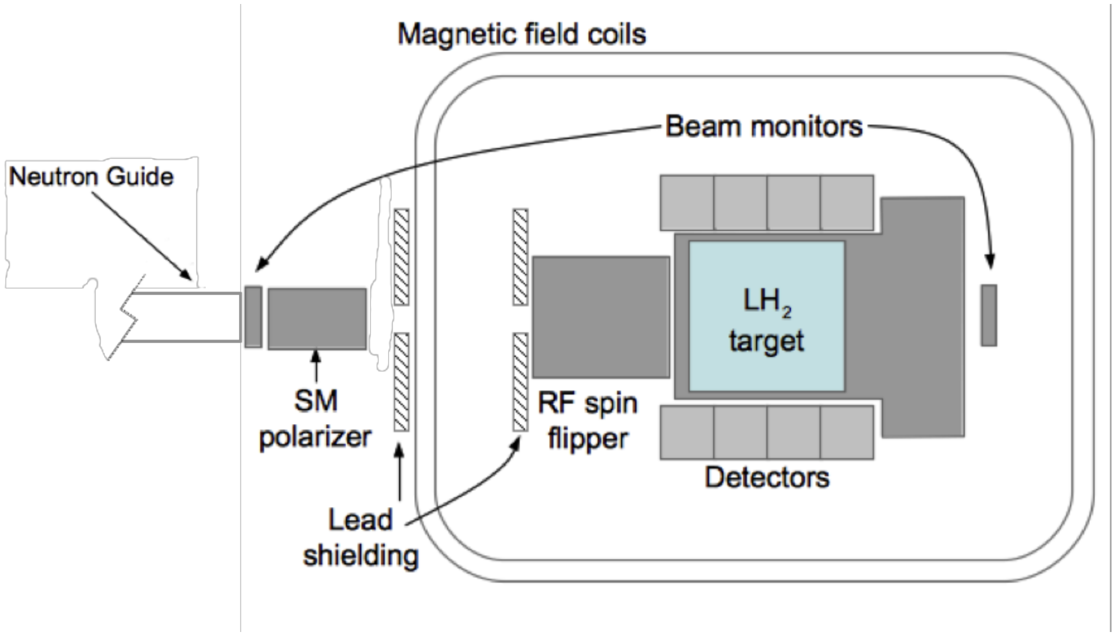
@ FnPB

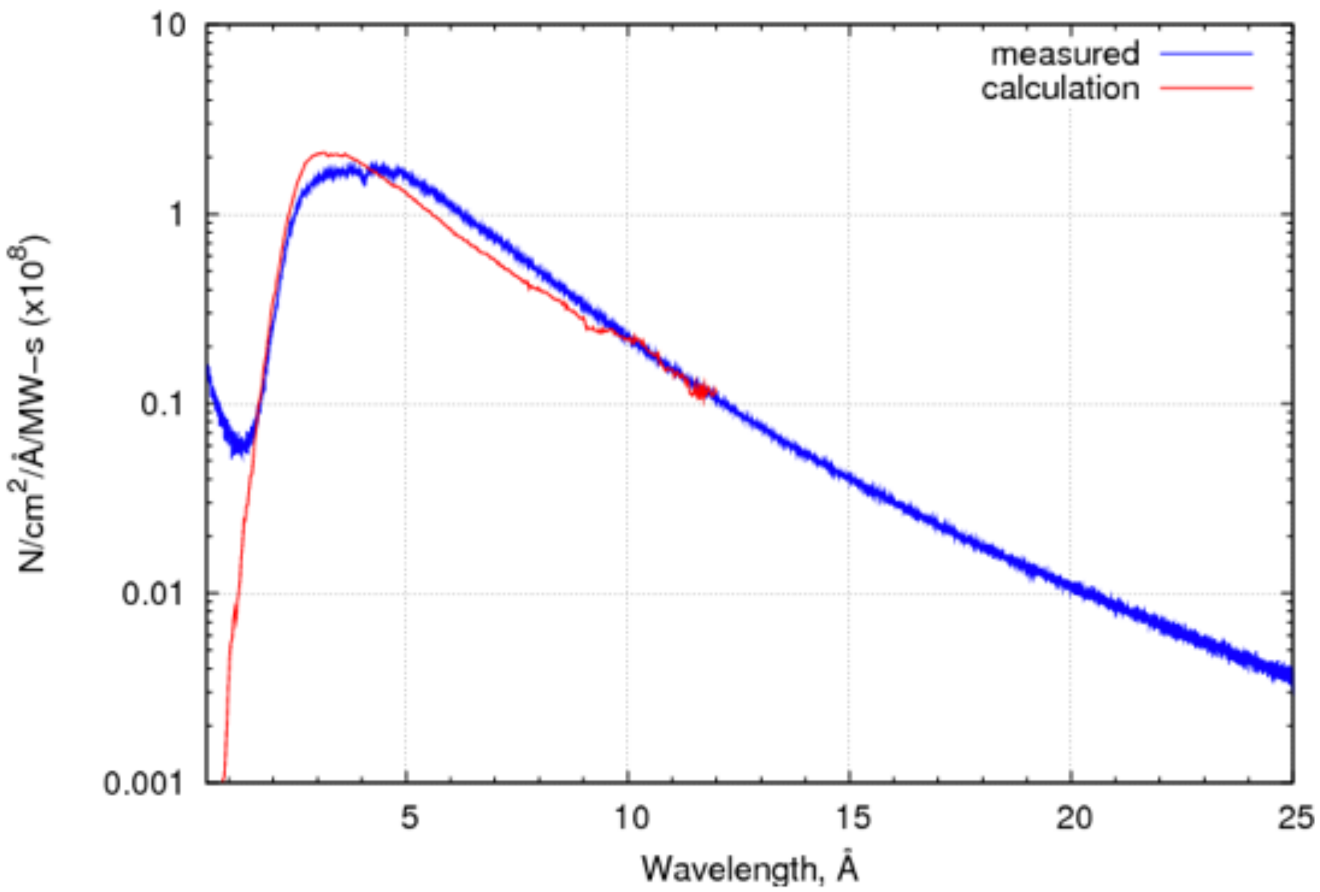


The experiment

Neutron flux

60 pulses per second





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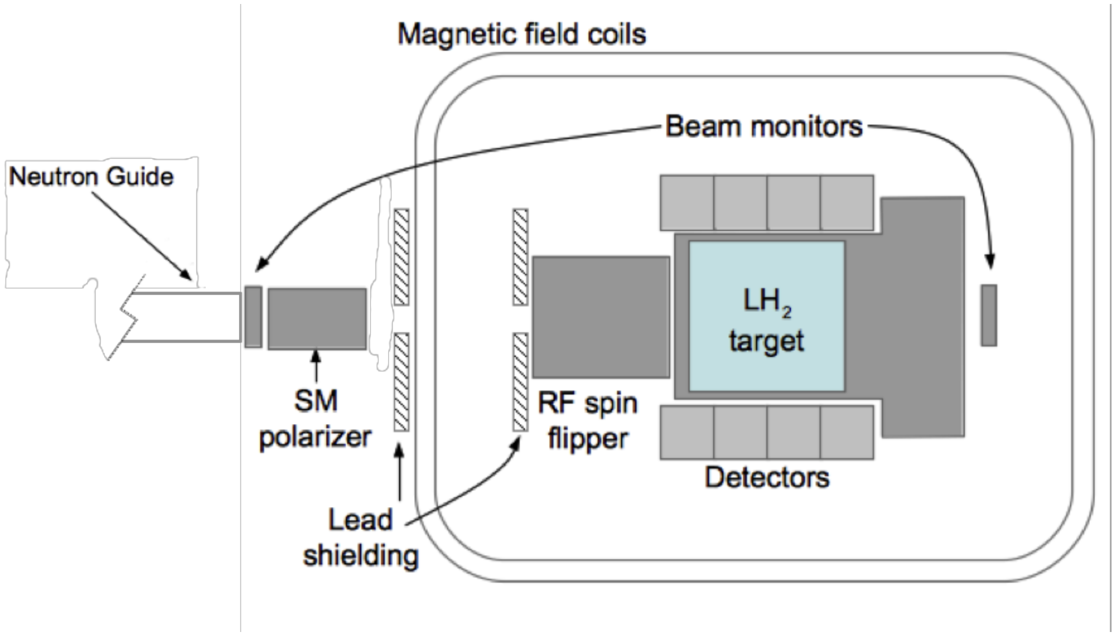

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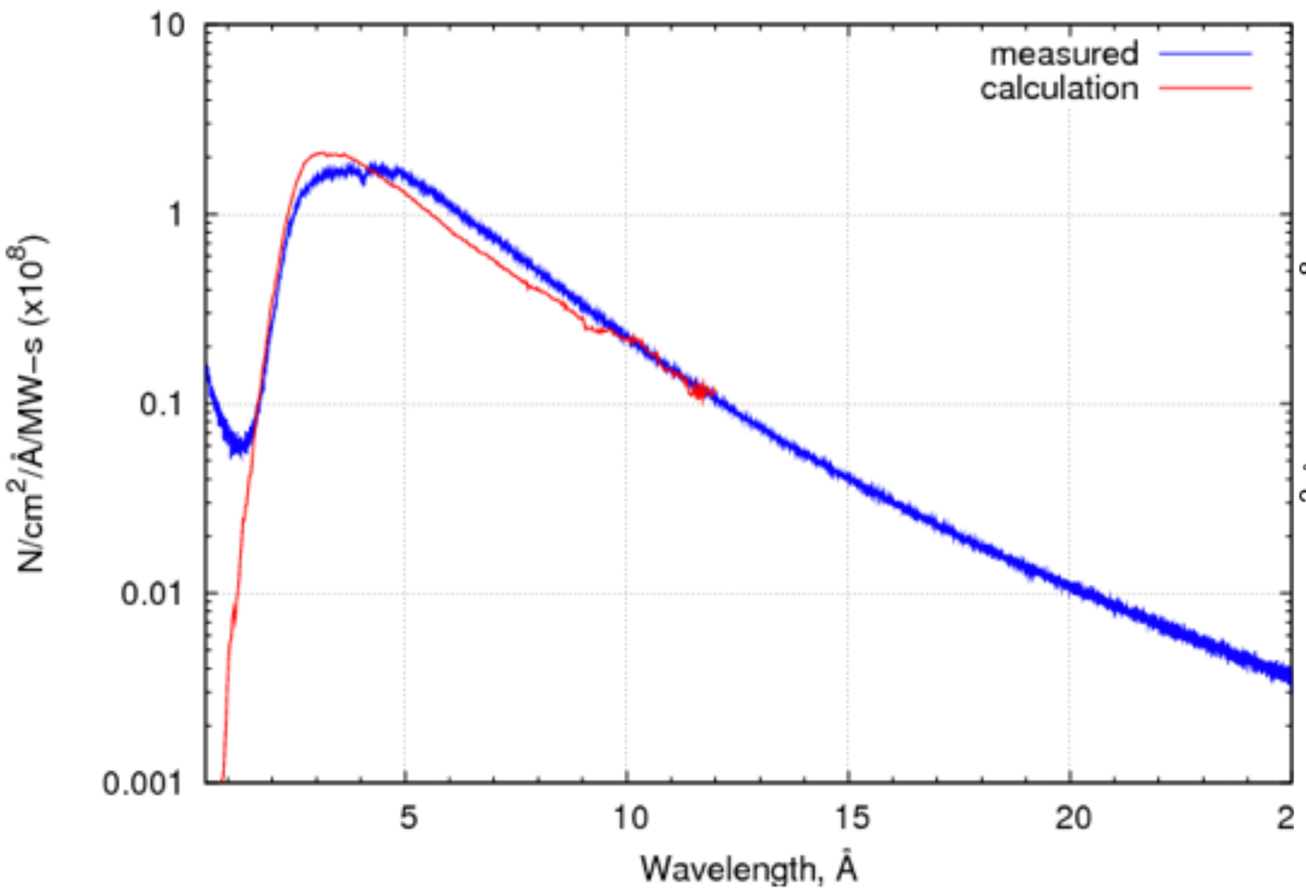

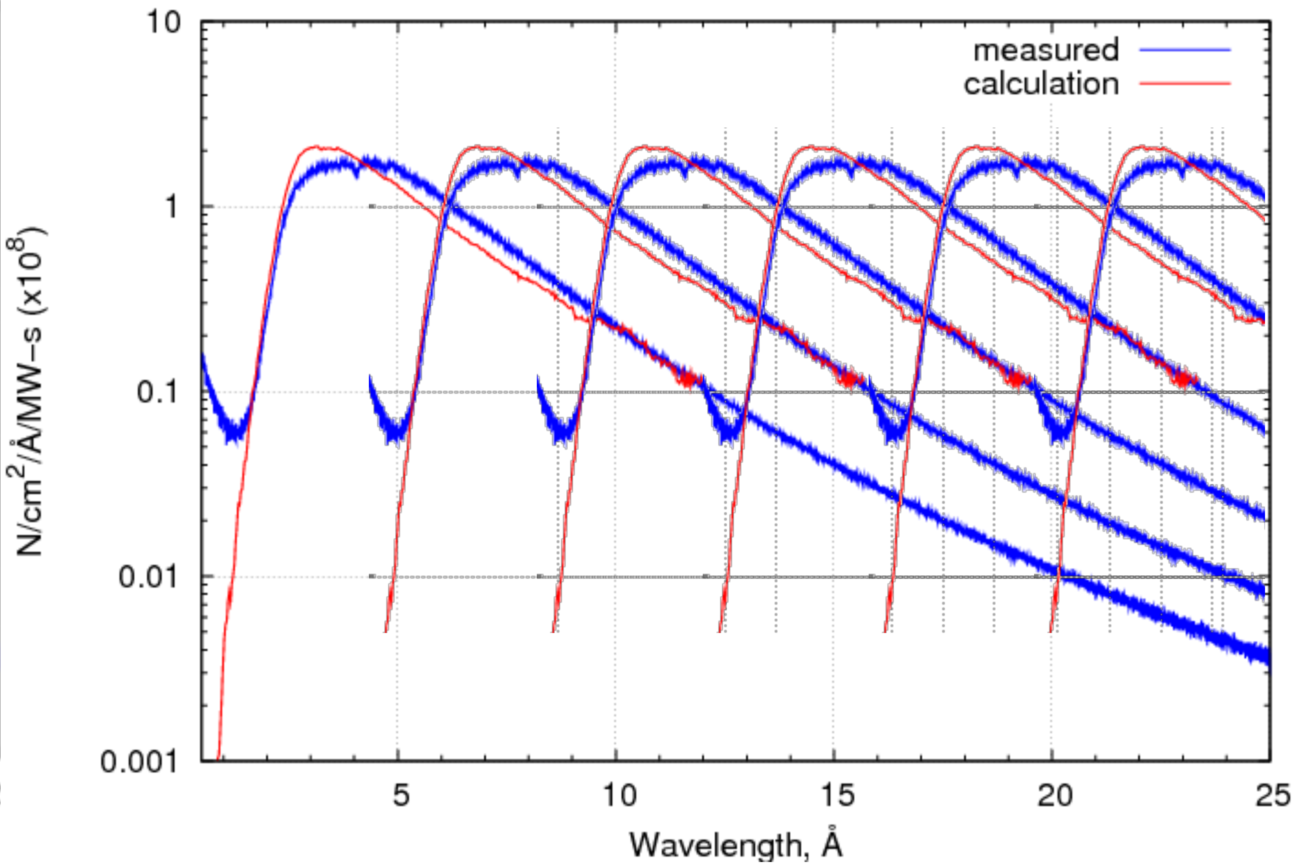

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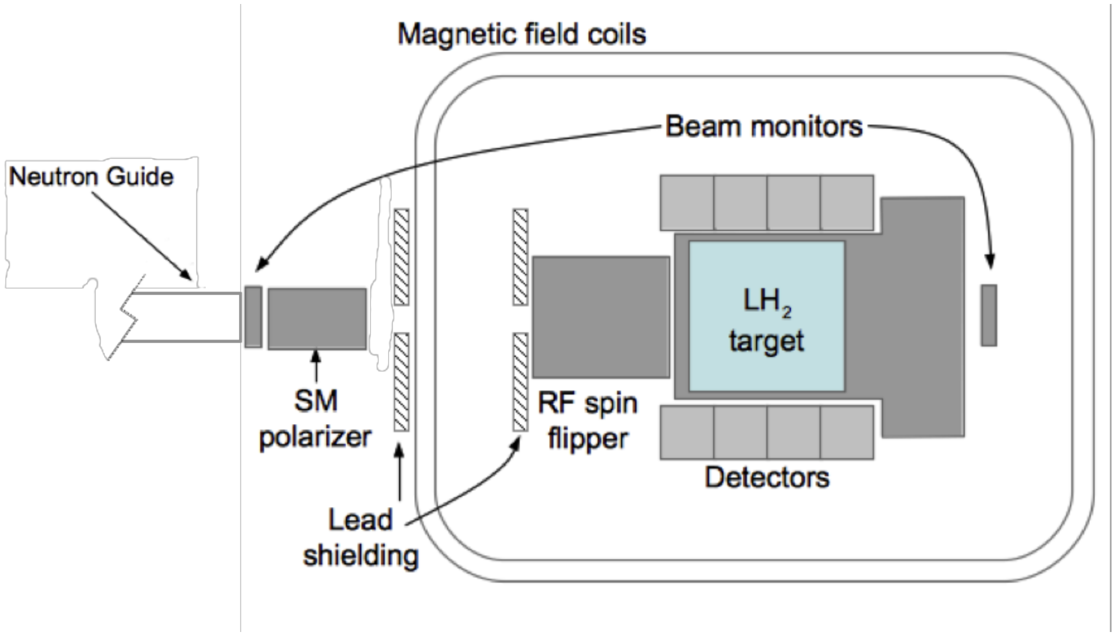

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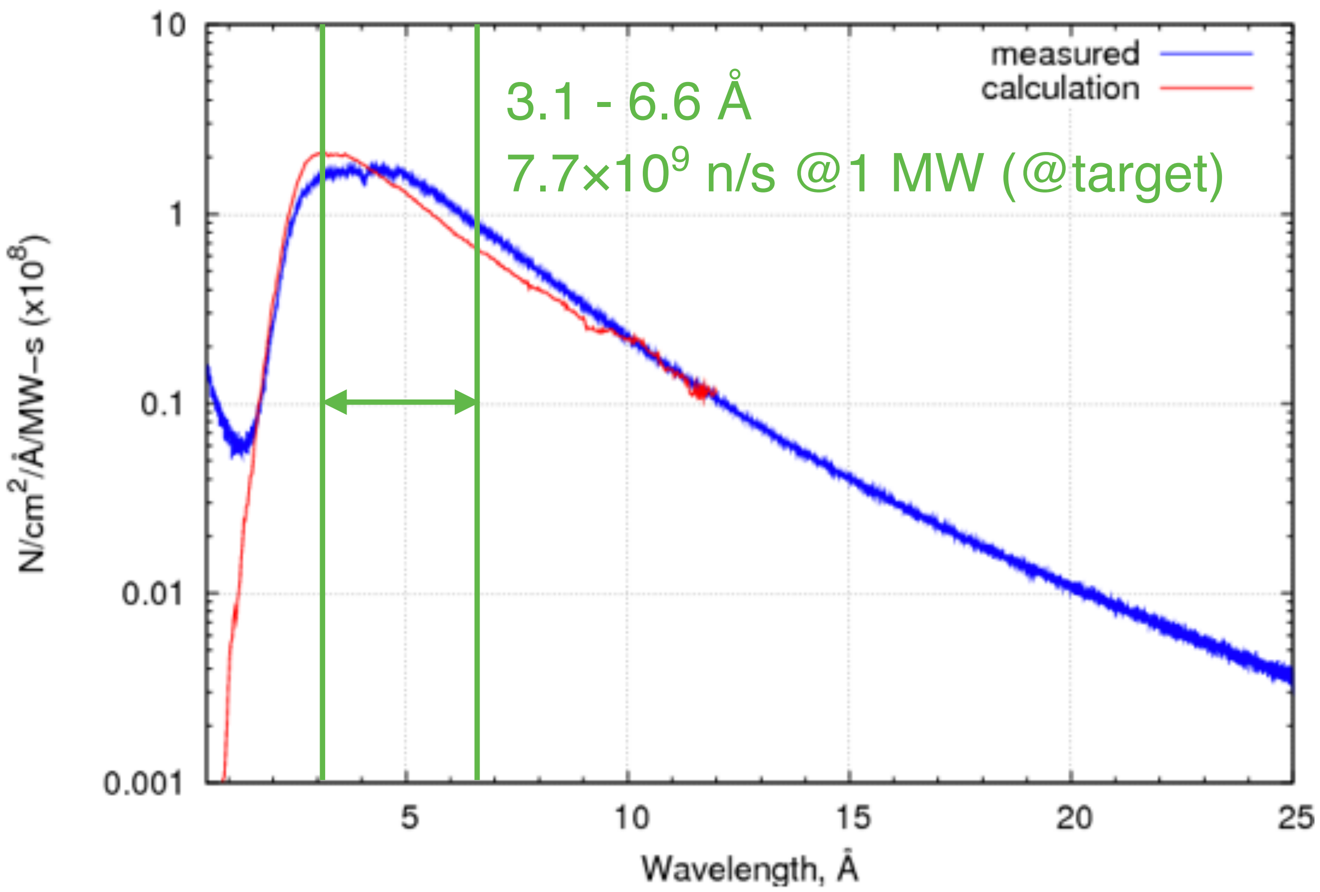

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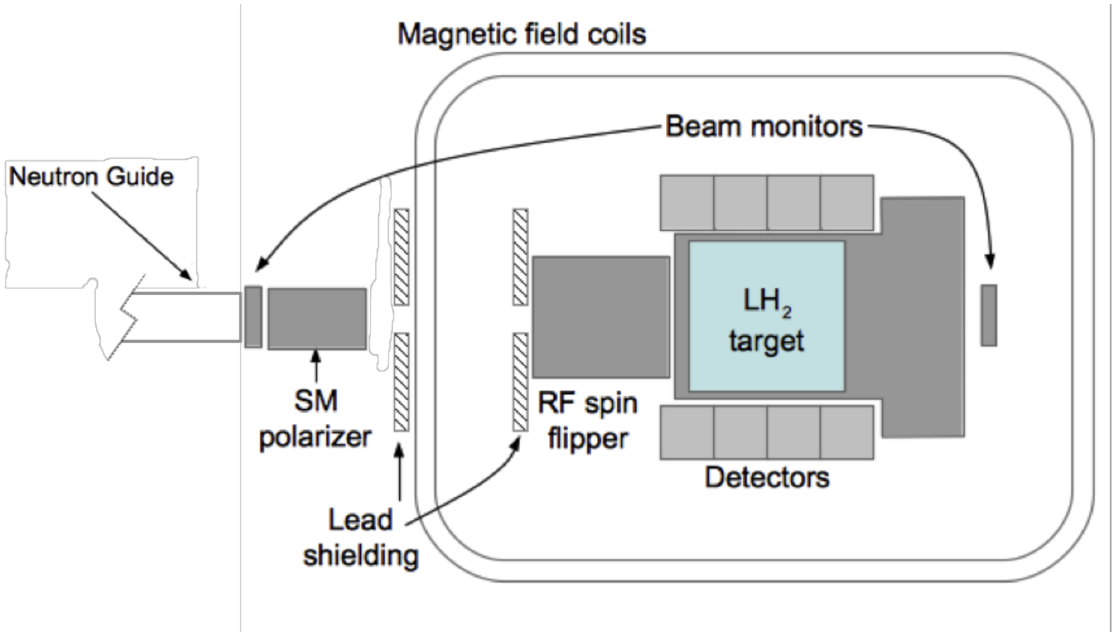

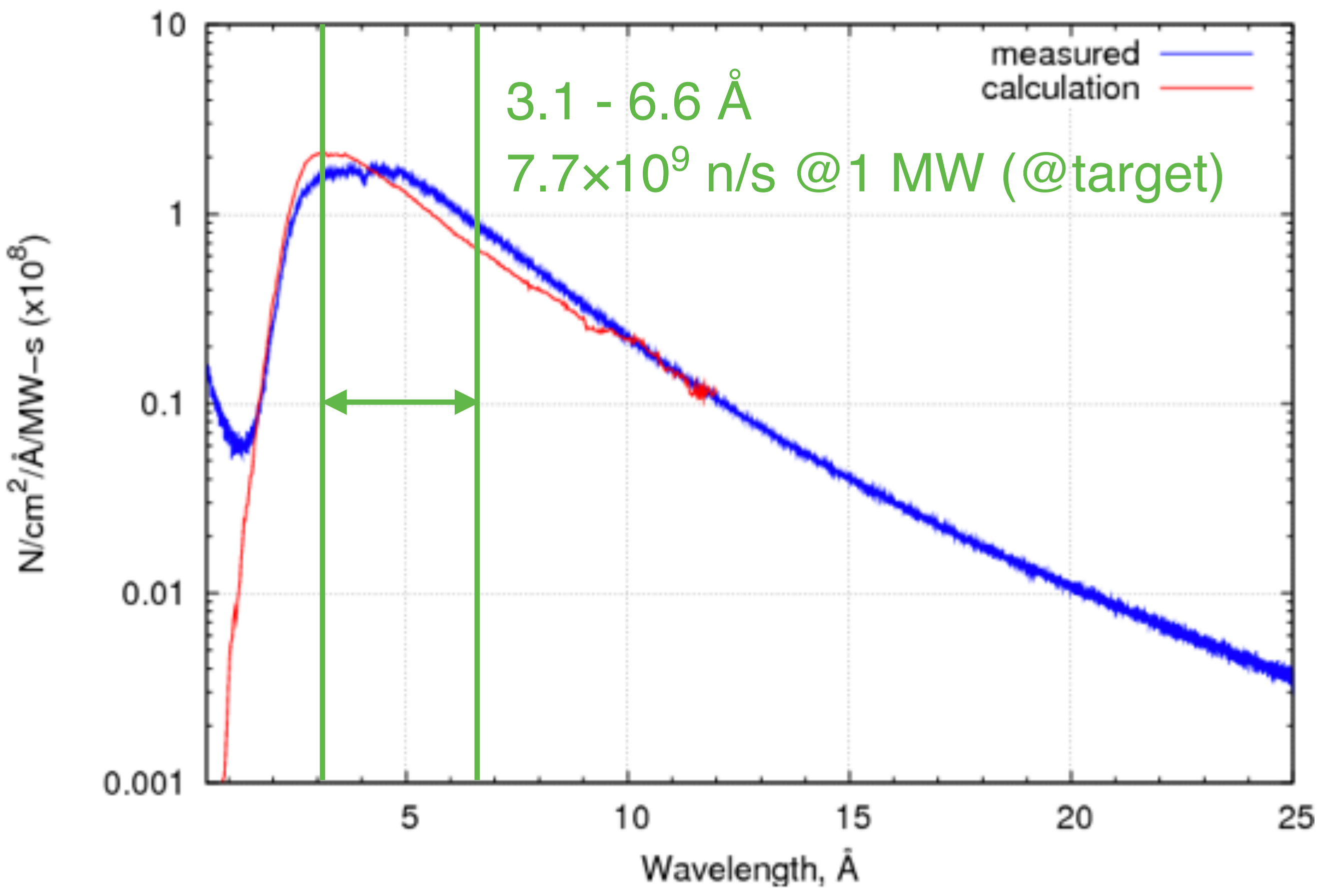

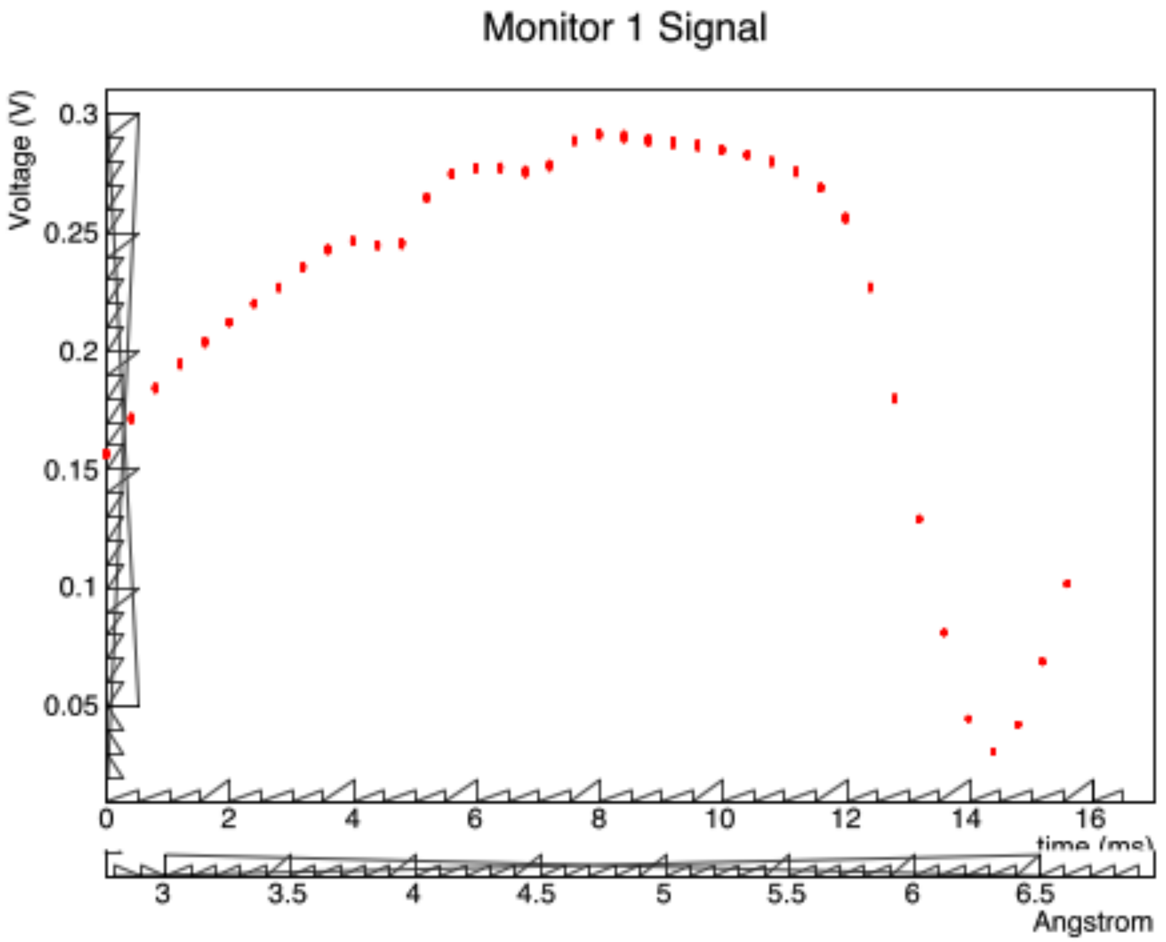

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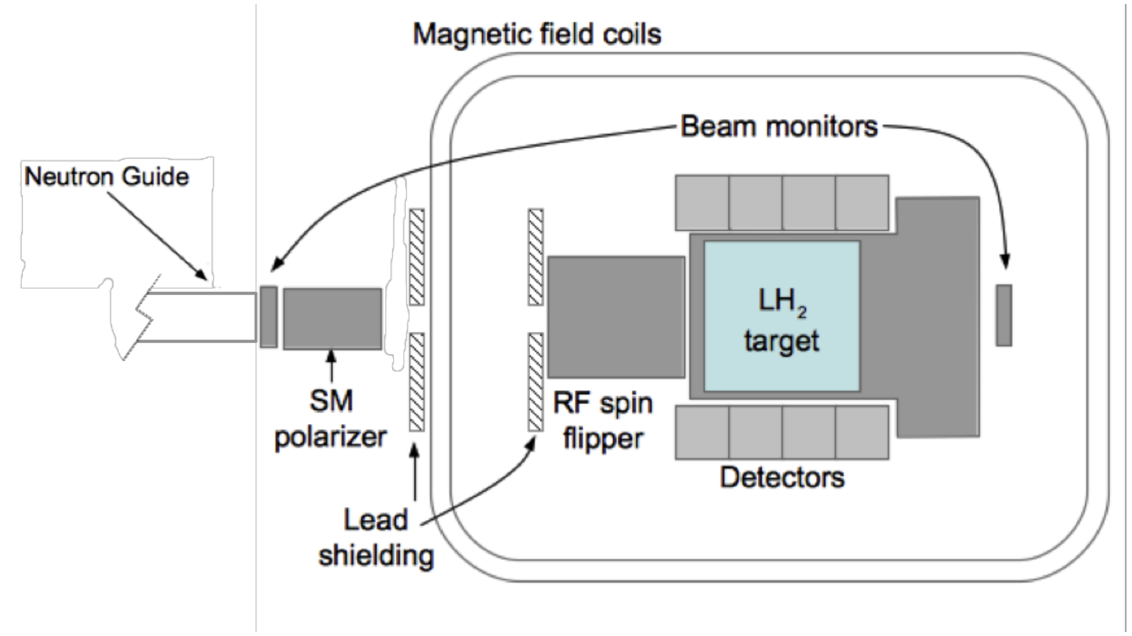

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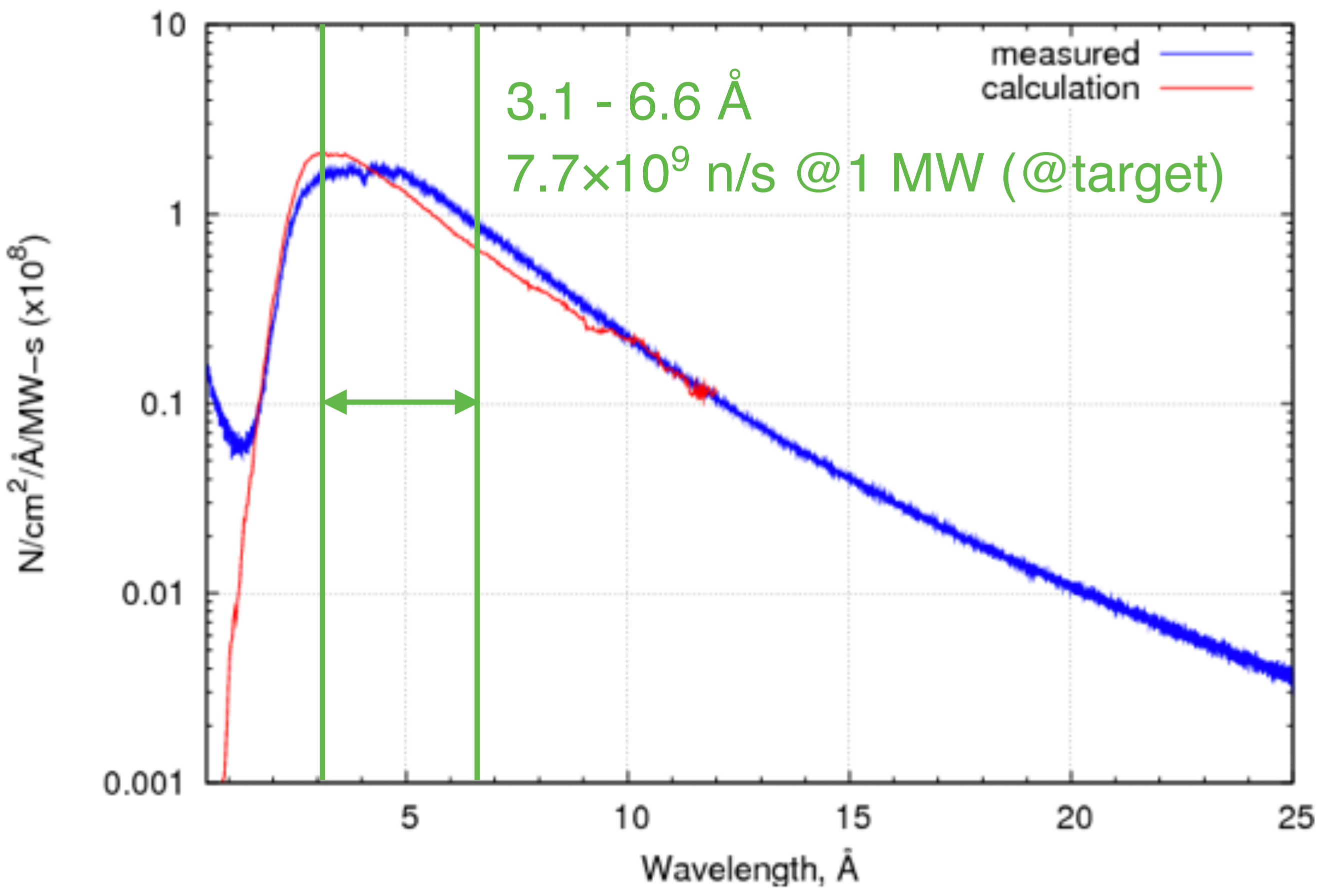

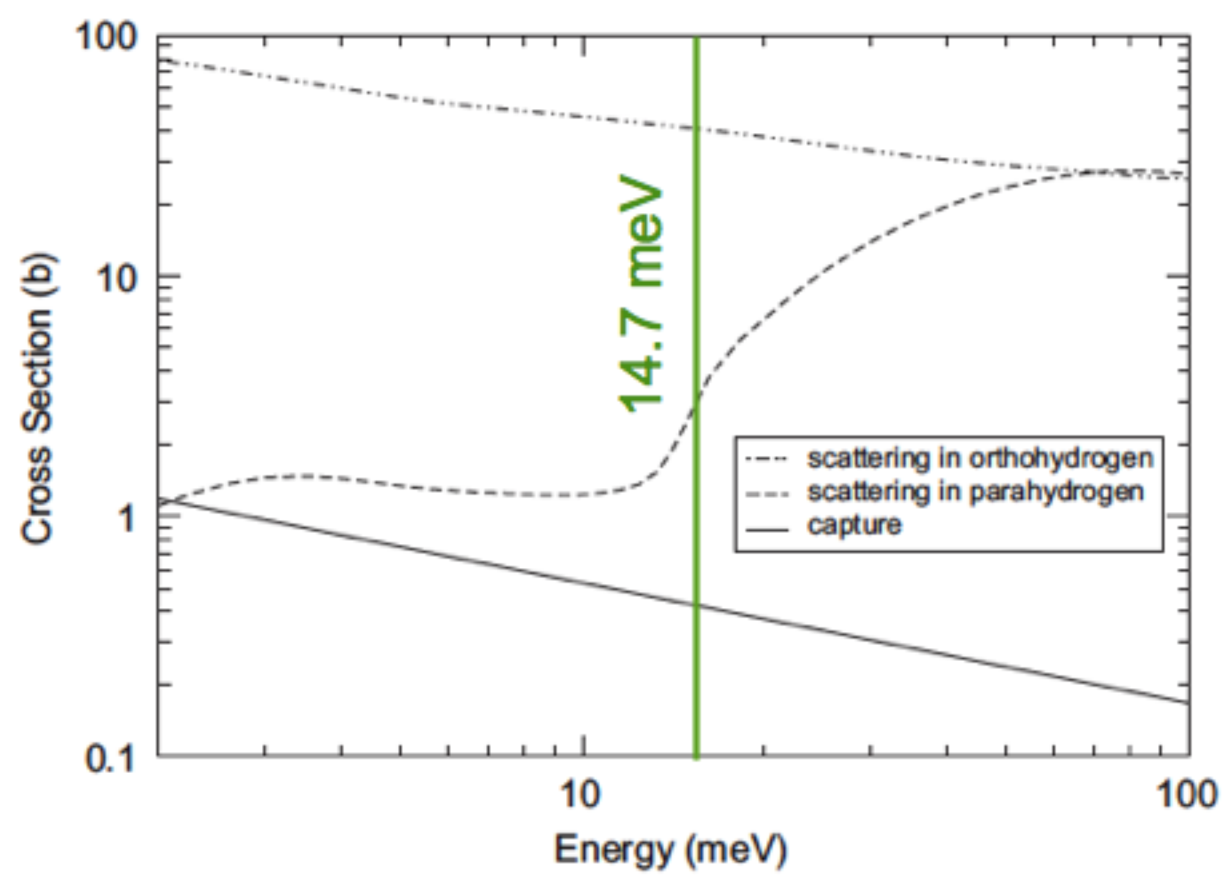

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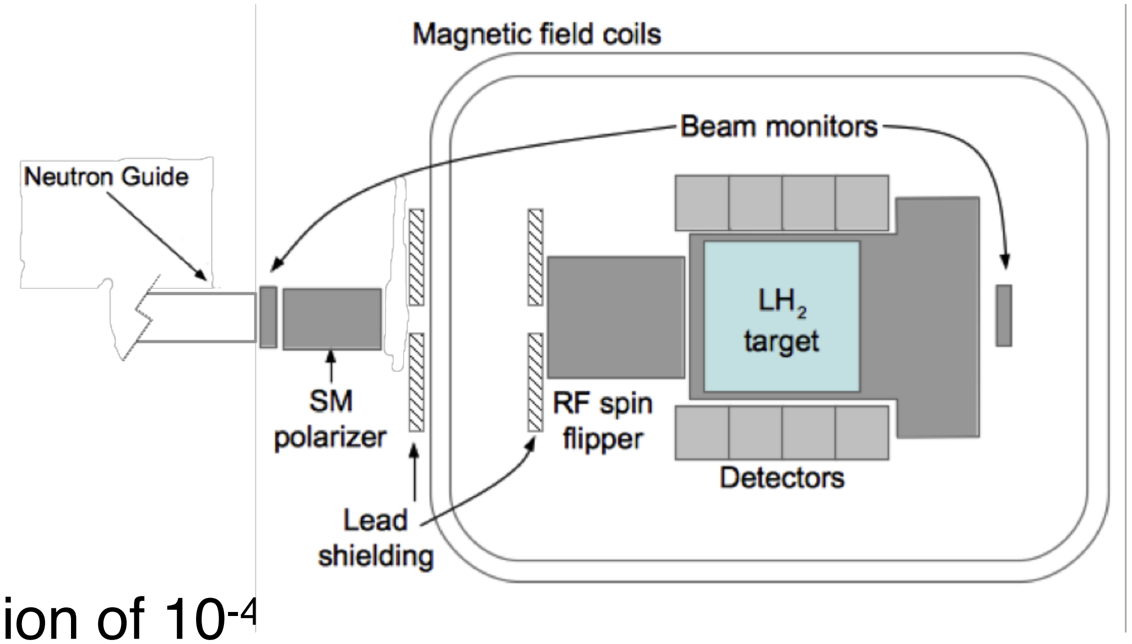
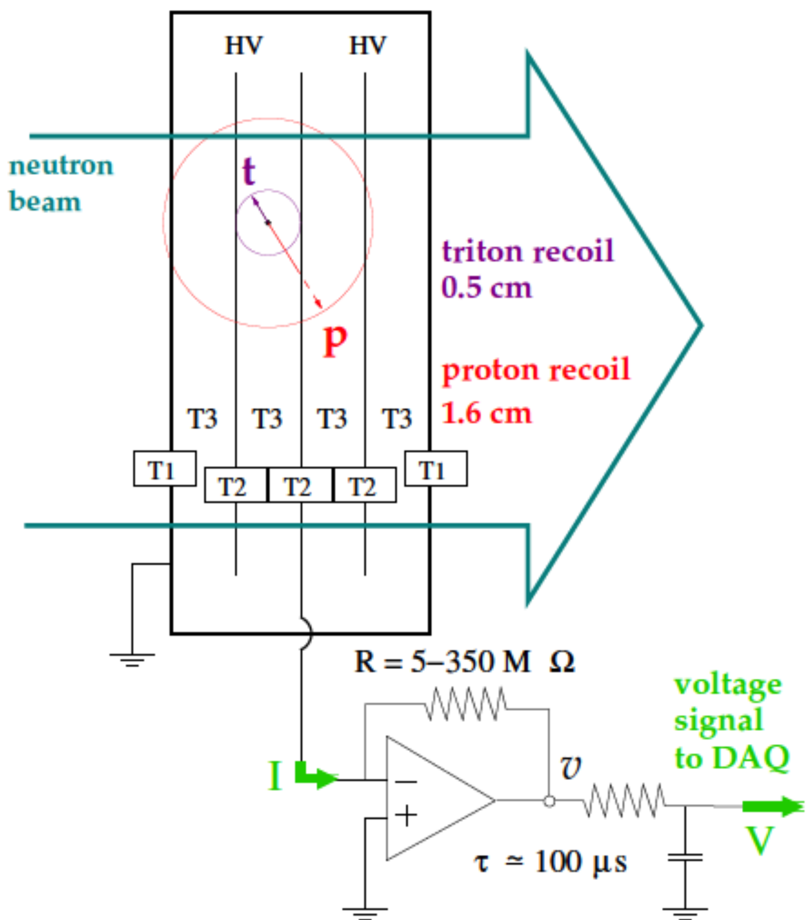
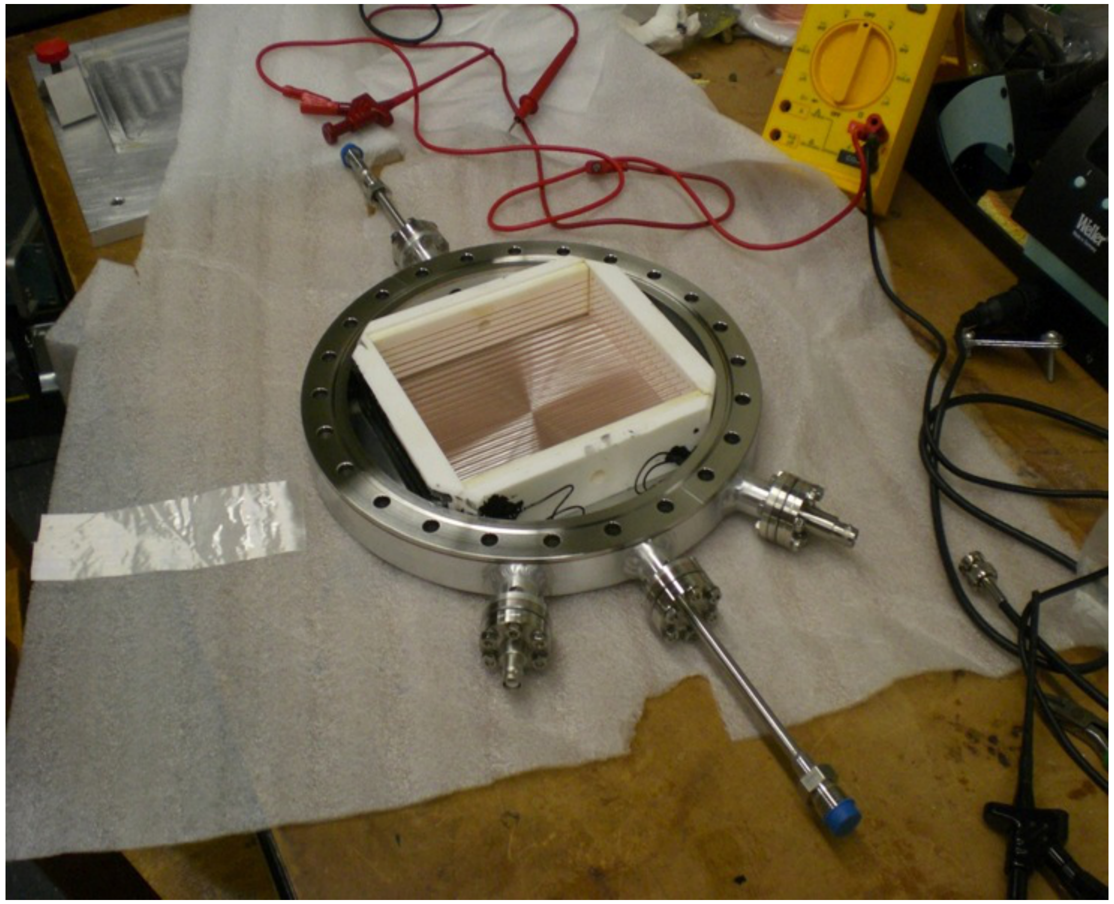


Beam monitors

- Ionization chamber with N_2 and some ^3He (1-2%)
- About 1% of the neutrons are absorbed
- Number of neutron per pulse determined to a precision of 10^{-4}





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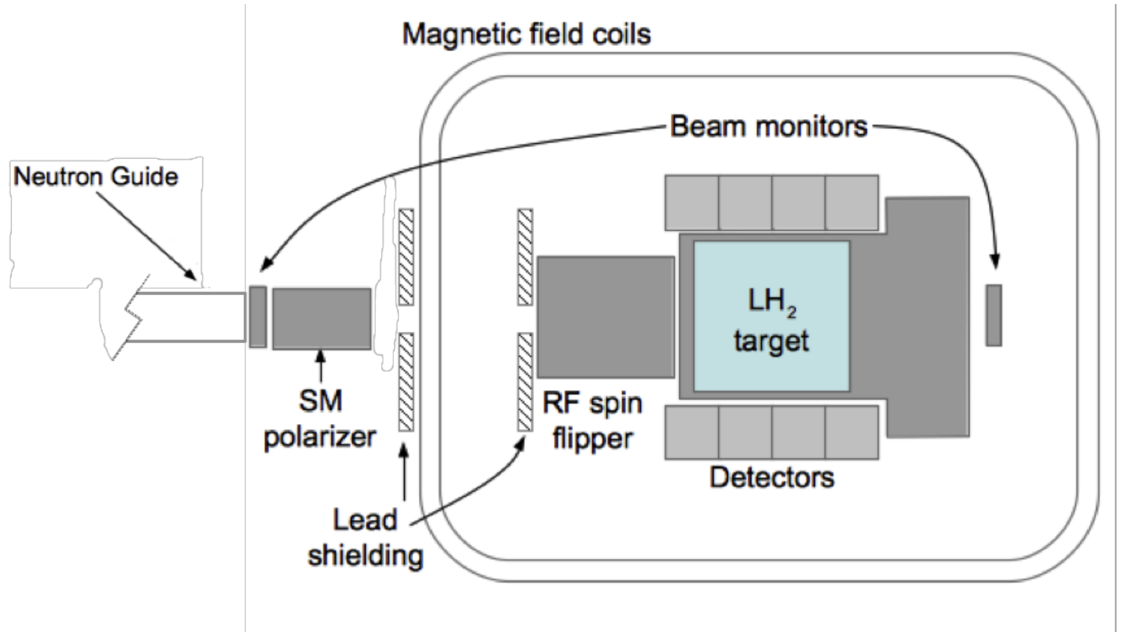
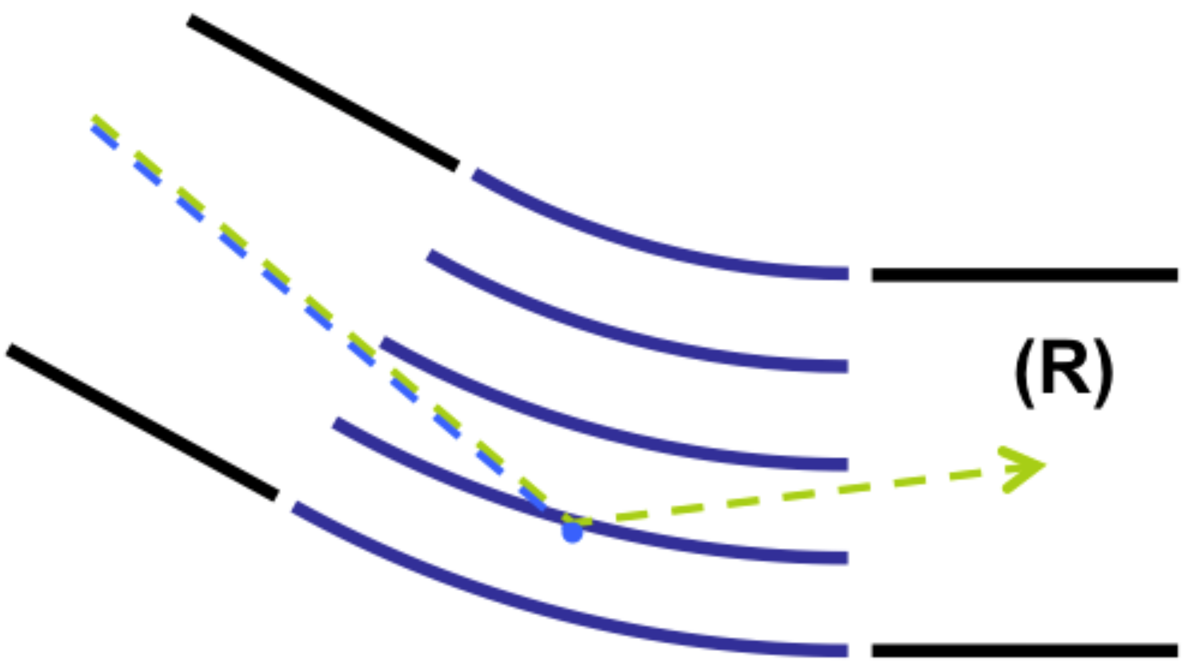


Super Mirror (SM) polarizer

- Magnetized Fe/Si SM
- Scattering length ***b***±***p***, with ***p*** the magnetic component

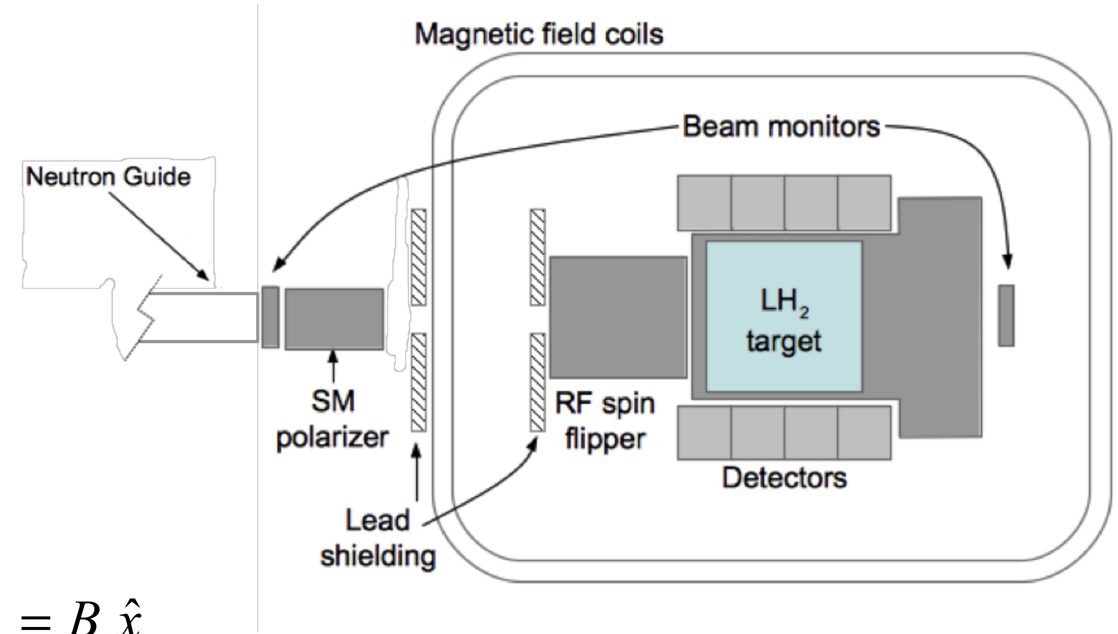


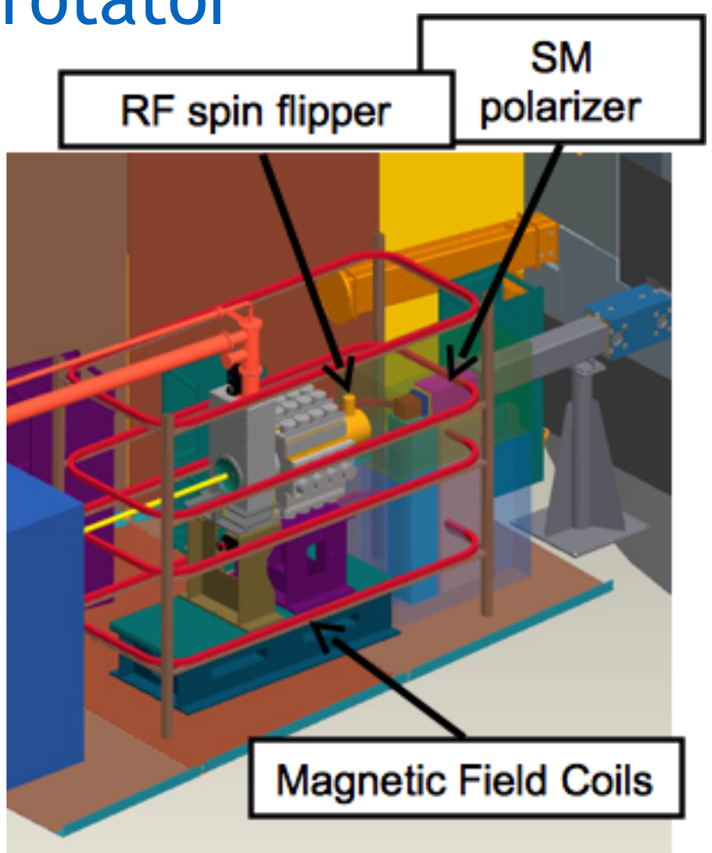
Fe/Si on boron float glass, no Gd

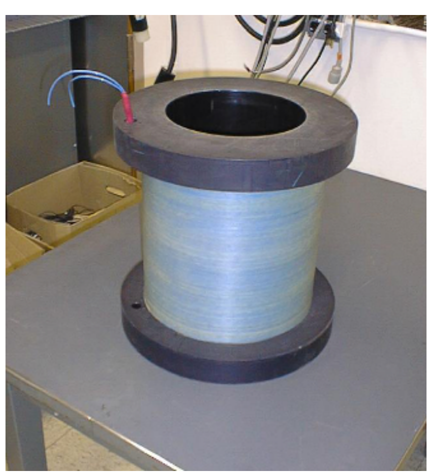
m=3.0	critical angle
n=45	channels
R=9.6 m	radius of curvature
L=40 cm	length
d=0.3mm	vane thickness
T=25.8%	transmission
P=95.3%	polarization
$N=2.2\times10^{10}$ n/s	output flux (chopped)

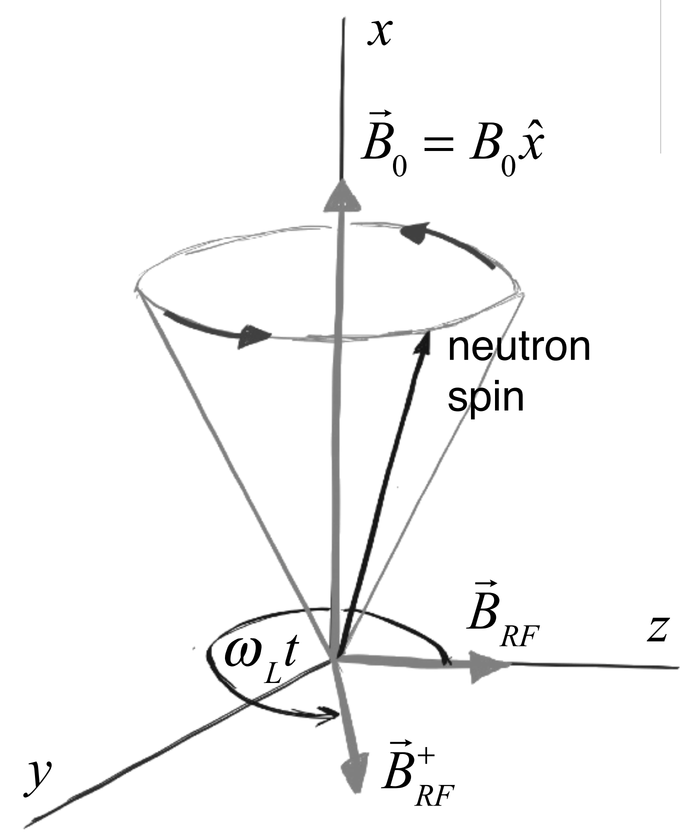
The experiment

Holding magnetic field and RF spin rotator





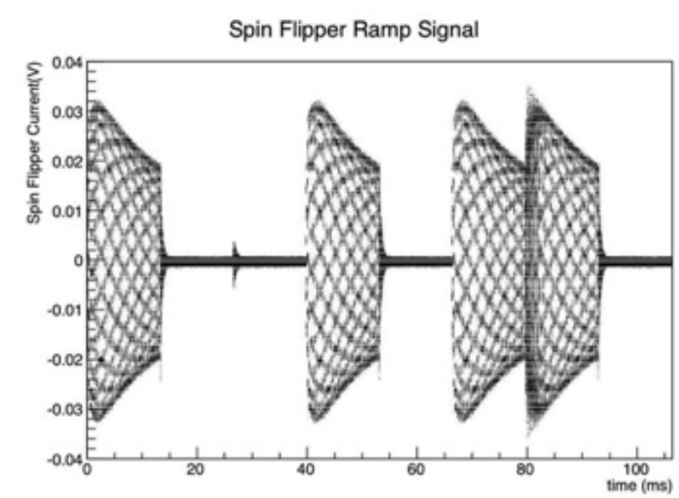




$$\vec{B}_{RF} = B_1\hat{z}\cos(\omega_L t) = \vec{B}^+_{RF} + \vec{B}^-_{RF}$$

$$\vec{B}^{\pm}_{RF} = \frac{B_1}{2}[\hat{z}\cos(\pm\omega_L t) - \hat{y}\sin(\pm\omega_L t)]$$

$$B_1 = \frac{n\pi\hbar}{\mu_n}\frac{1}{L}\frac{1}{t_{tof}}$$

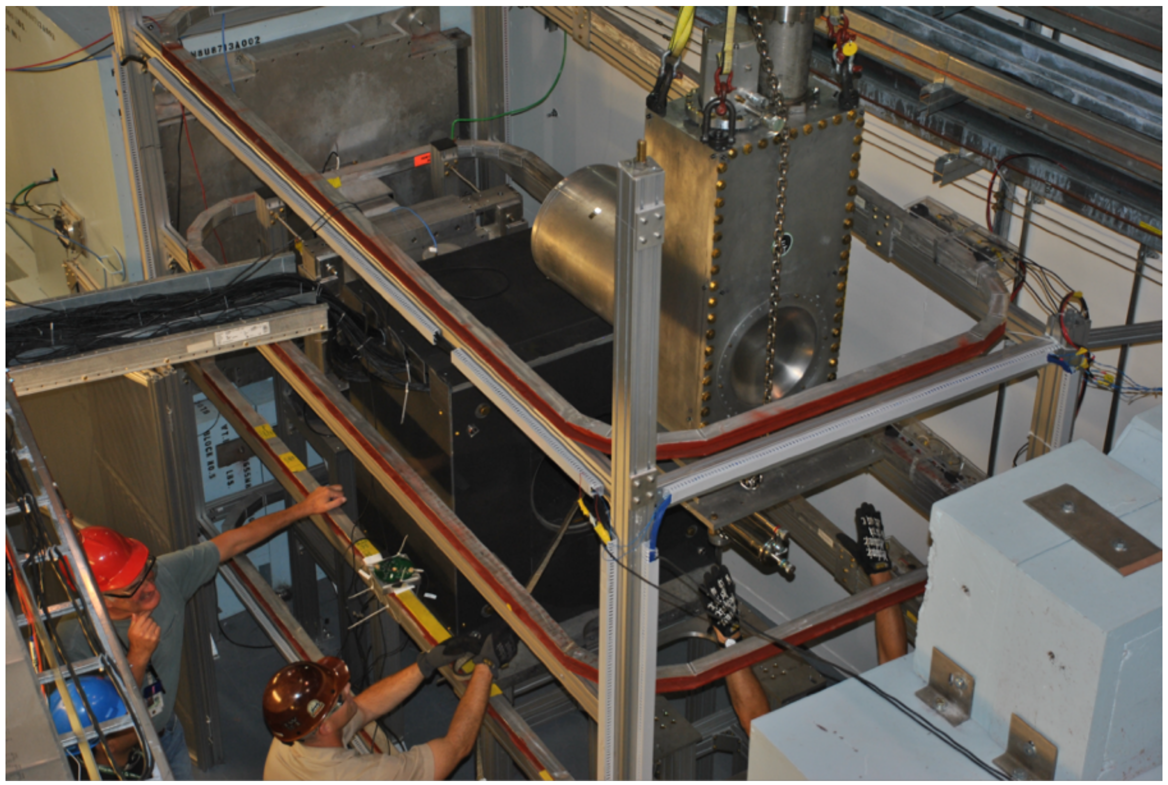


↓↑↑↓↑↓↓↑↑↓↓↑↓↑↑↓

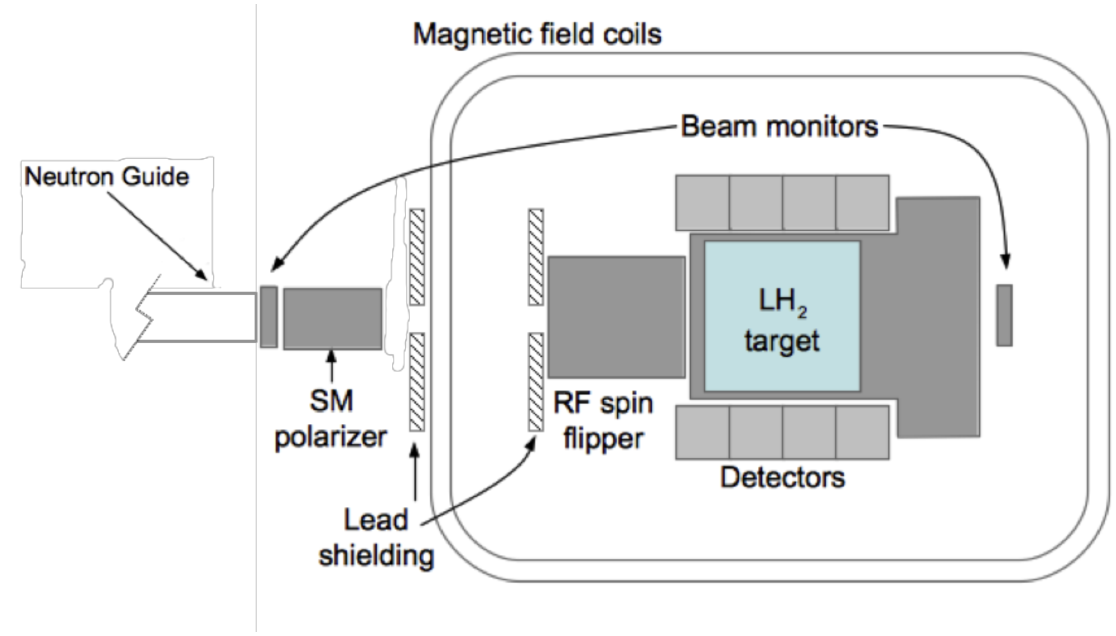
Seo et al., *Phys. Rev. ST AB* 11, 084701 (2008)

The experiment

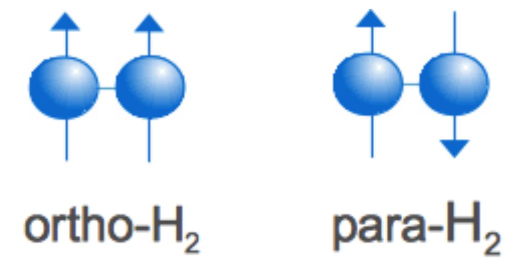
LH_2 target

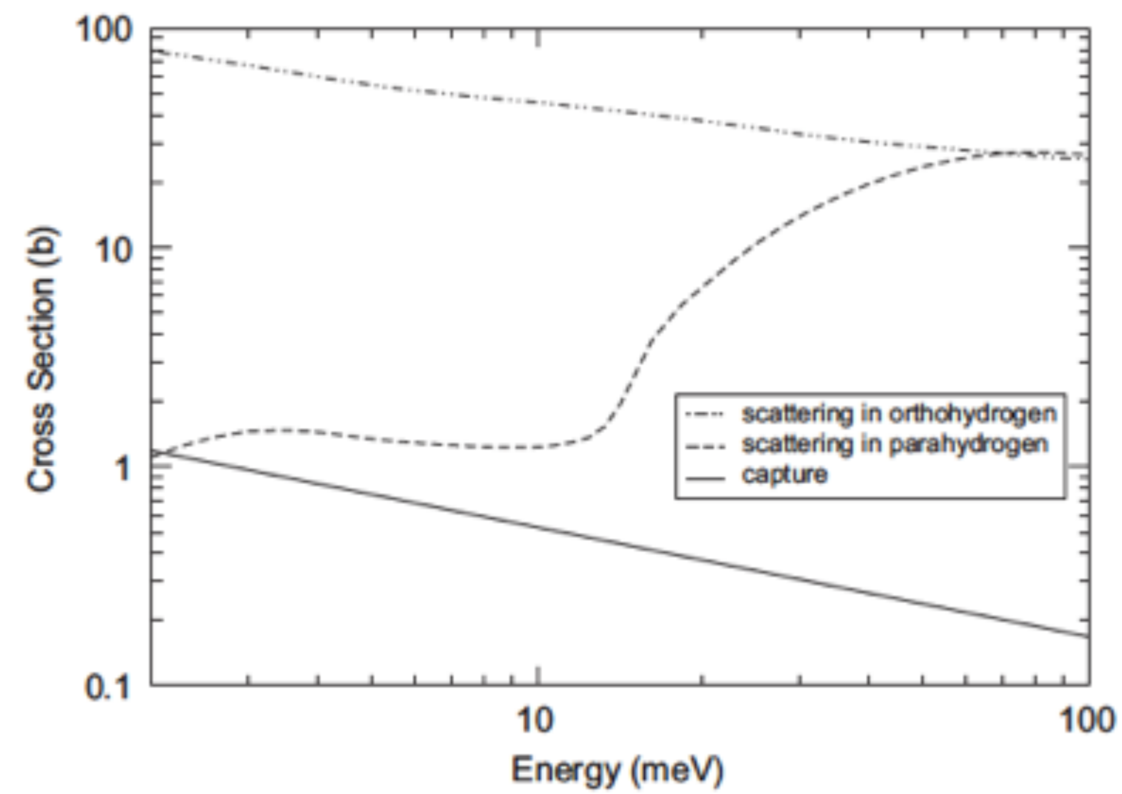


Santra et al., *Nucl. Instrum. and Meth. A* 620, 421 (2010)



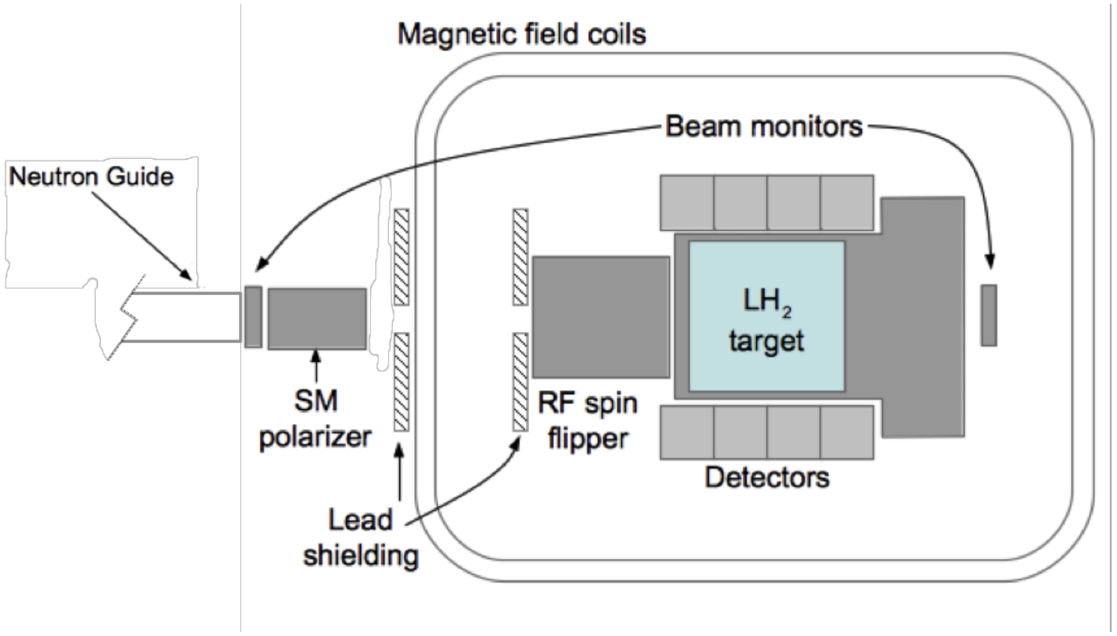
$f_{\text{ortho-H}_2} < 0.0015$



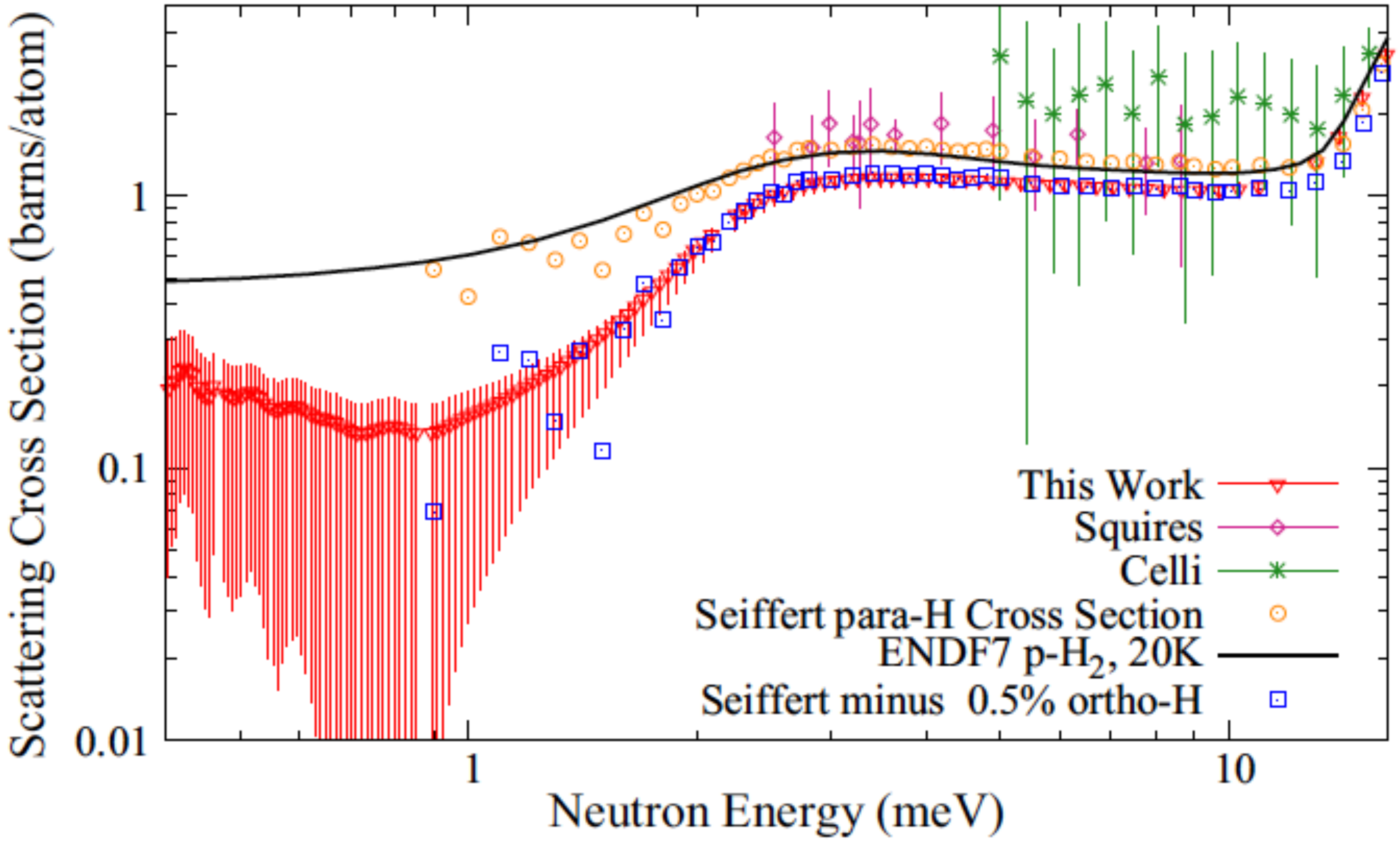


The experiment

LH_2 target



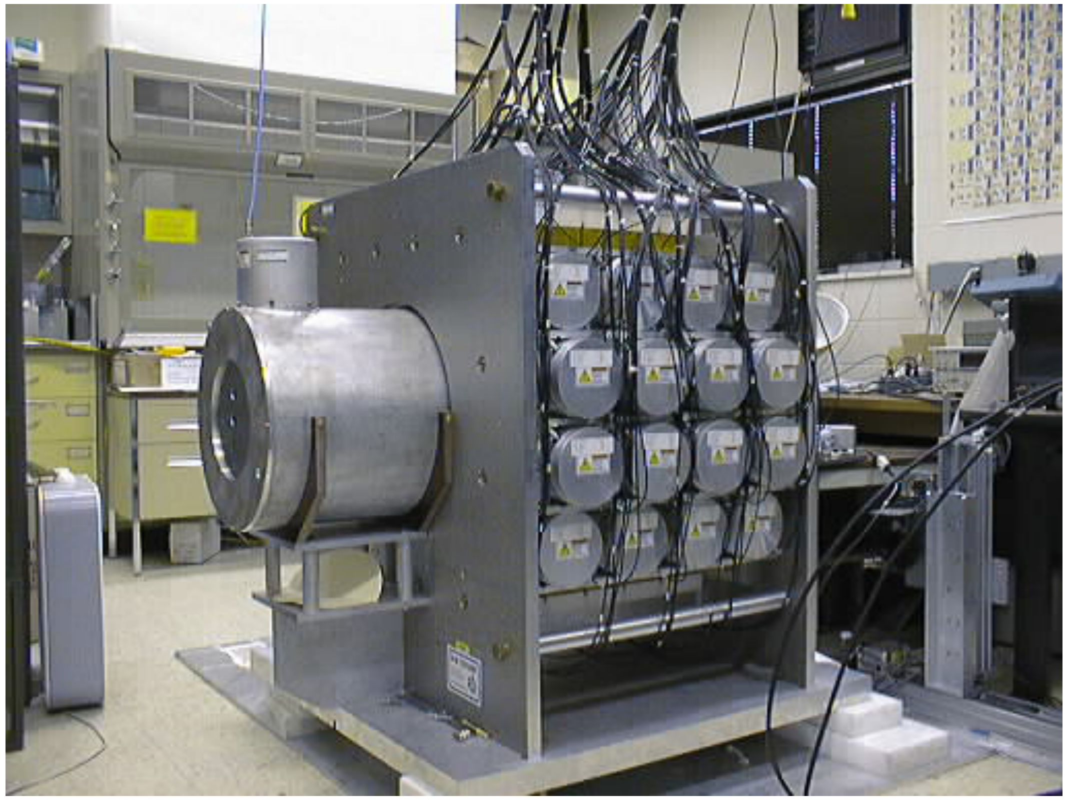
Scattering cross section of neutrons on para-H_2

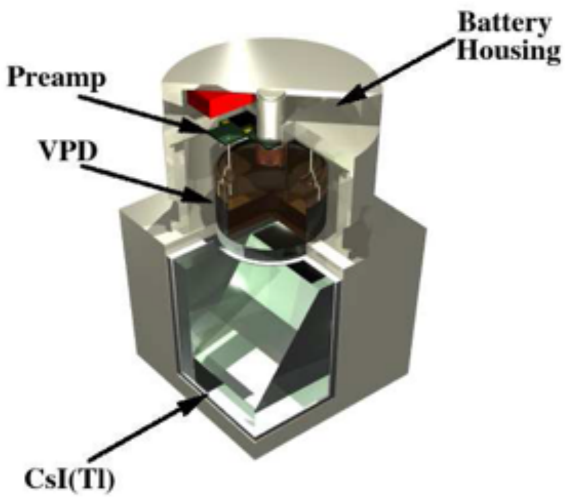


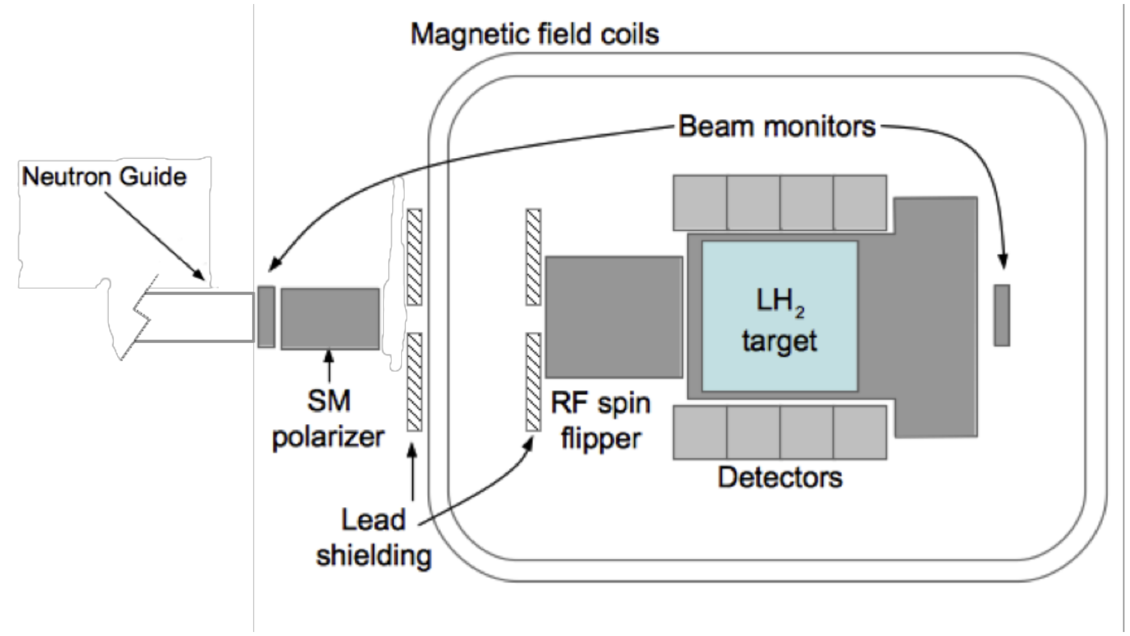
Grammer et al., *Phys. Rev. B* 91, 180301(R) (2015)

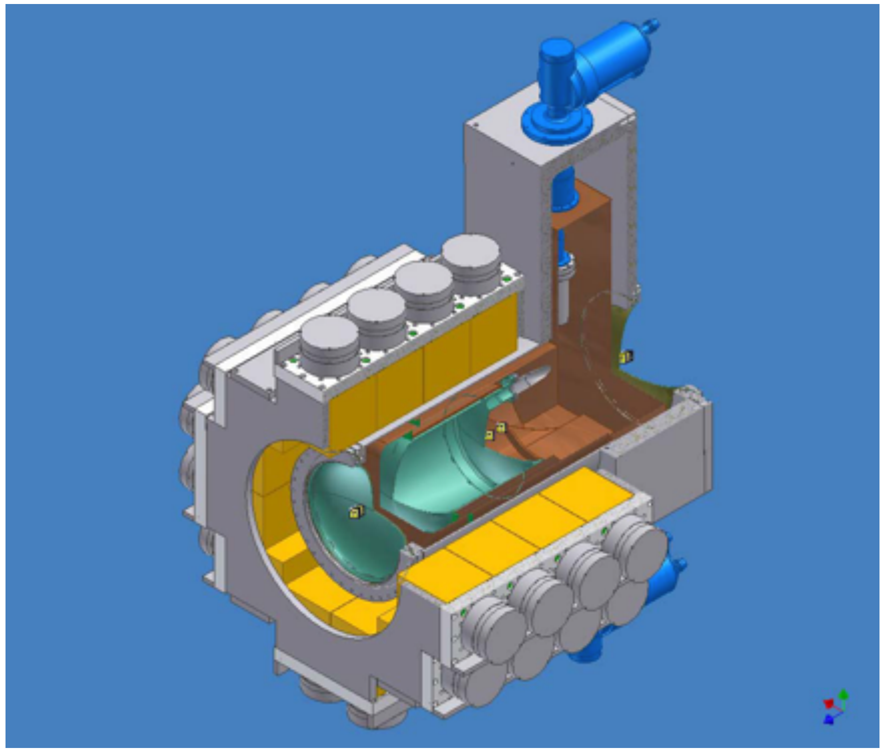
The experiment

Gamma-ray detector



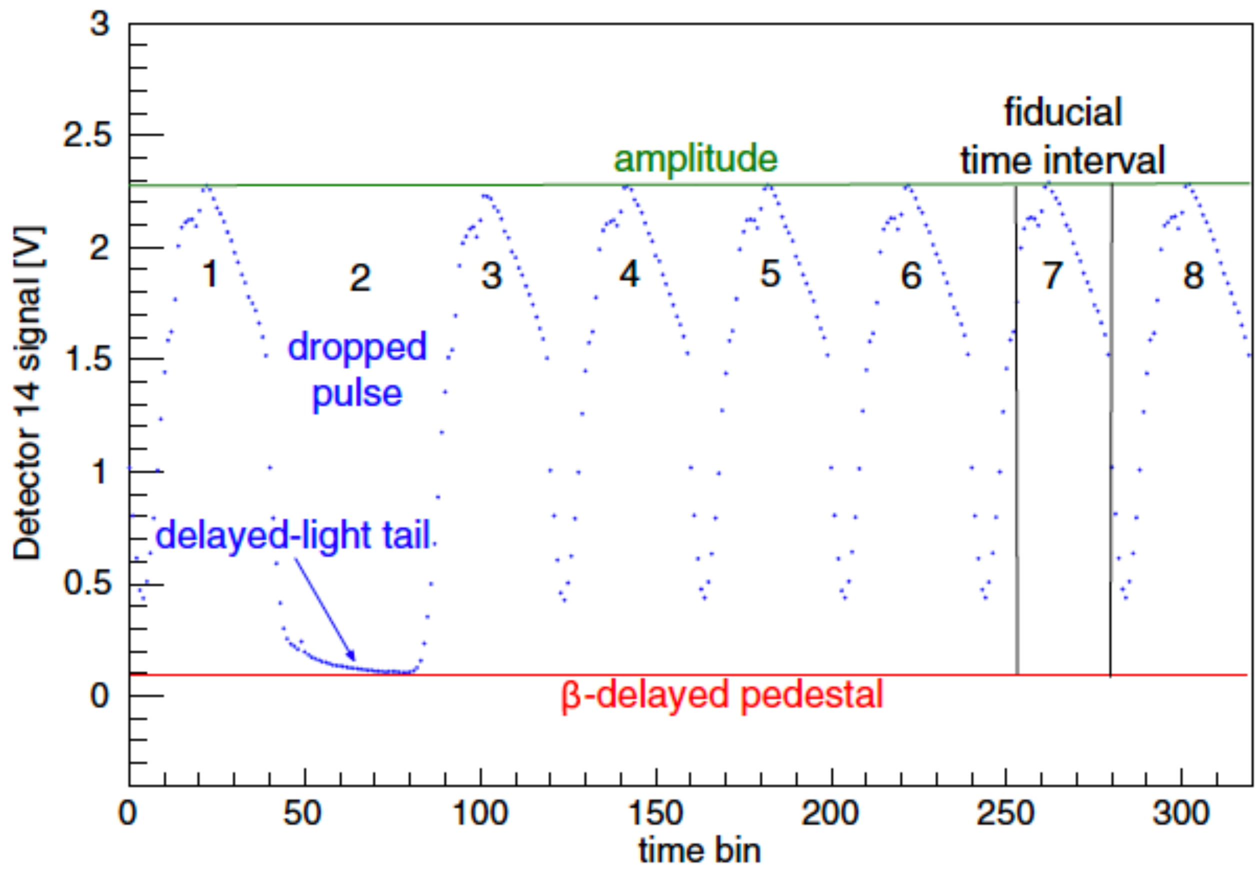






- 48 CsI detectors
- 3π acceptance
- current mode operation ($\sim 10^8$ Hz)

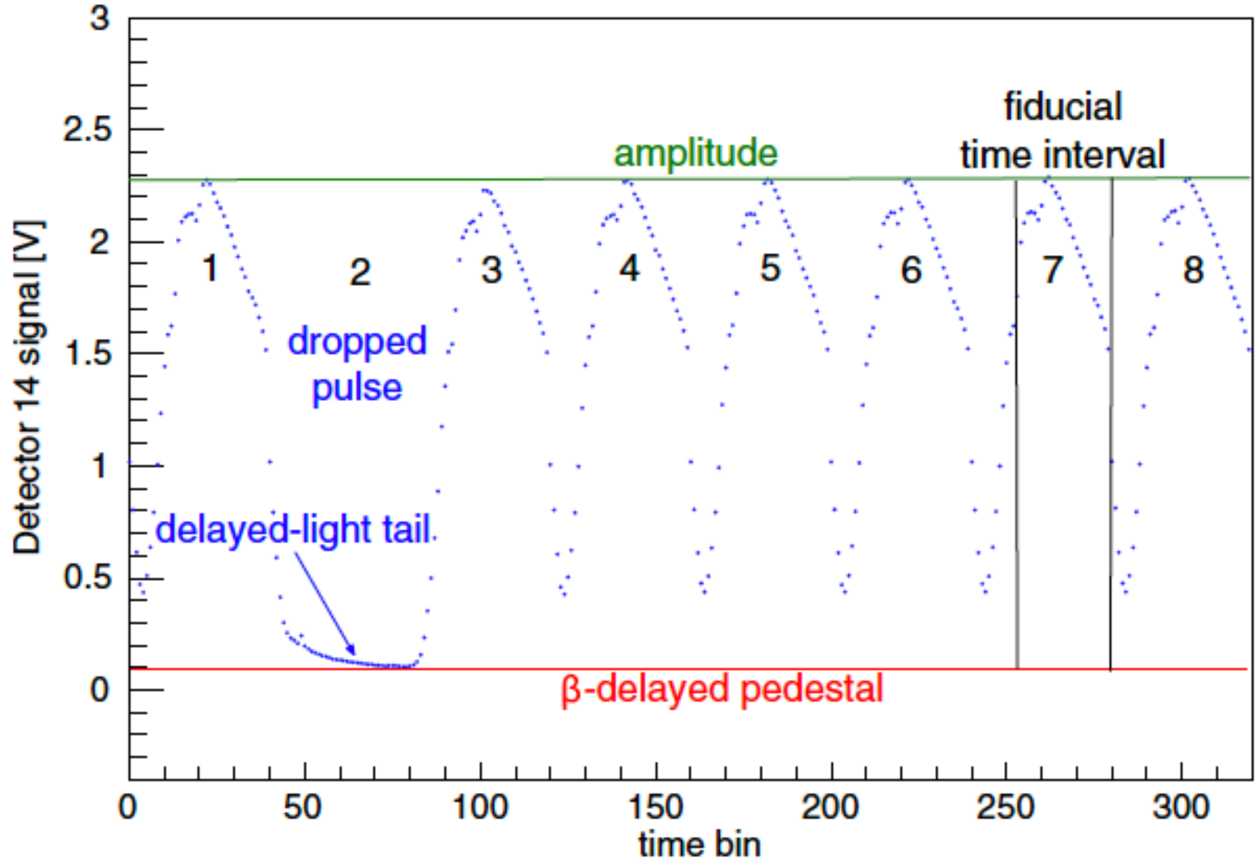
Data and cuts

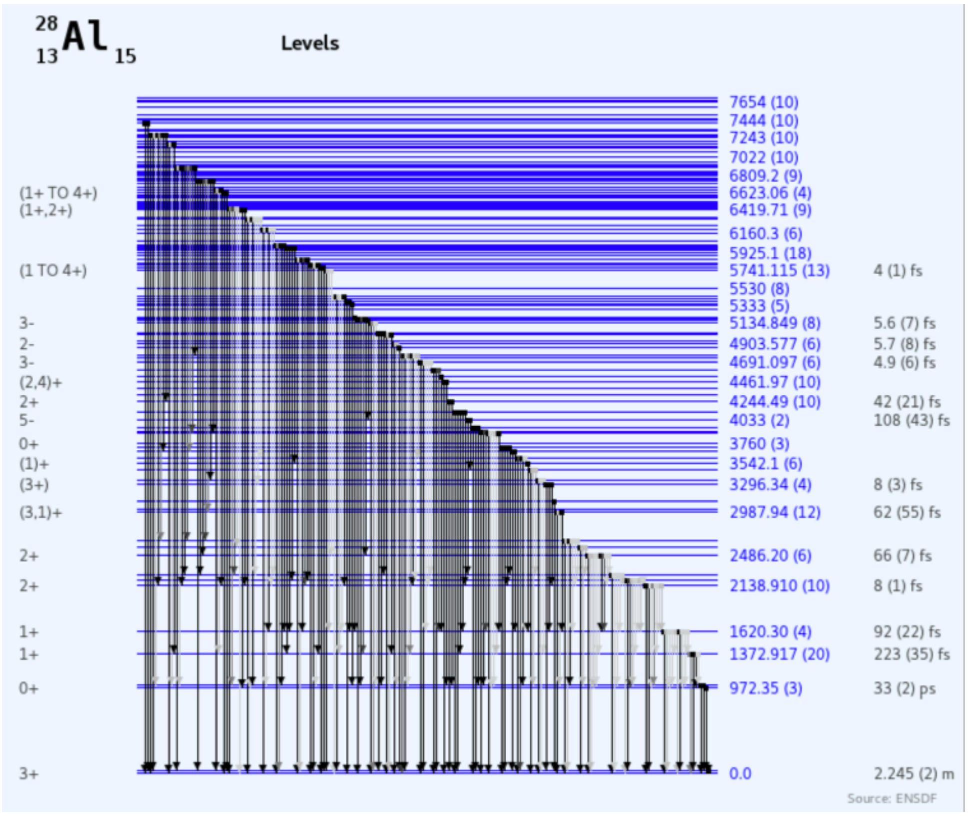


- 80% of γ's from capture on hydrogen
- 20% of γ's from capture on aluminum

Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

Data and cuts





Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

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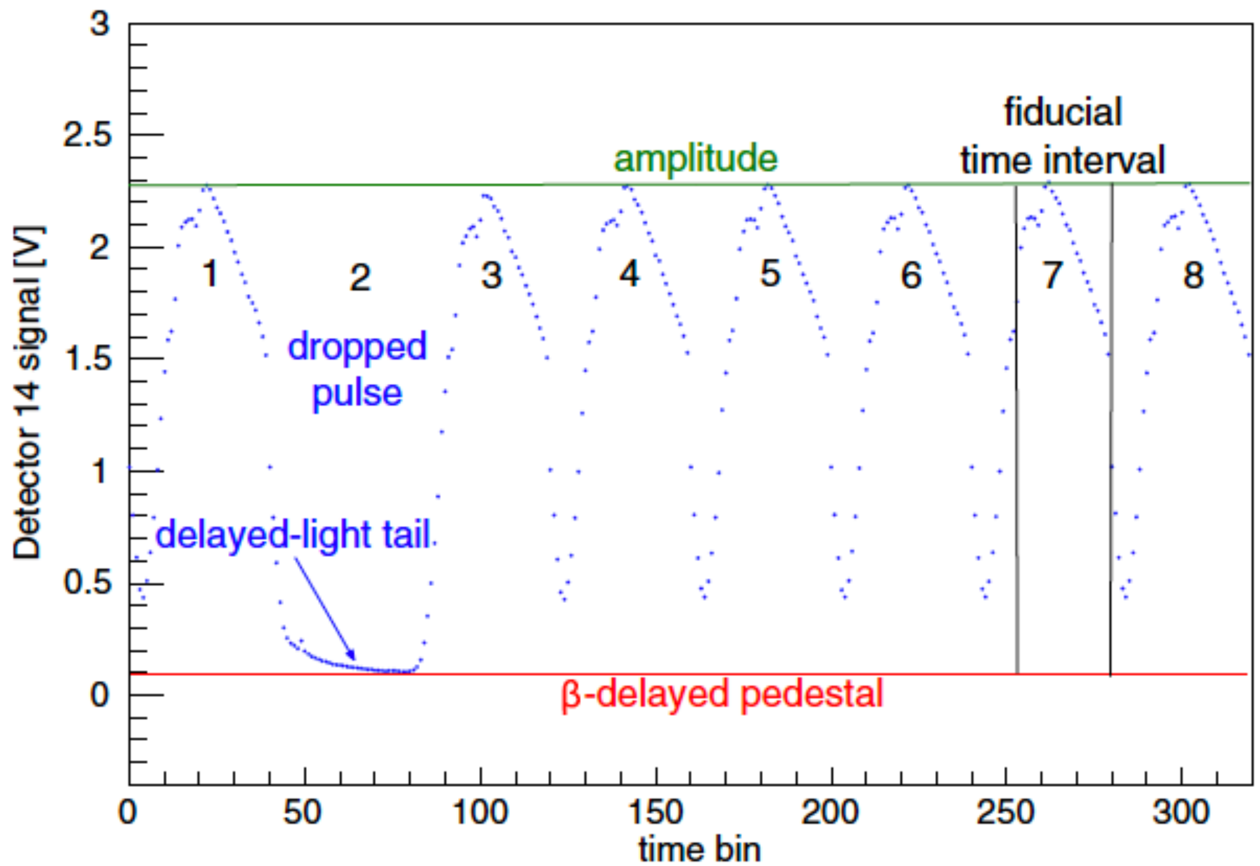
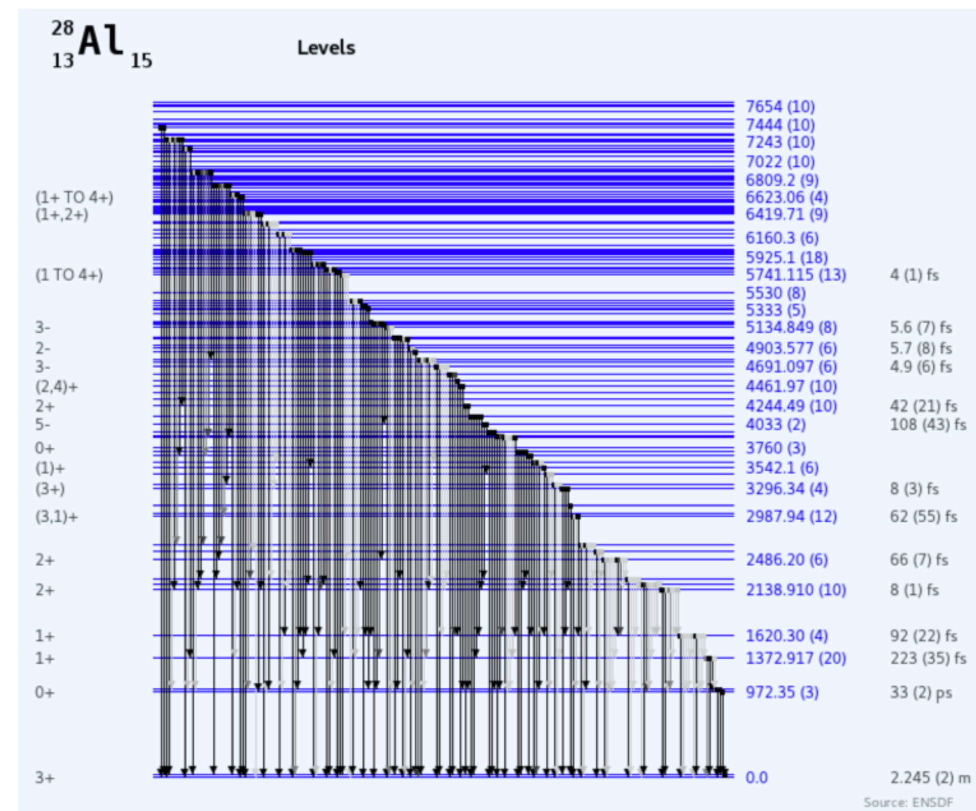
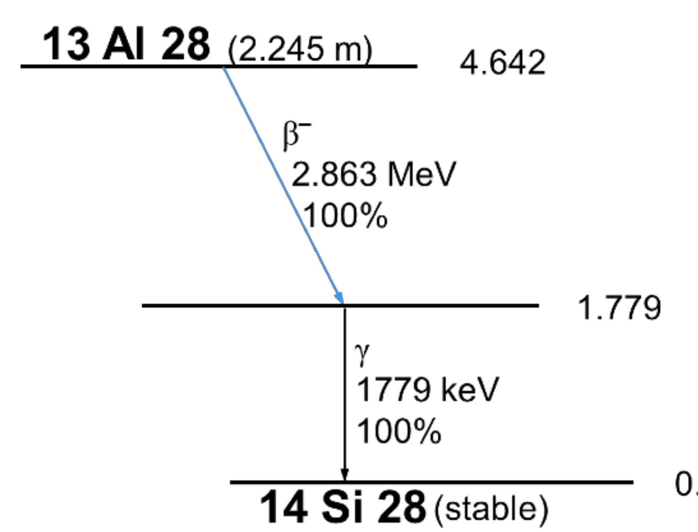
Data and cuts

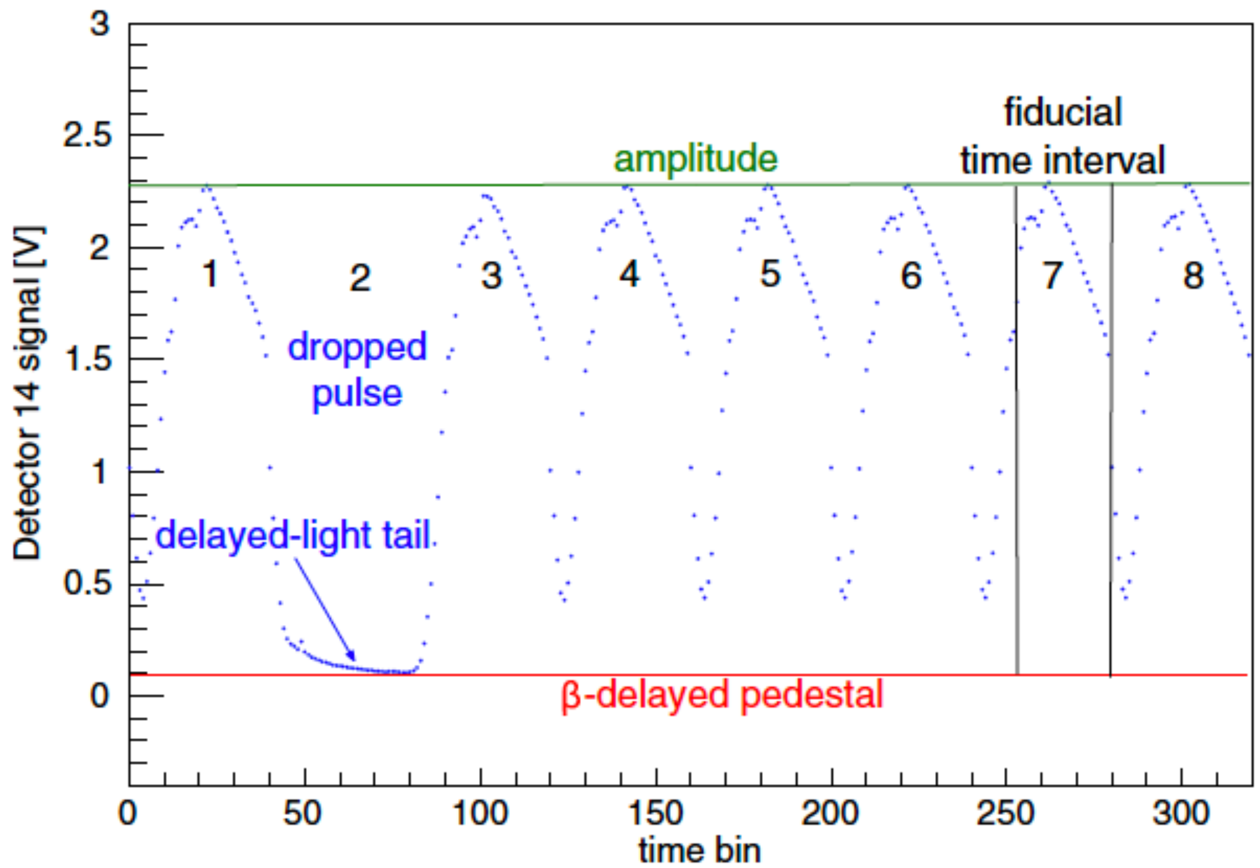






Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

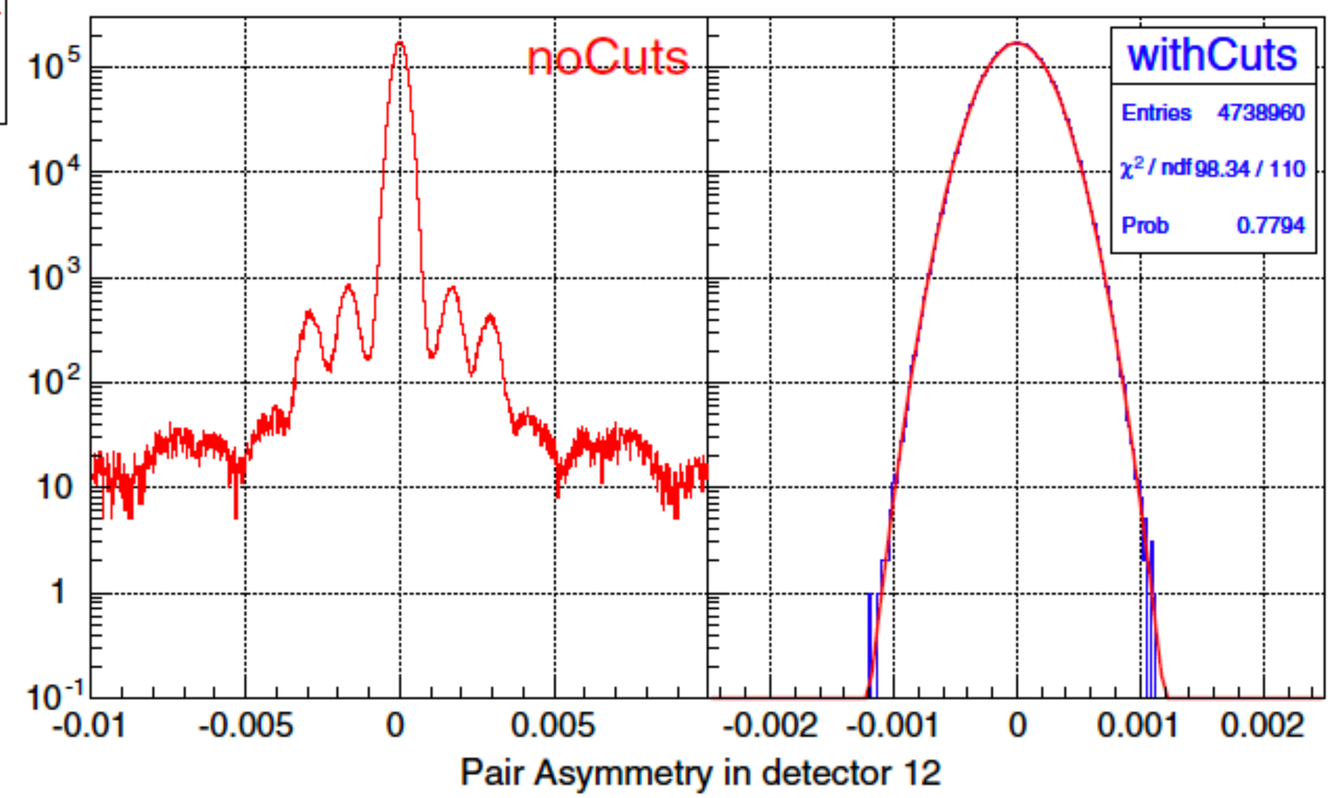
Data and cuts



- 80% of γ's from capture on hydrogen
- 20% of γ's from capture on aluminum

- 20% of the SS were eliminated:
  unstable beam power * -
  improper chopper phasing -
  RFSF errors -

*accounts for almost all eliminated data



Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

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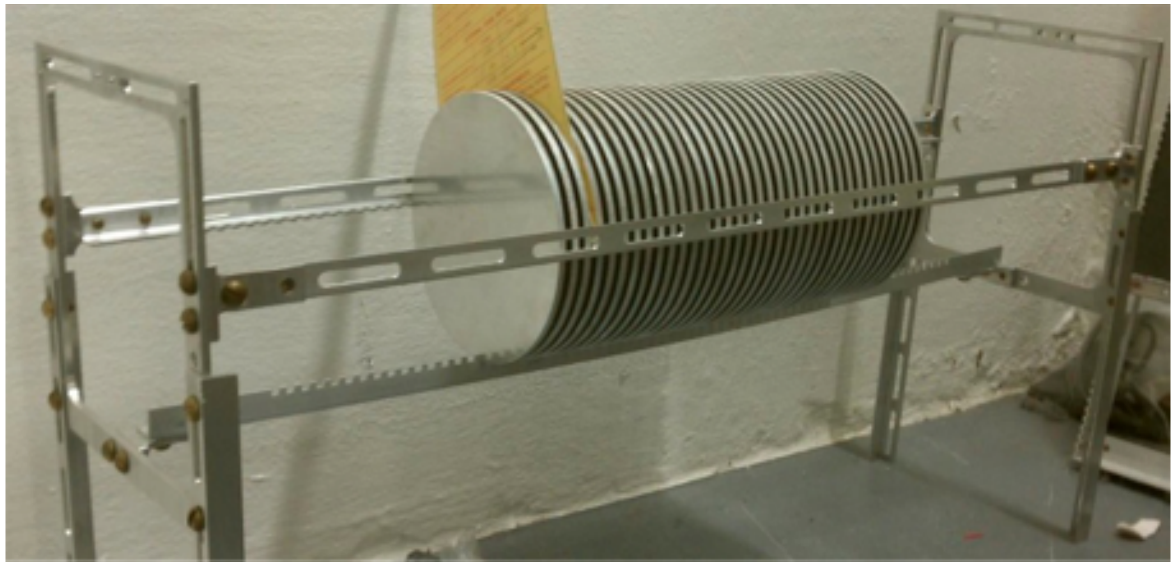
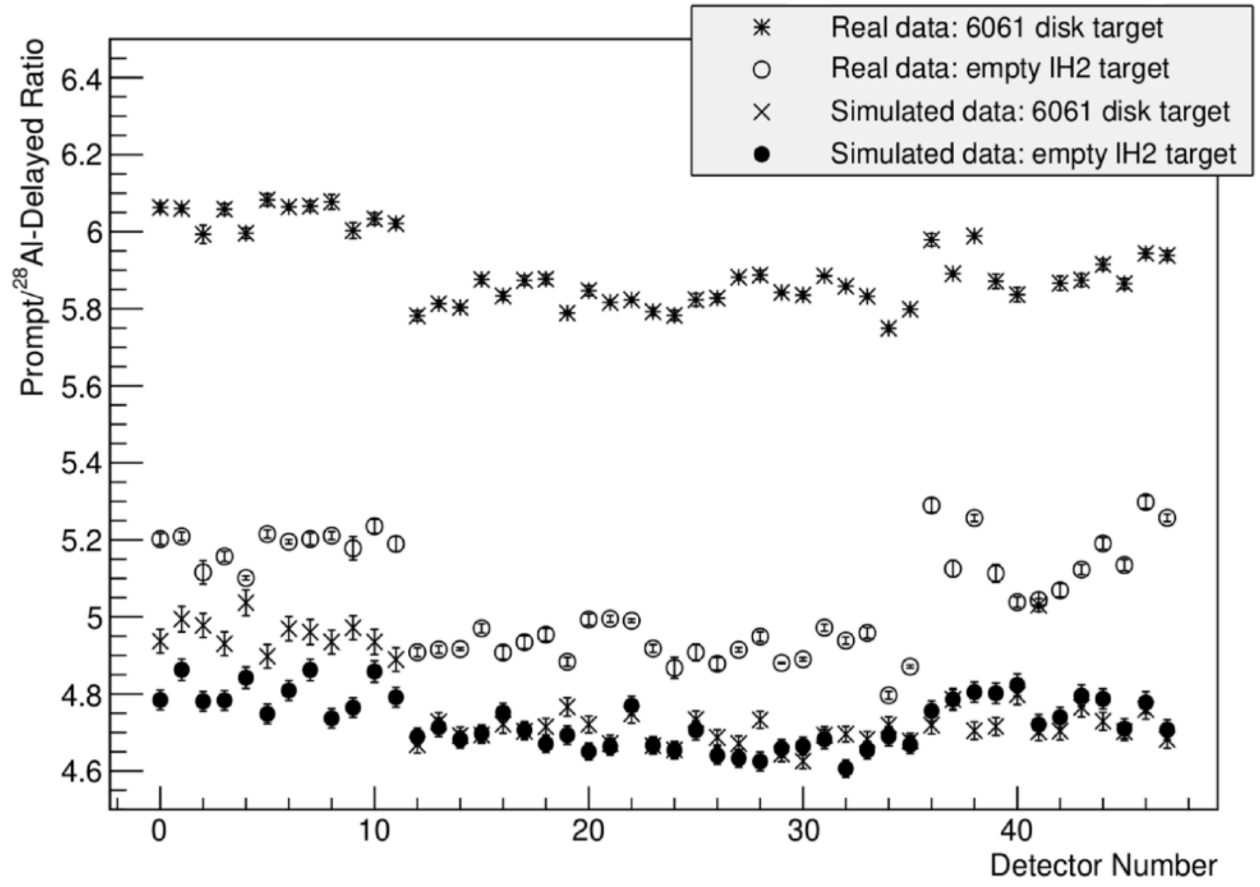
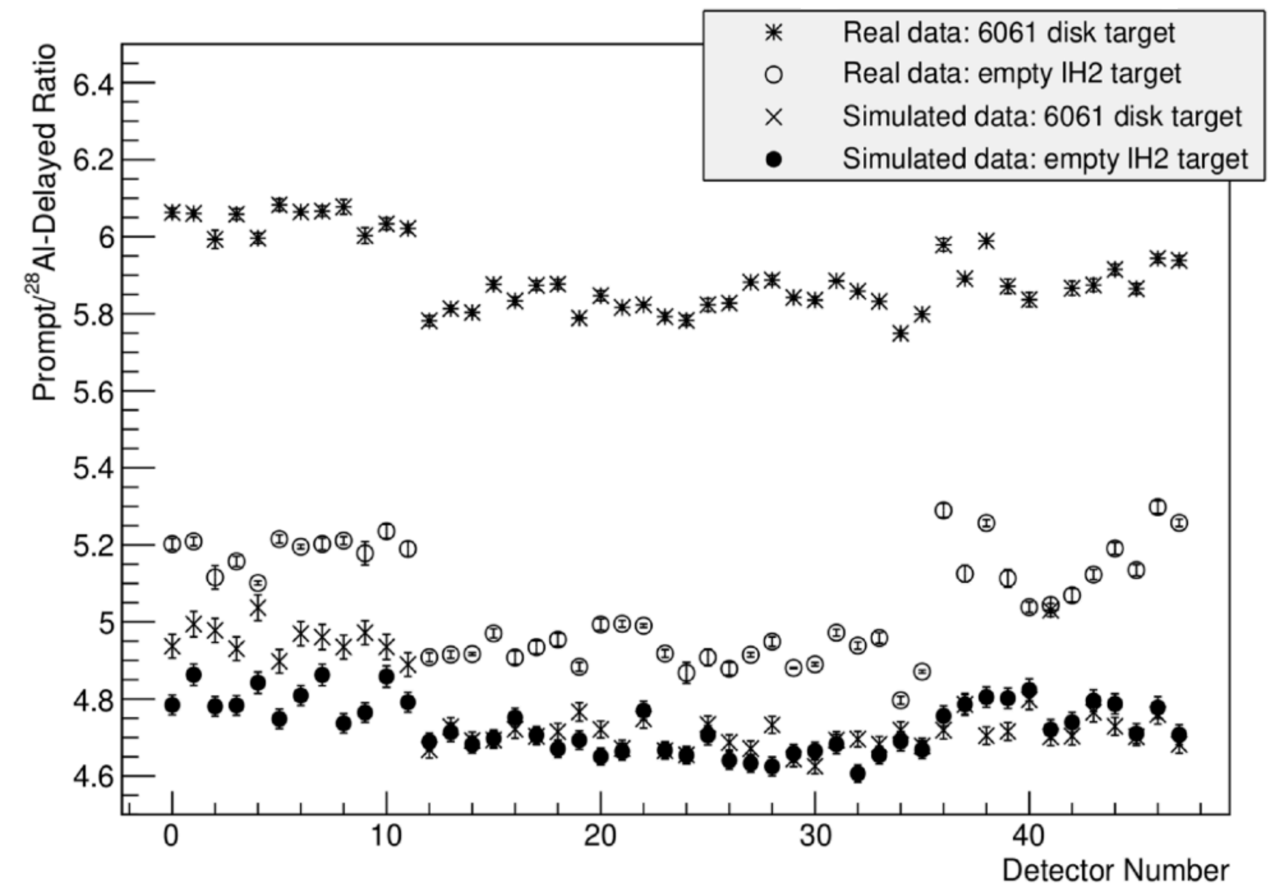
The aluminium background





- After the experiment was decommissioned and analysis was nearing completion, inconsistencies revealed the dedicated aluminium target was not the same alloy as the target vessel (nor aluminum 6061)
- The uncertainty goal of the experiment was not achievable without a new background subtraction strategy
- The experiment was partially mounted again in 2016 to perform measurements with background targets made out of the actual RFSF windows, target cryostat windows, target vessel windows and side walls

The aluminium background



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- The uncertainty goal of the experiment was not achievable without a new background subtraction strategy
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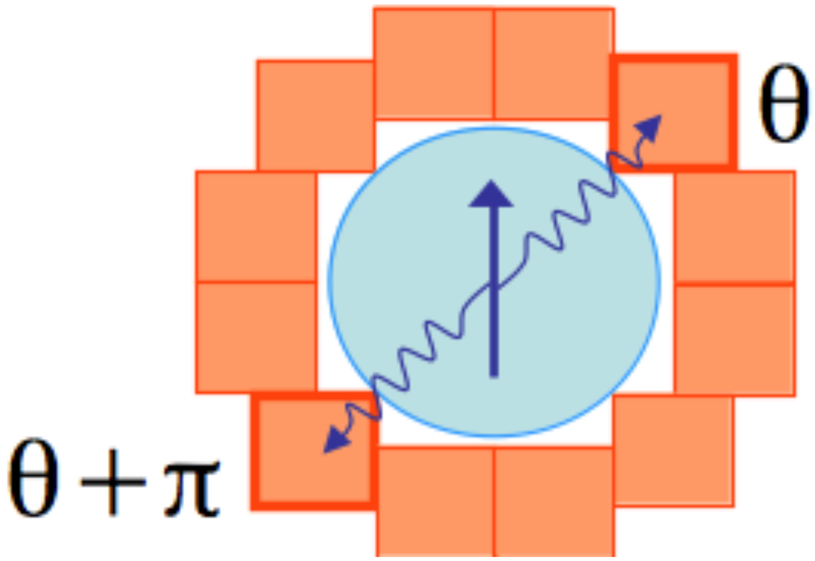
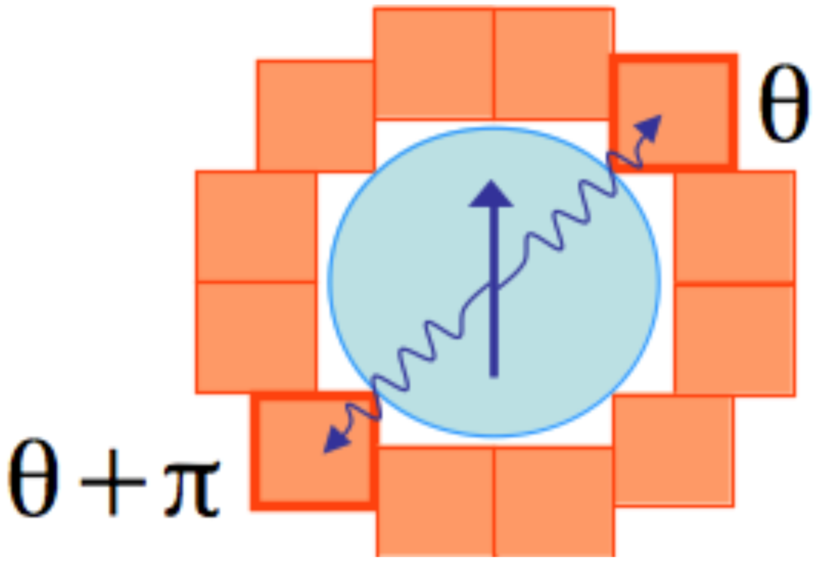
Extraction of A_γ

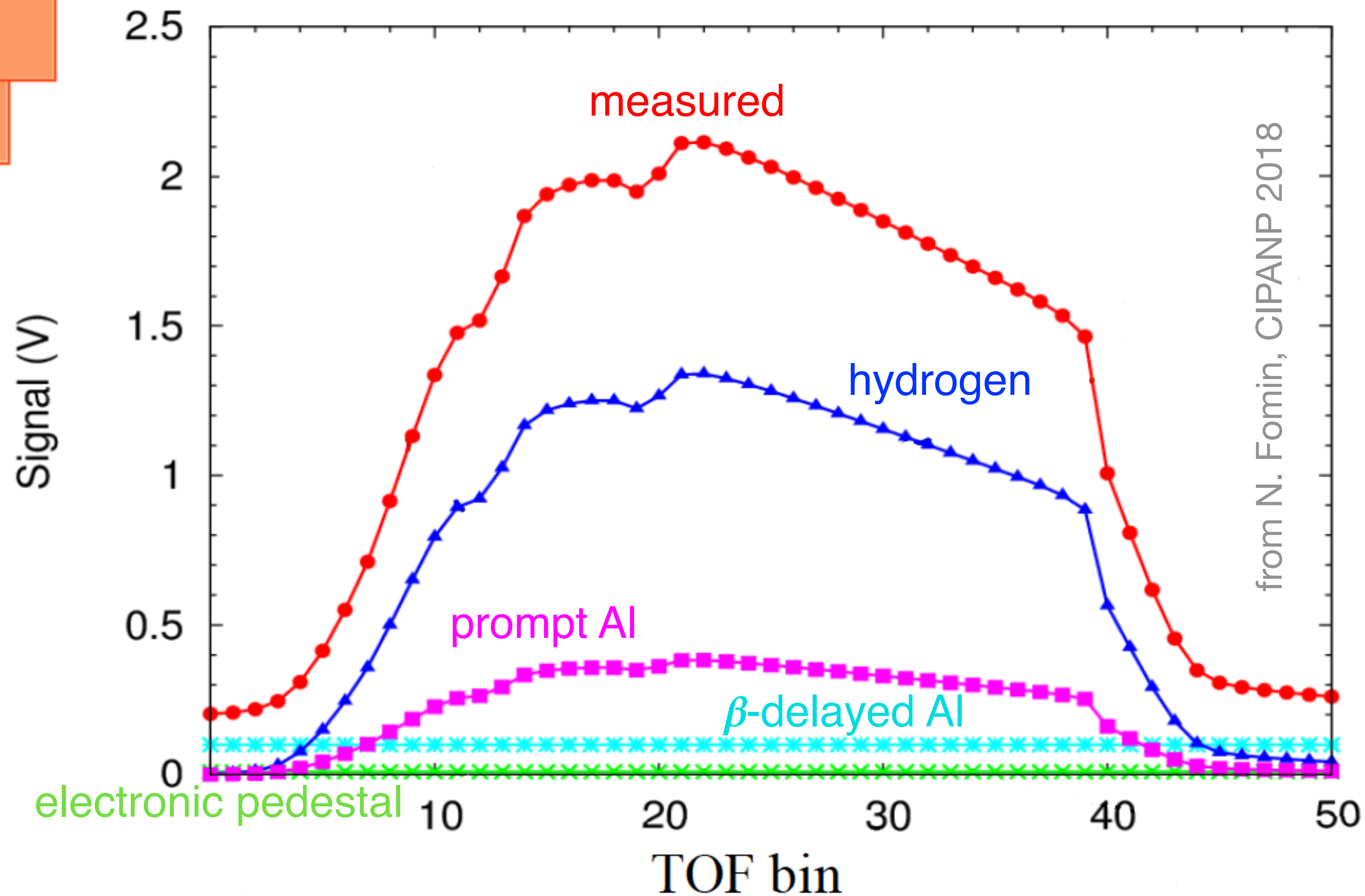


$$A_{\gamma,raw} = \frac{1}{2}\left(\frac{Y_\theta^{\uparrow} - Y_{\theta+\pi}^{\uparrow}}{Y_\theta^{\uparrow} + Y_{\theta+\pi}^{\uparrow}} + \frac{Y_\theta^{\downarrow} - Y_{\theta+\pi}^{\downarrow}}{Y_\theta^{\downarrow} + Y_{\theta+\pi}^{\downarrow}} \right)$$

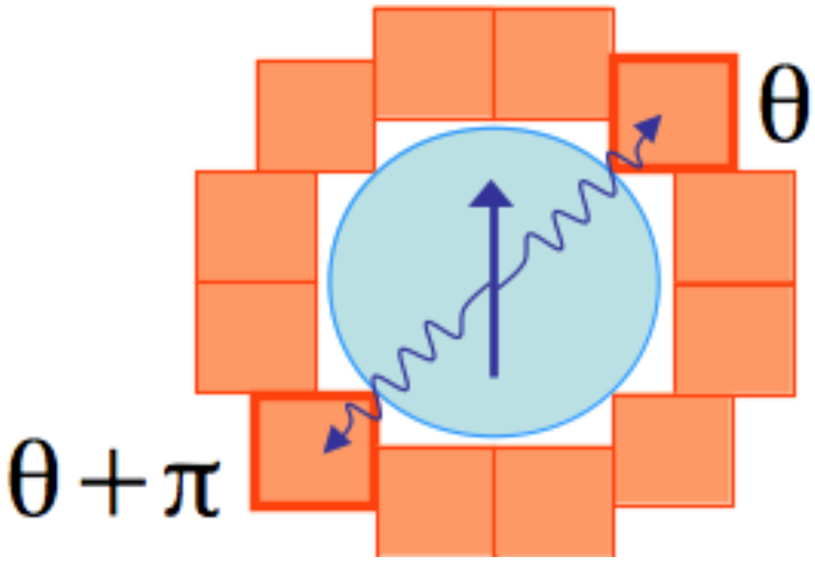
Extraction of A_γ



$$A_{\gamma,raw} = \frac{1}{2}\left(\frac{Y_\theta^\uparrow - Y_{\theta+\pi}^\uparrow}{Y_\theta^\uparrow + Y_{\theta+\pi}^\uparrow} + \frac{Y_\theta^\downarrow - Y_{\theta+\pi}^\downarrow}{Y_\theta^\downarrow + Y_{\theta+\pi}^\downarrow} \right)$$



Extraction of A_γ



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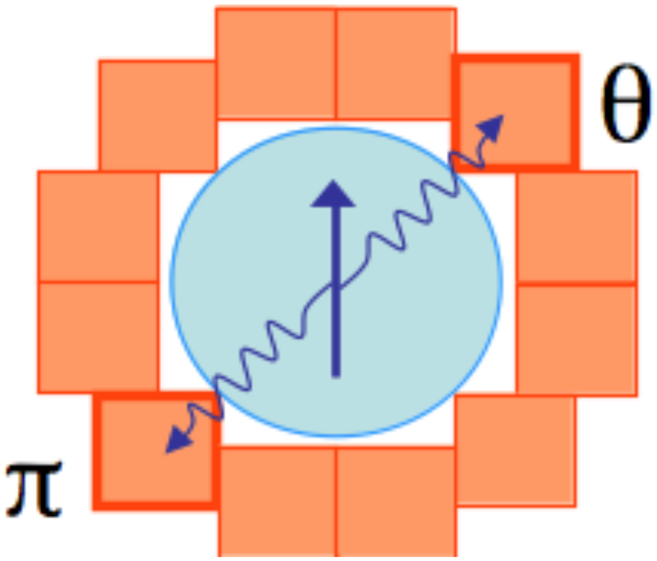
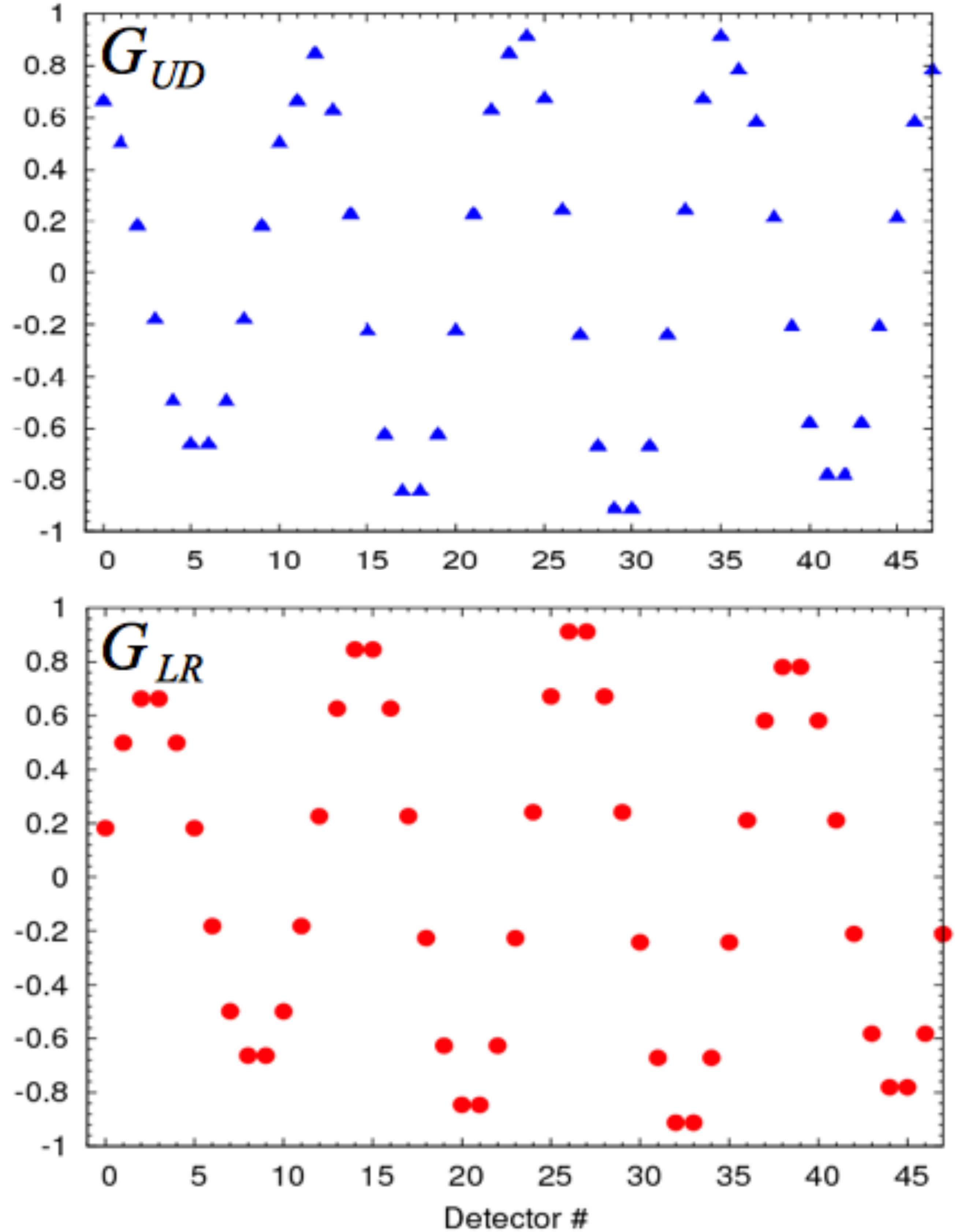
Corrections

$$A_{\gamma,raw} = \sum_i F_i G_i \frac{1}{P_{n,i} C_{d,i} \varepsilon_{SF,i}} A_{\gamma,i}$$

- Neutron polarization (P_n)
- Spin Flipper efficientcy (ε_{SF})
- Neutron depolarization (C_d)
- Fraction of prompt gammas from material target (F_i)
- Geometrical factors (G_{UD} and G_{LR}), which include the finite structure of the beam, the effective solid angle of the detector, the spatial distribution of the material in question and other effects

Extraction of A_γ



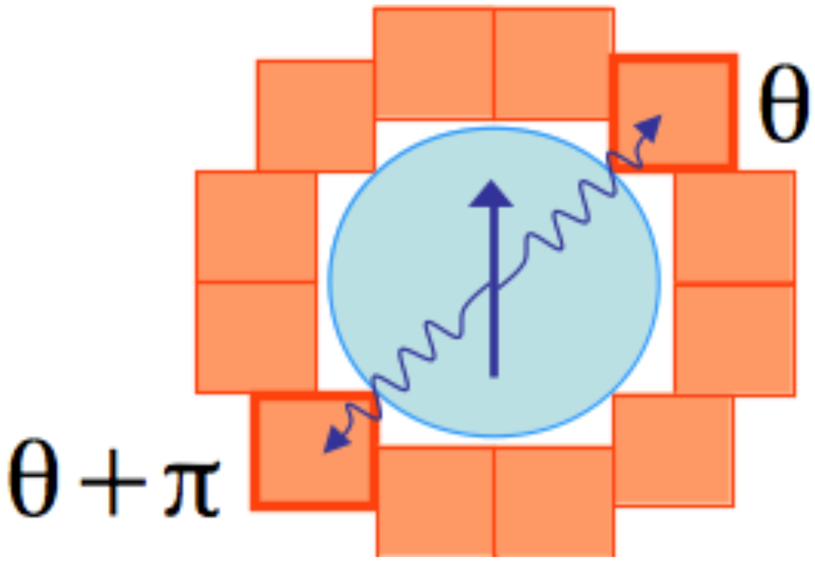


$$G_{UD,i} = \langle \hat{k}_\gamma \cdot \hat{\sigma}_n \rangle = \langle \hat{k}_\gamma \cdot \hat{y} \rangle$$

$$G_{LR,i} = \langle \hat{k}_\gamma \cdot (\hat{\sigma}_n \times \hat{k}_n) \rangle = \langle \hat{k}_\gamma \cdot \hat{x} \rangle$$

Calculated using a combination of MCNPX simulation and measurements with a gamma source

Extraction of A_γ

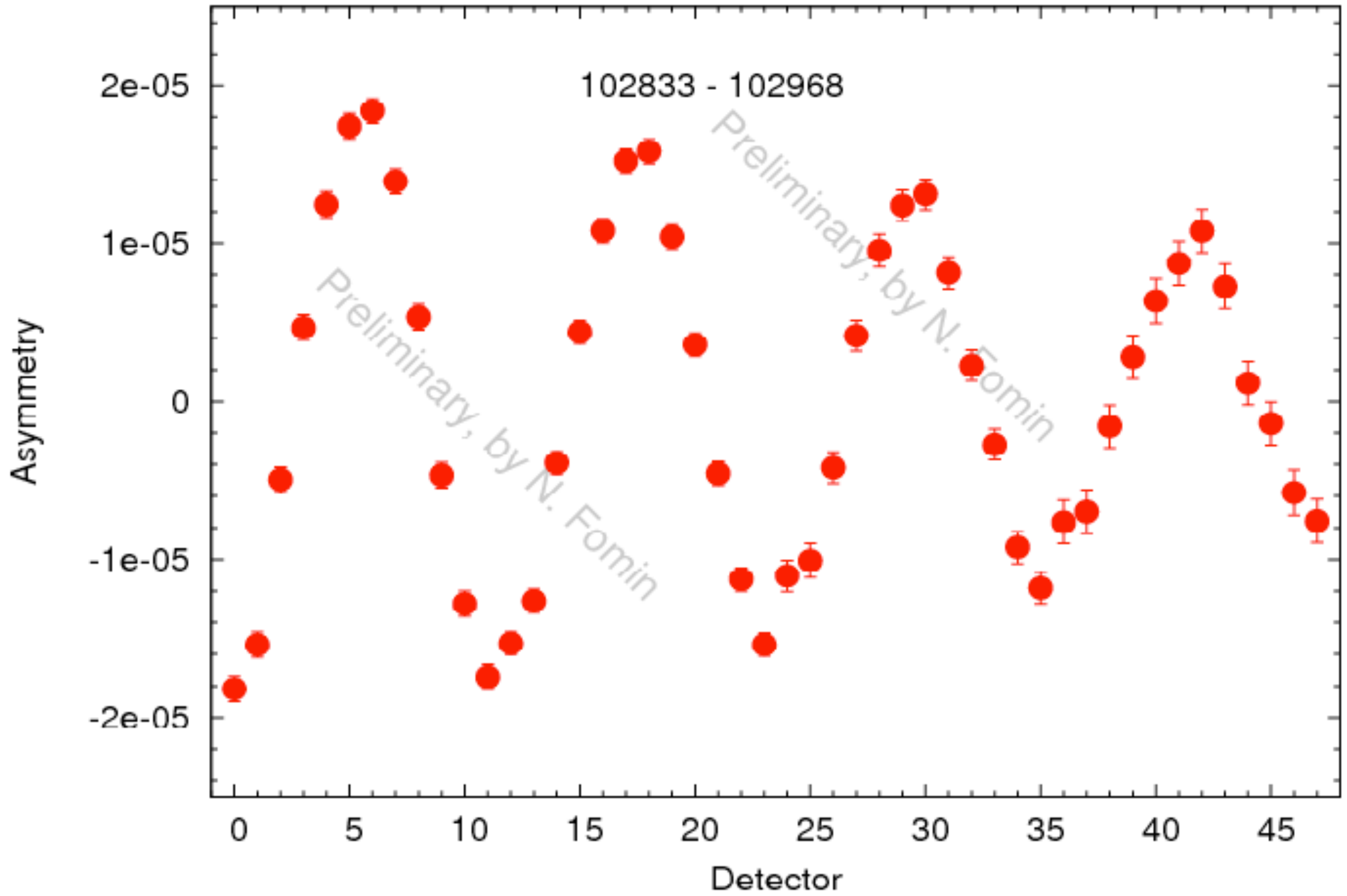


$$A_{\gamma,raw} = \sum_i F_i G_i \frac{1}{P_{n,i} C_{d,i} \varepsilon_{SF,i}} A_{\gamma,i}$$

Hydrogen and aluminum asymmetries simultaneously subtracted from a χ^2 minimization scheme

Chlorine asymmetry test

- Test of sensitivity with large and well known PV gamma asymmetry
- In $\vec{n} + {}^{35}\mathrm{Cl} \rightarrow {}^{36}\mathrm{Cl} + \gamma$, the PV effect is amplified by the mixing and interference of opposite parity states and the presence of close-lying degenerate states



Measurement	Asymmetry ($\times 10^{-6}$)
LANL	-29.1 ± 6.7
Leningrad	-27.8 ± 4.9
ILL	-21.2 ± 1.72
SNS (preliminary)	-25.9 ± 0.6

N. Fomin et al., *Phys. Rev. C* (to be published)

Final result and systematics

$$A_\gamma \sim [-3.0 \pm 1.4(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-8}$$

Source	Contribution
Prompt Al γ's: window thickness	1×10^{-9}
Prompt Al γ's: geometric factors	7×10^{-10}
^{28}Al bremsstrahlung	$<9 \times 10^{-11}$
False electronic asymmetry (LEDs off)	$<1 \times 10^{-9}$
False electronic asymmetry (LEDs on)	$<1 \times 10^{-9}$
Remaining systematic uncertainty [44]	$<3 \times 10^{-10}$
Total	$<2 \times 10^{-9}$

Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

Gericke et al. *Phys. Rev. C* 83, 015505 (2011)

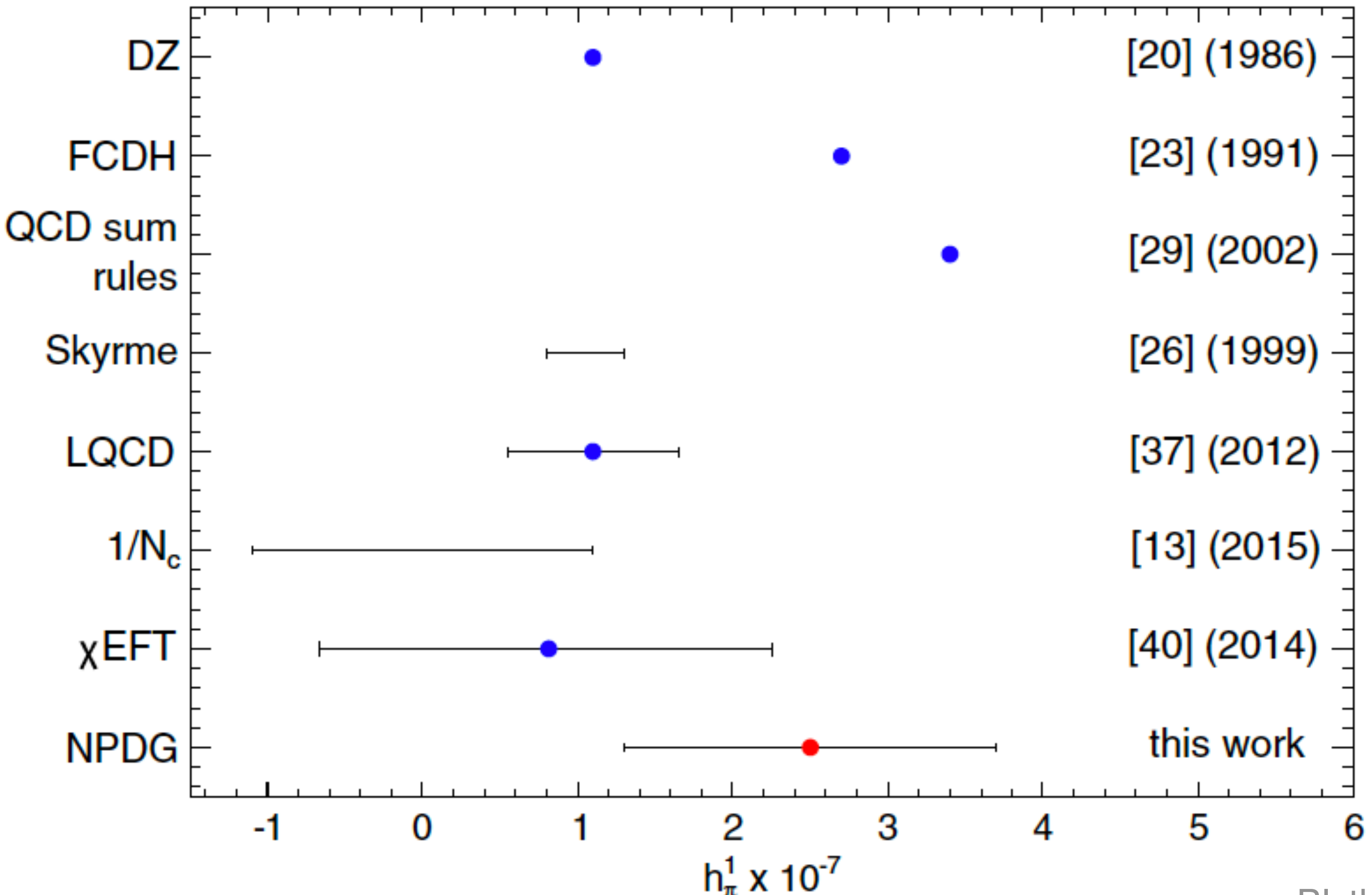
Description	Process	Invariant	Size
Stern-Gerlach	$\mu \cdot \nabla B$	$\mu \cdot \nabla B$	8×10^{-11}
Mott-Schwinger	$\vec{n} + p \to \vec{n} + p$	$s_n \cdot k_i \times k_f$	6×10^{-9}
PA left-right	$\vec{n} + p \to d + \gamma$	$k_\gamma \cdot s_n \times k_i$	7×10^{-10}
γ-ray circ. polarization	$\vec{n} + p \to d + \vec{\gamma}$	$k_n \cdot P_\gamma$	7×10^{-13}
β decay in flight	$\vec{n} \to e^- + p + \bar{\nu}$	$s_n \cdot k_\beta$	3×10^{-11}
Radiative β decay	$\vec{n} \to e^- + p + \bar{\nu} + \gamma$	$s_n \cdot k_\gamma$	2×10^{-12}
Capture on ^{6}Li	$\vec{n} + {}^6\text{Li} \to {}^7\text{Li}^* \to \alpha + T$	$s_n \cdot k_\alpha$	2×10^{-11}
^{28}Al β decay, external	$\vec{n} + {}^{27}\text{Al} \to {}^{28}\text{Al} \to {}^{28}\text{Si} + e^-$	$s_n \cdot k_\beta$	1.0×10^{-8}
^{28}Al β decay, internal	$\vec{n} + {}^{27}\text{Al} \to {}^{28}\text{Al} \to {}^{28}\text{Si} + e^-$	$s_n \cdot k_\beta$	1.9×10^{-10}
^{28}Al prompt γ rays	$\vec{n} + {}^{27}\text{Al} \to {}^{28}\text{Al} + \gamma's$	$s_n \cdot k_\gamma$	$(-0.8 \pm 2.8) \times 10^{-7}$

In DDH

$$A_\gamma = [-3.0 \pm 1.4(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-8}$$

$$A_\gamma \approx -0.114 h_\pi^1$$

$$h_\pi^1 = [2.6 \pm 1.2(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-7}$$



Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

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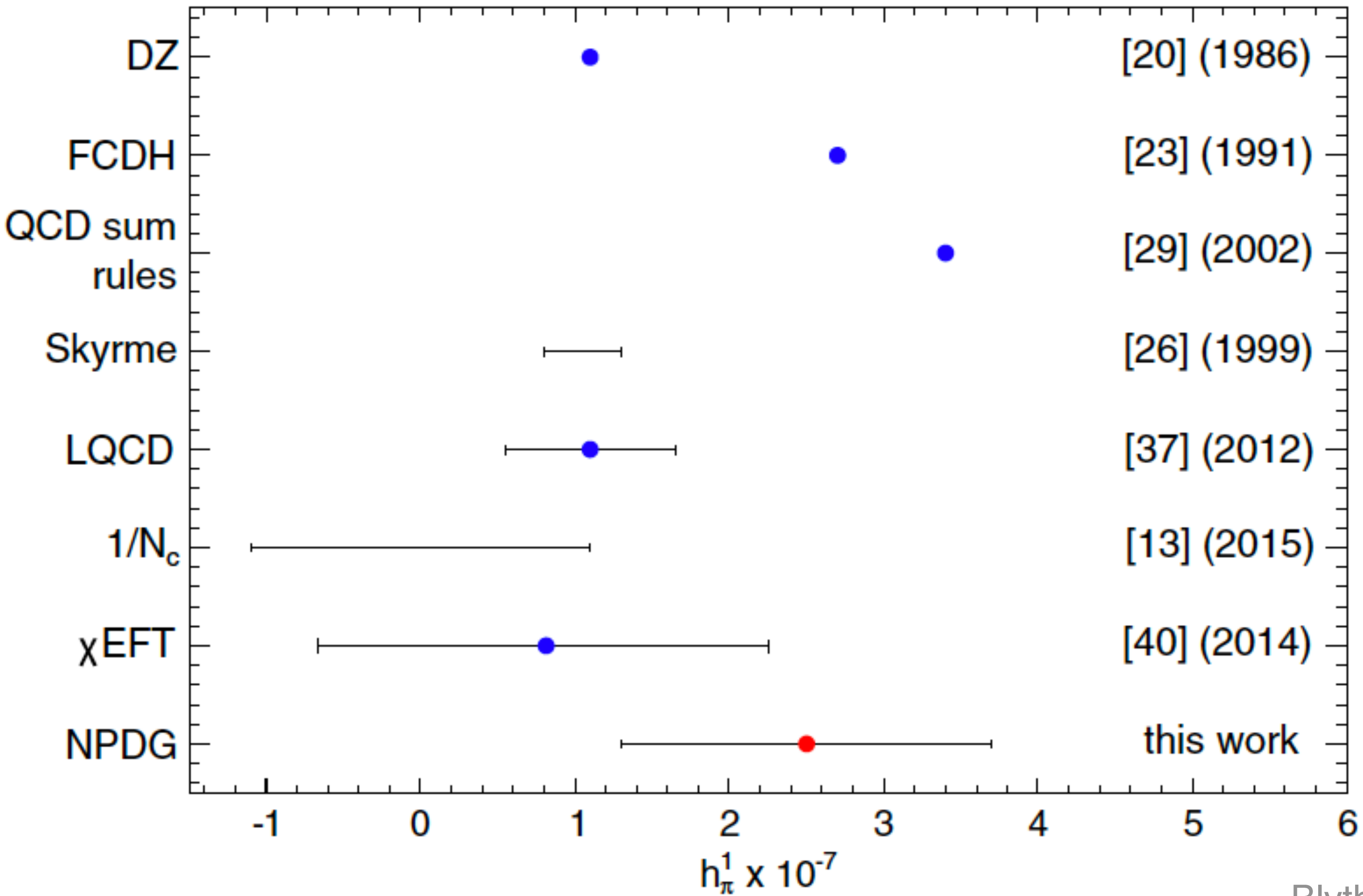
Also since P_γ in ^{18}F contains on all the ΔI=1 weak-couplings and A_γ only depends on h_π^1, one can find a constraint on heavy mesons to be

$$0.4 h_\rho^1 + 0.6 h_\omega^1 = 8.5 \pm 5.0$$



Blyth, Fry, Fomin et al., *Phys. Rev. Lett.*, in press (2018)

In EFT + 1/N$_c$ expansion

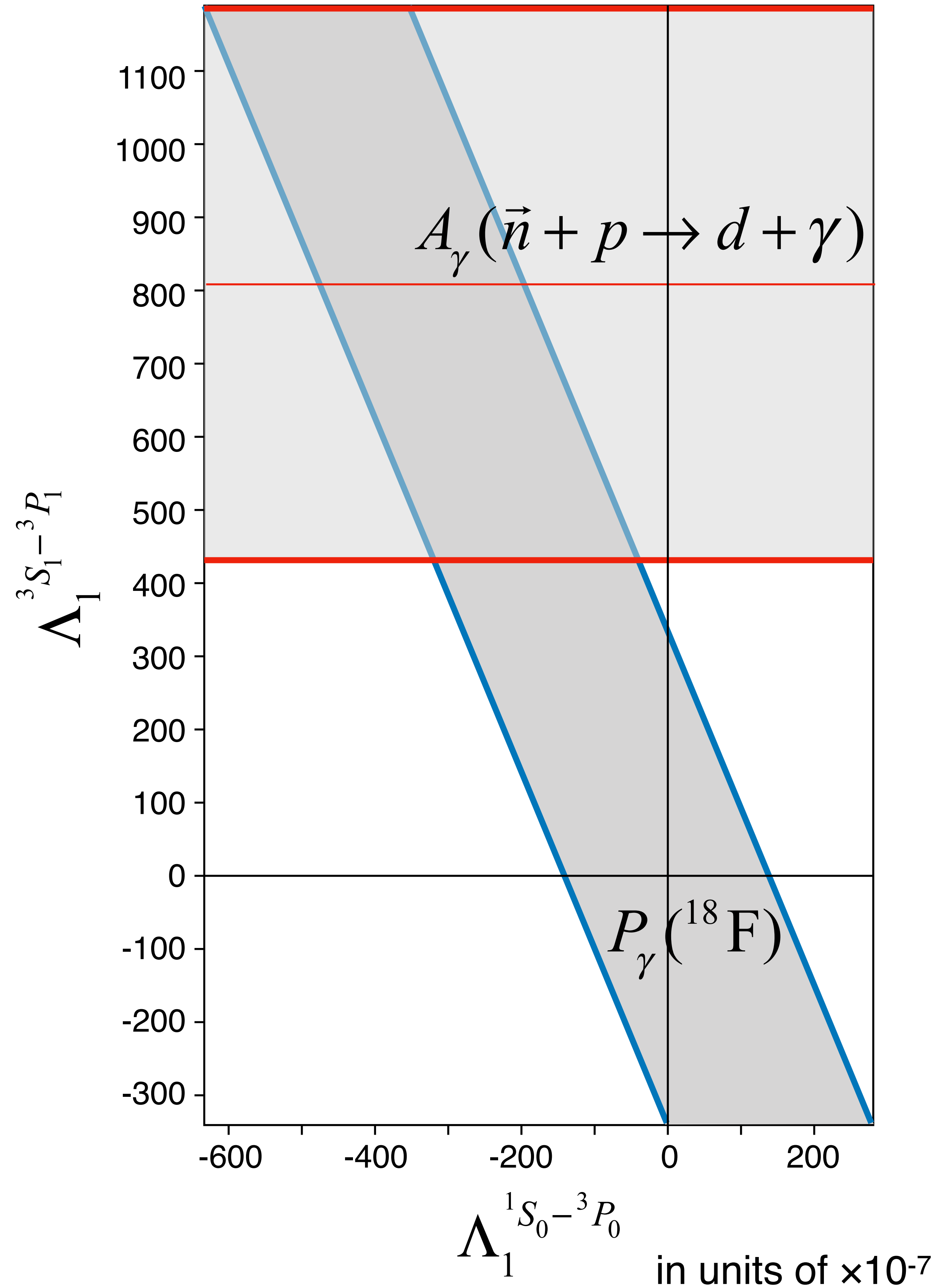
Constraints on NNLO parameters

$$A_\gamma = [-3.0 \pm 1.4(\text{stat.}) \pm 0.2(\text{syst.})] \times 10^{-8}$$

$$A_\gamma \sim -(3.7 \times 10^{-4}) \Lambda_1^{^3S_1 - ^3P_1}$$

$$\left| 2.42 \Lambda_1^{^1S_0 - ^3P_0} + \Lambda_1^{^3S_1 - ^3P_1} \right| < 340, \quad P_\gamma(^{18}\text{F})$$

Haxton, Holstein, *Prog. Part. Nucl. Phys.* 71, 187 (2013)
Gardner, Haxton, Holstein, *Annu. Rev. Nucl. Part. Sci.* 67, 69-95 (2017)



in units of $\times 10^{-7}$

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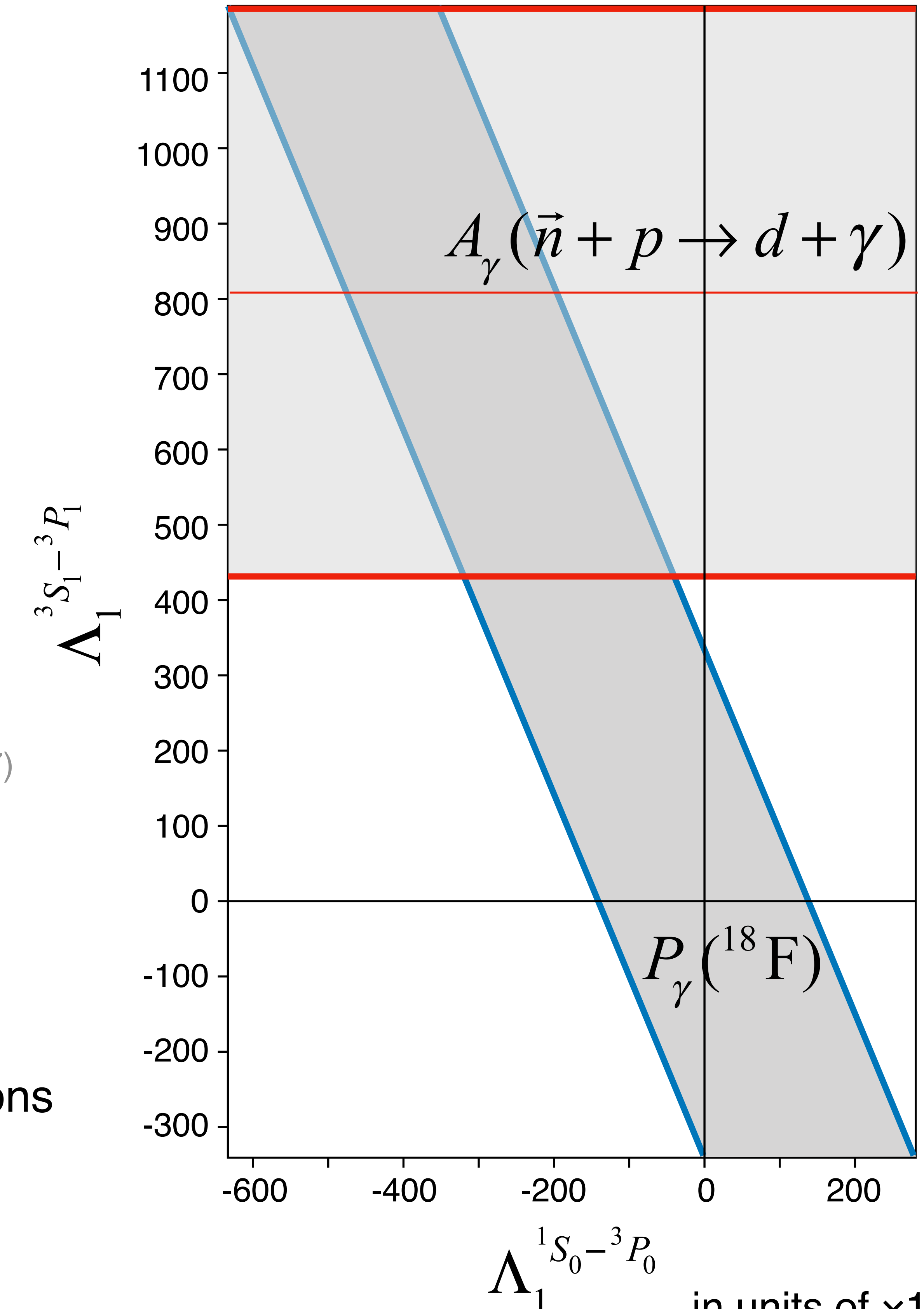

in units of $\times 10^{-7}$

Test for the large-Nc expectations

Improvement possibilities

- One either has to do this measurement on a pulsed neutron beam or at least pulse the beam in some way so that one can analyze the transient signals in the gamma detectors.
- We were not limited by systematics. In this experiment they were $\sim 2\times10^{-9}$. This could be decreased to about 1×10^{-9}.
- It would be nice to try to find something better than aluminum. A different Al alloy or one could try Titanium for the target vessel.
- Put the lithium plastic (neutron absorber) inside the hydrogen target vessel?
- $\sim$4300 hours life time with average beam power about 1 MW at SNS for the LH_2 running gave a statistical error of $\sim 1.4\times10^{-8}$. Other potential beams/sources?

Final comments

- The NPDGamma has achieved the most precise and direct determination of h_π^1 in a two-body system without nuclear corrections, and it is the best constraint for future investigation of the HWI.

- The result, combined with ^{18}F, implies a larger linear combination than what DDH predicts: $0.4h_\rho^1+0.6h_\omega^1=8.5\pm5.0$. On the other hand the result seems to be in agreement with large-N_c expectations.

- Several few-body system experiments with neutrons have been performed (NPDGamma, n-^3He, NSR ^4He -statistically limited) or are planned for the future (NSR ^4He, NDTGamma,…)

- Additional theoretical and experimental work in exactly calculable few-body systems is needed to establish a complete determination of the HWI.

The NPDGamma collaboration

Arizona State University

Argonne National Laboratory

University of Virginia

Indiana University

The University of Tennessee

Los Alamos National Laboratory EST. 1943

Oak Ridge National Laboratory

IFIN-HH

Universidad Nacional Autónoma de México

University of Nevada, Reno 1874

University of New Hampshire

University of Michigan

University of Kentucky

Paul Scherrer Institut PSI

University of Manitoba

NC State University

Mississippi State University

Northwestern University Feinberg School of Medicine

Middle Tennessee State University

KEK

Massachusetts Institute of Technology

Western Kentucky University

BARC

NIST

TUNL

Joint Institute for Nuclear Research
Science Bringing Nations Together

The NPDGamma collaboration

R. Alarcon, L. Alonzi, E. Askanazi, S. Baeßler, S. Balascuta, L. Barrón-Palos, A. Barzilov, D. Blyth, J.D. Bowman, N. Birge, J.R. Calarco, T.E. Chupp, V. Cianciolo, C.E. Coppola, C. Crawford, K. Craycraft, D. Evans, C. Fieseler, N. Fomin, E. Frlez, J. Fry, I. Garishvili, M.T.W. Gericke, R.C. Gillis, K.B. Grammer, G.L. Greene, J. Hall, J. Hamblen, C. Hayes, E.B. Iverson, M.L. Kabir, S. Kucuker, B. Lauss, R. Mahurin, M. McCrea, M. Maldonado-Velázquez, Y. Masuda, J. Mei, R. Milburn, P.E. Mueller, M. Musgrave, H. Nann, I. Novikov, D. Parsons, S.I. Penttila, D. Počanić, A. Ramírez-Morales, M. Root, A. Salas-Bacci, S. Santra, S. Schröder, E. Scott, P.-N. Seo, E.I. Sharapov, F. Simmons, W.M. Snow, A. Sprow, J. Stewart, E. Tang, Z. Tang, X. Tong, D.J. Turkoglu, R. Whitehead, and W.S. Wilburn