Precision Measurements of Neutron Beta Decay with NoMoS at PERC

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Inpc 2016
International Nuclear Physics Conference

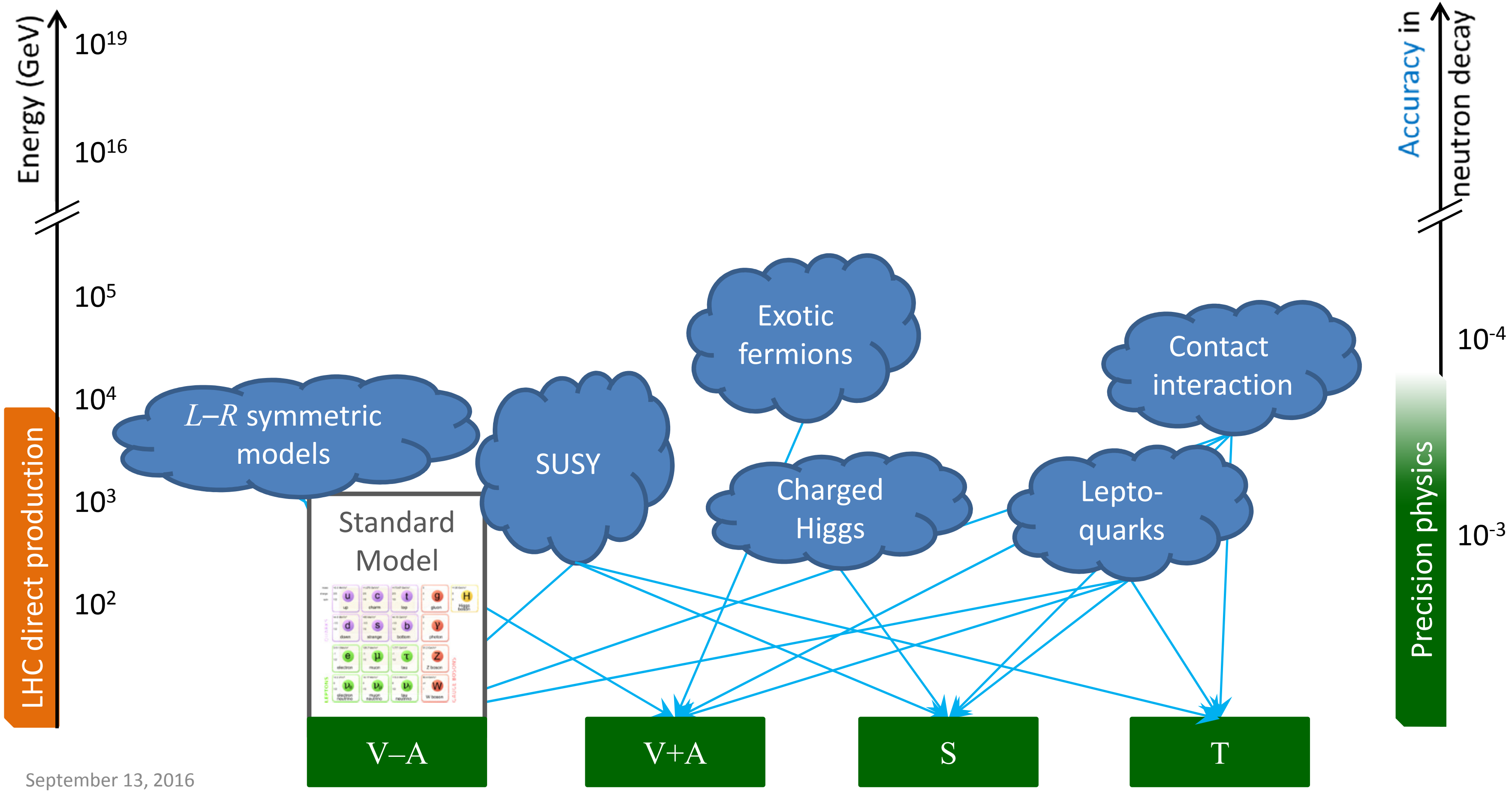
Adelaide, Australia
September 11 – 16, 2016

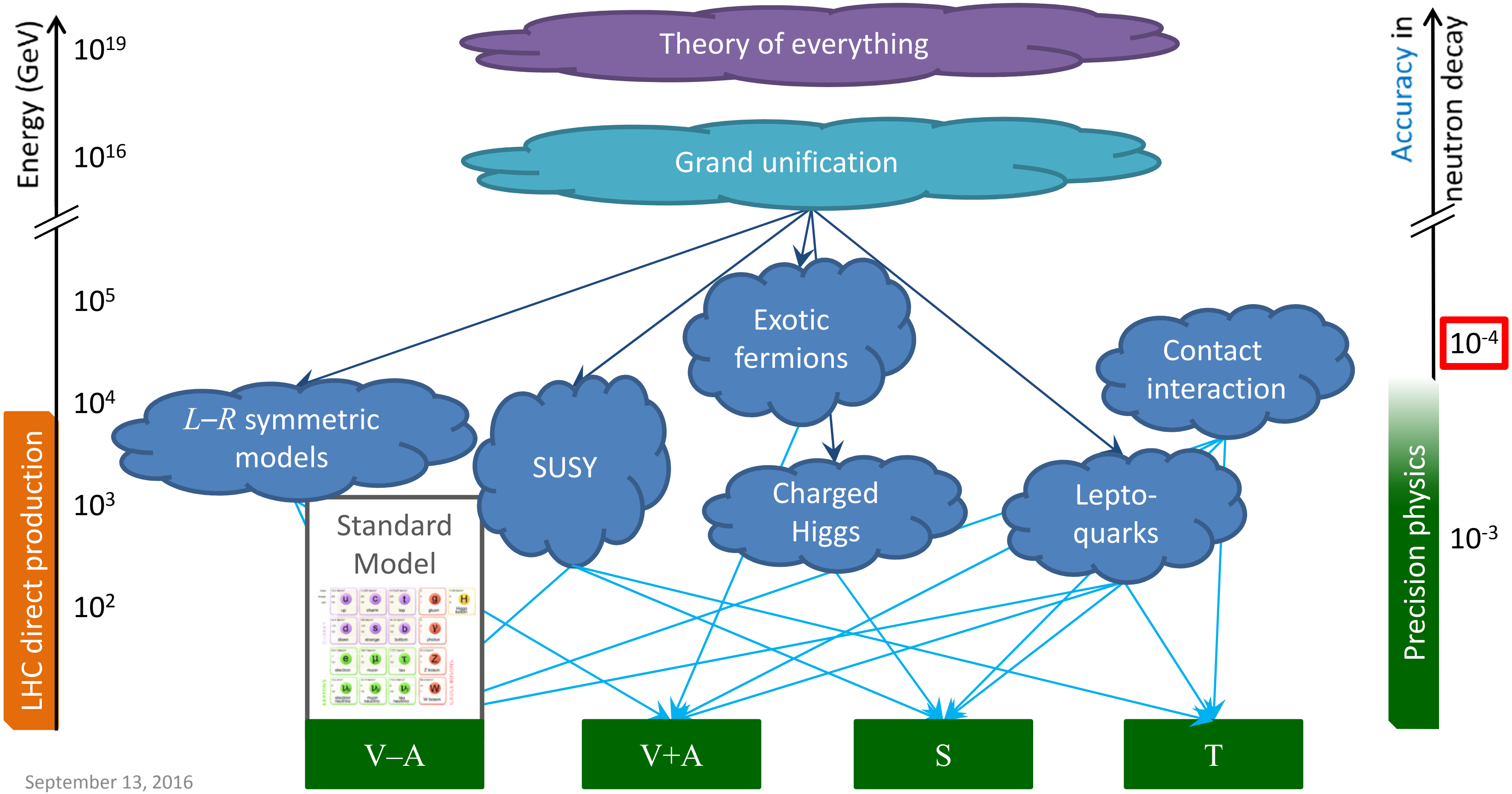
‘There are many examples in physics showing that *higher precision* revealed new phenomena, inspired new ideas, or *confirmed or dethroned well-established theories*.’

Wolfgang Paul
Electromagnetic Traps for Charged and Neutral Particles
Nobel Lecture, December 8, 1989

PRECISION MEASUREMENTS

Experimental approach to `physics beyond´




Energy (GeV)
10^19
10^16
10^5
10^4
10^3
10^2
LHC direct production
Theory of everything
Grand unification
Exotic fermions
Contact interaction
L–R symmetric models
SUSY
Charged Higgs
Lepto-quarks
Standard Model
V–A
V+A
S
T
Accuracy in neutron decay
10^-4
10^-3
Precision physics

Outline

- Precision measurements
- Neutron β-decay (theory)
  - within SM
  - beyond SM
- Neutron β-decay (experiment)
  - Overview
  - PERC
  - NoMoS
  - ANNI
- Summary and Outlook

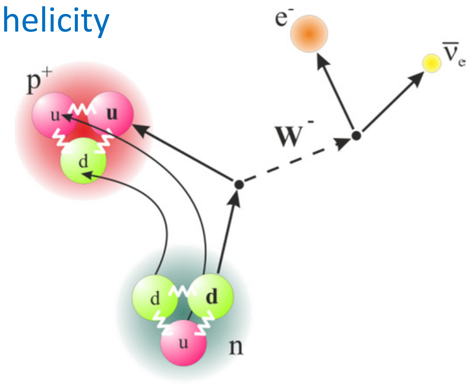
NEUTRON β-DECAY (THEORY)

Neutron β-decay

$\mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^- + \bar{\nu}_\mathrm{e} + 782.334\,\mathrm{keV}$:

- prototype of weak interactions
- described by $V-A$ theory: $H_{\mathrm{V-A}} = \frac{G_\mathrm{F} V_{\mathrm{ud}}}{\sqrt{2}} \langle \mathrm{p} | \gamma_\mu \left(1 + \frac{g_\mathrm{A}}{g_\mathrm{V}} \gamma^5 \right) | \mathrm{n} \rangle \langle \mathrm{e}^- | \gamma_\mu (1 - \gamma_5) | \nu_\mathrm{e} \rangle + \mathrm{h.c.}$

quark mixing   nucleon structure   helicity



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- lifetime:

coupling strength

$$\tau_\mathrm{n} = \frac{1}{|V_\mathrm{ud}|^2} \frac{(4908.7 \pm 1.9)\,\mathrm{s}}{(1+3|\lambda|^2)} = 880.3(1.1)\,\mathrm{s}$$

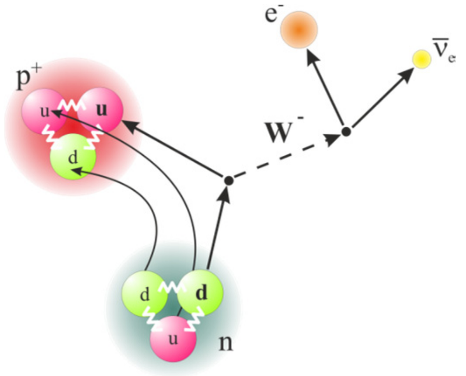
1×10^{-3}

Fri 11:40 SY

$$\lambda = g_\mathrm{A}/g_\mathrm{V}$$

$$g_\mathrm{V} = G_\mathrm{F} \cdot V_\mathrm{ud}$$

μ-decay



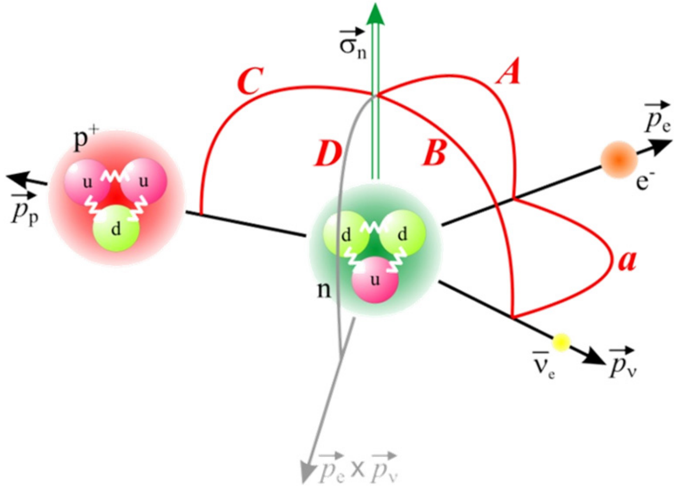
A. Czarnecki et al., PR D70, 093006 (2004)

The neutron alphabet

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} \overbrace{G_F^2 |V_{ud}|^2 (1+3|\lambda|^2)}^{\propto \tau_n^{-1}} p_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \vec{\sigma}_n \rangle}{\vec{\sigma}_n} \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

J.D. Jackson et al., PR106, 517 (1957)



The neutron alphabet *within SM*

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} \overbrace{G_F^2 |V_{ud}|^2 \left(1+3|\lambda|^2\right)}^{\propto \tau_n^{-1}} p_e E_e (E_0 - E_e)^2$$

J.D. Jackson et al., PR106, 517 (1957)

$$\times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\vec{\sigma}_n\rangle}{\vec{\sigma}_n} \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu}\right)\right]$$

- 2 unknown parameters

  V_{ud}, $\lambda = g_A / g_V$

- 20 or more observables

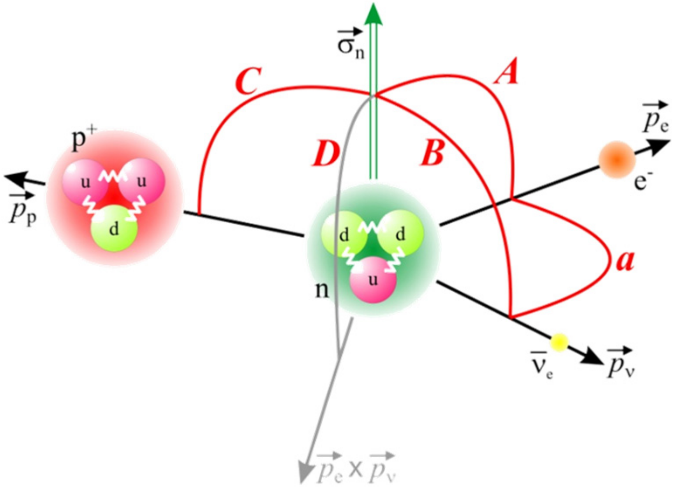
  $\tau_n, a, b, A, B, C, D, \ldots$

  $$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \quad , \quad A = -2\frac{|\lambda|^2 + \mathrm{Re}(\lambda)}{1+3|\lambda|^2}$$

  $$A(T_e) = A \cdot \left(1 + c + \underbrace{a_{WM}(T_e, \lambda, f_2)}_{\approx 2\%}\right)$$

- yet unmeasured

  b, f_2



The neutron alphabet *beyond SM*

$$\frac{d^3\Gamma}{dE_e d\Omega_e d\Omega_\nu} = \frac{1}{2(2\pi)^5} \overbrace{G_F^2 |V_{ud}|^2 \left(1+3|\lambda|^2\right)}^{\propto \tau_n^{-1}} p_e E_e (E_0 - E_e)^2$$

J.D. Jackson et al., PR106, 517 (1957)

$$\times \left[1 + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + \frac{\langle \vec{\sigma}_n \rangle}{\vec{\sigma}_n} \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right)\right]$$

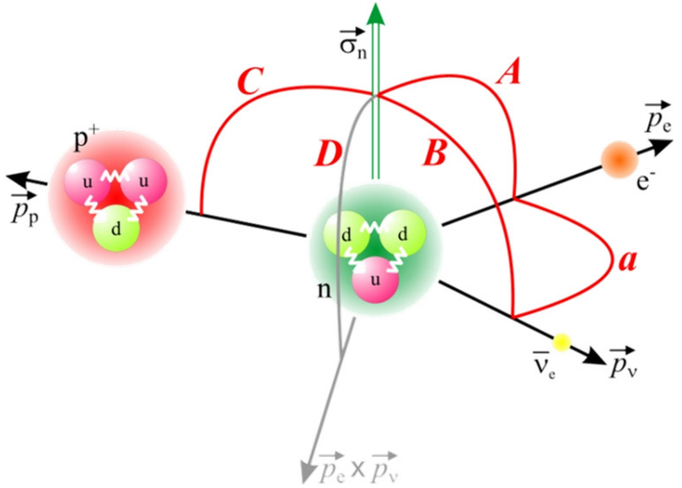
- 9 unknown parameters:
  V_{ud}, L_j, R_j, $j=V, A, S, T$
- 20 or more observables:
  τ_n, a, b, A, B, C, D, …

$$\xi a = |L_V|^2 - |L_A|^2 - |L_S|^2 + |L_T|^2 + |R_V|^2 - |R_A|^2 - |R_S|^2 + |R_T|^2$$

$$\xi b = 2\Re\left(L_S L_V^* + 3L_A L_T^* + R_S R_V^* + 3R_A R_T^*\right)$$ yet unmeasured

$$\xi A = -2\Re\left(|L_A|^2 + L_V L_A^* - |L_T|^2 - L_S L_T^* - |R_A|^2 - R_V R_A^* + |R_T|^2 + R_S R_T^*\right)$$

$$\xi = |L_V|^2 + 3|L_A|^2 + |L_S|^2 + 3|L_T|^2 + |R_V|^2 + 3|R_A|^2 + |R_S|^2 + 3|R_T|^2$$



F. Glück *et al.*, NP A593, 125 (1995)

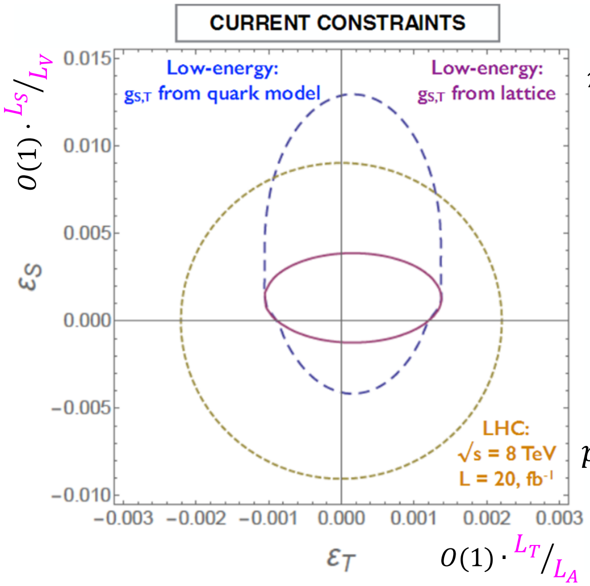
Current status of neutron alphabet

Observable	Standard Model	Status PDG 2015
Lifetime	$\tau_n = \frac{1}{\lvert V_{ud}\rvert^2} \frac{(4908.7 \pm 1.9)\,\mathrm{s}}{(1+3\lvert\lambda\rvert^2)}$	$\Delta\tau_n/\tau_n = 1 \times 10^{-3}$
Ratio of weak coupling constants	$\lambda = g_A/g_V = \lvert\lambda\rvert e^{i\phi}$	$\Delta\lambda/\lambda = 2 \times 10^{-3}$
Electron-neutrino correlation	$a = \frac{1-\lvert\lambda\rvert^2}{1+3\lvert\lambda\rvert^2}$	$\Delta a/a = 3.9 \times 10^{-2}$
Fierz interference term	$b = 0$	yet unmeasured
Beta asymmetry	$A = -2\frac{\lvert\lambda\rvert^2 + \lvert\lambda\rvert\cos\phi}{1+3\lvert\lambda\rvert^2}$	$\Delta A/A = 8 \times 10^{-3}$
Neutrino asymmetry	$B = 2\frac{\lvert\lambda\rvert^2 - \lvert\lambda\rvert\cos\phi}{1+3\lvert\lambda\rvert^2}$	$\Delta B/B = 3 \times 10^{-3}$
Proton asymmetry	$C = -0.27484(A+B)$	$\Delta C/C = 1.1 \times 10^{-2}$
Triple correlation	$D = 2\frac{\lvert\lambda\rvert\sin\phi}{1+3\lvert\lambda\rvert^2} \equiv 0 \qquad \phi = 180^\circ$	$D = (-1 \pm 2) \times 10^{-4}$ $\phi = (180.02 \pm 0.03)^\circ$

K.A. Olive et al. (Particle Data Group), Chin. Phys. C38, 090001 (2014)

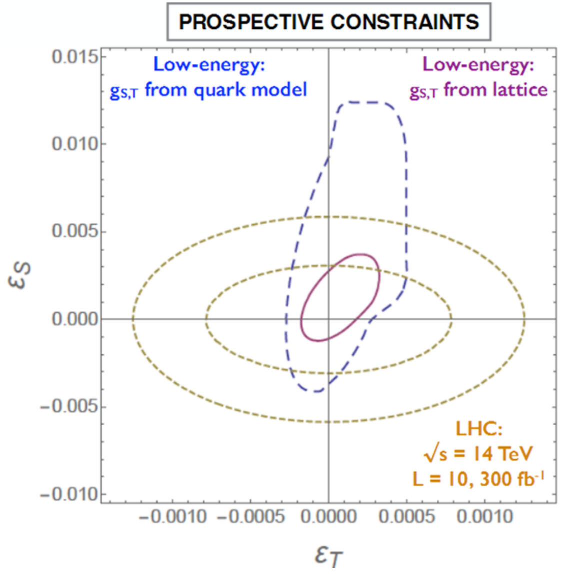
Prospects for S and T interactions in LHC era

$$d\Gamma_b = \left(1 + b\frac{m_e}{E_e}\right) d\Gamma_{\mathrm{SM}}$$



$\pi \to e\nu\gamma, 0^+ \to 0^+$

$pp \to e\nu + \mathrm{X}$



b, B, $b_{^6He}$ at 10^{-3} level

- 10^{-3} level b measurements complementary to improved LHC results

T. Bhattacharya et al., LA-UR-16-20522, arXiv:1606.07049 (2016)
see also: O. Naviliat-Cuncic & M. González-Alonso, Ann. Phys. (Berlin) 525 (2013) 600

Why investigate neutron β-decay?

Thu 11:30

- Provide value of λ for other fields of research
  - Big Bang nucleosynthesis, energy generation in Sun, neutron star formation
  - detection efficiency of neutrino and LHC detectors
  - key benchmark for LQCD calculation of hadron structure (exascale computing)

- Study structure of weak interaction
  - value of weak magnetism form-factor f_2 predicted (CVC hypothesis)
  - *but* large theoretical uncertainties

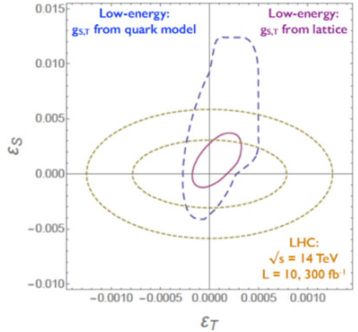
$$V_\mu = \left\langle p \middle| \gamma_\mu - i f_2 \sigma_{\mu\nu} \frac{q^\nu}{2M} \middle| n \right\rangle$$

$$f_2 = \kappa_p - \kappa_n \approx 3.7058$$

- Test the Standard Model of particle physics
  - self-consistency of the Standard Model
  - unitarity of Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{td} & V_{tb} \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- Search for \`physics beyond´ and new symmetry concepts
  - right-handed admixtures, exotic scalar and tensor admixtures
  - left-right symmetry, supersymmetry (SUSY), leptoquarks, etc.
  - SUSY deviations from CKM unitarity ≥ 10^{-4} fall in LHC inaccessible region
  - 10^{-3} level b measurements complementary to improved LHC results



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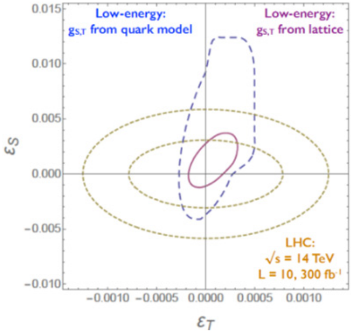
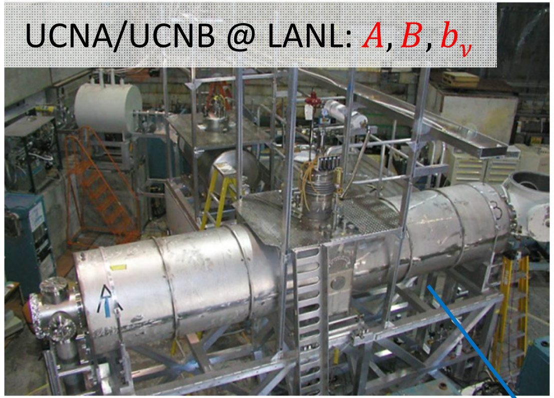
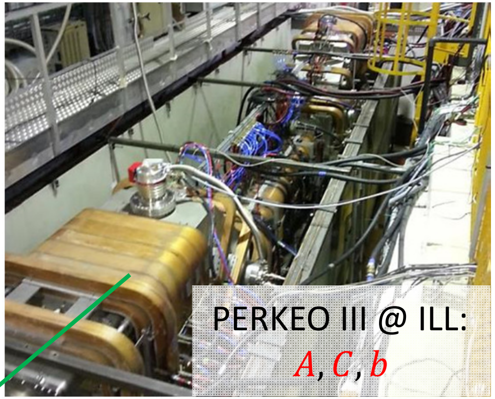
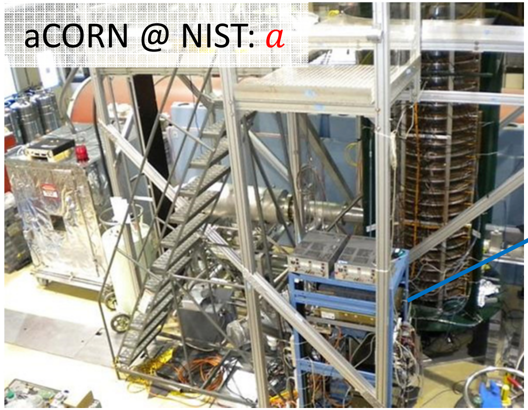


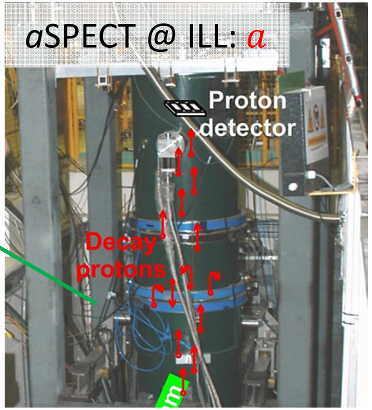
NEUTRON β-DECAY (EXPERIMENT)

`Current´ experiments worldwide



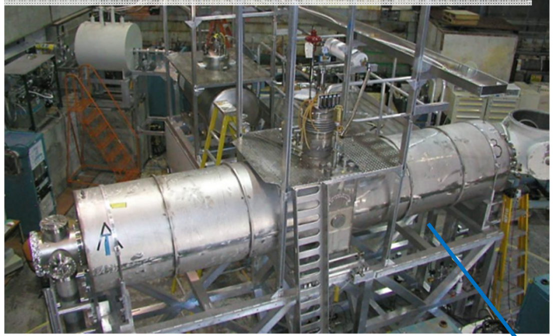




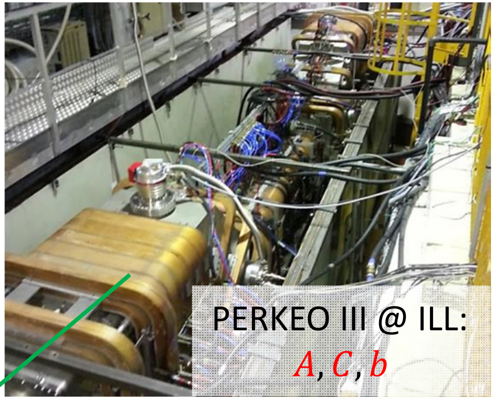


Experiments to measure Fierz term b

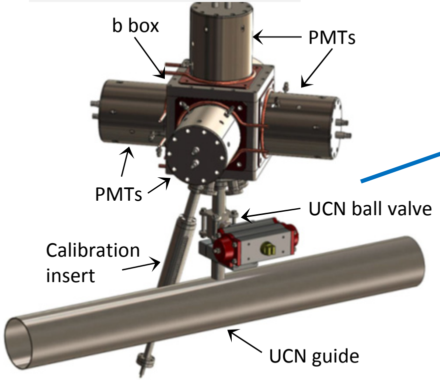
UCNA/UCNB @ LANL: A, B, b, b_ν



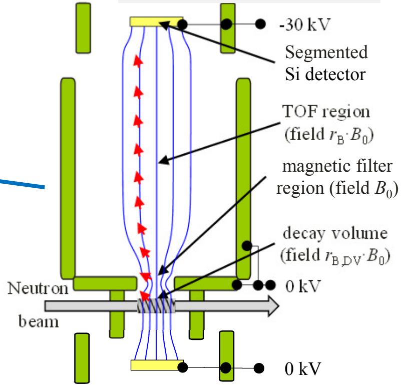
PERKEO III @ ILL: A, C, b



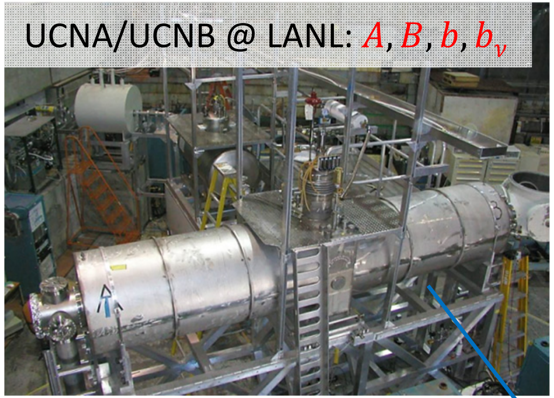
UCNb @ LANL: b

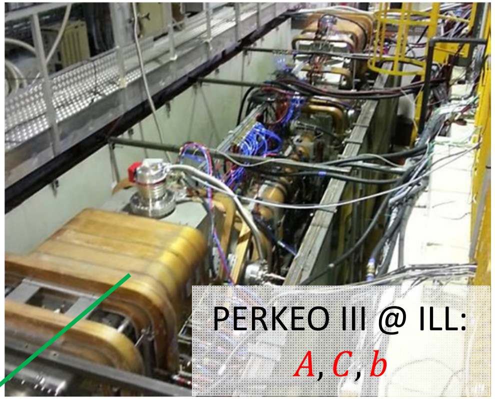


Nab @ SNS: a, b

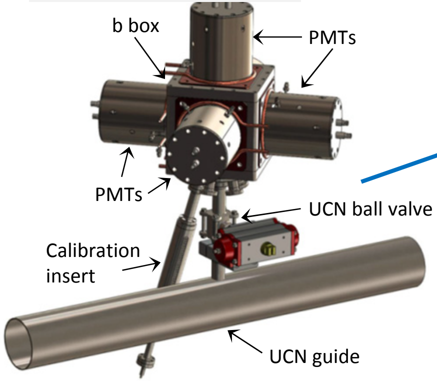


Experiments to measure Fierz term b

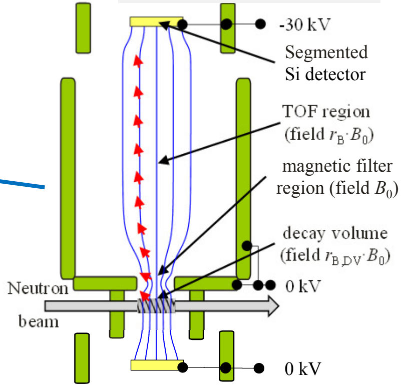




UCNb @ LANL: b

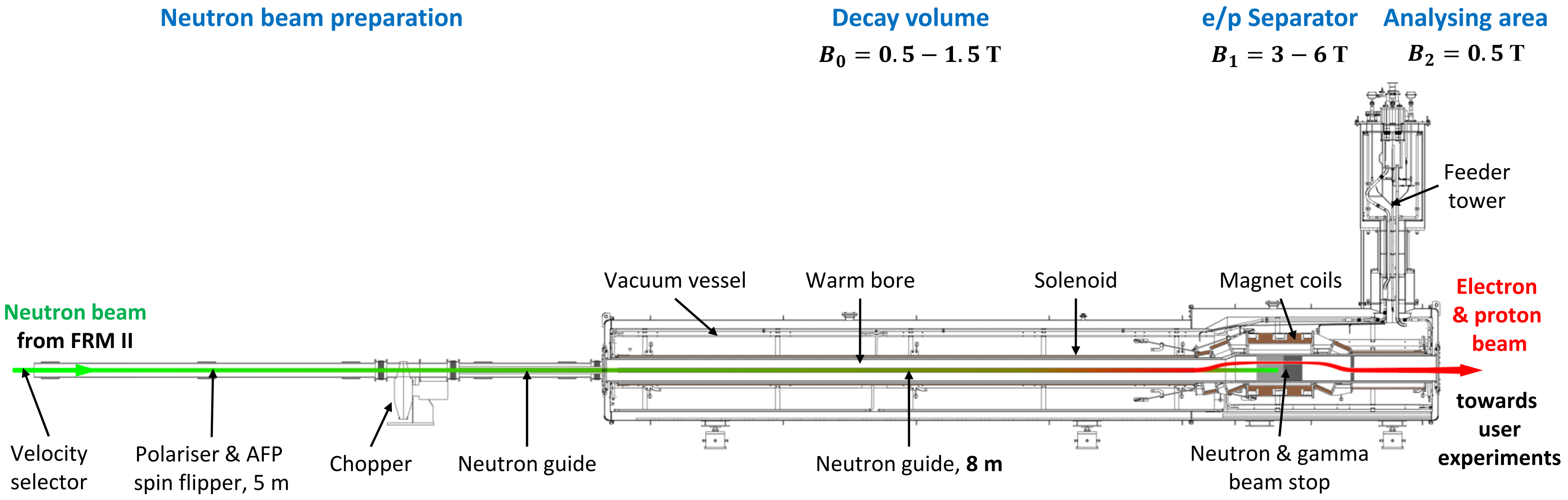


Nab @ SNS: a, b



Proton and Electron Radiation Channel

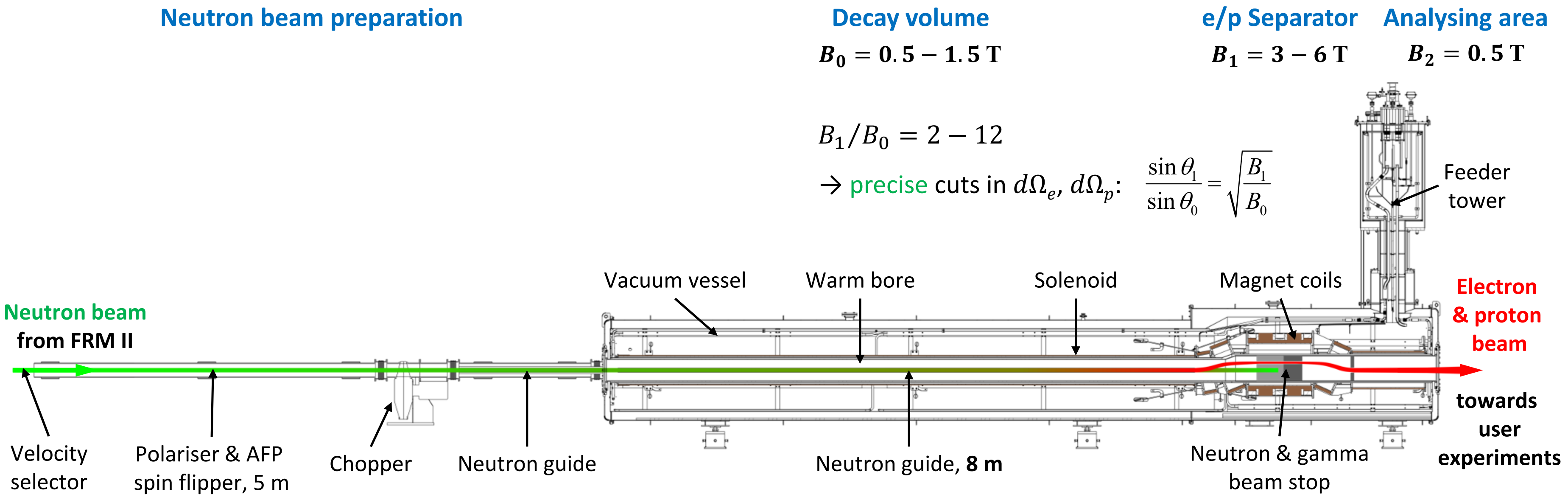
New facility PERC



Statistics	high flux ϕ=2×10^{10} cm^{-2}s^{-1} and high decay rate = 1×10^{6} m^{-1}s^{-1}
Sensitivity	improved by up to 2 orders of magnitude to sub-10^{-4}-level

D. Dubbers et al., NIM A 596, 238 (2008)
G. K. et al., J. Phys.: Conf. Ser. 340, 012048 (2012)

New facility PERC



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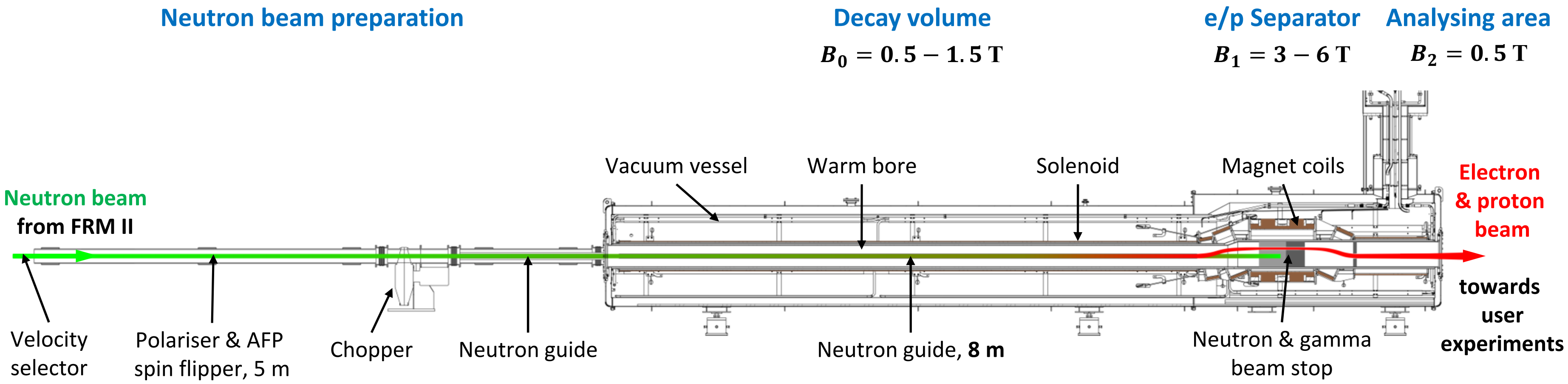
D. Dubbers et al., NIM A 596, 238 (2008)
G. K. et al., J. Phys.: Conf. Ser. 340, 012048 (2012)

C. Klauser, PhD, TU Wien, 2013
C. Klauser et al, JPCS340, 012011 (2012)

New facility PERC



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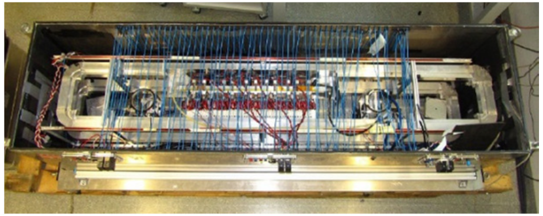
Sensitivity	improved by up to 2 orders of magnitude to sub-10^{-4}-level
Systematics	≤ 10^{-4} (for e$^-$), especially $\Delta P/P$=10^{-4}
Versatility	a, b, A, B, C, f_2, …
Status	manufacturing within 11, commissioning within 17 months

C. Klauser, PhD, TU Wien, 2013
C. Klauser et al, JPCS340, 012011 (2012)

D. Dubbers et al., NIM A 596, 238 (2008)
G. K. et al., J. Phys.: Conf. Ser. 340, 012048 (2012)

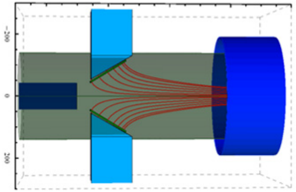
Status of PERC (excerpt)

Magnetic spin resonator



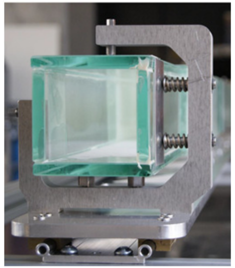
C. Gösselsberger, PhD, TU Wien, 2013

Active electron dump



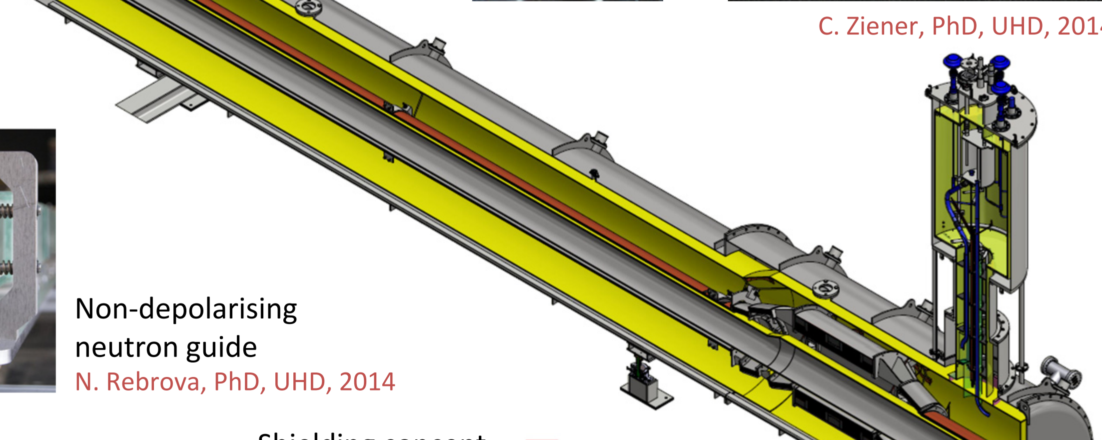
C. Ziener, PhD, UHD, 2014

Rail system for neutron guide

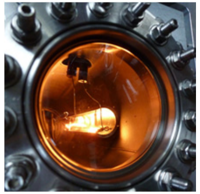


Non-depolarising neutron guide

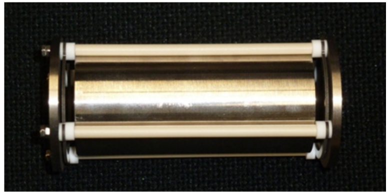
N. Rebrova, PhD, UHD, 2014



Ti wire getter pump

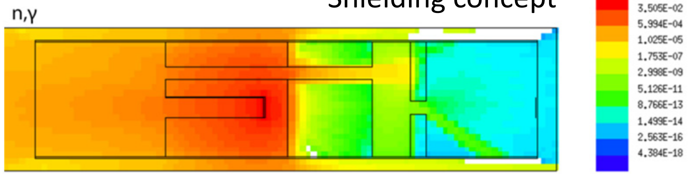


Ion getter pump



C. Ziener, PhD, UHD, 2014

Shielding concept

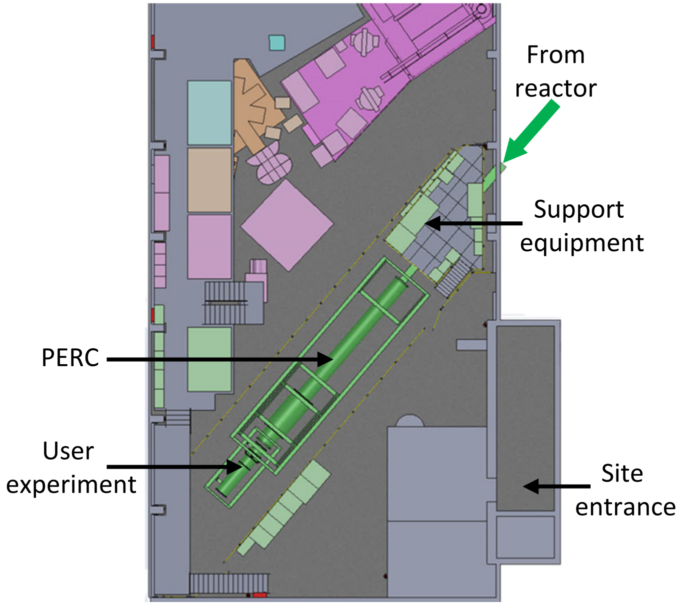


S. Haas, DI, TU Wien, 2013

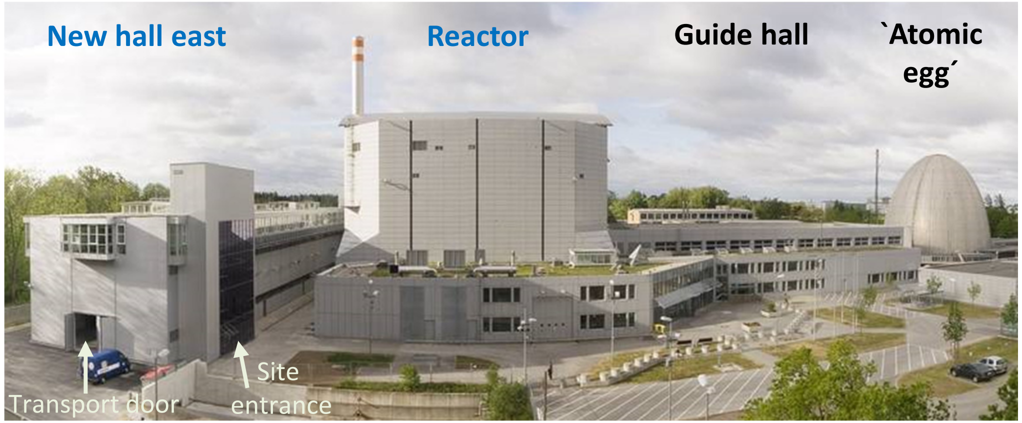
Superconducting magnet system

Beam site MEPHISTO @ FRM II / Garching (DEU)

Hall layout



J. Klenke, JLSRF 1, A21 (2015)



- `empty´ new hall
- neutron guide: L = 40 m, R = 3 km, m = 2.5, □ = 6x10.6 cm^2
- expected flux: 2×10^{10} n /cm^2/s (equal to PF1B at ILL)
- expected mean wavelength: 4.5 Å
- only very few neighbours → low background
- easy ground level access, fixed installation

PERC Collaboration

H. Abele[1], M. Beck[2], J. Bosina[1,3,4], D. Dubbers[5], J. Erhart[1], H. Fillunger[1,3], C. Gösselsberger[1], S. Haas[1], P. Haiden[1], W. Heil[2], A. Hollering[6], M. Horvath[1], E. Jericha[1], C. Klauser[1,4], J. Klenke[6], M. Klopf[1], G. K.[1,3], T. Lauer[6], K. Lehmann[6], H. Lopez[5], W. Mach[1], B. Märkisch[7] (Spokesperson), R.K. Maix[1,7], H. Mest[6], A. Pethukov[4], L. Raffelt[3], N. Rebrova[3], C. Roick[3], H. Saul[1,4,6], U. Schmidt[5], T. Soldner[4], C. Theroine[7], R. Virot[4], X. Wang[1], B. Windelband[5], C. Ziener[5], O. Zimmer[4], J. Zmeskal[3]

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3 SMI

4 ill NEUTRONS FOR SCIENCE

5 UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

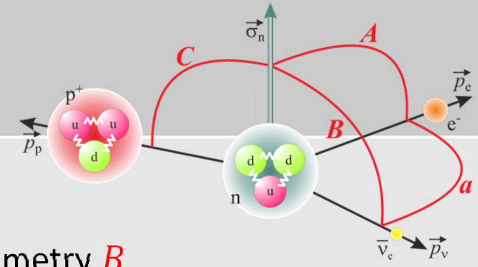
6 FRM II Forschungs-Neutronenquelle Heinz Maier-Leibnitz

7 TUM Technische Universität München

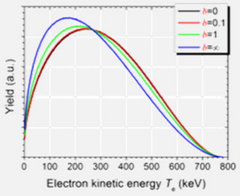
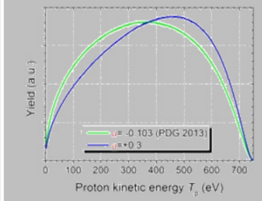
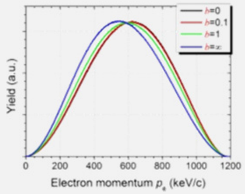
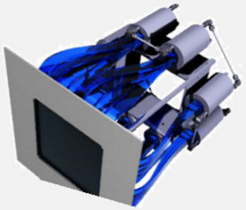
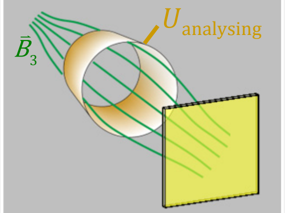
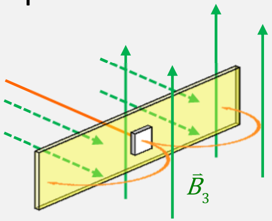
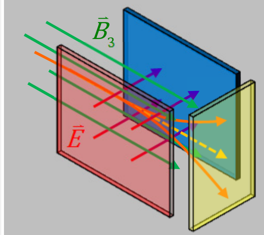
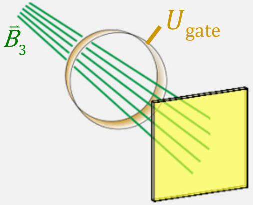

PERC Collaboration, FRM II, Winter 2014

Scientific objectives of PERC

Observable	Physics case
Beta asymmetry A, electron-neutrino-correlation a	➢ Input for cosmology, astrophysics, neutrino physics ➢ Tests of the SM (unitarity of quark mixing, conservation of weak vector currents) ➢ Search for right-handed currents, S, T admixtures
Neutrino asymmetry B, proton asymmetry C	➢ Search for right-handed currents, S, T admixtures
Longitudinal electron polarization	➢ Search for $\mathcal{T}$ reversal and $\mathcal{CP}$ violation ➢ Search for S, T admixtures
Energy spectra of electrons (b, f_2) and protons, energy dependence of correlation coefficients	➢ Search for S, T admixtures ➢ Weak magnetism in electroweak interaction ➢ Radiative corrections ➢ Search for Lorentz invariance violation



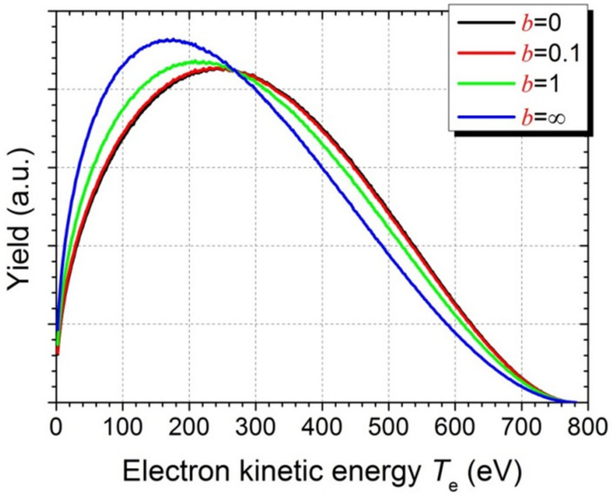
User experiments @ PERC

Observable	e Energy	p Energy	e/p Momenta	p Velocity	p TOF
					
Measurement principle	e Detector	MAC-E Filter	Magnetic spectrometer	Wien filter	Electrostatic chopper
					
Detector	Scintillator, silicon detector	Silicon detector	Spatial-resolving detector	Spatial-resolving detector	Silicon detector
Example	PERKEO I – III, UCNA	aSPECT, PERKEO III			

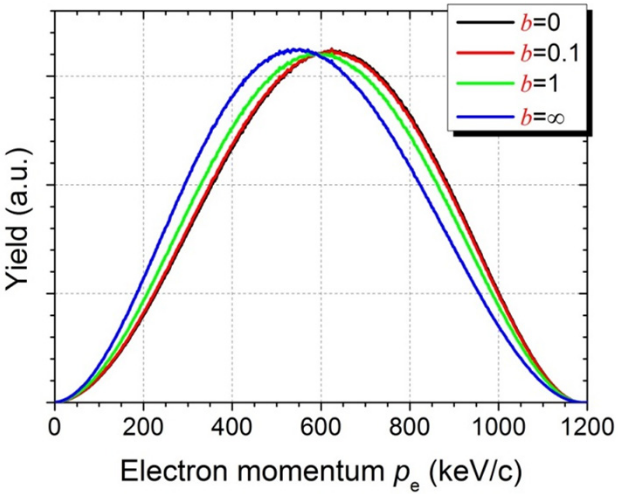
Prospects for Fierz term b @ PERC

$$d\Gamma_b = \left(1 + b\frac{m_e}{E_e}\right) d\Gamma_{SM}$$

Electron energy spectrum

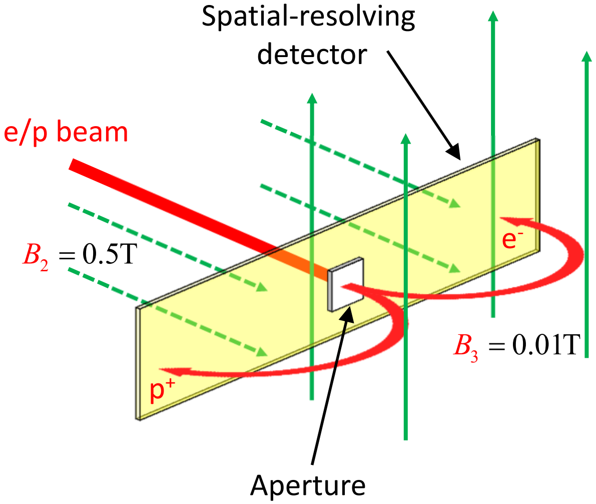


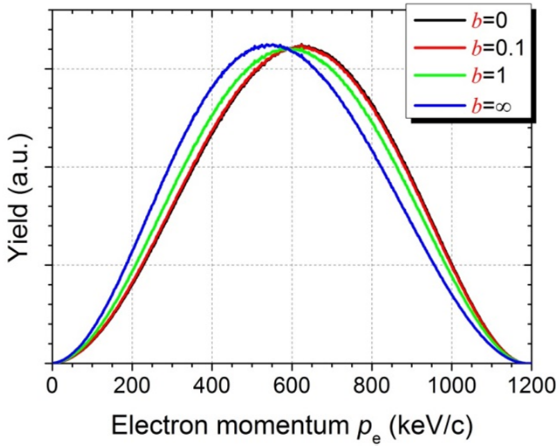
Electron momentum spectrum



– limited energy resolution of scintillation detectors

Magnetic spectrometer @ PERC





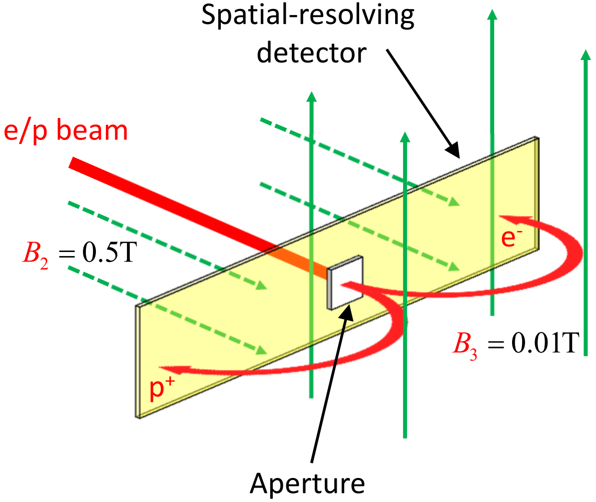
+ large drift distances $\mathcal{O}$(dm)

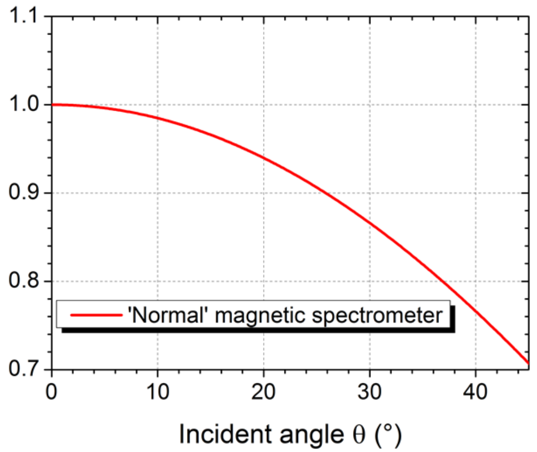
– no low momentum measurements

Radius of gyration:

$$r(p,\theta) = \frac{p_\perp}{|q| B_3} = \frac{p}{|q| B_3}\cos\theta$$

Magnetic spectrometer @ PERC





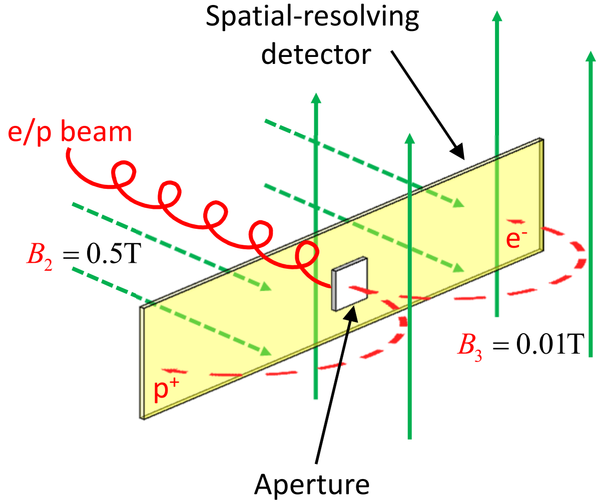
+ large drift distances $\mathcal{O}$(dm)

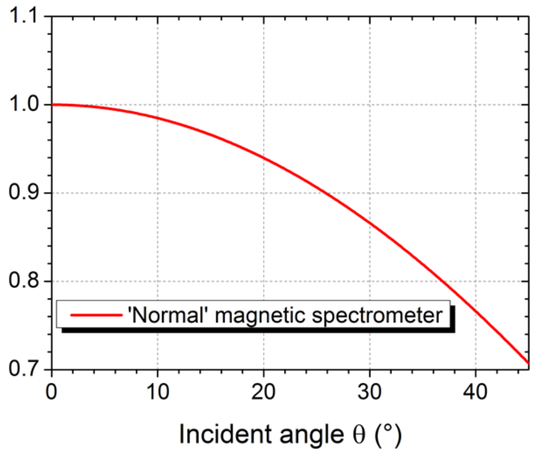
– no low momentum measurements
– large corrections for θ

Radius of gyration:

$$r(p,\theta) = \frac{p_\perp}{|q| B_3} = \frac{p}{|q| B_3} \cos\theta$$

Magnetic spectrometer @ PERC





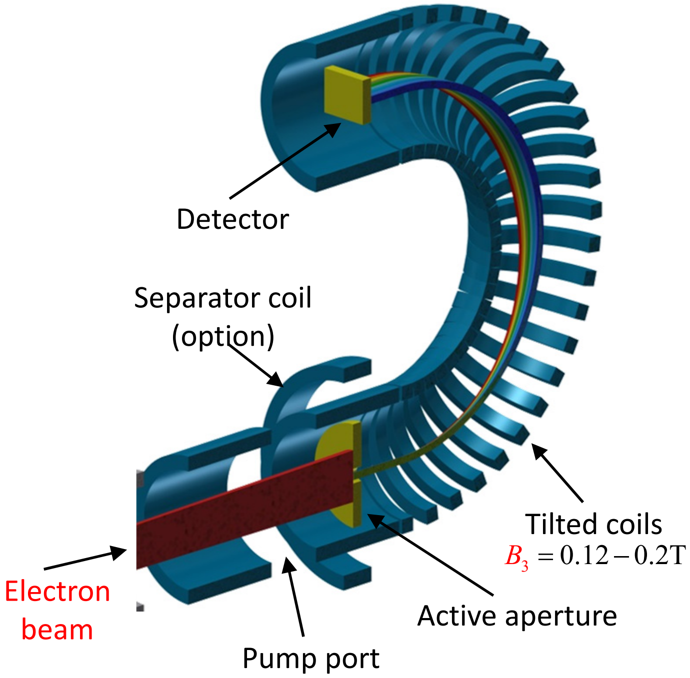
Radius of gyration:

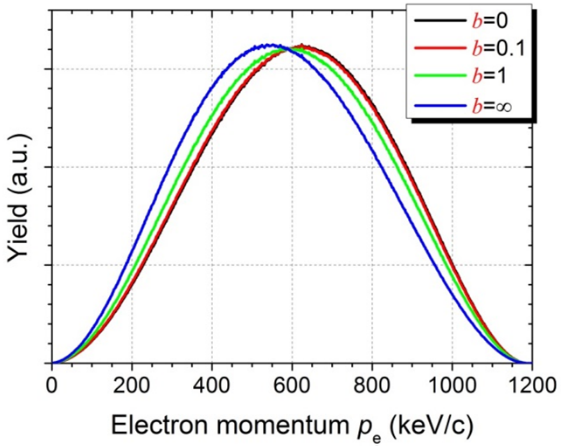
$$r(p,\theta) = \frac{p_\perp}{|q| B_3} = \frac{p}{|q| B_3} \cos\theta$$

+ large drift distances $\mathcal{O}$(dm)

– no low momentum measurements
– large corrections for θ
– non-adiabatic transport of particles
– B_2-field coupled with B_3-field
– pitch angles easily distorted

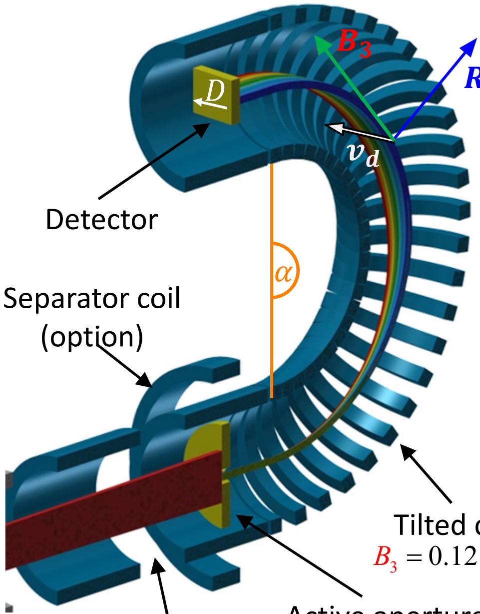
R×B drift momentum spectrometer

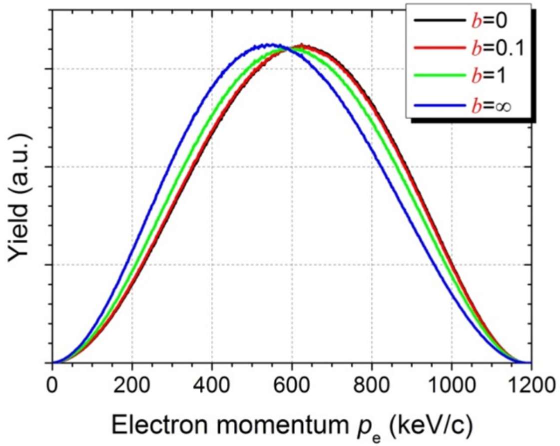




$$r(p,\theta) = \frac{p_\perp}{|q|B_3} = \frac{p}{|q|B_3}\cos\theta$$

R×B drift momentum spectrometer



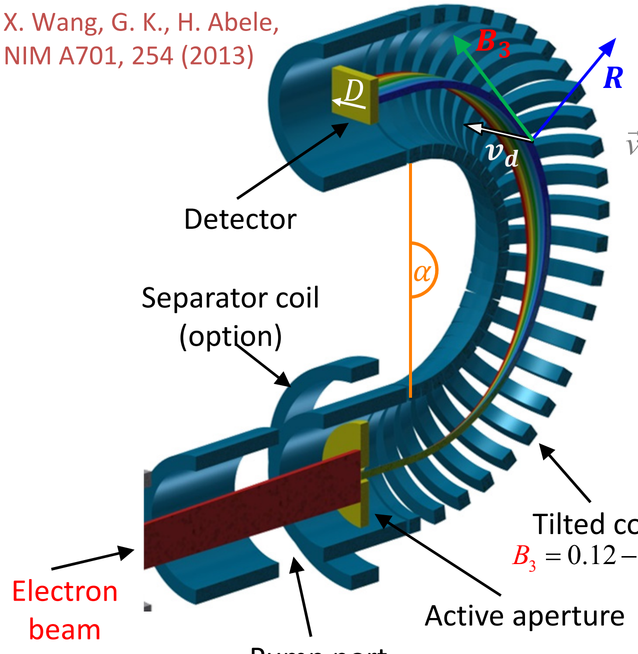


$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3}\cdot\alpha\cdot\frac{1}{2}(\cos\theta + \frac{1}{\cos\theta})$$

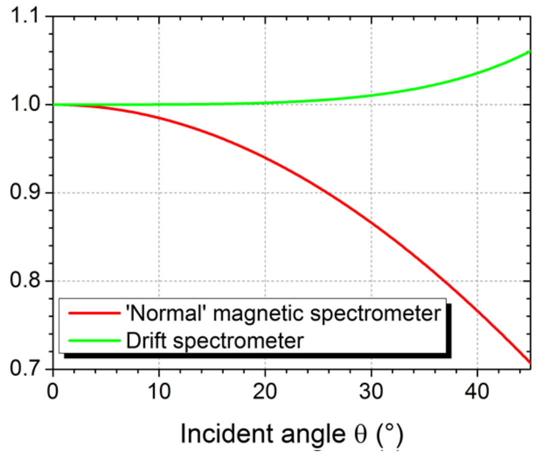
+ low momentum measurements
+ adiabatic transport of particles

R×B drift momentum spectrometer

X. Wang, G. K., H. Abele, NIM A701, 254 (2013)



$$\vec{v}_d \propto \frac{\vec{R} \times \vec{B}_3}{qR^2 B_3^2}$$

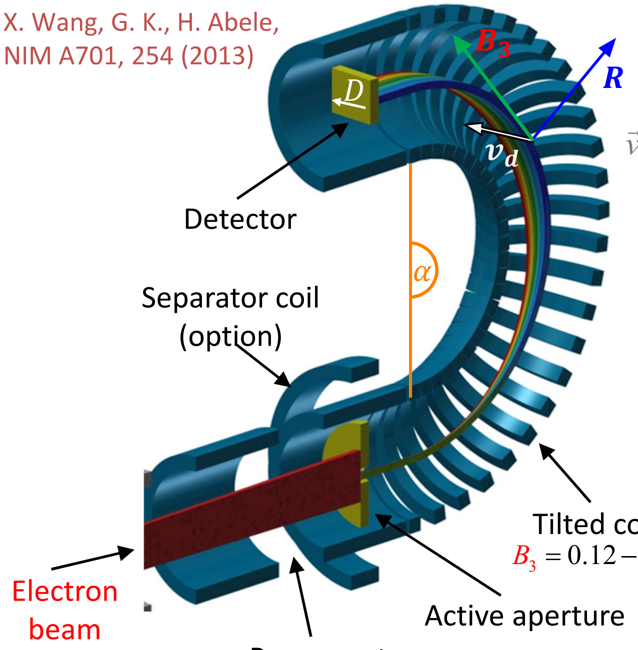


$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3} \cdot \alpha \cdot \frac{1}{2}(\cos\theta + \frac{1}{\cos\theta})$$

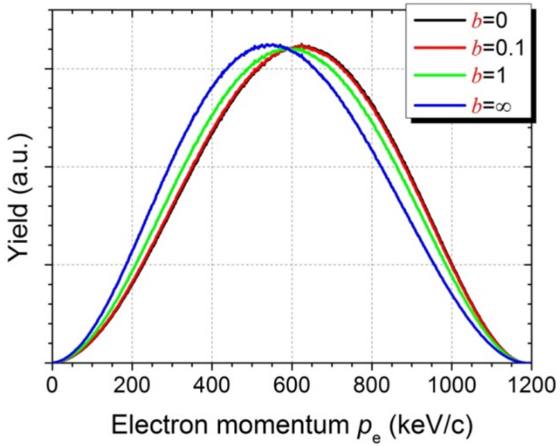
- \+ low momentum measurements
- \+ adiabatic transport of particles
- \+ small corrections for θ
- \+ large acceptance of θ

R×B drift momentum spectrometer

X. Wang, G. K., H. Abele,
NIM A701, 254 (2013)



$$\vec{v}_d \propto \frac{\vec{R}\times\vec{B}_3}{qR^2B_3^2}$$



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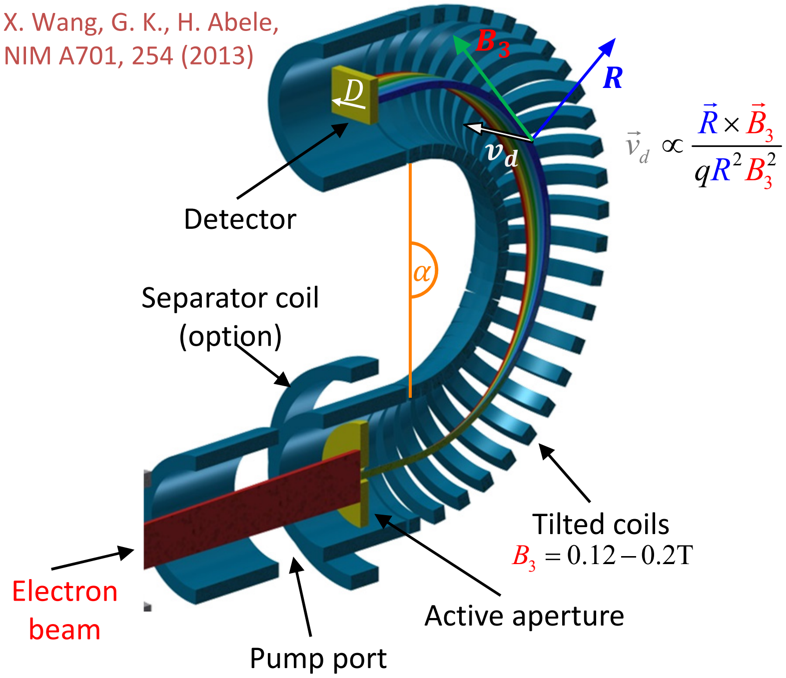
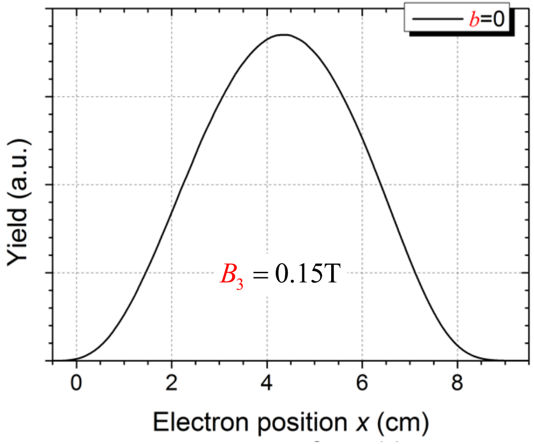
R×B drift momentum spectrometer

X. Wang, G. K., H. Abele,
NIM A701, 254 (2013)



$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3}\cdot\alpha\cdot\frac{1}{2}(\cos\theta + \frac{1}{\cos\theta})$$



+ low momentum measurements
+ adiabatic transport of particles
+ small corrections for θ
+ large acceptance of θ
+ high resolution: $\Delta p/p = 14.4$ keV/c /mm

1.2% /mm

– small drift distances $\mathcal{O}$(cm)

NoMoS

Neutron decay prOducts MOmentum Spectrometer

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN *New Frontiers Group at* SMI

NoMoS Physics programme

G. Konrad, PoS(EPS-HEP2015)592

Research focus:

- Weak magnetism form factor f_2
  - study structure of weak interaction
- Beta asymmetry parameter A, electron-neutrino correlation coefficient a
  - determine weak coupling constants ratio $\lambda = g_A / g_V$
  - test CKM unitarity
- Fierz interference term b
  - non-zero value indicates existence of scalar or tensor interactions
  - caused by, e.g., yet unknown charged Higgs bosons or leptoquarks
- Oscillatory, sidereal effects in the case of Lorentz invariance violation

Goal:

Electron and proton spectroscopy on sub-10^{-4}- respectively 10^{-3}-level

NoMoS Physics programme

G. Konrad, PoS(EPS-HEP2015)592

Research focus:

- Weak magnetism form factor f_2
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- Fierz interference term b
- Oscillatory, sidereal effects in the case of Lorentz invariance violation

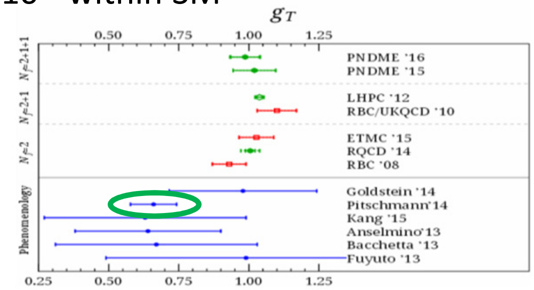
Goal:

Electron and proton spectroscopy on sub-10^{-4}- respectively 10^{-3}-level

Theoretical prerequisite:

cooperation with M. Pitschmann *et al.*, TU Wien

- Extension of analysis of correlation coefficients a, A, B, C, and D to order 10^{-5} within SM
- Completion of analysis of non-standard correlation coefficients N, G, R, Q, and L to order 10^{-3} within SM
- Most precise evaluation possible of g_S and g_T within SM and beyond
  M. Pitschmann et al., Phys. Rev. D91 (2015) 074004
- ✓ Comprehensive analysis of standard correlation coefficients to order 10^{-4}
  A. Ivanov *et al.*, Phys. Rev. D88, 073002 (2013)



NoMoS Collaboration

H. Abele[1], J. Bosina[1,2,3], C. Brousse[2,4], J. Erhart[1], H. Fillunger[1,2], M. Klopf[1], G. K.[1,2], M. Pitschmann[1], T. Soldner[3], K. Suzuki[2] , X. Wang[1], J. Zmeskal[2]

1 ATOMINSTITUT

2 SMI

3 NEUTRONS FOR SCIENCE

4 ECAM ECOLE D'INGENIEURS Strasbourg - Europe

Supported by

ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

TU WIEN

SLOW NEUTRONS DFG SPP 1491

bmwfw Bundesministerium für Wissenschaft, Forschung und Wirtschaft

DFG Deutsche Forschungsgemeinschaft

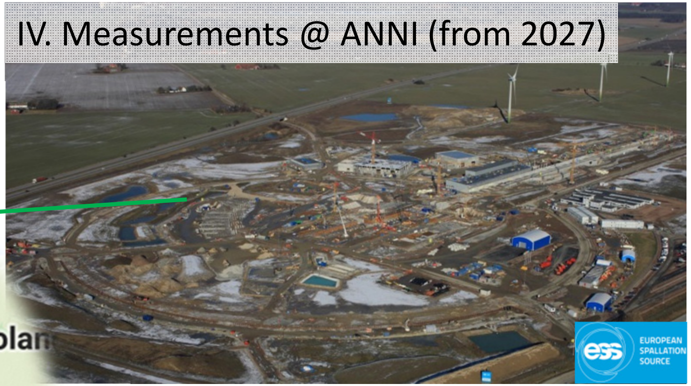
Nationalstiftung für Forschung Technologie Entwicklung

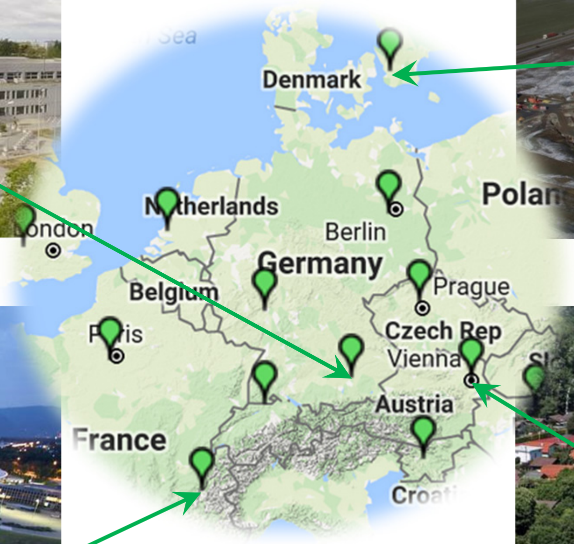
NEUTRONS FOR SCIENCE

FWF Der Wissenschaftsfonds.

Two Ph.D. positions open

Preliminary measurement plan of NoMoS





ANNI

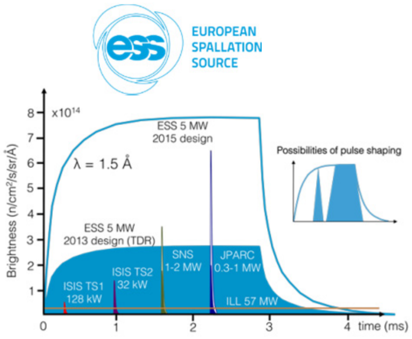
A COLD NEUTRON BEAM FACILITY FOR PARTICLE PHYSICS AT THE ESS

ANNI Overview

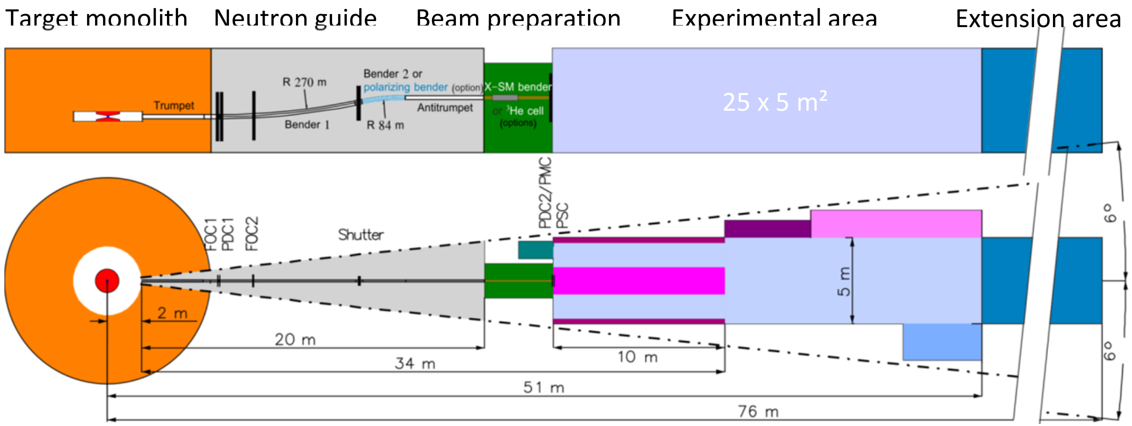
SY 3

Scientific case

- neutron beta decay
- hadronic weak interaction
- electromagnetic properties
- technical developments
- etc.



First pulsed source with higher time-averaged flux than ILL



Parameter	Value
Capture flux full spectrum	1.8×10^{10} n /cm²/s
Capture flux 2 – 8 Å	1.4×10^{10} n /cm²/s
Particle flux @ 8.9 Å	5.8×10^{8} /cm²/s/Å
Divergence distribution FWHM	42 mrad horizontal, 22 mrad vertical
Instantaneous bandwidth	0.43 Å

C. Theroine et al., *ESS instrument construction proposal ANNI*, 2015
E. Klinkby, T. Soldner, J. Phys.: Conf. Ser. [ECNS2015] (2016), accepted

ANNI Collaboration

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Gertrud Konrad[1,2]
Bastian Märkisch[3]
Ulrich Schmidt[4]
Torsten Soldner[5]
Camille Theroine[3,6]

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2 SMI
3 TUM TECHNISCHE UNIVERSITÄT MÜNCHEN
4 UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386
5 ILL NEUTRONS FOR SCIENCE
6 ess EUROPEAN SPALLATION SOURCE

New partners very welcome!

Summary and Outlook

- Neutron alphabet
  - deciphers the Standard Model of particle physics
  - observables in neutron β-decay are abundant
- Precision measurements of neutron β-decay
  - address important open questions of particle physics, astrophysics, and cosmology
  - 10^{-3} level b measurements complementary to improved LHC results
- New facility PERC at FRM II
  - clean and bright source of neutron decay products
  - sensitivity improved to sub-10^{-4}-level
  - systematics $\leq 10^{-4}$
- ÖAW New Frontiers Group NoMoS
  - novel R×B drift spectrometer for momentum spectroscopy
  - comprehensive physics programme
- Future possibilities: ANNI facility at ESS

Thanks to my colleagues @ SMI and TU Wien

BACKUP

Error budget of PERC

Source of error	|Size| of correction	Size of error
Non-uniform neutron beam	2.5×10^{-4}	5×10^{-5}
Other edge effects on e/p-window	4.0×10^{-4}	1×10^{-4}
Magn. mirror effect, contin's neutron beam	1.4×10^{-2}	2×10^{-4}
Magn. mirror effect, pulsed neutron beam	5.0×10^{-5}	$< 10^{-5}$
Non-adiabatic e/p-transport	5.0×10^{-5}	5×10^{-5}
Background from neutron guide	2.0×10^{-3}	1×10^{-4}
Background from neutron beam stop	2.0×10^{-4}	1×10^{-5}
Backscattering of e/p-window	1.0×10^{-3}	1×10^{-4}
Backscattering off e/p beam dump	5.0×10^{-5}	1×10^{-5}
Backscattering off plastic scintillator	2.0×10^{-3}	4×10^{-4}
… same with active e/p-beam dump	–	1×10^{-4}

D. Dubbers et al., NIM A596 (2008) 238 and arXiv:0709.4440

Neutron beam polarisation	$< 10^{-4}$	$< 10^{-4}$

C. Klauser et al., J. Phys.: Conf. Ser. 340 (2012) 012011
C. Klauser, Ph.D. thesis, TU Wien, 2013