NoMoS

Beyond the Standard Model Physics in Neutron Decay

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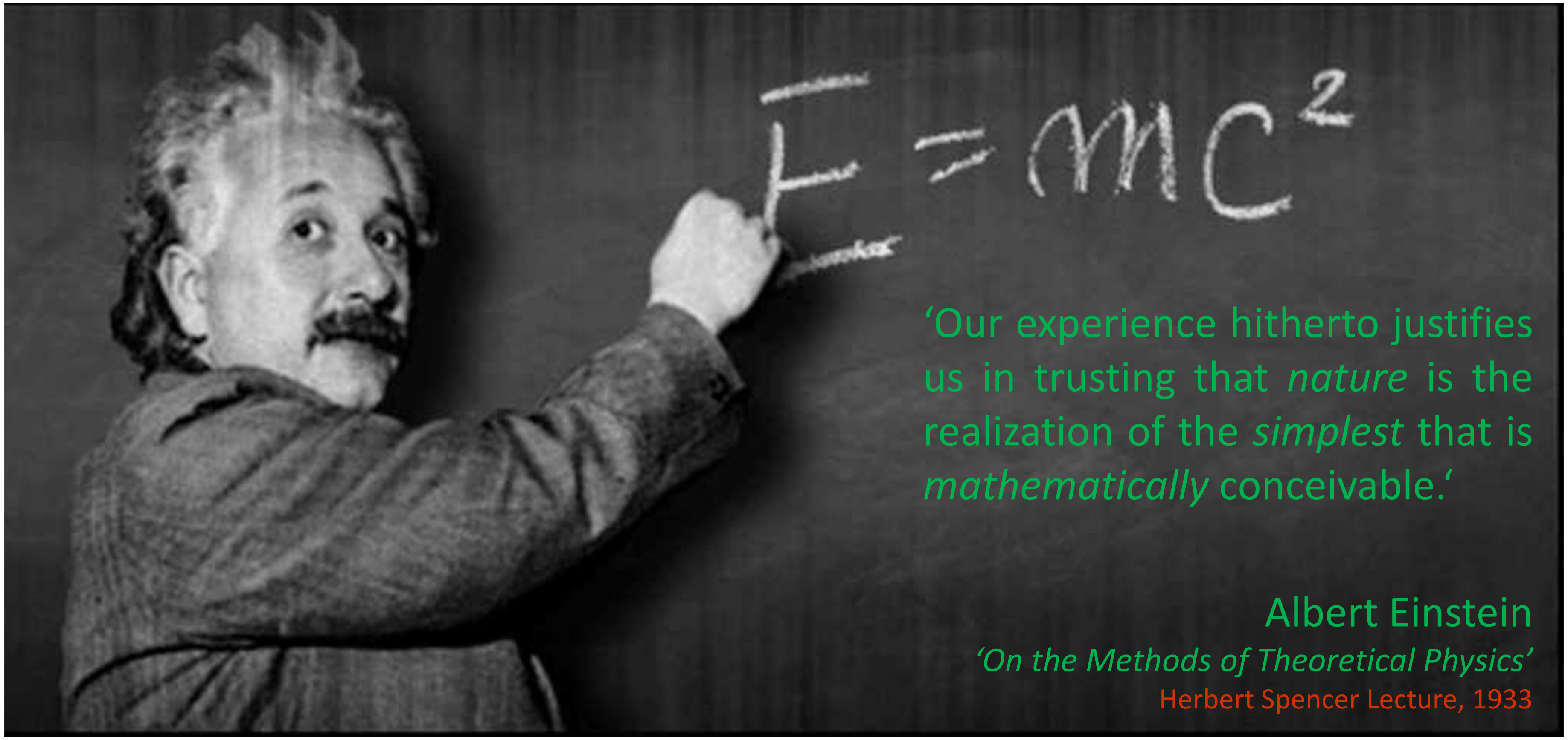
Kitzbühel, Austria,
June 26 – July 1, 2016

Alexander von Humboldt Kolleg
'From the Vacuum to the Universe'

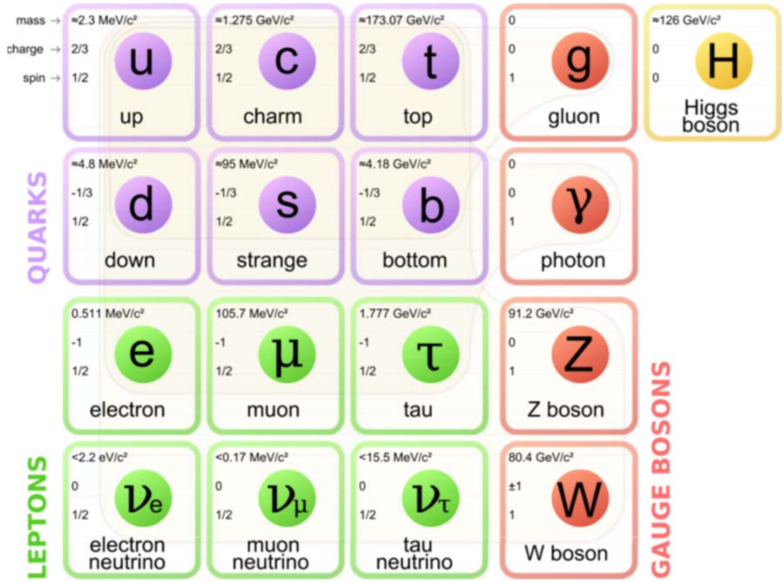


LAWS IN NATURE

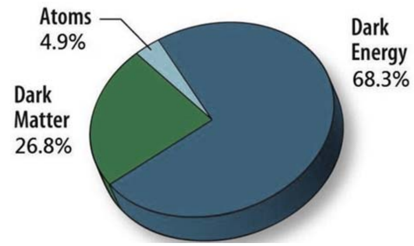
nomos tes physeos

The Standard Model

Present best theory of fundamental particles and interactions



- gravitation not incorporated!
- three generations?
- left-right asymmetry?
- excess of matter in universe?
- nature of dark matter?
- nature of dark energy?
- neutrino oscillations?
- etc.



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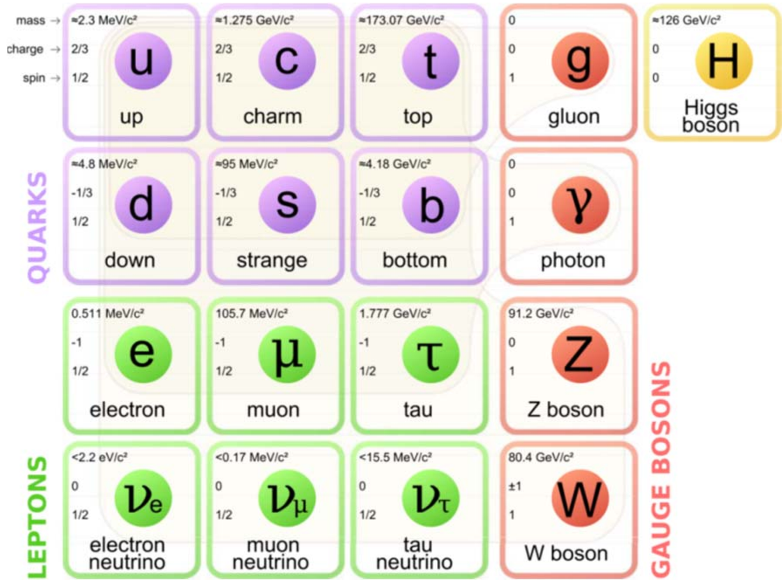

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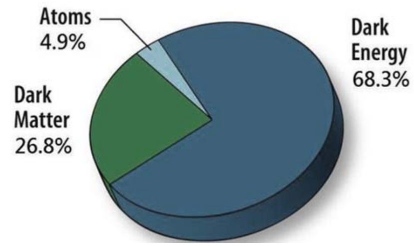


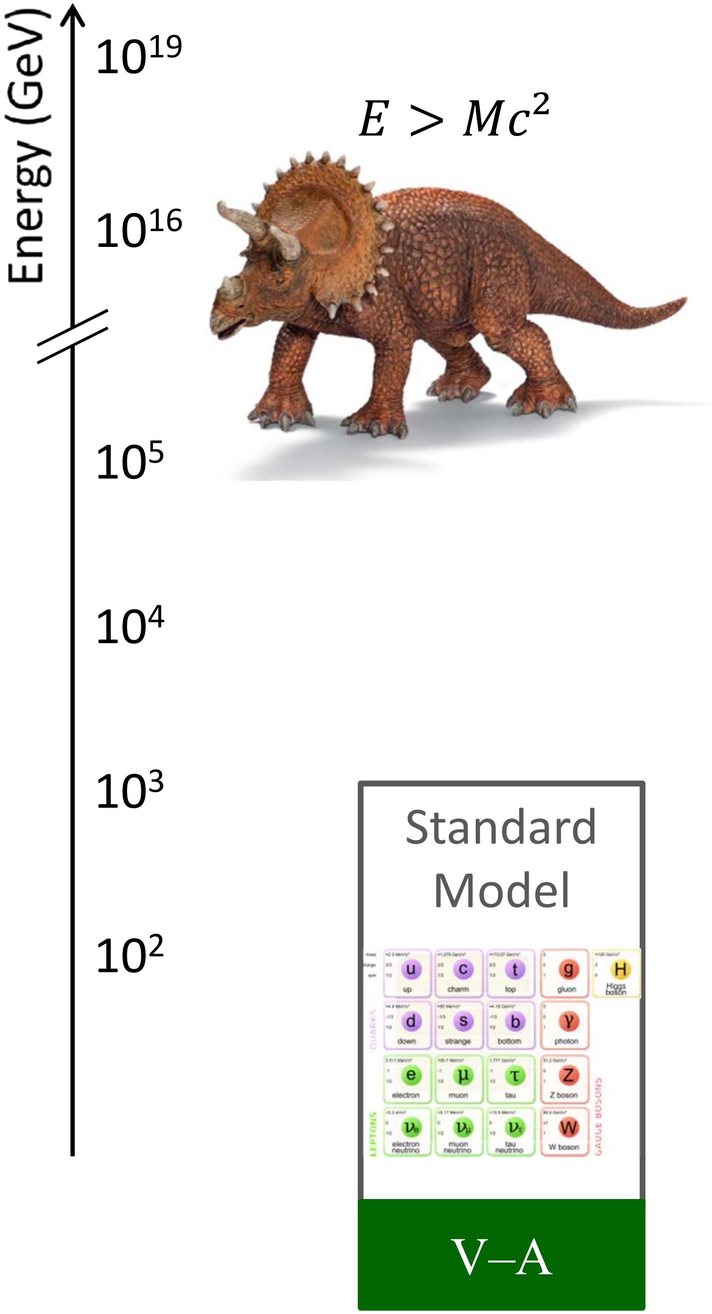
$n \rightarrow p + e^- + \bar{\nu}_e + 782.334\text{keV}$:

- prototype of weak interactions
- described by V–A theory:

$$H_{V-A} = \frac{G_F V_{ud}}{\sqrt{2}} \langle p | \gamma_\mu \left(1 + \frac{g_A}{g_V} \gamma^5 \right) | n \rangle \langle e^- | \gamma_\mu (1 - \gamma_5) | \nu_e \rangle + h.c.$$

quark mixing   nucleon structure   helicity

Experimental approach to Standard Model



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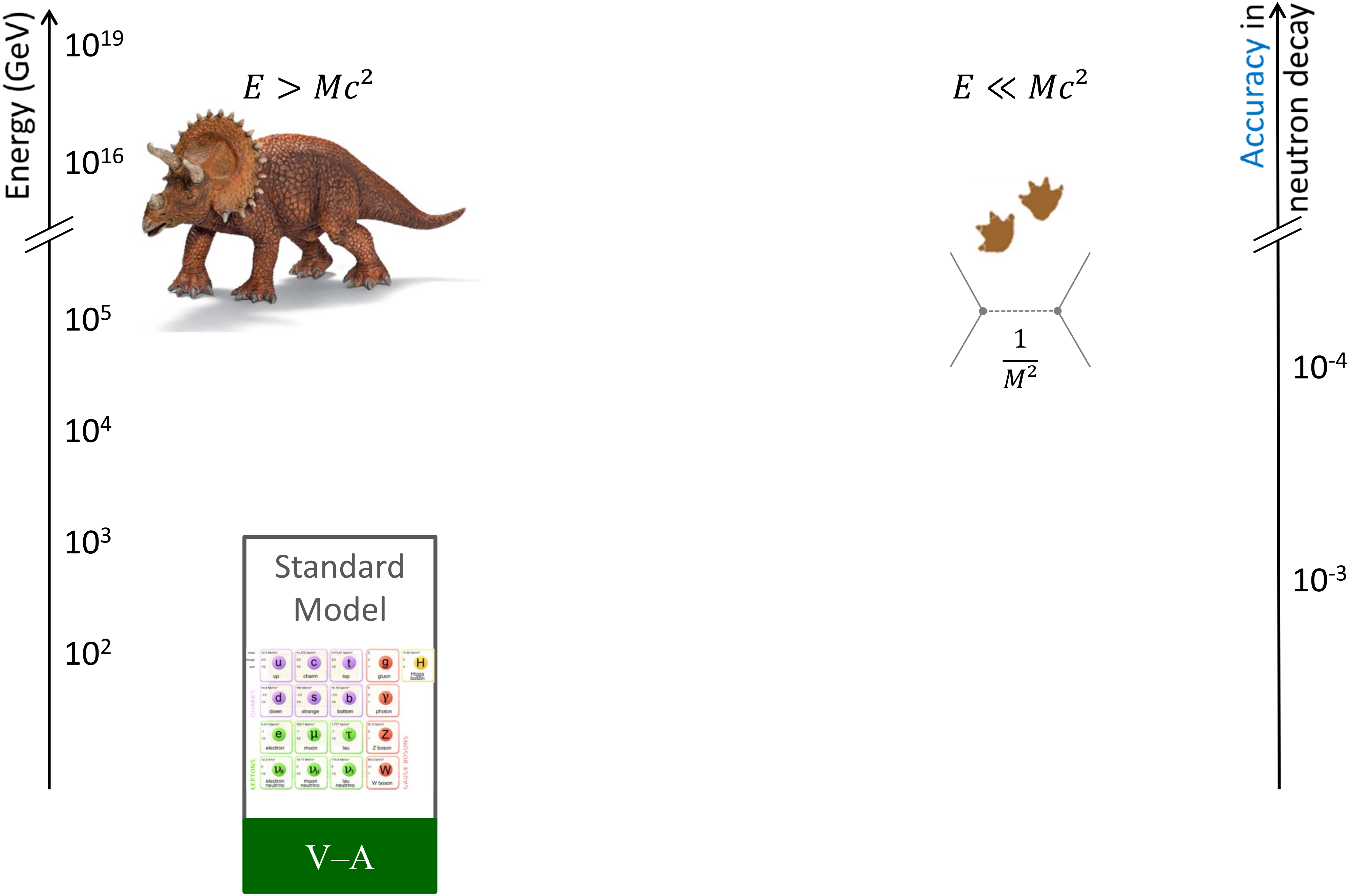
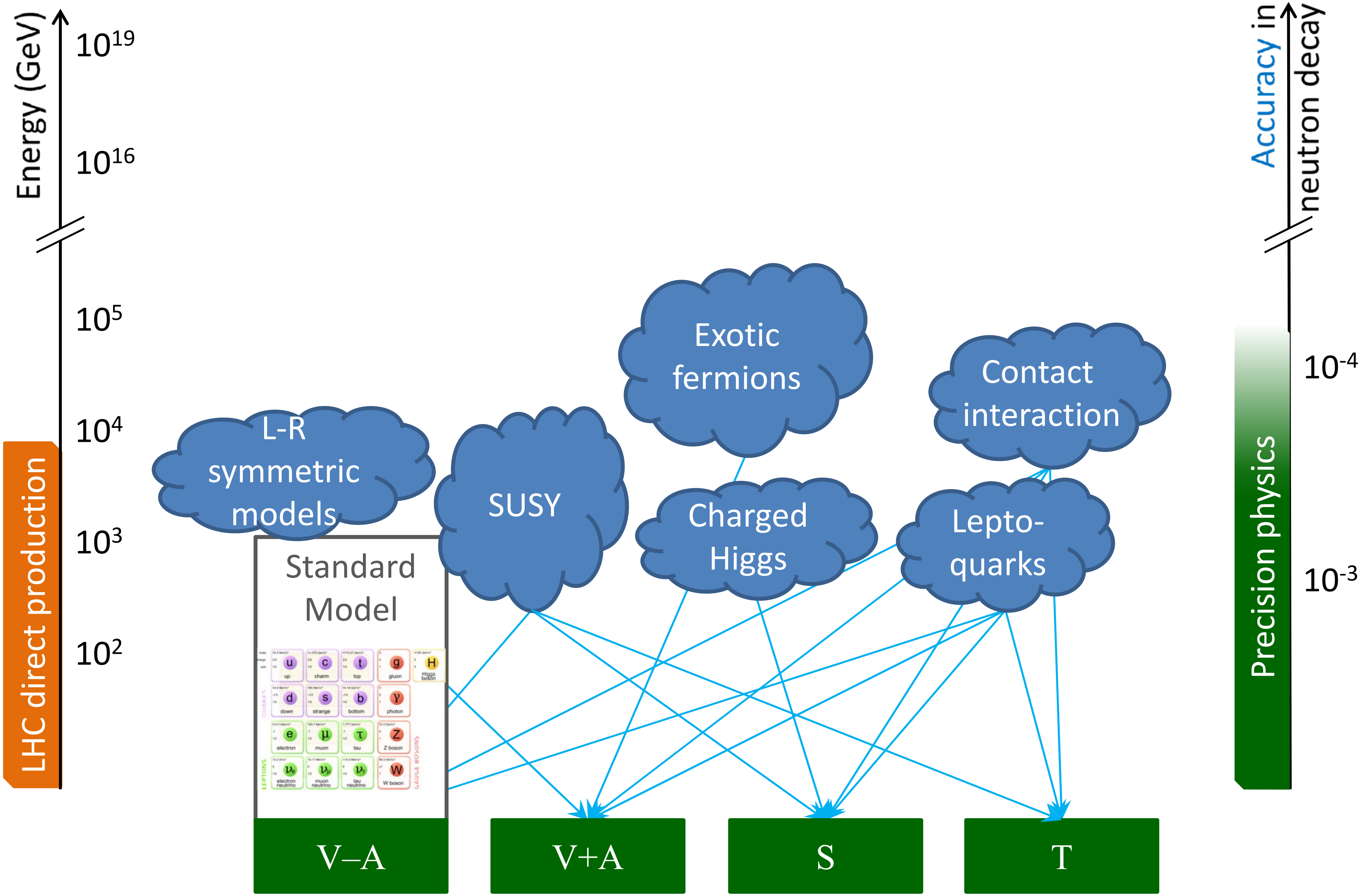


Experimental approach to ‘physics beyond’



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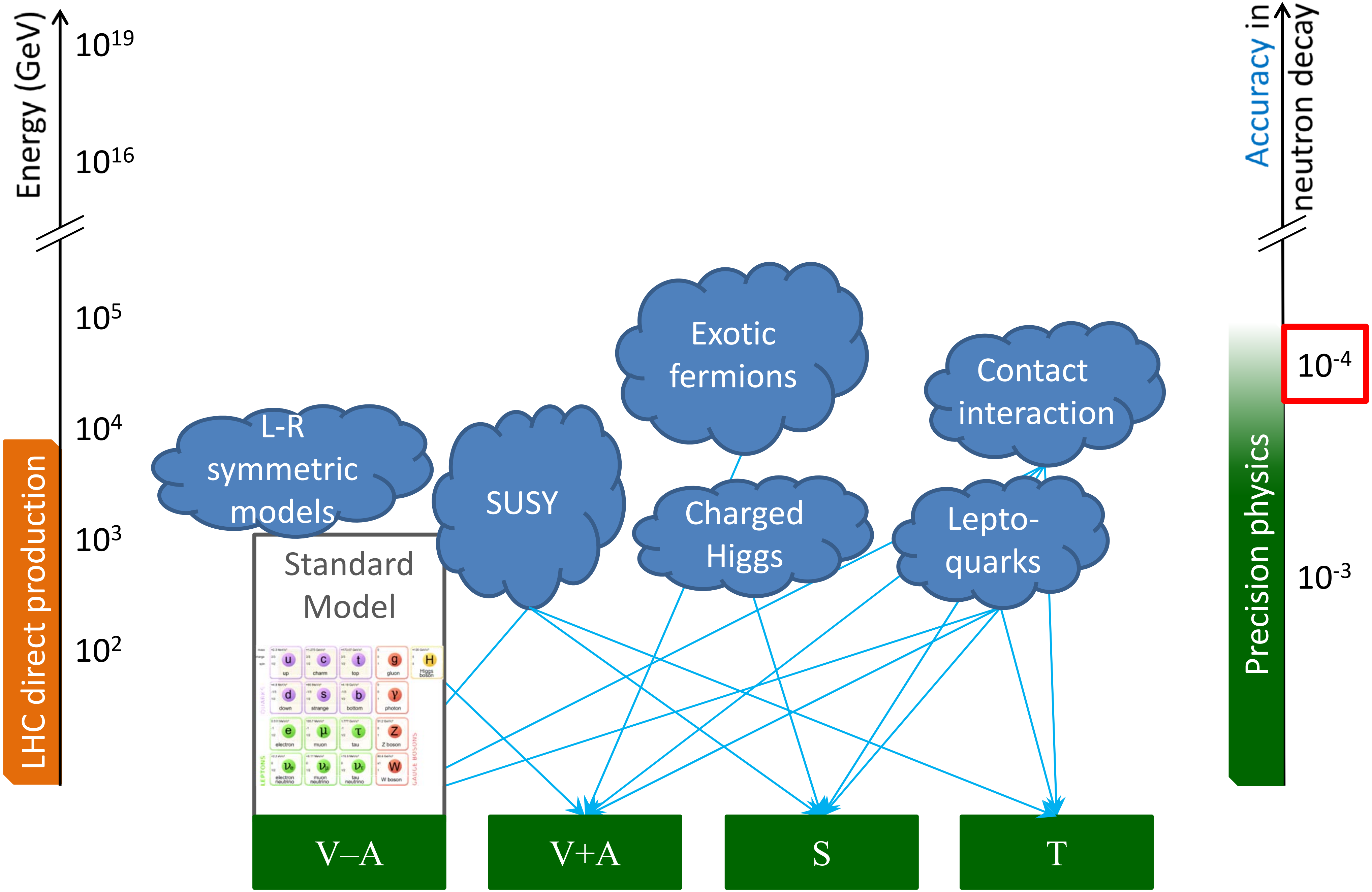
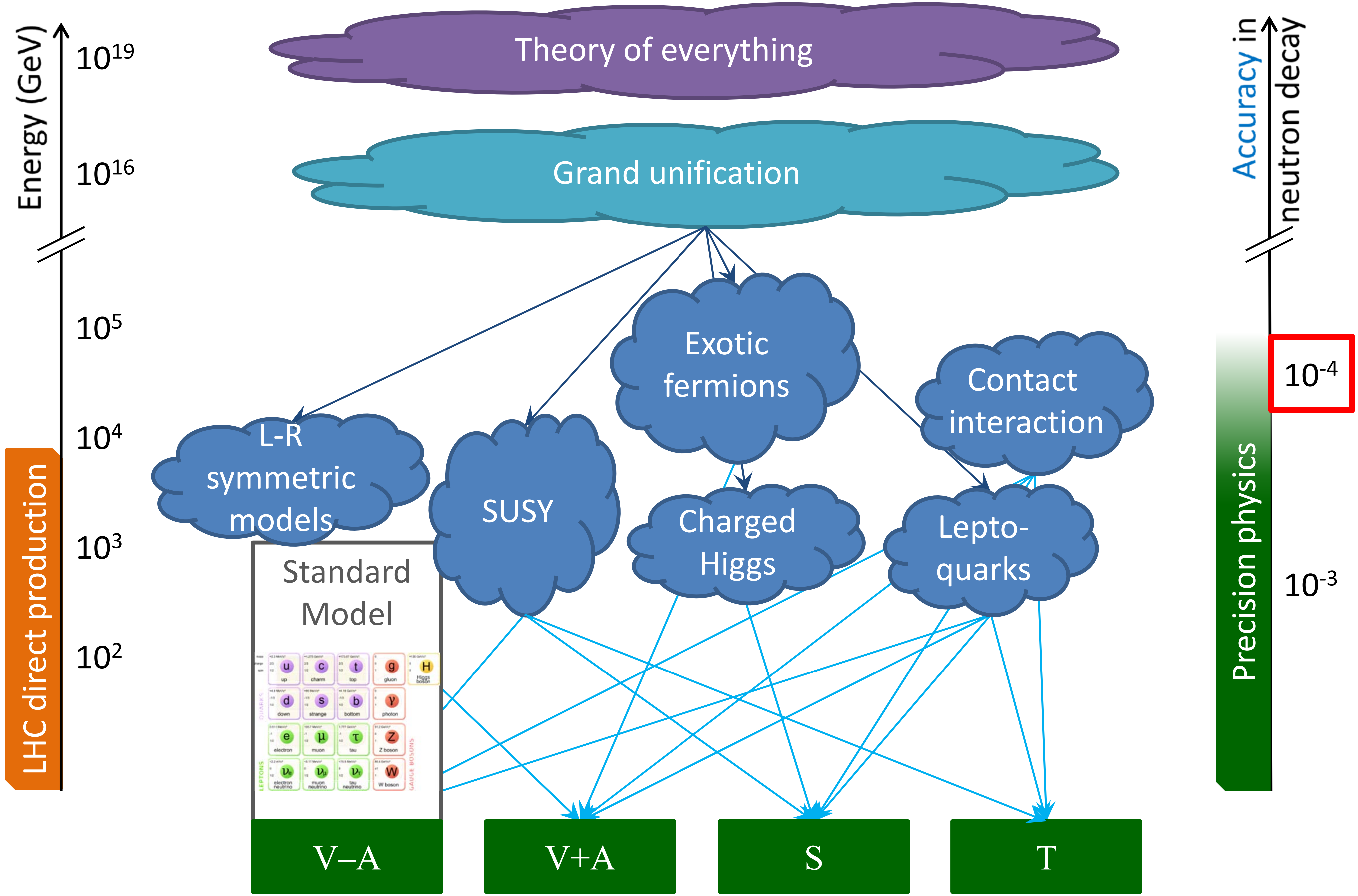
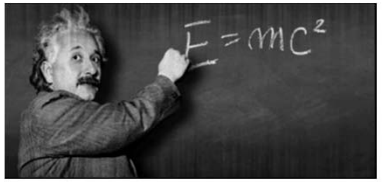


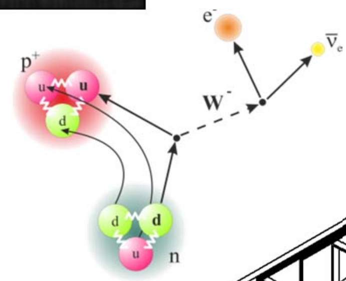

Energy (GeV)
10^19
10^16
10^5
10^4
10^3
10^2
LHC direct production
Theory of everything
Grand unification
Exotic fermions
Contact interaction
L-R symmetric models
SUSY
Charged Higgs
Lepto-quarks
Standard Model
V–A
V+A
S
T
Accuracy in neutron decay
10^-4
10^-3
Precision physics

Outline

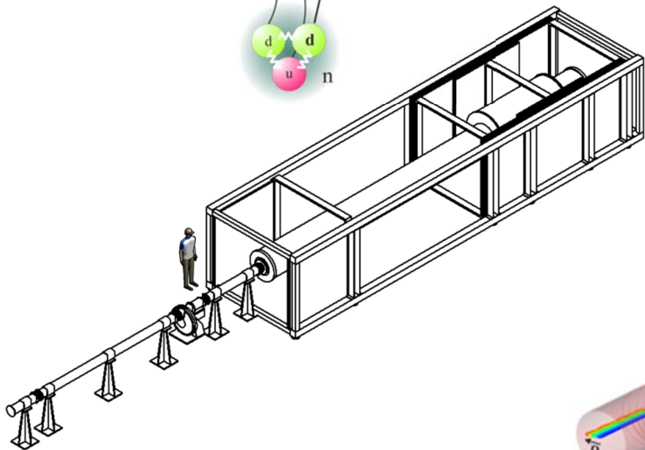
- Laws in Nature



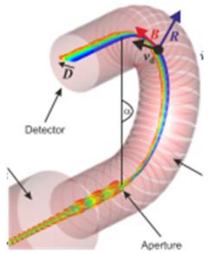
- The Neutron



- Neutron β-decay experiments
  - at facility PERC



- ÖAW New Frontiers Group NoMoS



- Summary & Outlook

THE NEUTRON

Properties of the Neutron

- **Charge:** $< 10^{-21}$ e — neutral
- **Mass:** 1838.683 m_e — 939.565 MeV/c²
- **Spin:** ½ ħ
- **Lifetime:** 880.3(1.1) s — 1×10^{-3}

$$n \to p + e^- + \overline{\nu}_e + Q$$

$$Q = (m_n - m_p - m_e - m_\nu) \cdot c^2 = 782.334\,\text{keV}$$

coupling strength

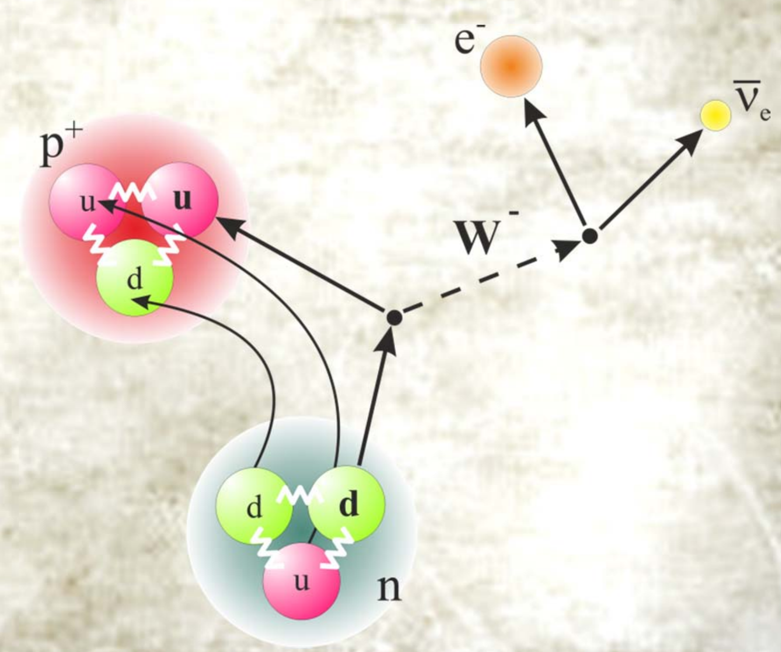
$$\tau_n = \frac{1}{|V_{ud}|^2} \frac{(4908.7 \pm 1.9)\,s}{(1 + 3|\lambda|^2)}$$

$|V_{ud}|$: quark mixing

$$\lambda = g_A / g_V$$

$$g_V = G_F \cdot V_{ud}$$

G_F: μ-decay



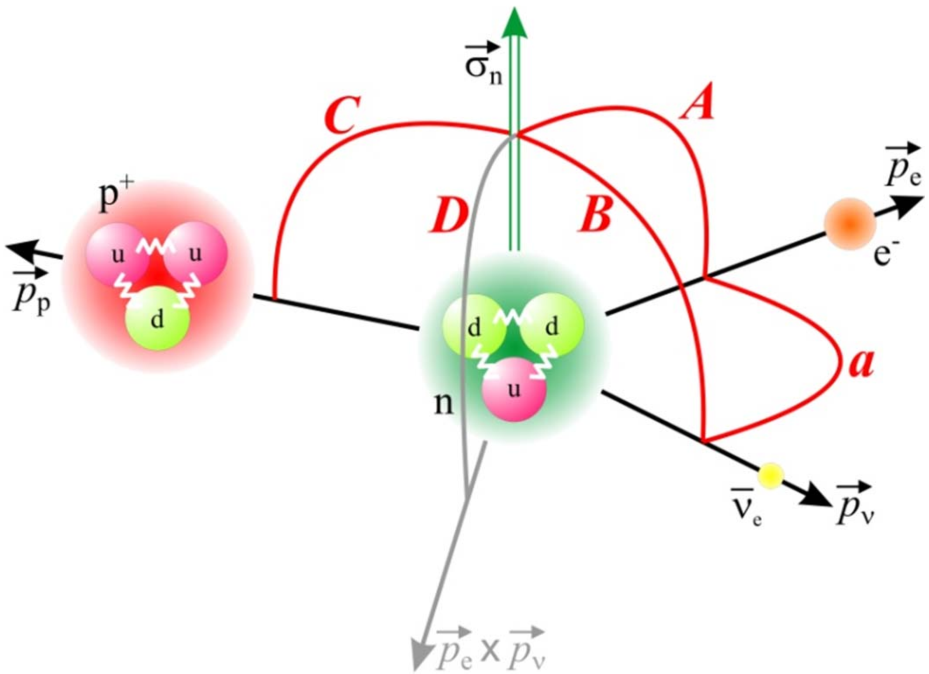
A. Czarnecki et al., PR D 70, 093006 (2004)

The neutron alphabet

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

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

J.D. Jackson *et al.*, PR **106**, 517 (1957)



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- 2 unknown parameters

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

- 20 or more observables

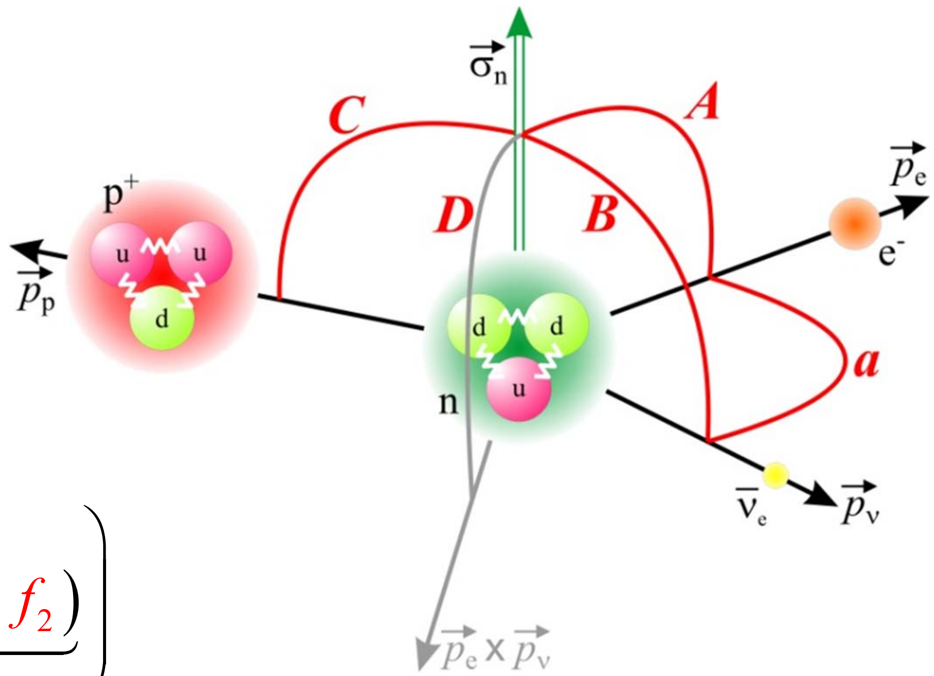
  τ_n, a, b, A, B, C, D, ...

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

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

- yet unmeasured

  b, f_2



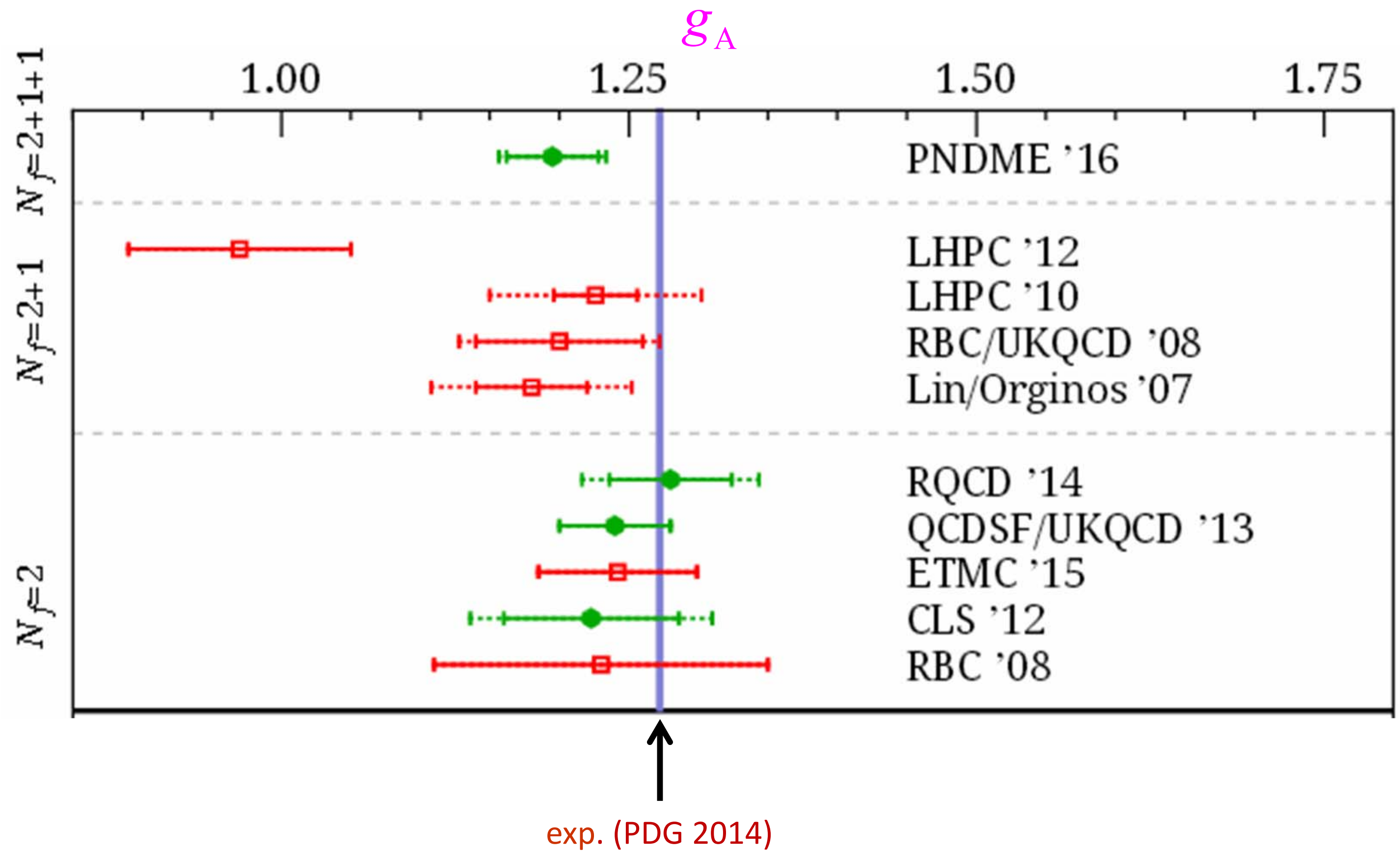
Current status of neutron alphabet

Observable	Standard Model	Status PDG 2014
Lifetime	$\tau_n = \frac{1}{\lvert V_{ud}\rvert^2} \frac{(4908.7 \pm 1.9)\,s}{(1+3\lvert\lambda\rvert^2)}$	$\Delta\tau_n/\tau_n = 1\times10^{-3}$
Ratio of weak coupling constants	$\lambda = g_A / g_V = \lvert\lambda\rvert e^{i\phi}$	$\Delta\lambda/\lambda = 2\times10^{-3}$
Neutrino-electron correlation	$a = \frac{1-\lvert\lambda\rvert^2}{1+3\lvert\lambda\rvert^2}$	$\Delta a/a = 3.9\times10^{-2}$
Fierz interference term	$b = 0$	yet unmeasured
Beta asymmetry	$A = -2\frac{\lvert\lambda\rvert^2 + \lvert\lambda\rvert\cos\phi}{1+3\lvert\lambda\rvert^2}$	$\Delta A/A = 8\times10^{-3}$
Neutrino asymmetry	$B = 2\frac{\lvert\lambda\rvert^2 - \lvert\lambda\rvert\cos\phi}{1+3\lvert\lambda\rvert^2}$	$\Delta B/B = 3\times10^{-3}$
Proton asymmetry	$C = -0.27484(A+B)$	$\Delta C/C = 1.1\times10^{-2}$
Triple correlation	$D = 2\frac{\lvert\lambda\rvert\sin\phi}{1+3\lvert\lambda\rvert^2} \equiv 0 \qquad \phi = 180°$	$D = (-1 \pm 2)\times 10^{-4}$ $\phi = (180.02 \pm 0.03)°$

K.A. Olive et al. (Particle Data Group), Chin. Phys. C **38**, 090001 (2014)

Why investigate neutron β-decay?

- 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)



T. Bhattacharya et al., LA-UR-16-20522, arXiv:1606.07049 (2016)

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

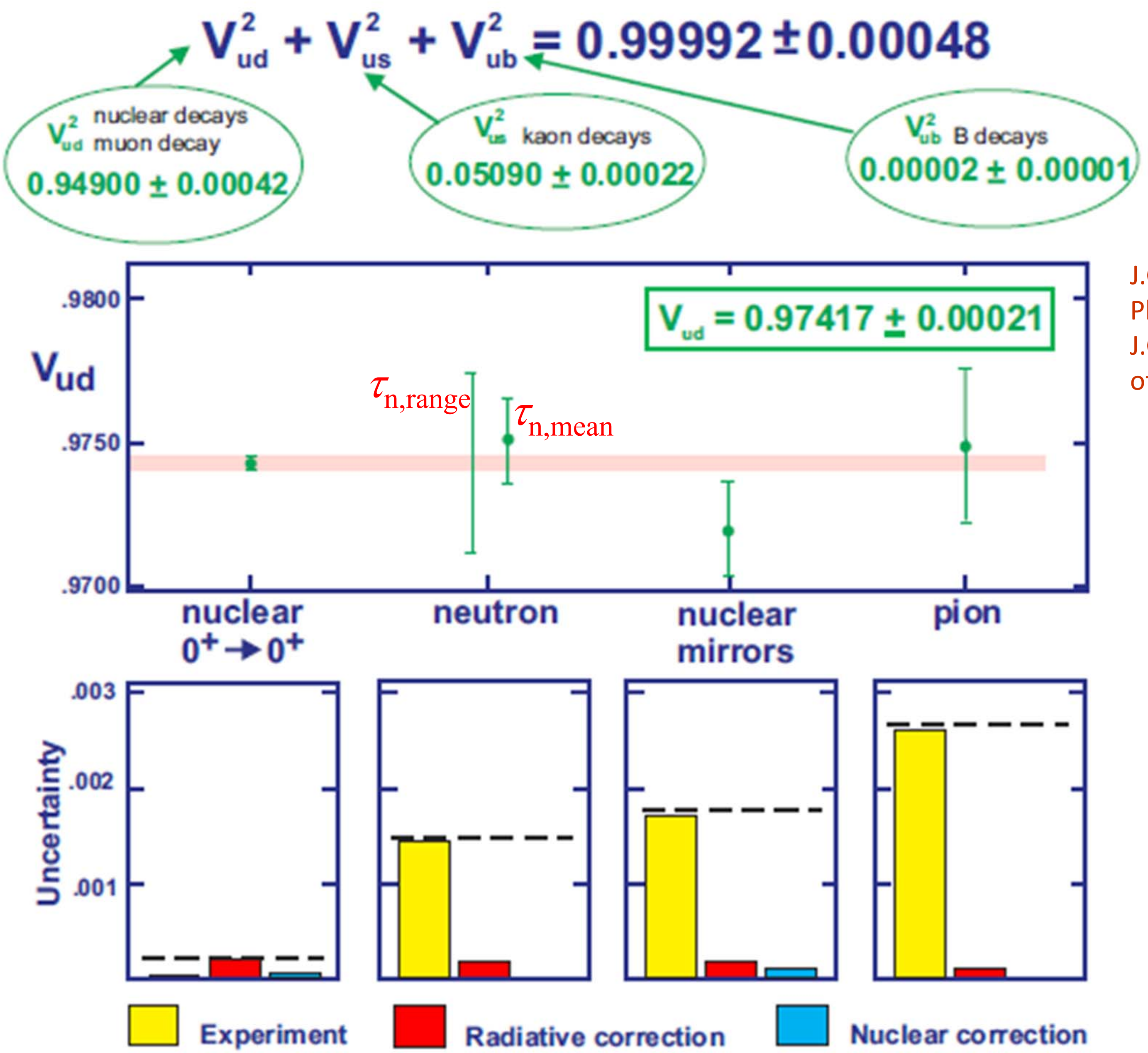
$$V_\mu = \left\langle \mathrm{p} \left| \gamma_\mu - i f_2 \sigma_{\mu\nu} \frac{q^\nu}{2M} \right| \mathrm{n} \right\rangle$$

$$f_2 = \kappa_\mathrm{p} - \kappa_\mathrm{n} \approx 3.7058$$

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

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

CURRENT STATUS OF CKM UNITARITY



J.C. Hardy and I.S. Towner, Phys. Rev. C 91, 025501 (2015)
J.C. Hardy and I.S. Towner, in: Proc. of CIPANP2015, arXiv:1509.04743

Courtesy of J. Hardy

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- Search for ‘physics beyond‘ and new symmetry concepts

Neutron decay correlations

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

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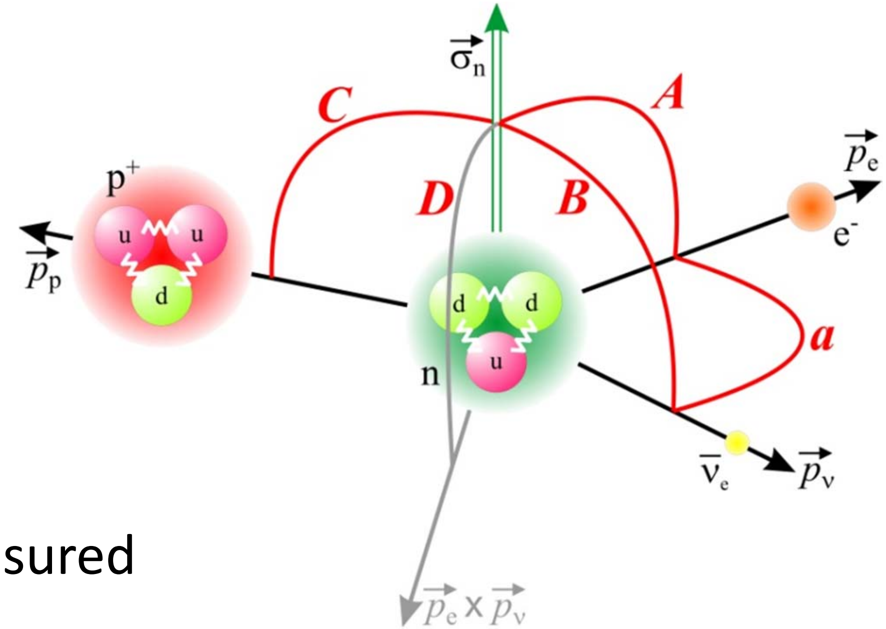
J.D. Jackson *et al.*, PR **106**, 517 (1957)

- 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

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

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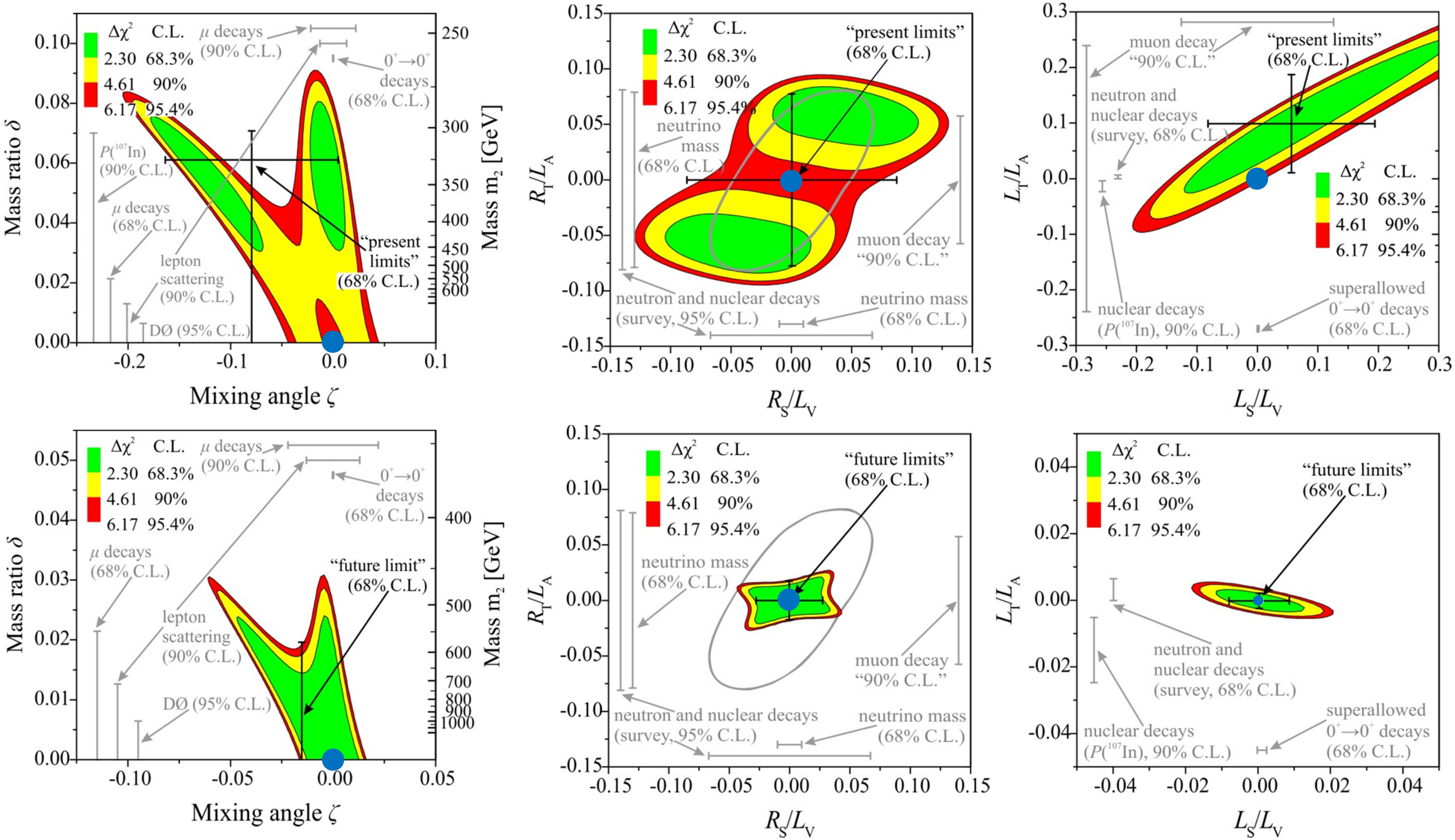
F. Glück *et al.*, NP A **593**, 125 (1995)

Sensitivity to ‘new physics’

Right-handed V+A | Right-handed S, T | Left-handed S, T

Present 2015

Future toy model



G. Konrad *et al.,* in: Proc. BEYOND 2010, World Scientific, 660, 2011, arXiv: 1007.3027v2 (2010)

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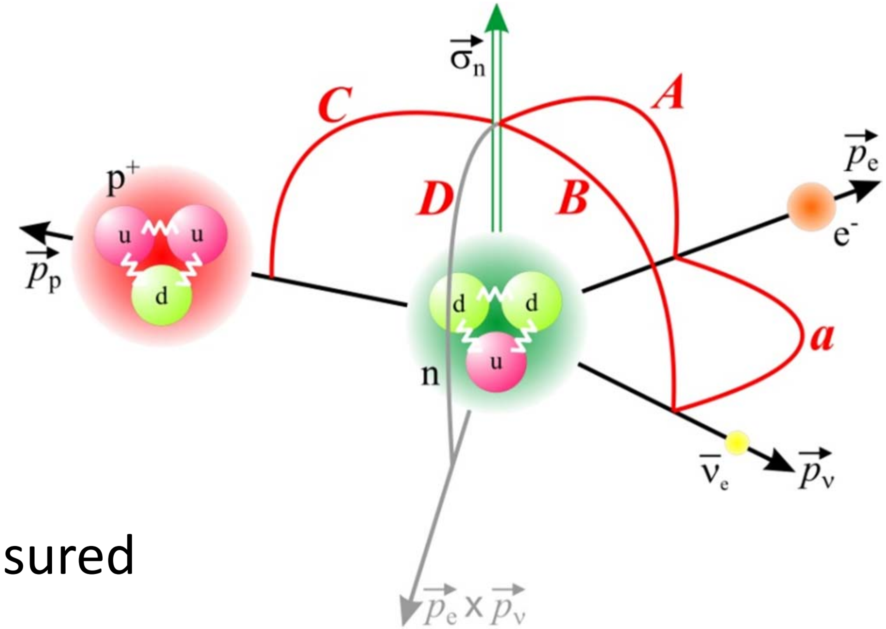

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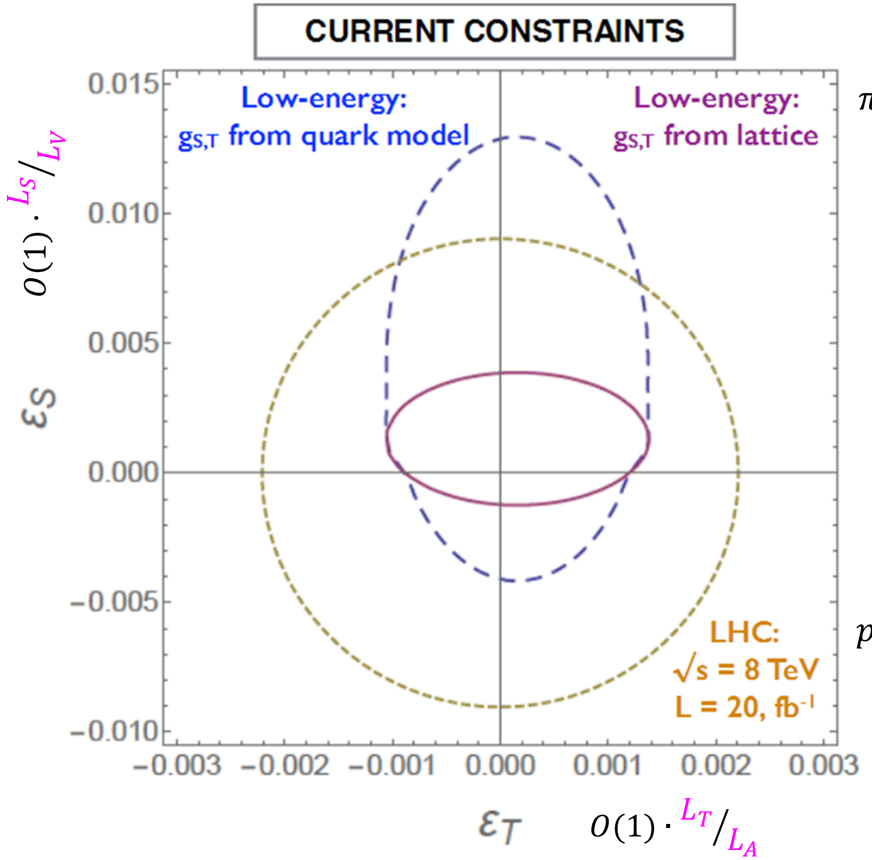
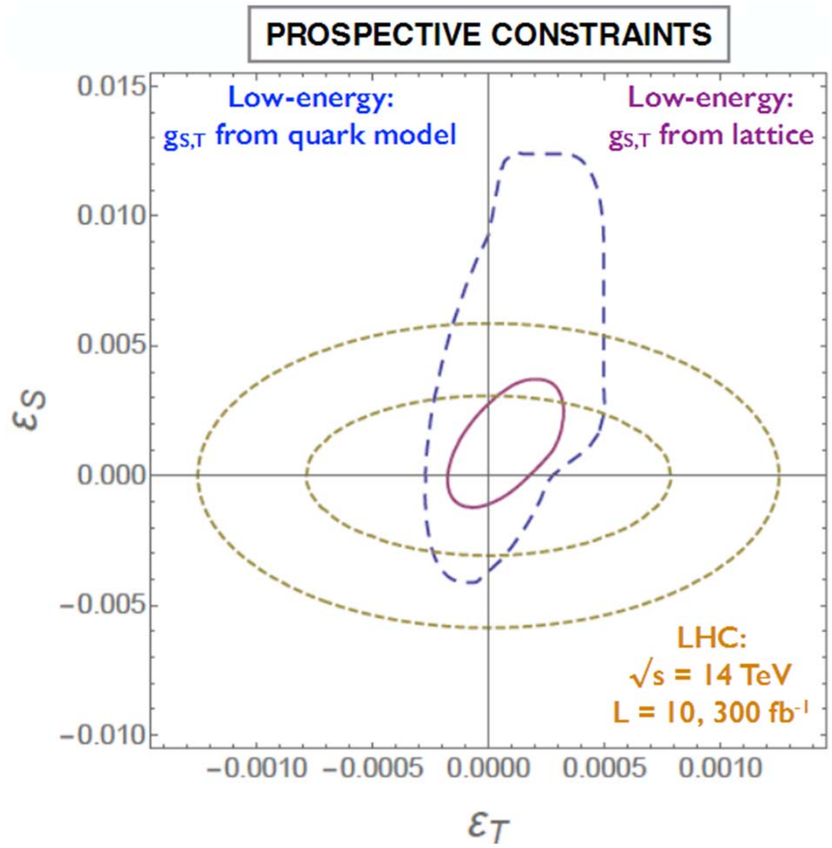
Prospects for S, T interactions in LHC era

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



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

$pp \to e\nu + X$



- 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

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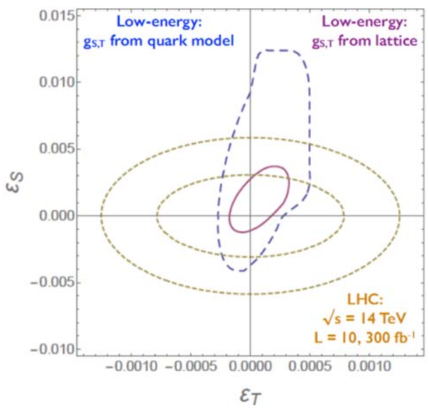
- Search for 'physics beyond' and new symmetry concepts
  - right-handed admixtures, exotic scalar and tensor admixtures
  - left-right symmetry, supersymmetry (SUSY), leptoquarks, etc.
  - SUSY deviations from CKM unitarity ≥ 10^{-4} fall in LHC inaccessible region
  - 10^{-3} level b measurements complementary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



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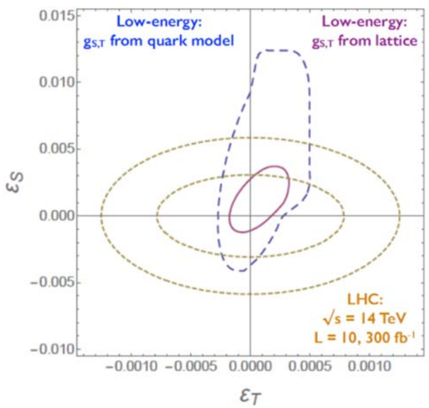
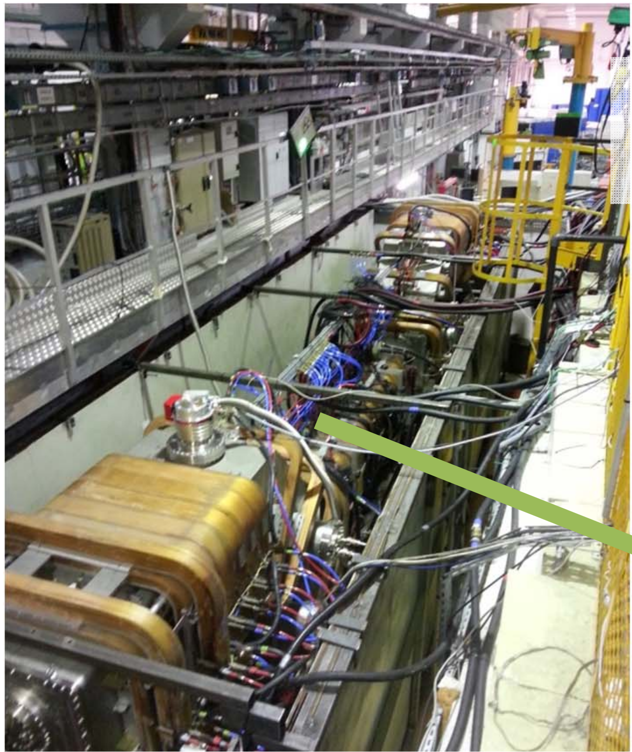
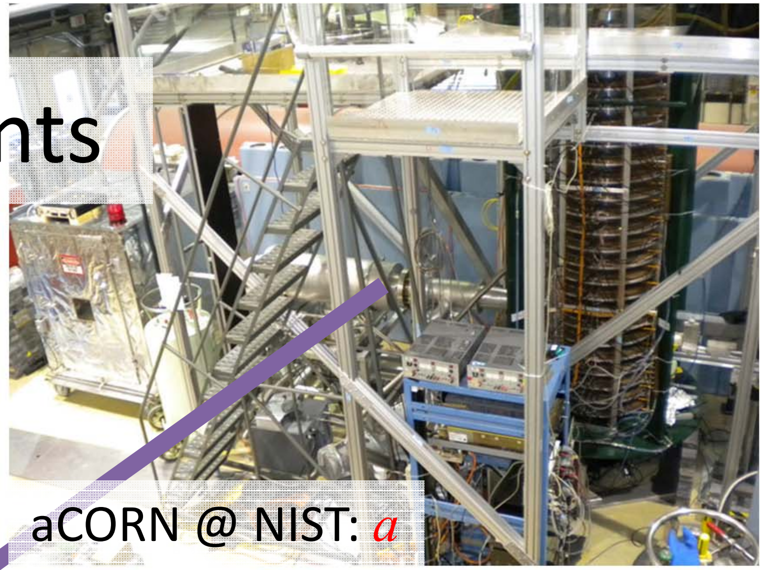


Neutron β-Decay Experiments

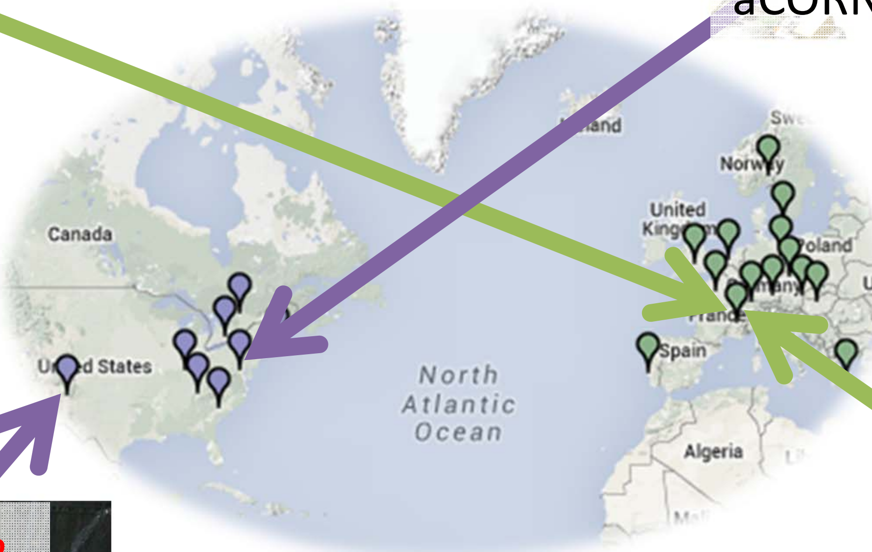
Current experiments

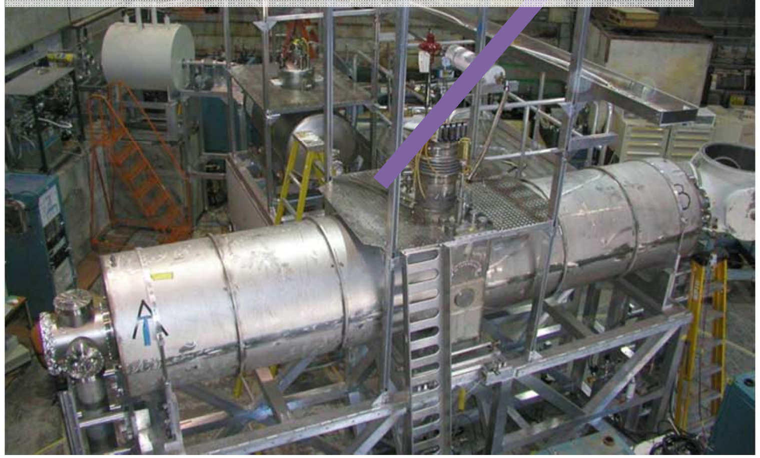


PERKEO III @ ILL: *A, B, C, b*

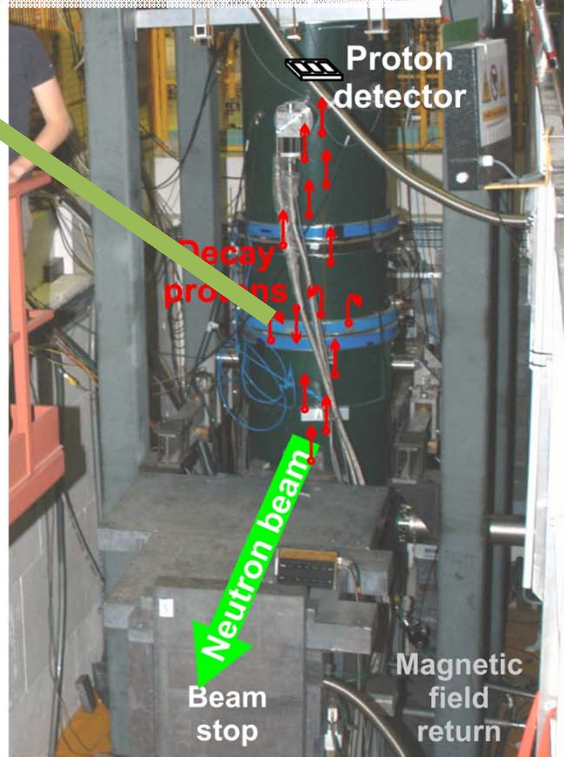


aCORN @ NIST: *a*



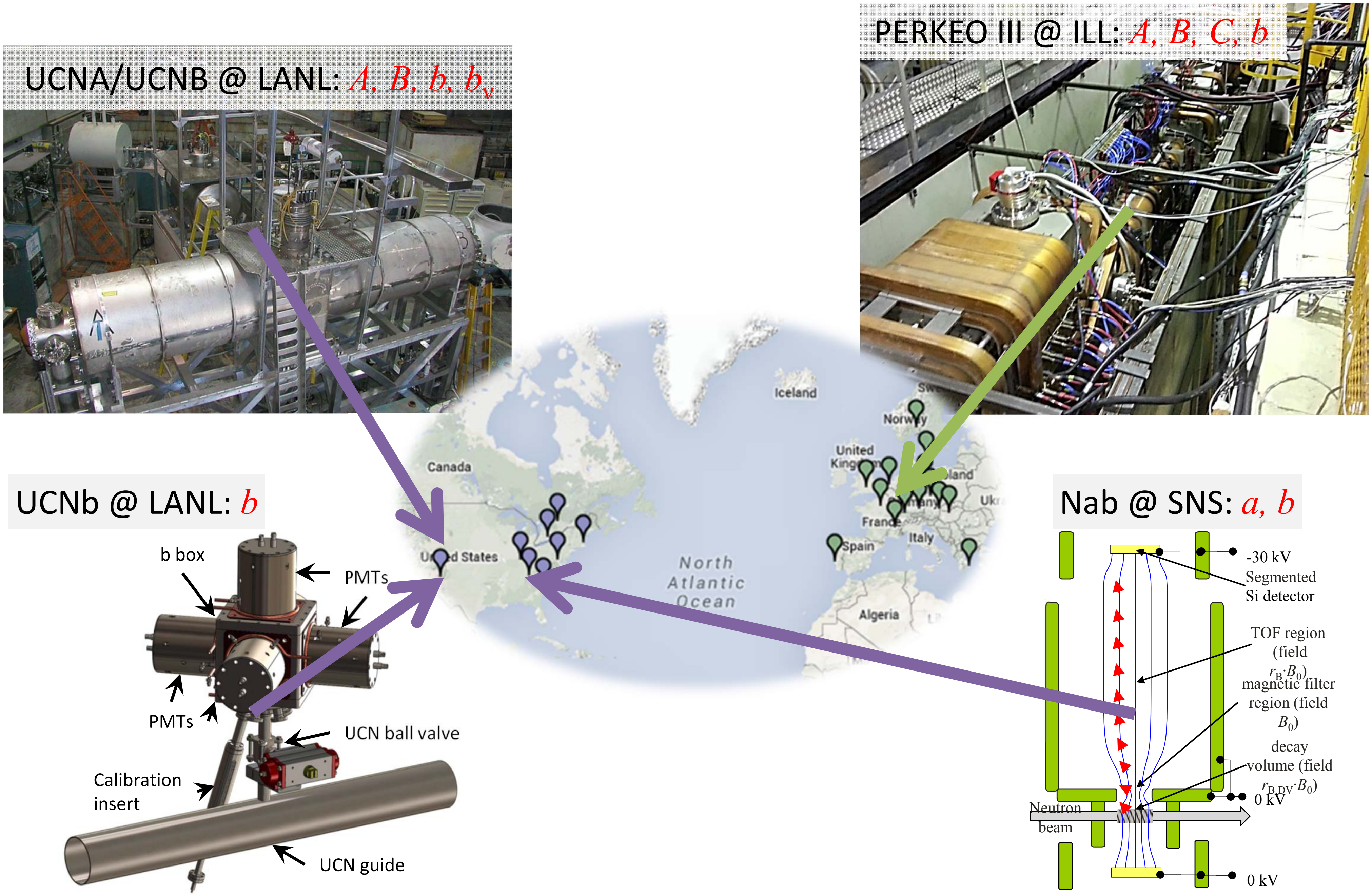


UCNA/UCNB @ LANL: *A, B,* b_ν



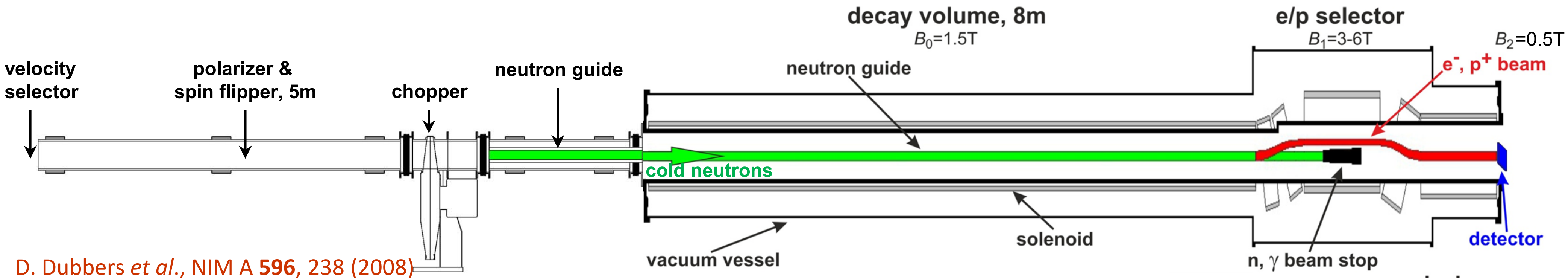
*a*SPECT @ ILL: *a*

Experiments to measure Fierz term *b*



Proton and Electron Radiation Channel

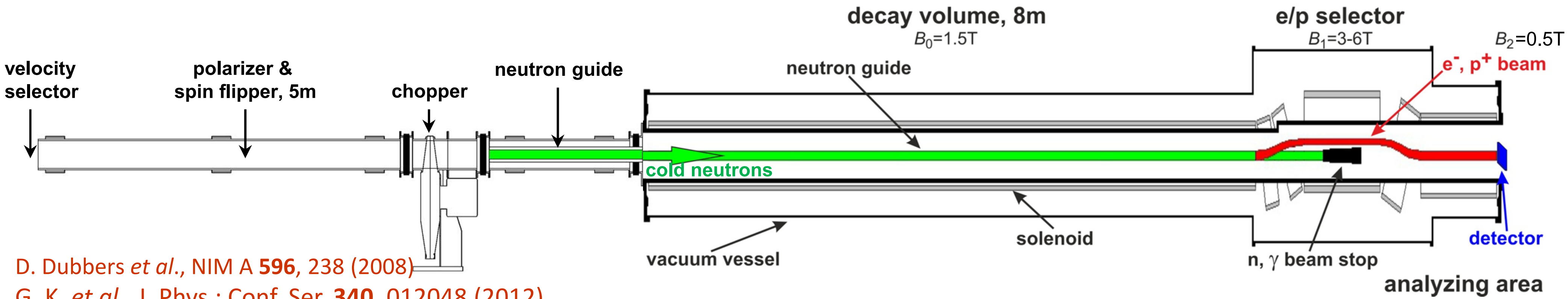
The new facility PERC



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

- Statistics: high flux $\phi=2\times10^{10}$ cm^{-2}s^{-1} and high decay rate $=1\times10^{6}$ m^{-1}s^{-1}
- Sensitivity:
  - improved by up to 2 orders of magnitude to sub-10^{-4}-level
  - highest phase space $d\Omega_e$, $d\Omega_p$ densities

The new facility



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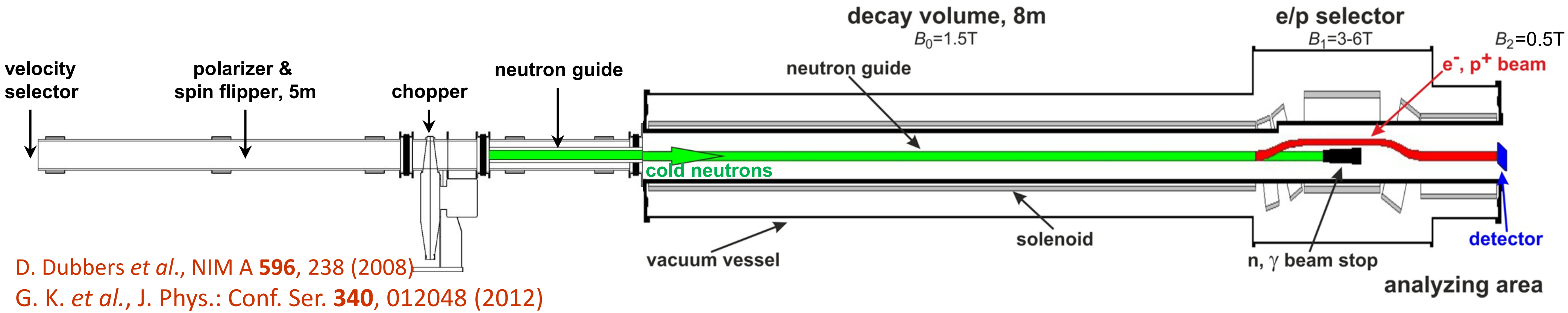
  - ≤ 10^{-4} (for e^-), especially $\Delta P/P = 10^{-4}$

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

The new facility PERC



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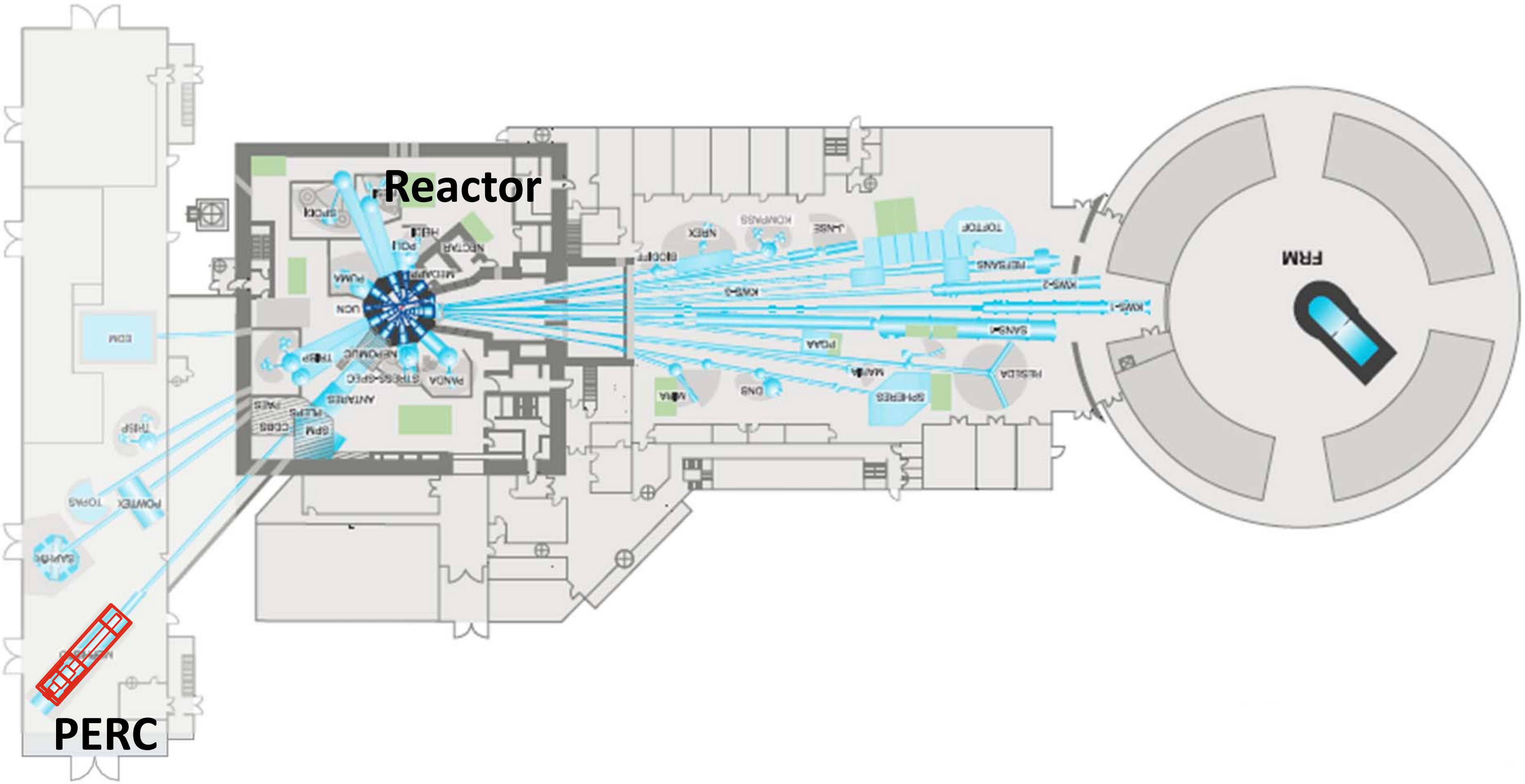
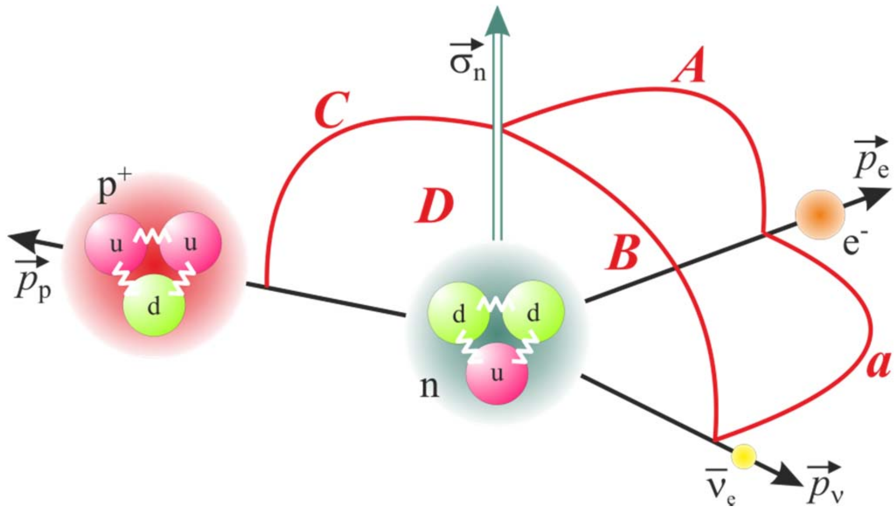
C. Klauser, PhD thesis, TU Wien, 2013
C. Klauser *et al.*, J. Phys.: Conf. Ser. **340**, 012011 (2012)

- Versatility: $a, b, A, B, C, f_2, \ldots$
- Status:
  - manufacturing within 12, commissioning within 18 months
  - beam site at FRM II/Garching (DE) under construction

Facility, FRM II/Garching (DE)



Experiments at PERC

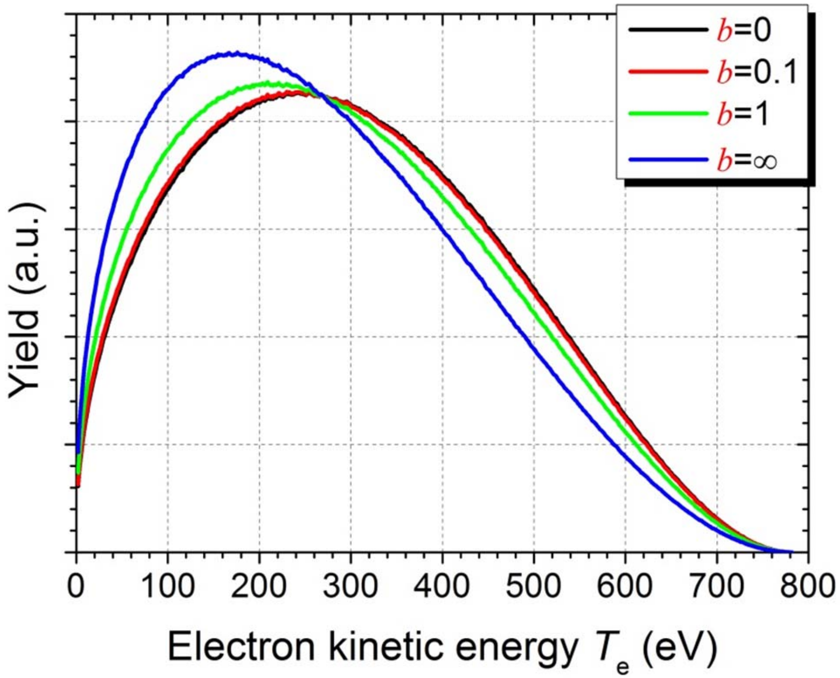


Observable	Correlations	Measurement principle	Examples
β and p momenta	a, A, b, f_2	Magnetic spectrometer PLUS position sensitive detectors	
β energy	A, B, b, f_2, g_2 radiative corrections	β energy sensitive detectors such as scintillation OR silicon detectors	PERKEO I-III UCNA
p energy	a, C	Retardation spectrometer PLUS p detector	*a*SPECT, PERKEO III
p velocity	a, C	Wien filter PLUS position sensitive detector	
p TOF	a	p beam pulsed by electric gate voltage PLUS p detector	

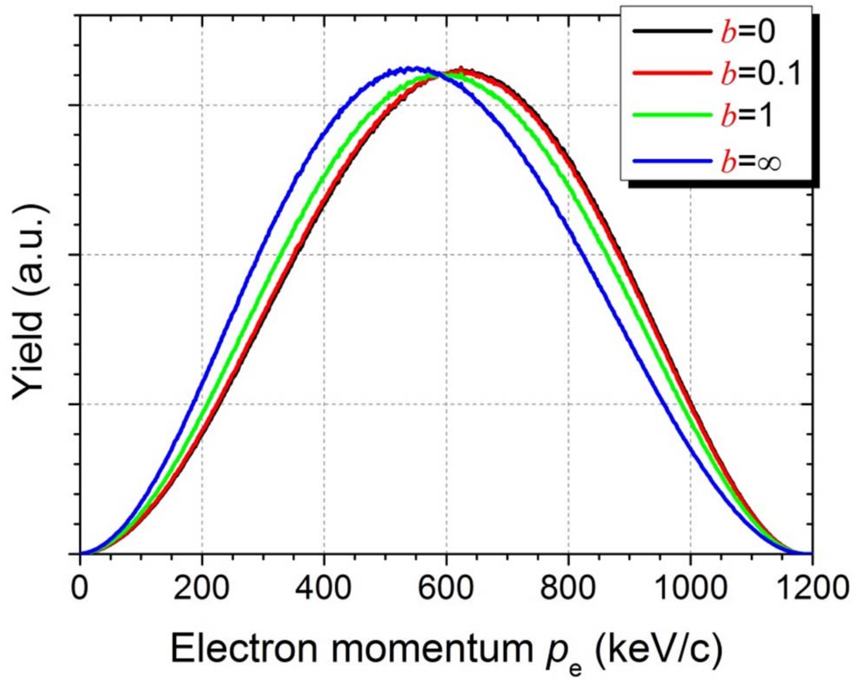
Prospects for Fierz term *b* @ PERC

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

Electron energy spectrum

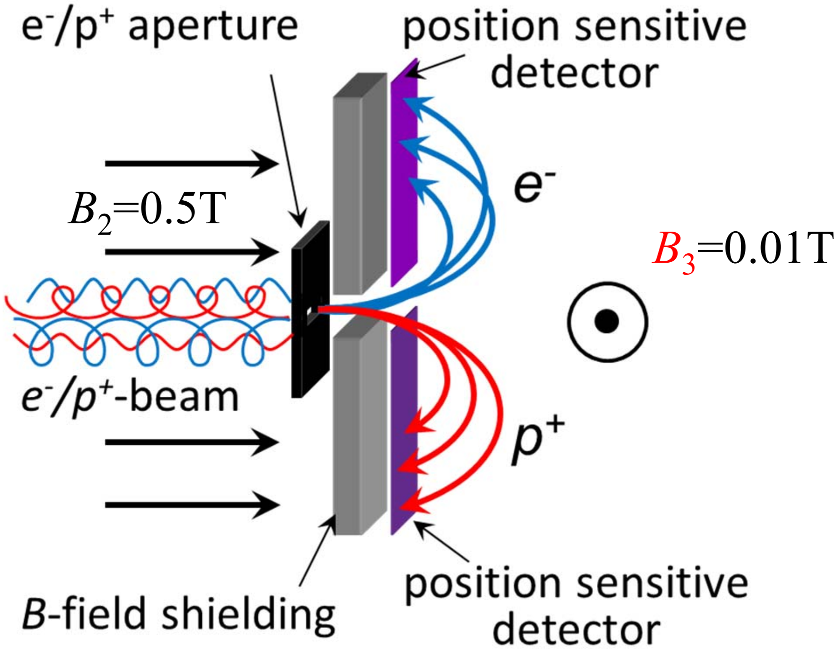


Electron momentum spectrum



– limited energy resolution of scintillation detectors

Magnetic spectrometer @ PERC

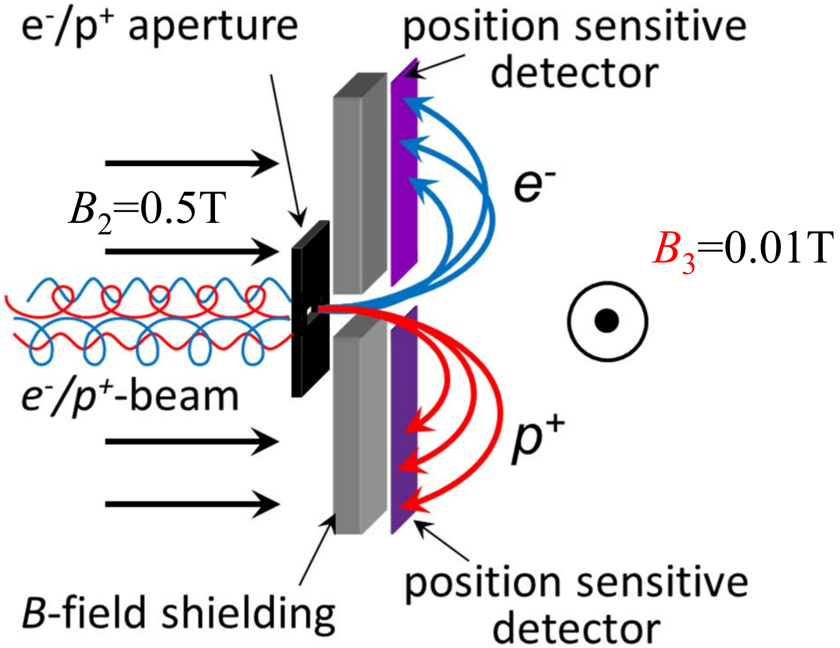


Radius of gyration:

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

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

Magnetic spectrometer @ PERC



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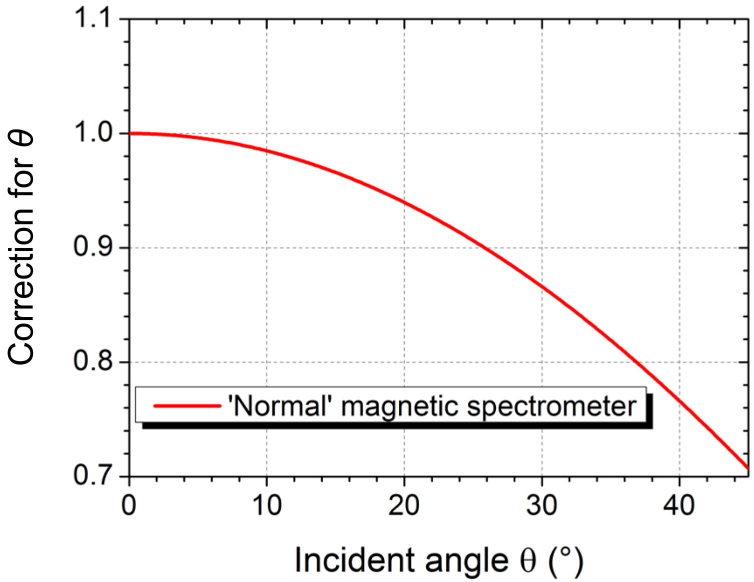
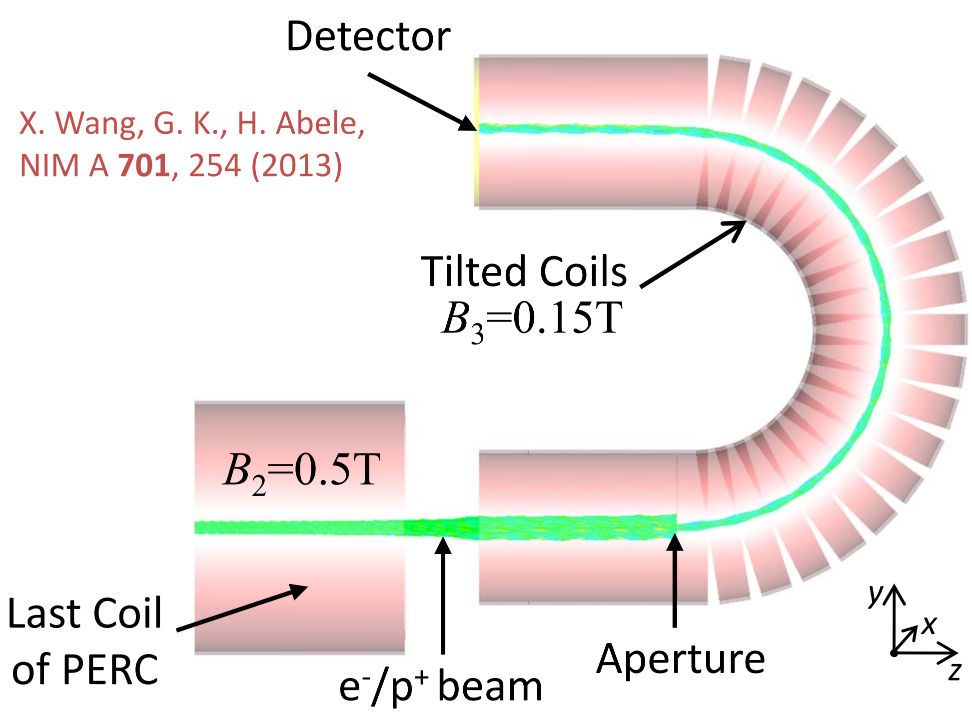


\+ large drift distances $\mathcal{O}$(dm)

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

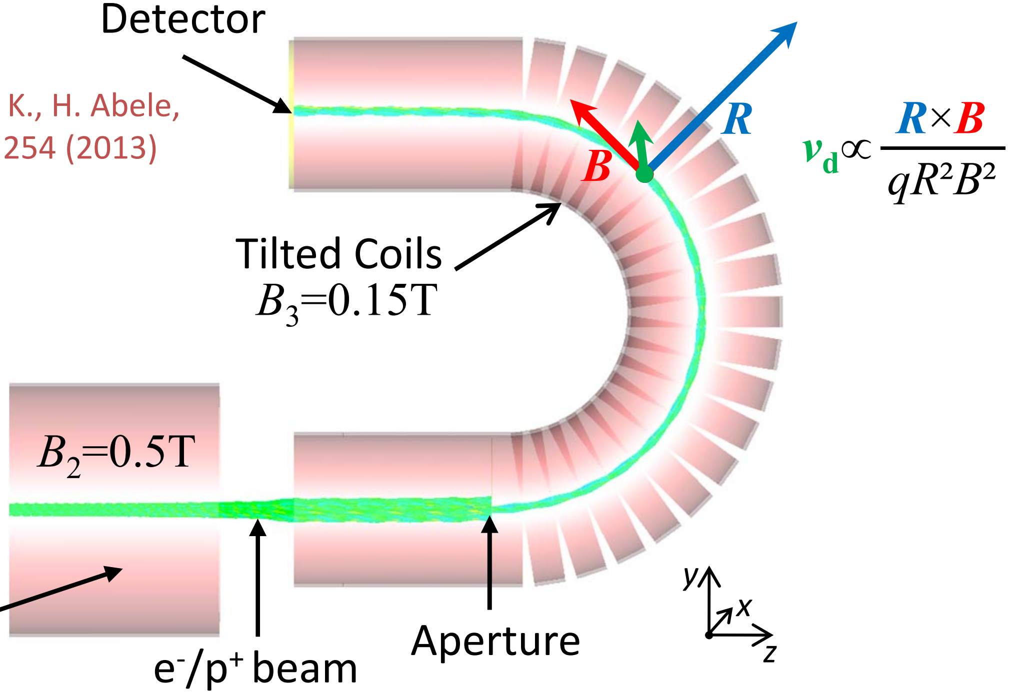
R×B drift momentum spectrometer

X. Wang, G. K., H. Abele,
NIM A **701**, 254 (2013)

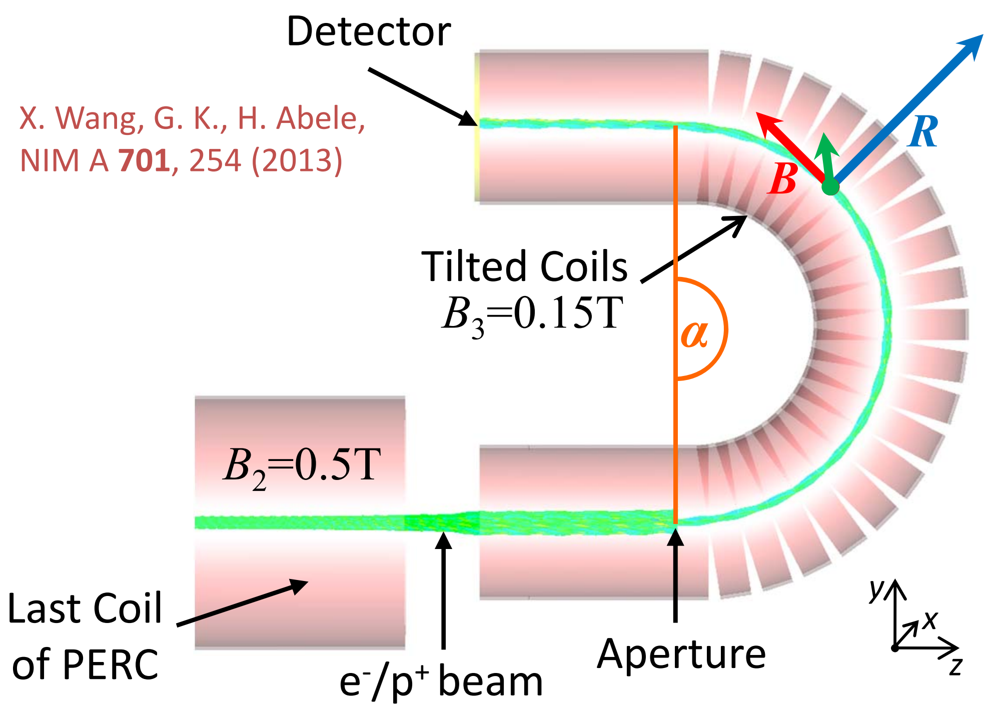


R×B drift momentum spectrometer

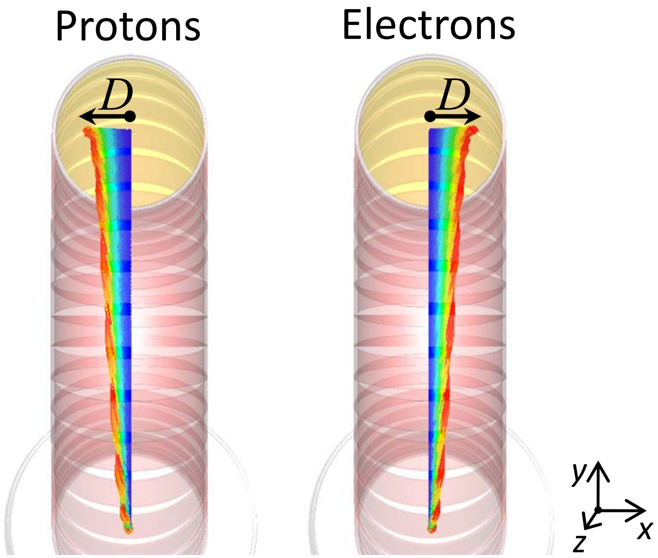
X. Wang, G. K., H. Abele, NIM A **701**, 254 (2013)



R×B drift momentum spectrometer



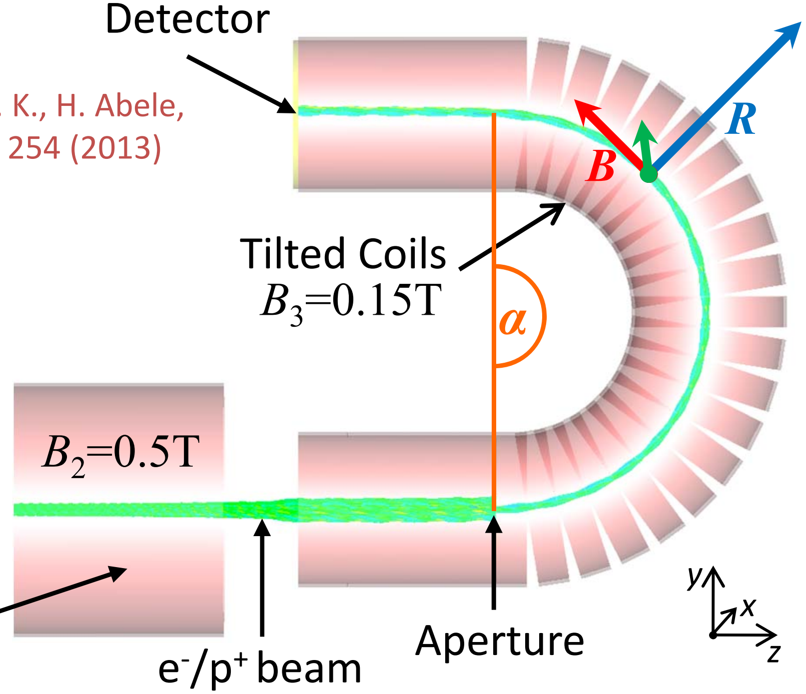
$$v_d \propto \frac{\mathbf{R}\times\mathbf{B}}{qR^2B^2}$$



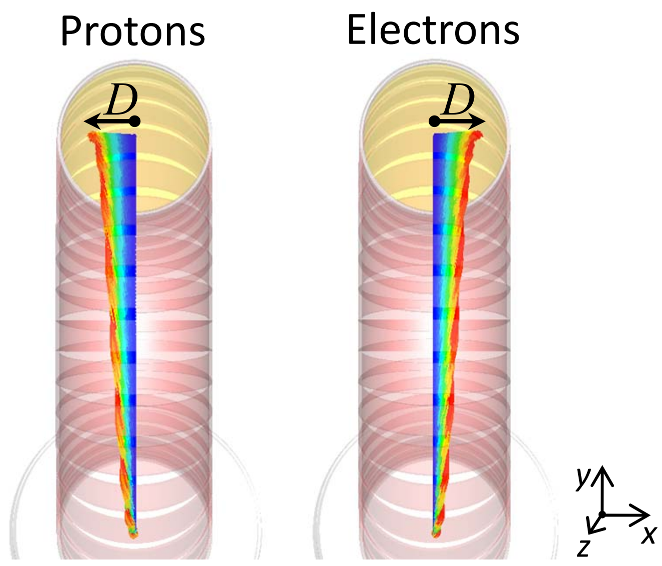
$$D(p,\theta) = \int_T v_d \mathrm{d}t = \frac{p}{qB_3}\cdot\alpha\cdot\frac{1}{2}\left(\cos\theta + \frac{1}{\cos\theta}\right)$$

R×B drift momentum spectrometer

X. Wang, G. K., H. Abele, NIM A **701**, 254 (2013)



$$v_d \propto \frac{\boldsymbol{R}\times\boldsymbol{B}}{qR^2B^2}$$



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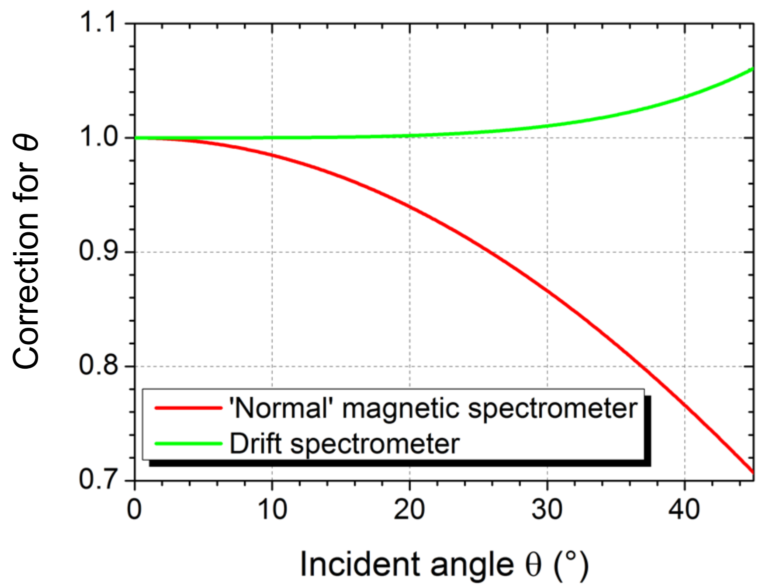
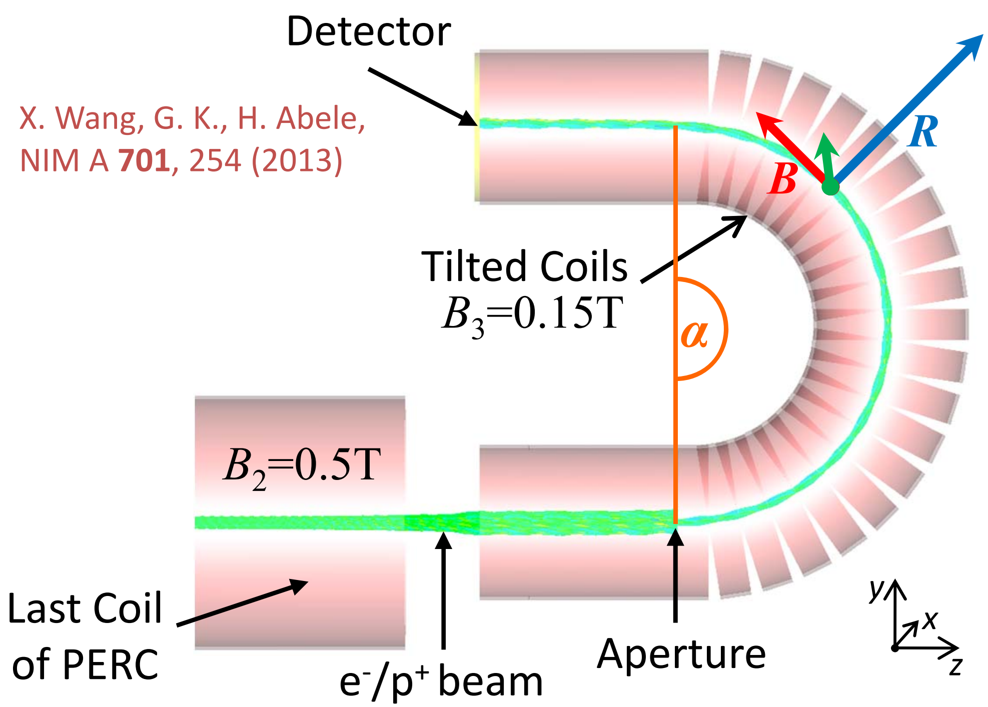


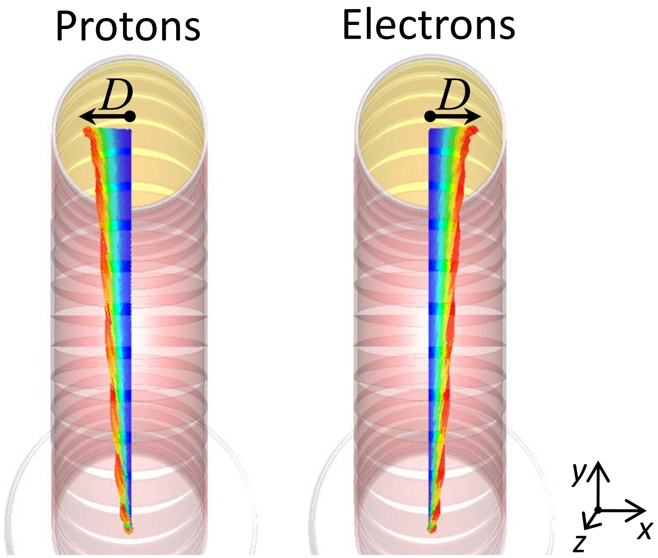
+ adiabatic transport of particles
+ low momentum measurements
+ small corrections for θ
+ large acceptance of θ

R×B drift momentum spectrometer

X. Wang, G. K., H. Abele, NIM A **701**, 254 (2013)



$$v_d \propto \frac{R \times B}{qR^2B^2}$$



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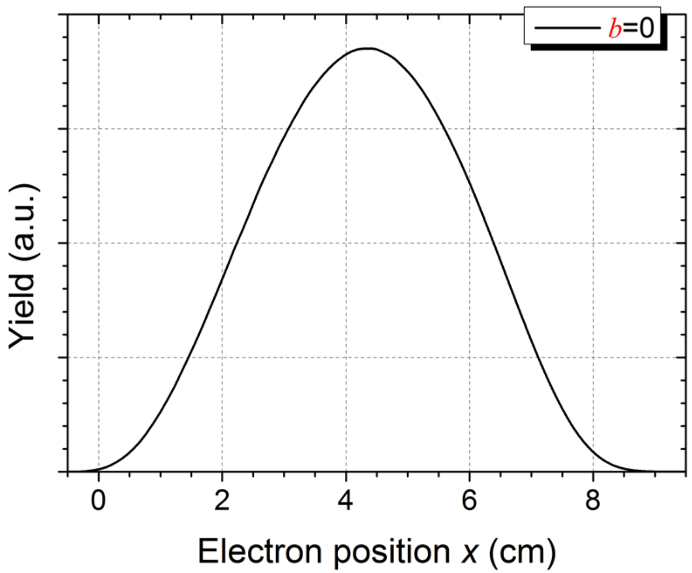


- \+ adiabatic transport of particles
- \+ low momentum measurements
- \+ small corrections for θ
- \+ large acceptance of θ
- \+ high resolution: $\Delta p/p = 14.4$ keVc^{-1}mm^{-1}

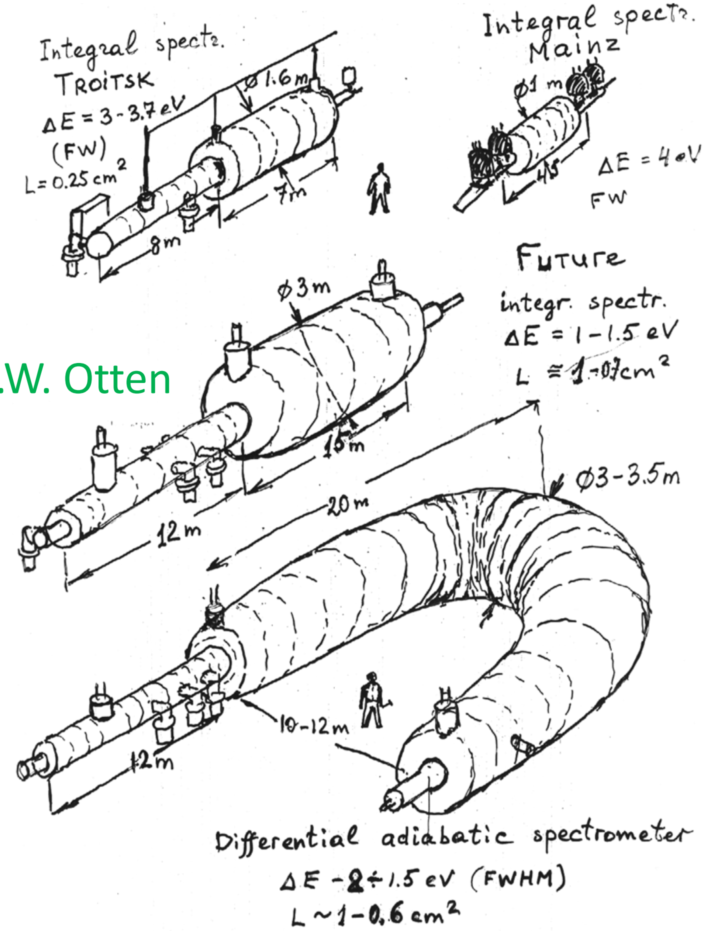
1.2%mm^{-1}

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

Analogous ideas

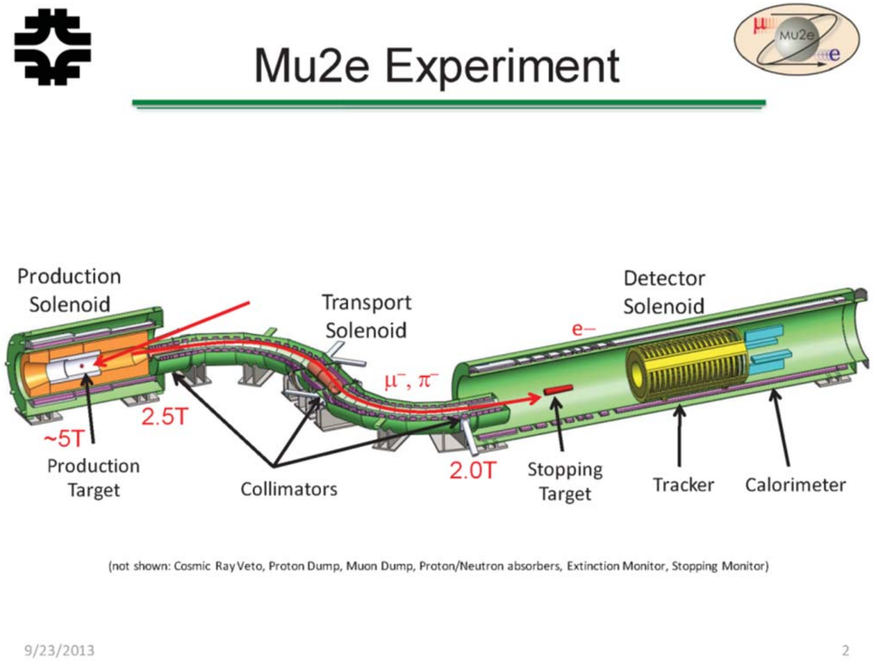
Proposal by E.W. Otten

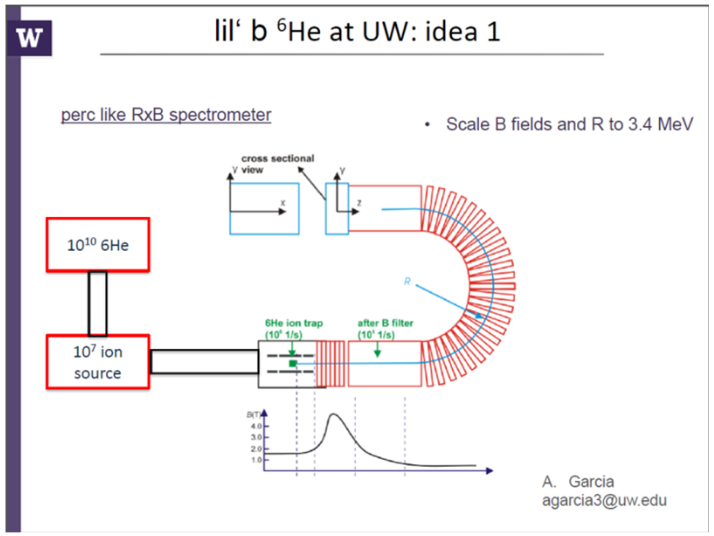
→ KATRIN



Proposal by V.M. Lobashev

V.M. Lobashev, Prog. Part. Nucl. Phys. **40**, 337 (1998)





NoMoS

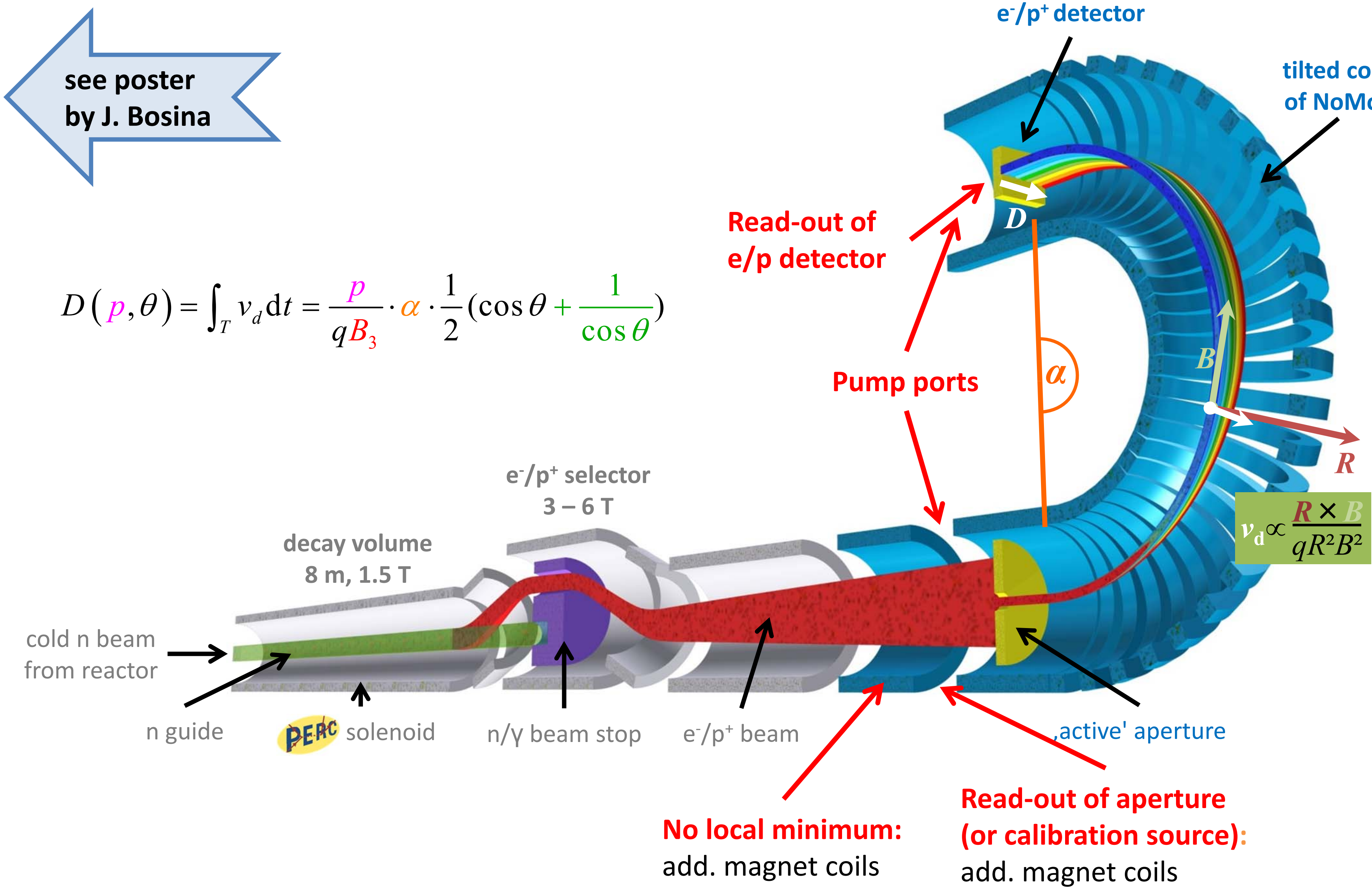
Neutron Decay Products Momentum Spectrometer

ÖAW New Frontiers Group at SMI

Realization of **R×B** spectrometer

see poster by J. Bosina

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



NoMoS Physics programme

G. Konrad, PoS(EPS-HEP2015)592

Research focus:

- Weak magnetism form factor f_2
  - study the structure of the weak interaction
- β-asymmetry parameter A, electron-antineutrino 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 the sub-10^{-4}- respectively 10^{-3}-level

NoMoS Physics programme

G. Konrad, PoS(EPS-HEP2015)592

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- Oscillatory, sidereal effects in the case of Lorentz invariance violation

Goal:

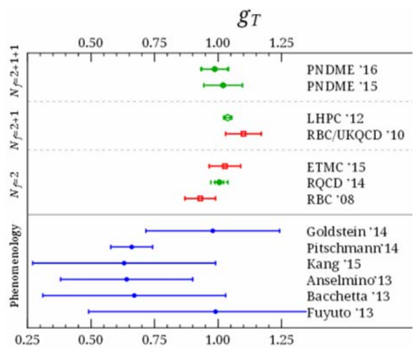
electron and proton spectroscopy on the sub-10^{-4}- respectively 10^{-3}-level

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 the Standard Model (SM)
- Completion of analysis of non-standard correlation coefficients N, G, R, Q, and L to order 10^{-3} within the SM
- Most precise evaluation possible of g_S and g_T within SM and beyond

M. Pitschmann et al., Phys. Rev. D 91 (2015) 074004



✓ comprehensive analysis of standard correlation coefficients to order 10^{-4}

A. Ivanov *et al.*, Phys. Rev. D**88**, 073002 (2013)

Preliminary measurement plan

Summary & 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 and cosmology
  - can continue to probe for SUSY in regions where it is not accessible to LHC
  - 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

Vienna / NoMoS groups

H. Abele[1], J. Bosina[2,3], J. Erhart[1], H. Fillunger[2], M. Horvath[1], E. Jericha[1], M. Klopf[1], G. K.[1,2], W. Mach[1], D. Moser[1,3], H. Saul[1,3], X. Wang[1]

[1]ATI, TU Wien, Austria [2]SMI, Vienna, Austria [3]ILL, Grenoble, France