# Probing TeV scale physics with neV neutrons

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# Outline

- Why study the free neutron?
- Neutron β-decay in SM
- EFT – "communication protocol" between "***ENERGY***" and "***PRECISION***" frontiers
- Search for BSM with neutron β-decay
- Neutron Electric Dipole Moment
- Other exotics with neutrons
- Summary and outlook

# Why study the free neutron?

- **Main goal of Particle Physics**:
  ***Establish consistent picture of Nature's fundamental interactions***
  - **High Energy PP**:
    - Operates at TeV scale ($10^{12}$ eV)
      $\Rightarrow$ study of 2nd (s, c, $\mu$, $\nu_\mu$) and 3rd (b, t, $\tau$, $\nu_\tau$) particle families
  - **Low Energy PP (e.g. with neutrons)**:
    - Operates at neV scale ($10^{-9}$ eV)
      $\Rightarrow$ study of 1st (u, d, e, $\nu_e$) particle family
    - Reveals respectable sensitivity:
      - Energy: $\Delta E/E \sim 10^{-11} \div 10^{-13}$ ($\Delta E \sim 10^{-23}$ eV)
      - Momentum: $\Delta p/p \sim 10^{-10} \div 10^{-11}$
      - Spin polarization: $\Delta s/s \sim 10^{-7}$
  - *Fundamental neutron physics provides more than **20** observables reach in information which is difficult to achieve (or not achievable at all) in other fields of Particle Physics*

**"ENERGY frontier"**

**"PRECISION (intensity) frontier"**

# Neutrons: cold (CN) and ultra-cold (UCN)

- **Cold neutrons**: $E_{\mathrm{kin}}^{\mathrm{CN}} \sim 5\ \mathrm{meV}$, $\quad \upsilon^{\mathrm{CN}} \sim 1\ \mathrm{km/s}$
- **Ultra-cold neutrons** – can be stored in material or magnetic traps $\quad \boxed{E_{\mathrm{kin}} < V_{\mathrm{F}} - \boldsymbol{\mu}_{\mathrm{n}} \cdot \mathbf{B} + mgh}$

$$V_{\mathrm{F}} = \frac{2\pi\hbar}{m} bN$$

$V_{\mathrm{F}}$ – Fermi pseudo-potential,
$b$ – scattering length,
$N$ – number density

- $V_{\mathrm{F}}(\mathrm{Be}) \leftrightarrow E_{\mathrm{kin}} = 252$ neV,
- $\mu_{\mathrm{n}} B(1\ \mathrm{T}) \leftrightarrow E_{\mathrm{kin}} = 60$ neV,
- $mgh(1\ \mathrm{m}) \leftrightarrow E_{\mathrm{kin}} = 100$ neV

- $\upsilon^{UCN} < 8$ m/s,
- $T^{UCN} < 4$ mK,
- $\lambda^{UCN} > 50$ nm

- **UCN production via moderation of CN**:
  - Earth gravitational field and/or scattering from turbine blades (ILL)
  - Super-thermal process e.g. in solid $D_2$ (PSI, LANL, GUM) or super-fluid He (ILL; in development)

# Neutron β decay

# Neutron β decay in Standard Model

- **Only 2 SM parameters establish neutron β decay:**

$$H = \frac{G_F}{\sqrt{2}} V_{ud} \quad \bar{p} \left\{ \gamma_\mu \left(1 + \lambda \gamma_5\right) + \frac{\mu_p - \mu_n}{2m_p} \sigma_{\mu\nu} q^\nu \right\} n \;\; \bar{e} \gamma^\mu \left(1 - \gamma_5\right) \nu_e$$

$V_{ud}$ – CKM matrix element

$\lambda \equiv \frac{g_A}{g_V}$ – axial-to-vector coupling constant ratio

- **Can be extracted from:**
  - Neutron lifetime

$f$ – phase space factor
$\delta_R$ – radiative correction (model independent)
$\Delta_R$ – radiative correction (model dependent)

$$\tau^{-1} = \frac{G_F^2 m_e^2}{2\pi^3} \left|V_{ud}\right|^2 f \left(1 + \delta_R\right)\left(1 + \Delta_R\right)\left(1 + 3\lambda^2\right)$$

  - Angular distribution of decay products (correlation coefficients)

# Neutron β-decay correlations

- **For decay of polarized neutrons of (polarization ⟨J⟩/*J* ):**

$$\frac{d^2\Gamma}{dE_e d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + b\frac{m_e}{E_e} + \frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}}{E_e} + B\frac{\mathbf{q}}{E_\nu} + D\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right] + \ldots$$

$$+\sigma\cdot\left[G\frac{\mathbf{p}}{E_e} + H\frac{\mathbf{q}}{E_\nu} + K\frac{\mathbf{p}}{E_e+m_e}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + L\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu} + N\frac{\langle\mathbf{J}\rangle}{J}\right]$$

$$+\sigma\cdot\left[Q\frac{\mathbf{p}}{E_e+m_e}\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}}{E_e} + S\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\cdot\frac{\mathbf{q}}{E_\nu} + T\frac{\mathbf{p}}{E_e}\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{q}}{E_\nu}\right]$$

$$+\sigma\cdot\left[U\frac{\mathbf{q}}{E_\nu}\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}}{E_e} + V\frac{\mathbf{q}}{E_\nu}\times\frac{\langle\mathbf{J}\rangle}{J} + W\frac{\mathbf{p}}{E_e+m_e}\frac{\langle\mathbf{J}\rangle}{J}\frac{\mathbf{p}}{E_e}\times\frac{\mathbf{q}}{E_\nu}\right]$$

**p** – electron momentum  **q** – neutrino momentum
σ – electron spin sensing direction

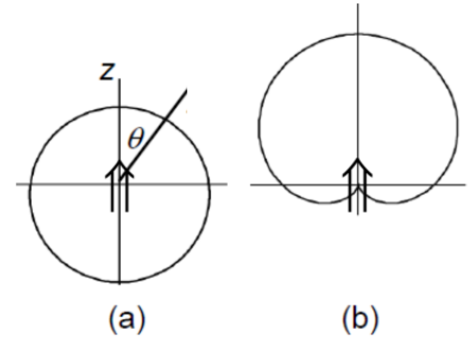
- **Coefficients *a*, *b*, ..., *W* are functions of** $\lambda$

J.D. Jackson et al., Phys. Rev. 106, 517 (1957); J.D. Jackson et al., Nucl. Phys. 4, 206 (1957); M.E. Ebel et al., Nucl. Phys. 4, 213 (1957)

# Neutron β-asymmetry *A*

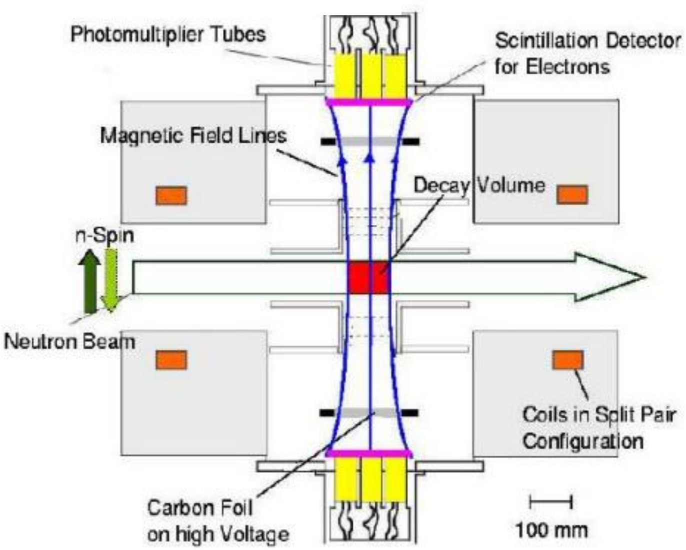
- ***A*** is the best measured correlation in n-decay

$$\frac{d^2\Gamma}{dE_e d\Omega_e} \sim 1 + \boldsymbol{A}\frac{\langle \mathbf{J} \rangle}{J} \cdot \frac{\mathbf{p}}{E_e} = 1 + \boldsymbol{A} P_n \beta \cos\theta$$




Angular distributions of (a) electrons, (b) antineutrinos

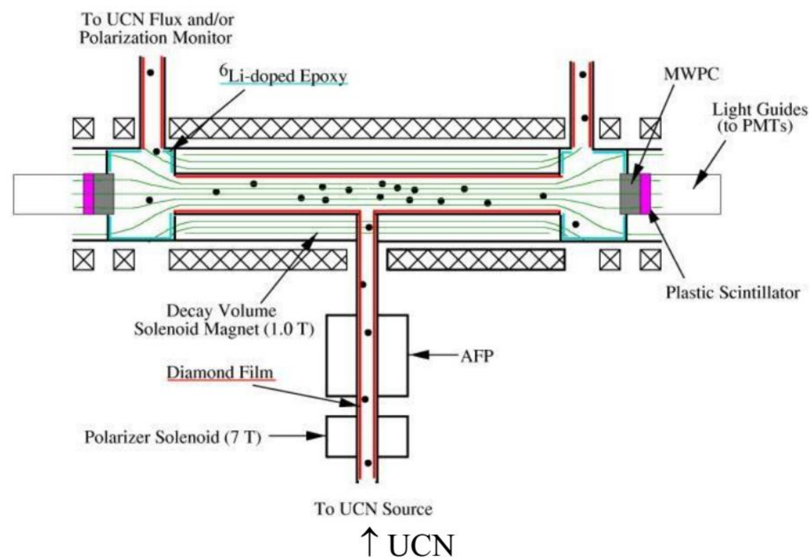
## PERKEO II@ILL:




*A* = -0.1193 ± 0.0003

Mund et al., PRL 110 (2013) 172502

## UCNA@LANSCE:




*A* = -0.1195 ± 0.0110

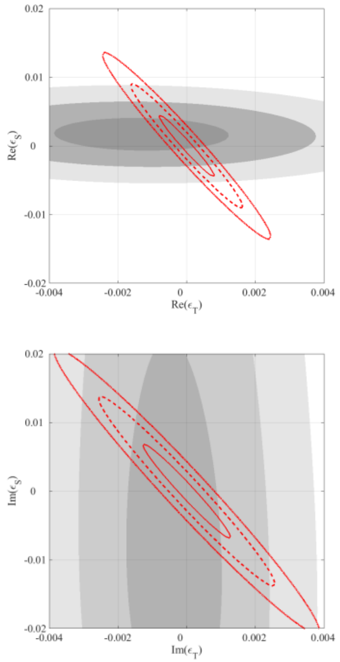
Mendenhall et al., PRC 97 (2013) 032501

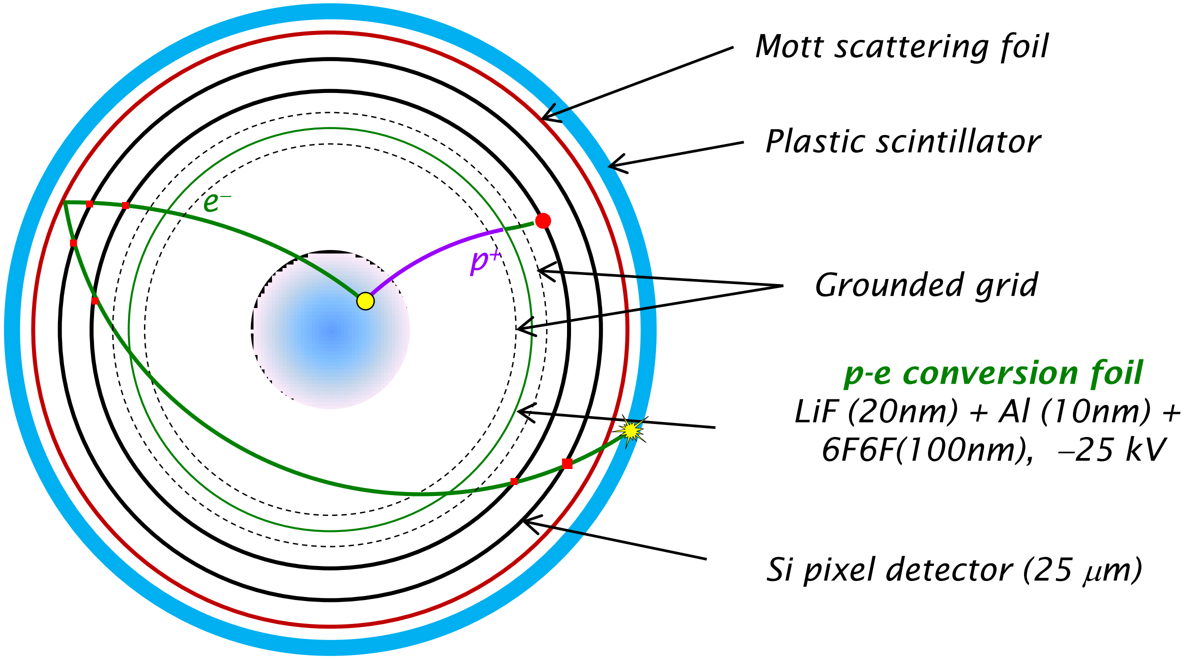
# Neutron β-decay correlations worldwide

| Experiment | Correlation and anticipated precision | Location and status |
|---|---|---|
| aSPECT | $a$ ($3\times10^{-4}$) | FRM-2 (ongoing) |
| aCORN | $a$ ($5\times10^{-4}$) | NIST (ongoing) |
| Nab/aBBa/PANDA | $a$ ($\sim10^{-4}$), $b$ ($3\times10^{-4}$), $A$, $B$, $C$ ($\sim10^{-4}$) | SNS (planned) |
| emiT | $D$ ($\sim10^{-4}$) – measured | NIST (completed) |
| PERC | $a$, $b$, $A$ ($3\times10^{-5}$), $B$, $C$, $D$ (?) | FRM-2 (construction) |
| PERKEO | $A$ ($2\times10^{-4}$), $B$, $C$ ($2\times10^{-3}$) – measured | ILL (ongoing) |
| UCNA | $A$ ($2.5\times10^{-3}$) | LANL (ongoing) |
| UCNB | $B$ ($<10^{-3}$) | LANL (ongoing) |
| nTRV | $N$, $R$ ($\sim10^{-2}$) - measured | PSI (completed) |
| BRAND | $a$, $A$, $B$, $D$, $H$, $L$, $N$, $R$, $S$, $U$, $V$ ($\sim5\times10^{-4}$) | ESS (planned) |

# BRAND project

- Systematic exploration of electron spin dependent correlations: ***H***, ***L***, ***N***, ***R***, ***S***, ***U***, ***V***
- Linear sensitivity to BSM scalar and tensor couplings
- Competitive to Fierz term *b*; completely different systematics




- **"HE" approach**: particle tracking, vertex reconstruction, pixel detectors
- L-o-I submitted to ESS

# Neutron lifetime experiments

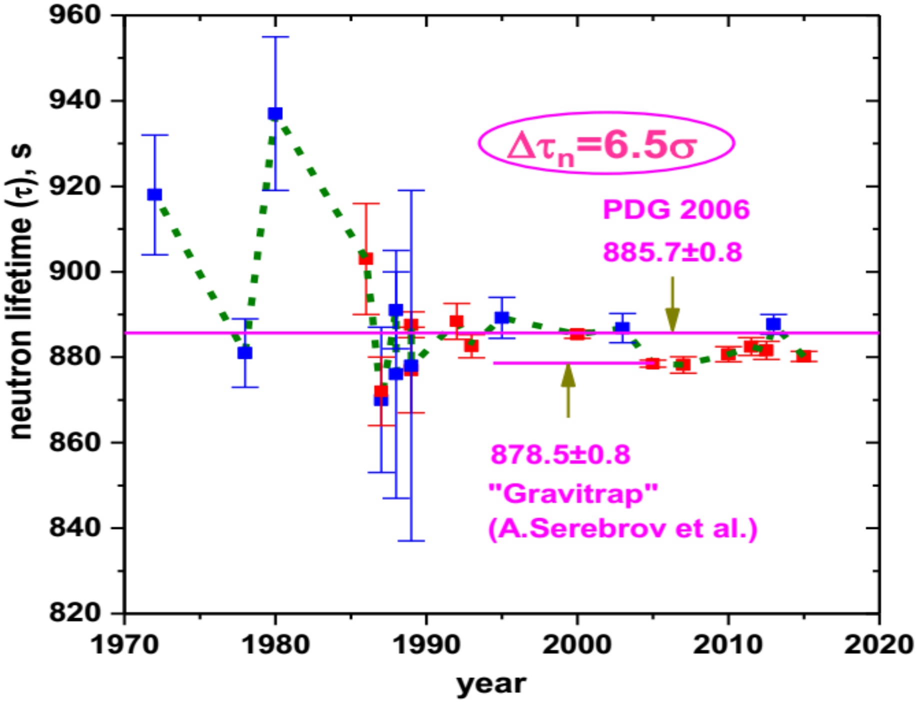
- **"In-beam"**
  - Register rate of decay products from well defined fiducial volume with well determined fluence rate

$$-\frac{dN}{dt} = \frac{1}{\tau} N$$

- **"Bottle"**
  - Measure change with time of neutron ensemble confined in storage bottle

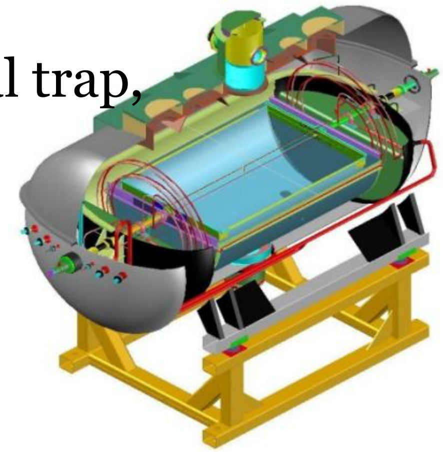
$$\frac{N_1}{N_2} = e^{-\frac{1}{\tau}(t_1 - t_2)}$$

- **Different kind of systematic effects**
  - "**In-beam**" limited by uncertainties of the decay volume and the beam fluence
  - "**Bottle**" suffer from disappearance channels different than decay
- **We know $\tau_n$ with:**
  - ~1 s statistical accuracy
  - Few s systematic uncertainty
- **Total uncertainty ~0.5 %**

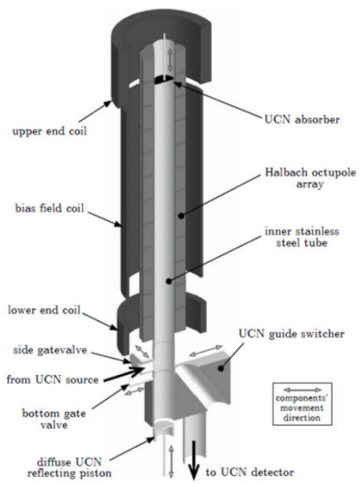


# Neutron lifetime – future projects – efforts for $\sigma(\tau_n)$ ~0.1 s

- Gravitational trap, PNPI-ILL



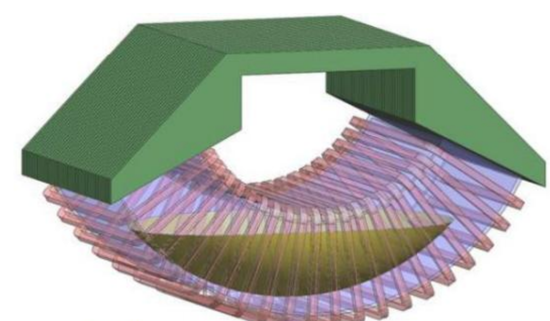
- **HOPE** magneto-gravitational trap, ILL




- **PENELOPE** magneto-gravitational trap, TUM

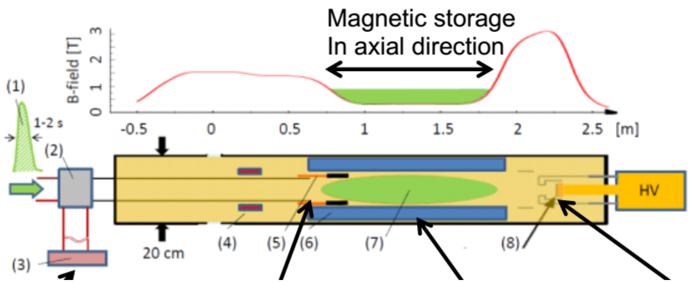
R. Picker et al.,
J. Res. NIST 110 (2005) 357

- **UCNτ** magneto-gravitational trap, LANL



Walstrom et al., **LANL**
Nucl. Instr. Meth. A 599 (2009) 82

- **τSPECT** – gravitational trap, Mainz



# CKM unitarity – testing SM

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

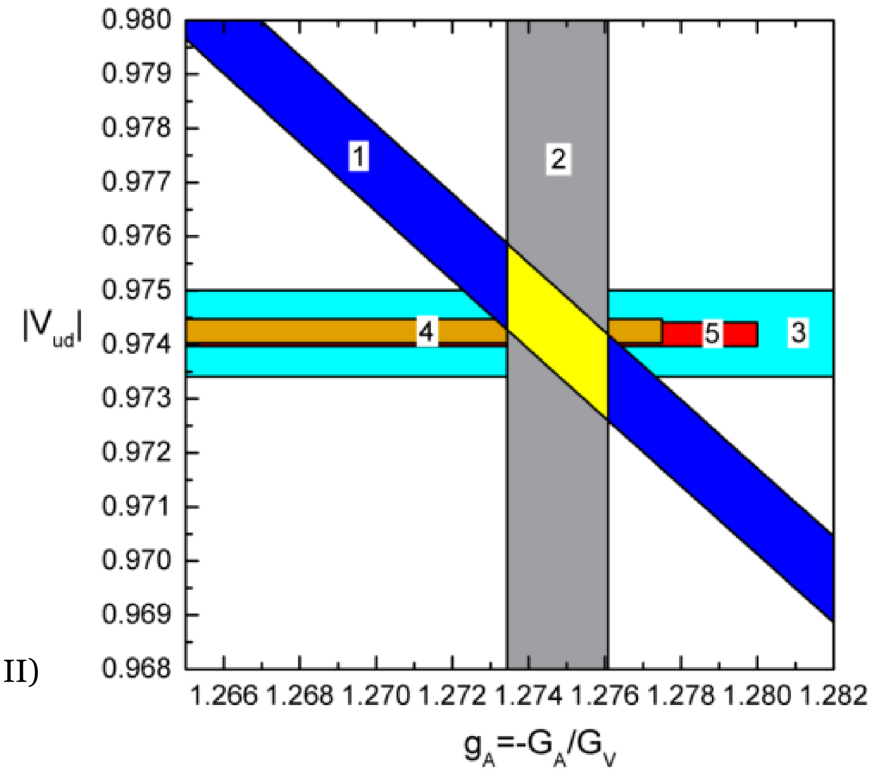
- Unitarity condition requires:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

- $V_{ub}$ is small ($V_{ub} = 3.6(7)\times10^{-3}$) so the unitarity test involves essentially only $V_{ud}$ and $V_{us}$

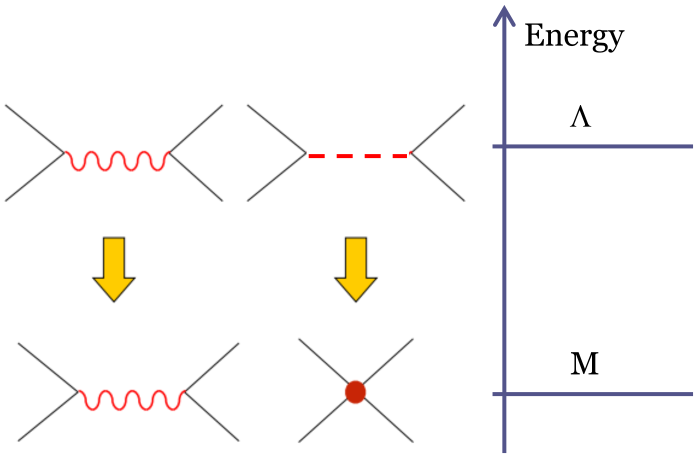
- $V_{ud}$ from:
  - **Nuclear superallowed β-decays**: sophisticated nuclear structure calculations, some problems with $Q$-values
  - **From pion β-decay**: theoretically cleanest, statistically not competitive
  - **From neutron β-decay**: theoretically clean

A. Serebrov (2016)




1. Neutron decay
2. Neutron β-asymmetry *A* (PERKEO II)
3. Neutron β-decay (PDG 2015 + PERKEO II)
4. Unitarity
5. 0⁺ → 0⁺ nuclear transitions

# EFT approach in β-decay




- For experiments at energy significantly lower than BSM scale ($\Lambda_i$):

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum \frac{1}{\Lambda_i^2} \mathcal{L}_i \approx \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum \alpha_i \mathcal{O}_i^{(6)}$$

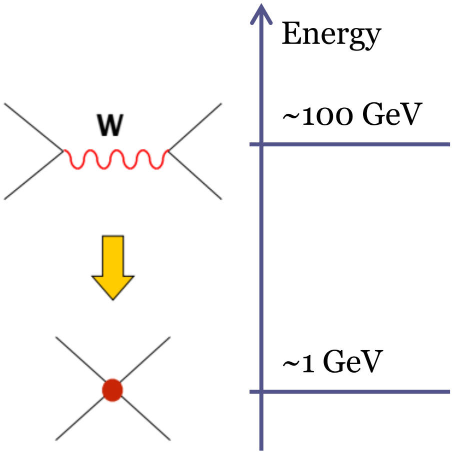
$\mathcal{O}_i^{(6)}$ – dimension-6 operators

$\alpha_i$ – *Wilson coefficients* $\alpha_i = \Lambda^2 f_i \left( g_{\text{BSM}}, M_{\text{BSM}} \right)$

Observables for $E << \Lambda$: $\mathcal{R} = \mathcal{R}_0 \left( 1 + \frac{\mathcal{O}(M)}{\Lambda} + \frac{\mathcal{O}(M^2, E^2, ME)}{\Lambda^2} + \ldots \right)$

- Semi-leptonic processes, partonic level, exchanged W-boson is heavy – SM interaction Lagrangian takes the contact (V-A)×(V-A) form

$$\mathcal{L}_{\text{SM}} = -\frac{G_F V_{ud}}{\sqrt{2}} \bar{e} \gamma_\mu (1-\gamma_5) \nu_e \cdot \bar{u} \gamma^\mu (1-\gamma_5) d$$



# EFT approach in β-decay (cont.)

- **Model independent EFT parameters**

V. Cirigliano et al., Nucl. Phys. B 830 (2010)
T. Bhattacharya et al., Phys. Rev. D 85 (2012)
V. Cirigliano et al., JHEP 1302 (2013)
M. Gonzalez-Alonso et al., Ann. Phys. 525 (2013)
M. Gonzalez-Alonso et al., Phys. Rev. Lett. 112 (2014)

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} \;=\; & -\frac{G_F V_{ud}}{\sqrt{2}} \left[\, (1+\epsilon_L)\;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \right.\\
& + \tilde{\epsilon}_L \;\; \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
& + \epsilon_R \;\; \bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \tilde{\epsilon}_R \;\; \bar{e}\gamma_\mu(1+\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
& + \epsilon_S \;\; \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d \;+\; \tilde{\epsilon}_S \;\; \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}d \\
& - \epsilon_P \;\; \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \;-\; \tilde{\epsilon}_P \;\; \bar{e}(1+\gamma_5)\nu_e \cdot \bar{u}\gamma_5 d \\
& + \epsilon_T \; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \\
& \left. + \tilde{\epsilon}_T \; \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \right] + \text{h.c.}\;.
\end{aligned}
$$

- Valid also for $\pi^{\pm} \to \pi^0 e^{\pm}\nu$

- **Low-energy simplifications**:
  - Neglect RH neutrinos – $\tilde{\epsilon}_{L,R,S,P,T} = 0$
  - Pseudo-scalar contribution (non-relativistic limit) – $\epsilon_P = 0$

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} \;=\; & -\frac{G_F V_{ud}}{\sqrt{2}} \;[1+\text{Re}\,(\epsilon_L+\epsilon_R)] \times \\
& \times \{\bar{e}\gamma_\mu(1-\gamma_5)\nu_e \cdot \bar{u}\gamma^\mu\,[1-(1-2\epsilon_R)\,\gamma_5]\,d \\
& + \epsilon_S \;\; \bar{e}(1-\gamma_5)\nu_e \cdot \bar{u}d \\
& + \;\epsilon_T \;\; \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_e \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d\} + \text{h.c.}
\end{aligned}
$$

# Nucleon-level effective couplings

- Lee-Yang effective Lagrangian (leading order, momentum transfer):

$$
\begin{aligned}
-\mathcal{L}_{n\to pe^-\bar{\nu}_e} = \;& \bar{p}\, n\ \left(C_S \bar{e}\nu_e - C'_S \bar{e}\gamma_5\nu_e\right) \\
&+ \bar{p}\gamma^\mu n \left(C_V \bar{e}\gamma_\mu\nu_e - C'_V \bar{e}\gamma_\mu\gamma_5\nu_e\right) \\
&+ \bar{p}\sigma^{\mu\nu} n \left(C_T \bar{e}\sigma_{\mu\nu_e}\nu_e - C'_T \bar{e}\sigma_{\mu\nu}\gamma_5\nu_e\right) \\
&- \bar{p}\gamma^\mu\gamma_5 n \left(C_A \bar{e}\gamma_\mu\gamma_5\nu_e - C'_A \bar{e}\gamma_\mu\nu_e\right) \\
&+ \bar{p}\gamma_5 n\ \left(C_P \bar{e}\gamma_5\nu_e - C'_P \bar{e}\nu_e\right) + \text{h.c.}\ .
\end{aligned}
$$

$$C_i,\ C'_i\ \ (i \in \{V, A, S, T\})$$

$$C_i = \frac{G_F}{\sqrt{2}} V_{ud}\, \overline{C}_i$$

$$\langle p|\bar{u}\Gamma d|n\rangle = g_\Gamma\, \bar{\psi}_p \Gamma \psi_n$$

- Effective nucleon-level couplings can be expressed in parton-level parameters:

$$
\begin{aligned}
\overline{C}_V &= g_V\left(1 + \epsilon_L + \epsilon_R + \tilde{\epsilon}_L + \tilde{\epsilon}_R\right) \\
\overline{C}'_V &= g_V\left(1 + \epsilon_L + \epsilon_R - \tilde{\epsilon}_L - \tilde{\epsilon}_R\right) \\
\overline{C}_A &= -g_A\left(1 + \epsilon_L - \epsilon_R - \tilde{\epsilon}_L + \tilde{\epsilon}_R\right) \\
\overline{C}'_A &= -g_A\left(1 + \epsilon_L - \epsilon_R + \tilde{\epsilon}_L - \tilde{\epsilon}_R\right)
\end{aligned}
$$

$$
\begin{aligned}
\overline{C}_S &= g_S\ \left(\epsilon_S + \tilde{\epsilon}_S\right) \\
\overline{C}'_S &= g_S\ \left(\epsilon_S - \tilde{\epsilon}_S\right) \\
\overline{C}_P &= g_P\ \left(\epsilon_P - \tilde{\epsilon}_P\right) \\
\overline{C}'_P &= g_P\ \left(\epsilon_P + \tilde{\epsilon}_P\right) \\
\overline{C}_T &= 4\, g_T\ \left(\epsilon_T + \tilde{\epsilon}_T\right) \\
\overline{C}'_T &= 4\, g_T\ \left(\epsilon_T - \tilde{\epsilon}_T\right)
\end{aligned}
$$

- *Form factors are the key ingredients for translation of hadron-level coupling constants to parton-level parameters*

# EFT approach in β-decay (cont.)

- $g_A$ from experiment (Lattice QCD still not accurate):

$$g_A \to g_A \,\mathrm{Re}\left[\frac{1+\epsilon_L-\epsilon_R}{1+\epsilon_L+\epsilon_R}\right] \approx g_A\left[1-2\mathrm{Re}(\epsilon_R)\right] + \mathcal{O}\left(\epsilon_i^2\right)$$

- 6 parameters left for probing:
  - $\epsilon_L + \epsilon_R$ – can be absorbed in $V_{ud}$ (CKM unitarity tests)
  - Real parts of $\epsilon_S$ and $\epsilon_T$
  - Imaginary parts of $\epsilon_R$ , $\epsilon_S$ and $\epsilon_T$

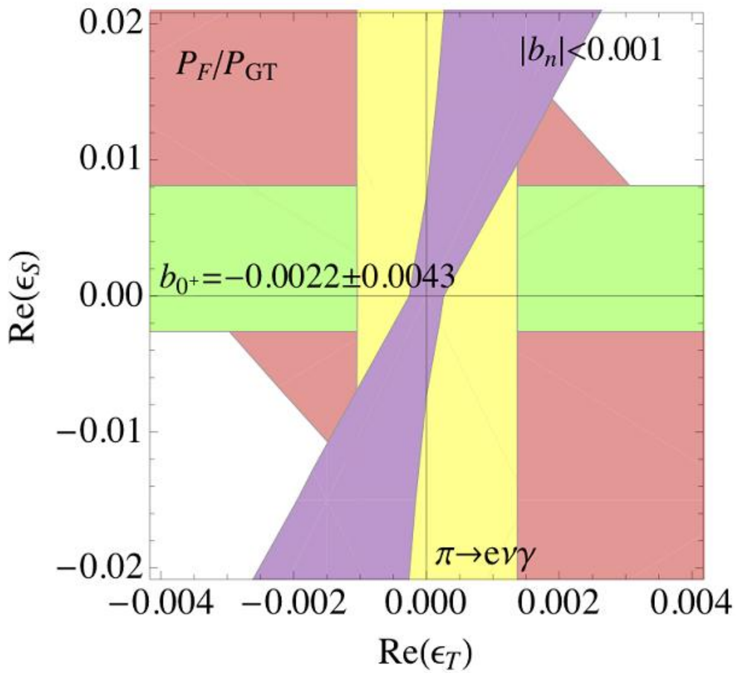
⇓

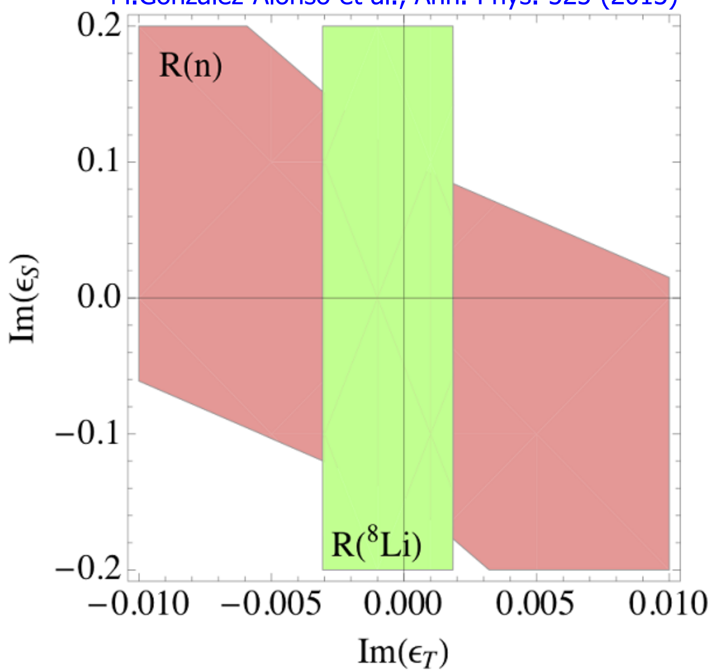
- FF from Lattice QCD calculation
- Modest knowledge of $g_S$ and $g_T$ is still sufficient for present accuracy level of experimental observables

| | $g_S$ | $g_T$ |
|---|---|---|
| Adler et al.'1975 | 0.60(40) | 1.45(85) |
| PNDME 2011 | 0.80(40) | 1.05(35) |
| LHPC 2012 | 1.08(32) | 1.04(02) |
| PNDME 2013 | 0.66(24) | 1.09(05) |

# Current (and near-future) experimental limits from β-decay

M.Gonzalez-Alonso et al., Ann. Phys. 525 (2013)




- ***Most wanted is Fierz term $b_n$ – to be extracted from spectrum shape – challenging***
- ***Electron spin dependent correlation (BRAND) can do the job as well – challenging (different systematics)***

# Limits from high energy

- Electrons and missing transverse energy (MET) channel

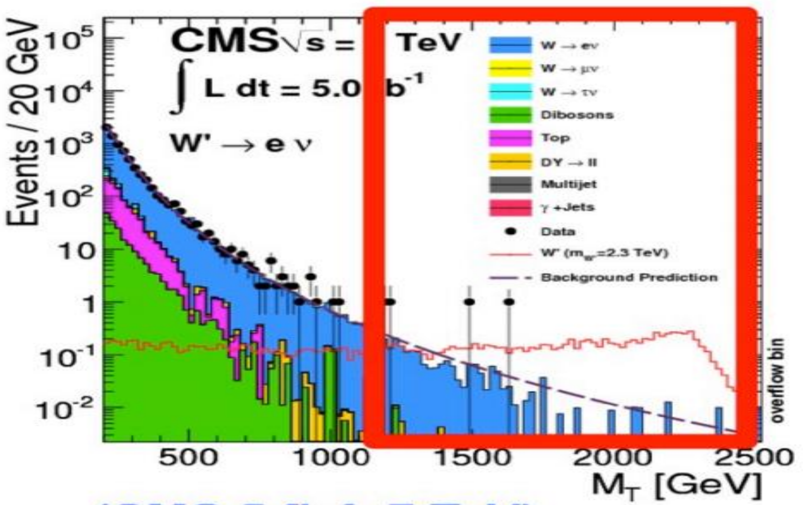
$$\sigma(pp \to e + \mathrm{MET} + X)$$

- Underlying partonic process is the same as in β-decay $(\bar{u}d \to e\bar{\nu})$
- If BSM particles are too heavy to be produced on-shell → EFT analysis appropriate
- Express weak scale Lagrangian in terms of EFT parameters and calculate cross section

$$\begin{aligned}\sigma(m_T > \overline{m}_T) \quad = \quad & \sigma_W \left[ \left| 1 + \epsilon_L^{(v)} \right|^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] \\ & -2\,\sigma_{WL}\,\mathrm{Re}\left(\epsilon_L^{(c)} + \epsilon_L^{(c)}\epsilon_L^{(v)*}\right) + \sigma_R\left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2\right] \\ & +\sigma_S\left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2\right] + \sigma_T\left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2\right]\end{aligned}$$

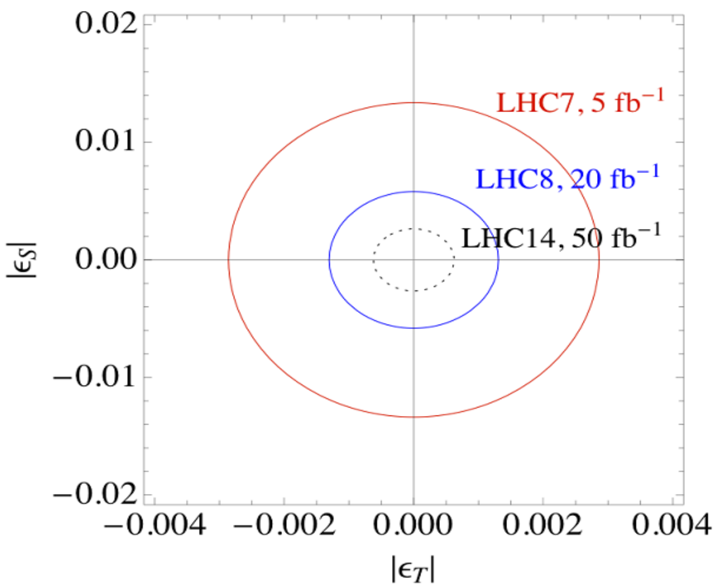
# CMS results

$$|\epsilon_{S,P}|, |\tilde{\epsilon}_{S,P}| < 5.8 \times 10^{-3} \ ,$$
$$|\epsilon_T|, |\tilde{\epsilon}_T| < 1.3 \times 10^{-3} \ ,$$
$$|\tilde{\epsilon}_R|, |\mathrm{Im}\ \epsilon_L^{(c)}| < 2.2 \times 10^{-3} \ ,$$
$$\mathrm{Re}\ \epsilon_L^{(c)} \in (-1.1, 4.5) \times 10^{-3}$$

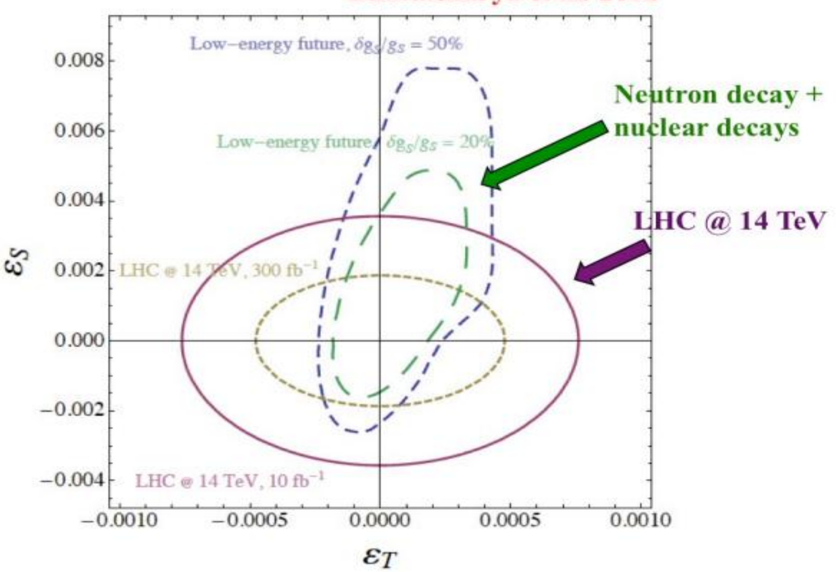



(CMS 5 fb⁻¹, 7 TeV)

M. Gonzalez-Alonso et al., Ann. Phys. 525 (2013)




Bhattacharya et al.'2012



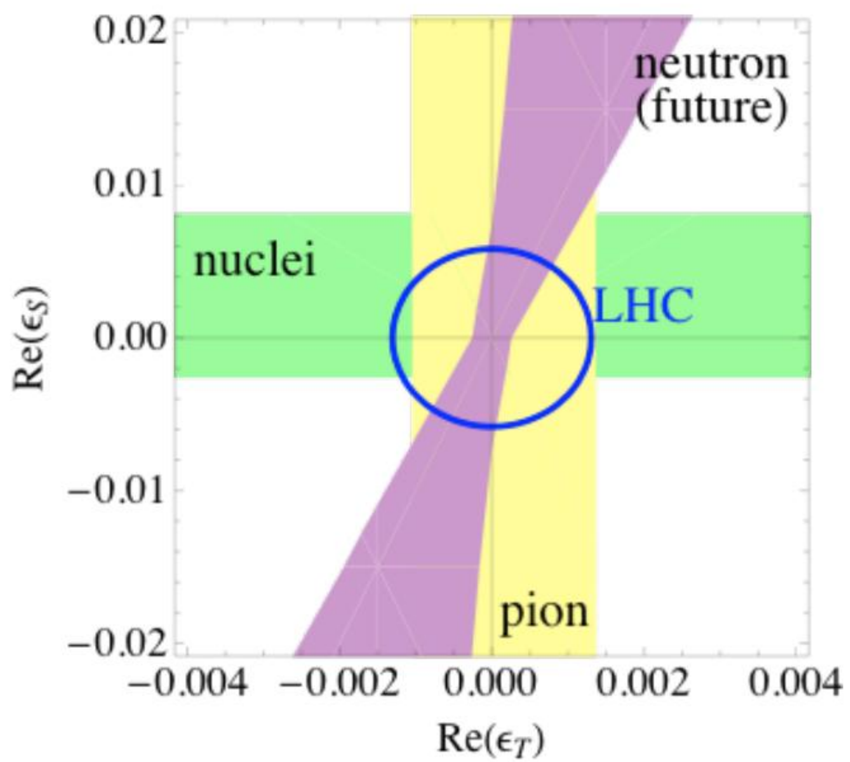
# LE-HE competition

- Benefits for β-decay analysis from better determination of $g_S$ and $g_T$ FF

| | $g_S$ | $g_T$ |
|---|---|---|
| Adler et al.'1975 | 0.60(40) | 1.45(85) |
| PNDME 2011 | 0.80(40) | 1.05(35) |
| LHPC 2012 | 1.08(32) | 1.04(02) |
| RQCD 2014 | 1.02(35) | 1.01(02) |
| PNDME 2013/15 | 0.72(32) | 1.02(08) |
| ETMC 2015 | 1.21(42) | 1.03(06) |
| χQCD 2015 | $0.66(03)_{stat}$ | - |
| CVC | 1.02(11) | - |
| PNDME 2016 (*) | 0.98(11) | 0.994(46) |

(*) to appear

M. Gonzalez-Alonso (2016)




- *The dream scenario would be that LHC finds a BSM particle on-shell and β-decay has to confirm it in observables (off-shell corrections)*

# Neutron EDM

# EDM of elementary particles

- Not degenerated spin ½ particle:
  - Spin is the reference direction for magnetic ($\mu$) and electric ($d$) dipole moments
  - Hamiltonians for interaction with magnetic and electric fields are

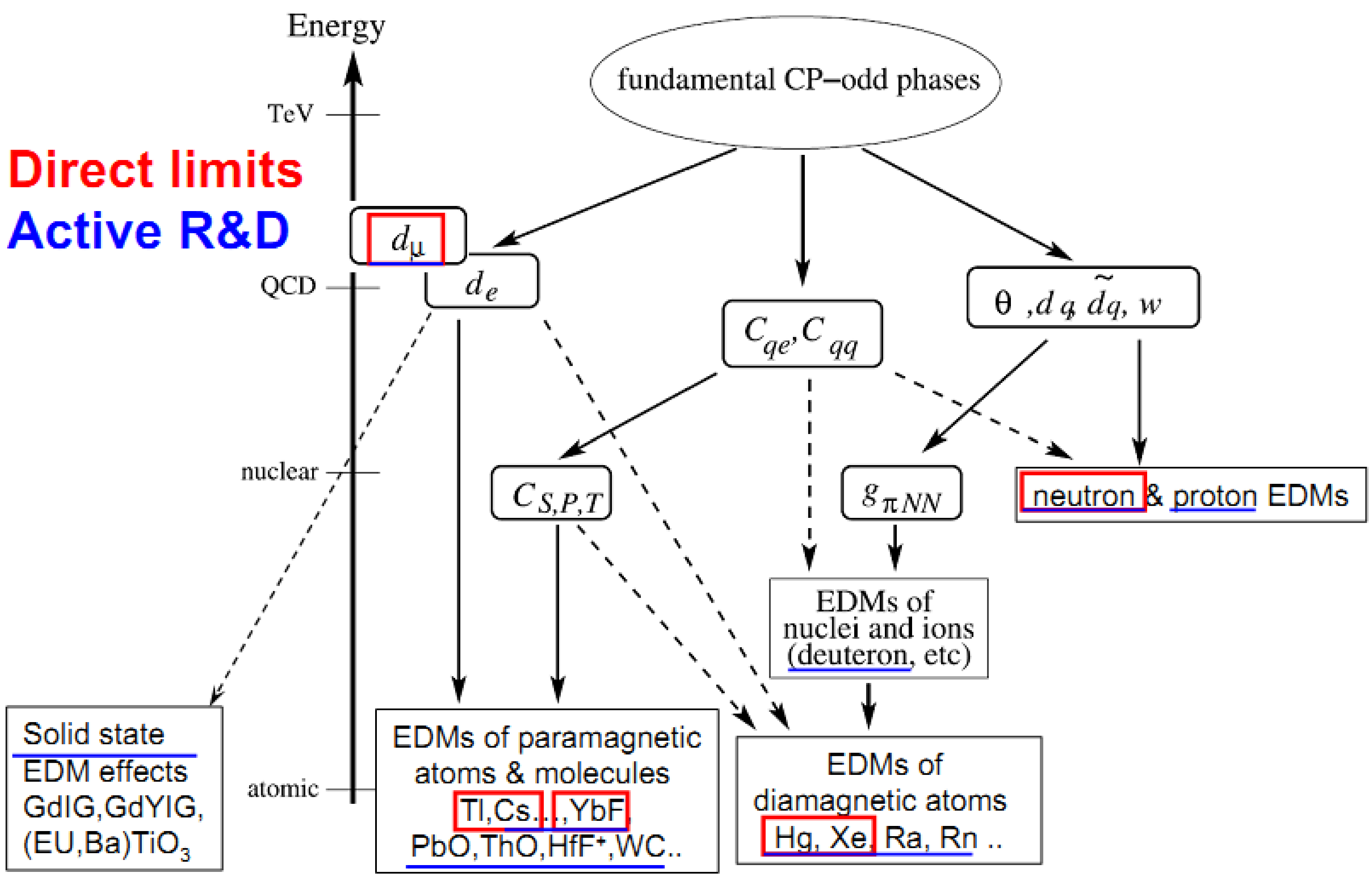
$$H_{\mathrm{M}} = -\boldsymbol{\mu}\cdot\mathbf{B} = -\mu\,\boldsymbol{\sigma}\cdot\mathbf{B} \qquad H_{\mathrm{E}} = -\mathbf{d}\cdot\mathbf{E} = -d\,\boldsymbol{\sigma}\cdot\mathbf{E}$$

  - $d$ is T-odd and P-odd
  - $d \neq 0 \Rightarrow$ T is violated and CP is violated (through CPT theorem)

- SM predictions for $d$ are:

$$d_e \simeq 10^{-40}\, e\cdot\mathrm{cm} \qquad d_n \simeq 10^{-31}\, e\cdot\mathrm{cm}$$

# CP violation and permanent EDM

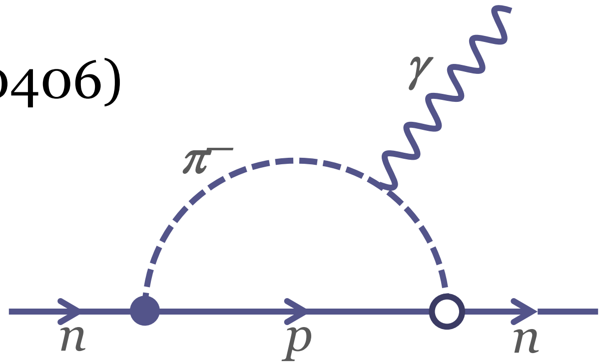



Pospelov & Ritz, Ann. Phys. 318 (2005) 119

# Neutron EDM

- **Neutron EDM** – ideal tool for search of CP-violation sources beyond SM: *no "SM-background" seen in e.g. K- and B-systems (ε, ε')*
- "**Strong CP problem**" ($\theta$-term)
  - Fine tune is needed to accommodate very small EDM values ($\theta < 2\times10^{-10}$)
  - Axions? (Zavattini et al., PRL 96 (2006) 110406)

$$\mathcal{L}_{\rm QCD} \approx \mathcal{L}_{\rm QCD}^{\theta_{\rm QCD}=0} + \theta_{\rm QCD}\frac{g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu}$$

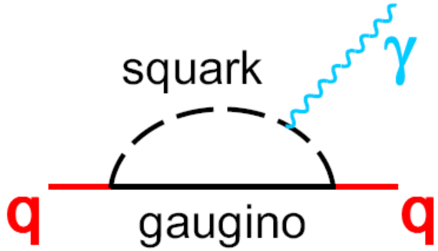



$$d_n \approx 10^{-16}\, e\cdot{\rm cm}\times\theta_{\rm QCD} \quad\Rightarrow\quad \theta_{\rm QCD} \le 10^{-10}$$

Why is $\theta_{\rm QCD}$ so small?

# Neutron EDM (cont.)

- "**SUSY CP problem**" ("overproduction" of EDM in SUSY models)




$$d_q = (\text{loop factor}) \times \frac{m_q}{\Lambda^2} \times \sin\varphi_{\text{CP}}$$

loop factor ~ $\alpha/\pi$
scale of SUSY breaking $\Lambda \sim$ GeV
$\varphi_{\text{CP}}$ – CP-phase

$$d_{u,d} = 3\times 10^{-24}\, e\cdot\text{cm}$$

n EDM: $\Rightarrow$ $d_{u,d}$ are 10-100 times less !

Pospelov & Ritz, hep-ph/0504231

# Neutron EDM

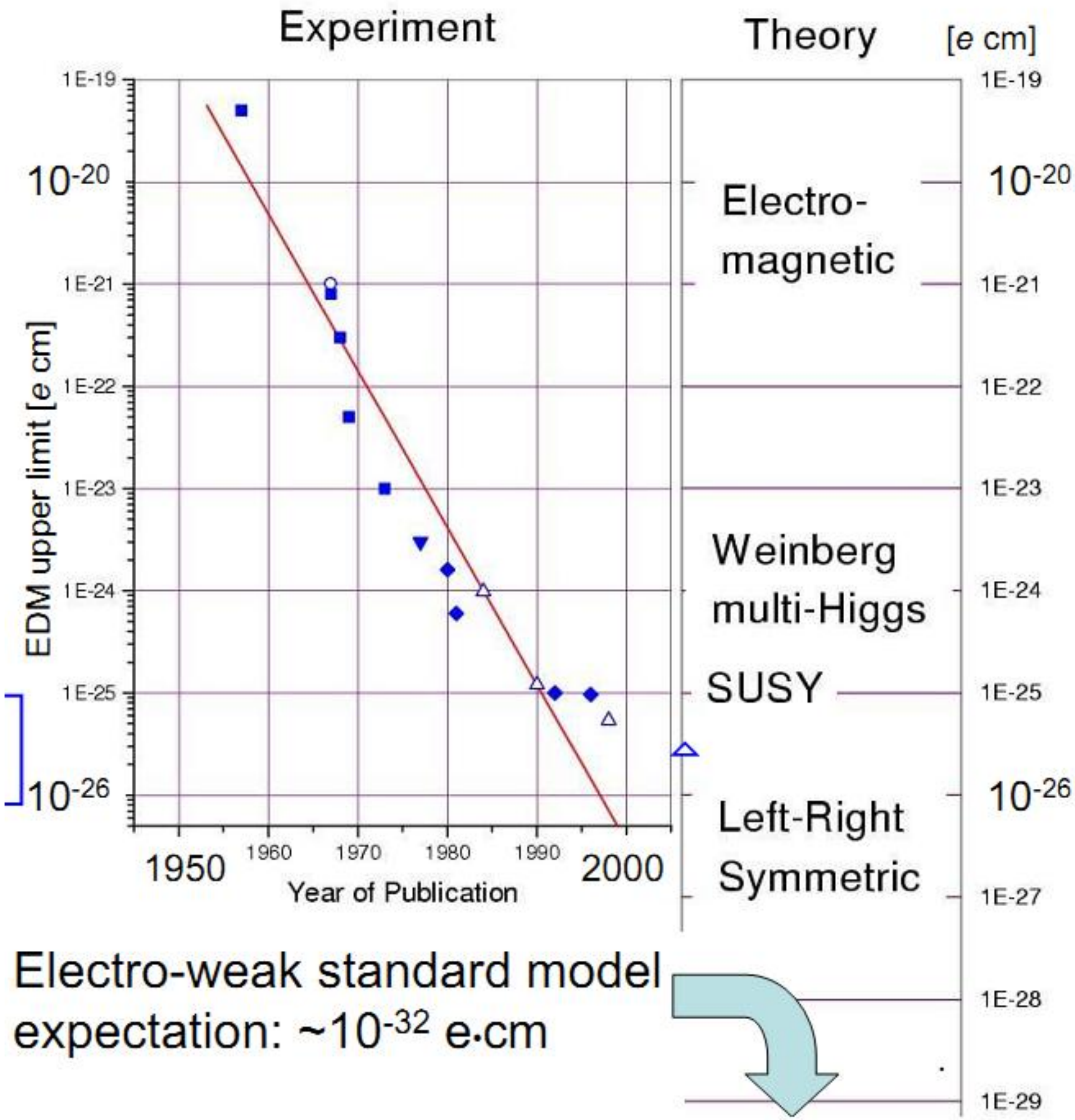
- Present experimental limit:

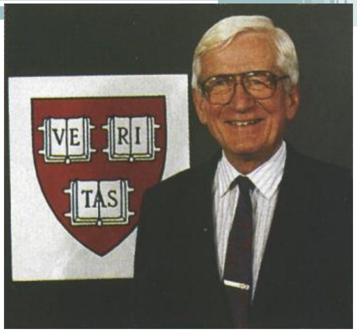
$$d_n < 3.0\times10^{-26}\, e\cdot \text{cm}$$

C.A.Baker et al., PRL97 (2006) 0609055
J.M. Pendlebury et al., PRD 92(2015)092003

- Anticipated accuracy of new experiments:

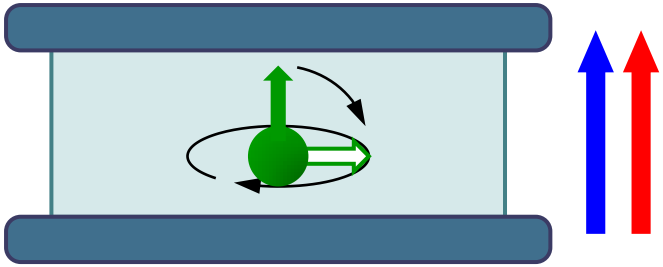
$$d_n \sim 10^{-28}\, e\cdot \text{cm}$$



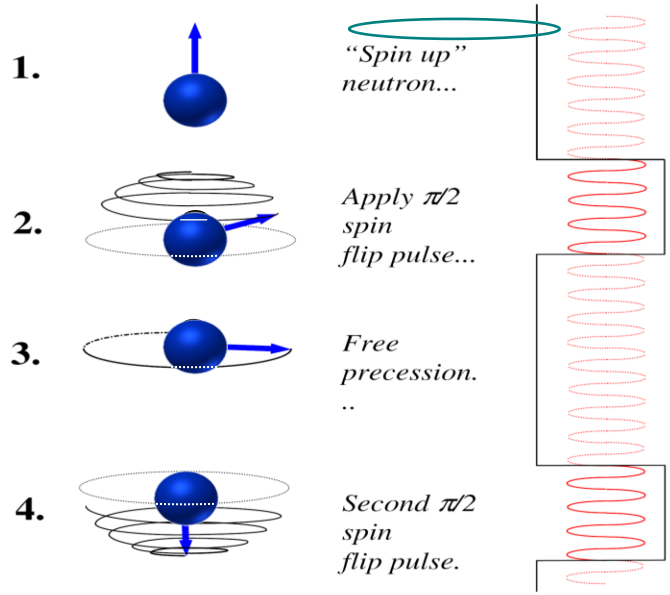


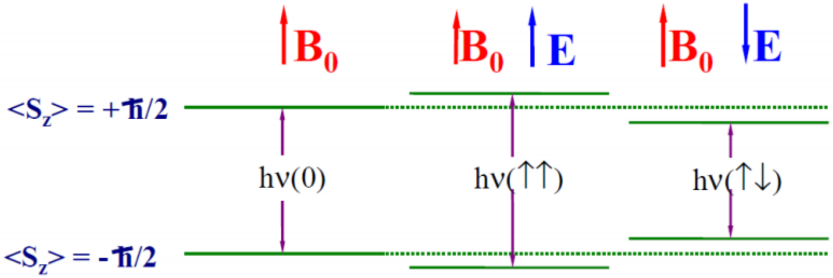
# Neutron EDM measurement

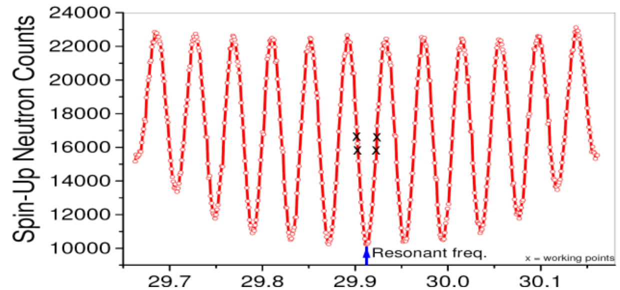
- Measure energy shift for $\boldsymbol{B_0}$, $\boldsymbol{E_0}$ fields aligned parallel and anti-parallel
- Ramsey method of separated oscillating fields



$$h\nu_{\uparrow\uparrow} = 2\,(\mu B + d_n E)$$
$$h\nu_{\uparrow\downarrow} = 2\,(\mu B - d_n E)$$
$$h\Delta\nu = 4\, d_n E$$



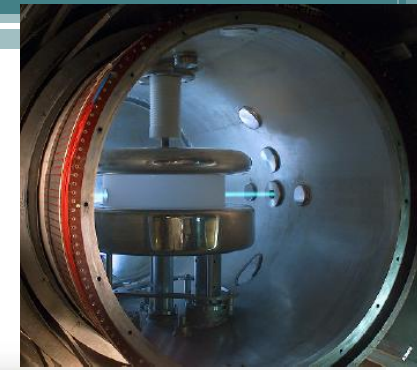



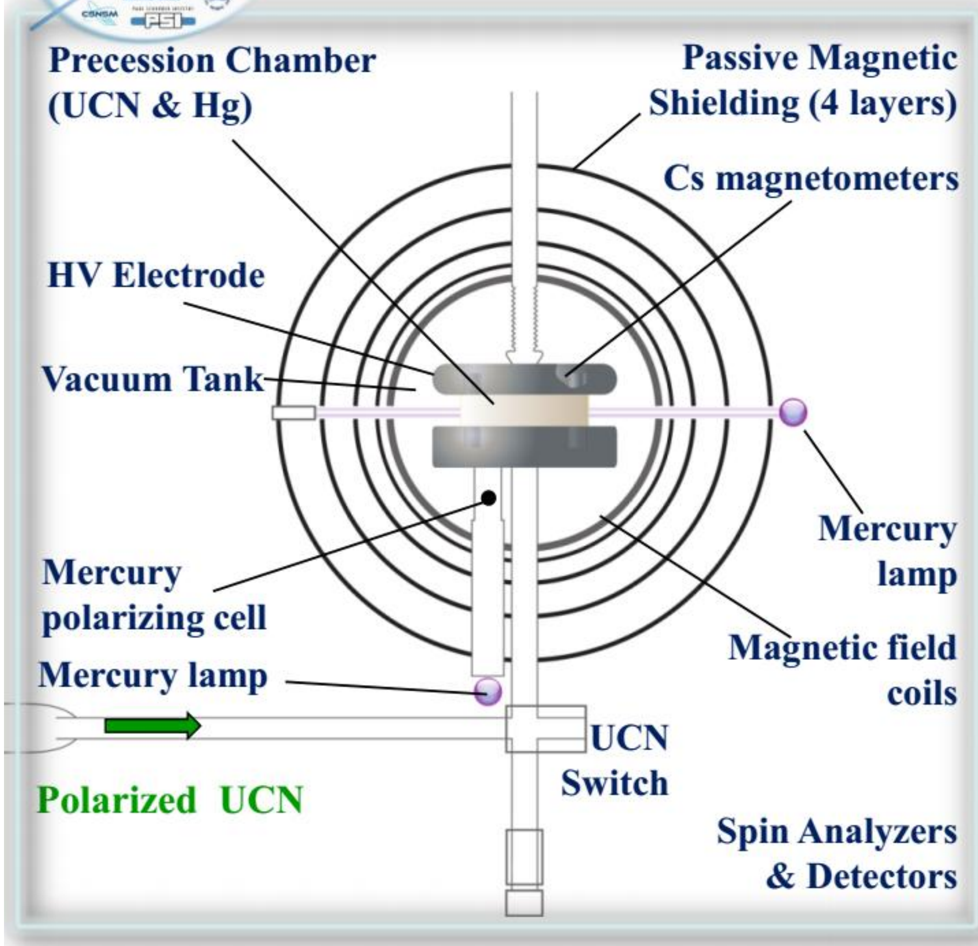




$$d_n = 5\times10^{-28}\, e\cdot\mathrm{cm}, \quad E_0 = 15\ \mathrm{kV/cm}$$
$$\Rightarrow \quad h\nu = 3\times10^{-23}\ \mathrm{eV}$$

$$\sigma(d_n) = \frac{\hbar}{2\alpha E T\sqrt{N}}$$

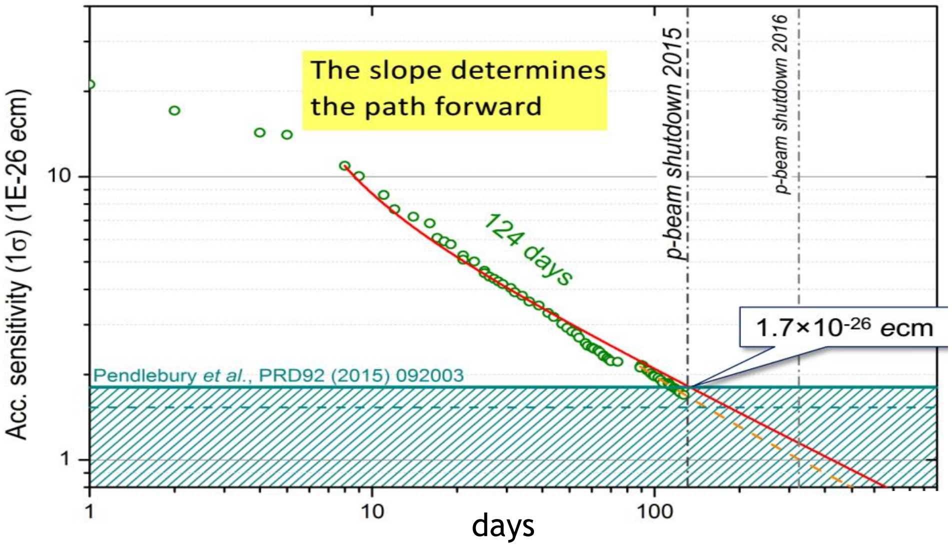
# Neutron EDM at PSI





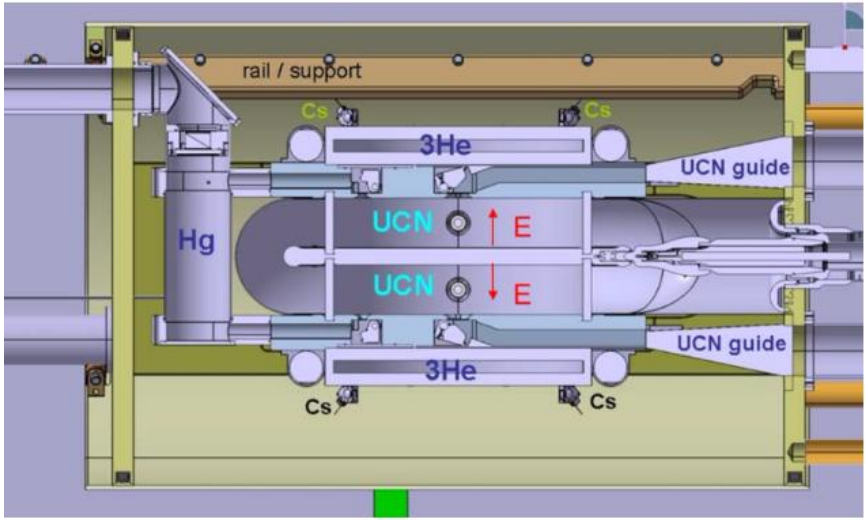

# Neutron EDM at PSI

- **Best sensitivity per day** (ever) reached in 2015: $1.1\times10^{-26}$ e·cm/day
- **Data taking** – two campaigns (2016, 2017) with present setup in view




- **New spectrometer** (double chamber) in construction – to be installed in 2018
- **Ultimate goal**:

$$\sigma(d_n) < 5\times10^{-28}\text{e·cm}$$



# Neutron EDM projects worldwide

- **Operational**:
  - PNPI+ILL+PTI@ILL - upgrading
  - nEDM@PSI – takes data upgrade to n2EDM in 2018

- **R&D and construction**:
  - @RCNP/TRIUMF (Canada)
  - @FRM-2 (Germany)
  - @SNS (USA)
  - @PNPI (Russia)
  - @LANL (USA)

- **Possible future projects**:
  - @PIK (Russia)
  - @J-PARK (Japan)
  - @ESS (Sweden)

- ***All projects aim at 1 – 2 orders of magnitude improvement***

# “Exotics”

# Neutron in fundamental physics

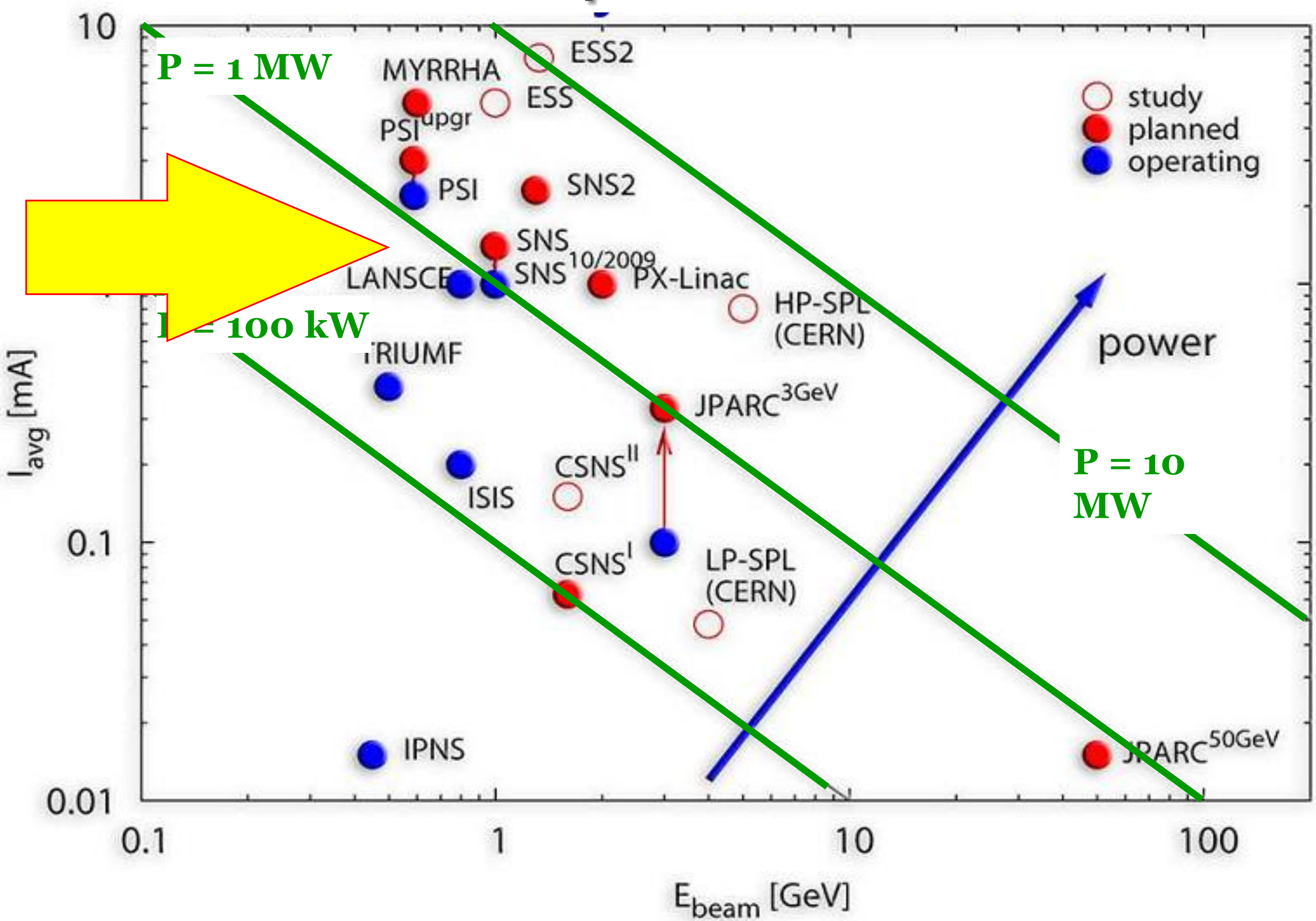
- **Neutron lifetime – bariogenesis – CMB**
- **n-n̄ oscillations**
  - Baryon number violation
- **n-n' oscillations** (neutron ↔ mirror neutron)
  - Expected oscillation times of $\tau_{n\text{-}n'} \sim 1 \div 1000$ s
  - Could explain transport of UHE protons over large distances
  - Dark matter
  - Poor limit can be improved with UCN's by 3 orders of magnitude
- **Neutrons test Lorentz Invariance and/or CPT**
  - Neutron EDM spectrometer is an accurate clock
- **Neutrons and gravitation**
  - Quantum states in Earth field
  - Extra dimensions
- **Neutron interferometry**
  - Berry's topological phase
  - Aharonov-Bohm, Aharonov-Cashier squeezed states

# Summary and outlook

- **Neutron observables**:
  - *Directly test SM and search for TeV scale physics beyond SM*
- **The dream scenario**:
  - *LHC finds BSM particle(s) on-shell and $\beta$-decay has to confirm it in observables (off-shell corrections)*
- **Fundamental neutron research is**:
  - *Important for Particle Physics*
  - *Addressed in several labs worldwide*
  - *Promising as new installations (CN-beams, UCN) are under construction*
- **New results**:
  - *Expected soon from variety of ongoing and planned projects*

# Backup slides

# Intensive proton beams

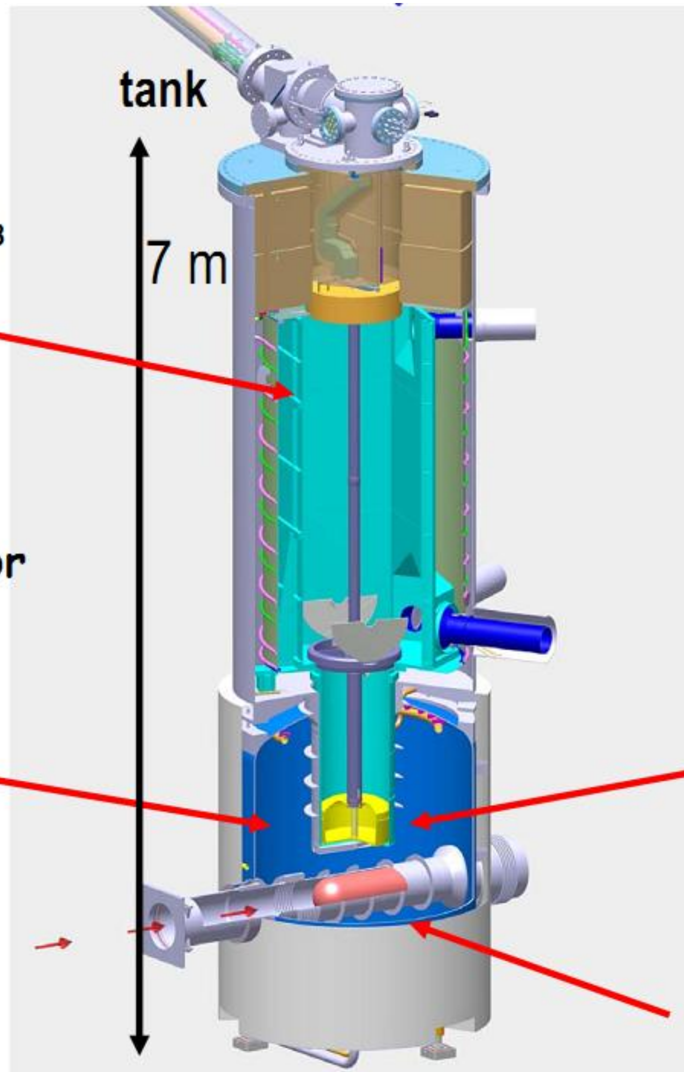


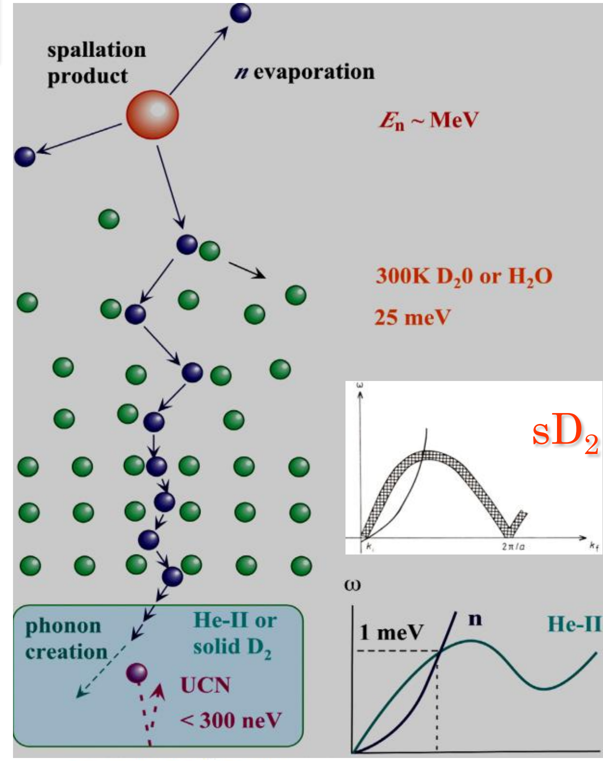
# UCN spallation source at PSI

DLC coated
UCN storage volume
height 2.5 m, ~ 2 m³
$\rho_{UCN}$ ~ 2000 cm$^{-3}$

heavy water moderator
→ thermal neutrons
3.6m³ $D_2O$

pulsed
1.3 MW p-beam
600 MeV, 2.4 mA,
1% duty cycle



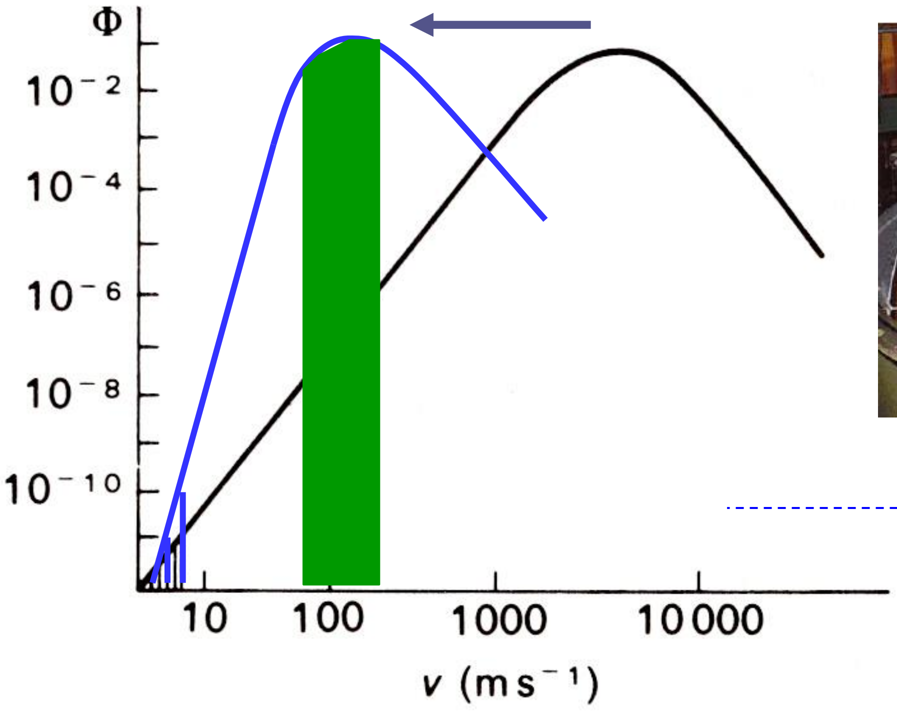



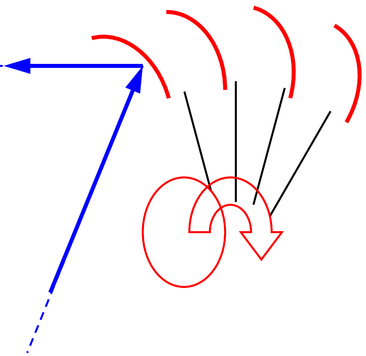

cold UCN-converter
30 dm³ solid $D_2$ at 5 K

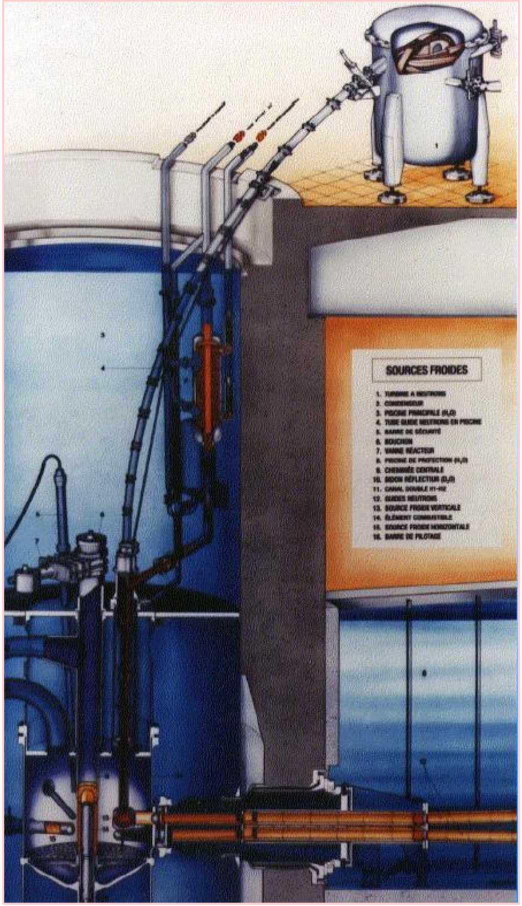
spallation target (Pb/Zr)
(~ 8 neutrons/proton)

# UCN at ILL Grenoble


- Vertical extraction of CN
- Kinetic deceleration (Steyerl's turbine)



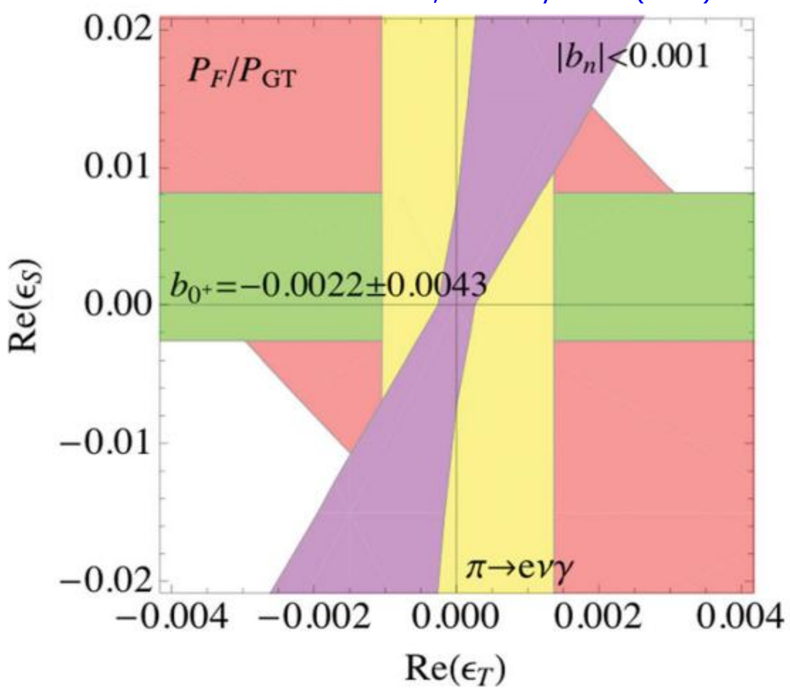



- Limitation of UCN density is due to Liouville's theorem

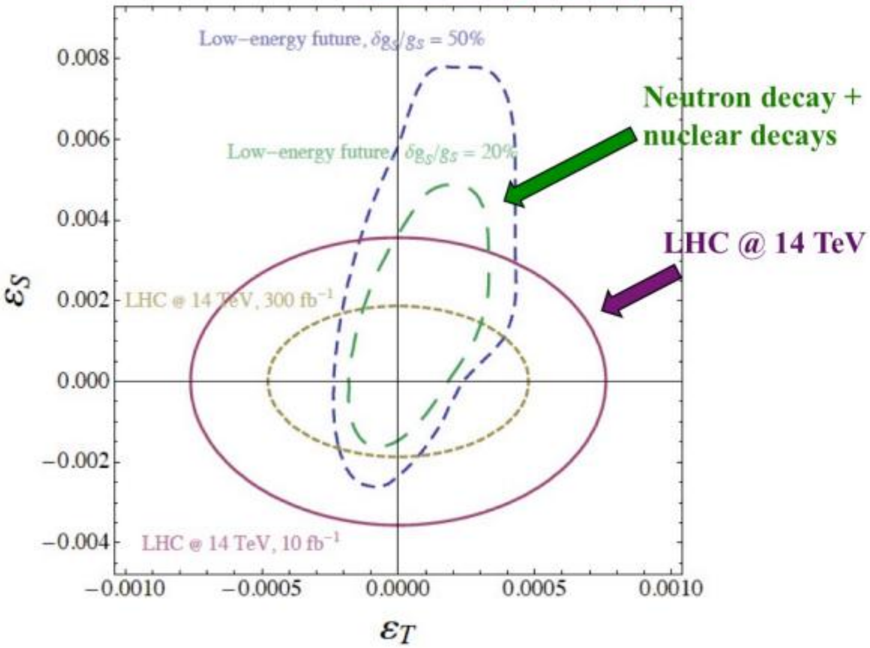
# LE-HE competition

- Next generation neutron and nuclear β-decay experiments will compete even with full luminosity LHC results

M. Gonzalez-Alonso et al., Ann. Phys. 525 (2013)




Bhattacharya et al.'2012




- *The dream scenario would be that LHC finds a BSM particle on-shell and β-decay has to confirm it in observables (off-shell corrections)*