Fundamental Physics Possibilities @ ESS

Valentina Santoro

Outline

- Current status of particle physics
- Why fundamental physics @ ESS
- Possible particle physics experiment @ ESS

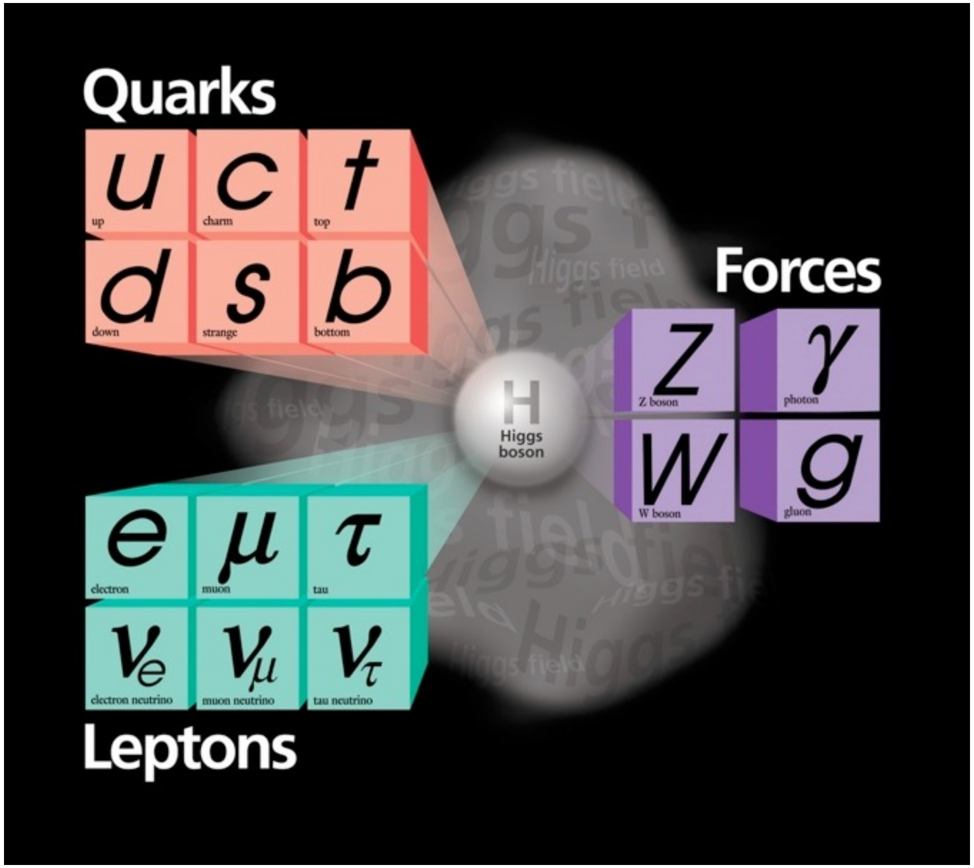
Two important points

- We are leaving in an interesting time

- ESS fundamental physics measurements can be complementary and competitive with LHC measurements

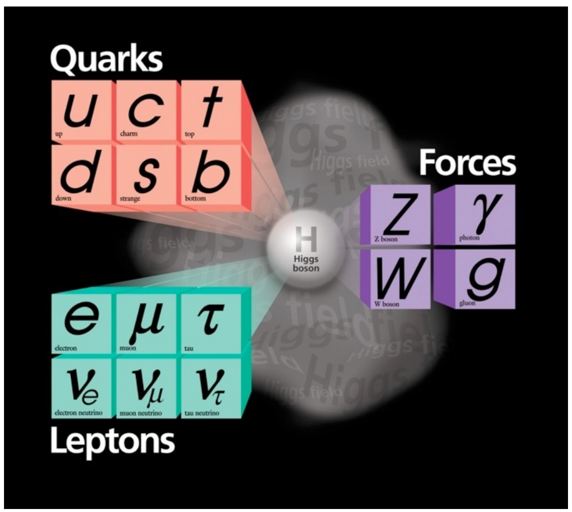
Standard Model today

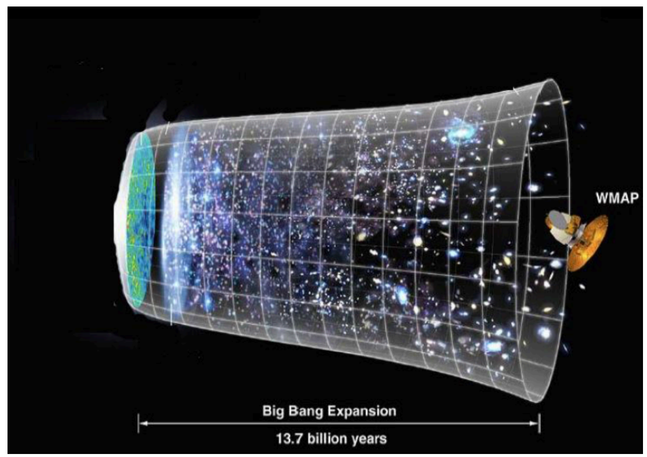
- Higgs discovery completes the Standard Model
  - Fully consistent, complete, precise description of strong, electromagnetic and weak interactions
- Even generate fermion masses



Lacking in the Standard Model (I)

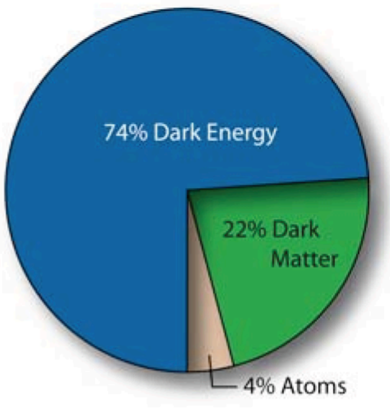
Standard Model + General Relativity = Universe ???



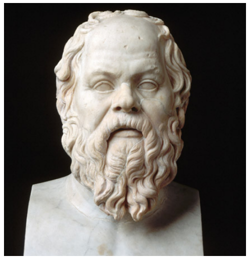


We are able only to account for 5% of the energy content of the universe

Lacking in the Standard Model (II)

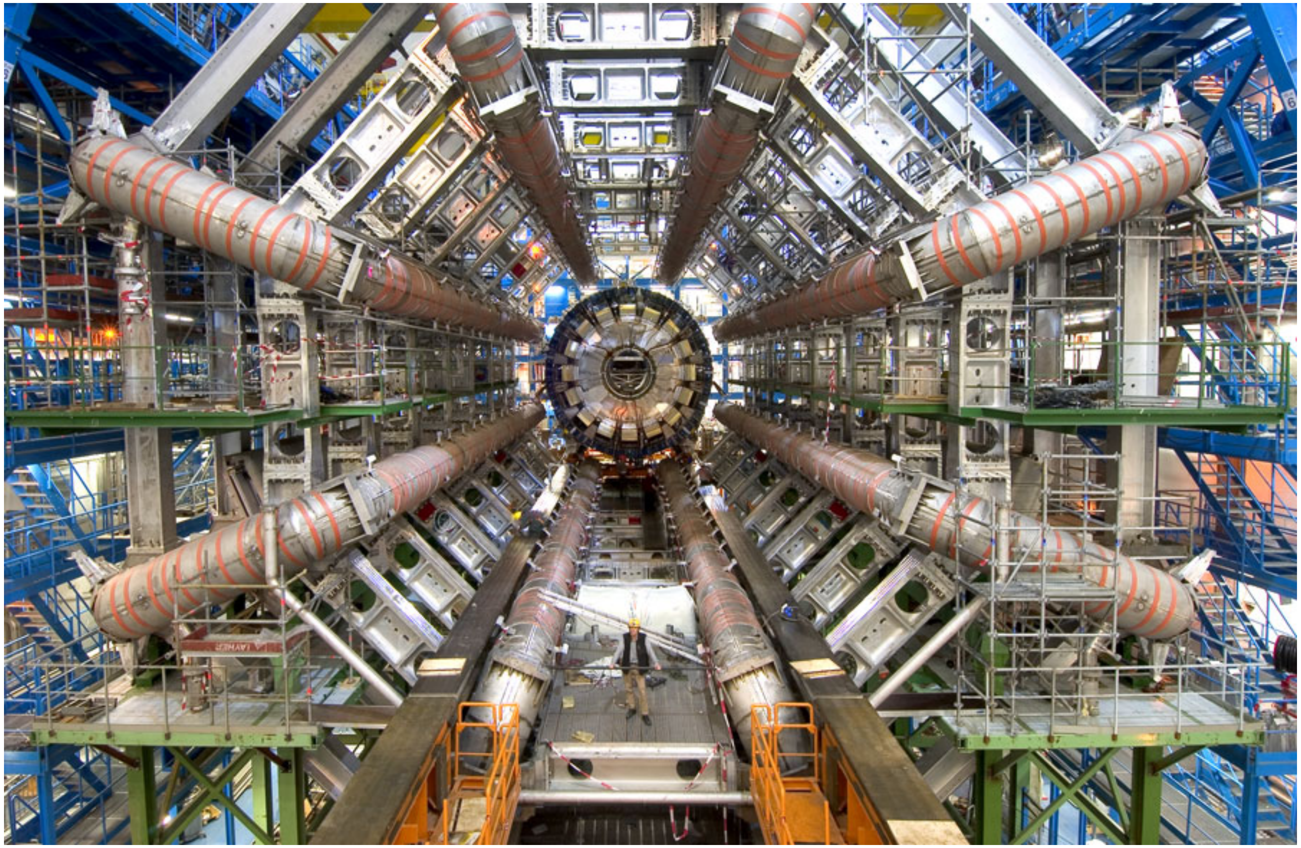


- What is the Universe REALLY made of?
- Particle physicist's answer: stable particles - protons, neutrons, electrons, neutrinos
- But astronomical observations indicate that th known particles make only about 4% of the stuff in the Universe!!!
- We have to look for a new kind of matter new kind of physics BSM (Beyond the standard model)



"The only true wisdom is in knowing you know nothing"
Socrates

To answer all the present questions from Standard Model people built LHC



Found the Higgs but so far nothing more …..

How do you search for new physics?

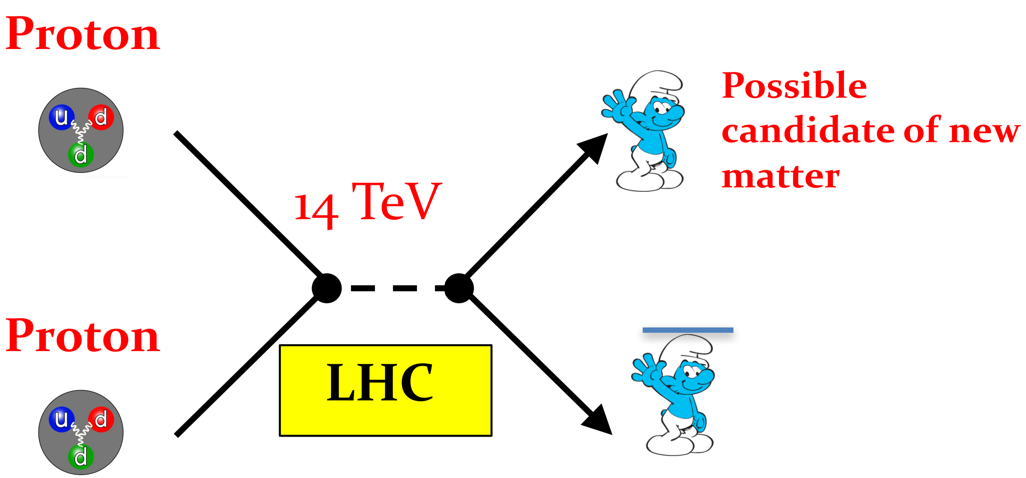
We have to look for a new kind of matter

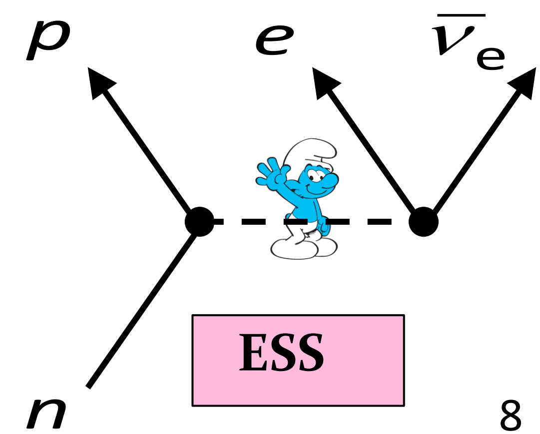
Many ideas from theoretical physicists (SUSY, GUT .....)

The way to find Beyond the Standard Model physics

Direct Searches
Produce new particles as real particles in pp collisions

Indirect Searches
New particles will appear as virtual particles in quantum loops





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Indirect searches for New Physics is the key of the Fundamental and particle physics at ESS

Fundamental & Particle Physics @ ESS

Standard Model of particle physics (SM)

Precision experiments

Beyond SM
New interactions

Neutron antineutron oscillation beamline (NNbar)

Baryon asymmetry of the Universe

Cold neutron beamline (ANNI)

Neutron beta decay

Hadronic parity violation

Electromagnetic properties of the neutron

UCN beamline

Gravity resonance spectroscopy

Neutron interferometry

Neutron beta decay

Fundamental & Particle Physics @ ESS

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Standard Model of particle physics (SM)

Precision experiments

Beyond SM
New interactions

Neutron antineutron oscillation beamline (NNbar)

Letter of intent, cost ~ x 10 higher than ESS instruments 1-22, requires external funding

Cold neutron beamline (ANNI)

Full ESS Proposal, public user beamline, strong support by SAC (Scientific Advisory Committee) , but not prioritized among first 15 instruments: instruments 16-22

UCN beamline

Gravity resonance spectroscopy

Letter of intent, public user beamline, after or alternatively to NNbar

The nn bar proposal @ ESS

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Neutron-Anti-Neutron Oscillations at ESS

12-13 June 2014, CERN, Geneva, Switzerland

Neutral particle oscillations have proven to be extremely valuable probes of fundamental physics. Kaon oscillations provided us with our first insight into CP-violation, fast Bs oscillations provided the first indication that the top quark is extremely heavy, B oscillations form the most fertile ground for the continued study of CP-violation, and neutrino oscillations suggest the existence of a new, important energy scale well below the GUT scale. Neutrons oscillating into antineutrons could offer a unique probe of baryon number violation.

The construction of the European Spallation Source in Lund, with first beam expected in 2019, together with modern neutron optical techniques, offers an opportunity to conduct an experiment with at least three orders of magnitude improvement in sensitivity to the neutron oscillation probability.

At this workshop the physics case for such an experiment will be discussed, together with the main experimental challenges and possible solutions. We hope the workshop will conclude with the first steps towards the formation of a collaboration to build and perform the experiment.

Organising committee:

G. Brooijmans (Columbia University)
S. Chattopadhyay (Cockroft Institute)
R. Hall-Wilton (European Spallation Source)
Y. Kamyshkov (University of Tennessee)
E. Klinkby (Technical University of Denmark and European Spallation Source)
M. Lindroos (European Spallation Source and Lund University)
L. Mapelli (CERN)
M. Mezzetto (INFN Padova)
H. M. Shimizu (Nagoya University)
W. M. Snow (Indiana University)
T. Soldner (Institut Laue Langevin)
C. Theroine (European Spallation Source)

Register before
19 May on
www.nnbar-at-ess.org

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CERN

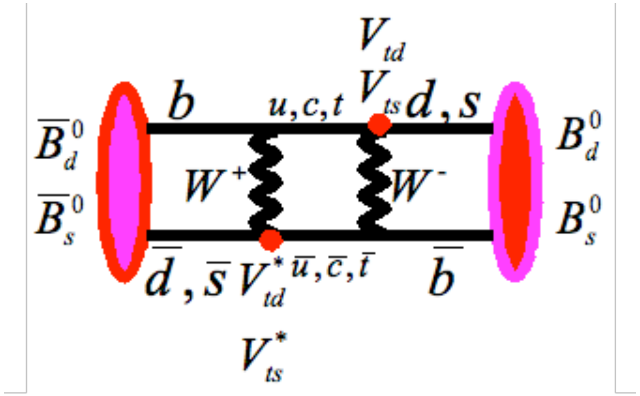
A New Search for Neutron-Anti-Neutron Oscillations

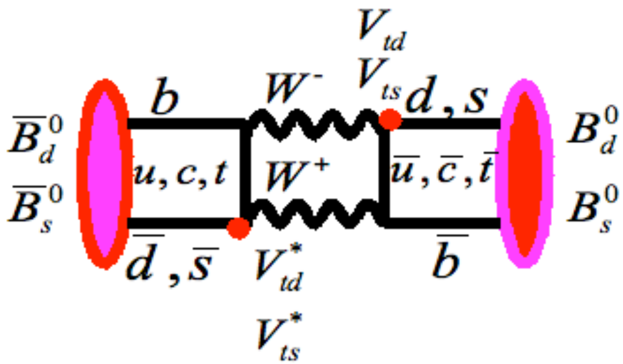
Abstract

The observation of neutrons turning into antineutrons would constitute a discovery of fundamental importance for particle physics and cosmology. Observing the $n\text{–}\bar{n}$ transition would show that baryon number (B) is violated by two units and that matter containing neutrons is unstable. It would provide a clue to how the matter in our universe might have evolved from the $B=0$ early universe. If seen at rates observable in foreseeable next-generation experiments, it might well help us understand the observed baryon asymmetry of the universe. A demonstration of the violation of $B-L$ by 2 units would have a profound impact on our understanding of phenomena beyond the Standard Model of particle physics.

The Power of Oscillations

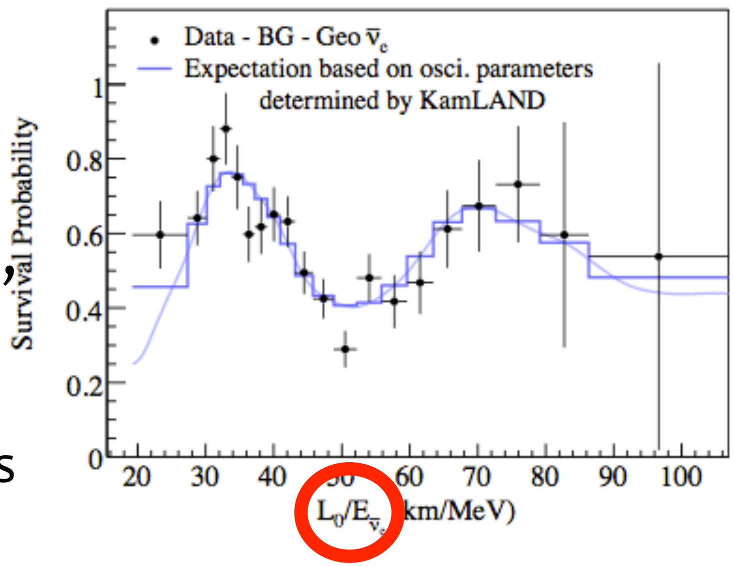
- Neutral particle oscillations have played large role in particle physics
  - K^0-$\bar{K}^0$ oscillations (**ΔS = 2**) at the core of our initial understanding of CP-violation
  - B meson oscillations (**ΔBeauty = 2**):
    - Sensitive to CKM elements
    - CP-violation "workhorse"
    - Probe m_t^2/m_W^2
    - ➡ First indication of large top mass! (1987)
- Sensitive probes of high mass



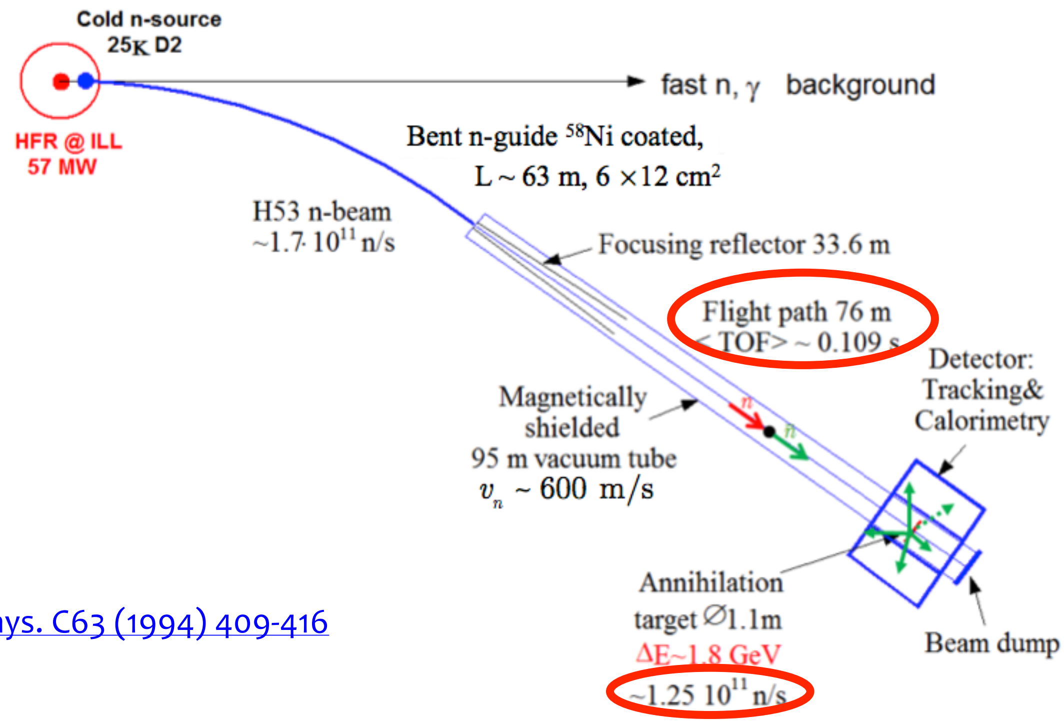


Neutrino Oscillations

- Neutrino oscillations unambiguously establish neutrinos are massive
  - Since neutral, **Majorana** mass term allowed
    - If exists, **ΔL = 2**!
  - If both Dirac and Majorana mass terms, mixing induces see-saw effect, *explaining* small neutrino masses
    - Two scales: Dirac and Majorana mass terms
      - Lead to observed scales $m_\nu \sim m_D^2/M$ and $m_N \sim M$
    - Dirac scale could be close to other fermions
      - Suggests a Majorana (ΔL=2) scale 10^6 - 10^{10} GeV
  - **ΔB = 2** at a similar energy scale?



Search for neutron antineutron oscillation @ ILL



Baldo-Ceolin et al, [Z.Phys. C63 (1994) 409-416]

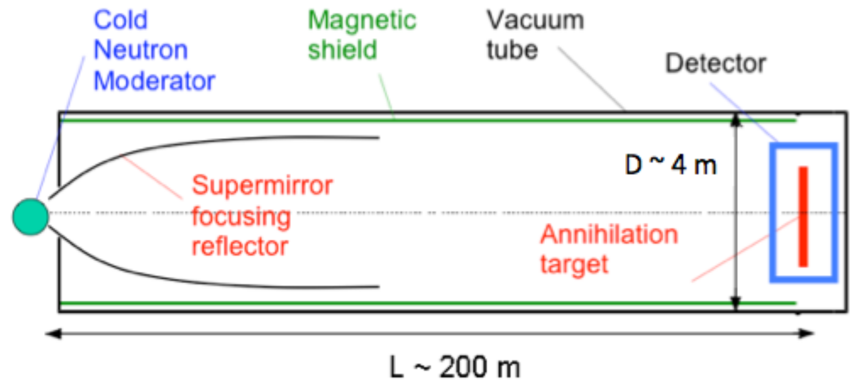
- $Nt^2 = 1.5\ 10^9$s, $P < 1.6\ 10^{-18}$ (run lasted ~1 year) and $\tau > 0.86\ 10^8$s

(**N** is the free neutron flux reaching the annihilation target and **t** is the neutron observation time.)

– Many subtle optimizations to minimize losses and backgrounds

NNbar experiment Conceptual Design

- Increase number of neutrons
  - Flux
    - Moderator brightness and area
  - Angular acceptance
  - Longer run
- Increase time-of-flight
  - Colder neutrons
  - Longer beamline



- Keep (or even increase) detection efficiency (~50%), keep background at ~0
  - Exploit current, established hardware and software technologies
- Better B_{Earth} suppression (B field < 5 nT)
  - Improved passive (+ active?) shield

See e.g. NNbarX (Babu et al.), http://arxiv.org/abs/arXiv:1310.8593

Potential Gains wrt ILL

Brightness		≥ 1
Moderator Temperature	<TOF> driven by colder neutrons, ~quadratic (t^2)	≥ 1
Moderator Area	Needs large aperture	2
Angular Acceptance	2D, so quadratic sensitivity	40
Length	Scale with t^2, so L^2	5
Run Time	ILL run was 1 year	3
Total		≥ 1000

x 1000 in probability, reach τ ~ 2-3 x 10^9 s

Improve by 10^3

Why the Search for Neutron- Anti-Neutron Oscillations is interesting to pursuit

- Baryon Number Violation at the core of our existence
- Physics of Baryon Number Violation of utmost importance
  - Standard Model tells us about interactions
    - But *nothing* about nature of quarks and leptons
  - Standard Model is now complete
    - Understanding fermions is our biggest gap
    - Our existence, Grand Unification our best hints
  - Baryon Number Violation excellent probe
    - We *know* it exists
    - Observation will tell us about mechanism, and Grand Unification, and maybe neutrinos
- **Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare**

NNbar Collaboration

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Expression of Interest for
A New Search for Neutron-Anti-Neutron Oscillations at ESS

	Name	Affiliation
Main proposer	Gustaaf Brooijmans	Columbia University
Co-proposers	Torsten Åkesson	Lund University
	David Baxter	Indiana University
	Hans Calen	Uppsala University
	Lorenzo Calibbi	Université Libre de Bruxelles
	Luis Castellanos	University of Tennessee
	Joakim Cederkäll	Lund University
	Peter Christiansen	Lund University
	Christophe Clément	Stockholm University
	Brian Cole	Columbia University
	Caterina Doglioni	Lund University
	Claes Fahlander	Lund University
	Gabriele Ferretti	Chalmers University of Technology
	Peter Fierlinger	TU Munich
	Matthew Frost	University of Tennessee
	Franz Gallmeier	University of Tennessee, Oak Ridge National Laboratory
	Kenneth Ganezer	California State University Dominguez Hills
	Richard Hall-Wilton	ESS
	Vincent Hedberg	Lund University
	Lawrence Heilbronn	University of Tennessee
	Andreas Heinz	Chalmers University of Technology
	Go Ishikawa	Nagoya University
	Håkan Johansson	Chalmers University of Technology
	Tord Johansson	Uppsala University
	Leif Jönsson	Lund University
	Yuri Kamyshkov	University of Tennessee
	Masaaki Kitaguchi	Nagoya University
	Esben Klinkby	ESS, Technical University of Denmark
	Balasz Konya	Lund University
	Andrzej Kupsc	Uppsala University
	Mats Lindroos	ESS
	Else Lytken	Lund University
	Bernhard Meirose	University of Texas, Dallas
	David Milstead	Stockholm University
	Rabindra Mohapatra	University of Maryland
	Thomas Nilsson	Chalmers University of Technology
	Anders Oskarsson	Lund University
	Robert Pattie	Los Alamos National Laboratory
	Christoffer Petersson	Chalmers University of Technology
	David Phillips	North Carolina State University
	Amlan Ray	VECC, Kolkata, India
	Filippo Resnati	CERN
	Arthur Ruggles	University of Tennessee
	Utpal Sarkar	Physical Research Laboratory, Ahmedabad, India
	Alexander Saunders	Los Alamos National Laboratory
	Hirohiko M. Shimizu	Nagoya University
	Robert Shrock	Stony Brook University
	David Silvermyr	Lund University
	Samuel Silverstein	Stockholm University
	Oxana Smirnova	Lund University
	Per Erik Tegner	Stockholm University

ANNI: a cold neutron beam for particle physics @ ESS

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ESS Instrument Construction Proposal
ANNI – a cold neutron beam facility for Particle Physics

We propose the cold neutron beam facility ANNI for particle physics at the ESS. The proposed instrument will outperform all existing and planned cold neutron beam facilities in the field. It makes full use of the ESS pulse structure. User experiments which used pulsed beams at continuous sources will gain between one and two orders of magnitude in event rate. The time structure of the neutron beam enables powerful techniques to suppress systematic effects. These were rarely employed in the past due to related large intensity losses at continuous sources. At the proposed beam line they will be a natural asset.

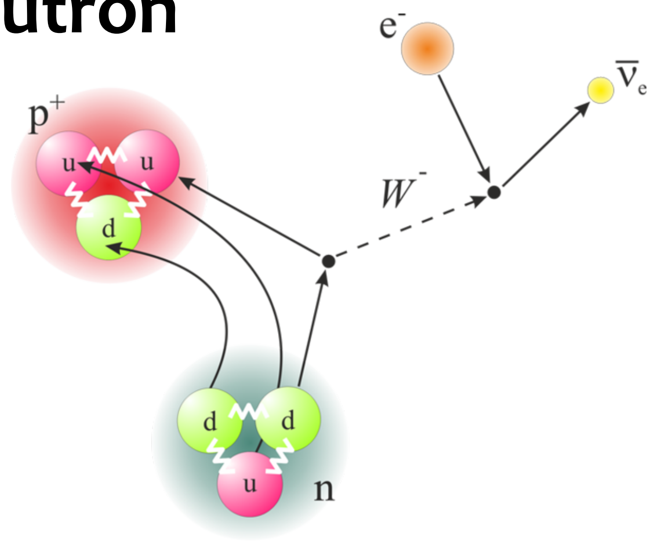
The instrument will enable new science. Measurements in neutron beta decay will gain one order of magnitude in accuracy. Experiments will probe a broad band of new physics models beyond the Standard Model at mass scales from 1 to 100 TeV, far beyond the threshold of direct particle production at accelerators. For the first time, the tiny effects of hadronic weak interaction will be resolved for calculable systems and studied systematically. This will enable quantitative tests of the non-perturbative limit of quantum chromodynamics. Beam methods to measure electromagnetic properties of the neutron will improve substantially. This promises a systematically different access to these fundamental properties which are related to matter formation in the Universe or the unification of fundamental forces.

ANNI: Cold beam @ ESS – Science case

✓ **Neutron beta decay correlation coefficients**

✓ **Hadronic weak interaction**

✓ **Electromagnetic properties of neutron**



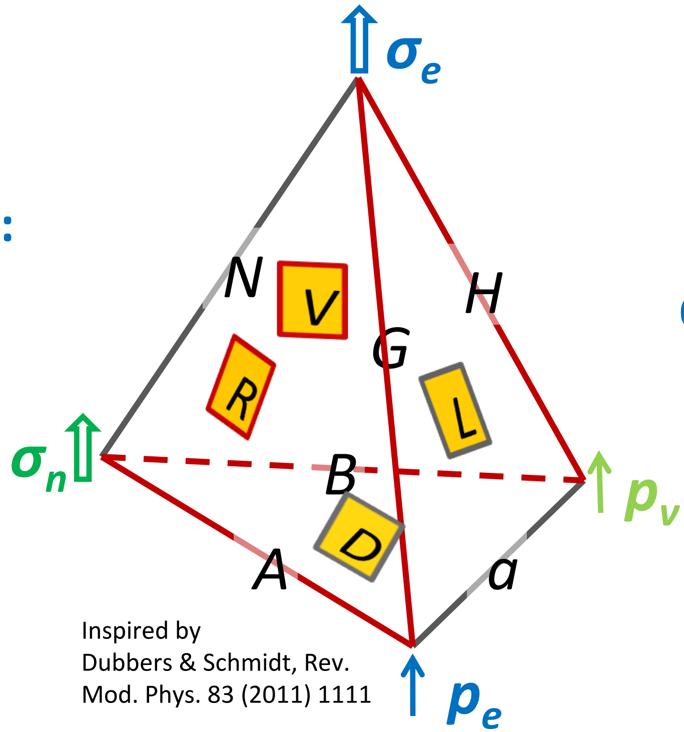
Neutron beta decay correlation coefficients

The differential decay probability of the free neutron can be expanded in correlations between the involved particles (momenta or spin) parametrized by correlation coefficients

$n \rightarrow p\ e\ \underline{\nu}_e$

4 "detectable" quantities:

- Neutron spin
- Electron momentum
- Electron spin
- Neutrino momentum



Inspired by Dubbers & Schmidt, Rev. Mod. Phys. 83 (2011) 1111

- P conserving
- P violating
- T violating

Correlations:

6 twofold $\underline{p_e p_\nu}$, $\underline{\sigma_n p_e}$

4 threefold $\sigma_n(p_e \times p_\nu)$

5 fourfold $(\sigma_e p_e)(p_e p_\nu)$

1 fivefold $(\sigma_e p_e)(\sigma_n(p_e \times p_\nu))$

+ Fierz term (e-spectrum)

+ lifetime

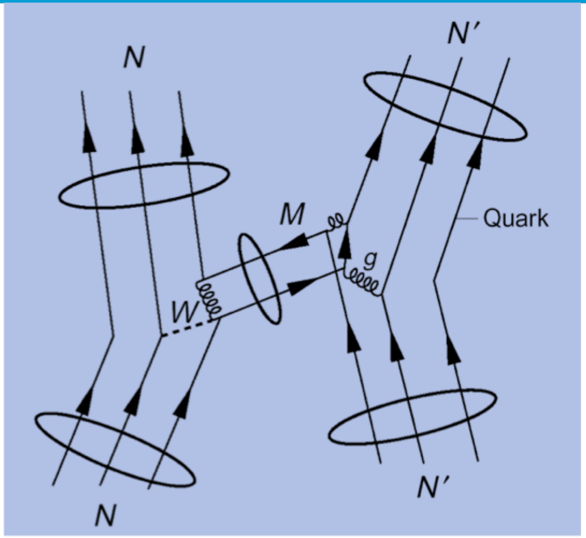
+ rare decay modes (H, γ)

Measuring several correlation coefficients in the neutron beta decay provides broad band probes for physics beyond the standard model

Hadronic weak interaction

Least understood weak interaction

- Complicated by nuclear structure
- Strongly suppressed by $M_{\pi}^{2}/M_{W}^{2} \sim 10^{-7}$
- Unique PV (parity-violation) signature



Motivation

- ***W*,*Z* range 0.002 fm → probe of short-range quark correlations in QCD nonperturbative regime**
- nuclear PV – test of nuclear structure models
- test of EFT in $\Delta S = 0$ sector ($\Delta I=1/2$ rule not understood)
- physics input to PV electron scattering experiments

Neutron EDM

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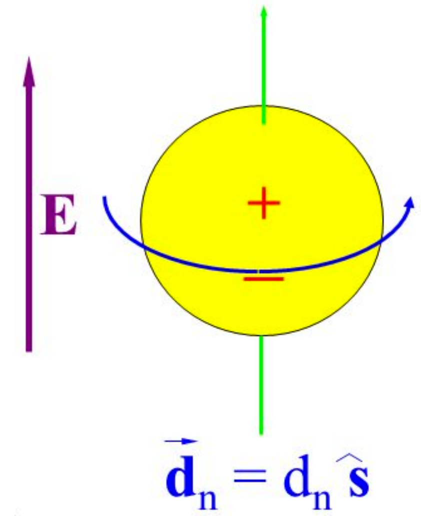
- The electrical neutrality of neutrons are not required by the SM.
- Standard Model EDMs are due to CP violation in the quark mixing matrix CKM
- The neutron EDM is Standard Model is predicted to be **10^{-32} e · cm**

- The current experimental neutron limit is

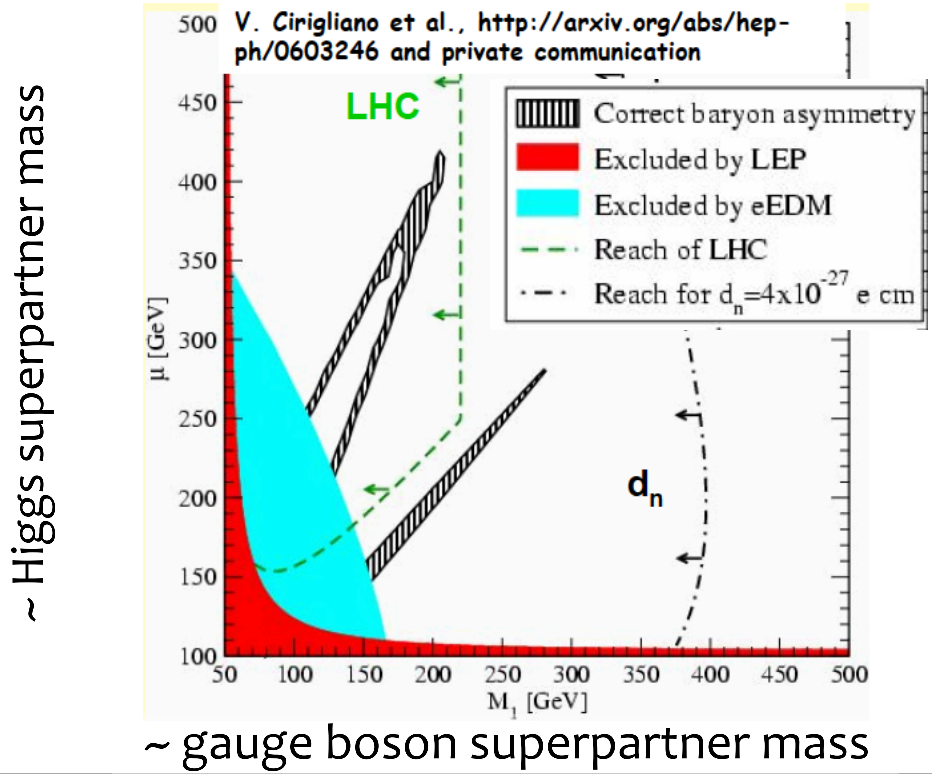
  $d_n < 2.9 \cdot 10^{-26}$ e · cm (@ 90% CL)
- A large class of grand unified theories (with additional CP violation BSM) set a lower bound for the neutron EDM of

  $d_n > 3 \cdot 10^{-28}$ e · cm



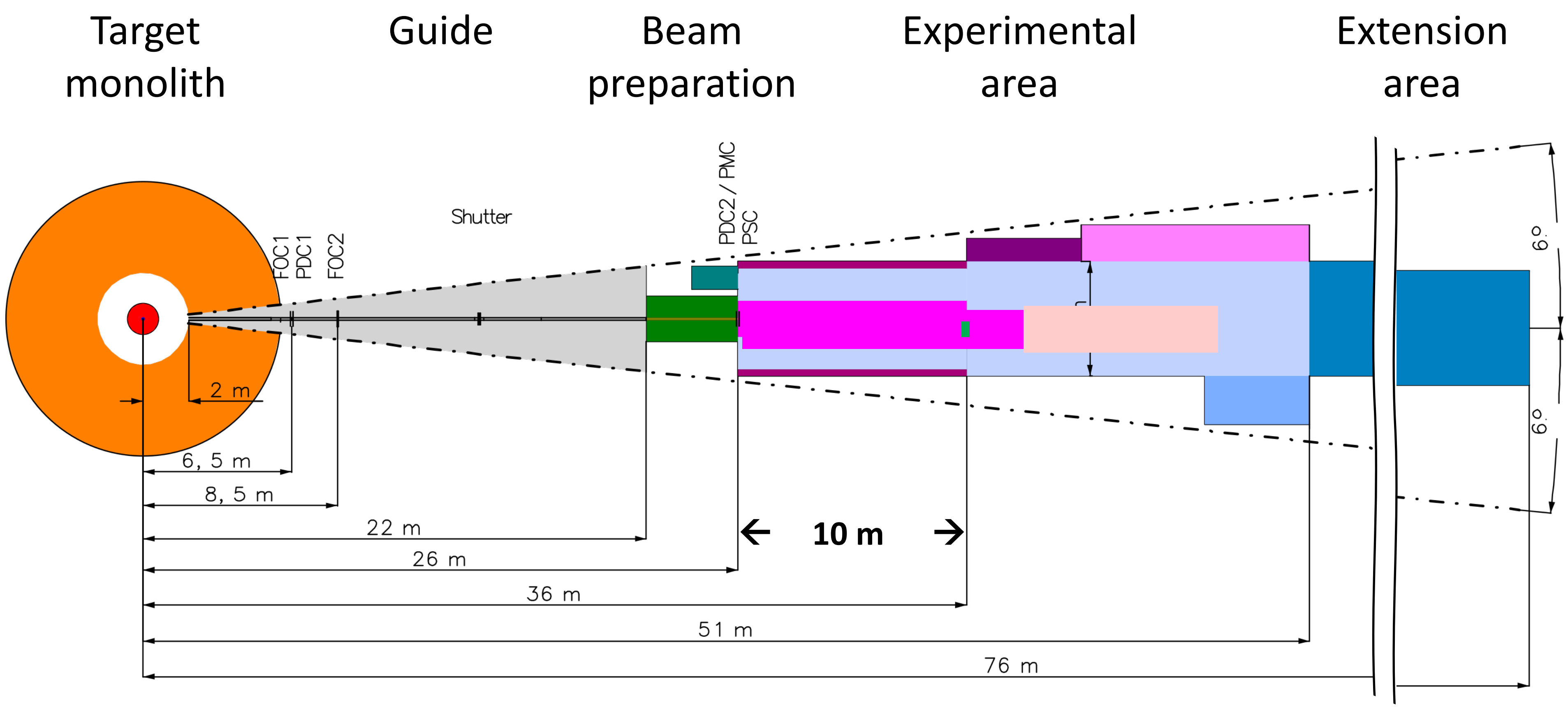
Possible impacts of non-zero EDM

- **Must be new physics**
- Sharply constraint model beyond the Standard Model



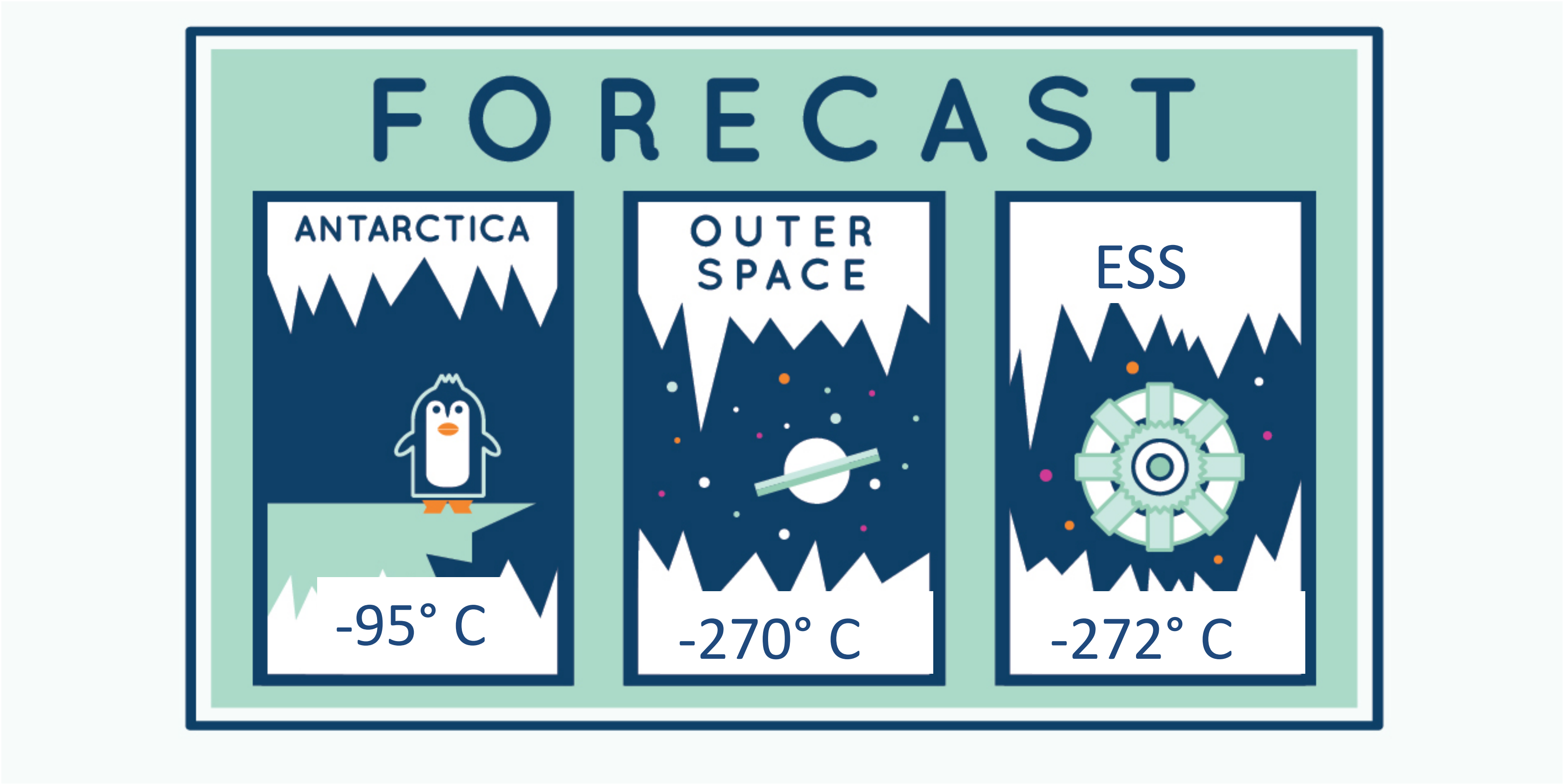
The ANNI beamline can reach a sensitivity of $5 \cdot 10^{-28}$ e·cm in a 100 days @ ESS this sensitivity is envisaged by future UCN experiments

ANNI – Overview



Full ESS Proposal, strong support by SAC (Scientific Advisory Committee) could be instruments 16-22

Ultra Cold Neutron Sources UCN

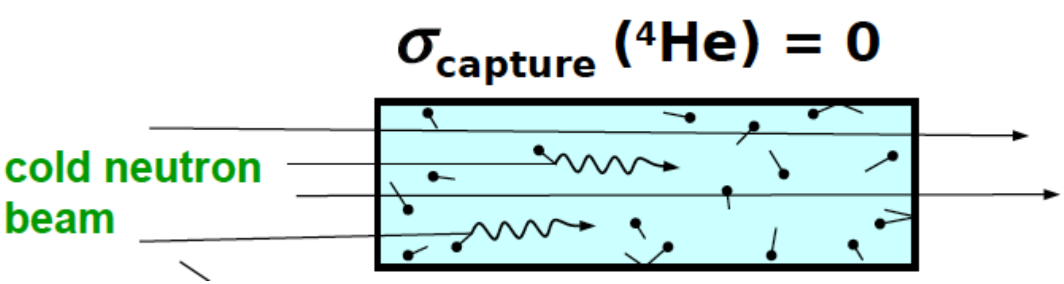


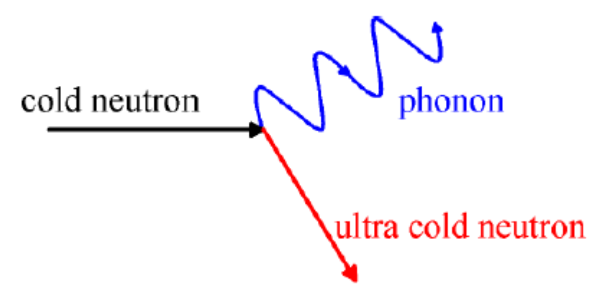
UCN source @ ESS (I)

- Ultracold neutrons (UCN) have energies in the neV range, this is sufficiently low to allow them to be totally reflected under any angle of incidence.

- This property enables experimentalists to store them in ”neutron bottles” made of suitable materials with small cross sections for neutron absorption.

- The production of the UCN is mostly based on superfluid Helium (^4He) installed at the end of neutron guide where





UCN source @ ESS (II)

Production, transportation and storage is motivated by the study of several neutron properties:

- **Measurement of the neutron lifetime** (its value impacts the abundance of light chemical elements in big-bang nucleosynthesis)

- **Measurement of the neutron electric dipole moment (EDM)**

- **Observation of the gravitational interactions of the neutrons**

In a previous experiment ILL physicists have observed quantized state of matter under the influence of gravity for the first time.

(V Nesvizhevsky et al. 2001 Nature 415 297).

The ESS Ultra cold neutron source will be one order of magnitude better than current UCN source

Conclusion I

- Search for n-$\bar{n}$ oscillation strongly motivated:
  - ΔB=2 baryon number violation appears in many models
  - Probe scales from 10^5 - 10^{12} GeV
  - Connection with baryogenesis, neutrino masses, …

- The proposed Cold Beam Line @ ESS (ANNI) will outperform all existing beam line for particle physics by at least 1-2 order of magnitude allowing several measurements

- With one order of magnitude higher UCN density, the ESS source will be the best ultra cold neutron source in the world

Conclusion II

- ESS is a wonderful machine that offers to the Fundamental Physics community several attractive possibilities
- All these possibilities will improve current measurements at least of one order of magnitude (in some case even 3 order of magnitudes)
- Searches for fundamental physics at ESS complementary and competitive with LHC searches
- **Ready for a bright future …..**

" The real voyage of discovery consists not in seeking new landscapes, but in having new eyes."

Marcel Proust

BACK –UP SLIDES

Lacking in the Standard Model (I)

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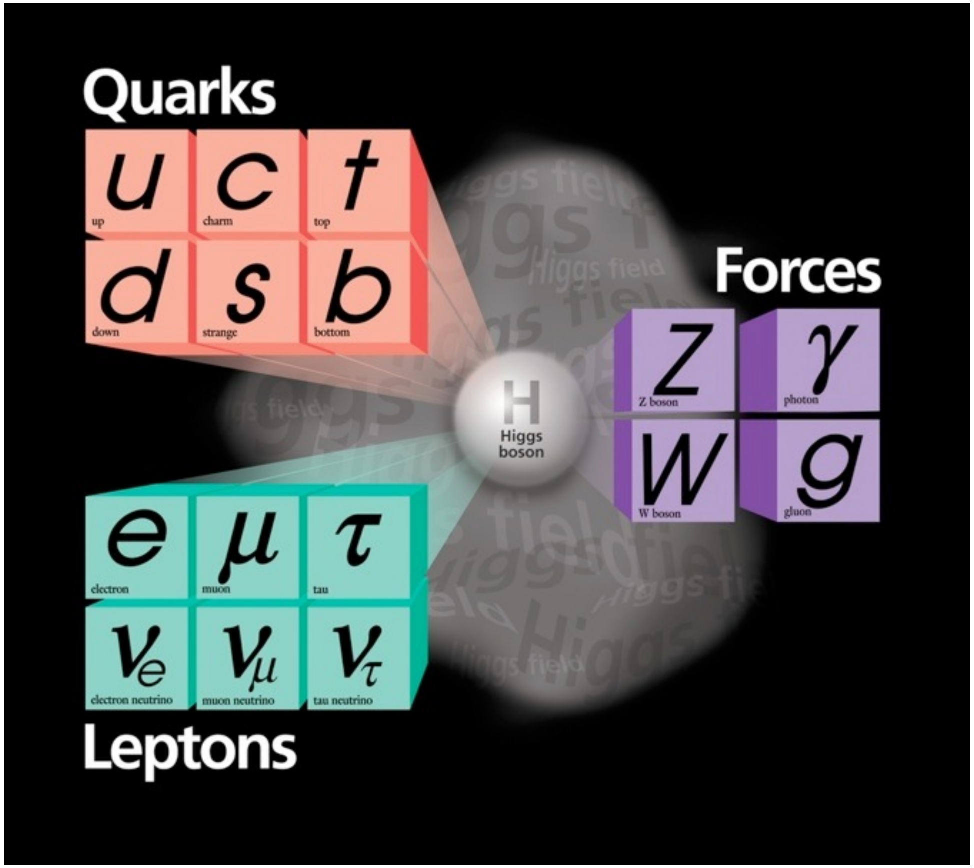
- Clear structure in fermionic sector unexplained
  - No understanding of the “charges”
  - Evidence of selective principle(s)
    - E.g. no neutral colored fermions
    - q(down) = q(e)/N_c
  - Interpreted as evidence for (grand) unification
    - Grand or less grand? (One or more scales?)



The Heisemberg Uncertainty Principle (1)

- Classical physics
  - Measurement uncertainty is due to limitations of the measurement apparatus
  - There is no limit in principle to how accurate a measurement can be made

- Quantum Mechanics
  - There is a fundamental limit to the accuracy of a measurement determined by the <u>Heisenberg uncertainty principle</u>
  - If a measurement of position is made with precision Δx and a simultaneous measurement of linear momentum is made with precision Δp, then the product of the two uncertainties can never be less than $h/2\pi$

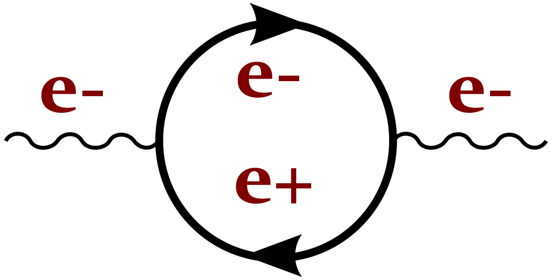
$$\Delta x \Delta p_x \geq h$$

The Heisemberg Uncertainty Principle (II)

– The time-energy uncertainty relation (time is to energy as position to momentum)

$$\Delta E \Delta t \geq h$$

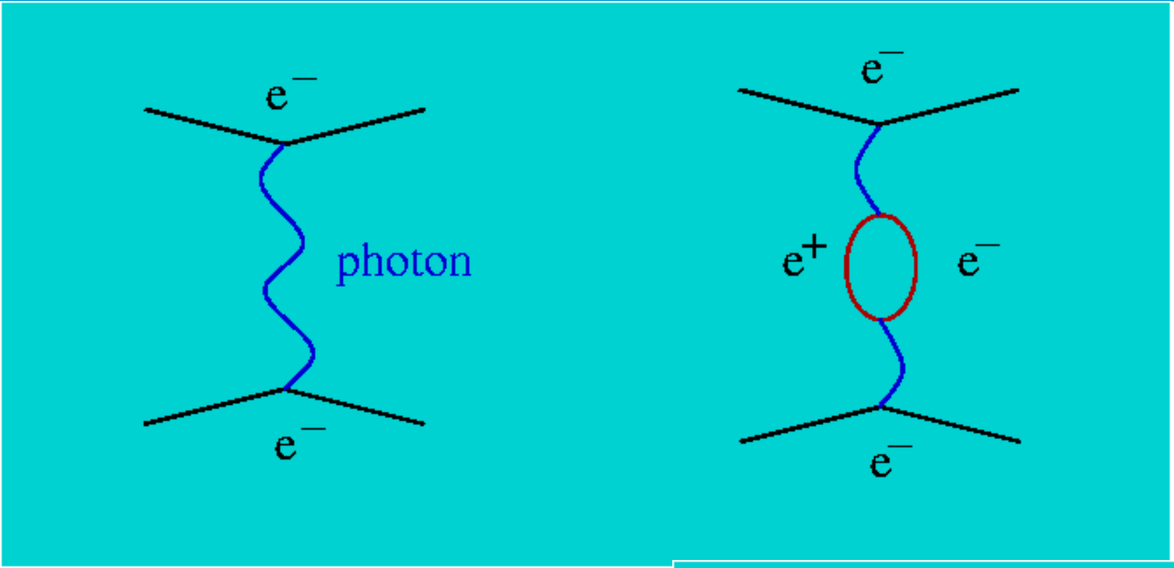
– This equation has direct impact on the quantum vacuum it means the vacuum can borrow energy for short periods
– The borrowed energy can be used to create particles $E=mc^2$



(You can't just create an electron because of charge conservation - but can create electron positron pair)

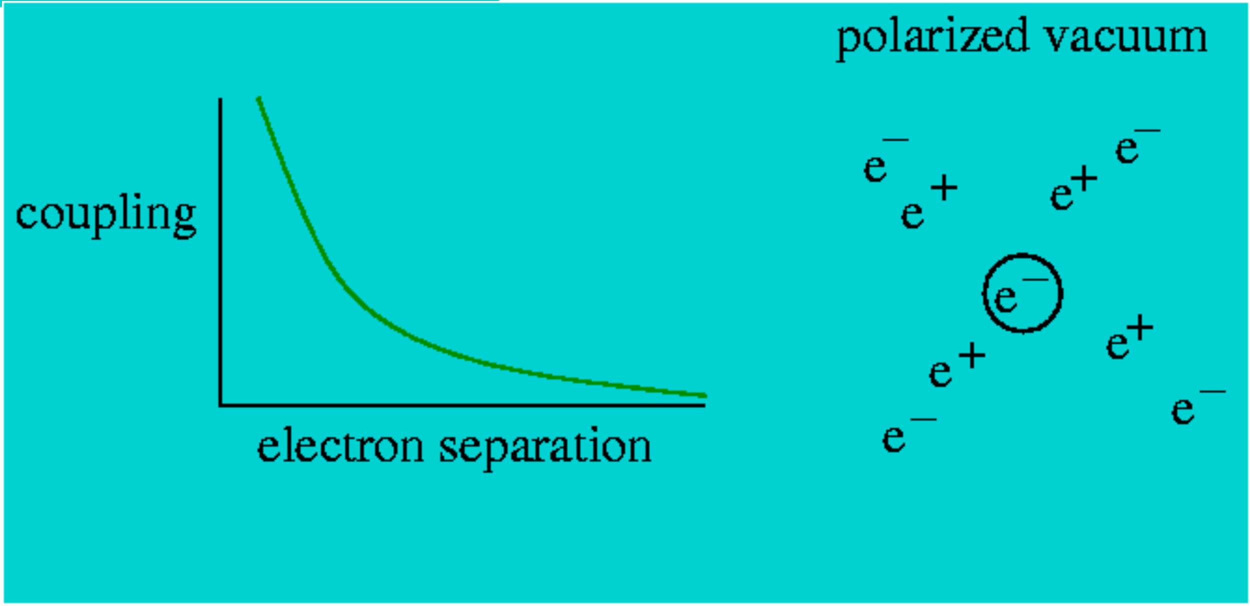
The quantum vacuum is a seeing mass of particles appearing and disappearing constantly.... These particles are called virtual particles

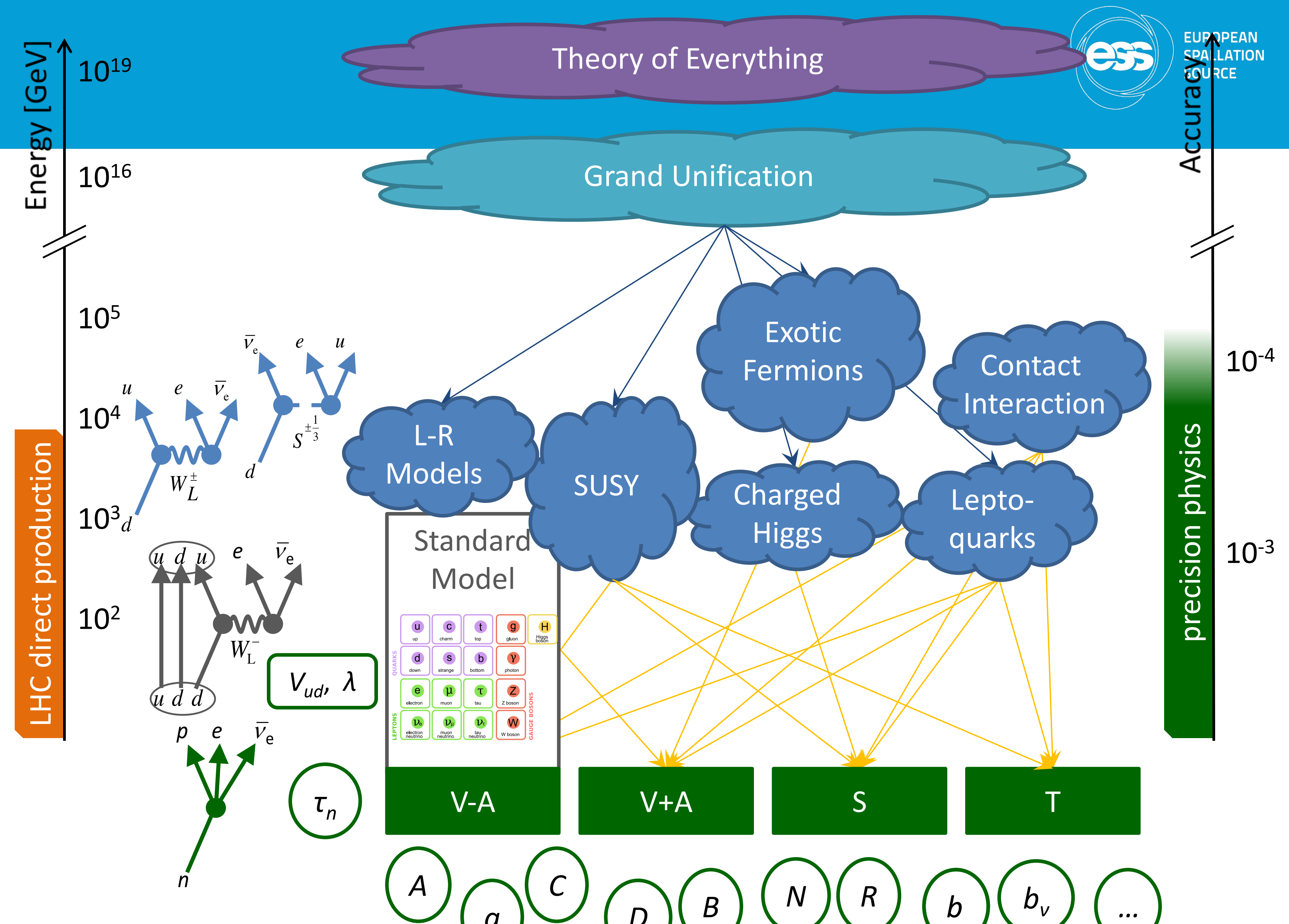
How Can You Tell?



The "virtual" particle pairs interfere in electron scattering processes.

The effective charge seen in two electron scattering depends on the separation of the electrons.




Theory of Everything
Grand Unification
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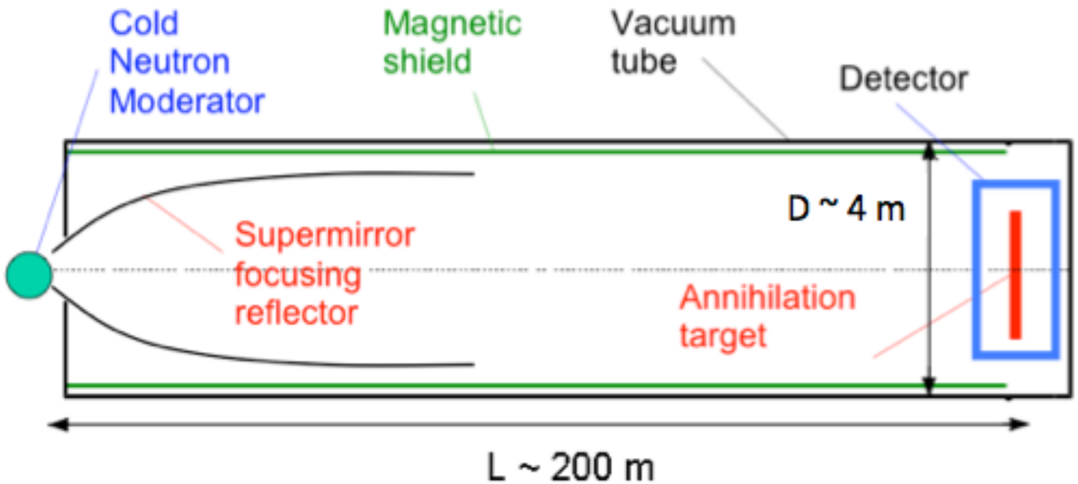
Energy [GeV]
10^{19}
10^{16}
10^{5}
10^{4}
10^{3}
10^{2}
Accuracy
10^{-4}
10^{-3}
precision physics
LHC direct production
L-R Models
SUSY
Exotic Fermions
Contact Interaction
Charged Higgs
Lepto-quarks
Standard Model
V_{ud}, λ
τ_n
V-A
V+A
S
T
A
a
C
D
B
N
R
b
b_ν
...

I HAVE NO SPECIAL TALENTS. I AM ONLY PASSIONATELY CURIOUS.

- ALBERT EINSTEIN

Nnbar experiment Conceptual Design



See e.g. NNbarX (Babu et al.), http://arxiv.org/abs/arXiv:1310.8593

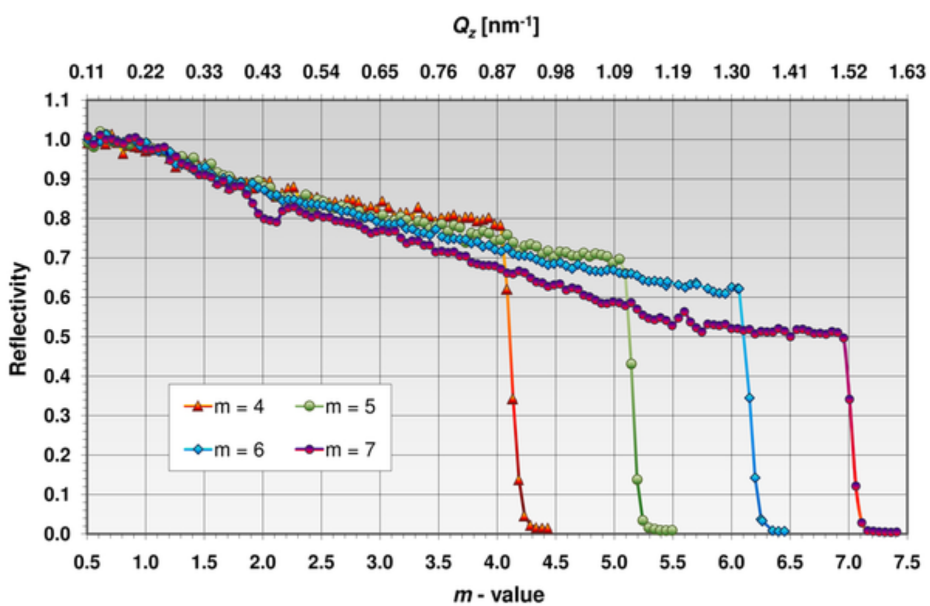
- High-m super-mirror
- Residual B field < 5 nT
- Good vacuum < 10^{-5} Pa

Detector

- Anti-neutron annihilation target
  - High annihilation probability, low Z, high transparency to neutrons
    - ILL experiment used a carbon foil, 130 μm thick
- Annihilation produces pions, <n> ~ 5
- Background suppression:
  - Precise annihilation vertex identification
  - Good mass resolution
  - Beam time structure? (Mainly for background control samples)

Supermirror

- Crucial in acceptance gain
  - 2D, so acceptance scales quadratically
  - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers



(Swiss Neutronics)

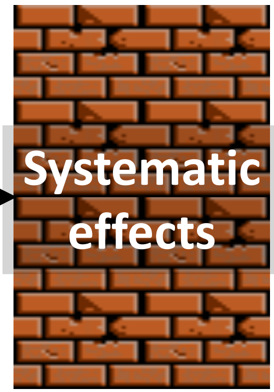
Active R&D at Nagoya University, with devices used at JPARC

Ni reflectivity → 0 defines m=1

Neutron EDM

EUROPEAN SPALLATION SOURCE

Ultracold neutrons

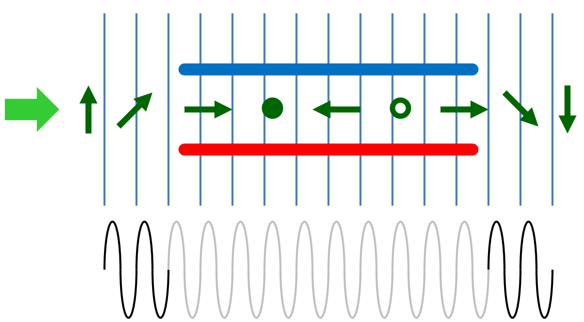


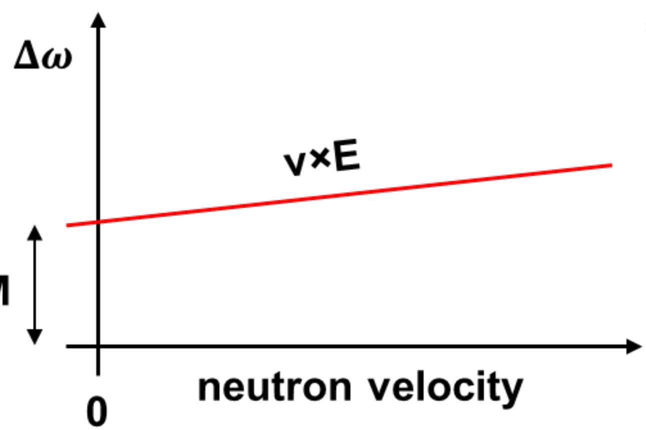
Systematic effects

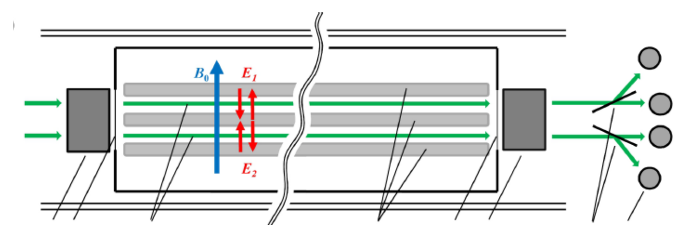
Beam method

$d_n < 10^{-28}$ *e*cm?
→ No electroweak baryogenesis

Pulsed cold beam







F. Piegsa, Phys. Rev. C 88 (2013) 045502

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arXiv:1309.7022

A very intense neutrino super beam experiment for leptonic CP violation discovery based on the European spallation source linac

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14 participating institutes from 10 different countries, among them ESS and CERN (US "snowmass" process)