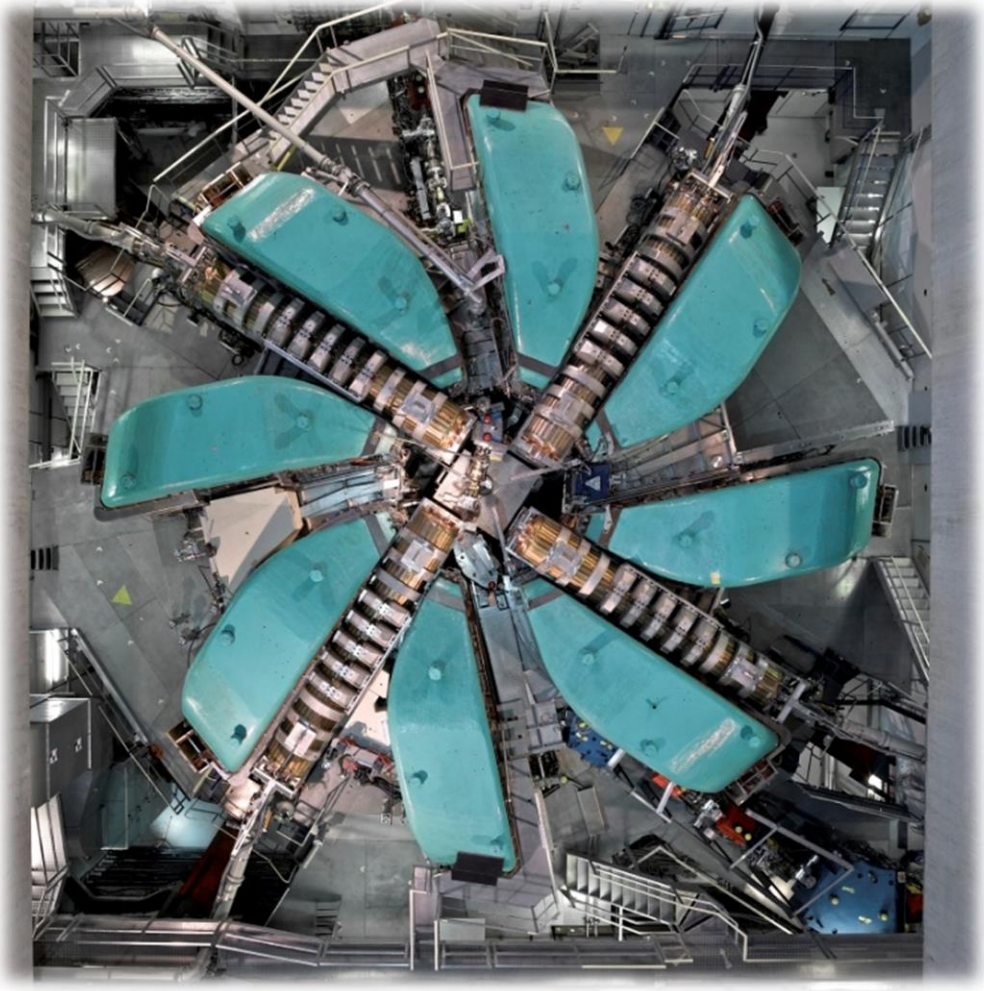
Intensity Frontier Particle Physics

K.Kirch, ETH Zurich – PSI Villigen, Switzerland



Need: High intensities

Perform:

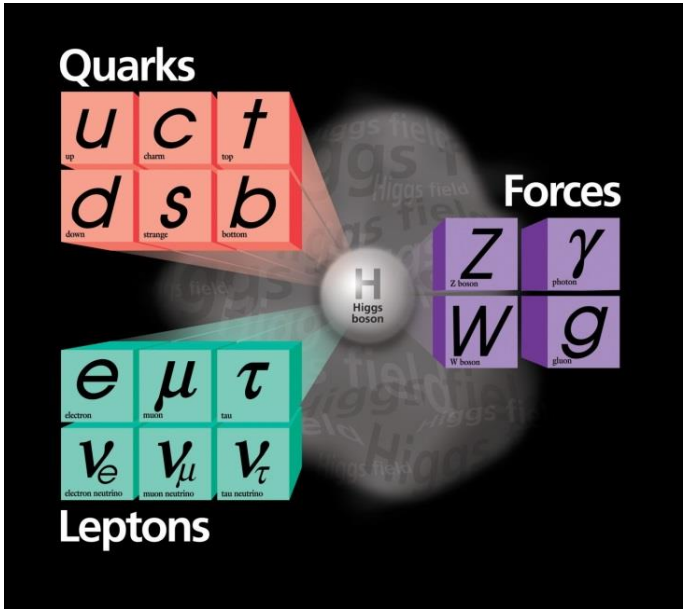
- Precision measurements

- Searches and
  Symmetry Tests

The Standard Model of Particle Physics

- is extremely successful …

  (with some issues concerning neutrino masses, muon g-2, B-decays, …)



- … but does not explain
  - Gravity, Dark matter
  - Dark energy
  - 3 families
  - QCD theta term
  - Values and structure of particle masses and couplings
  - Baryon Asymmetry of the Universe
  - Conservation of baryon and charged lepton number
  - …

Intensity Frontier Particle Physics

- Has a very large and diverse community
- Besides particle physics it has strong connections to other fields, especially to nuclear and atomic physics
- It can be performed at high and at low energies, w and w/o accelerators, at electron and at proton machines:

  High power proton drivers have arguably the largest impact

Examples of recent community efforts in Europe and the US:

Fundamental Physics at the Intensity Frontier

Workshop held December 2011 in Rockville, MD

arXiv:1205.2671

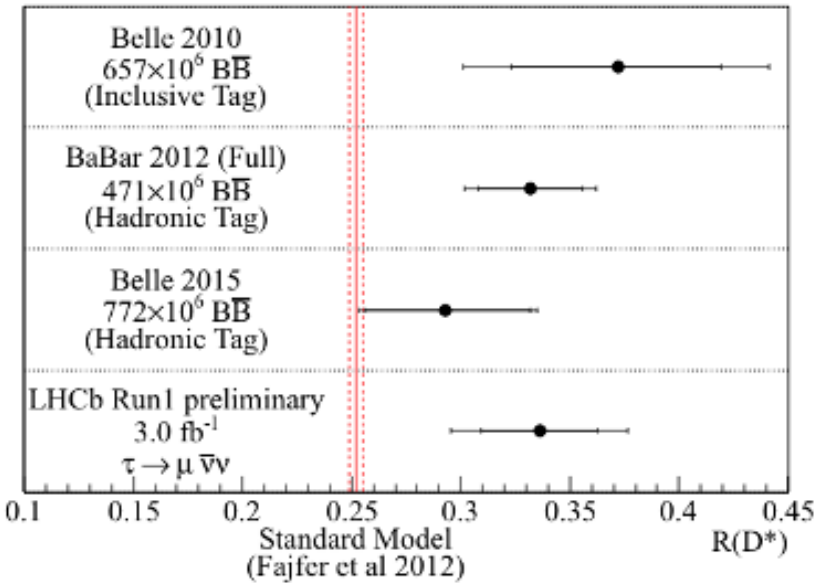
Flavour physics of leptons and dipole moments *

Working Group 3 of the CERN Workshop "Flavour in the era of the LHC"

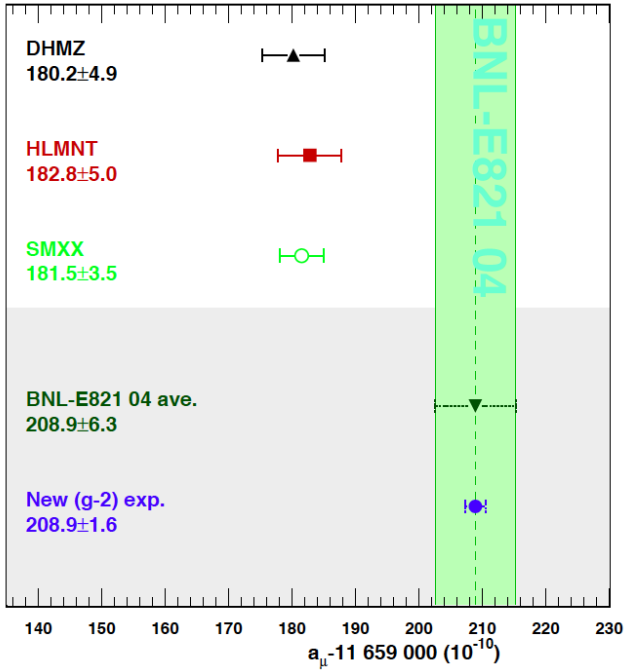
arXiv:0801.1826

A few recent and not so recent excitements

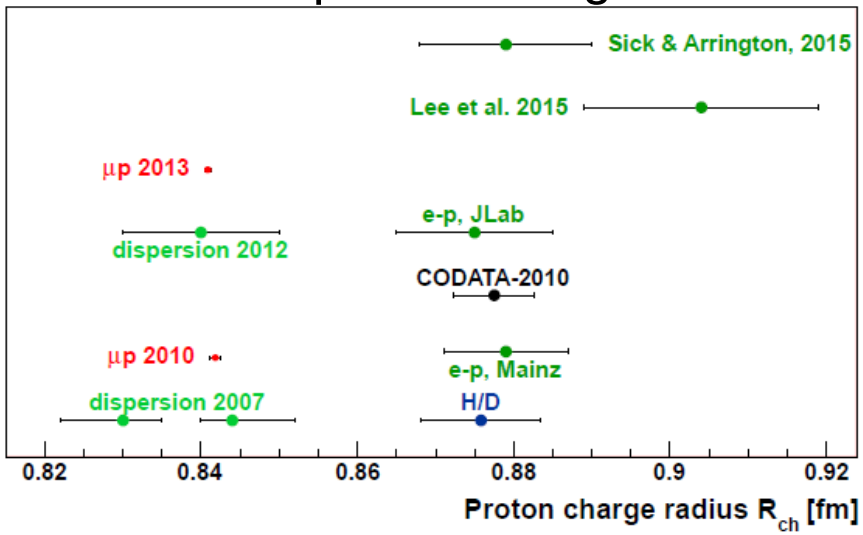
- Tension in B decays to D* and leptons:



- Tension in muon g-2:

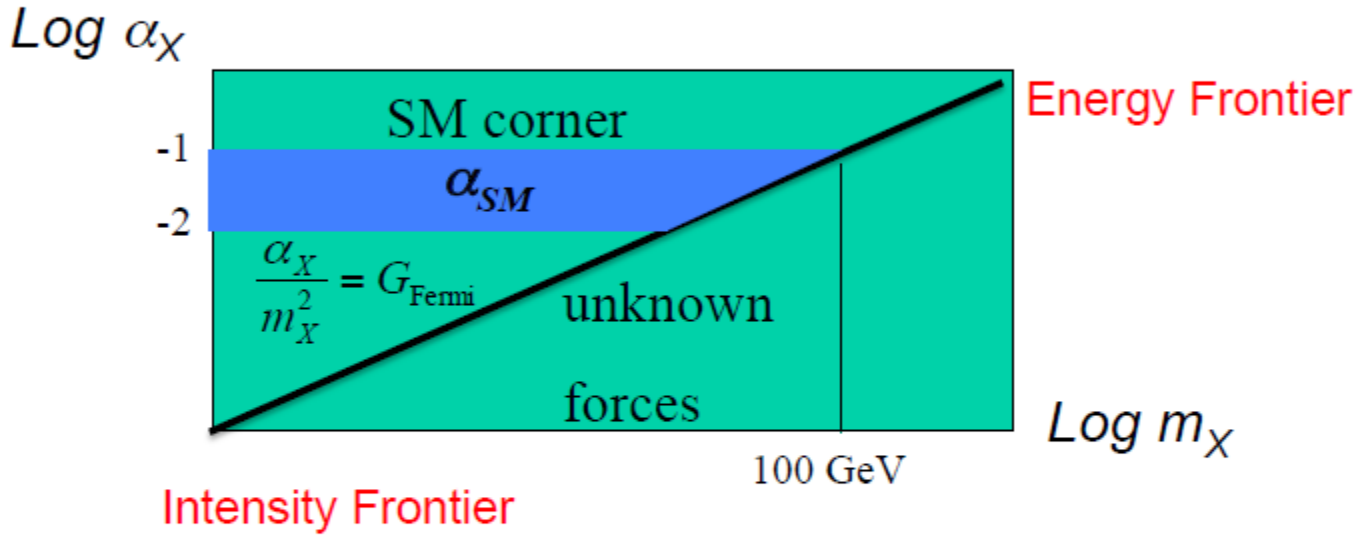


- Tension in proton charge radius:



Intensity and Energy Frontiers

Maxim Pospelov's version:

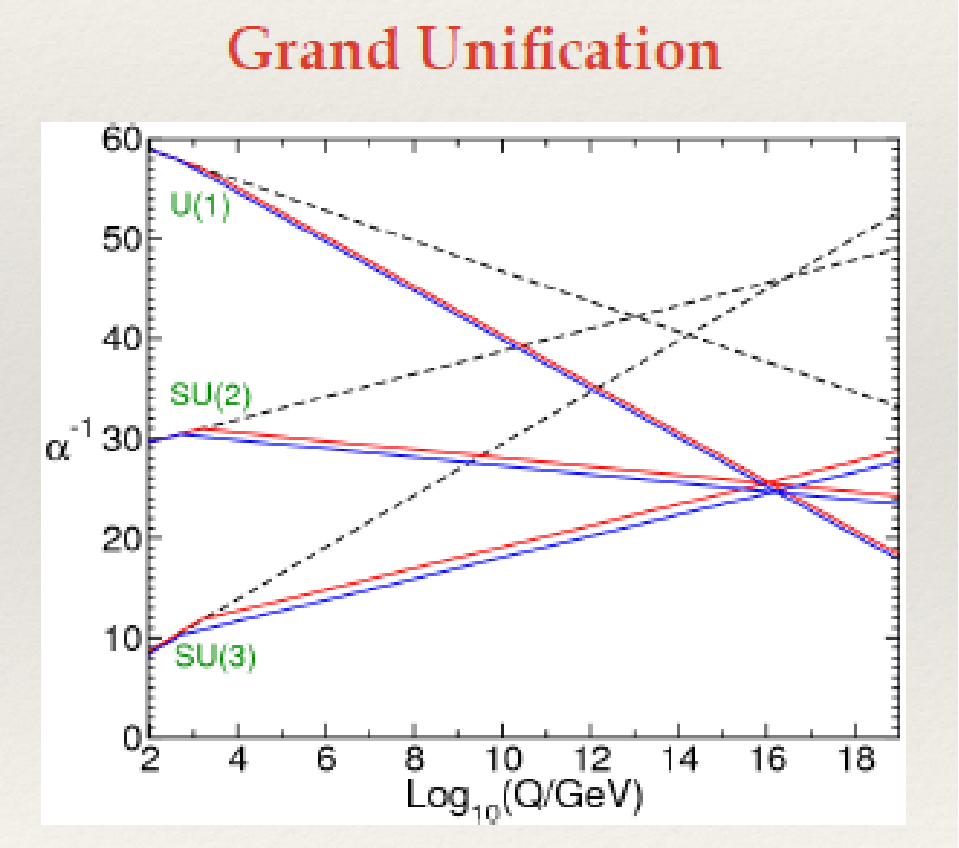


$$V(r) = \frac{\alpha_X}{r}\exp(-r/\lambda_X) = \frac{\alpha_X}{r}\exp(-rm_X) \longrightarrow \text{Amplitude} \approx \frac{\alpha_X}{q^2 + m_X^2}$$

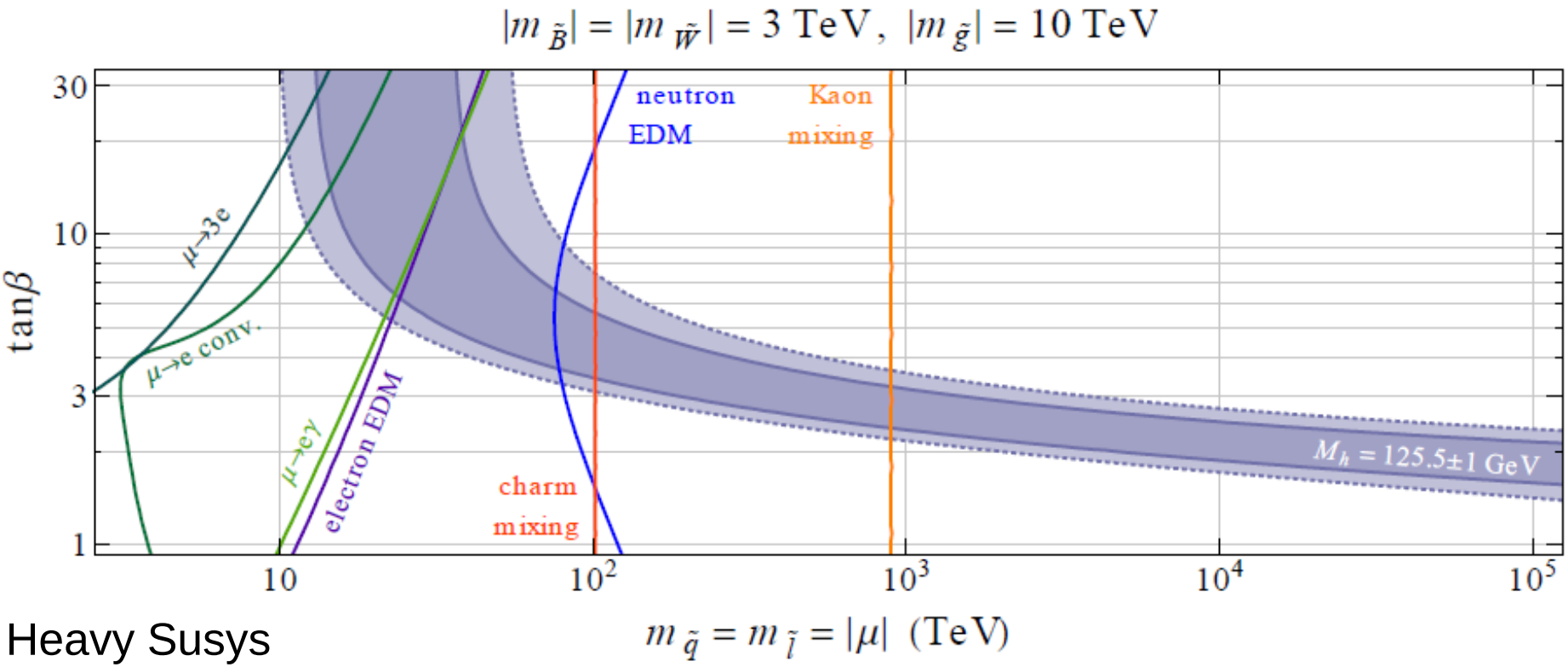
LHC can realistically pick up New Physics with $\alpha_X \sim \alpha_{SM}$, and $m_X \sim$ 1TeV, while having no success with $\alpha_X < 10^{-6}$, and $m_X \sim$ GeV.

Very high energy example

- GUT scale physics
  - proton decay
    intensity frontier
    neutrino detectors
  - nnbar oscillations
    dedicated experiment



Multi-TeV example



Heavy Susys

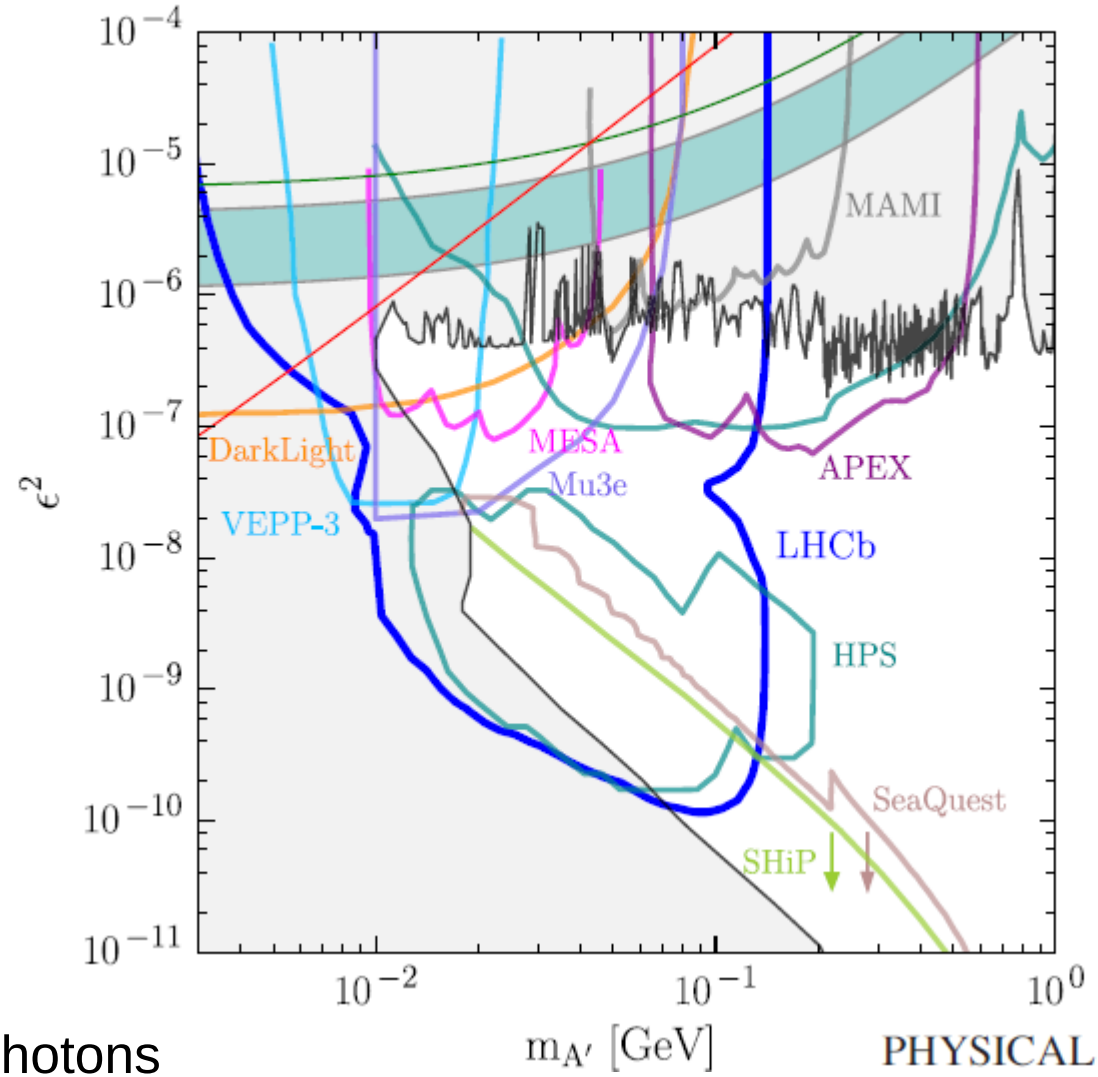
a large host of low energy observables can probe squarks and sleptons with masses far above the direct reach of current and future colliders

Wolfgang Altmannshofer

Altmannshofer, Harnik, Zupan, arxiv1308.3653

Sub-GeV example

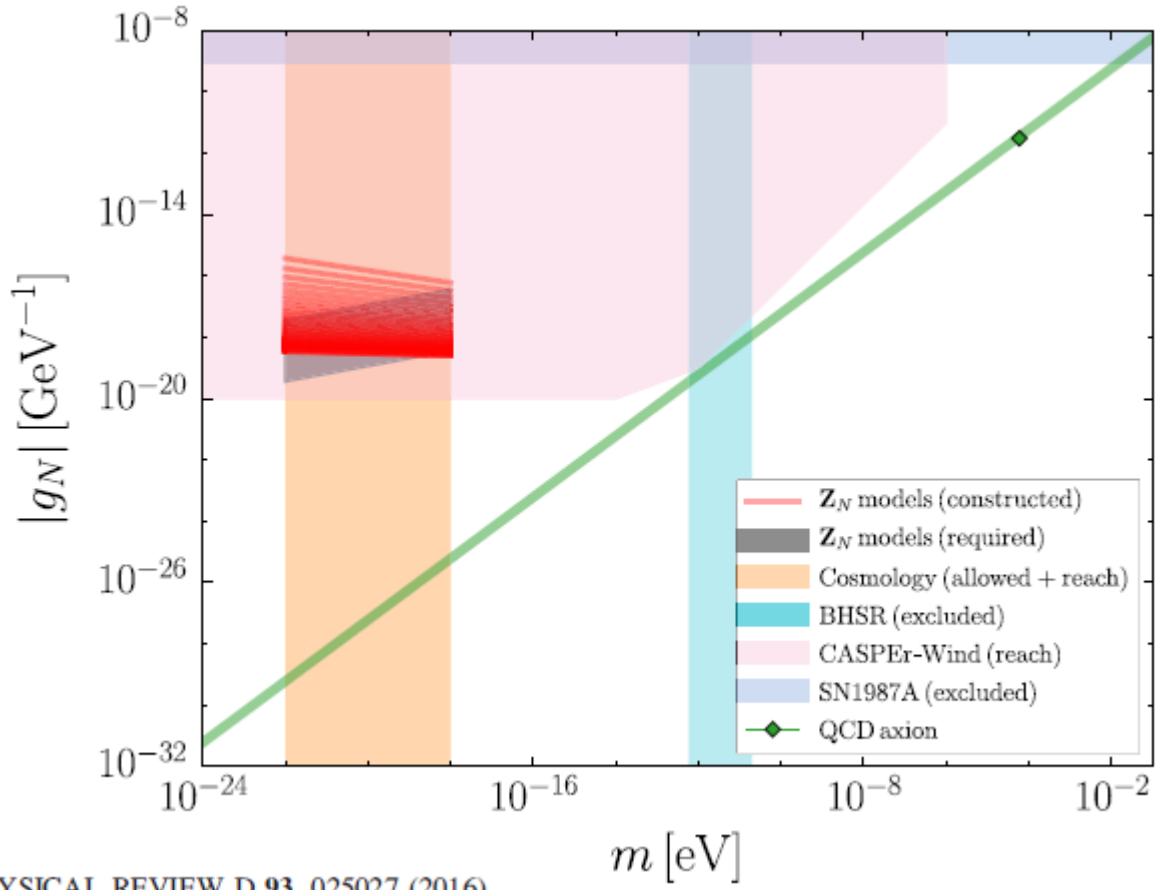
PHILIP ILTEN, JESSE THALER, MIKE WILLIAMS, and WEI XUE



Dark Photons

PHYSICAL REVIEW D **92,** 115017 (2015)

Ultra-low energy example



Axions &
Ultralight bosons

PHYSICAL REVIEW D **93**, 025027 (2016)

An ultralight pseudoscalar boson

Jihn E. Kim[1,2] and David J. E. Marsh[3,4]

Intensity Frontier Particle Physics

- Many – if not most – precision measurements and searches need the highest possible intensities
- Indirect tests are extremely powerful, both, in absence of direct detection or complementing it
- New particles could be very heavy or very light, could couple strongly or very weakly …

  – need to check at many places!

    – need highest intensity proton drivers!

In this talk:
selected examples of intensity frontier physics at powerful proton drivers

- Muons: PSI, J-PARC, FNAL
  - MEG, Mu3e, COMET, Mu2e, g-2
- Neutrons: SNS, PSI, TRIUMF, ESS (& competing reactor sources)
  - npdg, Nab, nEDM, nnbar
- Antiprotons: CERN
  - Hbar
- Kaons: CERN, J-PARC
- Neutrinos, p-decay, … : J-PARC, T2K, HyperK, FNAL, NOvA, DUNE (&reactors and natural sources)
- Rare Isotopes: TRIUMF, CERN, …
- Higgs, B, HE fixed target: CERN, …

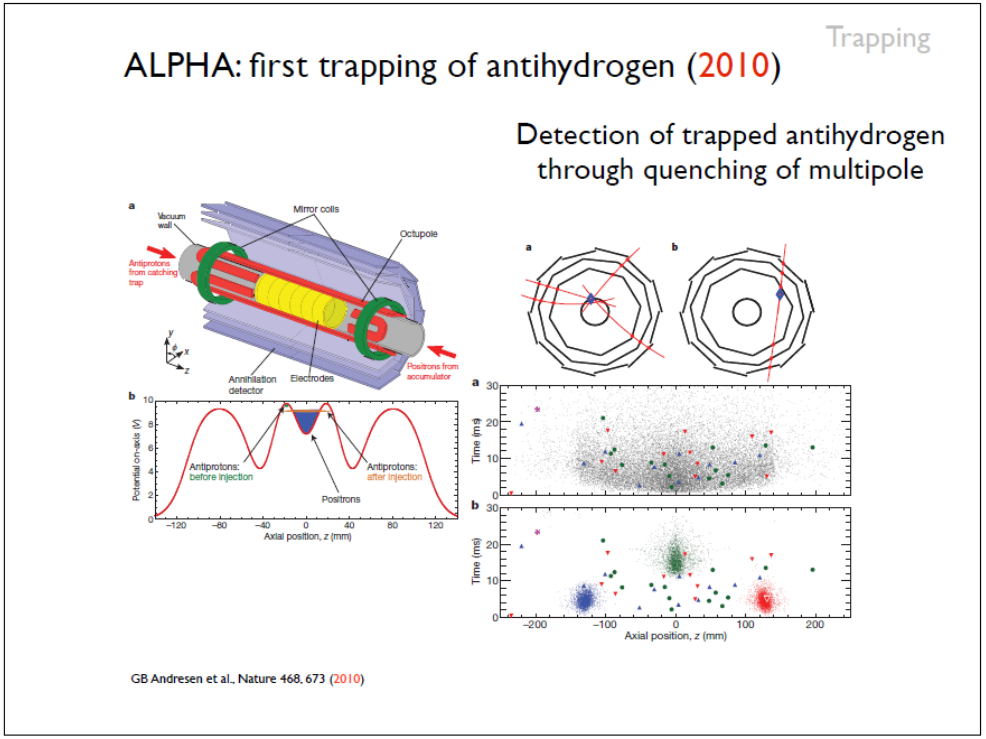
LF Exotics

CP P T B

CPT

Apologies to the many important experiments not covered here

Antiproton and Antihydrogen physics
at CERN's AD and ELENA



Aiming at

- Precision tests of CPT
  - comparison of the p and pbar mass, magnetic moment, …
  - Test of charge equality
  - comparison of spectroscopy of H and Hbar
- Test of antimatter gravity
- …

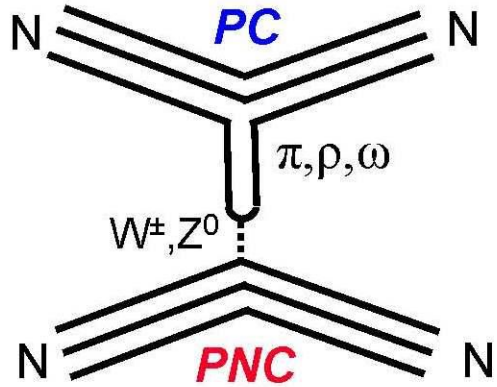
AEgIS, ALPHA, ASACUSA, ATRAP, BASE, GBAR

Fundamental Neutron Physics at the Spallation Neutron Source

The Fundamental Neutron Physics program at the SNS has three major themes:

1. The study of Hadronic Parity Violation in simple nuclei
2. Measurement of correlations in neutron beta decay
3. Search for a neutron electric dipole moment

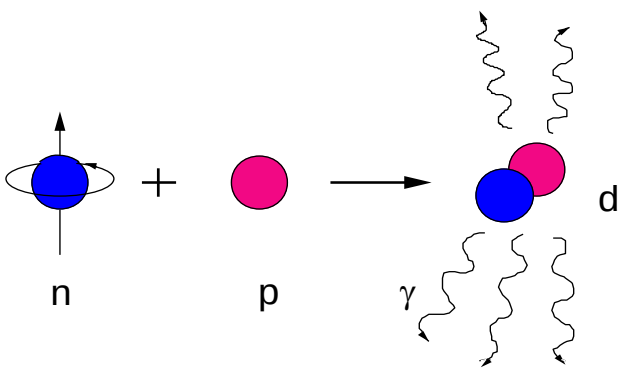
Hadronic Parity Violation in simple nuclei

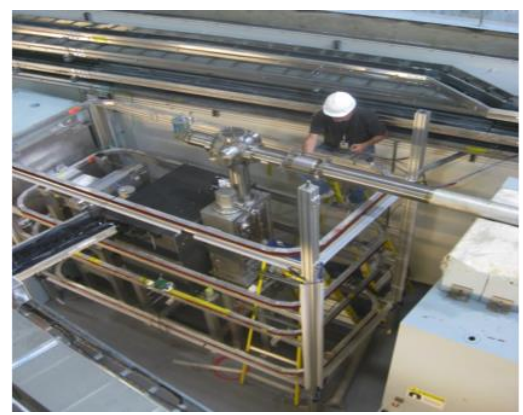


Direct $W^{+,-}$ or Z^0 is highly suppressed by range heavy boson.
Look instead for PV interference term from meson exchange.

Example: PV in n+p→d+γ

$$A_\gamma = \vec{\sigma}_n \cdot \vec{p}_\gamma$$



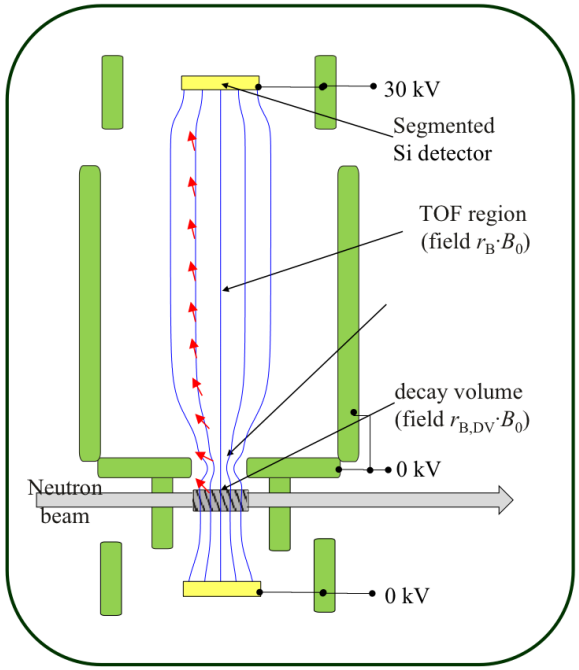


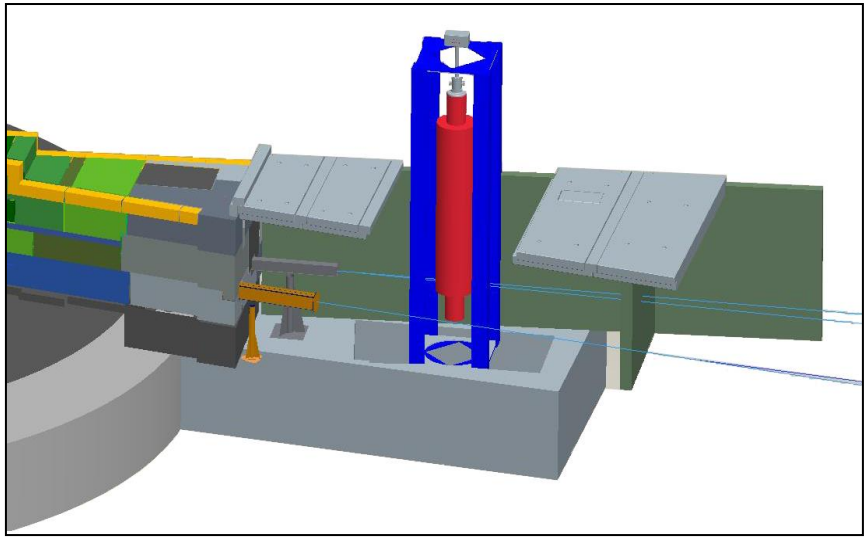
Status: Data collection complete, statistics at $<2\times10^{-8}$

Determination of correlations “a” and “b” in neutron decay

$$dw \propto \rho(E_e)\cdot(1+2|\lambda|^2)\cdot\{1+a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu}+b\frac{m_e}{E_e}+\vec{\sigma}_n\cdot(A\frac{\vec{p}_e}{E_e}+B\frac{\vec{p}_\nu}{E_\nu}+D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu})\}$$

Determine “a” by measurement of complete kinematics in unpolarized neutron decay.

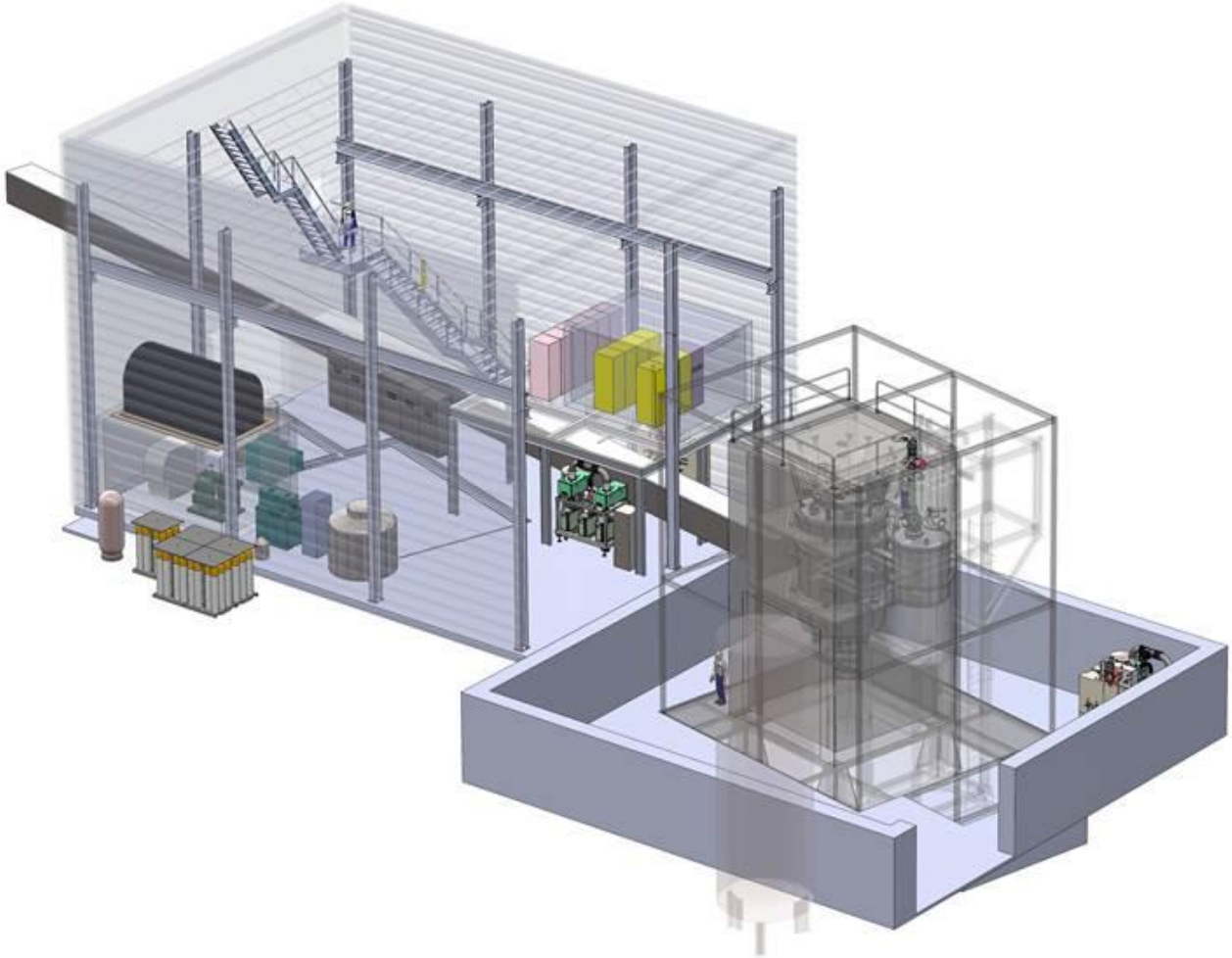




Status: Installation at SNS in summer 2016

Search for neutron electric dipole moment

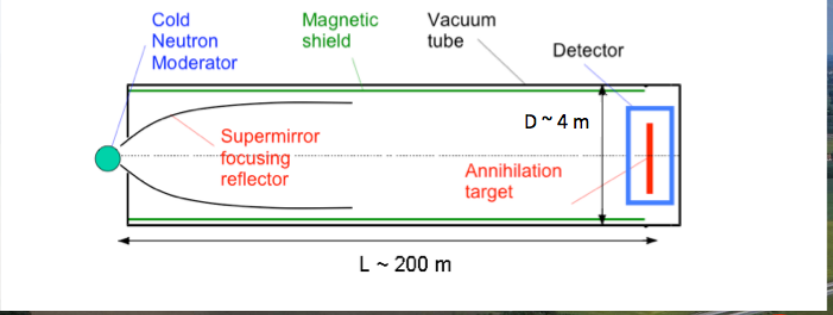
Fully cryogenic experiment using in-situ production of UCN within measurement volume and incorporating ^{3}He co-magnetometry

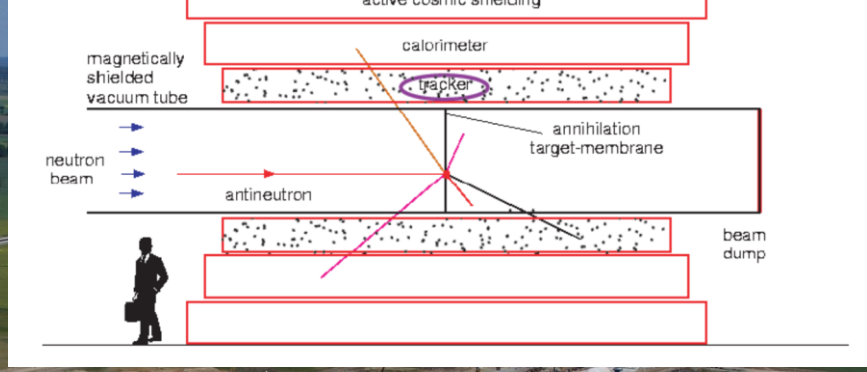


Status: Design on individual subsystems in progress
Installation at SNS planned for 2019

NNbar @ ESS

- 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
    - Grand Unification our best hint
  - Baryon Number Violation excellent probe
    - We *know* it exists
    - Observation will tell us about mechanism, and Grand Unification (and maybe neutrinos)
- ESS + modern neutron guiding technology allows to push sensitivity to free neutron oscillation probability by ~1000 wrt 1990's ILL experiment
- Opportunities to gain a factor 1000 in sensitivity to processes at core of our existence and understanding of universe are rare
  - Should **not** be squandered





NNbar Line

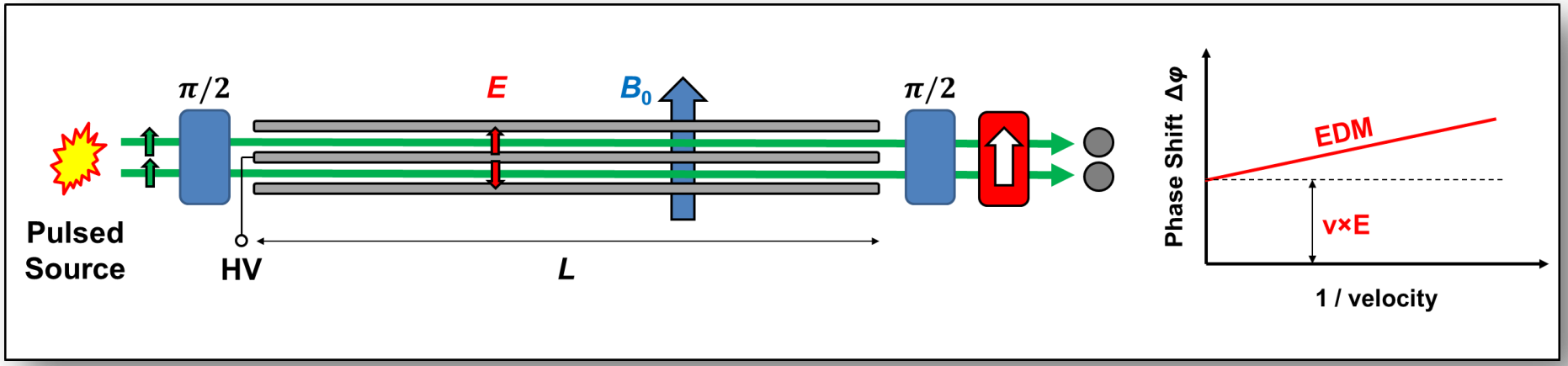
ESS, June 5, 2015

Blue: ESS

Green: NNbar

- 2014: ESS Construction Start
- 2018: Technical Design Report
- 2020: Construction start
- 2019-2022: ESS initial phase: commissioning, intensity ramp, experiments by "friendly" users
  - Experiment construction, commissioning, physics start
- 2023-2025: ESS Initial user program: reliable operations with public users; establish basis for future cost sharing
  - Physics run
- 2026+: ESS routine operations, completion of final public instruments
  - End run ~2026, complete data analysis; (if see signal have a big party)

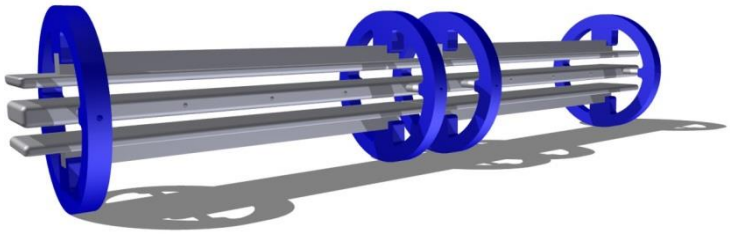
Neutron Beam EDM



Piegsa, PRC 88, 045502 (2013)

- Unique, complementary and novel approach: ideal for ESS
- Ramsey neutron beam-type experiment, sensitivity ~1E-27ecm
- Directly measures main systematic false effect (v×E)
- Proof-of-principle planned for PSI and ILL

2 Neutron beams
E > 50 kV/cm
B_0 = 200 μT
L = 5 m (proof-of-prin.)
L = 50 m (full-scale)

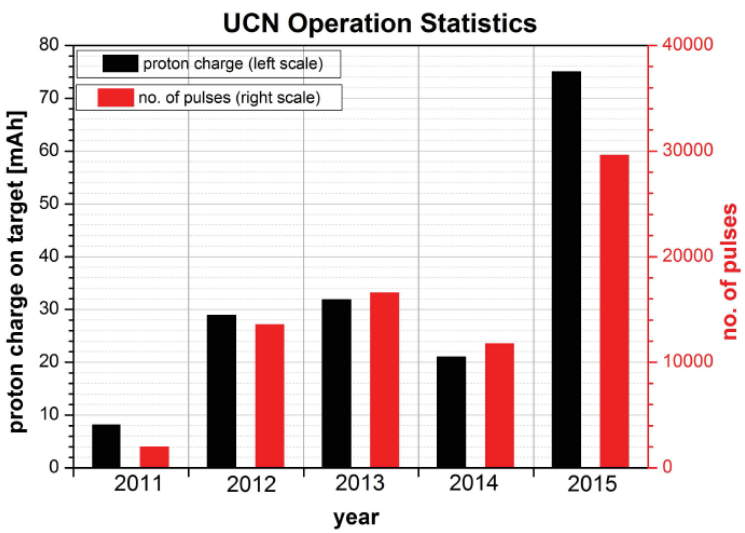


Ultracold Neutron Source & Facility

590 MeV Proton Cyclotron
2.2 .. 2.4 mA Beam Current

Ultra Cold Neutron Source

Excellent performance of HIPA and regular beam delivery to UCN



UCN-Source

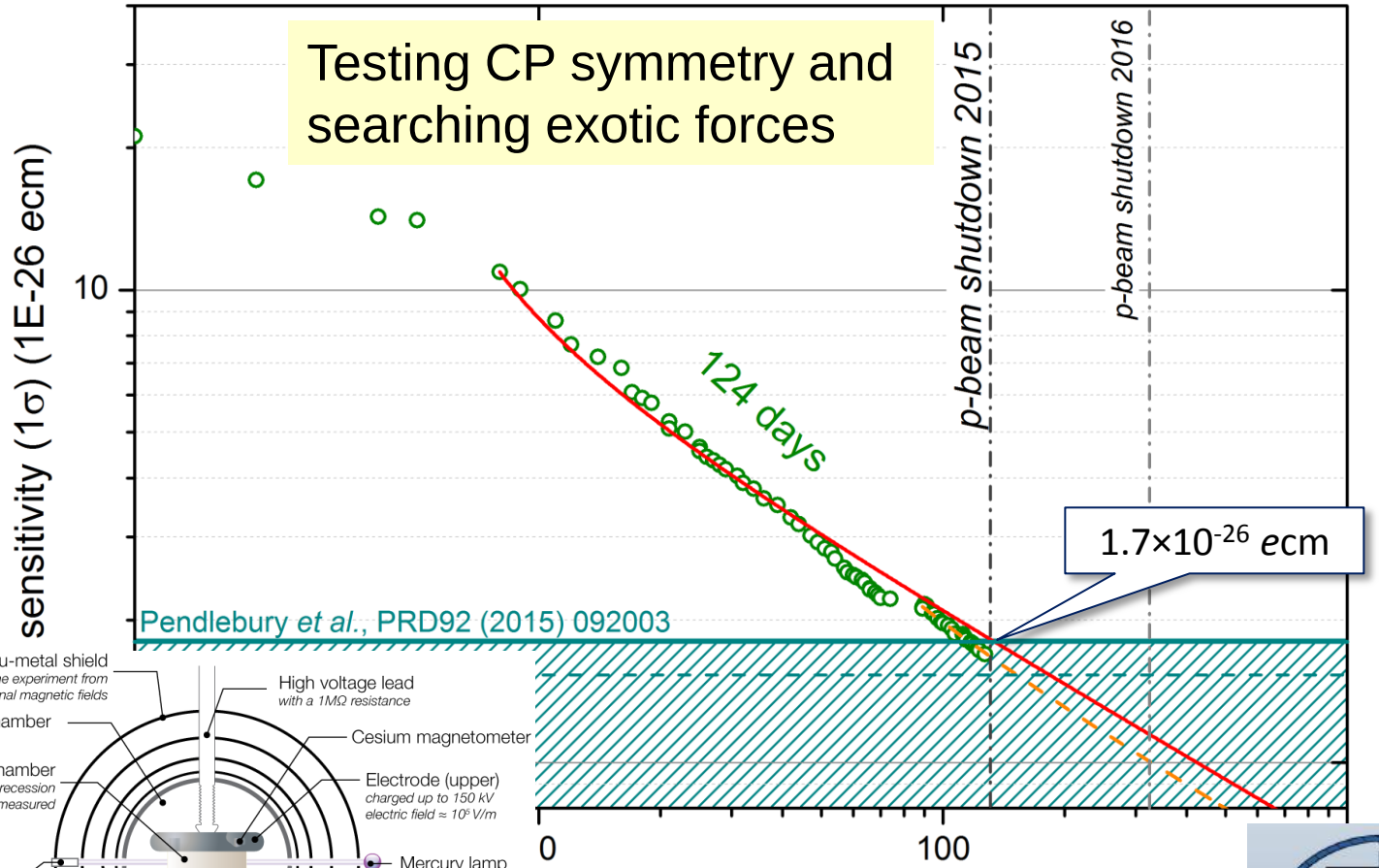
- 1st test: 12/2010
- Safety approval: 06/2011
- UCN start 08/2011
- Reliable performance 2012
- UCN to nEDM since 2012
  -> intensity 90x over 2010
- Increased duty factor 2015: 20 → 40 µA average
- 2016: towards 60µA

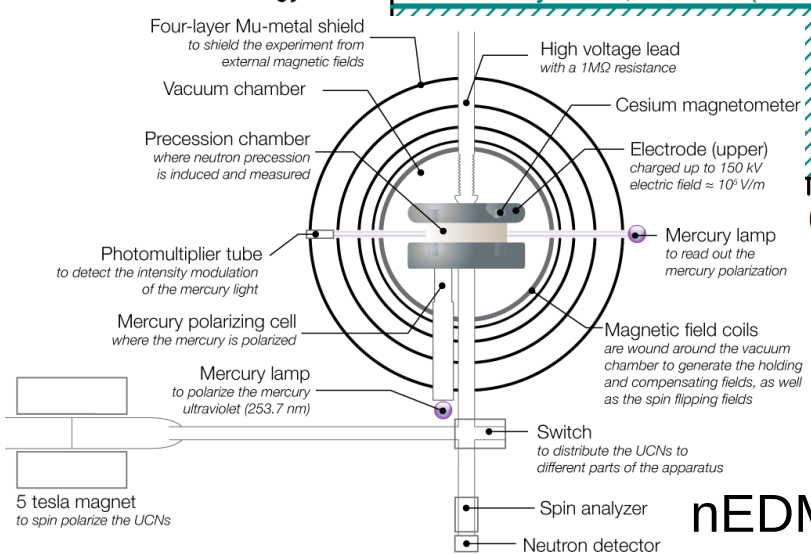
nEDM

Towards new limits and beyond

Neutron EDM search at PSI

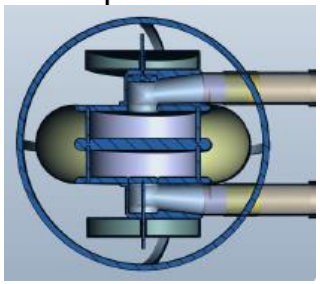
Testing CP symmetry and searching exotic forces





nEDM

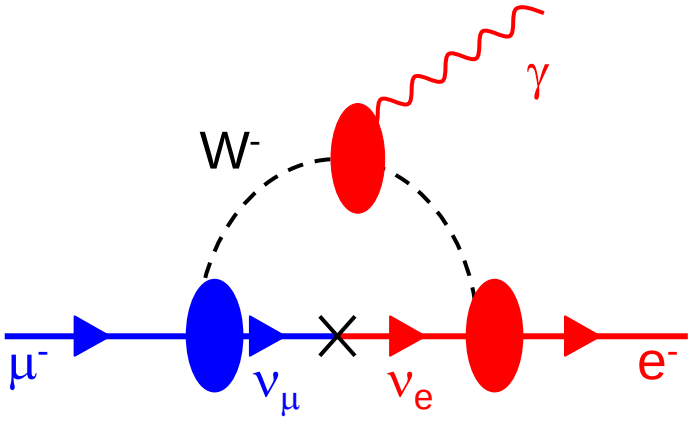
The slope determines the path forward



n2EDM

Charged Lepton Flavor Violation is small in the Standard Model

- Only known LFV so far: neutrino mixing
- cLFV suppressed by $(\delta m_\nu/m_W)^4$ and thus smaller than 10^{-50}
  → SM not observable
  → accidentally small !?
- Plenty of room for new physics



Expect from SM:

$BR(\mu\text{-}e\gamma) < 10^{-50}$

Experimentally so far:

$< 5.7 \times 10^{-13}$

PRL110(2013)201801

cLFV Searches: Current Situation

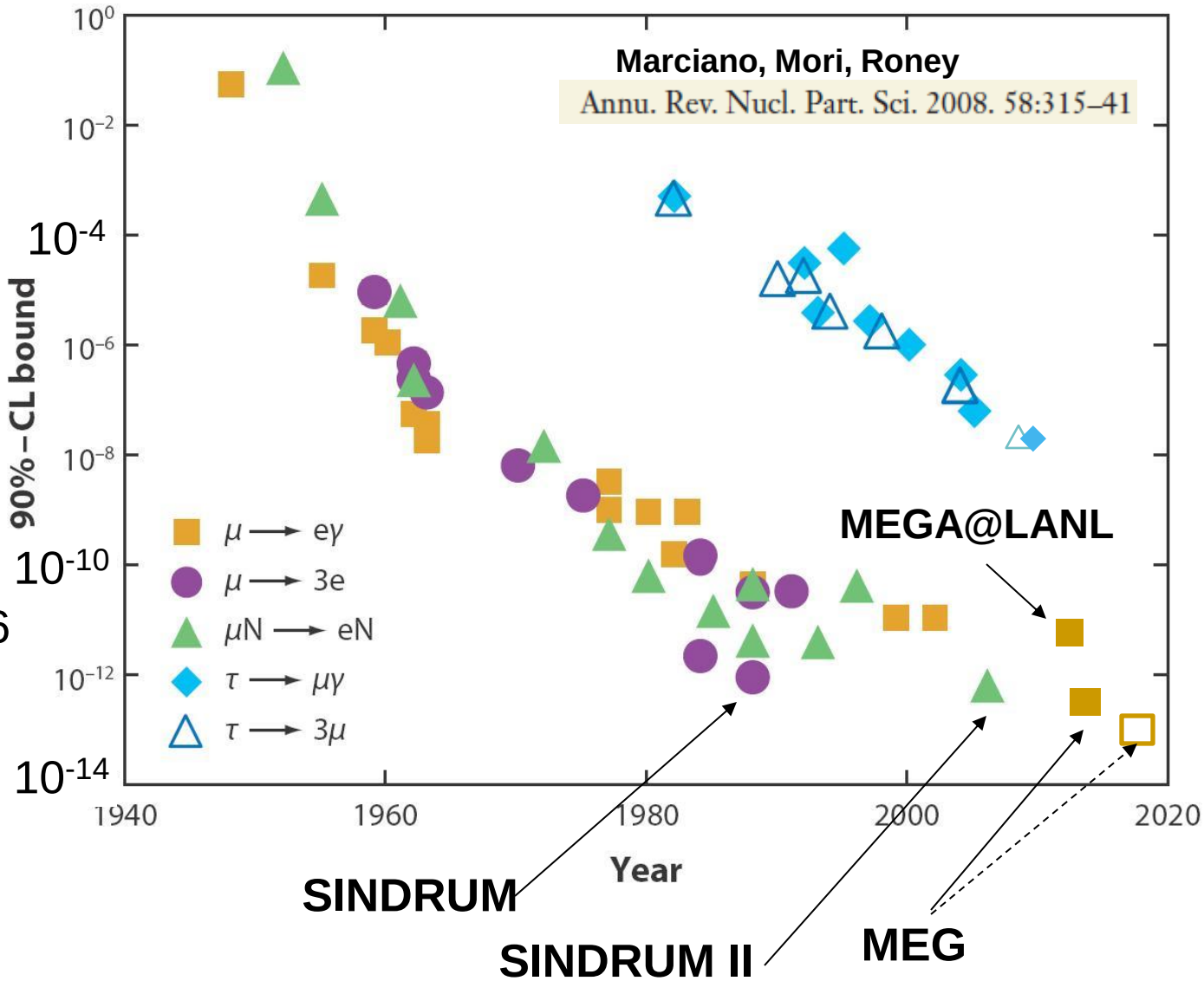
The present best limits on LFV are from muon experiments at PSI

$\mu^+ \rightarrow e^+ee$
BR < 1×10^{-12}
SINDRUM 1988

$\mu^- + Au \rightarrow e^- + Au$
BR < 7×10^{-13}
SINDRUM II 2006

$\mu^+ \rightarrow e^+ + \gamma$
BR < 5.7×10^{-13}
MEG 2013

[90 % C.L.]



Most sensitive LFV search

cLFV Searches: next steps

- $\mu^+ \to e^+ + \gamma$ to 4×10^{-14} with MEG II at PSI
- $\mu^+ \to e^+ee$ to 10^{-15} and 10^{-16} with Mu3e at PSI
- $\mu^- \to e^-$ conversion to $10^{-14} \ldots 10^{-16..17}$ and beyond with DeeMe, COMET at J-PARC and Mu2e at FNAL

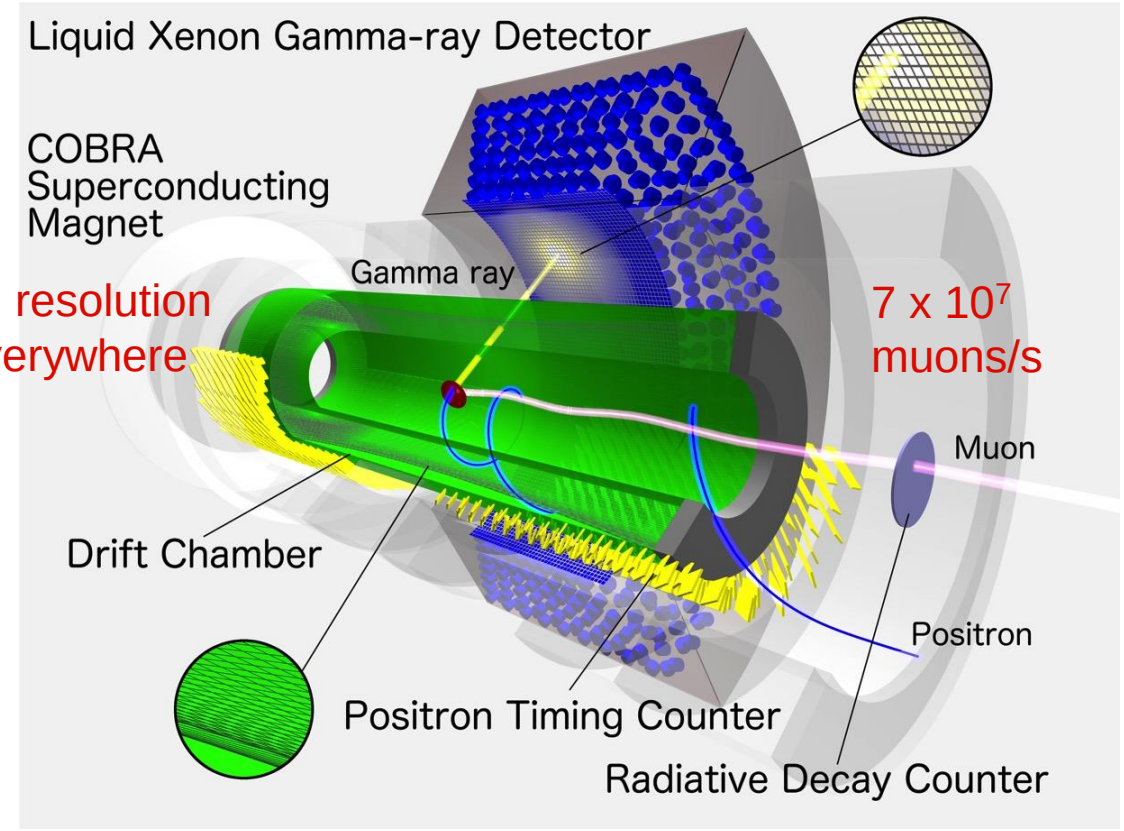
MEGII Status

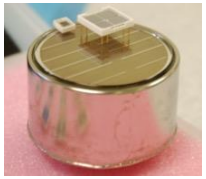
Key elements:

- Higher beam intensity
- Higher detector efficiency and resolution
- Improved calibration methods
- New DAQ system

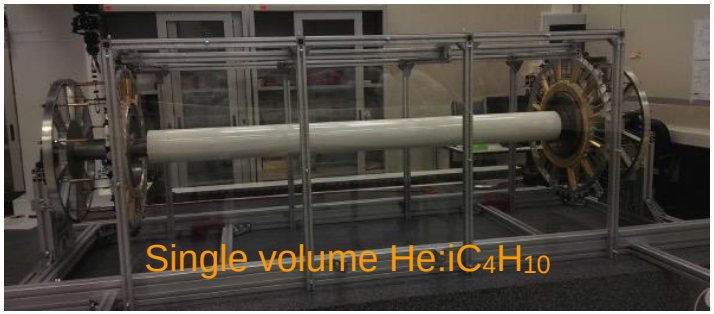
2013	2014	2015	2016	2017-20
Design	Construction	PreEng Run	Eng. Run	Run

Sensitivity [2017-20] ~ 4 x 10^{-14}





Better uniformity w/ 12x12 VUV SiPM



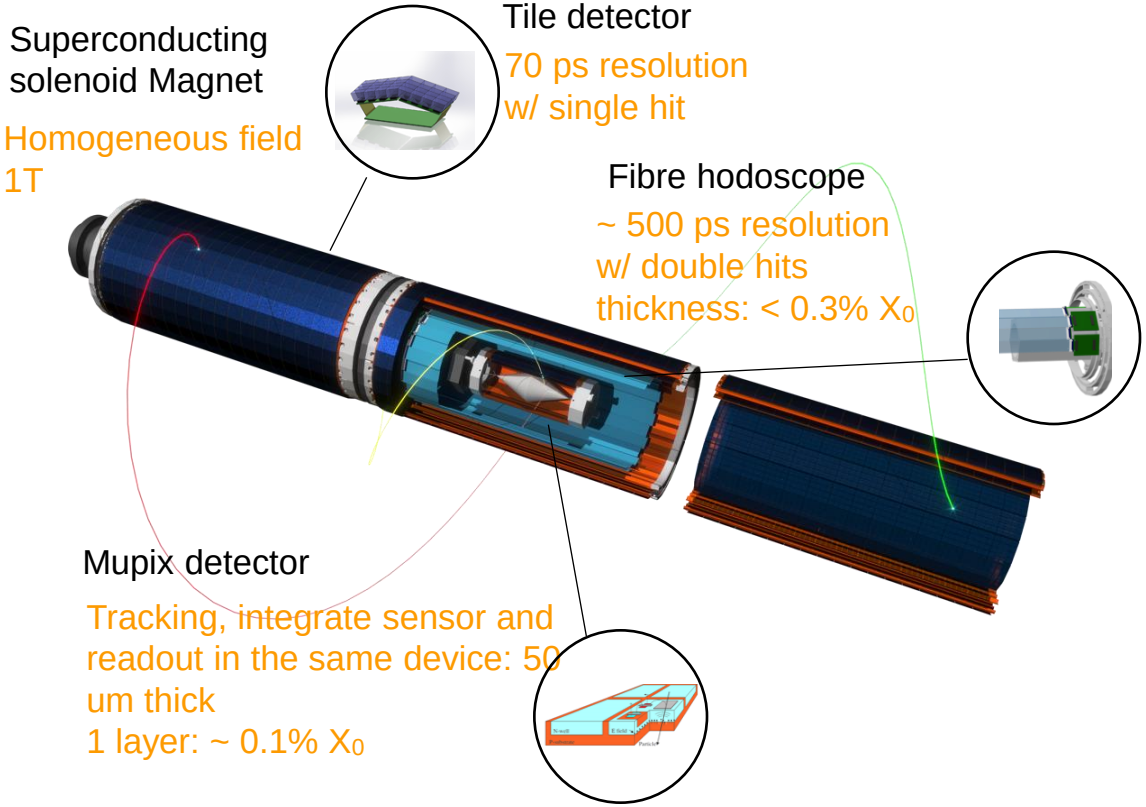
Mu3e Status

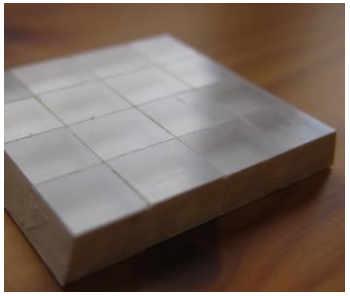
Key elements:

- Staged approach (here only phase I up to 10^8 muons/s)
- Impressive momentum resolutions
- Good timing also with minimal amount of material

Sensitivity phase I [2018-20] ~ 10^{-15}

(Final Sensitivity phase II [202x] ~ 10^{-16})

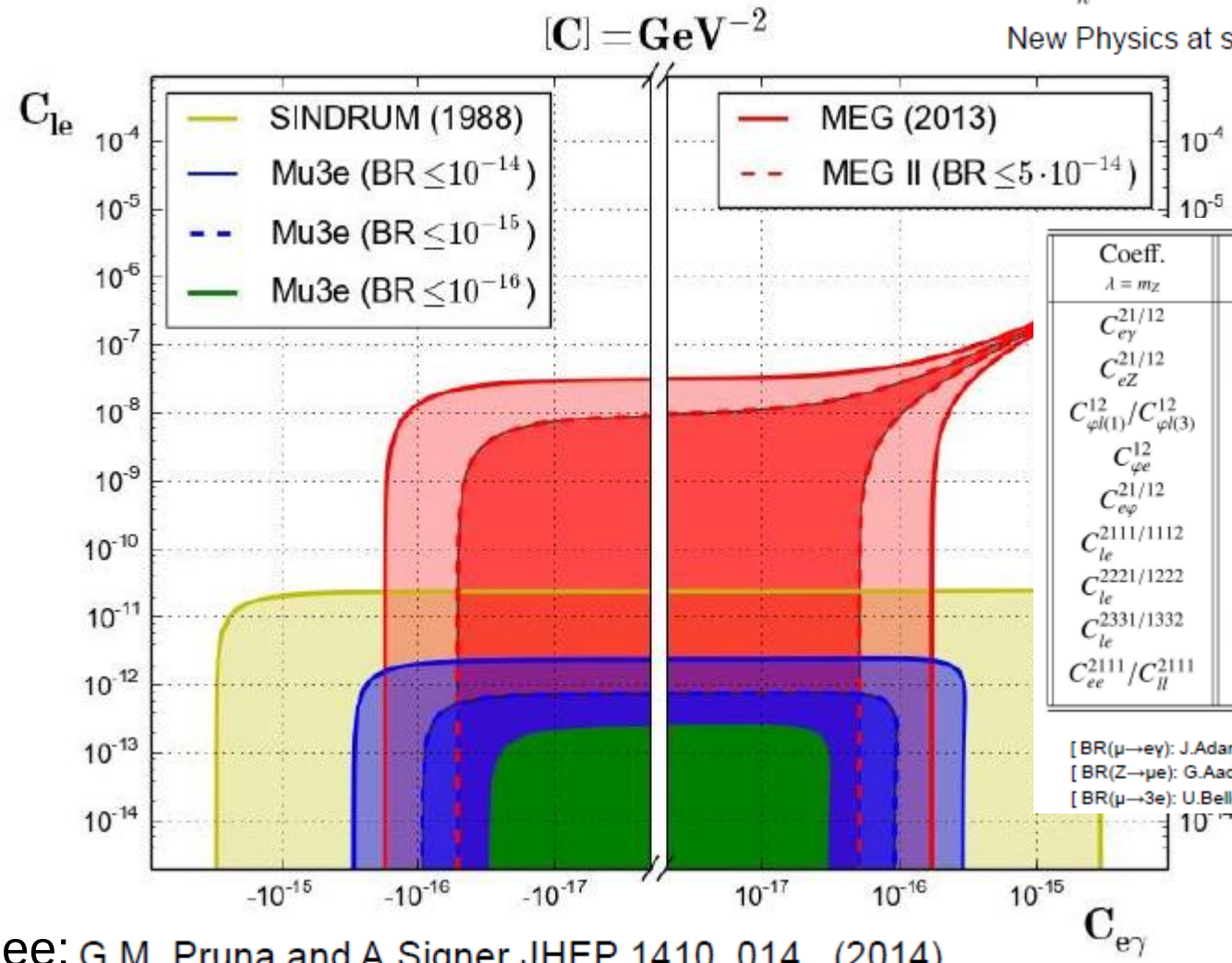




MEG and Mu3e complementarity

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_k C_k^{(5)} Q_k^{(5)} + \frac{1}{\Lambda^2}\sum_k C_k^{(6)} Q_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

New Physics at scale $\Lambda \gg M_Z$



Coeff. $\Lambda = m_Z$	$\mu^+ \to e^+\gamma$ BR$\leq 5.7\cdot 10^{-13}$	$Z \to e^\pm\mu^\mp$ BR$\leq 7.5\cdot 10^{-7}$	$\mu^+ \to e^+e^-e^+$ BR$\leq 1.0\cdot 10^{-12}$
$C_{e\gamma}^{21/12}$	$2.5\cdot 10^{-16}$		$3.8\cdot 10^{-15}$
$C_{eZ}^{21/12}$	$1.4\cdot 10^{-13}$	$3.9\cdot 10^{-8}$	$4.0\cdot 10^{-8}$
$C_{\varphi l(1)}^{12}/C_{\varphi l(3)}^{12}$	$2.5\cdot 10^{-10}$	$3.9\cdot 10^{-8}$	$3.5\cdot 10^{-11}$
$C_{\varphi e}^{12}$	$2.5\cdot 10^{-10}$	$3.9\cdot 10^{-8}$	$3.7\cdot 10^{-11}$
$C_{e\varphi}^{21/12}$	$2.8\cdot 10^{-8}$		$8.7\cdot 10^{-6}$
$C_{le}^{2111/1112}$	$4.4\cdot 10^{-8}$		$3.1\cdot 10^{-11}$
$C_{le}^{2221/1222}$	$2.1\cdot 10^{-10}$		
$C_{le}^{2331/1332}$	$1.2\cdot 10^{-11}$		
$C_{ee}^{2111}/C_{ll}^{2111}$			$1.1\cdot 10^{-11}$

[BR(μ→eγ): J.Adam et al. (MEG), Phys. Rev. Lett. 110, 201801, (2013)]
[BR(Z→μe): G.Aad et al. (ATLAS), Phys. Rev. D90, 072010, (2014)]
[BR(μ→3e): U.Bellgardt et al. (SINDRUM), Nucl.Phys. B299, 1, (1988)]

See: G.M. Pruna and A.Signer JHEP 1410, 014 , (2014)

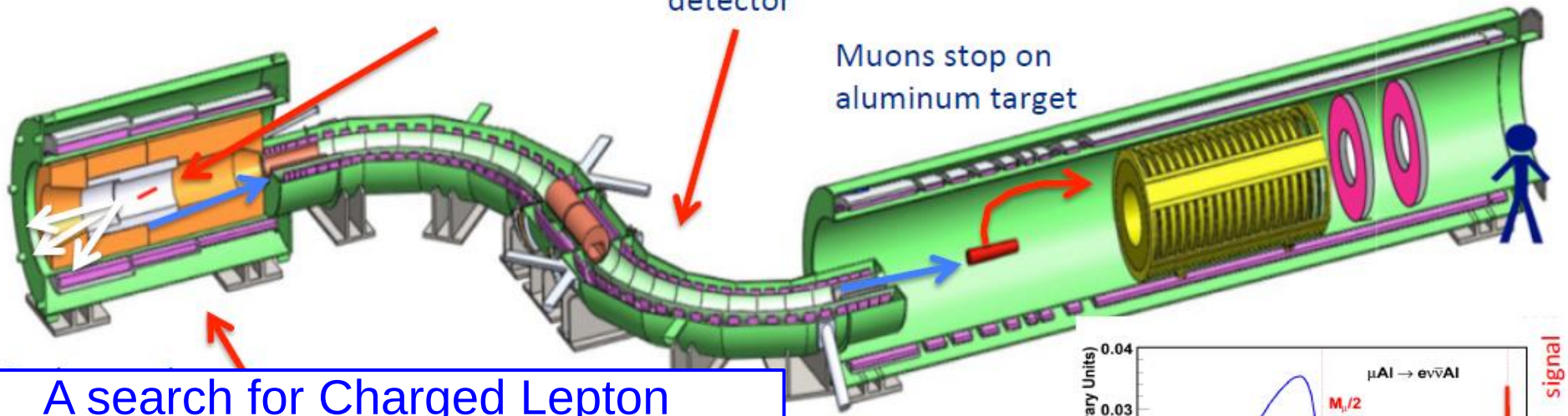
Mu2e experiment

Designed to maximize signal acceptance and remove backgrounds

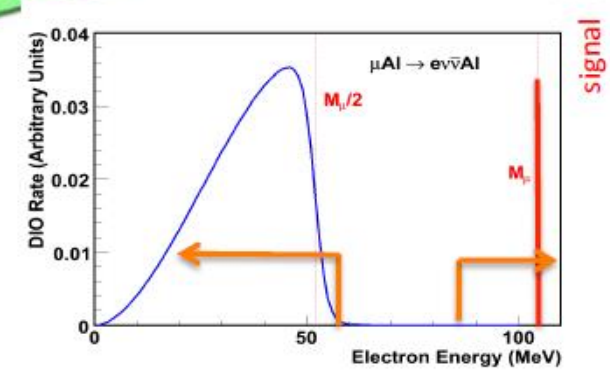
Protons enter here, hit target, make pions

Curved transport solenoid avoids line of sight from production target to detector

Muons stop on aluminum target



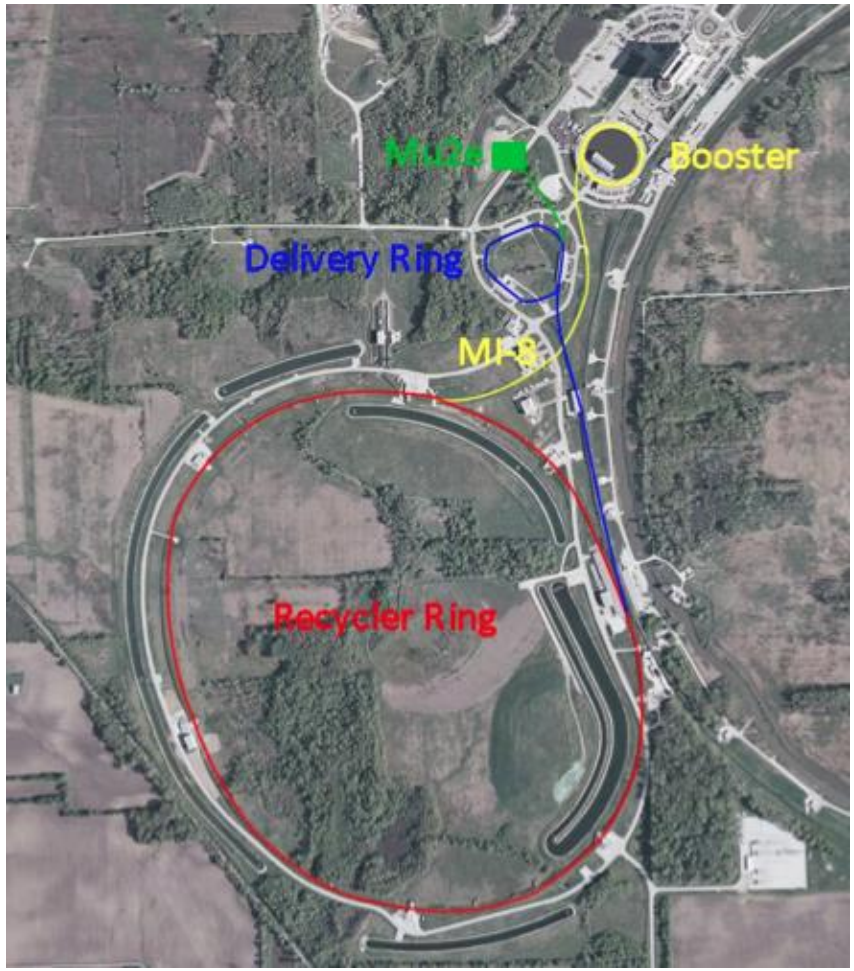
- A search for Charged Lepton Flavor Violation: $\mu N \rightarrow eN$
  - Expected sensitivity of 6×10^{-17} @ 90% CL, x10,000 better than SINDRUM-II
  - Probes effective new physics mass scales up to 10^4 TeV/c^2
  - *Discovery* sensitivity to broad swath of NP parameter space



"Hollow" tracker has ~0% acceptance for Michels and ~100% acceptance for signal

Fermilab

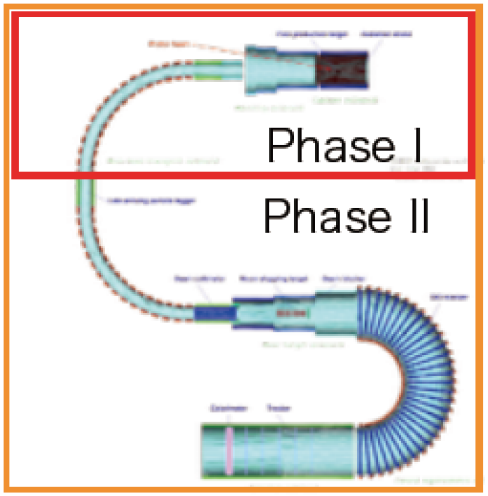
Mu2e Proton Beam line - Fermilab

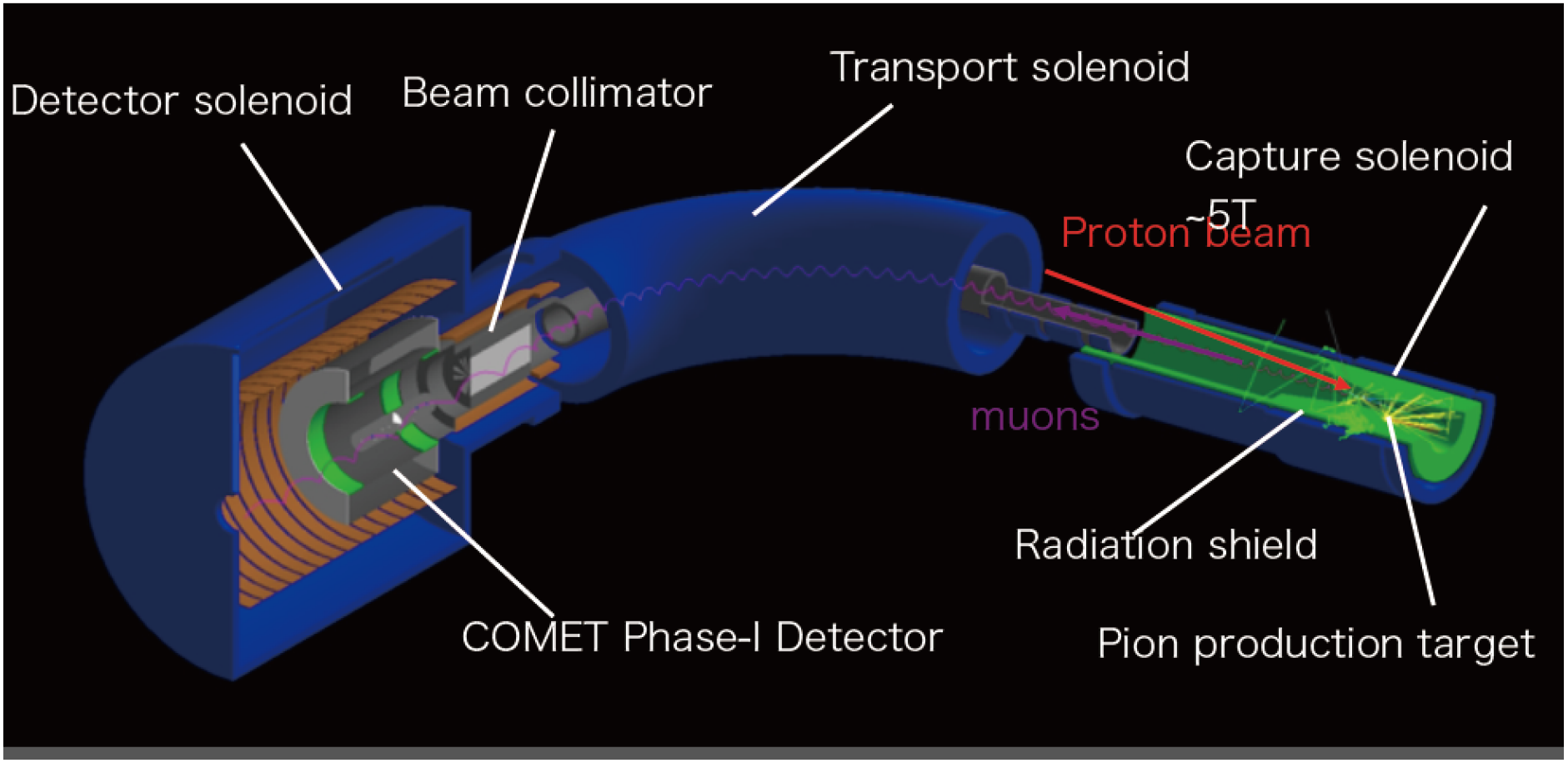


- Mu2e makes use of existing infrastructure at Fermilab
- Mu2e uses 8 kW of protons
  - From the Booster (8 GeV)
  - Re-bunched in the Recycler
  - Slow-spill from Delivery Ring
    - aka Accumulator/Debuncher for Tevatron anti-protons
    - Revolution period 1695 ns
- Mu2e can (and will) run simultaneously with NOvA
- Commissioning 2020

COMET Phase I

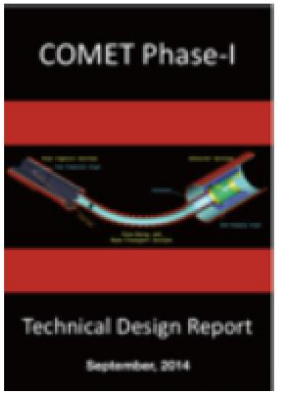
- Phase I
  - Beam background study and achieving an intermediate sensitivity of $<10^{-14}$
    - 8GeV, ~3.2kW, ~90 days of DAQ
- Phase II
  - 8GeV, ~56 kW, 1 year DAQ to achieve the COMET final goal of $< 10^{-16}$ sensitivity



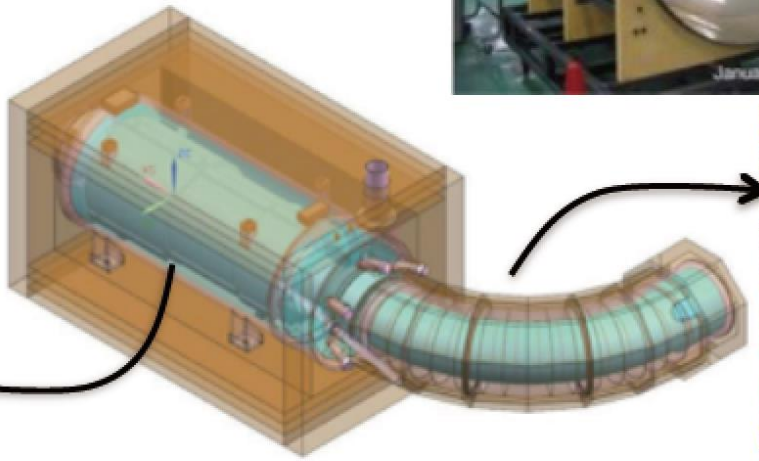


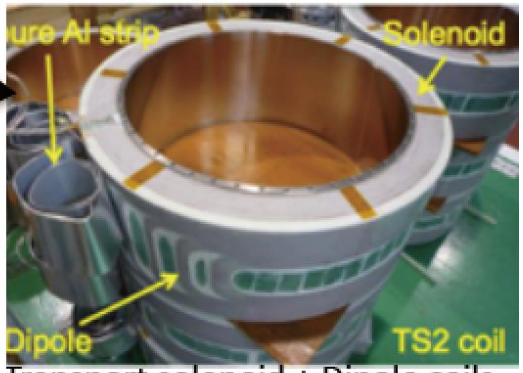
COMET Status

- Construction of Hadron South Exp. Building (completed in JFY 2014)
- Construction of new primary beam line
  - Strong support by the hadron beam line group
- Construction of pion/muon capture (in progress) & transport solenoid magnets (completed in JFY2014)
  - High field / high radiation tolerance
- Development and construction of detectors, Radiation tolerance test of detector components (in progress)
- Submission of Technical Design Report to J-PARC PAC (in Oct. 2014)



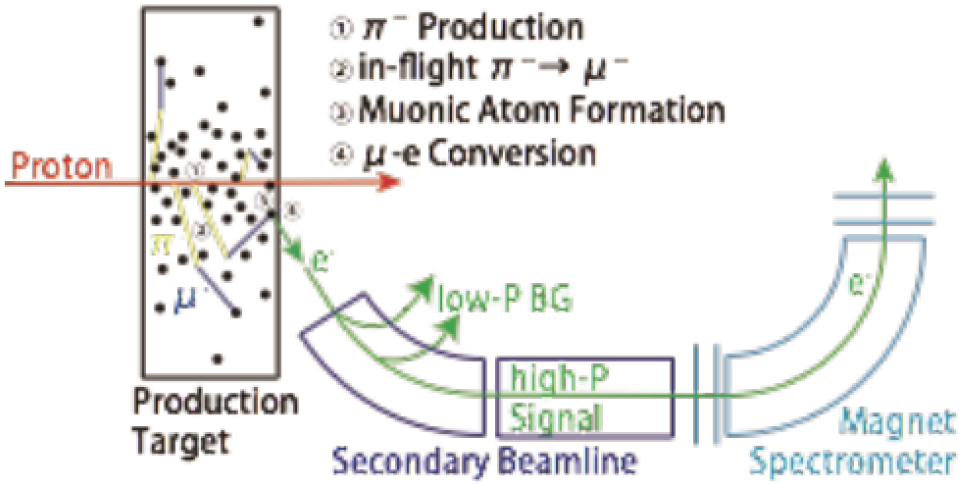
Capture Solenoid Coil Winding



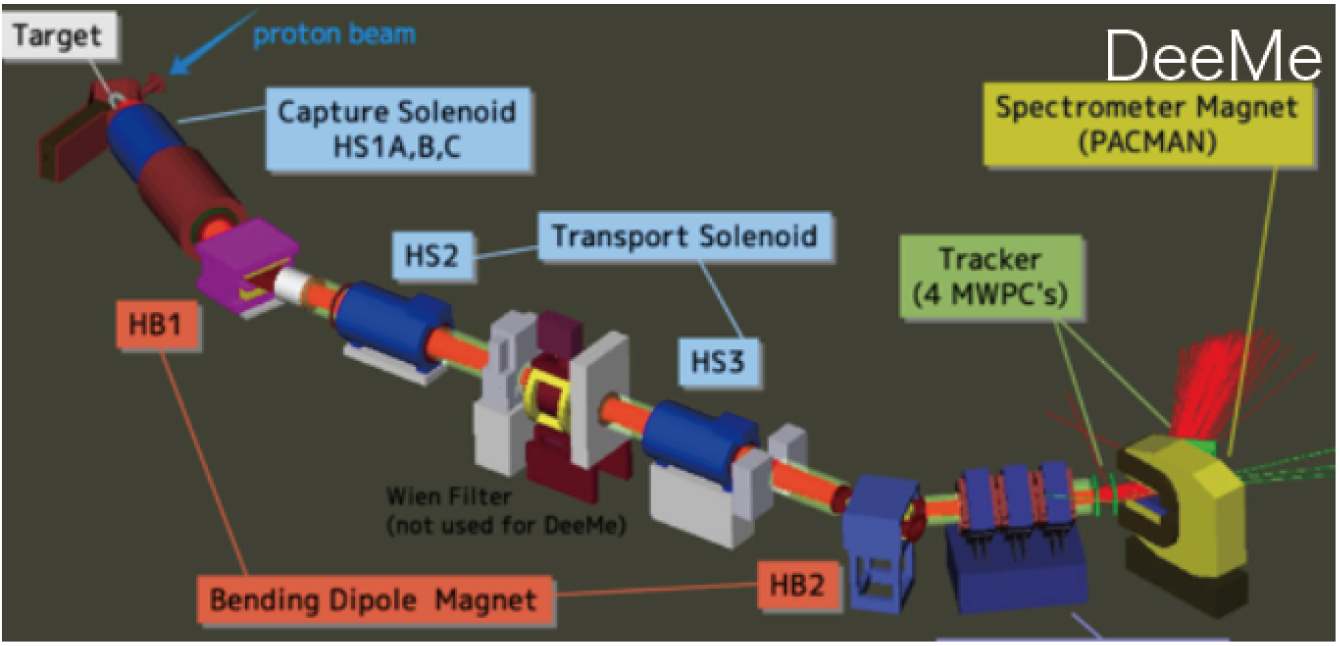


Transport solenoid + Dipole coils

DeeMe: Search for μ-e Conversion



- **IMSS/Muon PAC: Stage-2 Approved**
- **J-PARC/RCS**: High-Power High-Purity Pulsed Proton Beam.
- **Production Target as μ-stopping target**.
- **H-Line/MLF**: Large-Acceptance Beam line.
- **State-of-the-Art MWPC** Technology
- **S.E.S. — BR~5 x 10^{-15}**
  (8 x 10^7 sec of data taking with SiC target)
- Start the physics run with graphite target
  - S.E.S. — 1 x 10^{-13} (2 x 10^7 sec)
- Aiming to start the engineering run in **2015**.

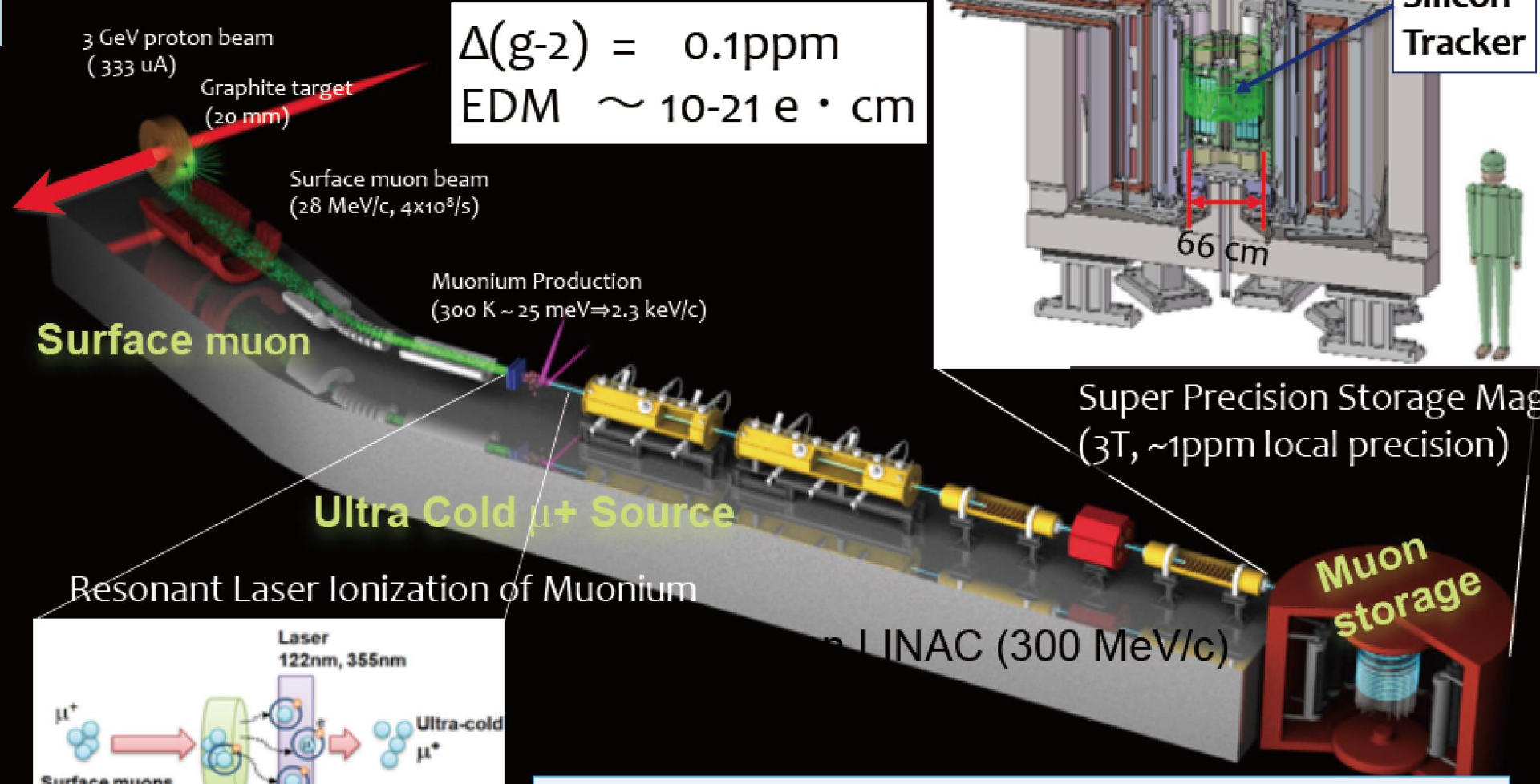


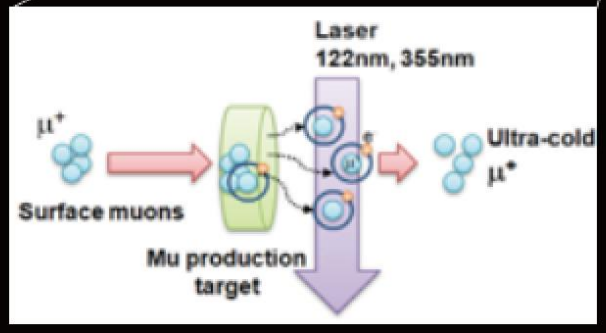
Magnet leased from TRIUMF is waiting for the installation at MLF

New Muon g-2/EDM Experiment at J-PARC with Ultra-Cold Muon Beam

$\Delta(g\text{-}2) = 0.1\text{ppm}$

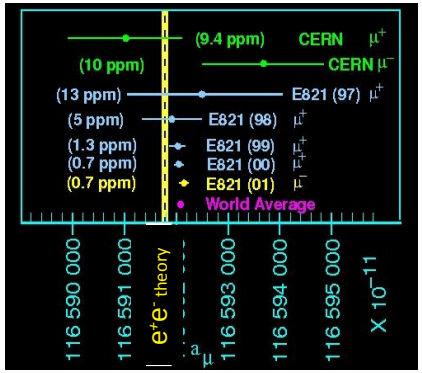
EDM $\sim 10^{-21}$ e・cm





1. Ultra-cold μ^+ beam is injected to storage magnet.
2. Pulse kicker stops muons in storage area
3. Positron tracker measures e+ from $\mu^+ \rightarrow e^+\nu\nu$ decay for the period of 33μs (5 x lifetime)

Tension between Theory and Experiment



$$\vec{\mu}_s = g_s \left(\frac{e\hbar}{2m}\right) \vec{s}$$

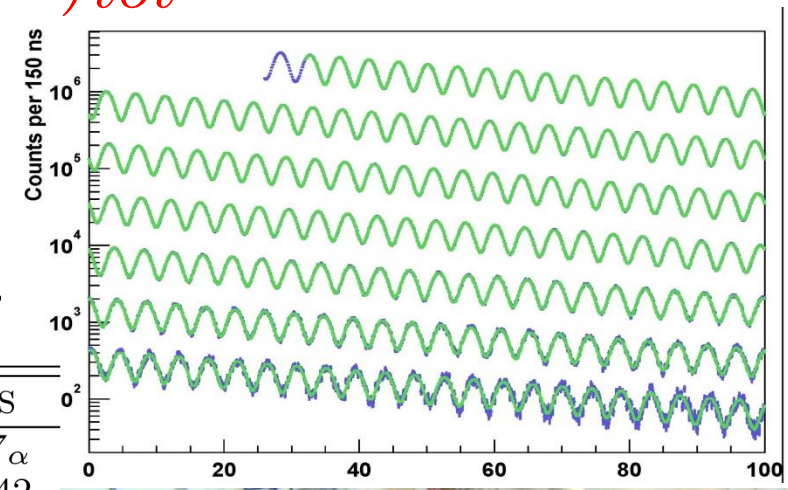
$$g = 2(1+a)$$

$$\omega_a = \omega_S - \omega_C = a\frac{qB}{m}$$

$$a_\mu^{exp} 116\,592\,091(54)_{st}(33)_{sy}(63)_{tot} \times 10^{-11}$$

$$\Delta^{(today)} = (288 \pm 80) \times 10^{-11}$$

Difference is between 3 to 4 σ, depending on the value of the strong interaction contribution used.



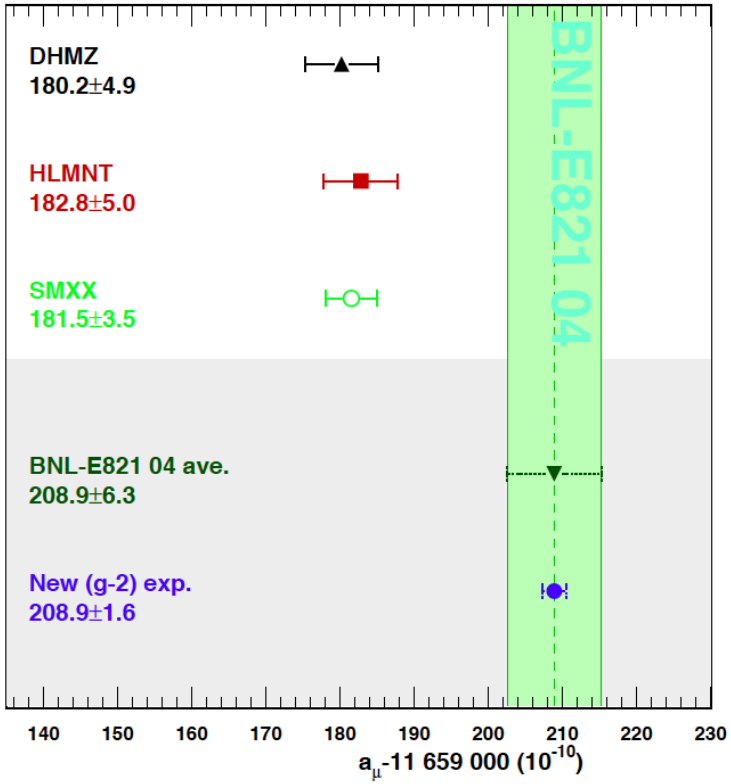
	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.022 \pm 0.077_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(lo)*	$6\,949 \pm 43$
HVP(ho)	-98.4 ± 0.7
H-LBL	105 ± 26
EW	$154 \pm 1 \pm 2$
Total SM	$116\,591\,803 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

Outlook for Fermilab Experiment E989

- Goal, factor of 4 improvement on total error.
- Theory is also improving, factor of 2 possible
- Magnet shimming underway
- Beamlines are under construction
- Detectors under construction
  - 24 6×9 PbF2 segmented calorimeters read out by SiPMs
  - 3 tracker arrays that go inside the vacuum chamber
- Systems being refurbished:
  - Vacuum chambers, electrostatic quadrupoles
- New fast muon kicker under development
- First beam on the pion production target in March 2017
- First muons stored May 2017
- Engineering run ⟶ BNL level data set by fall 2017
- Two years of data collection to follow

Expected future comparison between theory and experiment

Error	Dav	Hag	Future
$\delta a_\mu^{\mathrm{SM}}$	49	50	35
$\delta a_\mu^{\mathrm{HLO}}$	42	43	26
$\delta a_\mu^{\mathrm{HLbL}}$	26	26	25
$\delta(a_\mu^{\mathrm{EXP}} - a_\mu^{\mathrm{SM}})$	80	80	40

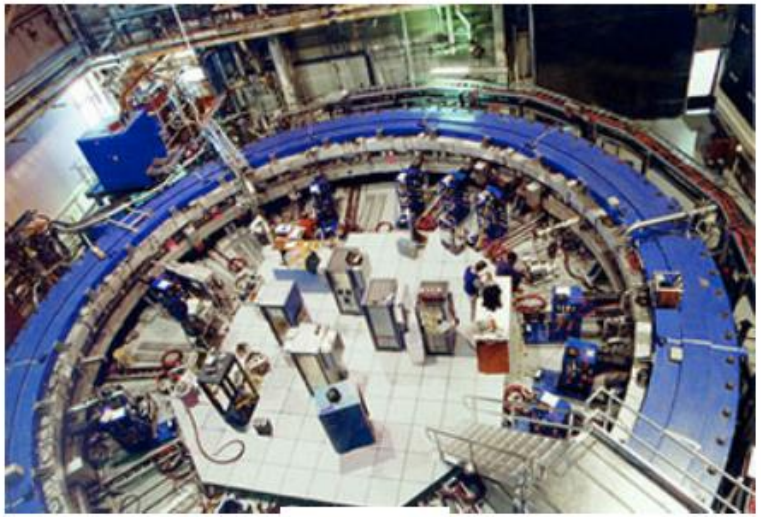


$$\delta a_\mu^{EXP} = 16 \times 10^{-11}$$

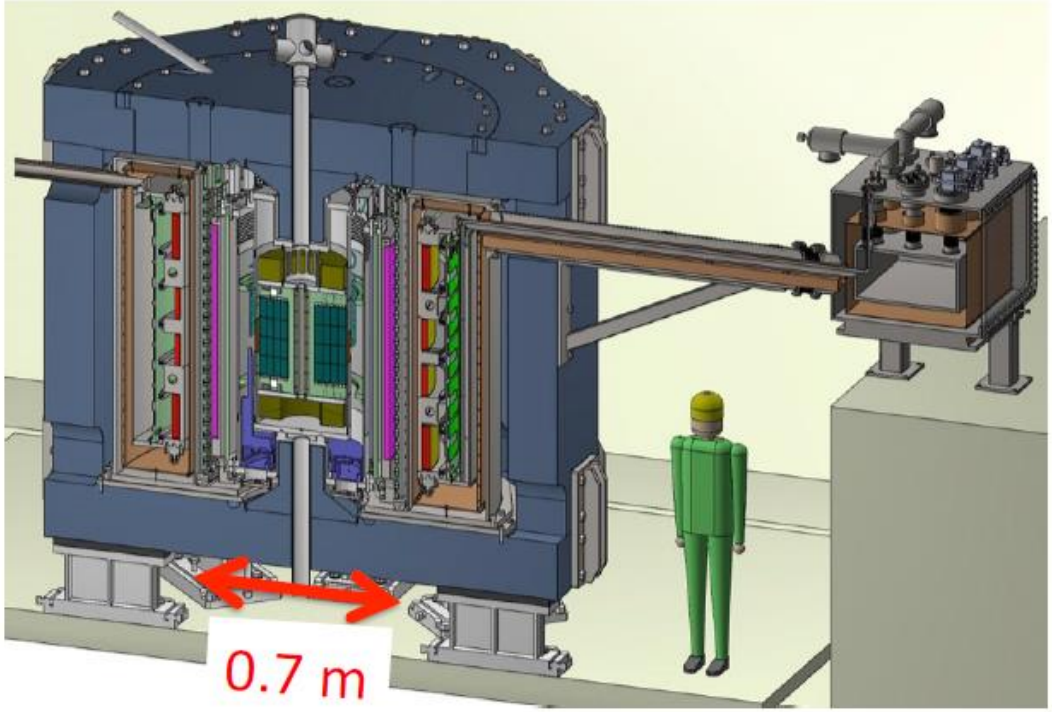
$$\Delta^{(today)} = (288 \pm 80) \times 10^{-11}$$

arXiv:1407.4021v2 [hep-ph] 21 Jul 2014

JPARC muon g-2



14 m



CERN III, BNL, FNAL all use 3.1 GeV muons

'magic' momentum that cancels effects from the E fields required to store the muon beam

Requires a larger ring-> hard to meet uniformity goals

JPARC experiment uses ~300 MeV muons. Allows for a much smaller ring

Order of magnitude improvement in field quality 'out of the box' with an MRI magnet

Expect to be competitive with FNAL but on a longer time frame

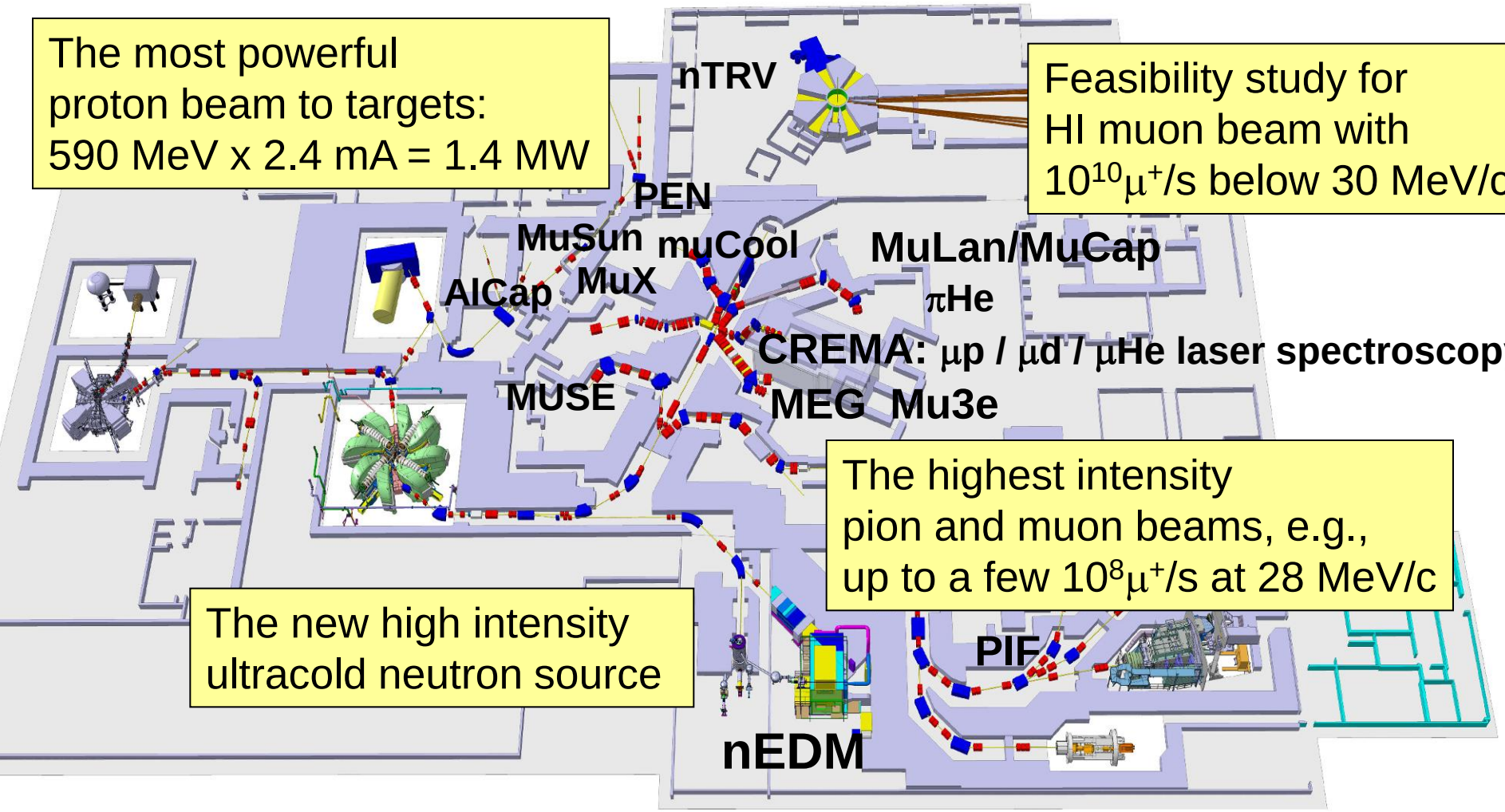
Fermilab

The intensity frontier at PSI: π, μ, UCN

Precision experiments with **the lightest unstable particles** of their kind

The most powerful
proton beam to targets:
590 MeV x 2.4 mA = 1.4 MW

Feasibility study for
HI muon beam with
$10^{10}\mu^+$/s below 30 MeV/c



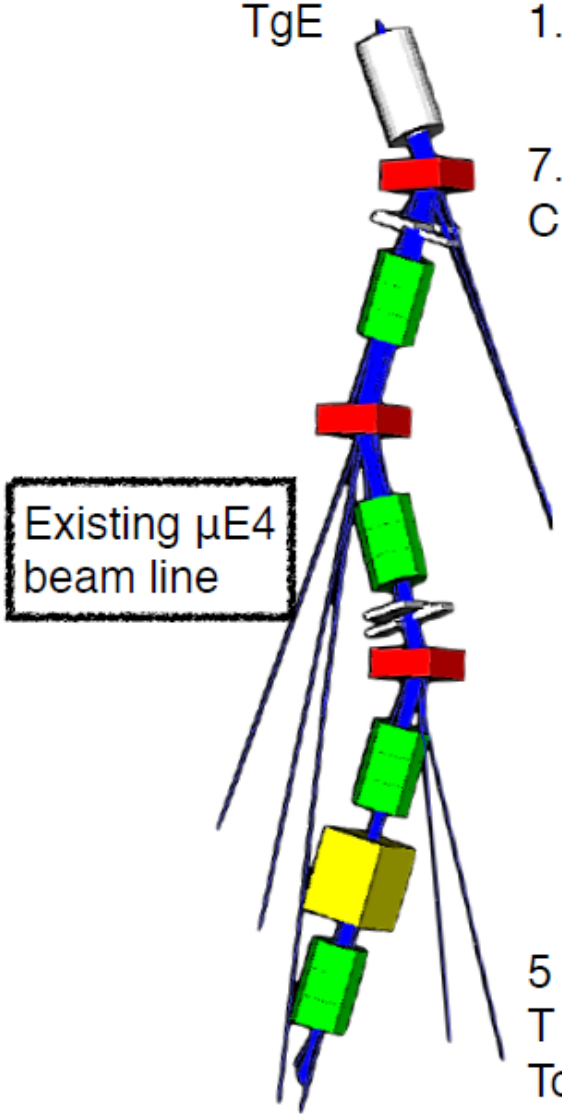
The highest intensity
pion and muon beams, e.g.,
up to a few $10^8\mu^+$/s at 28 MeV/c

The new high intensity
ultracold neutron source

Swiss national laboratory with strong international collaborations

HiMB Project : 10^{10} μ^+/s below 30 MeV/c

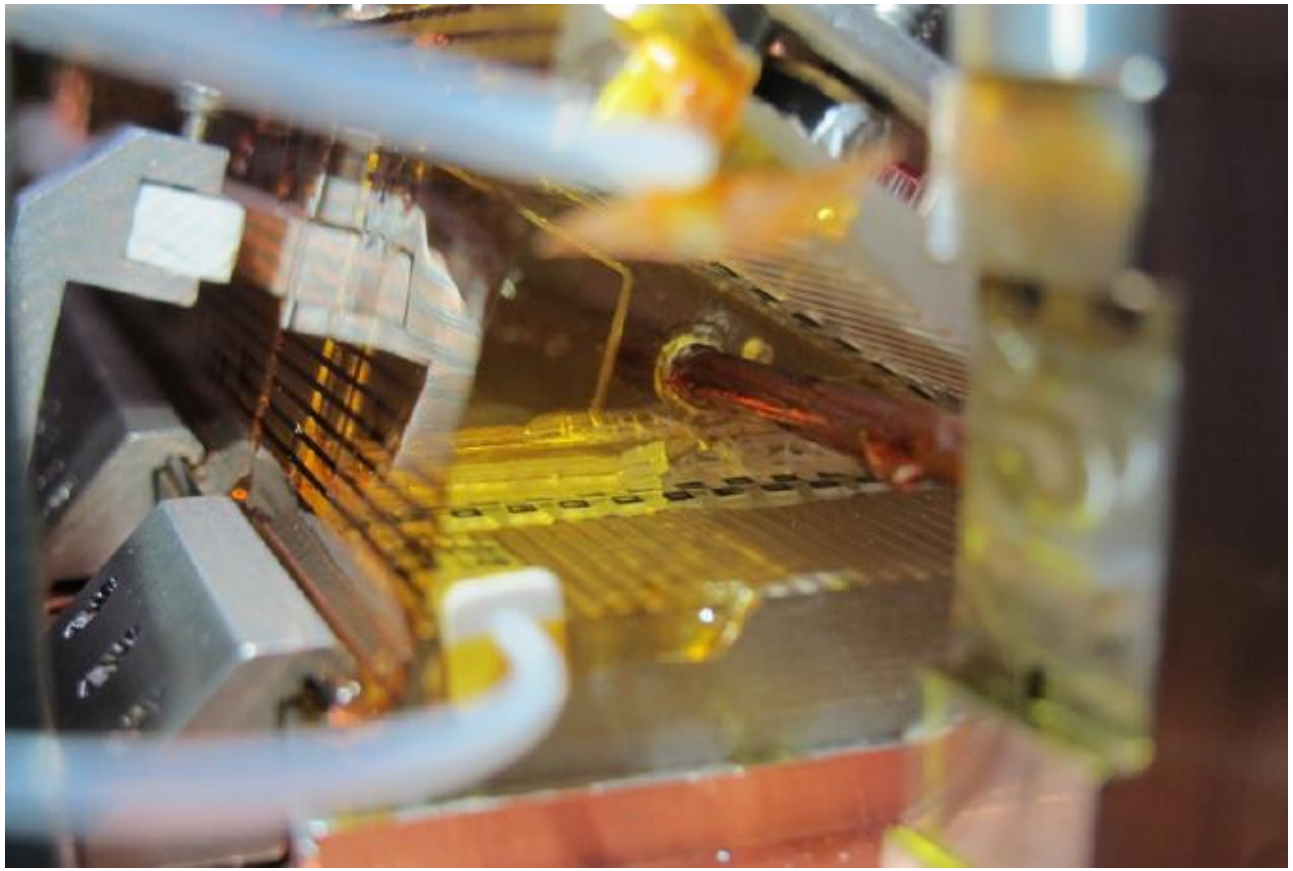
TgE		Source		modified TgM
	1.2 x 10^{11} μ^+/s		1.3 x 10^{11} μ^+/s	
	7.2 x 10^{9} μ^+/s C ~ 6%	Capture	3.4 x 10^{10} μ^+/s C ~ 26%	
	5 x 10^{8} μ^+/s T ~ 7% Total ~ 0.4%	Transmission	1.3 x 10^{10} μ^+/s T ~ 40% Total ~ 10%	



⇒ Gain due to high capture and transmission efficiency

The muCool project: an ultra-bright LE μ^+ beam

compressing phase space by 10 orders of magnitude while loosing only 3 orders in intensity



Will enable

- new M experiments
  - spectroscopy
  - gravity
- new g-2 / EDM
- new μSR techniques

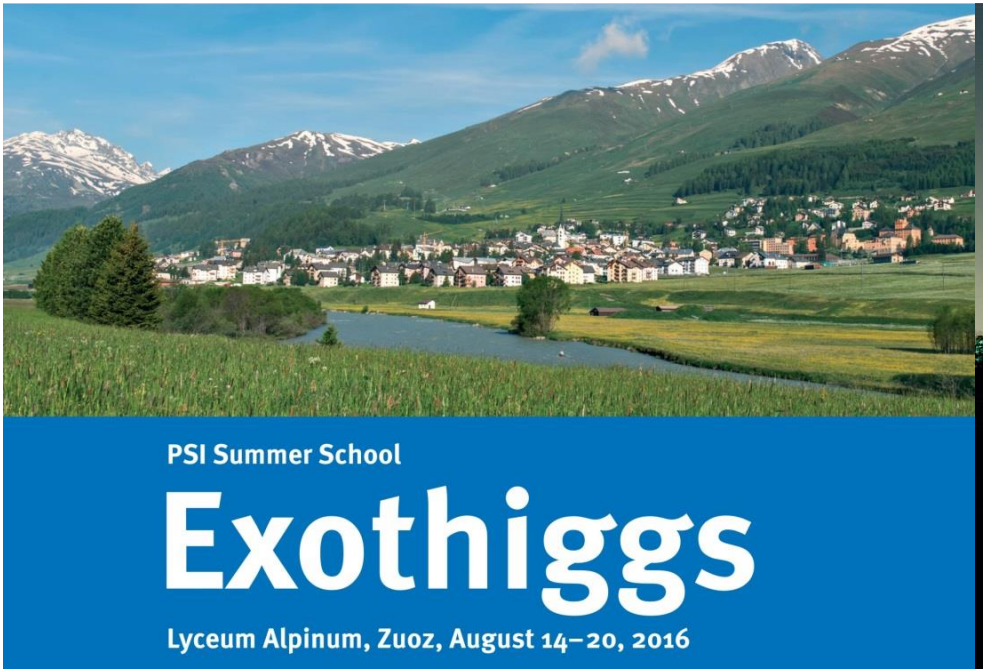
D. Taqqu, *PRL* **97**, 194801 *(2006)*

Y. Bao et al., *PRL* **112**, 224801 *(2014)*

G. Wichmann et al, NIM A **814**, 33-38 *(2016)*

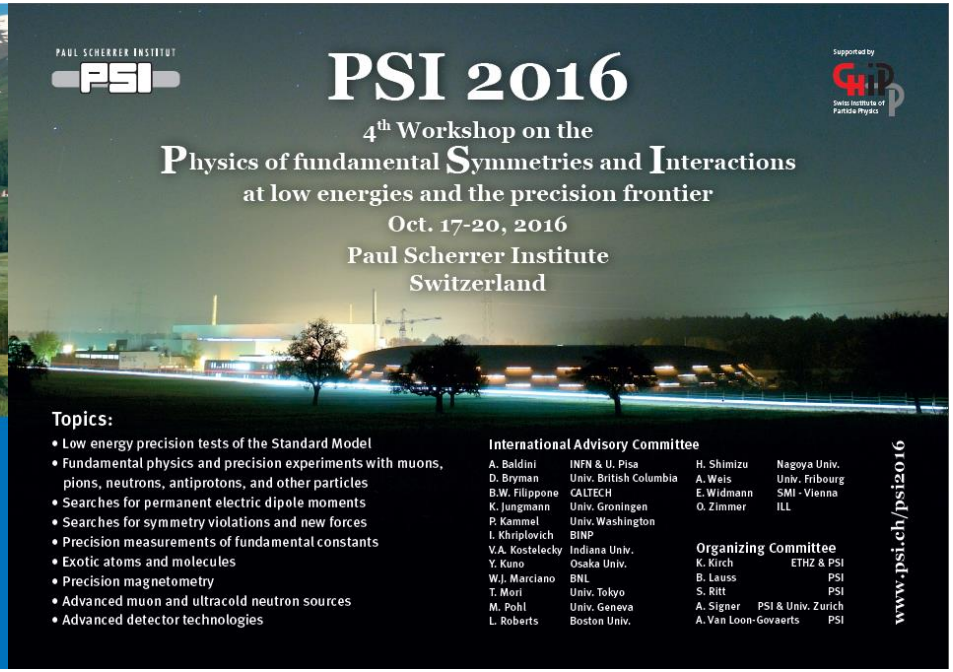
PSI Particle physics
organizes in 2016

www.psi.ch/particle-zuoz-school



August 14 – 20, 2016

www.psi.ch/psi2016



October 17 – 20, 2016

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- Aldo Antognini
- Stefan Ritt
- Andreas Knecht
- Andreas Eggenberger

Picture: K. Schuhmann