INT 18-2a “Fundamental Physics with Electroweak Probes of Light Nuclei”, 6/12 – 7/13/2018

Experimental searches for non-universal lepton interaction

Michael Kohl <kohlm@jlab.org> *

Hampton University, Hampton, VA 23668
Jefferson Laboratory, Newport News, VA 23606

* **Presently supported by DOE DE-SC0013941, NSF HRD-1649909, PHY-1505934 and PHY-1436680**

About M.K.

Born on March 7, 1969 in Hanau, 1988 Abitur

1989-1996 Techn. Univ. Darmstadt (Diploma “Dipl.-Phys.”)

1996-2003 Techn. Univ. Darmstadt & MAMI (Doctorate & Postdoc)
Pion electroproduction from He-3
Search for narrow nucleon resonances below pion threshold
A1 program: Form factors, pion production, correlations

2003-2007 MIT Bates & LNS (Postdoc & Research Scientist)
BLAST: Polarized electron scattering with internal polarized targets

Since 2008 Hampton University & Jefferson Lab
(Joint Tenure-Track Assistant Professor and Staff Scientist)
Hall C program @ JLAB: GEp-III, 2-Gamma, SANE, C-GEN
DarkLight @ JLAB-LERF: Dark-photon search
OLYMPUS @ DESY: Two-photon exchange
TREK @ J-PARC: Physics beyond the SM in kaon decays
MUSE @ PSI: Comparison μp and ep elastic scattering (proton radius puzzle)

2013: Tenure & Promotion (Associate Professor)
Since 2009: >$3.5 Mio in US grant funding from 11 awards

Present working group *

NSF postdoc (Ishara Fernando: MUSE)
shared / funded presently by NSF — Sri Lanka

DOE postdoc (Tongtong Cao: TREK/E36)
funded presently by DOE — China

PhD student (Jesmin Nazeer: DarkLight, GEMs)
funded presently by NSF — Sri Lanka

Master’s student (Tanvi Patel: MUSE, GEMs)
funded presently by NSF/EAGER — India / USA

PhD student (Bishoy Dongwi: TREK/E36)
funded presently by DOE — Namibia

Undergraduate students

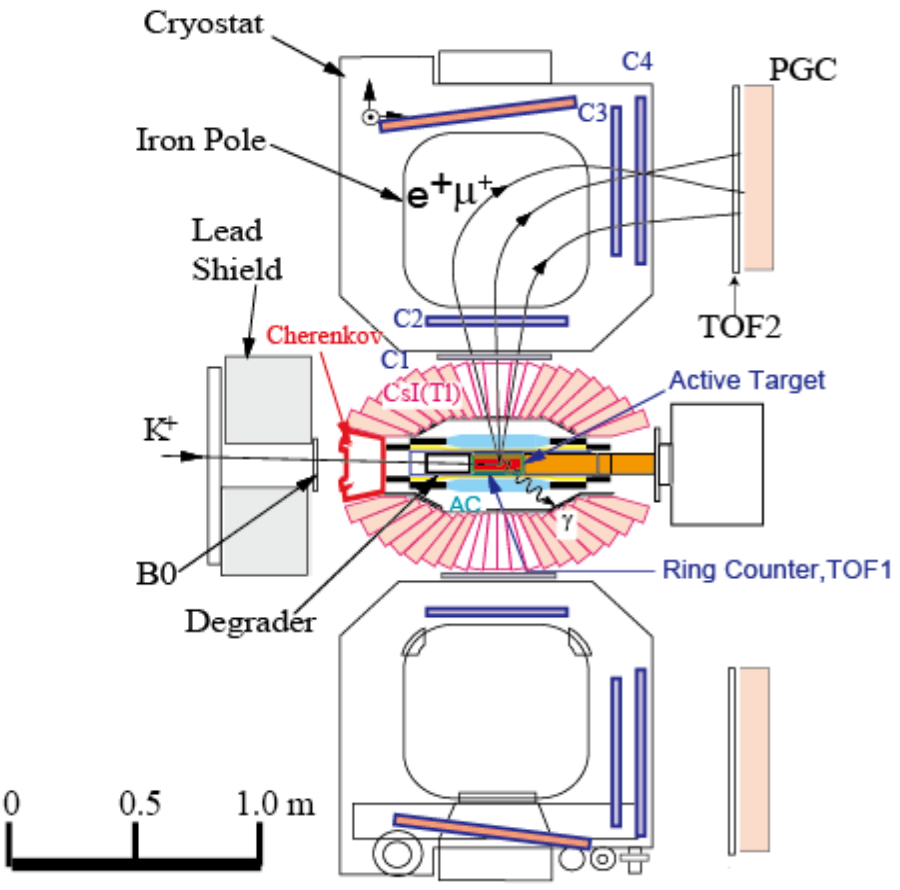
Letrell Harris, HU sophomore: GEMs — USA
Sterlyn McCoy, HU freshman: GEMs — USA
Angel Christopher, HU freshman: GEMs — Nigeria
funded presently by DOE and NSF

Lab Technician (Ameer Blake: GEMs)
funded presently by NSF — USA

* Presently supported by DOE DE-SC0013941, NSF HRD-1649909, PHY-1505934 and PHY-1436680

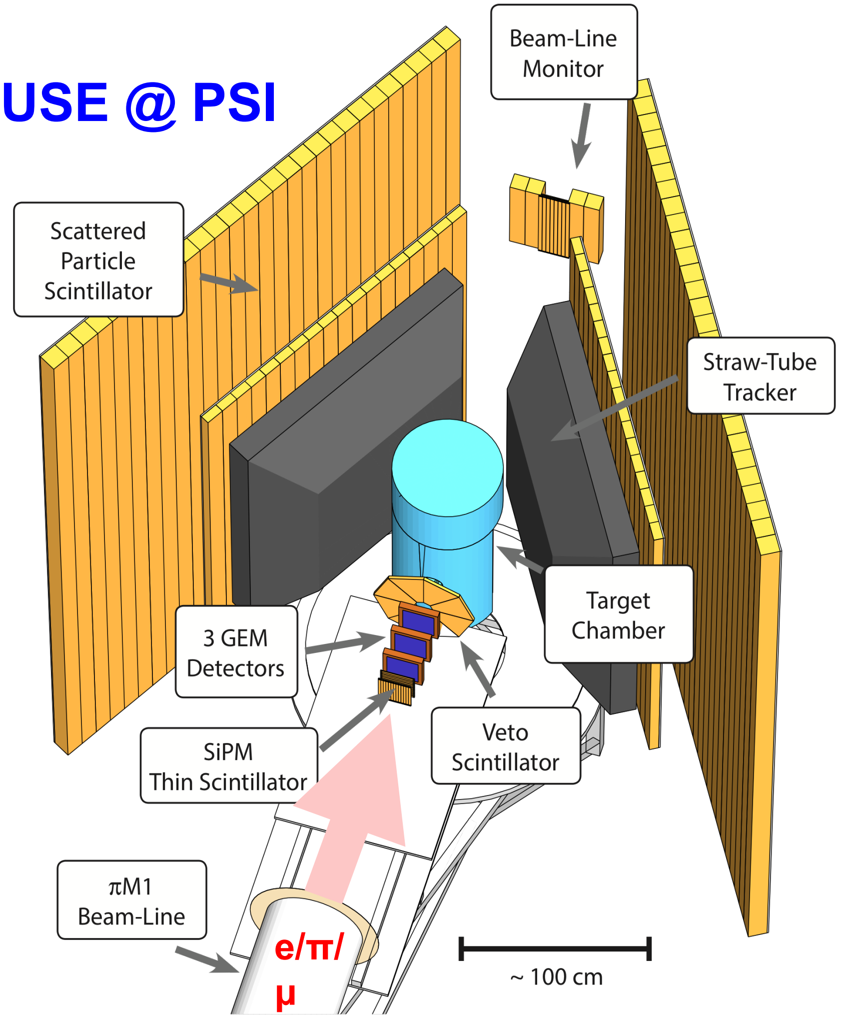
Outline

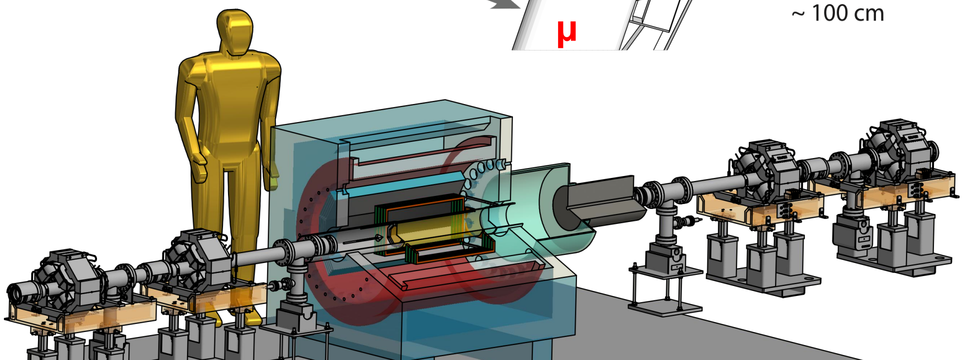
- **Lepton non-universality?**
- **MUSE (R_p) – status**
- **TREK/E36 (LFU) – status**
- **DarkLight (A') – status**



TREK @ J-PARC

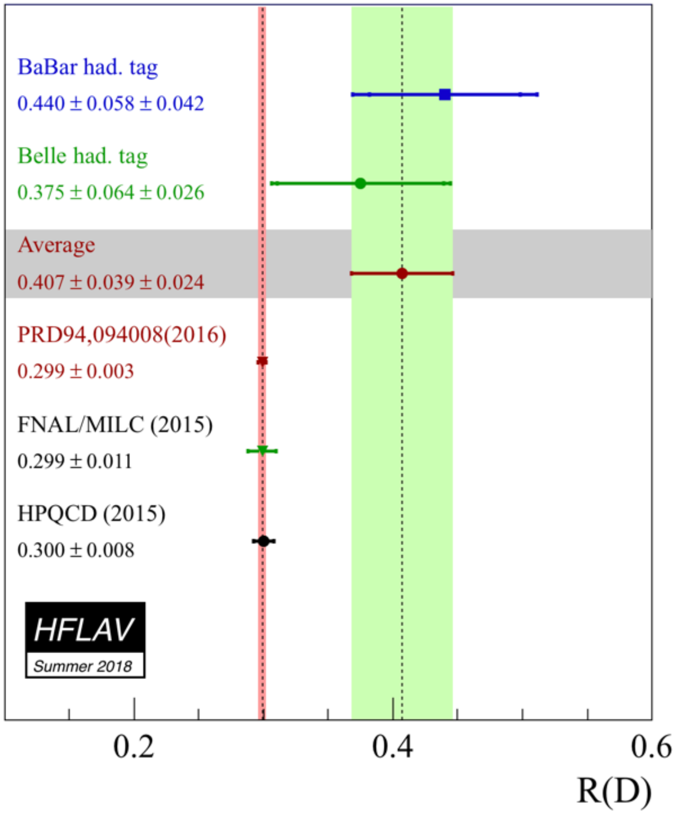
MUSE @ PSI

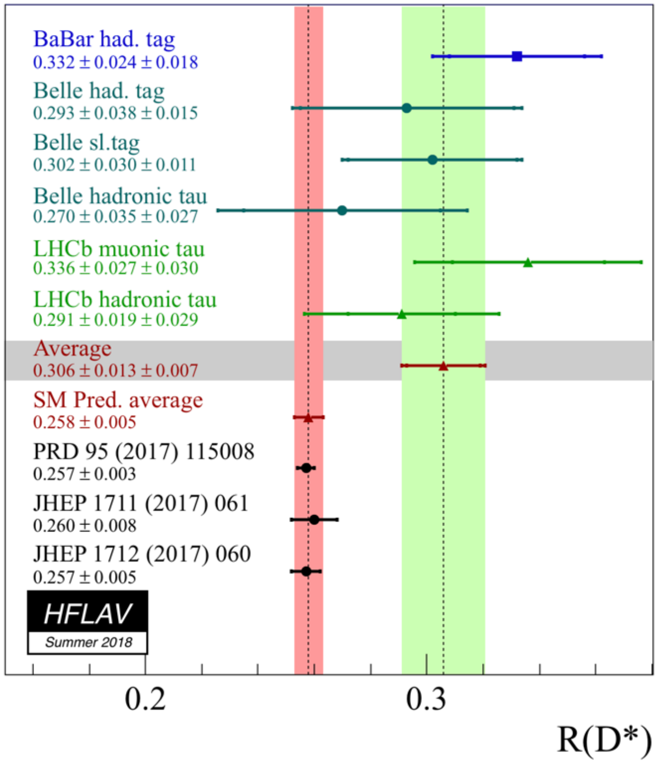




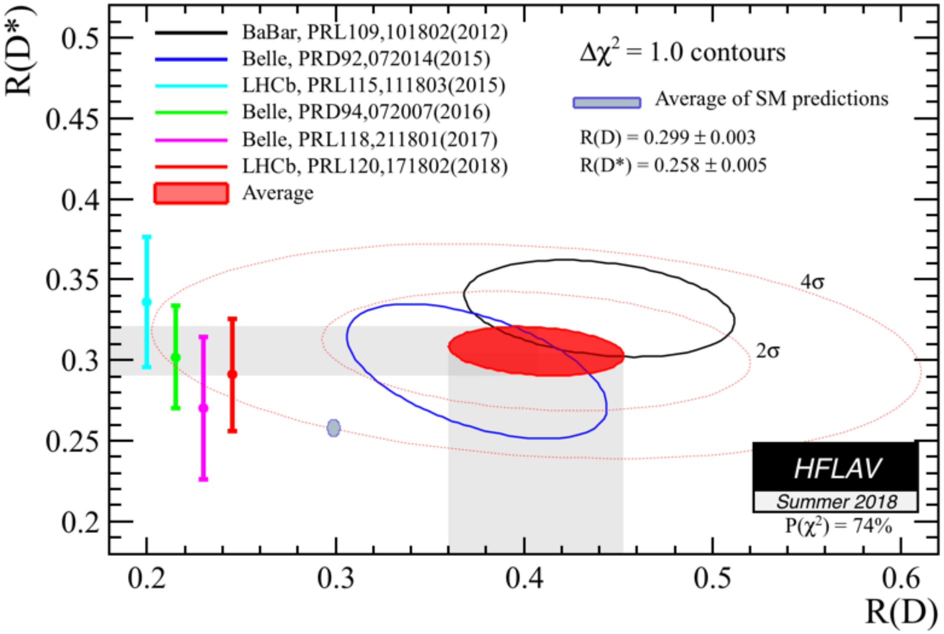
DARKLIGHT

Lepton non-universality in B-decays (τ-μ)



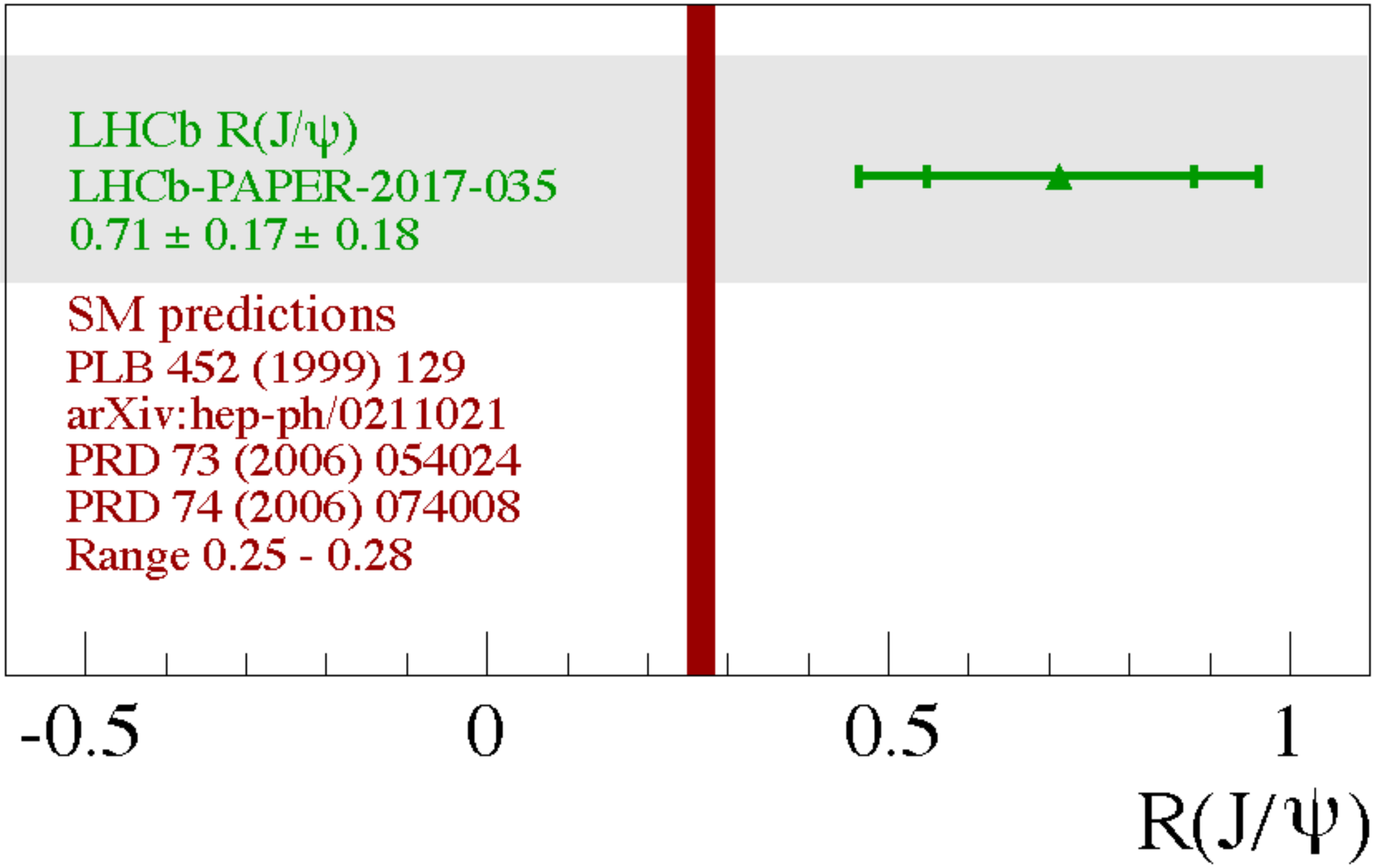


- **R(D$^{(*)}$) = Γ(B→D$^{(*)}$τ$^+$ν) / Γ(B→D$^{(*)}$μ$^+$ν)**
- **HFLAV summer 2018 update (slightly reduced significance)**
- **R(D), R(D*) Individually at 2.3-3.0σ**
  Combined at 3.6-3.8σ



Lepton non-universality in B-decays (τ-μ)

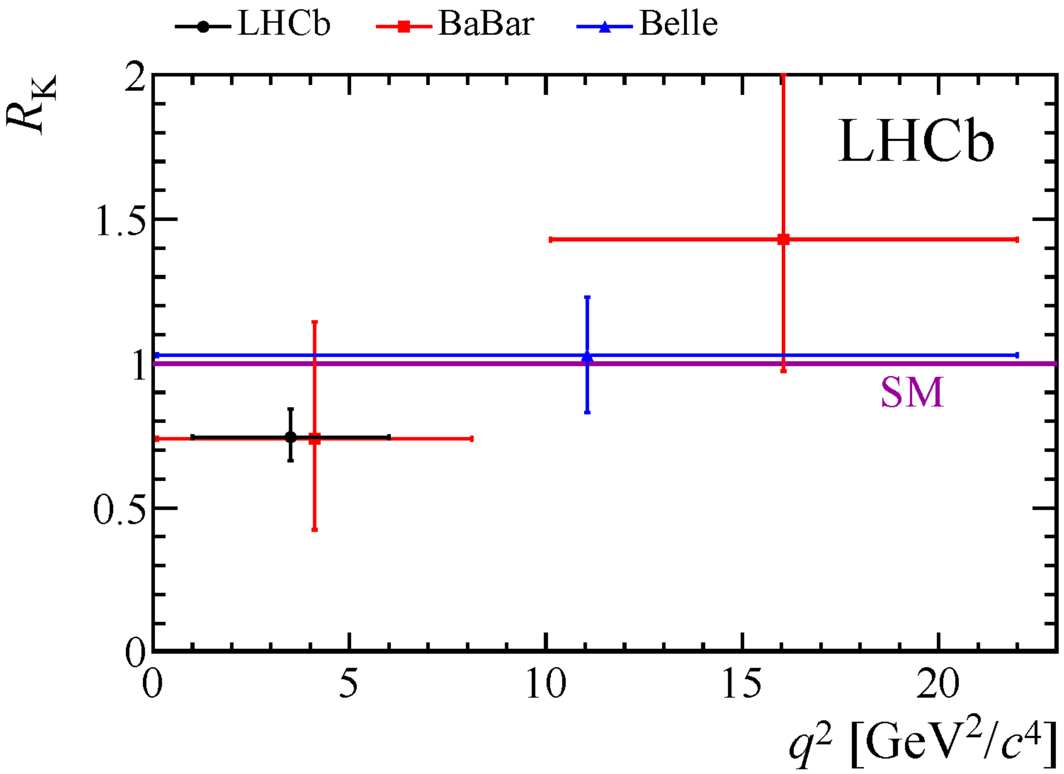
- Charmed meson J/ψ:
  $R(J/\psi) = \Gamma(B^+ \rightarrow J/\psi\ \tau^+\nu) / \Gamma(B^+ \rightarrow J/\psi\ \mu^+\nu)$
- Different from SM at ~2σ
- Less straightforward than $R(D^{(*)})$

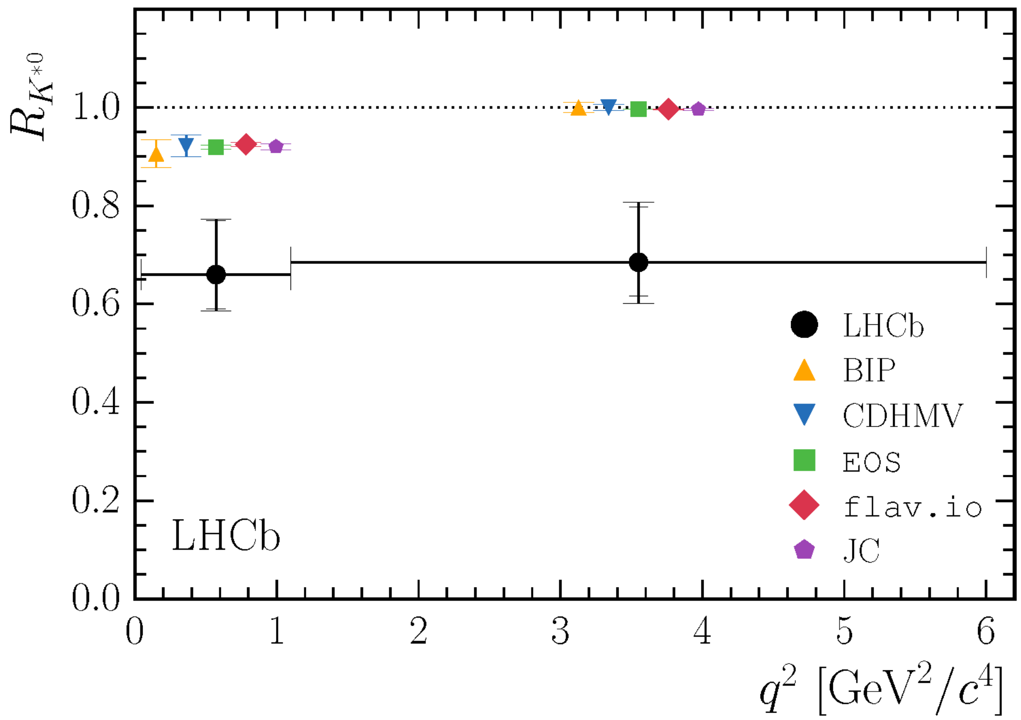


R. Aaji *et al.*, arXiv:1711.05623, PRL 120, 121801 (2018)

Lepton non-universality in B-decays (μ-e)

- LHCb: $R(K^{(*)}) = \Gamma(B \rightarrow K^{(*)} \mu^+\mu^-) / \Gamma(B \rightarrow K^{(*)} e^+e^-)$
- $R(K^{(*)})$ different from SM at the 2.5σ level; R(K) update awaited





R. Aaji et *al.*,
arXiv:1406.6482
PRL 113, 151601 (2014)

R. Aaji et *al.*,
arXiv:1705.05802
JHEP 08 (2017) 055

Experiments presented today

- The proton charge radius puzzle
  MUSE @ PSI to compare
  $\mu^{\pm}p$ and $e^{\pm}p$ elastic scattering

The nine muses

- Test of lepton flavor universality
  TREK/E36 @ J-PARC to compare
  $K^{+} \rightarrow e^{+} \nu / \mu^{+} \nu$ decays and search
  for $A' \rightarrow e^{+} e^{-}$ in $K^{+} \rightarrow \mu^{+} \nu A'$, $\pi^{+} A'$
  and $\pi^{0} \rightarrow \gamma A'$

- Search for a gauge boson $m_{A'}$ <100 MeV/c^{2}
  DarkLight @ JLAB
  Phase-1C: $A' \rightarrow e^{+} e^{-}$ in $e^{-} Z \rightarrow (e^{-} Z) A'$
  near 17 MeV/c^{2}

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  MUSE @ PSI to compare
  $\mu^{\pm}p$ and $e^{\pm}p$ elastic scattering
  I. Fernando (postdoc), Tanvi Patel (MS)

The nine muses

PAUL SCHERRER INSTITUT
PSI

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  T. Cao (postdoc), B. Dongwi (PhD)

J-PARC

- **Search for a gauge boson $m_{A'}$ <100 MeV/c^2**
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  near 17 MeV/c^2
  J. Nazeer (PhD)

DARKLIGHT

Jefferson Lab

Great opportunities for students and postdocs!

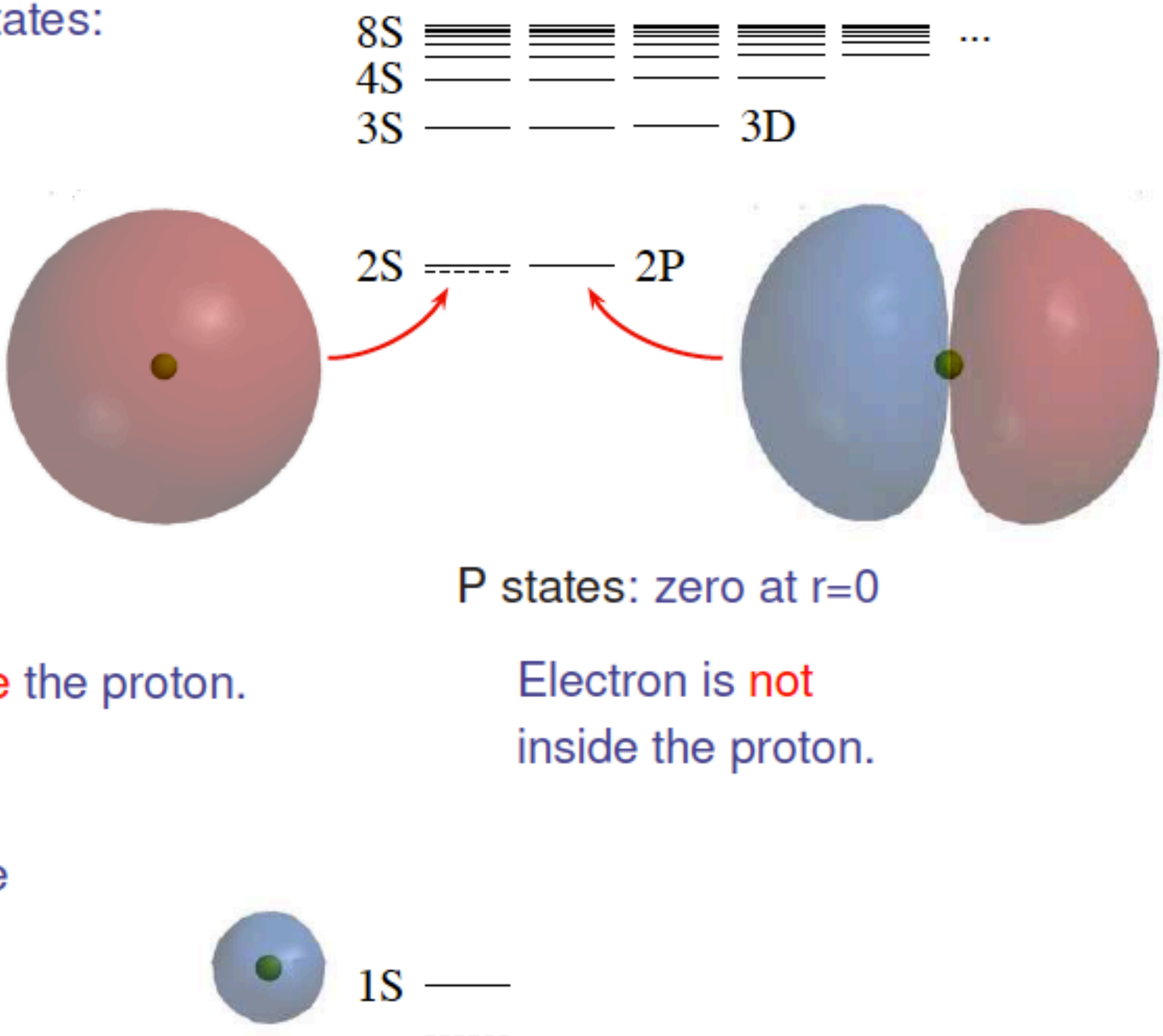
MUSE: MUon Scattering Experiment at PSI

- Motivation
- Proposed experiment
  - Muon beamline
  - Detector
  - Expected sensitivity
- Status & Schedule

Appollo and the nine muses

Atomic physics

Wave functions of S and P states:



S states: max. at r=0

Electron sometimes inside the proton.

S states are shifted.

Shift ist proportional to the

size of the proton

P states: zero at r=0

Electron is not inside the proton.

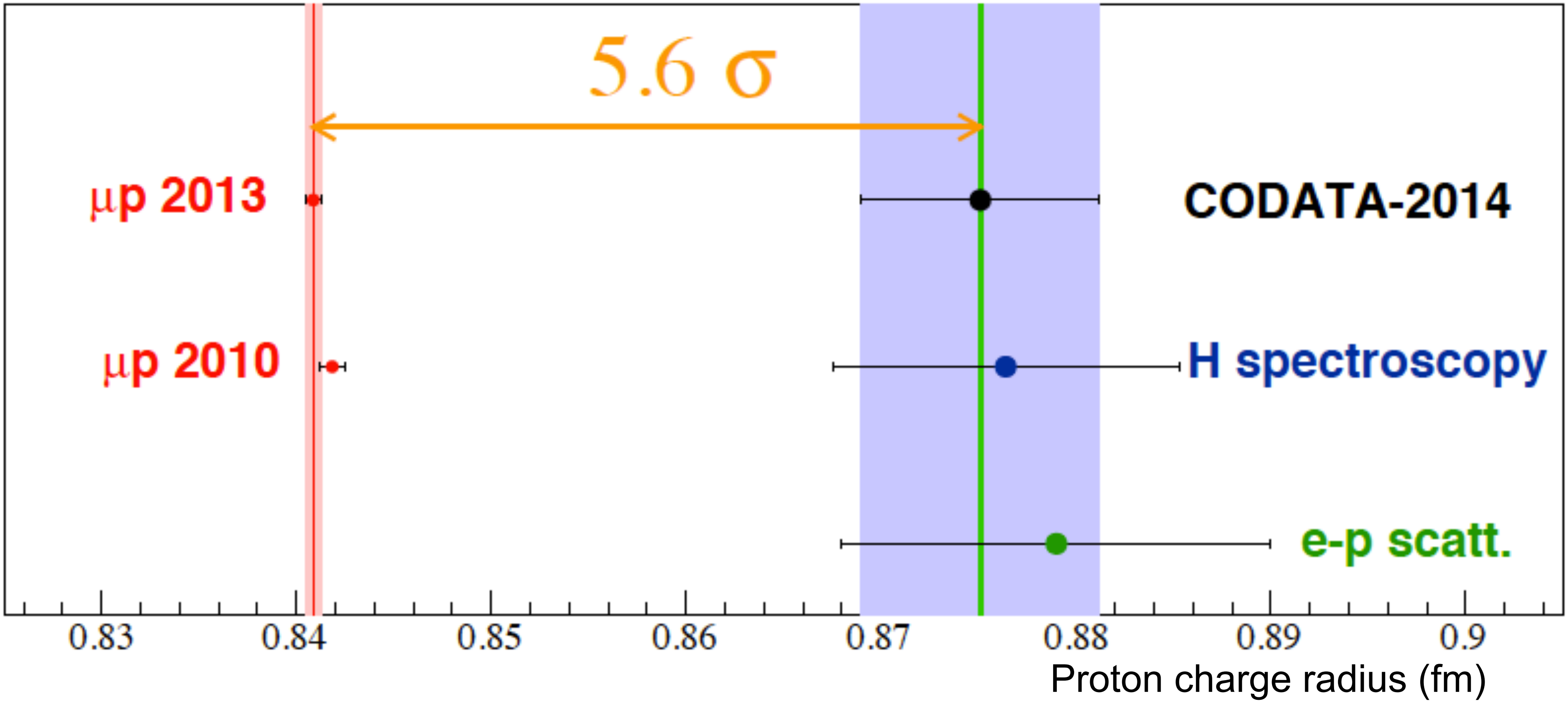
Slide by R. Pohl

Orbital pictures from Wikipedia

The proton radius puzzle

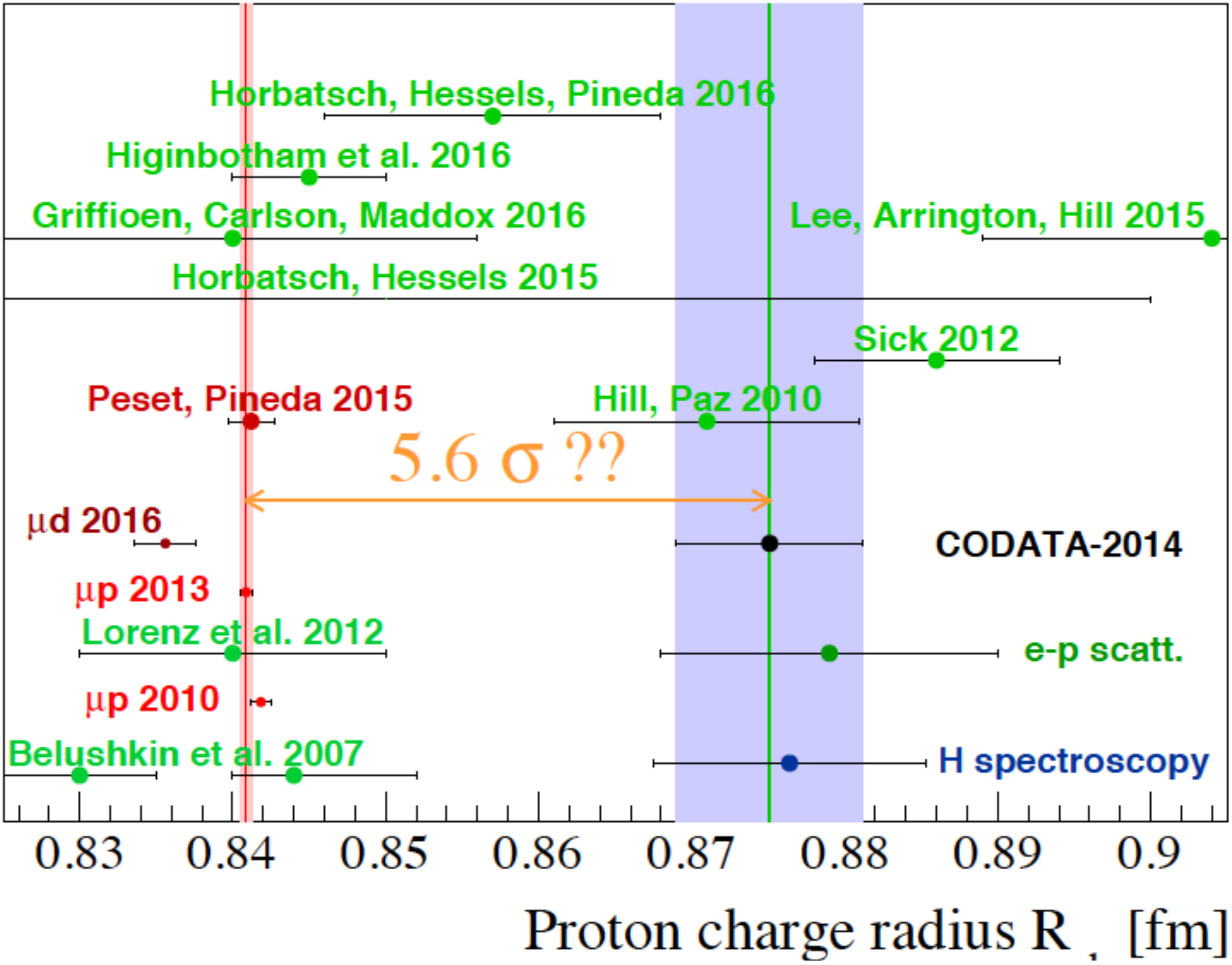
The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm **(CODATA2014)**
muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)
A. Antognini et al., Science 339, 417 (2013)

The proton radius puzzle



The proton radius puzzle in the media

April 2013

8 July 2010 | www.nature.com/nature | $10

nat

OIL SPILLS
There's more to come

PLAGIARISM
It's worse than you think

CHIMPANZEES
The battle for survival

NATUREJOBS
Researchers for hire

ASSOCIATION OF ASIA PACIFIC PHYSICAL SOCIETIES

AAPPS

Volume 23 | Number 2 | APRIL 2013 **Bulletin**

Proton Size Puzzle Reinforced

ISSN 0218 2203

Feature Articles
- Neutrino Oscillation and Mixing
- Status and Prospect of Telescope Array Experiment

Activities and Research News
- Proton Size Puzzle Reinforced
- Asia Pacific School/Workshop on Gravitation and Cosmology 2013

Institutes in Asia Pacific
- Department of Physics Yonsei University
- Department of Physics at Korea University

The proton radius puzzle in the media

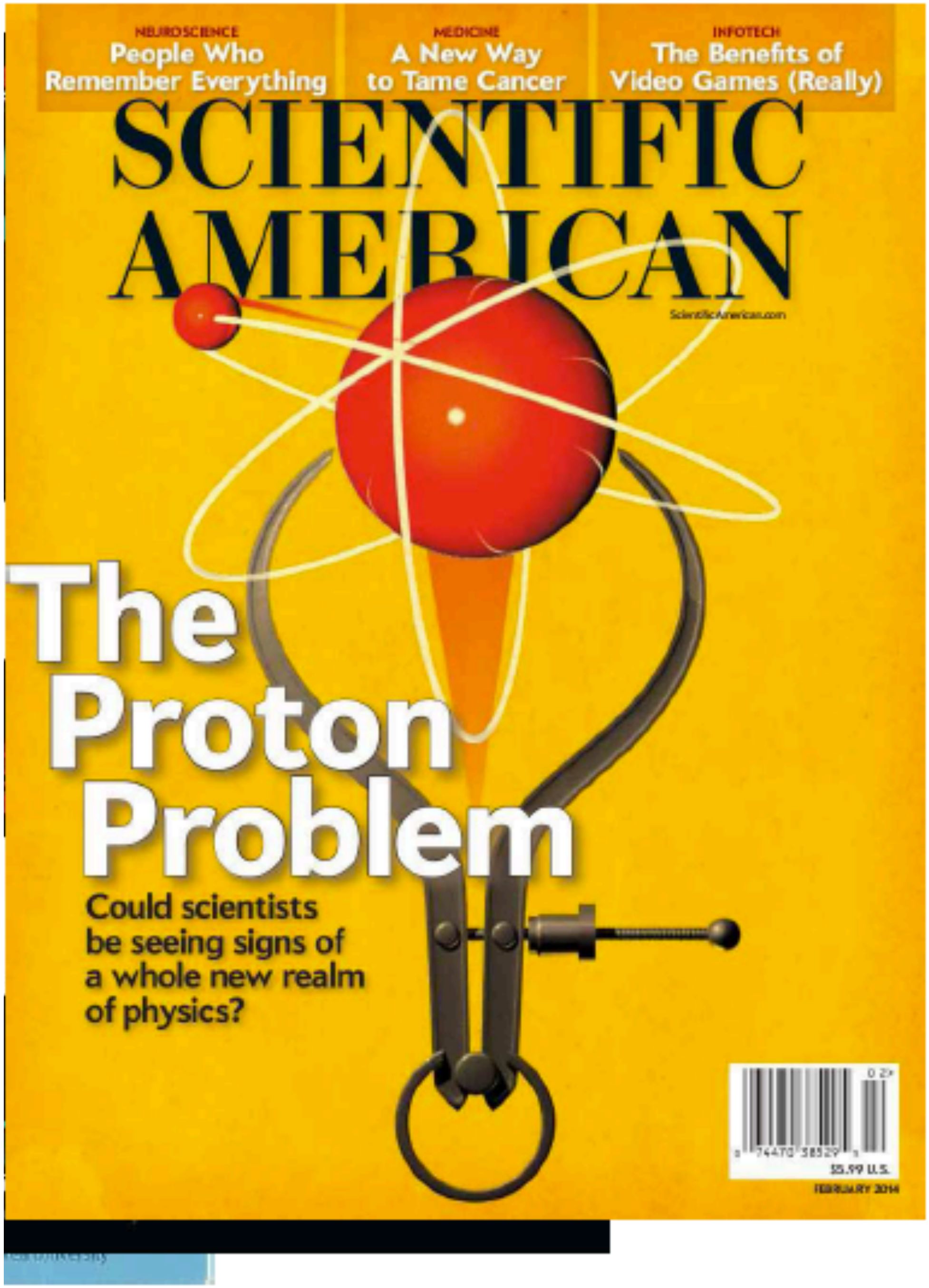
July 2013

The proton radius puzzle in the media

January 2014

The proton radius puzzle in the media

January 2014



New measurements are on their way

- **Proton Radius Workshops Trento (2012/16), Mainz (2014/18)**
- **Additional measurements needed / in preparation**
  - Spectroscopy with μD, μHe, and regular H; Rydberg constant
  - ep-, ed-scattering
    (PRad at Jlab, ISR-ep, ed elast at MAMI/A1; MAMI/A2; MESA; ProRad at Orsay; ULQ2 at Tohoku)
  - $\mu^{\pm}$p- and $e^{\pm}$p-scattering in direct comparison at PSI (MUSE) and possibly at CERN (COMPASS)
  - Searches for lepton universality violating light bosons
    (e.g. kaon decays such as TREK/E36 at J-PARC)

r_p (fm)	ep	μp
Spectroscopy	**0.8758 ± 0.077**	**0.84087 ± 0.00039**
Scattering	**0.8770 ± 0.060**	**???**

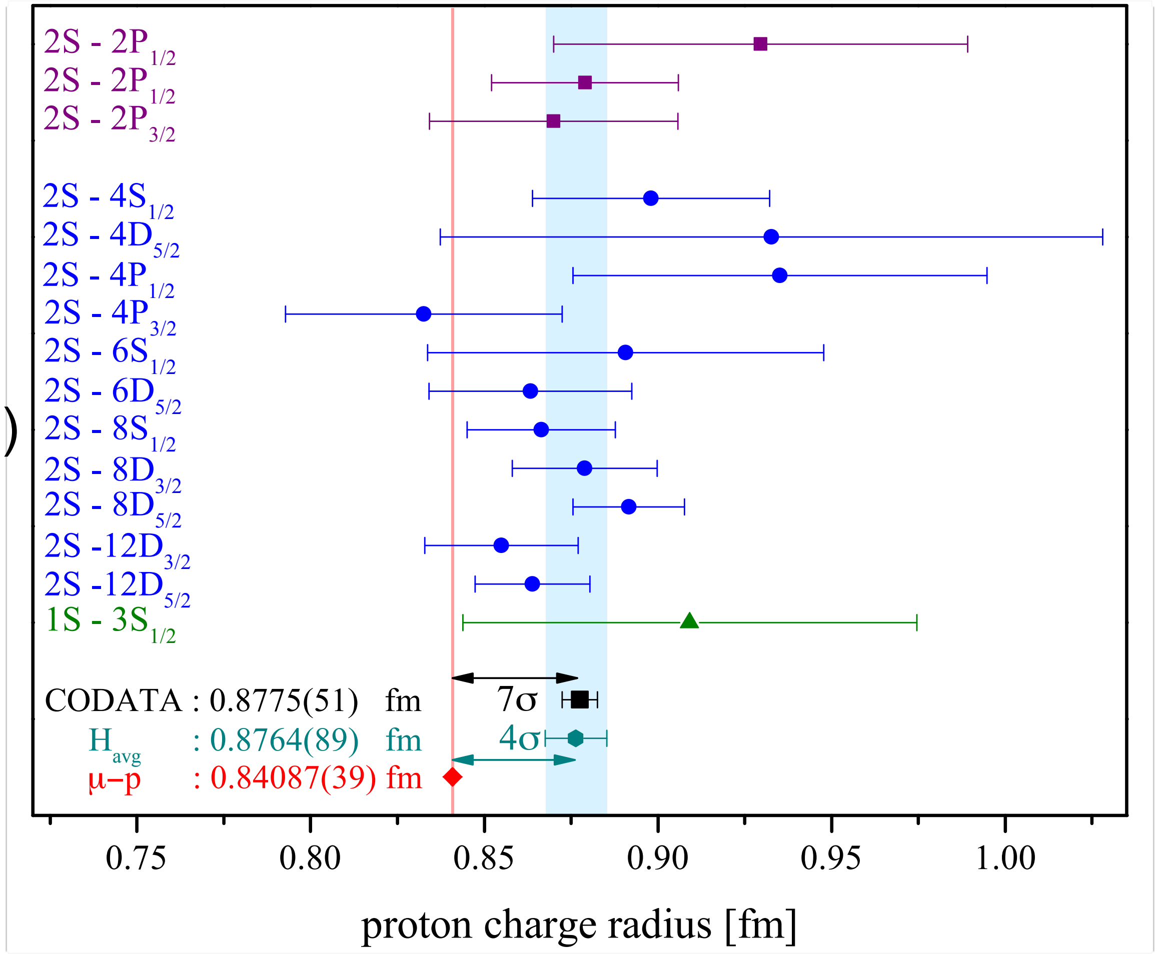
Need more precision for extraction from scattering
More insights from comparison of ep and μp scattering

New hydrogen spectroscopy

Spectroscopy of electronic Atoms and Ions:

- NPL, London: 2S-6S/D in atomic hydrogen
- MPQ, Garching:
    - 2S-4P in atomic hydrogen
    - 1S-3S in atomic hydrogen
    - He^+ (in preparation)
- LKB, Paris: 1S-3S atomic hydrogen
- YU, Toronto: 2S-2P „Lamb shift“

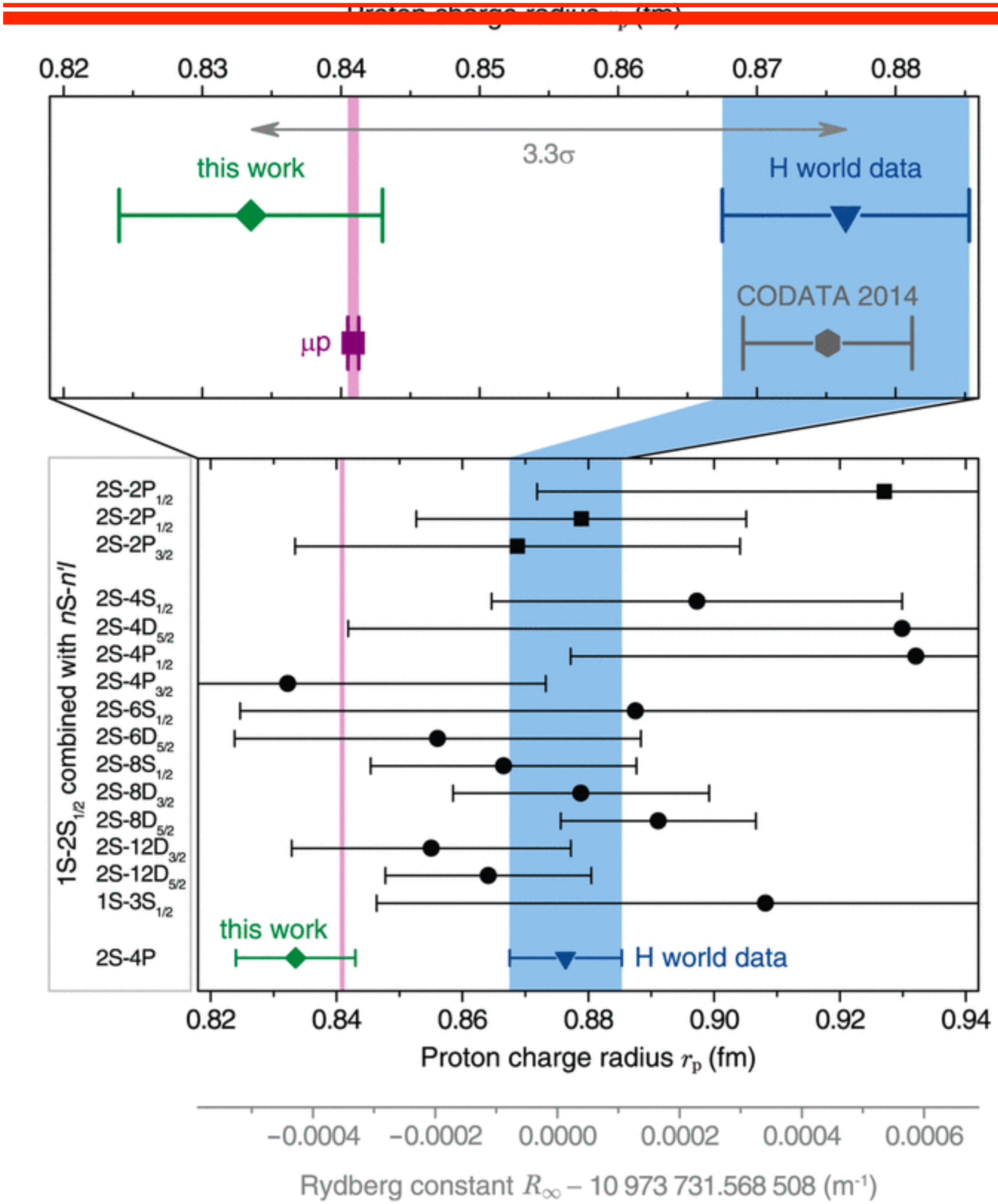
- VU, Amsterdam: He^+ (in preparation)
- NIST, Gaithersburg: highly charged ions



Spectroscopy of exotic atoms:

- ETH, Zurich (in preparation):
    - positronium (e^+e^-)
    - muonium (μ^+e^-)
- PSI, Villigen: μHe^+

New spectroscopy results: 2S-4P (Garching)



A. Beyer, L. Maisenbacher,
A. Matveev, R. Pohl, K. Khabarova,
A. Grinin, T. Lamour, D.C. Yost,
Th. Hänsch, N. Kolachevsky,
and Th. Udem,
Science 358, 79 (Oct. 6, 2017)

$\delta\nu \sim \Gamma / 10^4$

→ Small radius

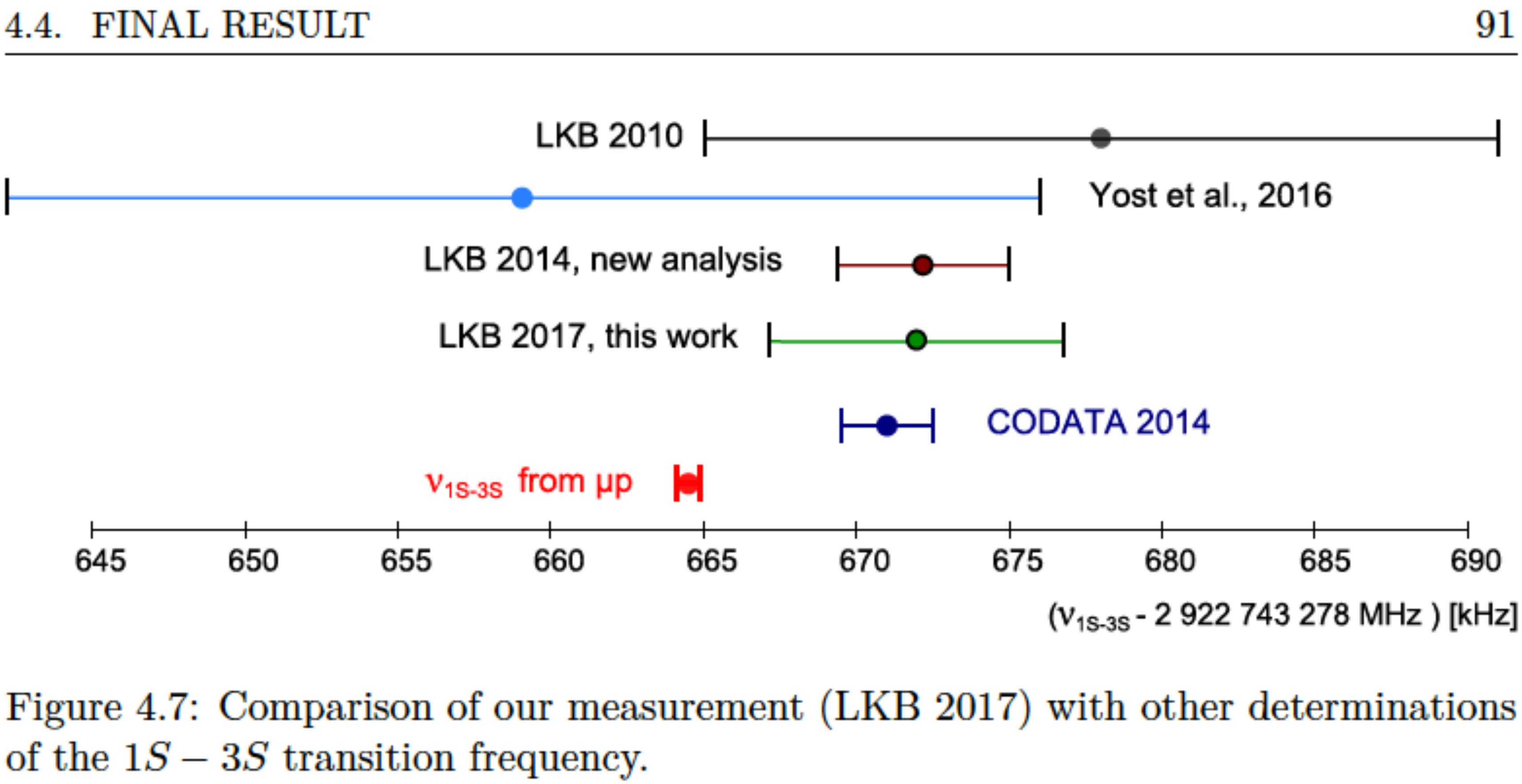
Puzzle solved?

No!

Puzzling?

Confusing?

New spectroscopy results: 1S-3S (Paris)



4.4. FINAL RESULT 91

Figure 4.7: Comparison of our measurement (LKB 2017) with other determinations of the $1S - 3S$ transition frequency.

Hélène Fleurbaey, *Frequency metrology of the 1S-3S transition of hydrogen: contribution to the proton charge radius puzzle,*
Université Pierre et Marie Curie (UPMC), 2017,
https://tel.archives-ouvertes.fr/tel-01633631

Combined with 1S-2S: R_p = 0.8799 +- 0.0138 fm → Large Radius!
(R. Pohl, private communication)

Motivation for μp scattering

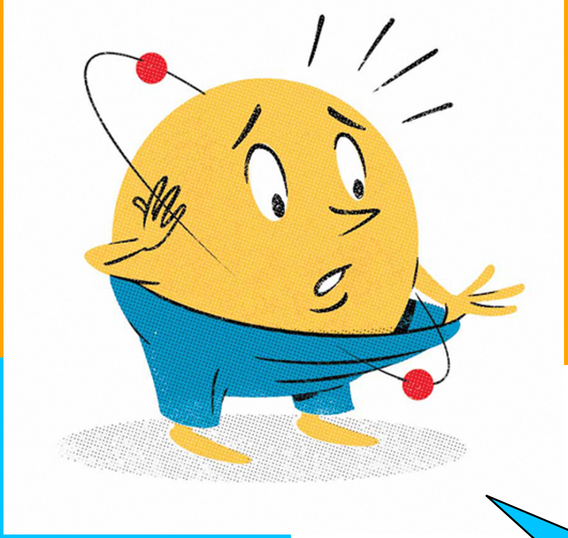
Spectroscopy

Electronic hydrogen

0.8758 ± 0.0077

Muonic hydrogen

0.84184 ± 0.00067
0.84087 ± 0.00039



Scattering

Electron scattering

0.8770 ± 0.0060

Muon scattering

???

Idea for MUSE developed by R. Gilman, G. Miller, and M.K. at PINAN2011, Morocco

Possible resolutions to the puzzle

- **The μp (spectroscopy) result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from muonic Lamb shift measurement
- **The ep (spectroscopy) results are wrong**
  Accuracy of individual Lamb shift measurements?
  Rydberg constant could be off by 5 sigma
- **The ep (scattering) results are wrong**
  Fit procedures not good enough
  Q^2 not low enough, structures in the form factors
- **Proton structure issues in theory**
  Off-shell proton in two-photon exchange leading to enhanced effects differing between μ and e
  Hadronic effects different for μp and ep:
  e.g. proton polarizability ($\mathit{effect} \propto m_l^4$)
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation, light massive gauge boson
  Constraints on new physics e.g. from kaon decays (TREK@J-PARC)

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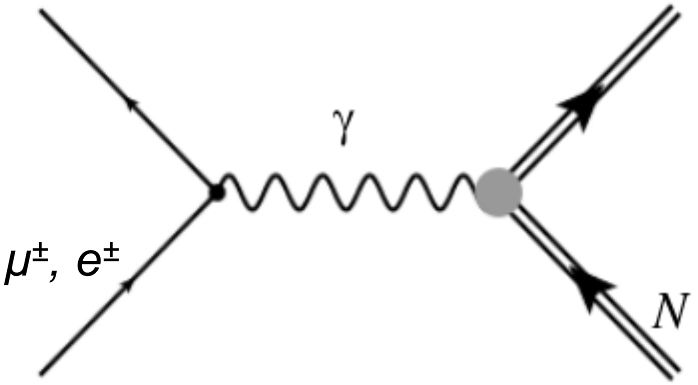
MUSE
will test

Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

$$J_e^\mu = -e\overline{u}_e\gamma^\mu u_e$$

$$J_N^\mu = \overline{\psi}_N\left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2M_N}\right]\psi_N$$

F_1, F_2 are the Dirac and Pauli form factors

Sachs form factors:

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

Fourier transform (in the Breit frame) gives spatial charge and magnetization distributions

Derivative in $Q^2 \rightarrow 0$ limit:

$$\begin{aligned} \langle r_E^2 \rangle &= -6\frac{dG_E^p(Q^2)}{dQ^2}\bigg|_{Q^2\to 0} \\ \langle r_M^2 \rangle &= -6\frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\bigg|_{Q^2\to 0} \end{aligned}$$

Expect identical behavior for any charged lepton – e±, μ±

MUSE: MUon Scattering Experiment at PSI

Use the world's most powerful low-energy separated e/π/μ beam for a direct test if μp and ep scattering are different:

- Simultaneous, separated beam of (e+/π+/μ+) or (e-/π-/μ-) on liquid H_2 target

→ Separation by time of flight

→ Measure absolute cross sections for ep and μp

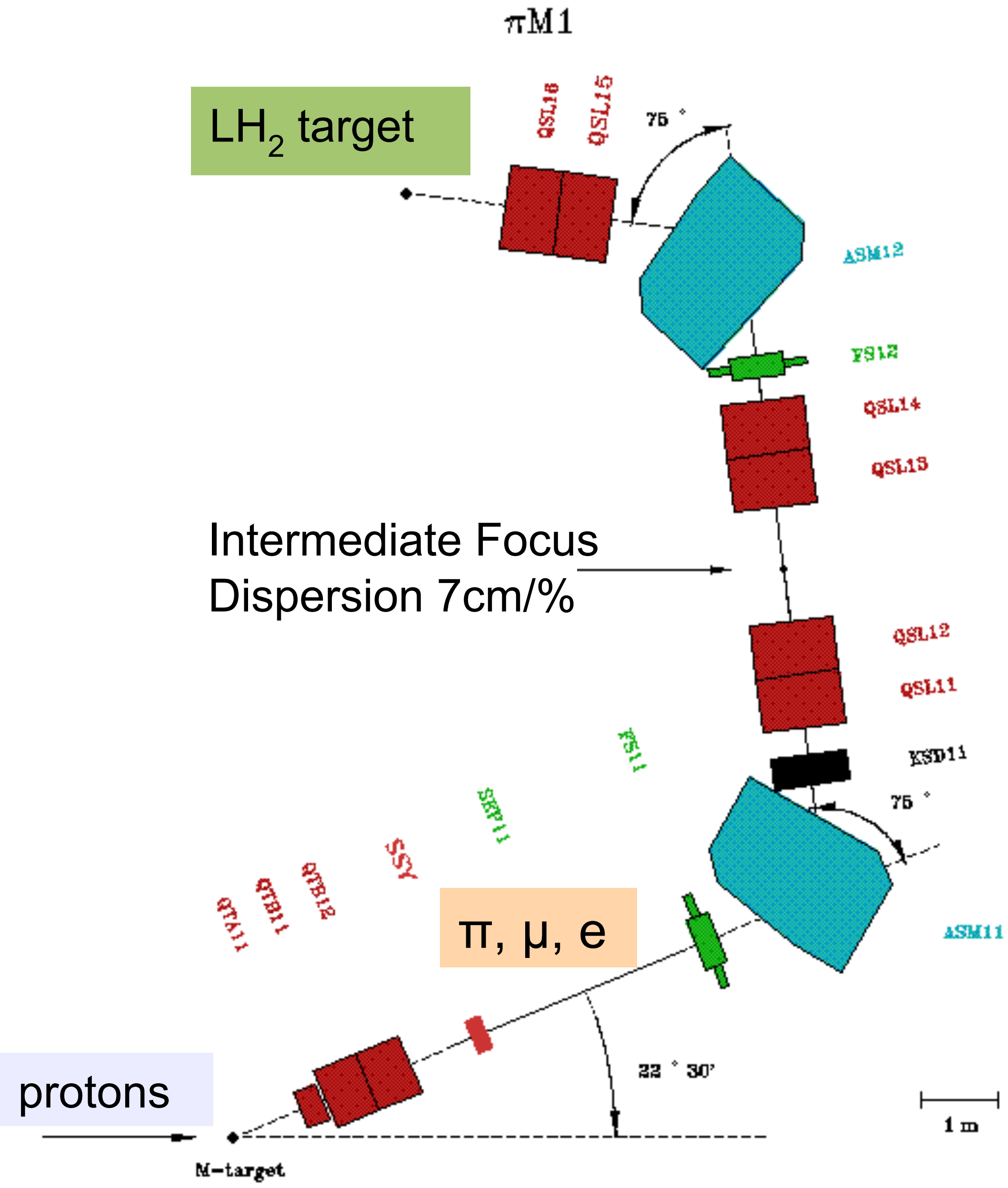
→ Measure e+/μ+, e-/μ- ratios to cancel certain systematics

→ If radii differ by 4%, then form factor slope by 8%, x-section slope by 16%

- Directly disentangle effects from two-photon exchange (TPE) in e+/e-, μ+/μ-
- Multiple beam momenta 115-210 MeV/c to separate G_E and G_M (Rosenbluth)

πM1 / MUSE beamline

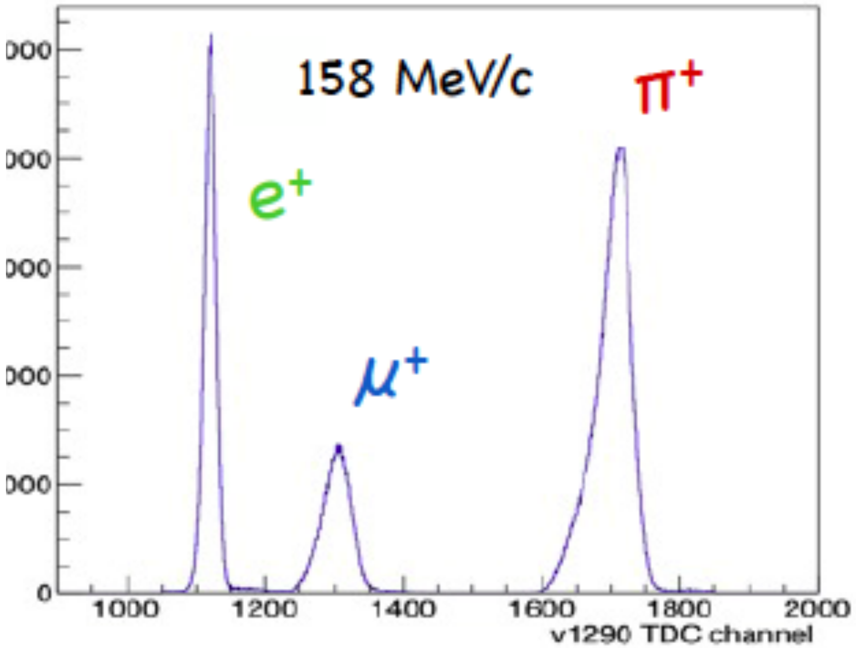
- πM1: 100-500 MeV/c RF+TOF sep. π, μ, e

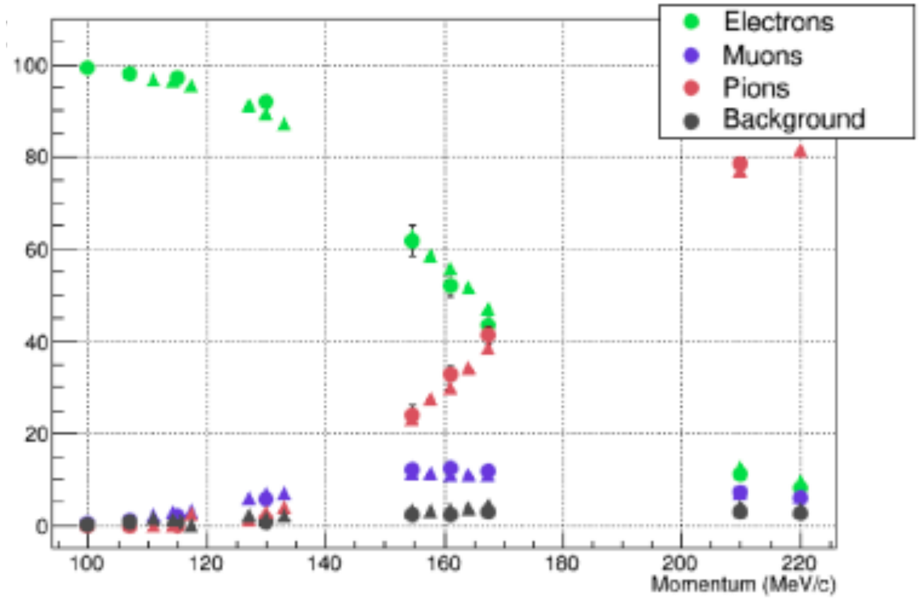

LH$_2$ target

Intermediate Focus
Dispersion 7cm/%

π, μ, e

protons





MUSE experiment layout

- Beam particle tracking
- Liquid hydrogen target
- Scattered lepton detection

Measure $e^{\pm}p$ and $\mu^{\pm}p$ elastic scattering

p = 115, 153, 210 MeV/c

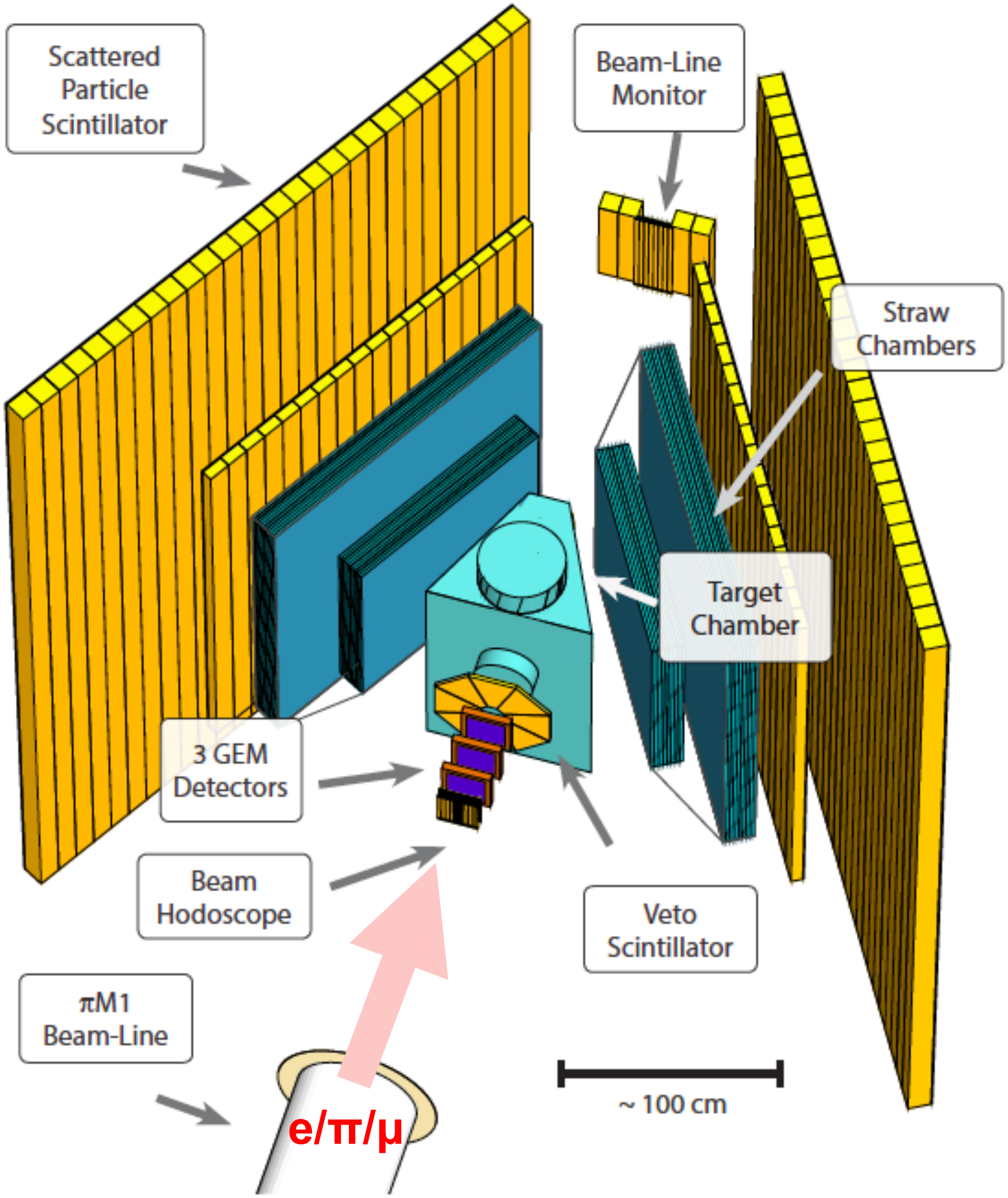
$\theta = 20^o$ to 100^o

$Q^2 = 0.002 - 0.07\ (GeV/c)^2$

$\varepsilon = 0.256 - 0.94$

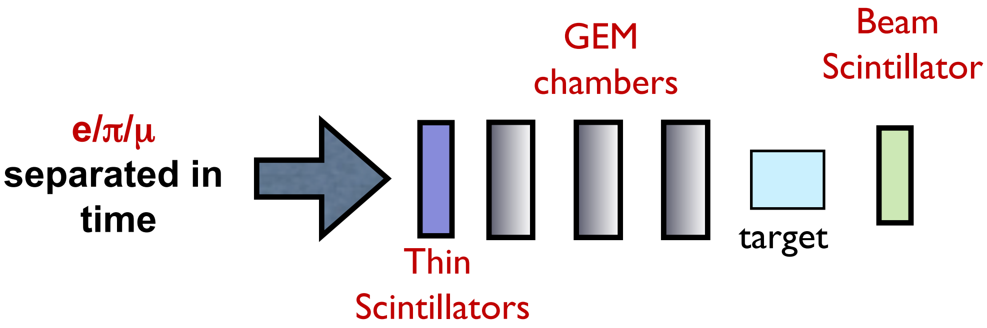
Challenges

- Secondary beam with π background – PID in trigger
- Non-magnetic spectrometer
- Background from Møller scattering and muon decay in flight



Beamline instrumentation

Beamline Elements:

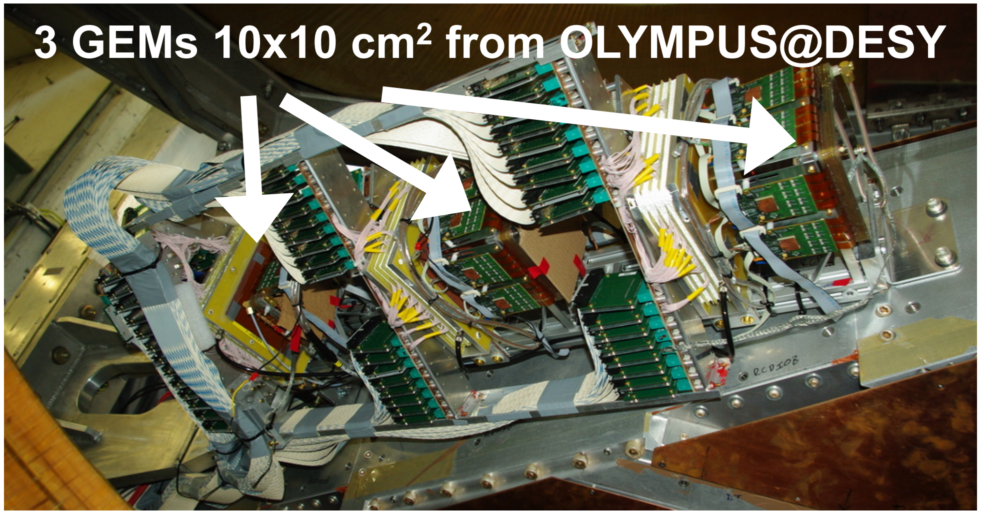


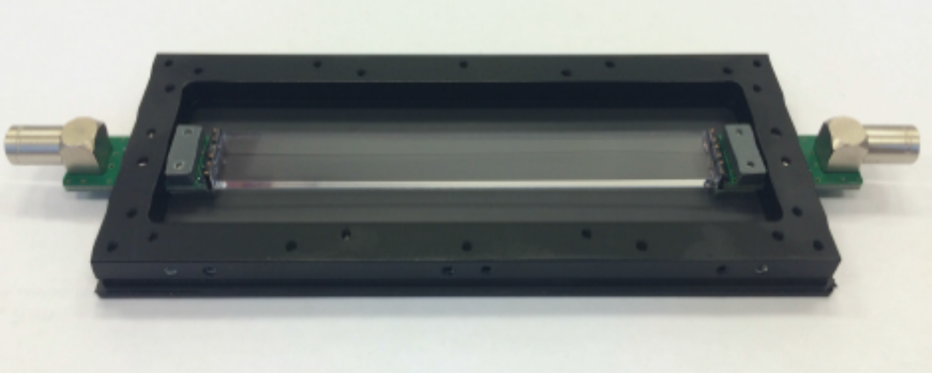
GEM telescope (Hampton University)

→ Incident track angle to ~0.5 mr intrinsic; <5 mr mult.sc.

→ Third GEM to reject ghost tracks

→ Existing chambers from OLYMPUS


3 GEMs 10x10 cm^2 from OLYMPUS@DESY


SiPM + 2 mm thin scintillators

Thin scintillators with SiPM+CFD readout (PSI/Rutgers/TAU):

→ Fast timing (~60ps): RF time and scattered particle TOF

→ Flux, PID, Trigger, TOF, momentum

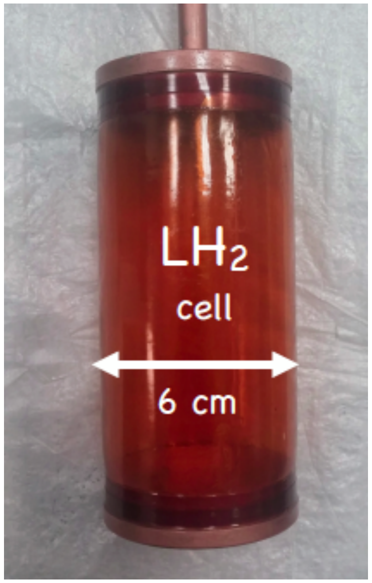
→ Reject false tracks in GEMs

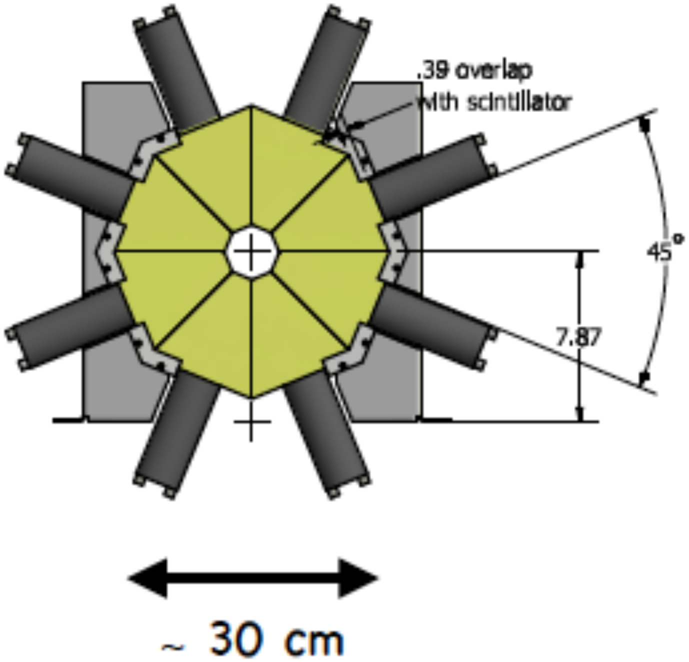
Target and veto

Low-power liquid hydrogen target

(UMich, Creare, PSI)

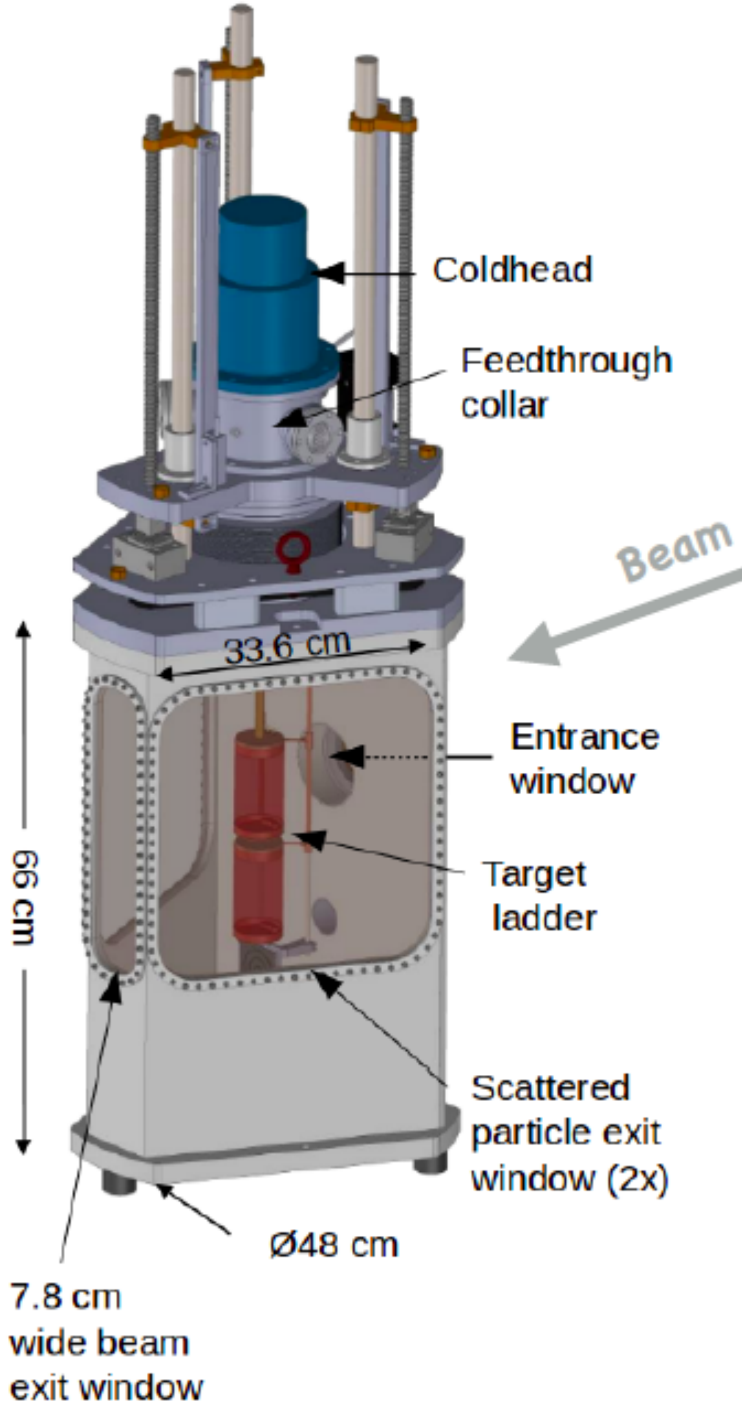
Target cell prototype





Veto scintillators (USC):

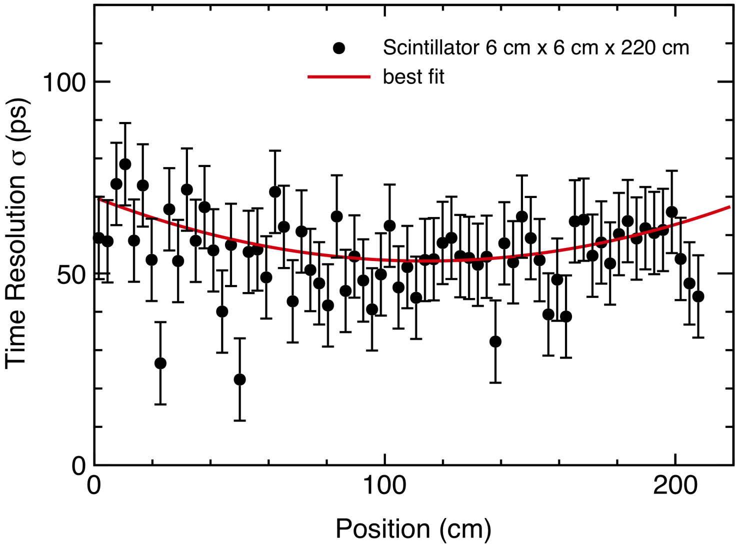
Annullar veto ring defines accepted beam aperture, smaller than transverse target cell diameter (6 cm)

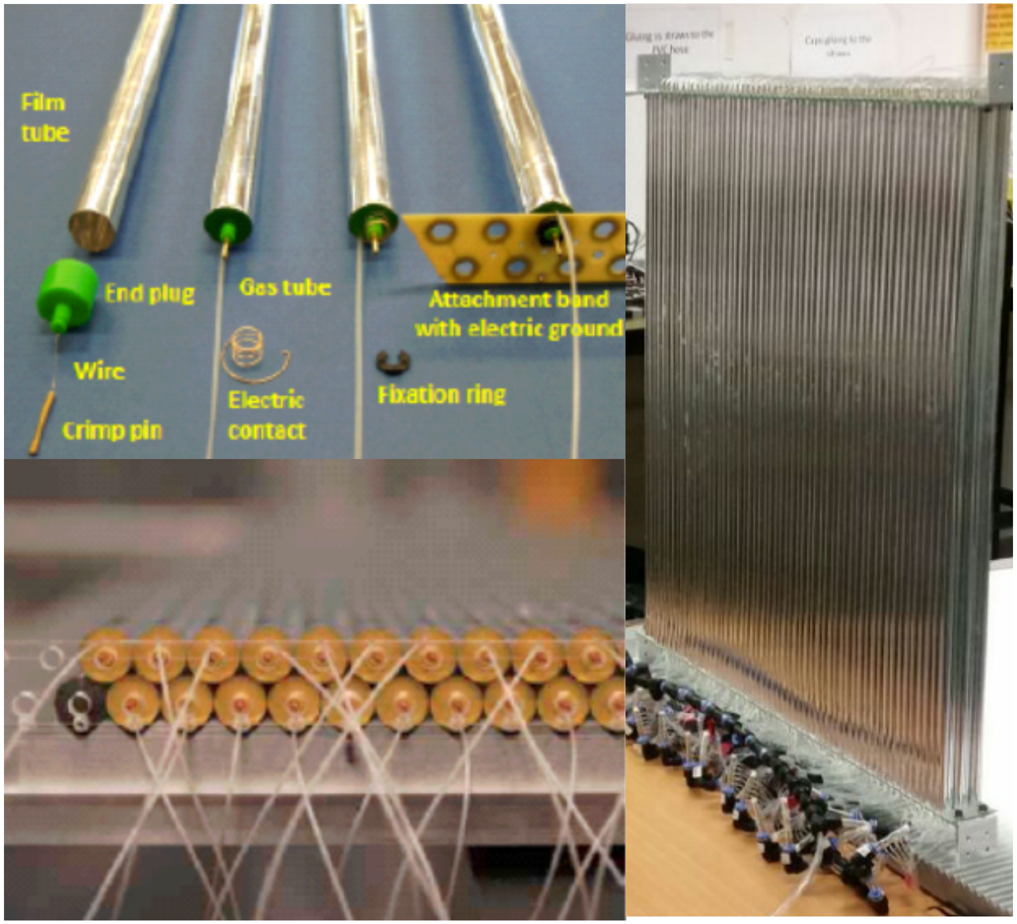


Main detector instrumentation

University of South Carolina:

- 2 planes of scintillators (CLAS12 design)
- 94 bars (2 sides + beam)
- High precision (~50 ps) timing
- PID and trigger, background rejection





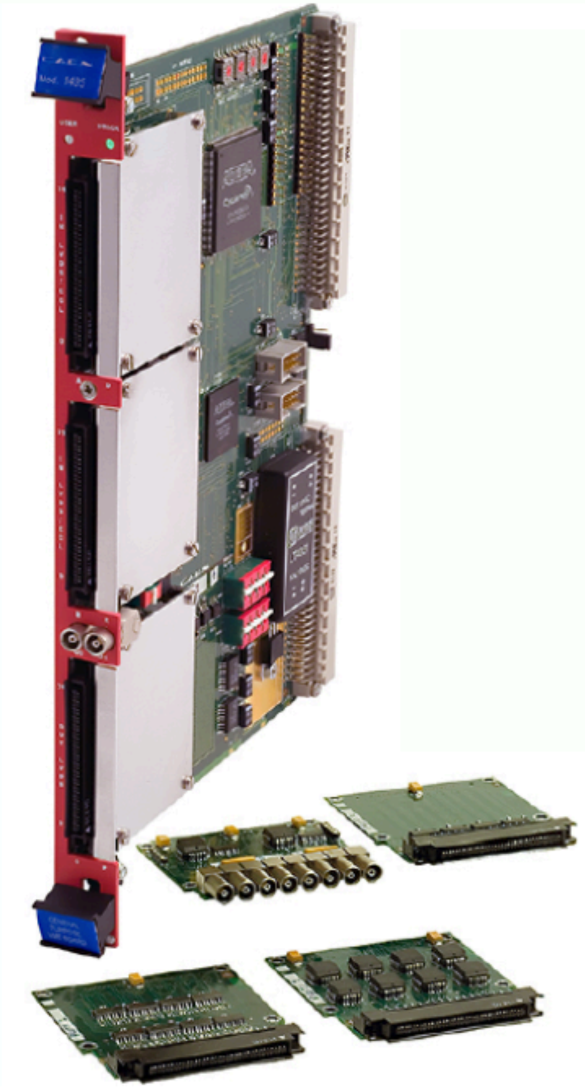
HUJI & Temple:

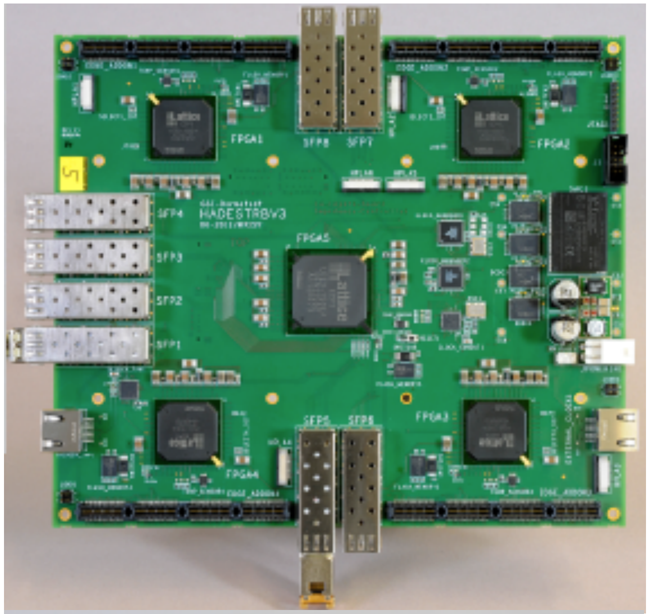
- Straw Tube Tracker (STT), ~3000 straws
- Determine scattered particle trajectory
- Existing PANDA design – 140 μm resol.
- Thin walls (25μm), overpressured (2 bar)
- Directly coupled to fast readout boards

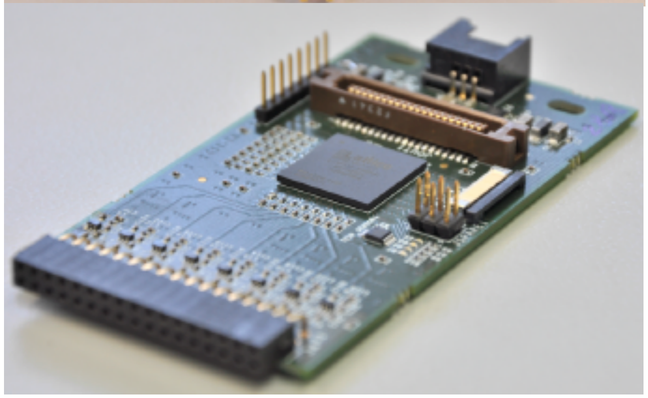
Trigger and DAQ

GWU, Montgomery College & Rutgers:

- FPGA design for beam PID (TRB or v1495)
- Beam scintillator + beam RF → beam PID
- Count particles and reject pions
- e or μ beam part. + scattered part. + no veto



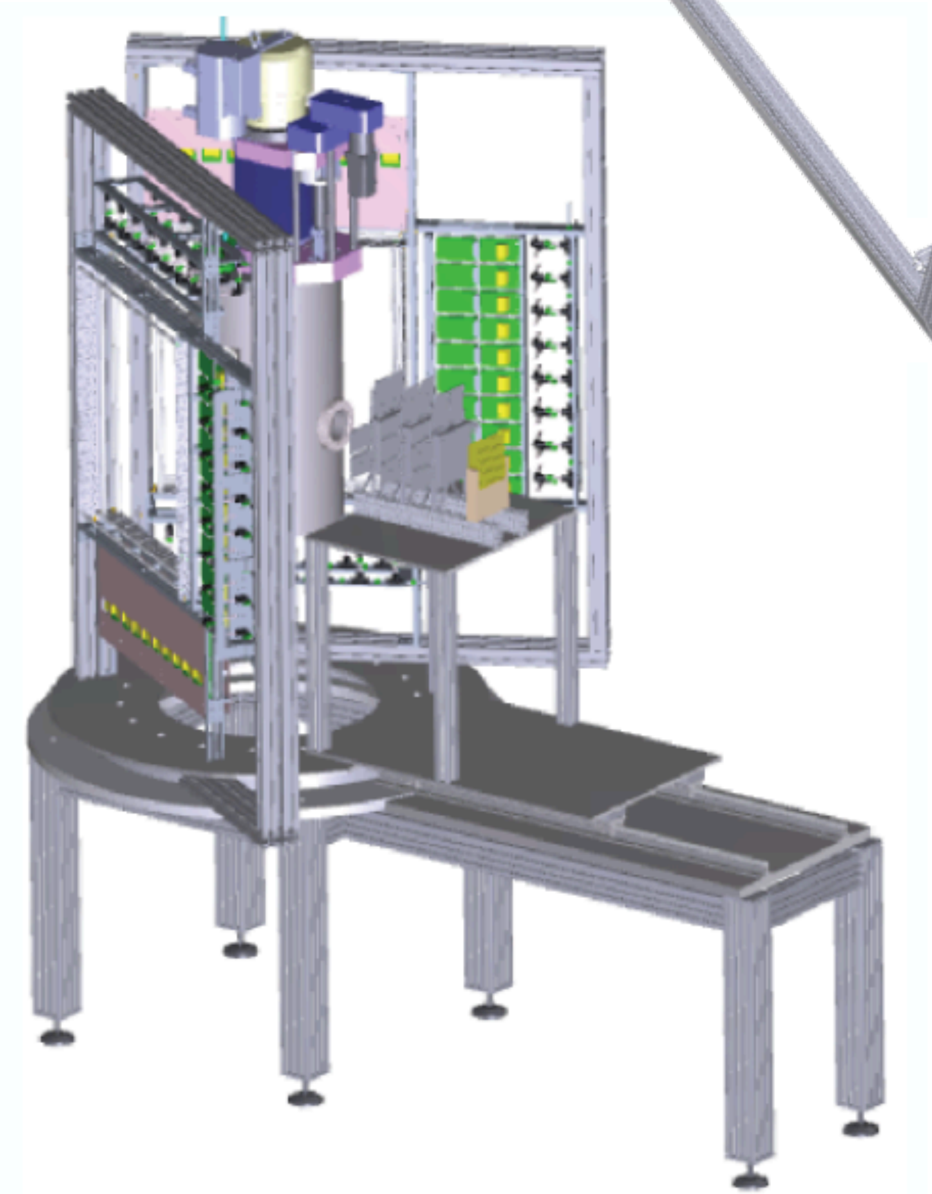


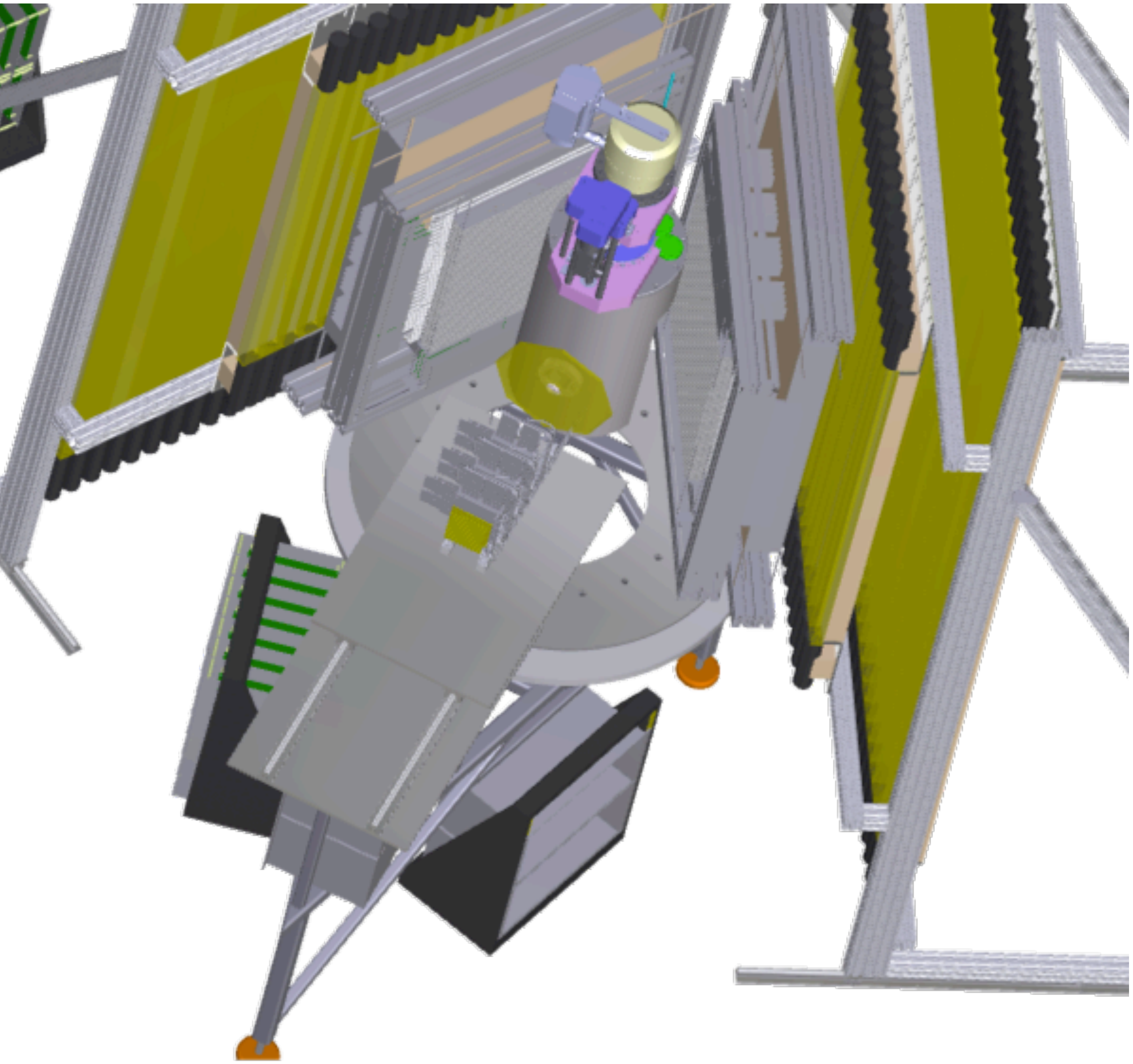


- Custom signal splitters
- FPGAs as front end discriminator/amplifier, custom designed TDCs (PADIWA/TRB3)
- High channel density (192ch/board)
- VME QDCs (MESYTEC)

Mechanical assembly

T. O’Connor (ANL)

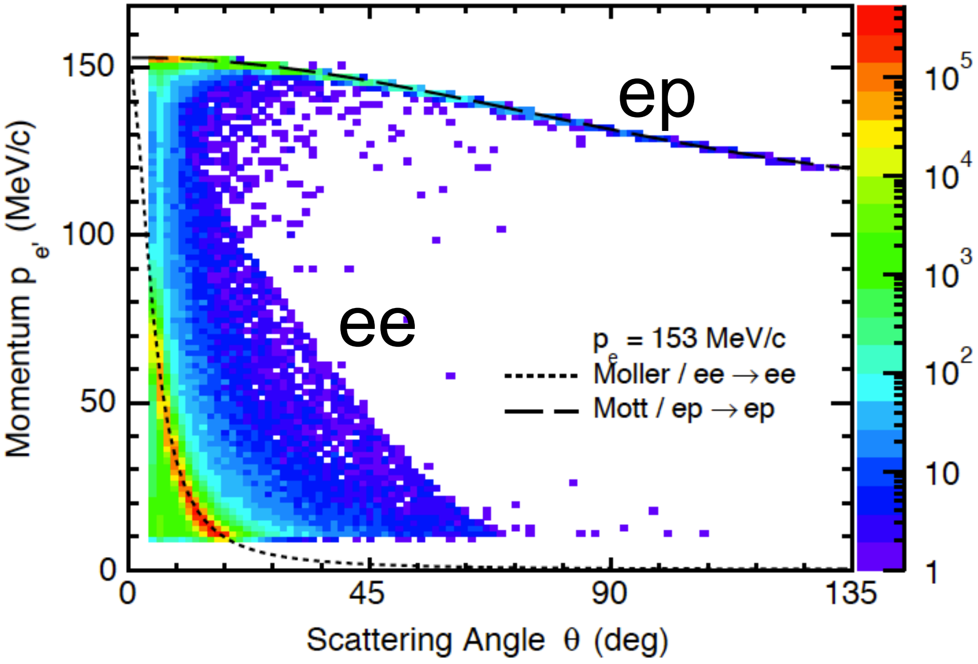


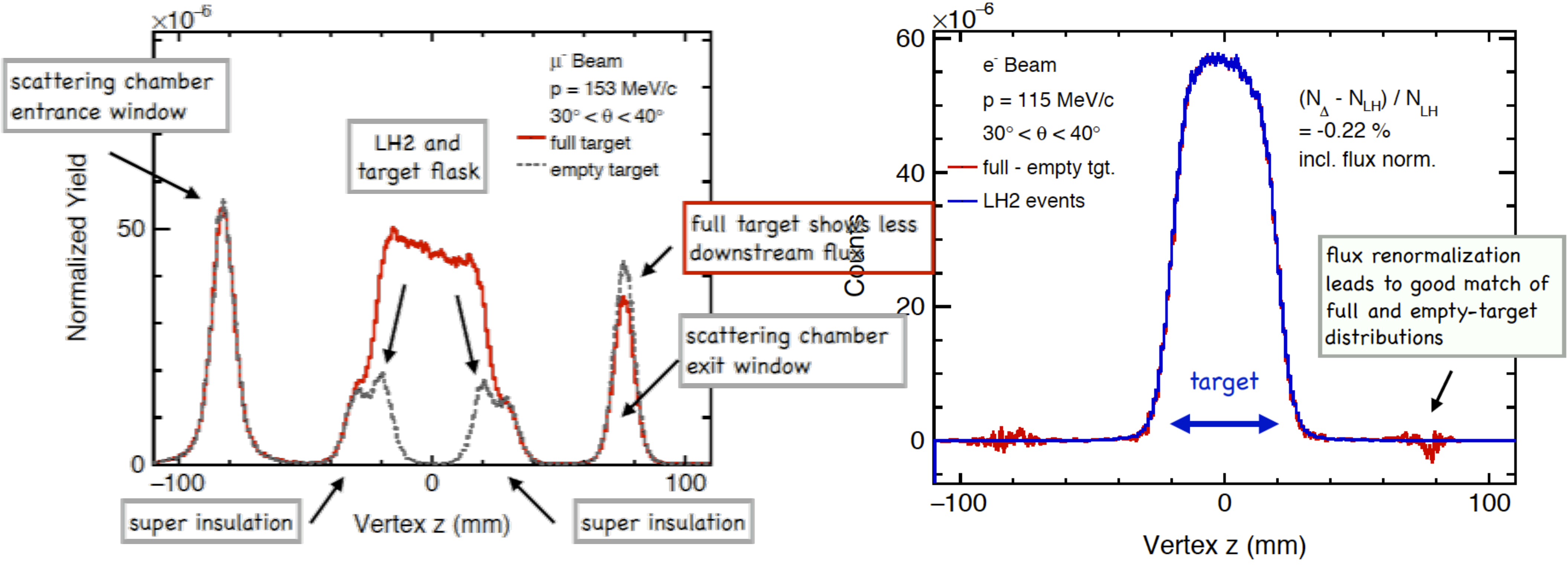


Rotating table
Retractable beam tracker
Dedicated alignment procedures

Simulations (S. Strauch, USC)

- Particle vertex and scattering-angle reconstruction meet MUSE requirements
- Background from target walls and windows can be cleanly eliminated or subtracted





scattering chamber entrance window

LH2 and target flask

full target shows less downstream flux

scattering chamber exit window

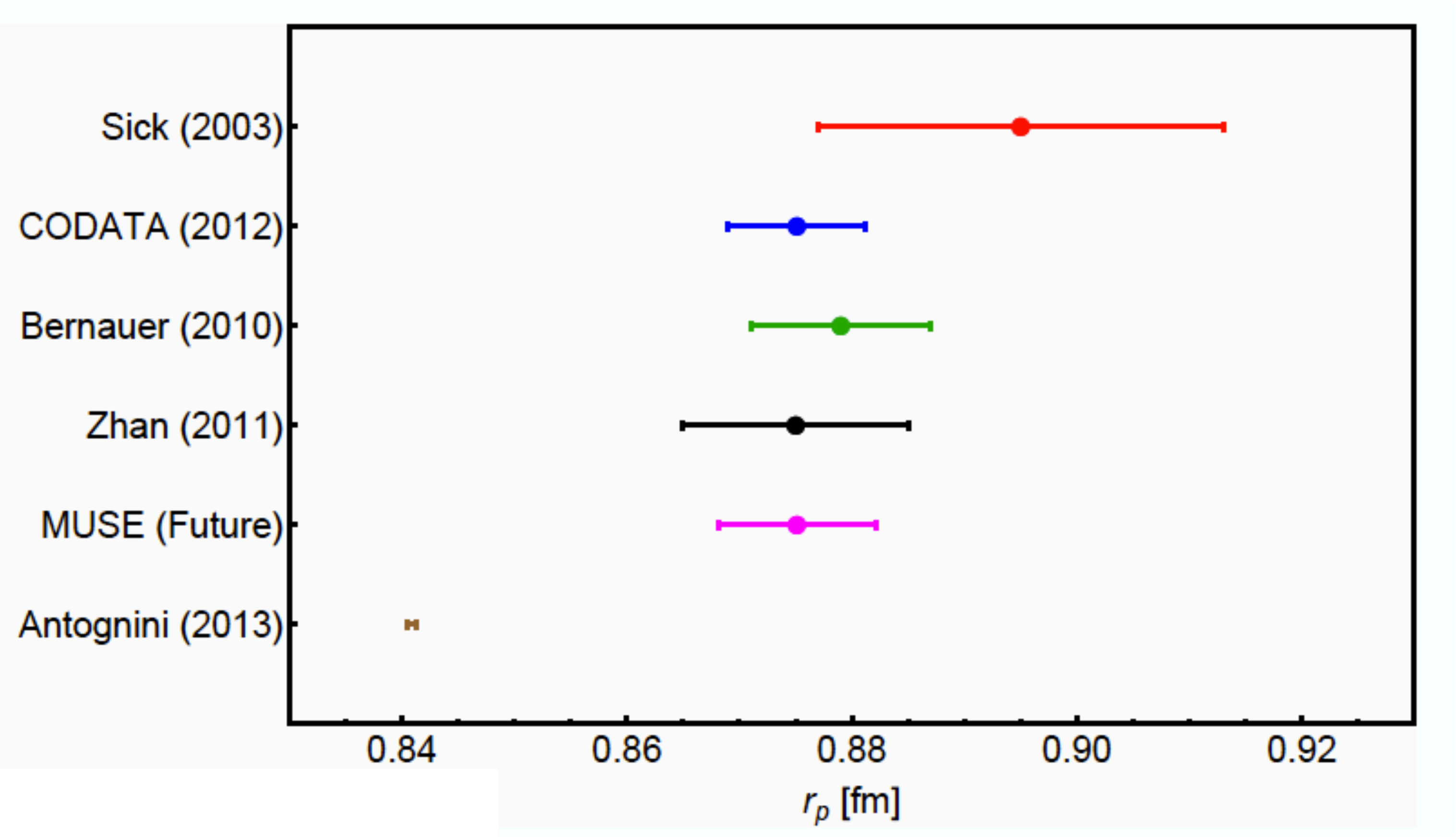
super insulation

super insulation

flux renormalization leads to good match of full and empty-target distributions

Projected sensitivity for MUSE

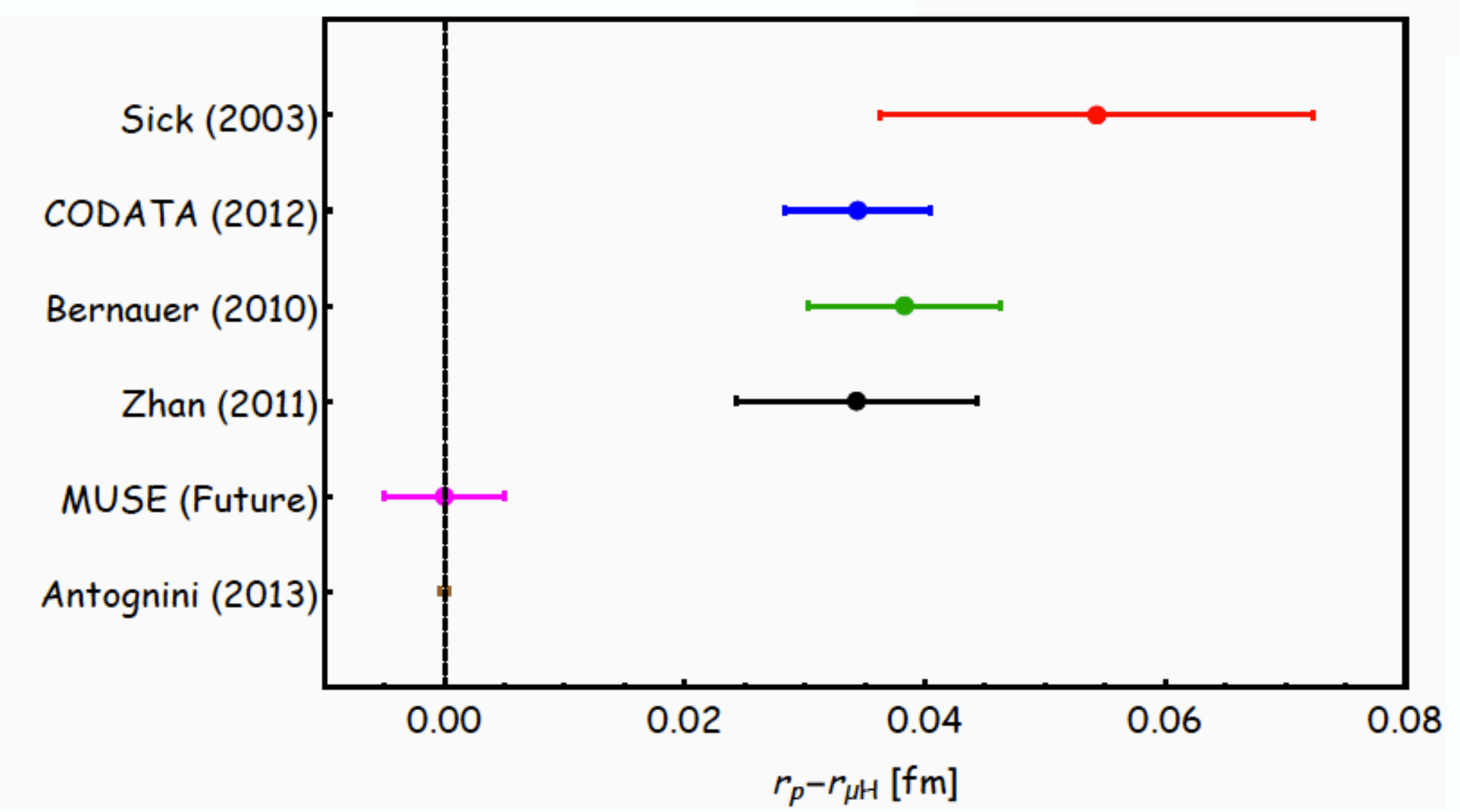
- **Cross sections** to <1% stat. for backward μ, <<1% for e and forward μ Absolute 2%, point-to-point relative uncertainties **few x10^{-3}**
- **Individual radius extractions** from $e^{\pm}$, $\mu^{\pm}$ each to **0.010 fm**
- Compare $e^{\pm}p$ and $\mu^{\pm}p$ for TPE. Charge-average to eliminate TPE.
- From e/μ xsec ratios: extract **e-μ radius difference** with minimal truncation error to **0.0045 fm or ~8σ** (1st-order fits)
- If no difference, extract **combined radius to 0.007 fm** (2nd-order fit)



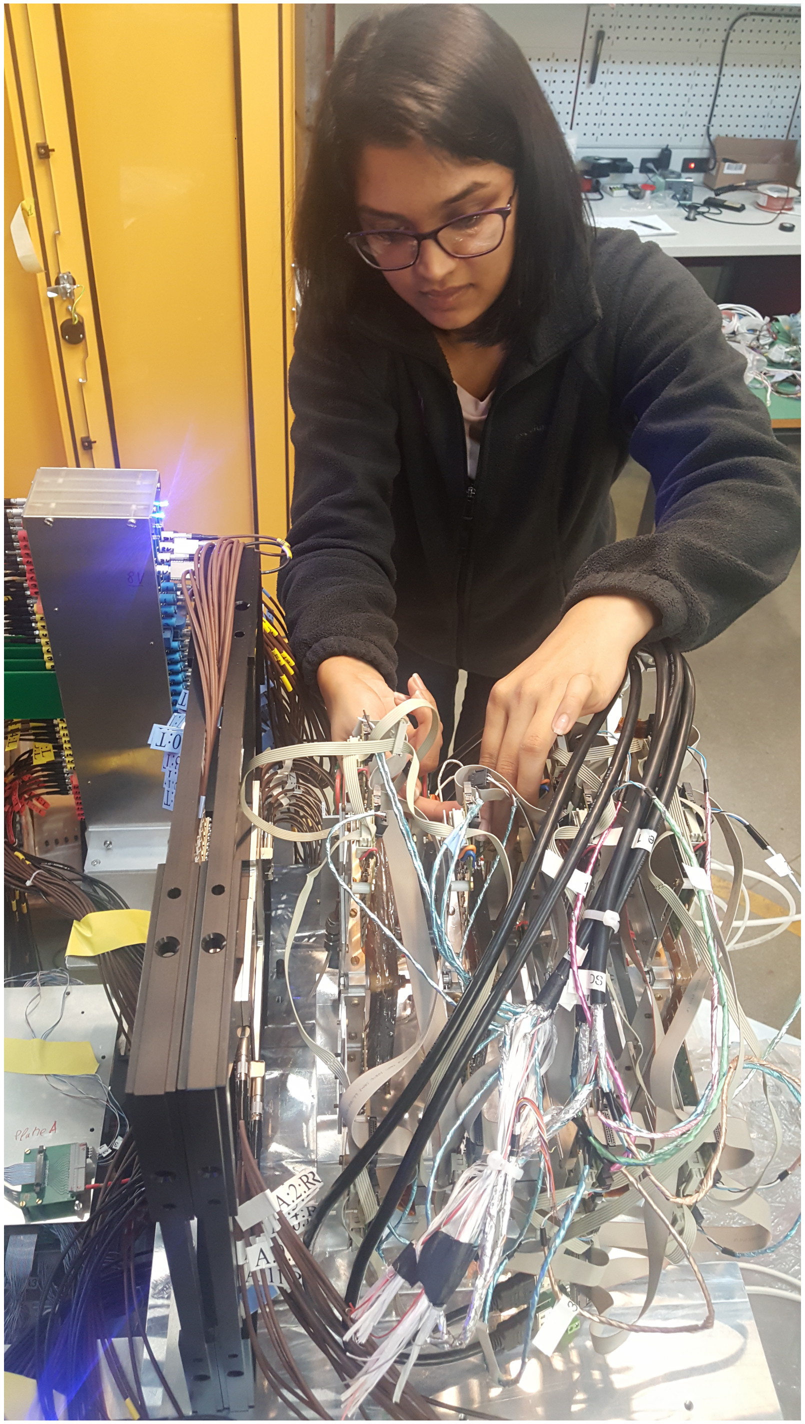
Projected sensitivity for MUSE

- Charge radius extraction limited by systematics, fit uncertainties
- Many uncertainties are common to all extractions in the experiment: Cancel in e+/e-, μ+/μ-, and μ/e comparisons
- R_e-R_μ = 0.034±0.006 fm (5.6σ), **MUSE: δ(R_e-R_μ) = 0.0045 fm (7.6σ)**

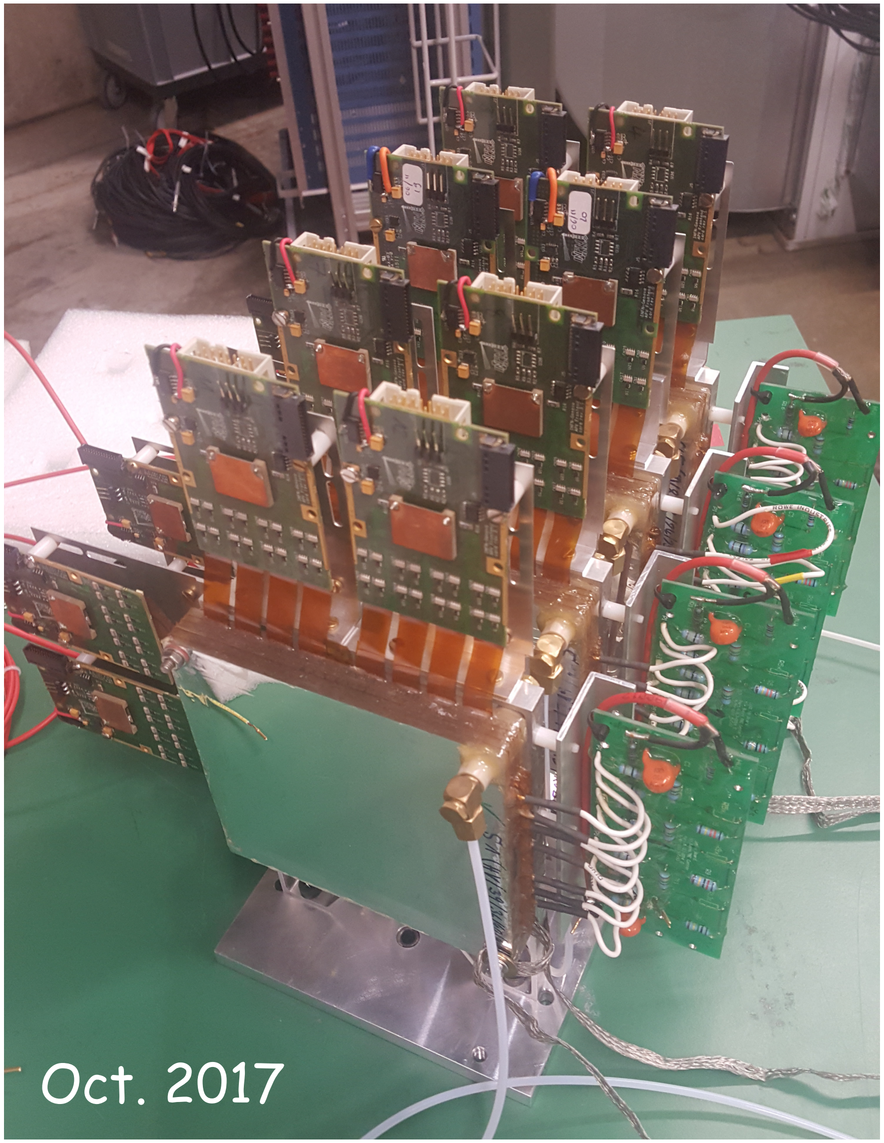
MUSE suited to verify 5.6σ effect (CODATA2014) with 7.6σ significance



Fall 2017 installation and commissioning



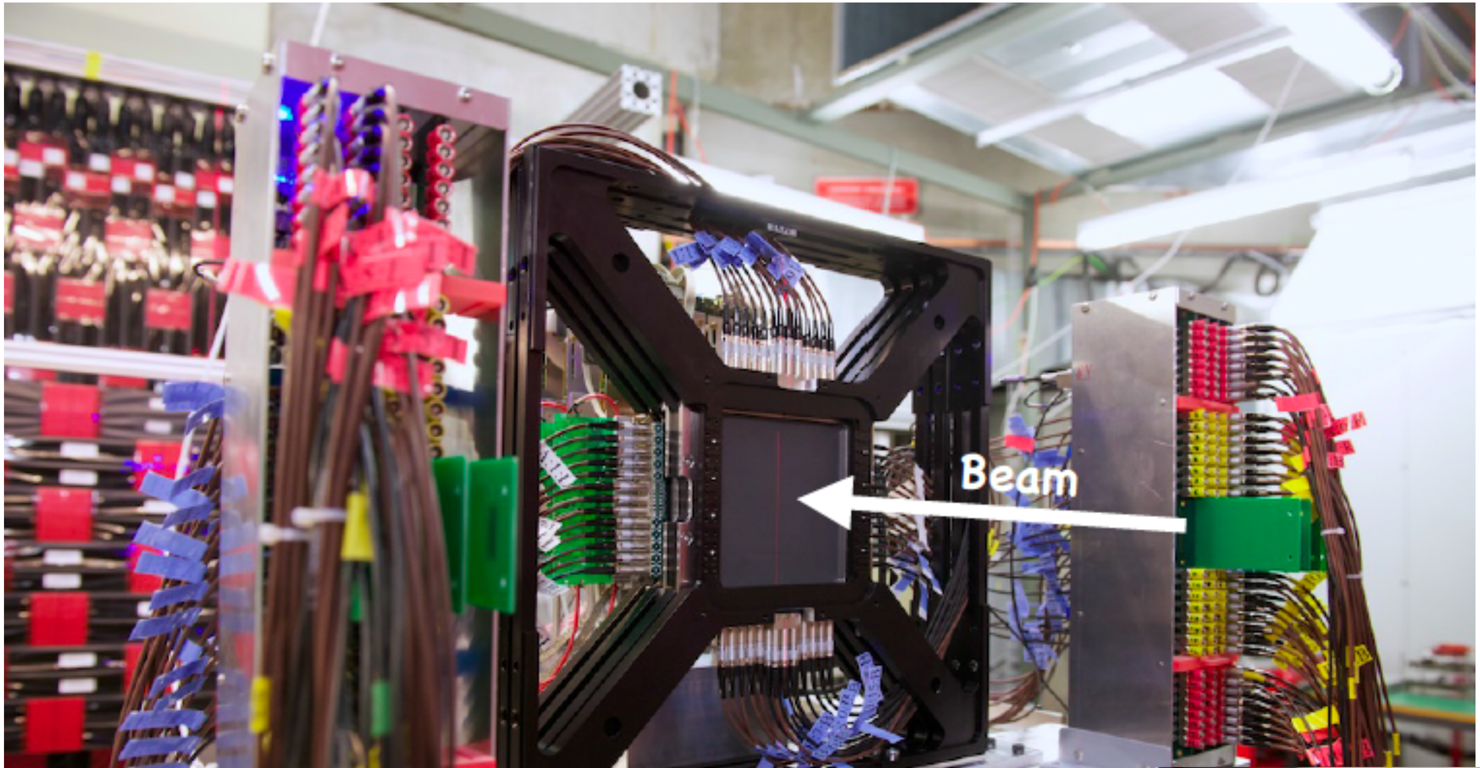
Telescope extended to 4 GEMs
~75 μm resolution, >98% efficiency



Oct. 2017

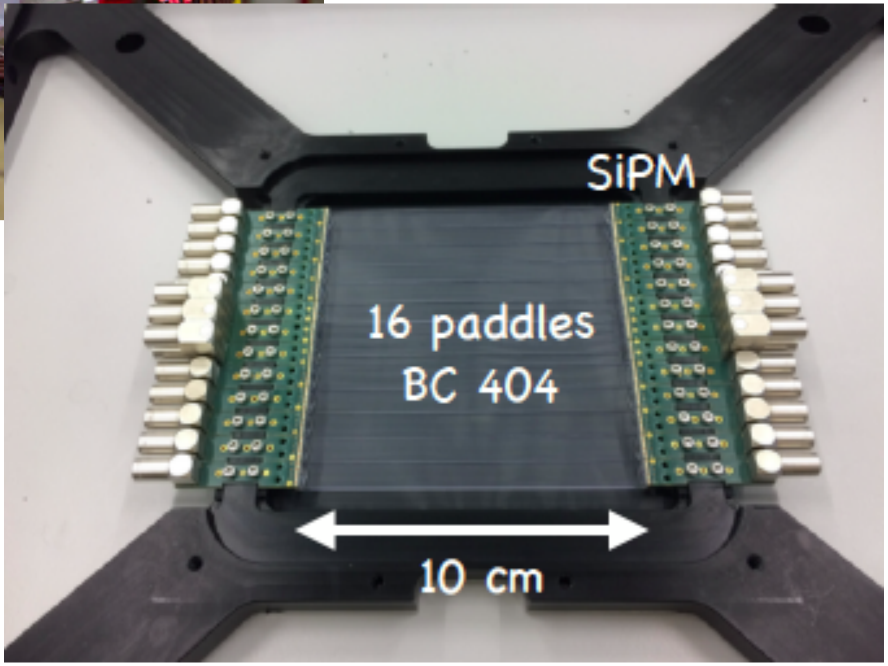
Tanvi Patel (Hampton U.)

Fall 2017 installation and commissioning

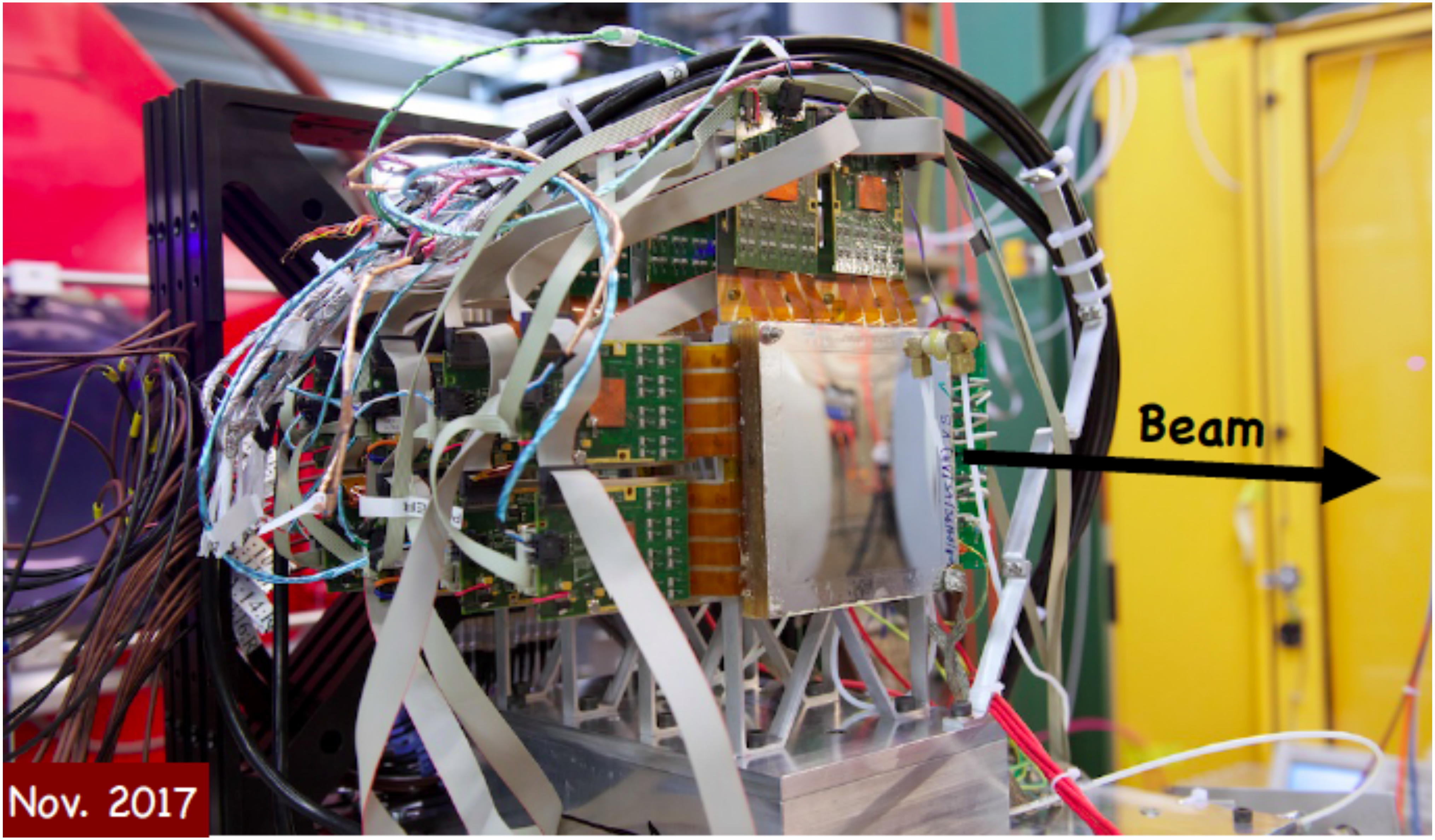


TAU, Rutgers, PSI

Beam hodoscope:
4(2) layers of narrow thin scintillators
Resolution ~80 ps, efficiency 99.8%

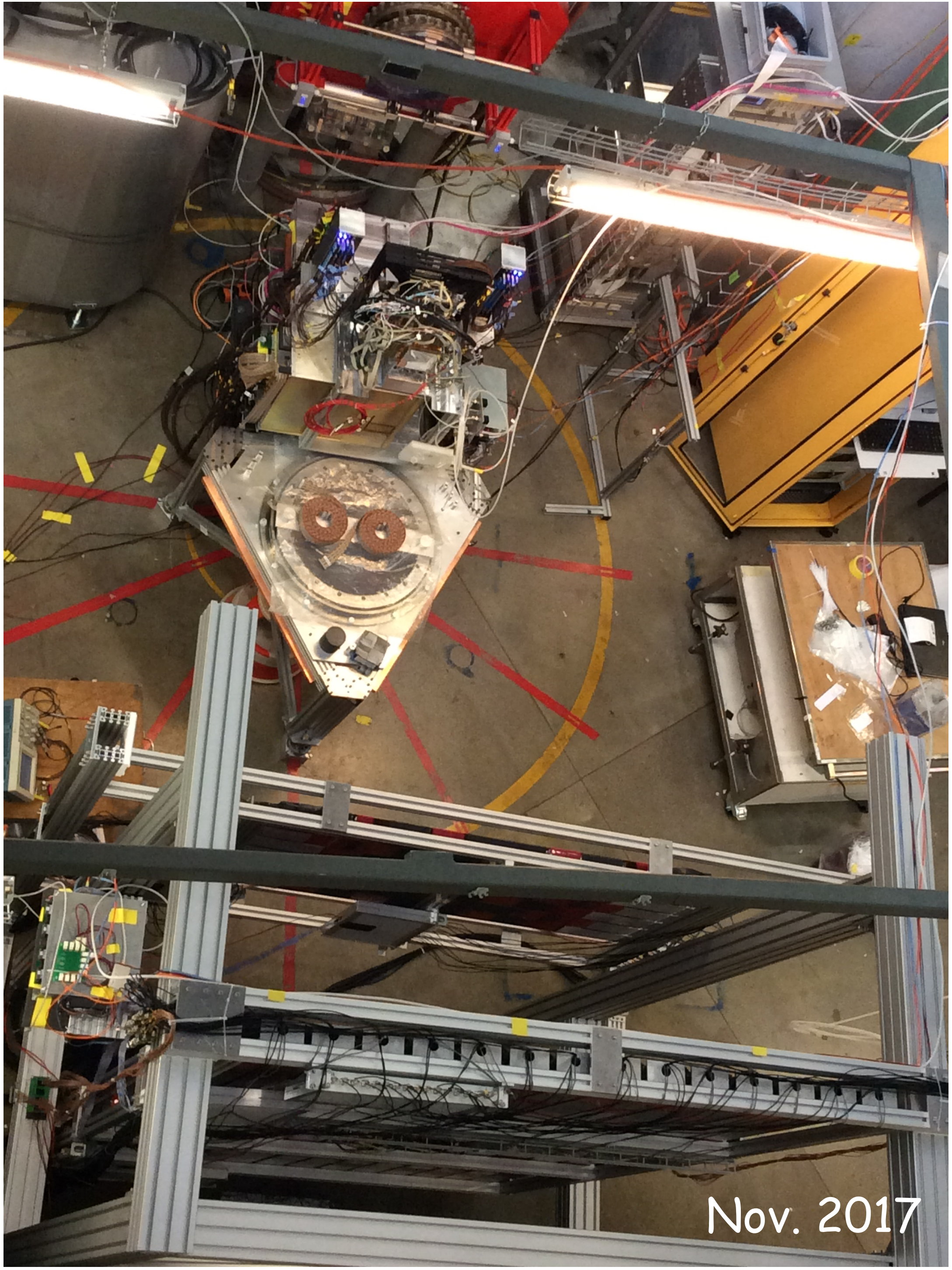


Fall 2017 installation and commissioning



Data taking with beam line elements: location and timing of tracks

Fall 2017 installation and commissioning

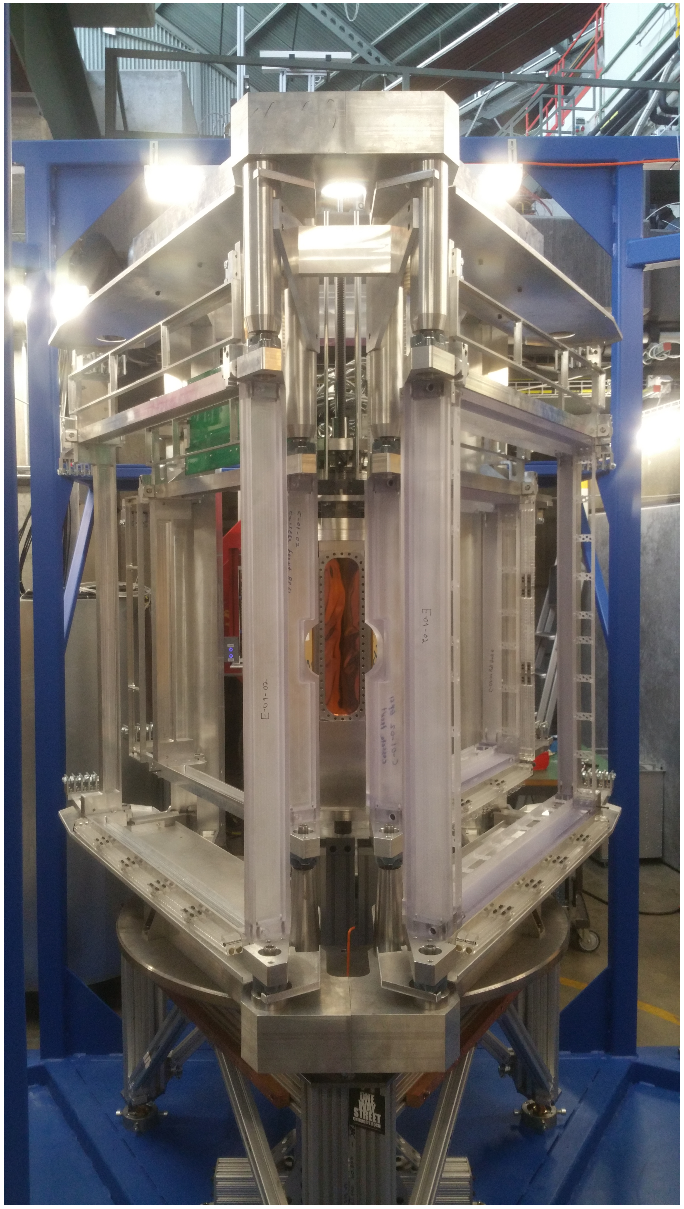
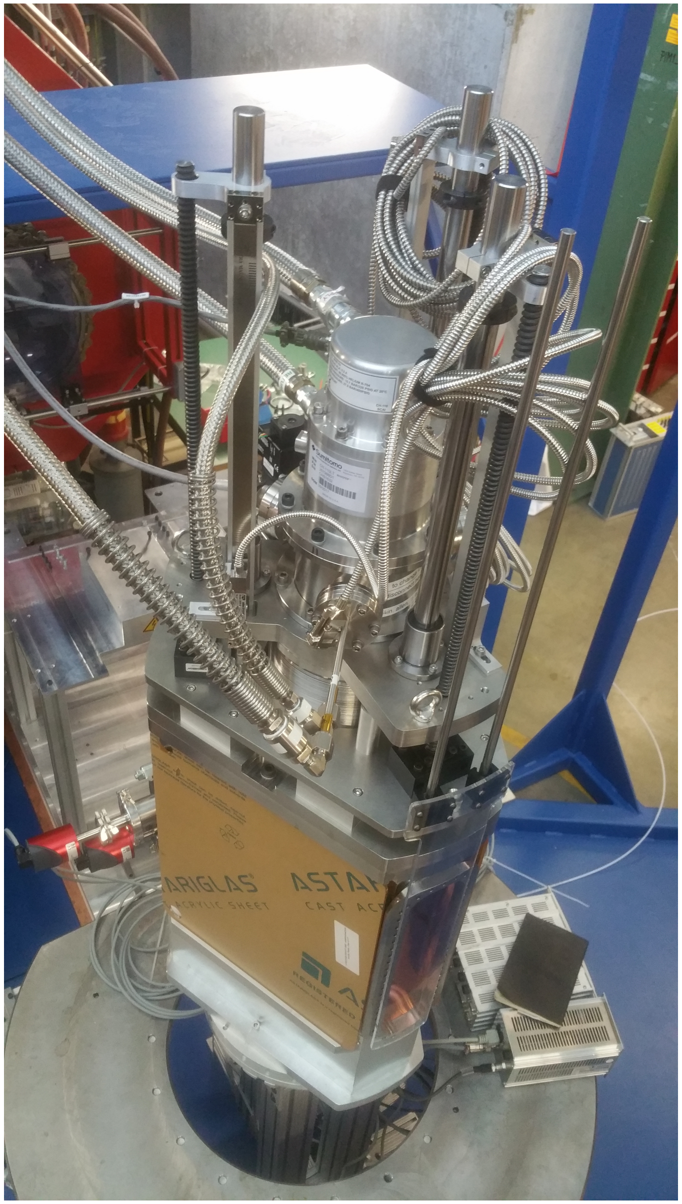
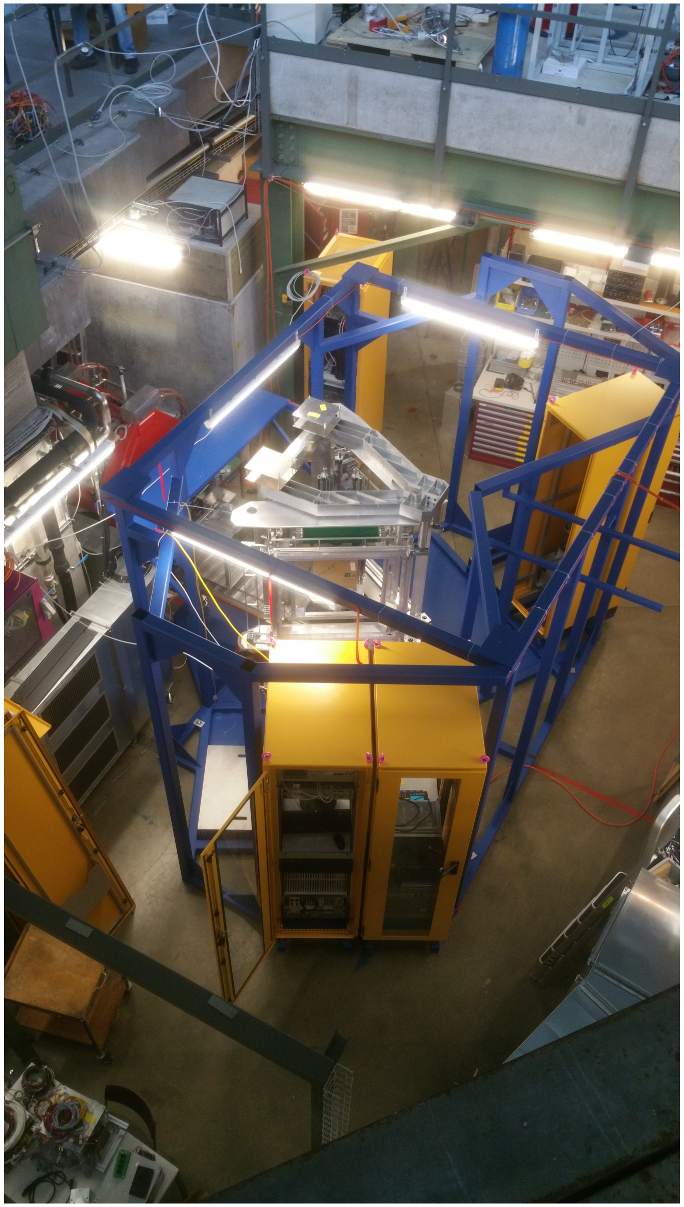

Nov. 2017

Scintillator walls: USC
Resolution 50-60ps

Ievgen Lavrukhin (GWU)

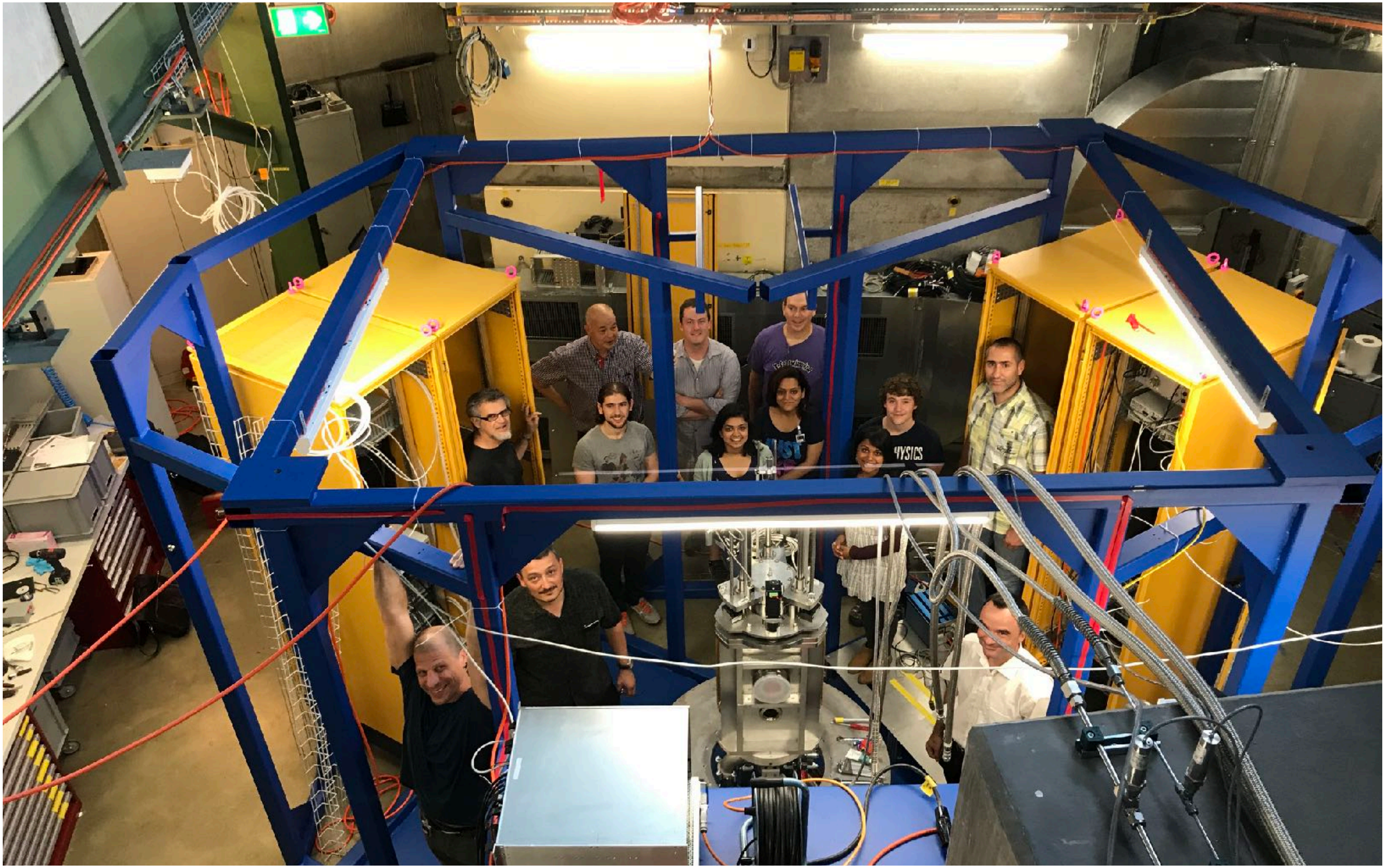
Spring/summer 2018 (cont’d)

Cryo target and chamber: UMich, Creare, PSI; Platform: ANL, PSI

Spring/summer 2018 (cont'd)

Collaboration Meeting at PSI on June 8-9, 2018



MUSE activities and status

- Proton puzzle alive and well in 2017 – 8 years later

- MUSE first proposed in 2012, PAC-approved in 2013
- R&D program with NSF, BSF, and DOE support 2014 – 2016

- Technical design report November 2015
- Collaborative funding proposal to NSF in Nov 2015: Mid-scale
- NSF technical review February 2016

- Restructuring in February 2016:
  R. Gilman (Project manager)
  E. Downie, G. Ron, S. Strauch (Spokespeople)
- Target conceptual design March 2016
- MOU with PSI April 2016
- Project management review May 2016 → award recommendation!

- Funding for construction has begun in fall 2016
- Construct and commission MUSE experiment 2016-2018
- Data taking 2x 6 months in 2019-2020

MUon Scattering Experiment – MUSE

63 MUSE collaborators from 24 institutions in 5 countries:

A. Afanasev[a], A. Akmal[b], J. Arrington[c], H. Atac[d], C. Ayerbe-Gayoso[e], F. Benmokhtar[f], N. Benmouna[b], N. Bern[b], J.C. Bernauer[g], E. Brash[h], W.J. Briscoe[a], T. Cao[i], D. Ciofi[a], E. Cline[j], D. Cohn[k], E.O. Cohen[l], C. Collicott[a], K. Deiters[m], J. Diefenbach[n], B. Dongwi[i], E.J. Downie[a], L. El Fassi[o], S. Gilad[g], R. Gilman[j], K. Gnanvo[p], R. Gothe[q], D. Higinbotham[r], Y. Ilieva[q], M. Jones[r], N. Kalantarians[i], M. Kohl[i], B. Krusche[s], G. Kumbartzki[j], I. Lavrukhin[a], L. Li[q], J. Lichtenstadt[l], W. Lin[j], A. Liyanage[i], N. Liyanage[p], W. Lorenzon[t], Z.-E. Meziani[d], P. Monaghan[h], K.E. Mesick[u], P. Mohan Murthy[g], J. Nazeer[i], T. O’Connor[c], C. Perdrisat[e], E. Piasetzsky[l], R. Ransome[j], R. Raymond[t], D. Reggiani[m], P.E. Reimer[c], A. Richter[v], G. Ron[k], T. Rostomyan[j], A. Sarty[w], Y. Shamai[l], N. Sparveris[d], S. Strauch[q], V. Sulkosky[p], A.S. Tadepalli[j], M. Taragin[x], and L. Weinstein[o]

[a]George Washington University, [b]Montgomery College, [c]Argonne National Lab, [d]Temple University, [e]College of William & Mary, [f]Duquesne University, [g]Massachusetts Institute of Technology, [h]Christopher Newport University, [i]Hampton University, [j]Rutgers University, [k]Hebrew University of Jerusalem, [l]Tel Aviv University, [m]Paul Scherrer Institut, [n]Johannes Gutenberg-Universität, [o]Old Dominion University, [p]University of Virginia, [q]University of South Carolina, [r]Jefferson Lab, [s]University of Basel, [t]University of Michigan, [u]Los Alamos National Laboratory, [v]Technical University of Darmstadt, [w]St. Mary’s University, [x]Weizmann Institute

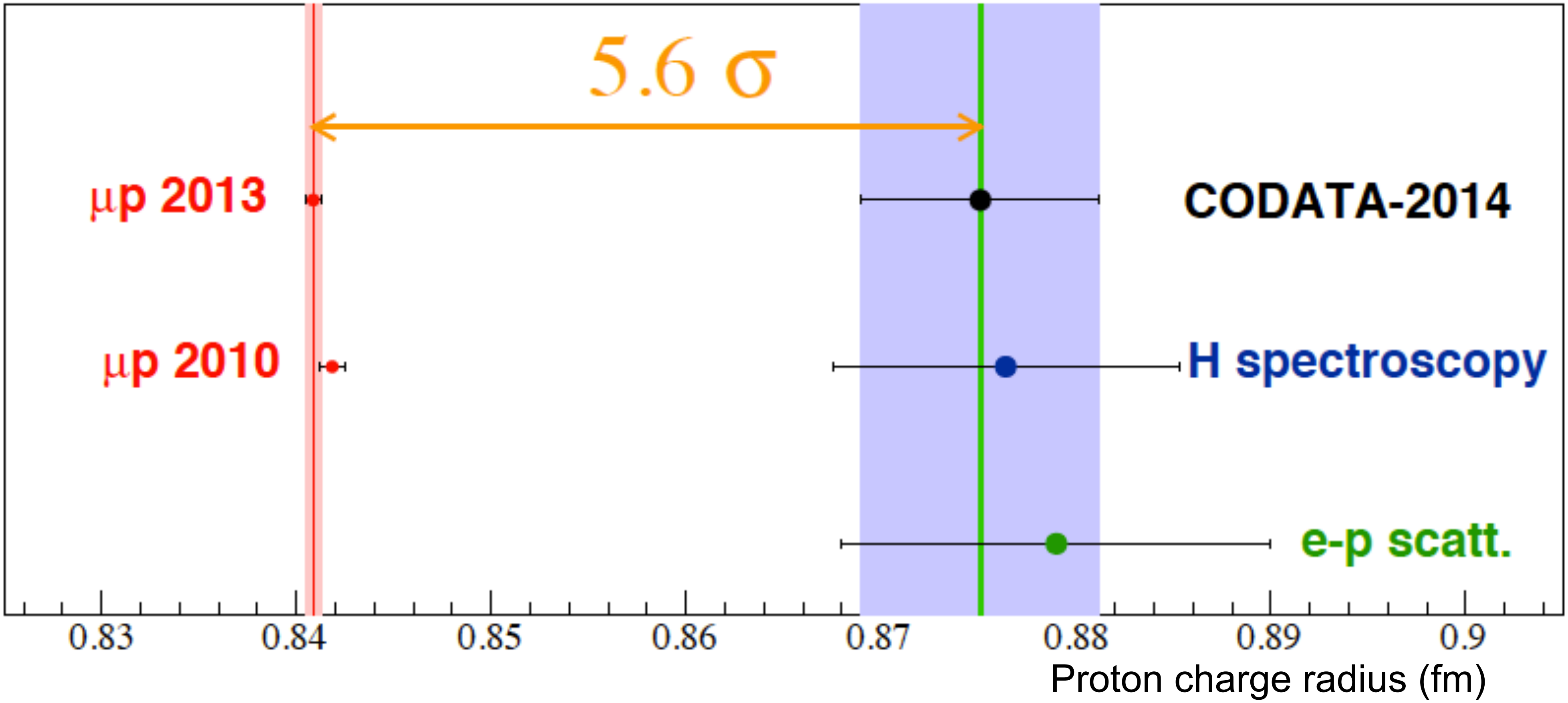
(Oct. 2016)

The proton radius puzzle

The proton rms charge radius measured with

electrons: 0.8751 ± 0.0061 fm **(CODATA2014)**

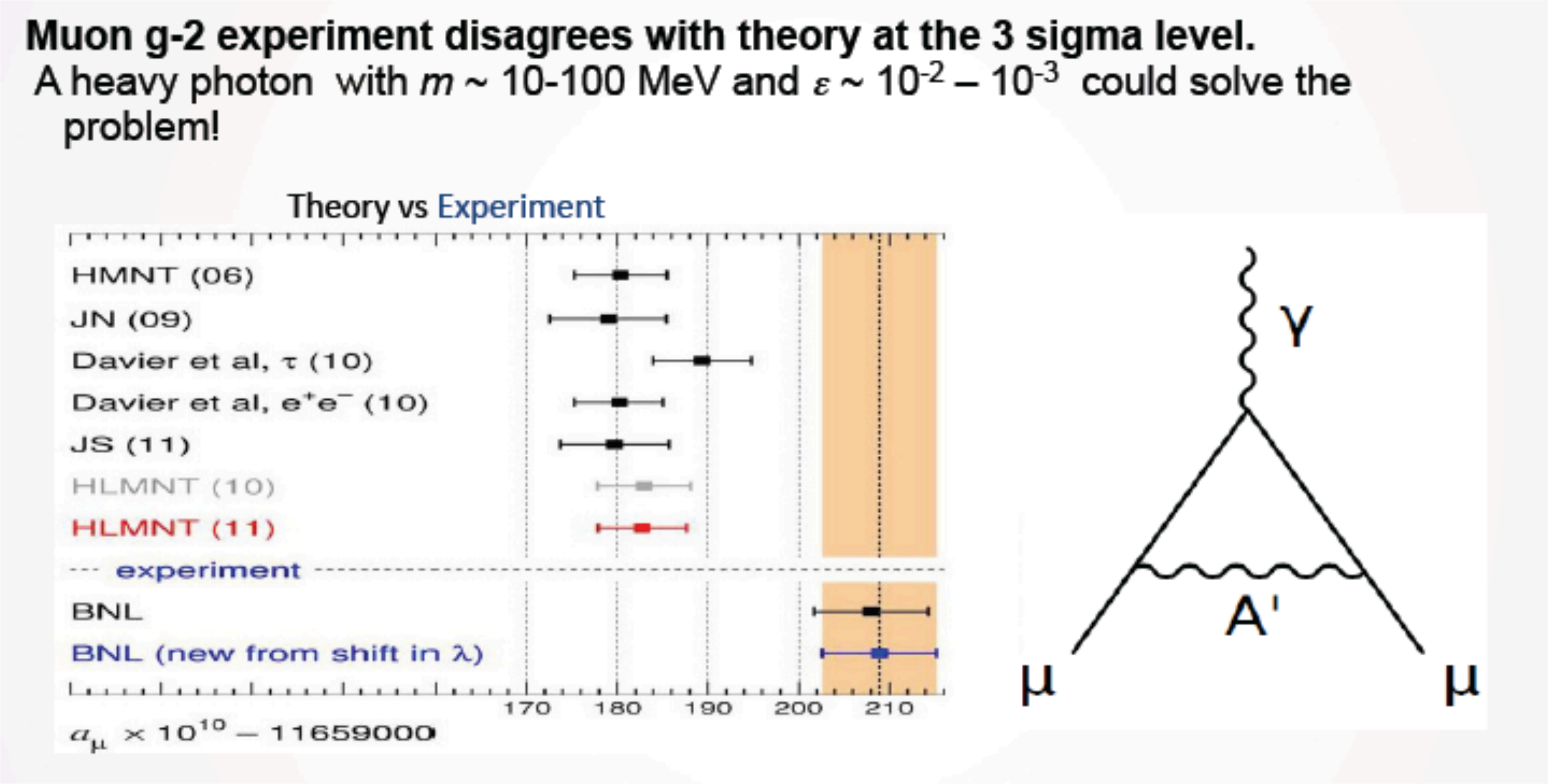
muons: 0.8409 ± 0.0004 fm



R. Pohl et al., Nature 466, 213 (2010)

A. Antognini et al., Science 339, 417 (2013)

Muon anomalous magnetic moment



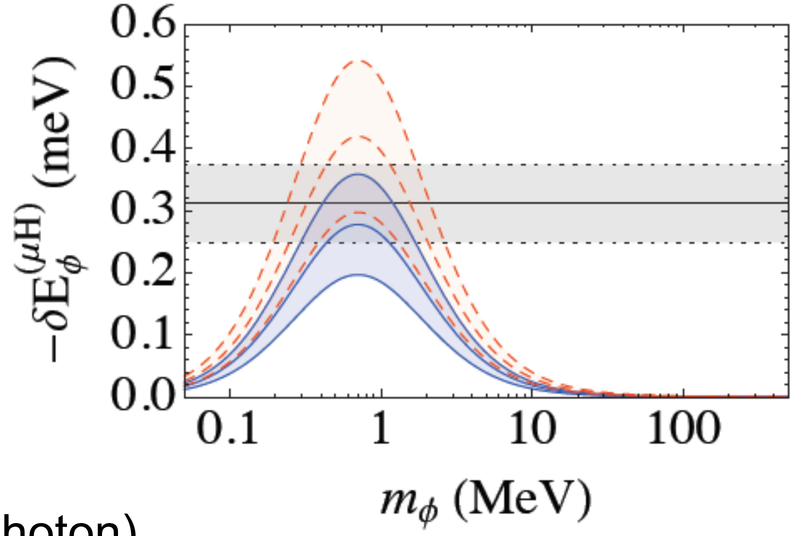
Muon g-2 experiment disagrees with theory at the 3 sigma level.
A heavy photon with $m \sim$ 10-100 MeV and $\varepsilon \sim 10^{-2} - 10^{-3}$ could solve the problem!

Anomaly ‘usually’ explained by SUSY with large tanβ
-> no evidence

A light boson and the proton radius puzzle

Jaeckel, Roy (arXiv:1008.3536)

- Hidden U(1) photon can decrease charge radius for muonic hydrogen, however even more so for regular hydrogen



Tucker-Smith, Yavin (arXiv:1011.4922)

can solve proton radius puzzle

- MeV particle coupling to p and μ (not e) consistent with g_μ-2

Batell, McKeen, Pospelov (arXiv:1103.0721):

can solve proton radius puzzle

- new e/μ differentiating force consistent with g_μ-2
- <100 MeV vector or scalar gauge boson V (poss. dark photon)
- resulting in large PV μp scattering

Carlson, Rislow (arXiv:1310.2786):

can solve proton radius puzzle

- new e/μ differentiating force consistent with g_μ-2
- Two fine-tuned scalar/pseudoscalar or vector/axial gauge bosons

Liu, McKeen, Miller (arXiv:1605.04612):

can solve proton radius puzzle

- Electrophobic scalar boson consistent with g_μ-2

Barger, Chiang, Keung, Marfatia (arXiv:1109.6652):

- Light bosons constrained by K → μν decay

Time Reversal Experiment with Kaons

- TREK Program
  - E06: Search for Time Reversal Symmetry Violation
  - E36: Test of Lepton Universality
  - Search for Heavy Neutrinos
  - Search for Light Bosons

Lower intensity

- TREK Apparatus
- Status

E36 data taking completed in 2015 !

http://trek.kek.jp

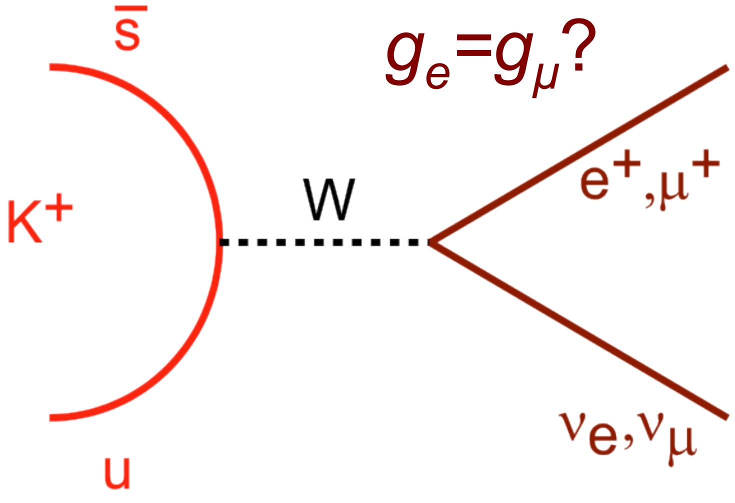
Timeline of TREK

- **2006: E06 (T-violation) Proposal (PAC1)**
- **2009: J-PARC PS and HF start operating**
- **2010: E36 (LFU/HNS) Proposal (PAC10)**
- **2011: E36 stage-1 recommended (PAC11)**
- **2012: E36 stage-1 approved (PAC15)**
- **2013: E36 stage-2 recommended (PAC17)**
- **2014: E36 stage-2 approved (PAC18)**
- **Detector preparation November 2014 – April 2015**
- **First commissioning run April 8 (24) – May 7, 2015**
- **Second commissioning run June 3 – 26, 2015**
- **Implemented improvements in summer 2015**
- **Production run October 14 – November 24, 2015**
- **Run extended until December 18, 2015**
- **2016-18: Analysis in progress**

Lepton universality in Standard Model K_{l2}

Standard Model:

- $$\Gamma(K_{l2}) = g_l^2 \frac{G^2}{8\pi} f_K^2 m_K m_l^2 \left(1 - \frac{m_l^2}{m_K^2}\right)^2$$



- **In the ratio of $\Gamma(K_{e2})$ to $\Gamma(K_{\mu2})$, hadronic form factors are cancelled**

- $$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{\underline{m_\mu^2}} \left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 \underline{(1+\delta_r)}$$

helicity suppression

radiative correction (Internal Brems.)

- **Strong helicity suppression of the electronic channel enhances sensitivity to effects beyond the SM**

- **Highly precise SM value**
  R_K^{SM}= (2.477±0.001) x 10^{-5} (with δ_r = -0.036); $\delta R_K/R_K$=0.04%
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

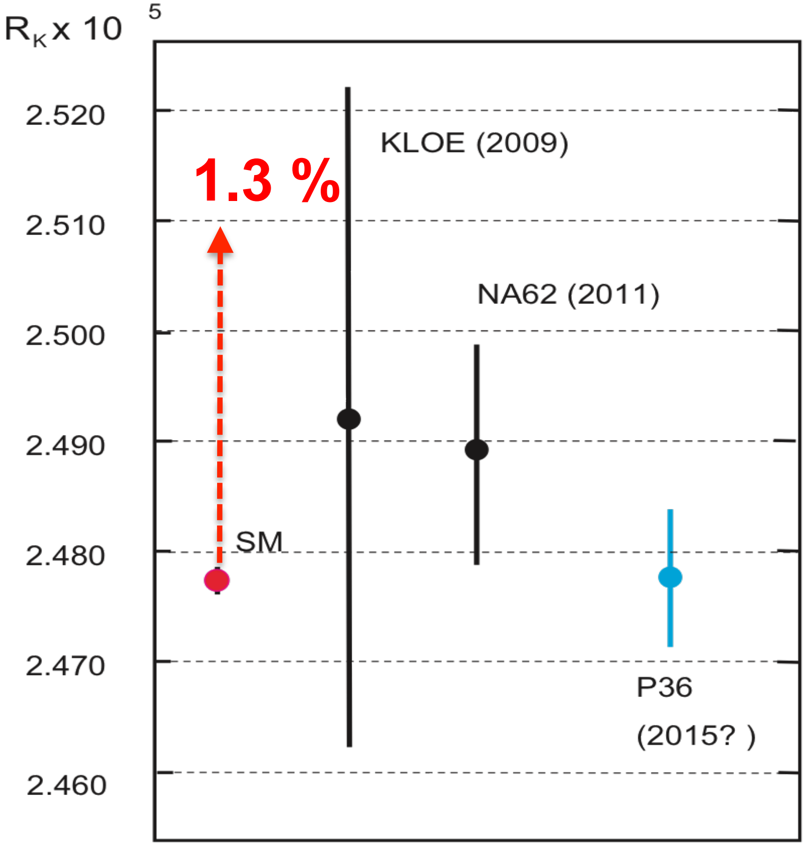
Experimental status of R_K

- **Highly precise SM value**
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$ (with $\delta_r = -0.036$), $\delta R_K/R_K$=0.04%
  V. Cirigliano, I. Rosell, Phys. Rev. Lett. 99, 231801 (2007)

- **KLOE @ DAΦNE (in-flight decay)**
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
  F. Ambrosino et al., Eur. Phys. J. C64, 627 (2009)

- **NA62 @ CERN-SPS (in-flight decay)**
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
  C. Lazzeroni et al., PLB719, 105 (2013)

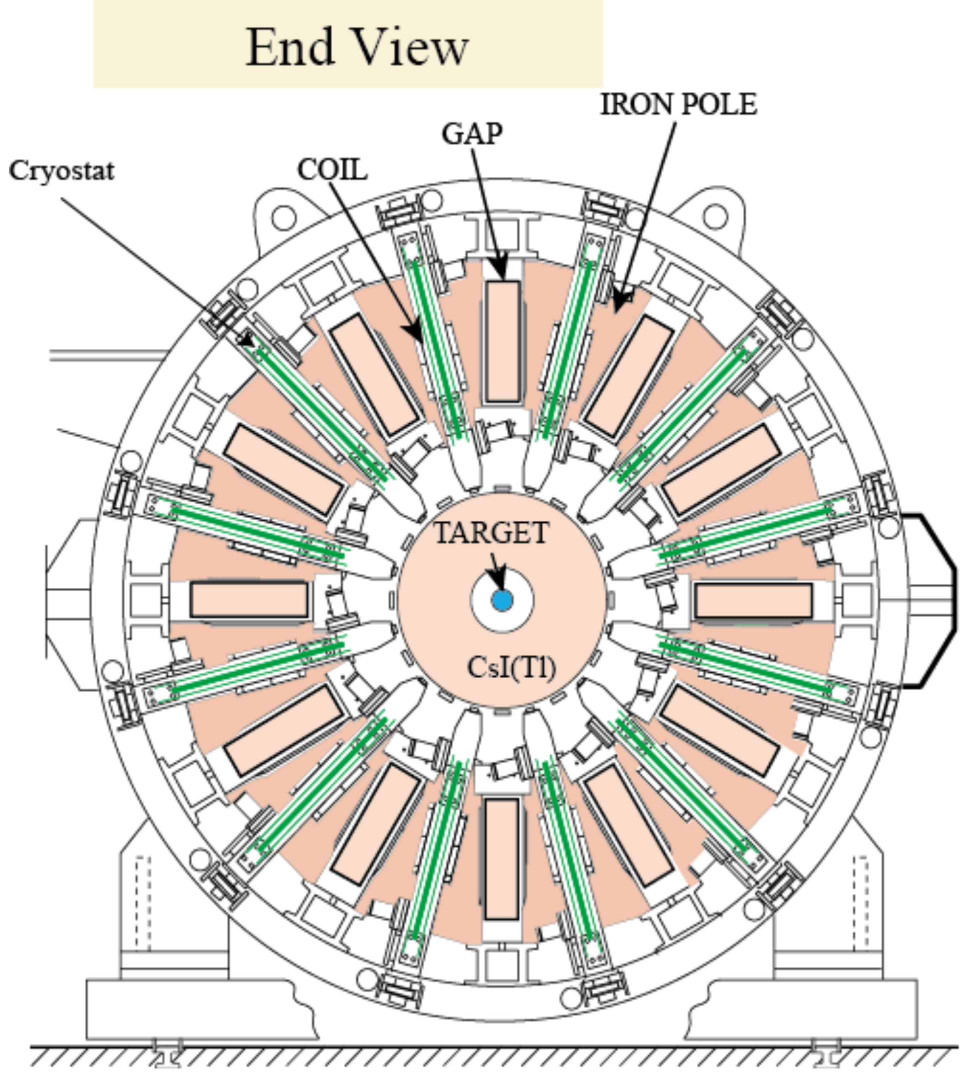
- **World average (2012)**
  $R_K = (2.488 \pm 0.009) \times 10^{-5}$, $\delta R_K/R_K$=0.4%

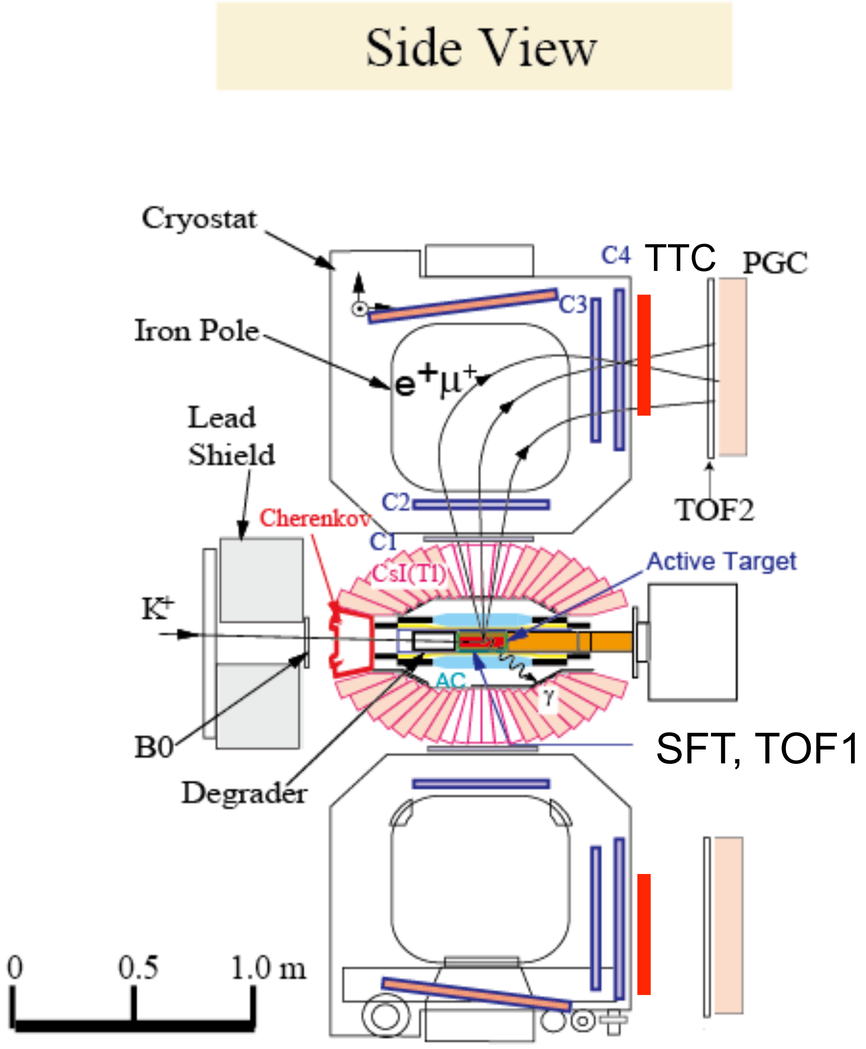


- **Systematics:**
  - **In-flight-decay experiments: kinematics overlap**
  - **E36 stopped K^+: detector acceptance and target**
  - **E36 complementary to in-flight experiments**

- **E36 goal: $\delta R_K/R_K = \pm$ 0.2% (stat) $\pm$ 0.15% (syst) [0.25% total]**

The TREK apparatus for E36





Modest upgrade of KEK-PS E246

Stopped K^+
- K1.1BR beamline
- Fitch Cherenkov
- K^+ stopping target

Tracking (π,μ,e)
- MWPC (C2, C3, C4)
- Spiral Fiber Tracker (SFT)

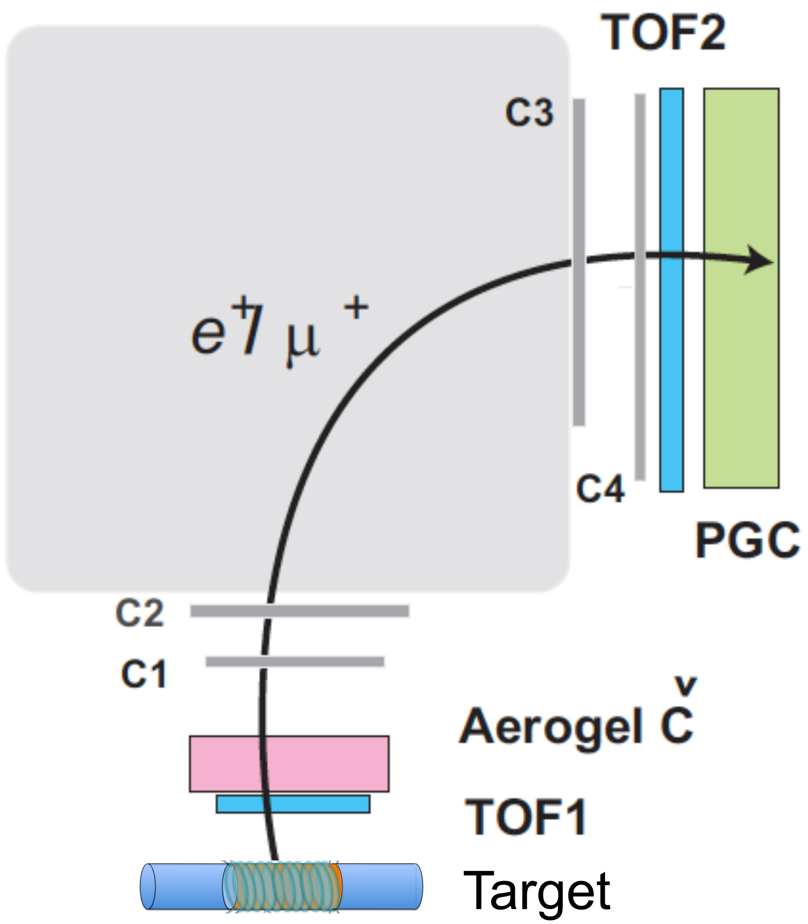
PID
- TOF1,2; TTC
- Aerogel Che. (AC)
- Pb glass (PGC)

Gamma
- CsI(Tl)
- Gap veto

μ^+/e^+ identification

PID with:

- **TOF**
- **Aerogel Č**
- **Lead glass**

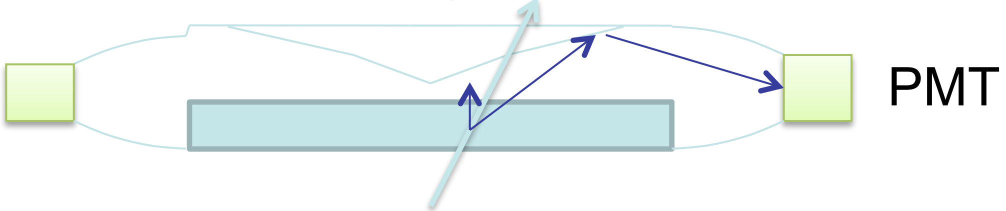


TOF

Flight length	250 cm
Time resolution	<100 ps
Mis-ID probability	$7\mathrm{x}\ 10^{-4}$

Aerogel Č counter

Radiator thickness	4.0 cm
Refraction index	1.08
e^+ efficiency	>98%
Mis-ID probability	3%



Lead glass (PGC)

Material	SF6W
Refraction index	1.05
e^+ efficiency	98%
Mis-ID probability	4%

$$P_{\mathrm{mis}}\ (\text{total}) = P_{\mathrm{mis}}\ (\text{TOF}) \times P_{\mathrm{mis}}\ (\mathrm{A}\check{\mathrm{C}}) \times P_{\mathrm{mis}}\ (\text{LG}) = 8 \times 10^{-7} < O(10^{-6})$$

Possible A' decay channels in TREK/E36

K^+ decays ~ 10^{10}

Signal 1: $K^+ \rightarrow \pi^+ A'$, $A' \rightarrow e^+e^-$

Background: BR($K^+ \rightarrow \pi^+ e^+ e^-$) ~ 2.9 x 10^{-7} ~ 2,900 ev.

Signal 2: $K^+ \rightarrow \mu^+ \nu A'$, $A' \rightarrow e^+e^-$

Background: BR($K^+ \rightarrow \mu^+ \nu \; e^+ e^-$) ~ 2.5 x 10^{-5} ~ 250,000 ev.

Add. background from $K^+ \rightarrow \mu^+ \nu \pi^0 \rightarrow \mu^+ \nu \; e^+ e^- (\gamma)$

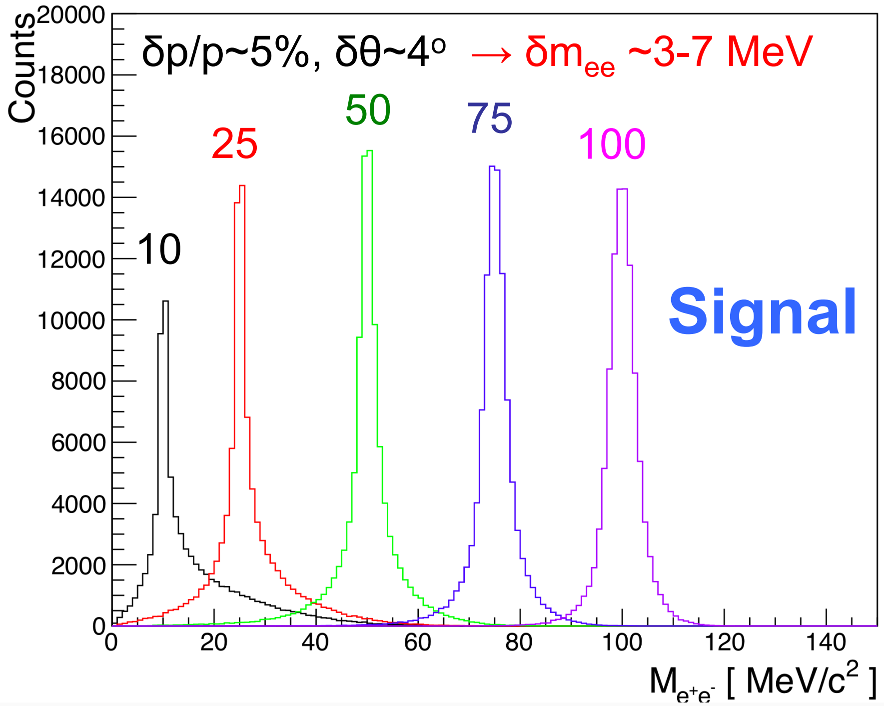
π^0 decays 1) 3x10^8 2) 2x10^9

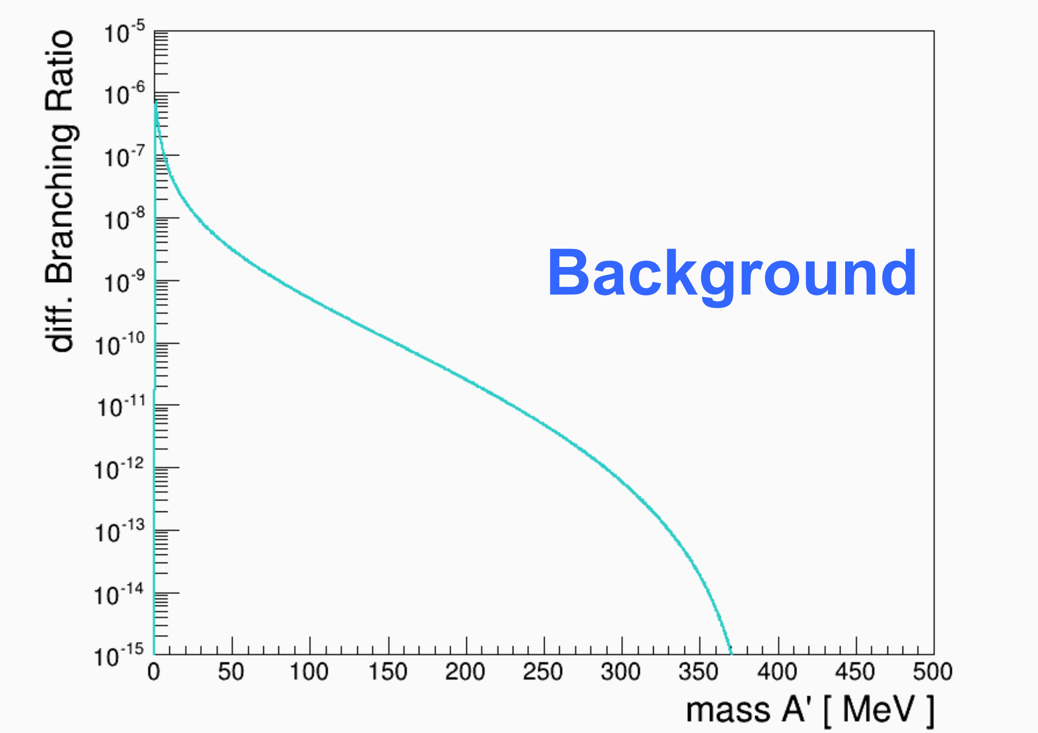
π^0 production: $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.3%) $K^+ \rightarrow \pi^+\pi^0$ (21.1%)

Signal 3: $\pi^0 \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$

Background: BR($\pi^0 \rightarrow \gamma \; e^+ e^-$) ~ 1.2% ~ 0.3 (2.3) x$10^7$ ev.

Search for a new particle in $K^+ \rightarrow \mu^+ \nu\, e^+ e^-$





Investigated for E36:

- Detect μ^+ in toroid, e^+e^- in CsI(Tl)
- Simulate achievable resolution for invariant mass m_{ee}
- Simulate QED background (radiative decay $K^+ \rightarrow \mu^+ \nu \; e^+ e^-$)
- Sensitivity from QED background fluctuation

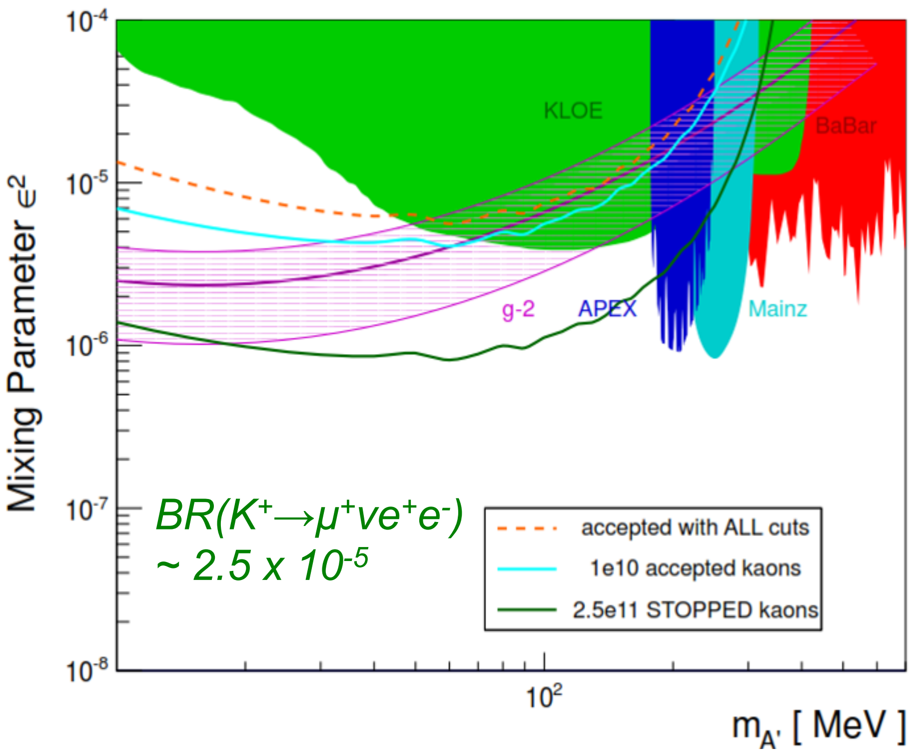
→ Exclusion limits for ε^2 versus m_{ee}

P. Monaghan, T. Cao, B. Dongwi (Hampton)

Dark photon / light neutral boson search

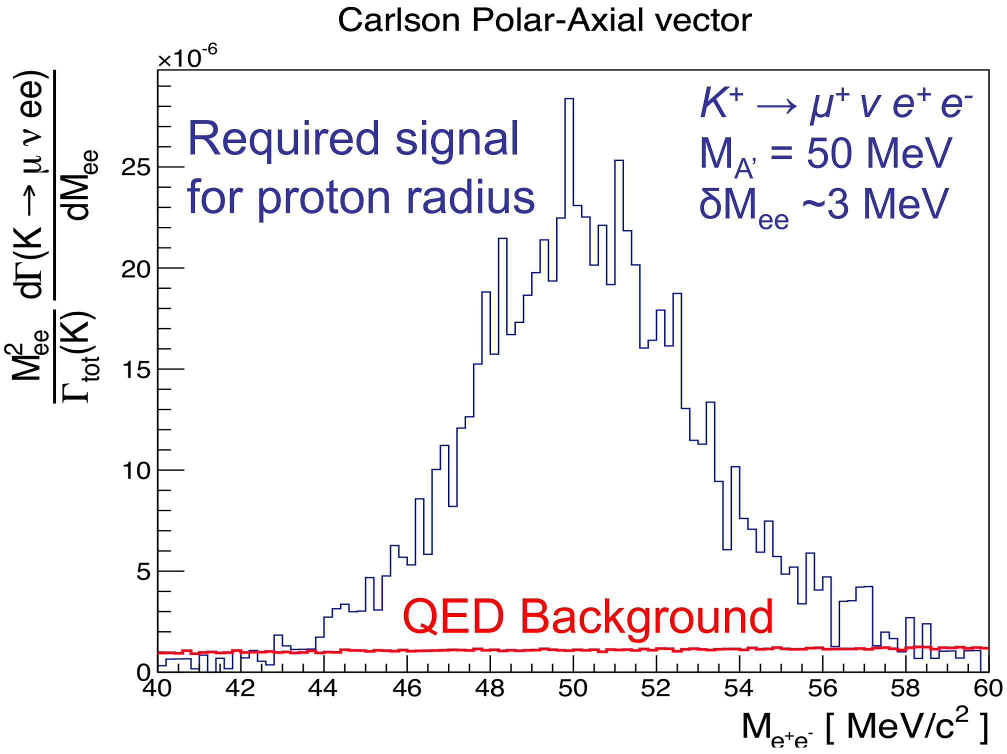
- **Dark photons (universal coupling) well motivated by dark matter observations (astronomical, direct, positron excess) and g_μ-2 anomaly**
- **Light neutral bosons (selective coupling) for proton radius puzzle**
- **Search for visible decay mode of $A' \rightarrow e^+e^-$ in K$^+$ decays**
  Kaons: $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  Pions: $\pi^0 \rightarrow \gamma A'$, using $K^+ \rightarrow \pi^+\pi^0$ (21.13%) and $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%)

E36: Dark photon exclusion limit



$BR(K^+ \rightarrow \mu^+ \nu e^+ e^-)$
$\sim 2.5 \times 10^{-5}$

E36: Light boson expected signal



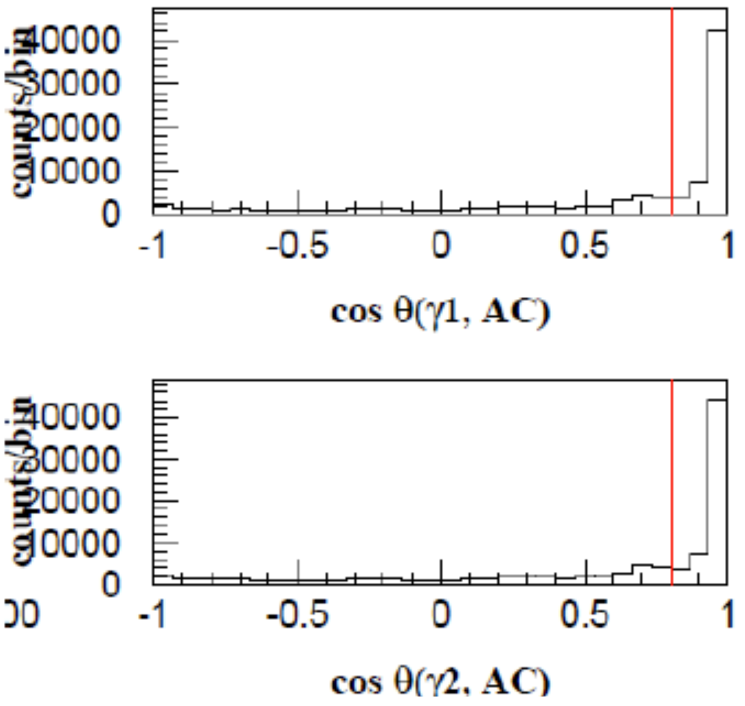
Required signal for proton radius

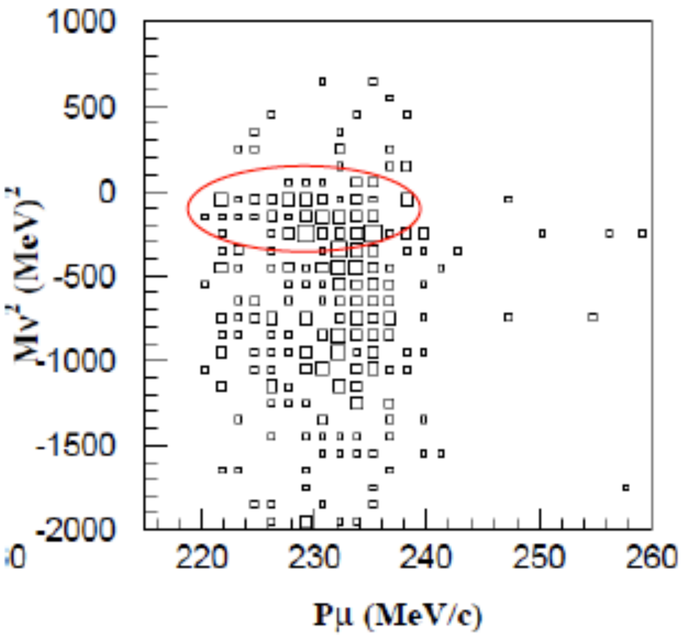
$K^+ \rightarrow \mu^+ \nu e^+ e^-$
$M_{A'}$ = 50 MeV
δM_{ee} ~3 MeV

Search for light boson events

- Search for visible decay mode of $A' \rightarrow e^+e^-$ in K^+ decays
  Kaons: $K^+ \rightarrow \mu^+ \nu A'$; $K^+ \rightarrow \pi^+ A'$ (also invisible decay);
  Pions: $\pi^0 \rightarrow \gamma A'$, from $K^+ \rightarrow \pi^+\pi^0$ (21.13%) and $K^+ \rightarrow \mu^+ \nu \pi^0$ (3.27%)
- DP trigger: 3+ TOF1 bars
- $K^+ \rightarrow \mu^+ e^+ e^- \nu$ decays recorded in E36 data with DP trigger
- Reconstruct $K^+ \rightarrow \mu^+ e^+ e^- \nu$ decays with μ^+ track in toroid and e^+e^- pair in the CsI(Tl) calorimeter
- e^+ and e^- are identified by the aerogel Cherenkov counters surrounding the K^+ stopping target
- Main background: $K^+ \rightarrow \pi^+ \pi^o$ and $K^+ \rightarrow \mu^+ \pi^o \nu$, with $\pi^o \rightarrow e^+ e^- \gamma$
- [Can also use $\pi^o \rightarrow e^+ e^- \gamma$ as another signal channel!]

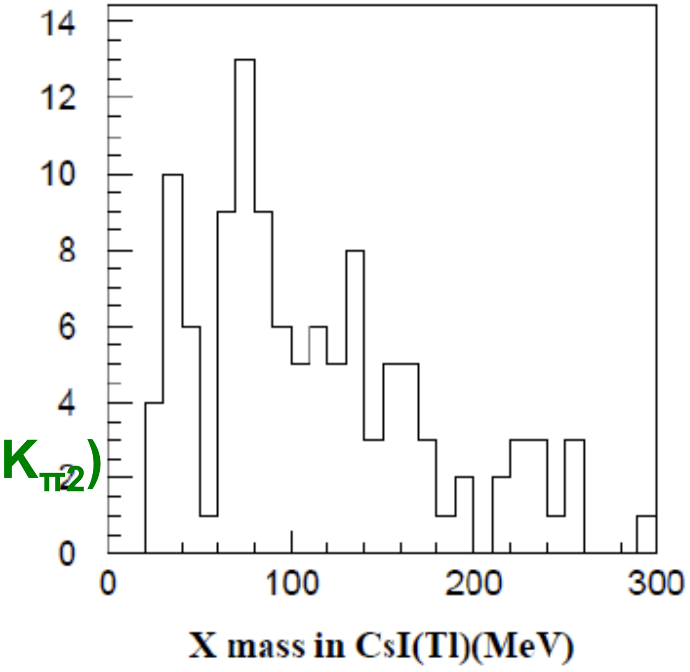
Search for light boson events





Evaluate $K^+ \rightarrow \mu^+ e^+ e^- \nu$ missing mass

Correlate CsI e^+e^- hits with AC sector



Select μ^+ momentum > 205 MeV/c ($K_{\pi 2}$)
Evaluate $A' \rightarrow e^+ e^-$ invariant mass

HAMPTON UNIVERSITY
The Standard of Excellence, An Education for Life

New Physics Search with the TREK/E36 experiment at J-PARC

Dr. Tongtong Cao, Bishoy Dongwi, Letrell Harris, Dr. Michael Kohl, Aruna Liyanaarachchi, Dr. Anusha Liyanage, Jesmin Nazeer
for the TREK Collaboration
Department of Physics, Hampton University, Hampton, VA, 23668, USA

J-PARC
J-PARC

OVERVIEW

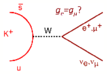
"In the world of *weak interactions* do *electrons* and *muons* behave the same?" That is the question.

The Standard Model (SM) represents our best description of the subatomic world and has been very successful at explaining how elementary particles interact under the influence of the four fundamental forces. However the following questions still linger:

- what is *dark matter?*
- what happened to all the antimatter after the big bang?
- why do neutrinos have mass?

INTRODUCTION

Lepton universality: In the SM e, μ and τ : Have different masses **but** identical coupling constants.



$$\Gamma(K_{l2}) = g_l^2 \left(\frac{G^2}{8\pi}\right) f_K^2 m_K m_l^2 \left[1 - \left(\frac{m_l^2}{m_K^2}\right)\right]^2$$

Decay width ratio

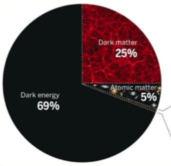
$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1 + \delta_r) \longrightarrow \textit{radiative corr.}$$

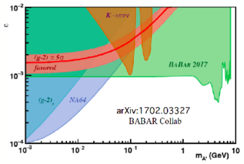
- Hadronic *form factors* cancel
- Strong *helicity* suppression of electronic channel enhances sensitivity to effects beyond SM
- SM: $R_K^{SM} = (2.477 \pm 0.001) \times 10^{-5}$ (very precise!)
  NA62: $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$ (in-flight K^+ decay)

$$\boxed{E36\ proposal:\ 0.25\%\ (0.20\%\ stat.+0.15\%\ sys.),\ stopped\ \mathrm{K}^+}$$

The mystery of Dark Matter

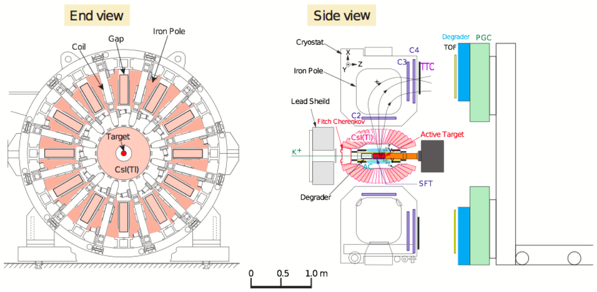
- Well motivated by dark matter observations (astronomical; direct: positron excess) and $g_\mu - 2$ anomaly
- Light neutral boson (selective coupling): proton radius puzzle
- Search for the A' with $Kaons$: $K^+ \to \mu^+ \nu A'$; $K^+ \to \pi^+ A'$ (also invisible decay)
- Also search for A' with $pions$: $\pi^0 \to \gamma A'$ (π^0 from $K_{\pi 2}$ and $K_{\mu 3}$)





TREK/E36 EXPERIMENT AT J-PARC

The E36 experiment was conducted at the Japan Proton Accelerator Research Complex (J-PARC) using the TREK detector system. E36 was successfully completed in the fall of 2015.



December 2014

- Installed detector components

February - June 2015

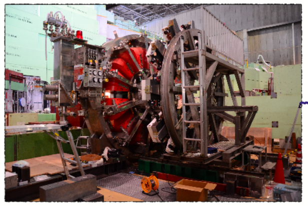
- Completed installation of C3 & C4
- Cabling and detector maintenance

September - December 2015

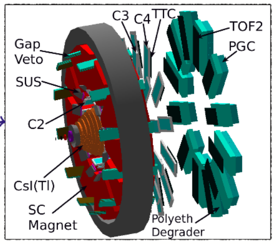
- Physics run and data taking

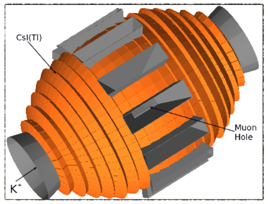
Stopped K^+	Tracking	Particle ID	Gamma ray
K1.1BR beamline	MWPC (C2, C3, C4)	Time of fl. (TOF)	CsI(TI)
K^+ stopping target	Spiral fib. tracker (SFT)	Aerogel Cheren.	
	Thin trig. counter (TTC)	Pb glass Counter	

LIVING IN A SIMULATION

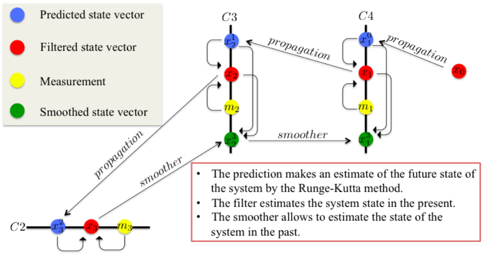


TREK/E36 detector system



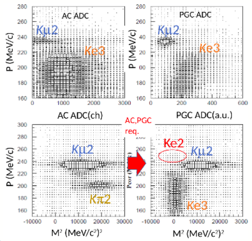


KALMAN FILTER



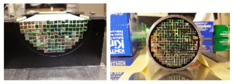
- The prediction makes an estimate of the future state of the system by the Runge-Kutta method.
- The filter estimates the system state in the present.
- The smoother allows to estimate the state of the system in the past.

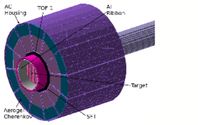
PARTICLE IDENTIFICATION

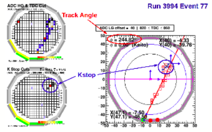


- e^+ are selected by aerogel cherenkov (AC), lead-glass counter (PGC) and TOF detectors
- PID will be performed by combing all three detectors

TARGET TRACKING



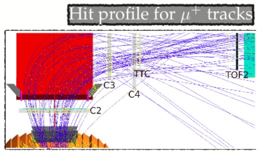


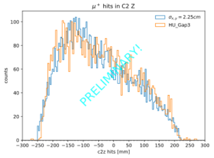


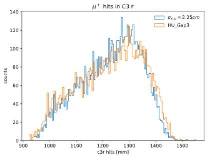
- Determination of K^+ stopping position lepton track length
- Measurement of lepton emission azimuthal angle to help determine SFT-Z
- Development of *target analysis algorithm* is nearly completed

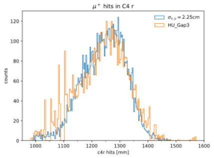
GEANT4 VERIFICATION

Hit profile for μ^+ tracks



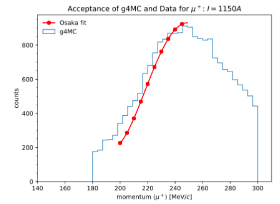






- Trigger on Target ⊗ TOF1 ⊗ TTC ⊗ TOF2
- Compare hit distribution between dispersive coordinates of MWPCs

ACCEPTANCE STUDY



- Comparison of acceptance calibration between *Monte Carlo* and experimental data

ACKNOWLEDGEMENTS

Japan Osaka University, Chiba University, Rikkyo University, KEK
Russia Russian Academy of Sciences (RAS)

Canada University of Saskatchewan, University of British Columbia, TRIUMF
USA University of South Carolina, University of Iowa, Hampton University

*This work has been supported by DOE awards DE-SC0003884 and DE-SC0013941

Bishoy Dongwi - EINN2017 Poster Prize

New Physics Search with the TREK/E36 experiment at J-PARC

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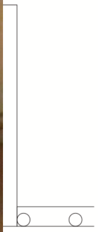
for the TREK Collaboration
Department of Physics, Hampton University, Hampton, VA, 23668, USA

tor Research Complex (J-PARC) using the TREK detector system.



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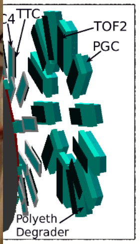
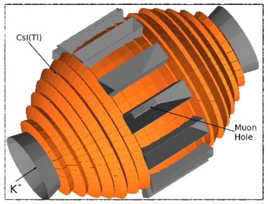
Gamma ray
CsI(TI)

tor system





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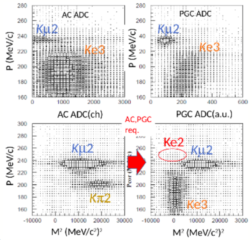

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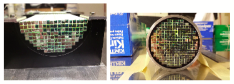

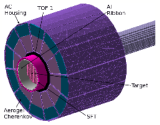

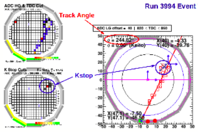

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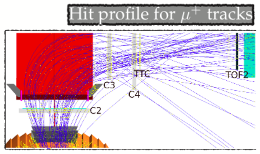

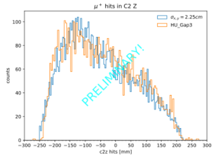

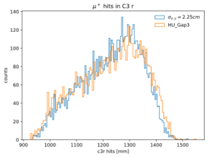

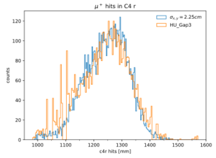

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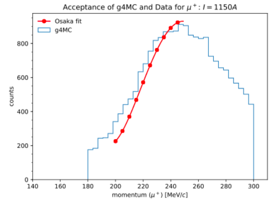

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Bishoy Dongwi - EINN2017 Poster Prize

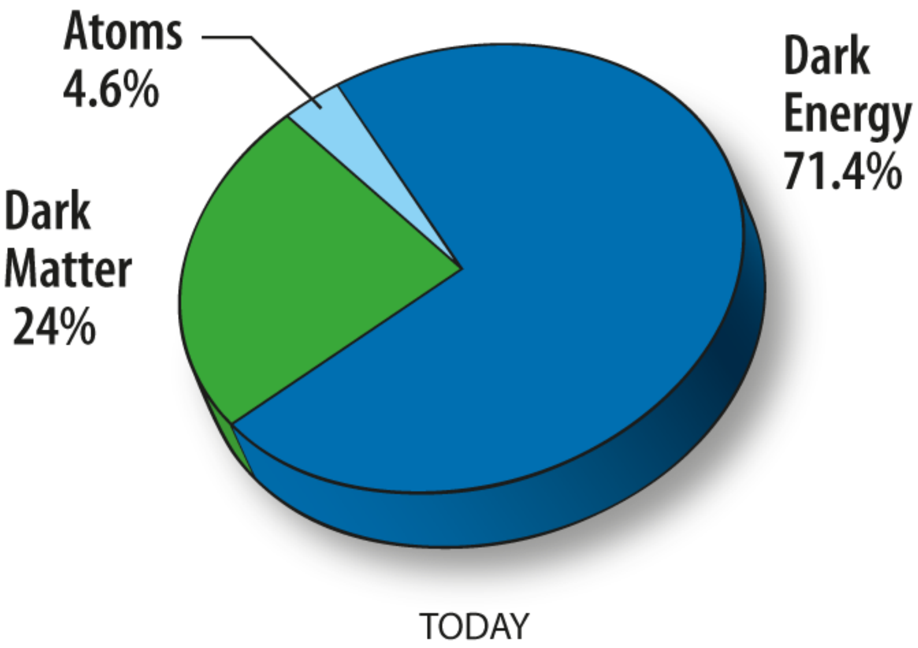
DarkLight

Jefferson Lab

DARKLIGHT

Detecting **A** **R**esonance **K**inematically with
e**L**ectrons **I**ncident on a **G**aseous **H**ydrogen **T**arget

Composition of the Universe



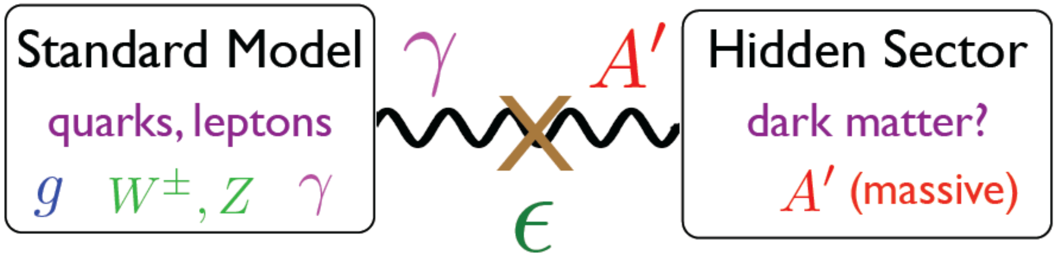
Big Bang Theory:
WMAP data fitted for relative densities

Ordinary matter: < 5%

Dark matter: Galactic scales
Dark energy: Inflation at largest scales

The nature of Dark Matter

Interaction with the Standard Model



Standard Model

quarks, leptons

g $W^{\pm}, Z$ γ

γ A'

ϵ

Hidden Sector

dark matter?

A' (massive)

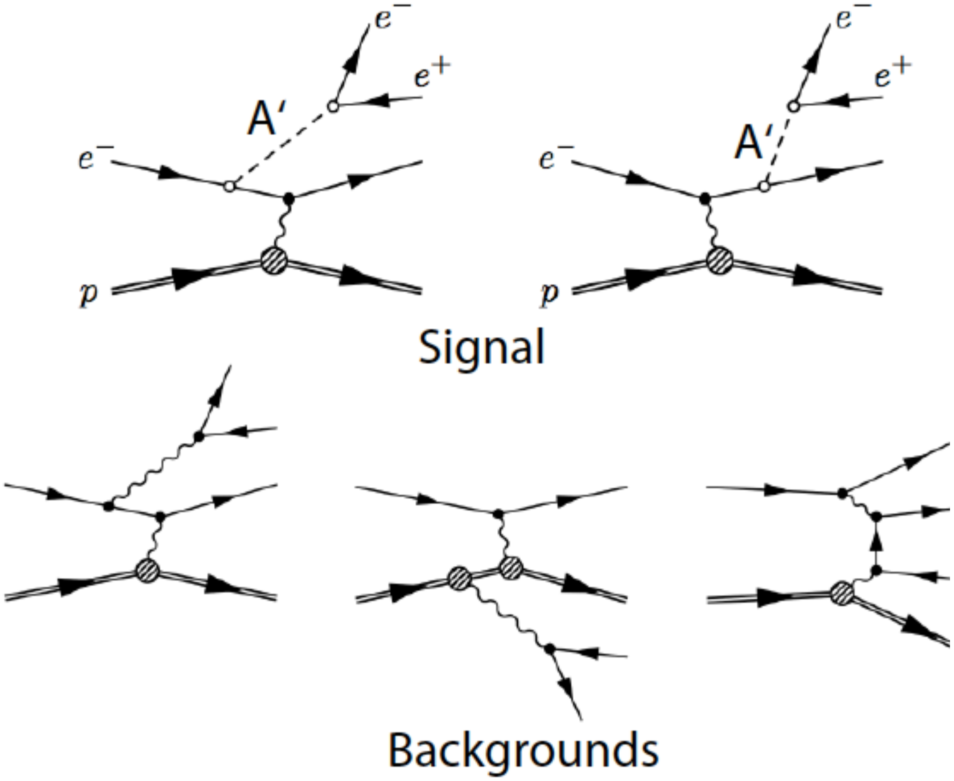
e.g. kinetic mixing

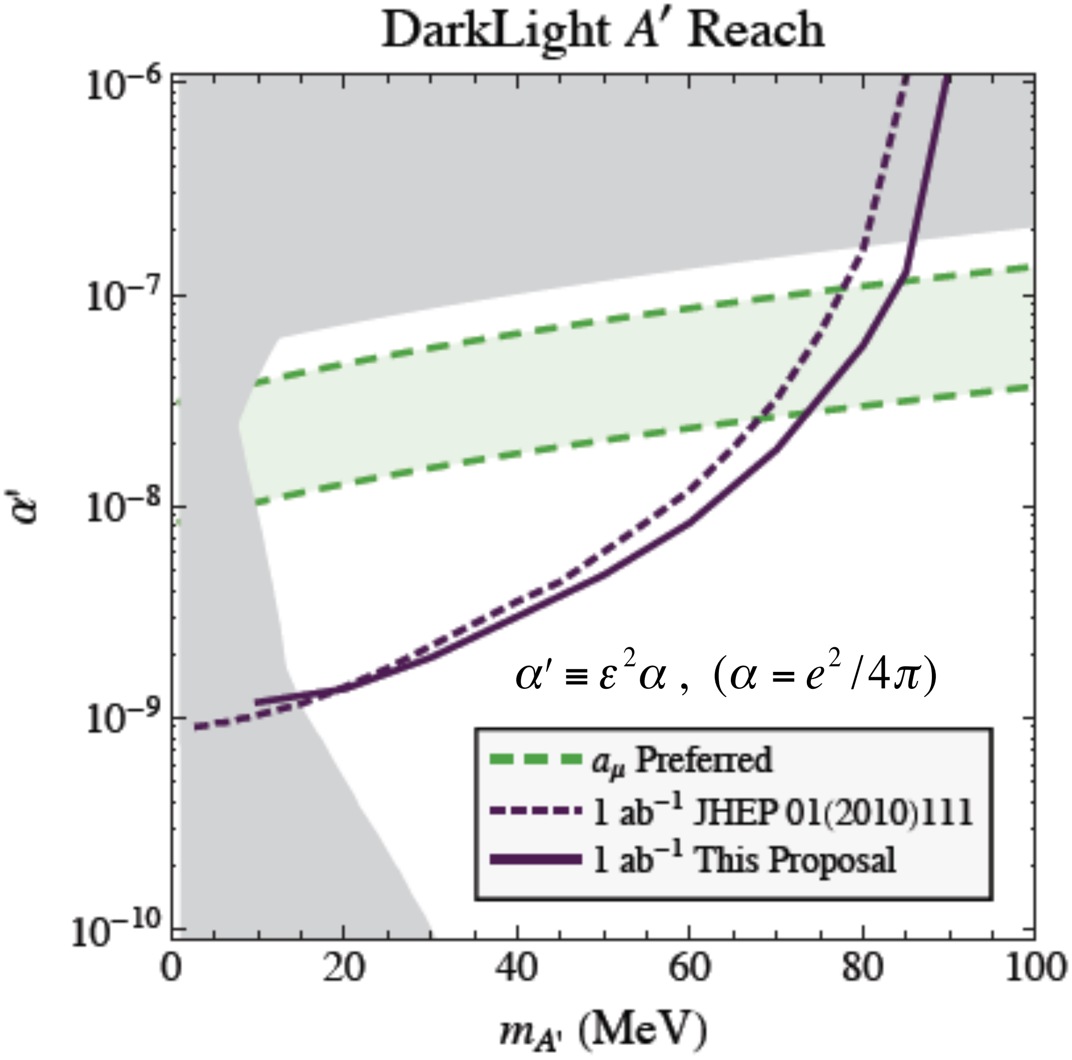
DarkLight

- Dark photons (universal coupling) well motivated by dark matter observations (astronomical, direct, positrons)
  in combination with g_μ-2 anomaly
- To be run at the Low Energy Recirculator Facility (LERF)
  at Jefferson Lab (alternatively, DL Phase-1C at CEBAF injector)
- Search for visible decays modes of $A' \to e^+e^-$ in $ep \to epA' \to epee$
- Search for invisible decays $A' \to X$ in $ep \to epX$
- DarkLight sensitive to dark photons with masses < 100 MeV/c^2
  in the region of the g_μ-2 welcome band
- DarkLight phase I:
  Funded (NSF-MRI) in 2014, H responsible for lepton tracker
  LERF: Run phase 1a in 2016, phase 1c in 2018/19
- DarkLight phase II:
  Ultimate reach, design in progress, 2019+

DarkLight sensitivity: visible decay

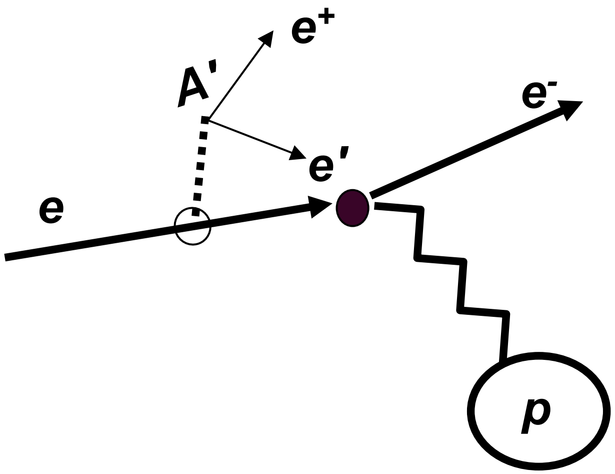
Goal: Explore $e^+ e^-$ invariant mass spectrum from 10-90 MeV using the process $e^- p \rightarrow e^- p \; e^- e^+$

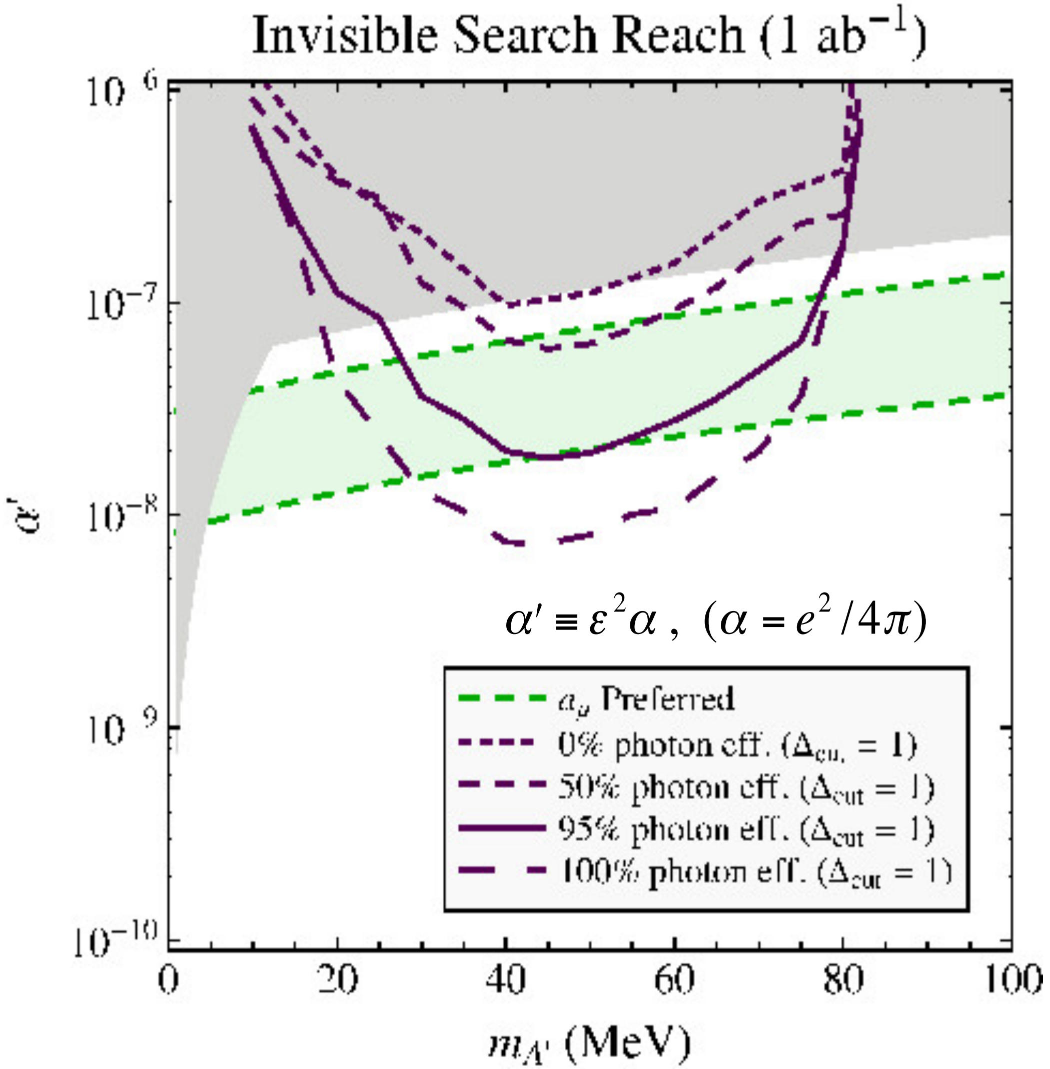




DarkLight sensitivity: invisible decay

- *ep → epA' ("invisible")* observe only final state electron and proton,
- Backgrounds' kinematics different enough that they can be controlled
- Requires photon veto *ep → epγ*

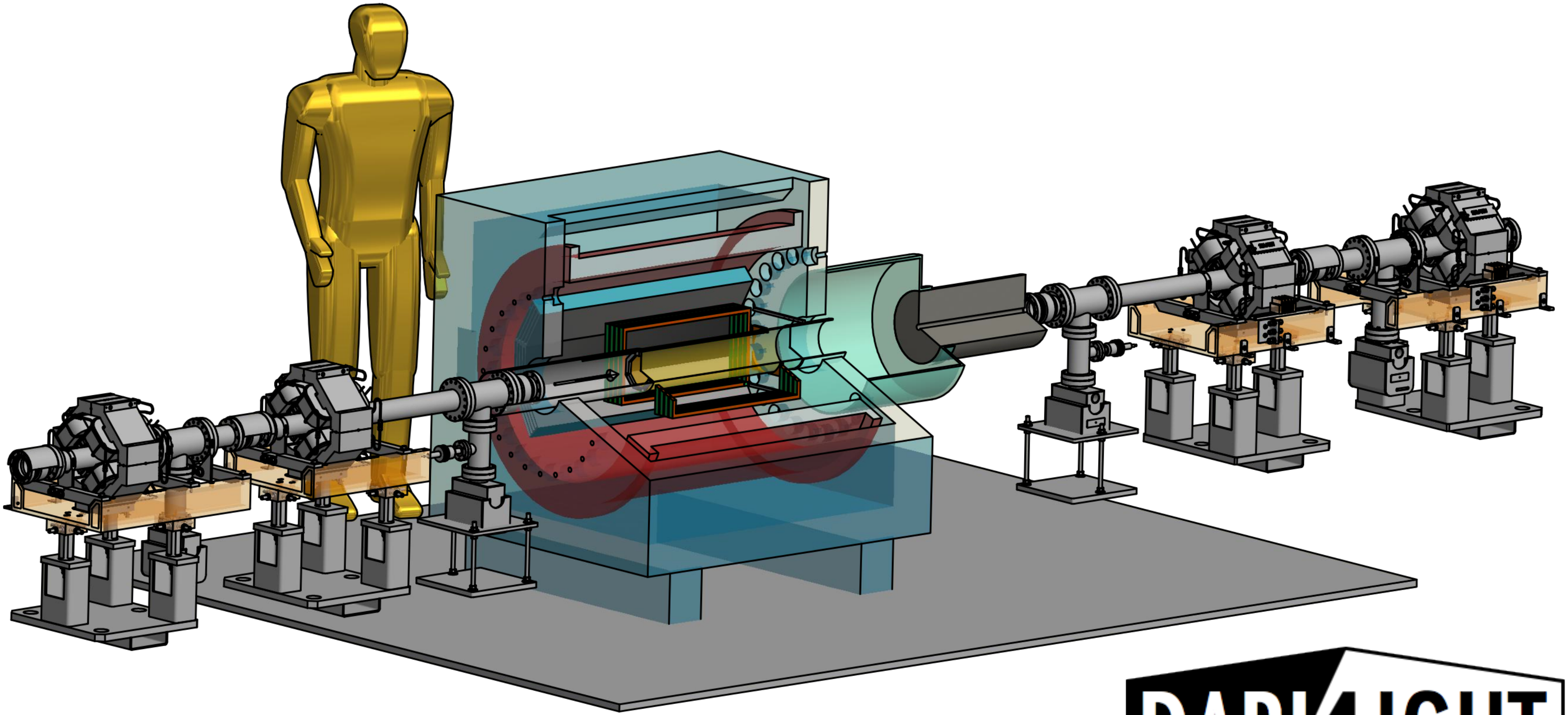




Kahn, Thaler Phys. Rev. D **86** (2012) 11501

DarkLight phases

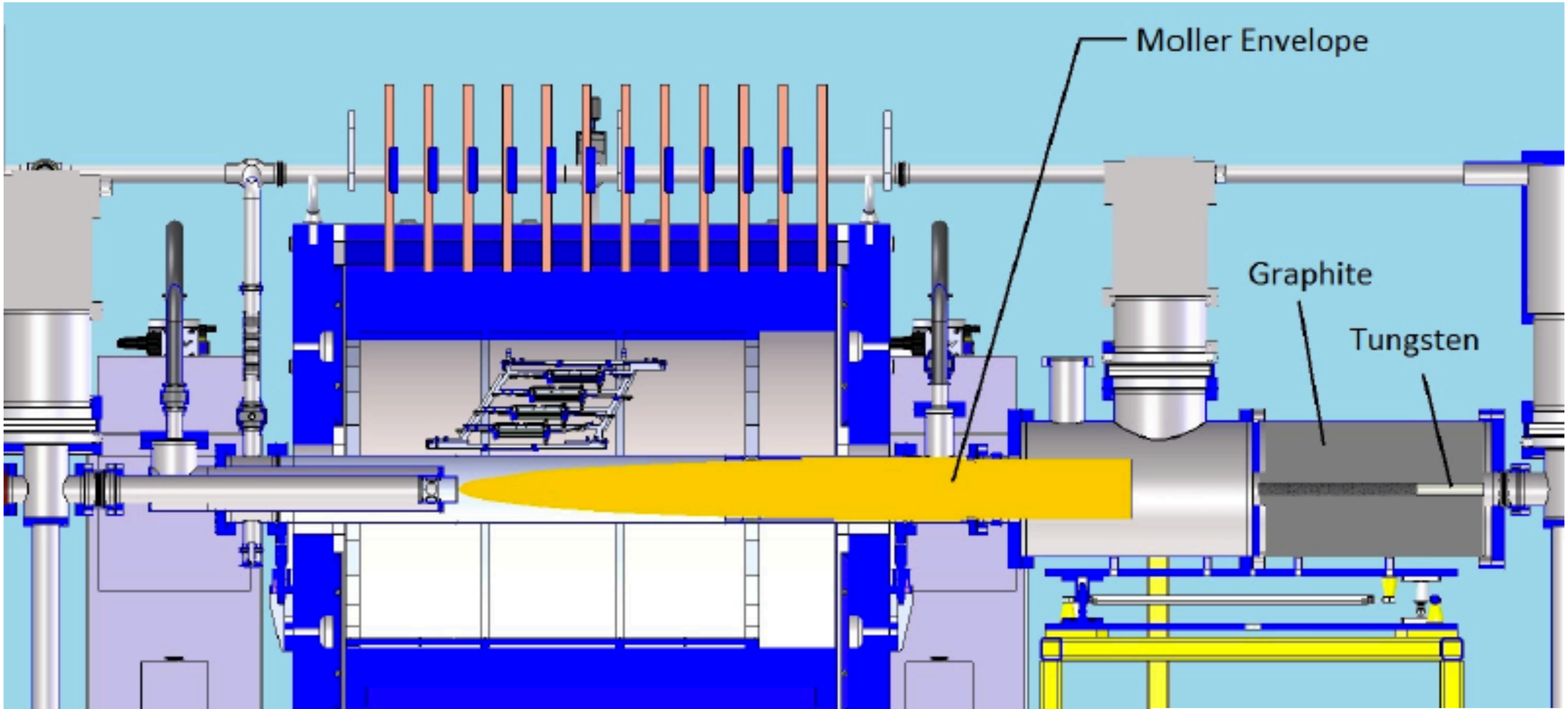
Phase 1A: Operation of ERL beam, target, and detectors (2016/17)
Phase 1B: Møller process, test of streaming readout (2017/18)
Phase 1C: Search for 17 MeV fifth force carrier (2018/19)
Phase 2: Full measurement

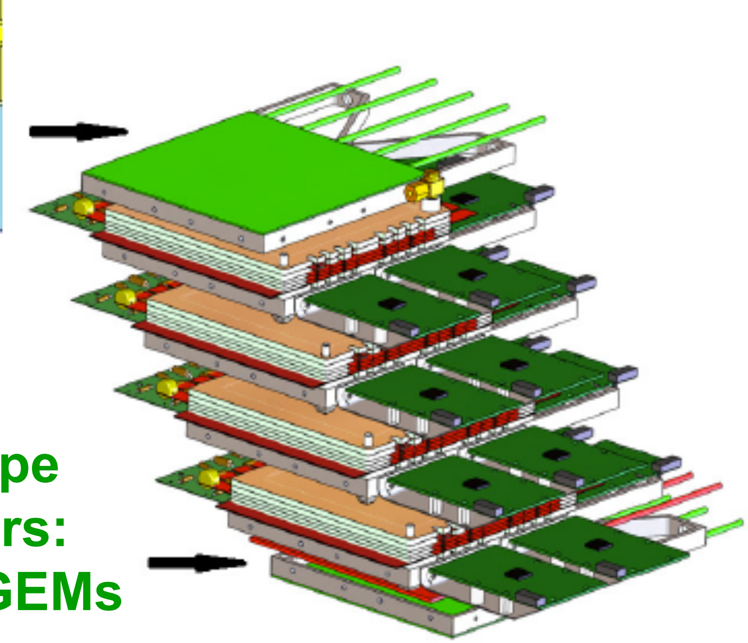


NSF/MRI award 2014 (HU)

DARKLIGHT

DarkLight phase 1a (2016/17)



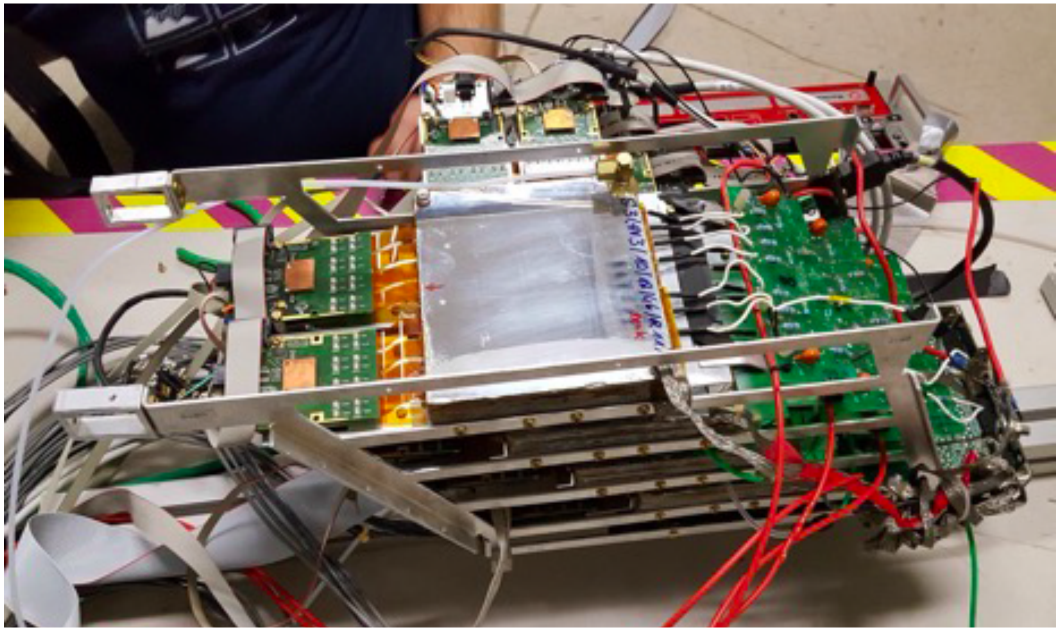


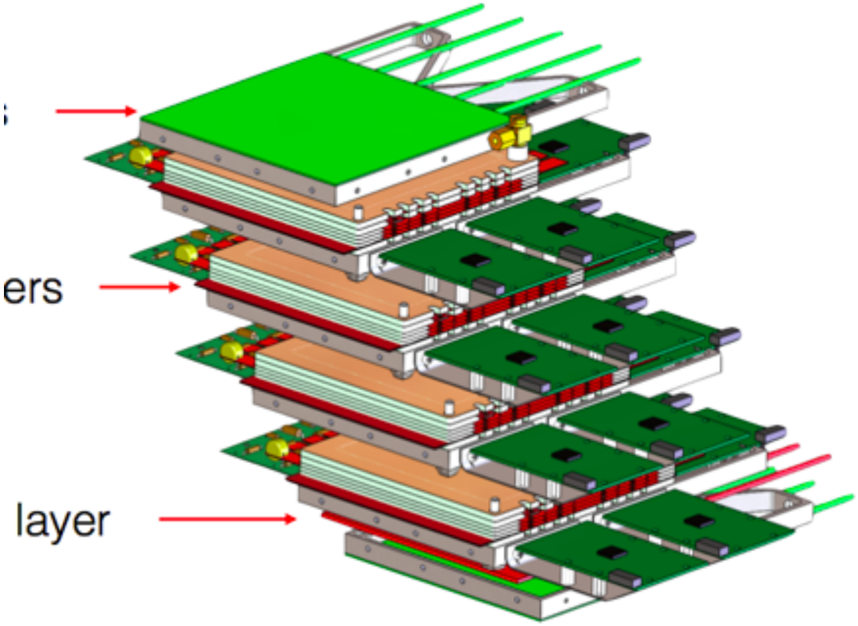
Prototype detectors: SiPM+GEMs

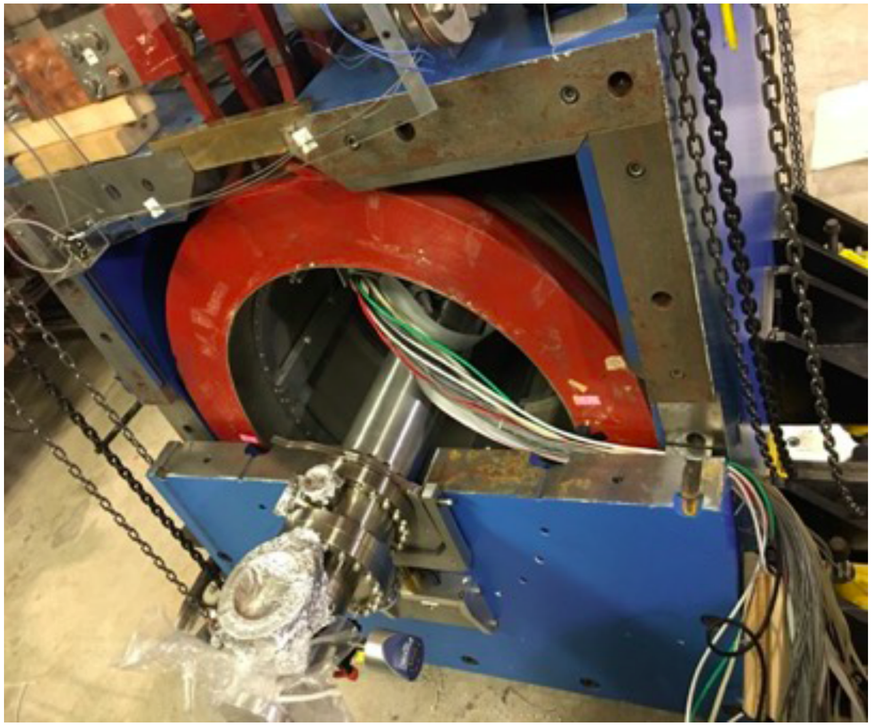
Demonstrated feasibility

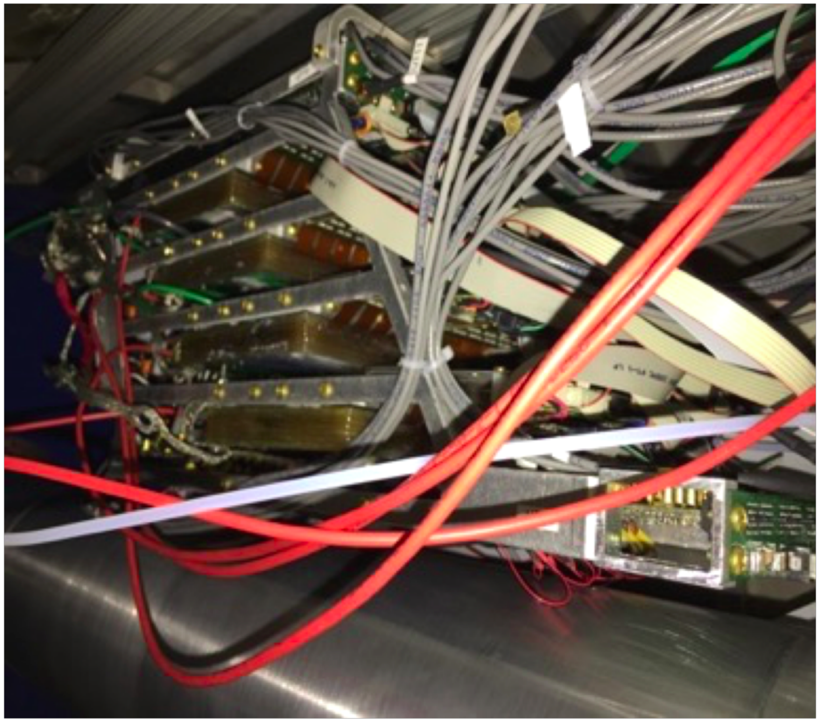
- ERL operation with target and solenoid
- Operation of detectors

DarkLight phase 1a (2016/17)

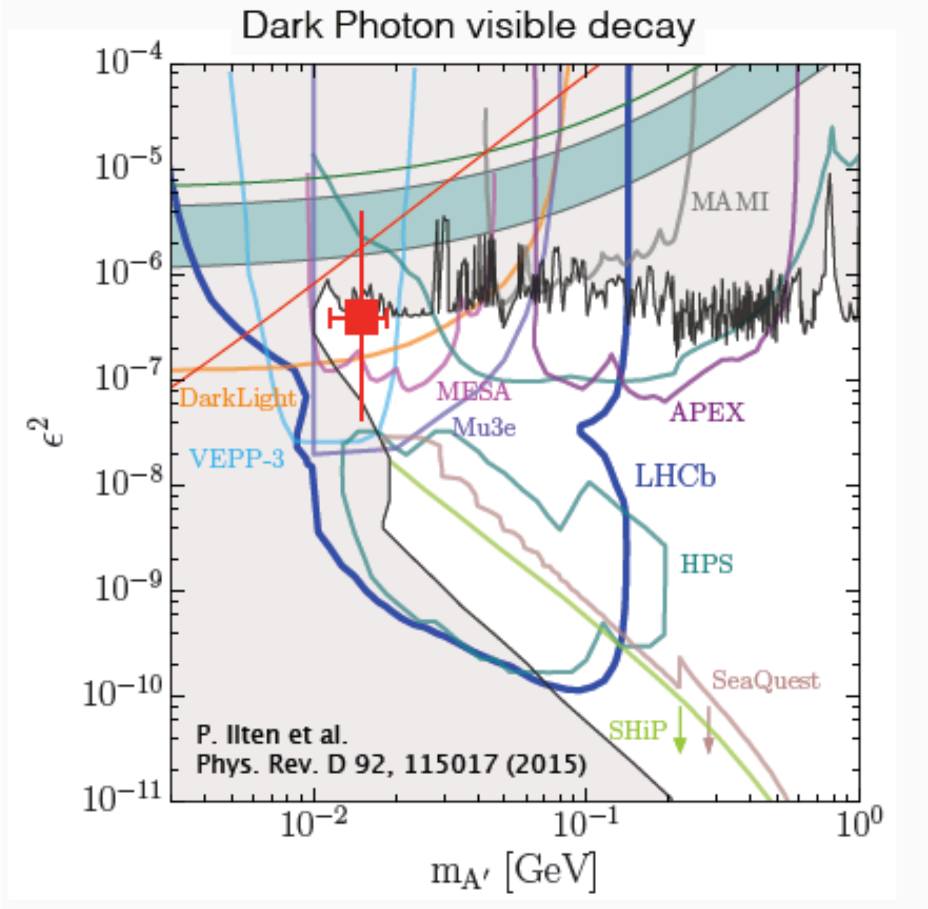






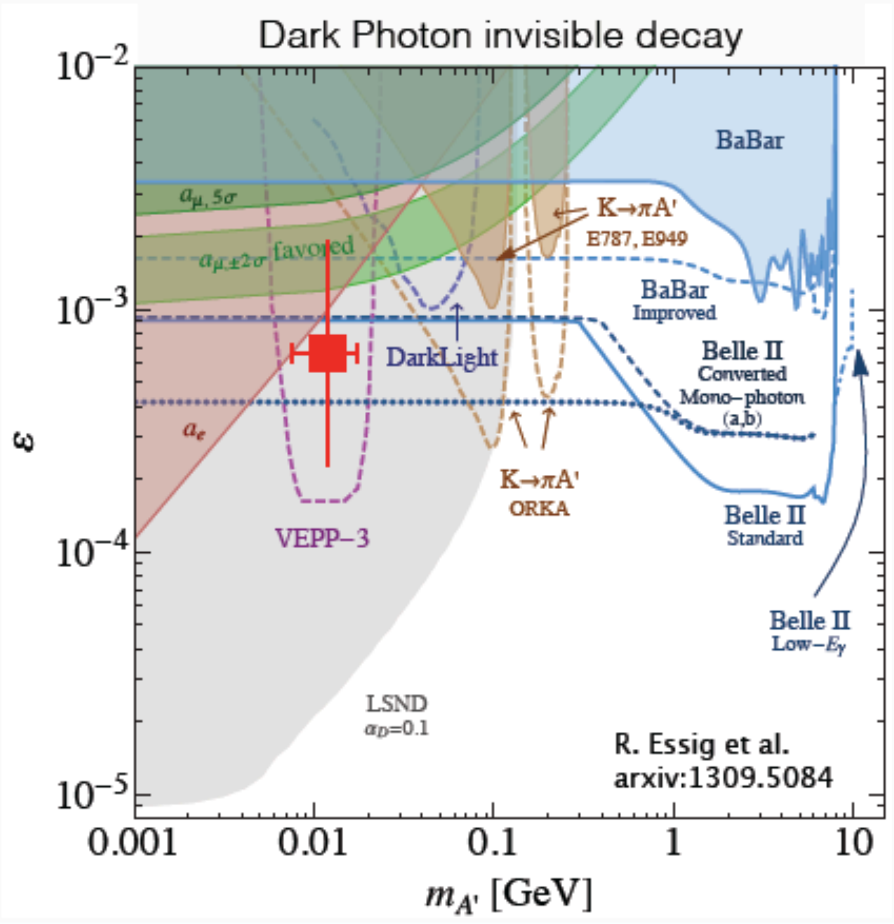


Protophobic boson



Dark Photon visible decay

P. Ilten et al.
Phys. Rev. D 92, 115017 (2015)



Dark Photon invisible decay

R. Essig et al.
arxiv:1309.5084

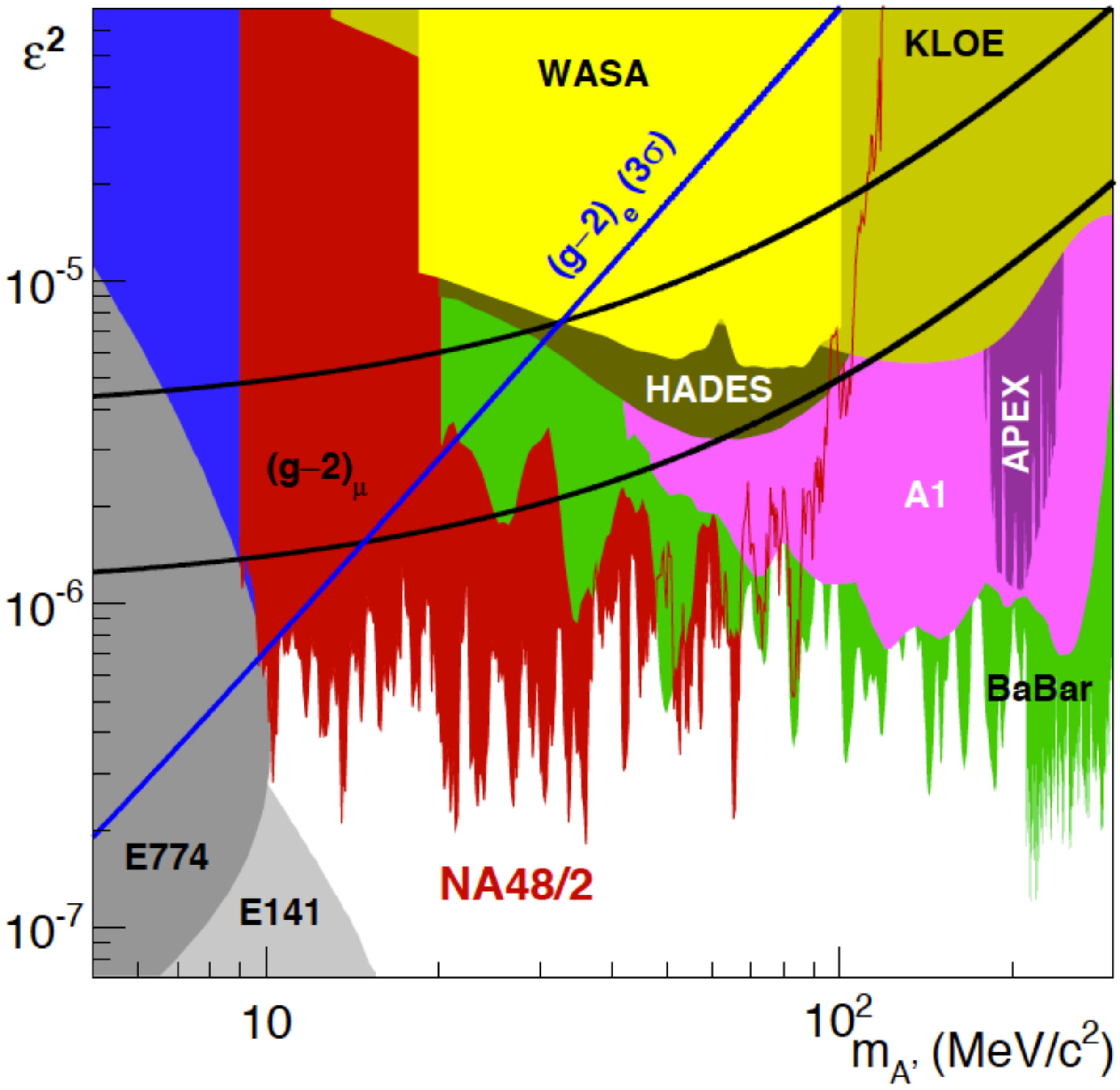
- Conflict with other measurements can be resolved if ϵ_p != ϵ_n
- (^{8}Be points approximate)

R. Corliss, MIT

A. J. Krasznahorkay *et al.*, PRL 116, 42501 (2016)
J. Feng *et al.*, arXiv:1604.07411 [hep-ph]; 1608.03591 [hep-ph]

Search for light U(1) gauge boson *A'*

- Light mediator of dark force coupled to SM via kinetic mixing; motivated by astrophysics, $g_\mu - 2$, (and proton radius puzzle R_p)

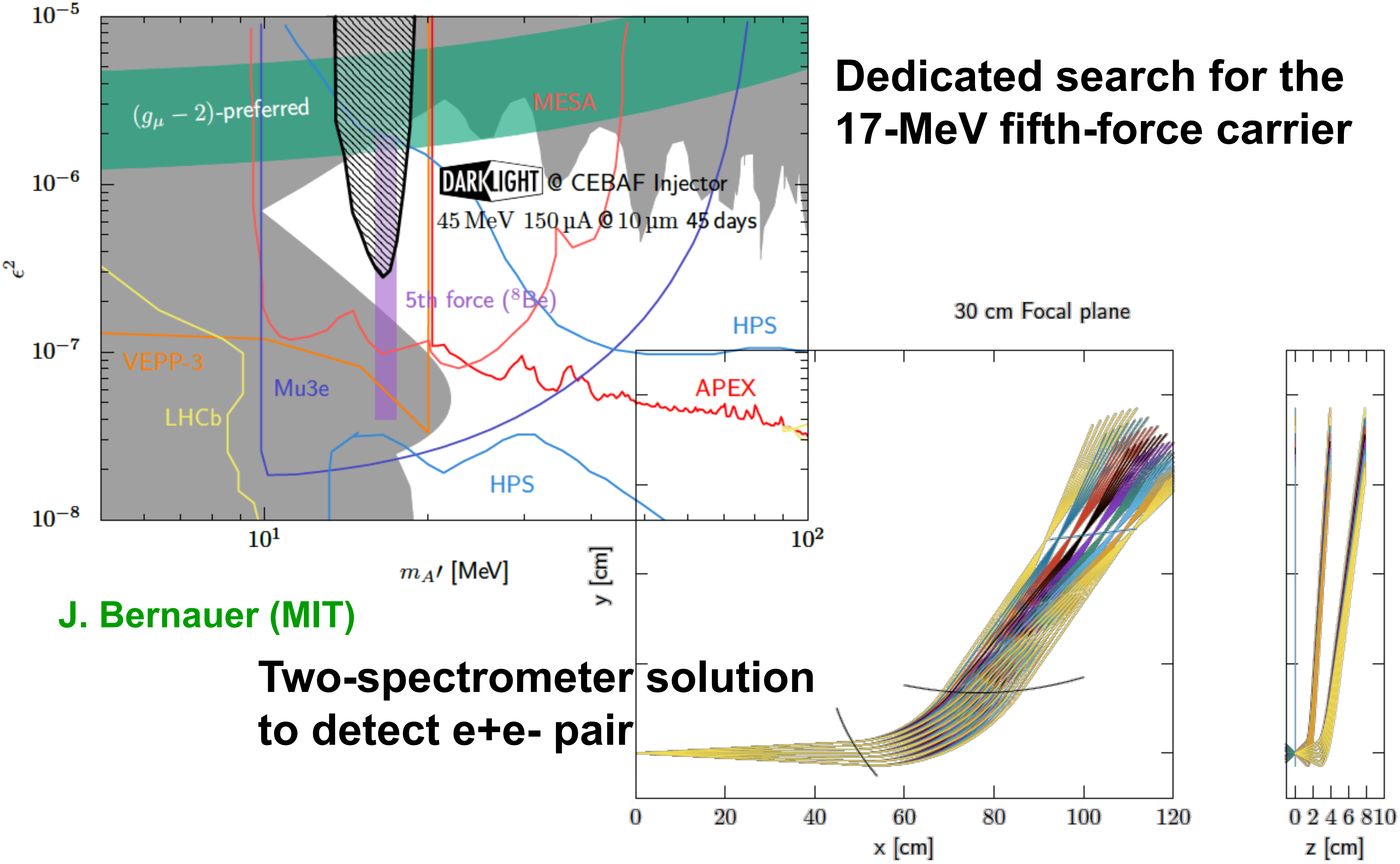


E. Goudzovski et al.
[NA48/2 collaboration],
arXiv:1504.00607

1.7e7 π^0 Dalitz decays

DarkLight phase 1c (in preparation)

Dedicated search for the 17-MeV fifth-force carrier



J. Bernauer (MIT)

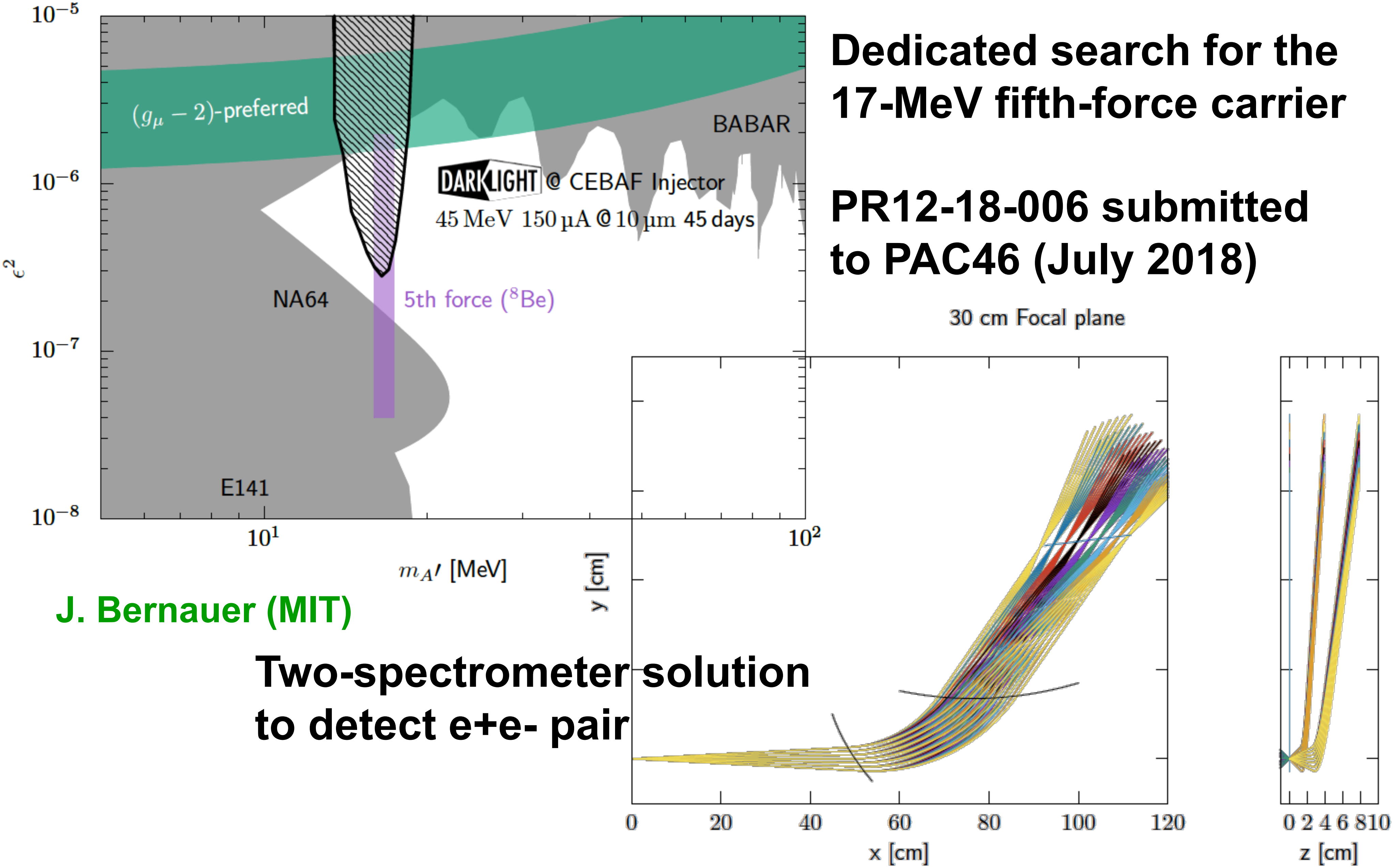
Two-spectrometer solution to detect e+e- pair

Construction of focal-plane detectors at Hampton U. (NSF/MRI)
2x 3 GEM elements ~25x40 cm^2 by fall 2018

DarkLight phase 1c (in preparation)

Dedicated search for the 17-MeV fifth-force carrier

PR12-18-006 submitted to PAC46 (July 2018)



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Summary

- Lepton universality is challenged (BaBar, Belle, LHCb)

- Proton radius puzzle to be studied with MUSE @ PSI:

  ➔ Size of TPE could be different for $\mu^{\pm}p$, $e^{\pm}p$

  ➔ μp and ep interaction could be fundamentally different

  Running in 2018-2019

- Non-universally coupled light bosons to explain a_μ and R_p puzzles

  ➔ Rare kaon decays with TREK/E36 @ J-PARC

  Data taken in 2015, under analysis

- Dark photons, protophobic bosons searched with DarkLight @ Jlab

  ➔ Staged approach in phases 1a, 1b, 1c, and 2

  Pioneering run in 2016, Program for 2017-2020

  Phase-1C: Dedicated search for the 17-MeV fifth-force carrier

Backup