HU experimental nuclear physics group seminar, Oct. 9, 2012

The proton radius puzzle

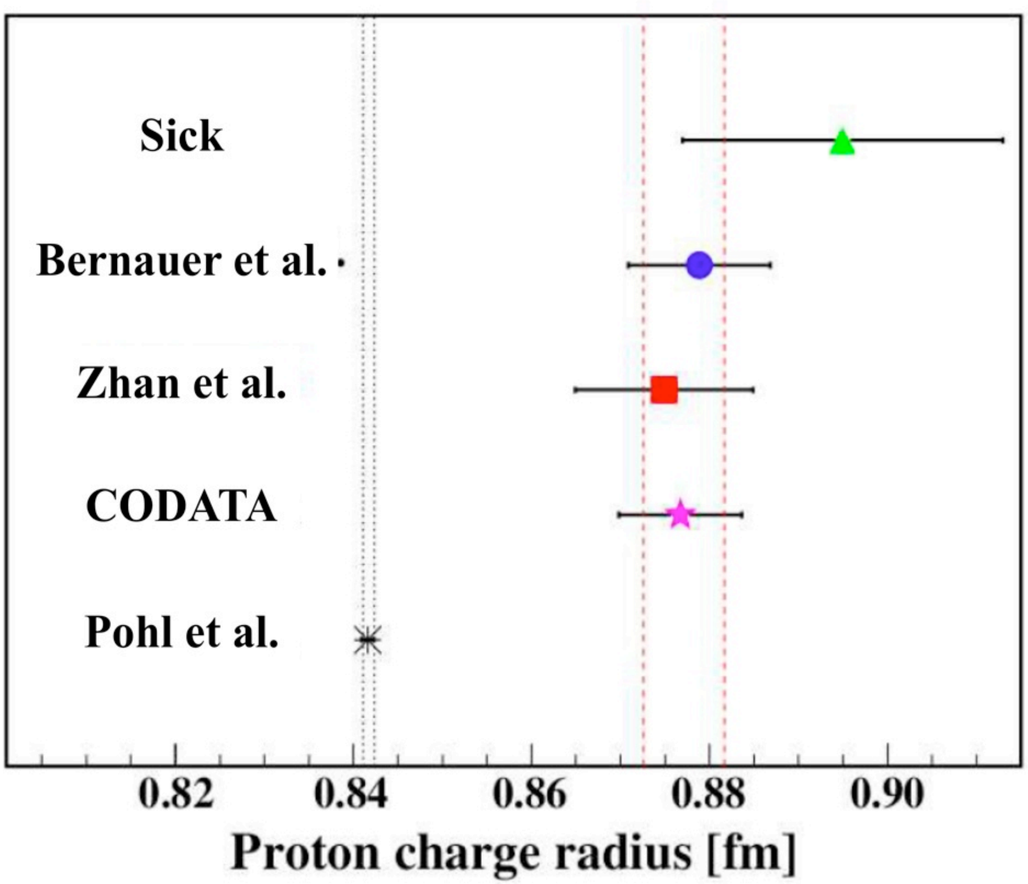
Michael Kohl

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

* Supported by NSF grants PHY-0855473 and 0959521, and DOE Early Career Award DE-SC0003884

The proton radius puzzle

- 7σ discrepancy between muonic hydrogen Lamb shift and combined electronic Lamb shift and electron scattering
- High-profile articles in Nature, NYTimes, etc.
- Special feature at many conferences



#	Extraction	$\langle r_E \rangle^2$ (fm)
1	Sick	0.895±0.018
2	Bernauer Mainz	0.879±0.008
3	Zhan JLab	0.870±0.010
4	CODATA	0.877±0.007
5	Combined 2-4	0.876±0.005
6	Muonic Hydrogen	0.842±0.001

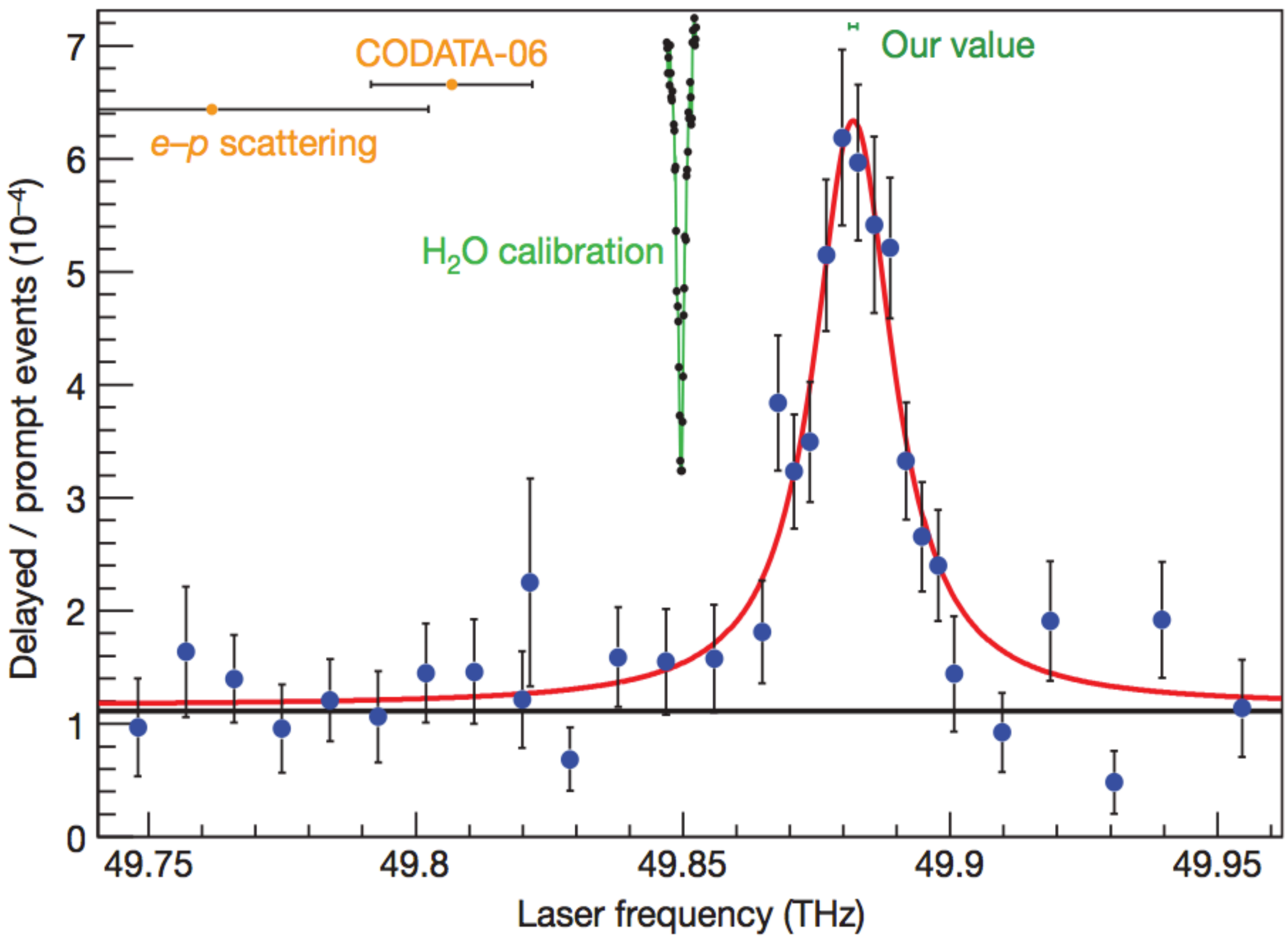
PSI muonic hydrogen measurements

R. Pohl et al., Nature 466, 09259 (2010): 2S⇨2P Lamb shift

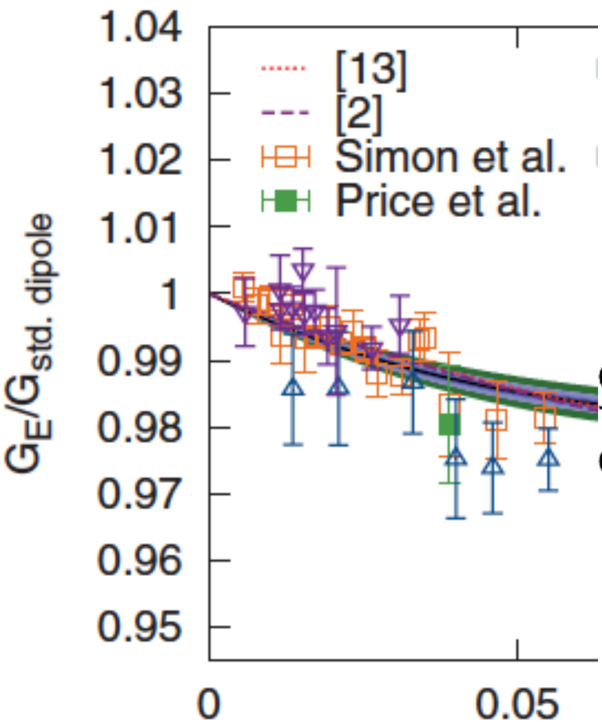
ΔE (meV) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3

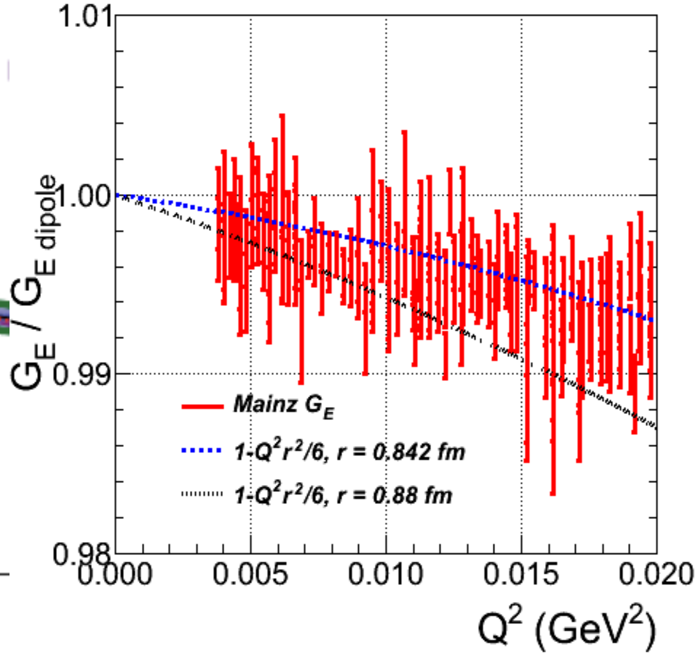
⇨ r_p = 0.842 ± 0.001.

Possible issues: atomic theory & proton structure

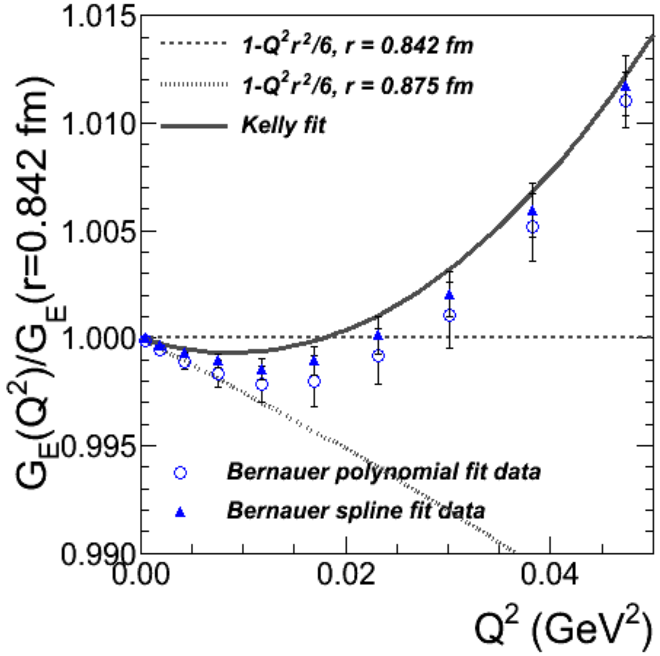


Proton radius from Mainz A1 data



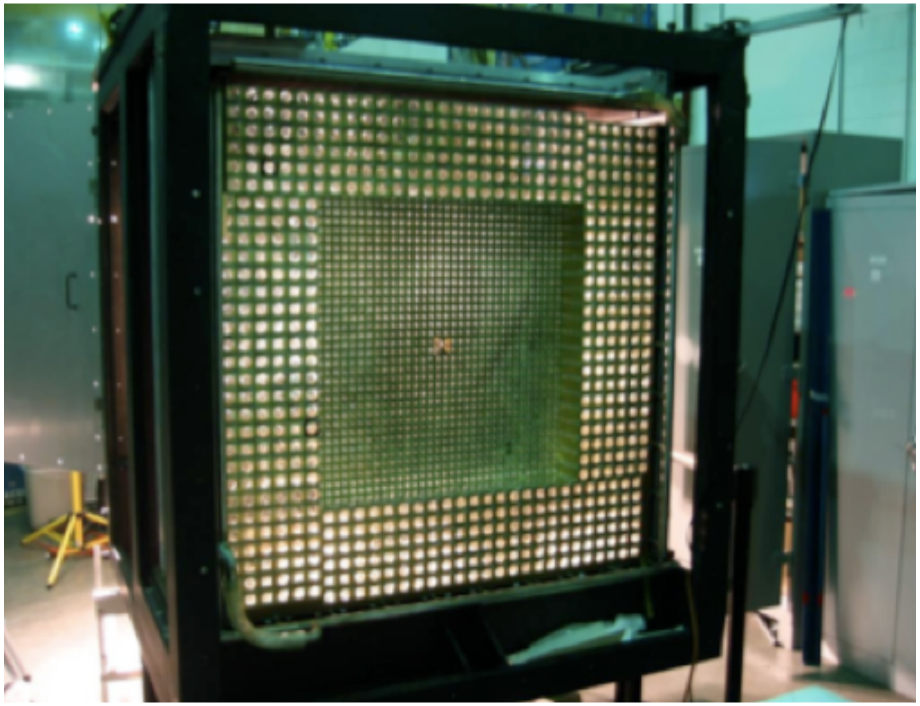


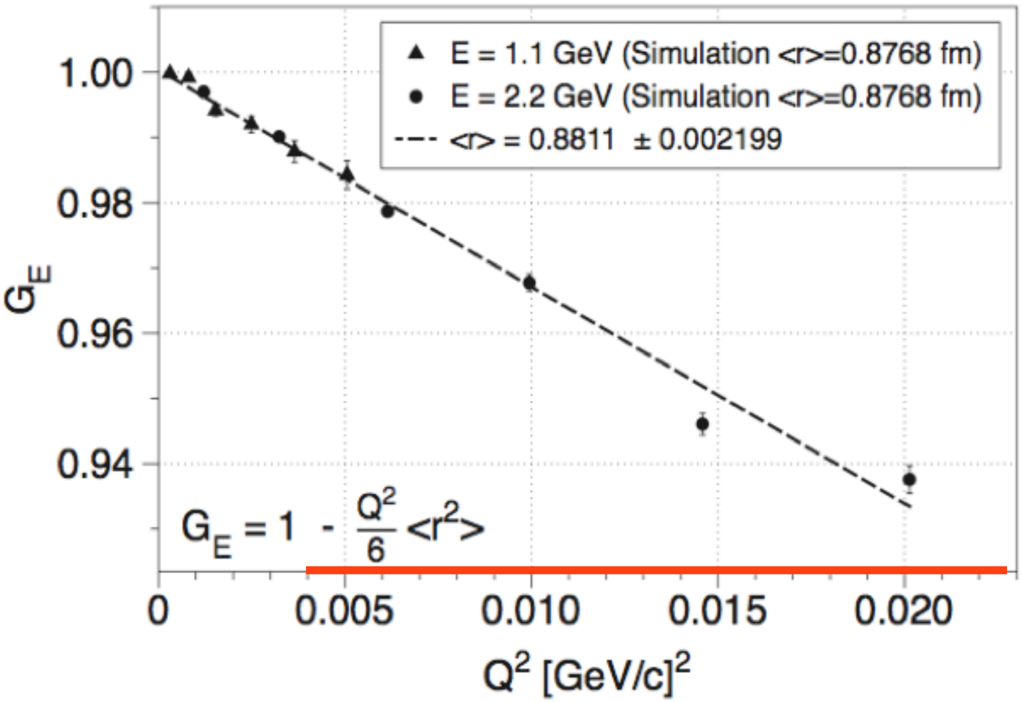
$G_E(Q^2) = 1 - Q^2r^2/6 + \ldots$



- Low Q^2 – J. Bernauer et al., PRL105 (2010) 242001
- Left: world + Mainz fit; Middle: Mainz raw data; Right rebinned G_E
- Large difference in slope between r = 0.84 and 0.88 fm
- Floating normalization, higher-order Q^2 terms present
- Need yet higher precision

The “PrimEx” proton radius proposal





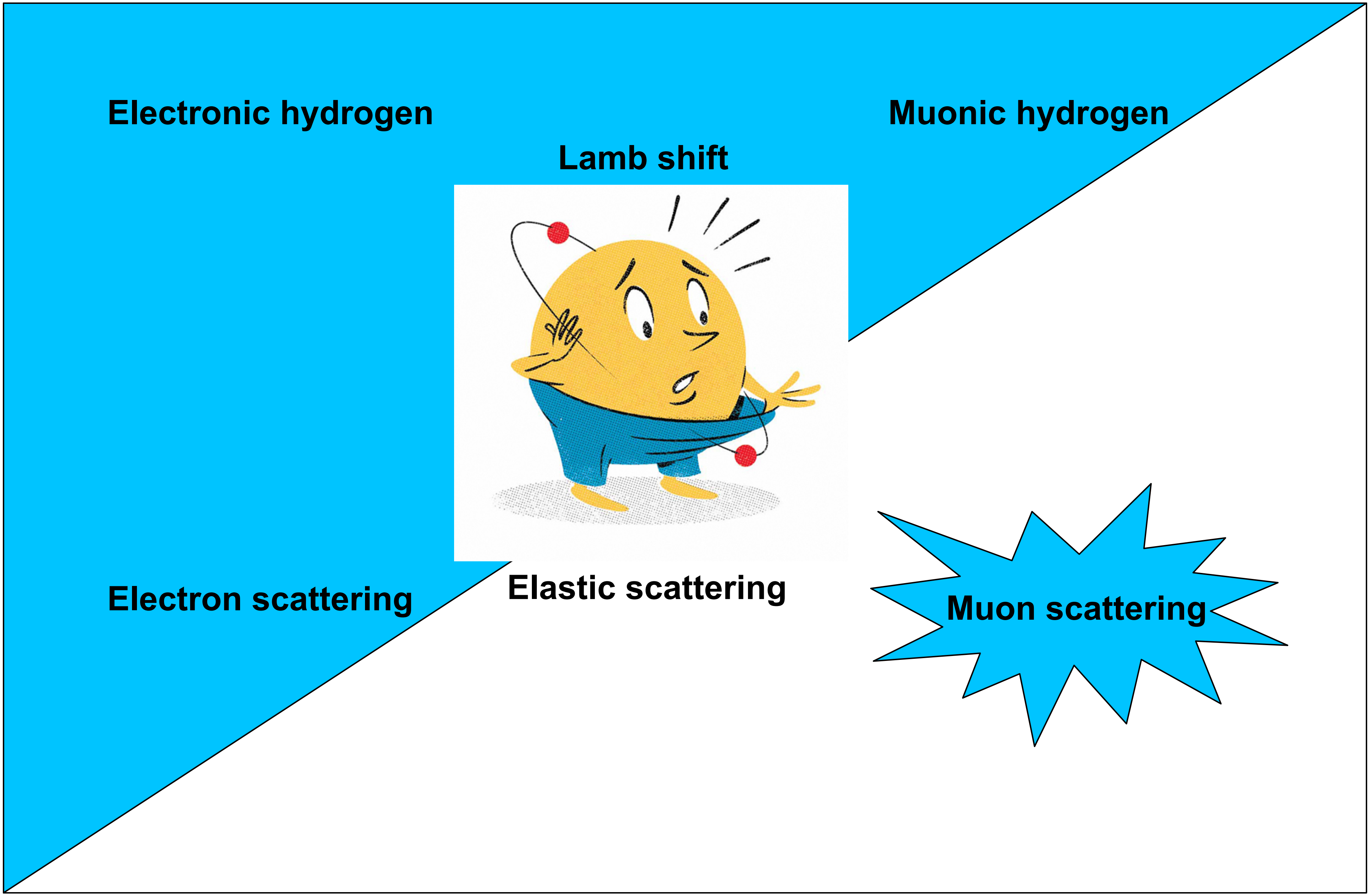
- Low intensity beam in Hall B @ Jlab into windowless gas target.
- Scattered ep and Moller electrons into HYCAL at 0º.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M.
- Conditionally approved by PAC38 (Aug 2011): ``Testing of this result is among the most timely and important measurements in physics.”
- Approved by PAC39 (June 2012), graded “A”

Possible resolutions to the puzzle

- **The μp result is wrong**
  Discussion about theory and proton structure for extracting the proton radius from Lamb shift measurement
- **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
- **Physics beyond Standard Model differentiating μ and e**
  Lepton universality violation
  Existing constraints on new physics

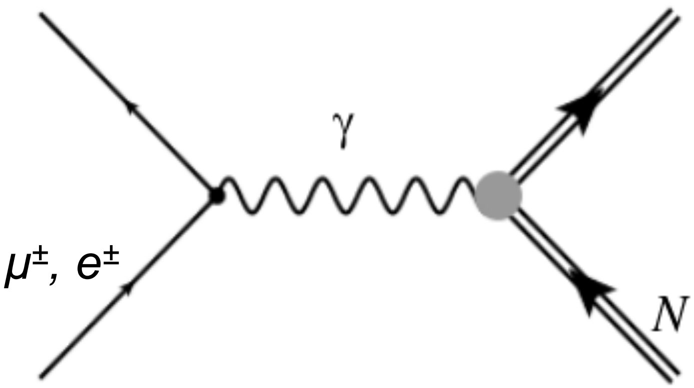
More insights from comparison of ep and μp scattering

Motivation for μp scattering



Lepton scattering and charge radius

Lepton scattering from a nucleon:



Vertex currents:

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

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

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 $Q^2 \to 0$ limit:

$$\langle r_E^2 \rangle = -6\left.\frac{dG_E^p(Q^2)}{dQ^2}\right|_{Q^2\to 0}$$

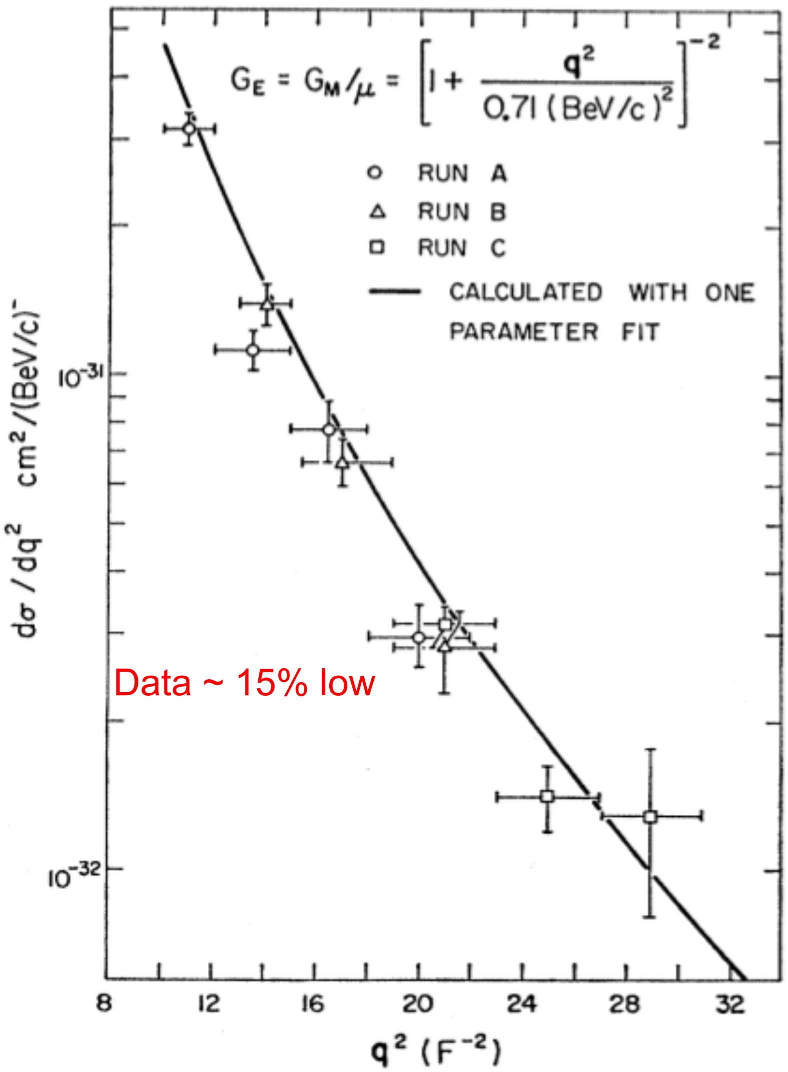
$$\langle r_M^2 \rangle = -6\left.\frac{dG_M^p(Q^2)/\mu_p}{dQ^2}\right|_{Q^2\to 0}$$

Expect identical result for ep and μp scattering

e-μ universality in lepton scattering

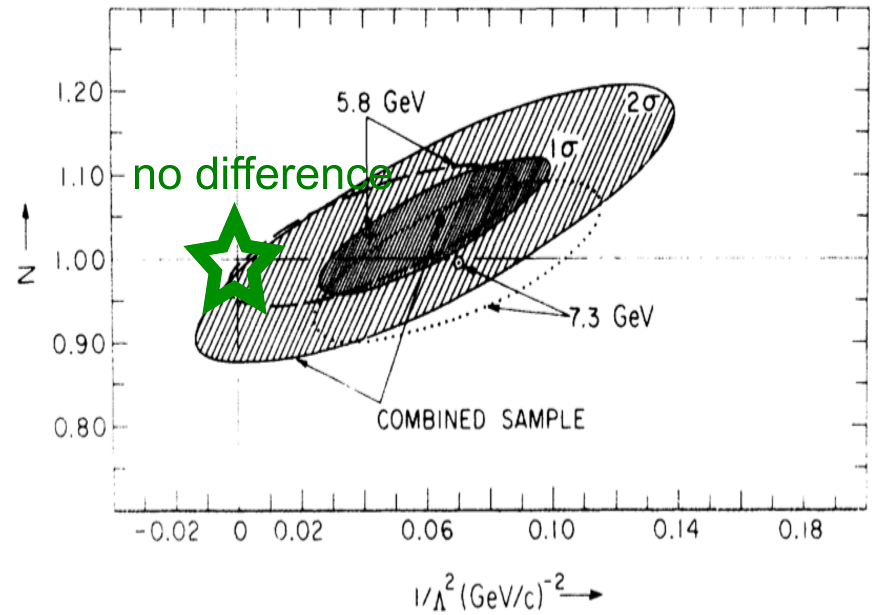
1960s-1970s: several experiments tested e-μ universality in scattering

Elastic μp scattering:
Ellsworth et al., Phys. Rev. 165 (1968)



Elastic μp: Kostoulas et al., PRL 32 (1974)

$$N \propto \frac{G_{\mu p}}{G_{ep}}$$



$1/\Lambda^2 = 0.006 \pm 0.016$ GeV^{-2}

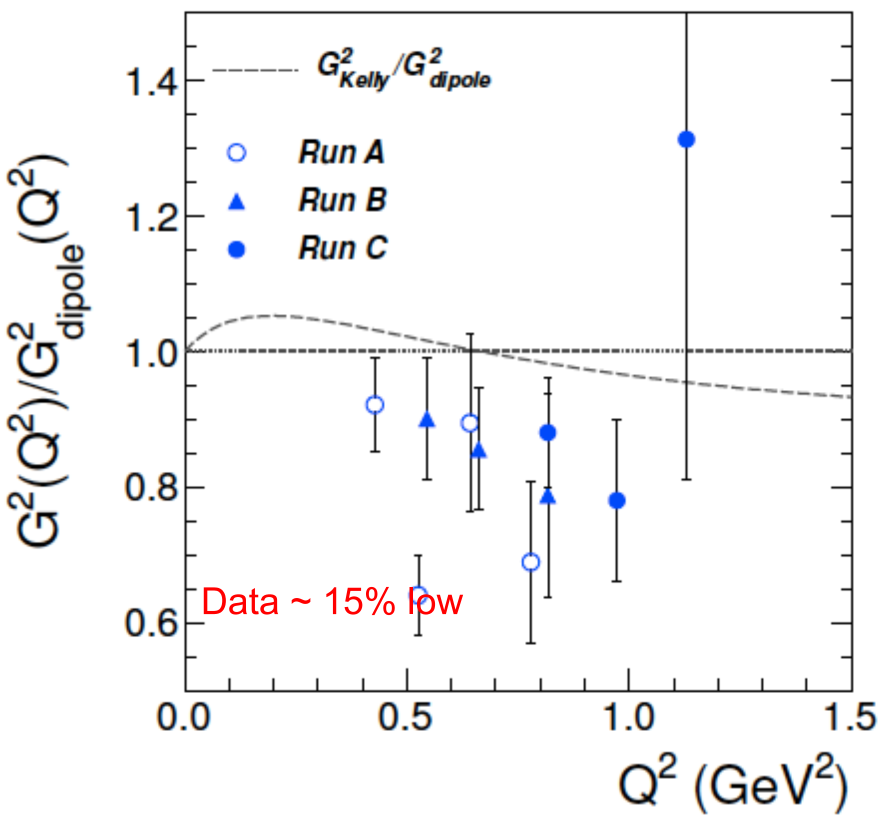
- DIS μp scattering: Entenberg et al., PRL 32 (1974)
  $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)
- e-C, and μ-C are in agreement

Constraints are not very good

e-μ universality in lepton scattering

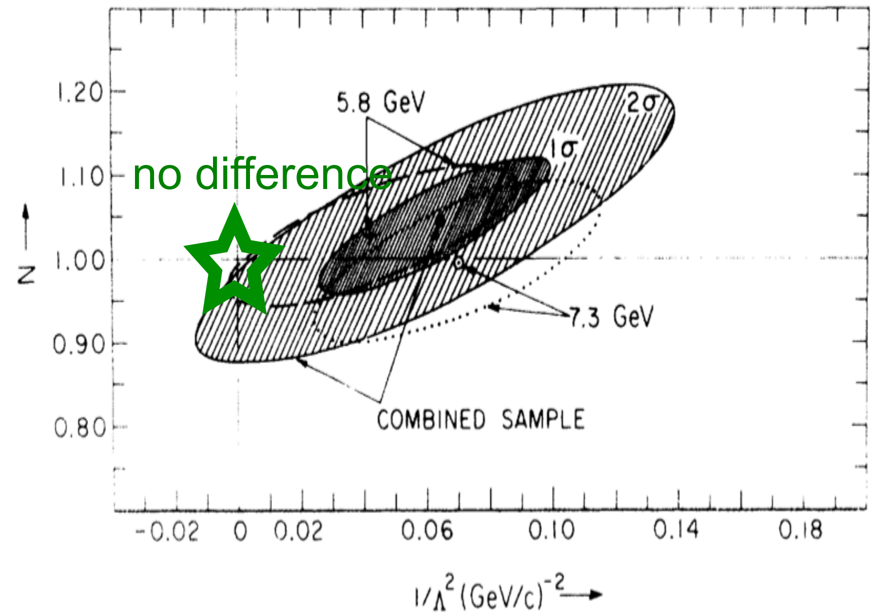
1960s-1970s: several experiments tested e-μ universality in scattering

Elastic μp scattering:
Ellsworth et al., Phys. Rev. 165 (1968)



Elastic μp: Kostoulas et al., PRL 32 (1974)

$$N \propto \frac{G_{\mu p}}{G_{ep}}$$



$1/\Lambda^2 = 0.006 \pm 0.016$ GeV^{-2}

- DIS μp scattering: Entenberg et al., PRL 32 (1974)
  $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)
- e-C, and μ-C are in agreement

Constraints are not very good

MUSE @ PSI

PAUL SCHERRER INSTITUT

PSI

The nine muses

MUSE Collaboration

~30 **MU**on proton **S**cattering **E**xperiment (MUSE) collaborators from 20 institutions

Spokespeople: R. Gilman, E. Piasetzky, G. Ron

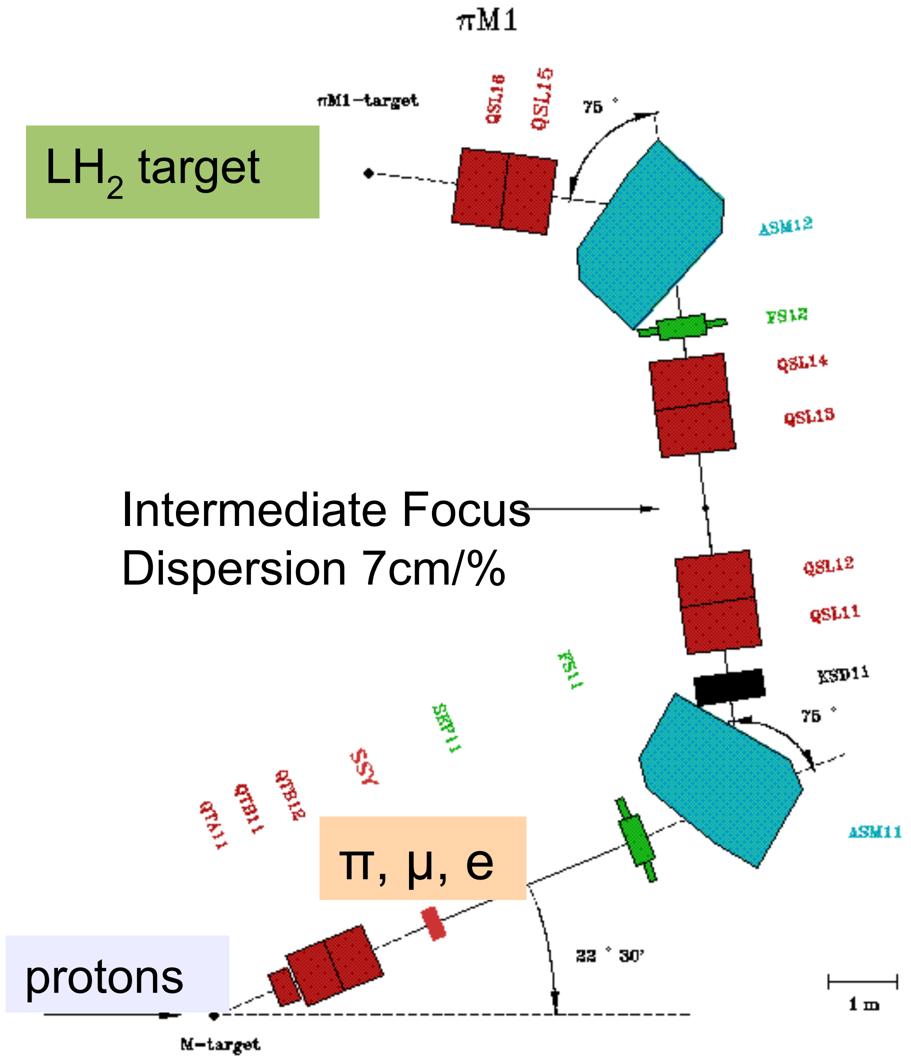
Argonne National Lab, Christopher Newport University, Technical University of Darmstadt, Duke University, George Washington University, Hampton University, Hebrew University of Jerusalem, Jefferson Lab, Massachusetts Institute of Technology, Norfolk State University, Paul Scherrer Institute, Rutgers University, University of South Carolina, Seoul National University, St. Mary's University, Tel Aviv University, Temple University, University of Virginia, College of William & Mary, Old Dominion University

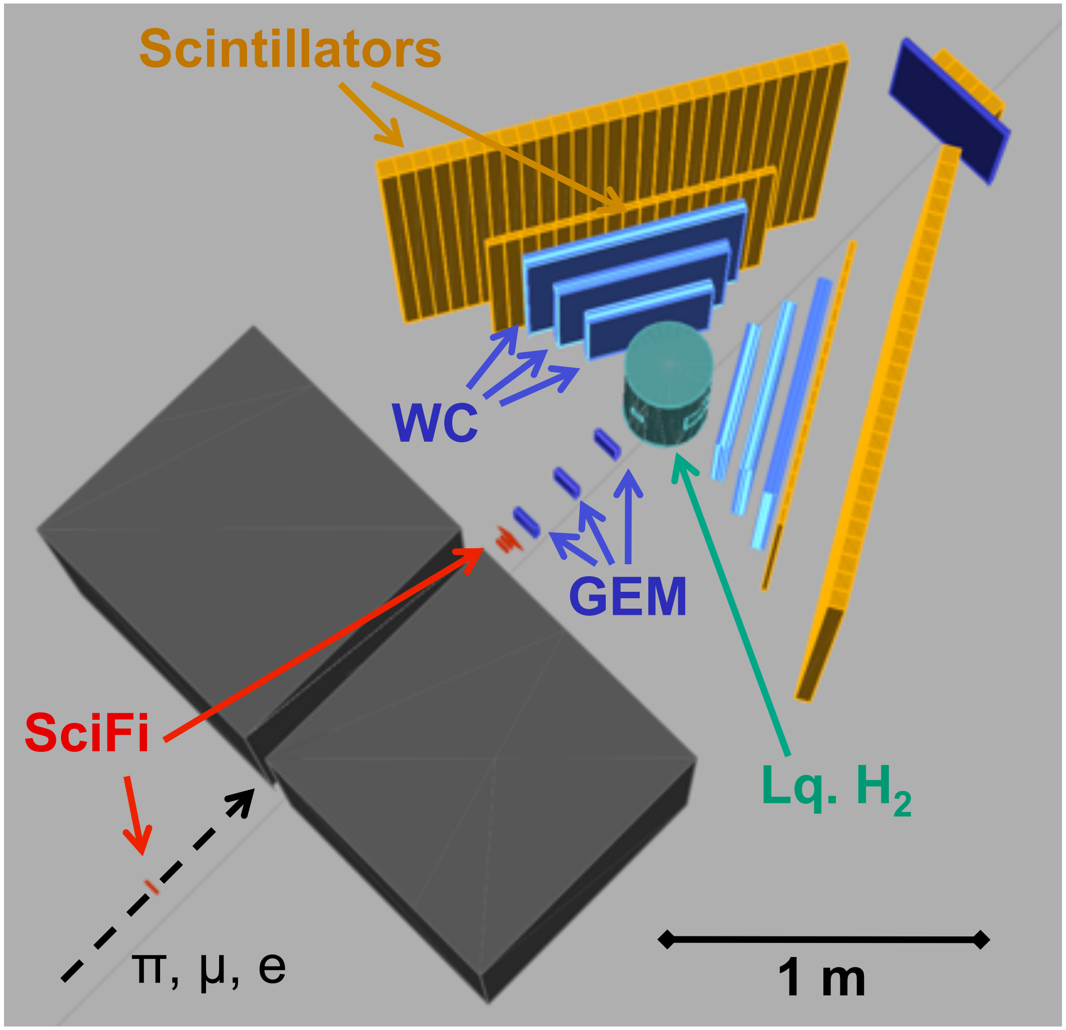
Proposal for $\mu^{\pm}p/e^{\pm}p$ scattering at PSI

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

- **Measure absolute cross section for μp scattering and cross section ratios to other species**
- **Simultaneously measure ep scattering**
  → μ/e ratio to cancel certain systematics
  → If radii differ by 4%, form factor slope differs by 8%, and cross section slope differs by 16%
- **Measure e+, e- and μ+, μ- on target**
  → Directly extract information on two-photon exchange (TPE) effect and compare for e, μ
- **Use multiple beam energies**
  → separate G_E and G_M with the Rosenbluth method

MUSE beamline and experiment layout





πM1: 100-500 MeV/c
Momentum measurement
RF+TOF separated π, μ, e

Beam particle tracking
Liquid hydrogen target
Scattered lepton detection

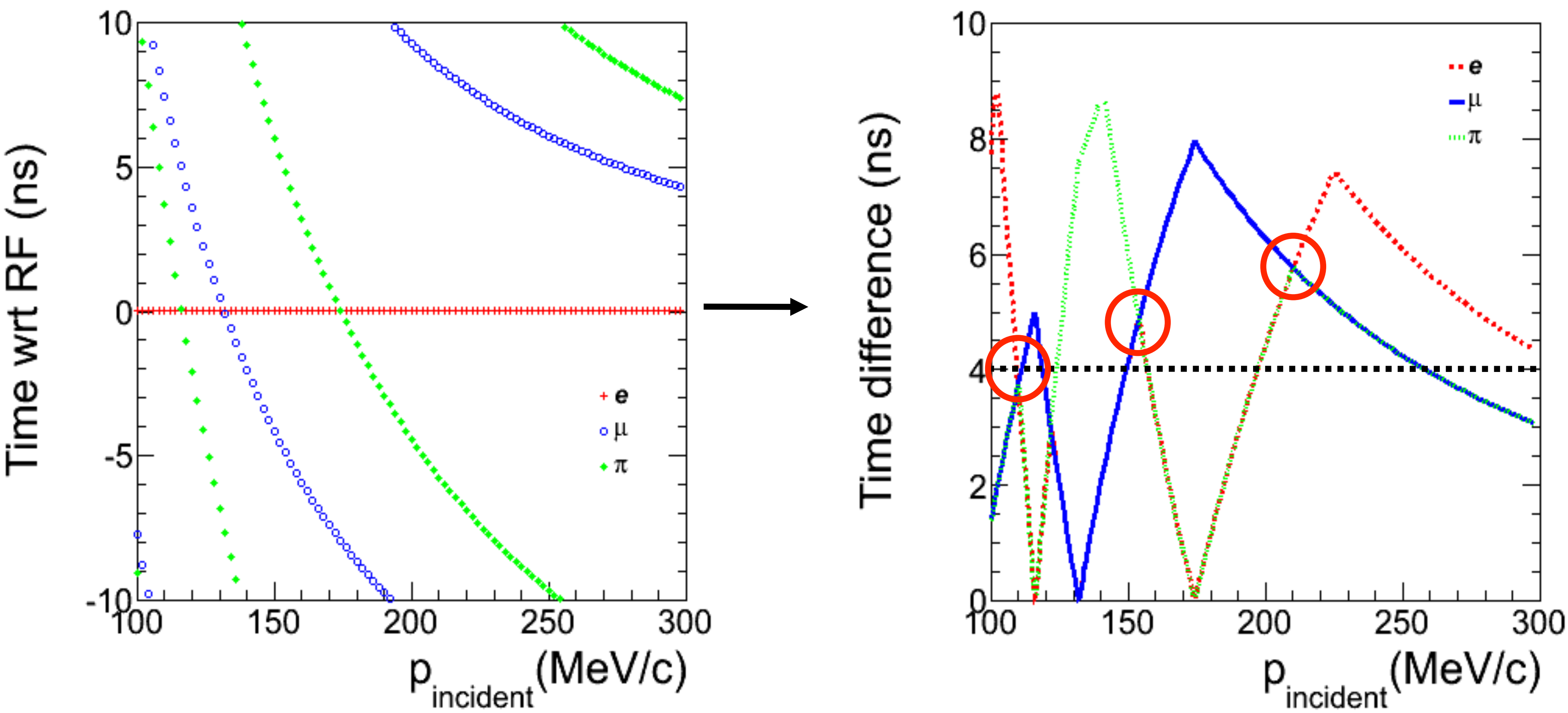
Separation of e, π, μ by RF time

Requirement: particle separation in time for PID

50 MHz RF → 20 ns between bunches

Timing of particles in target region wrt electron (β = 1)

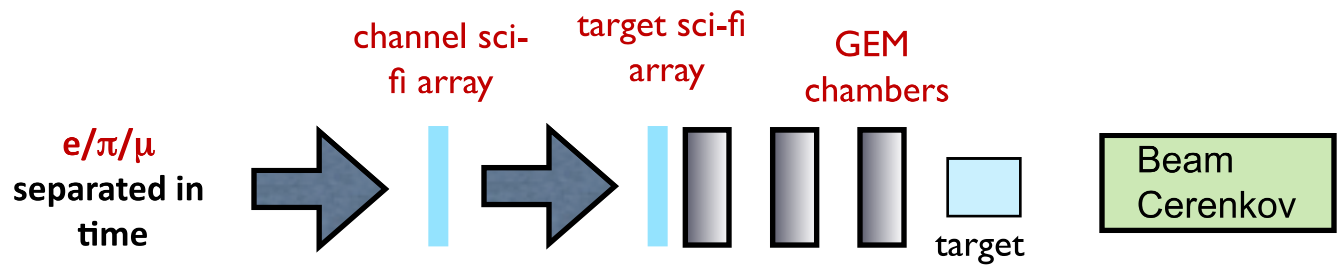
Minimum time separation of particles in target region



p = 115, 153, and 210 MeV/c

Beamline instrumentation

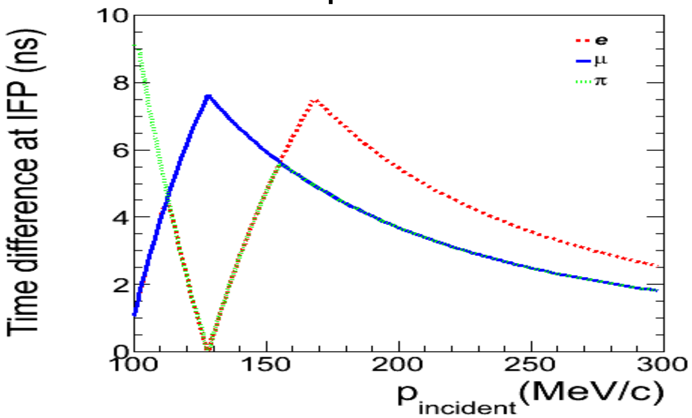
Beamline Elements:



Beam and target sci-fi arrays:

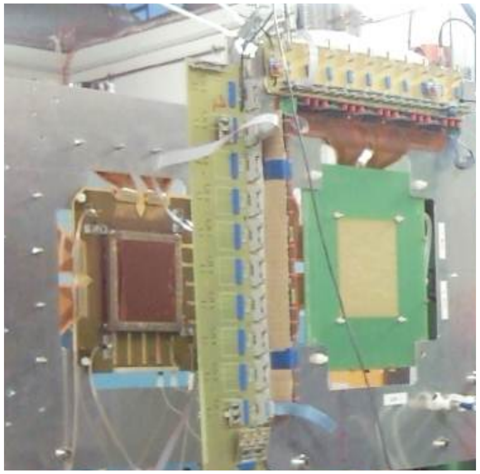
→ Flux, PID, TOF, momentum

Particles well separated at IFP:



GEM chambers:
→ Determine incident angle to 0.5 mr
→ Third GEM to reject ghost tracks
→ Existing chambers from UVa and OLYMPUS (Hampton University)

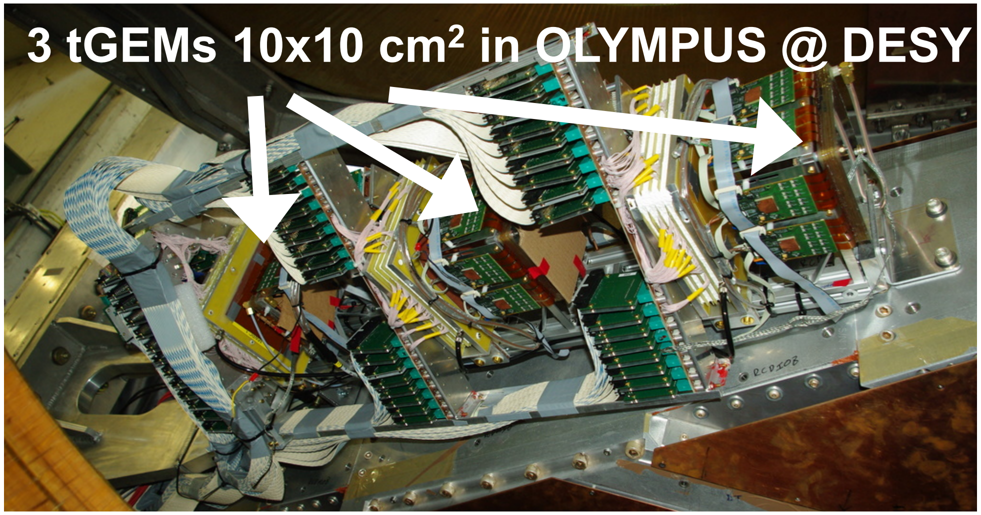
UVa GEM



COMPASS GEMs
routinely operated to ≈2.5 MHz/cm^2

Tested up to several 10s of MHz/cm^2

PSI: 10 MHz/1.5 cm^2 = 6.7 MHz/cm^2 (average) rate

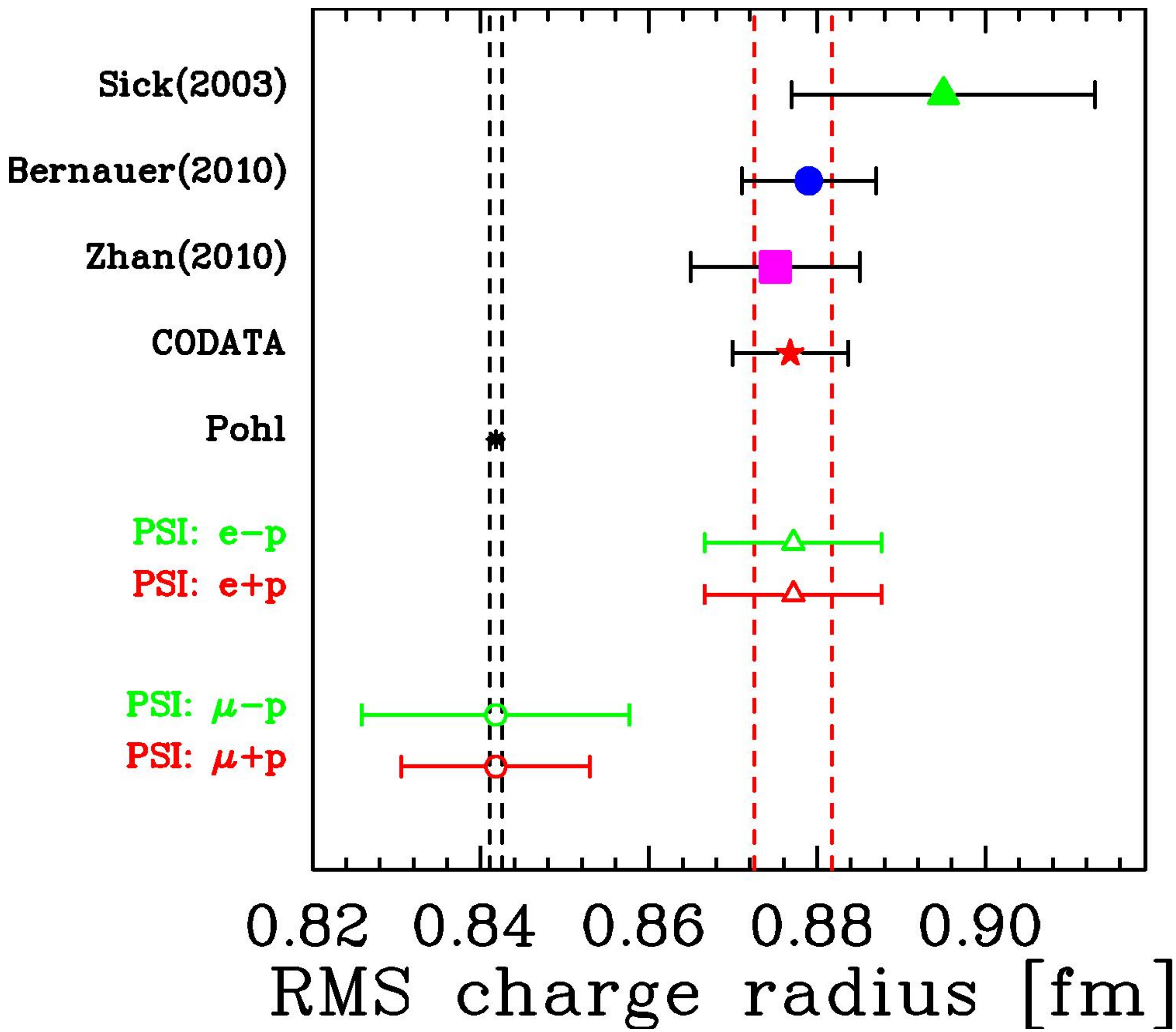


Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons



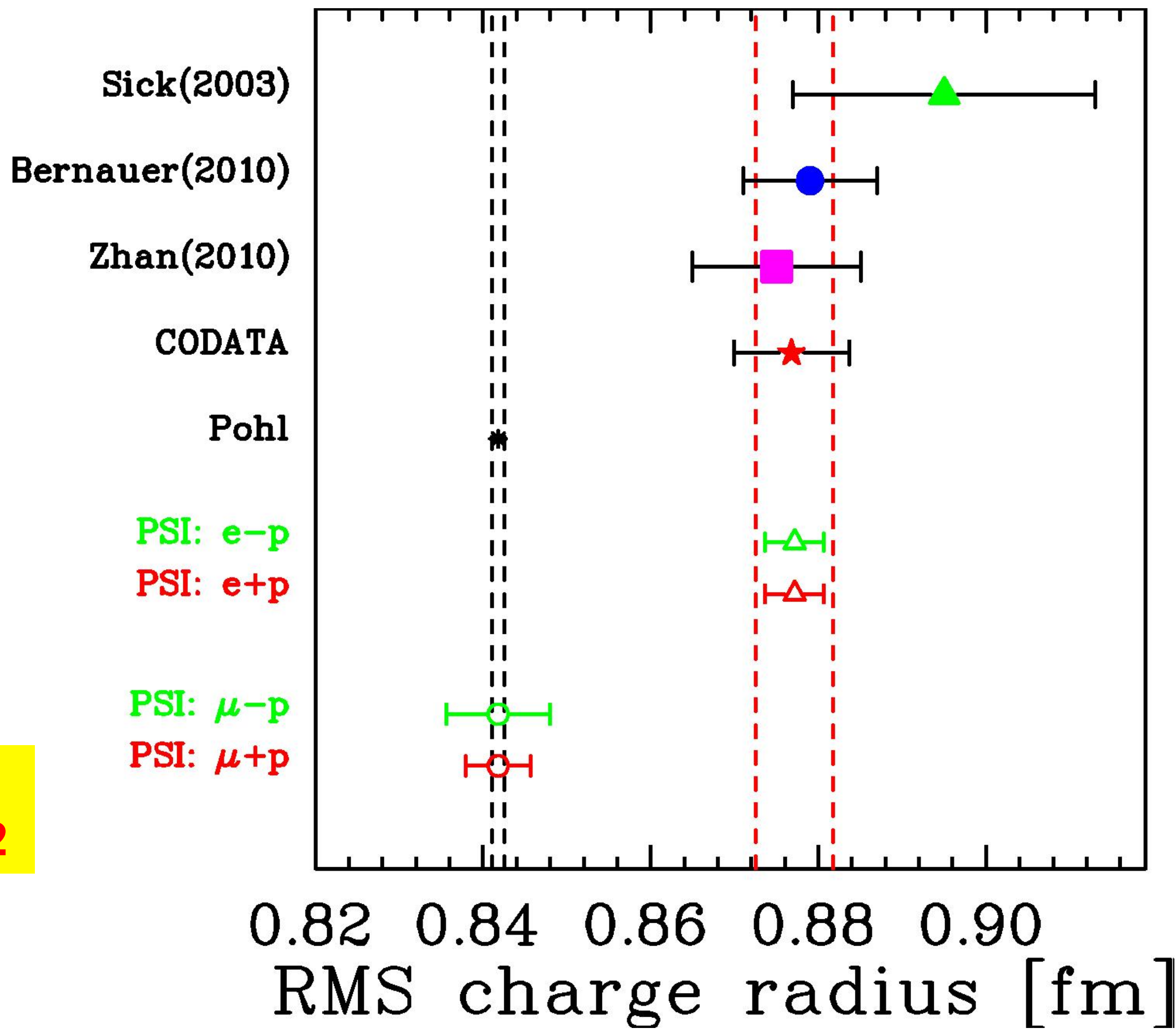
Projected sensitivity

Charge radius extraction limited by systematics, fit uncertainties

Comparable to existing e-p extractions, but not better

Many uncertainties are common to all extractions in the experiments: Cancel in e+/e-, μ+/μ-, and μ/e comparisons

Relative comparison reduces errors by factor of 2



Muon Scattering Experiment

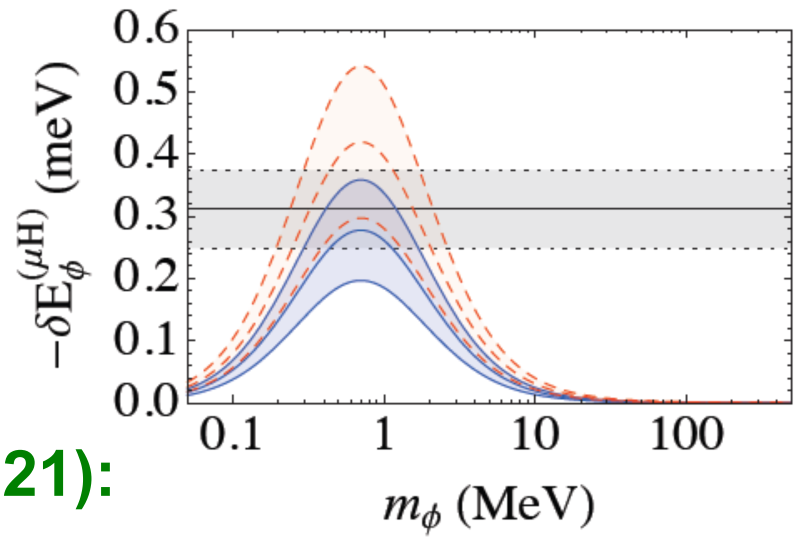
- **Proton Radius Puzzle** – a 7σ discrepancy between ep and muonic Lamb shift measurements
- **Still unresolved ~2 years later**
- **PSI Experiment**
  - Measure μp and ep scattering and compare directly
  - Measure e+/e- and μ+/μ- to study/constrain TPE effects
- **Technical Challenges** – particle ID, timing resolution, background rejection, momentum and flux determination
- **MUSE timeline**
  - Initial proposal February 2012
  - Technical Review July 2012
  - Engineering test run – Fall 2012
  - Construction 2013–2015
  - Production running 2015–2016 (6 months)

The nine muses

A dark photon 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)

- 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

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

- constrained by K → μν decay

DarkLight

DarkLight collaboration

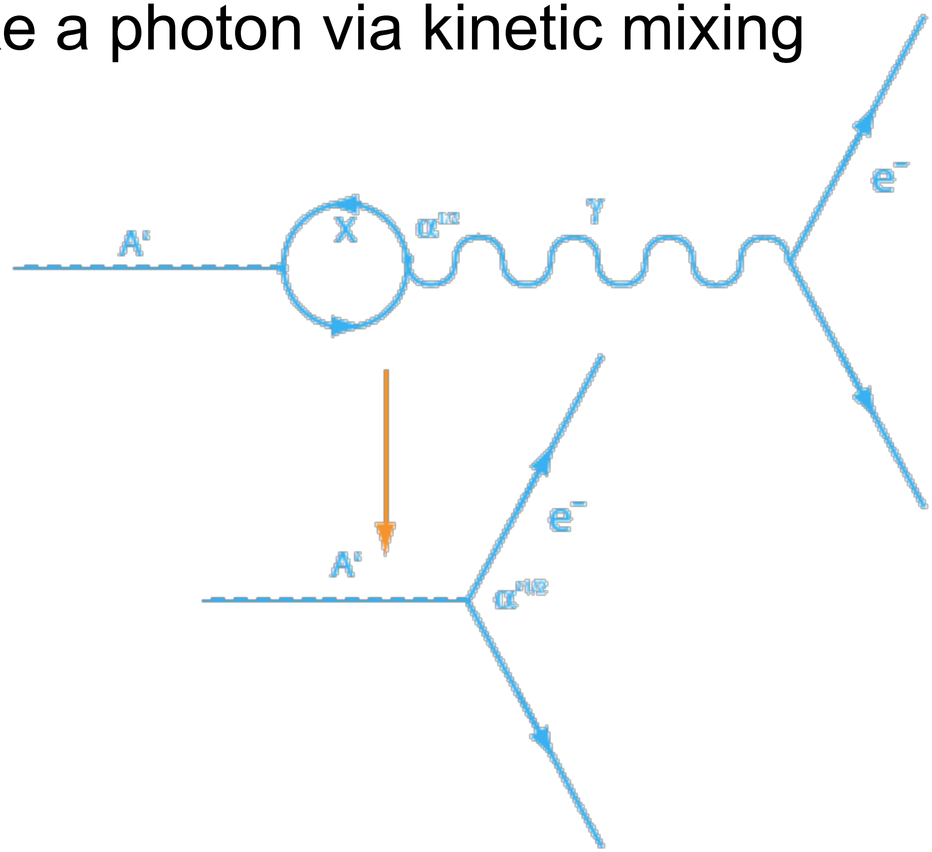
Spokespersons: Peter Fisher and Richard Milner

J. Balewski, J. Bernauer, W. Bertozzi, J. Bessuille, B. Buck, R. Cowan, K. Dow, C. Epstein, P. Fisher [2], S. Gilad, E. Ihloff, Y. Kahn, A. Kelleher, J. Kelsey, R. Milner, C. Moran, L. Ou, R. Russell, B. Schmookler, J. Thaler, C. Tschalaer, C. Vidal, A. Winnebeck
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA and the Bates Research and Engineering Center, Middleton MA 01949
S. Benson, C. Gould, G. Biallas, J. Boyce, J. Coleman, D. Douglas, R. Ent, P. Evtushenko, H. C. Fenker, J. Gubeli, F. Hannon, J. Huang, K. Jordan, R. Legg, M. Marchlik, W. Moore, G. Neil, M. Shinn, C. Tennant, R. Walker, G. Williams, S. Zhang *Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606*
M. Freytsis
Physics Dept., U.C. Berkeley, Berkeley, CA
R. Fiorito, P. O'Shea
Institute for Research in Electronics and Applied Physics University of Maryland, College Park, MD R. Alarcon, R. Dipert
Physics Department, Arizona State University, Tempe, AZ
G. Ovanesyan Los Alamos National Laboratory, Los Alamos NM
T. Gunter, N. Kalantarians, M. Kohl
Physics Dept., Hampton University, Hampton, VA 23668 and Jefferson Lab, 12000 Jefferson Avenue, Newport News, VA 23606
I. Albayrak, M. Carmignotto, T. Horn
Physics Dept., Catholic University of America, Washington, DC 20064
D. S. Gunarathne, C. J. Martoff, D. L. Olvitt, B. Surrow, X. Li
Physics Dept., Temple University, Philadelphia, PA 19122
E. Long *Physics Dept., Kent State University, Kent, OH, 44242*
R. Beck, R. Schmitz, D. Walther
University Bonn, D - 53115 Bonn Germany
K. Brinkmann, H. Zaunick
II. Physikalisches Institut Justus-Liebig-Universitt Giessen, D-35392 Giessen Germany
W.J.Kossler
Physics Dept., College of William and Mary, Williamsburg VA 23185

DARKLIGHT

DarkLight motivation

New theories of dark forces predict a dark force carrier in the mass range 0.01-1 GeV that couples like a photon via kinetic mixing



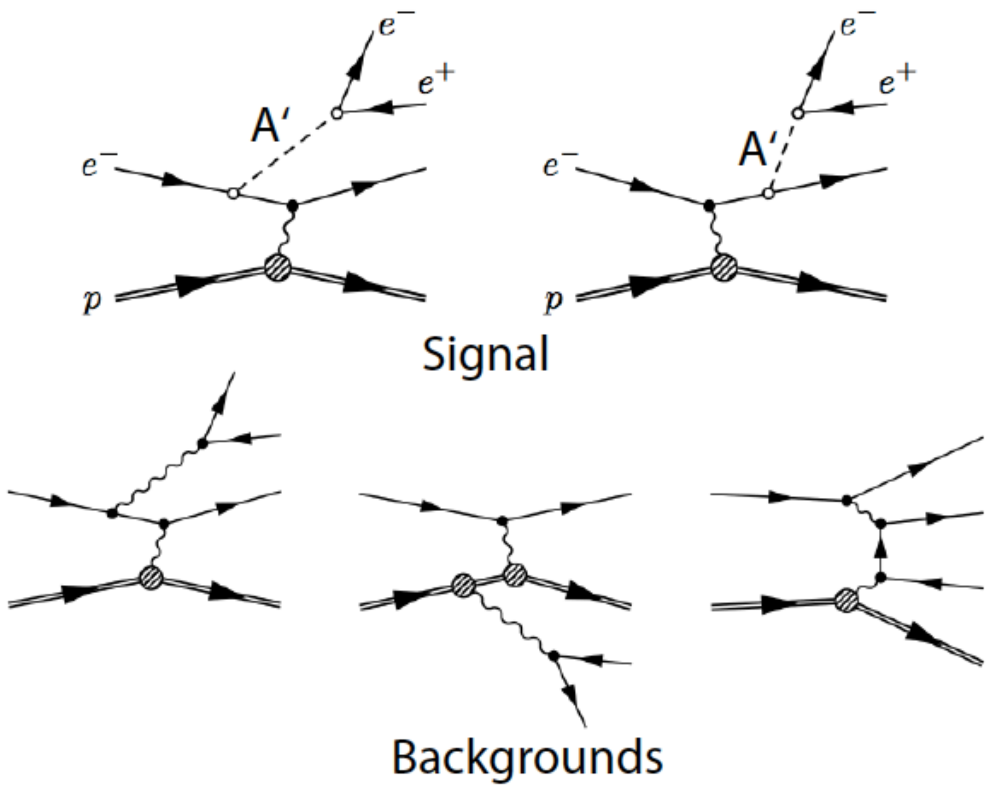
DarkLight concept:

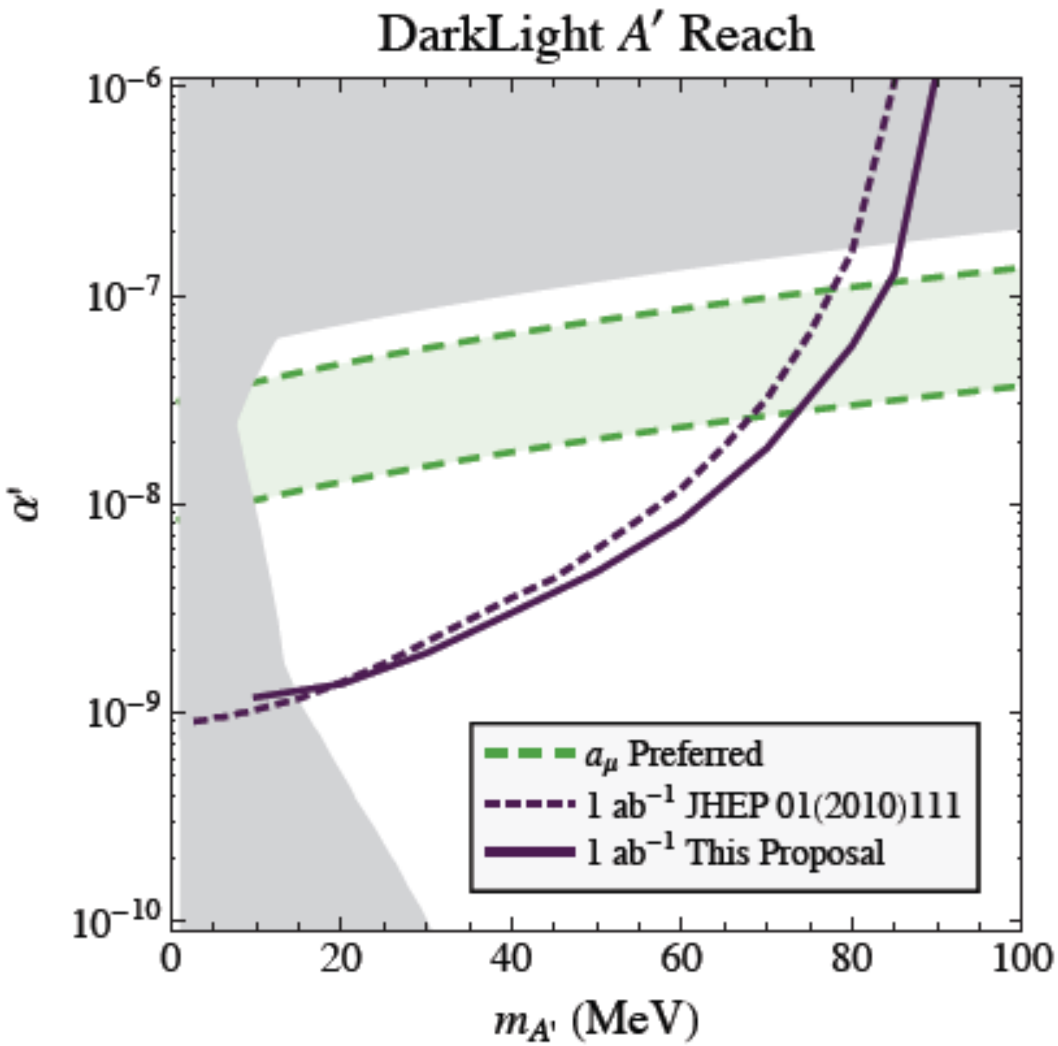
- Magnetic spectrometer
- Internal hydrogen target
- Free Electron Laser electron accelerator @ JLAB

Luminosity: 1 ab^{-1} per month

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

DarkLight sensitivity

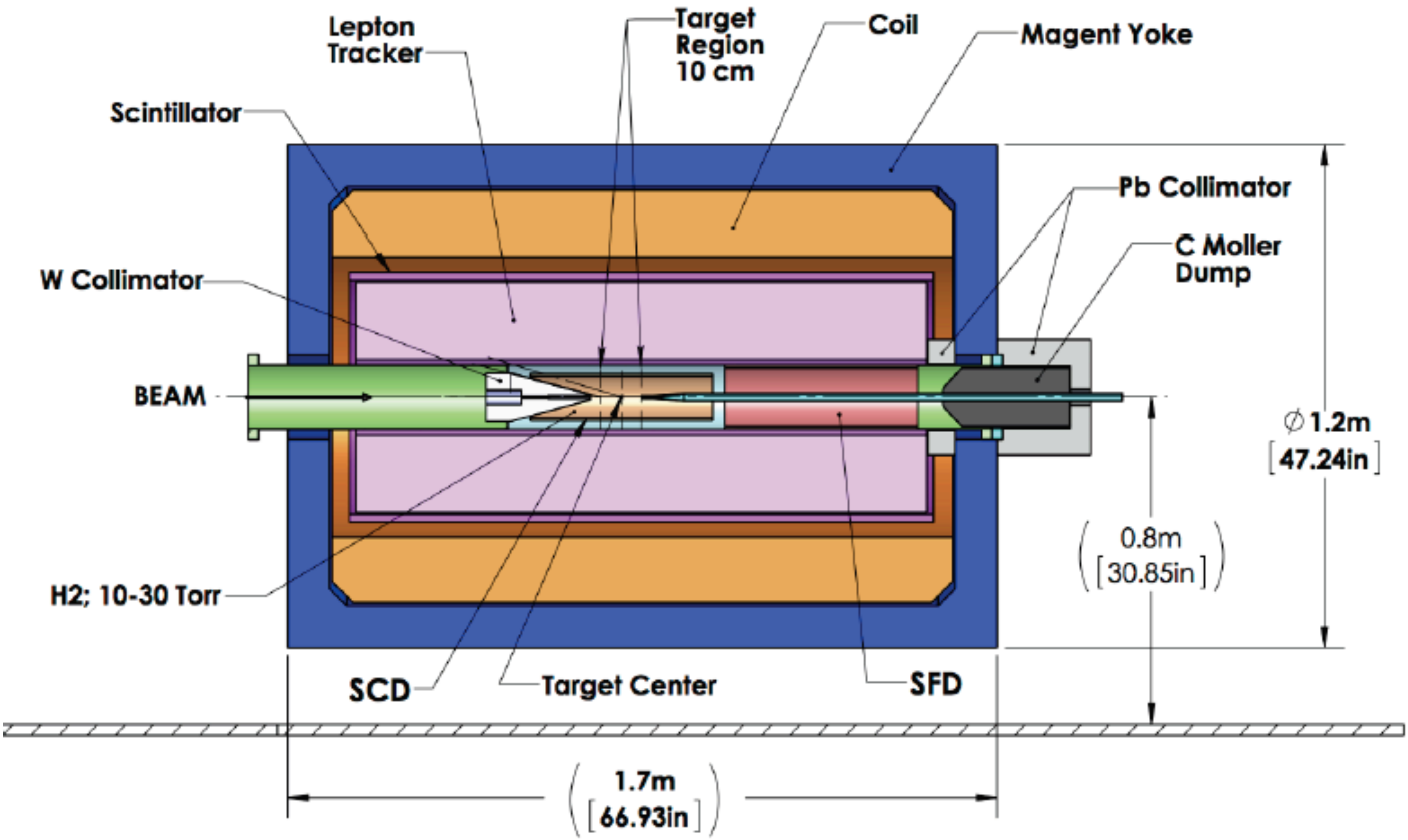




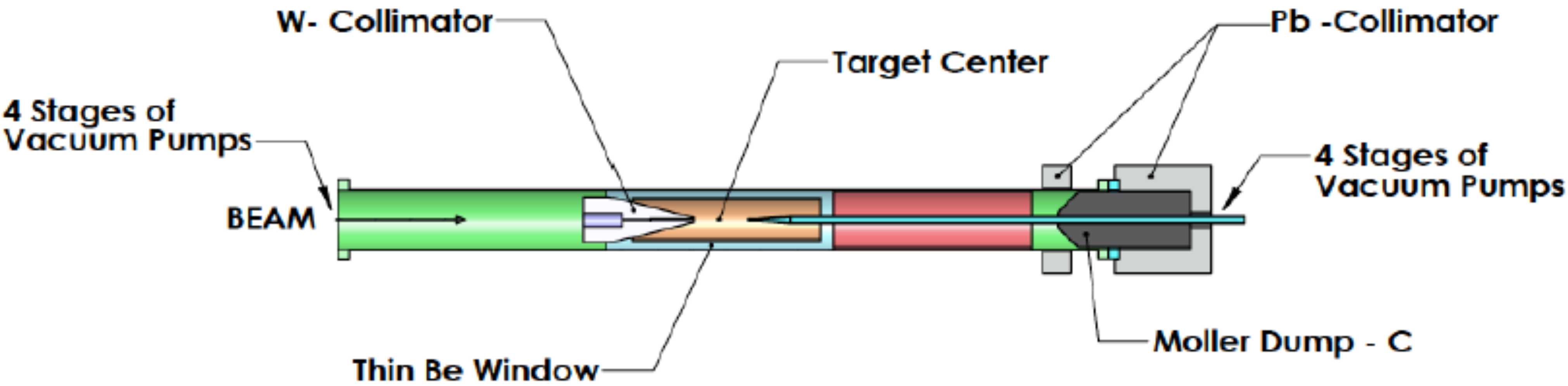
Goal: Explore $e^+ + e^-$ invariant mass spectrum from 10-90 MeV using the process $e^- + p \rightarrow e^- + p + e^- + e^+$

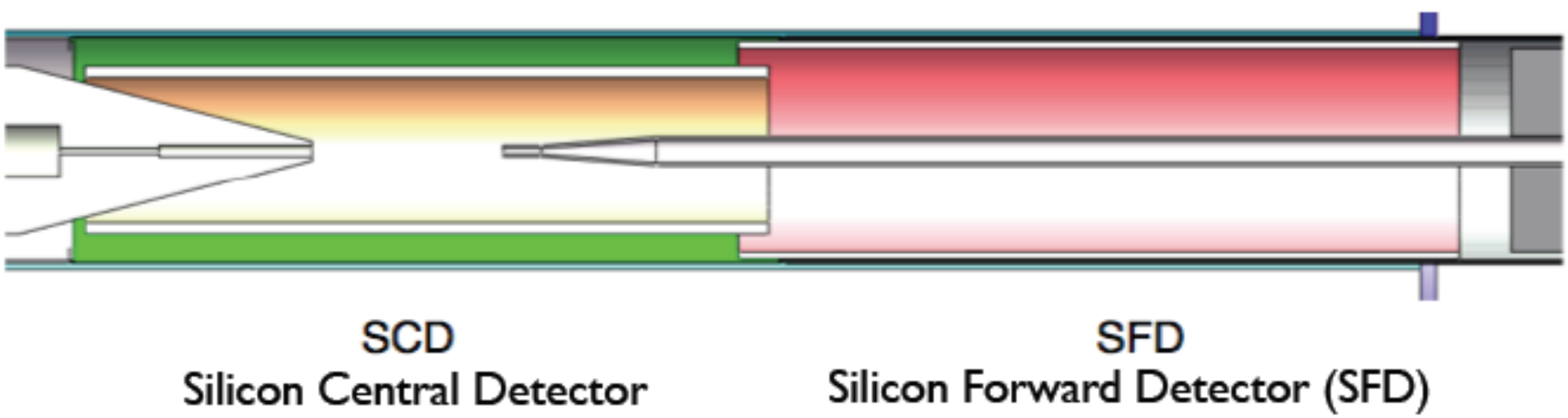
Experimental design

Internal target + solenoidal spectrometer w/ TPC

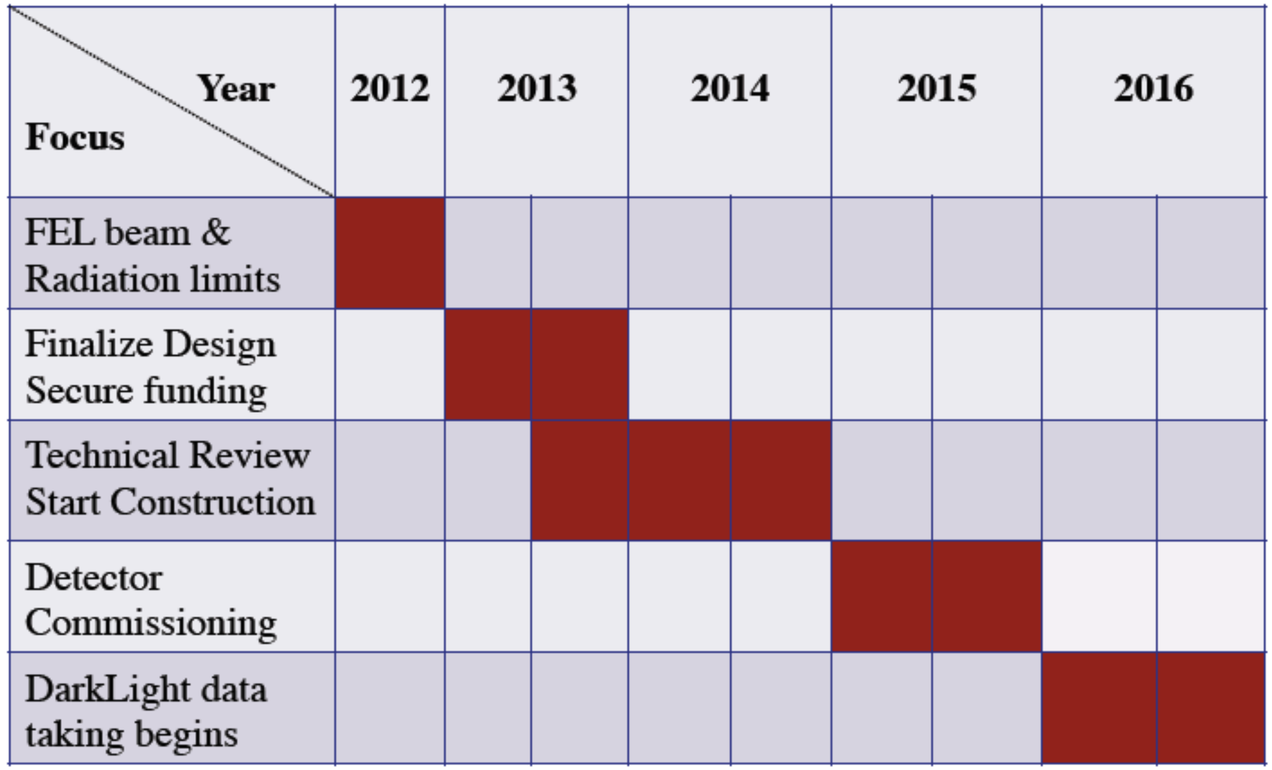


Target region





DarkLight timeline



- Presentation to PAC39 June 2012
- Initial test run July 2012
- Seek FY2013 funds for technical design
- Technical review summer 2013
- DarkLight construction begins Fall 2013
- DarkLight detector commissioning begins in 2015
- DarkLight data taking begins 2016

Lepton universality and the proton radius

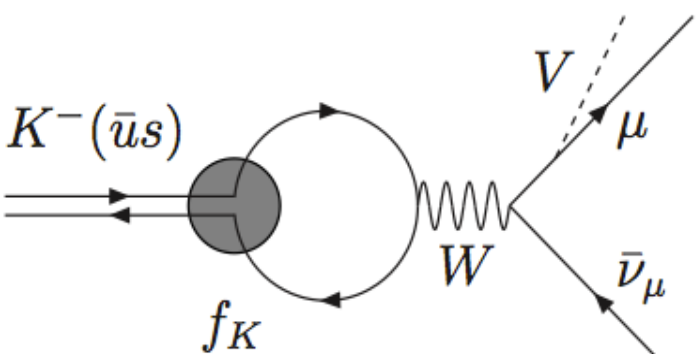
Batell, McKeen, Pospelov (arXiv:1103.0721):

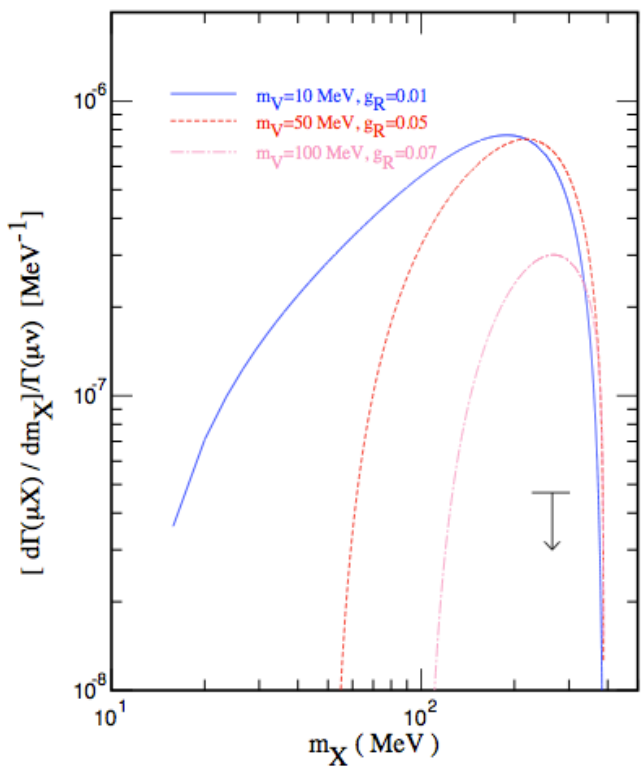
can solve proton radius puzzle

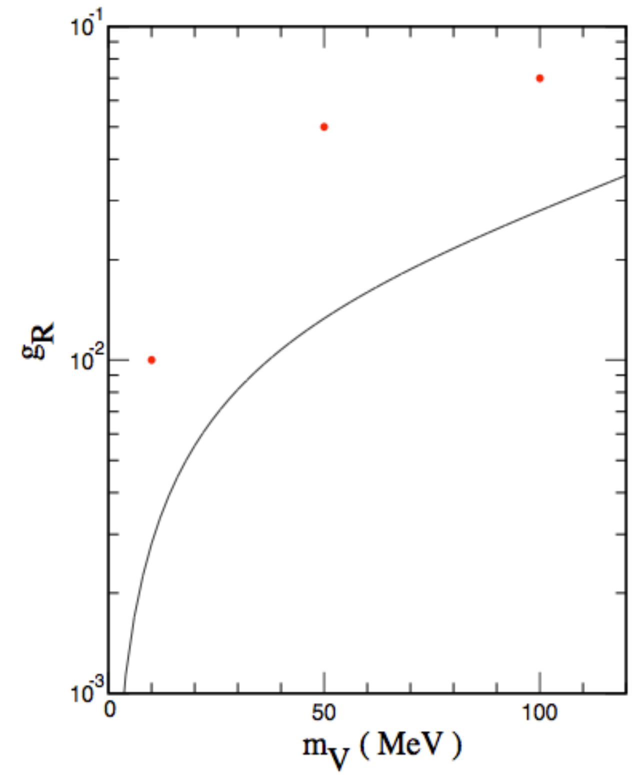
- new e/μ differentiating force consistent with g_μ-2
- <100 MeV gauge boson V or dark photon
- resulting in large PV μp scattering

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

- constrained by K → μν decay



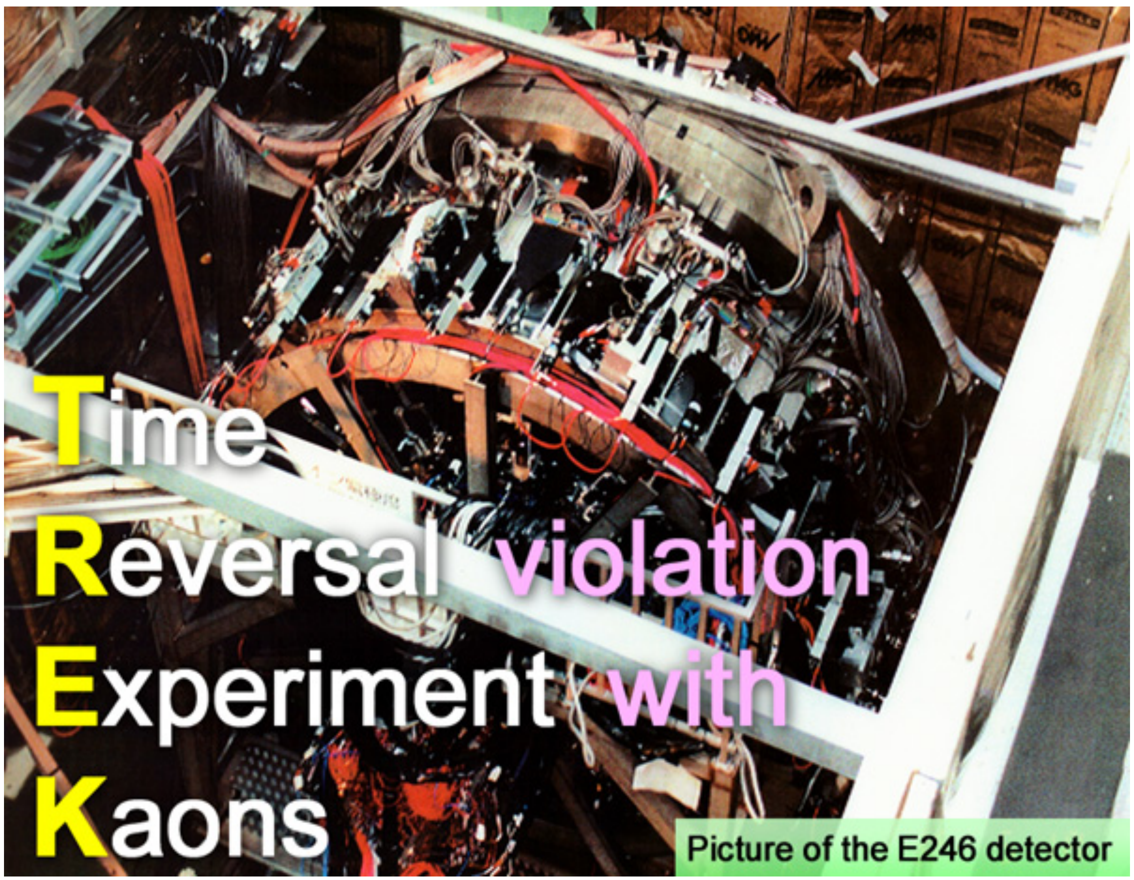


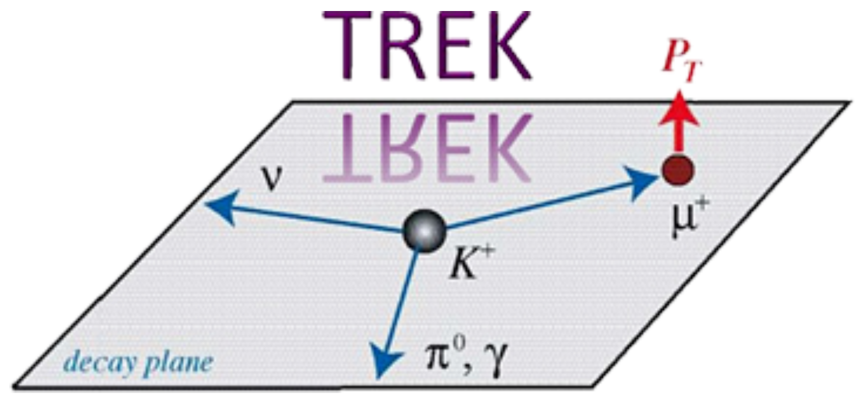


TREK/E06/E36 at J-PARC

Time Reversal violation Experiment with Kaons:

Search for New Physics beyond the Standard Model by Measurement of T-violating Transverse Muon Polarization in $K^+ \rightarrow \mu^+ \pi^0 \nu_\mu$ Decays





Official website:
http://trek.kek.jp

TREK (E36/E06) collaboration

~45 collaborators

Spokespeople:
M.K., J. Imazato, S. Shimizu

CANADA

University of Saskatchewan
Department of Physics and Engineering
University of British Columbia
Department of Physics and Astronomy
TRIUMF
Universite de Montreal
Laboratoire de Physique Nucleaire
University of Manitoba
Department of Physics

USA

Massachusetts Institute of Technology (MIT)
Laboratory for Nuclear Science &
Bates Linear Accelerator Center
University of South Carolina
Department of Physics and Astronomy
Iowa State University
College of Liberal Arts & Sciences
Hampton University & Jefferson Laboratory
Department of Physics

JAPAN

Osaka University
Department of Physics
Tohoku University
Research Center for ELectron Photon Science (ELPH)
Tokyo Institute of Technology (TiTech)
Department of Physics
Chiba University
Department of Physics
University of Tokyo
Department of Physics
Rikkyo University
Department of Physics
High Energy Accel. Research Organzation (KEK)
Institute of Particle and Nuclear Studies
Institute of Material Structure Science
Accelerator Laboratory

RUSSIA

Russian Academy of Sciences (RAS)
Institute for Nuclear Research (INR)

KOREA

Kyungpook National University
Korea University

VIETNAM

University of Natural Sciences

TREK/E36

- E06 (TREK)

“ **Measurement of T-violating transverse muon polarization (P_T) in $K^+ \rightarrow \pi^0 \mu^+ \nu$ decays** ”

Proposal to PAC 1 270 kW

Stage-1 approved since July 2006 (PAC1)

- E36 (Lepton Universality & Heavy Neutrino Search)

“ **Measurement of $\Gamma(K^+ \rightarrow e^+ \nu)$ / $\Gamma(K^+ \rightarrow \mu^+ \nu)$ and search for heavy sterile neutrinos using the TREK detector system** ”

Proposal to PACs 10,11,13,14,15 30 kW

Stage-1 approved since July 2012 (PAC15)

Limits of lepton universality (LU)

- **e, μ, and τ: Different masses, same gauge couplings, valid experimentally**
- **μ-e universality has been rather well established**
- **Recent summary by A. Pich, arXiv:1201.0537v1 [hep-ph] (2012)**

	$\Gamma_{\tau\to\nu_\tau e\bar{\nu}_e}/\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e}$	$\Gamma_{\tau\to\nu_\tau\pi}/\Gamma_{\pi\to\mu\bar{\nu}_\mu}$	$\Gamma_{\tau\to\nu_\tau K}/\Gamma_{K\to\mu\bar{\nu}_\mu}$	$\Gamma_{W\to\tau\bar{\nu}_\tau}/\Gamma_{W\to\mu\bar{\nu}_\mu}$
$\lvert g_\tau/g_\mu\rvert$	1.0007 ± 0.0022	0.992 ± 0.004	0.982 ± 0.008	1.032 ± 0.012
	$\Gamma_{\tau\to\nu_\tau\mu\bar{\nu}_\mu}/\Gamma_{\tau\to\nu_\tau e\bar{\nu}_e}$	$\Gamma_{\pi\to\mu\bar{\nu}_\mu}/\Gamma_{\pi\to e\bar{\nu}_e}$	$\Gamma_{K\to\mu\bar{\nu}_\mu}/\Gamma_{K\to e\bar{\nu}_e}$	$\Gamma_{K\to\pi\mu\bar{\nu}_\mu}/\Gamma_{K\to\pi e\bar{\nu}_e}$
$\lvert g_\mu/g_e\rvert$	1.0018 ± 0.0014	1.0021 ± 0.0016	0.998 ± 0.002	1.001 ± 0.002
	$\Gamma_{W\to\mu\bar{\nu}_\mu}/\Gamma_{W\to e\bar{\nu}_e}$		$\Gamma_{\tau\to\nu_\tau\mu\bar{\nu}_\mu}/\Gamma_{\mu\to\nu_\mu e\bar{\nu}_e}$	$\Gamma_{W\to\tau\bar{\nu}_\tau}/\Gamma_{W\to e\bar{\nu}_e}$
$\lvert g_\mu/g_e\rvert$	0.991 ± 0.009	$\lvert g_\tau/g_e\rvert$	1.0016 ± 0.0021	1.023 ± 0.011

- **Recent development of τ spectroscopy**
  - ✧ τ_τ, m_τ, $\tau_\tau/\tau_\mu = (m_\tau/m_\mu)^5(g_\tau/g_\mu)^2$, couplings to *W* and Z^0
- **LEP-II [PDG 2010]**

$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W\to\tau\,\bar{\nu}_\tau)}{\mathrm{BR}\,(W\to e\,\bar{\nu}_e)+\mathrm{BR}\,(W\to\mu\,\bar{\nu}_\mu)} = 1.055(23)$$

2.4 σ deviation

- **BABAR [Phys. Rev. D 82, 072005 (2010)]**

3.5 σ deviation

$$\mathcal{R}(D^{(*)}) = \mathcal{B}(\overline{B}\to D^{(*)}\tau^-\overline{\nu}_\tau)/\mathcal{B}(\overline{B}\to D^{(*)}\ell^-\overline{\nu}_\ell)$$

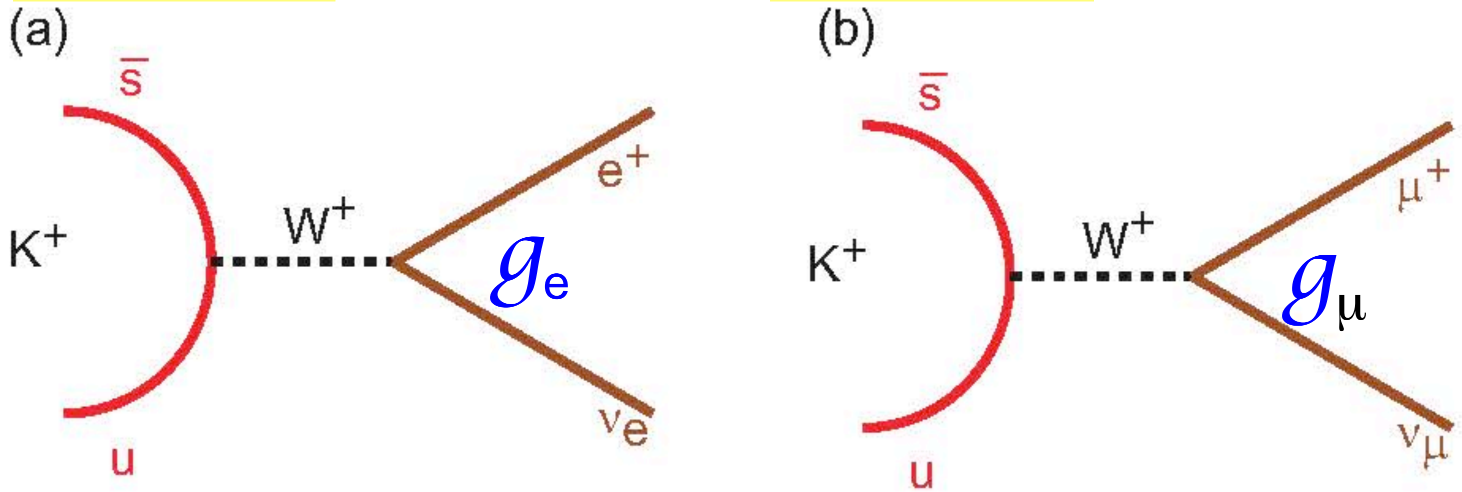
- **Possible link to proton charge radius puzzle** **7 σ deviation**

r_e (μH) = 0.842 ± 0.001 fm, r_e (CODATA) = 0.877 ± 0.007 fm

Search for LU violation in K_{l2} decays

Typical test in particle decay at low energy

$K \rightarrow e\nu$ $K \rightarrow \mu\nu$



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

$$g_e = g_\mu \; ?$$

Precise measurement of decay width ratio:

$$R_K = \Gamma(K_{e2}) \, / \, \Gamma(K_{\mu 2})$$

Lepton universality in Standard Model K_{l2}

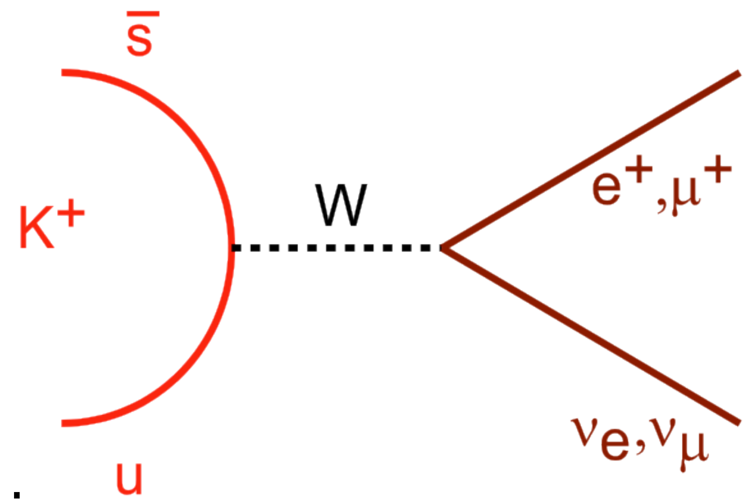
$$R_K^{SM} = \frac{\Gamma(K^+ \to e^+\nu)}{\Gamma(K^+ \to \mu^+\nu)} = \frac{m_e^2}{m_\mu^2}\left(\frac{m_K^2 - m_e^2}{m_K^2 - m_\mu^2}\right)^2 (1+\delta_r)$$

helicity suppression

radiative correction (Internal Brems.)

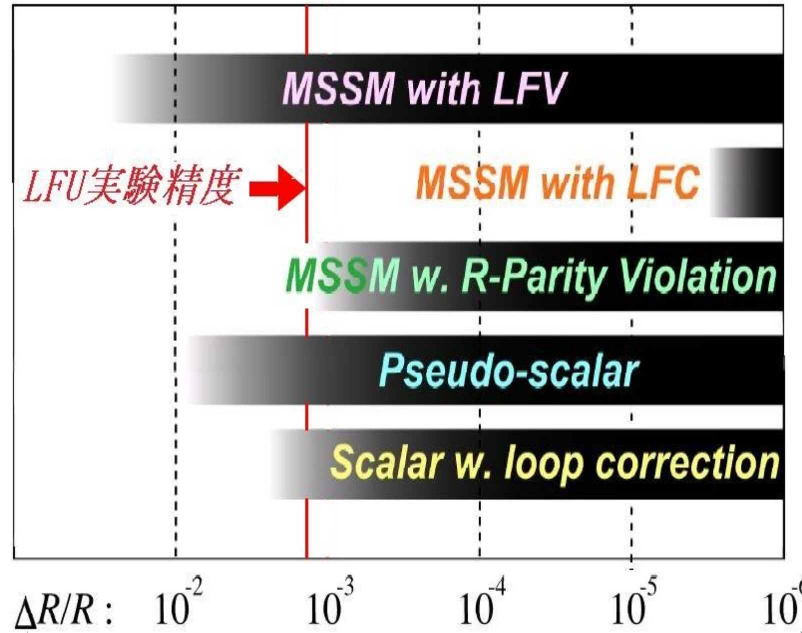
Standard Model:

- $\Gamma(K_{l2}) = g_l^2\,(G^2/8\pi)\, f_K^2 m_K m_l^2 \{1-(m_l^2/m_K^2)\}^2$
- In the ratio of Γ(Ke2) to Γ(Kμ2), hadronic form factors are cancelled
- 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}, $\delta R_K/R_K$=0.04%



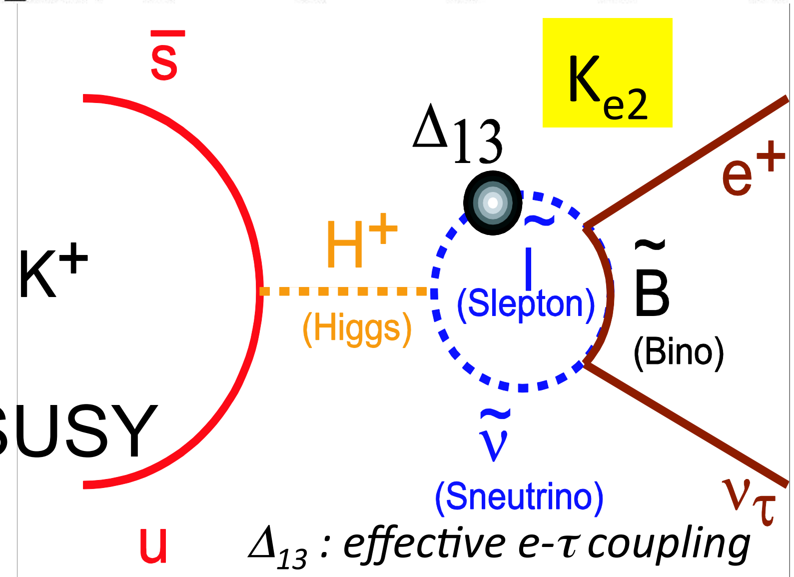
Lepton universality violation in K_{l2}

- Possible New Physics
  - MSSM with LFV
  - MSSM w. *R*-parity violation
  - Pseudo-scalar interaction
  - Scalar w. loop correction



- SUSY with LFV for K_{e2}

$$R_K^{LFV} = R_K^{SM}\left(1 + \frac{m_K^4}{M_{H^+}^4}\cdot\frac{m_\tau^2}{m_e^2}\Delta_{13}^2\tan^6\beta\right)$$

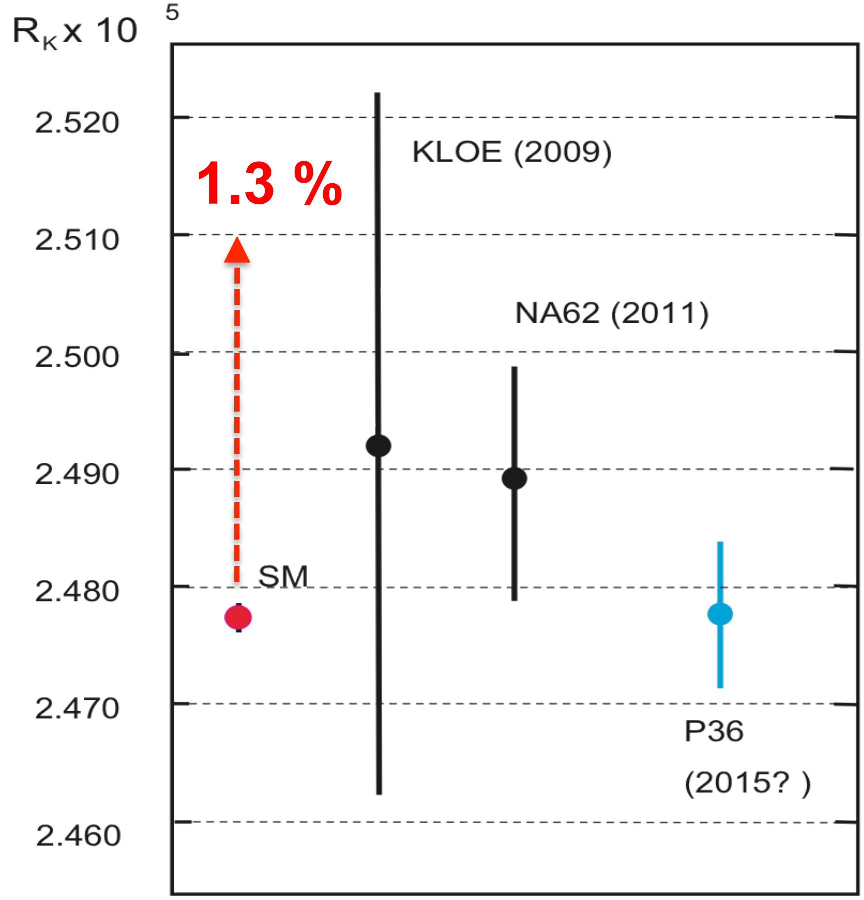


- Charged Higgs H^+ mediated LFV SUSY
- Large enhancement from m_τ^2/m_e^2
- A sizable effect of $\Delta R_K/R_K \sim 1.3\%$ possible

[A. Masiero, P. Paradisi, and R. Petronzio, Phys. Rev. D74 (2006) 011701]

Experimental status of R_K

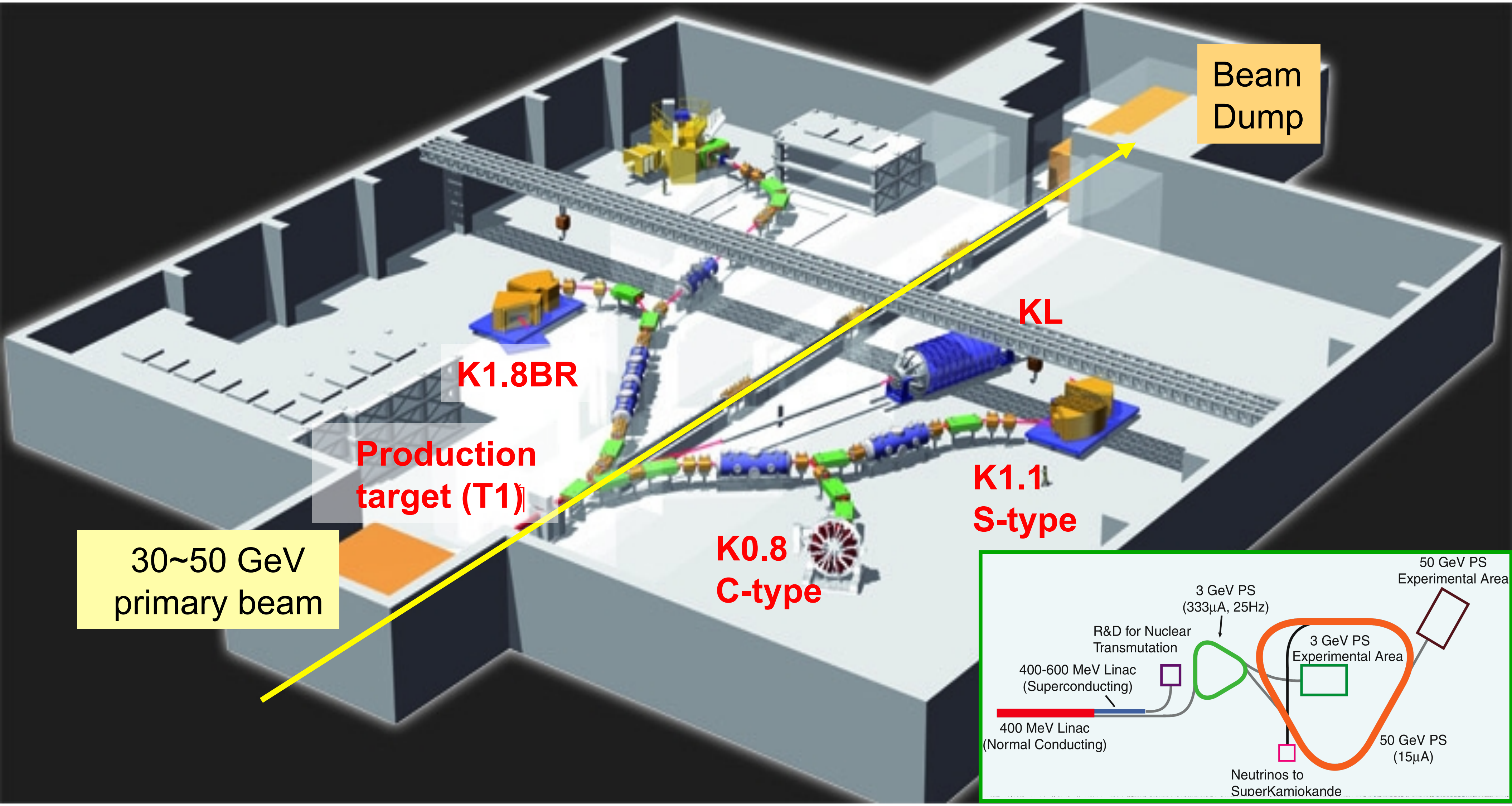
- Highly precise SM value
  $R_K = (2.477 \pm 0.001) \times 10^{-5}$, $\delta R_K/R_K = 0.04\%$
- KLOE @ DAΦNE (in-flight decay) (2009)
  $R_K = (2.493 \pm 0.025 \pm 0.019) \times 10^{-5}$
- NA62 @ CERN-SPS (in-flight decay) (2011)
  $R_K = (2.488 \pm 0.007 \pm 0.007) \times 10^{-5}$
- World average (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
  - P36 stopped K^+: detector acceptance and target
  - Thorough systematic error analysis: reported to PAC-13

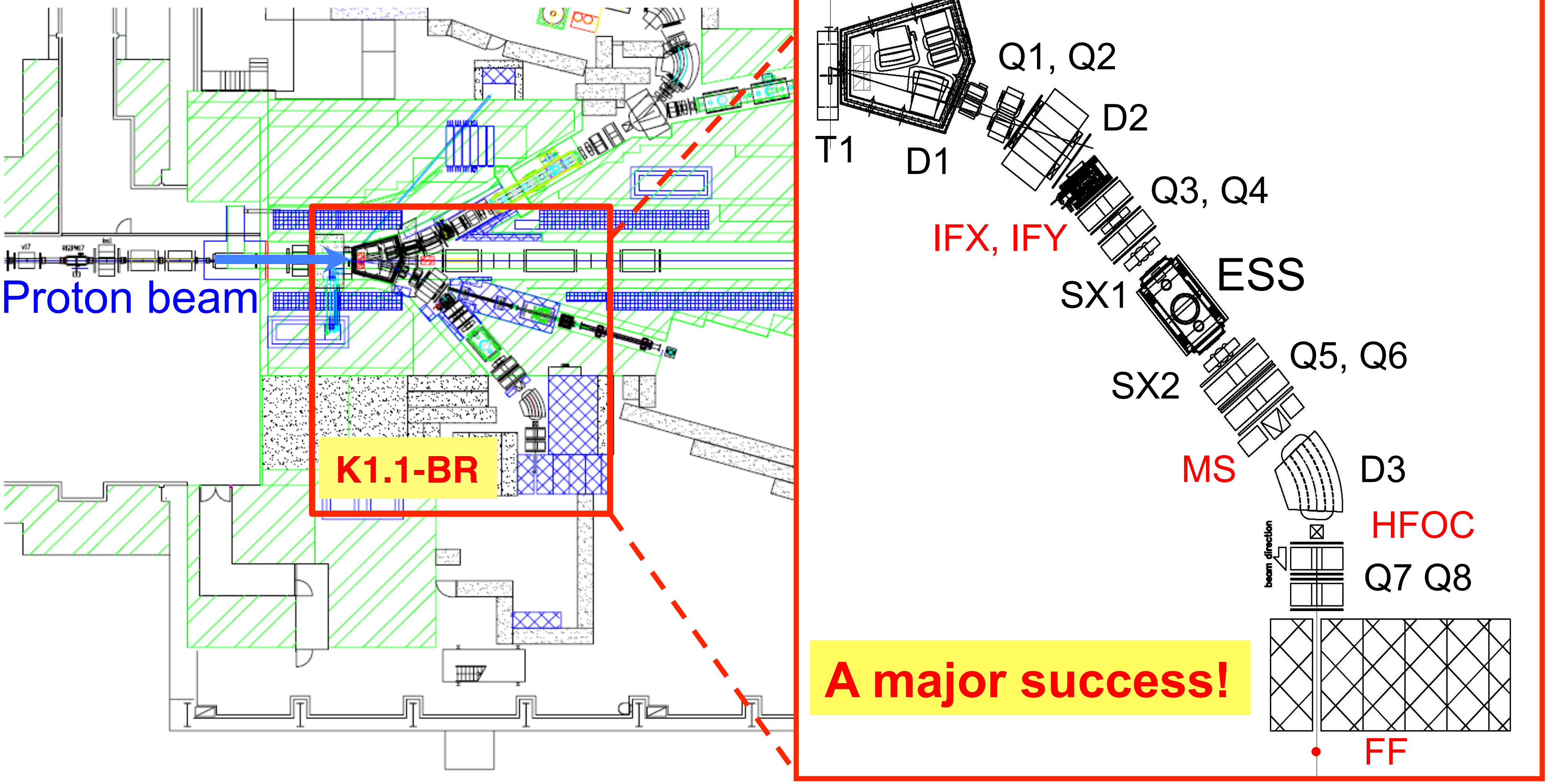
- P36 goal: $\delta R_K / R_K = \pm 0.2\%$ (stat) $\pm 0.15\%$ (syst) [0.25% total]

J-PARC Hadron Facility

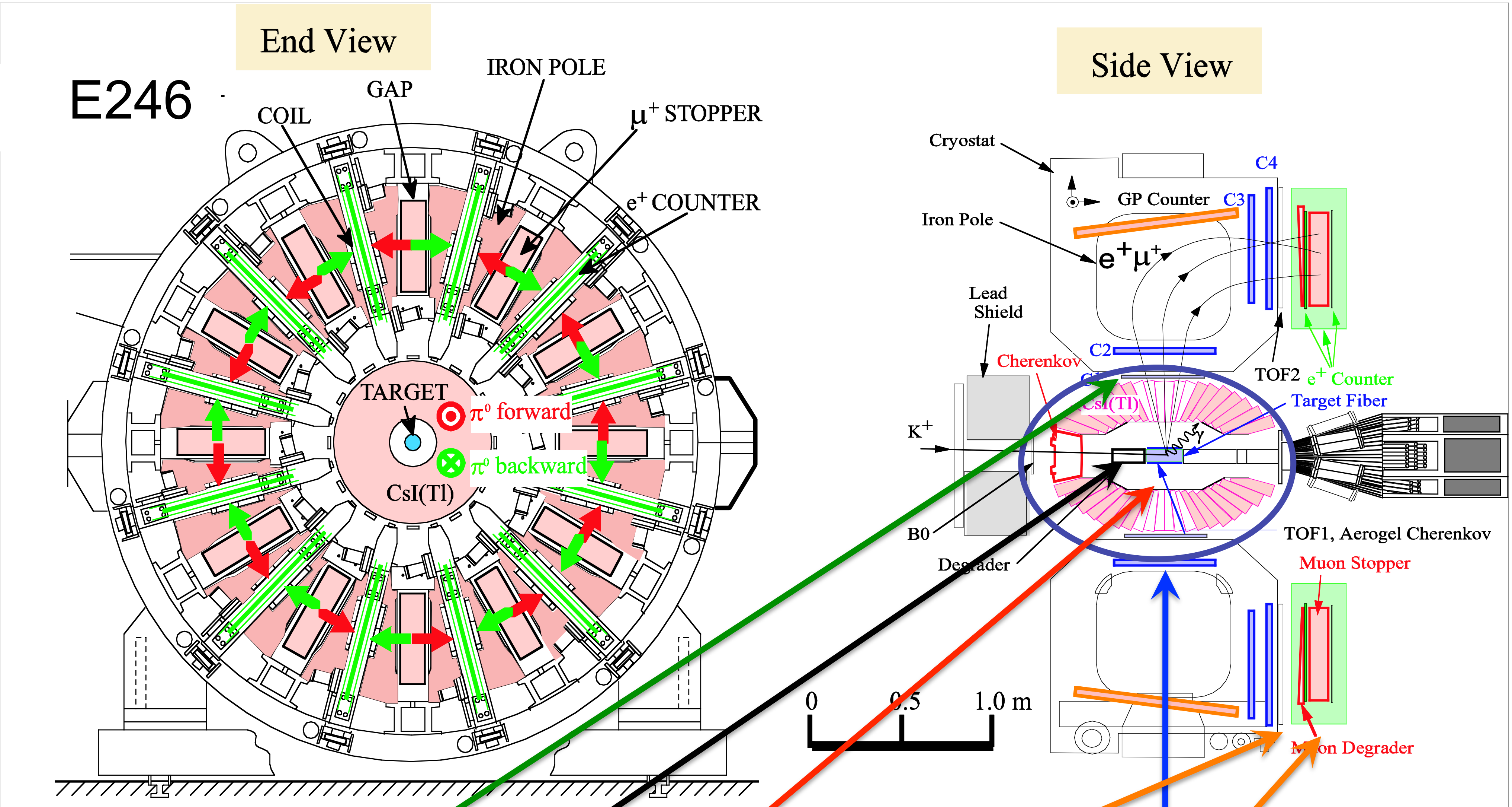


K1.1BR beamline

- K1.1BR completed in summer 2010 using the supplementary budget of FY09
- Commissioned in Oct. 2010 by TREK collaboration before earthquake
- **Re-commissioned successfully in June 2012 after re-alignment**
  - π/K ratio of ~1 observed
  - Kaon flux within expectation

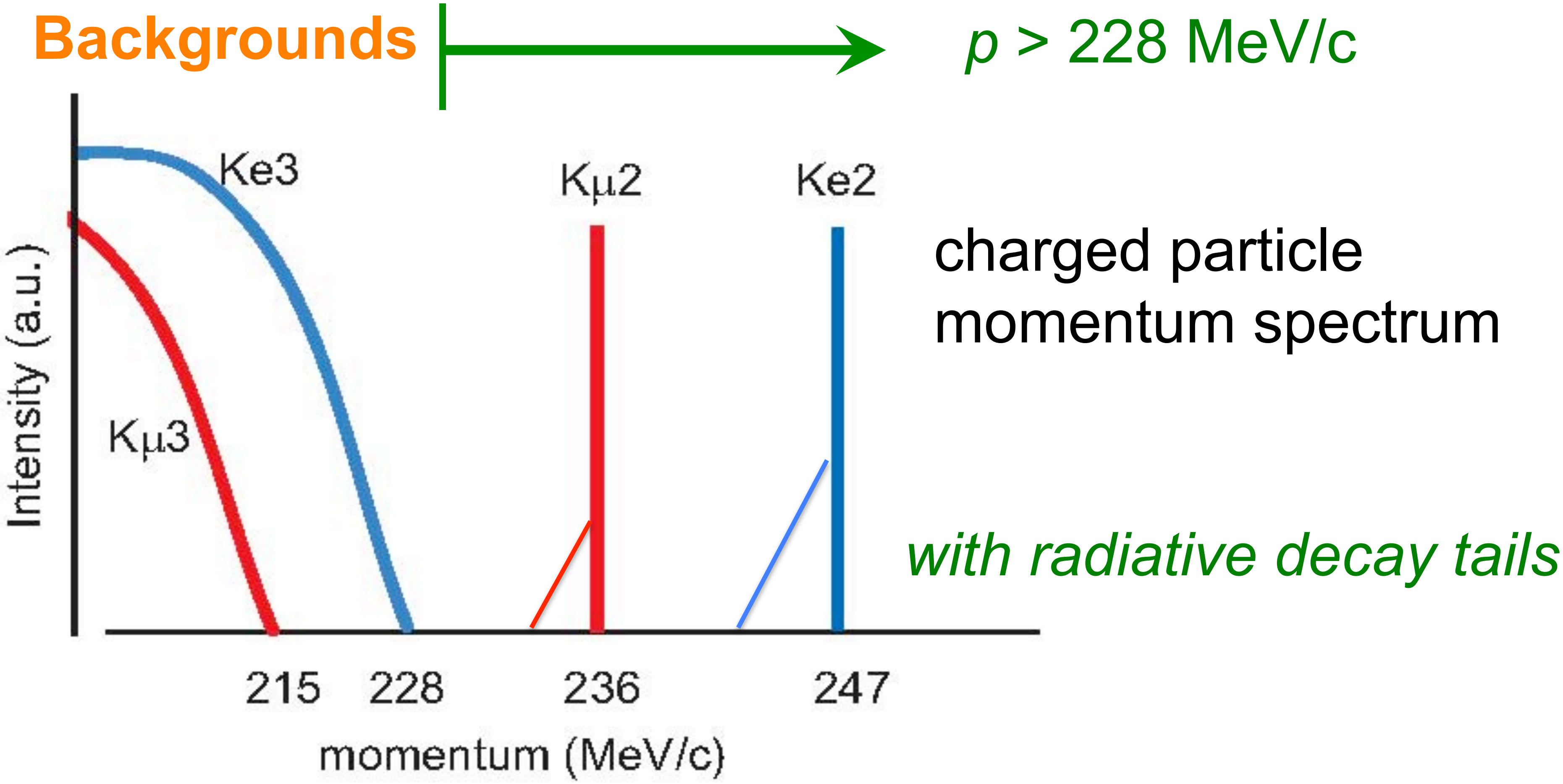


Target & E246/TREK detector upgrade



- C1 GEM
- Target
- Aerogel Cerenkov
- TOF, Leadglass
- CsI(Tl) readout

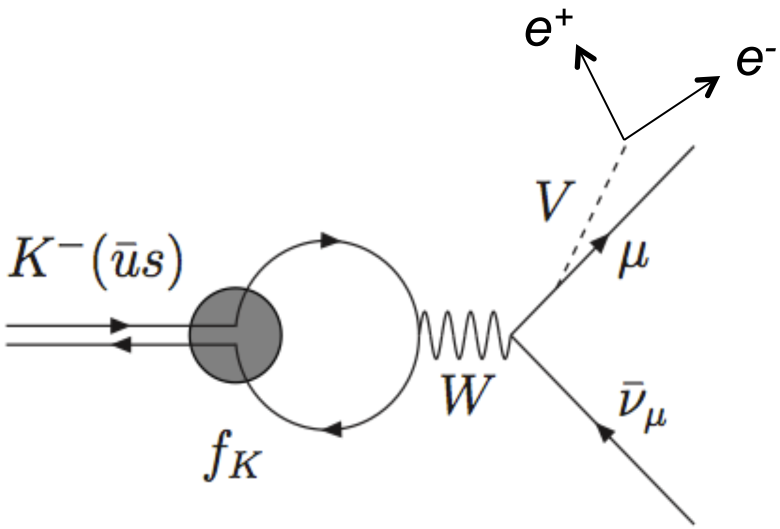
K_{e2} / $K_{\mu2}$ discrimination



- *e*/μ separation not only in momentum spectrum but with PID using TOF + Cherenkov counters
- Inclusion of radiative decay (CsI(Tl))
- Rejection of K_{e3} and $K_{\mu3}$

LFU and the proton radius puzzle

Indirectly: Search for violation of lepton universality in K_{l2}
Directly: Search for a light gauge boson (V), coupling to the muon leg, by full reconstruction of final state



Measure

$K_{\mu 2}$: $K^+ \rightarrow \mu^+ + \nu$ (expect ~10^{11} events)

$K_{\mu 2\gamma}(SD)$: $K^+ \rightarrow \mu^+ + \gamma + \nu$ (~10^9 events)

V: $K^+ \rightarrow \mu^+ + e^+ + e^- + \nu$ with $V \rightarrow e^+ + e^-$

Schedule

	FY2012	FY2013	FY2014		FY2015	
Detector	R&D	Construction and setup				
Cryogenics		Re-installation				
Experiment (time window)				Run		
(in the case of funding delay)						Run

- 2013–2014 Detector construction and commissioning
- 2014–2015 Running of E36 at K1.1BR
  (1500 kW*days "LFU" + 900 kW*days "HNS")
- If COMET is delayed anticipate longer use of K1.1BR

Summarizing …

A framework of new experiments

- What is the relevance of two-photon exchange in lepton scattering?
    - In which kinematic regions? High vs. low Q^2

A framework of new experiments

- **Two-photon exchange in lepton scattering**
  OLYMPUS @ DESY to compare
  e^+p and e^-p elastic scattering

A framework of new experiments

- **What is the relevance of two-photon exchange in lepton scattering?**
  - **In which kinematic regions? High vs. low Q^2**
- **What is the solution to the proton radius puzzle?**
  - **Wrong experiments, wrong or incomplete theory, or new physics?**
  - **Two-photon exchange different for μ and e?**

A framework of new experiments

- **Two-photon exchange in lepton scattering**
  OLYMPUS @ DESY to compare
  e^+p and e^-p elastic scattering

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

The nine muses

A framework of new experiments

- What is the relevance of two-photon exchange in lepton scattering?
  - In which kinematic regions? High vs. low Q^2
- What is the solution to the proton radius puzzle?
  - Wrong experiments, wrong or incomplete theory, or new physics?
  - Two-photon exchange different for μ and e?
- What is dark matter?
  - Is the dark force evidenced by a massive photon-like boson?

A framework of new experiments

- **Two-photon exchange in lepton scattering**
  OLYMPUS @ DESY to compare
  $e^{+}p$ and $e^{-}p$ elastic scattering

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

The nine muses

- **Search for a gauge boson $m_{A'}$ = 10-90 MeV/c^2**
  DarkLight @ JLAB to reconstruct the
  decay of $A' \rightarrow e^{+}+e^{-}$ in $e^{-}+p \rightarrow e^{-}+p+e^{+}+e^{-}$

A framework of new experiments

- What is the relevance of two-photon exchange in lepton scattering?
  - In which kinematic regions? High vs. low Q^2
- What is the solution to the proton radius puzzle?
  - Wrong experiments, wrong or incomplete theory, or new physics?
  - Two-photon exchange different for μ and e?
- What is dark matter?
  - Is the dark force evidenced by a massive photon-like boson?
- Can a light gauge boson explain simultaneously dark matter and the anomalies (a_μ and r_p)?
  - Possibly … but only if couplings to μ and e are different
- Two-photon exchange, proton radius, dark photon, and lepton flavor universality
  - Investigate TPE and r_p, search for dark photon, and test lepton flavor universality with high precision

A framework of new experiments

- **Two-photon exchange in lepton scattering**
  OLYMPUS @ DESY to compare
  e^+p and e^-p elastic scattering

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

The nine muses

- **Search for a gauge boson $m_{A'}$ = 10-90 MeV/c^2**
  DarkLight @ JLAB to reconstruct the
  decay of $A' \rightarrow e^+ + e^-$ in $e^- + p \rightarrow e^- + p + e^+ + e^-$

- **Test of lepton flavor universality**
  TREK/E36 @ J-PARC to compare
  $K^+ \rightarrow e^+ \nu \,/\, \mu^+ \nu$ decays