Columbian College
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THE GEORGE WASHINGTON UNIVERSITY

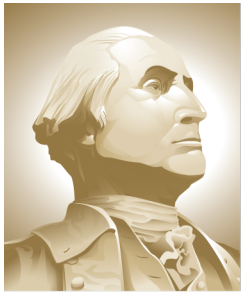
BVR 48: MUSE Status Report

Evangeline J. Downie
On behalf of the MUSE Collaboration

George Washington University
Washington DC, USA

Award DE-SC0012485

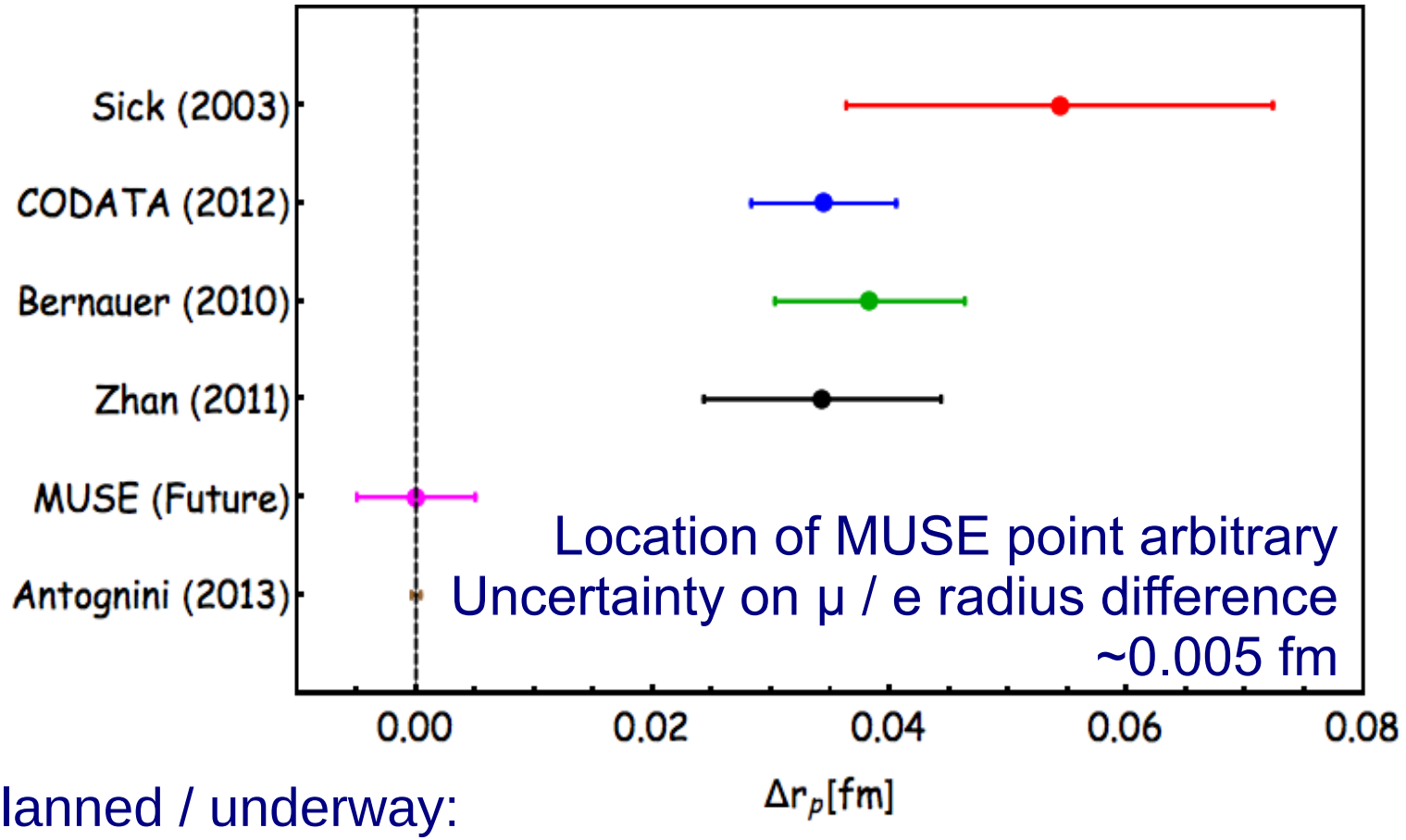
Awards PHY-1309130,1314148,1614850



THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

The Proton Charge Radius

- 2010: CREMA collaboration muonic H spectroscopy
- Inconsistent with the electron measurements
- **Charge radius 7σ smaller than CODATA value**



- New experiments planned / underway:

➔ Excitation spectrum ^{3,4}He (CREMA)

➔ Low q^2 e^- scattering Jlab / Mainz

➔ Muon scattering on proton (MUSE) at PSI (μ^+/μ^-, e^+e^-)

How Do We Resolve the Radius Puzzle?

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
  - ➔ **BSM:** scattering modified for Q^2 up to m^2_{BSM} (typically expected to be MeV to 10s of MeV), enhanced parity violation
  - ➔ **Hadronic:** enhanced 2γ exchange effects
- Experiments include:
  - ➔ Light muonic atoms for radius comparison in heavier systems
  - ➔ Redoing atomic hydrogen
  - ➔ Redoing electron scattering at lower Q^2
  - ➔ Muon scattering!

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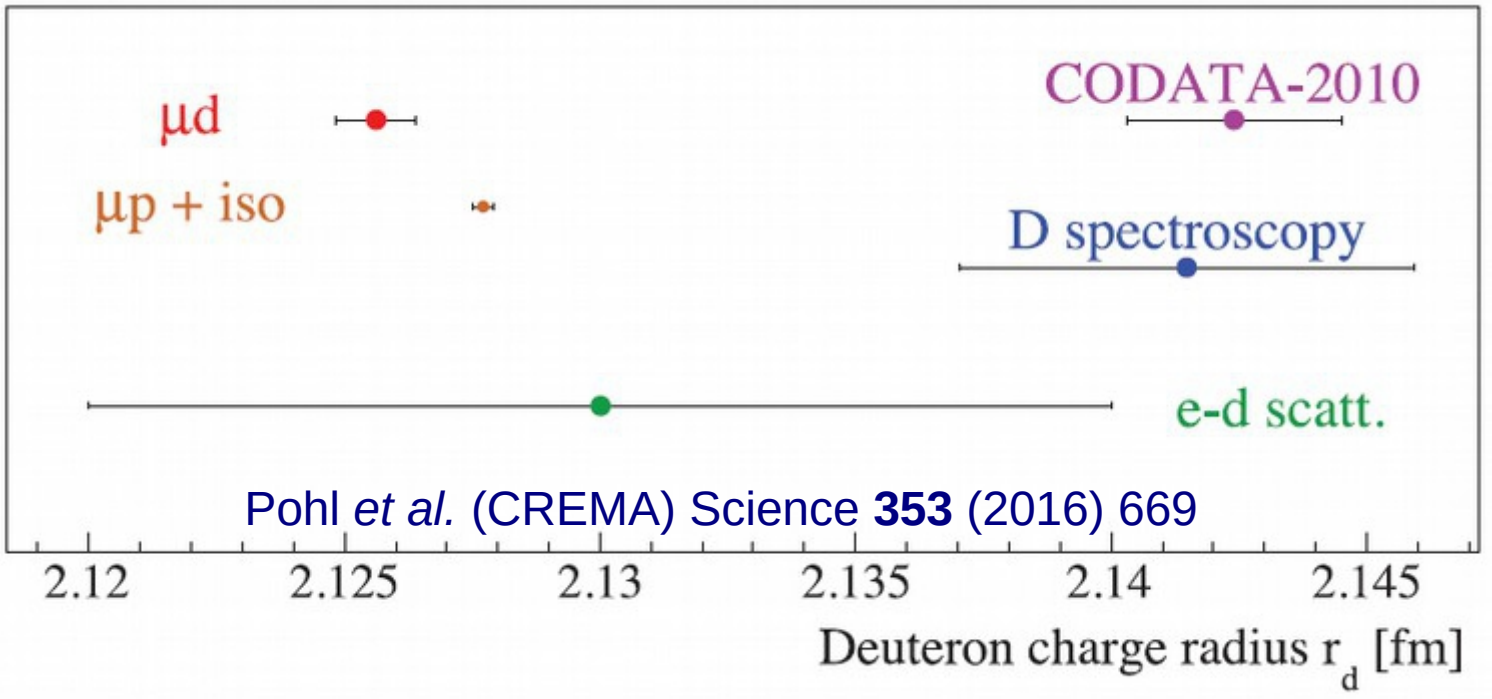
Light Muonic Atoms



- CREMA Collaboration moved on to heavier things
- Deuterium radius from μD agrees with μH (using isotope shift)
- Recent analysis gives 3.5σ difference between atomic and muonic D
  Pohl *et al.* arXiv:1607.03165v2 [atom-ph]
- Electron scattering on deuterium too imprecise for comparison

Light Muonic Atoms

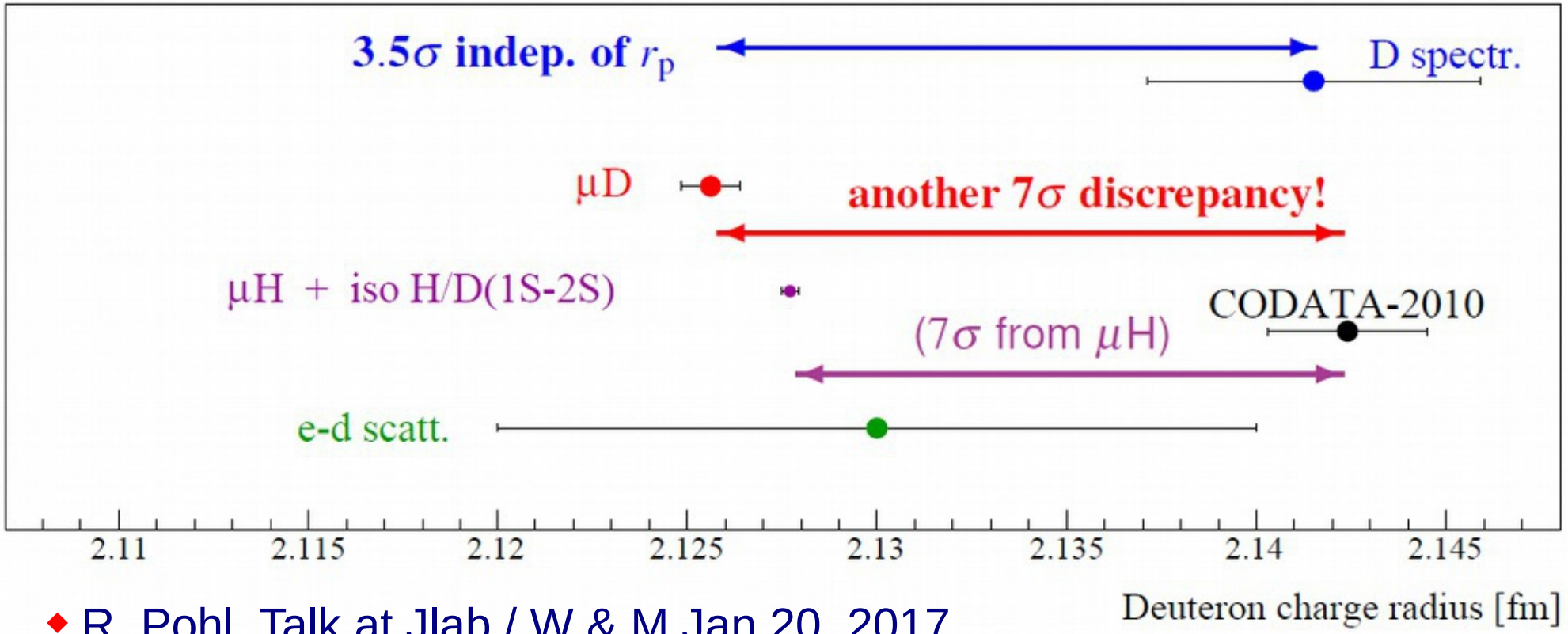
H/D isotope shift: $r_d^2 - r_p^2 = 3.82007(65)\ \text{fm}^2$ C.G. Parthey, RP *et al.*, PRL **104**, 233001 (2010)

CODATA 2010 $r_d = 2.14240(210)$ fm

r_p from μH gives $r_d = 2.12771(22)$ fm $\leftarrow 7\sigma$ from r_p

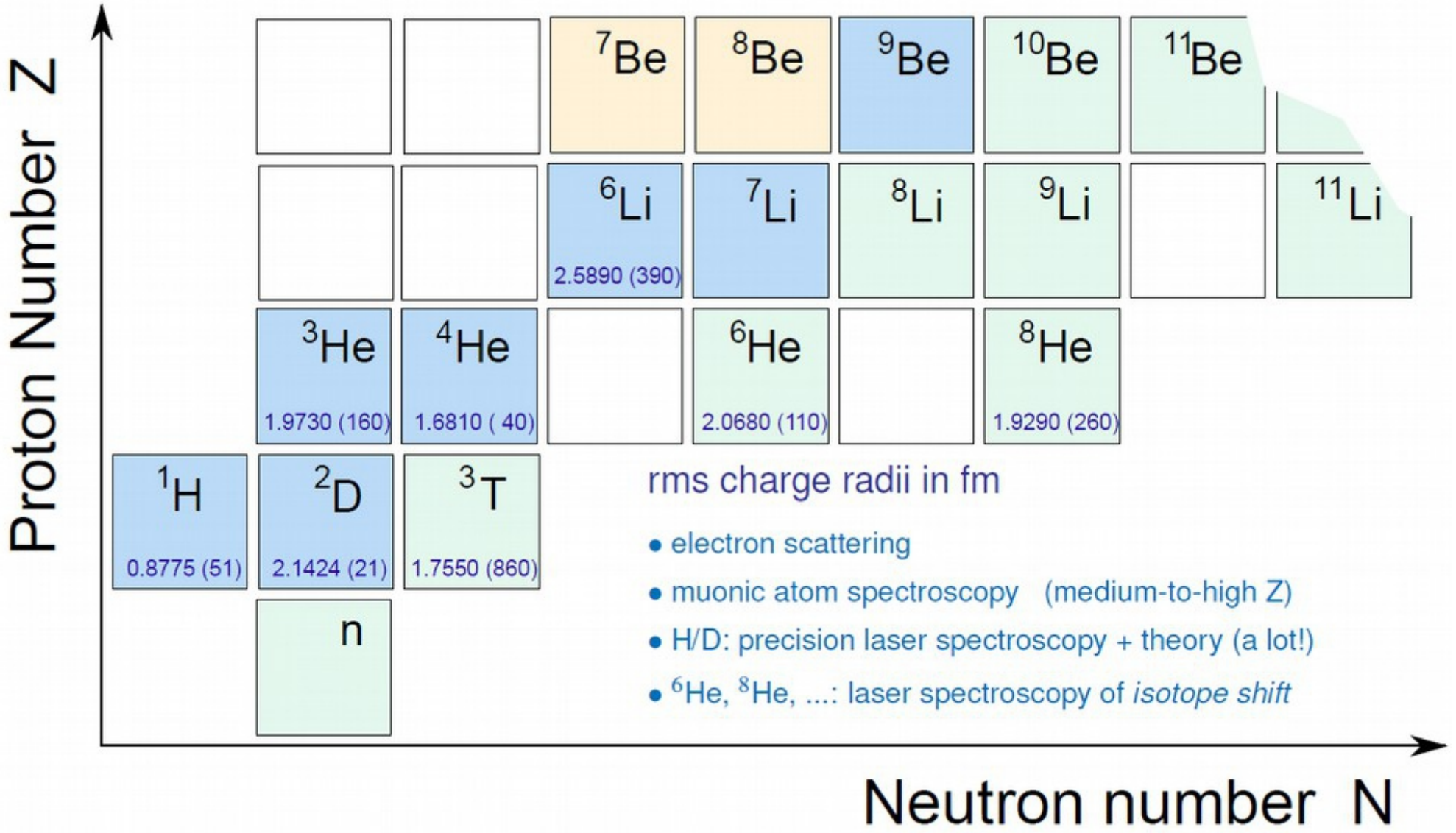
Muonic DEUTERIUM $r_d = 2.12562(13)_{exp}(77)_{theo}$ fm RP *et al.*, Science **353**, 417 (2016)

electronic D (r_p indep.) $r_d = 2.14150(450)$ fm $\leftarrow 3.5\sigma$ RP *et al.* arXiv 1607.03165



- R. Pohl, Talk at Jlab / W & M Jan 20, 2017

Light Muonic Atoms



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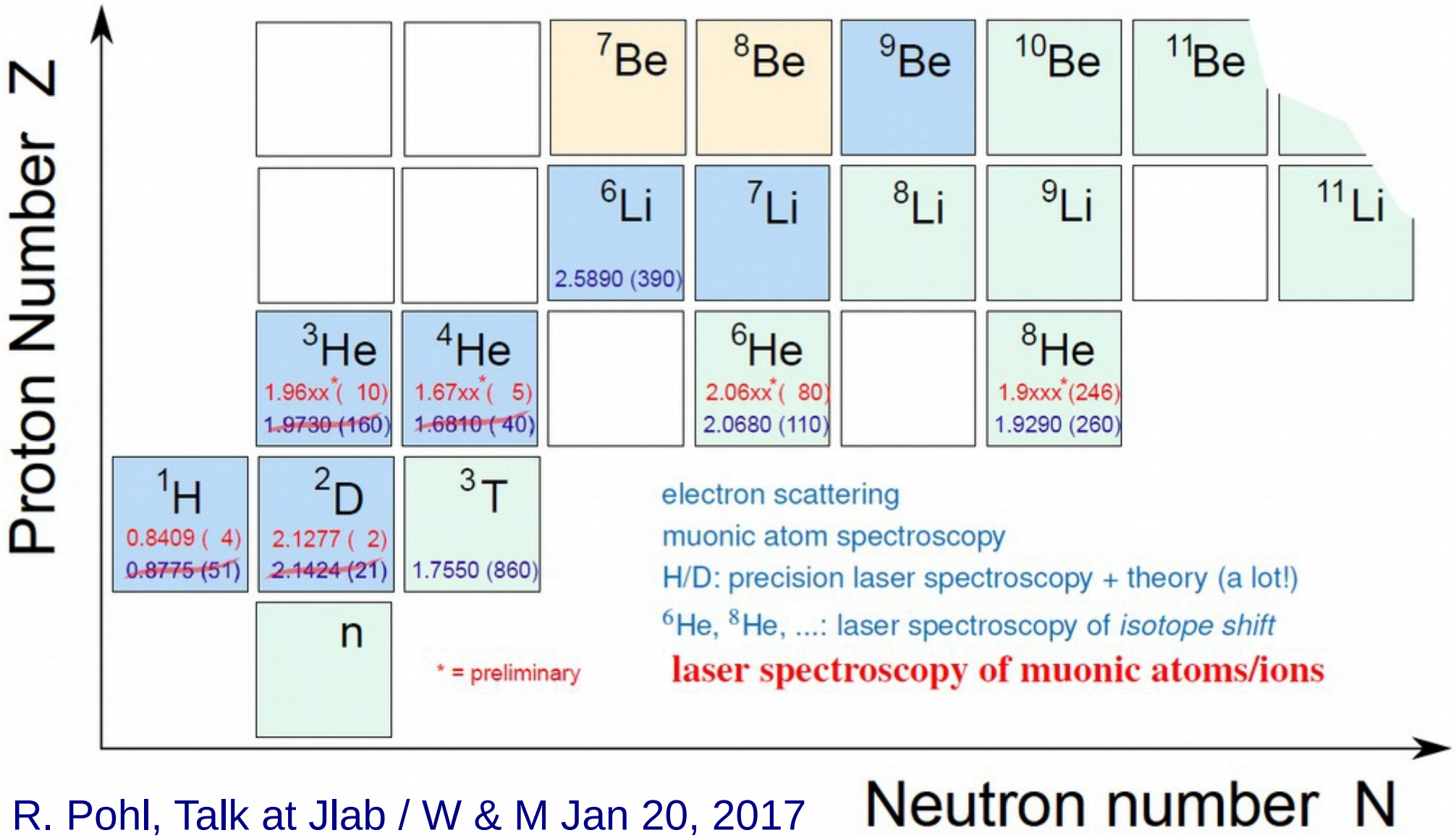
Light Muonic Atoms



- R. Pohl, Talk at Jlab / W & M Jan 20, 2017
- Helium isotopes seem to agree (preliminary results)
- Puzzle seen in H & D (Z=1 radius puzzle?)

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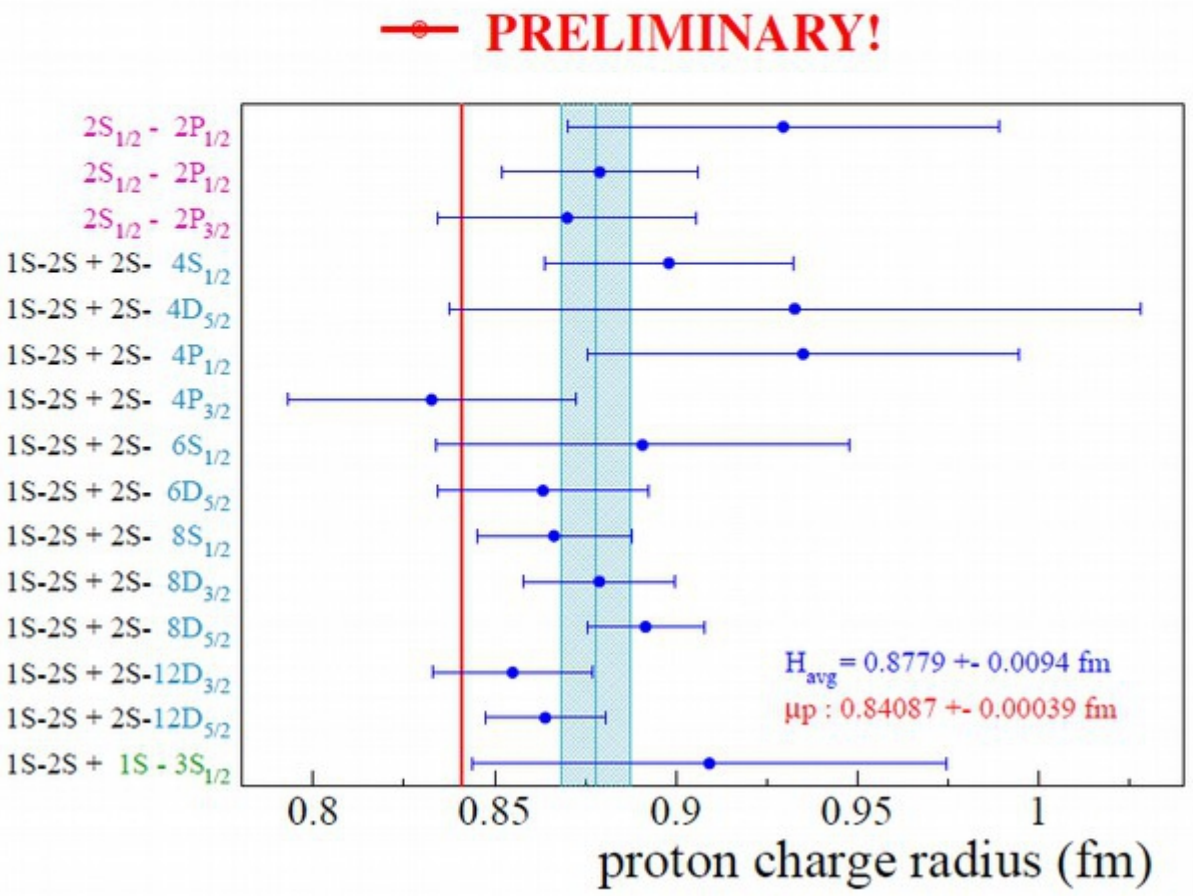
  - ➔ Muon scattering!

New hydrogen 2S→4P at MPQ!

Proton is small in regular hydrogen, too!

Proton radius puzzle is NOT "solved".

Our main systematics do NOT affect the previous measurements.



$2S \rightarrow 4P_{1/2}$ and $4P_{3/2}$

cold H(2S) beam

optically excited $(1S \rightarrow 2S)$

$\Delta\nu \sim 2\,\mathrm{kHz} \equiv \Gamma/10'000$!!!

Beyer, Maisenbacher, Matveev, RP, Khabarova, Grinin, Lamour, Yost, Hänsch, Kolachevsky, Udem, submitted (2016)

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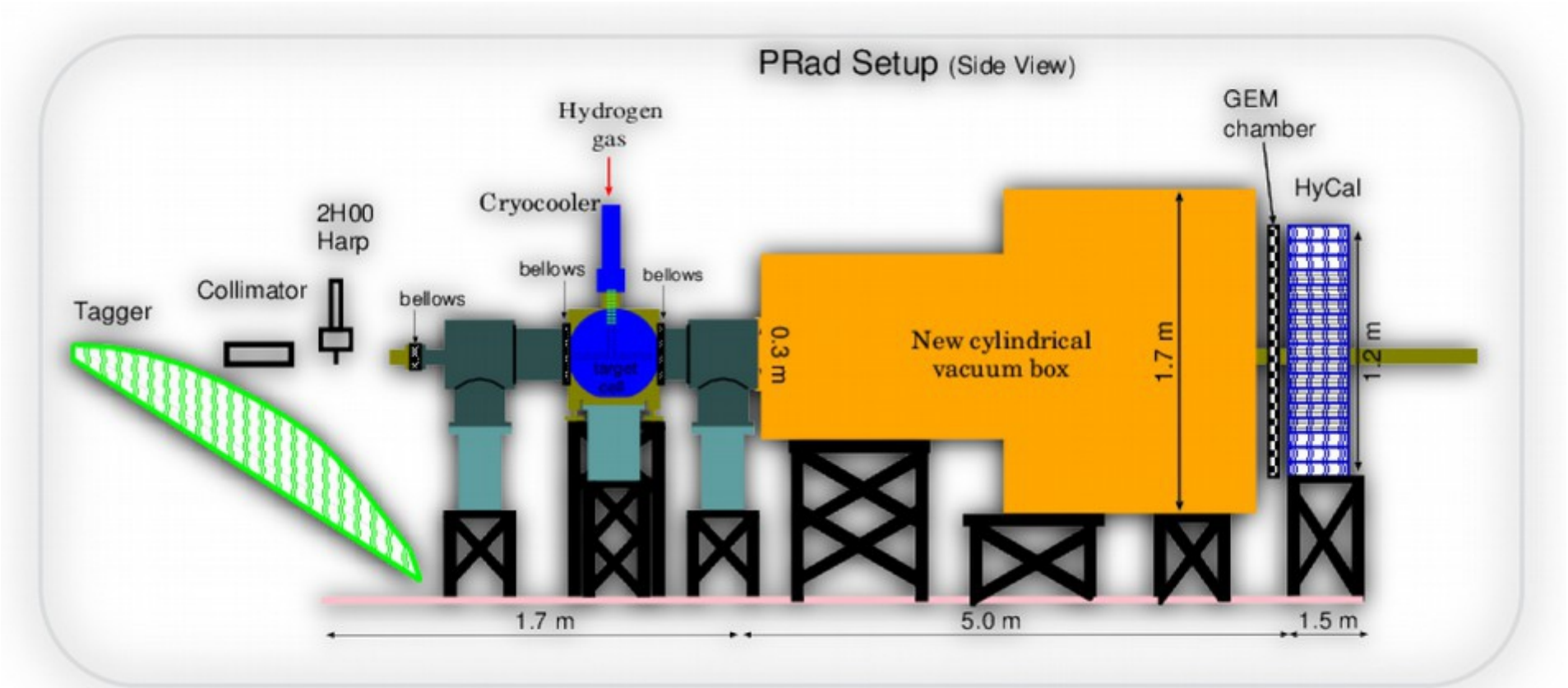
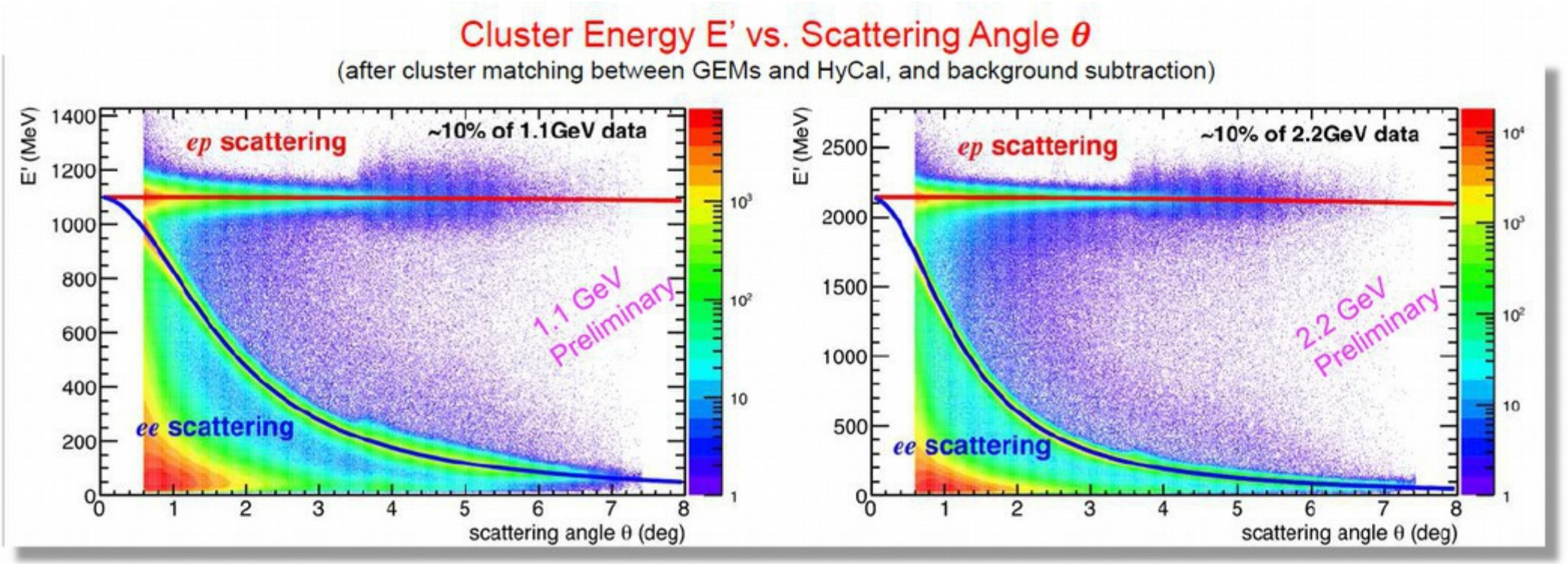
  - ➔ **Redoing electron scattering at lower Q^2**
    NB: Many efforts, not an exhaustive list!!!!
  - ➔ Muon scattering!

Jlab: PRad



- Low intensity beam in Hall B @ Jlab into windowless gas target
- Scattered ep and Moller electrons into HYCAL at 0 deg.
- Lower Q^2 than Mainz. Very forward angle, insensitive to 2γ, G_M
- Data taking: May & June 2016, 1.1 & .2.2 GeV beams, 1.3 billion H events

Jlab: PRad

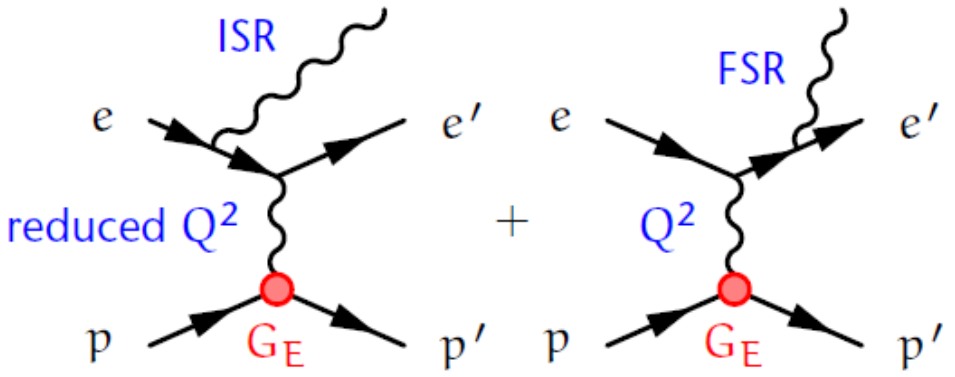


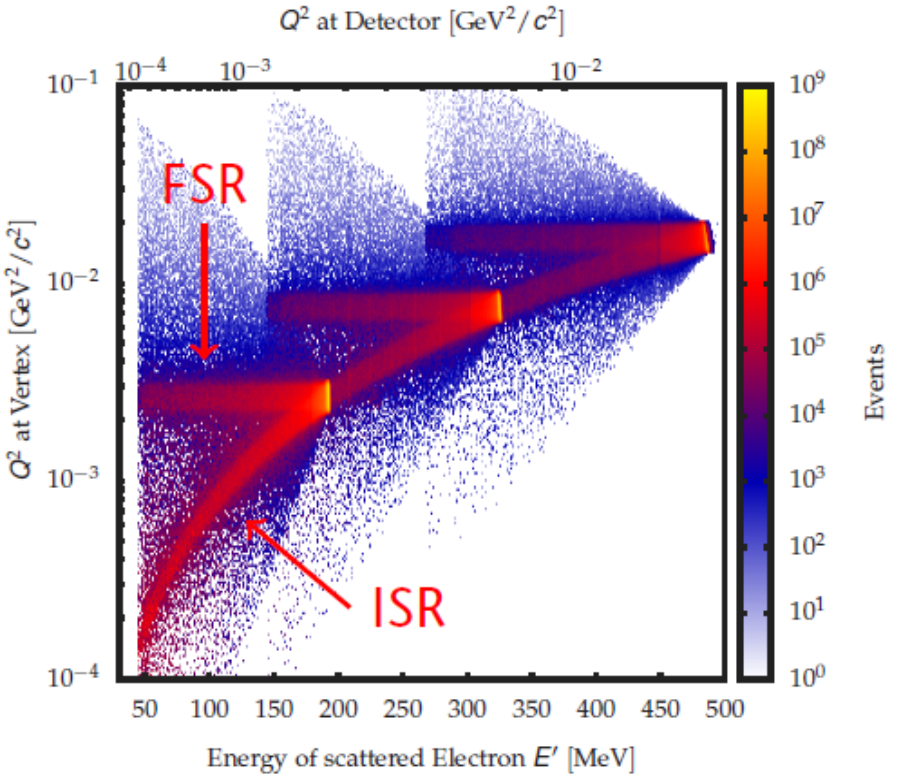
- HyCal calibration complete: expected energy resolutions achieved
- Preliminary result for HyCal trigger efficiency of >99.5%
- Detector alignment completed, matching of GEMS & HyCal achieved
- GEM position resolution of 72μm and preliminary efficiency of ~92%
- Cross section analysis ongoing

Mainz: ISR

Exploit information in radiative tail

- Dominated by coherent sum of two Bethe-Heitler diagrams: ISR and FSR
- ISR: Electron energy reduced $\rightarrow$ Lower Q^2 at given scattering angle
- Investigate G_E down to $Q^2 = 10^{-4}\,\mathrm{GeV}^2/c^2$
- ISR and FSR cannot be distinguished $\rightarrow$ Sophisticated simulation needed





Mainz: ISR

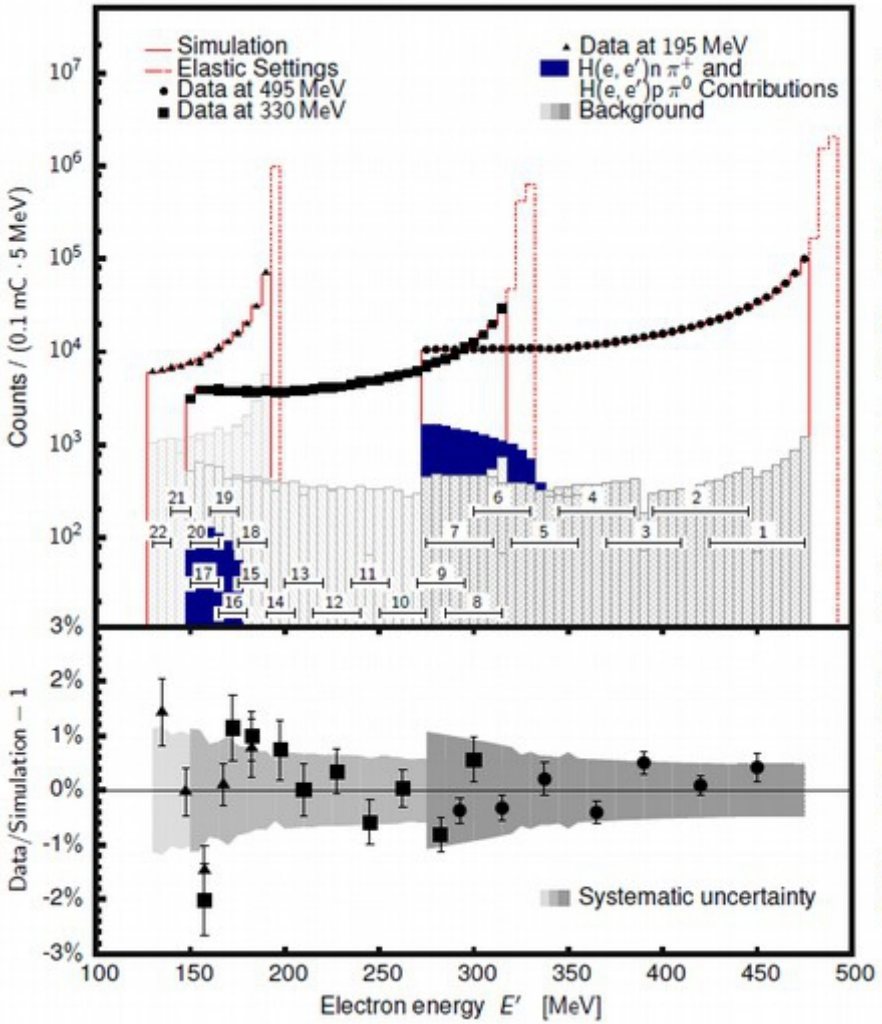


FIG. 2. (Color on-line) Comparison of the data to the simulation. **Top:** Circles, squares and triangles show the measured distributions at 495 MeV, 330 MeV and 195 MeV, respectively, normalized to the accumulated charge of 0.1 mC. The elastic data (dashed line) are omitted from the analysis. The simulations with G_E^p, given by parameterization of Bernauer [16] are shown with red lines. The measurements at 495 MeV, 330 MeV, 195 MeV were divided into seven $(1-7)$, ten $(8-17)$ and five $(18-22)$ energy bins, respectively, such that two neighboring settings overlap for a half of the energy acceptance. The residual contributions of target walls, target frame, spectrometer entrance flange and cryogenic depositions are shown with shaded areas. The full (blue) areas represent the contributions of the pion production processes. **Bottom:** Relative difference between the data and simulation. The points show the mean values for each kinematic point, while the error bars denote their statistical uncertainties. Gray bands demonstrate the systematic uncertainties.

- Experiment & analysis complete, paper submitted (arXiv:1612.06707)

Mainz: ISR

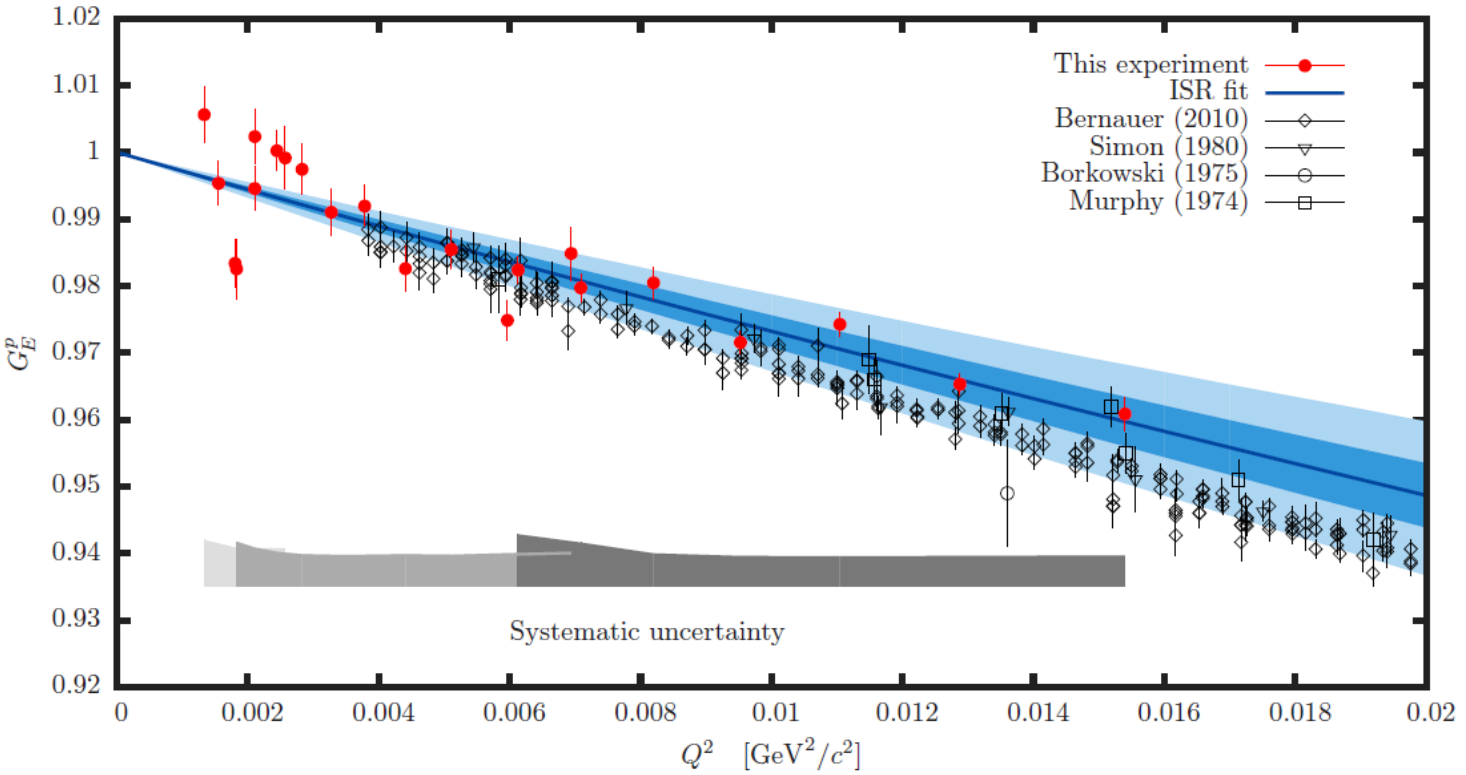
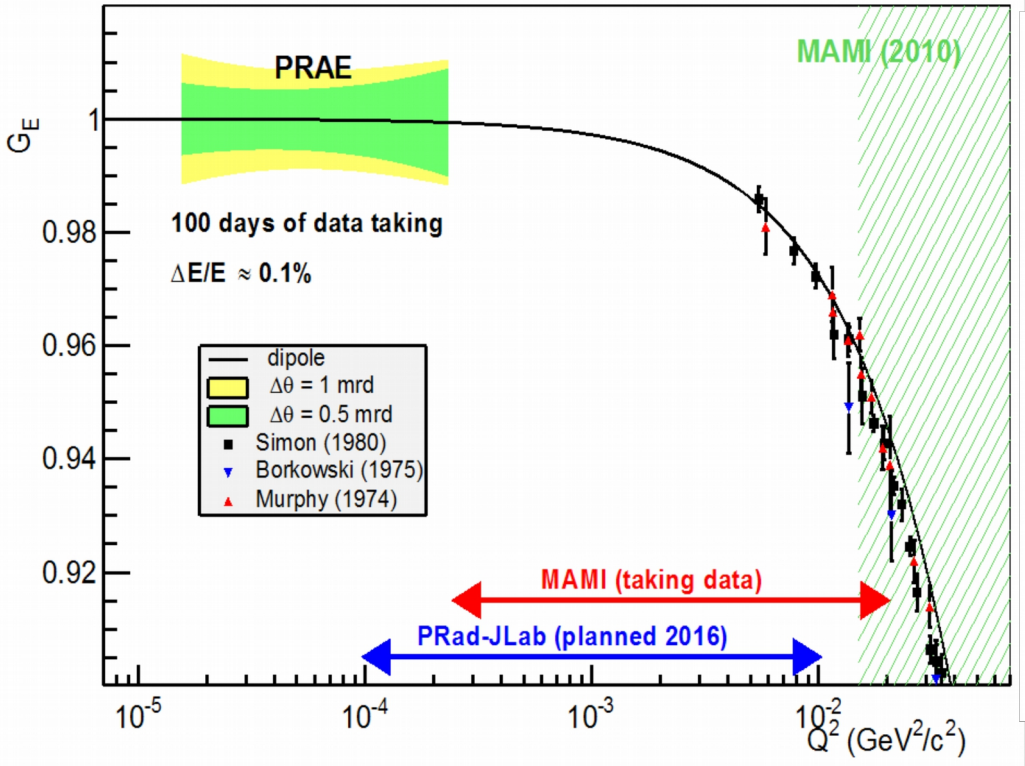


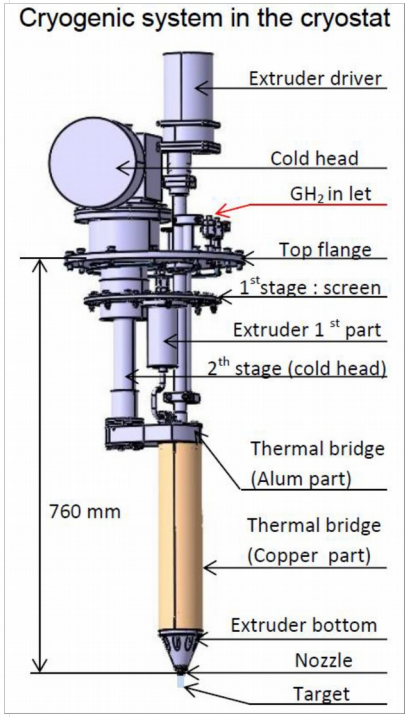
FIG. 3. (Color on-line) The proton electric form factor as a function of $Q^2(= Q^2_{\rm Out})$. Empty black points show previous data [19–22]. The results of this experiment are shown with full red circles. The error bars show statistical uncertainties. Gray structures at the bottom shows the systematic uncertainties for the three energy settings. The curve corresponds to a polynomial fit to the data defined by Eq. (2). The inner and the outer bands around the fit show its uncertainties, caused by the statistical and systematic uncertainties of the data, respectively.

- Experiment & analysis complete, paper submitted (arXiv:1612.06707)
- Result: $r_p = (0.810 \pm 0.035_{stat} \pm 0.074_{syst} \pm 0.003_{\Delta a \Delta b})$fm, not precise enough to differentiate
- New experiment with jet target (and MESA) planned

Platform for Research and Applications with Electrons: ProRad

J.-M. Ghéller et al. AIP Conf. Proc. 1573 (2014) 58



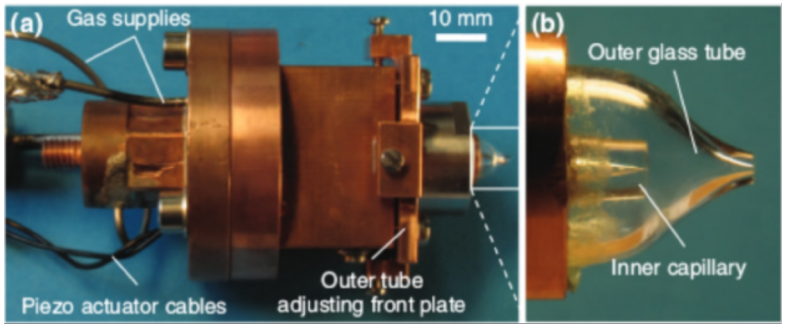


CHyMENE

Details from
Eric Voutier
LPSC, Grenoble
(France)

Bi-national ANR proposal with Francfort University submitted.

Droplet Sream



- New accelerator to be built in France,
- Beginning measurement 2020
- Measurements in unexplored Q^2-range
  - → **$1.5\times10^{-5} – 3\times10^{-4}$ $(GeV/c^2)^2$**
- Constrain Q^2-dependence of G_E and extrapolation to zero
- Non-magnetic spectrometer, frozen hydrogen wire / film target

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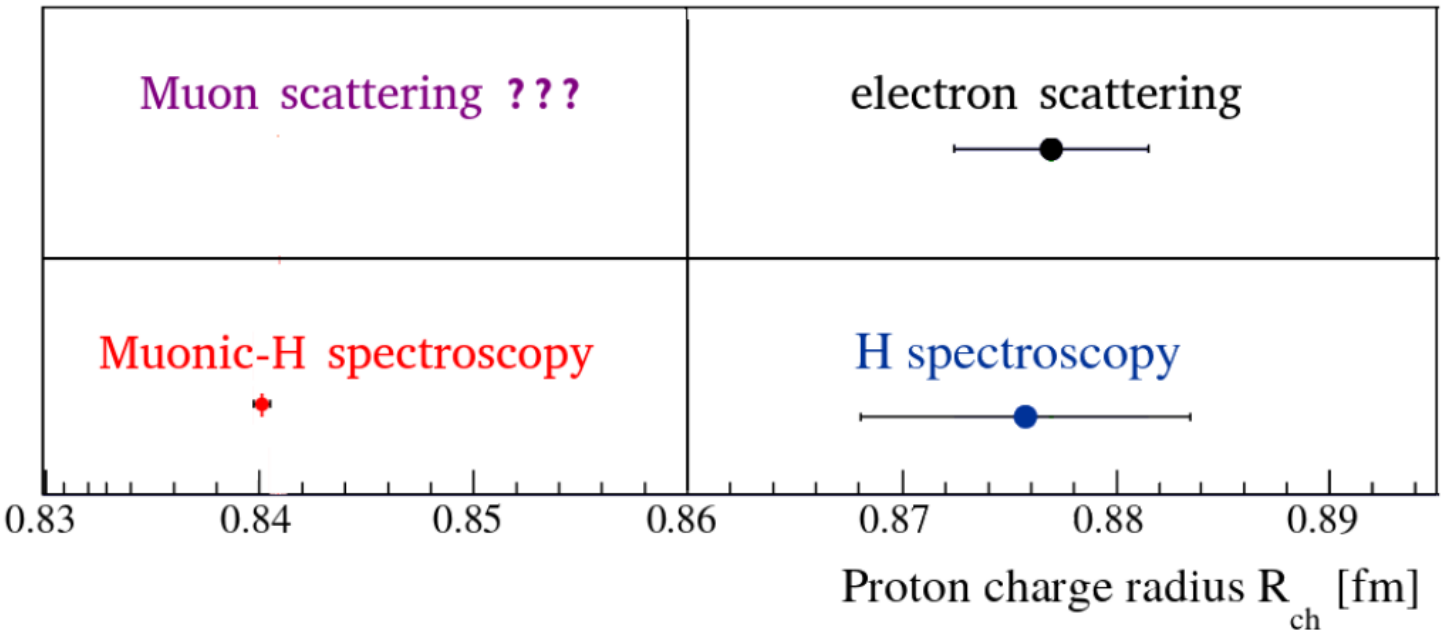
MUSE Experiment



- Simultaneous measurement of e^+/μ^+ e^-/μ^- at beam momenta of 115, 153, 210 MeV/c in πM1 channel at PSI allows:

➔Determination of two-photon effects

➔Test of lepton universality

➔Simultaneous determination of proton radius in both ep and μp scattering

MUSE Experiment

$\theta \approx 20^{o} - 100^{o}$

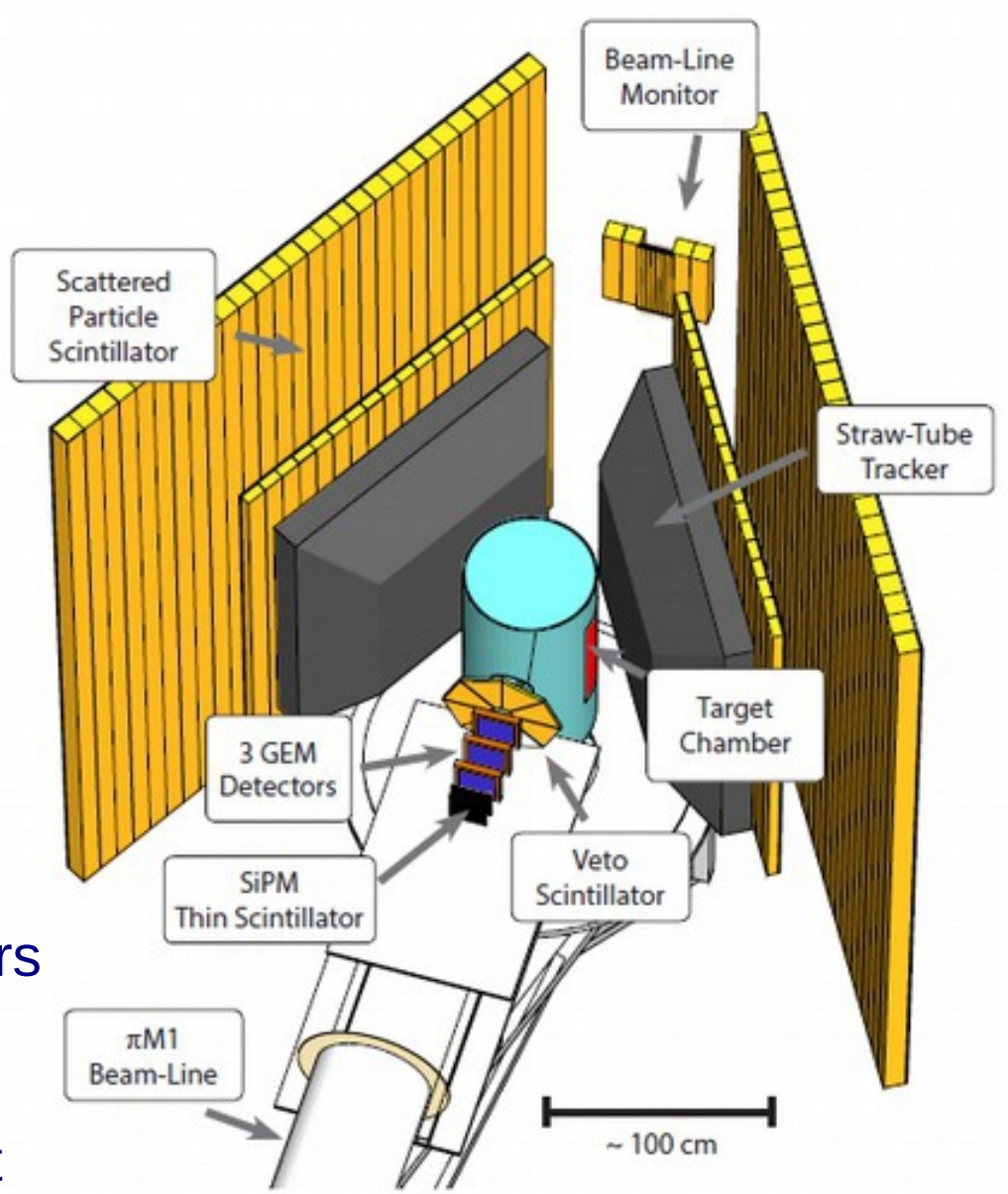
$Q^2 \approx 0.002 - 0.07\ GeV^2$

3.3 MHz total beam flux

≈ 2-15% μ's

≈ 10-98% e's

≈ 0-80% π's



- Low beam flux
  - ➔ Large angle, non-magnetic detectors
- Secondary beam
  - ➔ Tracking of beam particles to target
- Mixed beam
  - ➔ Identification of beam particle in trigger

MUSE Time-line of 2016

- Feb 1-2, 2016: NSF Technical Review
- **Feb 8-10, 2016: BVR 47**
- May 27, 2016: NSF Project Management Review
- June 20-24, 2016: Proton Radius Puzzle Workshop, Trento, Italy
  - ➔ New muonic deuterium result
  - ➔ Preliminary Garching atomic hydrogen 2S-4P result
  - ➔ Jlab PRAD took data
  - ➔ Conflicting viewpoints on ep scattering radius extractions
- June 30, 2016: 2-page physics “white paper” sent to NSF
- **September 15, 2016: NSF Midscale Construction Award**
  - ➔ Hampton received 300k NSF EAGER in September 2016
  - ➔ U Mich and HUJI+TAU BSF awards received slightly earlier
  - ➔ Construction project begins
  - ➔ From NSF+DOE: \$1.86M in 1st year, \$1.31M in 2nd year
  - ➔ \$0.43M being held as contingency

Experimental Status

- **Hiring is underway:**
  - ➔ Michigan postdoc on board, GW reviewing applicants

- Experimental design sufficiently complete for most purchasing decisions and construction – small issues continue to arise

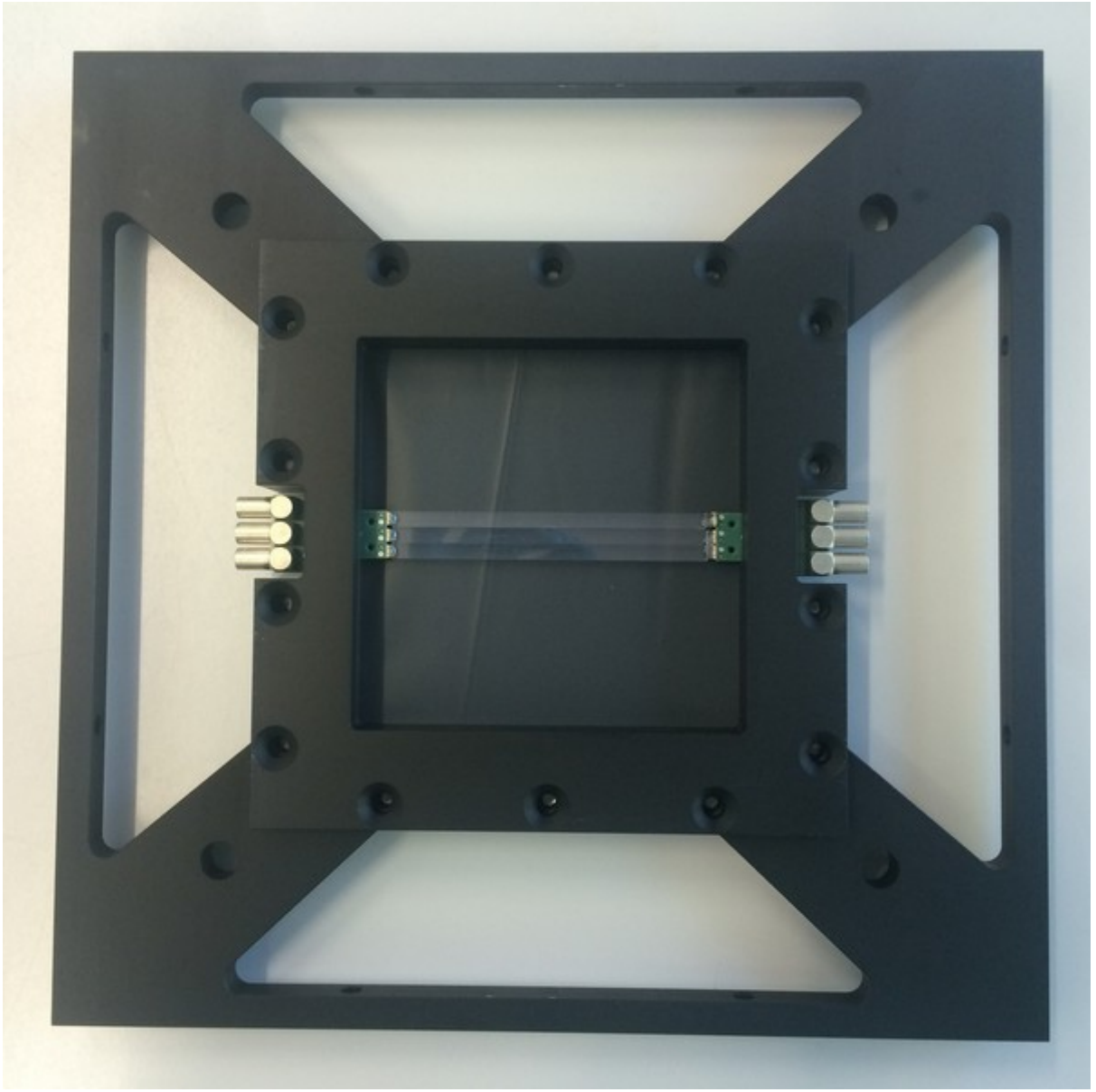
- **Four beam tests:**
  - ➔ May 9th - 20th
  - ➔ June 27th – July 15th
  - ➔ October 24th – November 4th
  - ➔ December 9th - 23rd

- **Detector & electronics tests:**
  - ➔ Optimized SiPM detector design
  - ➔ Verified timing detector performance
  - ➔ Demonstrated tracking detector function

- Verification of simulations, systematics tests

Timing Detectors: SiPM (Rutgers, TAU, PSI)

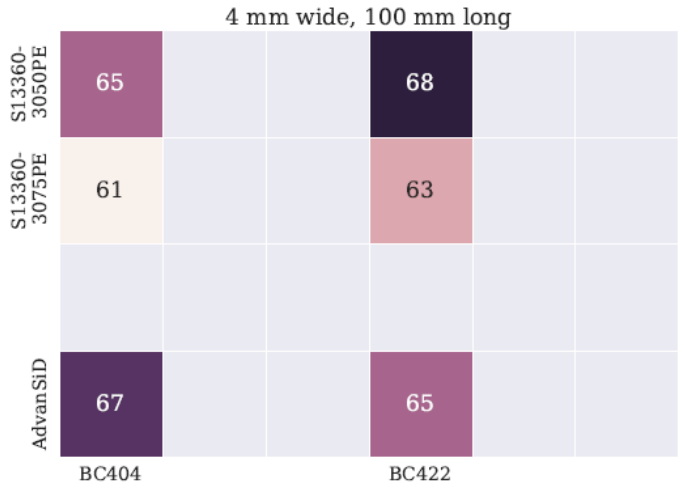
Critical Requirement: Timing resolution <100ps, Efficiency >99%

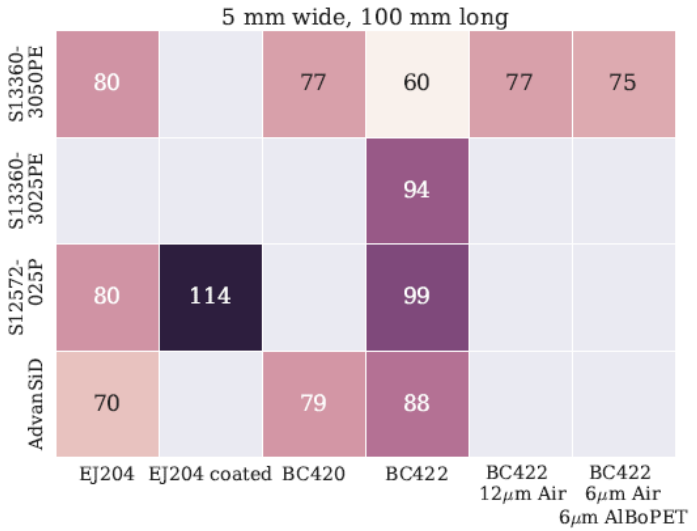


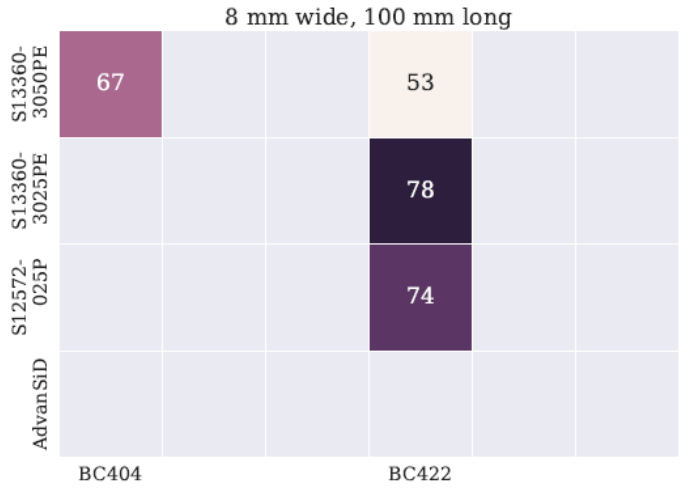
Many SiPM prototypes constructed and tested: cross talk less than 0.01%

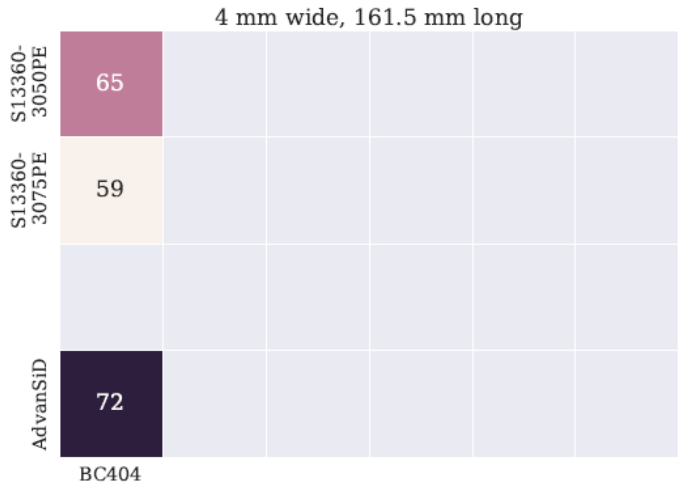
Timing Detectors: SiPM (Rutgers, TAU, PSI)

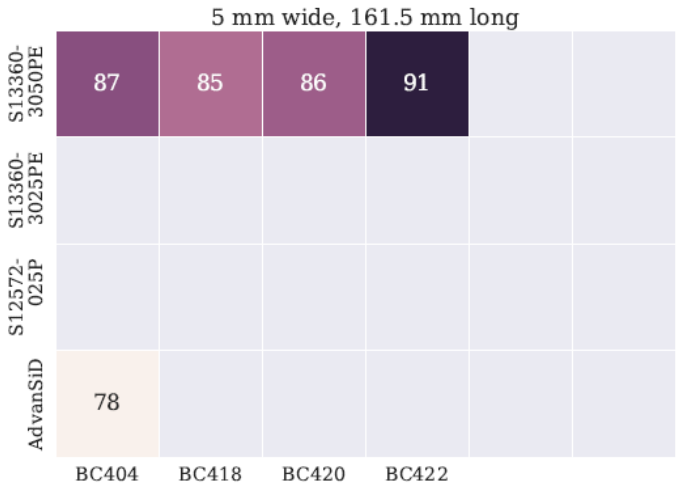
Critical Requirement: Timing resolution <100ps, Efficiency >99%

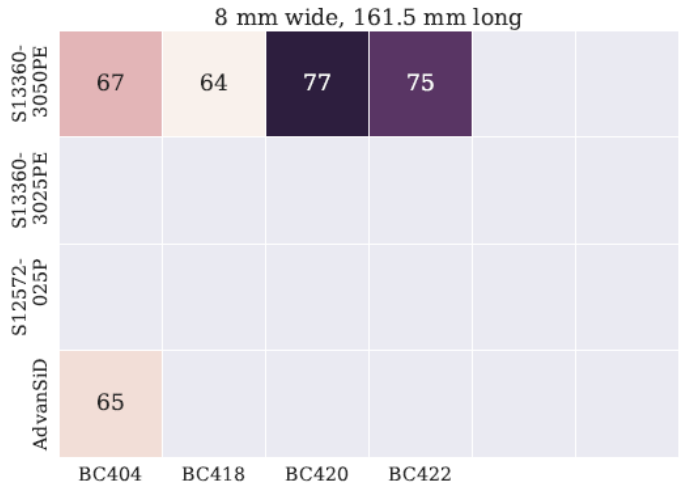






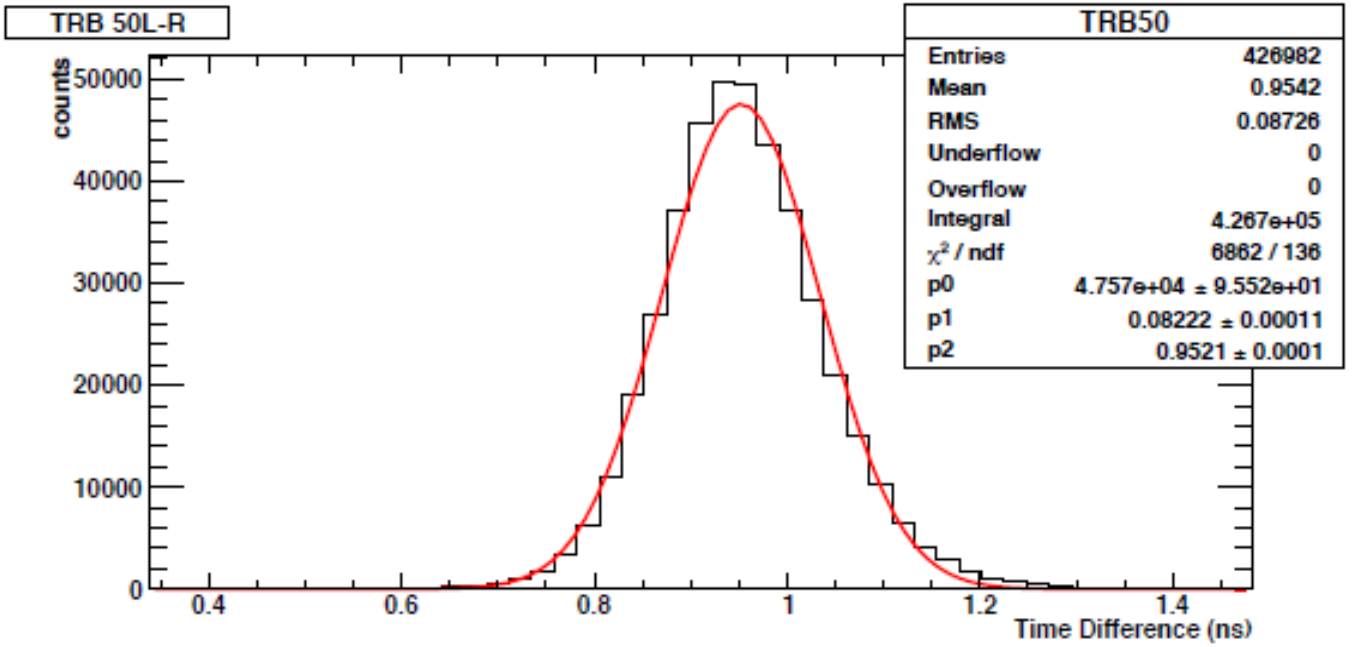






Timing Detectors: SiPM (Rutgers, TAU, PSI)

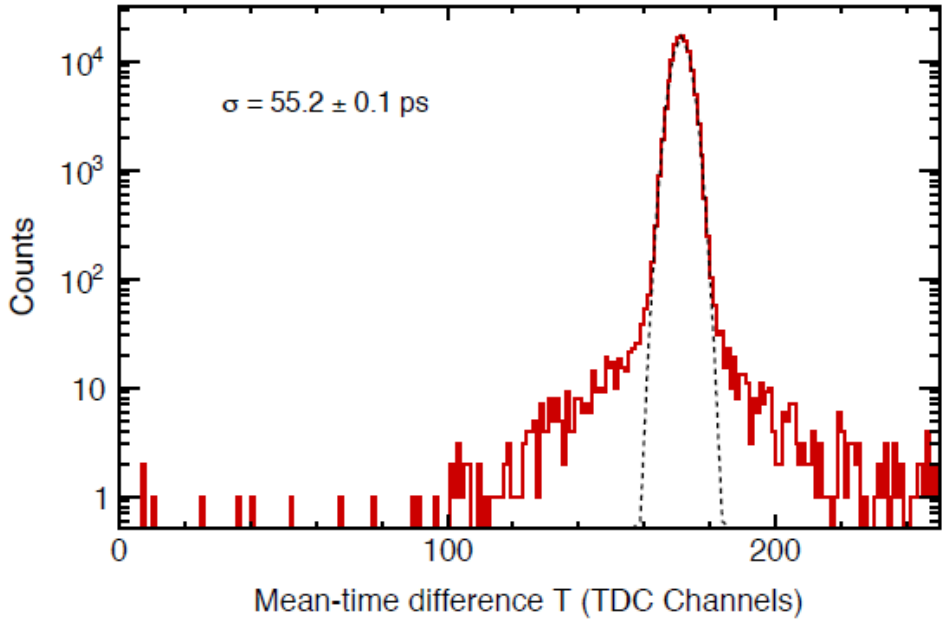
Critical Requirement: Timing resolution <100ps, Efficiency >99%



- Paddle: BC404,10 cm x 4 mm x 2 mm
- SiPM: Hamamatsu S13360-3075PE
- Readout: TRB3 with x1 PADIWA
- Paddle resolution: **87 ps / 2 = 44 ps**

Timing Detectors: Scattered Particle Scintillators (USC)

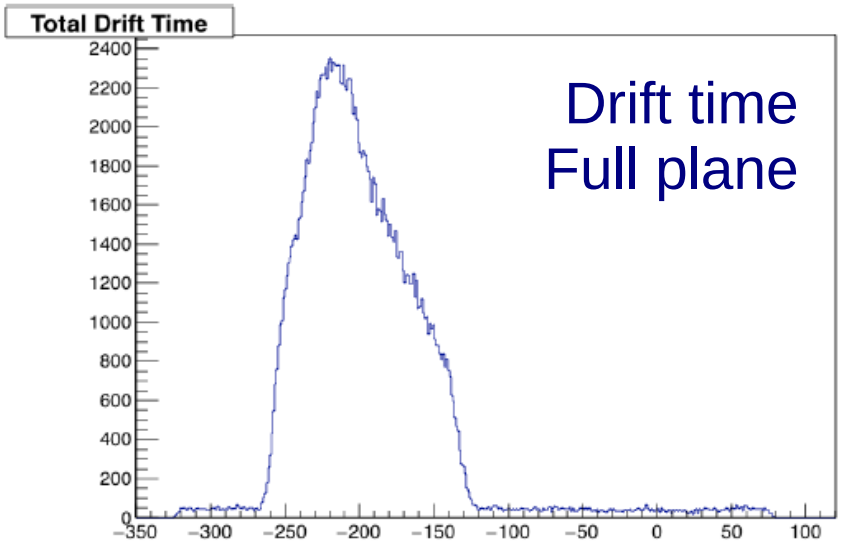
Critical Requirement: Timing resolution <100ps, Efficiency >99%

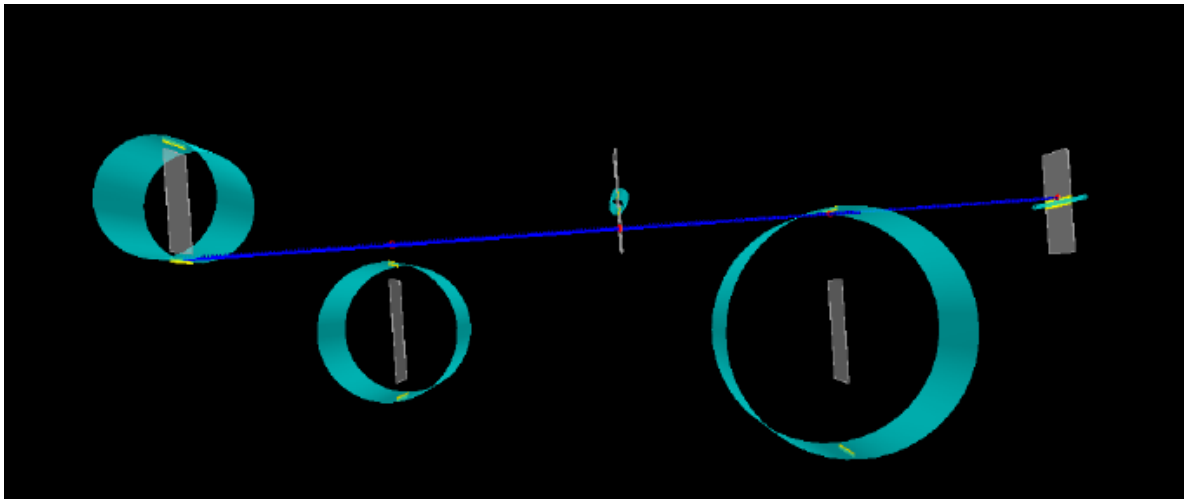


- Preliminary analysis (new material and PMTs) **55ps resolution**
- Center of bar, assuming all 3 bars have identical resolution
- Cosmic ray test – should be even better with data!
- **44 ps/√2 (SiPMs) + 55 ps√2 (scintillators) + 30 ps (geometry) ≈ 57 ps, ≪100 ps TOF specification**

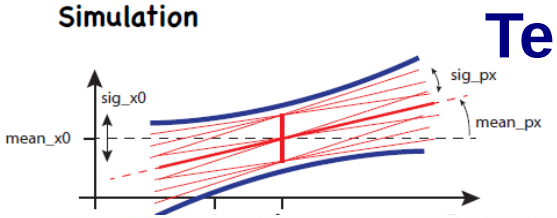
Straw Tube Trackers

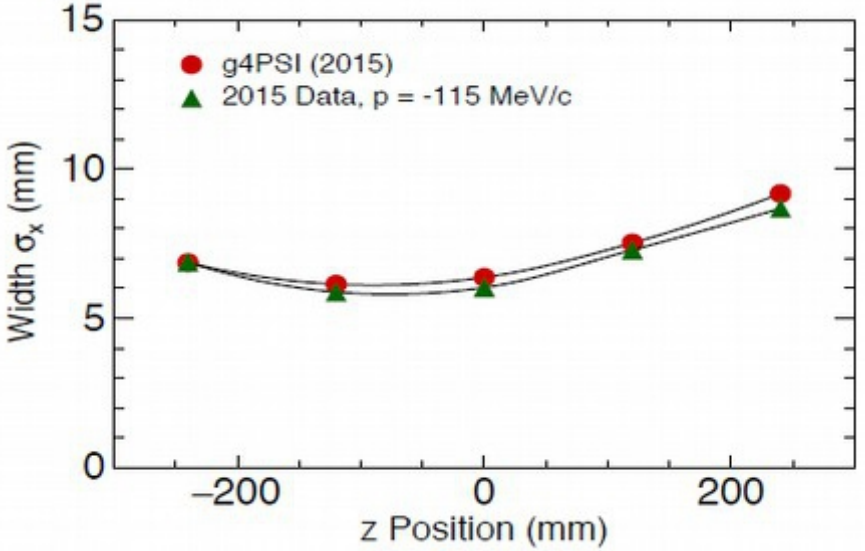
- Functioning prototype constructed
- Meets design expectations
- Tracks reconstructed in GenFit

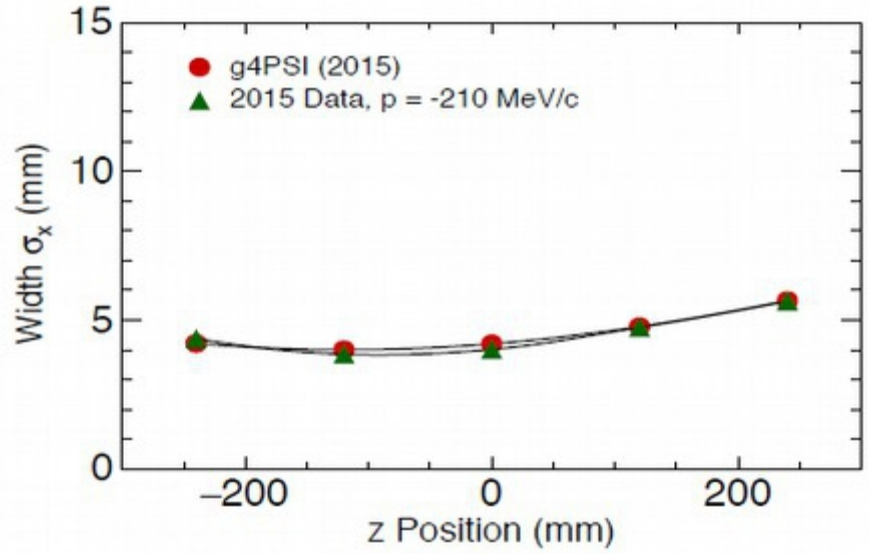




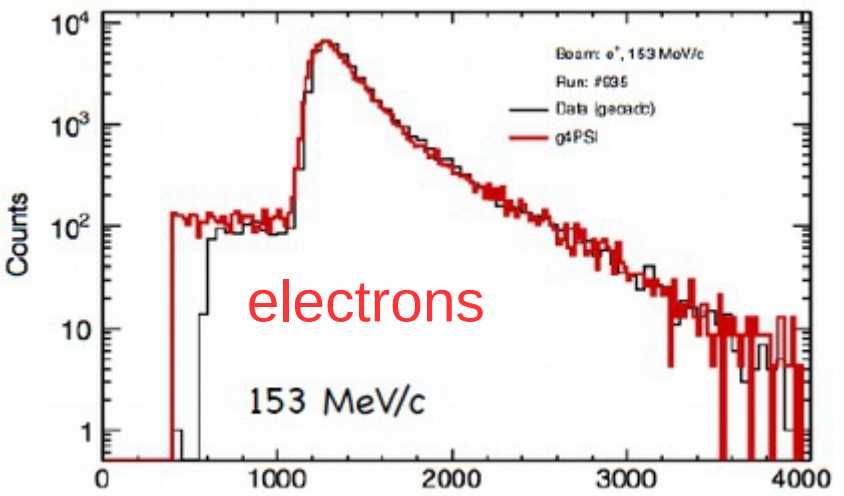
Test Beam & Simulation Comparison

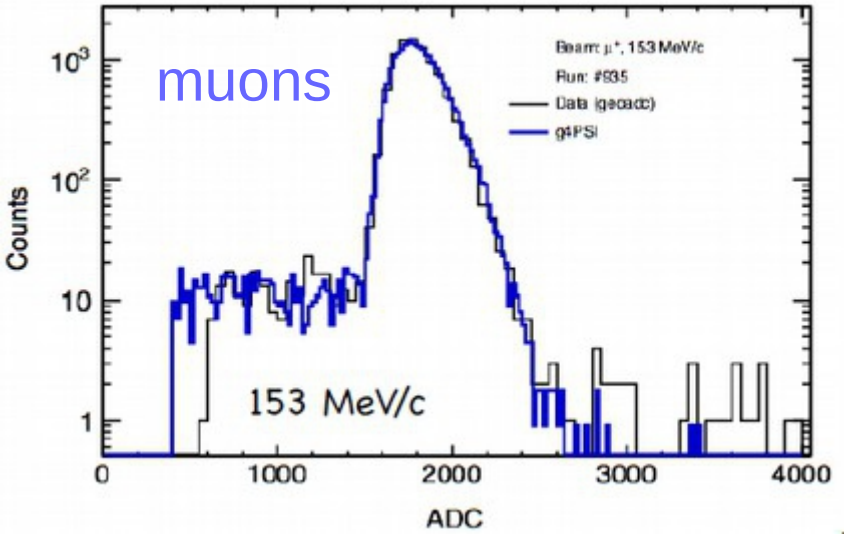






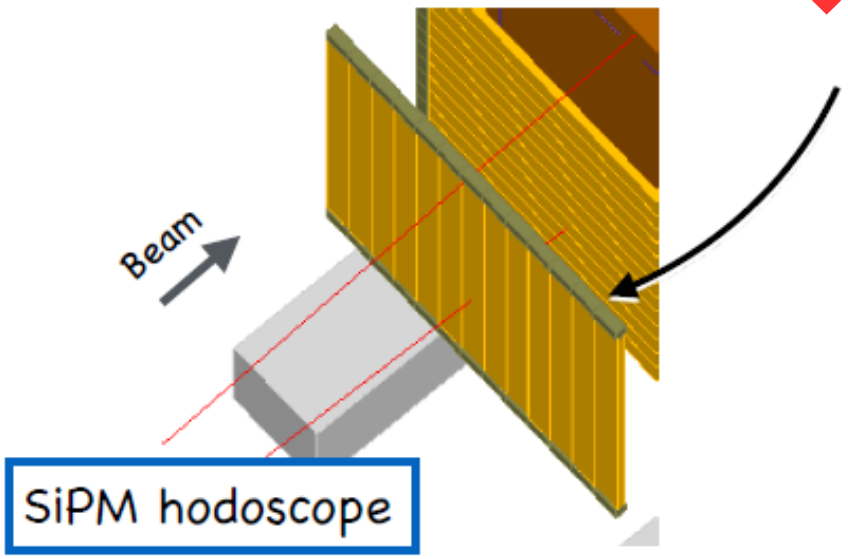
(2015) beam profile data agrees with simulation

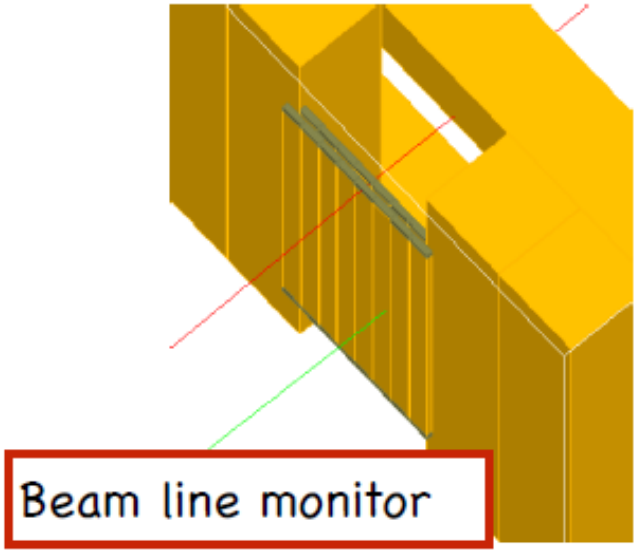




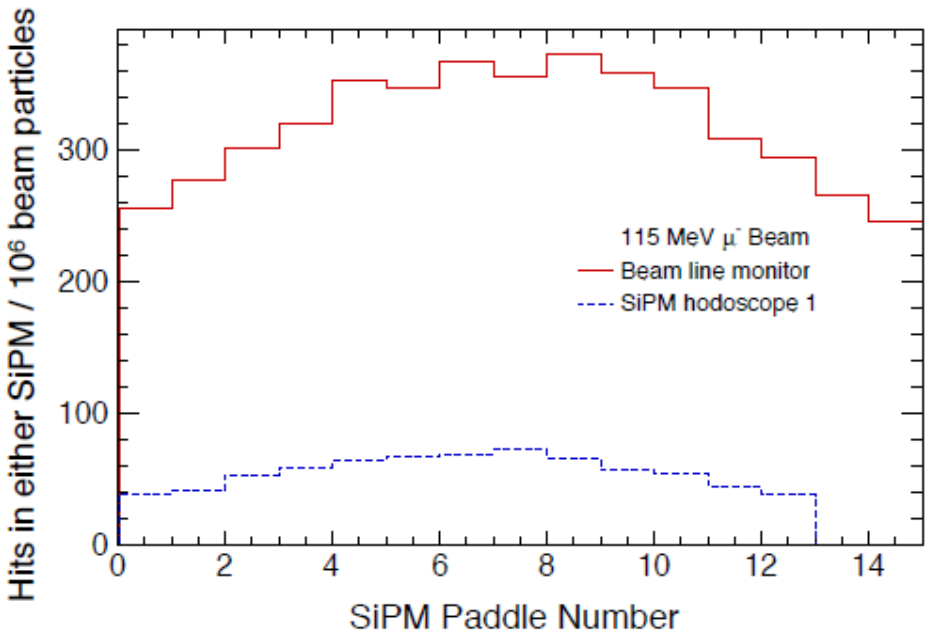
(2013) pulse height data agrees with simulation

Simulation Informing SiPM Design



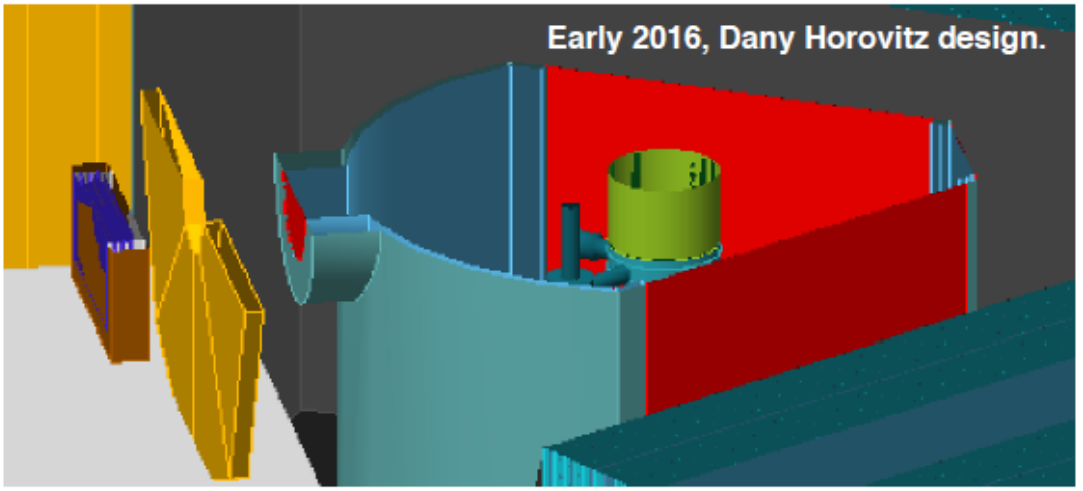


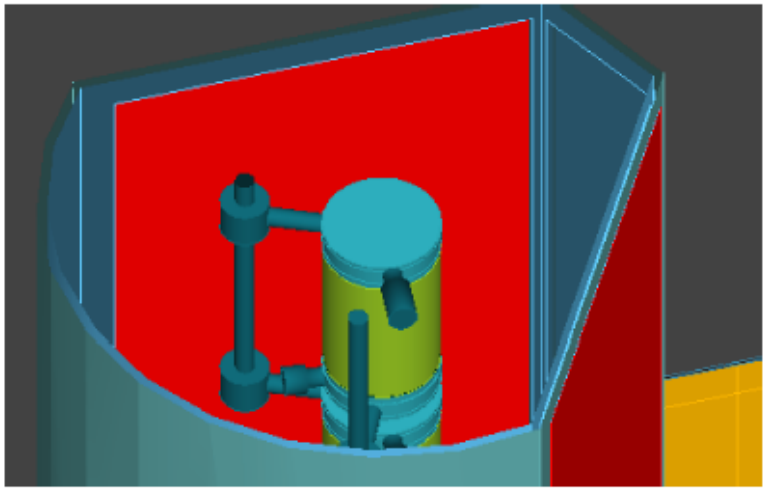
- SiPM elements in simulation can count SiPM hits

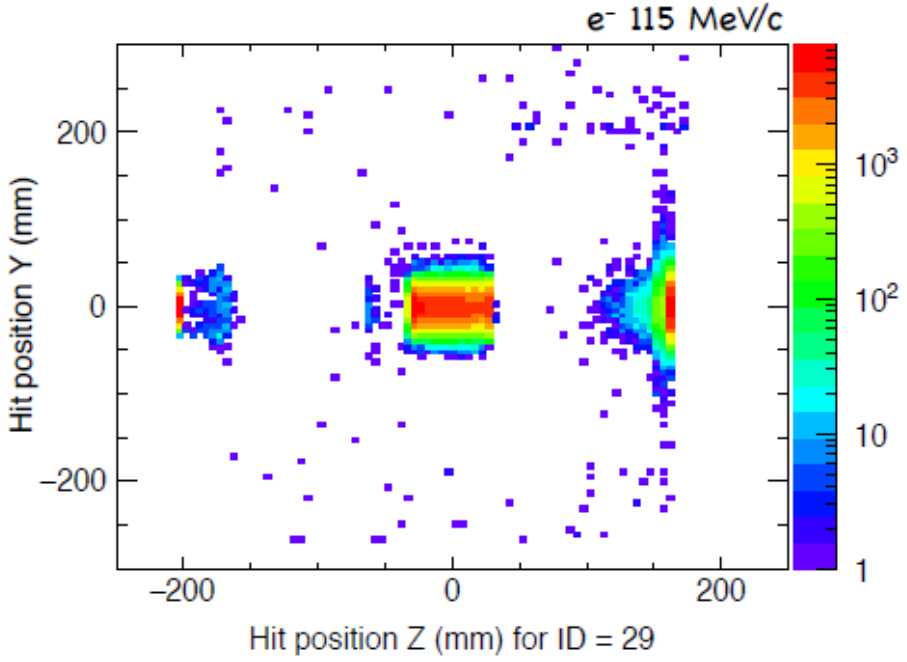


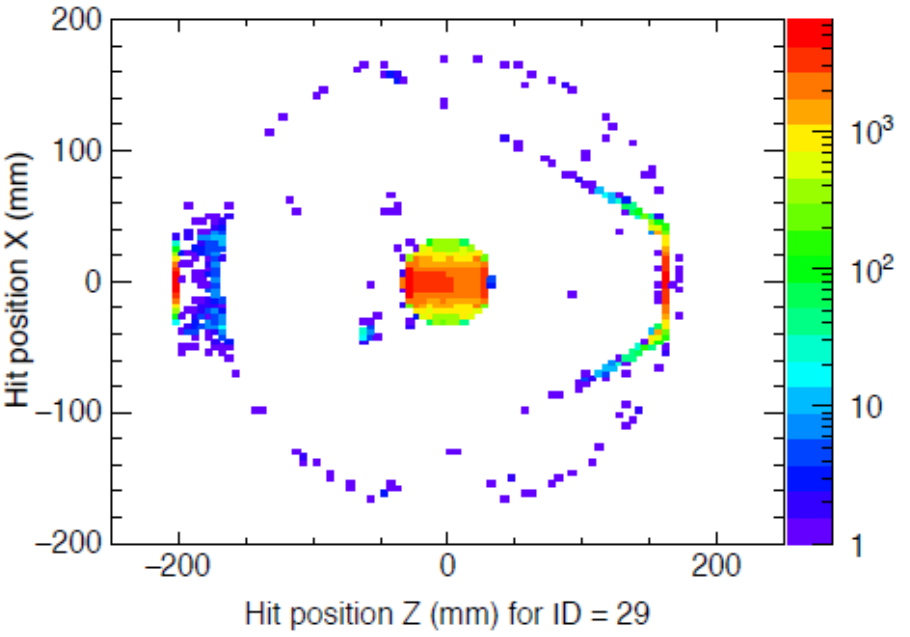
- Allows studies of potential radiation damage issues
- Beam monitor more affected than SiPM hodoscope at 115 MeV
- Increase b.m. paddles (200 → 300) mm

Simulation Informing Target Design





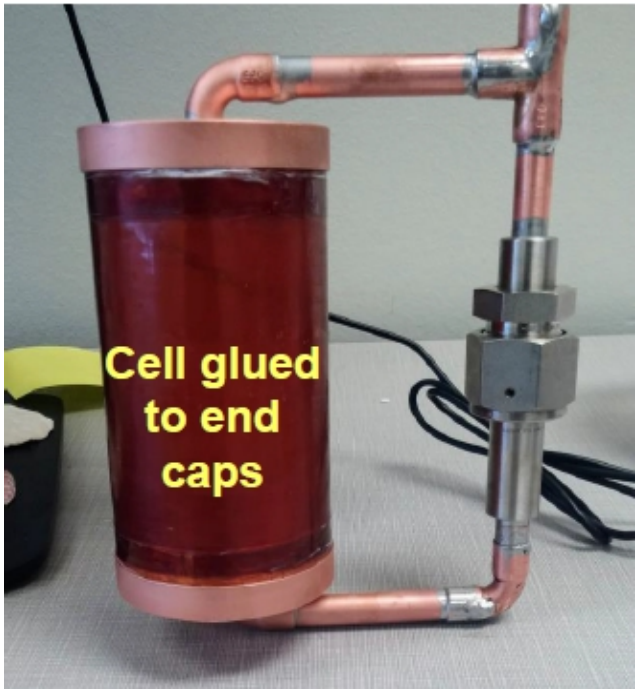


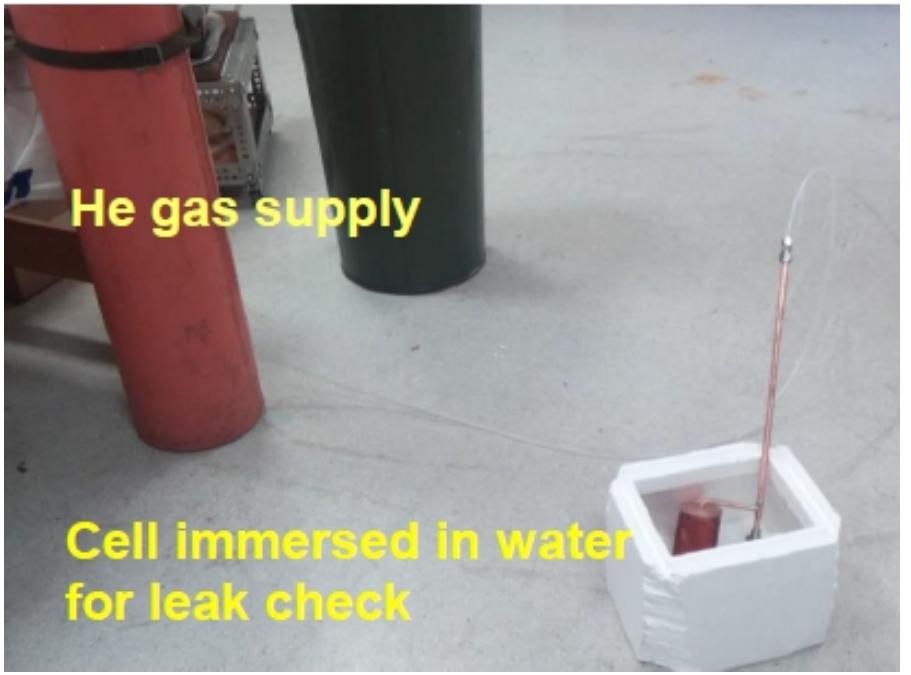


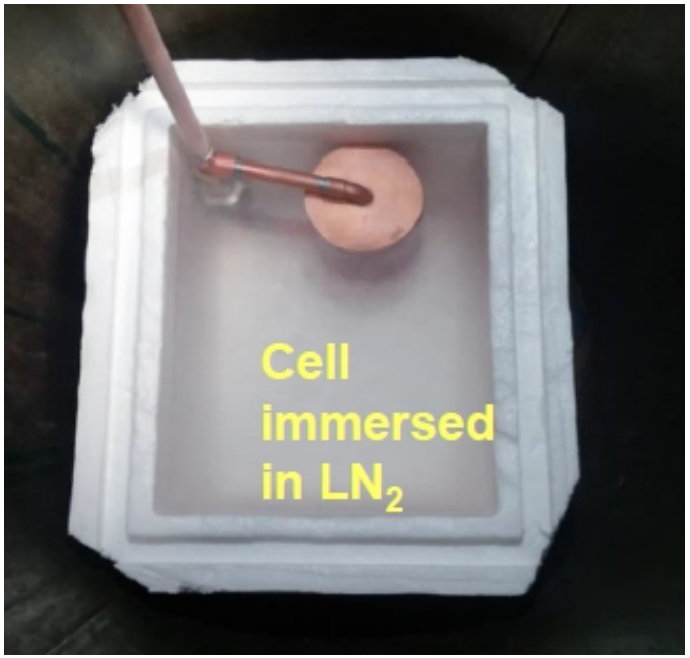
Side View

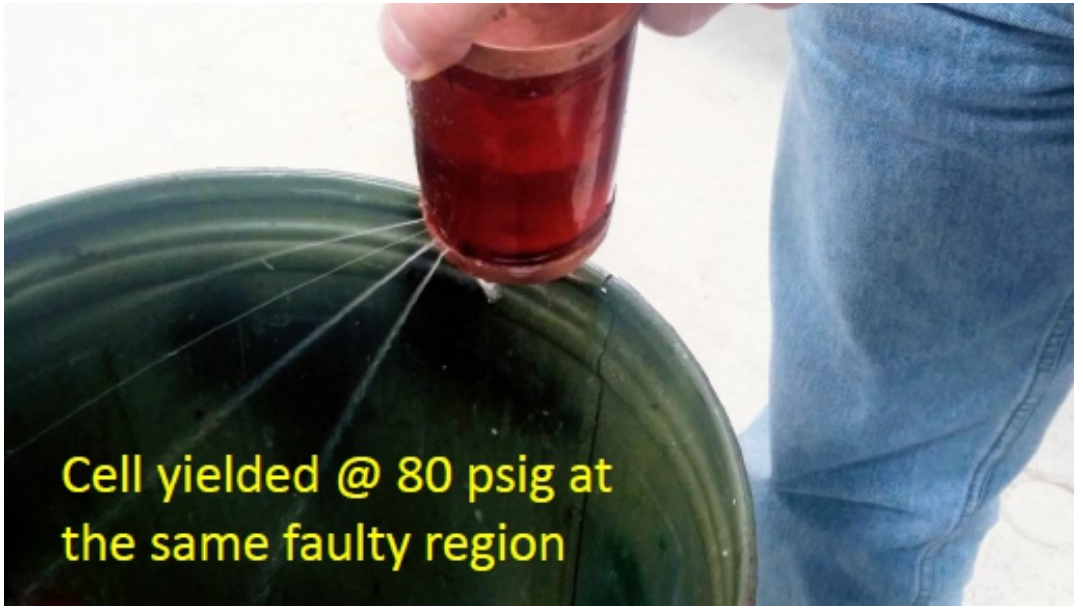
Top View

Target Progress



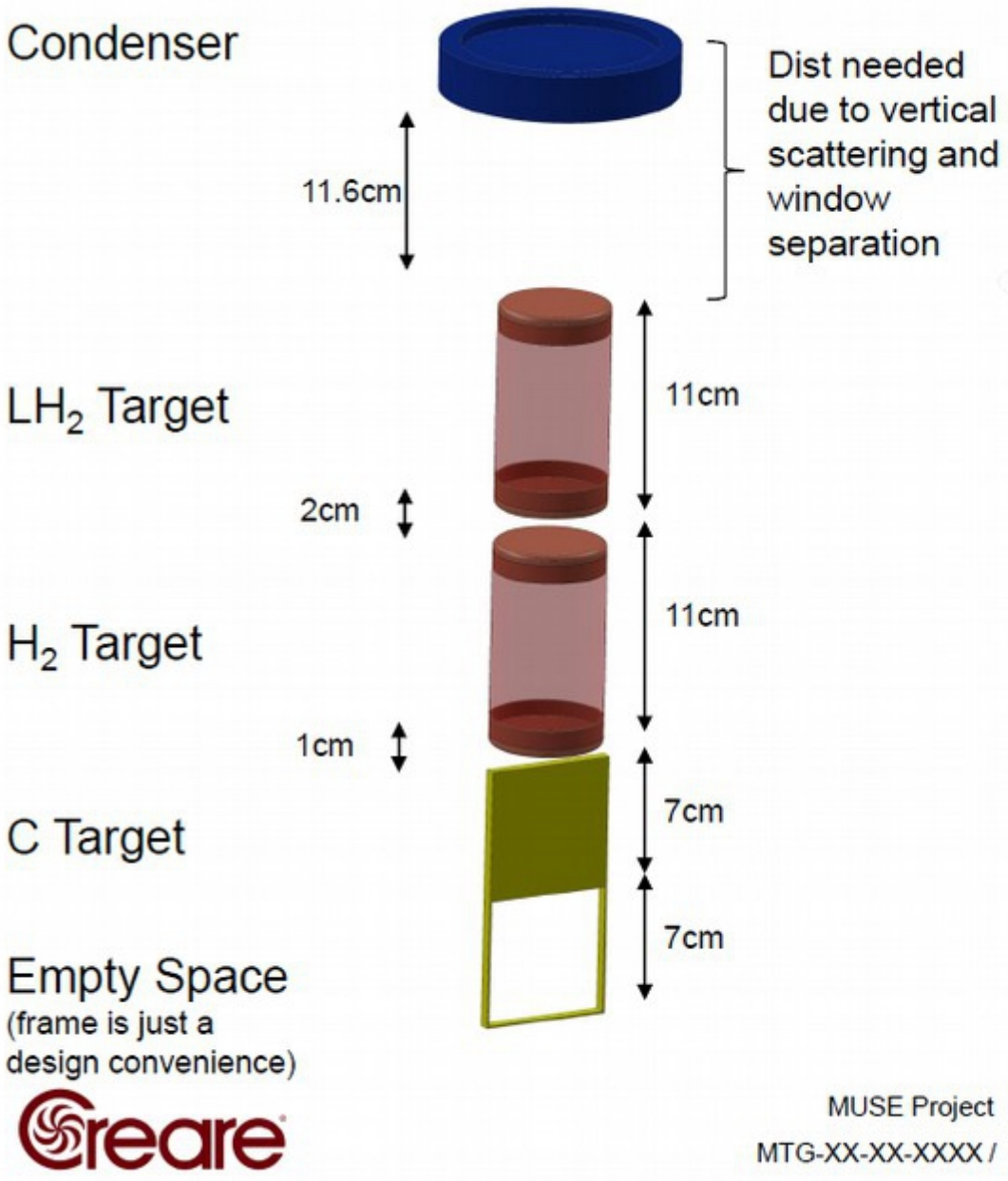


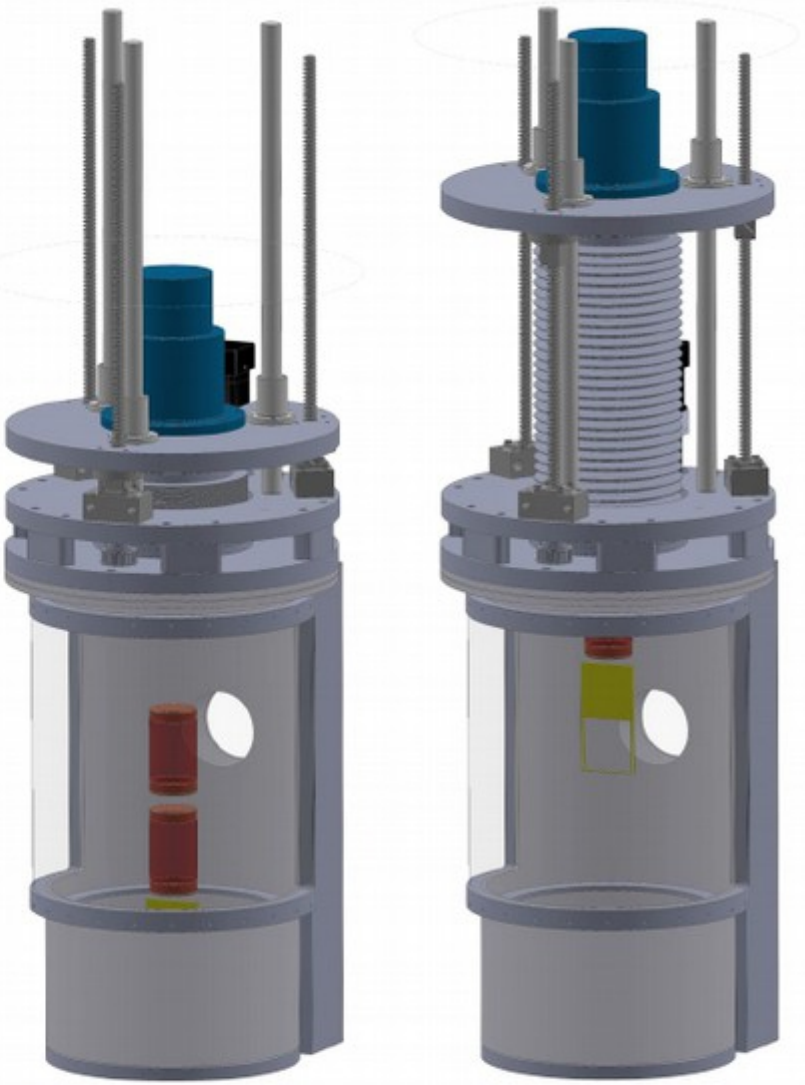




Leak developed on second cool down test at U. Mich

Target Progress





MUSE Project

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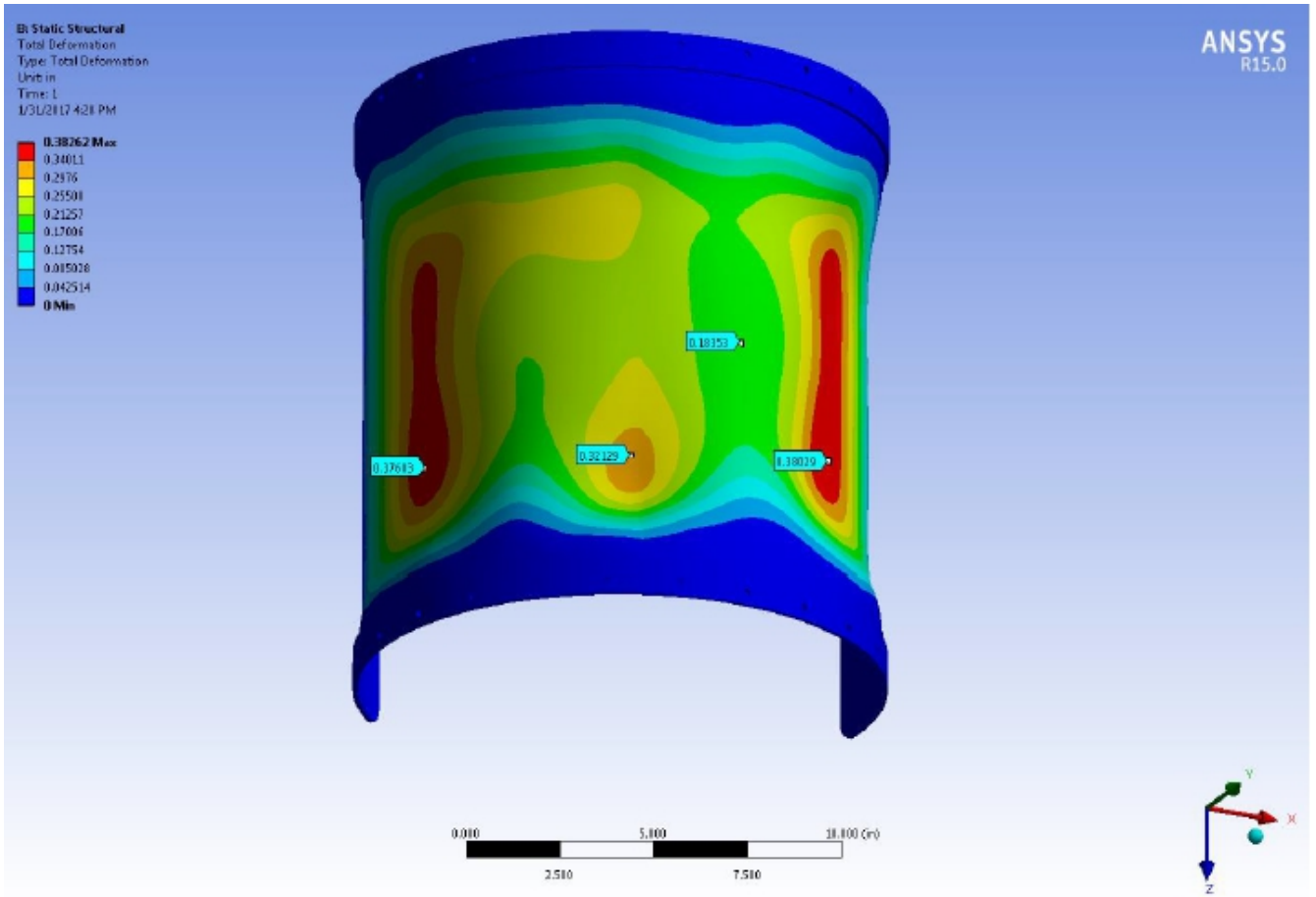
Creare contracted to design cryotarget

Target Progress



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MUSE Project

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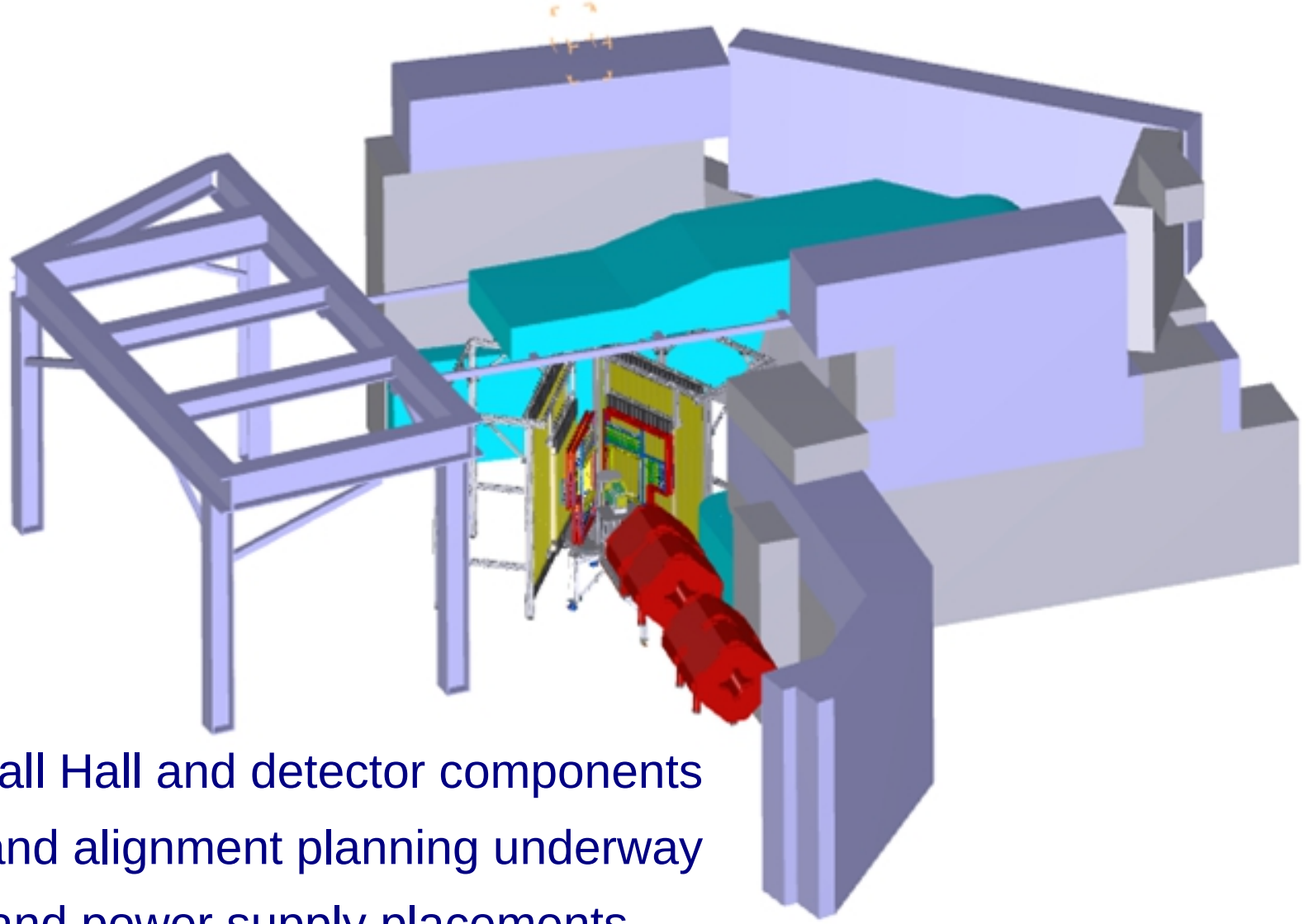
Creare performing extensive stress and strain calculations for vacuum chamber, cells, and windows

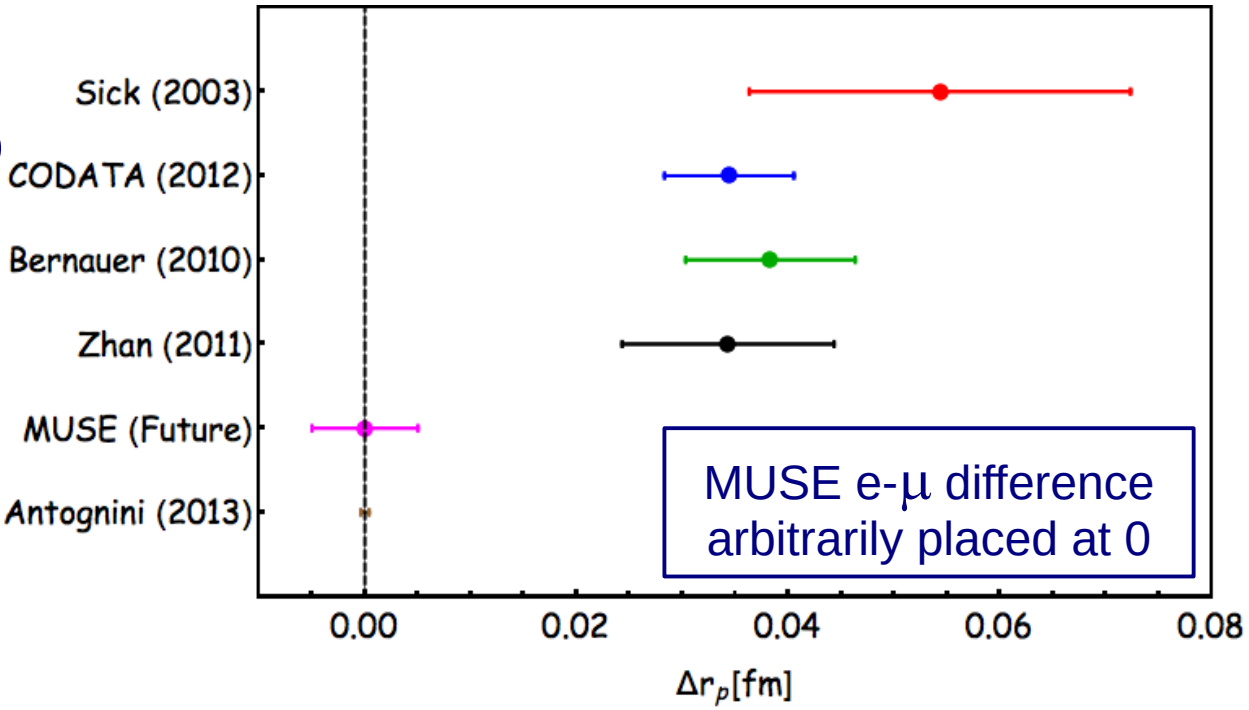
Integration, Assembly & Running

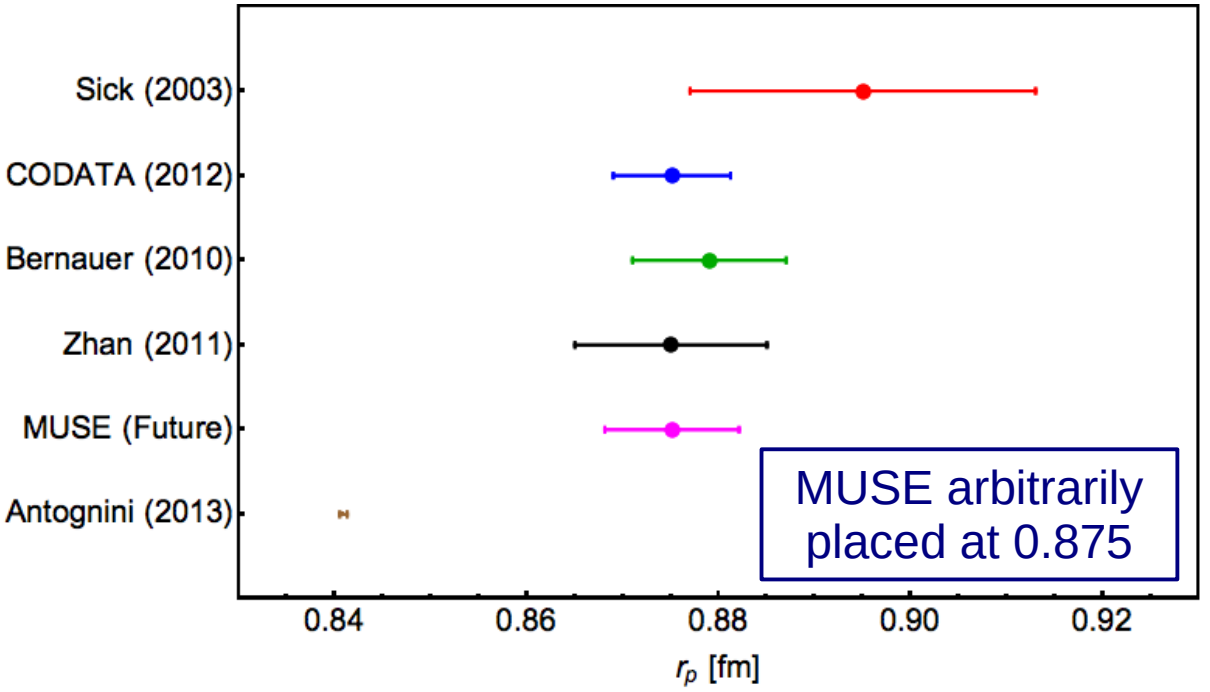


- Full CAD of all Hall and detector components
- Integration and alignment planning underway
- Electronics and power supply placements
- Preparing for dress rehearsal run in 2017 (beamline + 1 detector arm)
- MUSE detector system completely ready by summer 2018
- Experimental running in 2018 /19 (12 months total)

Anticipated MUSE Results

- Extract radius from ep and μp form factors
- MUSE will:
  - ➔ Verify the effect
  - ➔ Compare form factors
  - ➔ Compare cross sections
  - ➔ Test two photon effect
  - ➔ Solve the PRP?
- Error on radius difference:
  - ➔ **~0.005 fm**
- Absolute error on radius:
  - ➔ **~0.01 fm**





Thank you for your attention!

MUSE Main Systematic Uncertainties

Scintillator efficiency	0.1%
Solid angle	0.1%
Beam momentum offset	0.1%
Theta offset	0.2%
Multiple scattering	0.15%
Muon decay in flight	0.1%
Radiative corrections	0.1% μ; 0.5% e
Target wall subtraction	0.3%
Beam PID mis-ID	0.1%

- MUSE measuring relative cross sections
- Point-to-point uncertainties most important
- Uncertainties mostly well controlled: largest from angle and radiative corrections.
- 3 mom. x 2 pol. x 2 independent detectors → consistency check
- Multiple calibration measurements / simulations planned