The PRad Experiment

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Thomas Jefferson National Accelerator Facility

Outline

- The Proton Radius Puzzle
- PRad Setup
- Detectors Performance
- Analysis
- Summary

Outline

The Proton Radius Puzzle

- Different Methods of Measurement
- Elastic *ep* Scattering
- New Experiment Needed

PRad Setup

Detectors Performance

Analysis

Summary

Measurements of Form Factors

- First measurement at SLAC in 1961 through *ep* scattering
- 60 years of measurements, 4 possible different methods

Atomic Hydrogen Spectroscopy

Lamb shift measurements by MPQ and LKB

ep Scattering

Accelerator based experiments at Mainz, SLAC, JLab, etc

Muonic Hydrogen Spectroscopy

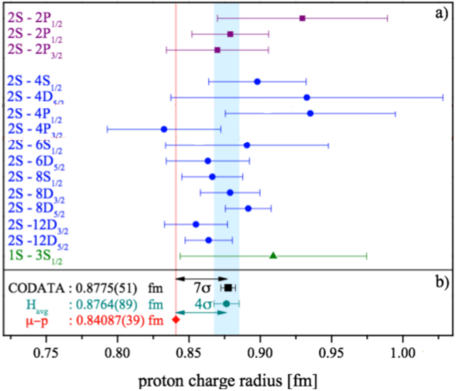
Lamb shift measurements by CREMA

μp Scattering

Future experiment PSI/MUSE

Spectroscopy Results

- Lamb shift measurements



- atomic hydrogen spectroscopy results compatible with *ep* scattering results
- muonic hydrogen spectroscopy results at 0.84 fm

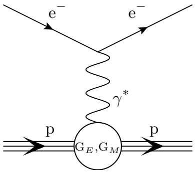
Elastic *ep* Scattering

- Elastic cross-section in the limit of the first Born approximation:

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \cdot \frac{E'}{E} \cdot \frac{1}{1+\tau} \cdot (G_E^{n2}(Q^2) + \frac{\tau}{\epsilon} G_M^{n\,2}(Q^2))$$

with:

$Q^2 = 4EE' sin^2\theta/2 \quad \tau = \frac{Q^2}{4M_p^2} \quad \epsilon = 1/(1+2(1+\tau)tan^2\theta/2)$



- Structureless proton:

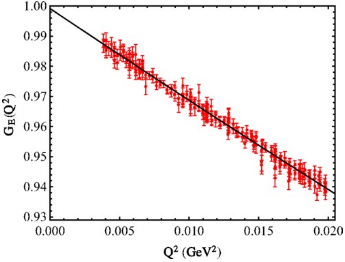
$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{\alpha^2(1-\beta^2 sin^2\theta/2)}{4k^2 sin^4\theta/2}$$

- G_E can be expressed using a Taylor expansion at low Q^2:

$$G_E = 1 - \frac{Q^2}{6} < r^2 > + \frac{Q^4}{120} < r^4 > + ...$$

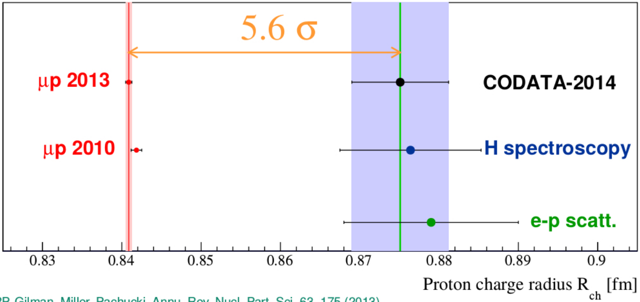
which gives:

$$< r^2 > = -6 \cdot \frac{dG_E^p}{dQ^2}\Big|_{Q^2=0}$$



Phys. Rev. C 93, 065207

The Proton Radius Puzzle



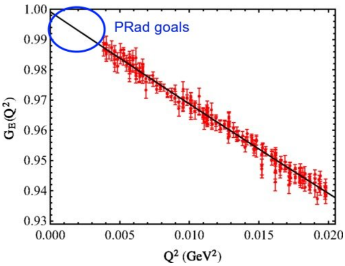
RP, Gilman, Miller, Pachucki, Annu. Rev. Nucl. Part. Sci. 63, 175 (2013).

$r_p(e^-) = 0.8770 \pm 0.0045 fm$ $\qquad$ $r_p(\mu^-) = 0.8409 \pm 0.0004 fm$

- Discrepancy between muonic hydrogen spectroscopy and atomic hydrogen (spectroscopy and scattering) measurements

The PRad Experiment

- Previous measurements have large systematic uncertainties and a limited coverage at small Q^2
- Requirements for PRad Experiment:
  - large Q^2 range
  - extend to very low Q^2
  - controlled systematics at sub-percent precision
- Choices:
  - Non magnetic spectrometer method
  - No target windows
  - high resolution high acceptance spectrometer
  - Normalization by Møller cross-section



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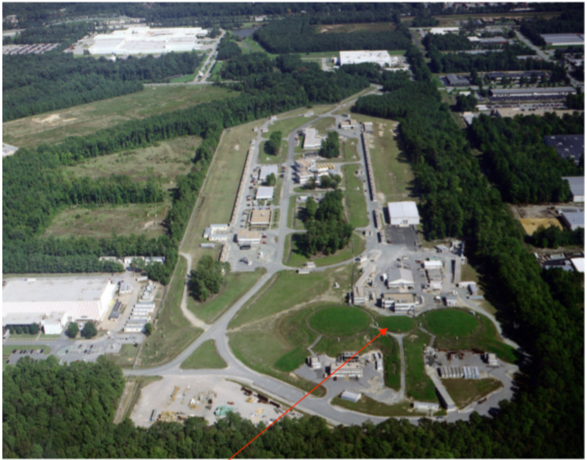
PRad Timeline

2011 - 2012	Initial proposal
2012	Approved by JLab PAC39
2012	Funding proposal for windowless H_2 gas flow target
2012 - 2015	Development, construction of the target
2013	Funding proposals for the GEM detectors
2013 - 2015	Development, construction of the GEM detectors
2015, 2016	Experiment readiness reviews
January/April 2016	Beam line installation
May 2016	Beam commissioning
May 24 - May 31	Detectors calibration
June 4 - June 15	1.1 GeV data taking
June 15 - June 22	2.2 GeV data taking

Outline

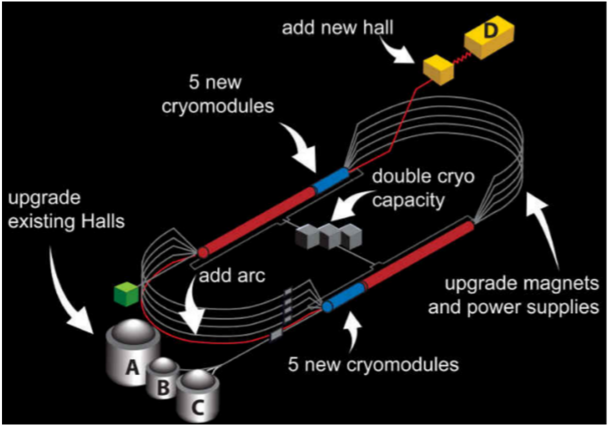
JLab Facility



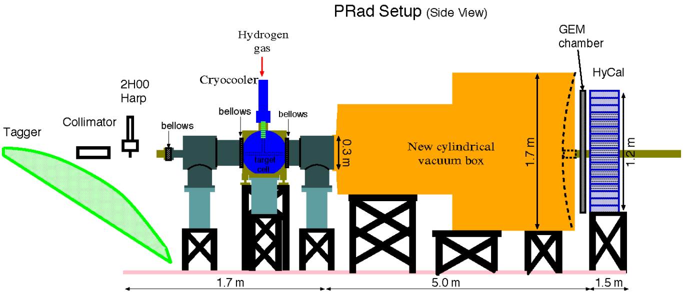
PRad was performed in Hall B at JLab

JLab 12GeV Upgrade

- First experiment finished using 12 GeV accelerator (not at full beam energy)



PRad Setup

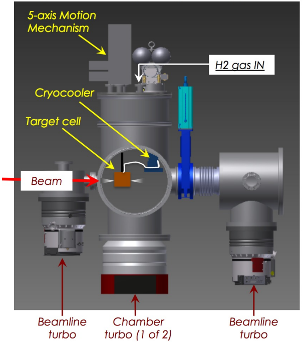


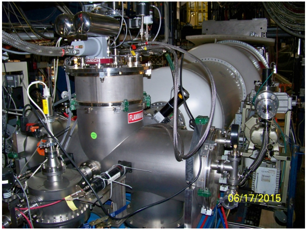
- Electron beam or tagged photon beam at ~ 1 GeV and ~ 2 GeV
- Windowless H_2 gas flow target
- Vacuum box
- GEM detectors
- Primex HyCal

Windowless H_2 Gas Flow Target

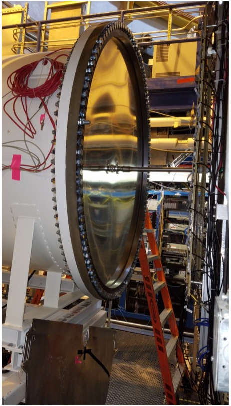
- gas target of cryogenically cooled hydrogen at 19.5 K
- beam opening: 2 mm, length: 4 cm
- cell density: $\sim 2 \cdot 10^{18}$ H atoms/cm^2
- pressures:
  - cell pressure: 471 mTorr
  - chamber pressure: 2.34 mTorr
  - vacuum chamber pressure: 0.3 mTorr

Developed and build by JLab target group





Vacuum Box



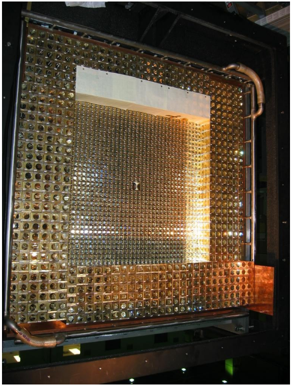
- 1.7 m diameter, 2 mm aluminum vacuum window

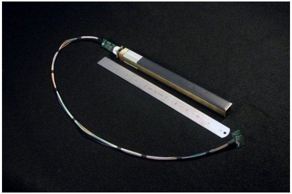
→ Limited background

Primex HyCal

Hybrid detector:

- Central part:
  - 34 x 34 matrix of $PbWO_4$ detectors
  - dimension of block: 2 x 2 x 18 cm^3
  - 2 x 2 blocks removed from the center for beam line to pass through
- Peripheral part:
  - 576 lead glass detectors
  - dimension of block: 4 x 4 x 45 cm^3
- Successfully used for Primex experiments

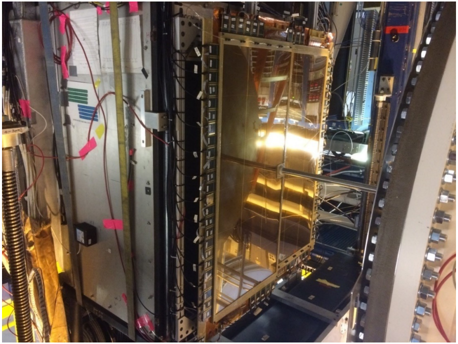


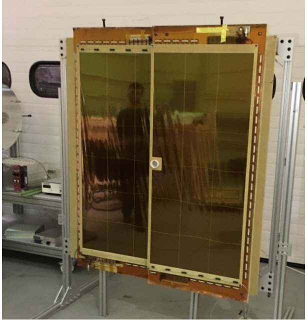


GEM Detectors

- Two large area GEM detectors: 55 cm x 123 cm
- Purpose:
  - improve spatial resolution by a factor 20 to 40 $\rightarrow$ 100 μm

  $\rightarrow$ to reduce uncertainties on θ and Q^2
- Central overlap between the 2 planes and central hole for the beam line





Developed and build by UVA

Outline

The Proton Radius Puzzle

PRad Setup

Detectors Performance

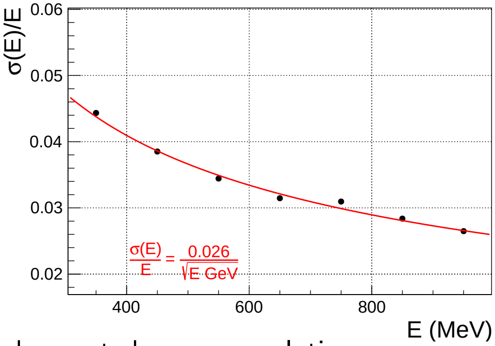
- HyCal Energy Resolution
- Trigger Efficiency
- GEM Matching Efficiency
- GEM Spatial Resolution

Analysis

Summary

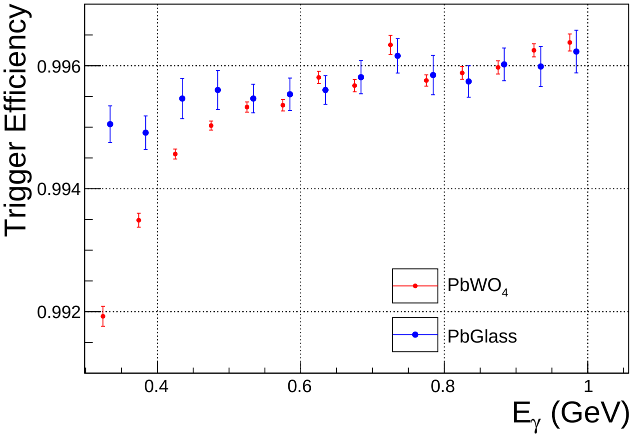
HyCal Energy Resolution

- Crystal energy resolution with statistical uncertainties



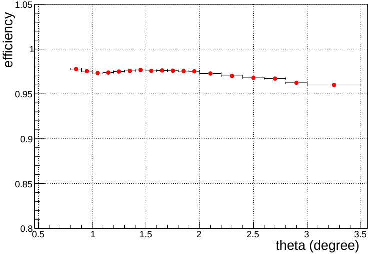
- Achieved expected energy resolution:
  - 2.5% at 1 GeV for crystal part
  - 6.1% at 1 GeV for lead glass part

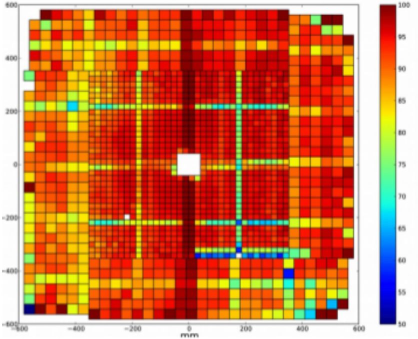
Trigger Efficiency



- Plateau from 500 MeV with an efficiency of 0.995
- Good uniformity

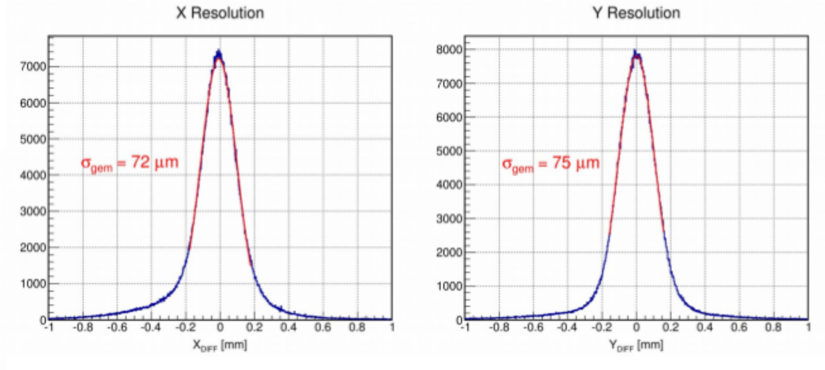
GEM Matching Efficiency





- GEM detection efficiency measured in both photon beam calibration (pair production) and production runs (ep and ee)
- Almost flat efficiency $> 97\%$ after removal of spacers and dead zones

GEM Spatial Resolution



- Really good spatial resolution $\sim 74\ \mu m$
- 20 to 40 times better than HyCal spatial resolution

Outline

Data Collected

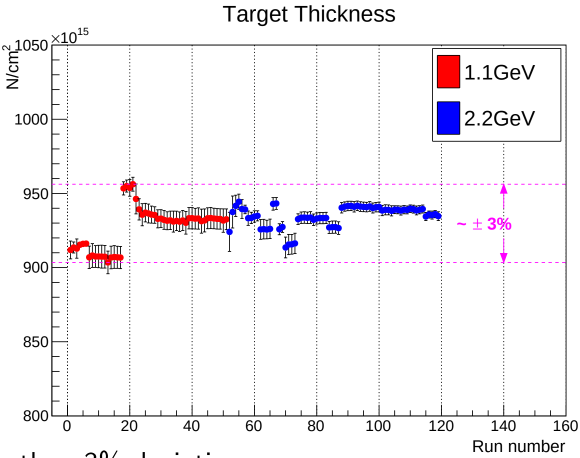
- Calibration with tagged photon beam
  - Every calorimeter module moved into the beam
  - Allows study of resolution, linearity, trigger efficiency

- 1.1 GeV electron beam
  - 4.2 mC
  - 604 M events with target
  - 53 M events with "empty target"
  - 25 M events with ^{12}C target for calibration

- 2.2 GeV electron beam
  - 14.3 mC
  - 756 M events with target
  - 38 M events with "empty target"
  - 10.5 M events with ^{12}C target for calibration

Target Stability

- Control of target properties (pressure, temperature, position) via EPICS

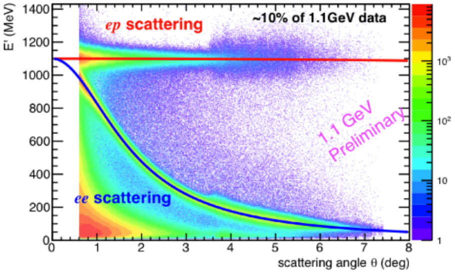


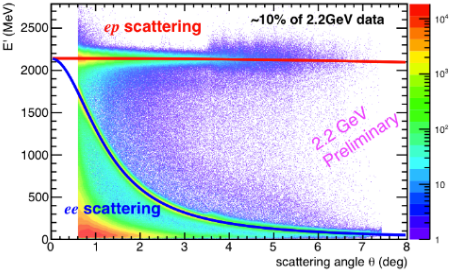
→ Less than 3% deviation

Weizhi Xiong

Phase Space

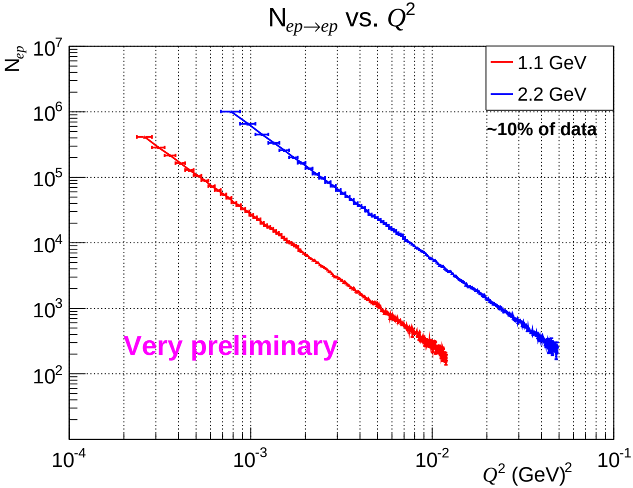
- Phase space after background subtraction





- Separation of *ep* and Møller phase space (for $\theta > 0.85 deg$ for 1 GeV)

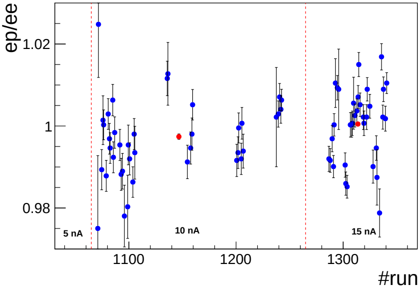
ep Yields

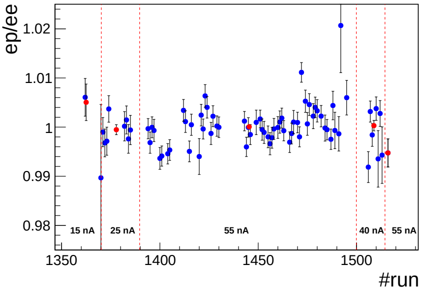


- 1.1 GeV data set: $Q^2 \in [2 \cdot 10^{-4}, 1.3 \cdot 10^{-2}]$ GeV^2
- 2.2 GeV data set: $Q^2 \in [8 \cdot 10^{-4}, 6 \cdot 10^{-2}]$ GeV^2

Yields Stability

- Stability of ratio ep/ee after background subtraction for different beam intensity





- Good stability for the 2GeV period

Extraction of Cross-section

- Normalization of *ep* cross-section by Møller cross-section:

$$\left(\frac{d\sigma}{d\Omega}\right)_{ep} = \frac{N_{exp}(ep \to ep\, in\, \theta_i \pm \Delta\theta)}{N_{exp}(ee \to ee)} \cdot \frac{\epsilon^{ee}_{geom}}{\epsilon^{ep}_{geom}} \cdot \frac{\epsilon^{ee}_{det}}{\epsilon^{ep}_{det}} \cdot \left(\frac{d\sigma}{d\Omega}\right)_{ee}$$

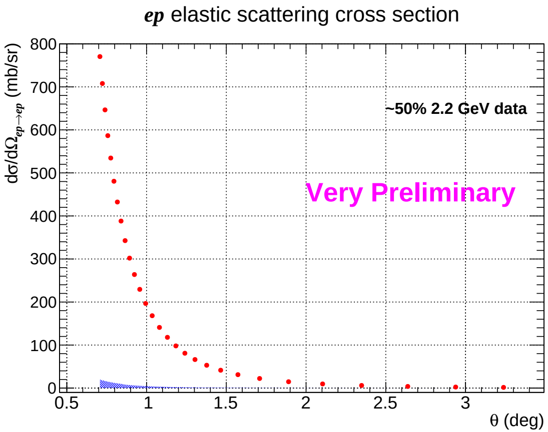
- Several event generators have been developped for *ep* and Møller scattering taking into account complete calculations of radiative corrections beyond ultra relativistic approximations
  - A. V. Gramolin et al., J. Phys. G Nucl. Part. Phys. 41(2014)115001
  - I. Akushevich et al., Eur. Phys. J. A 51(2015)1
- Geant4 is used to take into account all external radiative effects

$$\sigma^{Born}_{ep} = \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{exp} / \left(\frac{\sigma_{ep}}{\sigma_{ee}}\right)^{sim} \cdot \sigma^{Born}_{ee}$$

Preliminary *ep* Cross-section

PRoton Radius

- Preliminary *ep* cross-section for the 2.2 GeV data set
- Statistical uncertainties at $\sim 0.2\%$ per point
- Conservative point-to-point systematic uncertainties at $\sim 2\%$



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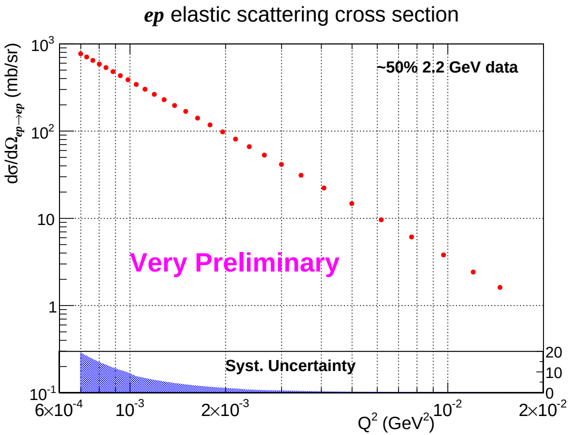

Summary

- The PRad experiment was uniquely designed to address the *Proton Radius Puzzle*
- The experiment was successfully performed in May-June 2016
- Wide range of Q^2 without normalization on more than two orders of magnitude ($2 \cdot 10^{-4}$ GeV^2 to $6 \cdot 10^{-2}$ GeV^2)
- Lowest Q^2 data set of ep elastic scattering ($2 \cdot 10^{-4}$ GeV^2)
- First preliminary extraction of the proton radius expected at the end of October

Thanks to JLab, Hall B, Accelerator Division and Target Group

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my research work is supported by NSF awards: PHY-1506388 and PHY-0855543