QCD, Hadron Spectroscopy, and Exotics

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and Bernhard Ketzer

Argonne NATIONAL LABORATORY

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QCD, Hadron Spectroscopy, and Exotics Overview

Session Topics

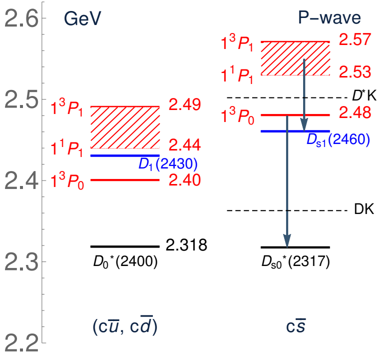
- Heavy Quarks and Spectroscopy
- Electromagnetic Nucleon Interactions
- Numerical Methods (with NFS)
- Light Quark Hadrons
- Proton Radius (with PPHI)

- Conveners
  - Raul Briceno, JLab
  - Bernhard Ketzer, Bonn
  - SR, ANL

Parallel 2

- **Model Independent Constraints on** $R(J/\psi)$
  Lamm, Maryland
- **Implication of Chiral Symmetry on the Heavy-Light Spectroscopy**
  Du, Universität Bonn
- **Precise Measurement of the** $D^{\star}(2010)^{+} - D^{+}$ **Mass Difference**
  Soffer, Tel Aviv
- **Dibaryon Searches in Decuplet Baryons from Lattice QCD**
  Gongyo, RIKEN
- **Single-Top Production in the Standard Model and Beyond**
  Kidonakis, Kennesaw State
- **Measurement of Polarization Observables in the Reaction** $\gamma p \to K^{+}\Lambda$
  Adhikari, Florida International

Positive parity ground state charm mesons



SU(3) partners

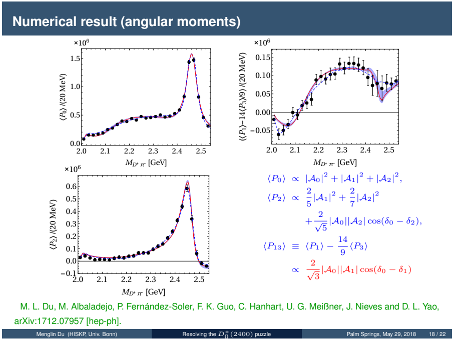
$D_0^*(2400)$, $D_1(2430)$

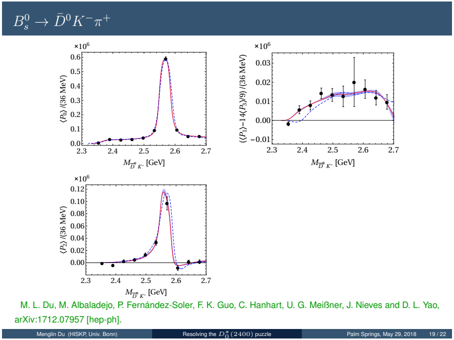
$D_{s0}^*(2317)$, $D_{s1}(2460)$

S. Godfrey and N. Isgur, PRD **32**, 189 (1985)

BaBar (2003), CLEO (2003); Belle (2004)

Chiral Symmetry on the Heavy-Light Spectroscopy, Du



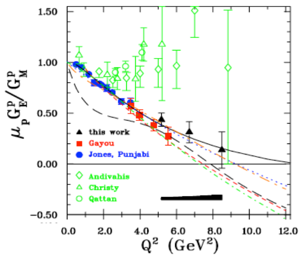


- χFT to help address D^* positive parity anomalies
- Identifies $D_{s0}^*(2317)$ and $D_{s1}(2460)$ as likely having molecular component
- Describes LHCb data for $B_s^0 \to \bar{D}^0 K^- \pi^+$ and finds two lighter states which would resolve puzzle

Parallel 5

- **Two-Photon Effects in Elastic Nucleon Form Factors**
  Vanderhaeghen, Mainz
- **High Q^2 Elastic Form Factor Program at Jefferson Lab**
  Puckett, UConn
- **Sum Rules Connecting Real and Virtual Compton Scattering on the Nucleon**
  Pascalutsa (for Vadim Lensky), Mainz
- **Proton Polarizabilities from a Partial-Wave Analysis of Compton Scattering Data**
  Pascalutsa, Mainz

Rosenbluth vs polarization transfer measurements of G_E/G_M of proton



Two methods: two different results

most likely: 2γ-exchange correction

Rosenbluth data

SLAC, JLab (Hall A, C)

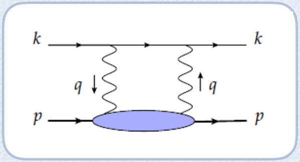
Polarization data

JLab (Hall A, C)

GEpI	Jones et al. (2000)
	Punjabi et al. (2005)
GEpII	Gayou et al. (2002)
GEpIII	Puckett et al. (2010)

12

Lamb shift: hadronic corrections



$$
\begin{aligned}
T^{\mu\nu}(p,q) &= \frac{i}{8\pi M}\int d^4x\, e^{iqx}\langle p|Tj^\mu(x)j^\nu(0)|p\rangle \\
&= \left(-g^{\mu\nu}+\frac{q^\mu q^\nu}{q^2}\right)T_1(\nu,Q^2) \\
&+ \frac{1}{M^2}\left(p^\mu-\frac{p\cdot q}{q^2}q^\mu\right)\left(p^\nu-\frac{p\cdot q}{q^2}q^\nu\right)T_2(\nu,Q^2)
\end{aligned}
$$

- Lower blob contains both elastic (nucleon) and in-elastic states
  Information contained in **forward, double virtual Compton scattering**

→ **Hadron physics input required**

- Described by two amplitudes T1 and T2: function of energy ν and virtuality Q^2
- Imaginary parts of T1 , T2: unpolarized structure functions of proton

$$
\begin{aligned}
\mathrm{Im}\, T_1(\nu,Q^2) &= \frac{1}{4M}F_1(\nu,Q^2) \\
\mathrm{Im}\, T_2(\nu,Q^2) &= \frac{1}{4\nu}F_2(\nu,Q^2)
\end{aligned}
$$

- ΔE evaluated through an integral over Q^2 and ν

$$
\begin{aligned}
\Delta E &= \Delta E^{el} \\
&+ \Delta E^{subtr} \\
&+ \Delta E^{inel}
\end{aligned}
$$

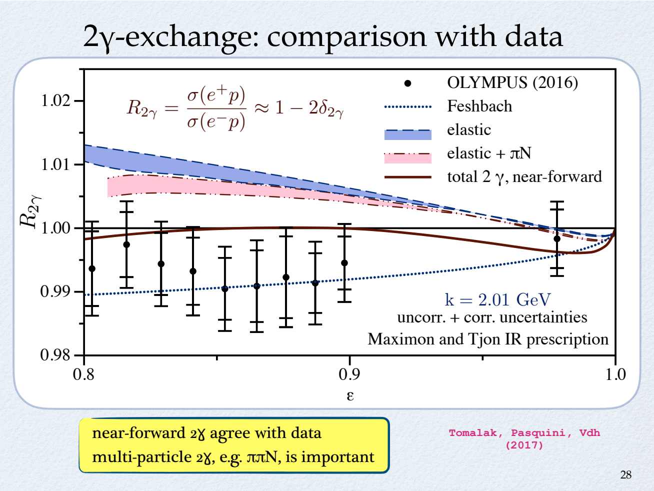
→ Elastic state: involves **nucleon form factors**

→ Subtraction: involves **nucleon polarizabilities**

→ Inelastic, dispersion integrals: involves **structure functions F1, F2**

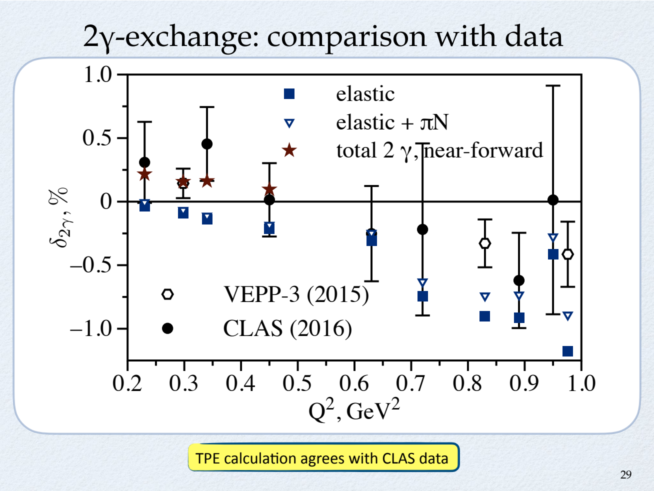
6

2γ Effects in Elastic Nucleon Form Factors, Vanderhaeghen



- New data from OLYMPUS studying 2γ still have puzzles with theory
- New full dispersive treatment of πN to constrain 2γ box diagrams

2γ Effects in Elastic Nucleon Form Factors, Vanderhaeghen



- Agreement better at lower Q^2 and larger ϵ
- Should be applied to magnetic radius extraction

Our PWA Anzatz

1. Determine l=1 multipoles in the following **model-independent** form:

$$\bar{f}_{EE}^{1+}(E_\gamma) = E_\gamma^2 \frac{M}{\sqrt{s}} \left[\frac{\alpha_{E1}}{3} + \frac{E_\gamma}{3} \left(\frac{-\alpha_{E1} + \beta_{M1}}{M} + \gamma_{E1E1} \right) + \left(\frac{E_\gamma}{M} \right)^2 f_1^R(E_\gamma) \right],$$

$$\bar{f}_{EE}^{1-}(E_\gamma) = E_\gamma^2 \frac{M}{\sqrt{s}} \left[\frac{\alpha_{E1}}{3} + \frac{E_\gamma}{3} \left(\frac{-\alpha_{E1} + \beta_{M1}}{M} - 2\gamma_{E1E1} \right) + \left(\frac{E_\gamma}{M} \right)^2 f_2^R(E_\gamma) \right],$$

$$\bar{f}_{MM}^{1+}(E_\gamma) = E_\gamma^2 \frac{M}{\sqrt{s}} \left[\frac{\beta_{M1}}{3} + \frac{E_\gamma}{3} \left(\frac{-\beta_{M1} + \alpha_{E1}}{M} + \gamma_{M1M1} \right) + \left(\frac{E_\gamma}{M} \right)^2 f_3^R(E_\gamma) \right],$$

$$\bar{f}_{MM}^{1-}(E_\gamma) = E_\gamma^2 \frac{M}{\sqrt{s}} \left[\frac{\beta_{M1}}{3} + \frac{E_\gamma}{3} \left(\frac{-\beta_{M1} + \alpha_{E1}}{M} - 2\gamma_{M1M1} \right) + \left(\frac{E_\gamma}{M} \right)^2 f_4^R(E_\gamma) \right],$$

$$\bar{f}_{EM}^{1+}(E_\gamma) = E_\gamma^3 \frac{M}{\sqrt{s}} \left[\frac{\gamma_{E1M2}}{6} + \frac{E_\gamma}{6} \left(\frac{-6\gamma_{E1M2} + 3\gamma_{M1E2} + 3\gamma_{M1M1}}{4M} - \frac{\beta_{M1}}{8M^2} \right) + \left(\frac{E_\gamma}{M} \right)^2 f_5^R(E_\gamma) \right]$$

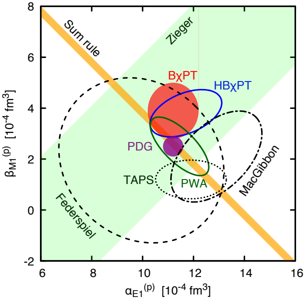
$$\bar{f}_{ME}^{1+}(E_\gamma) = E_\gamma^3 \frac{M}{\sqrt{s}} \left[\frac{\gamma_{M1E2}}{6} + \frac{E_\gamma}{6} \left(\frac{-6\gamma_{M1E2} + 3\gamma_{E1M2} + 3\gamma_{E1E1}}{4M} - \frac{\alpha_{E1}}{8M^2} \right) + \left(\frac{E_\gamma}{M} \right)^2 f_6^R(E_\gamma) \right]$$

After using sum rules,
4 global parameters (polarizabilities) and 4 energy-dependent (residual functions)

2. The l=2 multipoles are small and are either neglected or taken from ChPT

Compton Scattering PWA, Pascalutsa

Static polarizabilities of the proton



- **TAPS:** fit to TAPS/MAMI data based on fixed-t DRs of L'vov et al.
  Olmos de Leon et al., *EPJA* (2001)
- **BChPT:** "postdiction"
  Lensky & VP, *EPJC* (2010)
  Lensky, McGovern & VP, *EPJC* (2015)
- **HBChPT:** fit to world data
  Grießhammer, McGovern & Phillips, *EPJA* (2013)
- **PWA:** fit to world data
  Krupina, Lensky & VP, *PLB* (2018)

Partial-Wave Analysis (PWA):
differences between DR and ChPT extractions are due to database inconsistencies, improvements — new experiments — are needed!

23

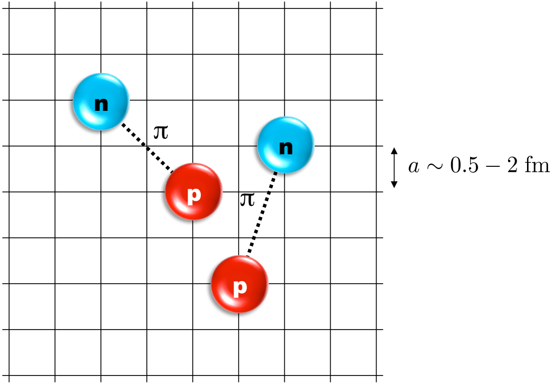
Vladimir Pascalutsa — Nucleon Polarizabilities— CIPANP — Indian Wells, CA— May 31, 2018

- New PWA below π threshold of proton Compton data
- Call for new 100 MeV backwards Compton Scattering data

Parallel 7

- **Status of Baryon-Baryon Interactions from Lattice QCD**
  Beane, UW
- **HOBET: The SM as an Effective Theory and its Direct Matching to LQCD**
  McElvain, UBC
- **Effective-Field-Theory Extrapolations of Lattice-QCD Predictions for Light Nuclei**
  Kirscher, CCNY
- **New Developments in Lattice Effective Field Theory**
  Lee, MSU

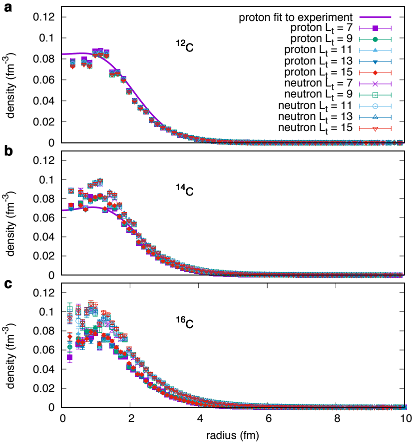
Lattice effective field theory

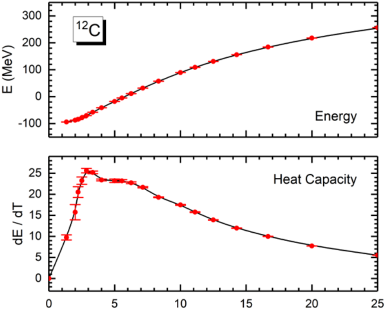


Review: D.L, Prog. Part. Nucl. Phys. 63 117-154 (2009)
TALENT summer school lectures: qmc2016.wordpress.ncsu.edu

3

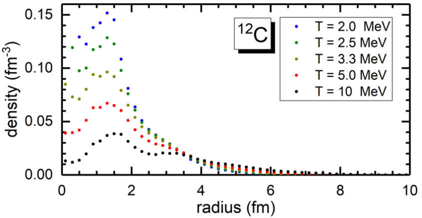
Lattice Effective Field Theory, Lee

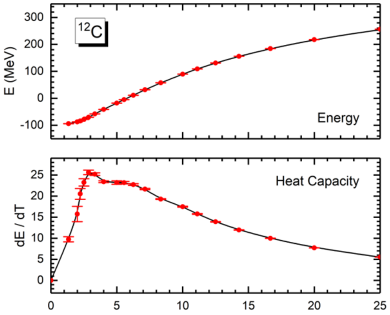




- Reconstructing nuclear properties such as radii
- Also able to study thermodynamic properties (heat capacities, α boiling)

Lattice Effective Field Theory, Lee





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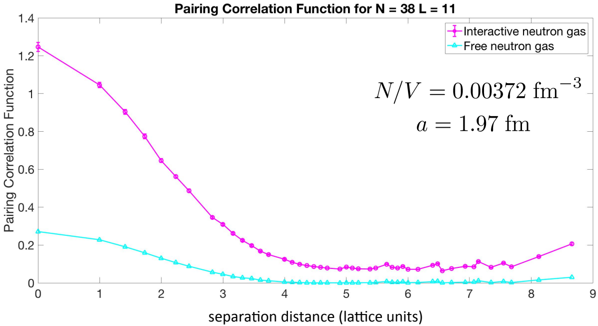
Lattice Effective Field Theory, Lee

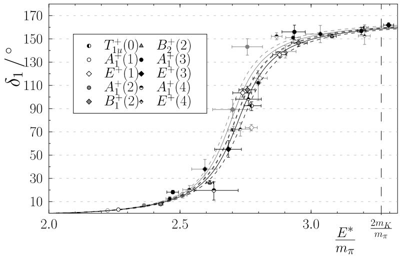


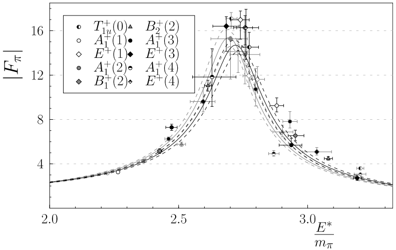
- Also seeing evidence of a superfluid state for diffuse neutron gas

Parallel 8

- **Analysis of $\eta\pi^0$ and $\eta^{'}\pi^0$ Systems at GlueX**
  Austregesilo, JLab
- **Toward Precise Determination of Resonant Hadron Scattering Amplitudes from Lattice QCD**
  Bulava, Southern Denmark
- **A Lattice QCD Study of the ρ Resonance**
  Leskovec, Arizona
- **Measurement of Transition Form Factors at BES-III**
  Redmer, Mainz
- **Unitary Reaction Models and PWA Formalisms**
  Pilloni, JLab

Finite volume/lattice spacing



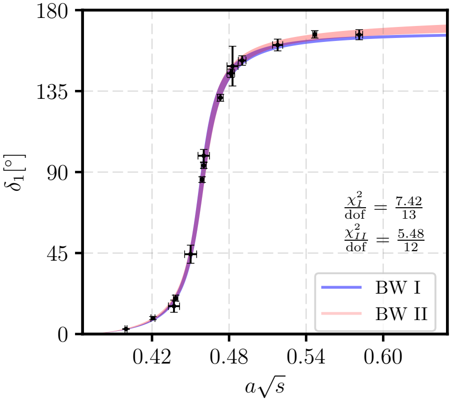


- Dark points: N200 $(L = 3.12\text{fm}, a = 0.065\text{fm}, \ m_\pi = 280\text{MeV})$
- Gray points: N401 $(L = 3.65\text{fm}, a = 0.076\text{fm}, \ m_\pi = 280\text{MeV})$

- Finite volume and cutoff effects not visible with our current statistics.

$I = 1$ P-wave $\pi\pi$ Scattering and the ρ Resonance

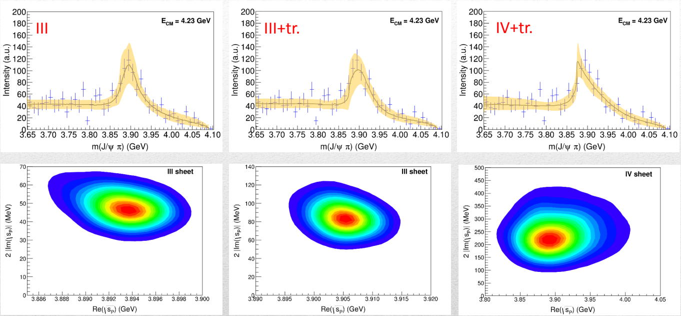
comparing $BW\ I$ and $BW\ II$



[Alexandrou et al.,]

- $BW\ I$:
  $am_\rho = 0.4609(16)$
  $g_{\rho\pi\pi} = 5.69(13)$
- $BW\ II$:
  $am_\rho = 0.4603(16)$
  $g_{\rho\pi\pi} = 5.77(13)$
  $(r_0/a)^2 = 9.6(5.9)$

Pole extraction



Scenario	III+tr.	IV+tr.	tr.
III	1.5σ (1.5σ)	1.5σ (2.7σ)	"2.4σ" ("1.4σ")
III+tr.	–	1.5σ (3.1σ)	"2.6σ" ("1.3σ")
IV+tr.	–	–	"2.1σ" ("0.9σ")

	III	III+tr.	IV+tr.
M (MeV)	$3893.2^{+5.5}_{-7.7}$	3905^{+11}_{-9}	3900^{+140}_{-90}
Γ (MeV)	48^{+19}_{-14}	85^{+45}_{-26}	240^{+230}_{-130}

Not conclusive at this stage

21

- Searching for resonances in $\eta\pi$ and $Z_c(3900)$ (tetraquark?)

Parallel 9

- **The Proton Radius Puzzle Why We All Should Care**
  Miller, UW
- **The Rydberg Constant and Proton Size from Atomic Hydrogen**
  Maisenbacher, Max Plank Inst. for Quantum Optics
- **Data Analysis and Preliminary Results of the Proton Charge Radius Experiment (PRad) at JLab**
  Ziong, Duke
- **Determination of the Protons Charge Radius by Simultaneous Measurement of Electron- and Muon-Proton Elastic Scattering with the MUSE Experiment at PSI**
  Reimer, ANL
- **Lattice QCD and the Proton Radius**
  Syritsyn, SBU
- **Nucleon Form Factors in Dispersively Improved Chiral Effective Theory**
  Weiss, JLab

4 % in radius: why care?

- Can't be calculated to that accuracy?
  Sergey Syritsyn

Is the muon-proton interaction the same as the electron-proton interaction?
violation of universality
connections with muon g-2?
connections with LHCb ?

Something happening here ???

Outline - a) review history experiments
b) List & explain possible resolutions

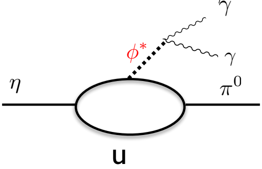
2

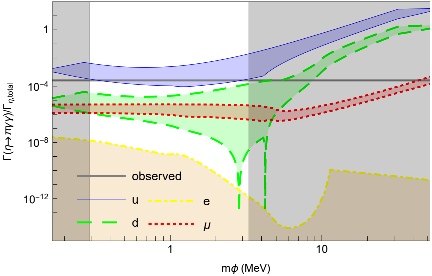
Constraining ϕ

Beam dump experiments do not see
$\phi \to e^+e^-$, $\phi \to \gamma\gamma$

Eta decay and muonic puzzles 1805.01028
Yu-Sheng Liu, Ian Cloet, GAM

Previously ϕ couples to p, n, e, μ
Now ϕ couples to $u, d, e\mu$





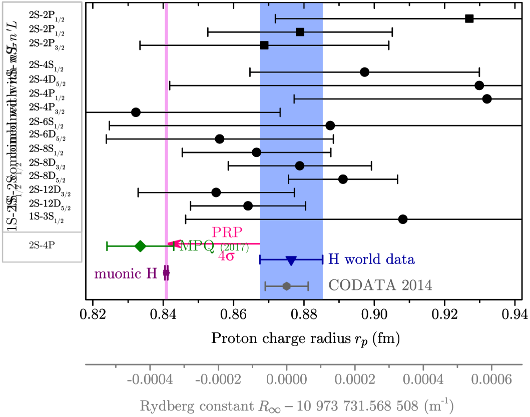
Allowed mass range from 200 KeV to 3 MeV

Proton Size from Atomic Hydrogen, Maisenbacher

Proton radius and Rydberg constant (2017)

$$\nu_{\mathrm{2S\text{-}4P}} = 616\,520\,931\,626.8\,(2.3)\,\mathrm{kHz}$$

$$R_\infty = 10\,973\,731.568\,076\,(96)\,\mathrm{m}^{-1},\, r_p = 0.8335(95)\,\mathrm{fm}$$



2S-4P (MPQ 2017): A. Beyer, L. Maisenbacher, A. Matveev *et al.*, *Science* **358**, 79 (2017)

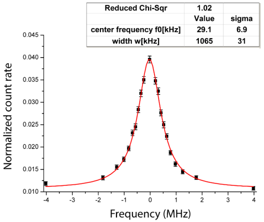
1S-3S transition

Two-photon transition from ground state

(First-order) Doppler-free excitation with two **205 nm** photons

Natural line width of Γ **= 1 MHz;**
proton radius puzzle: **~7 kHz**

Single 1S-3S line scan at MPQ

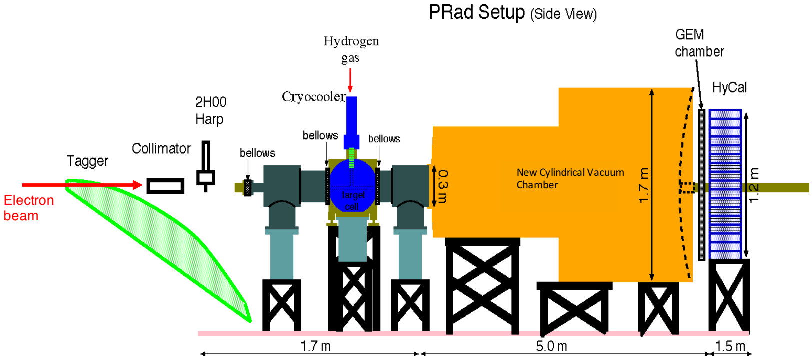


Two **complementary** measurements in progress:

	LKB (F. Nez *et al.*)	MPQ (Th. Udem *et al.*)
Excitation	CW laser	Picosecond frequency comb
Atom source	Room temperature beam	Cryogenic (7 K) beam
	Large (~ 130 kHz) second-order Doppler shift	Chirp of pulsed laser causes first-order Doppler shift
Most recent uncertainty	2.6 kHz (2018) [1]	17 kHz (2016) [2] preliminary: ~ 1 kHz (2018)

[1] 1S-3S (MPQ): D. C. Yost *et al.*, *Phys. Rev. A* **93**, 042509 (2016)
[2] 1S-3S (LKB): H. Fleurbaey *et al.*, *Phys. Rev. Lett.* **120**, 183001 (2018)

PRad Experimental Apparatus



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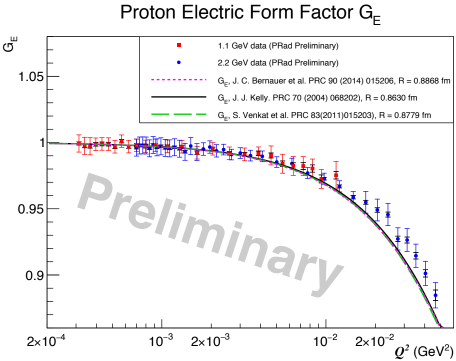
Form Factor G_E (Preliminary)

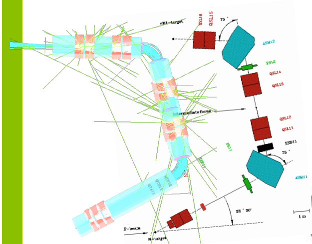
- Proton electric form factor G_E v.s. Q^2, with 2.2 and 1.1 GeV data (preliminary)
- Systematic uncertainties shown as colored error bars
- Preliminary G_E slope seems to favor smaller radius

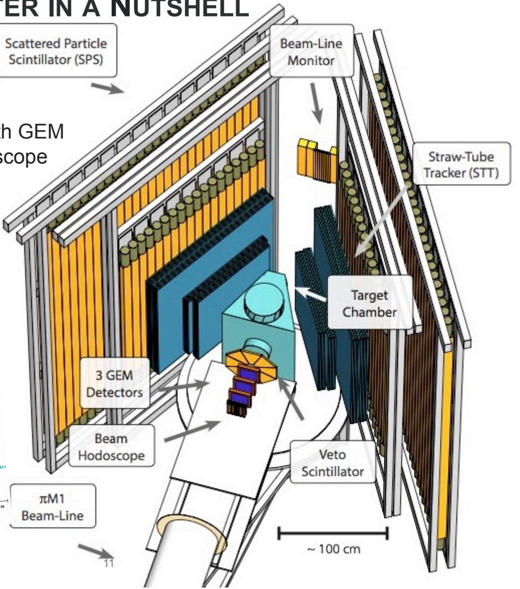


$e^{\pm}$ and $\mu^{\pm}$-Proton Elastic with the MUSE, Reimer

MUSE Spectrometer in a Nutshell

- Located on the πM1 beam line
- Measure incoming particle
  - position and direction with GEM
  - Timing with Beam Hodoscope and Scattered Particle Scintillators





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PROTON'S SIZE VS PROBE AND METHOD

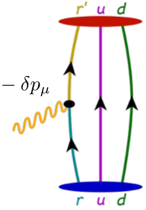
Method / Probe	Spectroscopy	Elastic scattering
Electron	 0.876(8)	 0.877(6)
Muon	 0.8409(4)	 ??

Derivatives wrt. Initial and Final Momenta

Evaluate the radius from varying the initial and final momenta
[B.Tiburzi, 1407.1459] $\frac{\partial^2}{\partial p'_i \partial p_i} \langle N(p') J^0 N(p) \rangle$

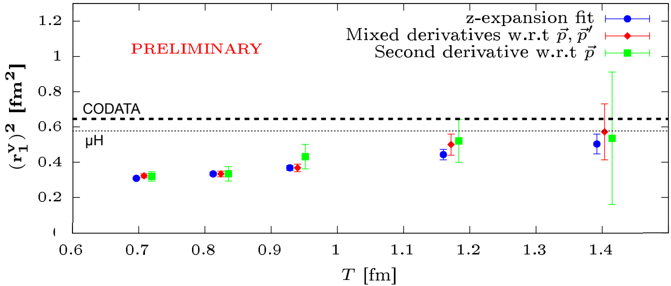
No tadpole insertions in propagator derivatives

$q_\mu = \delta p'_\mu - \delta p_\mu$

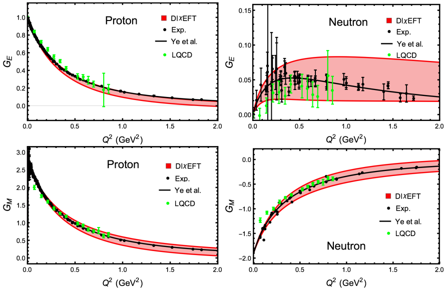


m_π =135 MeV *a*=0.116 fm 48^4 (BMWc)
[N.Hasan, LATTICE2017]

$$\frac{\frac{\partial}{\partial p'^j} \frac{\partial}{\partial p^j} C_3^0(\vec{p}', \vec{p}, T, \tau)|_{\vec{p}=\vec{p}'=0}}{C_2(\vec{0}, \tau)} = \frac{1}{4m^2}[F_1 + 2F_2] + \frac{1}{3} F_1 [r_1]^2$$



Results: Form factors



$$G_i(t) = \int_{4M_\pi^2}^{\infty} \frac{dt'}{\pi} \frac{\operatorname{Im} G_i(t')}{t' - t - i0}$$

Alarcon, Weiss, arXiv:1803.09748
Uncertainty bands: PDG range of nucleon radii

- Form factors evaluated using DR

  $\pi\pi$ isovector spectral function calculated in DIχEFT

  High-mass states described by effective pole, strength fixed by sum rules (charges, radii)

- Excellent agreement with data

  Not fit, but dynamical prediction. Theoretical uncertainty estimates

END