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WASHINGTON, DC

The MUSE experiment: Addressing the Proton Radius Puzzle via Elastic Muon Scattering

W. J. Briscoe
on behalf of the
MUSE Collaboration

Thanks to
E.J. Downie – GW
R. Gilman – Rutgers
G. Ron - Jerusalem

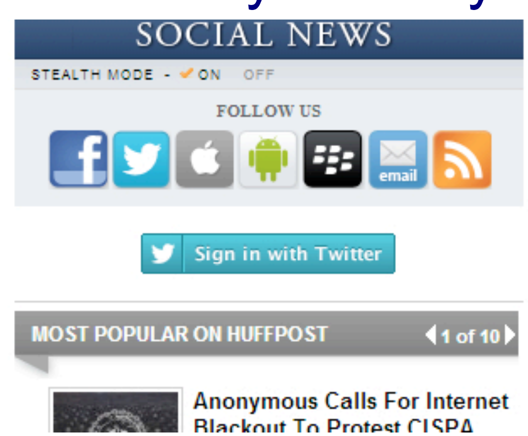
Outline

- Why measure the radius?
- What is a radius? How do we measure it?
- Electron scattering measurements
- The source of all the trouble: Pohl measurements
- Possible explanations
- The MUSE experiment
- Conclusions

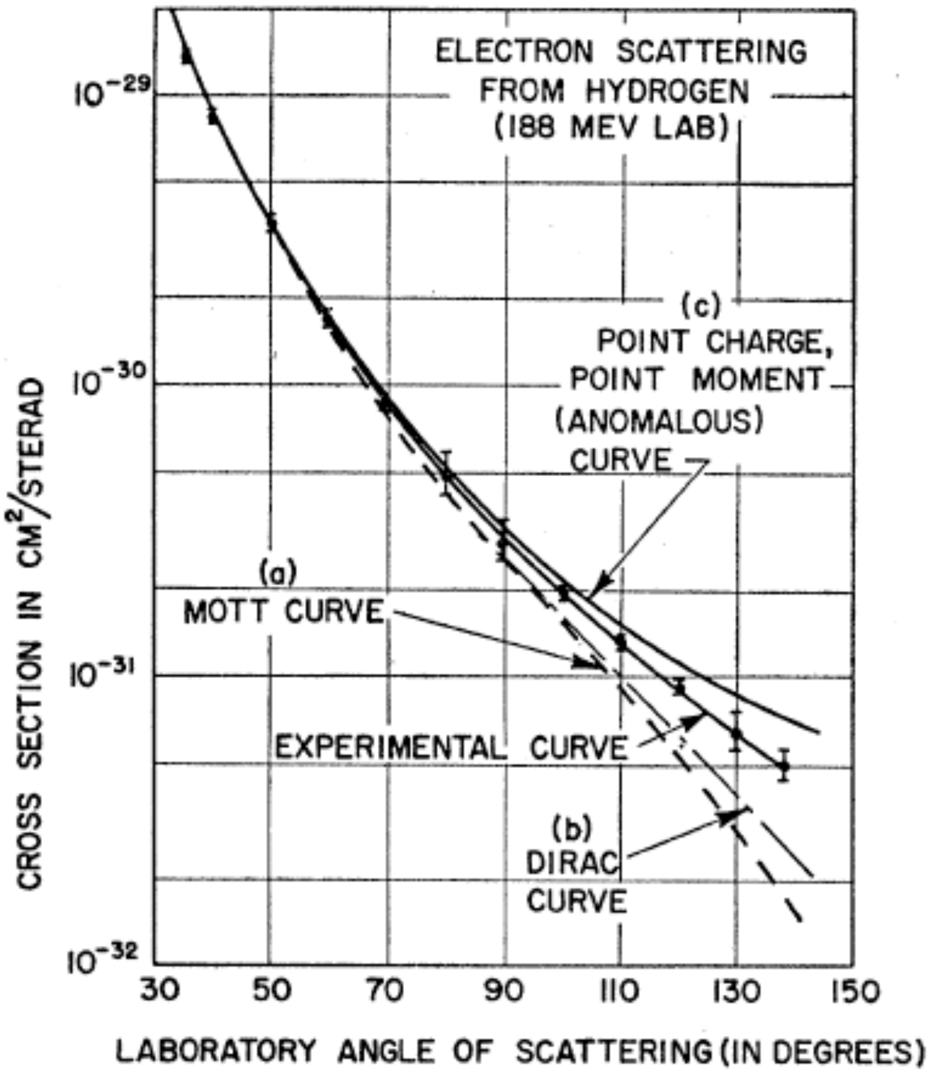
- It has raised public interest!
- Not just interesting:

➔ Tests our theoretical understanding of proton

➔ Radius of proton is dominant uncertainty in many QED processes



Electron Scattering Measurements 1950s



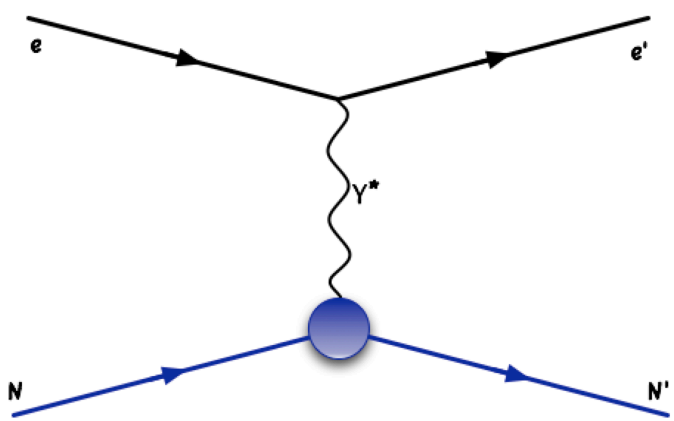
$$\langle r_E \rangle = 0.74(24)\ fm$$

- Fit to RMS radius Stanford 1956
- R.W. McAllister and R. Hofstadter, Phys. Rev. **102**, 851 (1956)

The Proton Radius

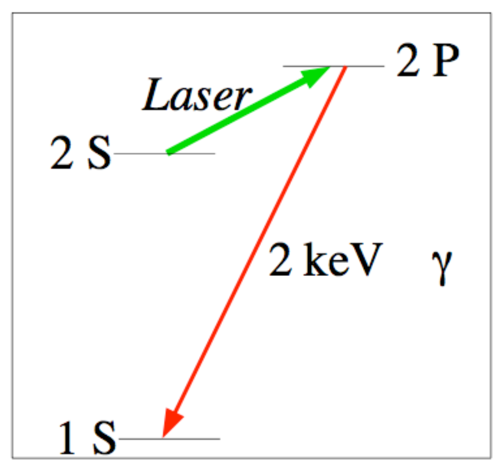
- What is a radius? How do we measure it?
- Classical physics: $r^2 = \int \rho(r) r^2 d^3r$
- Non-relativistic quantum mechanics: $r^2 = \int < \psi^*(r)|r^2|\psi(r) > d^3r$
- Relativistic quantum mechanics: $r^2 = -6dG(Q^2)/dQ^2|_{Q^2=0}$

Electron Scattering



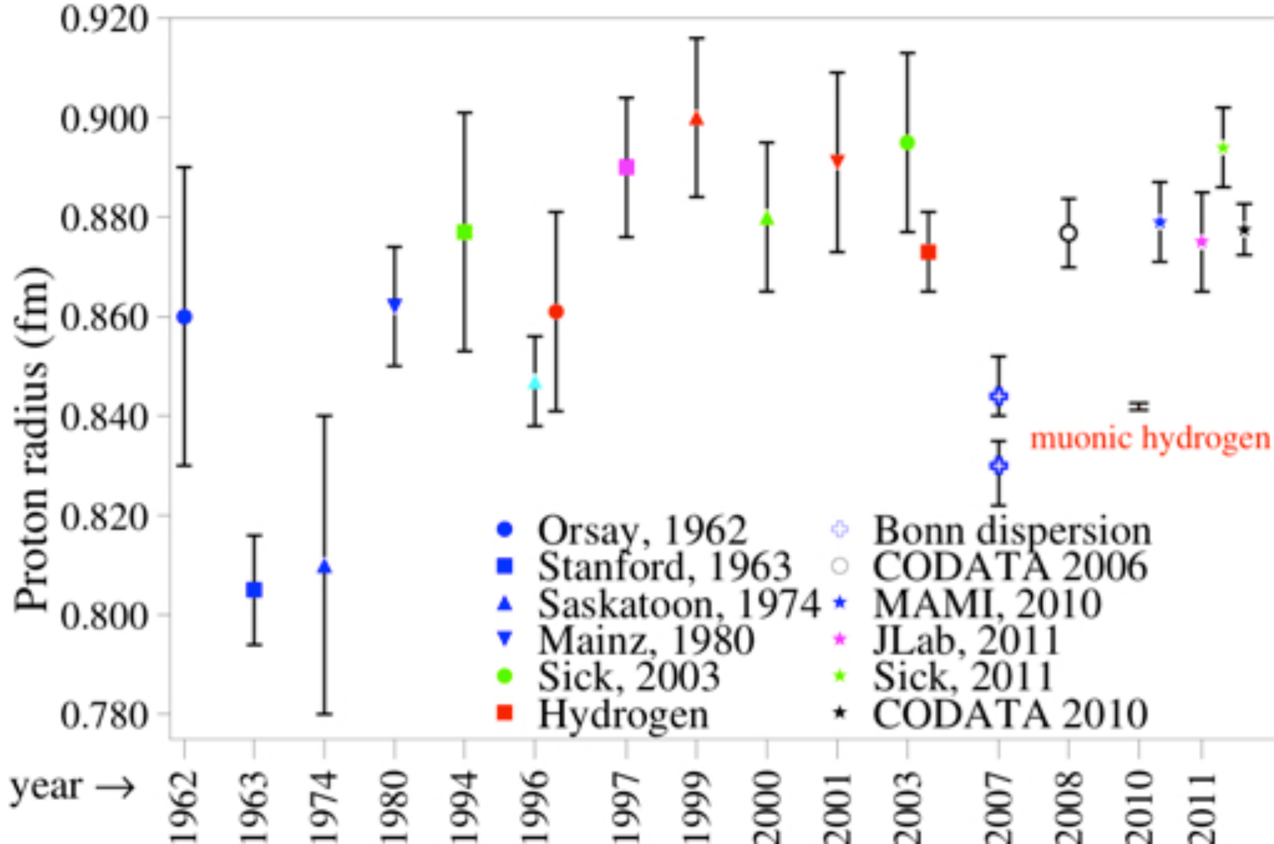
Fit form factor trend with q^2 to data, find slope as $q^2 \to 0$

Atomic Energy Levels



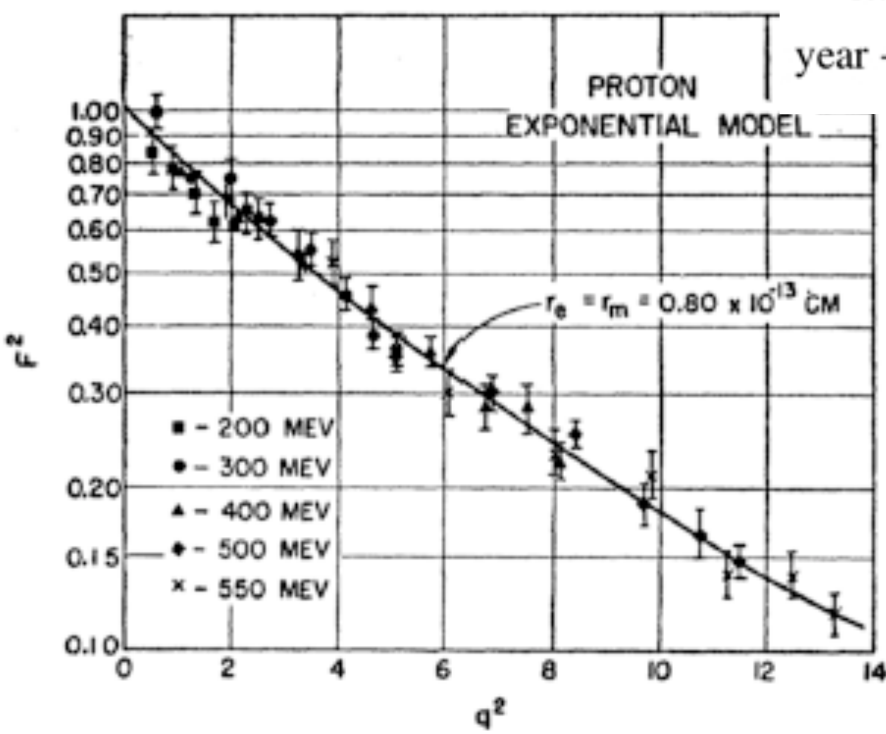
NRQM: finite size of proton perturbs energies of s states – r_p << r_{atomic}, so effect proportional to $\psi^2_a(r=0)$.

The Proton Radius as a Function of Time



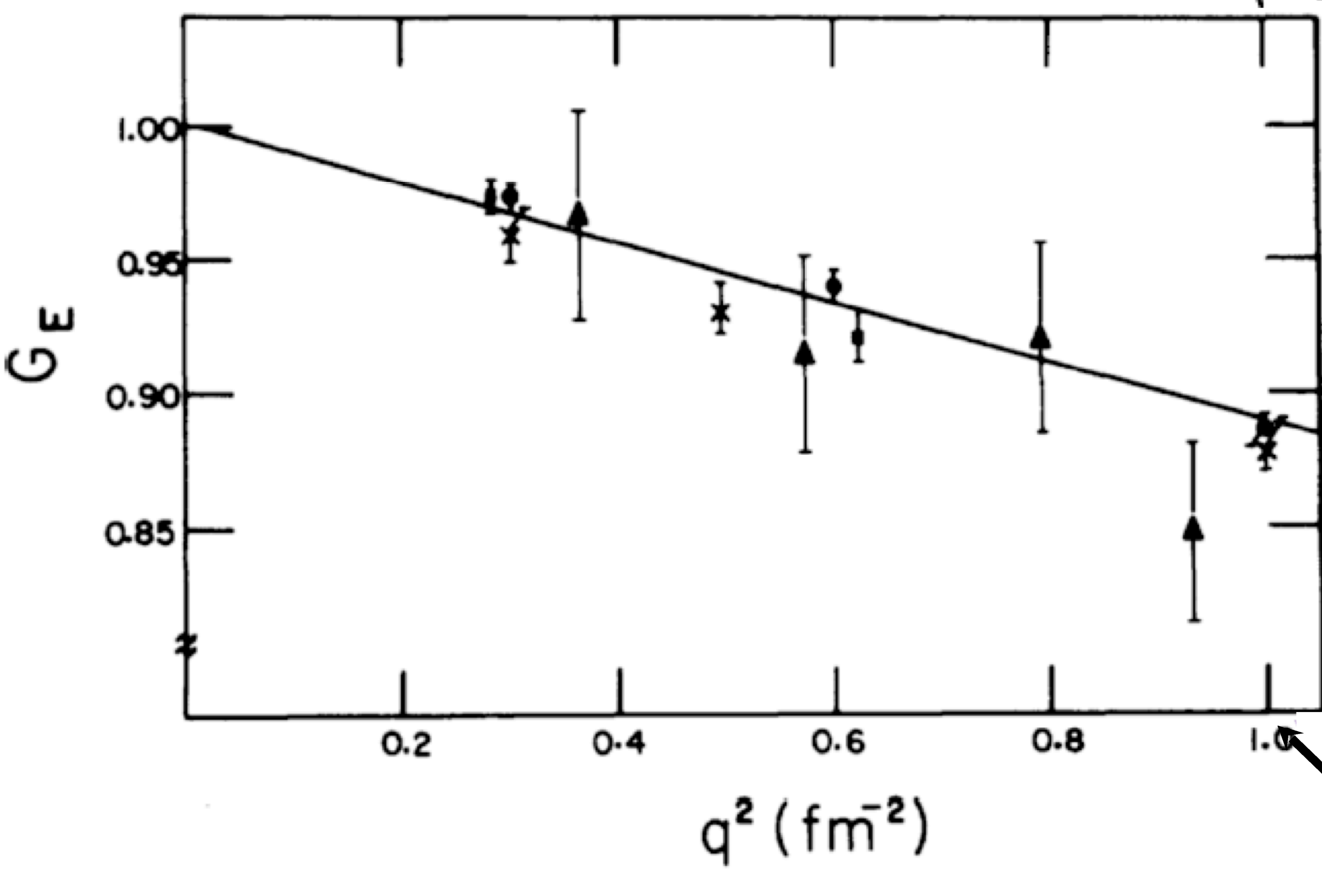
From Pohl, Gilman, Miller, Pachucki review, arXiv:1301.0905, AnnRevNPS, modified

Chambers and Hofstadter, Phys Rev 103, 14 (1956)



Low Q^2 in 1974

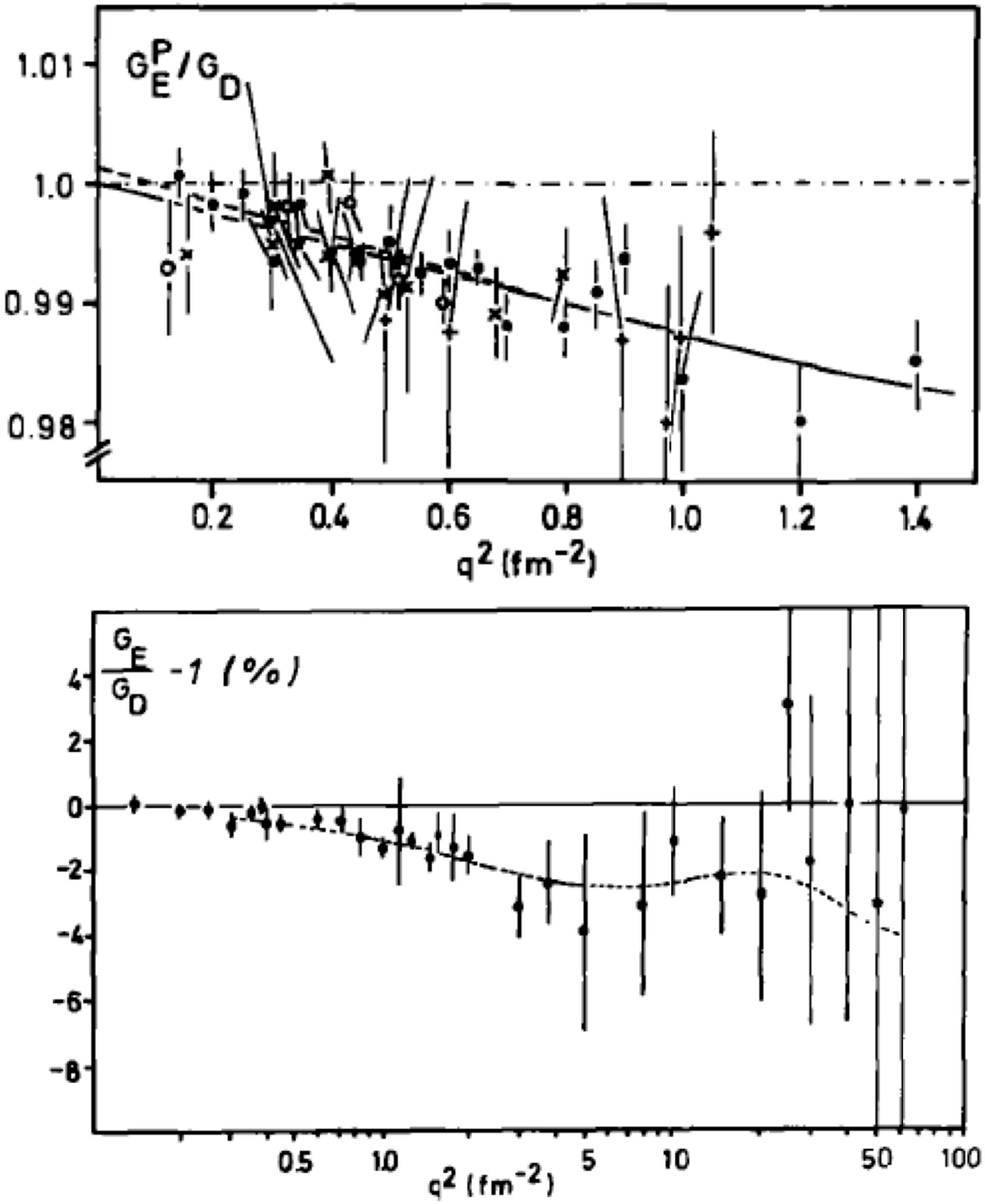
$$\langle r_E \rangle = 0.810(40)\ fm$$



$$Q^2 = 0.0389\ GeV^2$$

- Fit to $G_E(Q^2)=a_0+a_1Q^2+a_2Q^4$
- Saskatoon 1974
- J. J. Murphy, Y. M. Shin, D. M. Skopik, Phys. Rev. C **9**, 2125 (1974)

Low Q^2 in the Eighties

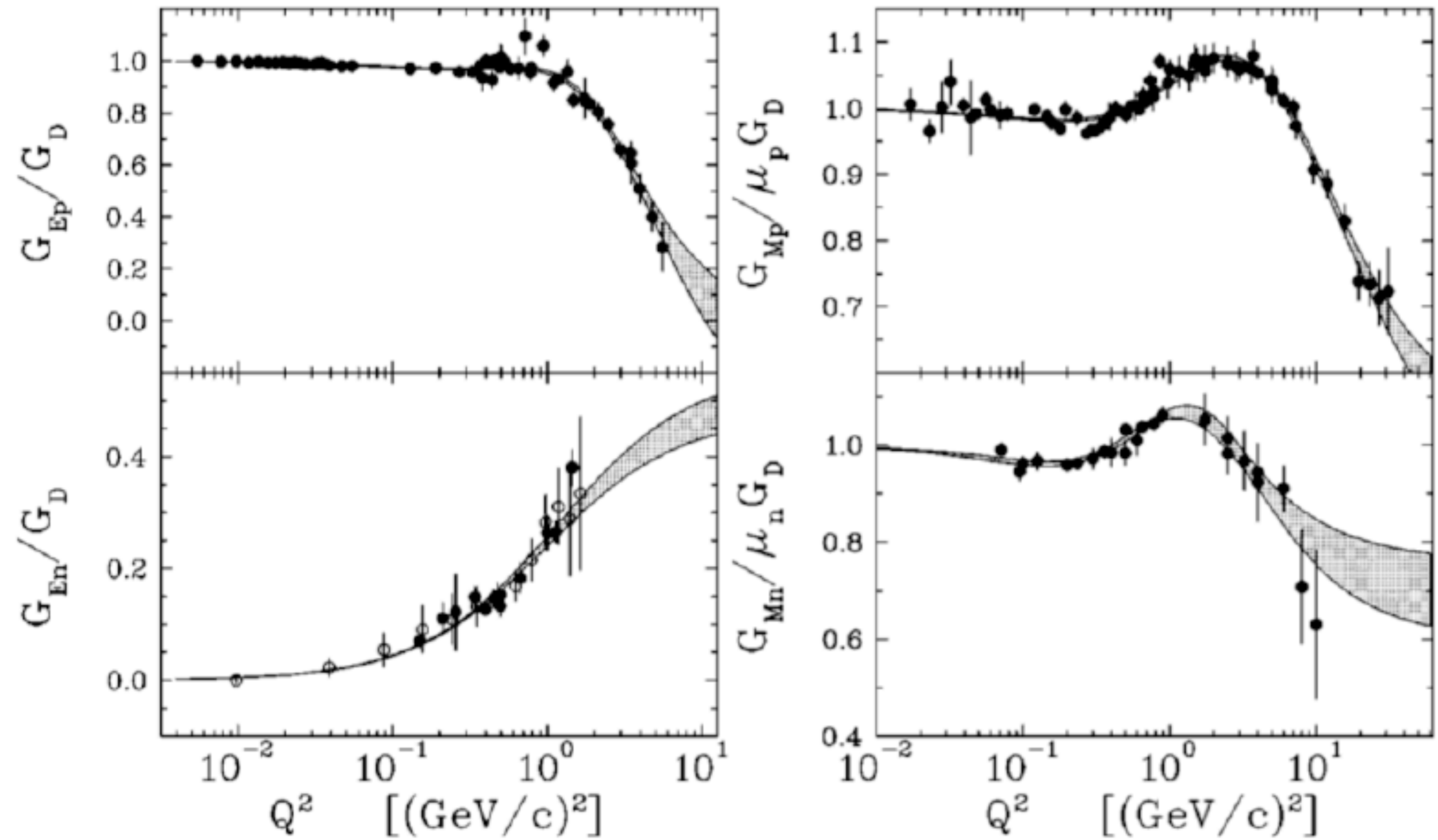


$$\langle r_E \rangle = 0.862(12)\ fm$$

$$G_D = \left(1 + Q^2/18.23 fm^2\right)^{-2} = \left(1 + Q^2/0.71 GeV^2\right)^{-2}$$

- From the dipole form get: r_E~0.81 fm
- G. G. Simon, Ch. Smith, F. Borkowski, V. H. Walther, NPA333, 381 (1980)

A Multitude of Fits



- Better measurements to higher Q^2 lead to a cornucopia of fits
  - J. J. Kelly, Phys. Rev. C70, 068202 (2004)

A Multitude of Radii

$$-6G'_E(0) = r_E^2$$

$$G^{E,M}_{\text{dipole}}(Q^2) = \left(1 + \frac{Q^2}{a^{E,M}}\right)^{-2}$$

$$G^{E,M}_{\text{double dipole}}(Q^2) = a_0^{E,M}\left(1 + \frac{Q^2}{a_1^{E,M}}\right)^{-2} + \left(1 - a_0^{E,M}\right)\left(1 + \frac{Q^2}{a_2^{E,M}}\right)^{-2}$$

$$G^{E,M}_{\text{polynomial, n}}(Q^2) = 1 + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}$$

$$G^{E,M}_{\text{poly+dipole}}(Q^2) = G_D(Q^2) + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}$$

$$G^{E,M}_{\text{poly x dipole}}(Q^2) = G_D(Q^2) \times \sum_{i=1}^{n} a_i^{E,M} Q^{2i}$$

$$G^{E,M}_{\text{inv. poly.}}(Q^2) = \frac{1}{1 + \sum_{i=1}^{n} a_i^{E,M} Q^{2i}}$$

r_E = 0.883 fm
r_M = 0.775 fm
Bernauer et al., PRL105, 242001 (2010)

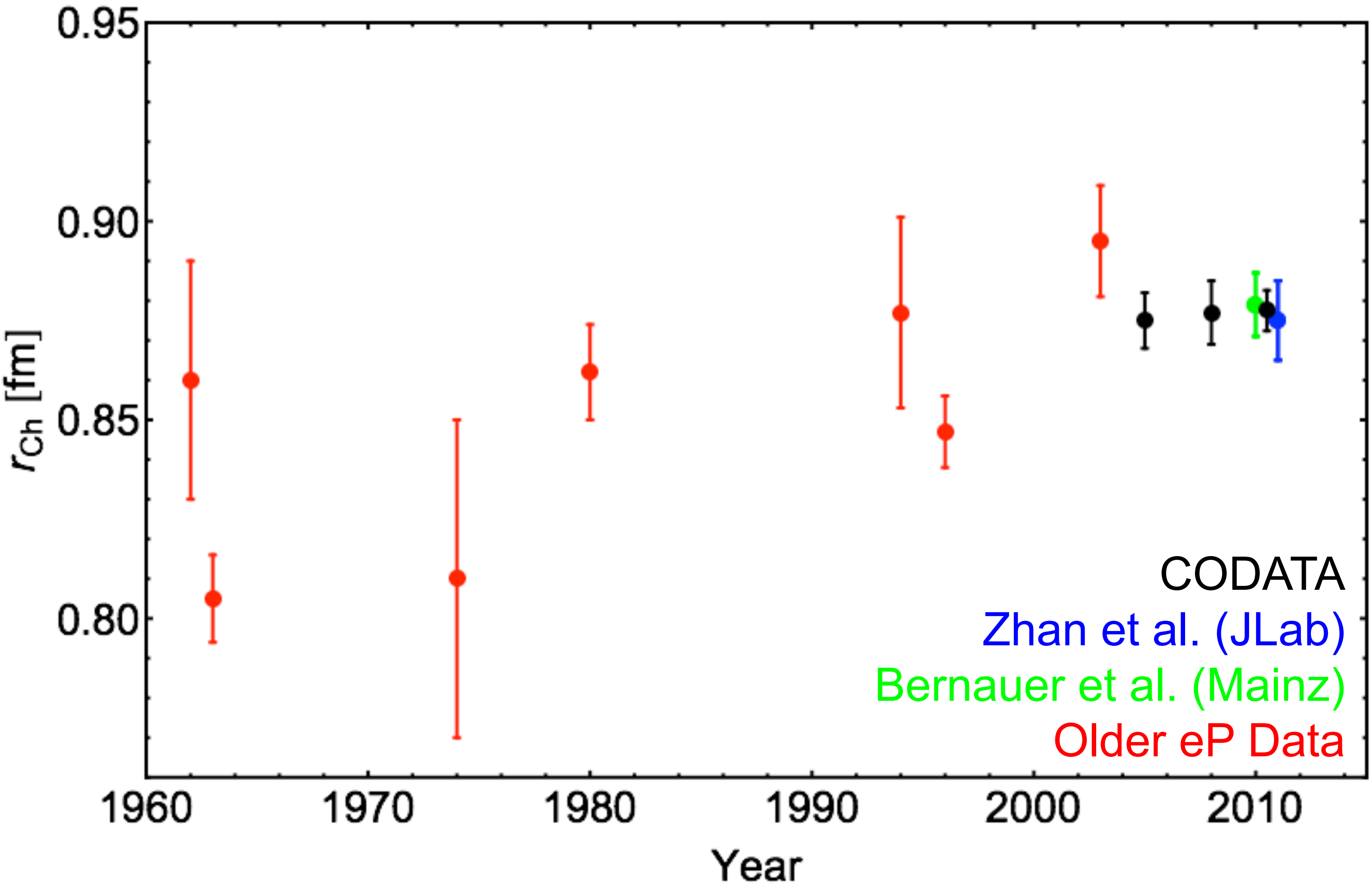
$$G(Q^2) = \frac{1}{1 + \frac{Q^2 b_1}{1 + \frac{Q^2 b_2}{1 + \cdots}}}$$

r_E = 0.901, r_M = 0.868 fm Arrington & Sick, PRC76, 035201 (2007
r_E = 0.875, r_M = 0.867 fm Zhan et al., PLB705, 59 (2011)

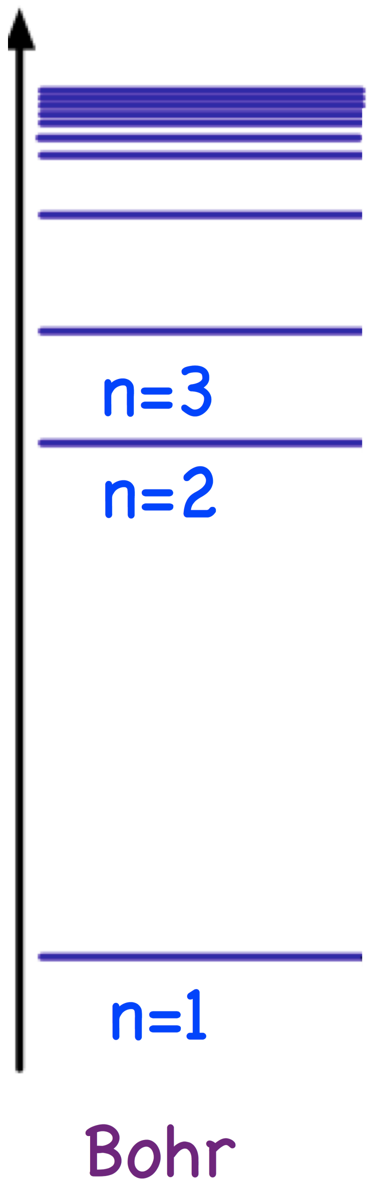
$$G(Q^2) \propto \frac{\sum_{k=0}^{n} a_k \tau^k}{1 + \sum_{k=1}^{n+2} b_k \tau^k}$$

r_E = 0.863, r_M = 0.848 fm
Kelly PRC70, 068202 (2004)

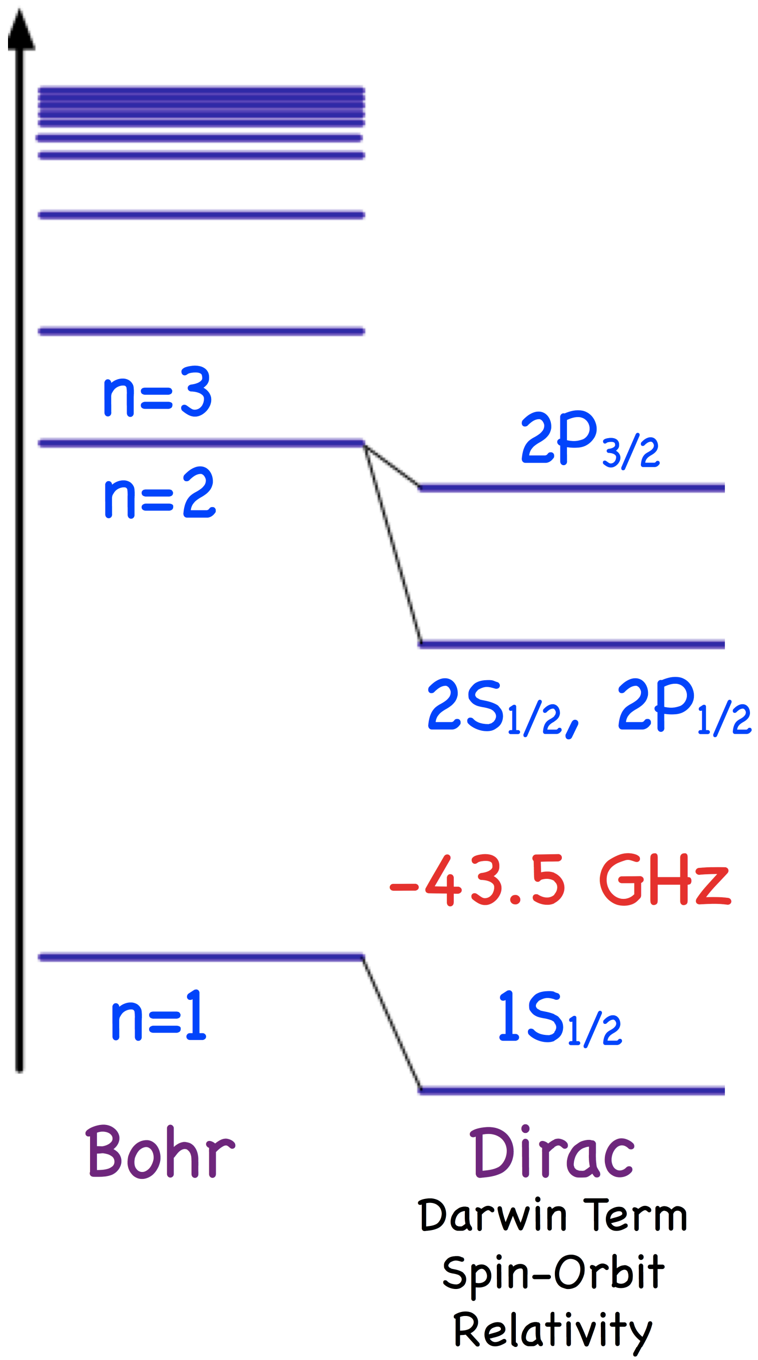
Time Evolution of the Radius from eP Data



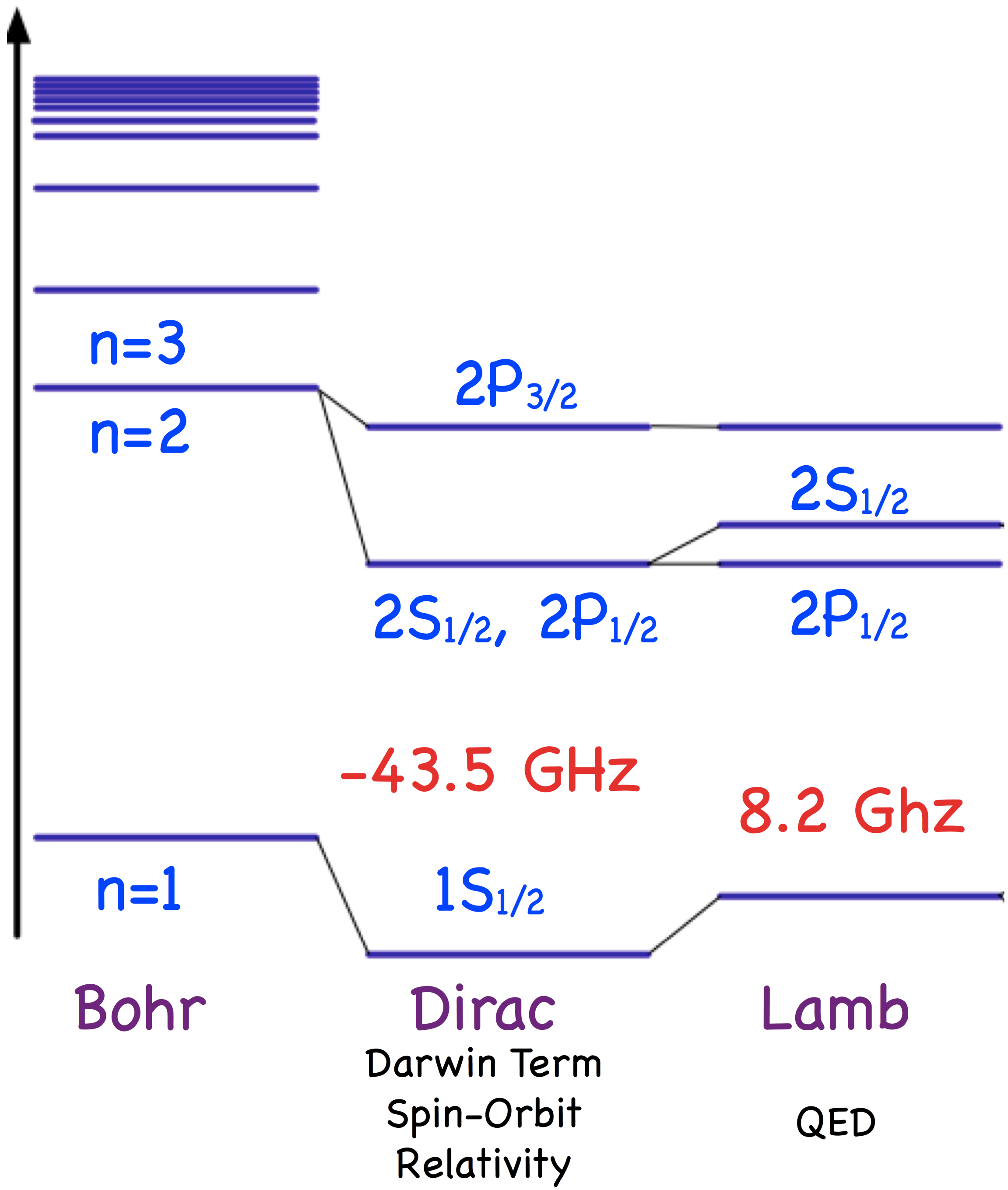
Components of the Hydrogen Energy Levels



Components of the Hydrogen Energy Levels



Components of the Hydrogen Energy Levels



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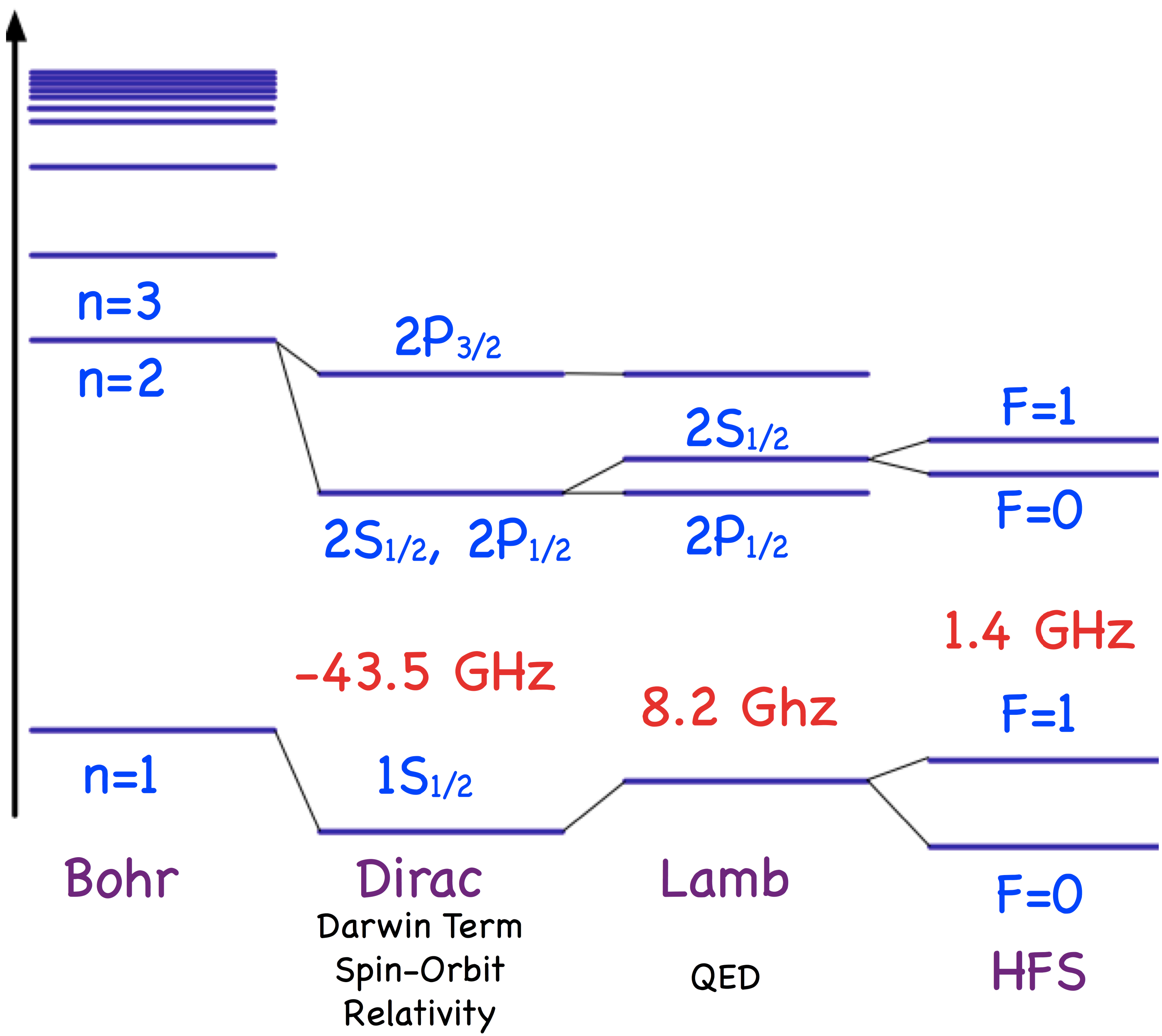
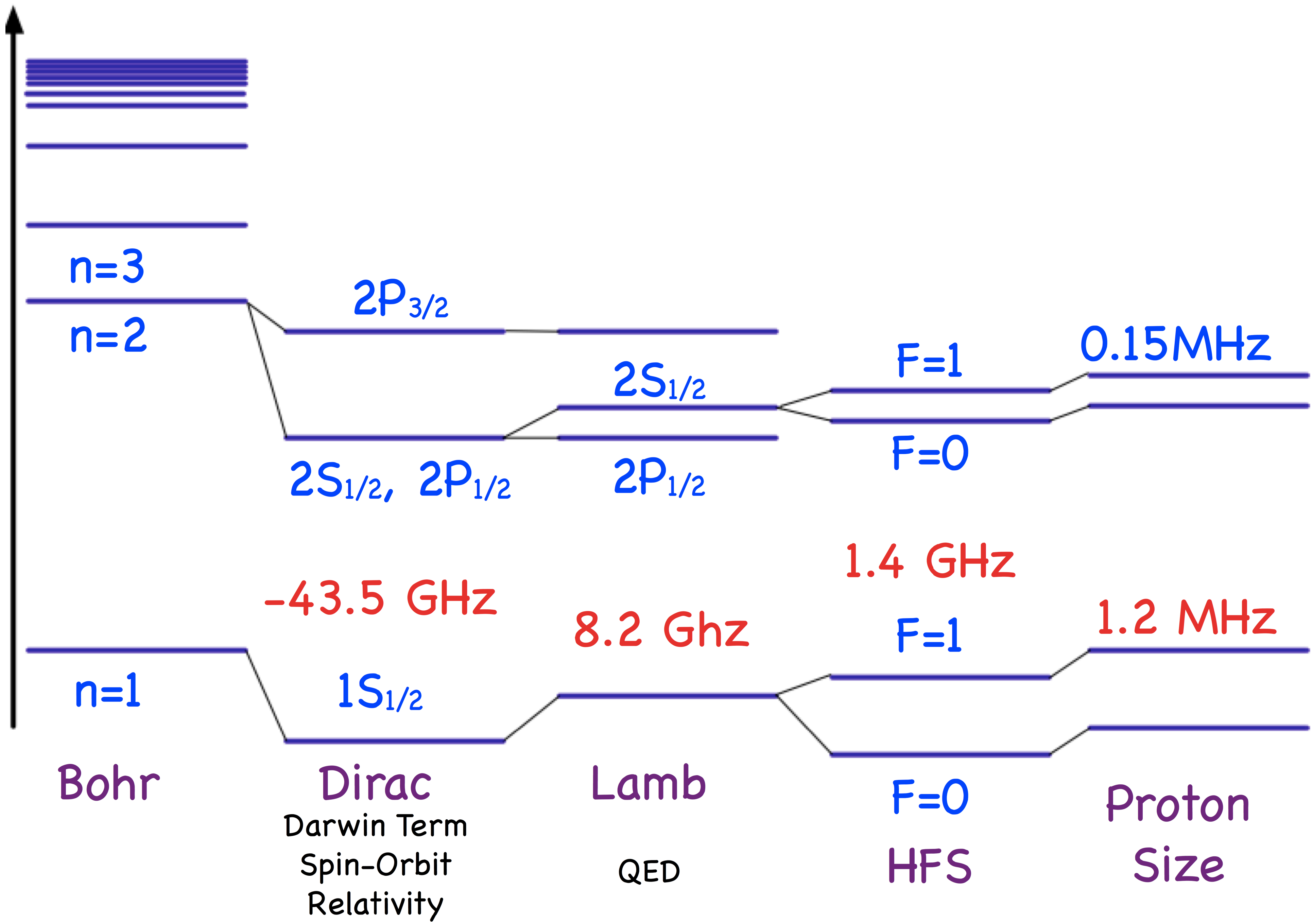
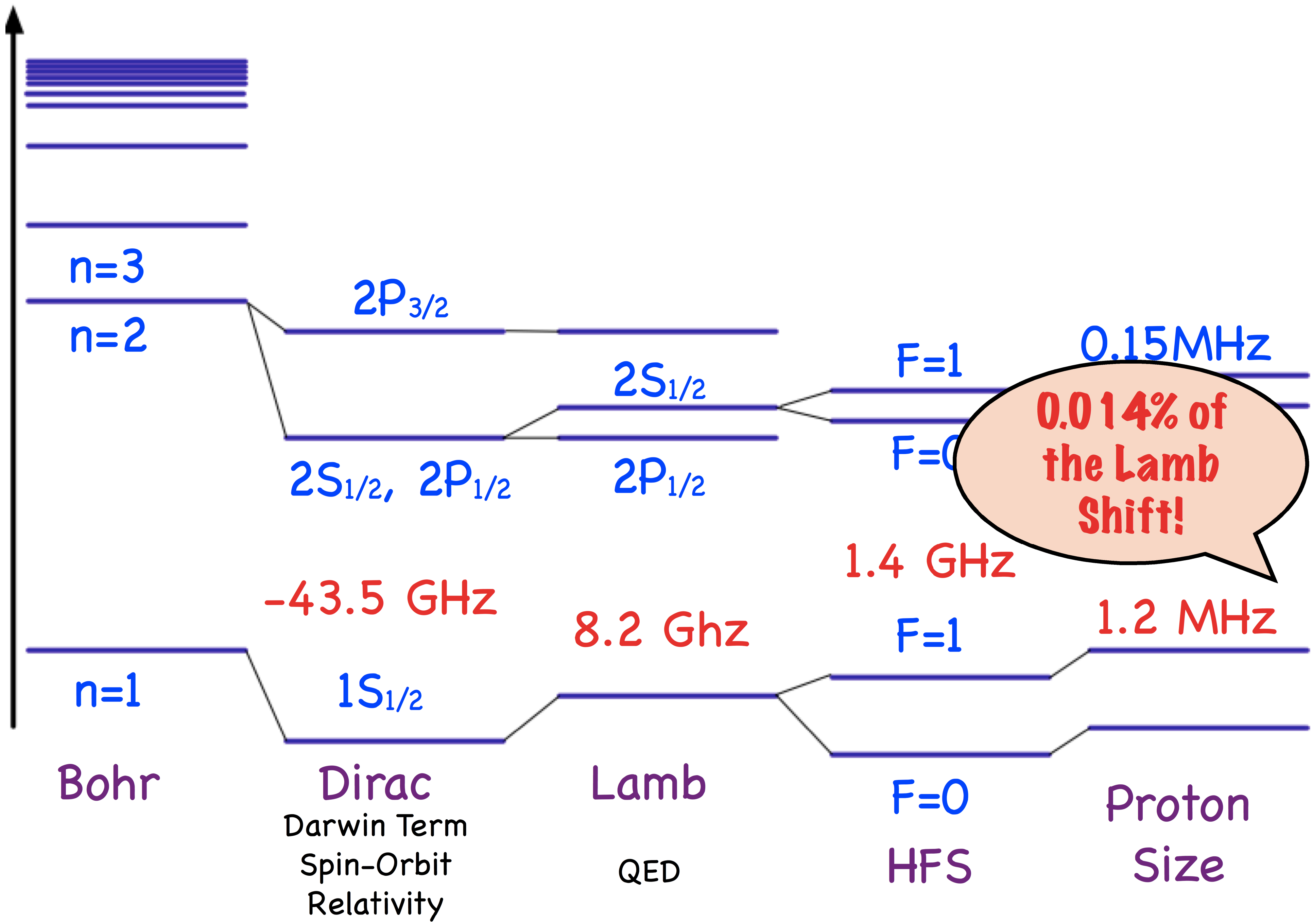


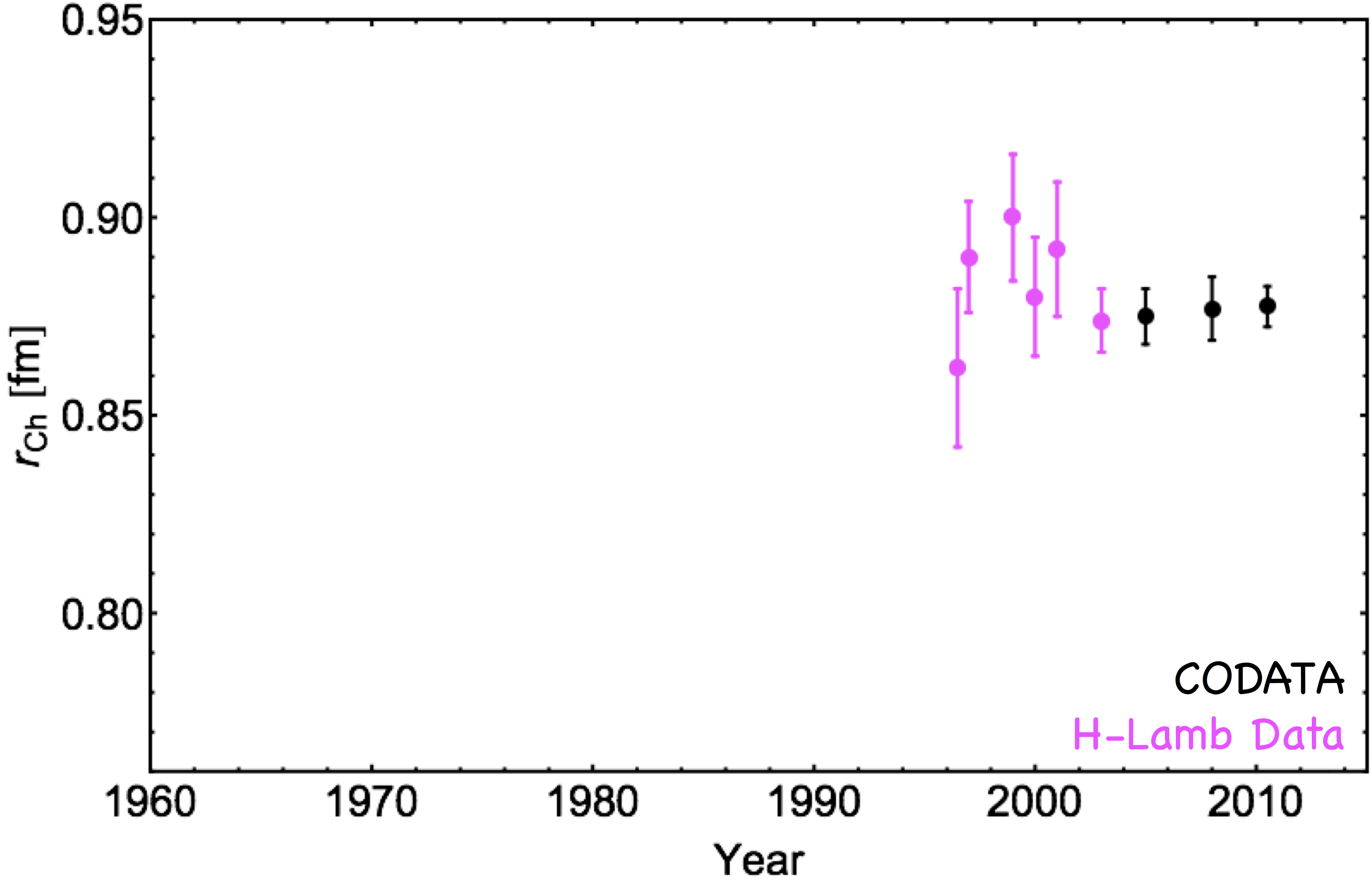
Components of the Hydrogen Energy Levels



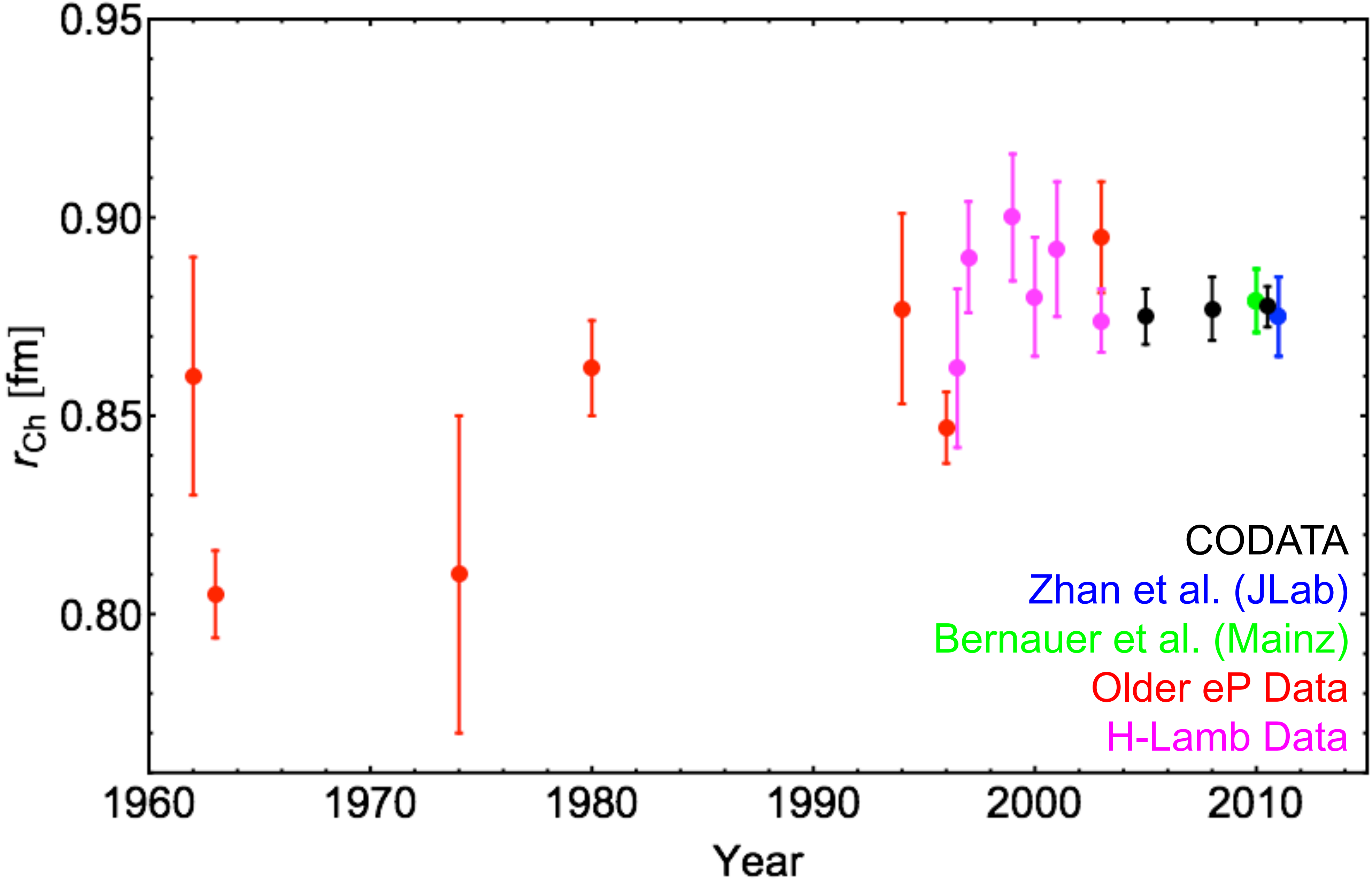
Components of the Hydrogen Energy Levels



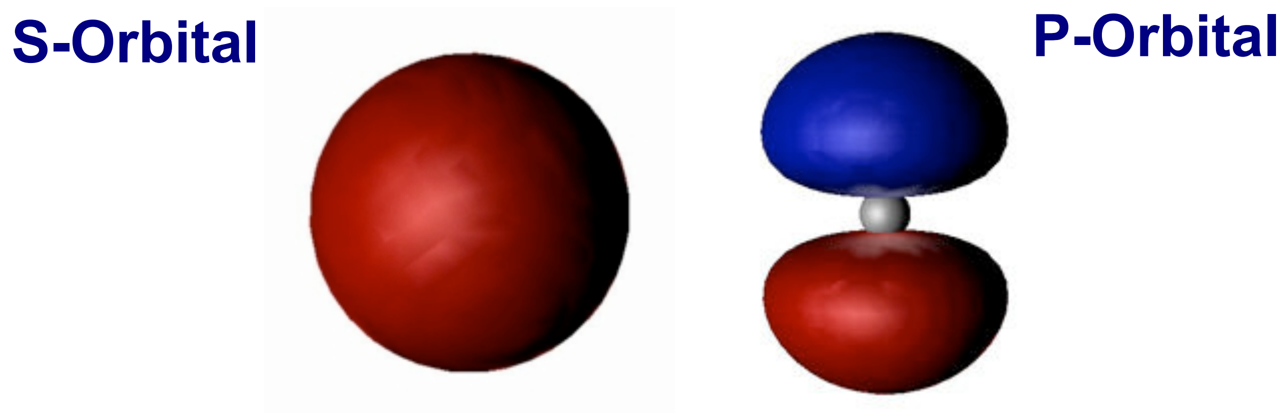
Time Evolution of the radius from Hydrogen Lamb Shift



Time Evolution of the radius from Hydrogen Lamb Shift and eP



Why measure with μH?



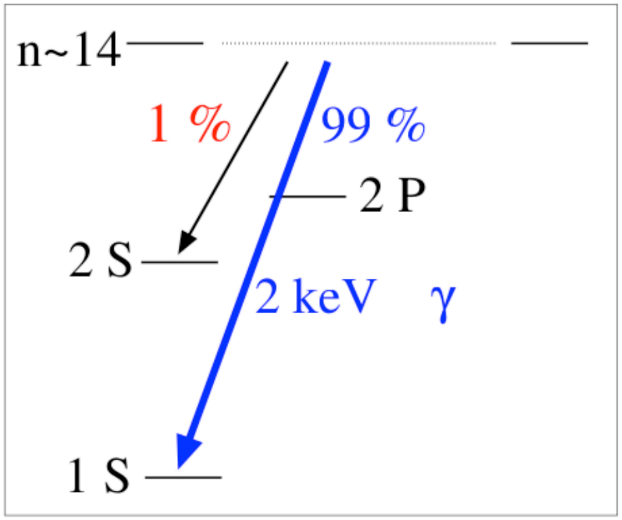
- While lepton is inside proton, attractive potential is lower
- Average potential reduced the longer lepton spends inside proton
- Strongly affects S orbitals, much less so P, so SP transitions change
- Probability for lepton to be inside proton = volume of P / volume of atom:

$$\sim \left(\frac{r_p}{a_B}\right)^3 = (r_p \alpha)^3 m^3$$

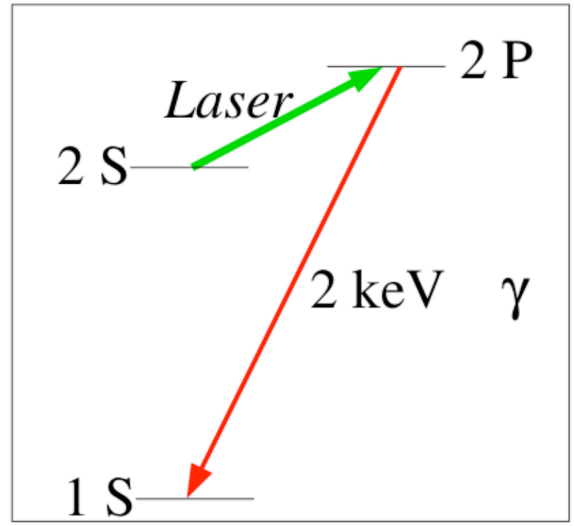
- m_μ =~205m_e –> μH is ~205^3 ~ **8 million times more sensitive to r_P**

Mechanics of measuring with μH

“prompt” ($t \sim 0$)



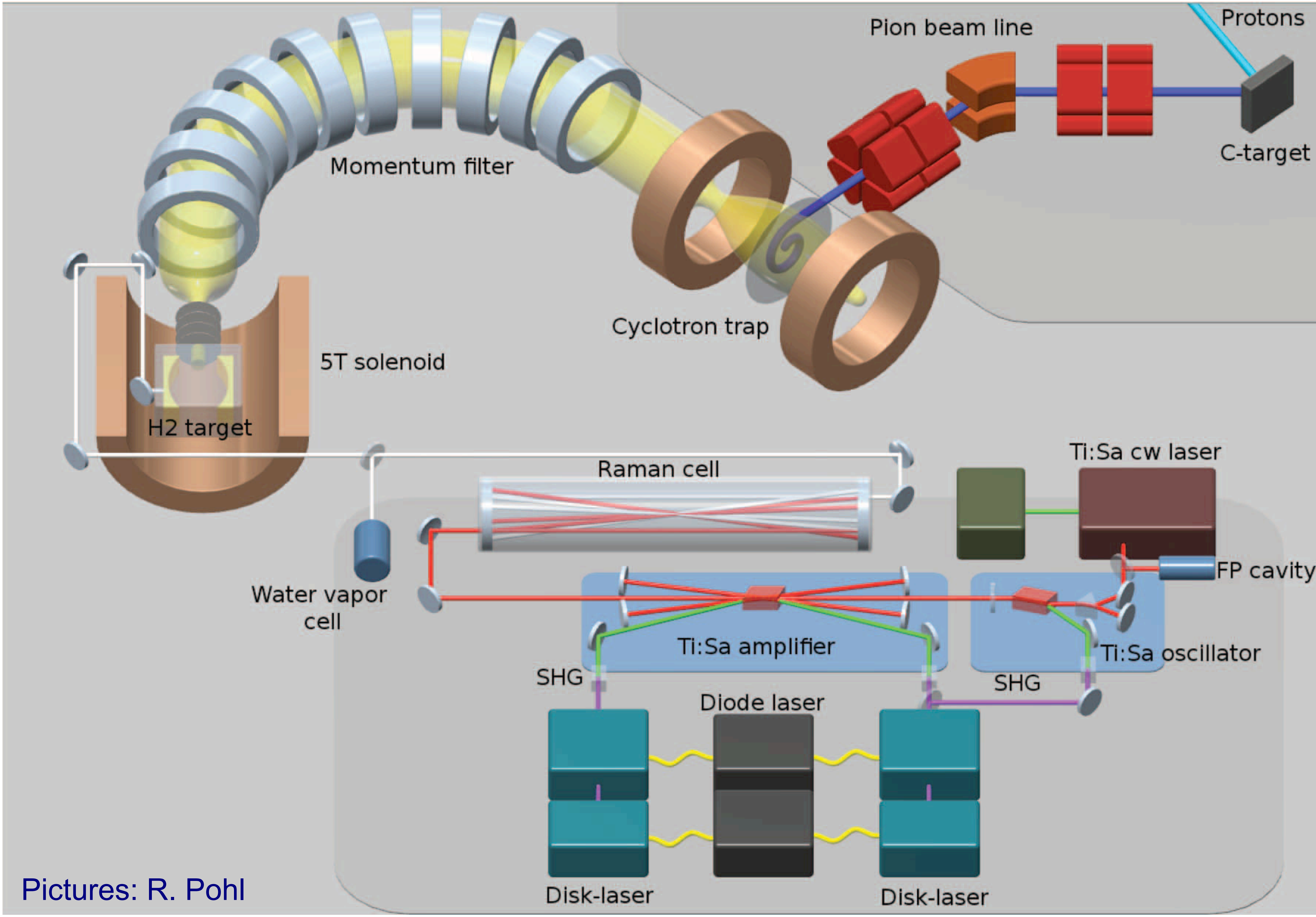
“delayed” ($t \sim 1\ \mu s$)



- Simple, but technically challenging!
- Form μH* by firing muon beam on 1mbar H_2 target
  - 99% decay to 1s, giving out fast γ pulse
  - 1% decay to longer-lived 2s state
- Excited to 2P state by tuned laser & decay with release of delayed γ
- Vary laser frequency to find transition peak → 2S to 2P ΔE → r_p

Pictures: R. Pohl

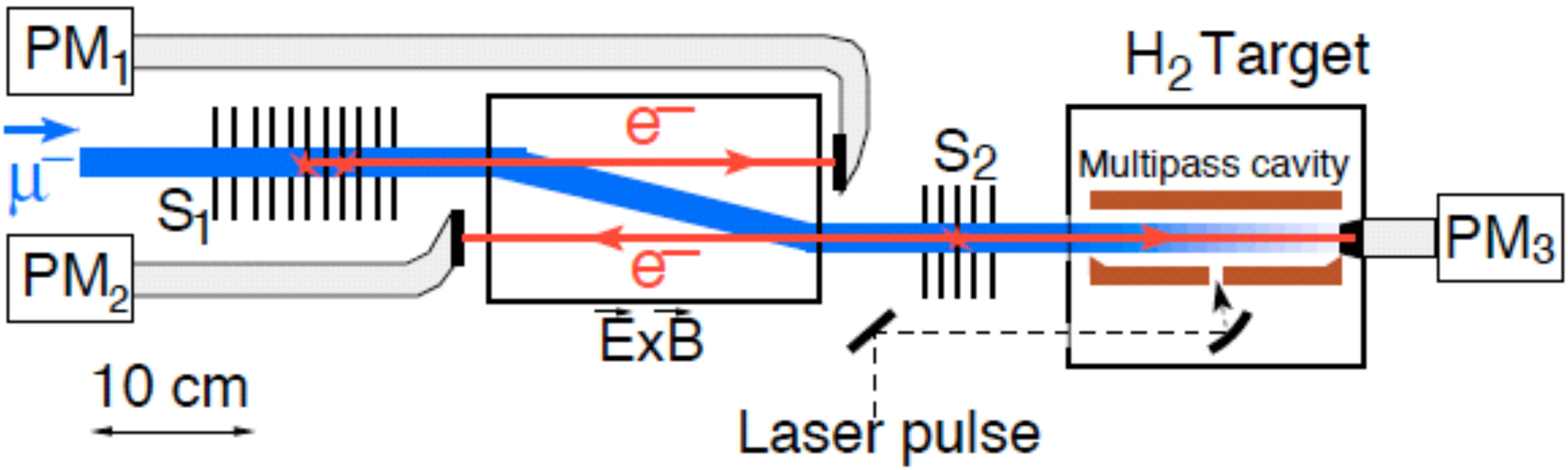
Mechanics of measuring with μH



Pictures: R. Pohl

Mechanics of measuring with μH

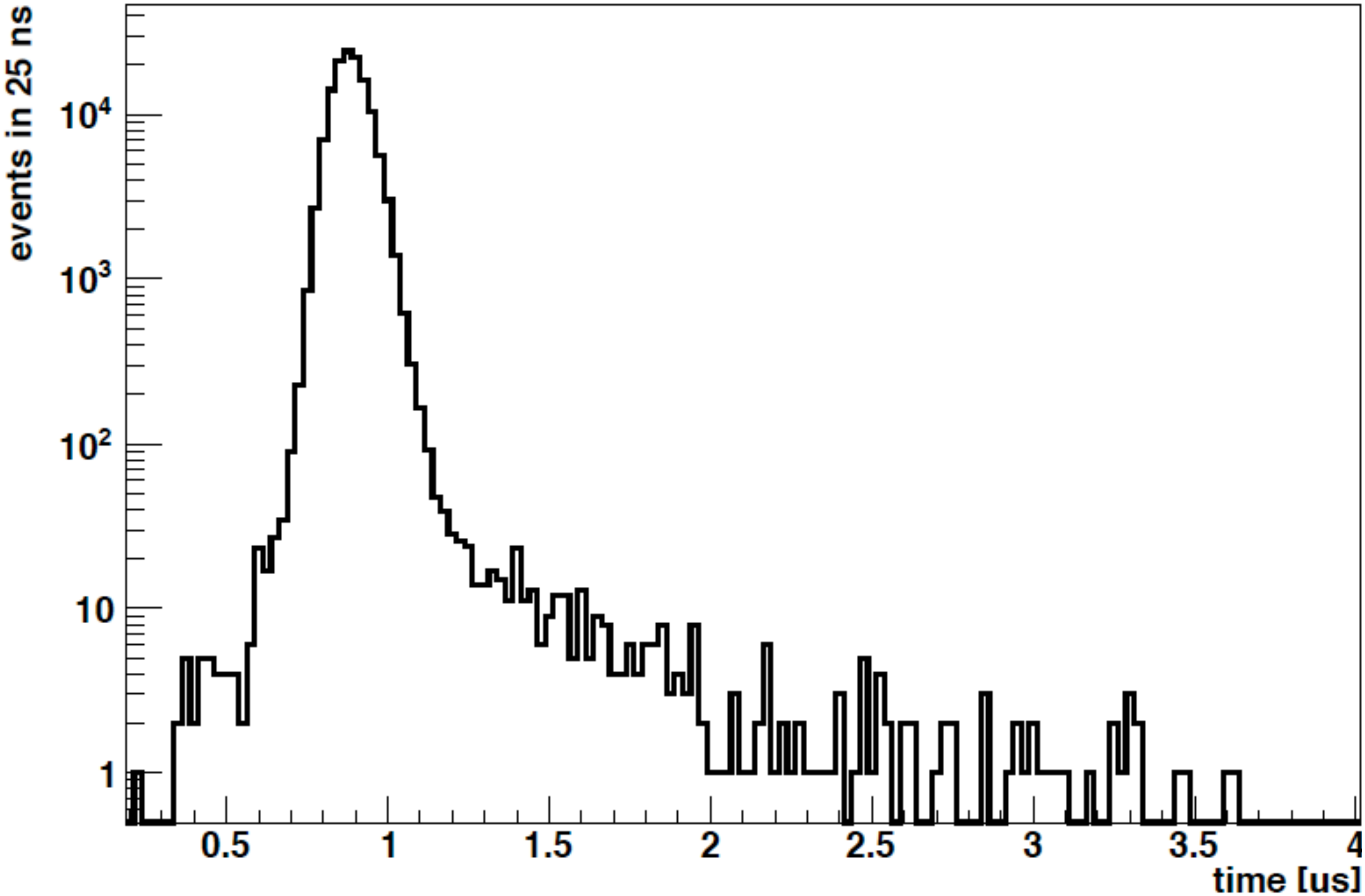
- μ from πE5 beamline at PSI (20 keV)
- μ's with 5 keV kinetic energy after carbon foils S1-2
- Arrival of the pulsed beam is timed by secondary electrons in PM1-3



Pictures: R. Pohl

Mechanics of measuring with μH

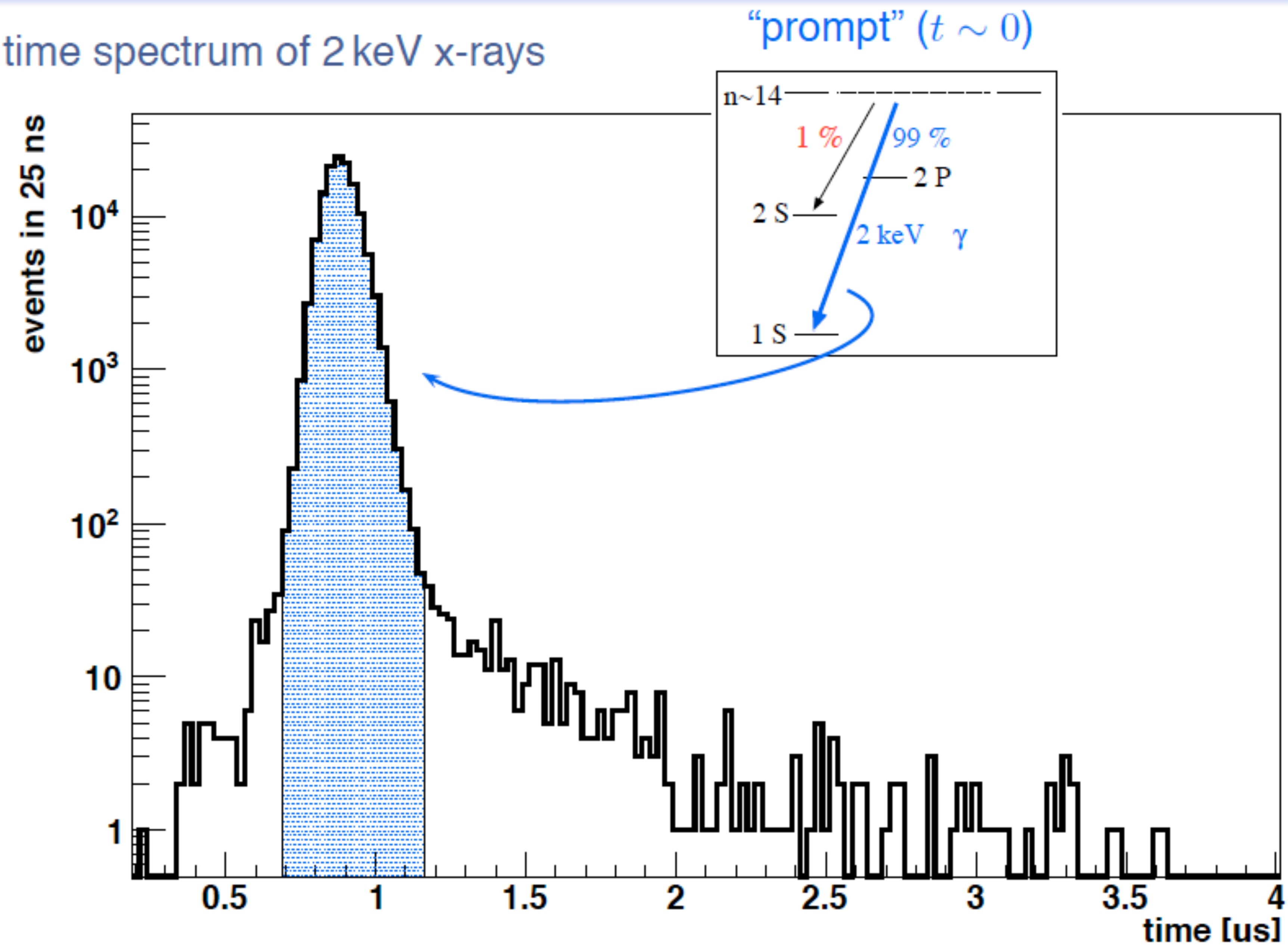
time spectrum of 2 keV x-rays (∼ 13 hours of data)



Pictures: R. Pohl

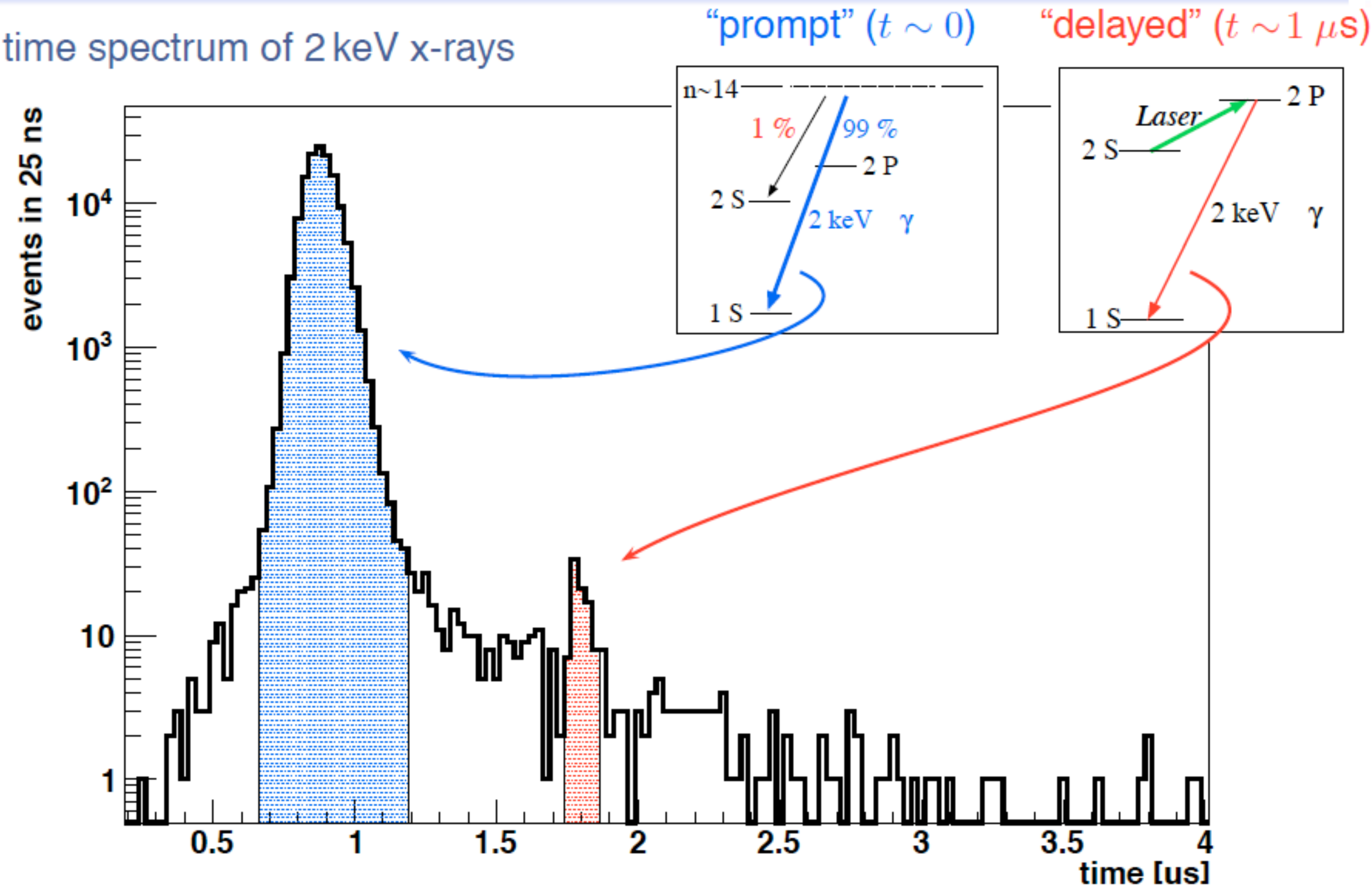
Mechanics of measuring with μH

time spectrum of 2 keV x-rays



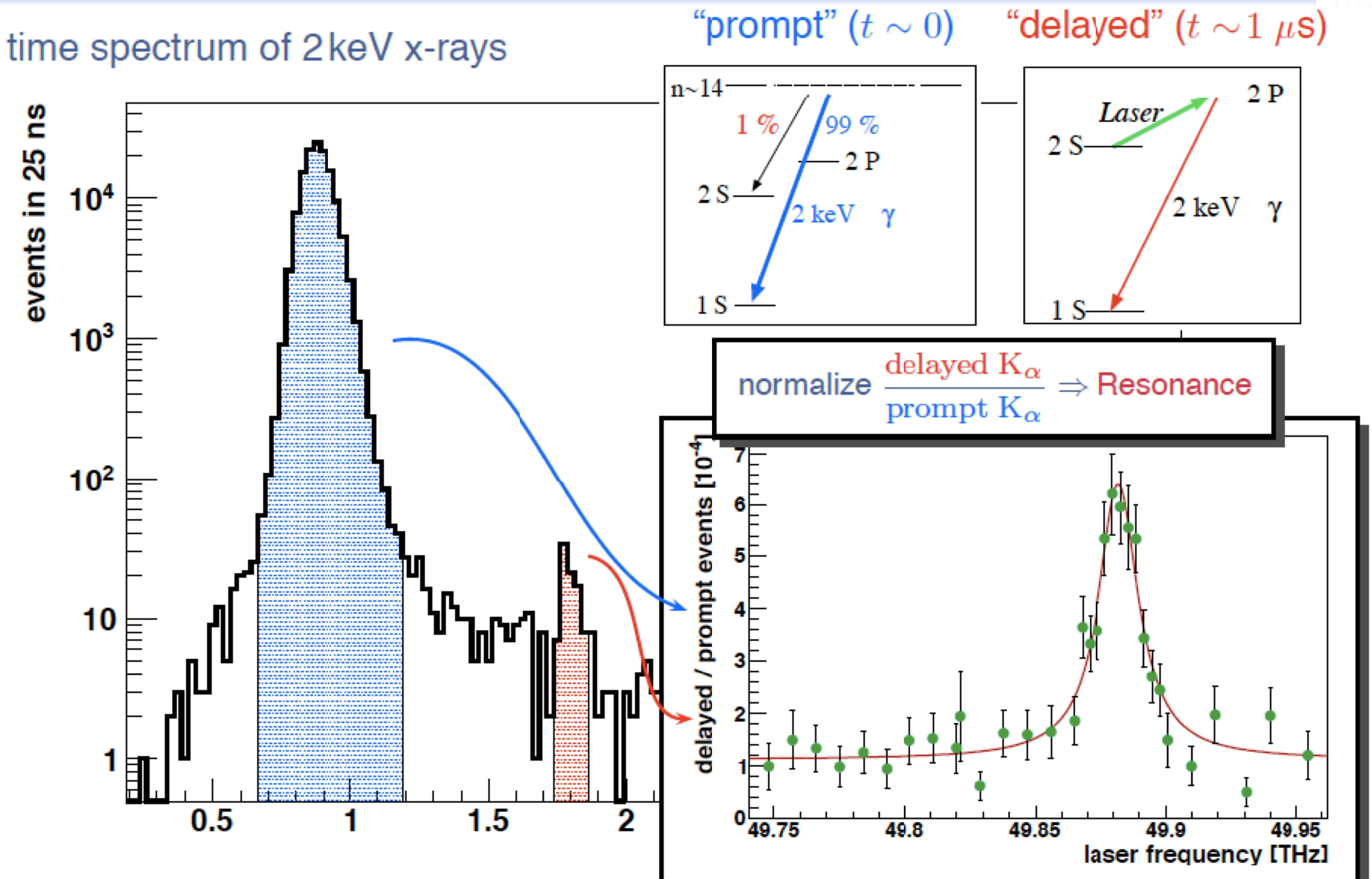
Pictures: R. Pohl

Mechanics of measuring with μH



Pictures: R. Pohl

Mechanics of measuring with μH

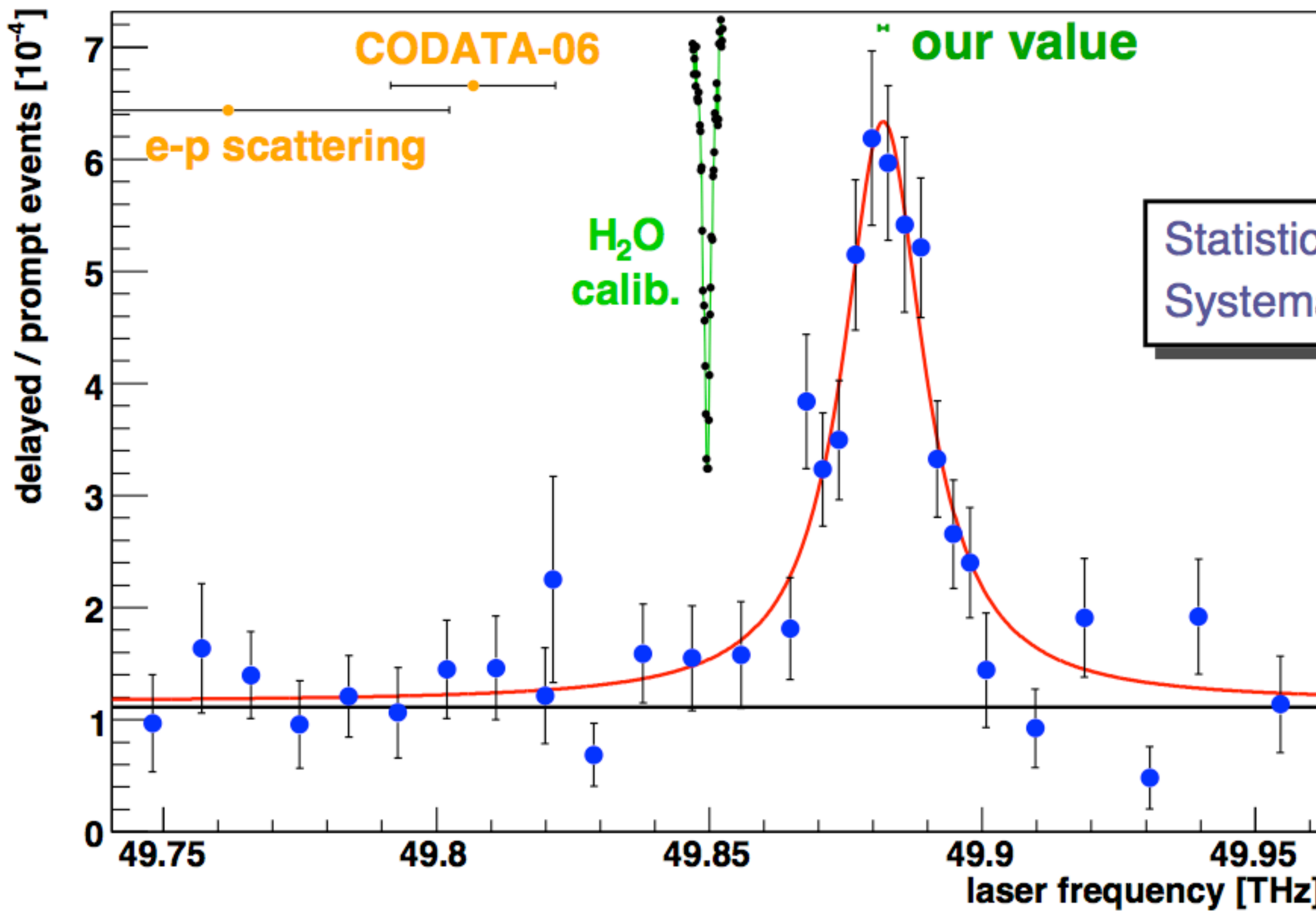


$$\Delta E(2P_{3/2}^{F=2} - 2S_{1/2}^{F=1}) = 209.9779(49) - 5.2262 r_p^2 + 0.0347 r_p^3 \ [\text{meV}]$$

The Proton Radius from excitation spectrum

Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty

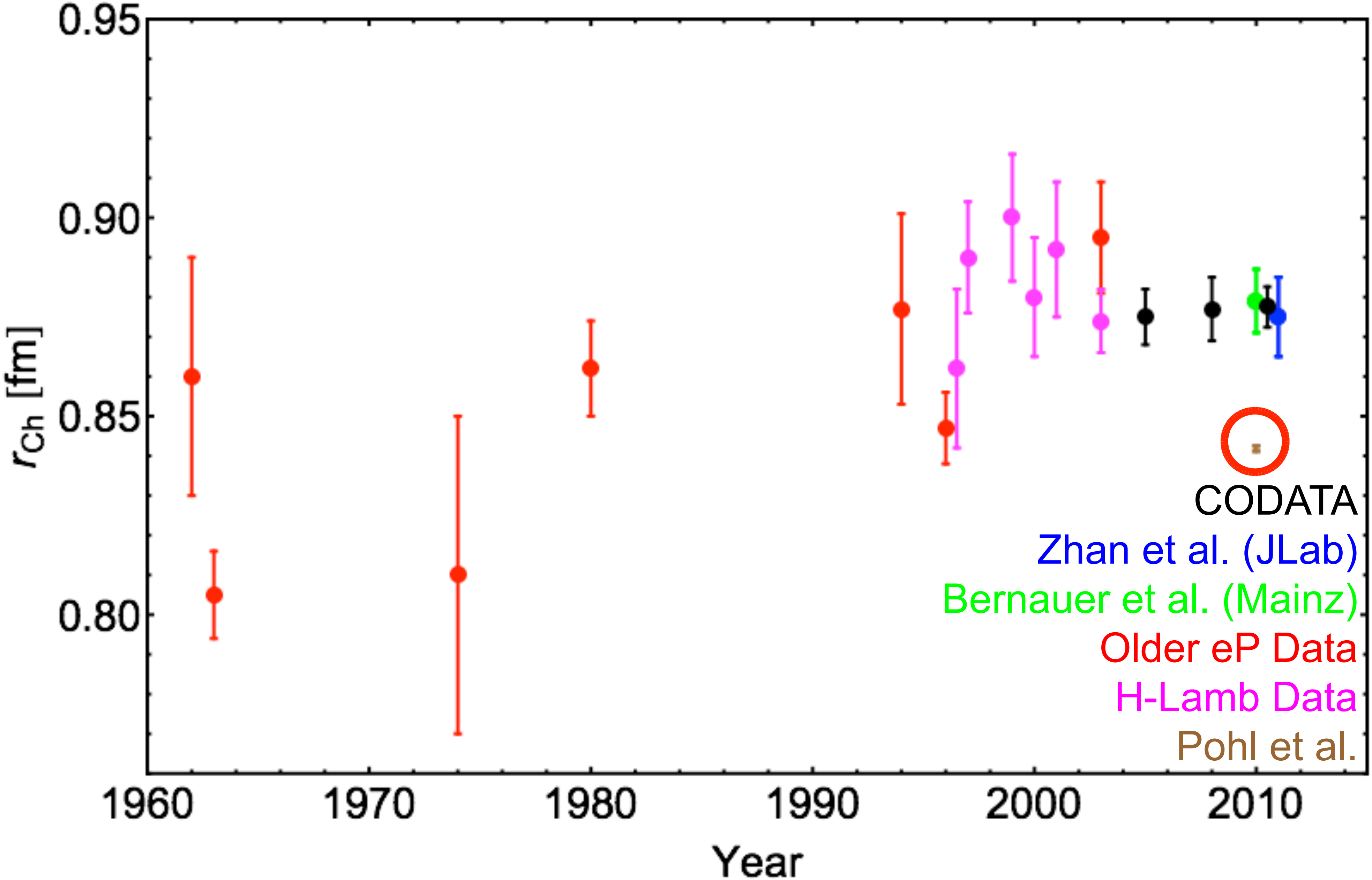


Statistics: 700 MHz
Systematics: 300 MHz

- Take ratio of delayed to prompt as a function of laser frequency:

Randolf Pohl et al., Nature 466, 213 (2010):
0.84184 ± 0.00067 fm 5σ off 2006 CODATA

Time evolution of the Lamb Shift Measurements & eP data



Sources of uncertainty

• Statistics	
Center position uncertainty ($\sim 4\%$ of Γ)	700 MHz
• Systematics	
Laser frequency (H_20 calibration)	300 MHz
AC and DC stark shift	< 1 MHz
Zeeman shift (5 Tesla)	< 30 MHz
Doppler shift	< 1 MHz
Collisional shift	2 MHz
• Total uncertainty of the line determination	760 MHz
• Theory: proton polarizability	1200 MHz
• Discrepancy with CODATA prediction	75 300 MHz

Systematic effects are small since they scale like $1/m$

Finite size effect scales like m^3

Pictures: R. Pohl

Curiouser & Curiouser...

- Latest paper: Aldo Antognini *et al*. Science **339**, 417 (2013)
- Further analysis of data taken in Pohl measurement & new data
- Magnetic radius agrees with e^- scattering data (0.87 ± 0.06 fm)
- Electric radius in agreement with Pohl 0.84087 ± 0.00039 fm
- 7σ from 2010 CODATA

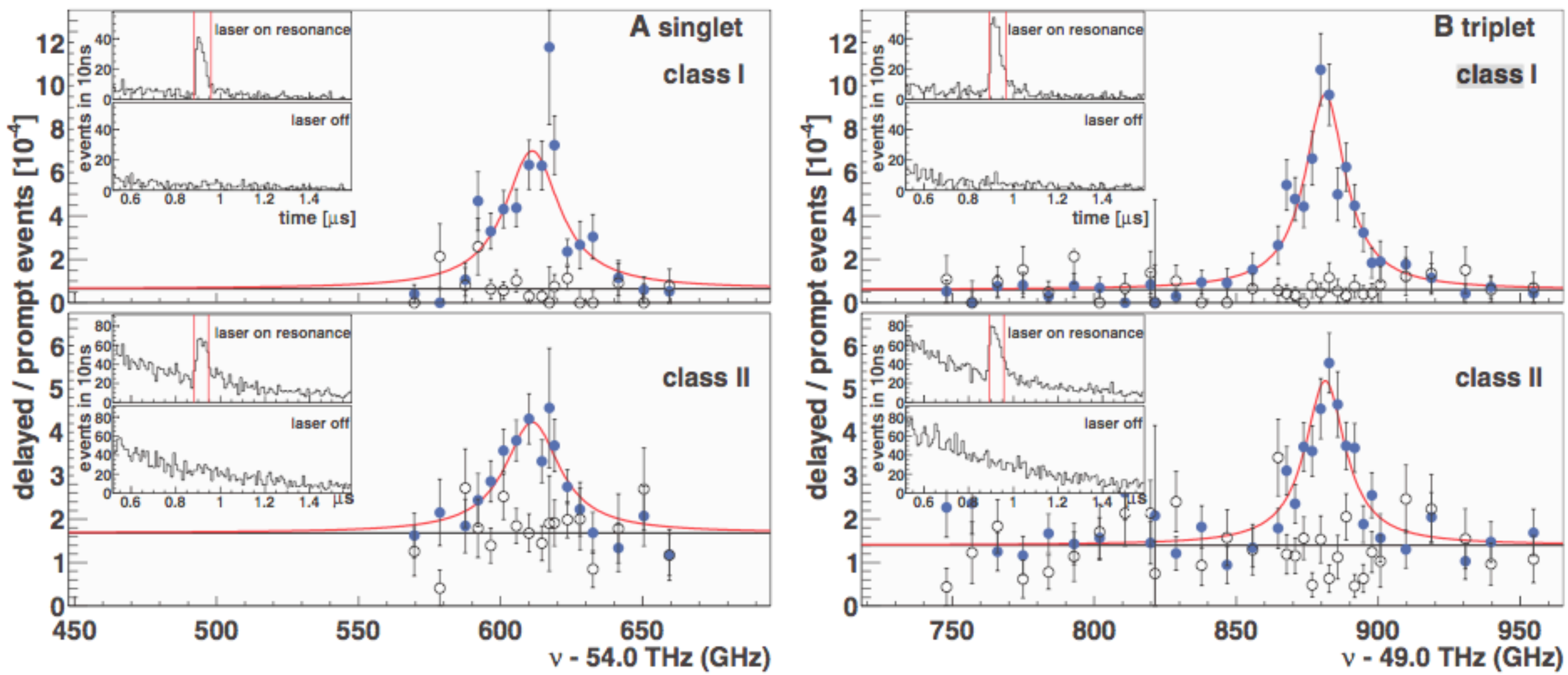


Fig. 3. Muonic hydrogen resonances (solid circles) for singlet ν_s (**A**) and triplet ν_t (**B**) transitions. Open circles show data recorded without laser pulses. Two resonance curves are given for each transition to account for two different classes, I and II, of muon decay electrons (*12*). Error bars indicate the standard error. (Insets) The time spectra of K_α x-rays. The vertical lines indicate the laser time window.

Why do the muon and electron give different proton radii?

- Assuming the experimental results are not bad, what are viable theoretical explanations of the Radius Puzzle?
- Novel Beyond Standard Model (BSM) Physics: Pospelov, Yavin, Carlson, ...: the electron is measuring an EM radius, the muon measures an (EM+BSM) radius
- Novel Hadronic Physics: G. Miller: currently unconstrained correction in proton polarizibility affects μ, but not e (effect $\propto m_l^4$)
- Basically everything else suggested has been ruled out - missing atomic physics, structures in form factors, anomalous 3rd Zemach radius, ...
- See Trento Workshop on PRP for more details:

http://www.mpq.mpg.de/~rnp/wiki/pmwiki.php/Main/WorkshopTrento

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 $Q^2 \sim m^2$ (typically expected to be a few MeV to 10's of MeV), enhanced parity violation
  - **Hadronic:** enhanced 2γ exchange effects
- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems
  - Redoing electron scattering at lower Q^2
  - **Muon scattering!**

How do we Resolve the Radius Puzzle

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MUSE tests these

- Experiments include:
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How do we Resolve the Radius Puzzle

Possible 2nd generation ex

- New data needed to test that the e and μ are really different, and the implications of novel BSM and hadronic physics
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MUSE tests these

- Experiments include:
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How do we Resolve the Radius Puzzle

Pos. 2nd generation expt.

- 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 $Q^2 \sim m^2_{BSM}$ (typically expected to be a few MeV to 10's of MeV), enhanced parity violation
  - **Hadronic:** enhanced 2γ exchange effects

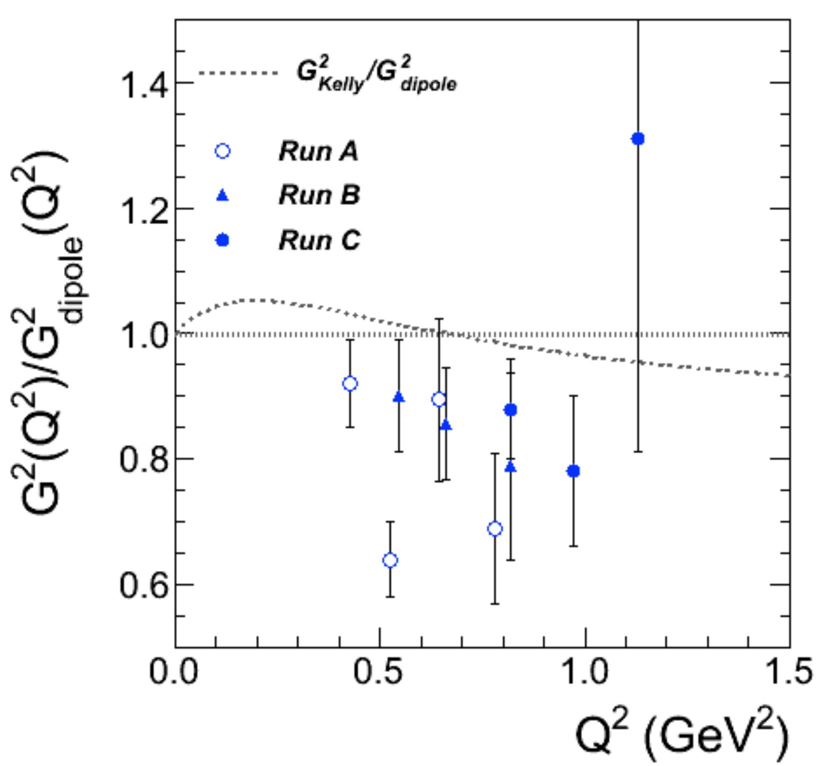
MUSE tests these

- Experiments include:
  - Redoing atomic hydrogen
  - Light muonic atoms for radius comparison in heavier systems **CREMA**
  - Redoing electron scattering at lower Q^2 **Jlab & Mainz**
  - **Muon scattering!**

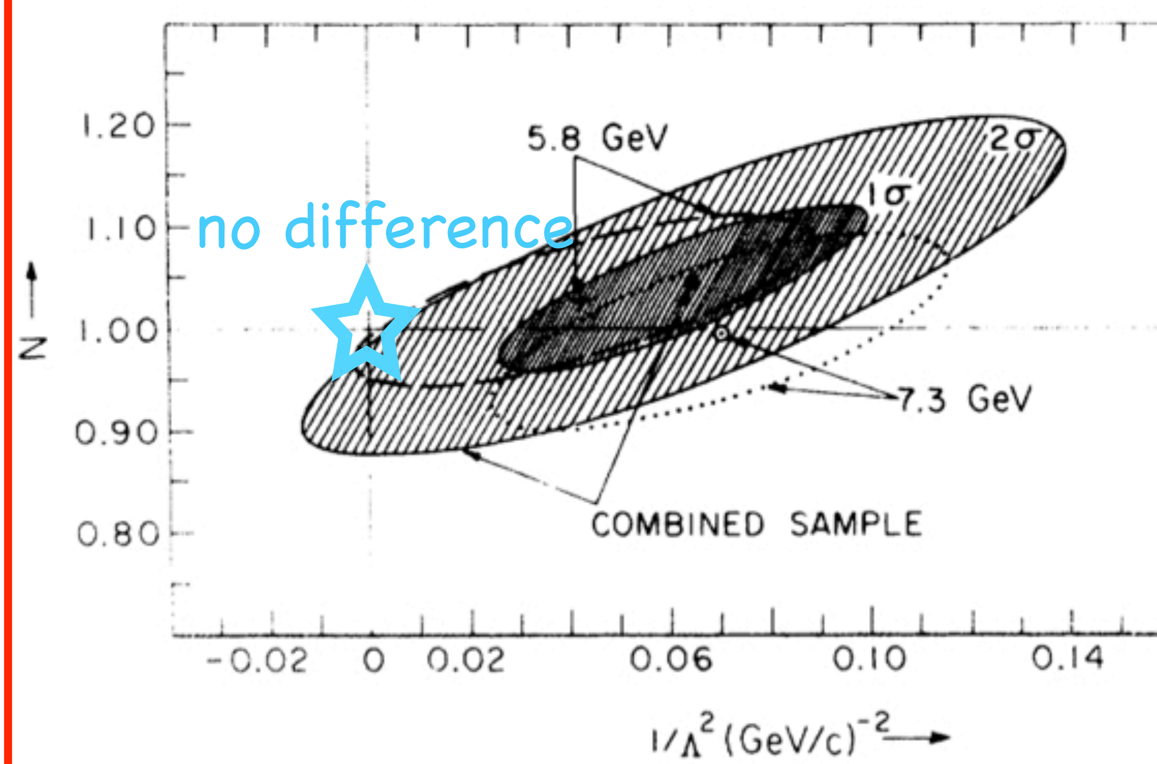
Previous e-μ Scattering Comparisons

- 1970's & 80's several scattering ep & μp tests
- Supported lepton universality at 10% level
- Insufficient precision to test proton radius issues

Ellsworth et al.: form factors from elastic μp



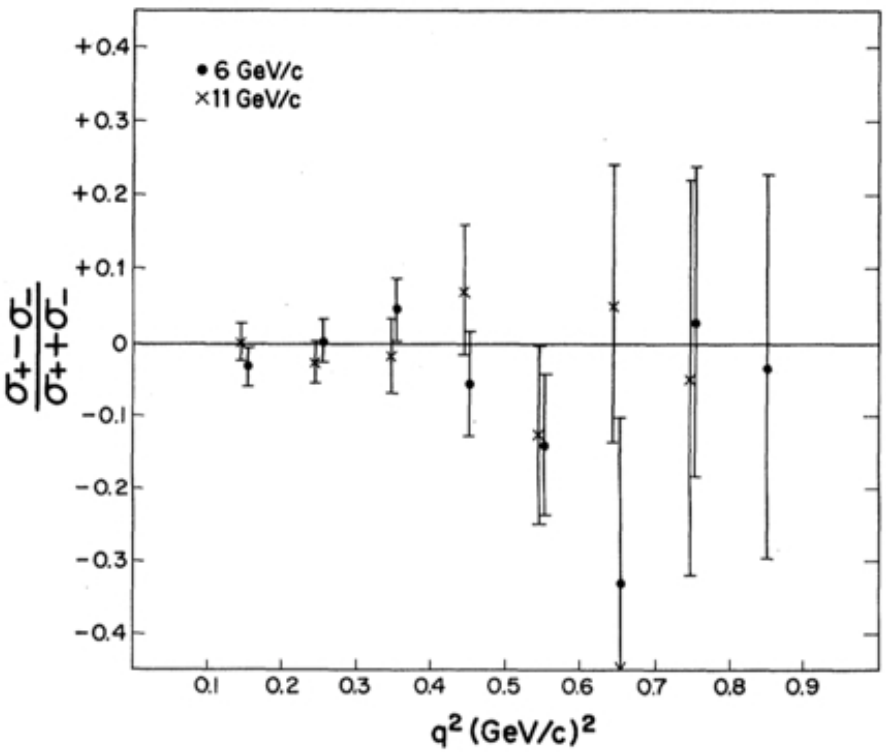
Kostoulas et al. parameterization of μp vs. ep elastic differences



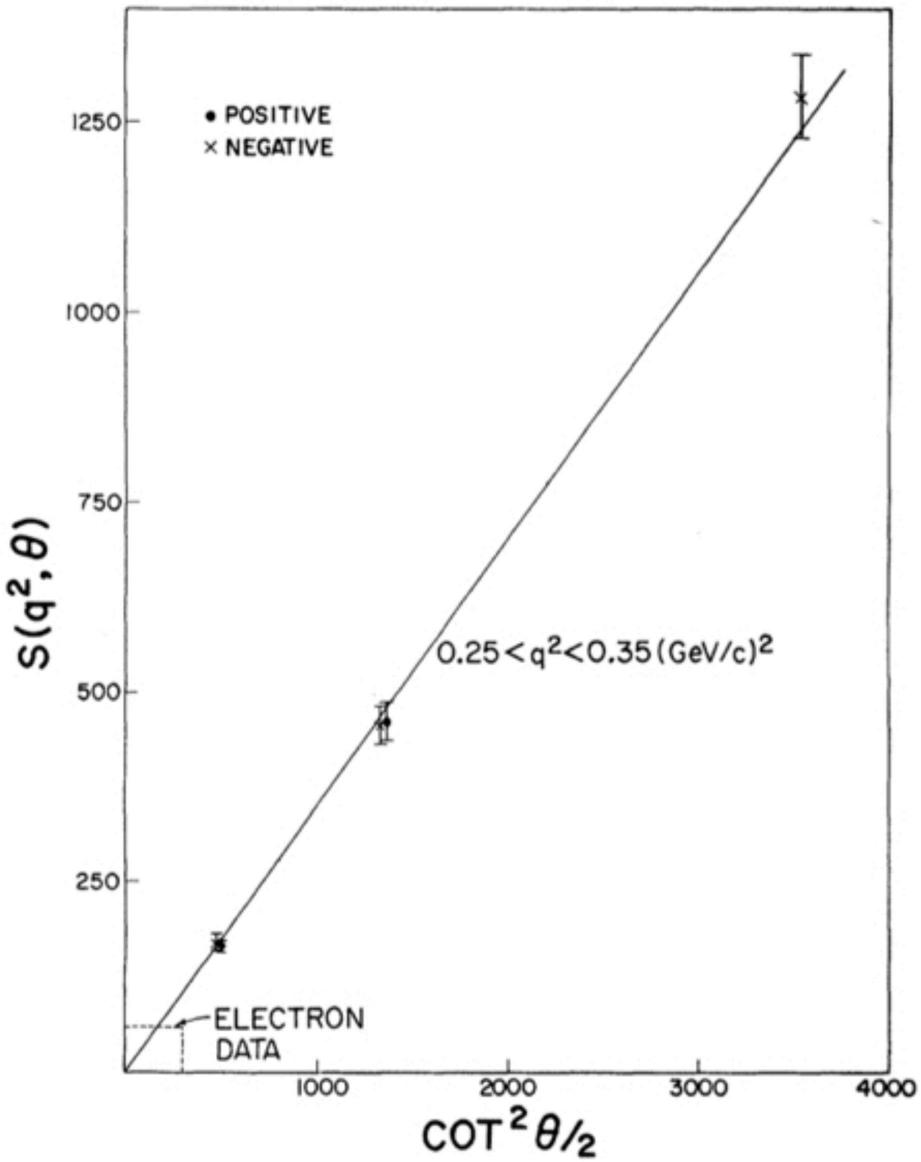
Entenberg et al DIS: $\sigma_{\mu p}/\sigma_{ep} \approx 1.0 \pm 0.04$ (±8.6% systematics)

Two-photon exchange tests in μp elastics

- Camilleri et al. PRL 23: No evidence for two-photon exchange effects, but very poor constraints by modern standards.



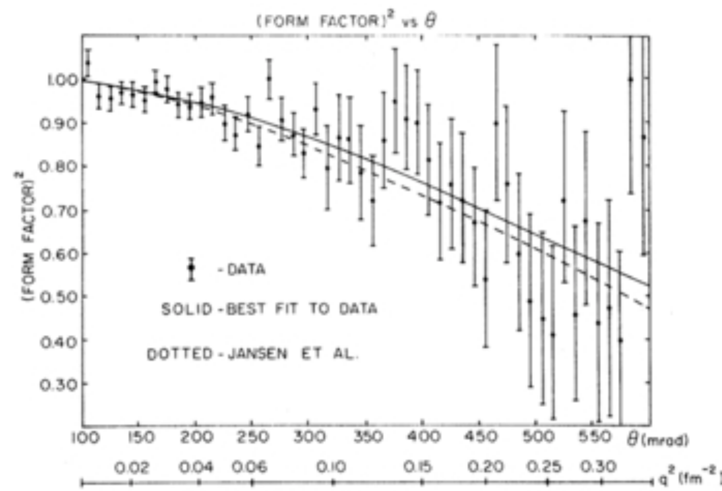
No difference between μ^+p and μ^-p elastic scattering



Rosenbluth plot is linear.

^{12}C Radius and e-μ Universality

- ^{12}C radius determined with $e^{12}C$ scattering and $\mu^{12}C$ atoms agree
  - ➔ Offermann et al. $e^{12}C$: 2.478 ± 0.009 fm
  - ➔ Schaller et al. $\mu^{12}C$ X rays: 2.4715 ± 0.016 fm
  - ➔ Ruckstuhl et al. $\mu^{12}C$ X rays: 2.483 ± 0.002 fm
  - ➔ Sanford et al. $\mu^{12}C$ elastic: $2.32^{+0.13}_{-0.18}$ fm



- Perhaps carbon is right, e's and μ's are the same.
- Perhaps hydrogen is right, e's and μ's are different.
- Perhaps both are right - opposite effects for proton and neutron cancel with carbon.
- But perhaps the carbon radius is insensitive to the nucleon radius, and μd or μHe would be a better choice?
- Also: A. Antognini et al: Muonic H + eH/D isotope shift ➯ r_d = 2.12771(22) fm vs. 2.130(10) fm from ed scattering.

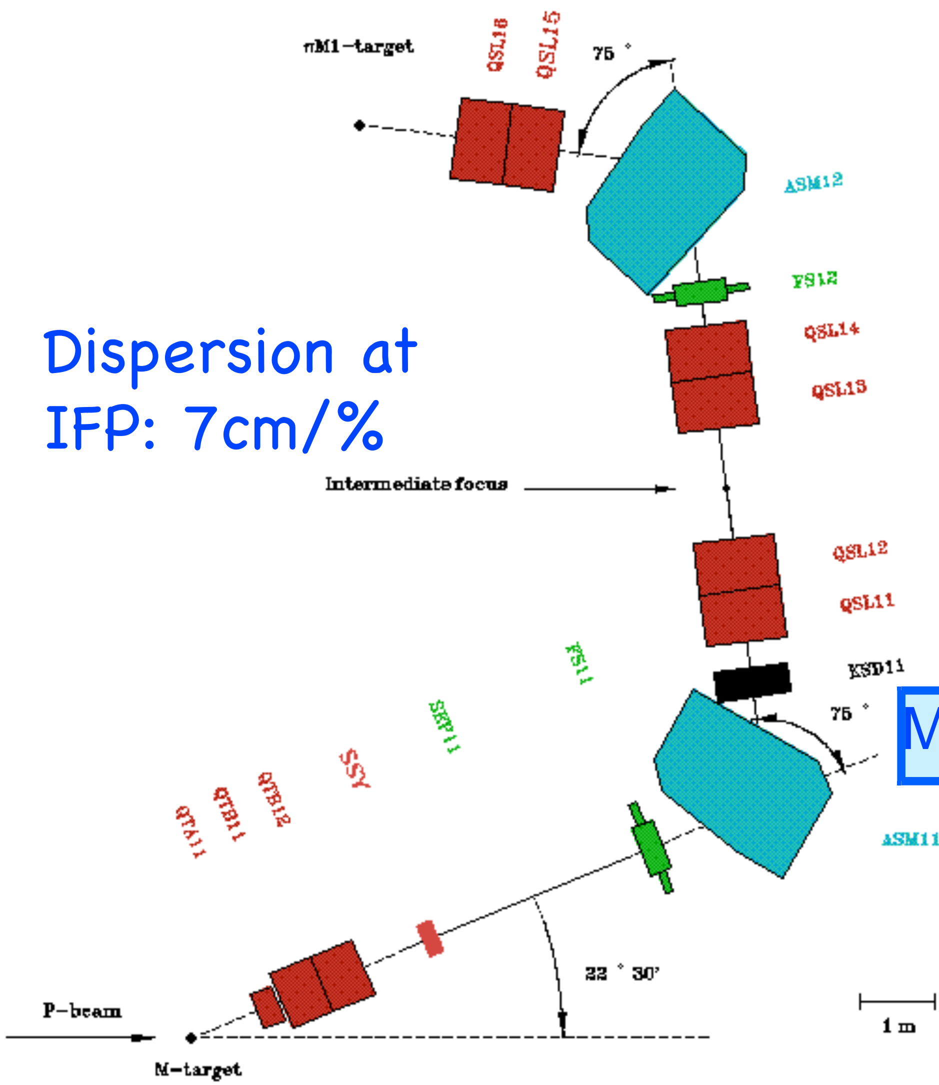
MUSE Experiment

r_p(fm)	**ep**	**μp**
atom	0.877±0.007	0.841±0.0004
scattering	0.875±0.006	**?**

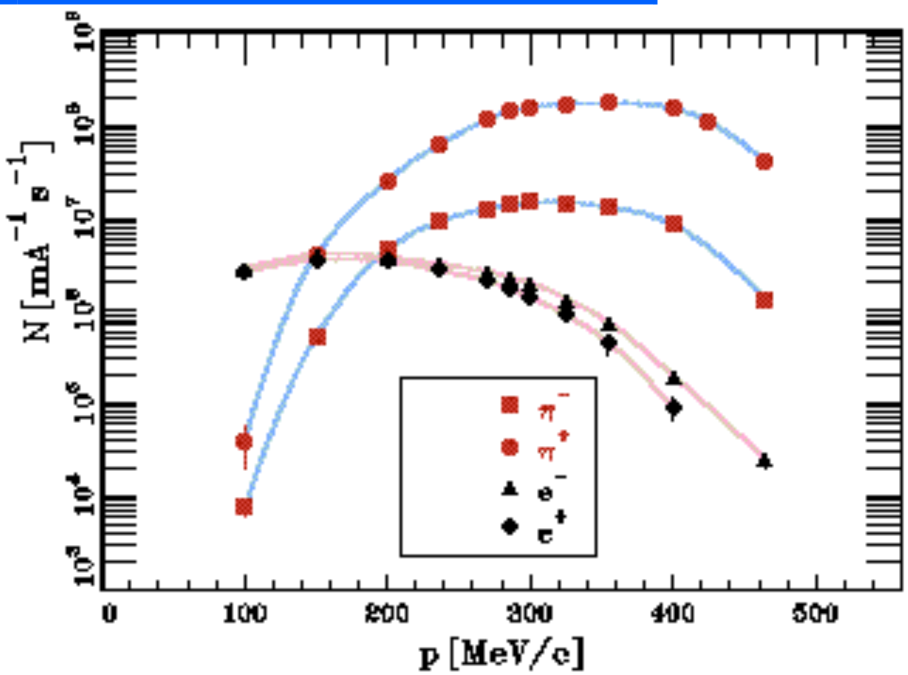
- Simultaneous measurement of e^+/μ^+ e^-/μ^- elastic scattering on the proton at beam momenta of 115, 153, 210 MeV/c in pM1 channel at PSI allows:
  - ➔ Determination of two photon effects
  - ➔ Test of Lepton Universality
  - ➔ Simultaneous determination of proton radius in both eP and mP scattering

PSI πM1 Channel Characteristics

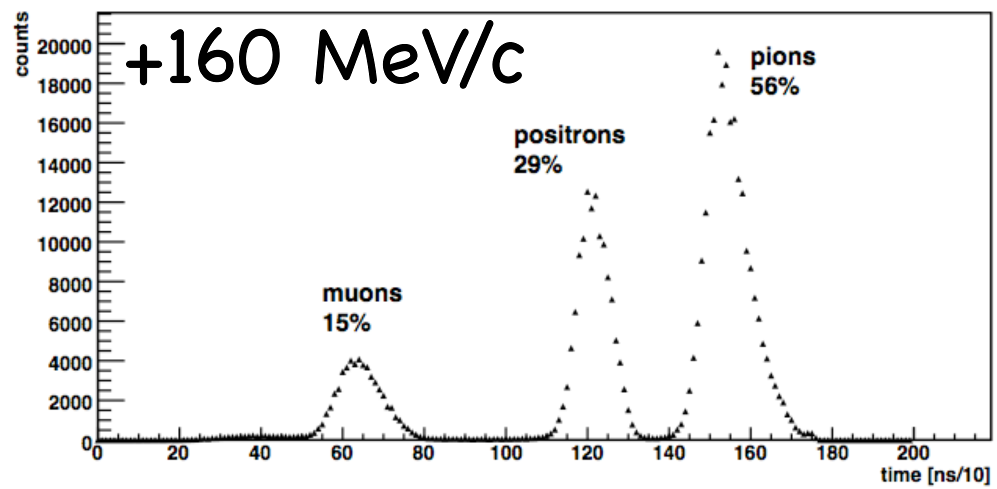
≈100 - 500 MeV/c mixed beam of μ's + e's + π's



Dispersion at IFP: 7cm/%



Momentum acceptance: 3% resolution: 0.1%

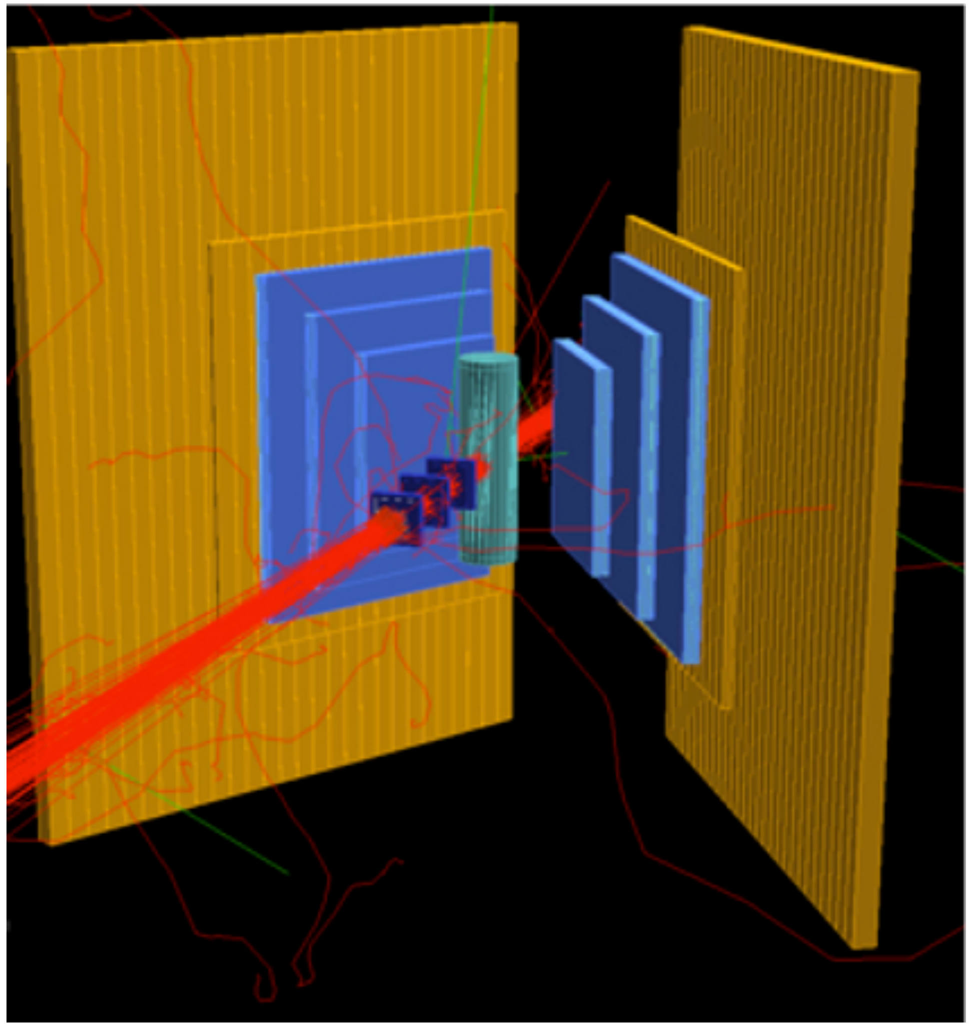


+160 MeV/c

Beam spot (nominal): 1.5 cm X x 1 cm Y, 35 mr X' x 75 mr Y'

Spots from 0.7x0.9 cm^2 up to 16x10 cm^2, $\Delta p/p$ from 0.1-3.0%, used previously.

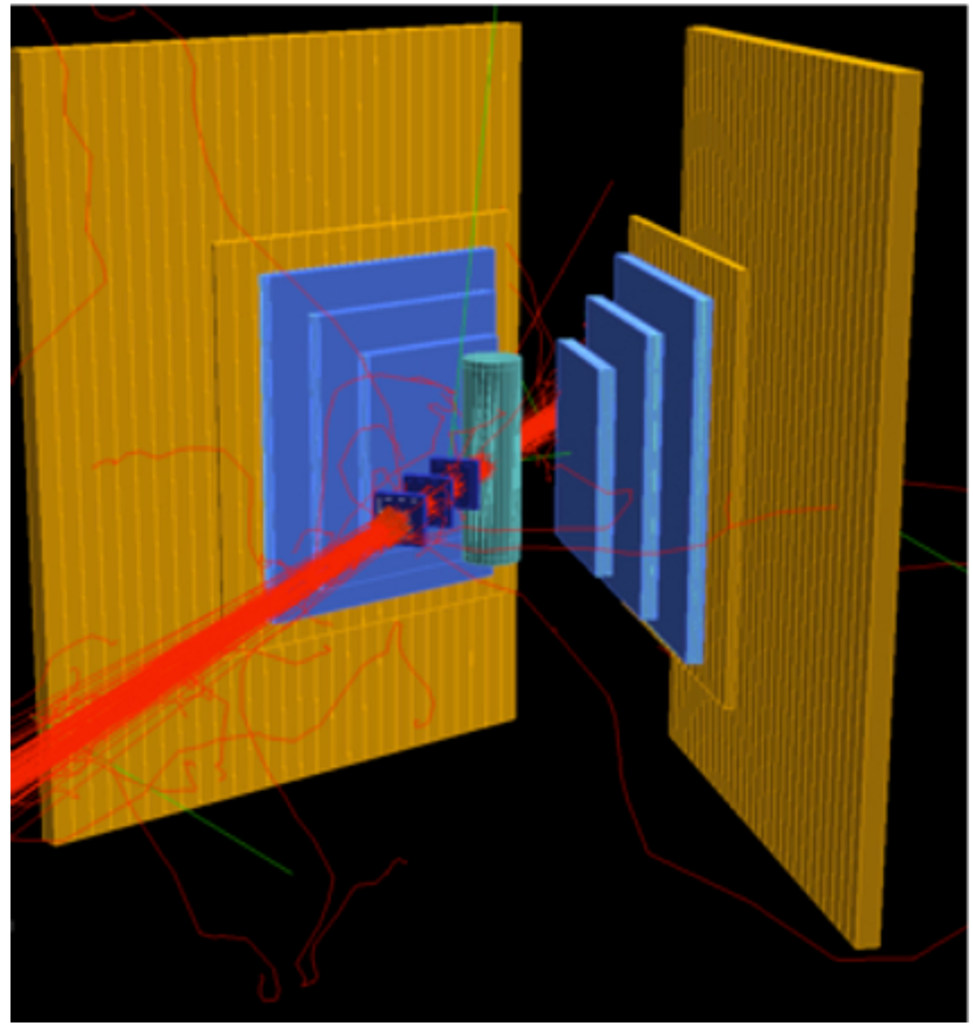
MUSE Experiment



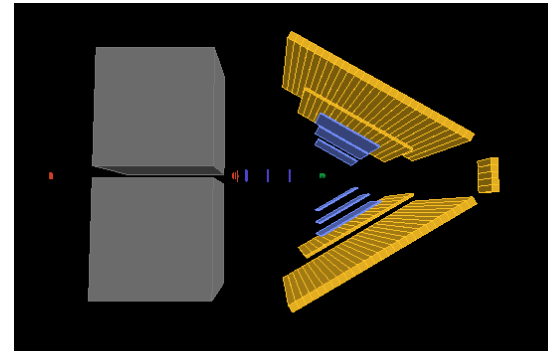
- Low beam flux. → Large angle, non-magnetic detectors.
- Secondary beam. → Tracking of beam particles to target.
- Mixed beam. → Identification of beam particle in trigger.

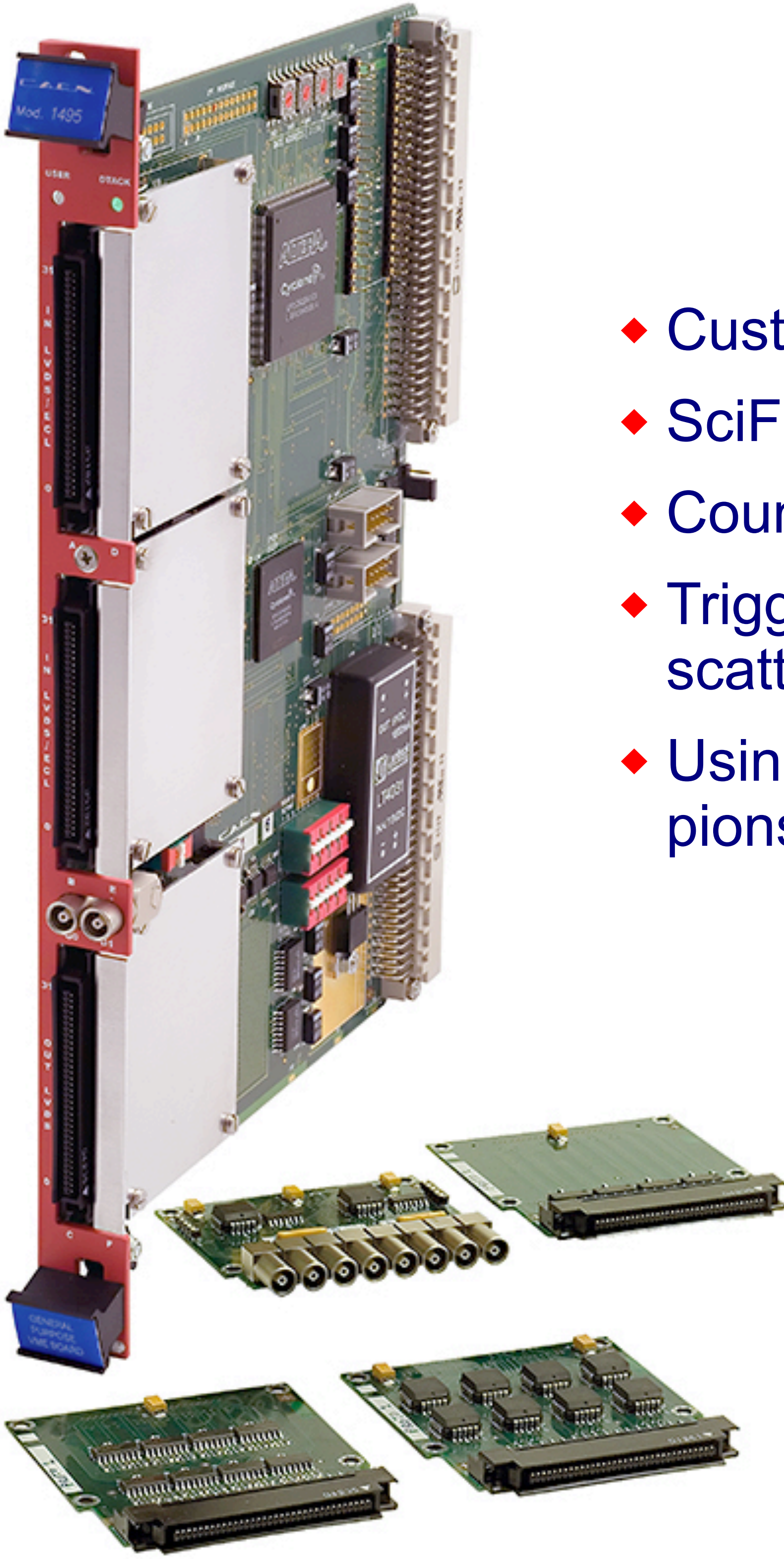
MUSE Experiment

- PSI πM1 channel
- $\approx$115, 153, 210 MeV/c mixed beams of $e^{\pm}$, $\mu^{\pm}$ and $\pi^{\pm}$
- FPGA trigger with beam PID
- $\theta \approx 20^{o} - 100^{o}$
- $Q^2 \approx 0.002 - 0.07$ GeV^2
- About 5 MHz total beam flux, $\approx$2-15% μ's, 10-98% e's, 0-80% π's
- Beam monitored with SciFi, ``quartz'' Cerenkov, GEMs
- Scattered particles detected with wire chambers and scintillators



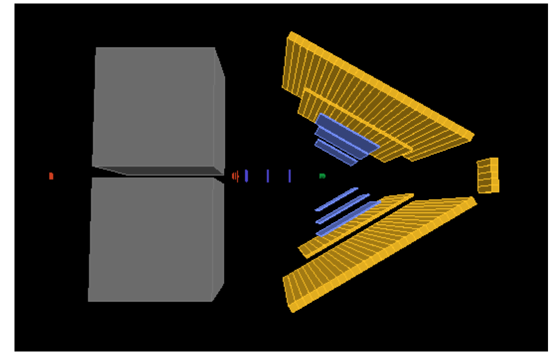
FPGAs
(Rutgers U.)





- Custom beam PID FPGA
- SciFi & RF signals → PID
- Count particle types & reject pions
- Trigger FPGA – CAEN v1495: beam PID + scattered particle = trigger
- Using one SciFi plane 99.9% efficient to reject pions or ID electrons & muons @ 153 / 210 MeV

SciFi Beam Detectors
(HUJI / Tel Aviv)



At target

- Timing (~1ns s) for PID in combination with beam RF
- Beam flux normalisations for absolute cross sections & triggering
- Position & time for correlations with GEMS

At IFP

- PID for triggering and position to determine momentum

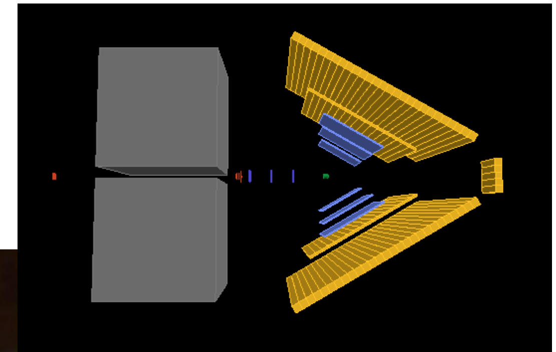
Combined

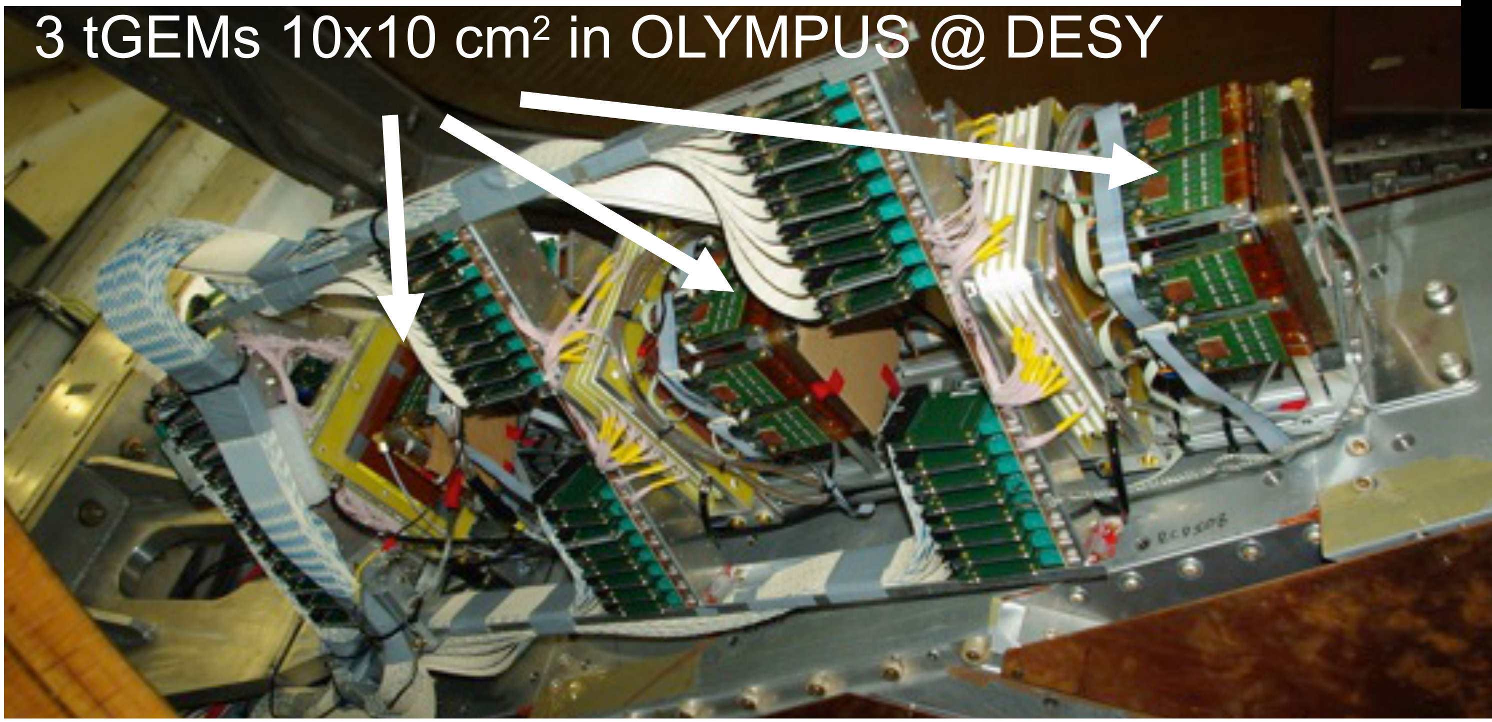
- TOF between counters for PID

Properties

- 2mm fibres, double-ended maPMT readout. XX' (XYU) orientations for IFP (target) detectors with ≈ 120 (100) fibres & 8cm active area

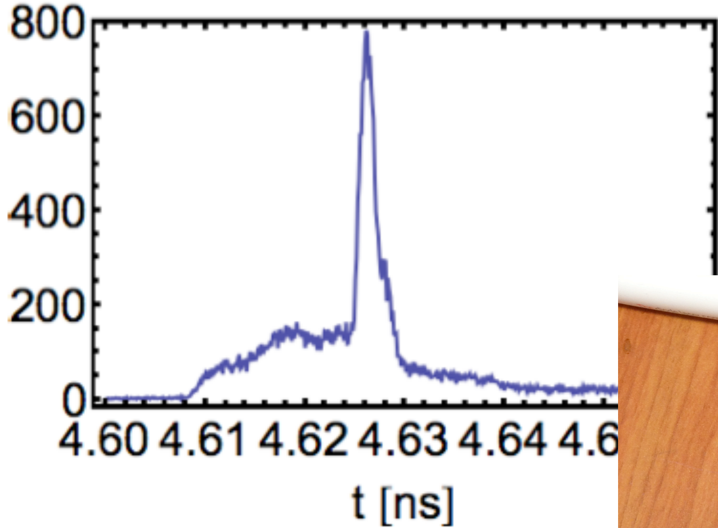
GEM Chambers
(Hampton U.)

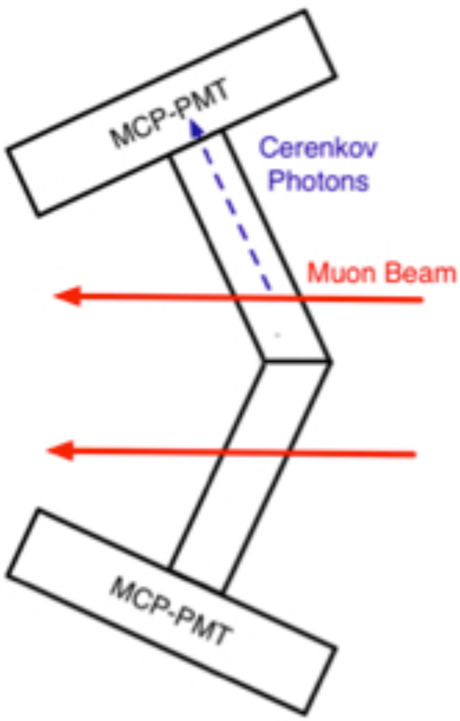


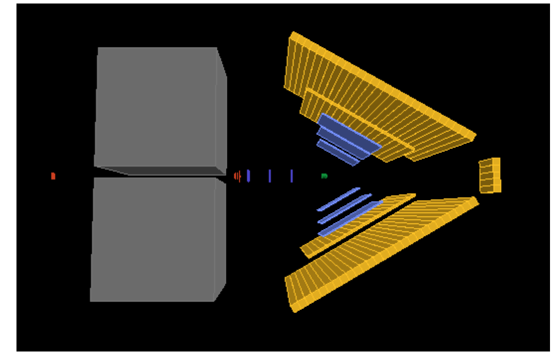


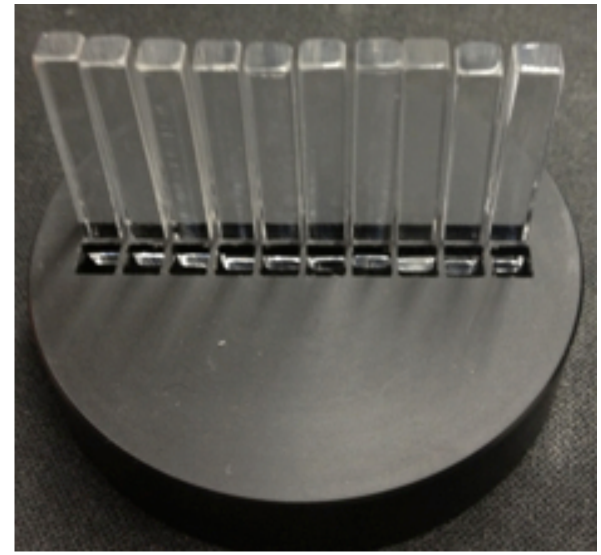
- Determine trajectory into target for scattering angle & Q^2
  - Third GEM to reject ghosts
- GEMS from DESY OLYMPUS experiment
  - On way to PSI
- Need work to speed up readout algorithm

Quartz Cerenkov (Hebrew U.)



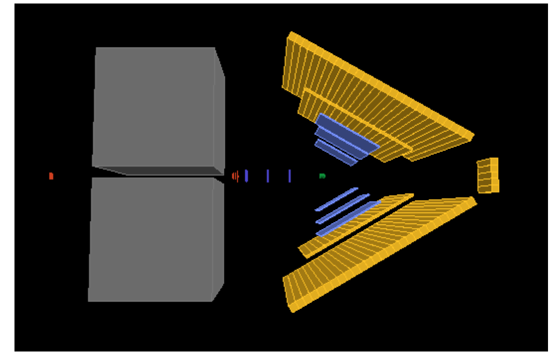




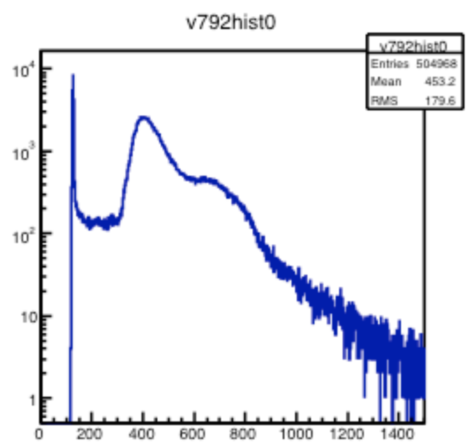


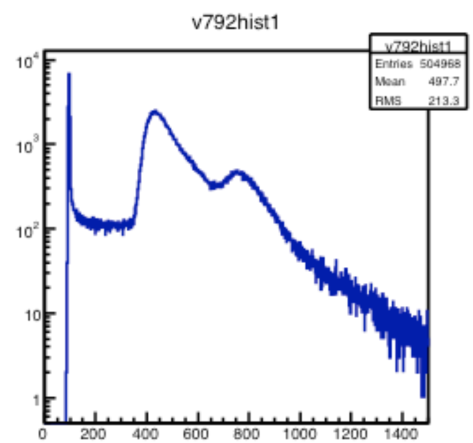
- Improved timing at target region
- Better RF time PID in analysis stage
  - Muon decay event rejection
- Quartz Cherenkovs Albrow et al. (FNAL) 10ps resolution
  - Quartz / Sapphire at Cerenkov angle
- MUSE fewer photons ≈100ps (≈50ps after corrections)

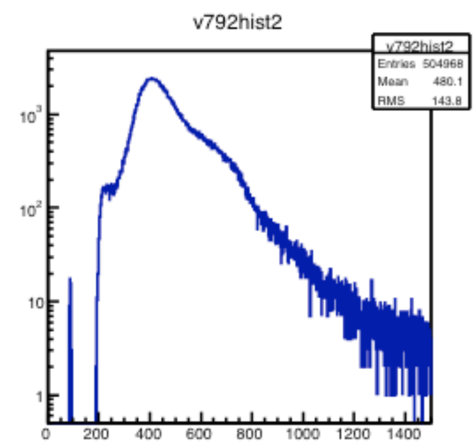
Beam Scintillators
(U. So. Carolina)

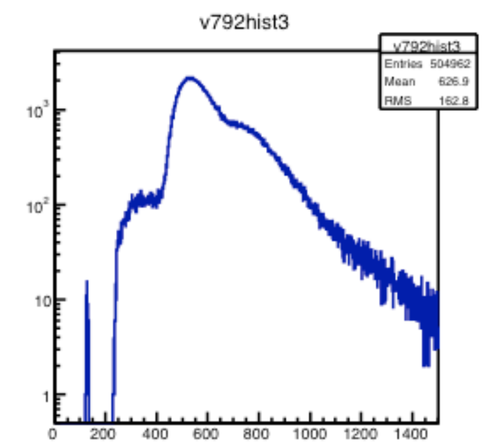


- Parasitic monitor of random, non-triggering beam particles
  - Same design as for CLAS 12
- Test run data verified simulations
- So. Carolina scintillator spectra:

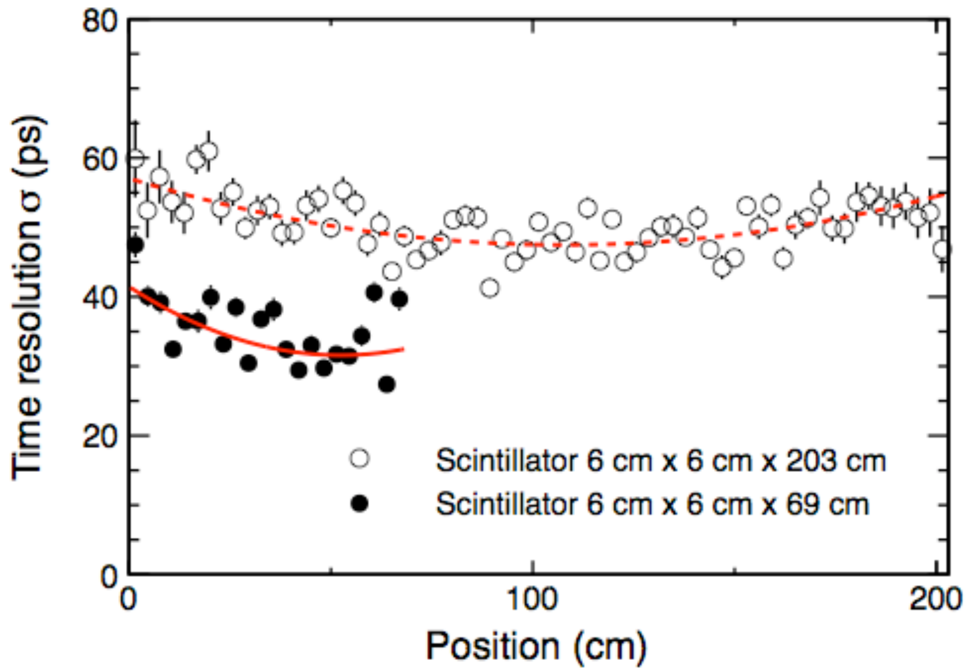


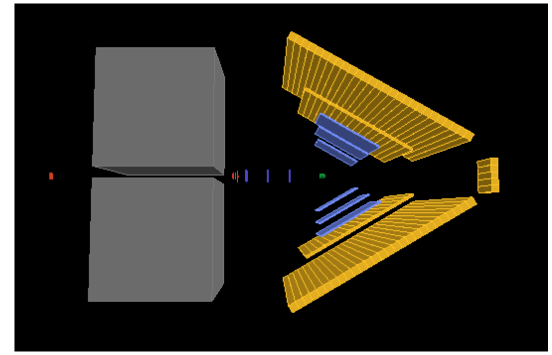






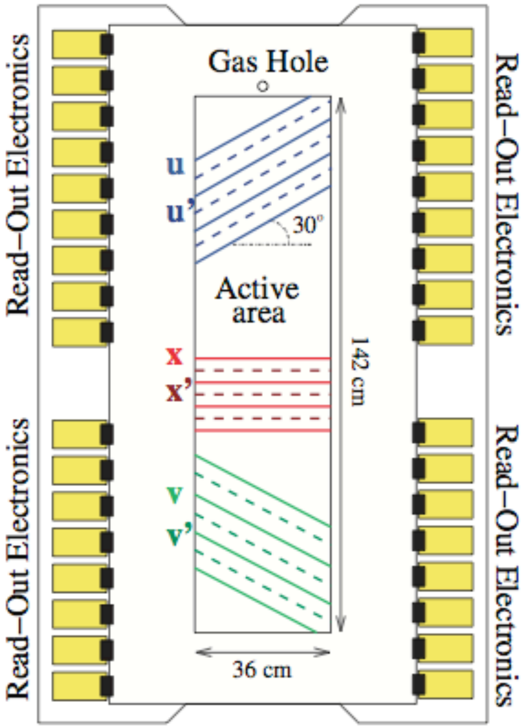
Scintillators
(U. So. Carolina)

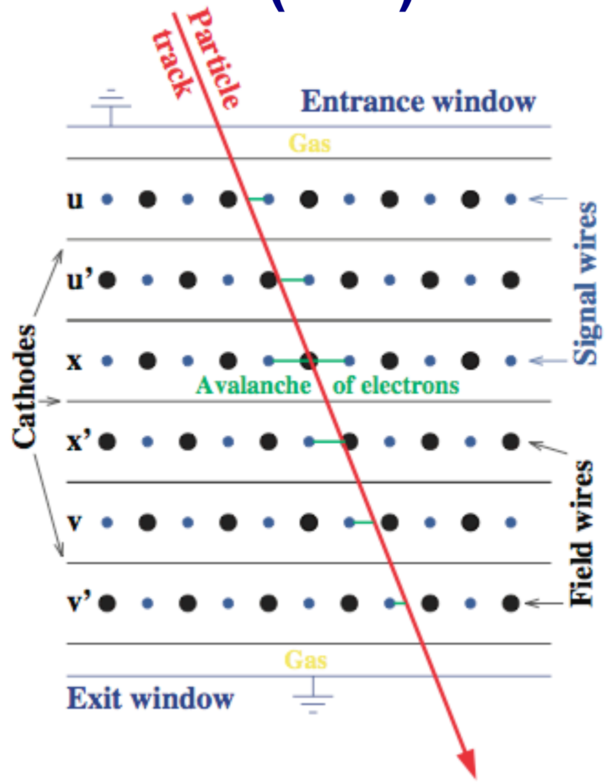


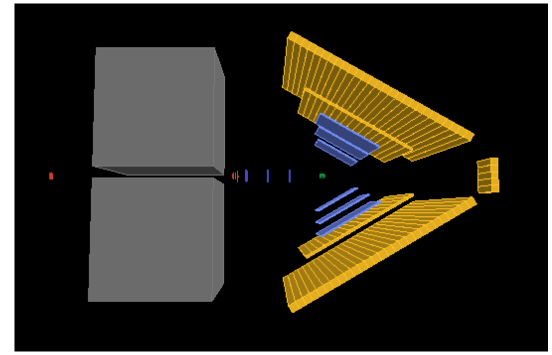


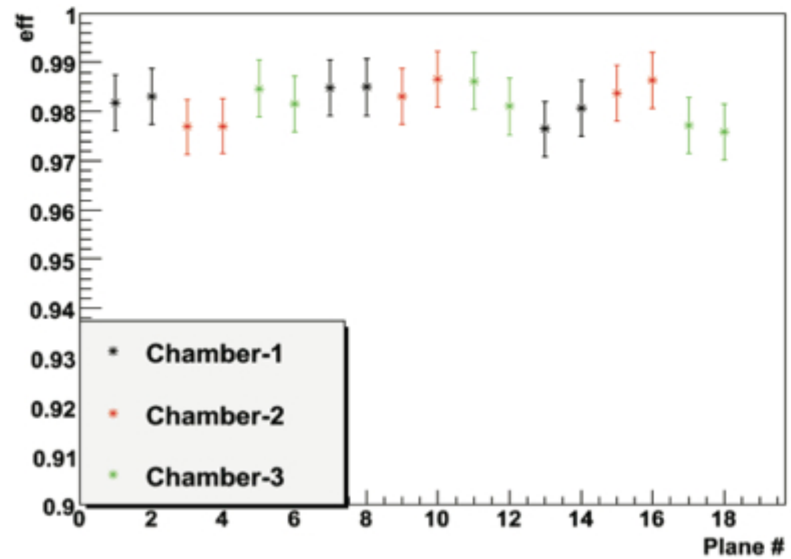
- Detect scattering particles depositing few MeV in each of two planes
- High precision timing for PID & rejection of electons from muon decay
- JLab CLAS12 design
- Front: 17 paddles, 6cm wide x 2cm thick x 103cm long, 50cm from target
- Rear: 27 paddles, 6cm wide x 6cm thick x 163cm long, 73cm from target
- Resolution: ≈40ps front, ≈50ps rear

Wire Chambers (MIT)







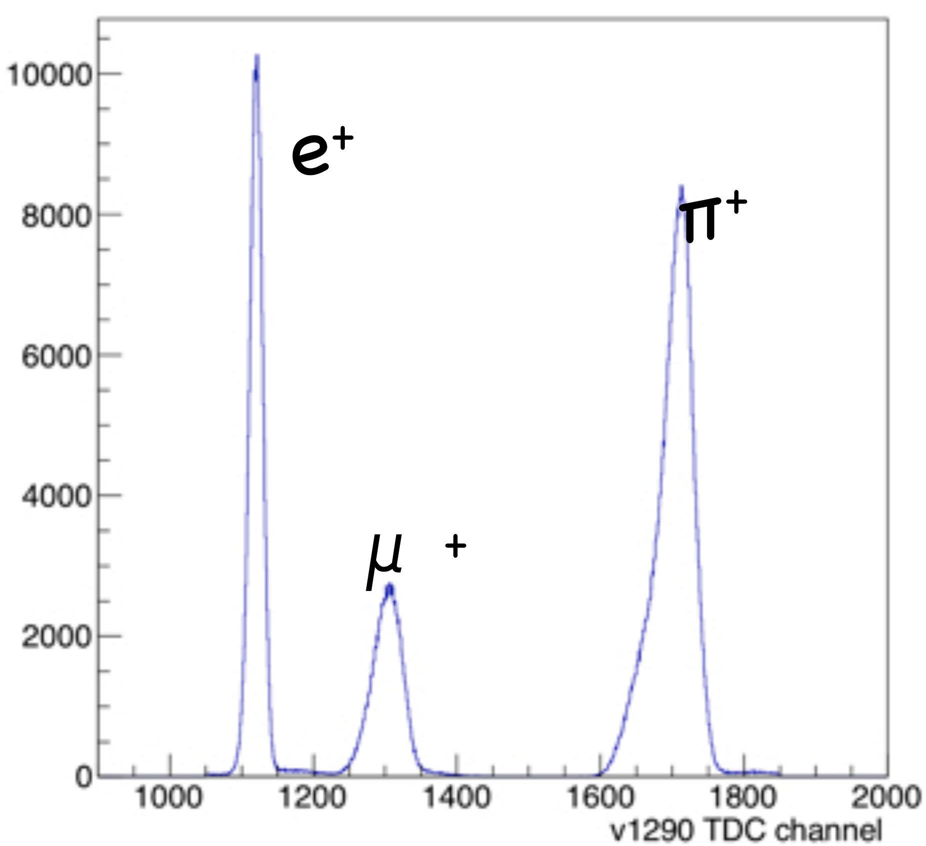


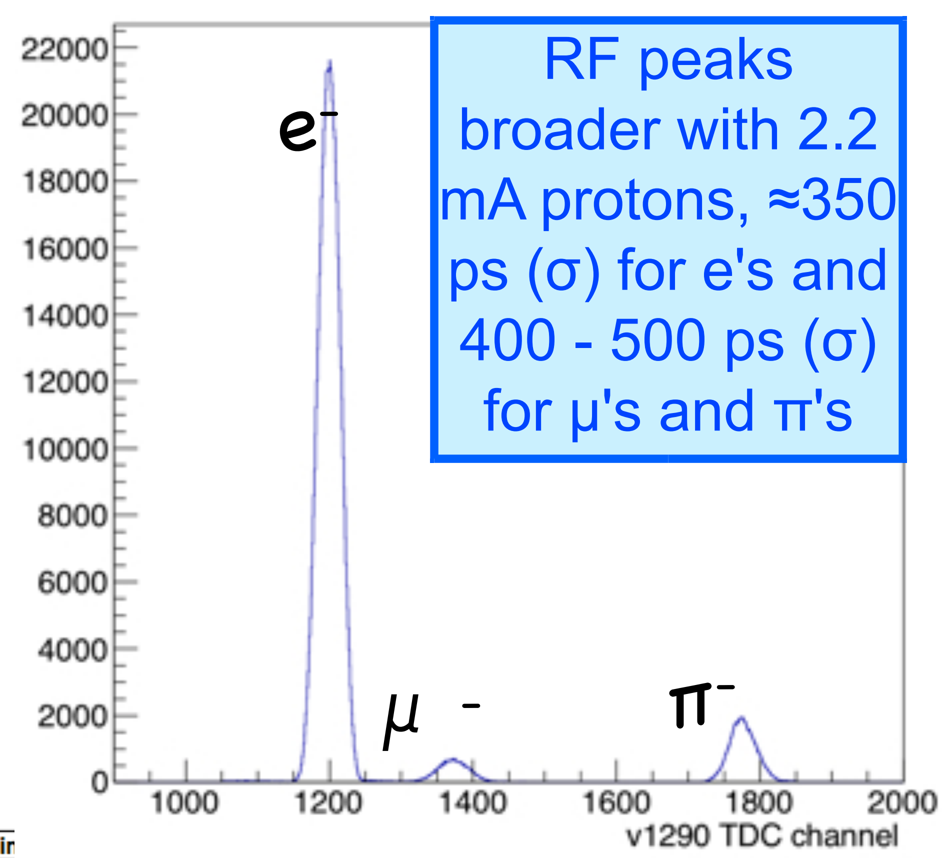
- Determine scattered particle trajectories with high efficiency & resolution
  - Copy of Hall A / Uva Bigbite design
- 98% plane efficiency & 98% tracking efficiency in harsh conditions
  - 3UU'VV'XX' chambers
- Wire position to 35mm, particle position to 100mm
- Calibrated relative to GEMs by rotating chambers into beam

MUSE μp Scattering at PSI

- μp and ep comparison:
- BSM physics could lead to different FF and radii although the effect in scattering experiments could go away once $Q^2 > m^2_{new}$
- Measure both $\mu^{\pm}p$ and $e^{\pm}p$ for 2γ exchange
- Proton polarisability effect enhances 2γ exchange
- MUSE is in the low Q^2 region, 0.002 - 0.07 GeV^2, (similar to Mainz and JLab experiments) for sensitivity to radius
- A variety of 2nd generation experiments (lower Q^2, $\mu^{\pm}n$, higher Q^2, PV, "heavy" nuclei ...) are already being considered.

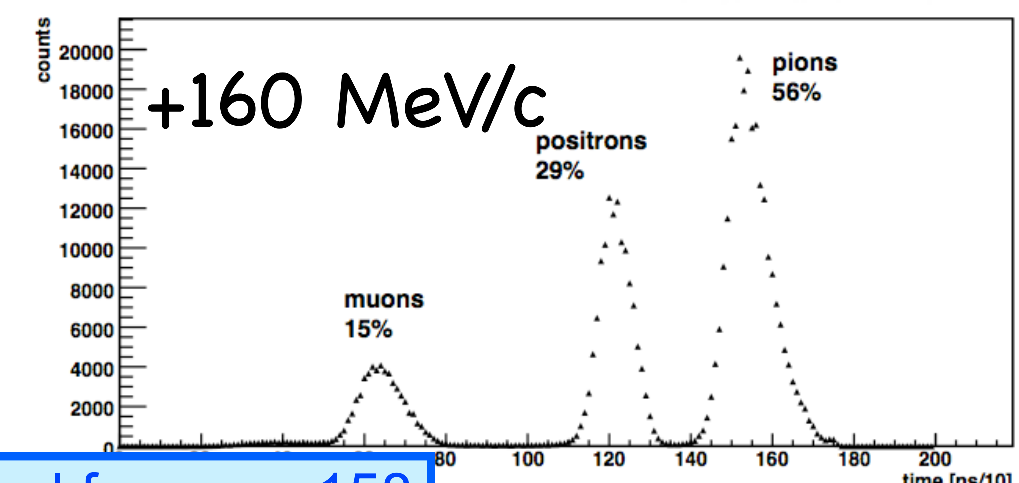
πM1 Channel - RF time in target region





RF peaks broader with 2.2 mA protons, ≈350 ps (σ) for e's and 400 - 500 ps (σ) for μ's and π's

Obtained RF time spectra for several momenta from ≈110 to 225 MeV/c, and used these to determine relative particle fluxes



Old spectra, for comparison - 160 reversed from our 158

πM1 Channel – Particle Fluxes

- Limiting flux to 5 MHz total, by cutting the 3% momentum bite
  - Flux of electrons 1.4 – 35 times larger than flux of muons

P (MeV/c)	p (MHz)	m (MHz)	e (MHz)	Momentum bite (%)
+115	0.43	0.43	4.0	1.8
+153	2.10	0.59	2.3	0.9
+210	4.1	0.39	0.54	0.2
-115	0.01	0.14	4.9	2.0
-153	0.55	0.17	4.3	1.3
-210	2.23	0.77	2.0	0.6

Beam Line Summary

- Good flux of μ's at target, much better flux of e's
  - Beam spot smaller than nominal (σ)
- Beam properties independent of particle type
  - Protons not an issue at our momenta
- Particles can be separated by ≈ns level RF timing at ≈115, 153, 210 MeV/c for our geometry
- Beam emittance requires event by event tracking into target with GEMs
- Time width of particles appears to be 500 ps (σ), except electrons appear to be ≈350 ps ⇨ necessitates high timing precision beam Cerenkov for rejection of μ decays

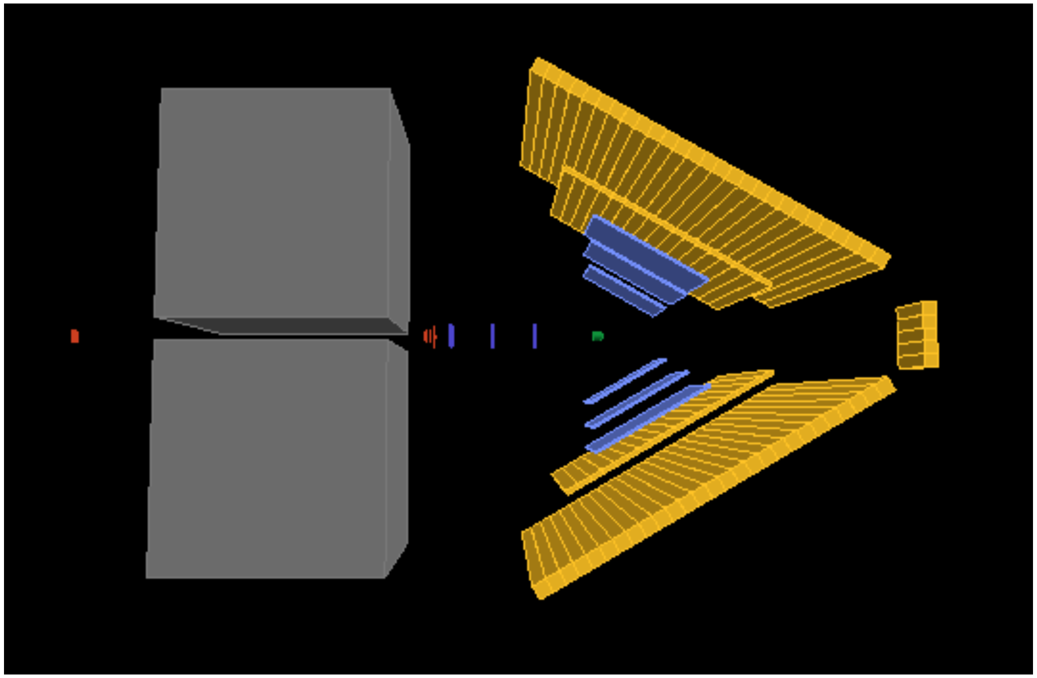
Next Few Years for MUSE

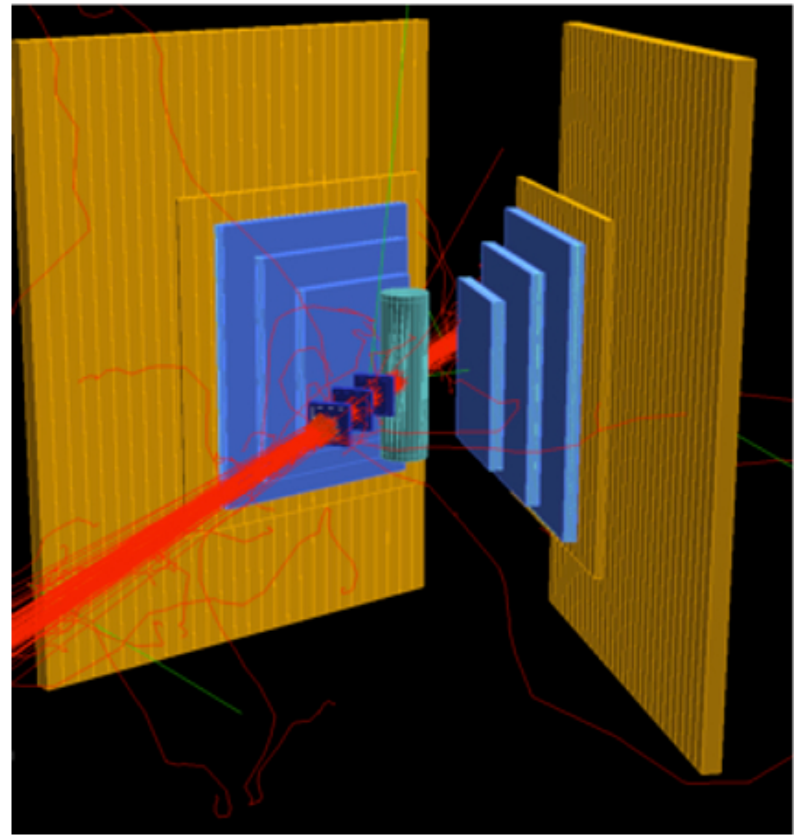
Feb 2012	First PAC presentation
July 2012	PAC / PSI Technical review
Fall 2012	1st test run in pM1 beamline
Jan 2013	PAC approval
Summer 2013	2nd test run in pM1 beamline
Fall 2013	Funding requests
Summer 2014	Money arrives? - start construction
Summer 2015	Start assembling equipment at PSI
Late 2015	Set up and have dress rehersal
2016 - 2017	2 6-month experiment production runs

Second Test Run

- Redo beam tests with GEMs
- "Quartz" Cerenkov test
- Mini-scattering experiment

Reference Design





- Beam: IFP SciFi → shielding wall → target SciFi → Cerenkov → GEM → target → beam monitor scintillators
  - Wire chanbers & scintillator walls for scattered particles
    - Standard technology
- Geant4 estimates, target collimator bg. v. sensitive to beam distributions
  - Custom FPGA trigger to record scattering events and reject π

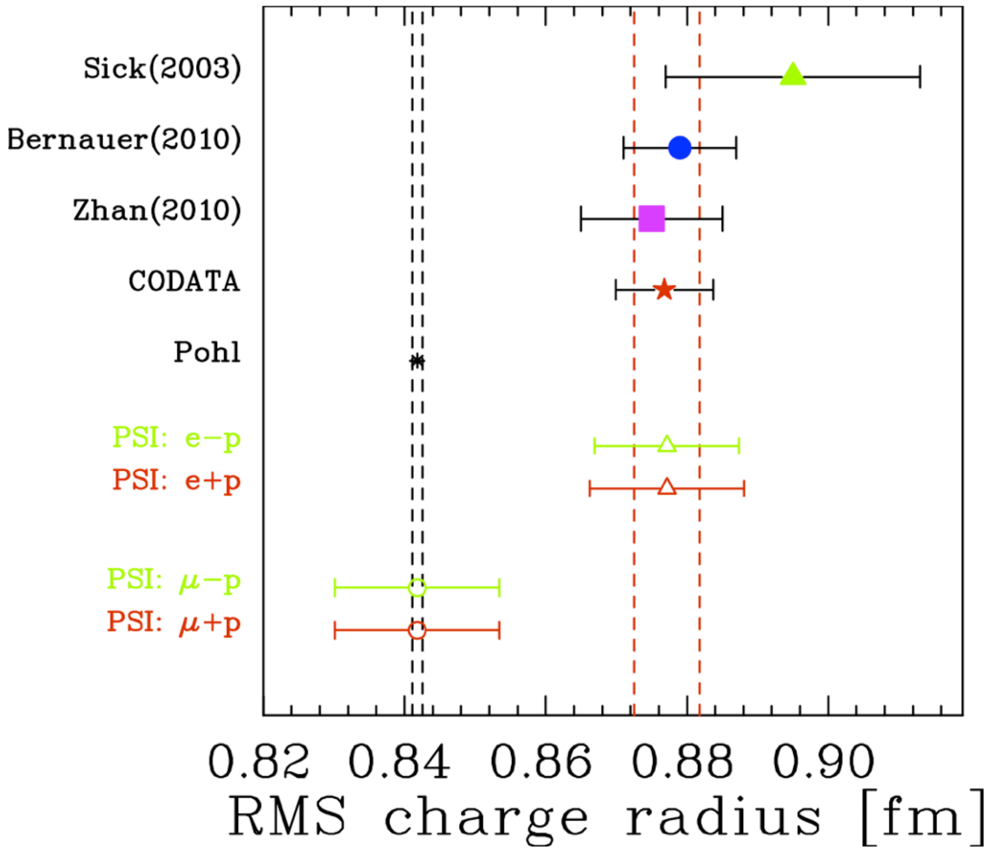
New Equipment Summary

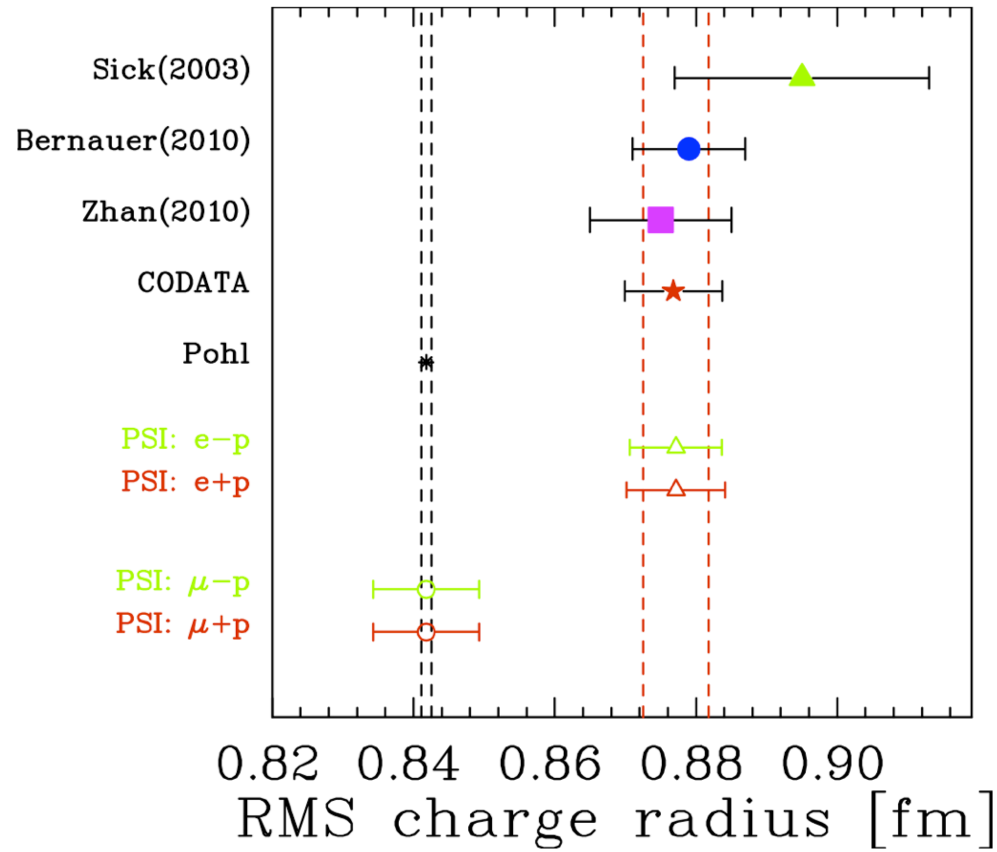
Detector	Who	Technology
Beam SciFi	Tel Aviv, St. Marys	conventional
GEMs	Hampton	detector exists
Quartz Cerenkov	Hebrew	prototyped
FPGAs	Rutgers	conventional
Target	Hebrew	conventional
Wire Chambers	MIT	Copy existing system
Scintillators	SC	Copy existing system
DAQ	GWU	Conventional, except TRB3 prototyped

For more information see proposal and TDR on website:

http://www.physics.rutgers.edu/∾rgilman/elasticmup

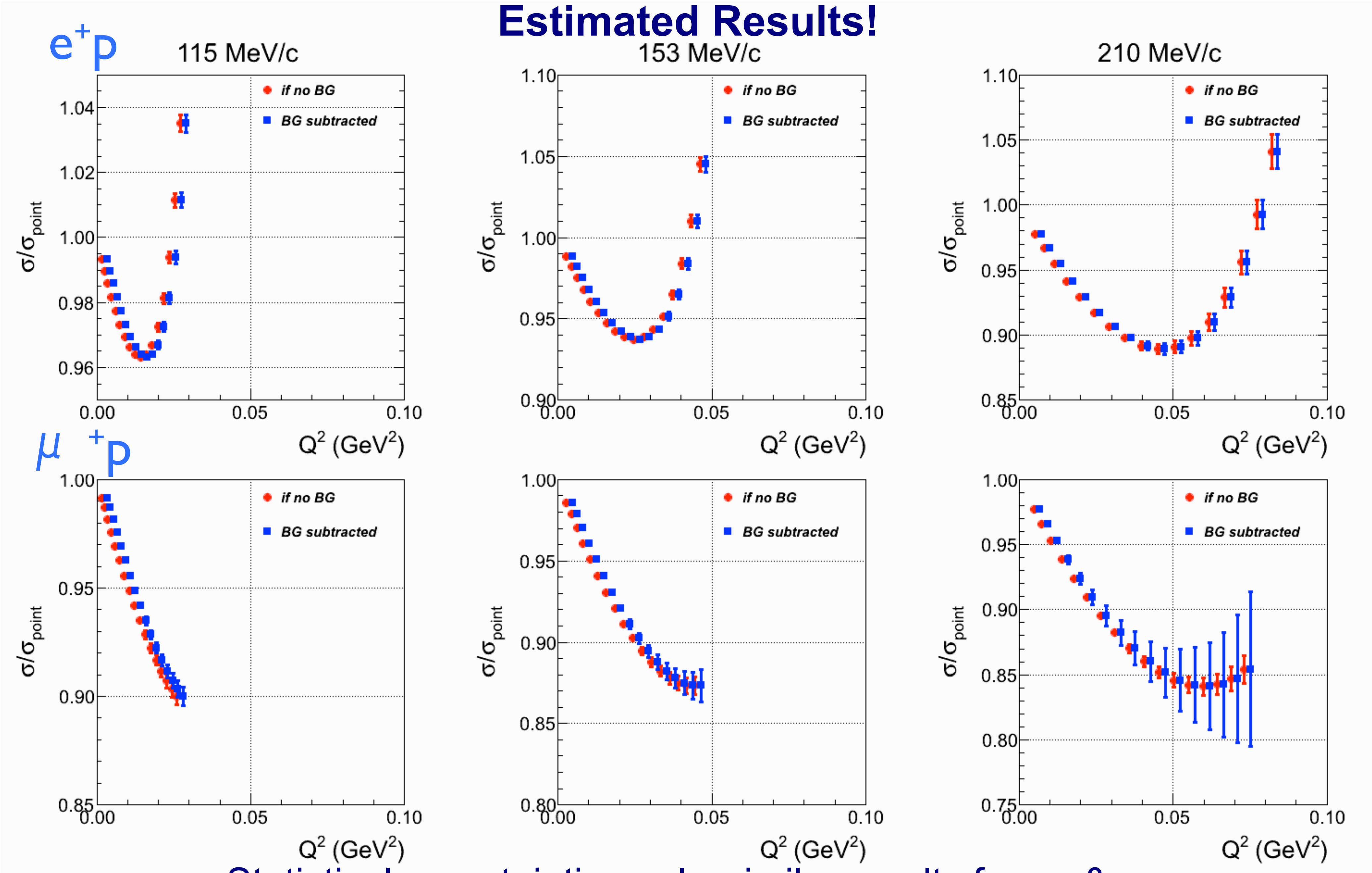
Physics





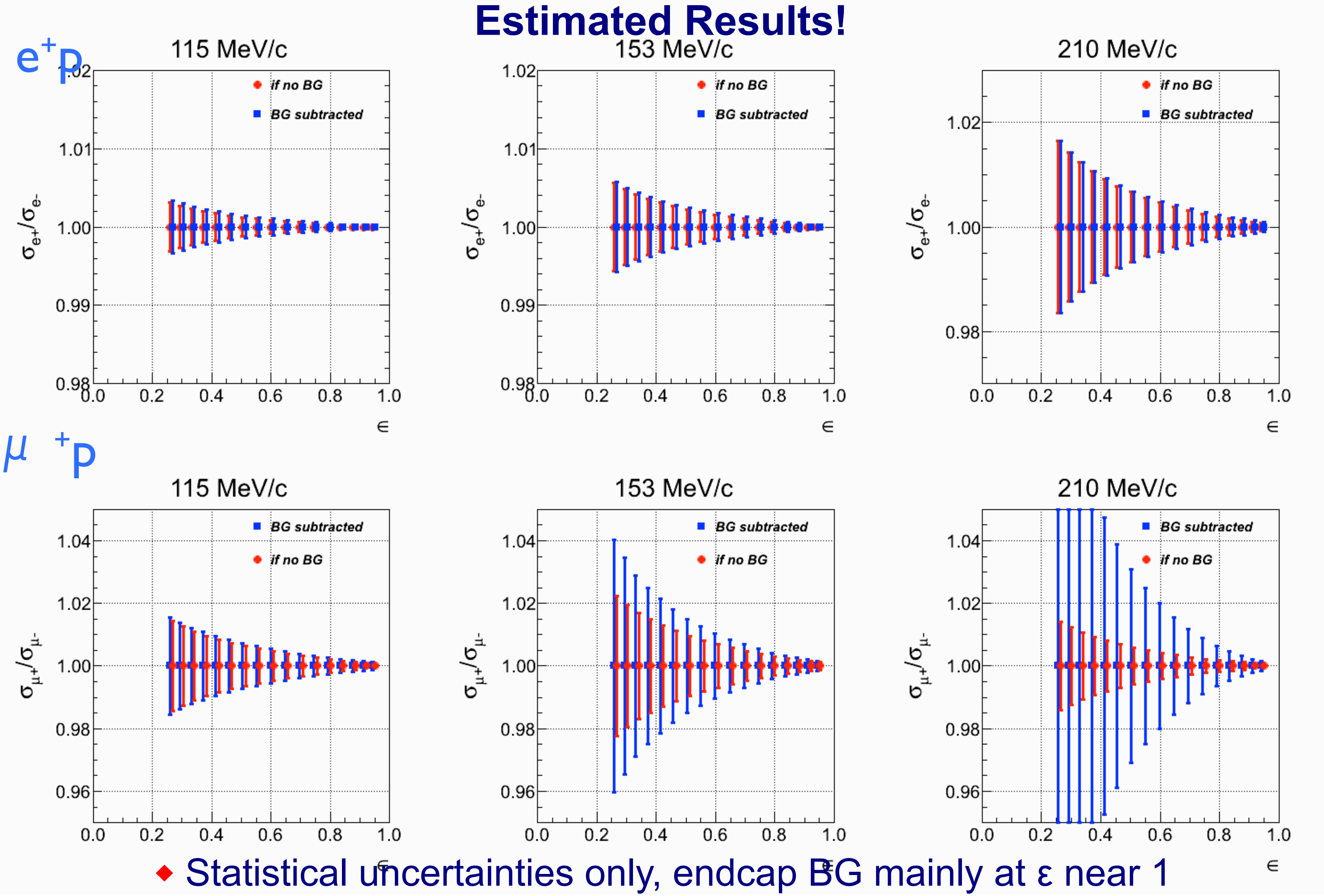
- Radius extraction from John Arrington
- Left: independent absolute extraction
- Right: extraction with only relative uncertainties

Estimated Results!



- Statistical uncertainties only, similar results for ep & mp
- 6 month run, equal time for each setting, $\theta_{scatter} = 20 – 100°$
- Uncertainities include endcap and m decay subtractions

Estimated Results!



- Statistical uncertainties only, endcap BG mainly at ε near 1
  - μ limited by decay rejection (conservatively estimated)
- $e^{+/-}$ mainly limited by radiative corrections, here 1γ cancels, prob. det. response

Outlook

- **The proton radius puzzle is a high-profile issue**
  - ➔ Explanation unclear
  - ➔ PSI MUSE tests interesting possibilities: Are μp and ep interactions different? If so, does it arise from 2γ exchange effects ($\mu^+ \neq \mu^-$) or BSM physics ($\mu^+ \approx \mu^- \neq e^-$)?
- Within 3-4 years (budgets willing) we should have new electron scattering results and start to see the muon scattering results, and possibly start to resolve the puzzle, perhaps seeing new physics!

MUSE Collaboration

The MUon proton Scattering Experiment collaboration (MUSE):

R. Gilman (Contact person),[1] E.J. Downie (Spokesperson),[2] G. Ron (Spokesperson),[3] A. Afanasev,[2] J. Arrington,[4] O. Ates,[5] F. Benmokhtar,[6] J. Bernauer,[7] E. Brash,[8] W. J. Briscoe,[2] K. Deiters,[9] J. Diefenbach,[5] C. Djalali,[10] B. Dongwi,[5] L. El Fassi,[1] S. Gilad,[7] K. Gnanvo,[11] R. Gothe,[12] K. Hafidi,[4] D. Higinbotham,[13] R. Holt,[4] Y. Ilieva,[12] H. Jiang,[12] M. Kohl,[5] G. Kumbartzki,[1] J. Lichtenstadt,[14] A. Liyanage,[5] N. Liyanage,[11] M. Meziane,[15] Z.-E. Meziani,[16] D. Middleton,[17] P. Monaghan,[5] K. E. Myers,[1] C. Perdrisat,[18] E. Piasetzsky,[14] V. Punjabi,[19] R. Ransome,[1] D. Reggiani,[9] P. Reimer,[4] A. Richter,[20] A. Sarty,[21] E. Schulte,[16] Y. Shamai,[22] N. Sparveris,[16] S. Strauch,[12] V. Sulkosky,[7] A.S. Tadepalli,[1] M. Taragin,[23] and L. Weinstein[24]

For more information see proposal and TDR on website:

http://www.physics.rutgers.edu/∾rgilman/elasticmup

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Thanks

Systematics

- We are mainly concerned with relative systematic uncertainties as we plan to normalize data. Renormalization consistent with estimated absolute systematic uncertainties adds confidence to the relative systematic uncertainty estimates and to the results.

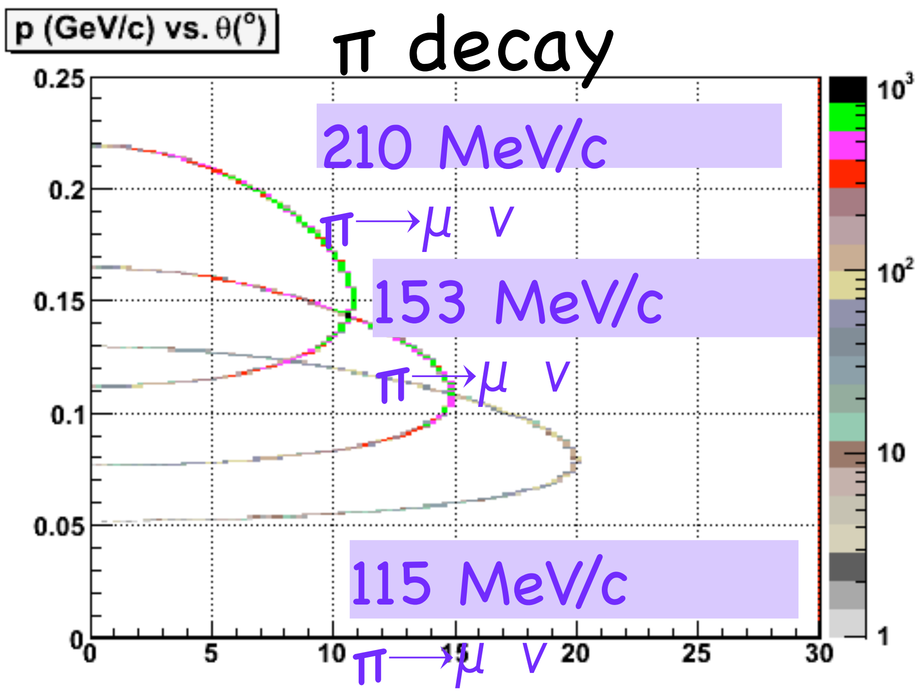
- For relative systematics, used when the data are normalized to the $Q^2 = 0$ point, most effects are at the 0.1% level: detector efficiencies, solid angle, ...

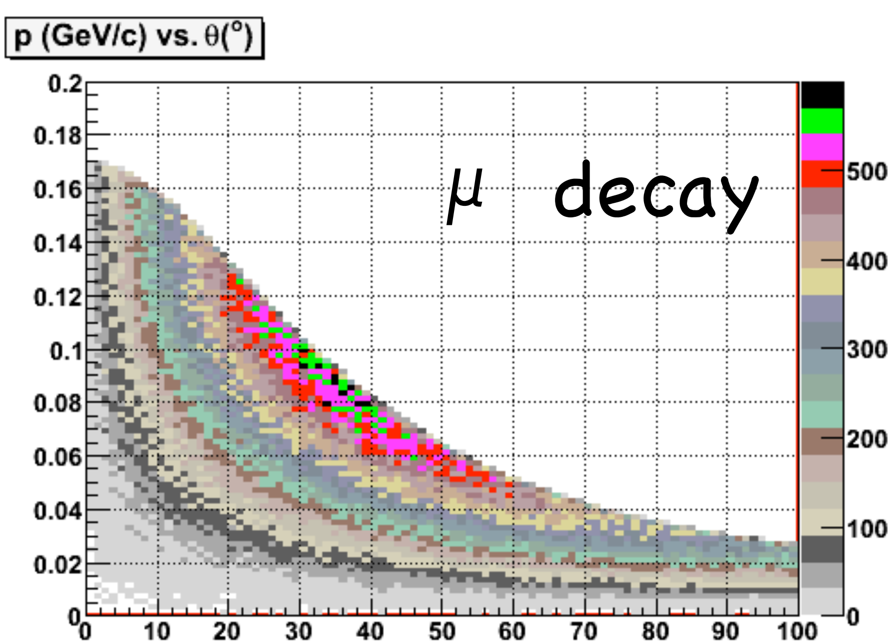
- The larger systematics are ≈0.3% for angle determination, and multiple scattering (shown earlier), and 0.5% for radiative corrections.

For more information see proposal and TDR on website:

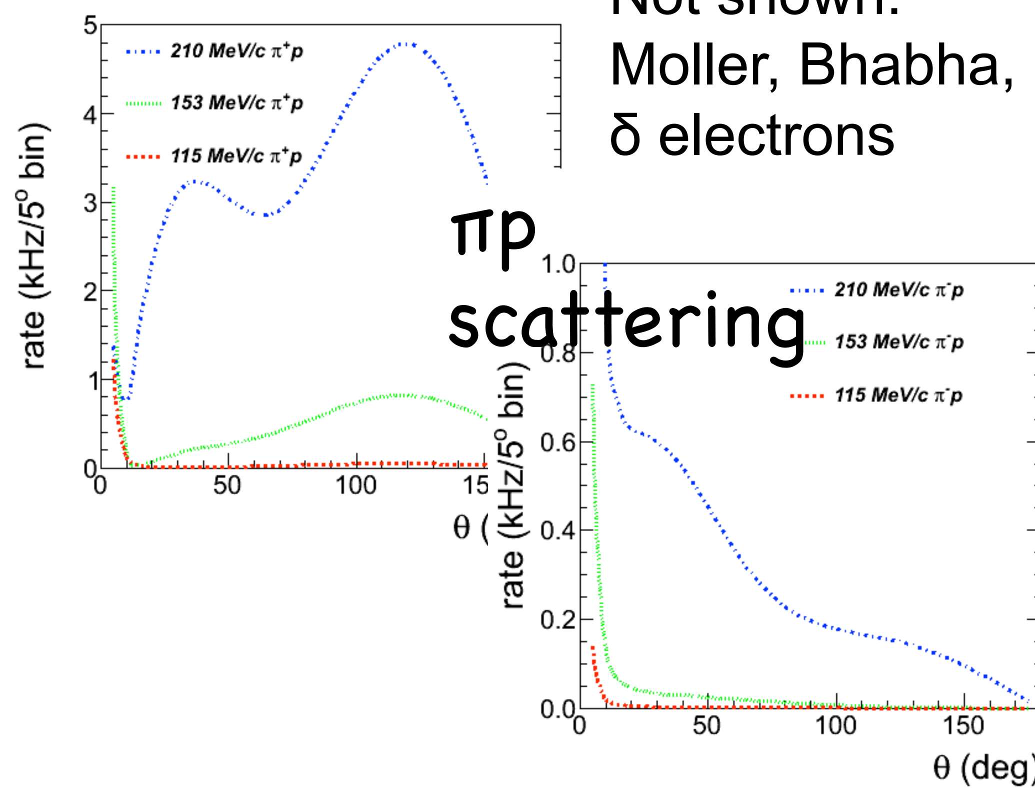
http://www.physics.rutgers.edu/∾rgilman/elasticmup

Backgrounds



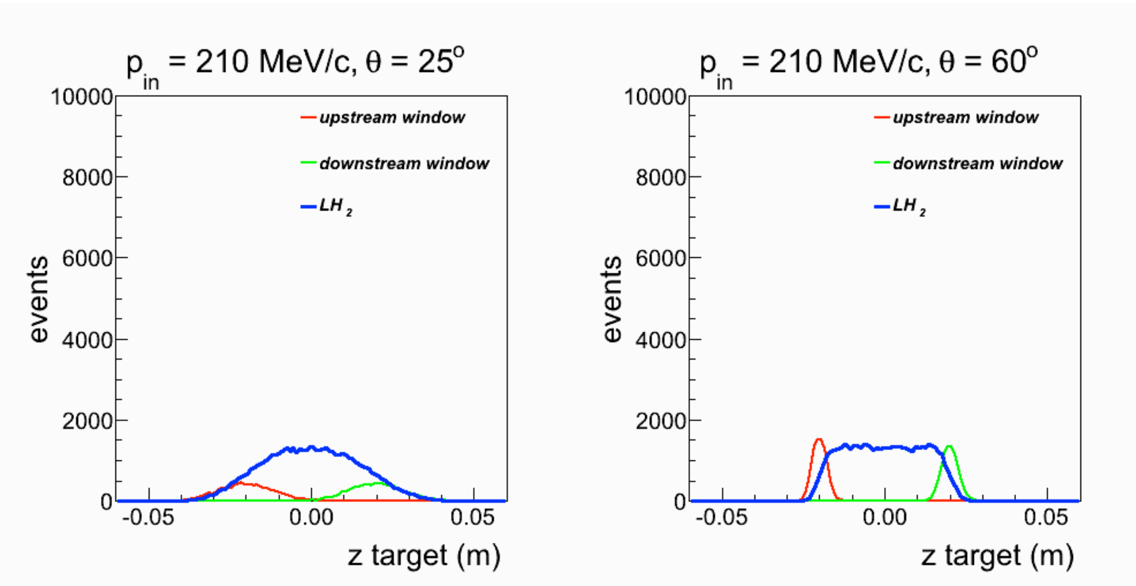


Used Geant4 to simulate many backgrounds. Most lead to rates in detectors but not many triggers, and can be rejected in analysis. The main issues are μ decays and end cap scattering, which cannot be removed at the trigger level.



Not shown:
Moller, Bhabha, &
δ electrons

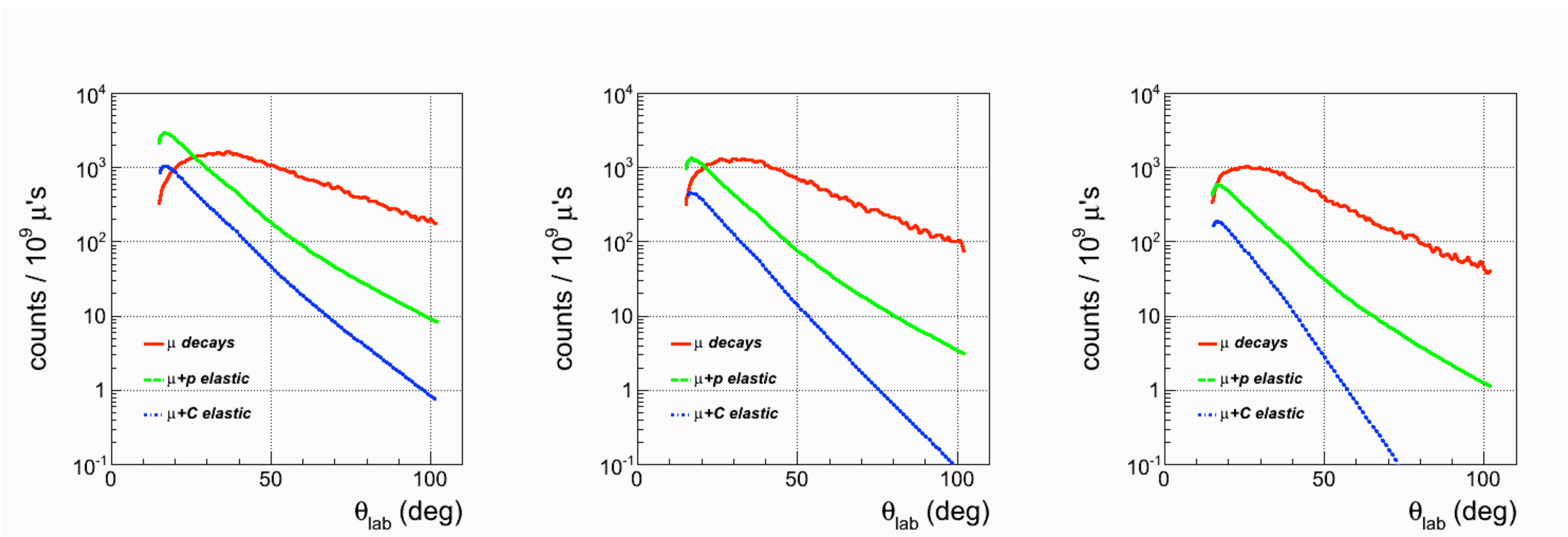
Backgrounds II



The main issues are μ decays and end cap scattering, which cannot be removed at the trigger level.

End cap scattering can only be removed by subtractions. (Might be able to reduce orders of magnitude with graphene windows.)

Estimated relative rates below.



Backgrounds III

The main issues are μ decays and end cap scattering, which cannot be removed at the trigger level.

Muon decays are largely removed by TOF from quartz Cerenkov to scintillators - 100% / 96% / 34% removed at 115 / 153 / 210 MeV/c