The frontiers of the virtual photon program @ MAMI

Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

MESON 2012

CRC1044

JG|U

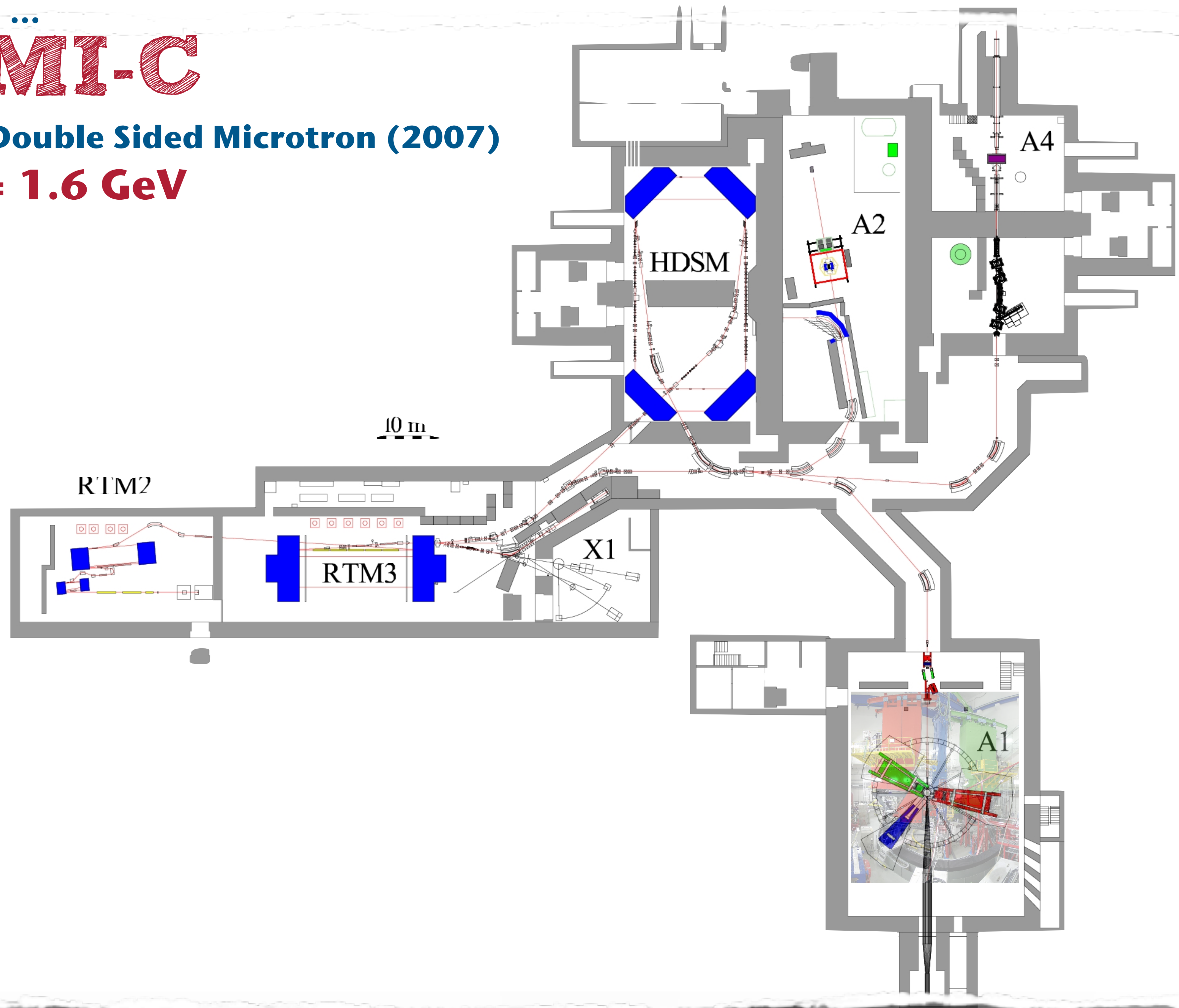
The MAMI/A1 Legacy

Upgrade to …

MAMI-C

Harmonic Double Sided Microtron (2007)

up to E = 1.6 GeV



HIGH

Intensity
up to 100 μA

Resolution
σ_E < 0.100 MeV

Polarization
up to 80% @ 40μA

Reliability
85% (7000 h/y)

The MAMI/A1 Legacy

Spectrometer A:

$$\begin{aligned} \alpha &> 20^\circ \\ p &< 735\,\frac{\mathrm{MeV}}{c} \\ \Delta\Omega &= 28\,\mathrm{msr} \\ \Delta p/p &= 20\% \end{aligned}$$

A1

Spectrometer B:

$$\begin{aligned} \alpha &> 8^\circ \\ p &< 870\,\frac{\mathrm{MeV}}{c} \\ \Delta\Omega &= 5.6\,\mathrm{msr} \\ \Delta p/p &= 15\% \end{aligned}$$

Spectrometer C:

$$\begin{aligned} \alpha &> 55^\circ \\ p &< 655\,\frac{\mathrm{MeV}}{c} \\ \Delta\Omega &= 28\,\mathrm{msr} \\ \Delta p/p &= 25\% \end{aligned}$$

$\Delta p/p < 10^{-4}$ FWHM

Coincidence and polarization meas.

KAOS Spectrometer

Hadron Physics at Low Energies

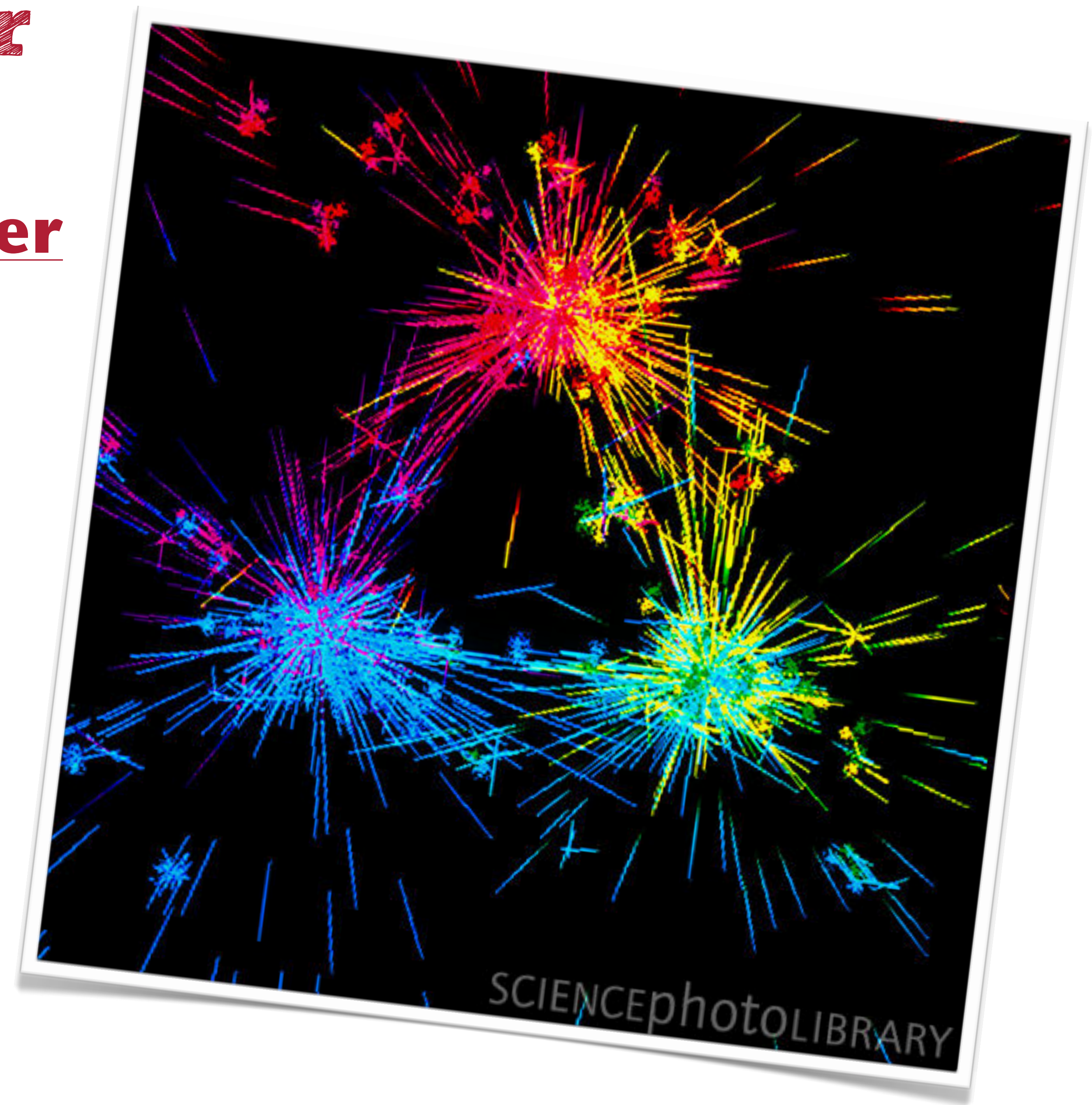
Effective laboratory for non-perturbative QCD

Fundamental Structure of Matter

Charge and magnetism distributions
Spin distribution
Quark momentum and flavour distribution
Polarizabilities
Strangeness Content

Theoretical Tools:

pQDC, OPE, Lattice QCD, ChPT



The Beauty of the Electromagnetic Probe

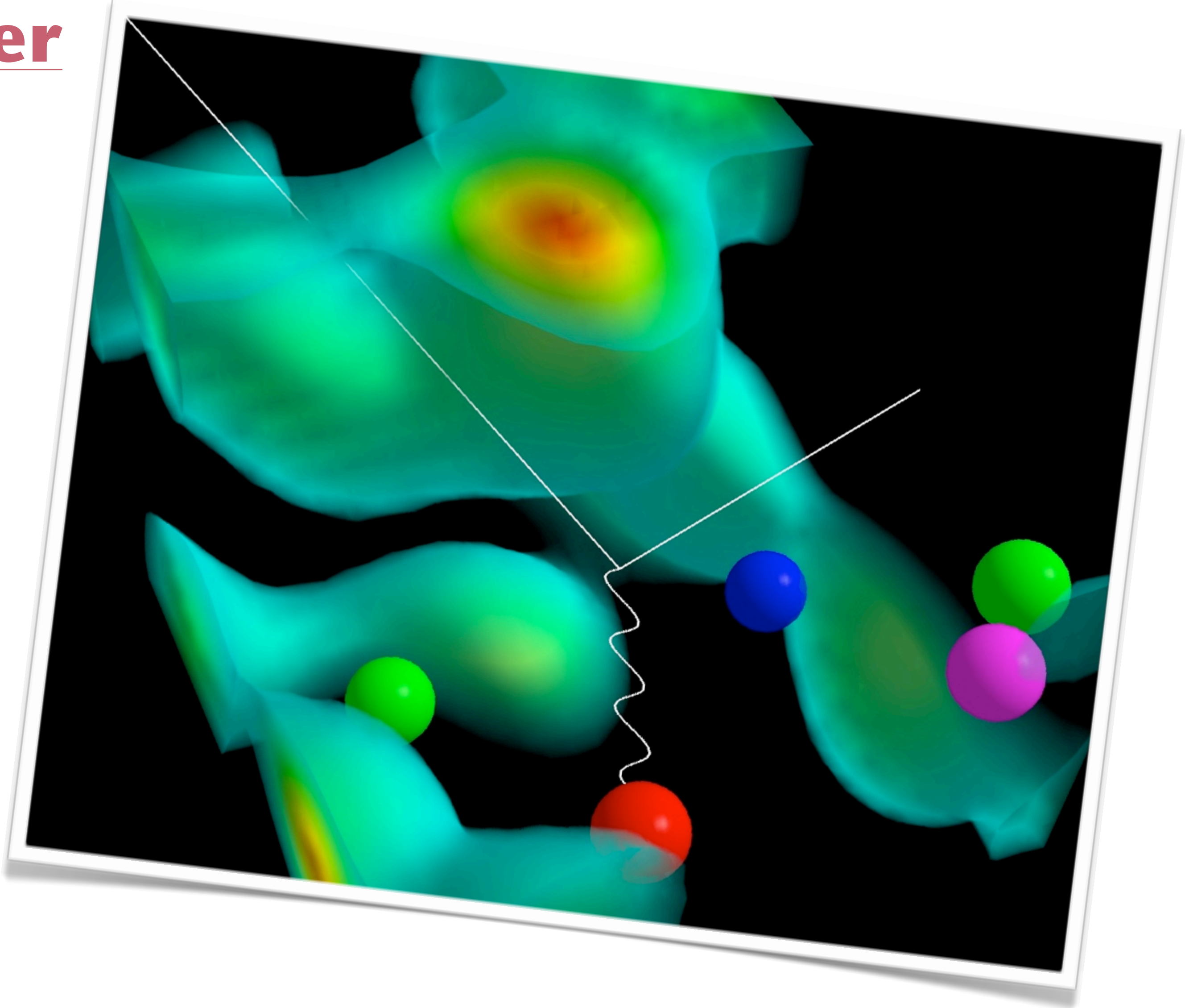
Effective laboratory for non-perturbative QCD

Fundamental Structure of Matter

Charge and magnetism distributions
Spin distribution
Quark momentum and flavour distribution
Polarizabilities
Strangeness Content

Theoretical Tools:

pQDC, OPE, Lattice QCD, ChPT



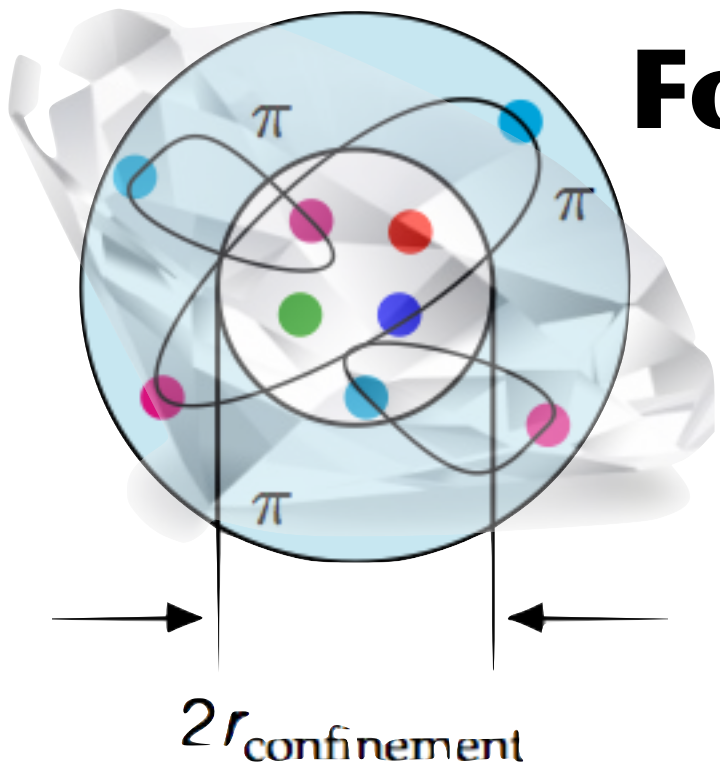
Clean probe of hadron structure

- Electron-vertex well-known from QED
- One-photon exchange dominates
- Higher-order exchange diagrams are suppressed
- Vary the wavelength of the probe to view deeper inside the hadron

"Diamonds are *for ever* ...

“ Diamonds are *for ever*…

Form Factors are *ethernal*”



What can we learn?

Low-Q ⇔ Long range structure

How big is the proton?

Is there evidence for a pion cloud?

Form factors from elastic ep scattering

Form Factors from Elastic ep scattering

Cross section for one photon exchange

(Rosenbluth-cross section + Separation at constant Q^2)

charge distribution

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \frac{1}{(1+\tau)} \left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2) \right]$$

distribution of magnetic moments

$$\text{with } \tau = \frac{Q^2}{4m_P^2} \text{ and } \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2} \right]^{-1}$$

... and the slope of G_E

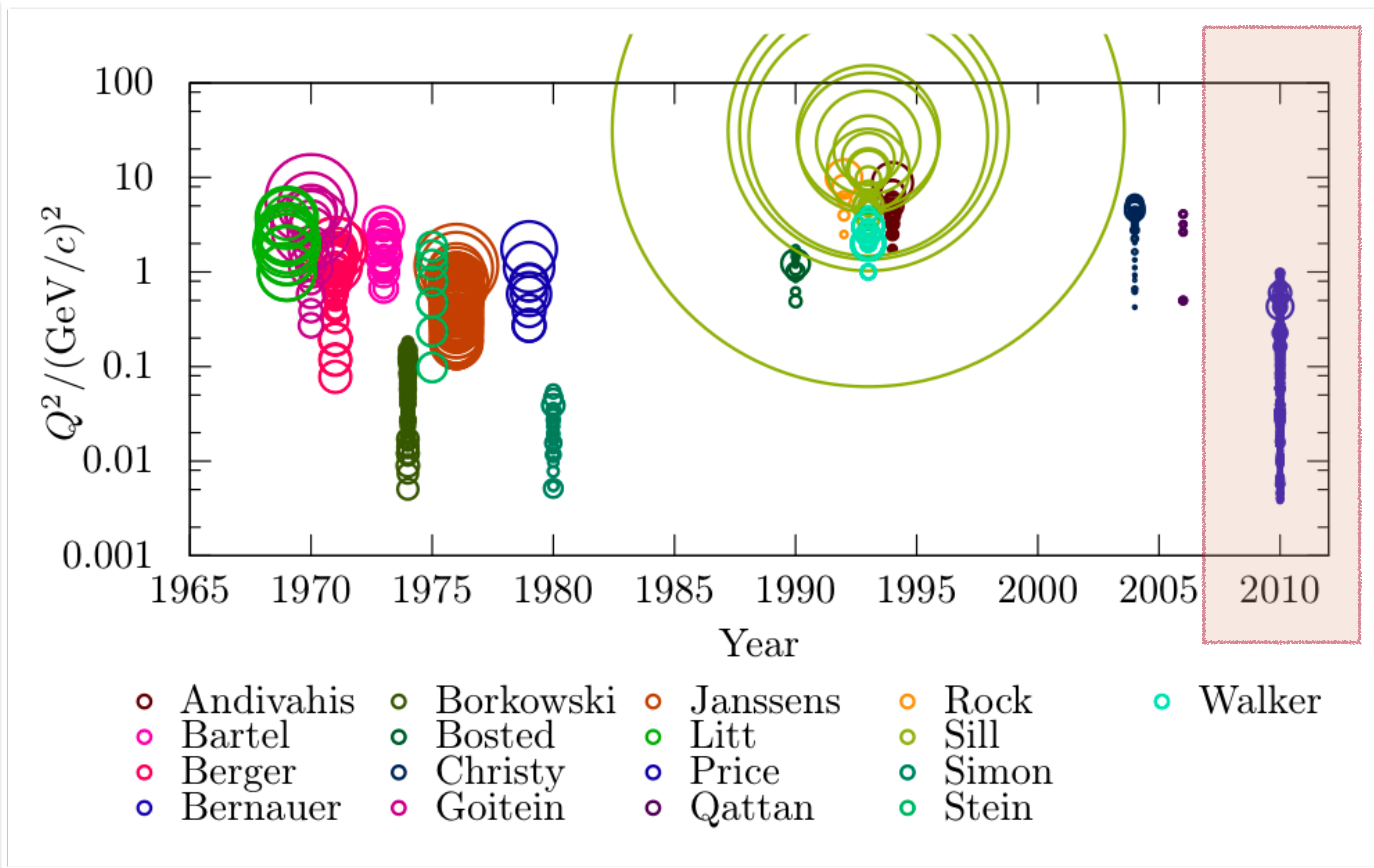
$$\langle r_E^2 \rangle = -6\hbar^2 \frac{d}{dQ^2} G_E(Q^2) \Big|_{Q^2=0}$$

✔ **Separated $G_E(Q^2)$ and $G_M(Q^2)$**

✖ **but contribution from two photon exchange (TPE)**

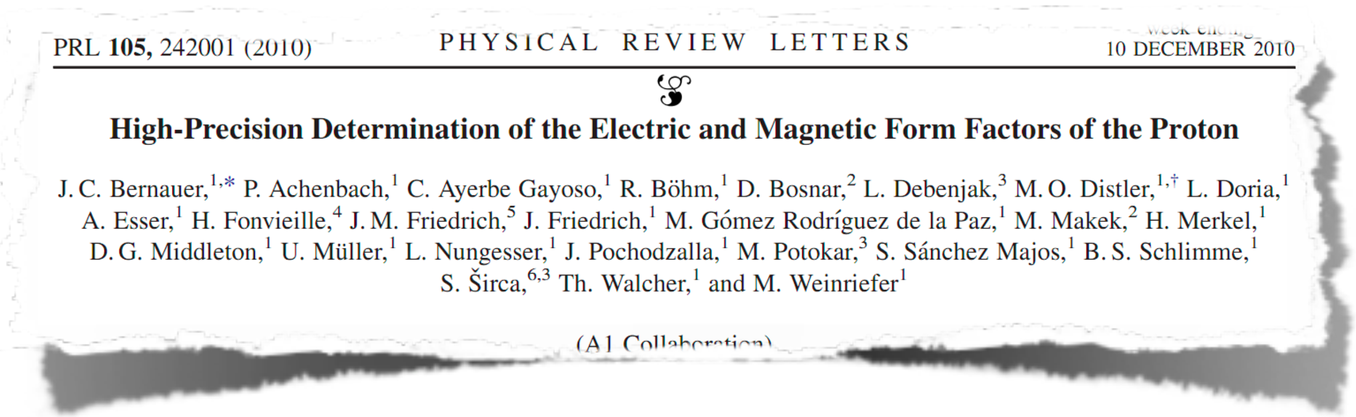
Form Factors from Elastic ep scattering

... as always in physics: What accuracy can be reached???



The latest MAMI measurement

The experiment designed for …
high precision by redundancy


PRL **105,** 242001 (2010) PHYSICAL REVIEW LETTERS 10 DECEMBER 2010

High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]

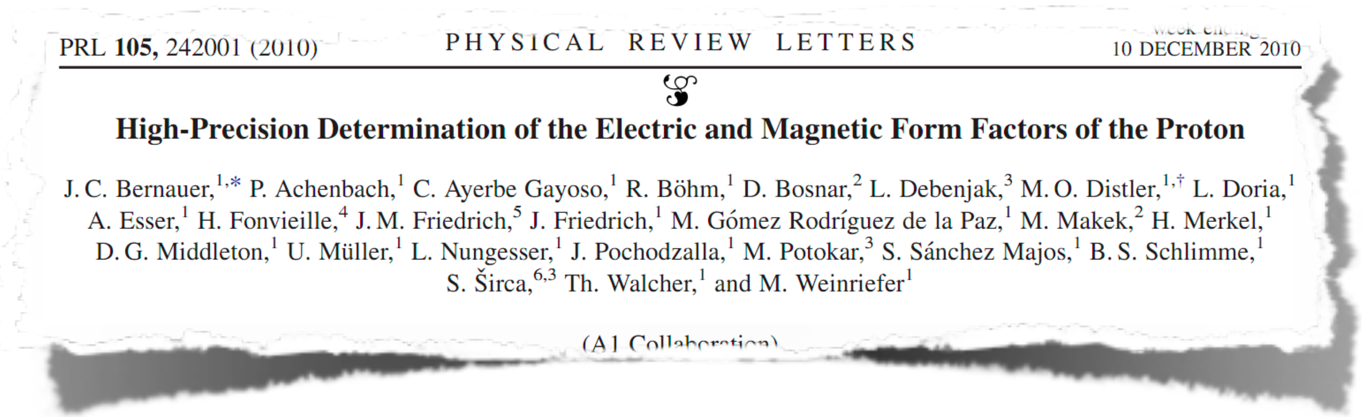
(A1 Collaboration)

- Statistical precision $\sigma < 0.1\%$
- $\delta\theta < 0.5$ mrad vertical and horizontal
- Control of luminosity and systematic errors

➛ All quantities measured by more than one method

Rosenbluth with a twist

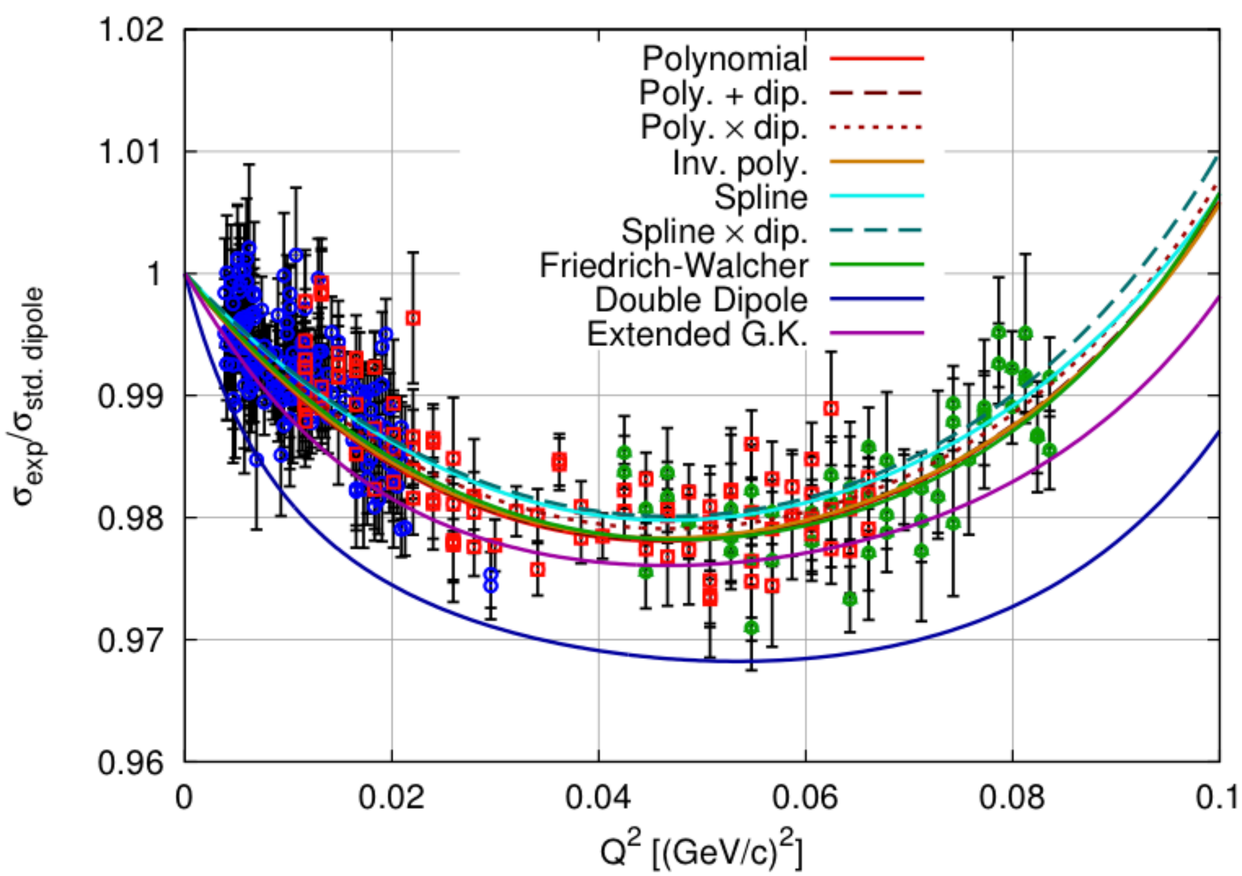
“Super-Rosenbluth Separation”: fit of form factor models **DIRECTLY to cross sections**

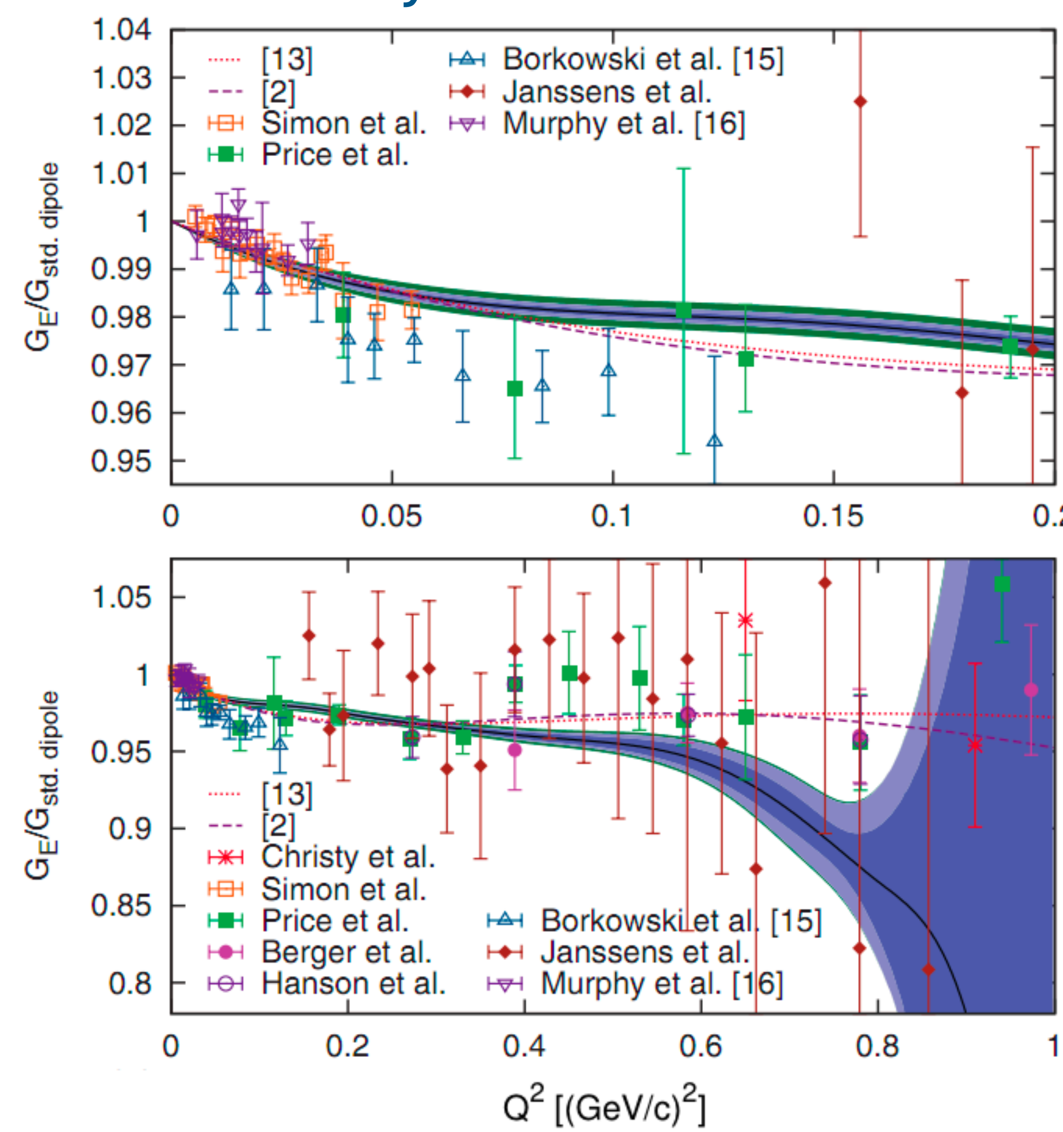

PRL **105**, 242001 (2010) PHYSICAL REVIEW LETTERS 10 DECEMBER 2010

High-Precision Determination of the Electric and Magnetic Form Factors of the Proton

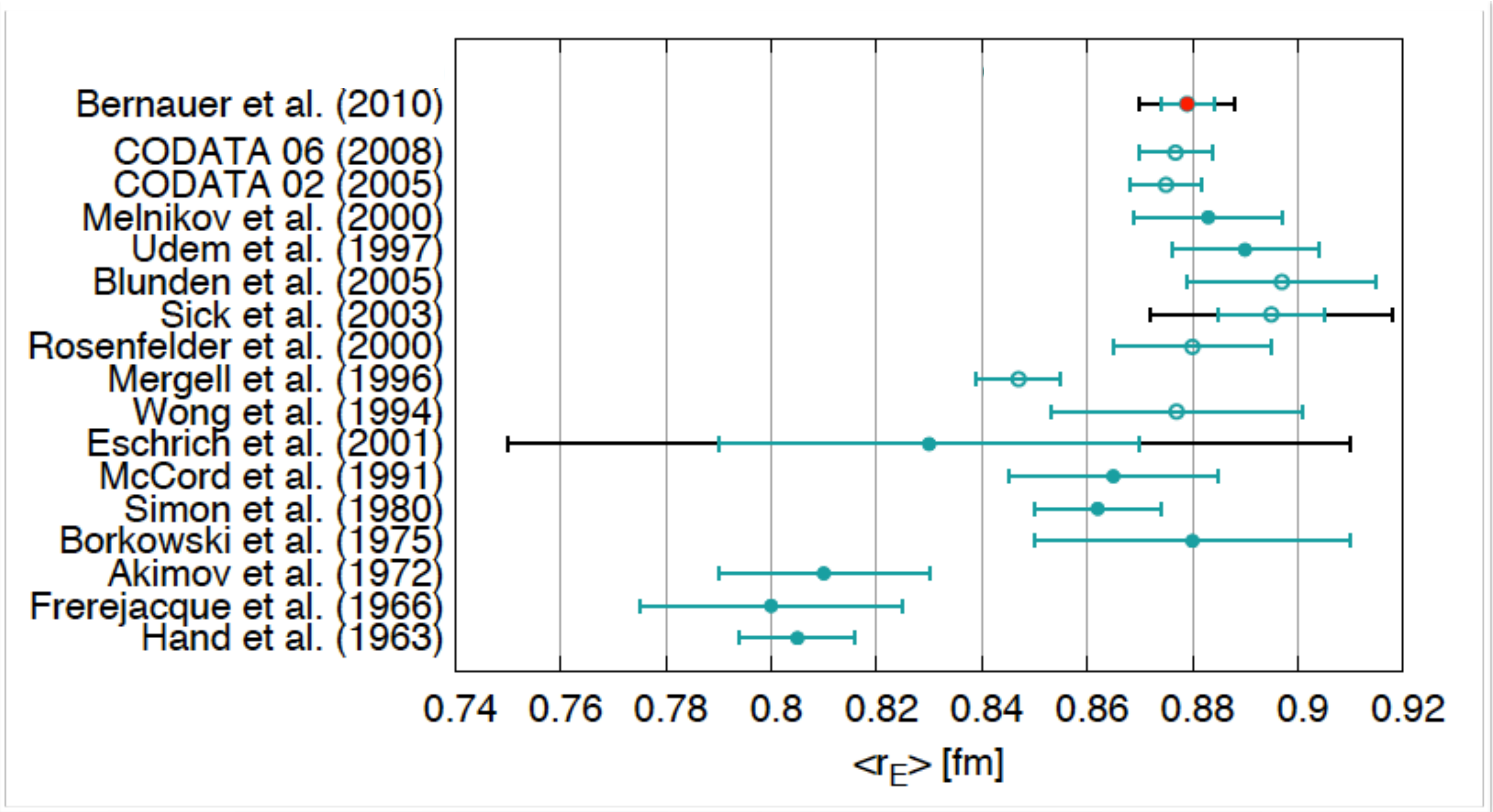
J. C. Bernauer,[1,*] P. Achenbach,[1] C. Ayerbe Gayoso,[1] R. Böhm,[1] D. Bosnar,[2] L. Debenjak,[3] M. O. Distler,[1,†] L. Doria,[1] A. Esser,[1] H. Fonvieille,[4] J. M. Friedrich,[5] J. Friedrich,[1] M. Gómez Rodríguez de la Paz,[1] M. Makek,[2] H. Merkel,[1] D. G. Middleton,[1] U. Müller,[1] L. Nungesser,[1] J. Pochodzalla,[1] M. Potokar,[3] S. Sánchez Majos,[1] B. S. Schlimme,[1] S. Širca,[6,3] Th. Walcher,[1] and M. Weinriefer[1]

- All Q^2 and ε data are used in one fit
- No projection to constant Q^2
  - ➛ no limit of kinematics
- One “estimator”
  - ➛ stat. theory “robust estimator”



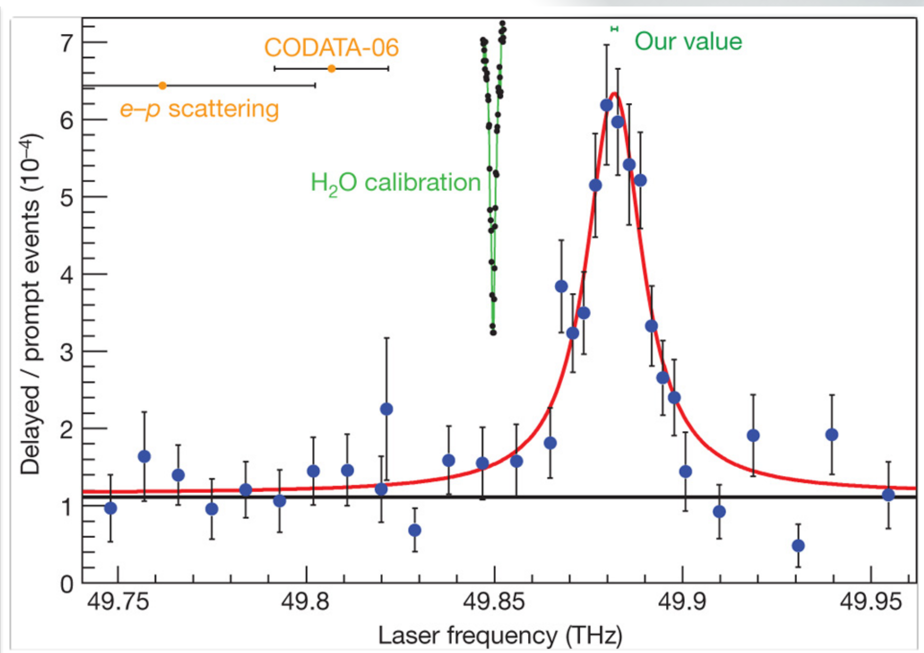


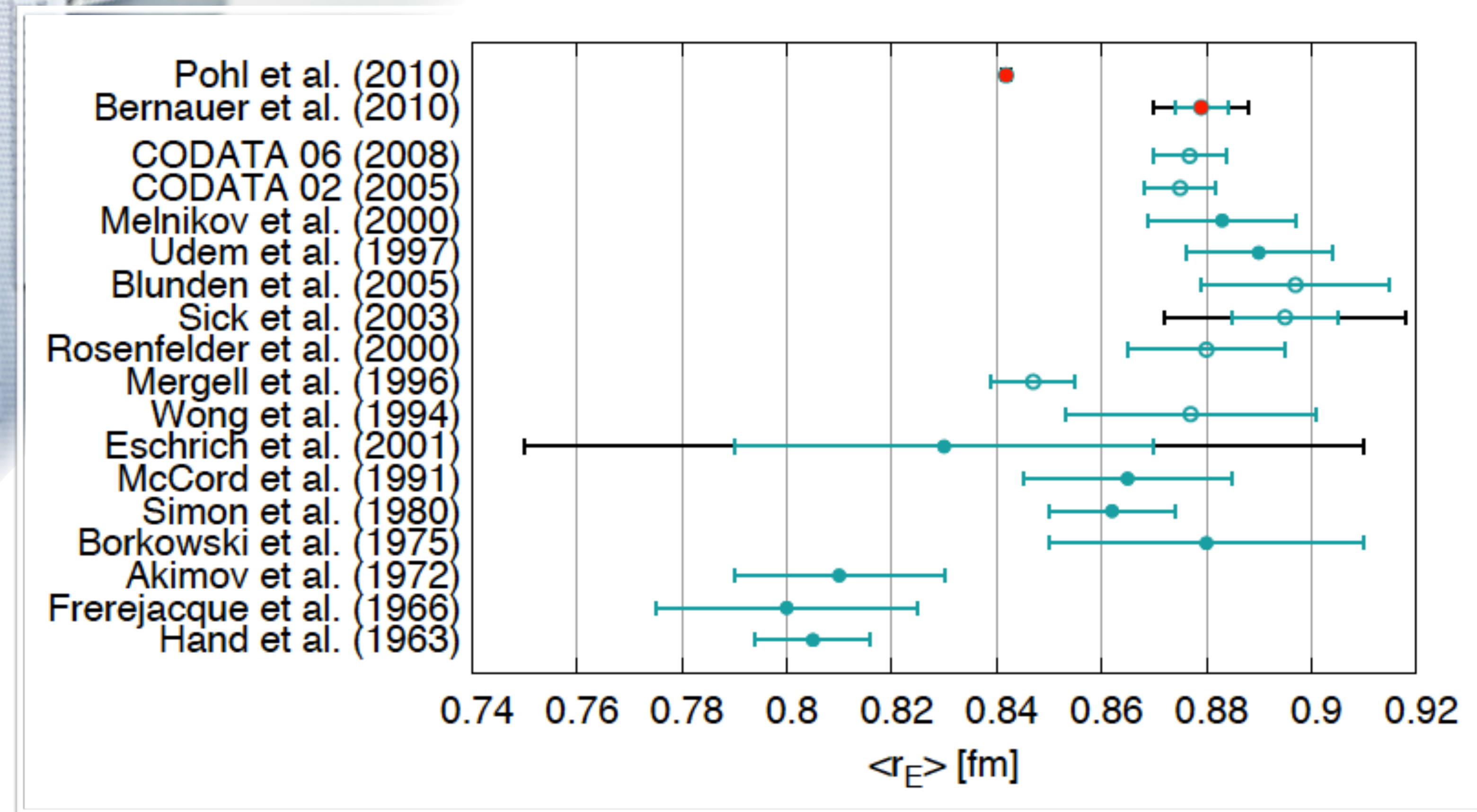
The Radius Puzzle



The Radius Puzzle

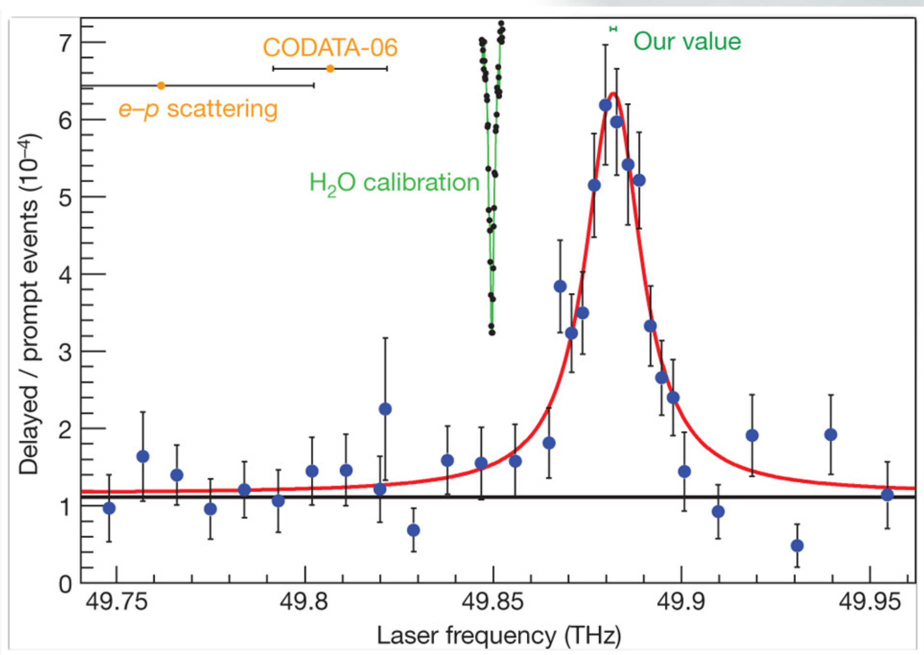
R. Pohl et al., Nature 466, (2010) 213

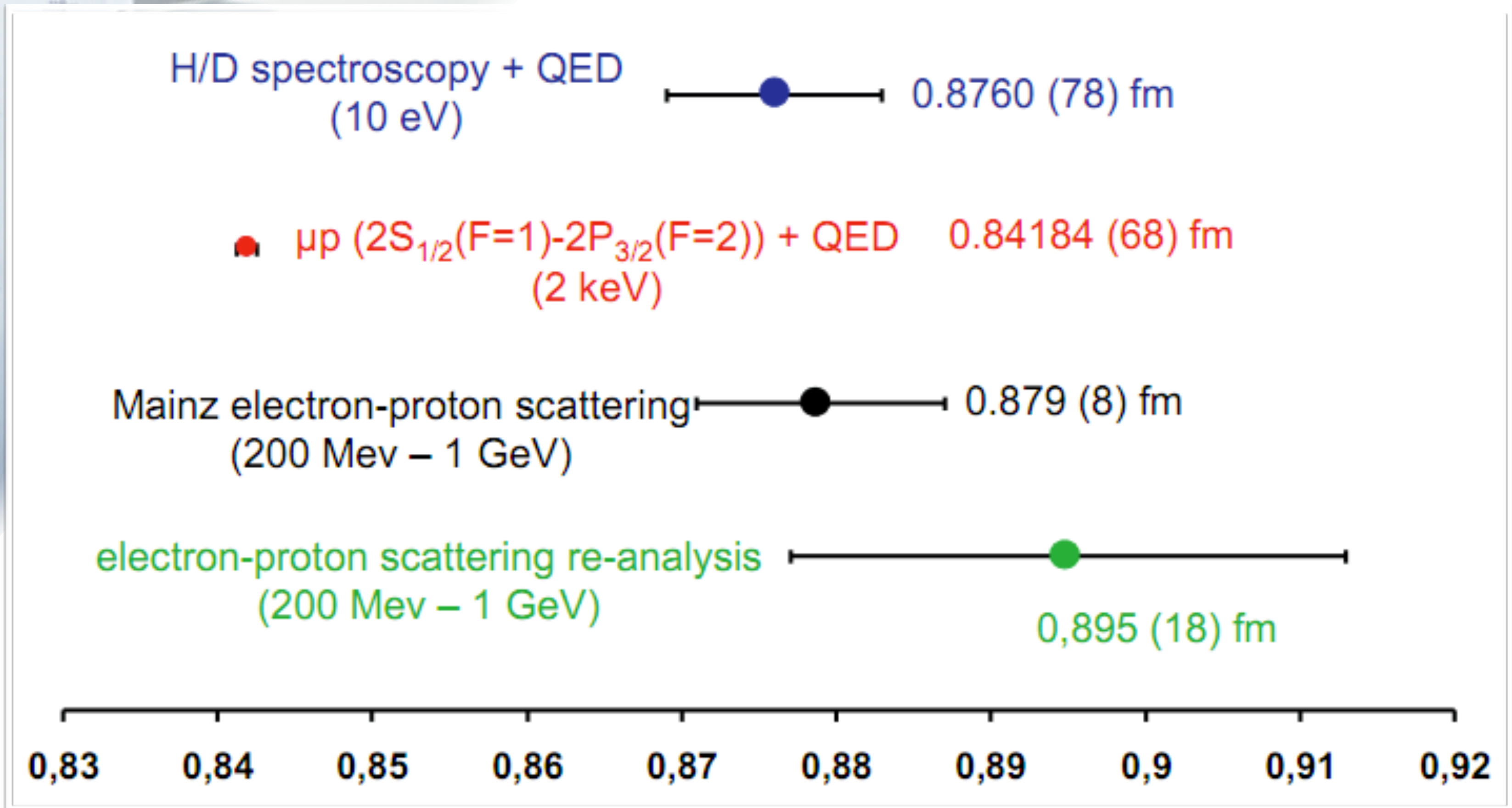




The Radius Puzzle

R. Pohl et al., Nature 466, (2010) 213

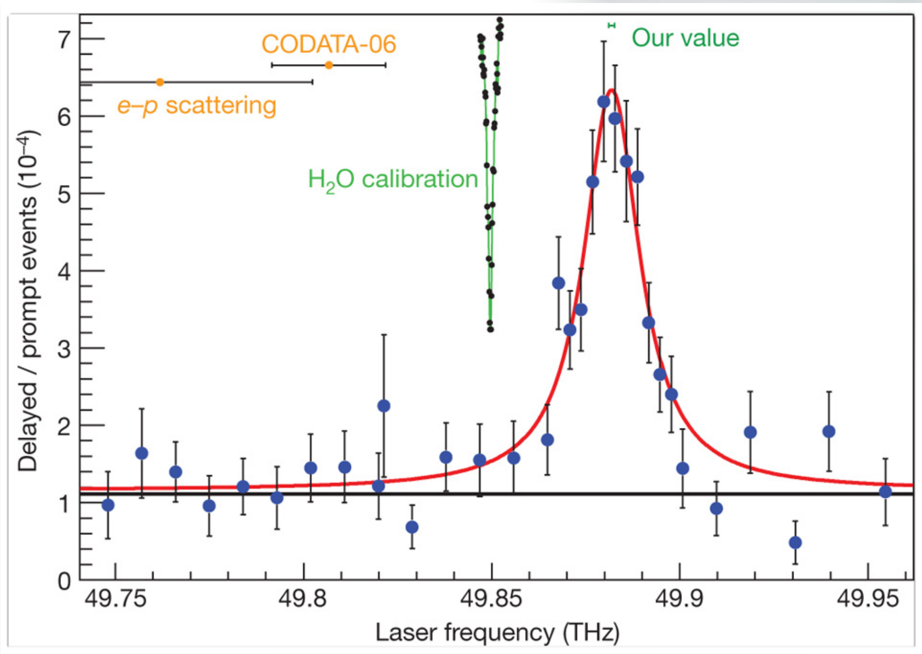


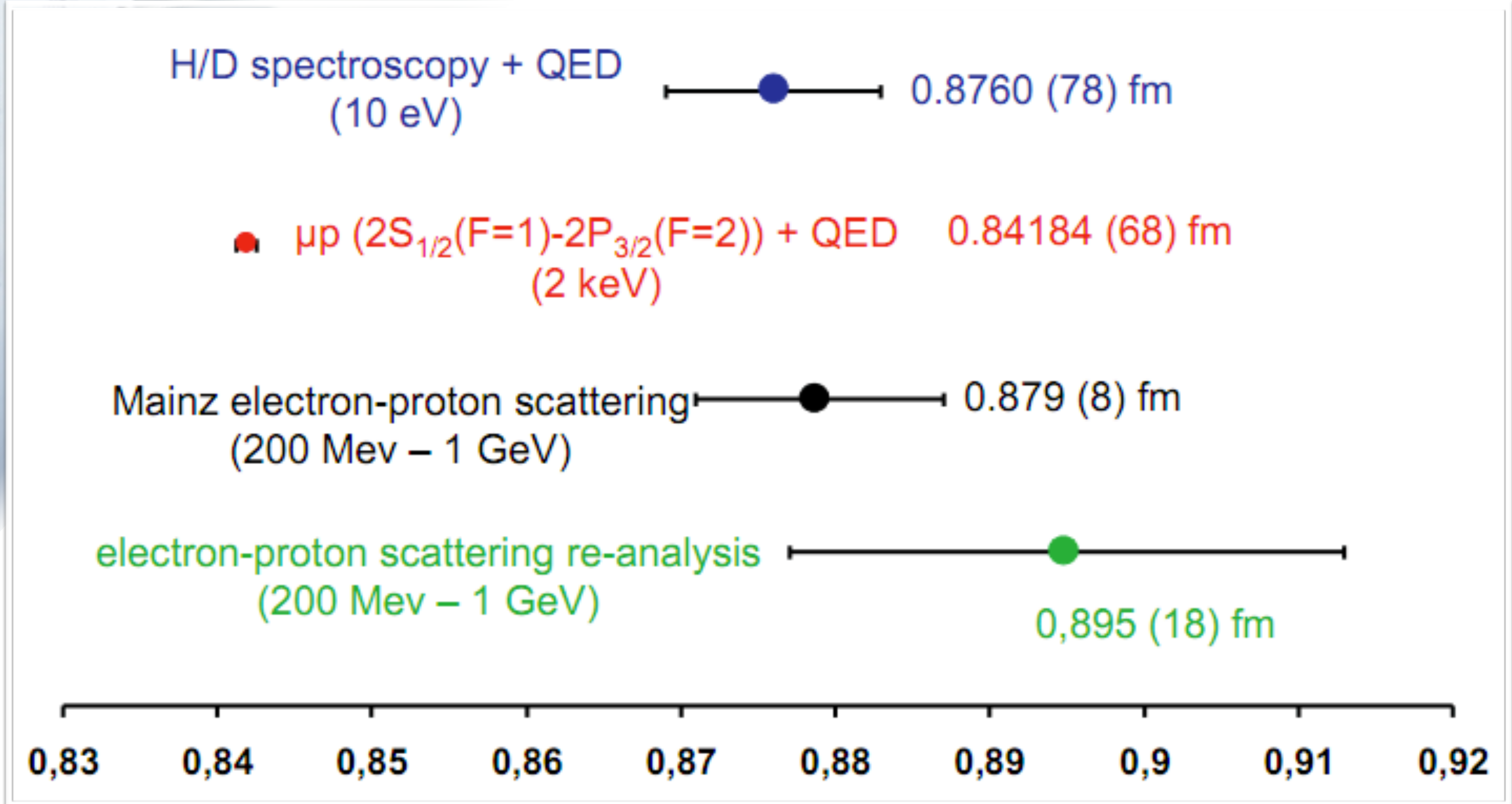


Discrepancy is between muonic and electronic measurements

The Radius Puzzle

R. Pohl et al., Nature 466, (2010) 213





What could be wrong?

or

Is it "new" physics?

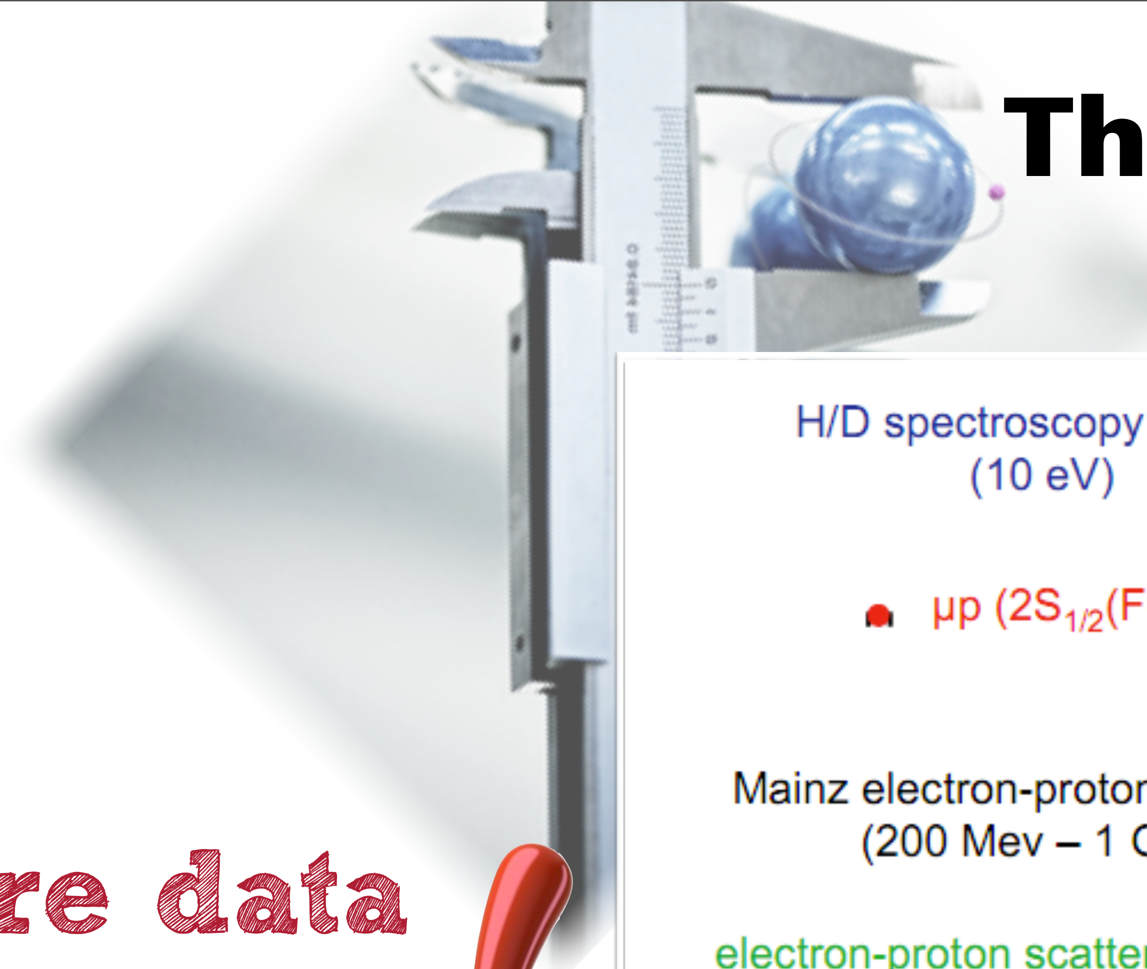
inSPIRE HEP

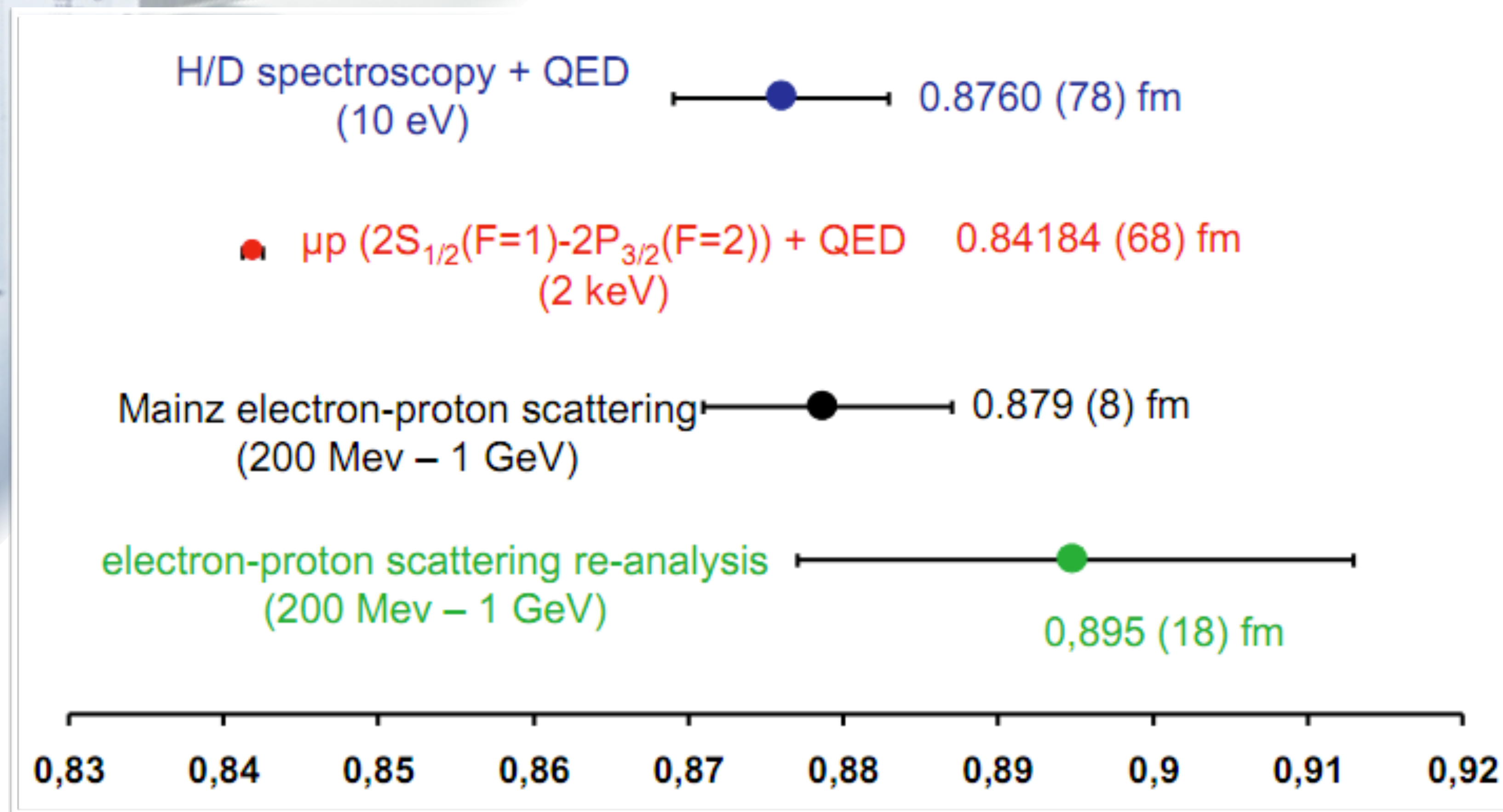
more than 50 citations

Exotic particles, contribution to the Lamb shift in μp,
higher Zemach moments, Two-Photon-Exchange,
structure corrections to hyperfine splitting,
radiative corrections, [...]

still an unresolved problem

The Radius Puzzle

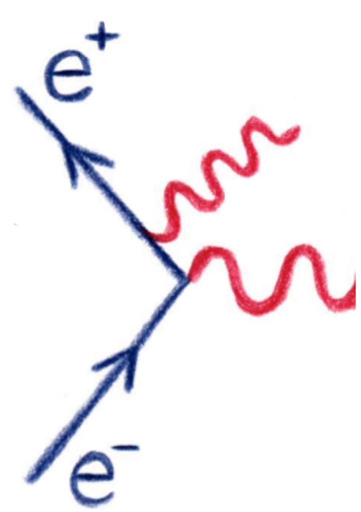


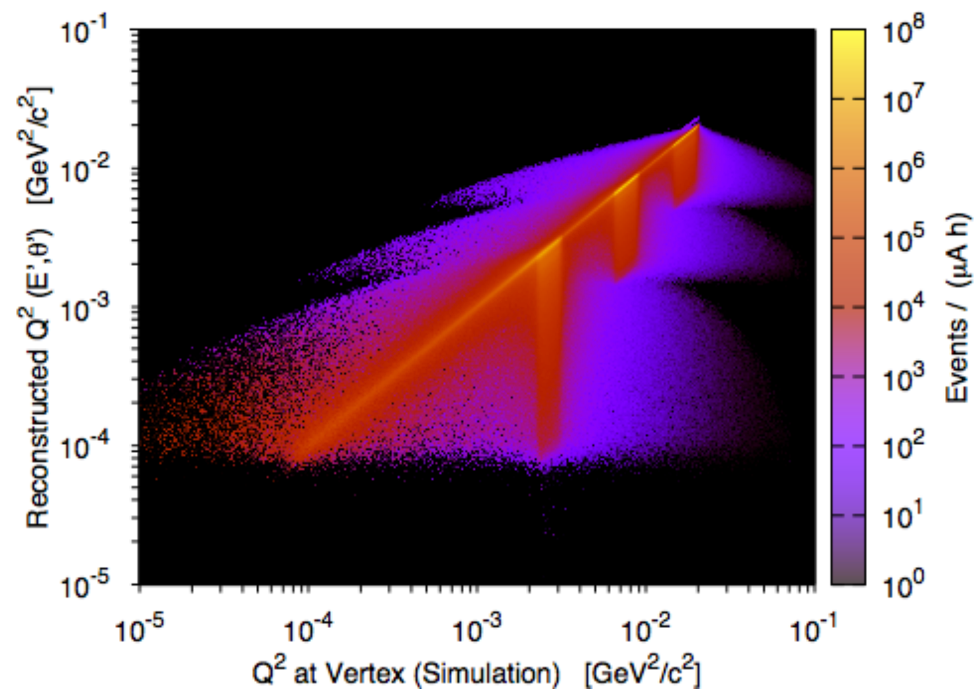


! More data are coming … !

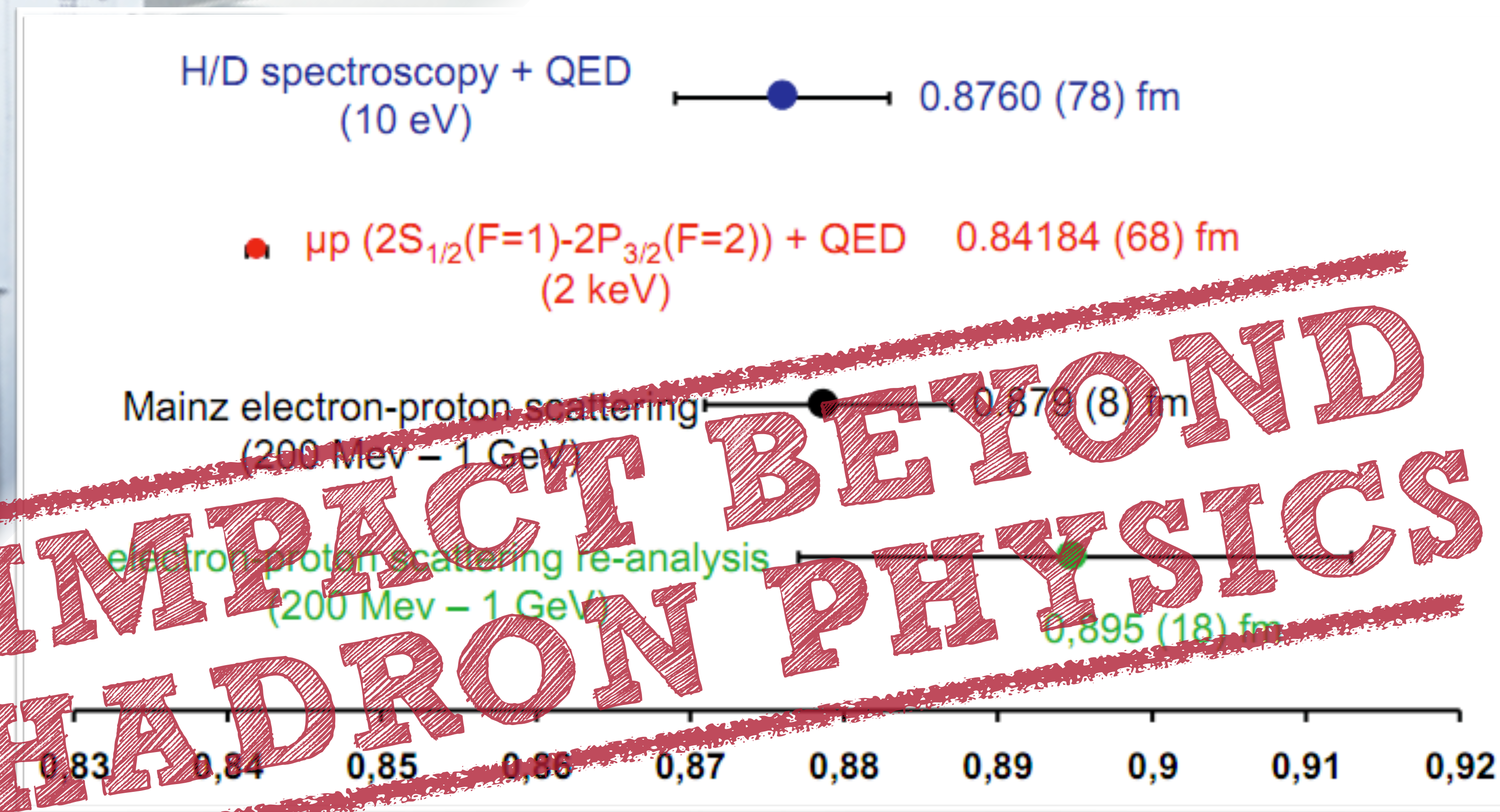
Known problems for extrapolation $Q^2 \rightarrow 0$

Initial State Radiation (MAMI)





The Radius Puzzle



! More data are coming ... !

Known problems for extrapolation $Q^2 \to 0$

Initial State Radiation (MAMI)

Muonic Lamb shift

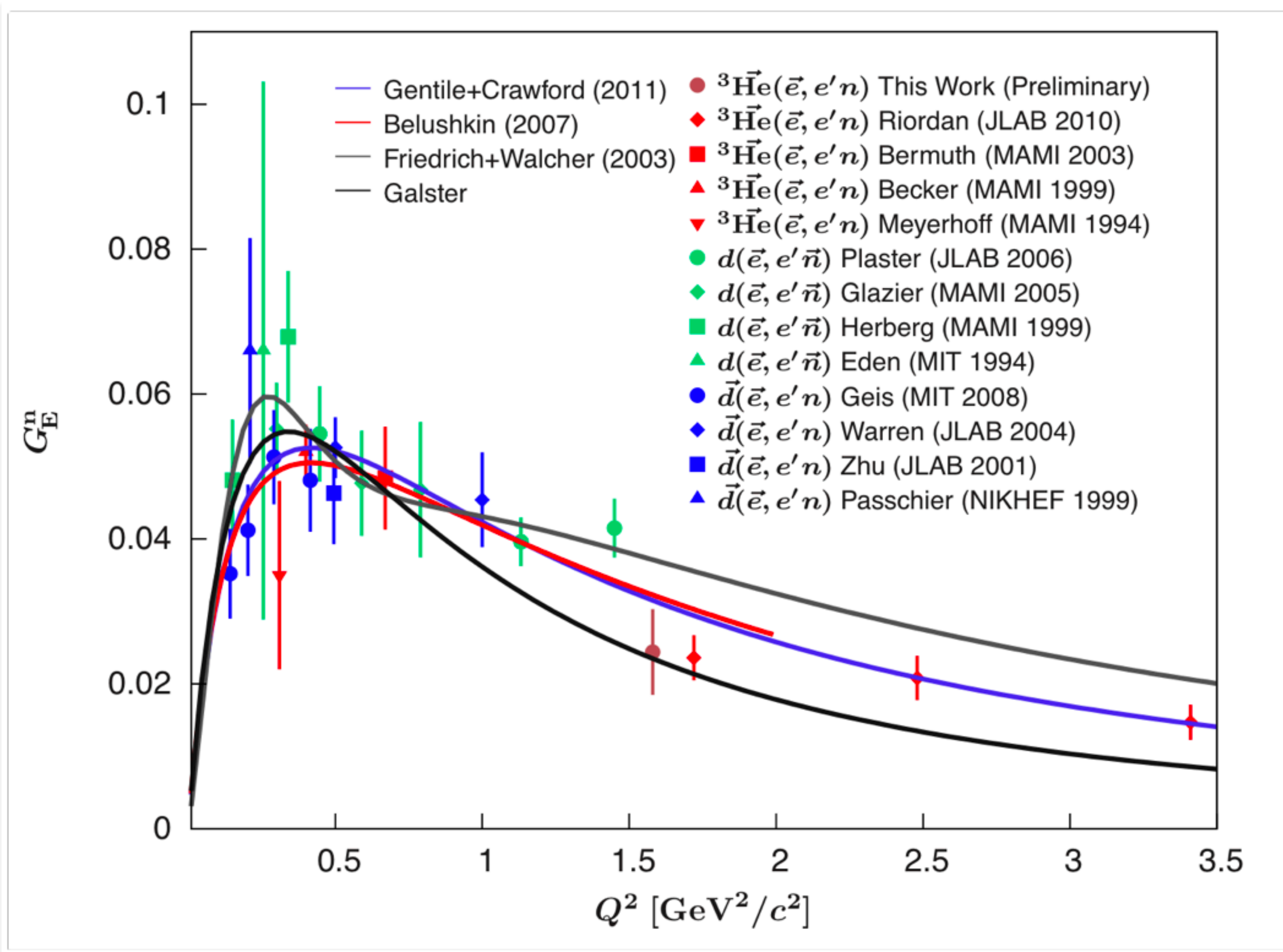
μD, μ-^{3}He, μ-^{4}He measurements (PSI)

New G_{Ep} measurements

Extension up to 1.6 GeV for proton and very low Q^2 for light nuclei (MAMI)

Few Nucleon Systems Form Factor

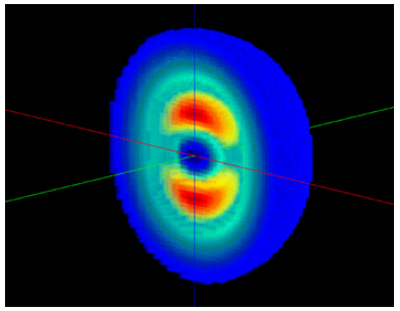
Neutron form factor



S. Schlimme PhD, JGU, Mainz (2012)

No FREE neutron target

use light nuclei (deuteron)



M. Garcon, J. W. Van Orden, Adv. Nucl. Phys. 26, 293 (2001).

Resolution and Consistency

NEW dedicated n-DET

WIDE range

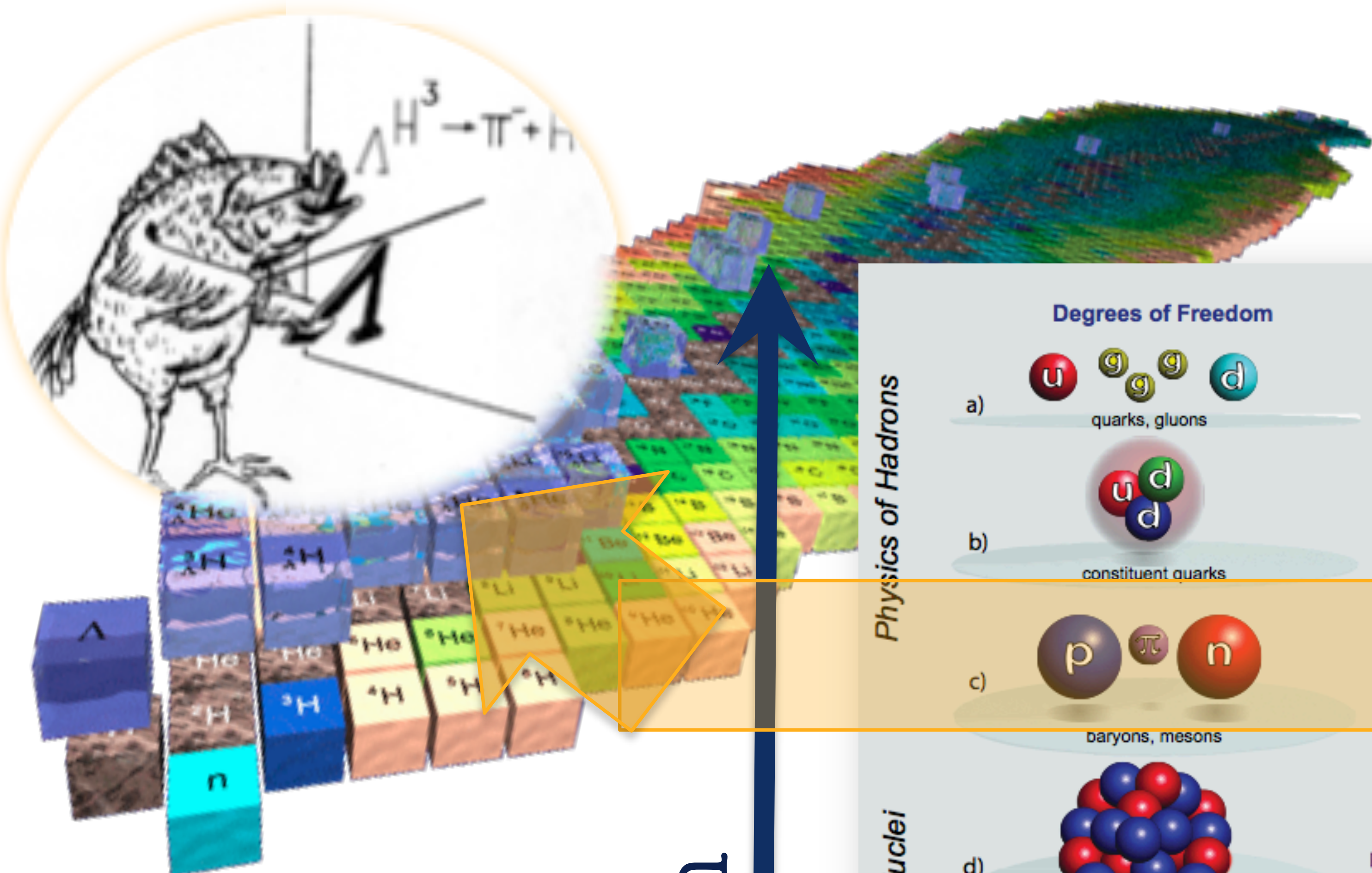
$Q^2 \approx$ 0.2 to 1.5 GeV^2/c^2

The Challenge:

“ Describing complexity in terms of fundamental interactions ”

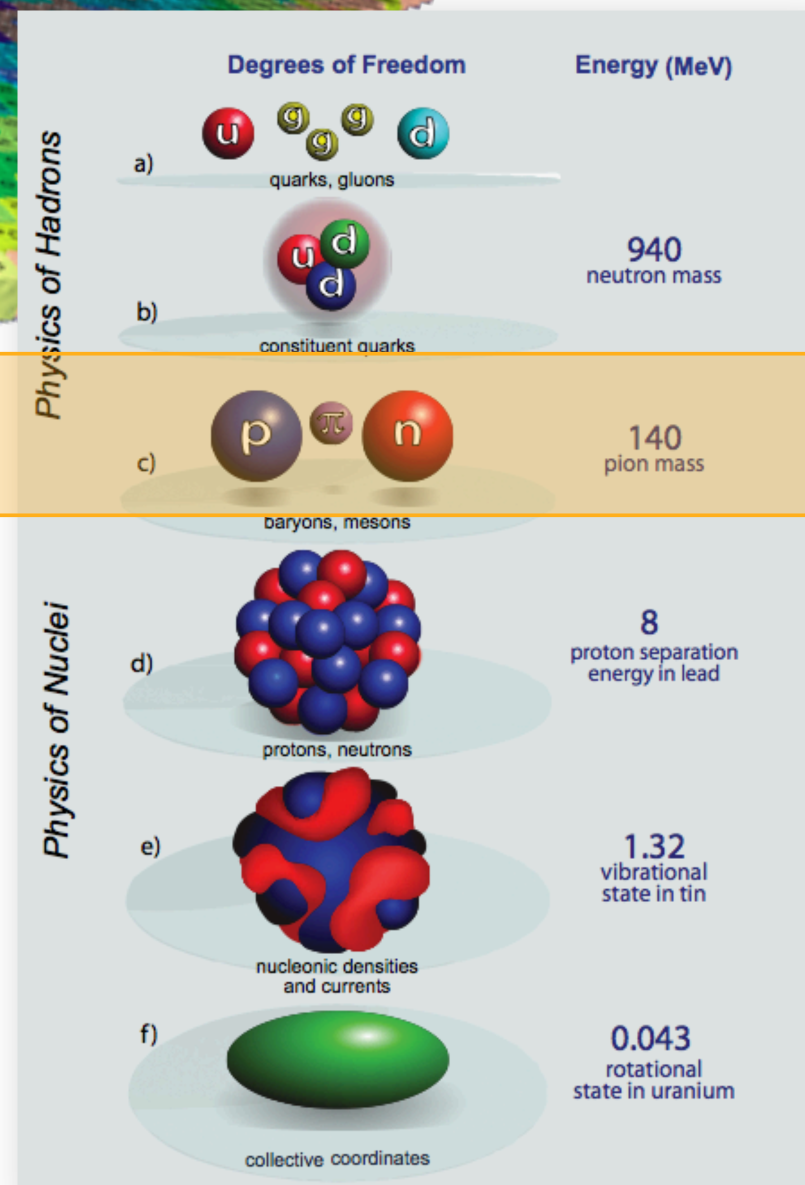
NuPECC Long Range Plan

Linking QCD to many body systems



“Hypernuclear physics is **neither fish nor fowl**. “
from a book review by J.D. Jackson, Science (1968)

Resolution



LRP Nuclear Science Advisory Committee(2008)

Simplicity

Hot and dense quark-gluon matter

Hadron structure

Hadron-Nuclear interface

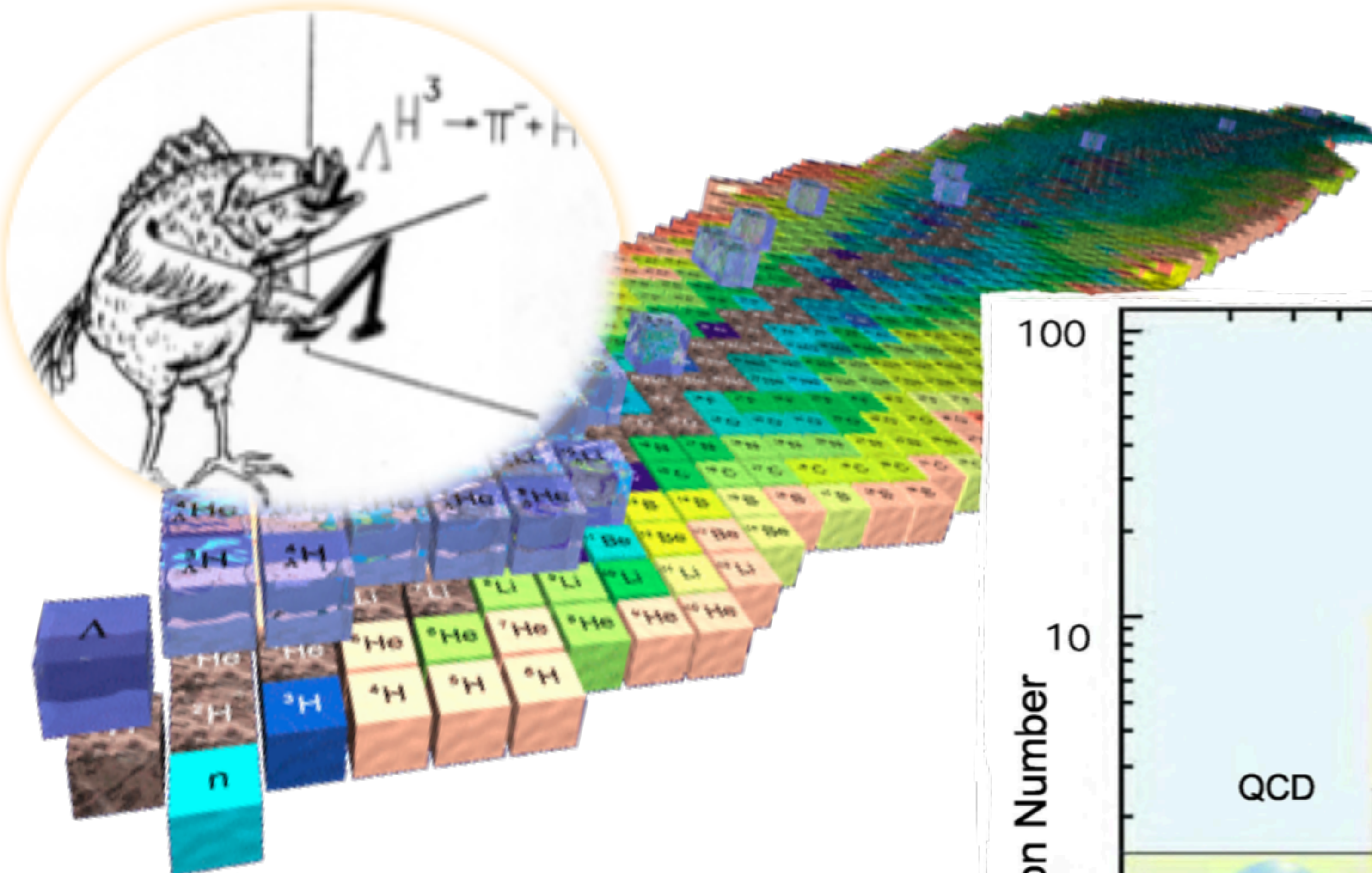
Nuclear structure
Nuclear reactions

Nuclear astrophysics

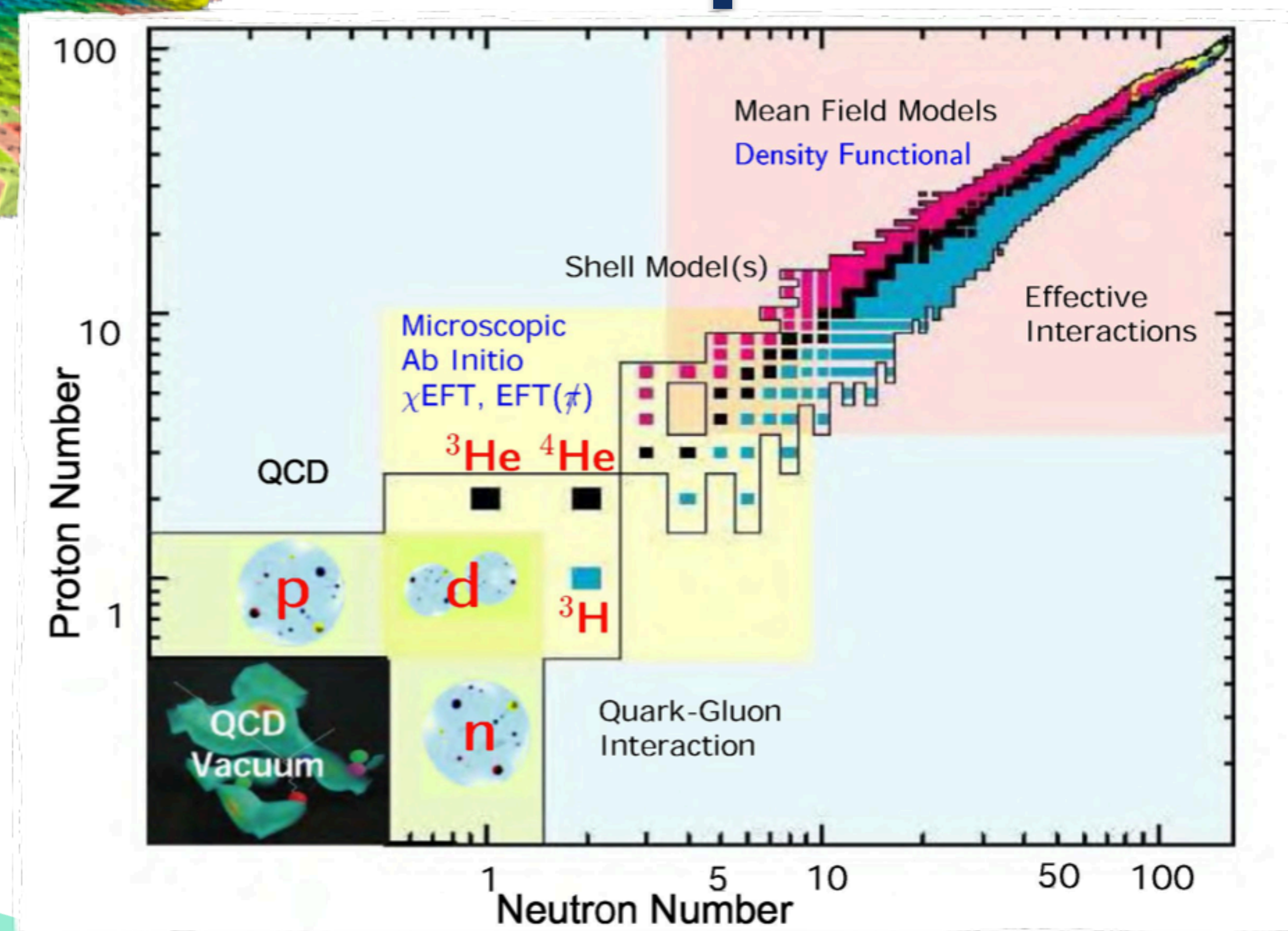
Applications of nuclear science

Complexity

Linking QCD to many body systems



Complexity



UNEDF SciDAC Collaboration
Universal Nuclear Energy Density Functional

Simplicity

Constrain modern calculation:

Precision Experiments

Relevant Observables

Strangeness Nuclear Physics

❶ Hyperons are NOT Pauli-blocked

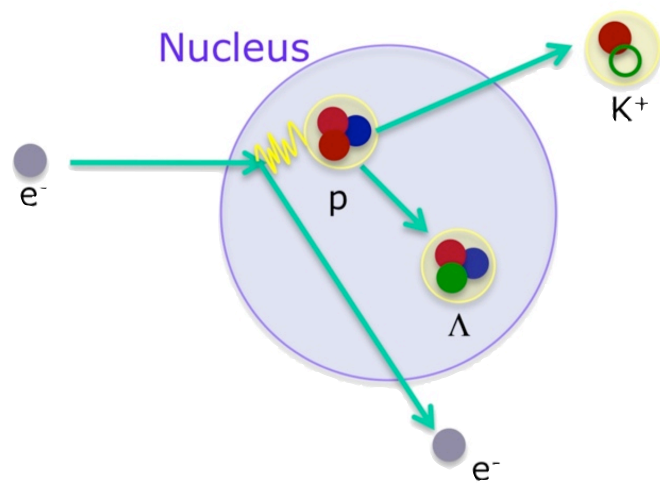
❷ Requires the knowledge of YN, YY, …

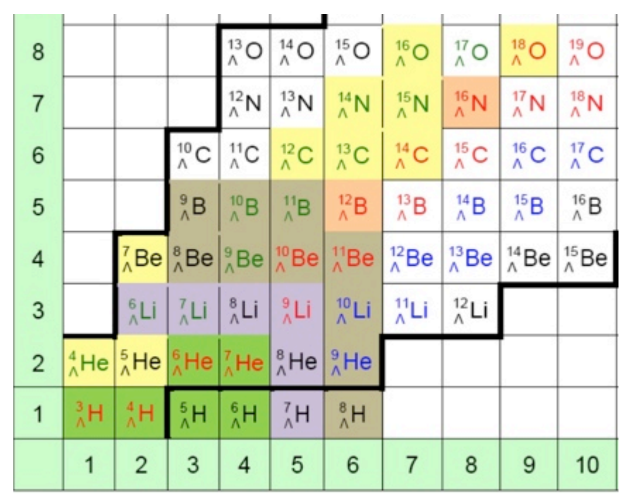
❸ Spectroscopy

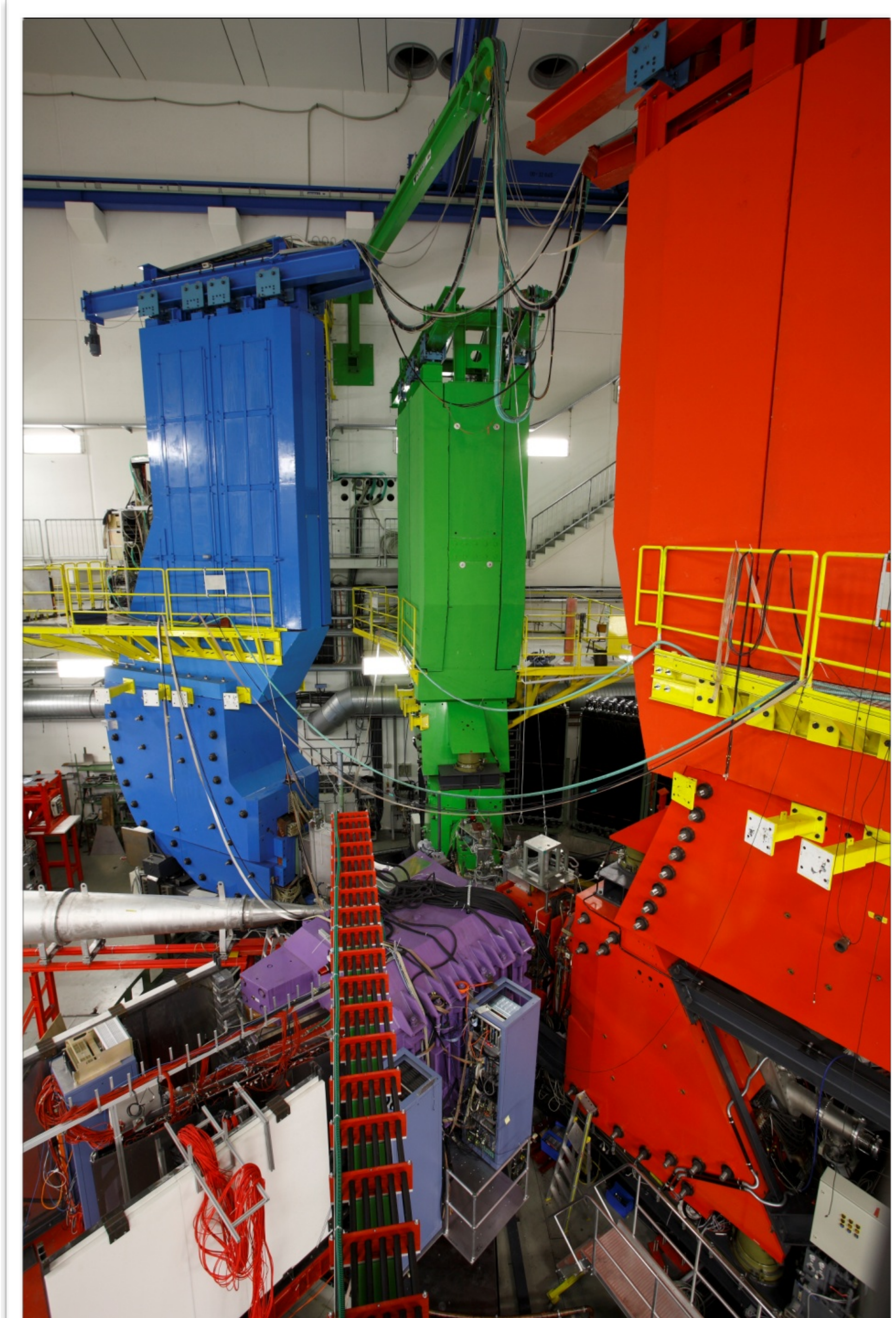
Strangeness Nuclear Physics @ MAMI

❶ Hyperons are NOT Pauli-blocked
❷ Requires the knowledge of YN, YY, …
❸ Spectroscopy

Electroproduction $Z(e,e',K^+)_{\Lambda}(Z-1)$



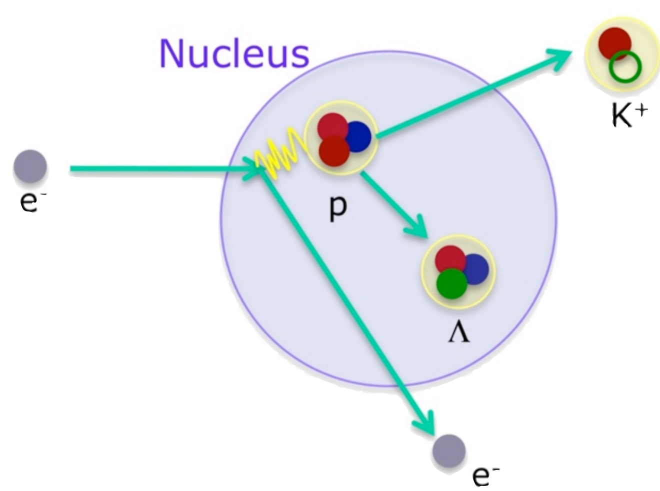


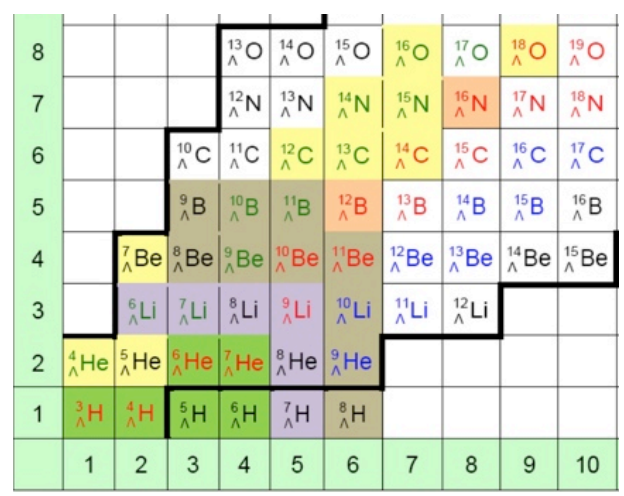


Strangeness Nuclear Physics @ MAMI

❶ Hyperons are NOT Pauli-blocked
❷ Requires the knowledge of YN, YY, …
❸ Spectroscopy

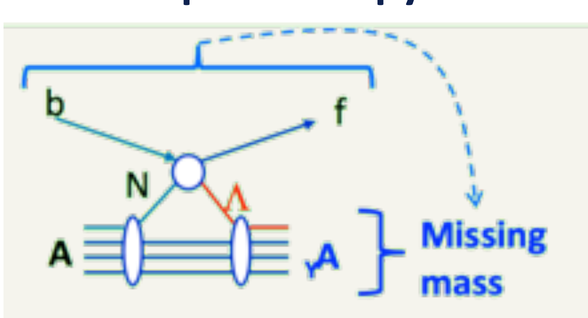
Electroproduction $Z(e,e',K^+)_\Lambda(Z-1)$



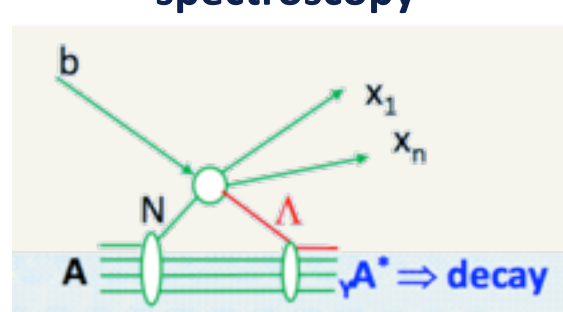


A two-fold way

DIRECT PRODUCTION
spectroscopy



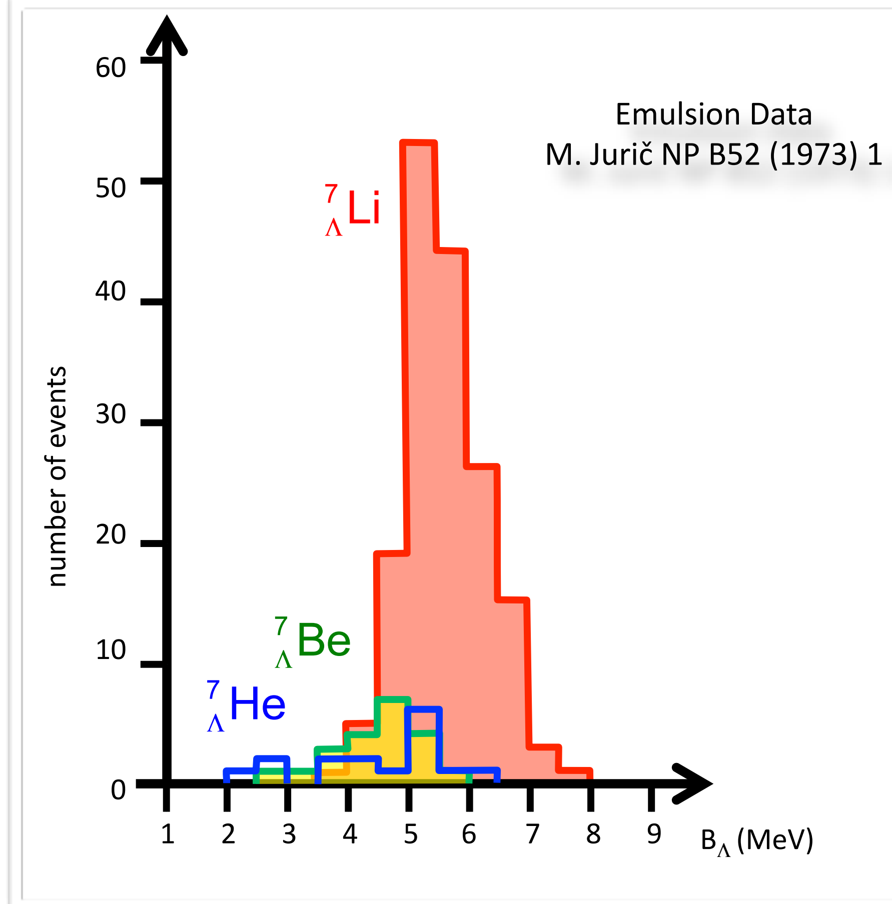
DECAY
spectroscopy



Decay Spectroscopy @ MAMI

❷ Requires the knowledge of YN, YY, ...

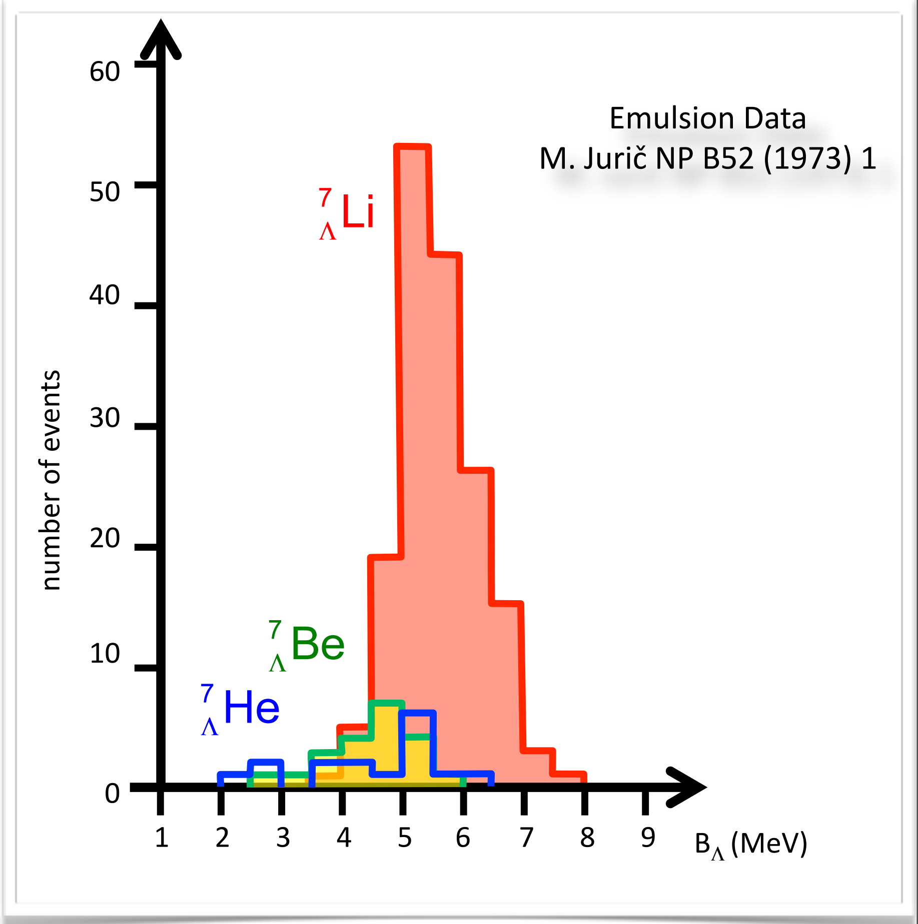
Precision is the key issue



Decay Spectroscopy @ MAMI

❷ Requires the knowledge of YN, YY, …

Precision is the key issue



ΛN Charge Symmetry Breaking?

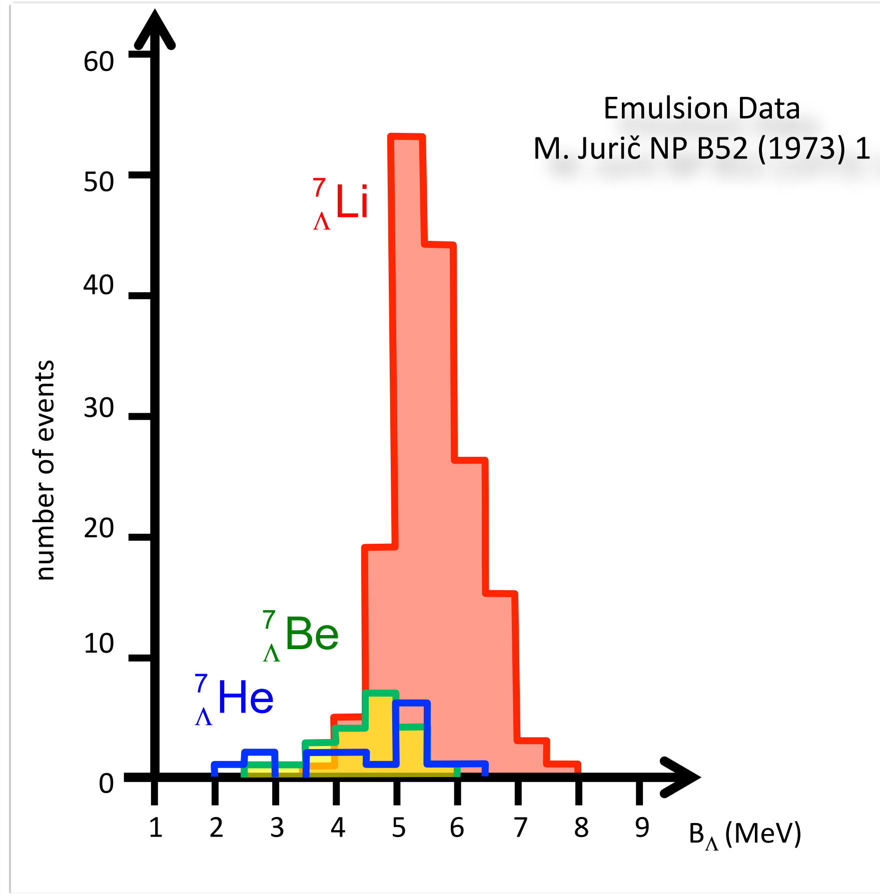
☝ EFT w/o strangeness agrees with data within ≈ 2%

Epelbaum, Krebs, Lee, Meißner PRL 104 (10) 142501

Decay Spectroscopy @ MAMI

❷ Requires the knowledge of YN, YY, …

Precision is the key issue

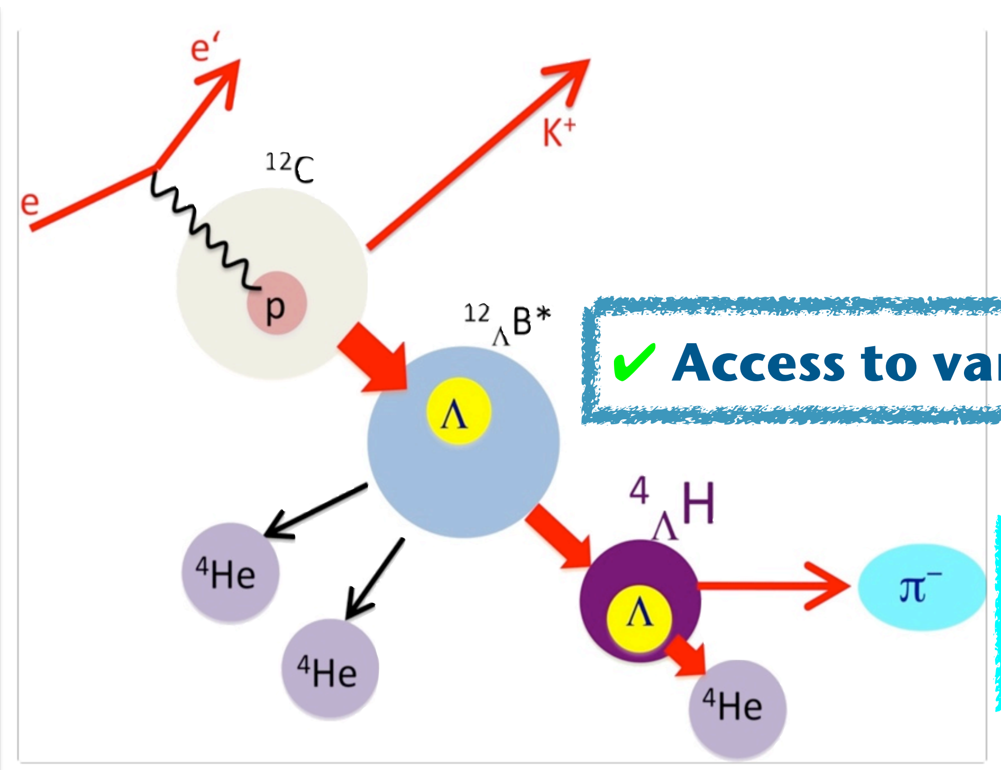


ΛN Charge Symmetry Breaking?

EFT w/o strangeness agrees with data within ≈ 2%

Epelbaum, Krebs, Lee, Meißner PRL 104 (10) 142501

☞High resolution decay π spectroscopy



✔ Access to variety of light and exotic hypernuclei

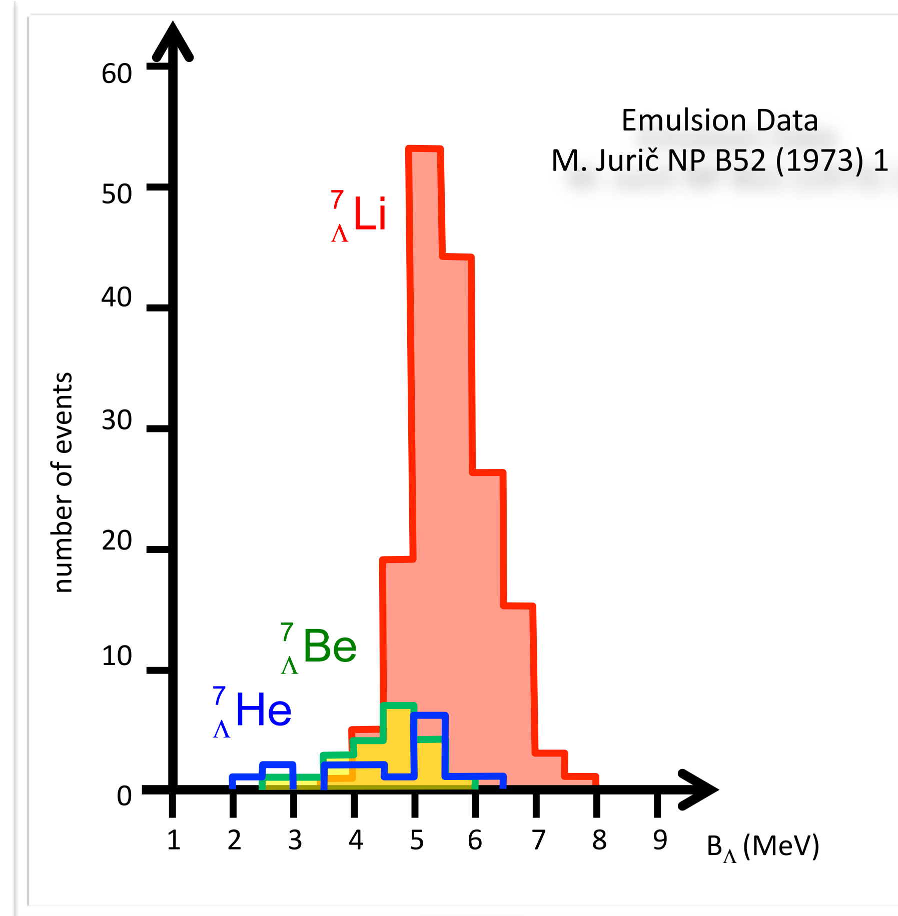
Weak mesonic two-body decay ➜ mono-energetic π

✔ Resolution (δB_Λ) limited by π^- momentum resolution

Decay Spectroscopy @ MAMI

❷ Requires the knowledge of YN, YY, …

Precision is the key issue

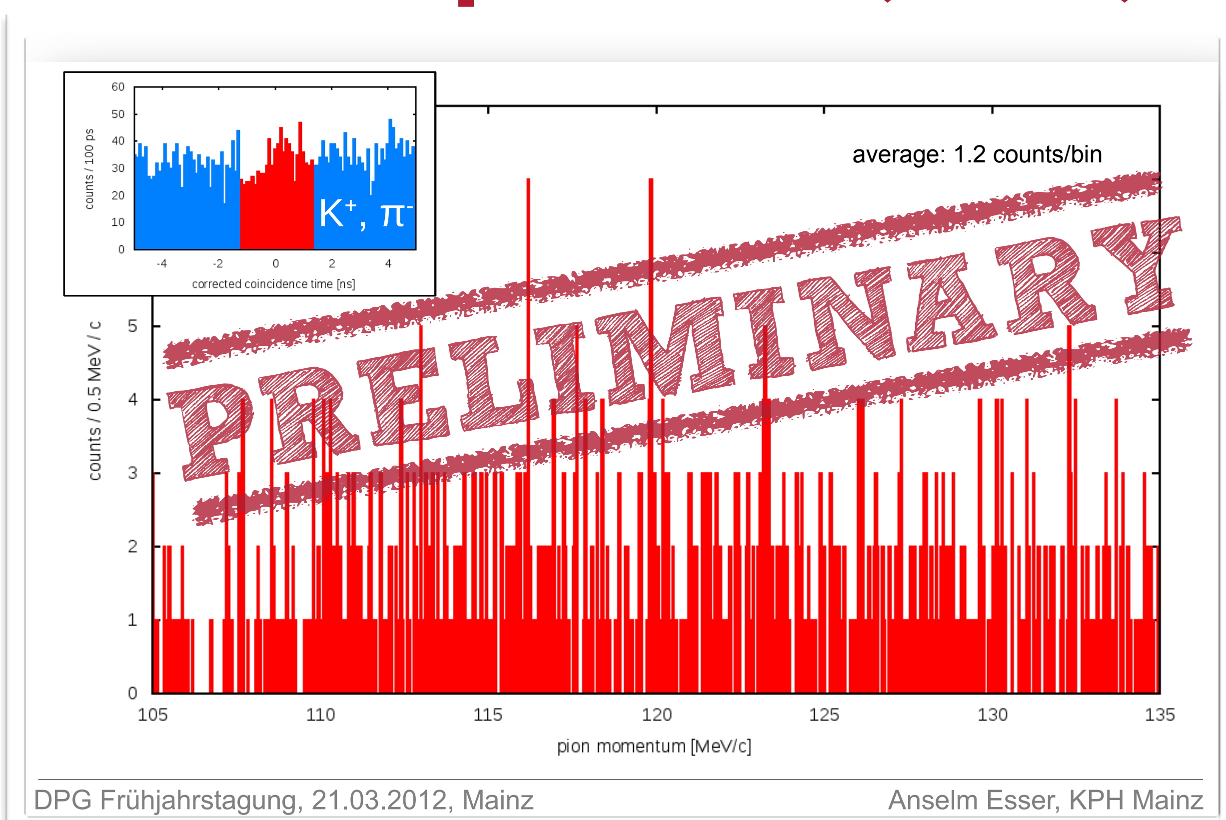


ΛN Charge Symmetry Breaking?

☝ EFT w/o strangeness agrees with data within ≈ 2%

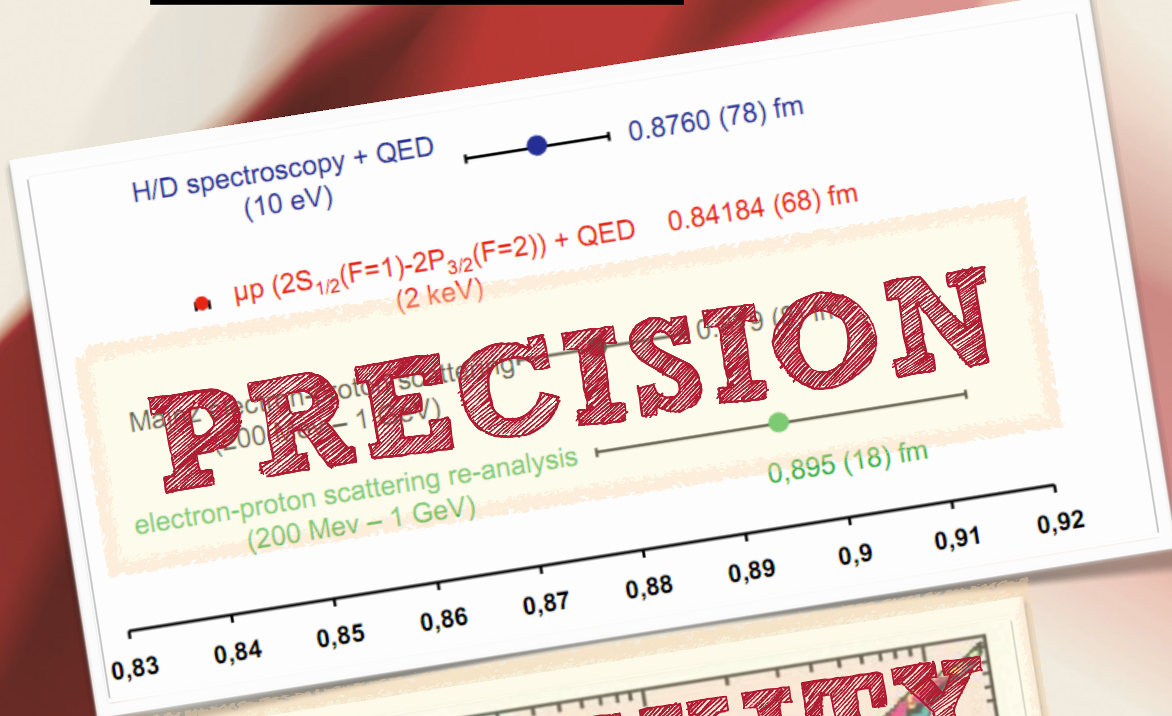
Epelbaum, Krebs, Lee, Meißner PRL 104 (10) 142501

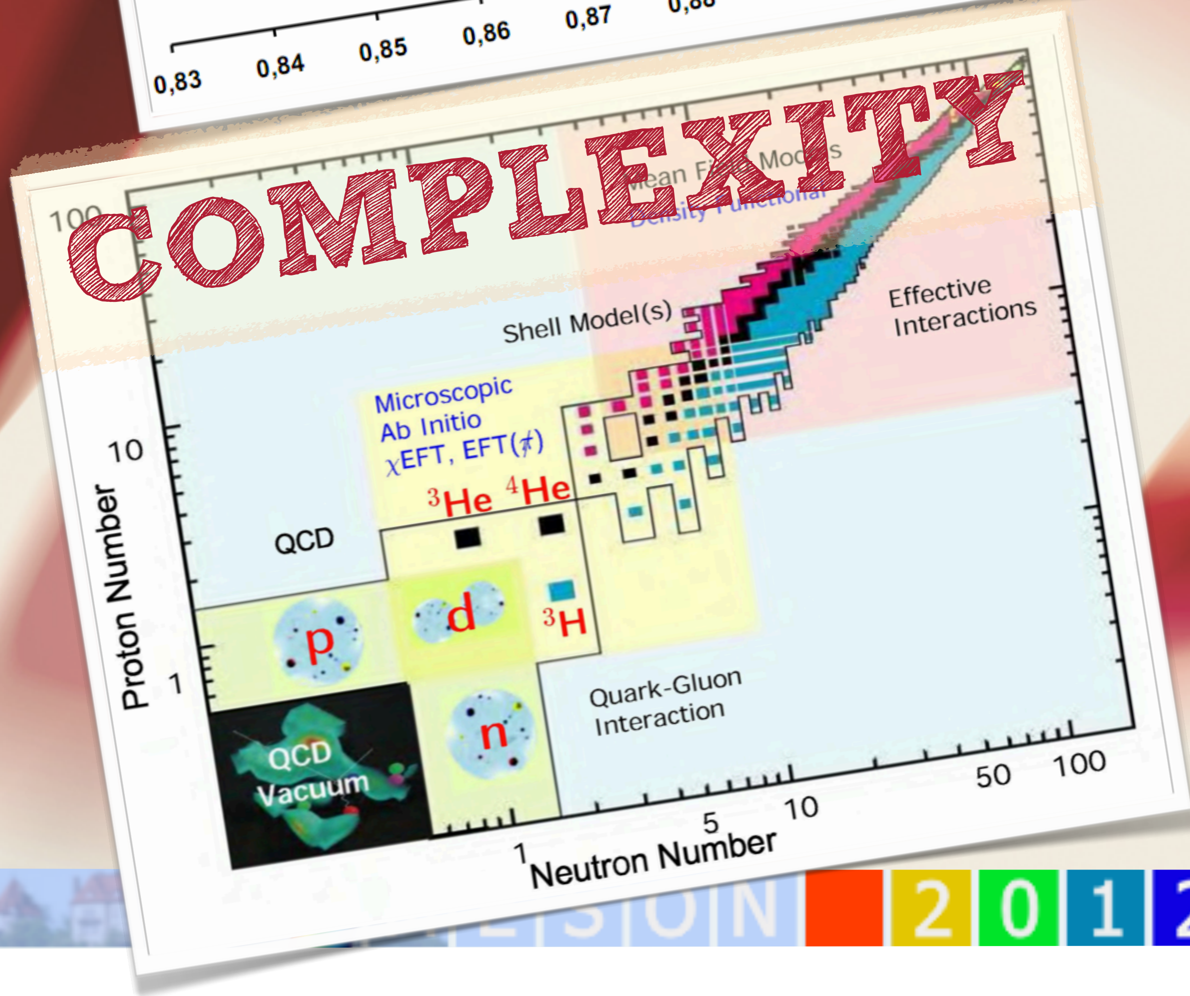
☞ Pilot experiment (2011)



- Zero-degree kaon tagging by KAOS
- High resolution spectrometers for π detection ($\Delta p/p \leq 10^{-4}$ FWHM)
- FPGA trigger setups for maximizing background suppression

The frontiers of the virtual photon program @ MAMI





Hadron physics plays a central and connecting role

Stay tuned for Meson 2014:

Form factors: proton vs. d (June 2012)
Magnetic and electric neutron FF measurements
ISR measurements at very low Q^2
Nucleon polarizabilities
Structure studies of few body systems w/o and w/ strangeness

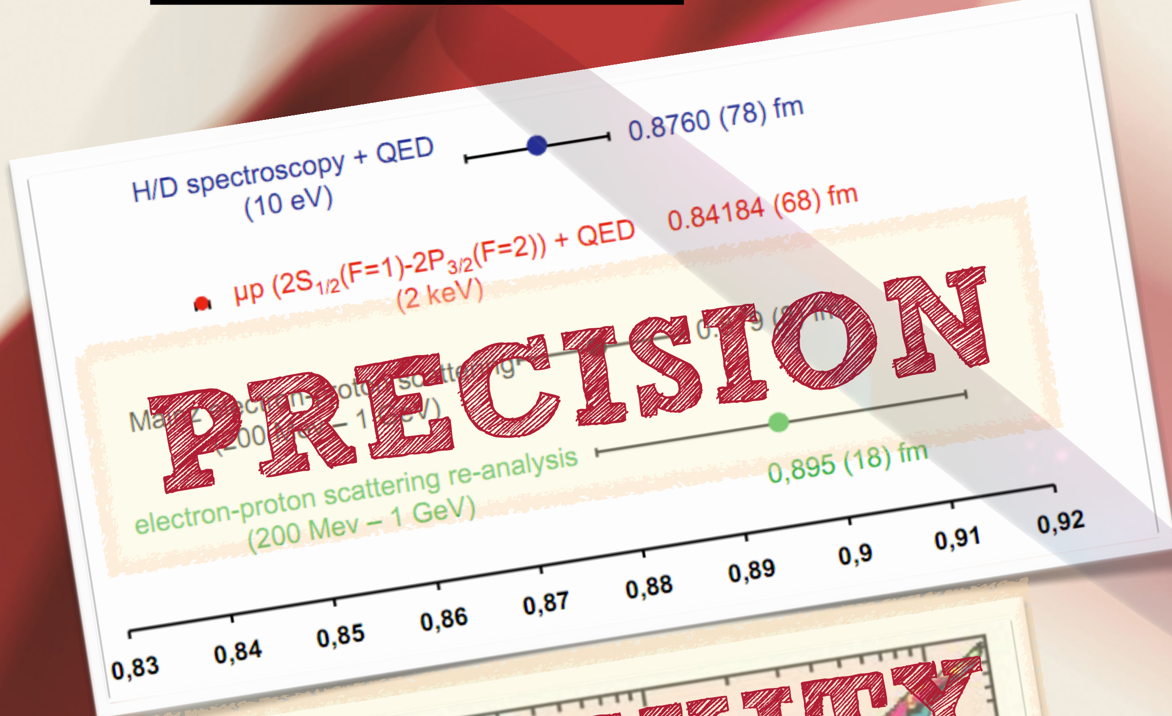
MESON 2012

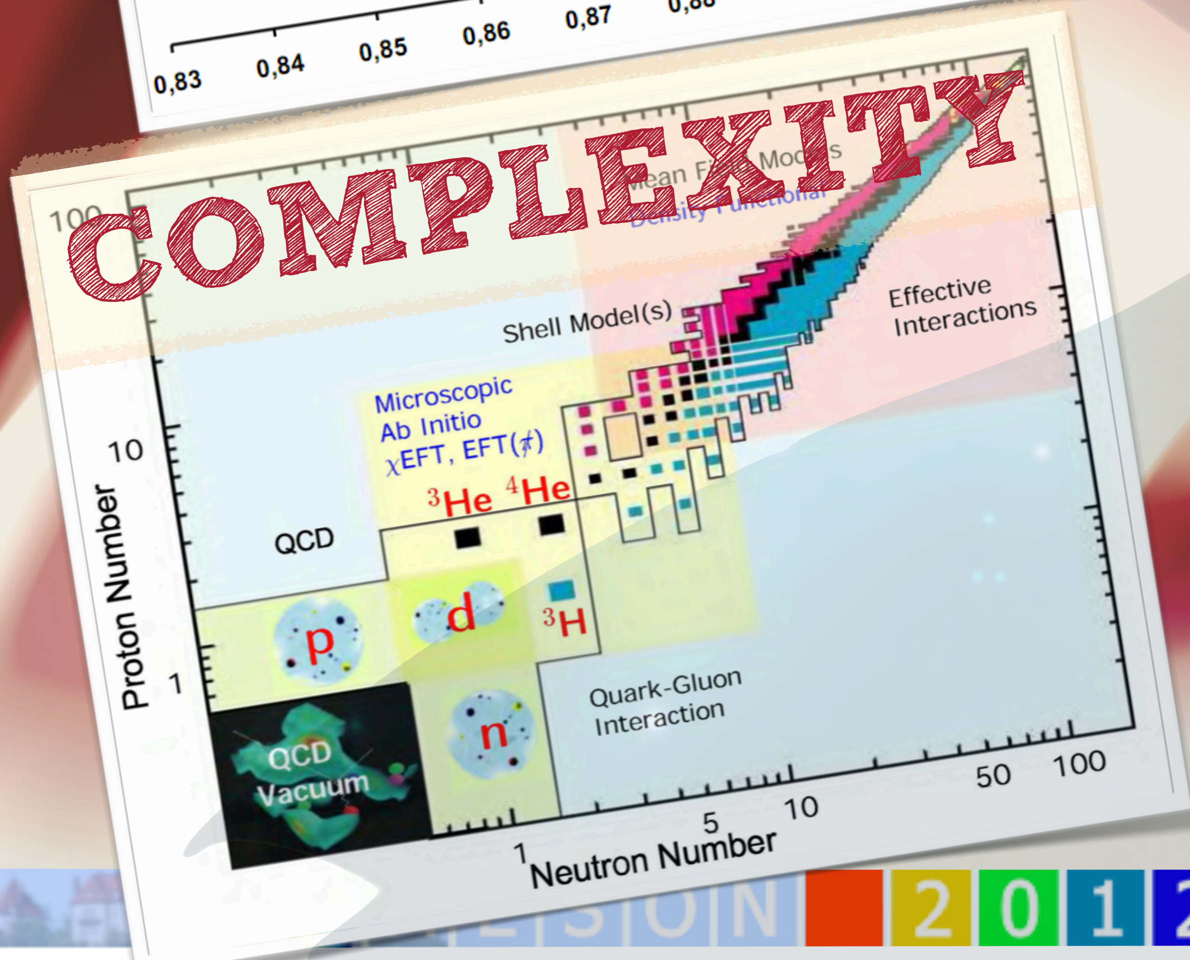
The Low Energy Frontier of the Standard Model

Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

CRC1044

The frontiers of the virtual photon program @ MAMI





Hadron physics plays a central and connecting role

Stay tuned for Meson 2014:

Form factors: proton vs. d (June 2012)
Magnetic and electric neutron FF measurements
ISR measurements at very low Q^2
Nucleon polarizabilities
Structure studies of few body systems w/o and w/ strangeness

.. and for the ...

DarkSide

MESON 2012

The Low Energy Frontier of the Standard Model

CRC1044

JG|U

Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

Probing Dark Forces @ GeV Scale

Dark Photon

Light weakly coupled U(1) gauge boson

N. Arkani-Hamed, et al., Phys. Rev. D 79 (2009) 015014

...it explains ...

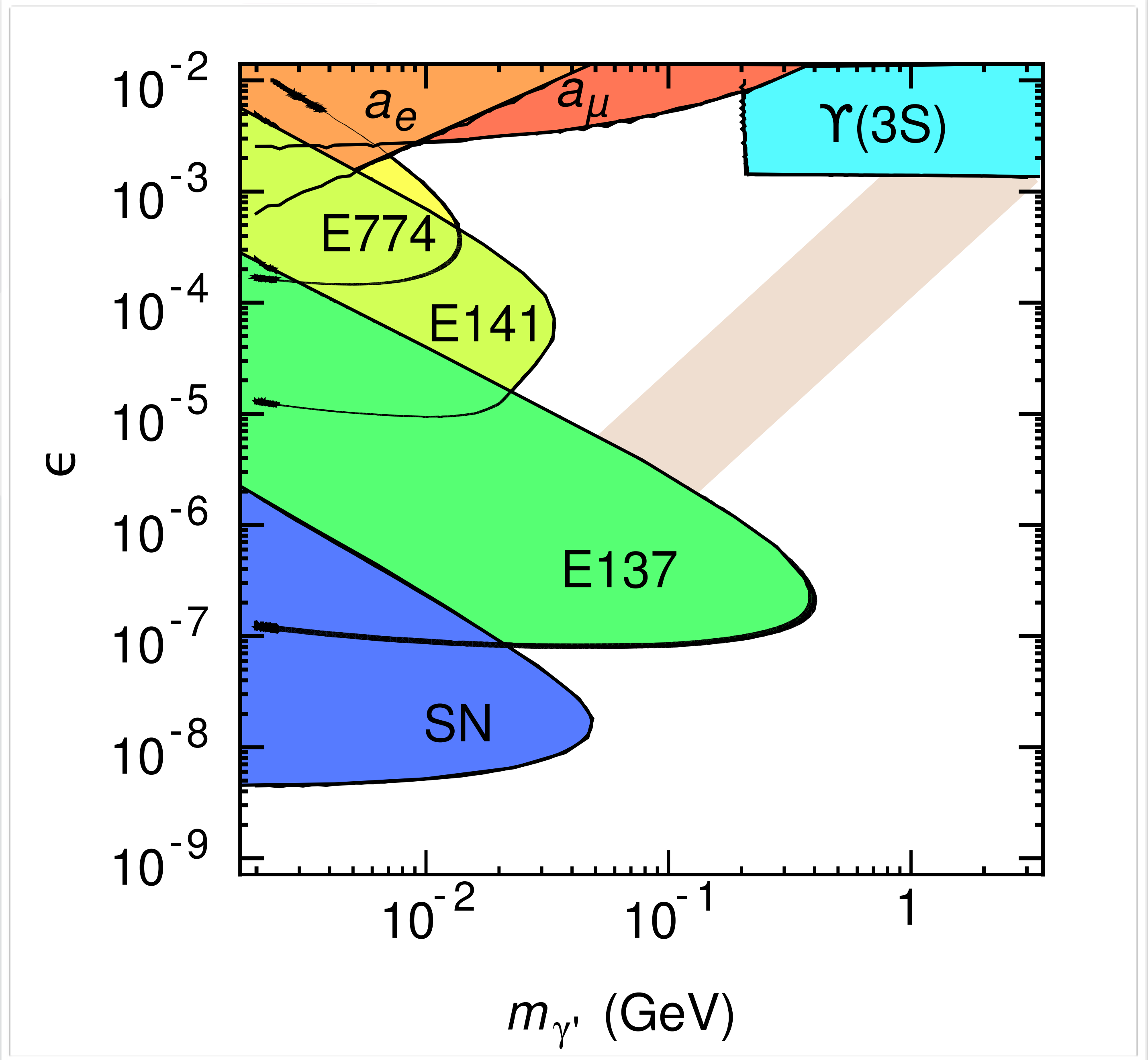
terrestrial anomalies
(DAMA, CDMS, XENON)
satellite anomalies
(PAMELA, FERMI)

$(g\text{-}2)_\mu$ anomaly

M. Pospelov, Phys. Rev. D80 (2009) 095002

Proton Radius Puzzle

D. Tucker-Smith and I. Yavin Phys. Rev. D83 (2011) 101702



Probing Dark Forces @ GeV Scale

Dark Photon

Light weakly coupled U(1) gauge boson

N. Arkani-Hamed, et al., Phys. Rev. D 79 (2009) 015014

...it explains ...

terrestrial anomalies (DAMA, CDMS, XENON)

satellite anomalies (PAMELA, FERMI)

$(g\text{-}2)_\mu$ anomaly

M. Pospelov, Phys. Rev. D80 (2009) 095002

Proton Radius Puzzle

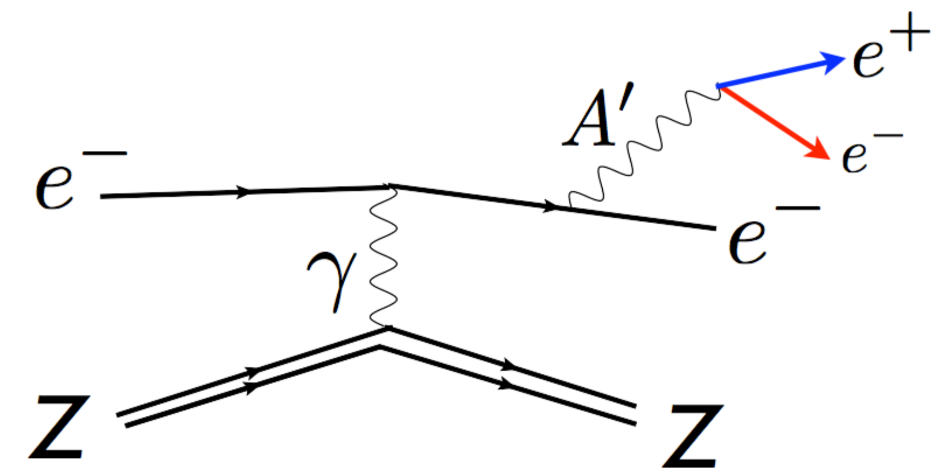
D. Tucker-Smith and I. Yavin Phys. Rev. D83 (2011) 101702

PHYSICAL REVIEW D **80**, 075018 (2009)

New fixed-target experiments to search for dark gauge forces

James D. Bjorken,[1] Rouven Essig,[1] Philip Schuster,[1] and Natalia Toro[2]
[1]*Theory Group, SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[2]*Theory Group, Stanford University, Stanford, California 94305, USA*

(Received 20 July 2009; published 28 October 2009)



➠ World wide effort (CERN, DESY, JLAB, MAMI, all e^+e^- colliders, ...)

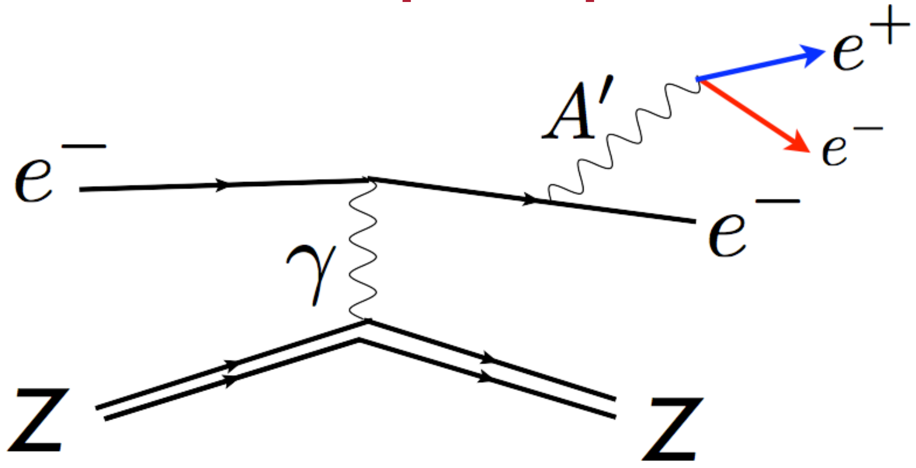
Prediction are testable:

Large cross section in leptons

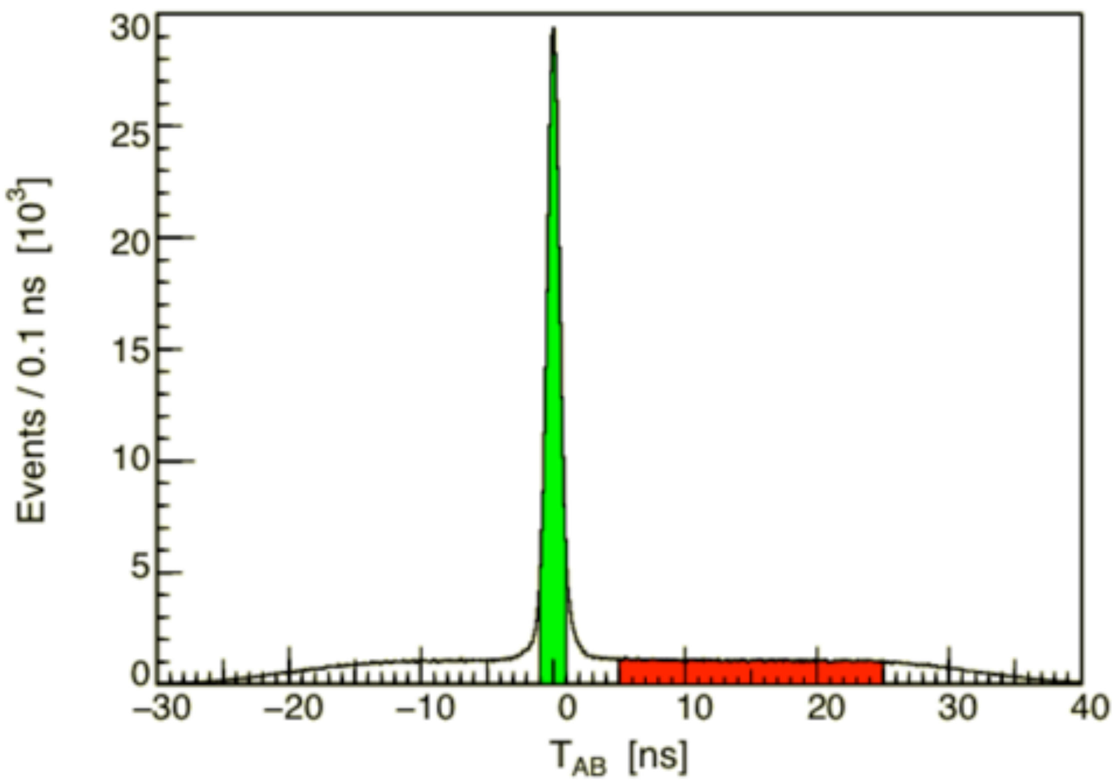
Search for the Dark Photon @ MAMI

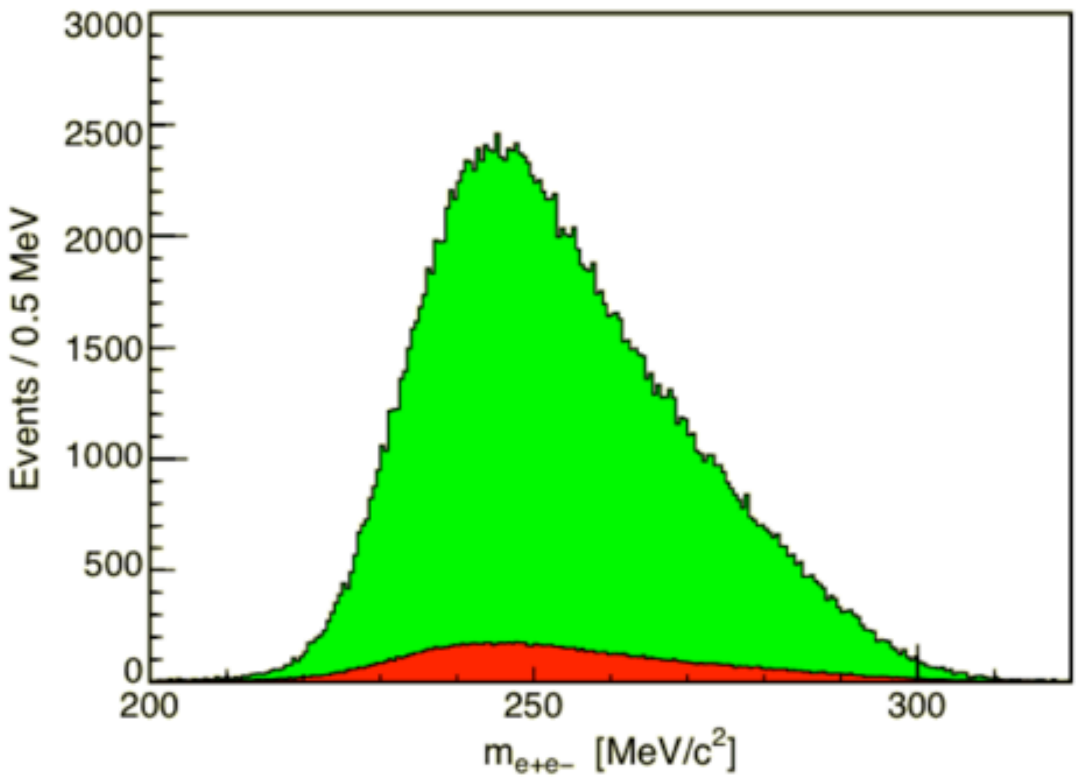
H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

Bump Hunt: Quasi-photoproduction off ^{181}Ta target



Beam current: 100μA
Luminosity: $L = 1.7\cdot10^{35}$ $(s\cdot cm^2)^{-1}$
Minimal angles for spectrometers
Geometry as symmetric as possible
(background reduction)





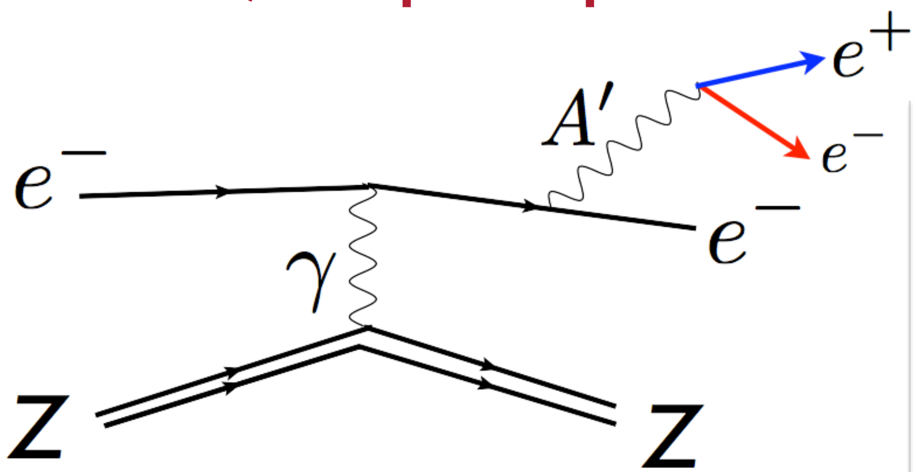
Coincidence time resolution ≈ **1 ns FWHM**
Almost no accidental background ≈ **5%**
Above background: only coincident e^+e^- pairs!

$\delta m_{e+e-} < 0.5 MeV/c^2$

Search for the Dark Photon @ MAMI

H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

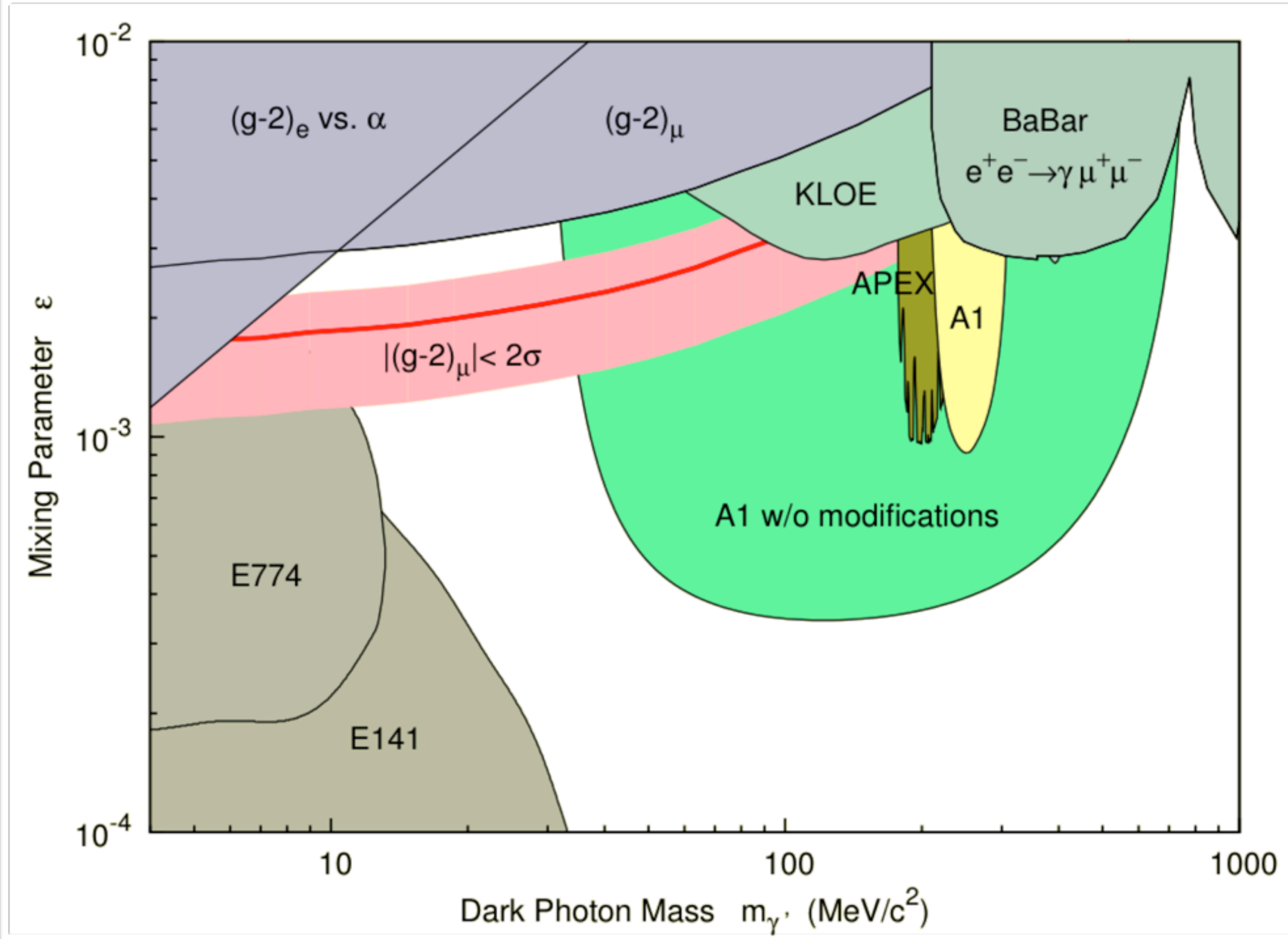
Bump Hunt: Quasi-photoproduction off ^{181}Ta target



➛ **Fight background ….**

… with high intensity …

… and resolution.



Feasibility:

Background (within 1%)

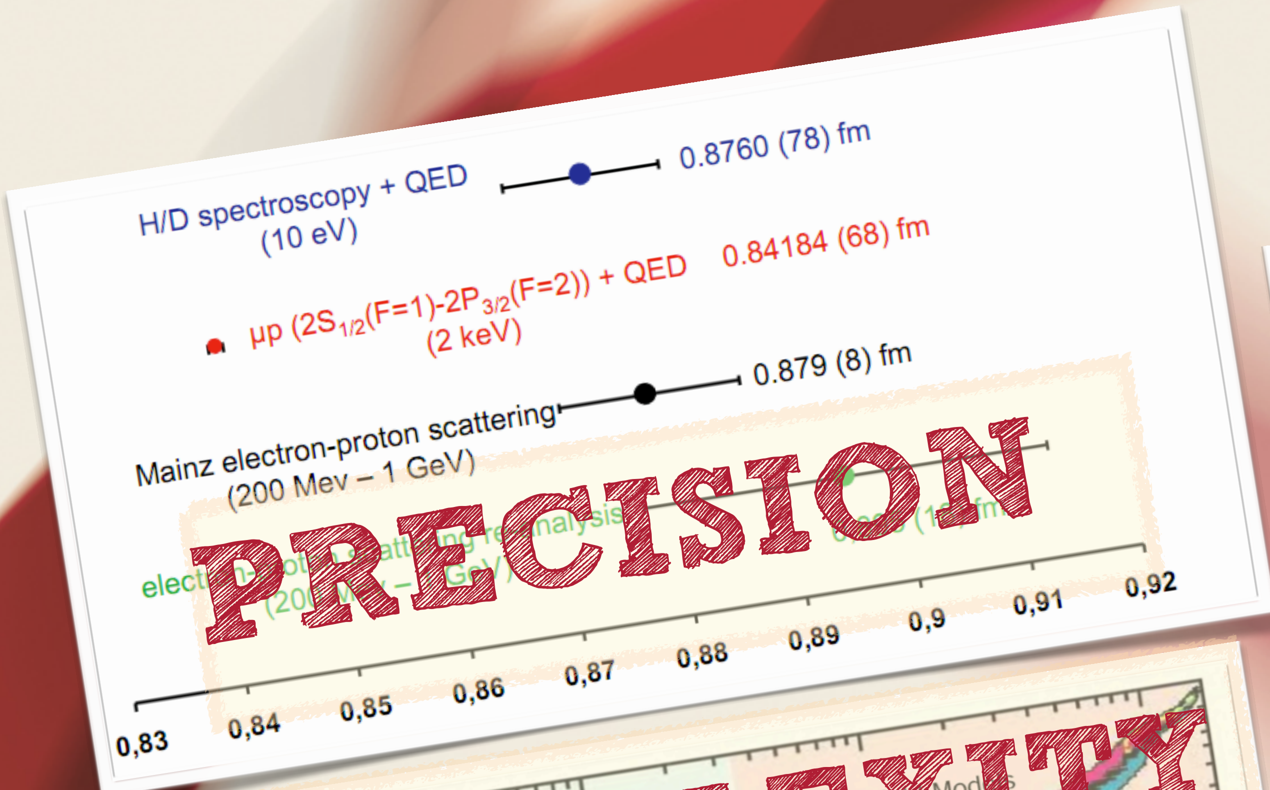
First exclusion limits 10^{-3}

4 days beam time!!

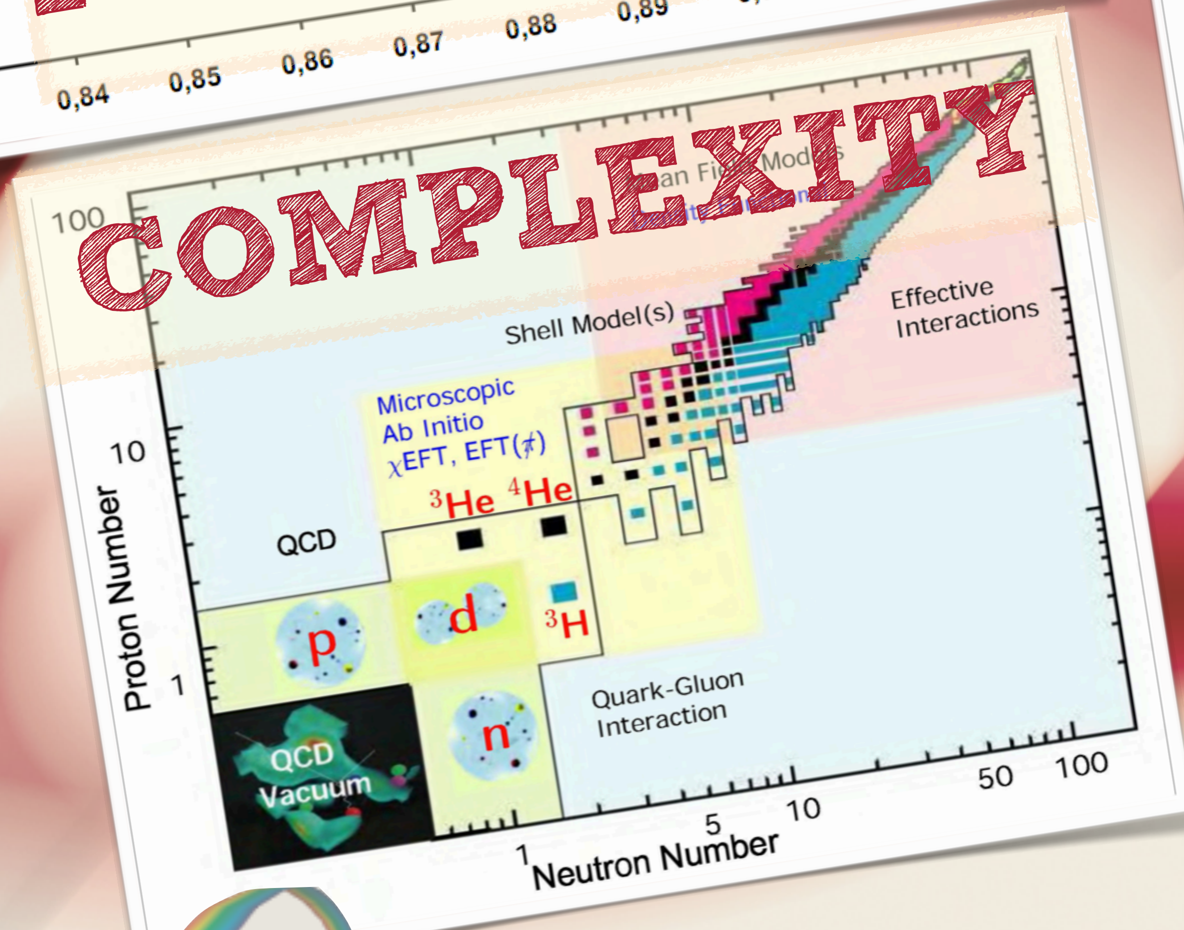
APEX: S. Abrahamyan et al., Phys. Rev. Lett. 107 (2011) 191804
KLOE: F. Archilli et al., Phys. Lett. B. 706 (2012) 251

..the search continues …

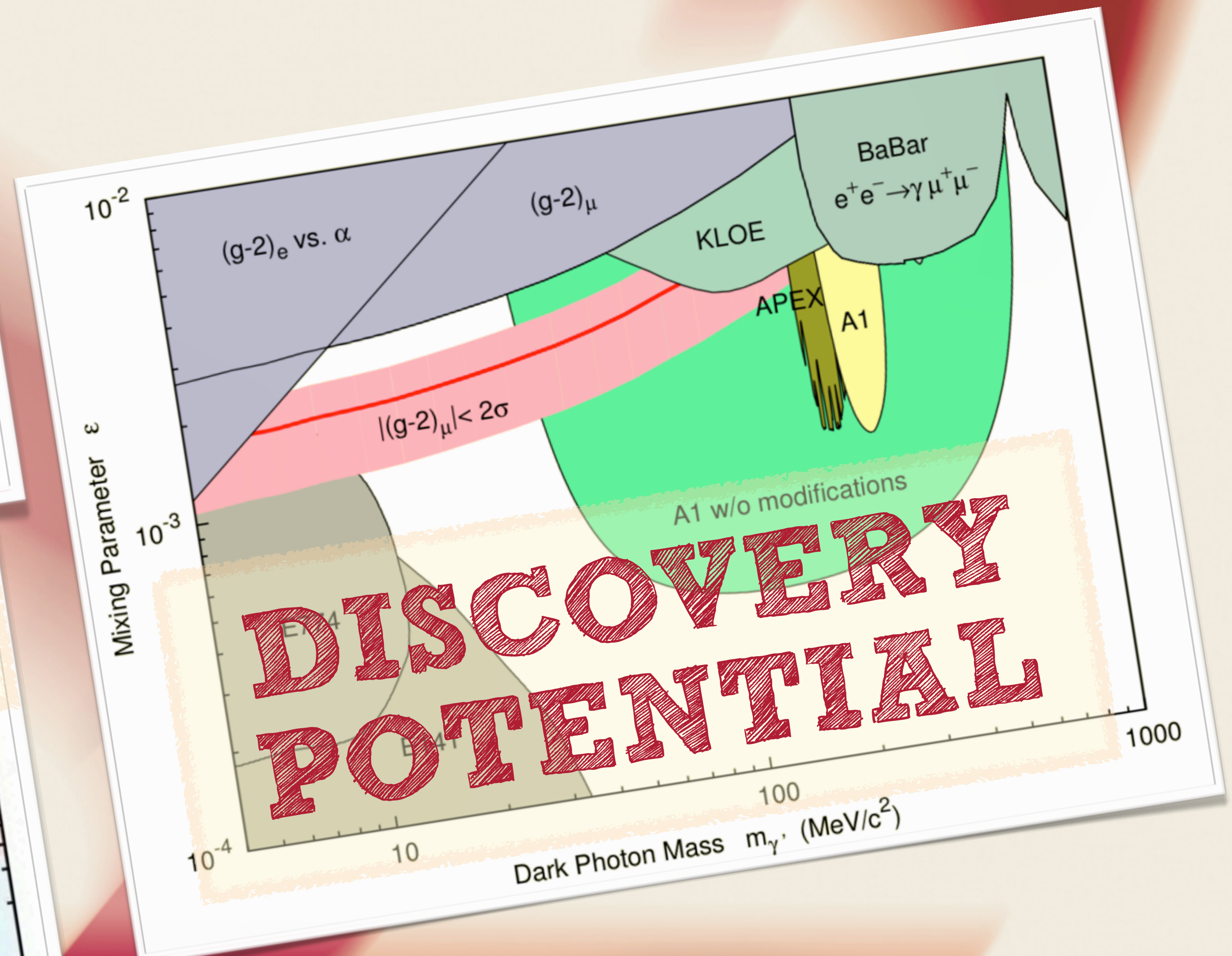
new $\varepsilon/m_{\gamma'}$ scan March 2012



PRECISION



COMPLEXITY



DISCOVERY POTENTIAL

The **frontiers** of the virtual photon program @ MAMI

MESON 2012

The Low Energy Frontier of the Standard Model

Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

CRC1044

JG|U

MESON 2012

Concettina Sfienti
Johannes Gutenberg-Universität - Institut für Kernphysik, Mainz

CRC1044

JG|U

Form Factors from Elastic ep scattering

Cross section for one photon exchange

(Rosenbluth-cross section + Separation at constant Q^2)

charge distribution

$$\frac{d\sigma}{d\Omega_e} = \left(\frac{d\sigma}{d\Omega_e}\right)_{Mott} \frac{1}{(1+\tau)}\left[G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right]$$

distribution of magnetic moments

$$\text{with } \tau = \frac{Q^2}{4m_P^2} \text{ and } \varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]^{-1}$$

… and the slope of G_E

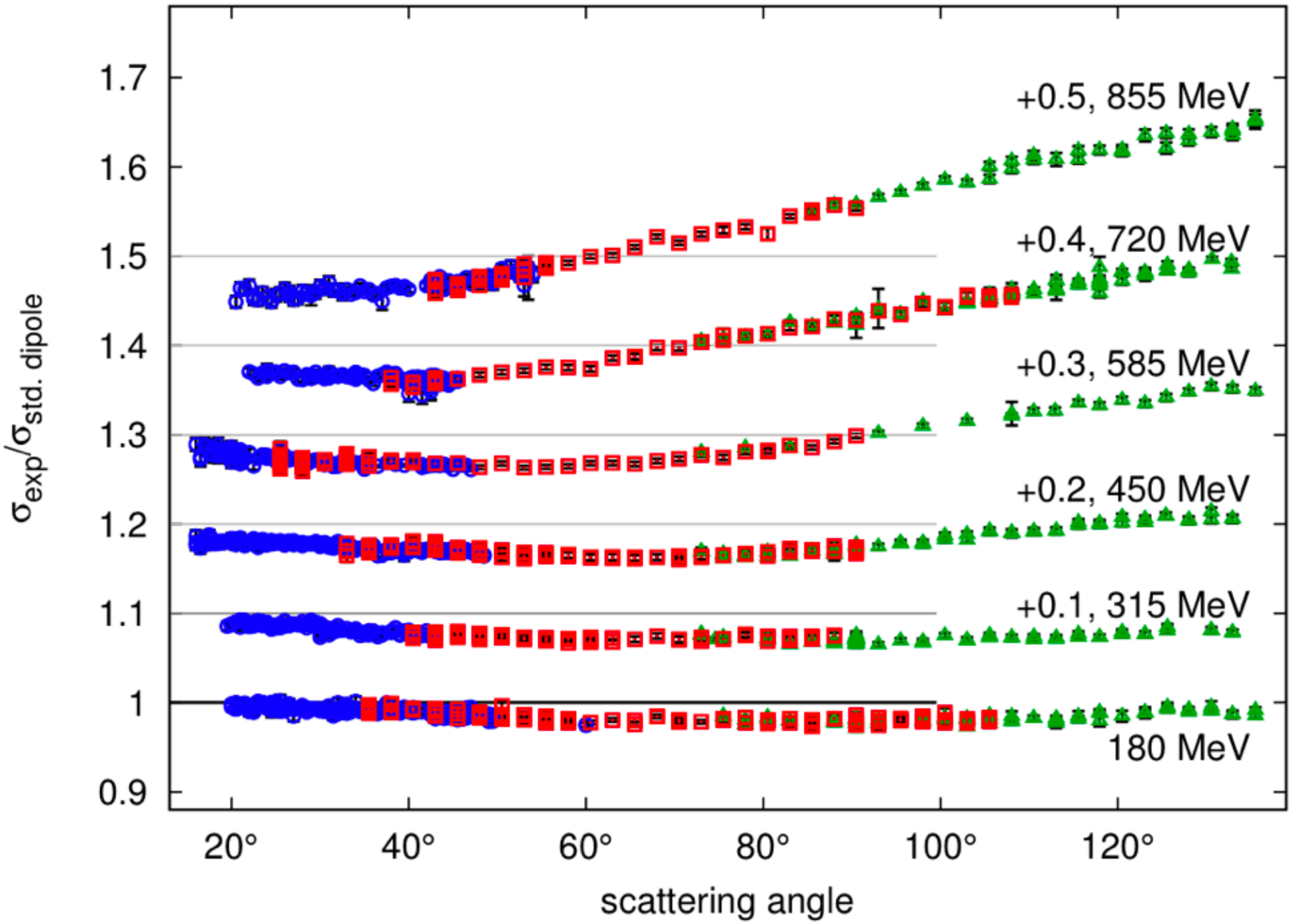
$$\langle r_E^2 \rangle = -6\hbar^2 \frac{d}{dQ^2} G_E(Q^2)\Big|_{Q^2=0}$$

Polarization transfer reaction: Measurement of recoil polarization

✔ Little contribution from TPE (?)

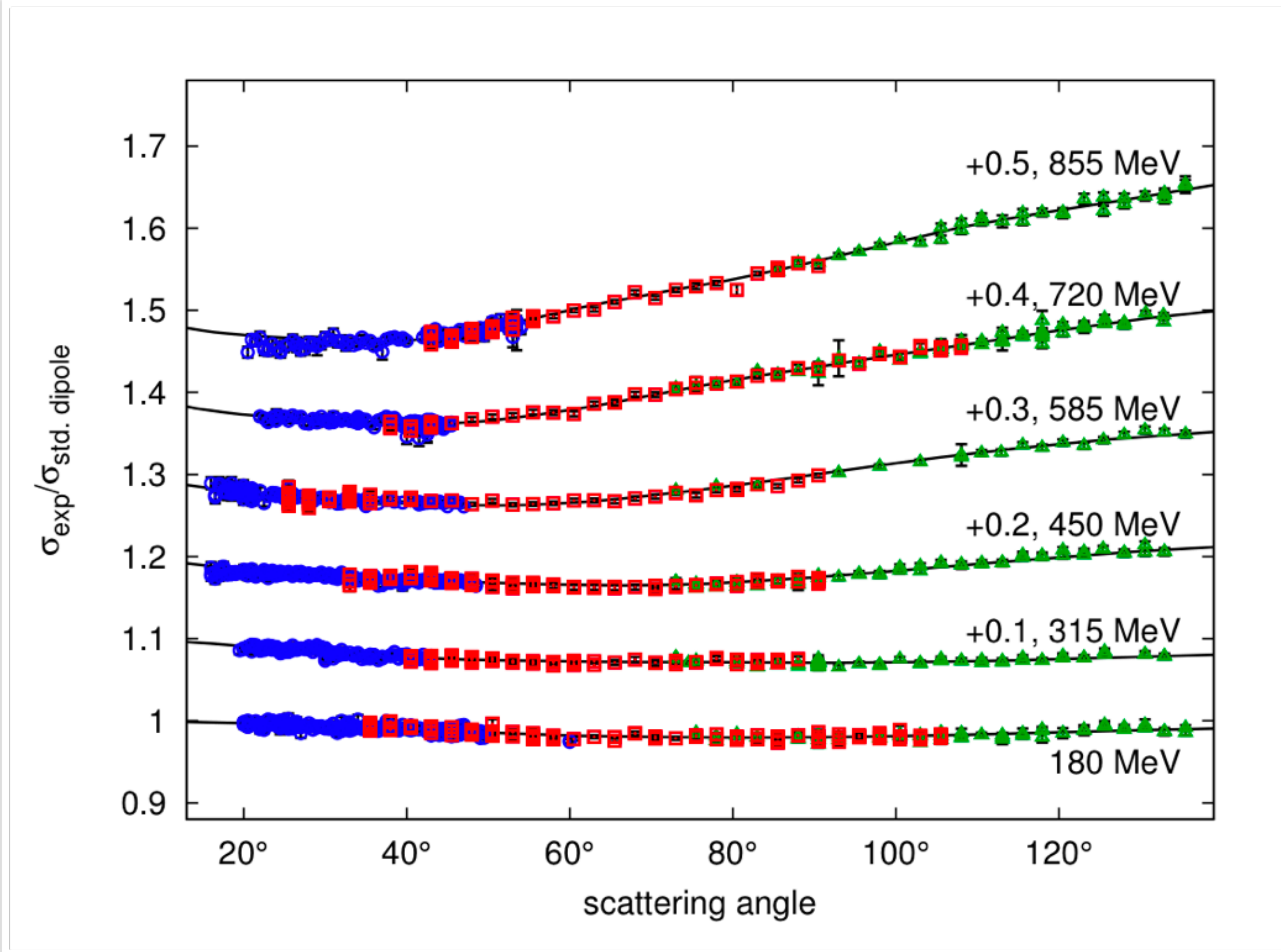
✖ Only ratio $G_E(Q^2)/G_M(Q^2)$ + difficult below $Q^2 \approx 0.2\ \mathrm{GeV}^2/c^2$

Cross sections/standard Dipole



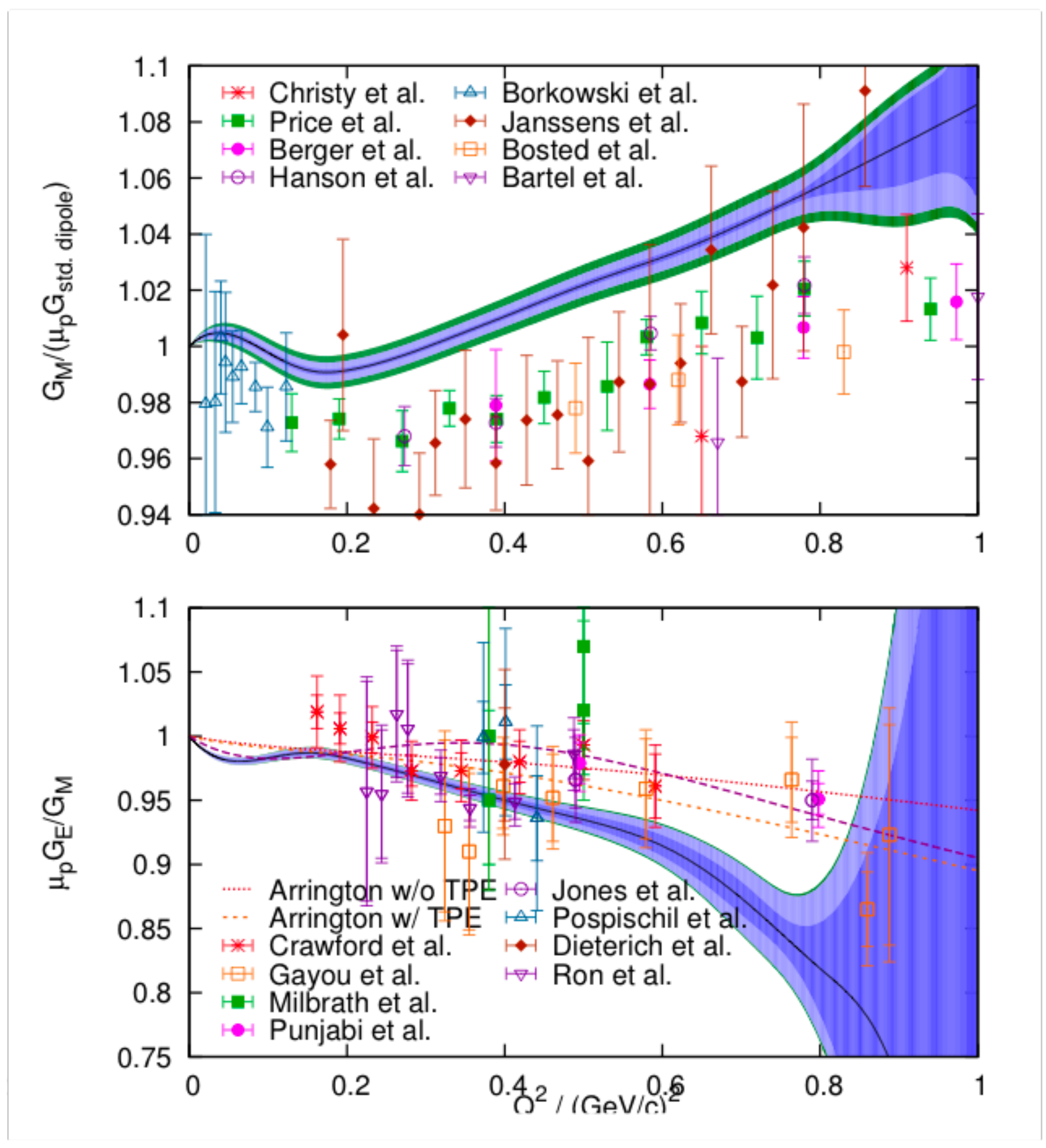
Jan C. Bernauer et al., Phys. Rev. Lett. 105, 242001 (2010)

Cross sections + spline fit

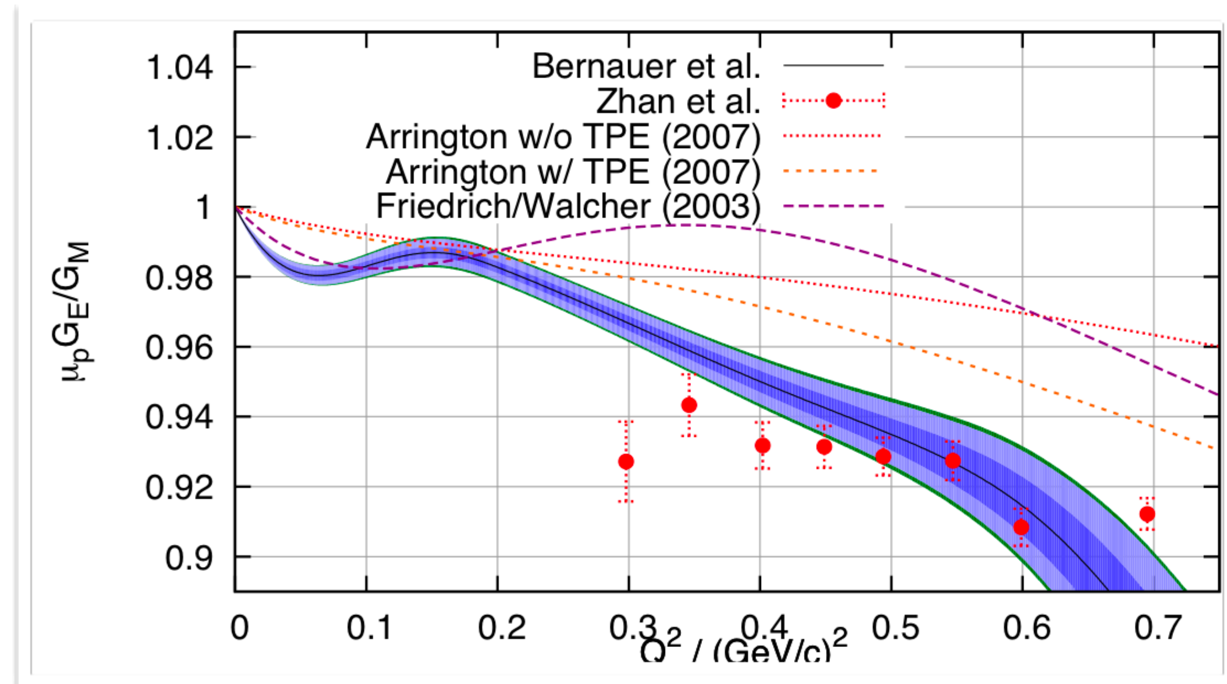


Jan C. Bernauer et al., Phys. Rev. Lett. 105, 242001 (2010)

Form Factor results: G_E/G_M ratio



Jan C. Bernauer et al., Phys. Rev. Lett. 105, 242001 (2010)



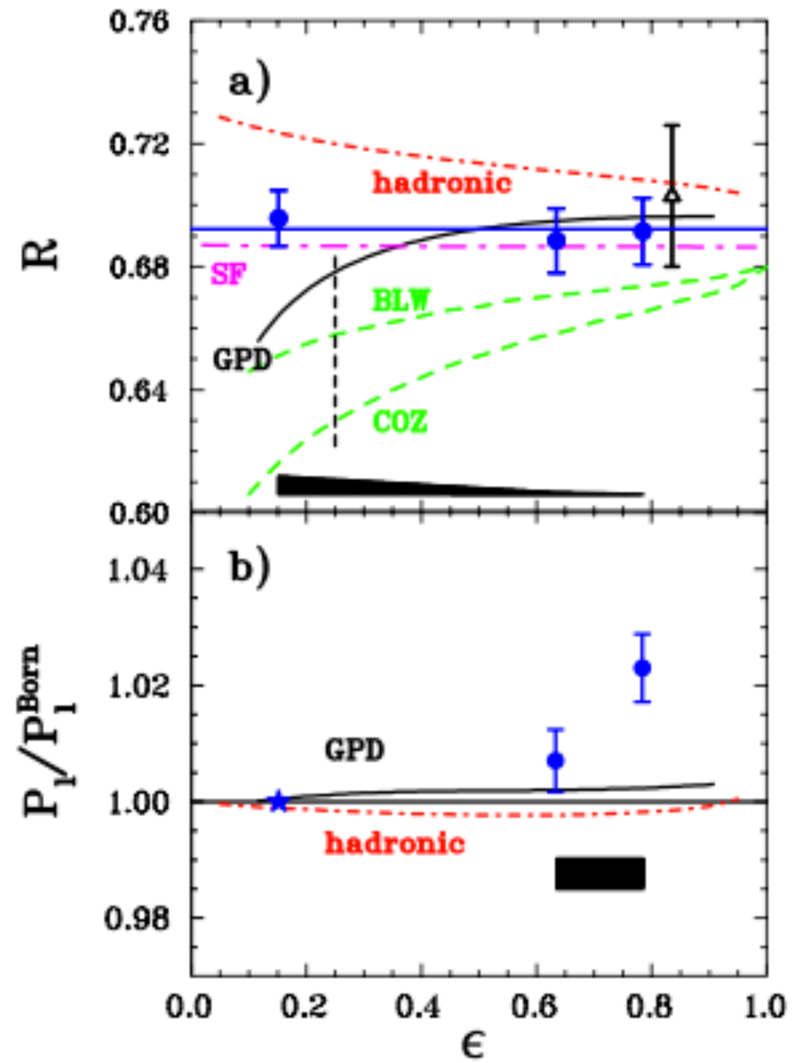
X. Zhan et al., arXiv:1102.0318
J. Arrington et al., Phys. Rev. C76 (2007) 035205

Comments on TPE

- Two-photon exchange (TPE) with and w/o excited intermediate states:
  Exchange of two hard photons

  Still not reliable and highly debated

  Figure shows a recent experimental result from JLab.

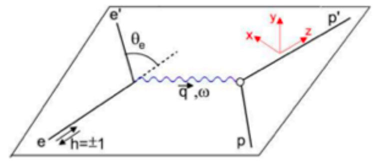


Meziane, M. et al.: *Search for effects beyond the Born approximation in polarization transfer observables in $\vec{e}p$ elastic scattering*, PRL 106, 132501 (2011), arXiv:1012.0339

Rosenbluth vs. Polarization Transfer

Polarization transfer reaction:

$$\vec{e} + p \to e + \vec{p}$$



Longitudinal and transverse polarization:

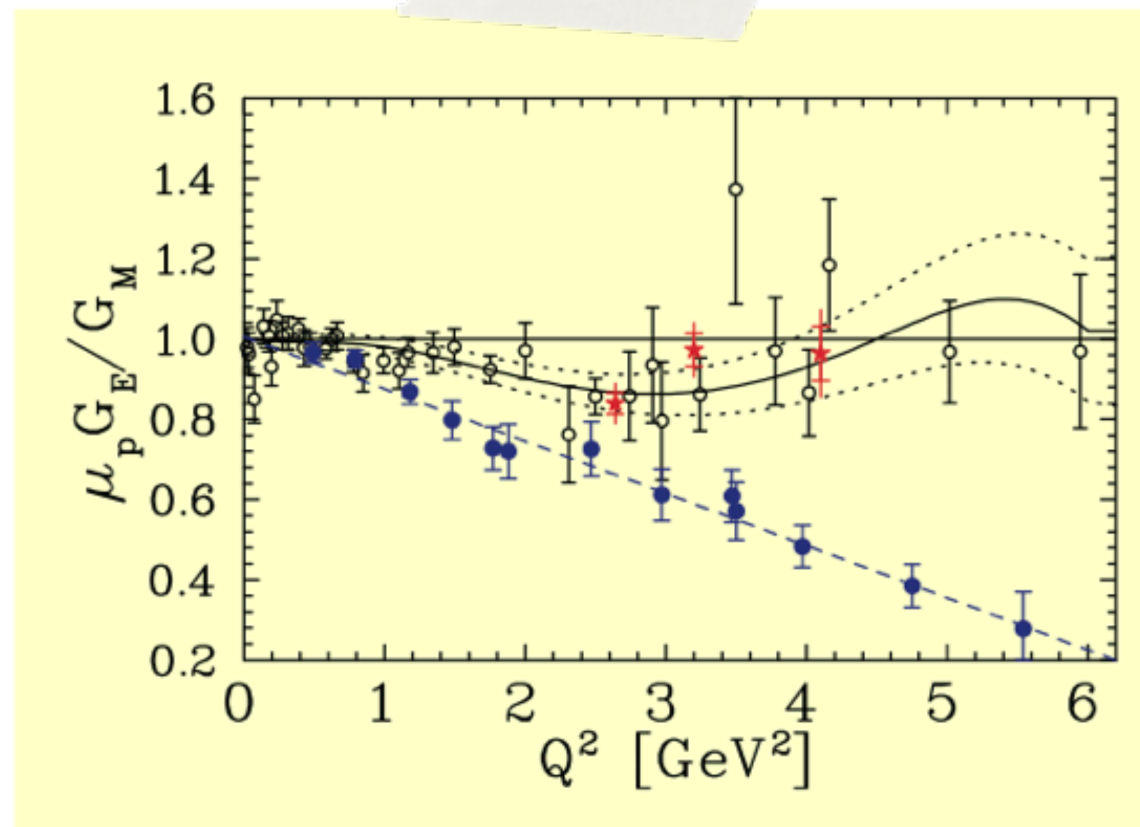
$$P_z = \frac{E+E'}{mI_0}\sqrt{\tau(1+\tau)}G_M^2 \tan^2\frac{\theta}{2}$$

$$P_x = -\frac{2}{I_0}\sqrt{\tau(1+\tau)}G_E G_M \tan\frac{\theta}{2}$$

$$I_0 = G_E^2 + \tau\left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]G_M^2$$

$$\Rightarrow \quad \frac{G_E}{G_M} = -\frac{P_x}{P_z}\frac{(E+E')}{2m}\tan\frac{\theta}{2}$$

- Signal proportional to $G_E(Q^2)$
- Systematic errors cancel out
- Requires measurement of recoil polarization



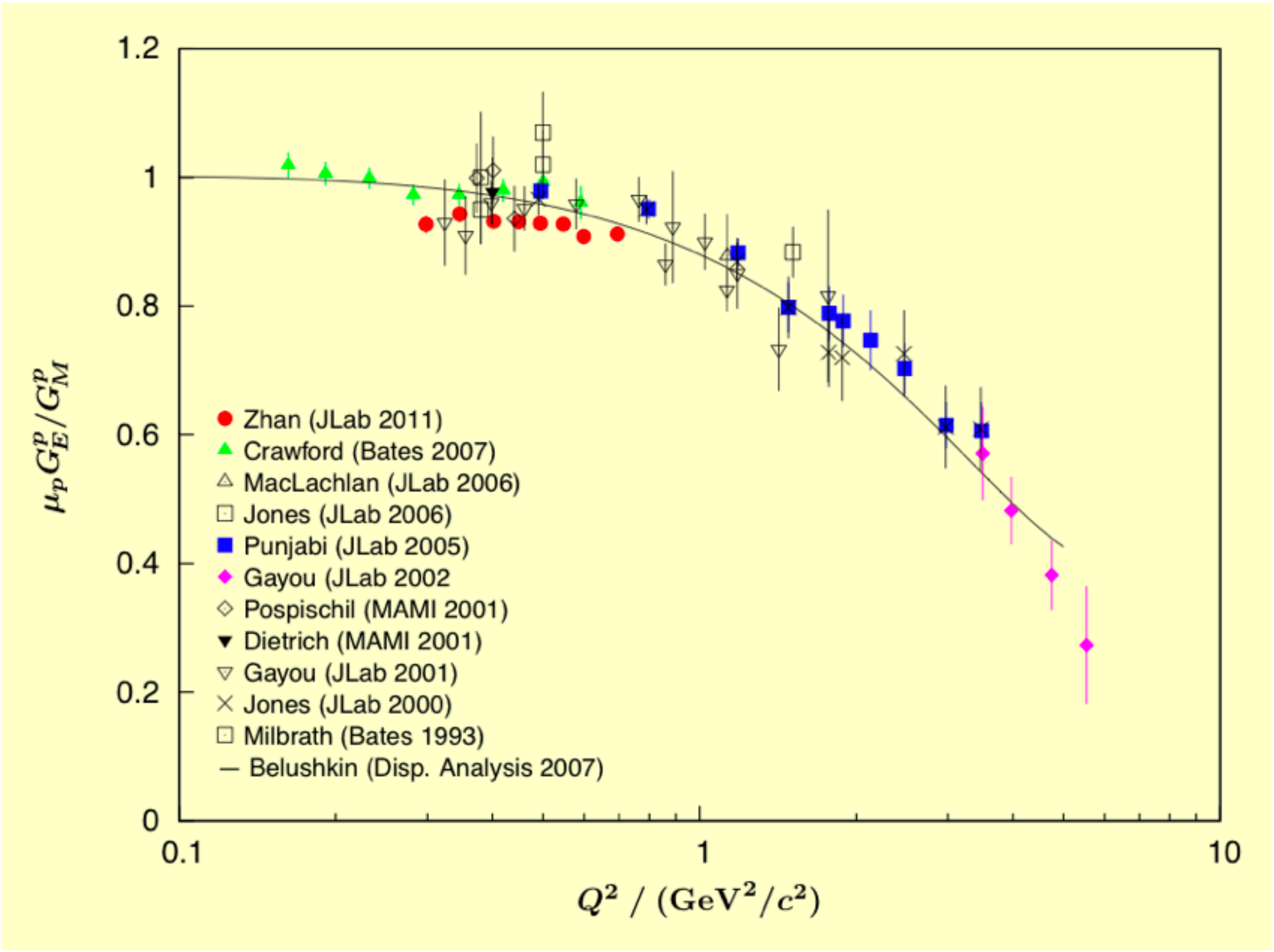
- Different results from different experimental techniques

⇒ 2-Photon Exchange

● M. K. Jones *et al.*, Phys. Rev. Lett. **84**, 1398 (2000), , O. Gayou *et al.*, Phys. Rev. Lett. **88**, 092301 (2002)

★ I. A. Qattan *et al.*, Phys. Rev. Lett. **94**, 142301 (2005)

Recent data on polarization transfer

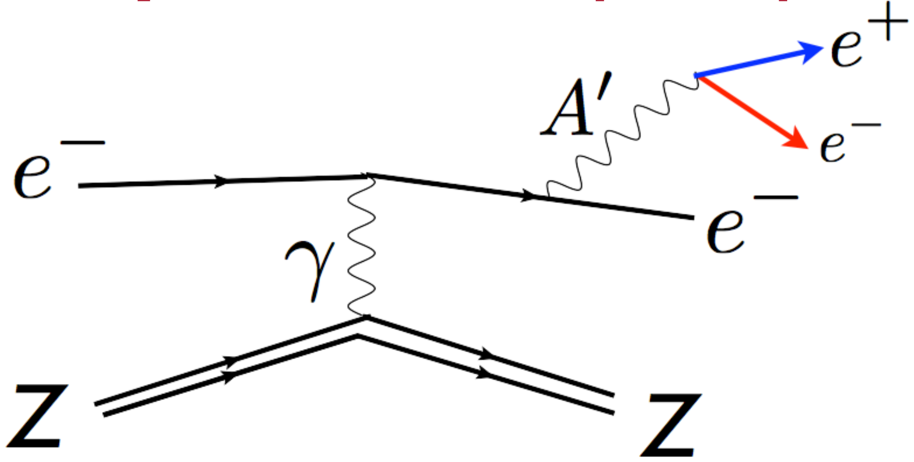


- Discrepancy at high Q^2 Rosenbluth $\not\leftrightarrow$ Polarization transfer
- High quality data not yet consistent at low Q^2

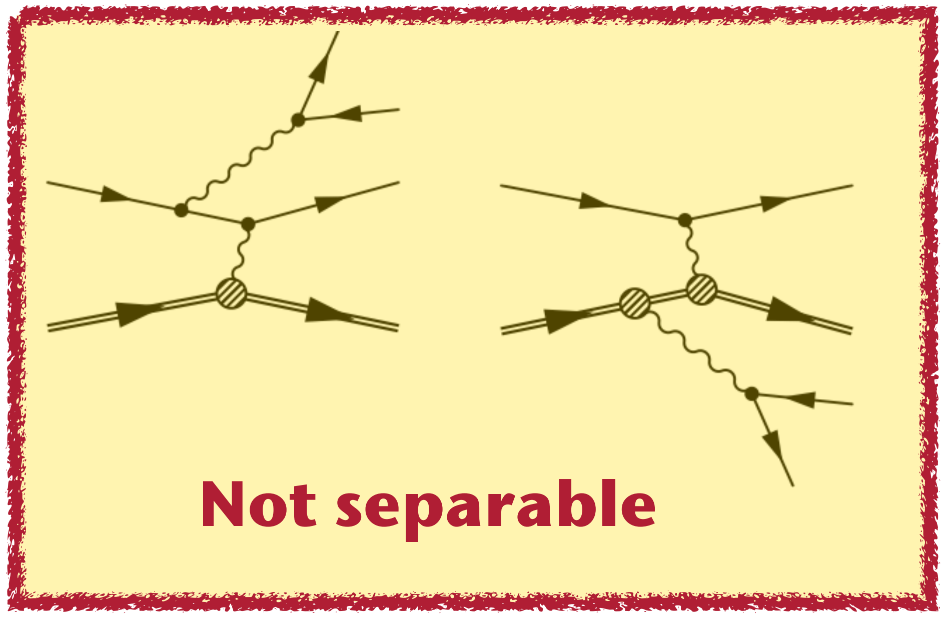
Search for the Dark Photon @ MAMI

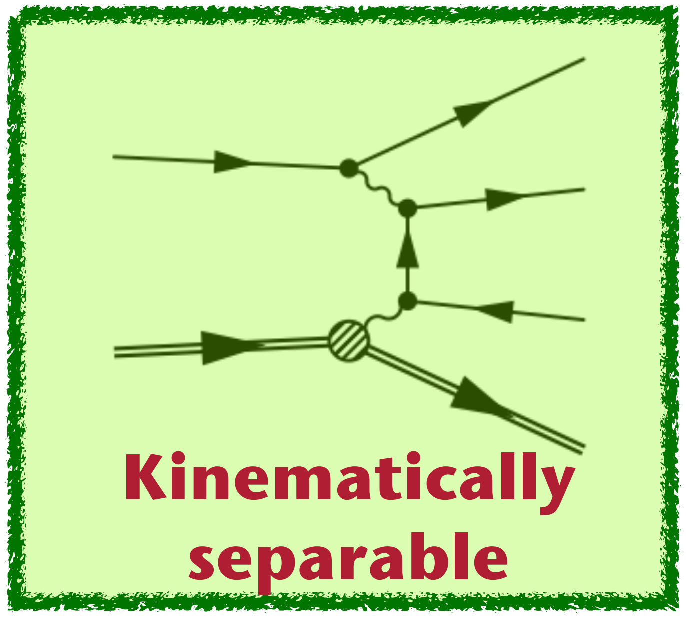
H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

Bump Hunt: Quasi-photoproduction off ^{181}Ta target



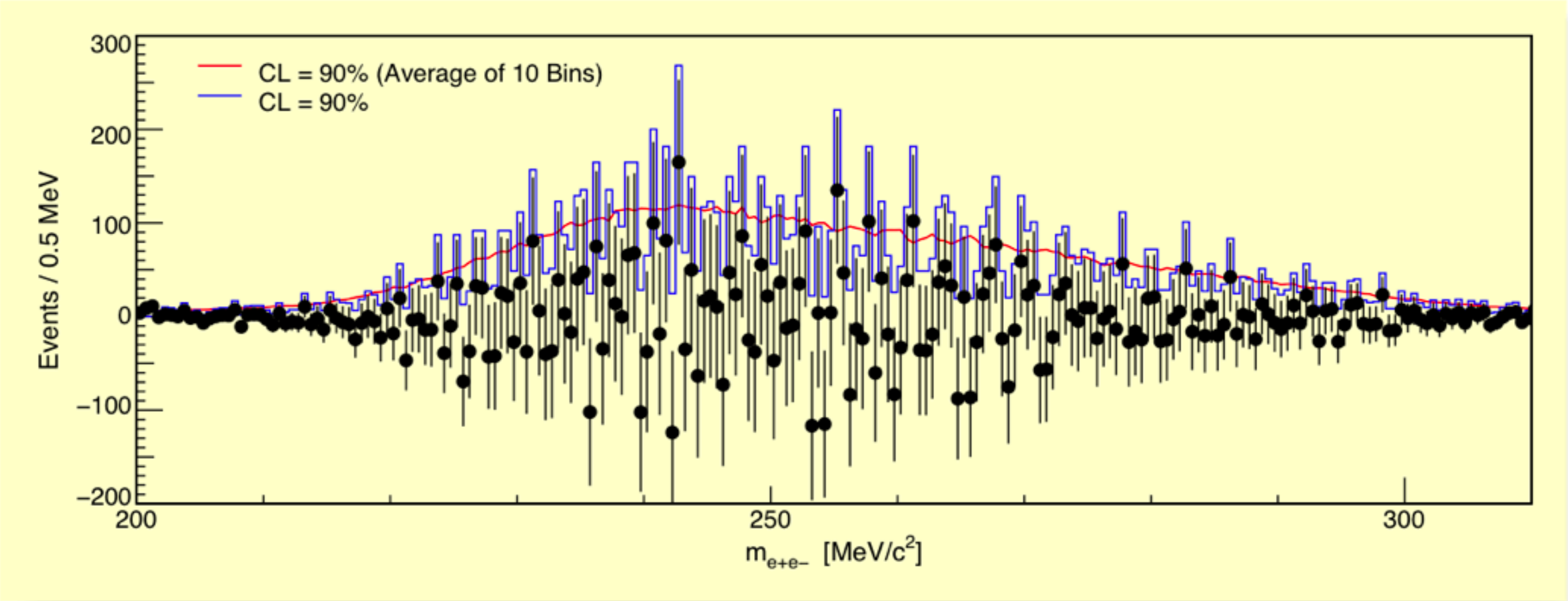
➢ **Fight background ….**





Exclusion limits

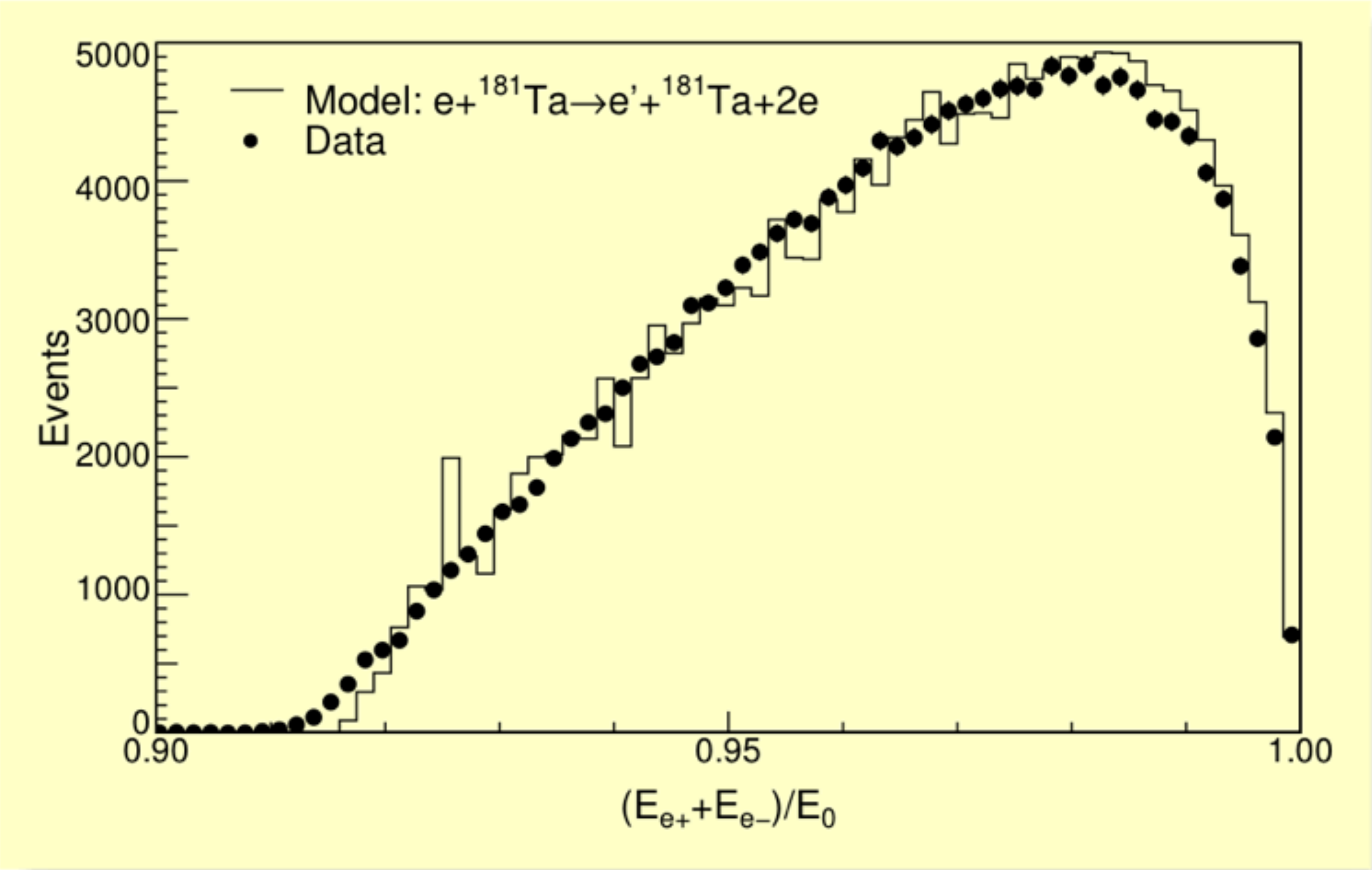
H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802



- Confidence interval by Feldman-Cousins algorithm
- "Model" for Background-subtraction:
  average of 3 Bins left and right of central bin
- Resolution $\delta m < 500\,\mathrm{keV}$ = bin width
- Averaging (mean of 10 bins) only for "subjective judgment"

Improved model

H. Merkel et al., Phys. Rev. Lett. 106 (2011) 251802

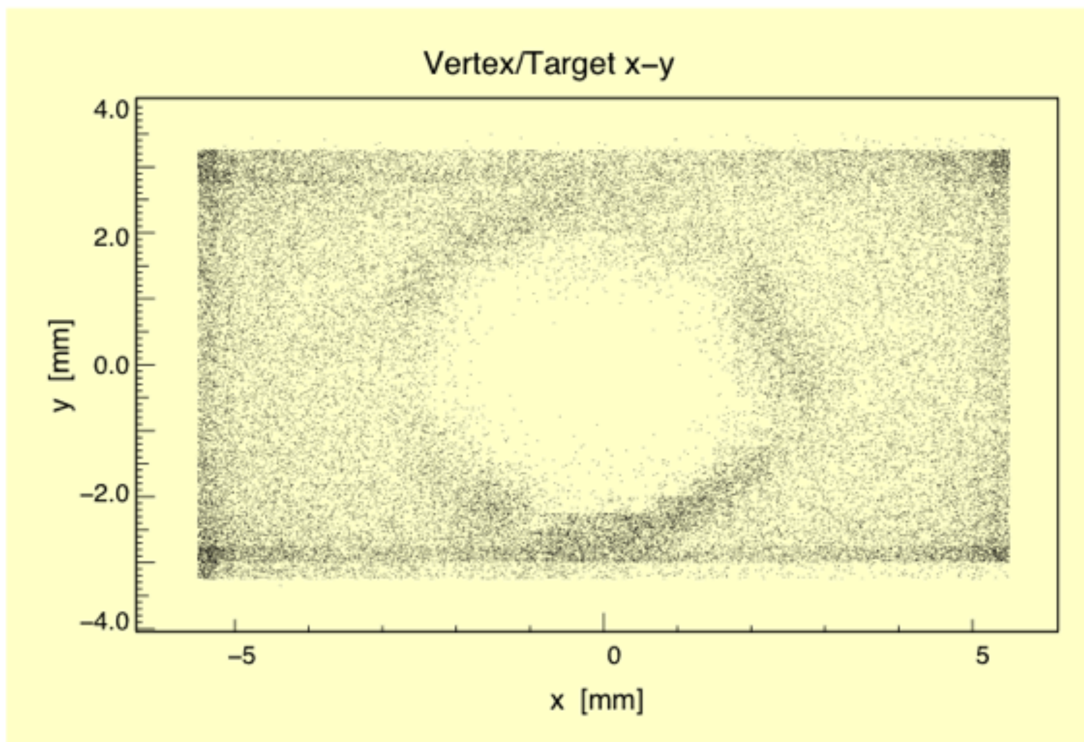


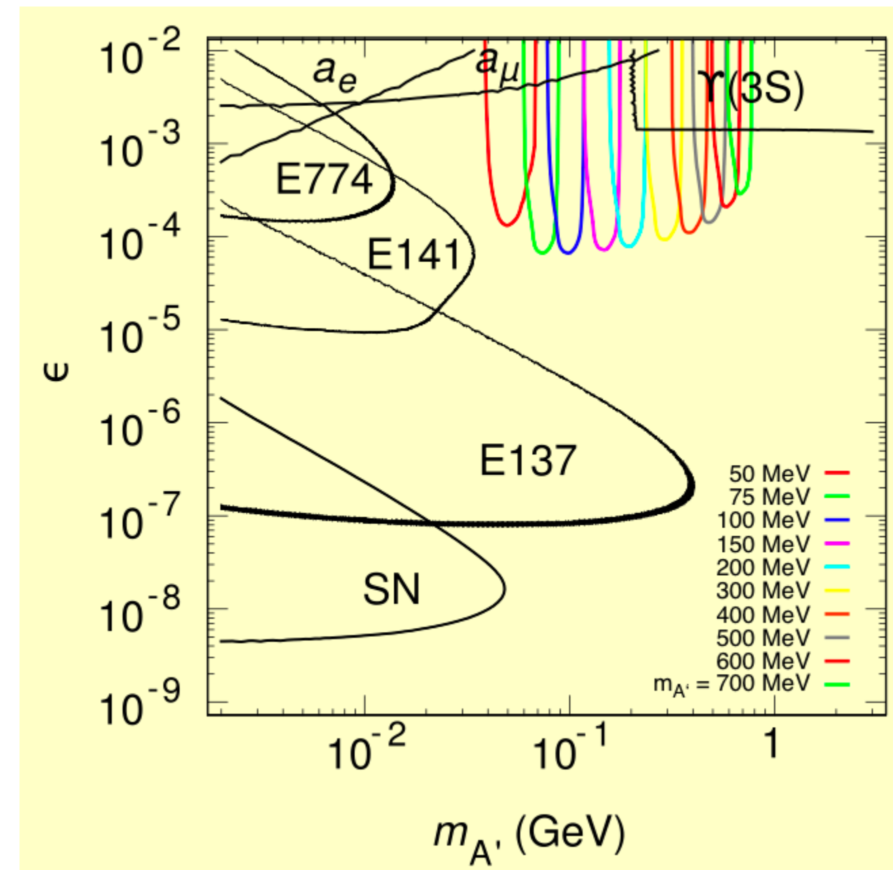
- Full Simulation
- Model: Coherent electroproduction production off heavy nucleus
- Q.E.D., nuclear form factor, coherent sum of all contributions, radiation corrections, . . .

⇒ Describes data within a few percent

Limitation of the experiment

$100\,\mu$A beam current for 20 min on 0.05 mm ^{181}Ta target (melting point: 3017 °C):





- Air activation
- Optimization of kinematics
- Target cooling
- Shielding

$\Rightarrow$ 1 order of magnitude higher count rates possible

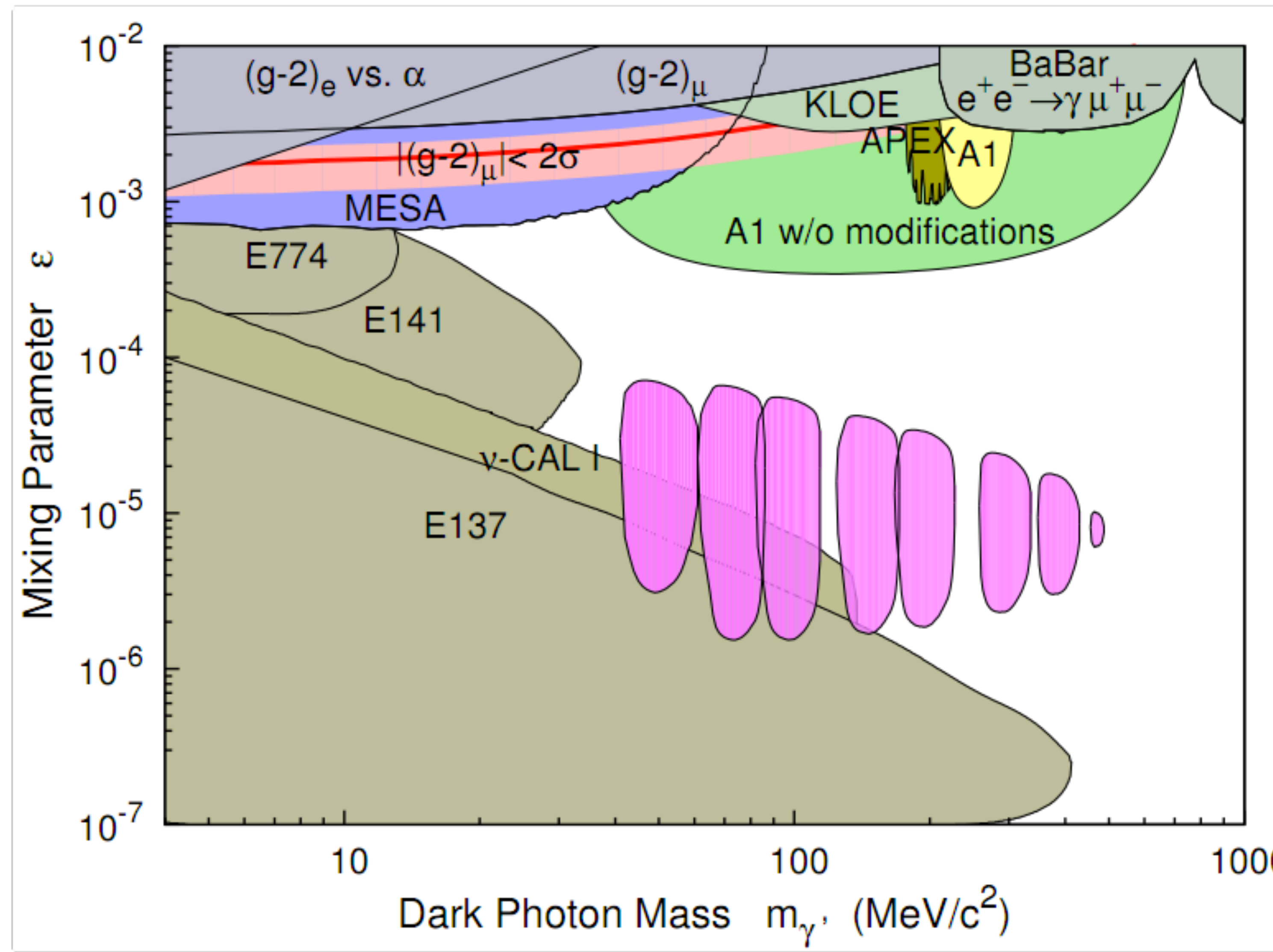
Hunting program

❶ **Pair production on heavy target**
$\varepsilon > 4 \cdot 10^{-4}$

❷ **Low energy – high current**
$m_{\gamma'} < 50$ MeV/c²

❸ **Finite production vertex**
$10^{-6} < \varepsilon < 10^{-4}$
Sensitivity to shorter decay length
☞ Beam stabilization, shielding, target cooling

The Intensity Frontier …



APEX: S. Abrahamyan et al., Phys. Rev. Lett. 107 (2011) 191804
KLOE: F. Archilli et al., Phys. Lett. B. 706 (2012) 251

Access to small mass region:

Low energy – high current accelerator
Minimize multiple scattering by **gas target**
4π detector @ 200 MHz with high resolution
DarkLight (JLab FEL), MESA at Mainz