The PRAE Multidisciplinary project at Orsay

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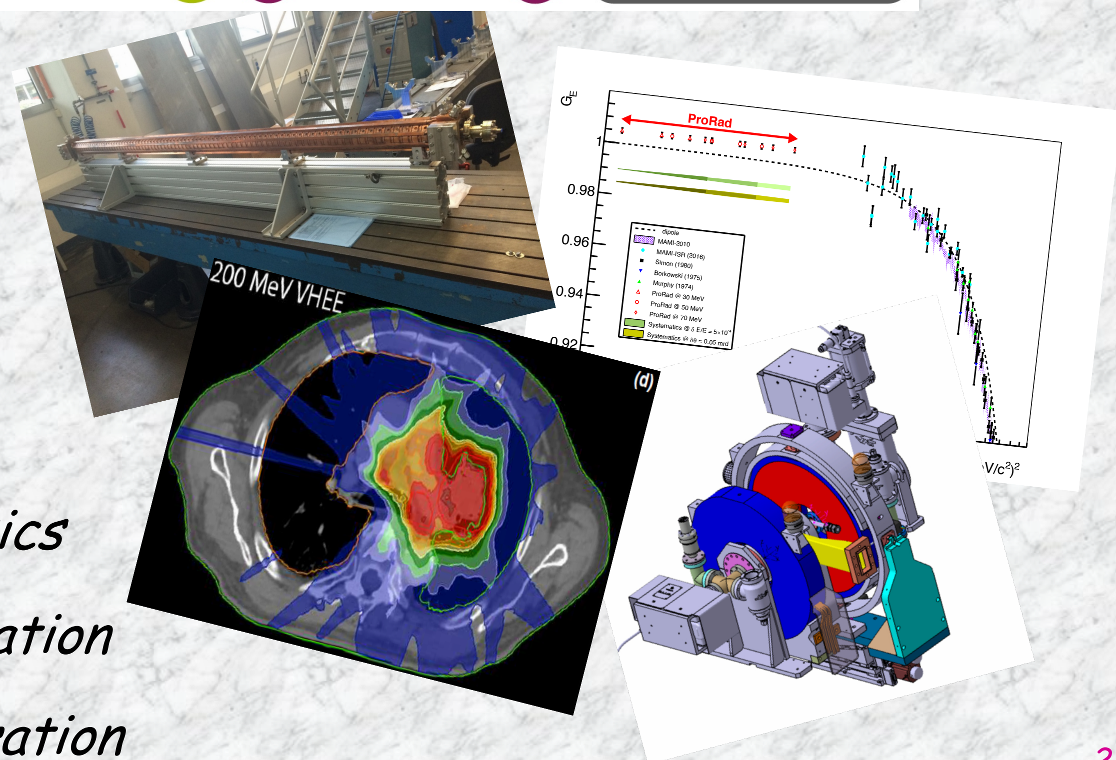
Orsay, France

http://workshop-prae2018.lal.in2p3.fr/

Platform for Research and Applications with Electrons

PRAE

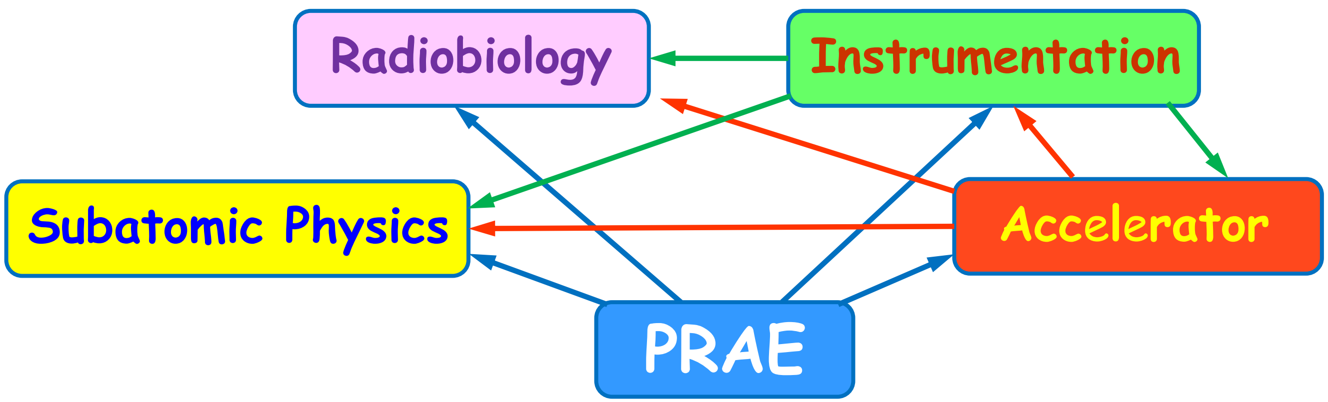


- *The PRAE project*
  - *The PRAE facility*
    - *Radiobiology*
      - *Subatomic physics*
        - *Instrumentation*
          - *Collaboration*

Platform for Research and Applications with Electrons

C. Vallerand, P. Duchesne et al.

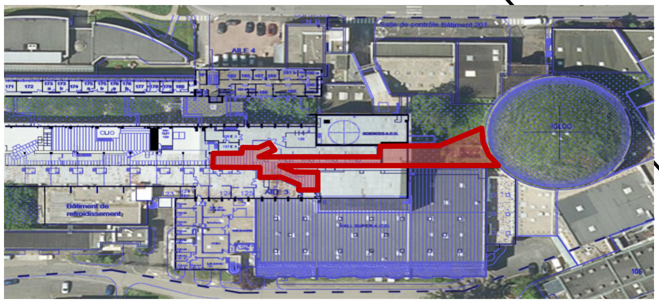
- **PRAE** aims at providing, on the Orsay campus, a **multidisciplinary facility** for innovative **R&D** in **radiobiology**, **instrumentation**, and **subatomic physics**… using a **high performance electron beam** in the **30-140 MeV** energy range.



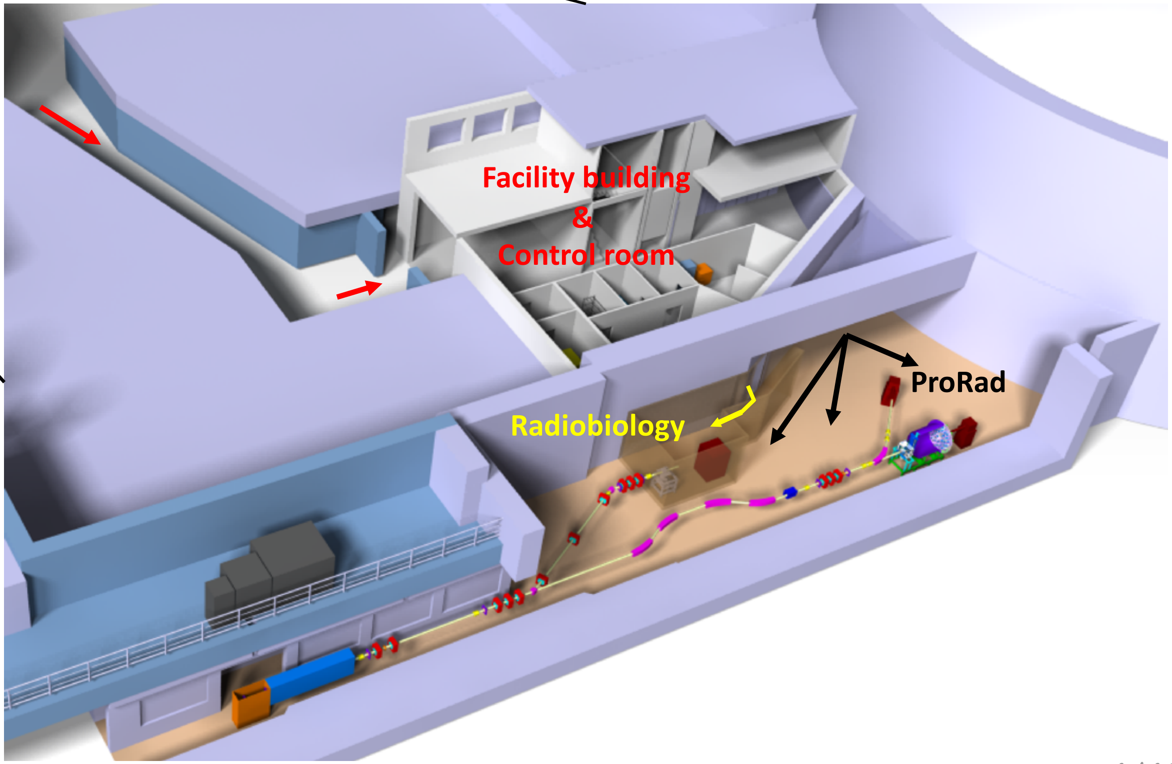
R. Delorme, D. Marchand, C. Vallerand, Nucl. Phys. News 29 (2019)

PRAE @ LAL.Orsay

D. Marchand et al. EPJ Web Conf. 138 (2017)



Former site of the Linear Accelerator

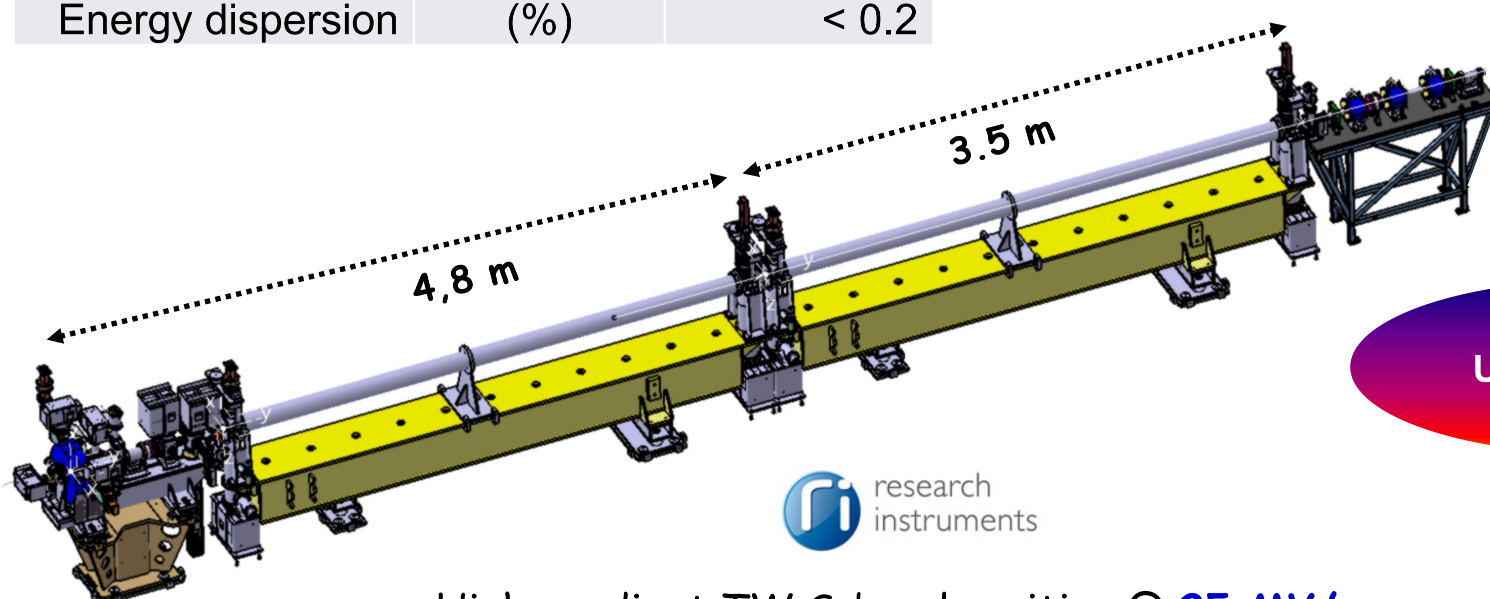


The Accelerator

A. Faus-Golfe et al.

Beam parameters		Phase I (II)
Maximum energy	(MeV)	70 (140)
Charge	(nC/bunch)	0.00005 – 2
Emittance	(mm.mrad)	3-10
Repetition rate	(Hz)	50
Bunch length	(ps)	< 10
Energy dispersion	(%)	< 0.2

S. Barsuk et al. JACoW (2017) THPVA079
A. Faus-Golfe et al. JACoW (2018) MOPML051



Up to 140 MeV

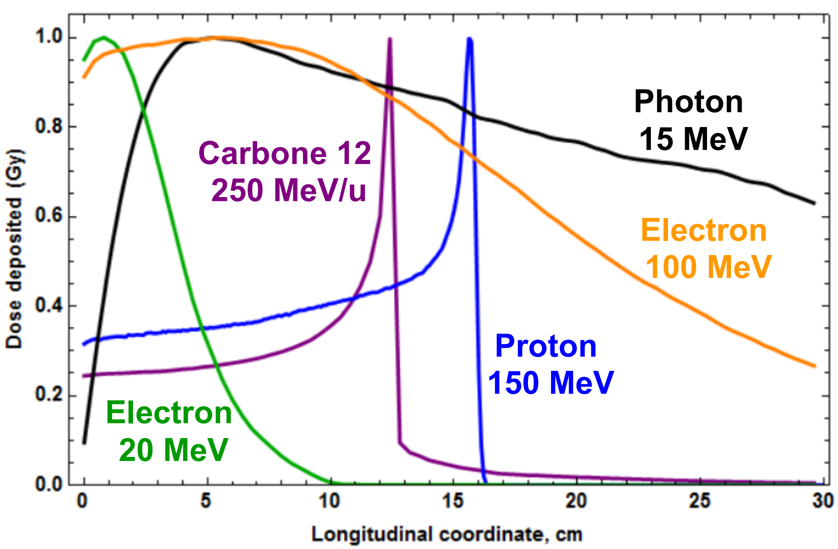
research instruments

High gradient TW S-band cavities @ **25 MV/m**

Challenge

R. Delorme, A. Faus-Golfe et al.

- An essential challenge of radiotherapy techniques is the development of **new methods** combining **higher treatment efficiency** of tumor cells while **improving treatment tolerances** in **better preserving healthy tissues** and **reducing radiation exposure**.



This compromise is all the more difficult to achieve that the **location** of the tumor, the **dose exposure** and **biological effects** are not **exactly known**.

Challenge

R. Delorme, A. Faus-Golfe et al.

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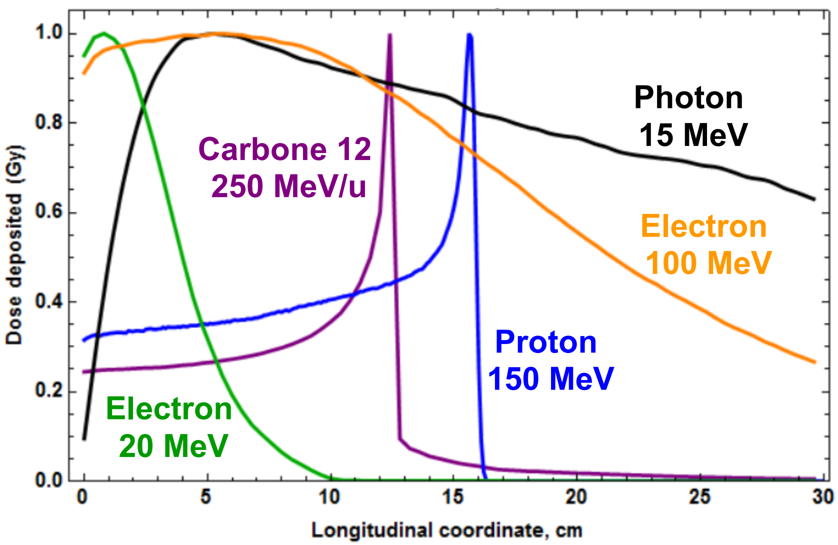

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The clinical potential of high energy electrons will be studied at PRAE.

Precision Measurements

E. Voutier, C. Le Galliard et al.

➢ The beam line for **Subatomic Physics** is designed to allow for **high-precision measurements**, and will comprise **advanced equipments** for **monitoring** and **control** of the beam.

Beam Precision

- Reduced **momentum dispersion** (a few 10^{-4})
- Accurate **energy** measurement (a few 10^{-4})
- Accurate **charge** knowledge before and after the interaction region ($<10^{-3}$)

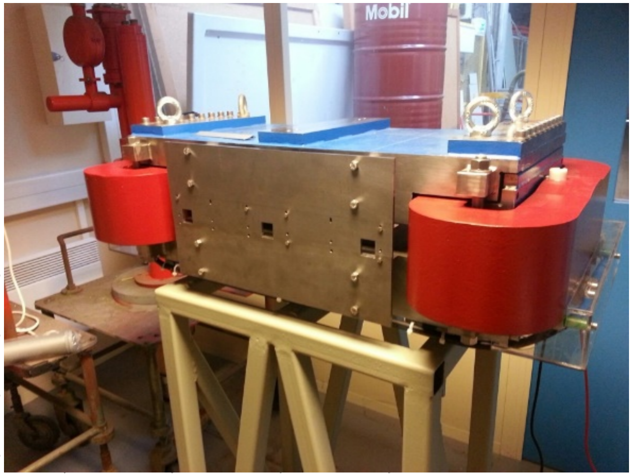
- Beam **position** feedback loop
- Beam **energy** feedback loop

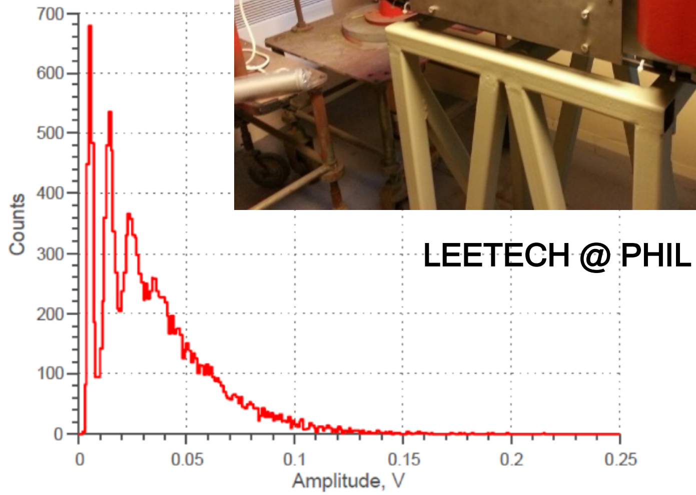
Detector R&D

B. Genolini, C. Le Galliard et al.

➢ Providing to users a **high-performance platform** to characterize the **time** and **charge response** of **detectors**.

V. Kubytskyi et al. JINST 12 (2017) P02011





Beam Performances

- **Accuracy** of the reference time (<10 ps)
- **Accuracy** of the beam charge (<0.2%)
- **Accuracy** of the beam position and profile

- **Single-electron** beam capabilities

The PRAE Team

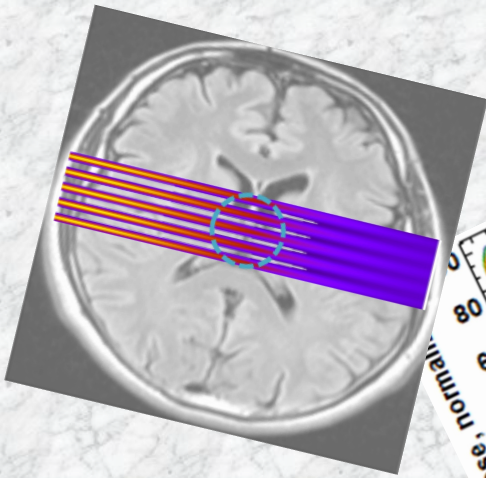
INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

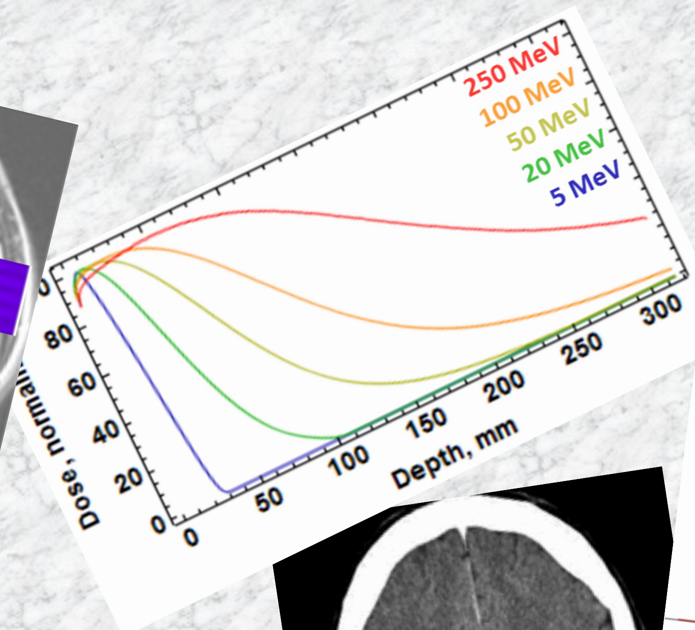
LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

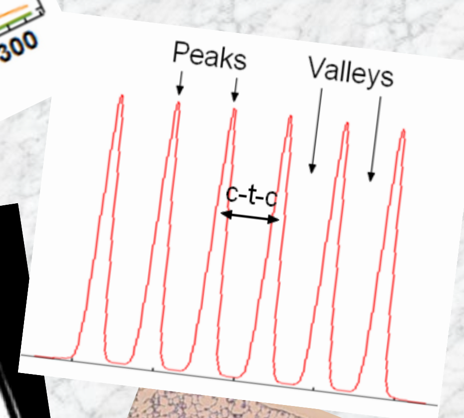
M. Alves, D. Auguste, P. Ausset, M. Baltazar, S. Barsuk, M. Ben Abdillah, L. Berthier, J. Bettane, S. Blivet, D. Bony, B. Borgo, C. Bourge, C. Bruni, J.-S. Bousson, L. Burmistrov, H. Bzyl, L. Causse, F. Campos, C. Caspersen, J-N Cayla, V. Chambert, V. Chaumat, J-L Coacolo, P. Cornebise, R. Corsini, O. Dalifard, V. Dangle-Marie, R. Delorme, R. Dorkel, N. Dosme, D. Douillet, R. Dupré, P. Duchesne, N. El Kamchi, M. El Khaldi, W. Farabolini, A. Faus-Golfe, V. Favaudon, C. Fouillade, V., Frois, L. Garolfi, Ph. Gauron, G. Gautier, B. Genolini, A. Gonnin, D. Grasset, X. Grave, M. Guidal, E. Guérard, H. Guler, Y. Han, S. Heinrich, M. Hoballah, J-M Horondinsky, H. Hrybok, P. Halin, G. Hull, D. Ichirante, M. Imre, C. Joly, M. Jouvin, M. Juchaux, W. Kaabi, S. Kamara, M. Krupa, R. Kunne, V. Lafarge, M. Langlet, P. Laniece, A. Latina, T. Lefebvre, C. Le Galliard, E. Legay, B. Lelouan, P. Lepercq, J. Lesrel, D. Longieras, C. Magueur, G. Macmonagle, D. Marchand, A. Mazal, J-C Marrucho, G. Mercadier, B. Mathon, B. Mercier, E. Mistretta, H. Monard, C. Muñoz Camacho, T. Nguyen Trung, S. Niccolai, M. Omeich, A. MardamBeck, B. Mazoyer, A. Pastushenko, A. Patriarca, Y. Peinaud, A. Perus, L. Petizon, G. Philippon, L. Pinot, P. Poortmanns, F. Pouzoulet, Y. Prezado, V. Puill, B. Ramstein, E. Rouly, P. Robert, T. Saidi, V. Soskov, A. Said, A. Semsoum, A. Stocchi, C. Sylvia, S. Teulet, I. Vabre, C. Vallerand, P. Vallerand, J. Van de Wiele, M.A. Verdier, P. Verelle, O. Vitez, A. Vnuchenko, E. Voutier, S. Wallon, E. Wanlin, M. Wendt, W. Wuensch, S. Wurth

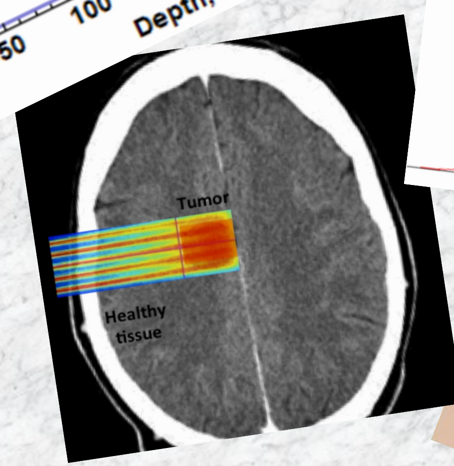
With the support of: institut Curie, CERN, CSNSM, IDEATE LIA, SLAC NATIONAL ACCELERATOR LABORATORY

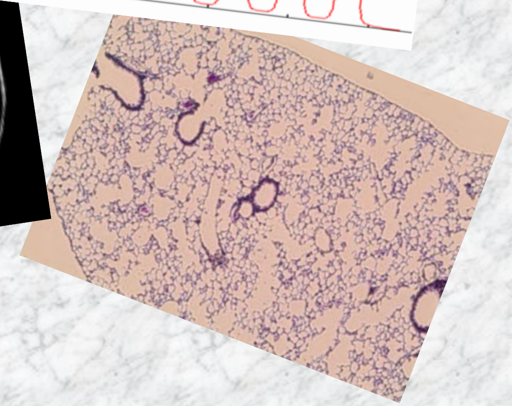
Very High Energy Electron Grid Therapy











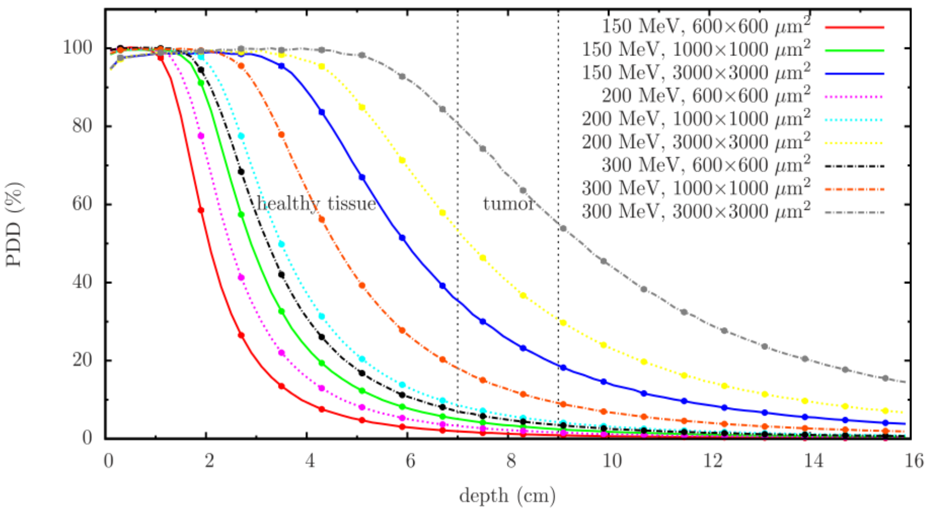
- Why electrons ?
  - SFRT
    - Grid therapy
      - eHGRT

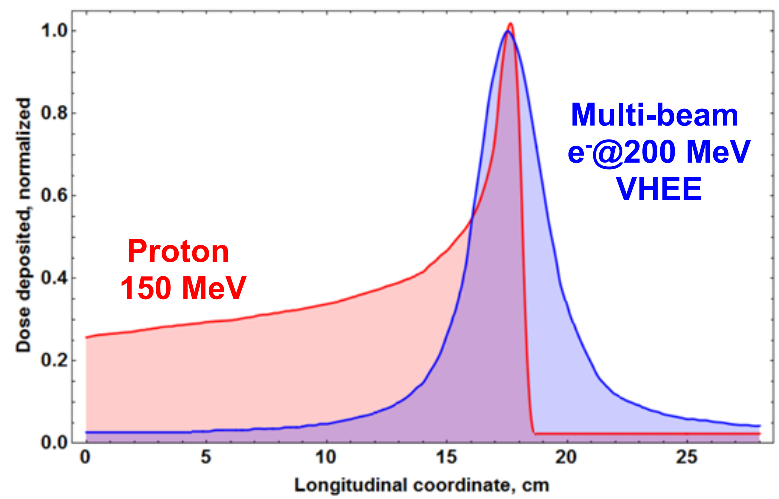
Very High Energy Electrons

VHEE

I. Martinez-Rovira, G. Fois, Y. Prezado Med. Phys. 42 (2015) 685

A. Lagzda, R.M. Jones, D. Angal-Kalinin, J. Jones, CALIFES Workshop (2016)





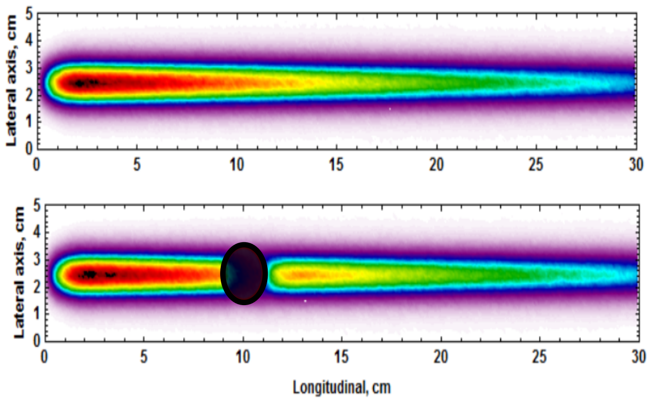
- **Simulations** suggest that the **depth deposition** of the same given dose **increases with** the electron **beam energy**, which compensates the rapid dose fall-off due to very small beam sizes.
- **Focused electron beams** within a multi-beam configuration would allow to deliver the same dose at the same depth than a proton beam while **reducing exposure of healthy tissue** at the entrance.

Comparative Capabilities

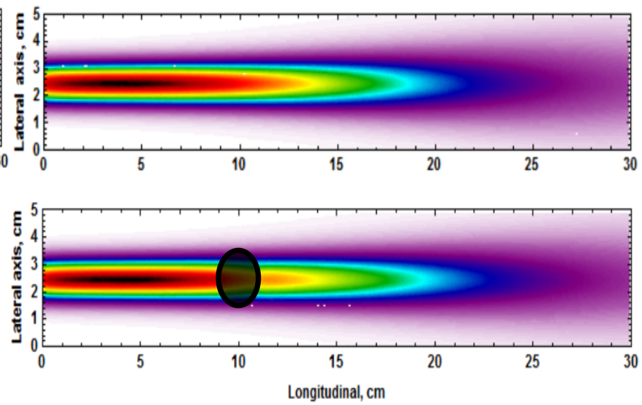
A. Lagzda et al. JACoW (2018) MOPML023

- ***Dose profile*** : VHEE can access deep-seated tumors with a flatter dose profile than photons and reduced penumbrae effects.

6 MV Photons

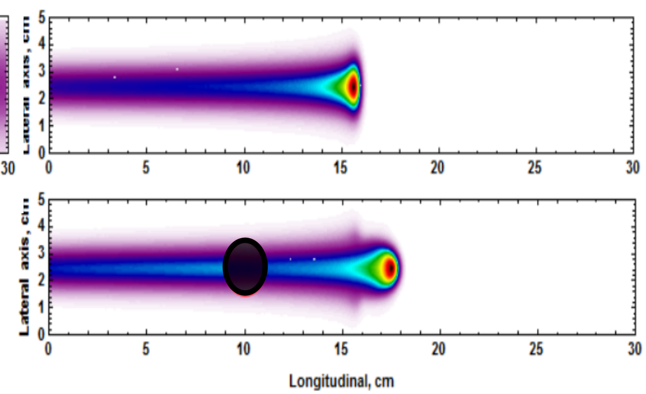


200 MeV Electrons



» ***Magnetic manipulation*** : electrons are more easily manipulated than protons, allowing for easy **pencil beam scan** capabilities.

150 MeV Electrons

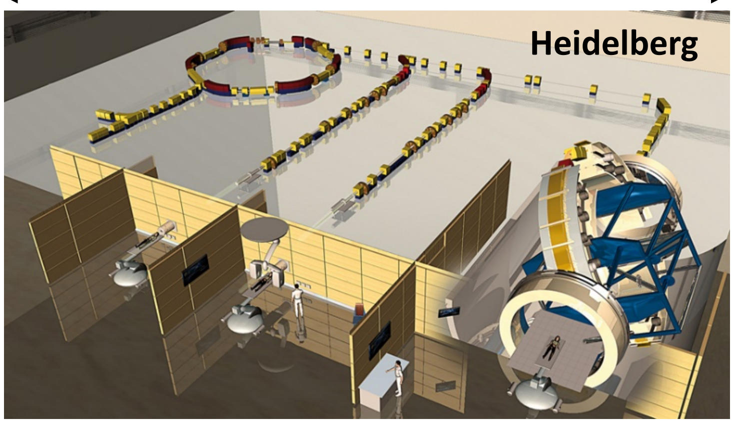


- ***Heterogeneities*** : dose deposition of VHEE is less sensitive to inhomogeneities of the irradiated media.

Facilities

➢ The **size**, the **construction** and the **running** costs of radiotherapy facilities directly **impact** the **number of patients** that can access such treatment.

Hadrontherapy center — 50 m



*~**130** hadron centers in the world*
50-100 M€

VHEE
~10 M€ ?

4 m — Standard medical accelerator

*~**500** in France*
~1 M€

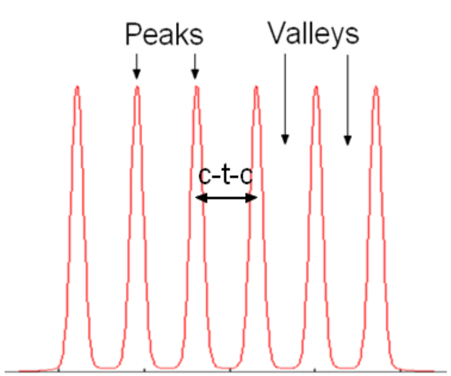
❑ **VHEE** beams would provide a **cost-effective** approach to cancer treatment, offering more **compact accelerators** and **easy beam manipulation**.

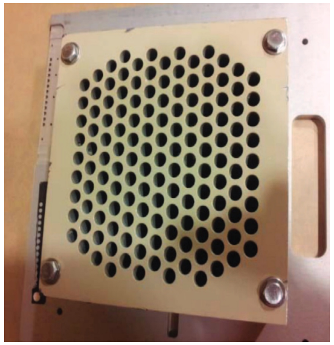
Mini-Beams

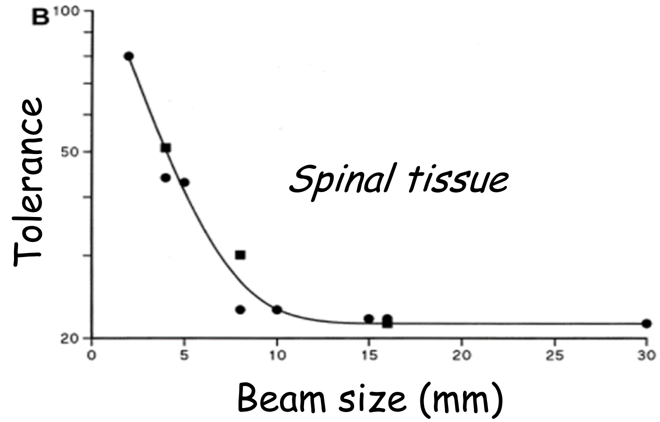
MBRT

M. Mohiuddin et al. Can. 66 (1990) 114 J.A. Penagarciano et al. Int. J Radiat. Oncol. Biol. Phys 76 (2010) 1369
H. Zhang et al. Tech. Can. Res. Trea. 15 (2016) 91

➢ The **spatial fractionation** of the dose exposure using a **grid of** centimeter **beams** is a known and demonstrated technique for the **palliative** treatment of cancers in **addition** to **conventional treaments**.







❑ Increase of the tolerance of healthy tissues of rats open the possibility to **increase the dose in tumors**.

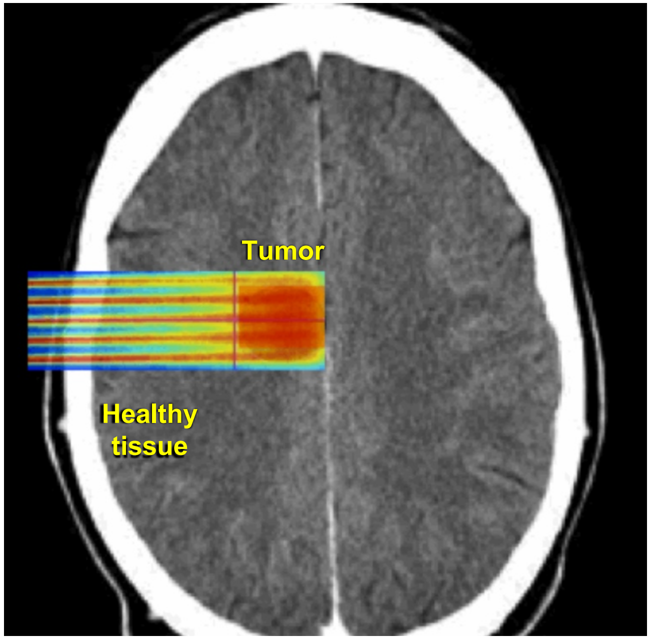
Dose-volume effect = the smaller the beam size, the higher the tolerance dose in healthy tissues.

Grid Therapy with High Energy Electrons

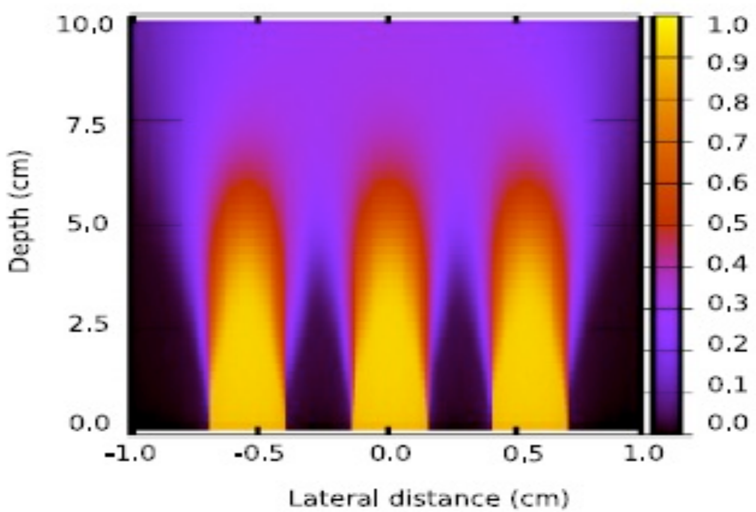
I. Martinez-Rovira, G. Fois, Y. Prezado Med. Phys. 42 (2015) 685 Y. Prezado et al. Sci. Rep. 7 (2017) 1 Y. Prezado et al. Sci. Rep. 8 (2018) 16479

- The **spatial fractionation** concept has been extented to **very small beam sizes**, and is investigated since 2014 with proton beams at the CPO.

Protons



Electrons

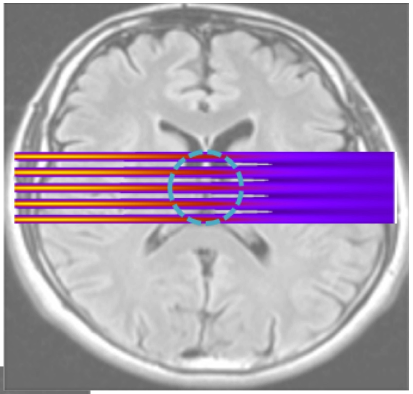


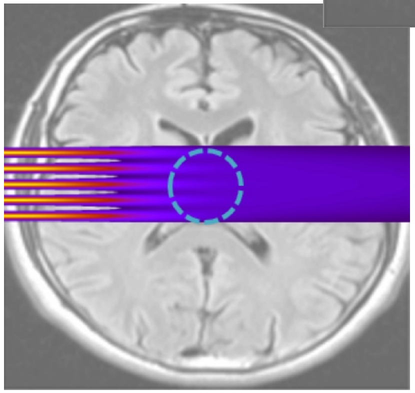
- **Grid therapy** approach using **millimetric VHEE** beams is now considered in Orsay.
- The small electron beams enlarge following **multiple scattering**, **sparing healthy tissue** and providing an **homogeneous illumination** at the tumor.

Radiobiology @ PRAE

- The **PRAE** facility is designed to **explore** and **evaluate VHEE therapy** and **Grid therapy** up to preclinical applications.

- **PRAE** will feature **unique in vivo capabilities**.
- ***PRAE intends to become a radiobiology user facility.***





eHGRT = VHEE+MBRT

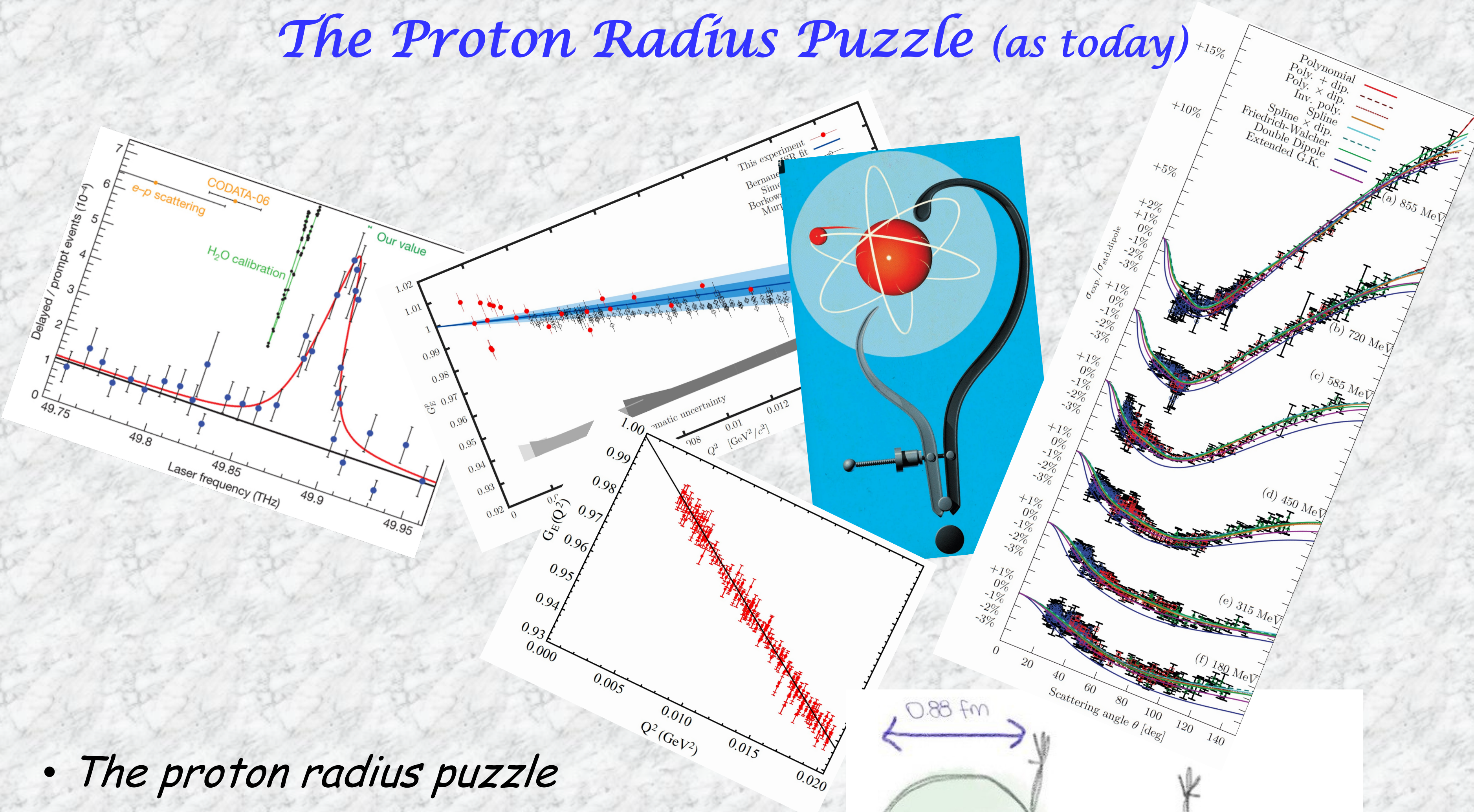
Radiobiology Beam

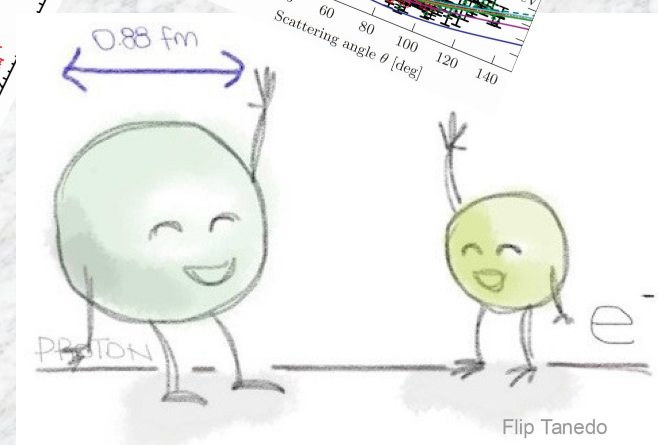
• **Small** beam **size**	150 μm < σ < 10 mm
• **Small** angular **dispersion**	0.1-0.4 mrad
• **Variable energy**	70-140 MeV
• **Dose** rate **dynamics**	0.035 Gy/s – 40 kGy/s

PRAE allows for other studies of VHEE beams :

- High dose rates for **FLASH therapy**
- Effect of **time structure** of pulsed beams on cells
- ...

The Proton Radius Puzzle *(as today)*



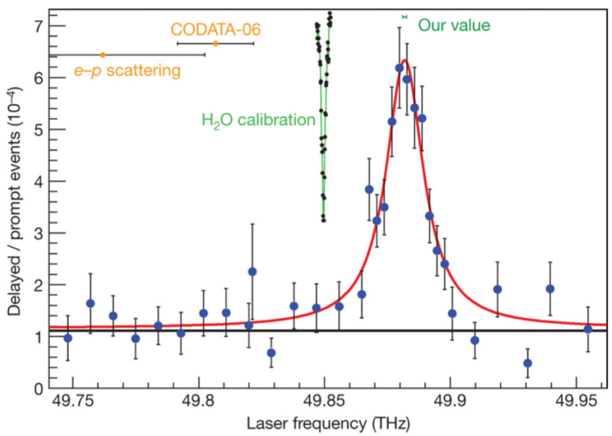


- *The proton radius puzzle*
  - *Low-Q^2 strategy*
    - *Experimental perspectives*

Really ??

R. Pohl et al. Nat. 466 (2010) 213

2S->2P Lamb shift in muonic hydrogen.



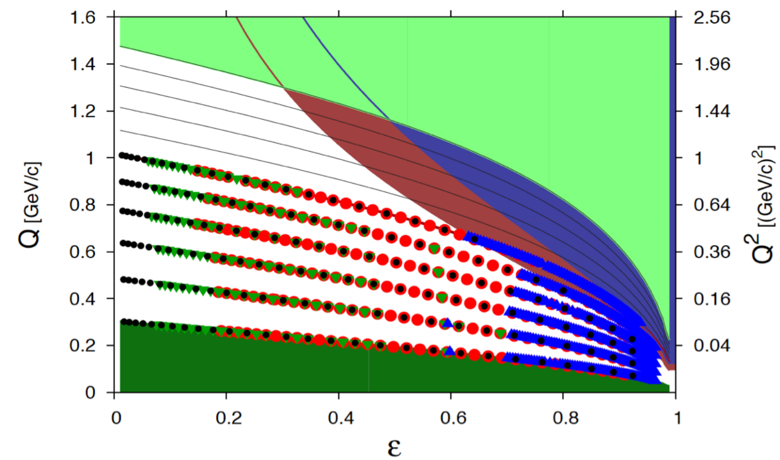
r_p = 0.84184±0.00067 fm

$$E_{nl} \sim -\frac{R_\infty}{n^2} + \delta_{l0}\frac{r_p^2}{n^3}$$

- **Model dependence** of proton structure corrections (polarisability, **2γ**).
- Shift of the **Rydberg** constant.

J.C. Bernauer et al. PRL 105 (2010) 242001

G_E(p) measurement in ep elastic scattering.



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$$< r_p^2 > = -\, 6(\hbar c)^2 \left.\frac{\partial G_E(Q^2)}{\partial Q^2}\right|_{Q^2=0}$$

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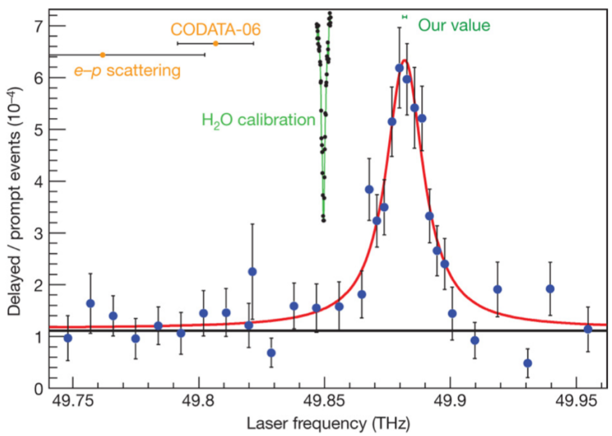

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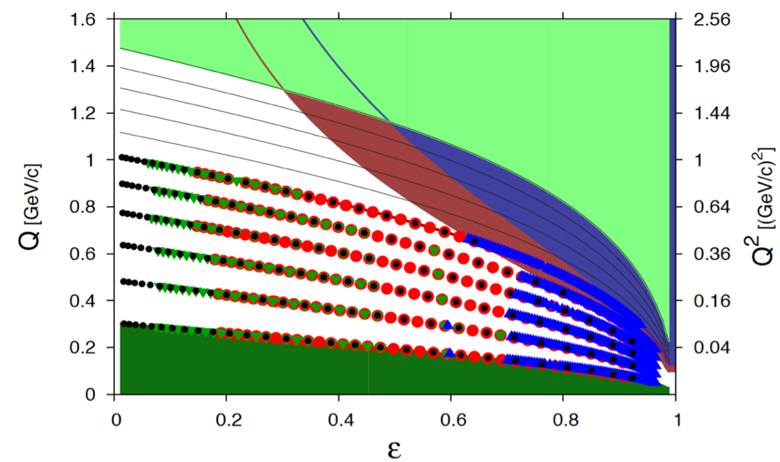

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Lepton universality violation = Physics beyond the Standard Model

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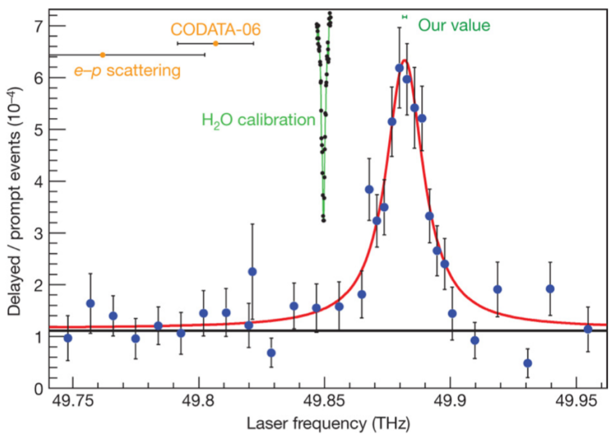

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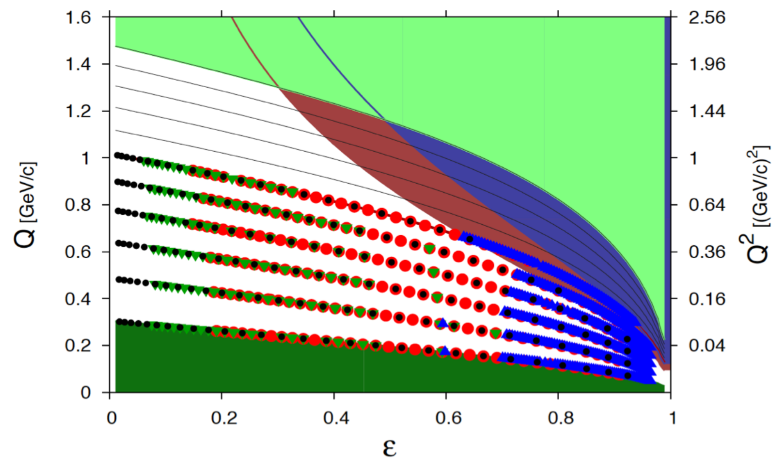

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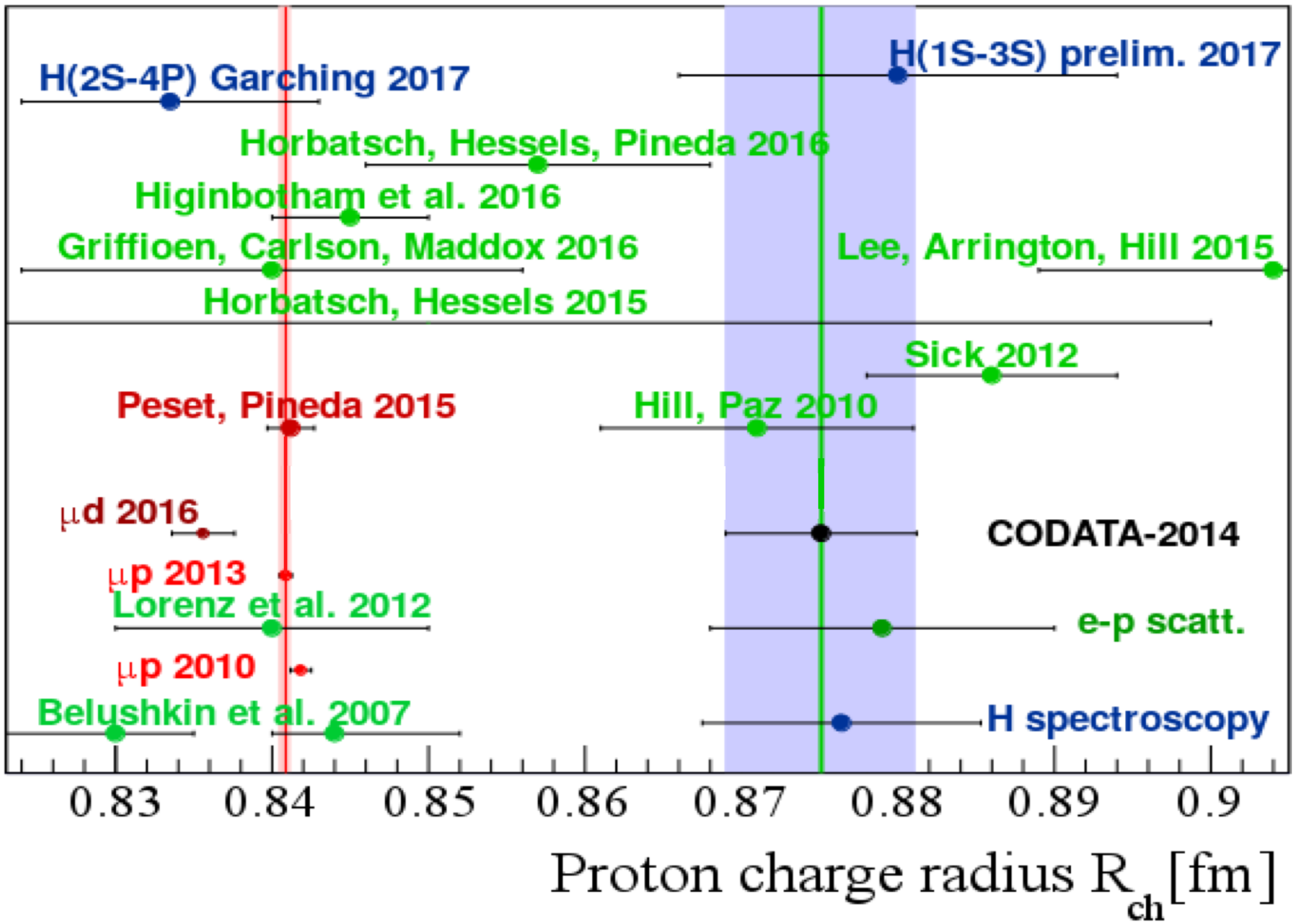
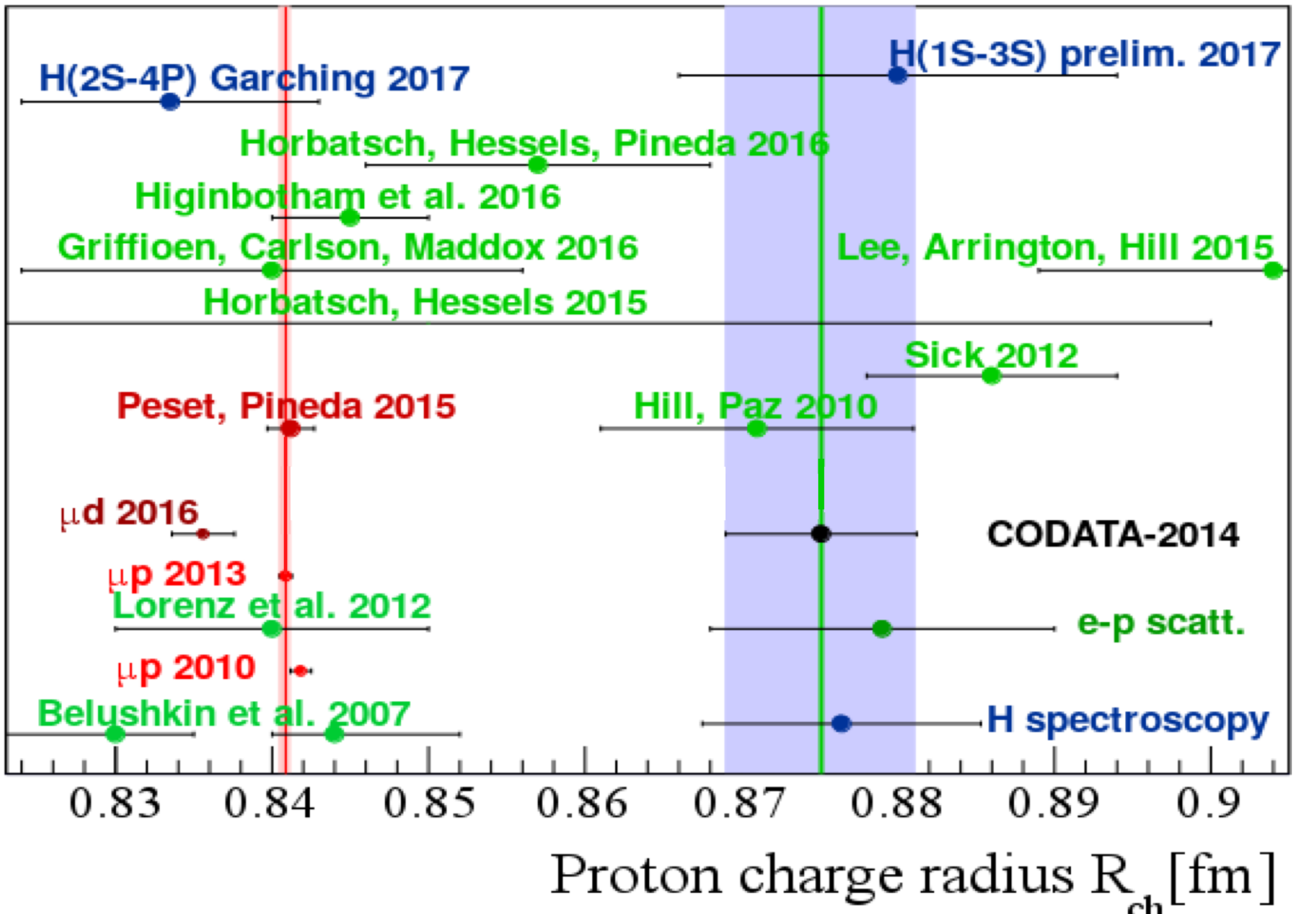
Proton Radius Confusion

R. Pohl courtesy



Proton Radius Confusion

R. Pohl courtesy

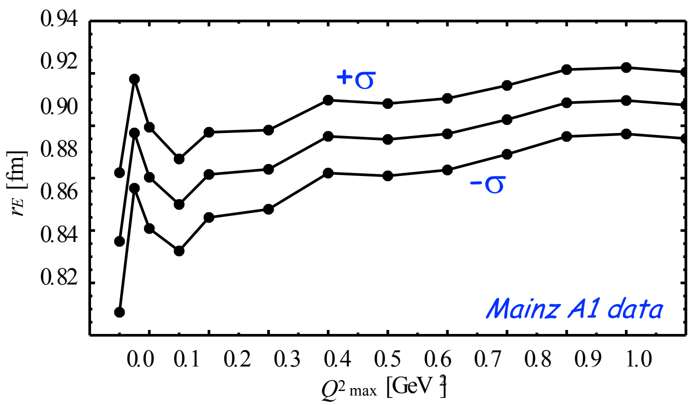


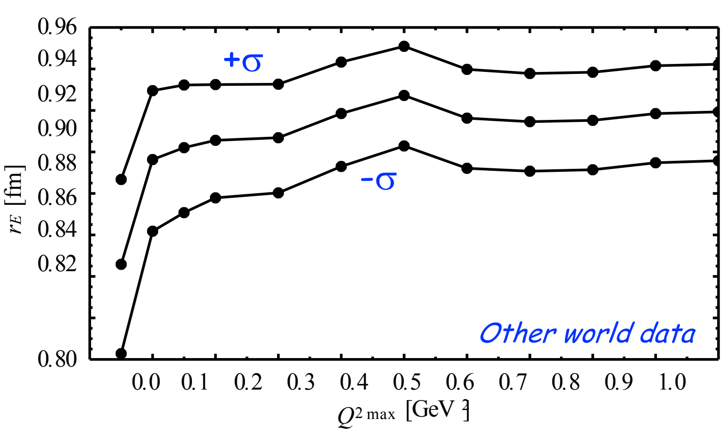
Need for more data !!

Fitting Data

D. Higinbotham, A. Amin Kabir, V. Lin, B. Norum, B. Sawatzky PRC 93 (2016) 055207   K. Griffioen, C. Carlson, S. Maddox PRC 93 (2016) 065207

G. Lee, J.R. Arrington, R.J. Hill PRD 92 (2015) 013013





- Extracting the **slope** of $G_E(Q^2)$ from scattering data requires some **lever arm** in Q^2.
- Too **large** a **lever arm** induces non-linear effects leading to the a **Q^2-dependent radius**.
- The slope at $Q^2=0$ is linked to **$G_E(Q^2)$** at larger Q^2 only if the **Q^2-fonctional** is **known**.

Fitting Data

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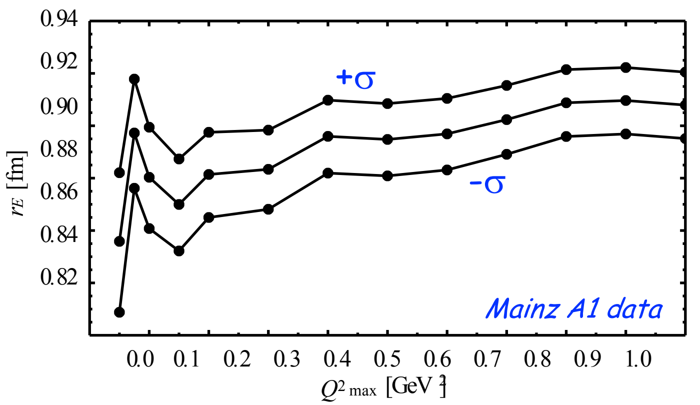
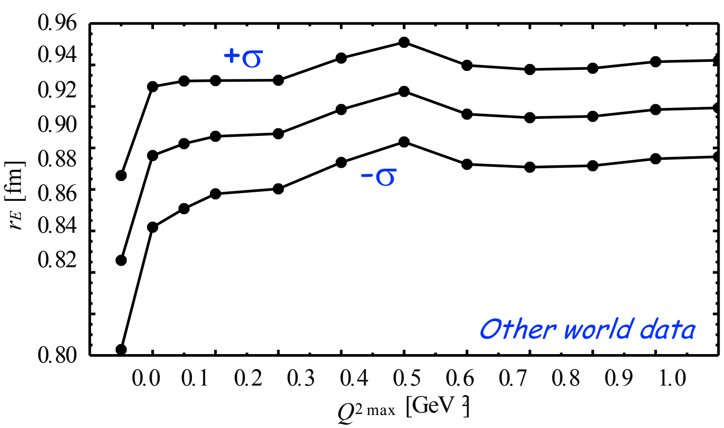
G. Lee, J.R. Arrington, R.J. Hill PRD 92 (2015) 013013



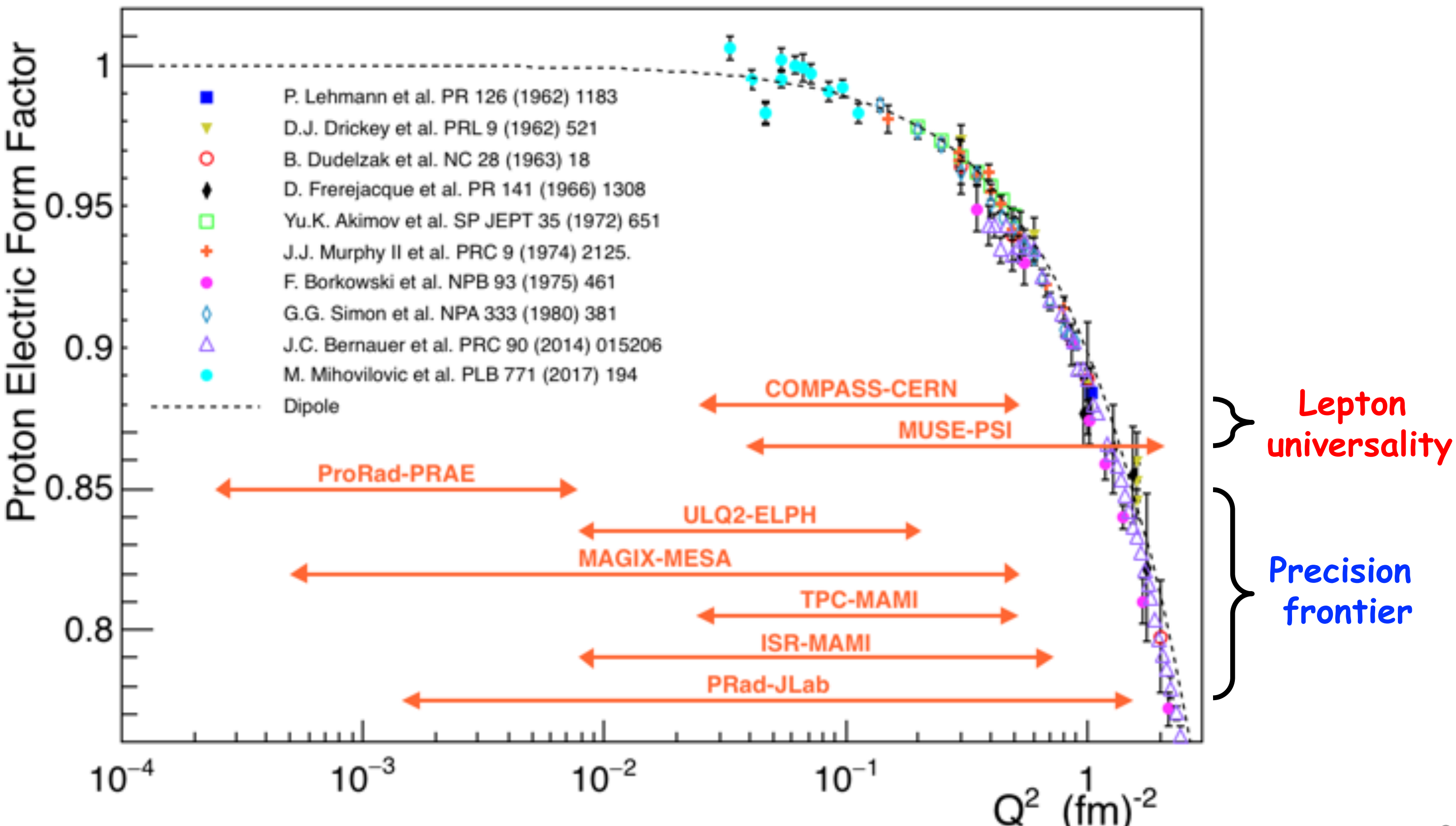


- Extracting the **slope** of $G_E(Q^2)$ from scattering data requires some **lever arm** in Q^2.
- Too **large** a **lever arm** induces non-linear effects leading to the a **Q^2-dependent radius**.
- The slope at Q^2=0 is linked to **$G_E(Q^2)$** at larger Q^2 only if the **Q^2-fonctional** is **known**.

Mandatory knowledge of $G_E(Q^2)$ at very small Q^2

Experimental Status

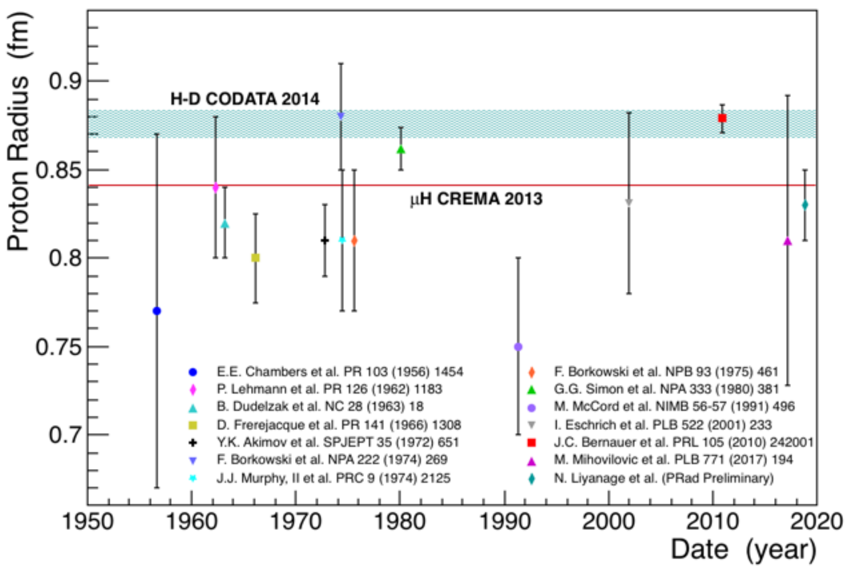
- An **unprecedented** experimental **effort** develops about **lepton scattering** at **low Q^2**.



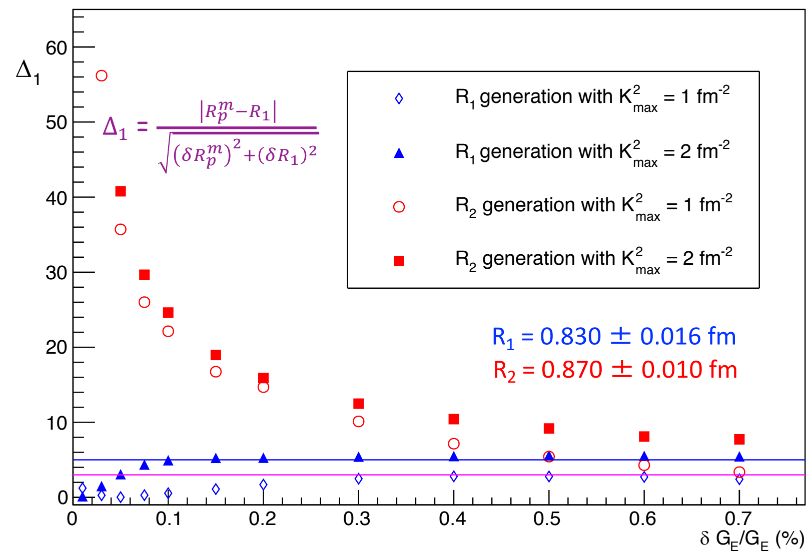
Precision Frontier

M. Hoballah et al. arXiv:1811.03545 (2018)

- It is **extremely unlikely** that any lepton scattering experiment will reach the **precision** of **muonic atom spectroscopy**.

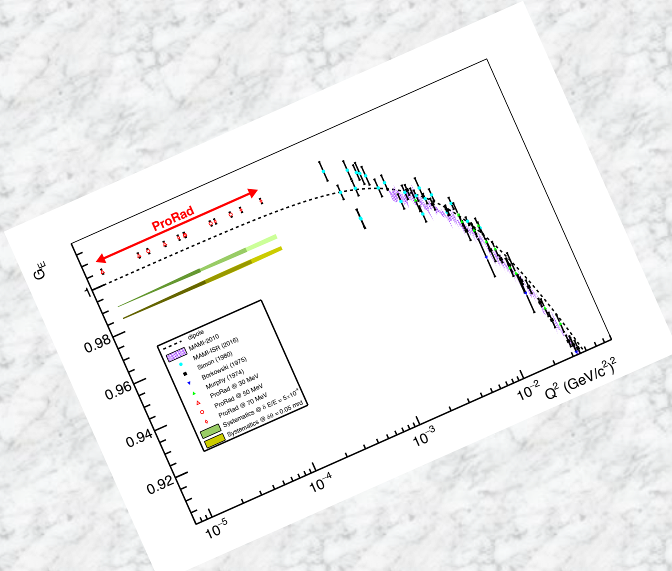


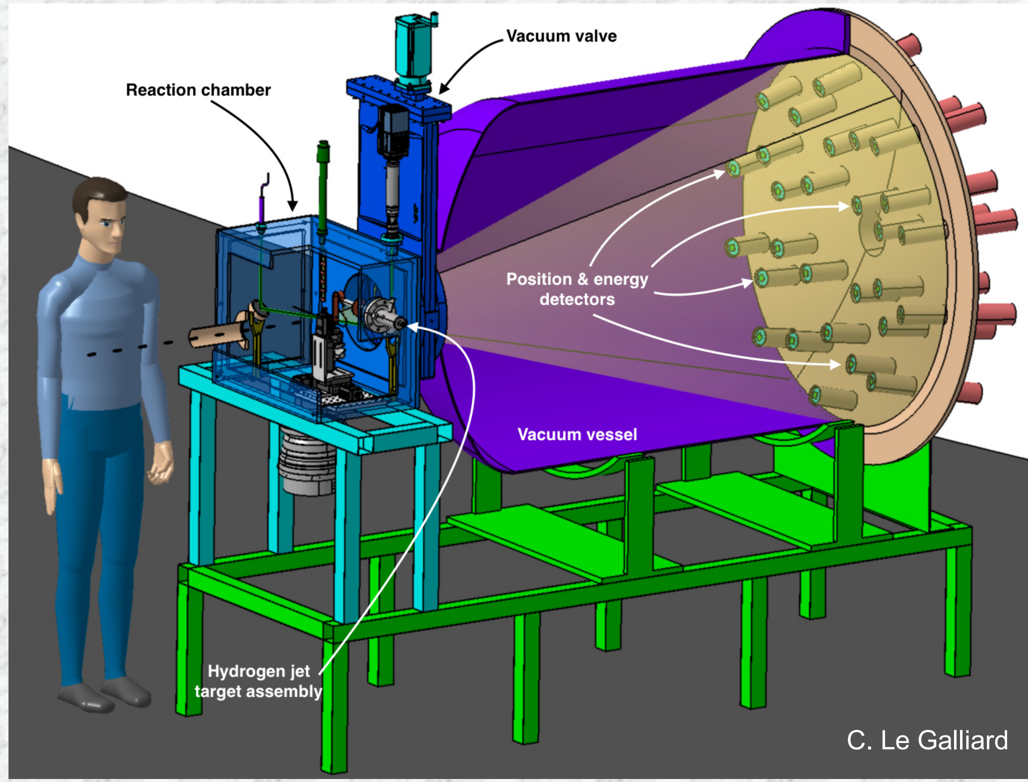
- **Existing data below 2 fm^{-2}** support different proton radius values depending on the **Q^2-range** under consideration.



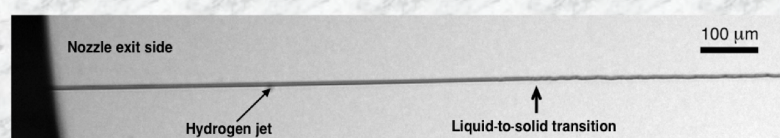
Establishing unambiguously the proton radius from electron scattering at low Q^2 requires a **0.1% accuracy on cross section** related experimental observables from **all** forthcoming **experiments**.

The ProRad Experiment at PRAE





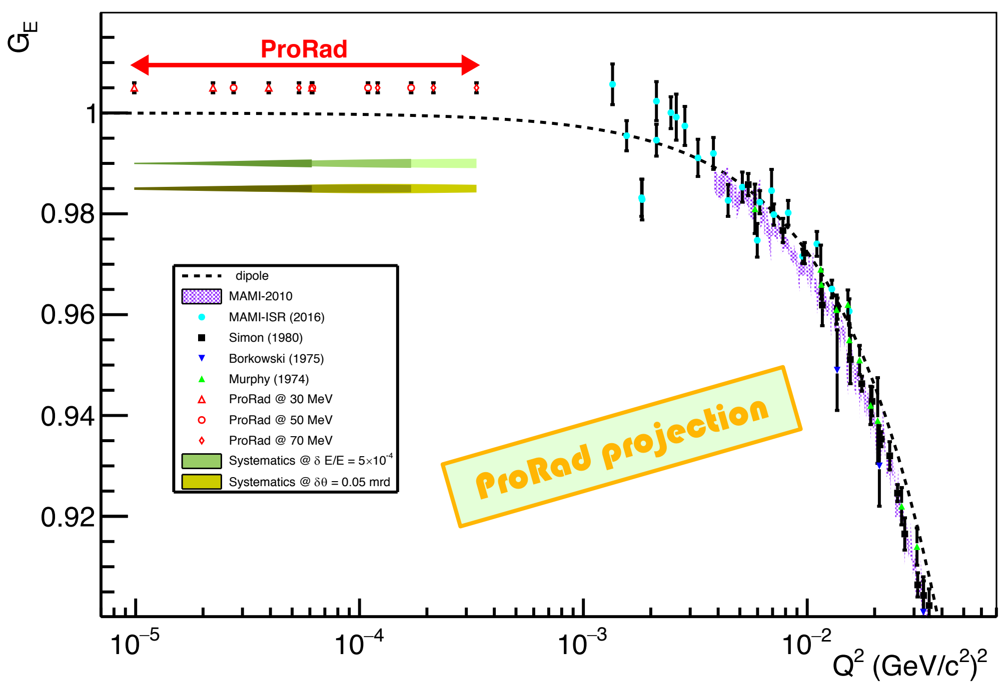
- *The ProRad experiment*
  - *PRAE beam control*
    - *Hydrogen target*
      - *Detector Assembly*
        - *Collaboration*



ProRad @ PRAE

(PRAE Collaboration) E. Voutier et al.

➢ **ProRad** will measure the proton **electric form factor** $G_E(Q^2)$ in the **unexplored domain** of **very low** energy **transfers** 10^{-5}-3×10^{-4} $(\mathrm{GeV}/c^2)^2$.



Expected results

- A better **experimental knowledge** of the Q^2-dependence of G_E.
- A **significant impact** on the **proton charge radius** determination, from the ProRad-data constraint of the **zero-momentum extrapolation** of G_E.

Within the ProRad range, any data different from 1 would be quite a surprise !!

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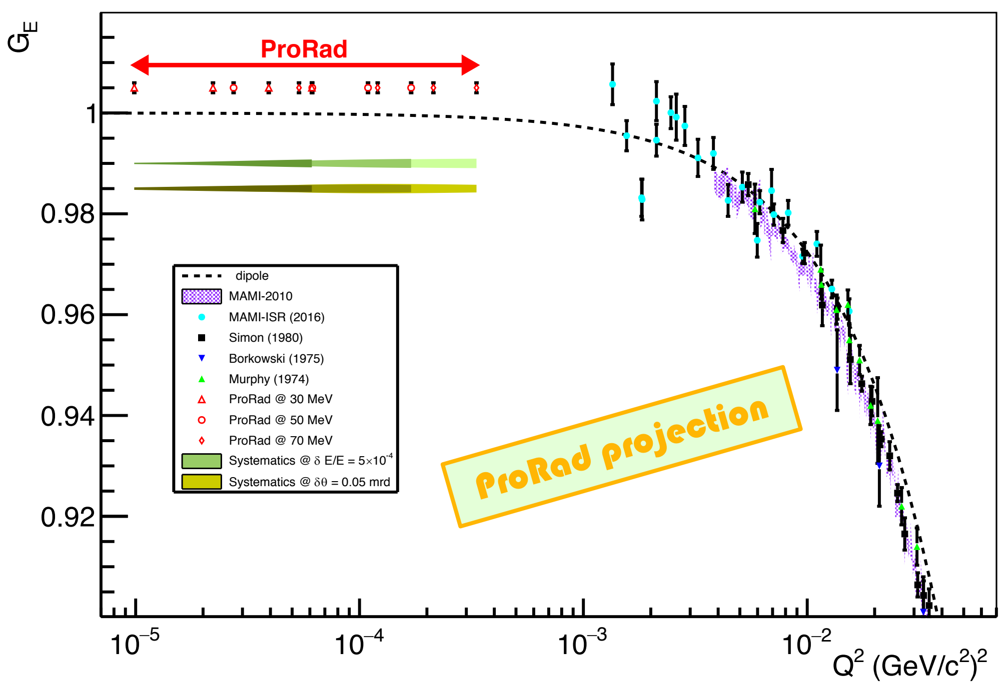

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Within the ProRad range, any data different from 1 would be quite a surprise !!

➡ ***Data taking planned for 2021-2022.***

Principle of Operation

$$\rho_\sigma(Q^2) = \left[\frac{d^2\sigma_{ep}}{d\theta d\varphi} \Big/ \frac{d^2\sigma_{ee}}{d\theta d\varphi}\right]^{1/2} \rightarrow r_p = \sqrt{-6(\hbar c)^2 \left.\frac{\partial G_E(Q^2)}{\partial Q^2}\right|_{Q^2=0}}$$

Experimental Method

- **0.1%** measurement of the **relative elastic scattering cross section $\rho_\sigma(Q^2)$ off protons** at fixed angles (**6°-15°**) and different beam energies **30-50-70 MeV**.
- **Simultaneous measurement** within the same detector of the known **Møller cross-section** off electrons from the **hydrogen target**.

Detector Concept

- Measurement of the **energy** and **angle** of scattered electrons.

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Detector Concept

- Measurement of the **energy** and **angle** of scattered electrons.

The essential difficulty of the experiment is about minimizing and mastering systematic errors.

Measurement

$$\frac{d^2\sigma_{ep}}{d\theta d\varphi} = \frac{Y(e^-p \to e^-p)}{\mathcal{L}_{H_2}\, A_e\, \epsilon_e\, \delta_{ep}} \qquad \frac{d^2\sigma_{ee}}{d\theta d\varphi} = \frac{Y(e^-e^- \to e^-e^-)}{\mathcal{L}_{H_2}\, A_e\, \epsilon_e\, \delta_{ee}}$$

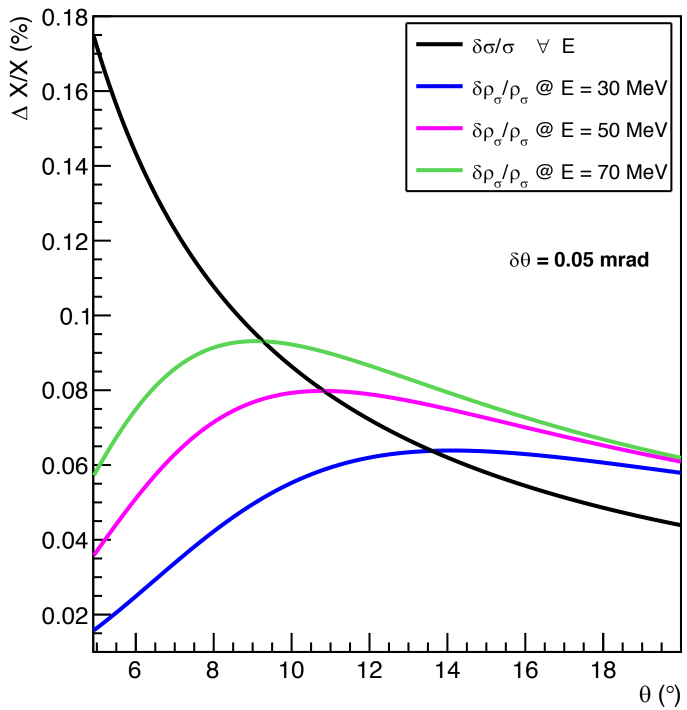
$$G_E^2(Q^2) = \rho_\sigma(Q^2)\,\frac{\delta_{ee}}{\delta_{ep}}\left(\frac{d^2\sigma_{ee}}{d\theta d\varphi}\Big/\frac{d^2\sigma_{ep}^{Mott}}{d\theta d\varphi}\right)_{th}\left[1+\mathcal{O}\left(\frac{Q^2}{M^2}\right)\right] - G_M^2(Q^2)\left[\mathcal{O}\left(\frac{Q^2}{M^2}\right) - \mathcal{O}\left(\frac{m^2}{M^2}\right)\right]$$

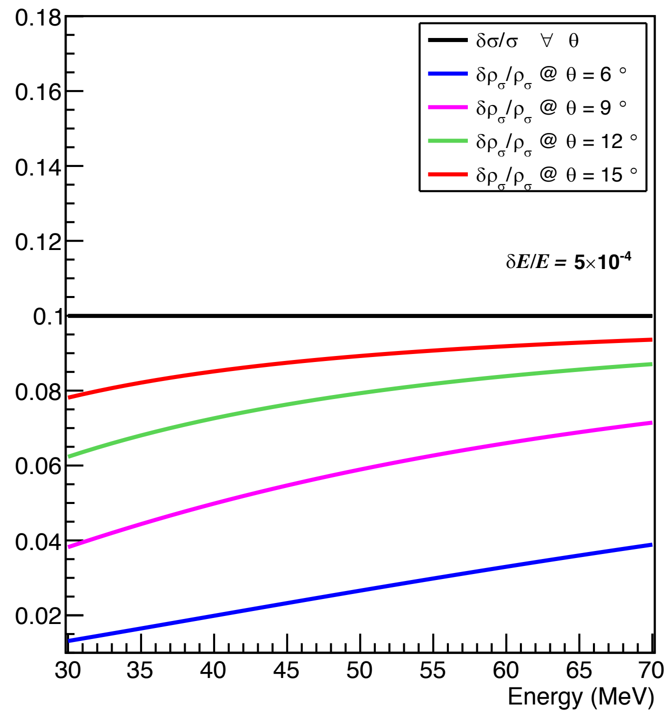
- Uncertainties related to **luminosity** disappear.
- **Acceptance** and **efficiency** effects also disappear but remain at the **systematic** level.

- **Radiative effects** must be controlled at a few **10^{-4}** accuracy.
- Correction from the **magnetic form factor** is very small and can be controlled with high enough accuracy.

Control of Systematics

- The determination of the theoretical **Møller/Mott** cross section ratio involves the **knowledge** of the **beam energy** and of the **electron scattering angle**.





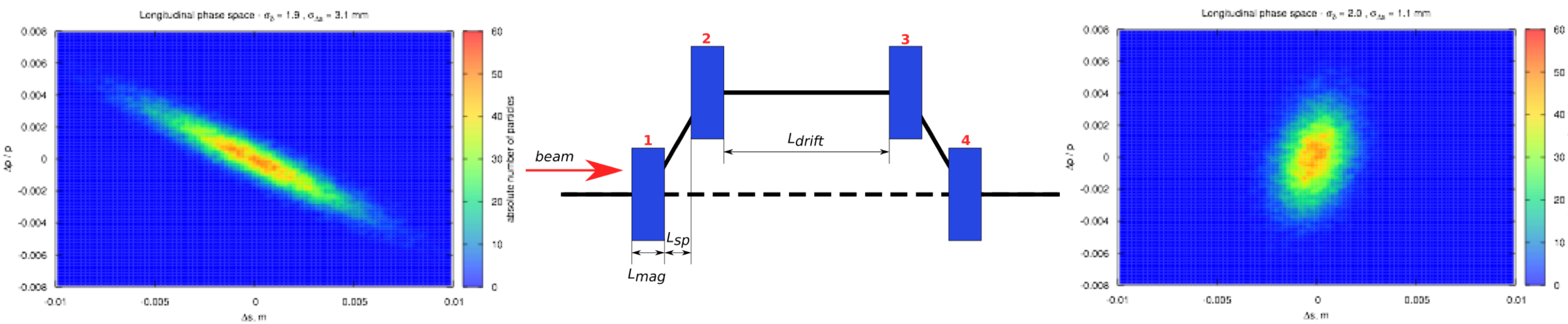
The detector should be designed to allow for a **0.1 mm accuracy** of its **location**.

The **beam energy** should be known with a **5×10^{-4}** accuracy.

Energy Compression

A.N. Dovbnya, N.G. Shevchenkov, V.A. Shendrik HEACC83 (1983) 526

- A **chicane** constituting of **4 identical dipoles** reduces the beam phase space.



$\theta = 60^{o}$

- A **dechirping passive structure** following the chicane allows to compress the beam momentum spread down to a few 10^{-4}.

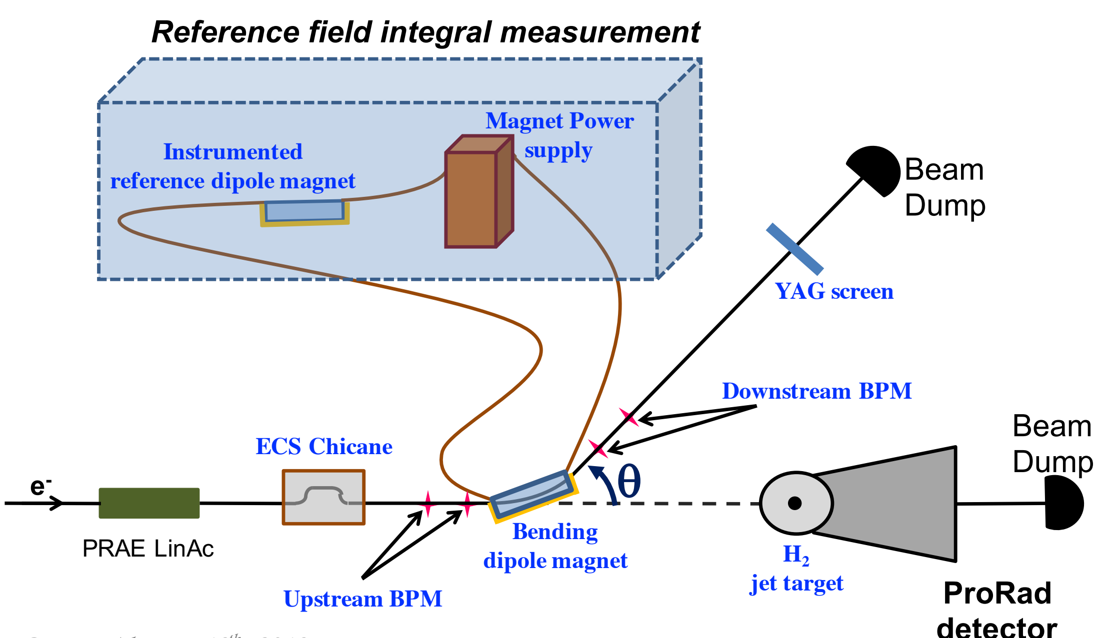
- This **innovative technique** relies on the action of the **wakefield** generated by the beam when passing through the passive structure. The **precision** of the **mechanics** of the structure is determinant for the dechirping operation.

Beam Energy Measurement

D. Marchand, Doctorate Thesis, UBP (1998)   J. Berthot, P. Vernin, NPN 9 (1999) 12   A. Alcorn et al. NIM A 522 (2004) 294

- The **ARC technique**, successfully developed at JLab, will be implemented at PRAE to provide a **5×10^{-4}** relative accuracy on the beam energy.

$$E = \frac{c}{\theta}\int B\,dl = \frac{c\,I_B}{\theta}$$

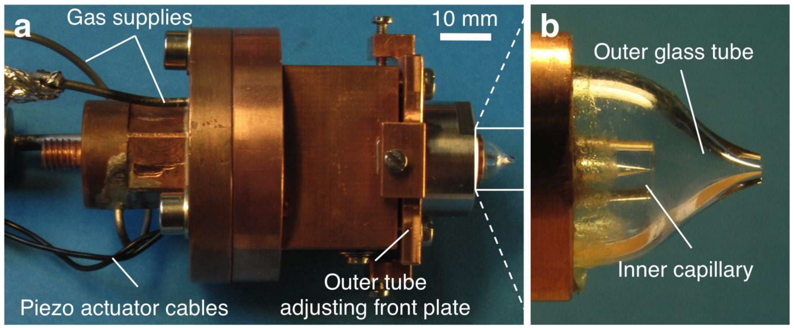


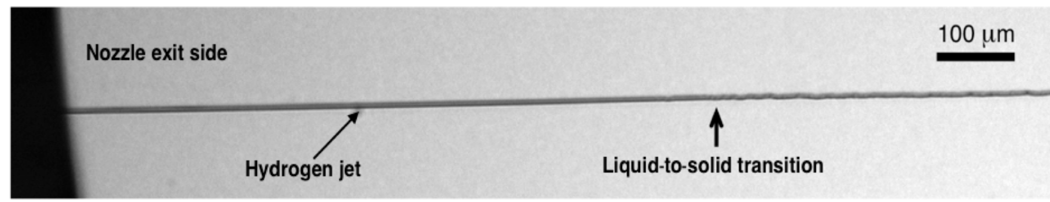
- Measurement of the **deviation** of the **beam** within an accurately **known magnetic field**.
  - Determination of the **beam position** at the entrance and exit of the bending magnet.
  - Determination of the **field integral** from deviations with respect to an identical reference magnet.
  - Measurement of the beam momentum dispersion with an optical imaging system.

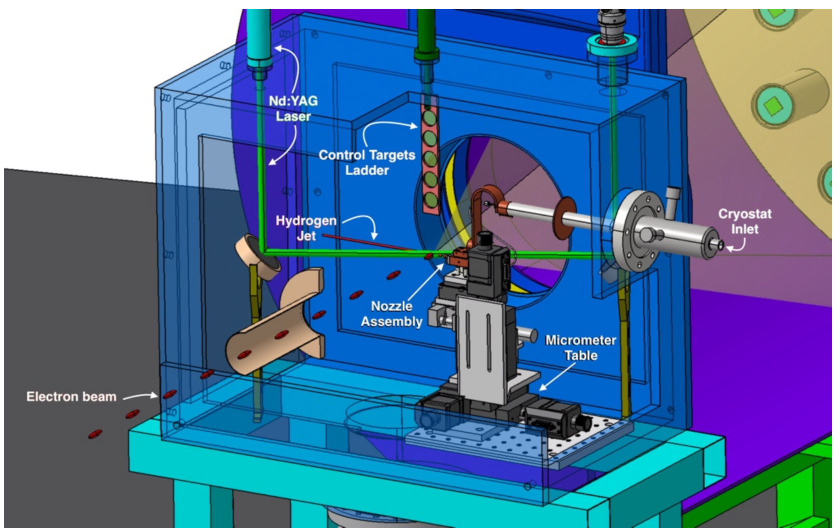
$$\frac{\delta I_B}{I_B} = \frac{\delta\theta}{\theta} = 2\times10^{-4}$$

Supercooled Liquid

M. Kühnel, J.M. Fernández, G. Tejeda, A. Kalinin, S. Montero, R.E. Grisenti, PRL 106 (2011) 245301





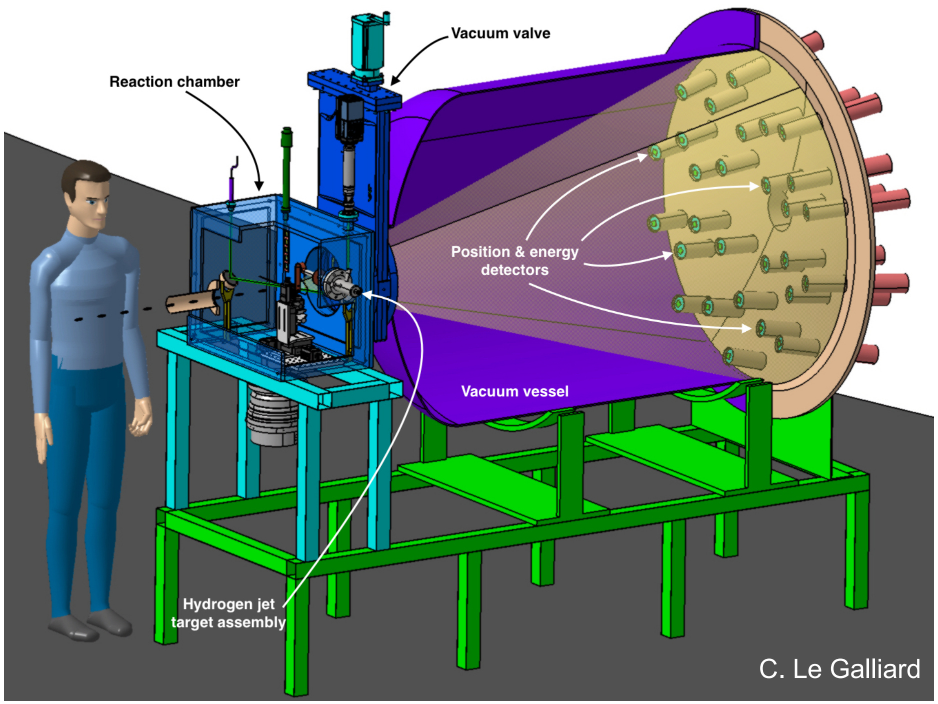


windows = background
thickness = background + inaccurate vertex
density = reduced data taking time

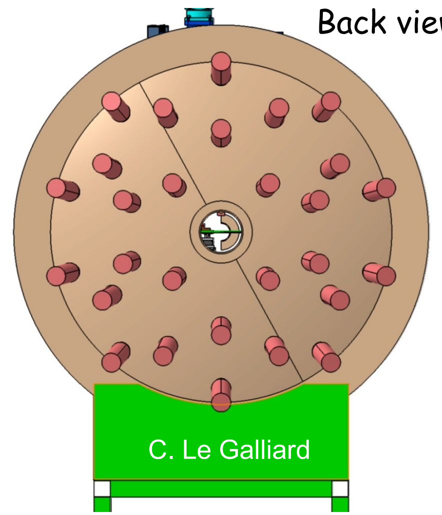
- ✓ ProRad requires a windowless **thin hydrogen target** of enough density.
- ✓ The supercooled liquid technology developped at **Frankfurt University** provides thin (5-15 μm) **solid hydrogen wires**.

Concept

- ✓ The detector is composed of **28** independent elementary cells constituting of two scintillator planes followed by a cylindrical **BGO crystal** ($\pi 2.5^2[3.5^2] \times 15$ cm^3).



Back view

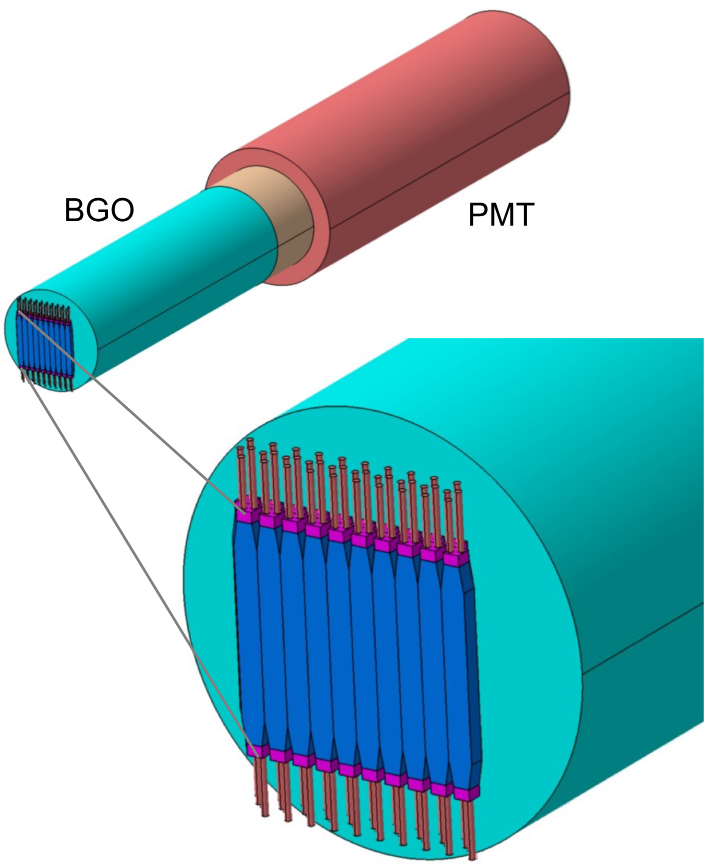


- Scattered electrons travel in **vacuum** over a **2 m** distance before reaching the detection area.
- Smallest angle crystals are the largest for **mimimizing energy leakage** effects.

Eric Voutier

Position Measurement

✓ The position detector is made out of two staggered planes of **scintillator stripes** (**20x4x1.3** mm^3) read-out at both ends with **SiPMs** (prototype configuration).

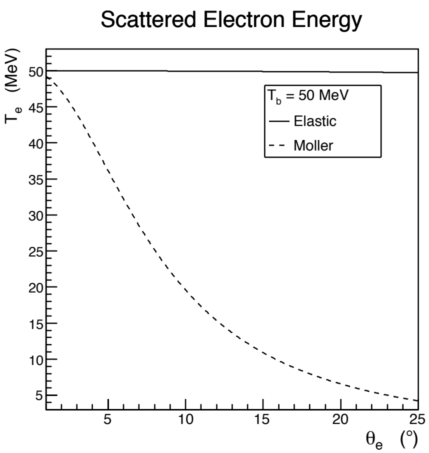


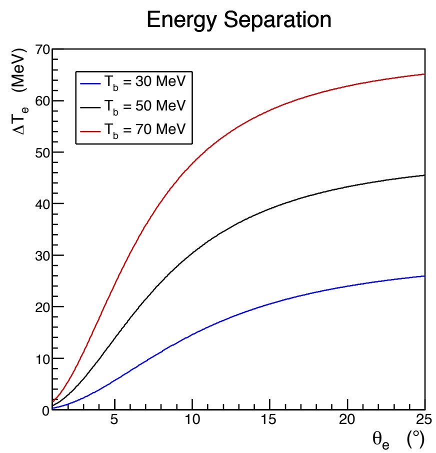
$$\int_{\Delta\Omega} \frac{d^2\sigma}{d\theta d\varphi} d\theta d\varphi = \left.\frac{d^2\sigma}{d\theta d\varphi}\right|_{\theta_0} \mathcal{A}_{\Delta\Omega}$$

- Scintillator stripes **acceptance effects** are **controlled** with **very high accuracy** through a Taylor development of the cross section at the stripe center.

- The position detector also serves as charged particles tagger.

Energy Measurement

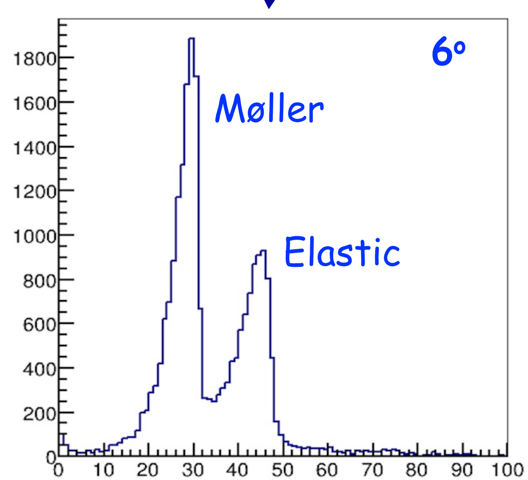


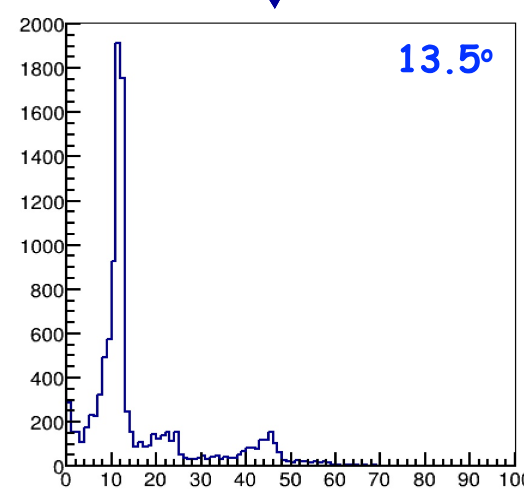


✓ At the same scattering angle, the **energy difference** between **Møller** and **elastic** electrons allows to **separate** processes.

❖ At **small angle**, separation of processes is **reduced**.

❖ At **large angle**, dynamics of cross sections generate **combinatorial effects**.





The ProRad Team

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ProRad is looking for collaborators

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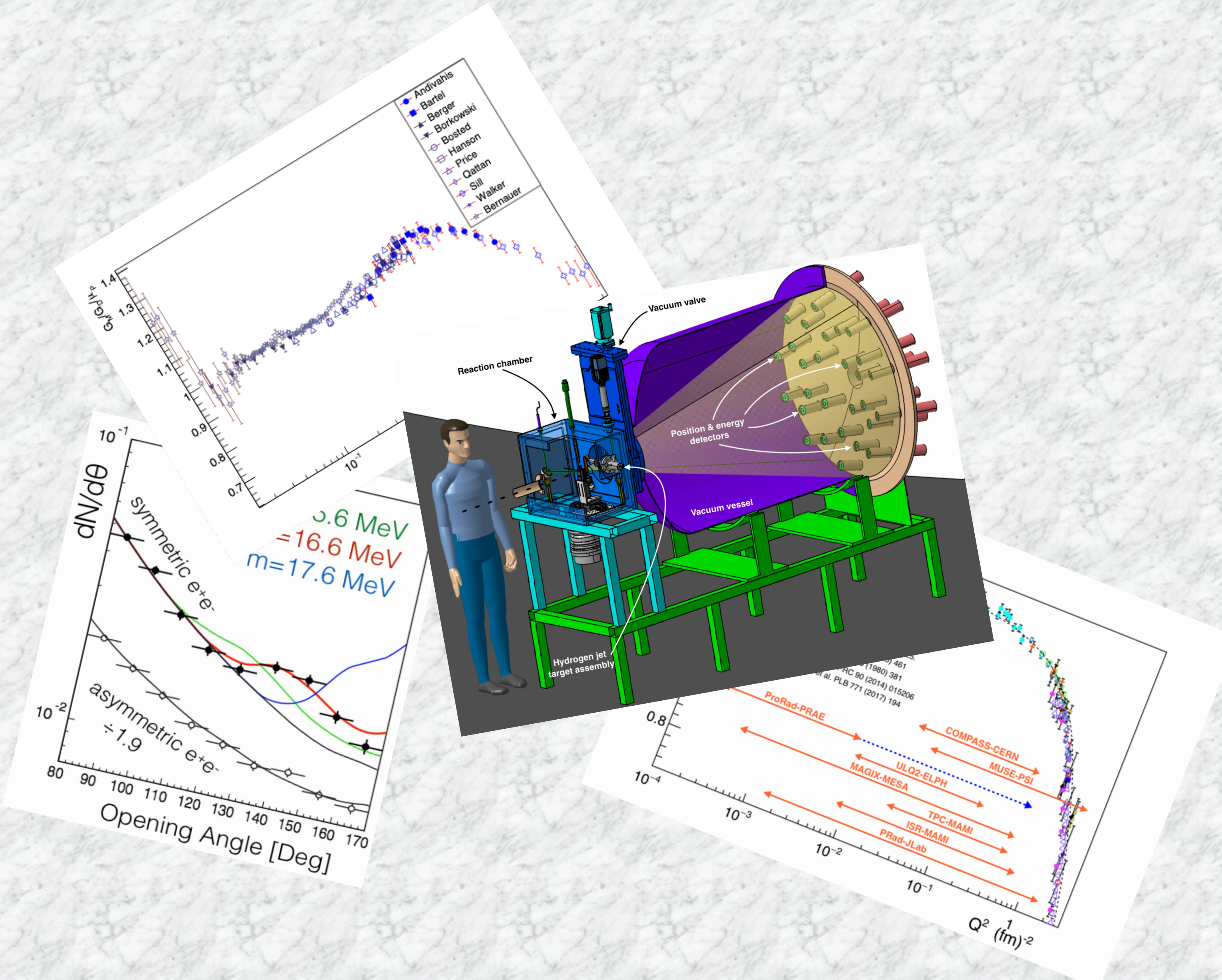
Consider joining adventure

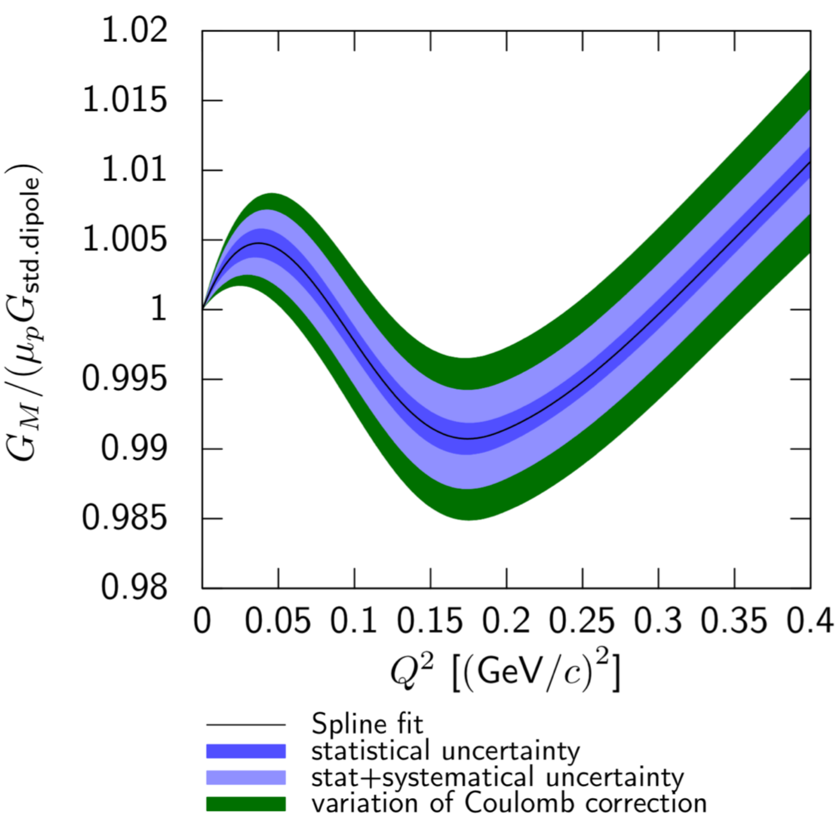
Experiments at PRAE



- $G_M(Q^2)$
  - … ?

Proton Magnetic Form Factor

J. Bernauer, PRAE International Workshop (2018)



- The magnetic form factor of the proton, $G_M(Q^2)$, is **not accurately known** at small momentum transfer. Particularly, the best fit of 2010 Mainz data suggests **unexpected deviations** from the dipole behaviour.

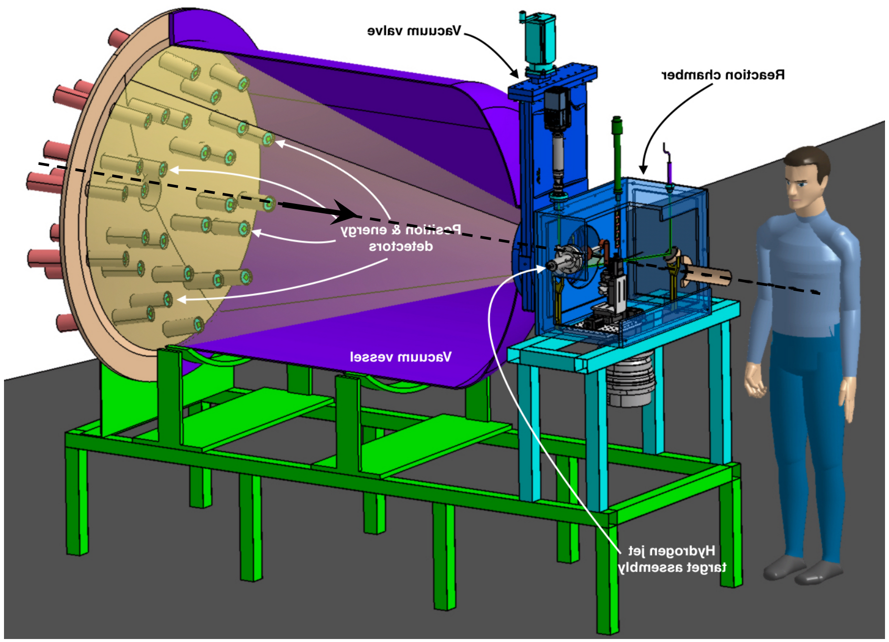
- The knowledge of $G_M(Q^2)$ provides an additional link to atomic spectroscopy through the **Zemach radius**.

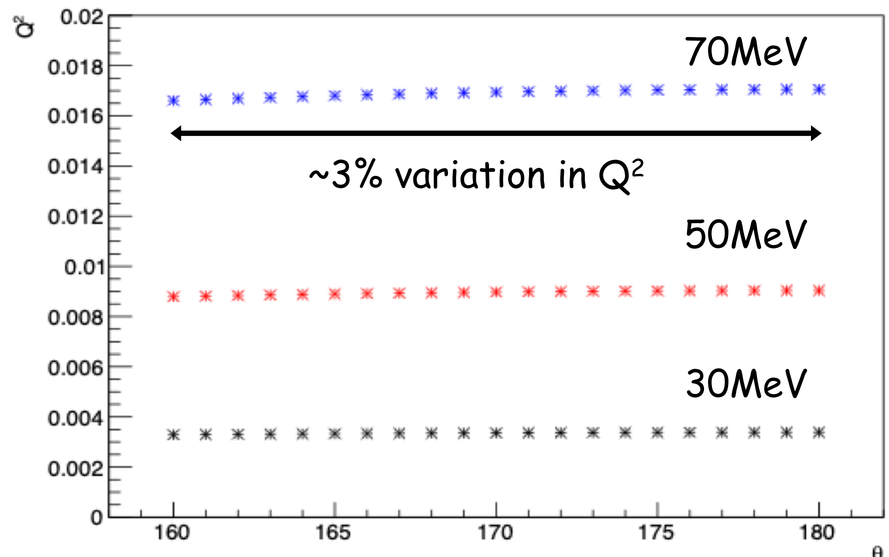
$$r_Z = -\frac{4}{\pi}\int_0^\infty \frac{dQ}{Q^2}\left(\frac{G_E(Q^2)G_M(Q^2)}{\mu_p} - 1\right)$$

Dominated by the small Q^2 deviation with respect to 1

ProRad @ Backward Angles

- ✓ **Rotating 180°** the ProRad detector and implementing a **1 cm** long **hydrogen** target allows to measure the elastic scattering cross section at large **backward angles** where $G_M(Q^2)$ significantly **contributes**.

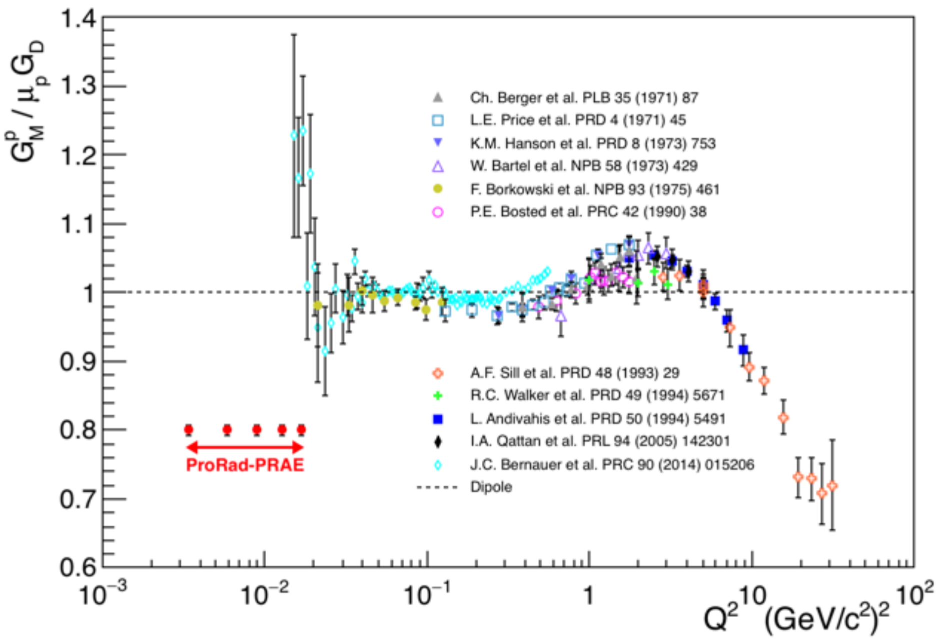


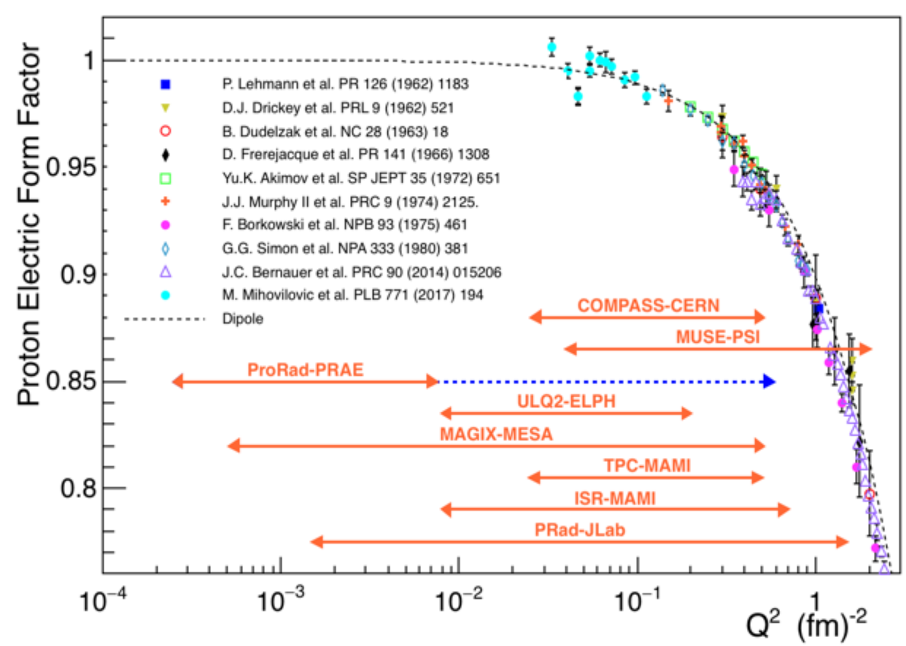


The Q^2 variation is small enough that the electric and magnetic form factors are separated without Rosenbluth separation.

Experimental Projections

✓ A **1%** measurement of the cross section will provide incredible $G_M(Q^2)$ data, **resolving inconsistencies** of the low-Q^2 existing data.





✓ It will **extend** the **Q^2-coverage** of $G_E(Q^2)$ ProRad data which, combined with forward angle data, will provide a **0.03 fm** determination of the proton radius, solely with ProRad data.

Eric Voutier
IPN ORSAY

In Short…

- A new **pulsed electron beam facility** with **high bunch charge** is under construction at Orsay.
- It intends to become a **user facility** for **radiobiology**, **subatomic physics** and **instrumentation** studies.

First beams are expected by the end of 2021

The founding scientific program of PRAE can potentially lead to **new approaches** in **radiotherapy** and **significant results** with respect to the **proton electromagnetic form factors**.

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Consider joining this venture as a **Contibutor**, a **Collaborator**, or a **User** in any of the scientific domains to be explored of **PRAE**.