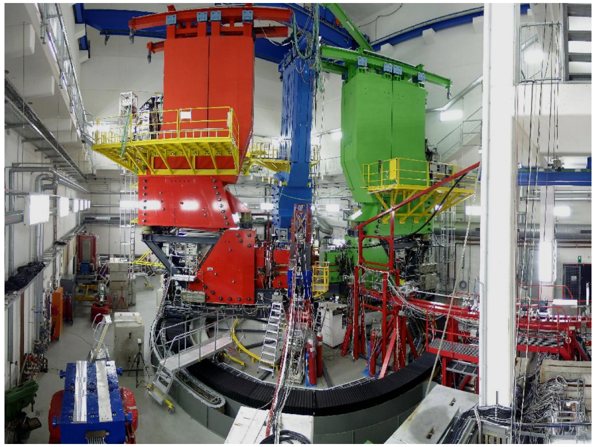
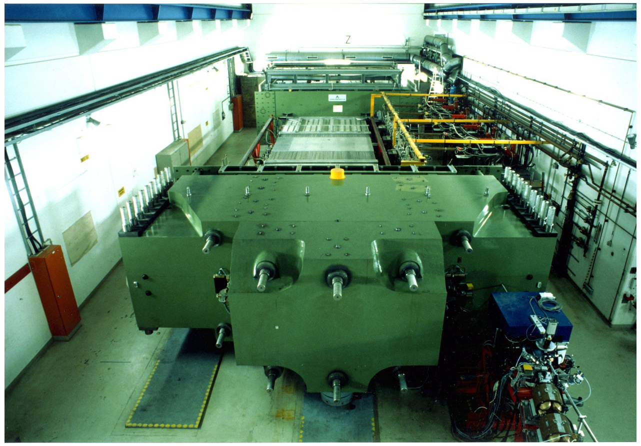
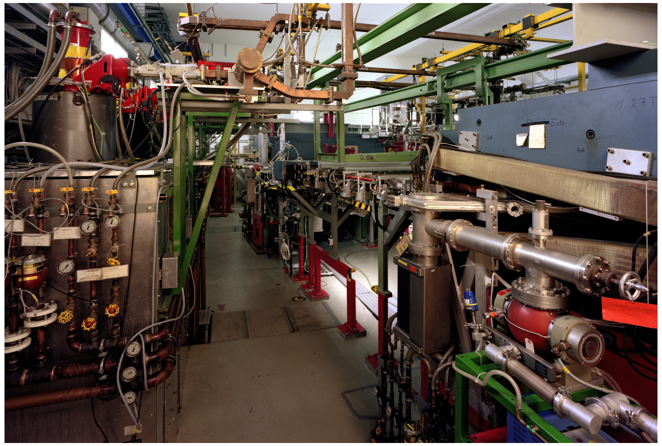
  

Investigating proton form-factors with initial-state radiation

Miha Mihovilovič

JGU Mainz and JSI

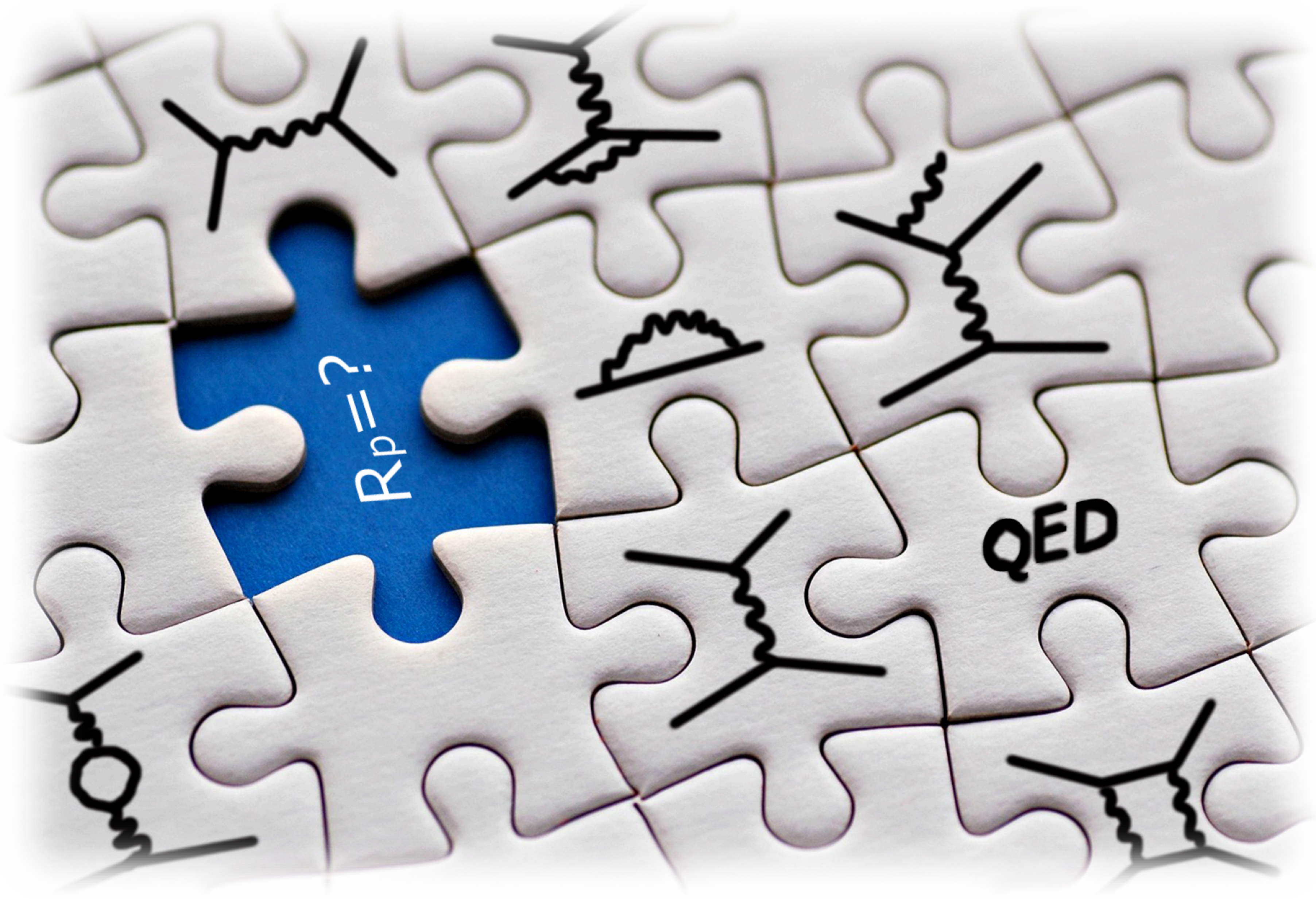
Physics Seminar @ JLab

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

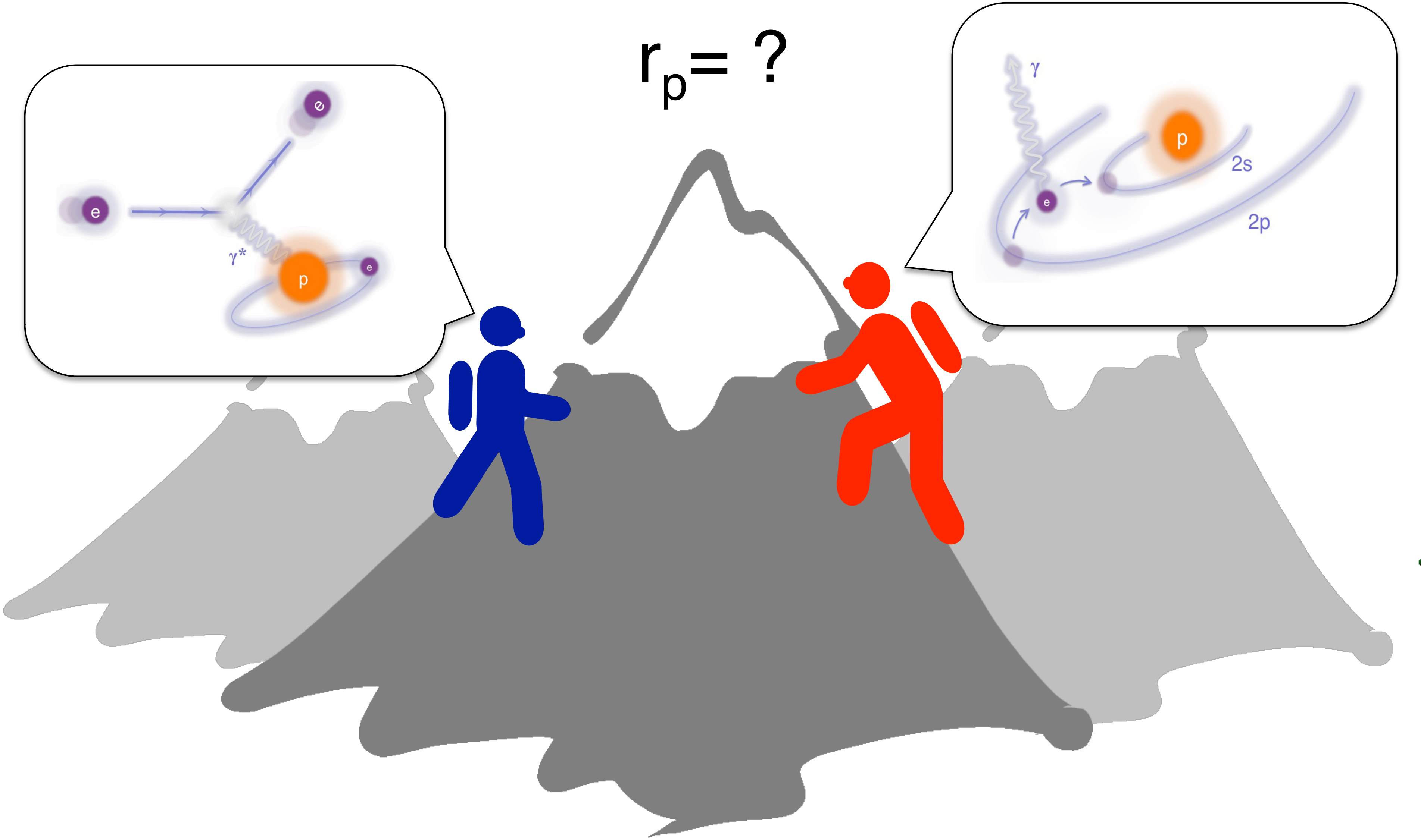
JG|U

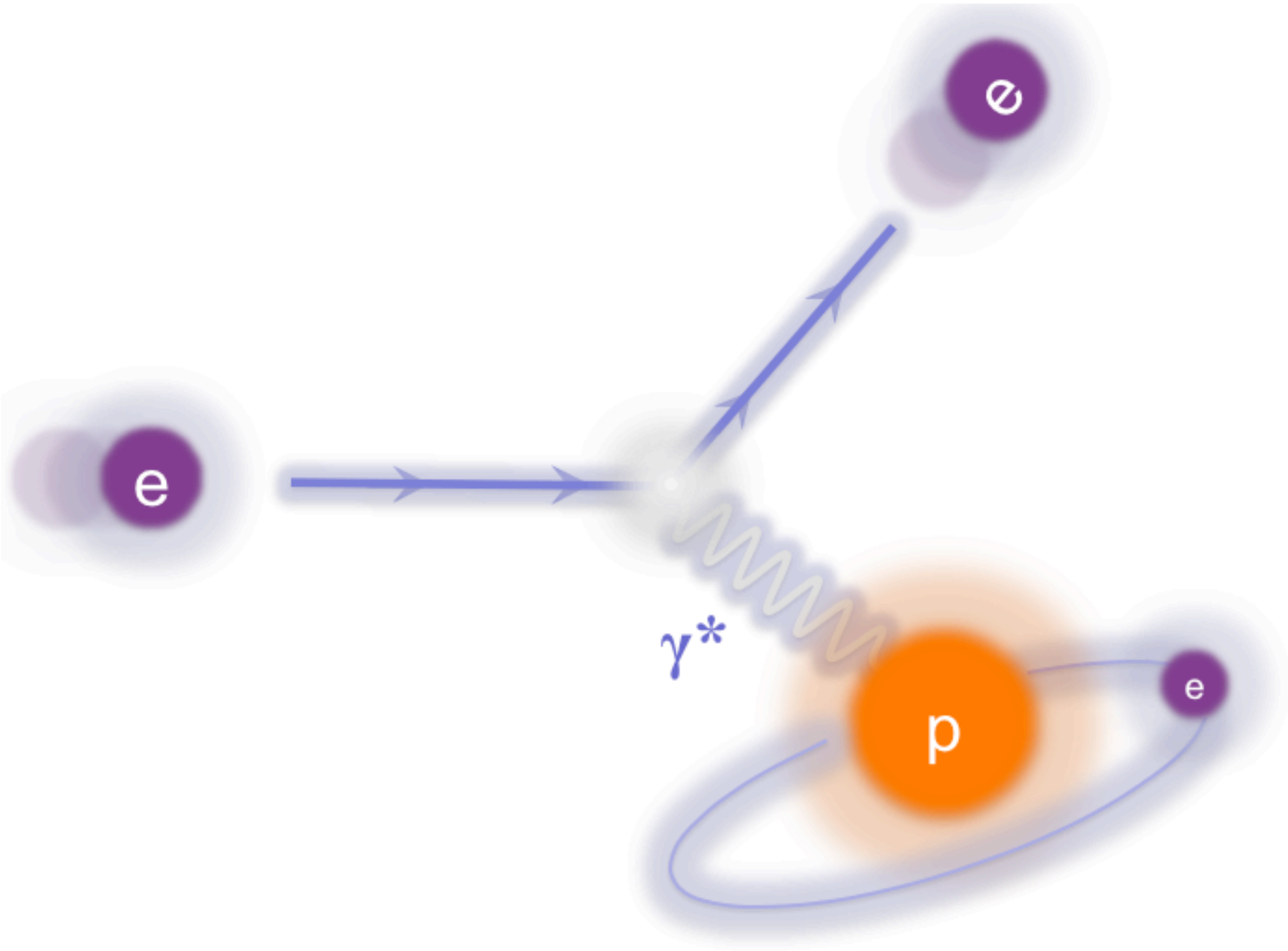
SLOVENIAN RESEARCH AGENCY

The Radius Puzzle



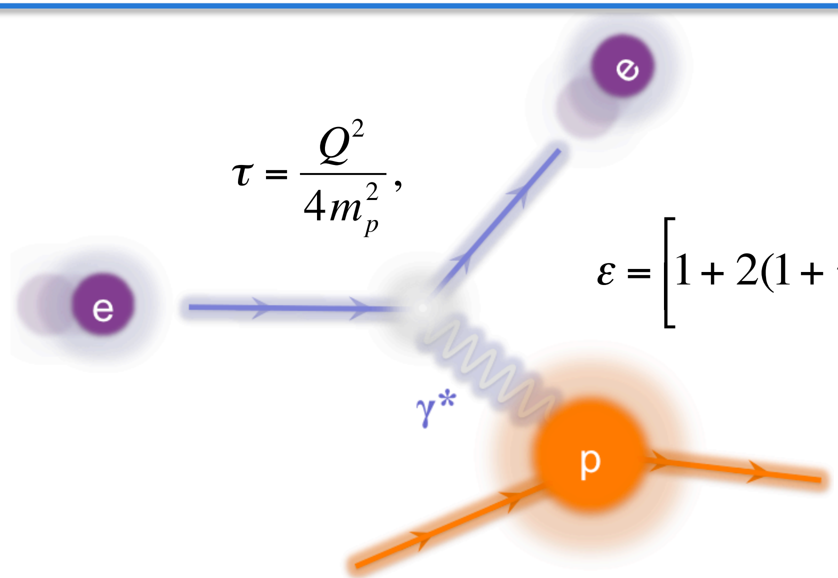
Two ways of climbing the mountain




e
e
γ*
p
e

Radius via Cross-section measurement

$$\tau = \frac{Q^2}{4m_p^2},$$



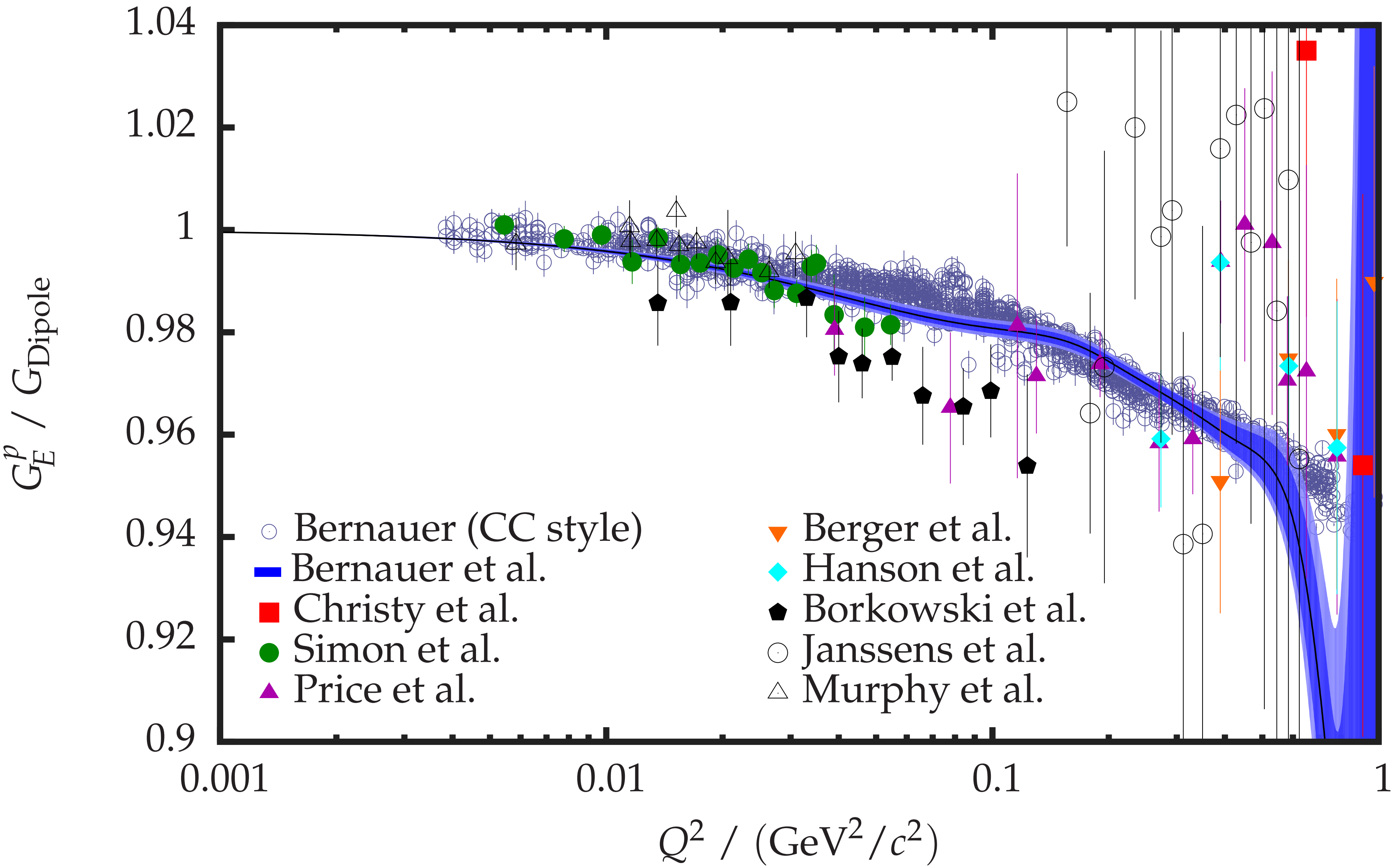
$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\frac{\vartheta_e}{2}\right]^{-1}$$

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

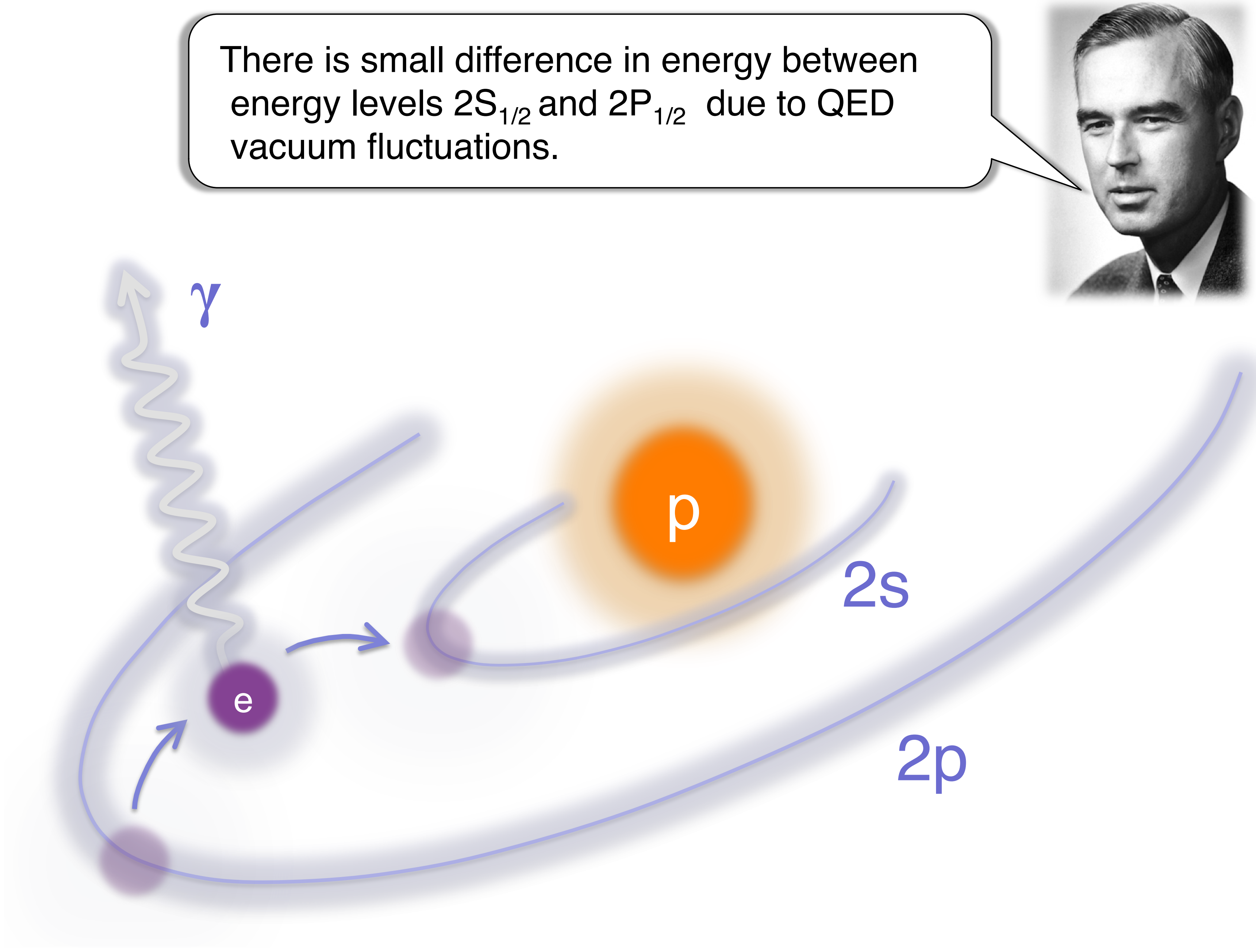
- Extraction of FF via Rosenbluth Separation.
- Best estimate for radius:

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

Proton's charge form-factor



- Radius from Bernauer's measurements: **r = (0.879 ± 0.008) fm**


There is small difference in energy between energy levels $2S_{1/2}$ and $2P_{1/2}$ due to QED vacuum fluctuations.
γ
p
e
2s
2p

Lamb shift in Hydrogen

- Change in level energy (approximately):

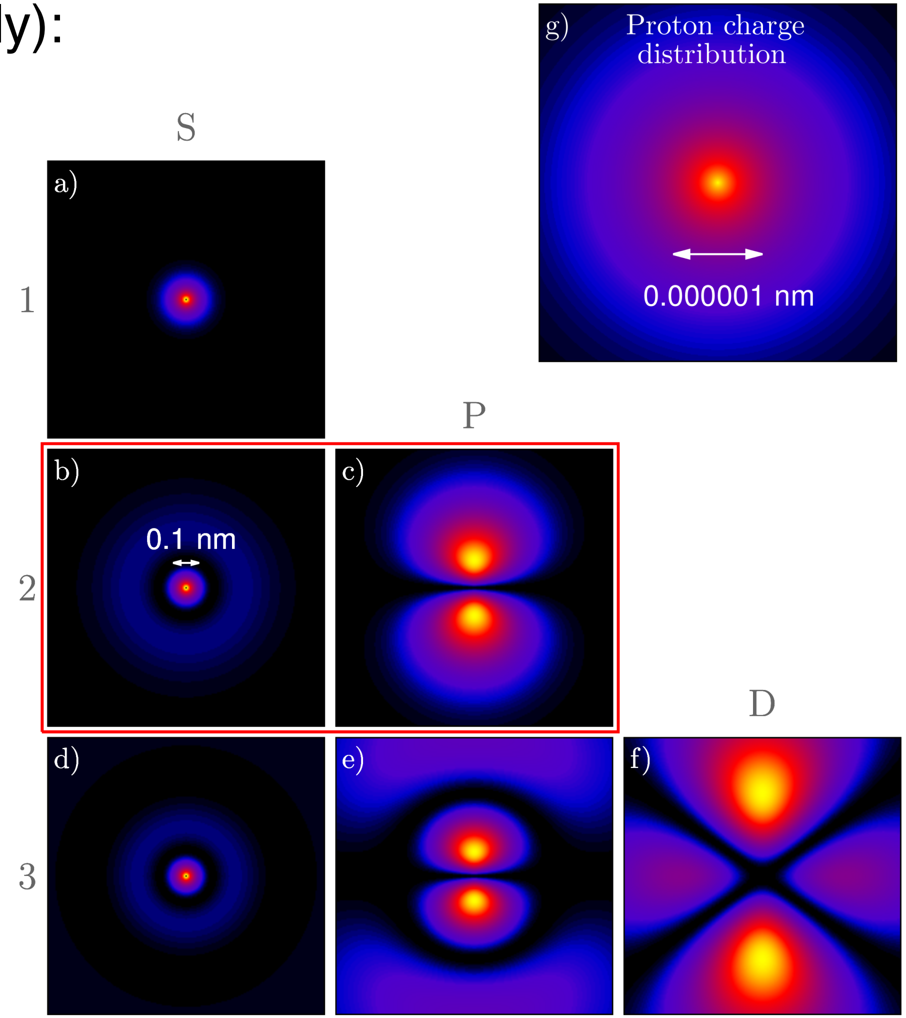
$$\Delta E^{nl}_{Lamb} \propto \left|\psi_{nl}(0)\right|^2$$

$$E(nS) \cong -\frac{R_\infty}{n^2} + \frac{\Delta E^{1S}_{Lamb}}{n^3}$$

$$\Delta E^{1S}_{Lamb} \cong \left(8.172 + 1.56\, r_p^2\right) MHz$$

- Significant effect in S-states and only tiny change in P-states.

- The center of the hydrogen atom is not empty. **Proton is here!**

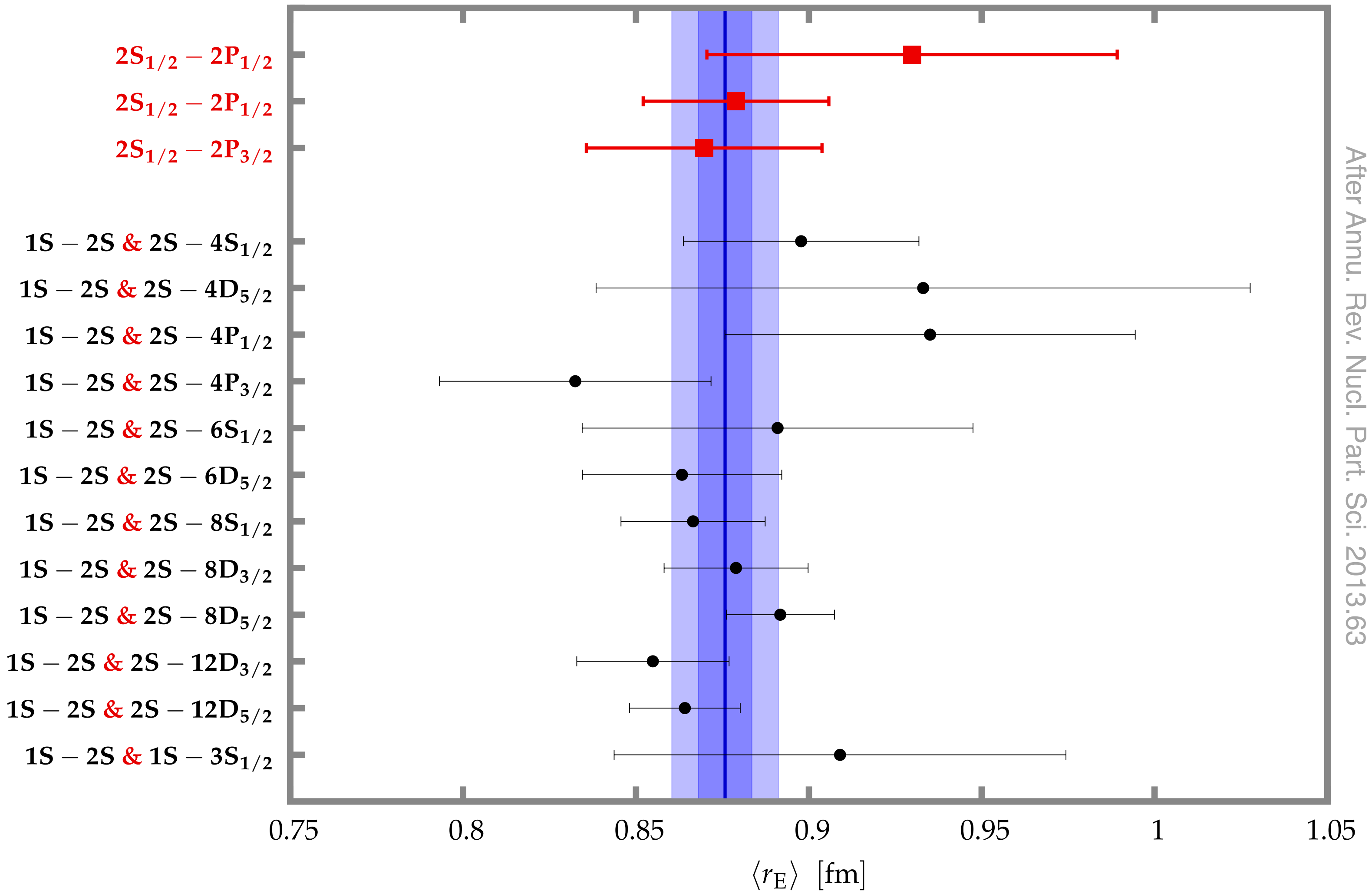


Electron probability densities for different states in eH

- Different **n-dependence** of the two terms allows the determination of R_∞ and r_p from at least two different measurements.

Spectroscopic measurements

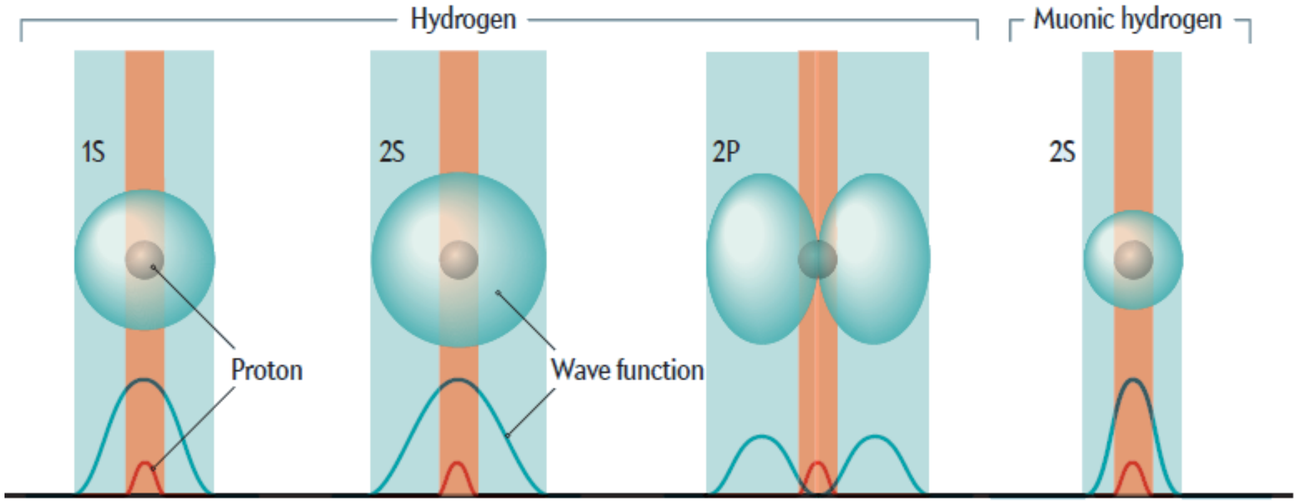
- Direct (RF) and indirect (laser) spectroscopy measurements:



- Radius from spectroscopic measurements: **r = (0.8758 ± 0.0077) fm**

μH Lamb shift measurements

- Due to larger mass muon much closer to the nucleus, resulting in a more **pronounced Lamb shift effect**.



Sci. Amer. Feb. 2014 , 34

- The largest signal is given by the $2S_{1/2}^{F=1}$ and $2P_{3/2}^{F=2}$ transition.

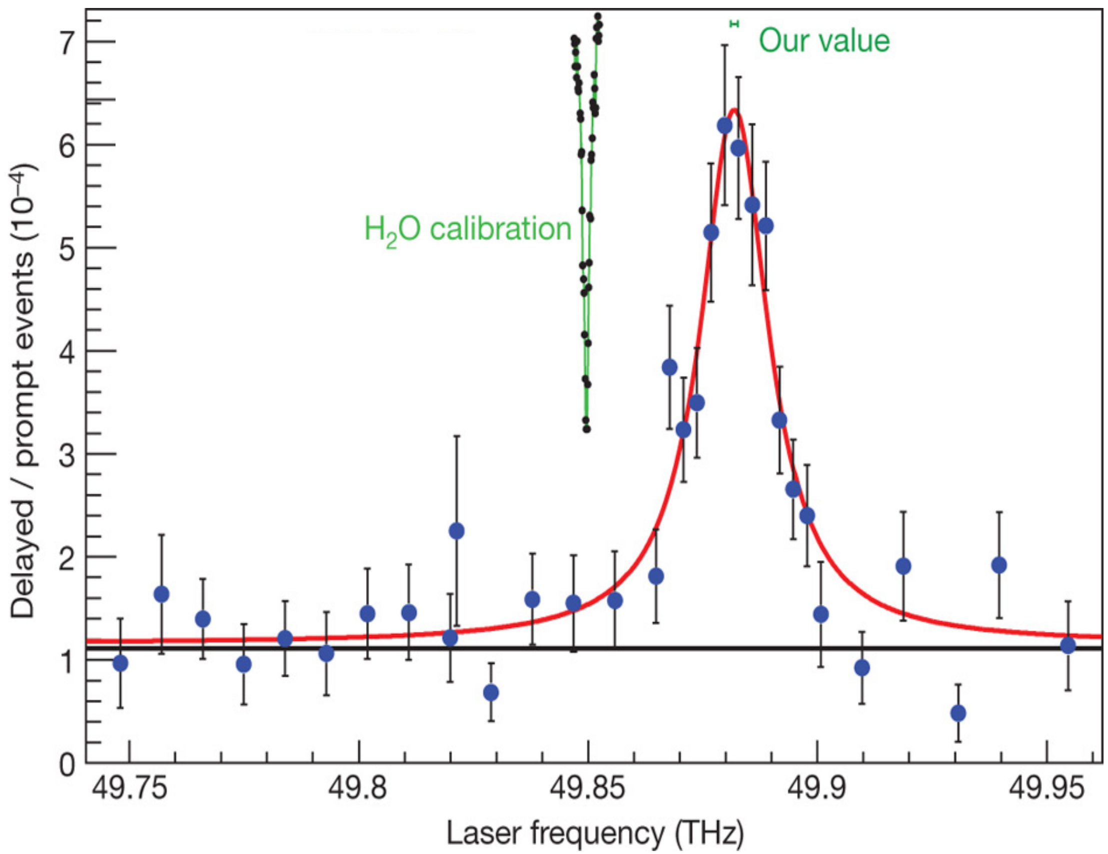
- The QED calculation predict:

$$\Delta E = 209.9779(49) - 5.2262\, r_p^2 + 0.0347\, r_p^3 meV$$

- Finite size of the proton contributes 1.8% of the energy difference.

CREMA Experiment @ PSI

Nature, Vol. 466, 2010



<u>The mean position of the peak:</u>

$$f_{2S-2P} = 49881.88(76)\ GHz$$

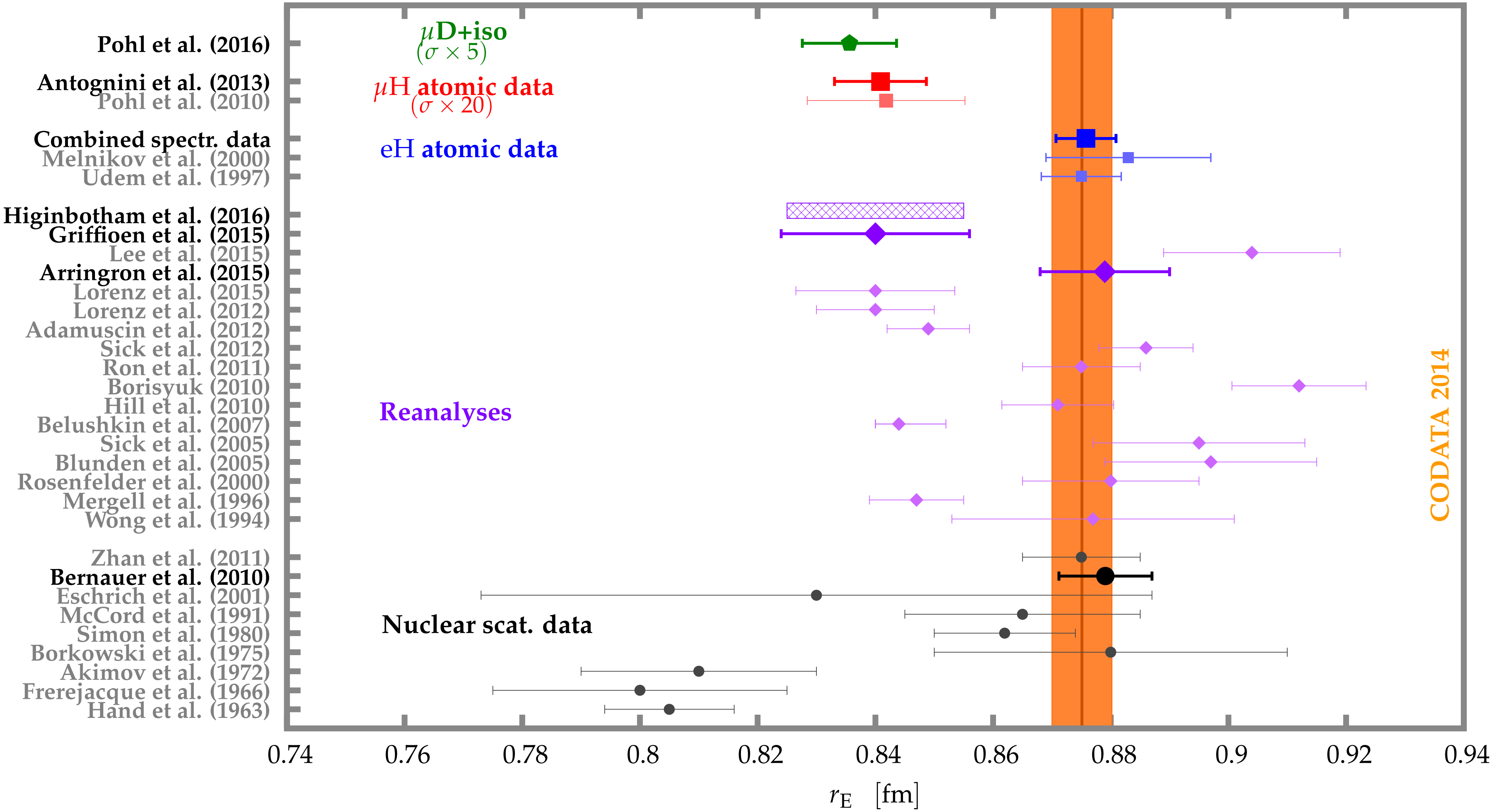
$$\Delta E = 206.2949(32)\ meV$$

<u>The resulting radius:</u>

$$r_p = 0.84184(36)(56)\ fm$$

The ever changing radius!

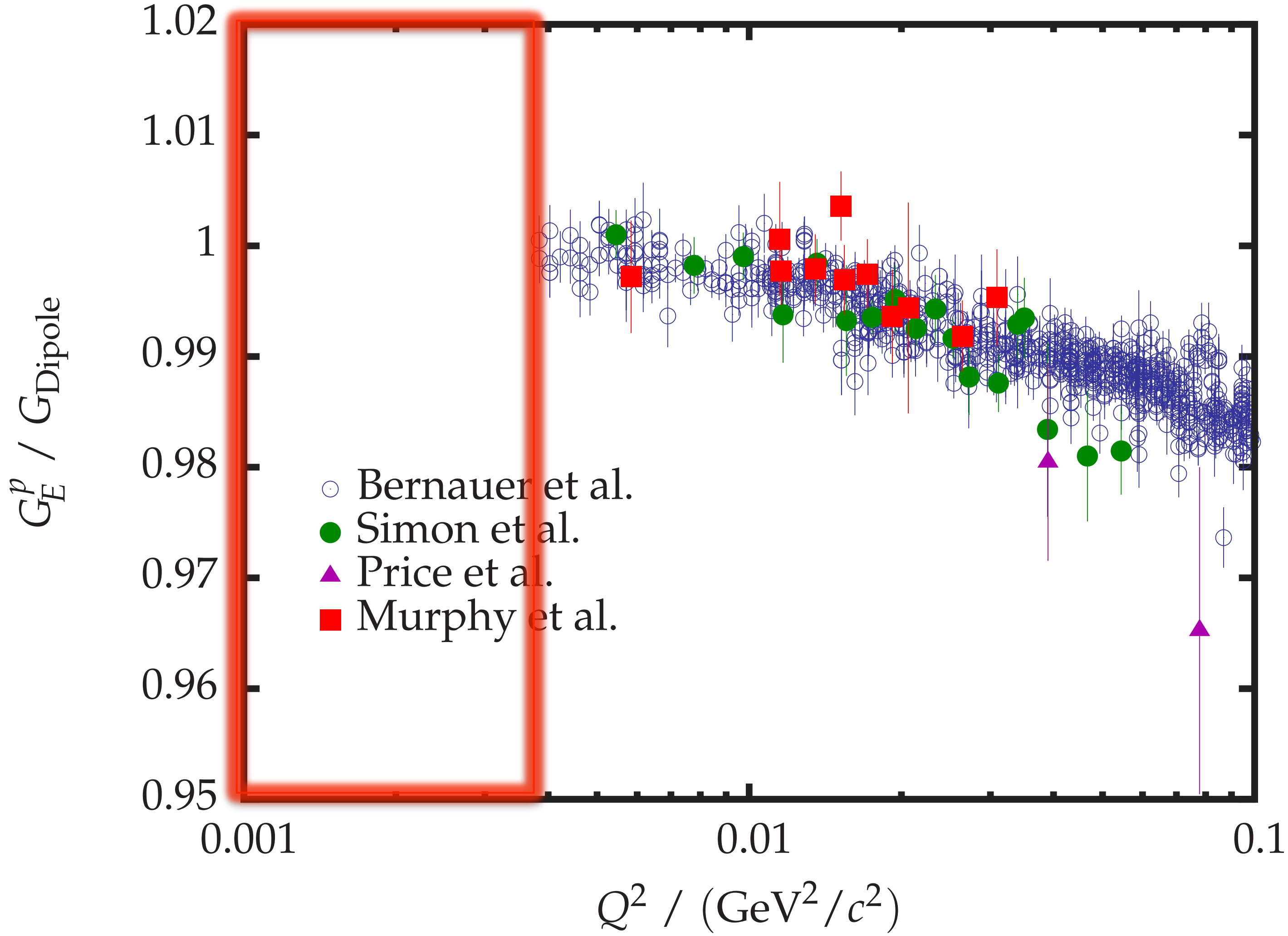
- The 6σ discrepancy in the r_p measurements.



Why is the puzzle so important?

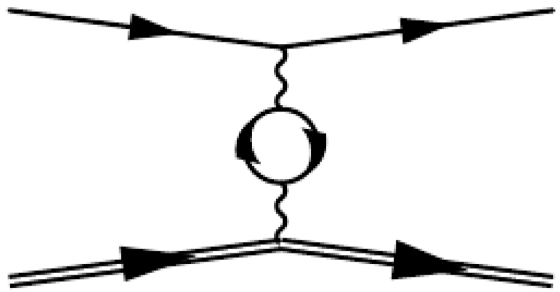
- Knowledge of basic properties of the nucleon.
- The radius is strongly correlated to the Rydberg constant.
- Problems in nuclear scattering data?
- Bringing different interpretations of nuclear scattering data to an agreement.
- Do we understand QED?

Proton's charge form-factor

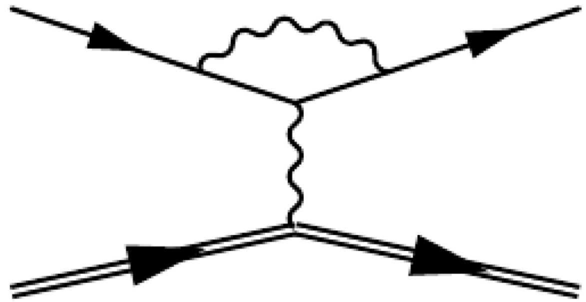


- Data available only for $Q^2 > 0.004$ (GeV/c)^2.
- **Need to avoid extrapolations to zero!**

Relating to Lamb shift measurements



$$Q^2_{vac} \geq 4m_e^2 \sim 10^{-6}\, GeV^2$$

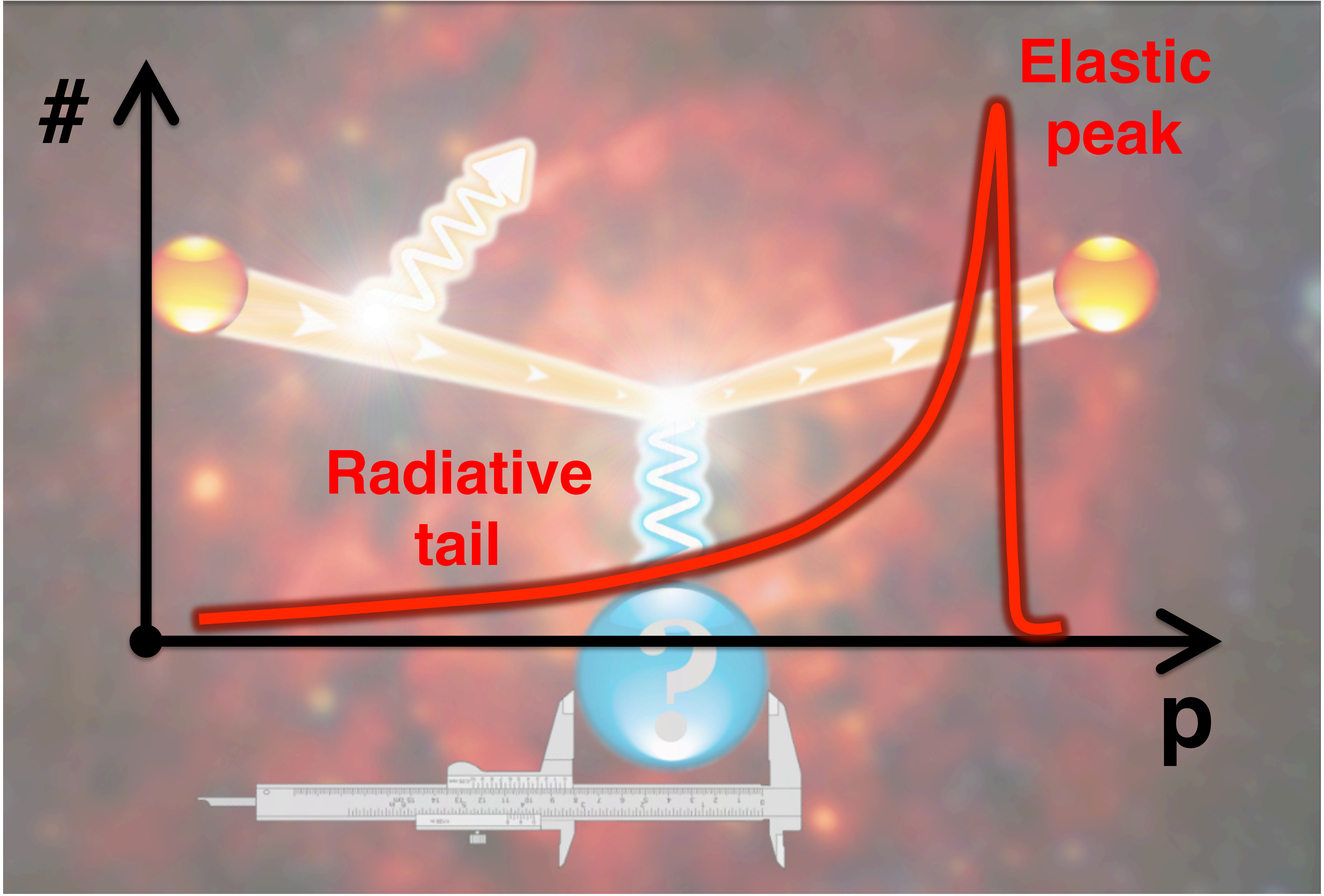


$$Q^2_{vertex} \geq \frac{\hbar^2}{R_e^2} \sim 10^{-9}\, GeV^2$$

Realistically accessible $Q^2 > 10^{-4}$ GeV^2.

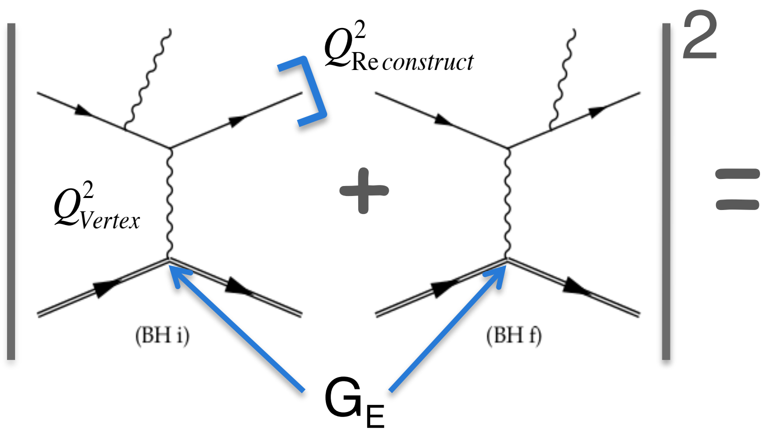
- Region of $Q^2 < 0.004$ (GeV)^2 is extremely hard to reach.
- Kinematic range is **limited by available experimental apparatus**.
- Novel techniques are needed to explore extremely low Q^2 regime.

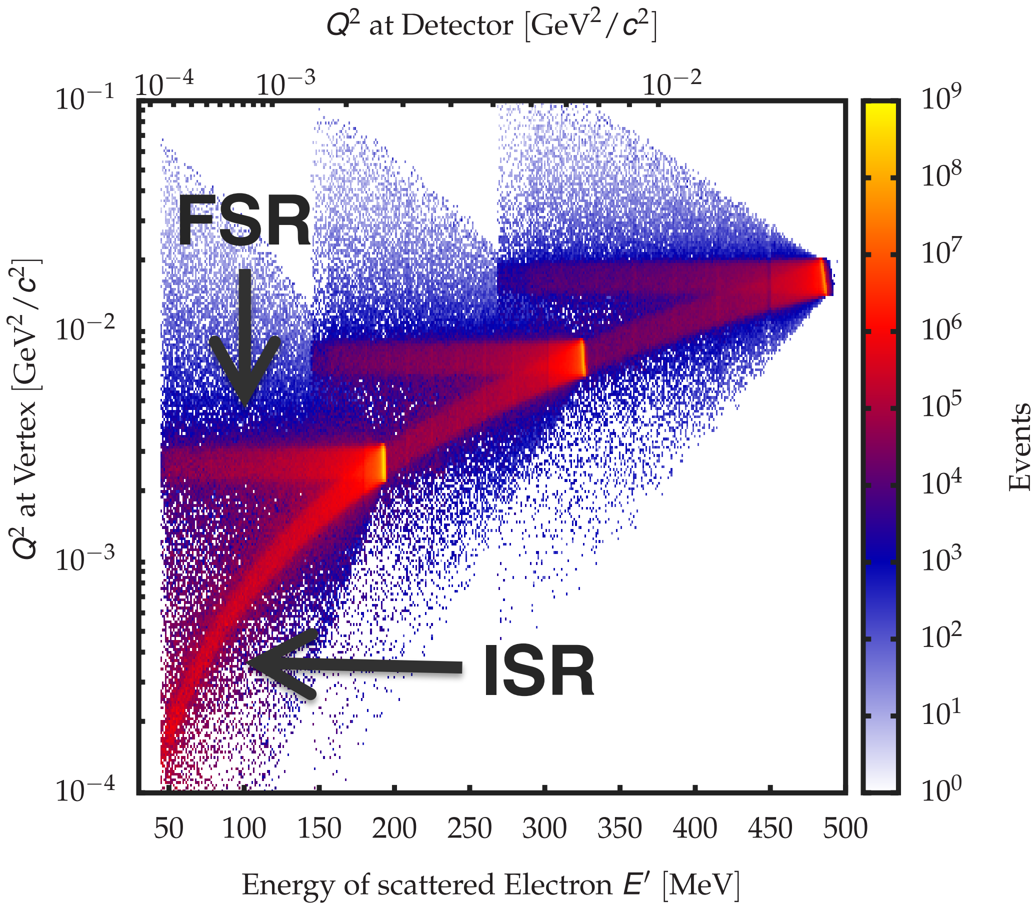
ISR Experiment at MAMI



Full Simulation

- Dominated by coherent sum of two Bethe-Heitler diagrams.



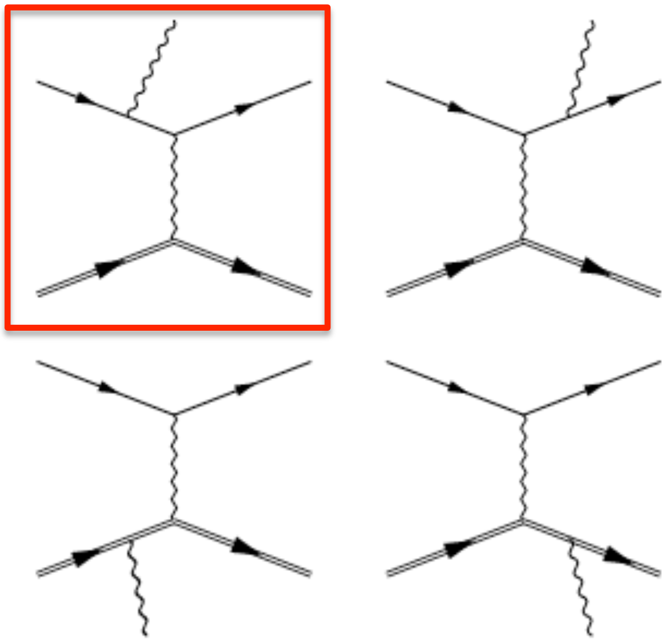


- By comparing data to simulation ISR information can be reached.
- **Measured δσ linearly proportional to the δG_E between data and model.**

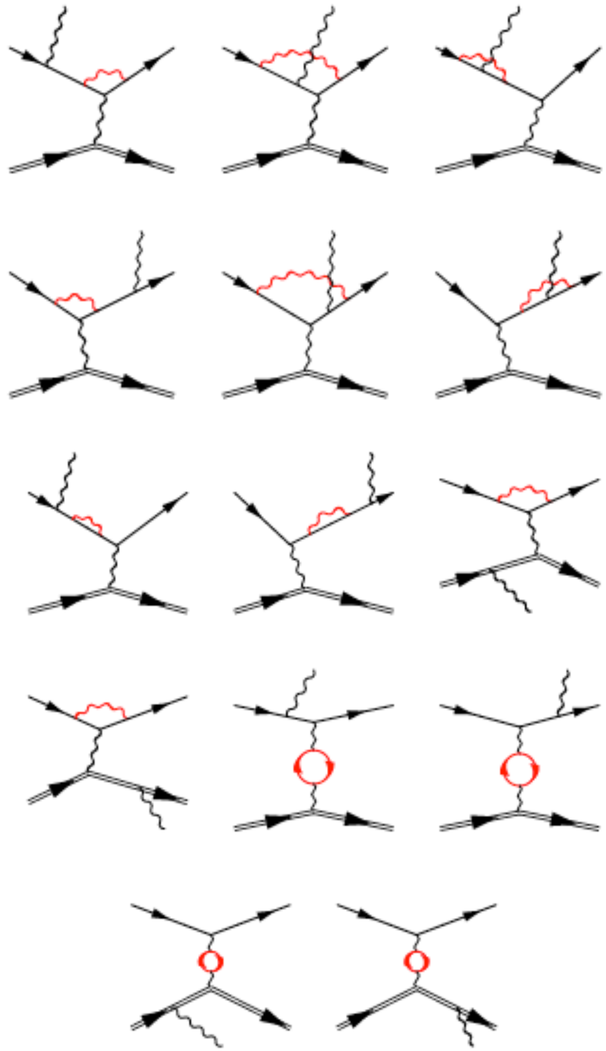
Simul++

- Based on standard A1 framework.
- Detailed description of apparatus.
- Exact calculation of the leading order diagrams:

ISR



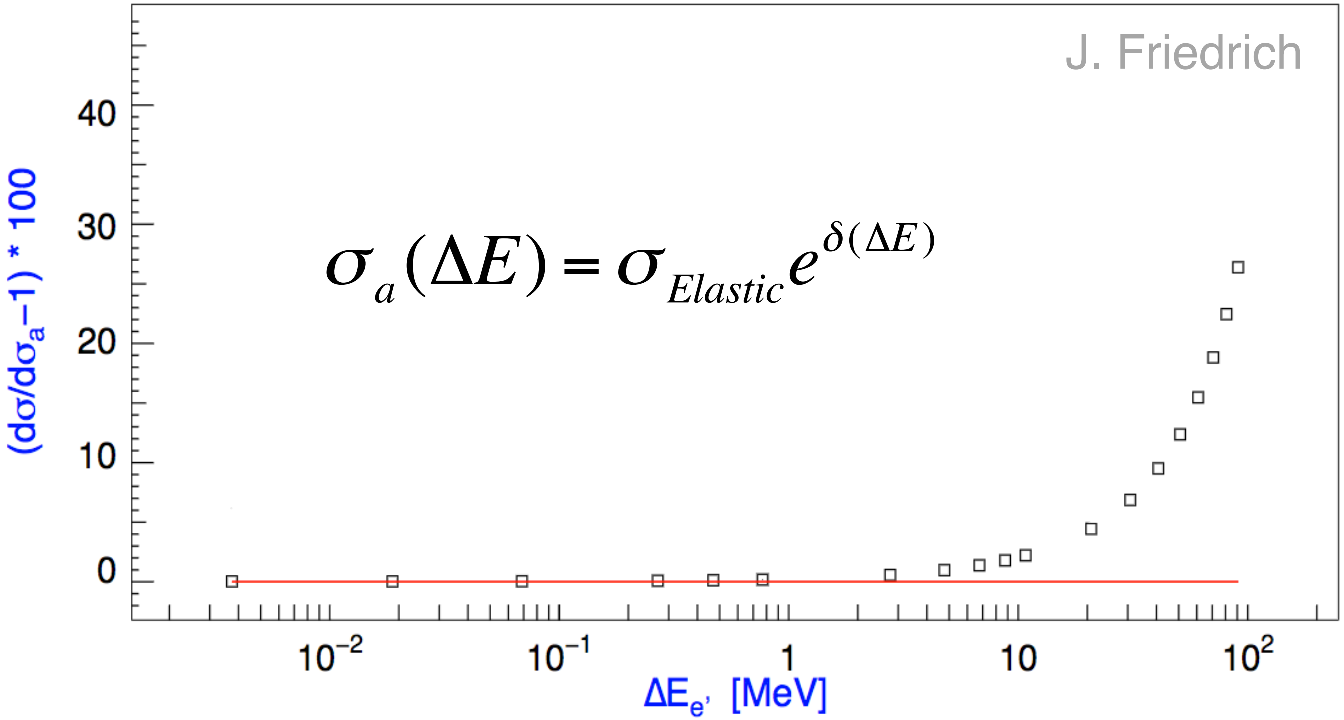
- The NL-order **virtual and real** corrections included via effective corrections to the cross-section.



…

Going beyond peaking approximation

- Traditional peaking approximations insufficient for such experiment.



- **Secondary objective:** Measurements at higher Q^2 for validating the radiative corrections in a region, where FFs are well known.

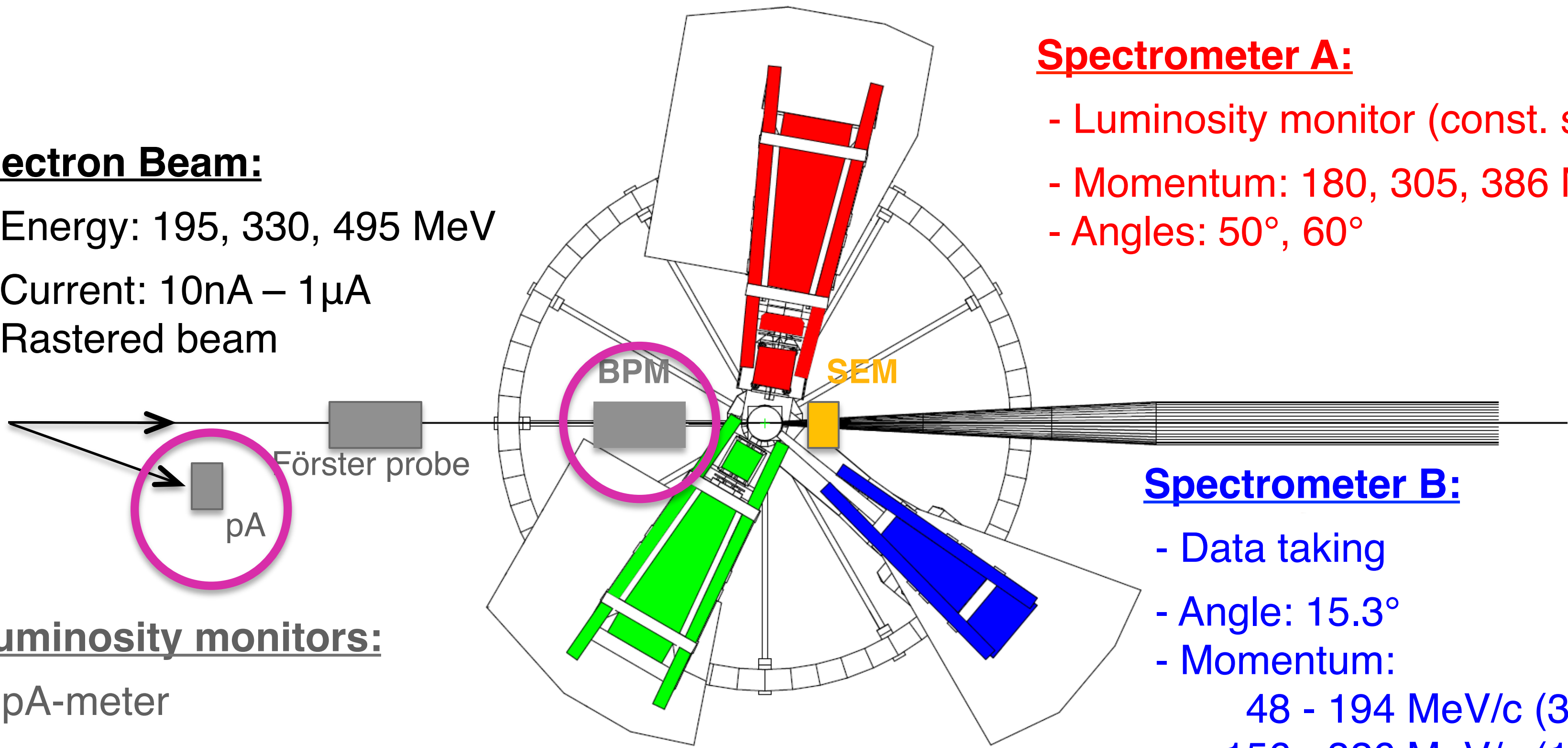
  Important for experiments, e.g. VCS, which require high-precision knowledge of the radiative corrections.

The ISR experiment

- Full experiment done in August 2013. Four weeks of data taking.

Electron Beam:

- Energy: 195, 330, 495 MeV
- Current: 10nA – 1μA
- Rastered beam



Spectrometer A:

- Luminosity monitor (const. setting)
- Momentum: 180, 305, 386 MeV/c
- Angles: 50°, 60°

Spectrometer B:

- Data taking
- Angle: 15.3°
- Momentum:
  48 - 194 MeV/c (35 setups)
  156 - 326 MeV/c (12 setups)
  289 - 486 MeV/c (9 setups)

Luminosity monitors:

- pA-meter
- Förster probe
- SEM

Spectrometer C:

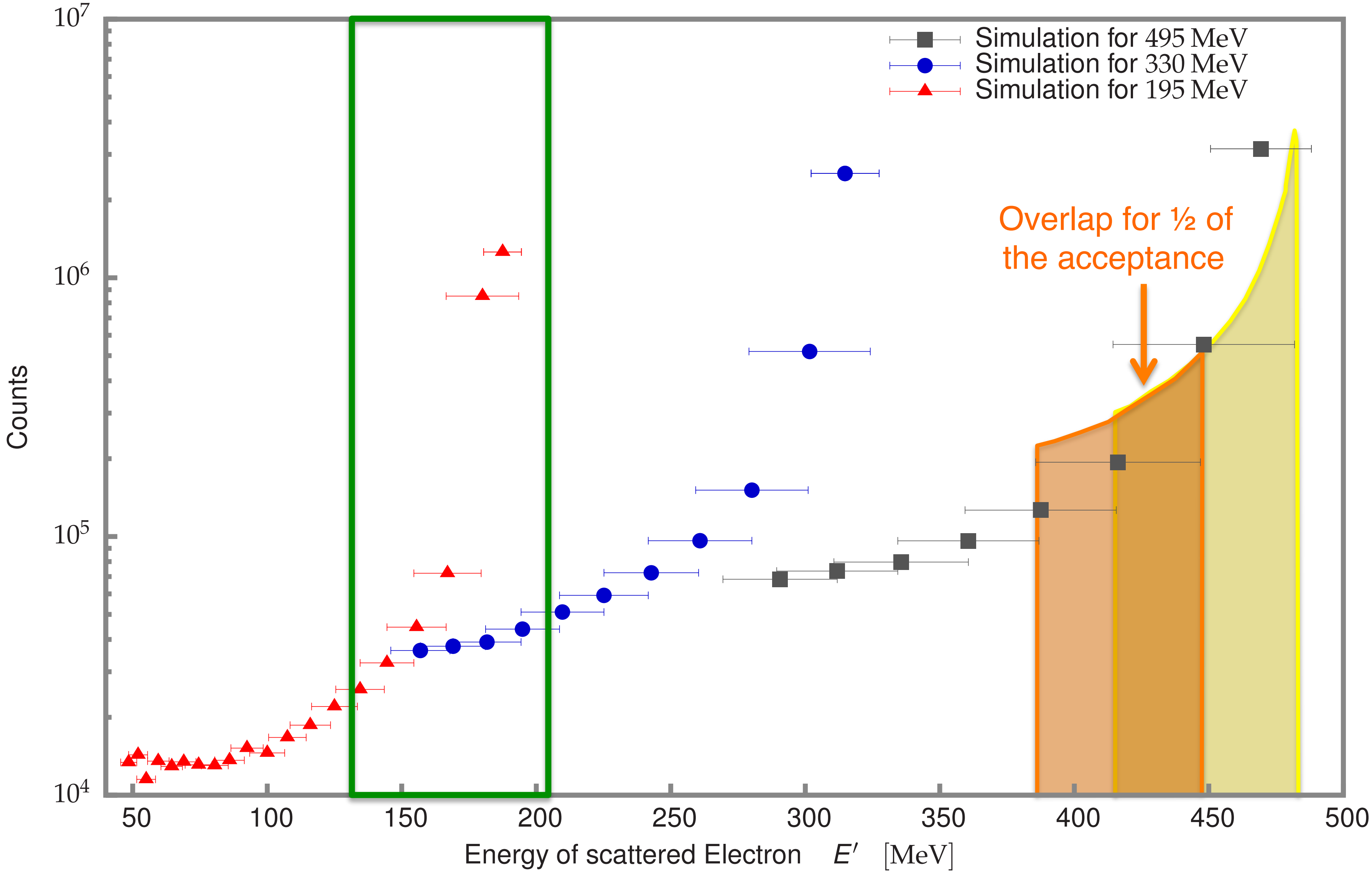
- Not used

Beam control module:

- Communicates with MAMI and ensures very stable beam.
- BPM and pA-meter measurements performed automatically every 3min.

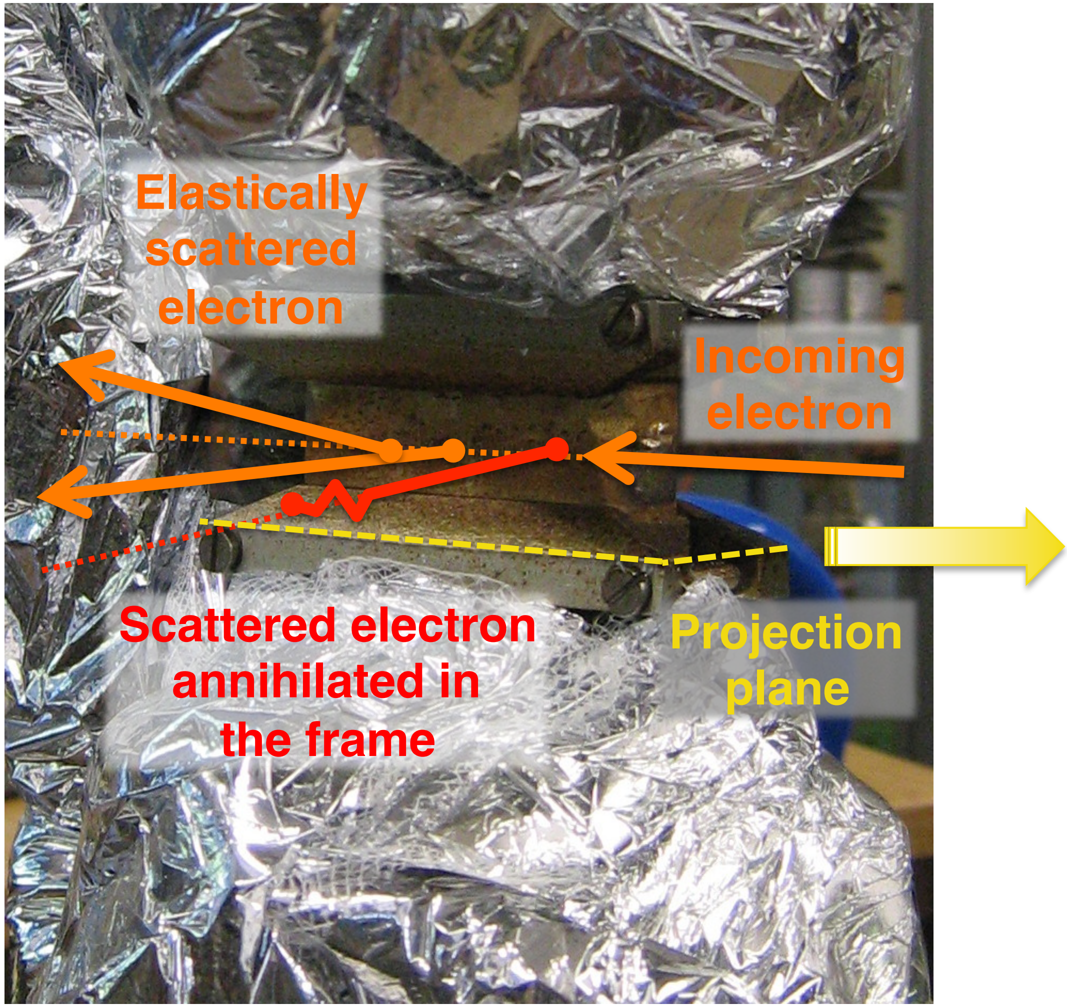
Kinematic settings

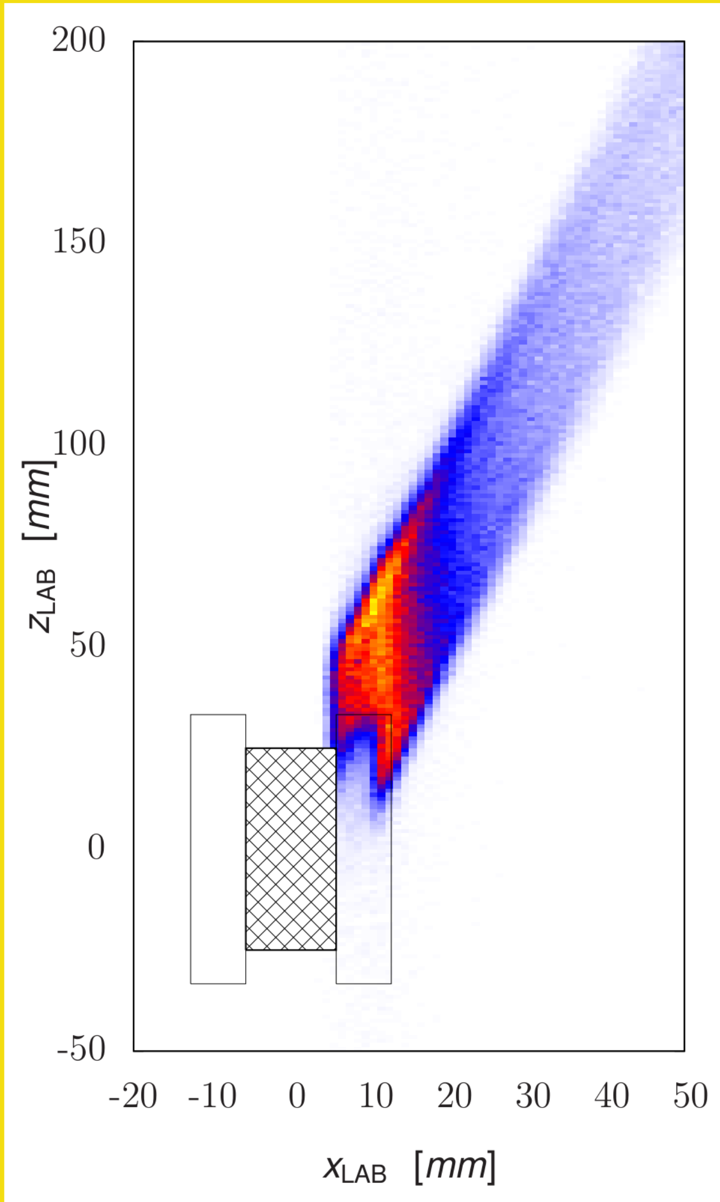
- Overlapping settings to control systematic uncertainty.



Target Frame contributions #1

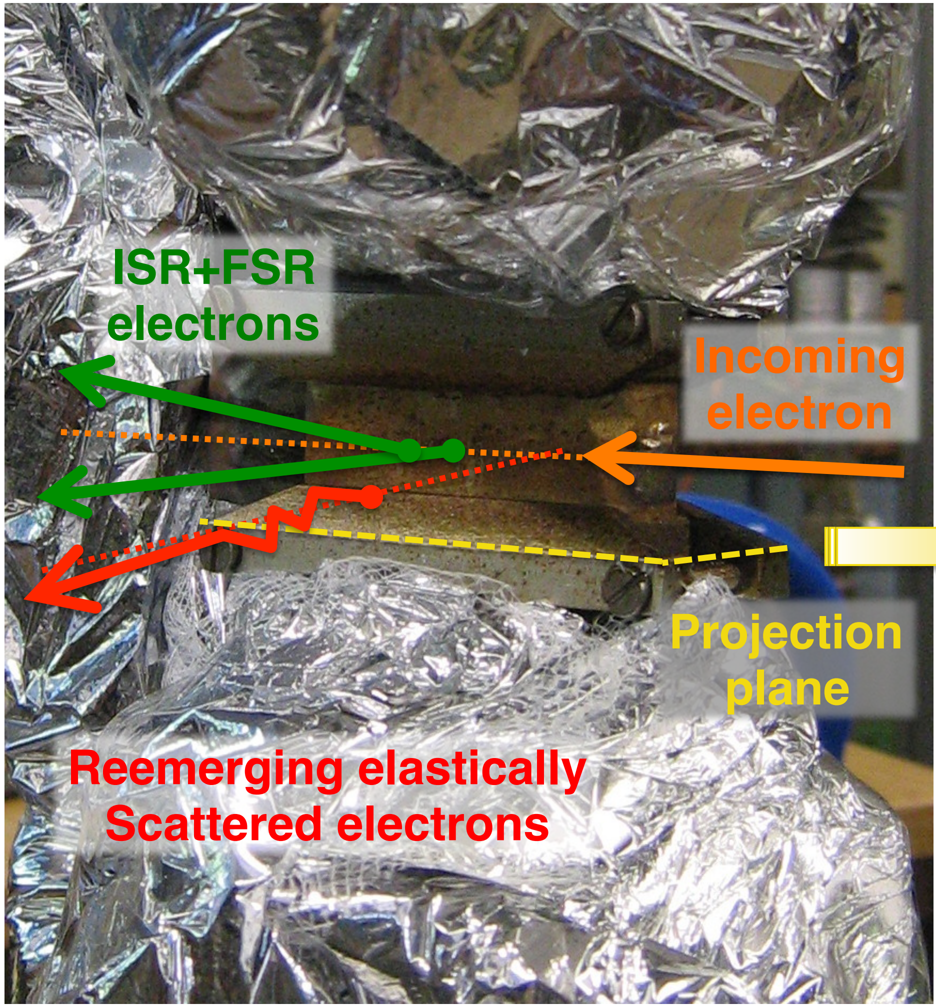
- Presence of target frame results in the deficiency of the elastic events .

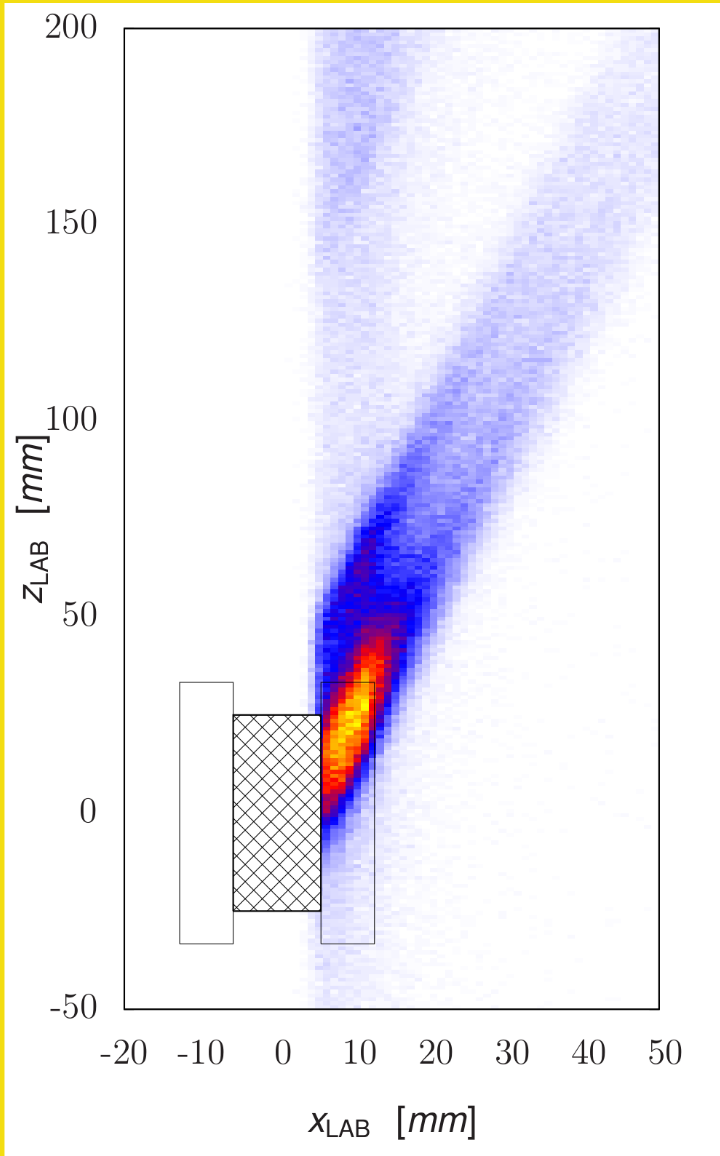




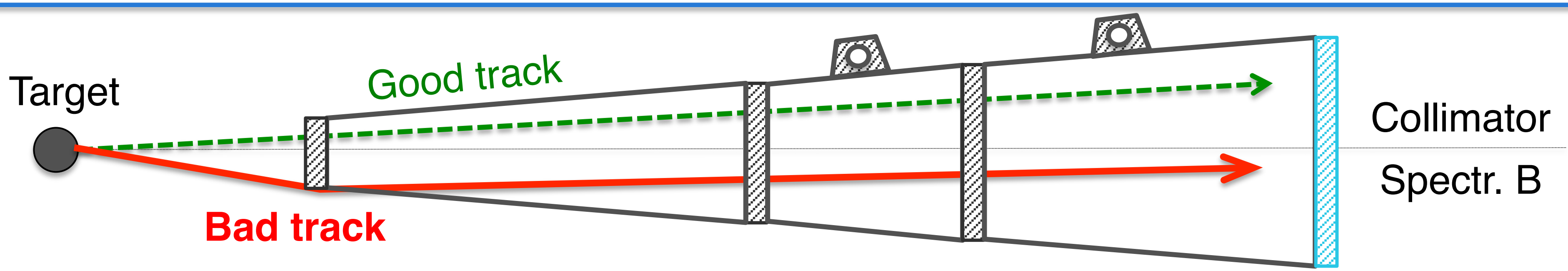
Target Frame contributions #2

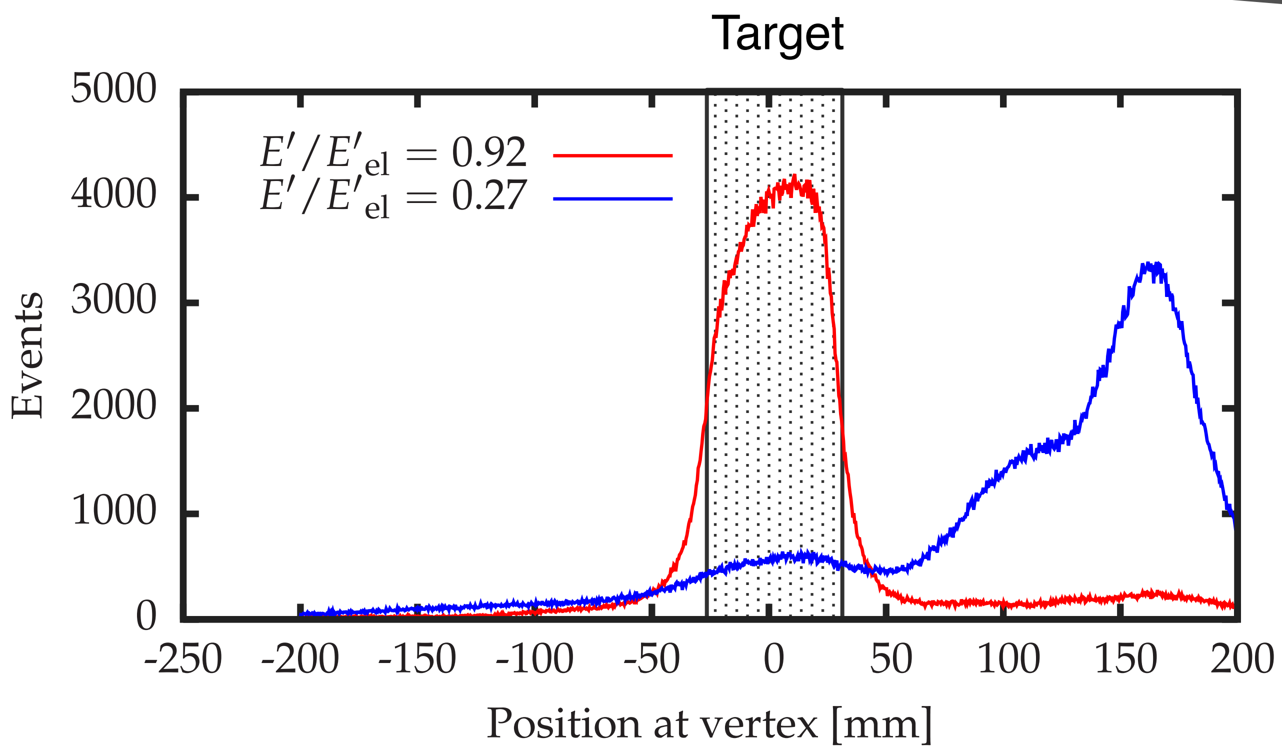
- … and in the abundance of bogus events in radiative tail of the elastic peak.





Entrance flange contributions

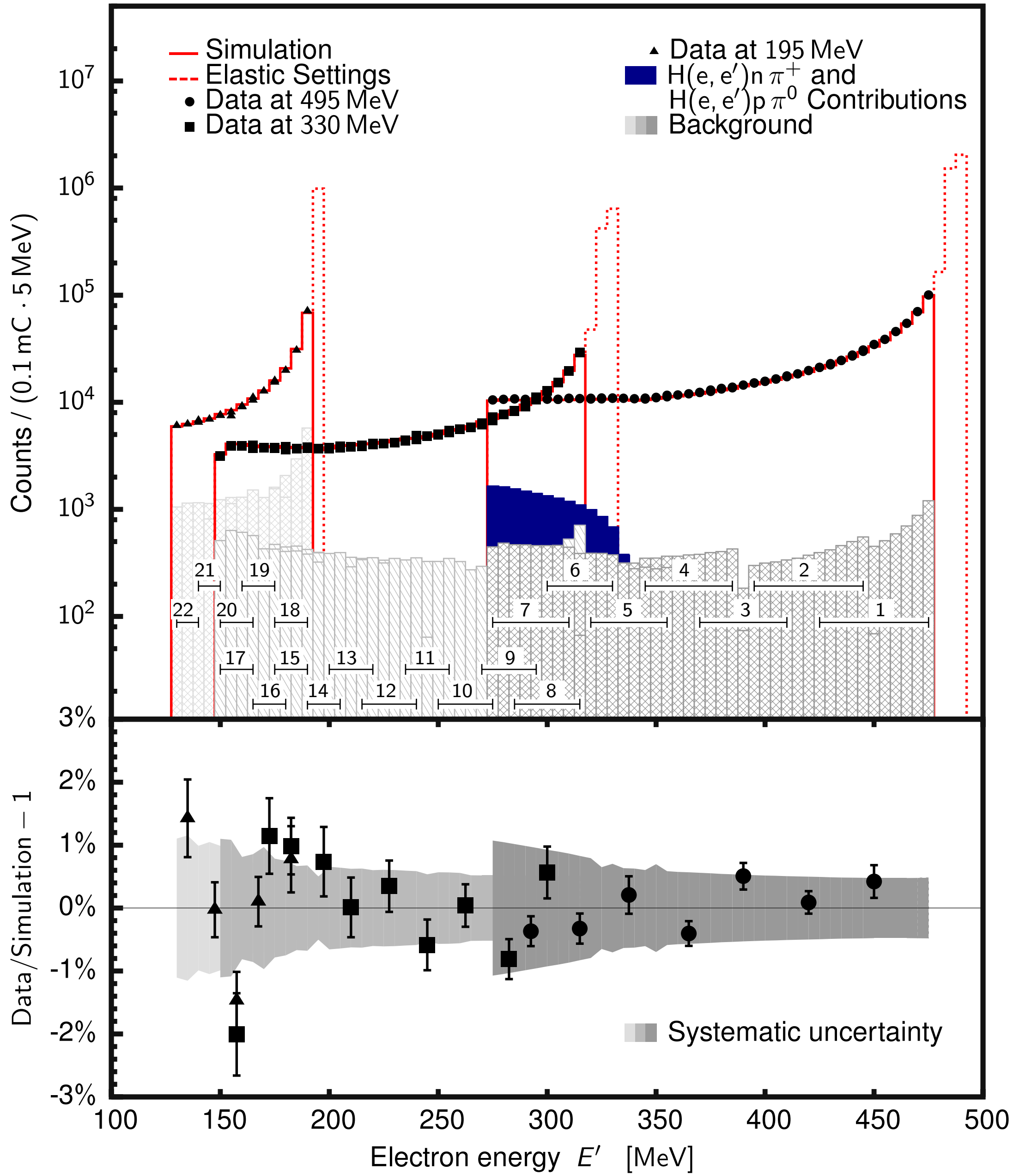




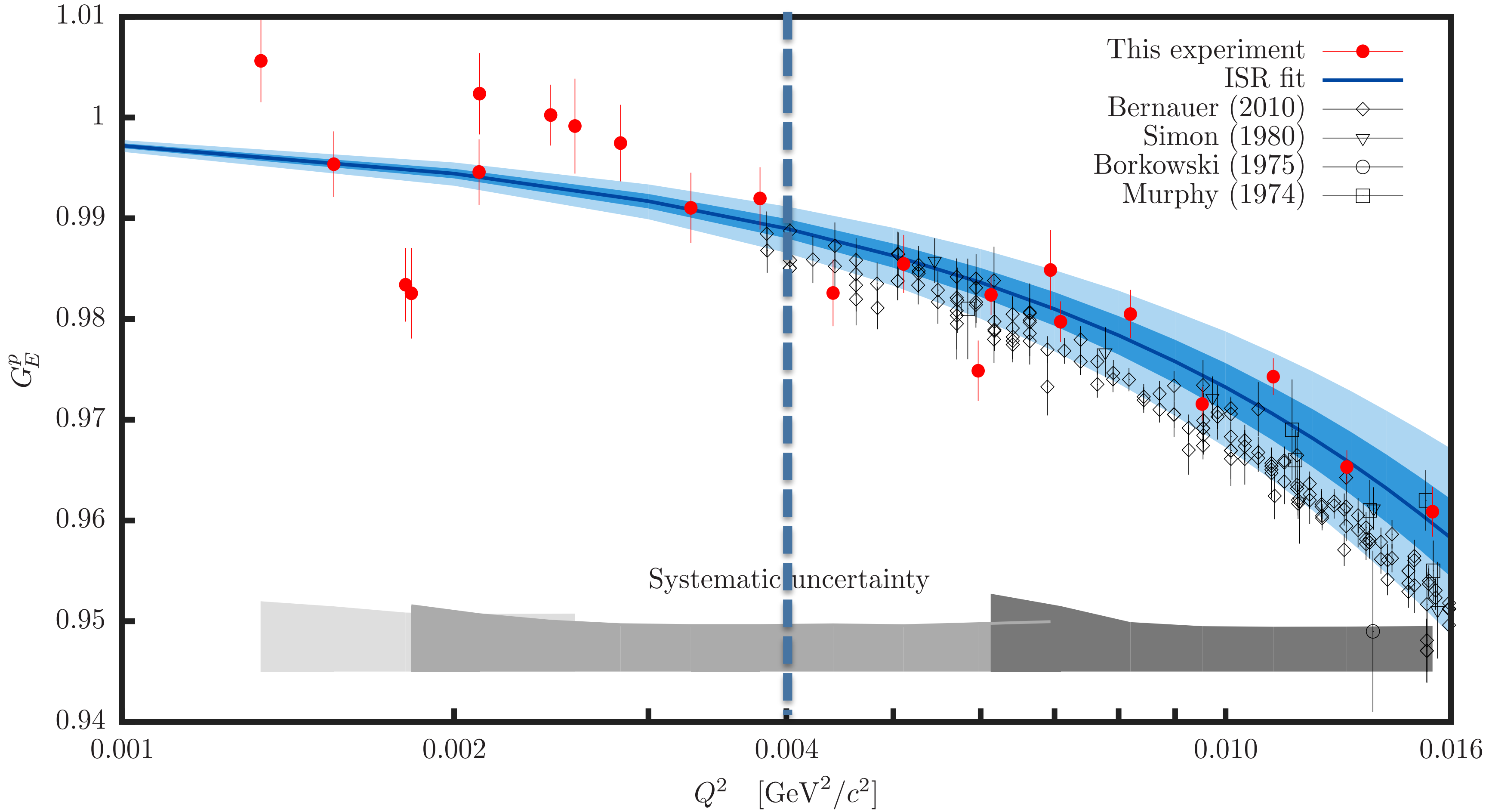
- Spec. B encompasses a long entrance flange.
- Events rescattered from the snout cover the whole vertex acceptance.

Results

- Existing apparatus limited reach of ISR experiment to E' ~ 130 MeV.
- Elastic points excluded.
- Simulation performed with Bernauer parameterization of form factors.
- A percent agreement between the data and simulation demonstrates that the radiative corrections are well understood!



ISR form-factors



- Assuming flawless description of radiative corrections, form factors can be extracted from the data.

- **First measurement of G_E^p at 0.001 GeV^2 ≤ Q^2 ≤ 0.004 GeV^2**

ISR Proton radius

- G_e^p modeled with the polynomial fit.

$$G_E^p(Q^2) = \boldsymbol{n}\left(1 - \frac{\mathbf{r_E^2}}{6}Q^2 + \frac{a}{120}Q^4 - \frac{b}{5040}Q^6\right)$$

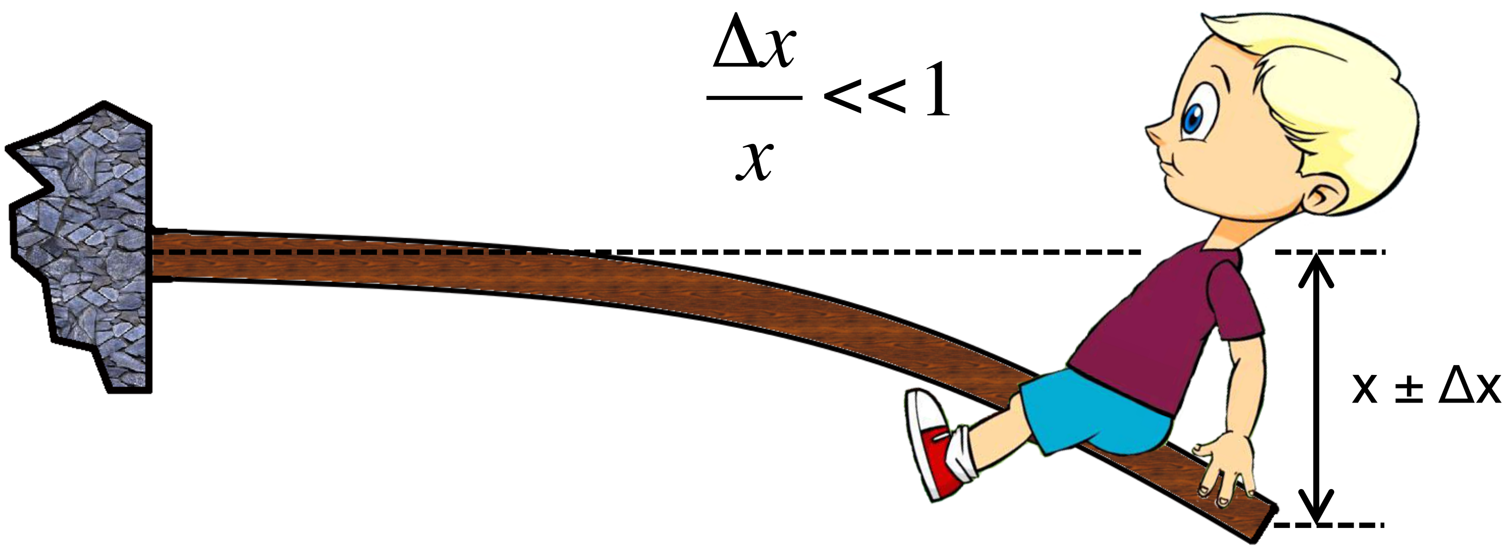
Terms (a,b) known from previous analyses [Distler et al.]

- The obtained radius:

$$r_E = \left(0.810 \pm 0.035_{stat.} \pm 0.074_{syst.} \pm 0.003_{\mathrm{mod.}}\right) fm$$

Lever arm is important

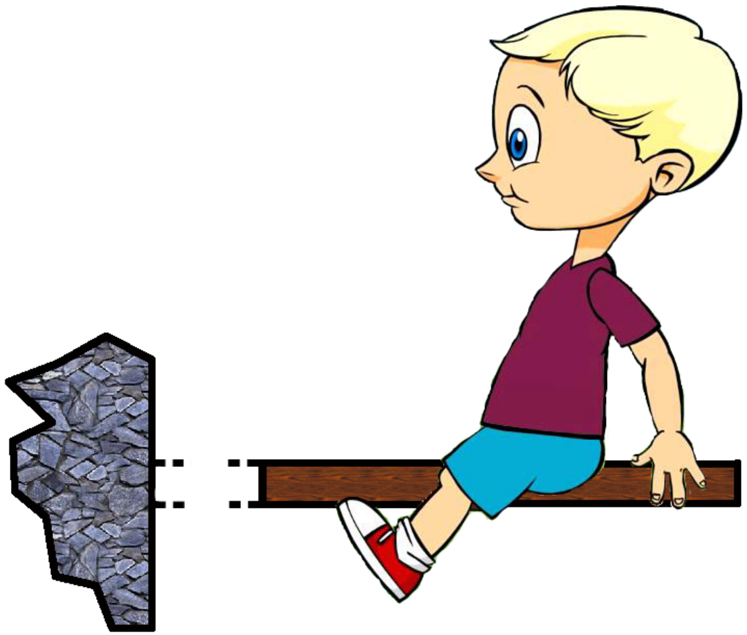
- Determining radius analogous to measuring elasticity of a rod!
- Measuring deviations x with fixed precision Δx.
- Measuring further away from pivot is relatively more precise.



- Not knowing the exact behavior of a rod near the pivot.

Problem of small lever arm

- Measuring near the pivot point gives us insufficient lever arm!



$$\frac{\Delta x}{x} \approx 1$$

- Insufficient precision to extract the elasticity (radius).
- No precise information on the absolute position of the origin.

ISR Proton radius

- G_e^p modeled with the polynomial fit.

$$G_E^p(Q^2) = \boldsymbol{n}\left(1 - \frac{\mathbf{r_E^2}}{6}Q^2 + \frac{a}{120}Q^4 - \frac{b}{5040}Q^6\right)$$

Terms (a,b) known from previous analyses [Distler et al.]

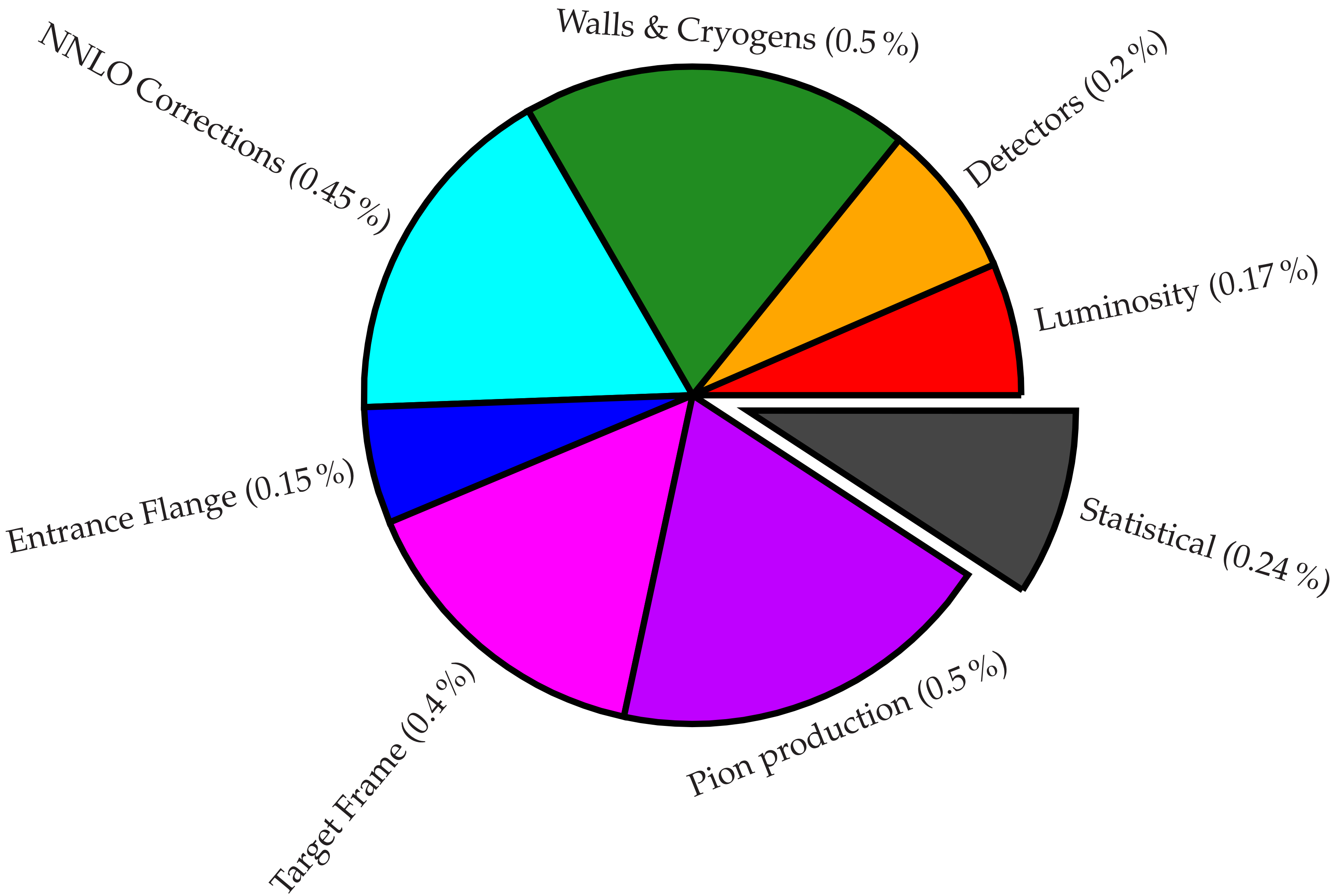
- The obtained radius:

$$r_E = \left(0.810 \pm 0.035_{stat.} \pm 0.074_{syst.} \pm 0.003_{\mathrm{mod.}}\right) fm$$

- The fit (with statistical errors only) reports the reduced χ^2 of 3.2.

Result is dominated by systematic effects!

Uncertainties

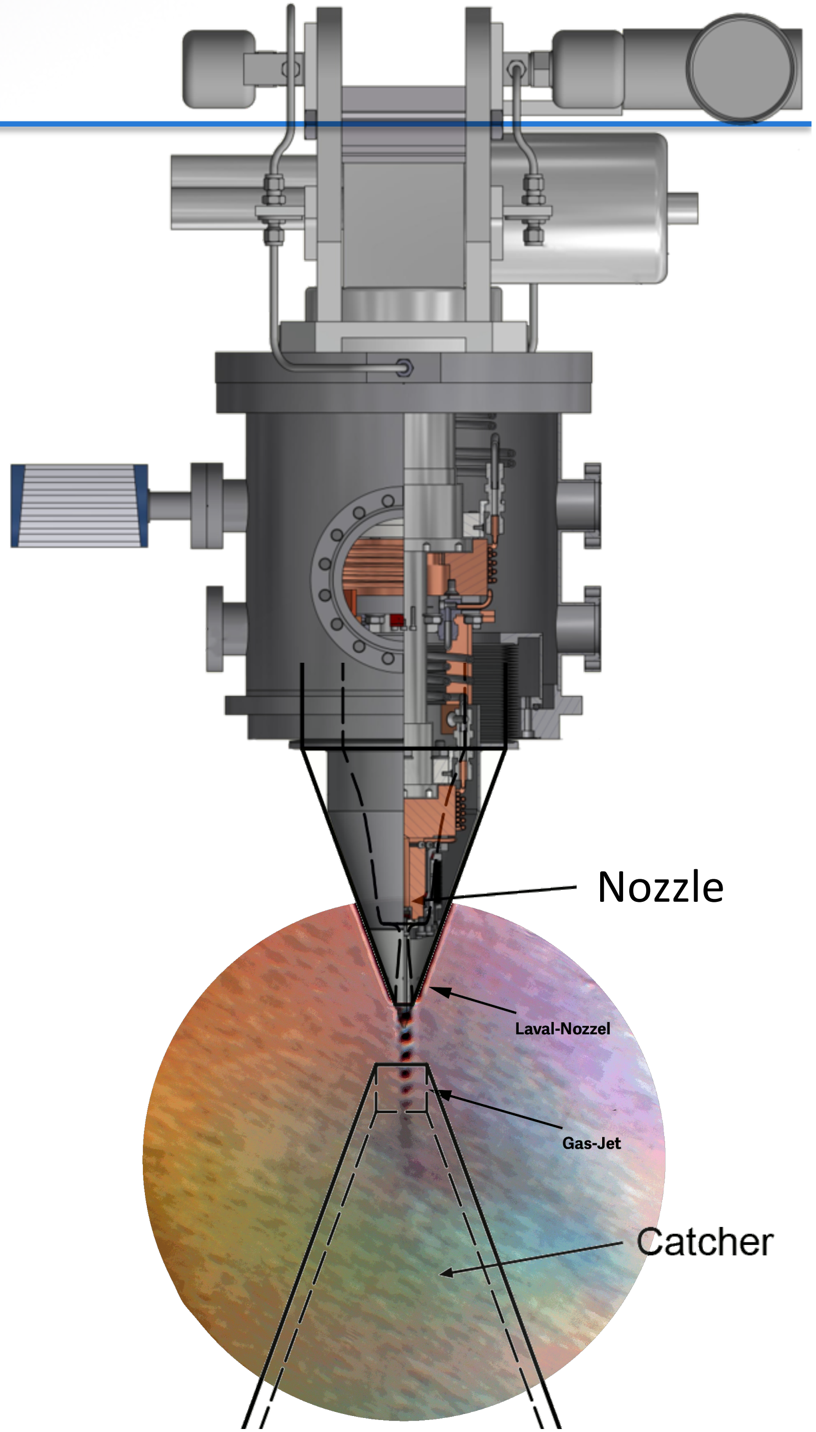


Total systematic uncertainty of cross-section $\leq$ 1.0 %

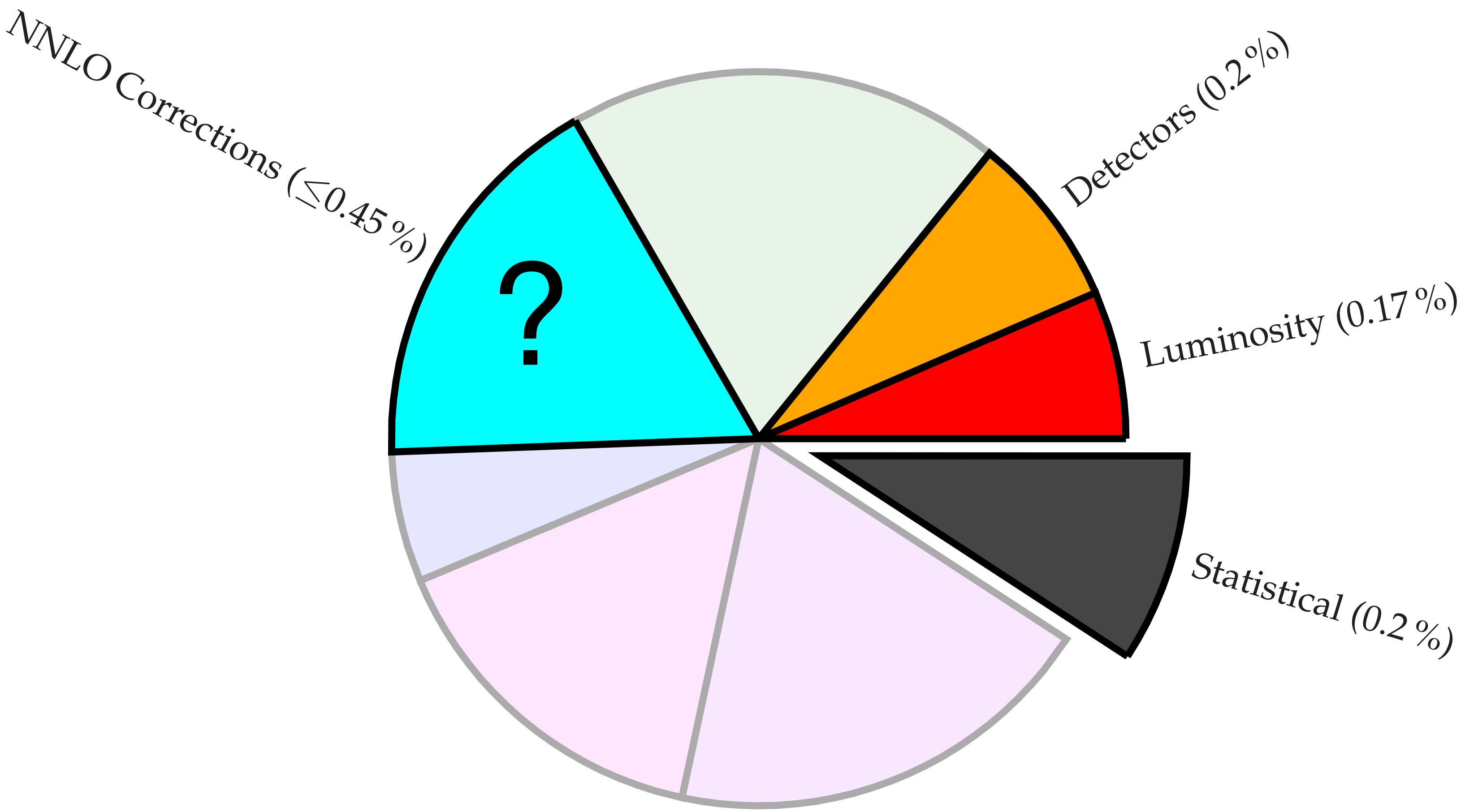
Hypersonic jet target

- Target developed for MAGIX, but could be used also in A1.

- No metal frame near the vertex.
- No target walls.
- Width of the jet 2mm (point-like target)



Expected uncertainties with JetISR



Total systematic uncertainty of cross-section $\leq$ 0.5 %

- Uncertainty of NNLO theoretical corrections will be reduced to 0.2% and total uncertainty to 0.3%.

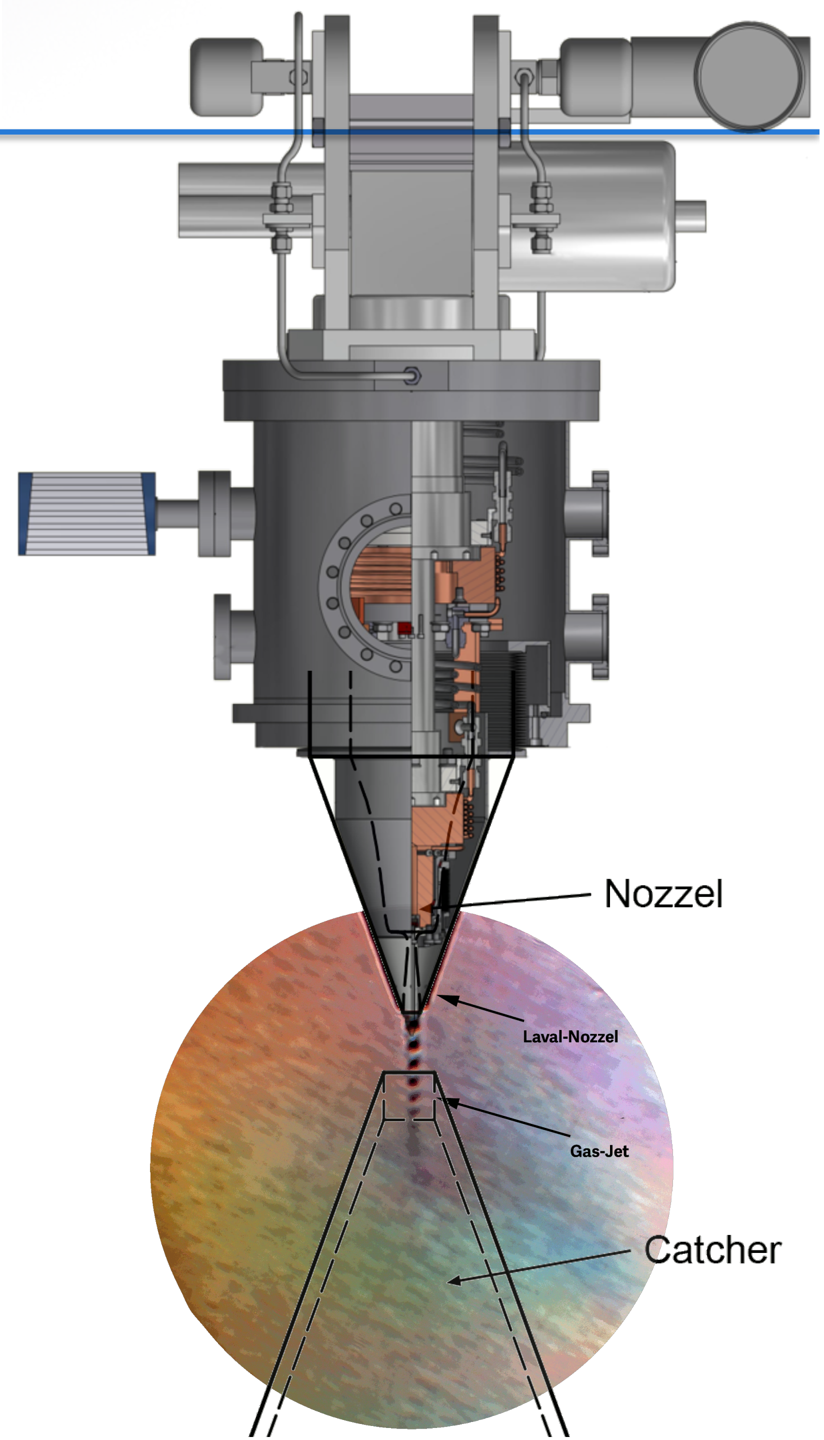
Hypersonic jet target

- Target developed for MAGIX, but could be used also in A1.

- No metal frame near the vertex.
- No target walls.
- Width of the jet 2mm (point-like target)

- Density of $\mathbf{10^{-4}\ g/cm^3}$ at 15 bar.
- Luminosity of $\mathbf{10^{34}/cm^2s}$ can be achieved at MAMI.

- **Experiment approved by PAC 2016**



Summary

- A pilot experiment has been performed at MAMI to measure G_E^p at very low Q^2.

- A new technique for FF determination based on ISR has been successfully validated.

- Reach of the first ISR experiment limited by unforeseen backgrounds.

- **The jet target opens possibility for reaching the ultimate goal of measuring form factors at 10^{-4} GeV^2.**

Thank you!