Proton charge radius with the ISR experiment

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A1 Collaboration
Institute for Nuclear Physics
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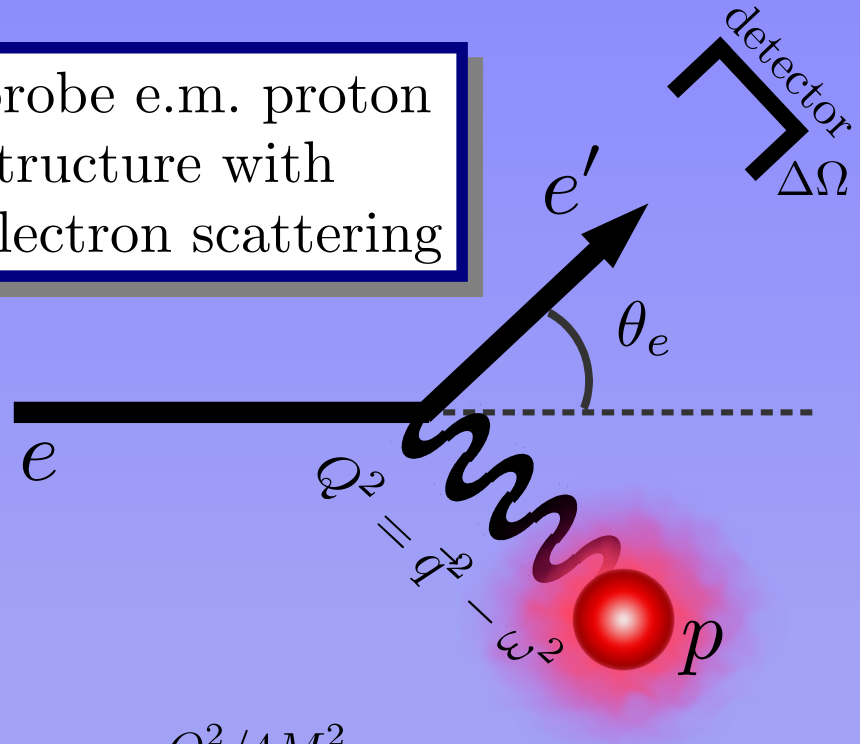
French-Ukrainian Workshop on the instrumentation developments for high energy physics

Nov. 6-8, 2017, LAL, Orsay, France

- elastic ep scattering
- proton radius
- ISR method
- experiment
- outlook

Elastic ep -scattering

probe e.m. proton structure with electron scattering



$$\tau = Q^2/4M^2$$

$$\epsilon^{-1} = 1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}$$

cross section for elastic ep scattering:

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}} \cdot \frac{1}{(1+\tau)}\left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon}G_{\mathrm{M}}^2(Q^2)\right]$$

$G_{\mathrm{E}}^2(Q^2) \leftrightarrow$ charge distribution

$G_{\mathrm{M}}^2(Q^2) \leftrightarrow$ magnetization distribution

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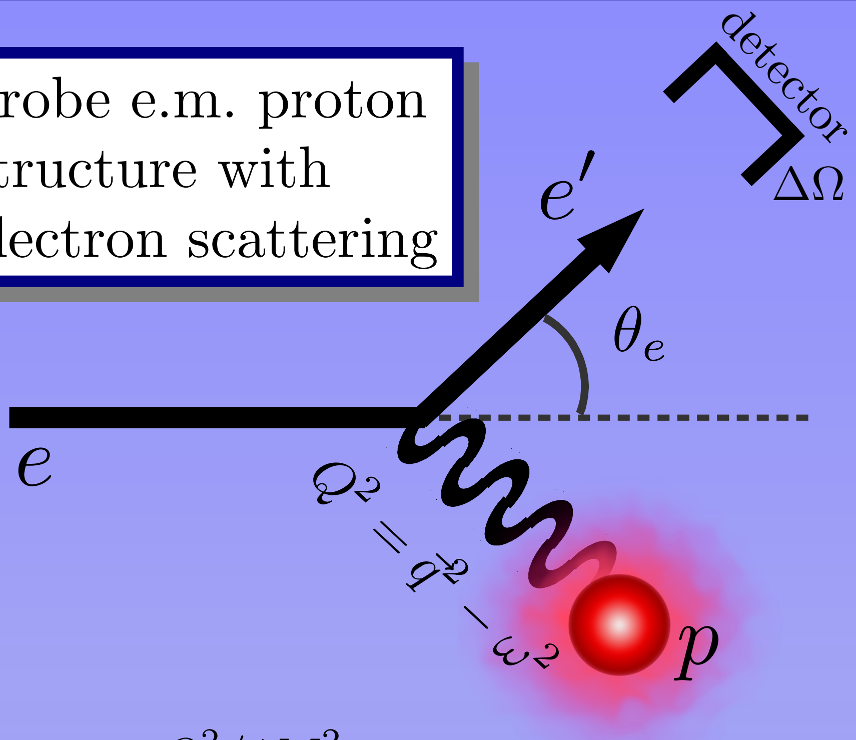

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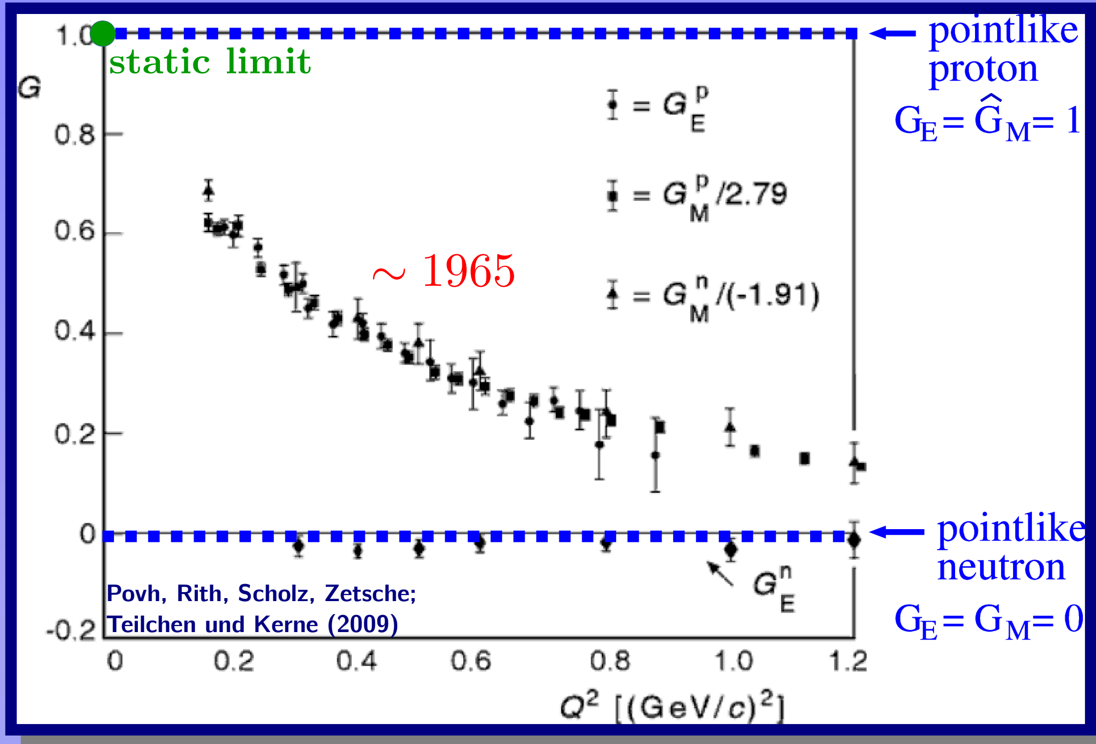

cross section for elastic ep scattering:

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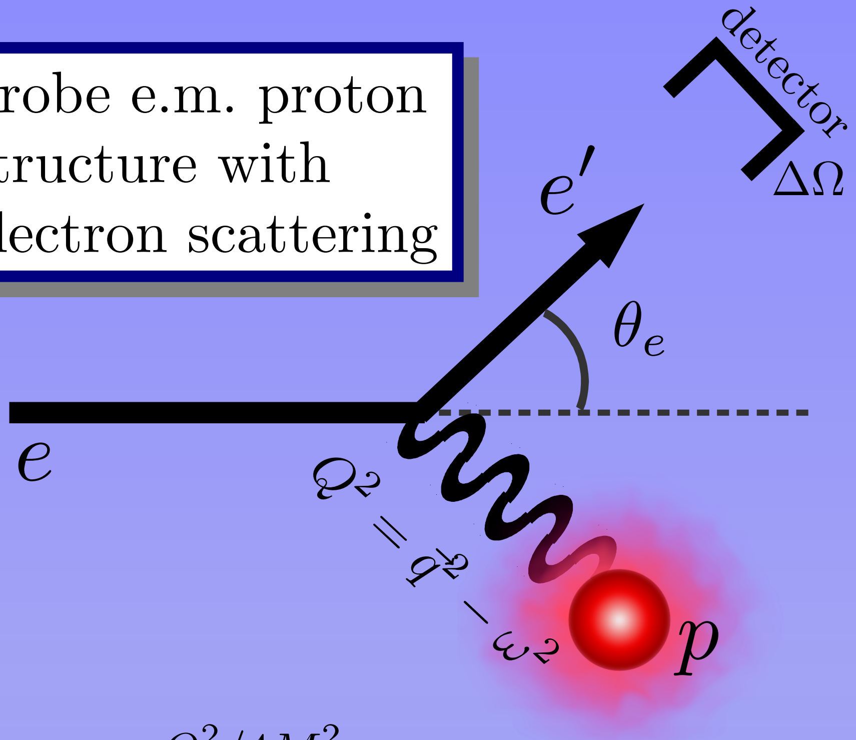

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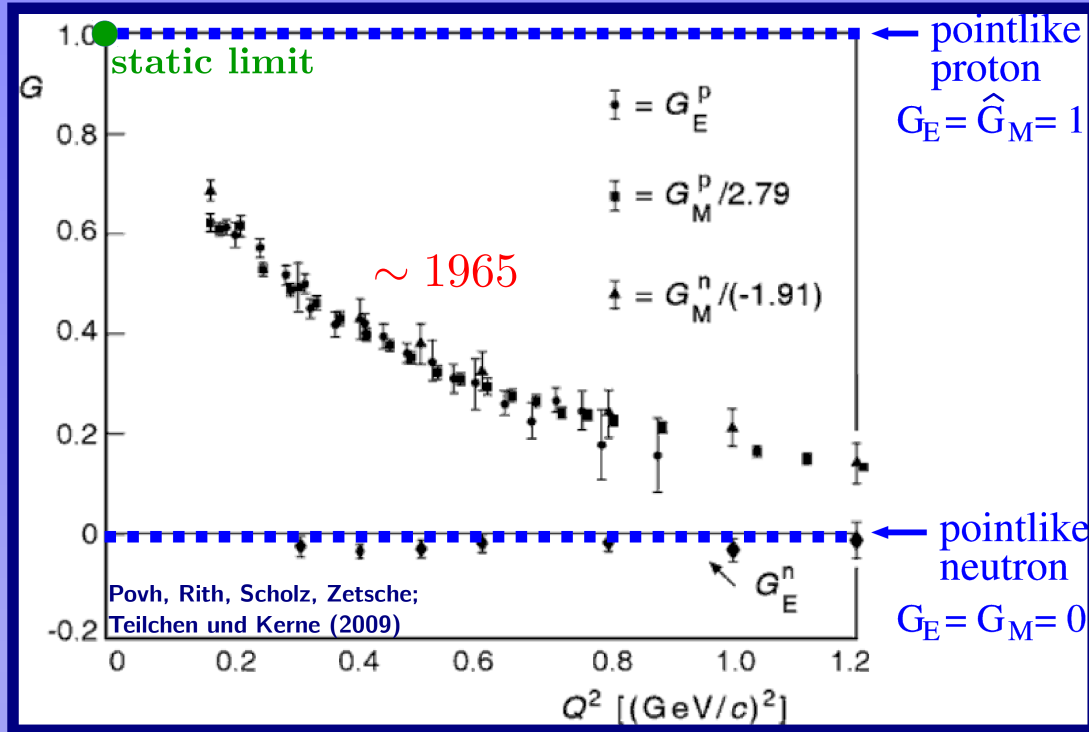

radius from slope: $\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{dG_E}{dQ^2}\right|_{Q^2=0}$

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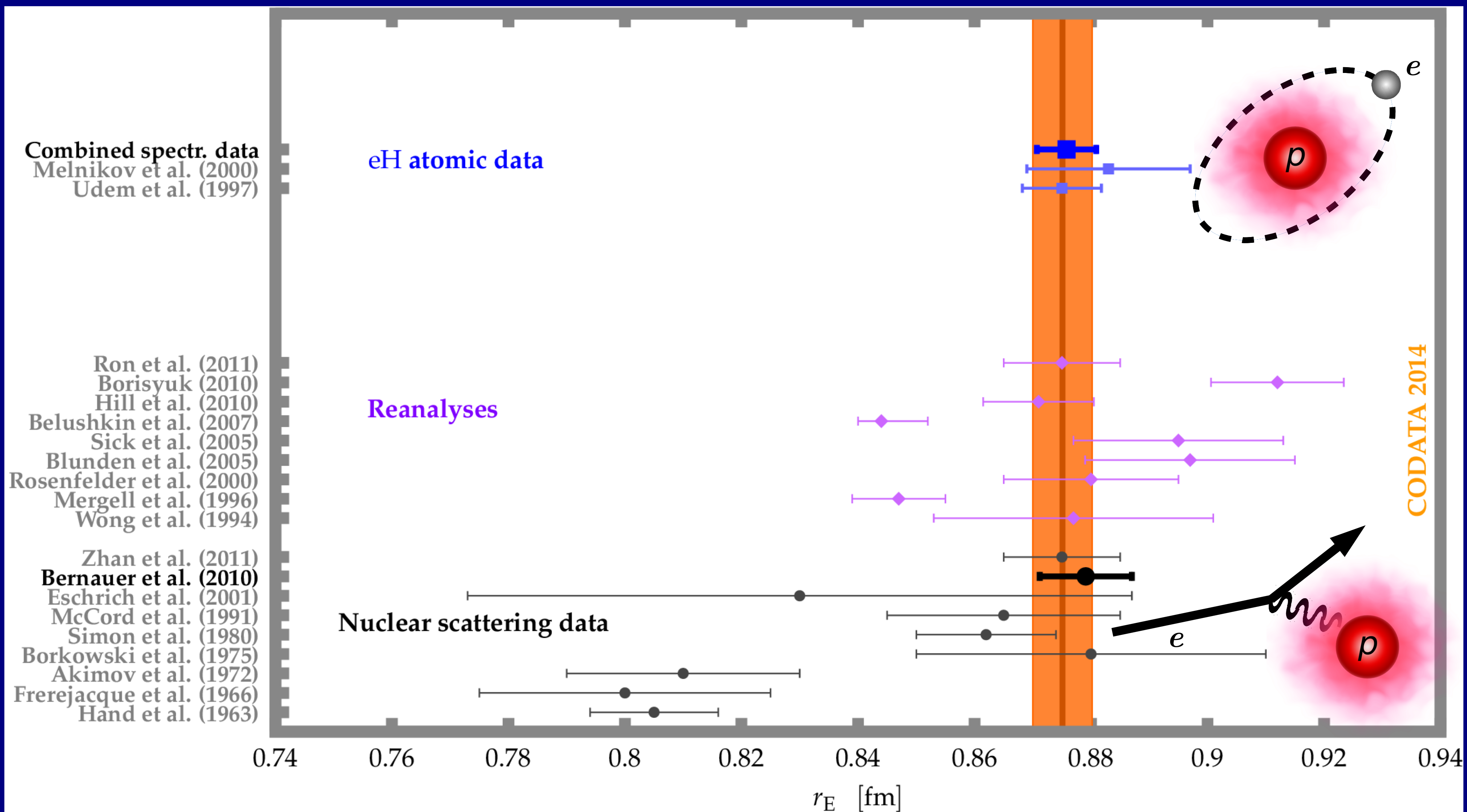
The proton radius puzzle



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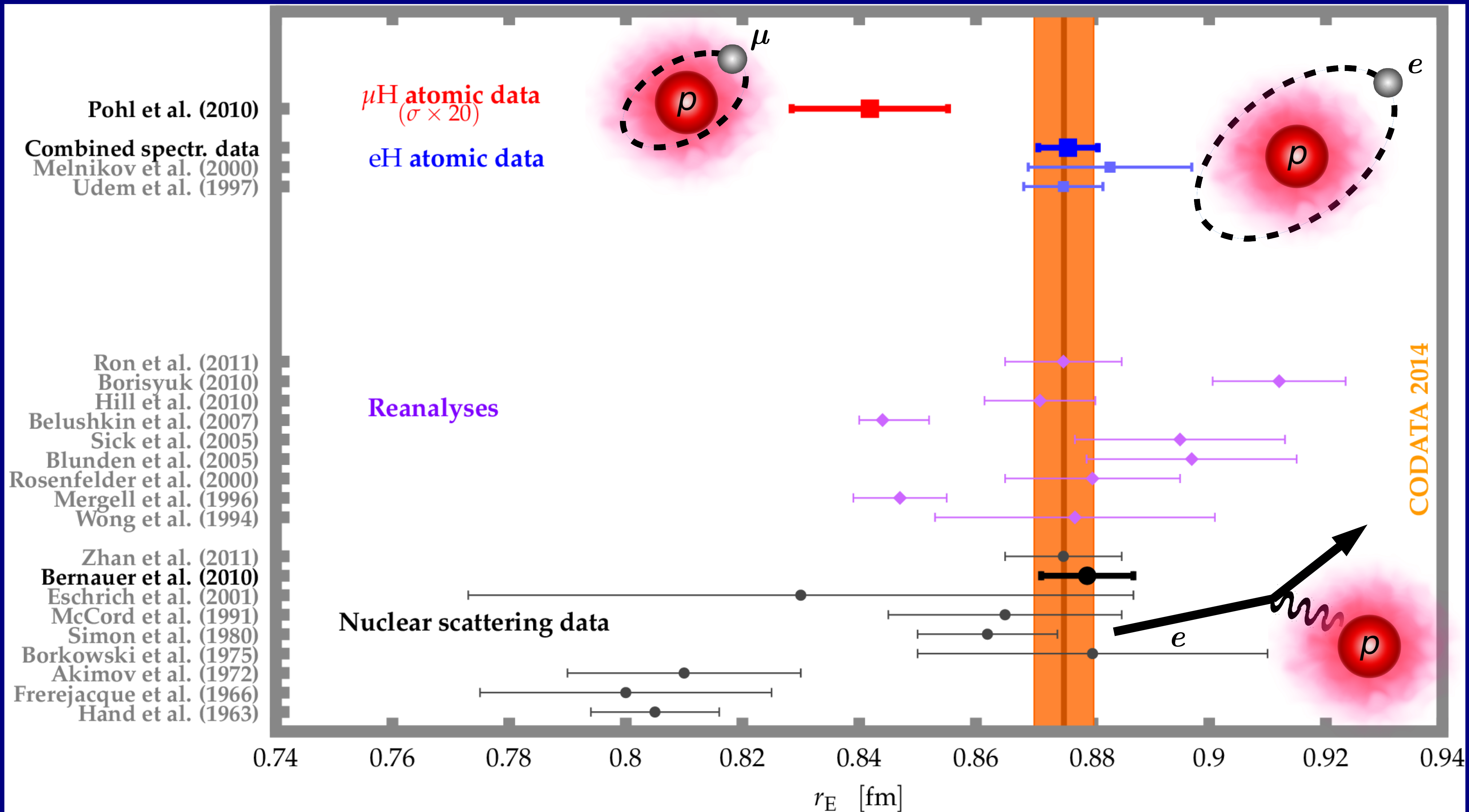

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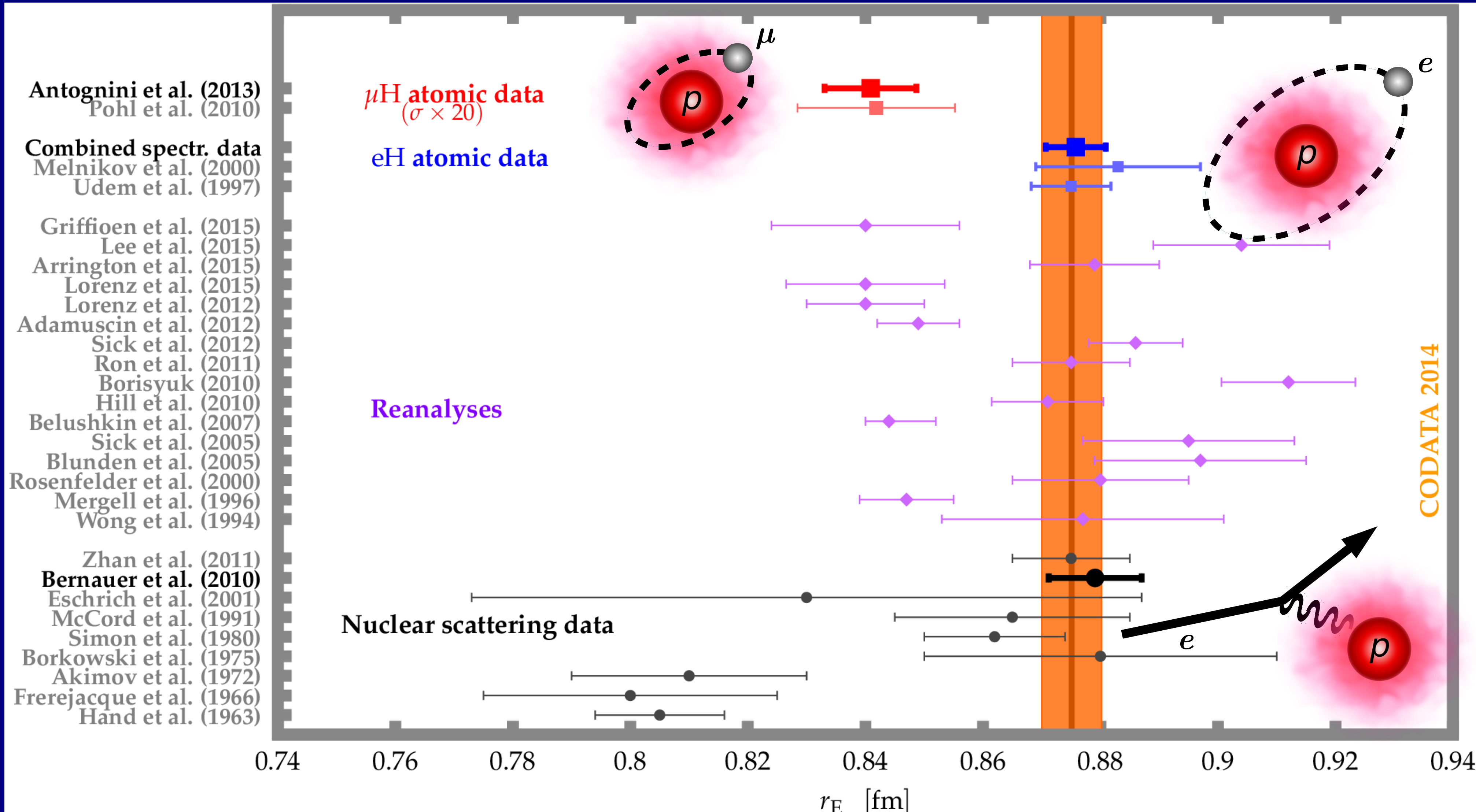
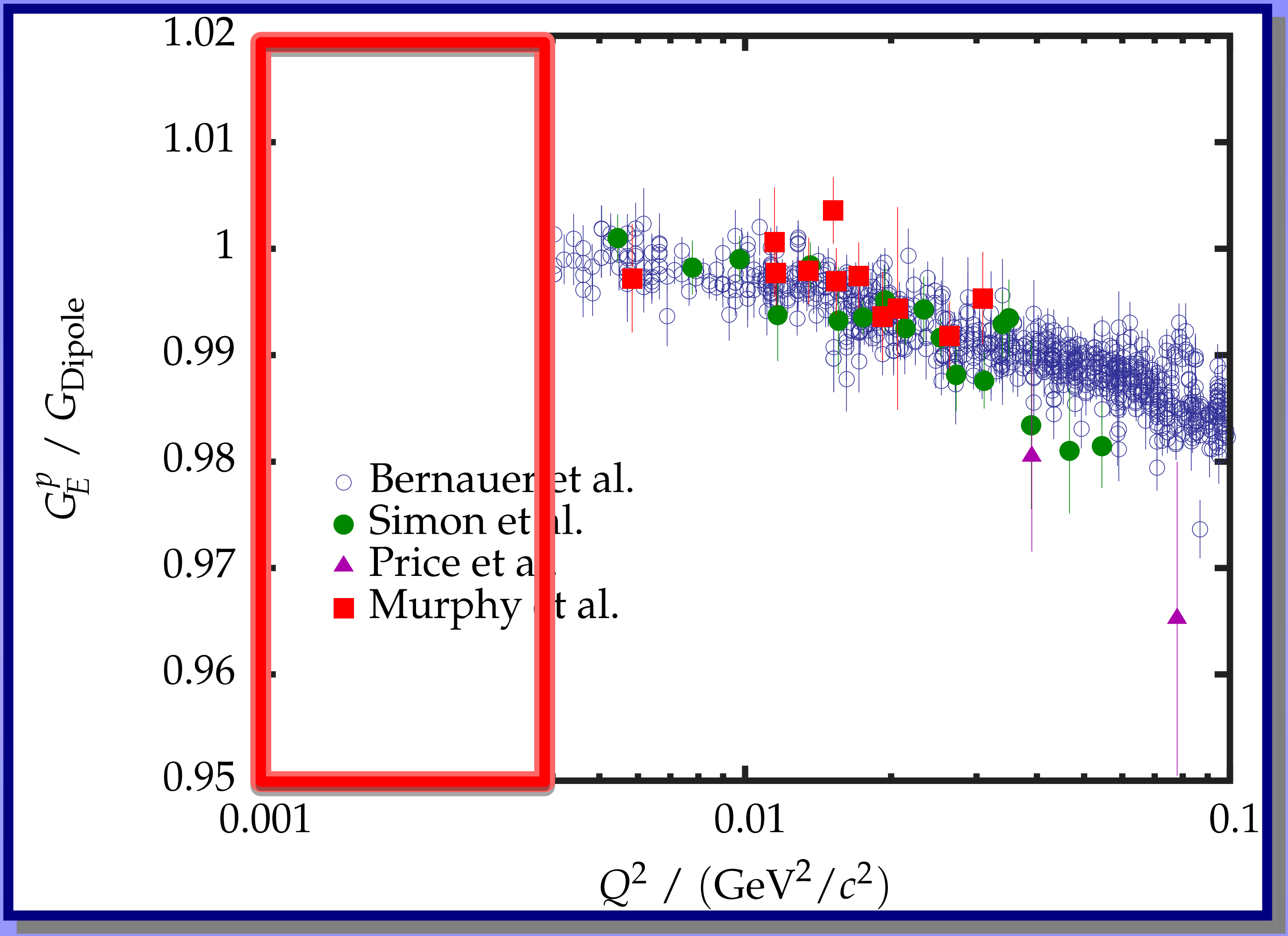


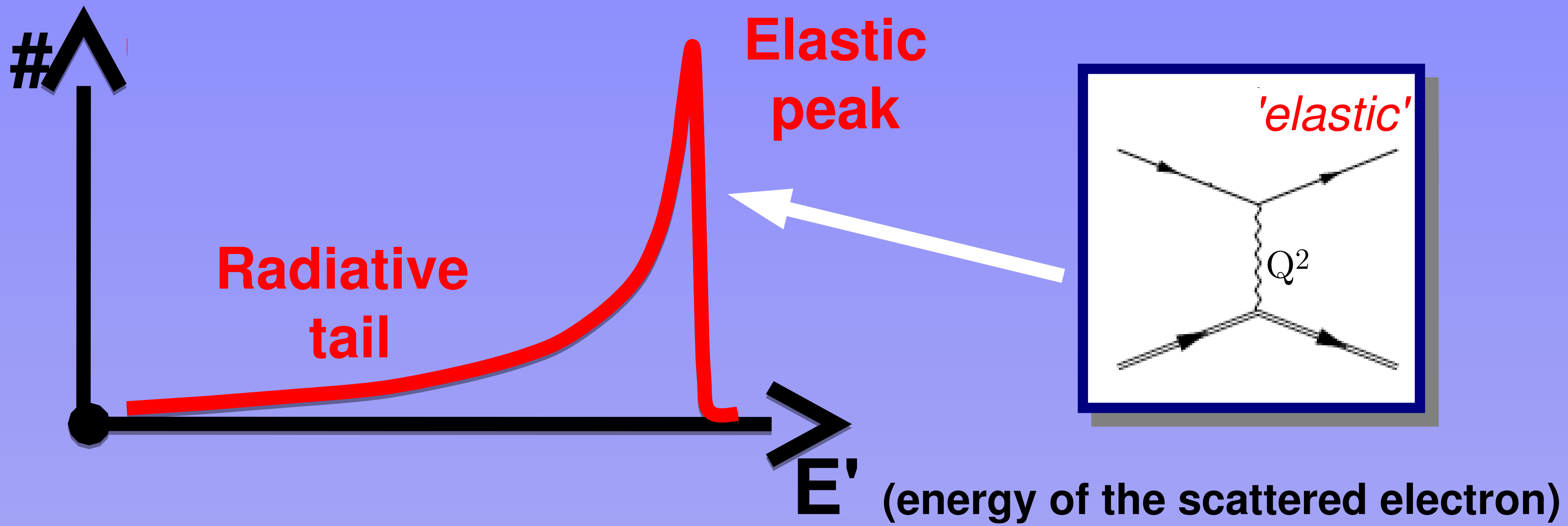
- The 6σ discrepancy in the r_p measurements.

Proton's charge form factor

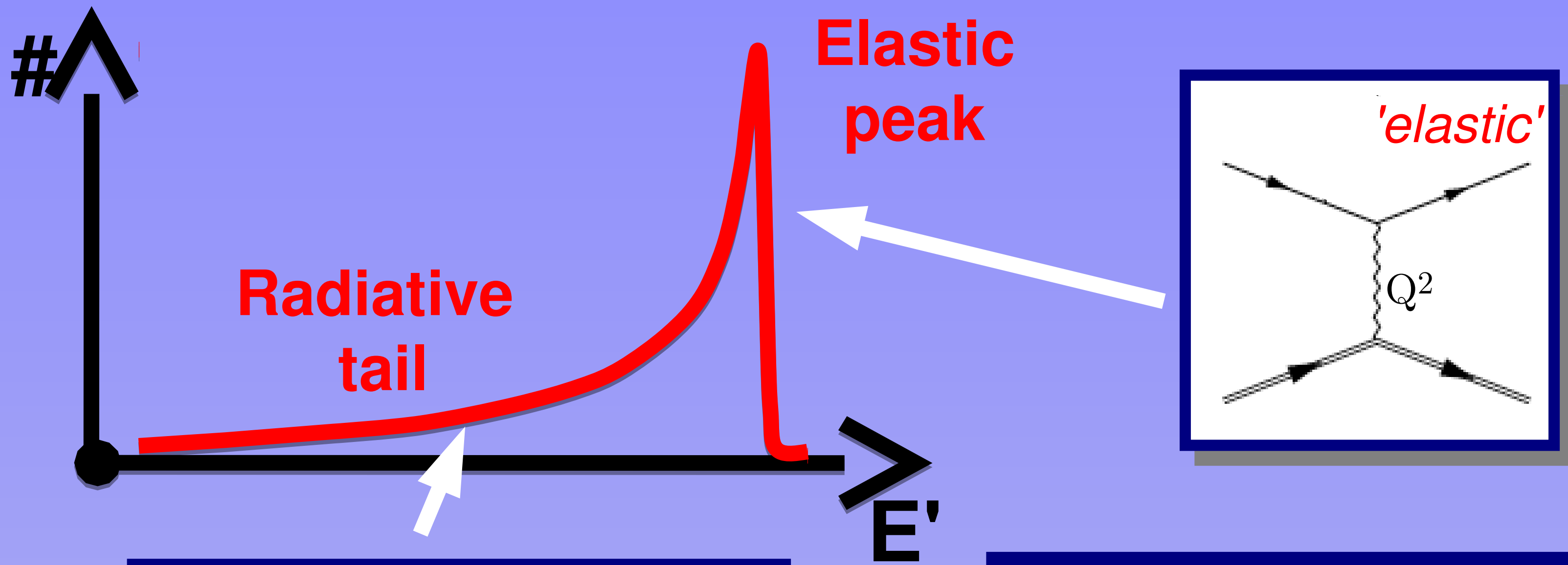


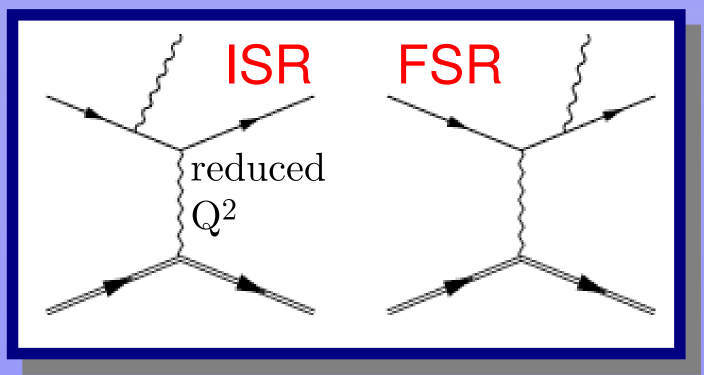
- **Data available only for $Q^2 > 0.004$ (GeV/c)^2.**
- **Extrapolations to zero are needed!** $\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{dG_E}{dQ^2} \right|_{Q^2=0}$

Initial State Radiation



Initial State Radiation

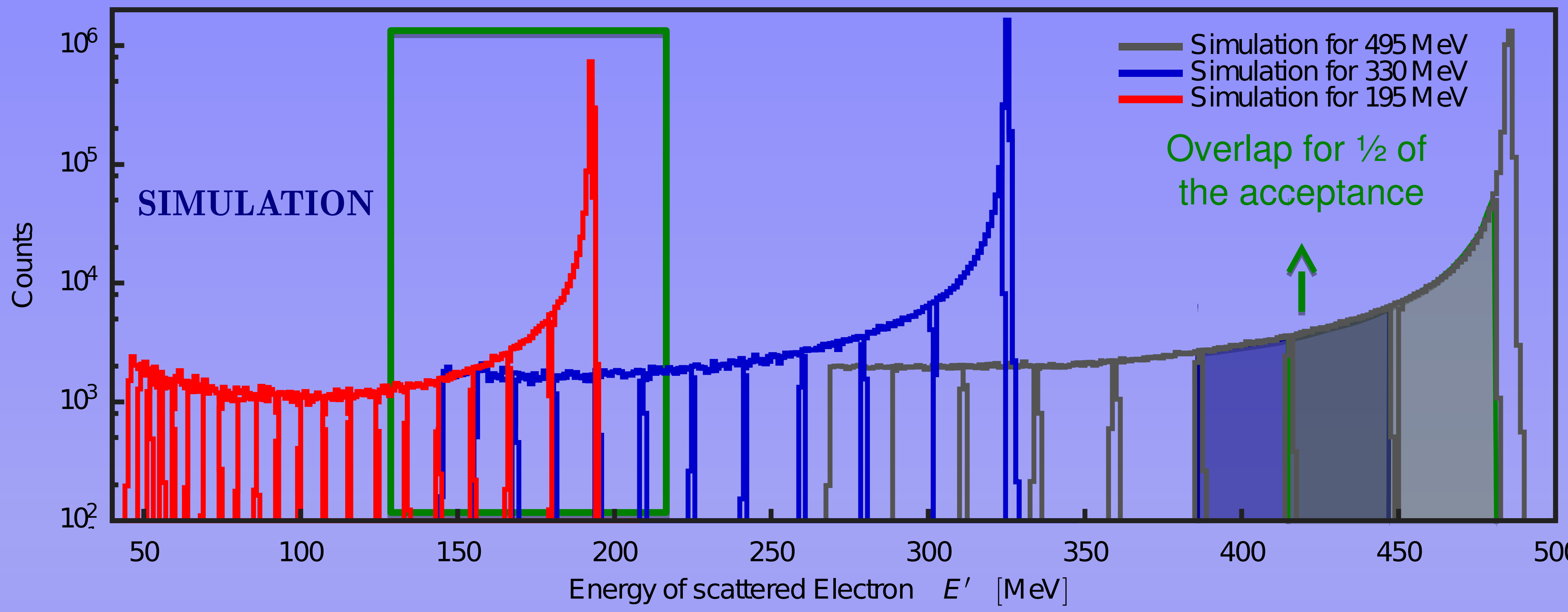


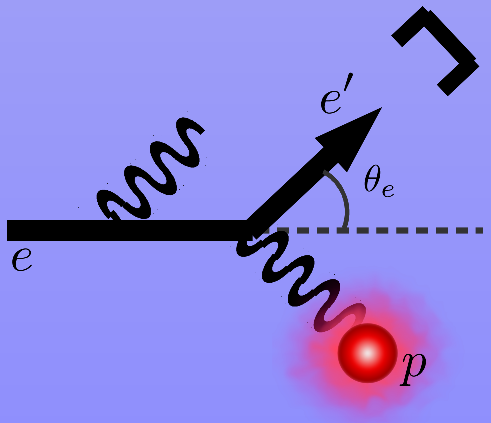


Exploit information in radiative tail

- **ISR**:
  photon radiation takes energy out of electron → access to lower Q^2 at given scattering angle
- Sophisticated simulation needed (FSR, ...)
- Allows investigating G_E at Q^2 down to 10^{-4} GeV^2

Kinematic settings





- Multiple beam energies: elastic results vs. ISR results
- Limited momentum acceptance: multiple settings
- Overlapping settings to control systematic uncertainty

- Performed at MAMI in 2013

Mainz Microtron (MAMI) - Electron Accelerator

Komitee für Beschleunigerphysik KfB | www.beschleunigerphysik.de (2016)

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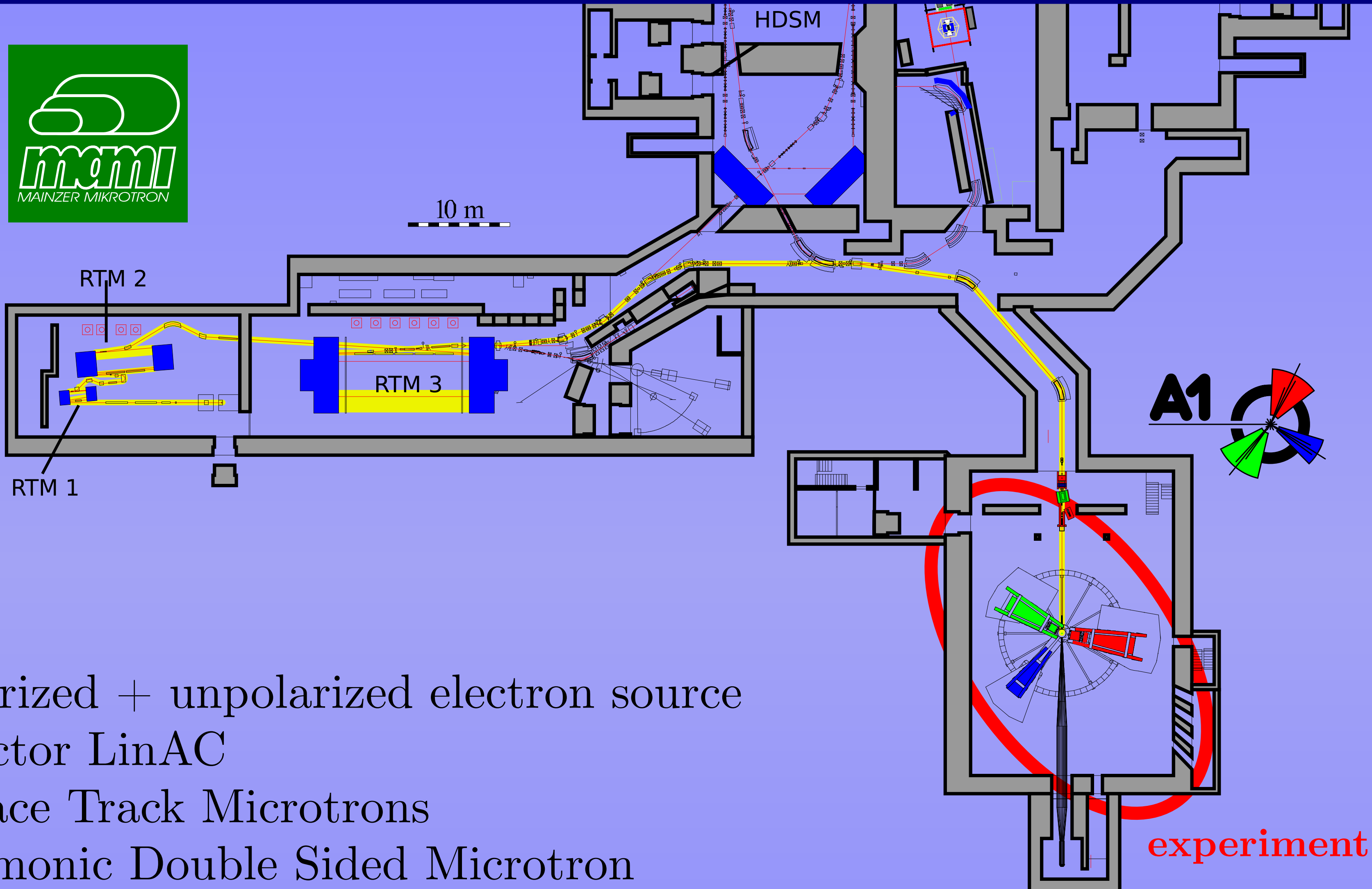
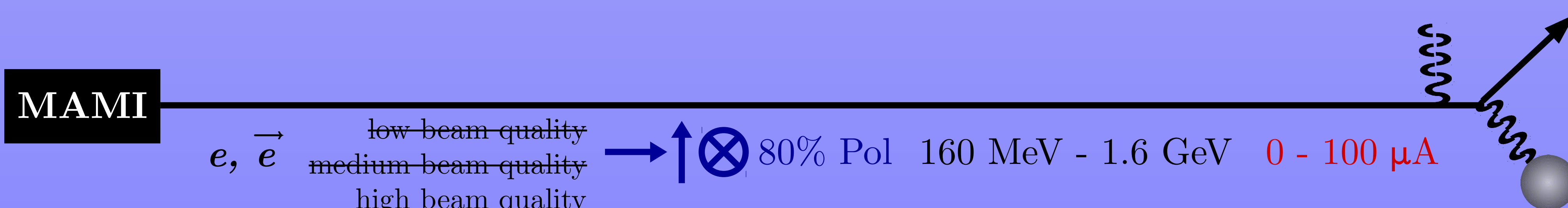
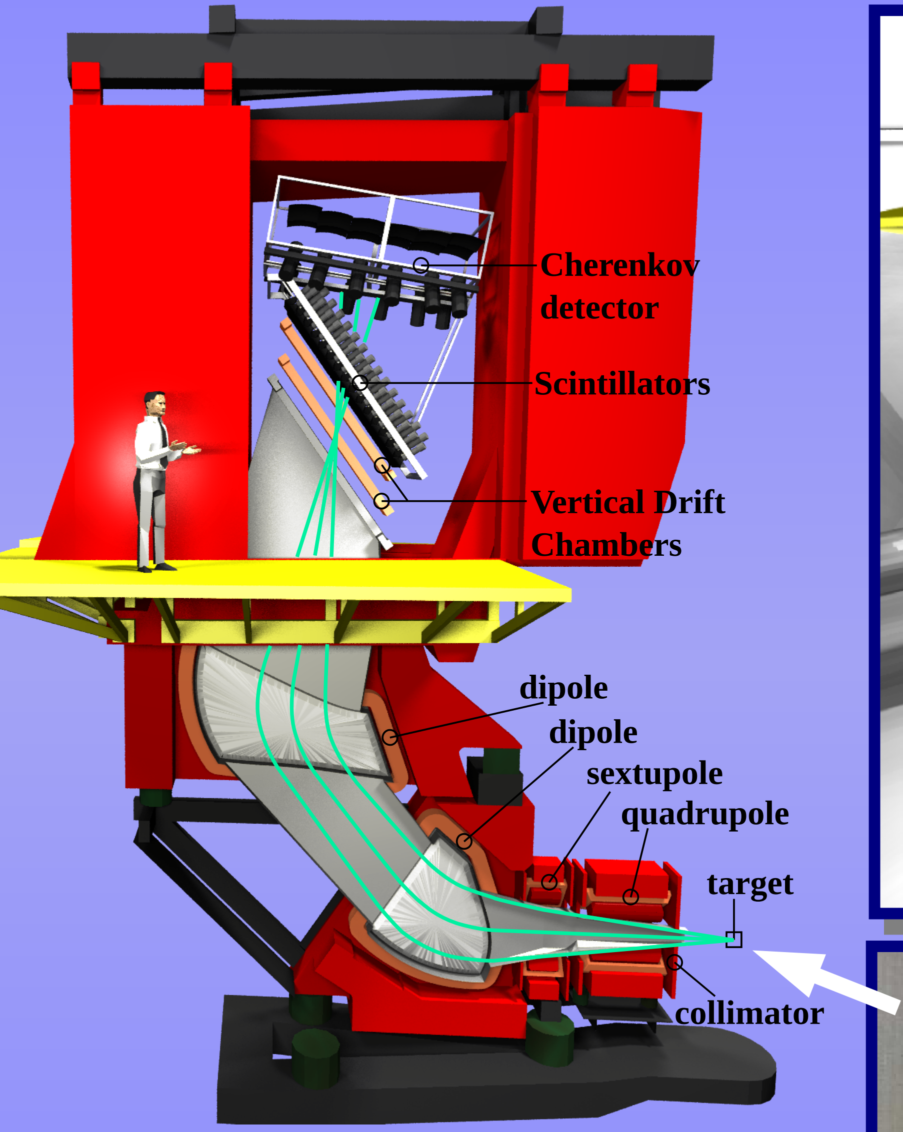
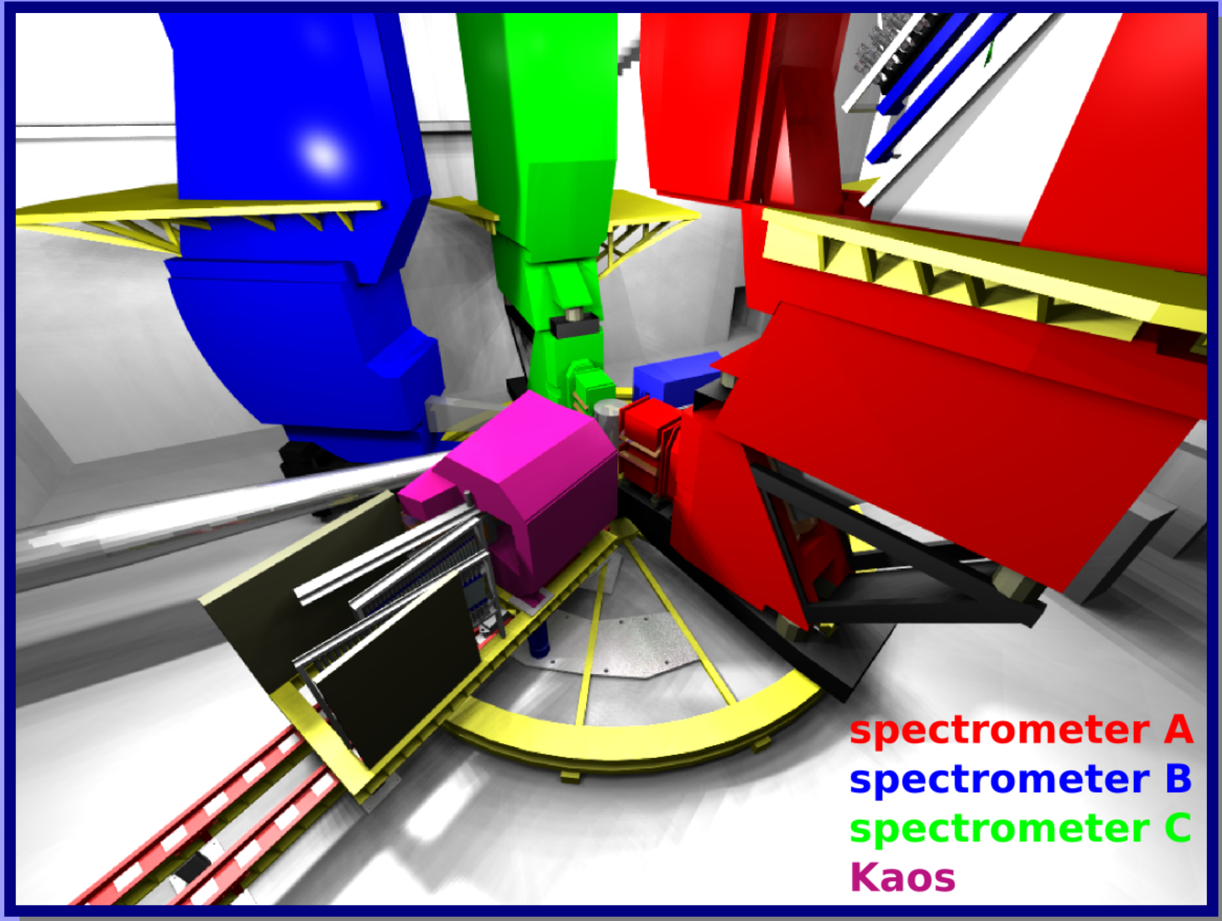


- polarized + unpolarized electron source
- Injector LinAC
- 3 Race Track Microtrons
- Harmonic Double Sided Microtron



The A1 setup





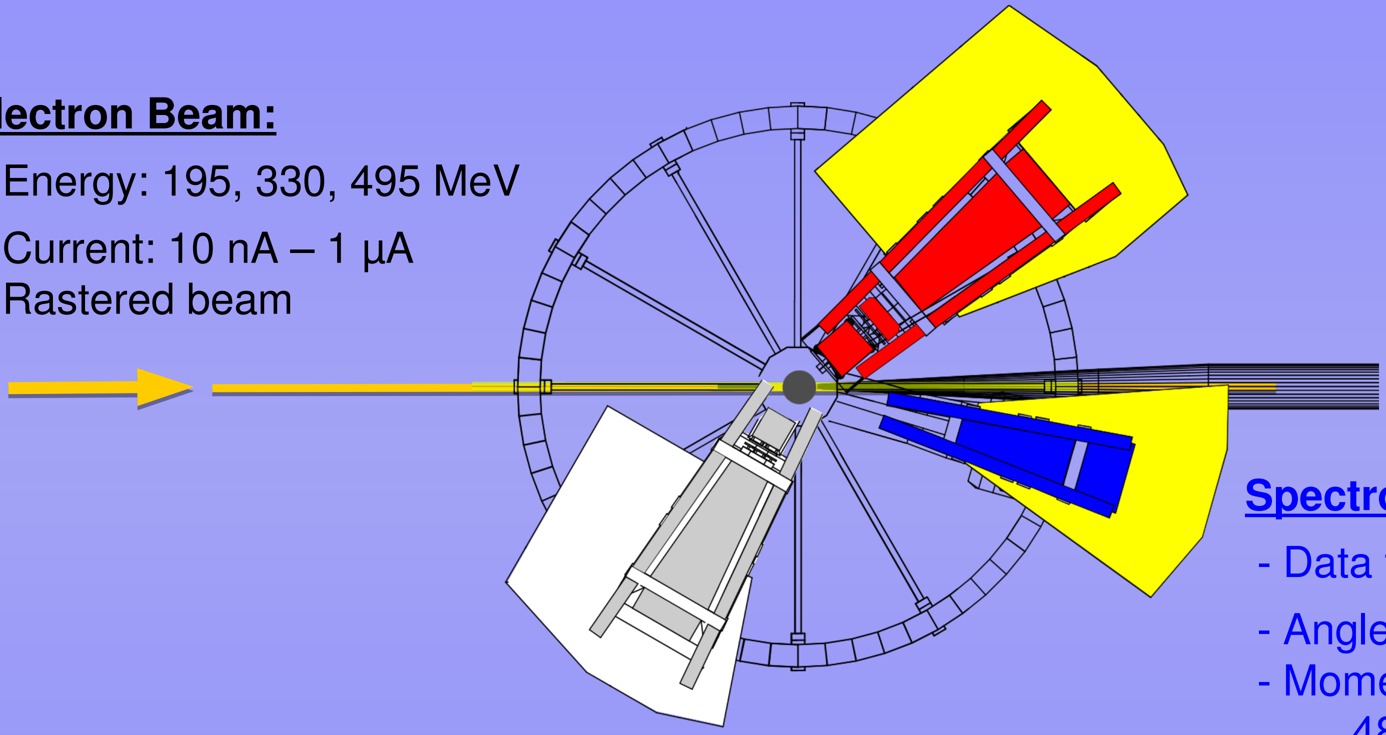
High resolution magnetic spectrometers

Liquid hydrogen target

The ISR experiment

Electron Beam:

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



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)

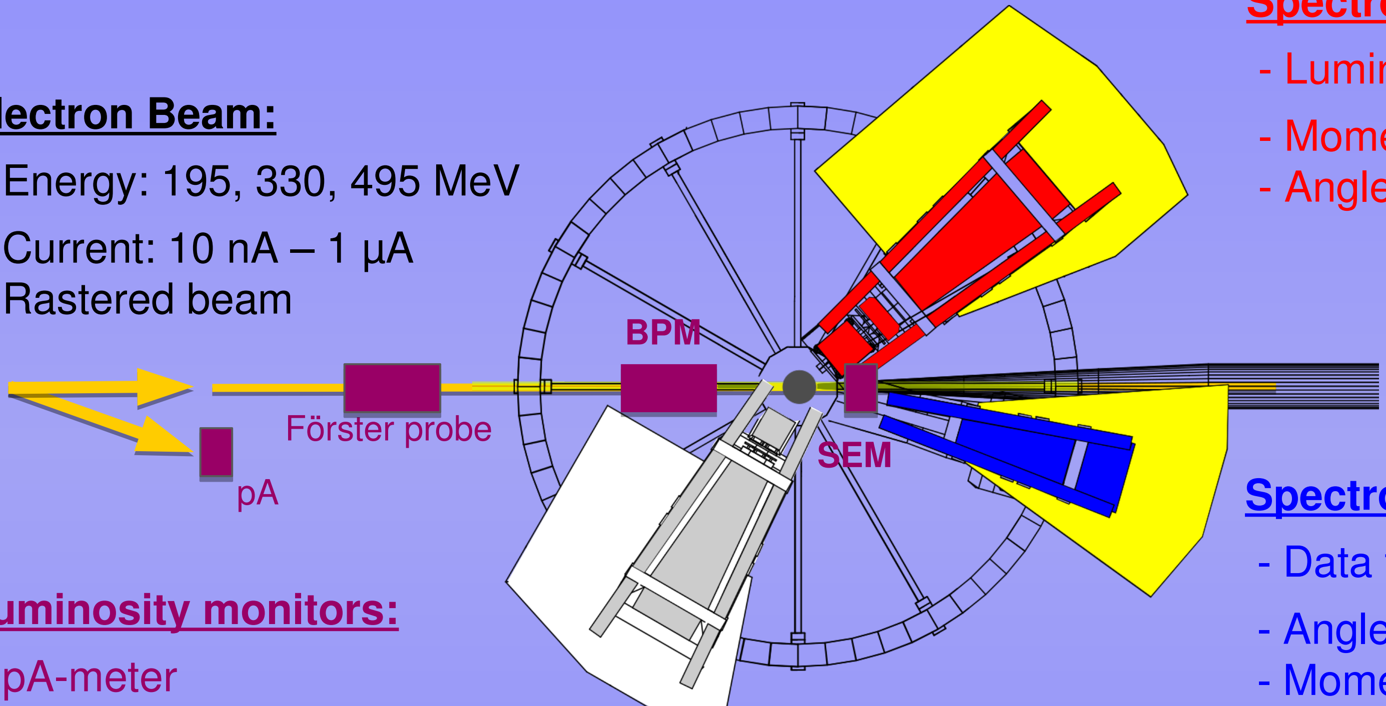
The ISR experiment

Electron Beam:

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

Luminosity monitors:

- pA-meter
- Förster probe
- SEM
- Spectrometer A



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)

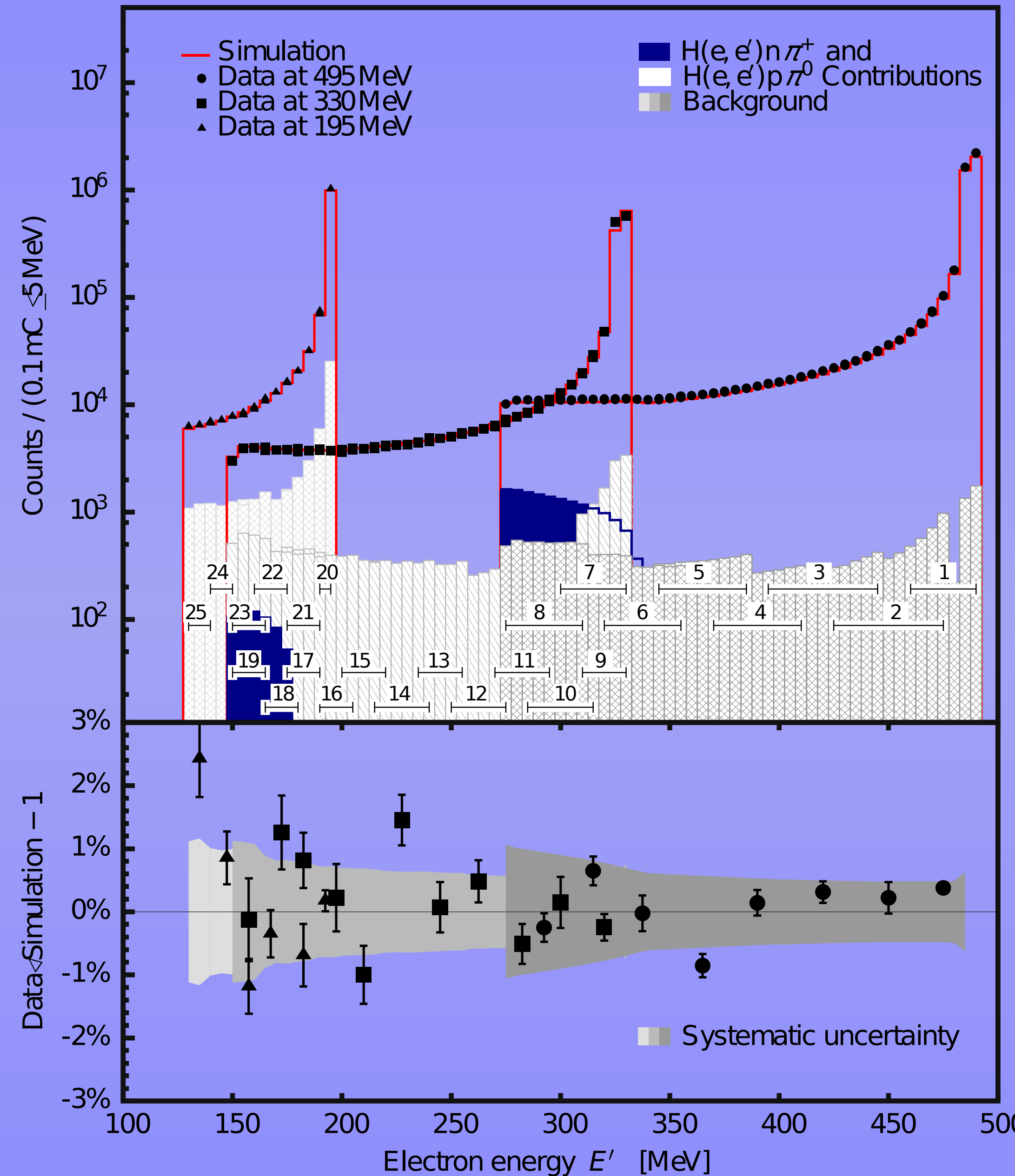
Spectrometer C:

- Not used

Results

Comparison data vs. simulation

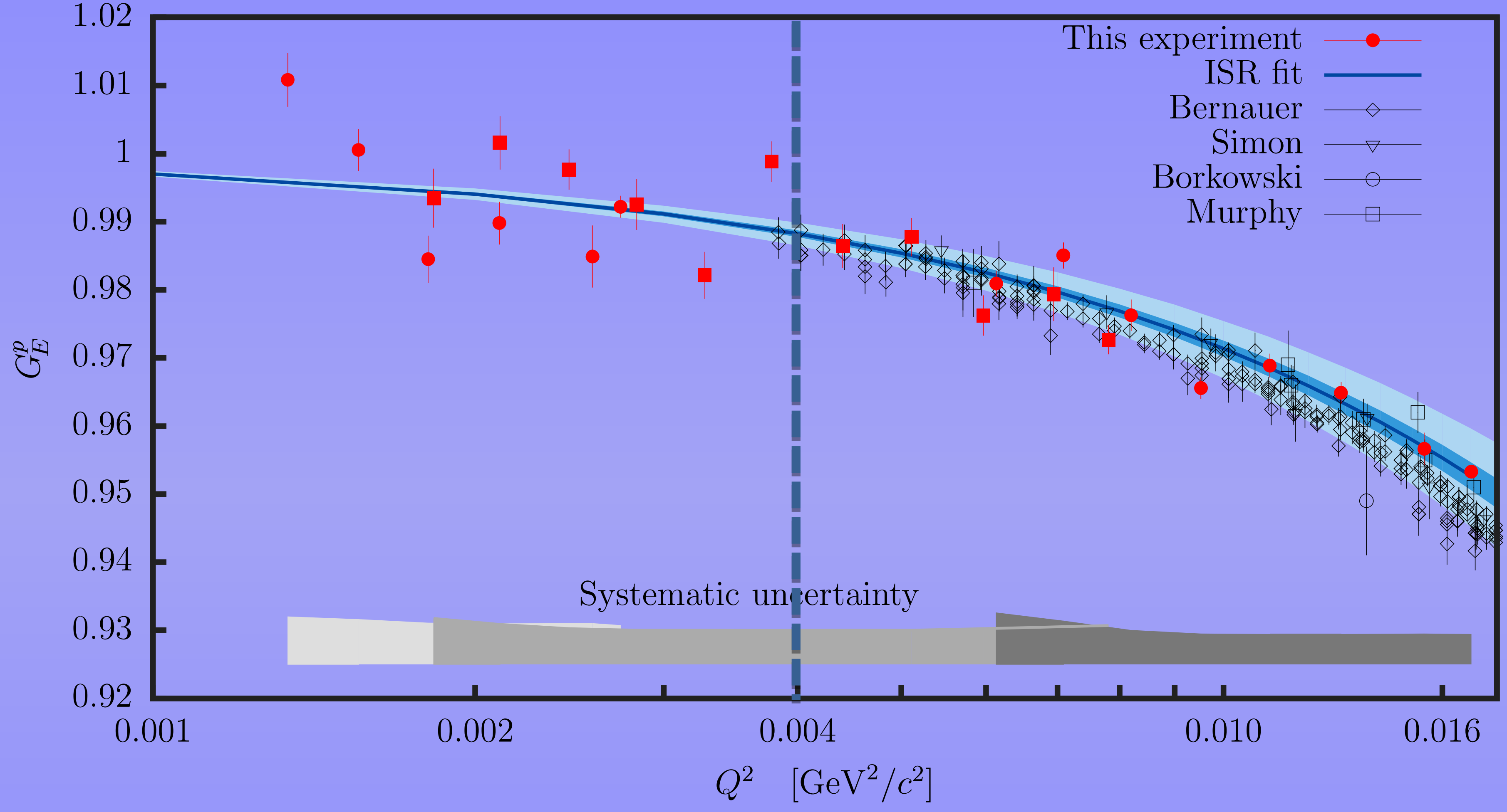
- Simulation performed with Bernauer parametrization of form factors
- A percent agreement demonstrates that radiative corrections are well understood, even 200 MeV away from elastic peak!
- Existing apparatus limited reach of ISR experiment to $E' \sim 130$ MeV
- Assuming flawless description of radiative corrections, form factors can be extracted from the data



M. Mihovilovic *et al.*, Phys. Lett. B 771 (2017) 194

Results: ISR form factor, radius

M. Mihovilovic *et al.*, Phys. Lett. B 771 (2017) 194



First measurement of G_E down to $Q^2 = 0.001$ GeV^2

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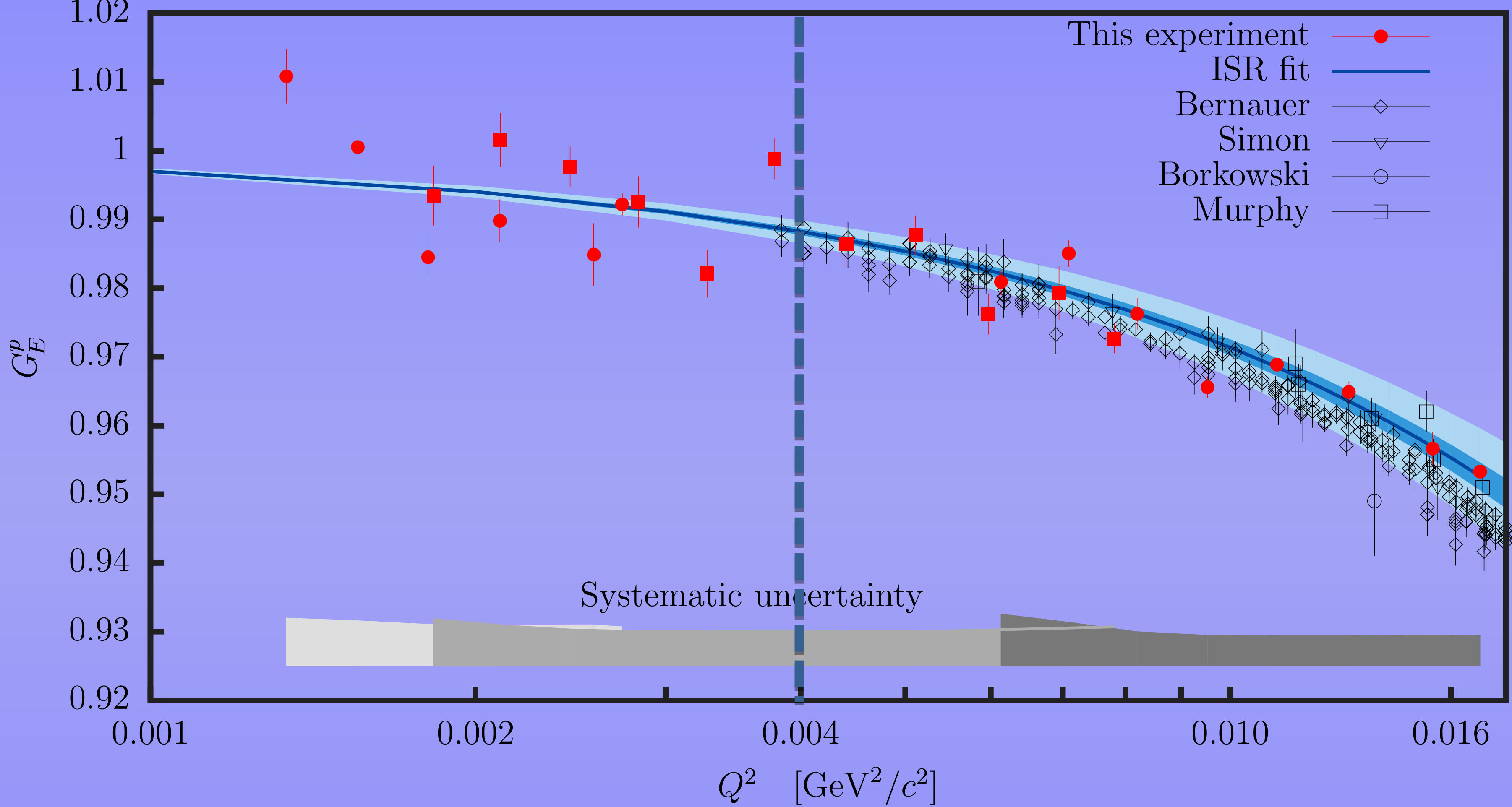
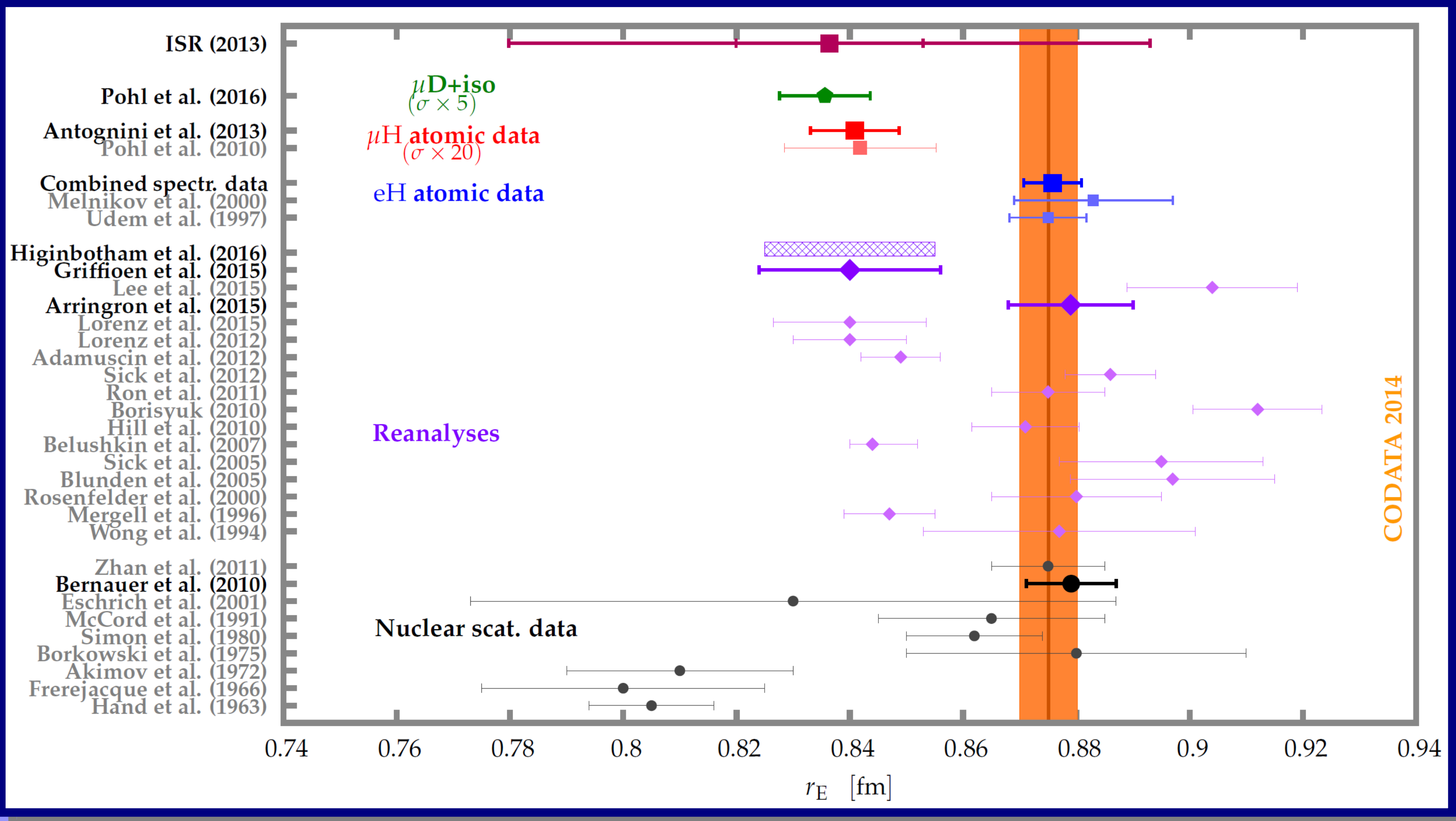


First measurement of G_E down to $Q^2 = 0.001$ GeV^2

$$r_\mathrm{E} = (0.836 \pm 0.017_\mathrm{stat.} \pm 0.057_\mathrm{syst.} \pm 0.003_\mathrm{mod.})\ \mathrm{fm}$$

The ISR proton radius



- Only ISR data considered in result.

The bitter truth

ISR - MVP

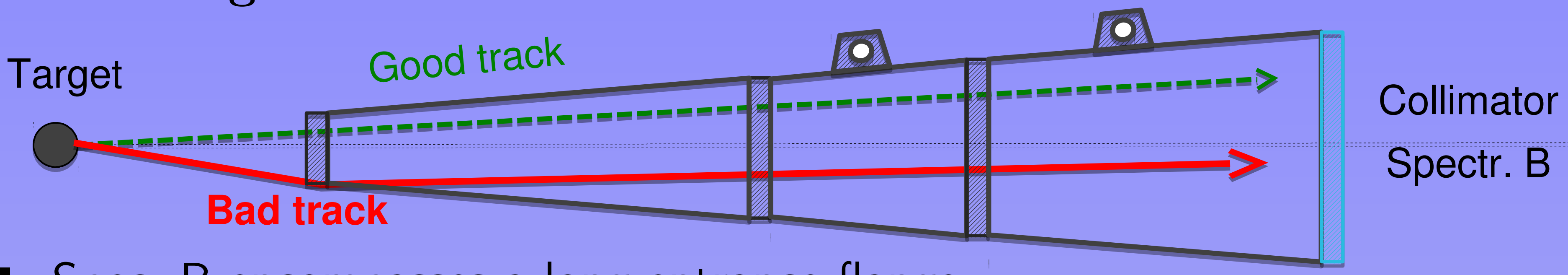
ISR - Mastermind

NOT EXACTLY THE DESIRED RESULT.

IMPROVE?

Limitations ISR (2013)

- **Entrance flange contributions**



  - Spec. B encompasses a long entrance flange.
  - Events rescattered from the snout cover the whole vertex acceptance.
  - spoils low E' data $\rightarrow$ **low Q^2 - data killer**

Limitations ISR (2013)

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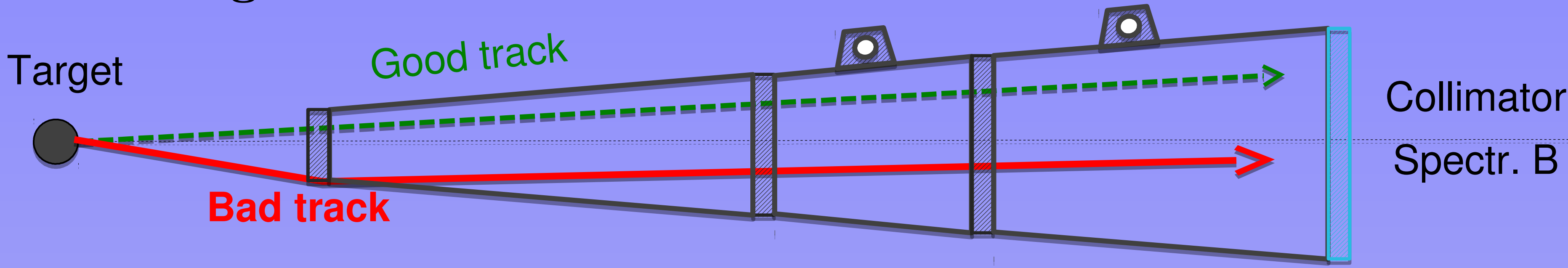

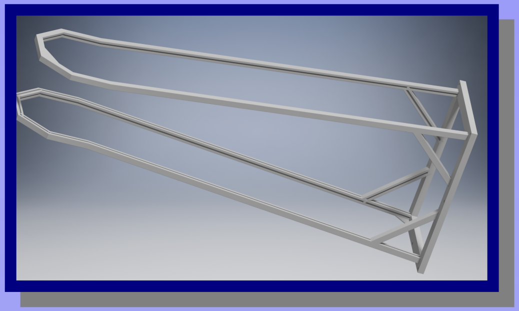

Replace by Helium-"balloon"
(X_0^{He}=570km) + foils

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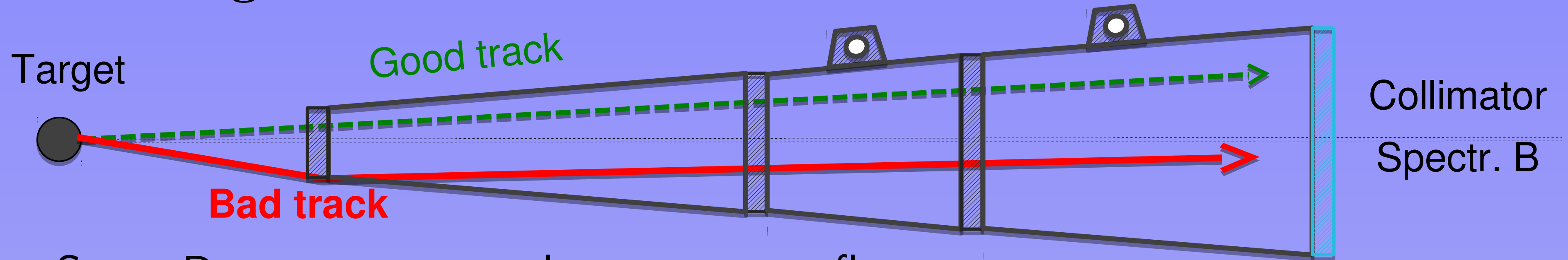

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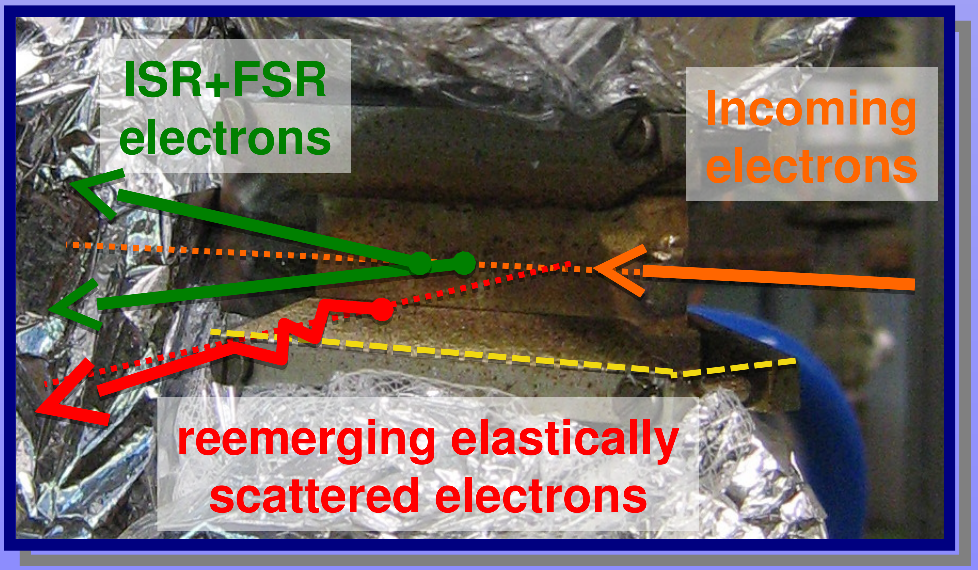
- **Target cell contributions**



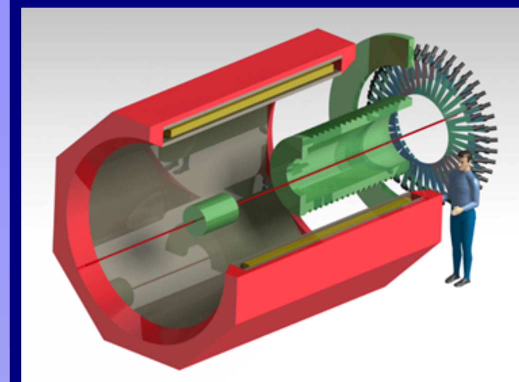
  - Background from target foils
    - empty cell measurements
  - spectra distorted by (thin) ice layer
  - rescattering on thick frame
  - hard analysis cuts
    $\rightarrow$ **introduces systematic errors**
    $\rightarrow$ **limits statistics**

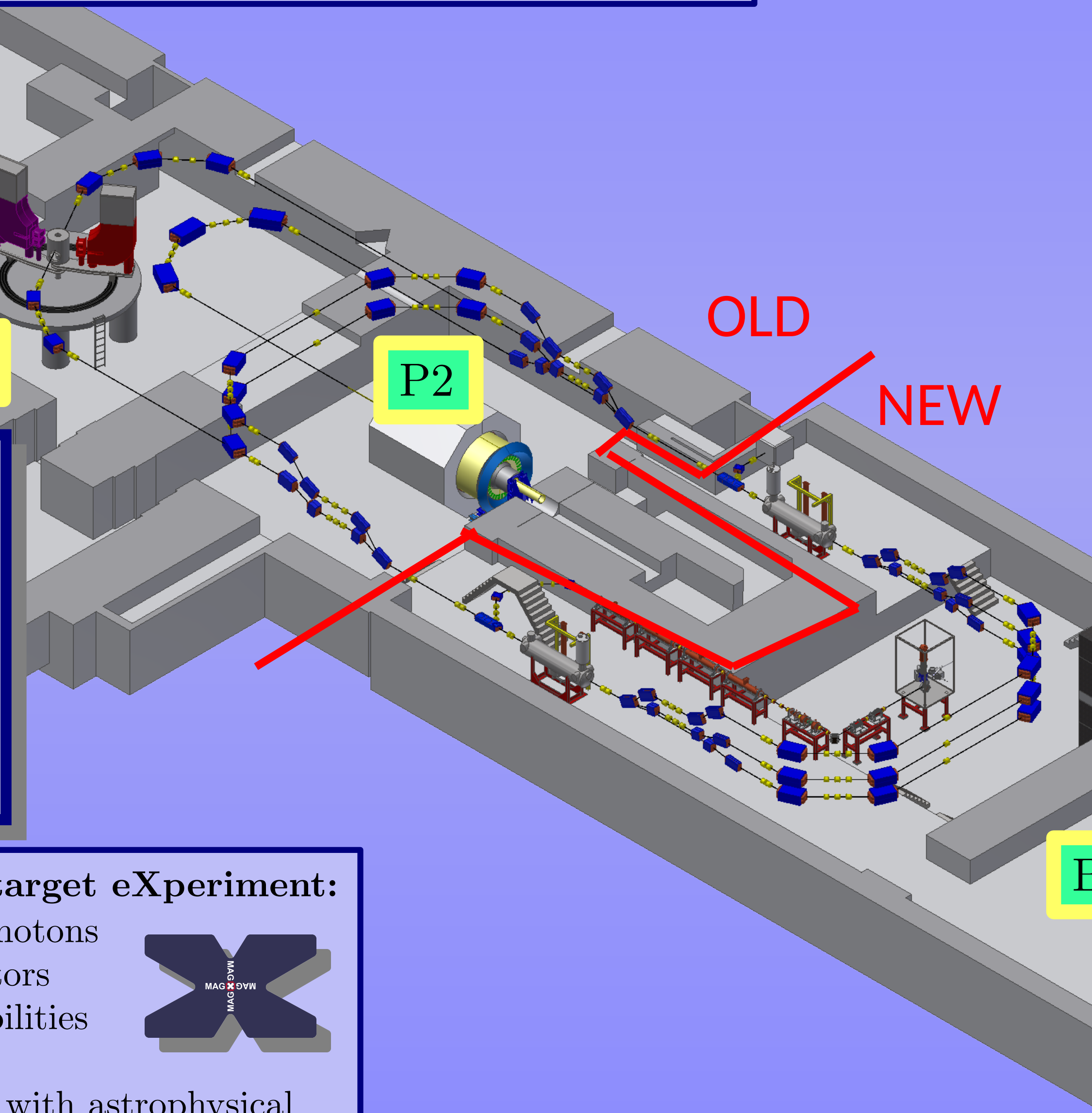
MESA - planned ERL next to MAMI

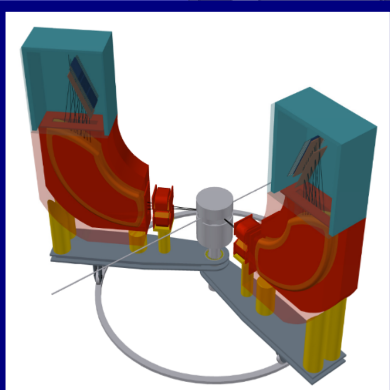
Mainz Energy-Recovering Superconducting Accelerator

ERL mode: 105 MeV, 1mA (later 10) unpolarized beam → MAGIX
EB mode: 155 MeV, 0.15mA polarized external beam → P2

P2: 0.13% measurement of $\sin^2\theta_W$
MREX: neutron skin studies







MesA Gas Internal target eXperiment:

- Search for dark photons
- Nucleon form factors
- Nucleon polarizabilities
- Few body physics
- Nuclear reactions with astrophysical relevance

Beam Dump eXperiment

Search for particles of the dark sector

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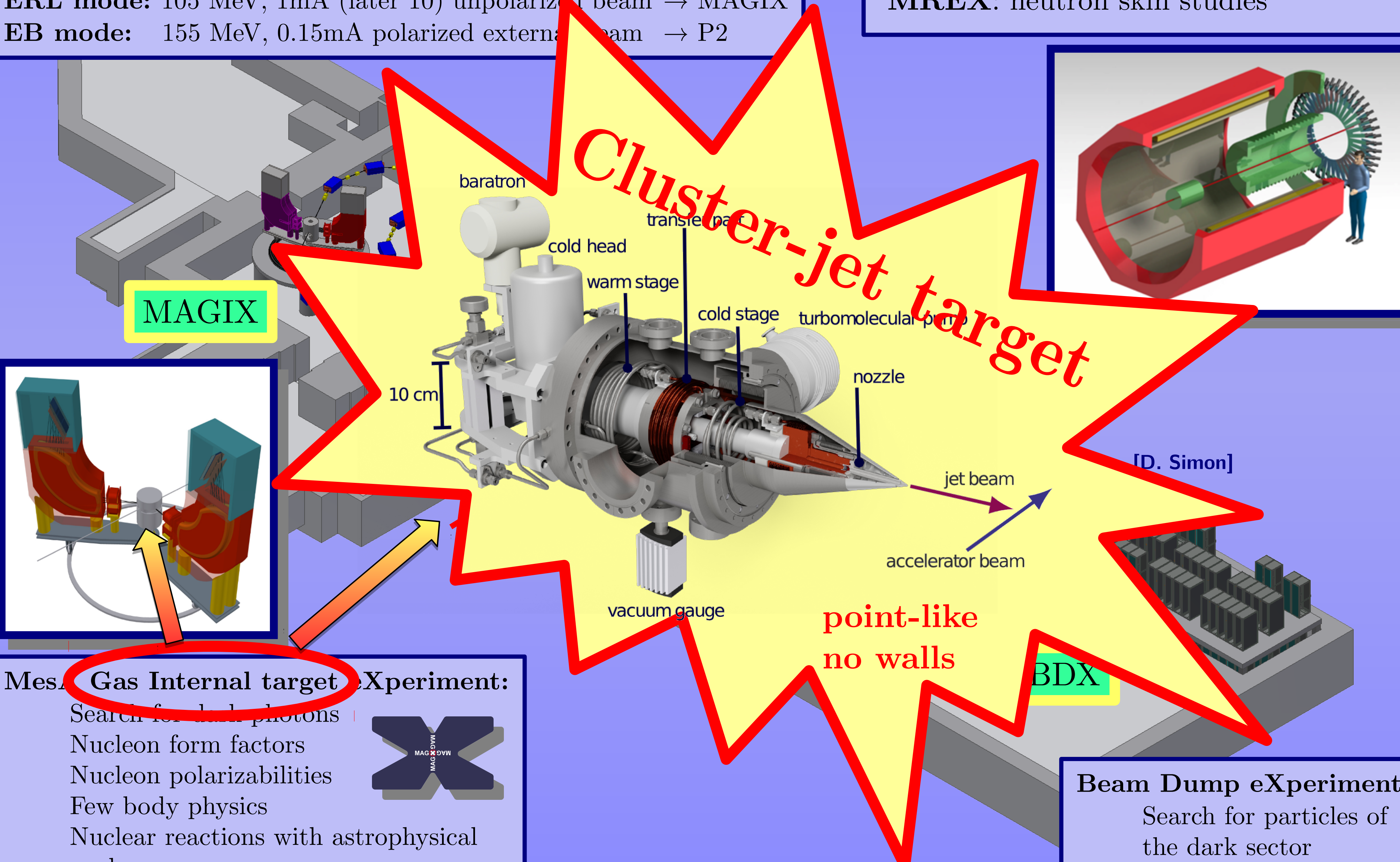

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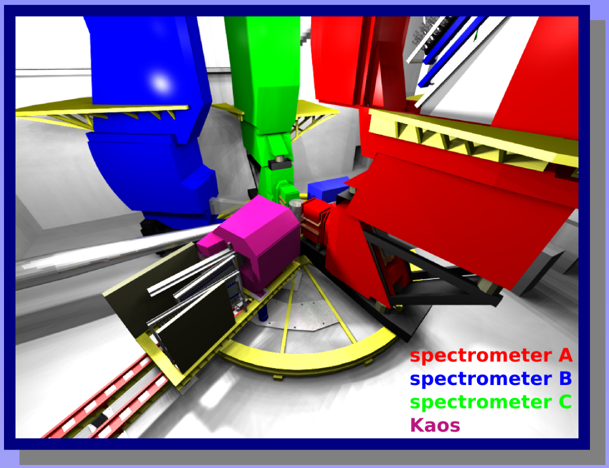
ISR with a Cluster-Jet Target?



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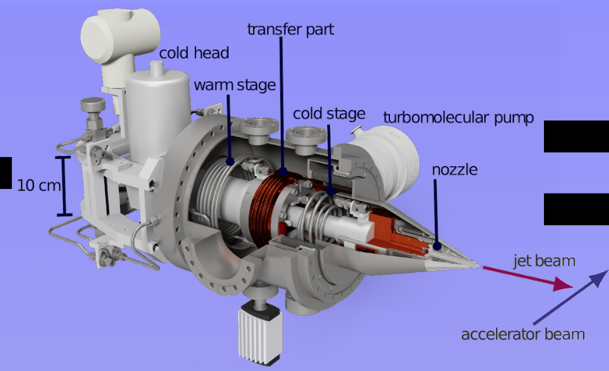
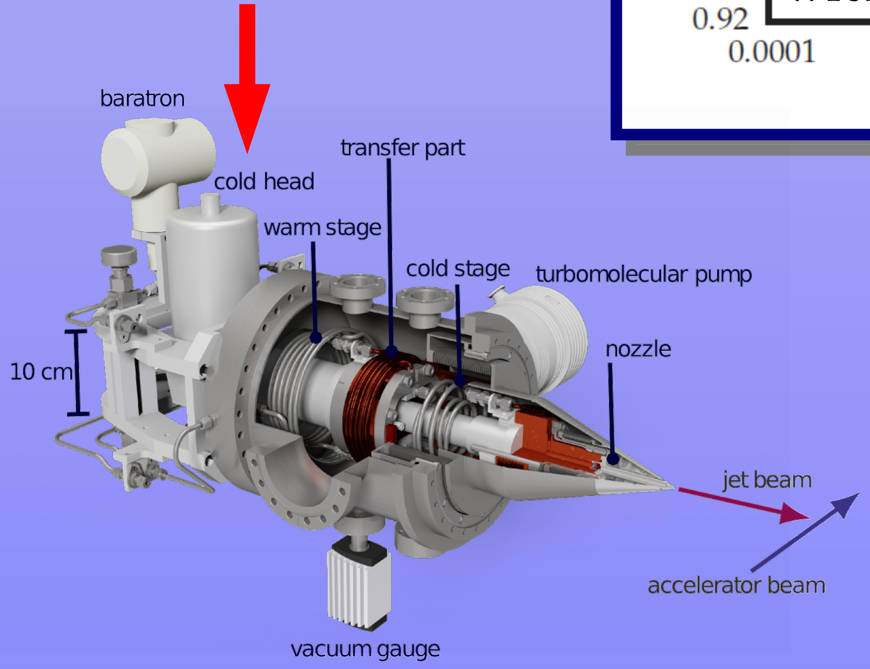


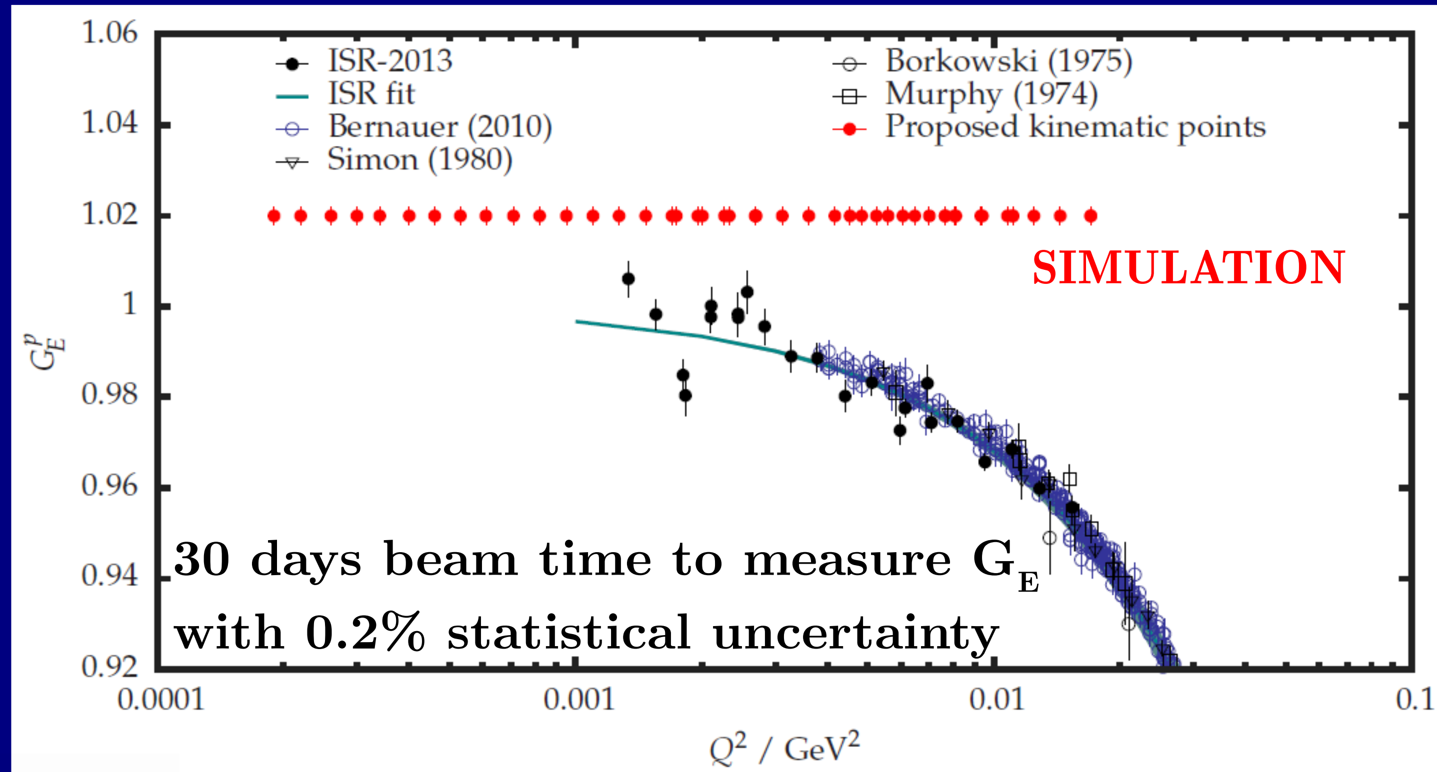
=

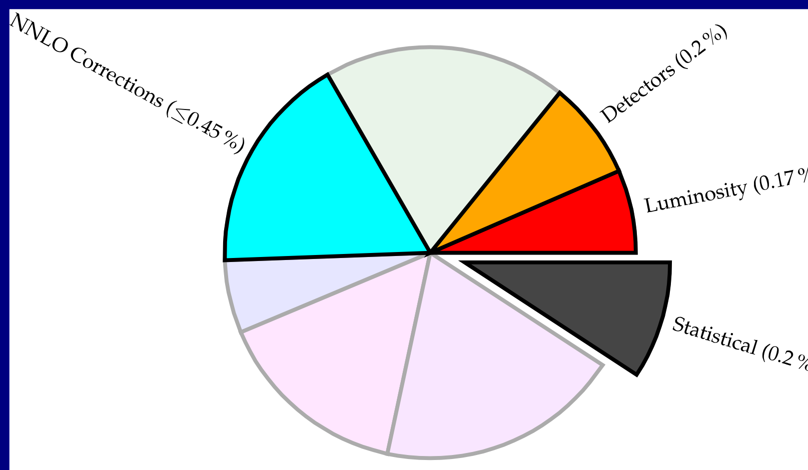
- Target developed for MAGIX, but could be used also in A1.
- No metal frame near the vertex.
- No target walls.
- Width of the jet: 2mm (point-like target)

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

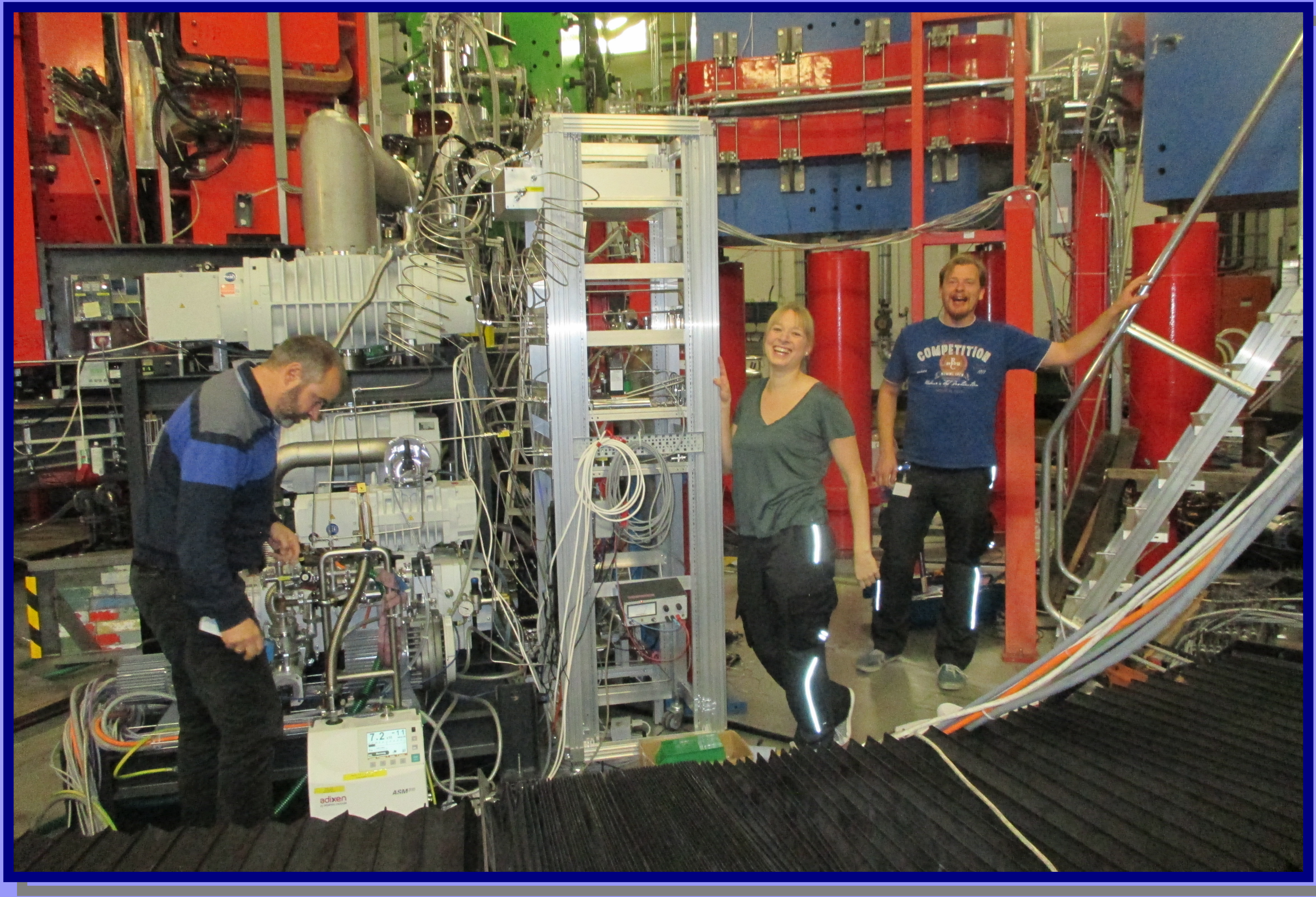
ISR with a Cluster-Jet Target?







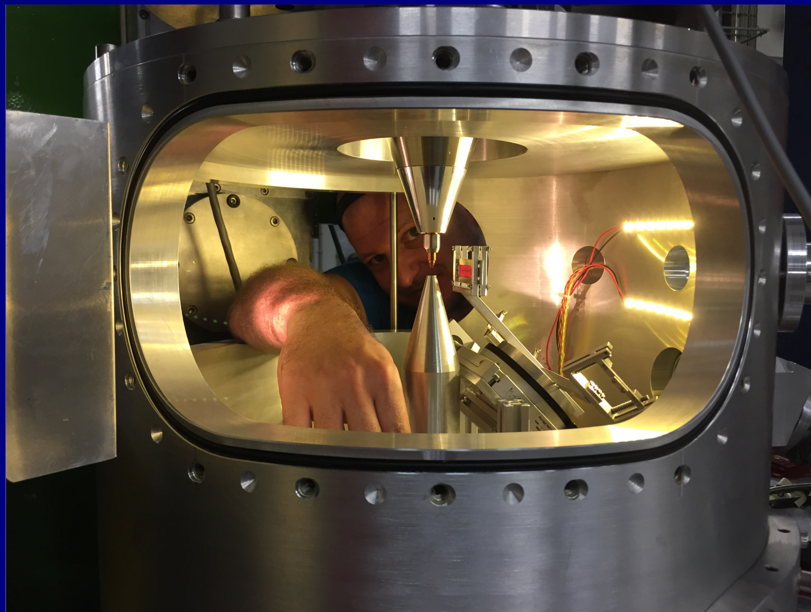
ISR with a Cluster-Jet Target!

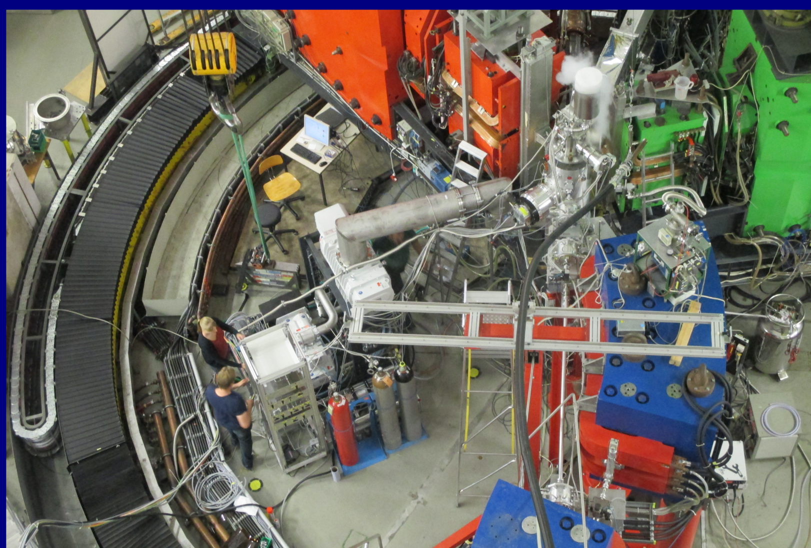


WWU MÜNSTER

A1 $\oplus$ ... MAGIX → ISR 2017/8

ISR with a Cluster-Jet Target!





1st commissioning beam time, Sept. 2017

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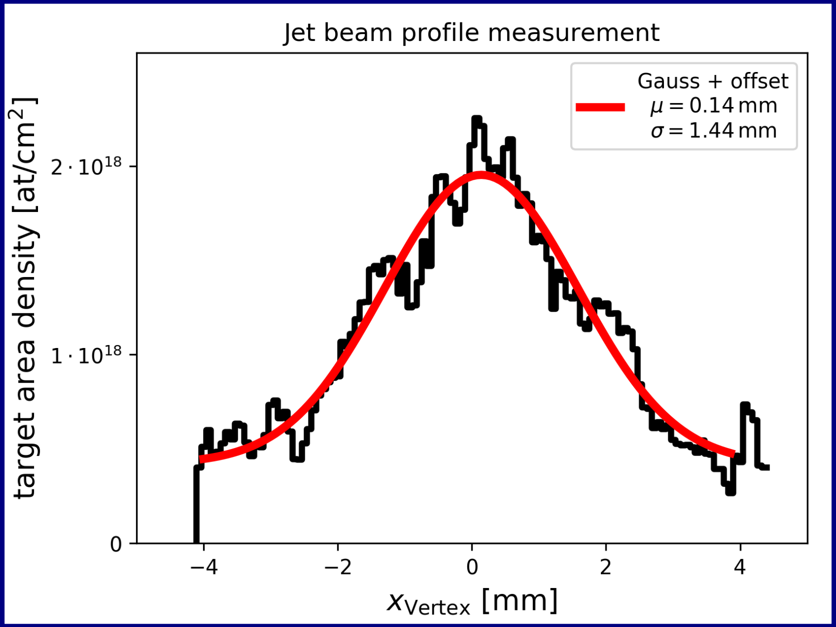
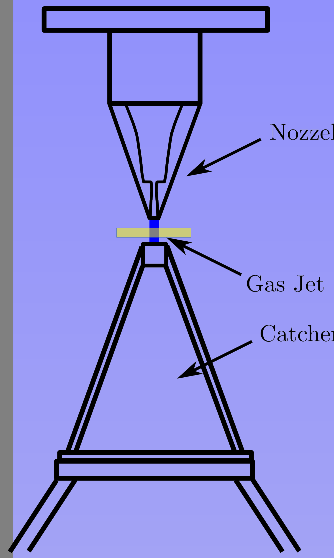
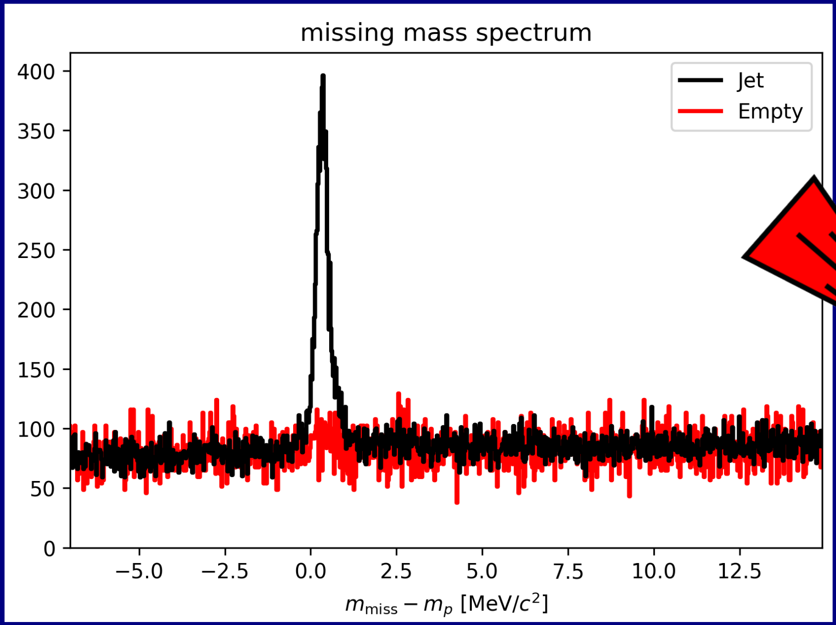
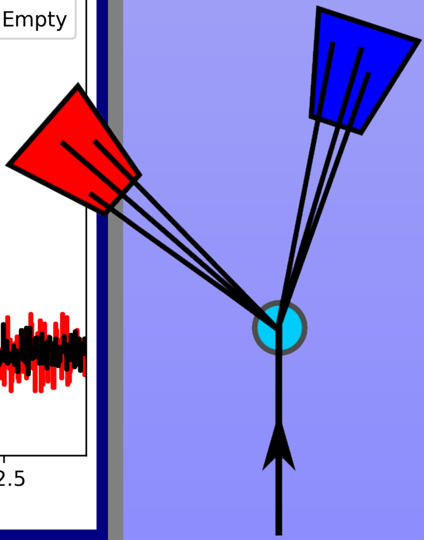




Achievements

- successful target installation
- jet profile measured with rastered electron beam
- jet density as expected
- measurement of several *elastic* settings

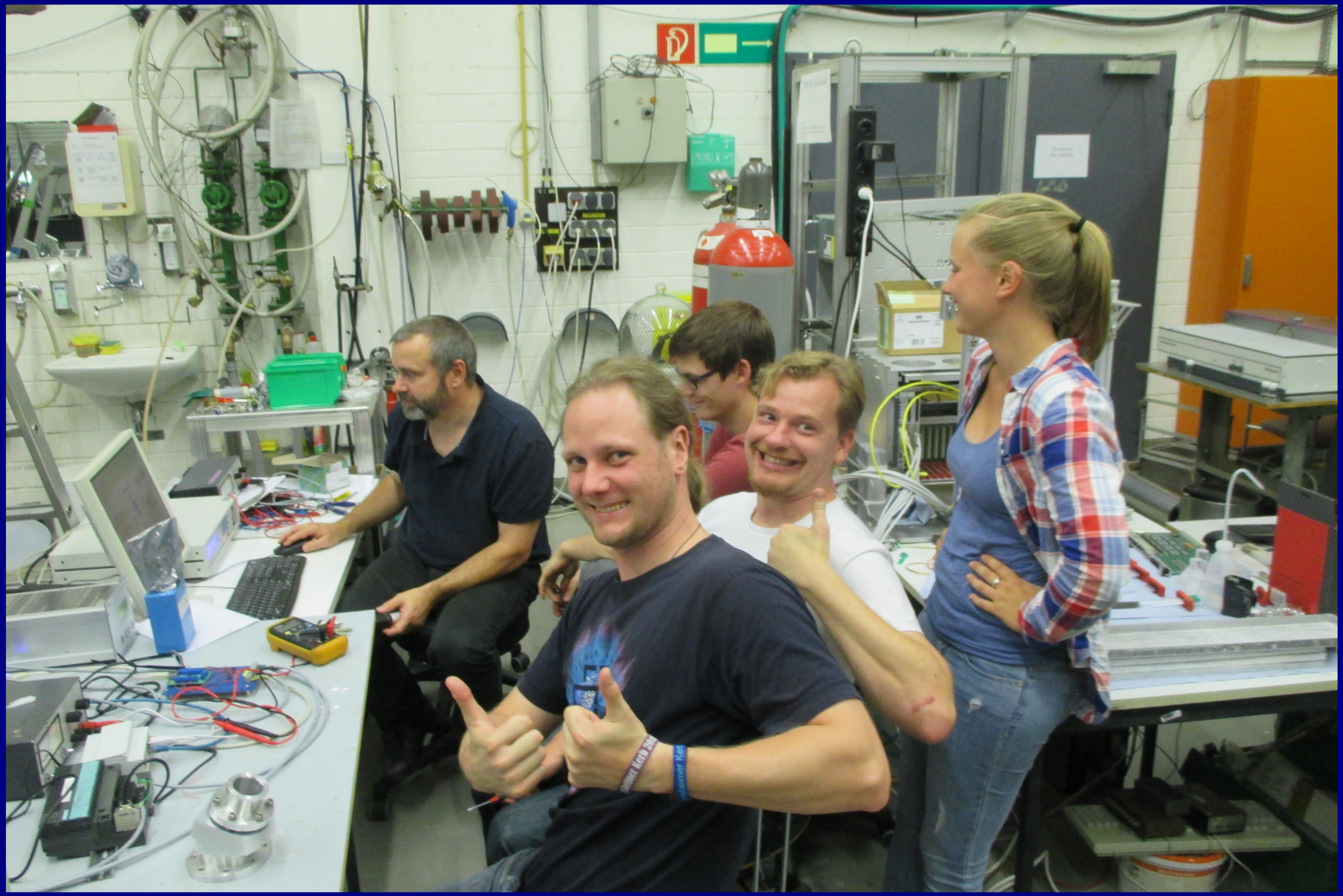




Technical problems

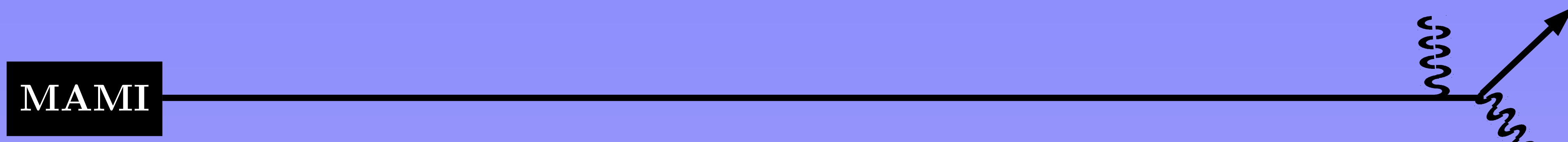
- pressure in scattering chamber
  - too high for turbo pump
  - foil at chamber entrance
  - beam straggling
- distance nozzle-catcher too small
  - significant background
- system not perfectly tight
  - nozzle freezing
  - gas recirculation not applicable

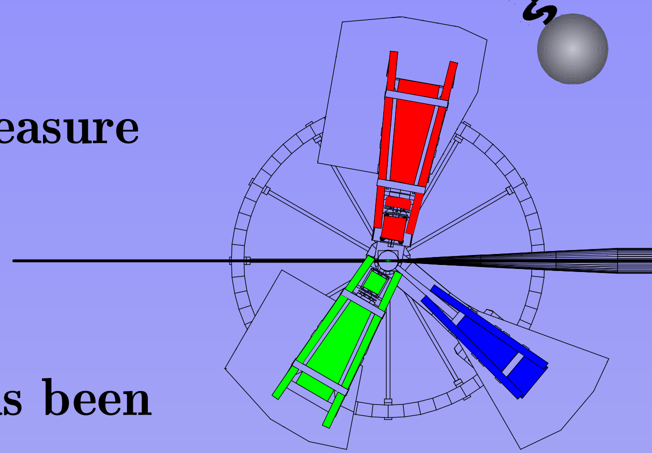
ISR with a Cluster-Jet Target



Optimistic! Beam time in two weeks..

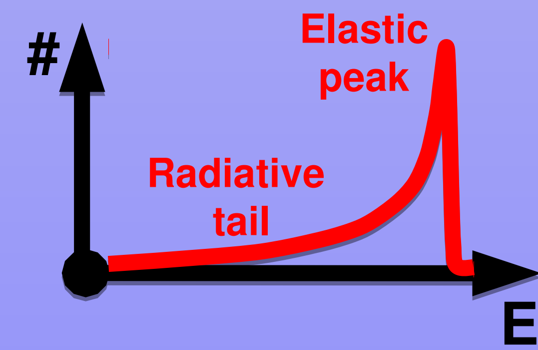
Summary





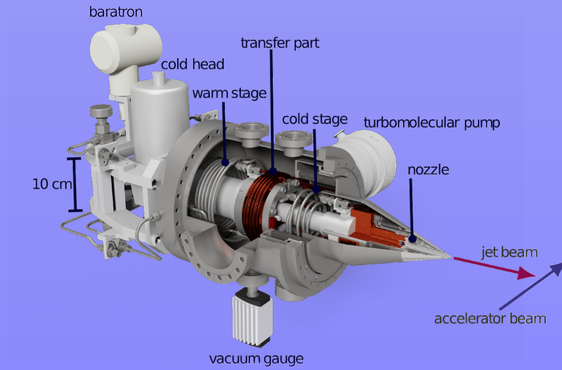
- A pilot experiment has been performed at MAMI to measure G_E^p at very low Q^2.

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

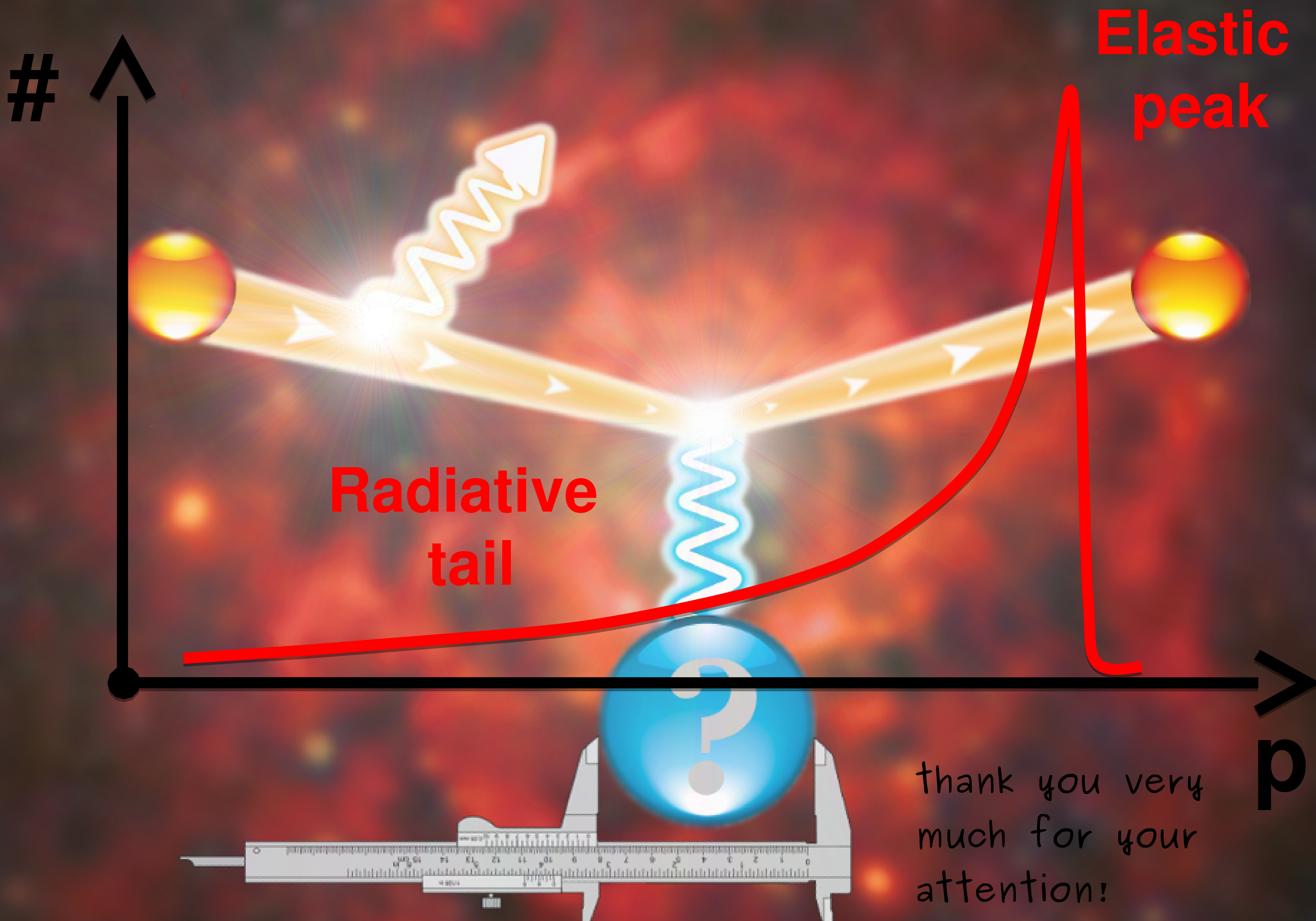


- Reach of the first ISR experiment limited by unforeseen backgrounds.

- The available jet target opens possibility for reaching the ultimate goal of measuring form factors down to 10^{-4} GeV^2, thus improving proton charge radius determination.



ISR Experiment at A1 / MAMI



thank you very much for your attention!

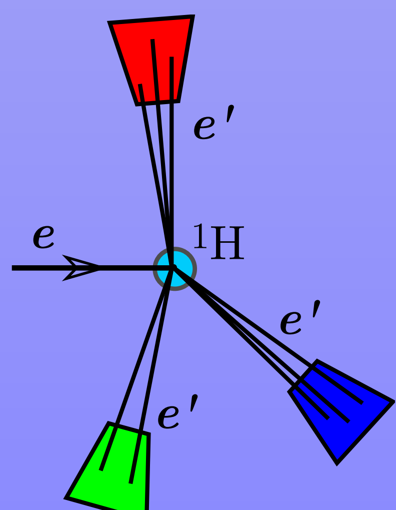
Proton form factors

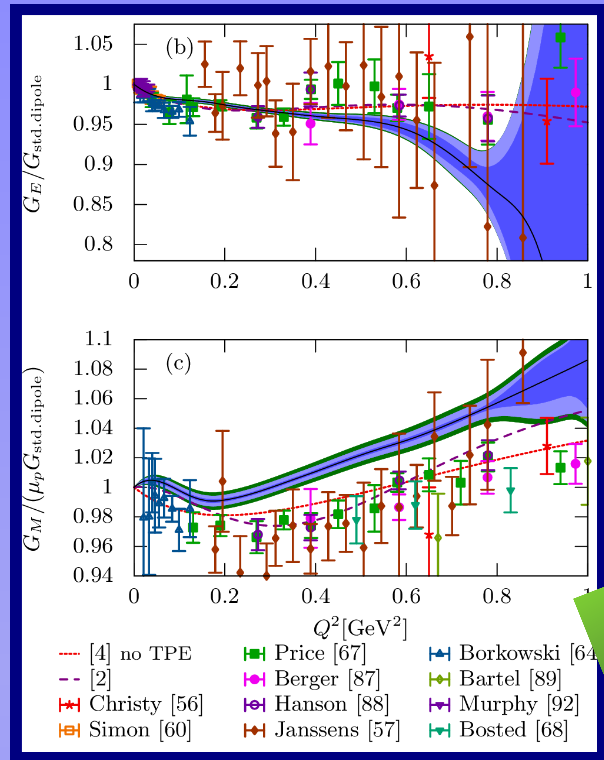
Form factor determination

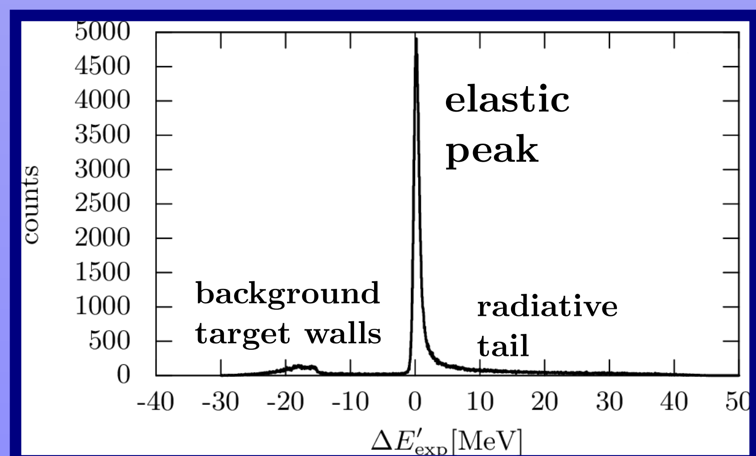
(1) measure elastic spectrum
(2) subtract background
(3) compare to simulation
(4) fit cross sections using appropriate form factor model(s)
(5) (determine radius from slope)

Extend Q^2 range

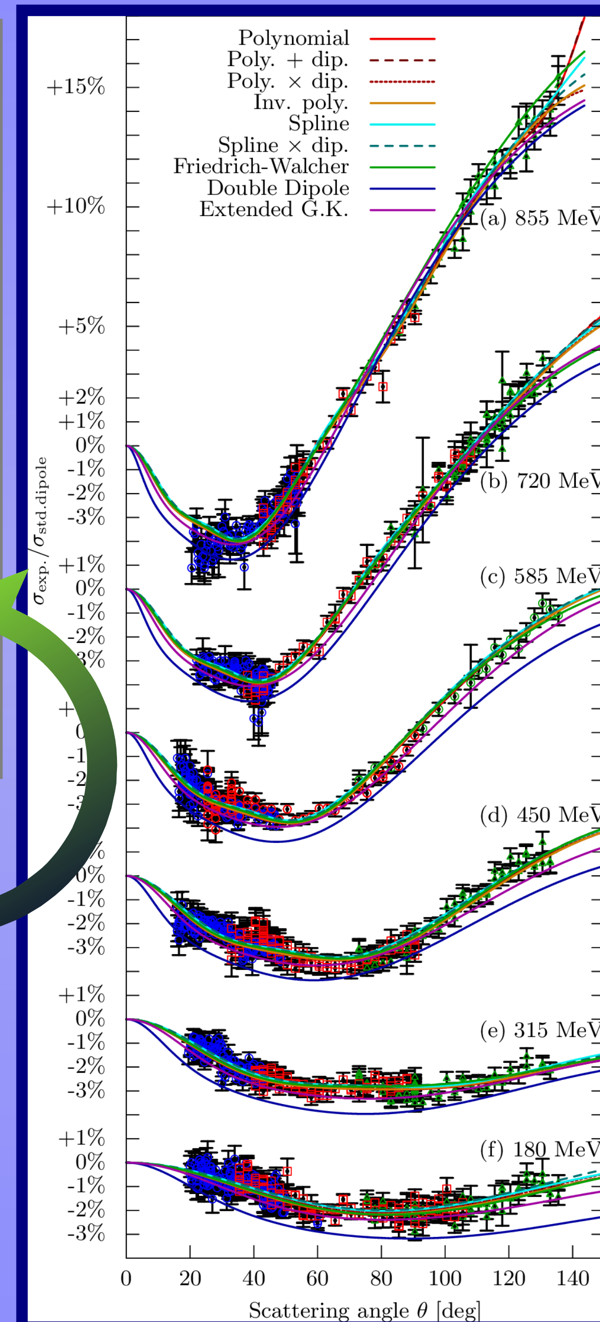
- large Q^2: similar measurements, higher beam energies
- smaller Q^2: novel technique: ISR





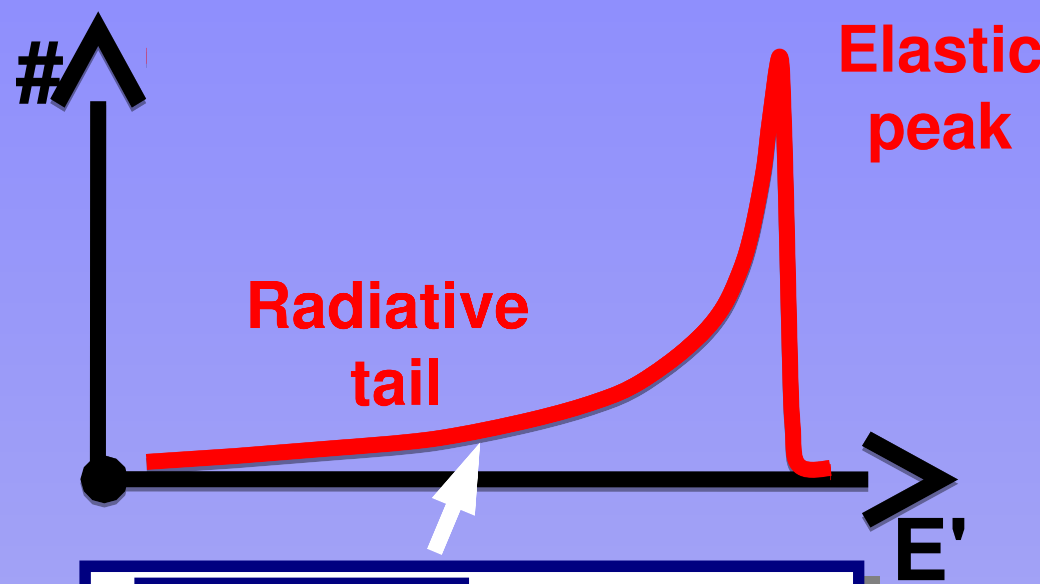


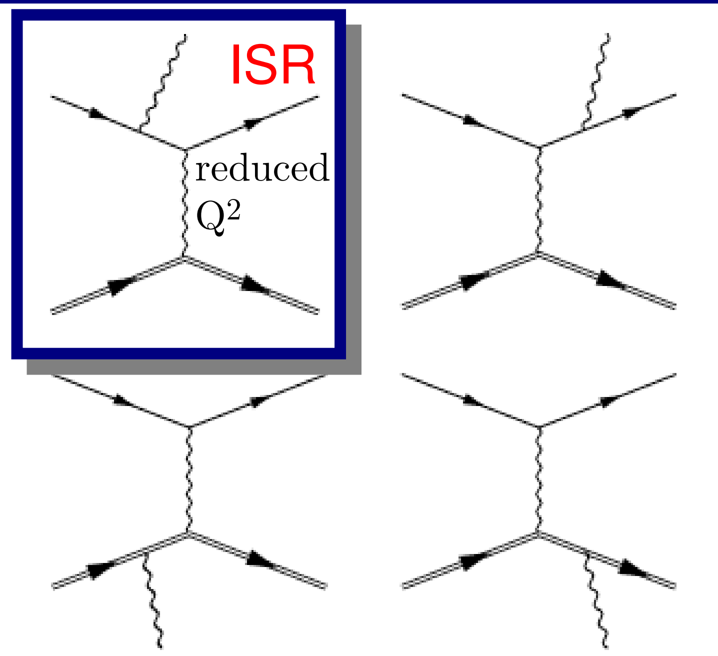
$\Delta E'$: measured - expected(elastic) electron energy



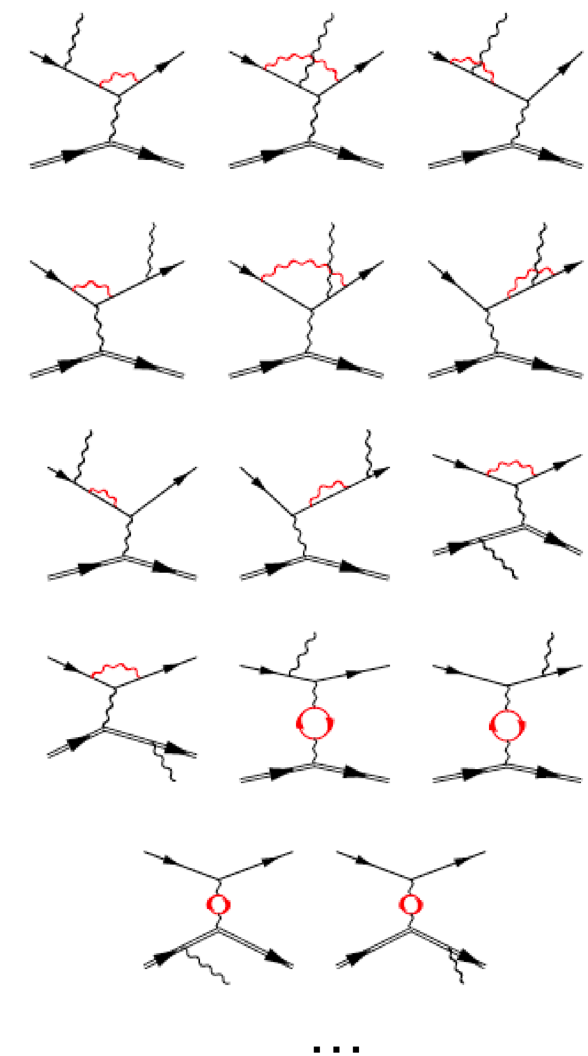
[J. C. Bernauer et al., Phys. Rev. C 90, 015206 (2014)]

Initial State Radiation





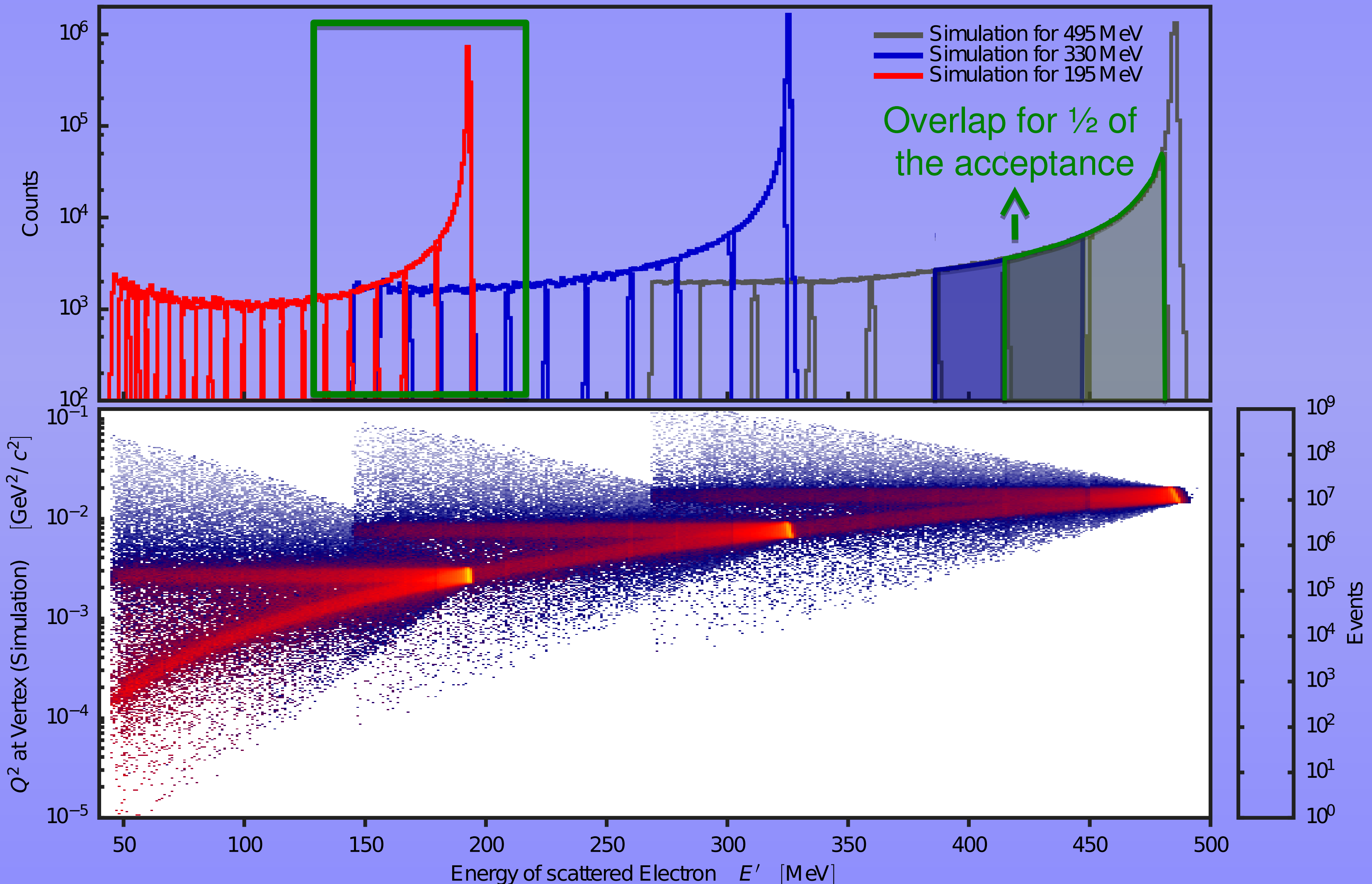
Exact calculation of LO diagrams



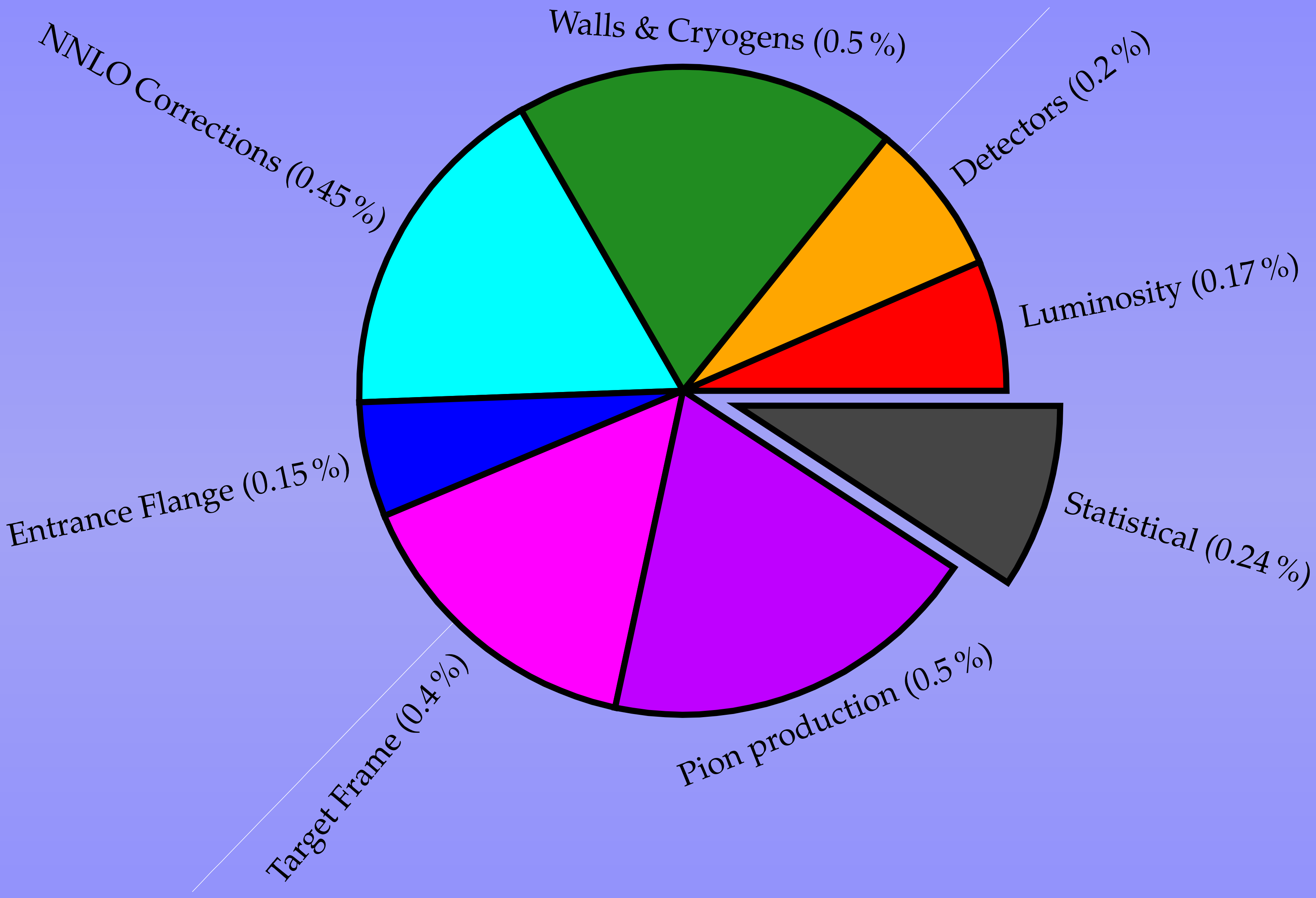
NLO virtual and real corrections included via effective corrections to cross-section

Kinematic settings

- Overlapping settings to control systematic uncertainty.



Uncertainties



Total systematic uncertainty of cross-section ≤ 1.0 %

ISR 2013 → ISR 2017

Benefits Jet-Target

- no background
  - Havar foil
  - cryogenic depositions
  - target frame (!?)
- small effects
  - external radiation
  - multiple scattering
  - ionization loss
- no extended target issues

Challenges

- fail-safe beam pos. stability
- luminosity determination / monitoring
- drastically reduced target thickness

$$\frac{70\,\mathrm{mg/cm^3}}{0.1\,\mathrm{mg/cm^3}} \cdot \frac{50\,\mathrm{mm}}{2\,\mathrm{mm}} = 17500$$