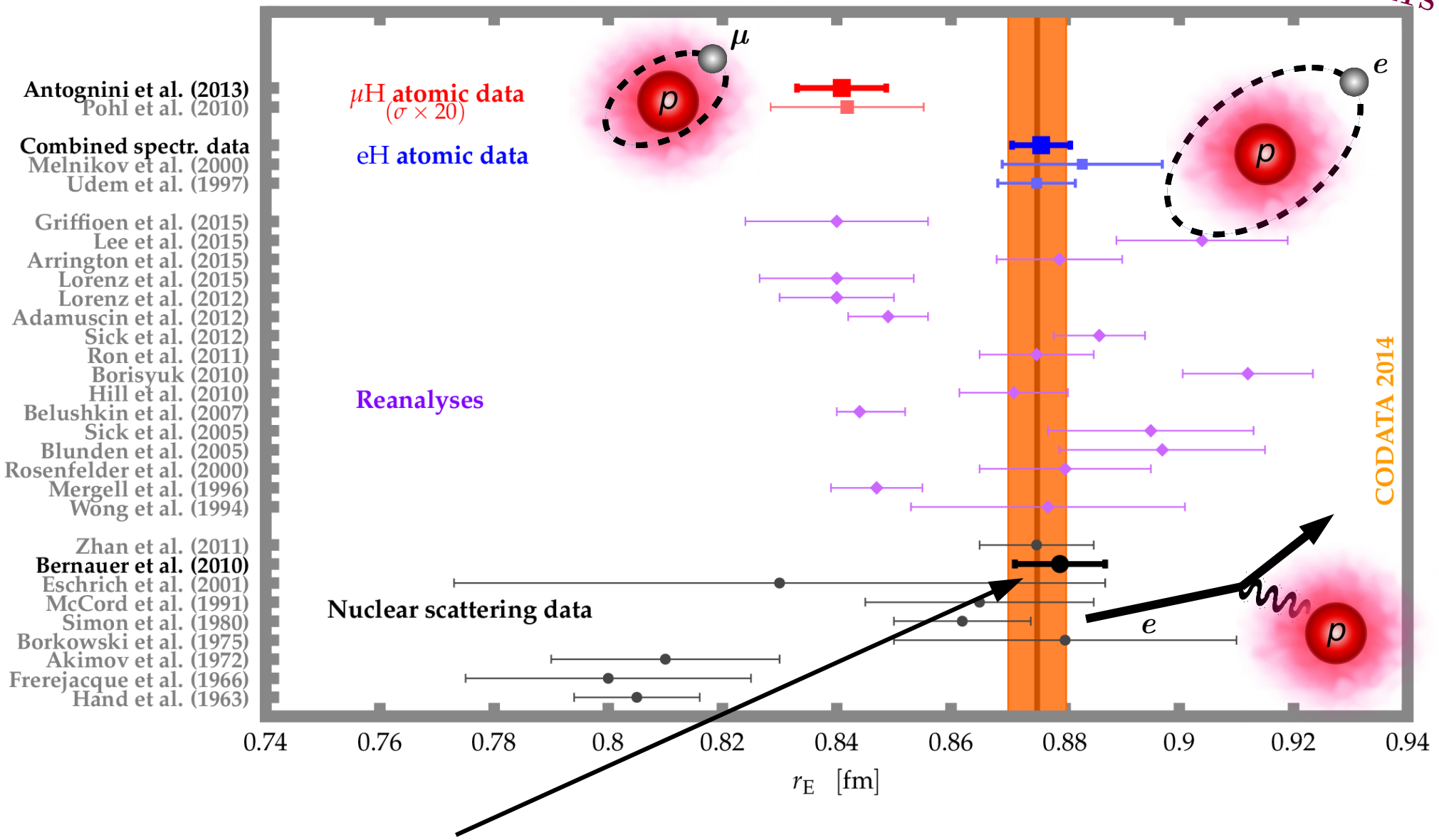
Measurement of the proton radius at A1 and MAGIX

Sören Schlimme
- large proton radius fraction -

The proton radius puzzle



Jan Bernauer, Michael Distler, Jörg Friedrich, Thomas Walcher, Harald Merkel, ..., Sören Schlimme, ...

Measurement of the proton radius at A1 and MAGIX

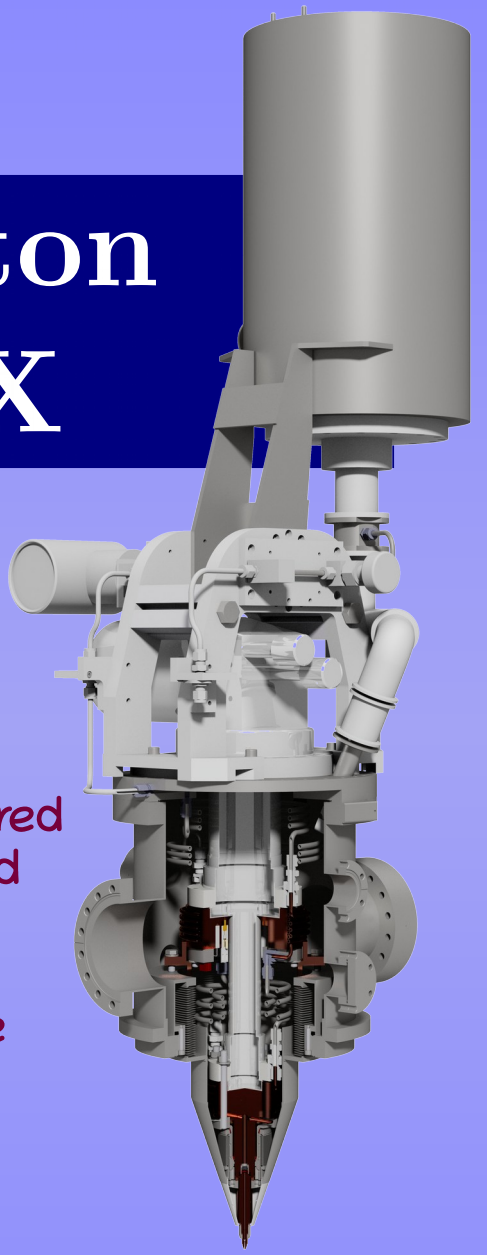
Sören Schlimme

Institute for Nuclear Physics
Johannes Gutenberg University Mainz

First A2 - TPC collaboration meeting

Mar. 9-10, 2020, Mainz, Germany

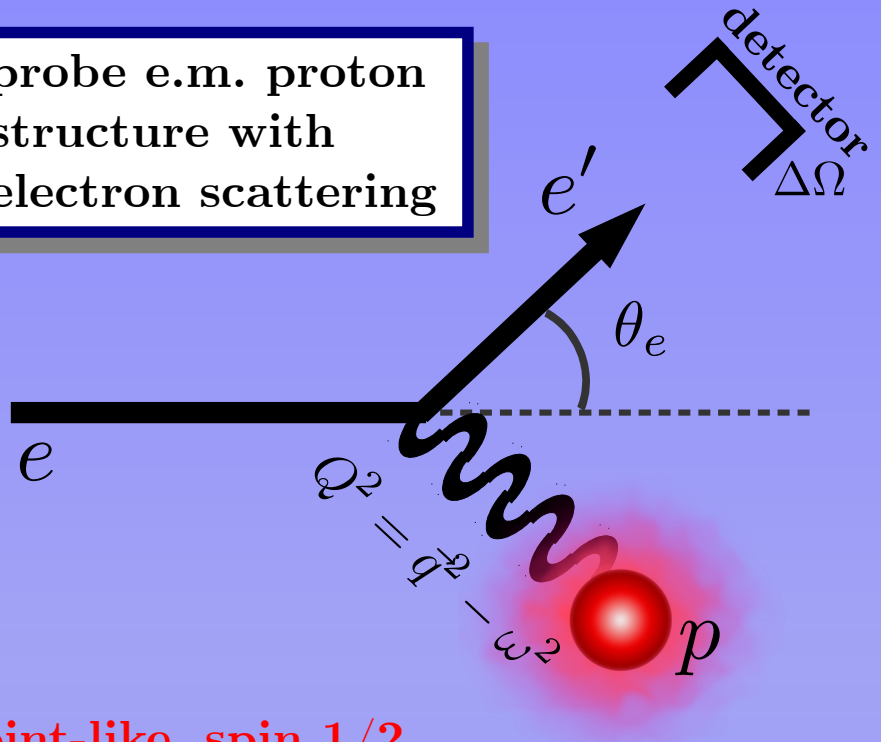
- previous A1 experiments
- current A1 experiments
- future MAGIX experiments

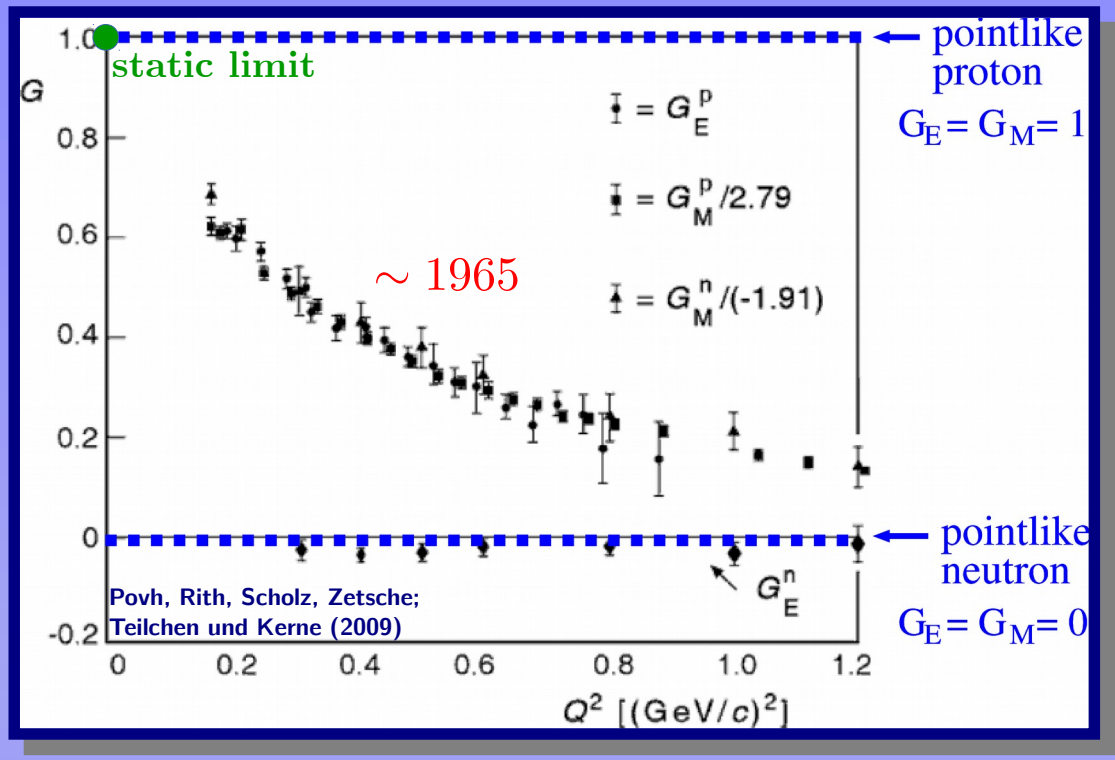


centered around this fancy device

Elastic ep-scattering: e.m. form factors

probe e.m. proton structure with electron scattering





point-like, spin 1/2

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}} \cdot \left(1 + 2\tau \tan^2\frac{\theta_e}{2}\right)$$

substructure, spin 1/2 (e.g., proton)

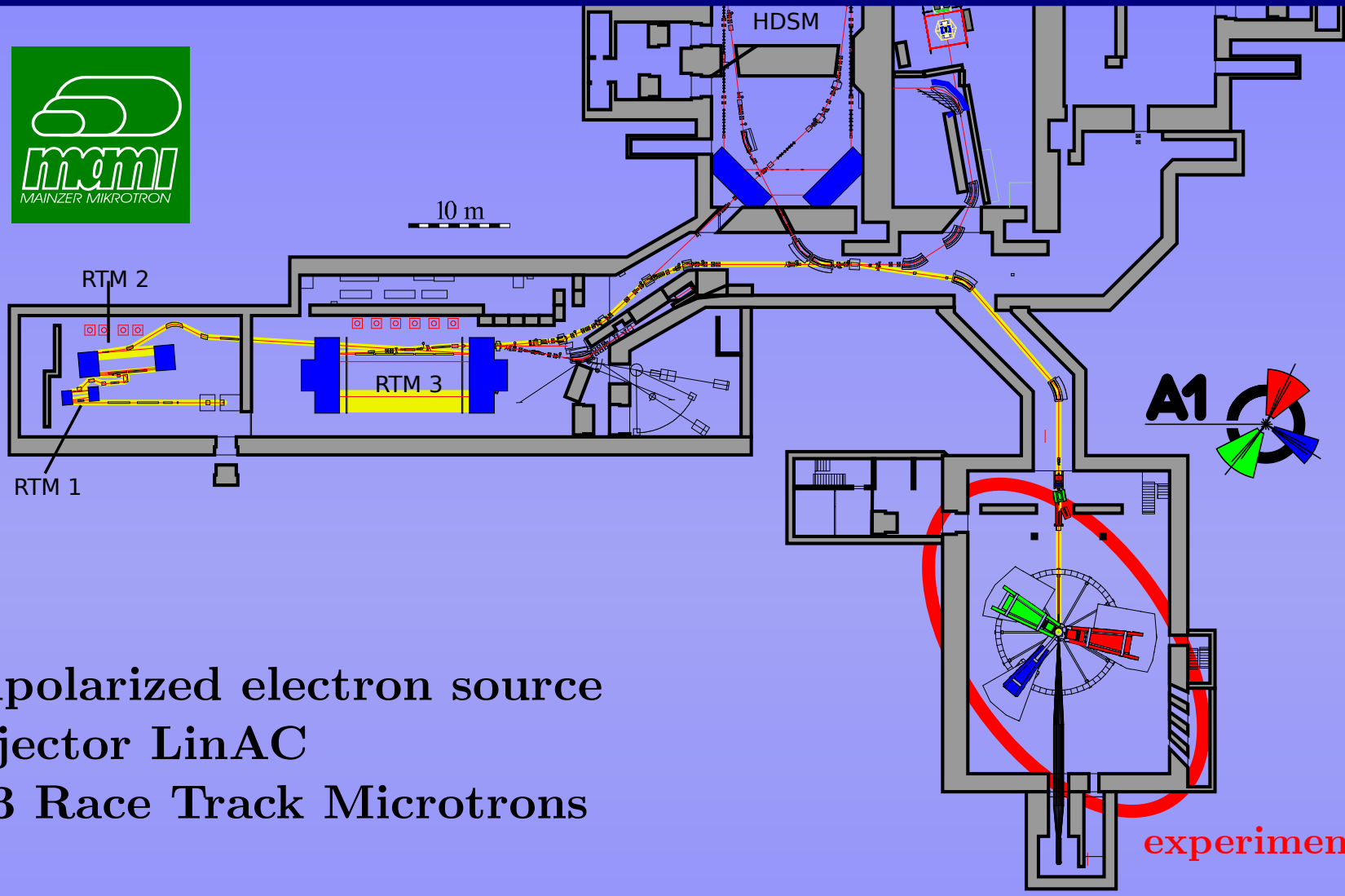
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}} \cdot \frac{1}{(1+\tau)}\left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon}G_{\mathrm{M}}^2(Q^2)\right]$$

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

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

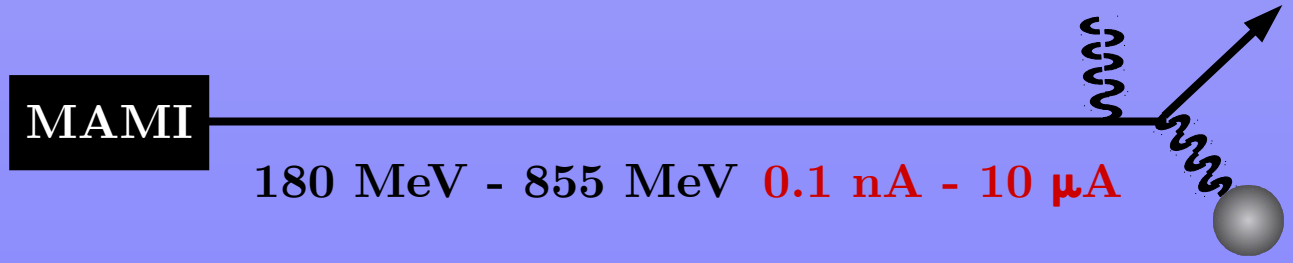
radius from slope: $\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0}$

Mainz Microtron (MAMI) - Electron Accelerator

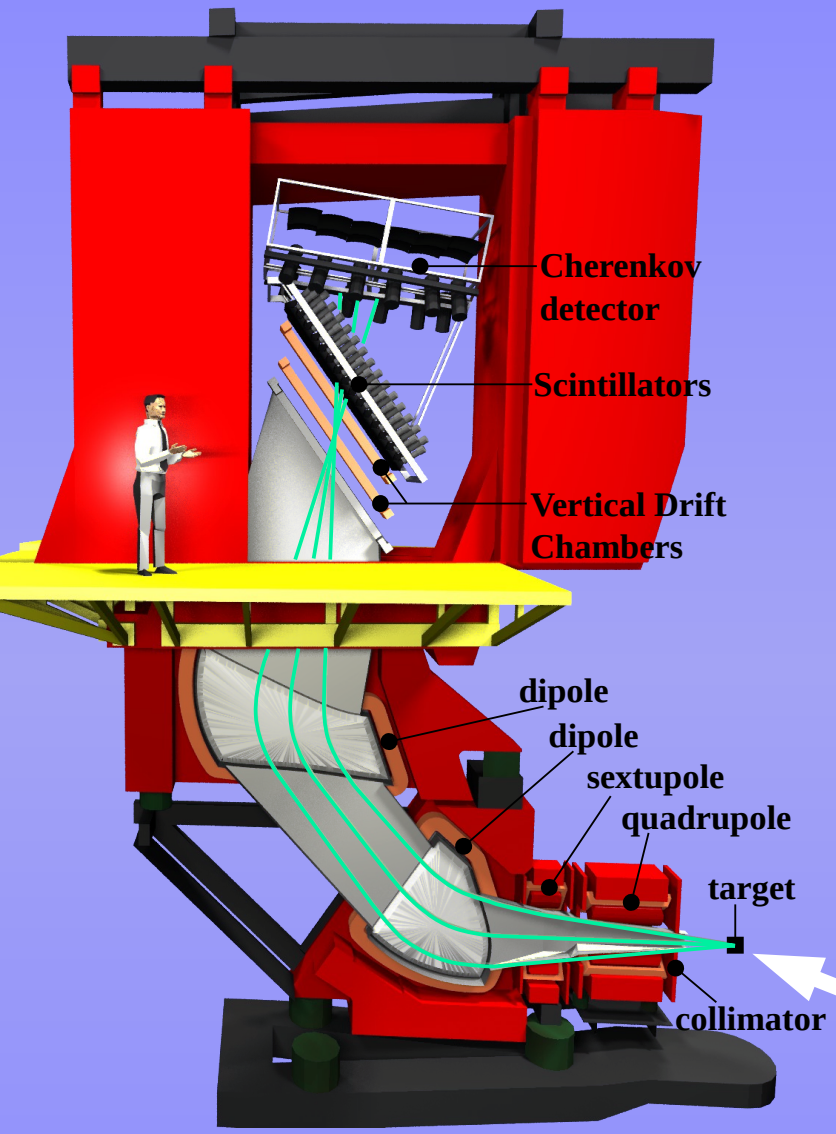


Used:

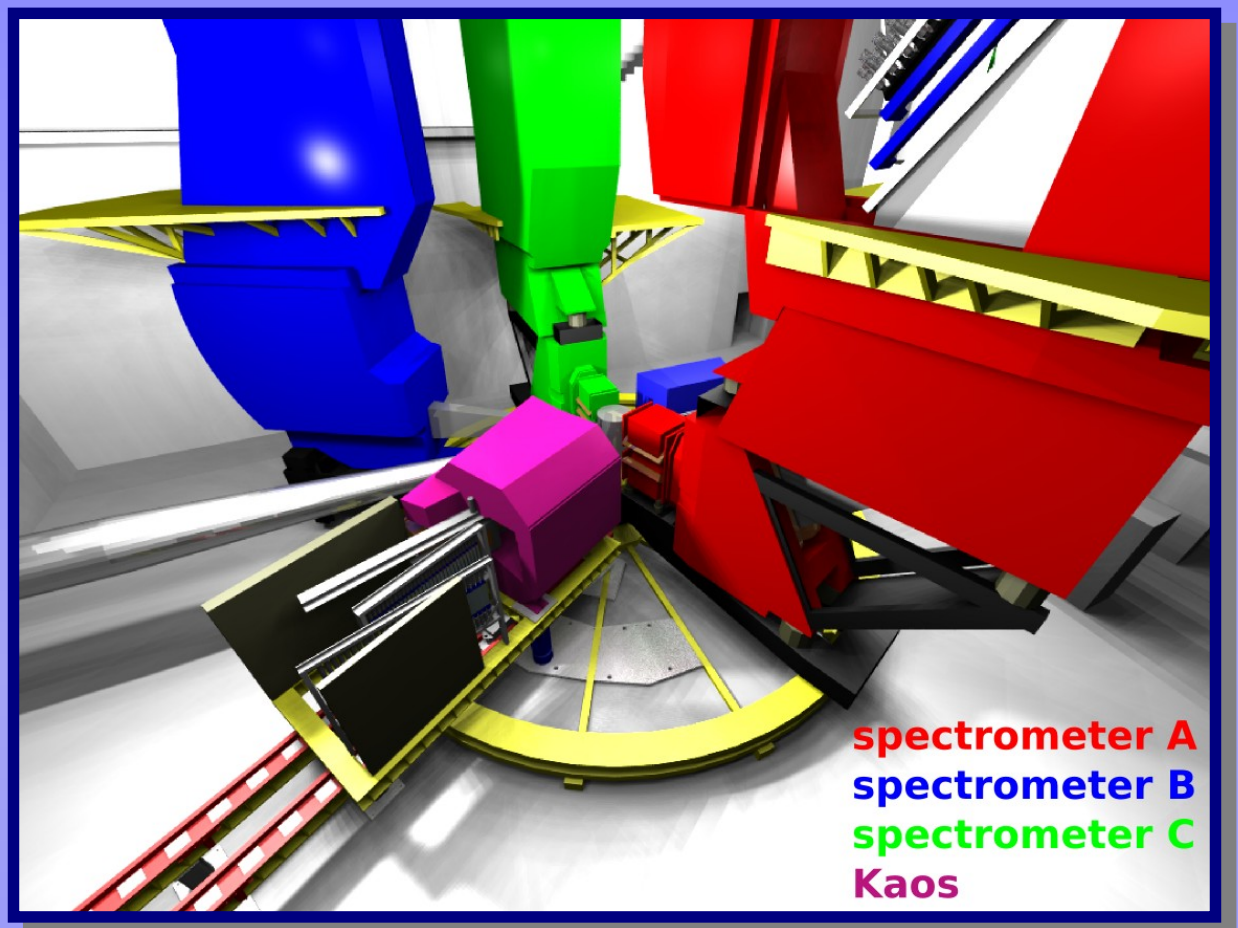
- unpolarized electron source
- Injector LinAC
- 2-3 Race Track Microtrons

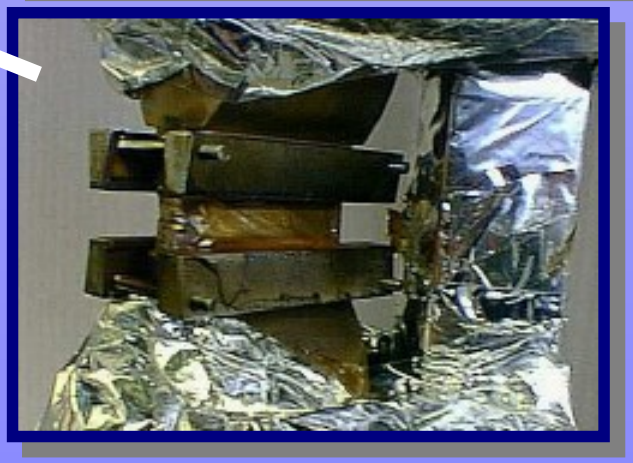


The A1 setup



High resolution magnetic spectrometers



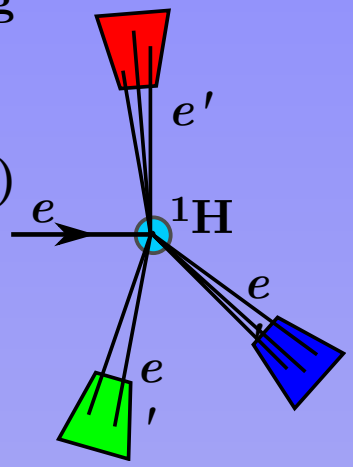


Liquid hydrogen target

Cross Section Determination

Counts

- identify and count el. events
- background handling
  - analysis cuts
  - subtraction
    - (empty cell data)
    - simulation



Luminosity

- target parameters
- beam current:
  pA meter, Förster probe(s)
- only move 1 spectrometer
  at a time
  - relative lumi monitoring

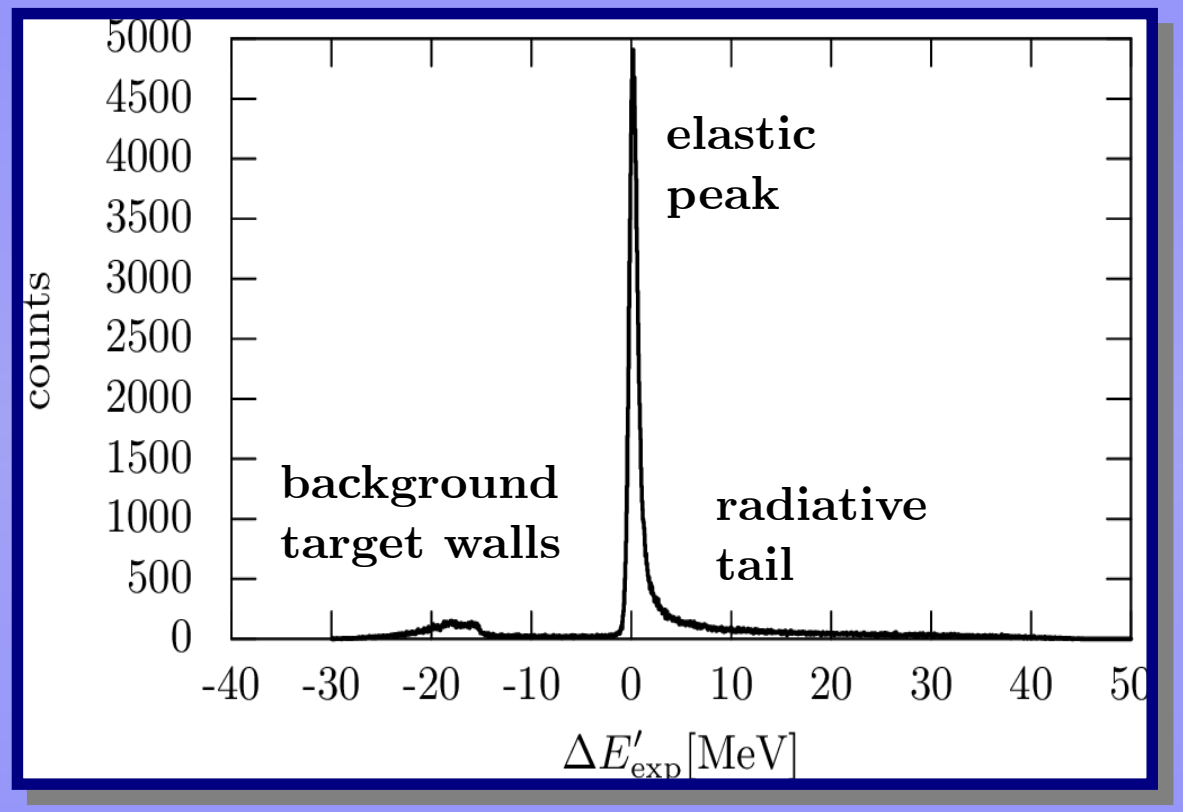
Angular acceptance

- well defined by collimator

Corrections

- dead time
- detector efficiency
- radiative corrections
- ...

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{N}{\int \mathrm{d}t L(t) \cdot \Delta\Omega} \cdot \mathrm{corr}$$



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

beneficial approach:
compare spectrum to simulation including rad. corr.
→ XS relative to the one used in simulation

Proton form factors, radius

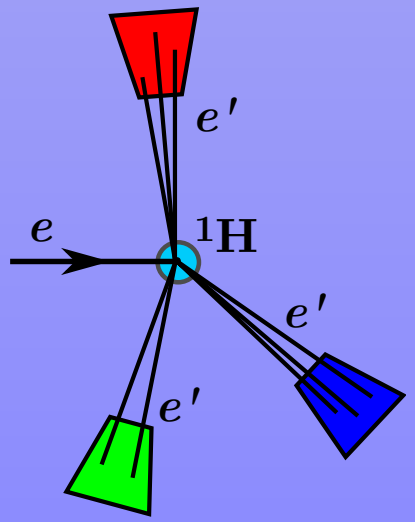
Form factor determination

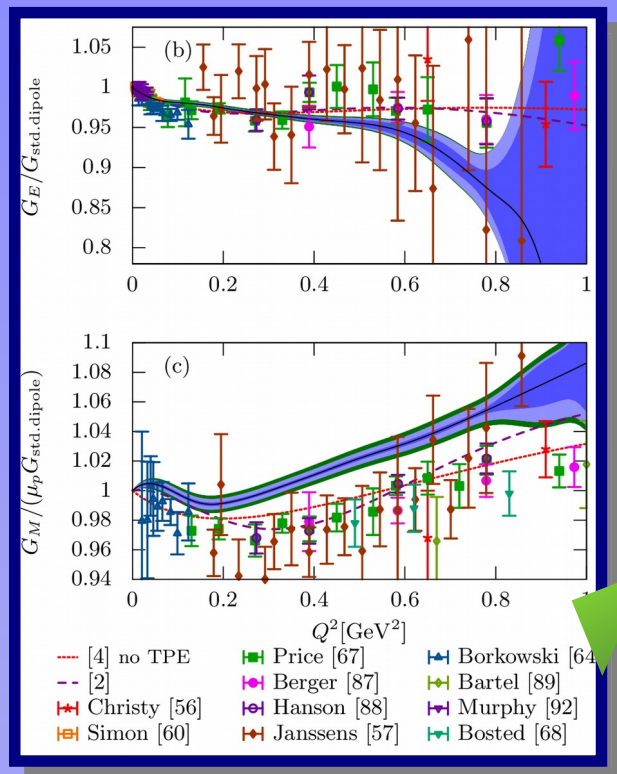
(1) measure elastic spectrum
(2) convert to XS

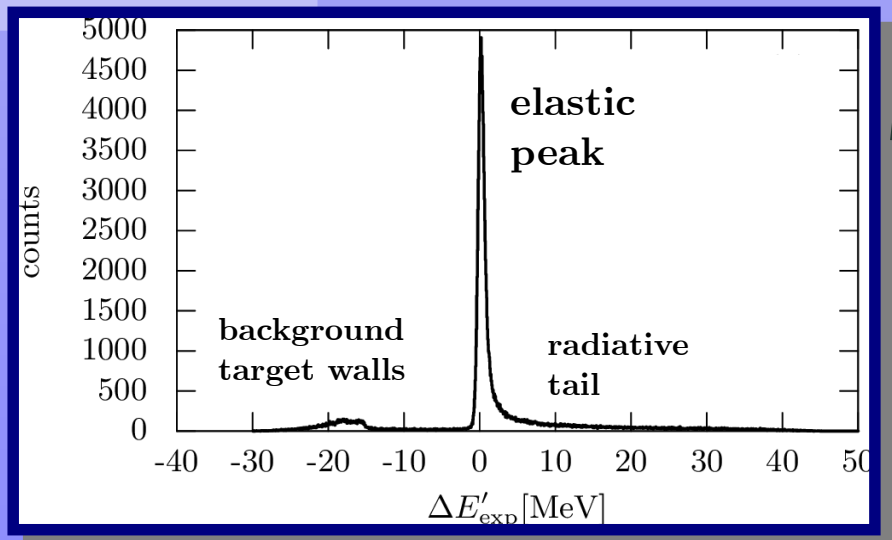
$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}} \cdot \frac{1}{(1+\tau)}\left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon}G_{\mathrm{M}}^2(Q^2)\right]$$

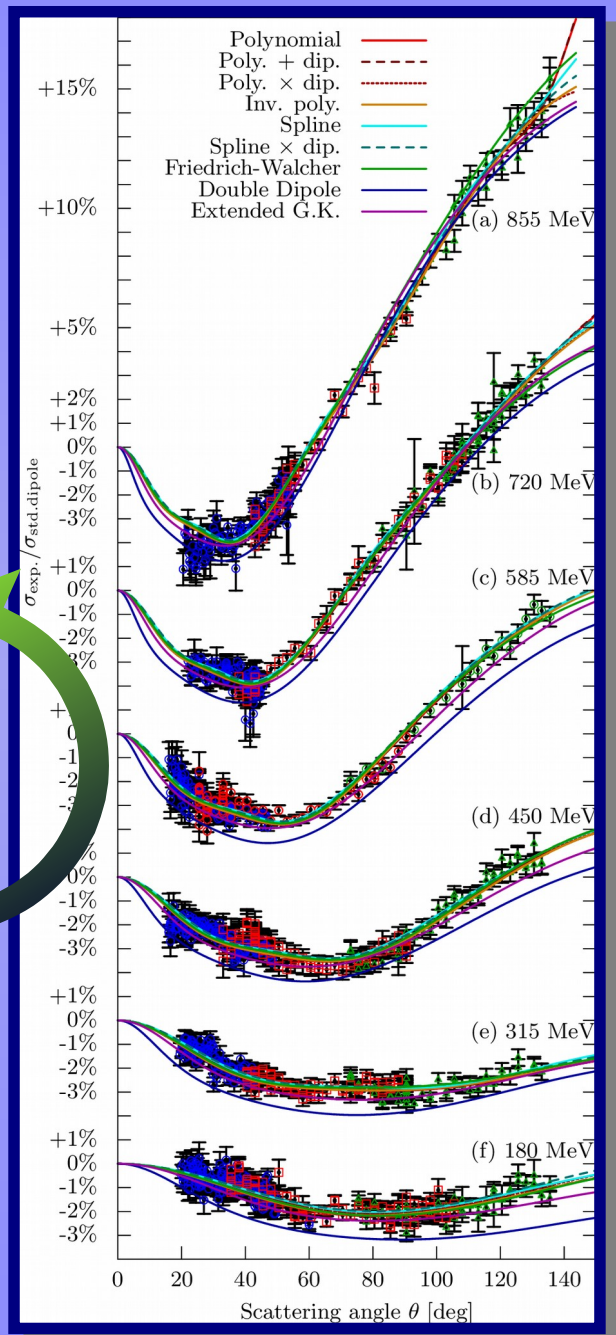
(3) take many, many data!
(4) extract form factors
- Rosenbluth separation
- fit cross sections using appropriate form factor model(s)

(5) determine radius from slope

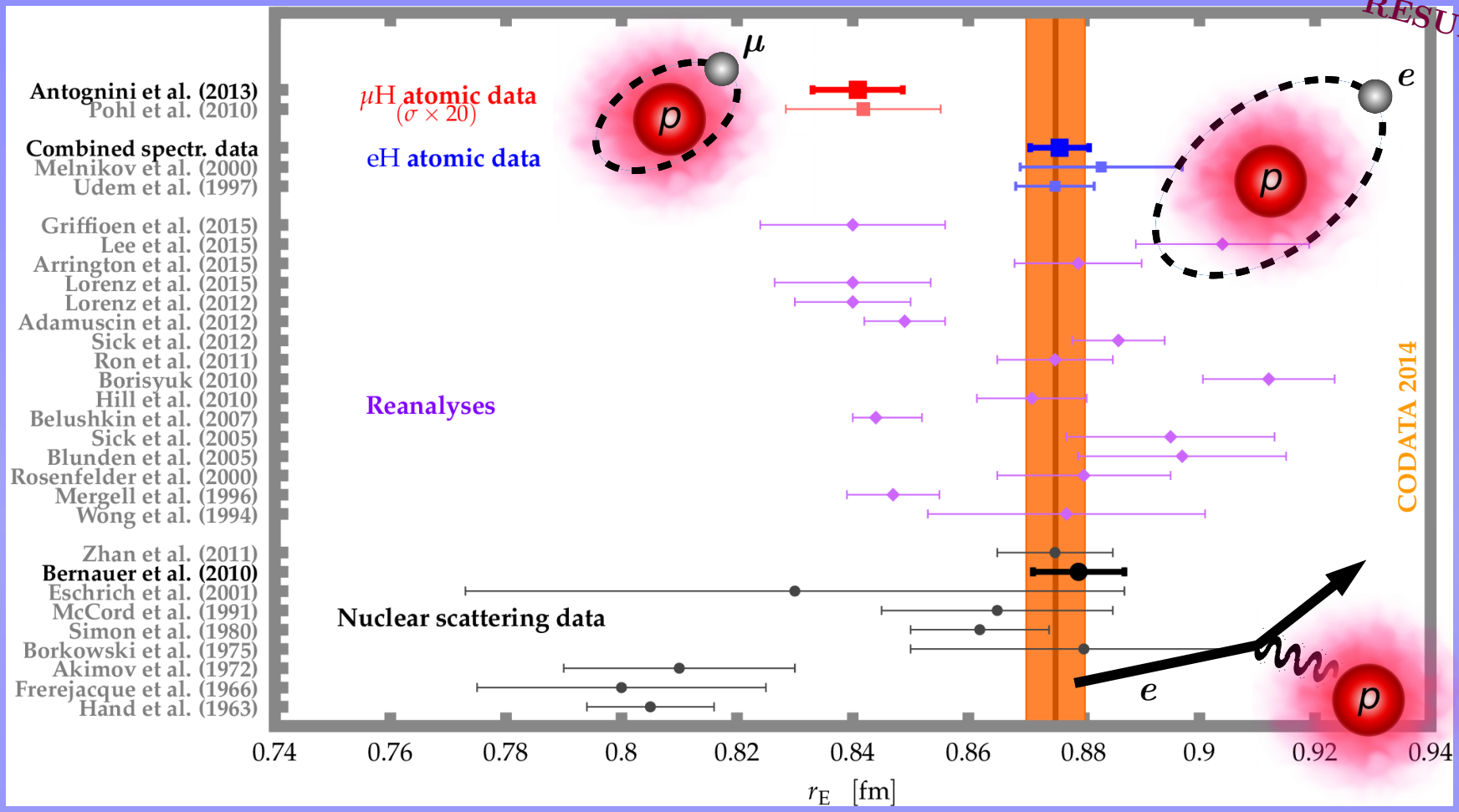






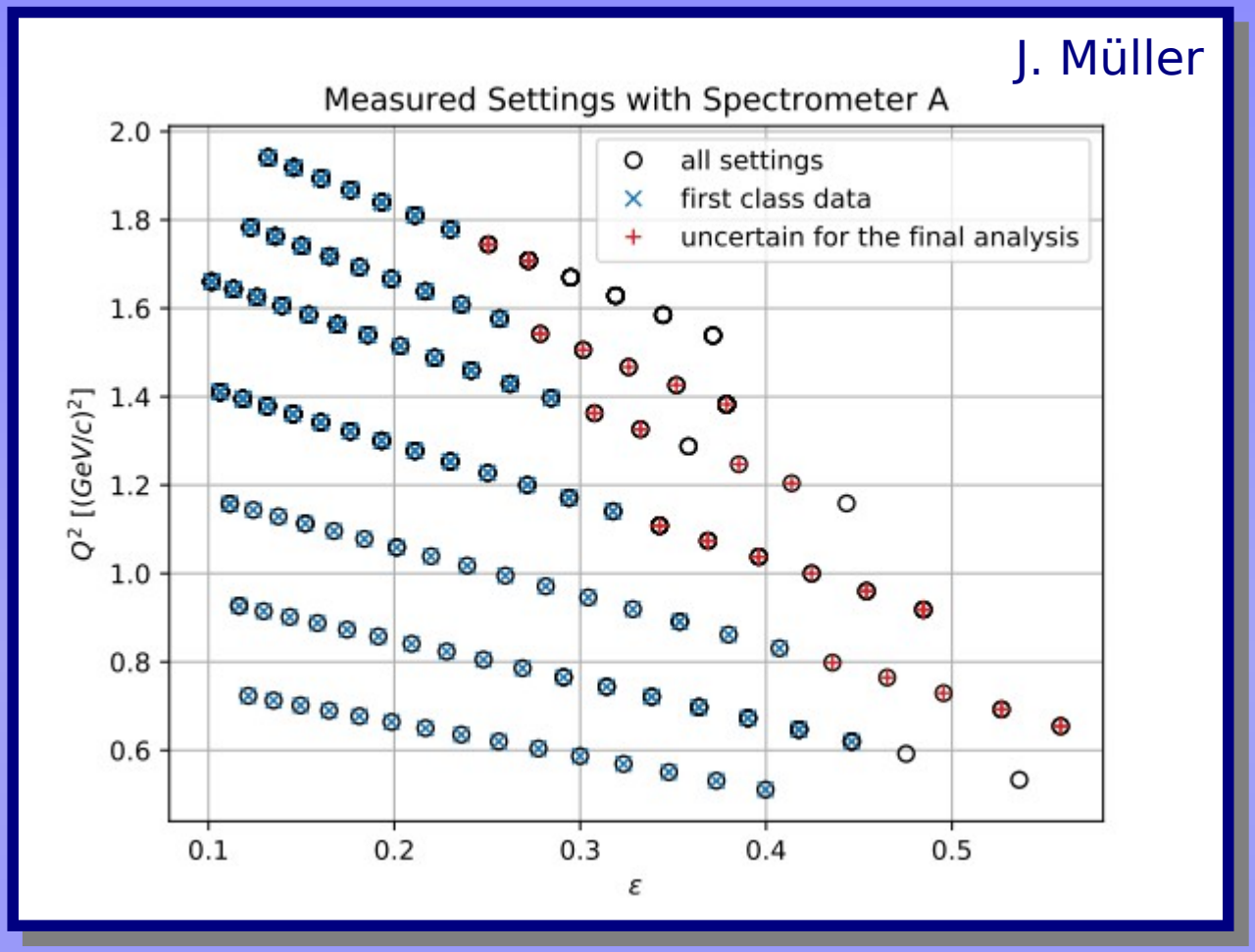


Proton Radius Result 2010



- Extension of the program: higher Q^2 data (MAMI-C)
  J. Müller, PhD thesis in progress

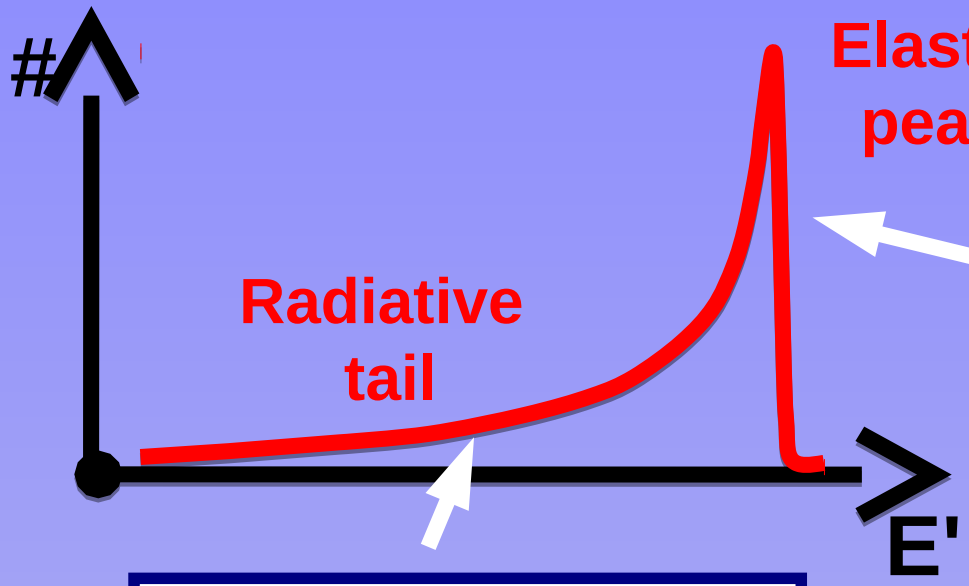
Extension of the program

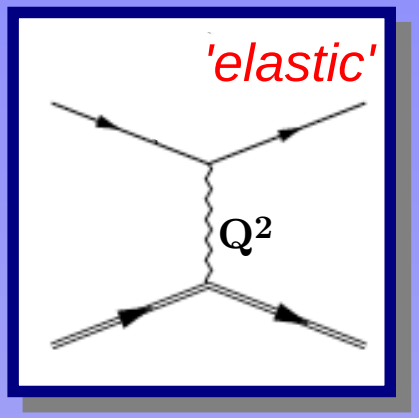


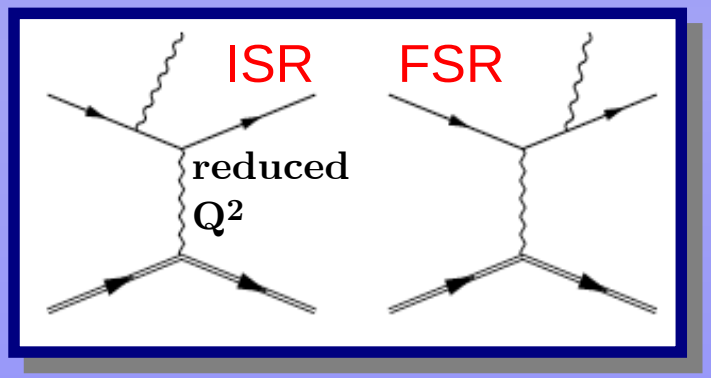
- Extension of the program: higher Q^2 data (MAMI-C)
  J. Müller, PhD thesis in progress
- Claim of community: need smaller Q^2 data
  [Bernauer et al.: > 0.004 (GeV/c)².]
  - how to do that at MAMI?

$$\langle r_E^2 \rangle = -6\hbar^2 \left. \frac{\mathrm{d}G_E}{\mathrm{d}Q^2} \right|_{Q^2=0}$$

Initial State Radiation





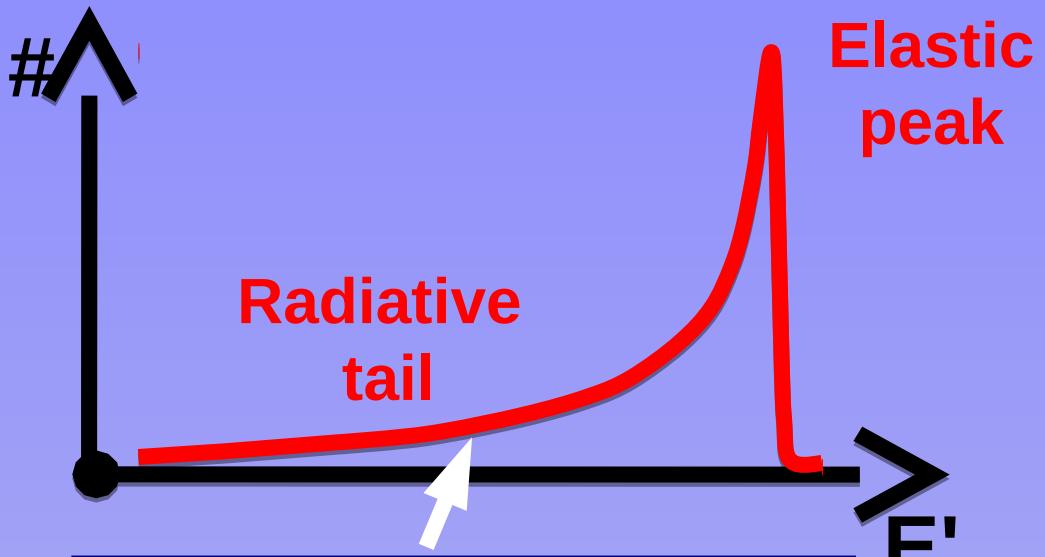


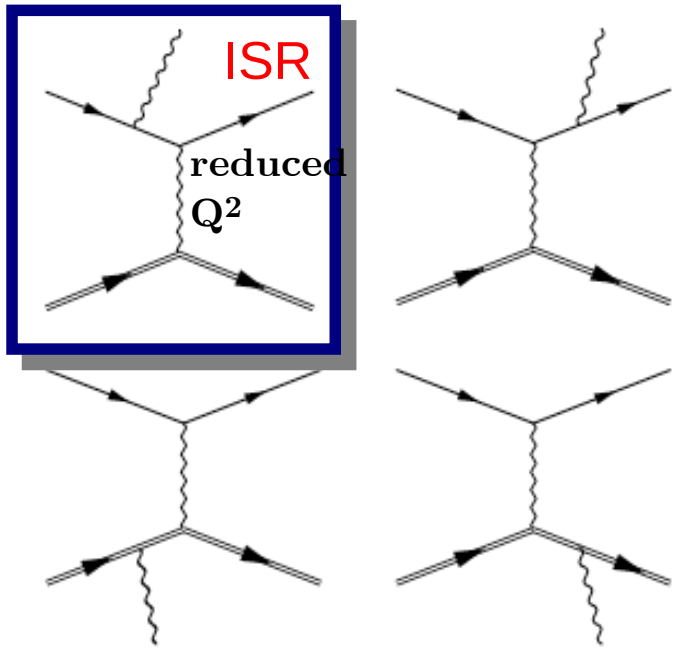
Sophisticated simulation needed (FSR, ...)

Exploit information in radiative tail

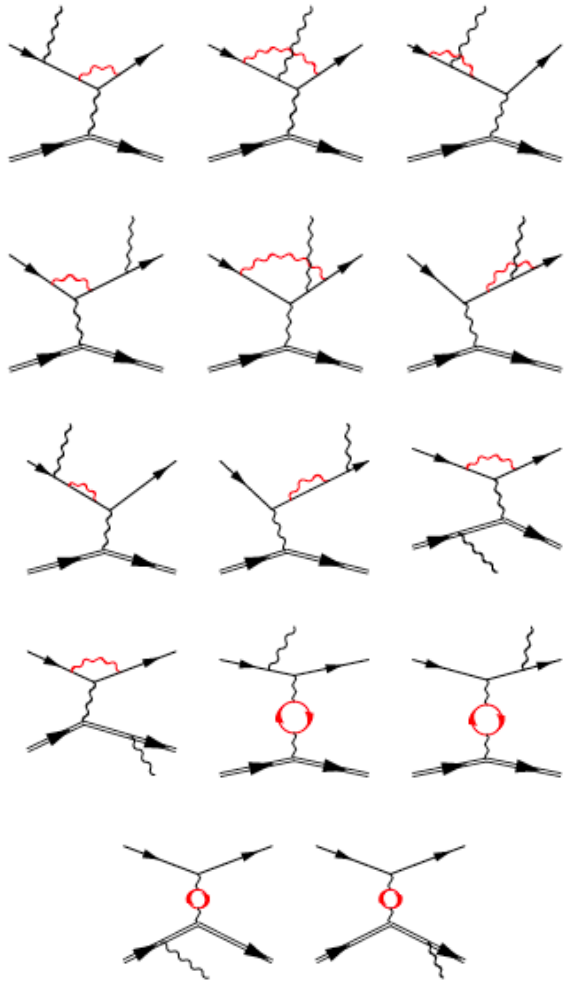
- ISR: photon radiation takes energy out of electron → access to lower Q^2 at given scattering angle
- Allows investigating G_E at Q^2 down to 10^{-4} GeV^2

Initial State Radiation





Exact calculation of LO diagrams



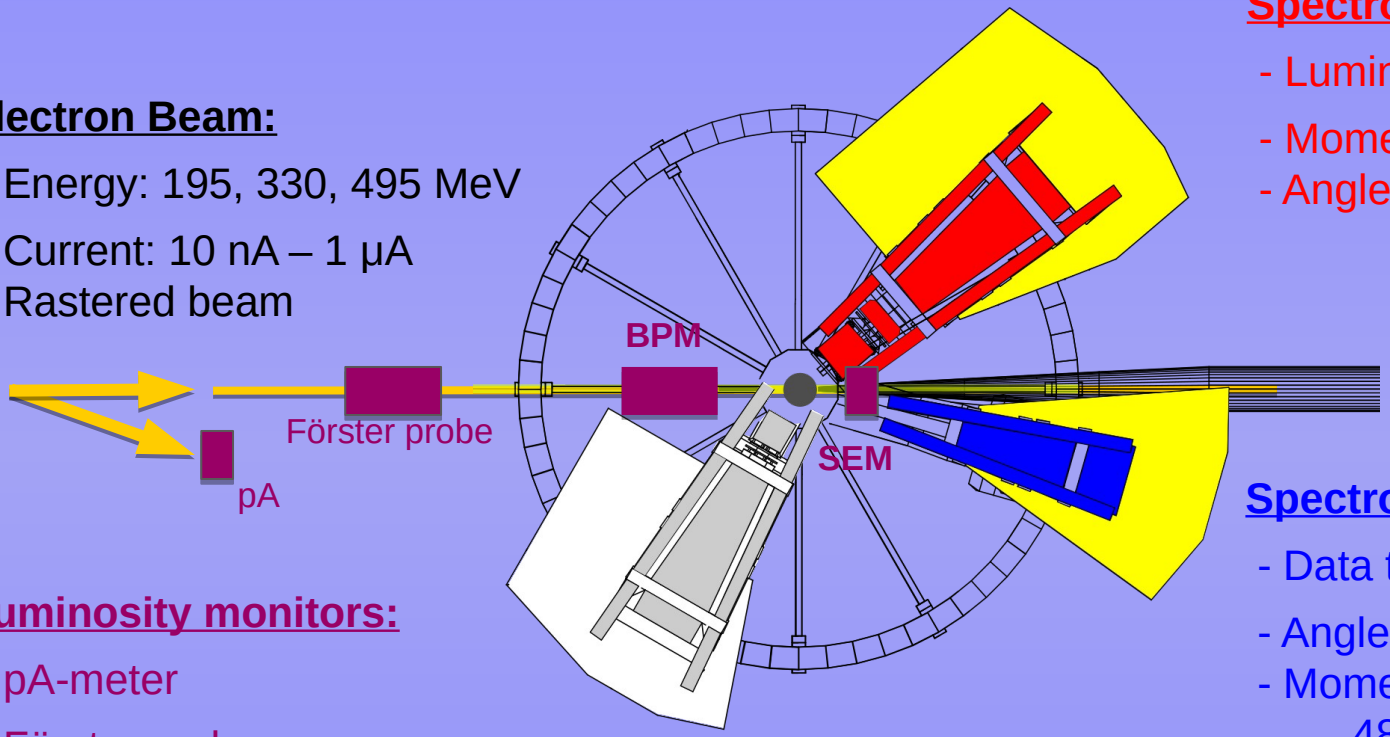
...

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

The ISR experiment

Electron Beam:

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

Spectrometer C:

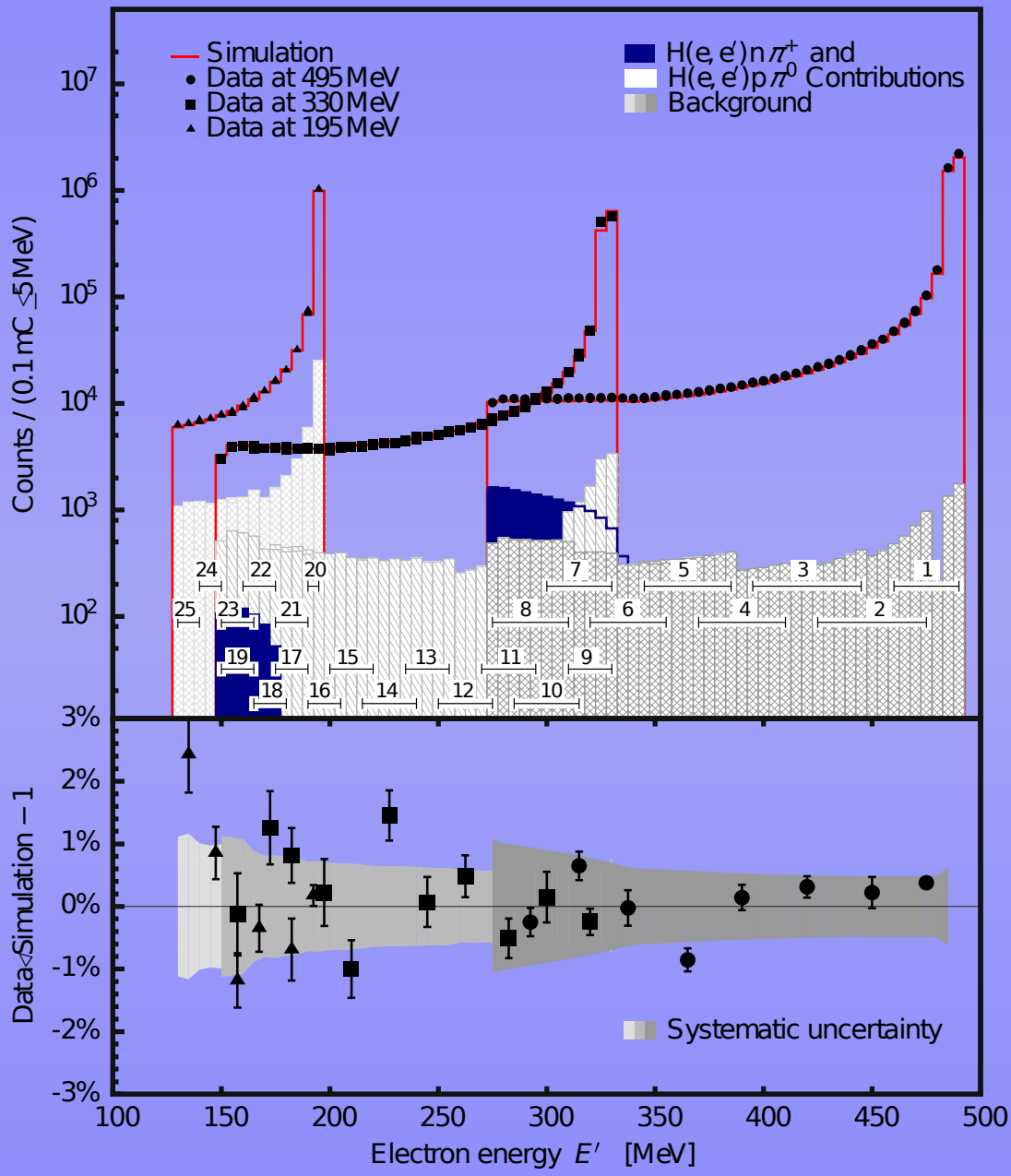
- Not used

Performed at MAMI in 2013

Results ISR 2013

Comparison data vs. simulation

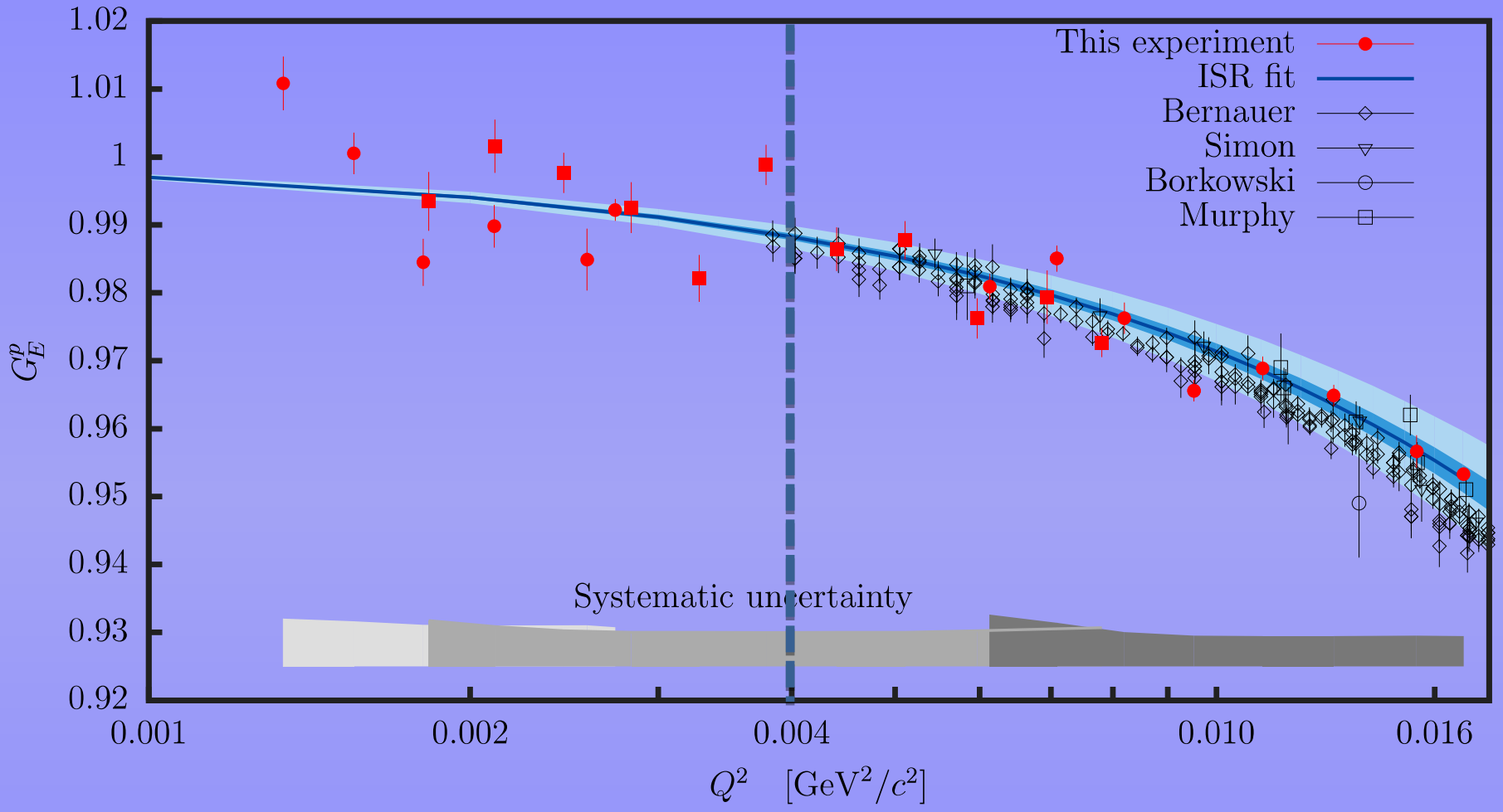
- Simulation performed with Bernauer et al. parametrization of FFs
- A percent agreement ↔ radiative corrections well understood, even 200 MeV away from elastic peak!
- Existing apparatus limited reach to $E' \sim 130$ MeV
- Assuming flawless description of radiative corrections, FFs can be extracted



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

Results ISR 2013: form factor, radius

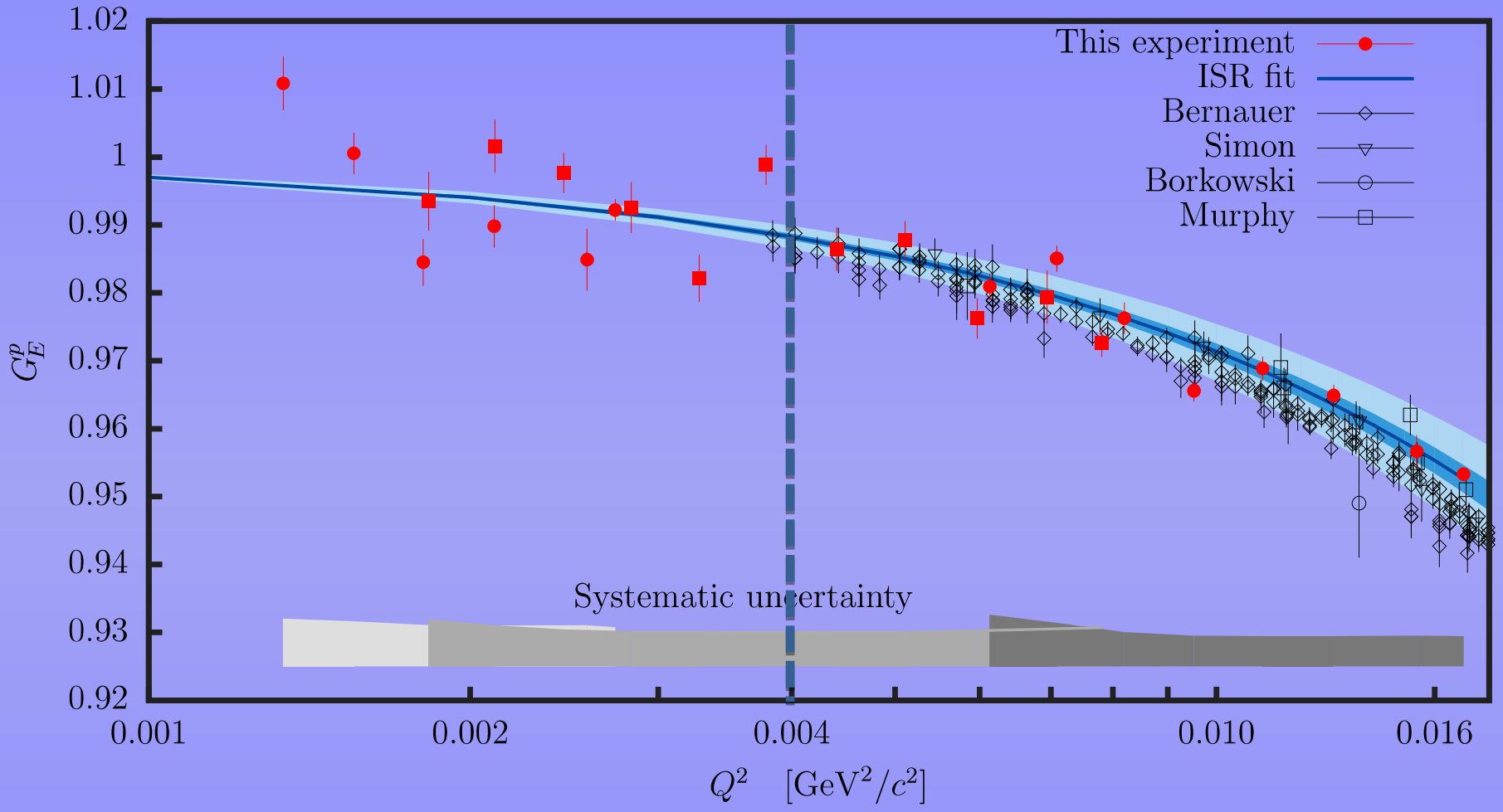
M. Mihovilovic *et al.*, Phys. Lett. B 771 (2017) 194



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

Results ISR 2013: form factor, radius

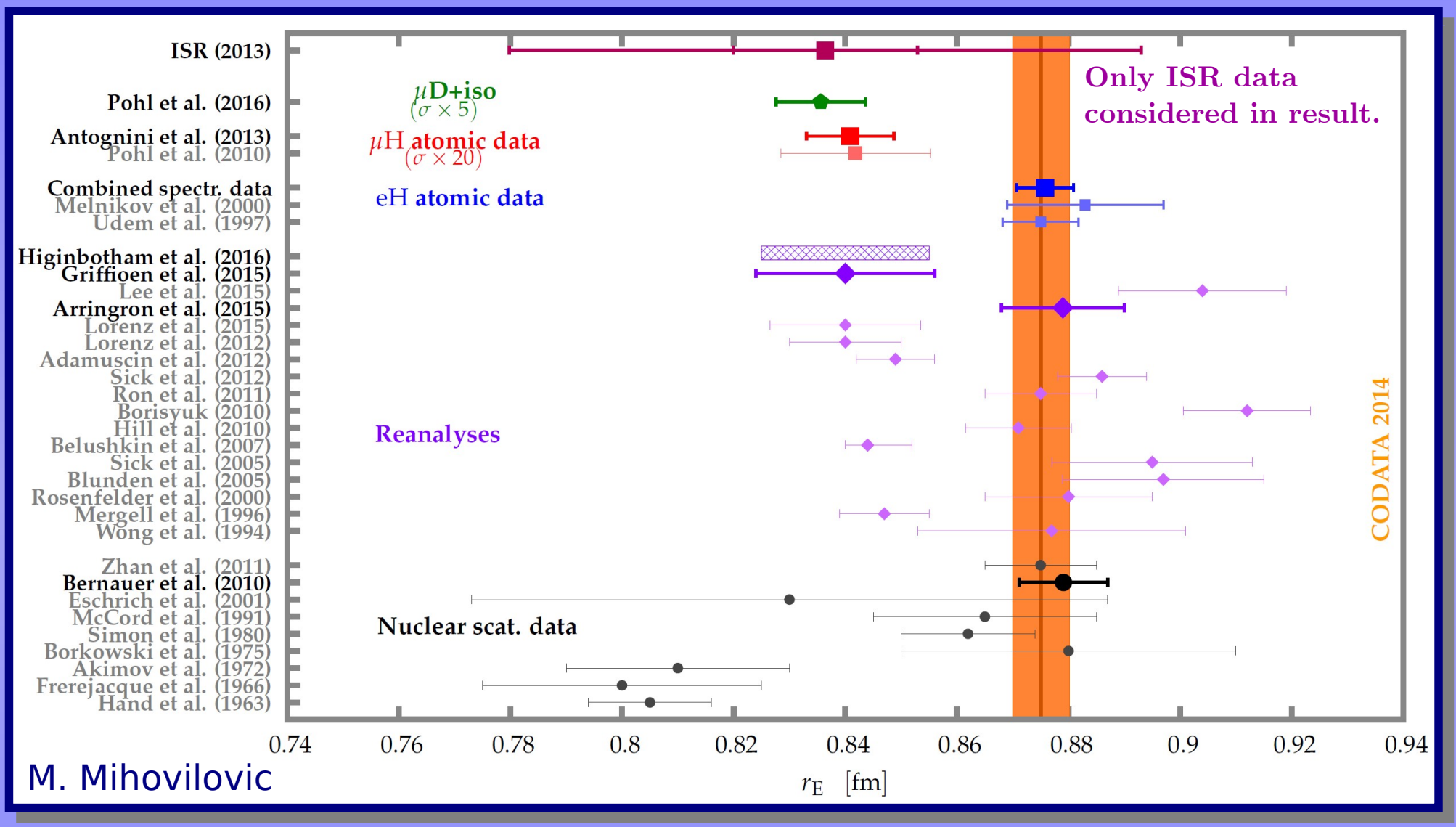
M. Mihovilovic *et al.*, Phys. Lett. B 771 (2017) 194



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

$$r_E = (0.836 \pm 0.017_{\text{stat.}} \pm 0.057_{\text{syst.}} \pm 0.003_{\text{mod.}})\ \text{fm}$$

Results ISR 2013: radius



M. Mihovilovic

Diplomatic.

Some improvement: arXiv:1905.11182 [nucl-ex]

Honestly:

ISR - MVP

ISR - Mastermind

NOT EXACTLY THE DESIRED RESULT.

IMPROVE?

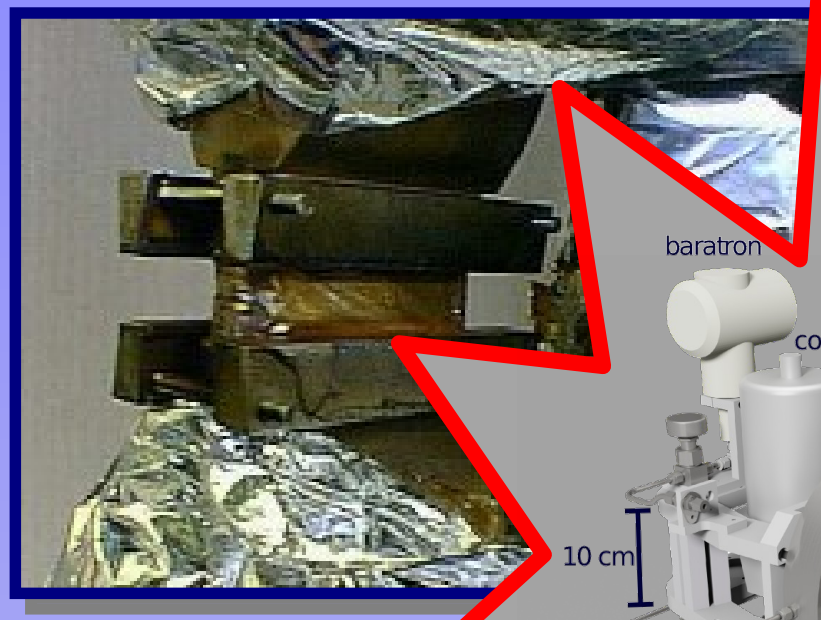
Common challenges elastic ep + ISR

Desirable:

thin, point-like target
without walls

- Background from target foils
  - empty cell measurements
    - not the same Eloss, multi scatt
    - not for all settings ep experiment
      - background model
- background from (thin) ice layer
- spectra distorted by (thin) ice layer
- rescattering on thick frame
- (avoidable) target length issues

Common challenges elastic ep + ISR



- Background from target foils
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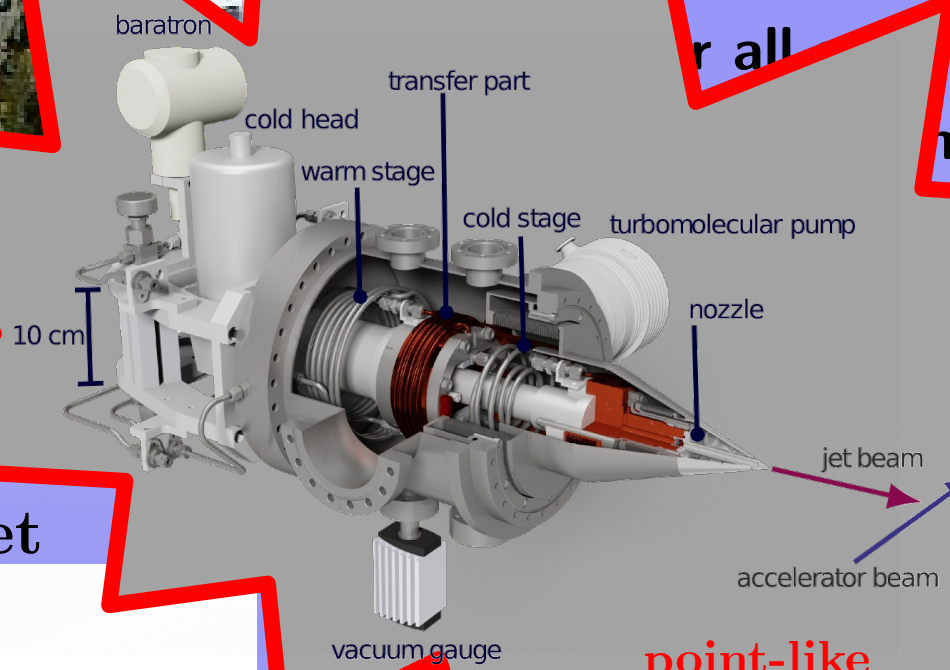
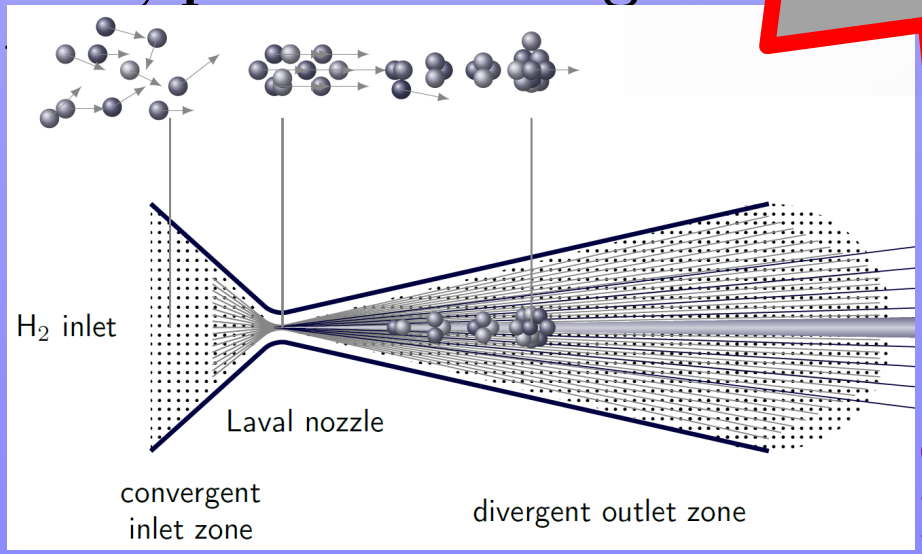
- r all gs ep experiment
- model
- ayer
- n) ice layer
- frame
- es



point-like
no walls

Desirable:

thin, point-like target



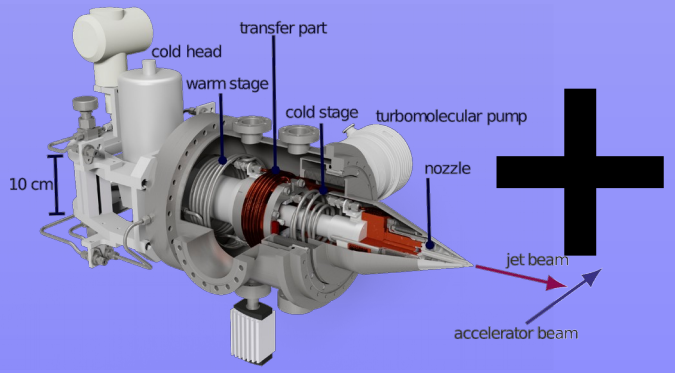
Gas Jet Target
of the future
MAGIX experiment

Common challenges elastic ep + ISR

- Background from target foils
  - empty cell measurements
    - not the same Eloss, multi scatt
    - not for all settings ep experiment
      - background model
- background from (thin) ice layer
- spectra distorted by (thin) ice layer
- rescattering on thick frame
- (avoidable) target length issues

Desirable:

thin, point-like target without walls



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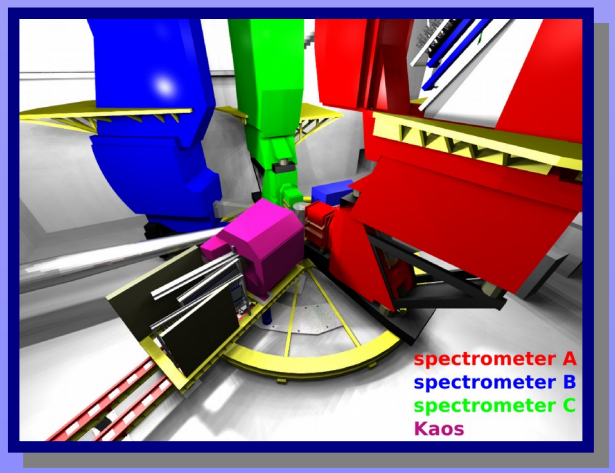

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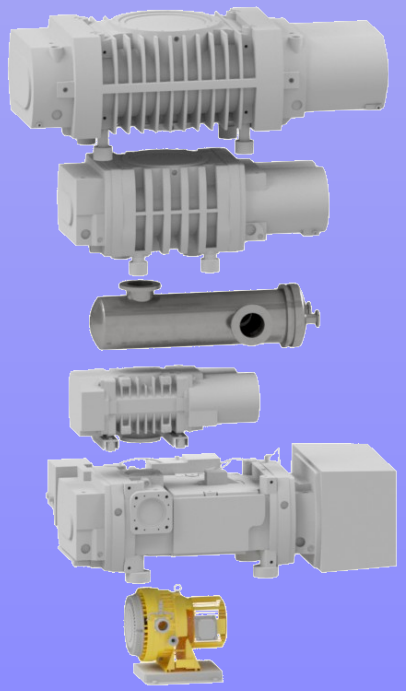
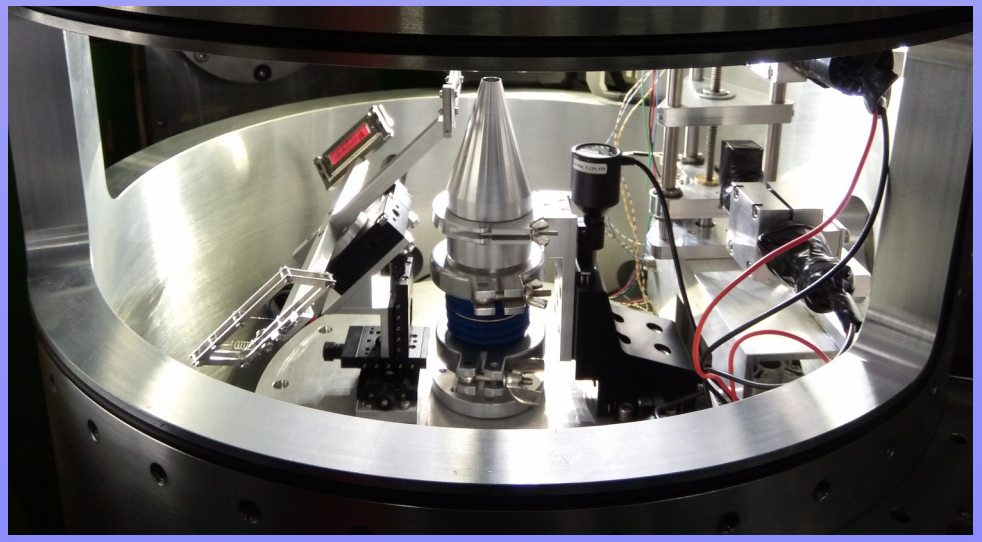
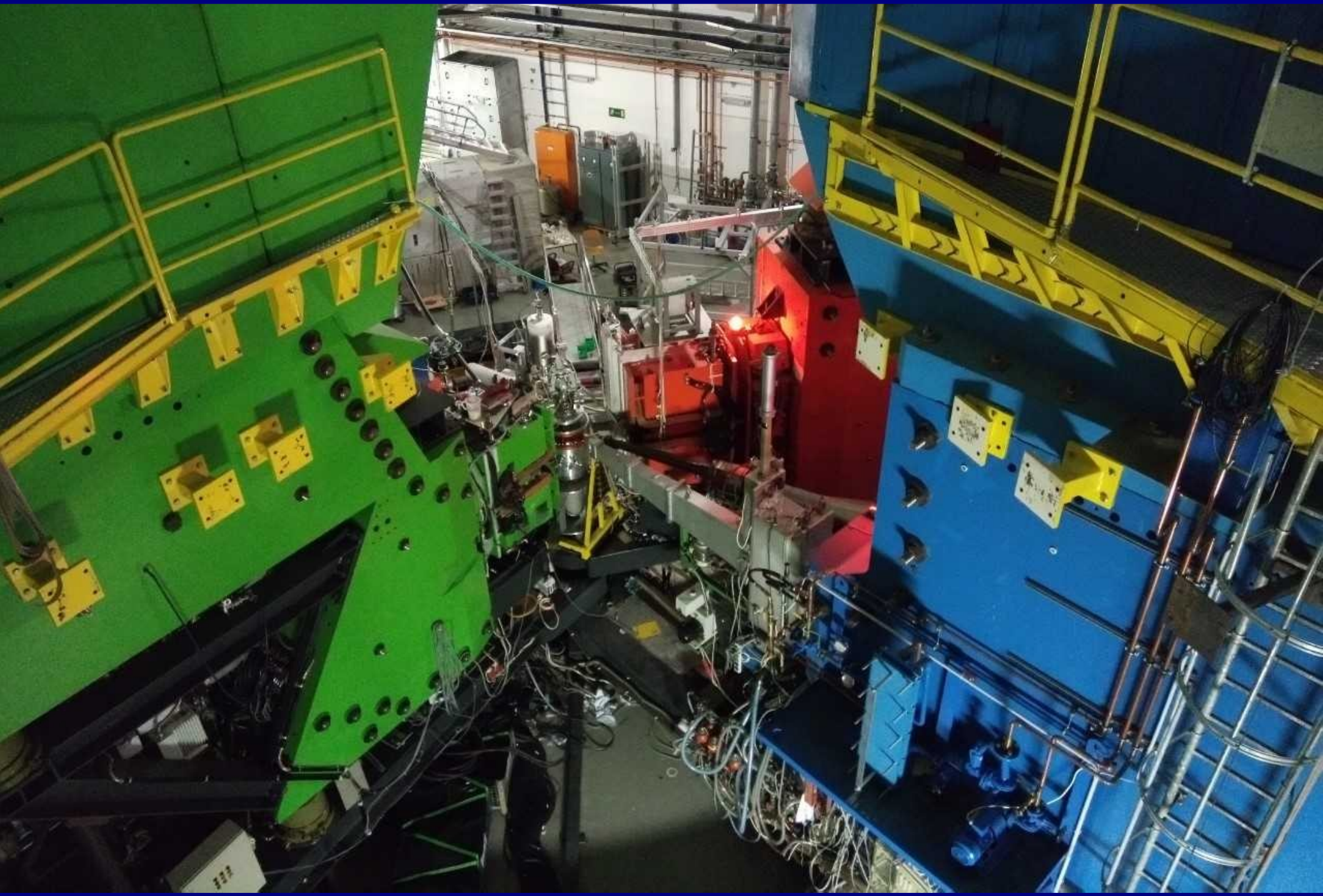
Shopping

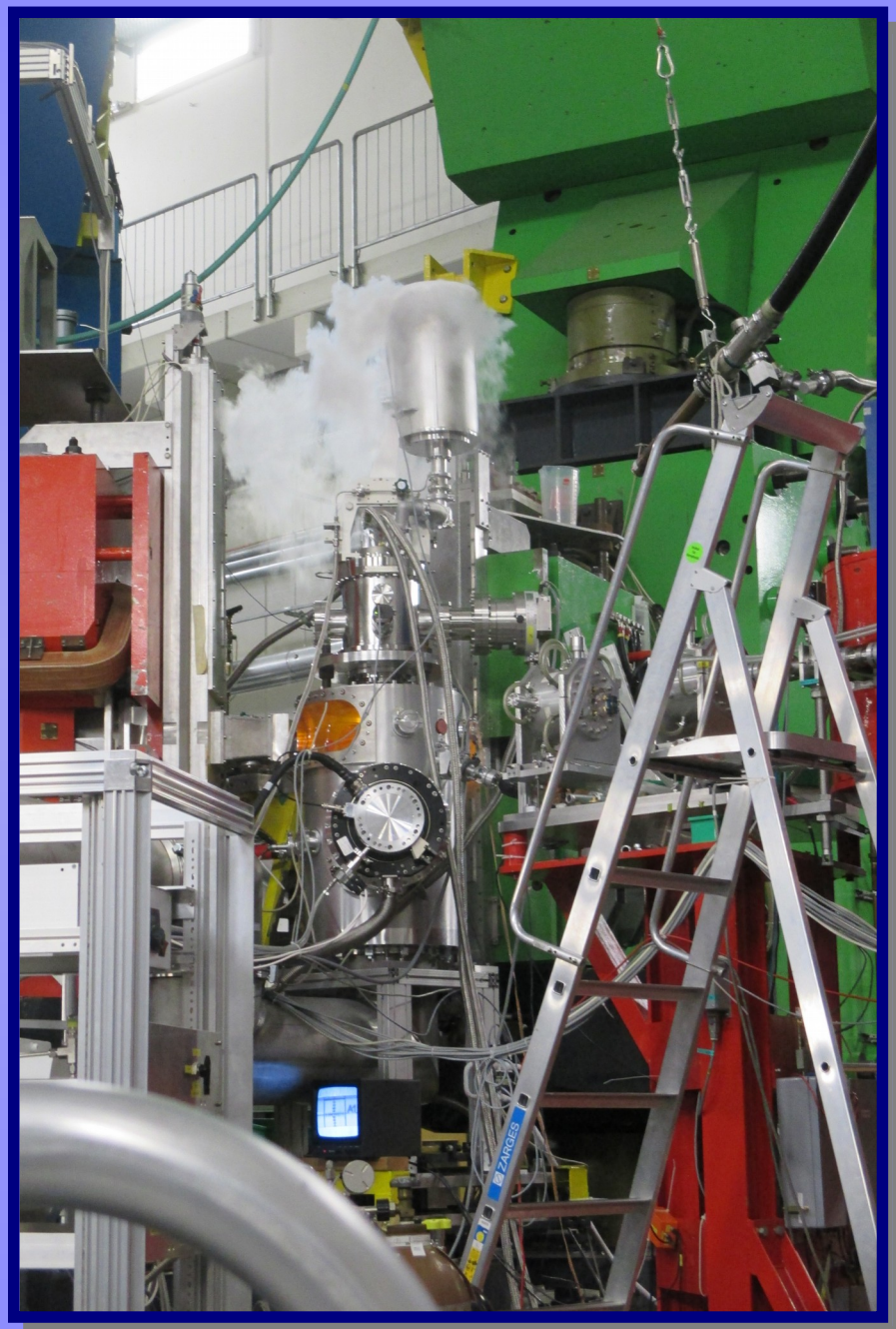


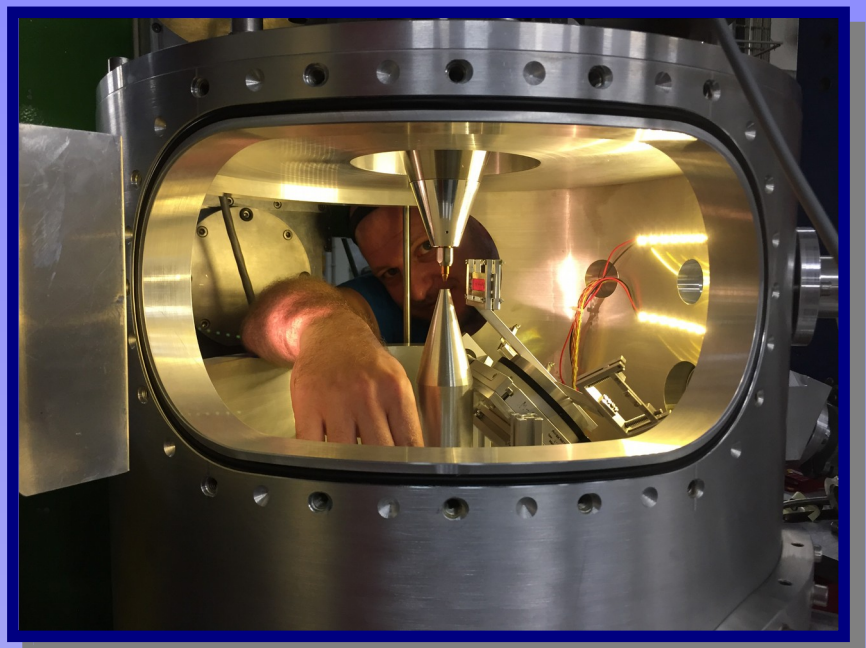


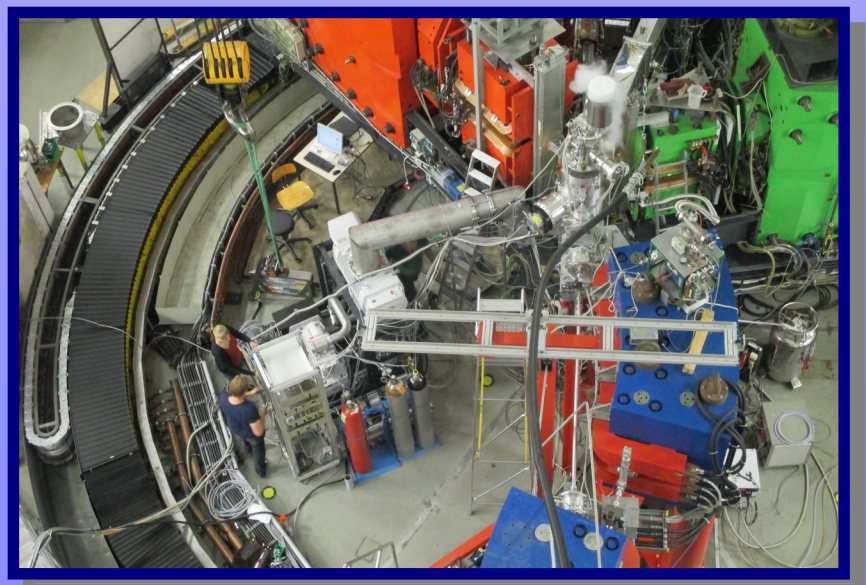
jet target installation at A1



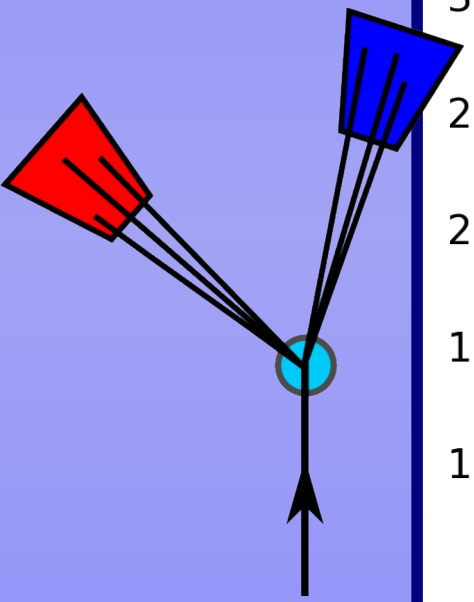
First tests 2017/2018

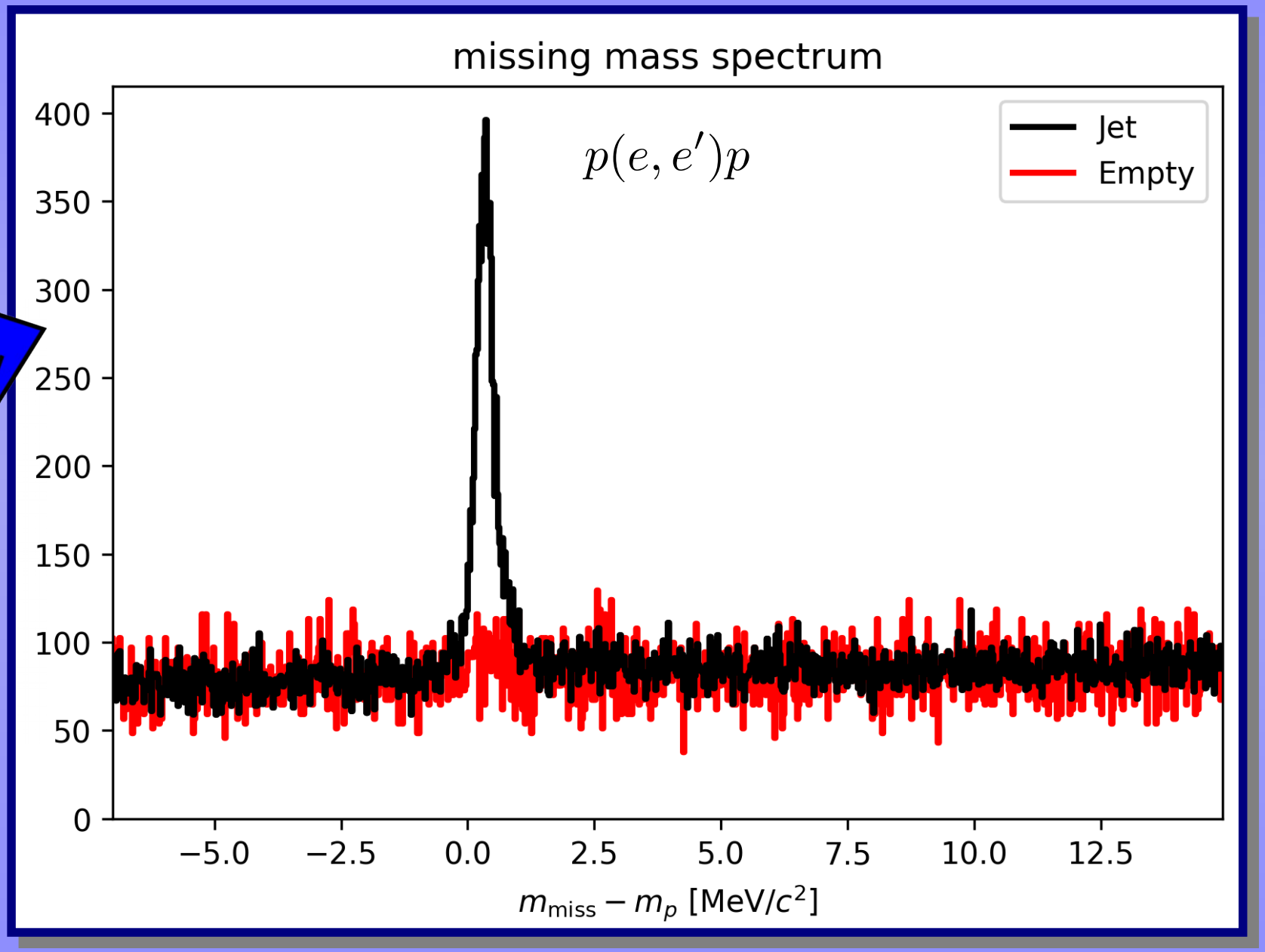




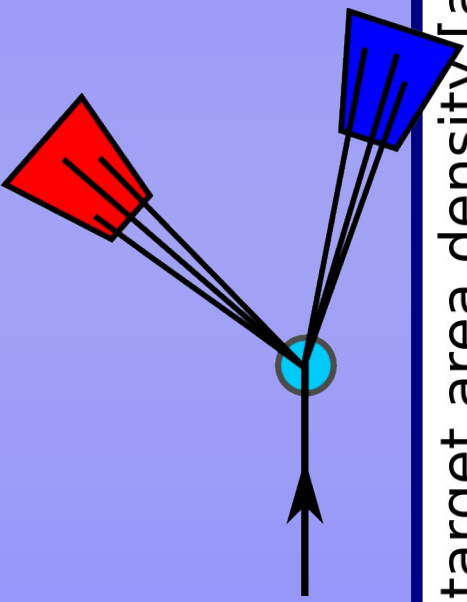


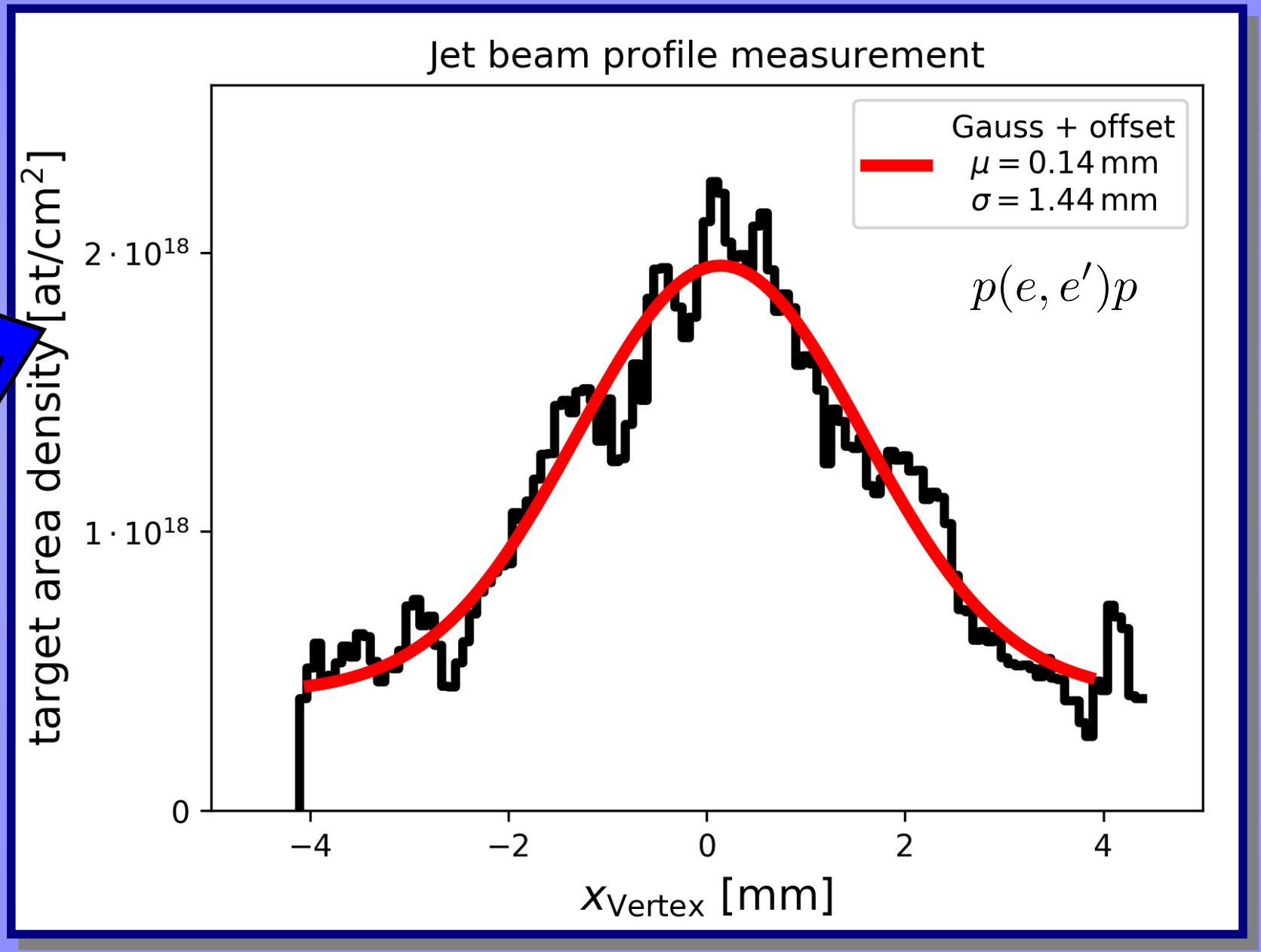
1st commissioning beam time, Sept. 2017





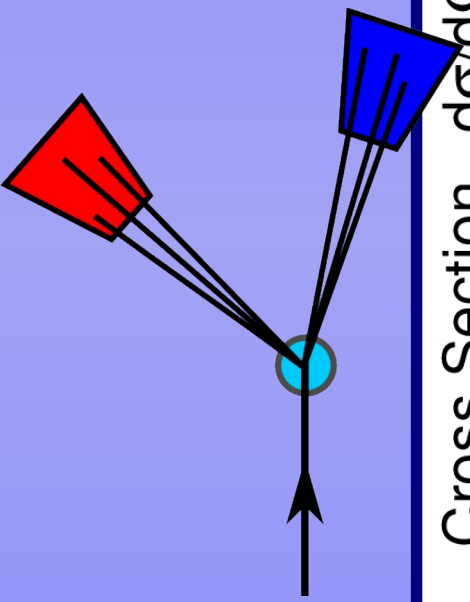
1st commissioning beam time, Sept. 2017

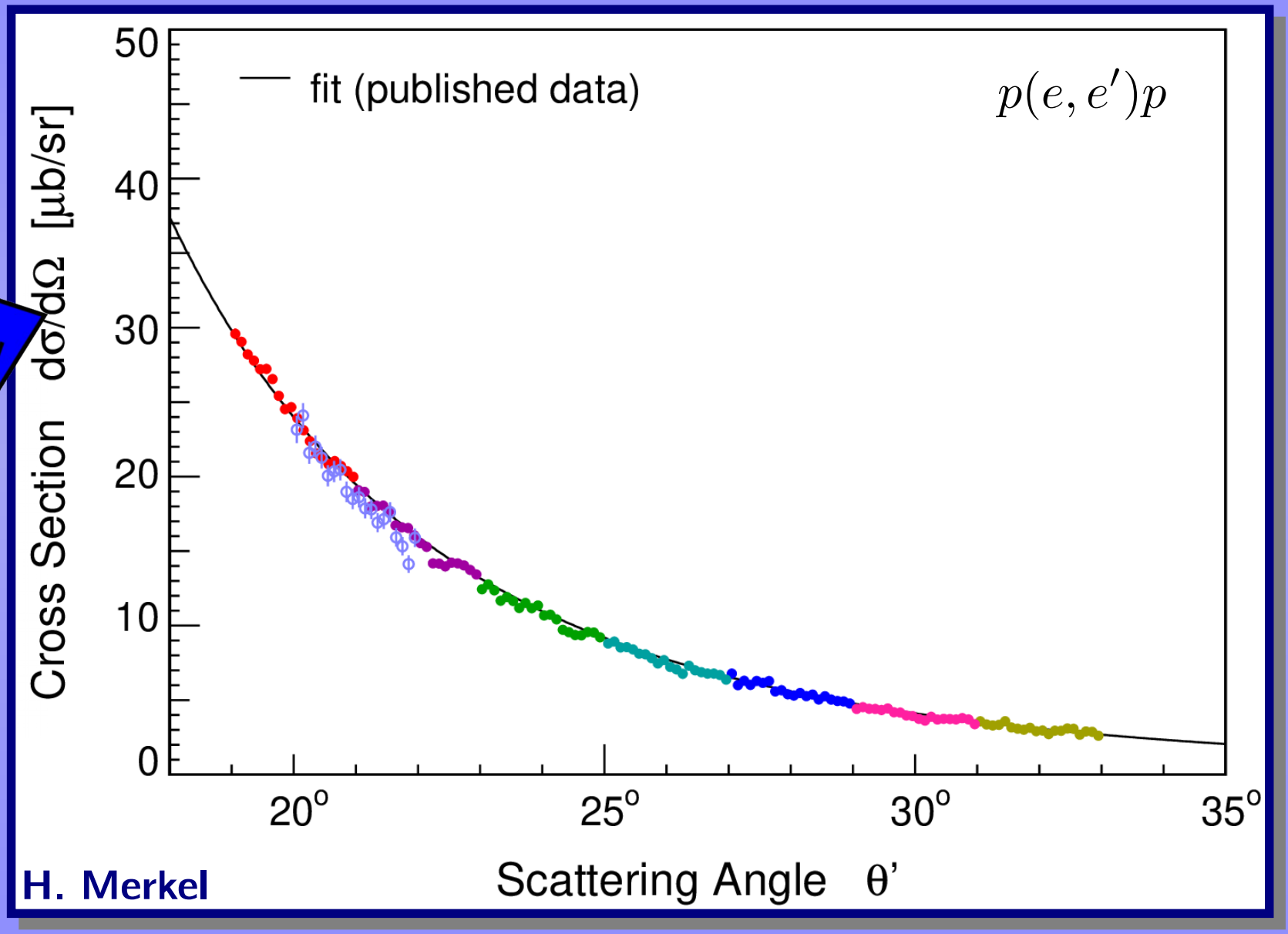




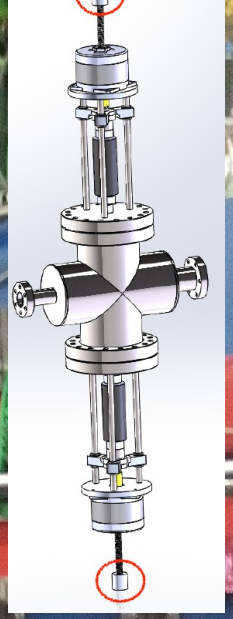
$> 10^{18}\mathrm{atoms/cm}^2$

beam time, April 2018

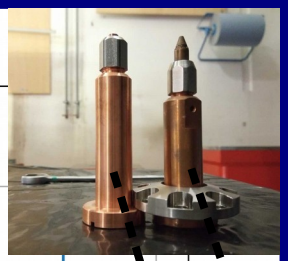




since then:
improve, repair,
replace, improve,
...



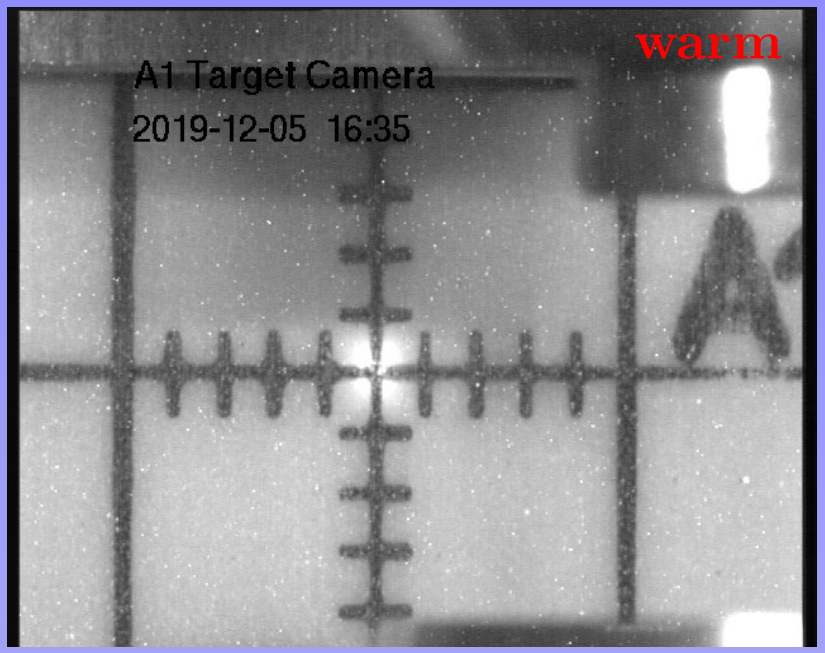
Philipp Brand

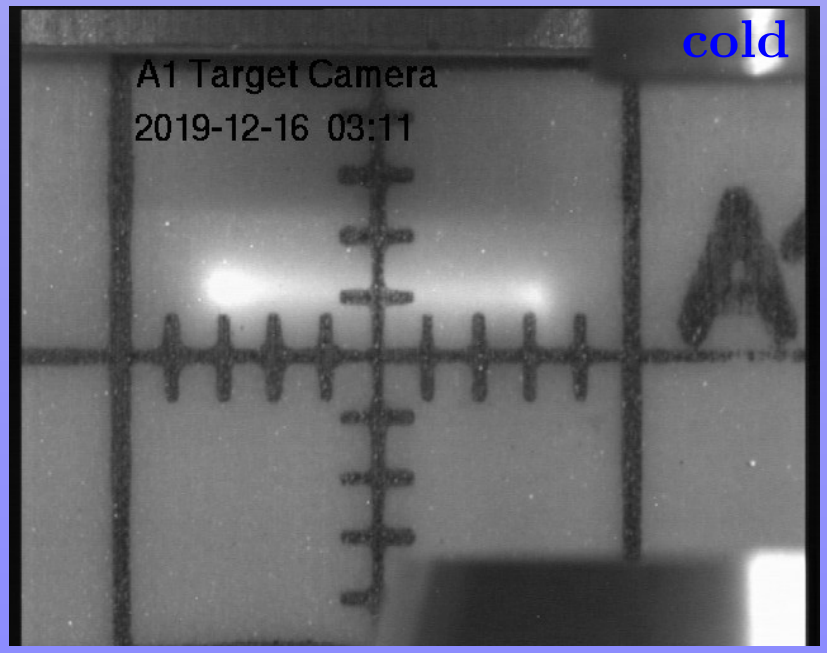


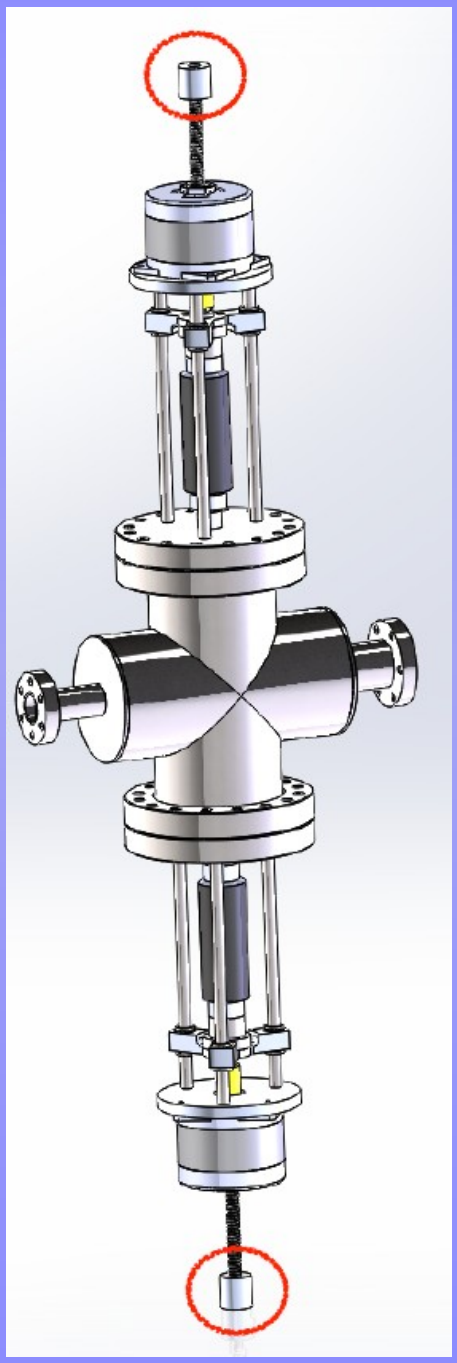
2018

2019

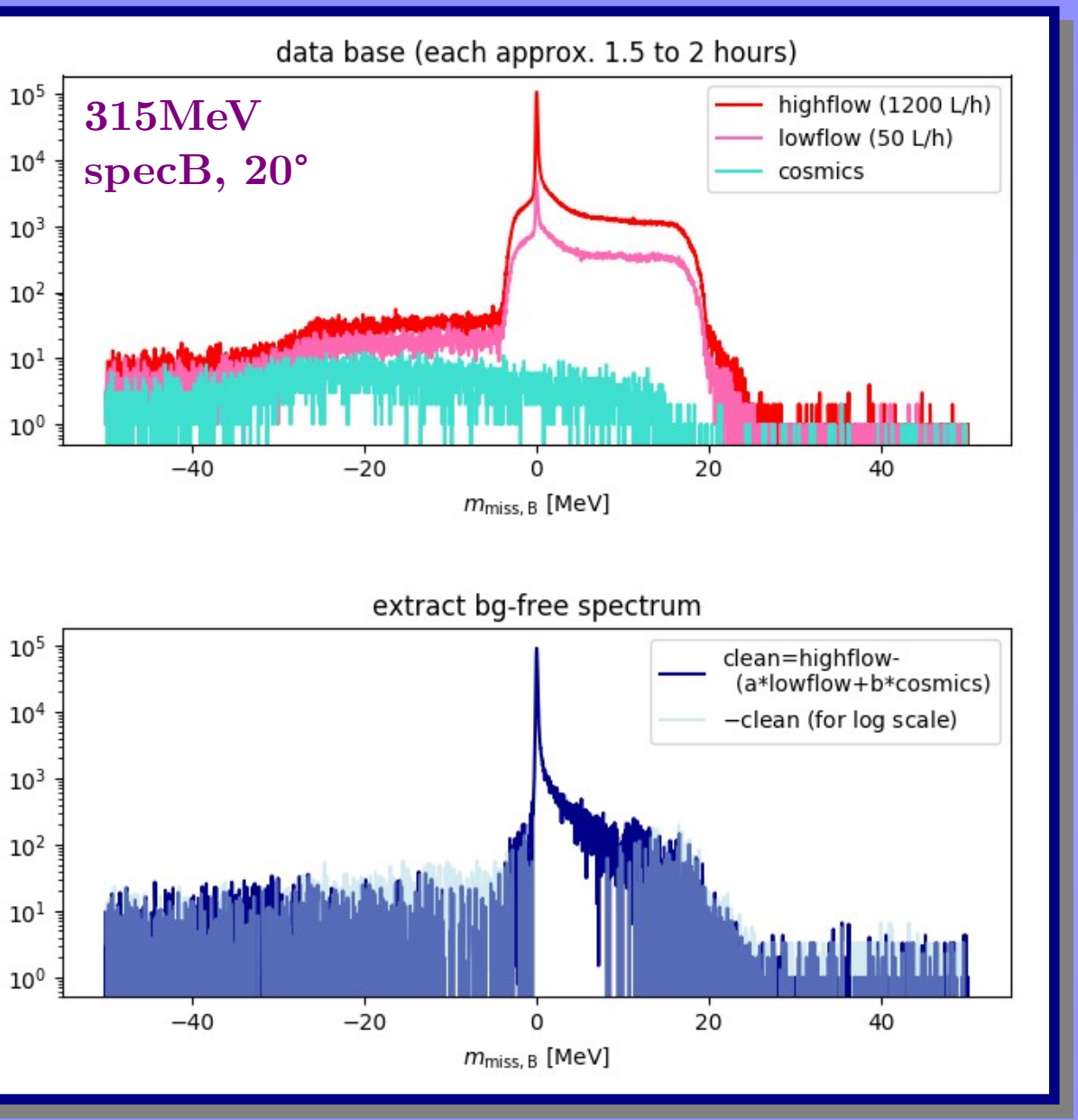
Collimator


warm
A1 Target Camera
2019-12-05 16:35


cold
A1 Target Camera
2019-12-16 03:11



Actual data quality



still some background from catcher/nozzle at percent level

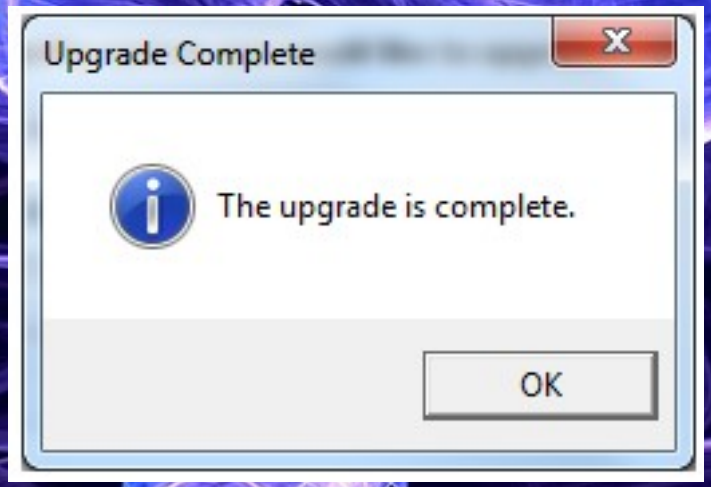
data with high gas flow: production data

data with low gas flow: background studies /subtraction

cosmics background: eventually significant for large angle settings

further reduce BG by veto detector inside scattering chamber, ...

Some upgrades (some complete)

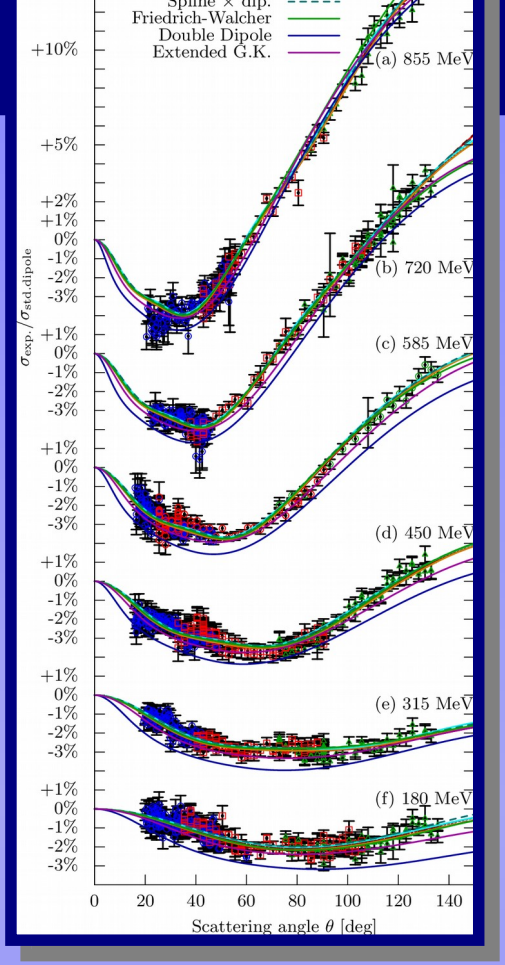


→ TIME TO HARVEST

Actual Experiment

Remeasure 2010-data with jet target

- **limited count rate! set priorities**
  - **specB: data**
  - **specA (30°): lumi monitor**
  - **not-so-dense as before**



Bernauer et al. (2010)

Actual Experiment

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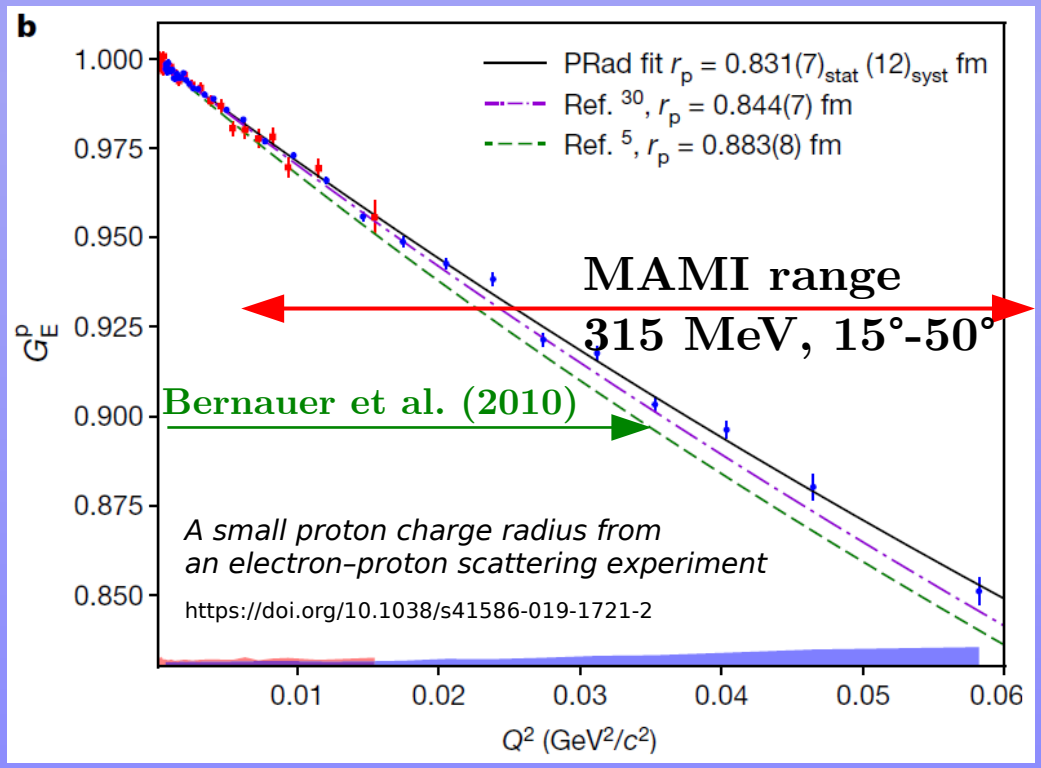

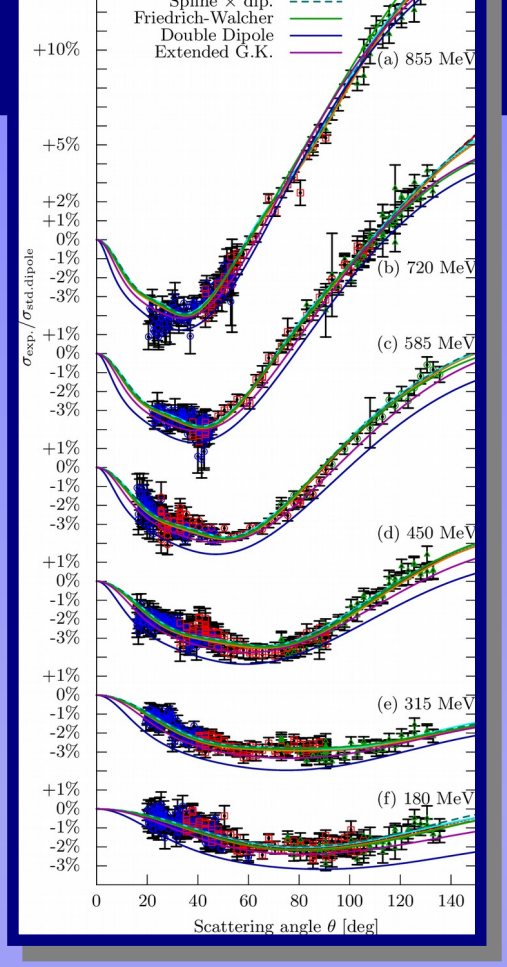

Bernauer et al. (2010)

PRAD result →

- start with 315 MeV
- continue with 195 MeV (not 180 MeV)
- ...

Actual Experiment

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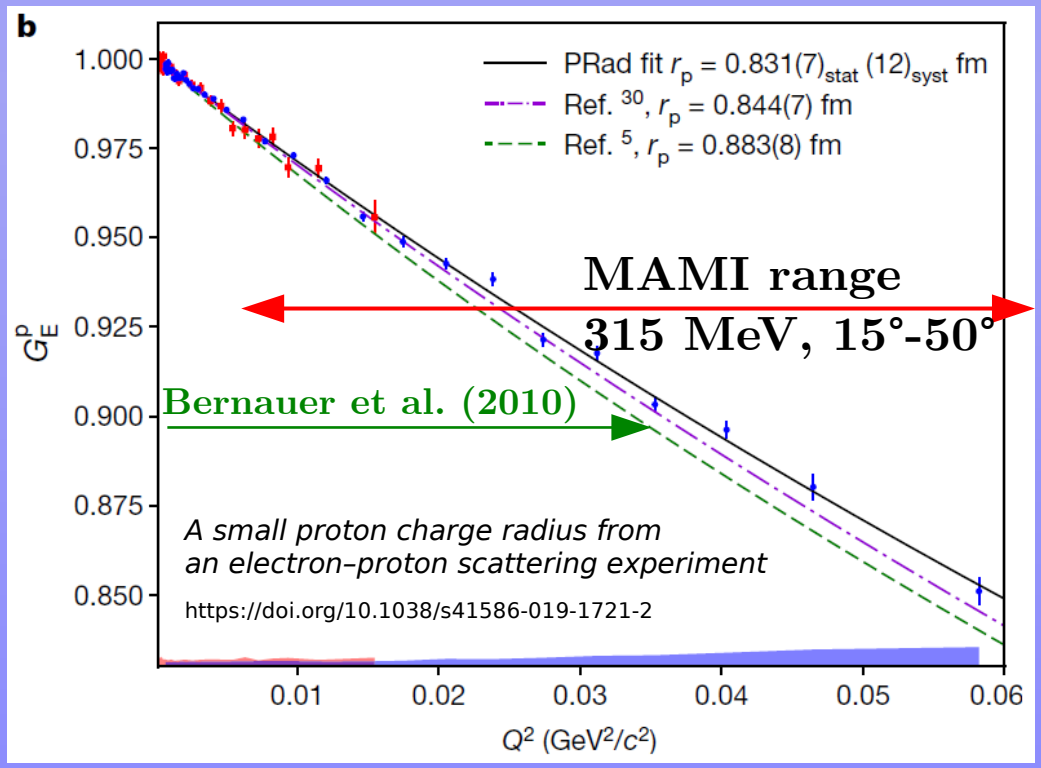
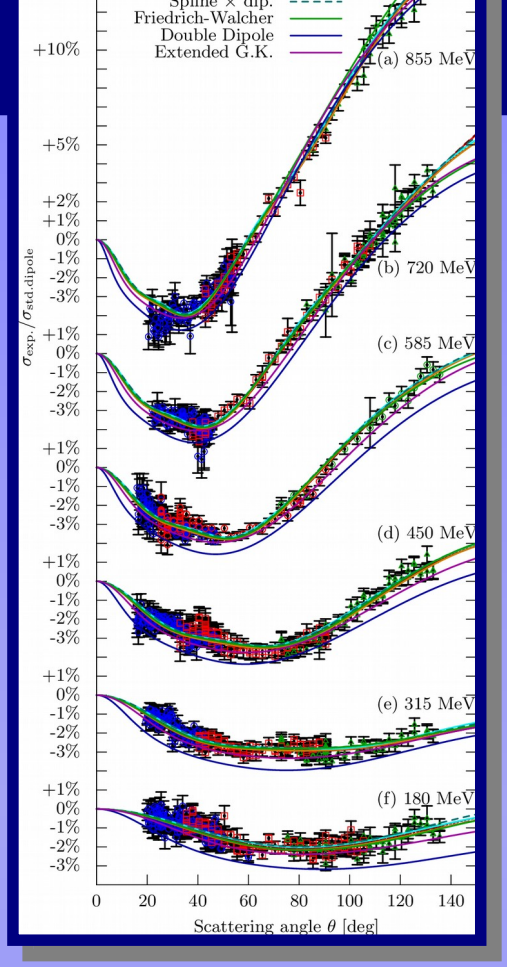




Bernauer et al. (2010)

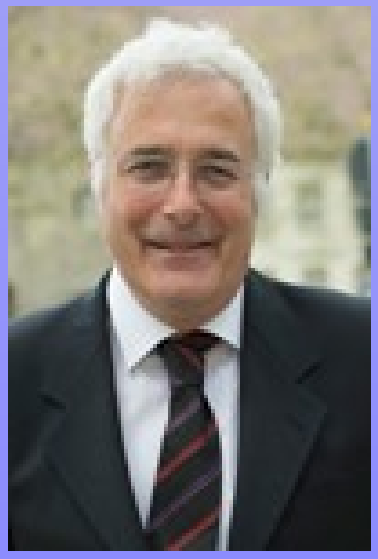
PRAD result →

- start with 315 MeV
- continue with 195 MeV (not 180 MeV)
- ...

data quality might improve,
but still not lower in Q^2....

Mainz - Electron Accelerators

man on a mission,
with visions and dreams!



Mainz - Electron Accelerators

use this (structure-less electron)

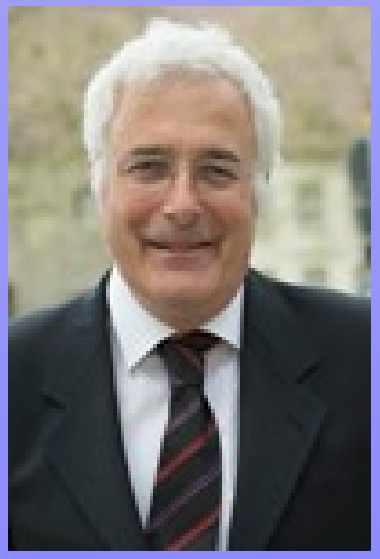
to study this (atomic nucleus)

or this (proton)

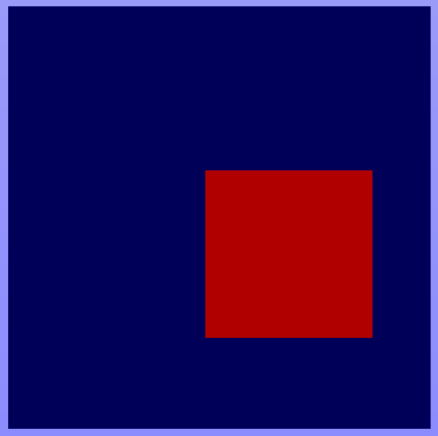
or this (neutron)

and much more!

man on a mission,
with visions and dreams!



electron accelerator
(MAMI)



scattering
experiments
(A1)

Mainz - Electron Accelerators

use this (structure-less electron)

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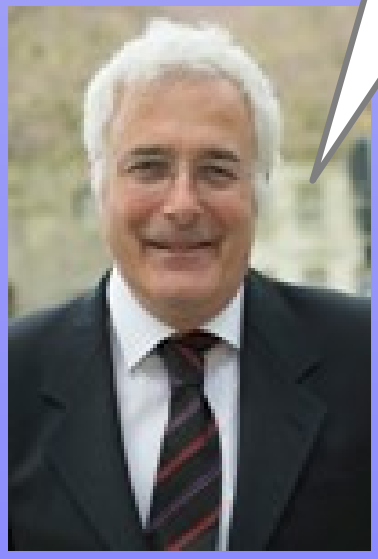
and much more!

hi-hi-hi !



electron accelerator (MAMI)

scattering experiments (A1)

electron accelerator (MESA)

scattering experiments (MAGIX)

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use this (structure-less electron)

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and much more!

world's largest microtron

MAMI

$e, \vec{e}$ 160-1600 MeV 0-100 μA

A1

magnetic spectrometer

MESA

$e, \vec{e}$ ~20-105 MeV

MAGIX

nobody likes the green one

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MESA

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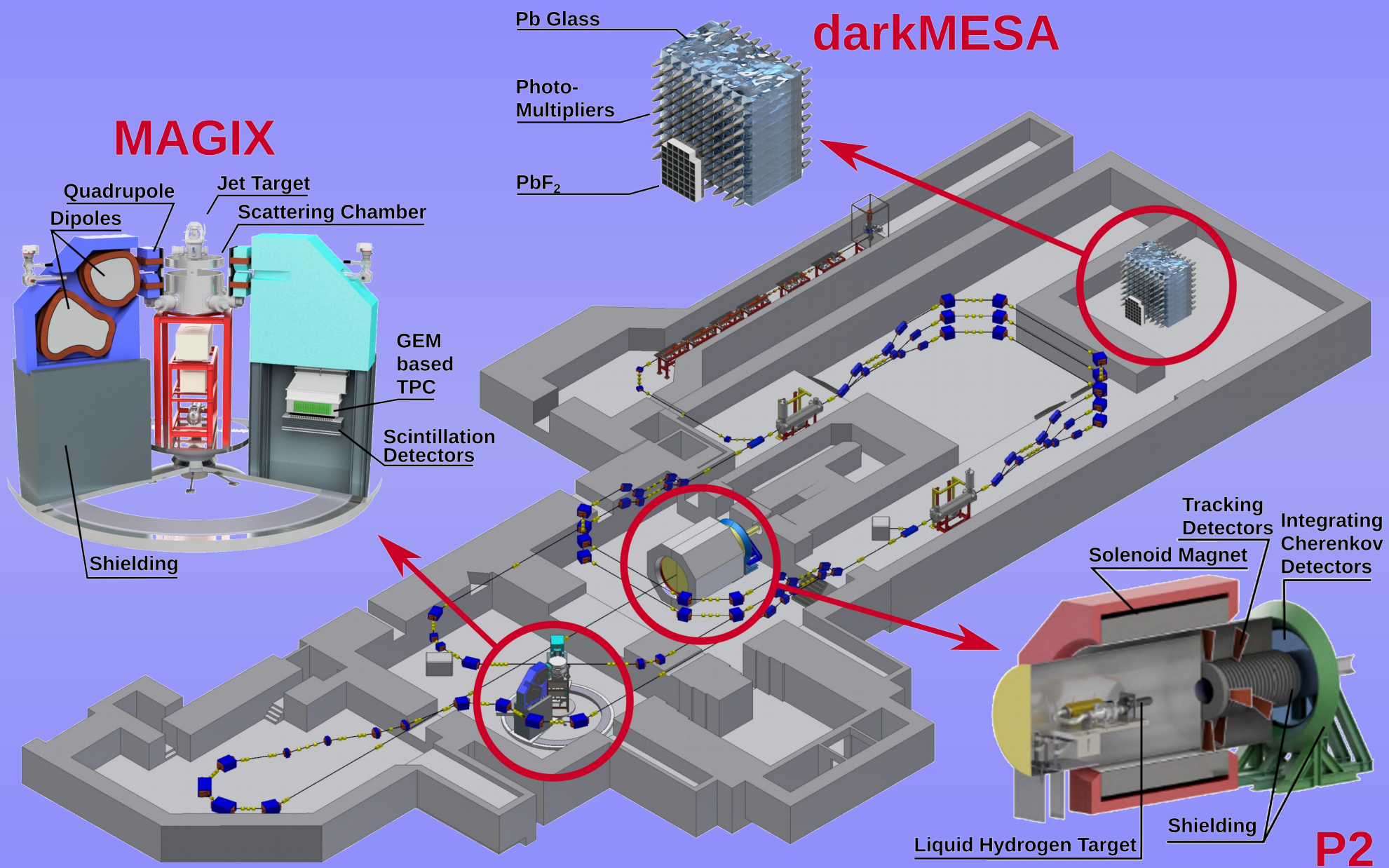
MAGIX

nobody likes the green one

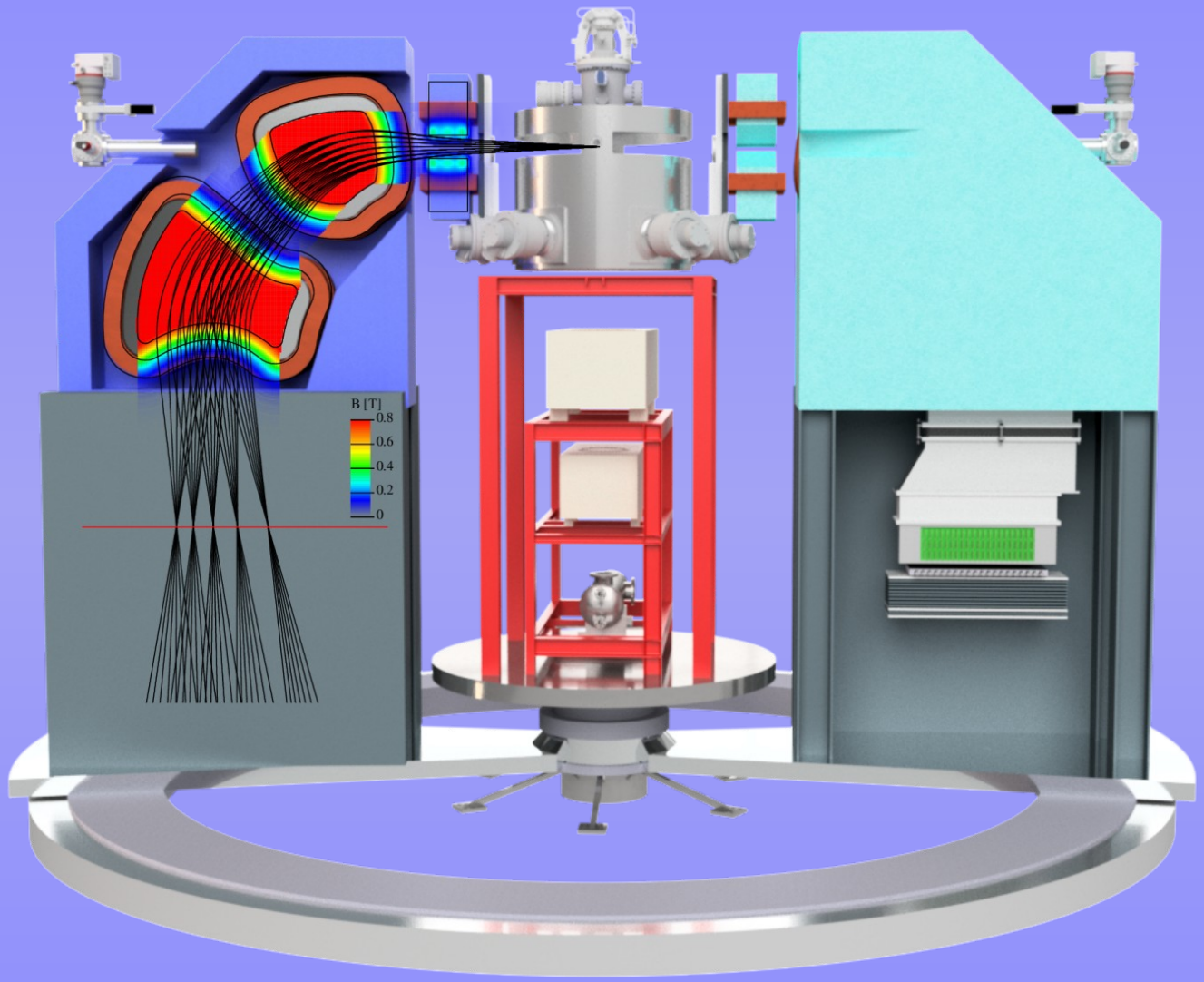
MESA + experiments



MAGIX - multi-purpose experiment

high-resolution magnetic spectrometers

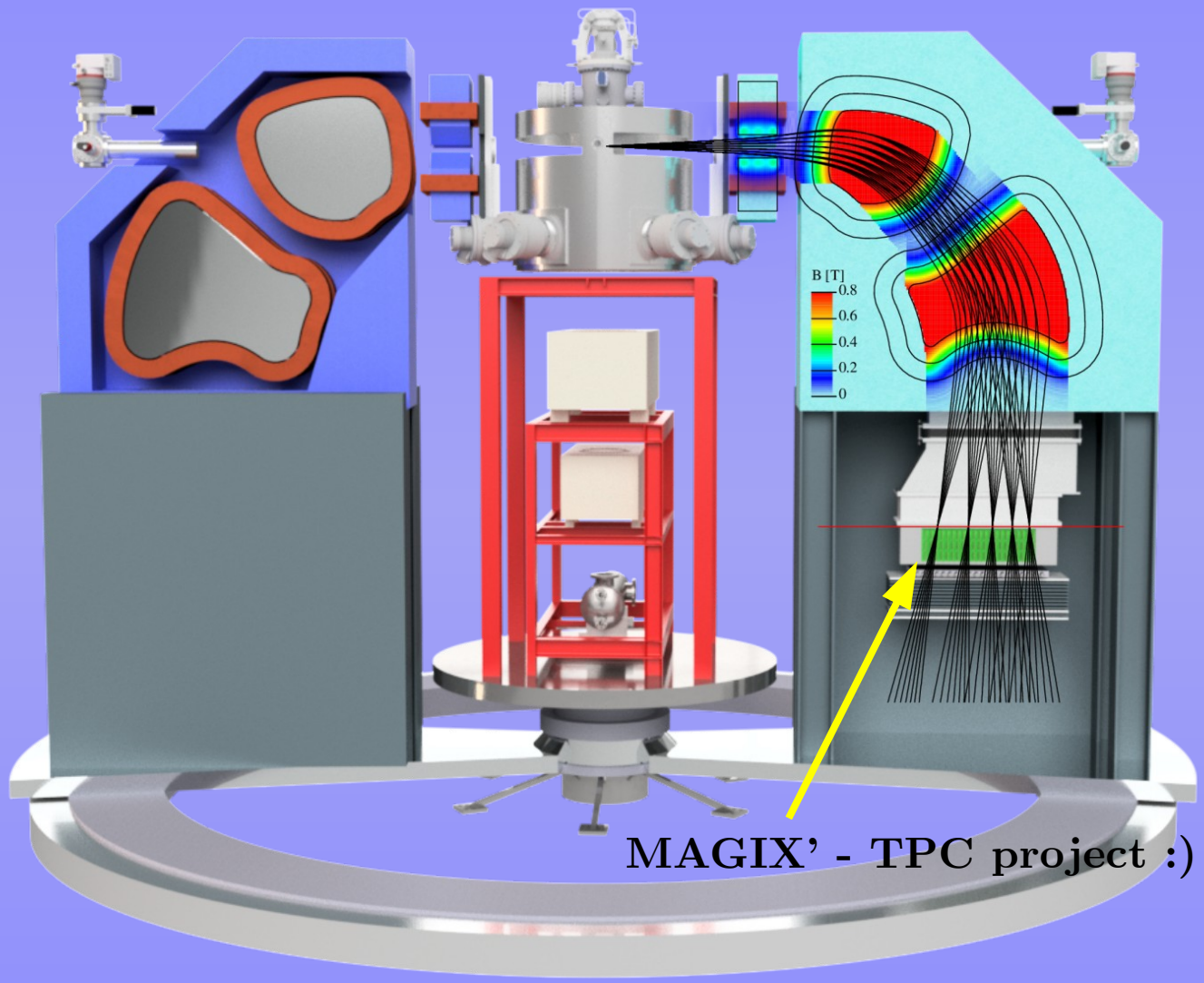
- rotatable, 15°-160°
- QDD



MAGIX - multi-purpose experiment

high-resolution magnetic spectrometers

- rotatable, 15°-160°
- QDD
- detectors in focal plane
- design resolution
  - momentum: 10^{-4}
  - angular: few mrad
  - vertex: few mm



MAGIX - multi-purpose experiment

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- detectors in focal plane
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  - momentum: 10^{-4}
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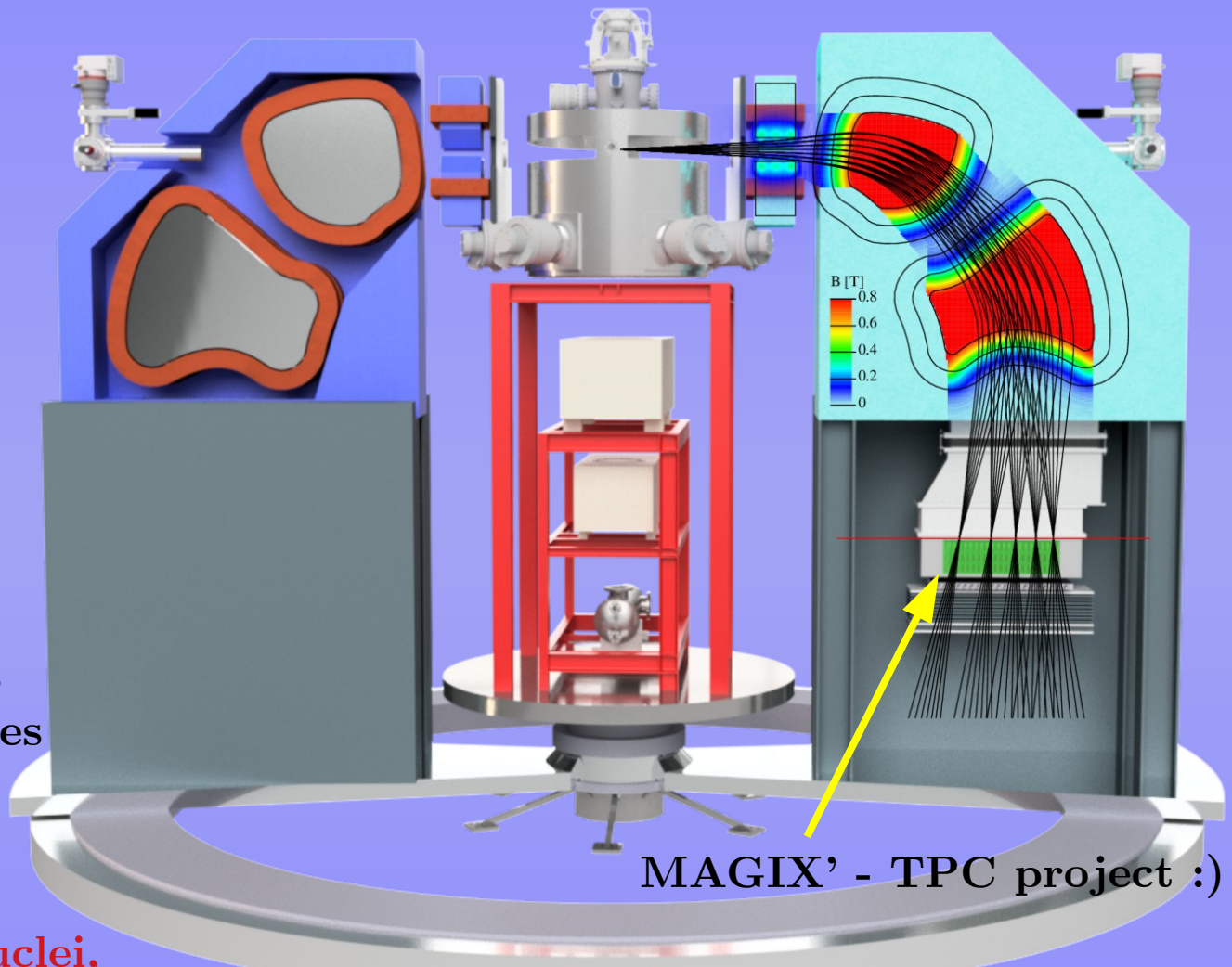
  - vertex: few mm

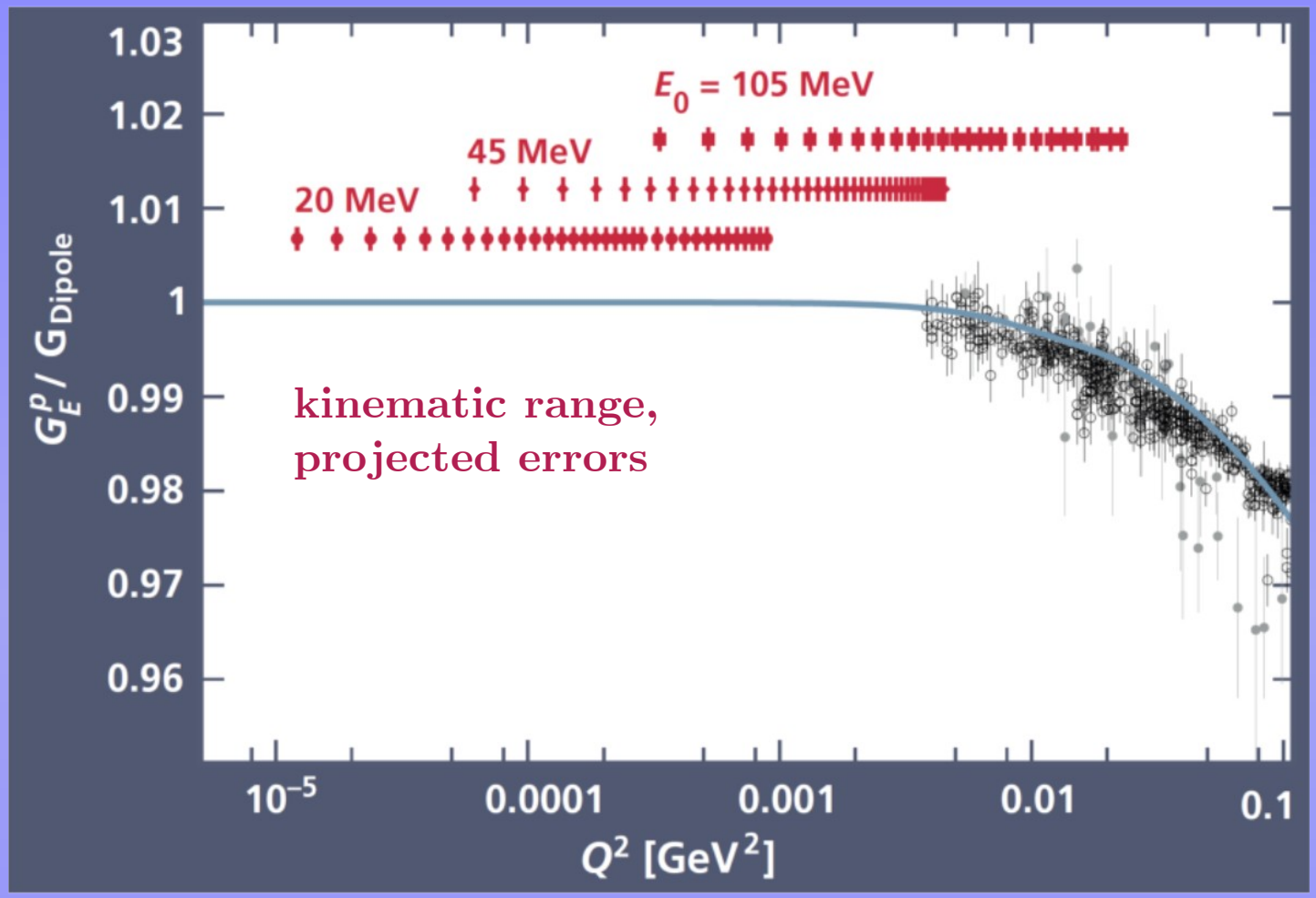
physics program

- dark photon search
- q.e. and inelastic processes at very low mom. transfers
- test of effective field theories in light nuclei
- nuclear reactions of astro-physical relevance
- e.m. structure of atomic nuclei, including proton charge radius measurement



	A1 @ MAMI	MAGIX @ MESA
E_{beam}	$160 - 1600$ MeV	$20 - 105$ MeV
I_{max}	$50 - 100\,\mu$A	1 mA
ρ_{target}	$\sim$ any	$\sim$ tiny

MAGIX: Proton e.m. form factor measurements



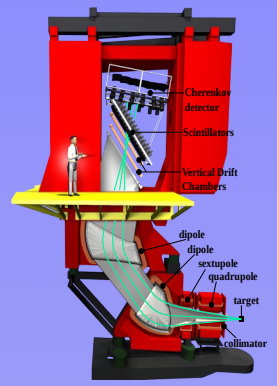
- 20 - 105 MeV beam energy
- jet target × 2 spectrometers
- up to 1000 µA beam current
  - uncertainties wil not be statistically limited
- down to 10^{-5} GeV²
  → proton radius!

Summary ongoing/planned experiments

Extension of the pFF measurements to high Q^2

- data acquired, analysis ongoing
- main data set with specA
- MAMI-C energies

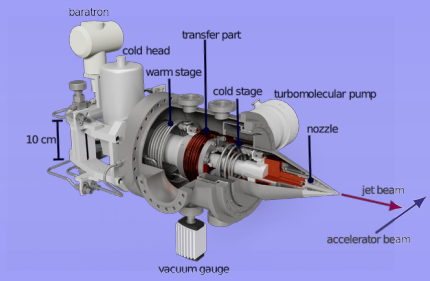
→ improve knowledge of higher moments of e./m. distribution of the proton ↔ fit models



Remeasurement of low Q^2 data with jet target

- data with specB
- luminosity monitoring with specA
- selected kinematics
  - 315 MeV, 195 MeV, ...
  - 15° - ≈50°

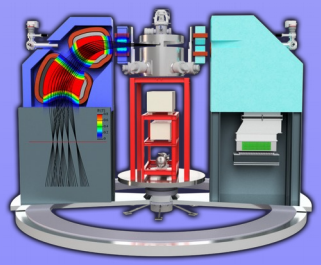
→ minimize systematic errors



Measurement of pFF data at MAGIX

- jet target × 2 spectrometers
- 20 MeV - 105 MeV
- 15° - 160° (?)

→ high-precision data at very low Q^2



Thank you very much for your attention!