Determination of the proton charge radius during the ULQ^2 experiment

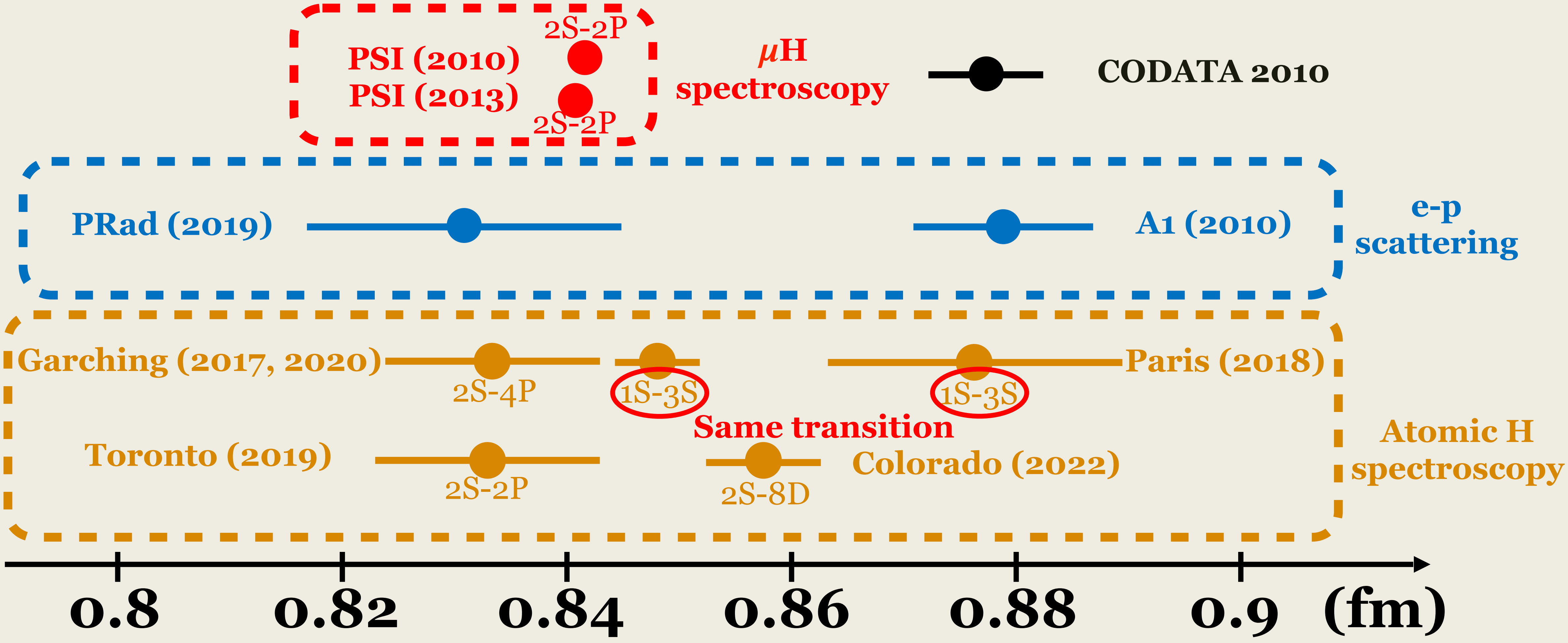
Clement Legris, on behalf of the ULQ^2 collaboration

RARiS Tohoku University

Contents

I. Proton charge radius puzzle

Proton charge radius puzzle



II. Determination of the proton charge radius with electron scattering

Electric form factor and proton charge radius

Momentum transfer:

$$Q^2 = |\vec{q}|^2 - \omega^2$$

$$Q^2 \sim 4EE' \sin\theta/2^2$$

Ultra-relativistic approximation

$$\tau = \frac{Q^2}{4M_p^2}, \epsilon^{-1} = 1 + 2(1+\tau)\tan^2\frac{\theta}{2}$$

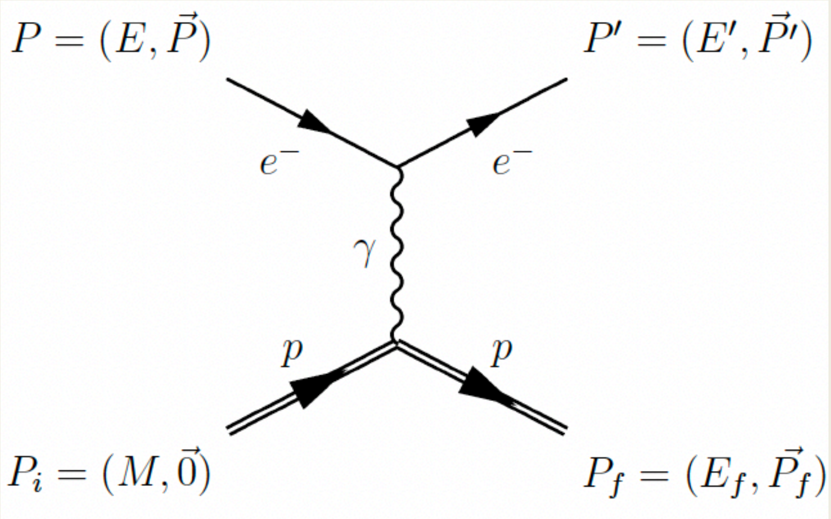
Cross section:

$$\left(\frac{d\sigma}{d\Omega}\right) \approx \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{E'}{E} \frac{G_E^2(Q^2) + \frac{\tau}{\epsilon} G_M^2(Q^2)}{1+\tau}$$

$$G_E(Q^2) = 1 - \frac{Q^2}{3!}\langle r_E^2 \rangle + \frac{Q^4}{5!}\langle r_E^4 \rangle + \ldots$$

$$R_E = \sqrt{\langle r_E^2 \rangle} \equiv \sqrt{-6 \lim_{Q^2 \to 0} \frac{dG_E}{dQ^2}}$$

G. Miller, Phys. Rev. C **99** (2019), 035202



Feynman diagram of the leading-order of the electron-proton scattering.

Q^2 as small as possible!

Specifications of the ULQ^2 experiment

Ultra Low Q^2

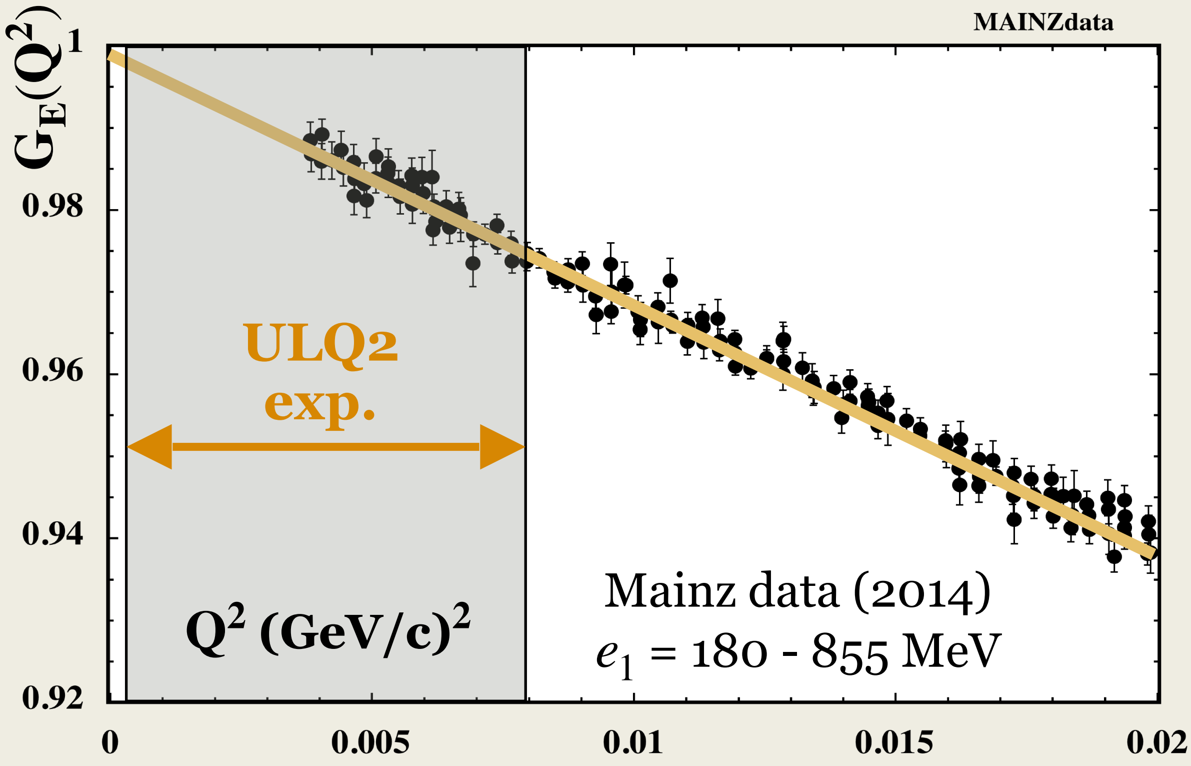
<u>Characteristics of the experiment:</u>

- Measurement of $G_E(Q^2)$ for extremely small values of Q^2:

  0.0003 (GeV/c)² $\leq Q^2 \leq$ 0.008 (GeV/c)²
- **Lowest beam energy for electron scattering in the world**:

  10 MeV $\leq E \leq$ 60 MeV
- Polyethylene (CH_2) target.

➡ **Absolute** cross-section measurement with 10^{-3} accuracy.



Momentum transfer range reached during the ULQ^2 experiment.

Absolute cross-section measurement

Simultaneous detection of e-p and e-^{12}C scatterings:

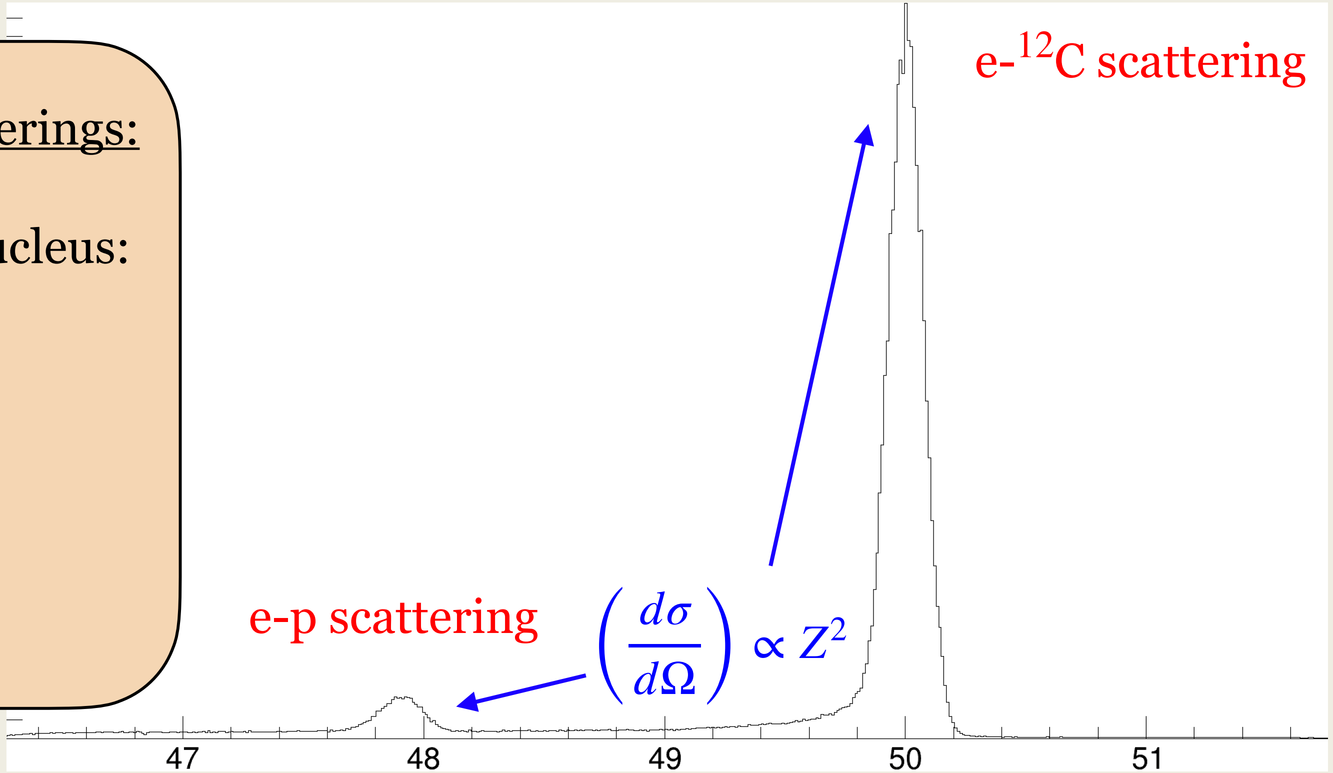
- Use of a CH_2 target.
- Momentum of a scattered electron on a X nucleus:

URL

$$P'_X \sim \frac{E}{1 + \frac{2E \sin \theta/2^2}{M_X}}$$

- E = 50.2 MeV, θ = 84°

➡ $P'_{^{12}C} \sim$ 50.0 MeV/c, $P'_H \sim$ 47.9 MeV/c



Simultaneous detection of e-p and e-^{12}C scattering with a CH_2 target (Experimental data).

Absolute cross-section measurement

Absolute cross-section of e+p scattering:

Event number

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-p} = \frac{N_{e-p}}{N_e N_p \Delta\Omega}$$

Detector solid angle

Beam dose

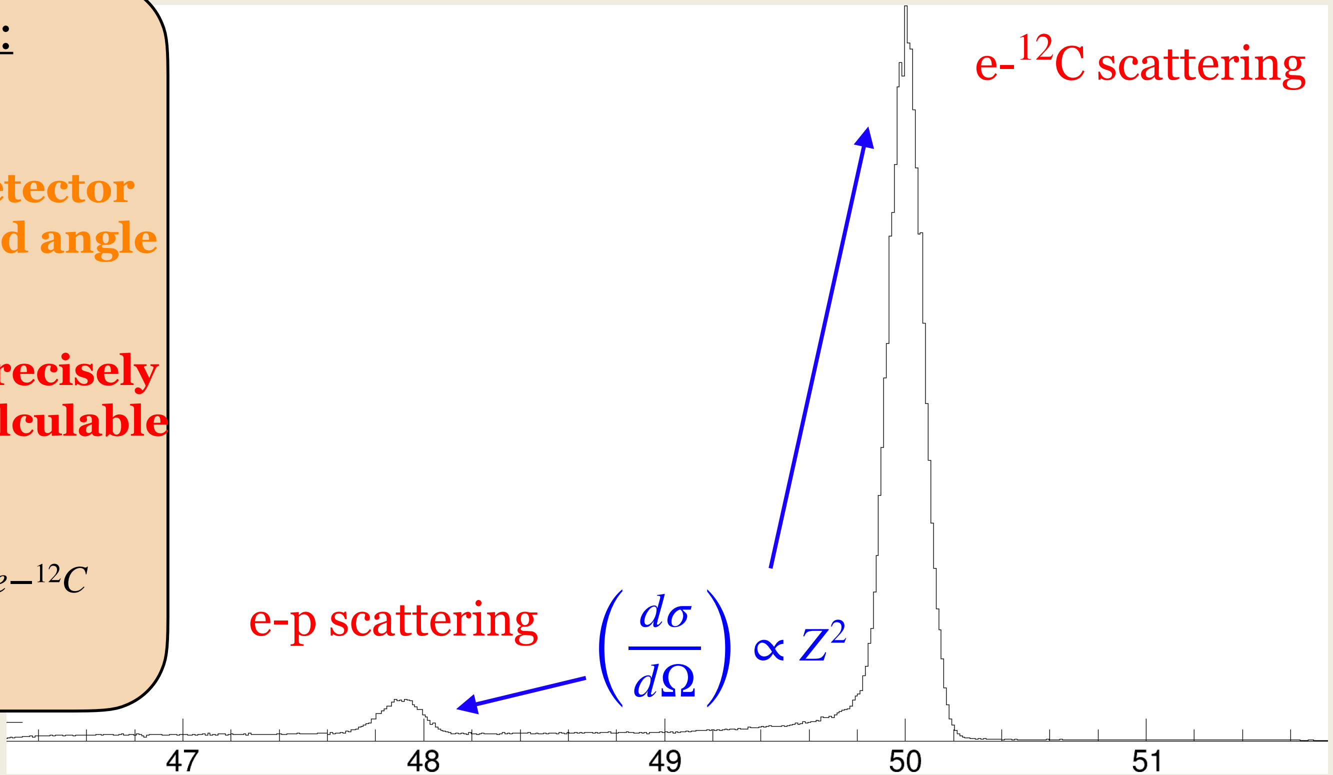
Target number

Precisely calculable

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-p} = \frac{N_{e-p}/N_{e-{}^{12}C}}{N_p/N_{{}^{12}C}}\left(\frac{d\sigma}{d\Omega}\right)_{e-{}^{12}C}$$

Ratio of H and C nuclei

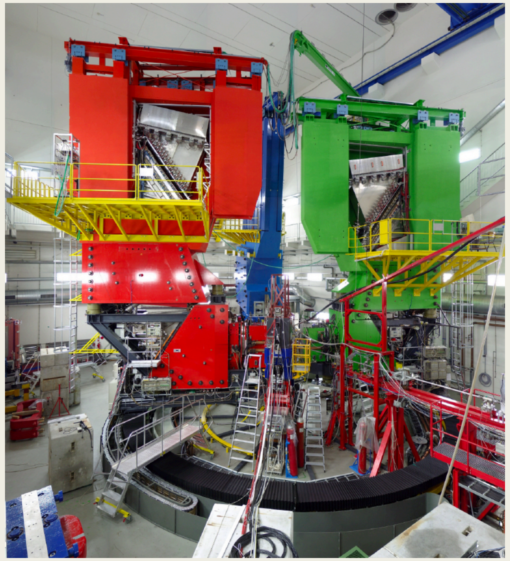
Required for precise measurement!



Simultaneous detection of e-p and e-^{12}C scattering with a CH_2 target (Experimental data).

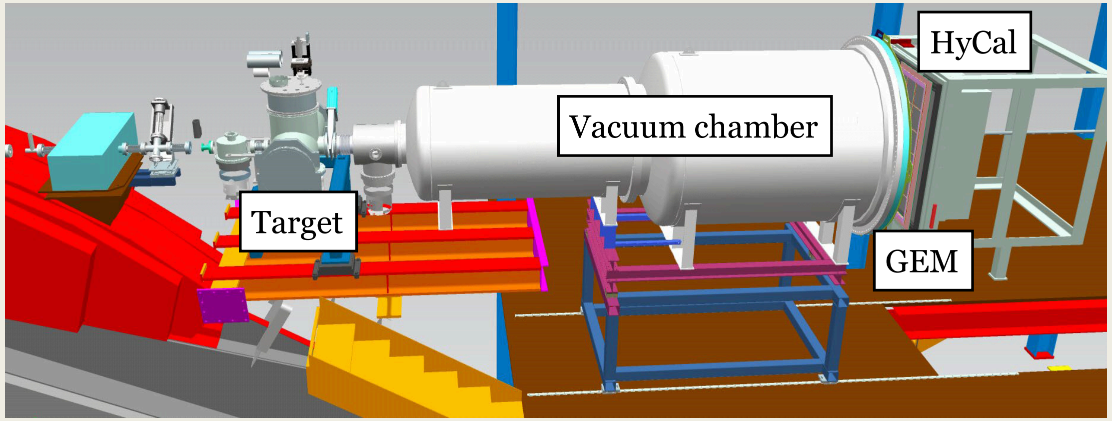
Previous experiments (e-p)

- A1 experiment (2010):
  - Medium energy (180-855 MeV) & many angles (15-130°) → $0.004 \leq Q^2[(\text{GeV/c})^2] \leq 1$
  - Liquid H cell & metal walls → large BG
  - Relative cross-section measurement



J. Bernauer, PhD thesis.

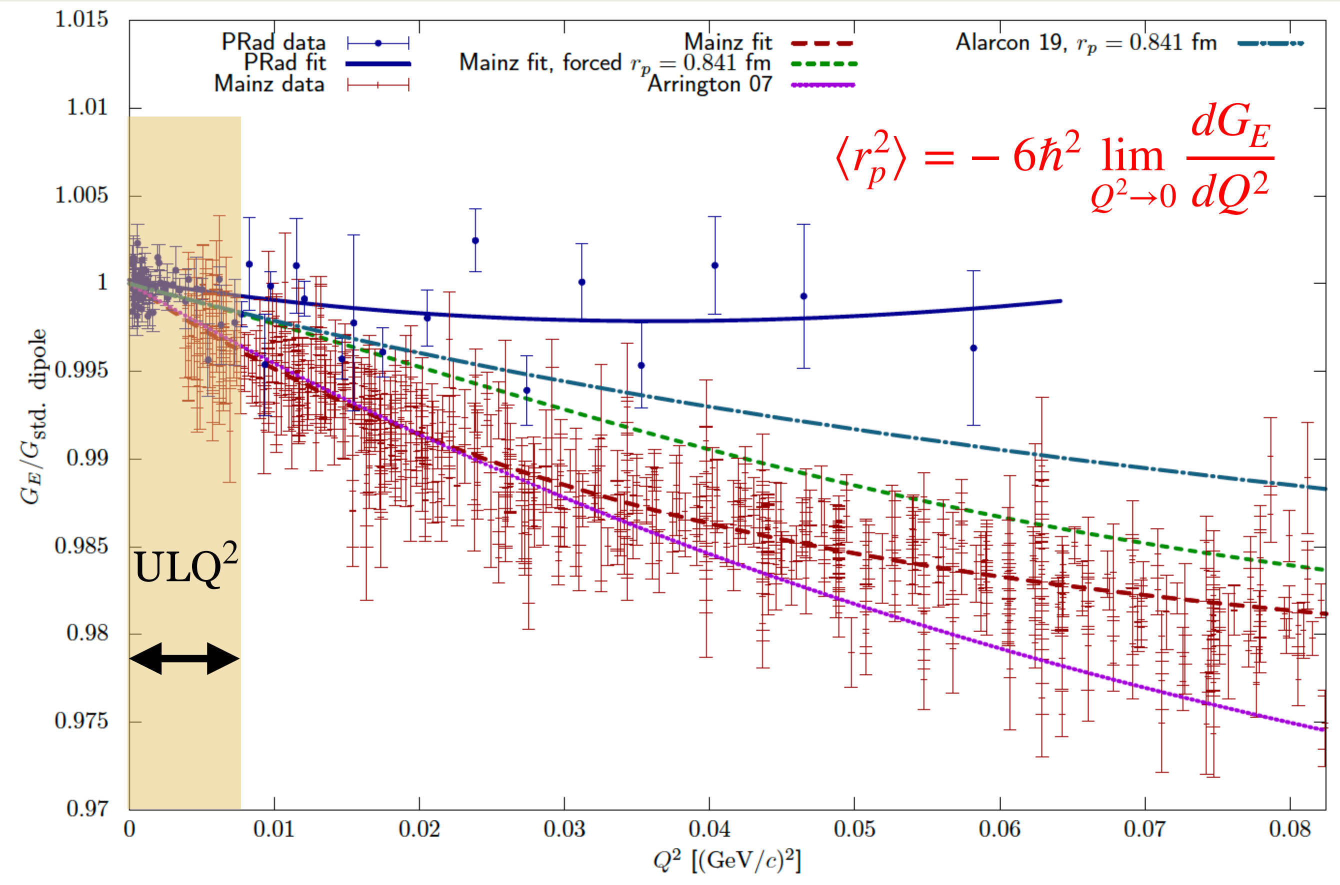
- PRad experiment (2019):
  - High energy (1.1 & 2.2 GeV) & small angles (0.7 - 7.0°) → $0.0002 \leq Q^2[(\text{GeV/c})^2] \leq 0.06$
  - Elastic/inelastic e-H scattering …
  - Absolute normalization to e-e scattering



W. Xiong *et al.*, Nature **575** (2019) 147.

Form factor discrepancy

- Electron scattering: Proton electric form factor



J. C. Bernauer, EPJ Web of Conf. **234**, 01001 (2020)

$$G_{std}(Q^2) = \frac{1}{\left(1 + \frac{Q^2}{\Lambda}\right)^2}$$

with $\Lambda = 0.71\ (\mathrm{GeV/c})^2$

Different Q^2-dependencies of the electric form factor

- ➡ Mainz (2010): $r_p = (0.879 \pm 0.008)$ fm
- ➡ PRad (2019) : $r_p = (0.831 \pm 0.014)$ fm

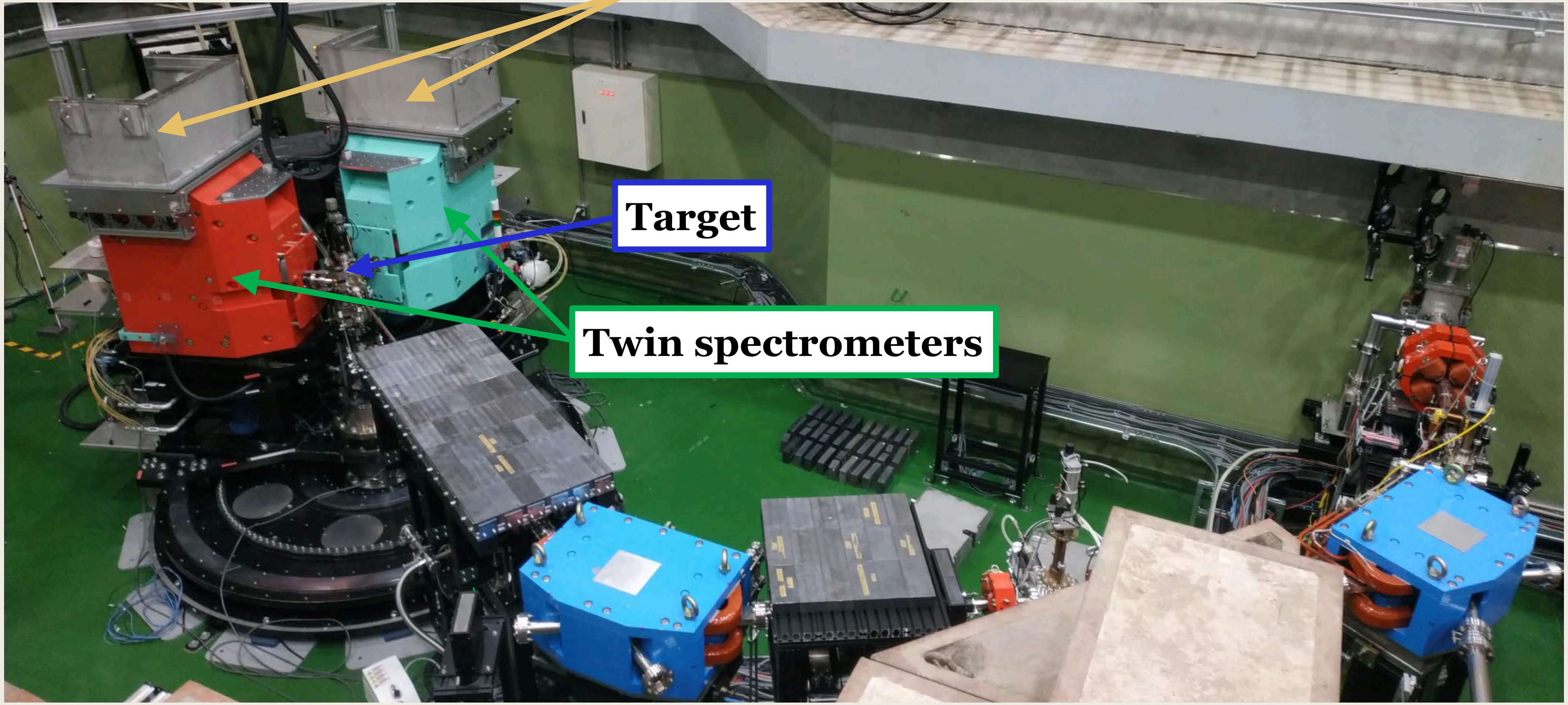
3σ discrepancy!

At least 1 experiment is wrong!

- ➡ Need data at low Q^2: ULQ^2!
- ➡ Most reliable measurement!

III. The ULQ^2 experiment

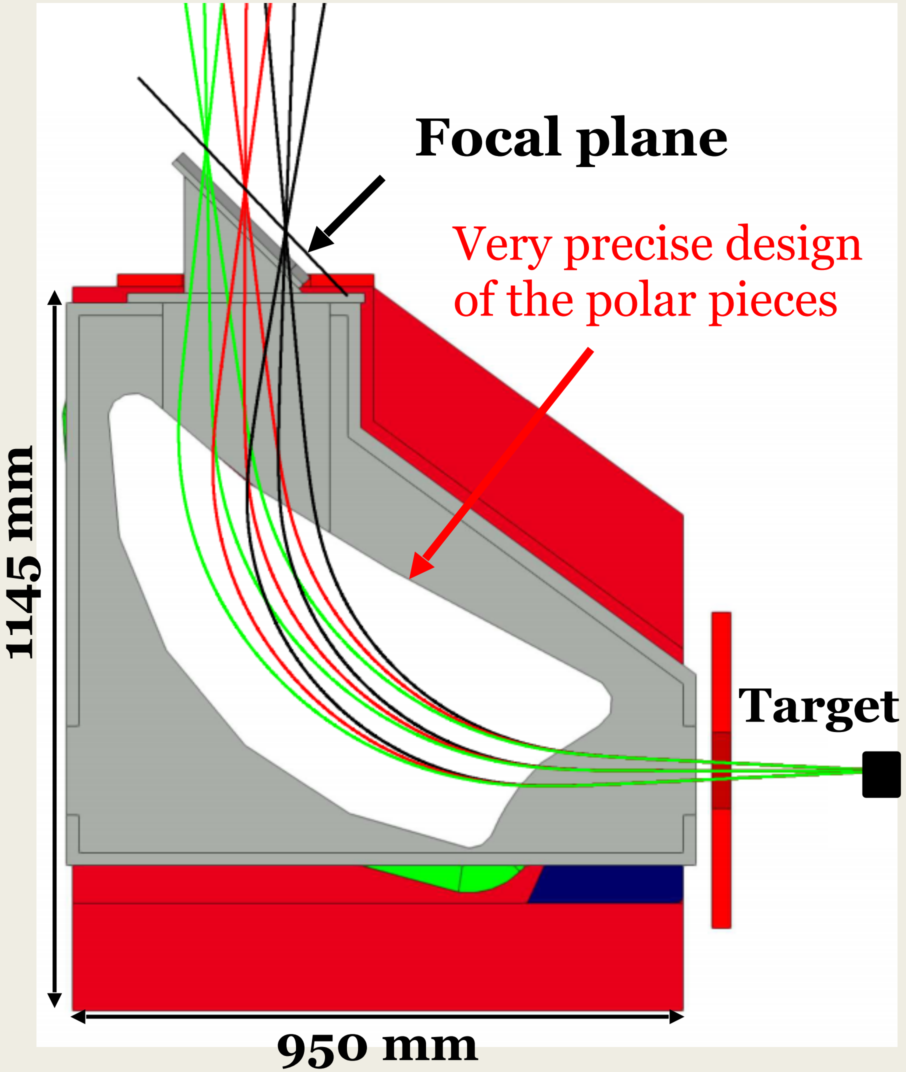
Beam line



Spectrometers

Spectrometer 1 ⟶ Data taking

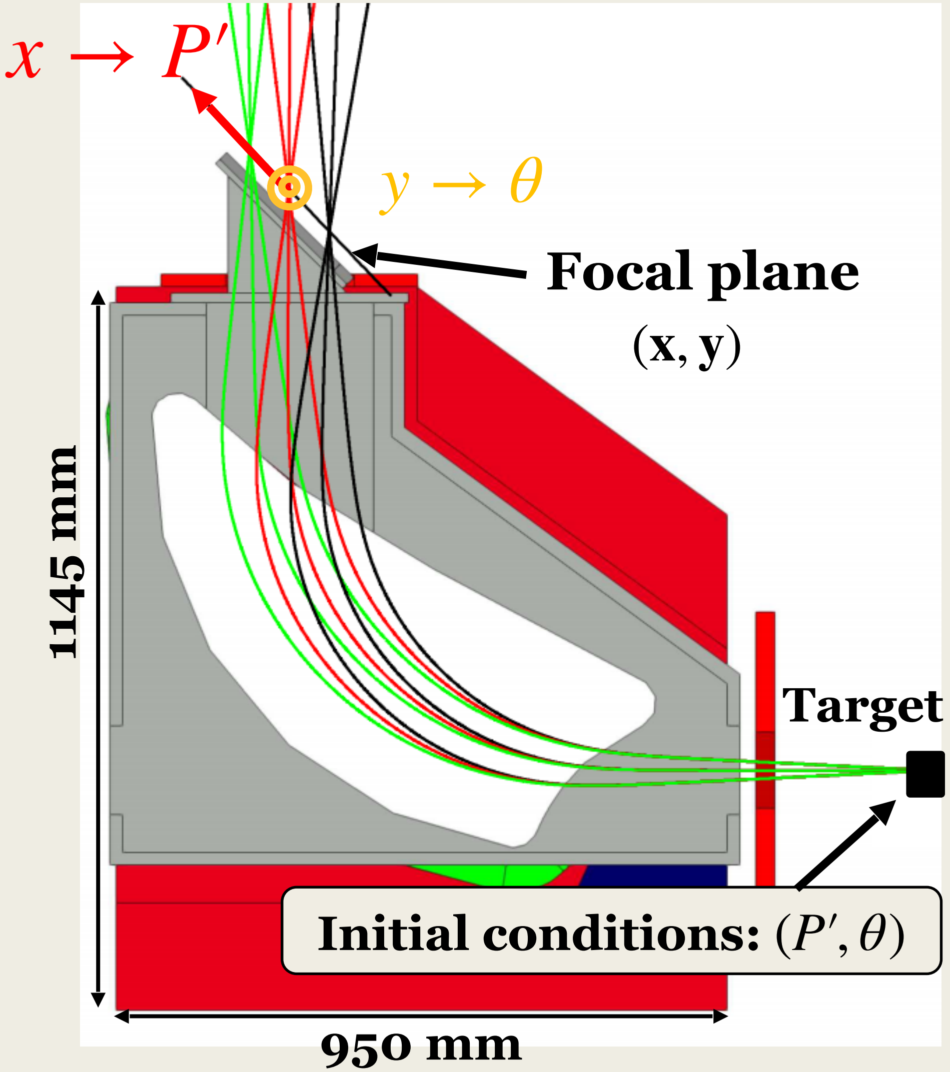
Spectrometer 2 ⟶ Target monitor



Measurement in the focal plane:

- ULQ^2 experiment uses very low energy electrons.
  - ➡ Strong multiple scattering: $\langle \theta_{MS} \rangle \propto \dfrac{1}{P'}$
  - ➡ Impossible to determine the path of the electrons.
- Single measurement of the electron position in the focal plane.
- Connected to the target chamber and under vacuum (< 1 mPa).

Spectrometers

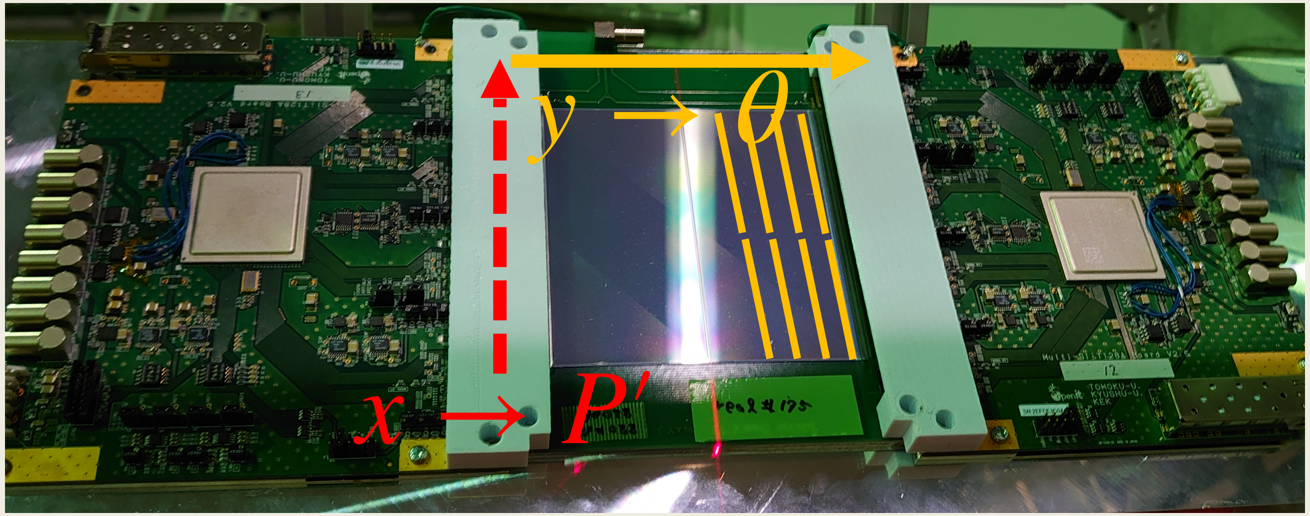


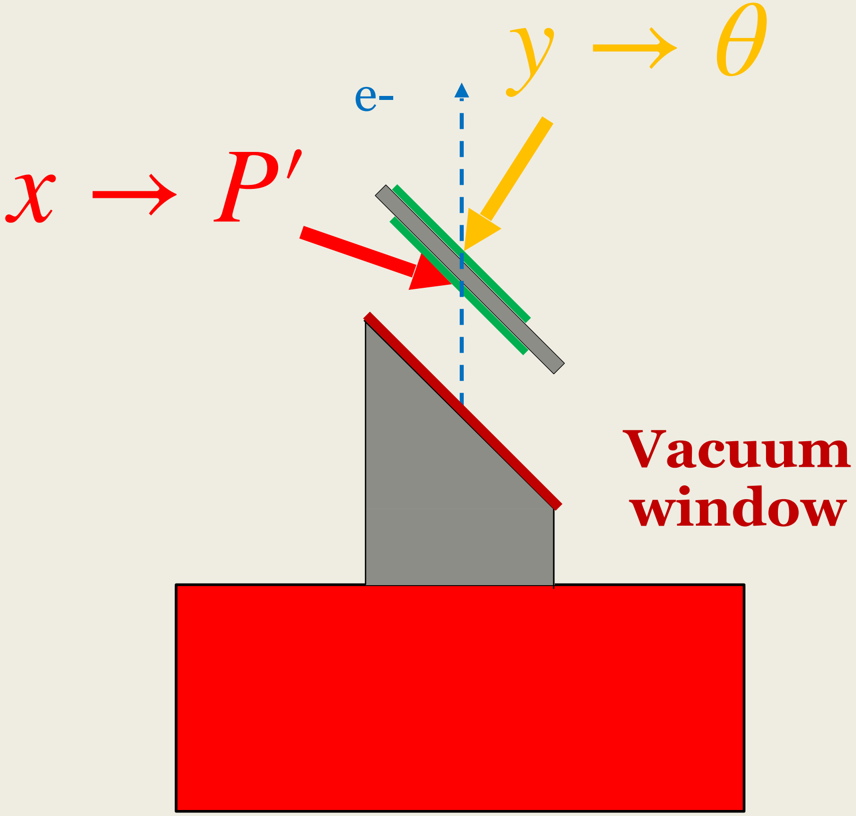
<u>Measurement in the focal plane:</u>

- Electrons focused in the focal plane depending on their momentum p and horizontal scattering angle θ.
- (P', θ) determined from the (x, y) position of the electrons on the detectors placed in the focal plane.
- To resolve e+p and e+C scattering peaks with Q^2= 0.0003 (GeV/c)^2,

Momentum resolution: $\sigma_p = \frac{\Delta P}{P} < 10^{-3}$

Detection system

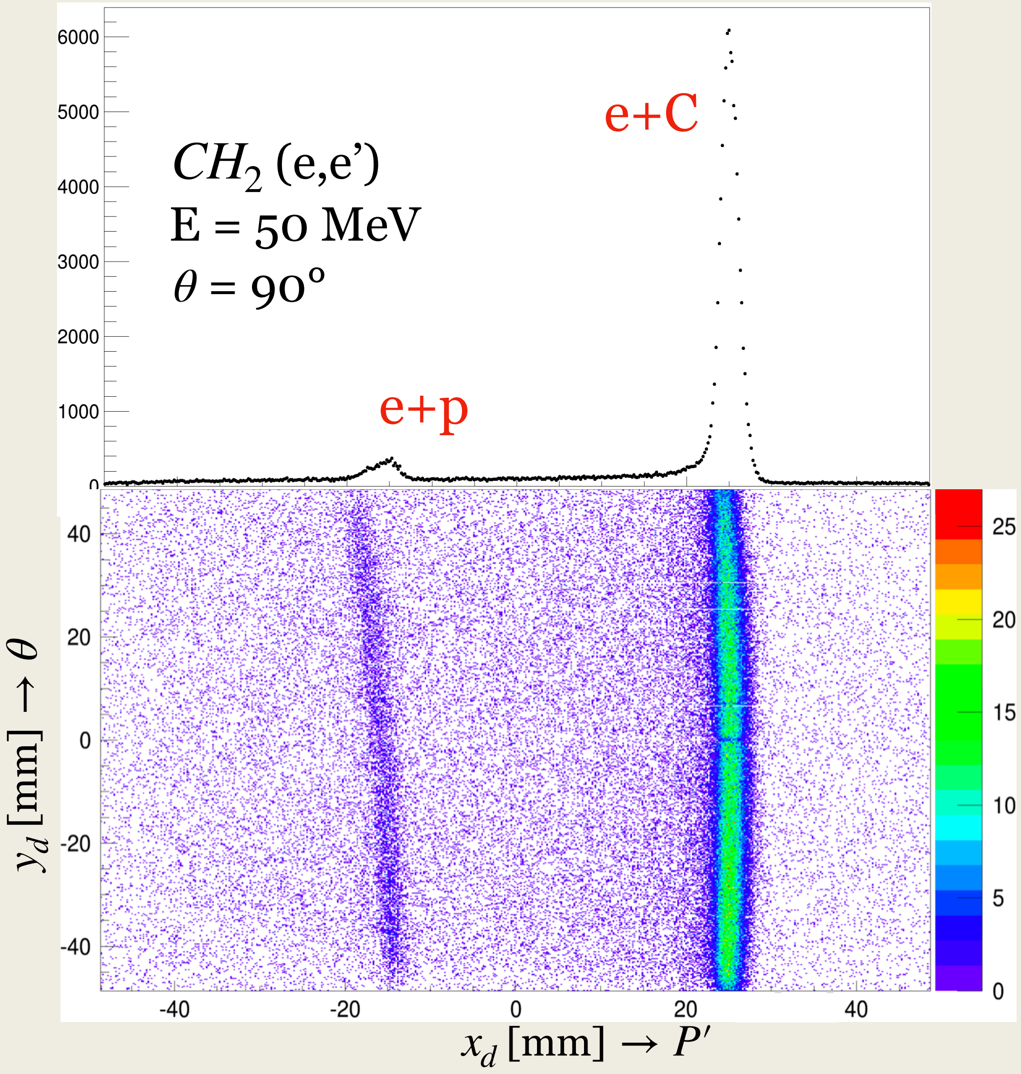


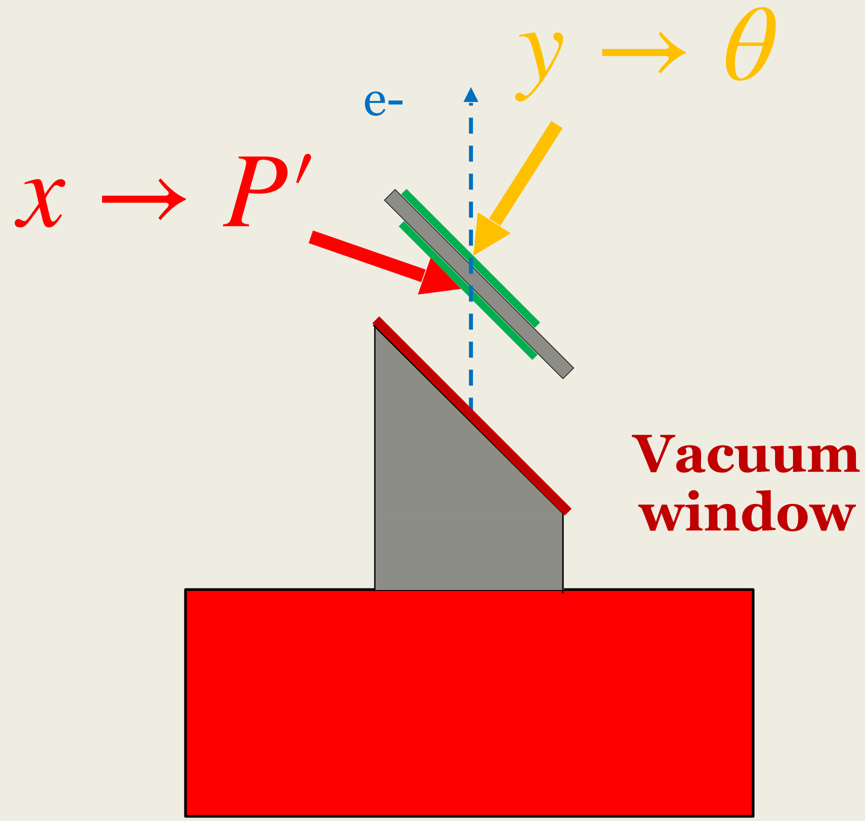


<u>Single Sided Silicon Strip Detectors (SSDs):</u>

- Developed with the J-PARC muon g-2/EDM collaboration.
- 2 detectors each made of 2 x 512 channels on each spectrometer.
- Located in the focal plane of the spectrometers.
- Channel width: 0.19 mm, thickness: 0.32 mm.

Detection system



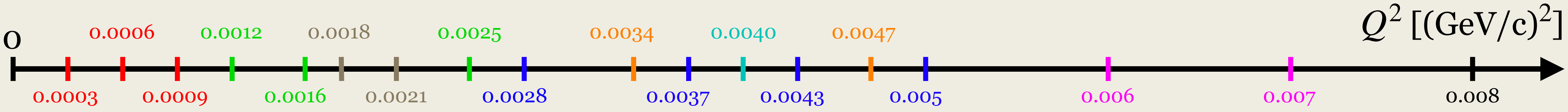


IV. Data taking and analysis

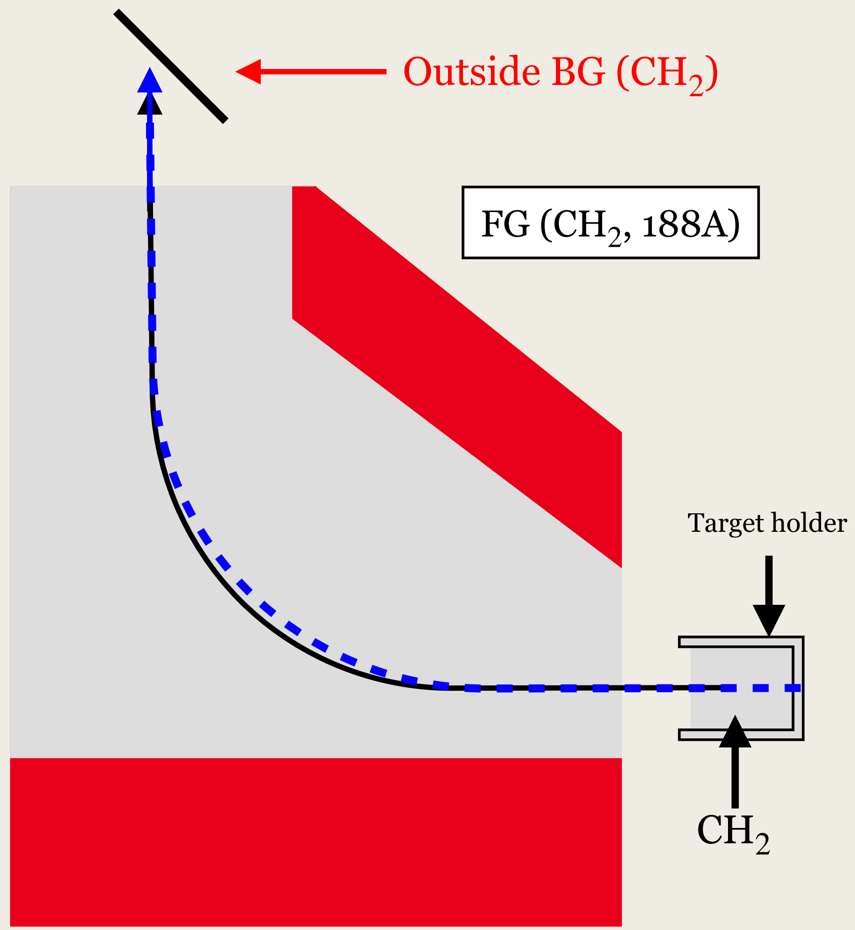
Current status

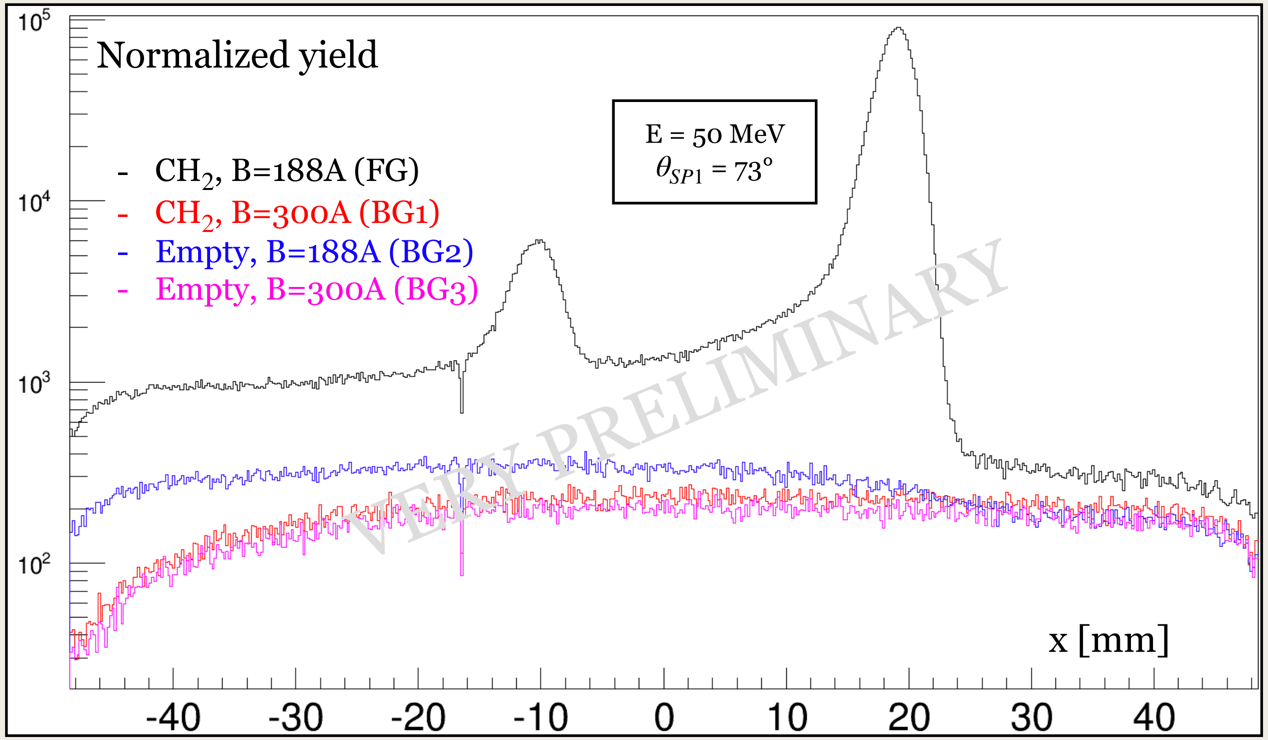
- Commissioning of the twin spectrometers:
  - ➡ COMPLETED!
- Determination of the detector efficiency:
  - ➡ Data taking completed!
  - ➡ Analysis underway
- Actual cross-section measurement:
  - ➡ 18 points with $3 \times 10^{-4} \leq Q^2 \leq 8 \times 10^{-3}$ (GeV/c)^2
  - ➡ Data taking completed!

23/05: 50 MeV
23/09: 42 MeV
23/10: 50 MeV
23/10: 21 MeV
24/01: 50 MeV
24/03: 50 MeV
24/04: 60 MeV
24/10: 60 MeV

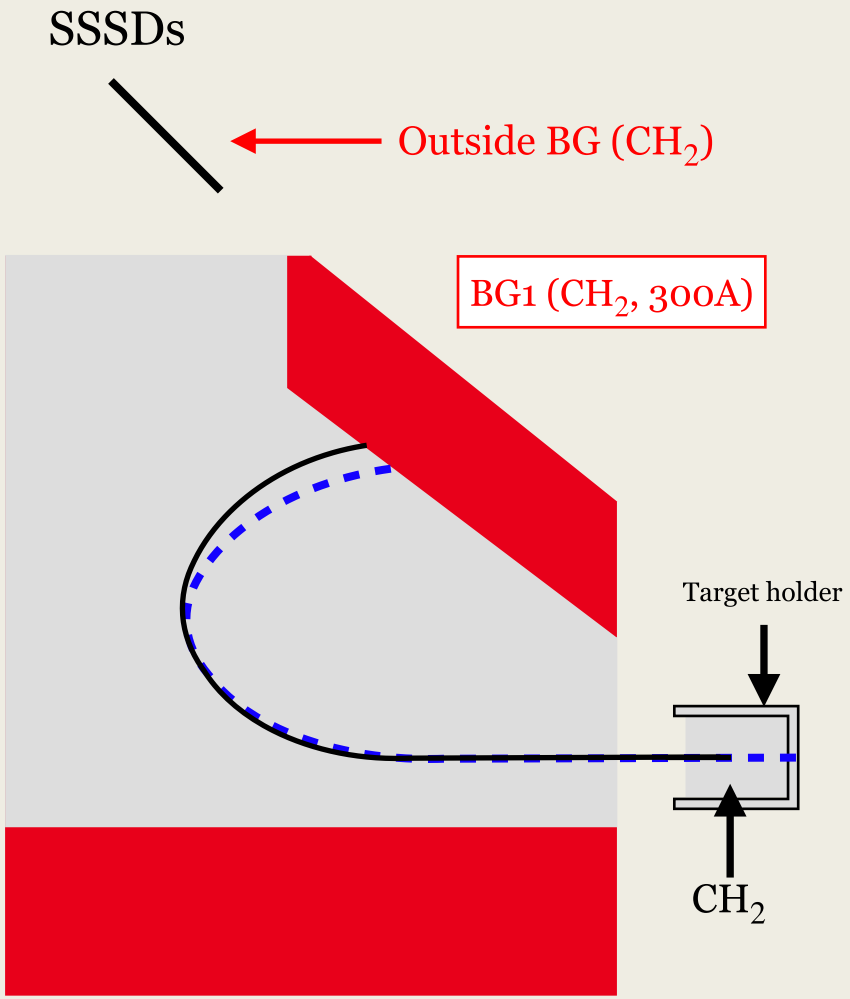


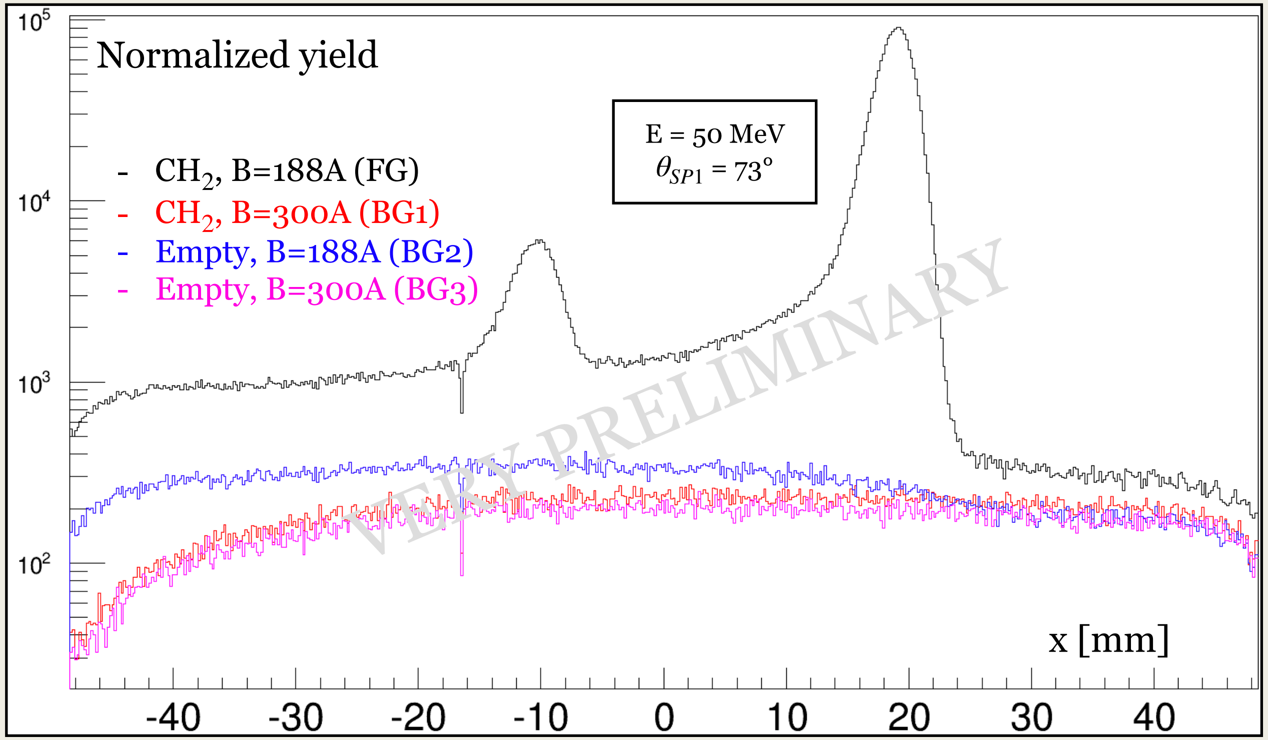
Measurement



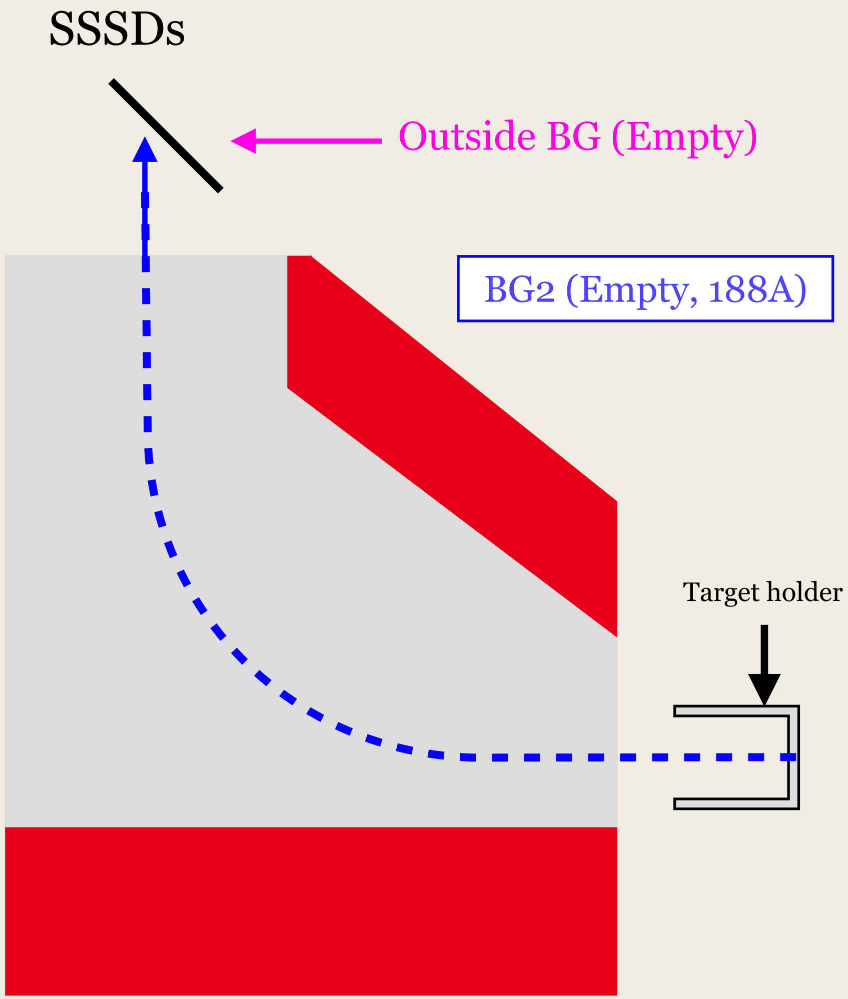


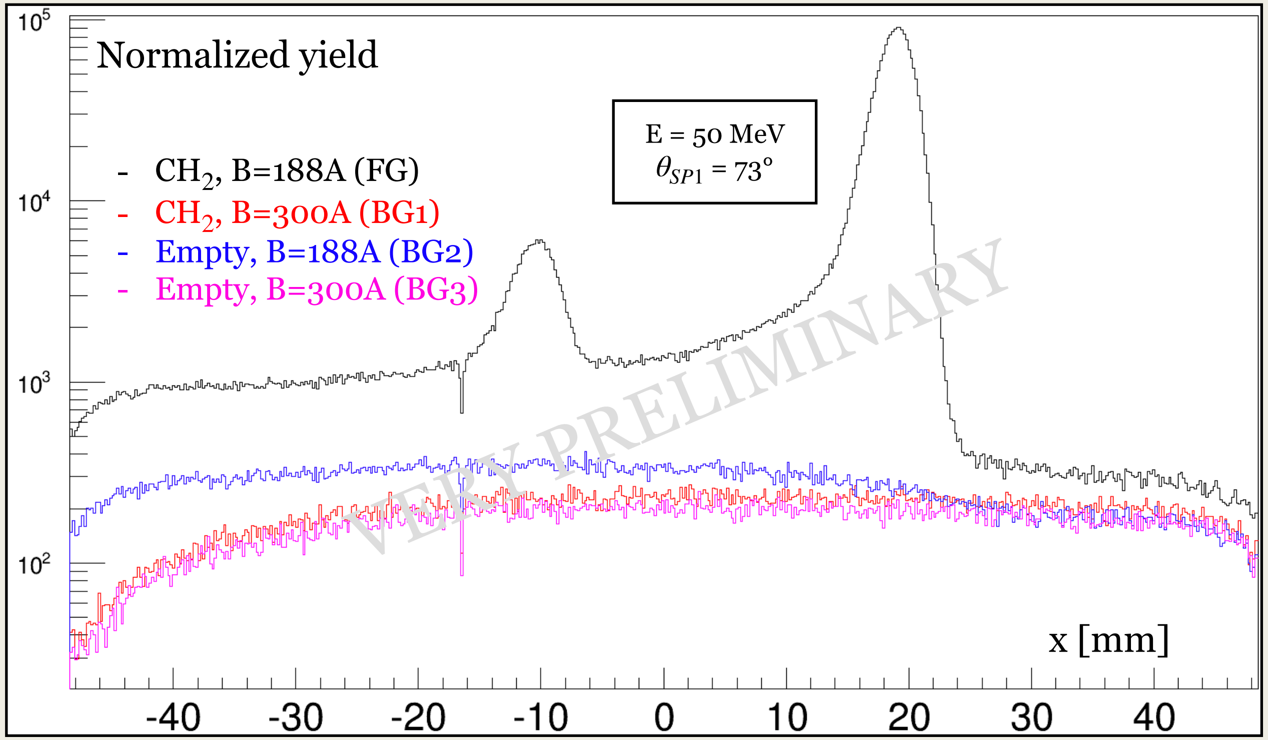
Measurement



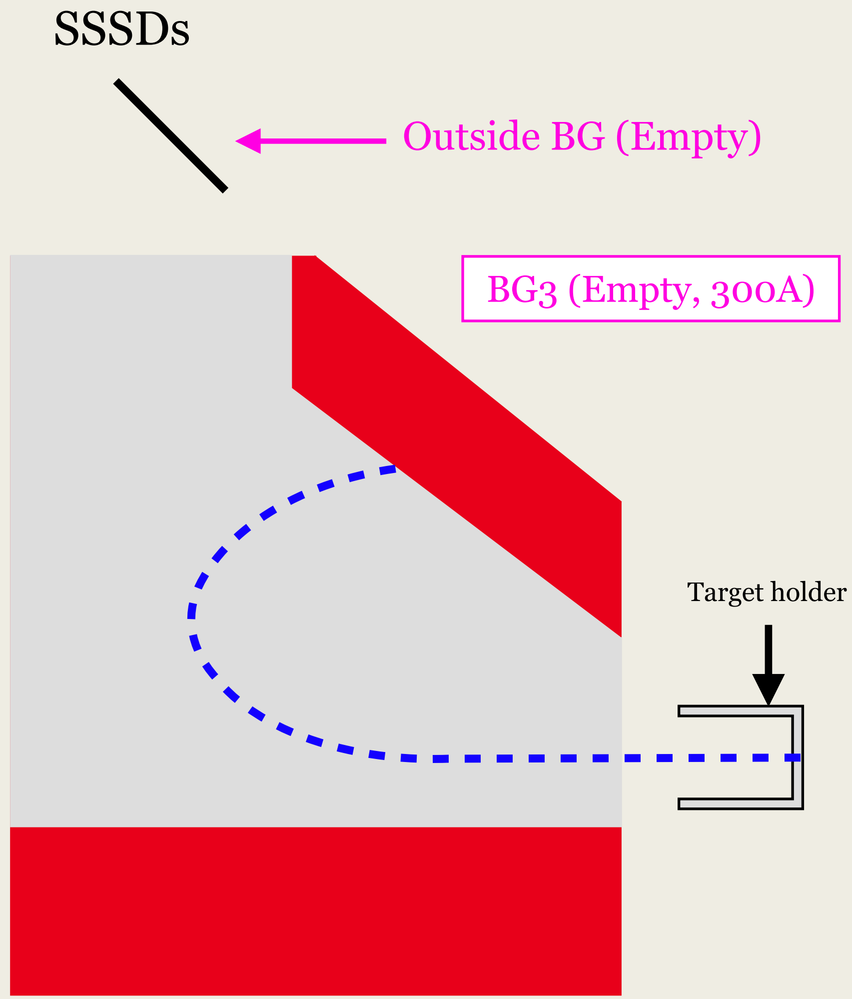


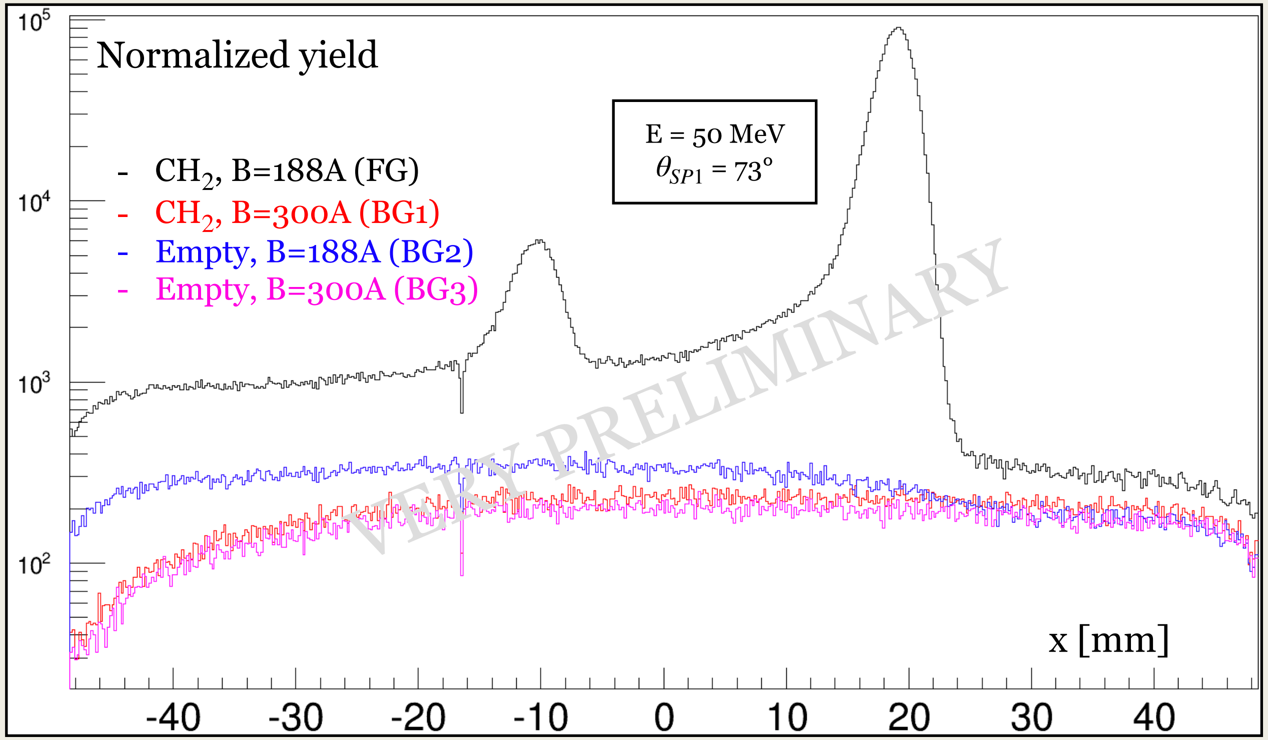
Measurement





Measurement



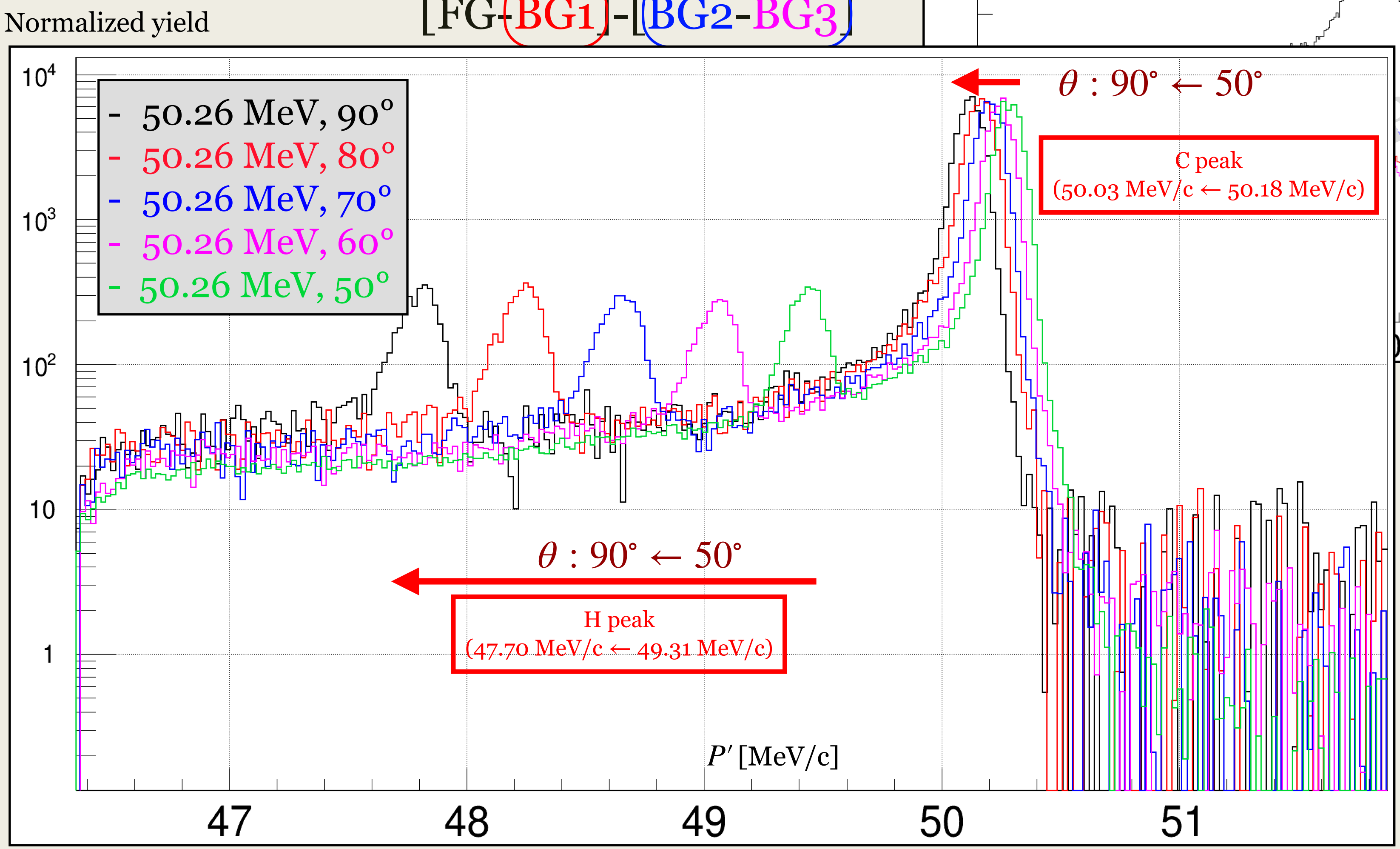


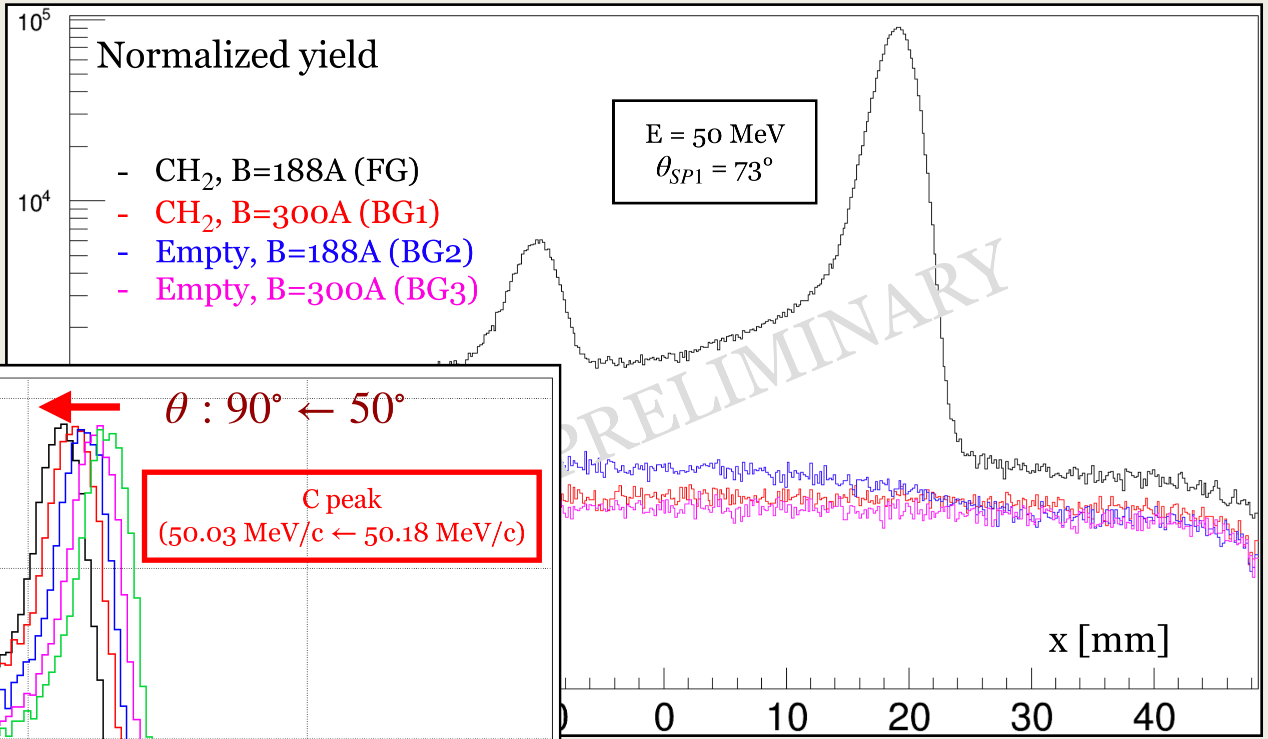
Measurement

Outside BG

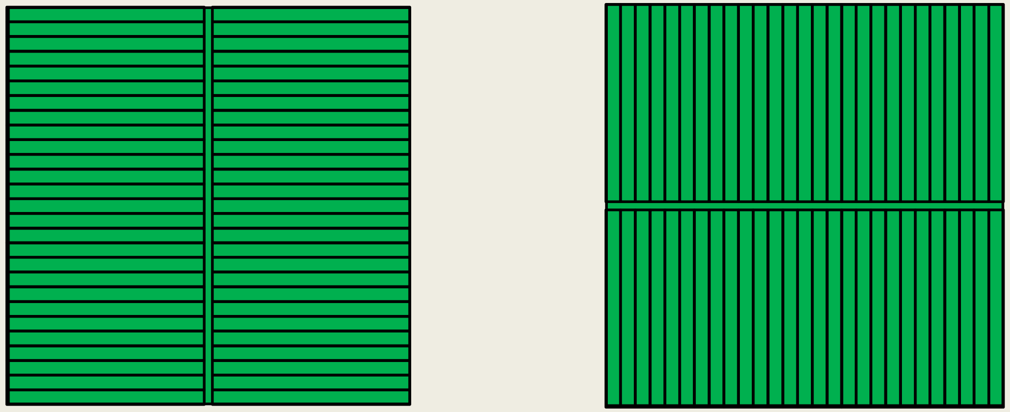
BG from target holder

[FG-BG1]-[BG2-BG3]

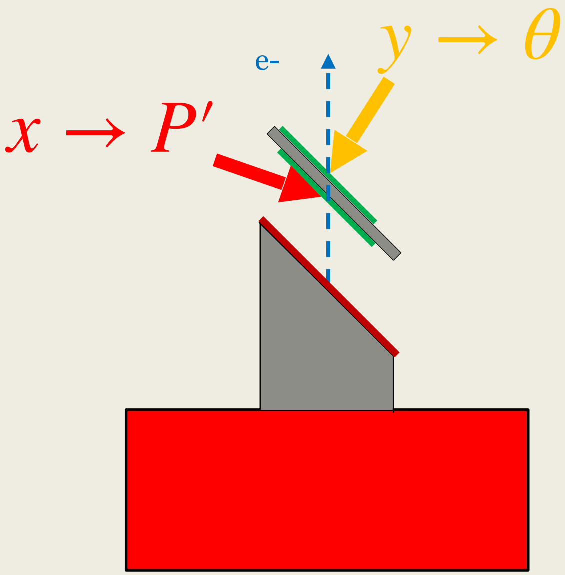


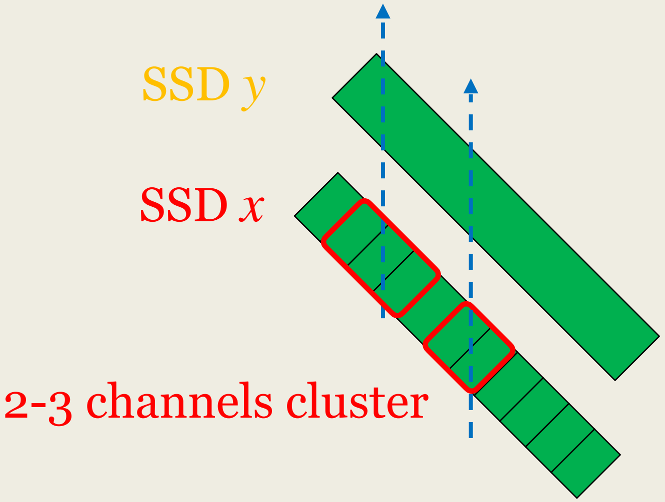


Analysis



SSD $x \rightarrow P'$ SSD $y \rightarrow \theta$

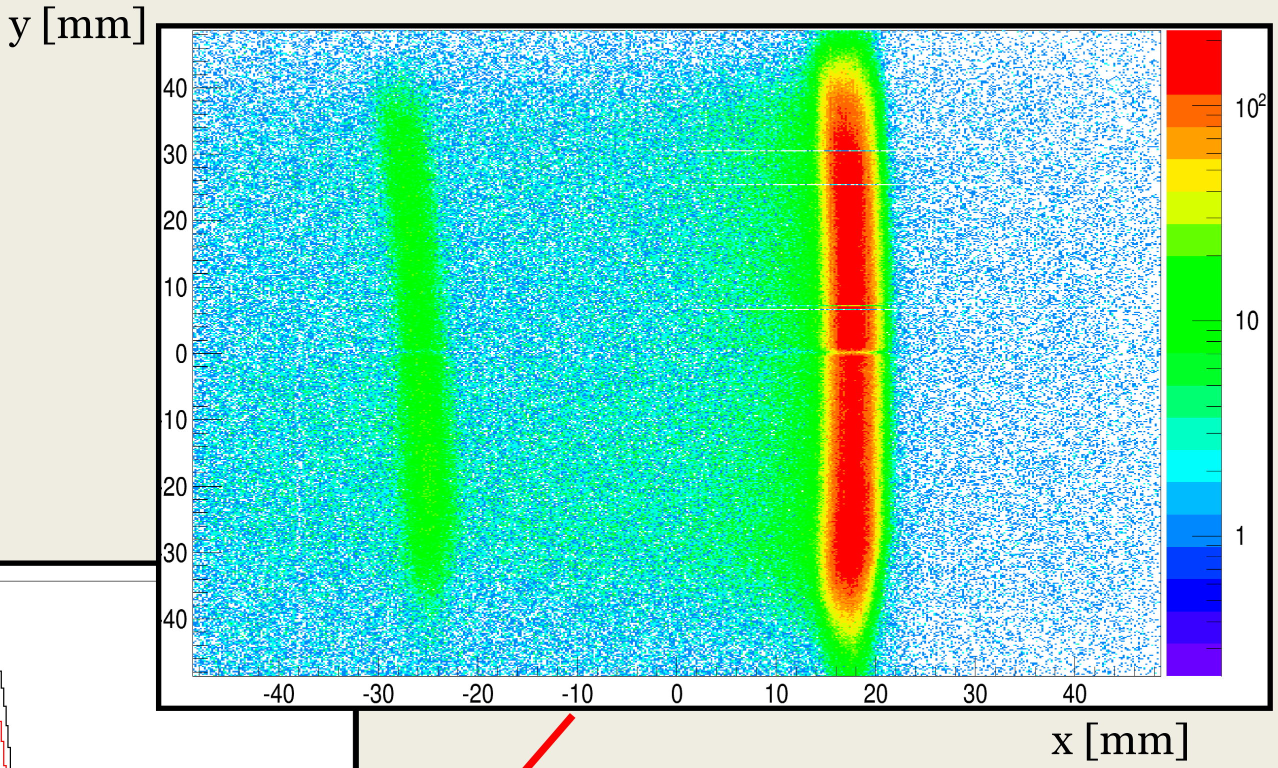




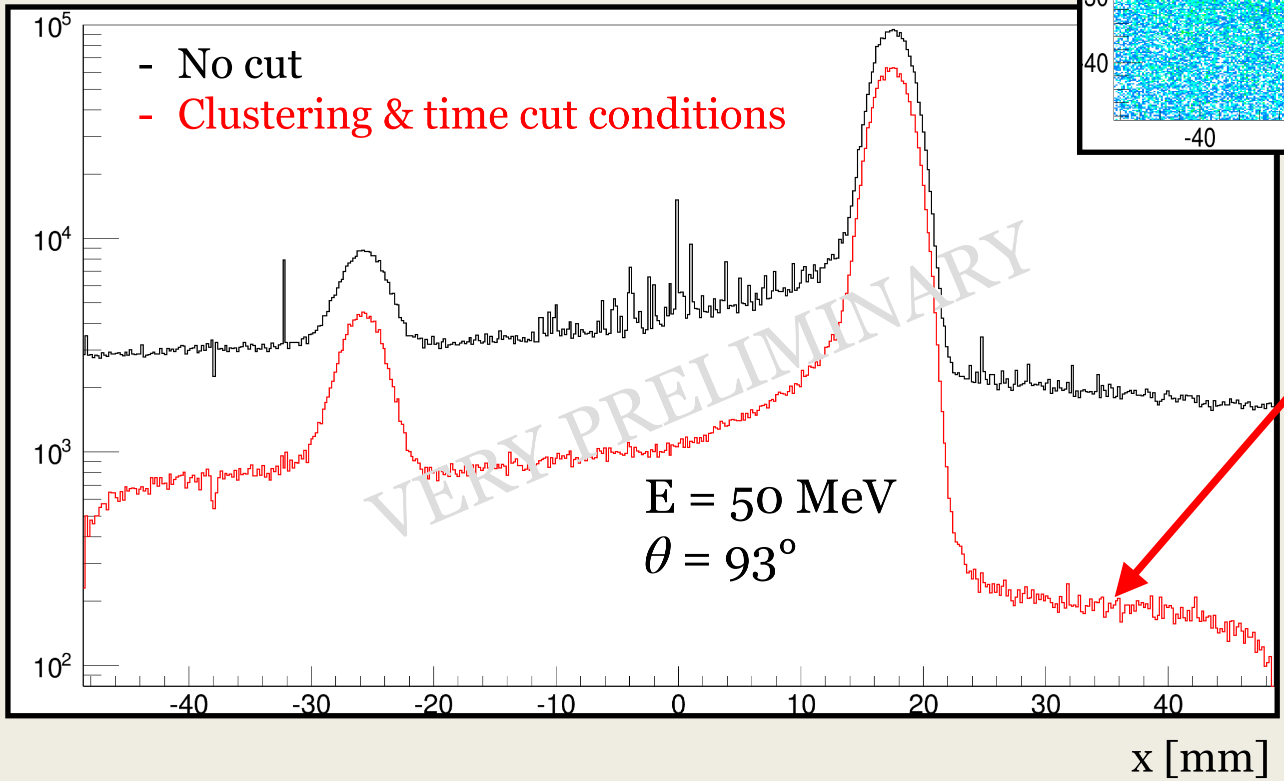
Analysis requirements:

- At least 2-channel clusters on x
- Time coincidence between x & y

Analysis



x projection

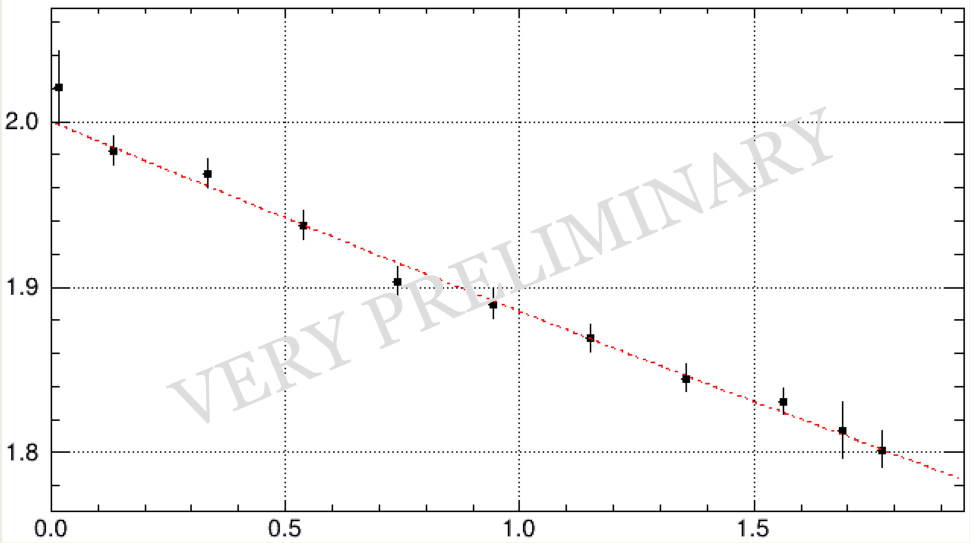


Analysis

$$\left(\frac{d\sigma}{d\Omega}\right)_{e-H} = \frac{N_{e-H}/N_{e-C}}{N_H/N_C}\left(\frac{d\sigma}{d\Omega}\right)_{e-C}$$

Evolution of H/C in the target with SP2:

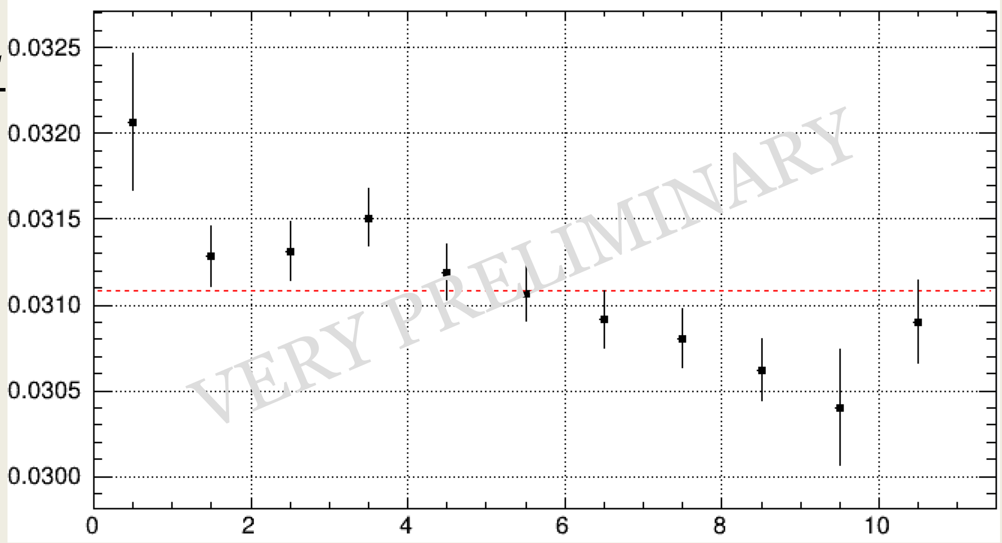
$\frac{N_H}{N_C}$



Beam charge [mC]

Cross-section ratio:

$\frac{N_{e-H}/N_{e-C}}{N_H/N_C}$



Run number

E = 50 MeV

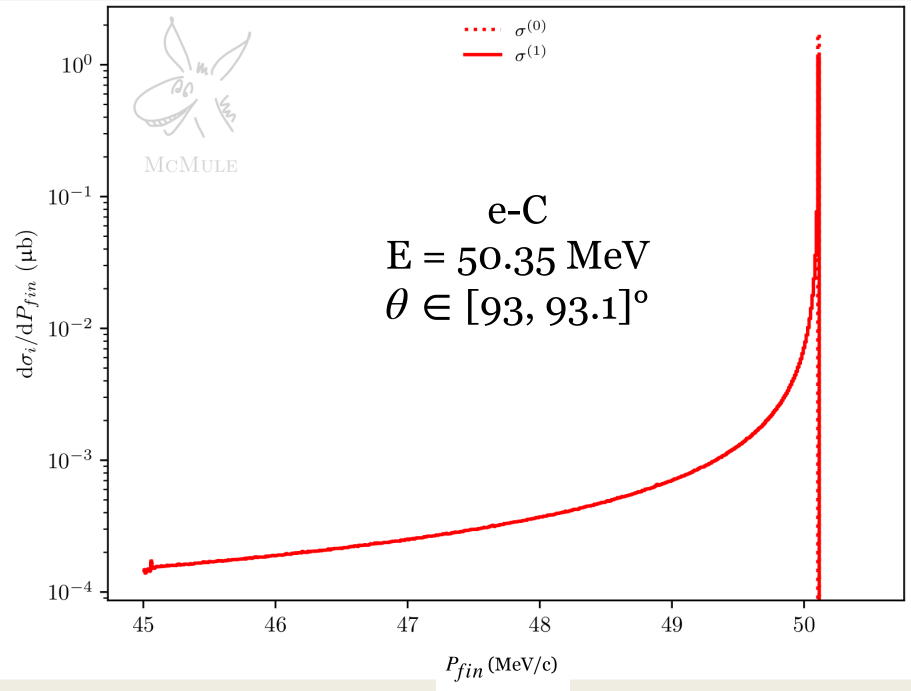
$\theta = 64.6°$

$Q^2 \approx 0.0028\ (\mathrm{GeV/c})^2$

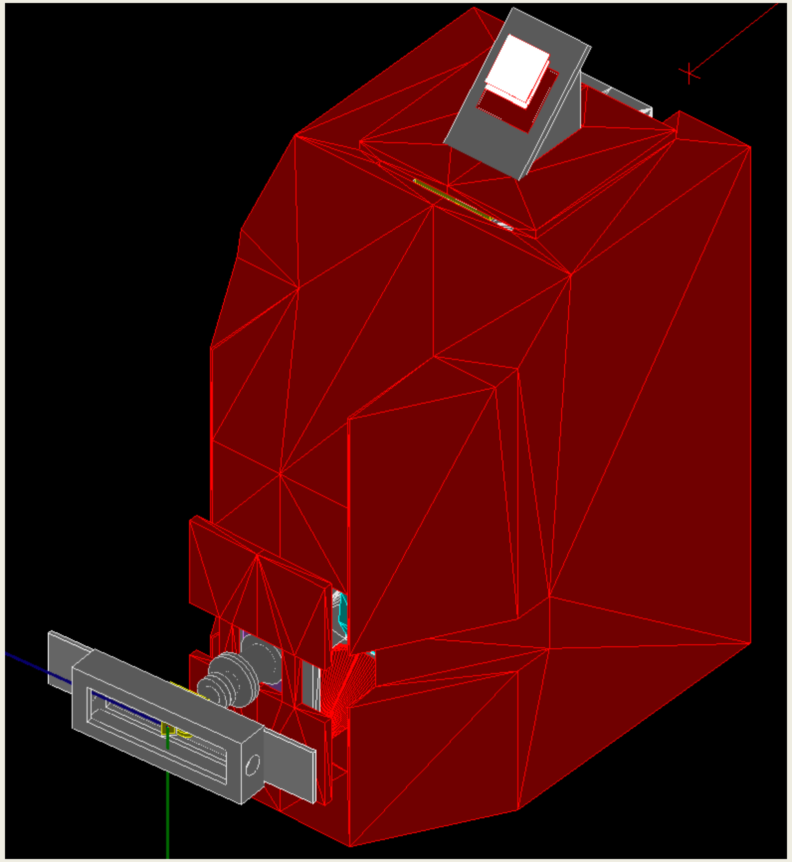
Simulation

P. Banerjee *et al.*, SciPost Phys. **9**, 027 (2020).

- McMule for e-H & e-C simulation of LO, NLO (NNLO if necessary)
  - ➡ Marco's talk on Thursday



Geant4 simulation



Simulation

P. Banerjee *et al.*, SciPost Phys. **9**, 027 (2020).

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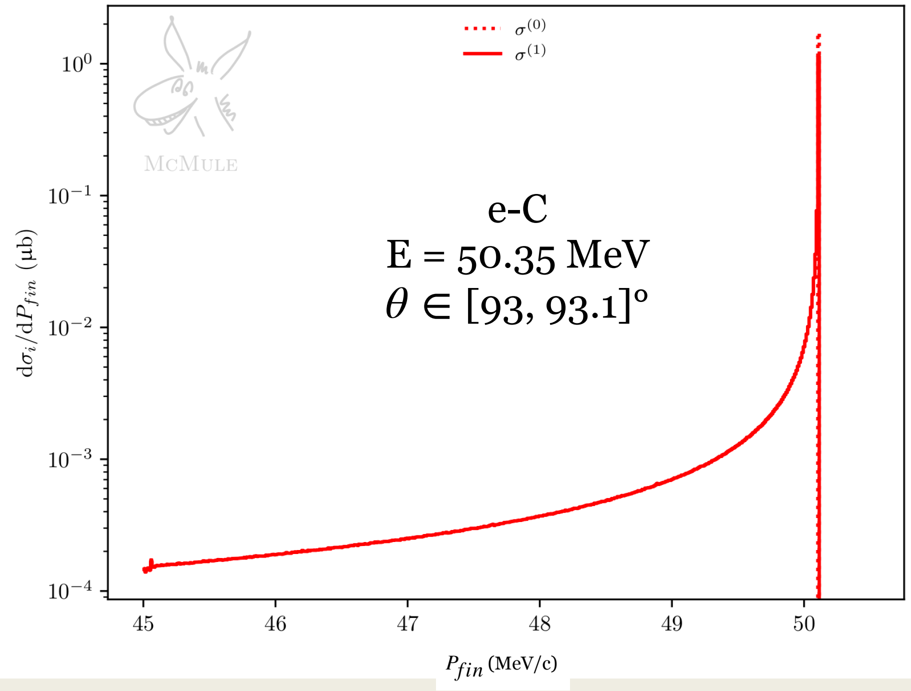
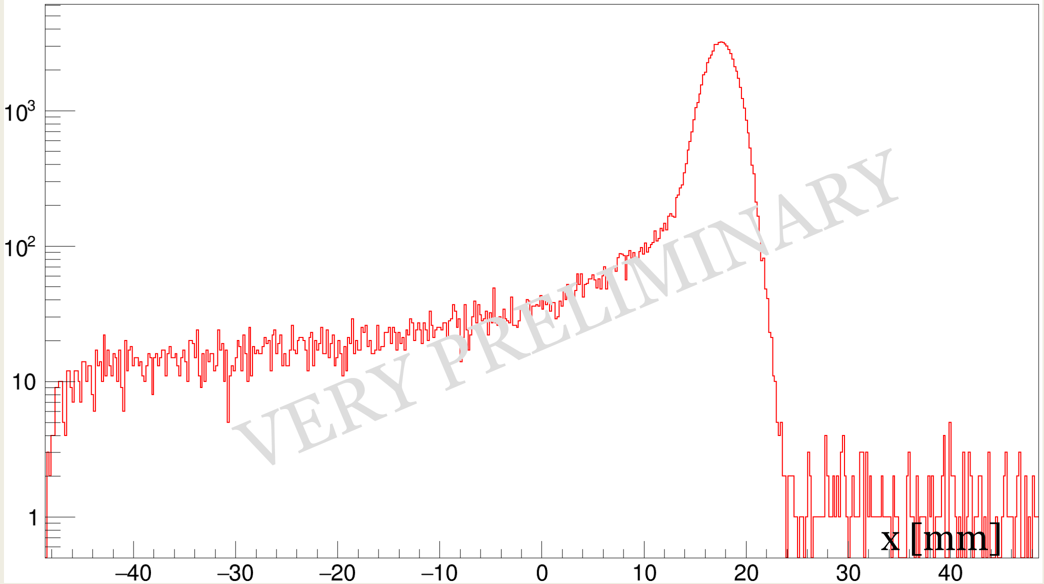
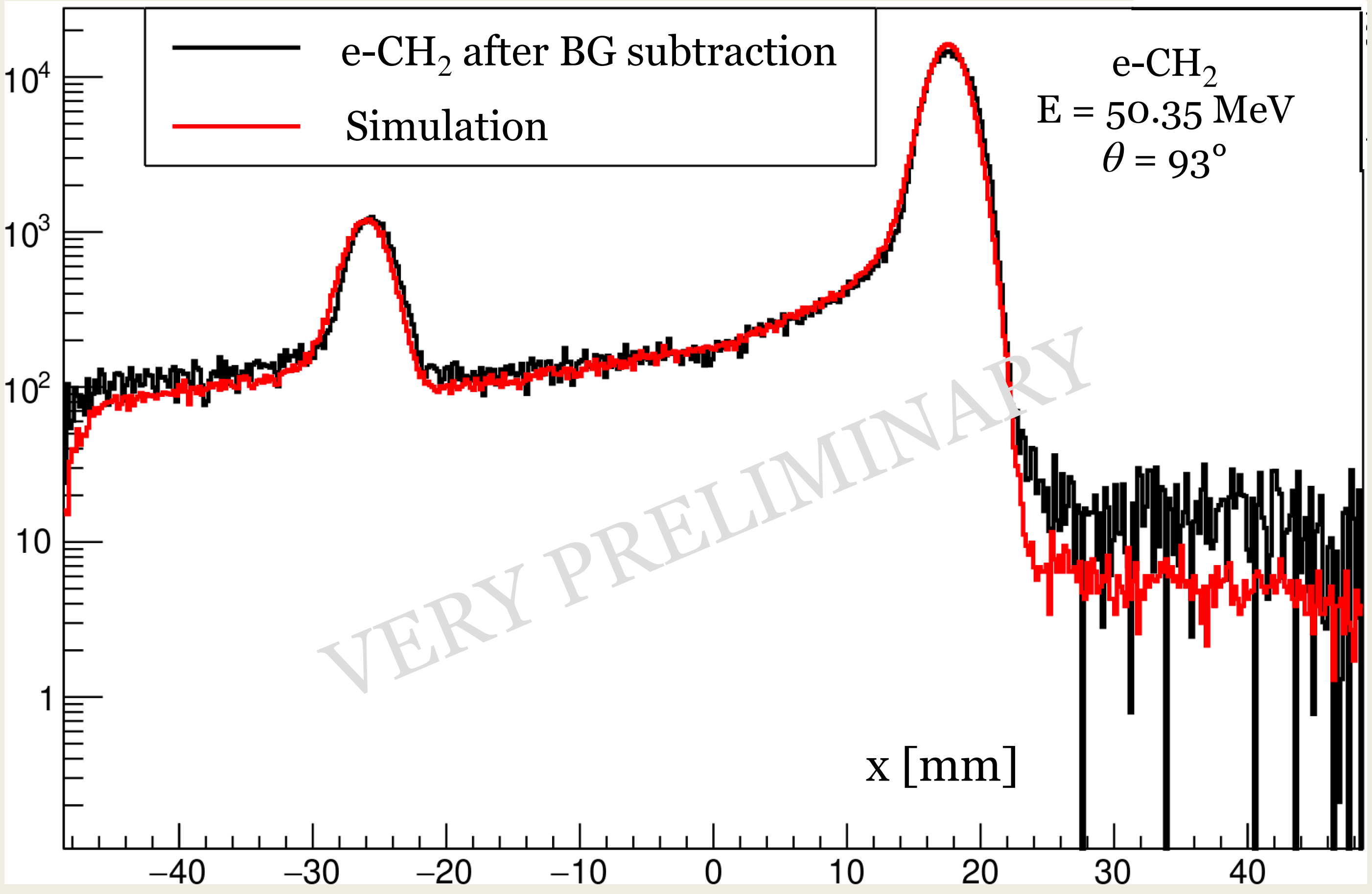


Add beam momentum spread

Geant4 simulation



Simulation



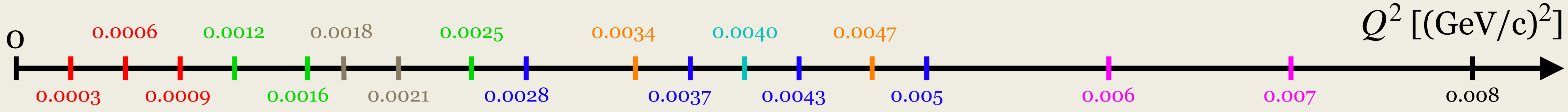
First e-CH_2 simulations:

➡ Many improvements are necessary

Conclusion

23/05: 50 MeV
23/09: 42 MeV
23/10: 50 MeV
23/10: 21 MeV
24/01: 50 MeV
24/03: 50 MeV
24/04: 60 MeV
24/10: 60 MeV

❑ Data taking COMPLETED



❑ Analysis going-on:

- ➡ Experimental data analysis well-advanced
- ➡ Simulation to be improved

➡ Results in 2025

Thanks to all ULQ^2 collaborators

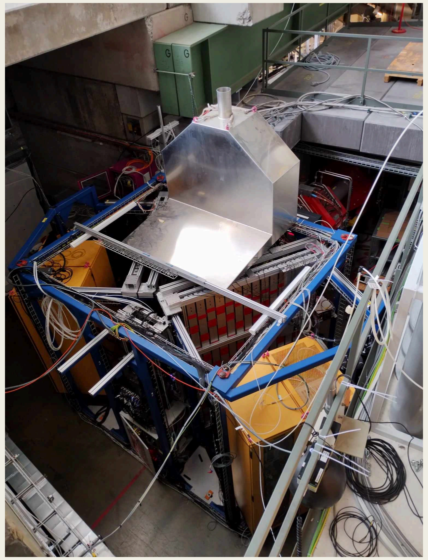
D. Abe[1], R. Danjo[1], O. Fujishima[2], T. Goke[1], Y. Honda[1], Y. Ishikura[1], K. Ishizaki[1], K. Haak[3], K. Hotta[1], R. Kagami[4], H. Kikunaga[1], H. Kobayashi[4], M. Kohl[5], C. Legris[1], Y. Maeda[2], Y. Maeda[4], D. Marchand[6], S. Miura[1], M. Miyabe[1], E. Morris[7], M. Mitsui[2], T. Muto[1], I. Nagasawa[1], Y. Nagano[8], K. Nanbu[1], R. Obara[1], T. Ohnishi[9], S. Sasaki[1], K. Shibata[1], T. Suda[1], M. Tachibana[4], K. Takahashi[1], D. Taki[1], T. Tamae[1], O. Tokiyasu[1], K. Tsukada[4], E. Voutier[6], T. Yamauchi[1] and K. Yoshimoto[1]

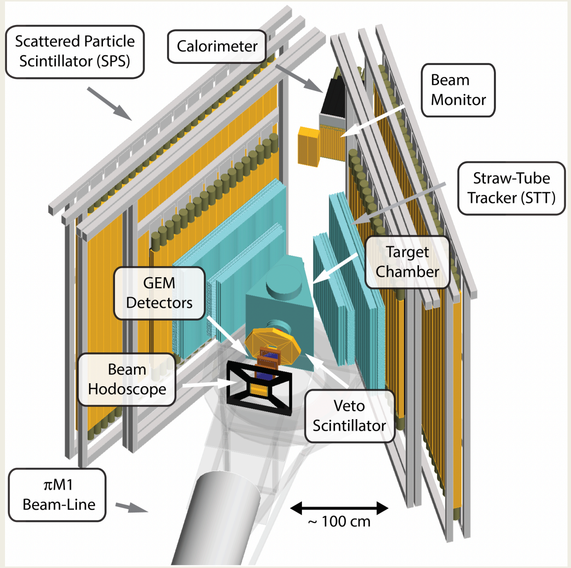
[1]Tohoku Univ., RARiS
[2]Miyazaki Univ., Dept. of Applied Phys.
[3]MSU, FRIB
[4]Kyoto Univ., ICR
[5]Hampton Univ., Phys. Dept.
[6]CNRS/IN2P3, IJCLab
[7]Univ. of Eat Anglia
[8]Yamagata Univ.
[9]RIKEN Nishina Center

THANK YOU FOR YOUR ATTENTION

Current experiments ($\mu^{\pm}$-p)

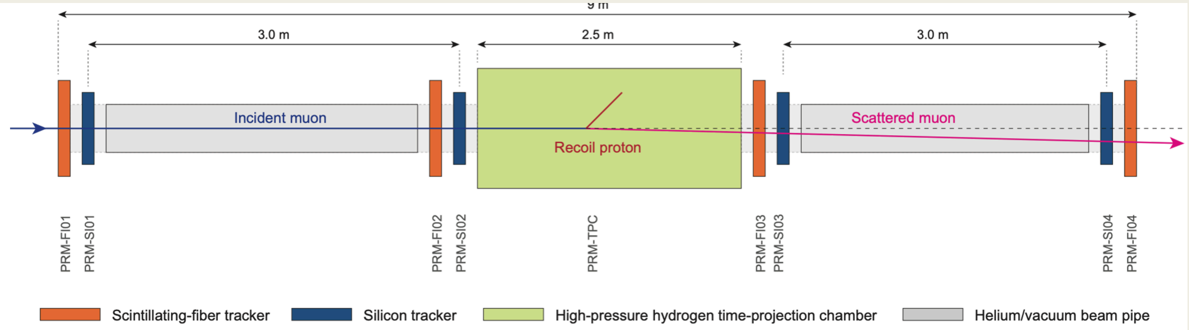
- MUSE experiment (PSI):
  - ➡ $e^{\pm}, \mu^{\pm} - p$ at 115, 153, 210 MeV/c & wide angle range (20-100°) $\rightarrow 0.002 \leq Q^2[(\mathrm{GeV/c})^2] \leq 0.08$
  - ➡ Liquid H_2 target





E. Cline *et al.*, SciPost Phys. Proc. **5**, 023 (2021).

- AMBER experiment (CERN):
  - ➡ $\mu^{\pm} - p$ at very high energy (100 GeV) & very small angles (less than 0.1°) $\rightarrow 0.001 \leq Q^2[(\mathrm{GeV/c})^2] \leq 0.04$
  - ➡ Recoiled proton detection with a high pressure TPC



J. Friedrich, PREN 2023.

Absolute cross-section measurement:
- ➡ Proton charge radius
- ➡ TPE measurement
- ➡ Lepton universality study

^{12}C cross section

- Several measurements of the electric form factor of ^{12}C with electron scattering

- Precise measurement of the carbon charge radius with $\frac{\delta r_C}{r_C} < 10^{-3}$ with μ^{12}C

➡ $r_{^{12}C} = 2.4829(19)$ fm

W. Ruckstuhl *et al*., Nucl. Phys. **A430** (1984) 685-712

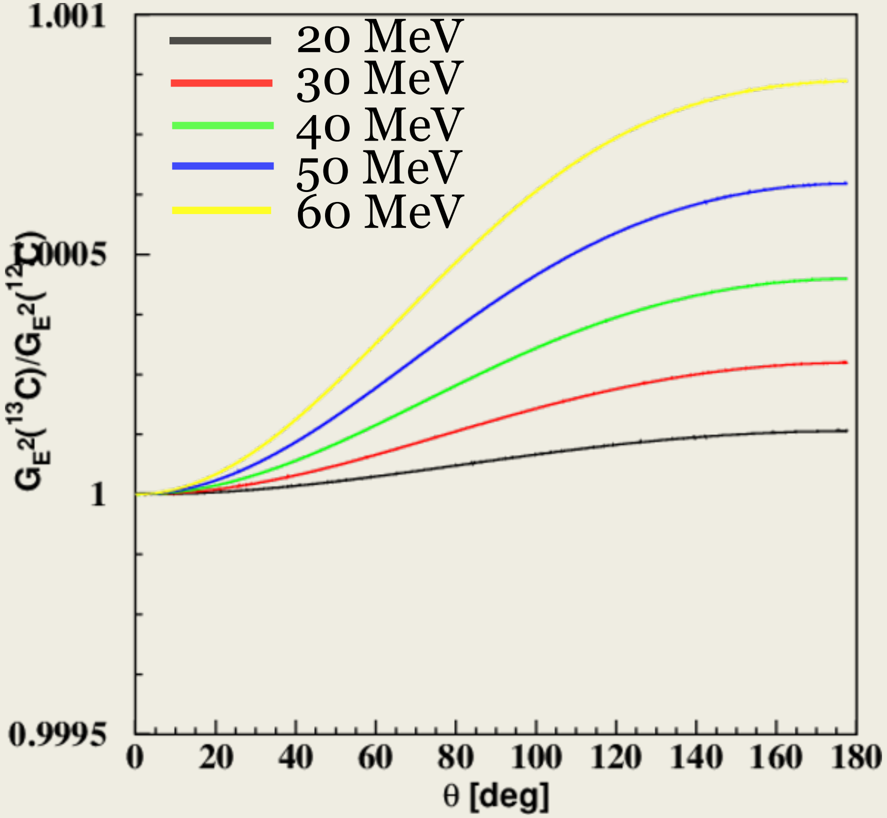
➡ Determination of the electric form factor of ^{12}C at low Q^2 with 10^{-3} accuracy

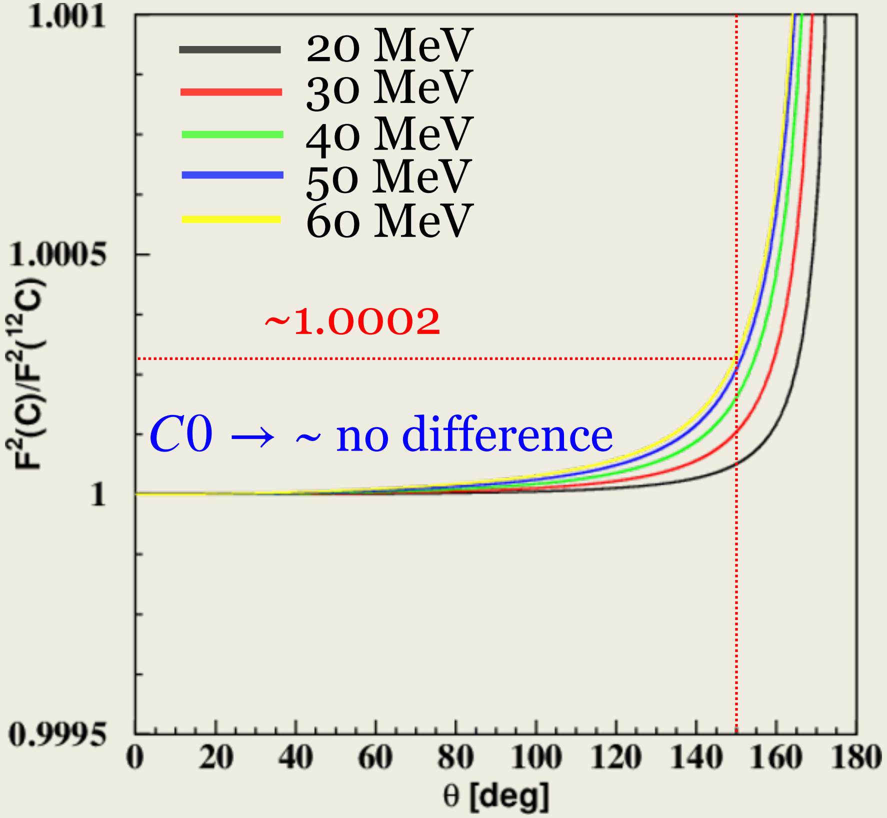
^{12}C vs natural C

$^{nat}C = 98.9\%^{12}C + 1.1\%^{13}C$

- Very small effect of ^{13}C ~ order of 10^{-4} in the context of the ULQ2 experiment

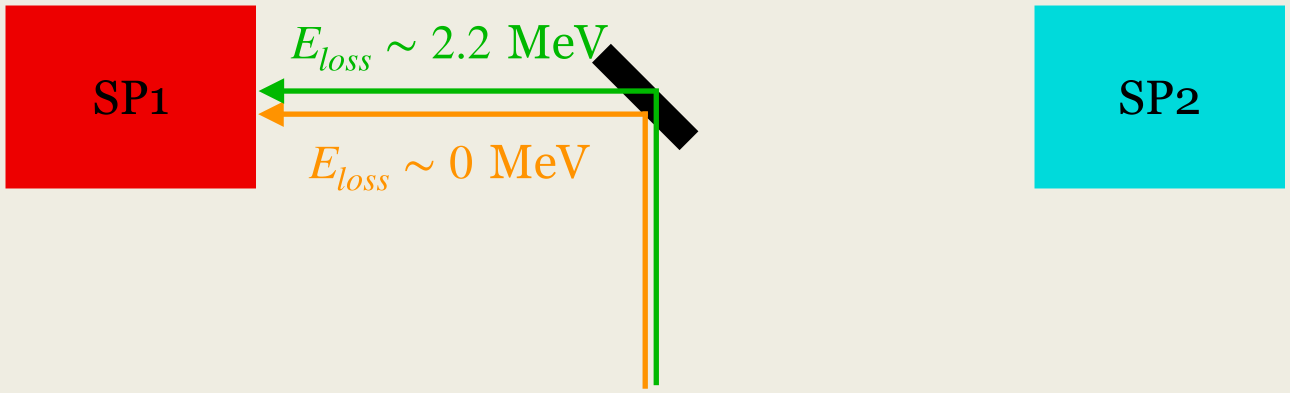
$M1 \rightarrow$ larger effect of ^{13}C



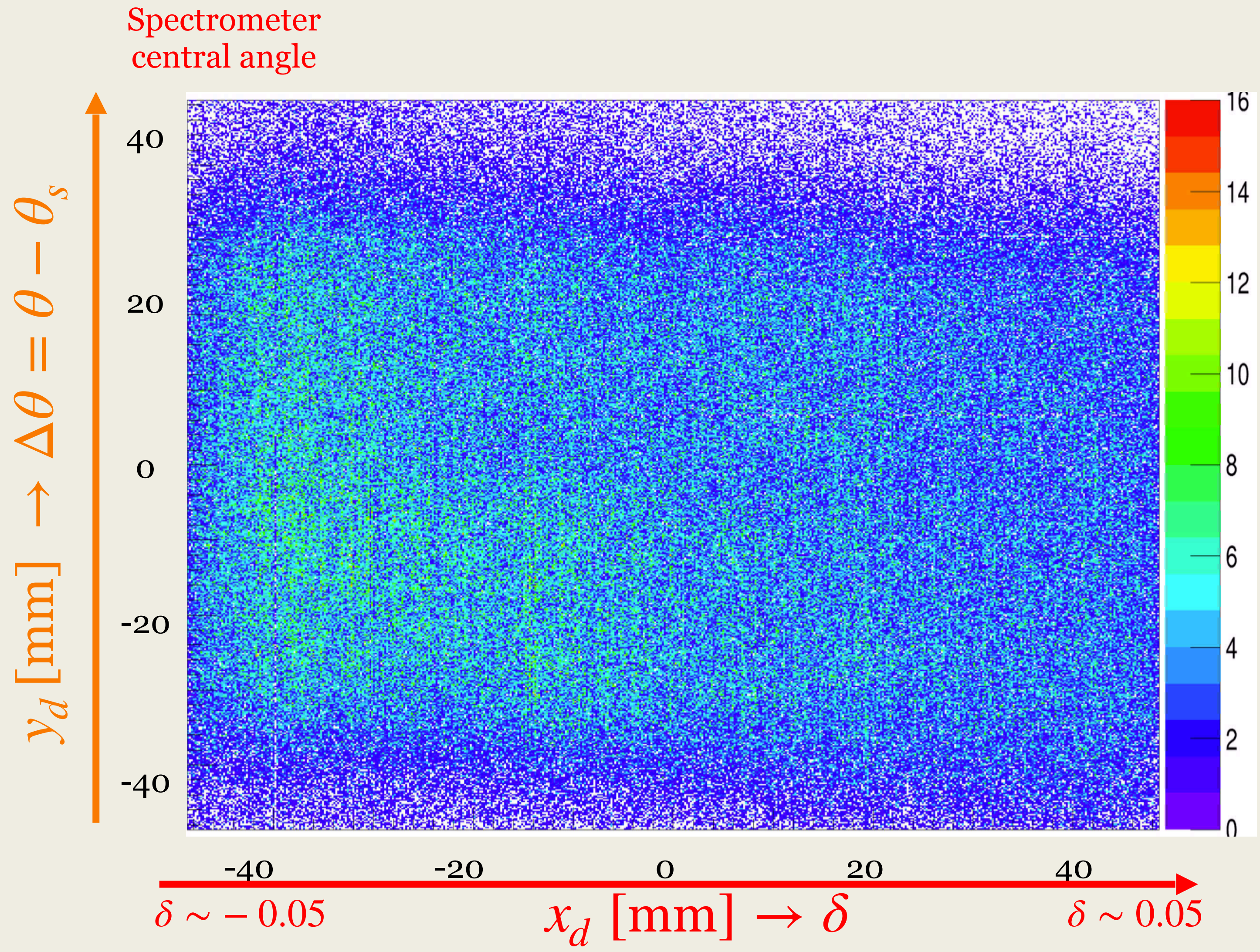


Detector efficiency

- Spectrometer momentum acceptance: ~10%
- Use of a 2-mm-thick C target → ΔE_{loss} = 2.2 MeV
- With E=10 MeV, $\frac{\Delta E_{loss}}{E} \sim 20\%$ → completely covers the detector surface



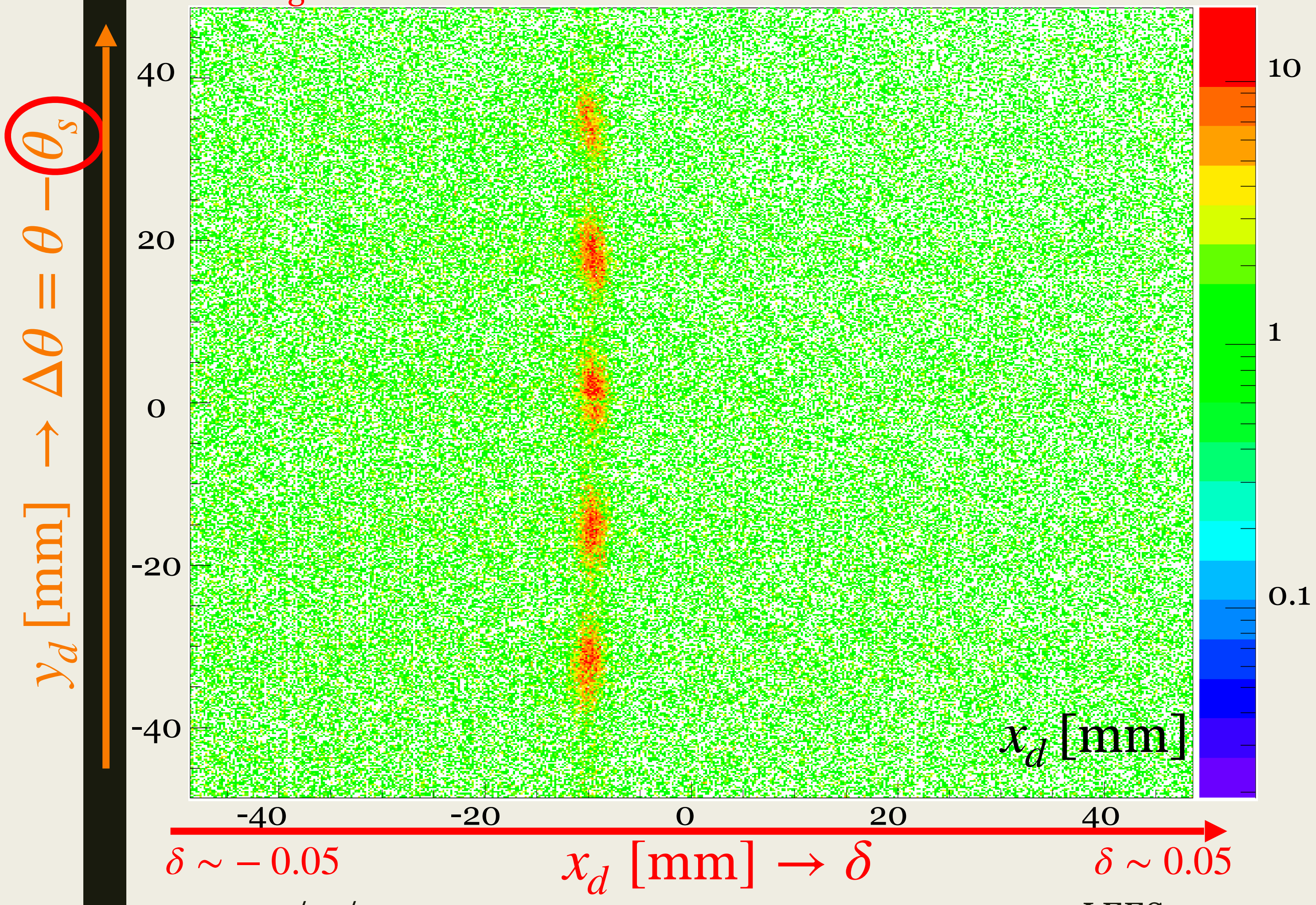
Detector efficiency



Spectrometer optics

Spectrometer central angle

Data taken with a sieve slit



Momentum dispersion Angular dispersion

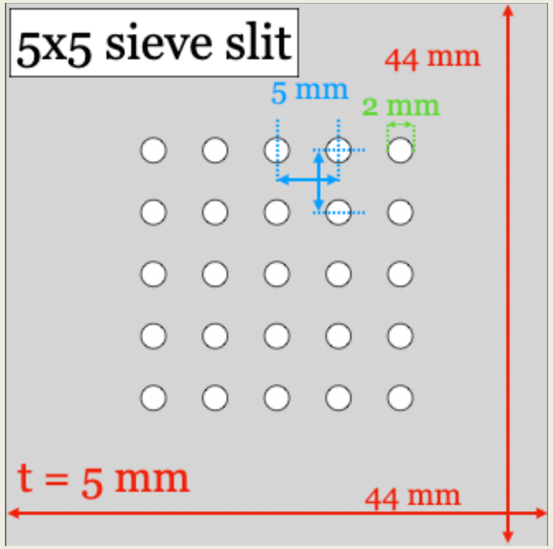
Relation between (x_d, y_d) and (P', θ):

$$x_d = (x_d|\delta)\delta + \dots$$

$$y_d = (y_d|\Delta\theta)\Delta\theta + \dots$$

$$\text{with } \delta = \frac{P' - P_c}{P_c}$$

$\propto B_C$ Spectrometer central momentum



Spectrometer optics

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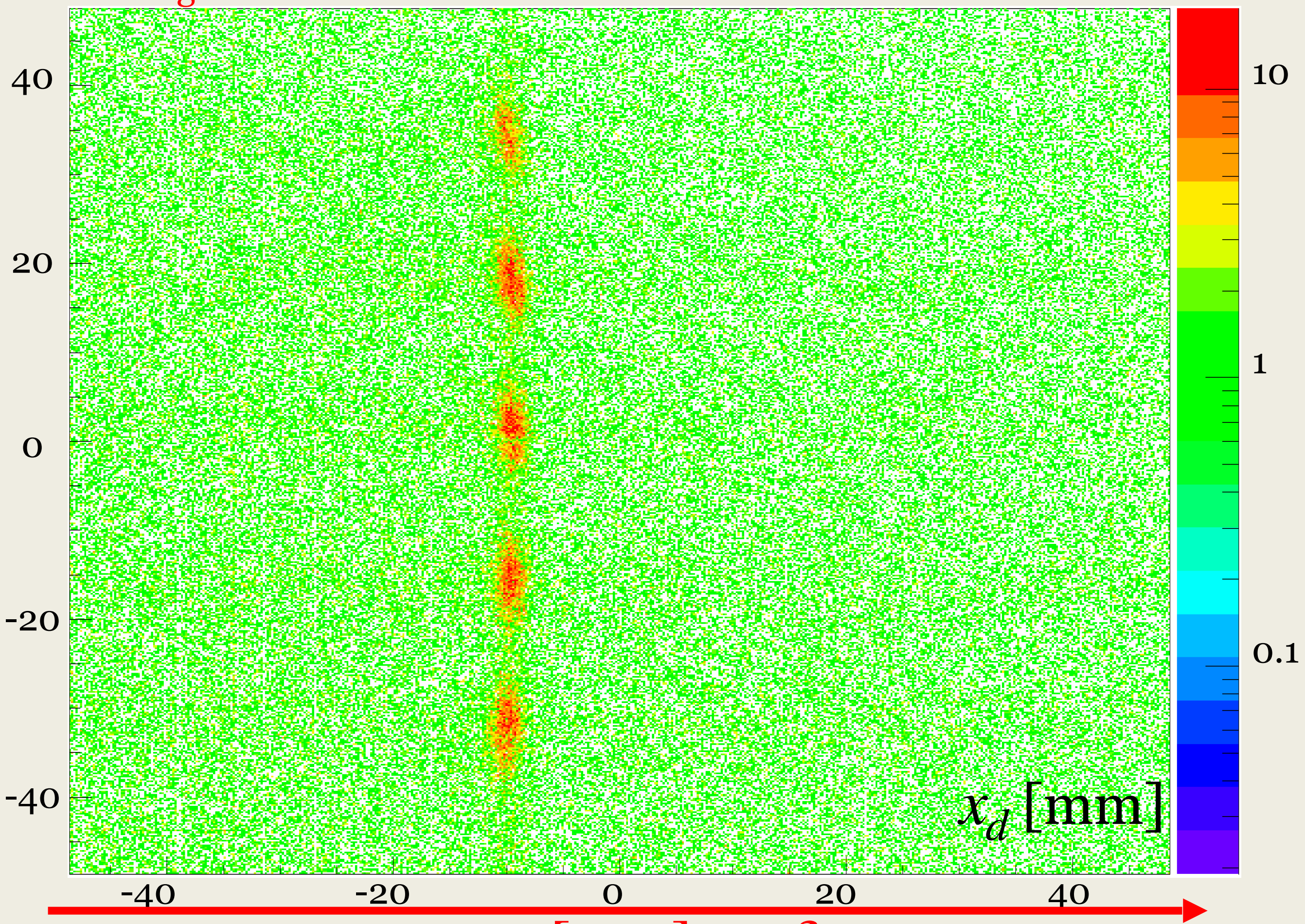

y_d [mm] $\rightarrow \Delta\theta = \theta - \theta_s$

$\delta \sim -0.05$ $\quad x_d$ [mm] $\rightarrow \delta$ $\quad \delta \sim 0.05$

Momentum dispersion Angular dispersion

Relation between (x_d, y_d) and (P', θ):

$$x_d = (x_d|\delta)\delta + \ldots$$

$$y_d = (y_d|\Delta\theta)\Delta\theta + \ldots$$

$$\text{with } \delta = \frac{P' - P_c}{P_c}$$

$\propto B_C$ Spectrometer central momentum

Commissioning results:

$(x_d|\delta)$ = 864.8(3) mm

$(y_d|\Delta\theta)$ = 1.000(4) mm/mrad

$$\sigma_p = \frac{\Delta p}{p} = 5.6 \times 10^{-4}$$

→ **High resolution spectrometers!**

Q^2 determination

- From x_d, we get δ but not directly P' …
- The beam energy derived from the current of upstream magnets is not precise enough …
- To get E and P', use of C and H peaks:

1st order

$$x_X \sim (x_d|\delta)\frac{P'_X - P_c}{P_c}$$

$$R \equiv \frac{P'_C}{P'_H} \sim \frac{1 + \frac{x_C}{(x_d|\delta)}}{1 + \frac{x_H}{(x_d|\delta)}}$$

URL

$$P'_X \sim \frac{E}{1 + \frac{2E\sin\theta/2^2}{M_X}}$$

$$R \equiv \frac{P'_C}{P'_H} \sim 1 + 2E\sin\theta/2^2\left(\frac{1}{M_H} - \frac{1}{M_C}\right)$$

Determination of the beam energy directly from the experimental data!

Precise determination of Q^2!