JOHANNES GUTENBERG UNIVERSITÄT MAINZ

SFB 1044 THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Workshop to Explore Physics Opportunities with Intense, Polarized Electron Beams up to 300 MeV
MIT, Cambridge, Massachusetts, March 2013

# Project P2
# The weak charge of the proton

D. Becker, K. Gerz, S. Baunack, K. Kumar, F. E. Maas
Institute for Nuclear Physics
JGU Mainz

MAMI MAINZER MIKROTRON

PS1C: Kathrin Gerz: “Measurement of Weinberg Angle via electron scattering from 12C-nuclei within the P2-experiment”

PS4C: David Balaguer Rios: “ Measurement of the parity violating asymmetry on deuterium and the axial form factor”

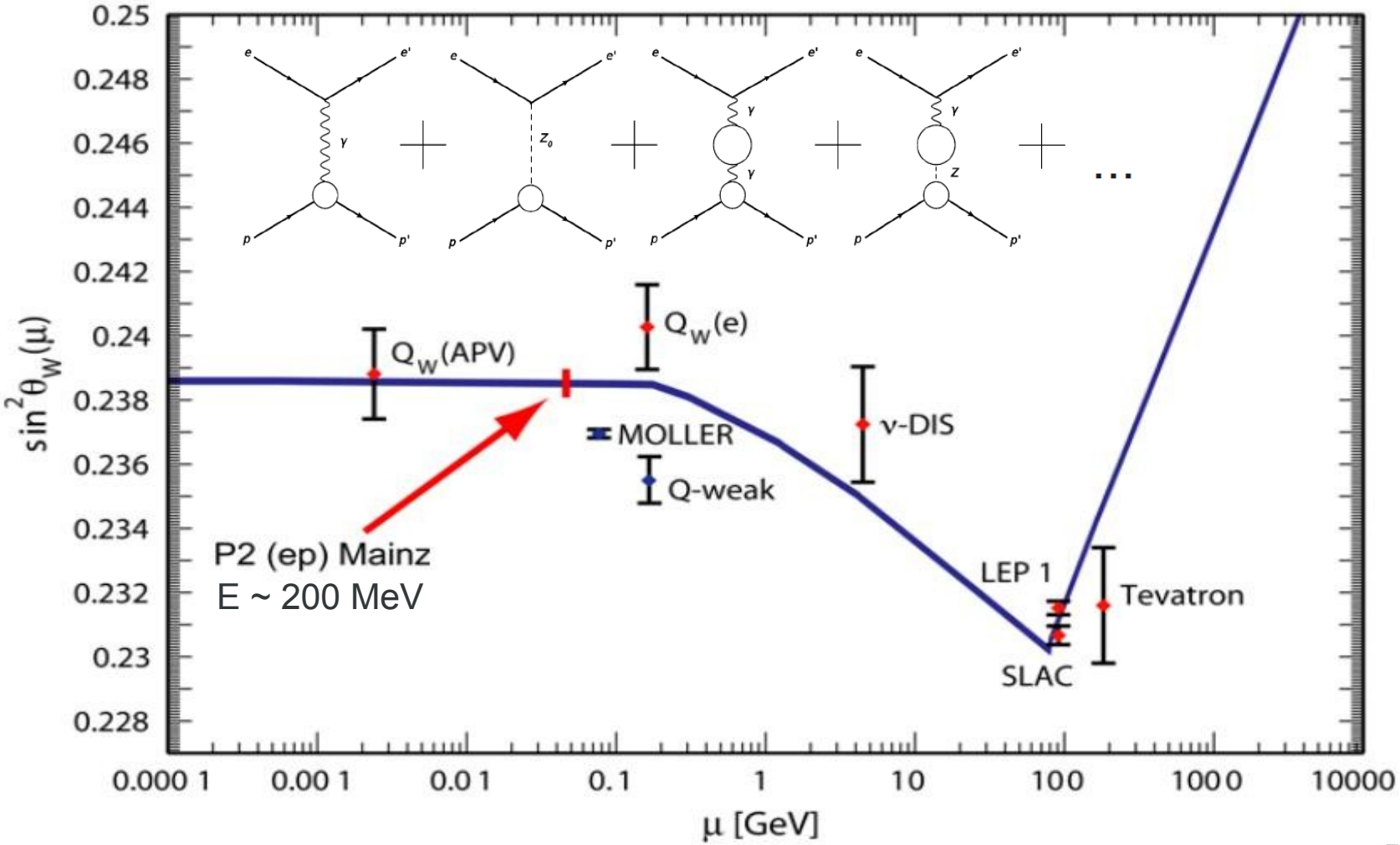
PRISMA

# Outline

- Brief introduction: A new high precision determination of the electroweak mixing angle
- Access to the weak mixing angle
- Achievable precision within P2
- Concept studies for the P2 experiment

# The electroweak mixing angle

At tree level: $Q_W(p) = 1 - 4 \cdot \sin^2(\theta_W)$




**P2 @ MESA/Mainz:**

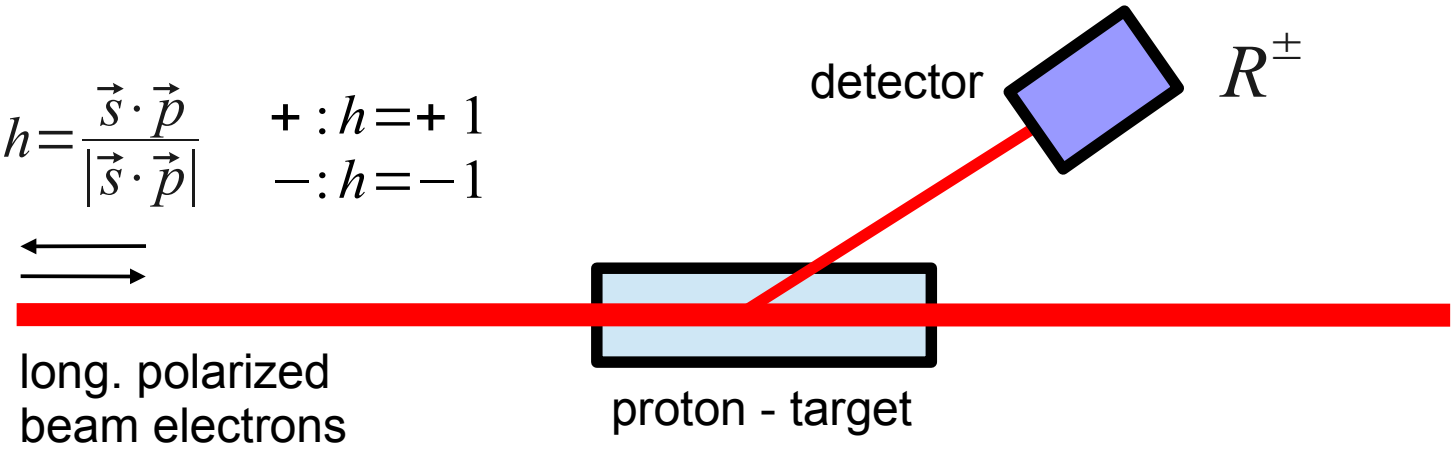
A new high precision measurement of $\sin^2(\theta_W)$:

$$\left(\frac{\Delta \sin^2(\theta_W)}{\sin^2(\theta_W)}\right) = 0.15\,\%$$

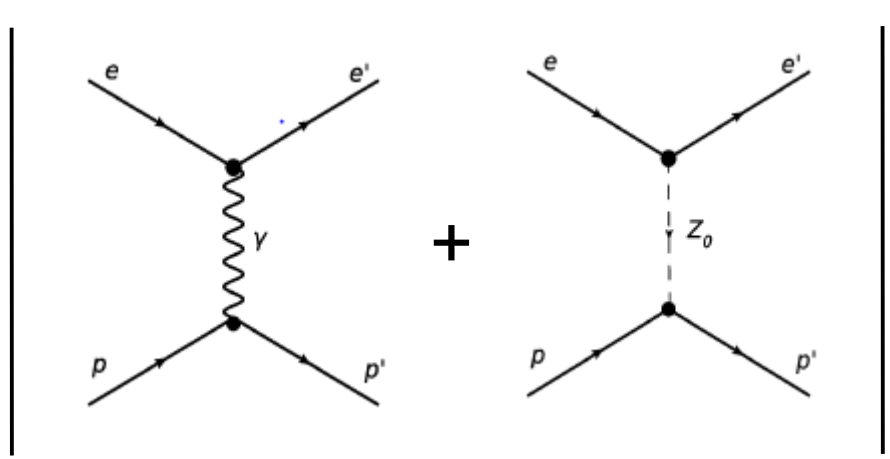
# Access to the weak mixing angle

# Elastic scattering of longitudinally polarized electrons off protons

$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|} \qquad \begin{array}{l} +: h = +1 \\ -: h = -1 \end{array}$$




Cross section: $\sigma_{ep} \sim$




$^2$ $\sim |M_\gamma + M_Z|^2$

The weak interaction is **parity violating**: $\sigma^+_{ep} \neq \sigma^-_{ep}$

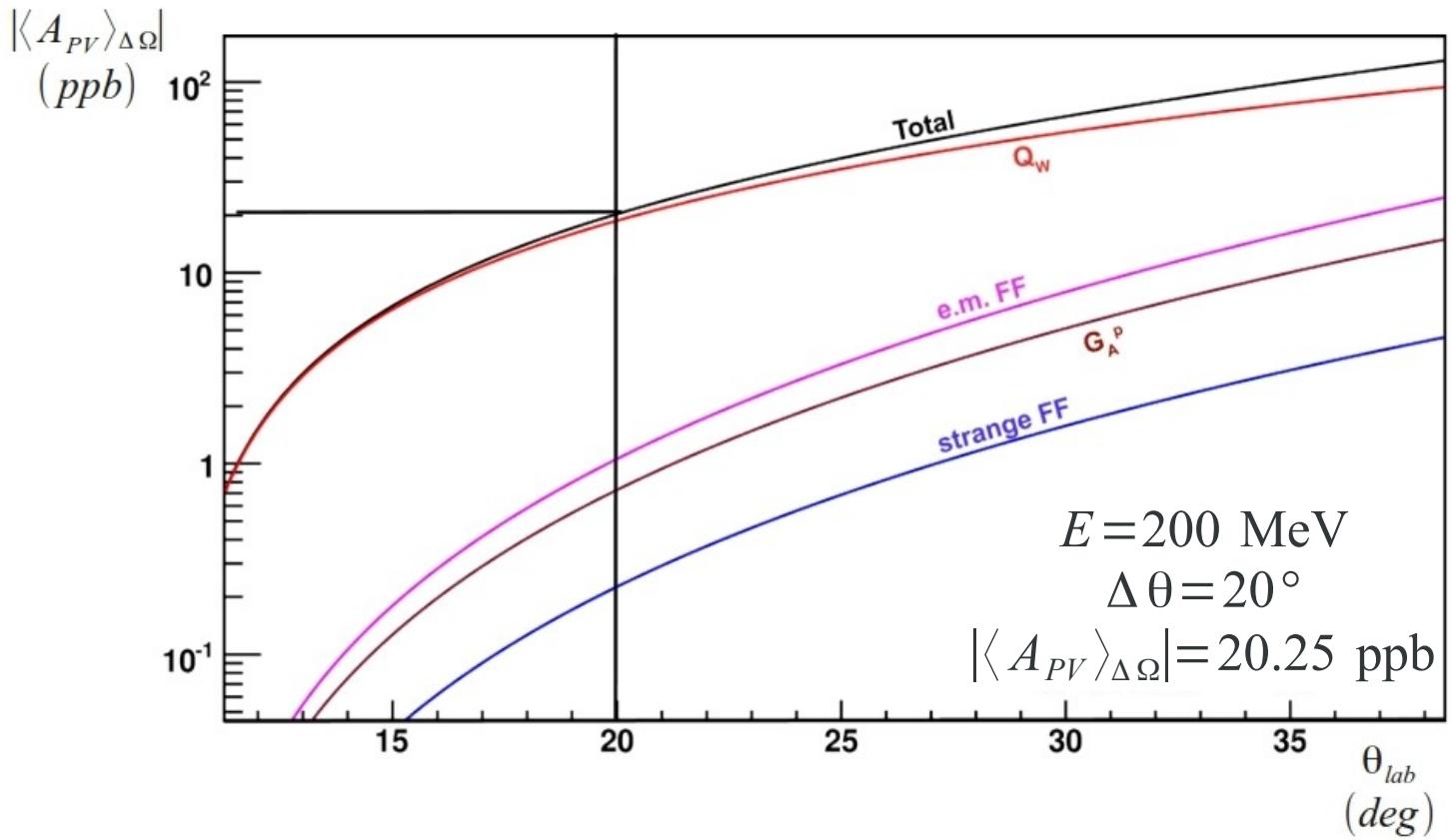
Define **parity violating asymmetry**: $A_{PV} = \dfrac{\sigma^+_{ep} - \sigma^-_{ep}}{\sigma^+_{ep} + \sigma^-_{ep}}$

# The parity violating asymmetry in elastic e-p-scattering

$$A_{PV} = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha} \cdot \left(Q_W(p) - F(Q^2)\right)$$

Proton structure: $F(Q^2) = F_{EM}(Q^2) + F_{Axial}(Q^2) + F_{Strange}(Q^2)$

Weak charge of the proton: $Q_w(p) = 1 - 4\sin^2(\theta_W)(\mu)$

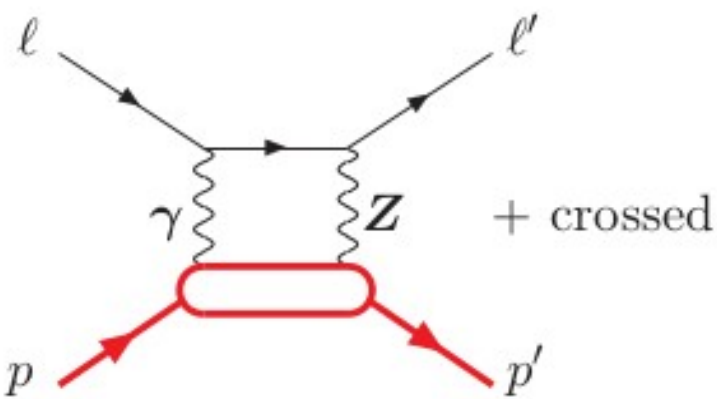



→ Measuring $A_{PV}$ at low momentum transfer $Q^2$ gives access to $Q_W(p)$.

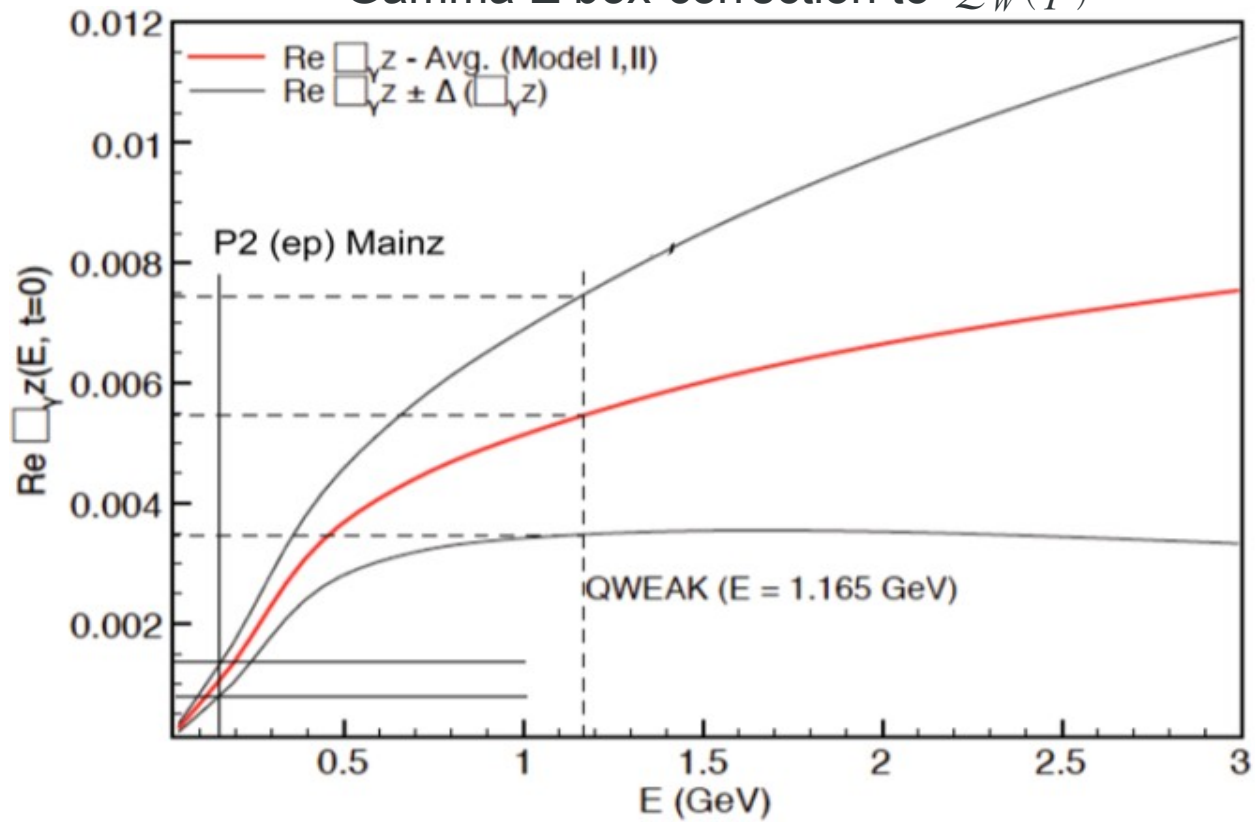
# Why measure at low beam energies?

$$Q^2 = 4EE'\sin^2(\theta_{lab}/2)$$

Low $Q^2$ : Lower beam energy and larger angle or vice versa?




Gamma-Z box-correction to $Q_W(p)$

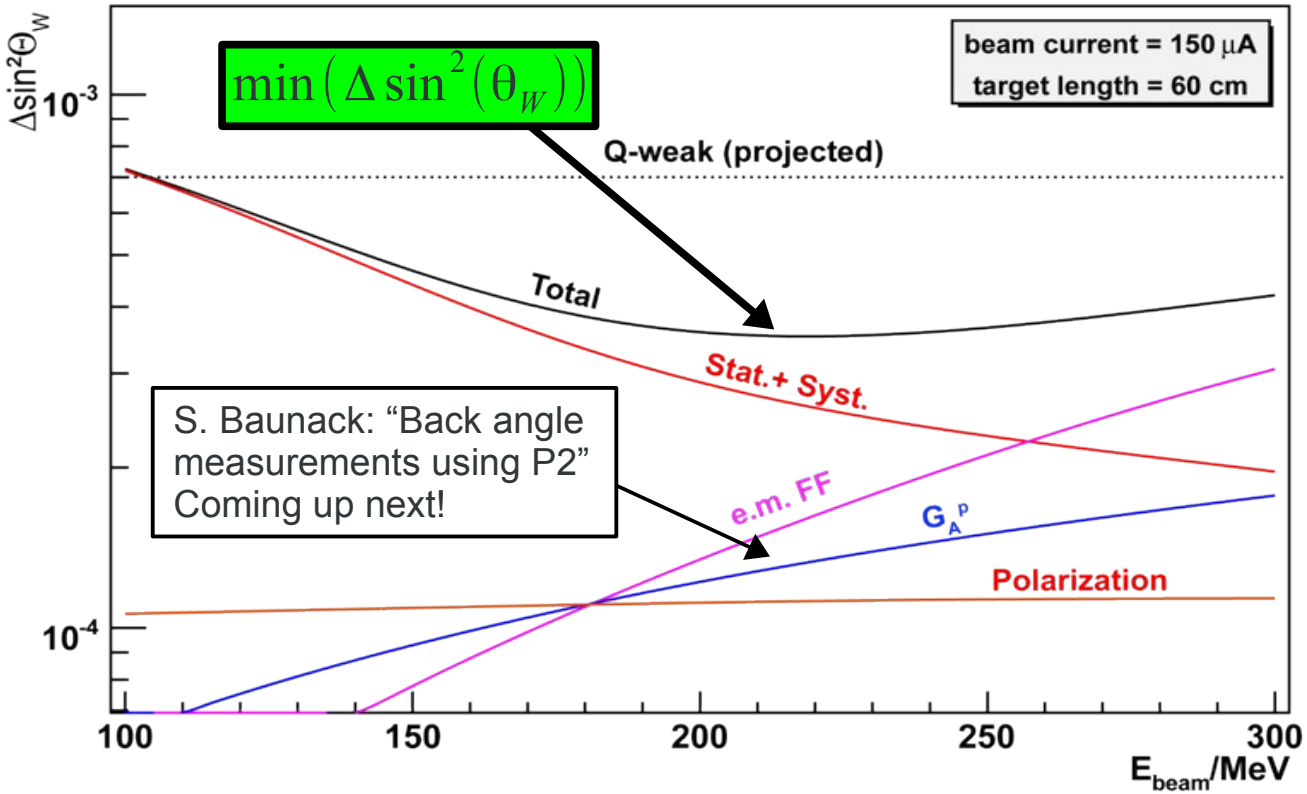



Gorchtein, Horowitz, Ramsey-Musolf 1102.3910 [nucl-th]

→ At low energies, the uncertainties of Gamma-Z-boxgraph contributions to $\sin^2(\theta_W)$ are negligible

# Achievable precision within P2

# Achievable precision @ P2




Proposed experimental conditions:

- Beam energy: 200 MeV
- Beam current: 150 μA
- Polarization: $85\,\% \pm 0.5\,\%$
- $\theta_{lab} = 20\,° \pm 10\,°$
- $\Delta\Phi = 2\pi$
- Target: 60 cm liquid hydrogen
- Measuring time: 10000 h

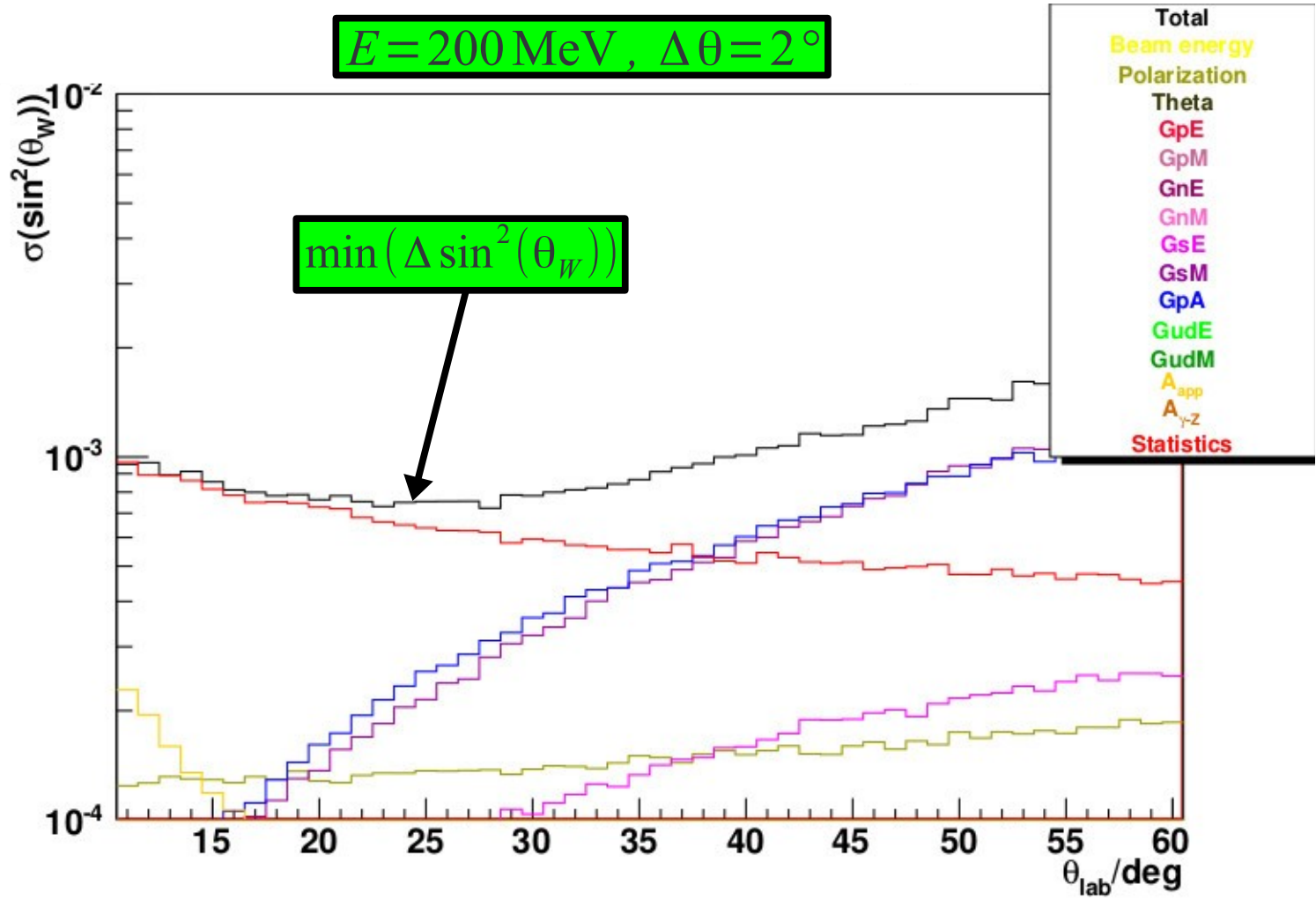
| | |
|---|---|
| $Q^2$ | 0.0029 $GeV^2$ |
| $A_{phys}$ | -20.25 ppb |
| $\Delta A_{tot}$ | 0.34 ppb (1.7 %) |
| $\Delta A_{stat}$ | 0.25 ppb (1.2 %) |
| $\Delta A_{sys}$ | 0.19 ppb (0.9%) |
| Rate | 0.44 $10^{12}$ Hz |
| $\Delta\sin^2\theta_{W\ stat}$ | 2.8 $10^{-4}$ |
| $\Delta\sin^2\theta_{W\ tot}$ | 3.6 $10^{-4}$ (0.15 %) |

# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

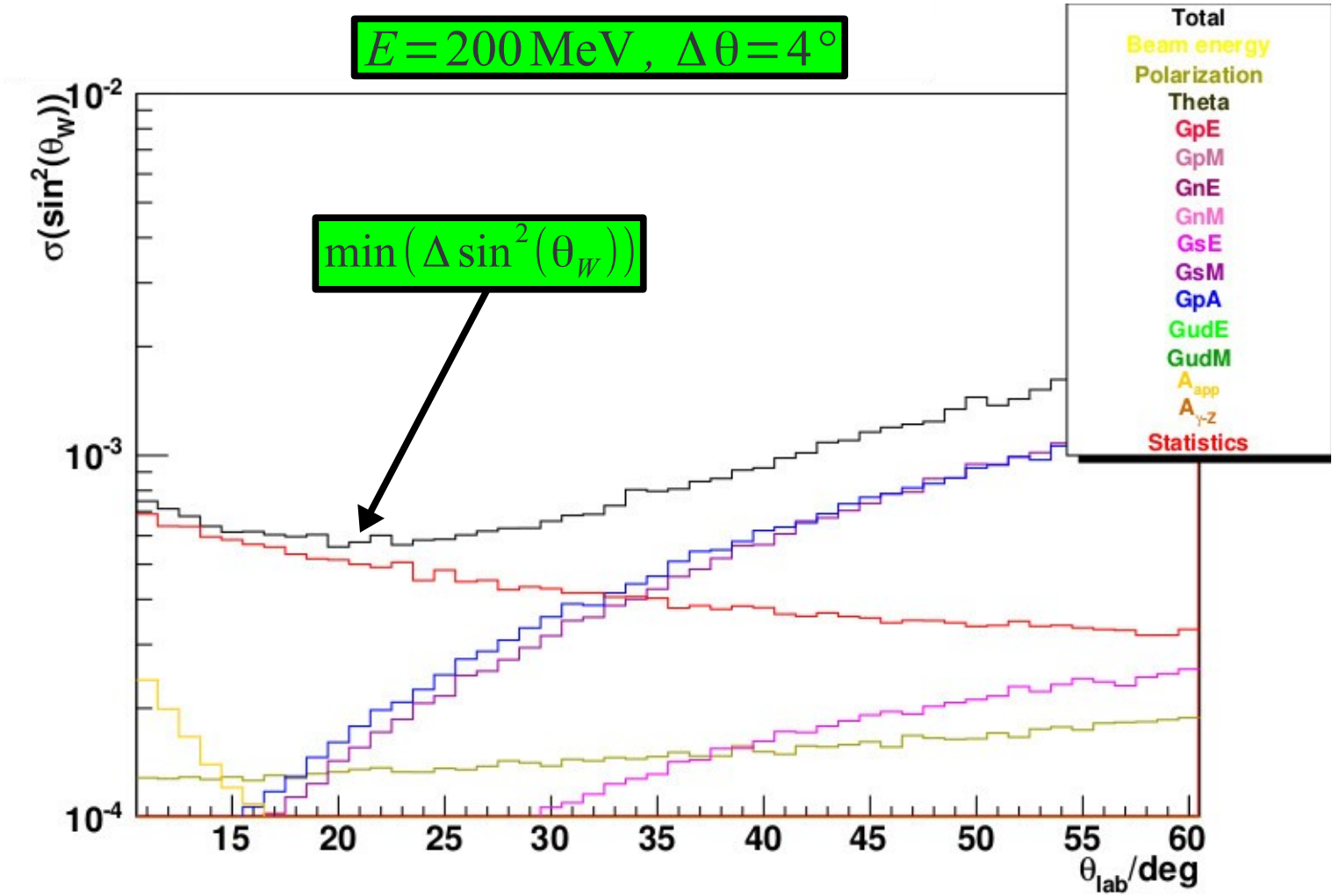


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

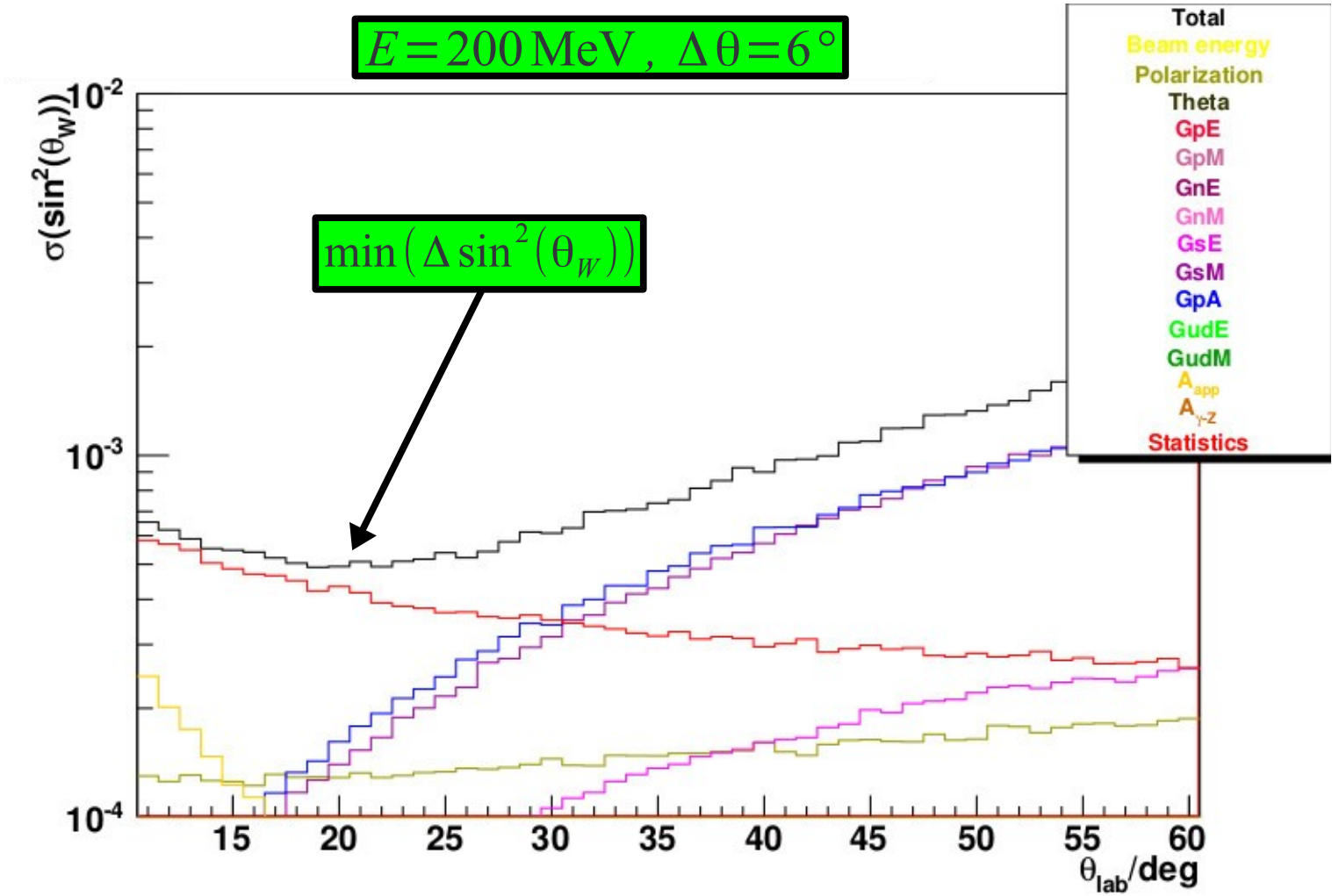


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

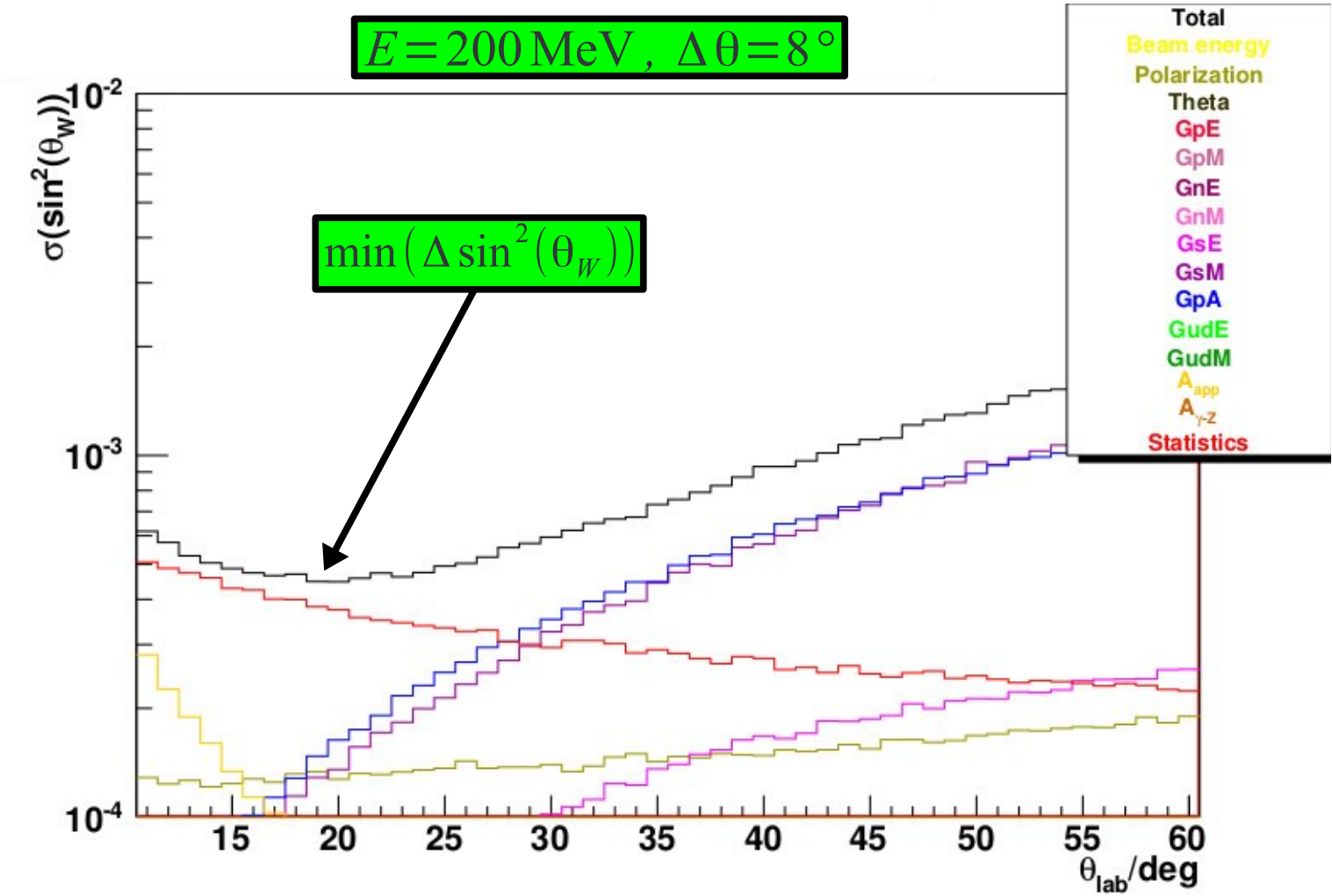


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

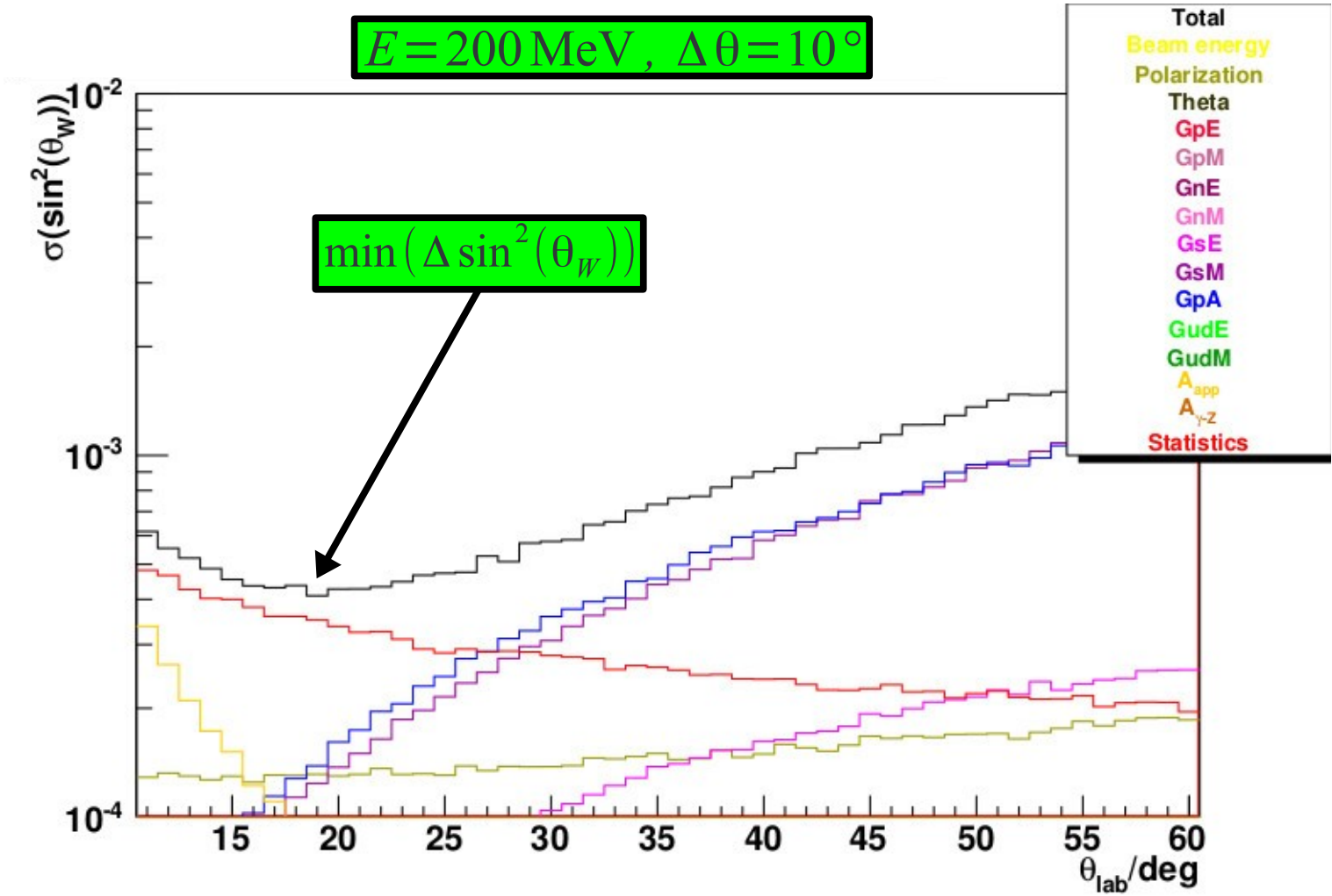


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

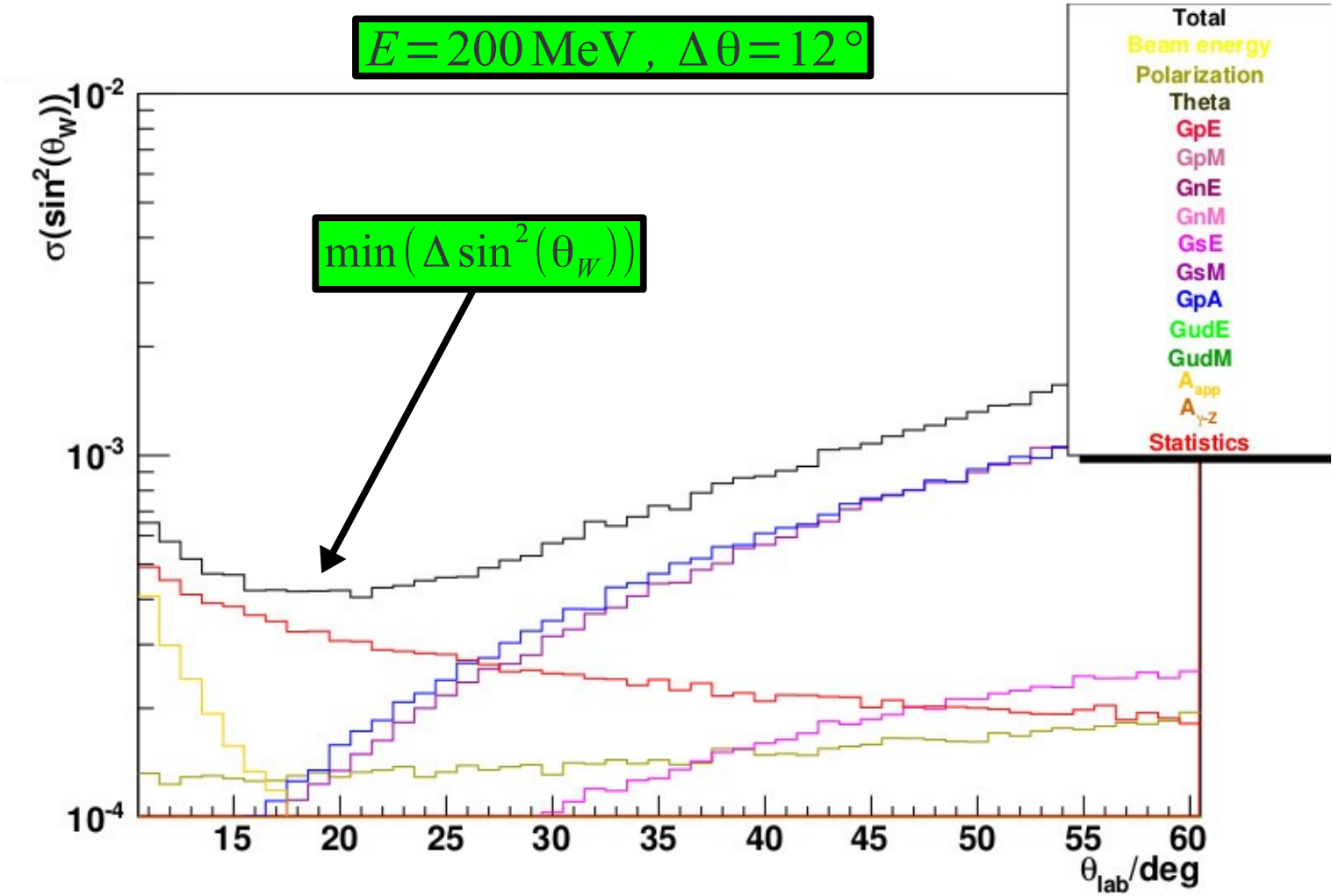


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

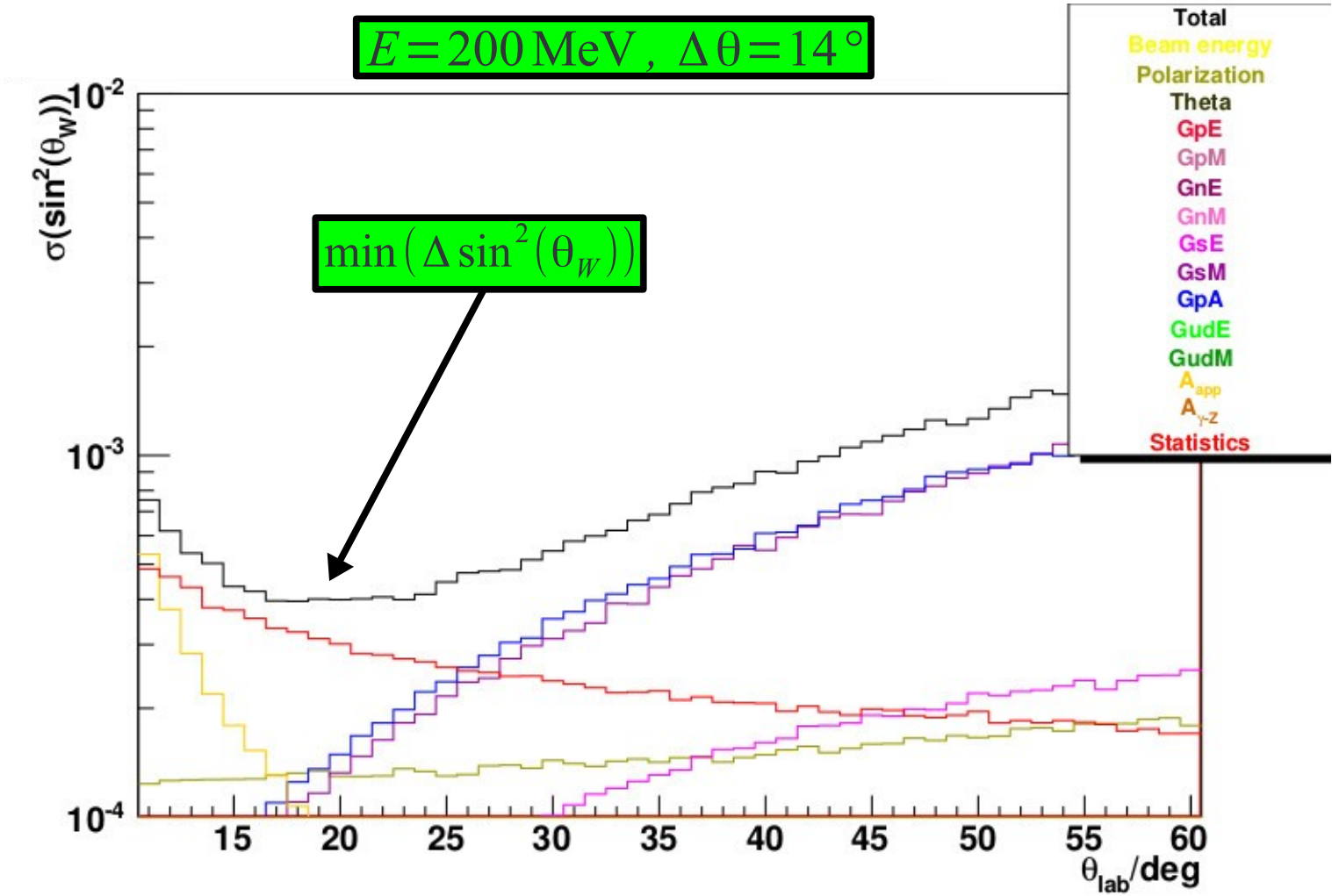


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

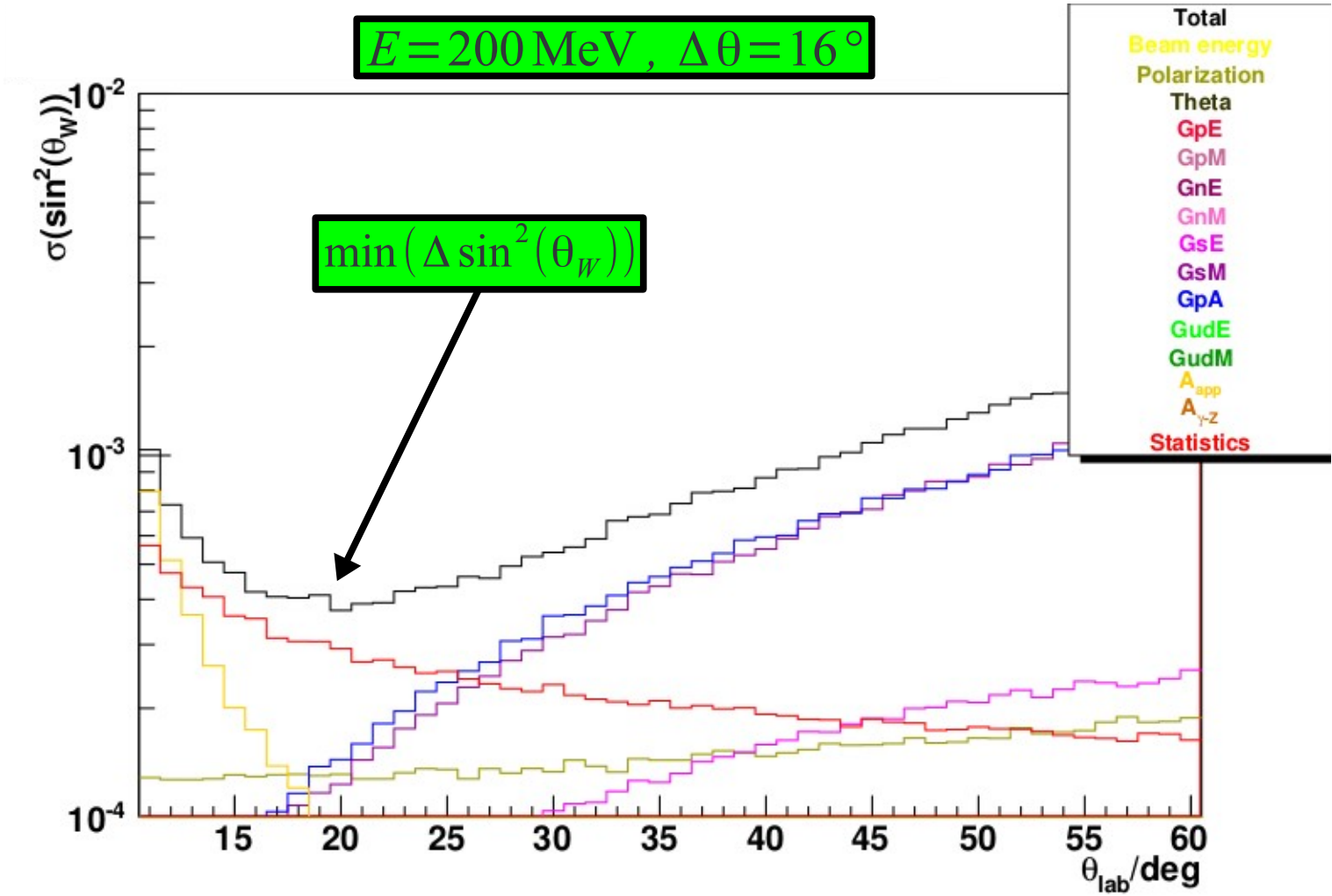


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

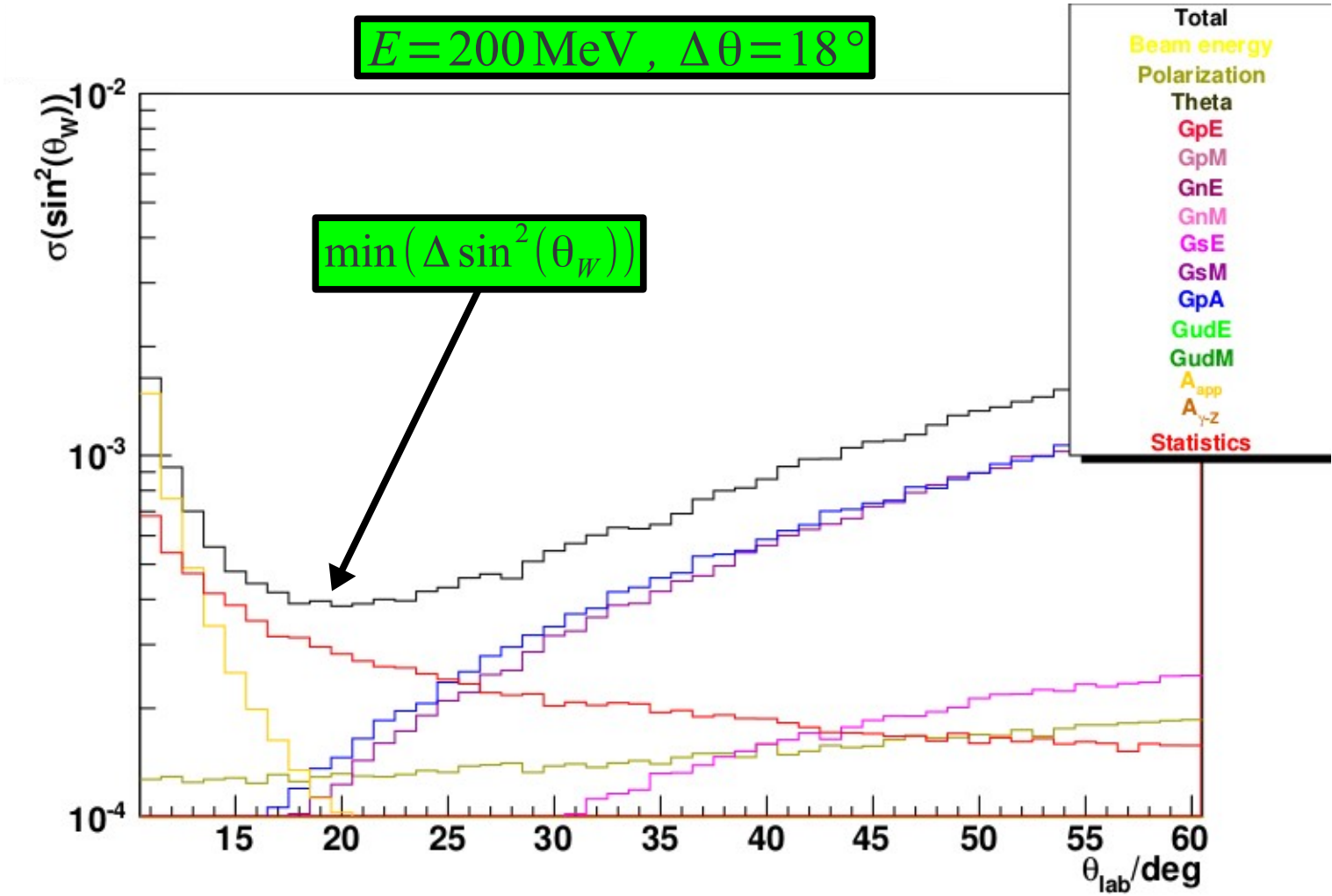


# Achievable precision @ P2

## Systematic variation of experimental conditions:

- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!

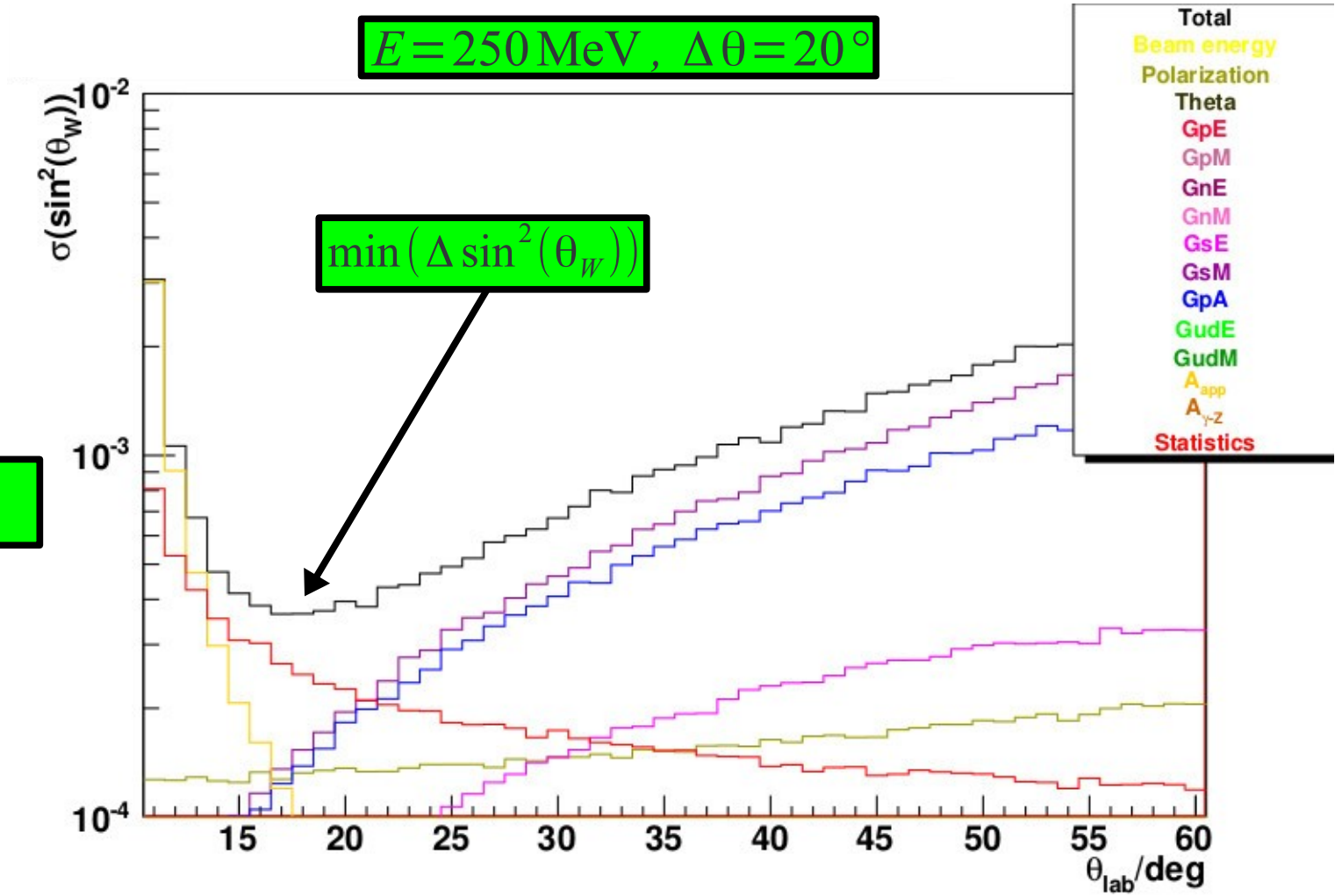


# Achievable precision @ P2

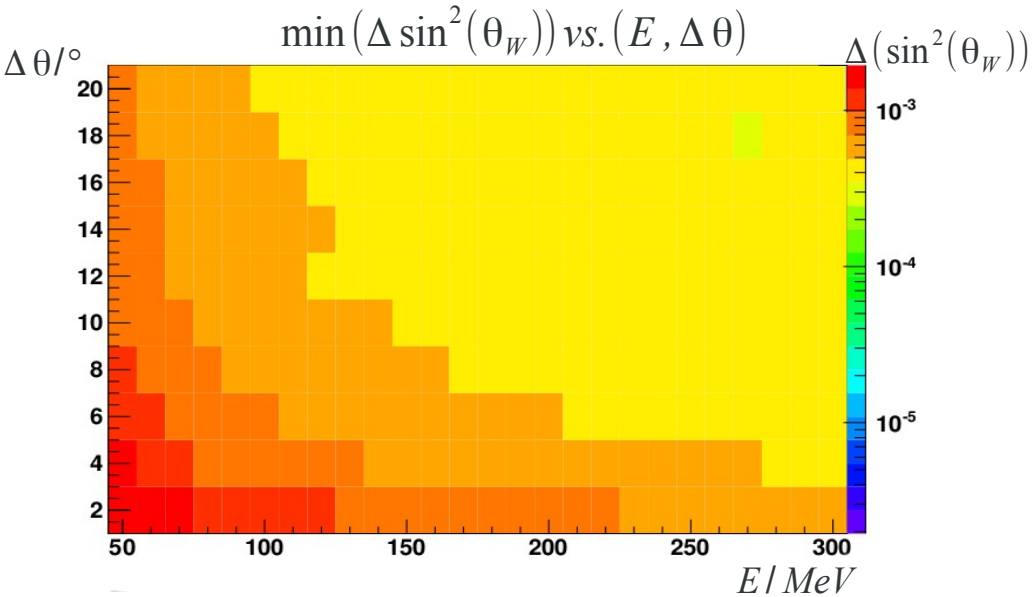
## Systematic variation of experimental conditions:

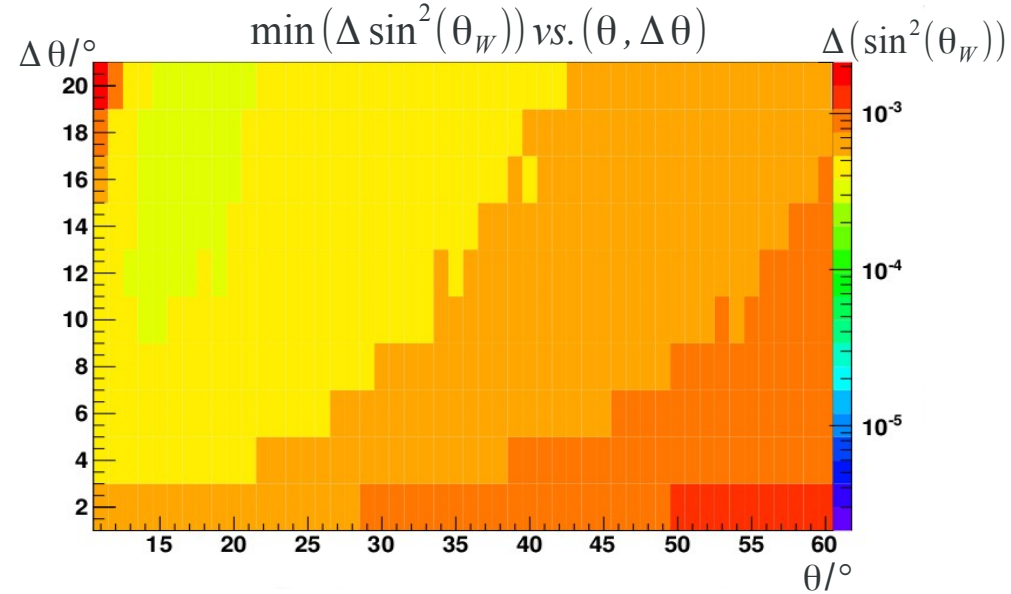
- Beam energy
- Central scattering angle
- Solid angle

All in all: 763 plots!



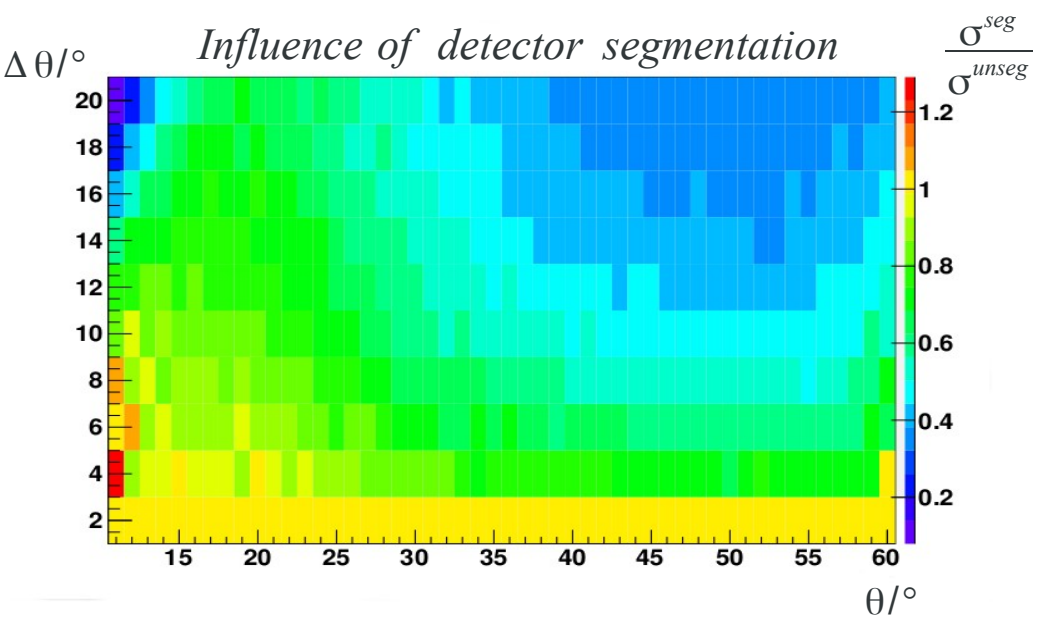
# Extensive scan of $\Delta(\sin^2(\theta_W))$ in $(E, \theta, \Delta\theta)$



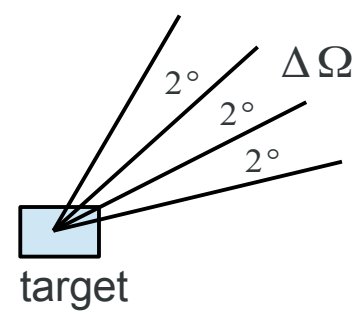

Broad energy region with $3\cdot10^{-4} \leqslant \Delta(\sin^2(\theta_W)) \leqslant 4\cdot10^{-4}$

$(E = 150\,\mathrm{MeV},\ \theta = 24°) \Leftrightarrow (E = 200\,\mathrm{MeV},\ \theta = 20°)$




$$\frac{\text{“Analyzing power not averaged over solid angle”}}{\text{“Analyzing power averaged over solid angle”}}$$

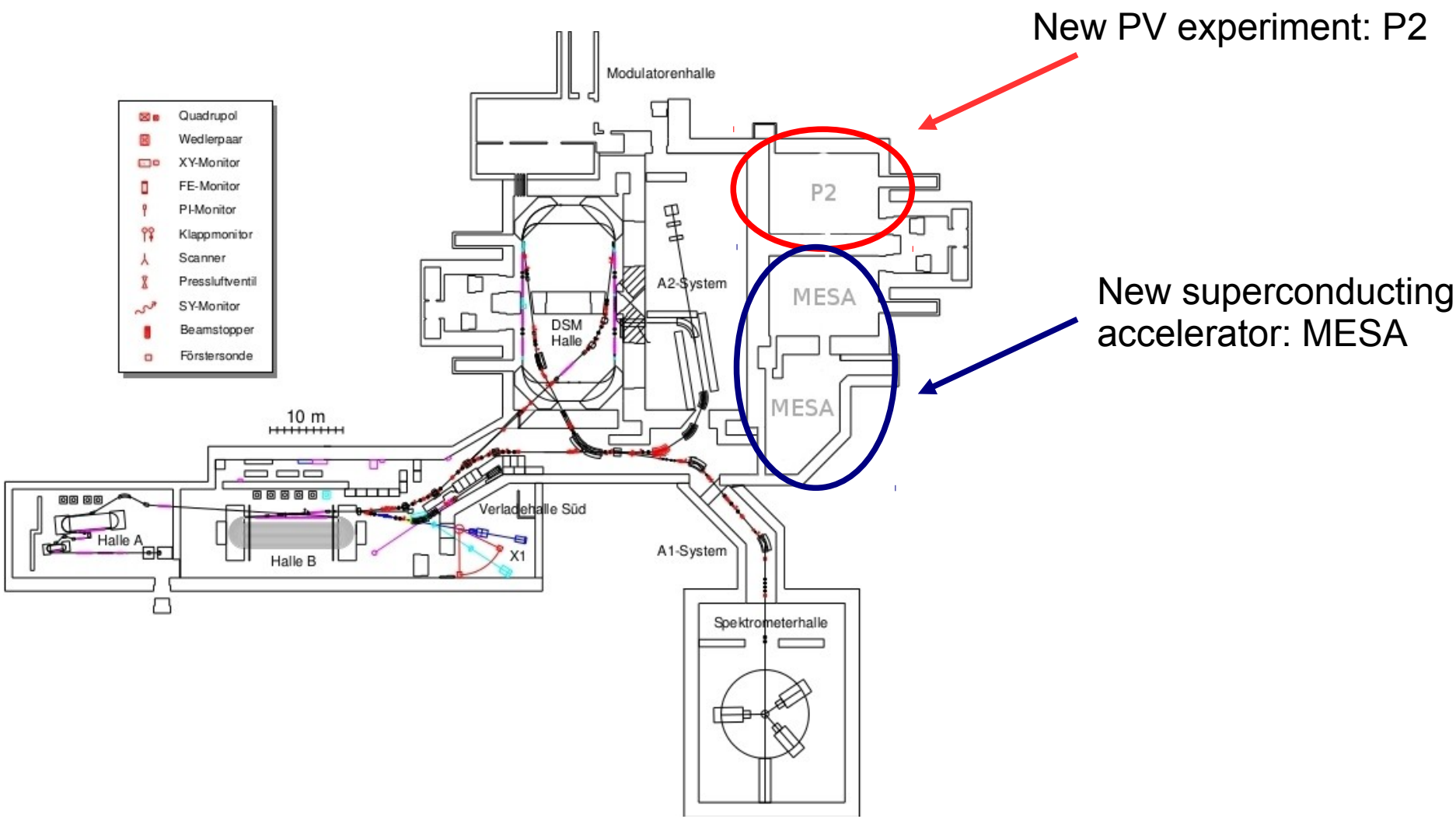
Segmentation:




Possible gain of factor 0.8 in precision!

# Concept studies for the P2 experiment with Geant4 & ROOT

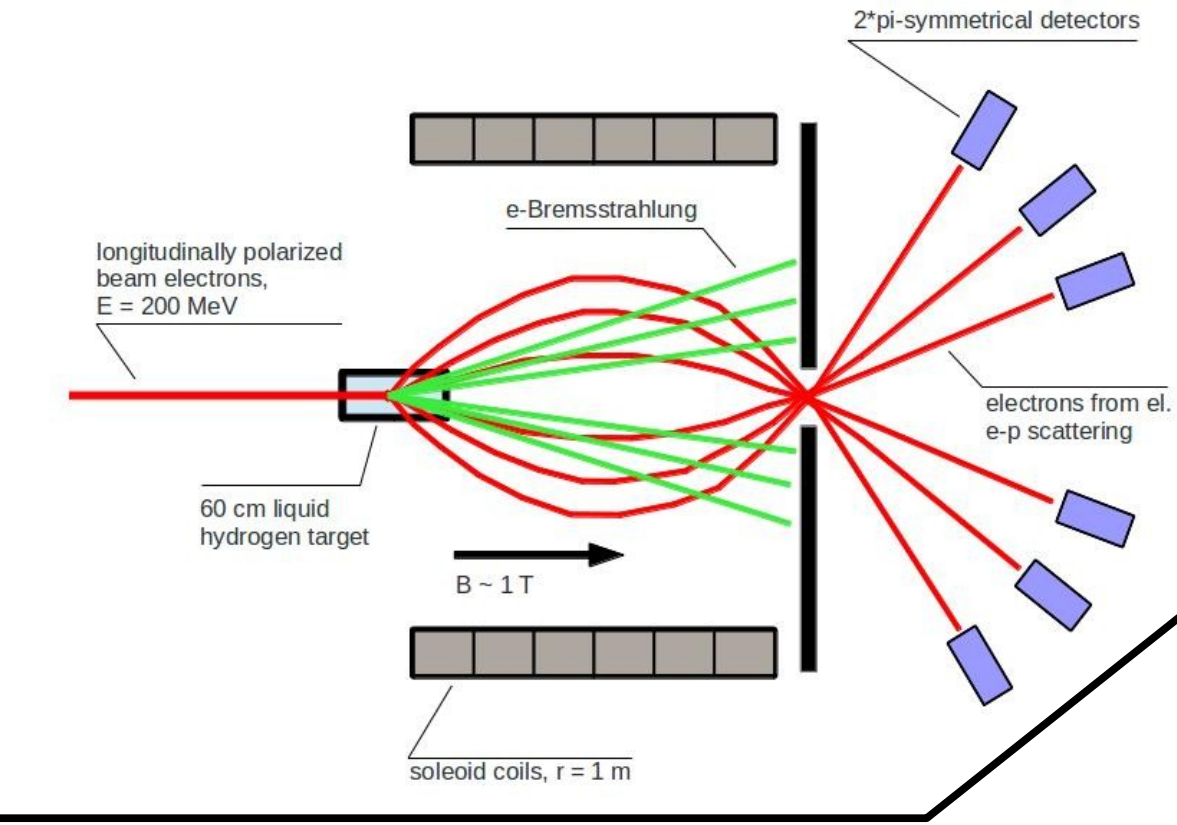
# MESA and P2: Setup in the MAMI accelerator facility




**beam current: 150 µA,**
**target length: 60 cm liquid hydrogen**

**→ dealing with high rates ~ 0.5 THz (el. e-p scattering)**
**→ integrating measurement**
**→ good separation from background (Moeller, Bremsstrahlung) needed**

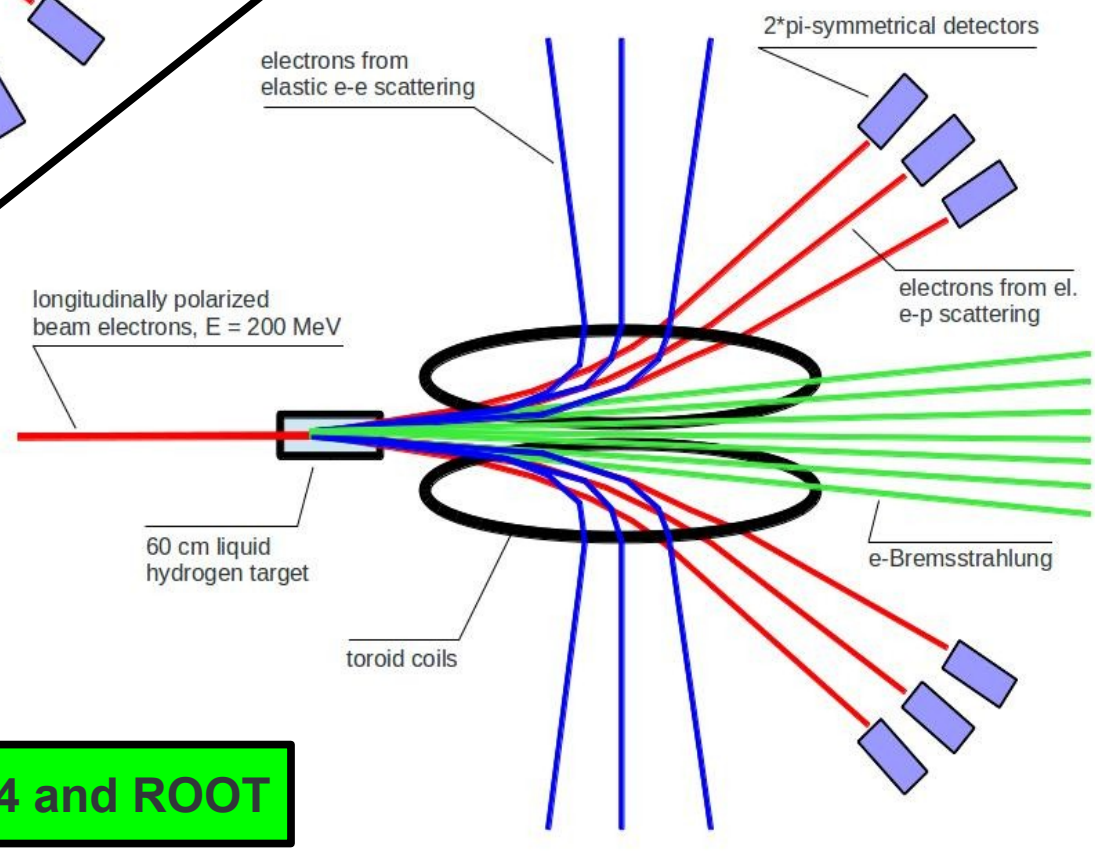
# Weapon of choice: Solenoid or Toroid?




**Solenoid:**

- Full azimuthal coverage
- Compact setup
- Superconducting coils

P. Souder in "Parity violation in electron scattering"
Proceedings of a workshop at CalTeck
Ed: E. J. Beise and R. D. McKeown
World Scientific, 1990

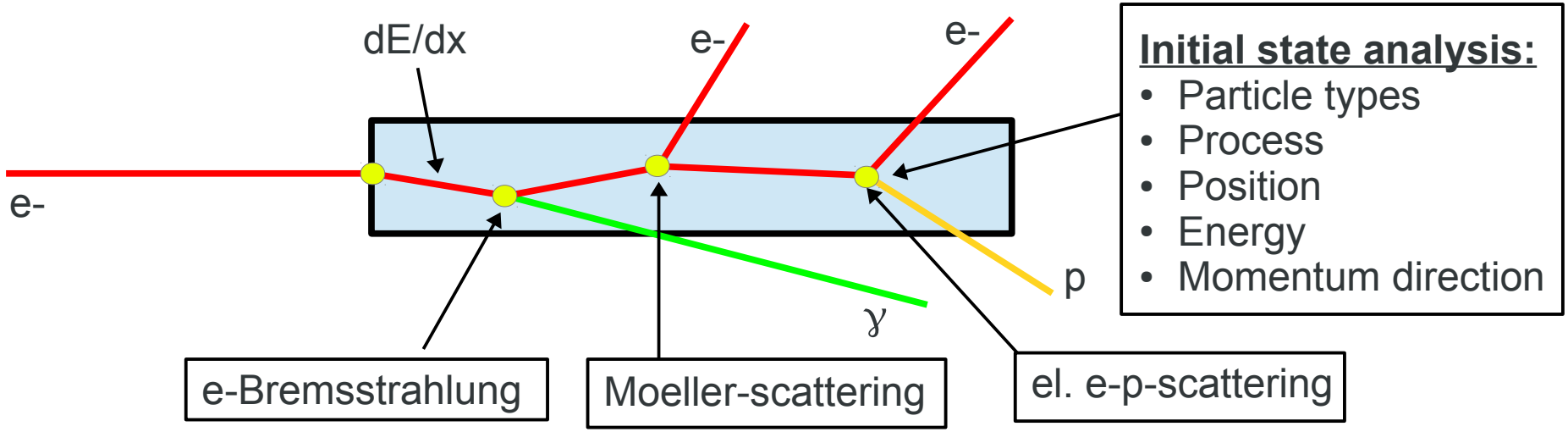



**Toroid:**

- Loss of ~50% solid angle
  → double measurement time
- Larger setup
- Copper coils

→ **Feasibility study with Geant4 and ROOT**

# Beam-target-interaction: Inital state generators



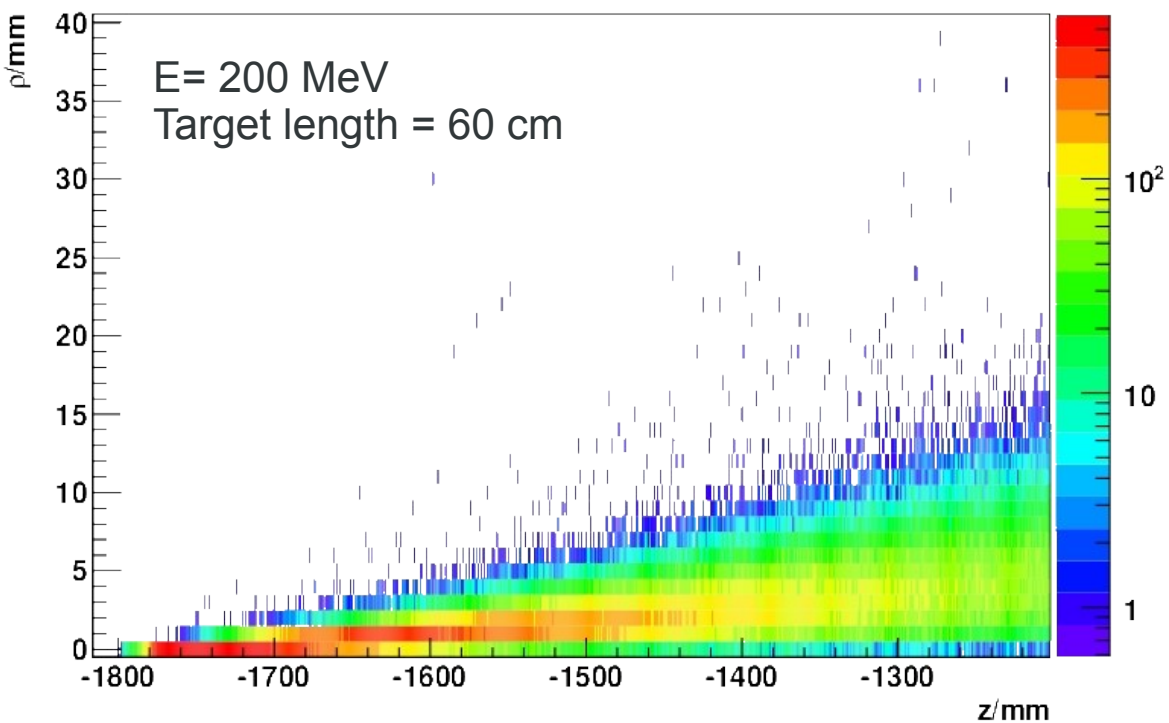

**Initial state analysis:**

- Particle types
- Process
- Position
- Energy
- Momentum direction

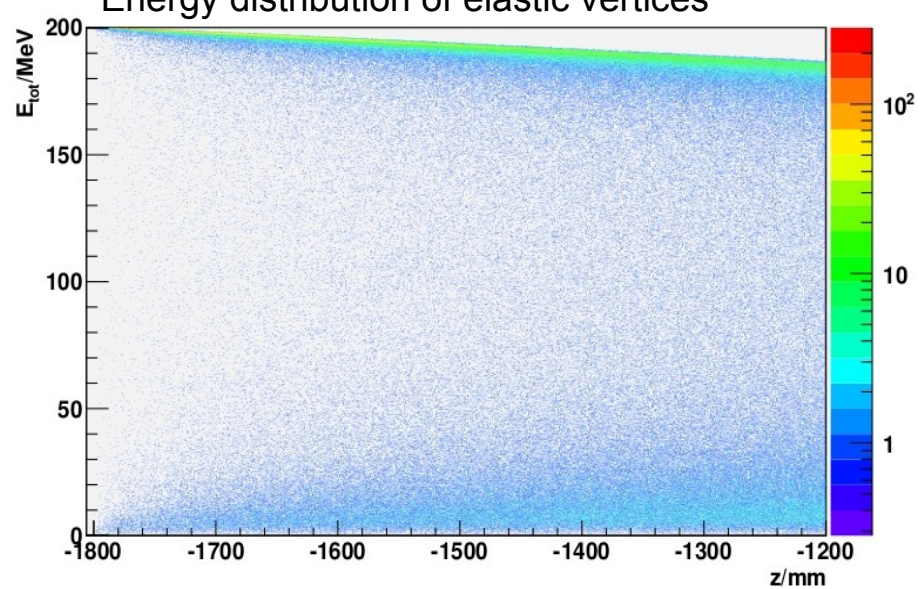
**Calculate realistic vertex distributions:**

- el. e-p-scattering
- Moeller-scattering
- e-Bremsstrahlung

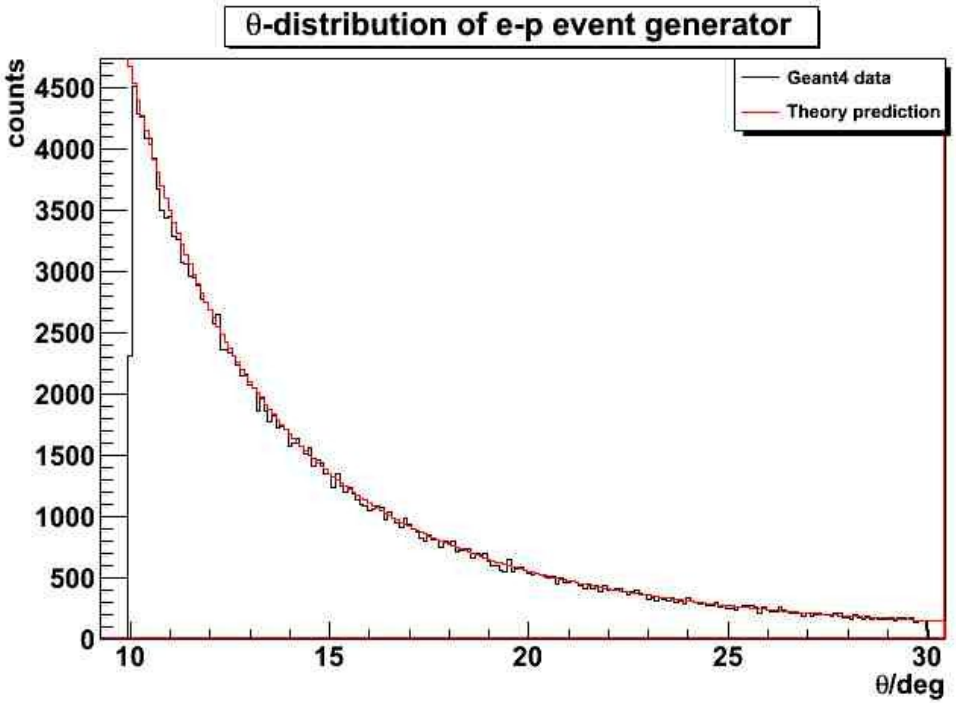
Density distribution of elastic vertices with electron energies between 180 MeV and 200 MeV

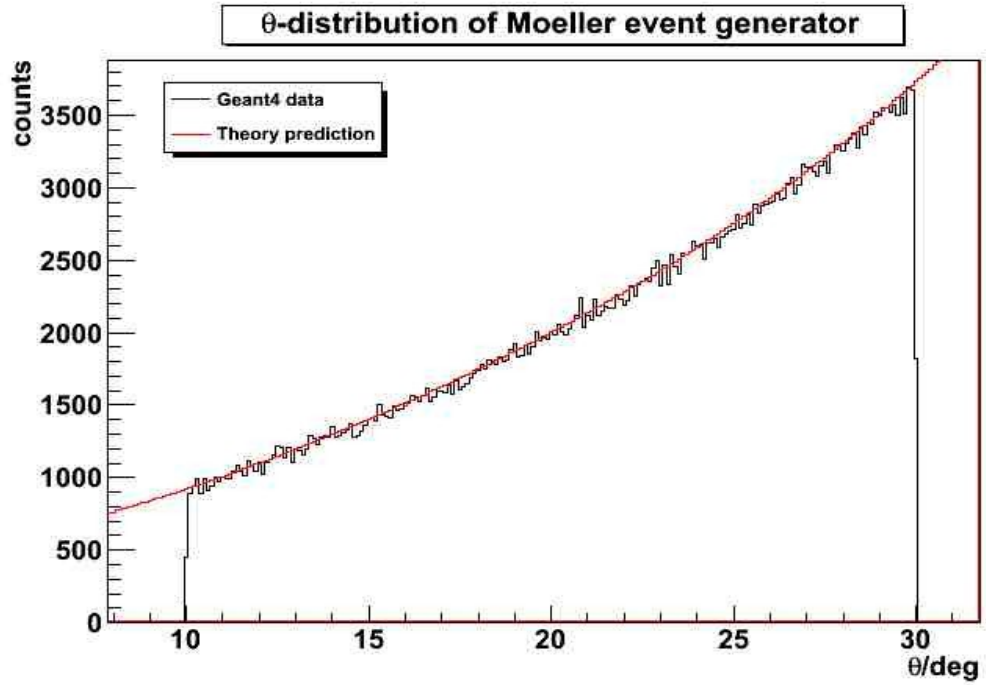


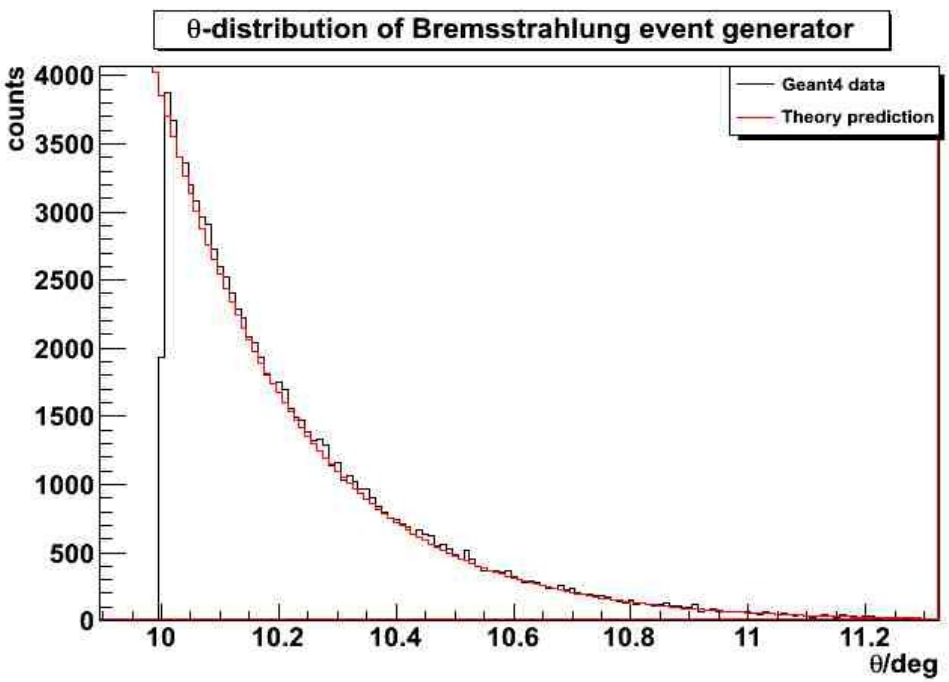

Energy distribution of elastic vertices



# For detector simulation: Validation of final state generators



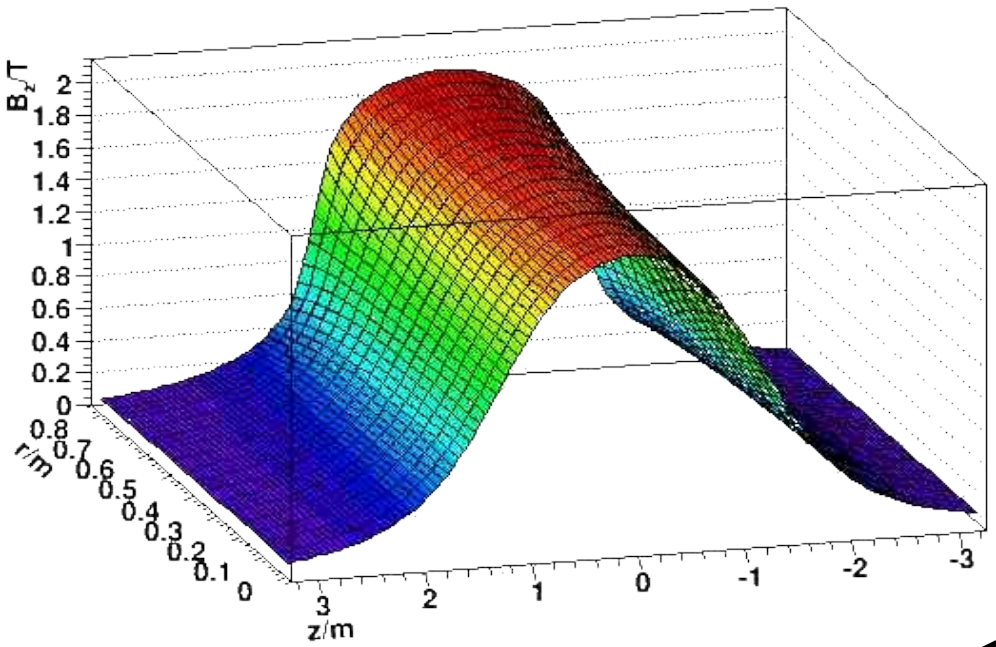




**Event generators for detector simulation:**

- el. e-p scattering
- Moeller scattering
- e-Bremsstrahlung

➔ Can use vertex distributions
➔ Generate events w.r.t preset solid angle

# Magnetic fieldmaps

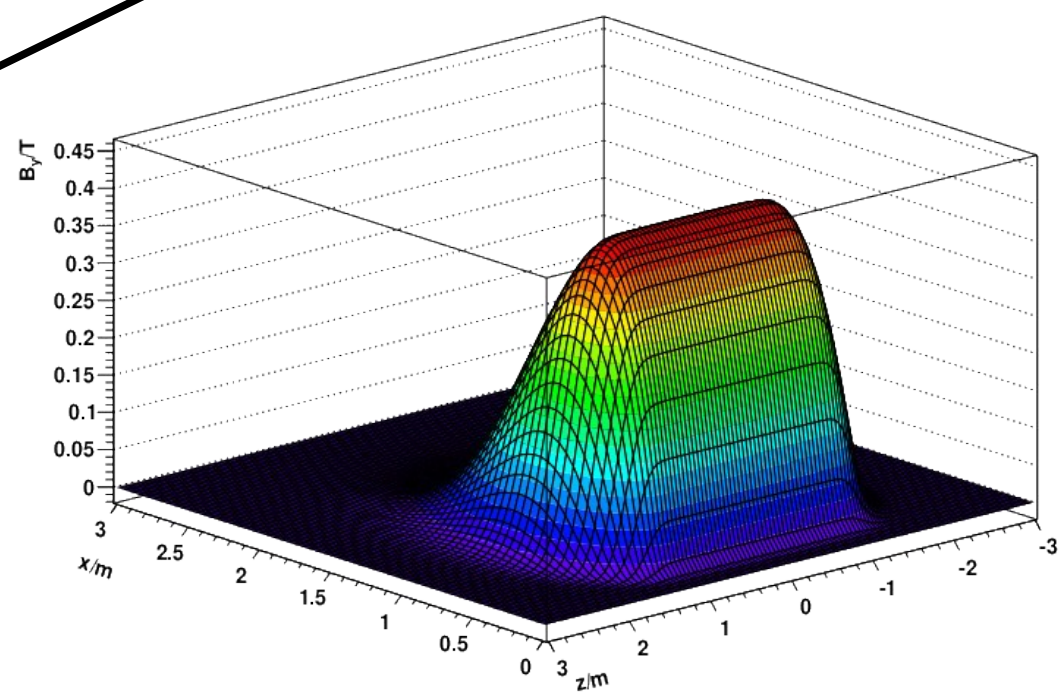



**ZEUS-like solenoid:**

- Biot-Savart calculation
- Coil radius ~ 1 m
- Coil length ~ 2.4 m
- B = 1.8 T

**QTOR-like toroid:**

- Biot-Savart calculation
- 8 coils
- Coil length ~ 3.6 m
- B = 0.4 T

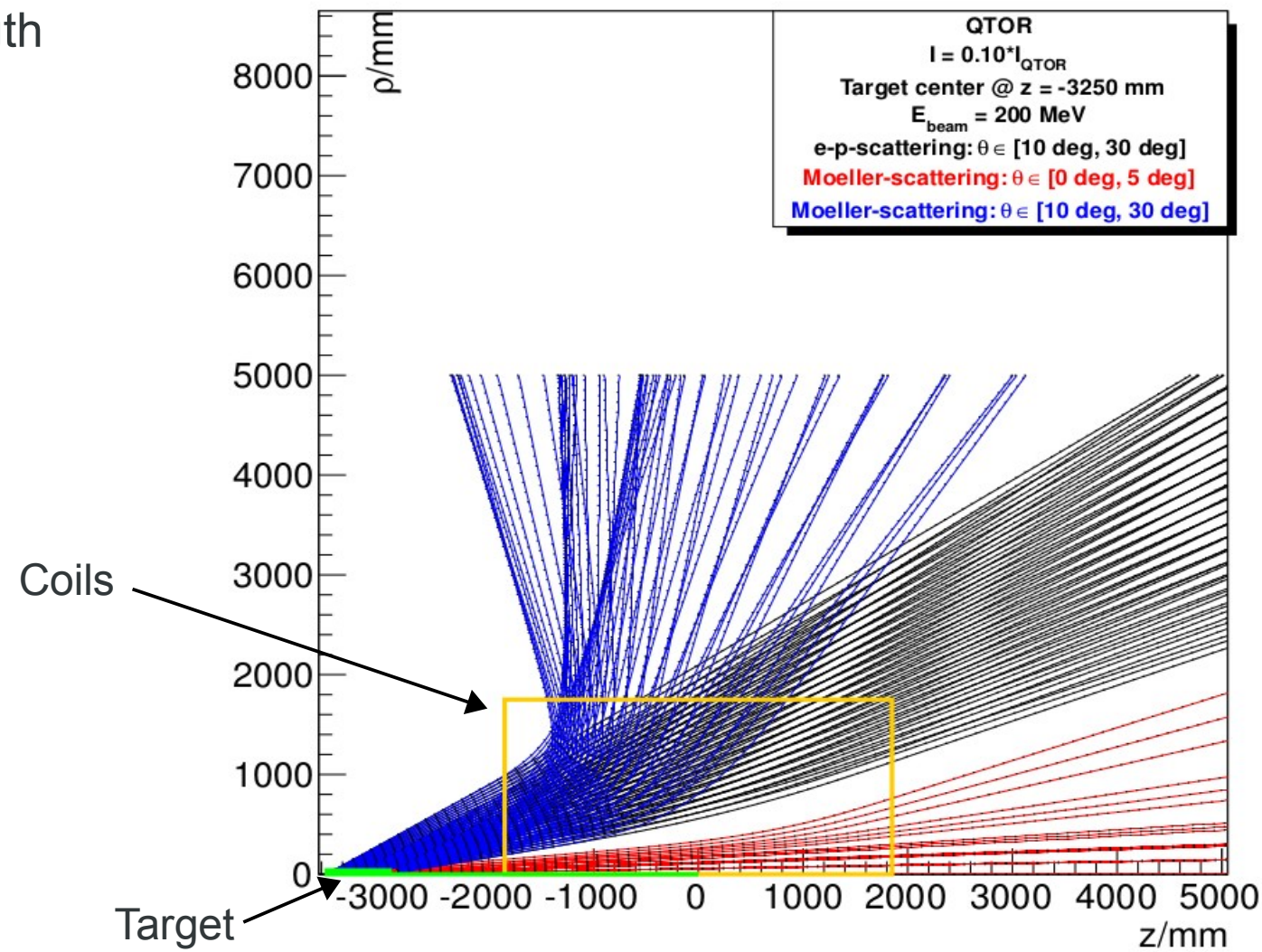


# Systematic raytrace scans

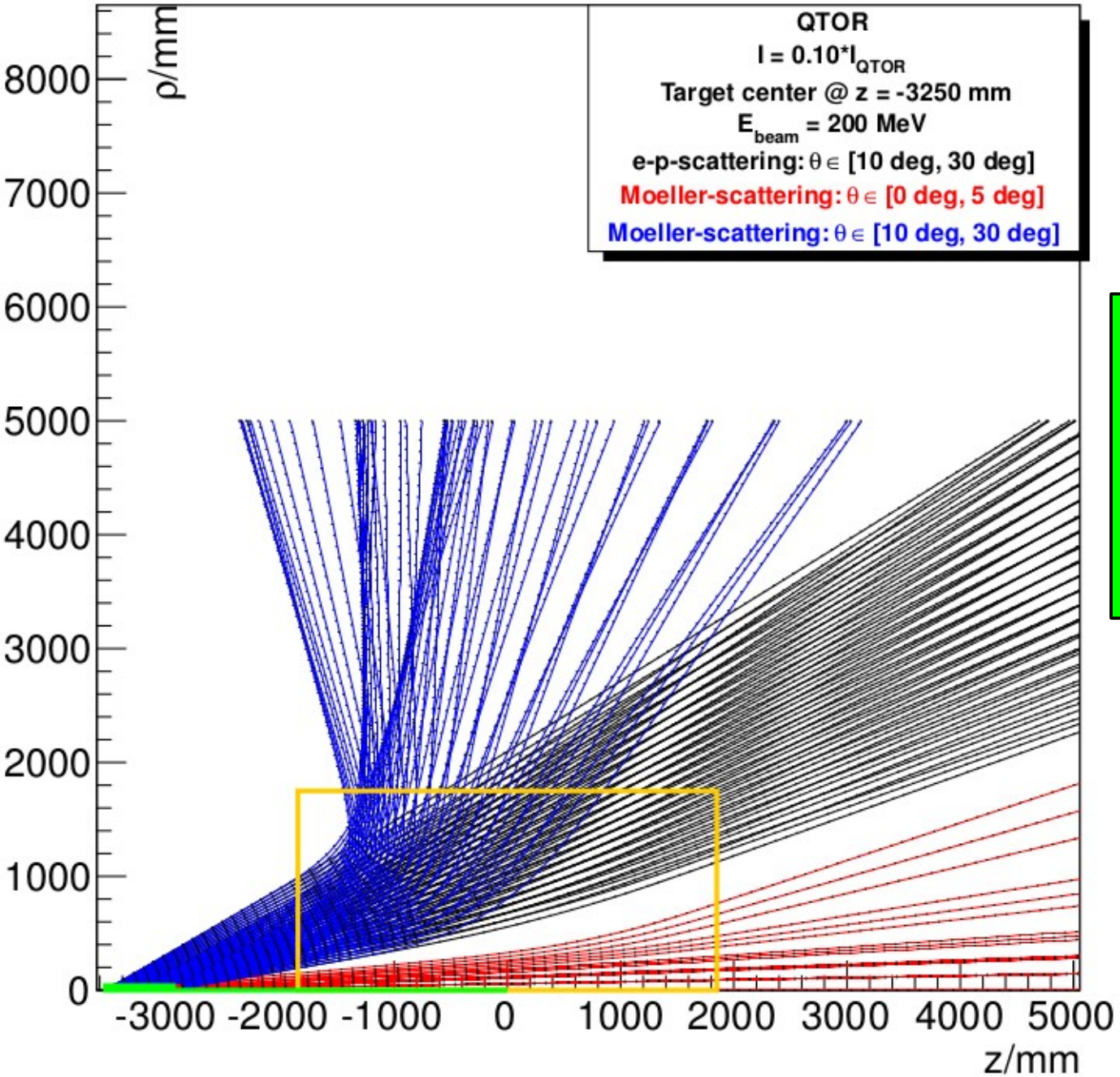
## For both solenoid and toroid: Raytrace scans varying

- Target position
- Target length (30 cm & 60 cm)
- Magnetic field strength
- Beam energy
- Solid angle

Projection of electron trajectories

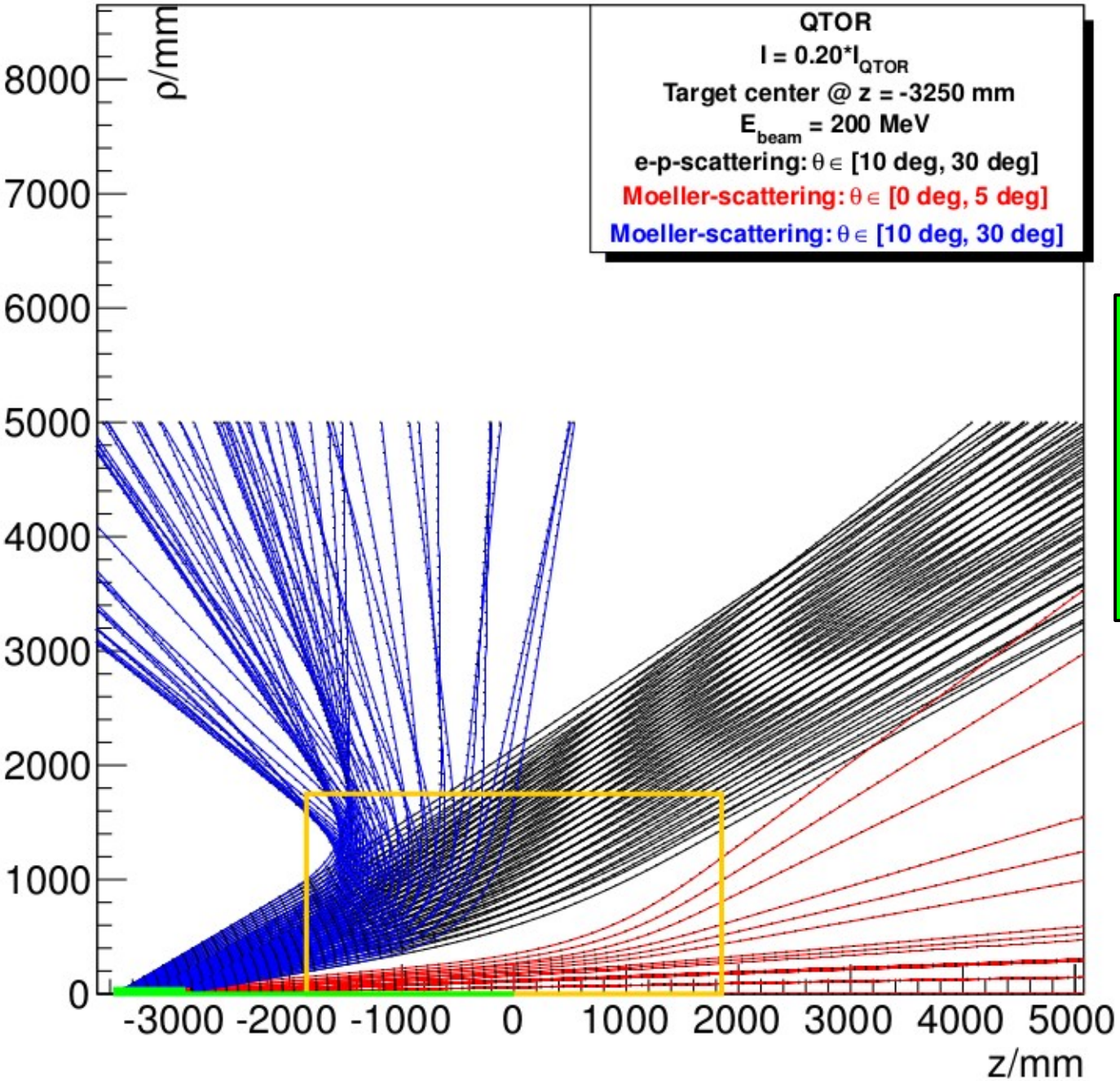


# Toroid simulation: Raytraces



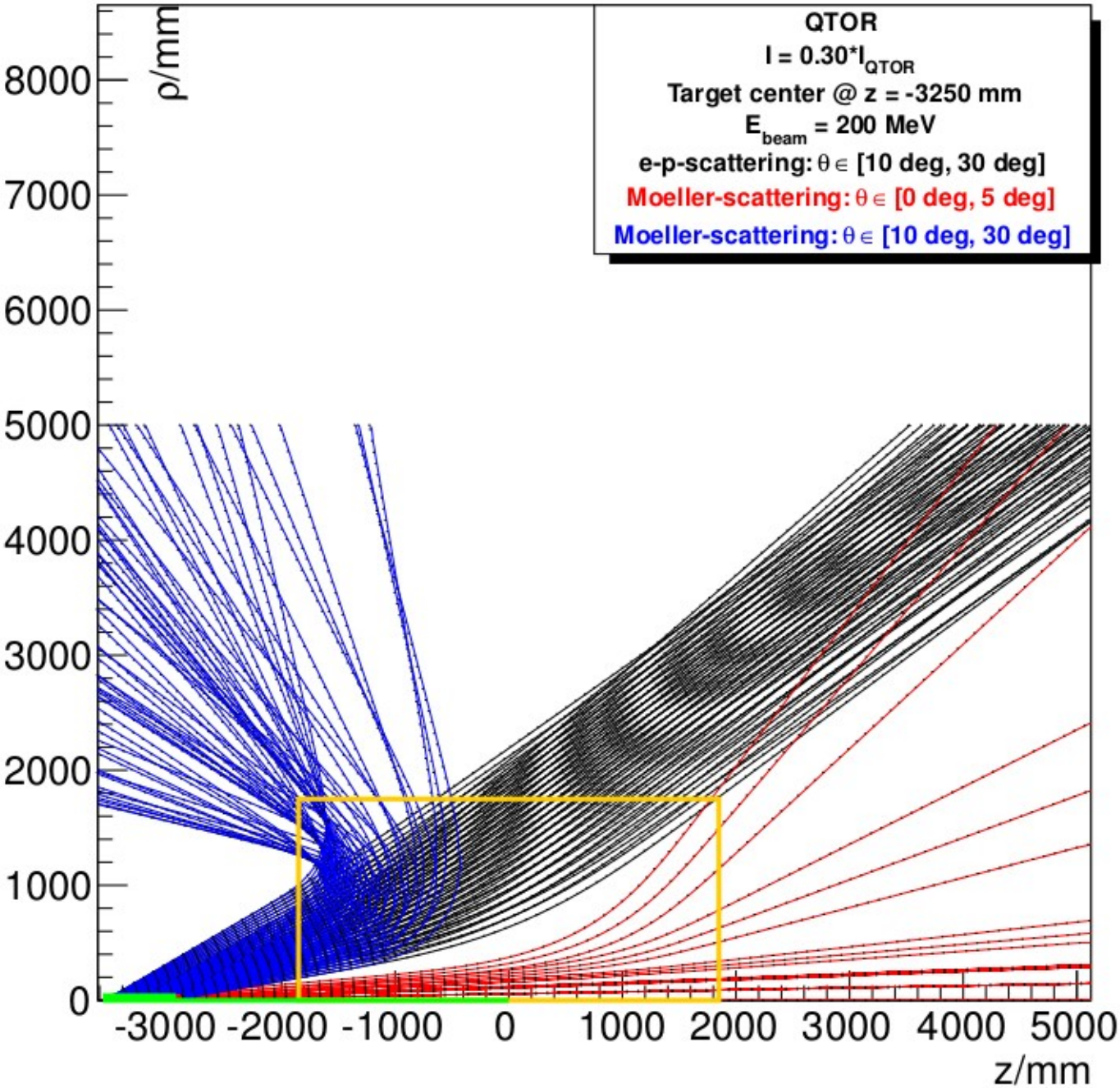

- B = 0.04 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



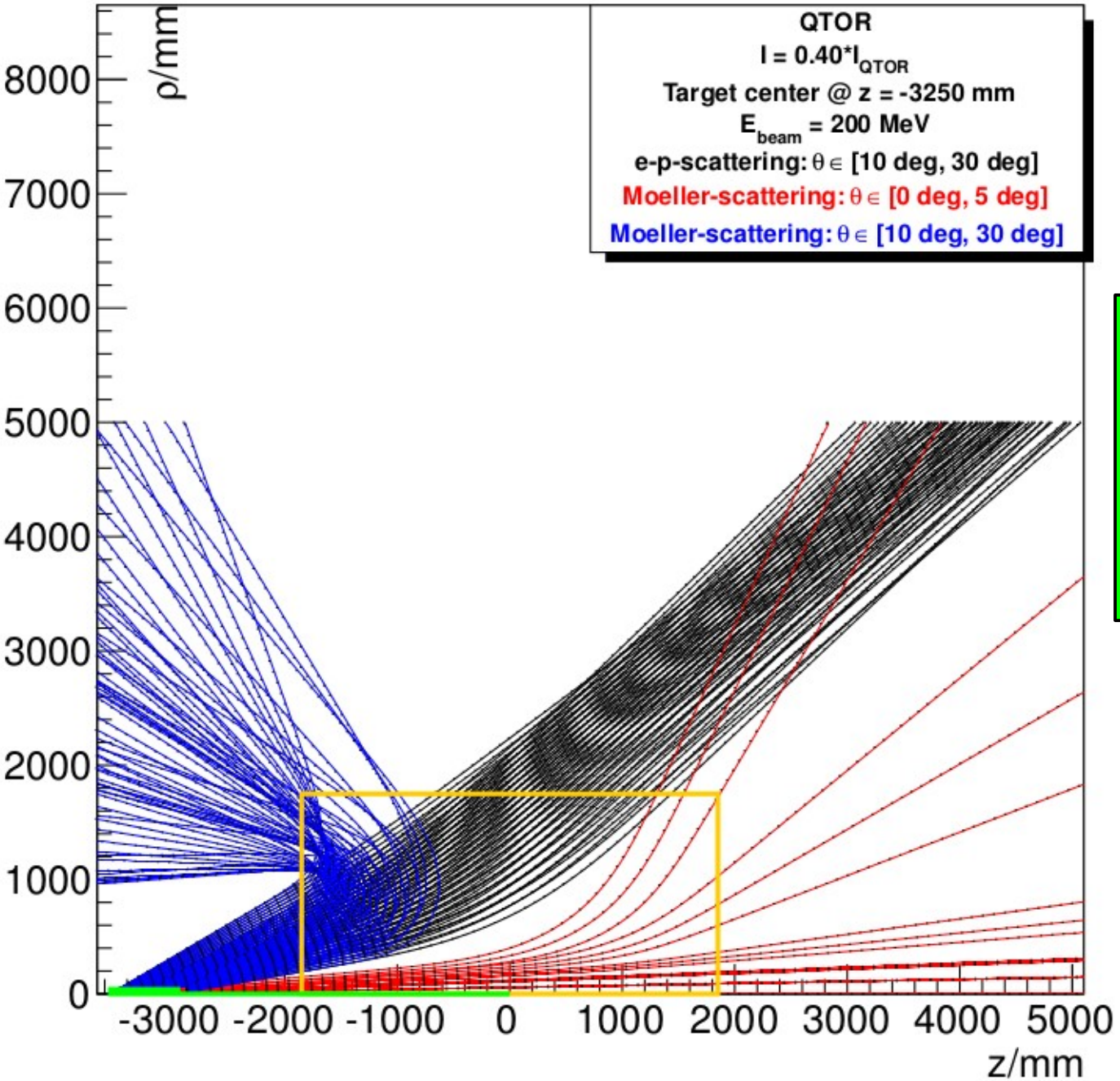

- B = 0.08 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



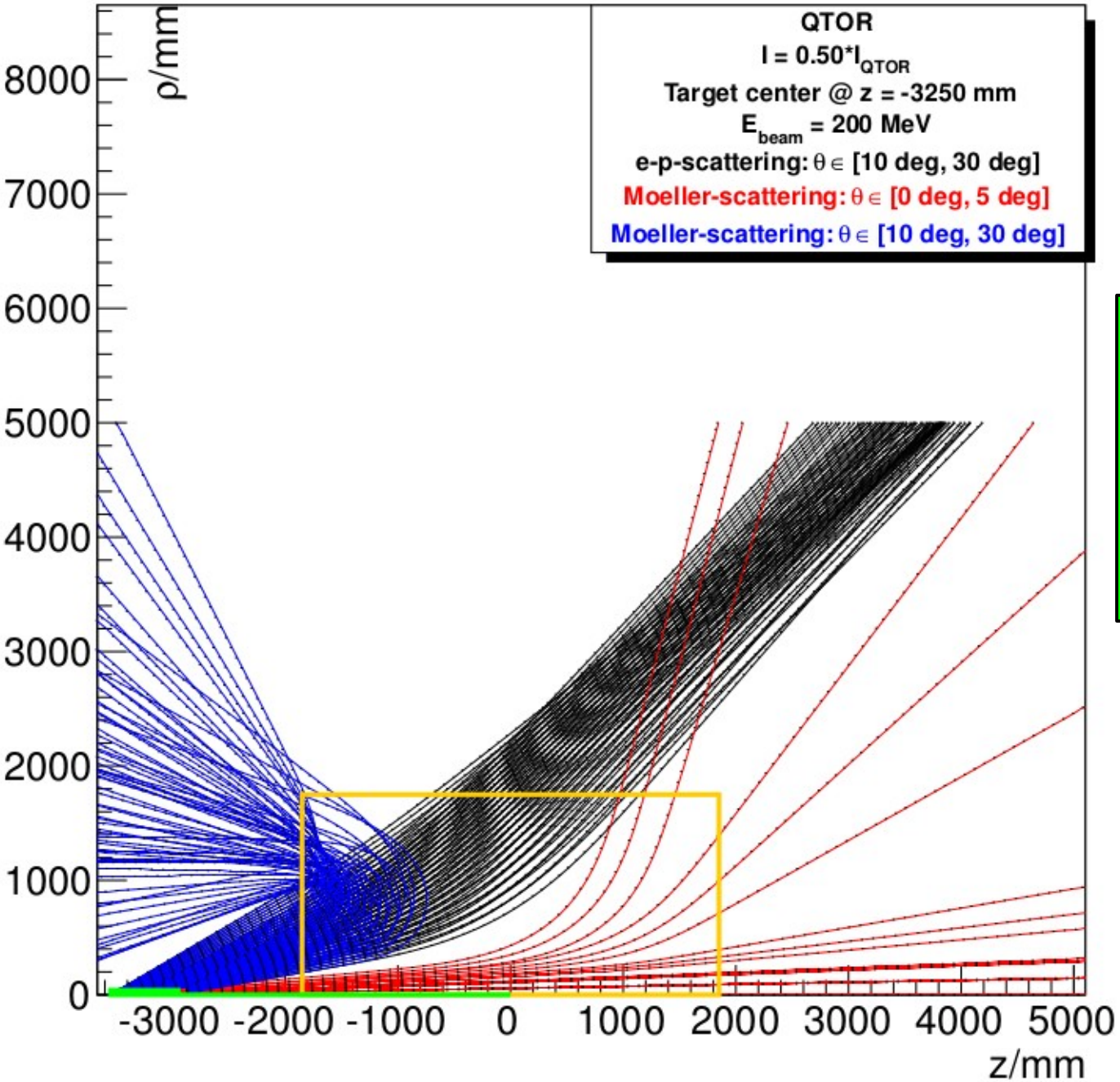

- B = 0.12 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



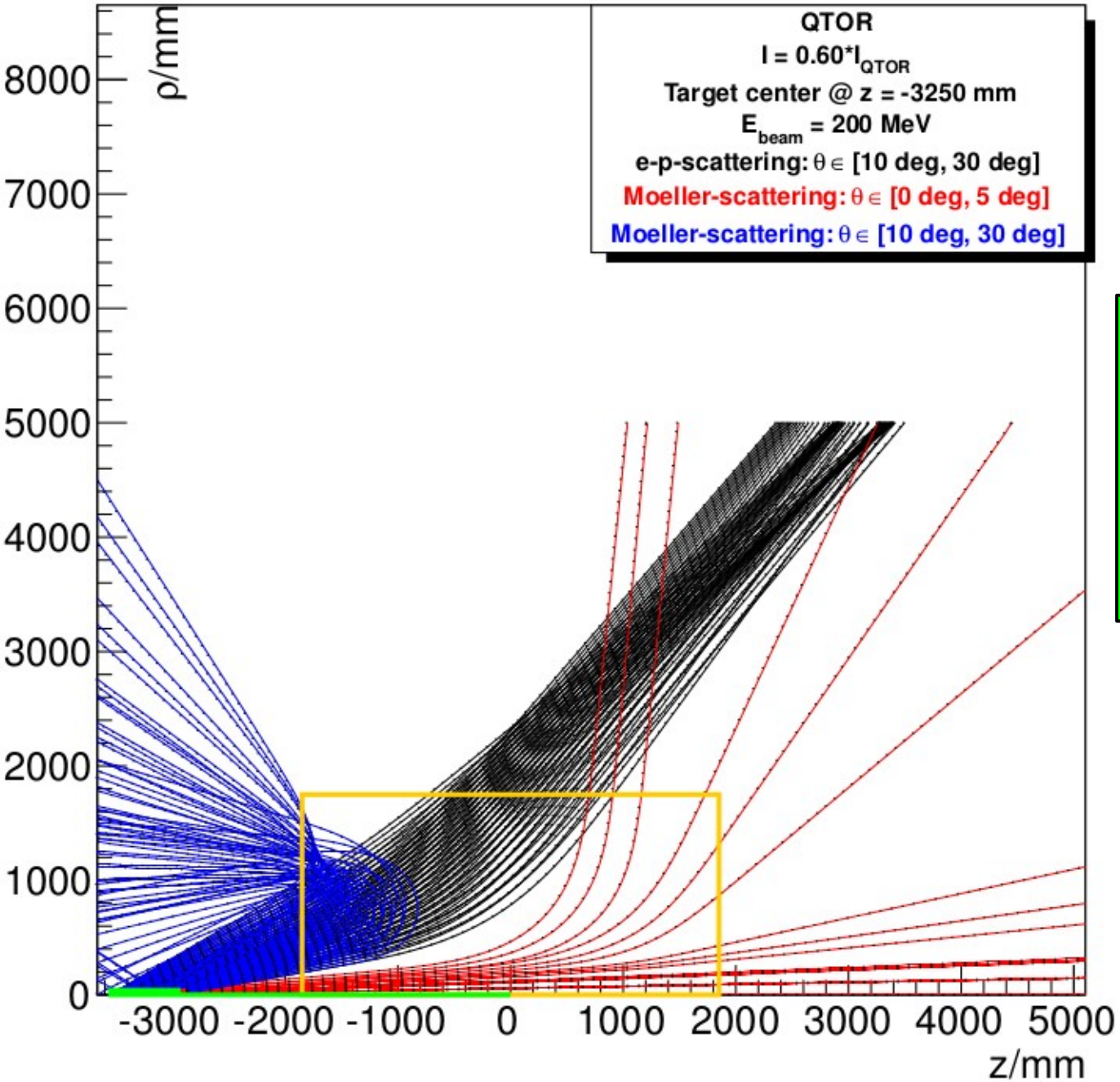

- B = 0.16 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



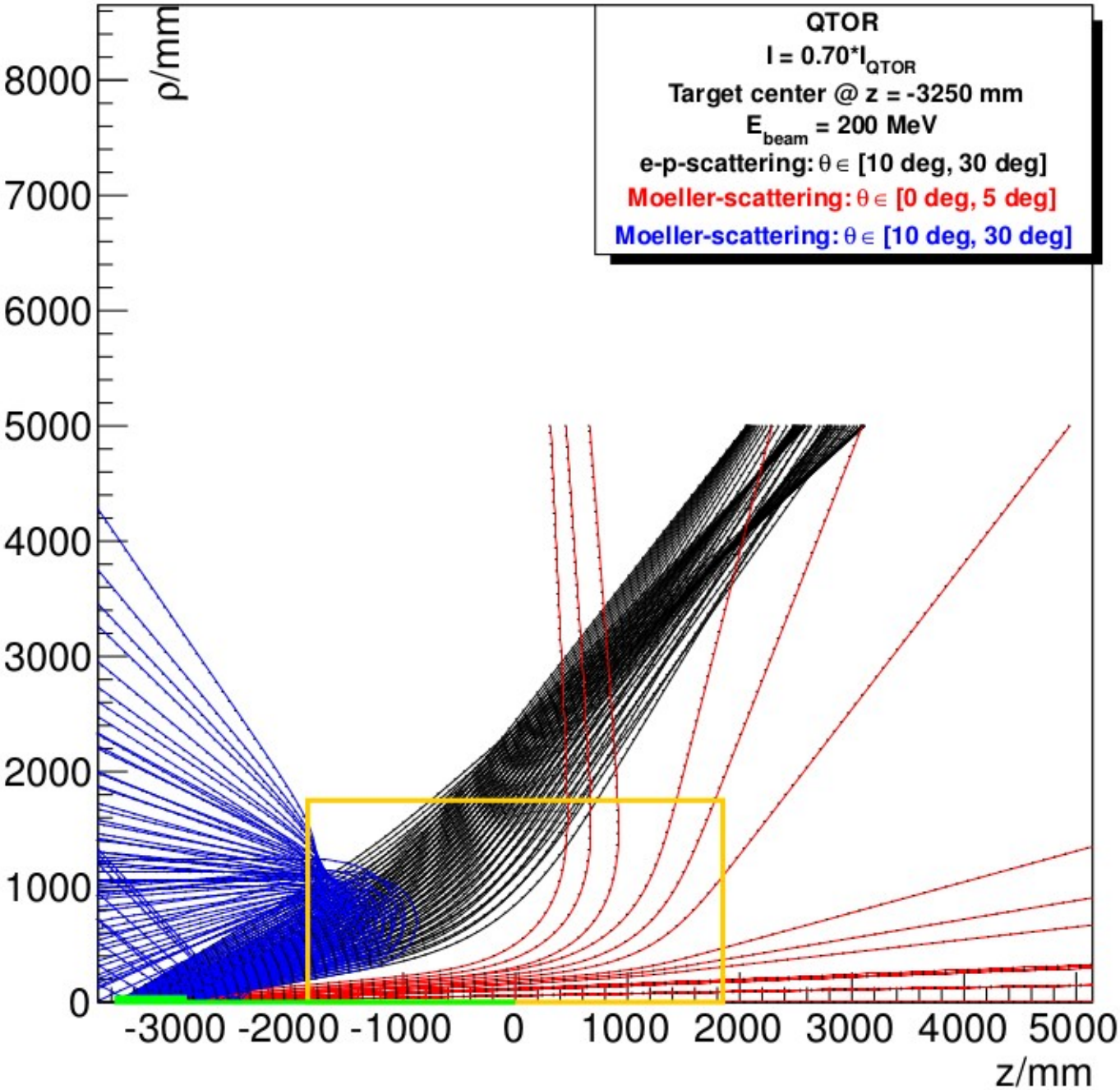

- B = 0.20 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



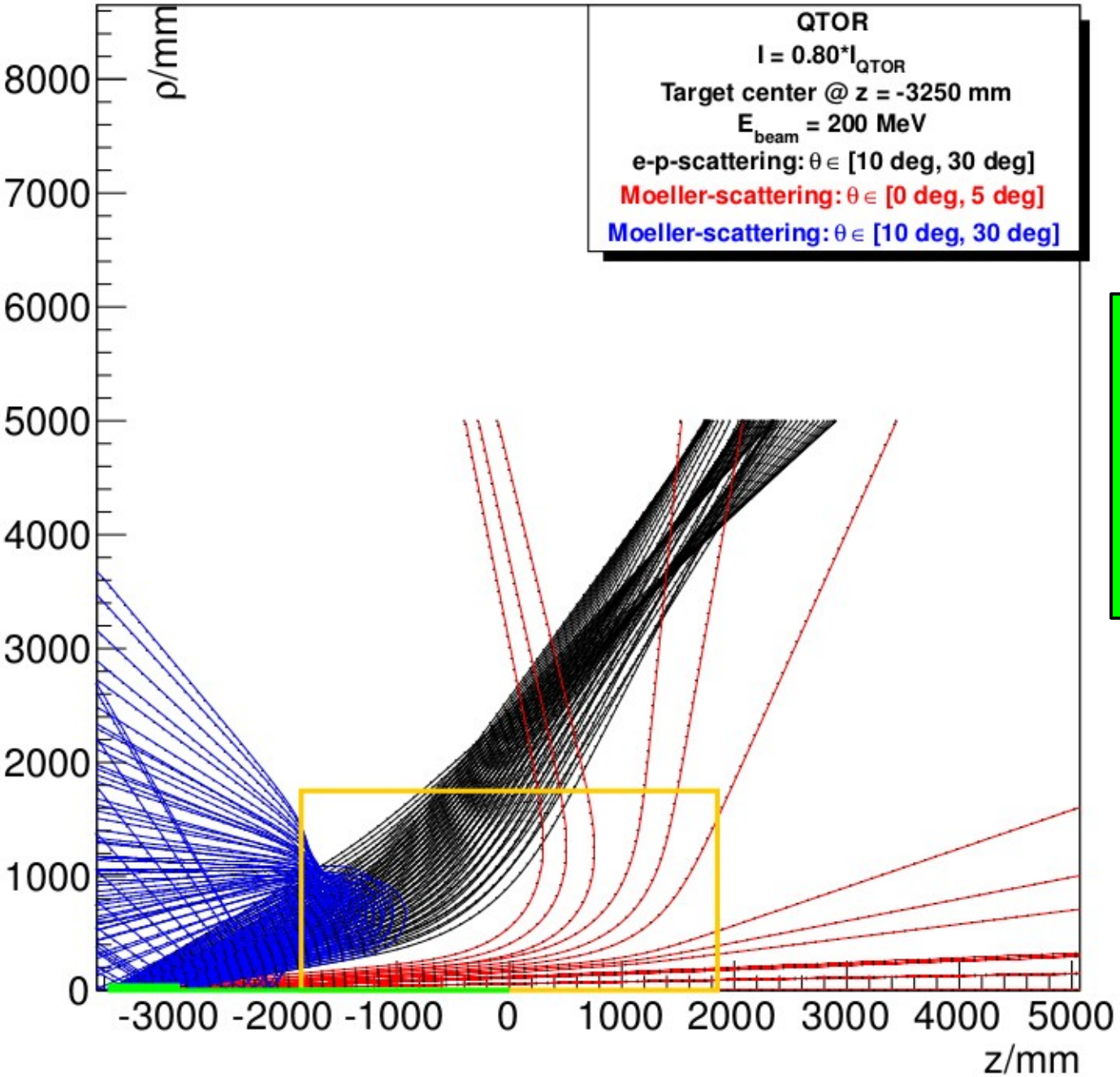

- B = 0.24 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



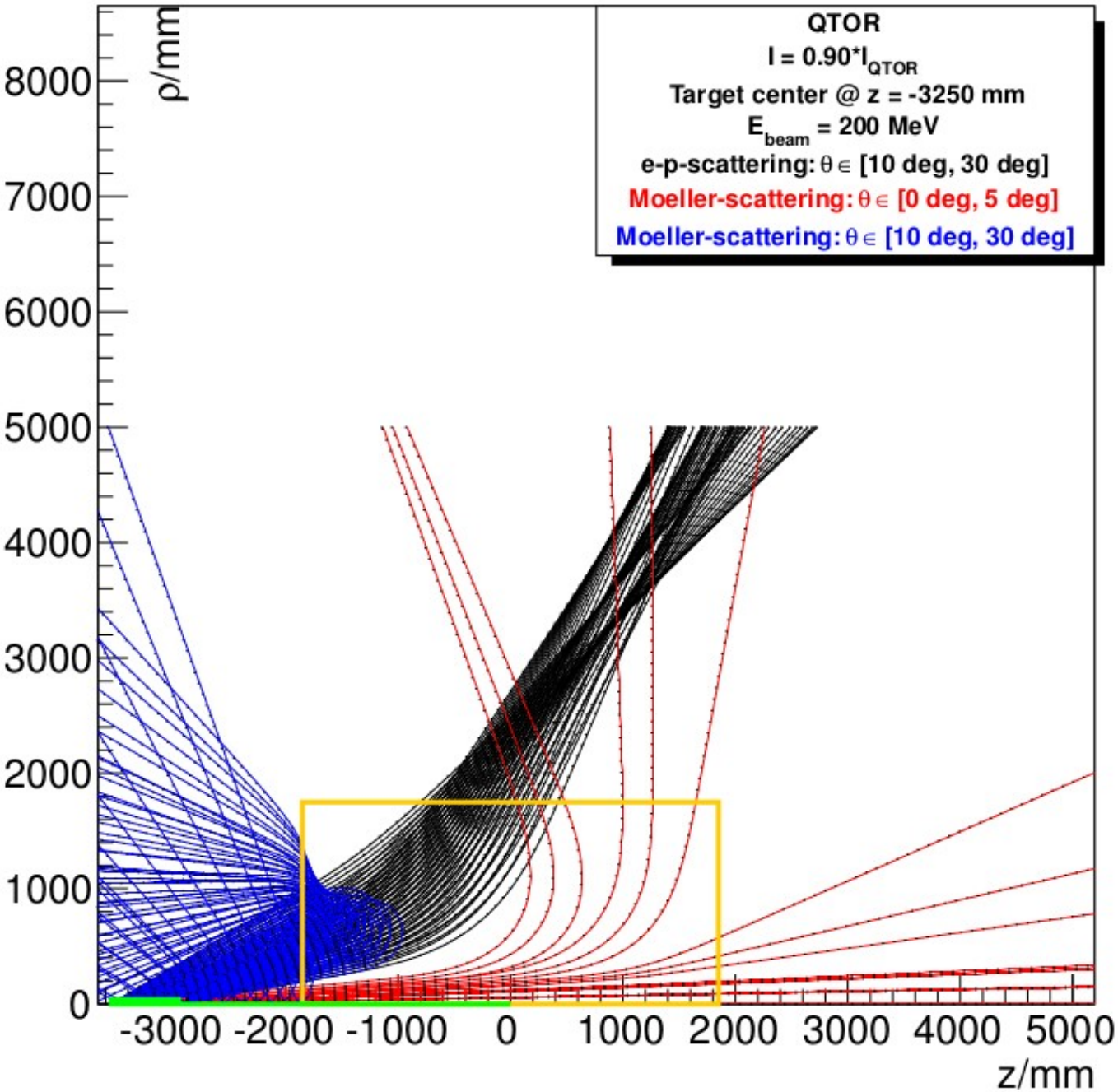

- B = 0.28 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



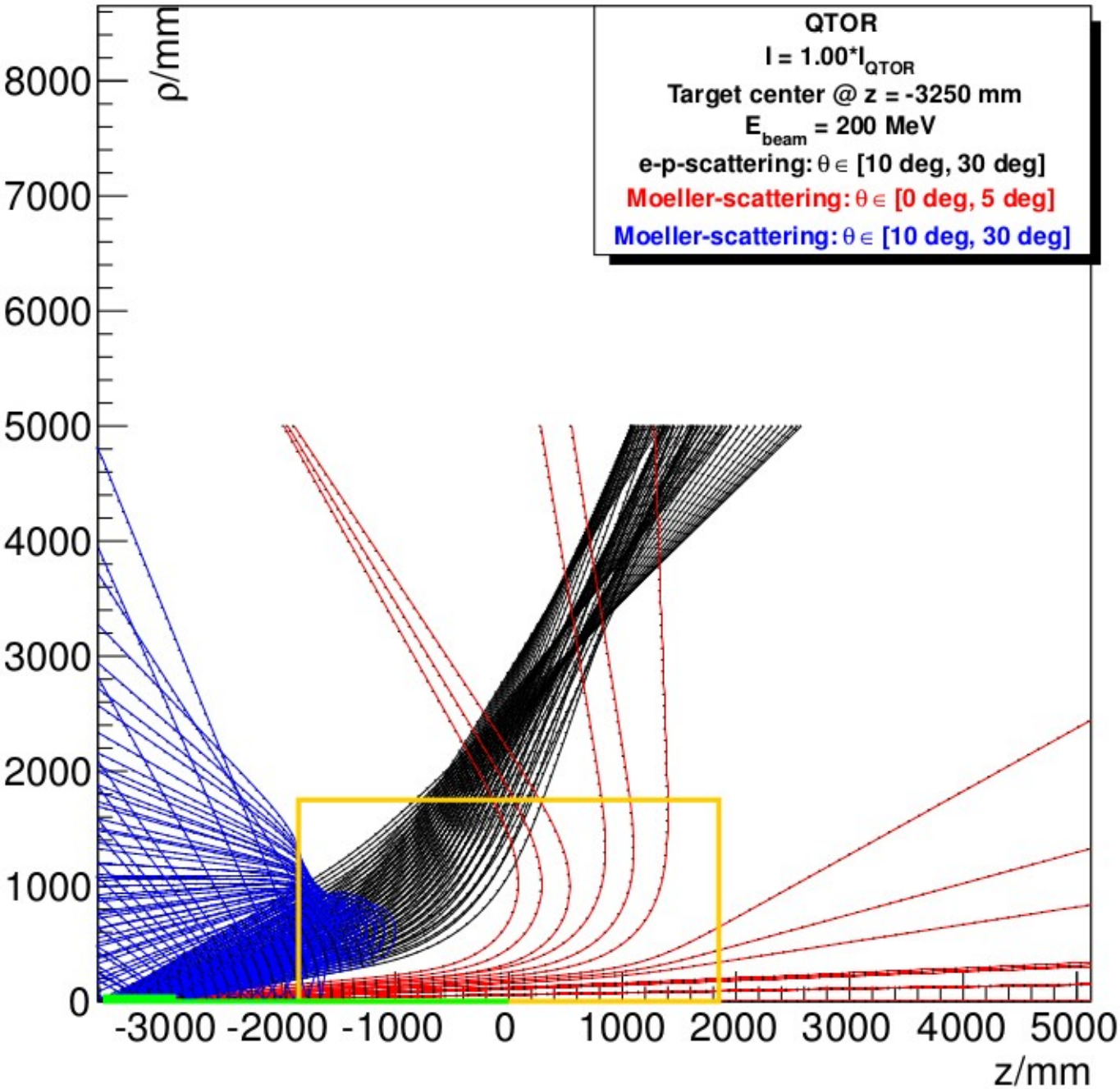

- B = 0.32 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



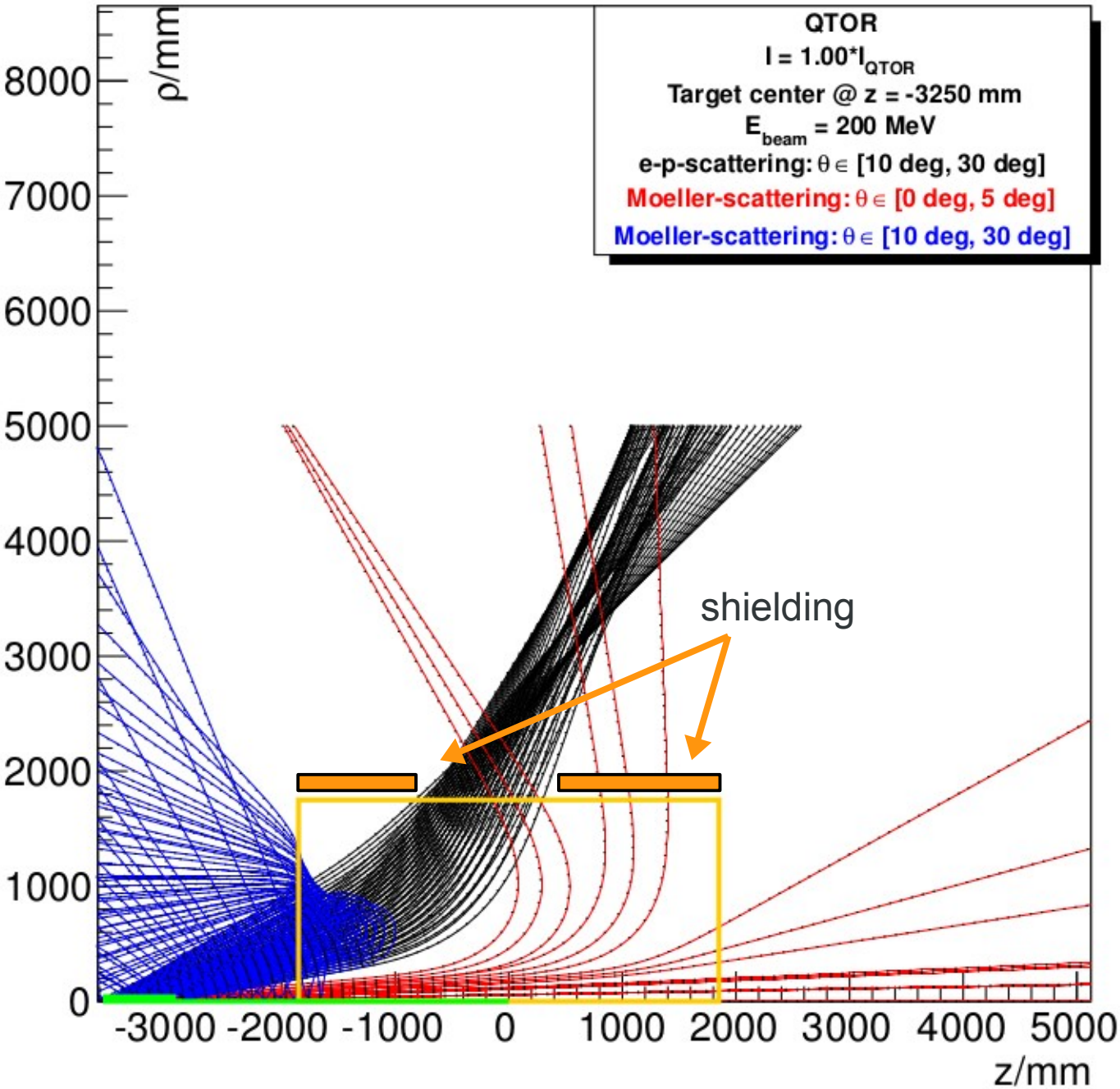

- B = 0.36 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces



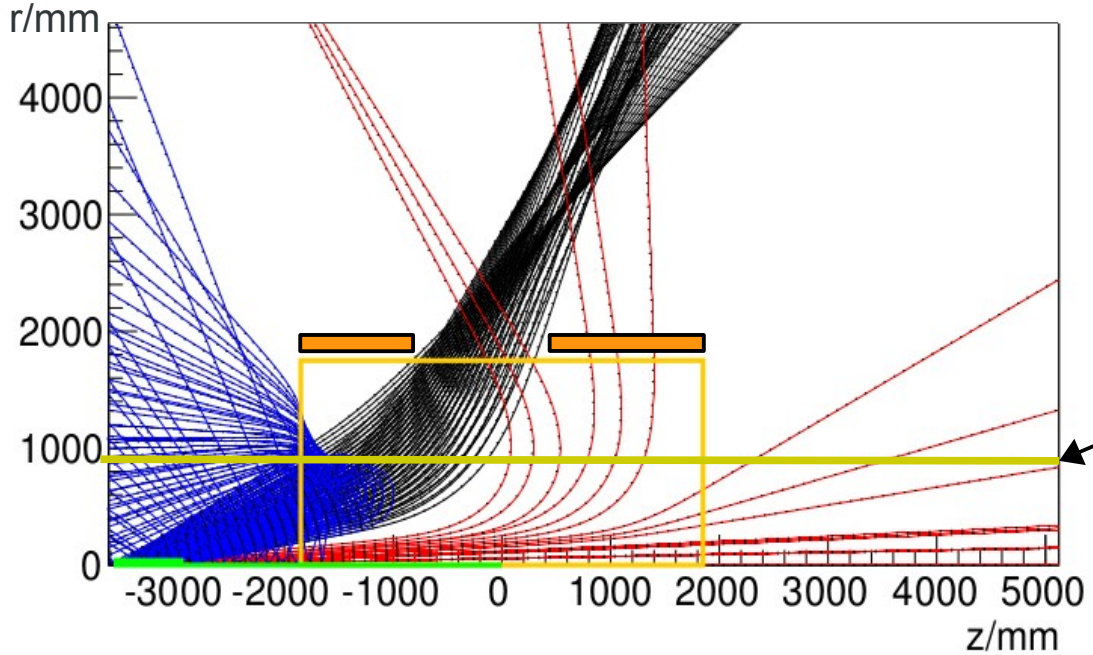

- B = 0.40 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

# Toroid simulation: Raytraces




- B = 0.40 T
- E = 200 MeV
- Target length = 60 cm
- Target center @ -3250 mm

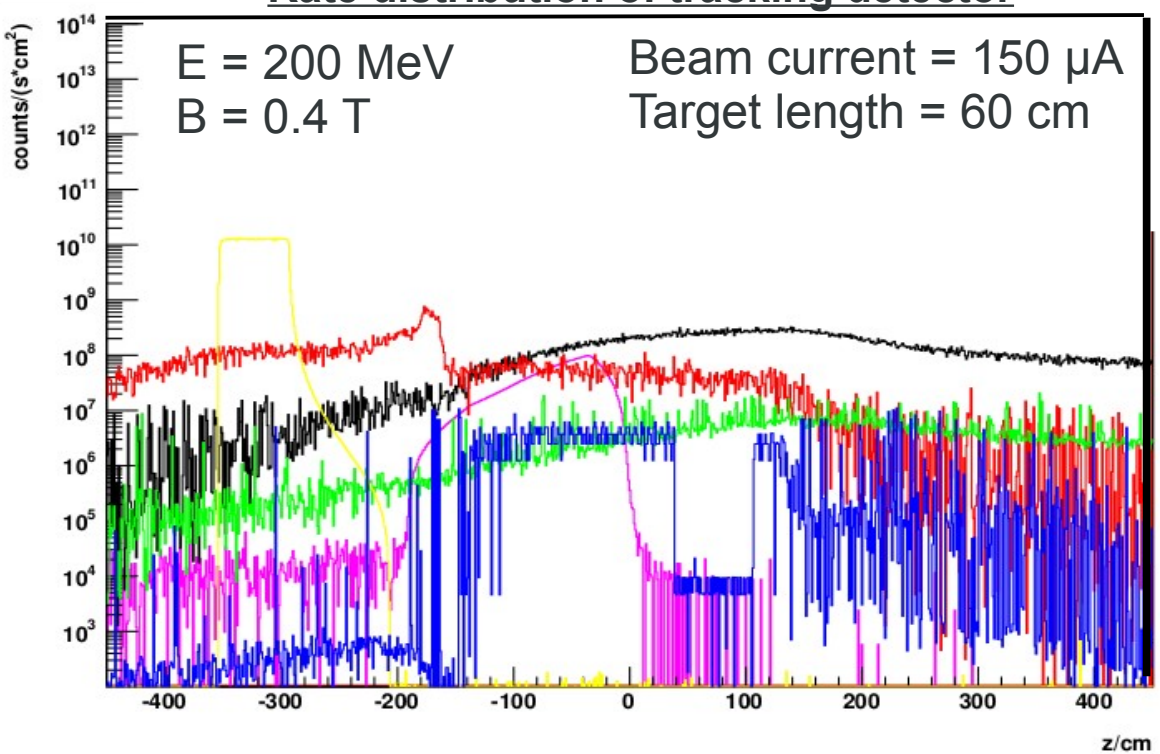
# Toroid full simulation




- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**
- Consists of vacuum
- Analyses particles that fly through

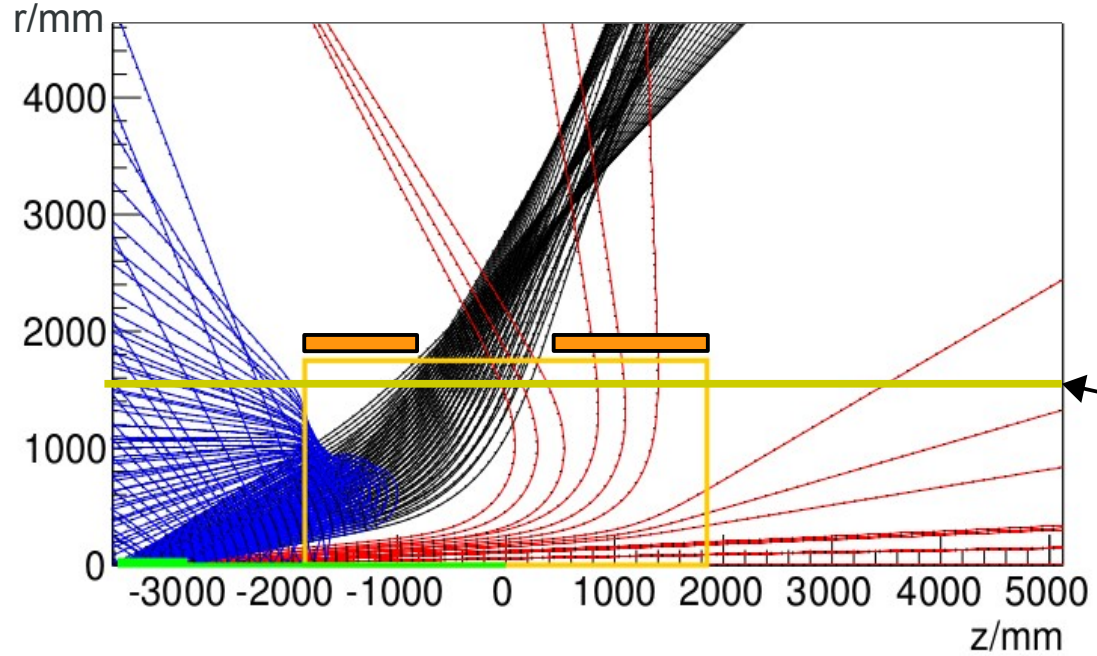
**Rate distribution of tracking detector**




- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**
- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

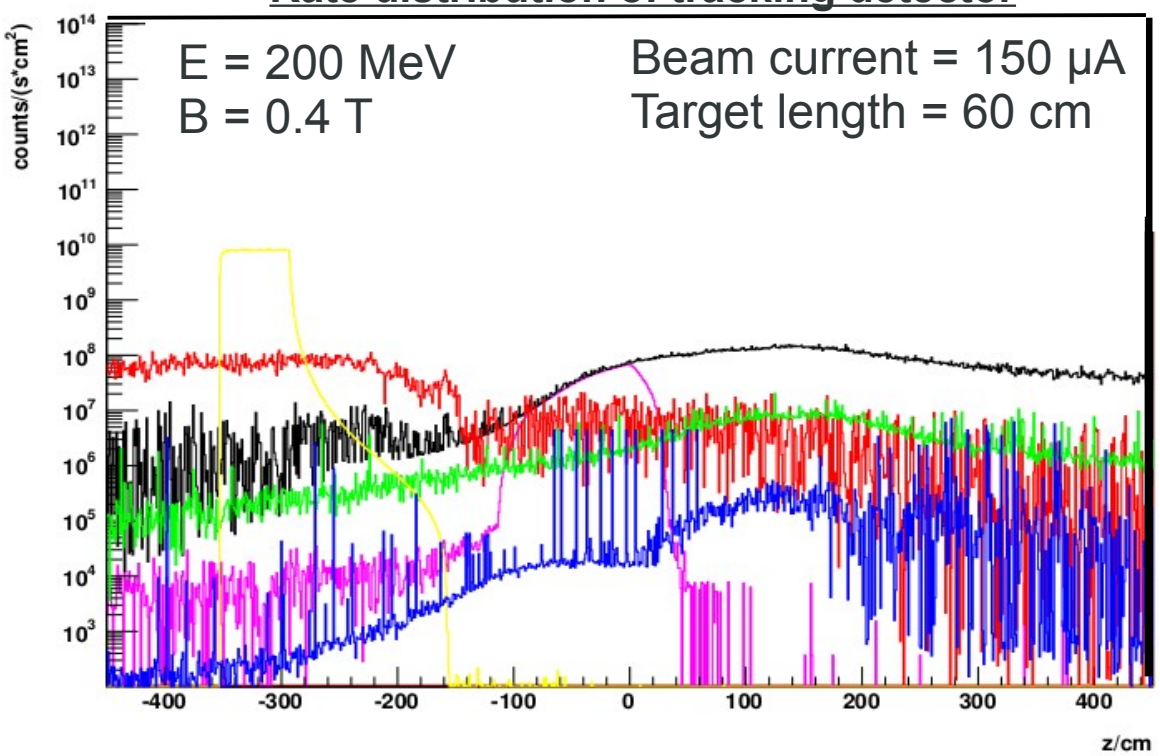
# Toroid full simulation




- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**
- Consists of vacuum
- Analyses particles that fly through

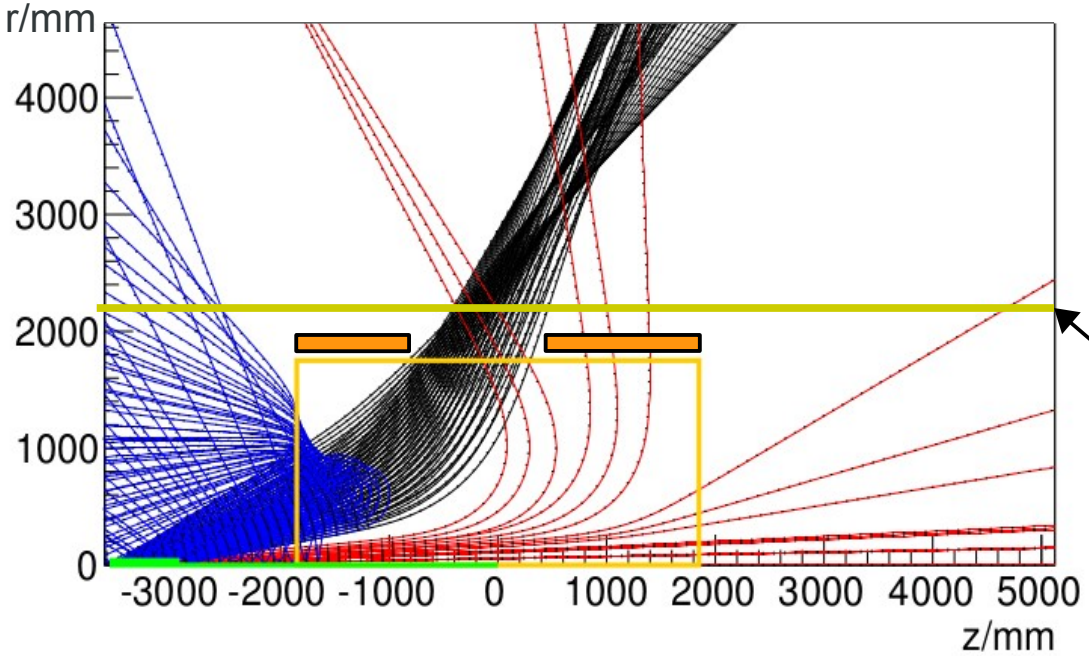
**Rate distribution of tracking detector**




- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**
- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

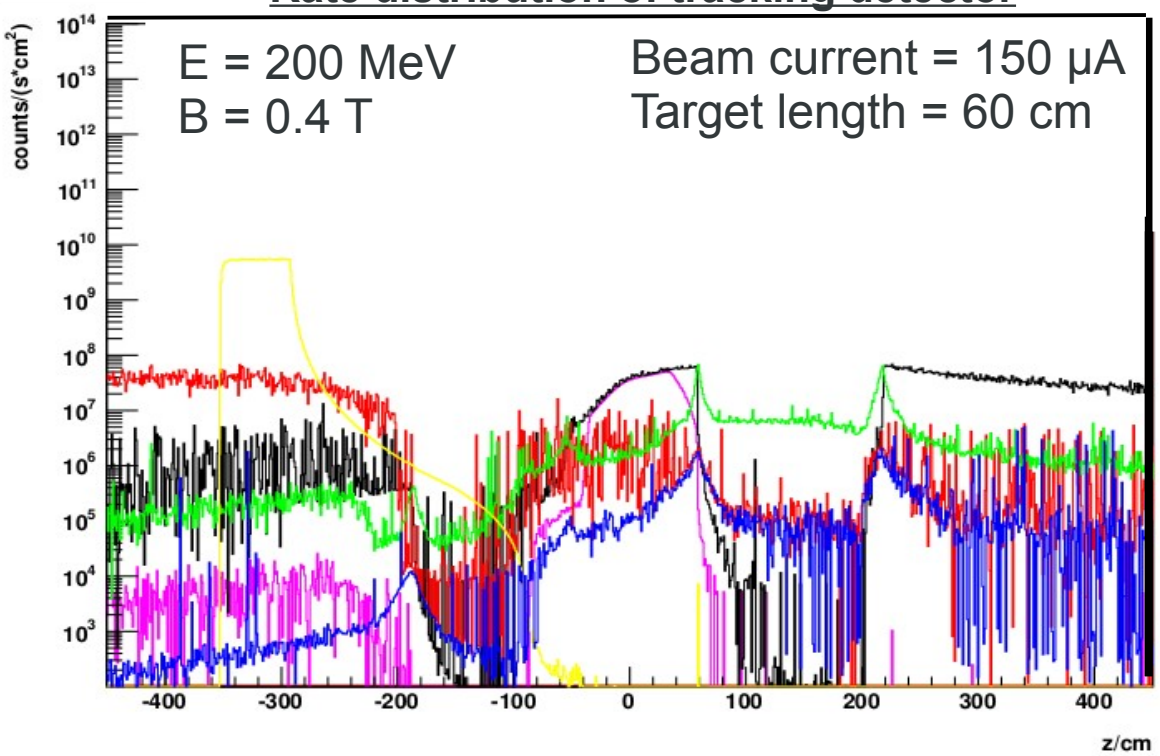
# Toroid full simulation




- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**
- Consists of vacuum
- Analyses particles that fly through

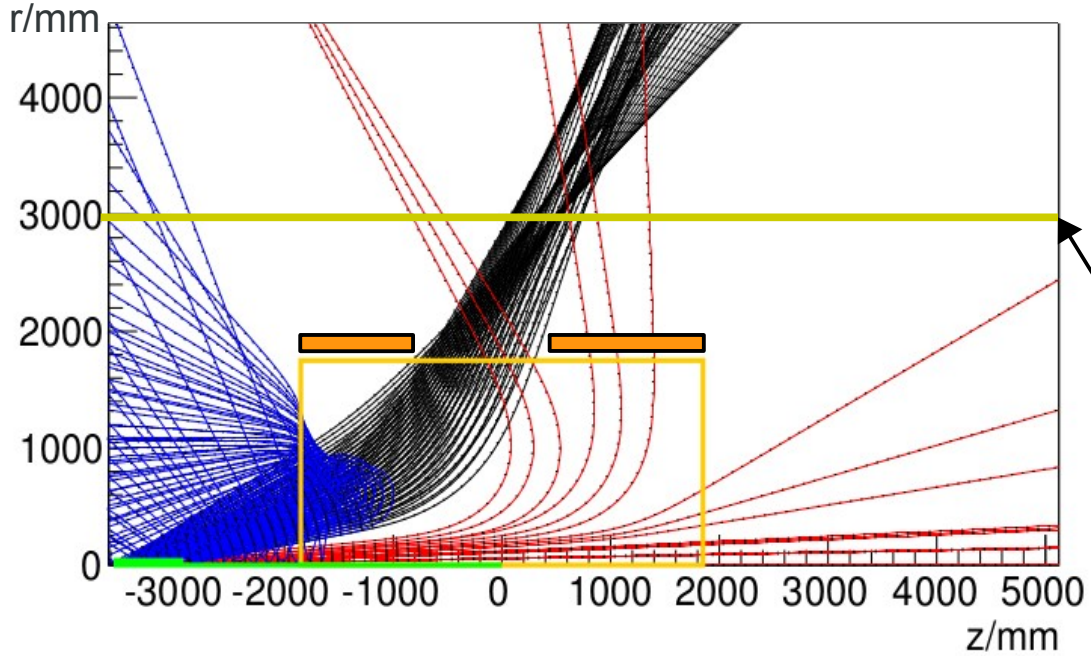
**Rate distribution of tracking detector**




- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**
- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

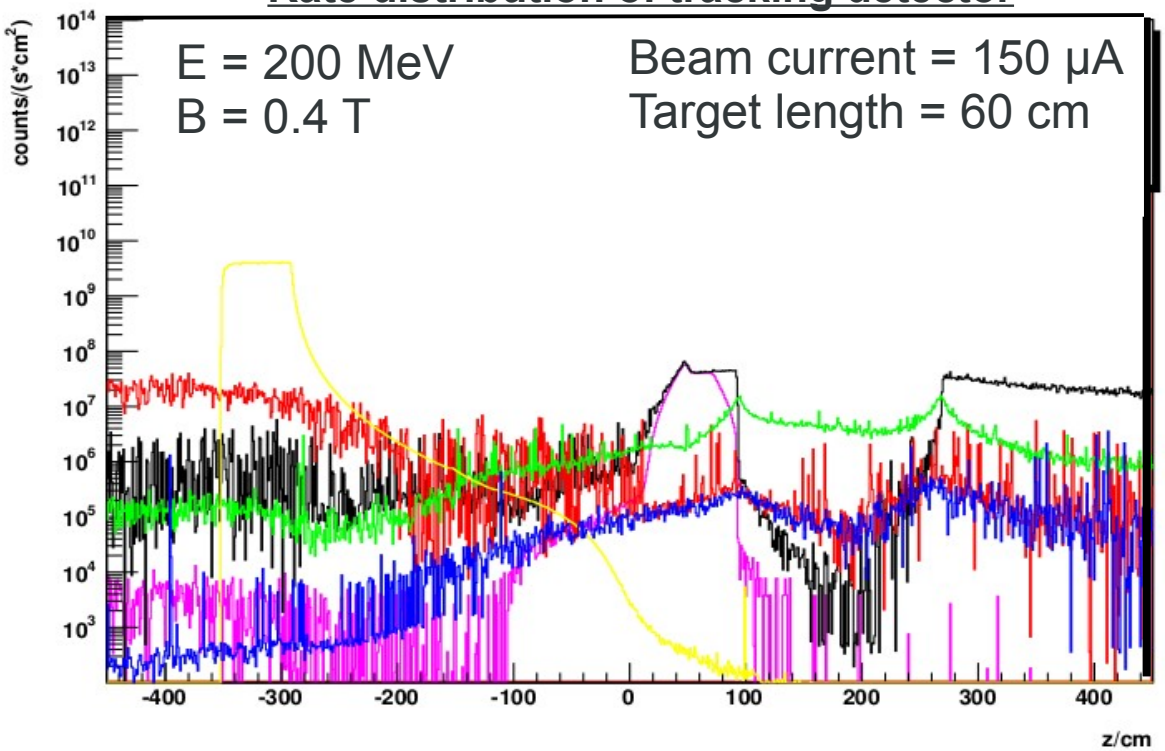
# Toroid full simulation




- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**
- Consists of vacuum
- Analyses particles that fly through

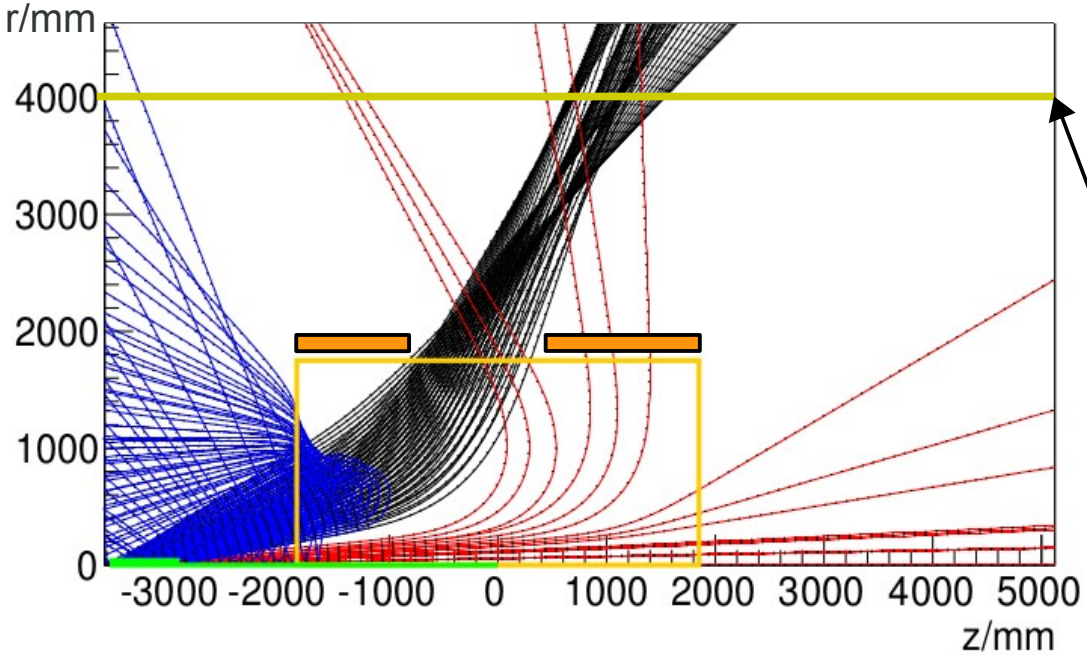
**Rate distribution of tracking detector**




- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**
- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

# Toroid full simulation

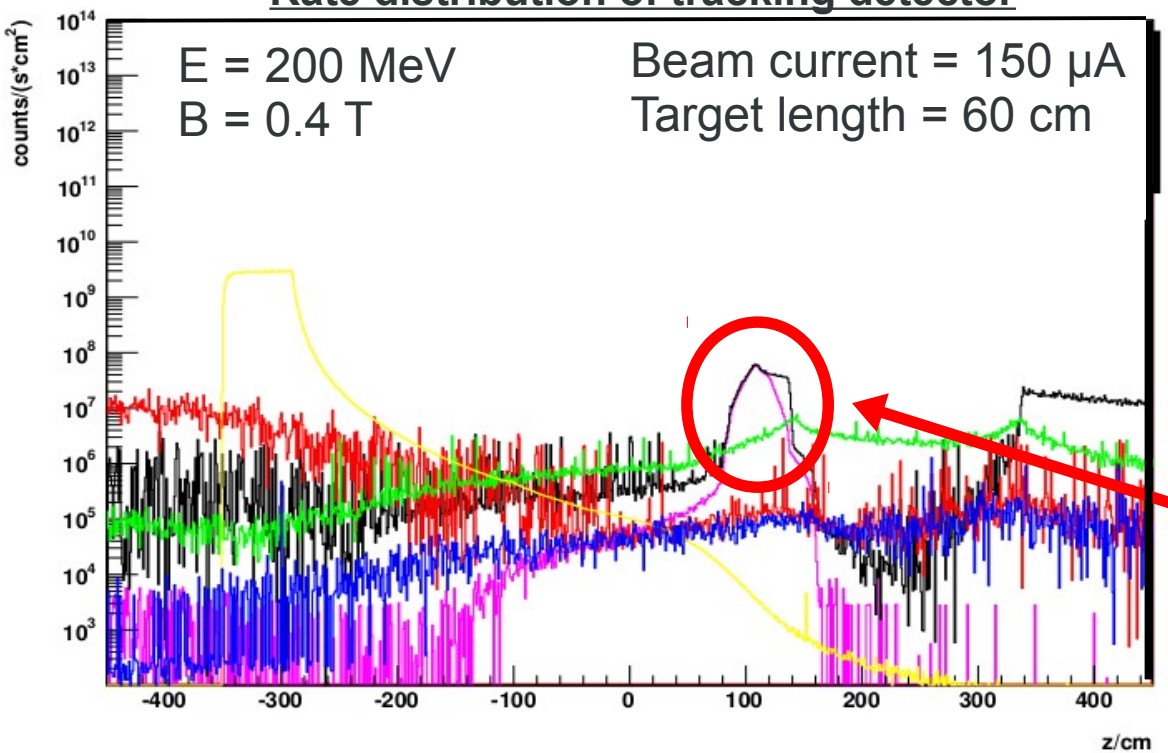



- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**

- Consists of vacuum
- Analyses particles that fly through

**Rate distribution of tracking detector**

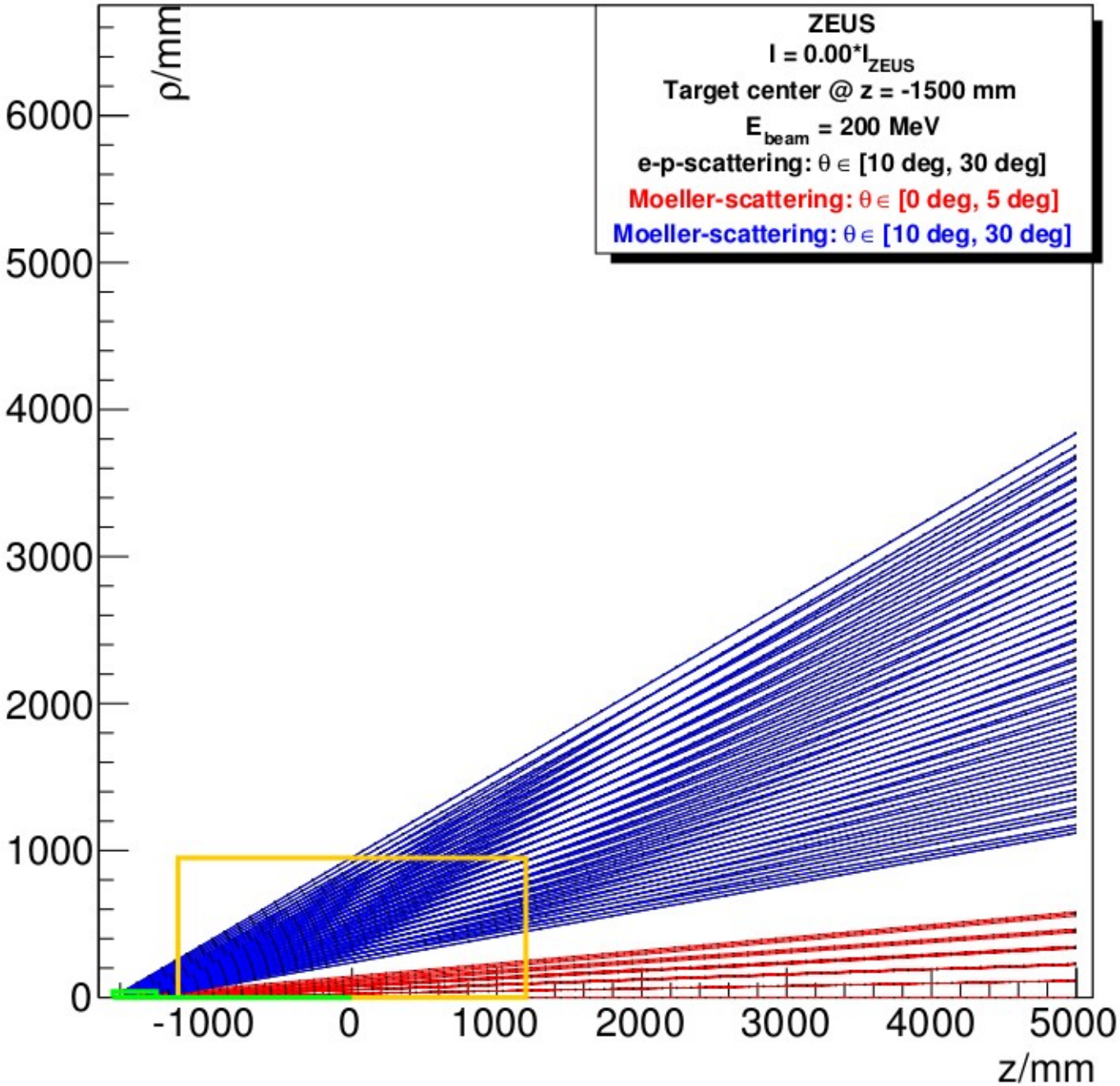



- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Dominated by el. e-p scattering**

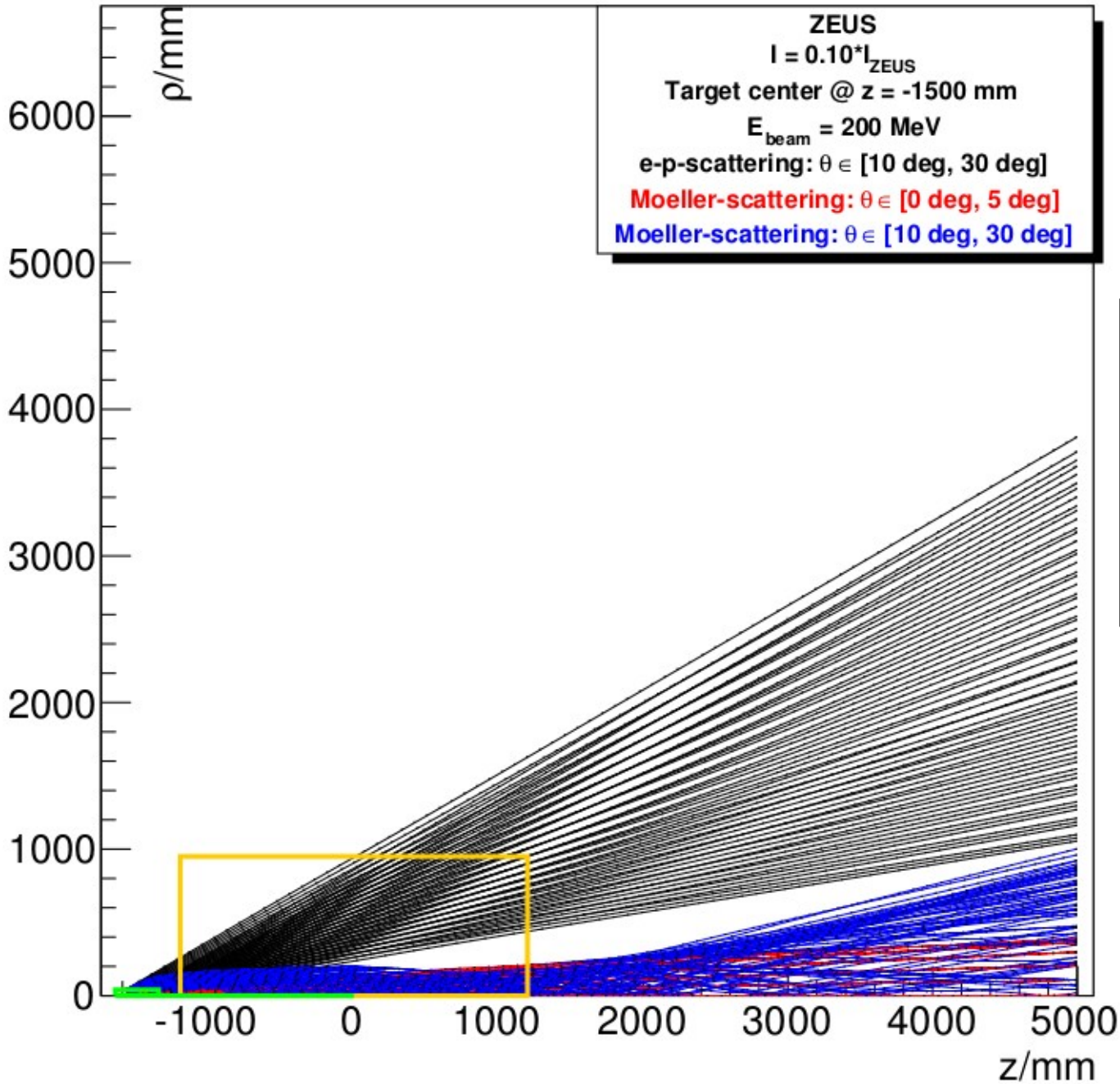
$\theta \in [10°, 30°]$

# Solenoid simulation: Raytraces



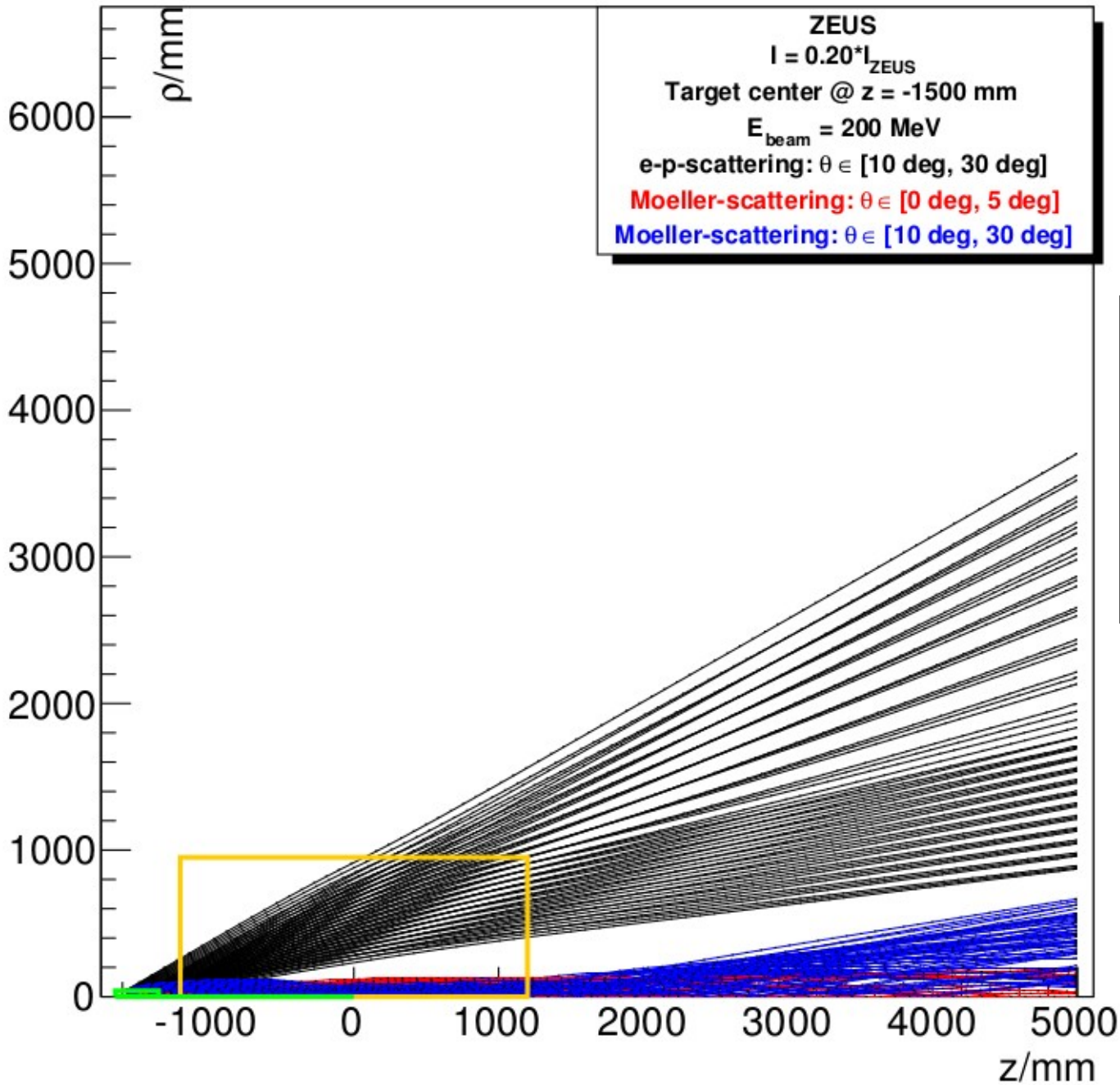

- B = 0.00 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



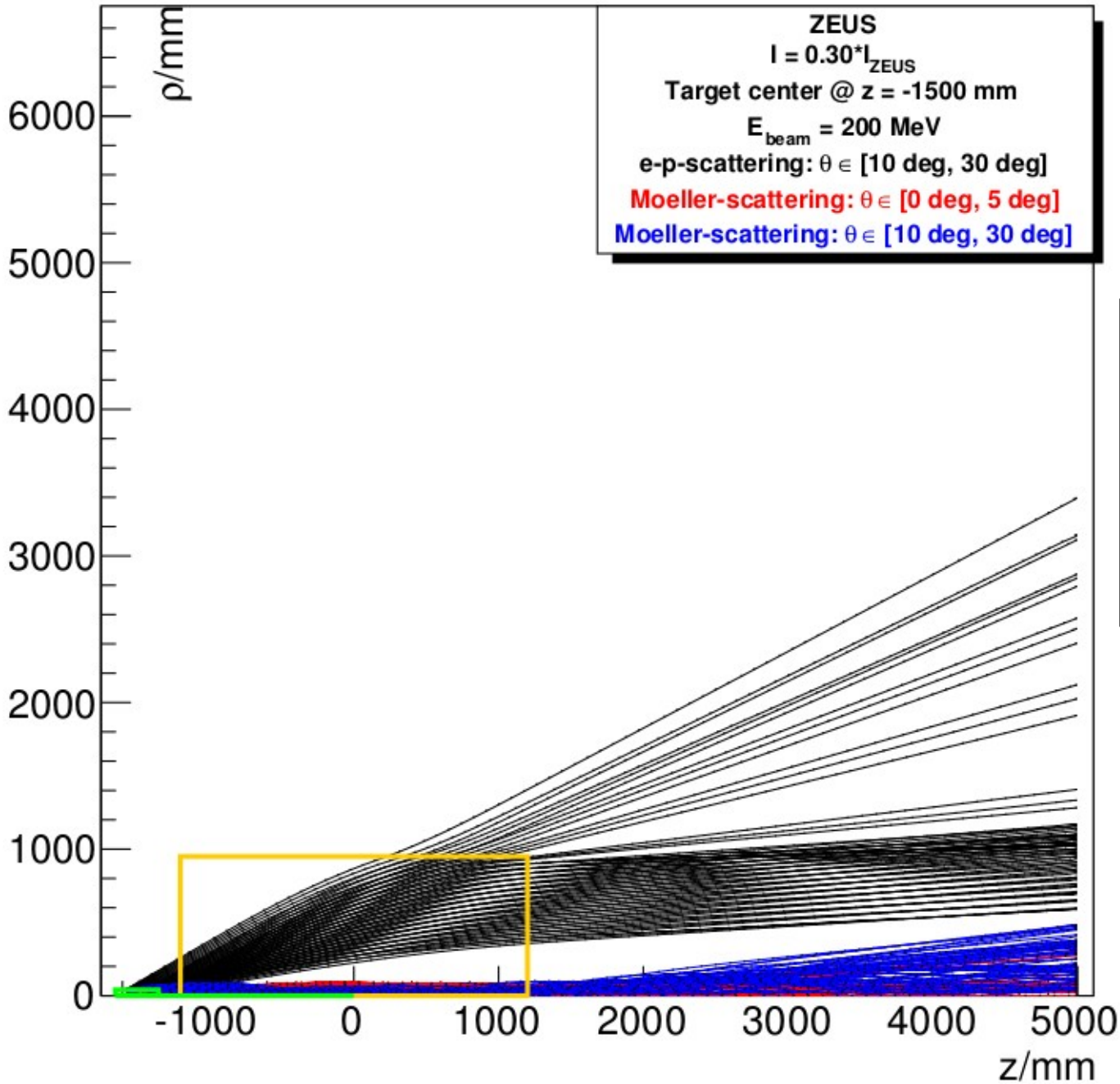

- B = 0.18 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



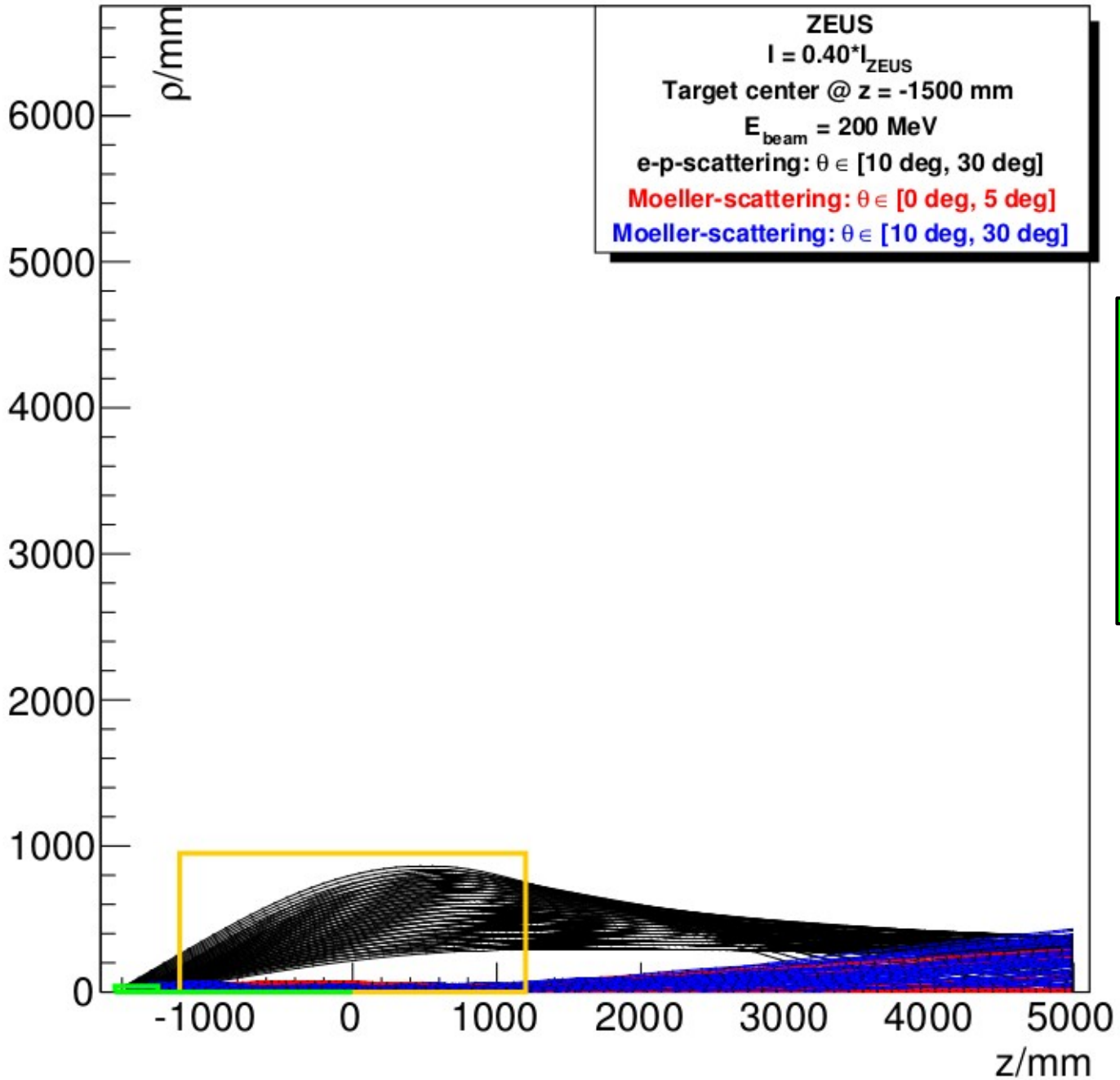

- B = 0.36 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



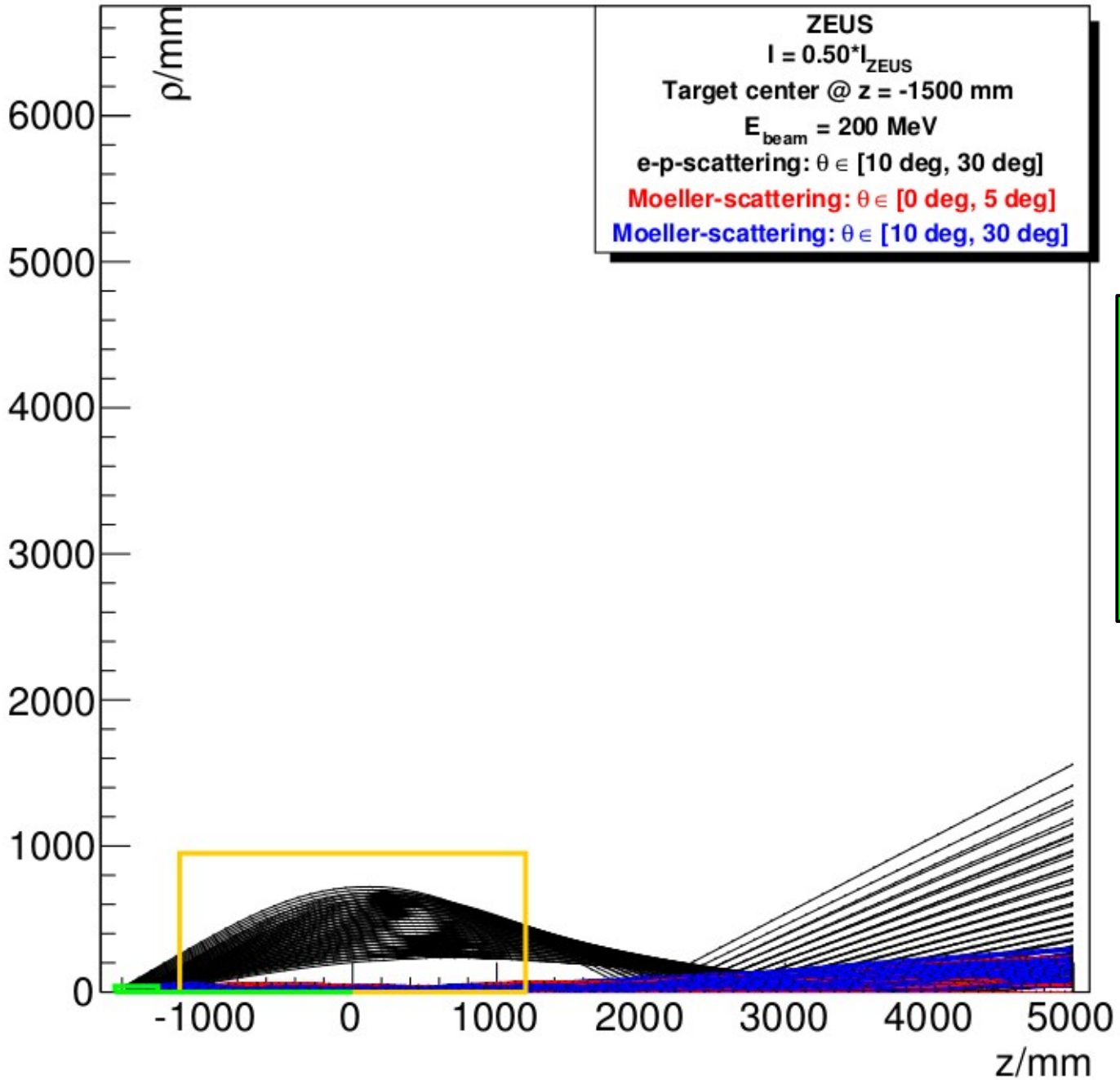

- B = 0.54 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



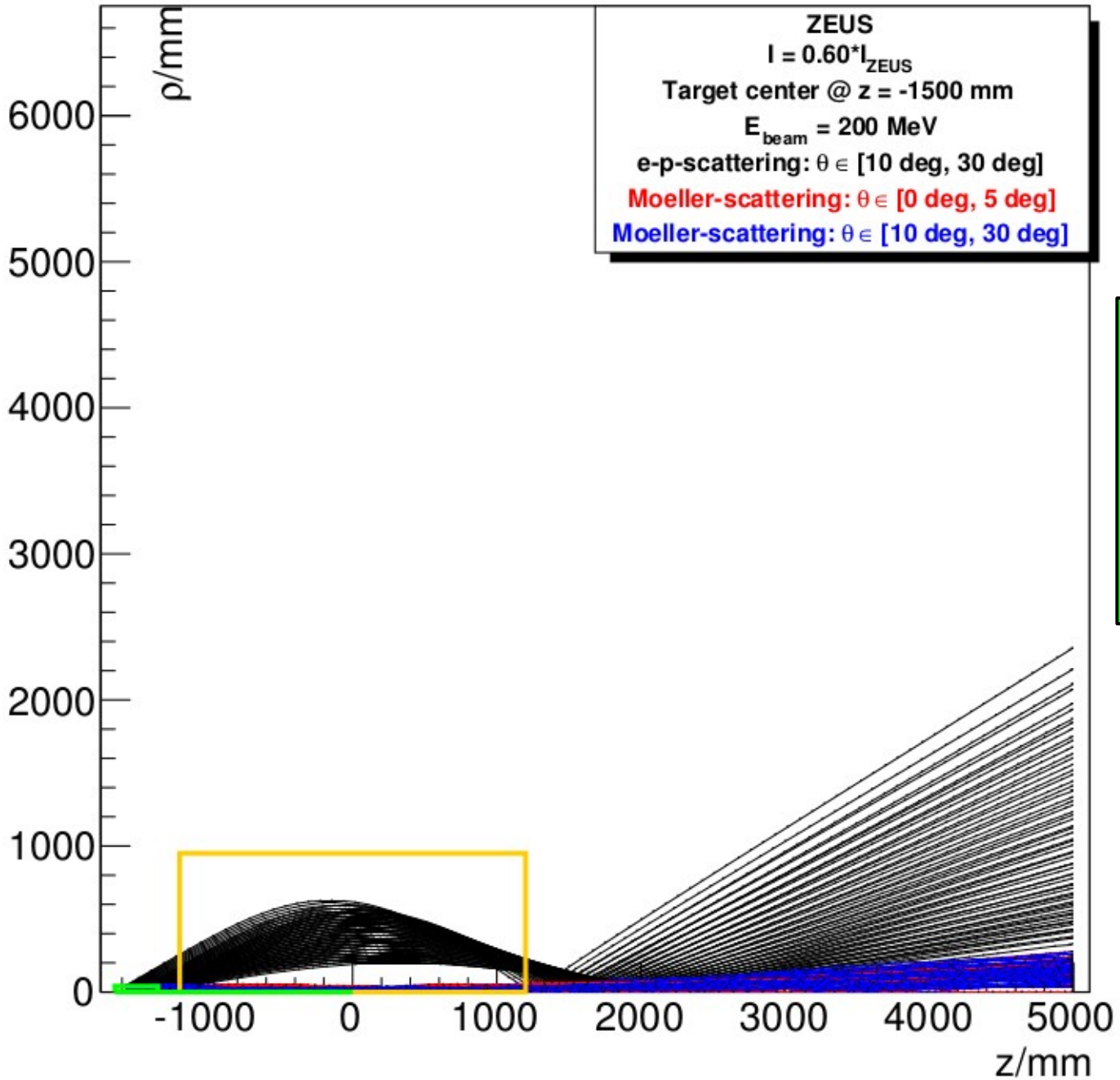

- B = 0.72 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



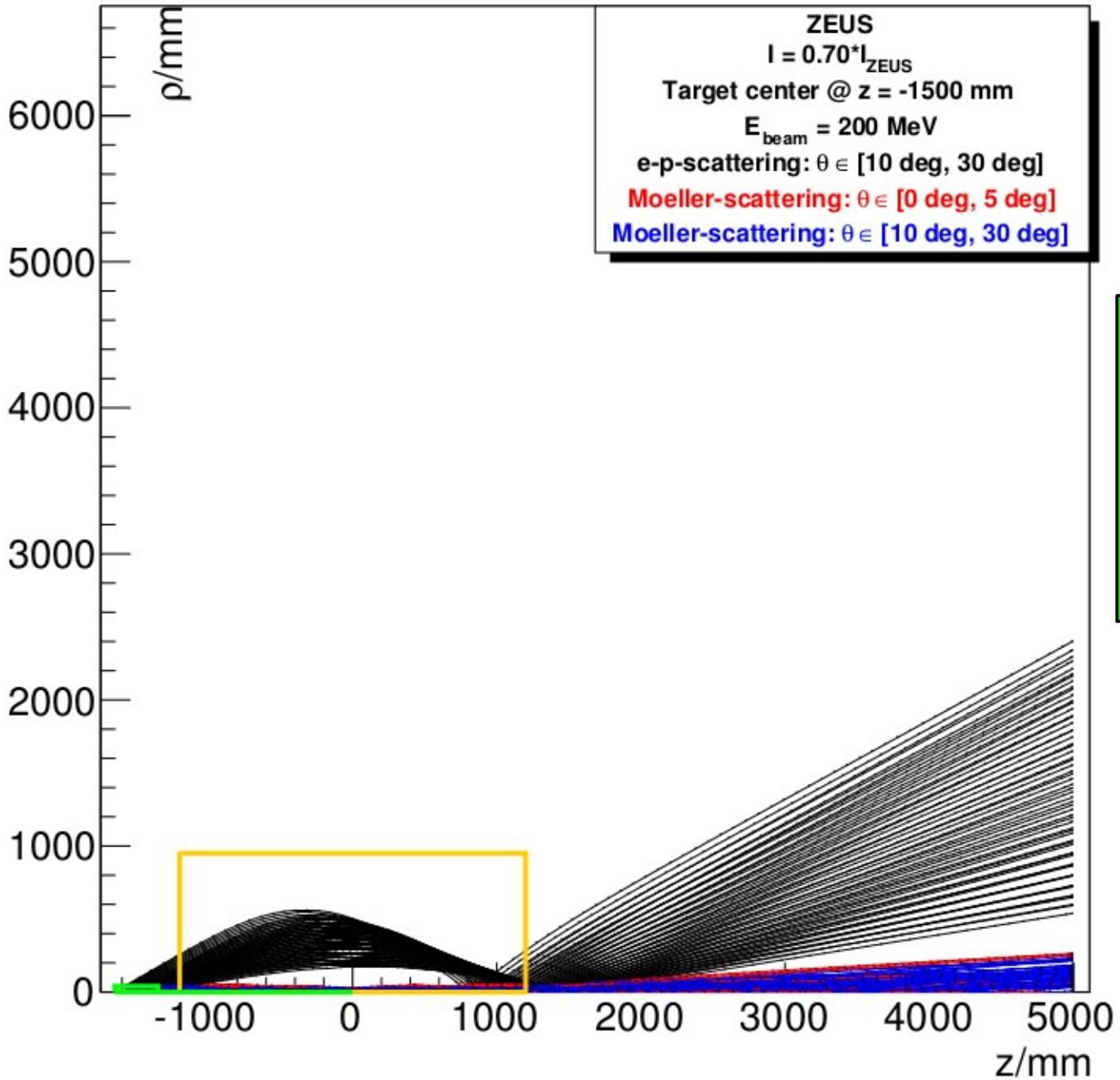

- B = 0.90 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



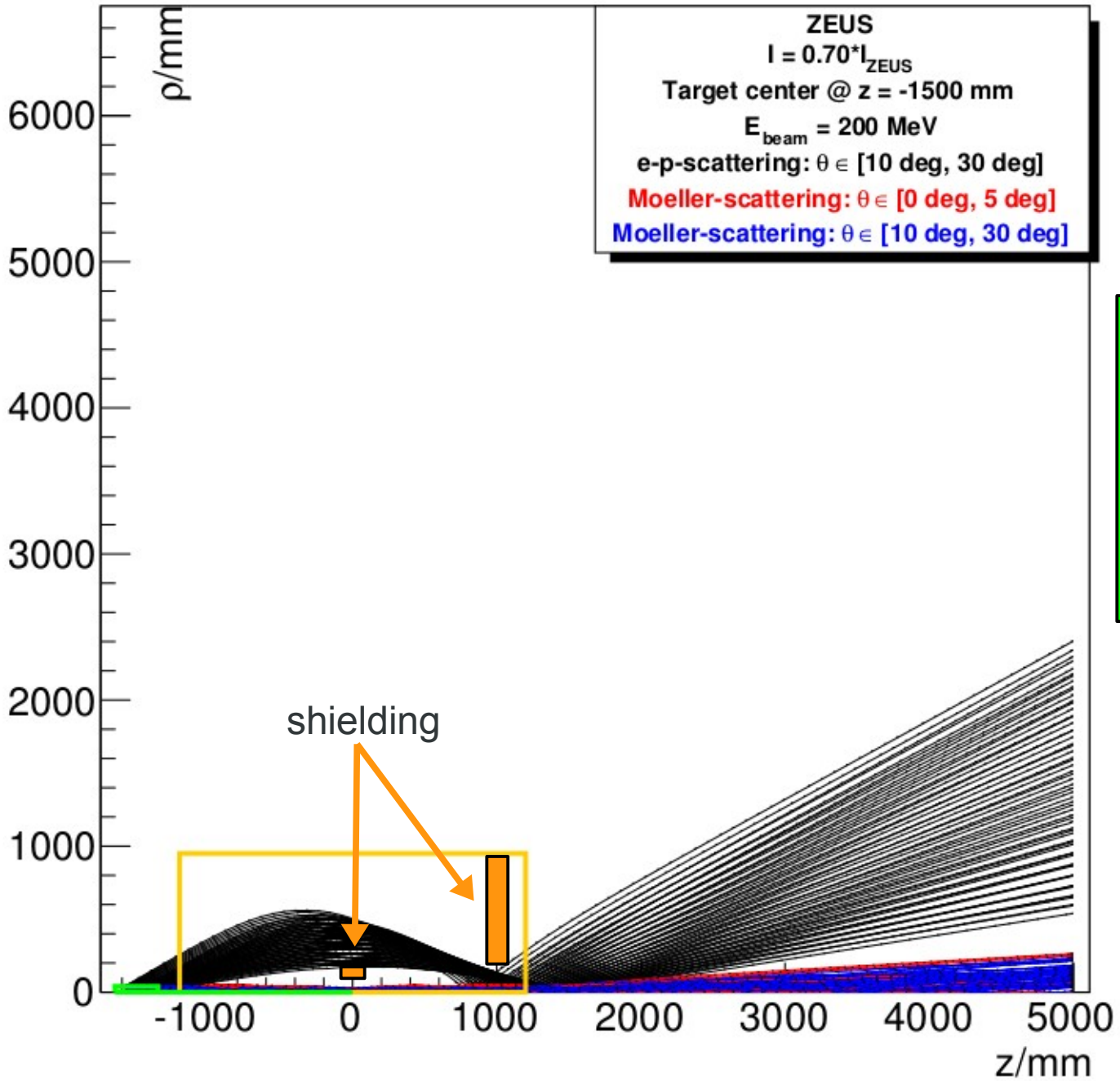

- B = 1.08 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces



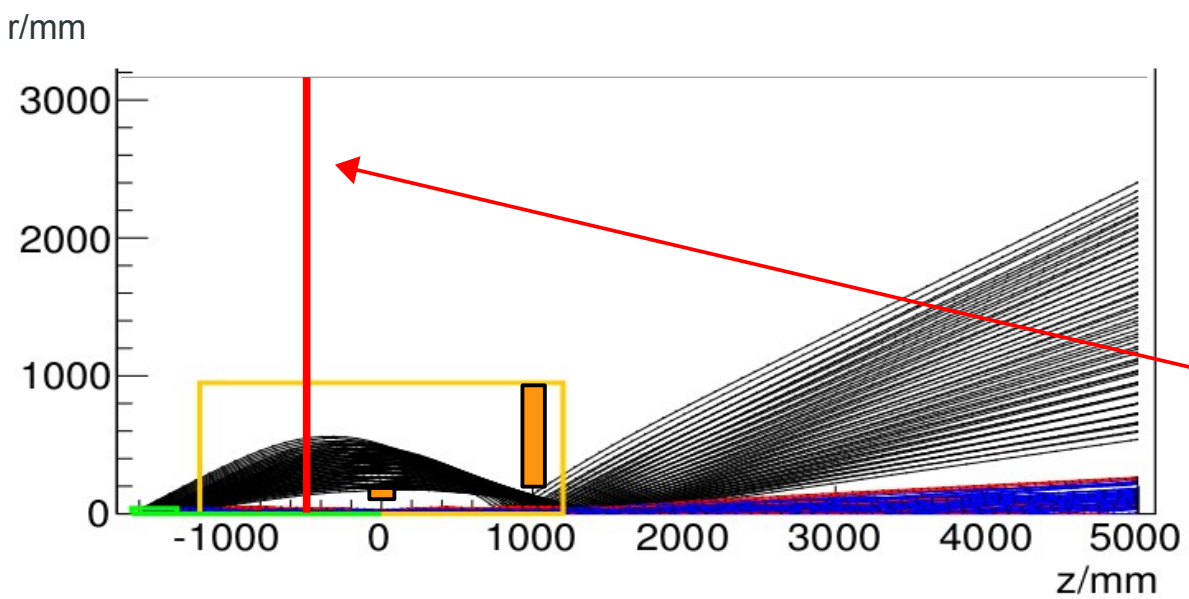

- B = 1.26 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid simulation: Raytraces




- B = 1.26 T
- E = 200 MeV
- Target length = 30 cm
- Target center @ -1500 mm

# Solenoid full simulation

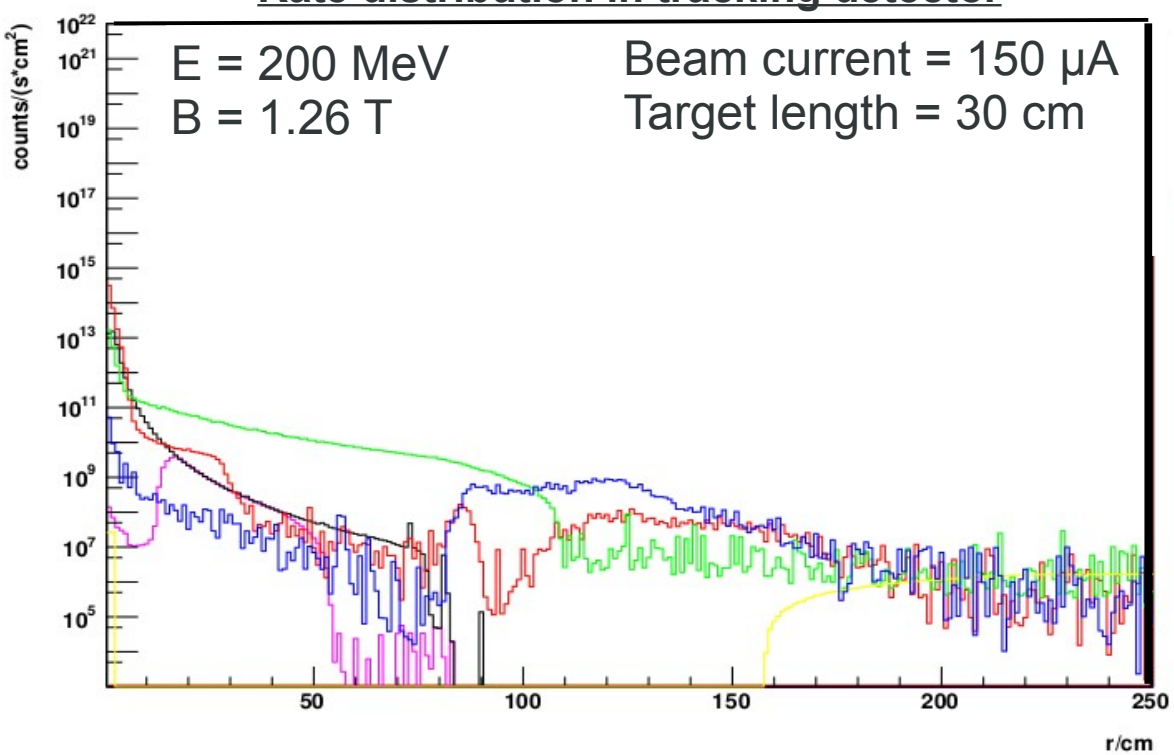



- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**

- Consists of vacuum
- Analyses particles that fly through

**Rate distribution in tracking detector**

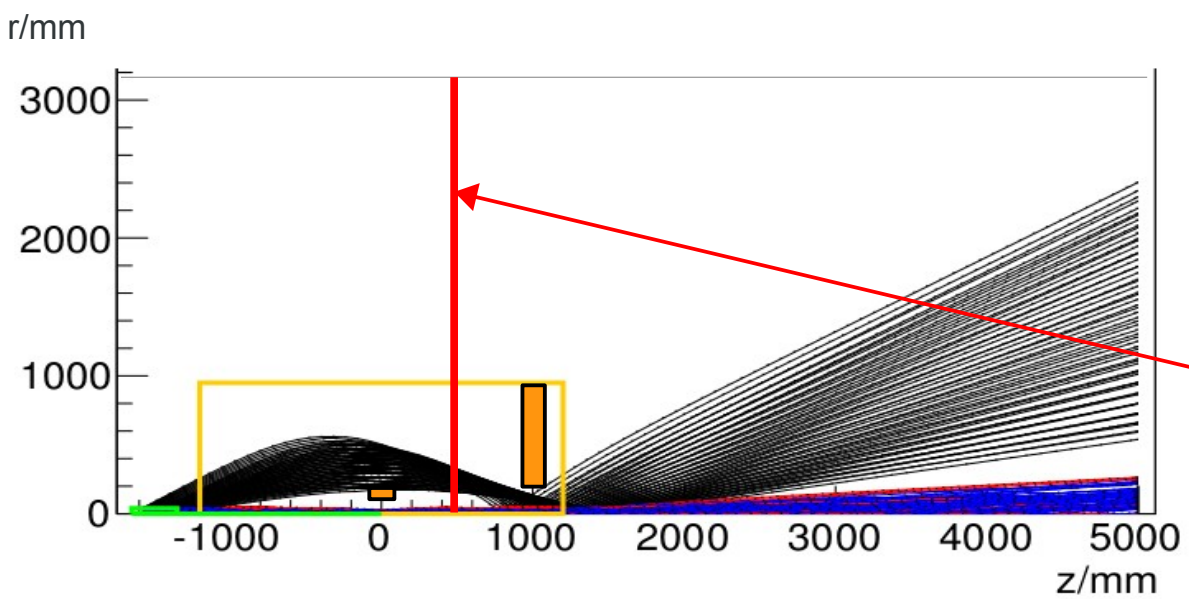



- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**

- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

# Solenoid full simulation

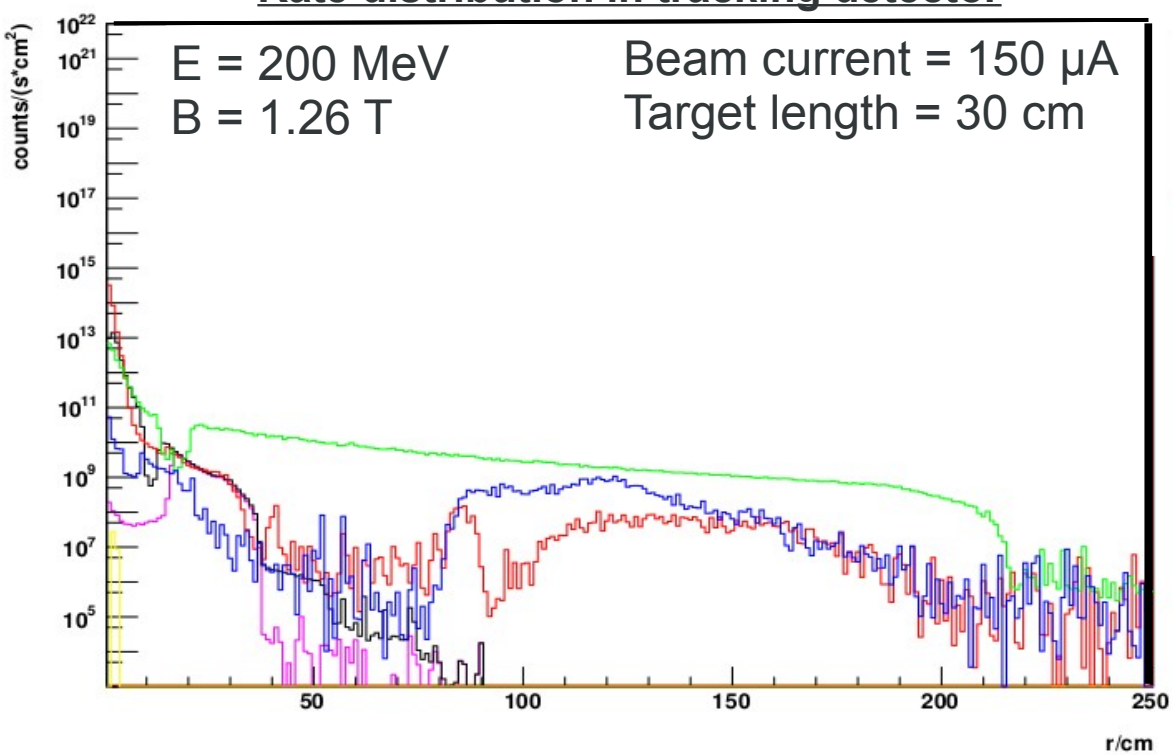



- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**

- Consists of vacuum
- Analyses particles that fly through

**Rate distribution in tracking detector**

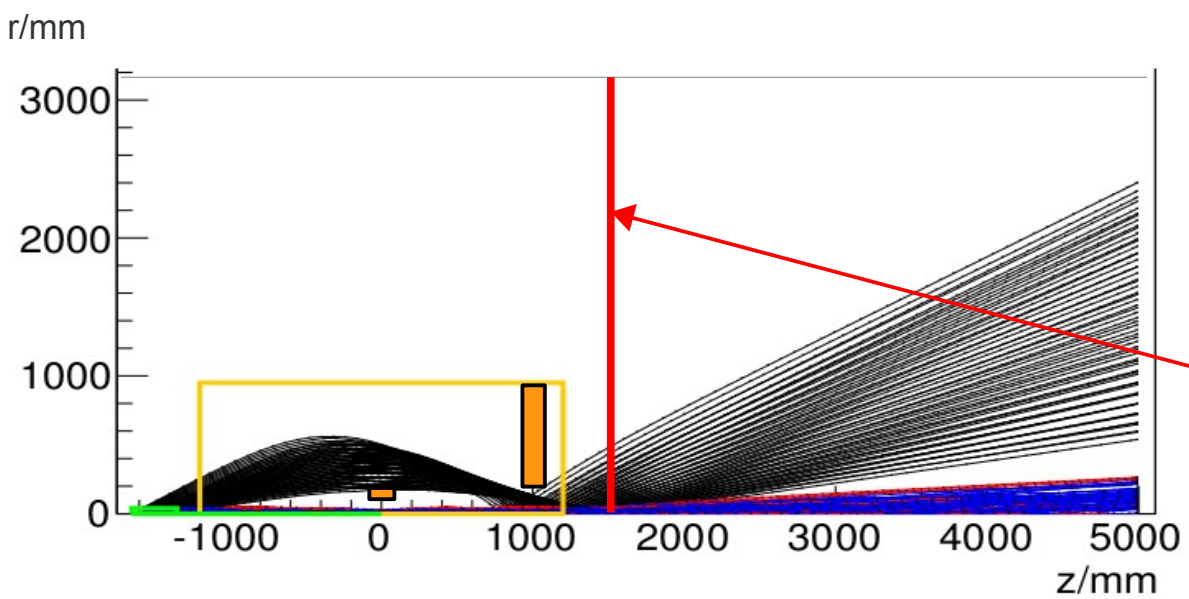



- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**

- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

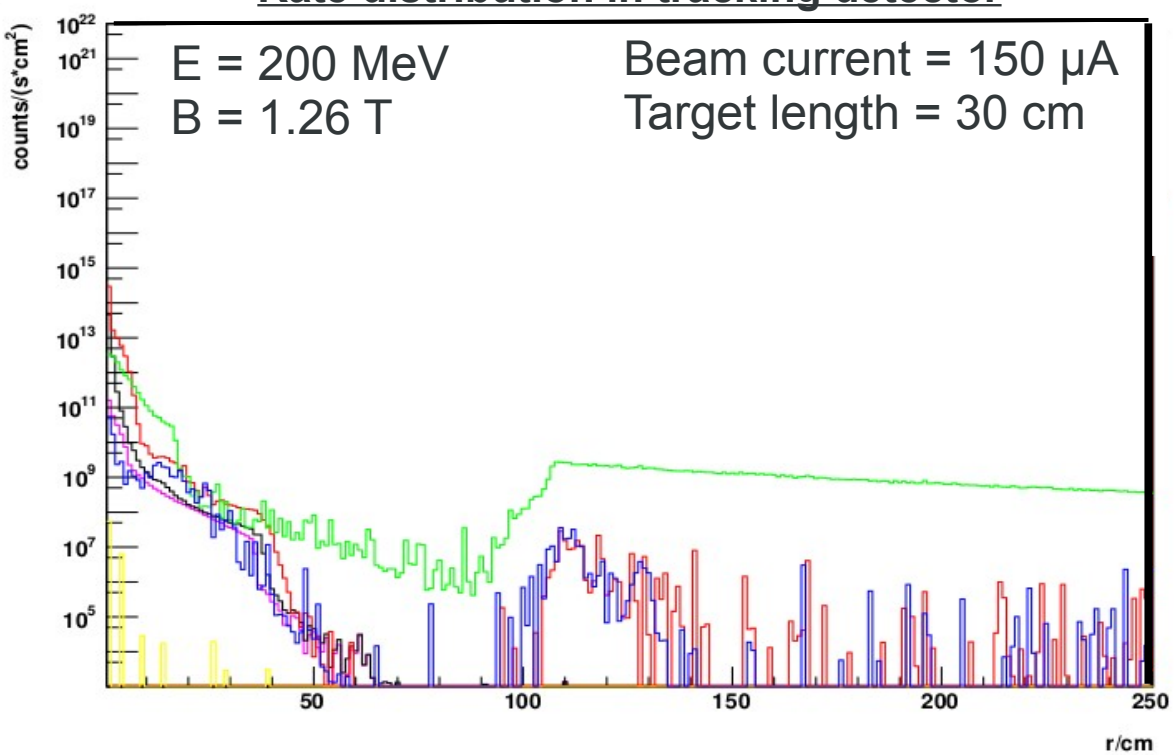
# Solenoid full simulation




- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**
- Consists of vacuum
- Analyses particles that fly through

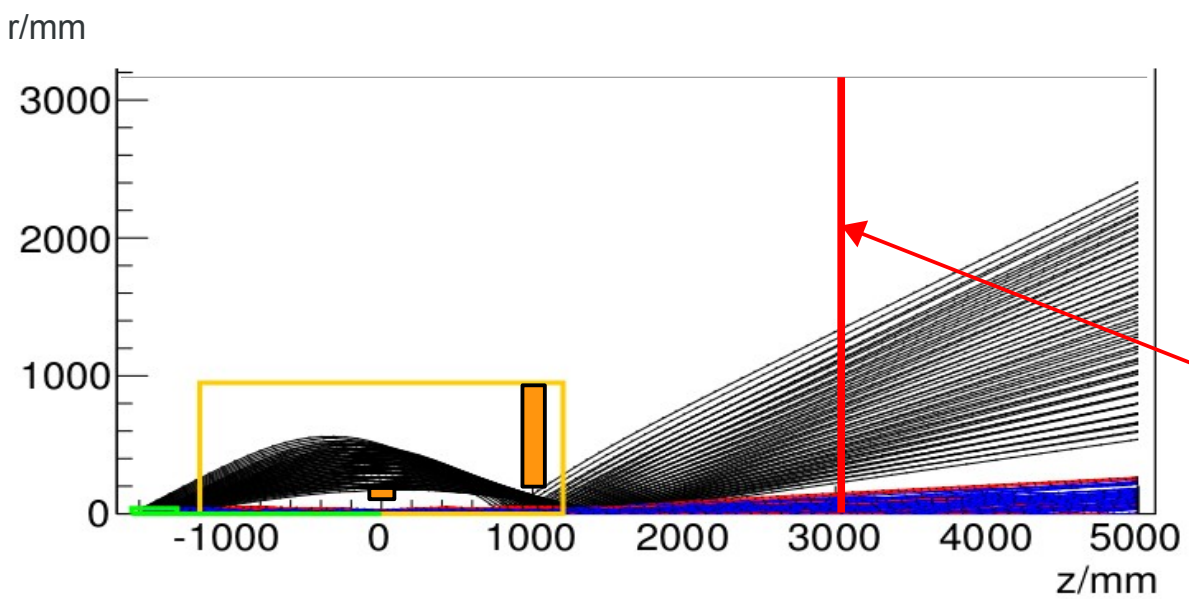
**Rate distribution in tracking detector**




- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**
- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

# Solenoid full simulation

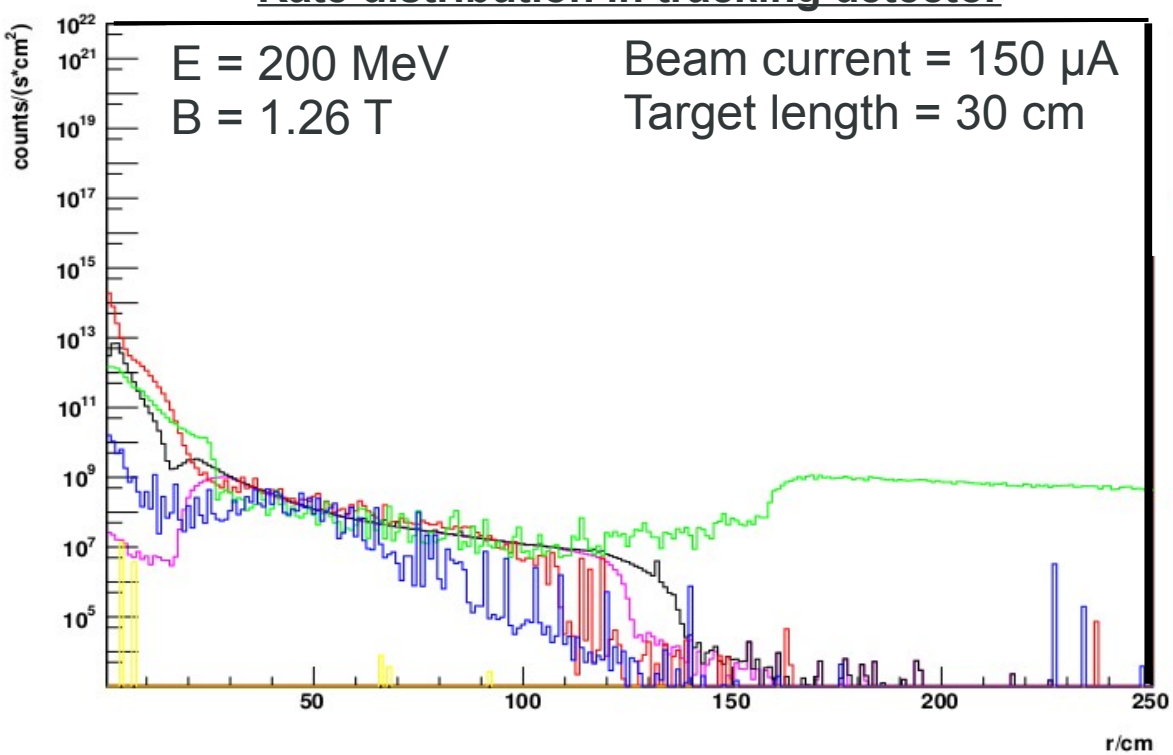



- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**

- Consists of vacuum
- Analyses particles that fly through

**Rate distribution in tracking detector**

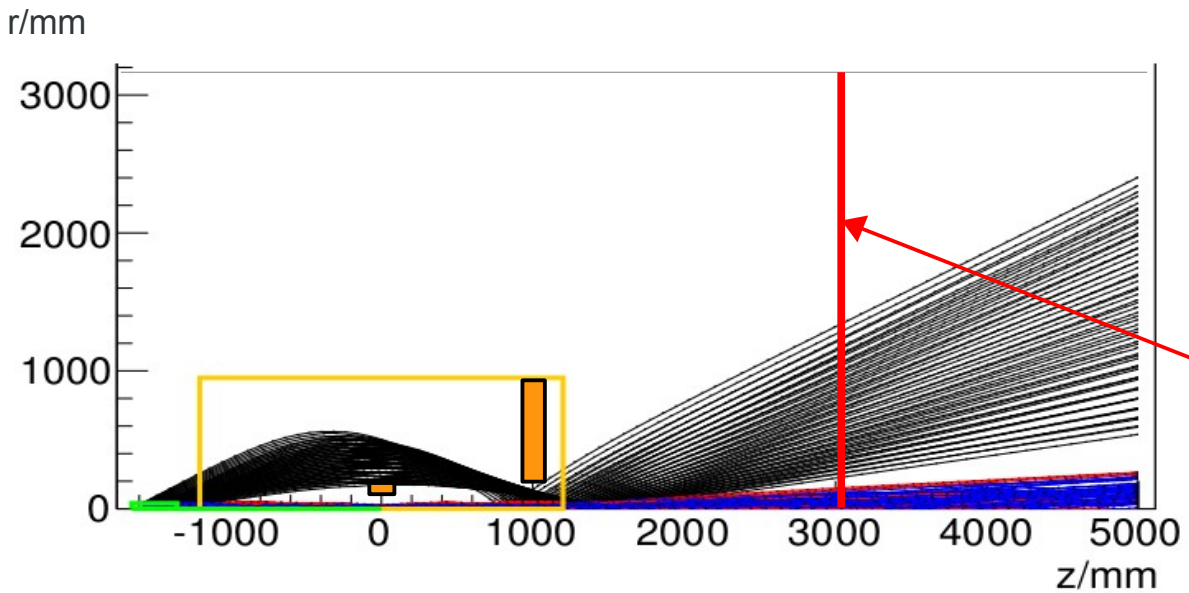



- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

**Full simulation:**

- Flat vertex distribution
- Energy loss in target volume after event generation
- Flat polar angle distribution, weightening in histogram with cross section

# Solenoid full simulation

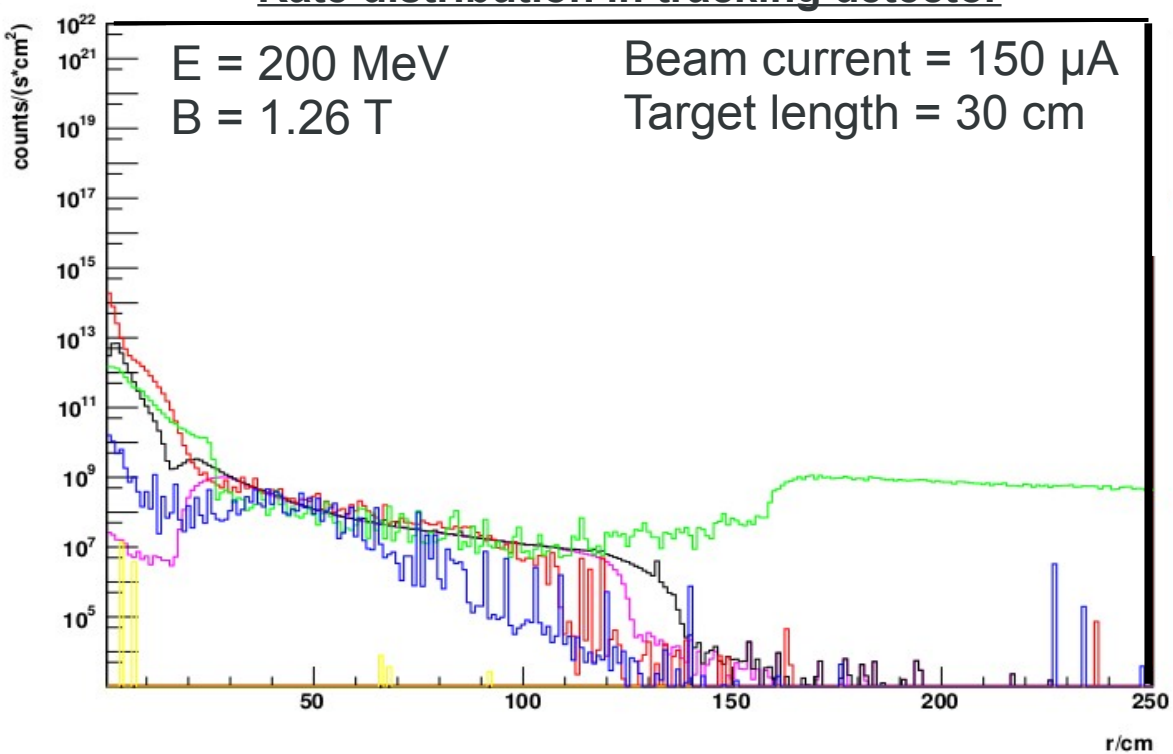



- el. e-p scattering
- Moeller scattering in [0°, 5°]
- Moeller scattering in [10°, 30°]

**Simple tracking detector:**

- Consists of vacuum
- Analyses particles that fly through

**Rate distribution in tracking detector**




- e-, el. e-p scattering, [10°, 30°]
- e-, el. e-p scattering, [1°, 75°]
- e-, background
- e+
- $\gamma$
- p

- **Better shielding required.**
- **Better separation of Moeller-e- needed.**

# Conclusion & Outlook

- Measurement of the proton weak charge yields $\sin^2(\theta_W)$, a key parameter of the standard model

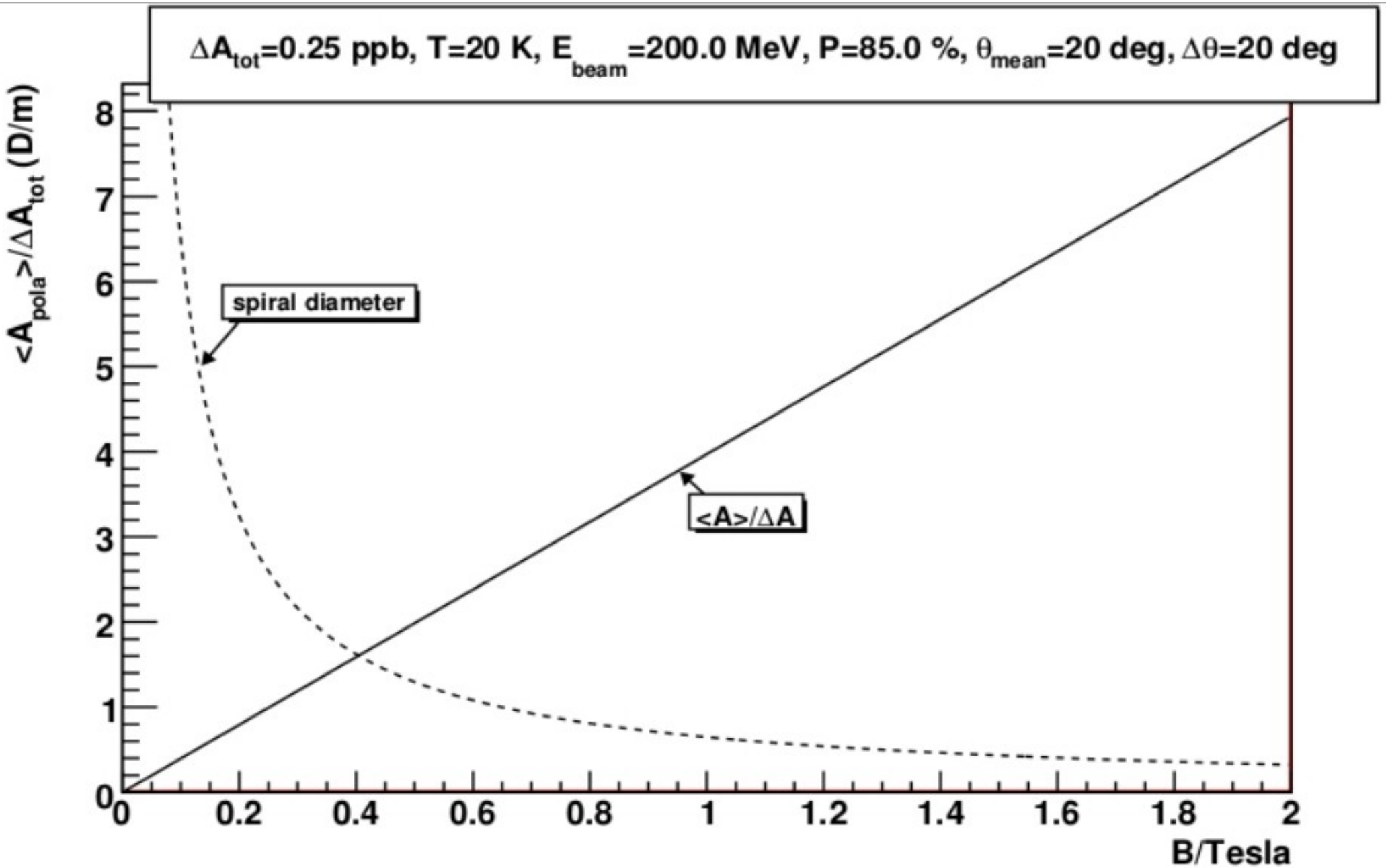
- P2: A new PV experiment in Mainz with precision goal $\left(\frac{\Delta \sin^2(\theta_W)}{\sin^2(\theta_W)}\right) = 0.15\,\%$ .

- $(E = 150\,\mathrm{MeV},\ \theta = 24\,°)$ equivalent to $(E = 200\,\mathrm{MeV},\ \theta = 20\,°)$ in terms of $\Delta \sin^2(\theta_W)$.

- Solenoid highly desirable, further investigation required
  - ➔ Add secondary solenoid to keep Moeller-e- attached to beamline
  - ➔ Model detector response for Cherenkov-counter (large reduction of gamma-contribution)

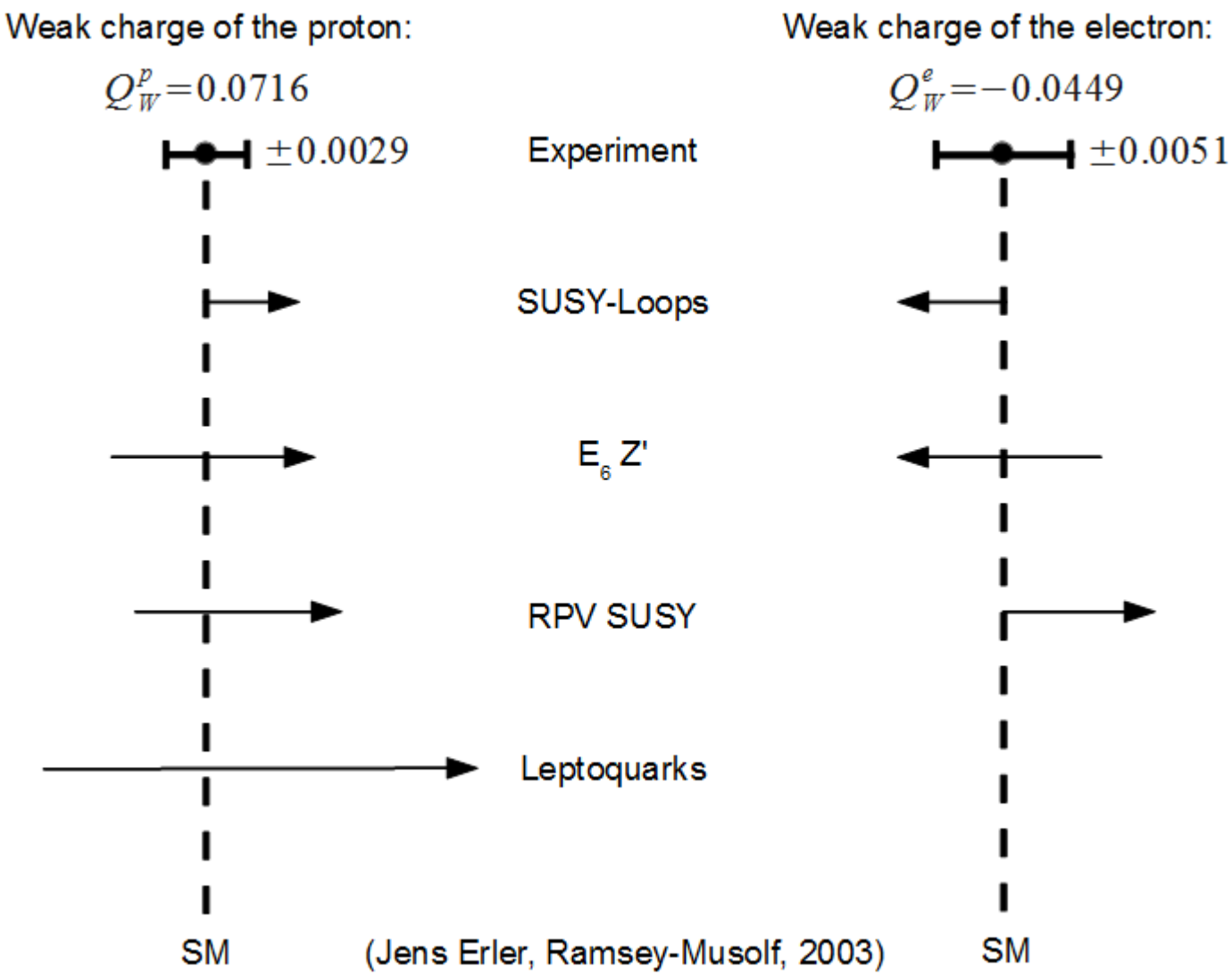
- Toroid: Feasable, fallback solution

# Backup slides


ΔA_tot=0.25 ppb, T=20 K, E_beam=200.0 MeV, P=85.0 %, θ_mean=20 deg, Δθ=20 deg
<A_pola>/ΔA_tot (D/m)
spiral diameter
<A>/ΔA
B/Tesla
0
1
2
3
4
5
6
7
8
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2

# Weak charges: Sensitivity to new physics

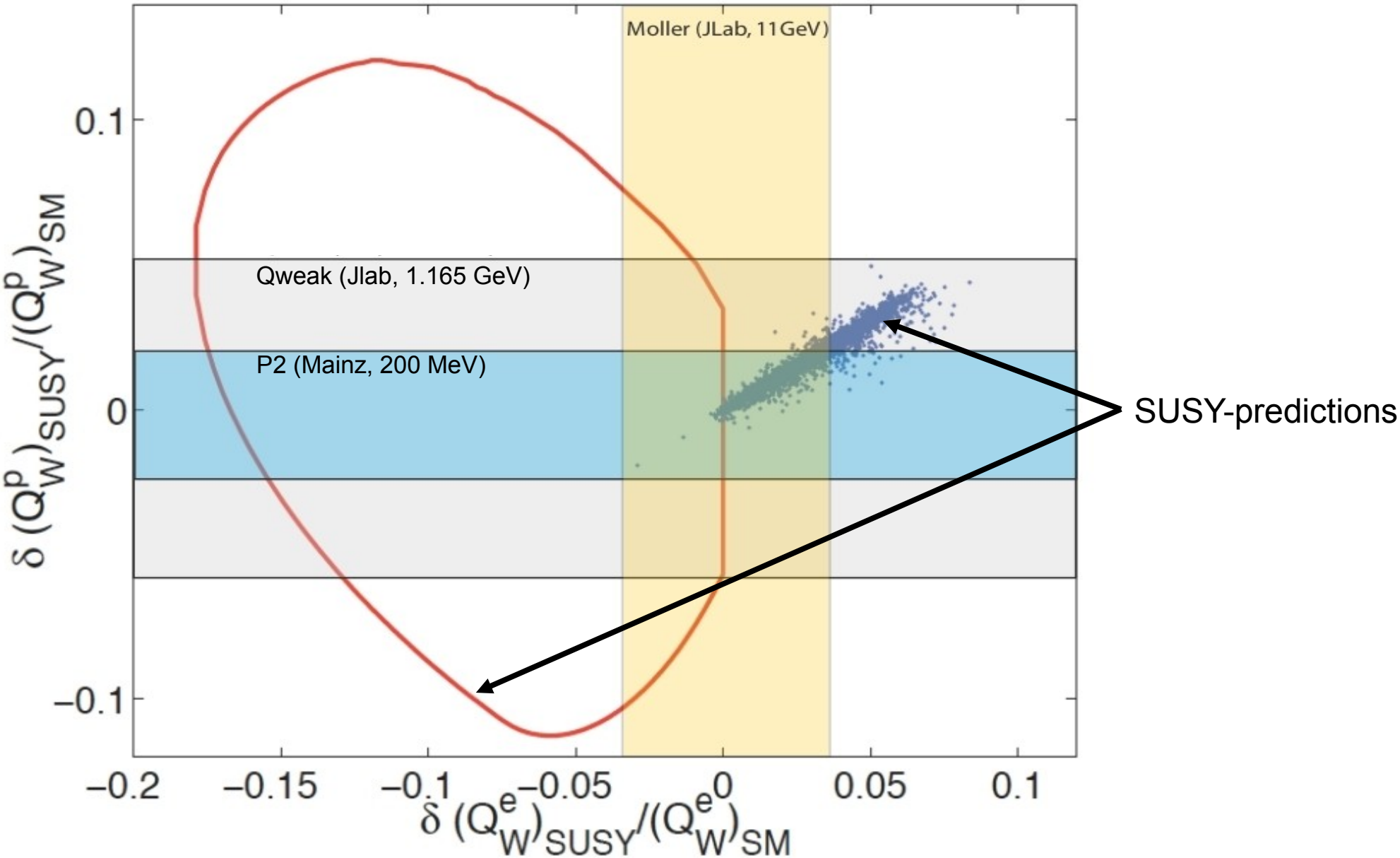
- Complementary access by weak charges of proton and electron




(Jens Erler, Ramsey-Musolf, 2003)

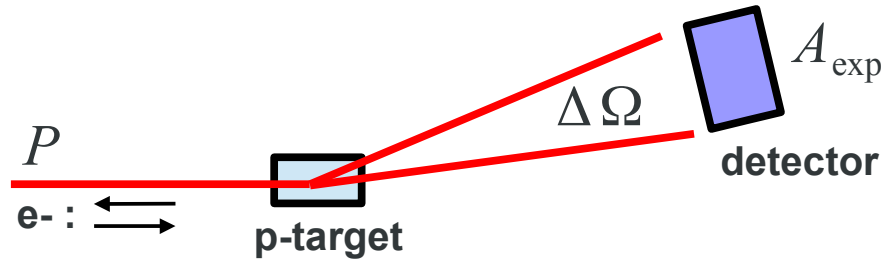
# Sensitivity to new physics

For example: Experimental restriction of SUSY-parameters




(Ramsey-Musolf and Su, 2005)

# Achievable precision @ P2: Monte Carlo method

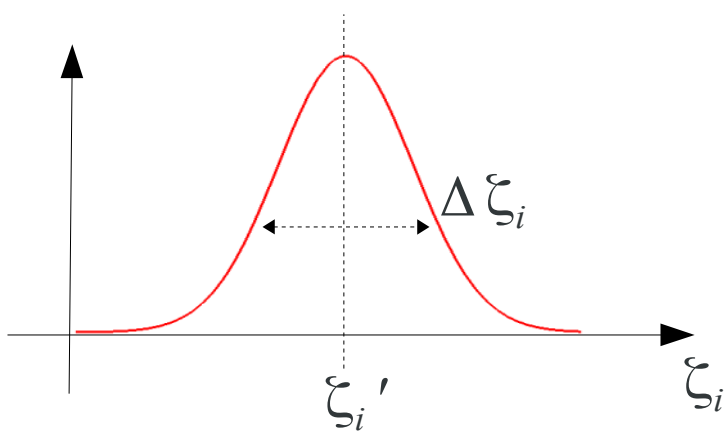



We are going to measure: $\boxed{A_{\exp} = P \cdot \langle A_{PV} \rangle_{\Delta\Omega} + A_{app}}$

$$A_{PV} = A_{PV}(E, \theta, \{FF\}, \sin^2(\theta_W))$$

$$\longrightarrow \quad \sin^2(\theta_W) = \sin^2(\theta_W)(\underbrace{E, P, \Delta\Omega, \{FF\}, A_{\exp}, A_{app}, Q_W^{\gamma-z}}_{=\{\zeta_i'\}})$$

Parameter uncertainties:



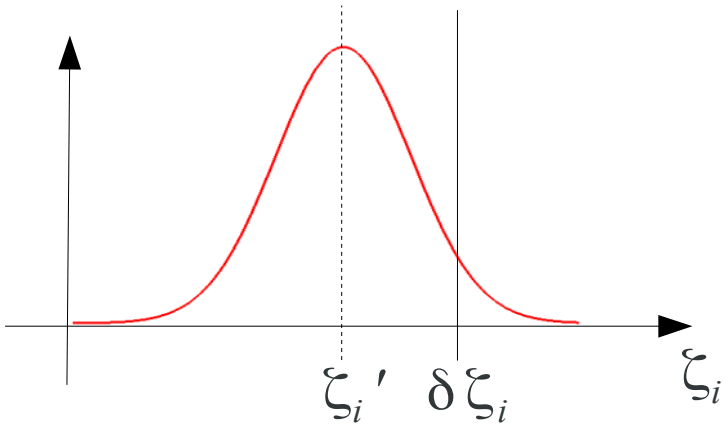

To include counting statistics:

$$\Delta A_{\exp} = \frac{1}{\sqrt{N}}$$

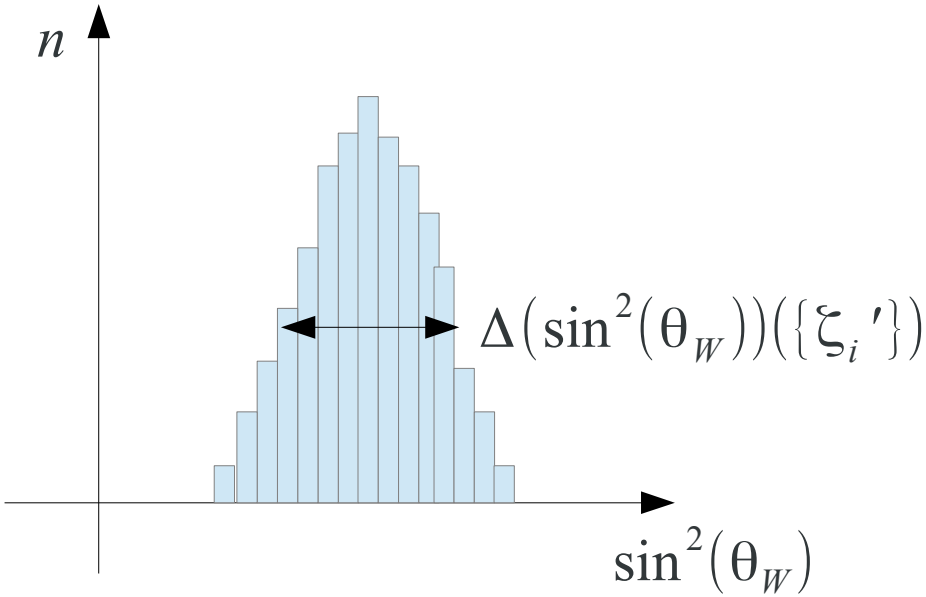
# Achievable precision @ P2: Monte Carlo method

Sample the input parameters:

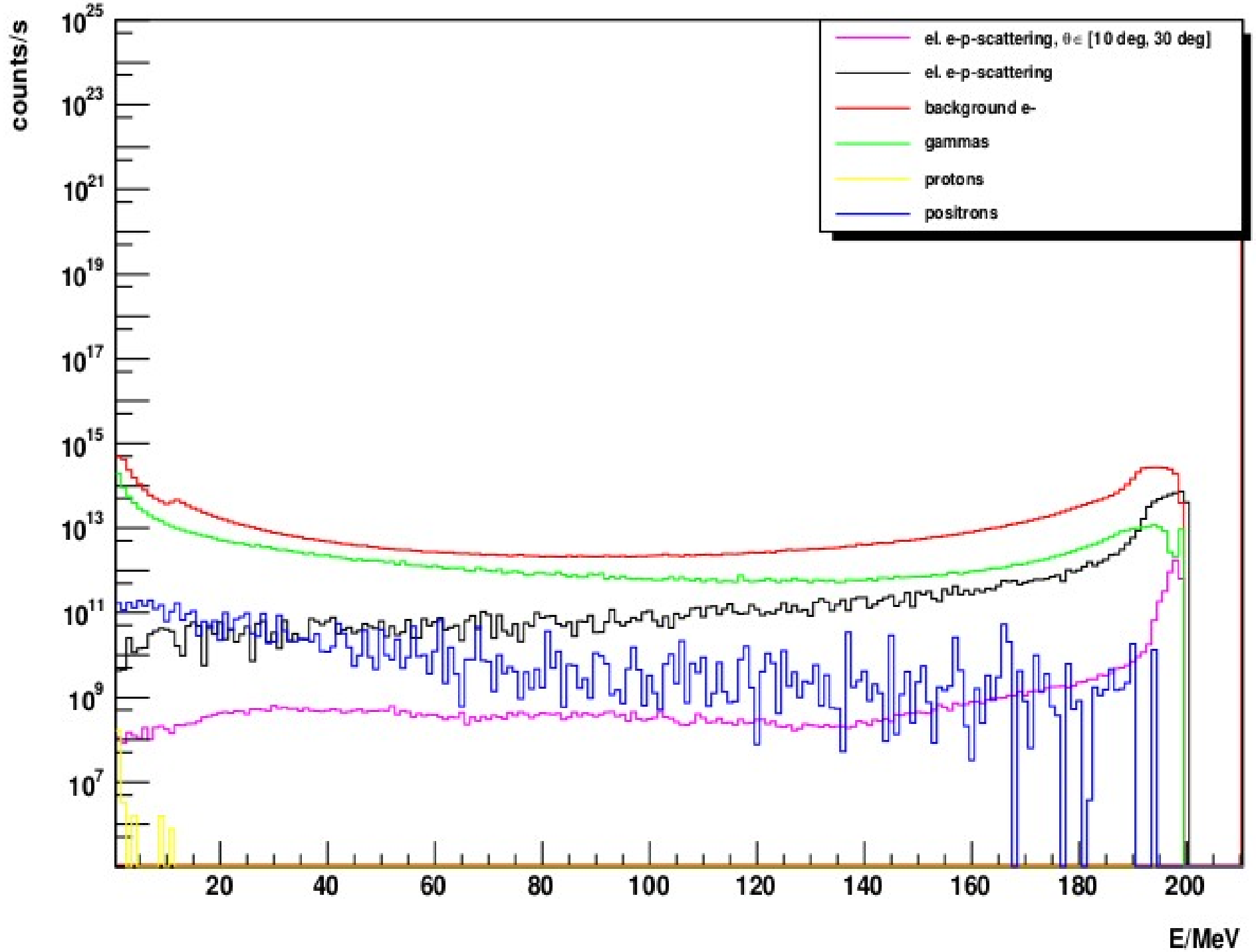
$$\sin^2(\theta_W)+\delta(\sin^2(\theta_W))=\sin^2(\theta_W)(\{\zeta_i'+\delta\zeta_i\})$$

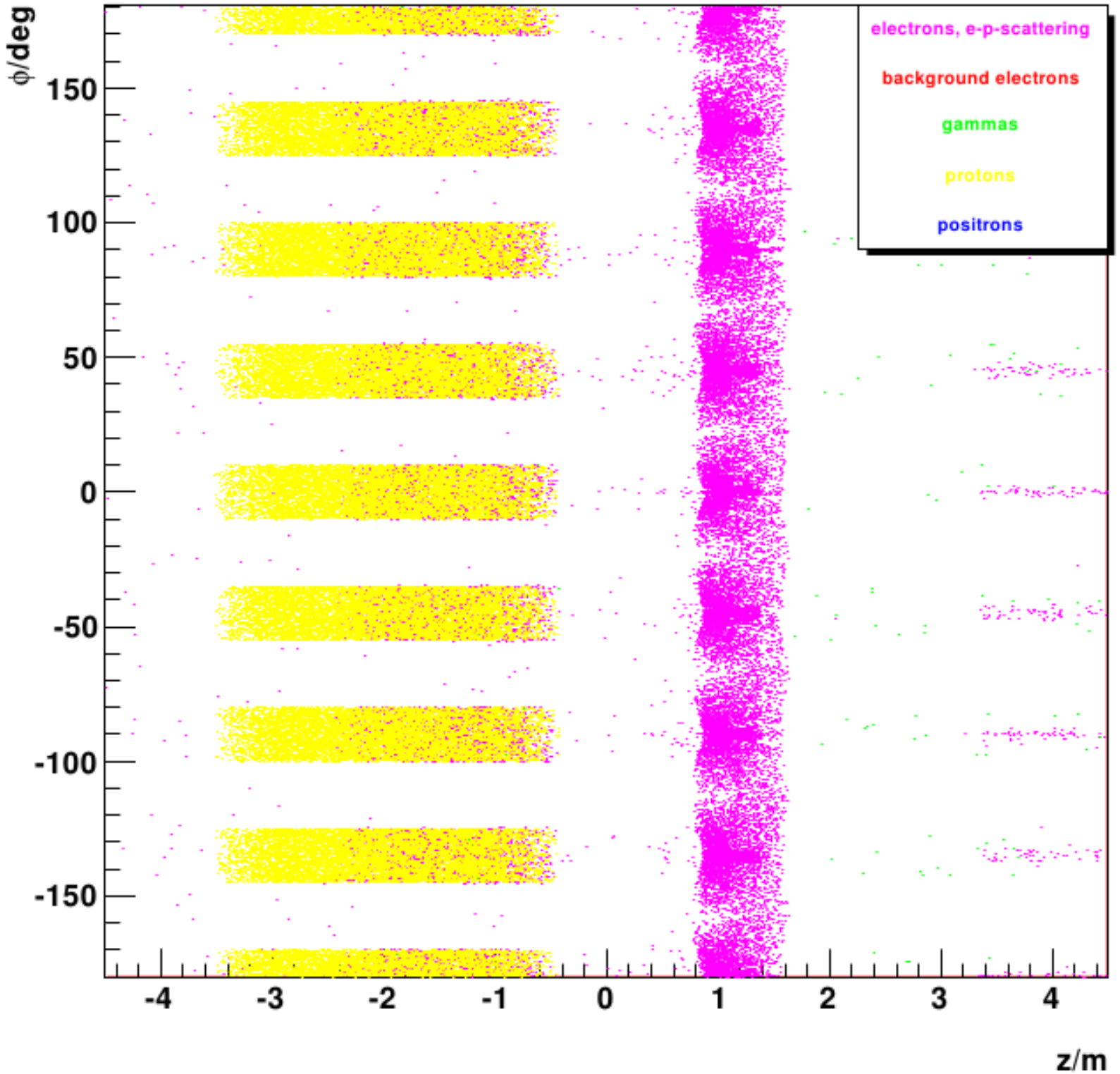



N iterations yield:



# Energy distribution in tracker 40 @ z = 3030 mm




electrons, e-p-scattering
background electrons
gammas
protons
positrons
ϕ/deg
150
100
50
0
-50
-100
-150
-4
-3
-2
-1
0
1
2
3
4
z/m