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Monte Carlo simulations of a solenoid spectrometer for Project P2

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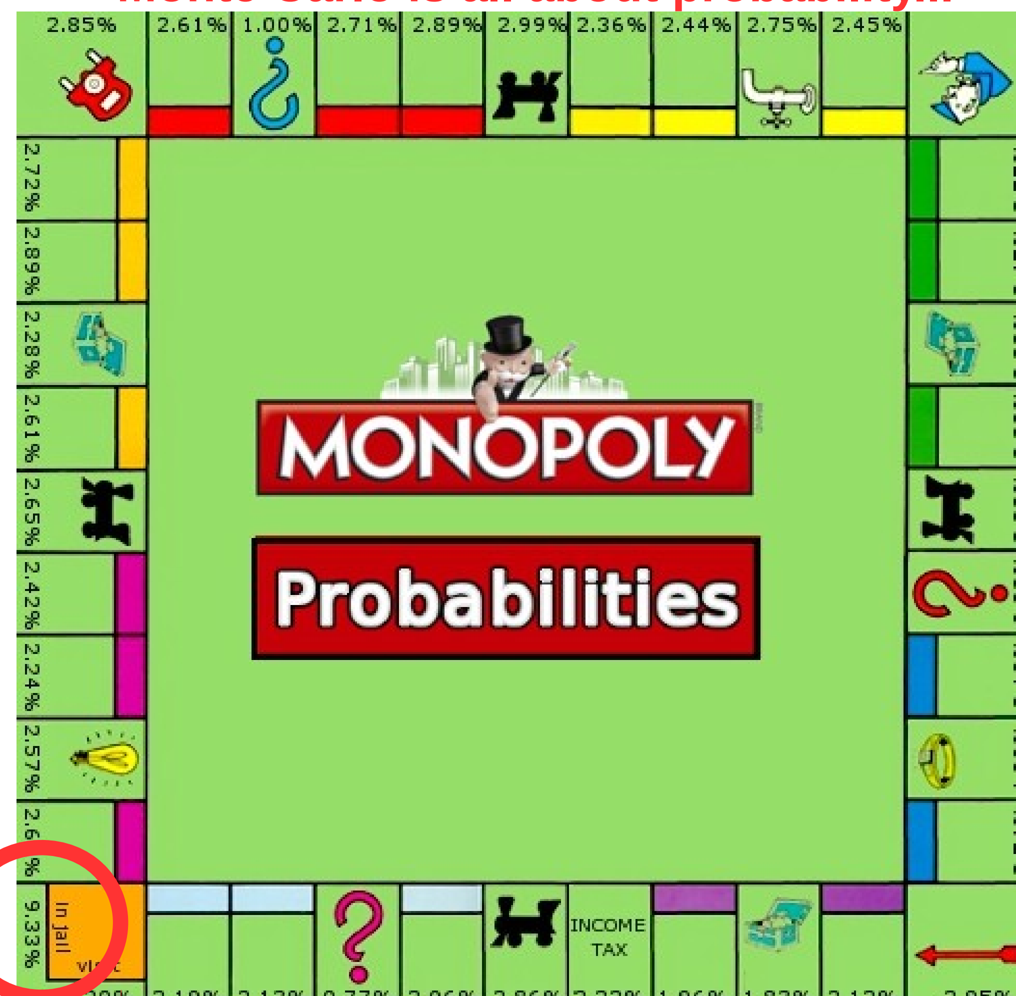
Outline

- **Project P2 @ MESA:**
  A new high precision determination of the electroweak mixing angle at low momentum transfer

- **P2 main dector concept:**
  Monte Carlo simulations of a solenoid spectrometer

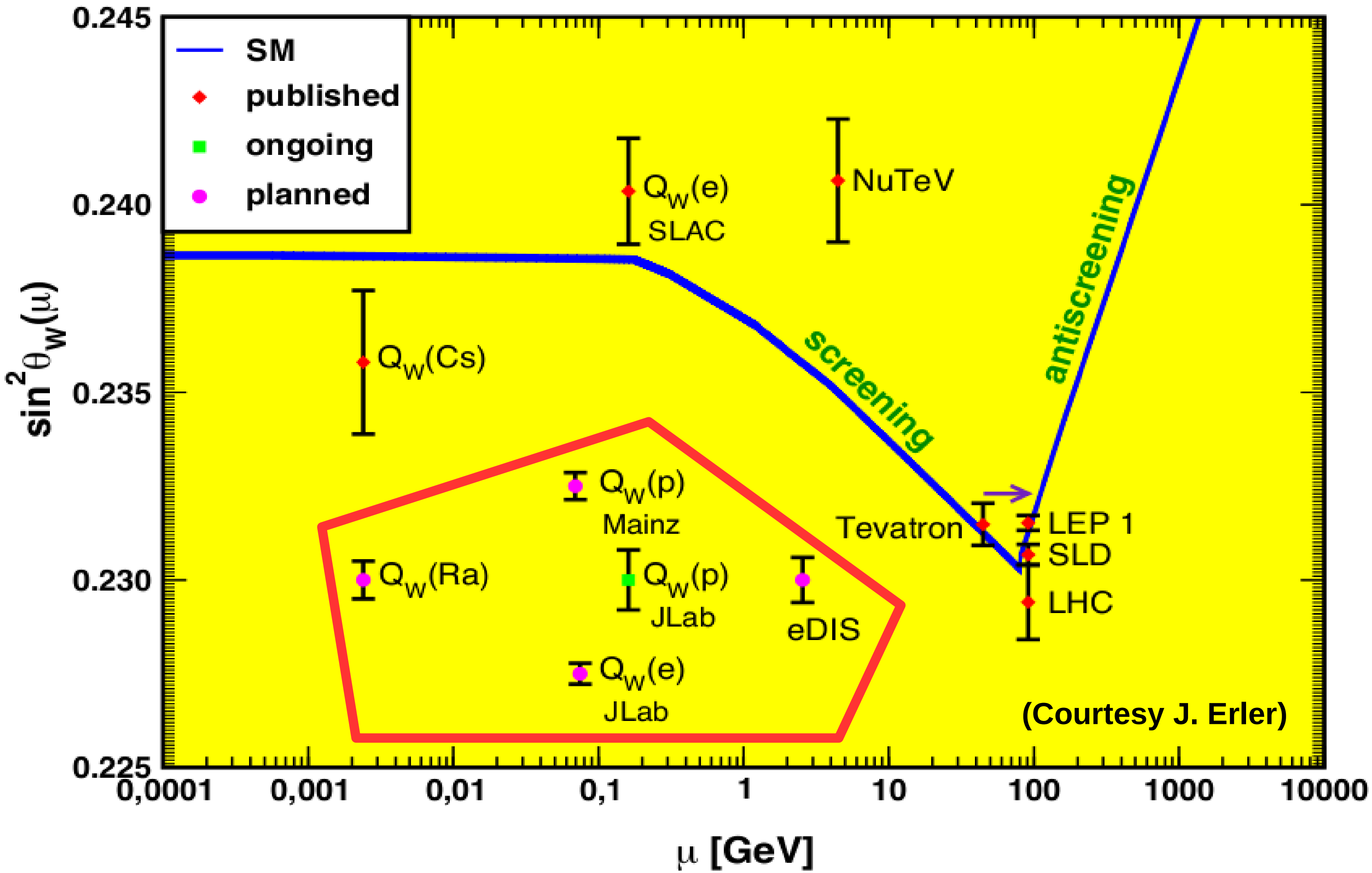
- Monte Carlo simulations regarding a precision measurement of the weak mixing angle at **higher beam energies and beam current**

Monte Carlo is all about probability...



Highest probability

The global situation

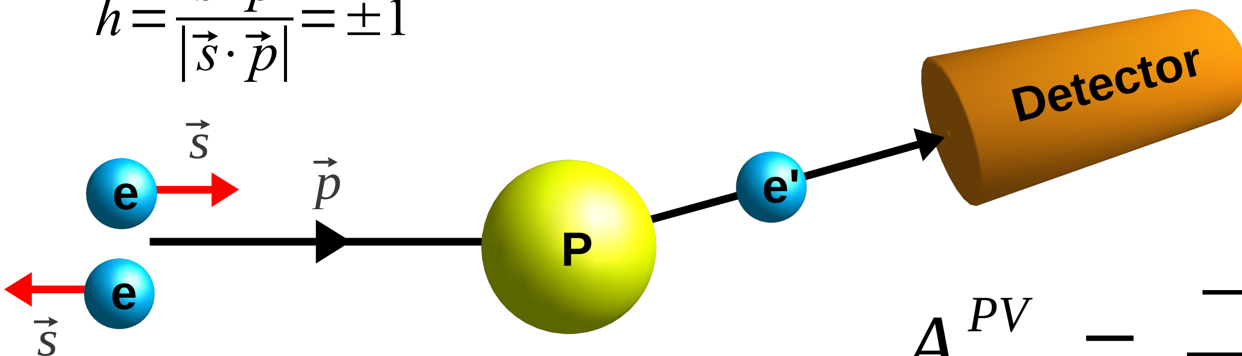


Project P2 @ MESA:

- New high precision determination of the proton weak charge $Q_w(p)$ at low $Q^2 \sim 6 \cdot 10^{-3}$ GeV²/c²
- Precision goal: $\Delta Q_w(p) = 1.9$ % $\Delta\sin^2\theta_w = 0.15$ %
- Measurement of $Q_w(p)$ through parity violation in elastic e-p scattering

Access to the weak mixing angle

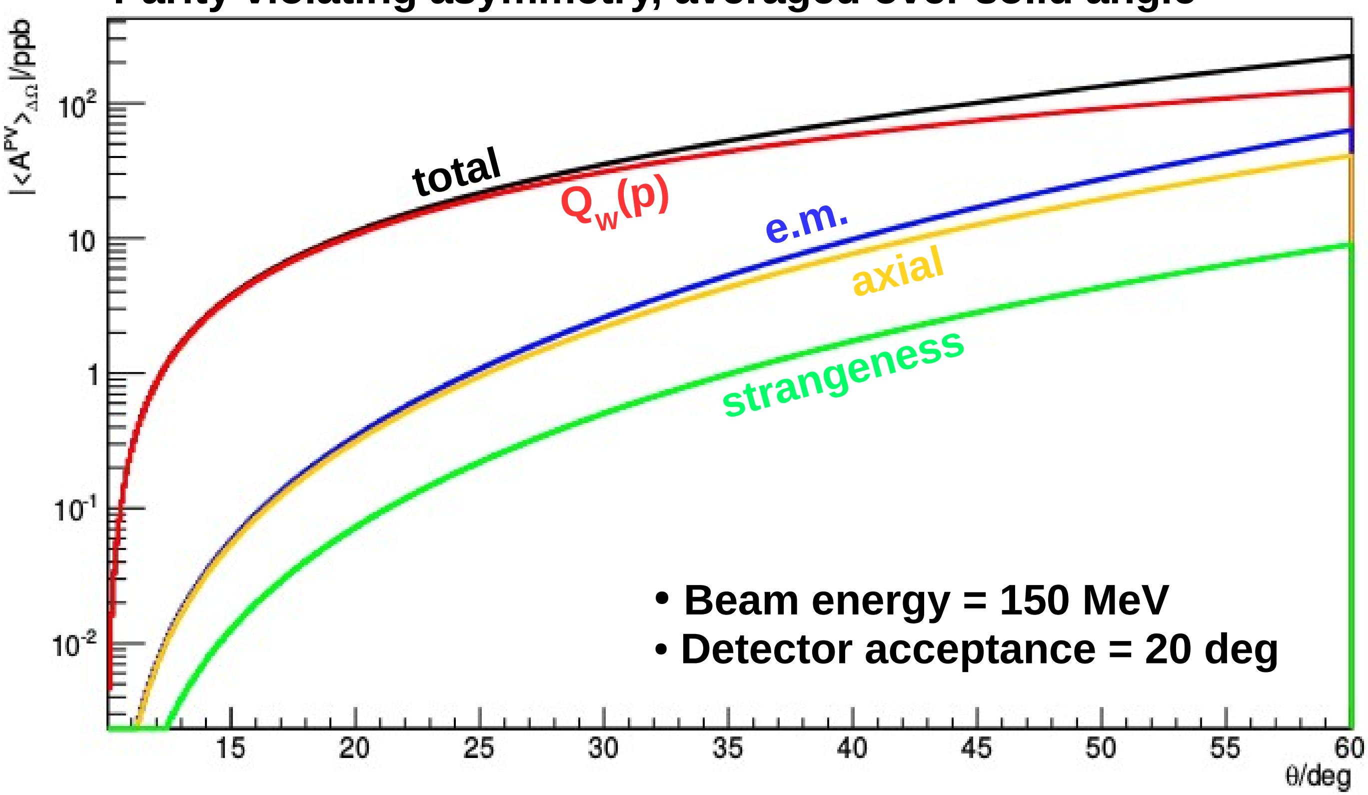
$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|} = \pm 1$$



Parity violating asymmetry in elastic e-p scattering:

$$A^{PV} = \frac{-G_F Q^2}{4\sqrt{2}\pi\alpha}\left[Q_W(p) - F(Q^2)\right]$$

Parity violating asymmetry, averaged over solid angle

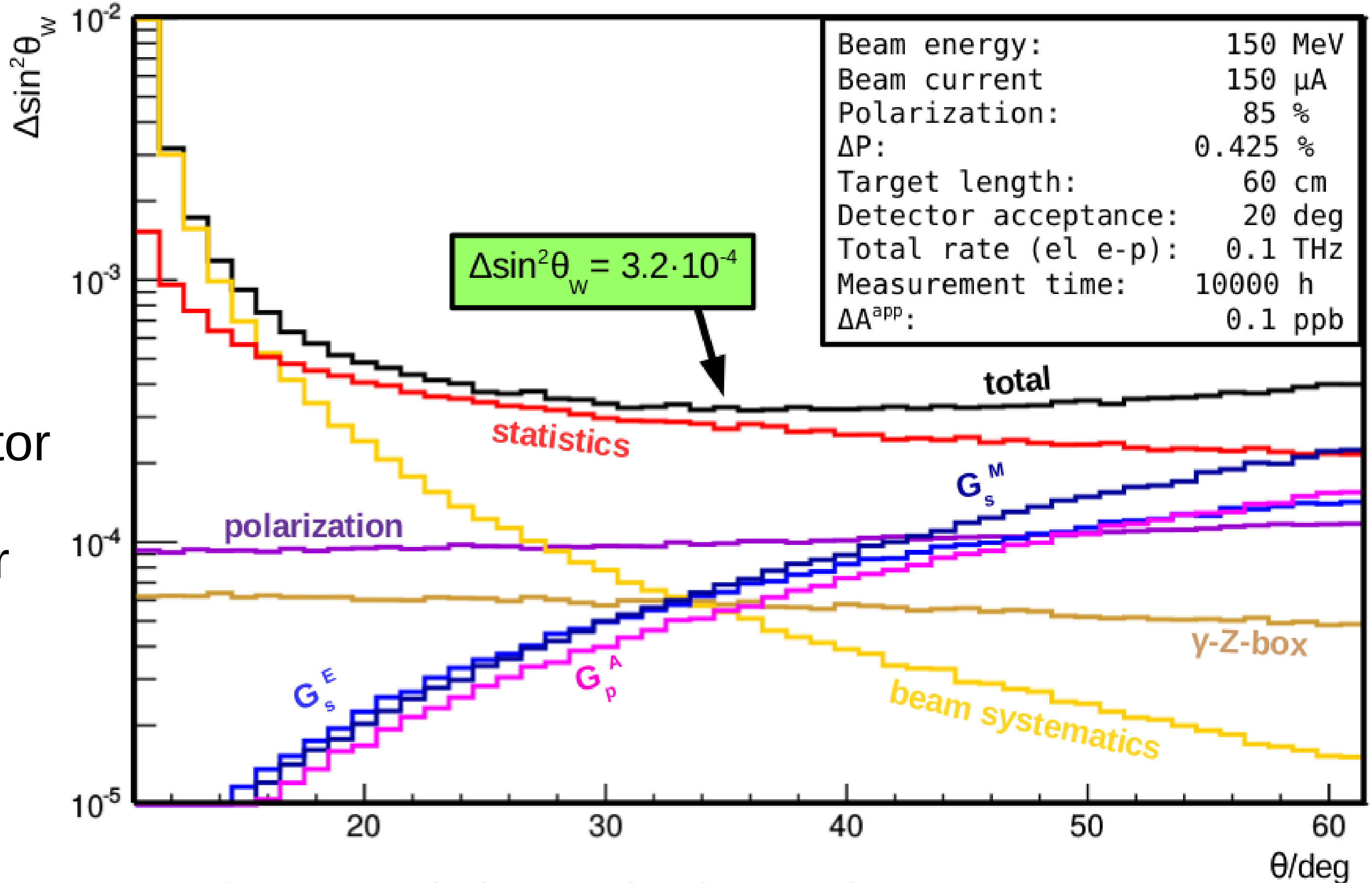


- $Q_W(p)$: Proton weak charge, $Q_W(p) = 1\text{-}4\cdot\sin^2(\theta_W)$ (tree level)
- $F(Q^2)$: Nucleon structure contribution, small at low Q^2

$$A^{PV} \sim \sin^2\theta_W$$

Prediction of achievable precision and choice of kinematics

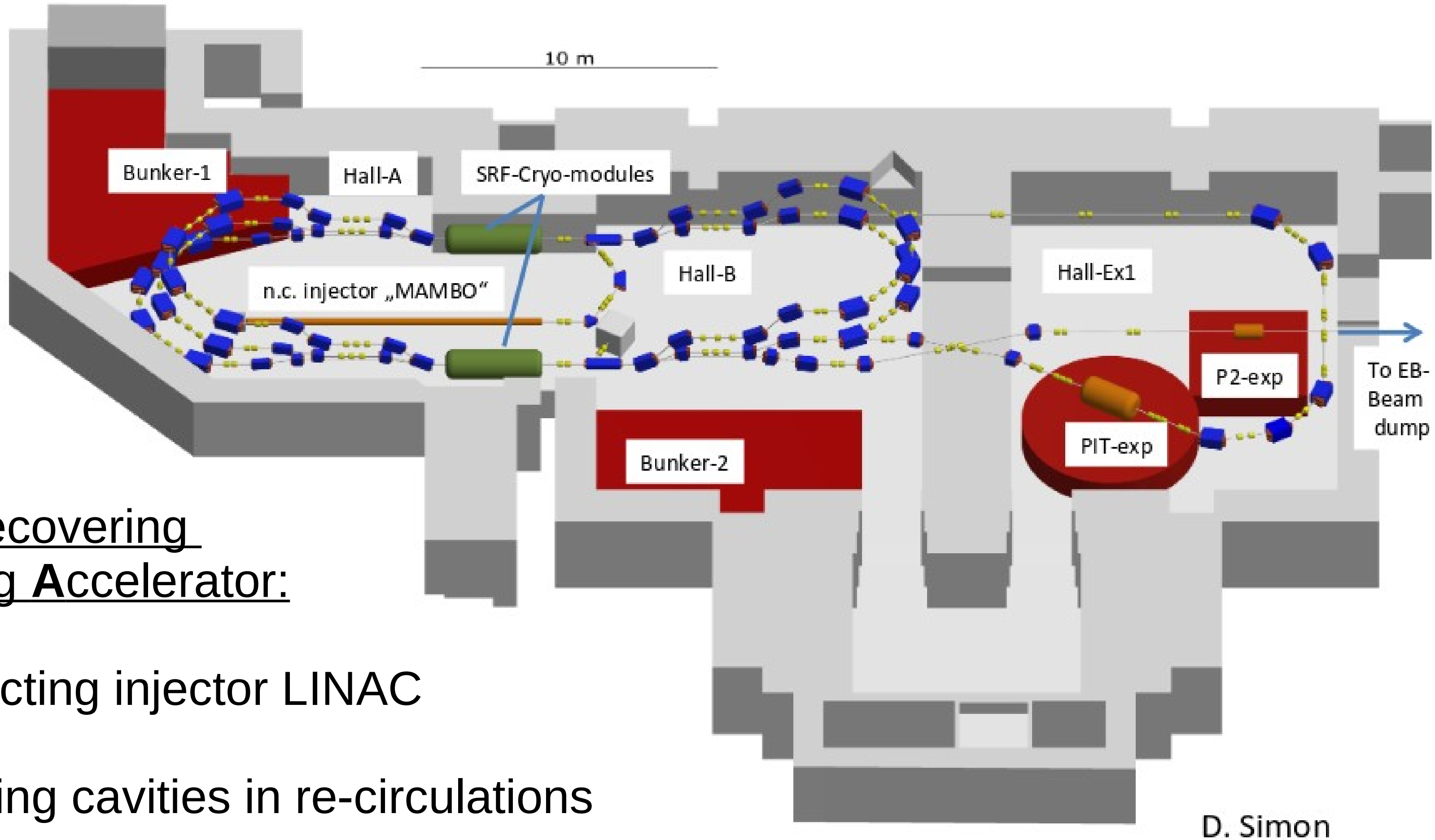
- Monte Carlo approach to error propagation calculation
- Assumption of back angle measurement of axial and strange magnetic form factor in P2
  → Reduction of form factor uncertainty by factor 4
- A^{PV} = -39.80 ppb
  ± 0.54 ppb (stat.)
  ± 0.34 ppb (other)



Form factor parametrizations: P. Larin and S, Baunack
γ-Z-box according to: Gorchtein, Horowitz, Ramsey-Musolf 1102.3910 [nucl-th]

$\Delta\sin^2(\theta_W) = 3.2 \cdot 10^{-4}$ (0.13 %)	**@**	**Beam energy:**	**150 MeV**
		Central scattering angle:	**35 deg**
		Detector acceptance:	**20 deg**

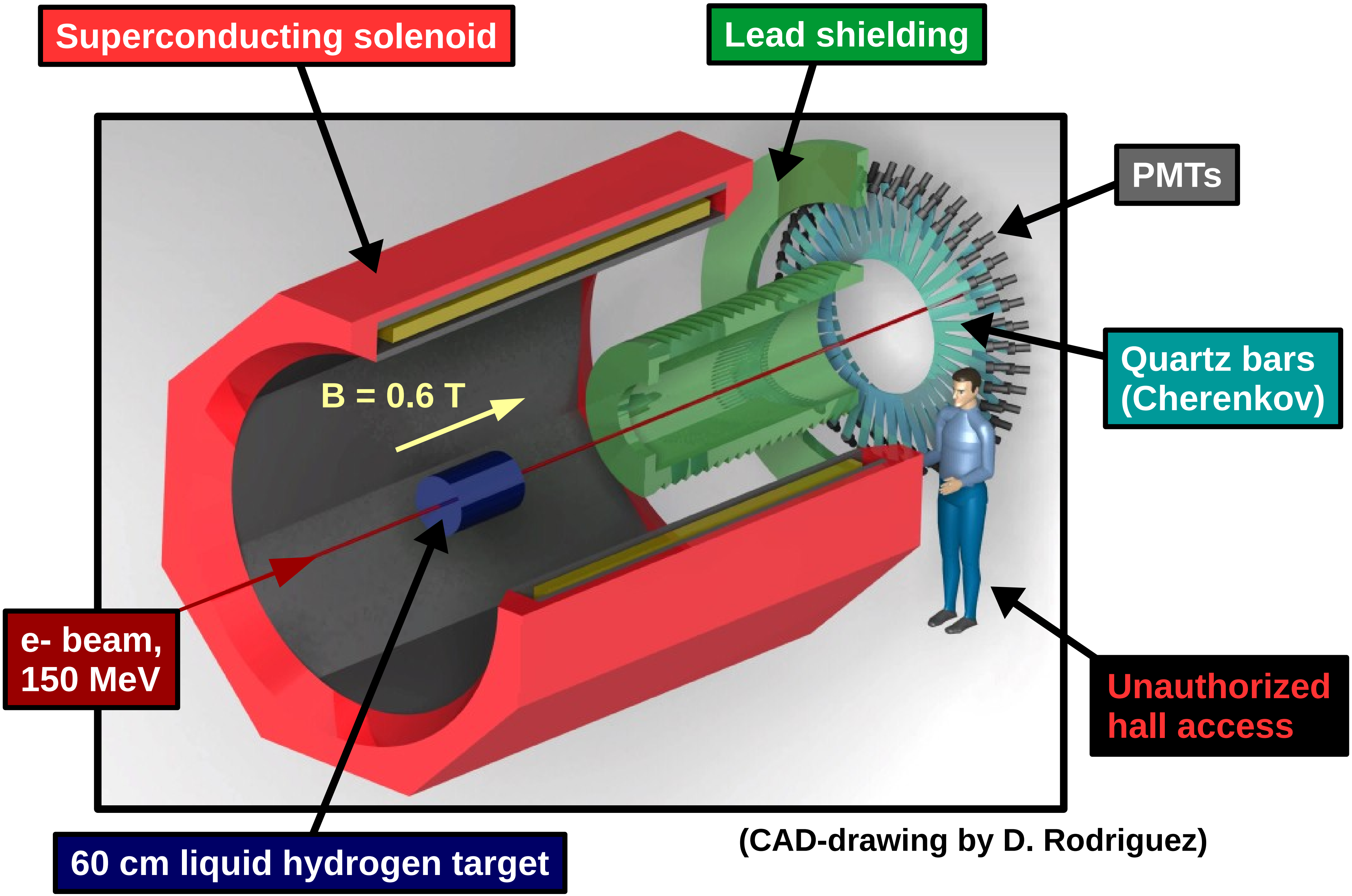
The new M.E.S.A. facility in Mainz



Mainz **E**nergy recovering **S**uperconducting **A**ccelerator:

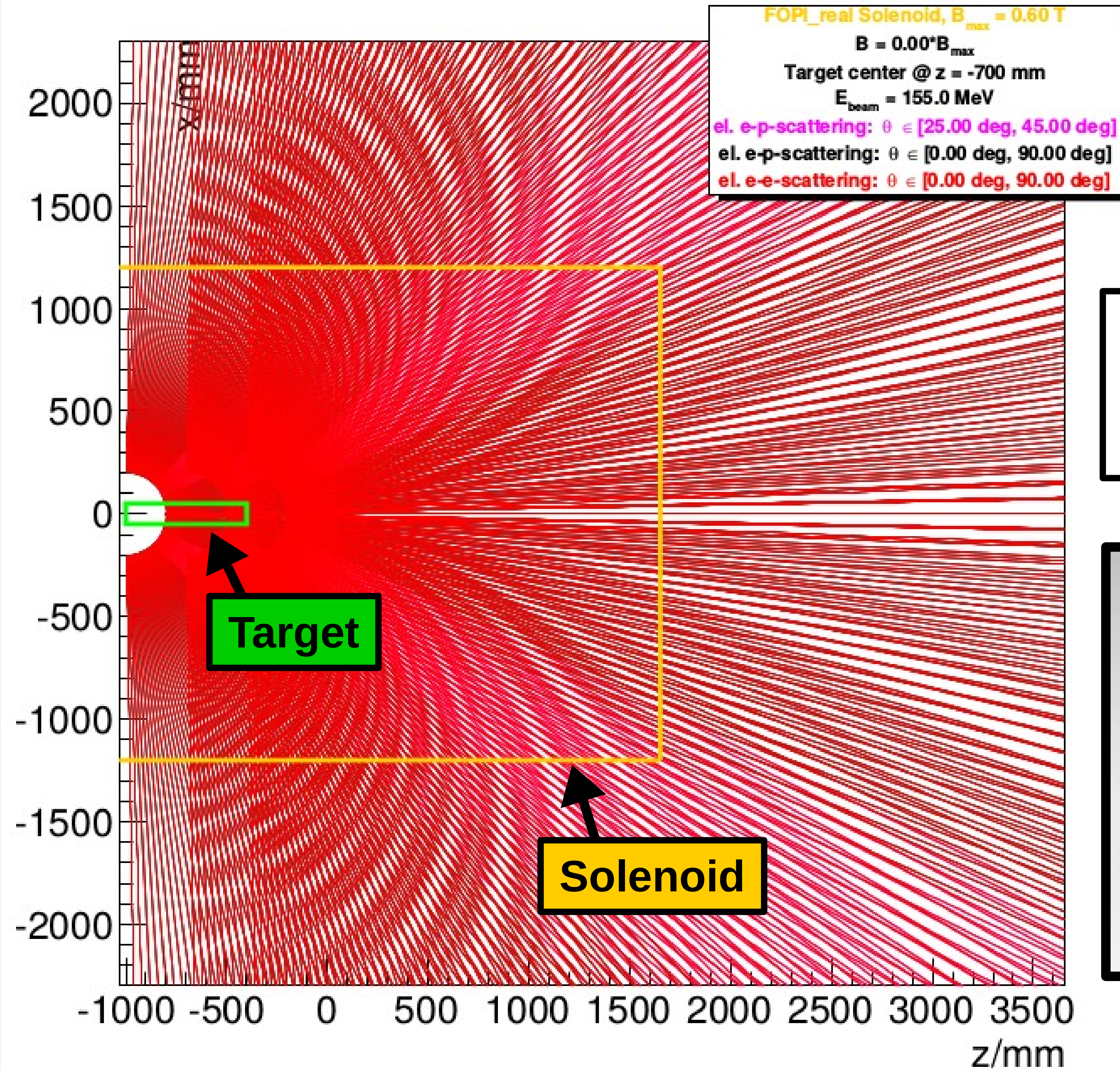
- Normal-conducting injector LINAC
- Superconducting cavities in re-circulations
- Energy recovering mode: Unpolarized beam, 10 mA, 100 MeV, pseudo-internal gas-target, L ~ $10^{35} cm^{-2}s^{-1}$
- External beam mode: P = 85%±0,5%, 150 µA, 155 MeV, L ~ 10^{39} $cm^{-2}s^{-1}$, $\langle \Delta A_{app} \rangle_{\Delta t} = 0.1$ ppb

Experimental setup under investigation



(CAD-drawing by D. Rodriguez)

Raytrace simulations in the magnetic field



Magnetic field: OFF

```
Beam energy = 155 MeV
Moller,       θ ϵ [ 0°, 90°]
Elastic e-p,  θ ϵ [25°, 45°]
Elastic e-p,  θ ϵ [ 0°, 90°]
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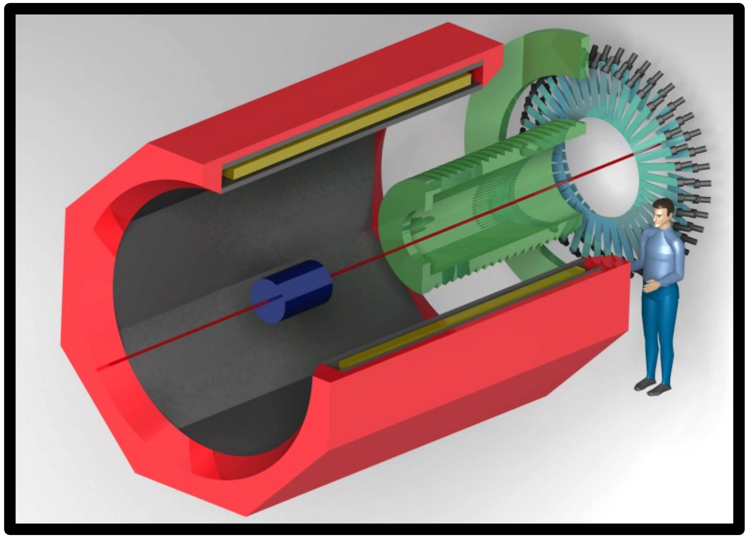
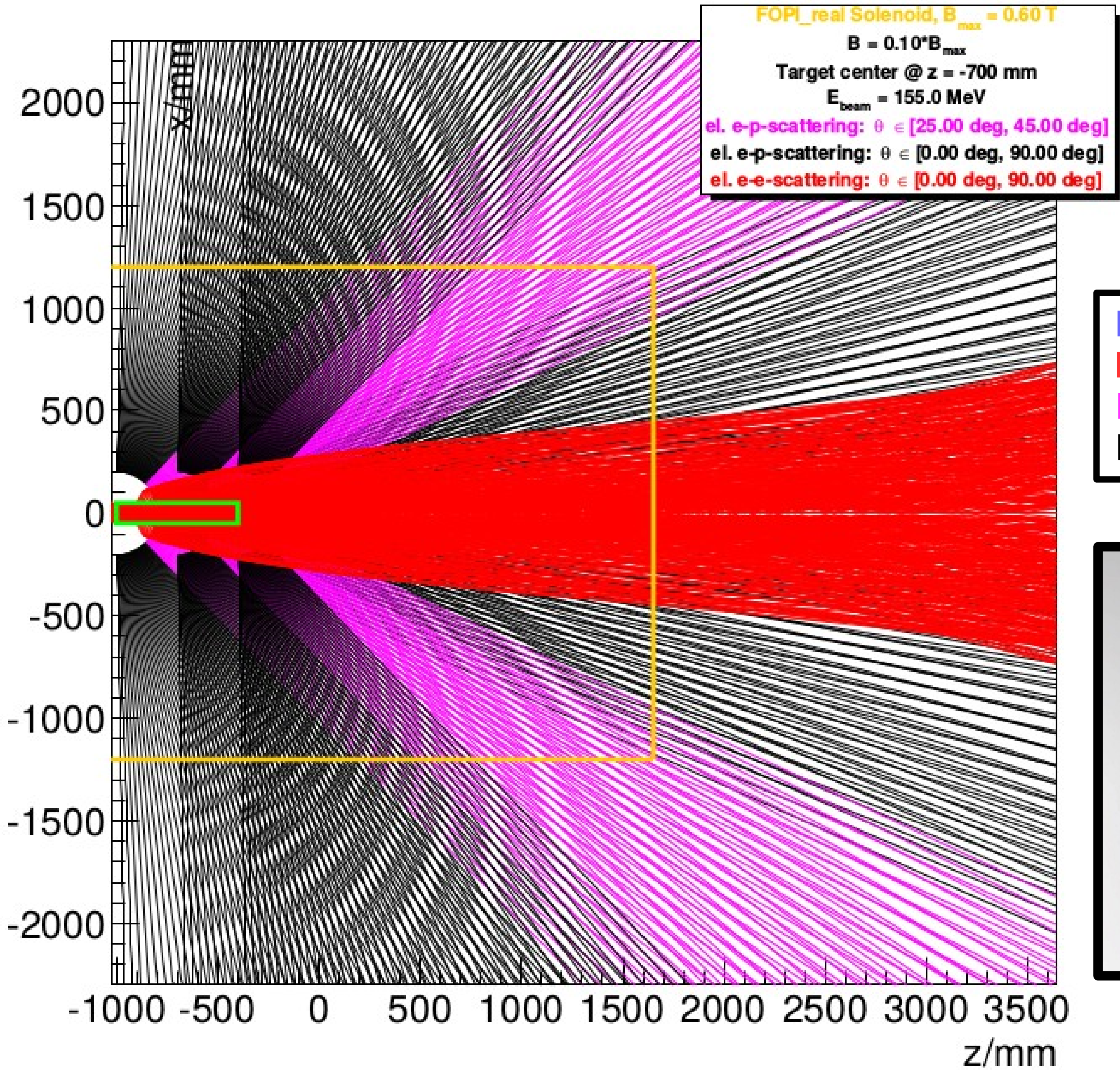
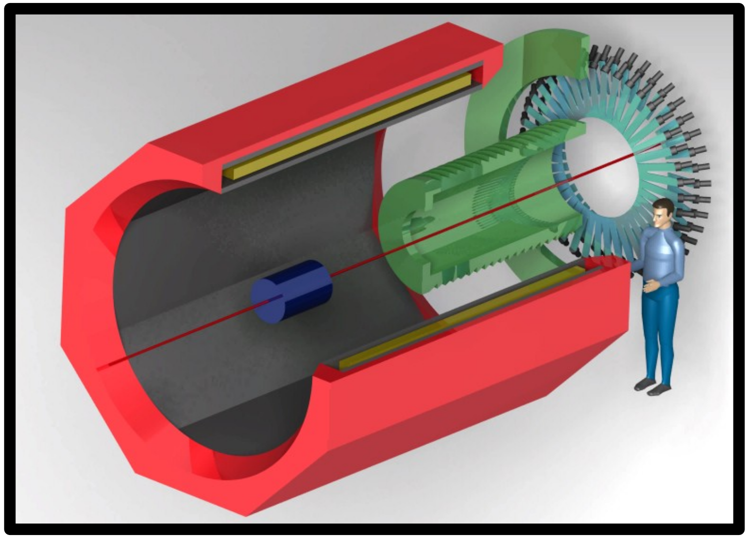


Raytrace simulations in the magnetic field

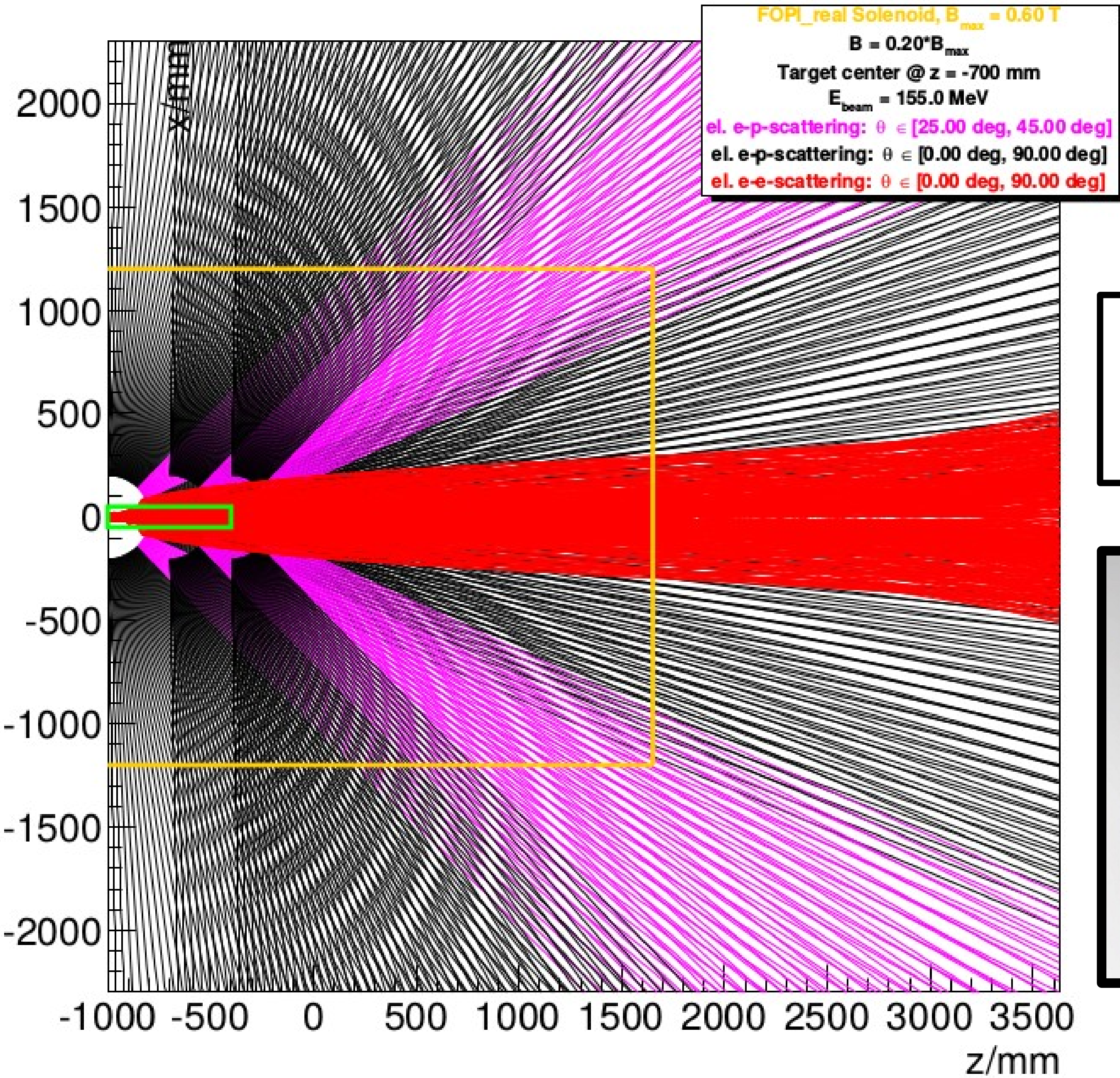


Magnetic field:
0.06 T

Beam energy = 155 MeV
Moller, θ ∈ [0°, 90°]
Elastic e-p, θ ∈ [25°, 45°]
Elastic e-p, θ ∈ [0°, 90°]

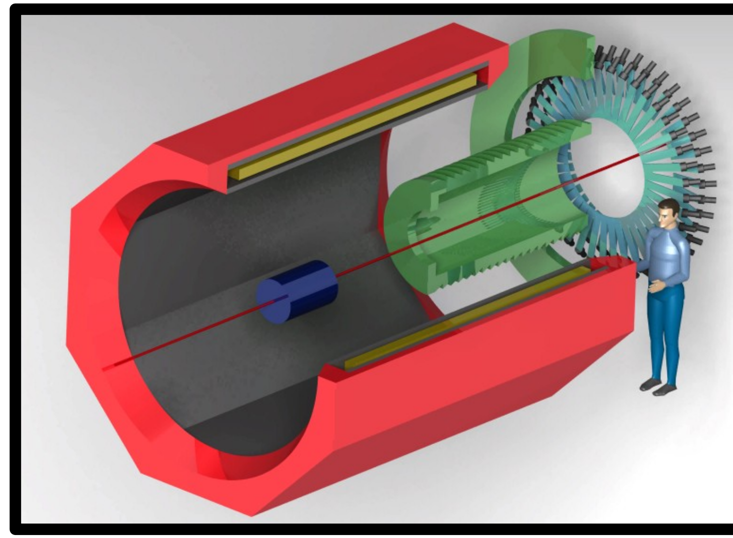


Raytrace simulations in the magnetic field

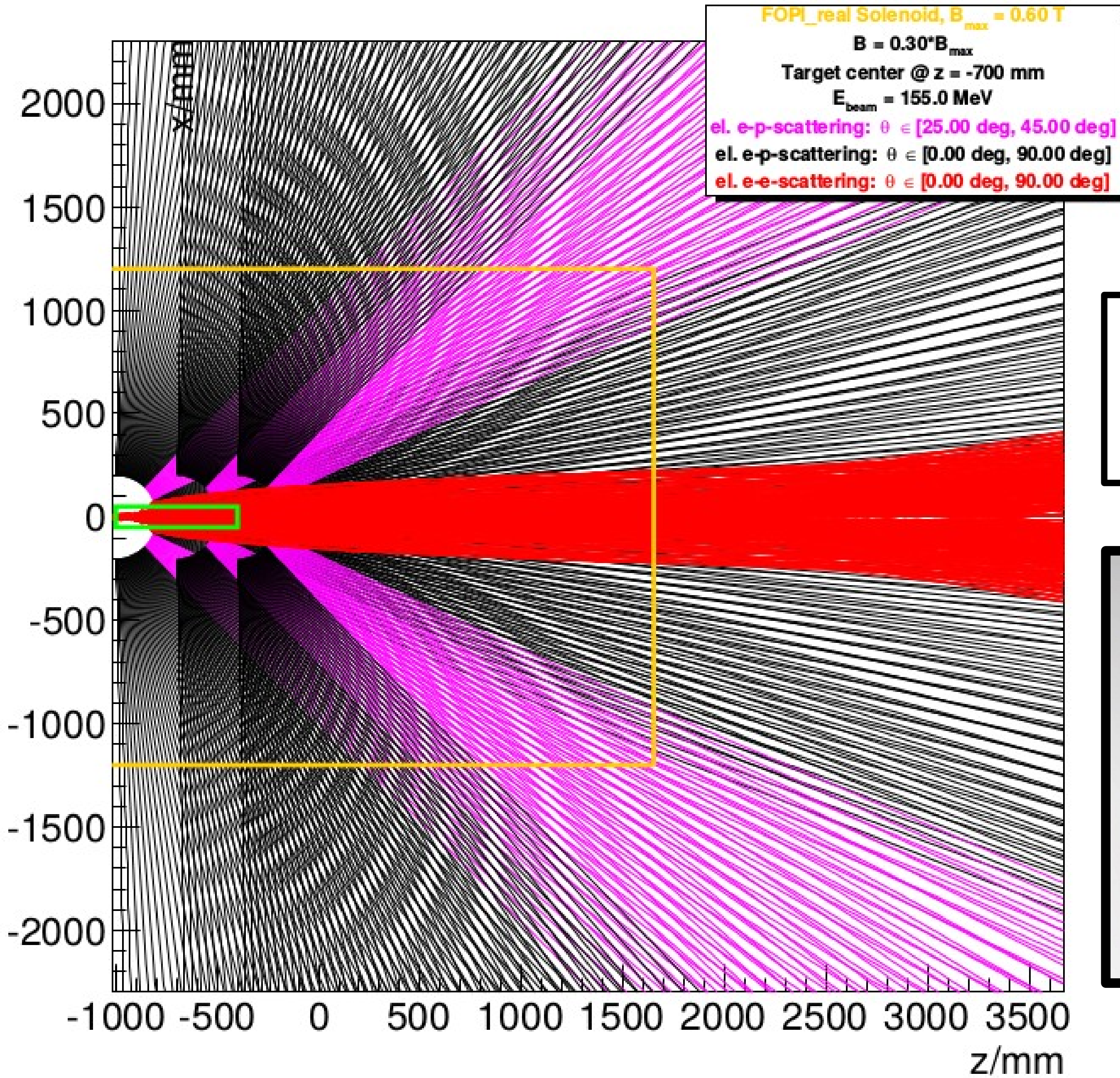


Magnetic field:
0.12 T

Beam energy = 155 MeV
Moller, θ ∈ [0°, 90°]
Elastic e-p, θ ∈ [25°, 45°]
Elastic e-p, θ ∈ [0°, 90°]

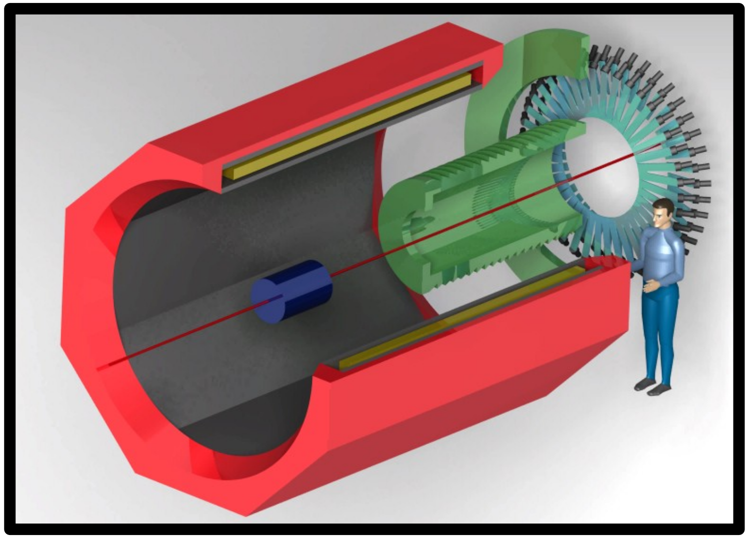


Raytrace simulations in the magnetic field

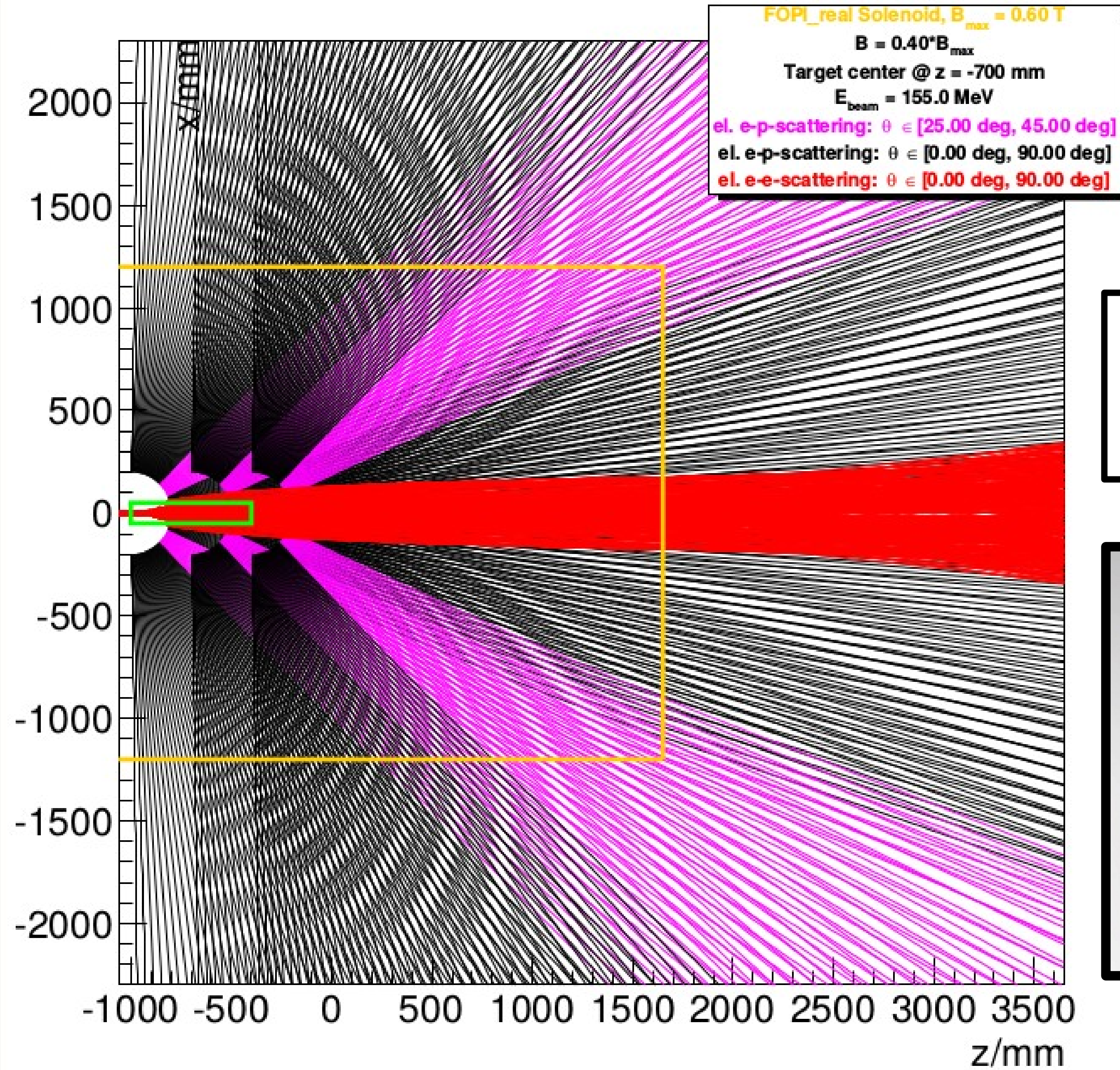


Magnetic field:
0.18 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

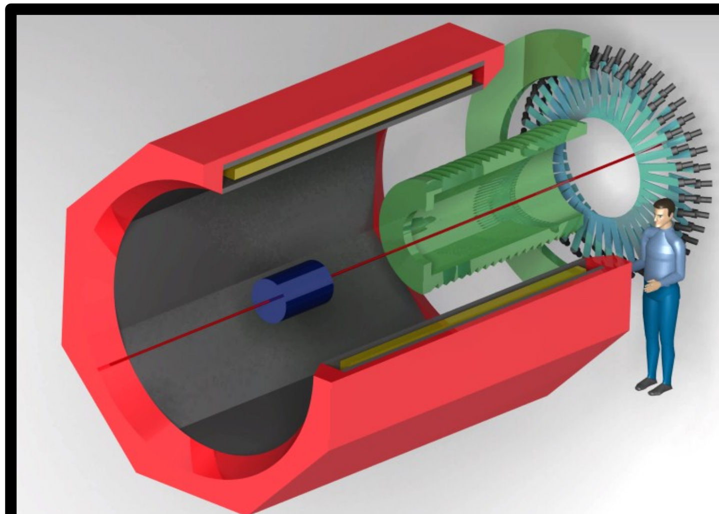


Raytrace simulations in the magnetic field

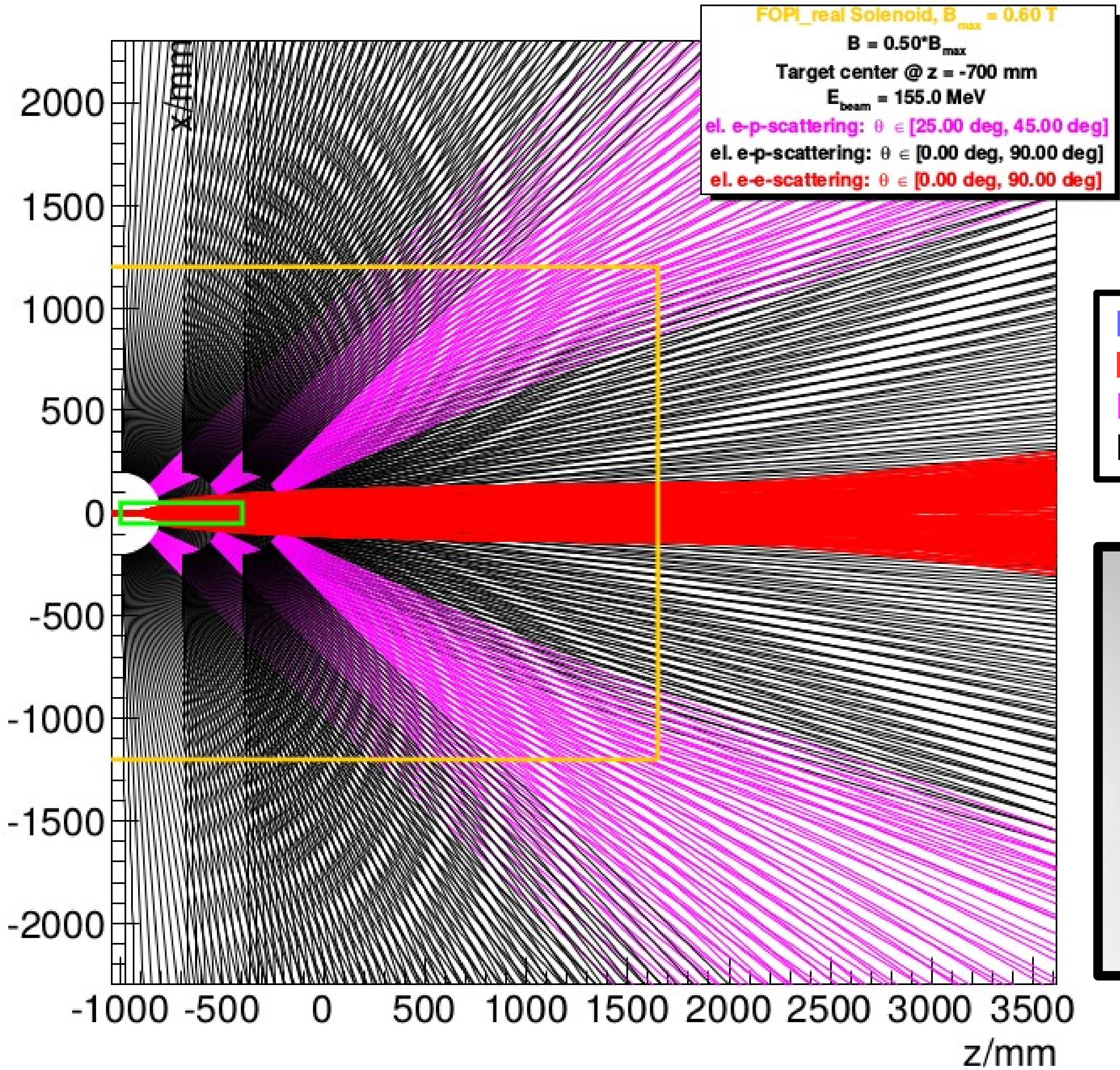


Magnetic field:
0.24 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

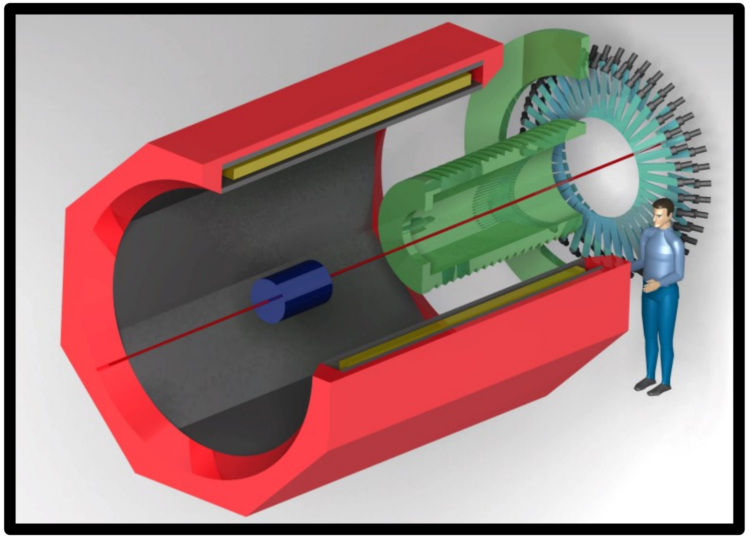


Raytrace simulations in the magnetic field

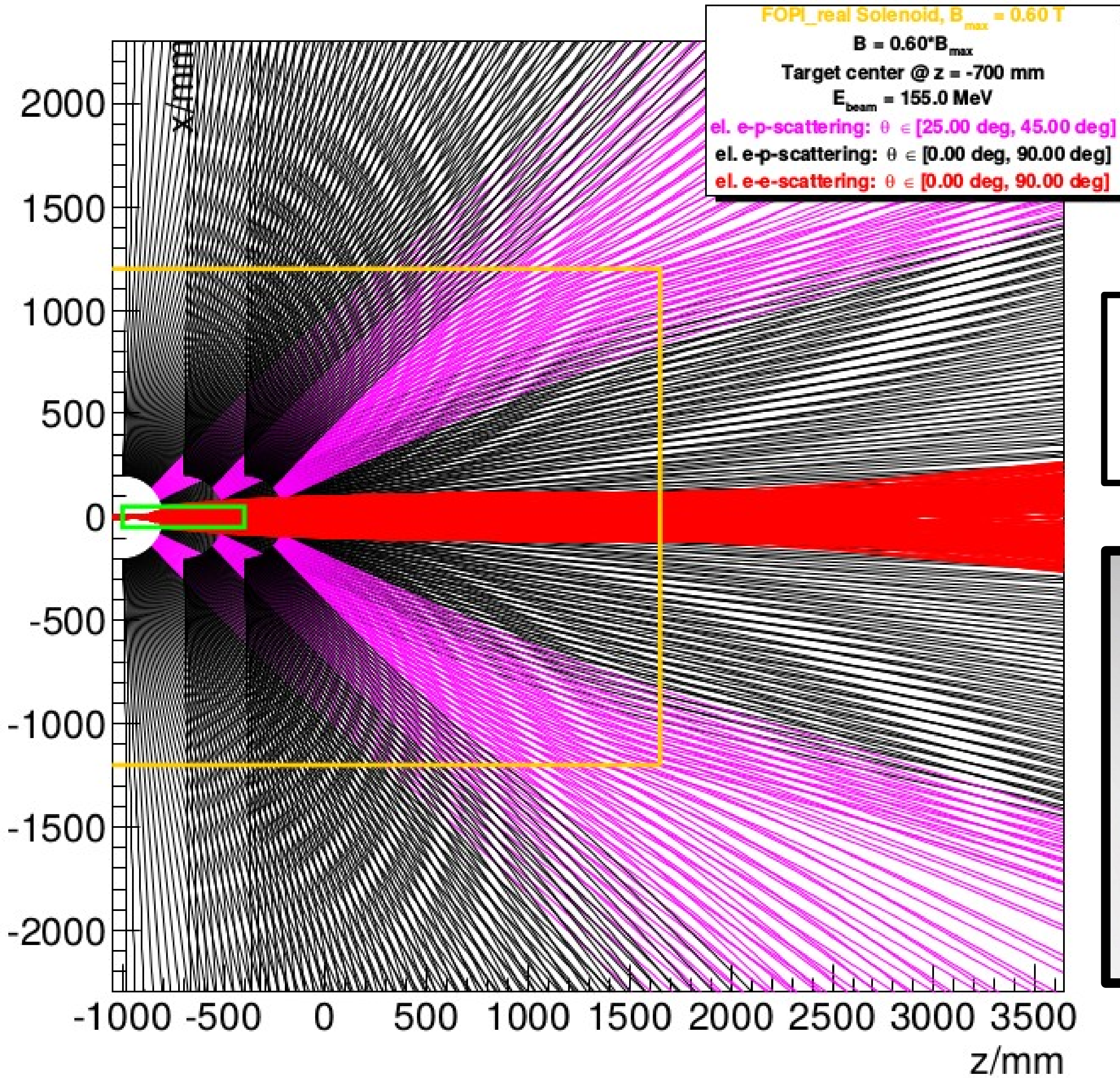


Magnetic field:
0.3 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

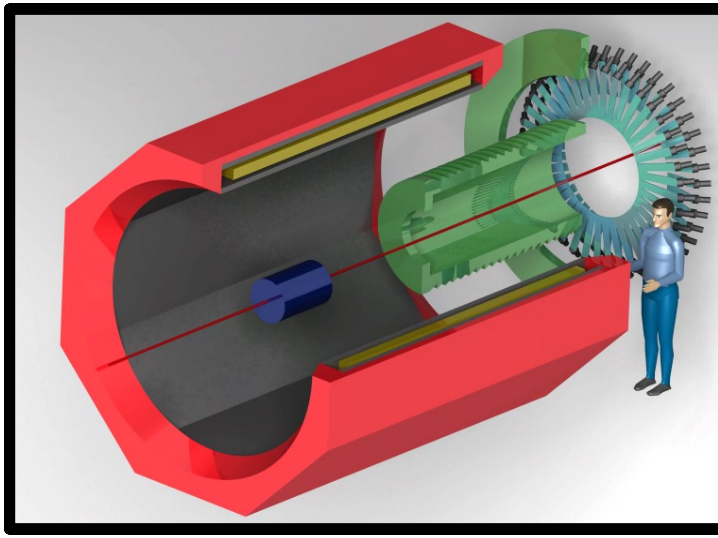


Raytrace simulations in the magnetic field

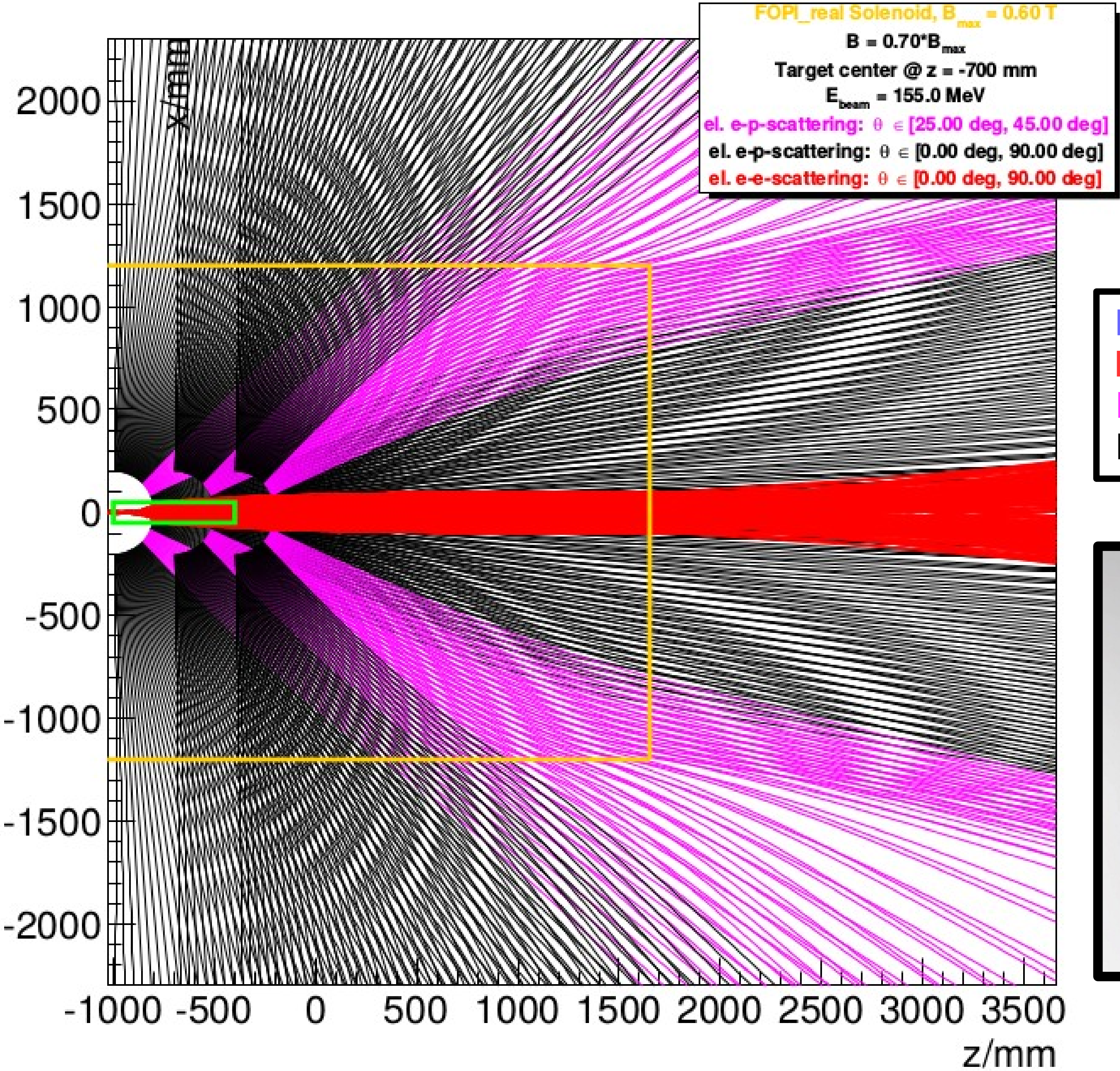


Magnetic field:
0.36 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

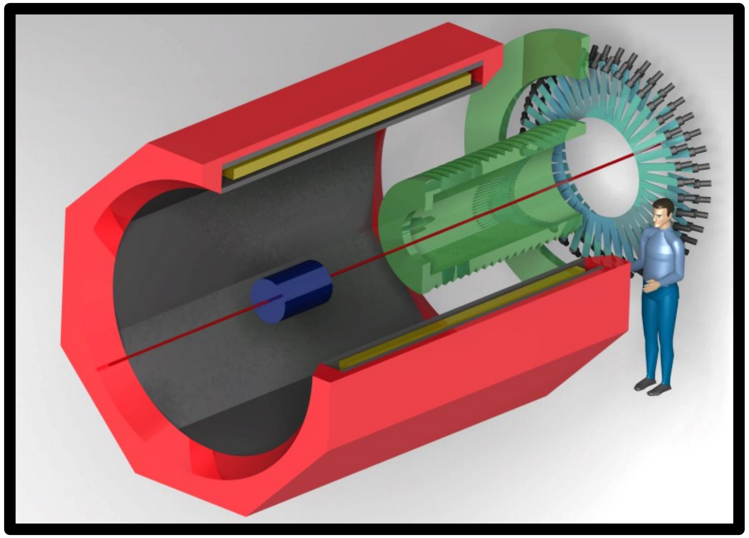


Raytrace simulations in the magnetic field

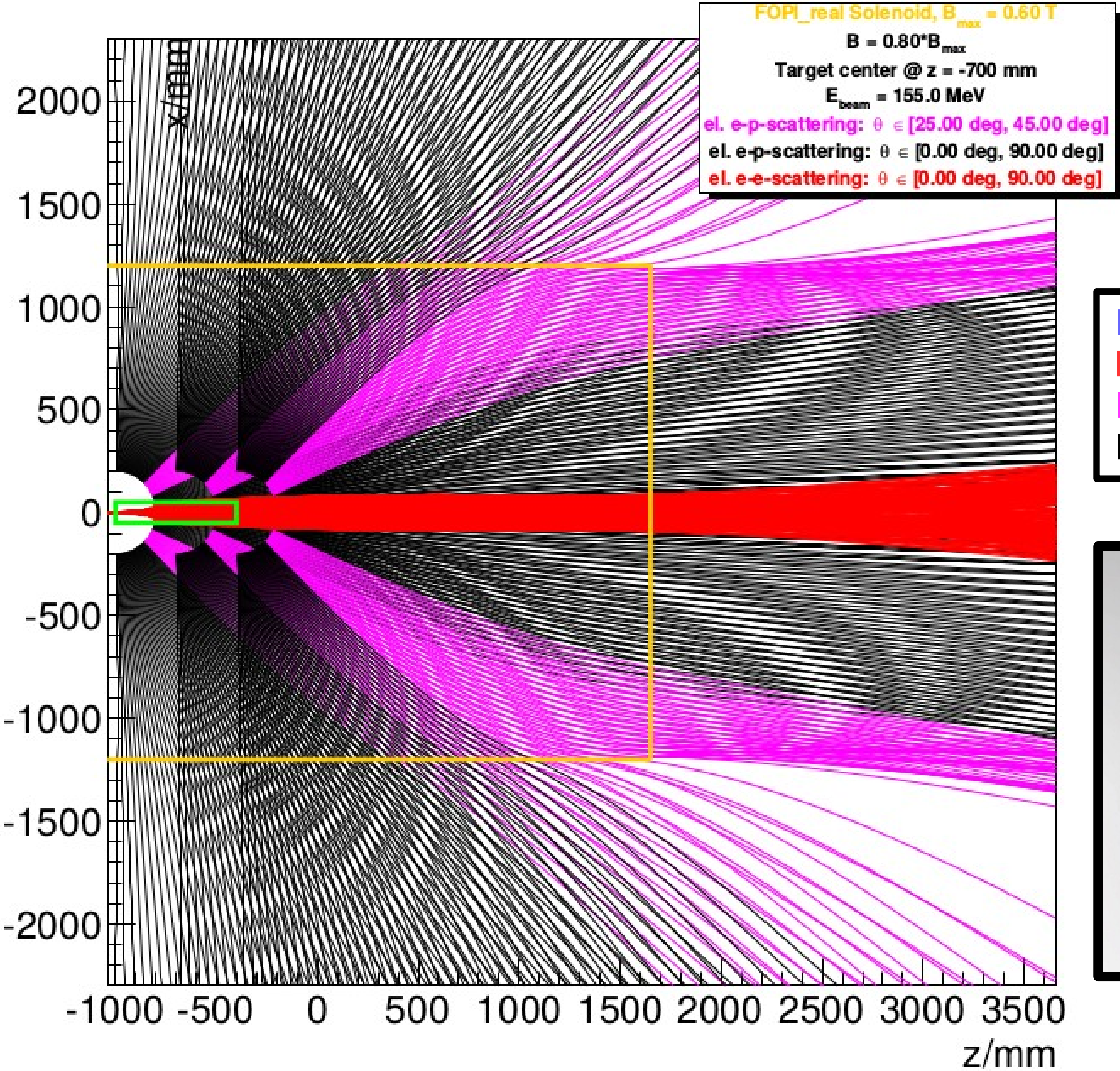


Magnetic field:
0.42 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]



Raytrace simulations in the magnetic field



Magnetic field:
0.48 T

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Beam energy = 155 MeV
Moller,      θ ϵ [ 0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [ 0°, 90°]
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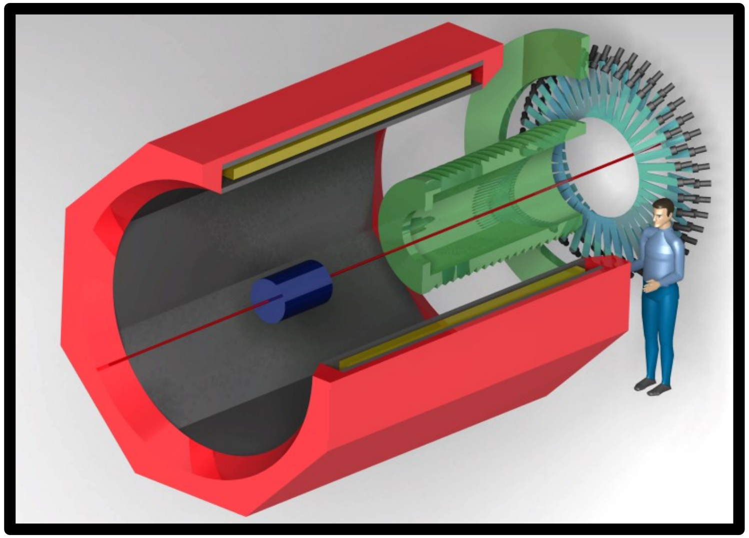
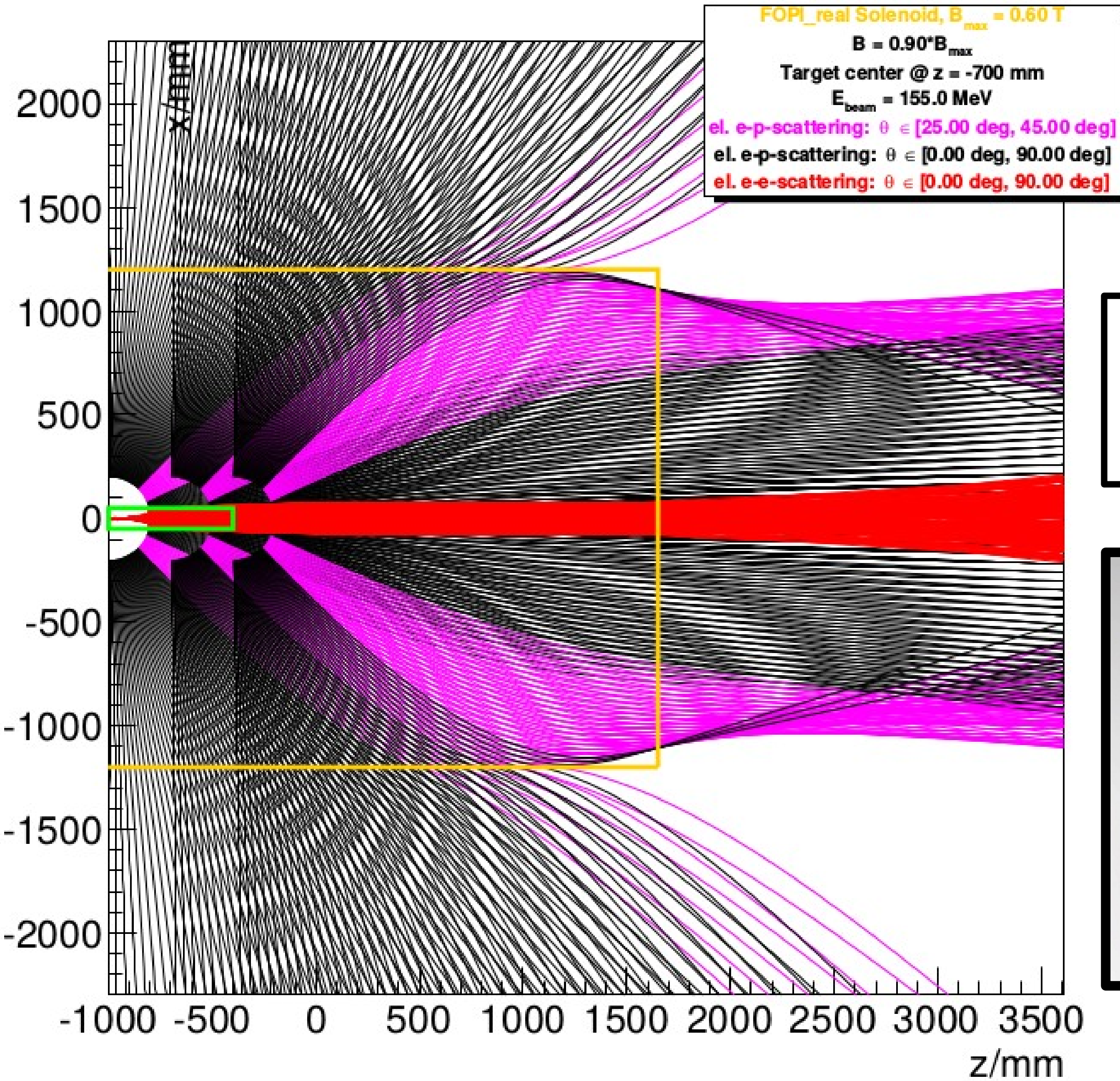
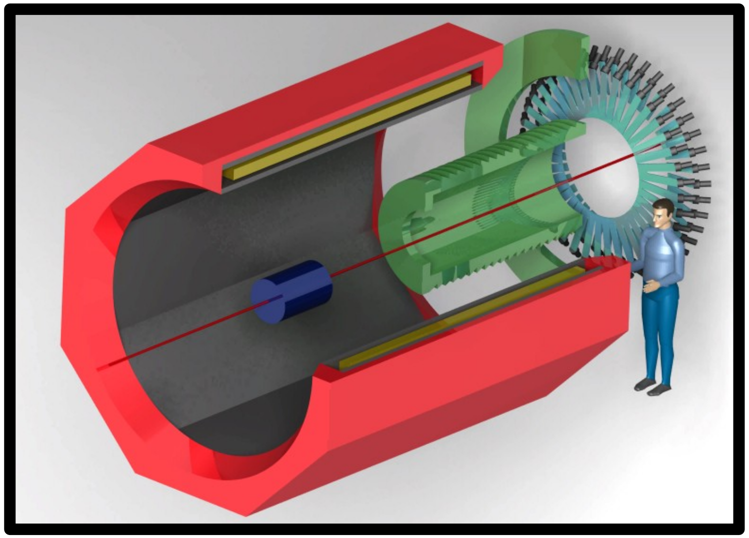


Raytrace simulations in the magnetic field

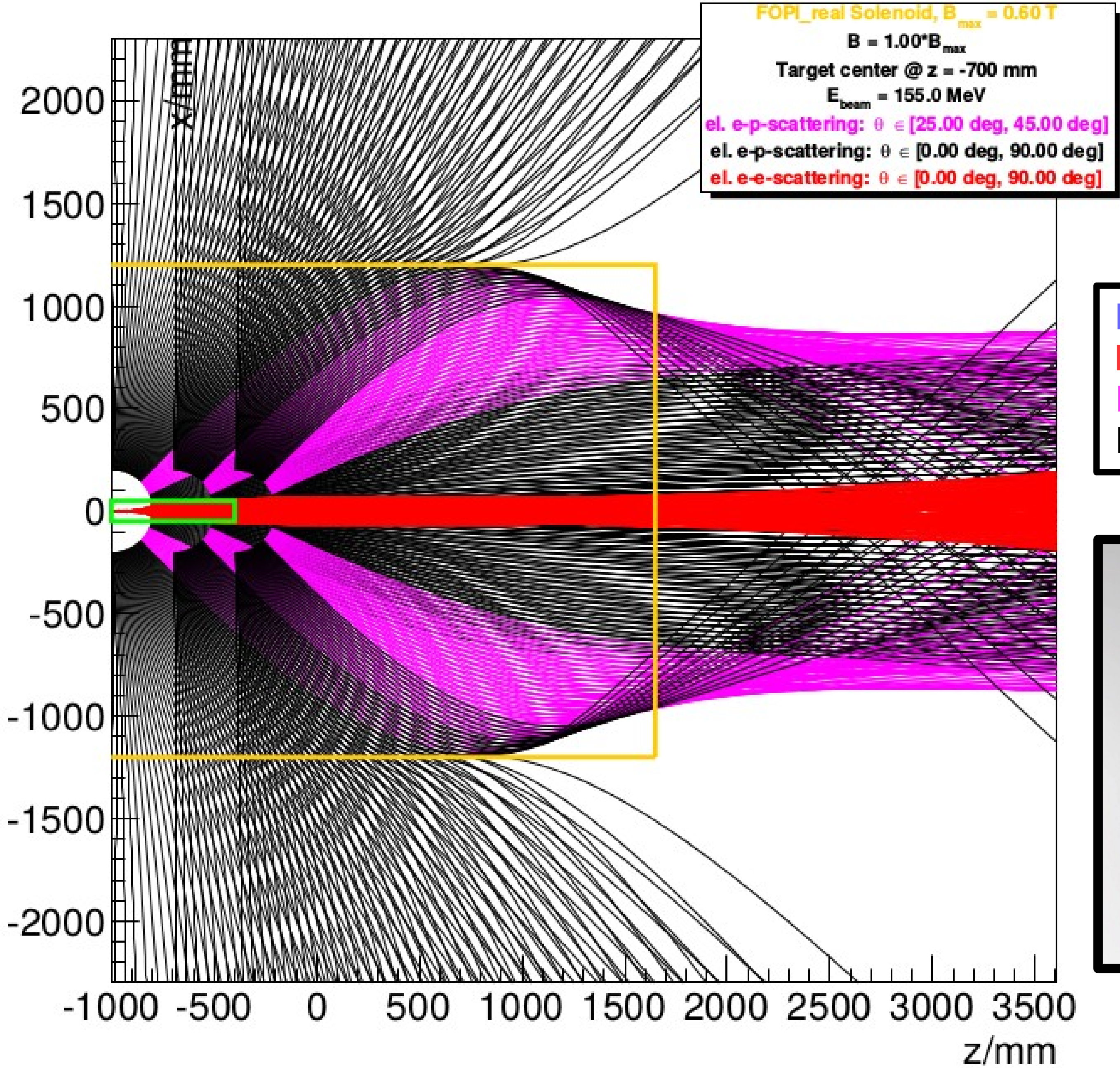


Magnetic field:
0.54 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

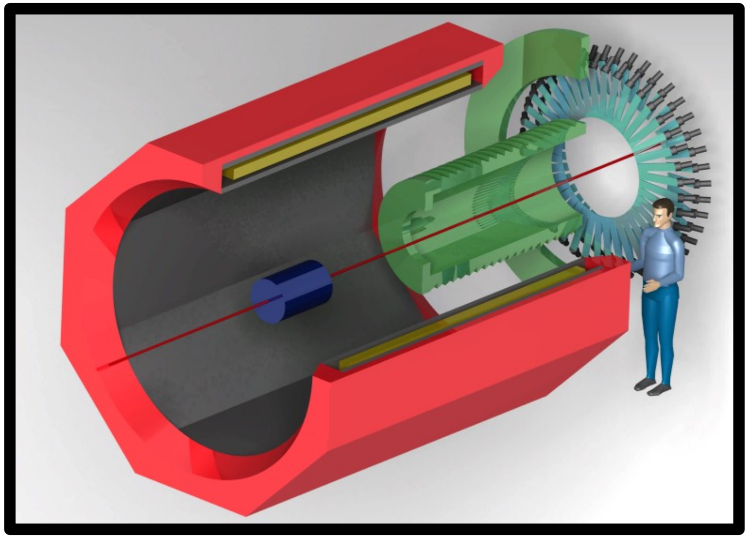


Raytrace simulations in the magnetic field

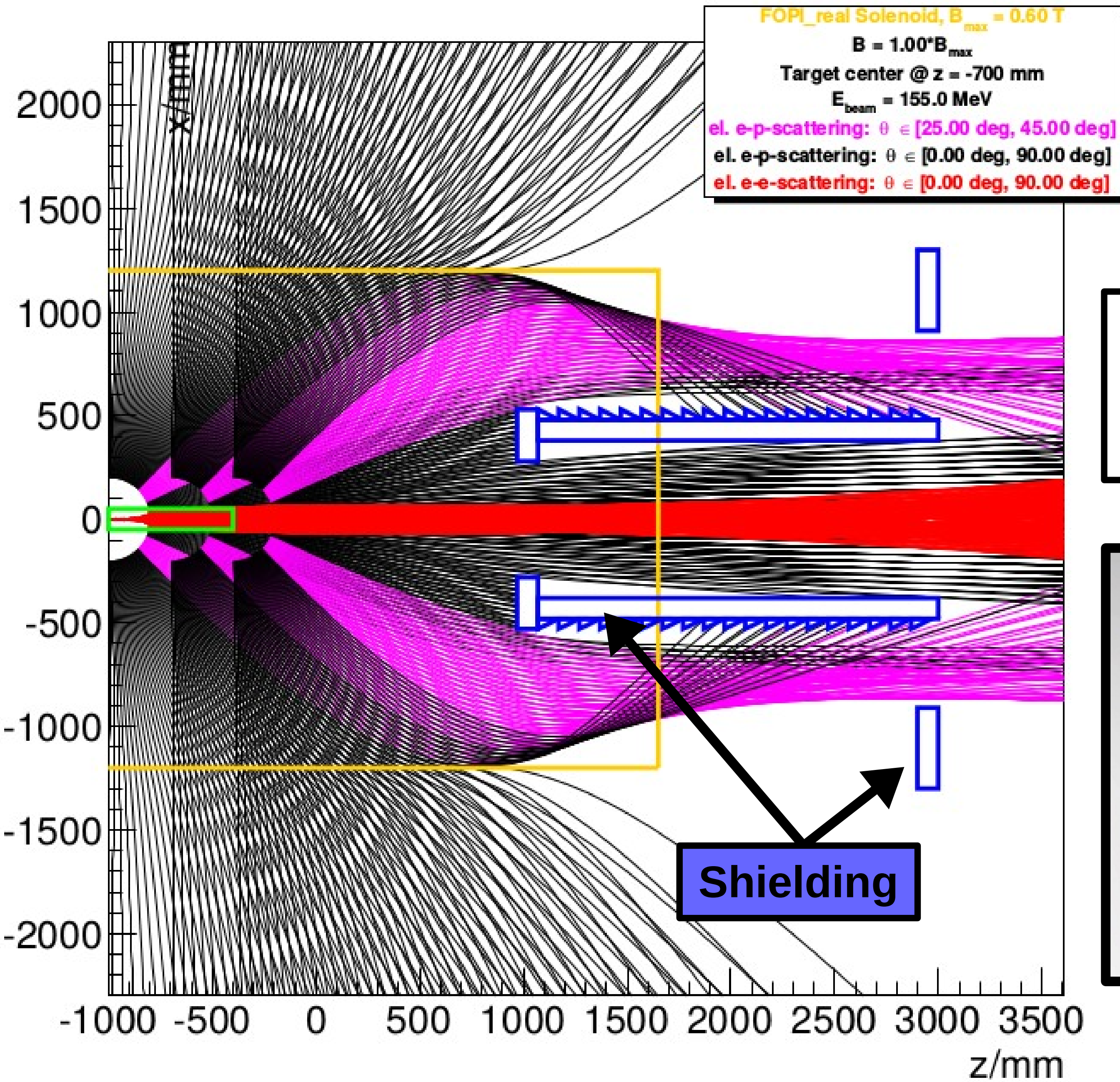


Magnetic field:
0.6 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

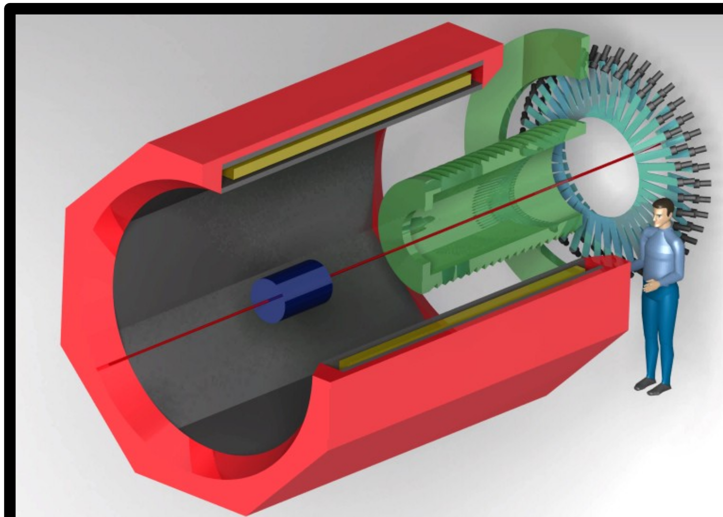


Raytrace simulations in the magnetic field

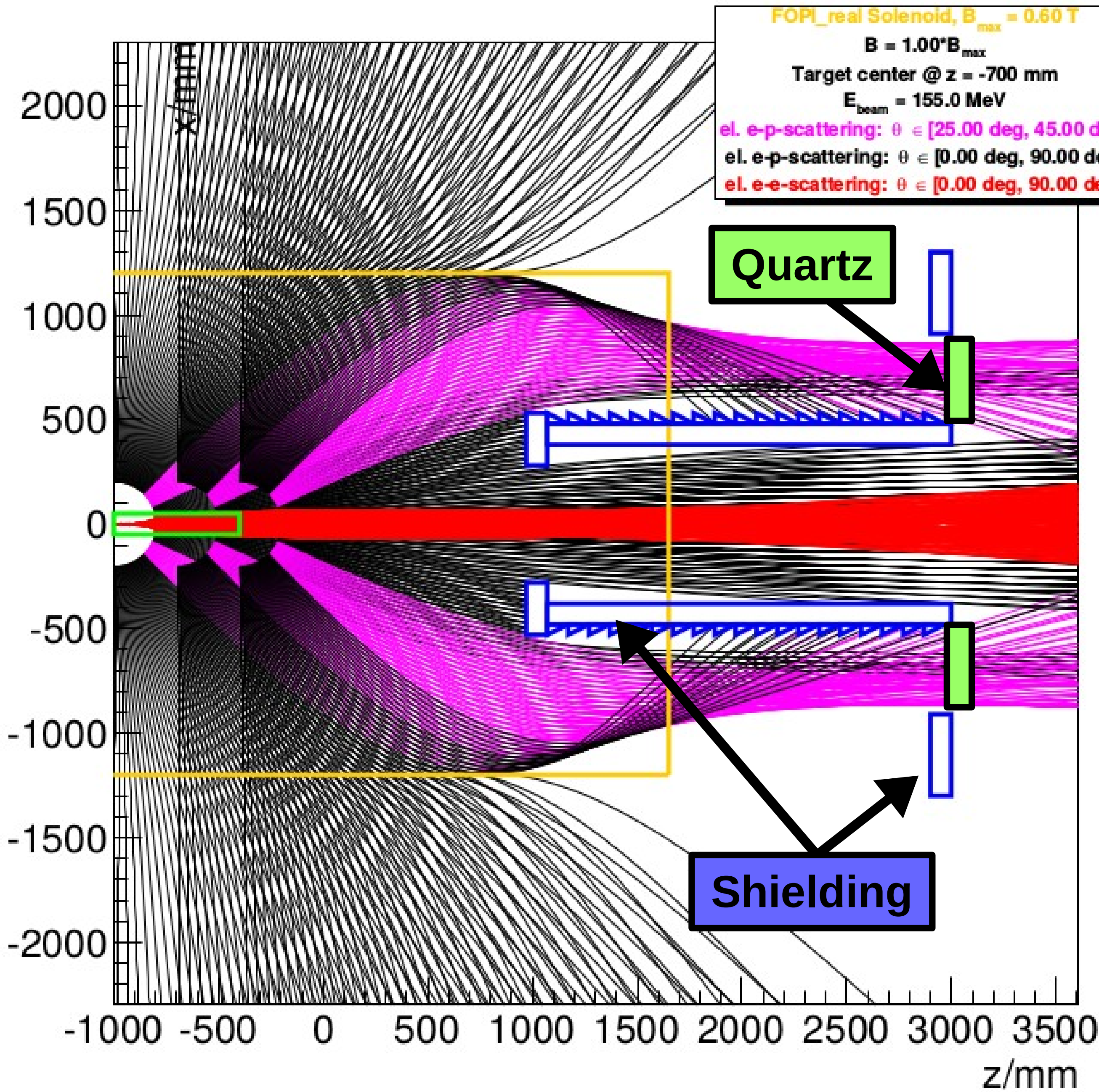


Magnetic field:
0.6 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

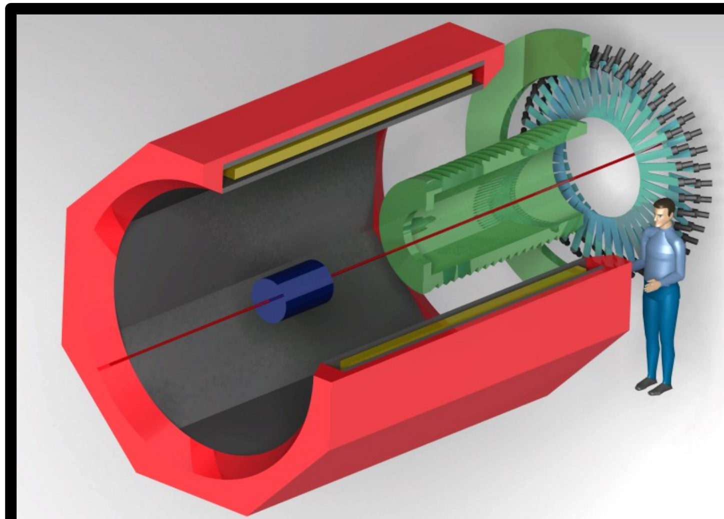


Raytrace simulations in the magnetic field



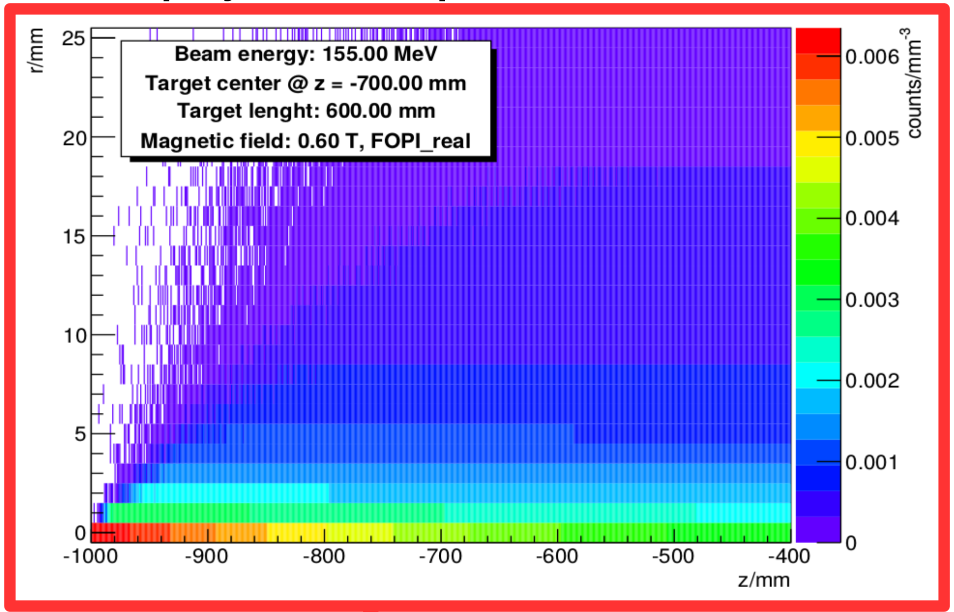
Magnetic field:
0.6 T

Beam energy = 155 MeV
Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [25°, 45°]
Elastic e-p, θ ϵ [0°, 90°]

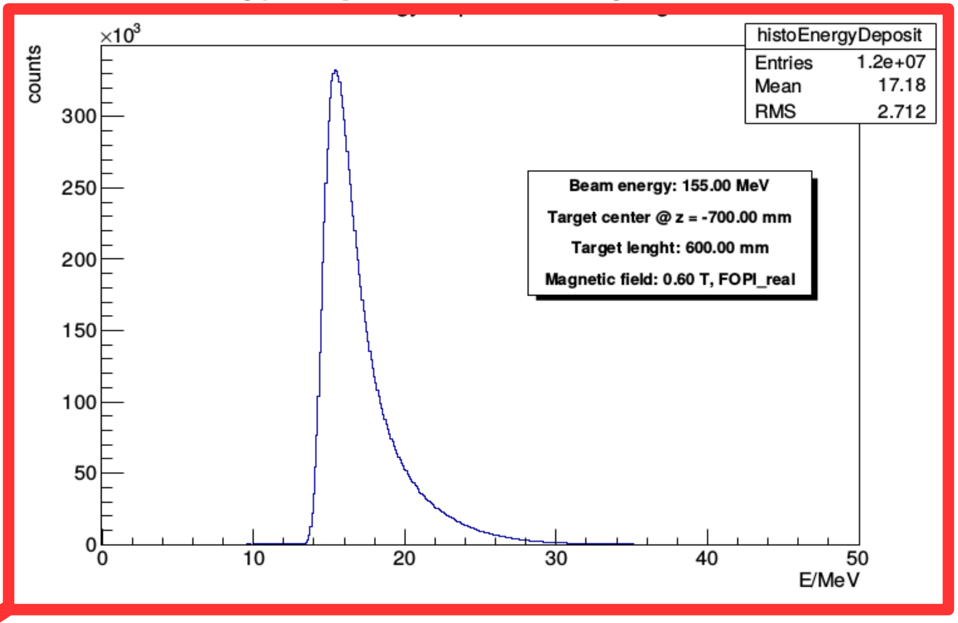


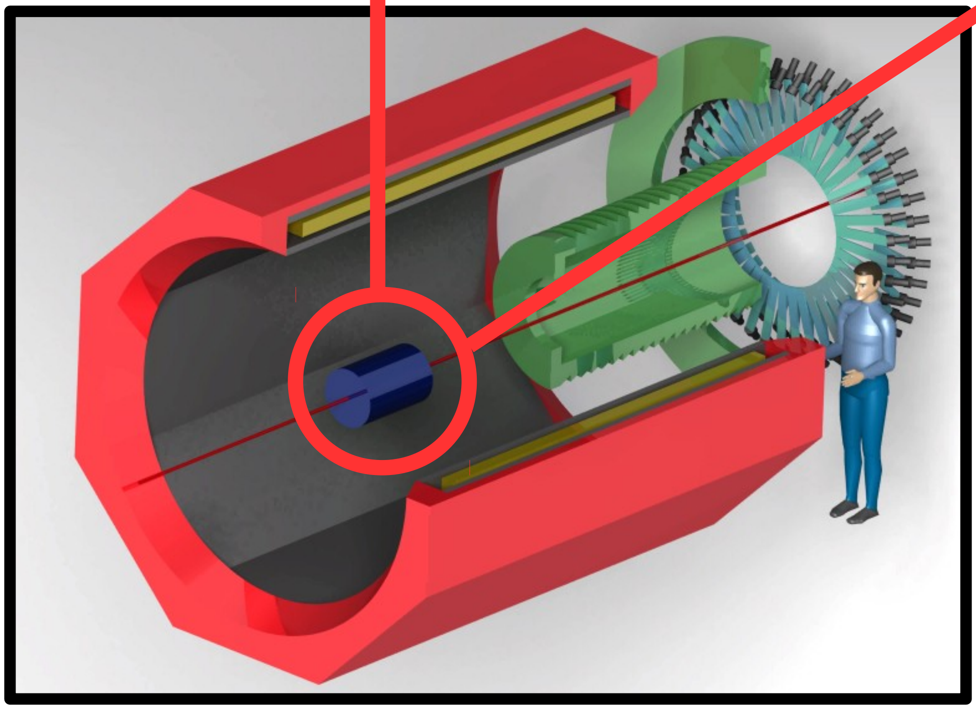
Geant4 Simulation of beam-target-interaction

Radial projection of spatial vertex distribution



Energy deposition in target volume

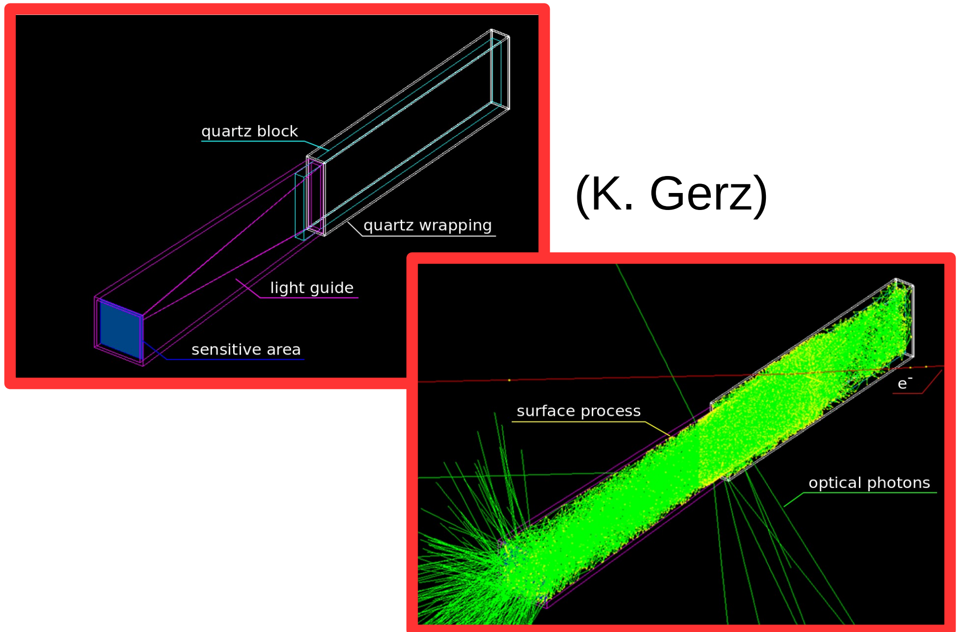




- Coherent simulation of elastic e-p scattering for P2 is impossible with Geant4
- Sample initial state distribution for elastic e-p scattering
  → To be used with event generator
- Use tree-level event generator for primary event-generation
- Prototype of event generator with radiative corrections available and currently under evaluation

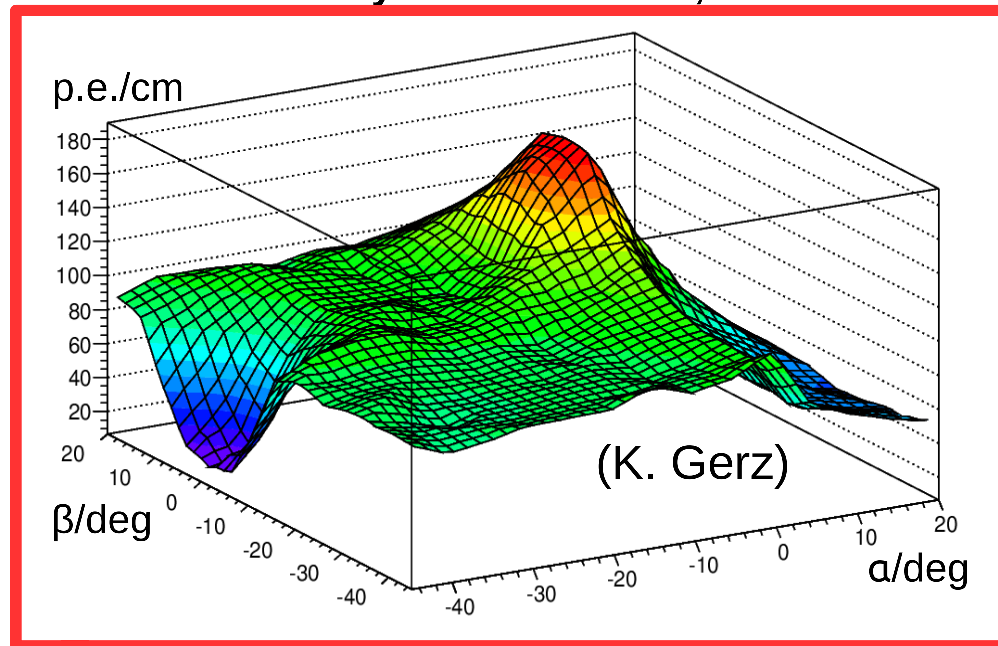
Geant4 Simulation of detector module response

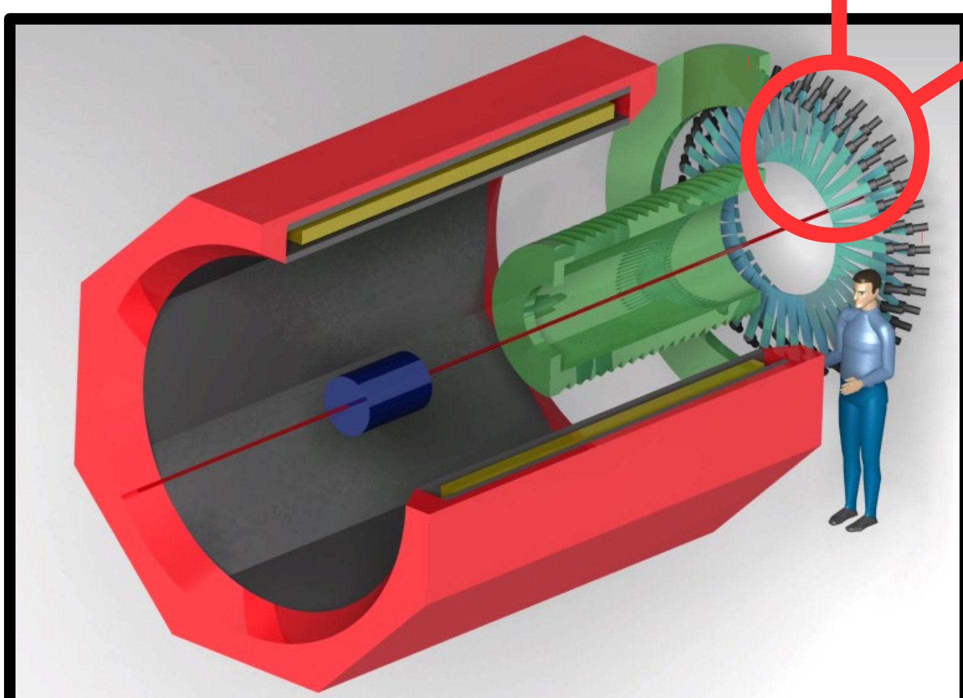
Tracking of optical photons in detector module



(K. Gerz)

Photo electron yield distribution, E = 155 MeV



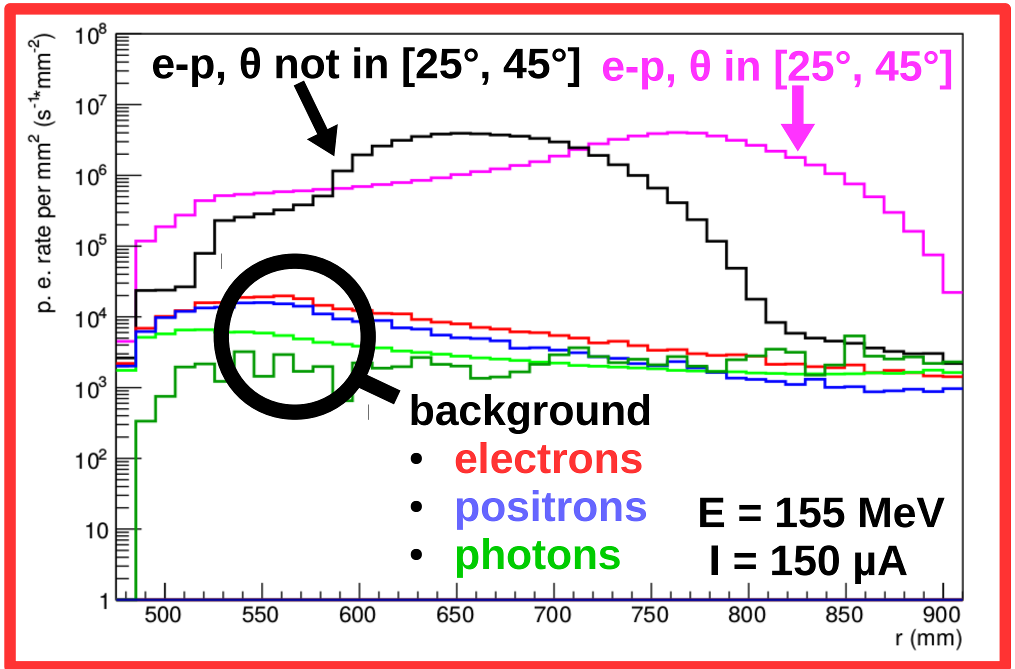


Create parametrization of photo electron yield for different

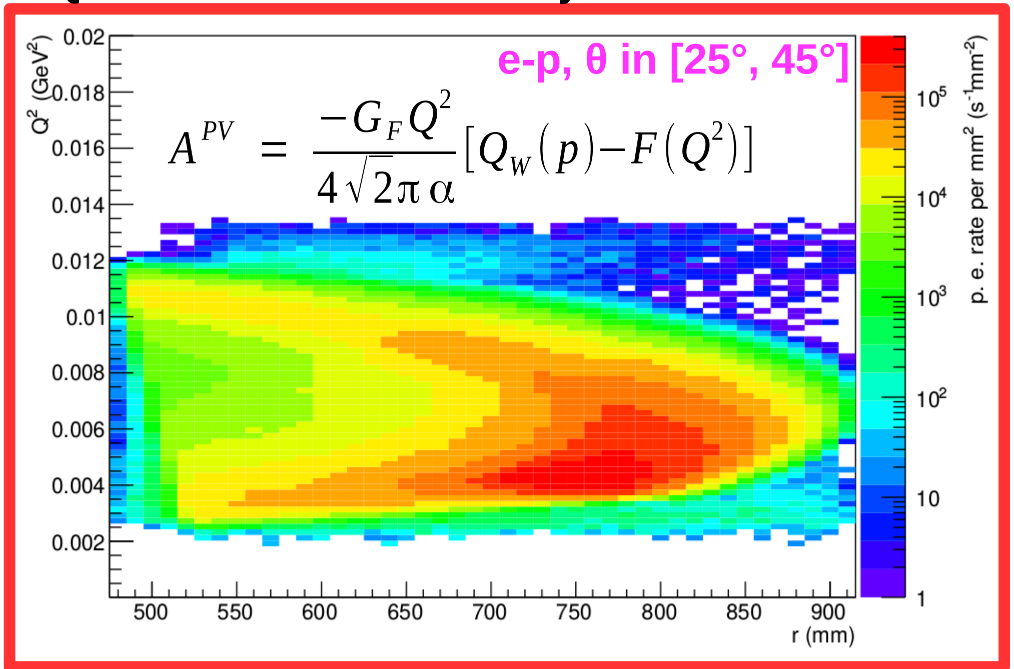
- Active materials
- Geometries
- Particle types
- Particle energies
- Impact angles

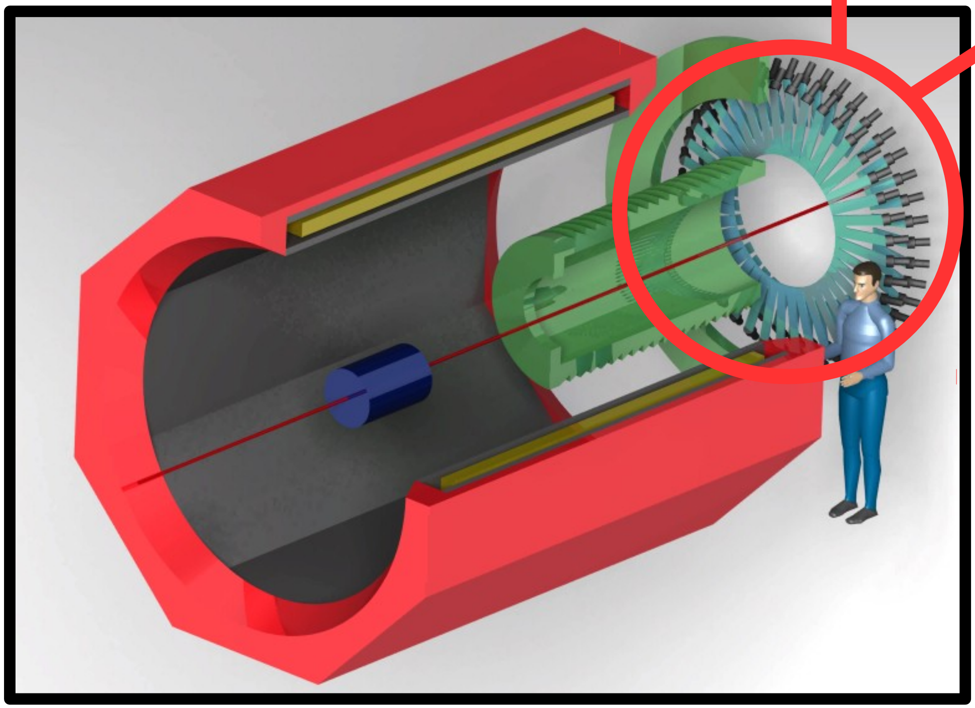
Geant4 Simulation of experimental setup

Photo electron rate distribution



Q² distribution of elastically scattered electrons





- Use initial state distribution with tree level event generator to simulate elastic e-p scattering
- Tracking in realistic map of magnetic field, CAD-interface for definition of geometry
- Use parametrization of detector response to predict distribution of photo electrons
- Use Q^2 distribution in error propagation calculation to predict the achievable precision in the weak mixing angle

Facts and Figures

The following results are based on error propagation calculations **including** the results of the Geant4 simulation of the experimental setup:

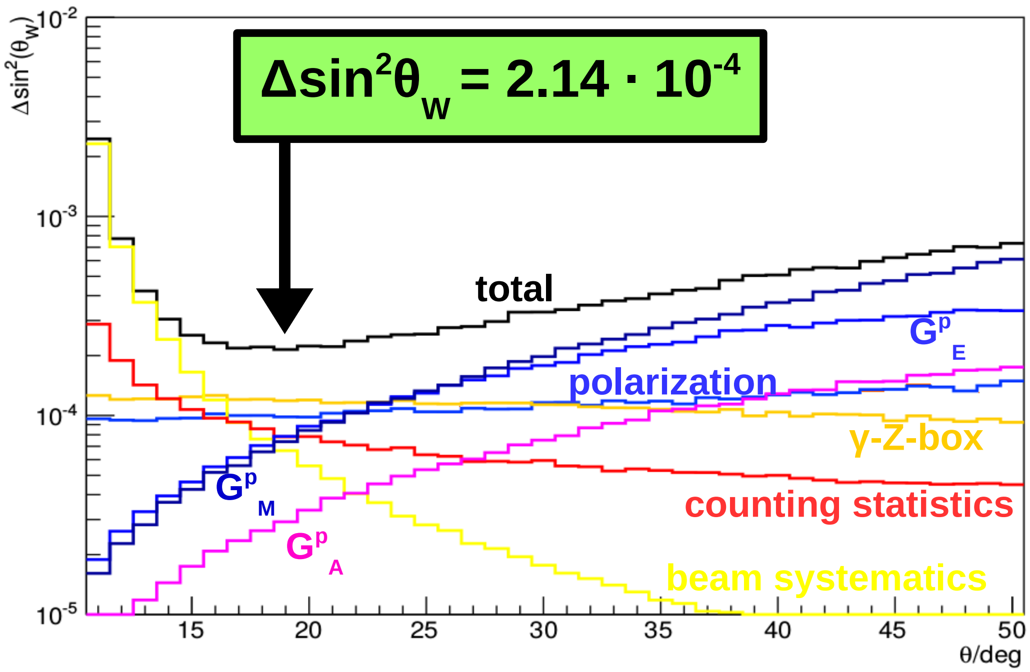
Beam energy	155 MeV	
Beam current	150 µA	
Polarization	85 %	± 0.425 %
Target	60 cm	liquid hydrogen
Detector acceptance	2π·20°	θ ϵ [25°, 45°]
Detector rate	0.5 THz	
Measurement time	1e4 h	
$\langle Q^2 \rangle$	4.49e-3 GeV^2/c^2	
A^{exp}	-28.35 ppb	

	Total	**Statistics**	**Polarization**	**Apparative**	**Form factors**	**Re($\square_{\gamma ZA}$)**
$\Delta \sin^2(\theta_W)$	**3.1e-4 (0.13 %)**	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	**0.44 (1.5 %)**	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

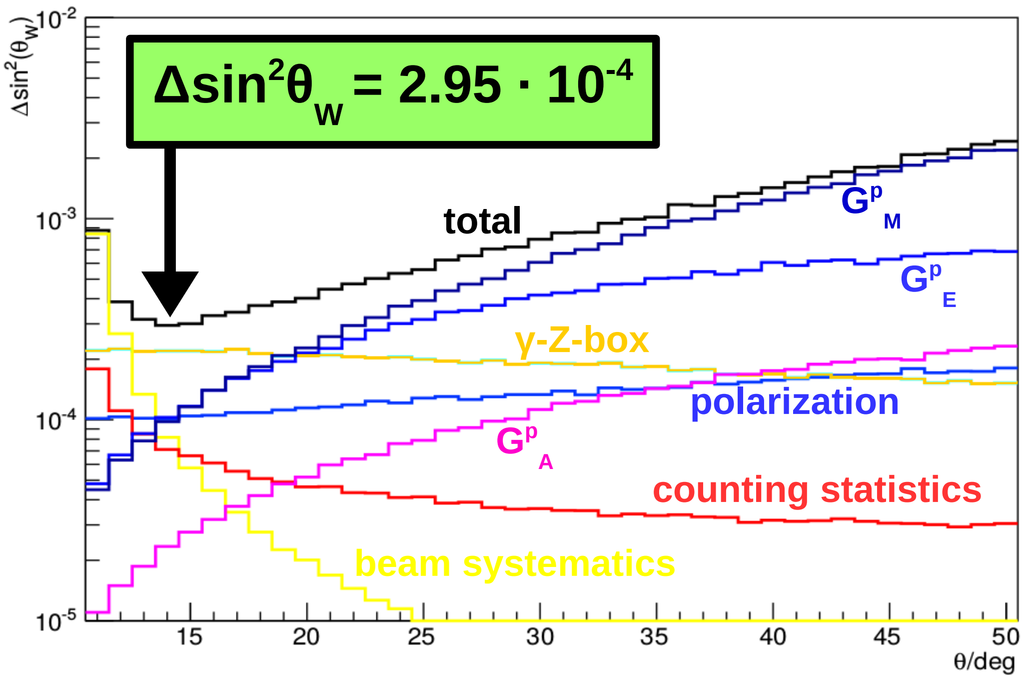
Achievable precision @ higher energies/beam current

Beam current:	**1 mA**
Polarization:	85 % ± 0.425 %
Target material:	liquid hydrogen
Target:	60 cm
Measurement time:	10000 h
Detector acceptance:	2π·20°
ΔA^{app}:	0.1 ppb

Beam energy: 300 MeV
Central scattering angle: 19°
A^{PV} = (-30.8 ± 0.34) ppb
$\langle Q^2 \rangle$ = 4.84e-3 GeV²/c²
Rate elastic e-p: 1.8 THz



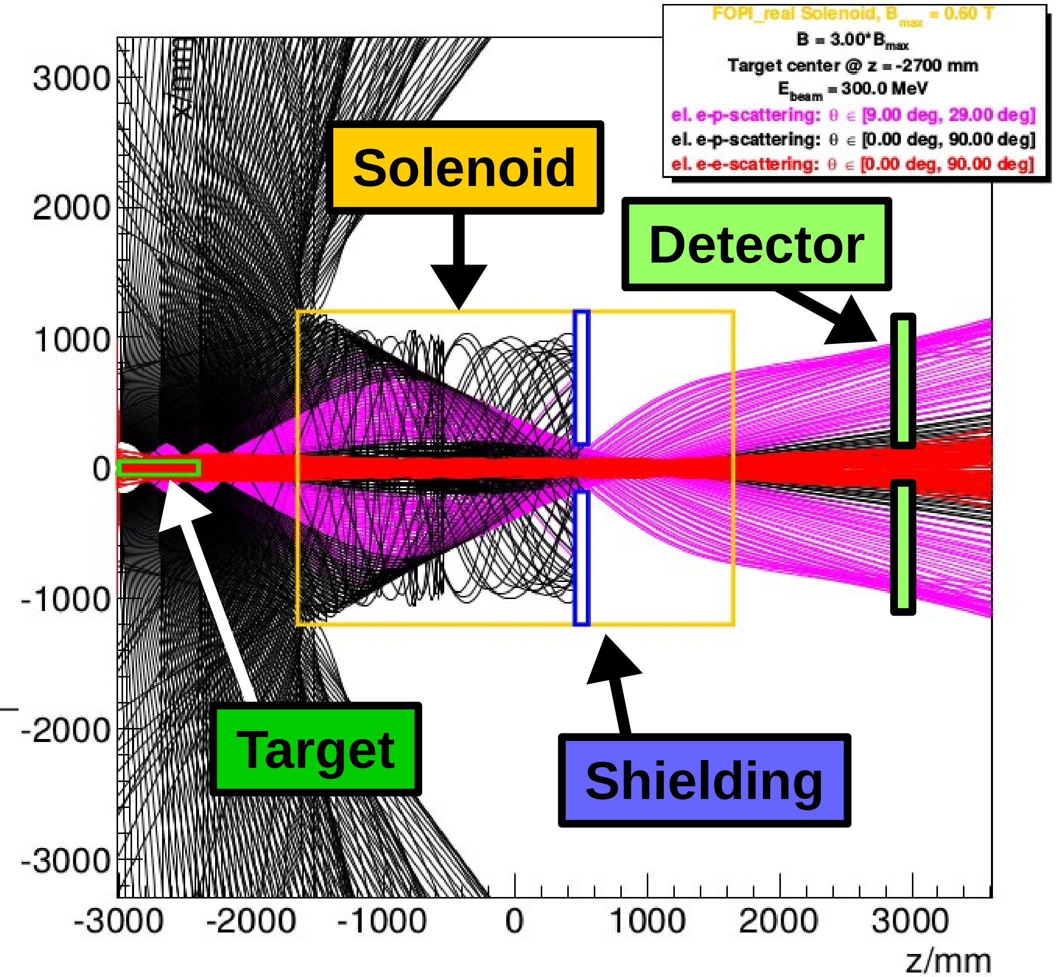
Beam energy: 500 MeV
Central scattering angle: 14°
A^{PV} = (-24.8 ± 0.36) ppb
$\langle Q^2 \rangle$ = 3.82e-3 GeV²/c²
Rate elastic e-p: 3.6 THz

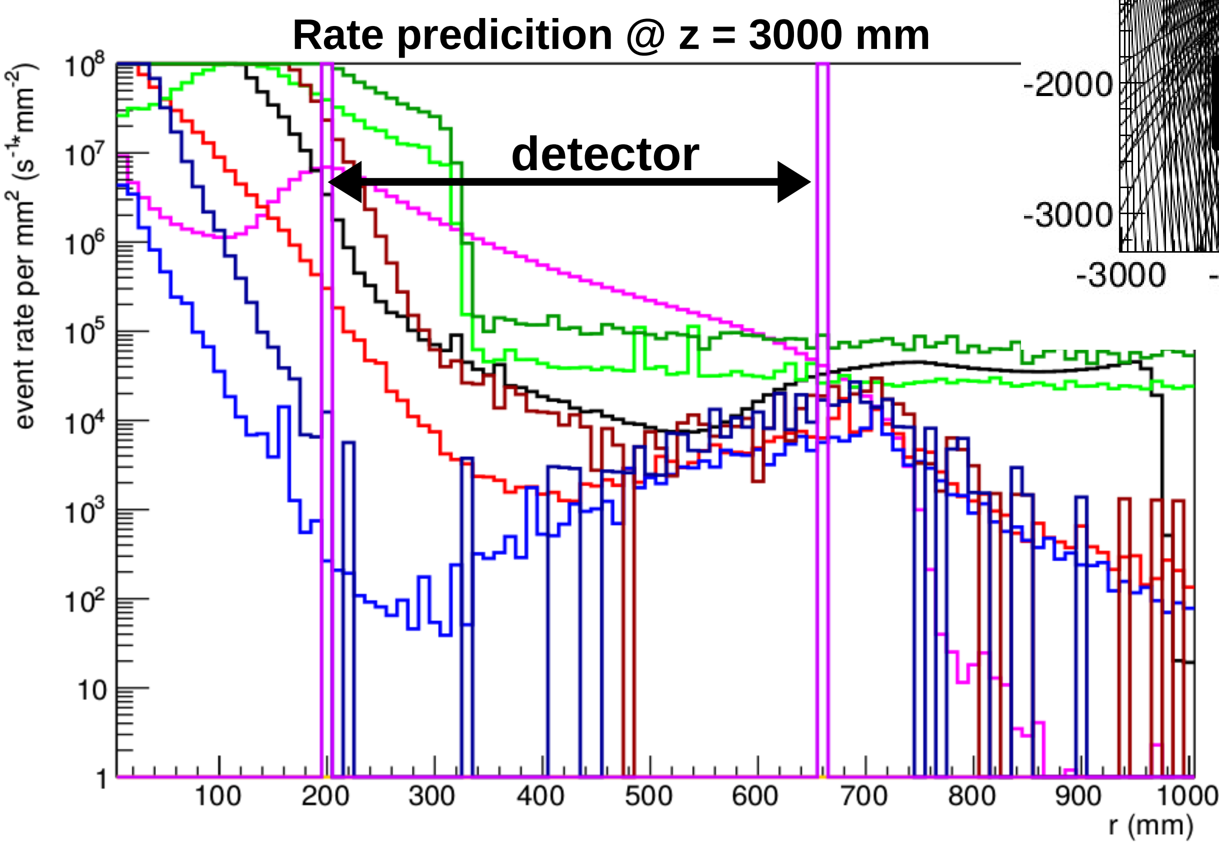


A very first idea for 300 MeV

Beam energy: 300 MeV
Beam current : 150 μA
Central magnetic field: 1.8 Tesla

Moller,   θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [9°, 29°]
Elastic e-p, θ ϵ [0°, 90°]



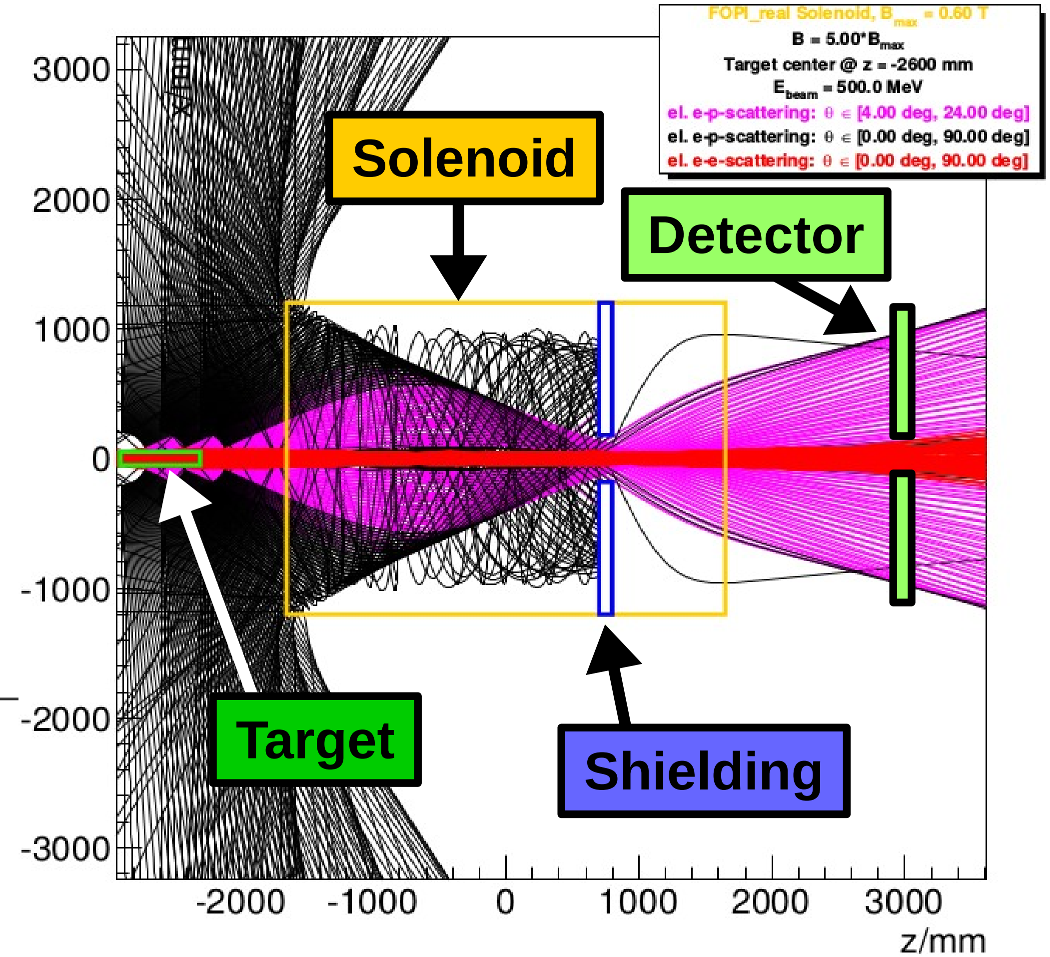


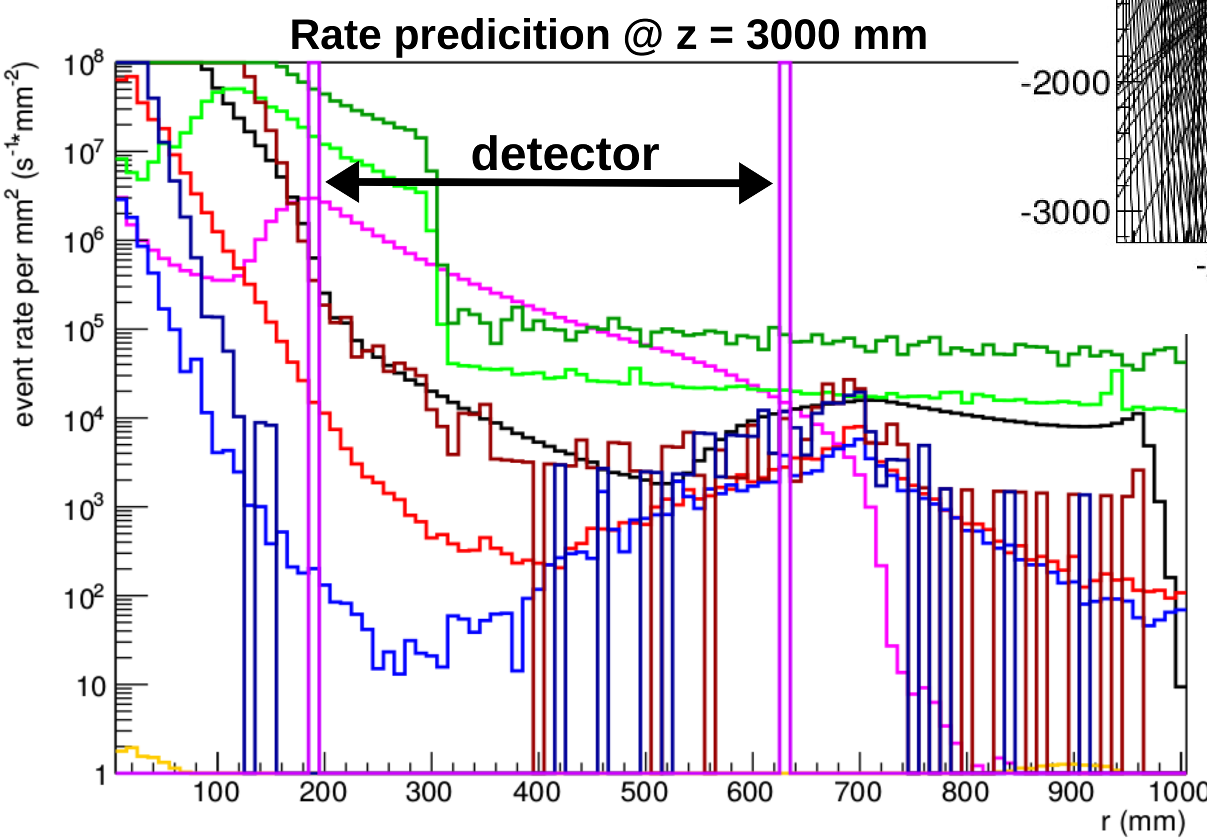
Elastic e-p, θ in [9°, 29°]
Elastic e-p, θ not in [9°, 29°]
Moller, e-p
Moller, background
Positrons, e-p
Positrons, background
Photons, e-p
Photons, background

A very first idea for 500 MeV

Beam energy: 500 MeV
Beam current: 150 μA
Central magnetic field: 3 Tesla

Moller, θ ϵ [0°, 90°]
Elastic e-p, θ ϵ [4°, 24°]
Elastic e-p, θ ϵ [0°, 90°]





Elastic e-p, θ in [4°, 24°]
Elastic e-p, θ not in [4°, 24°]
Moller, e-p
Moller, background
Positrons, e-p
Positrons, background
Photons, e-p
Photons, background

Summary

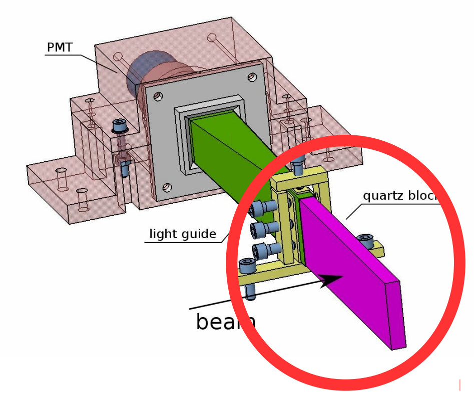
- **Project P2 @ MESA:**
  A new measurement of the weak mixing angle with precision goal:
  $\Delta Q_W(p) = 1.9\ \%$
  $\Delta \sin^2\theta_W = 0.15\ \%$

- **P2 main detector concept study:**
  Solenoid spectrometer and 2π-Cherenkov-detector
  → $\Delta \sin^2\theta_W = 0.13\ \%$

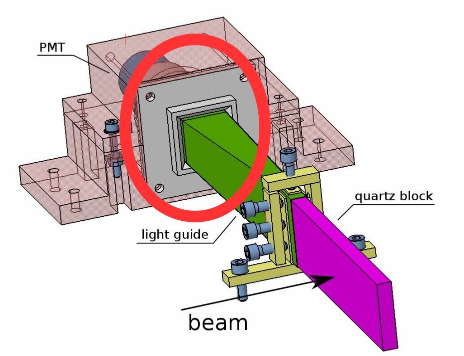
- **Measurement at higher beam energies and beam current:**
  → Very high precision in $\sin^2\theta_W$ at small scattering angles for 300 MeV
  → Most important contributions from gamma-Z-box and form factors
  → Experiment may be difficult to perform with a solenoid because of small scattering angles
  → Toroid may be better choice due to lower dependence on counting statistics

BACKUP SLIDES

Include simulated response of detector modules



Use results of detector module simulation to transform event rates into photo electron rates:



Event rate distribution:

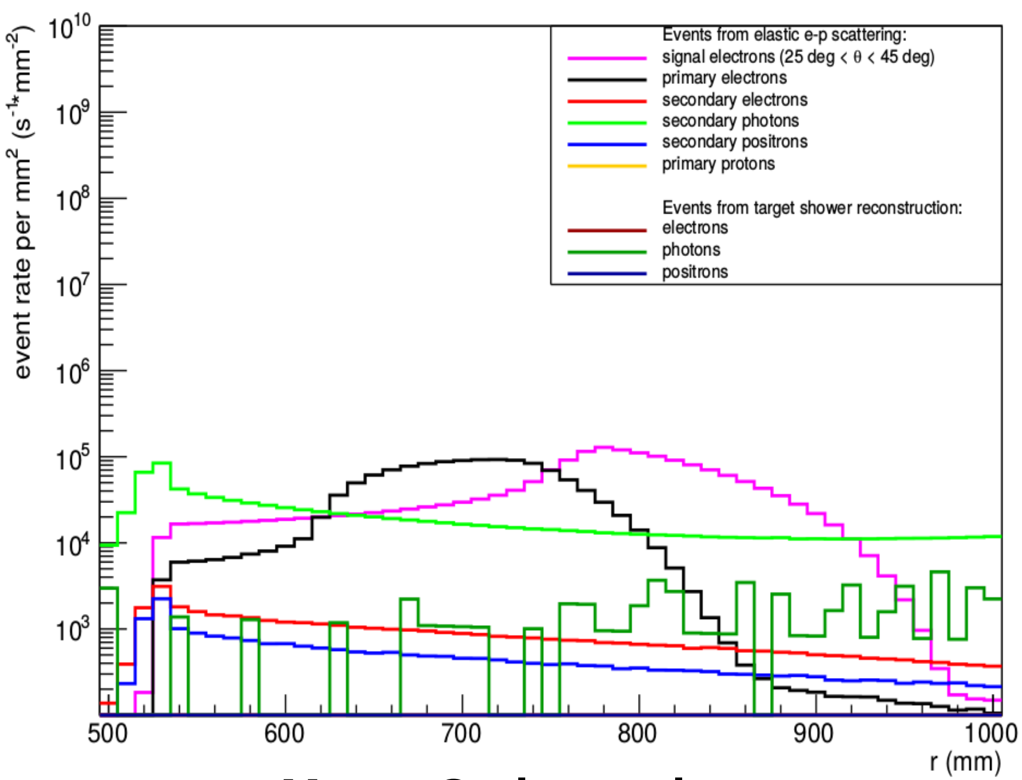
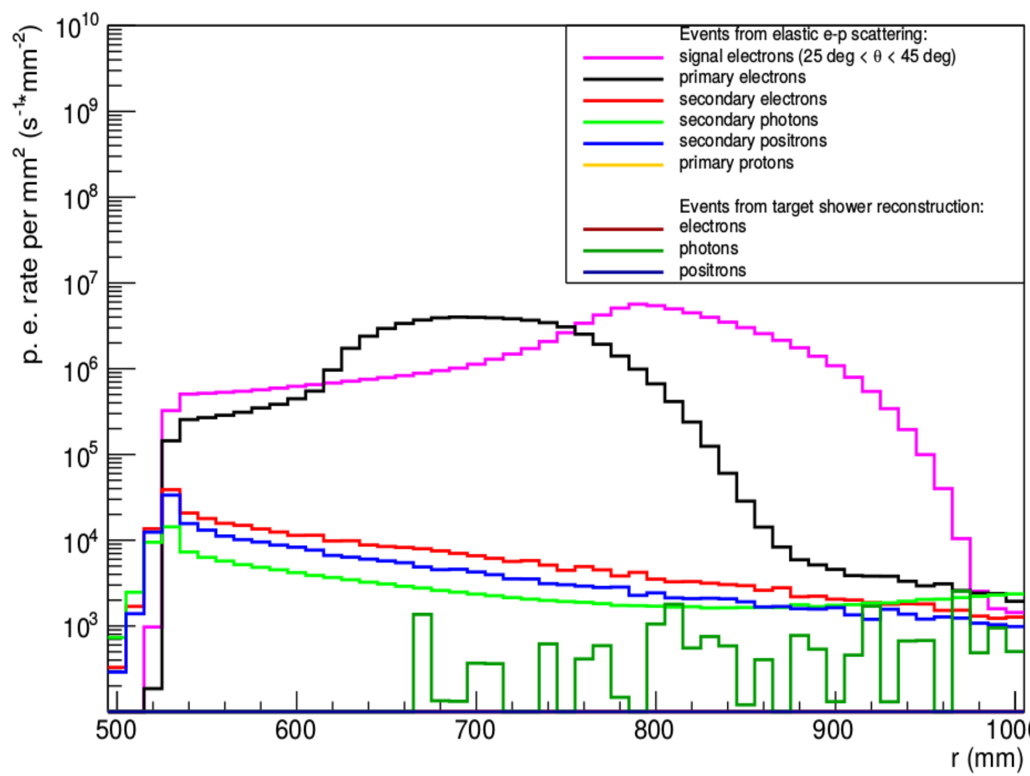


Photo electron rate distribution:



Monte Carlo results:

$$R^{ep}_{total} = 0.19\,\mathrm{THz}$$

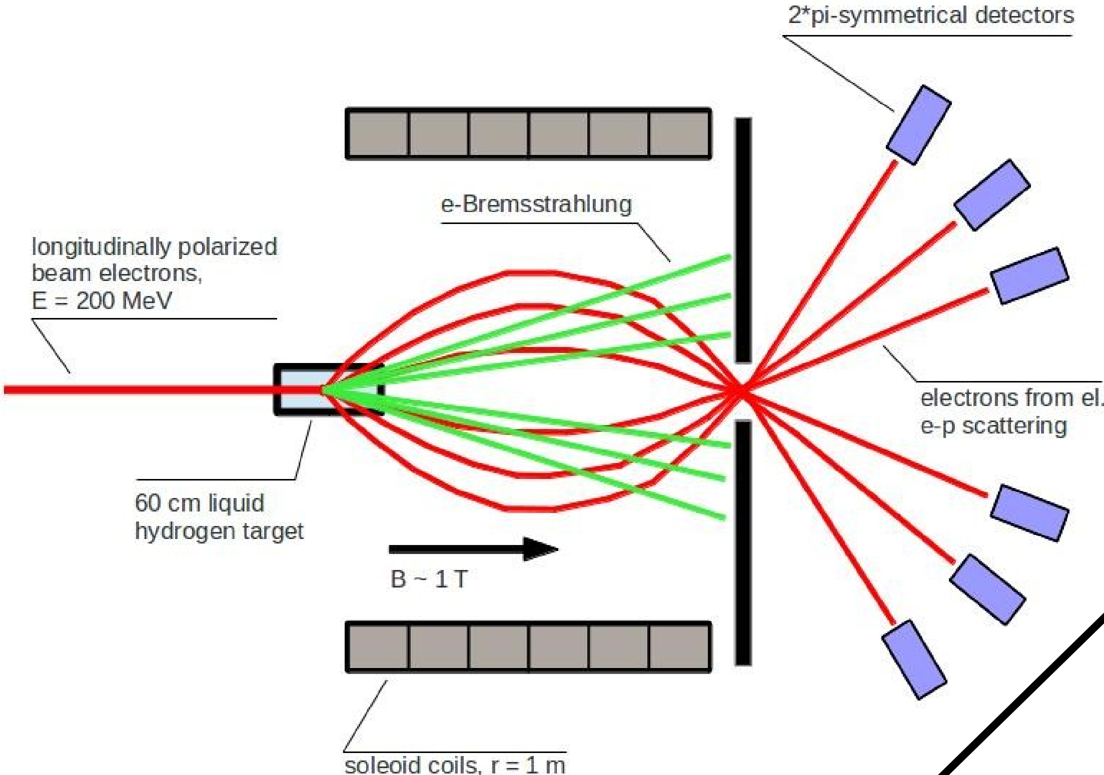
$$\langle A^{PV} \rangle_{L,\Delta\Omega} = -39.8\,\mathrm{ppb}$$

Monte Carlo results:

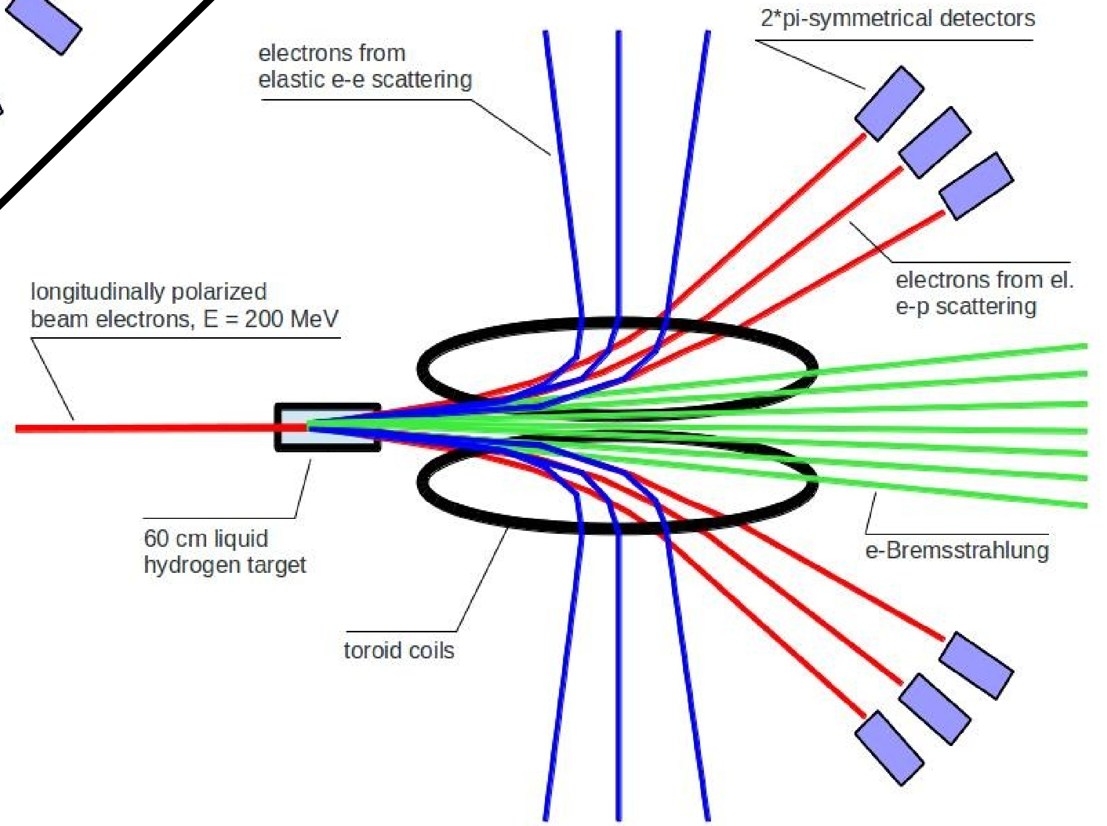
$$I^{cathode}_{total} = 1\,\mu\mathrm{A}$$

$$\langle A^{PV} \rangle_{L,\Delta\Omega} = -33.5\,\mathrm{ppb}$$

Weapon of choice: Solenoid or Toroid?



Solenoid:
- Full azimuthal coverage
- Compact setup
- Superconducting coils



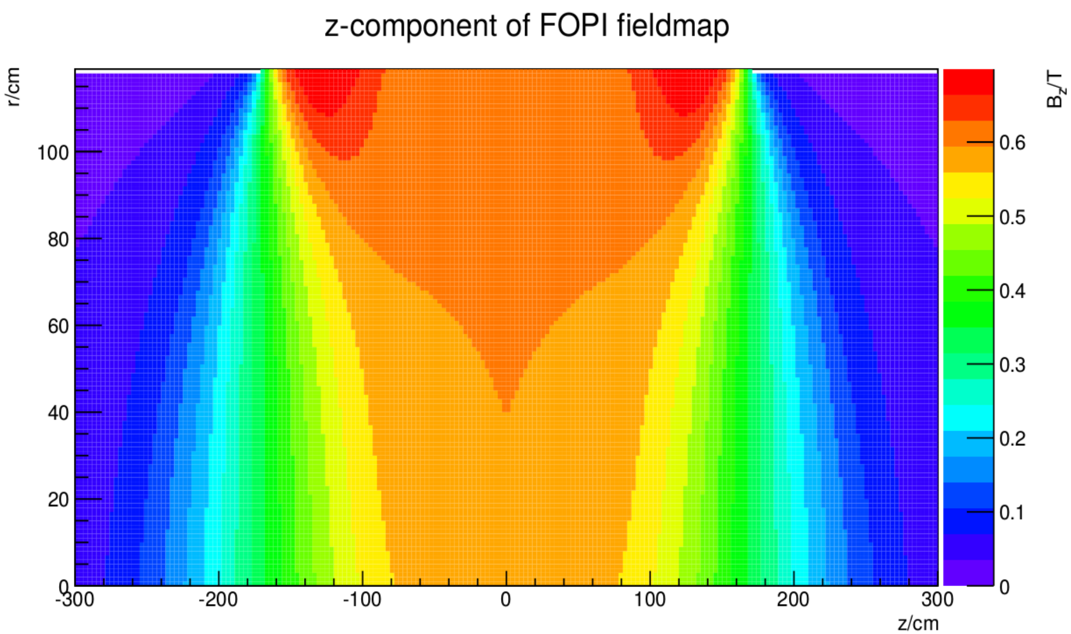
Toroid:
- Loss of ~ 50 % azimuth
  → double measurement time
- Larger setup
- Copper coils

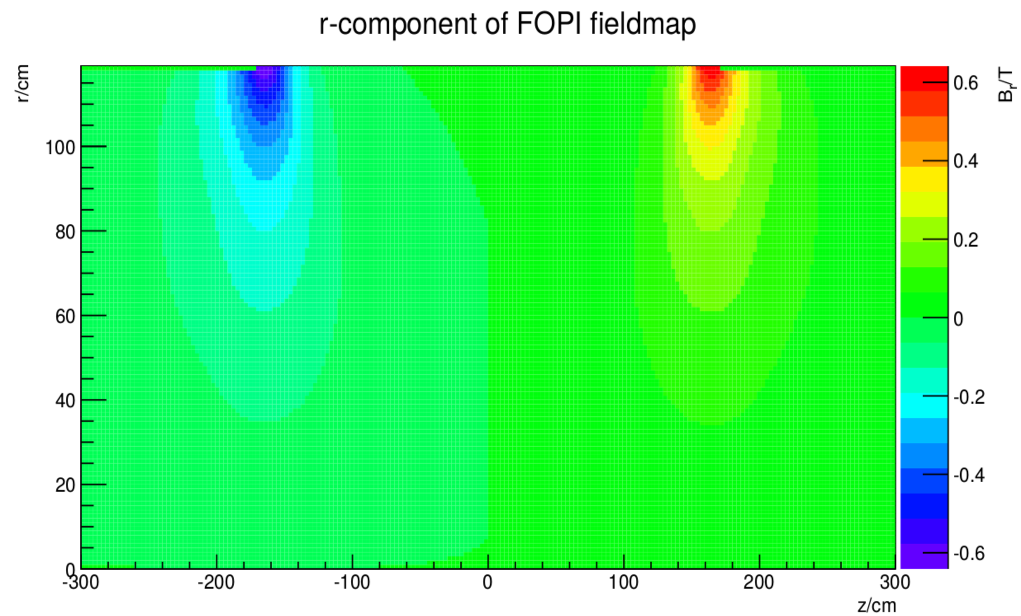
We would like to use a superconducting solenoid...

A promising candidate: The FOPI solenoid (GSI, Darmstadt)

- Field strength: 0.6 T
- Coil current: 725 A
- Stored energy: 3.4 MJ
- Material: Cu/Nb-Ti
- Cable length: 22.5 km

- Inner diameter: 2.4 m
- Total length: 3.8 m
- Total weight: 108.7 tons
- l-He consumption: 0.02 g/s, 0.6 l/h
- l-N consumption: 3 g/s, 13 l/h (perm. cooling)





(Courtesy Y. Leifels)

Use fieldmap with Geant4 to simulate the P2 experiment

$$A^{\exp} \sim \sin^2(\theta_W)$$

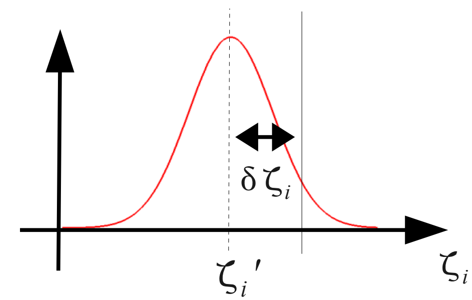
$$\longrightarrow \quad \sin^2(\theta_W) = Z(A^{\exp}, A^{app}, E, P, L, \Delta\Omega, \mathrm{Re}(\square_{\gamma Z}), \{f_i\})$$

Set of form factor fit parameters

Monte Carlo approach:

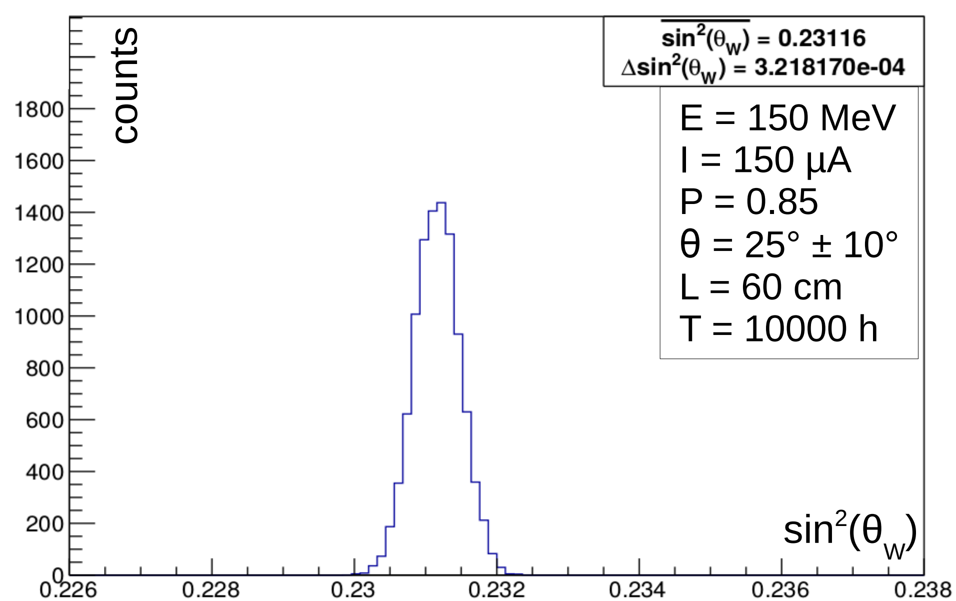
Sample distribution for $\sin^2(\theta_W)$ by assigning Gaussian distributions to each parameter $\zeta_i \in \{A^{\exp}, A^{app}, E, P, L, \Delta\Omega, \{f_i\}\}$.

$$\longrightarrow \quad \sin^2(\theta_W) + \delta\sin^2(\theta_W) = Z(\zeta_i' + \delta\zeta_i)$$



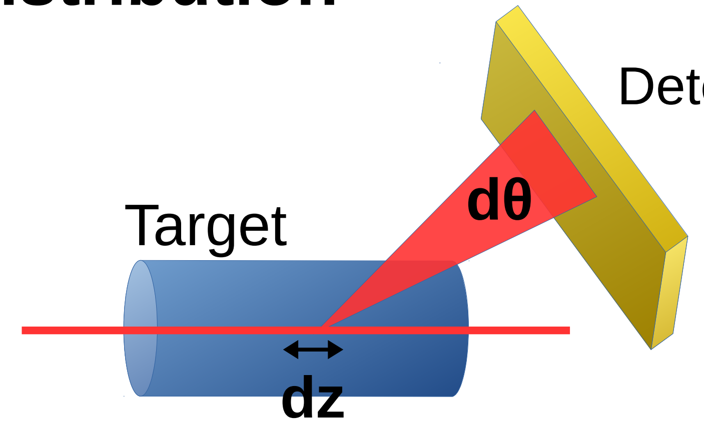
N sampling-iterations yield $\sin^2(\theta_W)$-distribution.

Extract $\Delta\sin^2(\theta_W)$ as standard deviation.



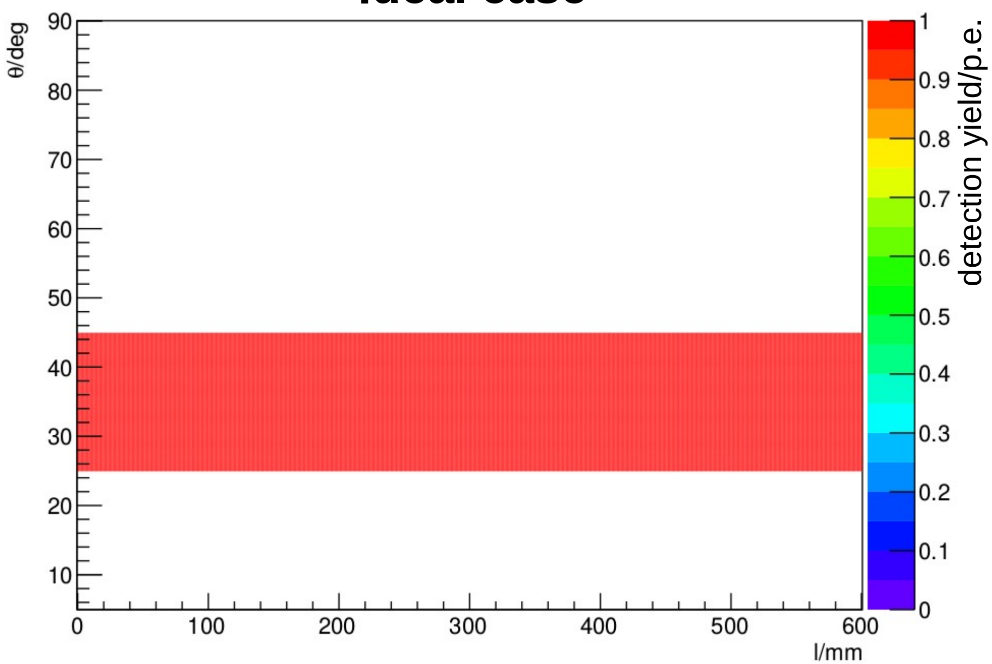
Choice of new weighting function: Detection yield distribution

$$\langle A^{PV} \rangle_{L,\Delta\Omega} = \frac{\int_0^L dz \int_{\Delta\Omega} d\Omega [(\frac{d\sigma}{d\Omega})^{Ros} \cdot \epsilon \cdot A^{PV}]}{\int_0^L dz \int_{\Delta\Omega} d\Omega [(\frac{d\sigma}{d\Omega})^{Ros} \cdot \epsilon]}$$

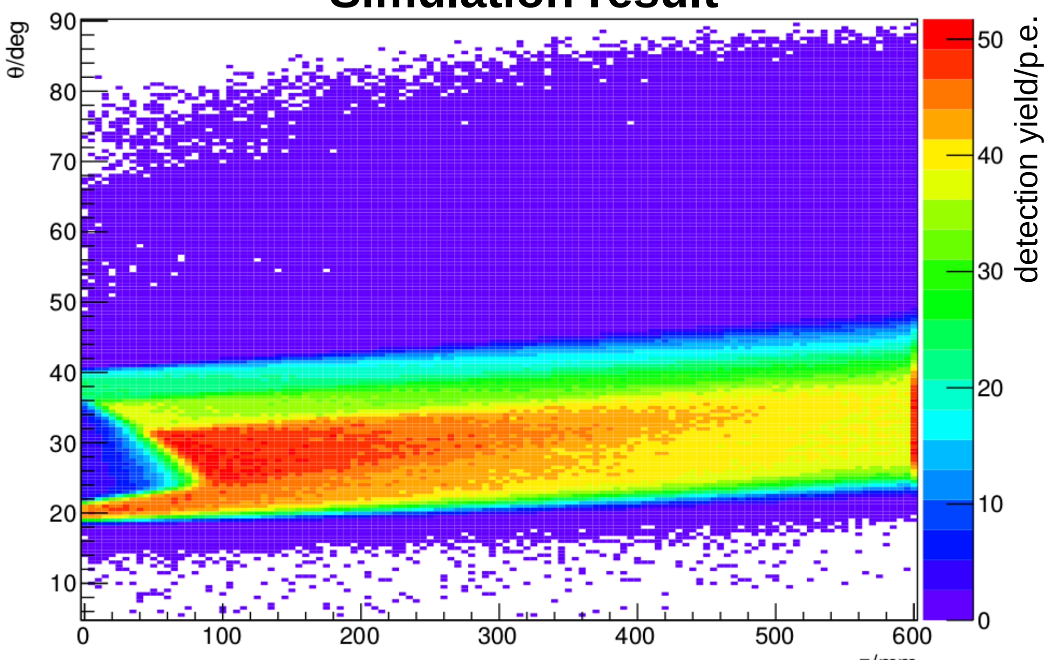


$$\epsilon(z,\theta) \equiv \frac{\text{Rate of photo electrons in detector, produced in target at position z with angle } \theta}{\text{Event rate according to Rosenbluth formula, produced in target at position z with angle } \theta}$$

Ideal case



Simulation result



What is the number of detected e-p events?

To determine $\Delta\sin^2(\theta_W)$, we sample the mapping:

$$\sin^2(\theta_W) = Z(A^{exp}, A^{app}, E, P, L, \Delta\Omega, \mathrm{Re}(\Box_{\gamma Z}), \{f_i\})$$

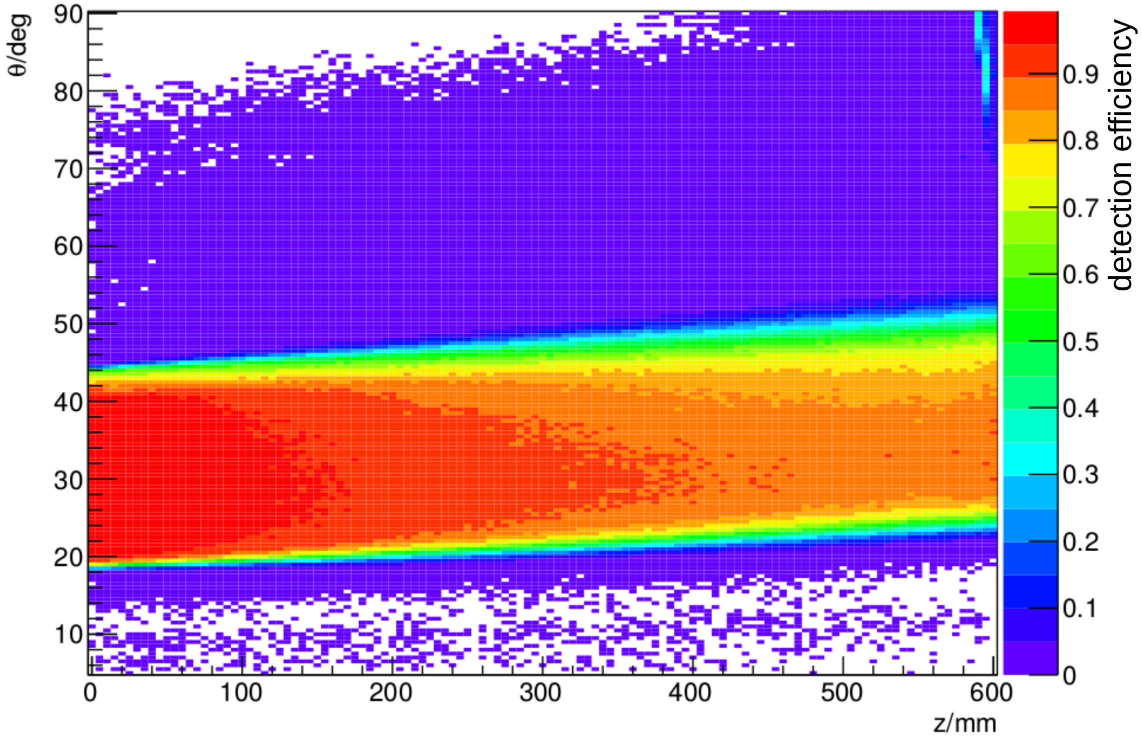
with

$\Delta A^{exp} \approx 1/\sqrt{N}$ and N: Total number of **detected e-p events**

$$N = \Phi \cdot \rho \cdot T \cdot \left\langle \frac{d\sigma}{d\Omega} \right\rangle_{L,\Delta\Omega} \cdot \Delta L_{eff} \cdot \Delta\Omega_{eff}$$

with

$$\left\langle \frac{d\sigma}{d\Omega} \right\rangle_{L,\Delta\Omega} = \frac{\int_0^L dz \int_{\Delta\Omega} d\Omega \left[\left(\frac{d\sigma}{d\Omega} \right)^{Ros} \cdot \epsilon \right]}{\int_0^L dz \int_{\Delta\Omega} d\Omega [\epsilon]},$$



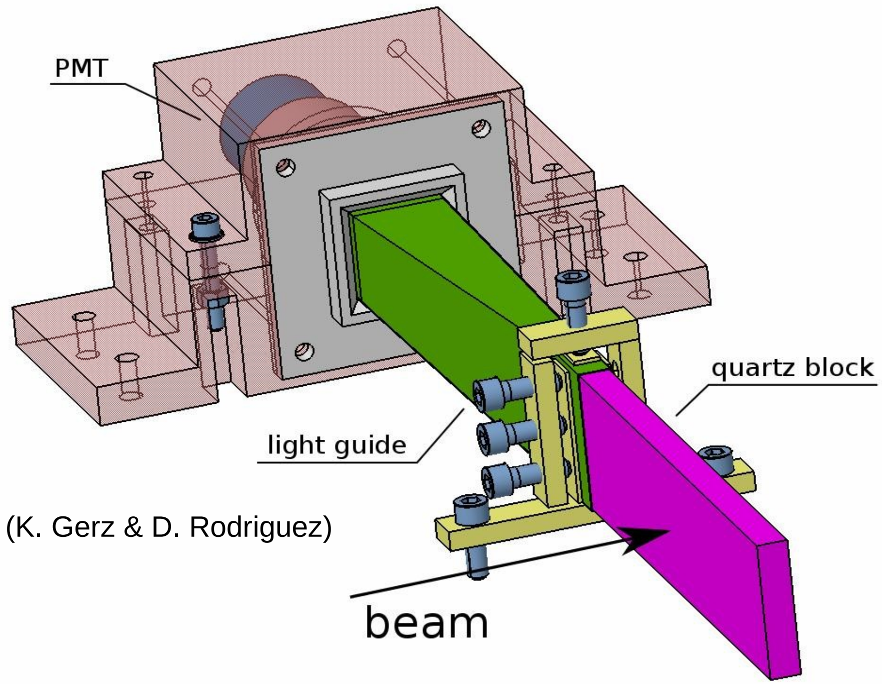
$$\Delta L_{eff} \cdot \Delta\Omega_{eff} = \int_0^L dz \int_{\Delta\Omega} d\Omega [y(z, \theta)]$$

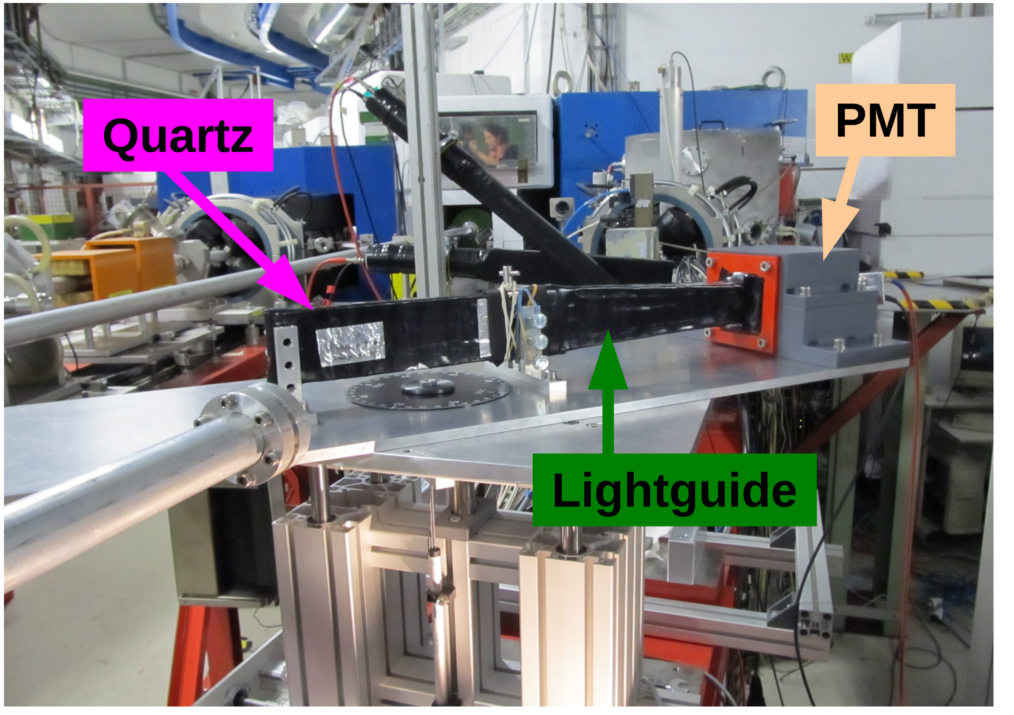
$y(z, \theta)$:

Detection efficiency distribution

Probability for an elastic e-p event with (z, θ) to produce a signal in the virtual detector

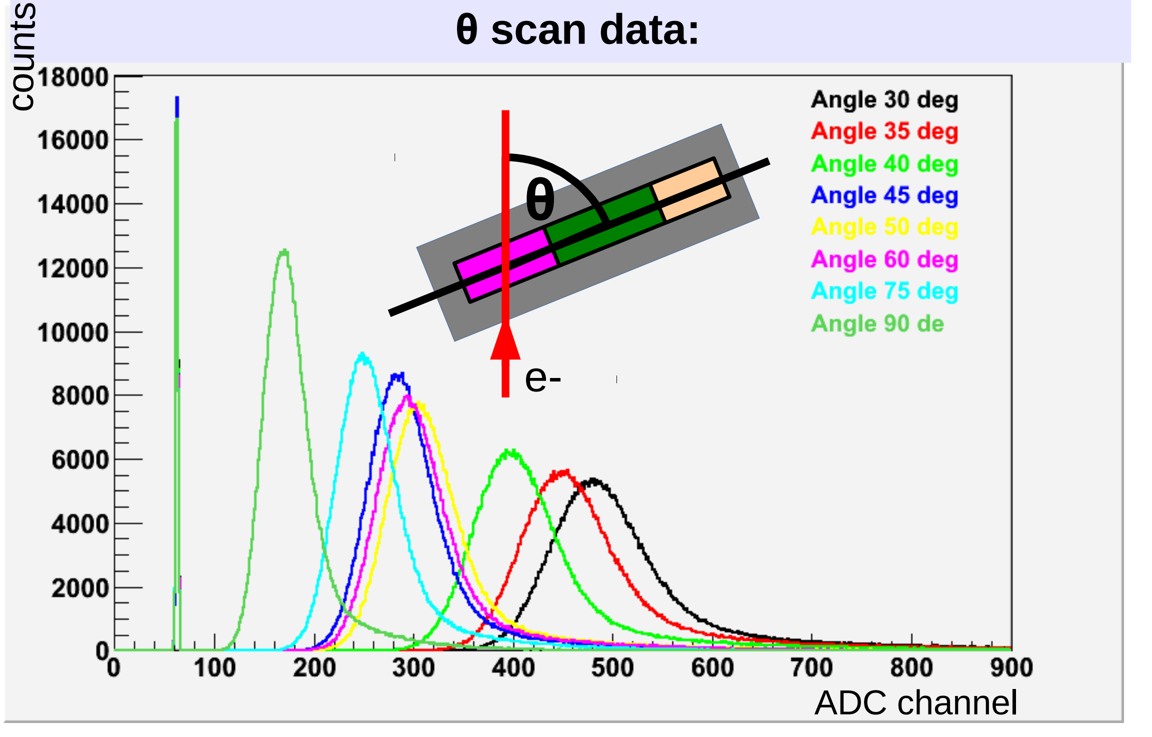
Prototype tests @ MAMI

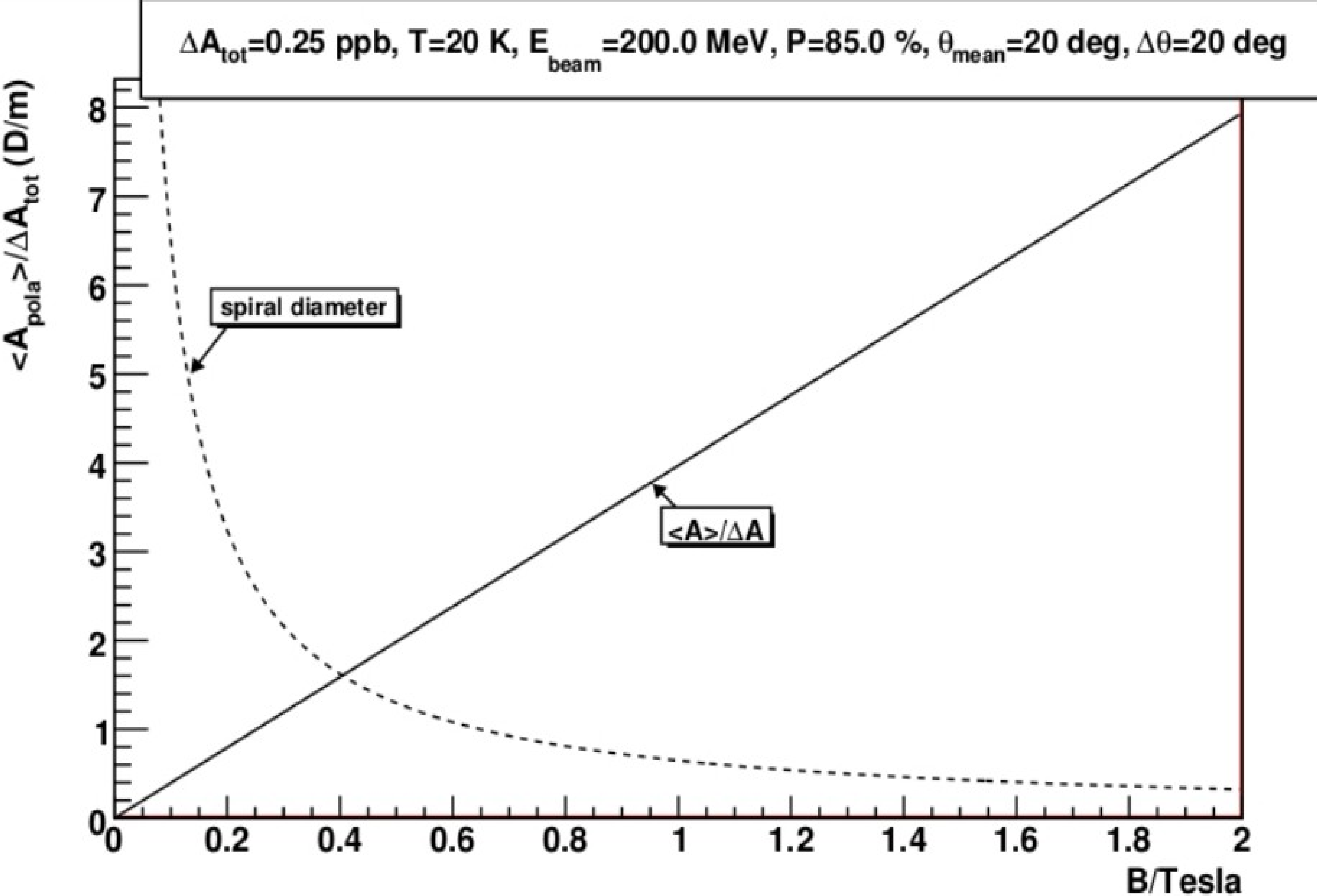




Measured the yield of photo electrons for different

- materials
  (quartzes, wrappings, lightguids, PMTs)
- geometries
- impact positions
- angles of incidence



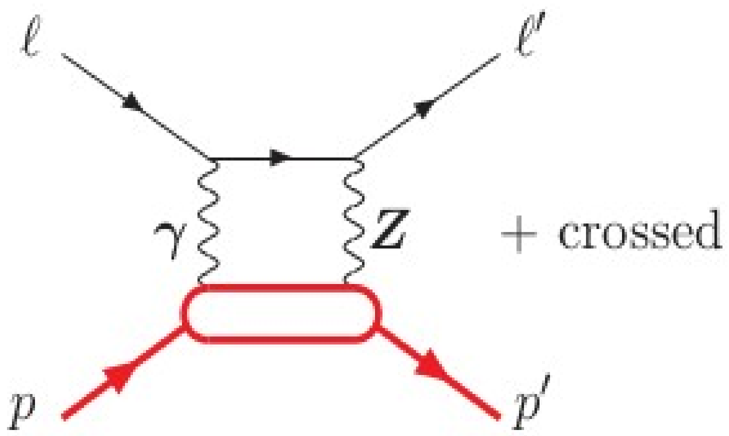

ΔA_tot=0.25 ppb, T=20 K, E_beam=200.0 MeV, P=85.0 %, θ_mean=20 deg, Δθ=20 deg
<A_pola>/ΔA_tot (D/m)
spiral diameter
<A>/ΔA
B/Tesla
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4
5
6
7
8

Low Q²?

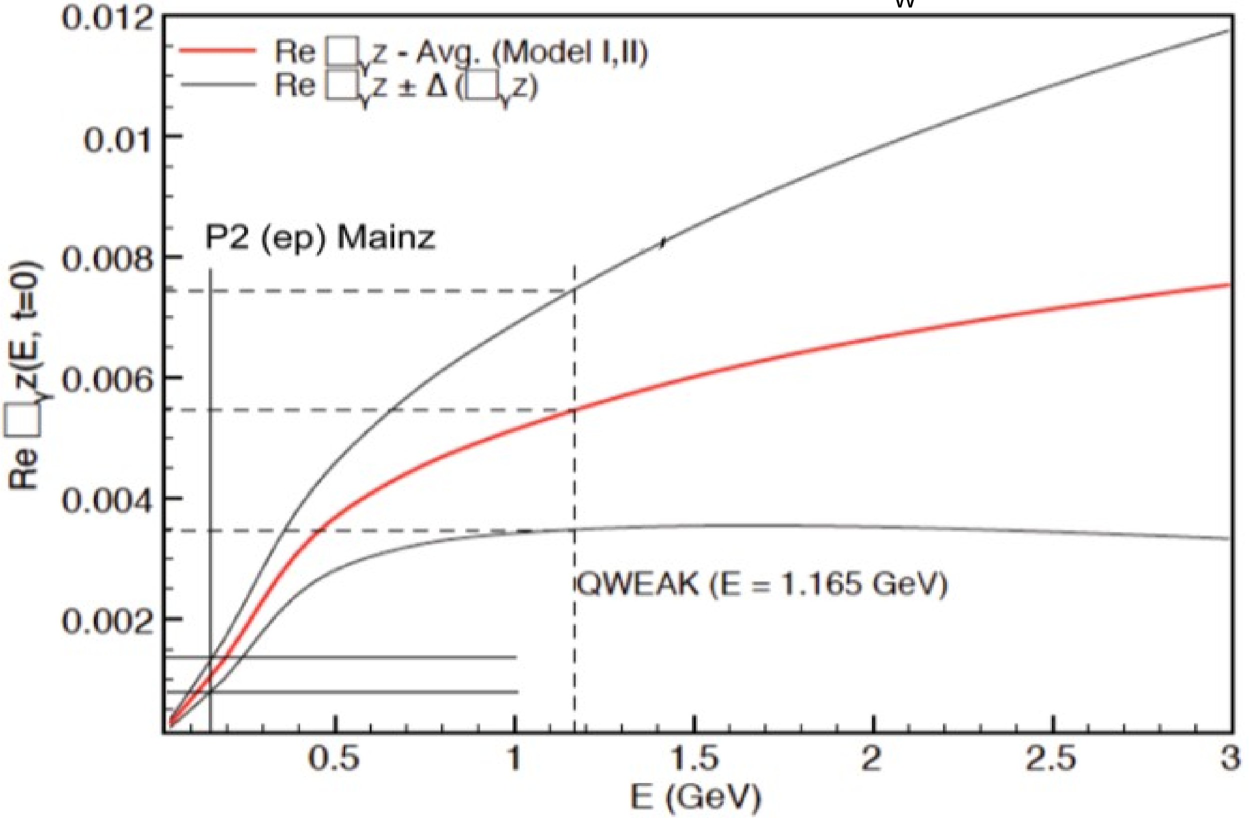
A^{PV} is dominated by $Q_w(p)$ at low values of Q^2.

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

Low Q²: Low beam energy and large angle or vice versa?



γ-Z-box correction to $Q_w(p)$



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

At low beam energies: Uncertainty of γ-Z-box contribution to $\sin^2(\theta_w)$ is negligible.