P2(^{12}C) – Measurement of the Weak Charge of the carbon-12 nucleus

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JG|U

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

PRISMA

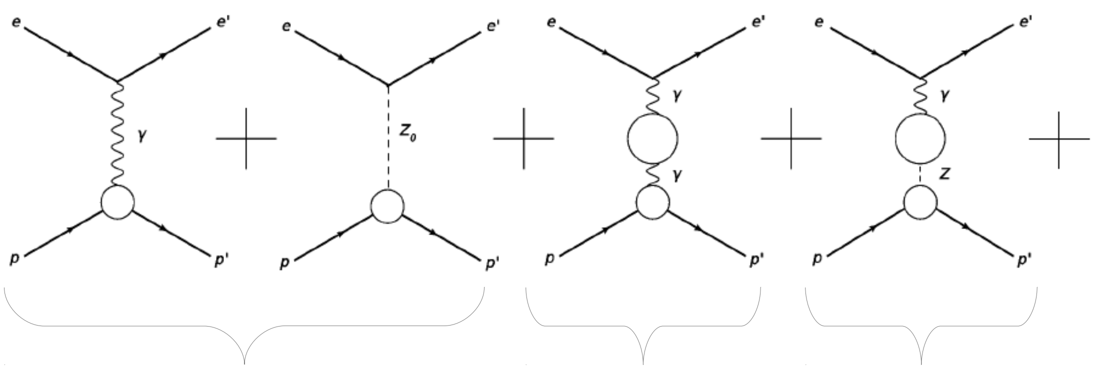
Table of contents

- Introduction: Weak mixing angle and the weak charge of ^{12}C

- Achievable sensitivity

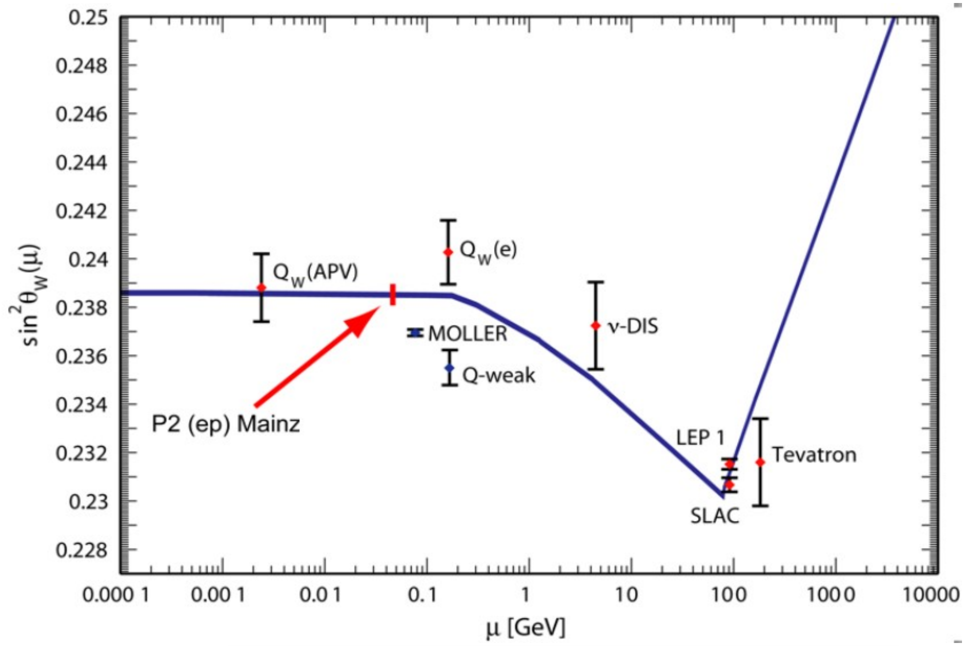
- Experimental realization: Feasibility study with solenoid spectrometer

MOTIVATION: Measurement of the Weak Mixing Angle



"tree level" α correction $\sin^2\Theta_W$ correction

Q²-dependency of $\sin^2\Theta_W$



Absorb quantum corrections by expressing the weak mixing angle as function of the transferred energy:

$$\boxed{\sin^2(\theta_W) \rightarrow [\sin^2(\theta_W)](\mu)}$$

SIGNIFICANT DEVIATION
=
SIGN FOR "NEW PHYSICS"

MOTIVATION FOR P2(^{12}C)

- Measurement of the Weak Mixing Angle with ^{12}C target
  - Original Idea: Faster measurement due to dependency of cross section on Z^2

$$\frac{d\sigma}{d\Omega} \sim Z^2$$

  - Simpler target: graphite instead of cryogenic hydrogen
  - Could we gain new information?

“NEW PHYSICS”

Parametrization of “new” quantum loop corrections:

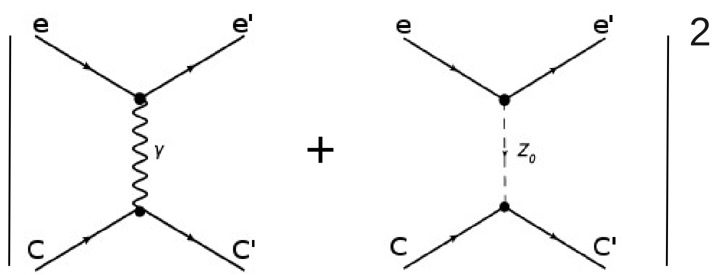
$$Q_W^C = -5.5080(5)[1 - 0.003T + 0.016S - 0.034X(Q^2) + \chi]$$
$$Q_W^p = +0.0708(9)[1 + 0.150T - 0.200S + 0.4X(Q^2) + 4\chi] \qquad \chi = m_Z^2 / m_{Z_\chi}^2$$
$$Q_W^e = -0.0458(6)[1 + 0.240T - 0.34S + 0.7X(Q^2) + 7\chi]$$
$$Q_W^{Cs} = \underbrace{-73.24(4)[1}_{\text{SM}} \underbrace{+ 0.010S - 0.023X(Q^2) - 0.9\chi]}_{\text{“NEW PHYSICS”}}$$

→ Measurements of different Weak Charges are complementary!

Measurement of Weak Charge of carbon is more sensitive to the “Dark Photon”

BASIC APPROACH: Classical Parity Violation Experiment

Cross section: $\sigma_{e^{12}C} \sim$

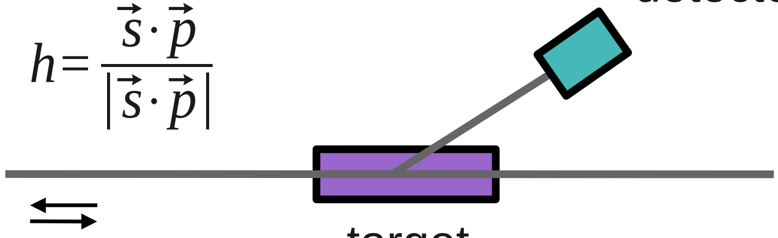


$\sim \quad |M_\gamma + M_Z|^2$

$\boxed{Q(C) = +6e}$ $\quad \boxed{Q_W(C) = -24\sin^2(\Theta_W)}$

The weak interaction is **parity violating** : $\longrightarrow \boxed{N^{\uparrow} \neq N^{\downarrow}}$

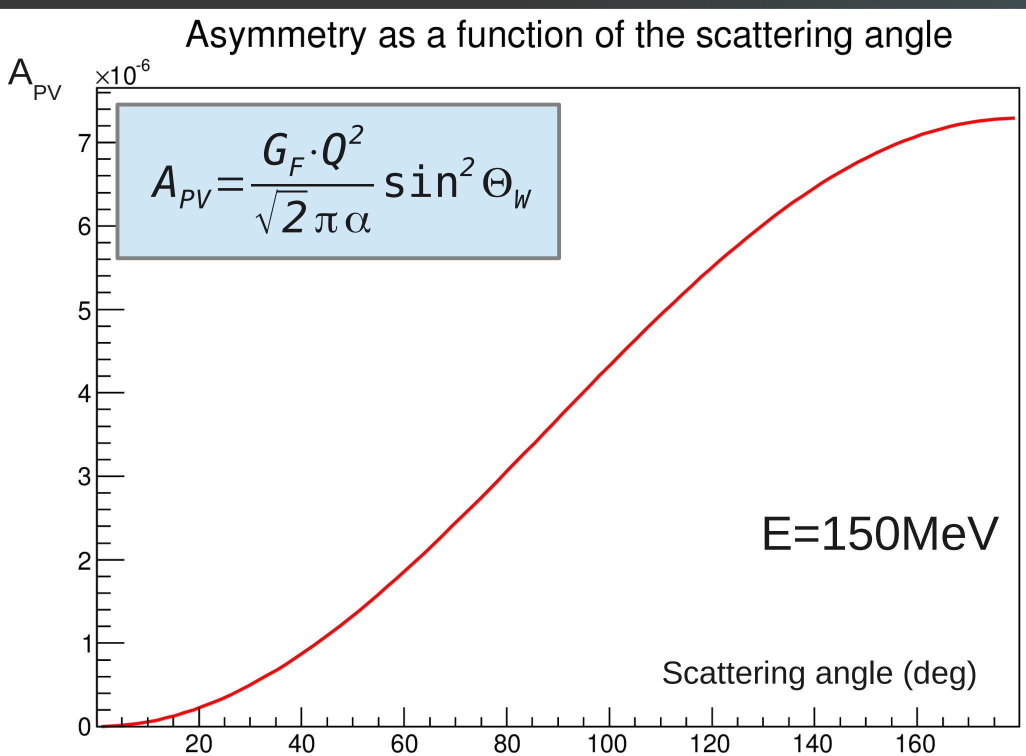
$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|}$$



$$A_{exp} = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = P \cdot A_{PV} + A_{app}$$

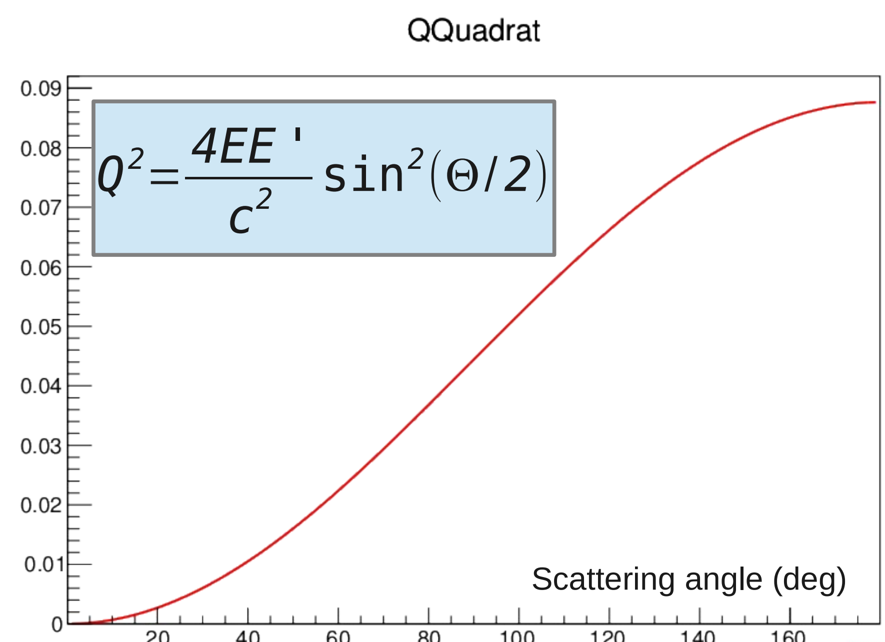
$$A_{PV} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

INTRODUCTION: The parity violating asymmetry



Spin: 0
Isospin: 0 → NO MAGNETIC FORM FACTORS

Electric form factors cancel out when computing parity violating asymmetry

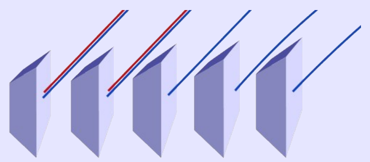


The parity violating asymmetry depends purely on Q^2 and the WEAK MIXING ANGLE

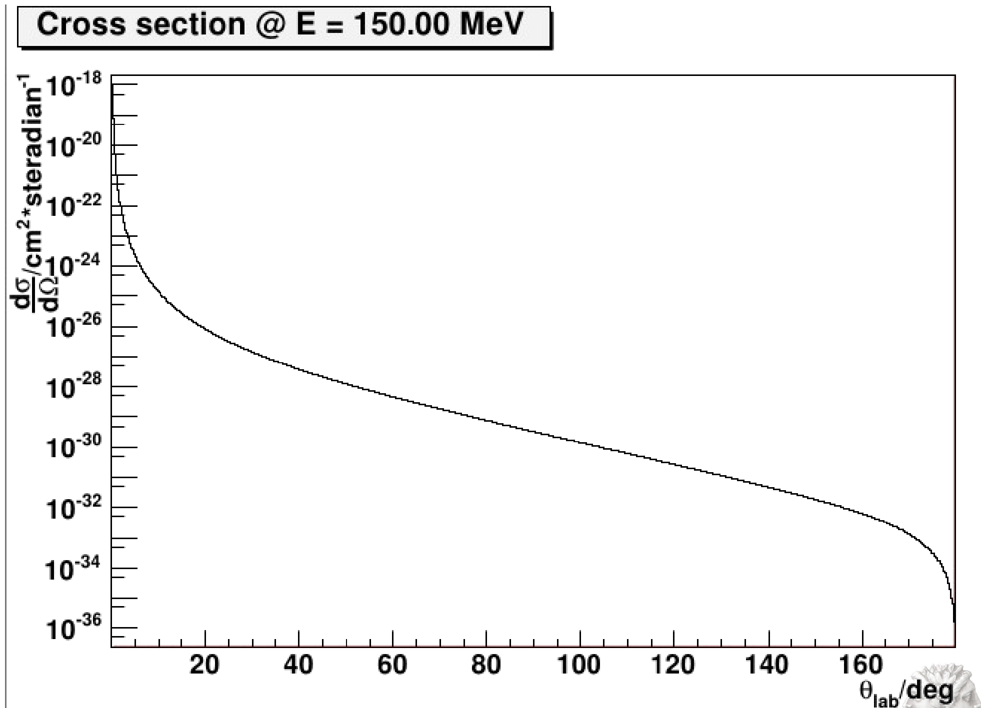
BASIC APPROACH

Measuring time	2500 h	
Beam polarization	85%	±0.3%
Beam energy	150MeV	±20ppm
Beam current	150µA	

Target: "5-finger" graphite
$5 g/cm^2$



Luminosity: $2.33 \cdot 10^{38} cm^{-2} s^{-1}$



MONTE CARLO ERROR PROPAGATION

$$A_{exp} \pm \delta A_{exp} = (P \pm \delta P) \cdot (A_{PV} \pm \delta A_{PV}) + (A_{app} \pm \delta A_{app})$$

Integration over detector acceptance

$\sin^2 \Theta_W$

$$A_{exp} \pm \delta A_{exp} = (P \pm \delta P) \cdot \frac{\int_{\Delta\Omega \pm \delta(\Delta\Omega)} d\Omega \frac{d\sigma}{d\Omega}(E \pm \delta E, \vartheta) \cdot A^{PV}(E \pm \delta E, \hat{s}_z^2 \pm \delta \hat{s}_z^2, \vartheta)}{\int_{\Delta\Omega \pm \delta(\Delta\Omega)} d\Omega \frac{d\sigma}{d\Omega}(E \pm \delta E, \vartheta)} + (A_{app} \pm \delta A_{app})$$

$\frac{1}{\sqrt{N}}$

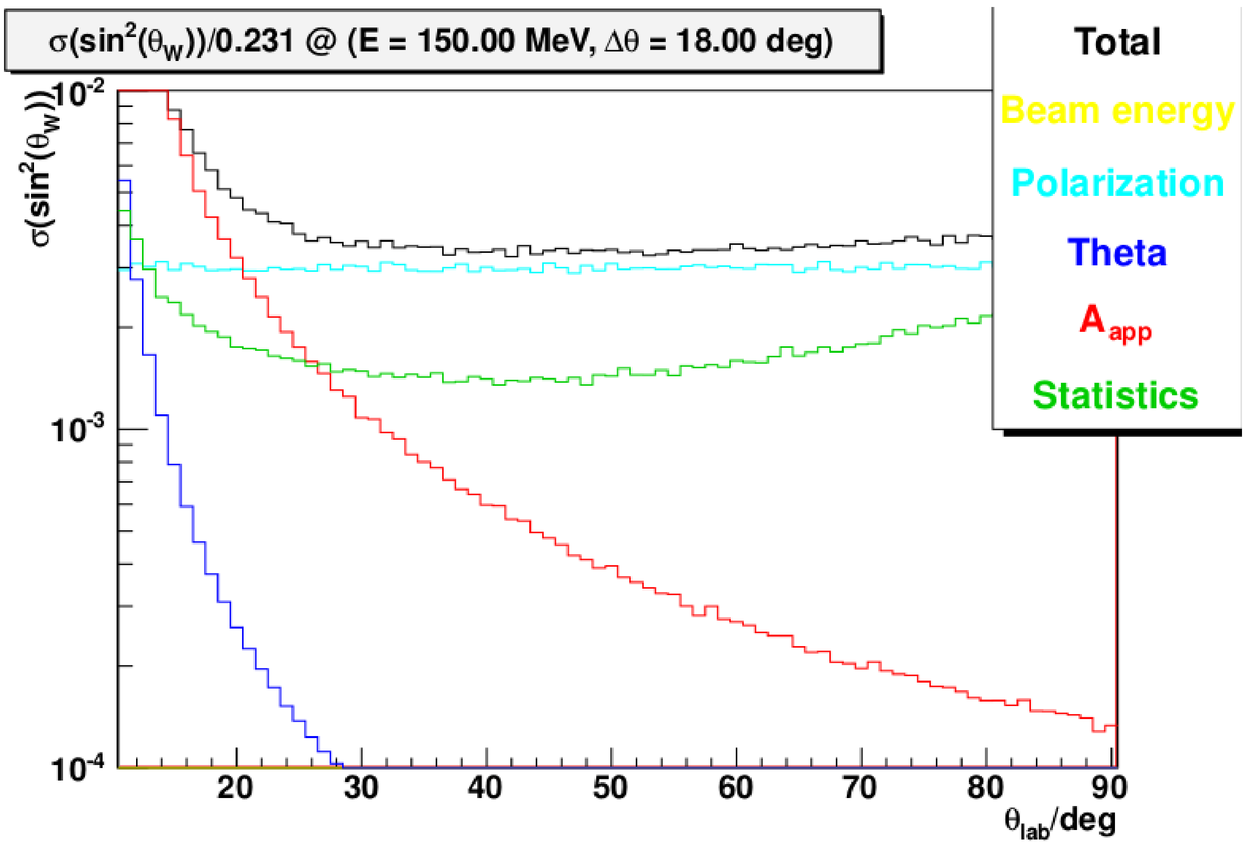
polarization

beam energy

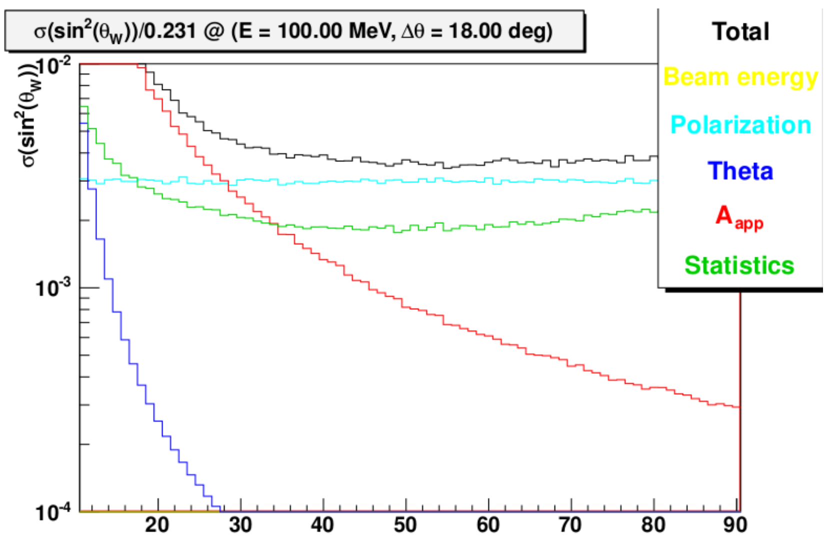
THIS WAS DONE FOR:

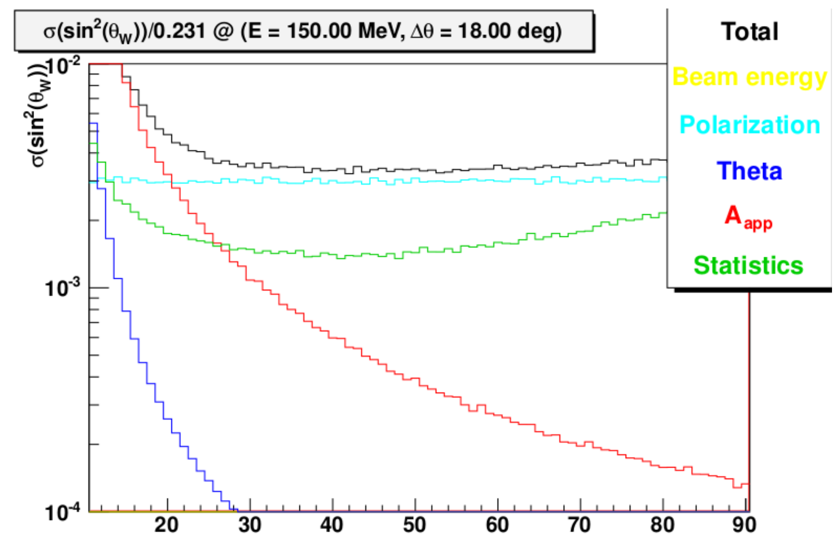
- Beam energies: E = 100MeV to 300MeV
- Detector acceptances: 2° and 20°

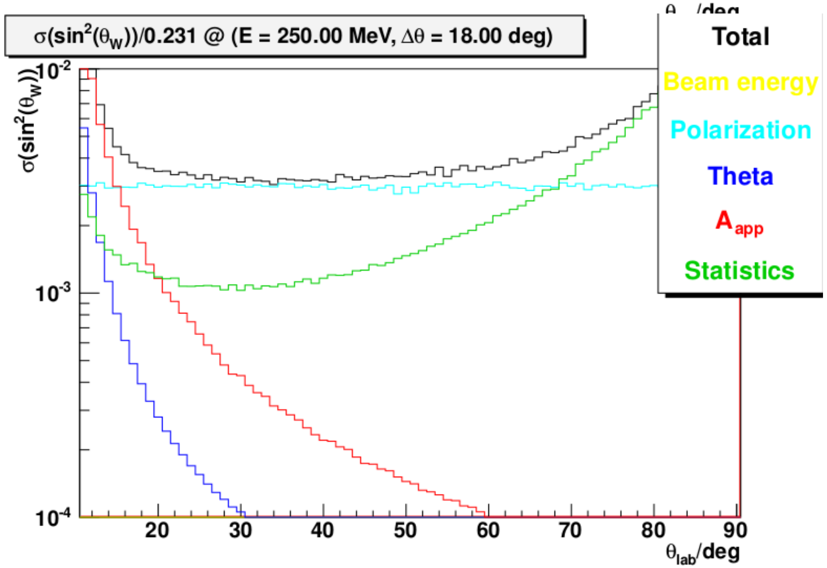
Achievable Precision for different BEAM ENERGIES

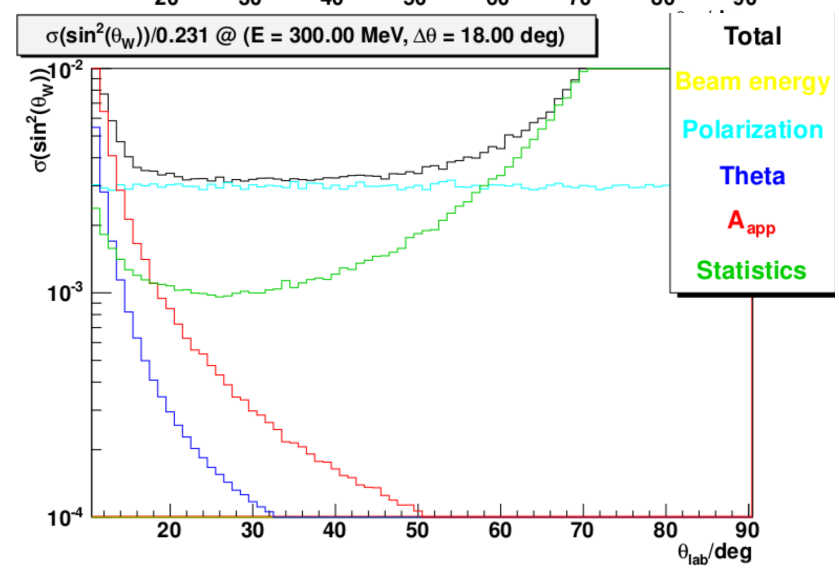


Achievable Precision for different BEAM ENERGIES

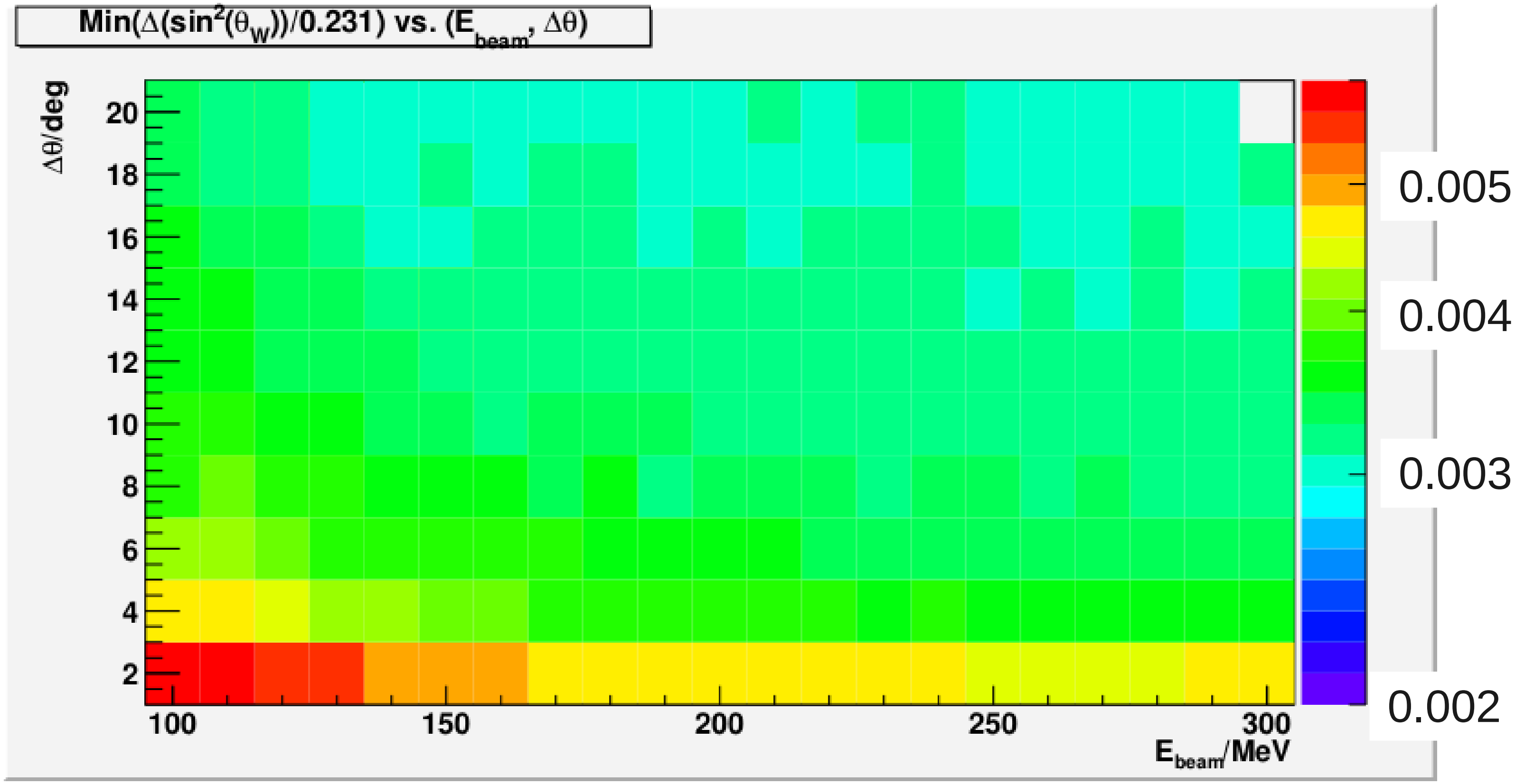








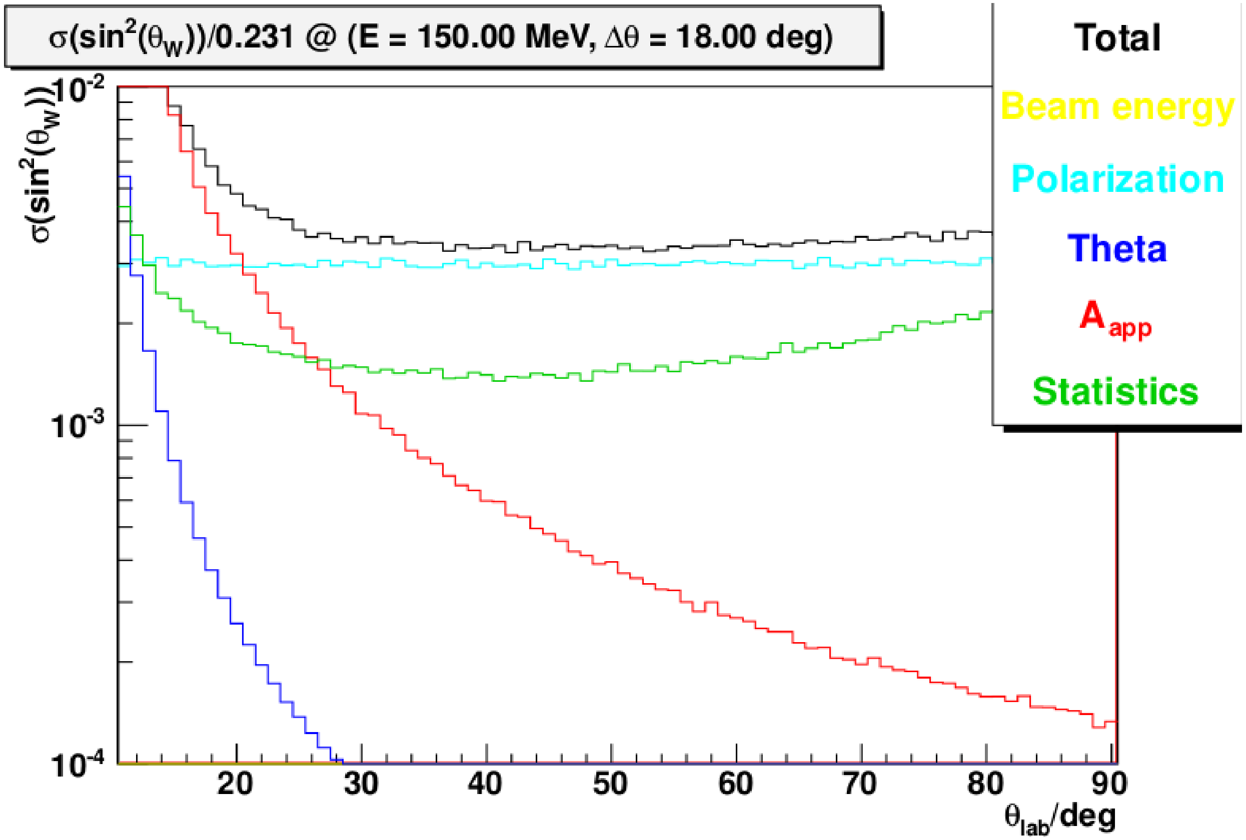
Achievable Precision at energies 100MeV<E<300MeV



Higher energies yield no significant benefit

$$\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} \approx 0.003$$

Achievable Precision from Monte Carlo sampling



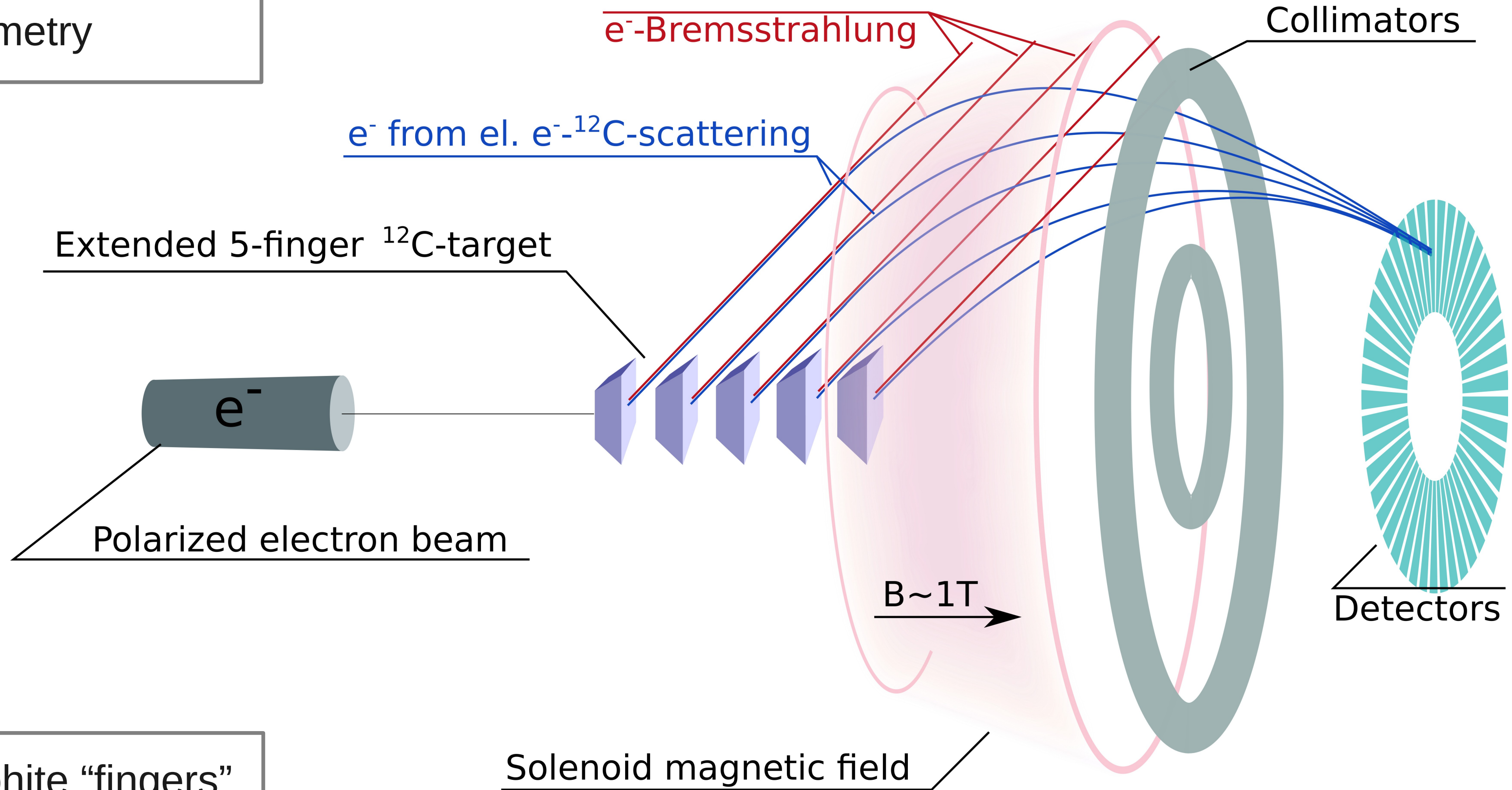
$$\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} \approx 0.003$$

At
- E = 150MeV
- Scattering angles about 40°

BUT: Measurement with P2 detector setup is not possible

EXPERIMENTAL REALIZATION

MESA:
- 150µA
- 150MeV-200MeV
- Polarimetry



Target:
- 5 graphite "fingers"
- 5 g/cm² total
- 36mm spacing

Feasibility study with Geant4

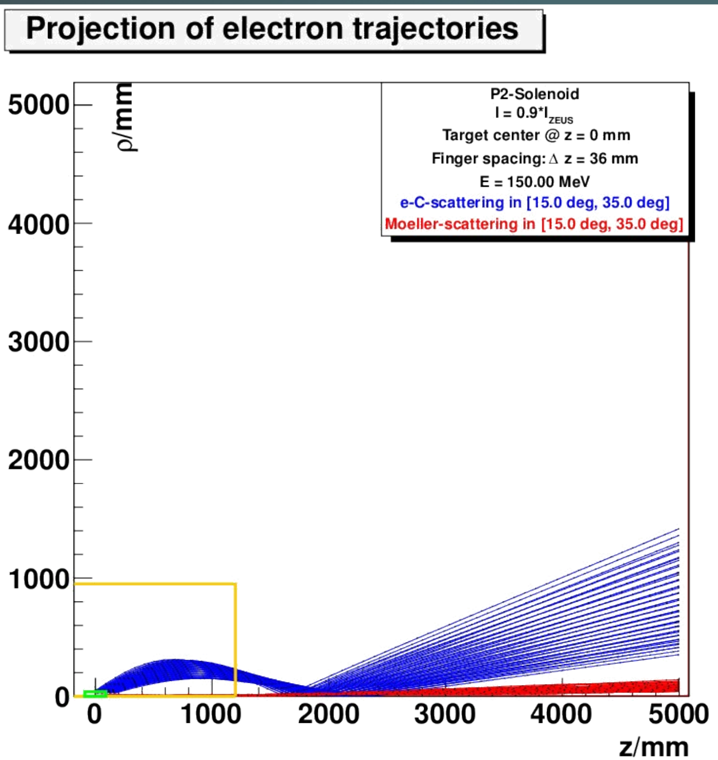
RAY TRACING PLOTS

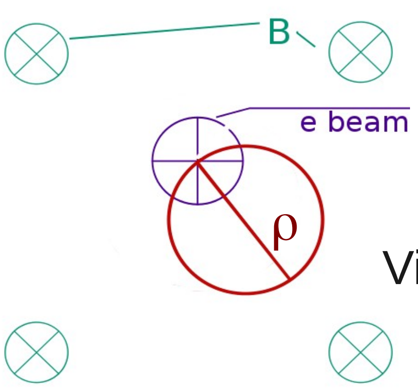
Objectives
- Can we filter scattered electrons of interest from background?
- How do we have to place target, collimators and detectors?

Method
- Rays with Geant4

- Vary target position
  z = -2000mm to 2000mm
  relative to solenoid center

- Vary magnetic field from
  B = 0.18T to 1.8T





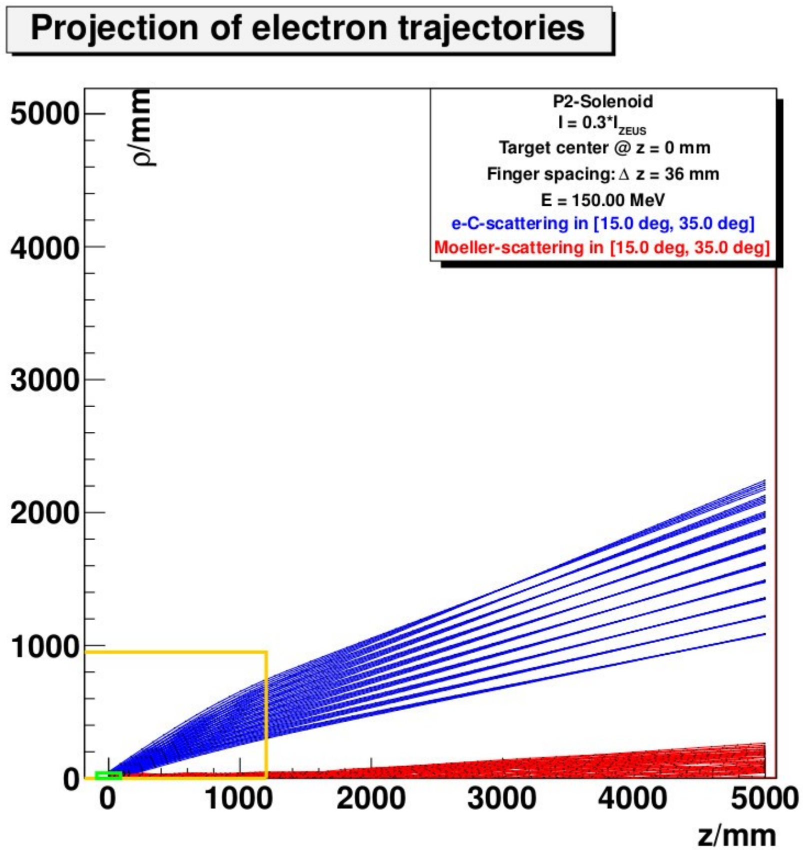
View with beam

Feasibility study with Geant4

RAY TRACING PLOTS

Magnetic field varied

B = 0.54T



INPUT

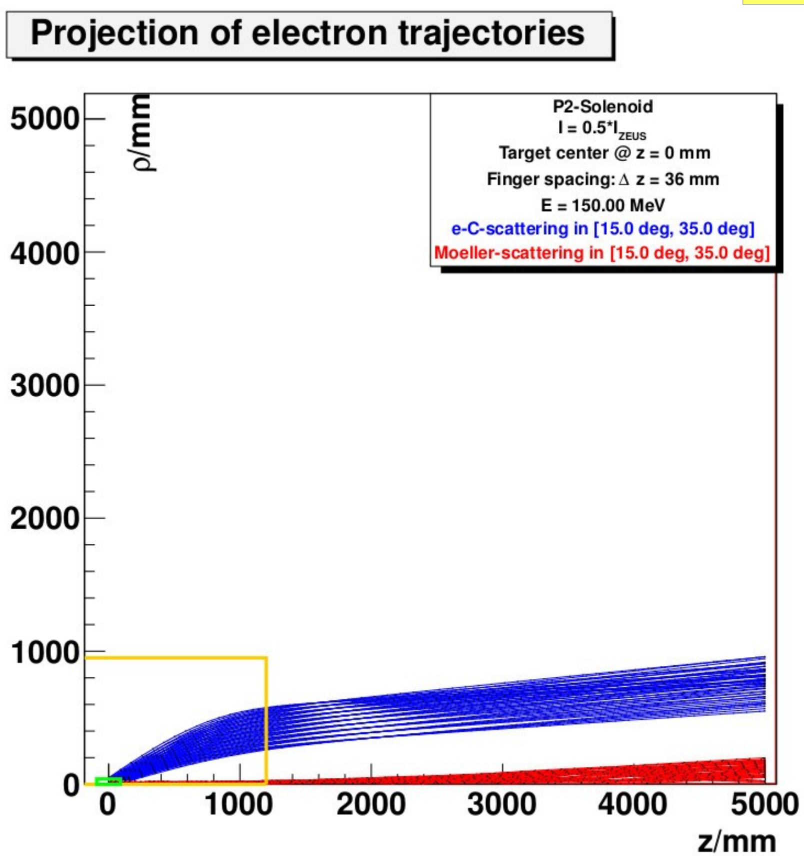
- 150MeV e^- beam
- 5g/cm² graphite target split into 5 fingers with 36mm spacing
- Target center = 0mm

Feasibility study with Geant4

RAY TRACING PLOTS

Magnetic field varied

B = 0.9T



INPUT

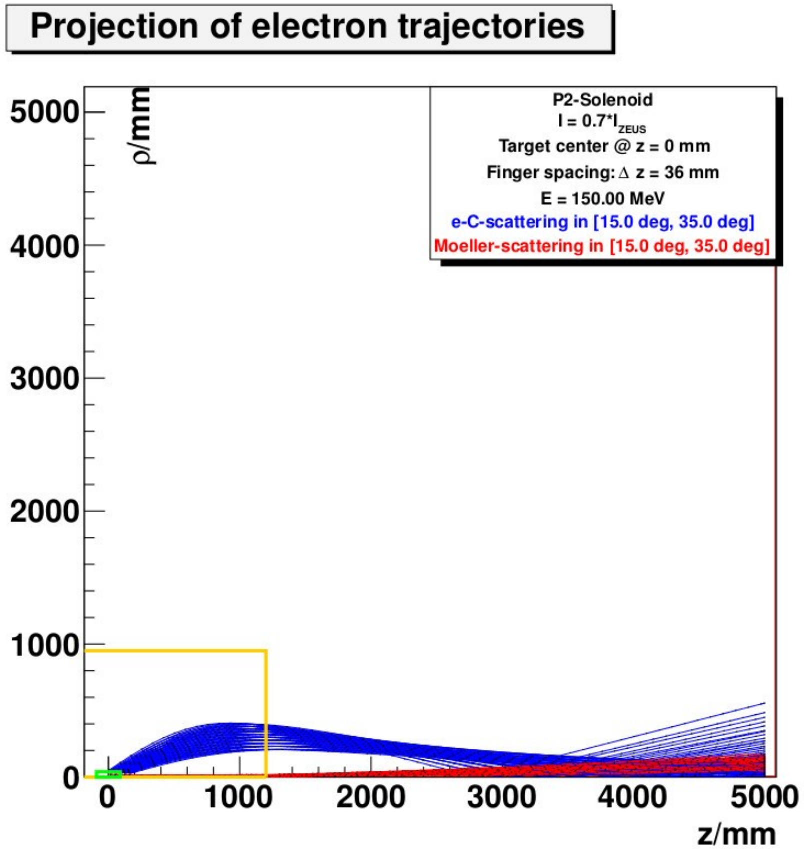
- 150MeV e^- beam
- 5g/cm² graphite target split into 5 fingers with 36mm spacing
- Target center = 0mm

Feasibility study with Geant4

RAY TRACING PLOTS

Magnetic field varied

B = 1.26T



INPUT

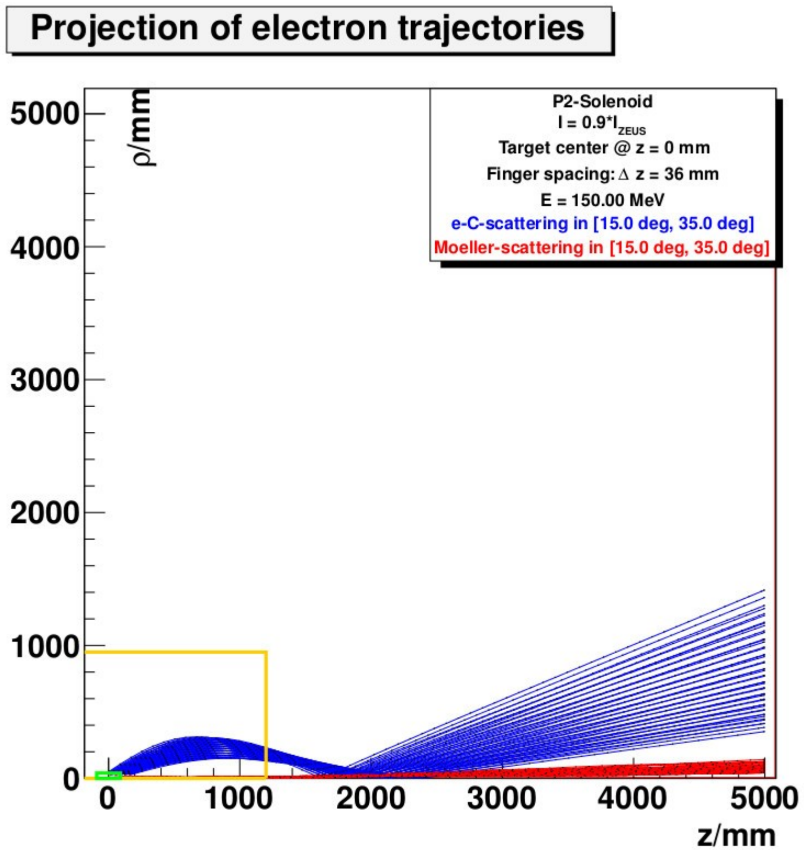
- 150MeV e^- beam
- 5g/cm² graphite target split into 5 fingers with 36mm spacing
- Target center = 0mm

Feasibility study with Geant4

RAY TRACING PLOTS

Magnetic field varied

B = 1.62T



INPUT

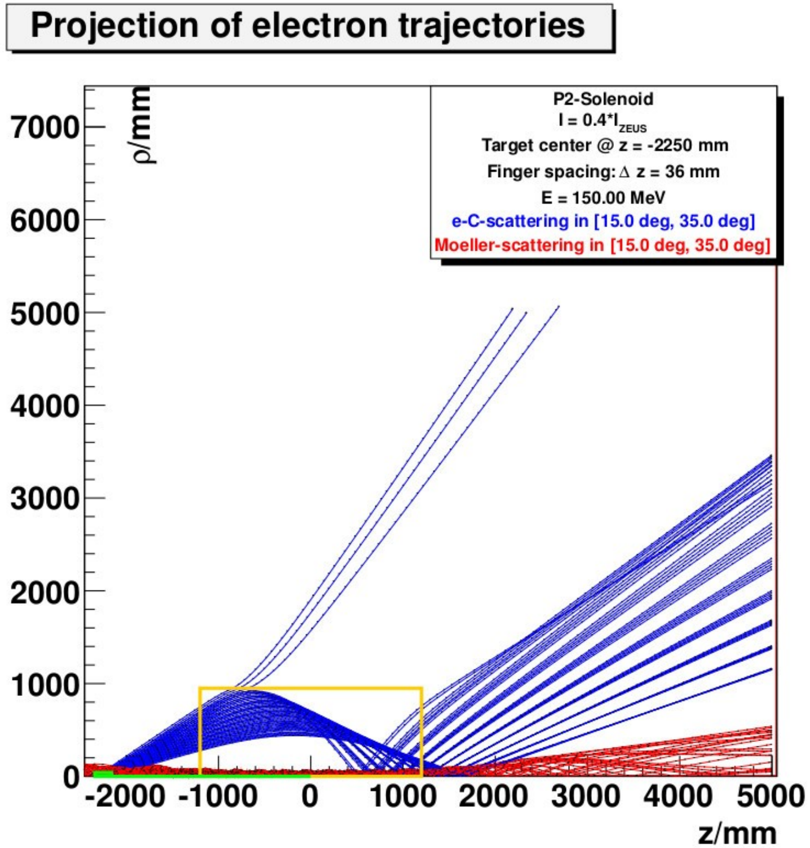
- 150MeV e^- beam
- 5g/cm² graphite target split into 5 fingers with 36mm spacing
- Target center = 0mm

Feasibility study with Geant4

RAY TRACING PLOTS

Target position varied

z = -2250mm



INPUT

- 150MeV e^- beam
- 5g/cm² graphite target split into 5 fingers with 36mm spacing
- B = 0.72T

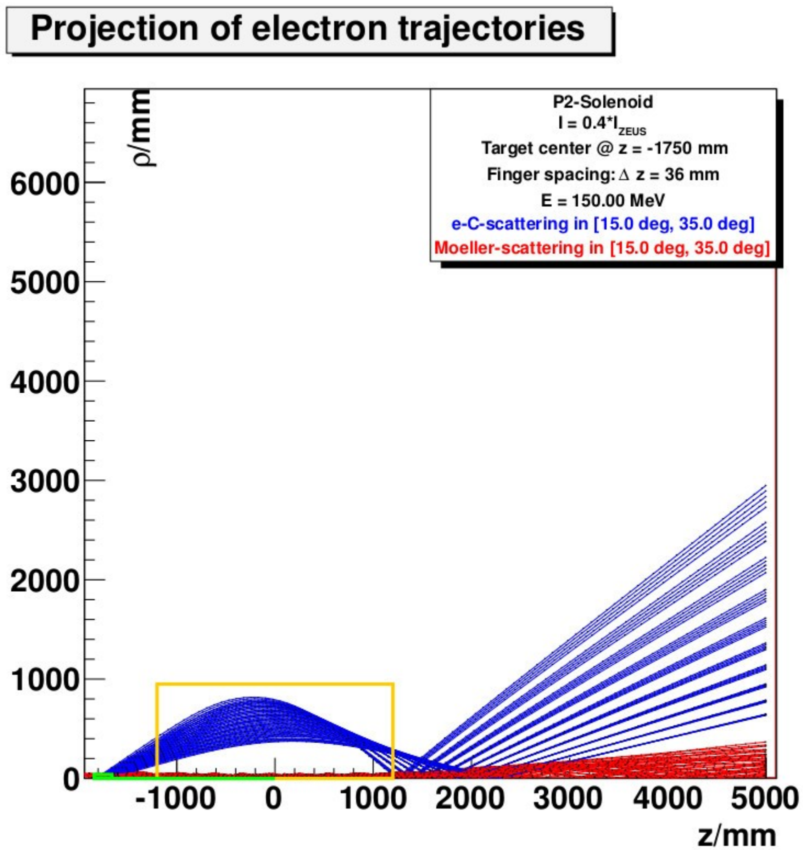
Target position varied

EXPERIMENTAL REALIZATION

RAY TRACING PLOTS

Target position varied

z = -1750mm



INPUT

- 150MeV e^- beam
- 5g/cm² graphite target split into 5 fingers with 36mm spacing
- B = 0.72T

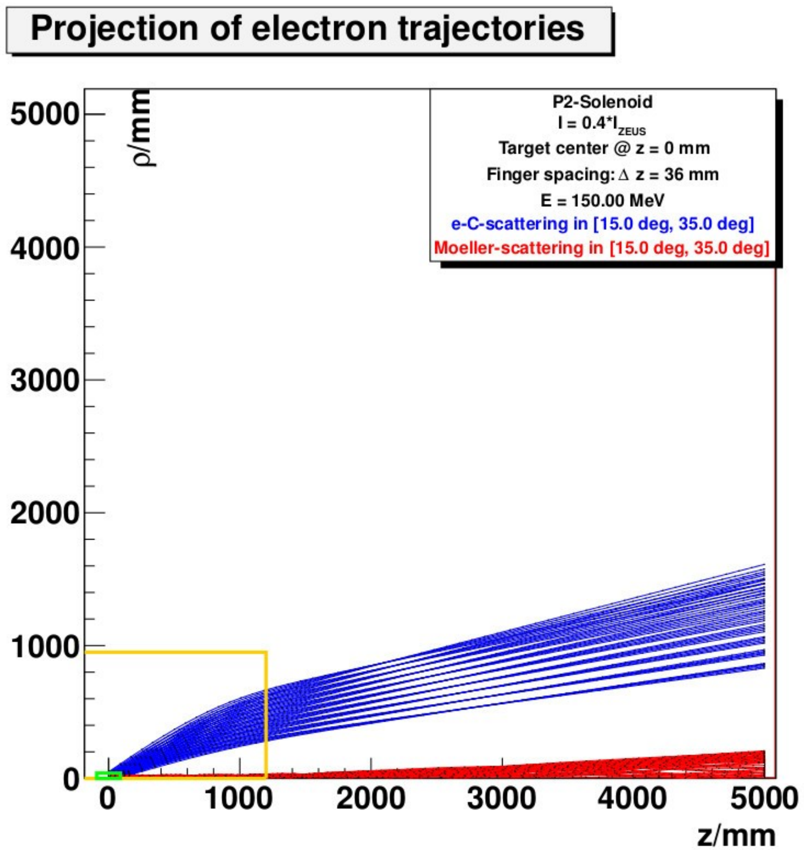
Target position varied

EXPERIMENTAL REALIZATION

RAY TRACING PLOTS

Target position varied

z = 0mm



INPUT

- 150MeV e^- beam
- $5g/cm^2$ graphite target split into 5 fingers with 36mm spacing
- B = 0.72T

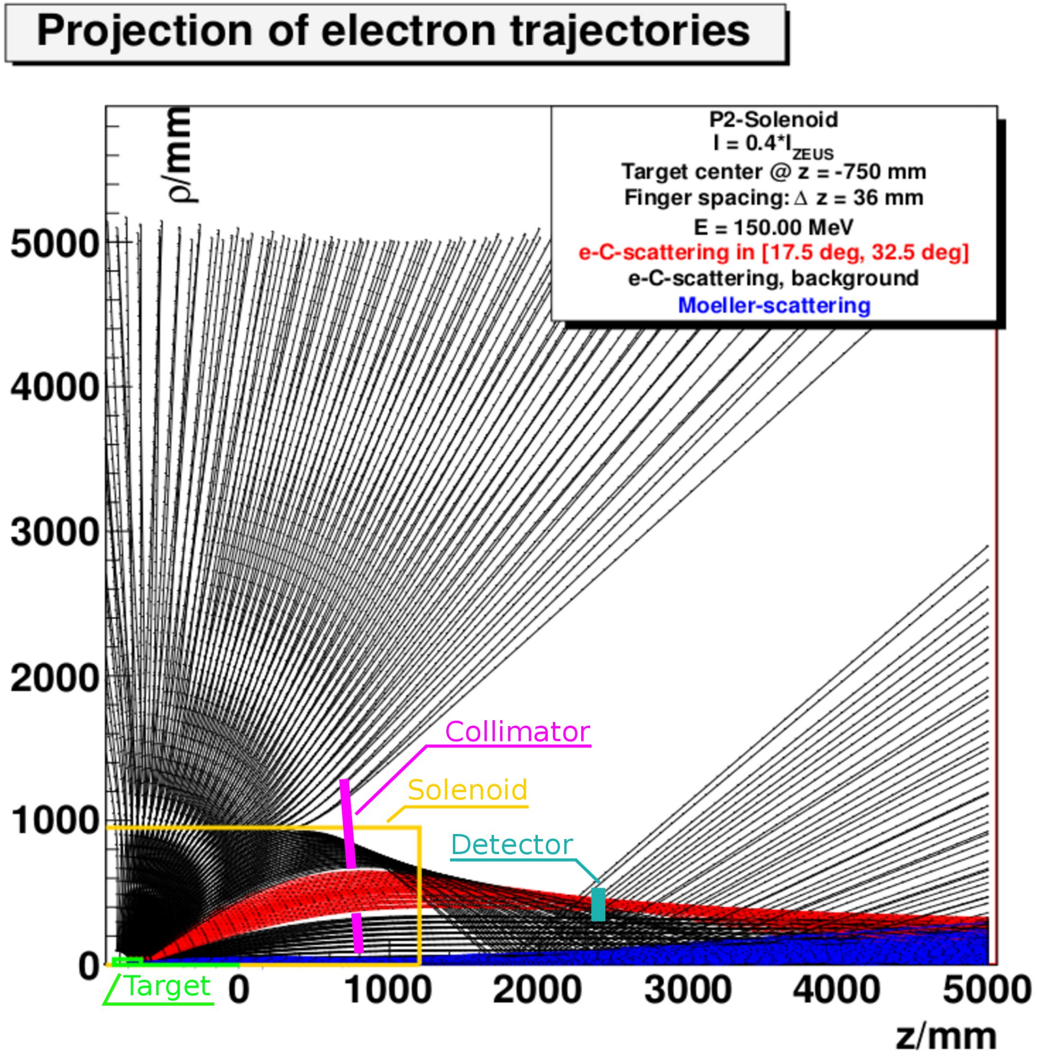
Target position varied

EXPERIMENTAL REALIZATION

RAY TRACING PLOTS

POSSIBLE SETUP

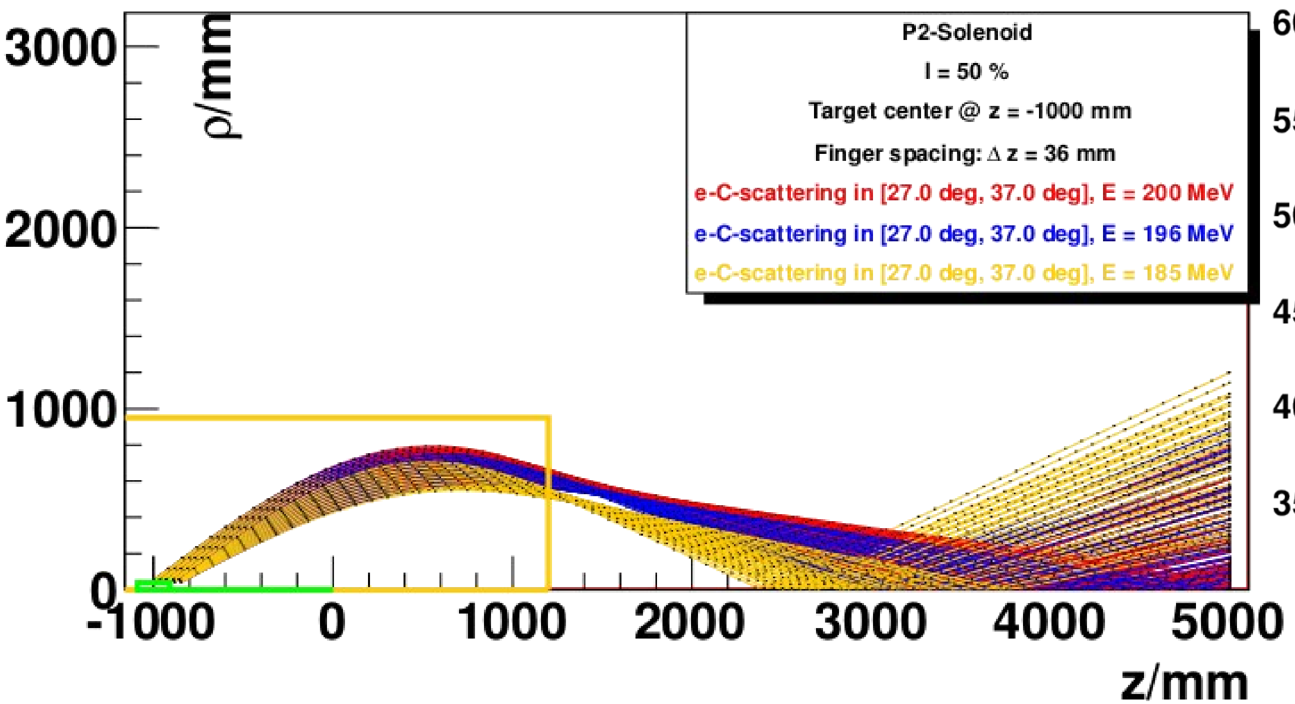
- Target position z = -750mm
- B = 0.72T

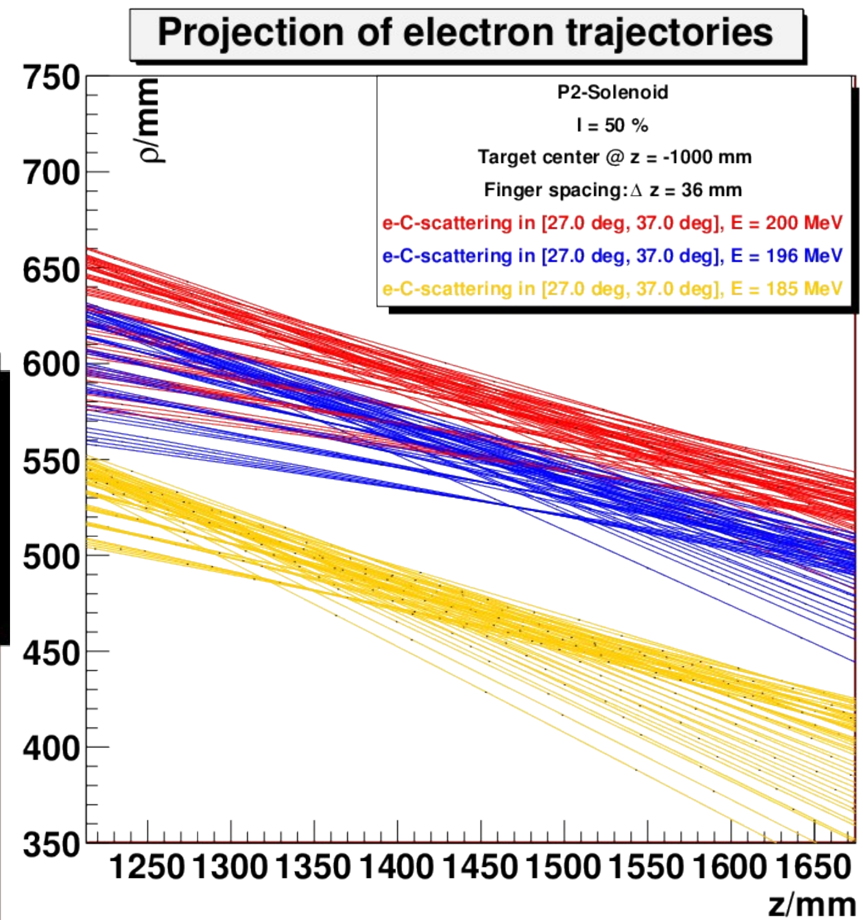


EXPERIMENTAL REALIZATION

GEANT4 RAY TRACING PLOTS

Separation of excited states





CONCLUSION

@ Beam energy E = 150MeV
Scattering angle Θ = 40° +- 9°
Target density d = 5g/cm²

Measuring time t = 2500h
Beam current I = 150µA

We can achieve $\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$

$$A_{PV} = \frac{G_F \cdot Q^2}{\sqrt{2}\pi\alpha}\sin^2\Theta_W$$

$$Q_W^C = -24\sin^2\Theta_W$$

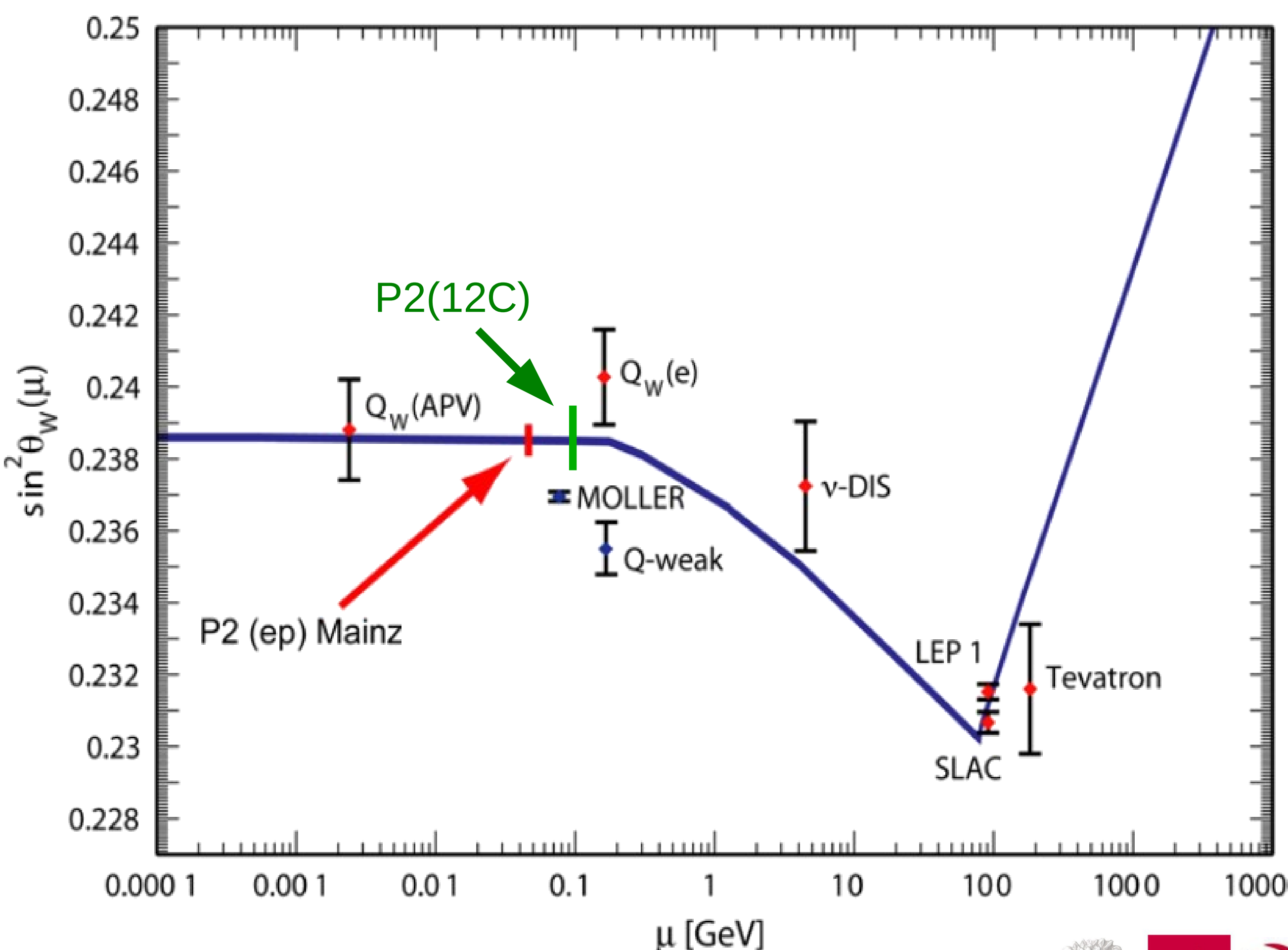
$$\frac{\delta A_{PV}}{A_{PV}} = \frac{\delta Q_W^C}{Q_W^C} = \frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$$

Reminder: With Hydrogen: $\frac{\delta A_{PV}}{A_{PV}} = 1.7\%$ $\frac{\delta Q_W^H}{Q_W^H} = 2\%$ $\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.15\%$

CONCLUSION

$$\frac{\delta \sin^2(\Theta_W)}{\sin^2(\Theta_W)} \approx 0.003$$

$$@Q^2 \approx 0.01$$



CONCLUSION

"NEW PHYSICS"?

$$Q_W^C = -5.5080(5)[1 - 0.003T + 0.016S - 0.034X(Q^2) + \chi]$$
$$Q_W^p = +0.0708(9)[1 + 0.150T - 0.200S + 0.4X(Q^2) + 4\chi]$$

$$\chi = m_Z^2 / m_{Z_\chi}^2$$

$$\frac{\delta Q_W^C}{Q_W^C} = 0.003 \longrightarrow \delta\chi = 0.003$$

$$\frac{\delta Q_W^P}{Q_W^P} = 0.02 \longrightarrow \delta\chi = 0.005$$

MEASUREMENT OF THE WEAK CHARGE OF THE CARBON NUCLEUS IS MORE SENSITIVE TO DARK PHOTON MASS

SUMMARY

- P2(12C) can measure the weak mixing angle and the weak charge of the carbon nucleus to a relative precision of 0.3%.
- P2(12C) is more sensitive to Z_{dark} than P2(lH).
- First feasibility studies with solenoid spectrometer are promising
- Detector setup for larger scattering angles is needed.

THANK YOU VERY MUCH!