SFB 1044
Institut für Kernphysik

Status of the P2 Experiment

A measurement of the Weak Mixing Angle at Low Energy

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SPIN 2018, Ferrara, Italy

September 2018

- Introduction:

  The Weak Mixing Angle and the Standard Model

- P2 Experiment Design

  Achievable precision in $\sin^2\Theta_W$
  Spectrometer Design

- Further Physics Program

- Summary

Standard Model: Open questions

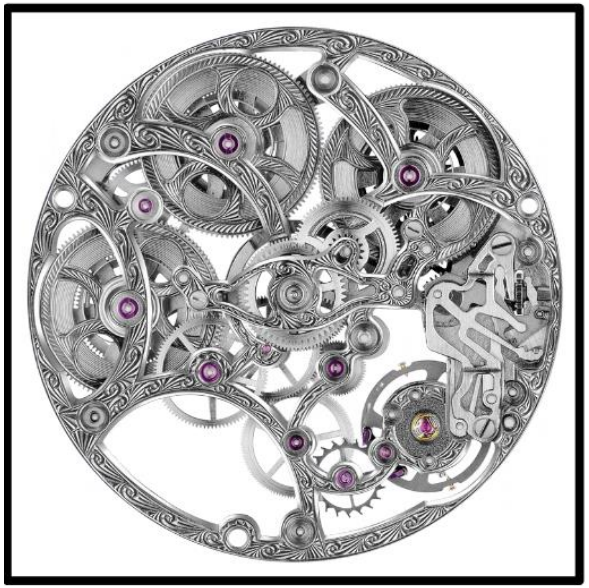
- Consistent description of all four fundamental interactions?

- Dark matter, dark energy?

Search for **New Physics**:

Option 1: Direct search for new particles at high energies

Option 2: Precise determination of Standard Model predictions at moderate energies



Standard Model: Open questions

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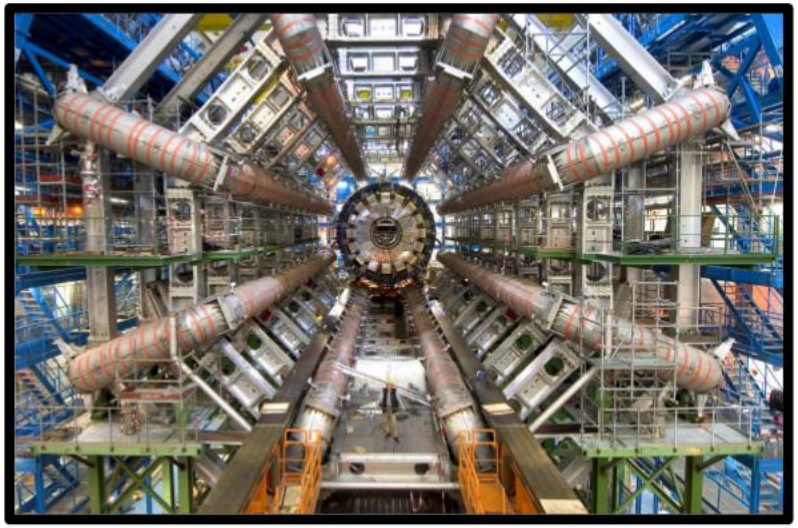
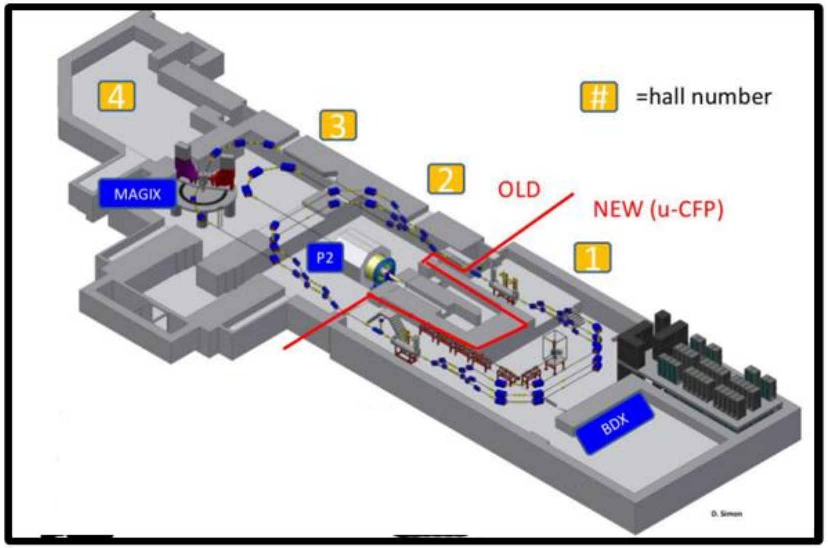
Search for **New Physics**:

Option 1: Direct search for new particles at high energies



Option 2: Precise determination of Standard Model predictions at moderate energies



The weak mixing angle

$\sin^2\Theta_W$: a central parameter in the Standard Model

Tree level relations:

- Electric charge $$e = \sqrt{4\pi\alpha} = g_1 \cos\theta_W = g_2 \sin\theta_W$$
- Masses of W and Z Boson $$\cos\theta_W = M_W / M_Z$$
- Myon decay constant $$G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}$$

Standard model relations for the weak mixing angle

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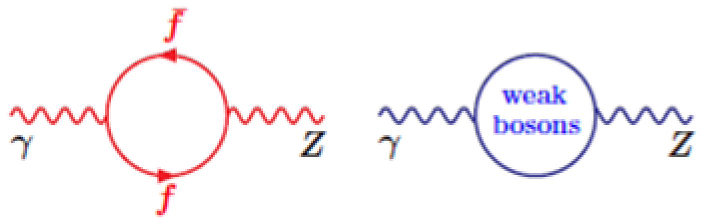
- Electric charge $e = \sqrt{4\pi\alpha} = g_1 \cos\theta_W = g_2 \sin\theta_W$
- Masses of W and Z Boson $\cos\theta_W = M_W / M_Z$
- Myon decay constant $G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}$

Including radiative corrections:



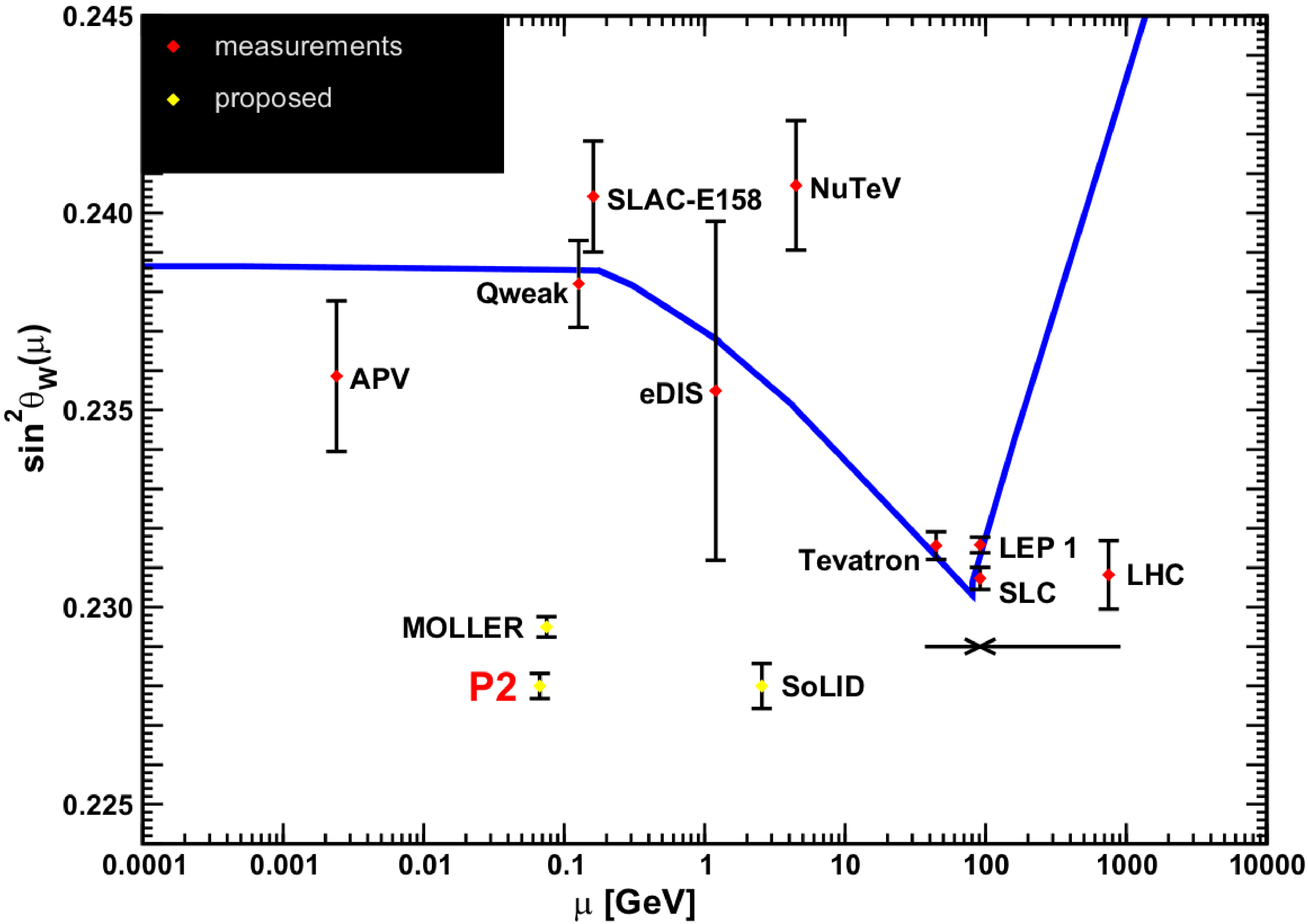
$$G_\mu = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W M_W^2}(1 + \Delta r)$$

with $\Delta r = \Delta r(\alpha, M_W, \sin\theta_W, m_{top}, M_{Higgs}, \ldots)$

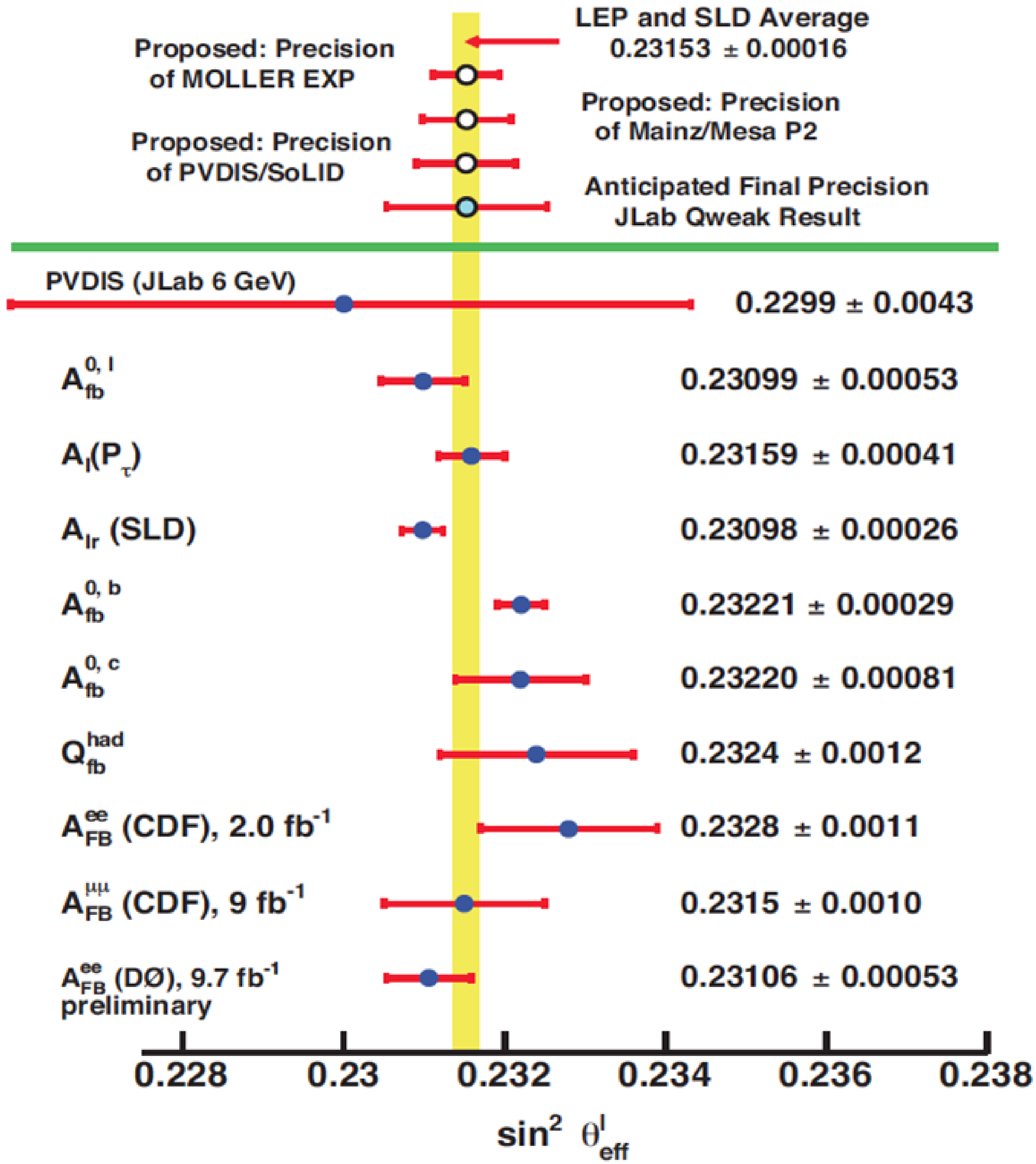
Absorb universal quantum corrections in an ***effective, running*** weak mixing angle:

$\sin^2\theta_W \rightarrow \sin^2\theta_{\text{eff}}$ or $\sin^2\theta_W(\mu)$ mit μ as energy scale

Scale dependency of $\sin^2\Theta_W$



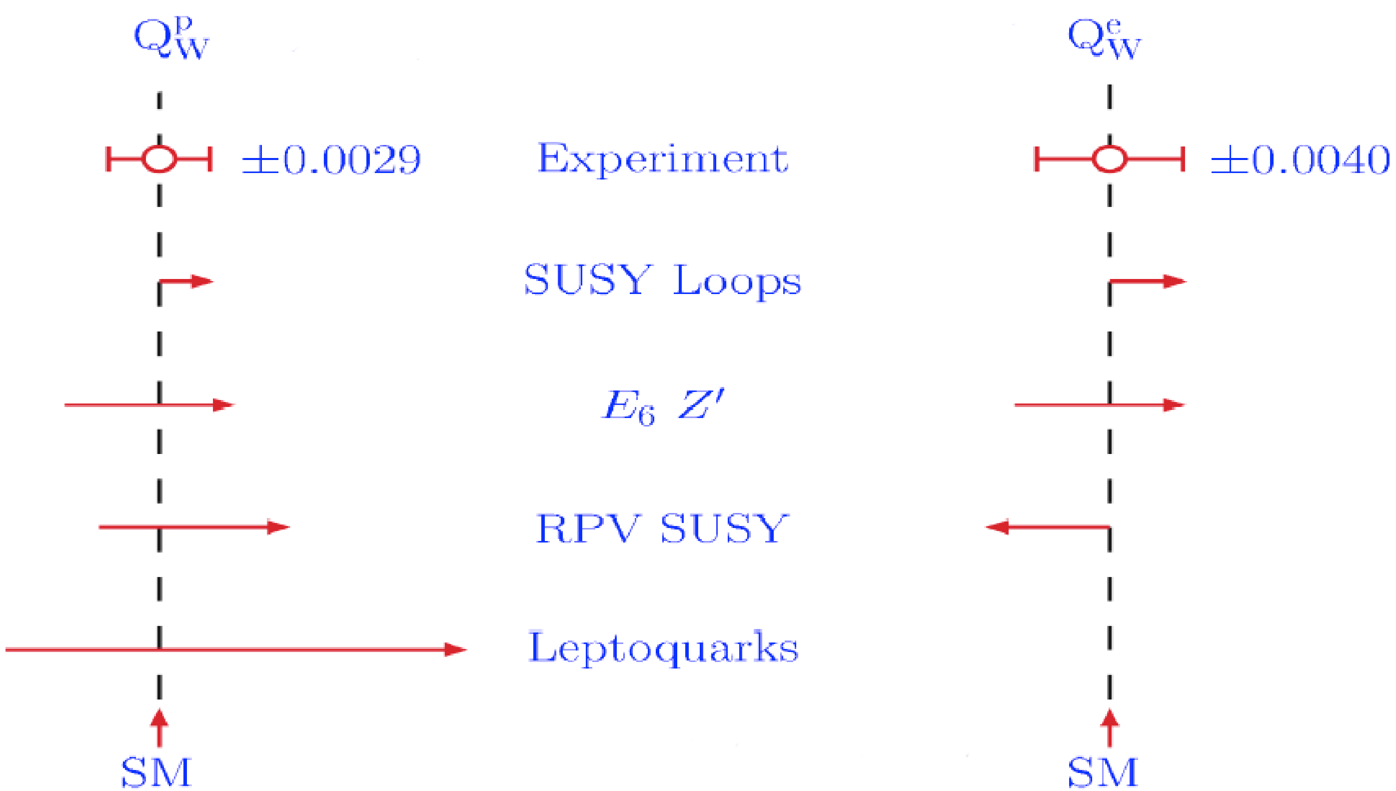
Measurements of $\sin^2\Theta_W$



Physics beyond the Standard Model

Weak charges of proton and electron (tree level):

Proton	$Q_W(p)$	=	$1-4\sin^2\Theta_W$
Electron	$Q_W(e)$	=	$-1+4\sin^2\Theta_W$

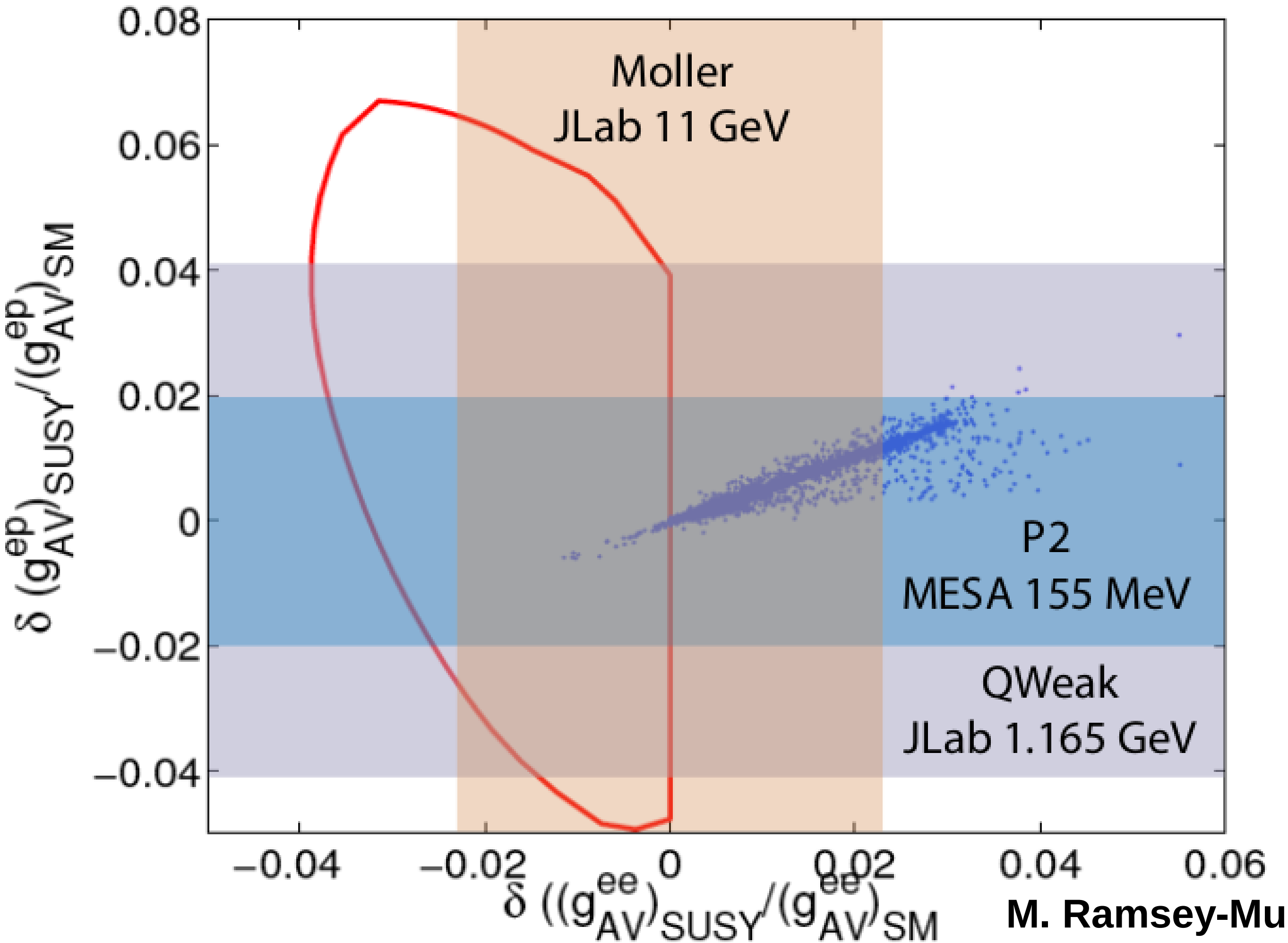


Standard Model extensions:

- Characteristic shifts in $Q_W(p)$ und $Q_W(p)$
- Measurements of $Q_W(p)$ and $Q_W(p)$ are complentary

Super Symmetric Models

Example: Super symmetric Standard Model extension (SuSy) with and without R-Parity violation

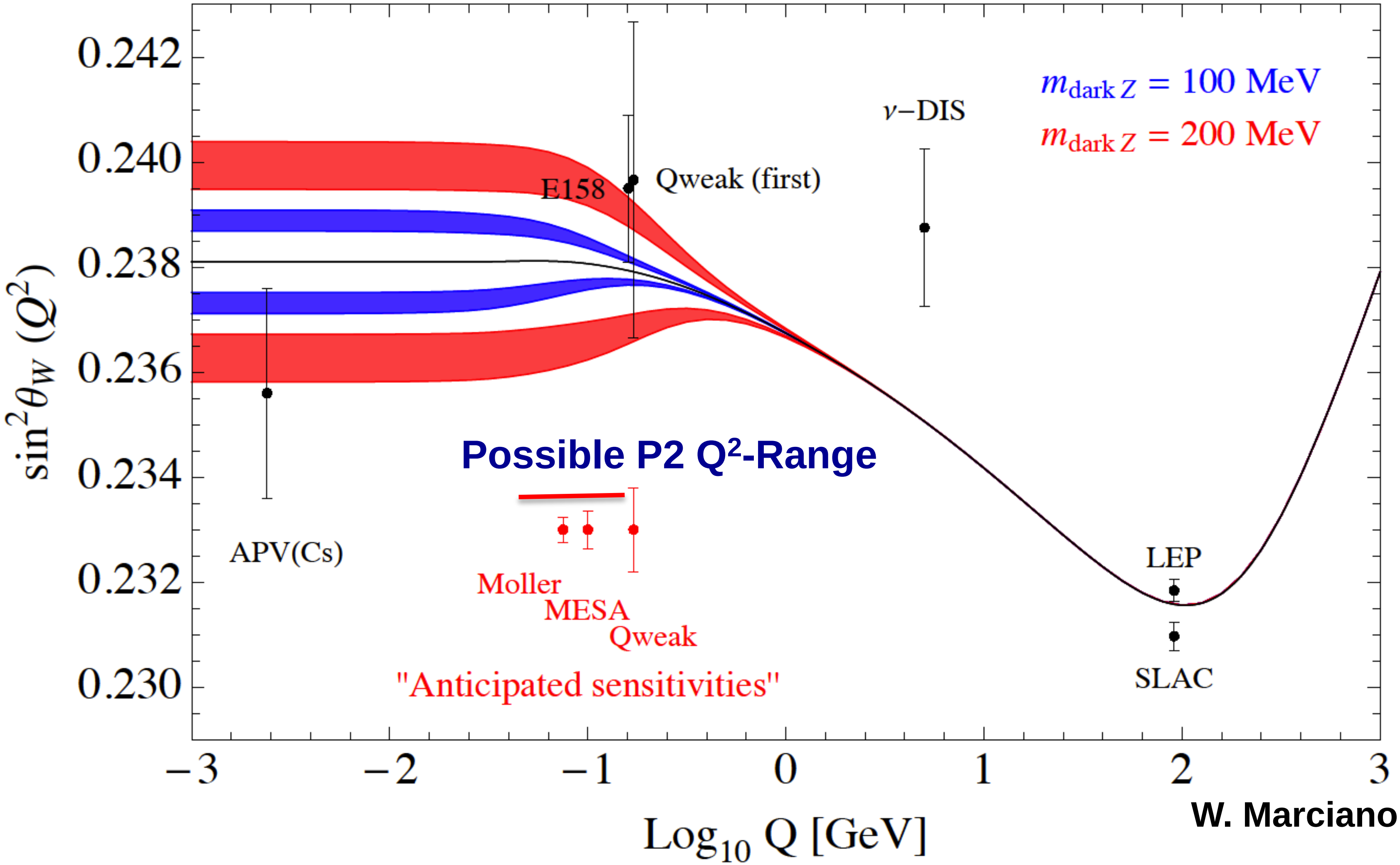


M. Ramsey-Musolf

Shifts in the weak charges of p und e-

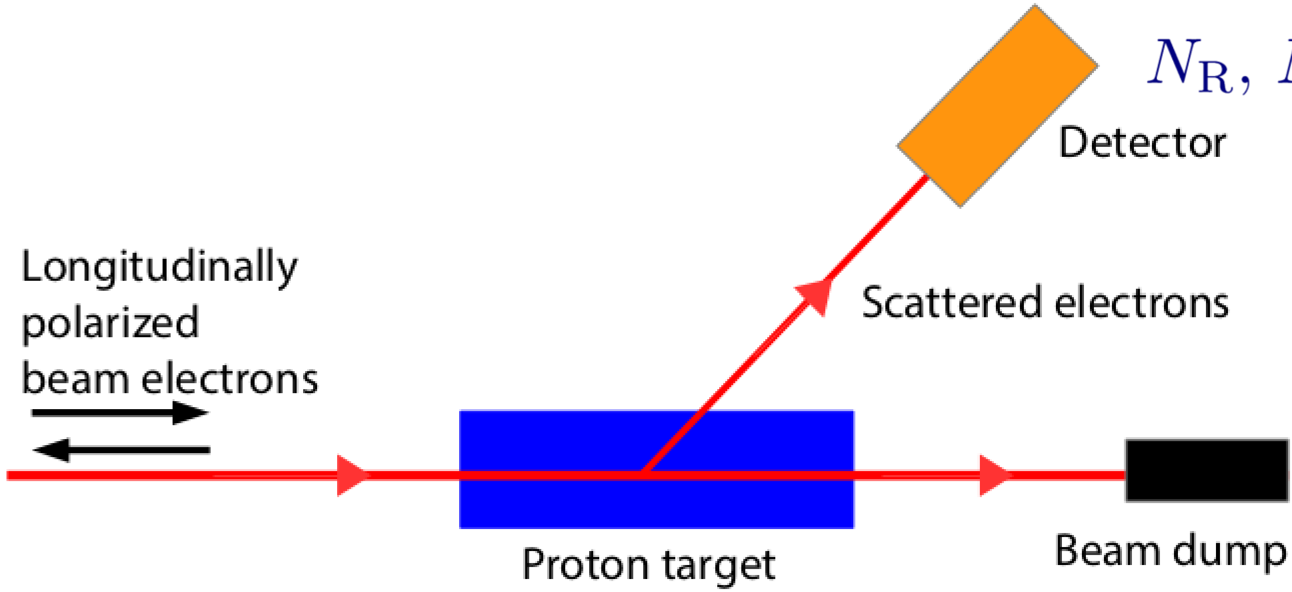
- Blue dots: Minimal super-symmetric models
- Red "Ellipse": Allowed range for R-parity violating super-symmetric models

Running of $\sin^2\theta_W$ and Dark Parity Violation



W. Marciano

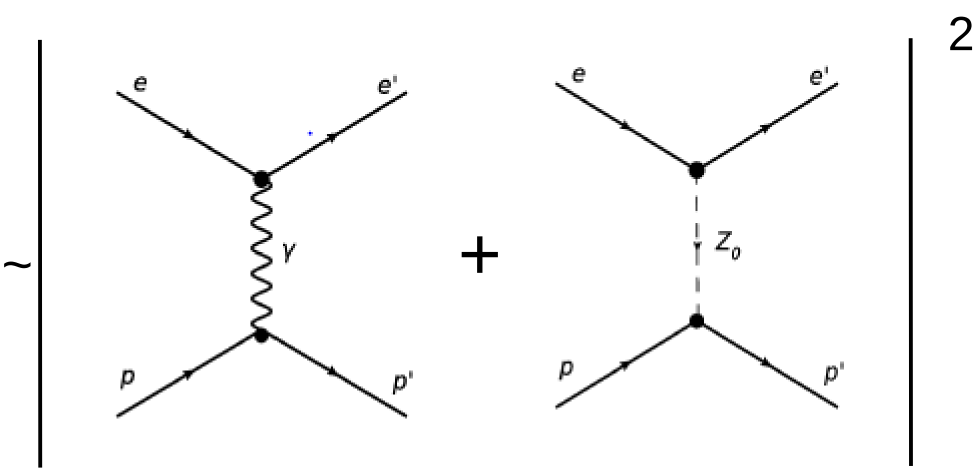
Parity violating electron scattering



$N_{\mathrm{R}},\ N_{\mathrm{L}}$

$$\Rightarrow A_{\mathrm{RL}} = \frac{N_{\mathrm{R}} - N_{\mathrm{L}}}{N_{\mathrm{R}} + N_{\mathrm{L}}}$$

Cross section: σ_{ep} ~



~ $|M_{\gamma} + M_Z|^2$

The weak interaction is **parity violating**: $M_Z^+ \neq M_Z^-$ ⟶ $|M_{\gamma} + M_Z^+|^2 \neq |M_{\gamma} + M_Z^-|^2$

⟶ $\boxed{\sigma_{ep}^+ \neq \sigma_{ep}^-}$

Parity violating electron scattering

Asymmetry in the cross section of elastic electron-proton scattering for left- and right-handed polarized electrons

$$A_{LR} = \frac{\sigma(e_\downarrow) - \sigma(e_\uparrow)}{\sigma(e_\downarrow) + \sigma(e_\uparrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(\mathcal{N}) - F(Q^2)\right)$$

The weak charge of the proton (tree level):

$$Q_W(p) = 1 - 4\sin^2\theta_W$$

$$\frac{\Delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{1 - 4\sin^2\theta_W}{4\sin^2\theta_W}\frac{\Delta Q_W(p)}{Q_W(p)}$$

1.5% precision in $Q_W(p)$ results in a precision of 0.13% in $\sin^2\Theta_W$

Precision Studies

The parity violating asymmetry can be written as

$$A^{\mathrm{PV}} = \frac{-G_{\mathrm{F}} Q^2}{4\pi\alpha_{\mathrm{em}}\sqrt{2}} \left[Q_{\mathrm{W}}(\mathrm{p}) - F(E_{\mathrm{i}}, Q^2)\right]$$

with the form factor contribution

$$F(E_{\mathrm{i}}, Q^2) \equiv F^{\mathrm{EM}}(E_{\mathrm{i}}, Q^2) + F^{\mathrm{A}}(E_{\mathrm{i}}, Q^2) + F^{\mathrm{S}}(E_{\mathrm{i}}, Q^2)$$

with

$$F^{\mathrm{EM}}(E_{\mathrm{i}}, Q^2) \equiv \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{n},\gamma} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{n},\gamma}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

$$F^{\mathrm{A}}(Q^2) \equiv \frac{\left(1 - 4\sin^2\theta_{\mathrm{W}}\right)\sqrt{1-\epsilon^2}\sqrt{\tau(1-\tau)}\, G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{A}}^{\mathrm{p},\mathrm{Z}}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

$$F^{\mathrm{S}}(E_{\mathrm{i}}, Q^2) \equiv \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{s}} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{s}}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2} + \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{u,d}} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{u,d}}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

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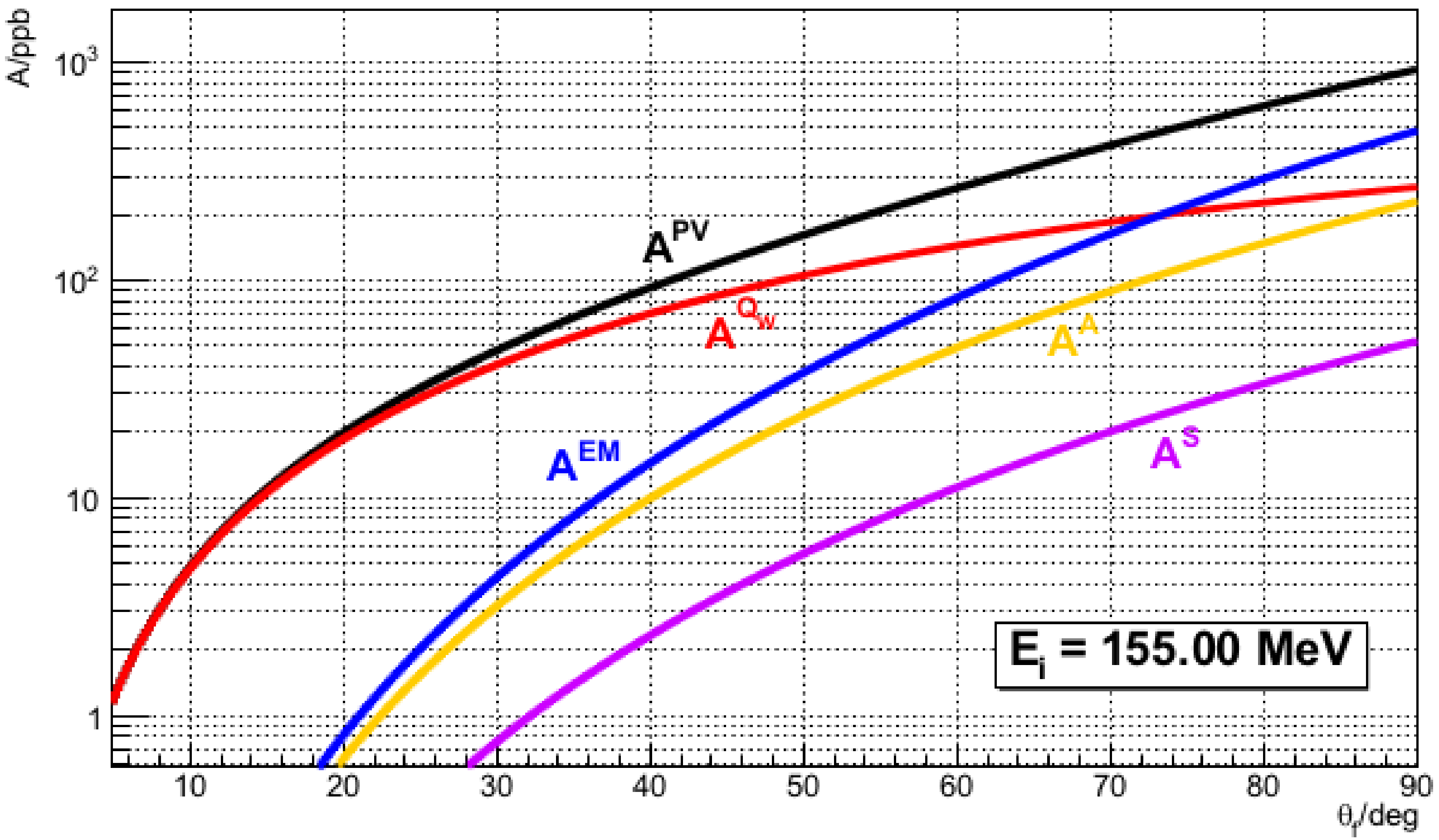
Asymmetry contributions for the MESA beam energy of 155 MeV



Precision Studies

The parity violating asymmetry can be written as

$$A^{\mathrm{PV}} = \frac{-G_{\mathrm{F}} Q^2}{4\pi\alpha_{\mathrm{em}}\sqrt{2}} \left[Q_{\mathrm{W}}(\mathrm{p}) - F(E_{\mathrm{i}}, Q^2) \right]$$

Prediction of the achievable precision:

- The measured asymmetry can be written as

$$\langle A^{\mathrm{raw}} \rangle_{\mathrm{sig}} = P \cdot \langle A^{\mathrm{PV}} \rangle_{\mathrm{sig}} + A^{\mathrm{false}}$$

- Solve this equation for $\sin^2\Theta_W$, denoted here as s^2_W

$$s^2_{\mathrm{W}} = s^2_{\mathrm{W}} \left(\langle A^{\mathrm{raw}} \rangle_{\mathrm{sig}},\ P,\ E_{\mathrm{beam}},\ \bar{\theta}_{\mathrm{f}},\ \delta\theta_{\mathrm{f}}, F(\{\kappa_k\}, Q^2), \Box_{\gamma \mathrm{Z}} \right)$$

- Perform error propagation calculation based on a Monte Carlo algorithm

Precision Studies

Input parameters for error propagation:

λ_l	$\langle\lambda_l\rangle$	$\Delta\lambda_l$
E_{beam}	variable	$0.13\,\mathrm{MeV}$
$\bar{\theta}_{\mathrm{f}}$	variable	$0°$
$\delta\theta_{\mathrm{f}}$	variable	$0.1°$
$\delta\phi_{\mathrm{f}}$	$360°$	$0°$
I_{beam}	$150\,\mu\mathrm{A}$	$0.001\,\mu\mathrm{A}$
P	0.85	0.00425
L	$600\,\mathrm{mm}$	$0\,\mathrm{mm}$
T	$1\times10^4\,\mathrm{h}$	$0\,\mathrm{h}$
A^{false}	0	$0.1\,\mathrm{ppb}$

Proton form factors of the proton from Bernauer et al.:

$$G_{\mathrm{E}}^{\mathrm{p},\gamma}(Q^2) = G_{\mathrm{dipole}}^{\mathrm{std}}(Q^2)\cdot G_{\mathrm{E}}^{\mathrm{poly}}(Q^2)$$

$$G_{\mathrm{M}}^{\mathrm{p},\gamma}(Q^2) = \mu_{\mathrm{P}}/\mu_{\mathrm{N}}\cdot G_{\mathrm{dipole}}^{\mathrm{std}}(Q^2)\cdot G_{\mathrm{M}}^{\mathrm{poly}}(Q^2)$$

$$G_{\mathrm{F}}^{\mathrm{poly}}(Q^2) = 1+\sum_{i=1}^{8}\left(\kappa_i^{\mathrm{p,\ F}}\cdot Q^{2i}\right)$$

$$G_{\mathrm{dipole}}^{\mathrm{std}}(Q^2) = \left(1+\frac{Q^2}{0.71\,\mathrm{GeV}^2}\right)^{-2}$$

Neutron form factors from M. El Yakoubi;

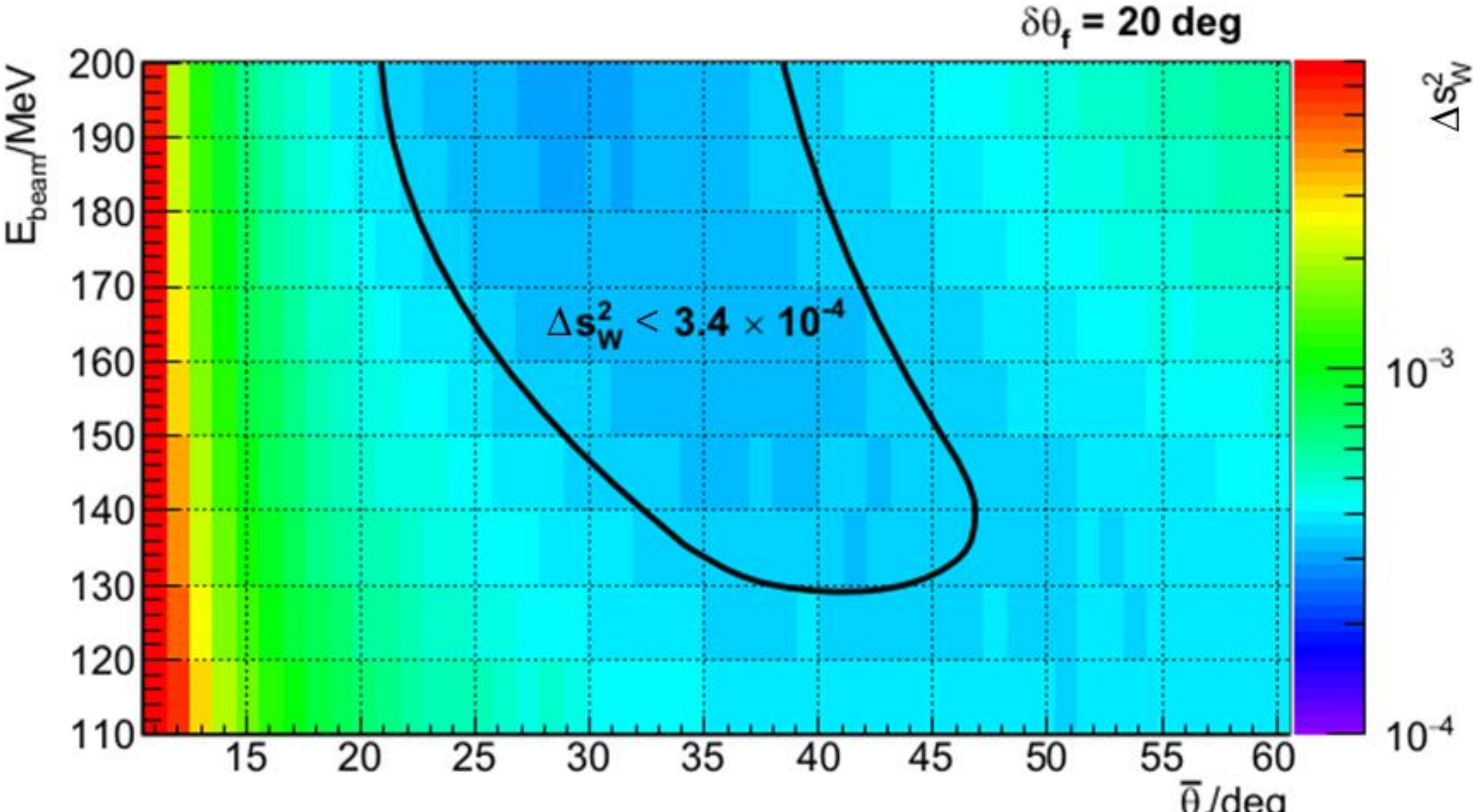
$$G_{\mathrm{E}}^{\mathrm{n},\gamma}(Q^2) = \frac{\tau\kappa_1^{\mathrm{n,E}}}{1+\tau\kappa_2^{\mathrm{n,E}}}\cdot G_{\mathrm{dipole}}^{\mathrm{std}}(Q^2)$$

$$G_{\mathrm{M}}^{\mathrm{n},\gamma}(Q^2) = \sum_{i=0}^{9}\kappa_i^{\mathrm{n,M}}Q^{2i}$$

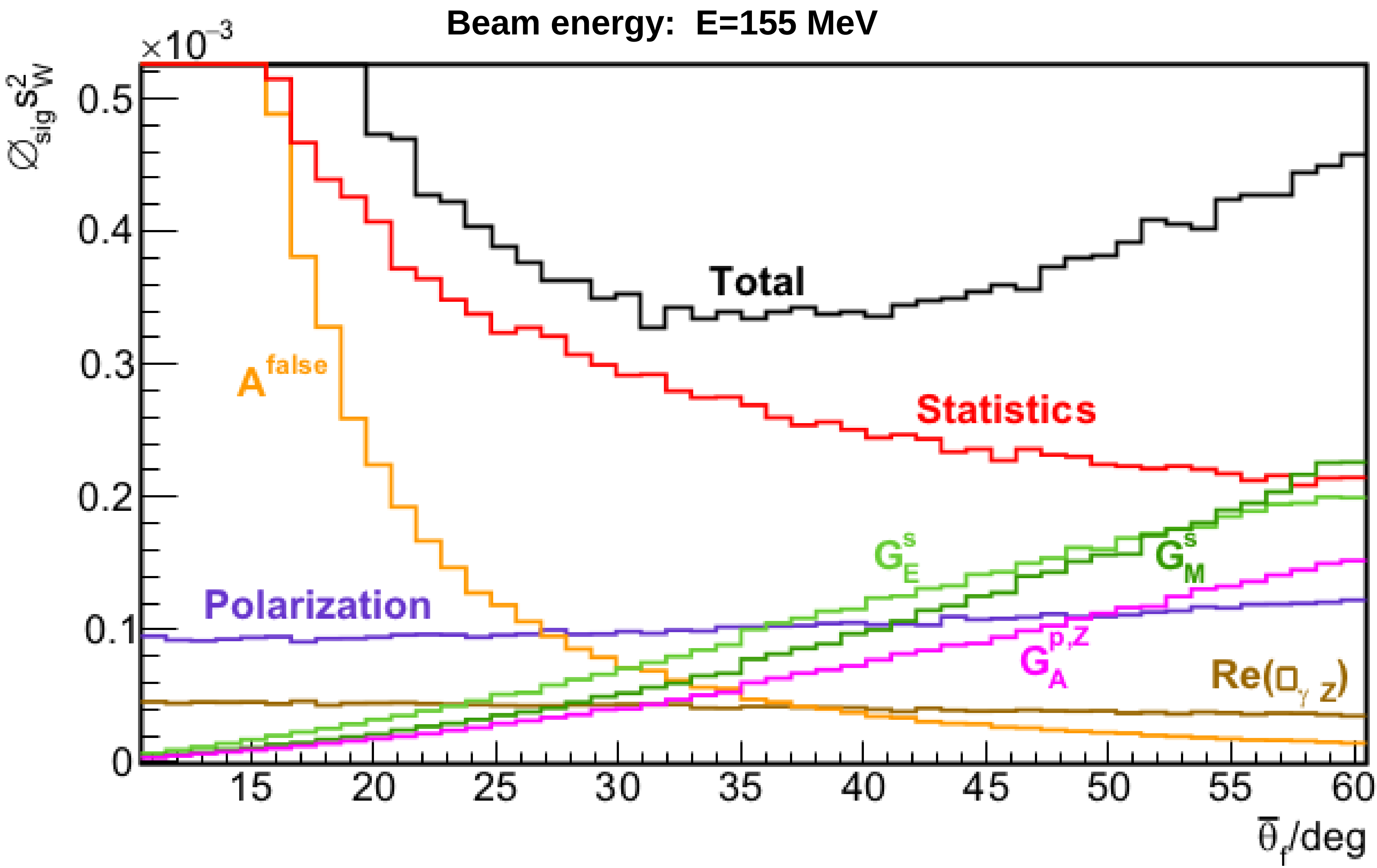
Strangeness and Isobreaking form factors...

Achievable precision in $\sin^2\Theta_W$

Find the optimal kinematics for the experiment:
Variation of the scattering angle and the beam energy



Achievable precision in $\sin^2\Theta_W$



Achievable precision in $\sin^2\Theta_W$

E_{beam}	$155\,\mathrm{MeV}$
$\bar{\theta}_{\mathrm{f}}$	35°
$\delta\theta_{\mathrm{f}}$	20°
s^2_{W}	$0.231\,16$
$\Delta_{\mathrm{exp}} s^2_{\mathrm{W}}$	3.7×10^{-4} $(0.16\,\%)$
$\Delta_{\mathrm{exp,\ stat}} s^2_{\mathrm{W}}$	3.1×10^{-4} $(0.13\,\%)$
$\Delta_{\mathrm{exp,\ P}} s^2_{\mathrm{W}}$	0.7×10^{-4} $(0.03\,\%)$
$\Delta_{\mathrm{exp,\ false}} s^2_{\mathrm{W}}$	0.6×10^{-4} $(0.03\,\%)$
$\Delta_{\mathrm{exp,\ t.w.}} s^2_{\mathrm{W}}$	1.2×10^{-4} $(0.05\,\%)$
$\Delta_{\mathrm{exp,\ t.p.}} s^2_{\mathrm{W}}$	0.1×10^{-4} $(0.00\,\%)$
$\Delta_{\mathrm{exp},\Box_{\gamma Z}} s^2_{\mathrm{W}}$	0.4×10^{-4} $(0.02\,\%)$
$\Delta_{\mathrm{exp,\ nucl.\ FF}} s^2_{\mathrm{W}}$	1.2×10^{-4} $(0.05\,\%)$

P2 Experiment conditions

Achievable precision in $\sin^2\Theta_W$

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s^2_{W}	0.231 16
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P2 Achievable precision

Achievable precision in $\sin^2\Theta_W$

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Achievable precision in sin²Θ$_W$

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Statistics: $\Delta_{\mathrm{exp,\ stat}} s_{\mathrm{W}}^2$	3.1×10^{-4} (0.13 %)
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$\Delta_{\mathrm{exp}, \Box_{\gamma Z}} s_{\mathrm{W}}^2$	0.4×10^{-4} (0.02 %)
Form factors: $\Delta_{\mathrm{exp,\ nucl.\ FF}} s_{\mathrm{W}}^2$	1.2×10^{-4} (0.05 %)

Achievable precision in $\sin^2\Theta_W$

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Achievable precision in sin²Θ$_W$

	E_{beam}	155 MeV
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False Asymmetries	$\Delta_{\text{exp, false}} s_{\text{W}}^2$	0.6×10^{-4} (0.03 %)
Target windows	$\Delta_{\text{exp, t.w.}} s_{\text{W}}^2$	1.2×10^{-4} (0.05 %)
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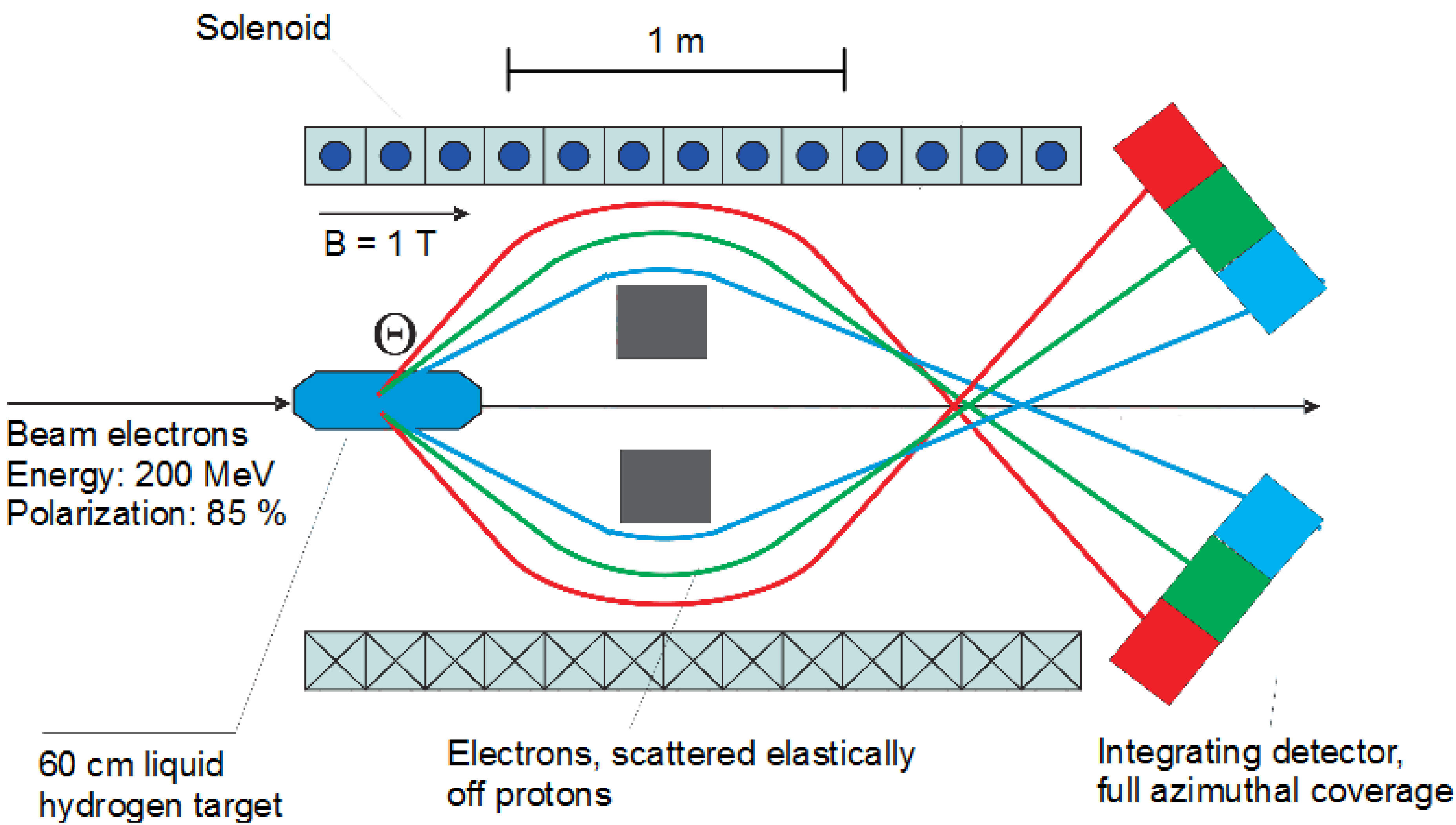
Form factors	$\Delta_{\text{exp, nucl. FF}} s_{\text{W}}^2$	1.2×10^{-4} (0.05 %)

Spectrometer design

Principle:

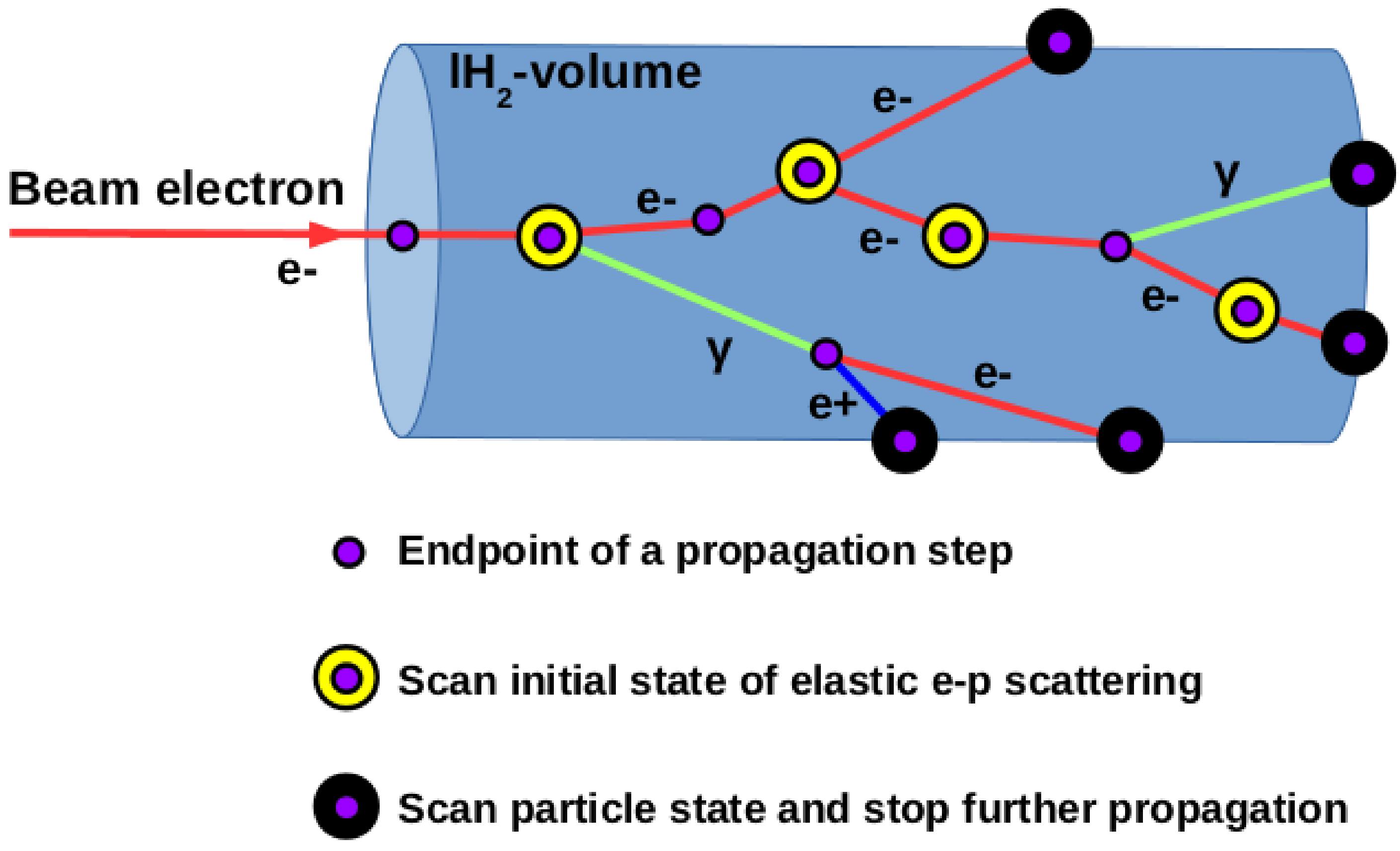
- Detect elastically scattered electrons
- Reject background events



Monte Carlo Studies

Full GEANT4 simulation with CAD Interface

First step: Generate ensemble of initial states in the target

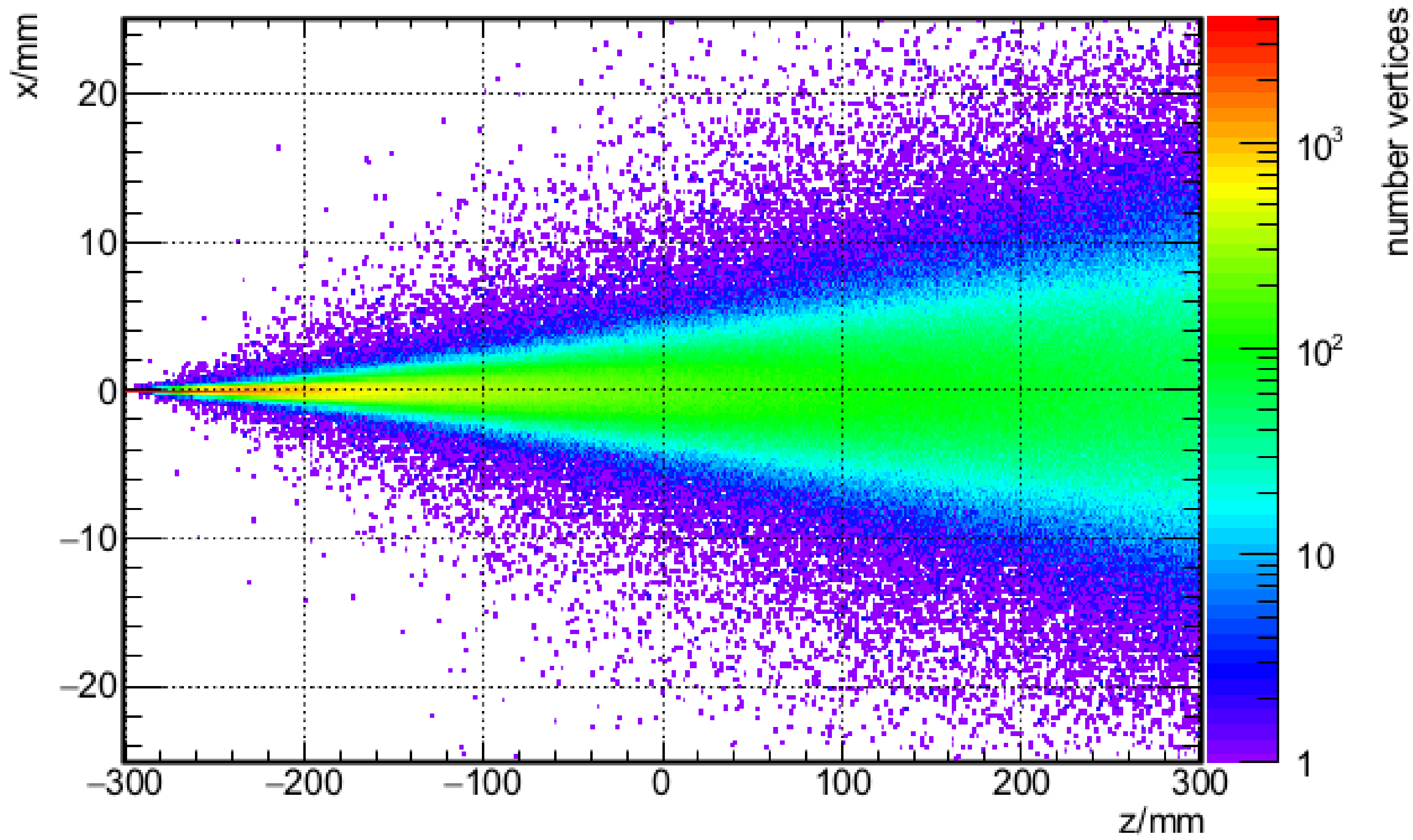


Monte Carlo Studies

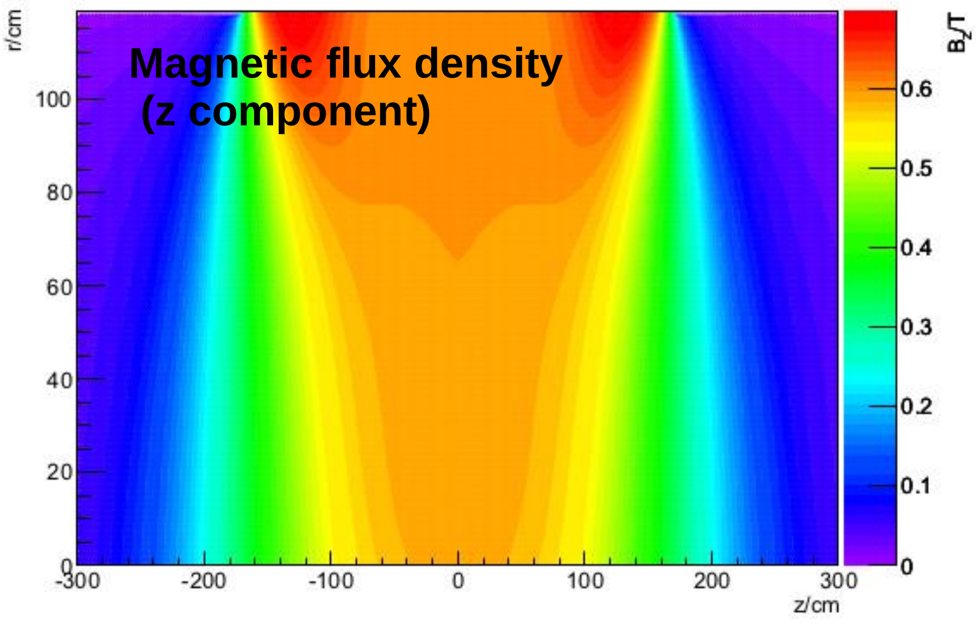
Full GEANT4 simulation with CAD Interface

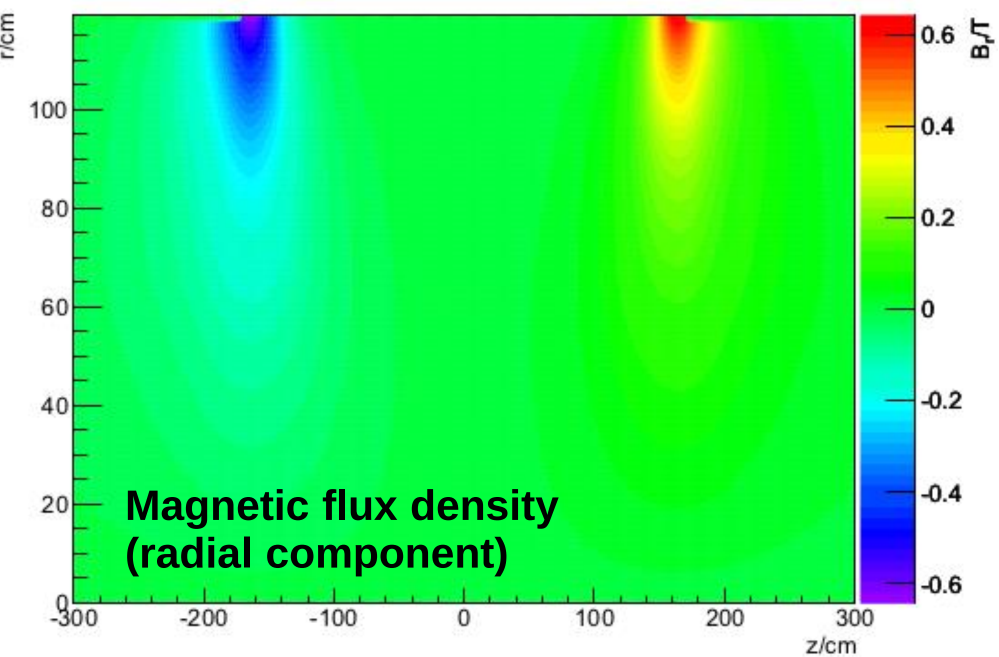
First step: Generate ensemble of initial states in the target

Spatial distribution of sampled vertices for ep scattering in the target

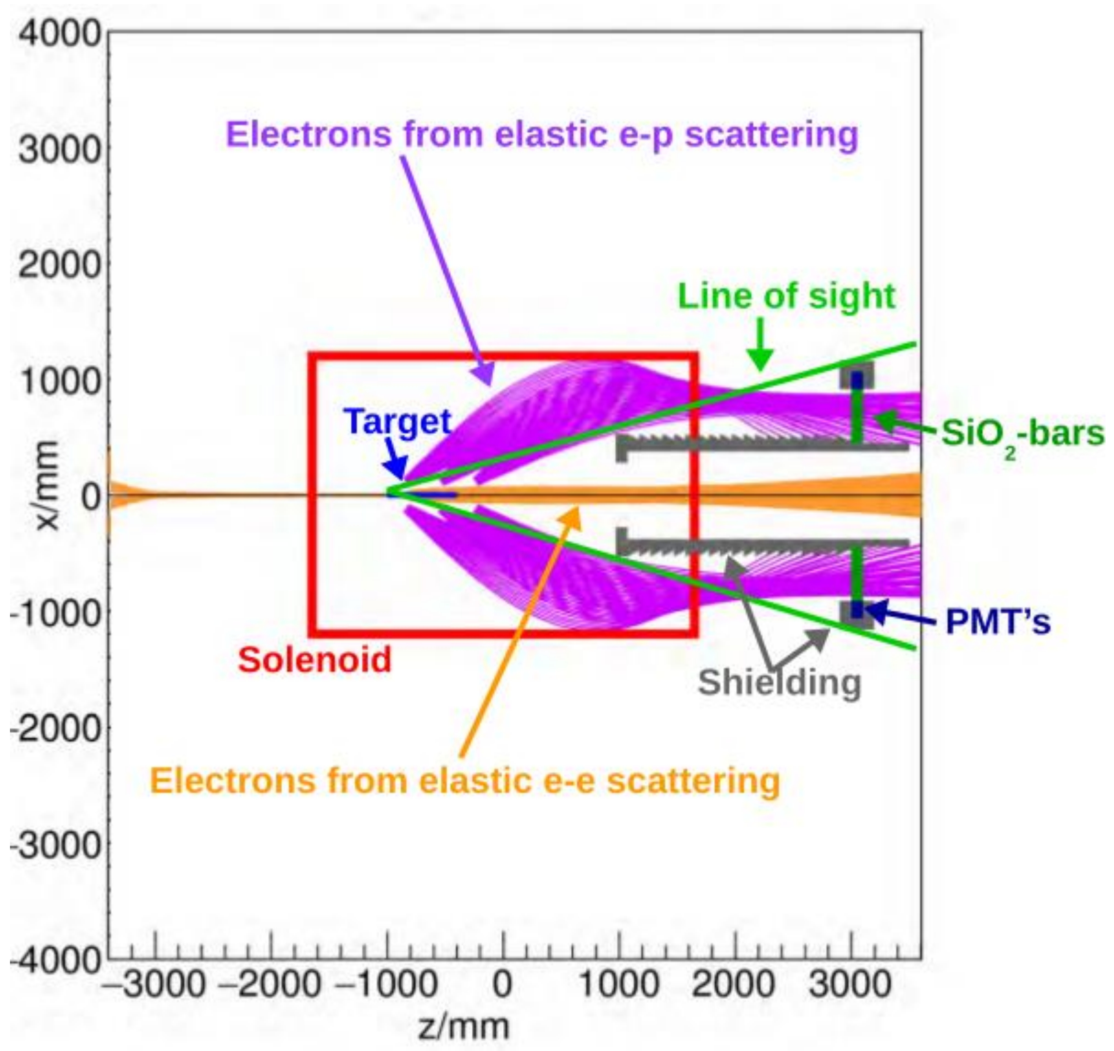


Monte Carlo Studies





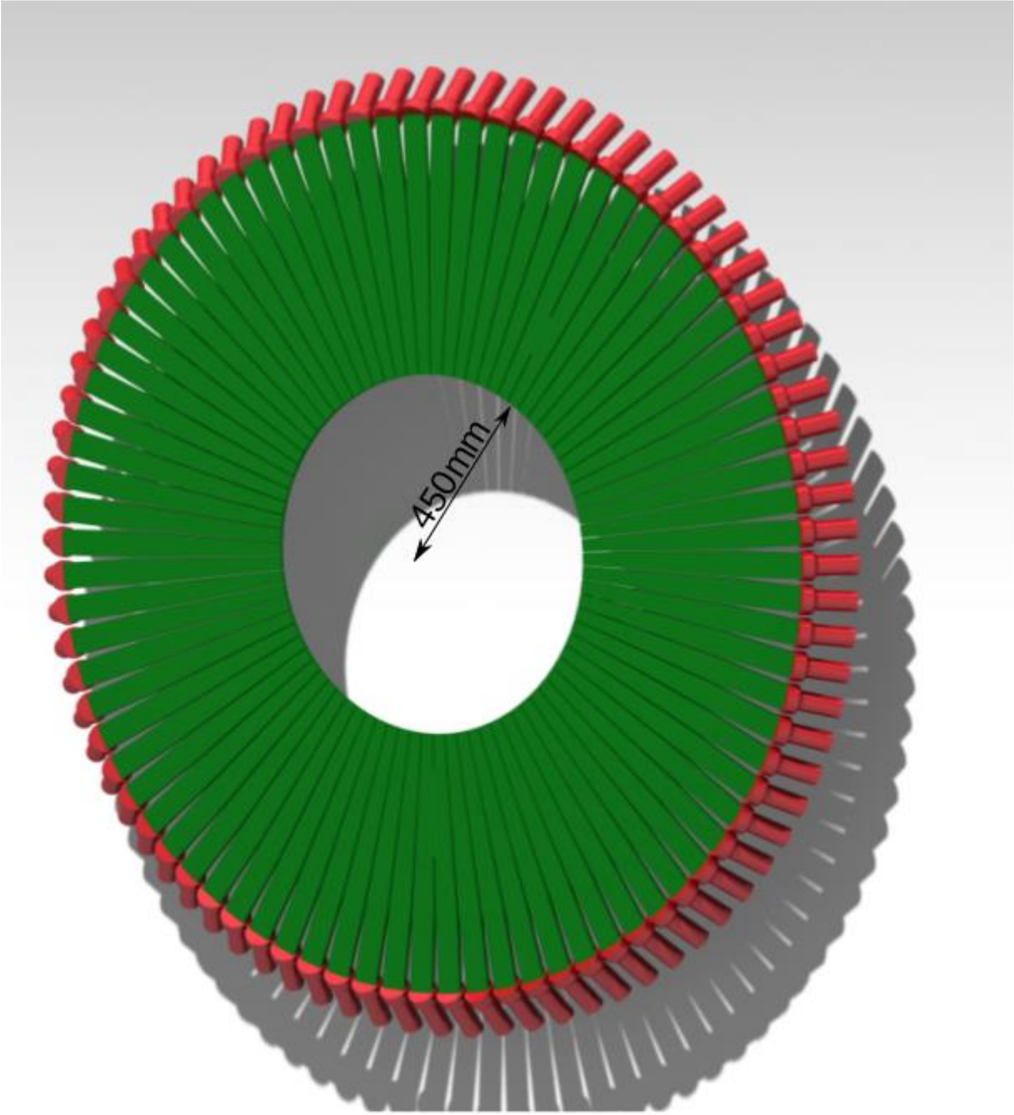
Second step: Particle tracking through the magnetic field



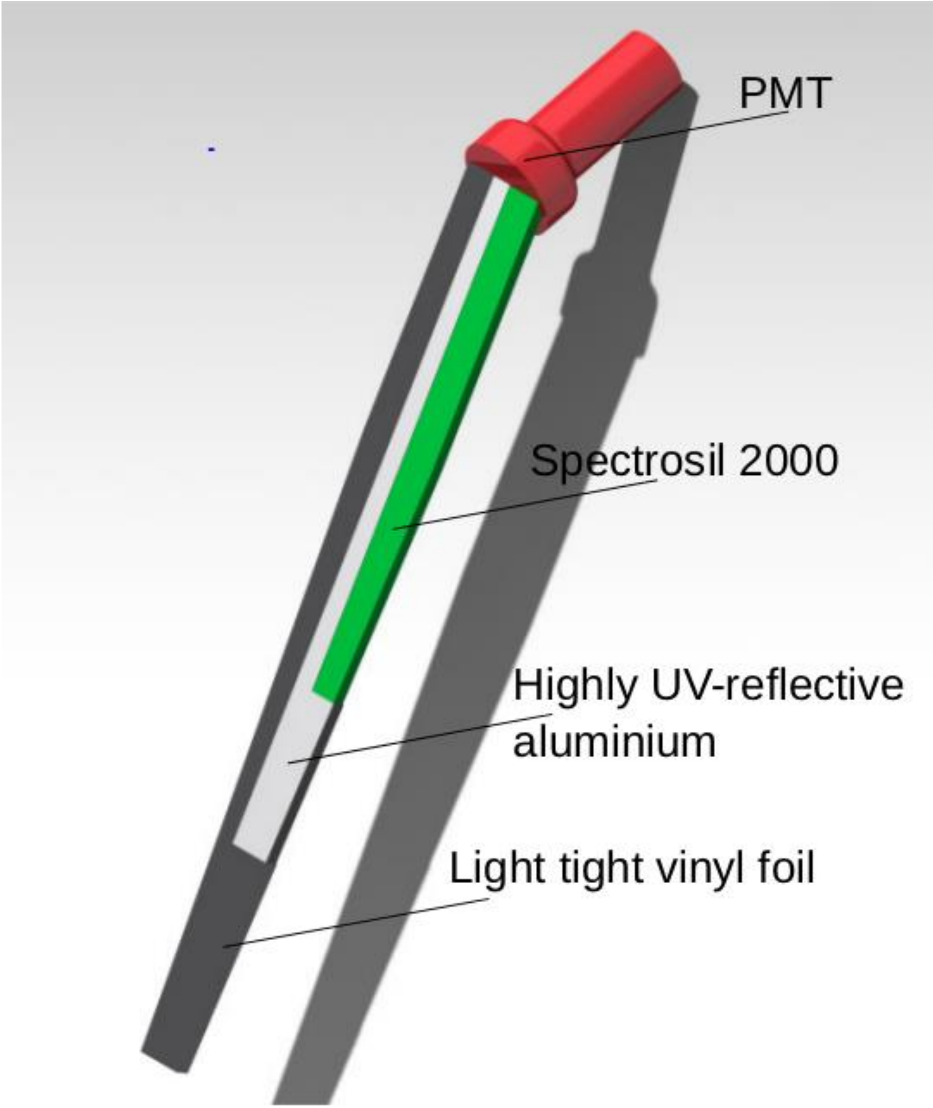
Detector development

Cover the whole azimuth with a radiation hard, fast detector

Ring detector consisting of 82 fused silica bars

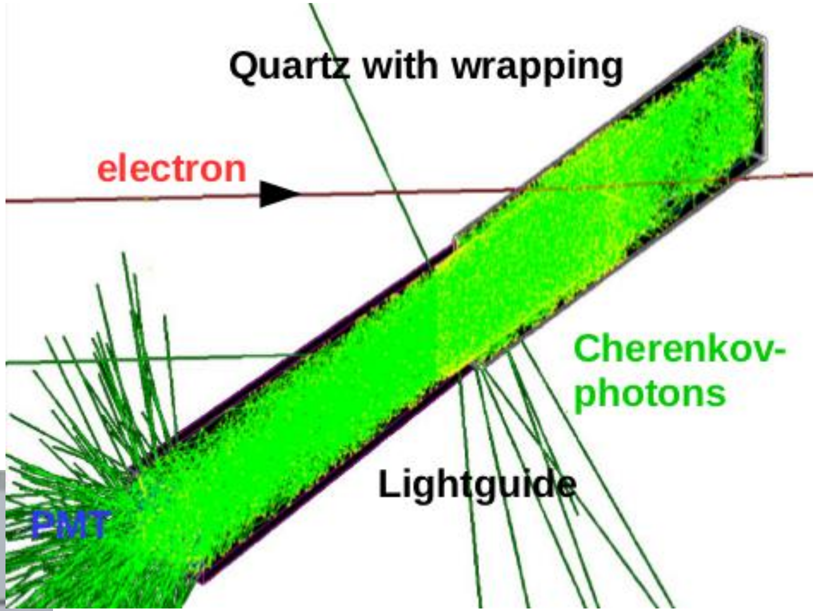


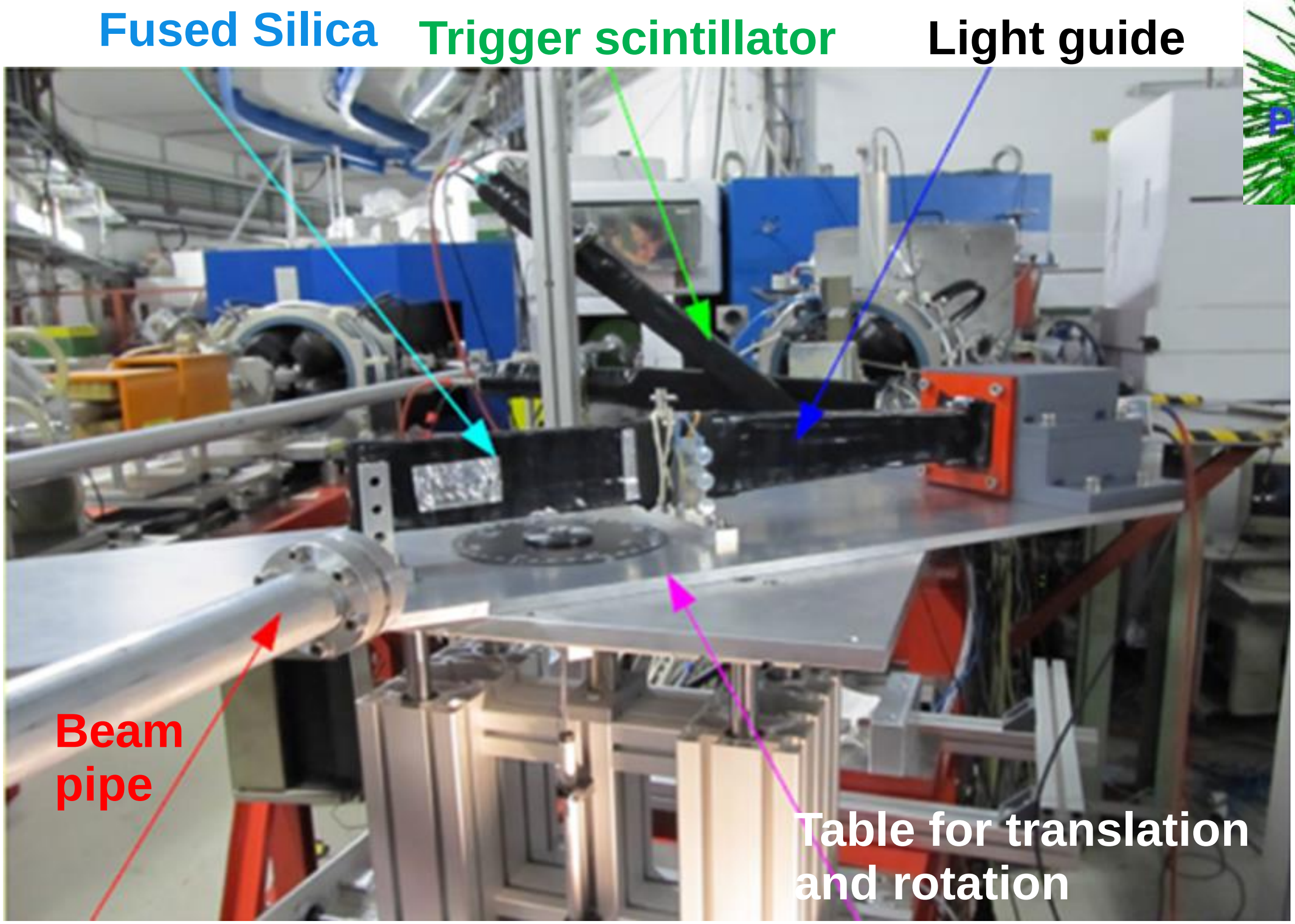
Single detector element



Monte Carlo Studies

- MC Simulations for generation of Cherenkov light within the fused silica bars and the propagation of the photons in the material

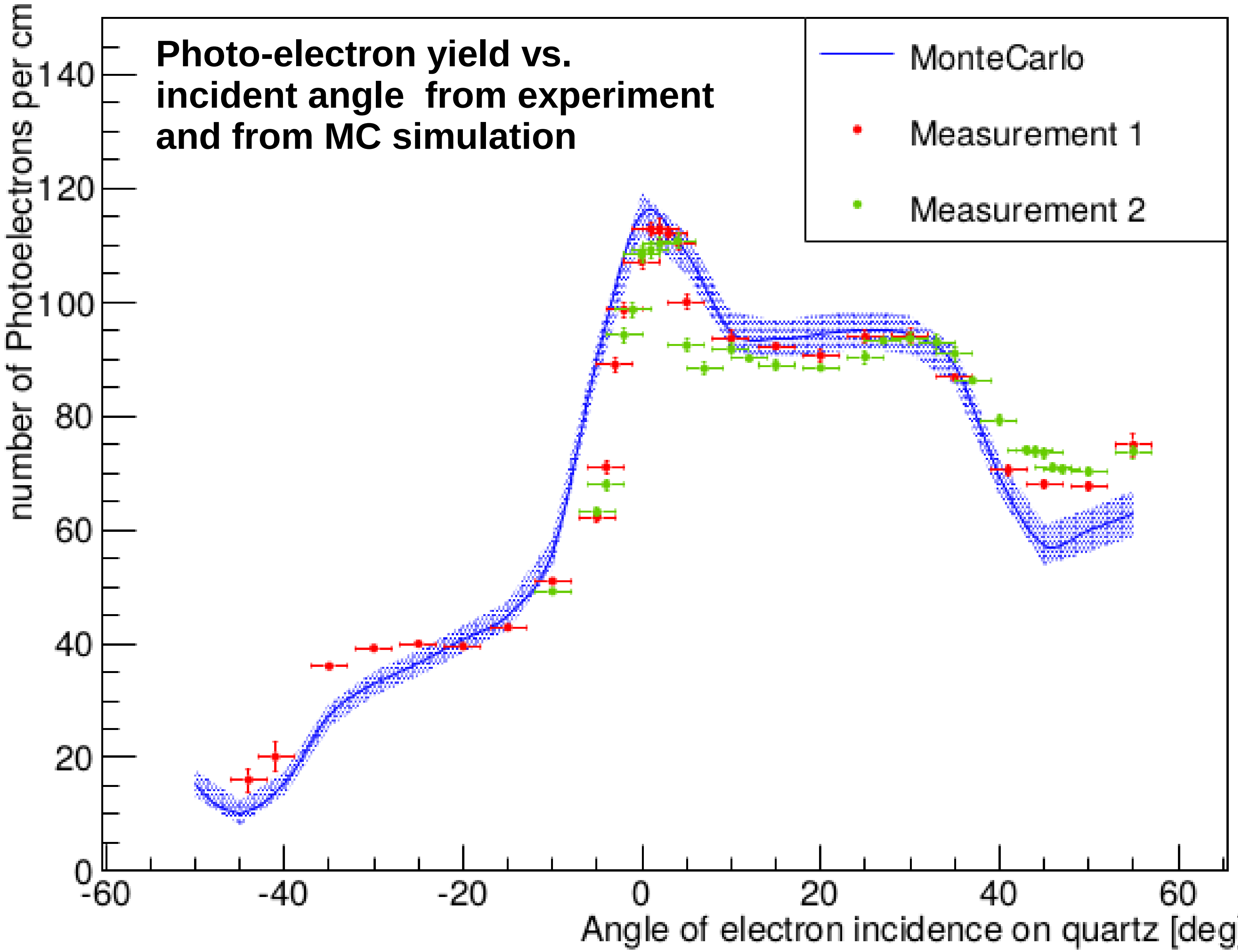




- Beamtests at MAMI
  - electrons
  - photons

Benchmark Simulations with Measurments

Cherenkov detectors: Comparison experiment with MC simulation



Result of Monte Carlo Studies

Predicted photo currents at the photocathodes from particles hitting the detector

Particle type	Photo current/μA
Elastic ep scattering:	
Primary electrons, $\theta_f \in [25^\circ, 45^\circ]$	8.20×10^{-1} (56.55 %)
Primary electrons, $\theta_f \notin [25^\circ, 45^\circ]$	4.98×10^{-1} (34.34 %)
Secondary electrons	4.92×10^{-2} (3.39 %)
Secondary photons	2.61×10^{-2} (1.80 %)
Secondary positrons	9.88×10^{-3} (0.68 %)
Background processes:	
Electrons	4.07×10^{-2} (2.81 %)
Photons	5.57×10^{-3} (0.38 %)
Positrons	1.28×10^{-3} (0.09 %)
Total	1.45

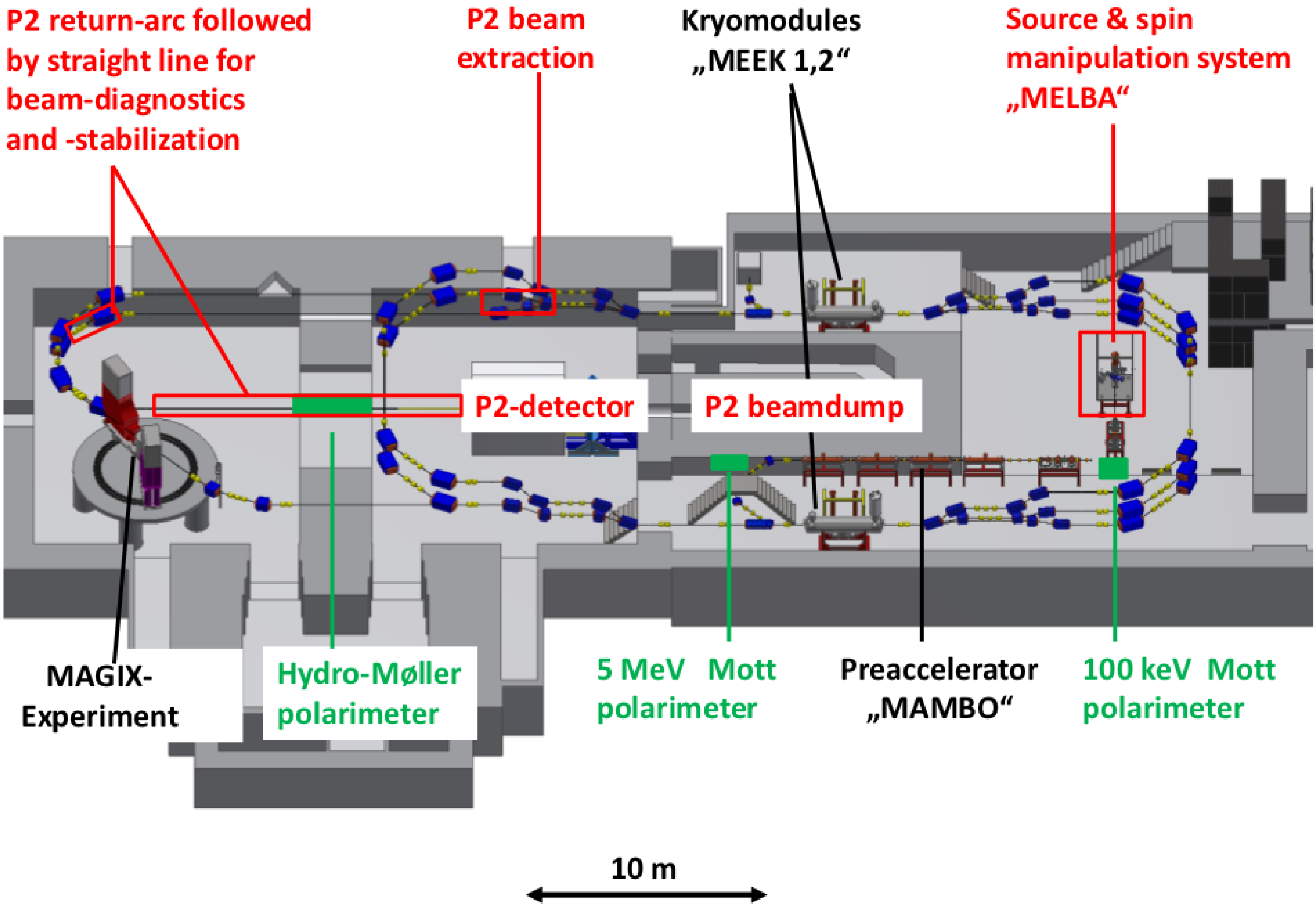
$$\langle Q^2 \rangle_{\text{exp}} = 4.82 \times 10^{-3}\,(\text{GeV/c})^2$$

$$\langle A^{\text{raw}} \rangle_{\text{exp}} = -24.03\,\text{ppb}$$

$$\Delta_{\text{tot}} \langle A^{\text{raw}} \rangle_{\text{exp}} = 0.58\,\text{ppb}$$

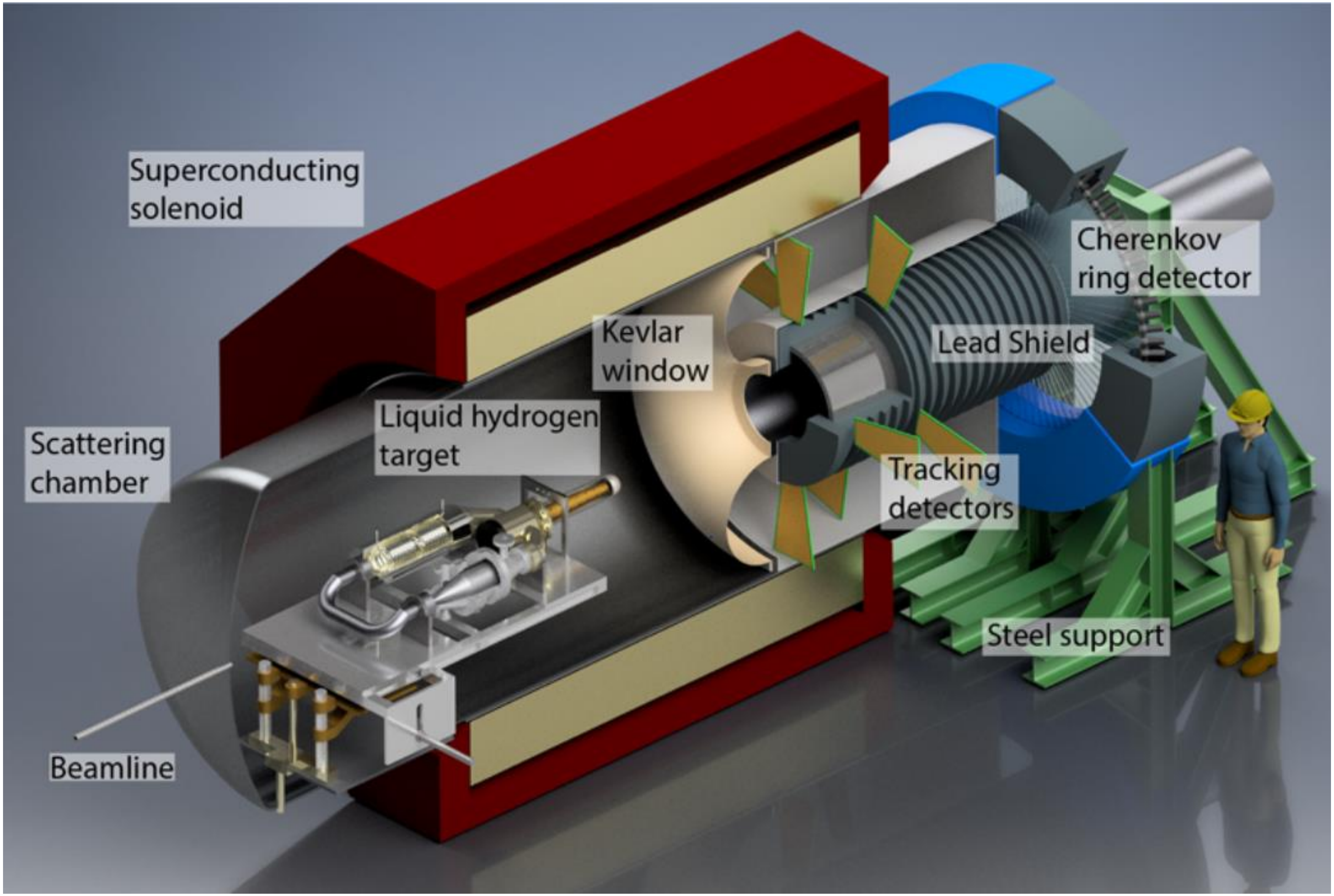
P2 experiment: Installation at a new accelerator facility

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



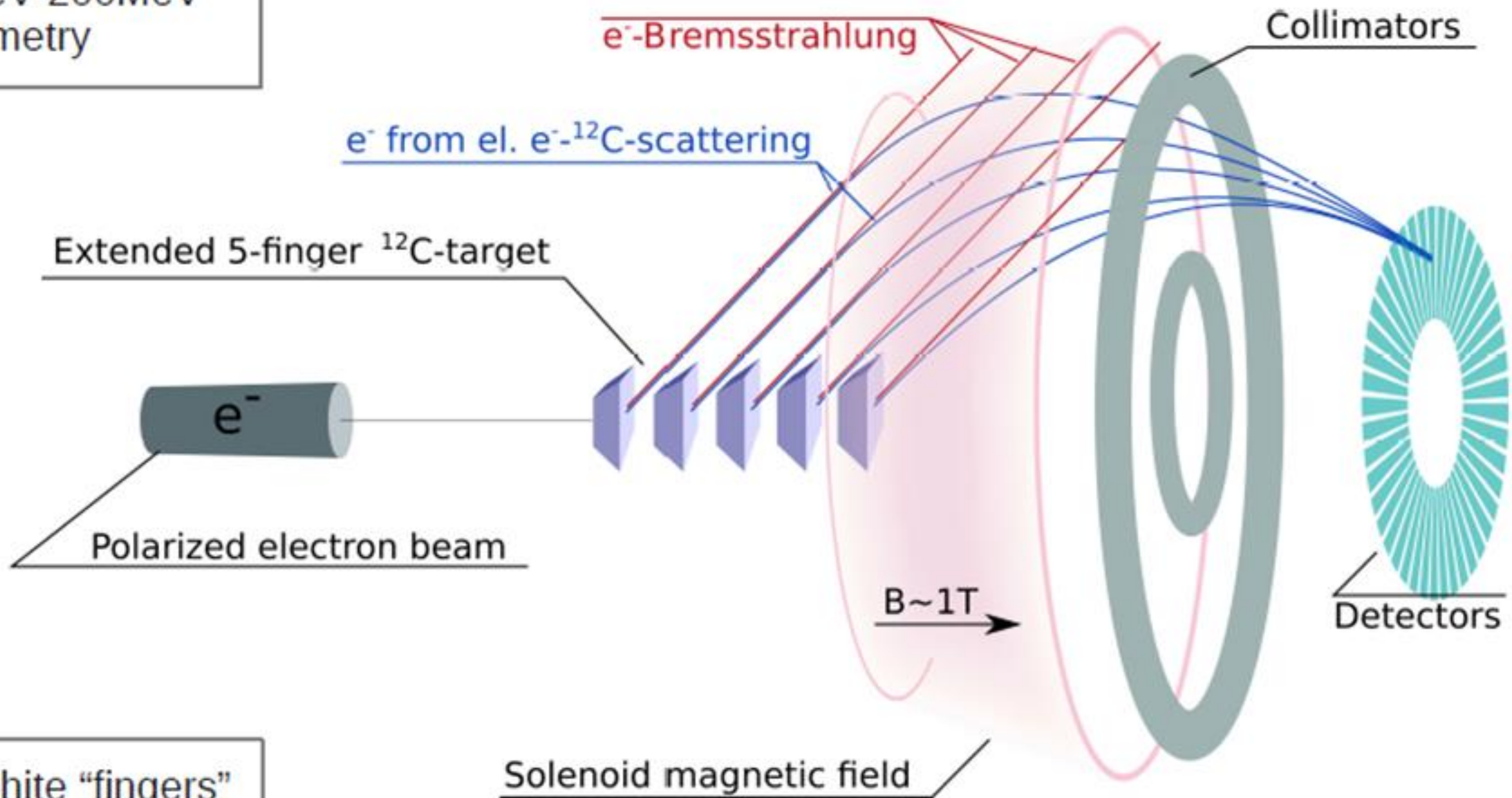
Spectrometer design

Current CAD design of the P2 apparatus



Further physics program: Measurement with ^{12}C

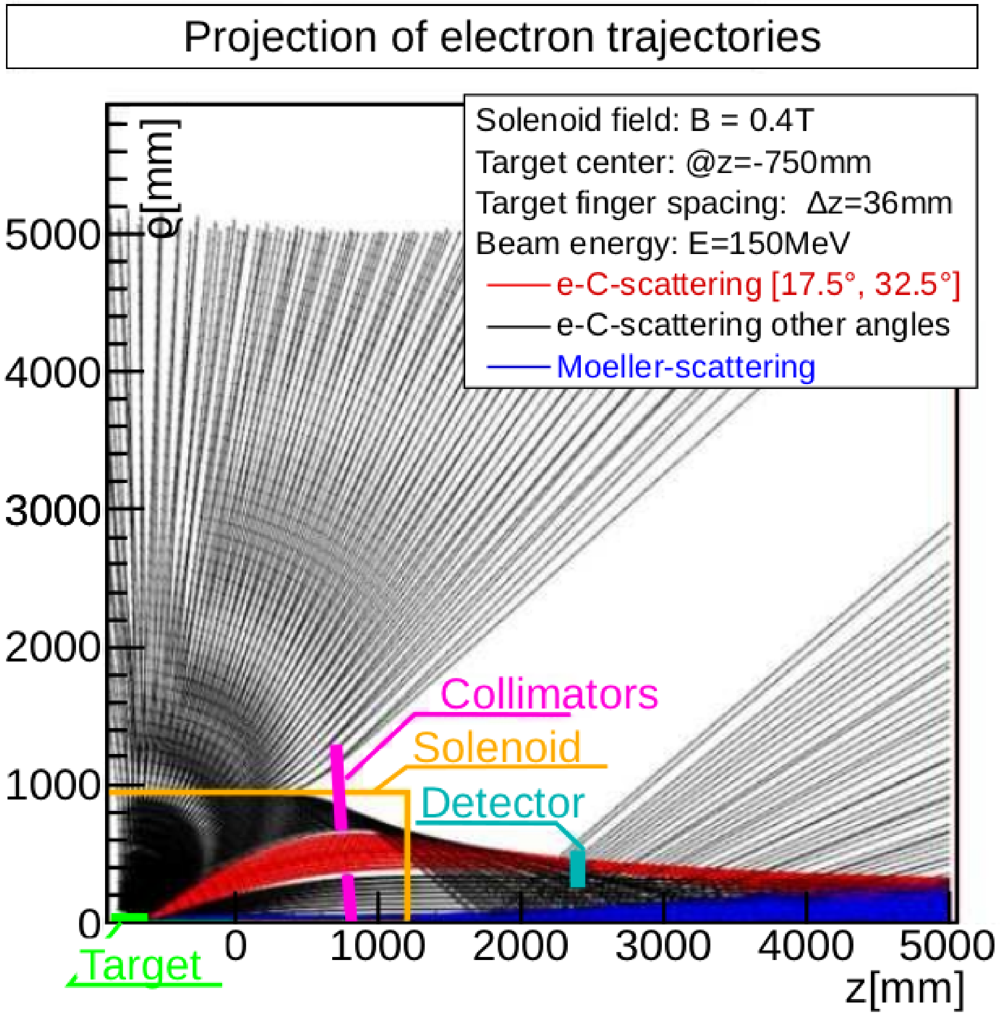
MESA:
- 150µA
- 150MeV-200MeV
- Polarimetry

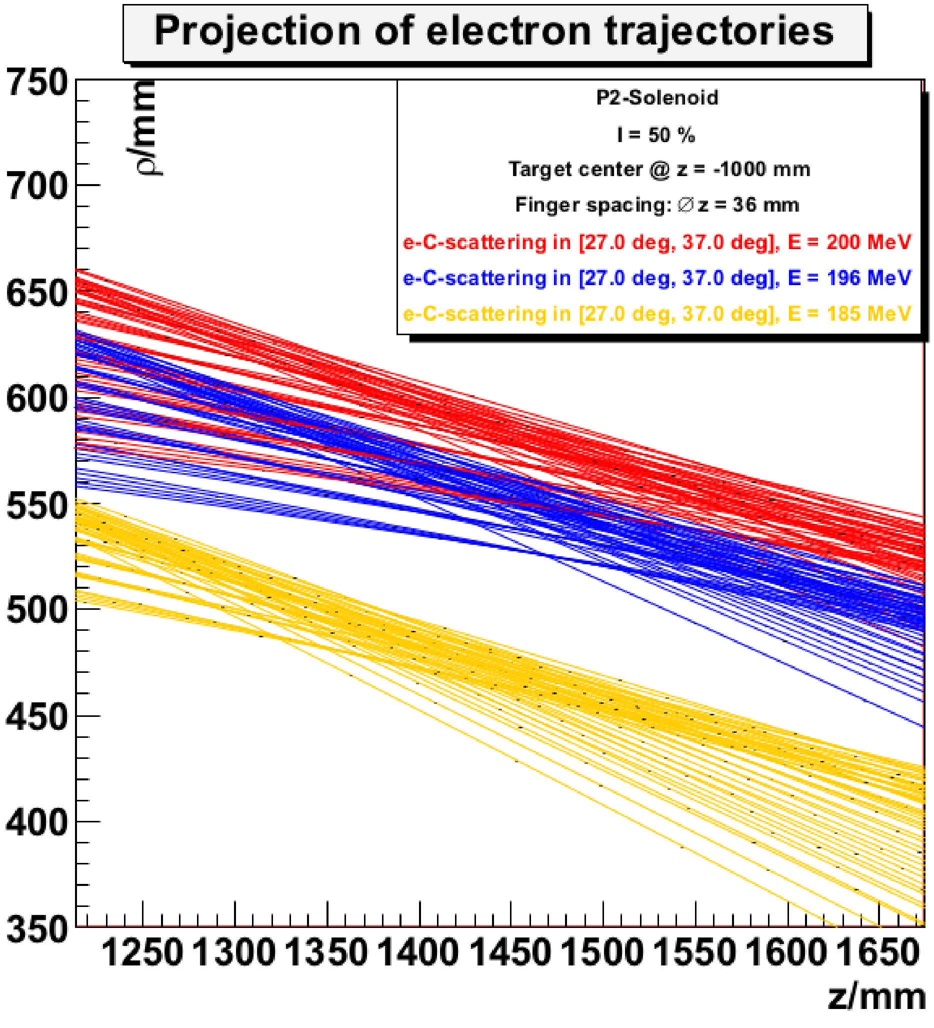


Target:
- 5 graphite “fingers”
- 5 g/cm² total
- 36mm spacing

Further physics program: Measurement with ^{12}C

Raytracing study for the P2 solenoid:

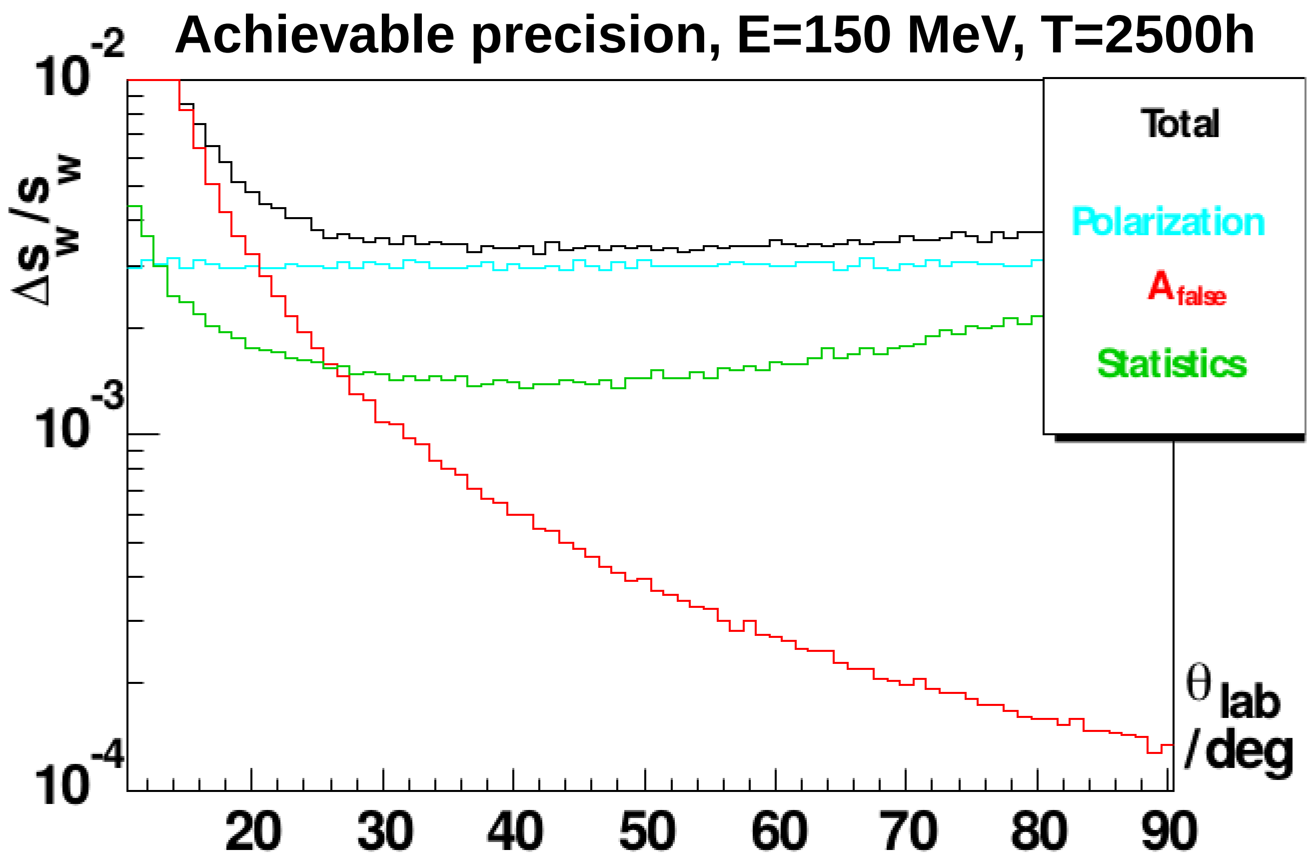




Further physics program: Measurement with ^{12}C

Weak charge of the ^{12}C nucleus: $Q_W(^{12}C) = -24 \sin^2 \theta_W$

Precision in the Weak Mixing Angle is dominated by Polarization uncertainty



Further physics program: Measurement with ^{12}C

- Complimentary sensitivity to certain classes of new physics models

- Weak charged of different targets expressed with the Peskin-Takeuchi parameters:

$$Q_{\rm W}(^{12}{\rm C}) = -5.510[1 - 0.003T + 0.016S - 0.033X - \chi],$$

$$Q_{\rm W}({\rm p}) = +0.0707[1 + 0.15T - 0.21S + 0.43X + 4.3\chi],$$

$$Q_{\rm W}({\rm e}) = -0.0435[1 + 0.25T - 0.34S + 0.7X + 7\chi],$$

$$Q_{\rm W}(^{133}{\rm Cs}) = -73.24[1 + 0.011S - 0.023X - 0.9\chi]$$

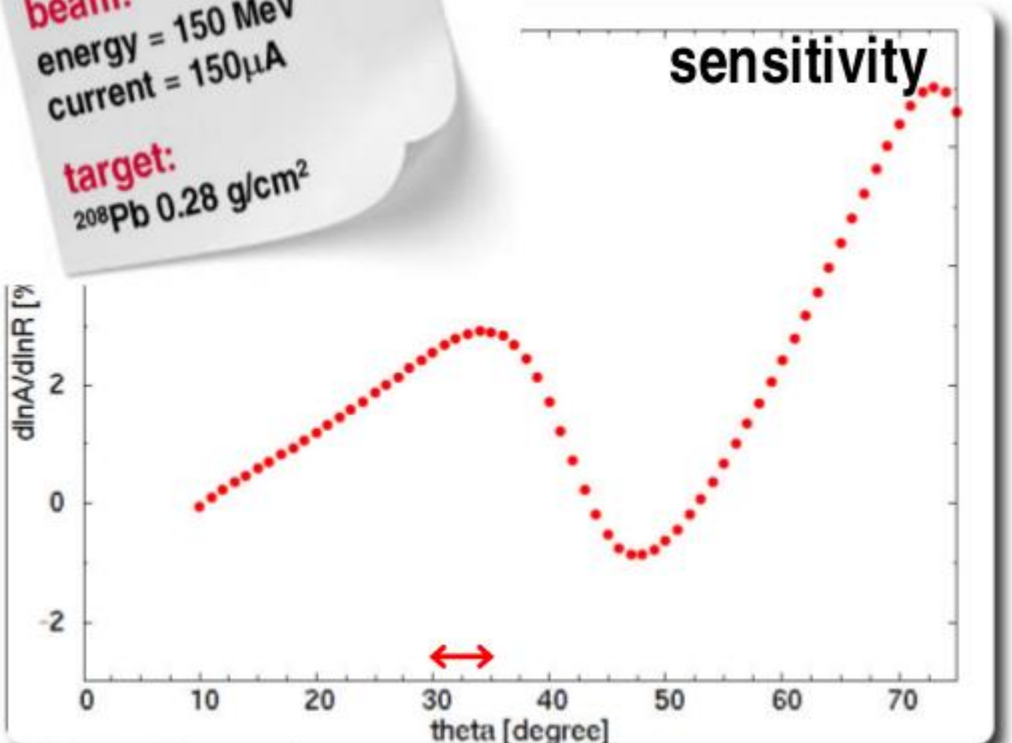
Further physics program: Neutron skin

MREX

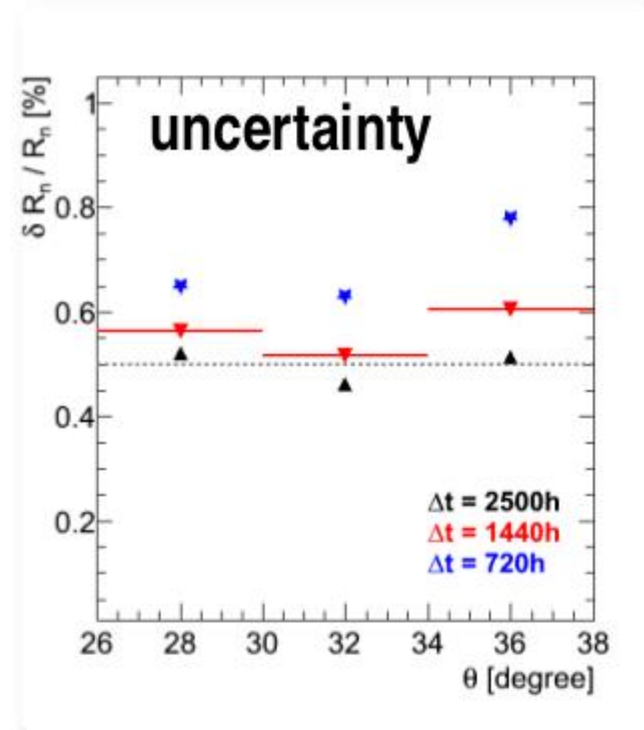
General condition:

beam:
energy = 150 MeV
current = 150μA

target:
^{208}Pb 0.28 g/cm²



Chuck Horowitz



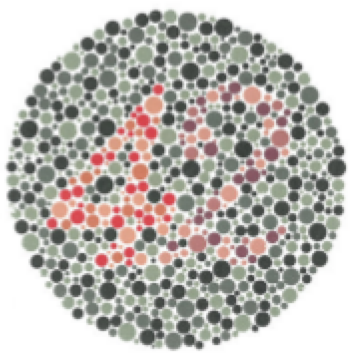
$\Delta\theta = 4°$: expected rate = 8.25 GHz, A_{PV} = 0.66 ppm, P = 85%, Q ≈ 86 MeV

1440h → $\delta R_n/R_n$ = 0.52% (^{208}Pb @ 155 MeV)

Further physics program: Neutron skin

ray trace simulation

MREX



resolve elastic?

ΔE (^{208}Pb) = 2.7 MeV

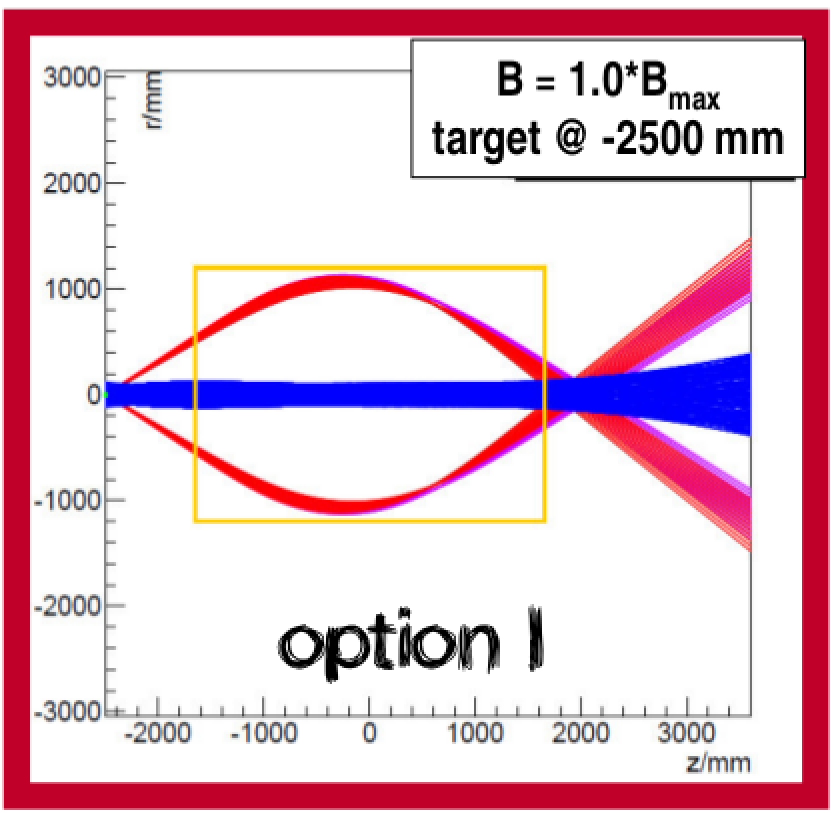
vary magnetic field strength

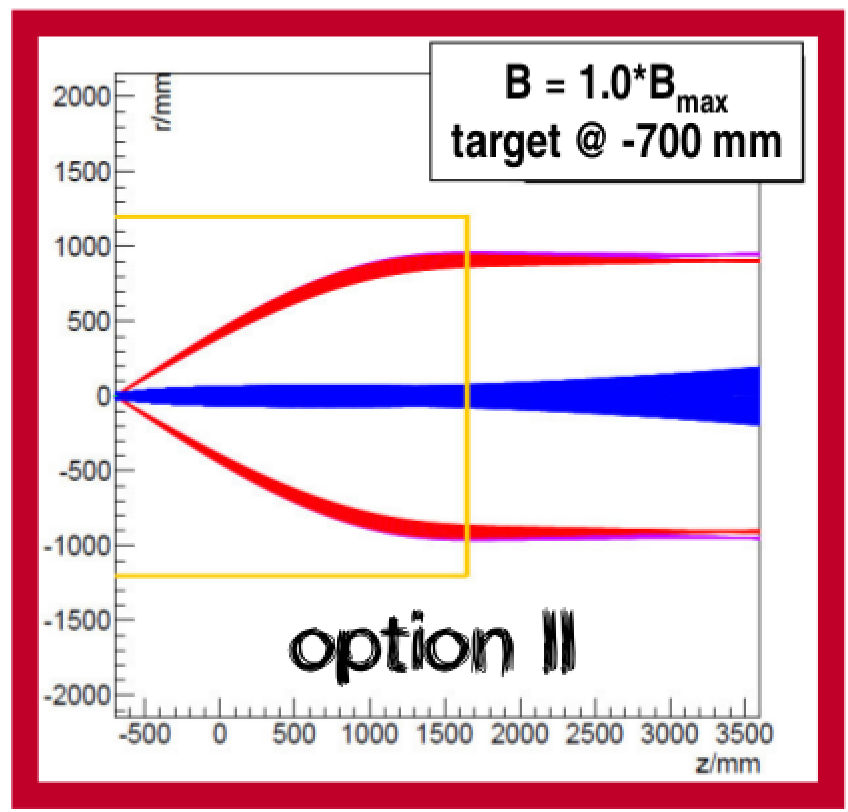
(0.1 T to 0.6 T)

+

scan of target position

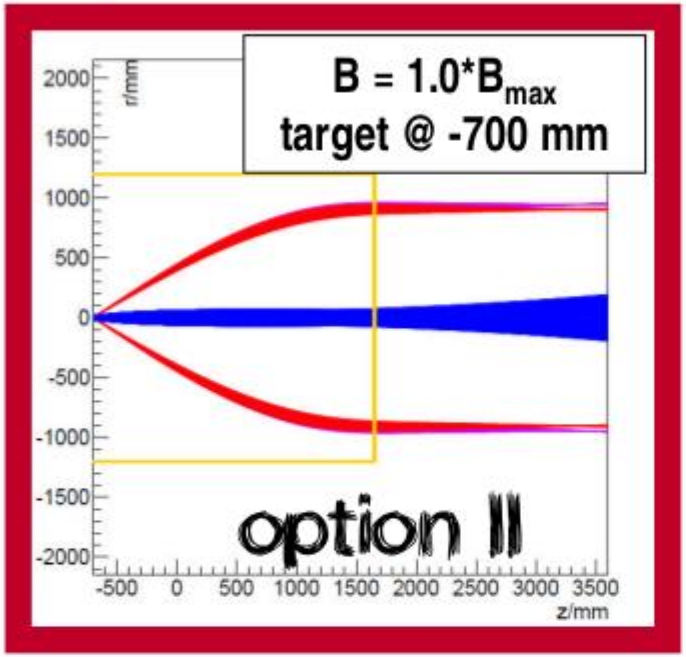
(-2500 mm to 0 mm)

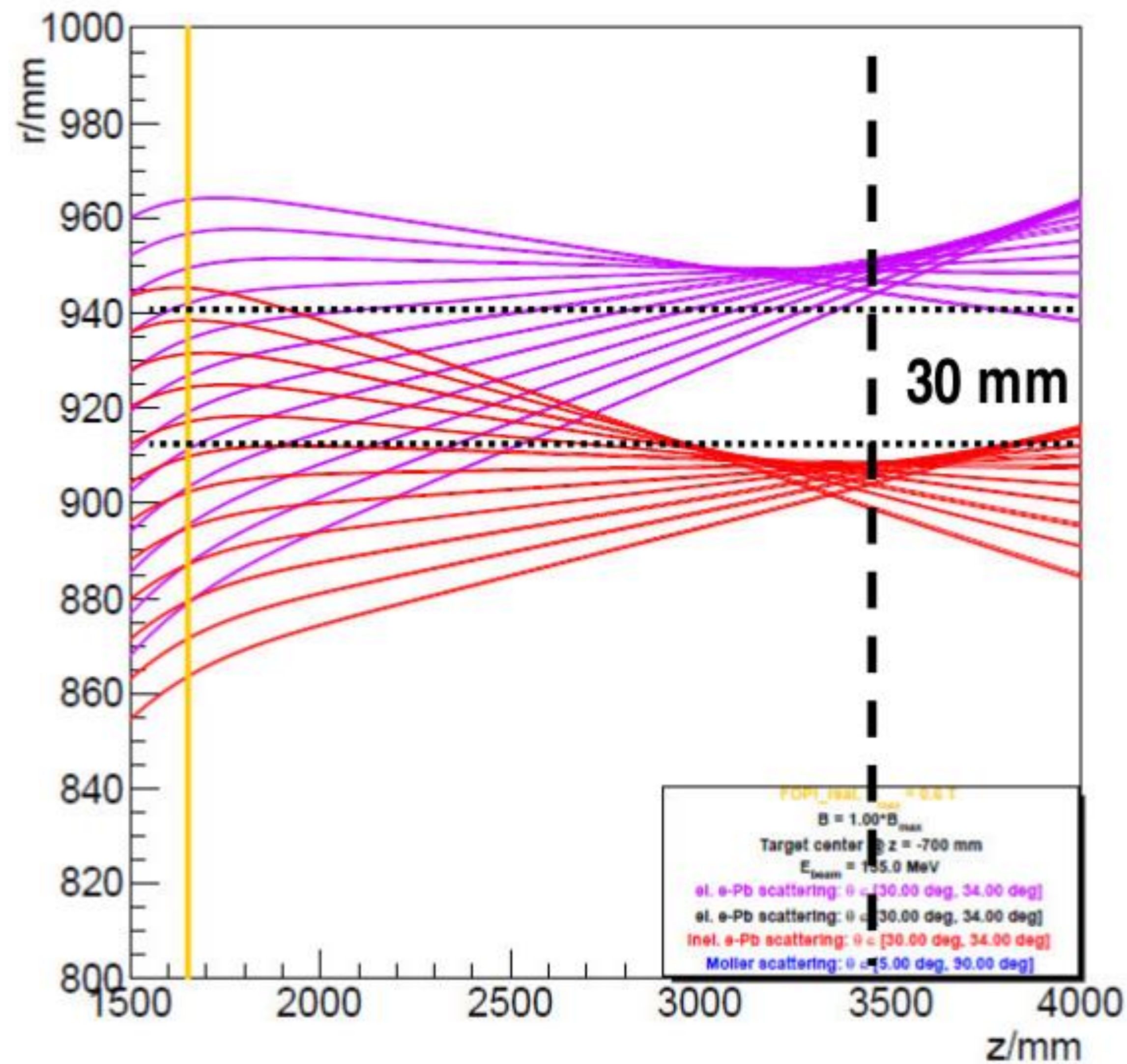




Further physics program: Neutron skin

ray trace simulation





PRO:

similar to P2 design

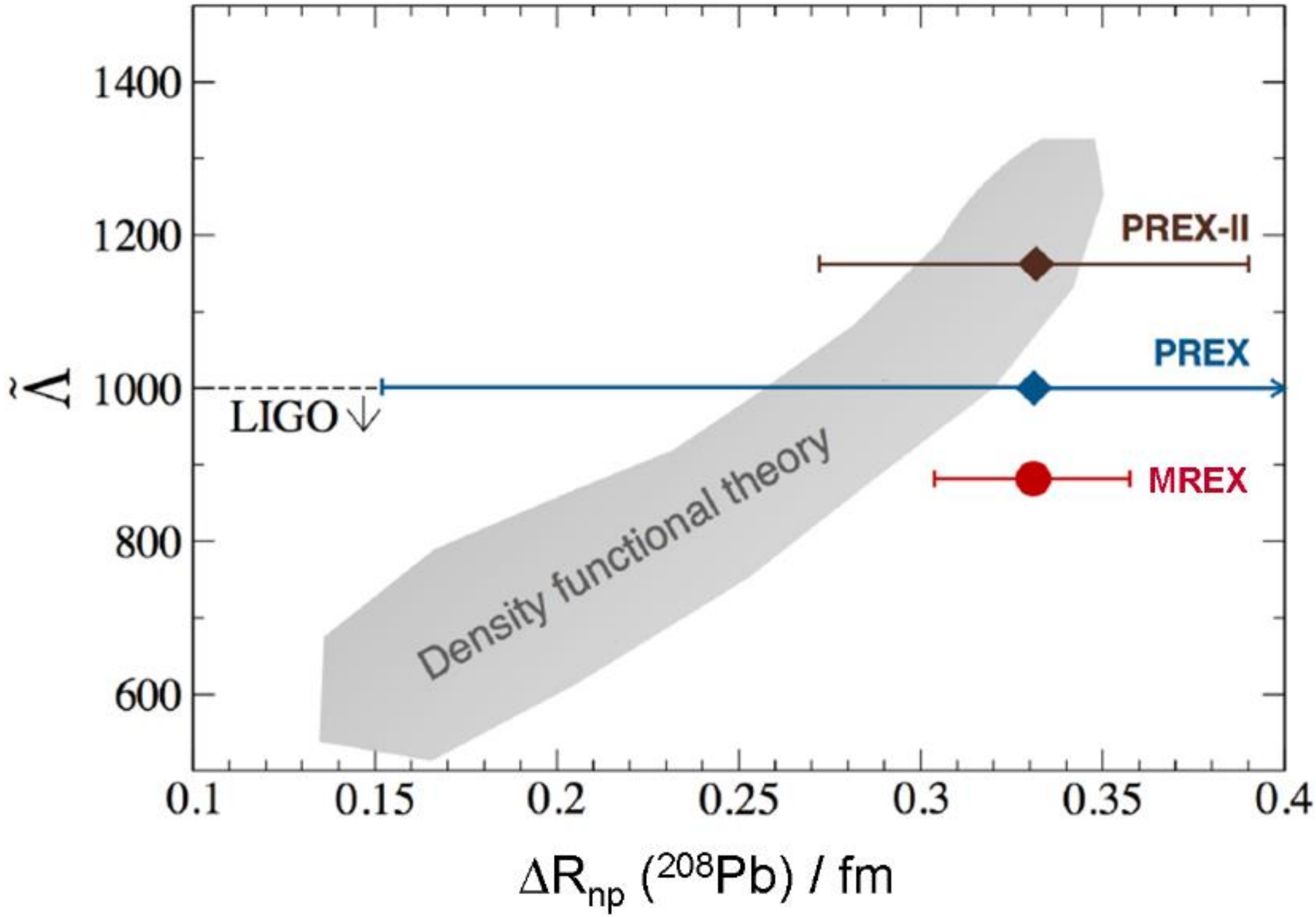
(maybe) easier shielding

CON:

(maybe) not enough space after the solenoid

Further physics program: Neutron skin

Projected precision compared to PREX:



Summary and outlook

- P2: A new experiment to measure the weak mixing angle at low energy
- Makes use of the polarized high current electron beam from the new MESA accelerator
- Extensive simulations and beam tests at MAMI
- $\Delta \sin^2\Theta_W = 3.7 \times 10^{-4}$ (0.16%) expected: Sensitive for BSM physics
- Construction is scheduled to begin end of year 2020