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SFB 1044
Institut für Kernphysik

$\sin^2 \theta_W = 0.238$

$\theta_W = 29{,}2°$

A new, high precision measurement of the weak mixing angle $\sin^2 \theta_W$

Frank Maas
(Helmholtz Institute Mainz,
Institute for Nuclear Phyiscs,
PRISMA cluster of excellence
Johannes Gutenberg University Mainz)

MITP-Workshop, "Bridging the Standard Model to New Physics with the Parity Violation Program at MESA", April 23 – May 4, 2018

SFB 1044 HIM PRiSMA

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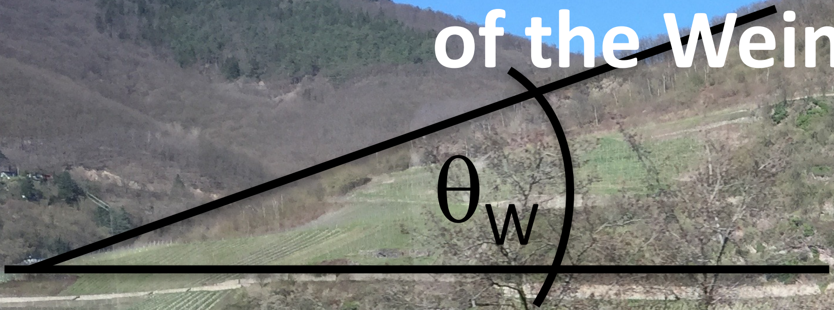
$\sin^2 \theta_W = 0.238$

$\theta_W = 29{,}2^\circ$

A new, high precision measurement of the Weinberg angle $\sin^2 \theta_W$



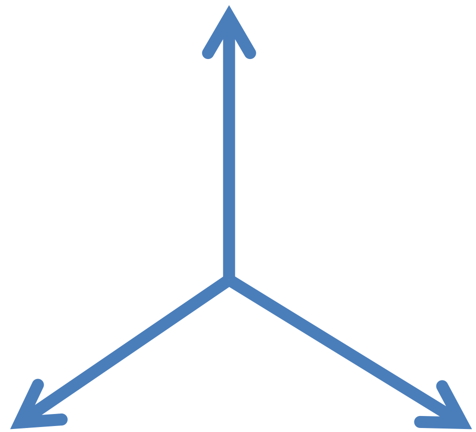
Frank Maas
(Helmholtz Institute Mainz,
Institute for Nuclear Phyiscs,
PRISMA cluster of excellence
Johannes Gutenberg University Mainz)

50 Jahre Beschleunigerphysik in Mainz, 15./16. Februar 2018

SFB 1044 HIM PRISMA

Search for New Physics: Various Methods

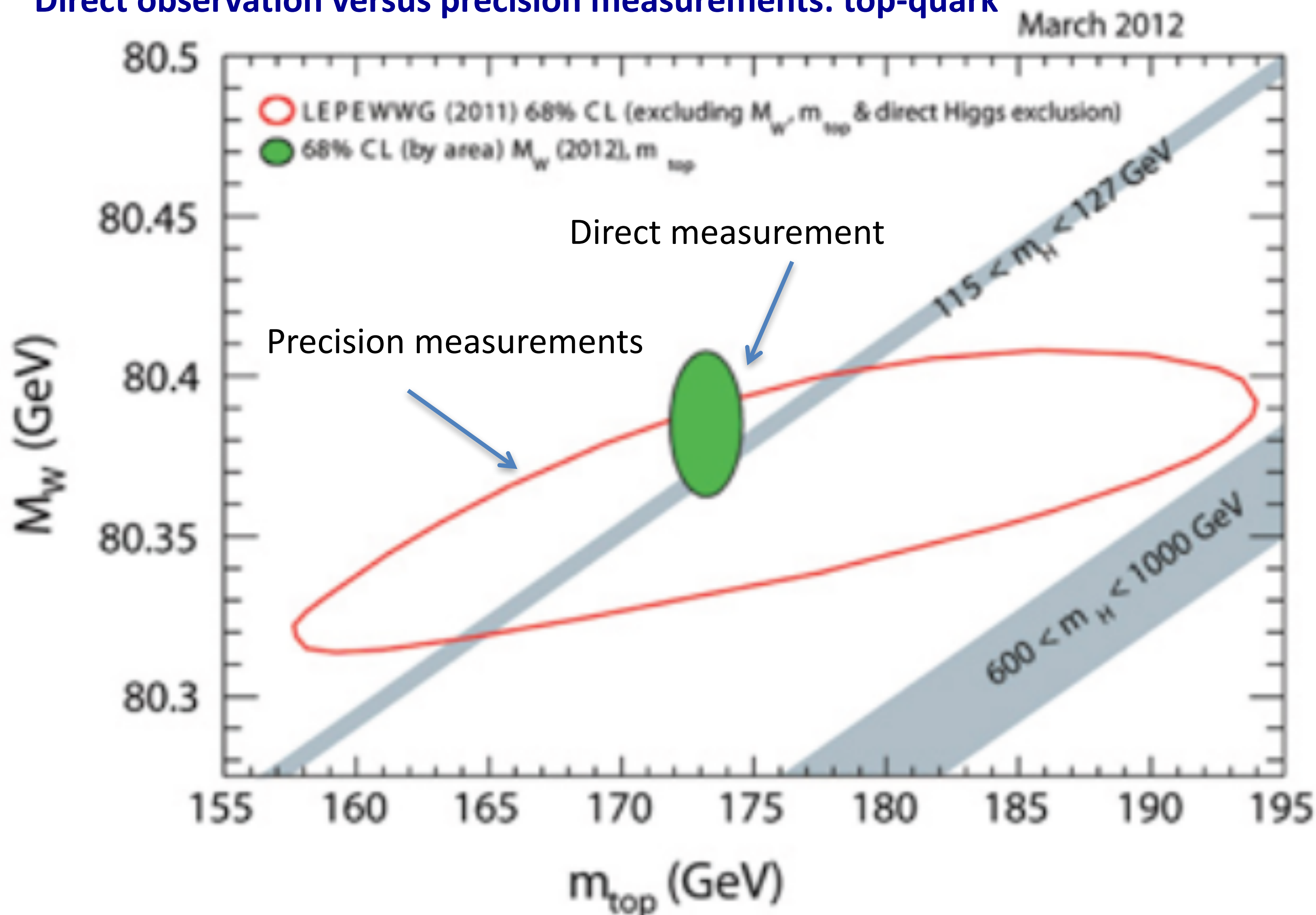
High Energy (LHC)



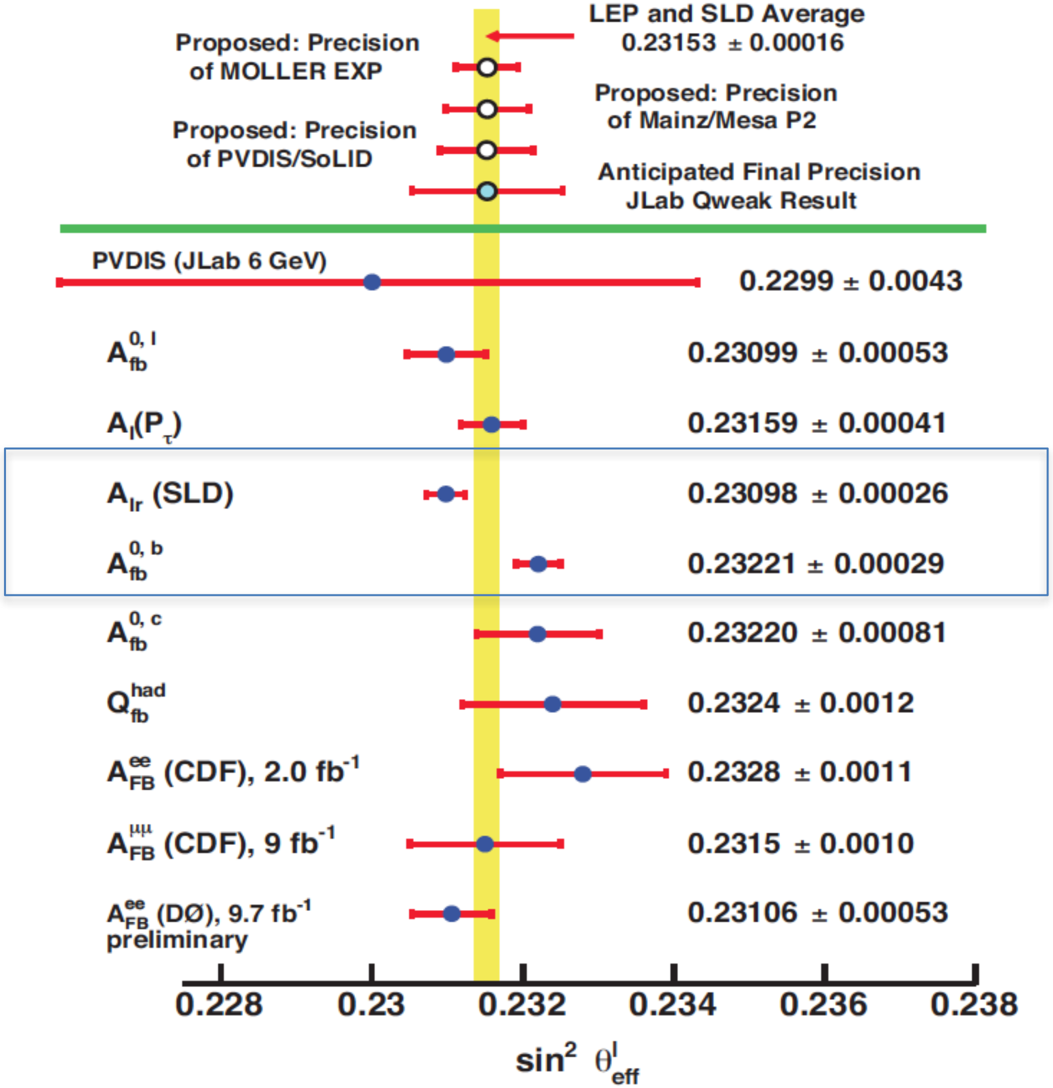
High Intensity
(B-decays)

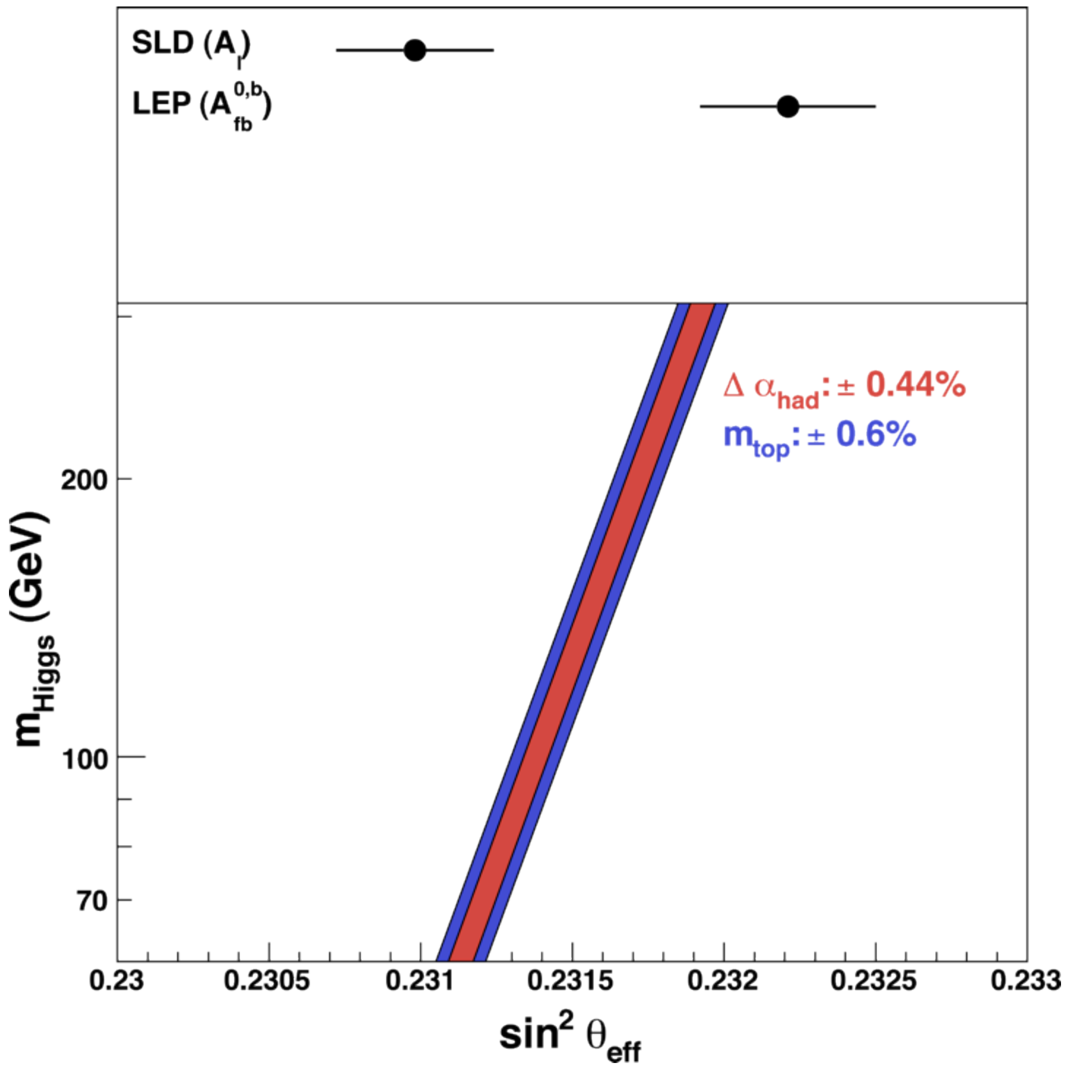
High Precision
($(g-2)_{\mu}$, EDM, $\sin^2\theta_W$, …)
(at low energy)

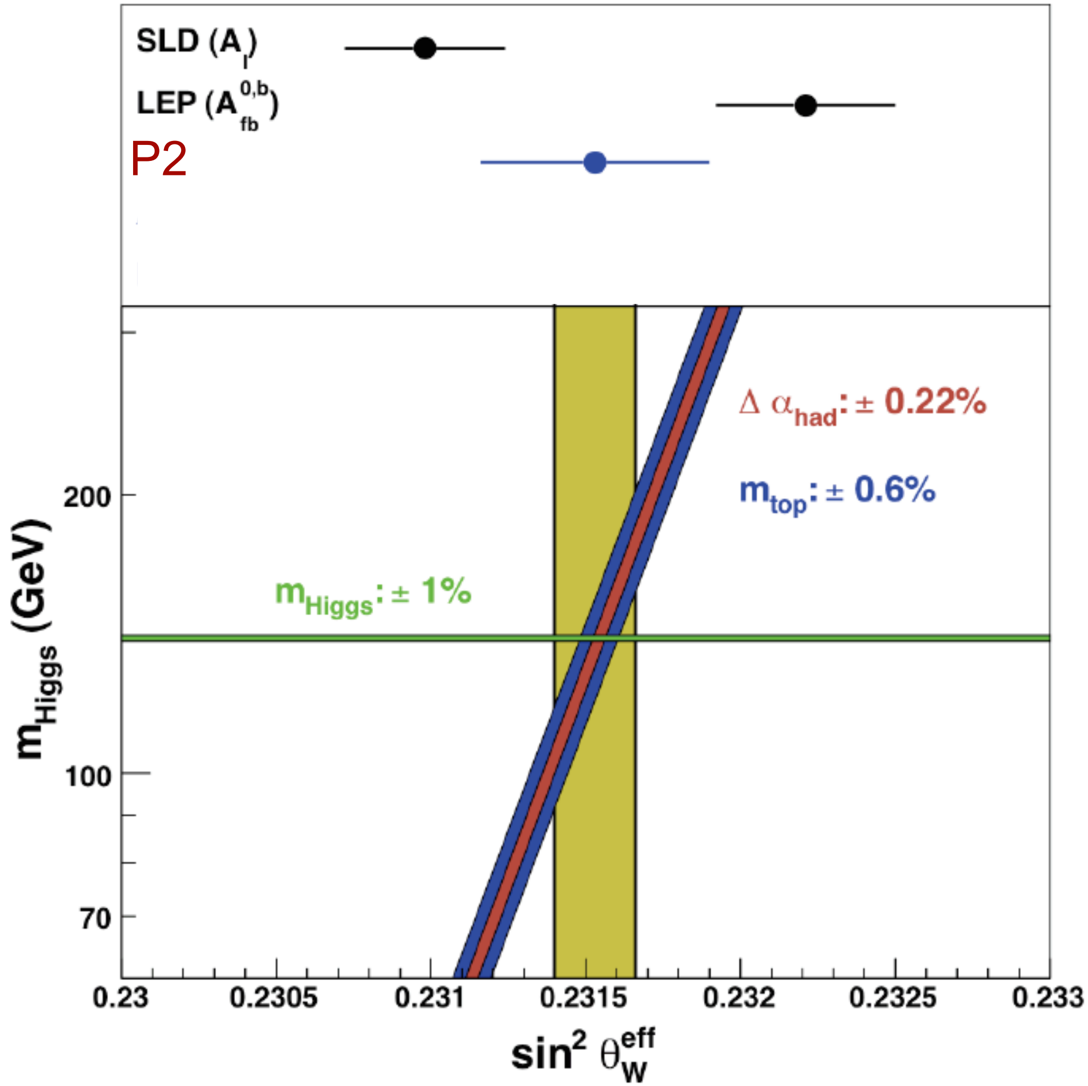
Direct observation versus precision measurements: top-quark



Summary: Measurements of $\sin^2\theta_{W(effective)}$

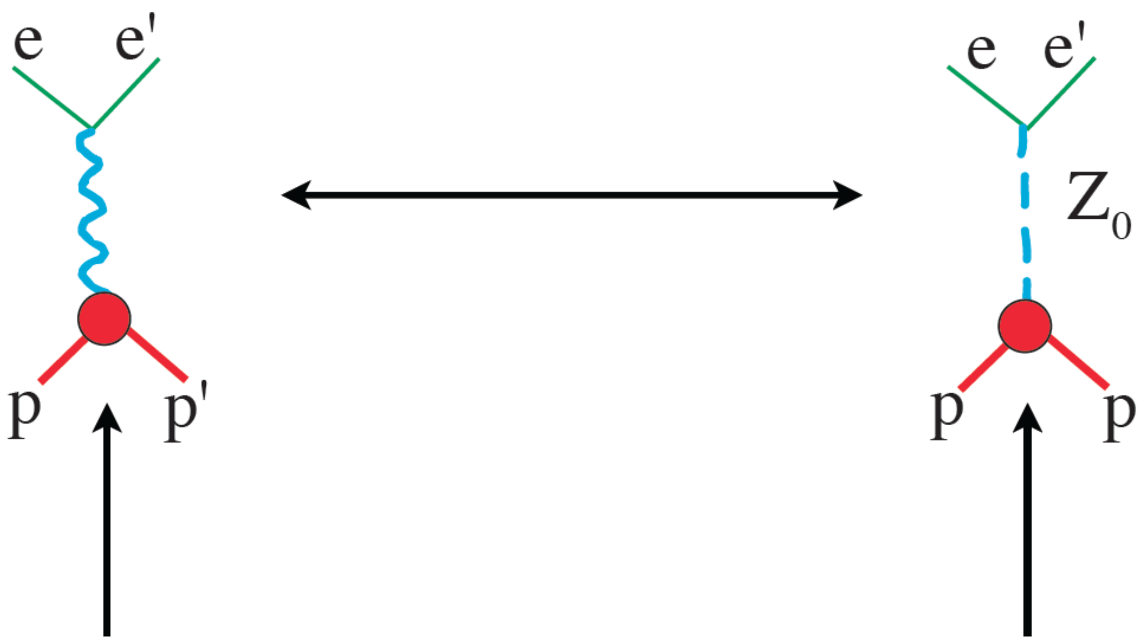



SLD (A_l)
LEP ($A_{fb}^{0,b}$)
$\Delta\ \alpha_{had}$: ± 0.44%
m_{top}: ± 0.6%
m_{Higgs} (GeV)
200
100
70
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2\theta_{eff}$


SLD (A_l)
LEP ($A_{fb}^{0,b}$)
P2
Δ α_{had}: ± 0.22%
m_{top}: ± 0.6%
m_{Higgs}: ± 1%
200
100
70
m_{Higgs} (GeV)
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2 \theta_W^{eff}$

The role of the weak mixing angle

The relative strength between the weak and electromagnetic interaction is determined by the weak mixing angle: $\sin^2(\theta_W)$

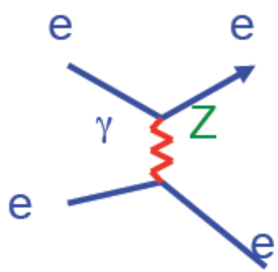


$Q_e(p) = +e$
electric charge of the proton

$Q_W(p) = 1 - 4\sin^2\theta_W$
weak charge of the proton

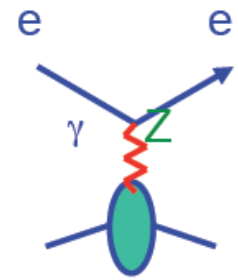
$\sin^2\theta_W$: a central parameter of the standard model

Møller Scattering



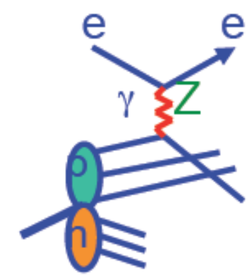
- Purely Leptonic

Q-Weak (JLab)
P2 (Mainz/MESA)



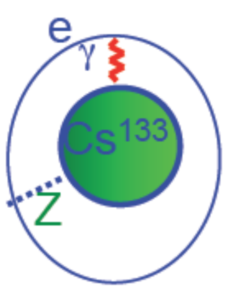
- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS



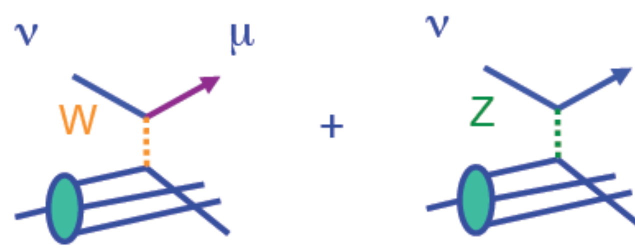
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Atomic Parity Violation



- Coherent quarks in entire nucleus
- Nuclear structure uncertainties
- $-376\ C_{1u} - 422\ C_{1d}$

Neutrino Scattering

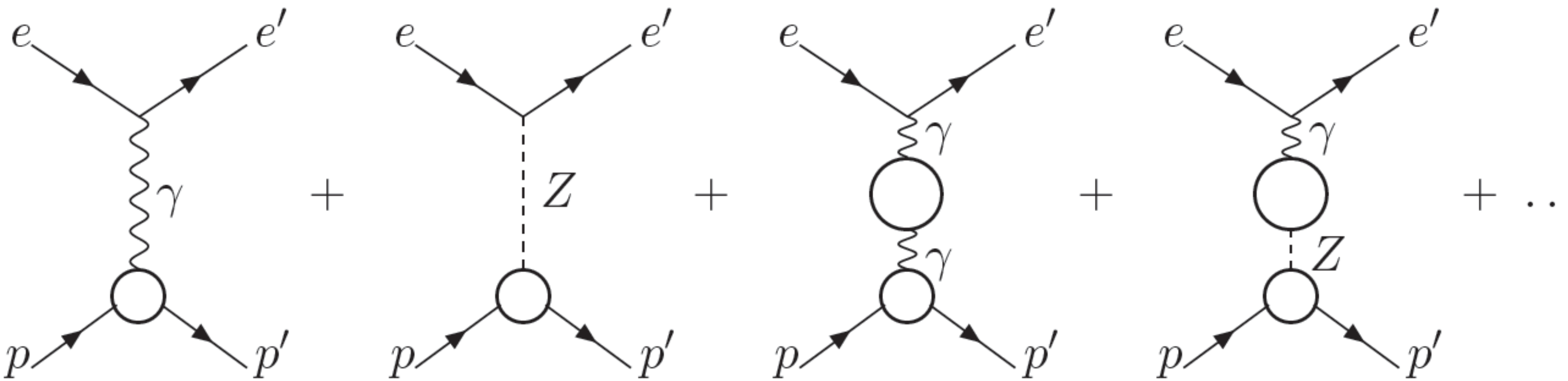


- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Courtesy of P. Reimer and R. Arnold

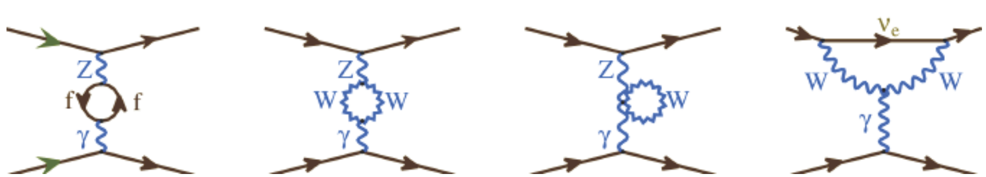
„running“ $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$

Precision measurements and quantum corrections:

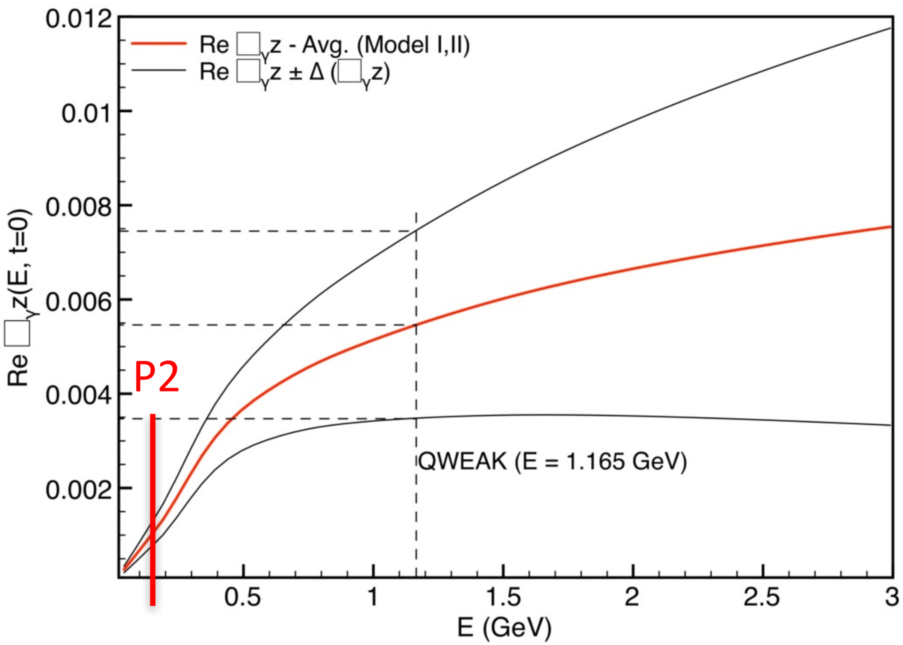


running α **running $\sin^2 \theta_W(\mu)$**

Universal quantum corrections: can be absorbed into a
scale dependent, „running“ $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$

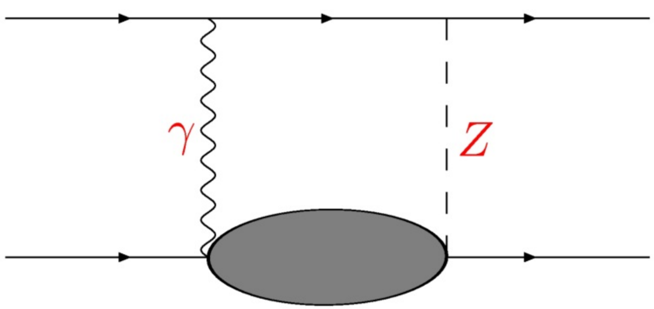


- γZ box graph contributions obtained by modelling hadronic effects:



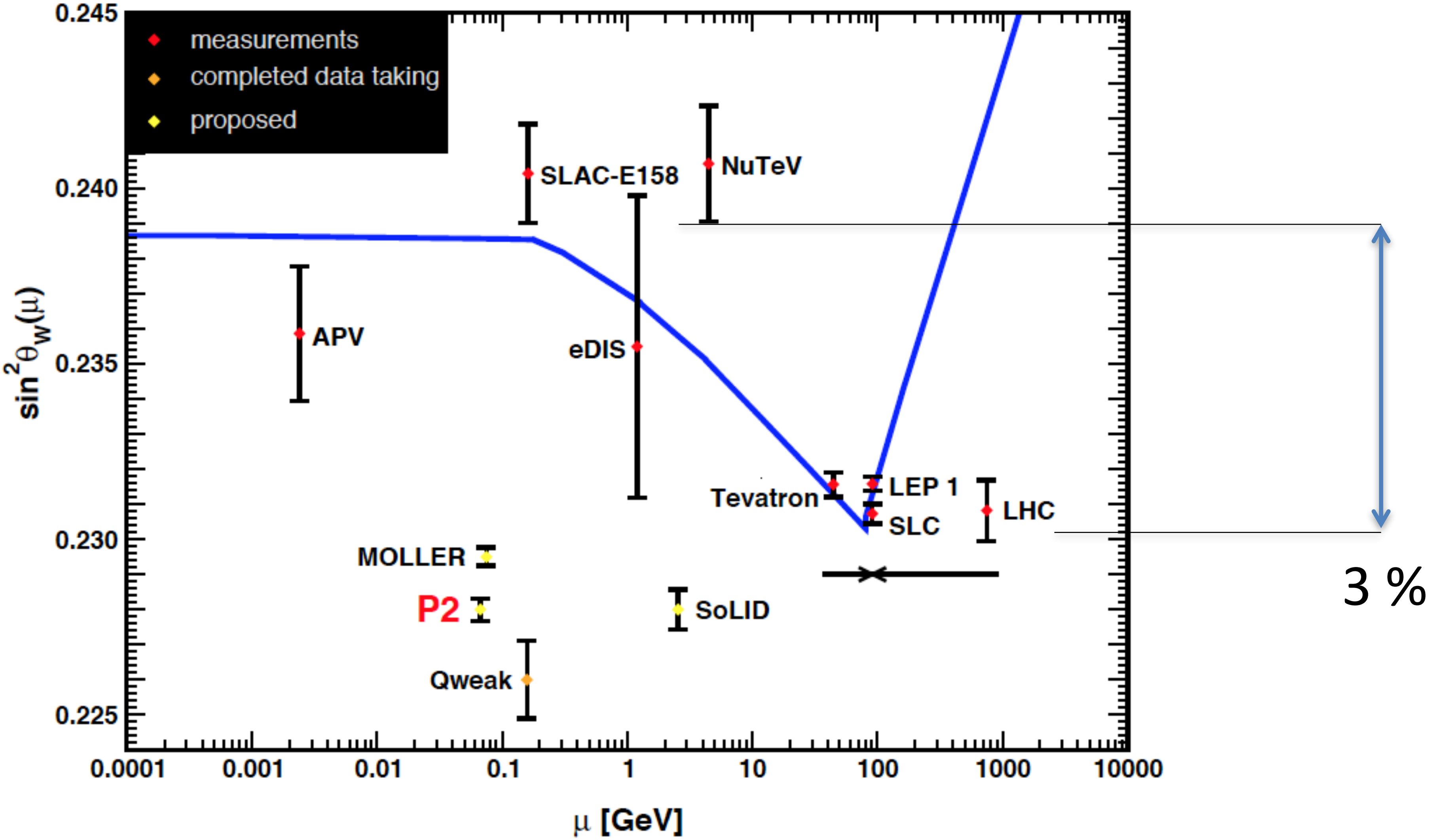
[Gorchstein, Horowitz & Ramsey-Musolf 2011]

- Hadronic uncertainties suppressed at lower energies
- Low beam energy experiment:
  P2 @ MESA



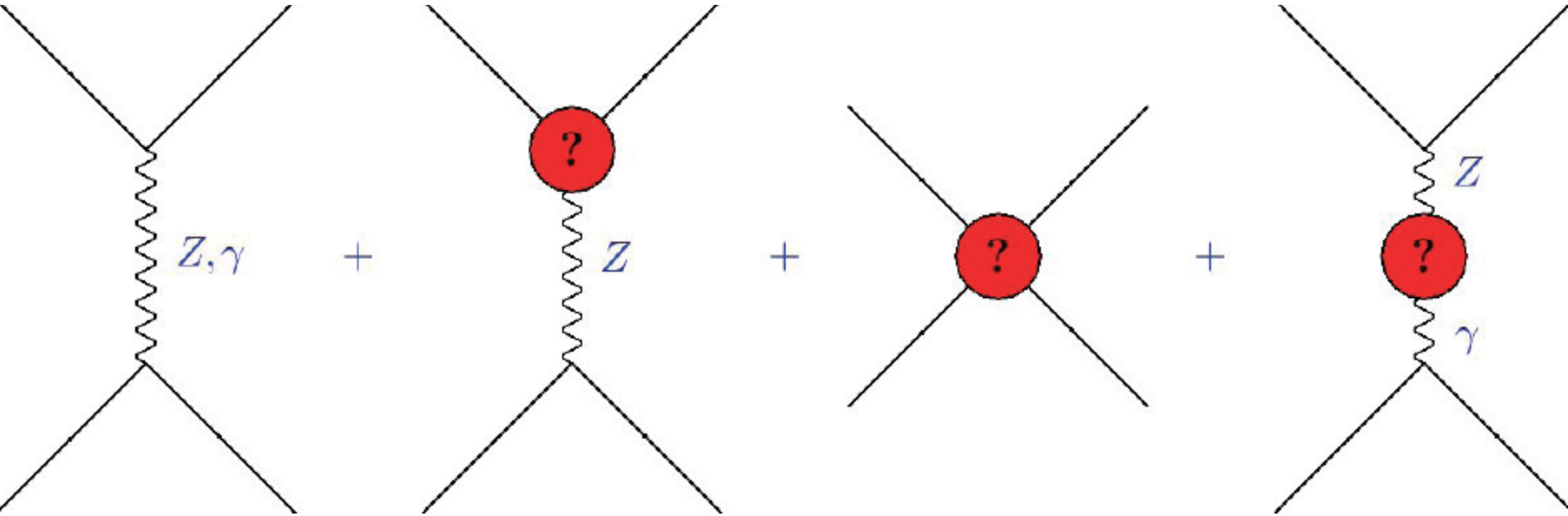
Progress in Theory

- Theory uncertainties in box diagrams
- 2 loop corrections
- Hadronic contributions in loops
- Auxiliary measurements
- PV-asymmetry in Carbon


measurements
completed data taking
proposed
0.245
0.240
0.235
0.230
0.225
sin²θW(μ)
SLAC-E158
NuTeV
APV
eDIS
Tevatron
LEP 1
SLC
LHC
MOLLER
P2
SoLID
Qweak
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
μ [GeV]
3 %

Sensitivity to new physics beyond the Standard Model

Sensitivity to new physics beyond the Standard Model



Extra Z

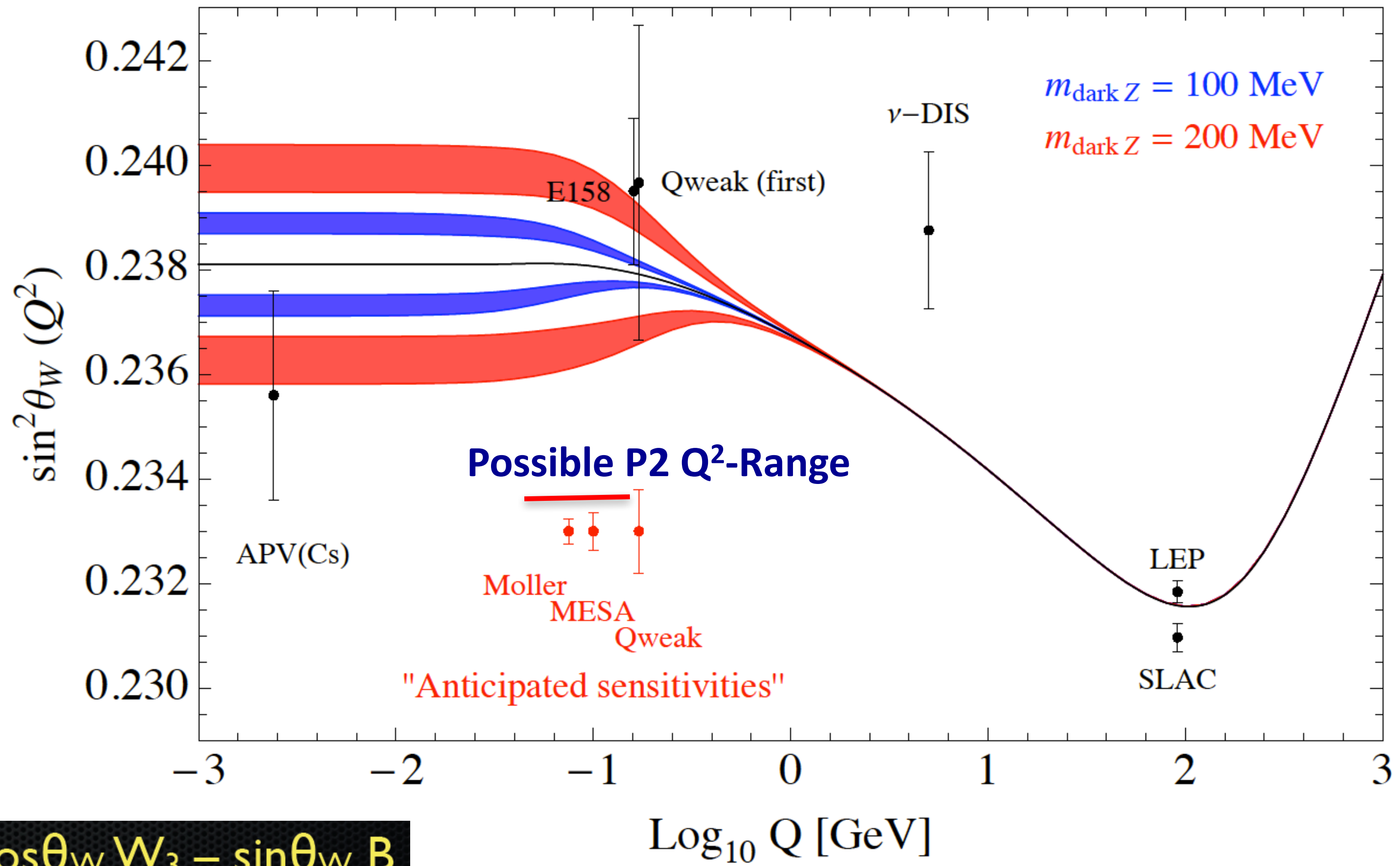
Mixing with Dark photon or Dark Z

Contact interaction

New Fermions

Dark Photon, Z-Boson

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

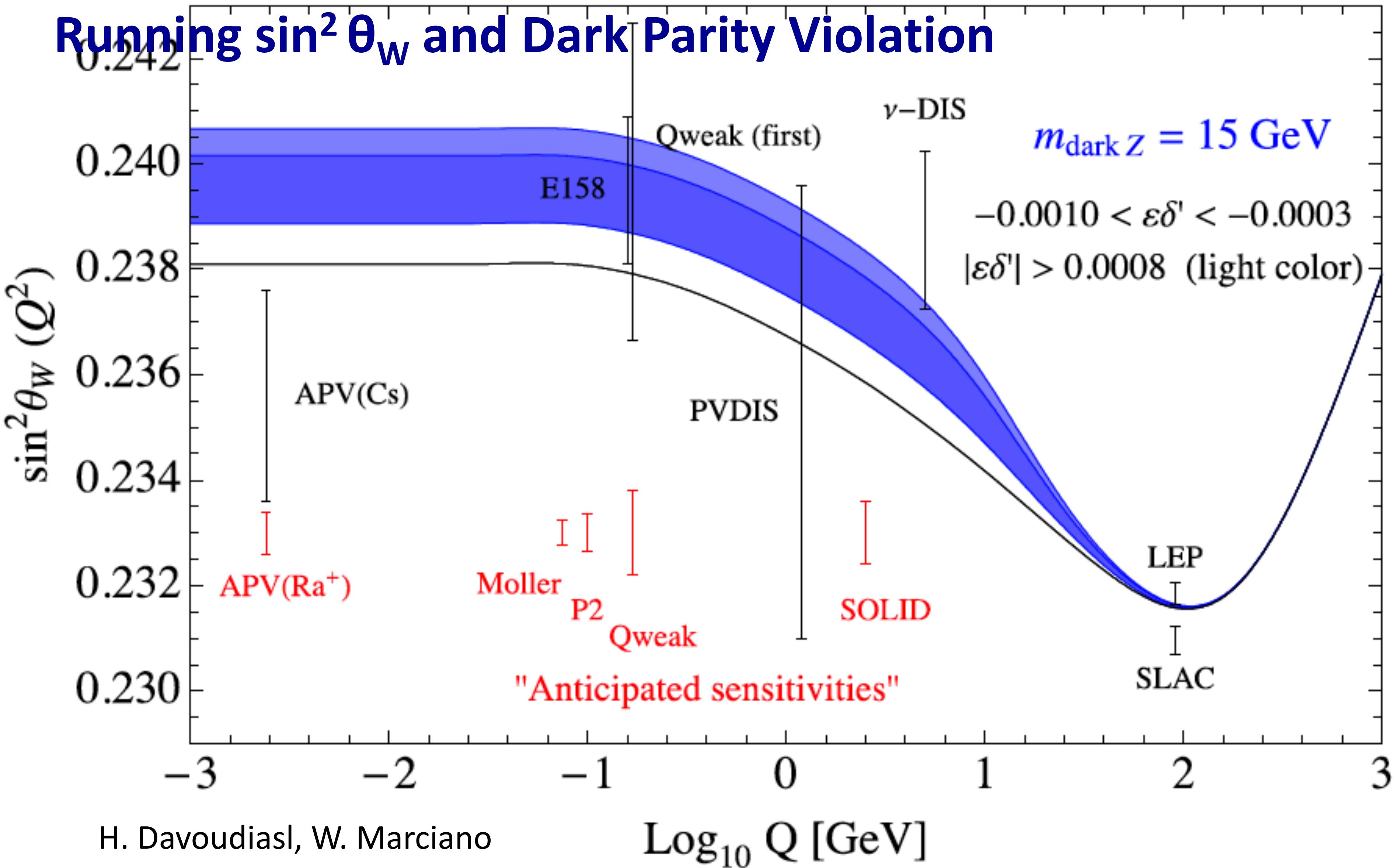


$Z = \cos\theta_W W_3 - \sin\theta_W B$

$A = \sin\theta_W W_3 + \cos\theta_W B$

Bill Marciano

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

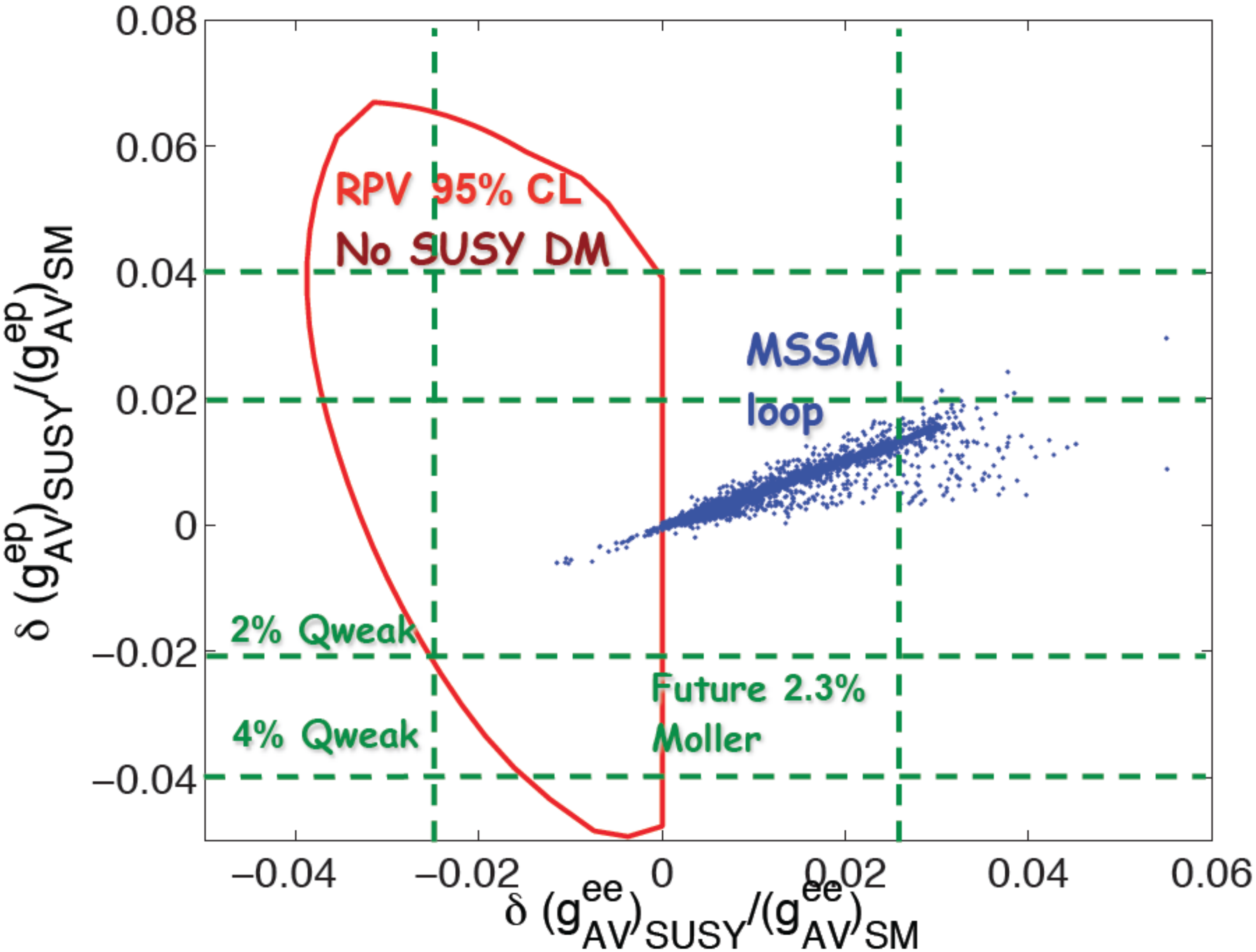


H. Davoudiasl, W. Marciano

Supersymmetry

Example: Supersymmetric standard model extensions

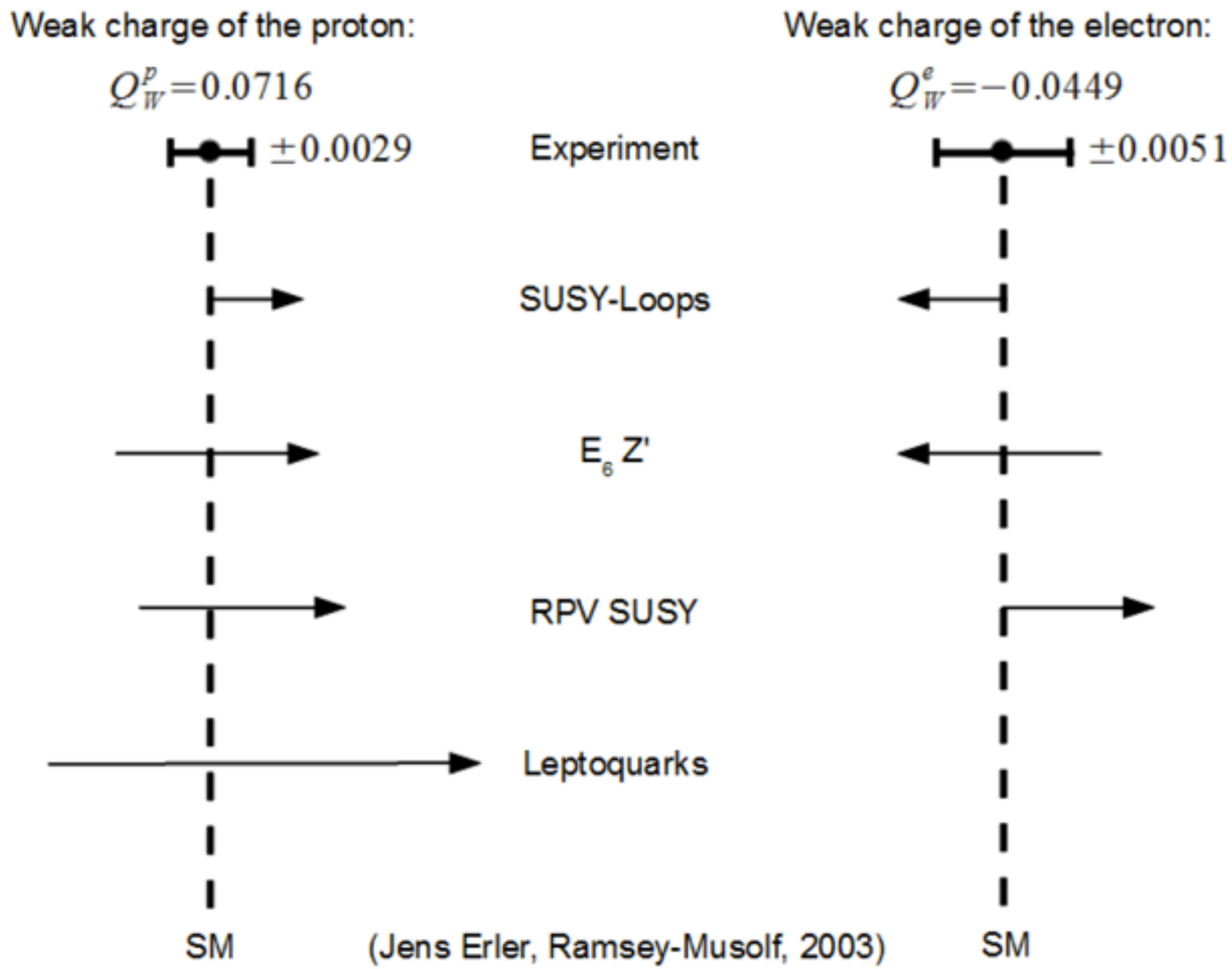
Kurylov, Ramsey-Musolf, Su (2003), updated



After LHC
Run 1

X. Su

- Complementary access by weak charges of proton and electron



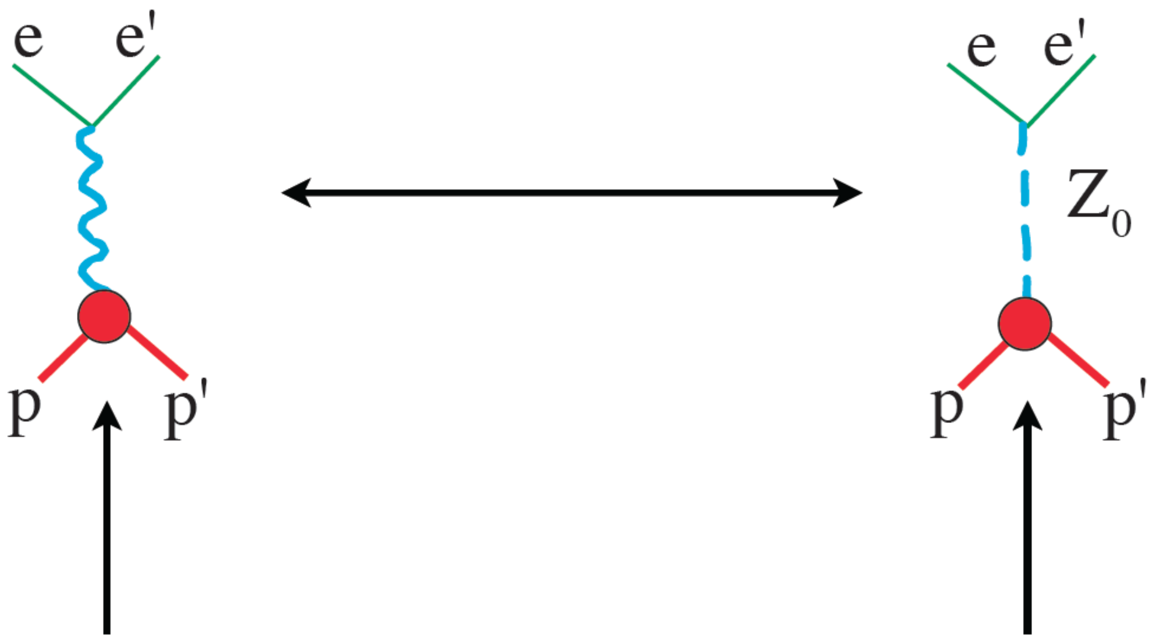
Weak Charge Of Proton:
Qweak (Jlab),
P2 (MESA)

Weak Charge Of Electron:
MOELLER (JLAB)

Weak Charge Of Quarks:
SOLID (PVDIS) (JLAB)

The role of the weak mixing angle

The relative strength between the weak and electromagnetic interaction is determined by the weak mixing angle: $\sin^2(\theta_W)$



$Q_e(p) = +e$
electric charge of the proton

$Q_W(p) = 1 - 4\sin^2\theta_W$
weak charge of the proton

$\sin^2\theta_W$: a central parameter of the standard model

Proton: special case

Proton Weak charge: $Q_W(p) = 1 - 4 \sin^2\theta_W$

Error: $\Delta Q_W(p) = 4\,\Delta\sin^2\theta_W$

Rel. error: $\Delta Q_W(p)/Q_W(p) = 4/\left((1/\sin^2\theta_W) - 4 \right)\ \ (\Delta\sin^2\theta_W/\sin^2\theta_W)$

Rel. error $\Delta\sin^2\theta_W/\sin^2\theta_W = \left((1/\sin^2\theta_W) - 4 \right)/4\ \ \Delta Q_W(p)/Q_W(p)$

Example: $\sin^2\theta_W\,(50\text{ MeV}) = 0.238$

$4/\left((1/\sin^2\theta_W) - 4 \right) \sim 20$

$\Delta Q_W(p)/Q_W(p) = 2\%$ from Experiment

$\Delta\sin^2\theta_W/\sin^2\theta_W = 0.1\ \%$ same precision as LEP, SLAC

Neutron Weak charge:

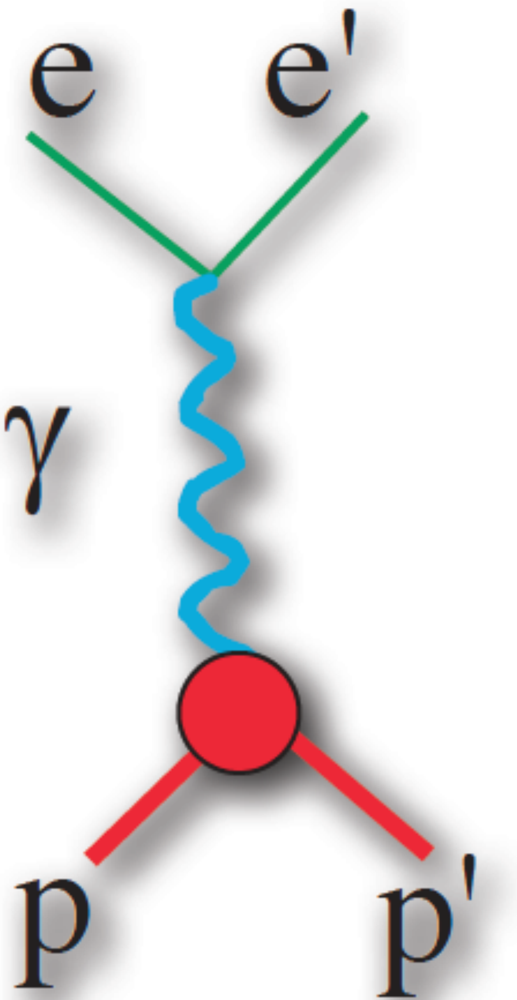
$\Delta Q_W(p)/Q_W(n) = \Delta\sin^2\theta_W/\sin^2\theta_W$

Physics sensitivity from contact interaction (LEP2 convention, $g^2 = 4pi$)

	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV Cs	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak I	19 %	0.0030	17.0 TeV
Qweak final	4.5 %	0.0008	33 TeV
PVDIS	4.5 %	0.0050	7.6 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV

Jens Erler

Experimental Method:
Parity Violating Electron Scattering



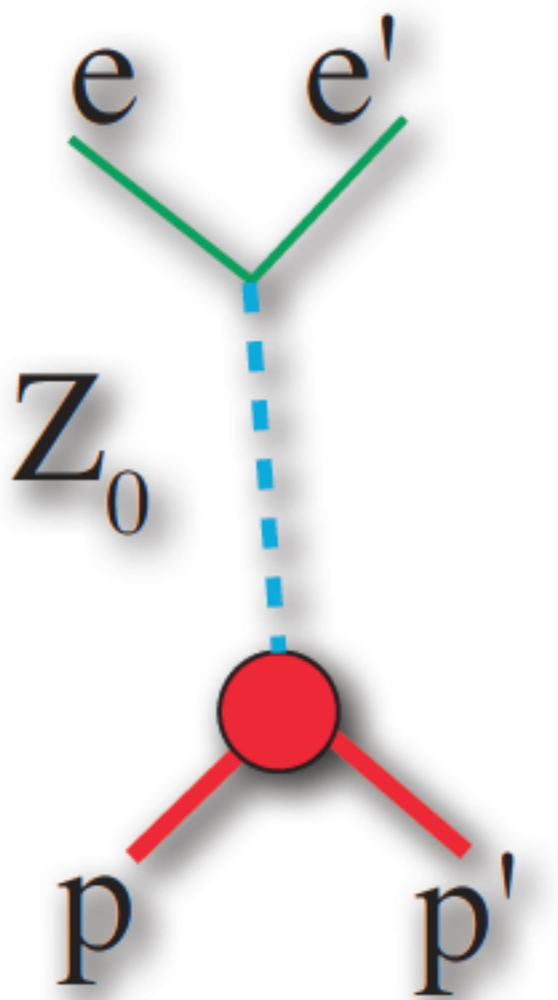
$$\sigma \sim \mathcal{M}\,\mathcal{M}^* \text{ Phasespace}$$

$$\sim \left(j_\mu \frac{1}{Q^2} J^\mu\right)\left(j_\mu \frac{1}{Q^2} J^\mu\right)^*$$

$$j_\mu \sim \overline{e}\,\gamma_\mu\, e \quad \text{Vector Current}$$

$$J^\mu_\gamma \sim \left\langle N \middle| q^u \overline{u}\,\gamma_\mu\, u + q^d \overline{d}\,\gamma_\mu d + q^s \overline{s}\,\gamma_\mu s \middle| N' \right\rangle$$

$$= \overline{\mathcal{P}}\left[\gamma^\mu F_1 - i\sigma^{\mu\nu} q_\nu \frac{\kappa_p}{2M_N} F_2\right]\mathcal{P}$$

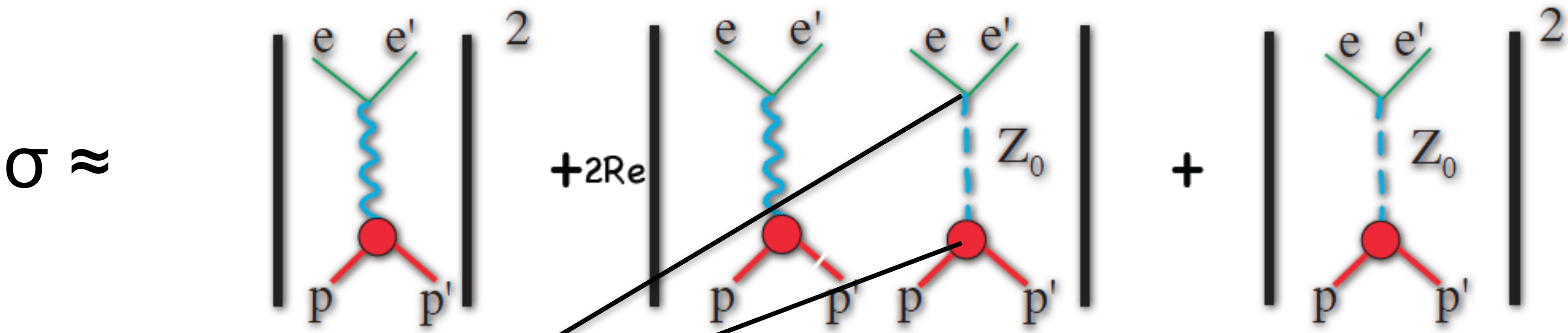


$$\tilde{q}^{d}{}_{V} = \tau_3 - 2q^{d}\,sin^2(\theta_W)$$

$$\tilde{J}^{\mu}_{Z} \sim \left\langle N|\tilde{q}^{u}\overline{u}\,\gamma_\mu\, u + \tilde{q}^{d}\overline{d}\,\gamma_\mu d + \tilde{q}^{s}\overline{s}\,\gamma_\mu s|N'\right\rangle$$

$$= \overline{\mathcal{P}}[\gamma^\mu \tilde{F}_1 - i\sigma^{\mu\nu}q_\nu \frac{\kappa_p}{2M_N}\tilde{F}_2]\mathcal{P}$$

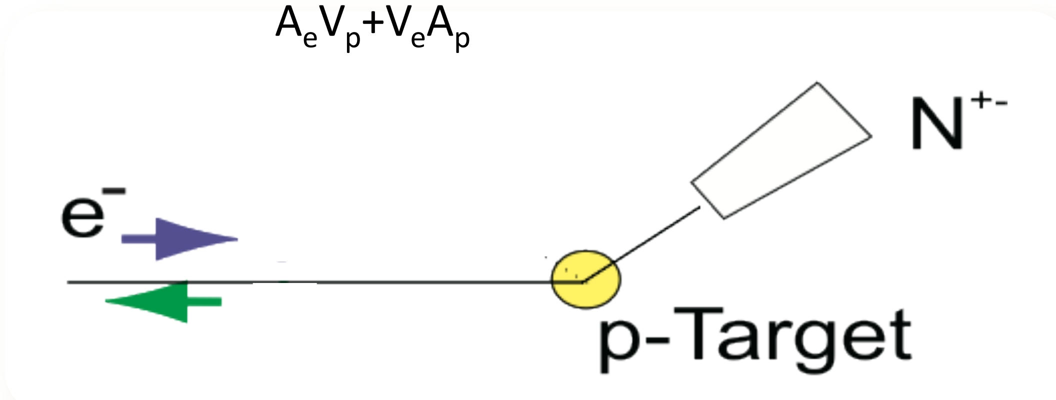
Parity Violating Asymmetry in elastic electron proton scattering



$(V\text{-}A)_e(V\text{-}A)_p$

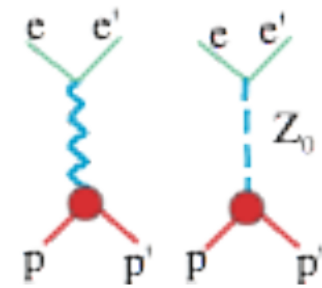
$A_eV_p+V_eA_p$

V-A coupling:
parity-violating
cross section asymmetry A_{LR}
longitudinally pol. electrons
unpolarised protons



Parity violating cross section asymmetry

$$A_{ep} = \left[\frac{G_F\, Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^{\gamma} G_E^{Z} + \tau G_M^{\gamma} G_M^{Z} - (1-4\sin^2\theta_W)\epsilon' G_M^{\gamma} G_A^{Z}}{\varepsilon (G_E^{\gamma})^2 + \tau (G_M^{\gamma})^2}$$



$$A_{\mathrm{RL}} = \underbrace{A_{\mathrm{V}} + A_{\mathrm{A}}}_{=A_0} + A_{\mathrm{S}}
\begin{cases}
A_{\mathrm{V}} = -a\rho'_{eq}\left[(1-4\sin^2\theta_W) - \dfrac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}\right] \\
A_{\mathrm{A}} = a\dfrac{(1-4\sin^2\theta_W)\sqrt{1-\epsilon^2}\sqrt{\tau(1+\tau)}G_M^p \tilde{G}_A^p}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} \\
A_{\mathrm{S}} = a\rho'_{eq}\dfrac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}
\end{cases}$$

e

$$a = -G_F q^2/4\pi\alpha\sqrt{2}, \quad \tau = -q^2/4M_{\mathrm{p}}^2, \quad \epsilon = [1 + 2(1+\tau)\tan^2\theta/2]^{-1}$$

Parity violating cross section asymmetry

tracking system

weak charge

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

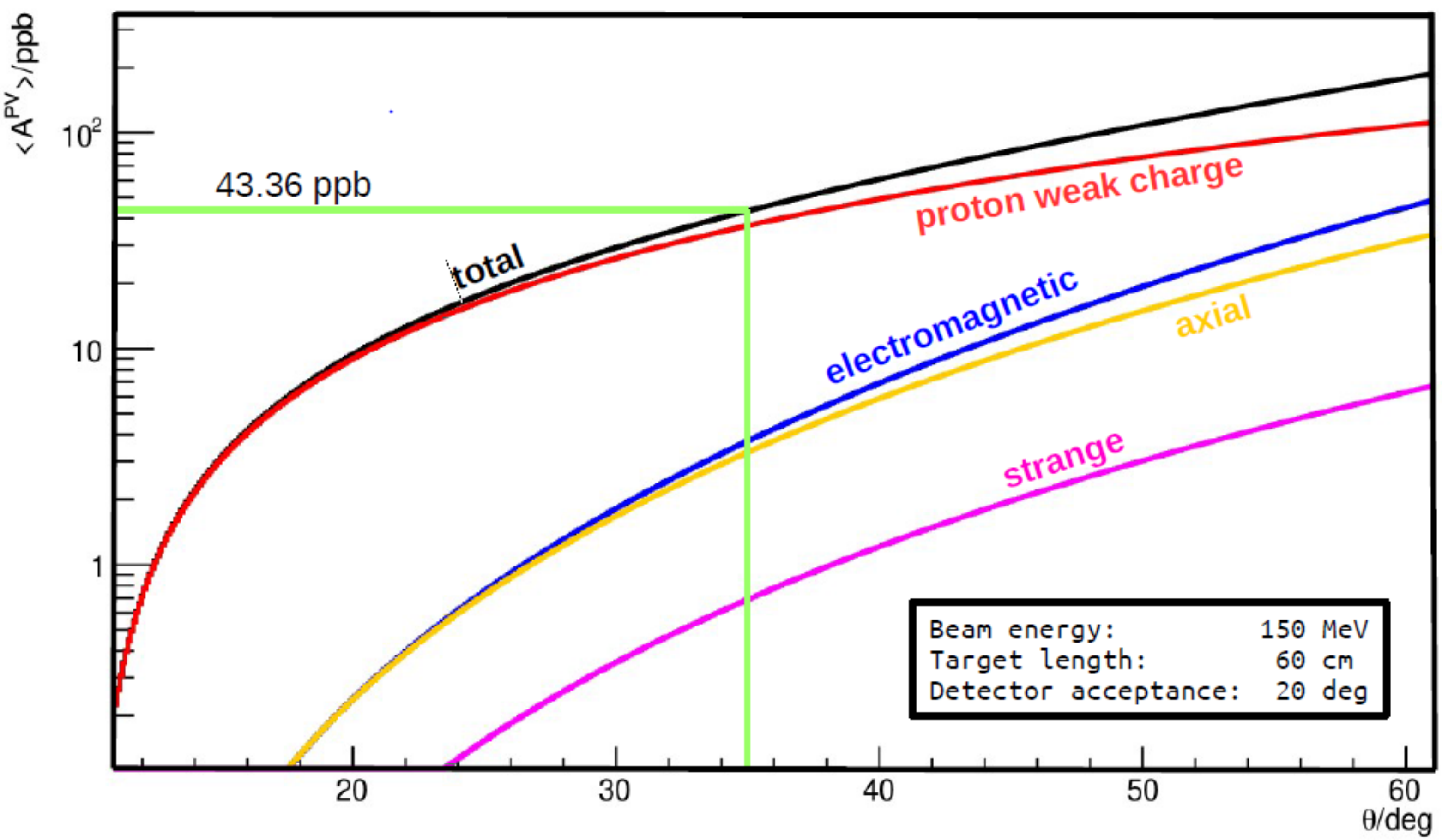
polarisation measurement

hadron structure

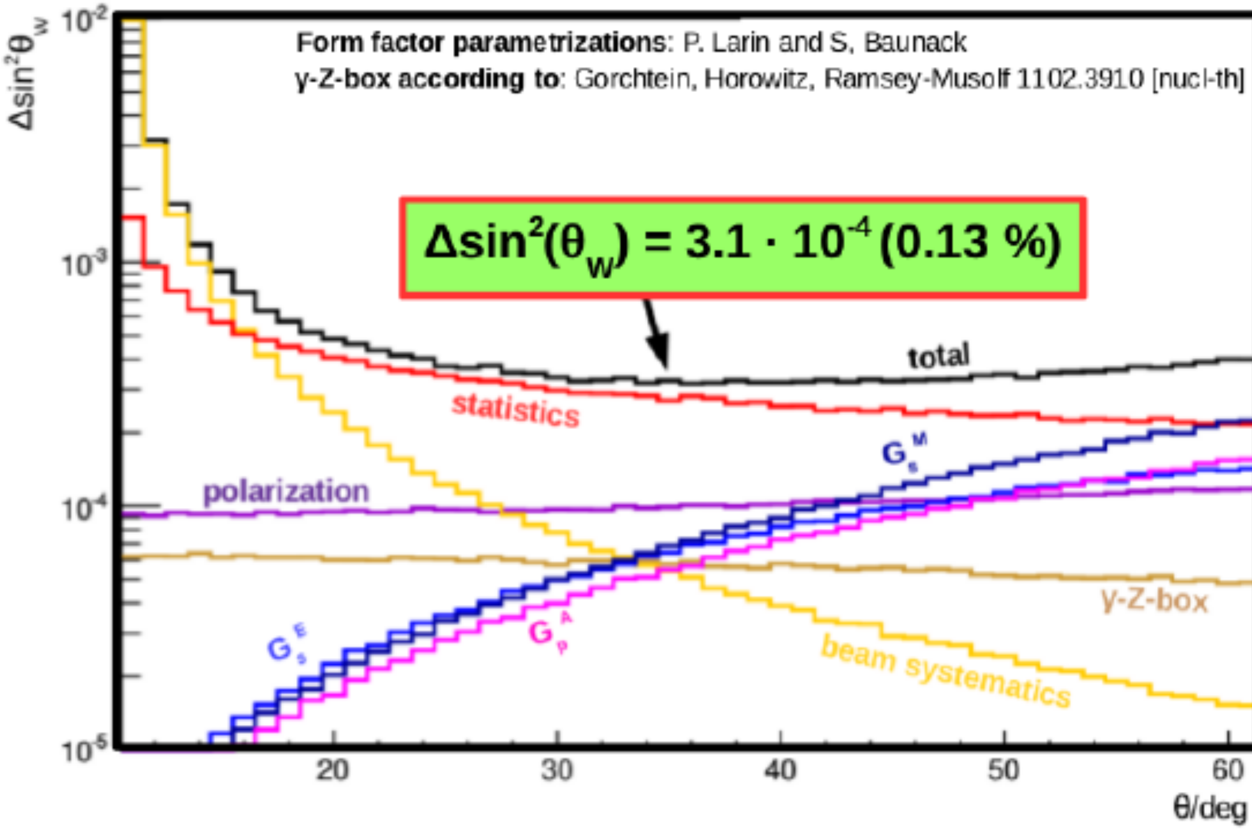
$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

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

- Contributions to $\Delta\sin^2\Theta_W$ for 35° central scattering angle, E=150 MeV, 10000 h of data taking



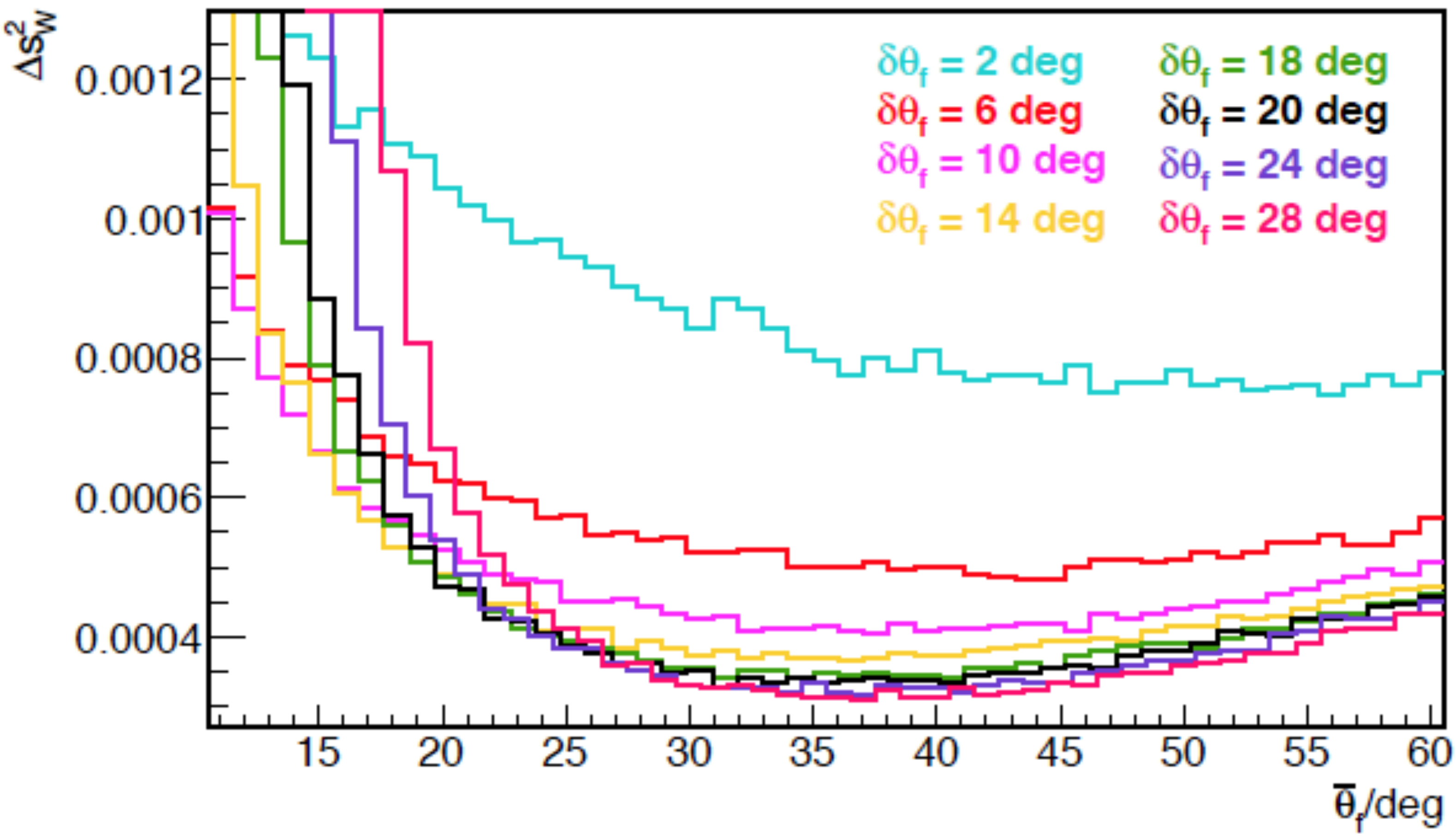
P2-Precision in $\sin^2\theta_W$



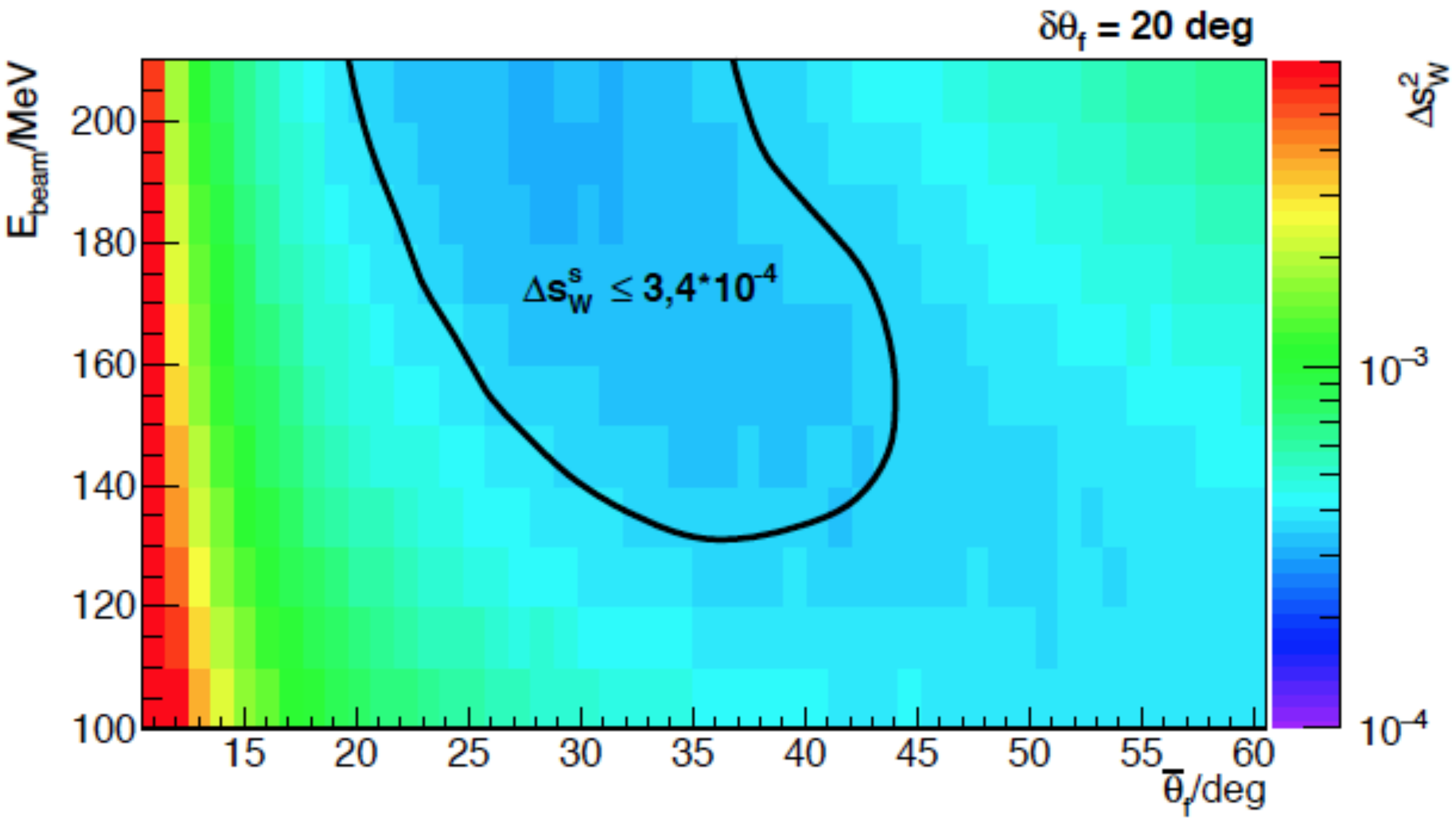
Beam energy:	155 MeV
Beam current:	150 µA
Polarization:	(85±0.5)%
Target:	60 cm lH2
Acceptance:	2π·(35°±10°)
Rate:	0.5 THz
Runtime:	10000 h
ΔA^{app}:	0.1 ppb

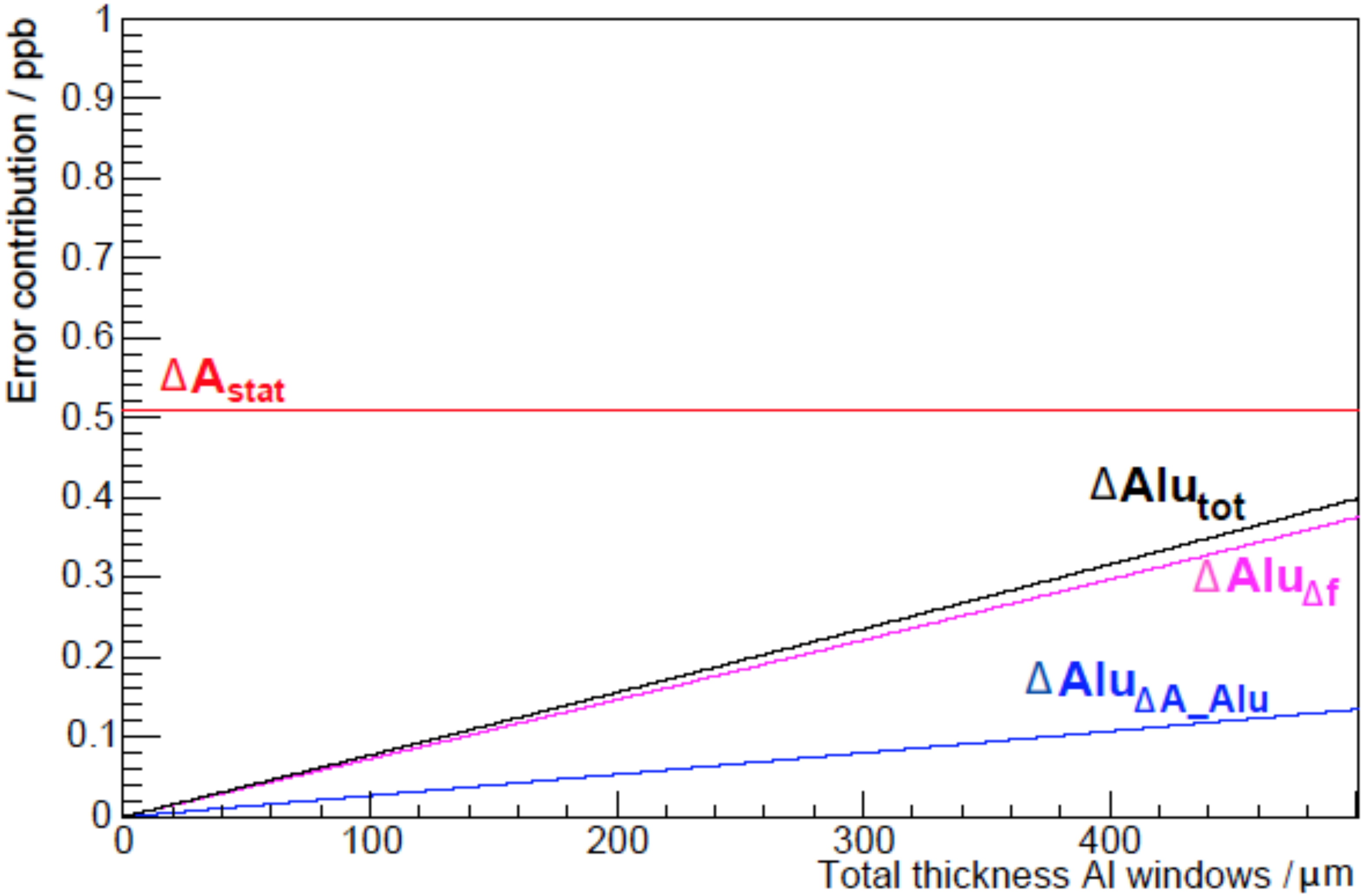
	Total	Statistics	Polarization	Apparative	FF	Re($\square_{\gamma ZA}$)
$\Delta\sin^2(\theta_w)$	3.1e-4 (0.13 %)	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	0.44 (1.5 %)	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

Optimization of acceptance in $\Delta\theta$



Optimization of beam energy and mean scattering angle θ

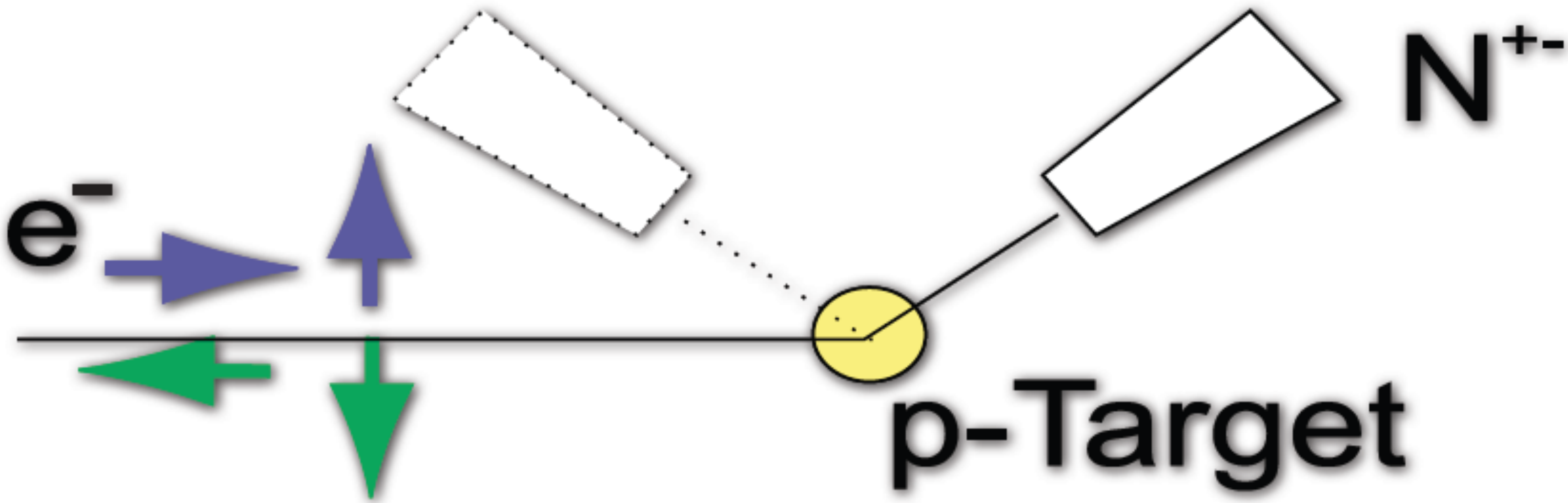




Error contribution / ppb
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ΔA_stat
ΔAlu_tot
ΔAlu_Δf
ΔAlu_ΔA_Alu
0
100
200
300
400
Total thickness Al windows / μm

E_{beam}	155 MeV
$\bar{\theta}_{\mathrm{f}}$	35°
$\delta\theta_{\mathrm{f}}$	20°
$\langle Q^2\rangle_{L=600\,\mathrm{mm},\ \delta\theta_{\mathrm{f}}=20°}$	$6 \times 10^{-3}\,(\mathrm{GeV/c})^2$
$\langle A^{\mathrm{exp}}\rangle$	-39.94 ppb
$(\Delta A^{\mathrm{exp}})_{\mathrm{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\mathrm{exp}})_{\mathrm{Statistics}}$	0.51 ppb (1.28 %)
$(\Delta A^{\mathrm{exp}})_{\mathrm{Polarization}}$	0.21 ppb (0.53 %)
$(\Delta A^{\mathrm{exp}})_{\mathrm{Apparative}}$	0.10 ppb (0.25 %)
$\langle s^2_{\mathrm{W}}\rangle$	0.231 16
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s^2_{\mathrm{W}})_{\Box_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s^2_{\mathrm{W}})_{\mathrm{nucl.\ FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2\rangle_{\mathrm{Cherenkov}}$	$4.57 \times 10^{-3}\,(\mathrm{GeV/c})^2$
$\langle A^{\mathrm{exp}}\rangle_{\mathrm{Cherenkov}}$	-28.77 ppb

Conceptually very simple experiments



$A = (N^+ - N^-)/(N^+ + N^-)$ $\Delta A = (N^+ + N^-)^{-1/2} = N^{-1/2}$

$A = 20 \times 10^{-9}$ 2% Measurement $N = 6.25 \times 10^{18}$ events

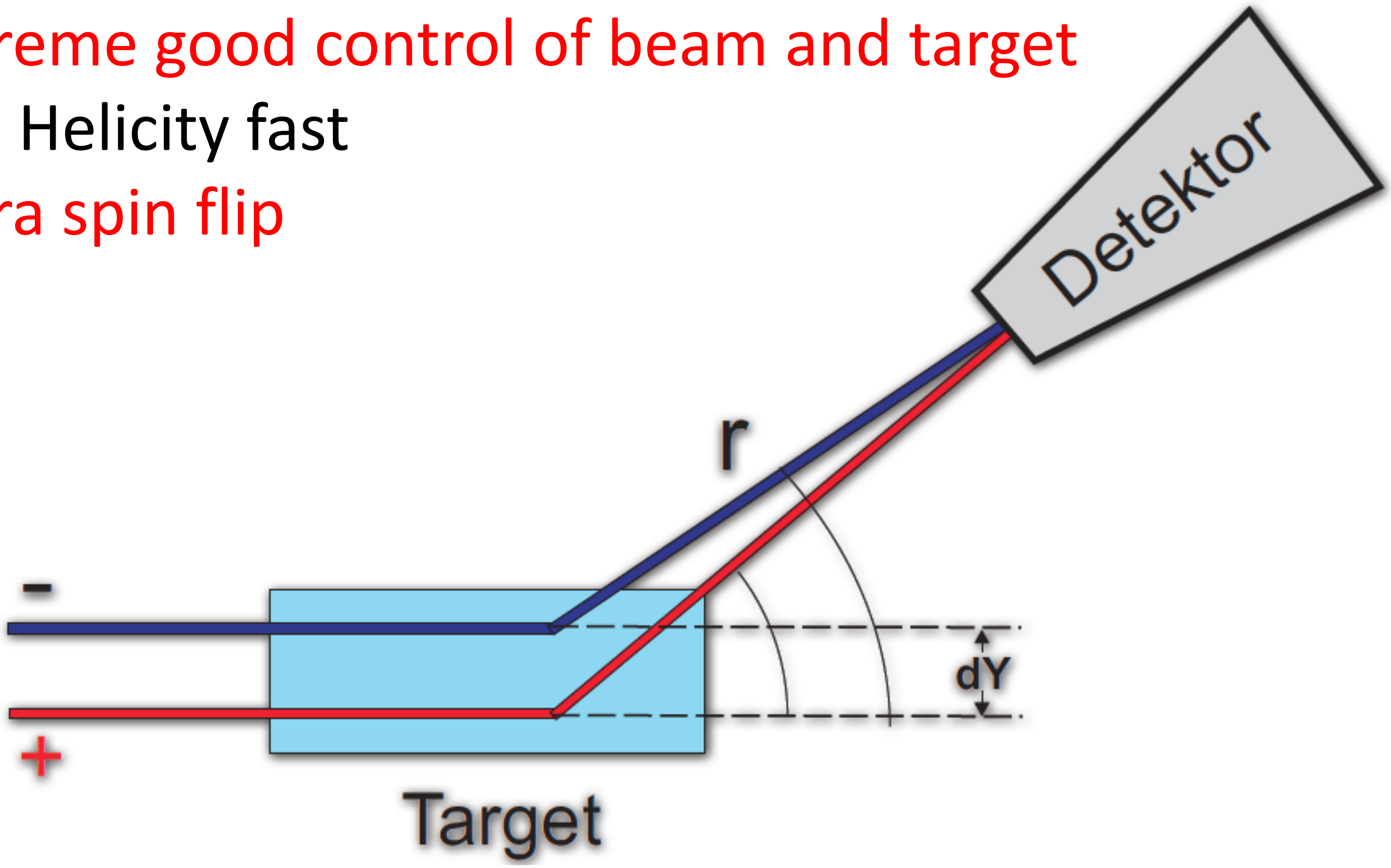
Highest rate, measure Q^2: Large Solid Angle Spectrometers

Apparative (false) asymmetries:

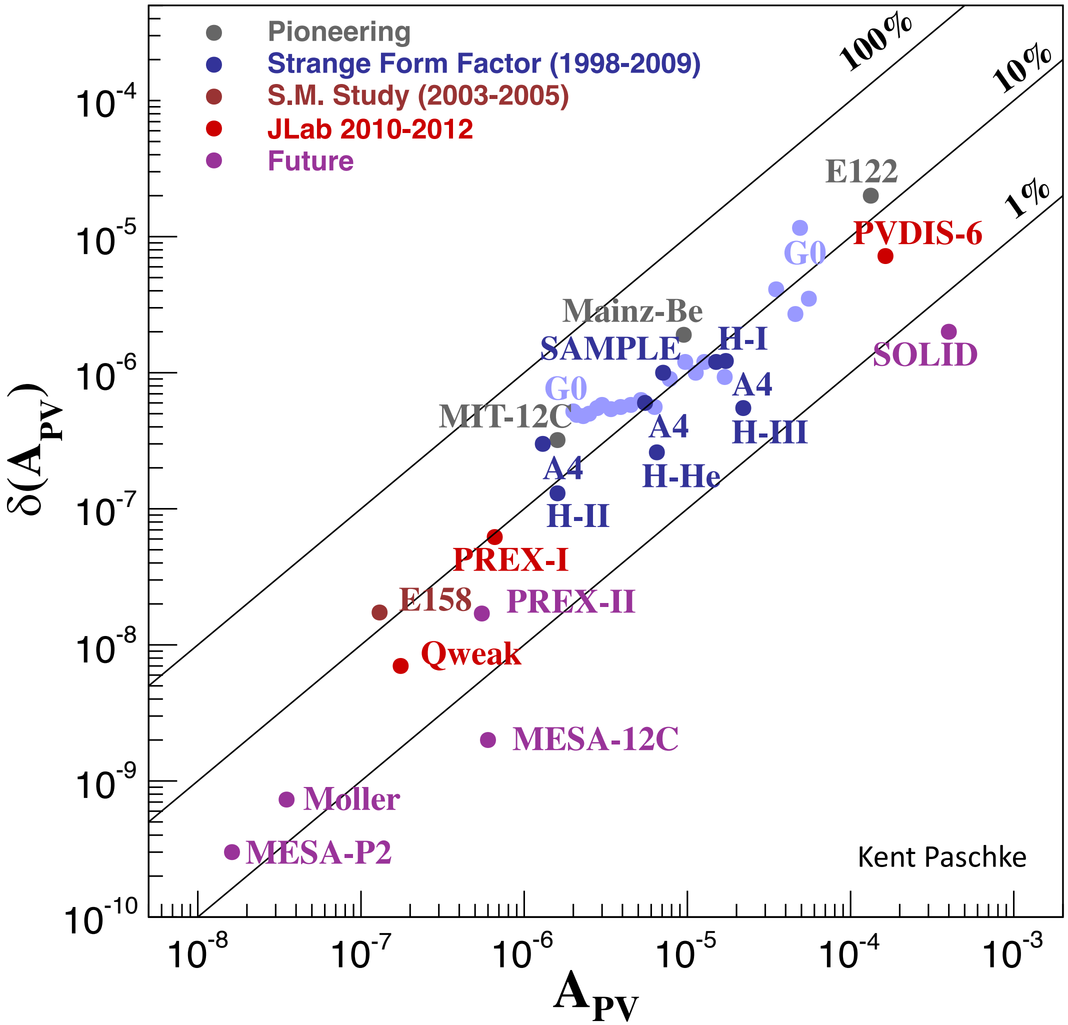
Extreme good control of beam and target

Flip Helicity fast

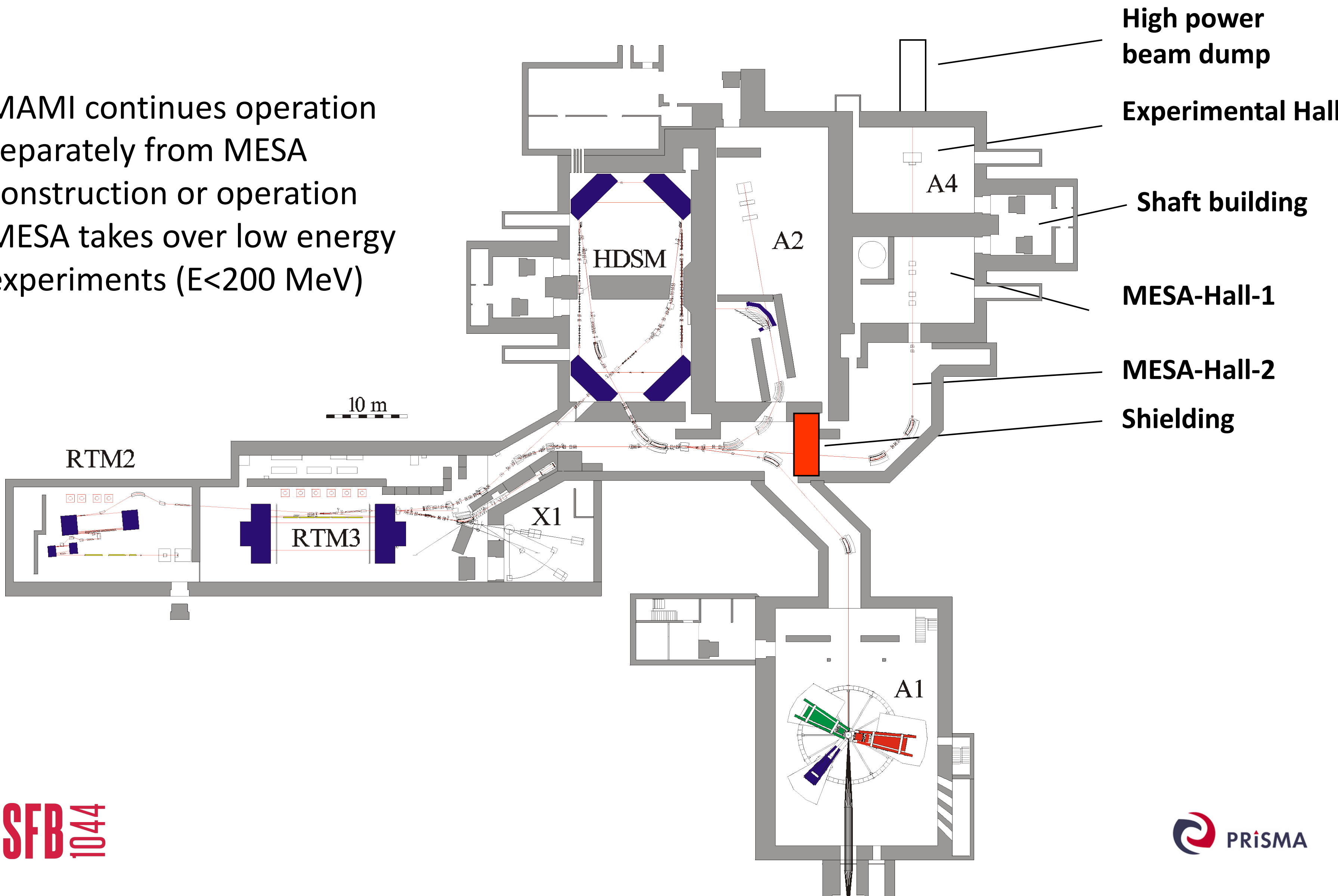
Extra spin flip



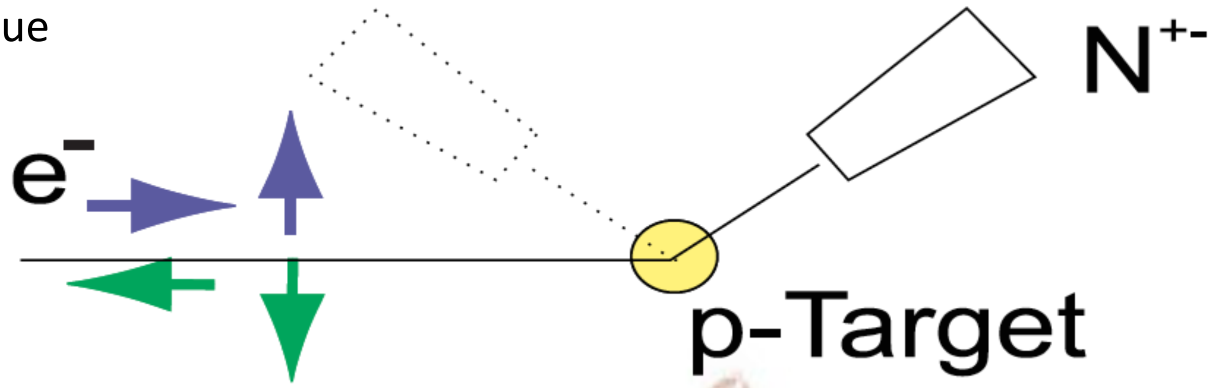
PVeS Experiment Summary



- MAMI continues operation separately from MESA construction or operation
- MESA takes over low energy experiments (E<200 MeV)



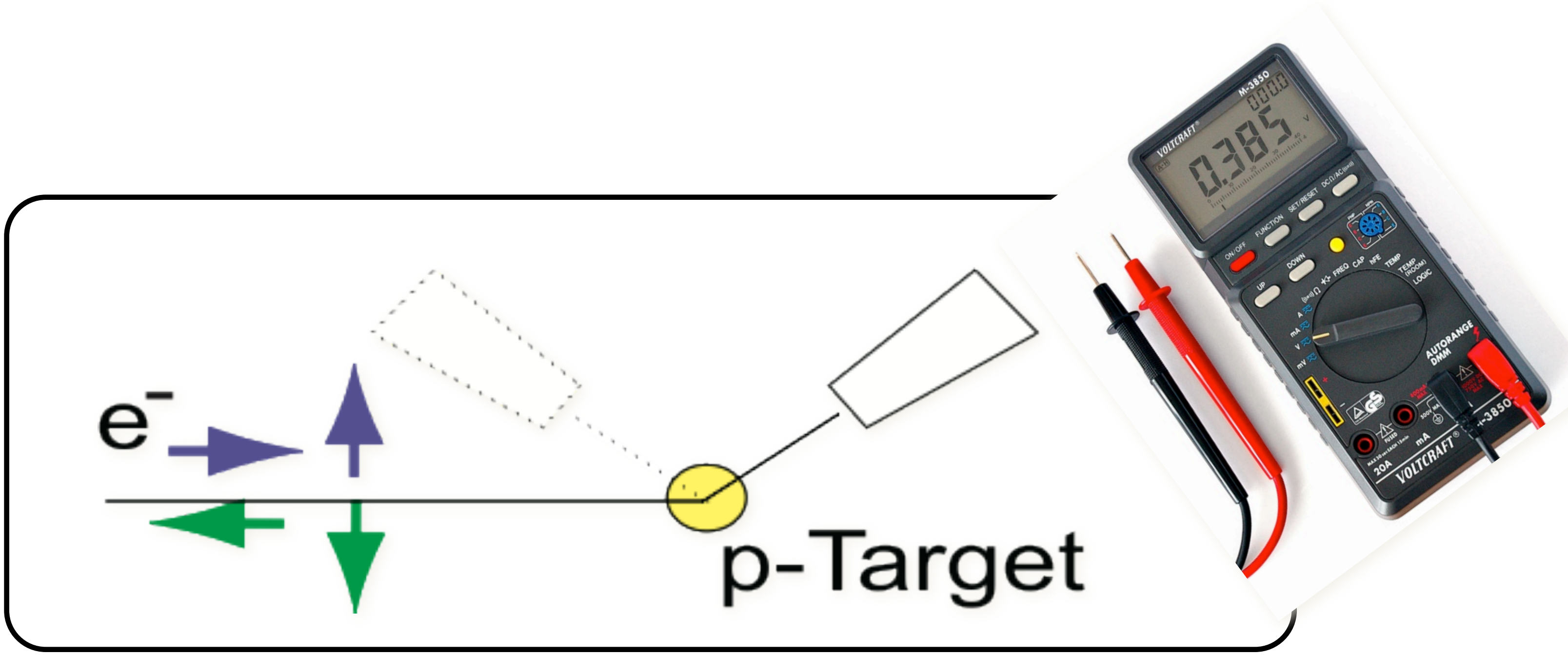
Counting Technique



Count scattered electrons:

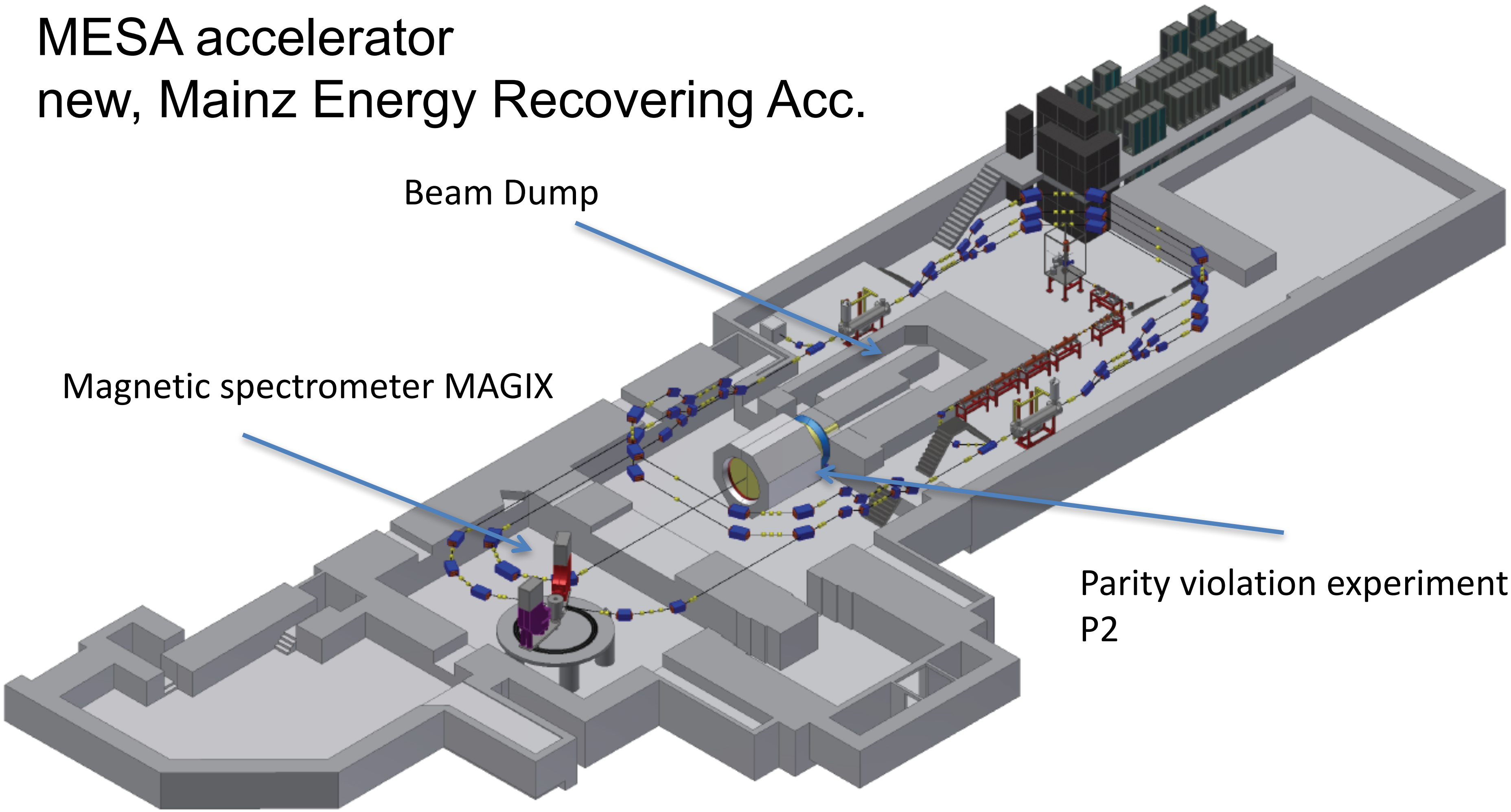
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy

Analogue Technique

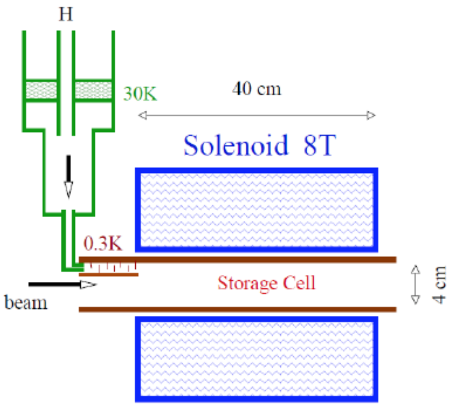


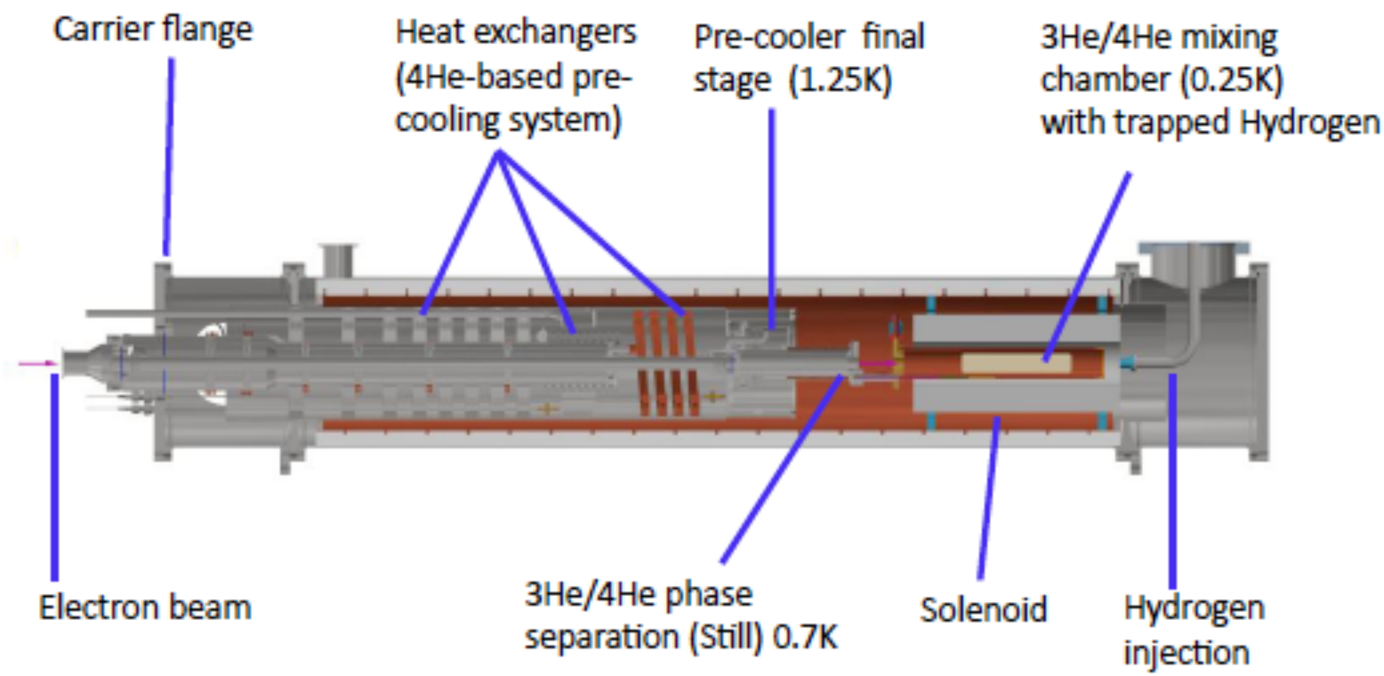
Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

MESA accelerator
new, Mainz Energy Recovering Acc.



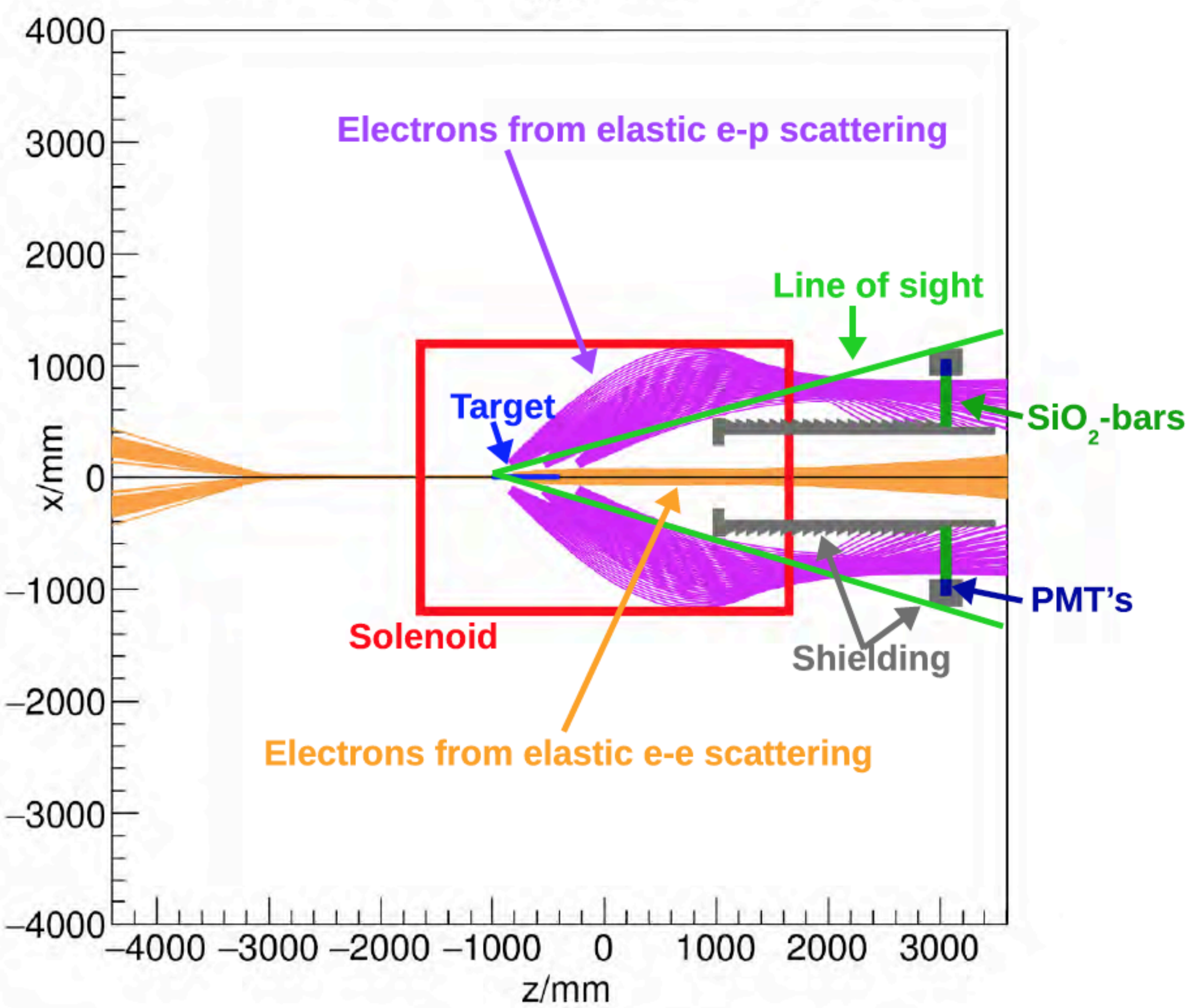
Hydro-Möller Polarimeter





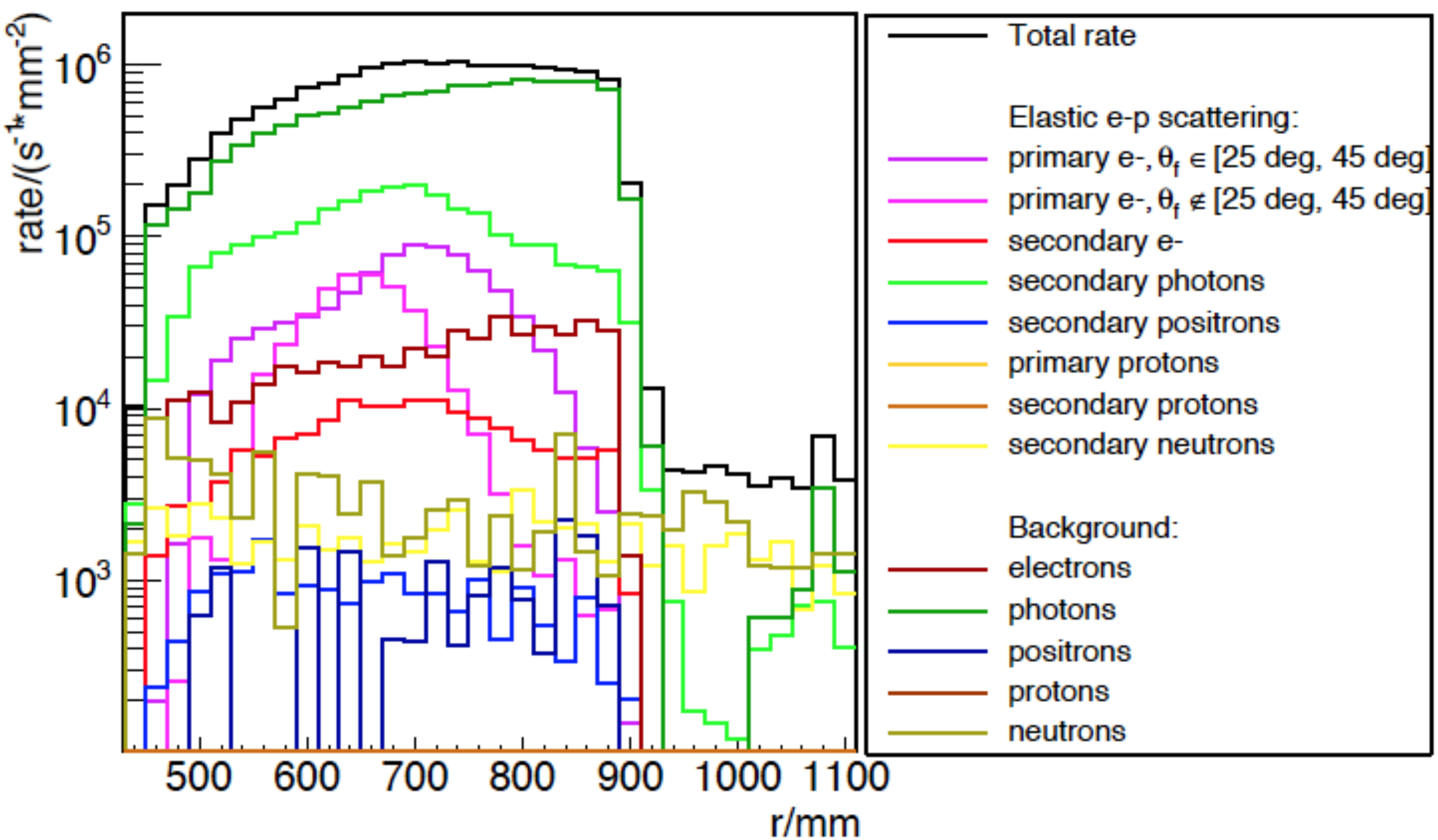
P2-experimental setup

Simple ray-tracing



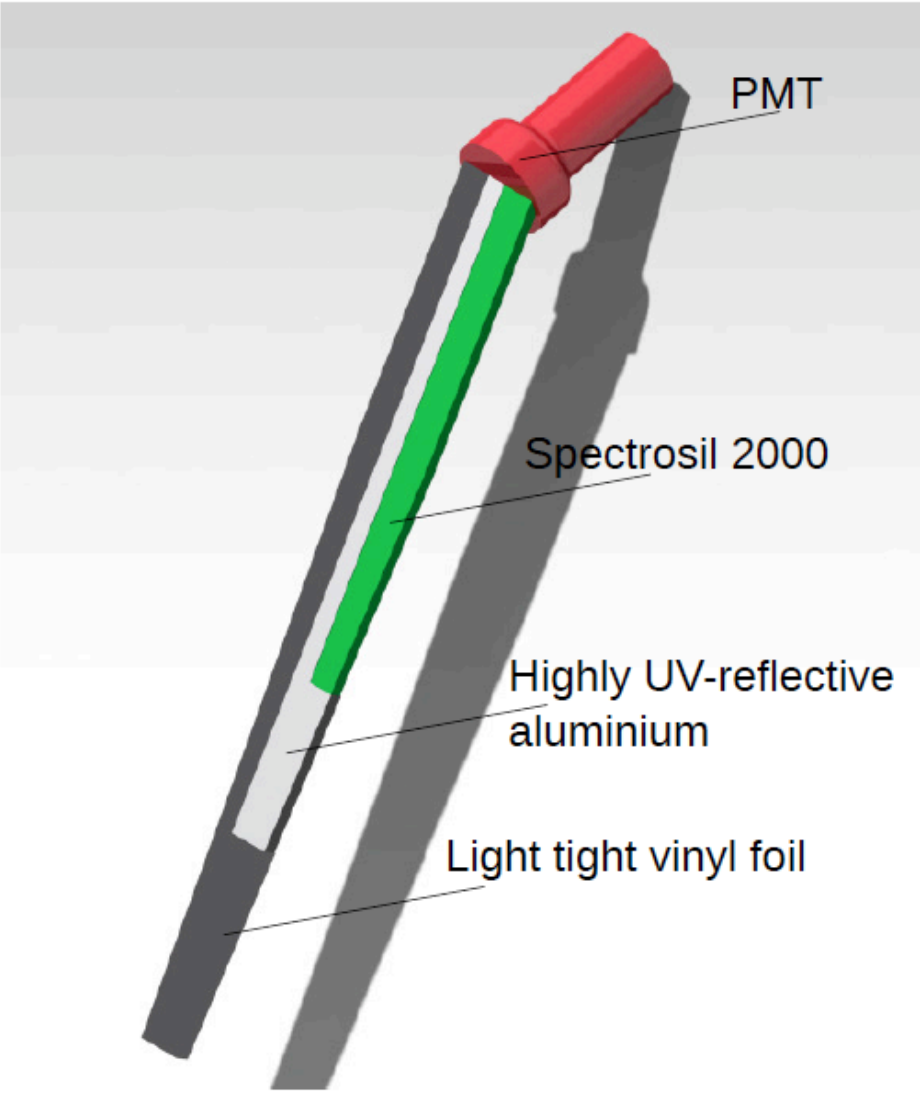
Particle rates

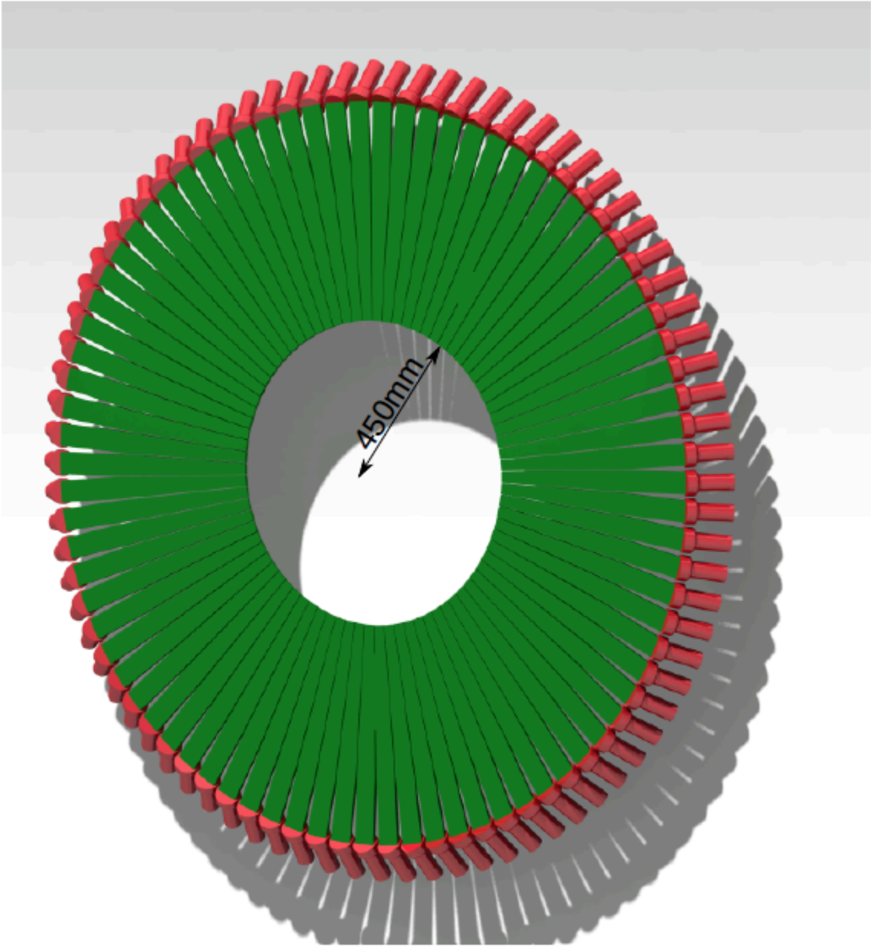
Full GEANT4 simulation



Dominik Becker

Full GEANT4 simulation



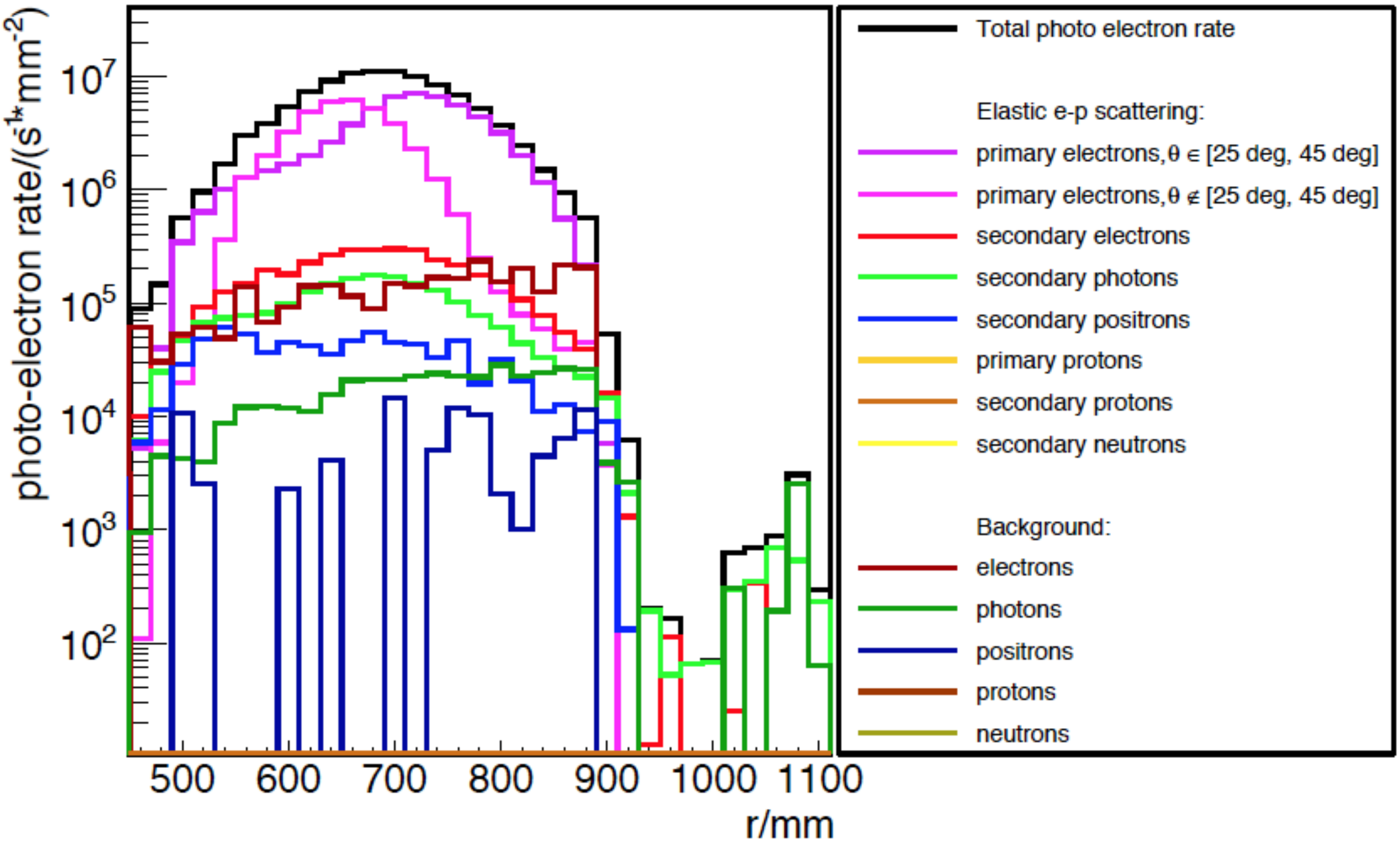


Kathrin Gerz

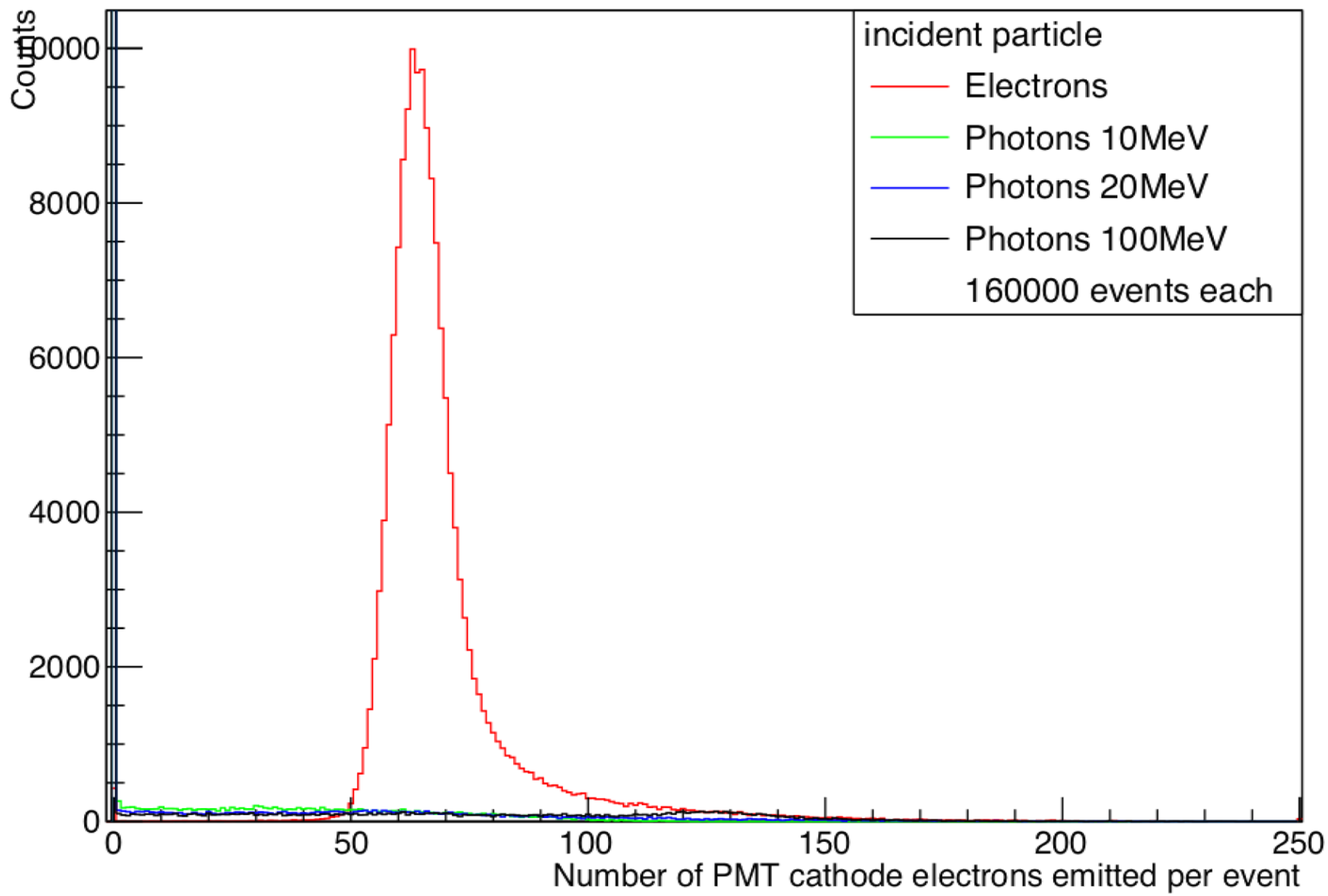
P2-Detector response

SFB 1044
Institut für Kernphysik

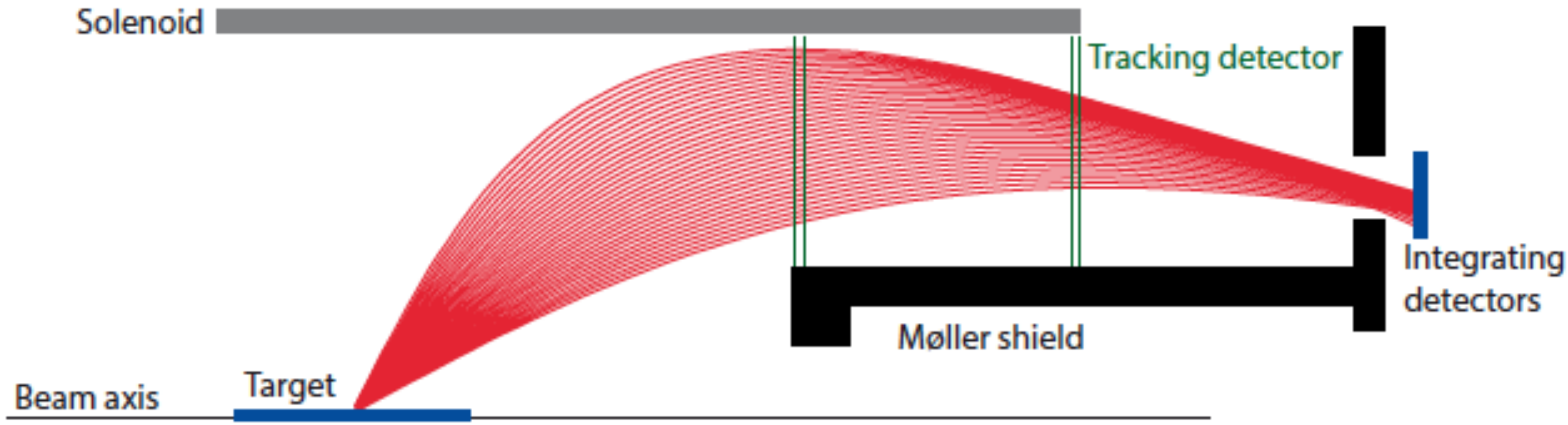
Full GEANT4 simulation

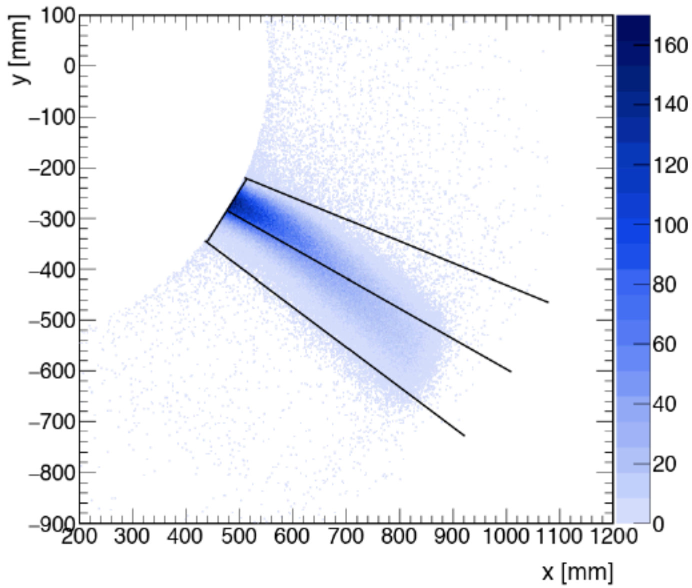


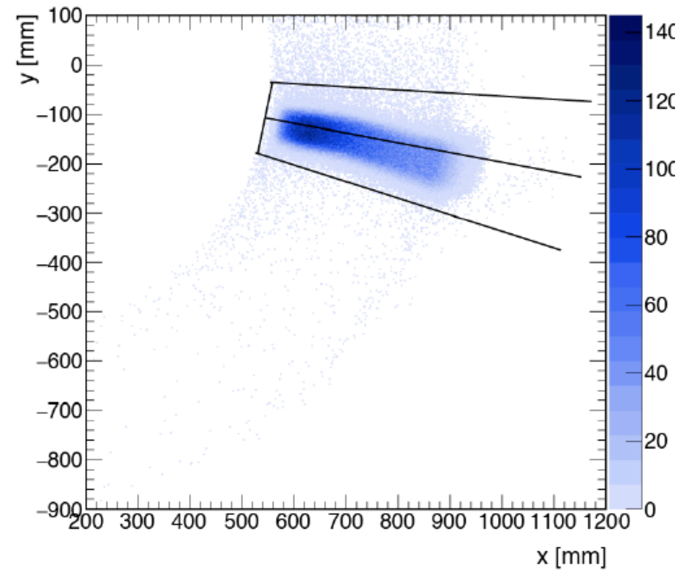
Number of PMT cathode electrons emitted per event

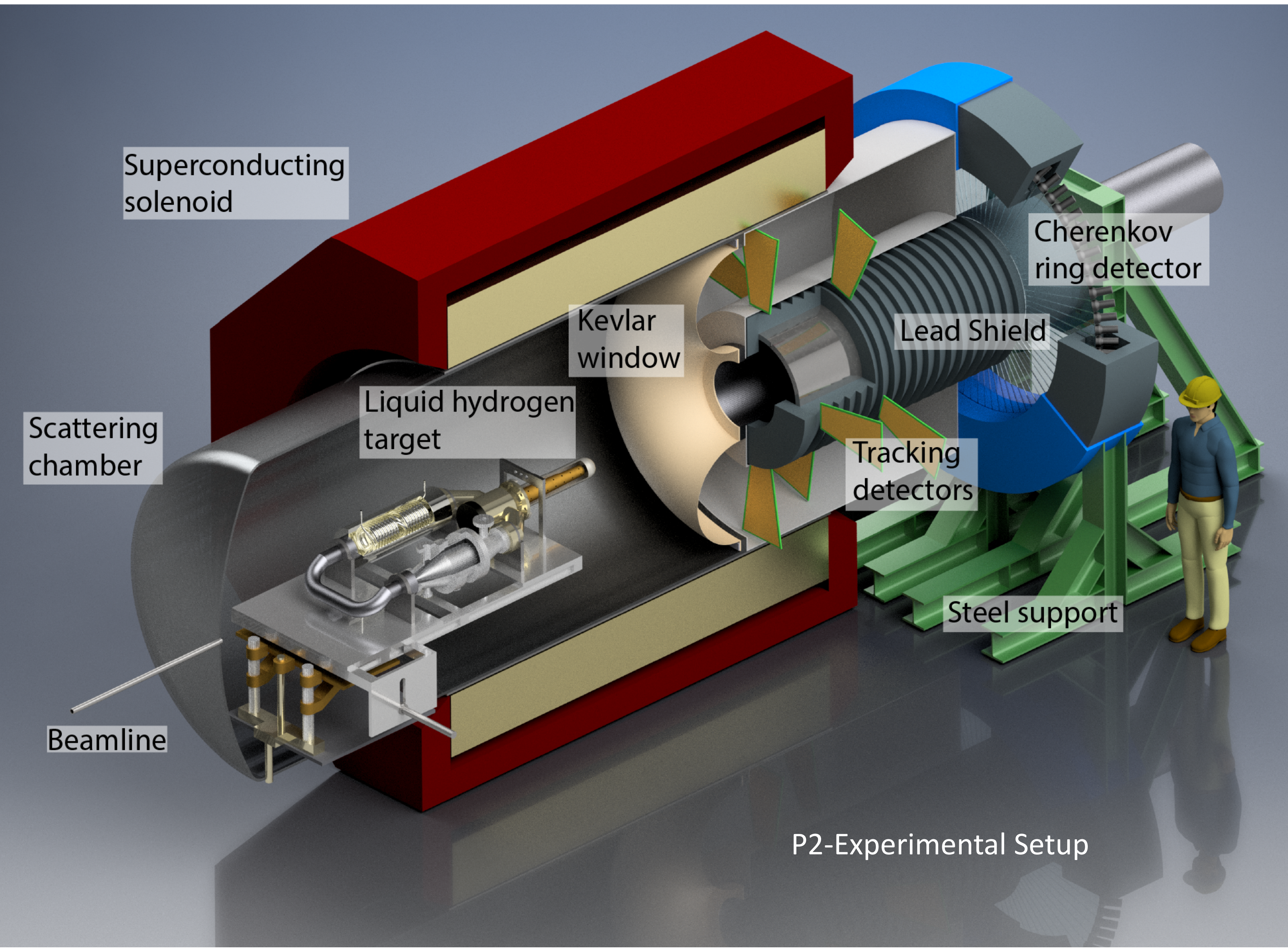


Q^2-Measurement





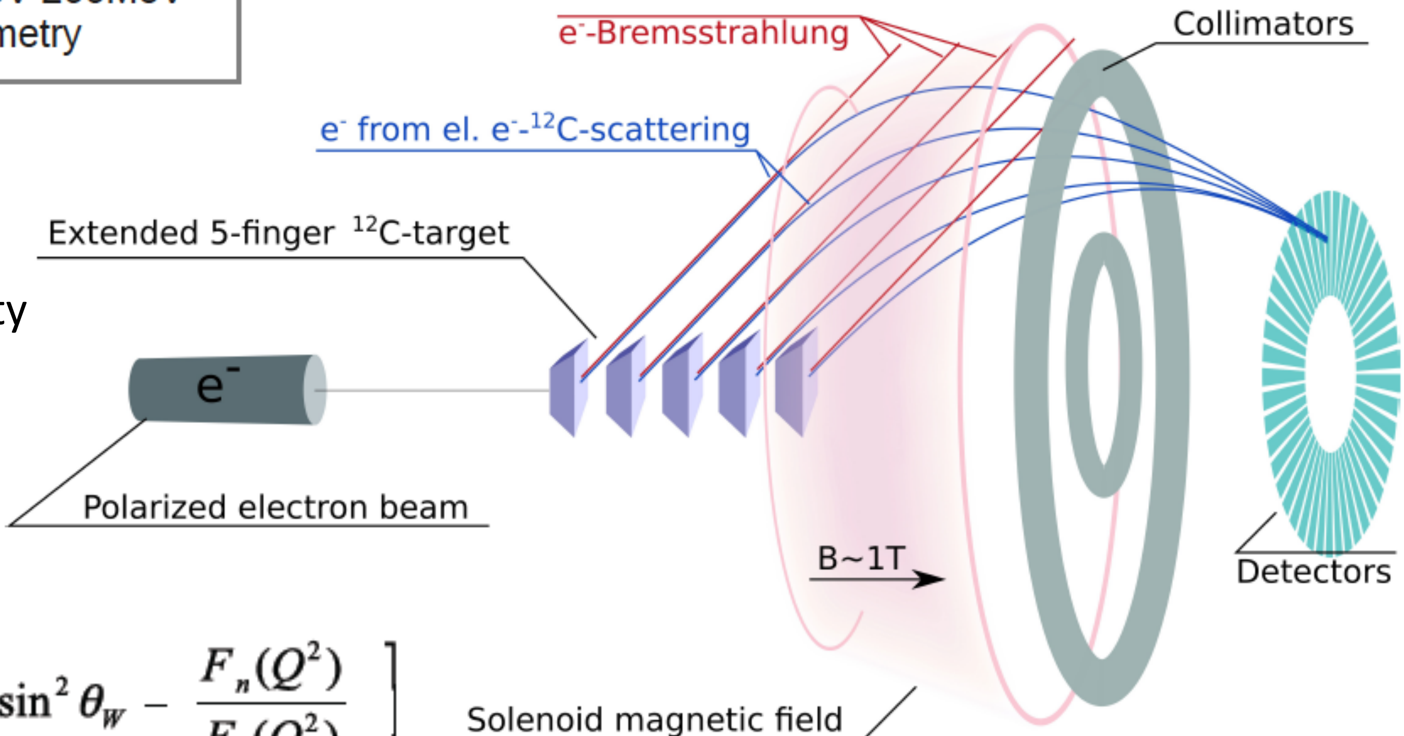



Superconducting solenoid
Cherenkov ring detector
Kevlar window
Lead Shield
Liquid hydrogen target
Scattering chamber
Tracking detectors
Steel support
Beamline
P2-Experimental Setup

Other Measurements:
Carbon, Lead

EXPERIMENTAL REALIZATION

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

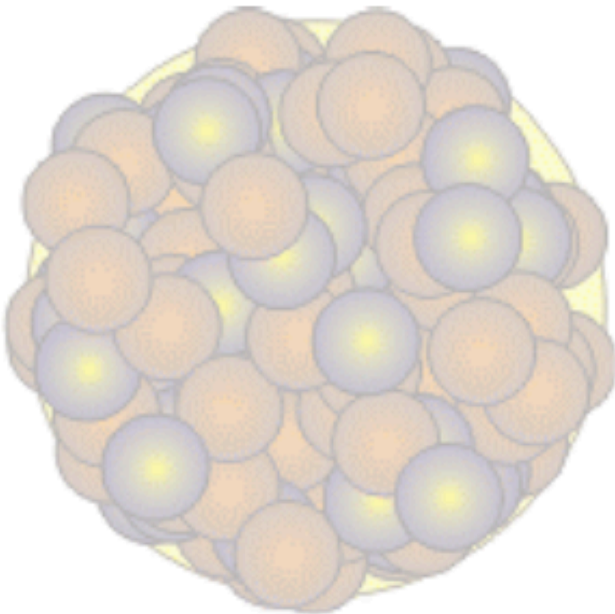


Enhanced sensitivity
To new physics

$$-N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

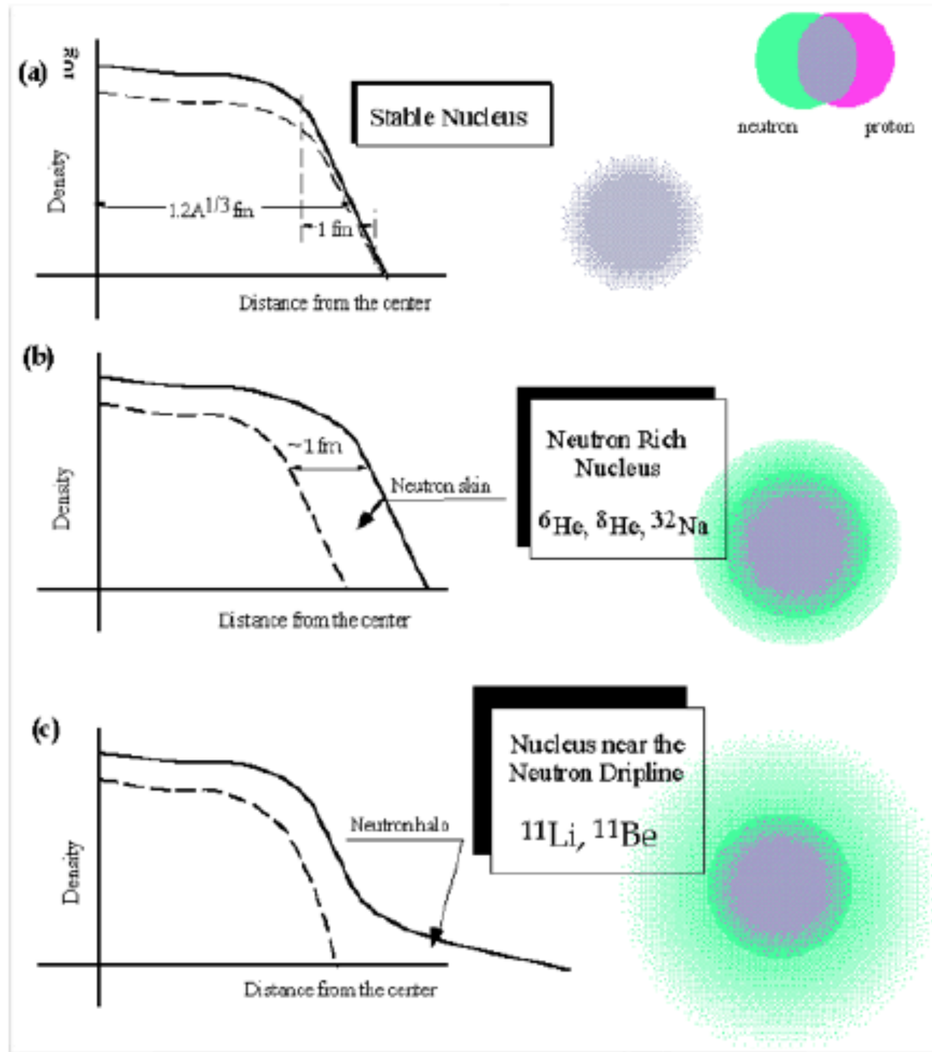
Neutron Skin for beginner

Where do the neutrons go?



Pressure forces neutrons out against surface tension

→ **EOS**



The P2 Experiment arXiv:1802.04759

A future high-precision measurement of the electroweak mixing angle at low momentum transfer

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[16] Physics Department, Syracuse University, Syracuse, USA
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- Parity violating electron scattering: "Low energy frontier" comprises a sensitive test of the standard model complementary to LHC

- Determination of $\sin^2(\theta_W)$ with high precision (similar to Z-pole)

- P2-Experiment (proton weak charge) in Mainz under preparation New MESA energy recovering accelerator at 155 MeV, target precision is 2 % in weak proton charge i.e. 0.15% in $\sin^2(\theta_W)$, Sensitivity to new physics up to a scale of 50 MeV up to 50 TeV
- Much more physics from PV electron scattering
- Together with Moeller@Jlab (electron weak charge) and SOLID@Jlab (quark weak charge) very sensitive test of standard model and possibility to narrow in on Standard Model Extension