JG|U

SFB 1044
Institut für Kernphysik

$\sin^2 \theta_W = 0.238$
$\theta_W = 29{,}2°$

Future PVES Experimen
New, high precision measu
of the weak mixing angle

θ_W

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

"The Electroweak Box Workshop", Amherst Center for Fu
September 428-30, 2017

SFB 1044 HIM PRISMA

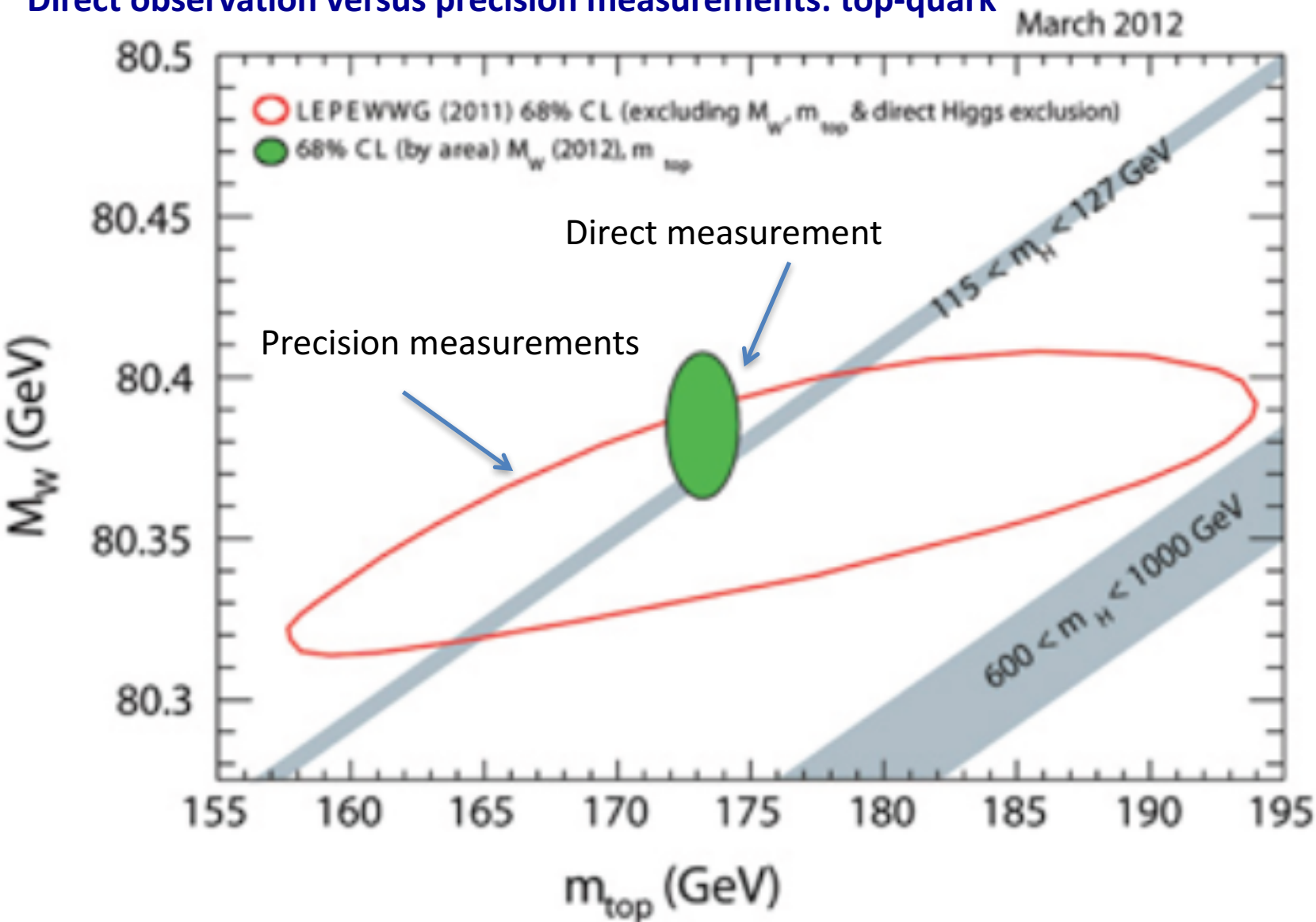
Search for New Physics: Various Methods

High Energy (LHC)

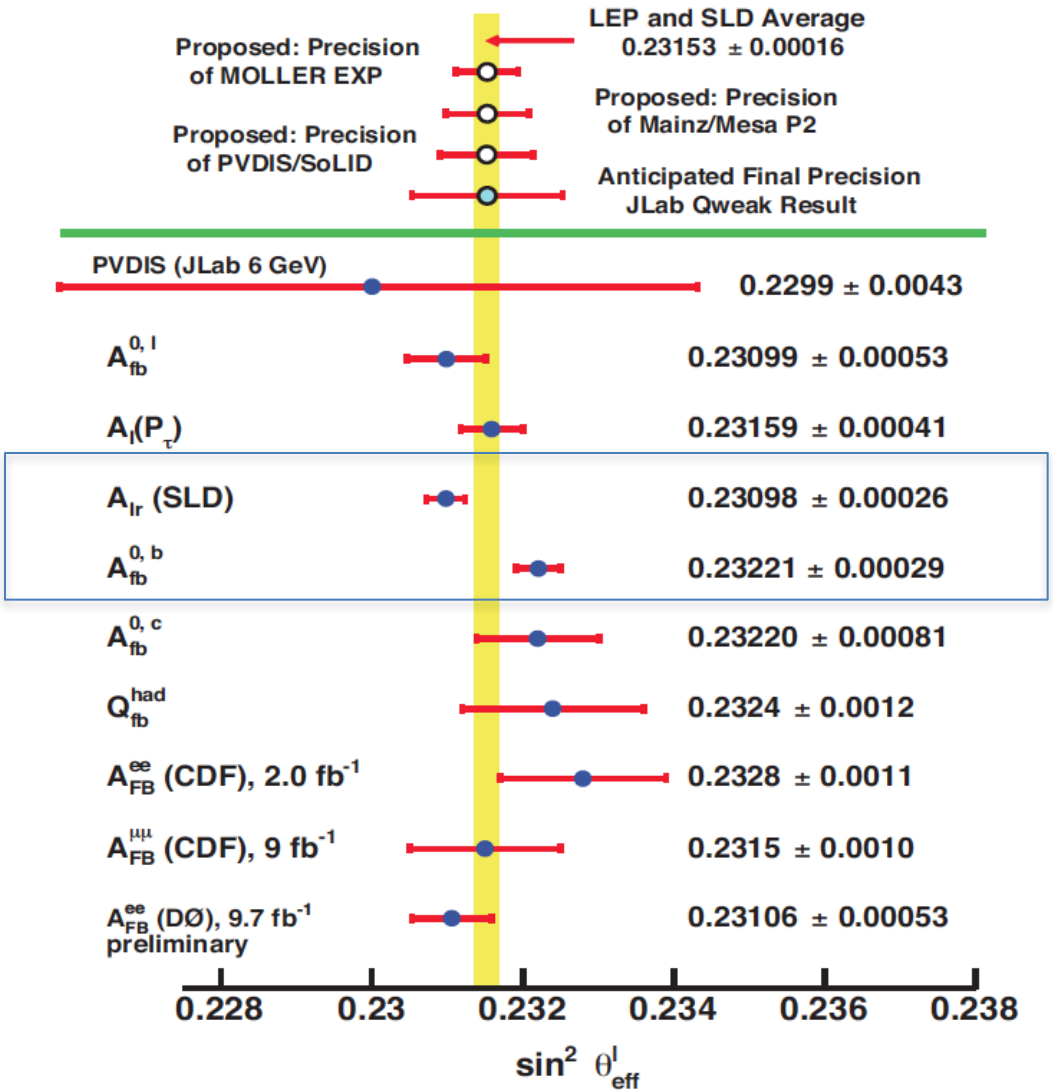
High Intensity
(B-decays)

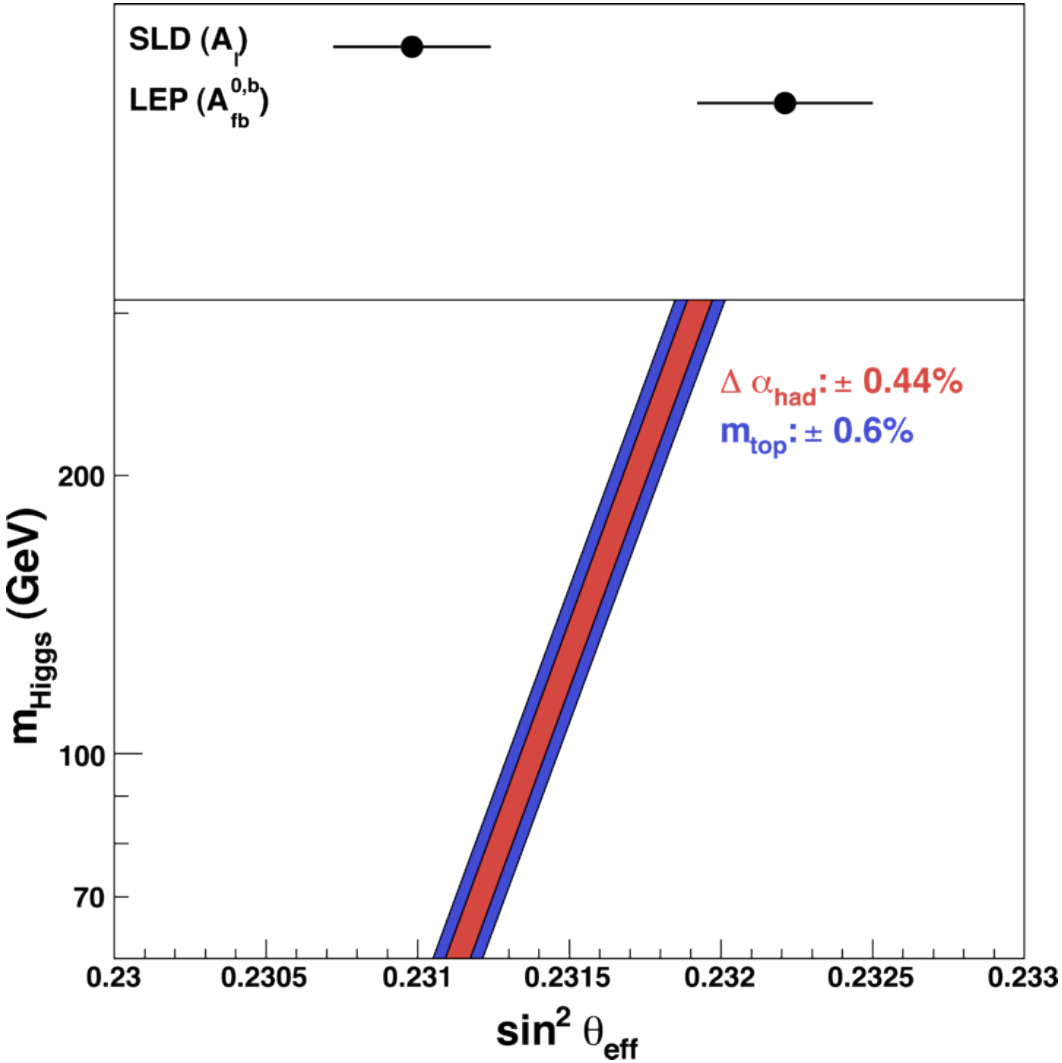
High Precision
($(g-2)_\mu$, EDM, $\sin^2\theta_W$, ...)
(at low energy)

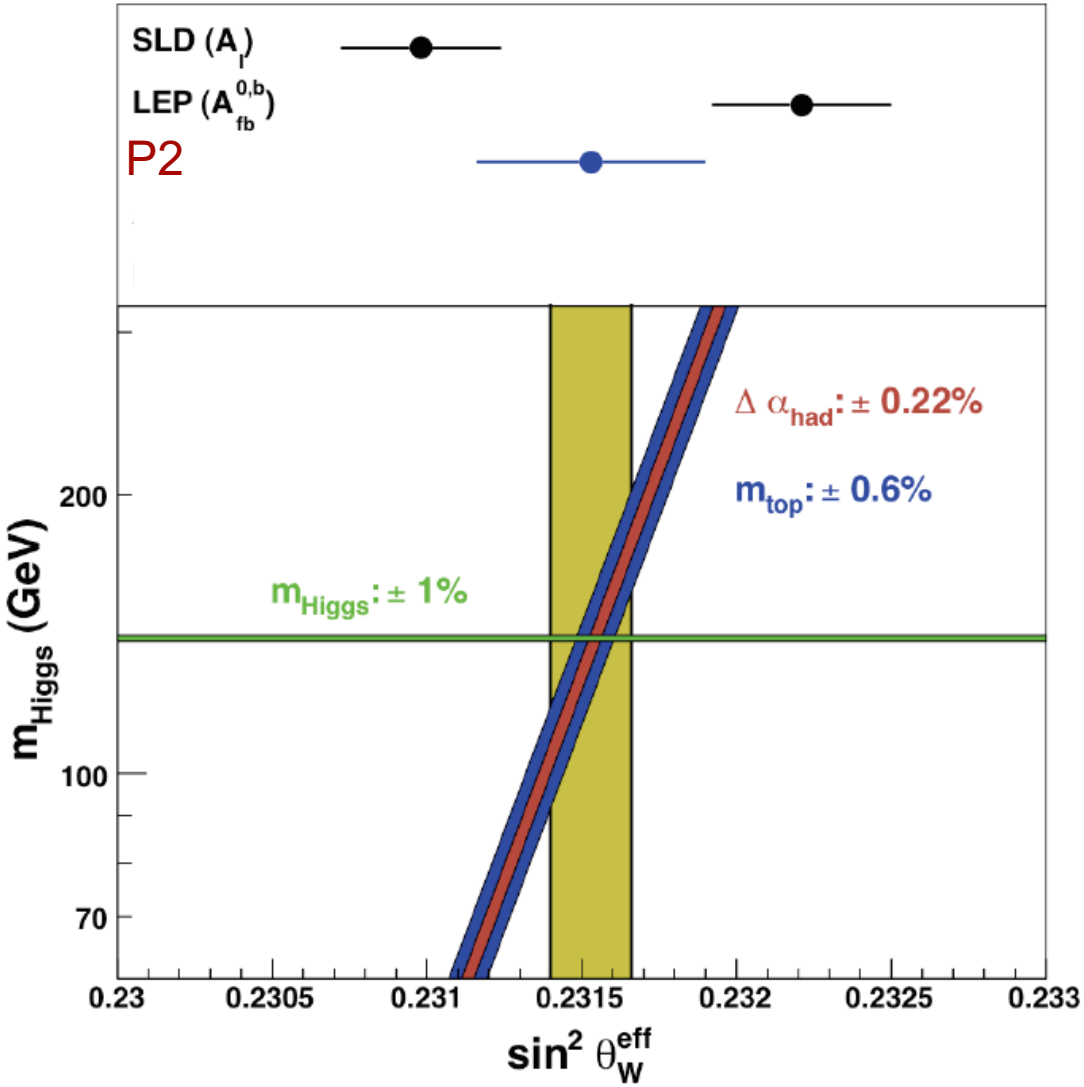
Direct observation versus precision measurements: top-quark



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

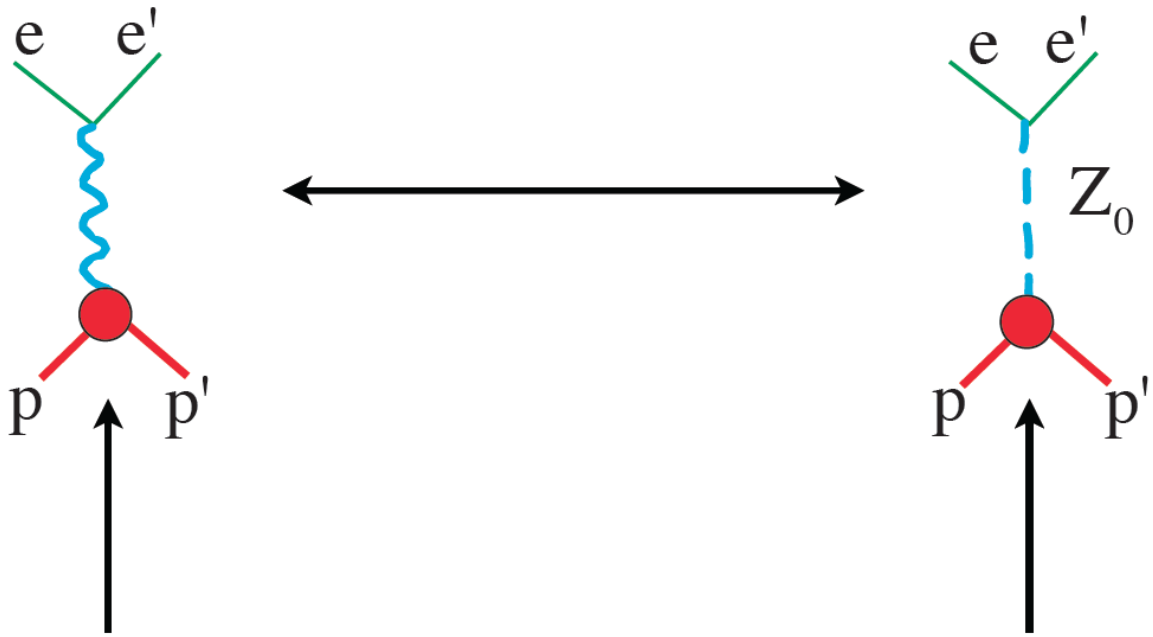



SLD (A_l)
LEP ($A_{fb}^{0,b}$)
$\Delta\alpha_{had}$: ± 0.44%
m_{top}: ± 0.6%
m_{Higgs} (GeV)
200
100
70
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2\theta_{eff}$


SLD (A_l)
LEP ($A_{fb}^{0,b}$)
P2
$\Delta\alpha_{had}$: ± 0.22%
m_{top}: ± 0.6%
m_{Higgs}: ± 1%
m_{Higgs} (GeV)
200
100
70
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: $\sin^2(\theta_W)$



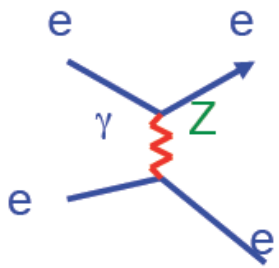
$Q_e(p) = +e$
electric charge of the proton

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

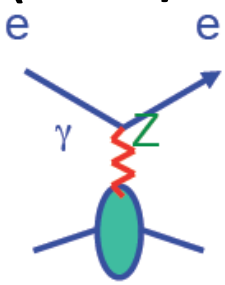
$\sin^2 \theta_W$: a central parameter of the standard model

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

Møller Scattering

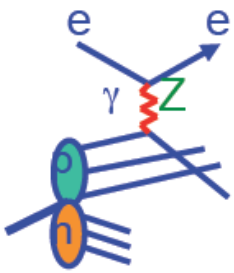


- Purely Leptonic



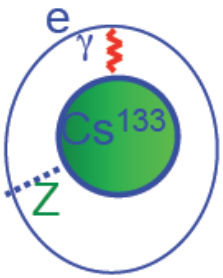
- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS



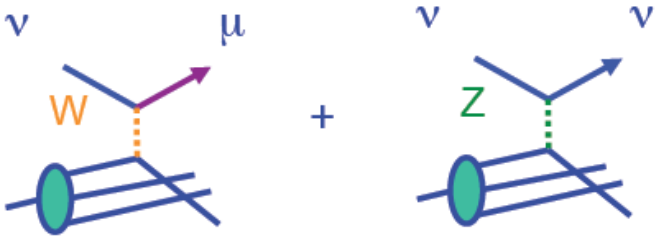
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Atomic Parity Violation



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

Neutrino Scattering



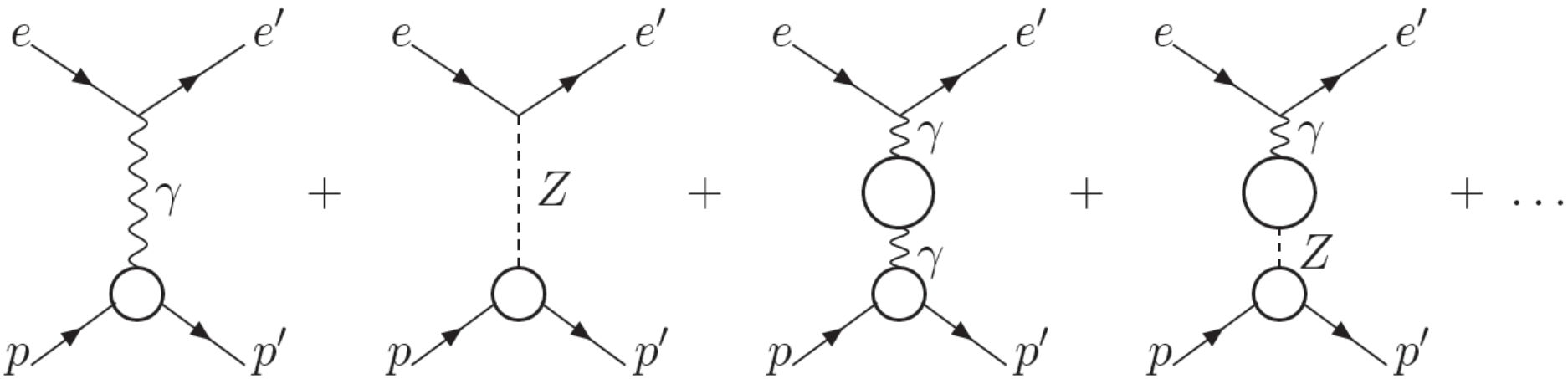
- Quark scattering (from nucleus)
- Weak charged and neutral current difference

S. Su

Courtesy of P. Reimer and R. Arnold

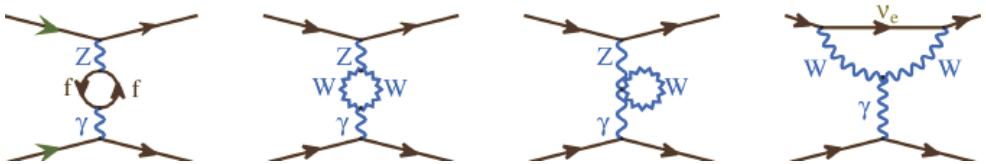
„running“ $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$

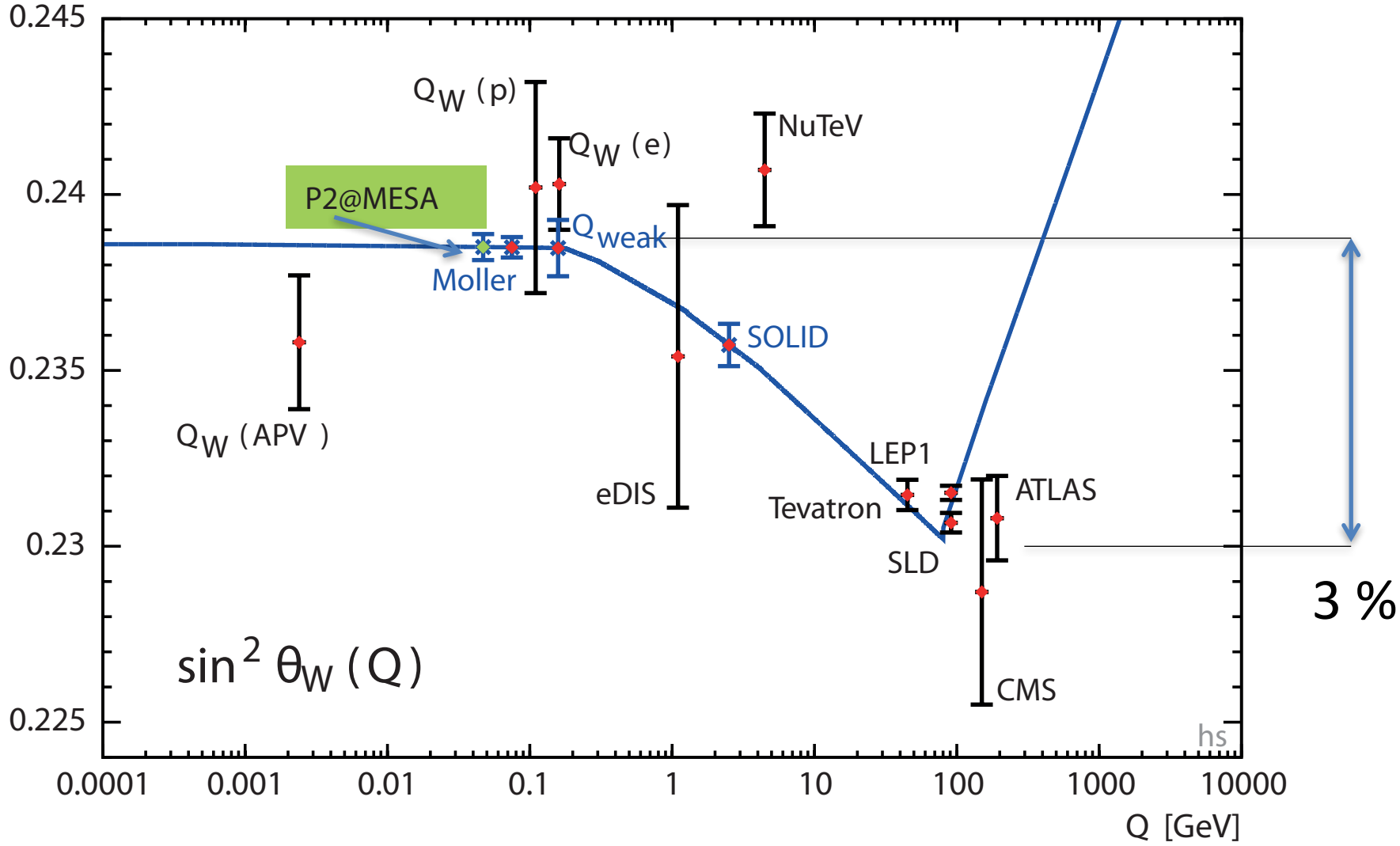
Precision measurements and quantum corrections:



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

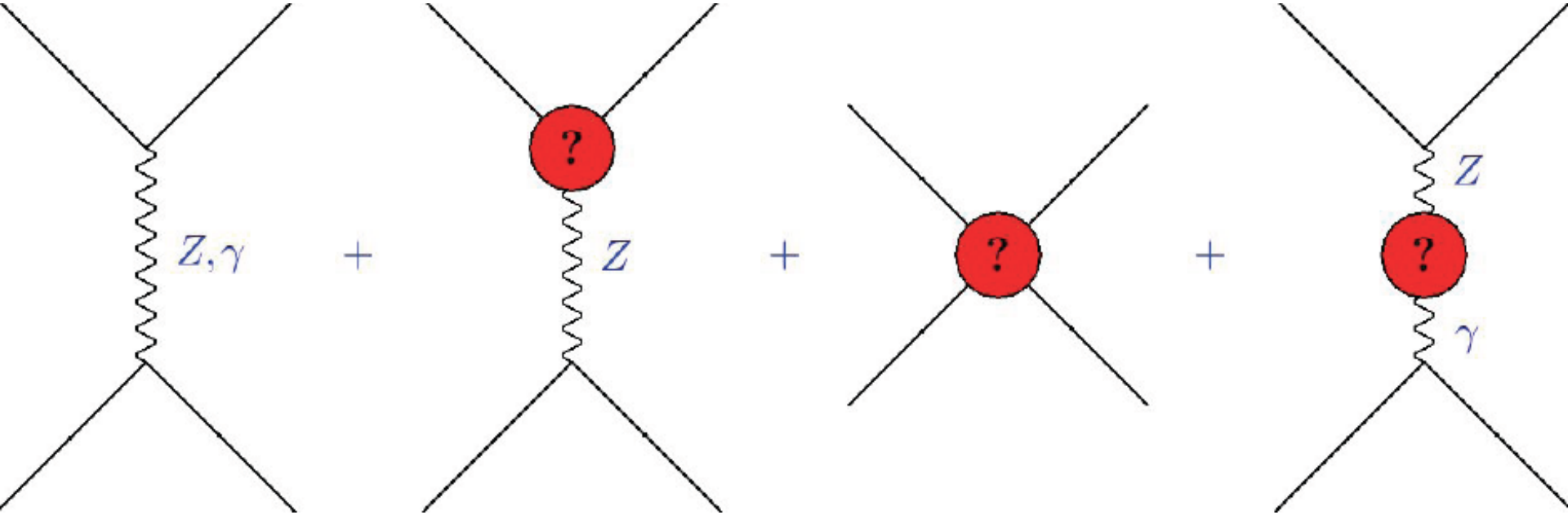
Universal quantum corrections: can be absorbed into a scale dependent, „running“ $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$




0.245
0.24
0.235
0.23
0.225
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Q [GeV]
Q_W (p)
Q_W (e)
NuTeV
P2@MESA
Q_{weak}
Moller
SOLID
Q_W (APV)
eDIS
LEP1
Tevatron
ATLAS
SLD
CMS
3 %
$\sin^2\theta_W(Q)$
hs

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

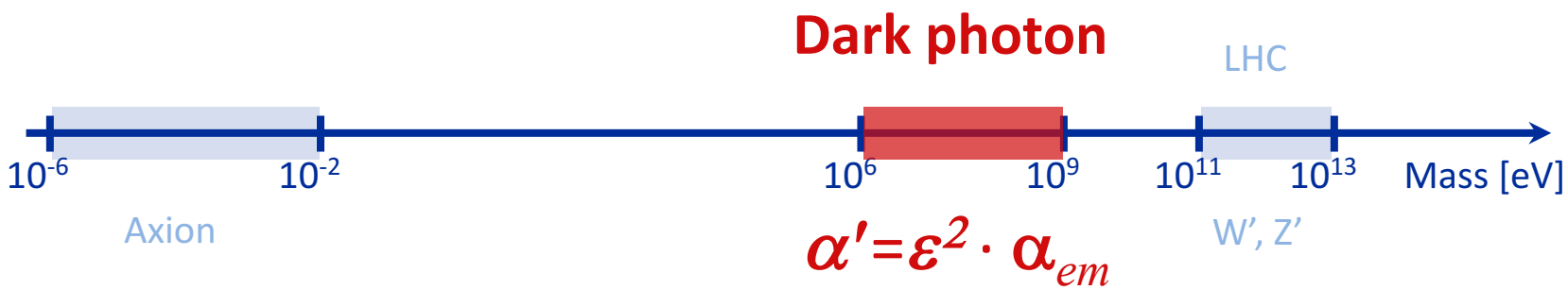
Contact interaction

New
Fermions

Dark Photon, Z-Boson

New massive force carrier of extra $U(1)_d$ gauge group; predicted in almost all string compactifications

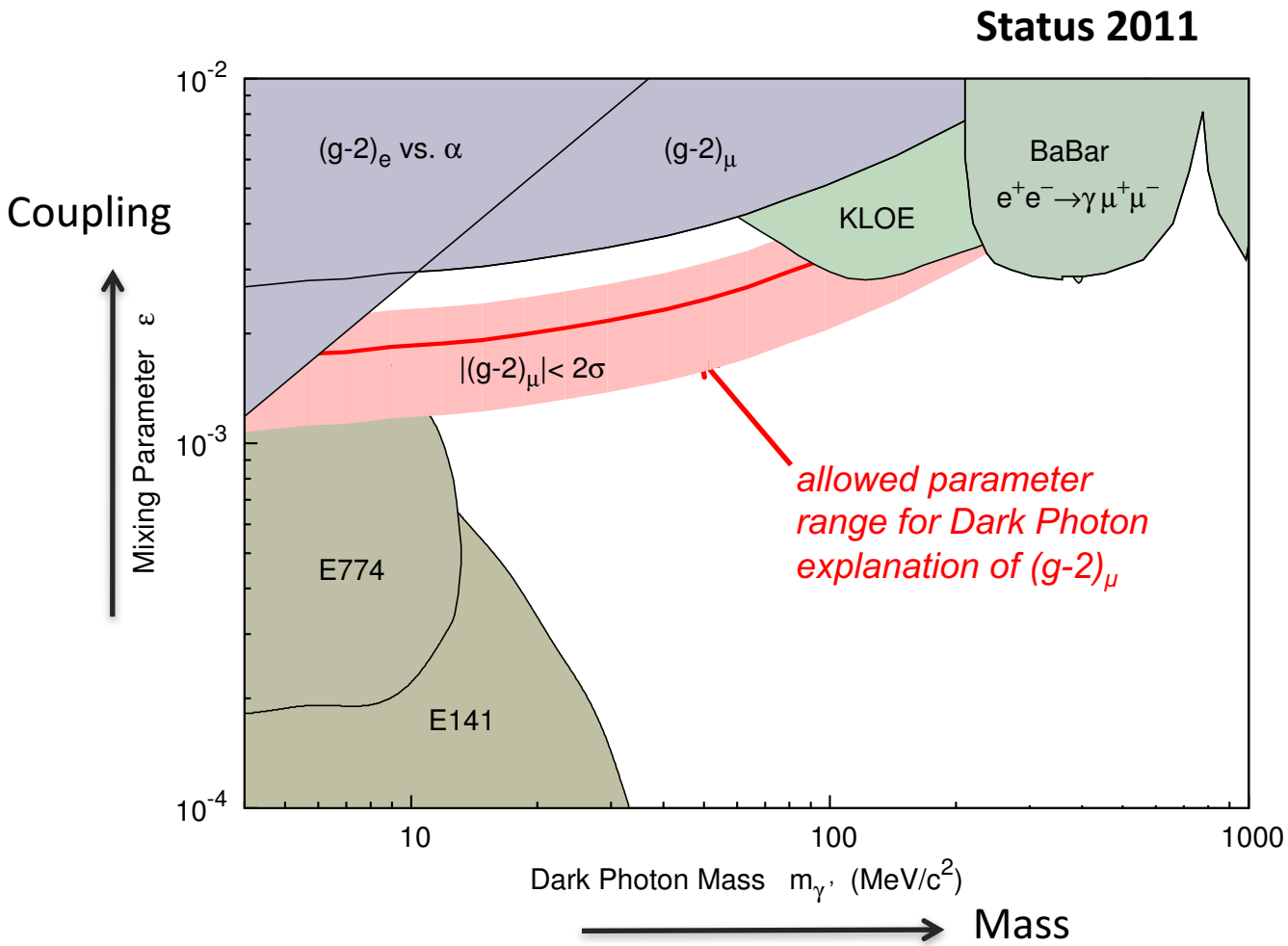
$$Z = \cos\theta_W W_3 - \sin\theta_W B$$
$$A = \sin\theta_W W_3 + \cos\theta_W B$$

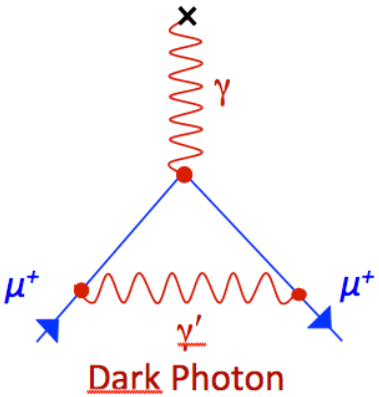


Search for the O(GeV/c^2) mass scale in a world-wide effort

- Could explain large number of **astrophysical anomalies**
  Arkani-Hamed et al. (2009)
  Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)

- Could (have) explained presently seen **deviation of >3σ** between **$(g-2)_\mu$** Standard Model prediction and direct $(g-2)_\mu$ measurement
  Pospelov(2008)

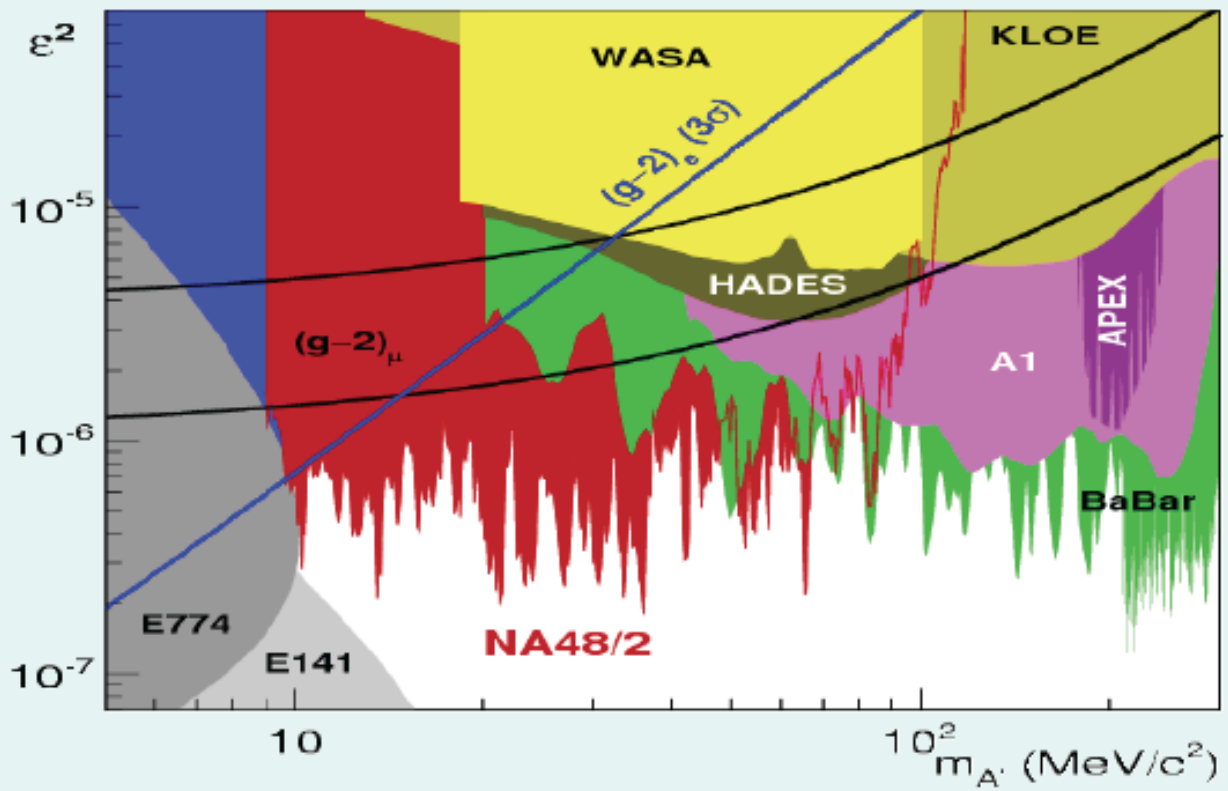

Status 2011
Coupling
Mixing Parameter ε
10^{-2}
10^{-3}
10^{-4}
$(g-2)_e$ vs. α
$(g-2)_\mu$
BaBar
$e^+e^- \to \gamma \mu^+\mu^-$
KLOE
$|(g-2)_\mu| < 2\sigma$
E774
E141
allowed parameter range for Dark Photon explanation of $(g-2)_\mu$
10
100
1000
Dark Photon Mass $m_{\gamma'}$ (MeV/c^2)
Mass


γ
μ^+
μ^+
γ'
Dark Photon

NA48/2 Updated Bounds on Dark Photon

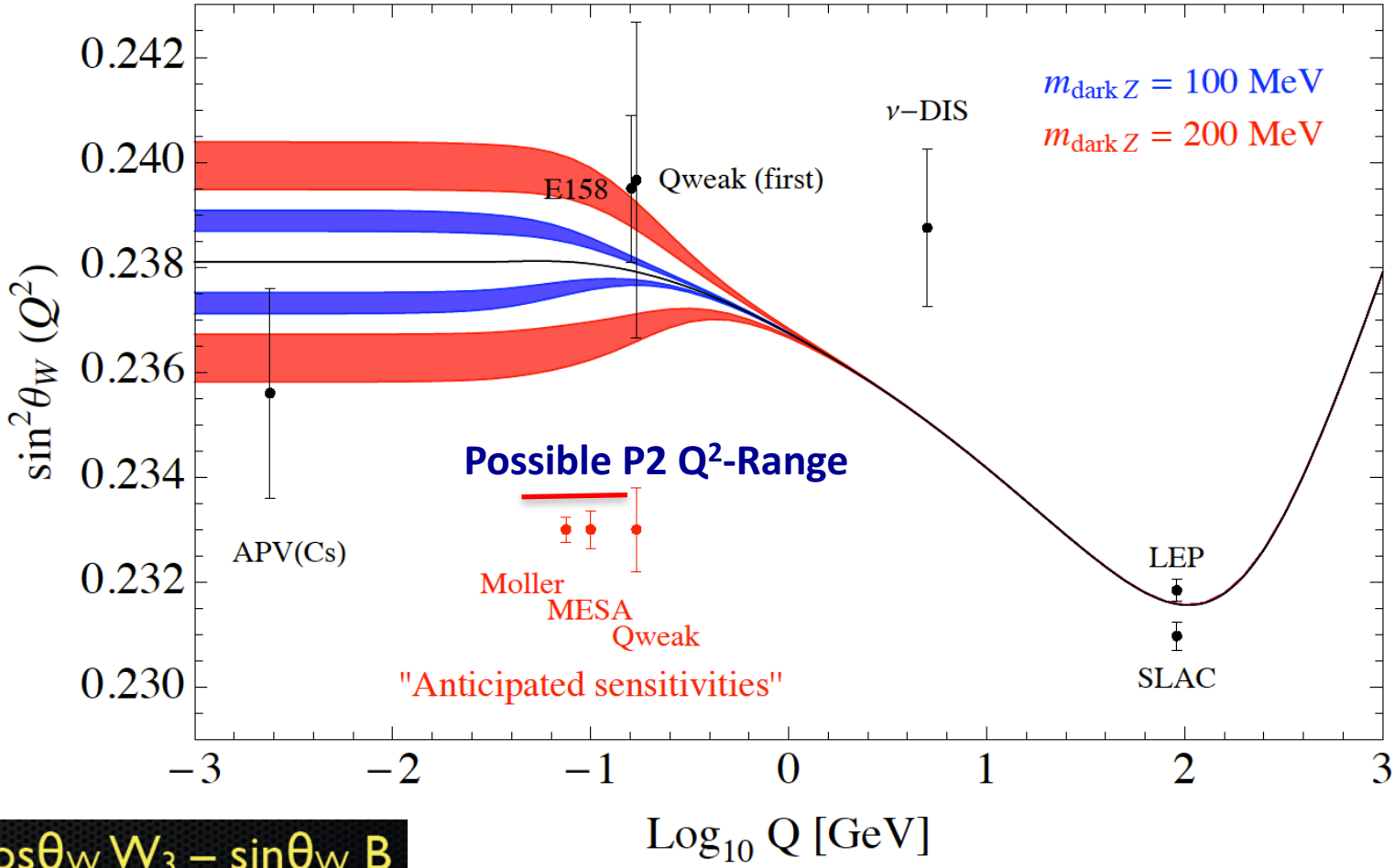
g_μ-2 discrepancy solution ruled out

Assumes BR(Z_d ➔ e+e-) ~1



H. Davoudiasl, W. Marciano

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

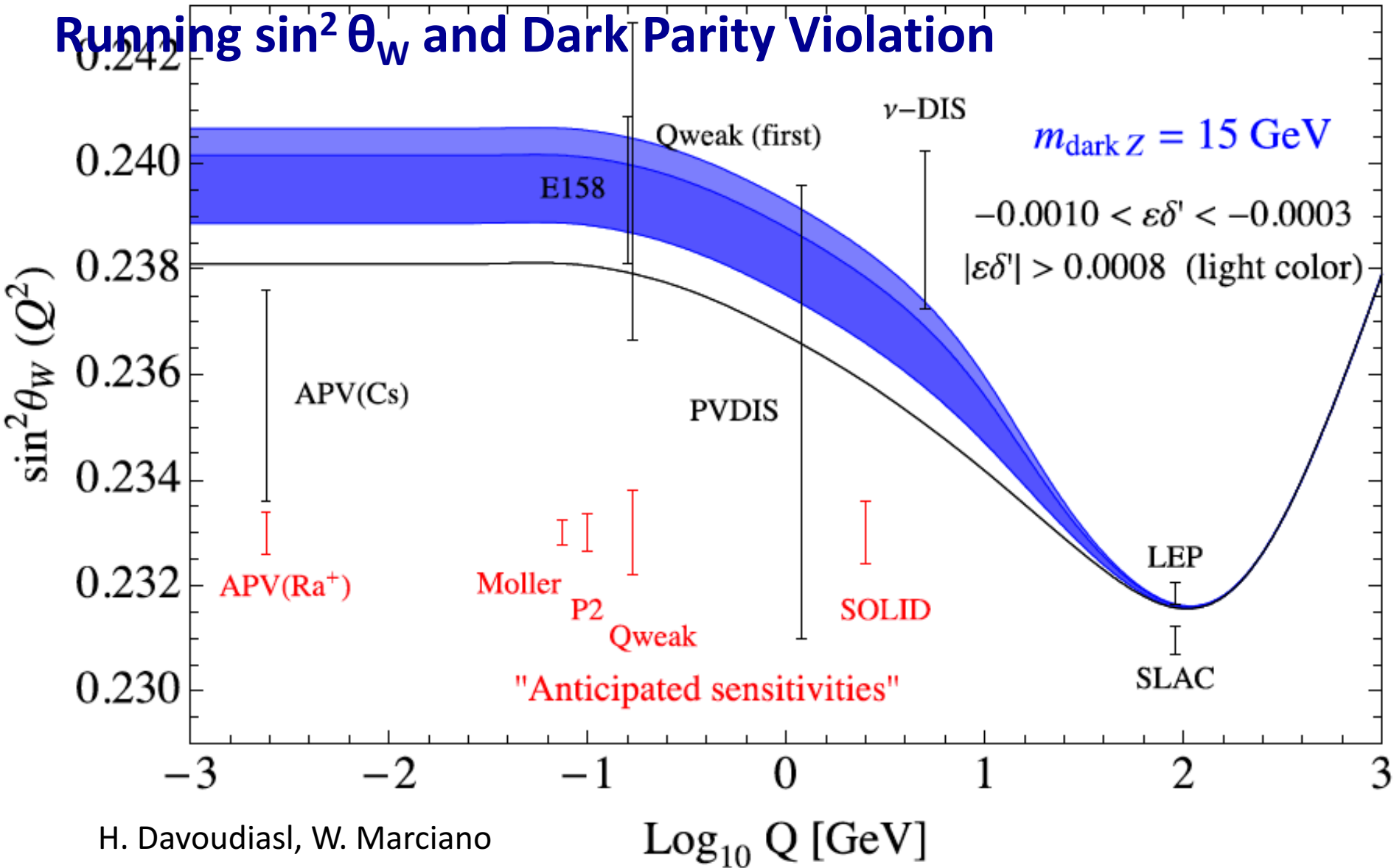


$Z = \cos\theta_W W_3 - \sin\theta_W B$

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

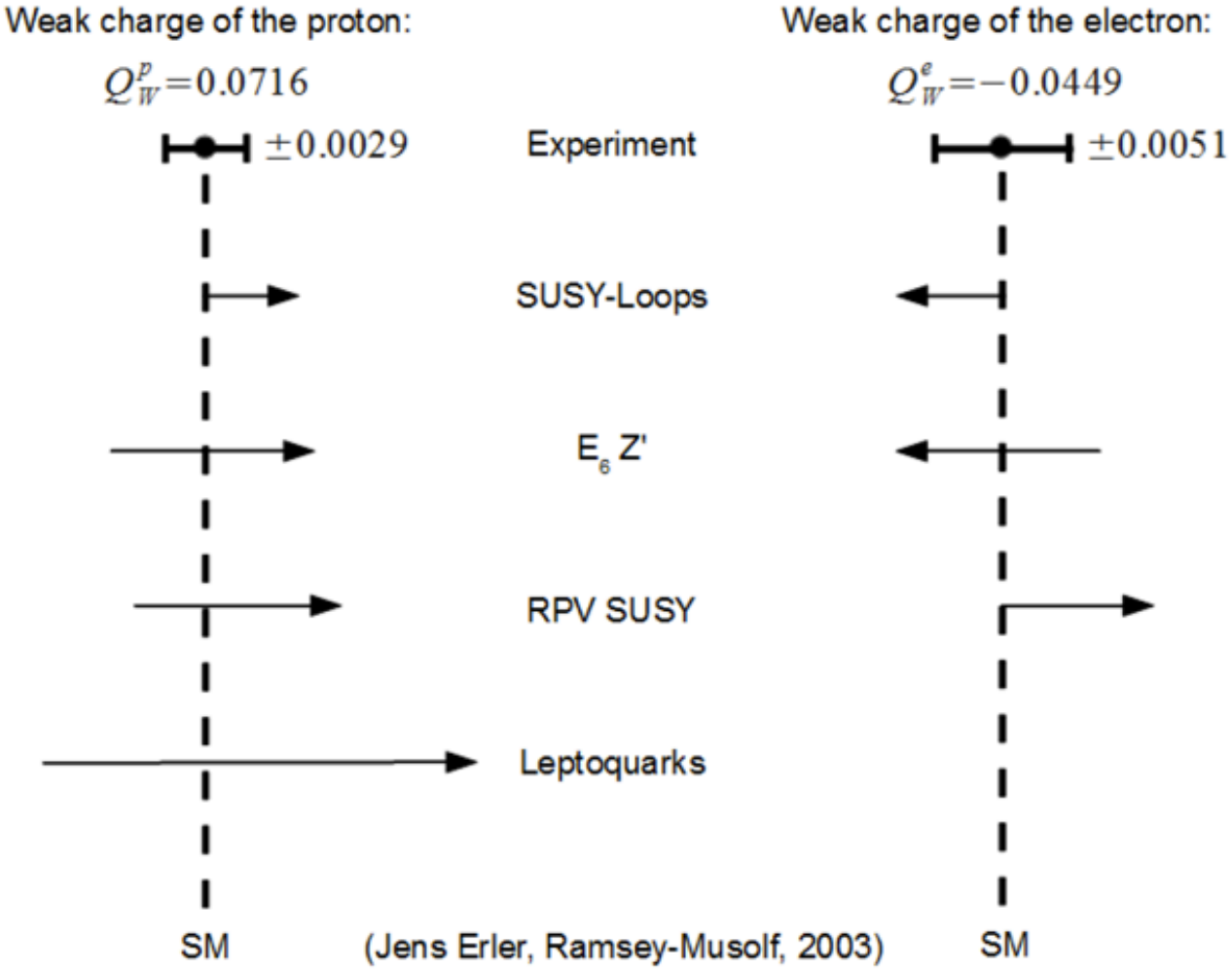
Bill Marciano

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



H. Davoudiasl, W. Marciano

- Complementary access by weak charges of proton and electron



(Jens Erler, Ramsey-Musolf, 2003)

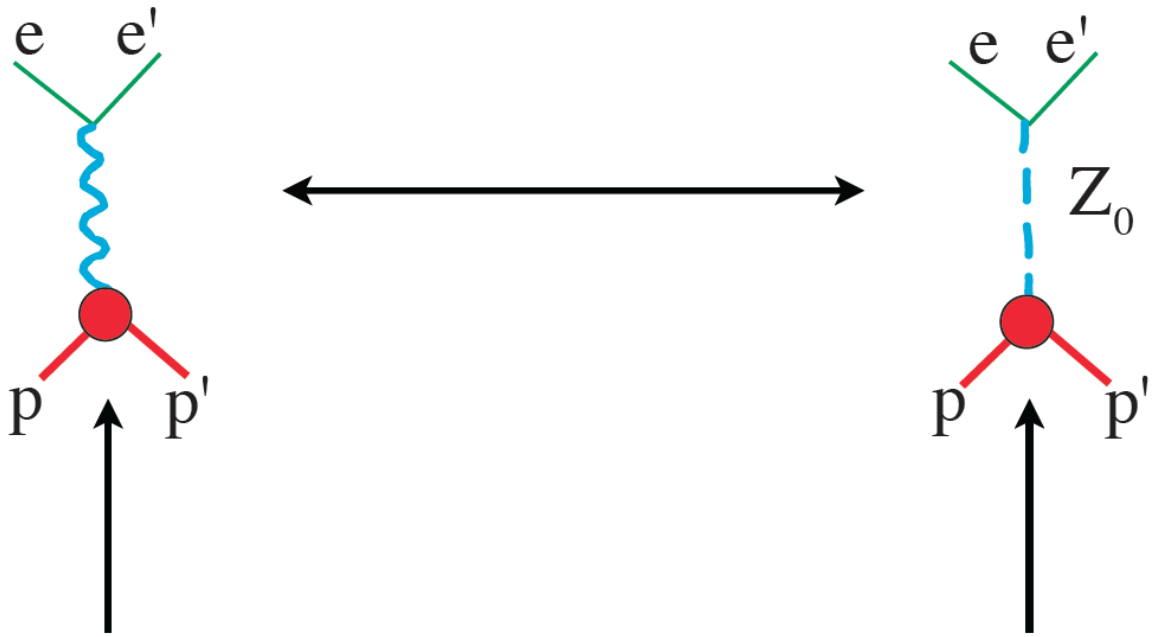
Weak Charge Of Proton: Qweak (Jlab), P2 (MESA)

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

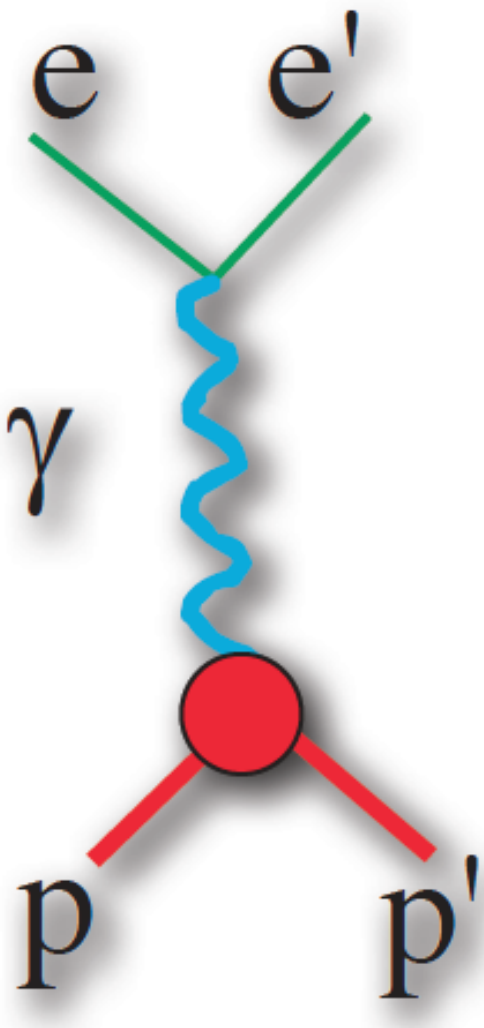
Proton: special case

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:	$\Delta Q_W(p)/Q_W(p)$	=	$4/(\ (1/\sin^2 \theta_W) - 4\ )\ \ (\Delta \sin^2 \theta_W/\sin^2 \theta_W)$
Rel. error	$\Delta \sin^2 \theta_W/\sin^2 \theta_W$	=	$(\ (1/\sin^2 \theta_W) - 4\ )/4\ \ \ \Delta Q_W(p)/Q_W(p)$
Example:	$\sin^2 \theta_W$ (50 MeV)	=	0.238
	$4/(\ (1/\sin^2 \theta_W) - 4\ )$	~	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

Experimental Method:
Parity Violating Electron Scattering



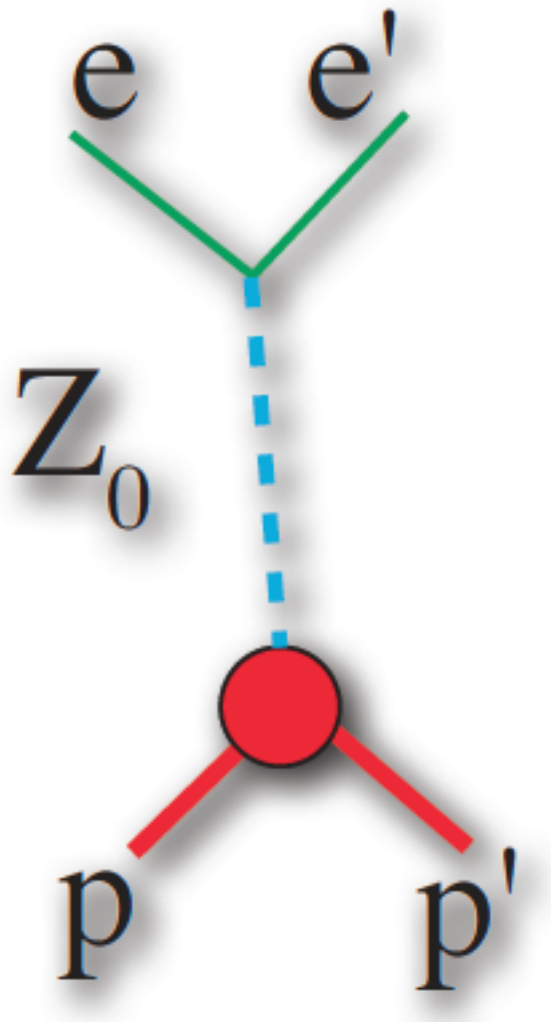
$$\sigma \sim \mathcal{M}\,\mathcal{M}^{*} \text{ Phasespace}$$

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

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

$$J_\gamma^\mu \sim \left\langle N | q^u \bar{u}\,\gamma_\mu\, u + q^d \bar{d}\,\gamma_\mu d + q^s \bar{s}\,\gamma_\mu s | N' \right\rangle$$

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



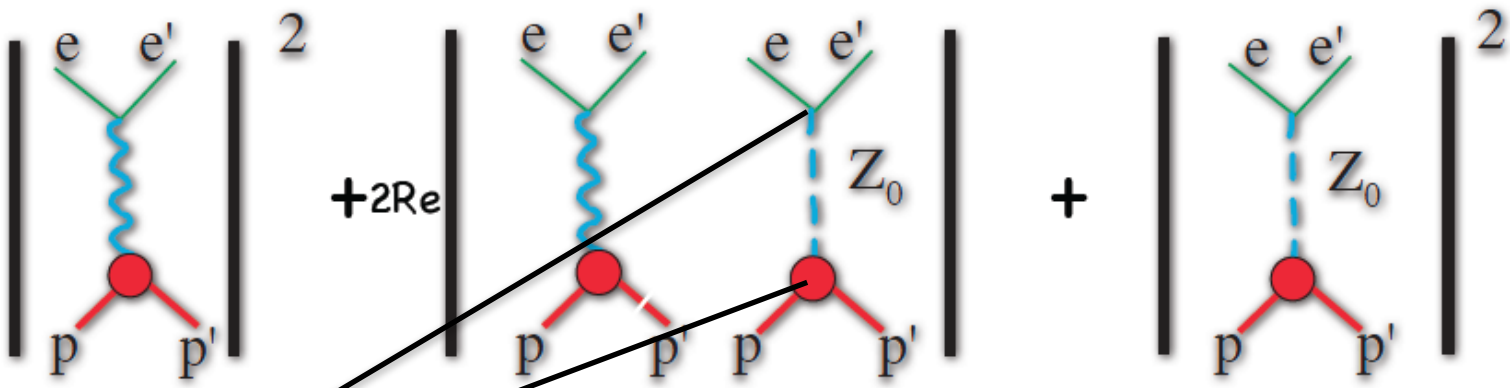
$$\tilde{q}^{d}{}_{V} = \tau_3 - 2q^{d} sin^2(\theta_W)$$

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

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

Parity Violating Asymmetry in elastic electron proton scattering

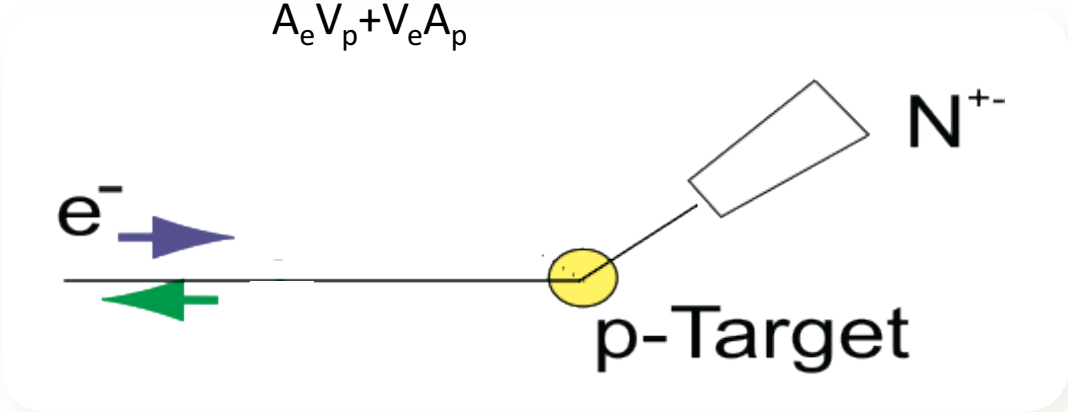
$\sigma \approx$



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

$A_eV_p+V_eA_p$

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



Parity violating cross section asymmetry

tracking system

weak charge

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

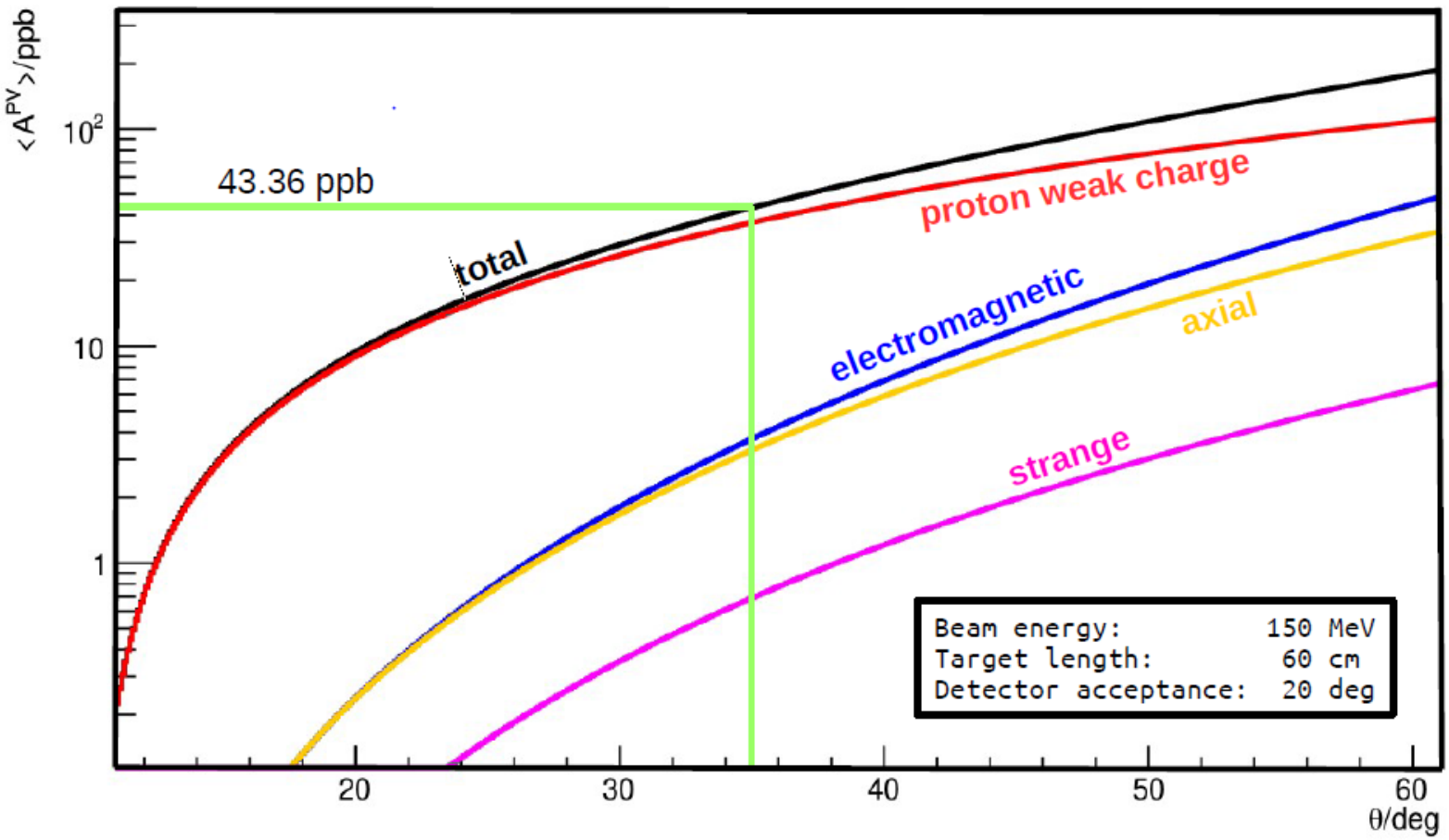
polarisation measurement

hadron structure

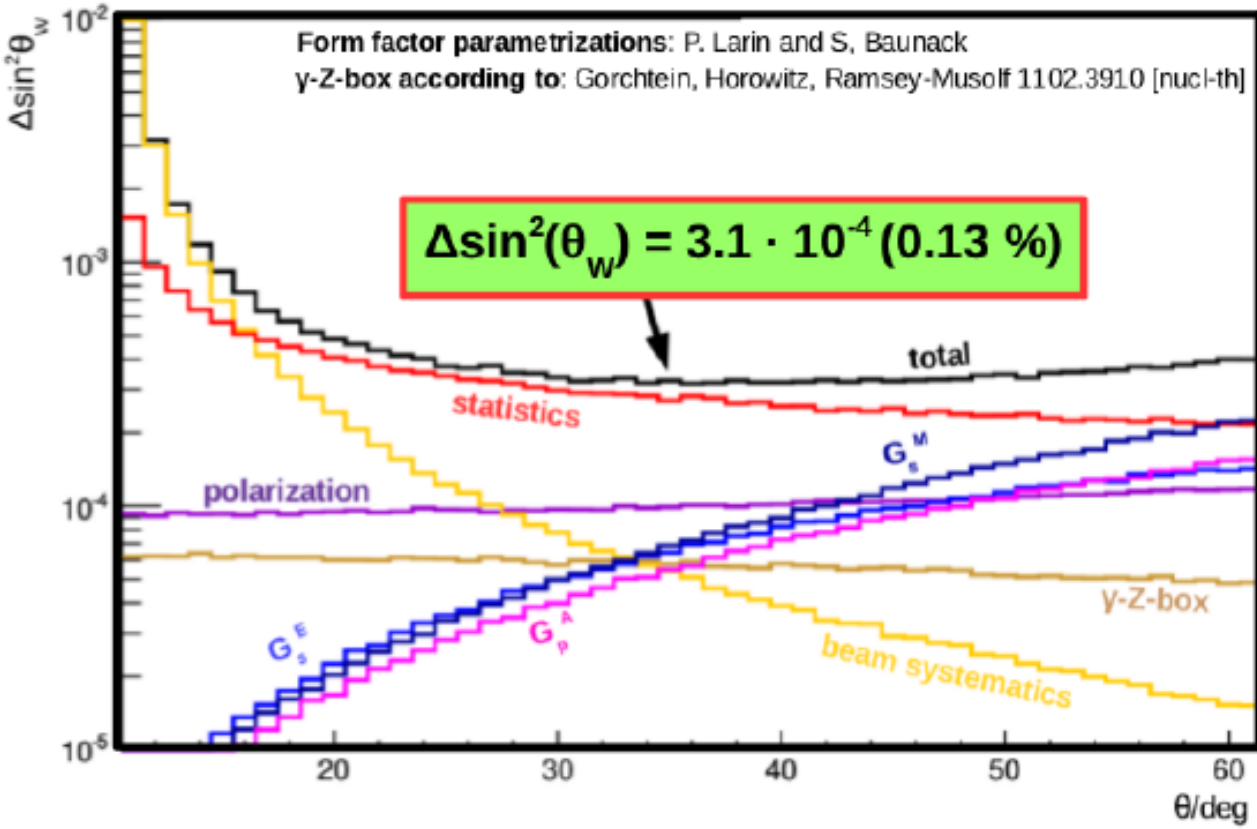
$$Q_W = 1 - 4\sin^2\theta_W(\mu)$$

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

- 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°)

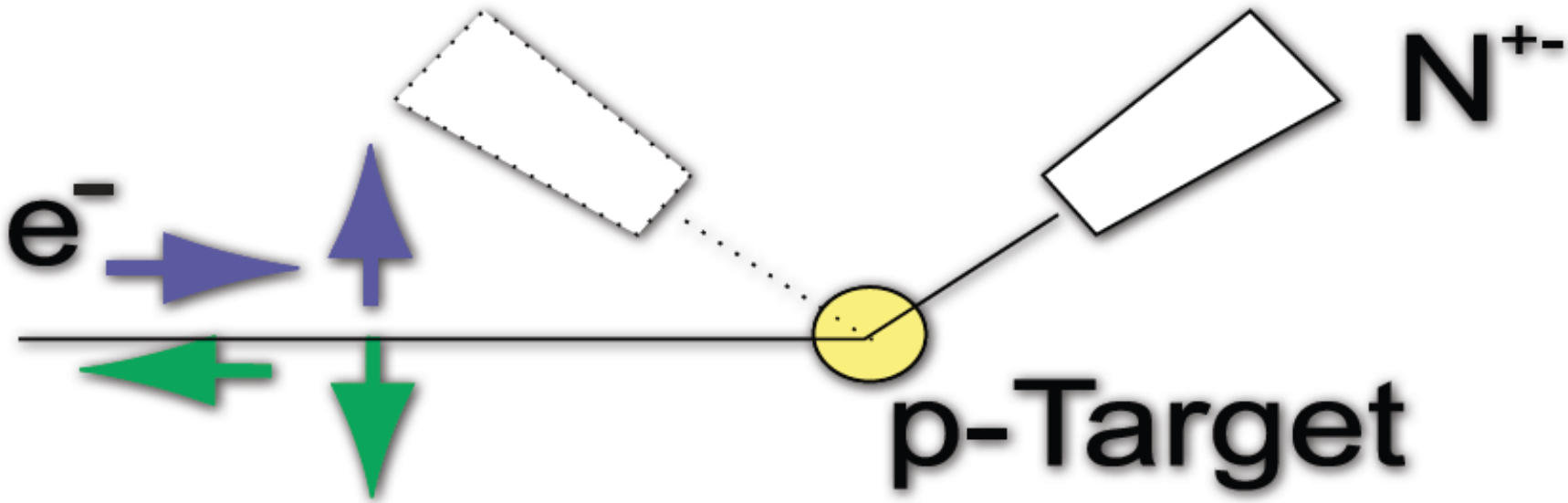
Rate: 0.5 THz

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 %)

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

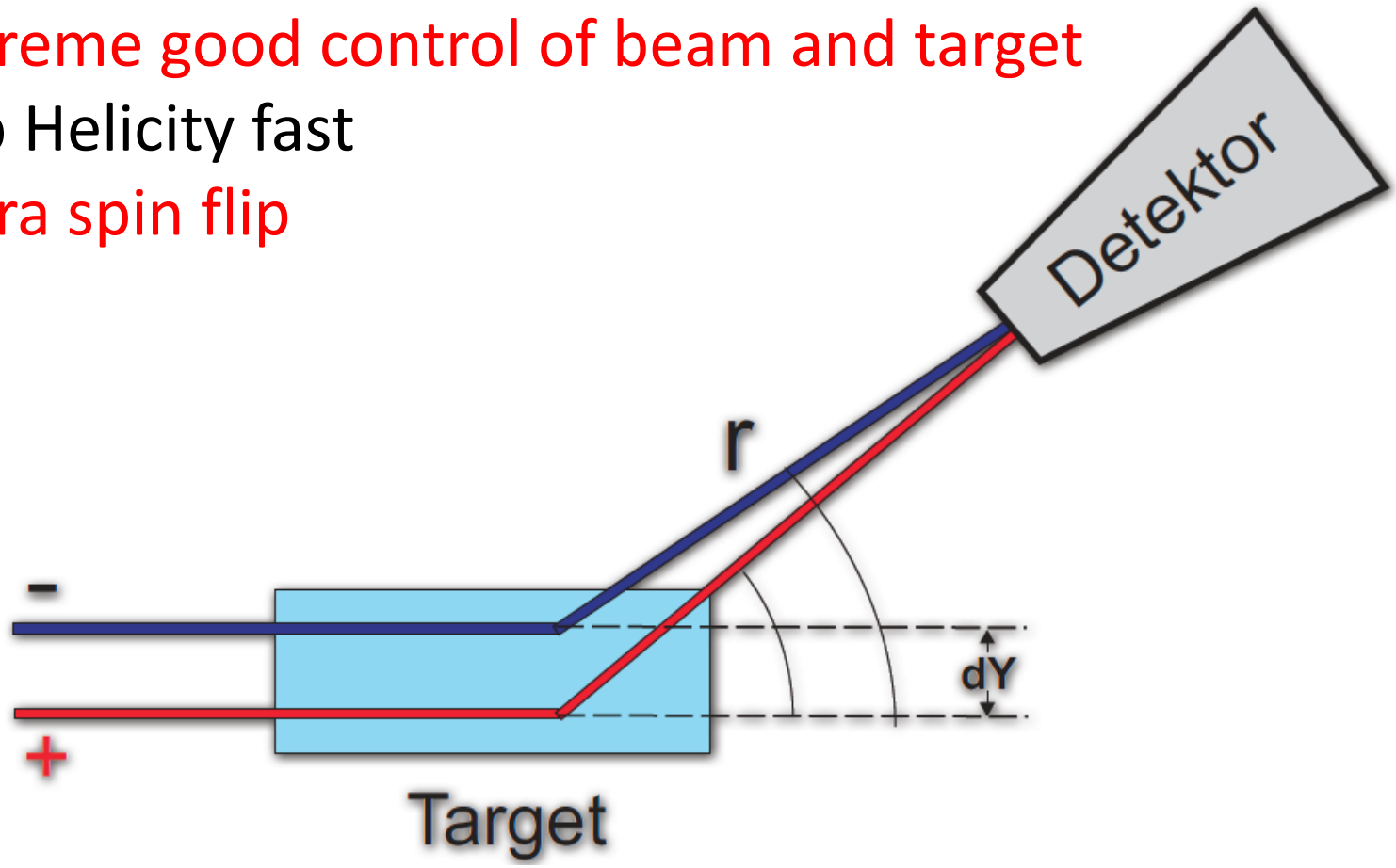
Highest rate, measure Q^2: Large Solid Angle Spectrometers

Apparative (false) asymmetries:

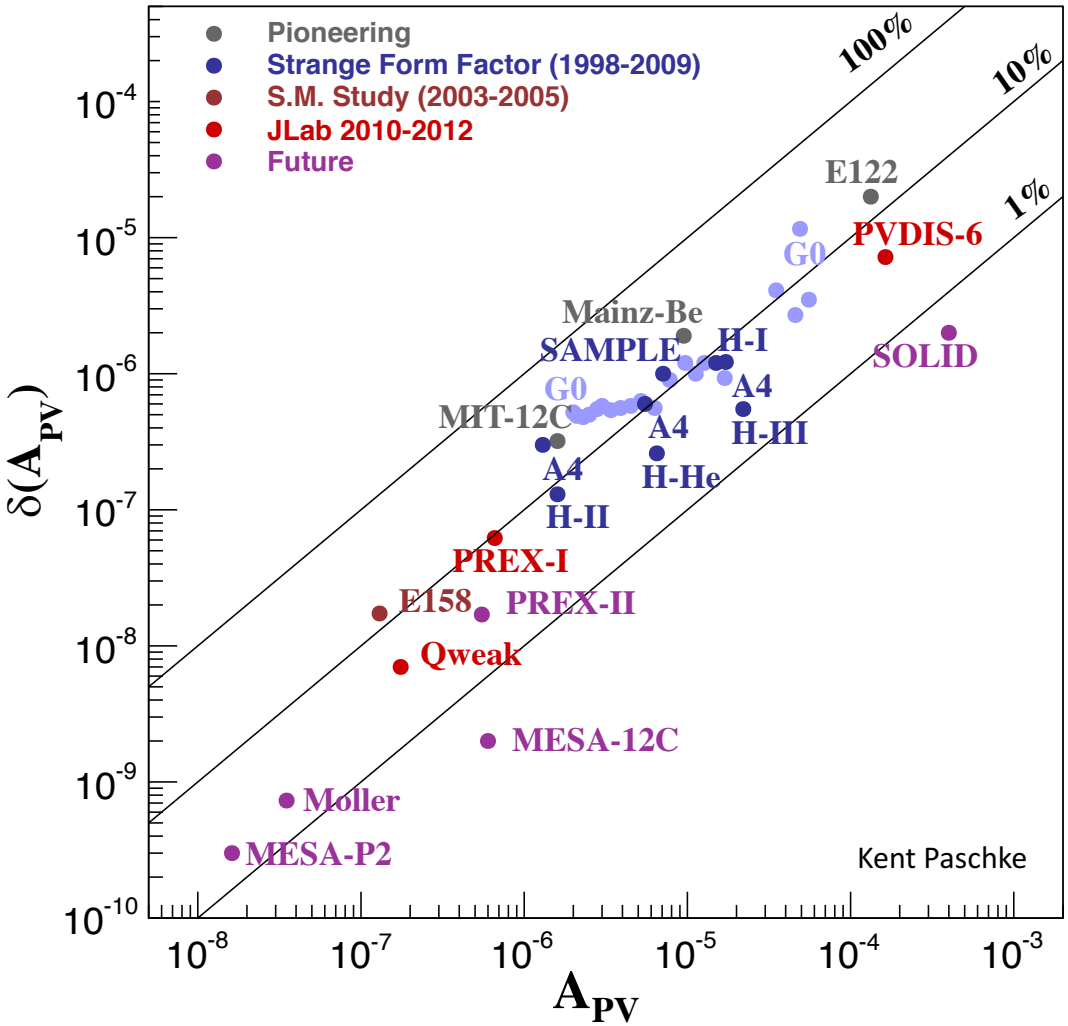
Extreme good control of beam and target

Flip Helicity fast

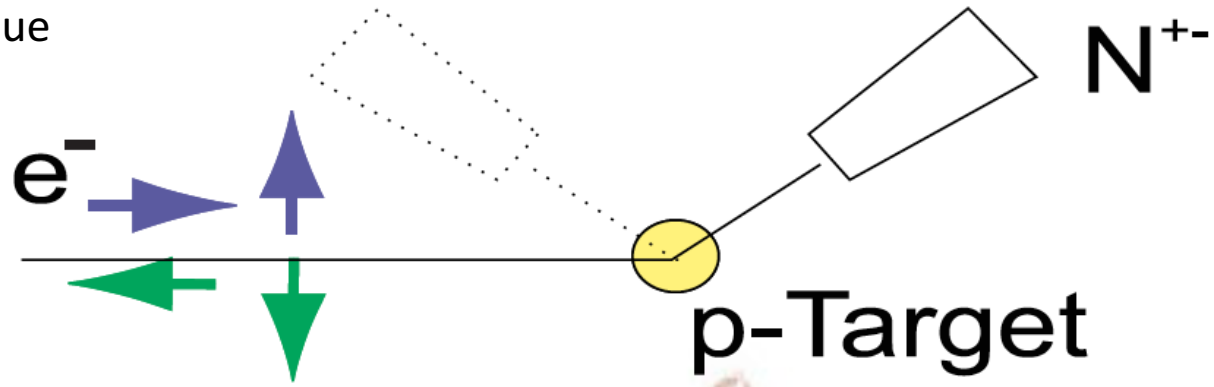
Extra spin flip



PVeS Experiment Summary

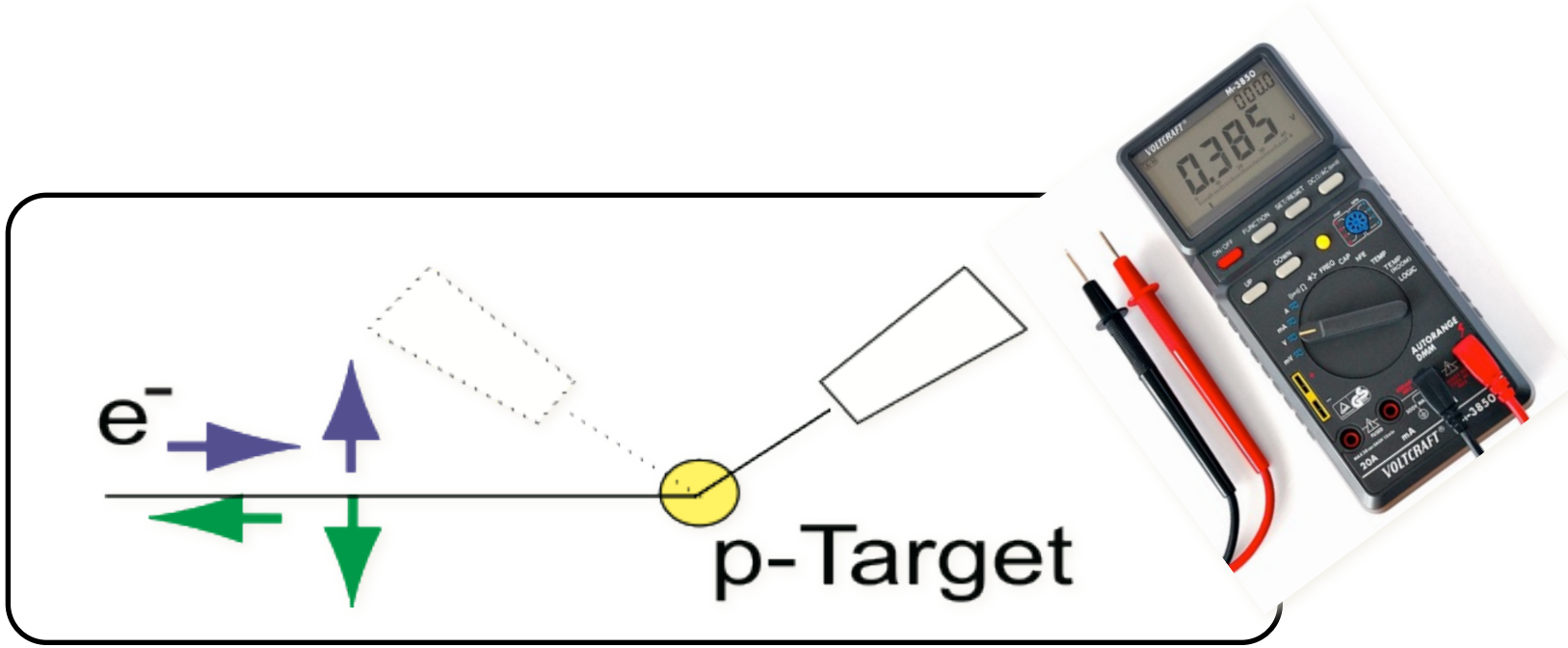


Counting Technique



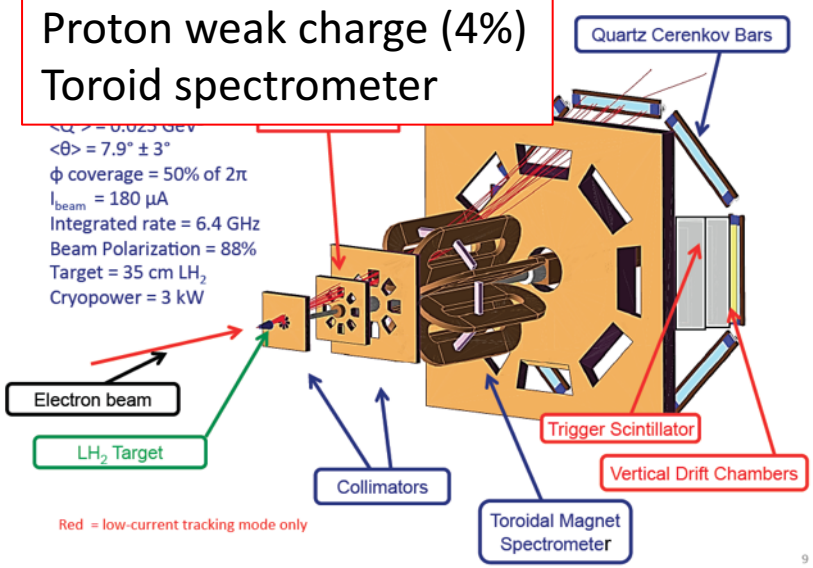
Count scattered electrons:
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy

Analogue Technique

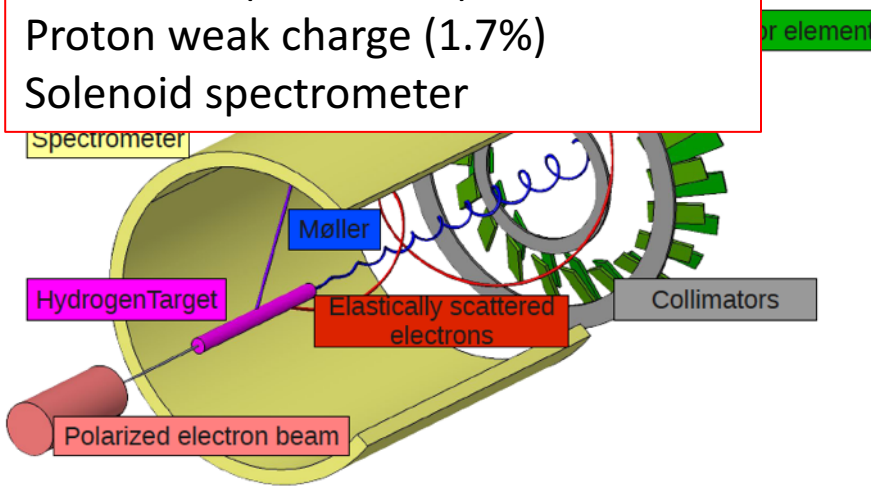


Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

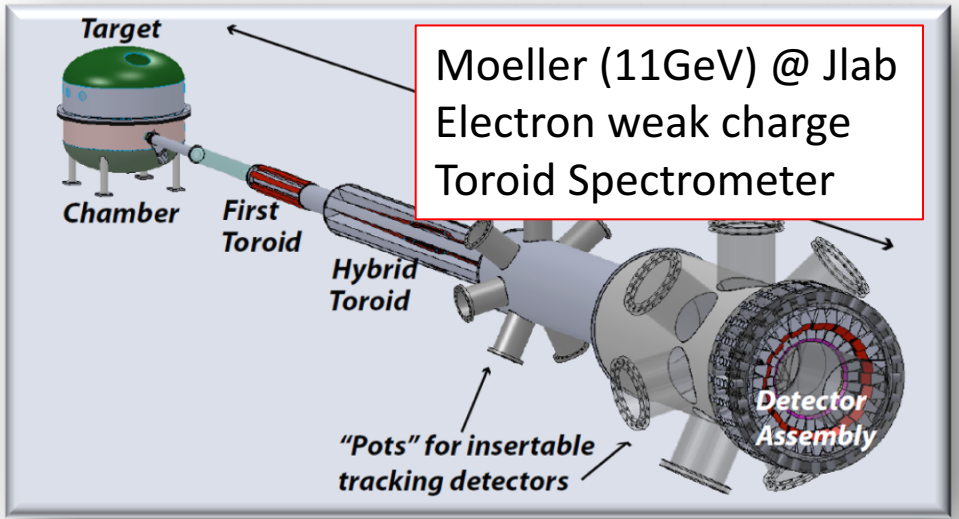
Qweak (1GeV) @ Jlab
Proton weak charge (4%)
Toroid spectrometer



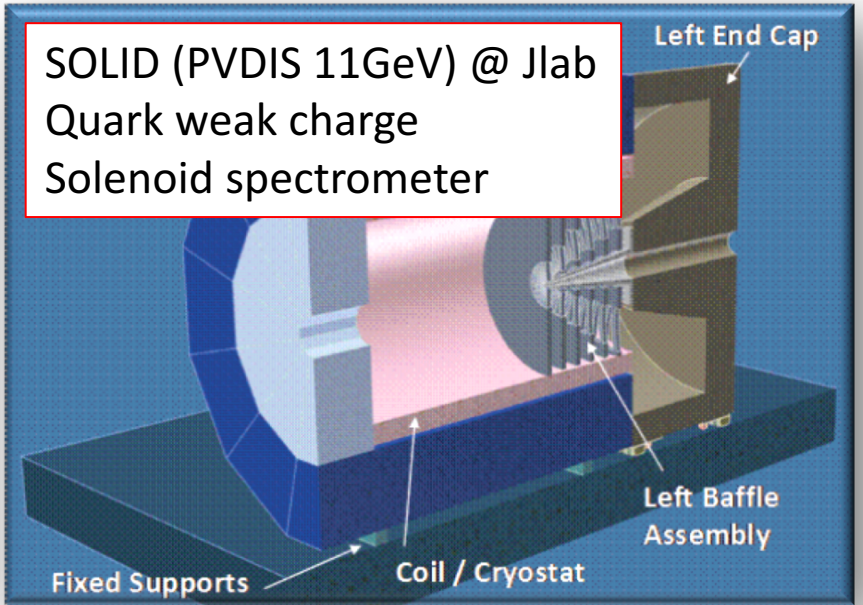
P2@MESA (0.150 GeV) @ Mainz
Proton weak charge (1.7%)
Solenoid spectrometer



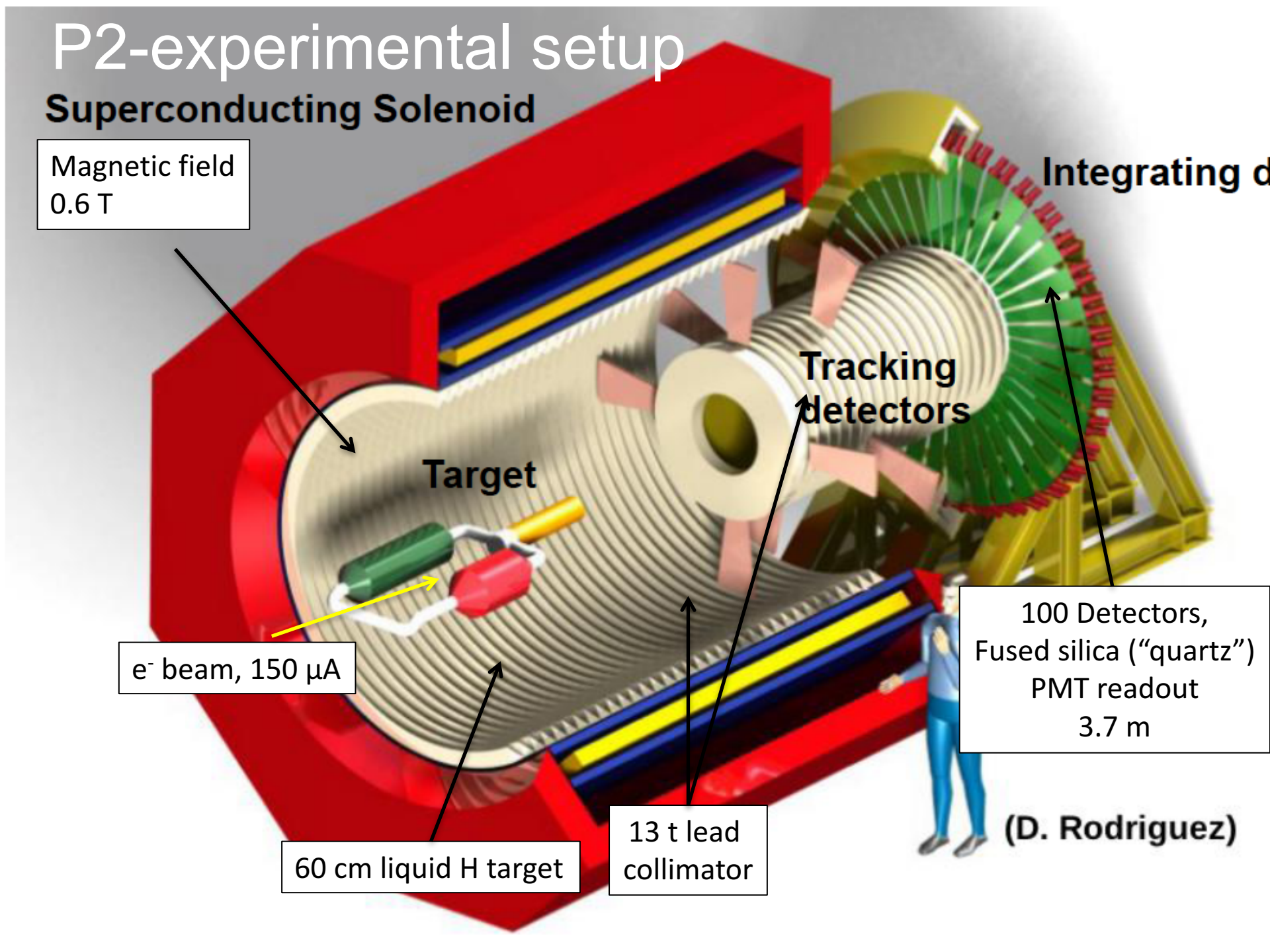
Moeller (11GeV) @ Jlab
Electron weak charge
Toroid Spectrometer



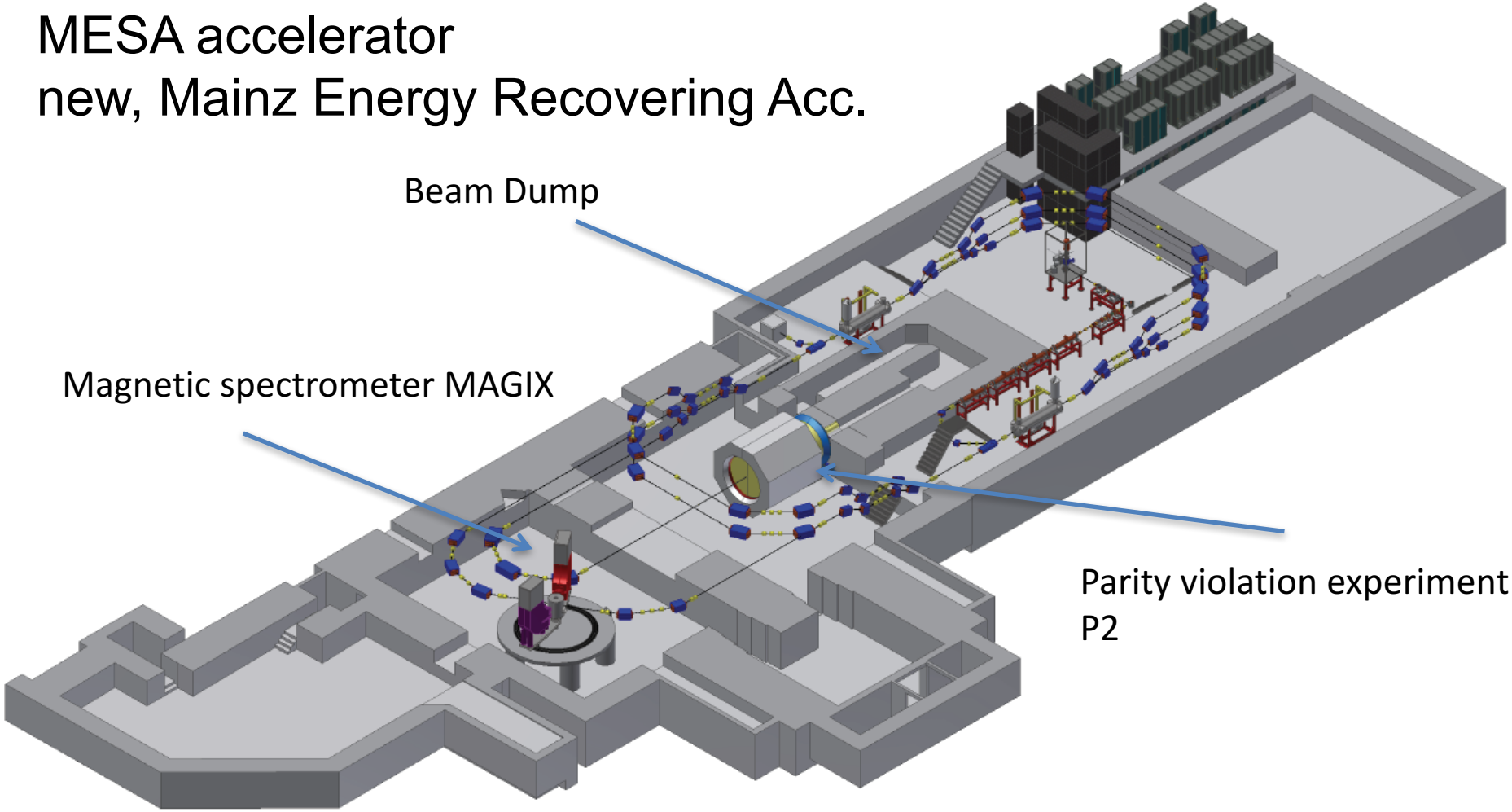
SOLID (PVDIS 11GeV) @ Jlab
Quark weak charge
Solenoid spectrometer



P2-experimental setup



MESA accelerator
new, Mainz Energy Recovering Acc.



- 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 (same as Z-pole)

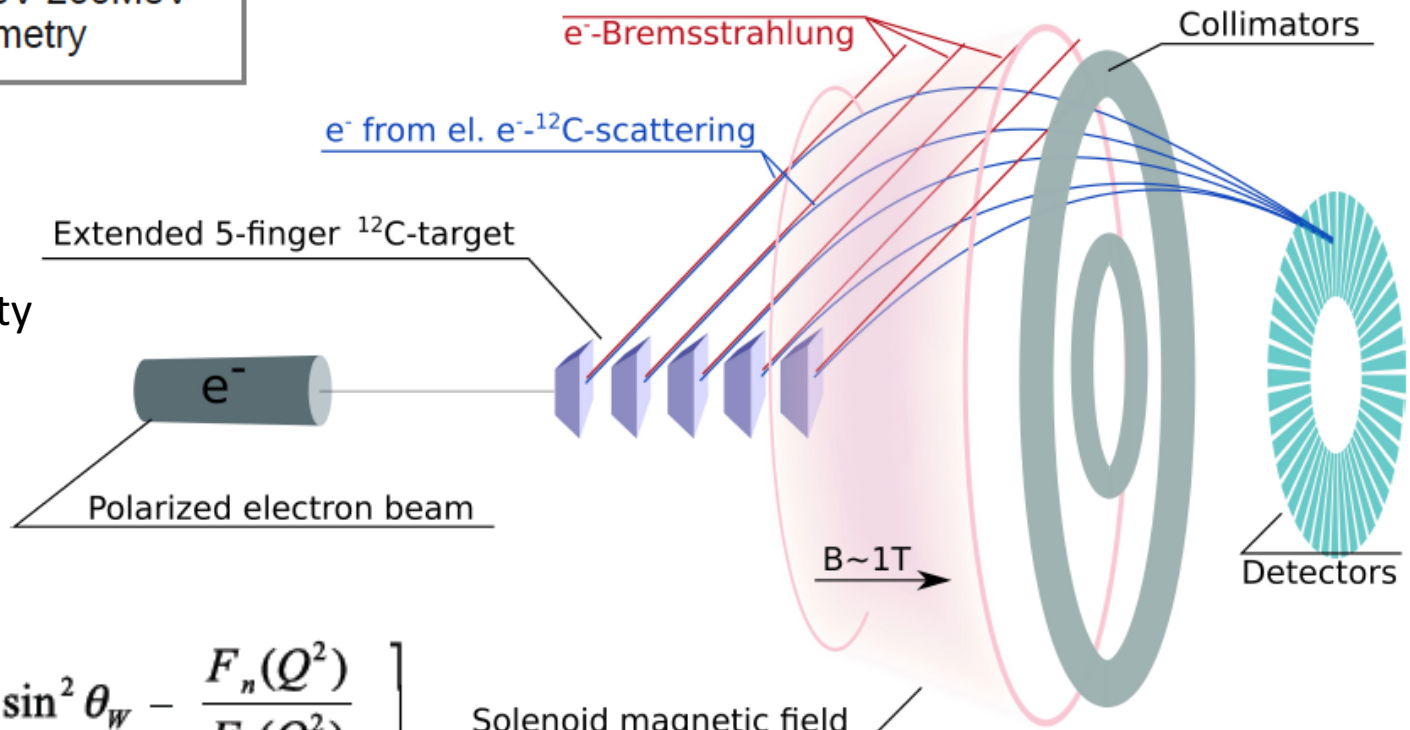
- P2-Experiment (proton weak charge) in Mainz under preparation New MESA energy recovering accelerator at 155 MeV, target precision is 1.7% in Qweak i.e. 0.13% in $\sin^2(\theta_W)$, Sensitivity to new physics up to a scale of 49 TeV
- Much more physics from PV electron scattering
- Together with Moeller@Jlab (electron weak charge) and SOLID@Jlab (quark weak charge) very sensitive test of standard model and possibility to narrow in on Standard Model Extension

Other Measurements:
Carbon, Lead

EXPERIMENTAL REALIZATION

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

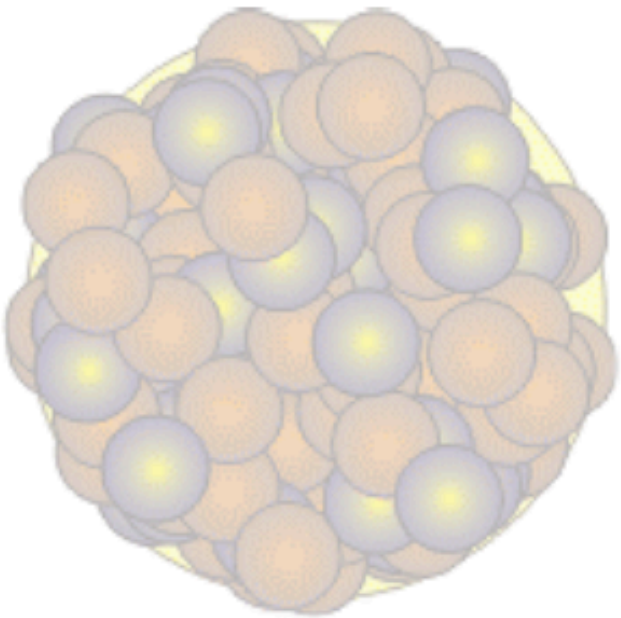
Enhanced sensitivity
To new physics

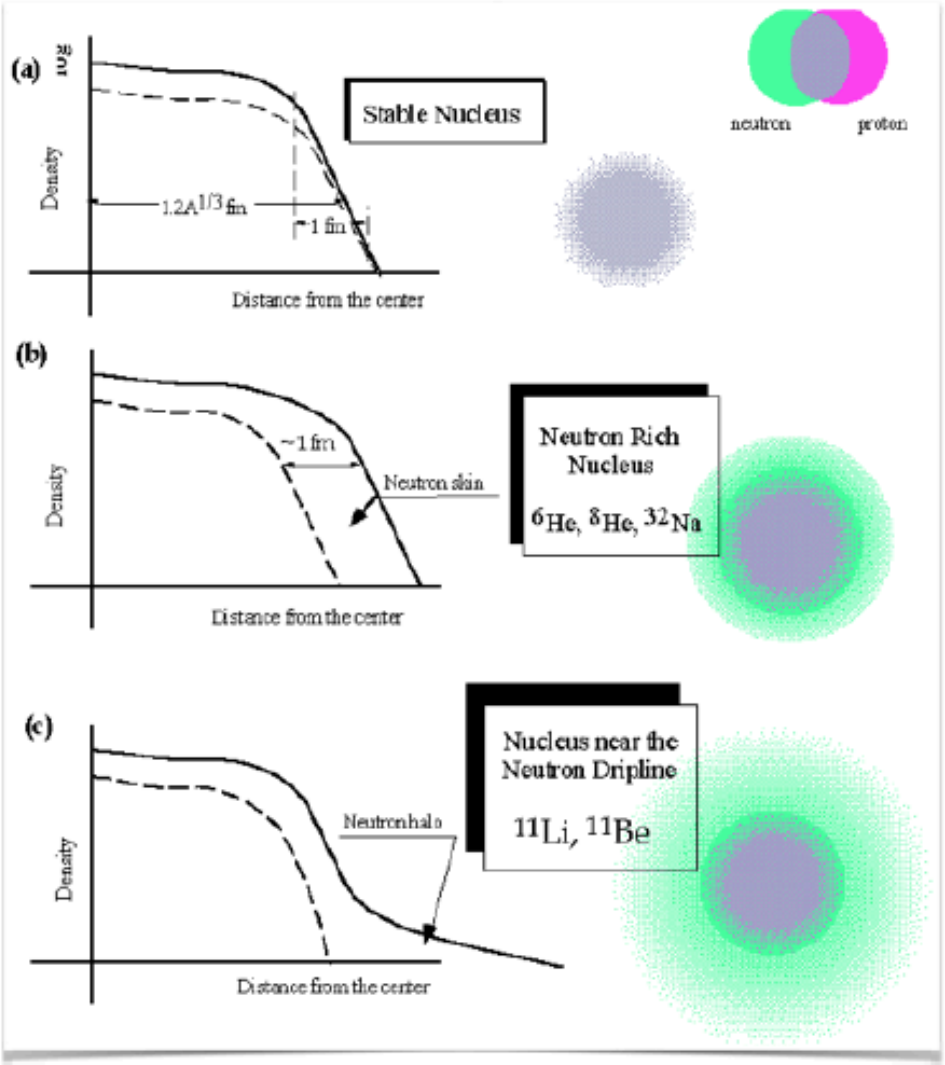


$$-N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

Neutron Skin for beginner

Where do the neutrons go?

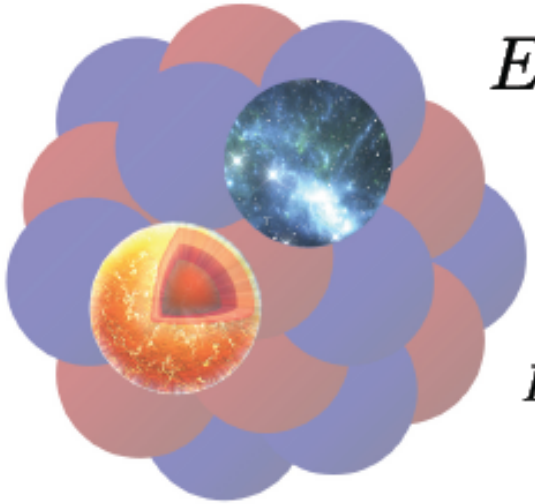




Pressure forces neutrons out against surface tension

→ **EOS**

Measurement of neutron distribution in nuclei deceisive for Neutron star properties



$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

↓

symmetry energy

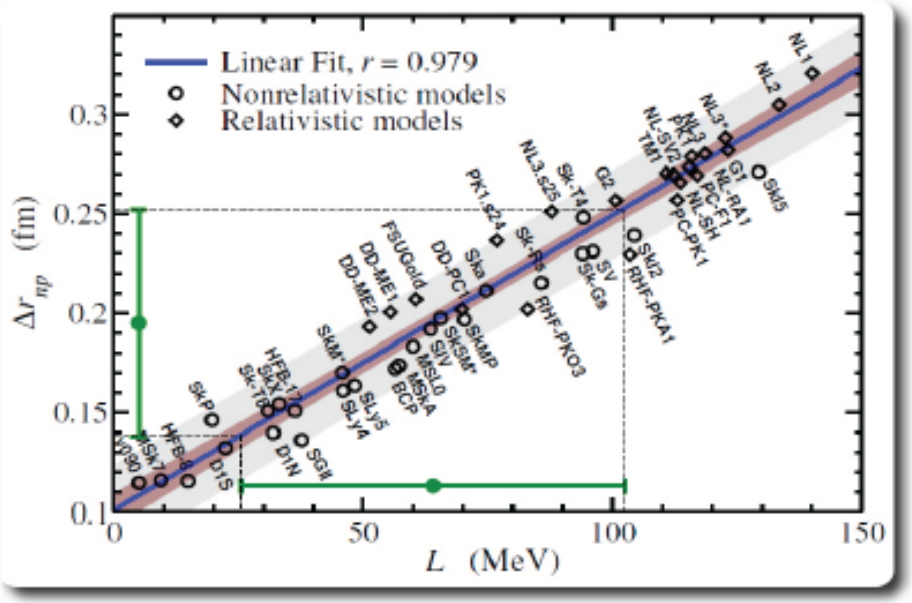
$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$

slope parameter

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

curvature parameter

$$K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho_0}$$



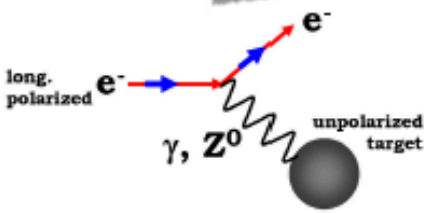
X. Roca-Maza et al., PRL 106 (2011) 252501

M. Thiel

MREX

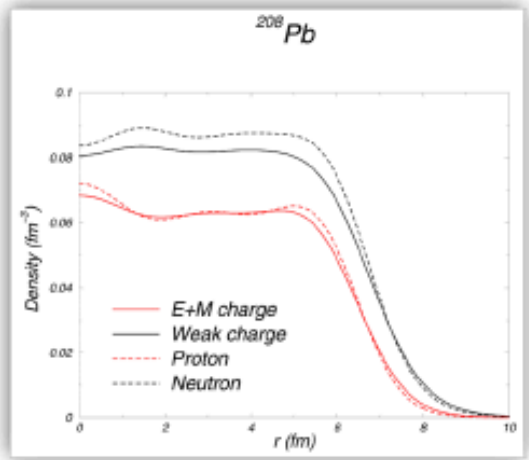
Enormously Clean … Extraordinarily Expensive!

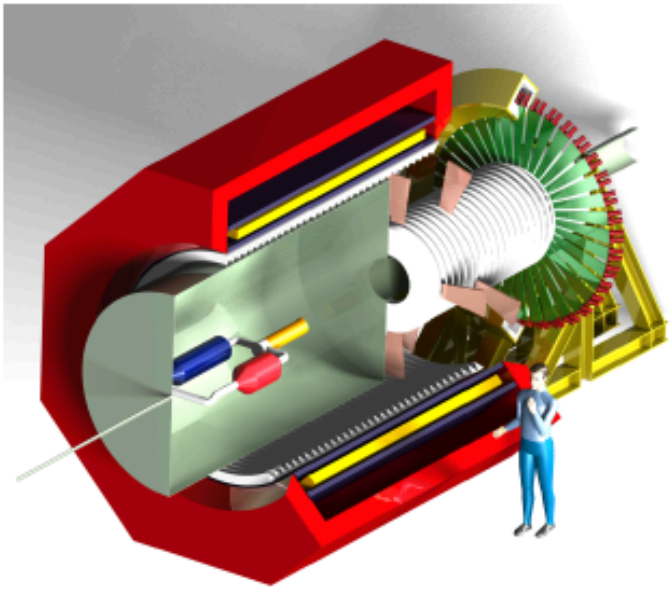
PVES



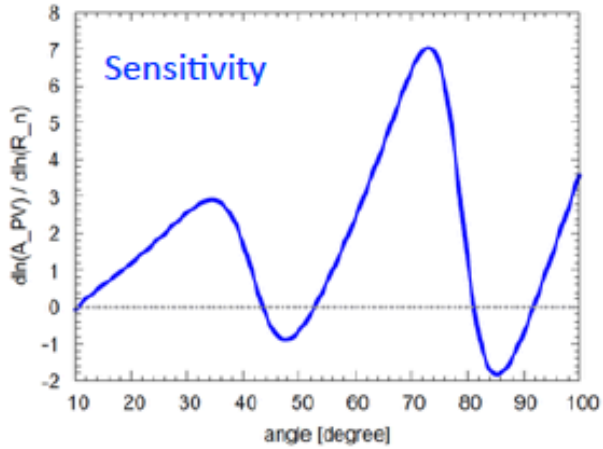
$$A_{PV} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1-4\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

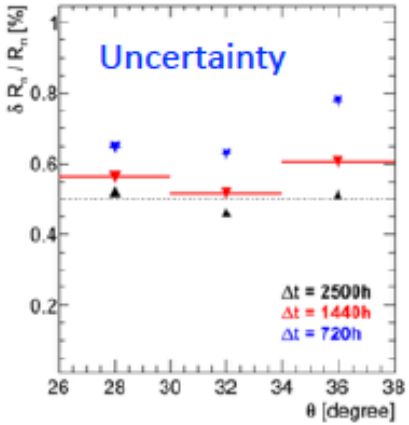
$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\; j_0(qr)\;\rho_{n,p}(r)$$





Full azimuthal coverage⇔4xstat





Assuming same PREX luminosity:

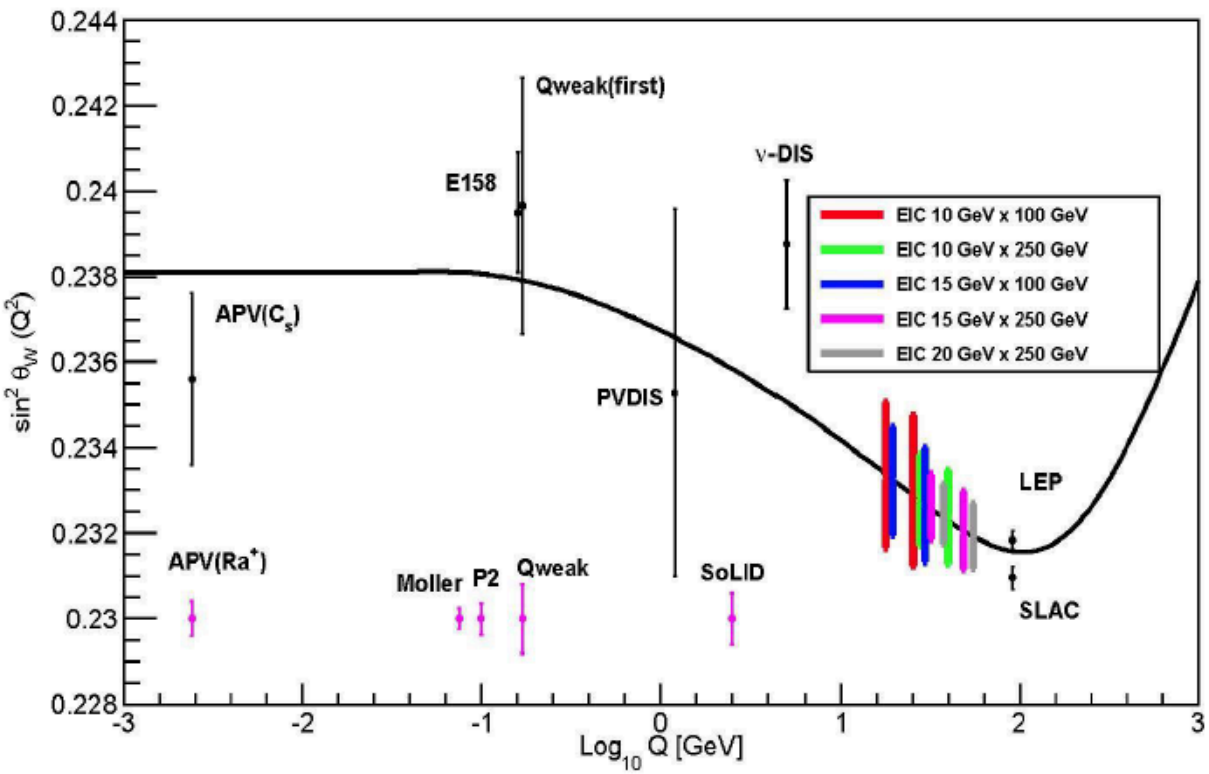
$\Delta\theta=4^o$: Rate=8.25 GHz, A_{PV}=0.66 ppm

1440h → $\delta R_n/R_n$ = 0.5%

(assuming 1% syst. $\delta A_{PV}/A_{PV}$)

CONCETTINASFIENTI

World data of $\sin^2\Theta_W$ including EIC projections



- 200 days of dedicated run
- Can reach similar precision to SoLID measurement
- Interesting Q^2 region never been measured or planned

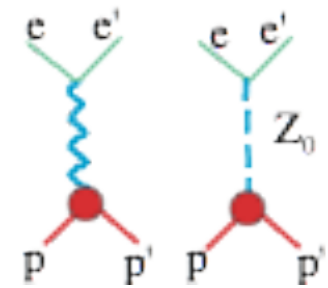
Yuxiang Zhao (SBU)

MESA: Beam parameter

Beam Energy ERL/EB [MeV]	105/155 (105/205)
Operation mode	1300 MHz, c.w.
Elektron-sources	1.) Polarised : NEA GaAsP/GaAs superlattice , 200keV (?) 2.) unpolarised KCsSb, 200keV
Bunch Charge EB/ERL [pC] 7.7pC=10mA@1300MHz	0.15/0.77 (0.15/7.7)
Norm. Emittance EB/ERL [µm]	0.1/<0.5 (0.1/<1)
Spin Polarisation (EB-mode only)	> 0.85
Recirculations	2 (3)
Beampower at Exp. ERL/EB [kW]	100/22.5 (1050/30)
R.f.-Power installed [kW]	140 (180)

Parity violating cross section asymmetry

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



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

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

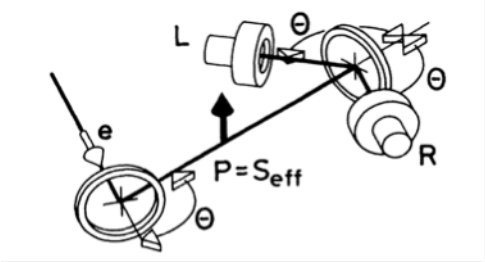
Polarimetry (<0.5%)

The double scattering Mott polarimeter:

A. Gellrich and J. Kessler, Phys. Rev. A 43, 204 (1991)

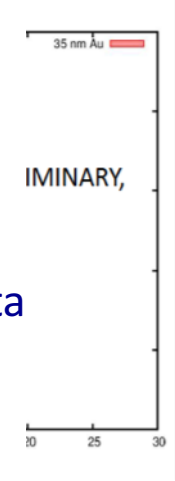
Mott Polarimeter:

- Measuring left/right asymetry to calculate spin polarisati
- Analysing power of target foils has to be extrapolated



Double Scattering Polarimeter (DSP):

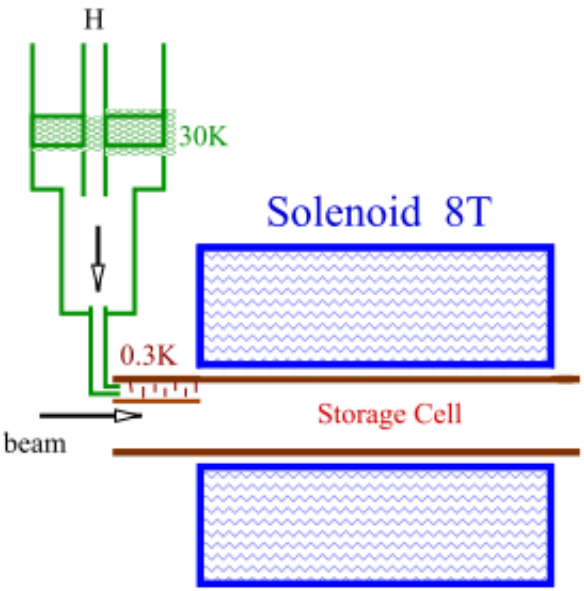
- Analysing power of the targets can be calculated directly from measurements
- Allows for higher precision measurement of spin polarisation



- Invasive polarimetry at the electron source

- Scattering chamber in operation, first double scattering data

Hydro Möller Polarimeter



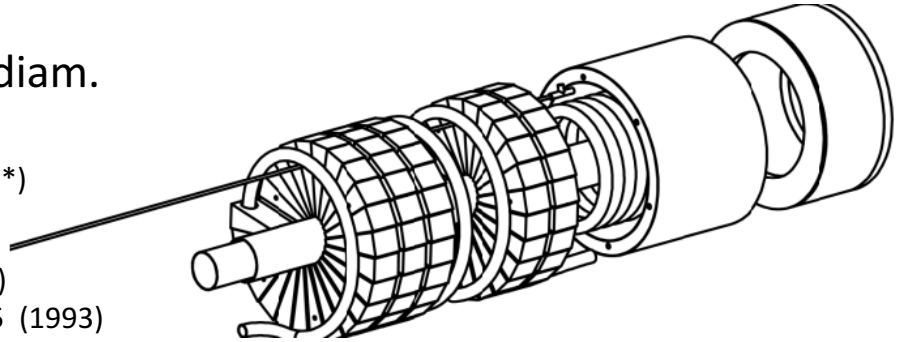
The promise:(*)

- **Hydro-Möller: Atomic trap with completely electron-spin polarized Hydrogen**
- **Online capability, high accuracy (<0.5%)**
- **Statistical efficiency approaches 0.5% in 2 hours (Target: $3*10^{-16}$ cm^{-2})**
- **Acceptance similar to conventional Möller**

(*)E. Chudakov, V. Luppov: IEEE Trans. Nucl. Sc. 51, 1533 (2004)

Complete trap with 77mm diam.
Cold bore 7T Solenoid
$\Delta B/B < 10^{-5}$ (1cm^3 Volume)(**)

(*): T. Roser et. al. NIM A **301** 42-46 (1990)
(**): W. Kaufmann et. al. NIM A **335** 17-25 (1993)

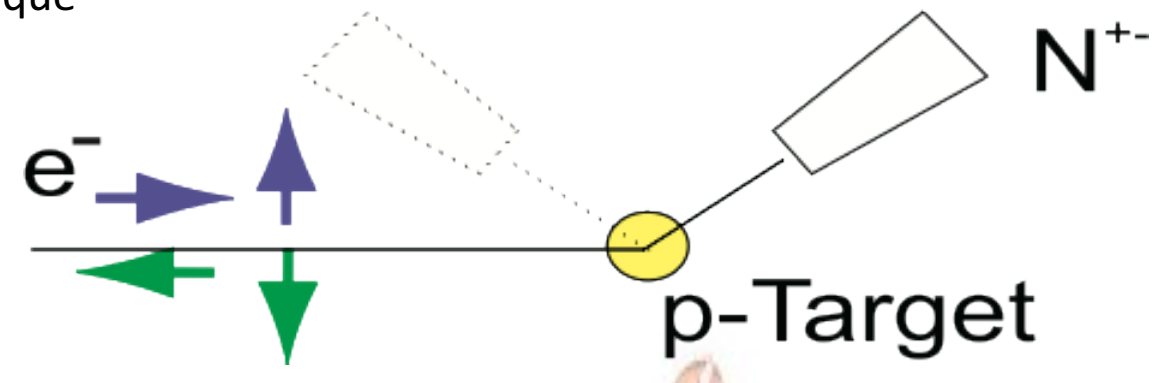


1.1K Stage heat exchangers
Presently in fabrication in KPH Machine shop

Patricia Bartolome, Valerie Tyukine

Detector Concept

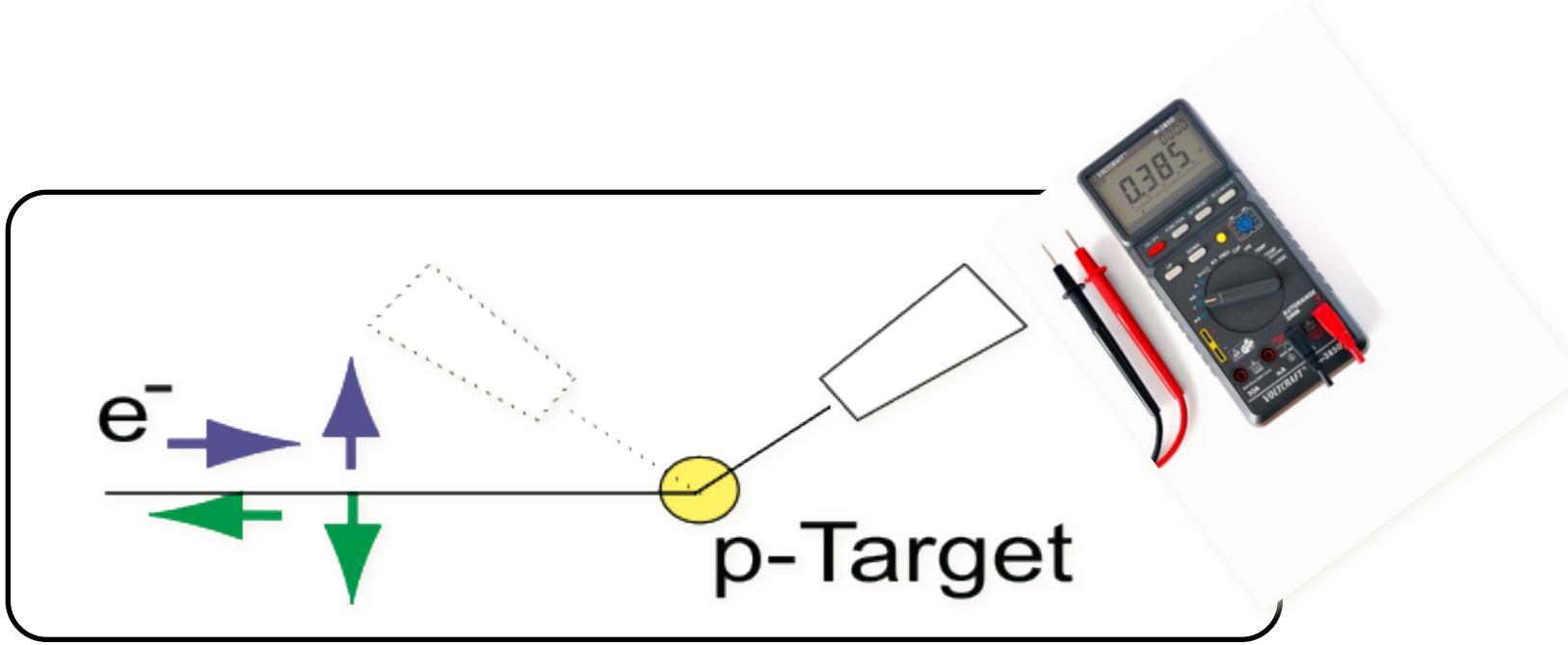
Counting Technique



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

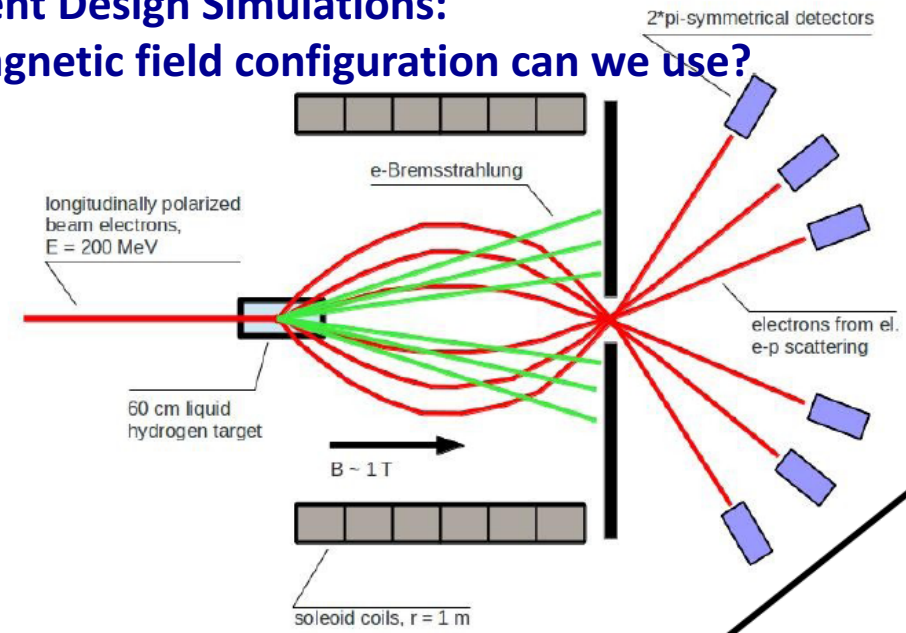
A4: 100 MHz
P2: 440 GHz

Analogue Technique



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

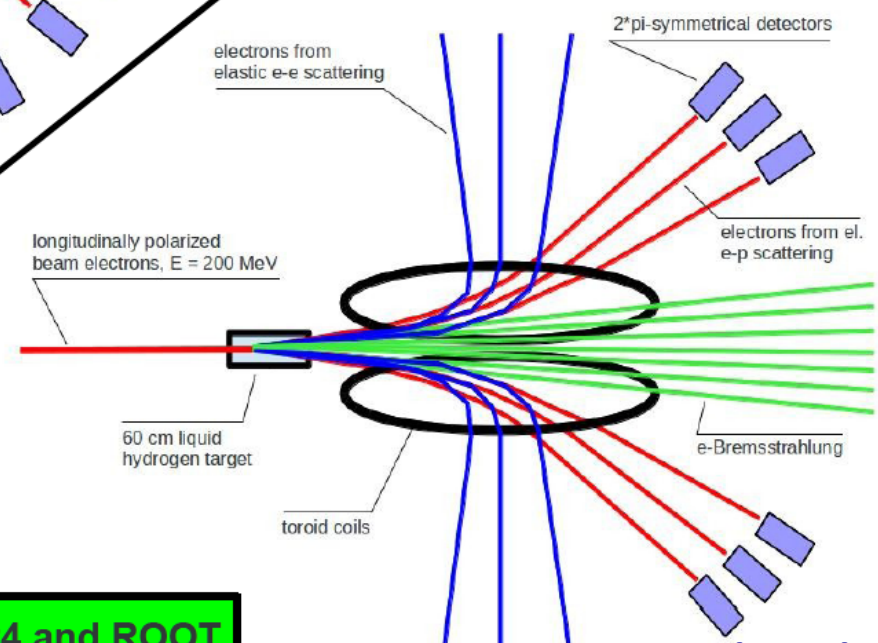
Experiment Design Simulations:
What Magnetic field configuration can we use?



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



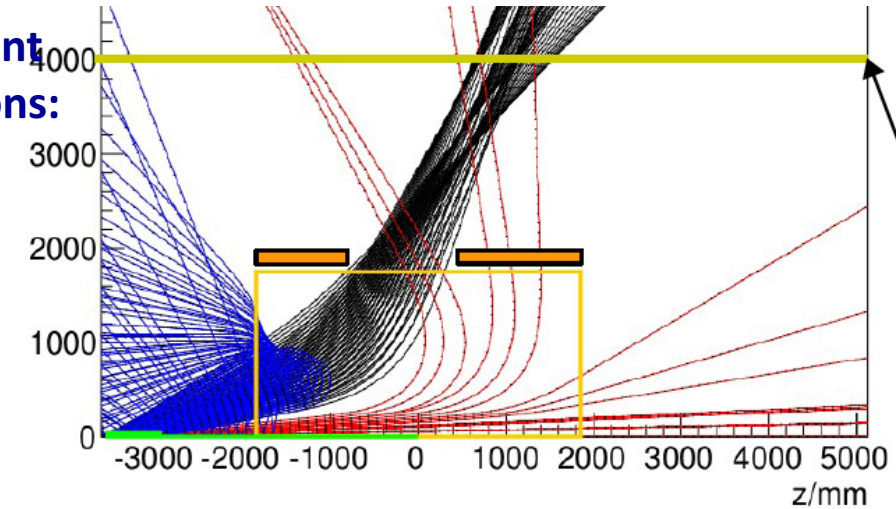
Toroid:

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

→ **Feasibility study with Geant4 and ROOT**

Dominik Becker

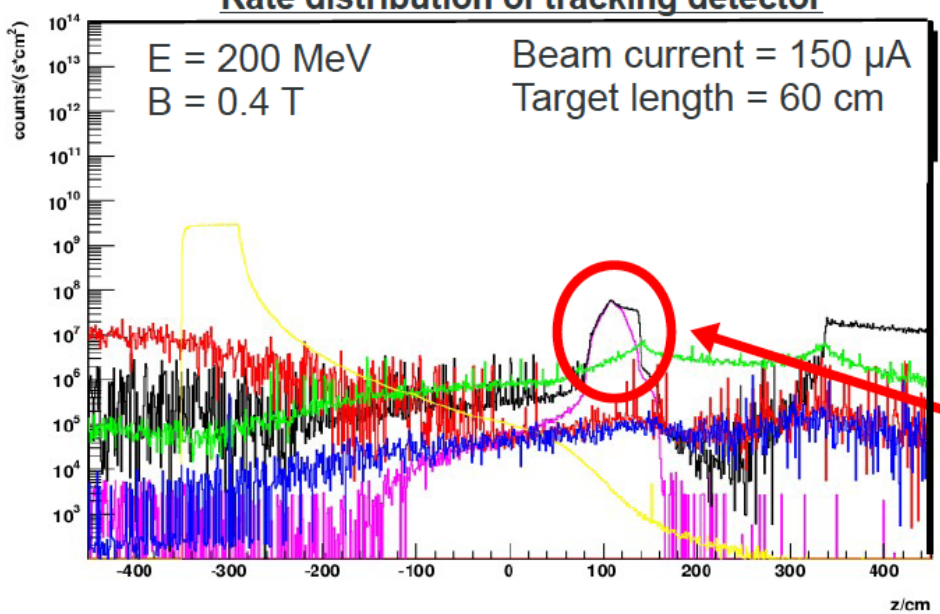
Experiment Simulations: Toroid possible!



- 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+
- γ
- p

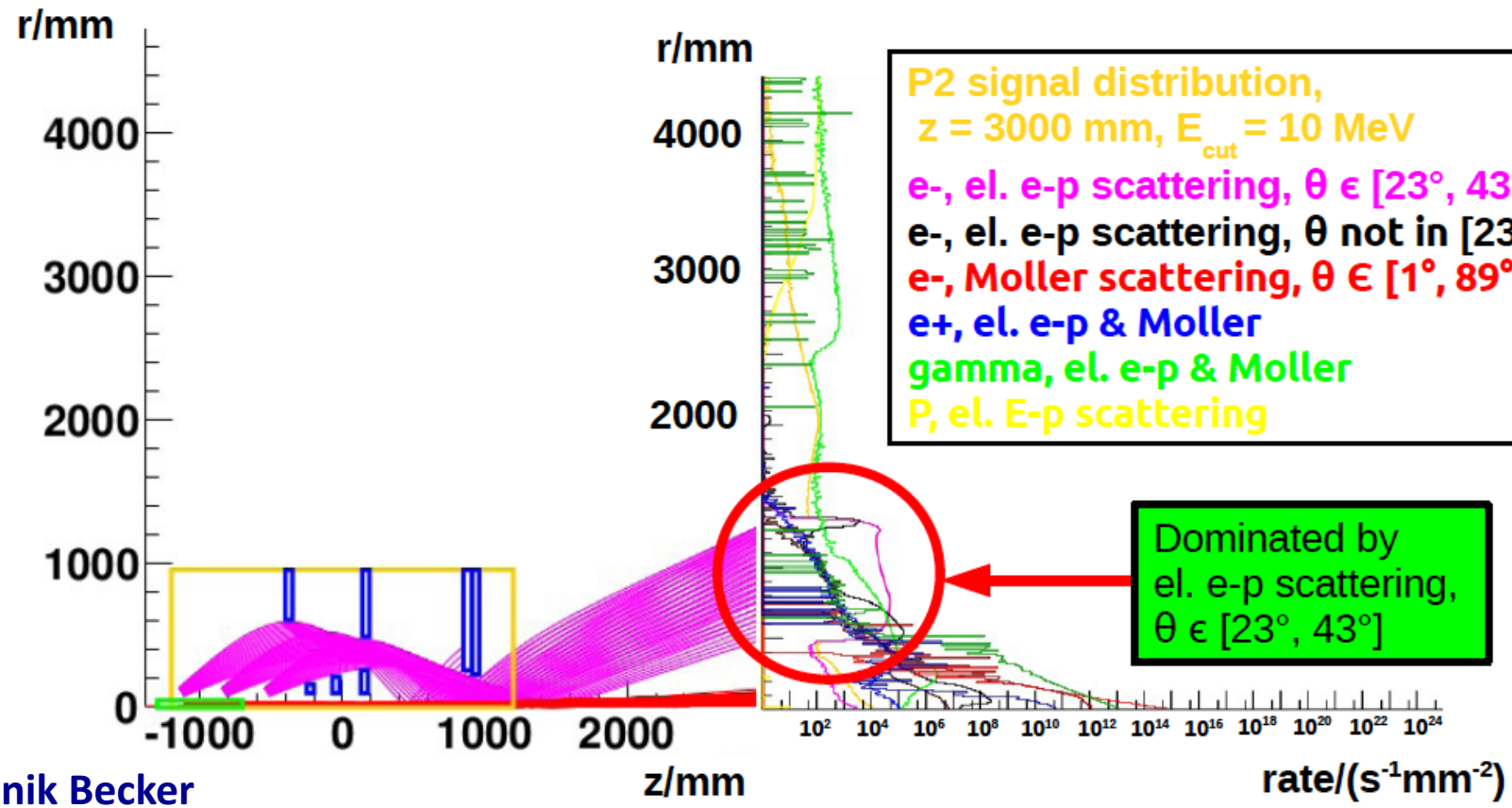
Dominated by el. e-p scattering
$\theta \in [10°, 30°]$

Dominik Becker

Experiment Design Simulations: Solenoid possible!

E = 150 MeV
B = 1.08 T
el. e-p scattering, θ ∈ [23°, 43°]
Moller scattering, θ ∈ [1°, 89°]

Primary event generators of Monte Carlo simulation:
el. e-p scattering, θ ∈ [1°, 90°]
Moller scattering, θ ∈ [1°, 89°]



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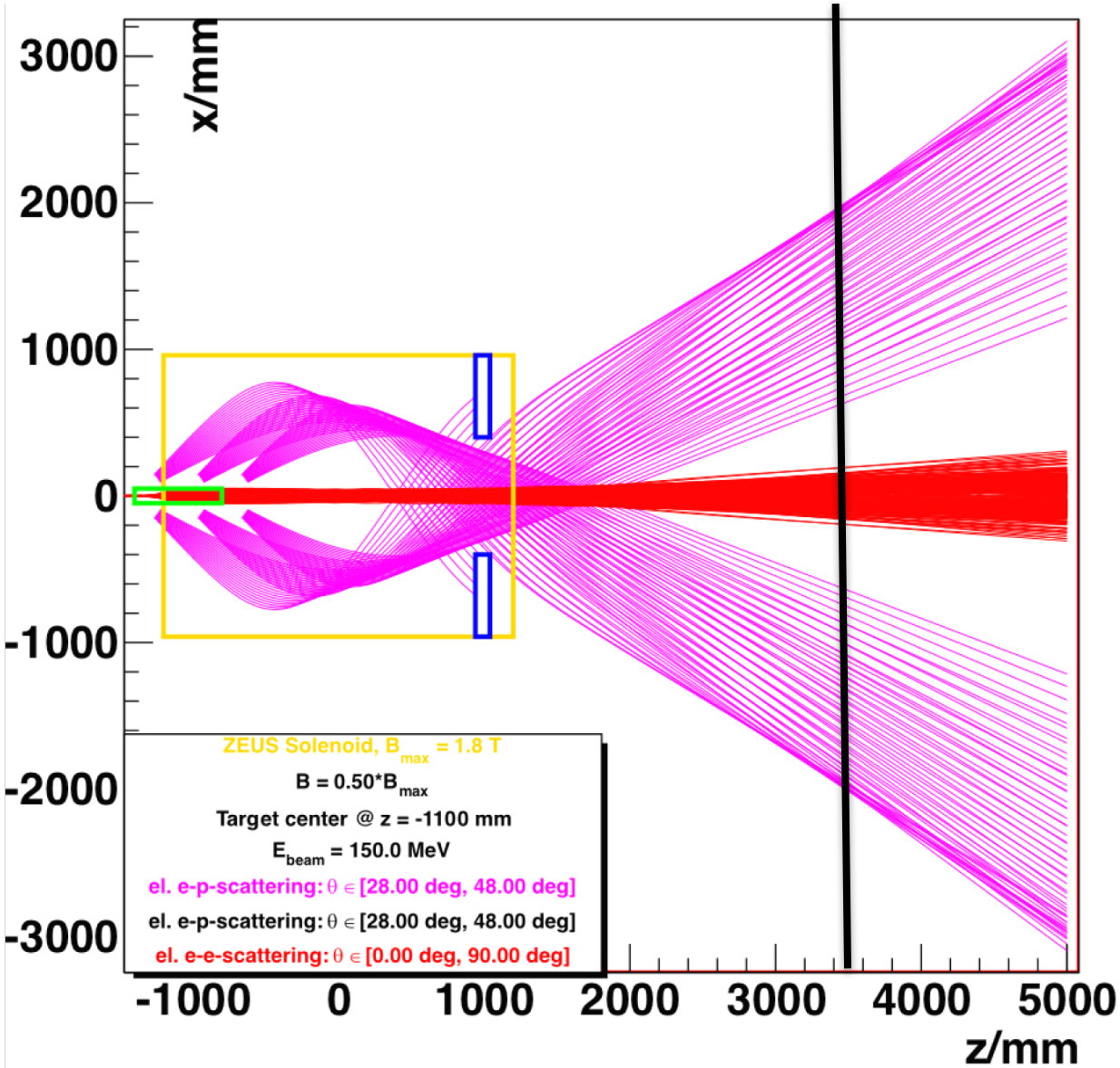

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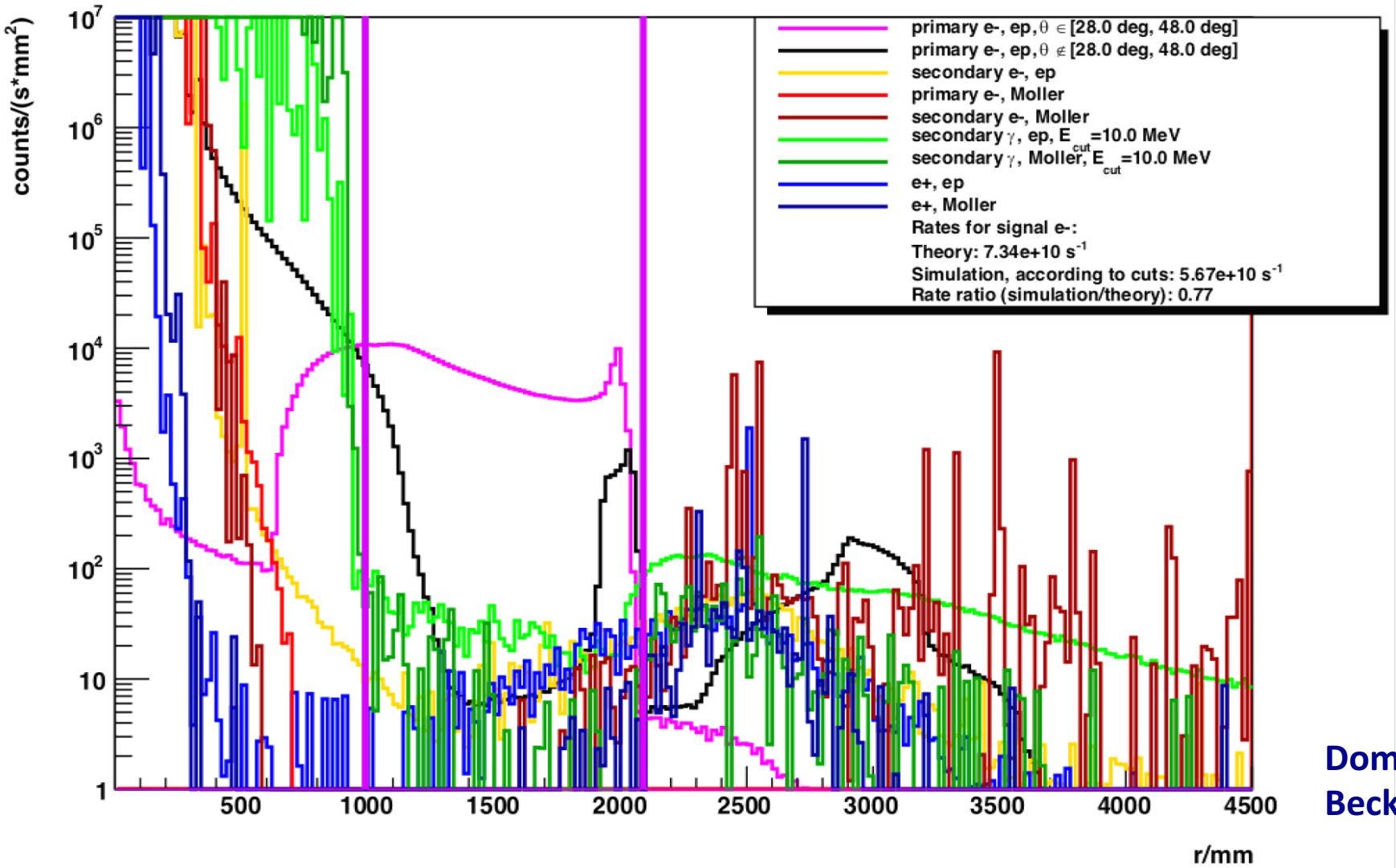
Rate distribution in tracking detector nb 1 @ z = 3500 mm



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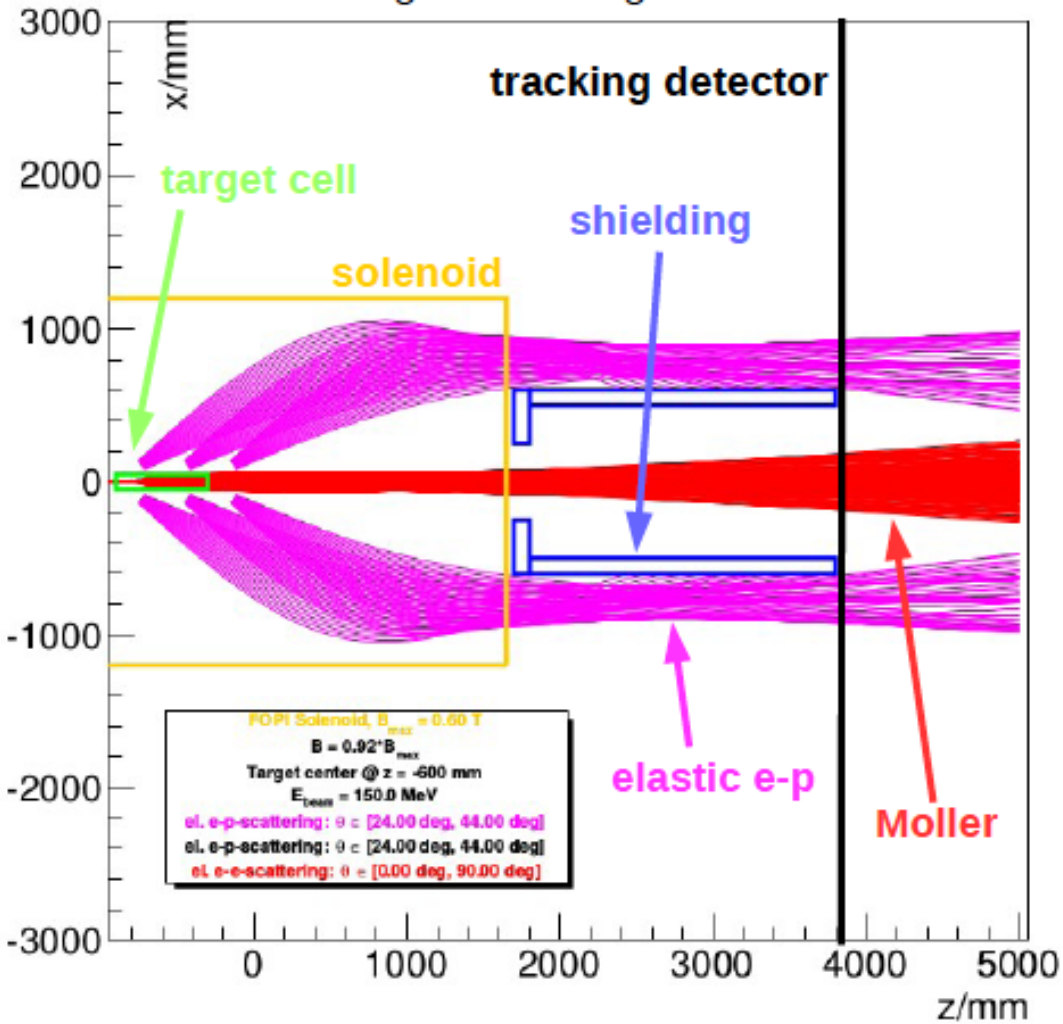
Tracking in the magnetic field



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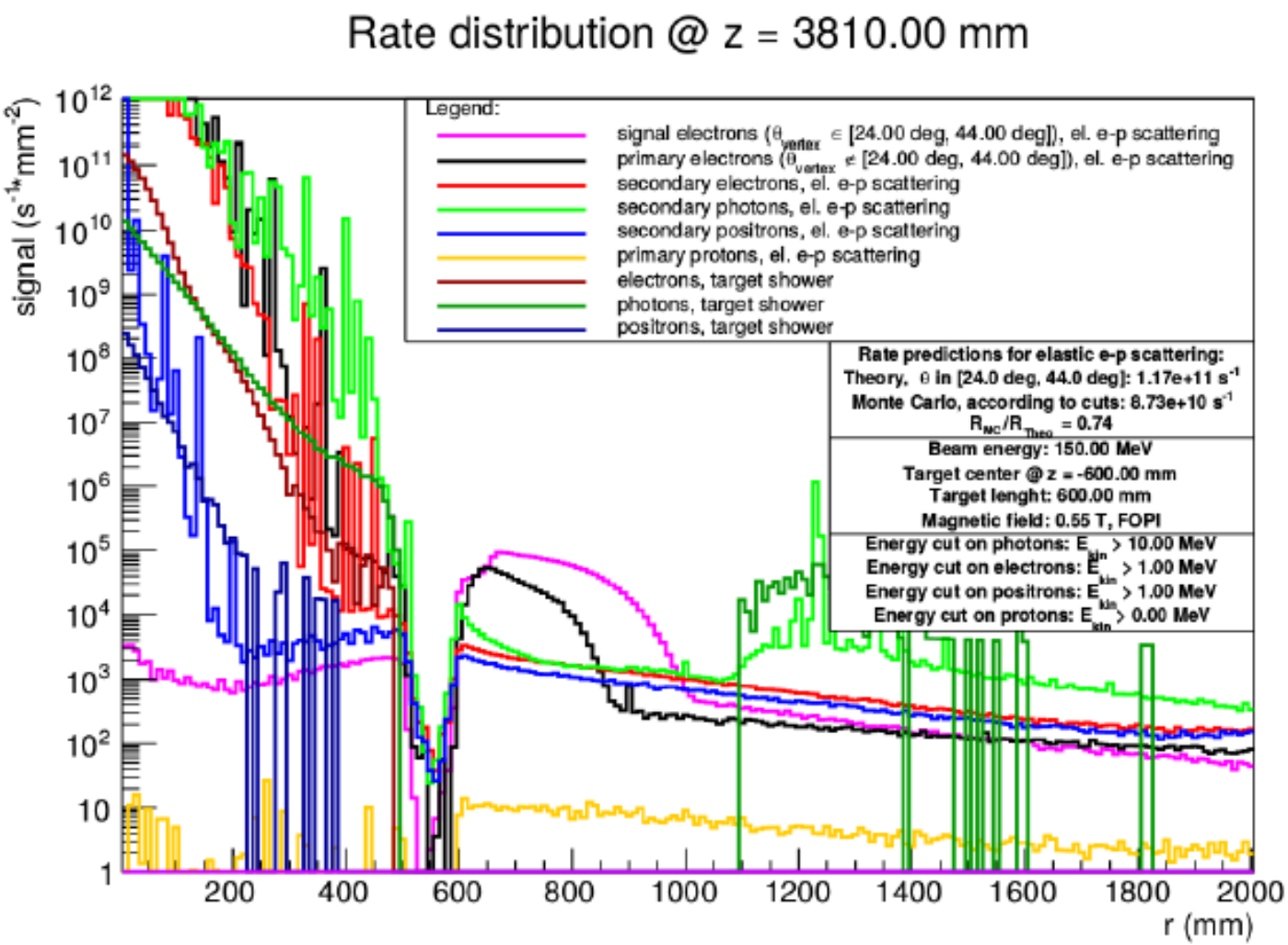

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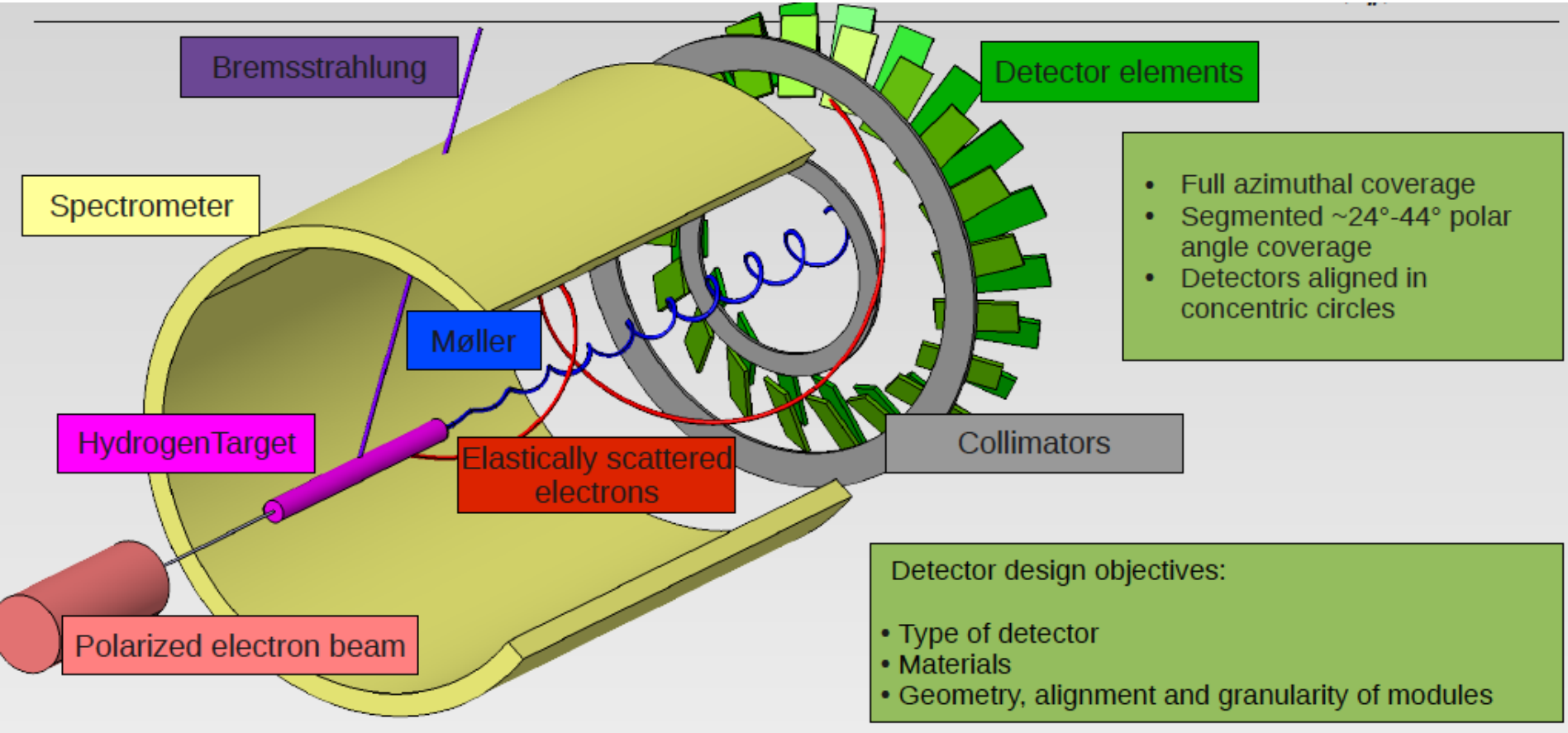
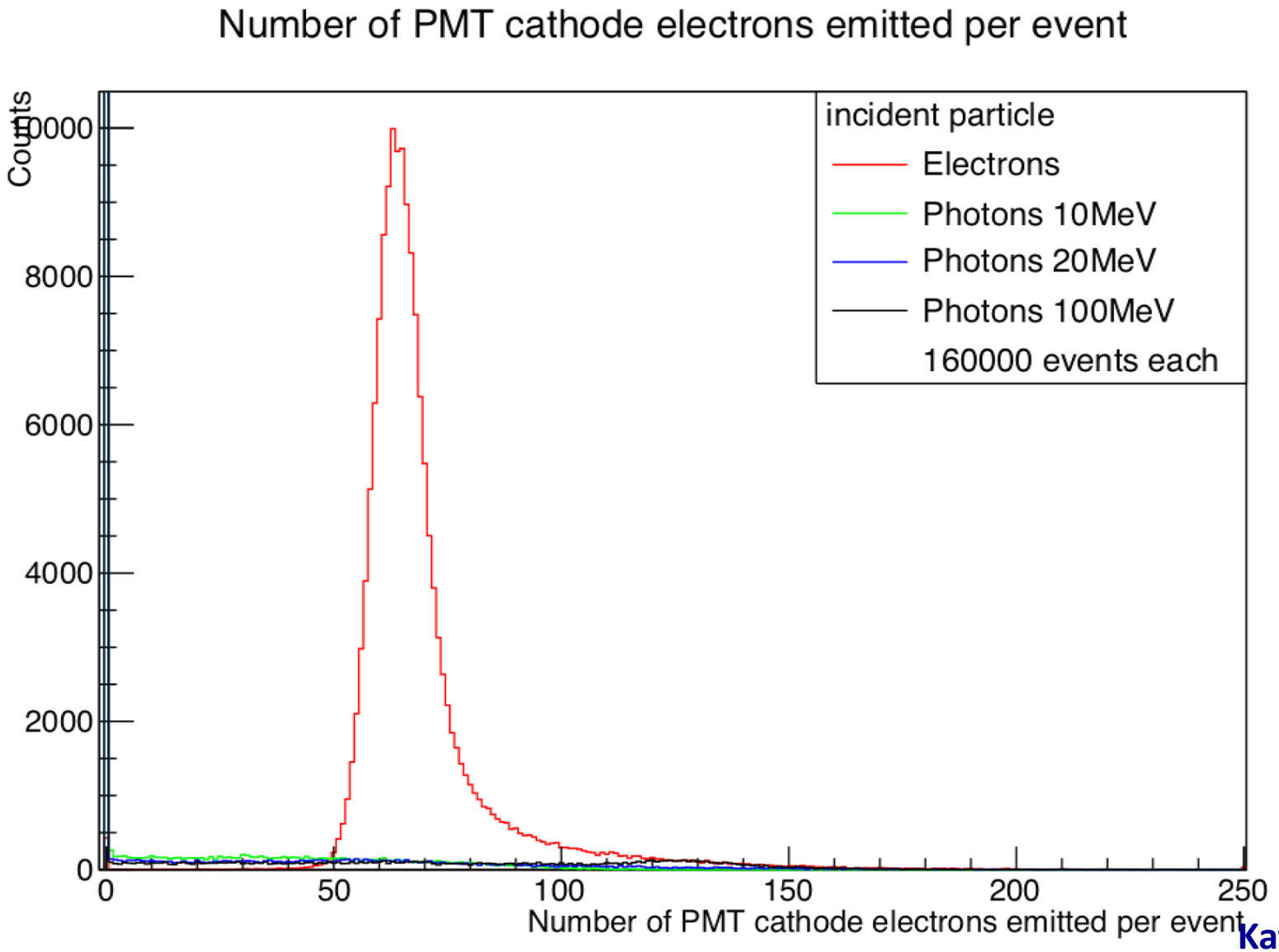


- Full azimuthal coverage
- Segmented ~24°-44° polar angle coverage
- Detectors aligned in concentric circles

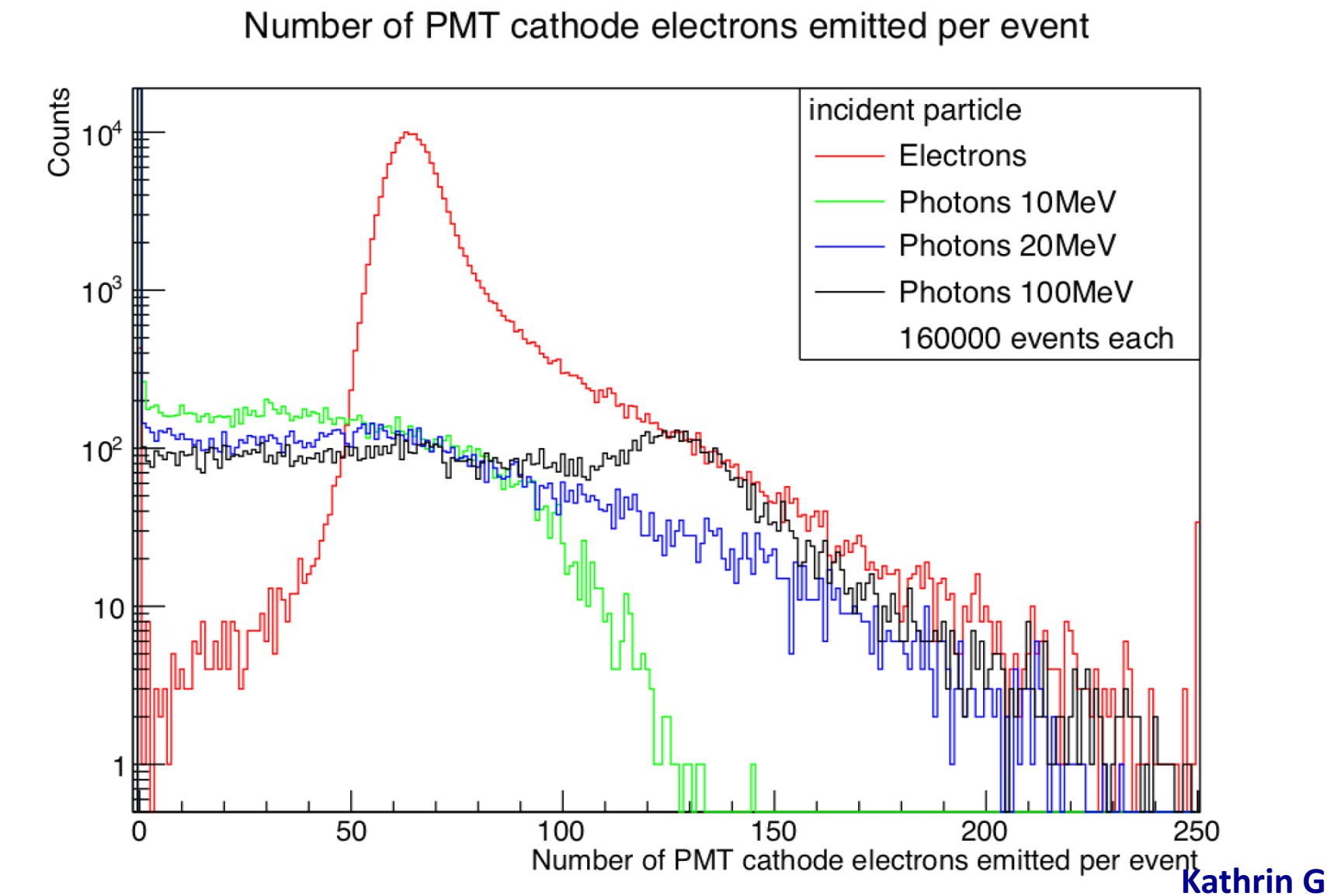
Detector design objectives:

- Type of detector
- Materials
- Geometry, alignment and granularity of modules

Kathrin Gerz



Kathrin Gerz



Kathrin Gerz