Parity Violating Electron Scattering Experiments

(High Precision determination of the weak mixing angle)

Frank Maas
(Helmholtz Institute Mainz, GSI Darmstadt and
Johannes Gutenberg University Mainz)

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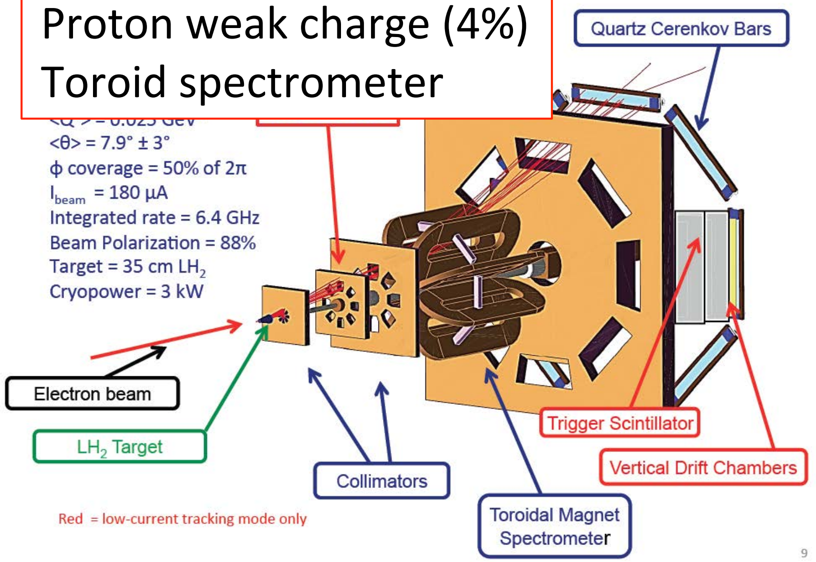
High Precision Determination of $\sin^2(\theta_W)$

Running of $\sin^2(\theta_W)$

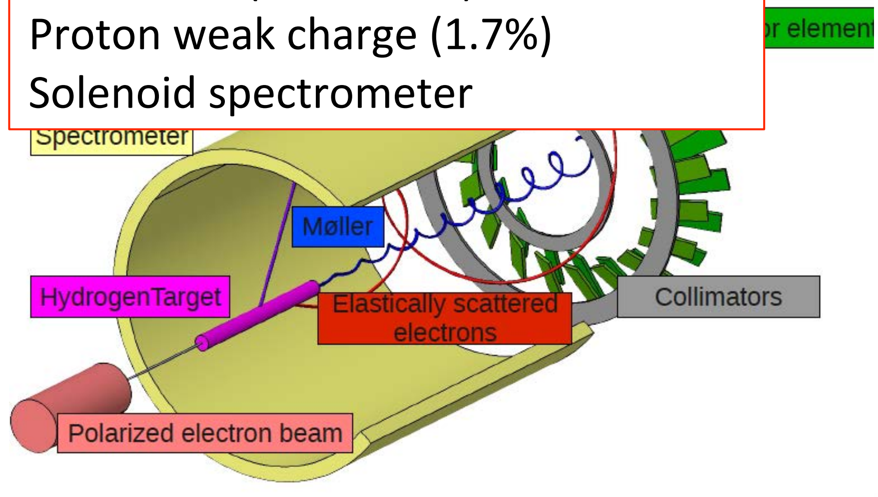
Sensitivity to new physics

Experimental Method

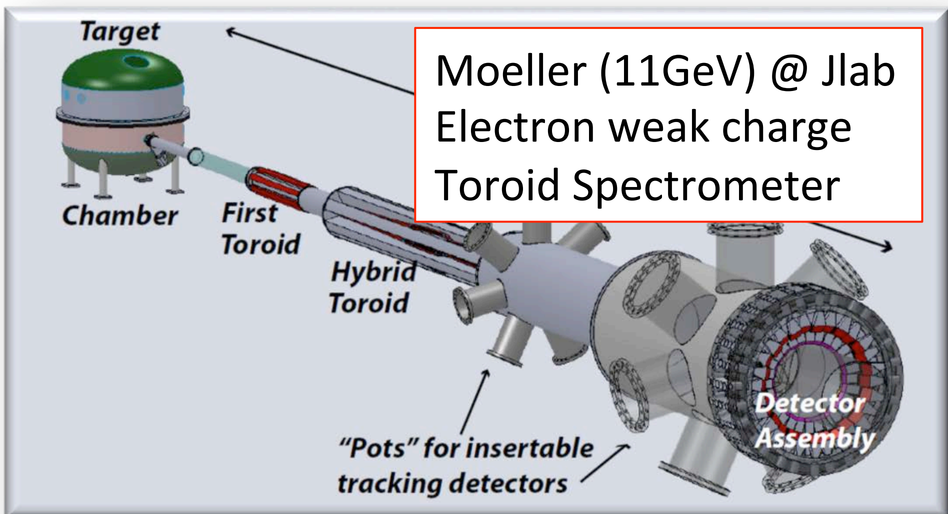
Qweak (1GeV) @ Jlab
Proton weak charge (4%)
Toroid spectrometer



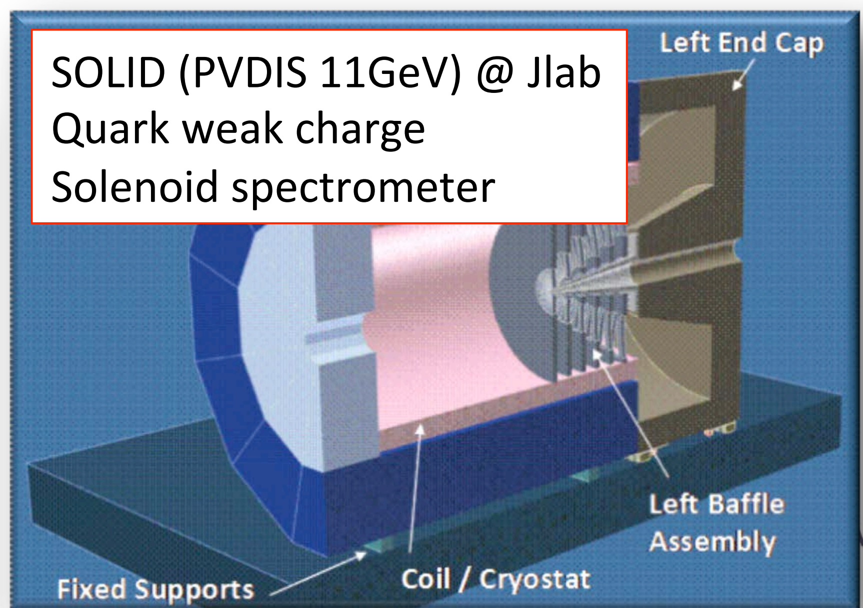
P2@MESA (0.150 GeV) @ Mainz
Proton weak charge (1.7%)
Solenoid spectrometer



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



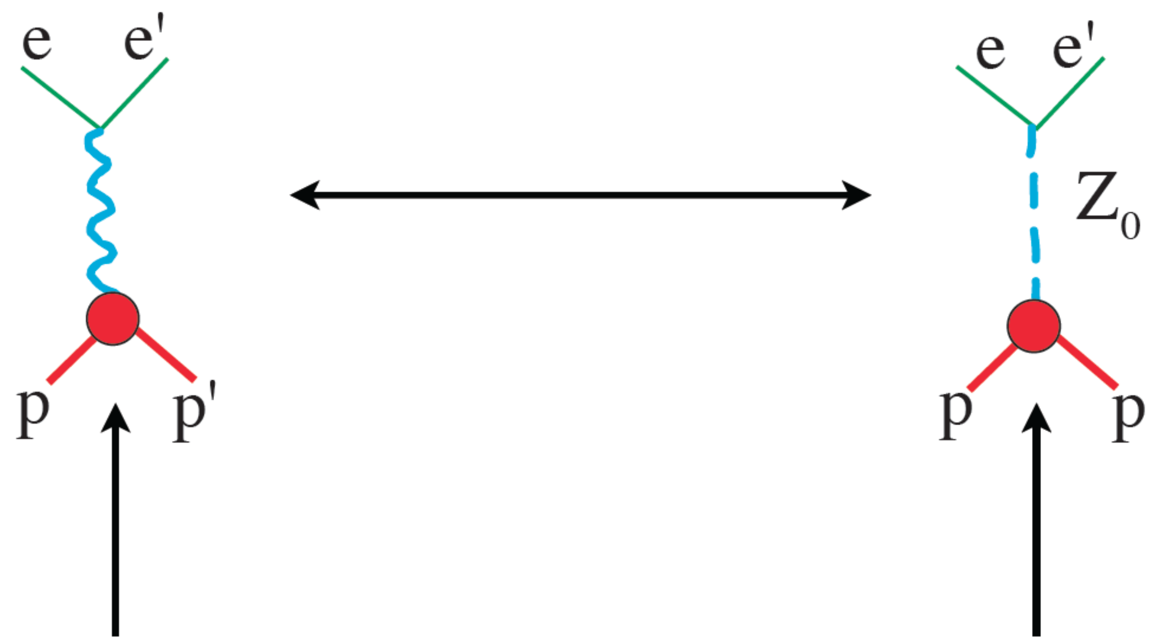
SOLID (PVDIS 11GeV) @ Jlab
Quark weak charge
Solenoid spectrometer



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

The role of the weak mixing angle

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

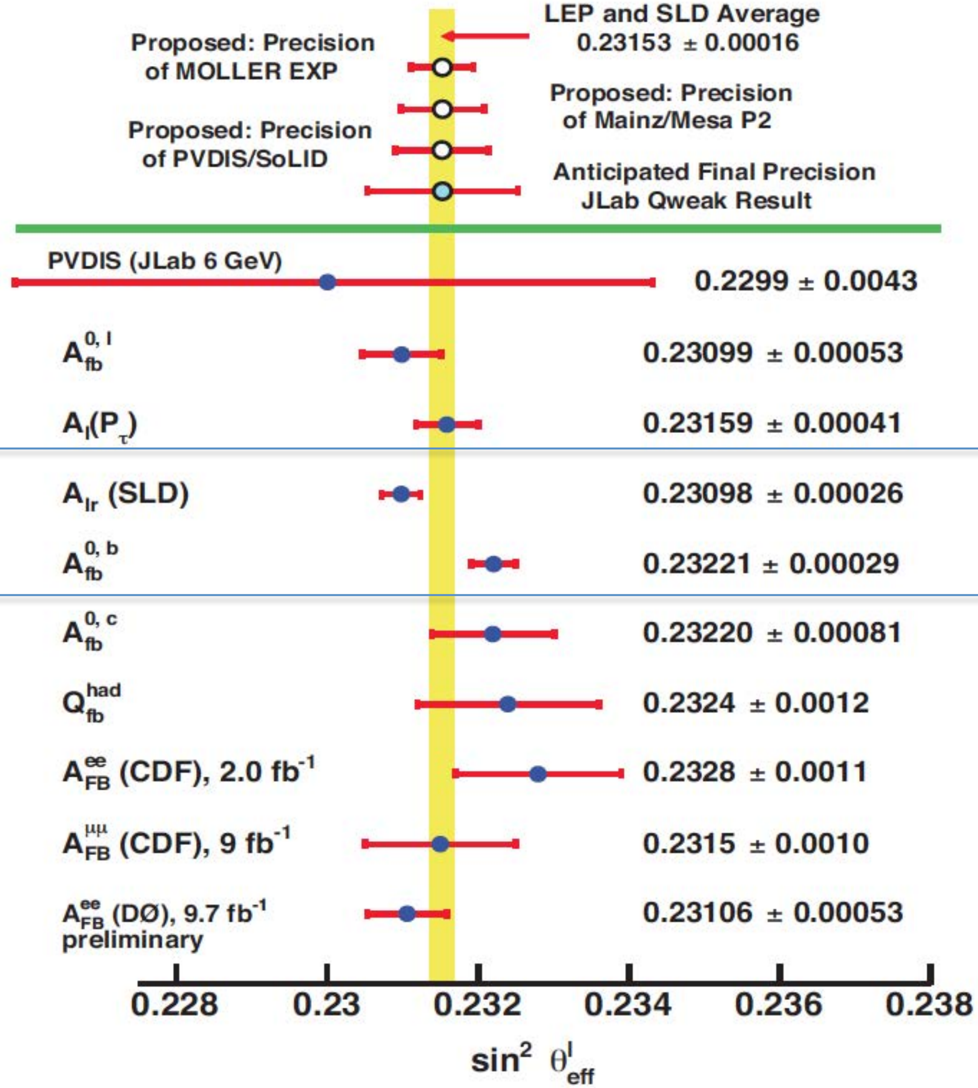


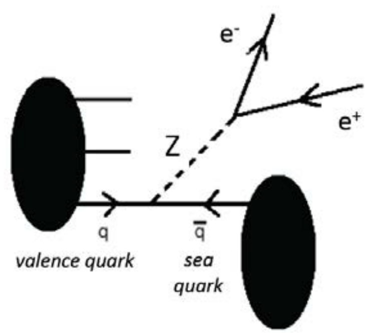
$Q_e(p) = +e$
electric charge of the proton

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

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

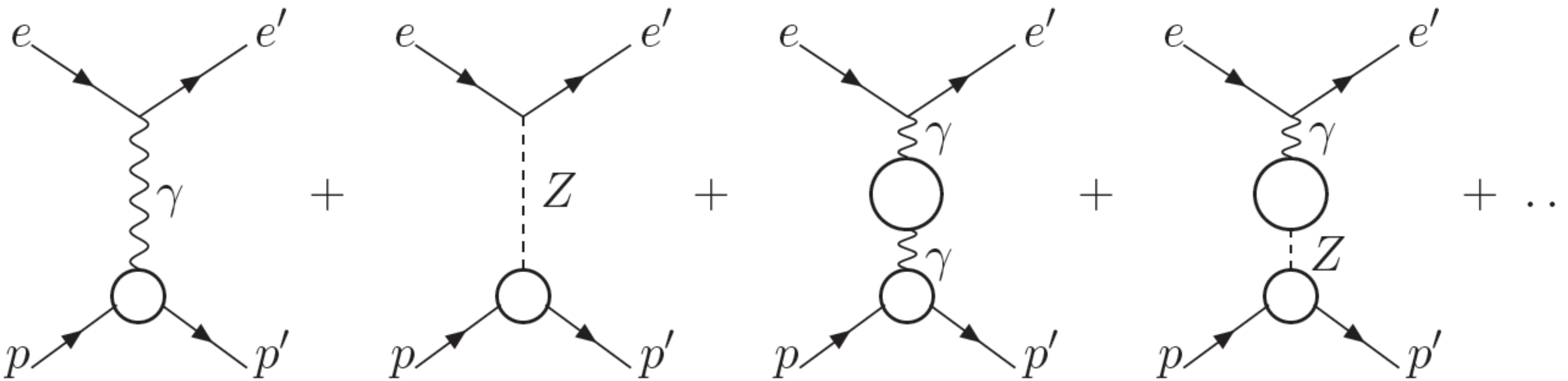
Summary: Measurements of $\sin^2\theta_{W(effective)}$





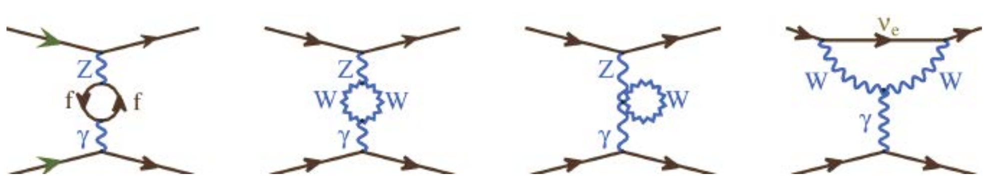
"Drell-Yan-Process"

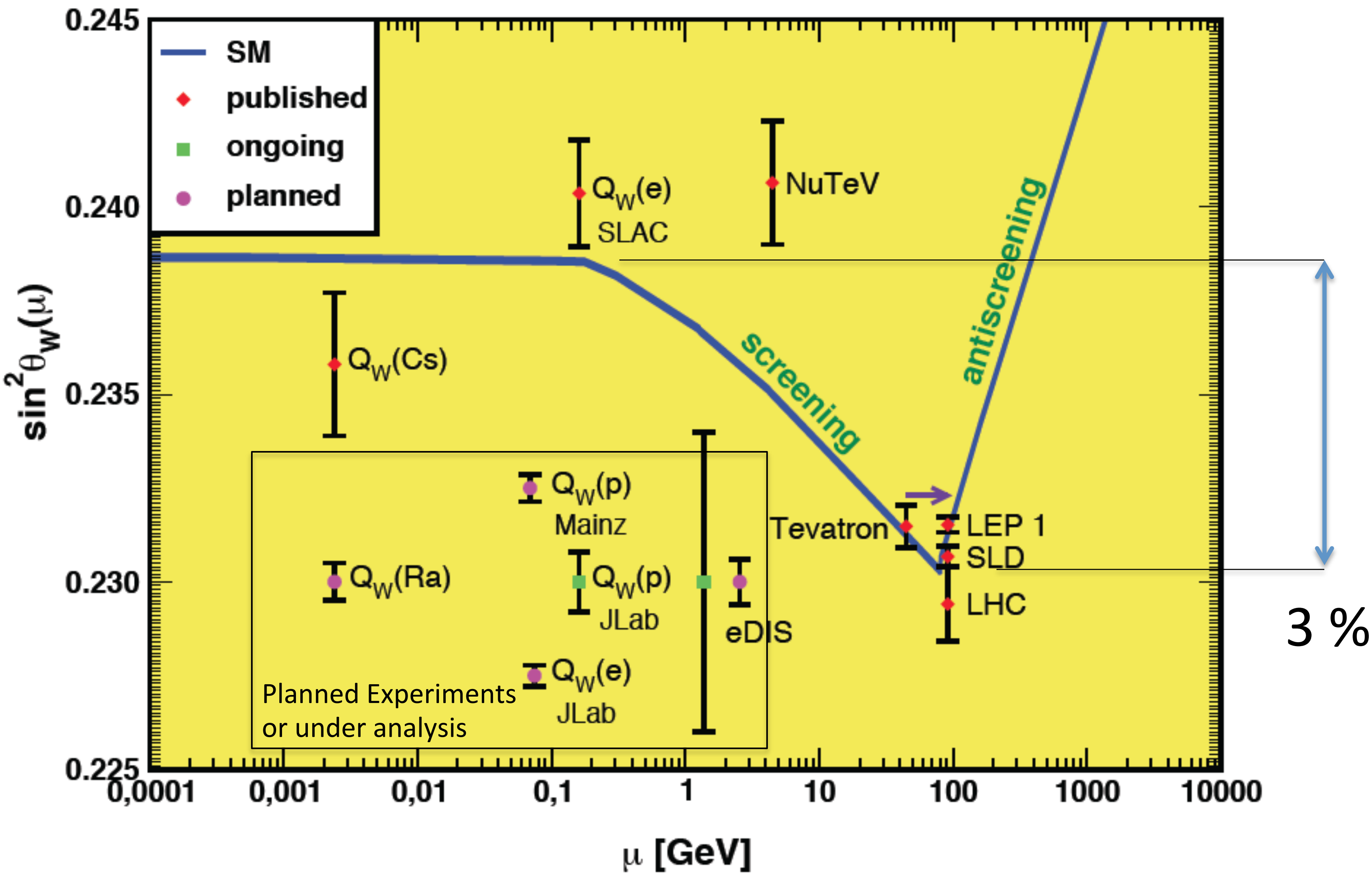
Precision measurements and quantum corrections:



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

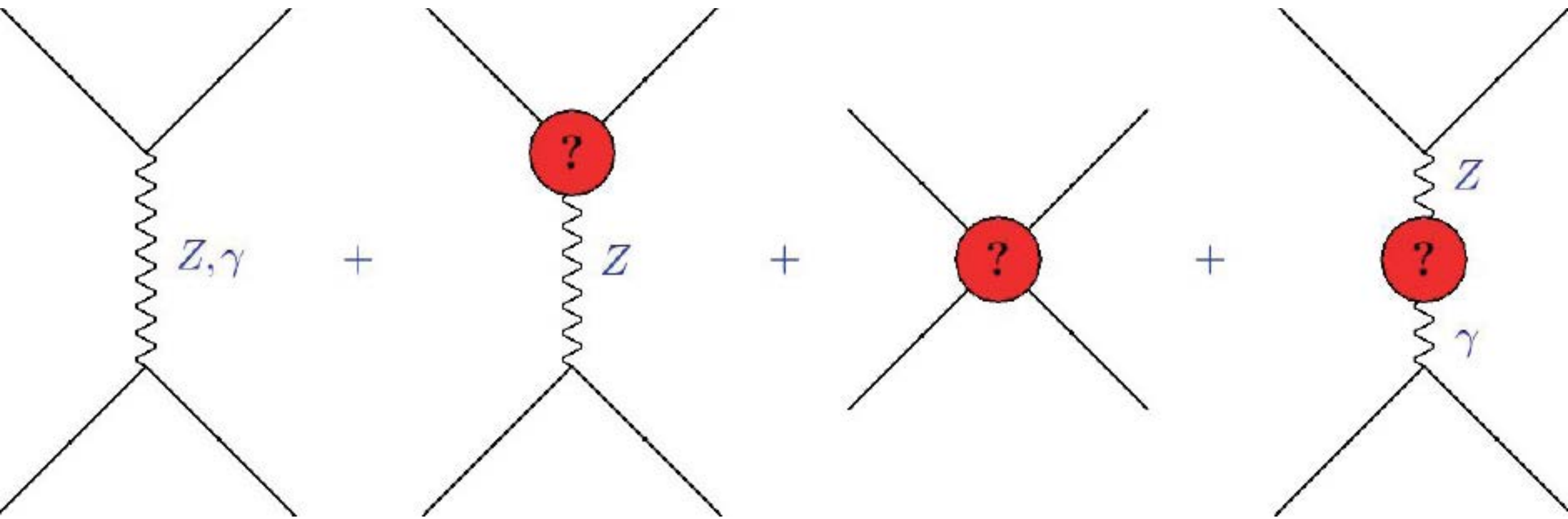
Universal quantum corrections: can be absorbed into a scale dependent, „running" $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$




SM
published
ongoing
planned
0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
0,0001
0,001
0,01
0,1
1
10
100
1000
10000
μ [GeV]
$Q_W(e)$
SLAC
NuTeV
$Q_W(Cs)$
screening
antiscreening
$Q_W(p)$
Mainz
$Q_W(Ra)$
$Q_W(p)$
JLab
$Q_W(e)$
JLab
eDIS
Tevatron
LEP 1
SLD
LHC
Planned Experiments
or under analysis
3 %

Sensitivity to new physics beyond the Standard Model

Sensitivity to new physics beyond the Standard Model



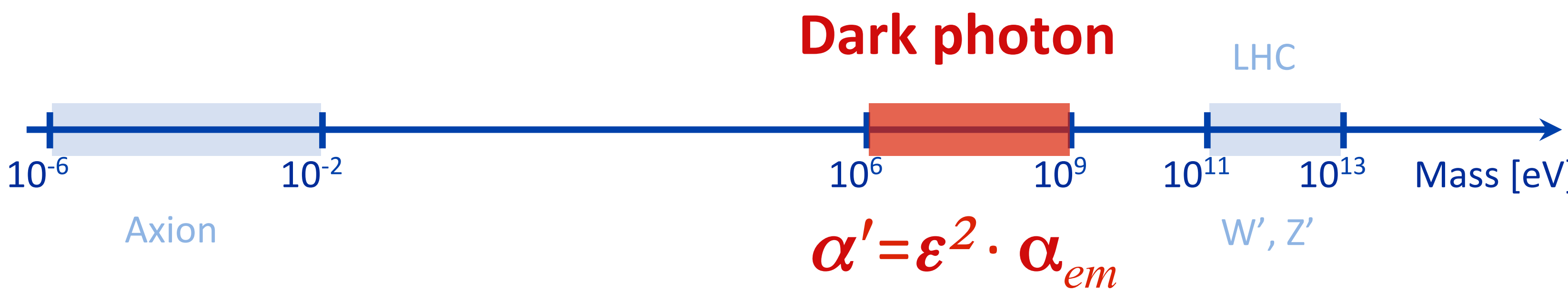
Extra Z

Mixing with Dark photon or Dark Z

Contact interaction

New Fermions

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

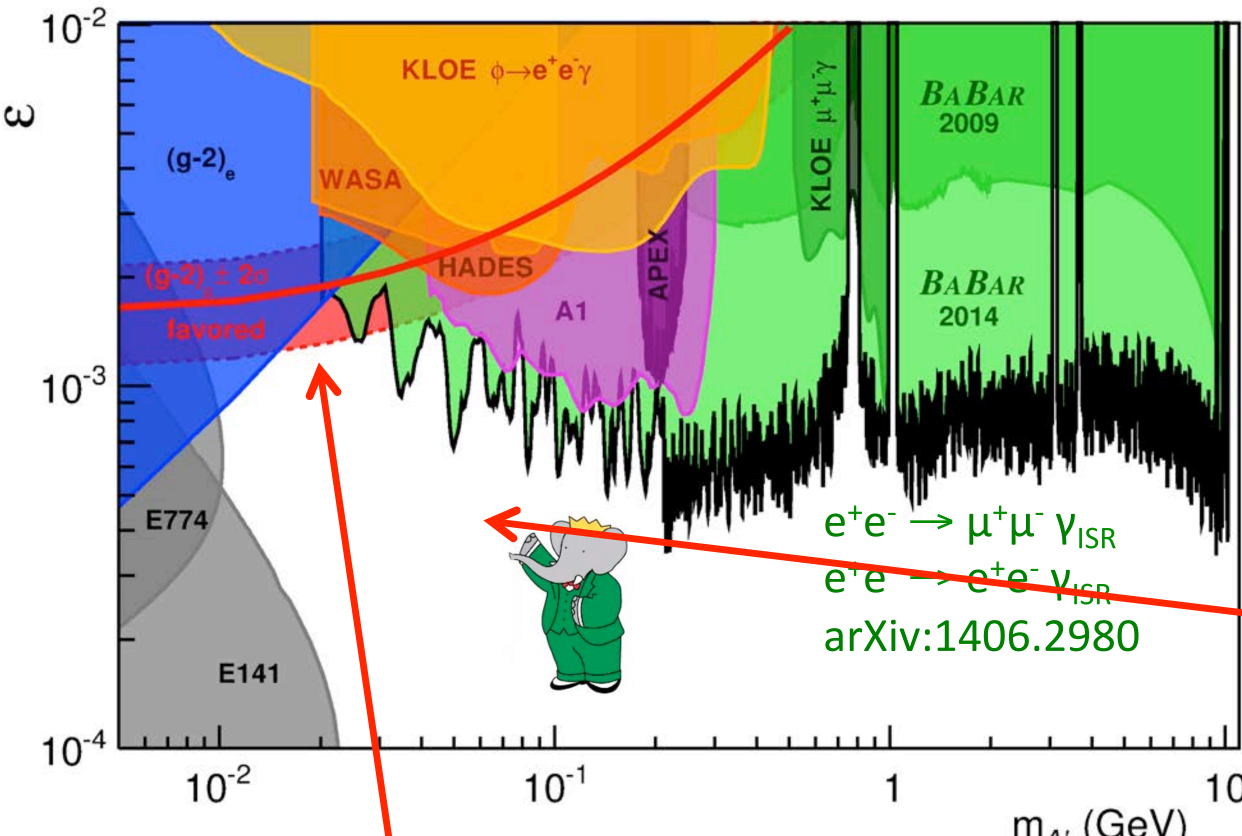


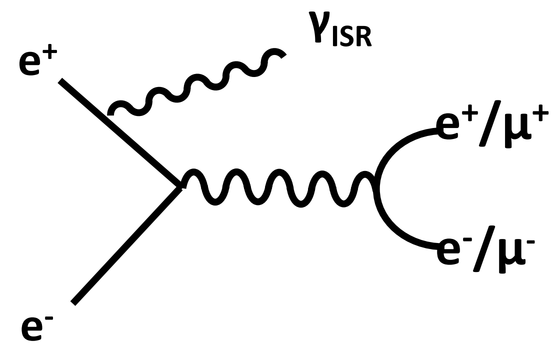
Search for the O(GeV/c²) mass scale in a world-wide effort

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

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

BABAR Dark Photon Search (arXiv:1406.2980)

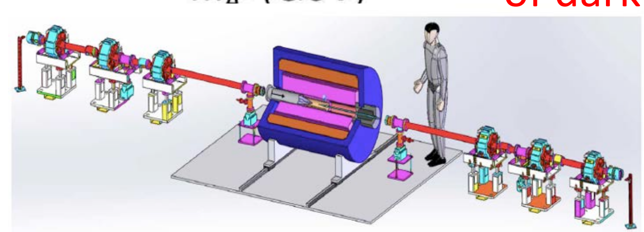


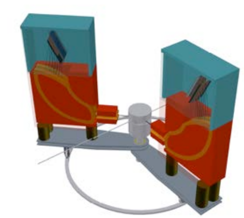


Analysis of the full data set (10 years)

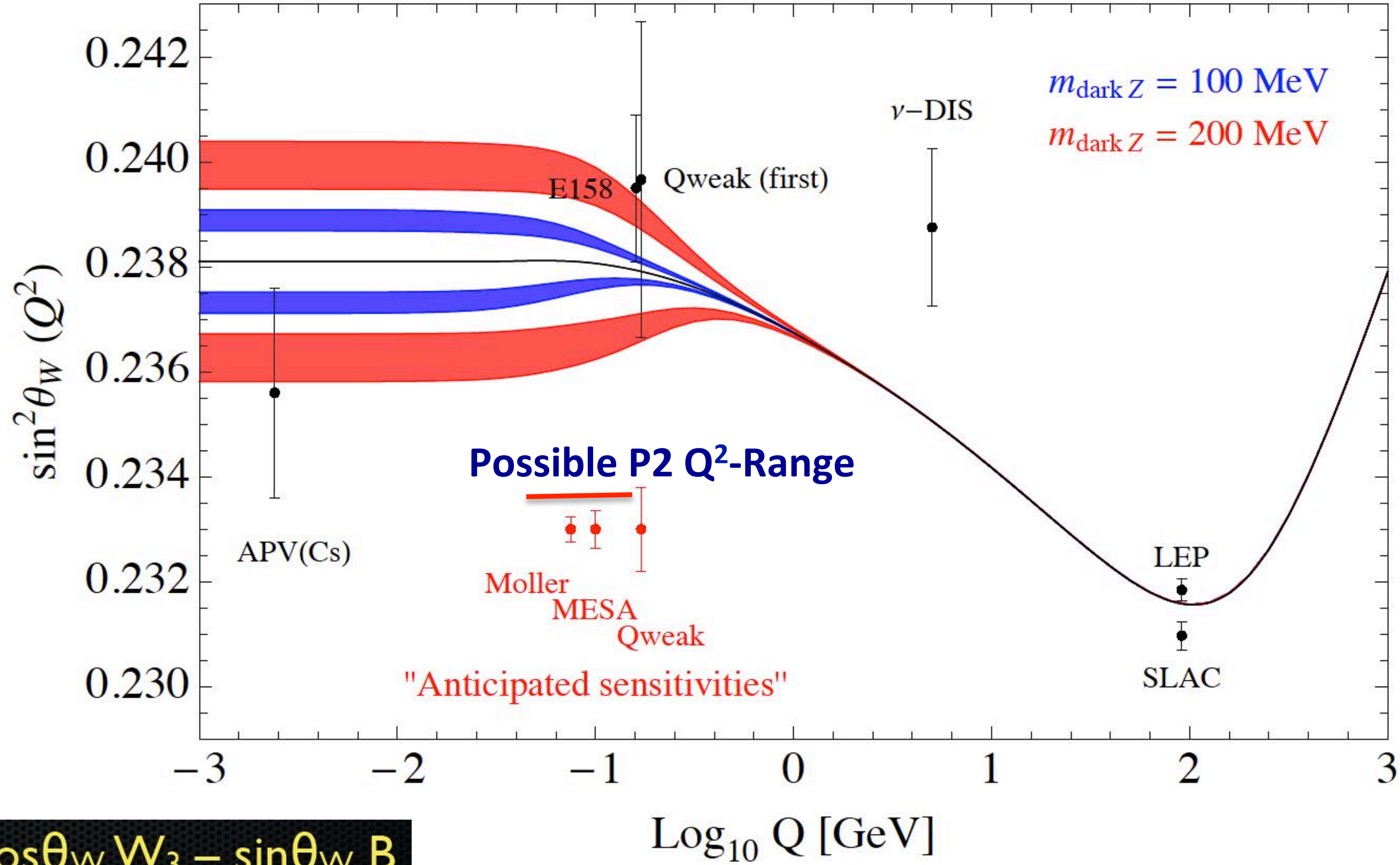
Entire remaining white region (JLAB APEX, HPS)
Interesting in view of dark sector

Remaining $(g-2)_\mu$ welcome region!?
Dark Light @ JLAB-FEL
MESA @ Mainz





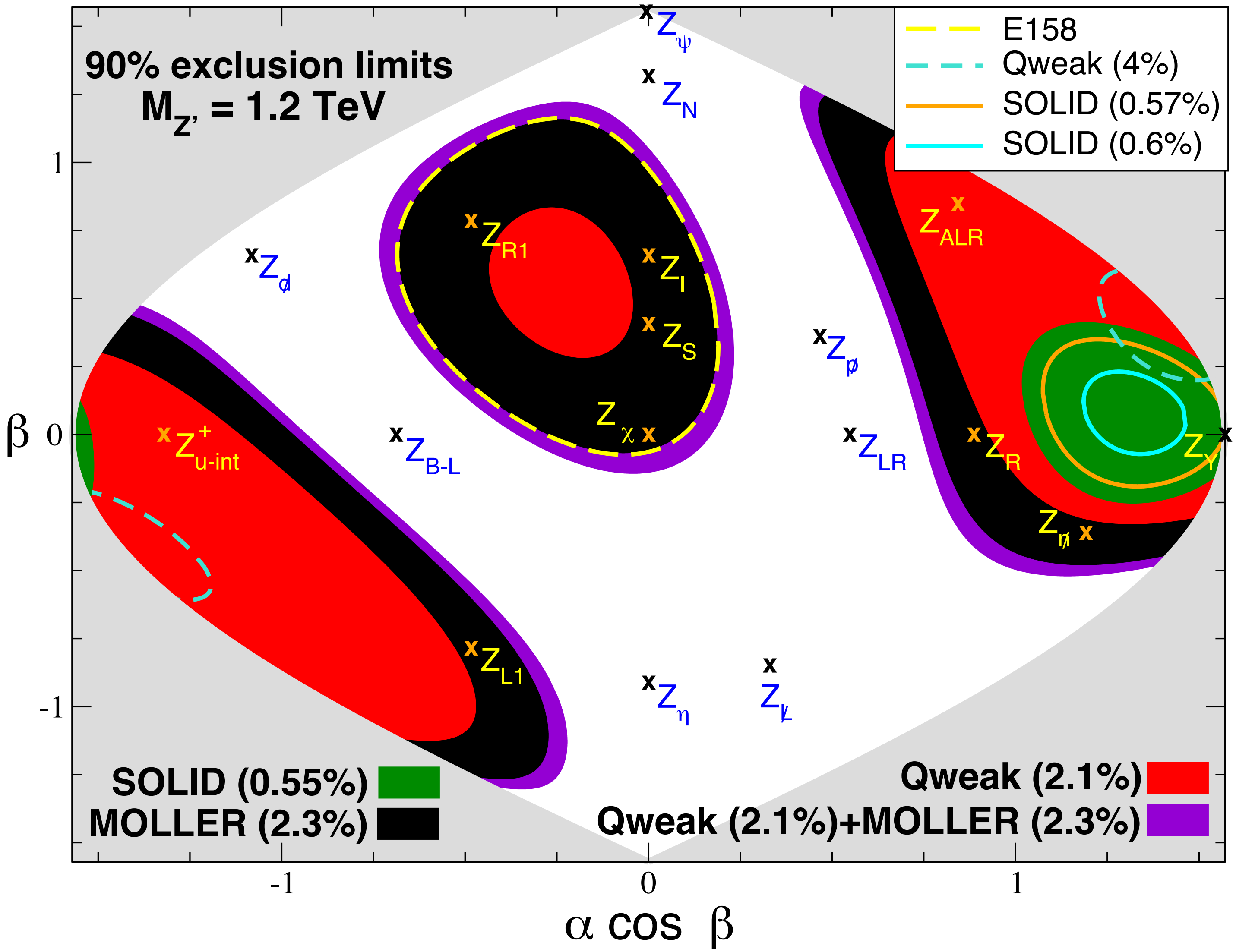
Running $\sin^2\theta_W$ and Dark Parity Violation



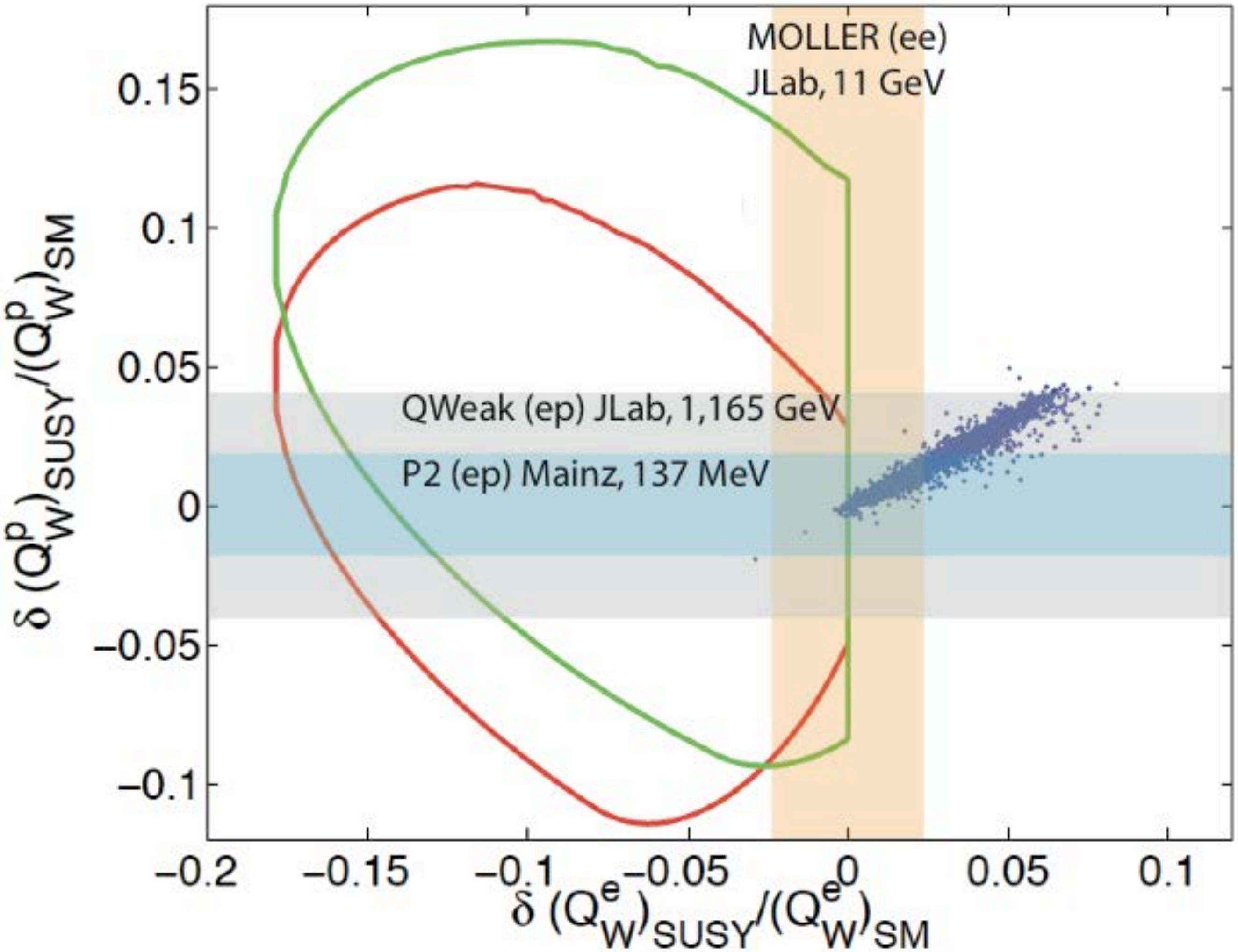
$Z = \cos\theta_W W_3 - \sin\theta_W B$

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

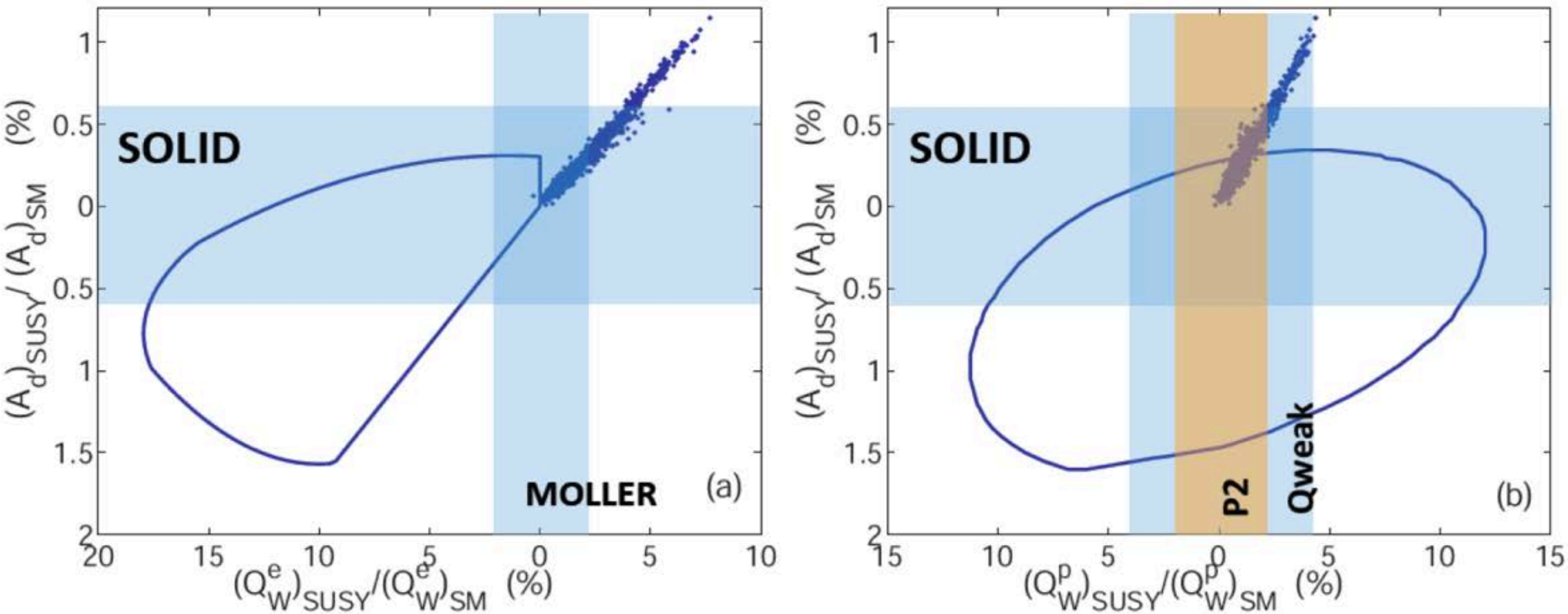
Bill Marciano


90% exclusion limits
M_Z' = 1.2 TeV
E158
Qweak (4%)
SOLID (0.57%)
SOLID (0.6%)
SOLID (0.55%)
MOLLER (2.3%)
Qweak (2.1%)
Qweak (2.1%)+MOLLER (2.3%)
Z_ψ
Z_N
Z_R1
Z_I
Z_S
Z_χ
Z_ALR
Z_LR
Z_R
Z_Y
Z_η
Z_B-L
Z_u-int^+
Z_L1
β
α cos β
1
0
-1

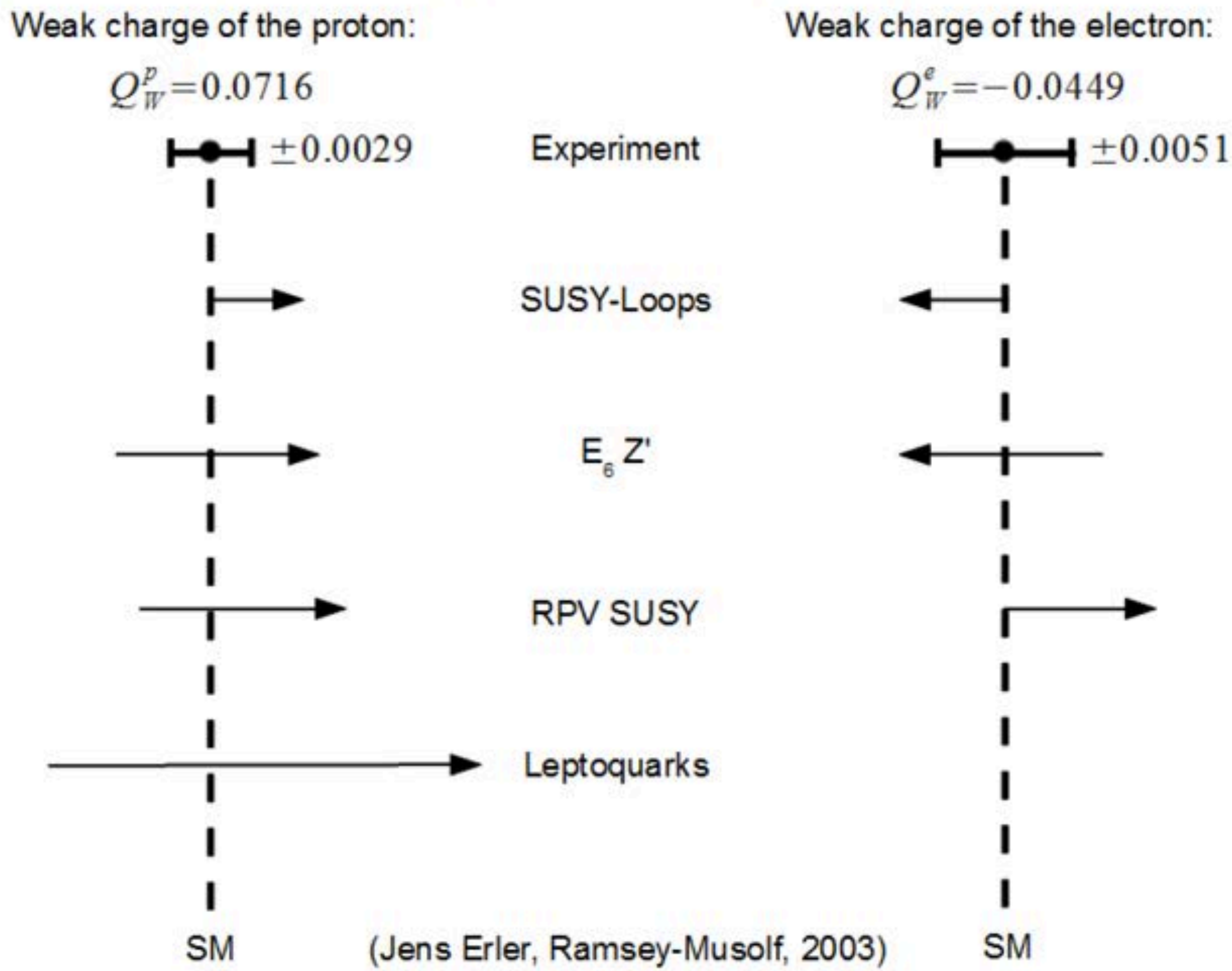
Example: supersymmetric Standard Model extensions



Ramsey-Musolf and Su, ***Phys. Rep. 456 (2008)***



- 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)

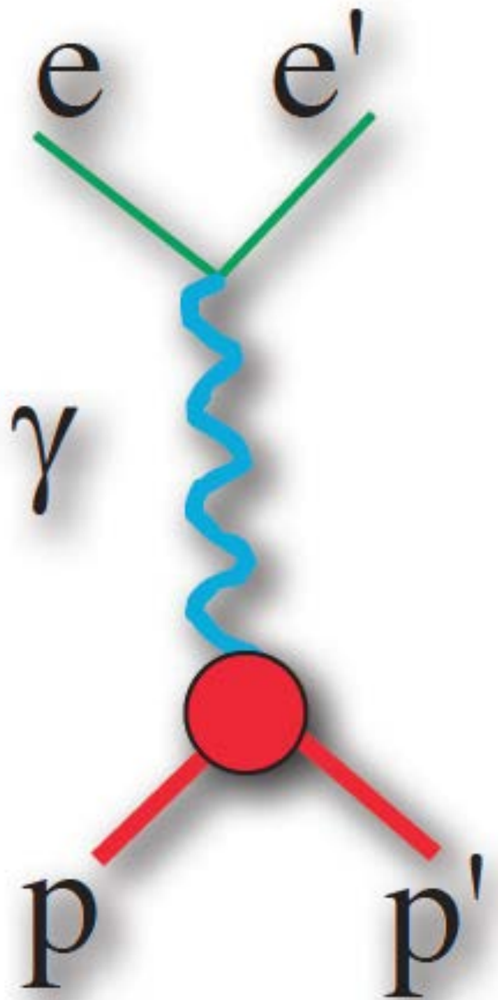
Weak Charge Of Quarks:
SOLID (PVDIS) (JLAB)

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

	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



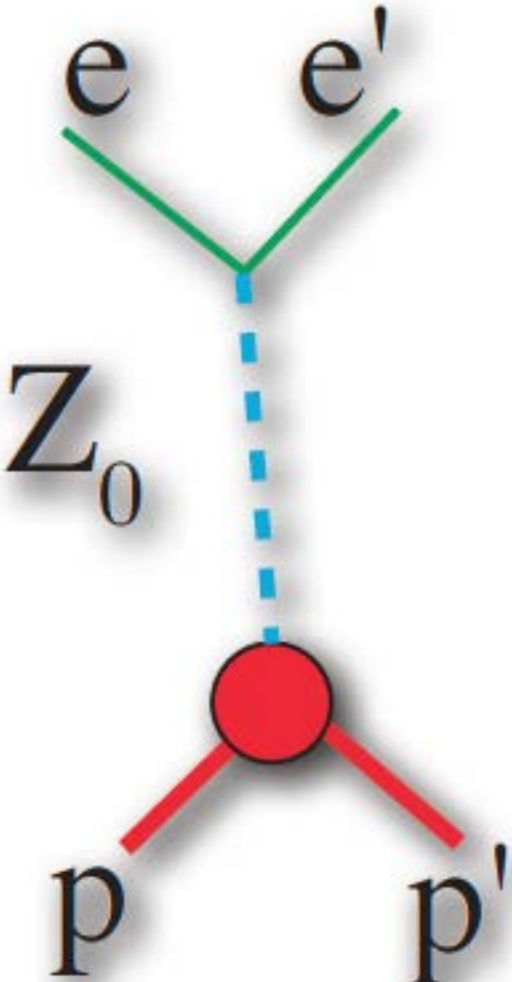
$$\sigma \sim \mathcal{M}\,\mathcal{M}^* \text{ Phasespace}$$

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

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

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

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

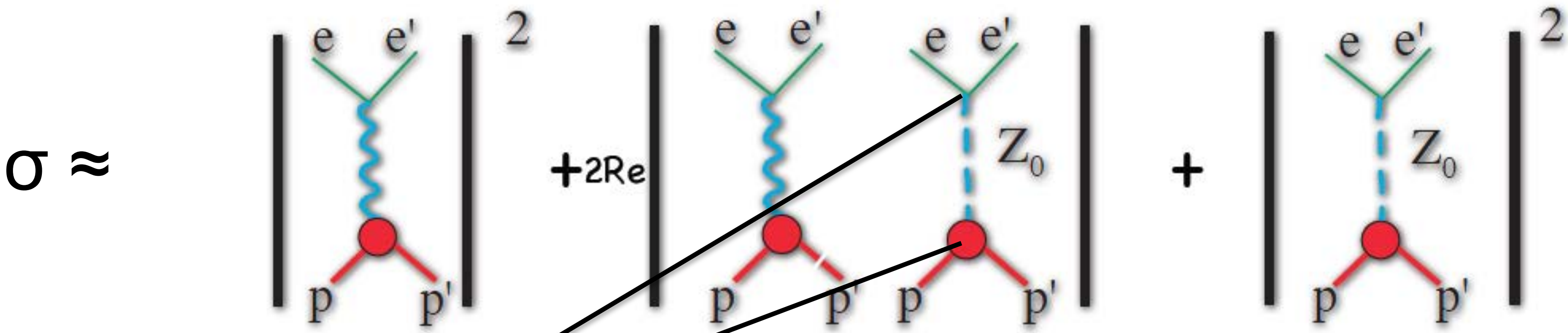


$$\tilde{q}^{d}{}_{V} \quad = \quad \tau_3 - 2q^{d}\, sin^2(\theta_W)$$

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

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

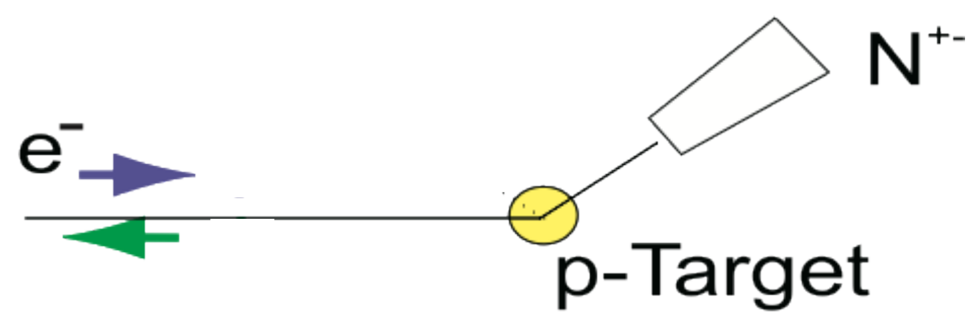
Parity Violating Asymmetry in elastic electron proton scattering



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

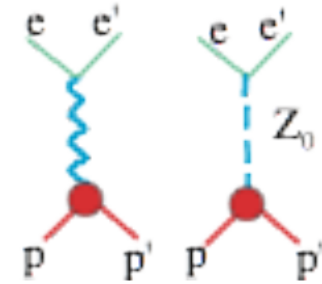
$A_eV_p+V_eA_p$

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



Parity violating cross section asymmetry

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



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

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

Parity violating cross section asymmetry

weak charge

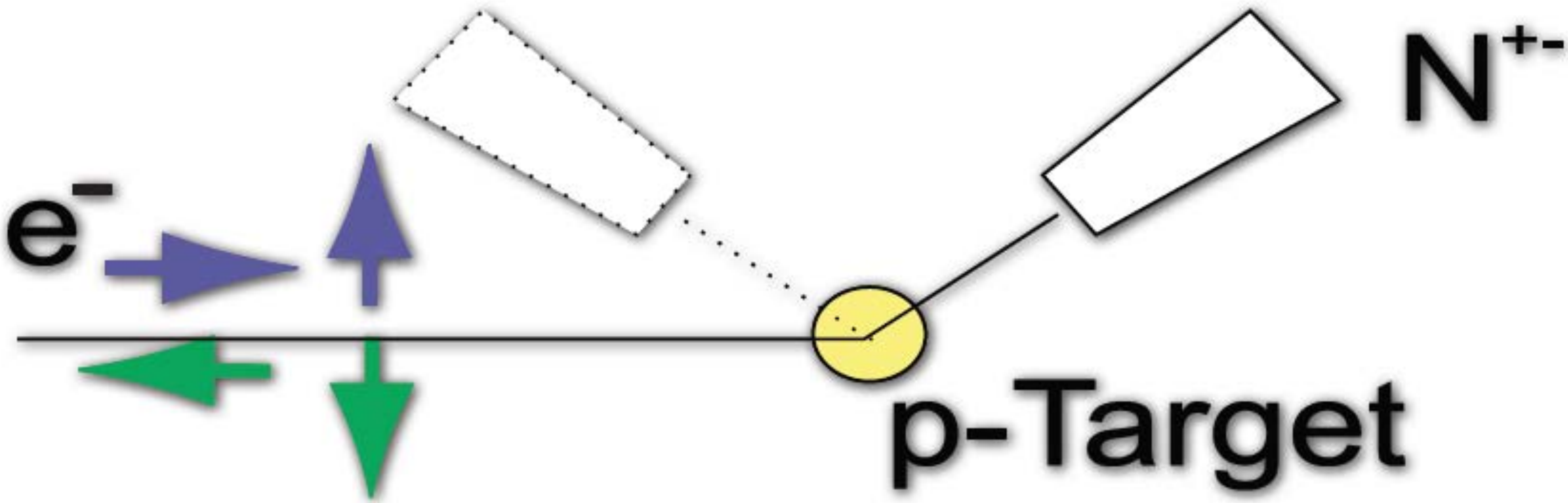
$$A_{LR} = \frac{\sigma(e\uparrow)-\sigma(e\downarrow)}{\sigma(e\uparrow)+\sigma(e\downarrow)} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

hadron structure

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

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

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

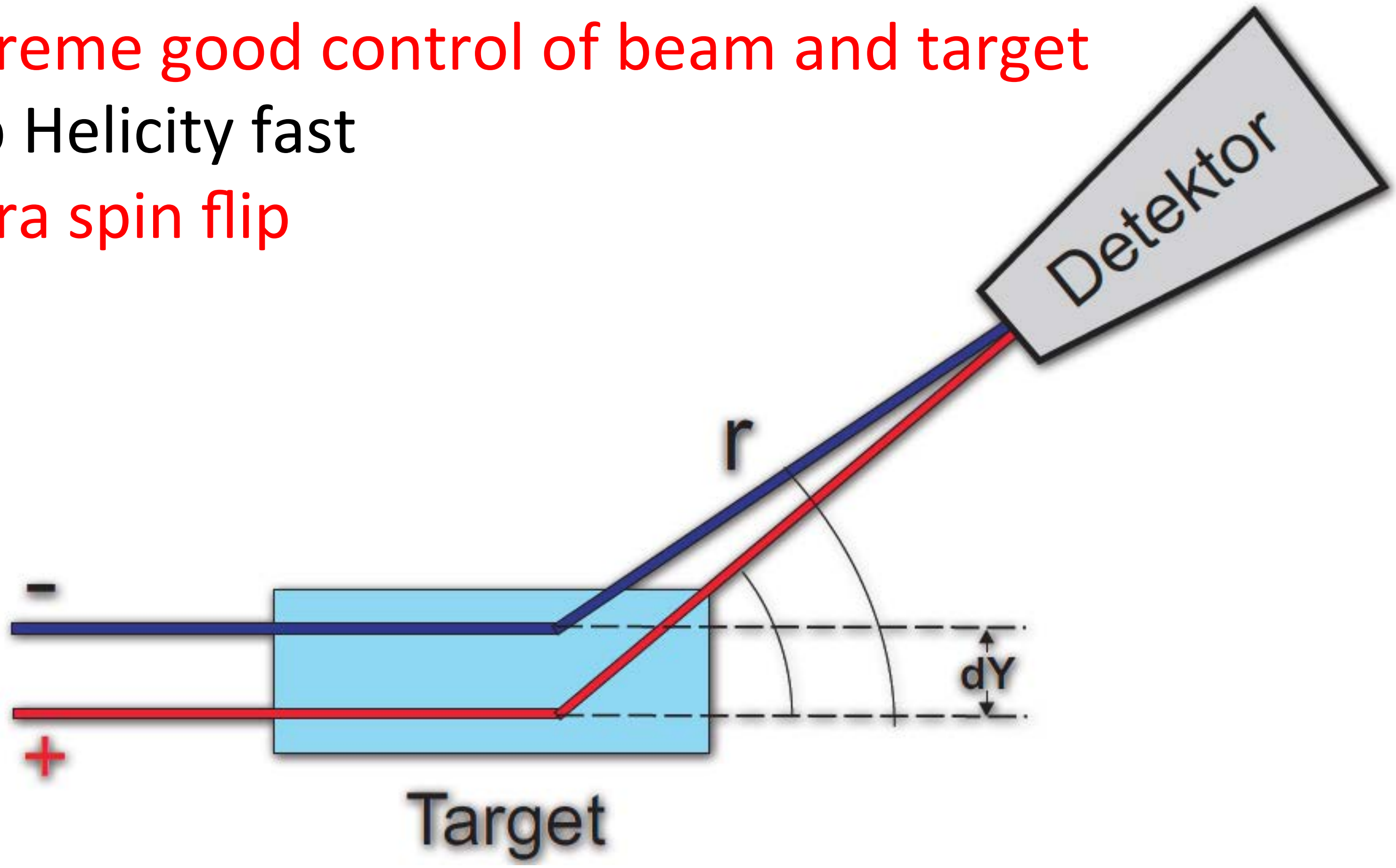
Highest rate, measure Q^2: Large Solid Angle Spectrometers

Apparative (false) asymmetries:

Extreme good control of beam and target

Flip Helicity fast

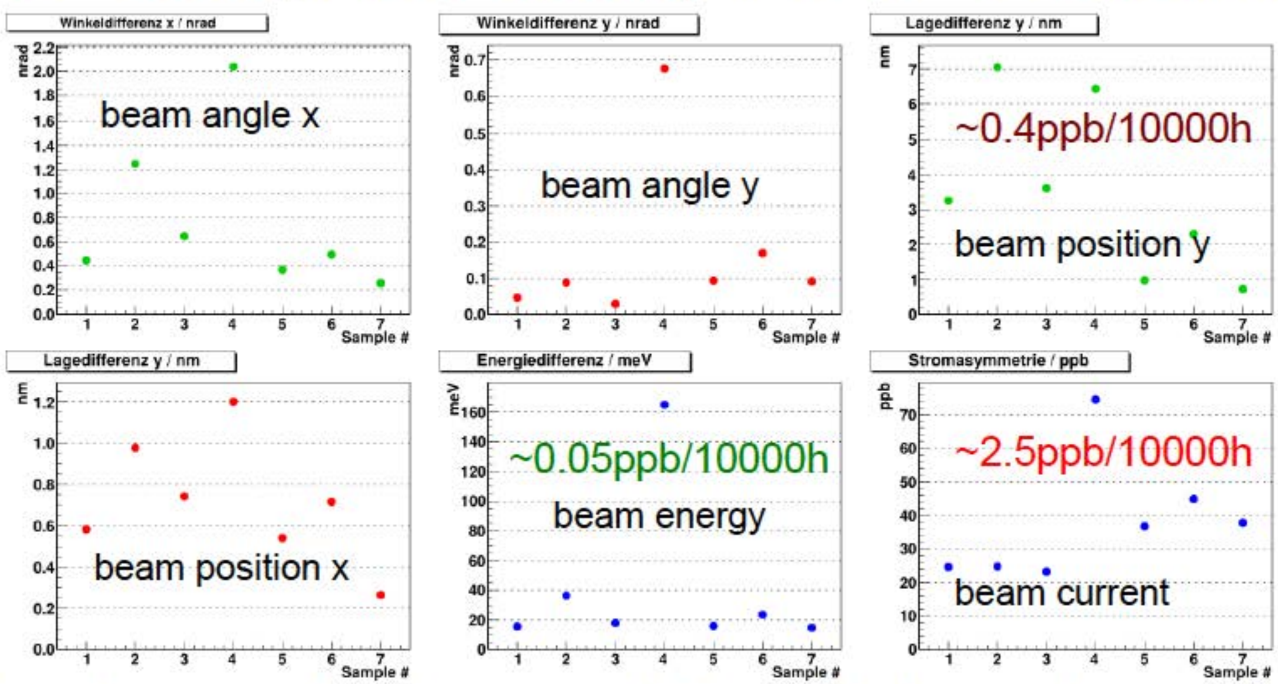
Extra spin flip



Topic D: Suppr. of false asymmetries

- >10 years of experience of beam delivery to a parity violation experiment

Systematics of A4 @210MeV, extrapolated to 10000h of data taking:



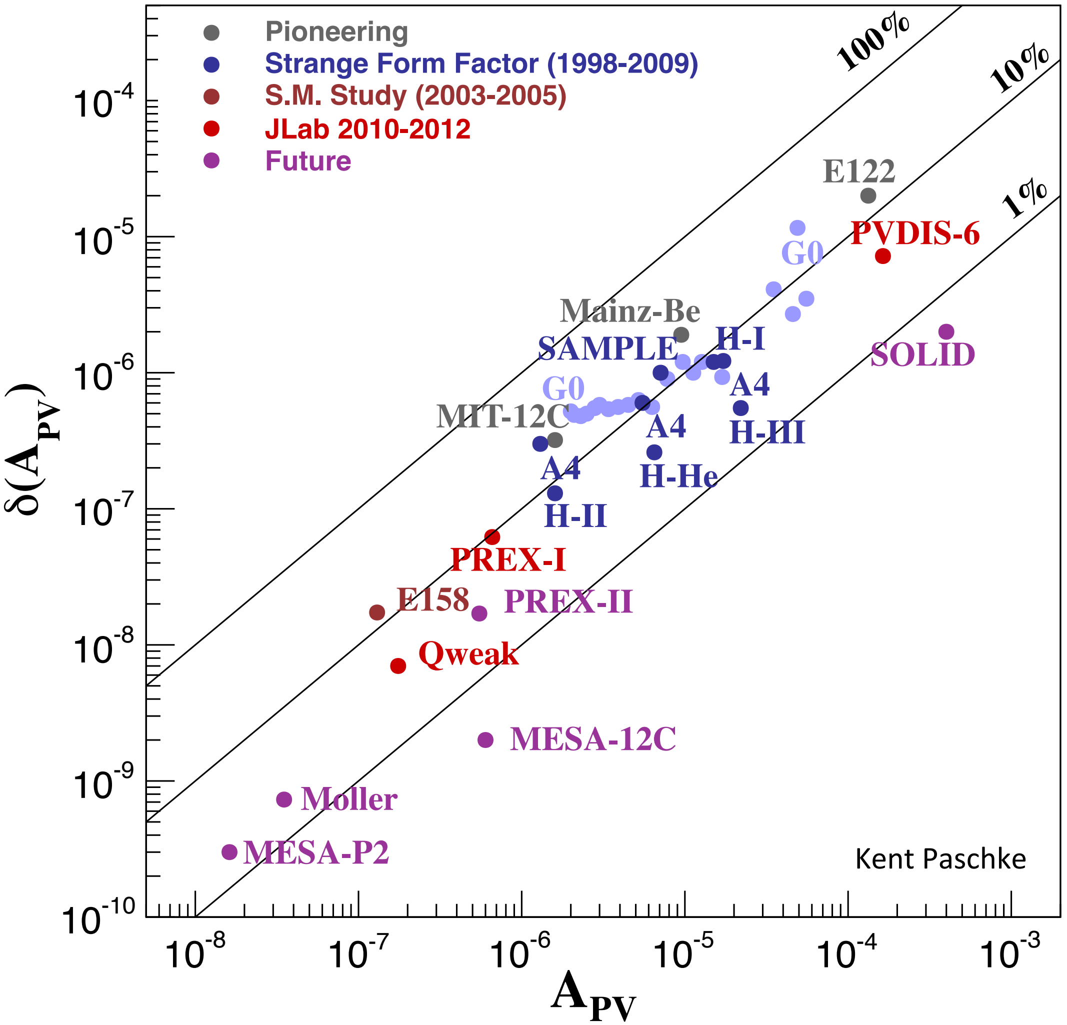
Need to improve by factors of 10 ~ 100, in total *max. 0.1ppb*!

dedicated simulations for P2 in preparation

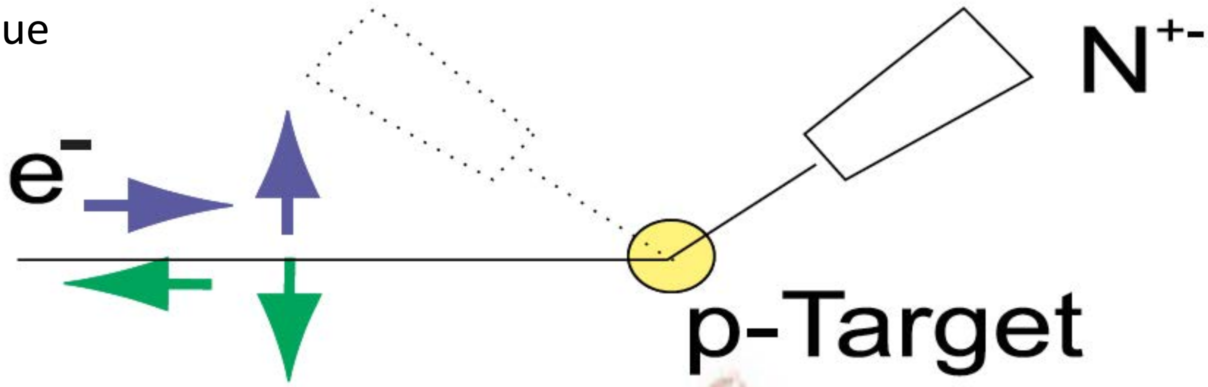
JG|U

SFB 1044
Institut für Kernphysik

PVeS Experiment Summary



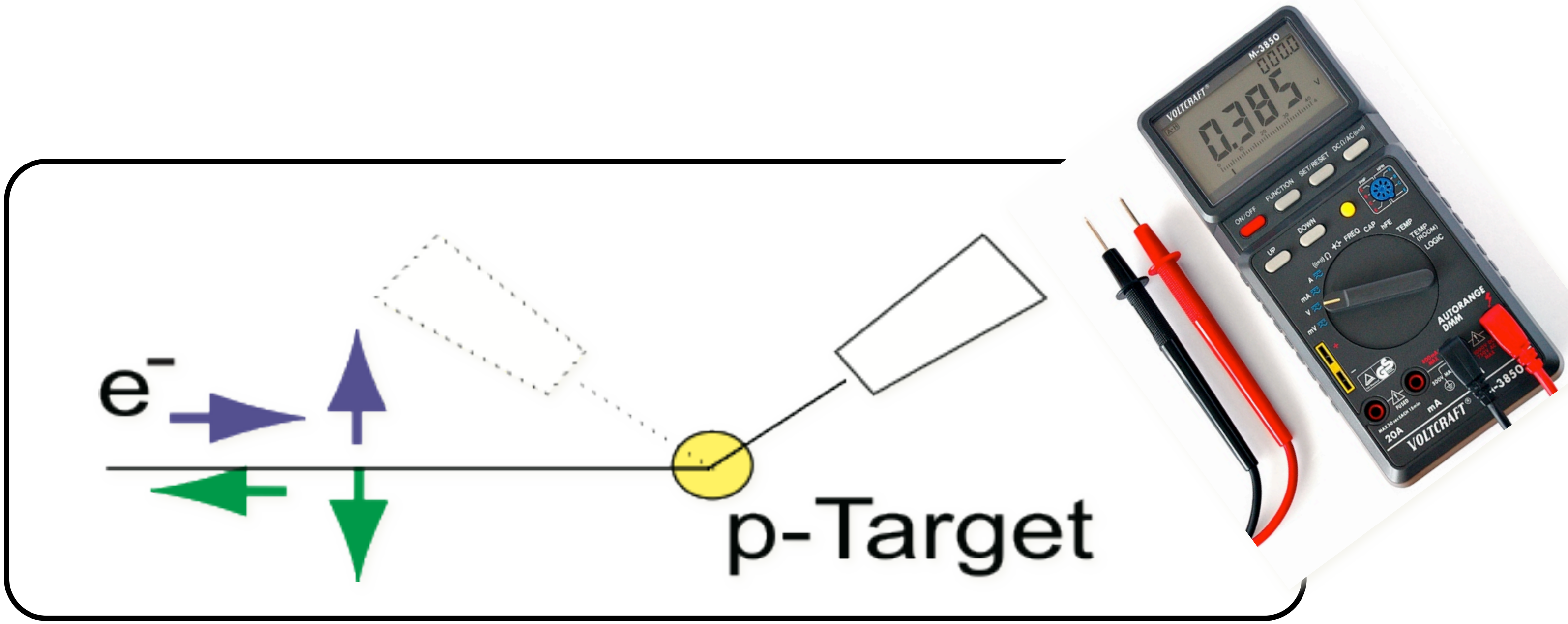
Counting Technique



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

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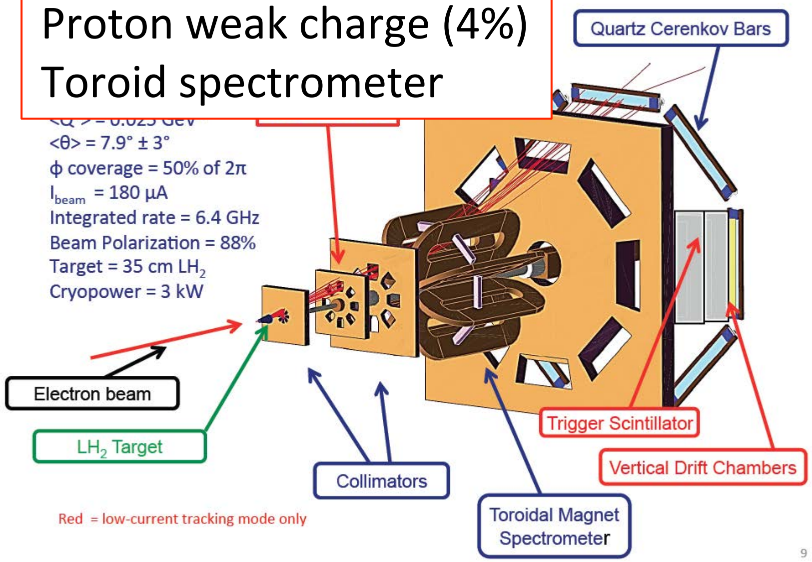
Proton weak charge (4%)
Toroid spectrometer



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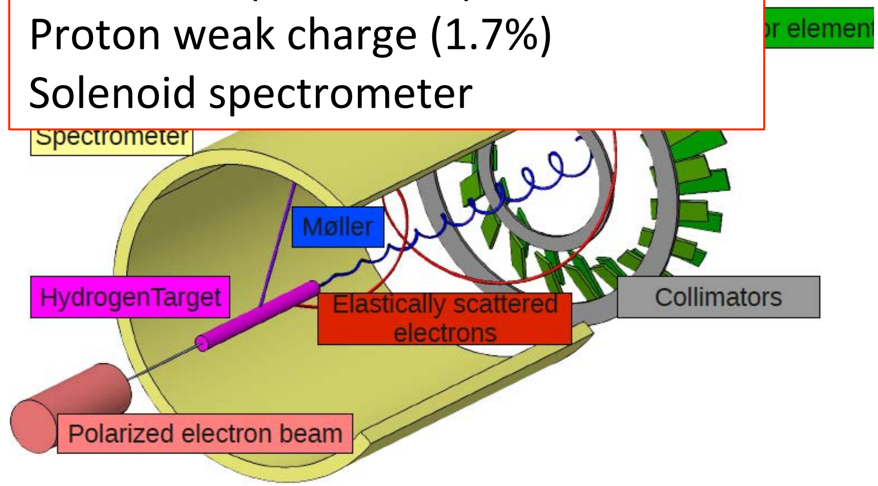

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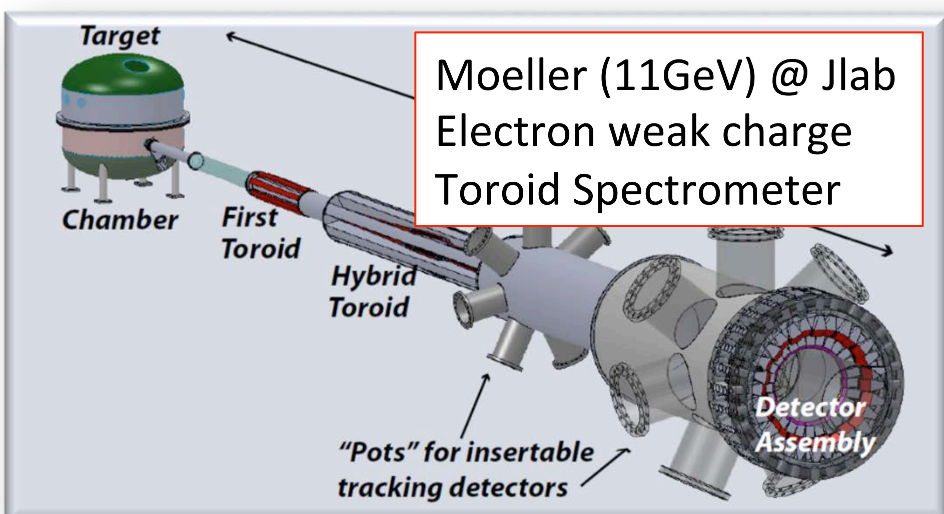
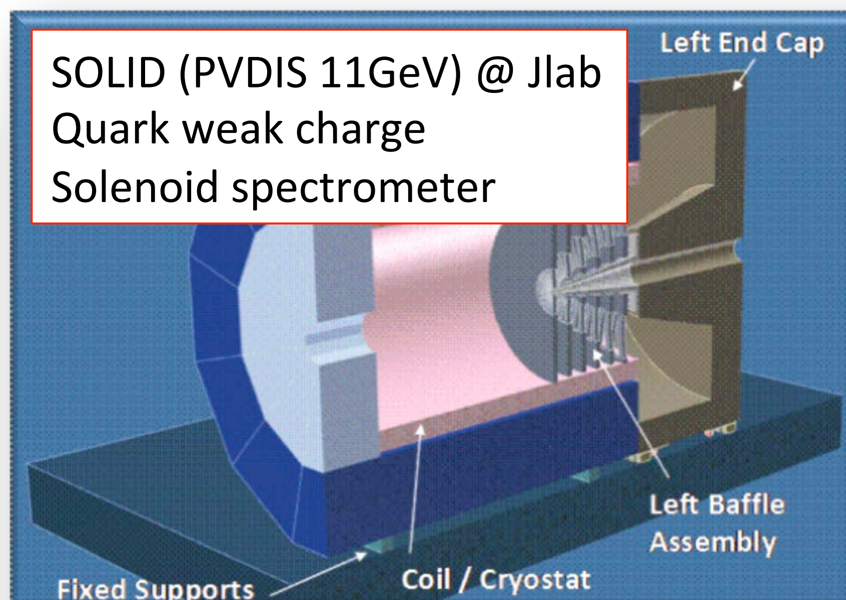


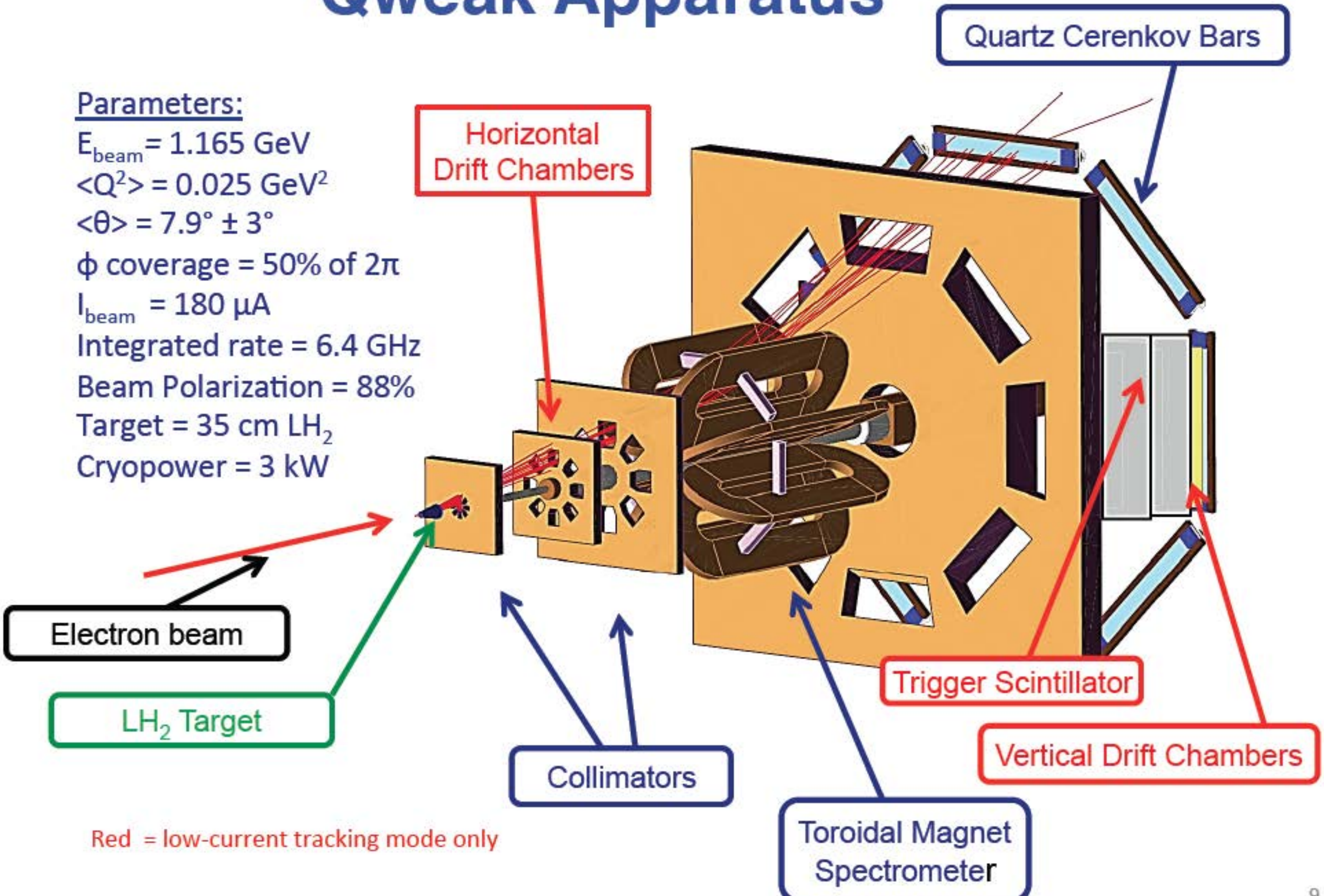
SOLID (PVDIS 11GeV) @ Jlab
Quark weak charge
Solenoid spectrometer



Qweak Apparatus

Parameters:

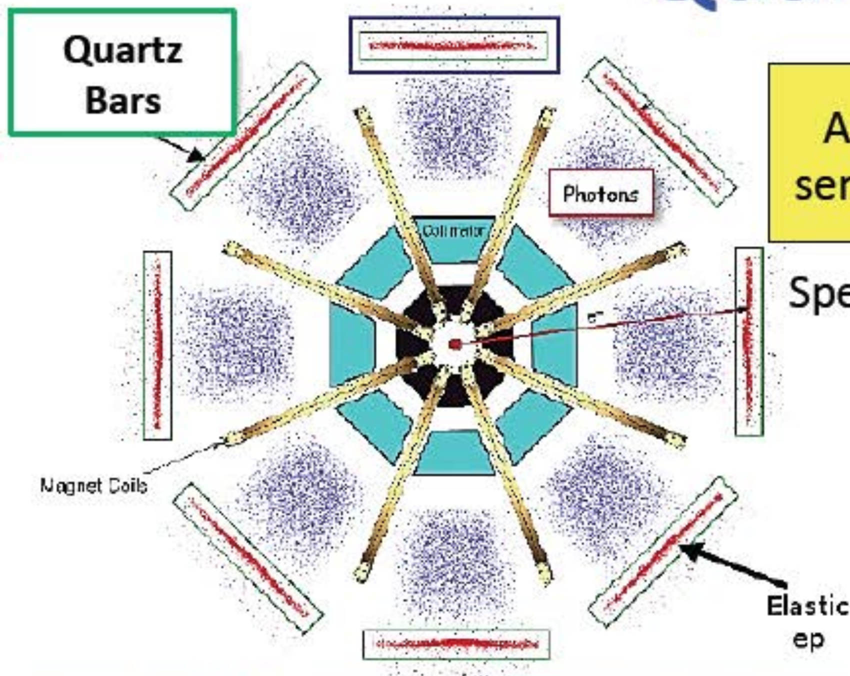
E_{beam} = 1.165 GeV
$<Q^2>$ = 0.025 GeV^2
$<\theta>$ = 7.9° ± 3°
ϕ coverage = 50% of 2π
I_{beam} = 180 µA
Integrated rate = 6.4 GHz
Beam Polarization = 88%
Target = 35 cm LH_2
Cryopower = 3 kW



Red = low-current tracking mode only

Apparatus (before all shielding)

Quartz Cerenkov Detectors

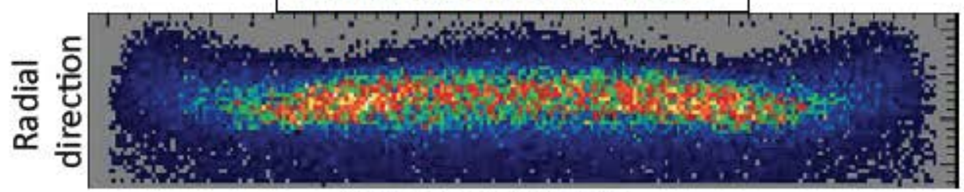


Azimuthal symmetry maximizes rate and decreases sensitivity to HC beam motion, transverse asymmetry.

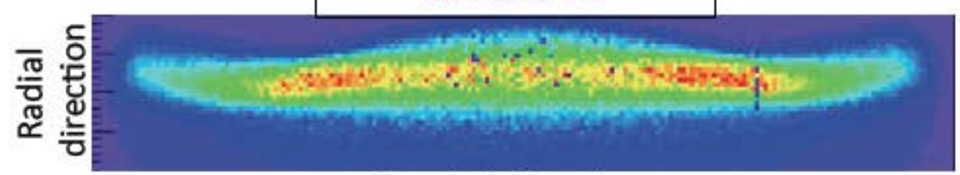
Spectrosil 2000: Eight bars, each 2 m long, 1.25 cm thick

- Rad-hard
- Non-scintillating, low-luminescence

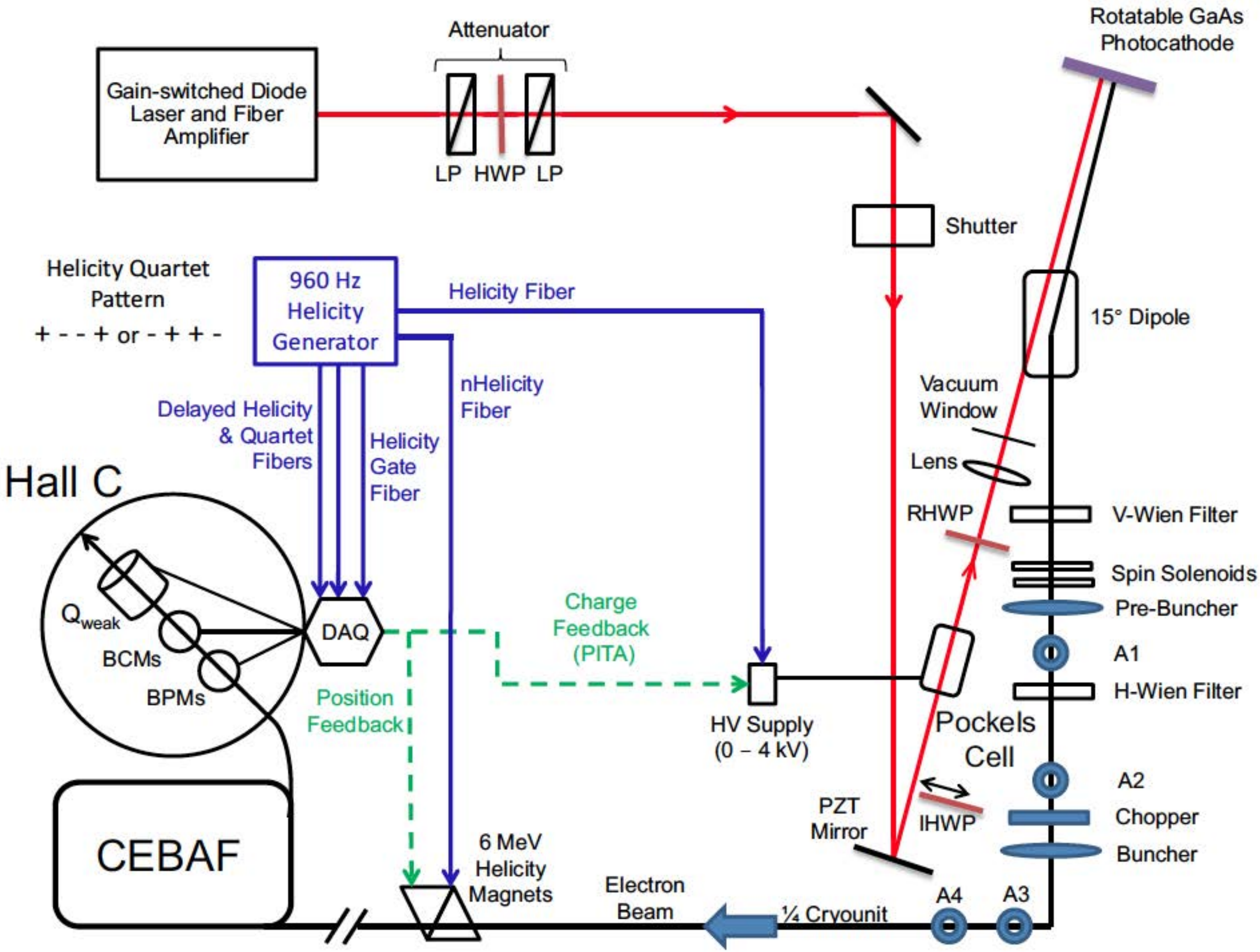
Simulation of MD face:



Measured

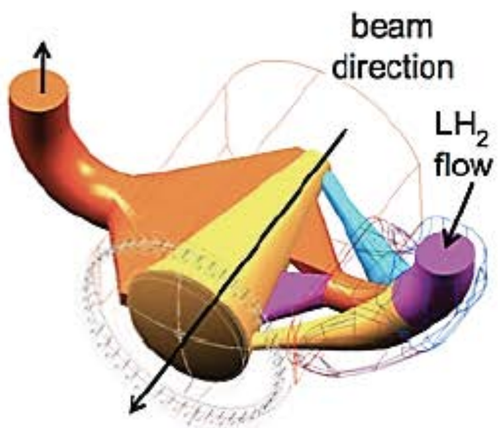


Yield 100 pe's/track with 2cm Pb pre-radiators
Resolution limited by shower fluctuations.


Attenuator
Rotatable GaAs Photocathode
Gain-switched Diode Laser and Fiber Amplifier
LP HWP LP
Shutter
Helicity Quartet Pattern
+ - - + or - + + -
960 Hz Helicity Generator
Helicity Fiber
15° Dipole
nHelicity Fiber
Vacuum Window
Delayed Helicity & Quartet Fibers
Helicity Gate Fiber
Lens
Hall C
RHWP
V-Wien Filter
Spin Solenoids
Pre-Buncher
Charge Feedback (PITA)
Q_{weak}
DAQ
A1
BCMs
H-Wien Filter
BPMs
Position Feedback
HV Supply (0 – 4 kV)
Pockels Cell
A2
PZT Mirror
IHWP
Chopper
CEBAF
6 MeV Helicity Magnets
Buncher
Electron Beam
A4
A3
¼ Cryounit

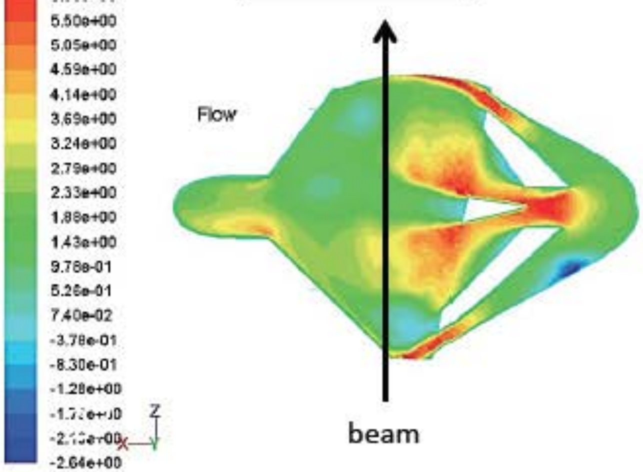
LH_2 Target Design

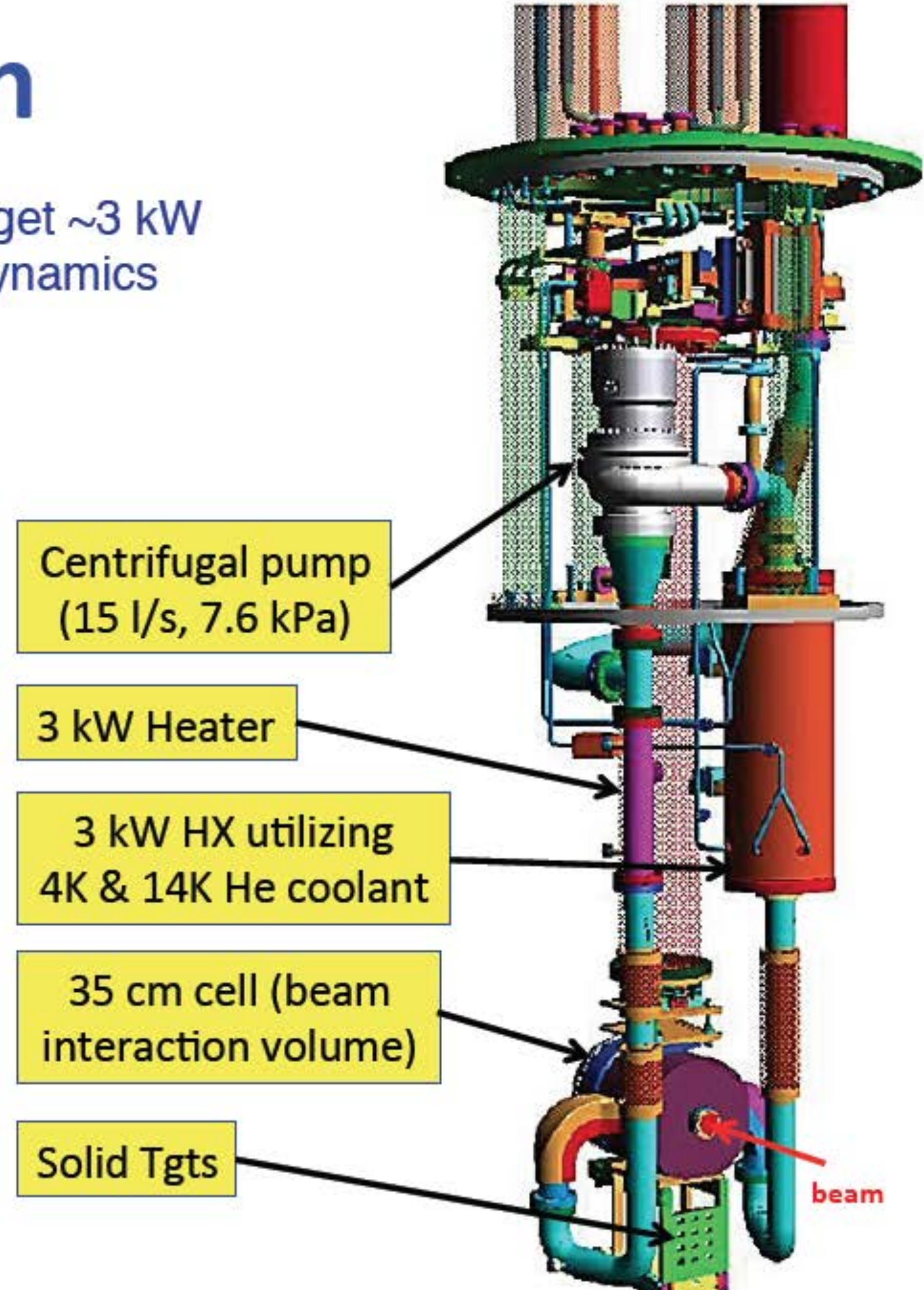
- World's highest power cryogenic target ~3 kW
- Designed with computational fluid dynamics (CFD) to reduce density fluctuations



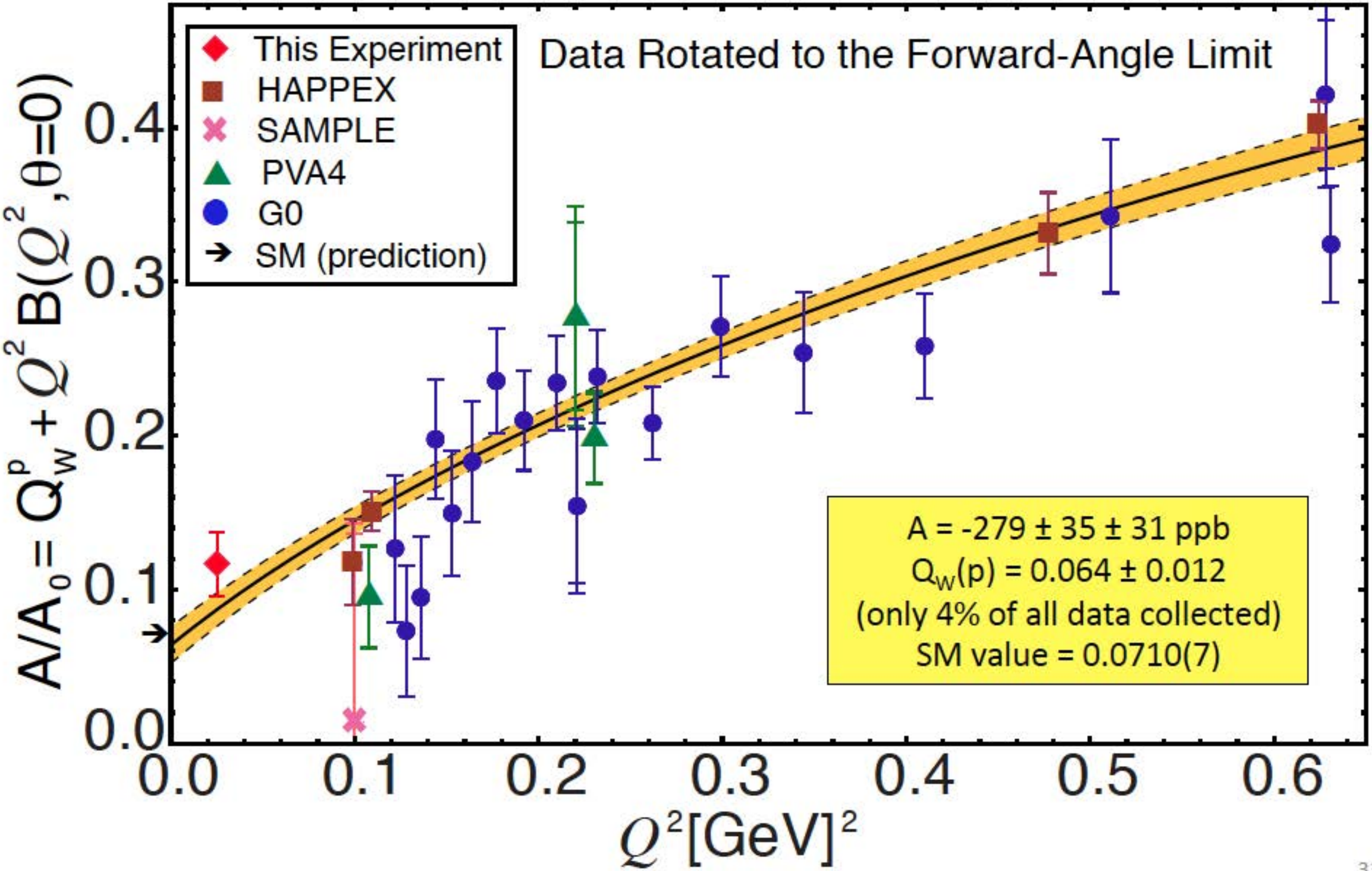
I_{Beam} = 180 uA
L = 35 cm (4% X_0)
P_{beam} = 2.2 kW
A_{spot} = 4x4 mm^2
V = 57 liters
T = 20.00 K
P ~ 220 kPa

Fluid velocity





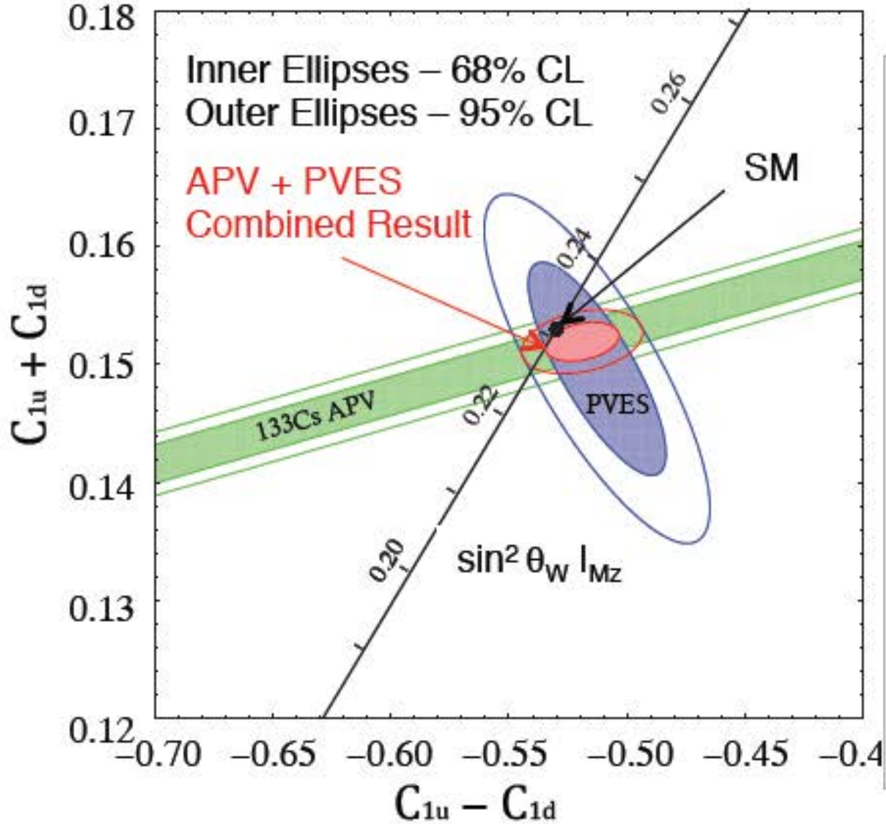
Global Fit of Q^2<0.63 $(GeV/c)^2$ PVES Data



Qweak Commissioning Run - PRL 111,141803 (2013)

Combined Analysis

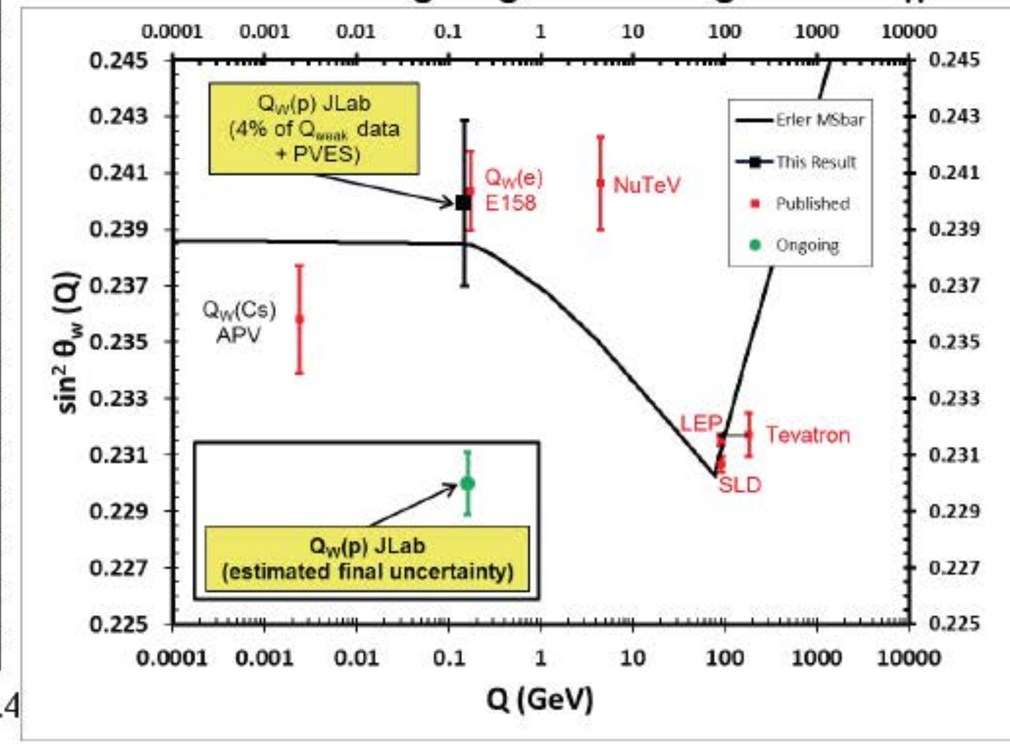
Extract: C_{1u}, C_{1d}, Q^n_W



Qweak + Higher Q^2 PVES

Extract: Q^p_W, $\sin^2\theta_W$

Weak Mixing Angle: Running of $\sin^2\theta_W$



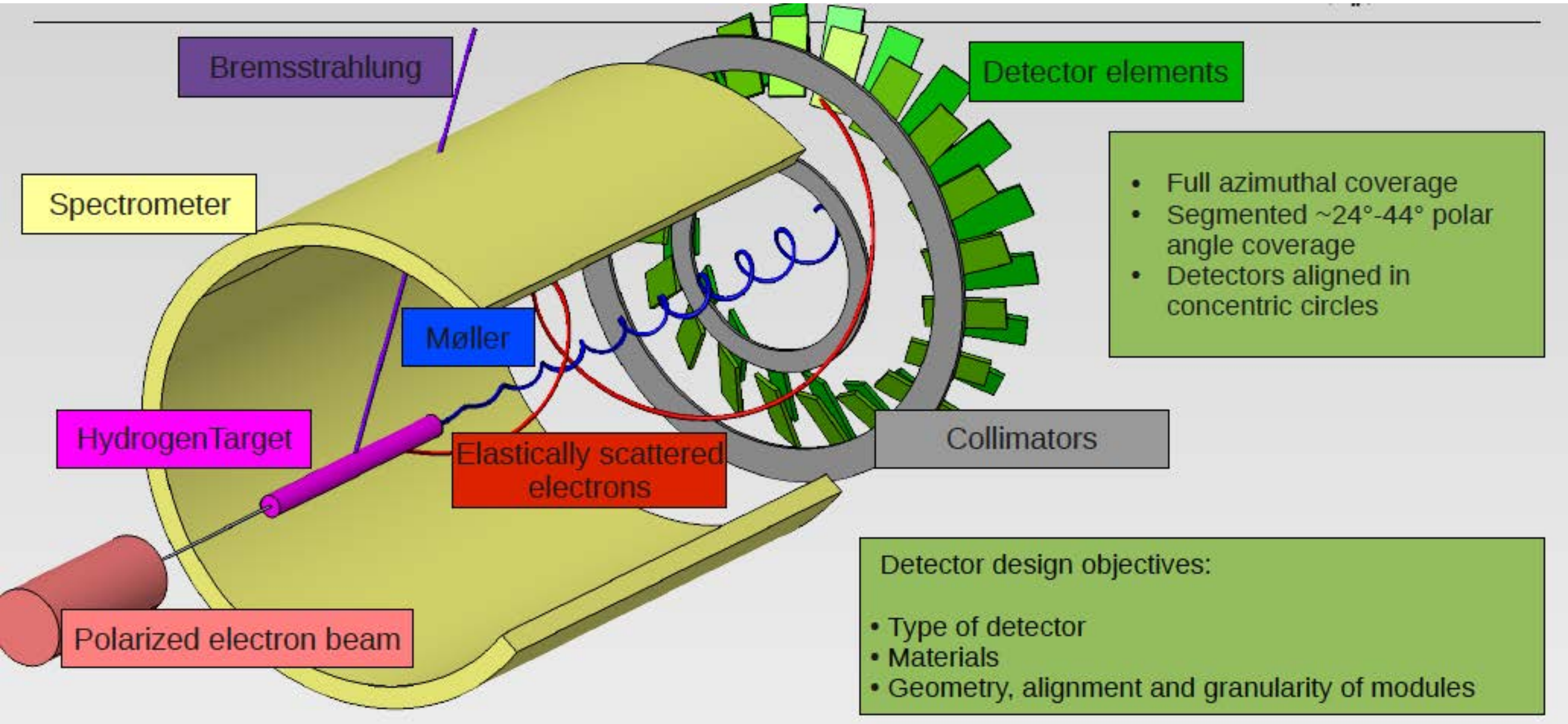
$Q^n_W = -2\,(C_{1u} + 2\,C_{1d})$
$= -0.975 \pm 0.010$

$C_{1u} = -0.184 \pm 0.005$
$C_{1d} = 0.336 \pm 0.005$

$Q^p_W = -2\,(2\,C_{1u} + C_{1d})$
$= 0.064 \pm 0.012$
SM prediction = 0.0710(7)

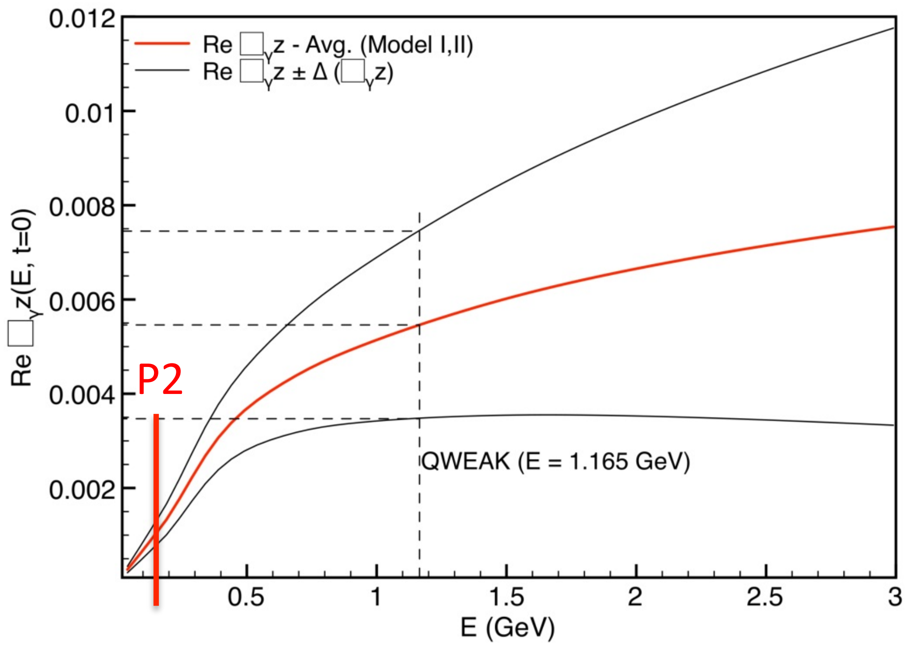
25x more production data still being analyzed, final result 2015

P2 Experiment at the new MESA accelerator in Mainz (low beam energy, very high precision)



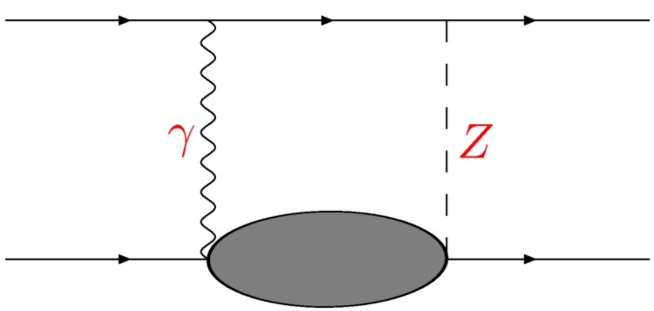
Kathrin Gerz

- 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

General Experiment Kinematics

Comparison: P2 with and without back angle measurement

Without back angle measurement

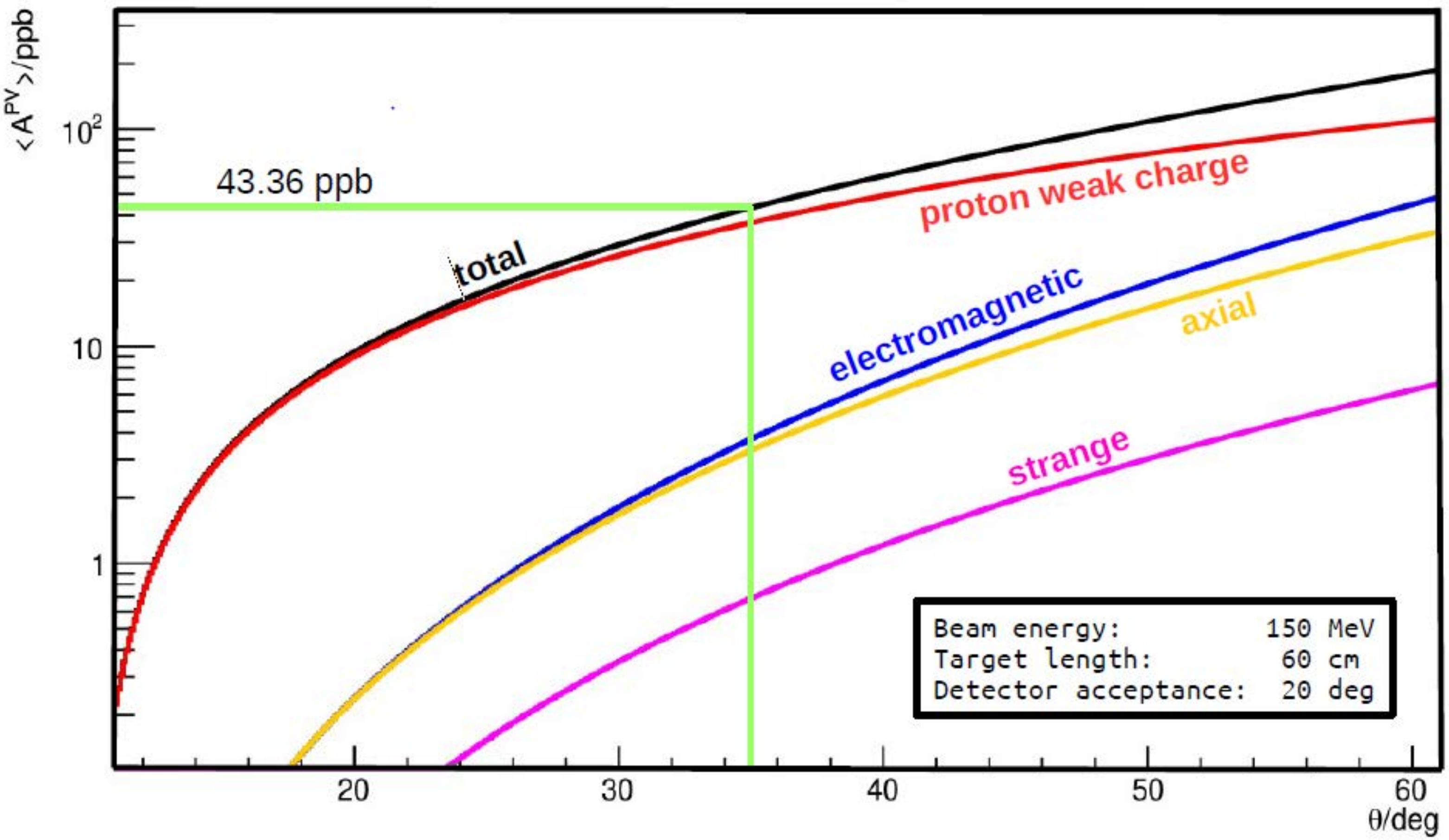
E/MeV	θ/deg	Δθ/deg	$\Delta\sin^2(\theta_W)/10^{-4}$	$\Delta\sin^2(\theta_W)/\sin^2(\theta_W)$
240	17	18	3.57	0.15 %
200	20	20	3.60	0.15 %
150	24	20	3.97	0.17 %
130	25	20	4.33	0.18 %

With back angle measurement

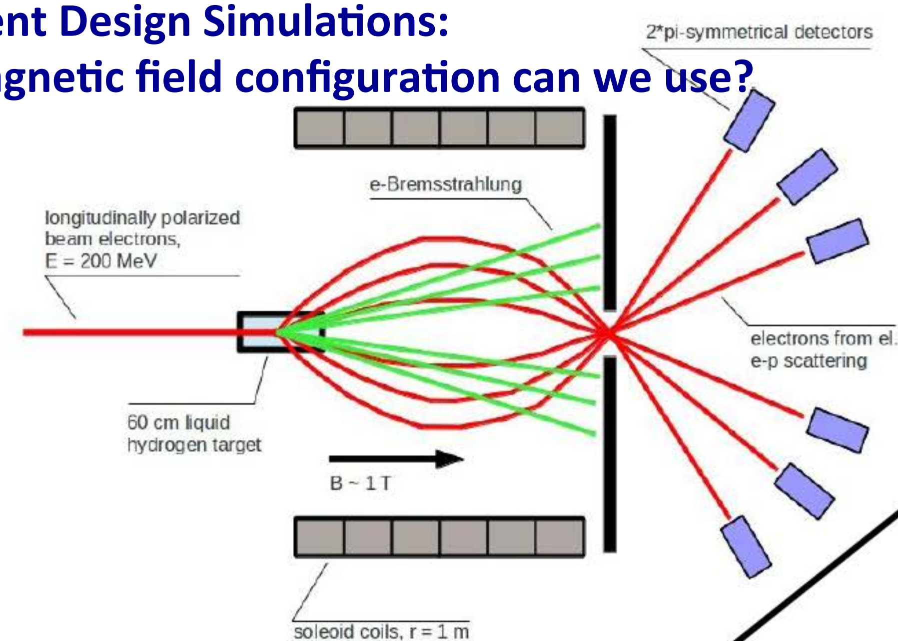
E/MeV	θ/deg	Δθ/deg	$\Delta\sin^2(\theta_W)/10^{-4}$	$\Delta\sin^2(\theta_W)/\sin^2(\theta_W)$
240	24	18	2.41	0.10 %
200	28	16	2.52	0.11 %
150	33	18	2.73	0.11 %
130	37	18	2.87	0.12 %

- $\Delta\sin^2(\theta_W)$ drops from $3.60 \cdot 10^{-4}$ to $2.52 \cdot 10^{-4}$ → possible reduction of Δt
- $\sin^2(\theta_W)$-measurement at larger scattering angles (more easy to measure)

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

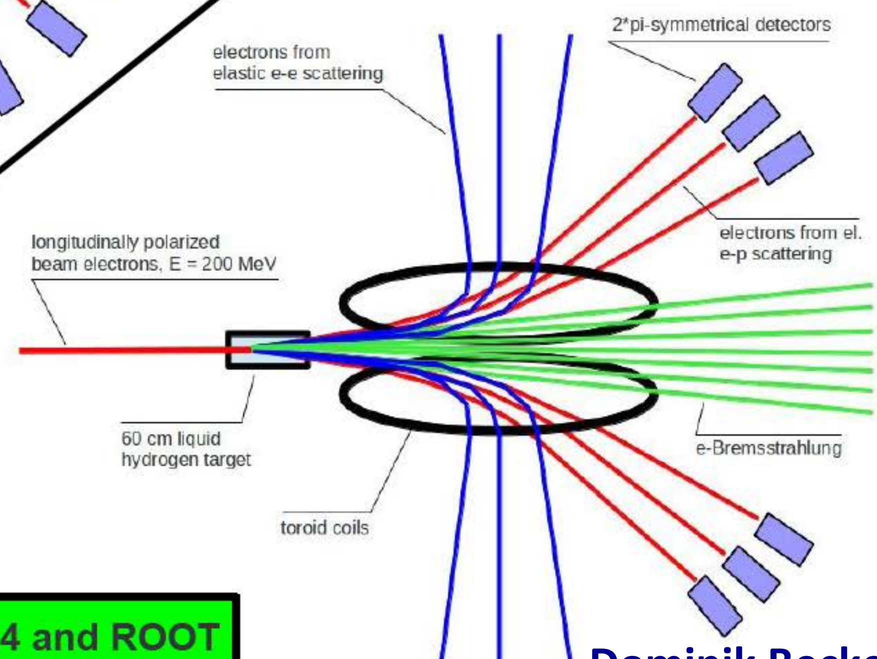


Experiment Design Simulations:
What Magnetic field configuration can we use?



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

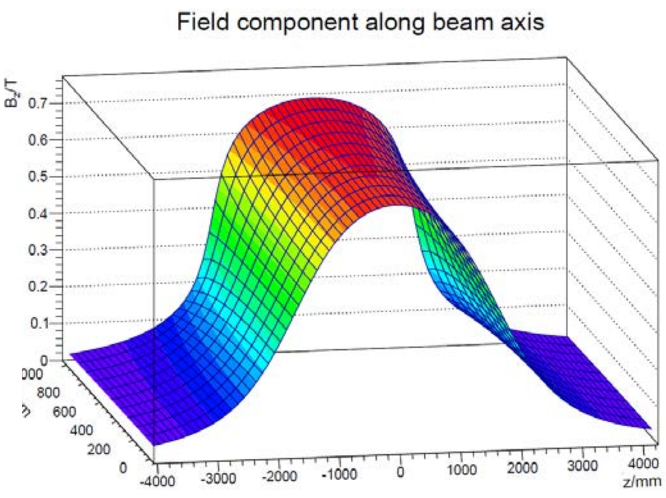


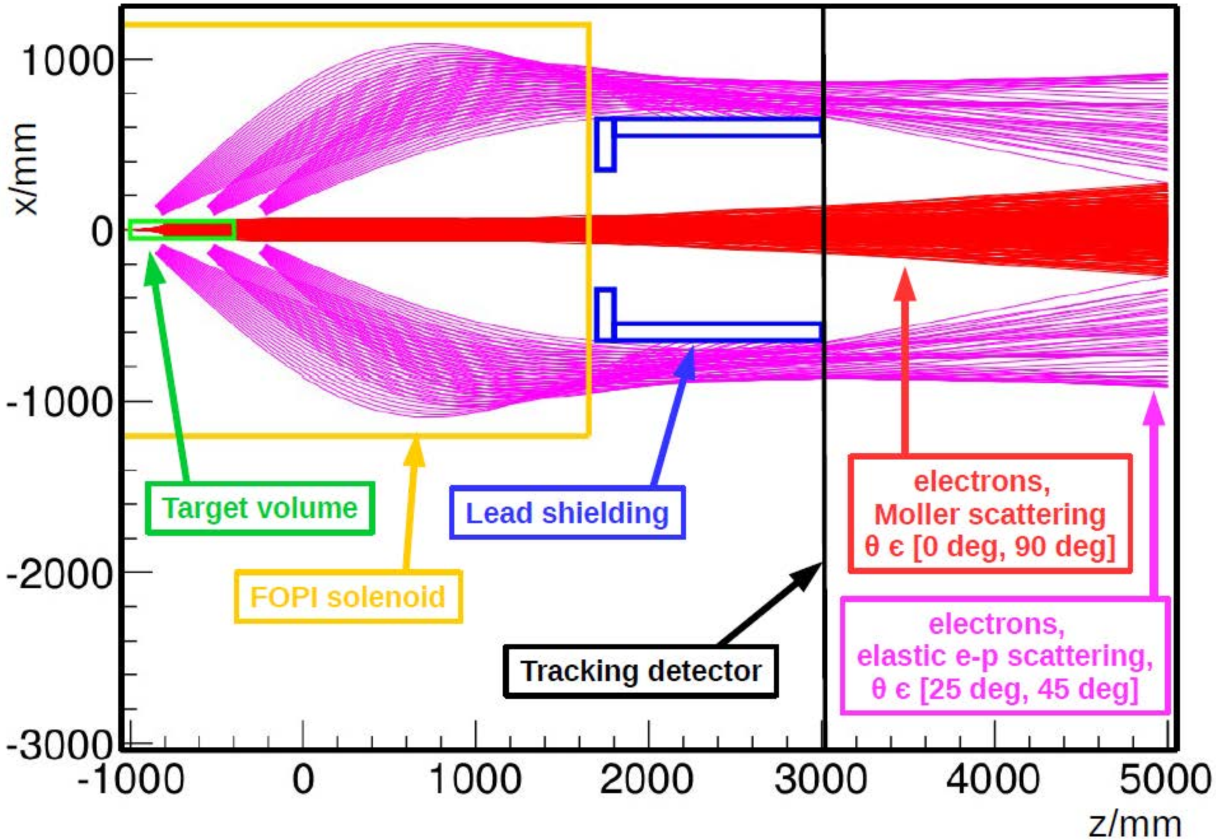
Toroid:
- Loss of ~50% solid angle
  → double measurement time
- Larger setup
- Copper coils

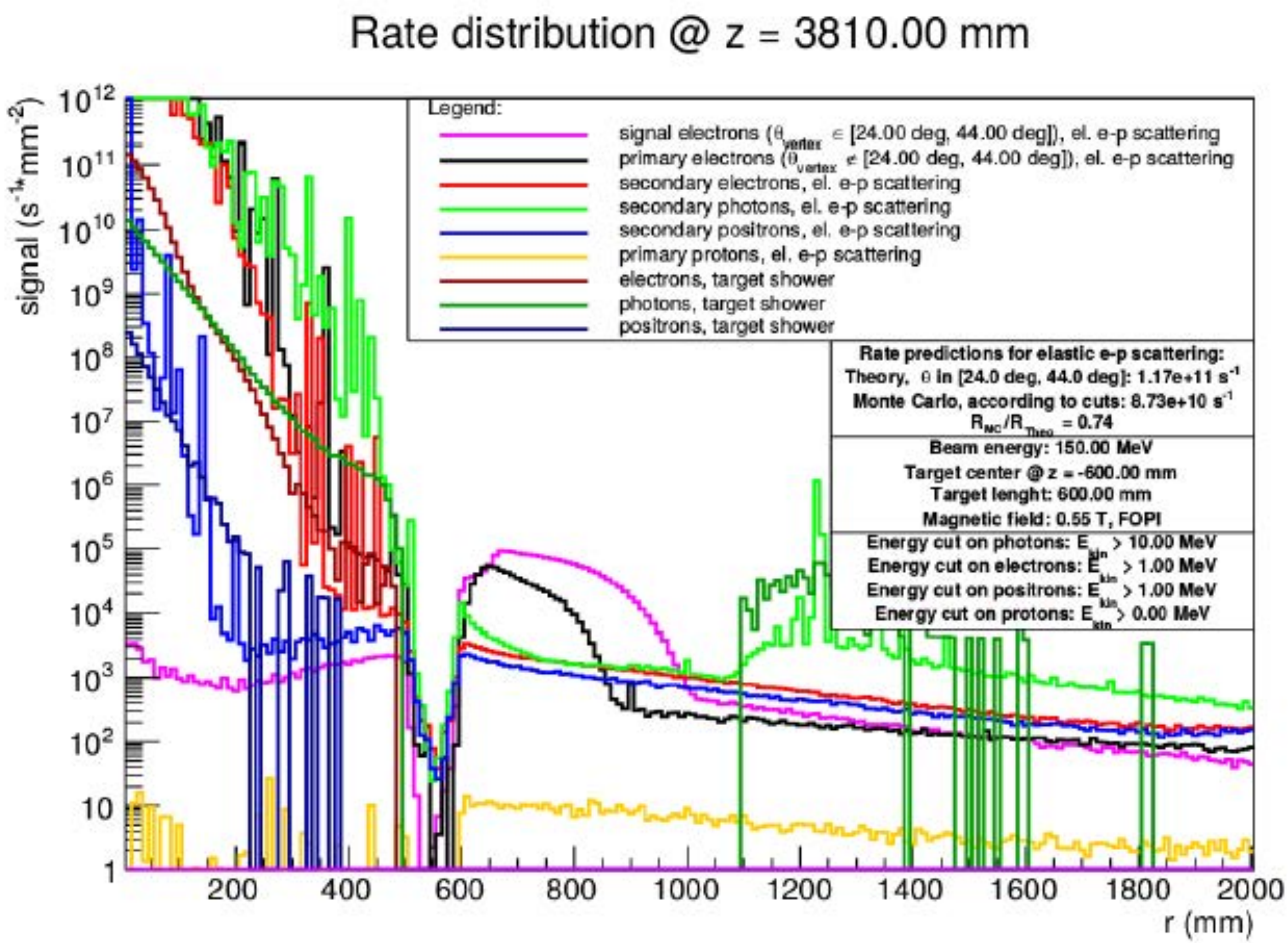
→ **Feasibility study with Geant4 and ROOT**

Dominik Becker

Design with FOPI-like Solenoid

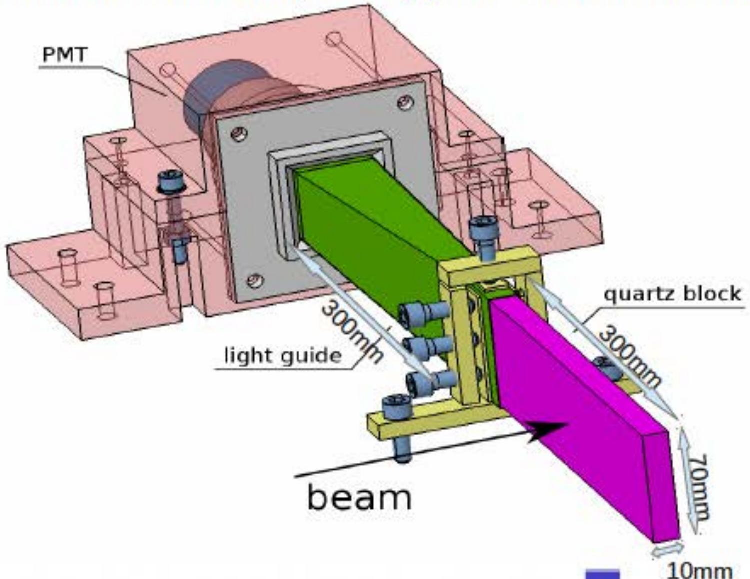






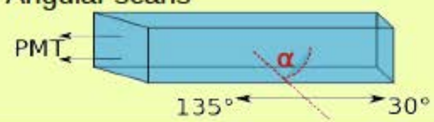
Dominik Becker

Detector module prototype tested at MAMI

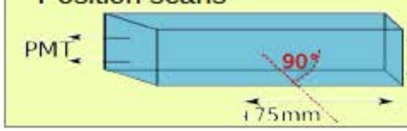


Outline of different setups and scan series 01/2014

Angular scans



Position scans



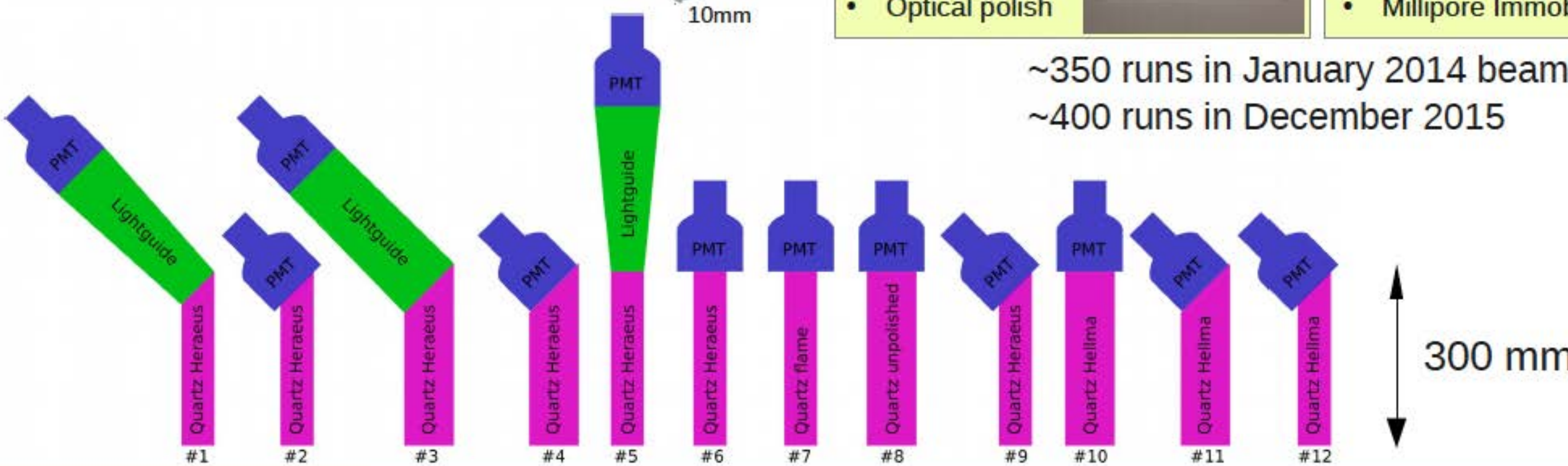
Quartz materials
- Heraeus Suprasil 2A
- Heraeus Spectrosil 2000

Geometries
- Quartz bars 10mm / 15mm
- w/ and w/o "outlet optic" (45° cut)
- Measurements w/ and w/o LG

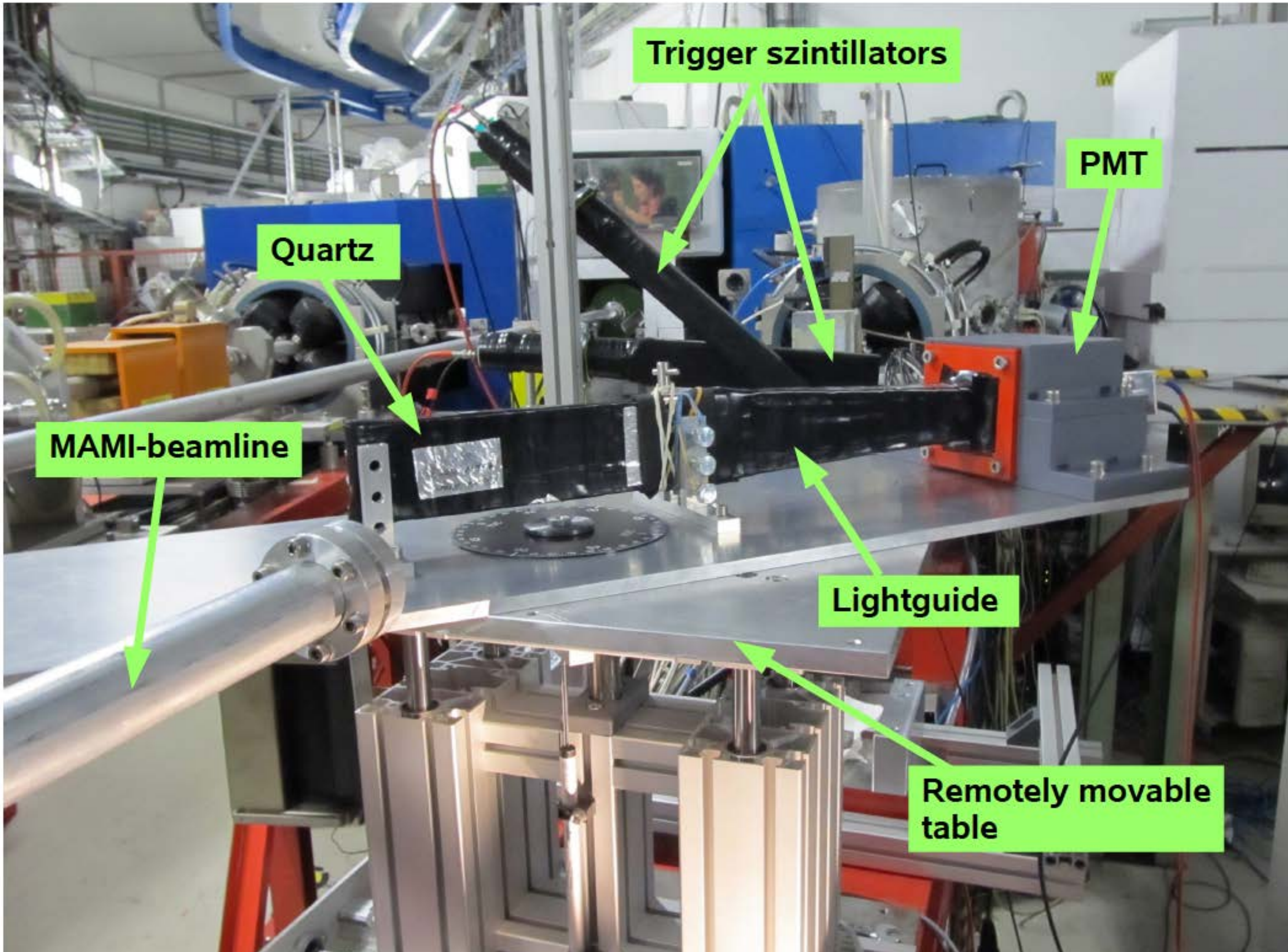
Polishes
- Flamepolished
- Mechanical
- Optical polish

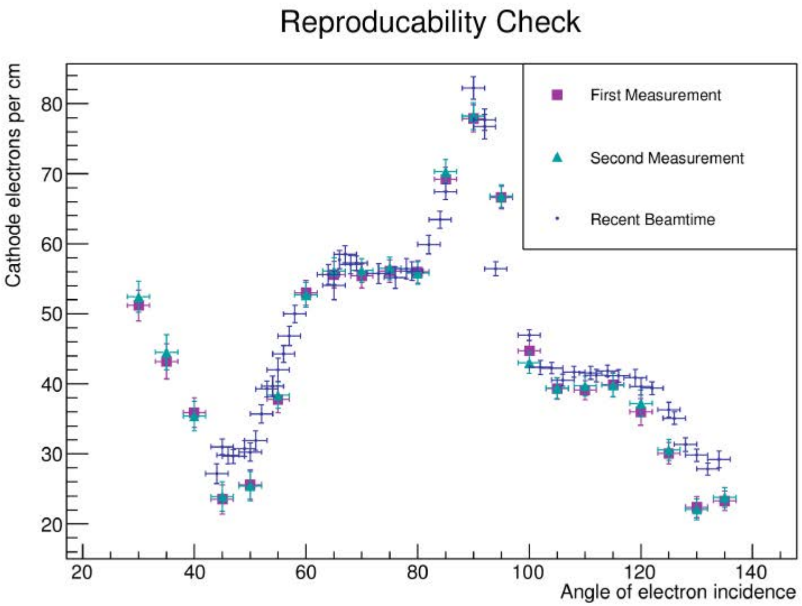
Reflective materials for wrap and LG
- Mylar
- Alanod 4300UP
- Millipore ImmobilonP

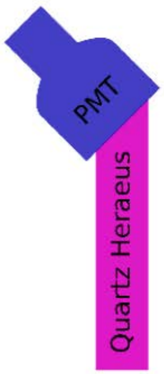
~350 runs in January 2014 beam time
~400 runs in December 2015



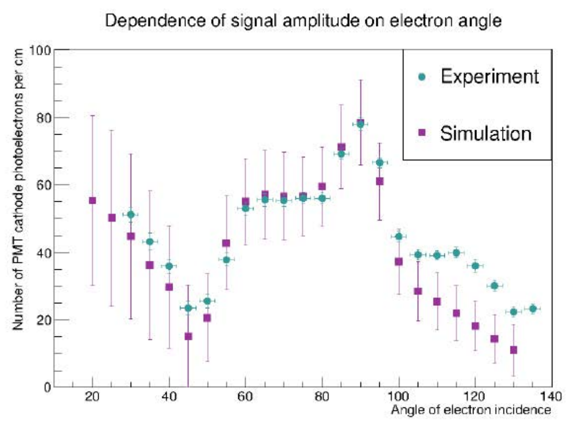
P2 Experimental setup (second testbeam January 2014)

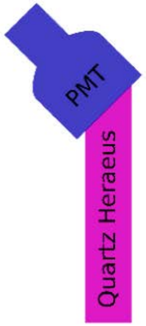






Comparison of experimental data with Simulation:



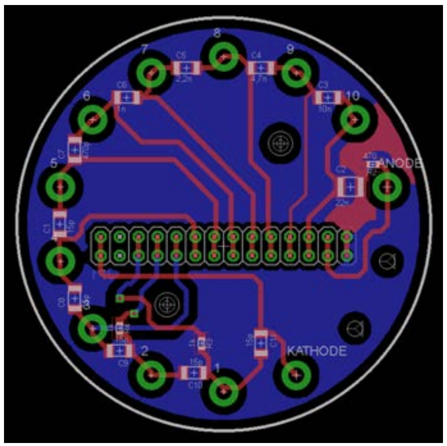


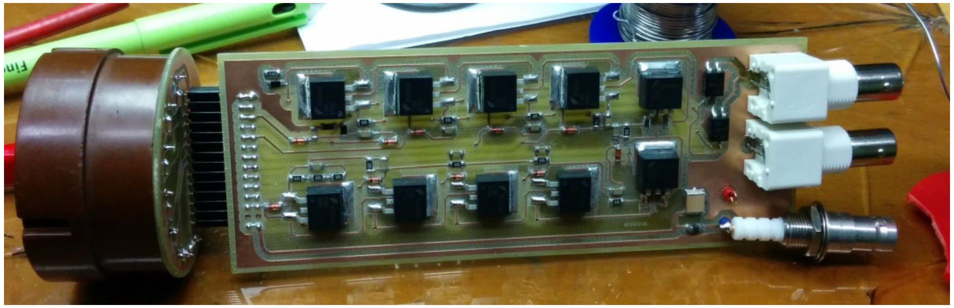
K. Gerz

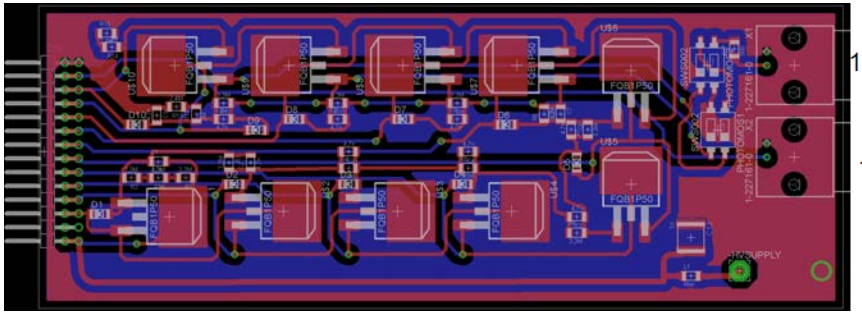
JG|U

SFB 1044
Institut für Kernphysik

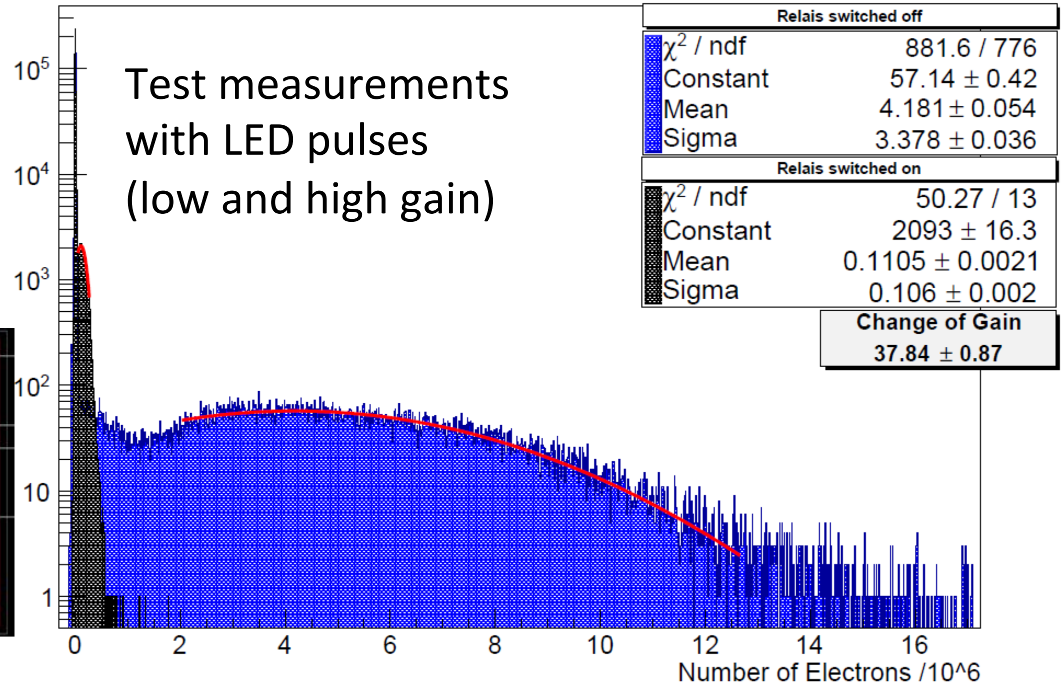
Development of PMT base with remotely switchable gain (high and low current mode)







Test measurements with LED pulses (low and high gain)

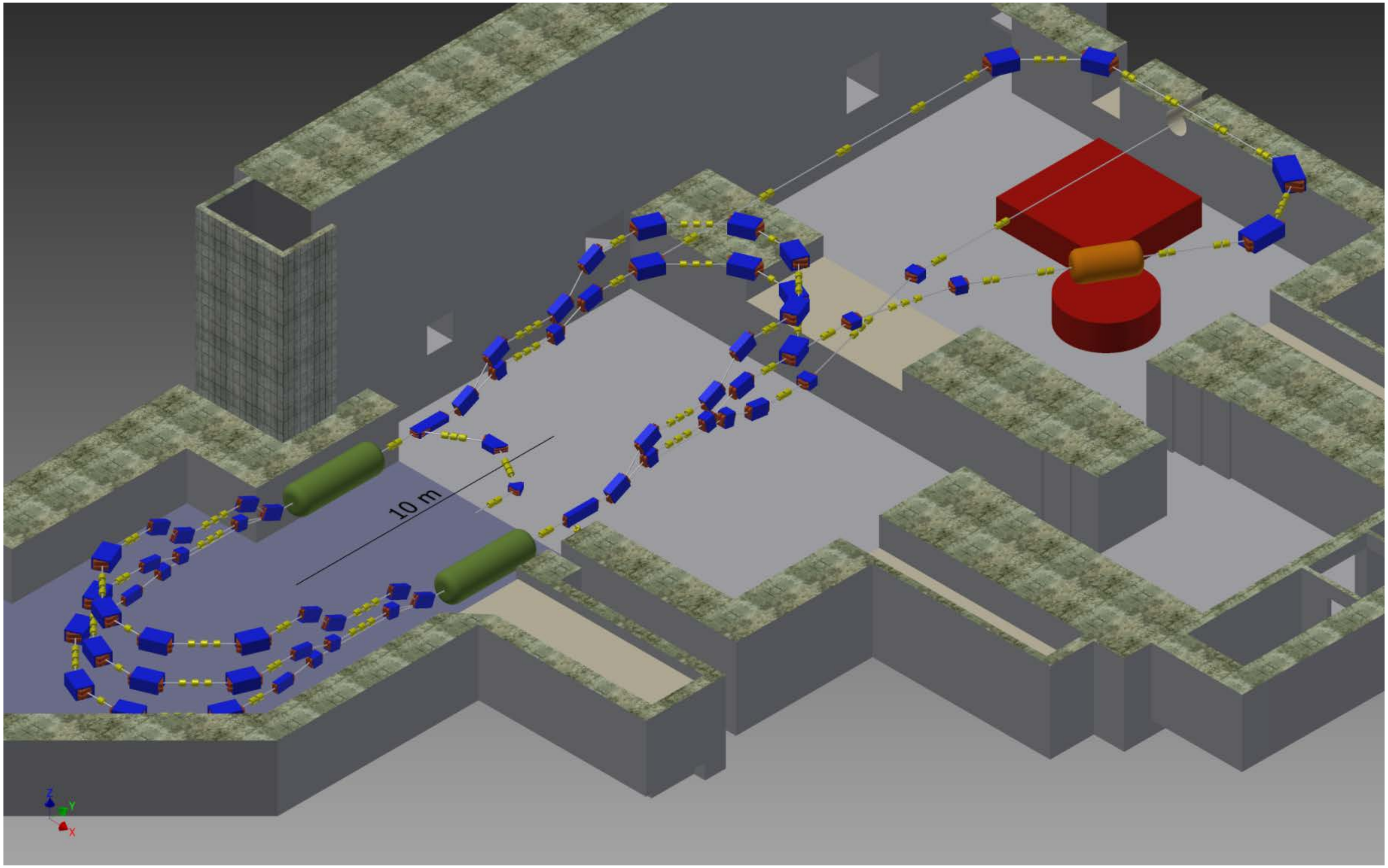


Th. Jennewein

MESA-Accelerator

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)


10 m

Parity violating electron scattering: "Low energy frontier" comprises a sensitive test of the standard model complementary to LHC

Qweak has presented first results from 4% of their data.
Target precision is 4% in Qweak i.e. 0.3% in $\sin^2(\theta_W)$

P2-Experiment (proton weak charge) in Mainz under preparation
New MESA energy recovering accelerator at 150 MeV
Target precision is 1.7% in Qweak i.e. 0.1% in $\sin^2(\theta_W)$
Sensitivity to new physics up to a scale of 6.4 TeV through Quantum corrections

Together with Moeller@Jlab (electron weak charge) and SOLID@Jlab (quark weak charge) possibility to narrow in on Standard Model Extension