SFB 1044

Institut für Kernphysik

Low Energy Tests of the Standard Model

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Outline

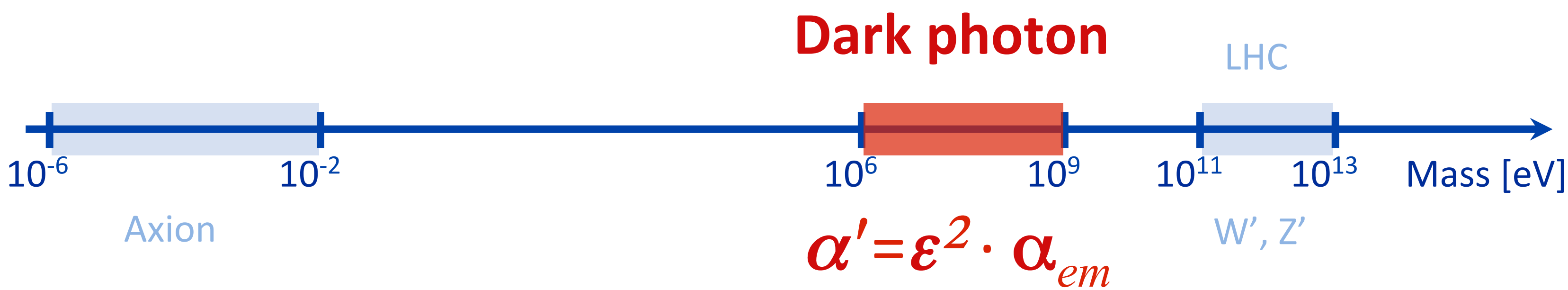
Dark Photon Search

MESA Accelerator

Precision Determination of $\sin^2(\theta_W)$ (P2 at Mainz)

Dark Photon Search

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



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

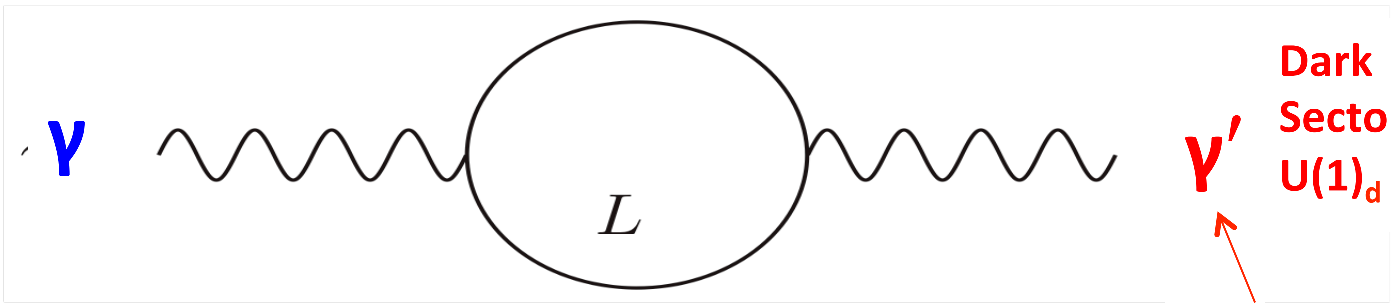
- Could explain large number of **astrophysical anomalies**
  Arkani-Hamed et al. (2009)
  Andreas, Ringwald (2010); Andreas, Niebuhr, Ringwald (2012)

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

Holdom 86

A portal to relate the dark sector to the SM world (coupling ~ ε^2)

Standard Model Sector U(1)



Dark Sector U(1)$_d$

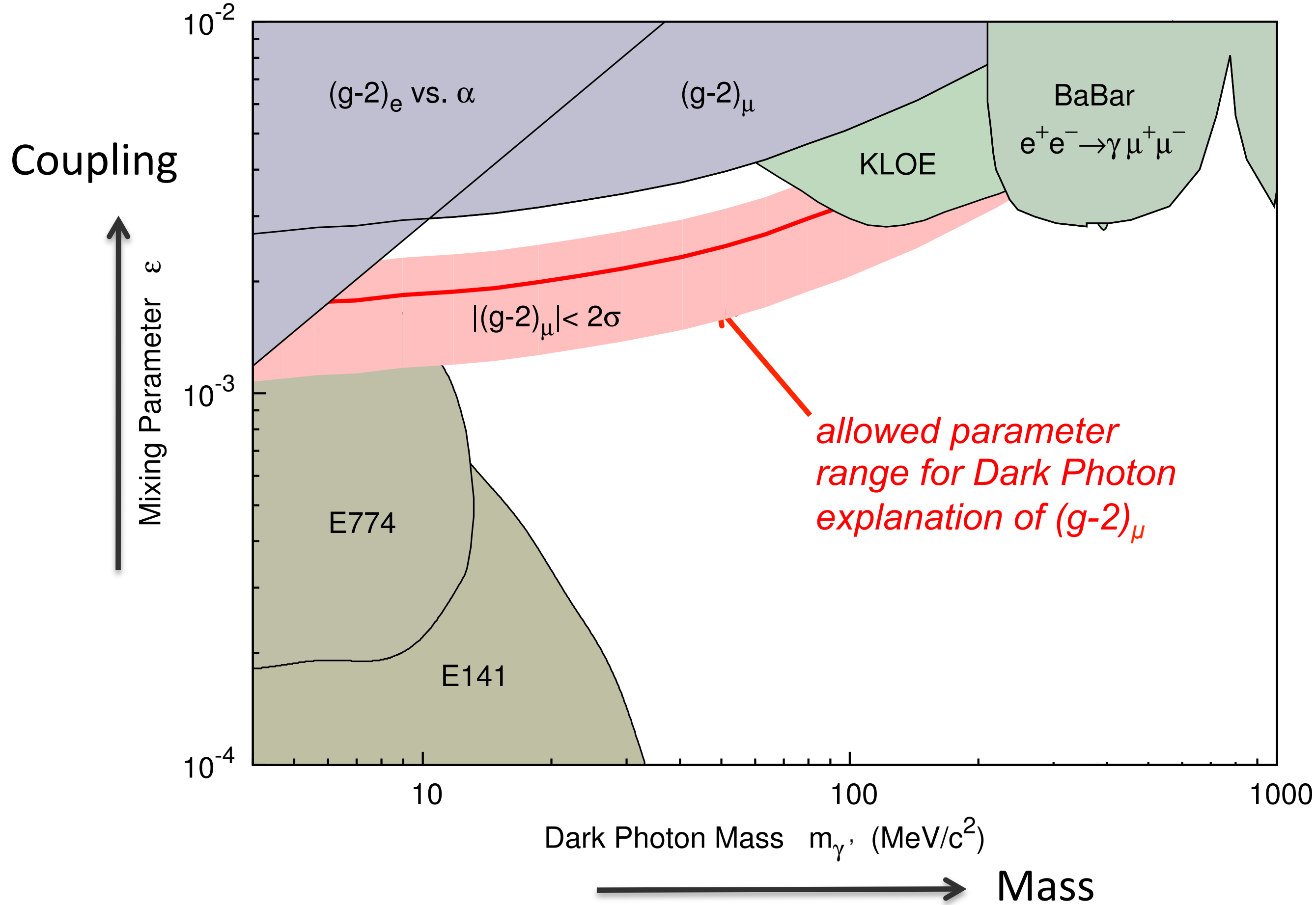
Heavy Charged Leptons *L*
(carry U(1)$_d$ charge)

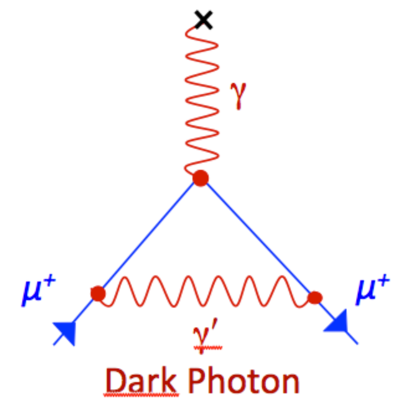
Dark Photon
(aka A′, U, Z_d, ...)

Features à la Arkani-Hamed: A theory of Dark Matter

- More than one Dark Matter particle → Dark Sector
- dm + dm → e+e- explains positron excess
- Astrophysical anomalies (PAMELA, FERMI, DAMA/LIBRA, INTEGRAL, ...) suggest dark photon mass on GeV mass scala (and lighter than $2M_p$)

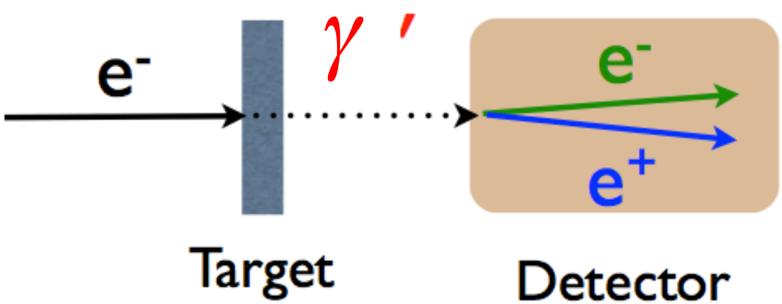
Status 2011

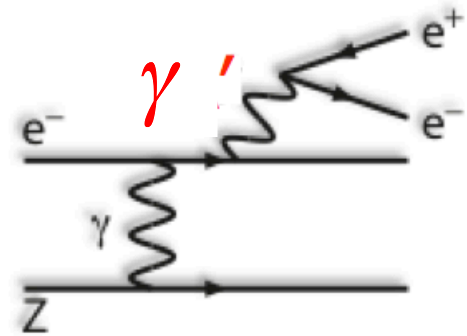

Coupling
Mixing Parameter ε
10^{-2}
10^{-3}
10^{-4}
$(g-2)_e$ vs. α
$(g-2)_\mu$
BaBar
$e^+e^- \rightarrow \gamma\,\mu^+\mu^-$
KLOE
$|(g-2)_\mu| < 2\sigma$
E774
E141
allowed parameter range for Dark Photon explanation of $(g-2)_\mu$
10
100
1000
Dark Photon Mass $m_{\gamma'}$ (MeV/c^2)
Mass


γ
μ^+
μ^+
γ'
Dark Photon

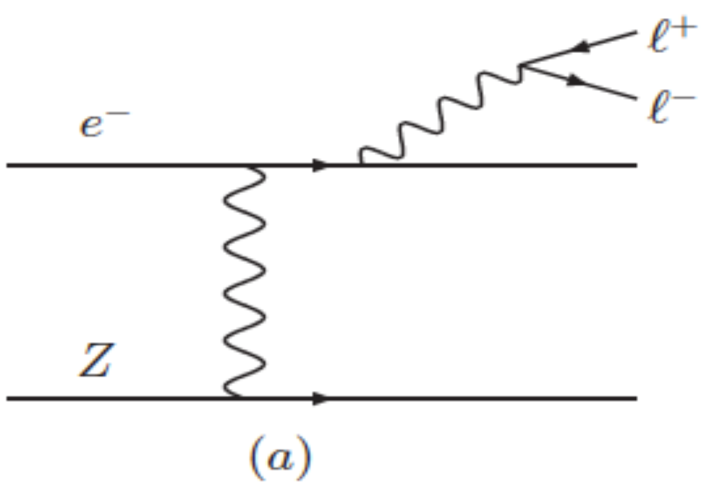
Low-energy, high-intensity accelerators (MAMI, JLAB) are ideally suited for Dark Photon searches!

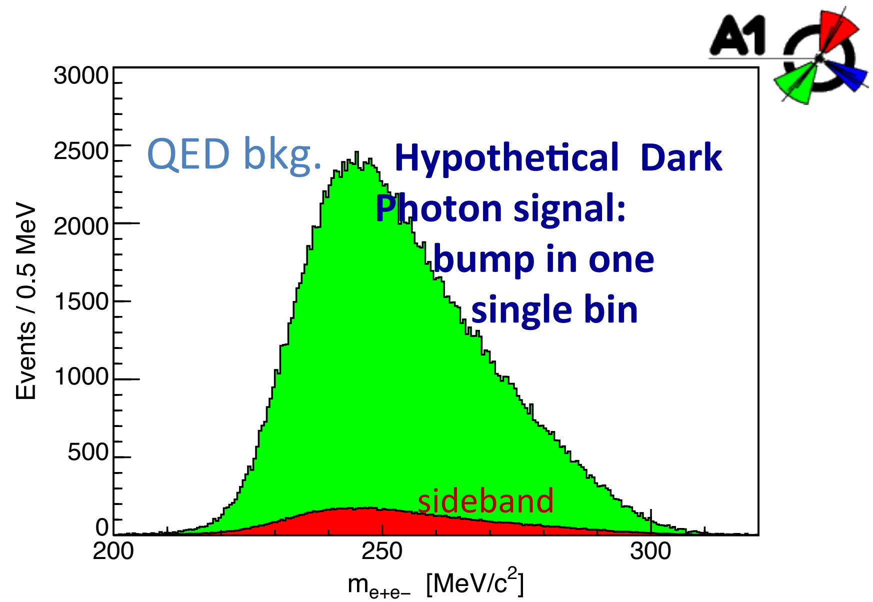
Bjorken, Essig, Schuster, Toro (2009)





QED background processes:

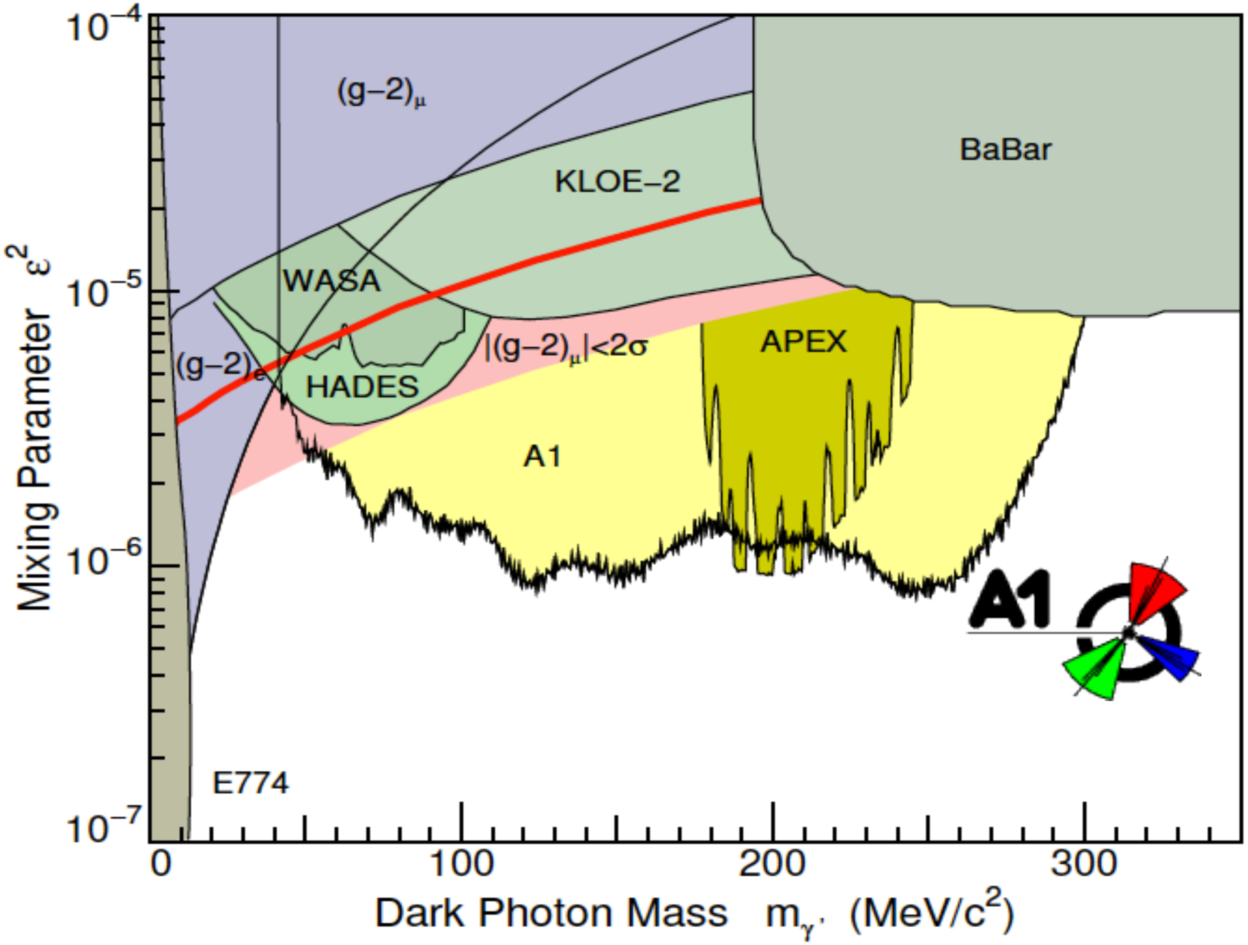


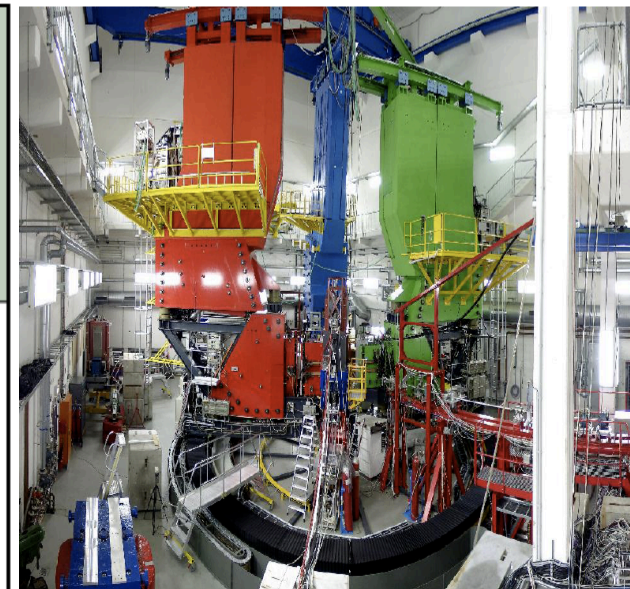


Enhance sensitivity by going to very thin targets

MAMI Results (A1 collaboration

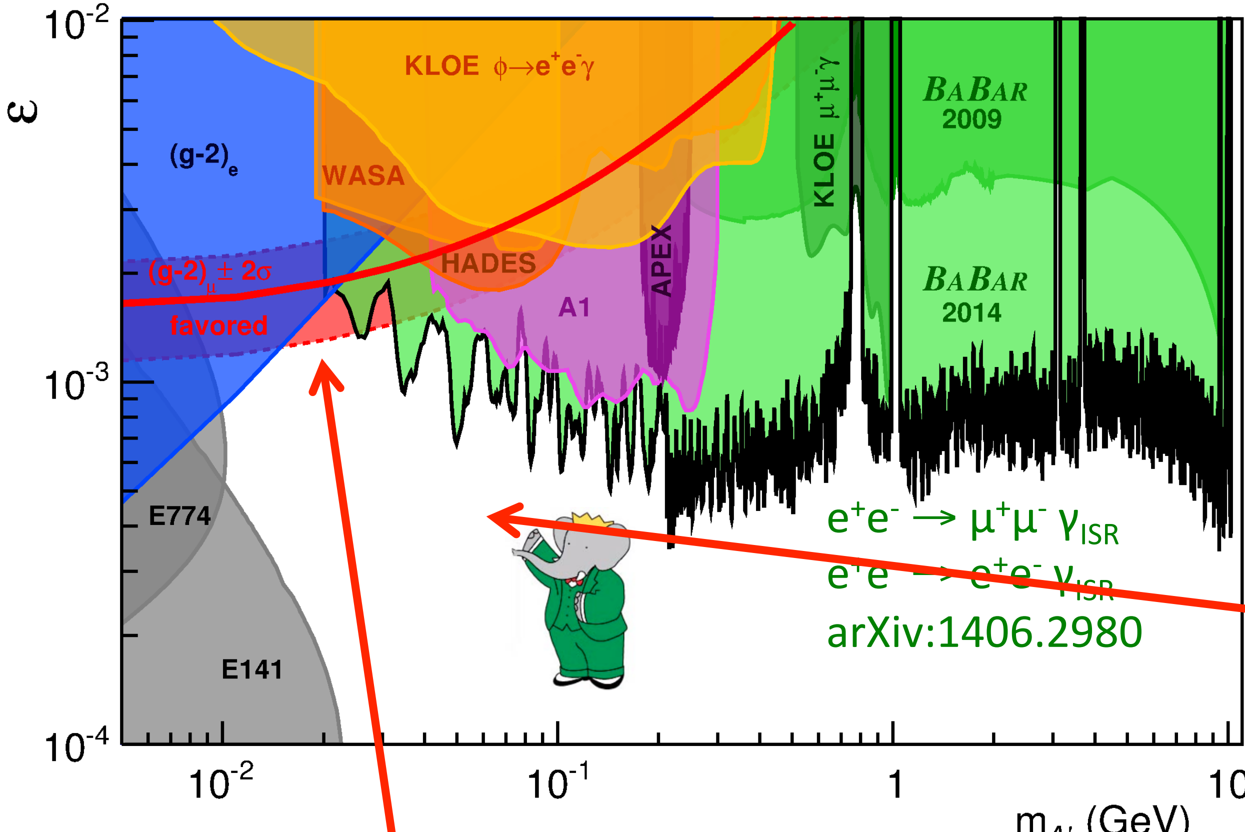
Phys. Rev. Lett. 112 (2014), 221802

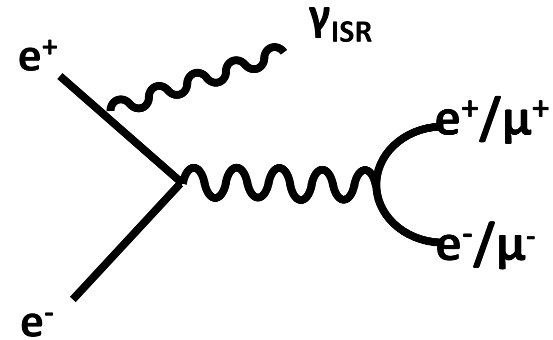




3 weeks of beamtime
3 spectrometer setup in Mainz at MAMI

BABAR Dark Photon Search (arXiv:1406.2980)

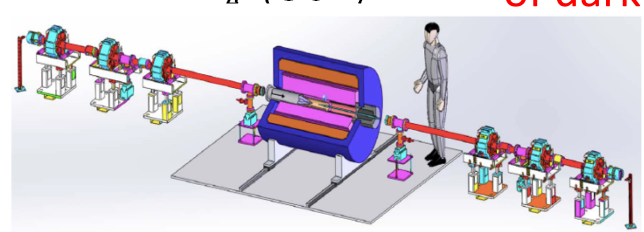


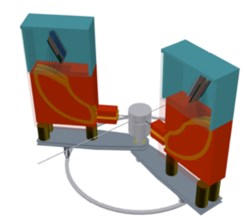


Analysis of the full data set (10 years)

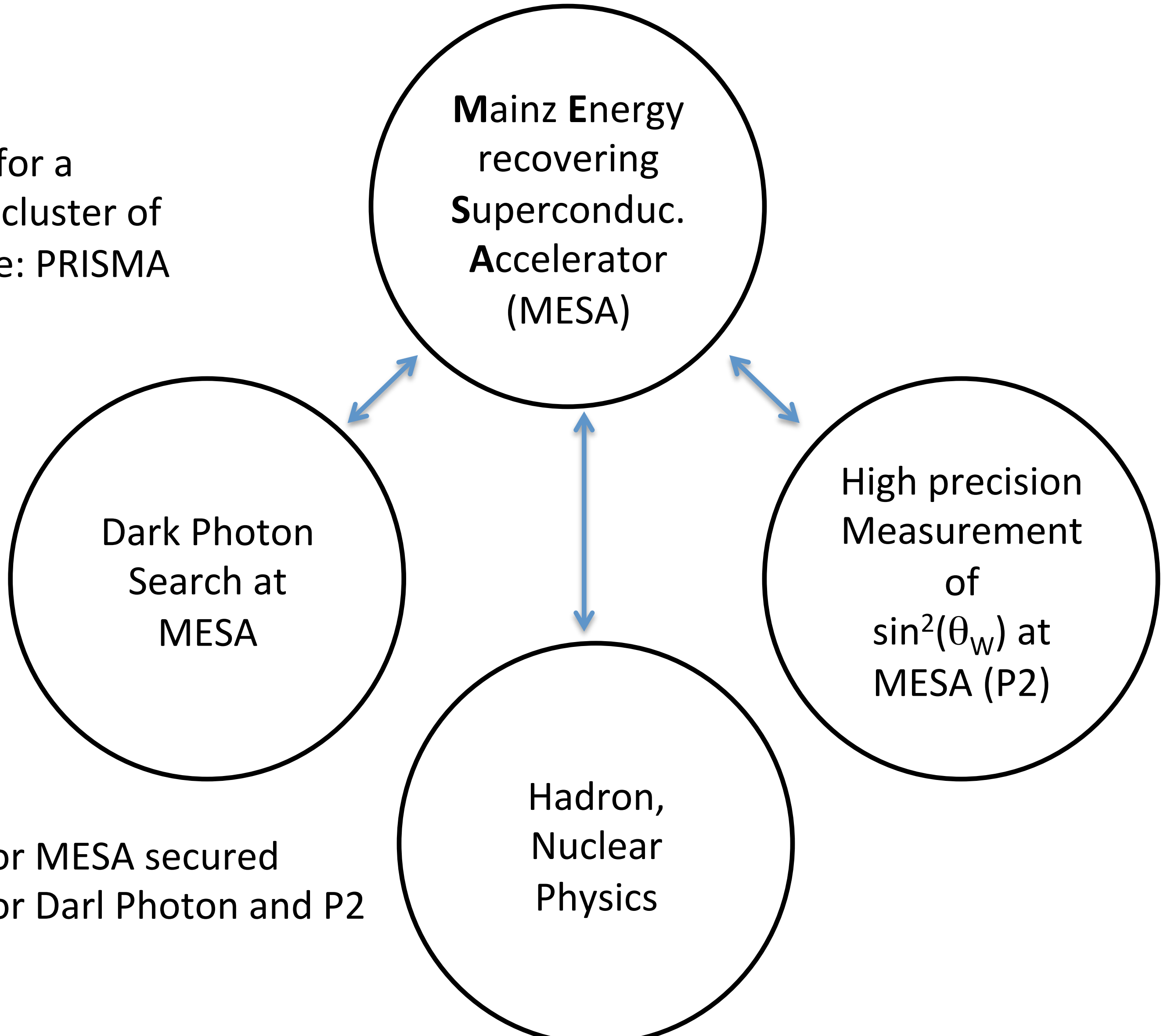
Entire remaining white region (JLAB APEX, HPS)
Interesting in view of dark sector

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





Proposal for a
Research cluster of
Excellence: PRISMA

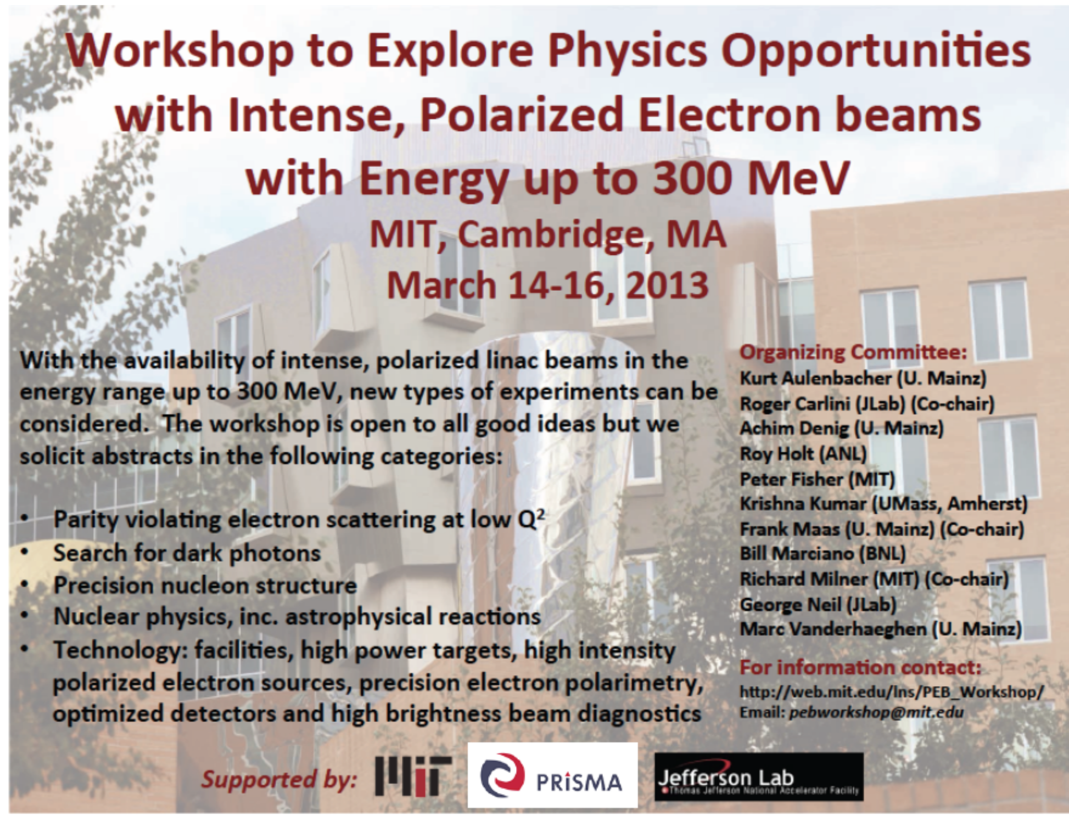


Funds for MESA secured
Funds for Darl Photon and P2

Physics Reach

Roger Carlini (co-chair)
Frank Maas (co-chair)
Richard Milner (co-chair)
+ many conveners

- Parity violation
- Hadron physics
- Astrophysical cross sections
- Nuclear physics
- Techniques
- …

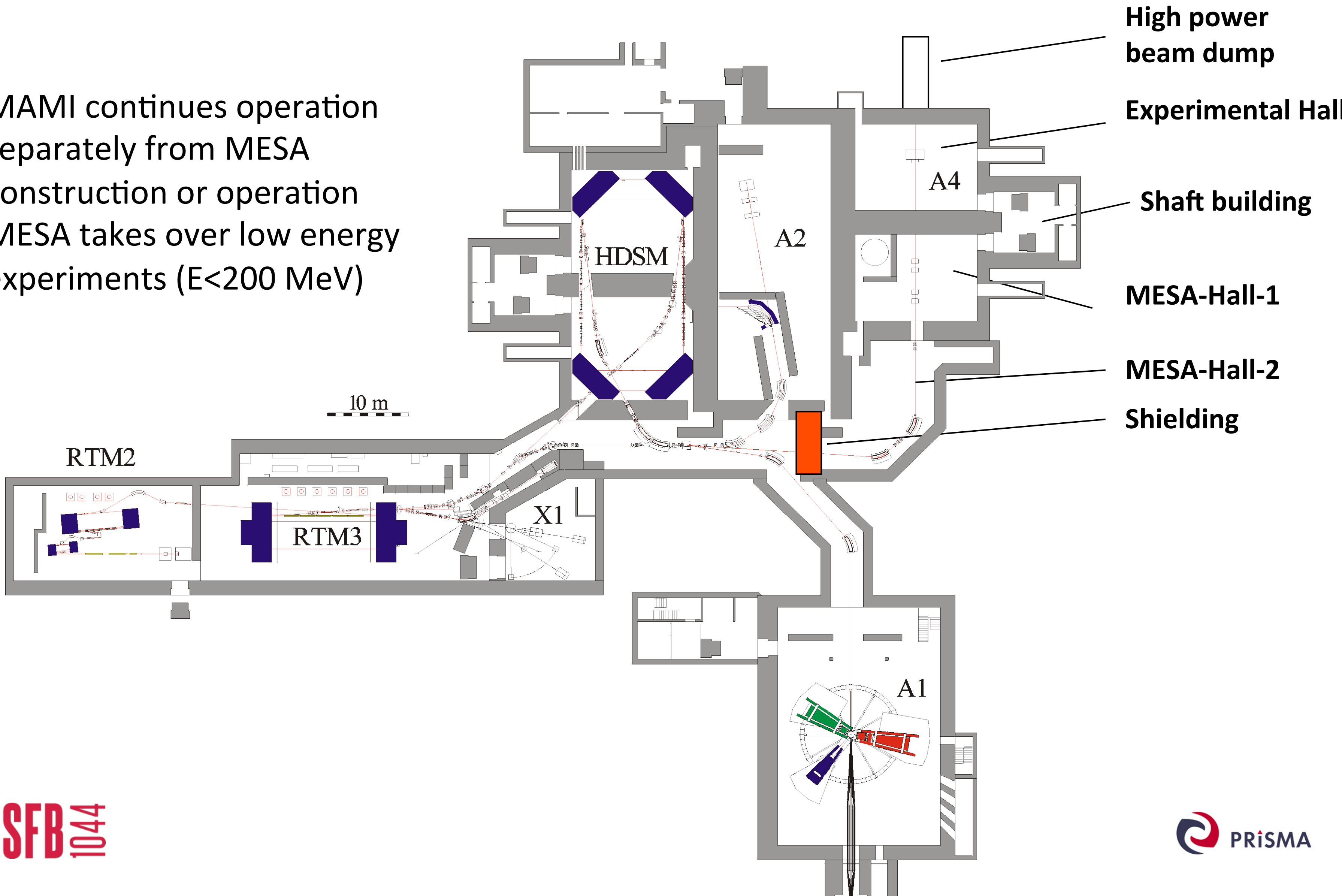


MESA-Accelerator

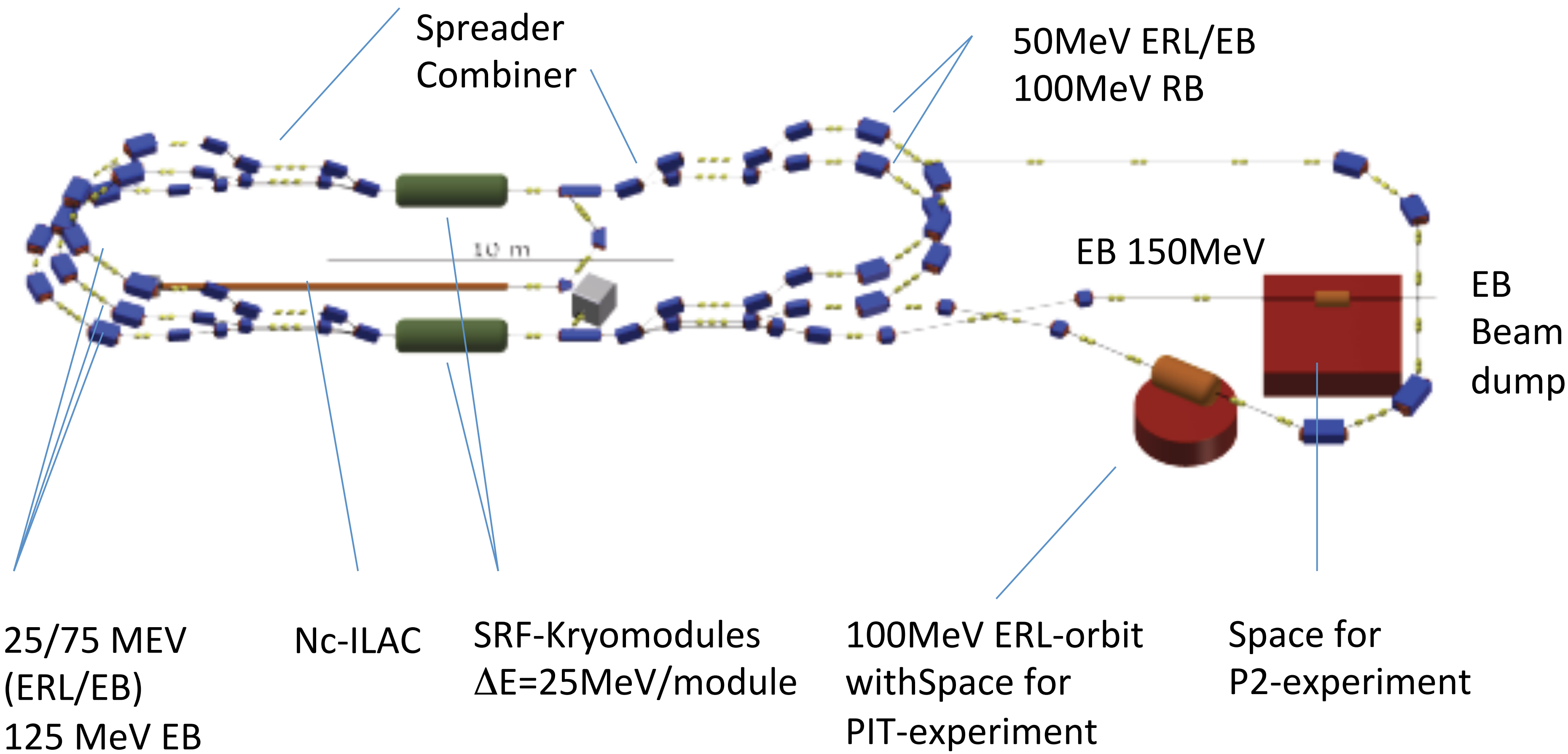
MESA: Beam parameter

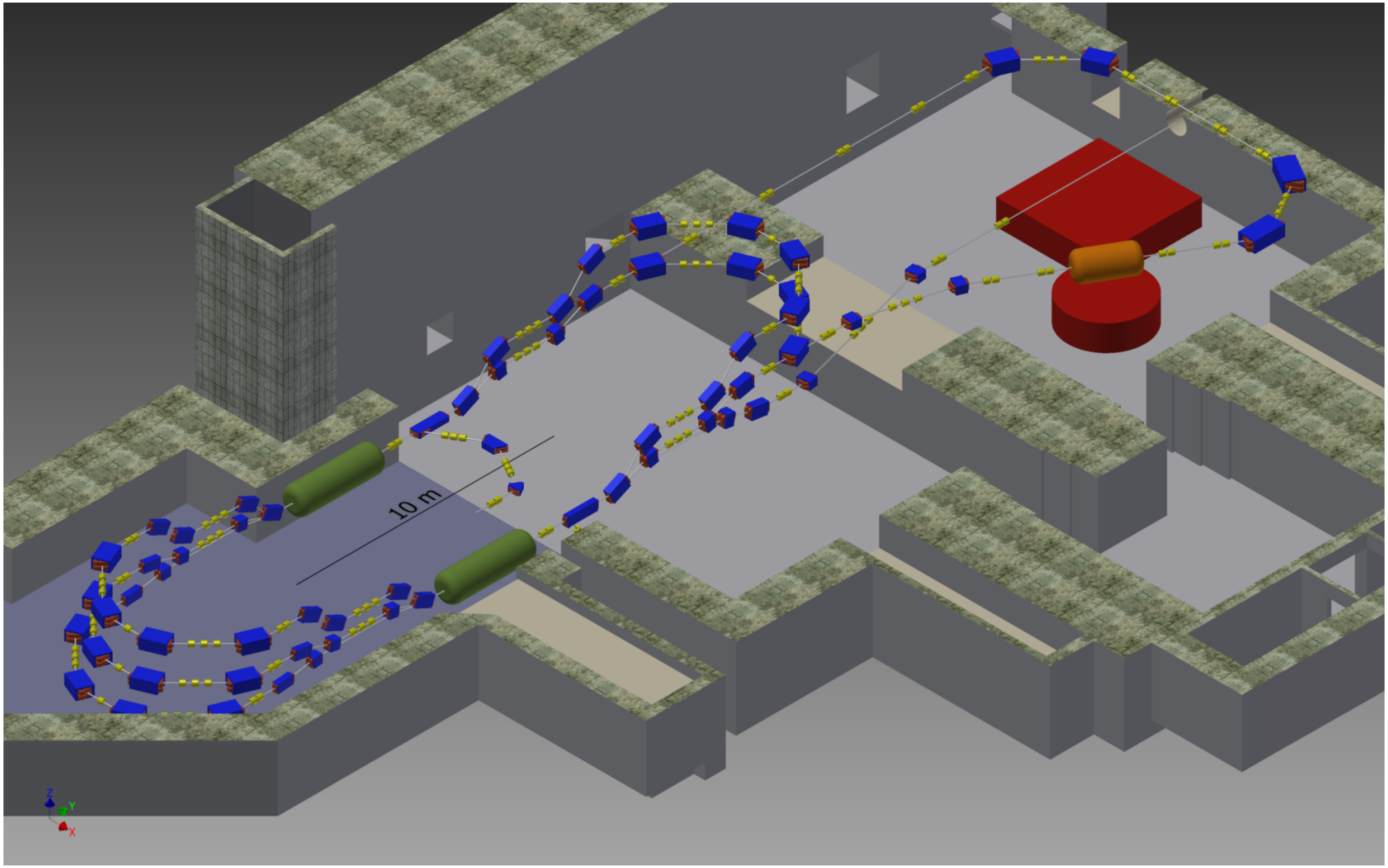
Beam Energy ERL/EB [MeV]	105/155 (105/205)
Operation mode	1300 MHz, c.w.
Elektron-sources	1.) Polarised : NEA GaAsP/GaAs superlattice , 200keV (?) 2.) unpolarised KCsSb, 200keV
Bunch Charge EB/ERL [pC] 7.7pC=10mA@1300MHz	0.15/0.77 (0.15/7.7)
Norm. Emittance EB/ERL [μm]	0.1/<0.5 (0.1/<1)
Spin Polarisation (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)

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



- MESA basic design finished, Solutions for EB and ER mode found
- Call for tender for cryomodules successful, price acceptable.
- Cryomodule specs in agreement with
  - a) liquifier capacity
  - b) with ER stage 1 parameters (>1mA) and
  - c) with P2 specs.
- Order for CM still in 2014, 2 years delivery time
- Continuous operation of MAMI during construction of
  shielding wall finished in spring 2014
- Compact design → full usage of MESA hall2 for experiments
  - sufficient space for P2
  - additional room for ER internal target experiments
- 100keV source suitable for MESA stage 1 in ER-mode, available source and Wien filters can be employed!

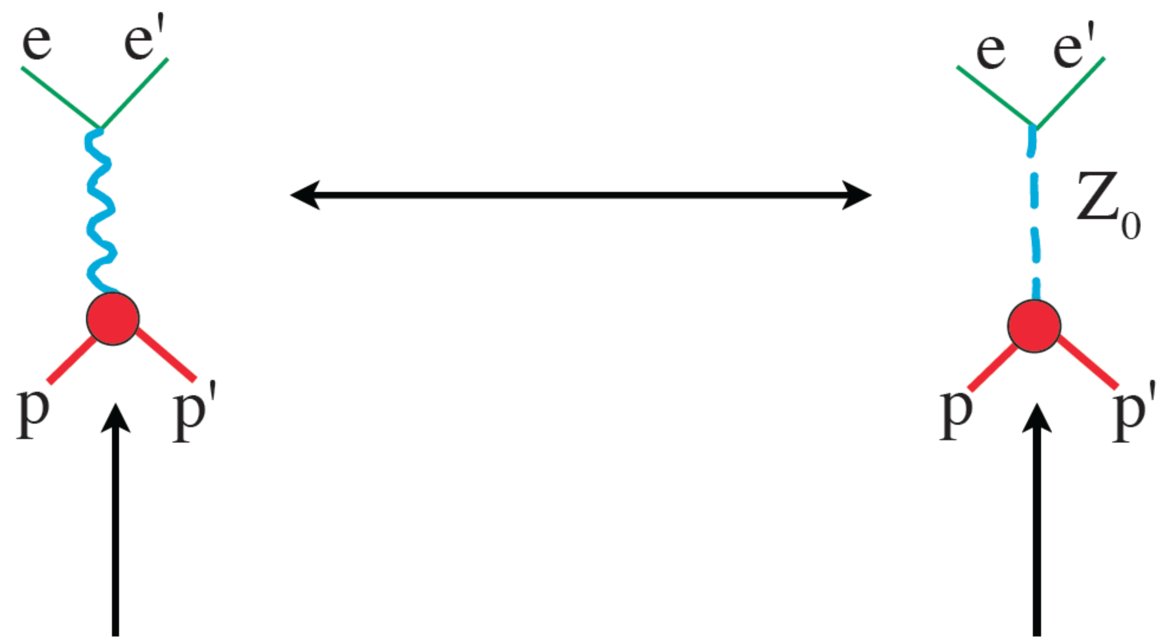

Spreader
Combiner
50MeV ERL/EB
100MeV RB
10 m
EB 150MeV
EB
Beam
dump
25/75 MEV
(ERL/EB)
125 MeV EB
Nc-ILAC
SRF-Kryomodules
ΔE=25MeV/module
100MeV ERL-orbit
withSpace for
PIT-experiment
Space for
P2-experiment


10 m

„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: $\sin^2(\theta_W)$

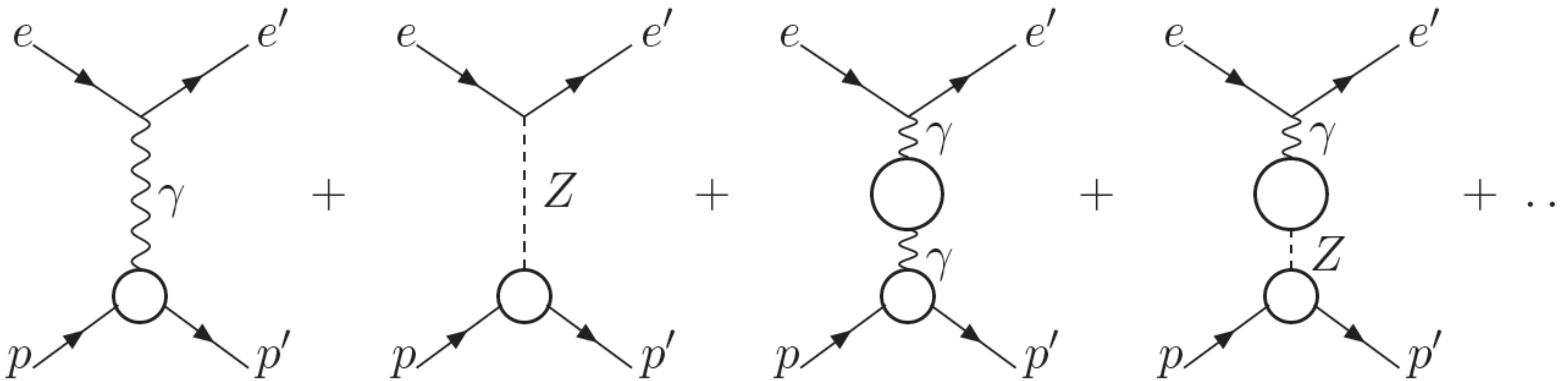


$Q_e(p) = +e$
electric charge of the proton

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

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

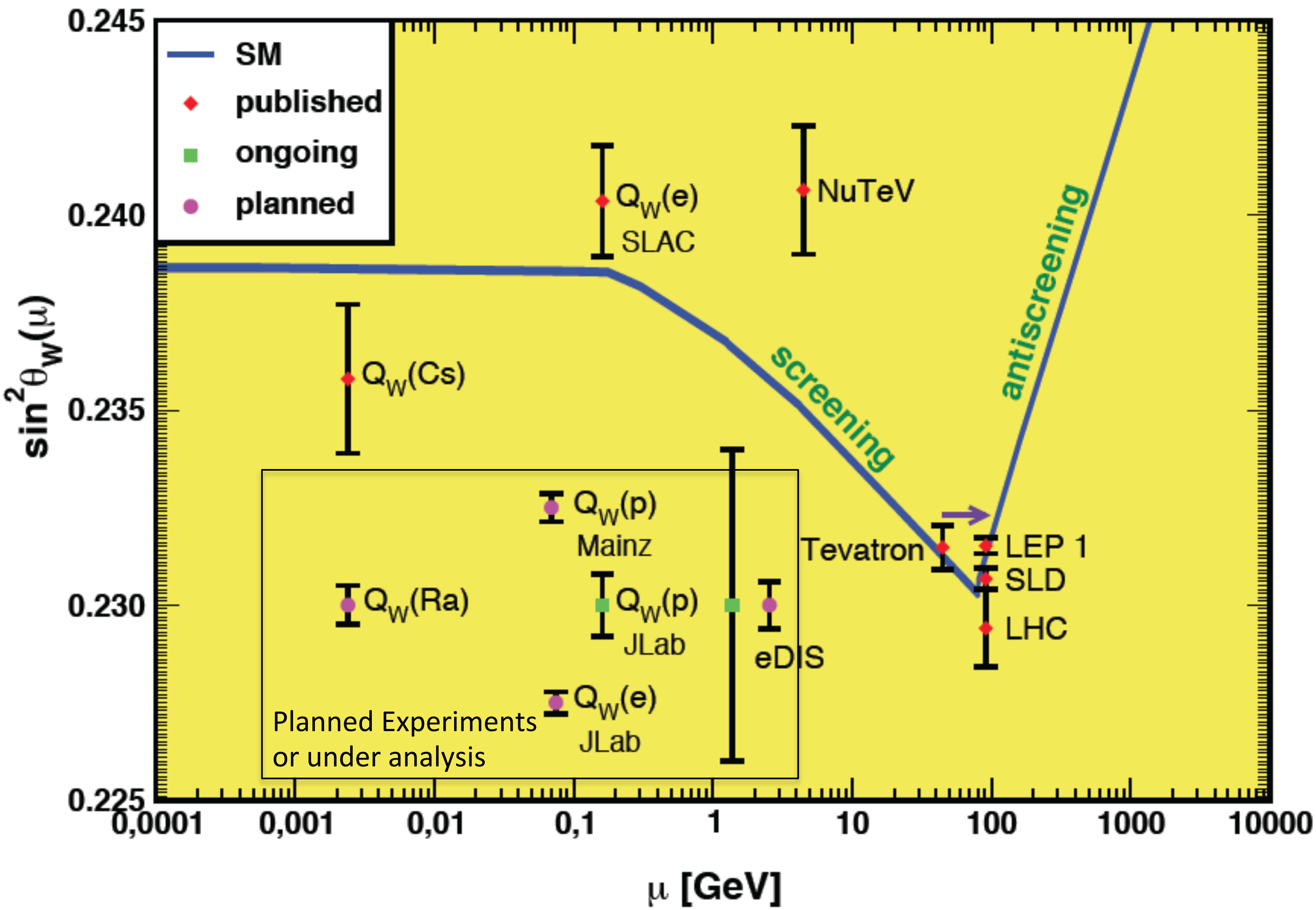
Precision measurements and quantum corrections:

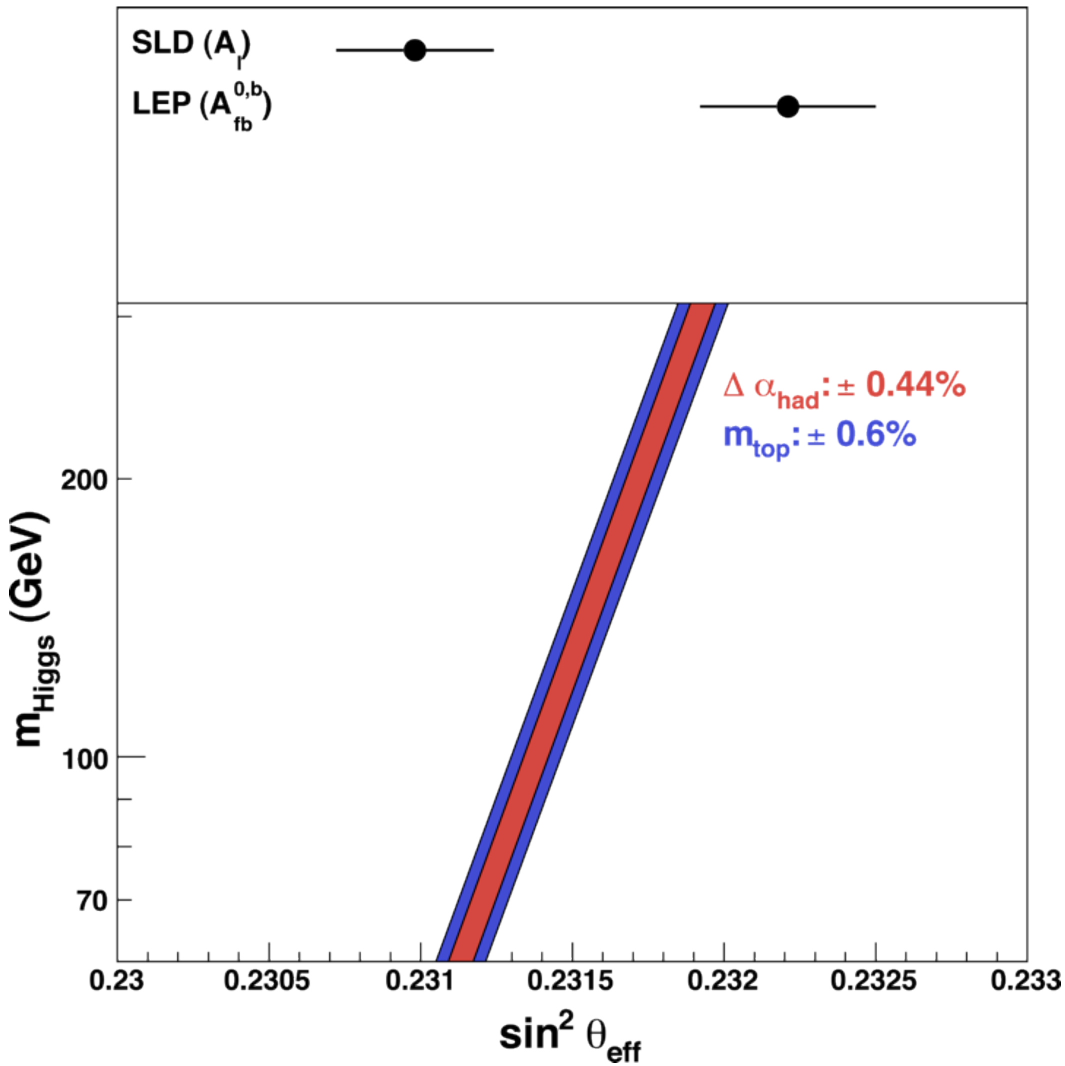


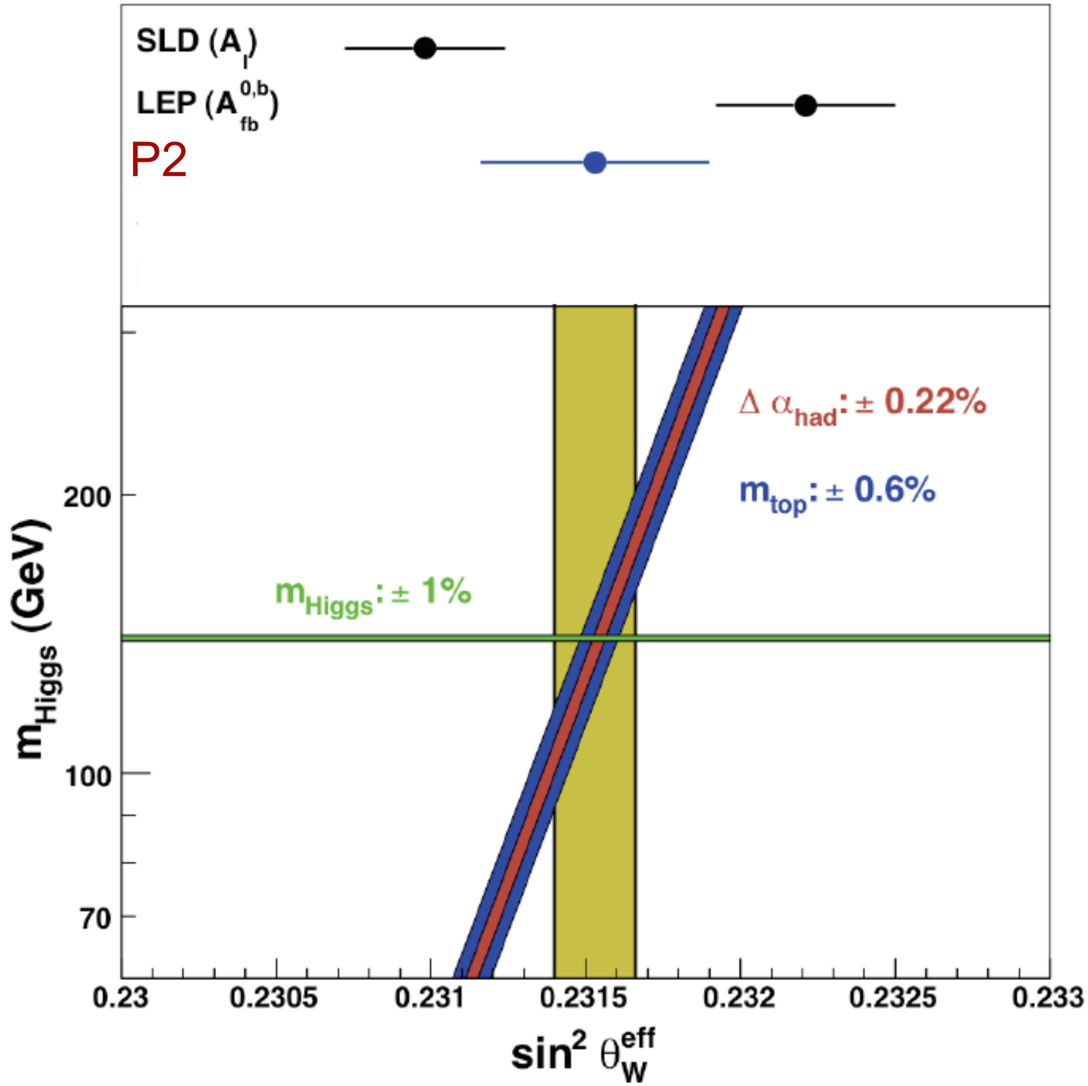
running α

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

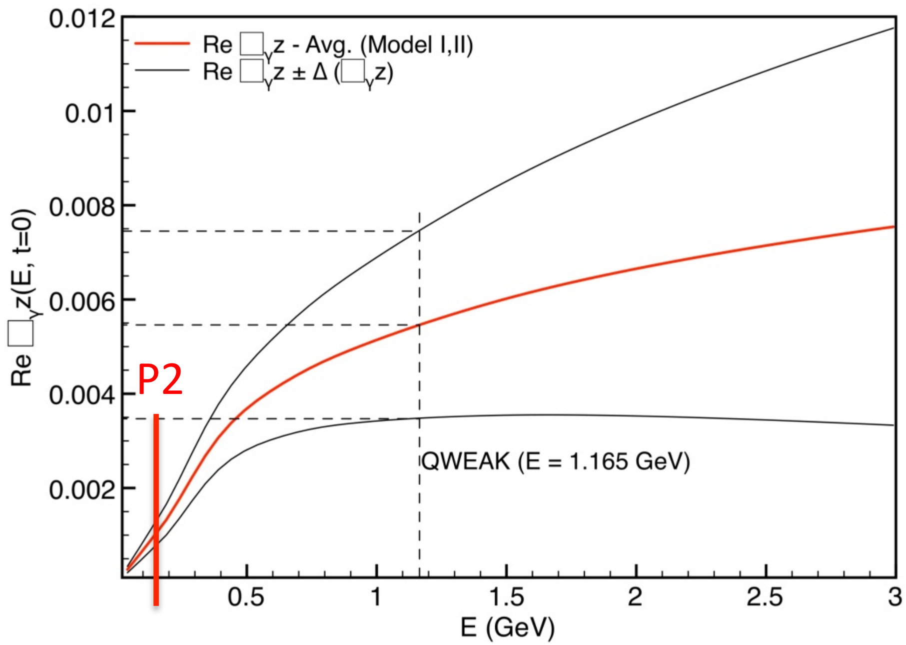
Universal quantum corrections: can be absorbed into a
scale dependent, „running" $\sin^2 \theta_{eff}$ or $\sin^2 \theta_W(\mu)$


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


SLD (A_l)
LEP (A_fb^0,b)
Δ α_had: ± 0.44%
m_top: ± 0.6%
200
100
70
m_Higgs (GeV)
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
sin² θ_eff

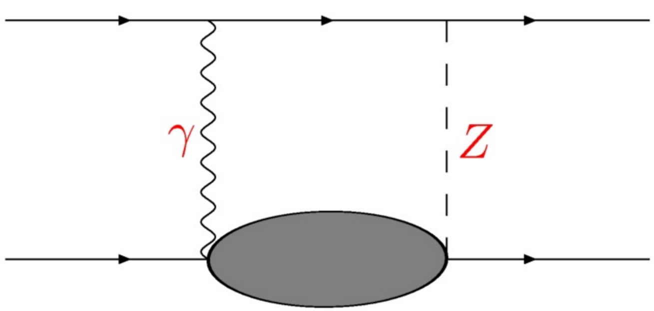

SLD (A_l)
LEP (A^{0,b}_{fb})
P2
Δ α_had: ± 0.22%
m_top: ± 0.6%
m_Higgs: ± 1%
m_Higgs (GeV)
200
100
70
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
sin² θ_W^eff

- 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

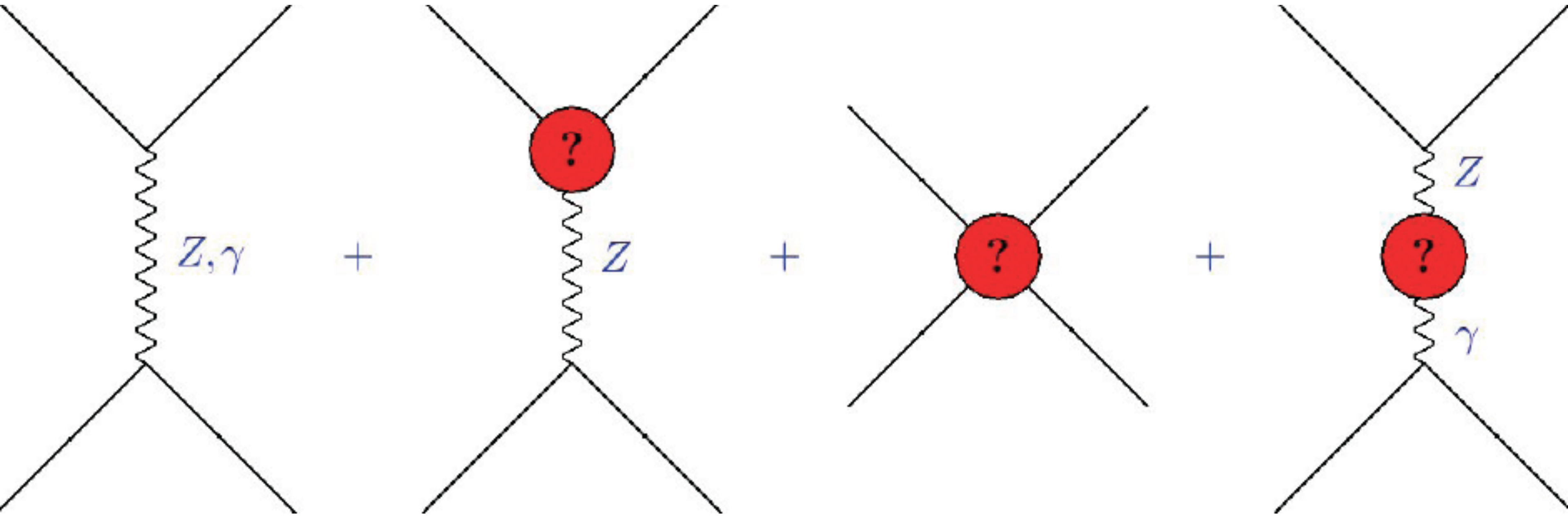


Progress in Theory

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

Sensitivity to new physics beyond the Standard Model

Sensitivity to new physics beyond the Standard Model

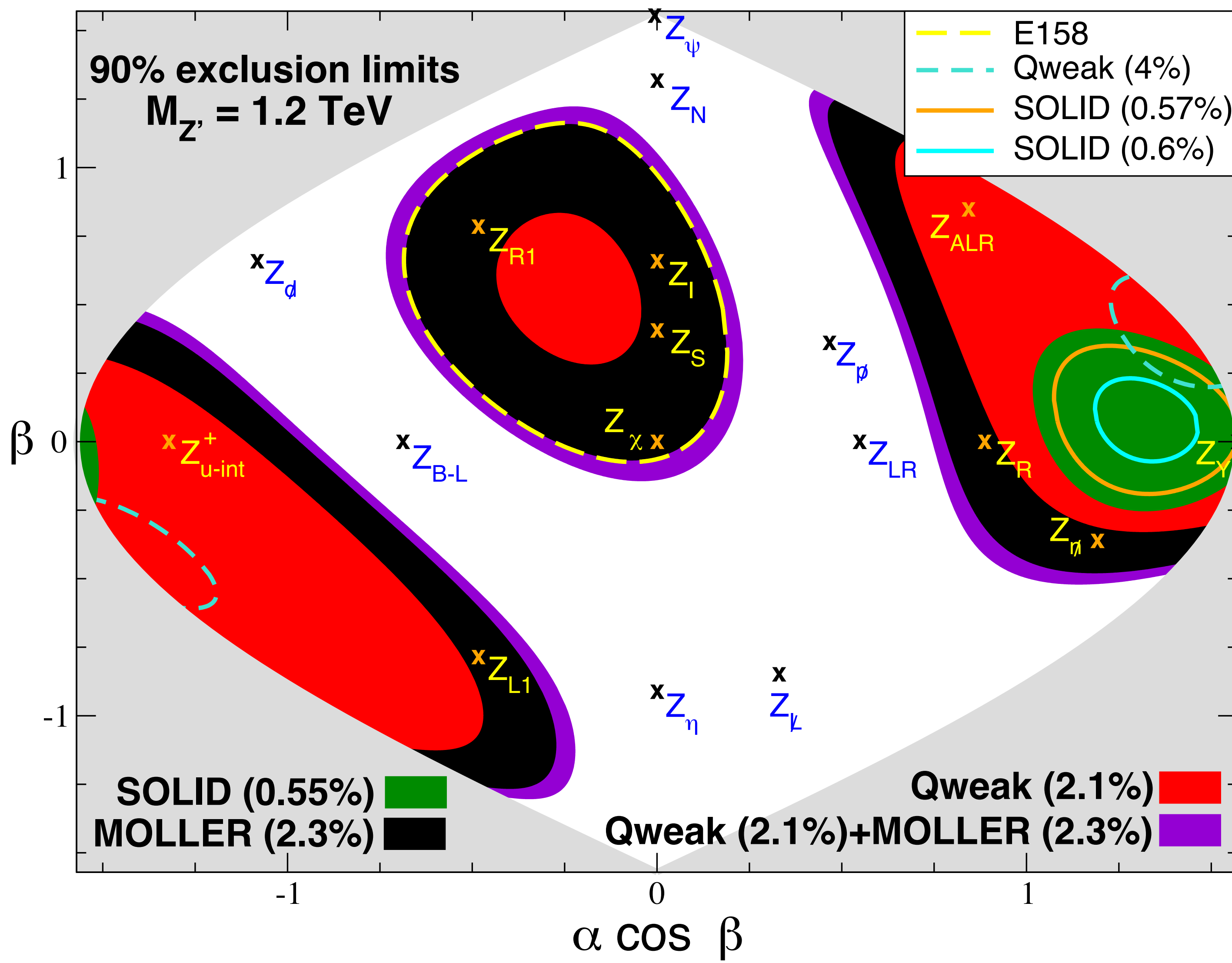


Extra Z

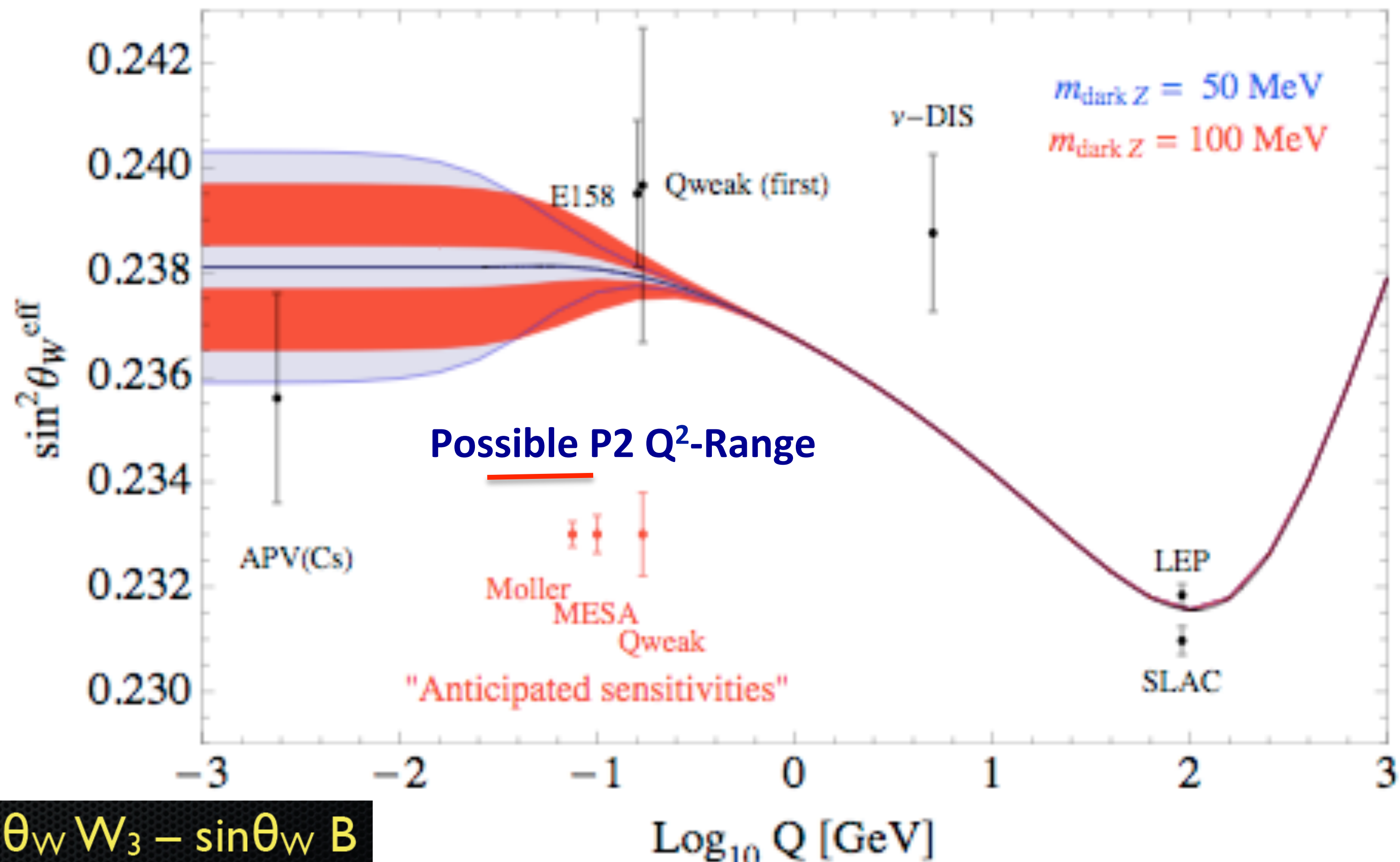
Mixing with Dark photon or Dark Z

Contact interaction

New Fermions


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

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

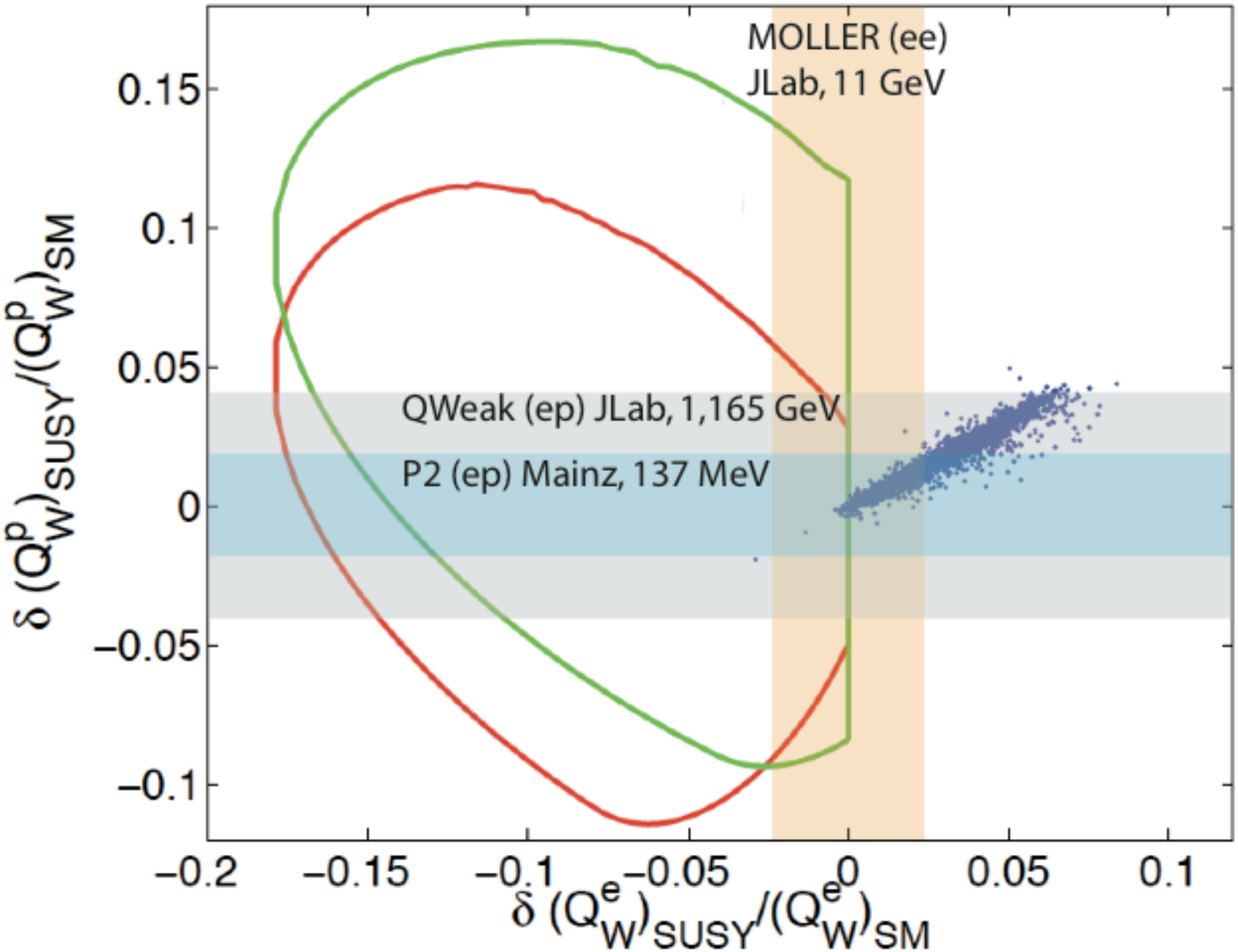


$Z = \cos\theta_W W_3 - \sin\theta_W B$

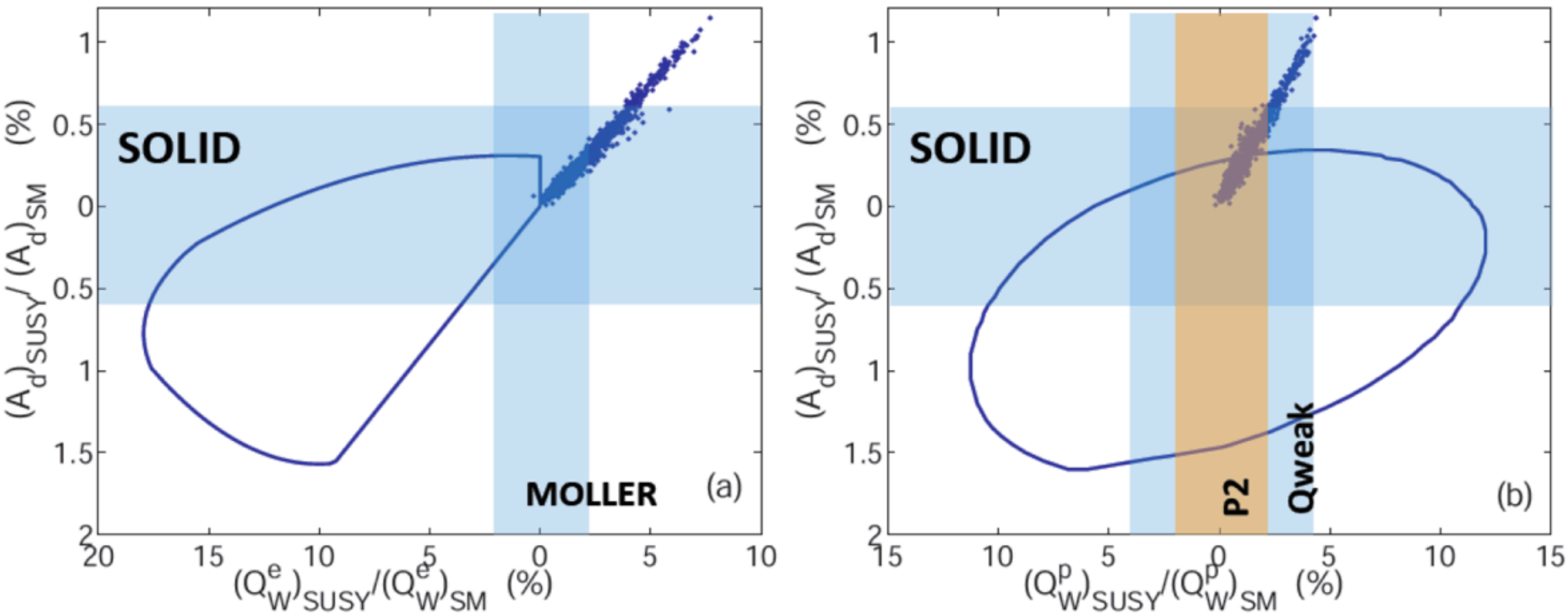
$A = \sin\theta_W W_3 + \cos\theta_W B$

Bill Marciano

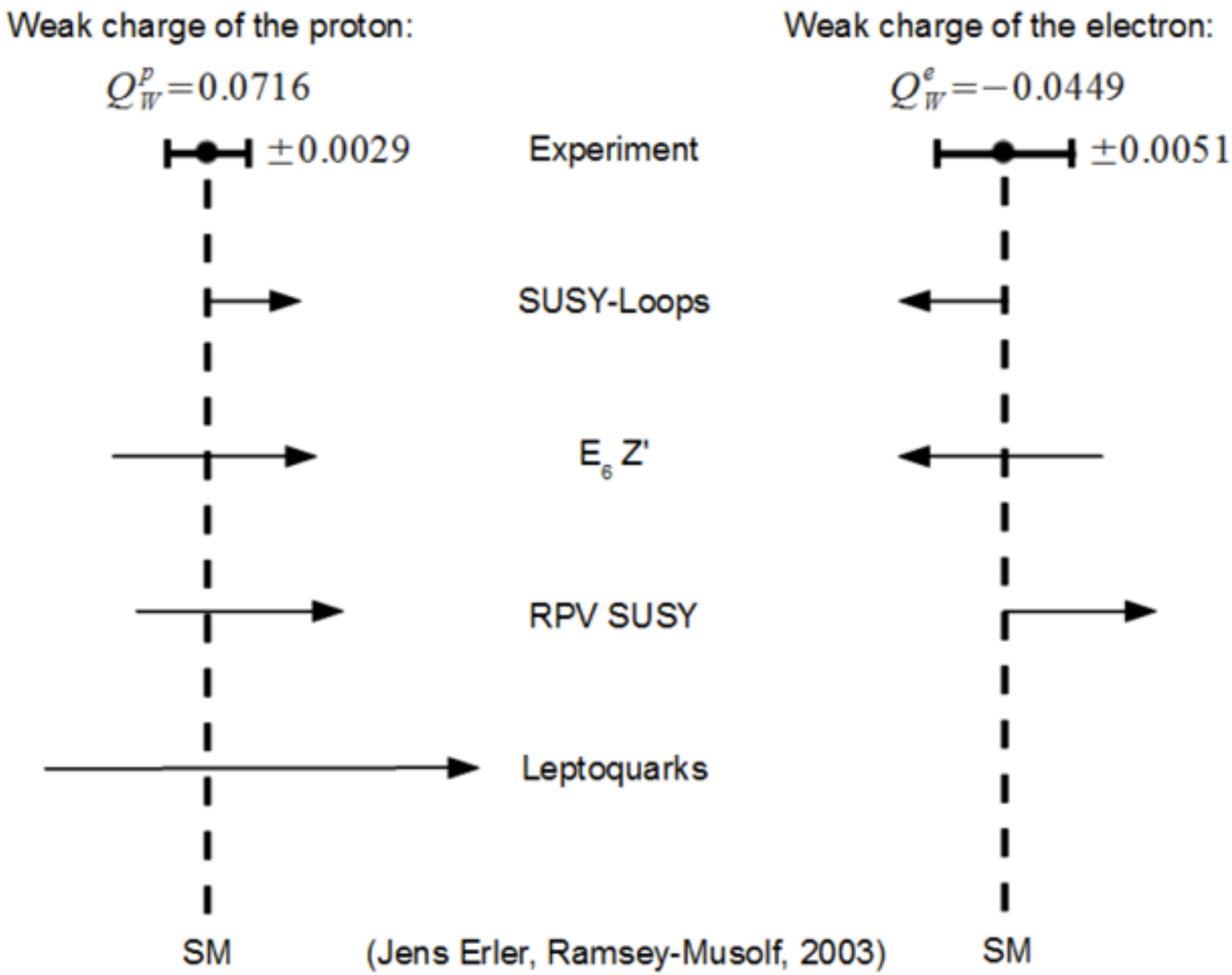
Example: supersymmetric Standard Model extensions



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



- Complementary access by weak charges of proton and electron



Weak Charge Of Proton: P2 (MESA)

Weak Charge Of Electron: MOELLER (JLAB)

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

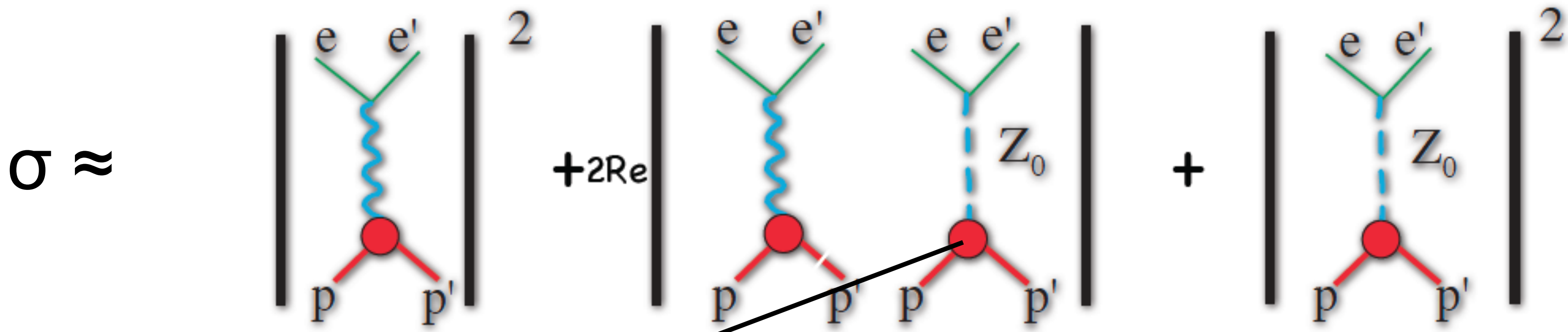
Physics sensitivity from contact interaction

	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

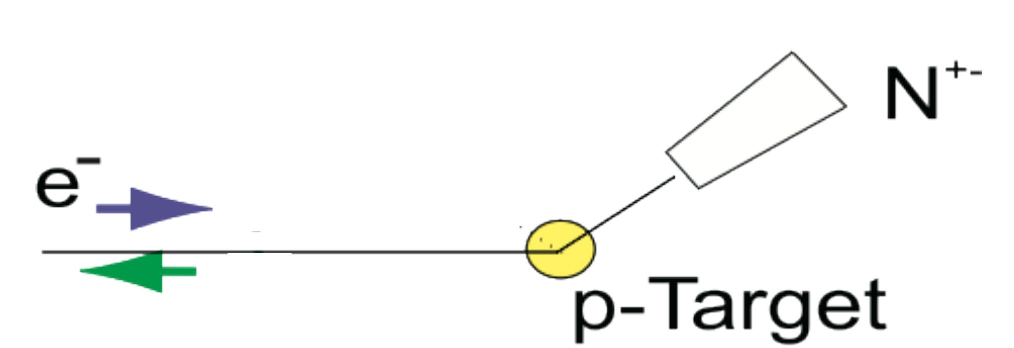
Jens Erler

Experimental Method

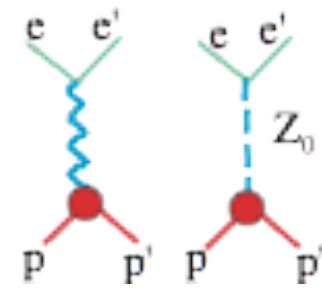
Parity Violating Asymmetry in elastic electron proton scattering



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



Parity violating cross section asymmetry



$$A_{\rm RL} = \frac{\sigma_{\rm R} - \sigma_{\rm L}}{\sigma_{\rm R} + \sigma_{\rm L}} \qquad q^2 \ll M_Z^2$$

$$= \frac{q^2}{M_Z^2} \frac{2 j_{\gamma,\mu} \langle J_\gamma^\mu \rangle \left(a_\mu \langle V_Z^\mu \rangle + v_\mu \langle A_Z^\mu \rangle \right)}{\left| j_{\gamma,\mu} \langle J_\gamma^\mu \rangle \right|^2} \sim 10^{-5}$$

$$A_{\rm RL} = \underbrace{A_{\rm V} + A_{\rm A}}_{= A_0} + A_{\rm S}$$

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

e

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

Parity violating cross section asymmetry

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

weak charge: Q_W

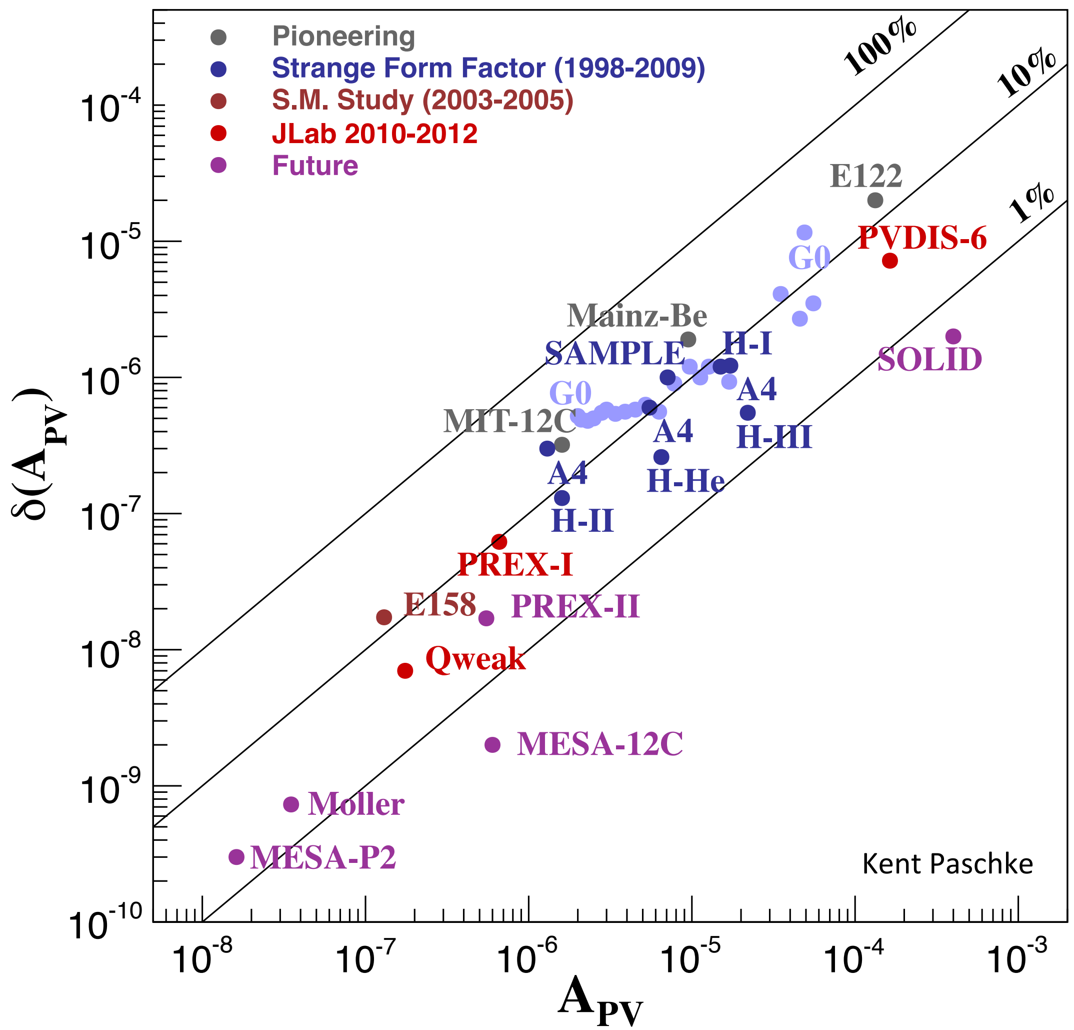
hadron structure: $F(Q^2)$

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

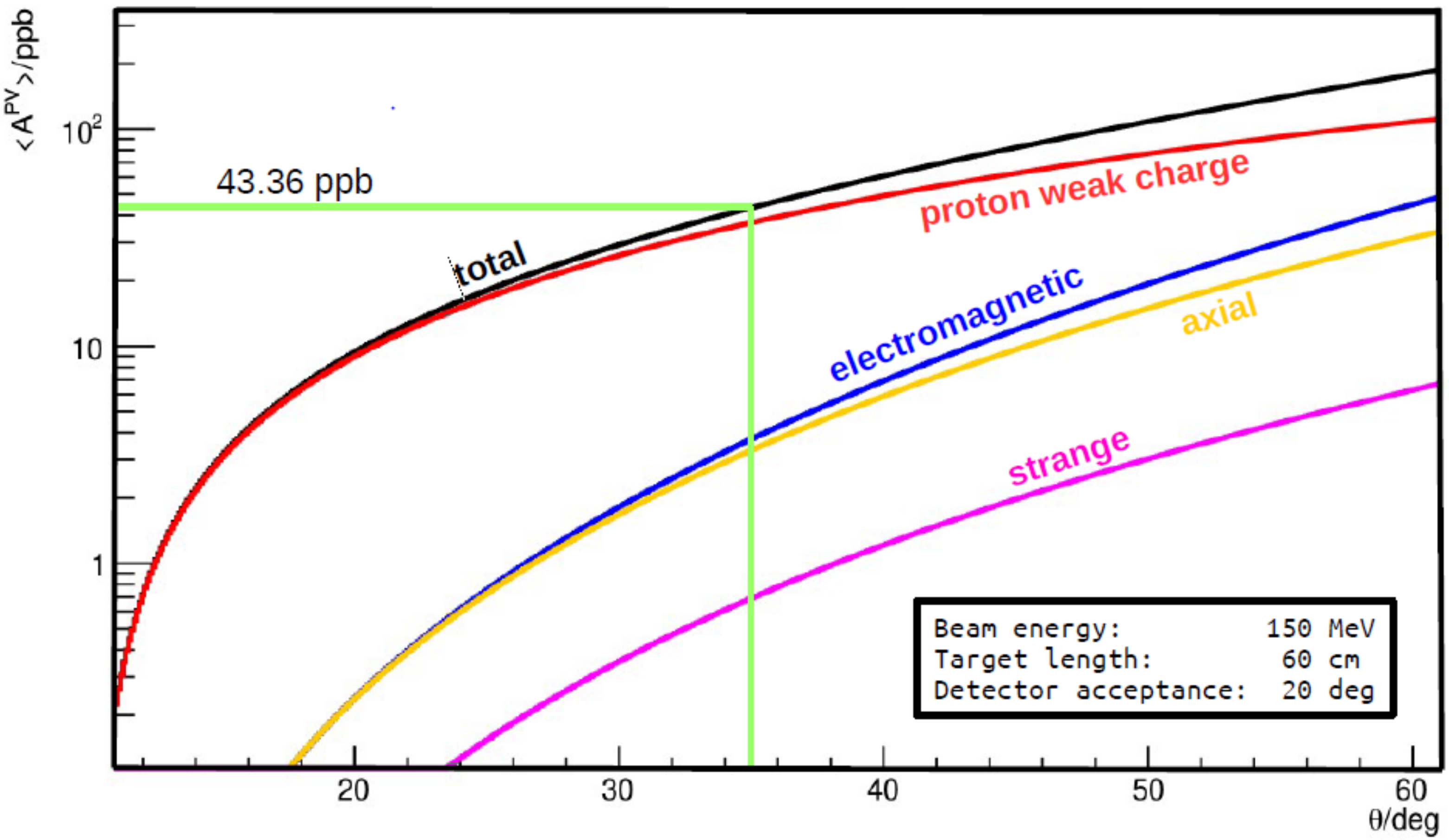
$$F(Q^2) = F_{EM}(Q^2) + F_{Axial}(Q^2) + F_{Strange}(Q^2)$$

Important input from other projects (S1, S3)

PVeS Experiment Summary



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



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 %

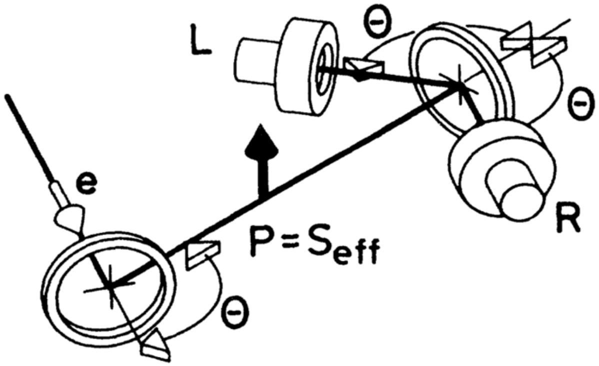
→

- $\Delta\sin^2(\theta_w)$ drops from $3.60\cdot10^{-4}$ to $2.52\cdot10^{-4}$ → possible reduction of Δt
- $\sin^2(\theta_w)$-measurement at larger scattering angles (more easy to measure)

Polarimetry (<0.5%)

The double scattering Mott polarimeter:

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



Mott Polarimeter:

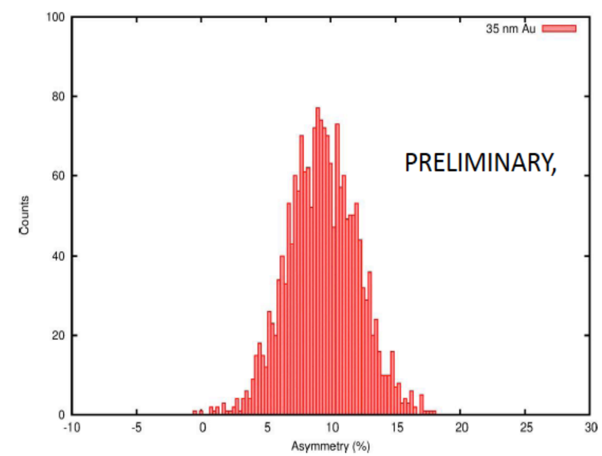
- Measuring left/right asymetry to calculate spin polarisati
- Analysing power of target foils has to be extrapolated

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

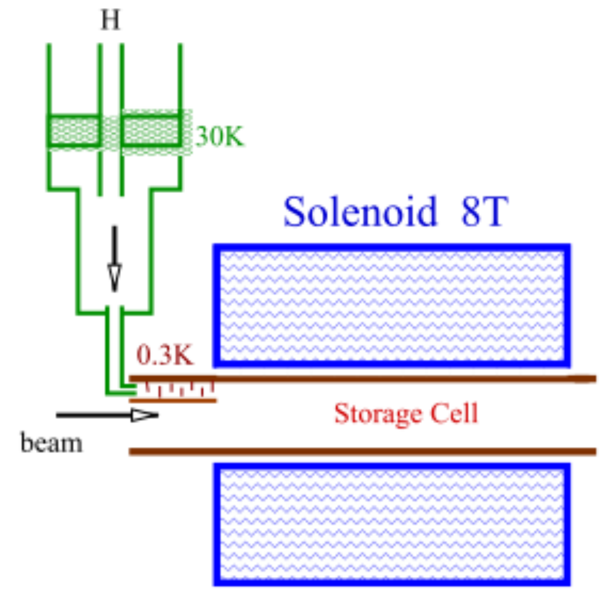
- Scattering chamber in operation, first double scattering data



Hydro Möller Polarimeter

The promise:(*)

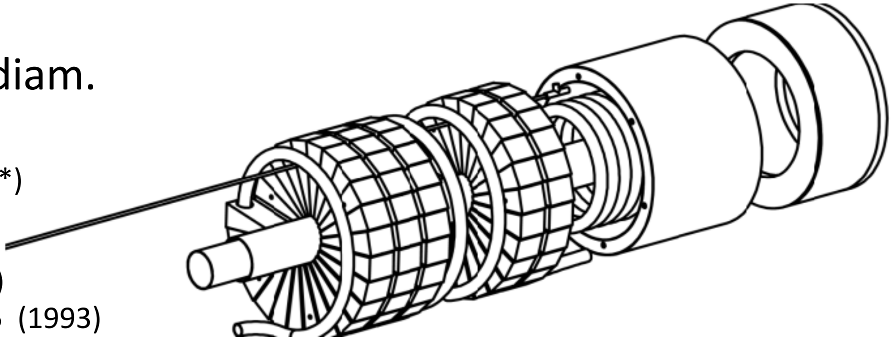
- **Hydro-Möller: Atomic trap with completely electron-spin polarized Hydrogen**
- **Online capability, high accuracy (<0.5%)**
- **Statistical efficiency approaches 0.5% in 2 hours (Target: $3*10^{-16}$ cm^{-2})**
- **Acceptance similar to conventional Möller**



(*)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)

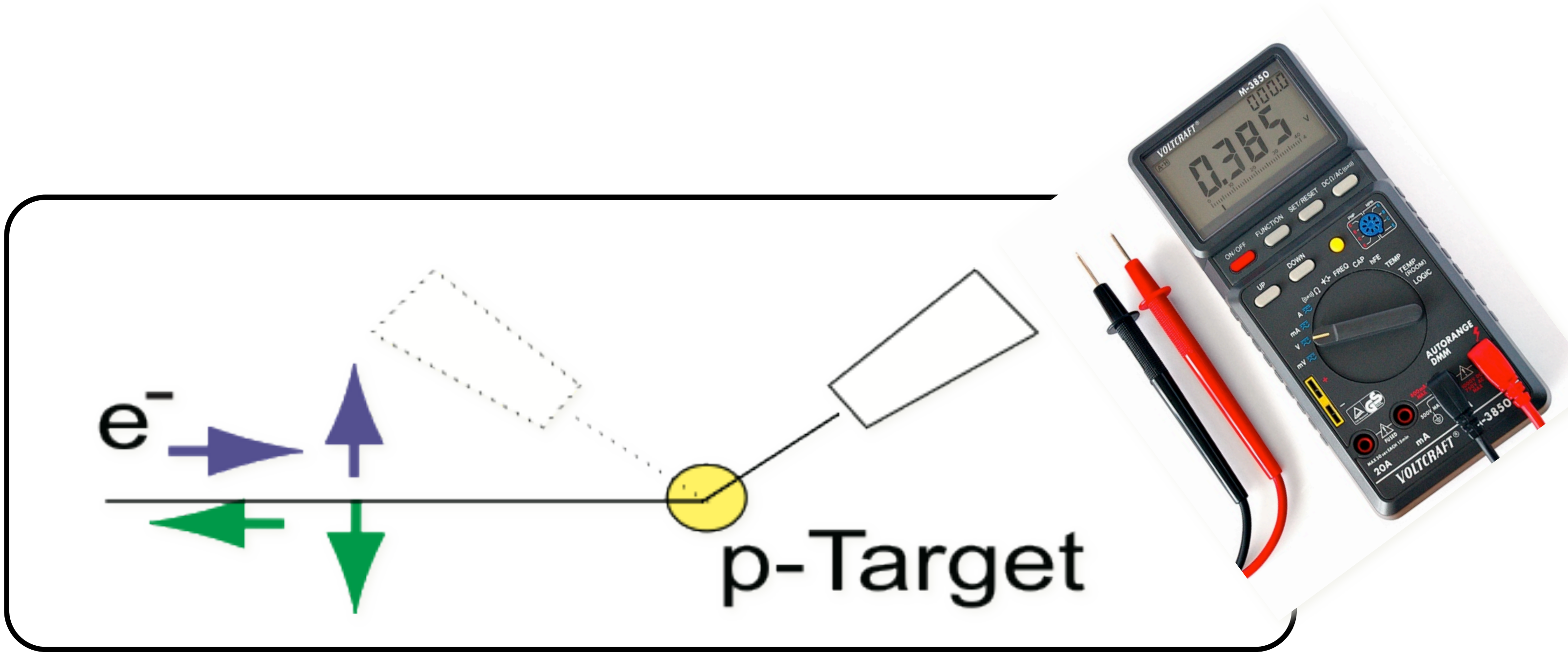


1.1K Stage heat exchangers
Presently in fabrication in KPH
Machine shop

Patricia Bartolome, Valerie Tyukine

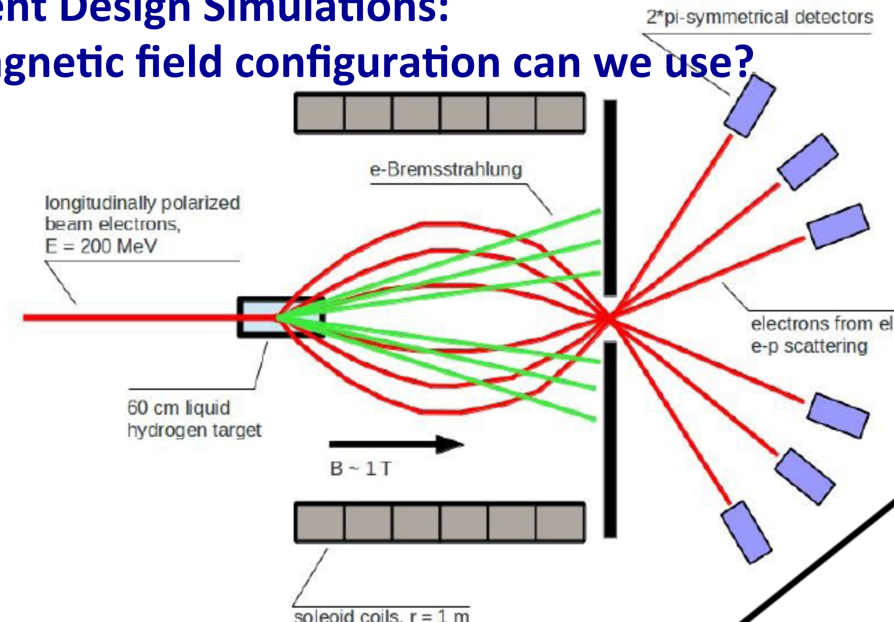
Detector Concept

Analogue Technique



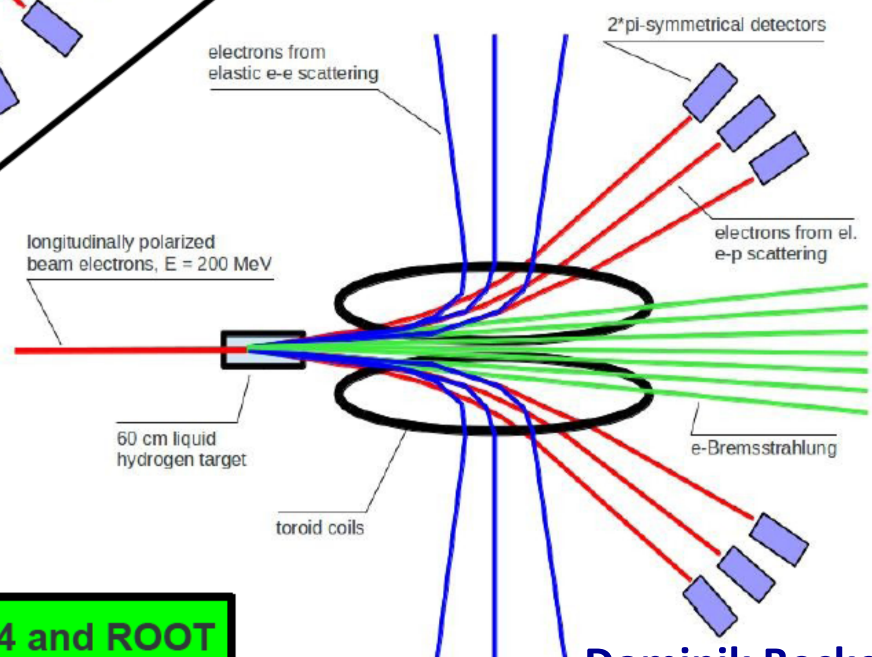
Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

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

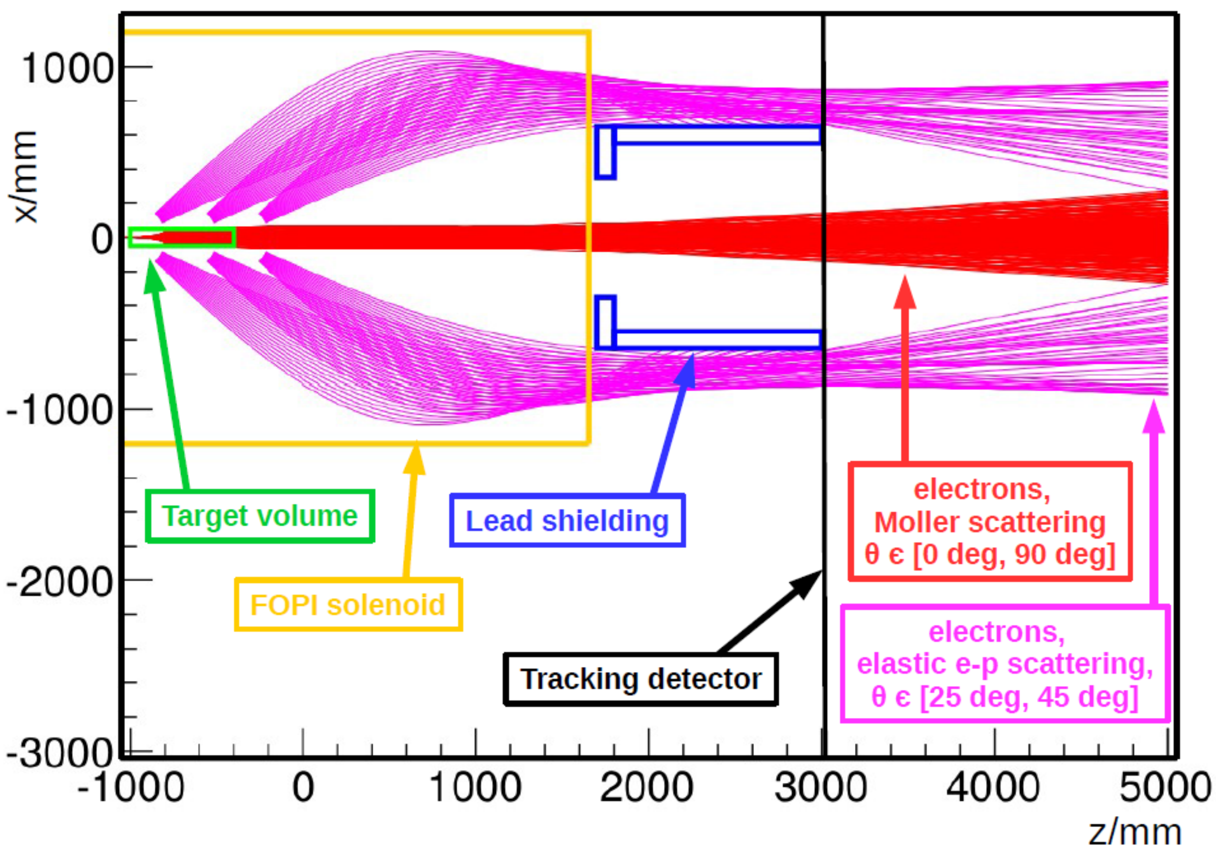


Toroid:
- Loss of ~50% solid angle
  → double measurement time
- Larger setup
- Copper coils

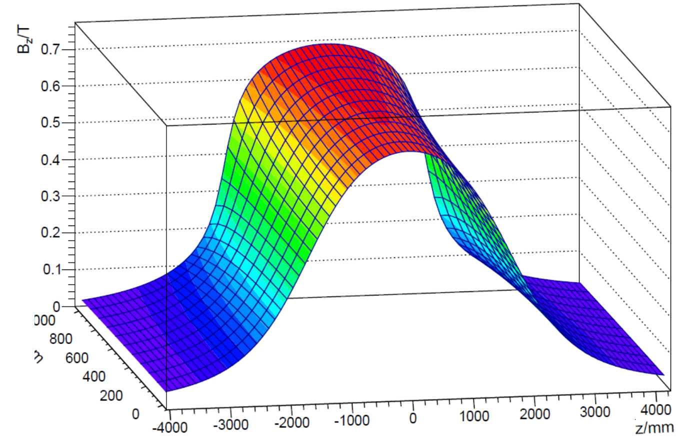
→ **Feasibility study with Geant4 and ROOT**

Dominik Becker

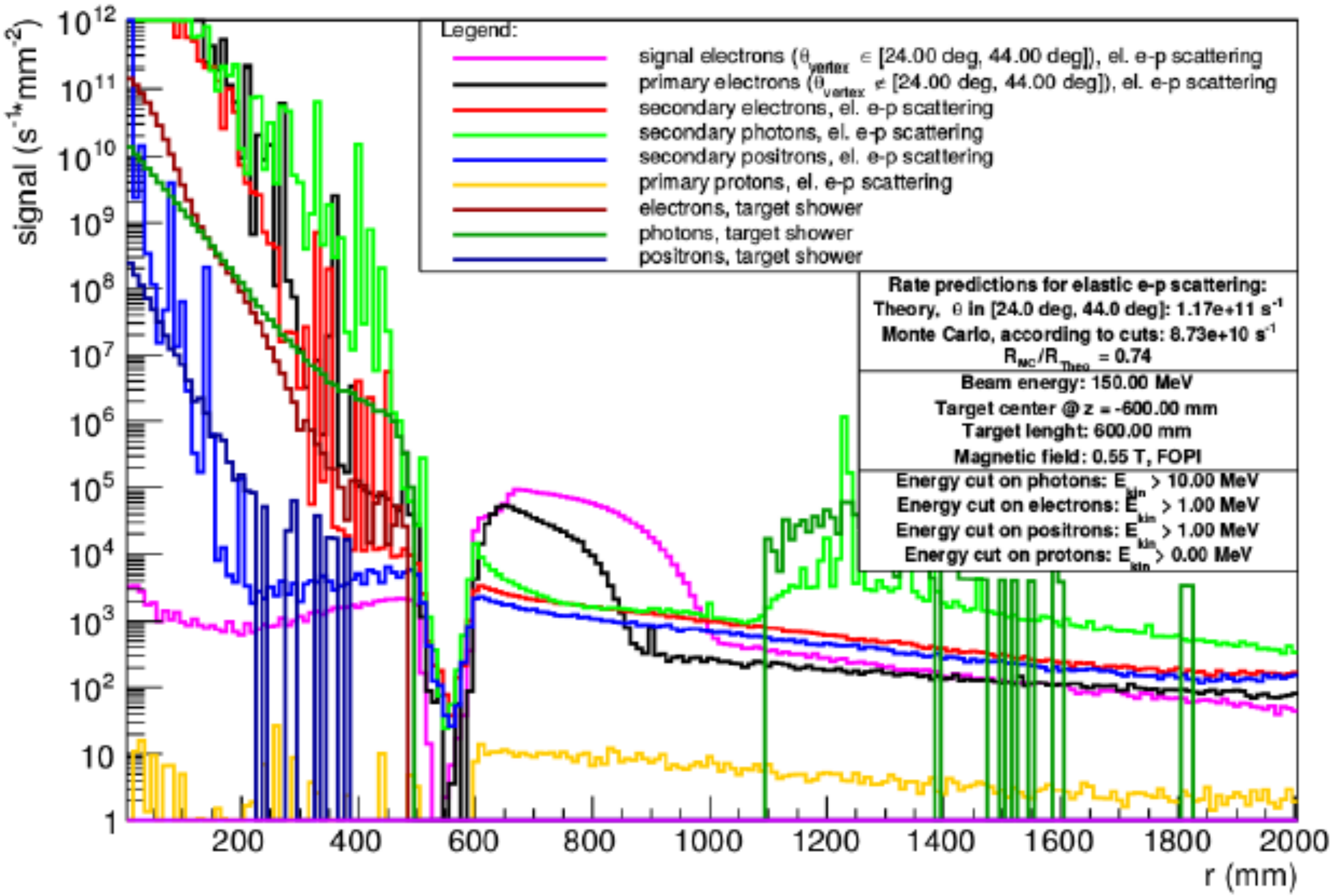
Design with FOPI-like Solenoid



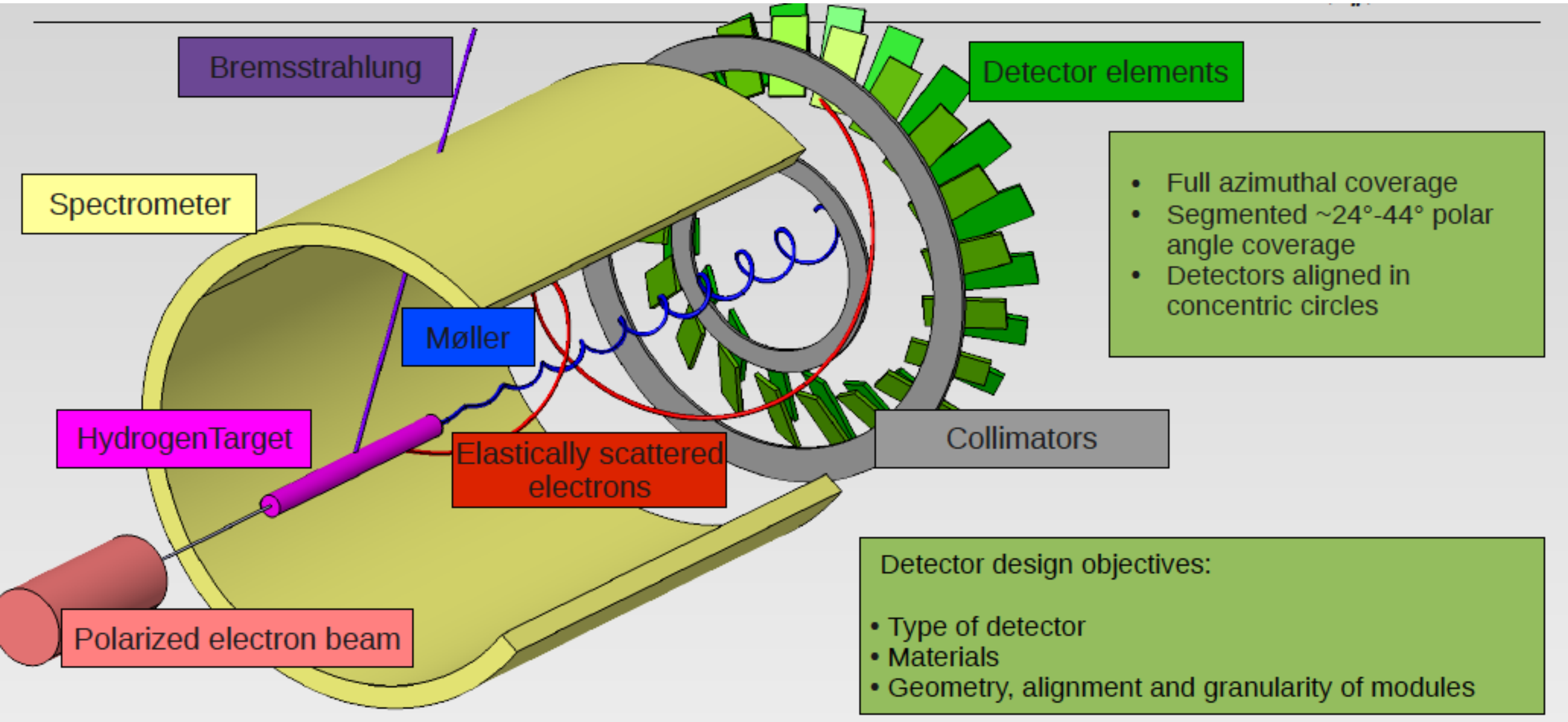
Field component along beam axis



Rate distribution @ z = 3810.00 mm

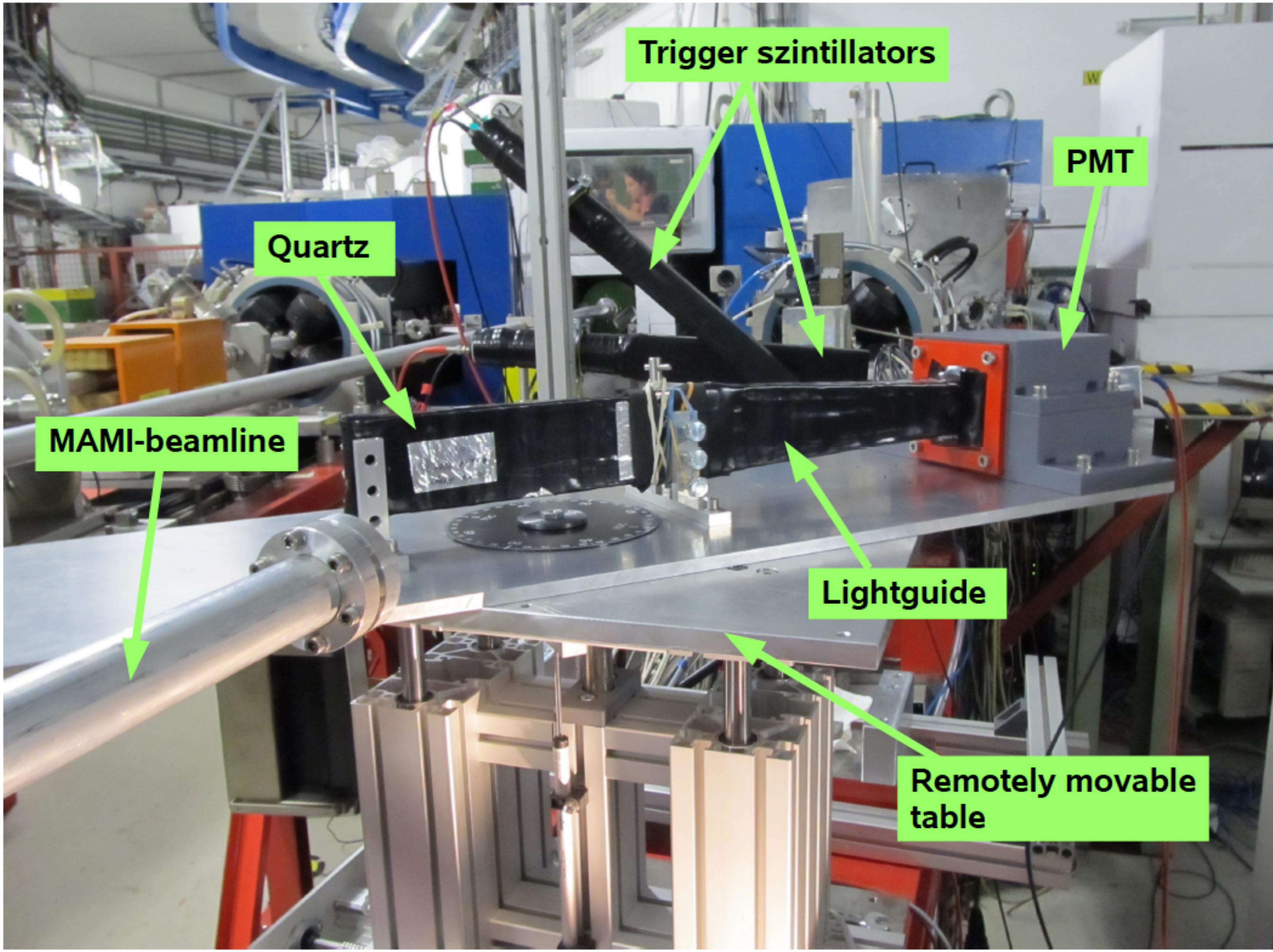


Dominik Becker

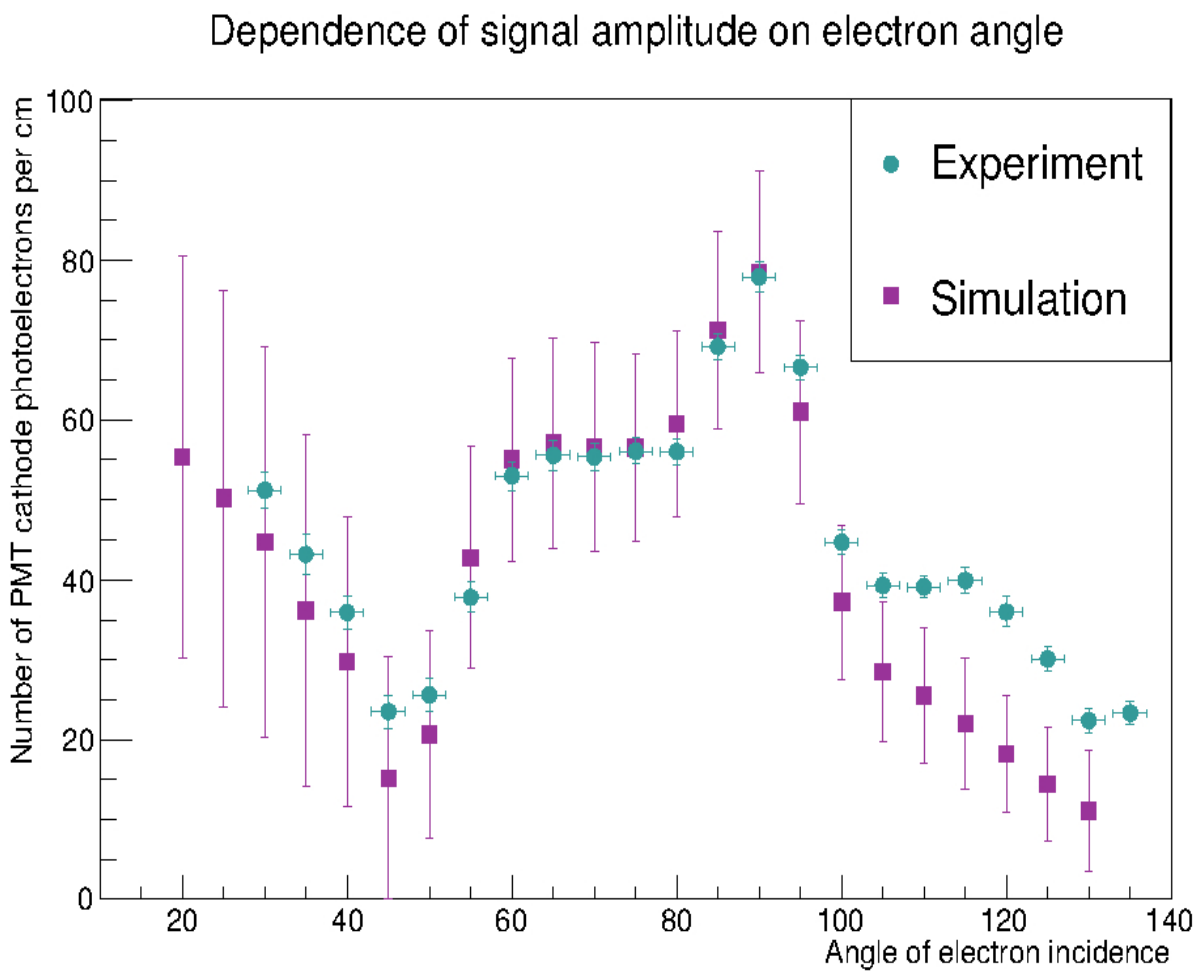


Kathrin Gerz

P2 Experimental setup (second testbeam January 2014)



DETECTOR RESPONSE: Comparision of data taken at MaMi and MonteCarlo Simulation



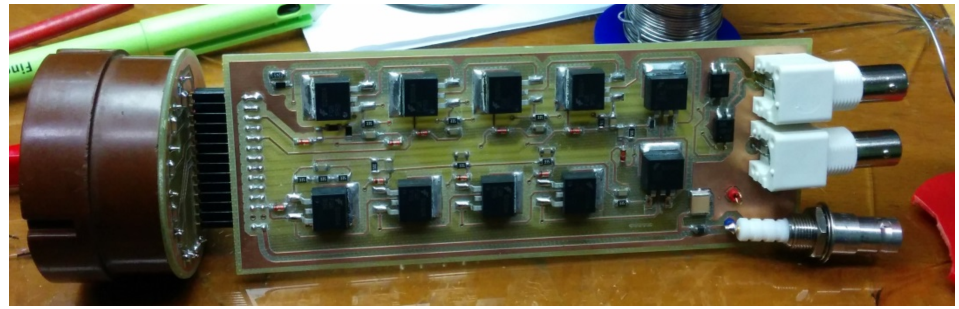
Primary particle: electron 855 MeV

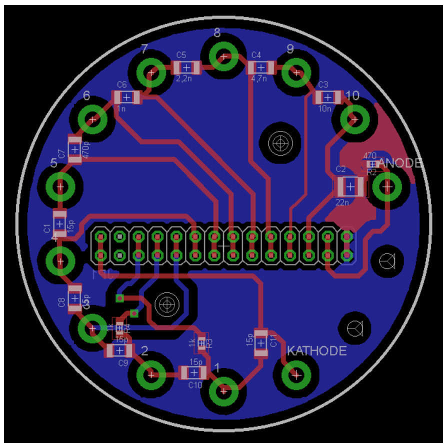
Cherenkov medium:
Hereaus Spectrosil 2000
300mm x 70mm x 10mm
45° cut as "outlet optic"

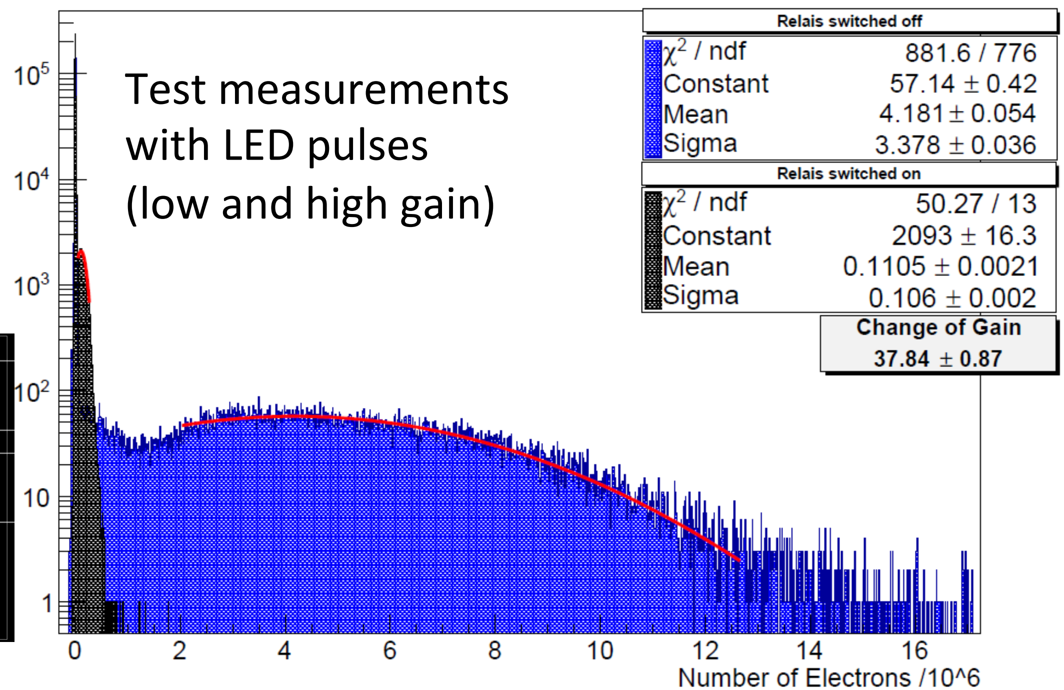
PMT:
UV-enhanced, quartz window tube
ET 9305 QKMB

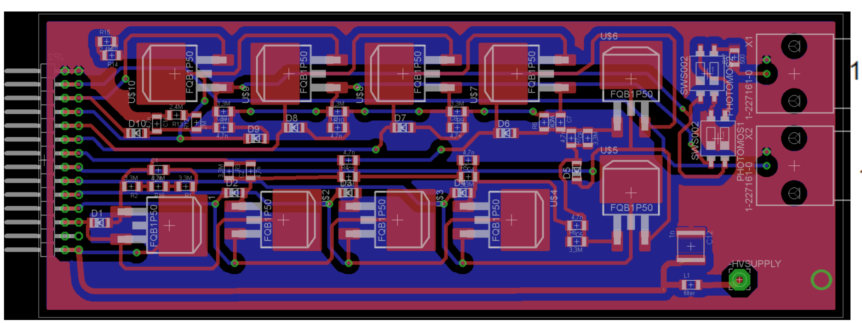
Kathrin Gerz

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









Th. Jennewein

Mainz has evolved to one of the main physics centers
in hadron and particle physics in Germany
1.6 Gev electron accelerator MAMI (normal conducting)
0.15 GeV electron accelerator MESA (supercond., energy recov.)

“Low energy frontier” comprises a sensitive test of the standard model
complementary to LHC

MAMI and MESA: Key facilities for low energy
precision hadron and particle physics:
- dark photon sensitive search
- weak mixing angle with 1ppm accuracy

Could only show a small collection of the full program