PVES program in Mainz (with the P2-Experiment)

EPIC 2024

PRISMA+

JG|U

HIM

Funded by the European Union

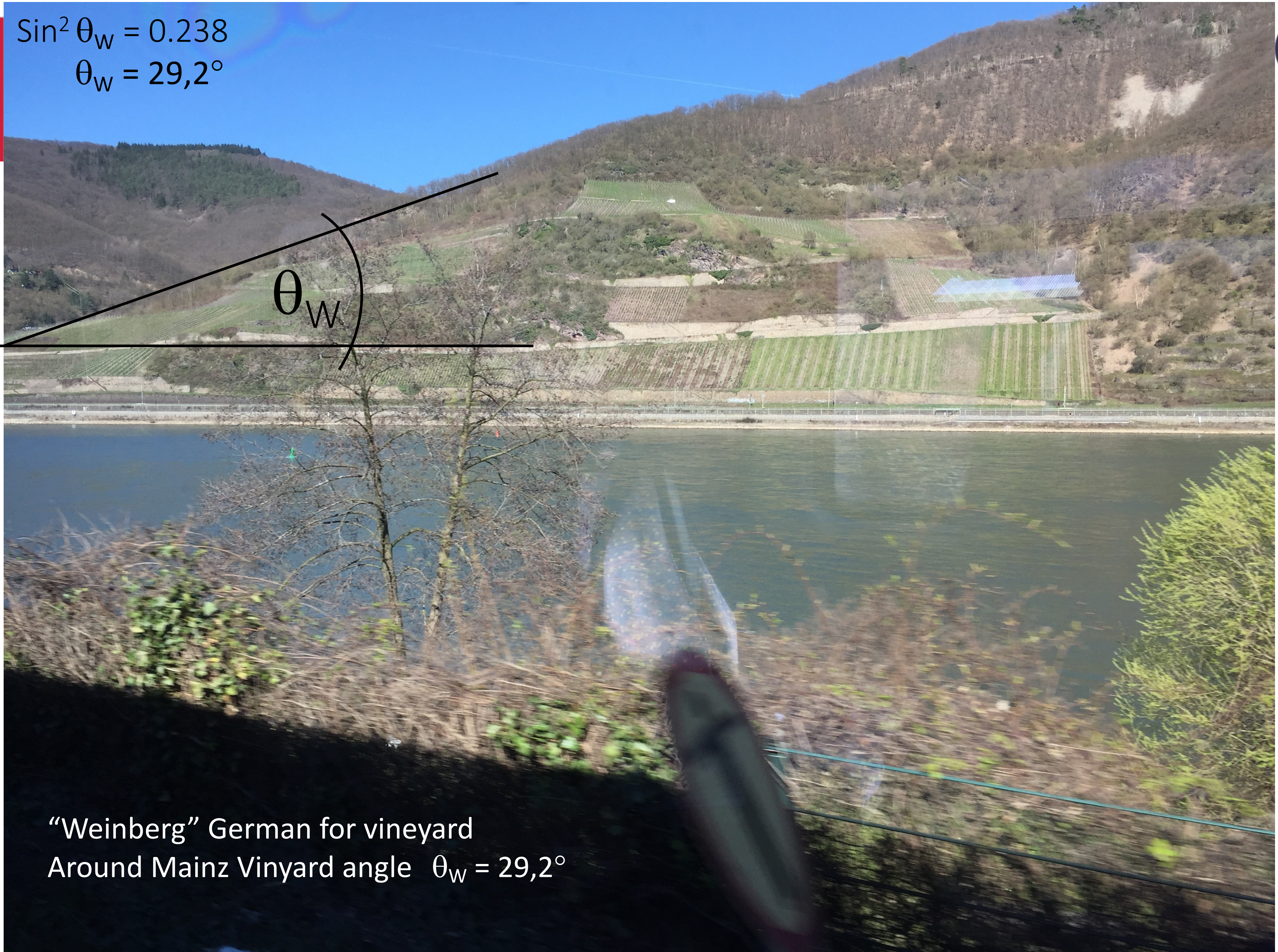
erc European Research Council
Established by the European Commission

Frank Maas, Institut für Kernphysik and
Helmholtz-Institut Mainz

EPIC 2024, Electroweak Physics Intersections
22-27 Sept 2024, Calaserena, Geremeas, Sardegna, IT

$\sin^2 \theta_W = 0.238$

$\theta_W = 29{,}2°$



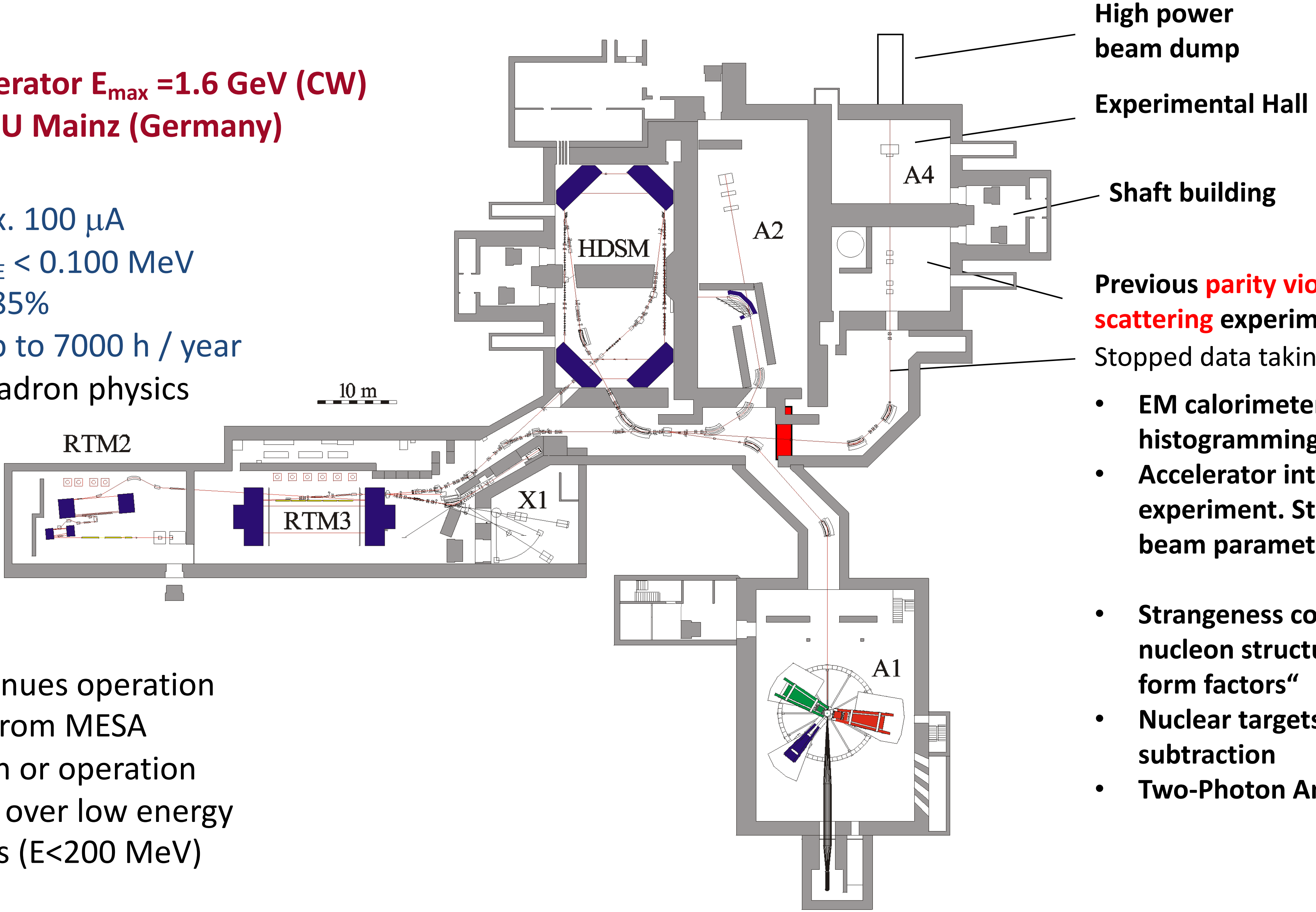
“Weinberg” German for vineyard
Around Mainz Vinyard angle $\theta_W = 29{,}2°$

MAinz MIcrontron MAMI. Electron accelerator up to 1.6 GeV

Electron Accelerator E_{max} =1.6 GeV (CW) operated at JGU Mainz (Germany)

Hallmarks

- Intensity max. 100 μA
- Resolution σ_E < 0.100 MeV
- Polarization 85%
- Reliability: up to 7000 h / year
- 30 years of hadron physics



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

Previous parity violation electron scattering experiment: A4

Stopped data taking in 2010

- **EM calorimeter, fast online histogramming**
- **Accelerator integral part of the experiment. Stabilisation of all beam parameters.**

- **Strangeness contribution to nucleon structure: „strangeness form factors“**
- **Nuclear targets for background subtraction**
- **Two-Photon Amplitude**

MAMI Electron accelerator

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operated at JGU Mainz (Germany)
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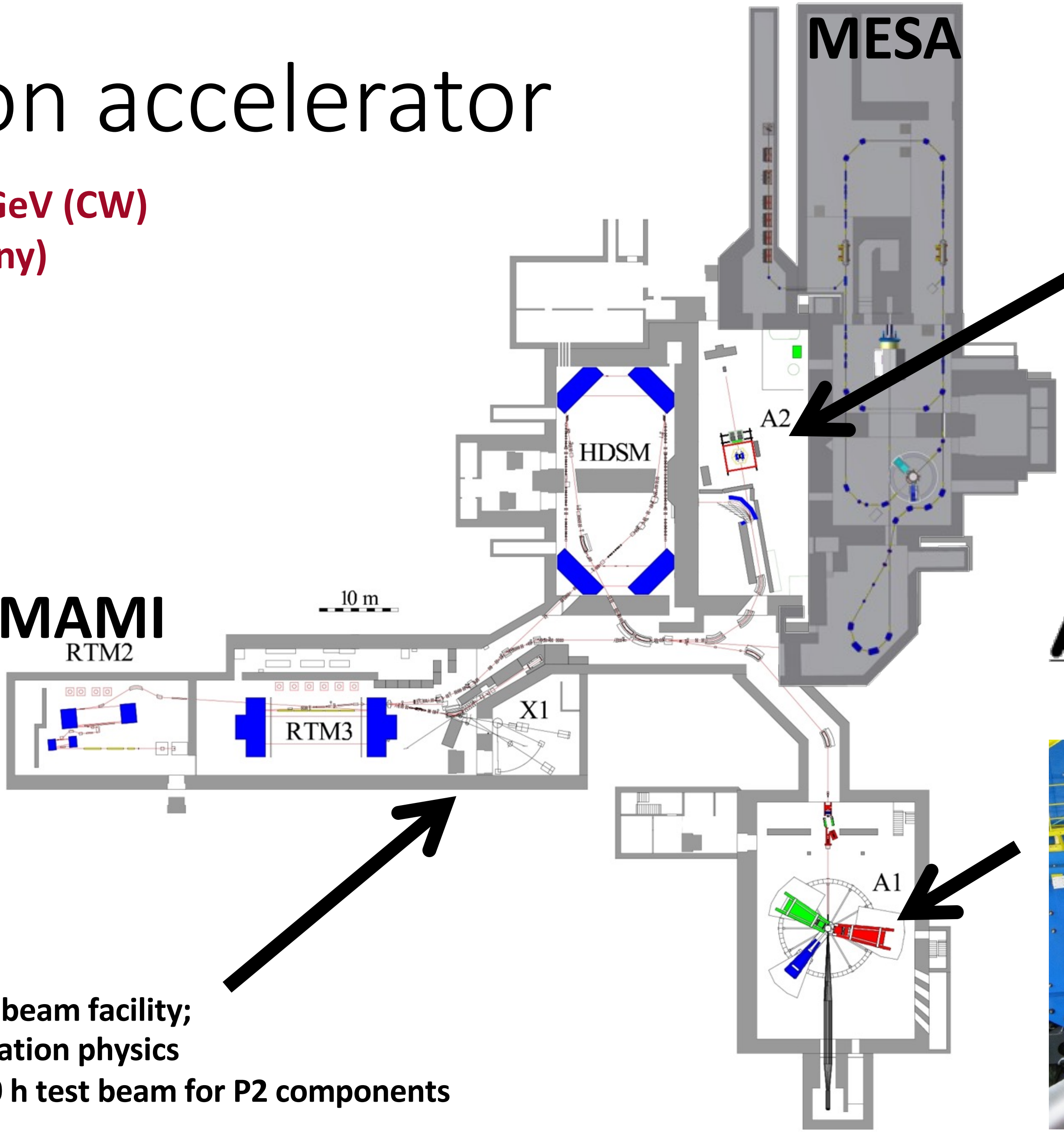
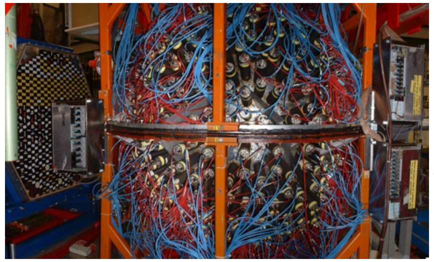
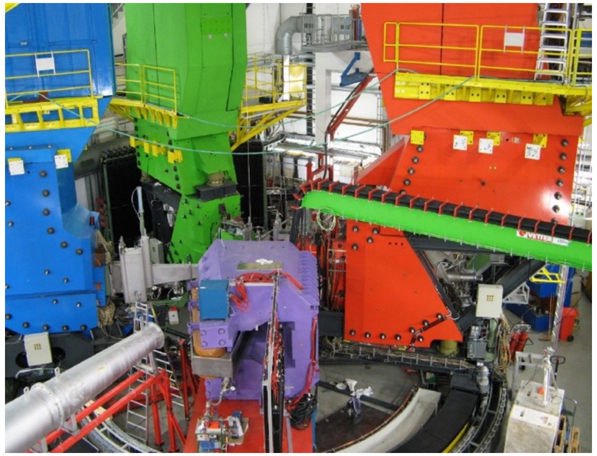




Tagged Photon Scattering (A2 hall)
Crystal Ball / TAPS calorimeters;
Polarized frozen-spin target

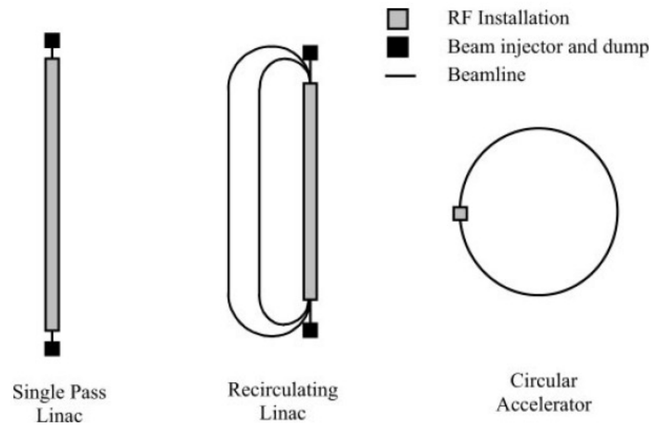
Electron scattering
(A1 hall)
High resolution
Magnetic spectrometers



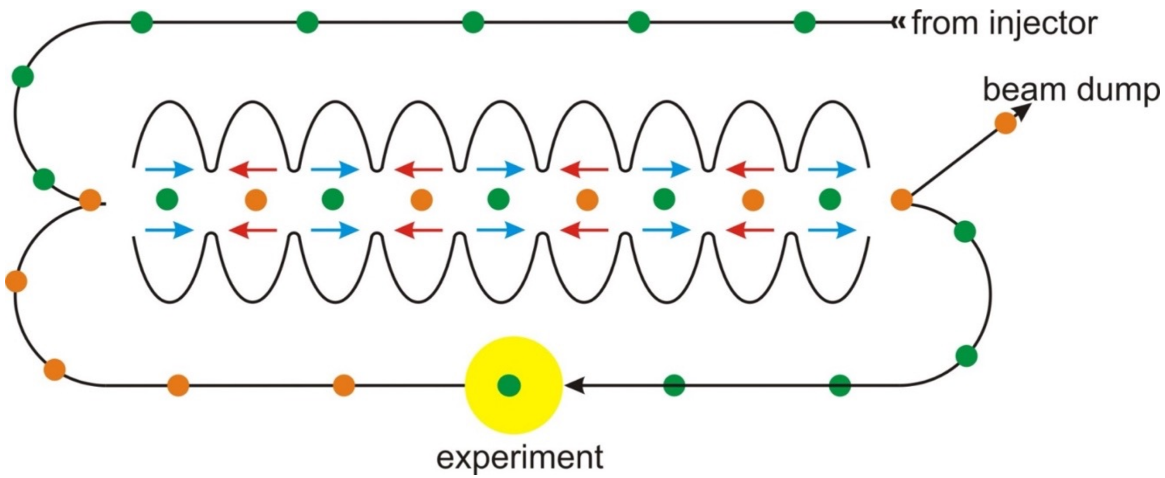
X1

Test beam facility;
Radiation physics
2000 h test beam for P2 components

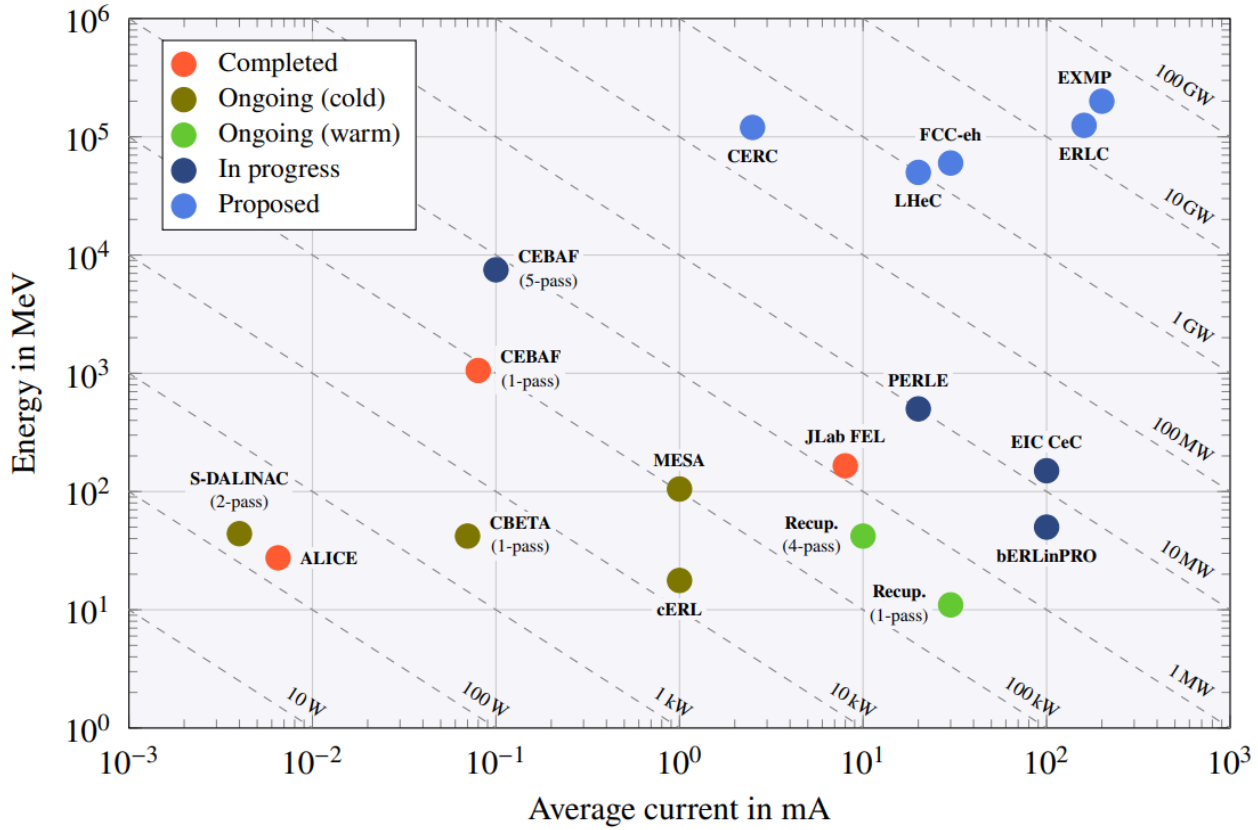
MESA Accelerator



Energy Recovering LINAC



ERLs world-wide (status fall 2022)



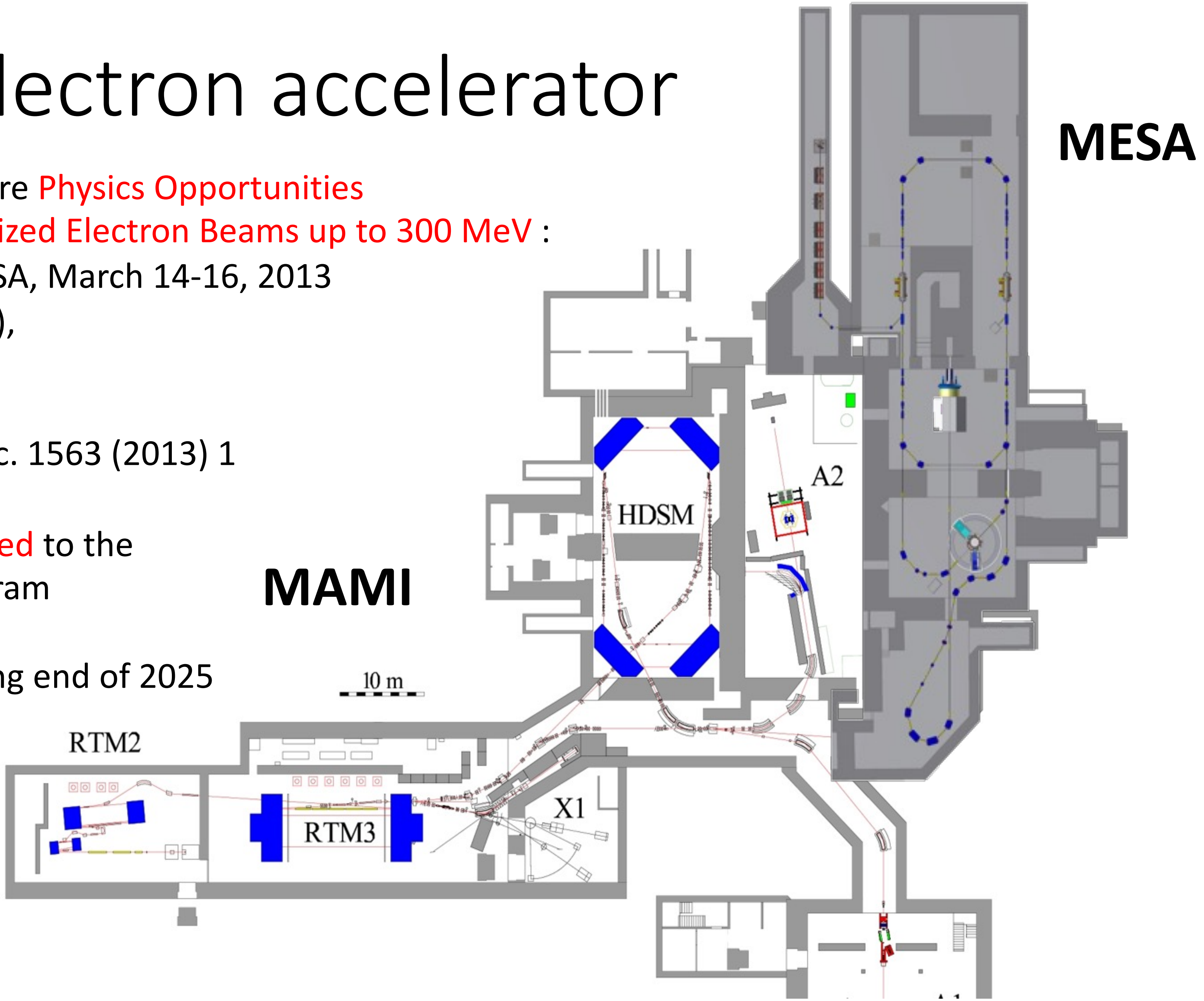
→ MESA is one of few ongoing ERL activities
→ The **first** ERL facility with a target in the beam for physics experiments

MESA Electron accelerator

Workshop to Explore Physics Opportunities
with Intense, Polarized Electron Beams up to 300 MeV :
Cambridge, MA, USA, March 14-16, 2013
Richard Milner(ed.),
Roger Carlini(ed.),
Frank Maas(ed.)
2013, AIP Conf.Proc. 1563 (2013) 1

MESA facility tailored to the experimental program

Start Commissioning end of 2025

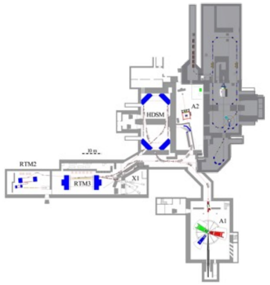


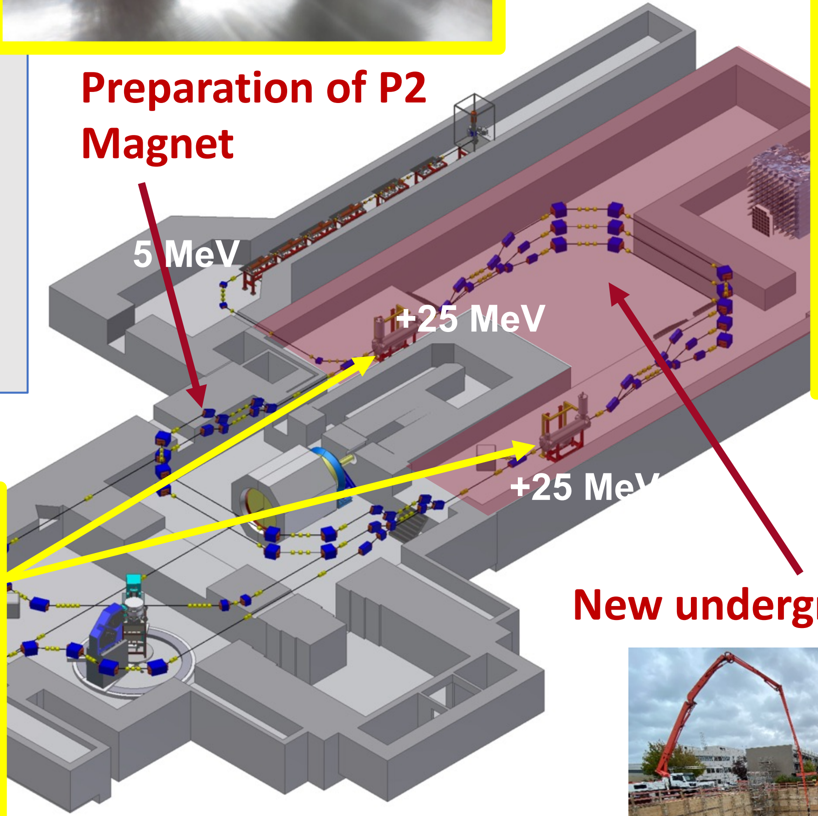
Mesa accelerator

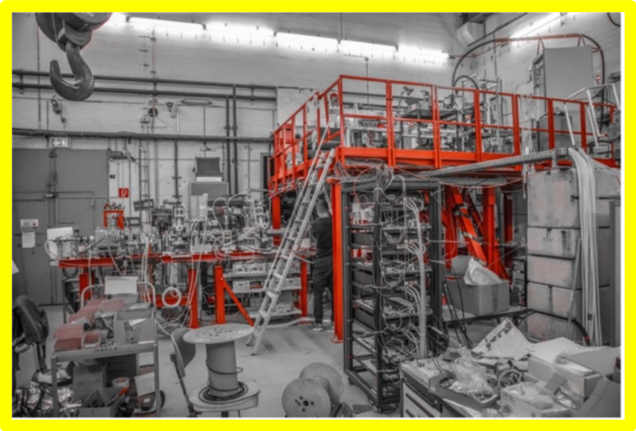
Key parameters MESA:

- Two operation modes: extracted beam (EB) or energy recovering (ERL)
- Max. beam energy 155 MeV (EB), 105 MeV (ERL)
- Beam current 150 μA (EB), 1 mA (ERL)
- Superconducting cavities
- Start commissioning 2024
- New research building (par. 91b GG)
- Can run in parallel to MAMI

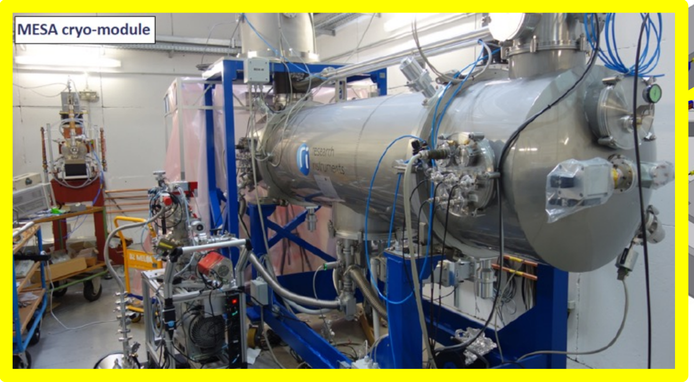
Preparation of P2 Magnet







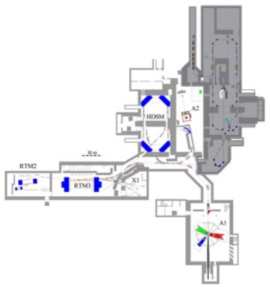
Polarized Source Test Setup



Cryomodules successfully tested

New underground experimental hall (par. 91b GG)

MESA experiments

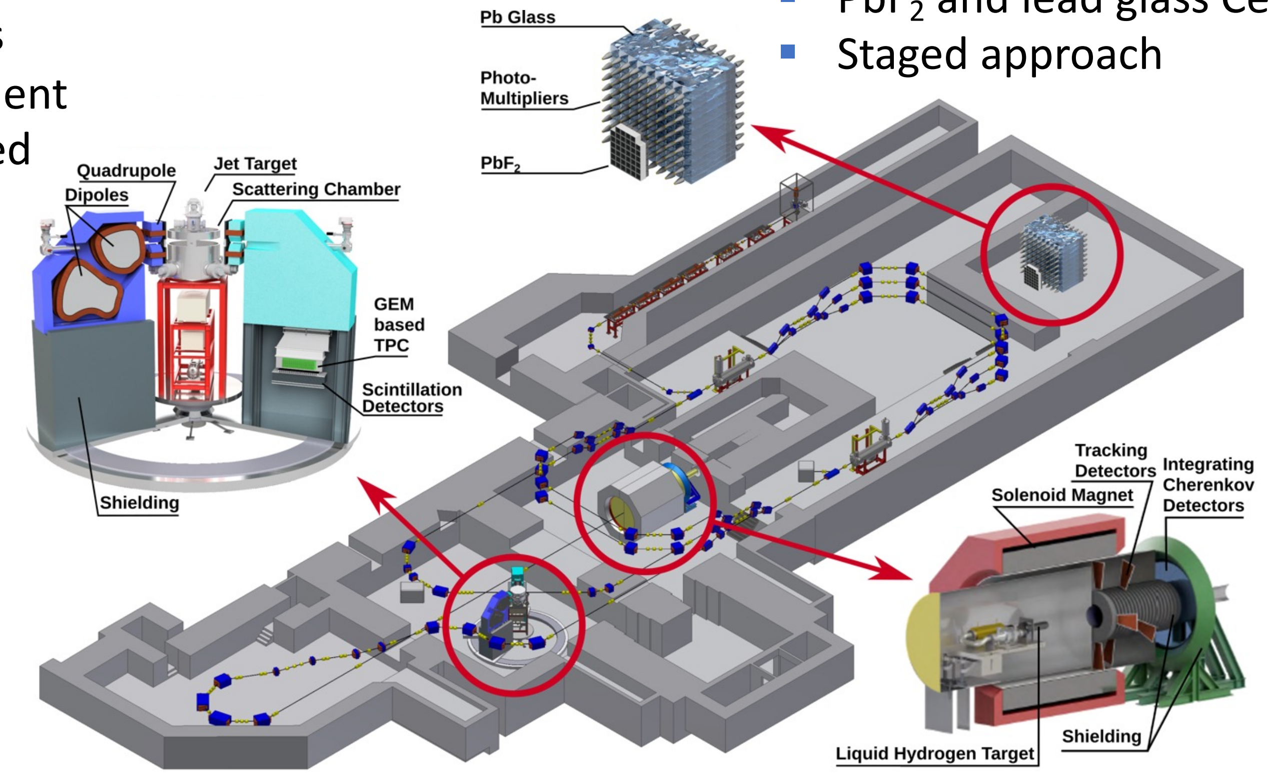


MAGIX experiment

- Operated in ERL mode of MESA
- Double-arm spectrometers
- Internal gas target experiment
- Gas jet target commissioned at A1/MAMI already

DarkMESA

- Beam dump experiment
- Direct detection of light dark matter
- PbF_2 and lead glass Cerenkov calorimeter
- Staged approach

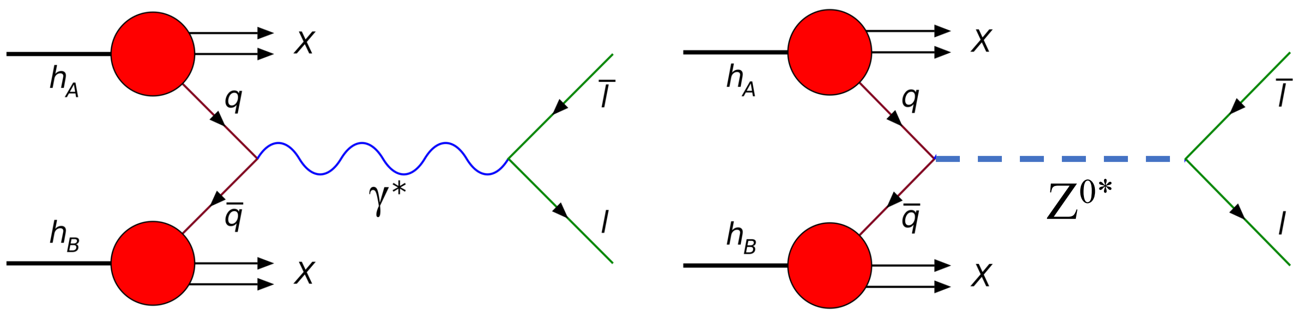


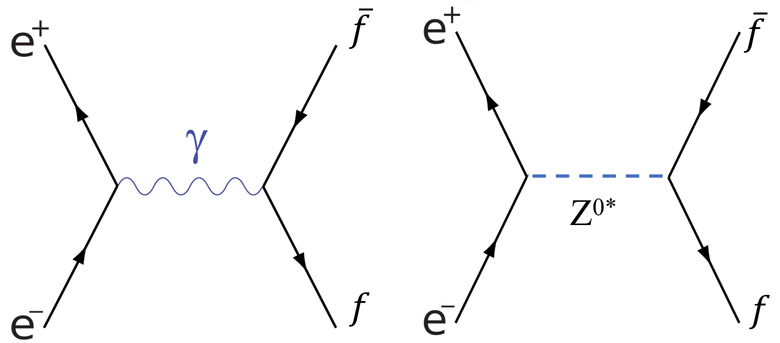
Main components of MAGIX and P2 presently constructed in industry and assembled in house (funding via major research instrumentation program of federal government)

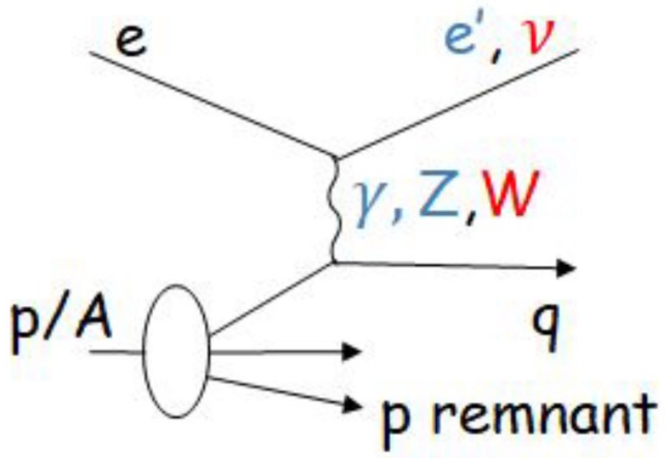
P2

- Extracted beam mode
- Parity violation experiment
- 10^{22} Electrons / a
- $\sin^2\theta_W$, neutron skin, etc.

Access to the weak mixing angle at high energy





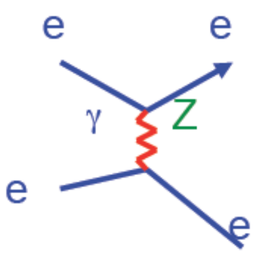


- e^+e^- collider: final state fermions
- $\bar{p}p$,pp collider: Drell-Yan process, PDFs needed
- EIC: deep inelastic scattering, PDFs needed
- Interference between photon exchange and neutral current process
- Cross section dominated by the Z-resonance
- Parity Violating Observables are large at Z-pole
- Imaginary part is large at the Z-pole, sensitivity to new physics suppressed

Access to the weak mixing angle at low energy

MOLLER (Jlab)

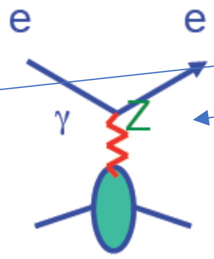
Møller Scattering



- Purely Leptonic

P2 (MESA/Mainz)

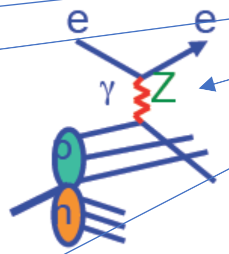
Q-Weak (JLab)



- Coherent quarks in p

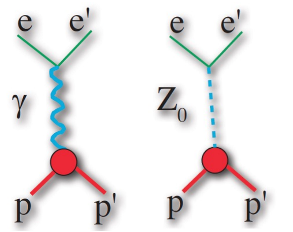
SOLID (Jlab)

e-DIS



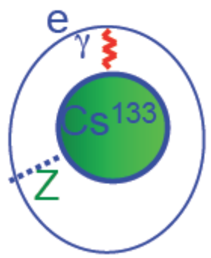
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Interference between electromagnetic and weak neutral current amplitude: Parity violating asymmetries



Yb,Dy,Sm (HIM/Mainz)

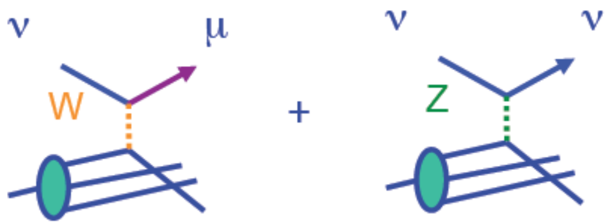
Atomic Parity Violation



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

Neutrino Scattering

Coherent Neutrino Scattering

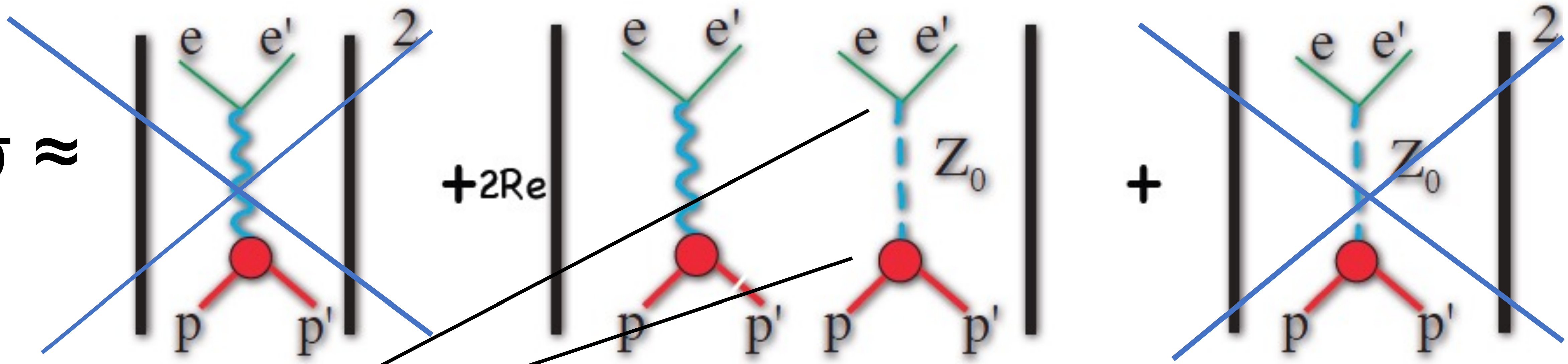


- Quark scattering (from nucleus)
- Weak charged and neutral current difference

Cross section measurements

Parity Violating in elastic electron proton scattering

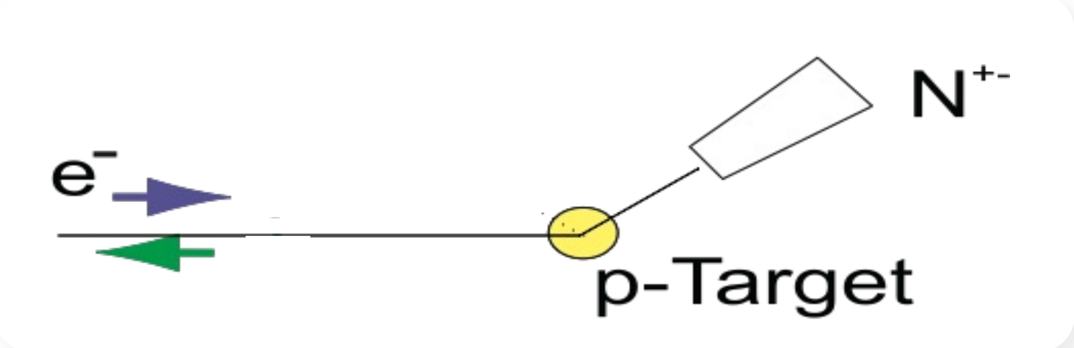
$\sigma \approx$

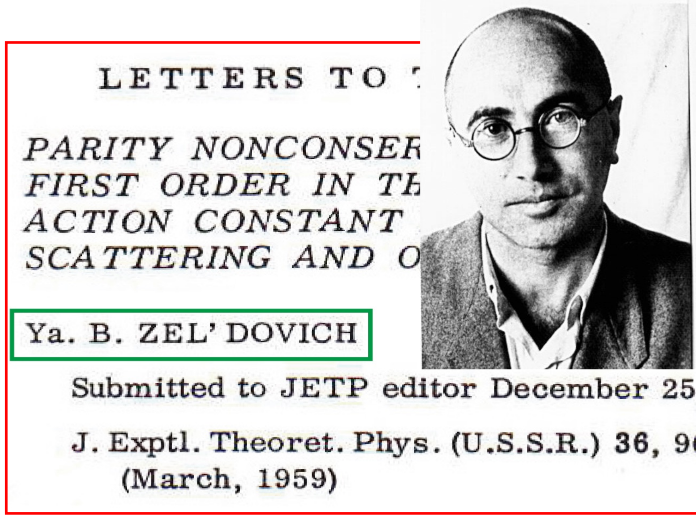


V-A coupling:
parity-violating
cross section asymmetry A_{LR}
longitudinally pol. electrons
unpolarised protons

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

$A_eV_p + V_eA_p$





LETTERS TO

PARITY NONCONSER
FIRST ORDER IN TH
ACTION CONSTANT
SCATTERING AND O

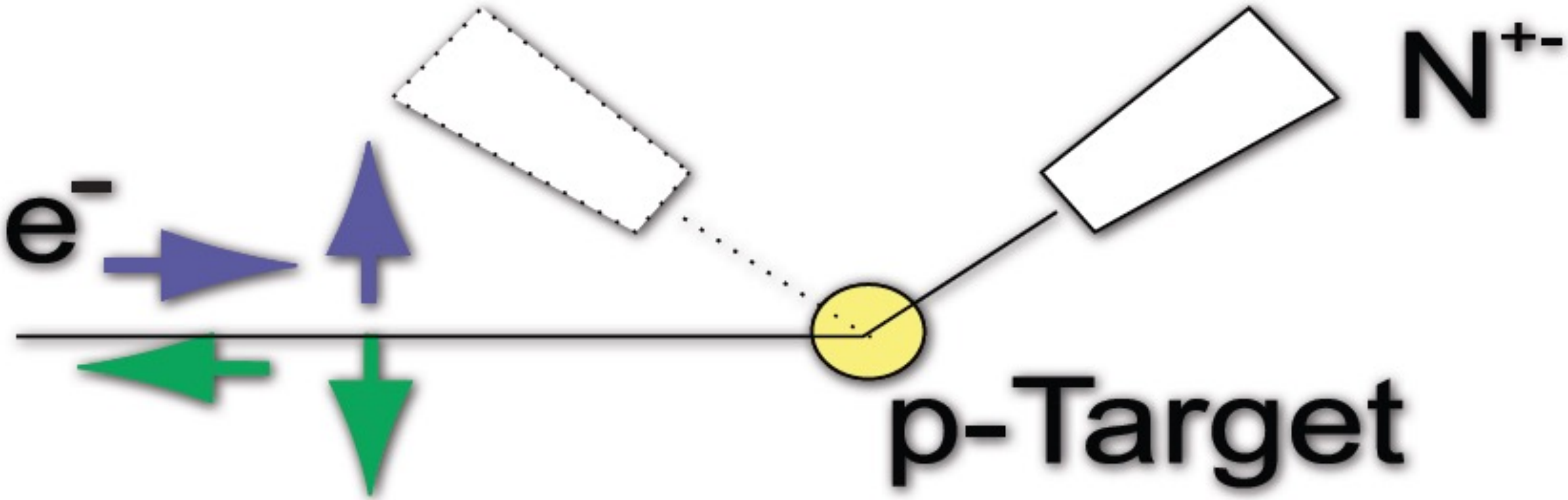
Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 9
(March, 1959)

Parity Violating Electron Scattering (PVES)

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

Physics topics:

Electron spin longitudinal (PVES)

- Weak vector charge of the proton
- Weak axial form factor of the proton
- Weak vector charge of the neutron (Carbon)
- Neutron Skin of Ca and Lead (MREX)

Electron Spin transverse

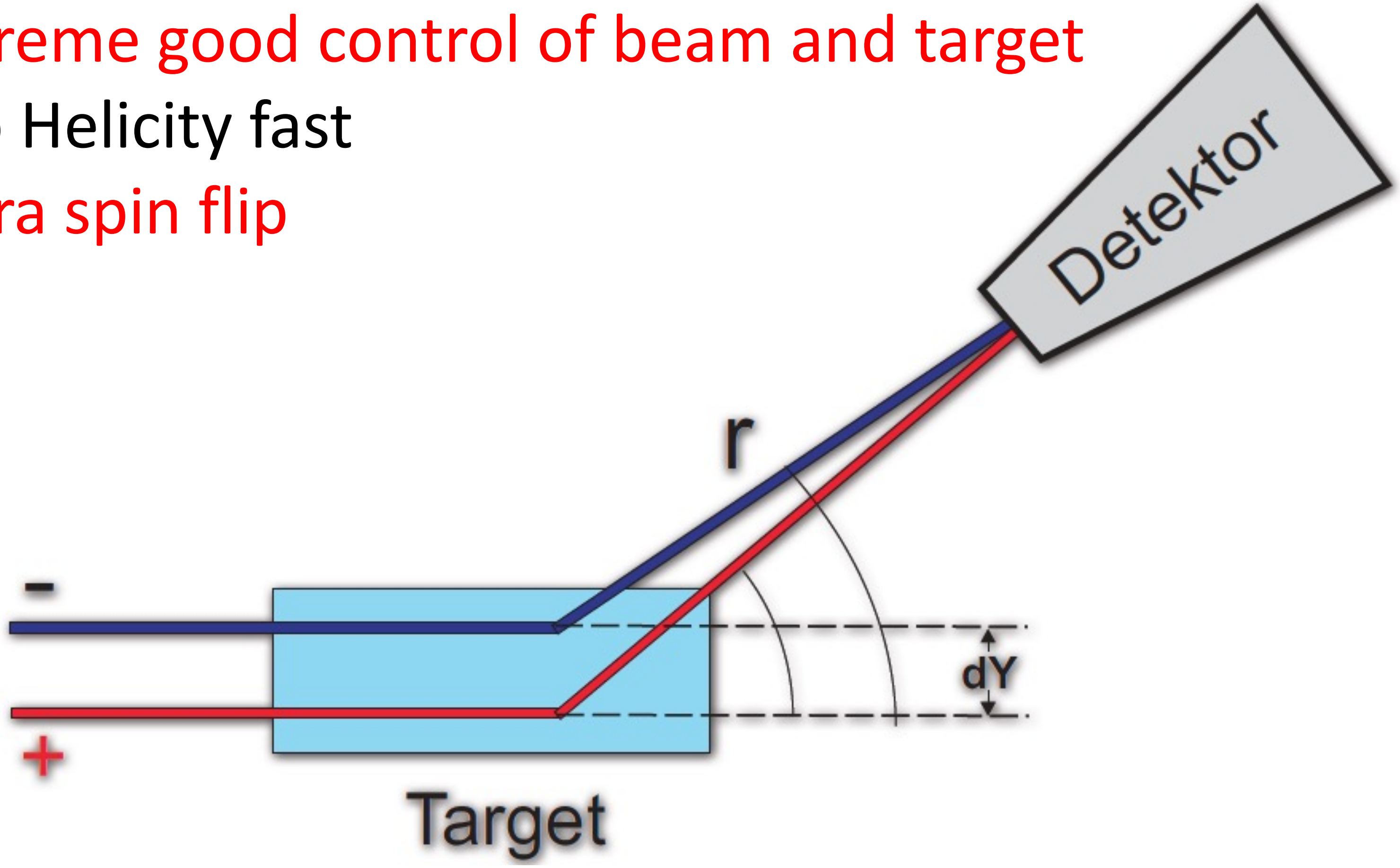
- Two photon exchange amplitude in elastic electron proton scattering
- Two photon exchange amplitude in electron nucleus scattering

False (related to apparatus) asymmetries:

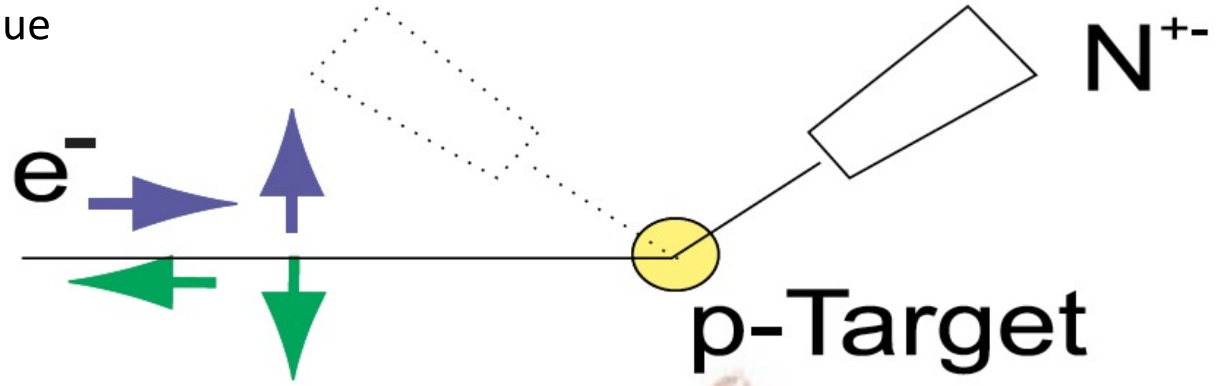
Extreme good control of beam and target

Flip Helicity fast

Extra spin flip

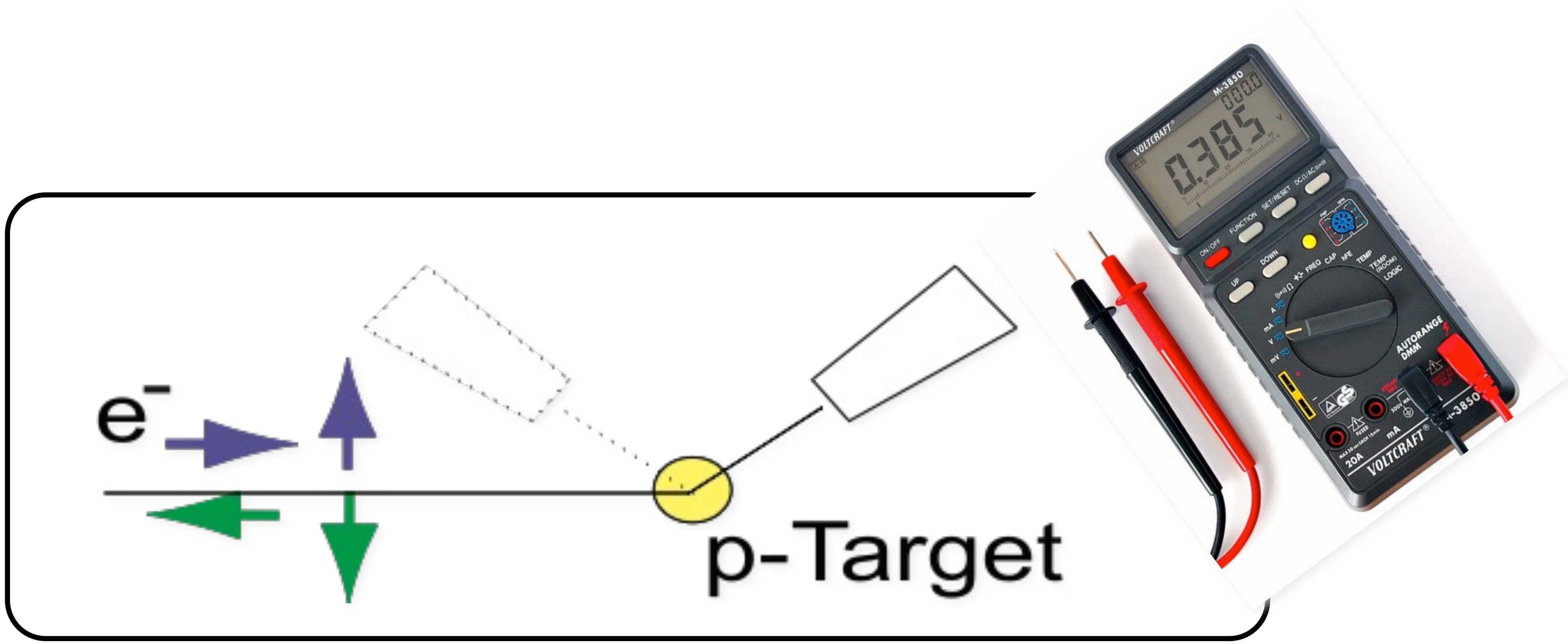


Counting Technique



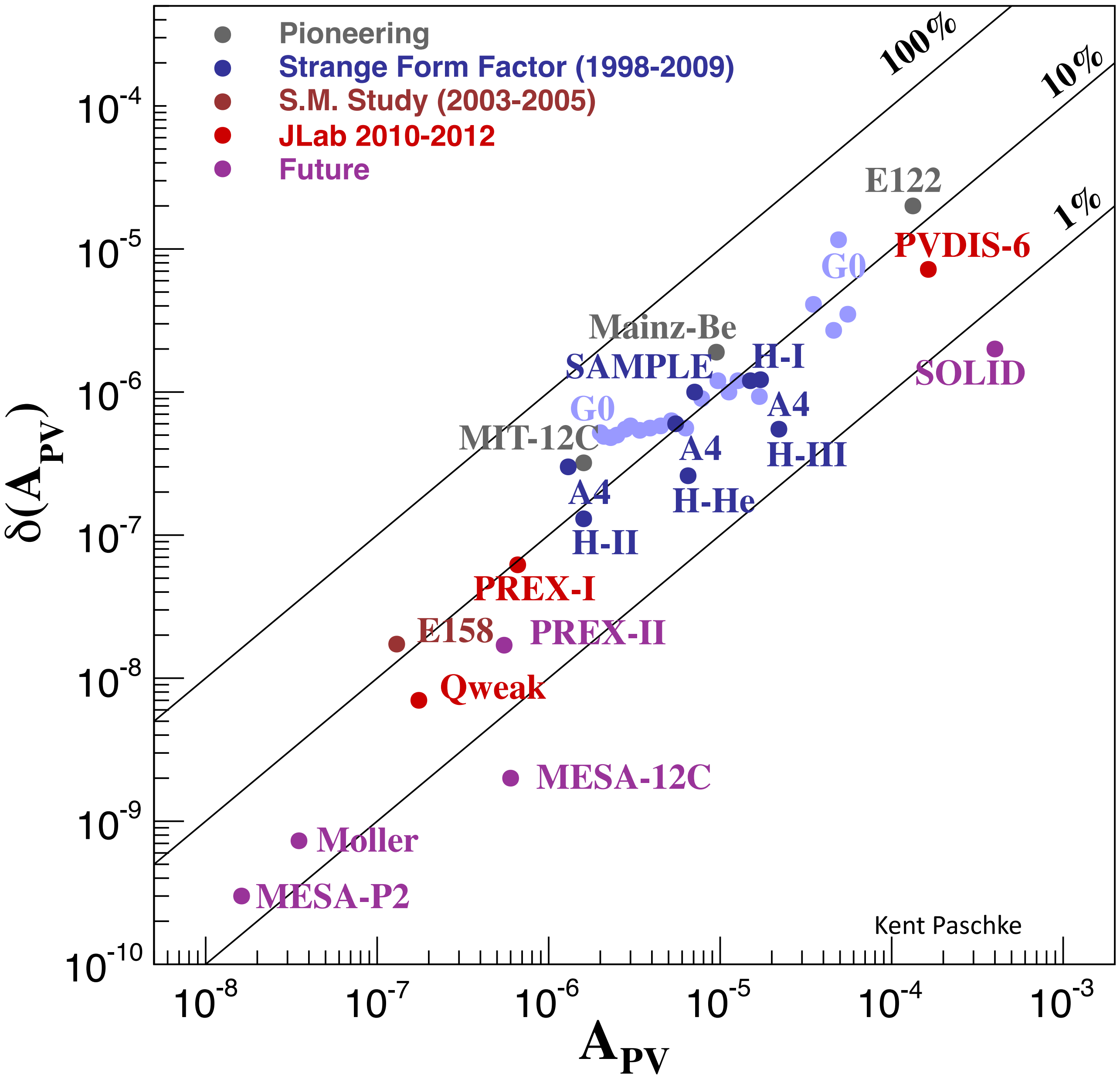
Count scattered electrons:
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy

Analogue Technique

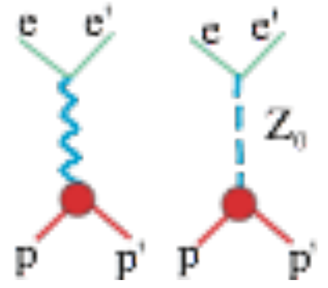


Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

PVeS Experiment Summary



Parity violating cross section asymmetry

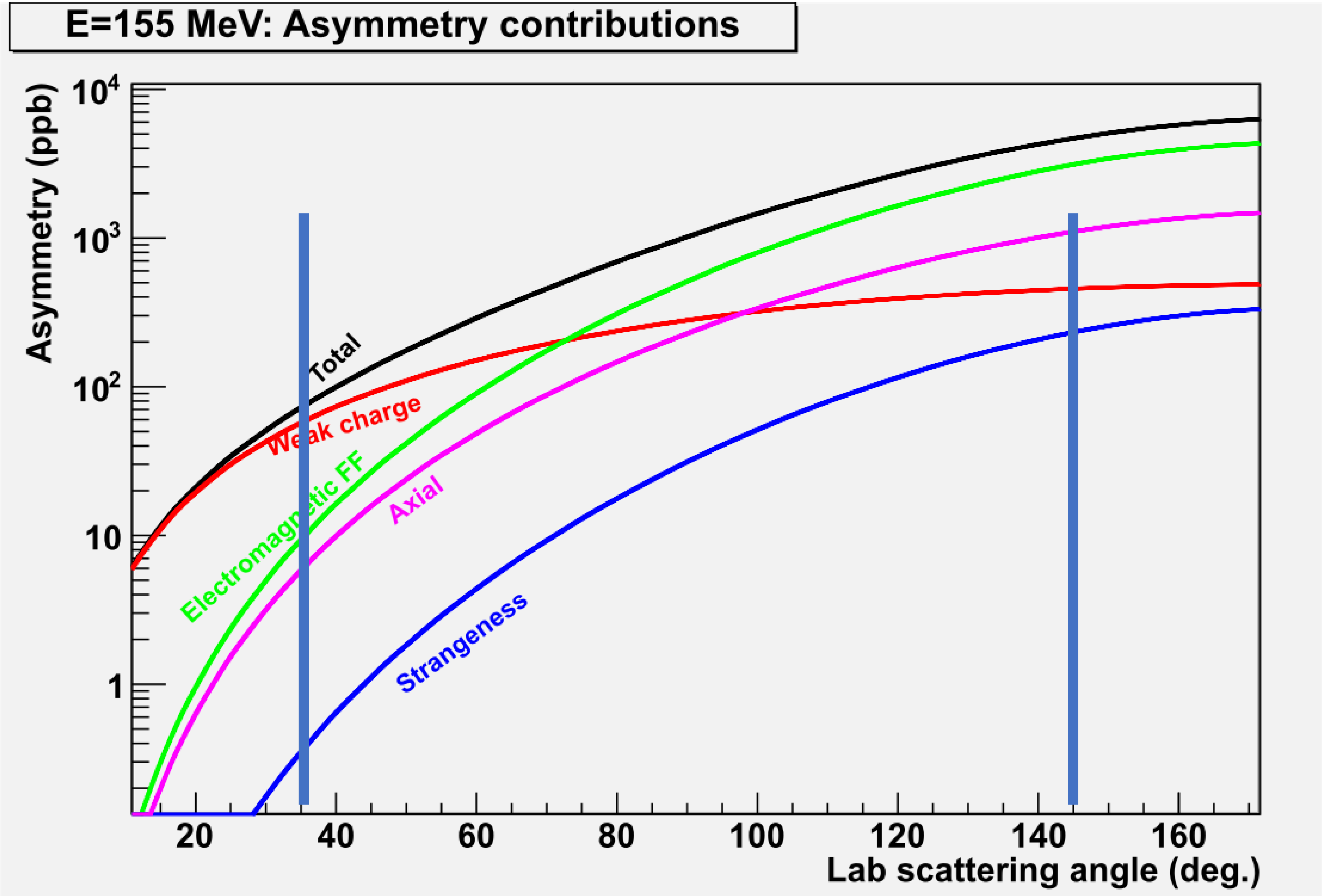


$$A_{ep} = \left[\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\right] \frac{\epsilon G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z - (1-4\sin^2\theta_W)\epsilon' G_M^\gamma G_A^Z}{\varepsilon (G_E^\gamma)^2 + \tau (G_M^\gamma)^2}$$

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

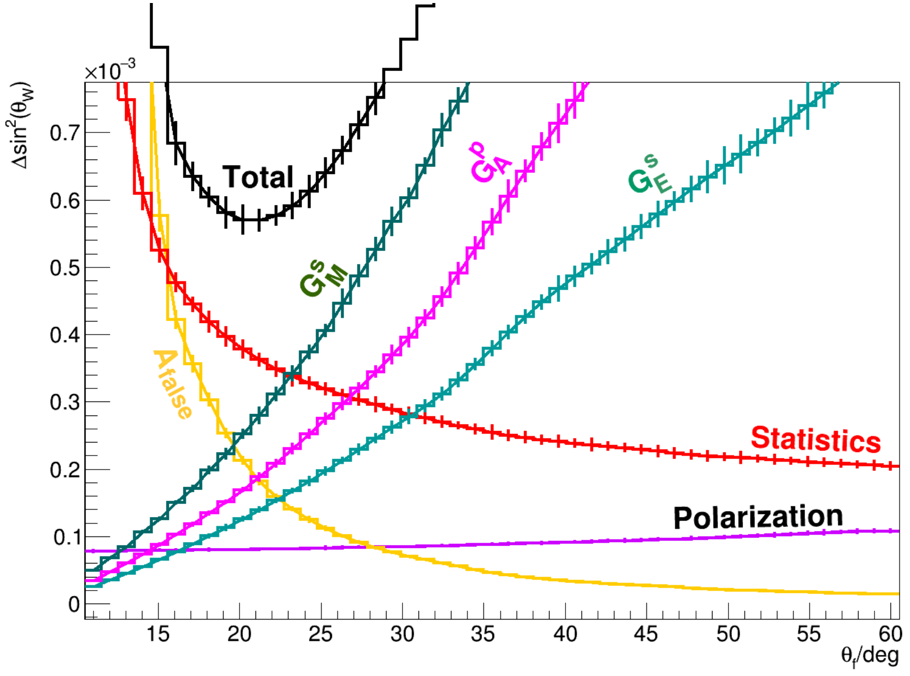
$$a = -G_F q^2/4\pi\alpha\sqrt{2}, \quad \tau = -q^2/4M_{\mathrm{p}}^2, \quad \epsilon = [1 + 2(1+\tau)\tan^2\theta/2]^{-1}$$

P2 parity violation experiment in Mainz: forward and backward angle measurements



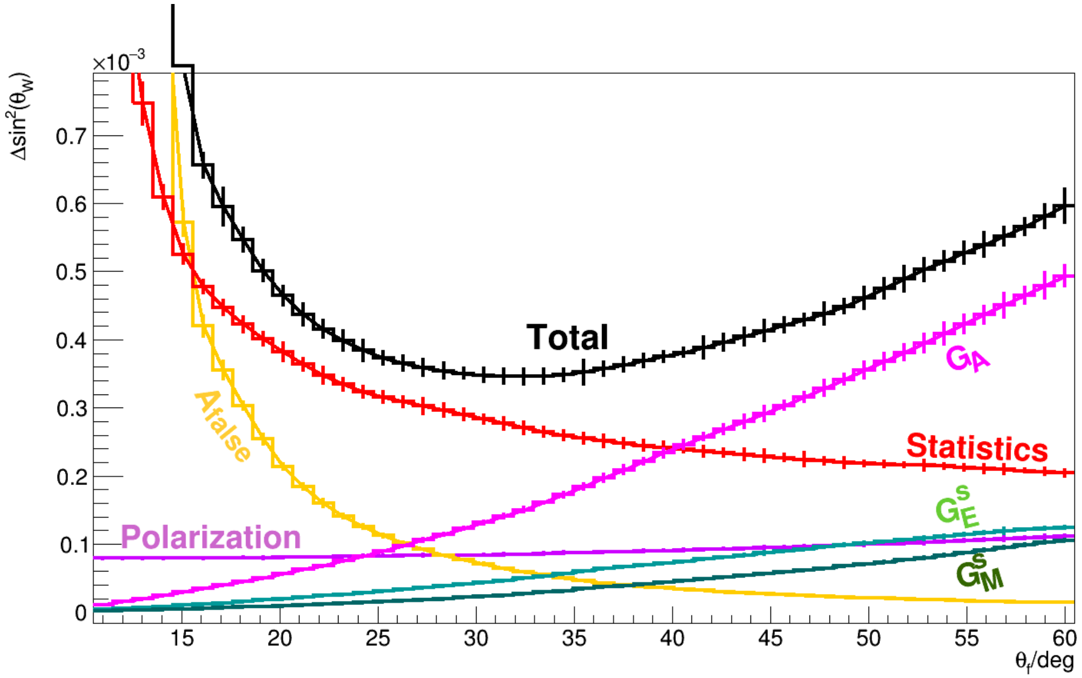
Auxiliary measurements at backward angles

Strange FF and axial FF from present data



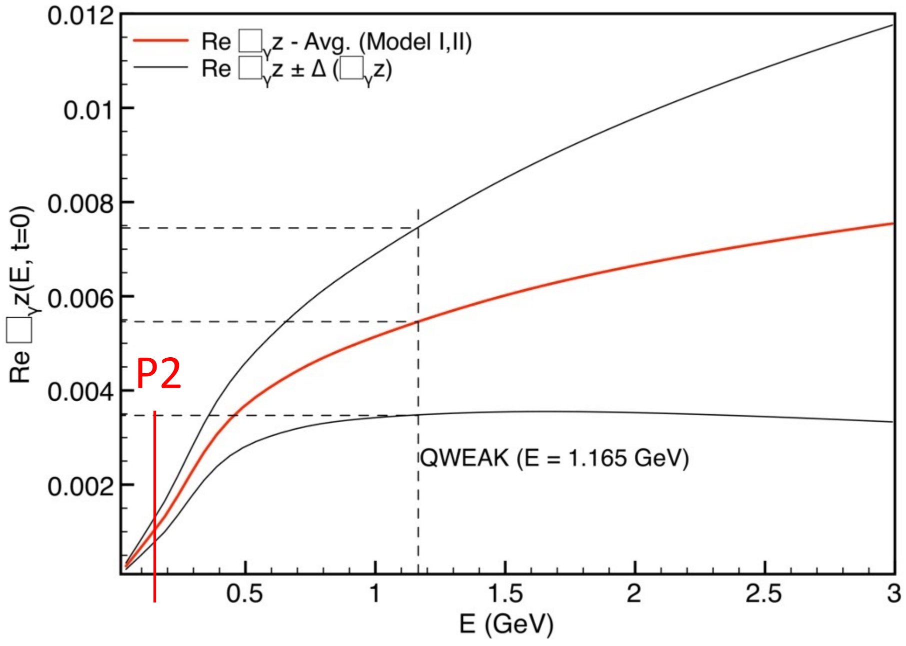
Present status (accuracy) of electric and magnetic strangeness form factor and axial form factor

Strange FF from lattice, axial FF with uncertainty/3



Accuracy of electric and magnetic strangeness form factor from recent lattice QCD calculations and axial form factor from backward angle measurement

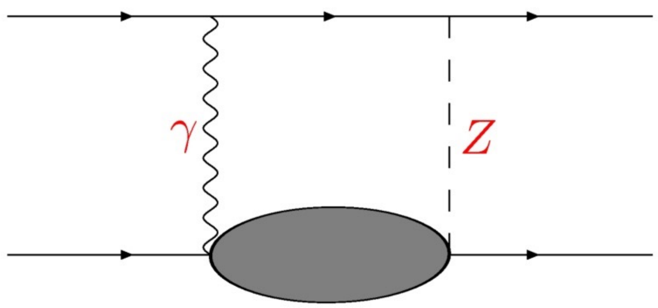
➢ γZ box graph contributions obtained by modelling hadronic effects:



[Gorchstein, Horowitz & Ramsey-Musolf 2011]

➢ Hadronic uncertainties suppressed at lower energies

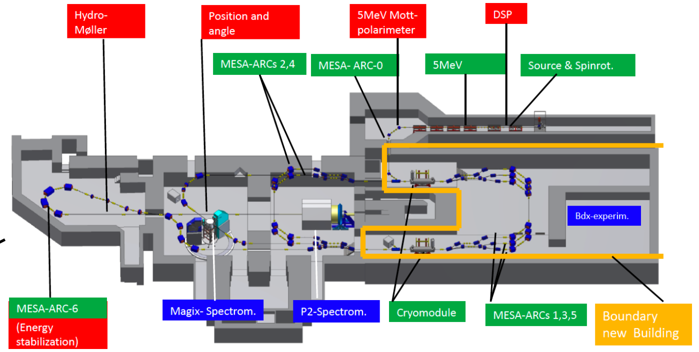
➢ Low beam energy experiment:
P2 @ MESA



Progress in Theory

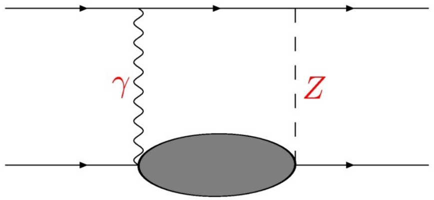
- Theory uncertainties in box diagrams
- 2 loop corrections
- Hadronic contributions in loops
- Auxiliary measurements
- PV-asymmetry in Carbon

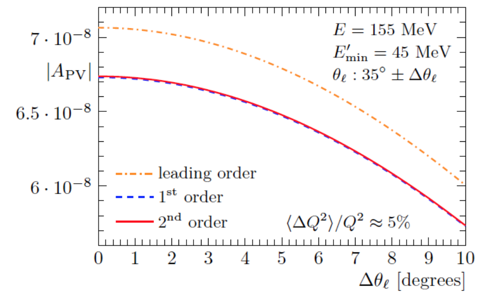
P2: Parity violating electron proton scattering at MESA/Mainz



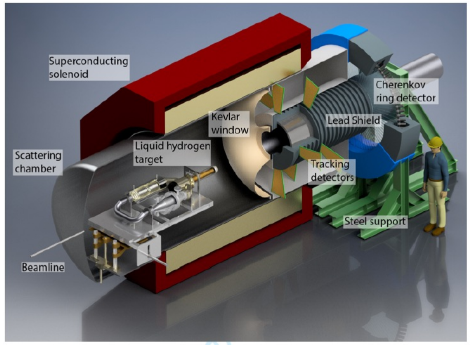
$$A_{LR}^{exp} = \frac{\sigma(\vec{e}p)-\sigma(\overleftarrow{e}p)}{\sigma(\vec{e}p)+\sigma(\overleftarrow{e}p)} = -P\,\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W(p) - F(Q^2)\right) + A_F$$

False asymmetries: control of target and accelerator



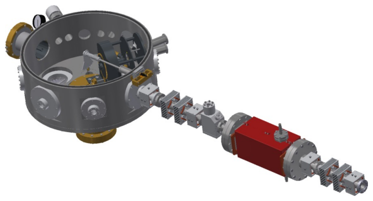


Cross section asymmetry A_{LR}^{exp}

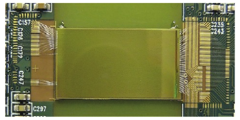


Magnetic spectrometer
Cherenkov detector
Read-out electronics
Data acquisition

Beam polarisation
P
Polarimetry

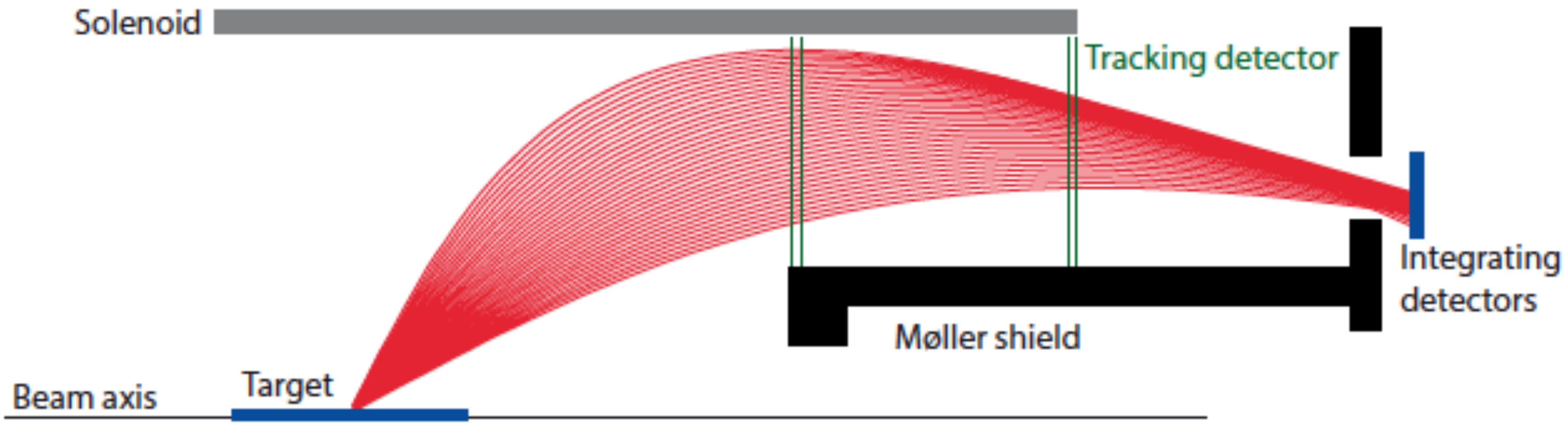


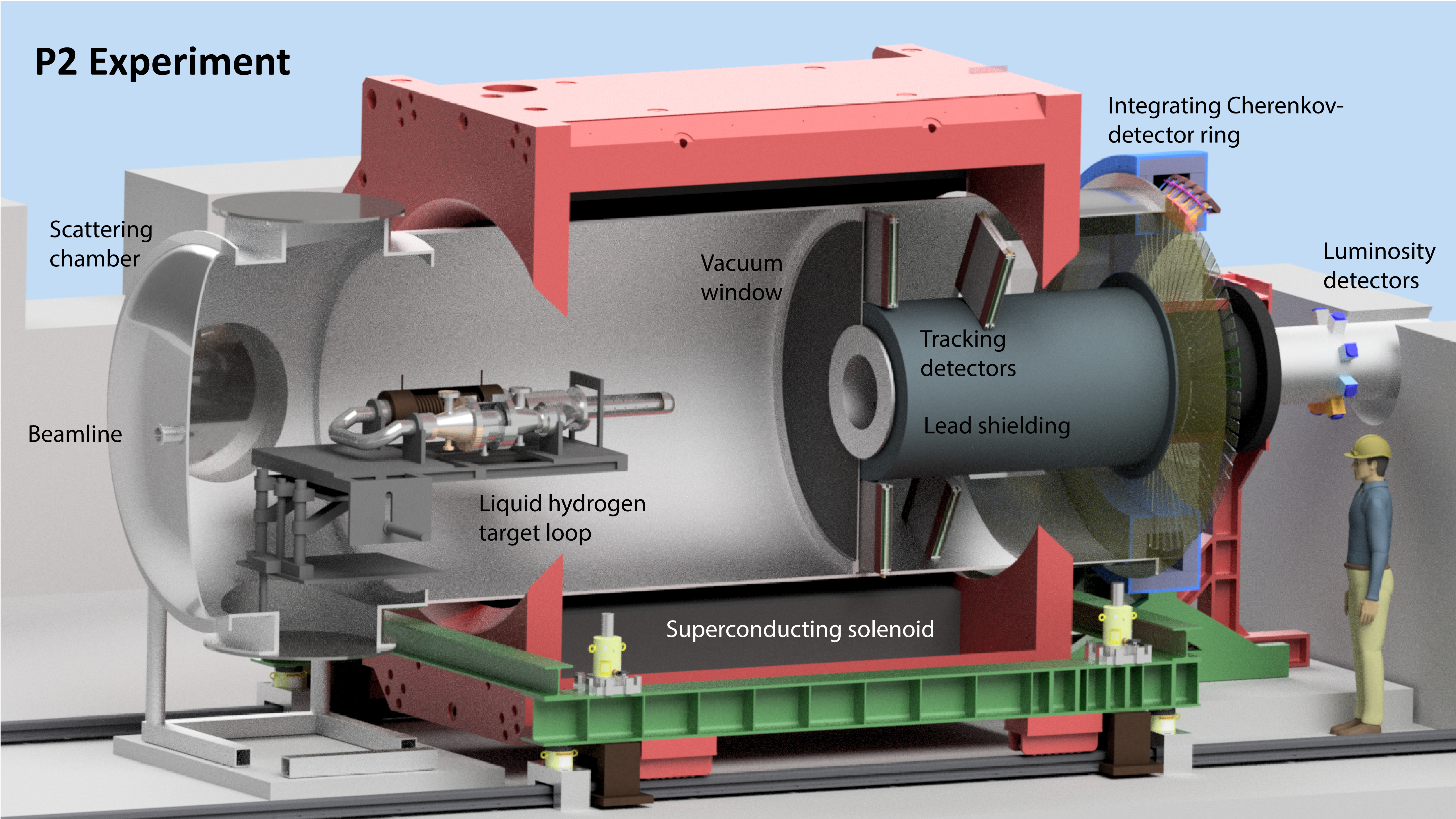
Momentum transfer $< Q^2 >$
Tracking system



Low Beam Energy, Low Q2
Theory:
QED corrections
EW corrections (two loop)
Hadron structure $F(Q^2)$,
Strangeness form factors
Measure:
Axial form factor

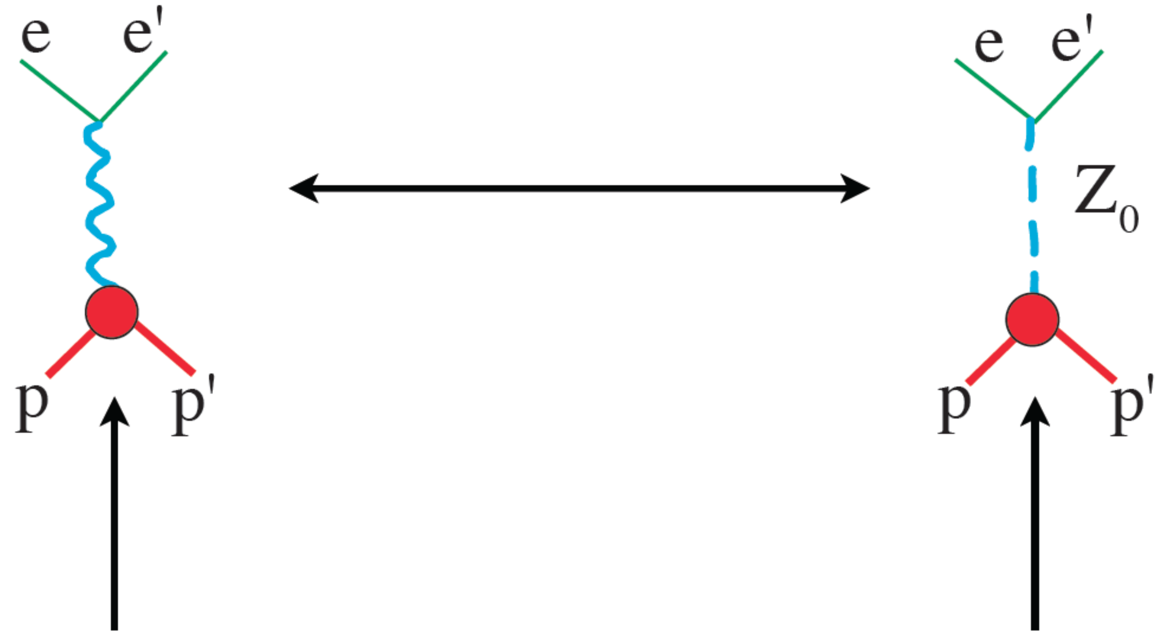
P2-experimental principle and Q^2-Measurement




P2 Experiment
Scattering chamber
Beamline
Liquid hydrogen target loop
Vacuum window
Tracking detectors
Lead shielding
Integrating Cherenkov-detector ring
Luminosity detectors
Superconducting solenoid

The role of the weak mixing angle

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

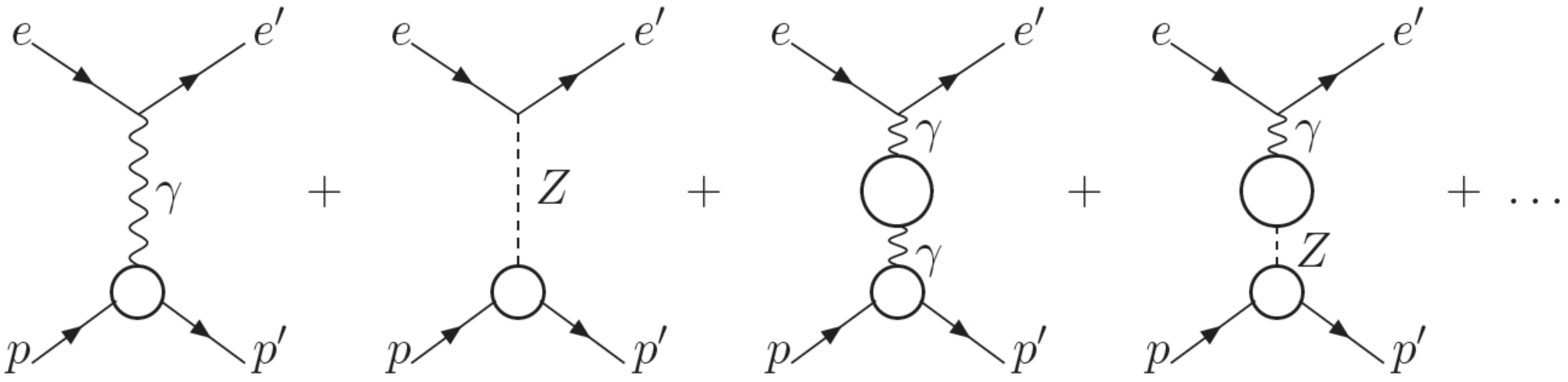


$Q_e(p) = +e$
electric charge of the proton

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

$\sin^2 \theta_W$: a central parameter of the standard model accessible through the weak charge

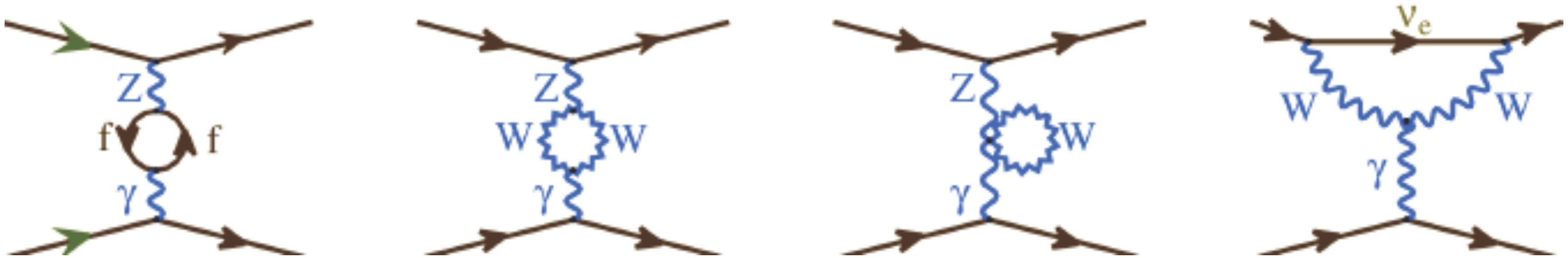
Precision measurements and quantum corrections:



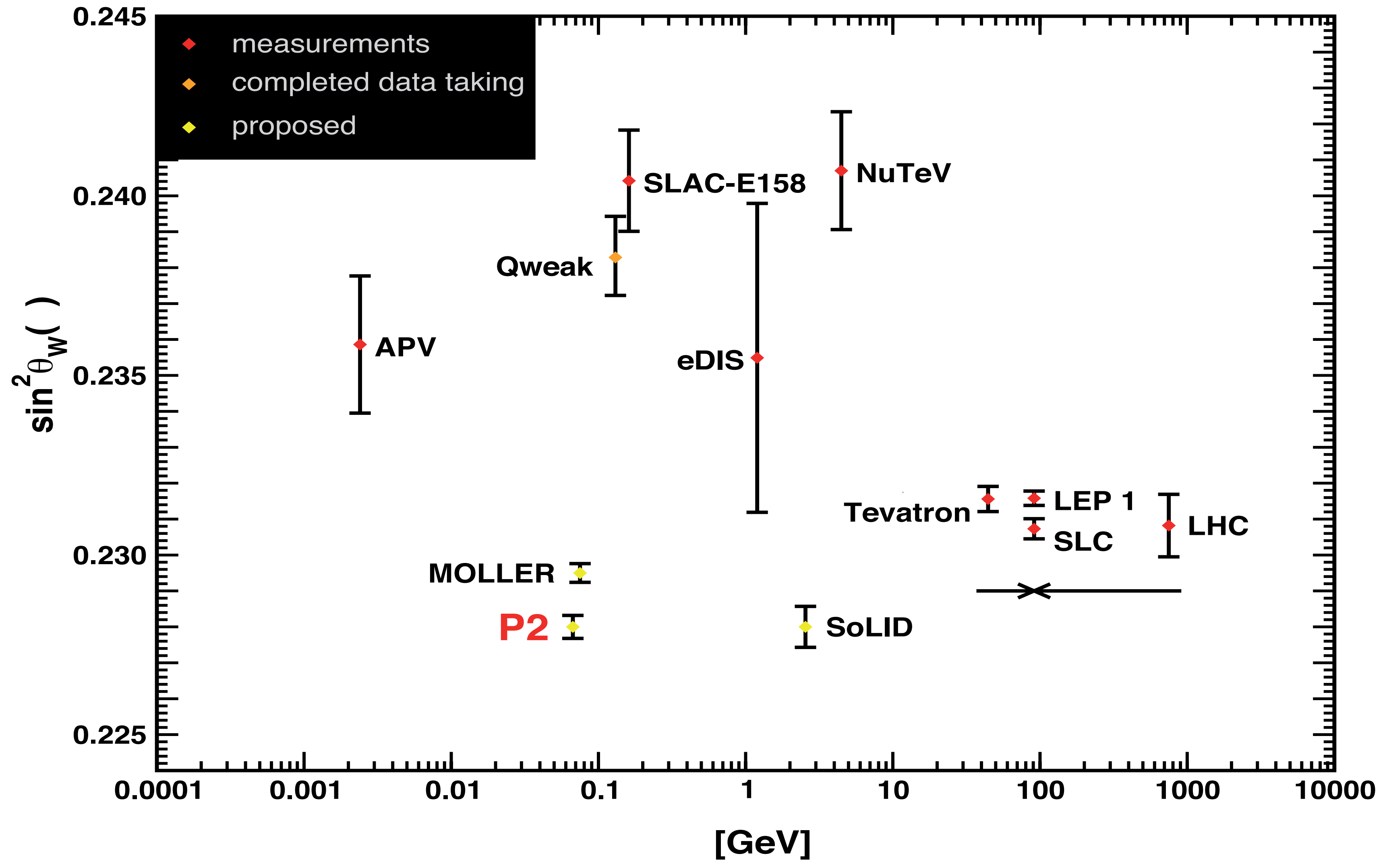
running α

running $\sin^2\theta_W(\mu)$
(P2)

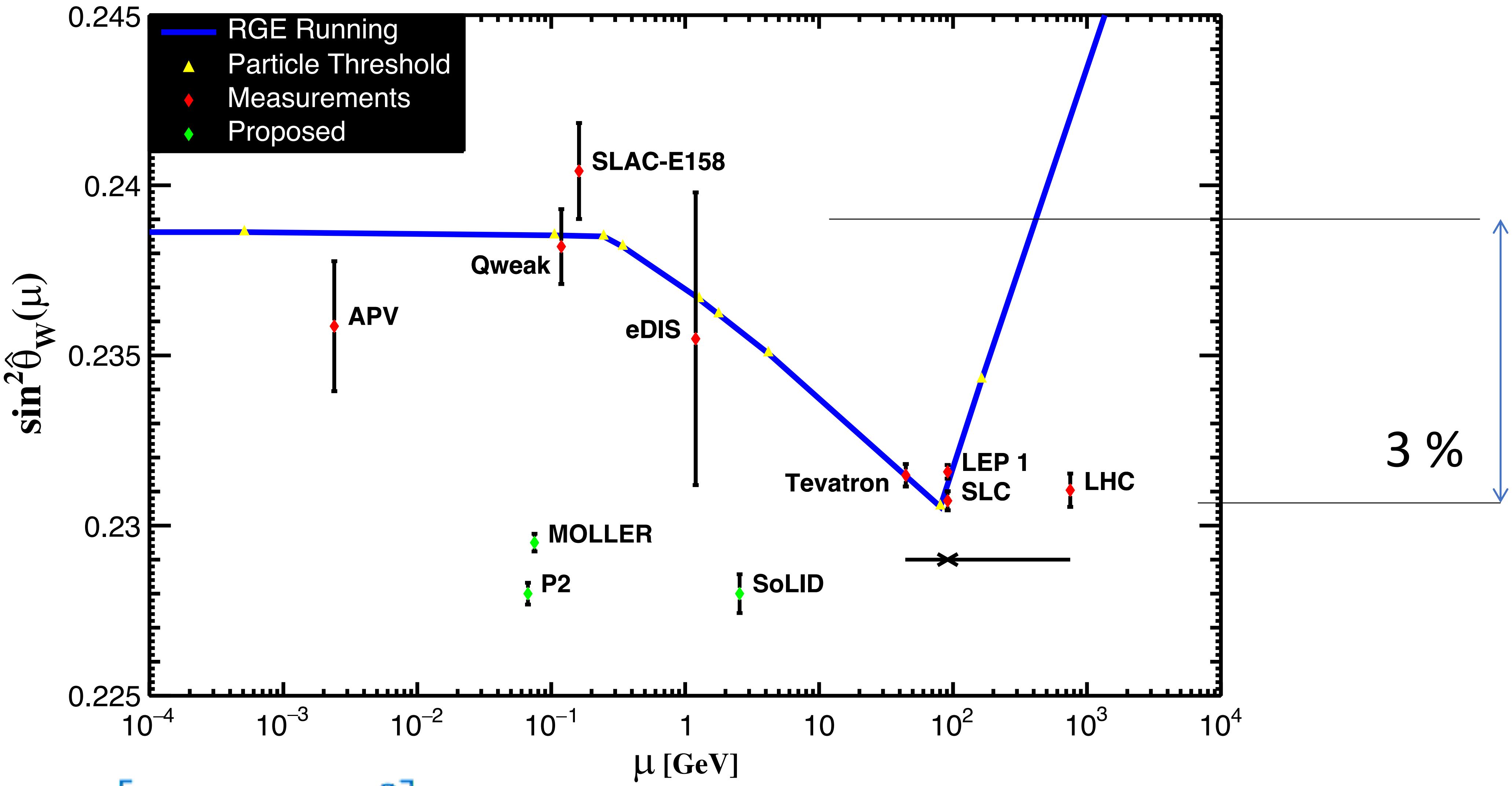
Universal quantum corrections: can be absorbed into a **scale dependent, „running“ $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$**



Measurements of the weak mixing angle



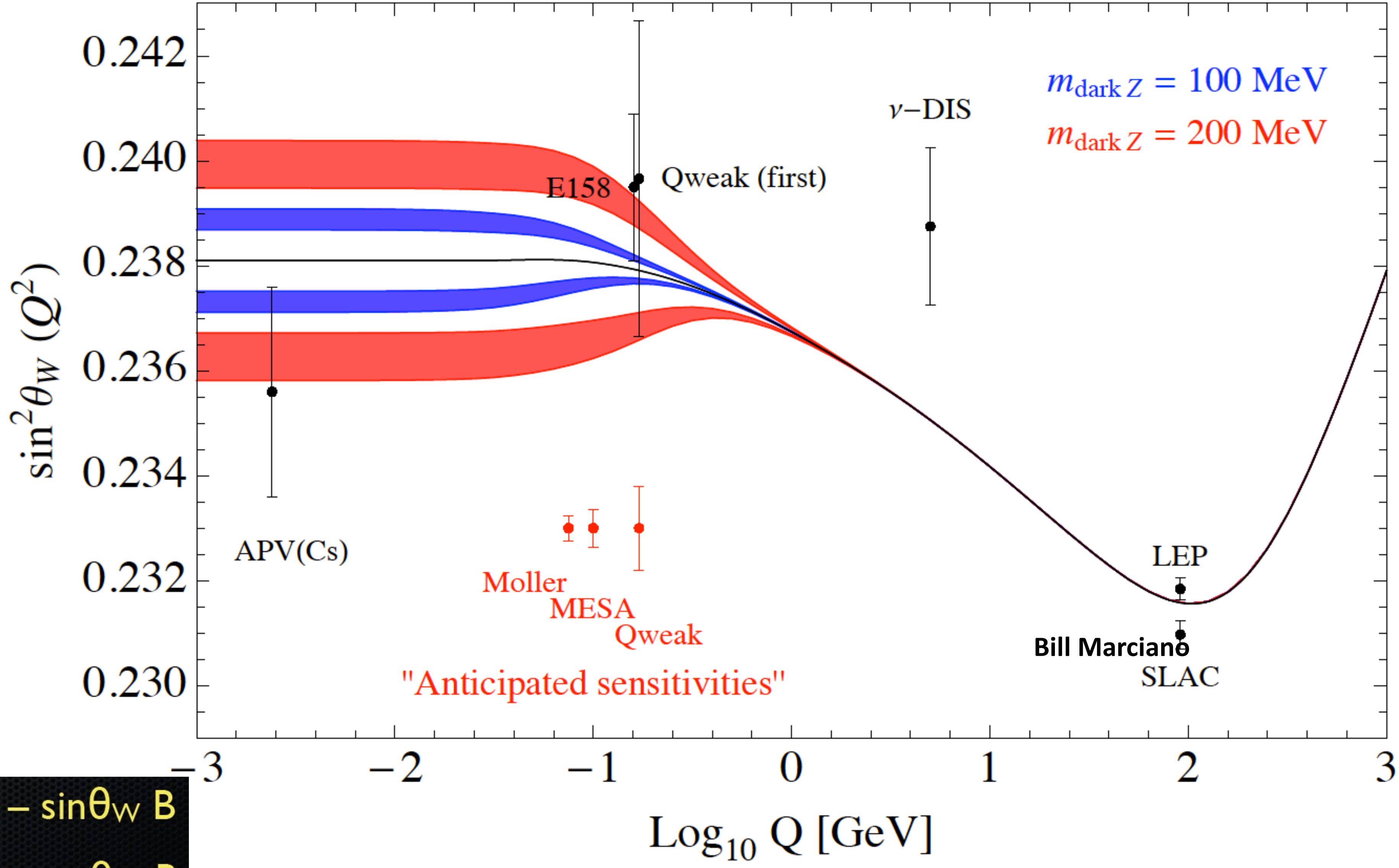
Running of the weak mixing angle



$$\left|A_Z + A_{new}\right|^2 \rightarrow A_Z^2\left[1 + \left(\frac{A_{new}}{A_Z}\right)^2\right]$$

On the Z-resonance A_Z imaginary and very large, largely reduced sensitivity to new physics

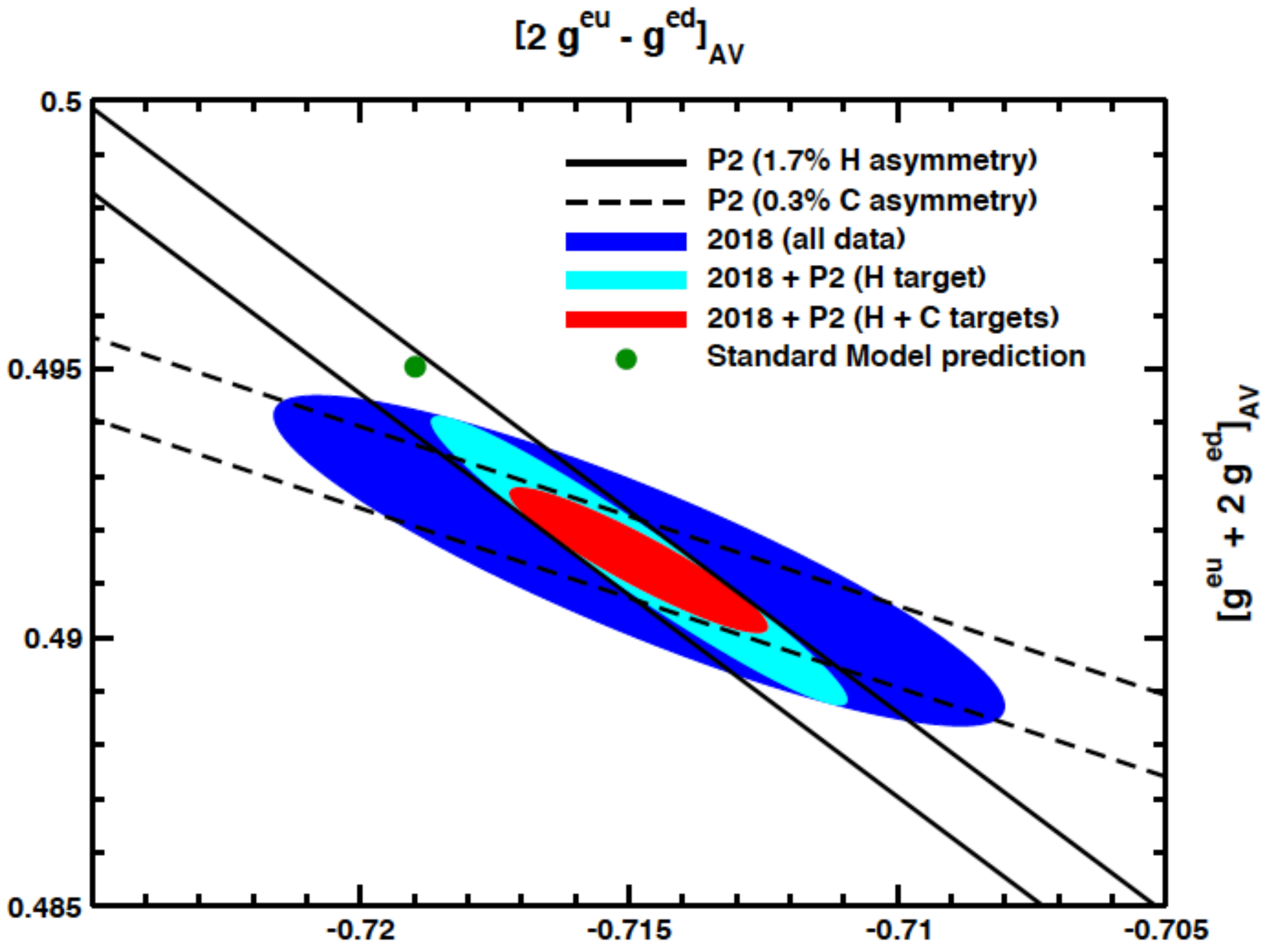
Running $\sin^2\theta_W$ and Dark Parity Violating Z



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

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

Constraints from PVES at MESA



- Quark-vector-electron-axial vector couplings
- Sensitivity down to masses of 70 MeV and up to masses of 50 TeV

Future wEFT constraints from APV and PVES

Adam Falkowski at Mainz MITP workshop: Impact on low energy measurements

Current QWEAK, PVDIS, and APV cesium experiments:

$$\begin{pmatrix} \delta g^{eu}_{AV} \\ \delta g^{ed}_{AV} \\ 2\delta g^{eu}_{VA} - \delta g^{ed}_{VA} \end{pmatrix} = \begin{pmatrix} 0.74 \pm 2.2 \\ -2.1 \pm 2.5 \\ -39 \pm 54 \end{pmatrix} \times 10^{-3}$$

Projections from combined P2, SoLID, and APV radium experiments:

$$\begin{pmatrix} \delta g^{eu}_{AV} \\ \delta g^{ed}_{AV} \\ 2\delta g^{eu}_{VA} - \delta g^{ed}_{VA} \end{pmatrix} = \begin{pmatrix} 0 \pm 0.70 \\ 0 \pm 0.97 \\ 0 \pm 7.4 \end{pmatrix} \times 10^{-3}$$

$$\mathcal{L}_{\rm wEFT} \supset -\frac{1}{2v^2}\sum_{q=u,d} g^{eq}_{AV}(\bar{e}\,\bar{\sigma}_\rho e - e^c\sigma_\rho\bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q + q^c\sigma^\rho\bar{q}^c)$$

$$-\frac{1}{2v^2}\sum_{q=u,d} g^{eq}_{VA}(\bar{e}\,\bar{\sigma}_\rho e + e^c\sigma_\rho\bar{e}^c)(\bar{q}\,\bar{\sigma}^\rho q - q^c\sigma^\rho\bar{q}^c)$$

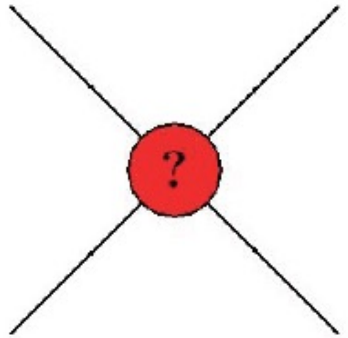
AA, Grilli Di Cortona, Tabrizi 1802.08296

AA, Gonzalez-Alonso in progress

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

Effective field theory approach (EFT)



Jens Erler

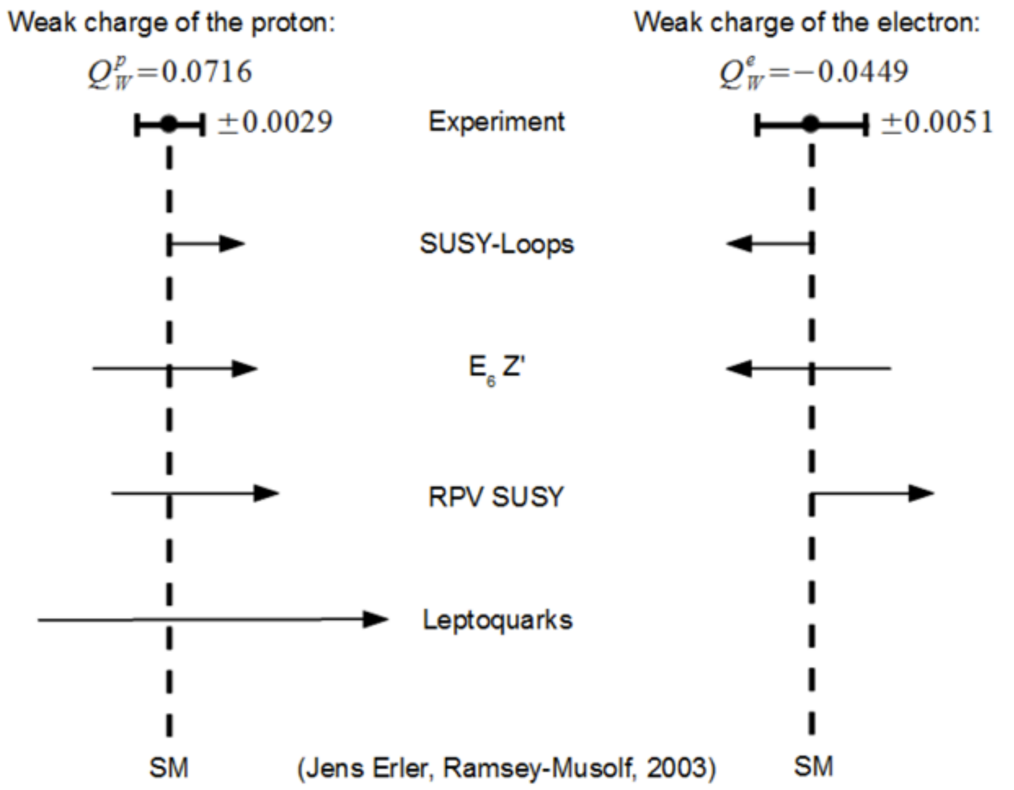
Three PV experiments with three different probes for new physics

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

Weak Charge Of Electron: MOLLER (JLAB)

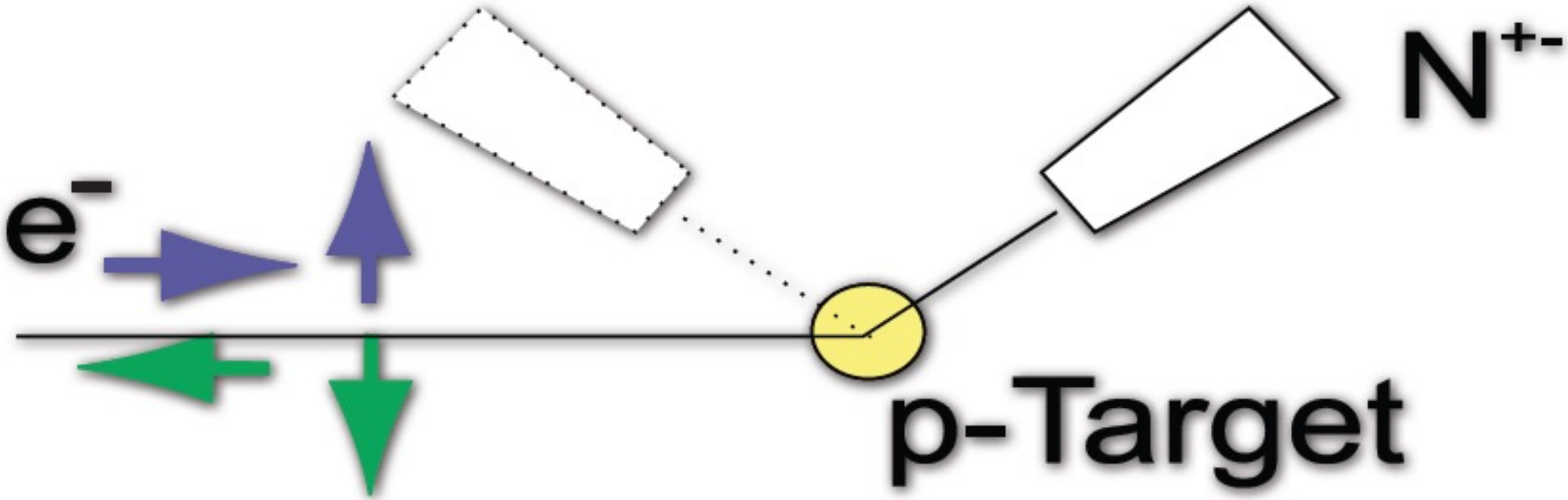
Weak Charge Of Quarks: SOLID (PVDIS) (JLAB)

- Complementary access by weak charges of proton and electron



Parity Violating Electron Scattering (PVES)

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

Physics topics:

Electron spin longitudinal (PVES)

- Weak vector charge of the proton
- Weak axial form factor of the proton
- Weak vector charge of the neutron (Carbon)
- Neutron Skin of Ca and Lead (MREX)

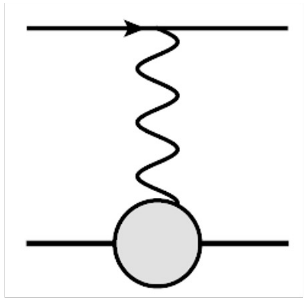
Electron Spin transverse

- Two photon exchange amplitude in elastic electron proton scattering
- Two photon exchange amplitude in electron nucleus scattering

Two photon exchange in elastic electron scattering

high-precision experiments ➔ need to go beyond Born approximation

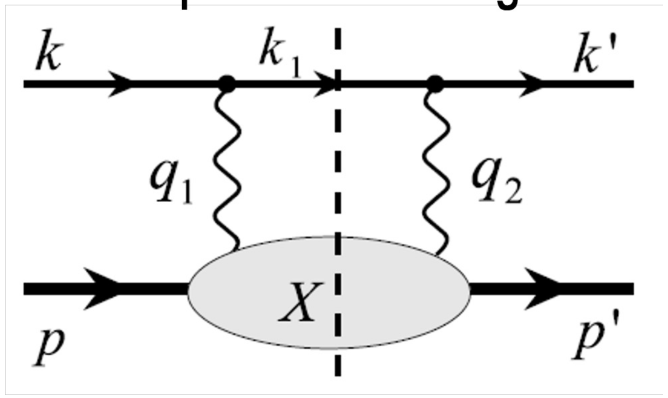
one-photon exchange



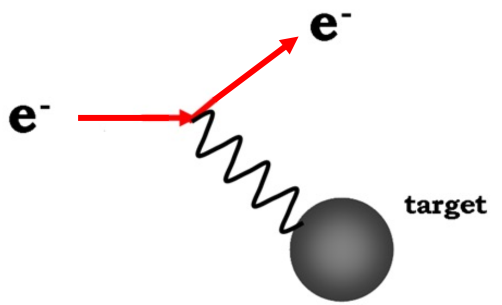
purely real

+

two-photon exchange



has imaginary part



interference of one- and two-photon exchange causes

beam-normal single spin asymmetry A_n

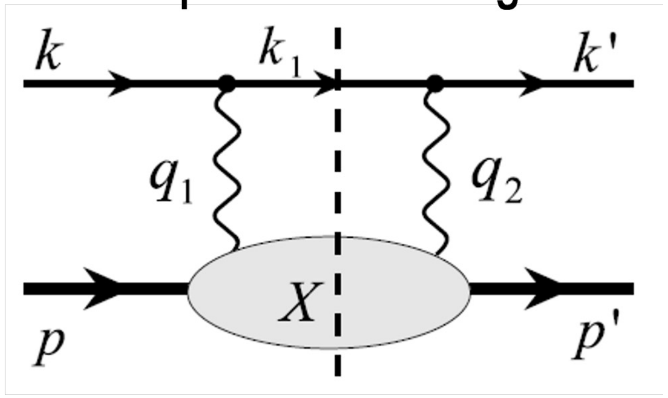
De Rújula et al., Nucl. Phys. B35, 365 (1971)

Talk by M. Thiel and P. Blunden

➔ **allows access of imaginary part of 2γ exchange amplitude**

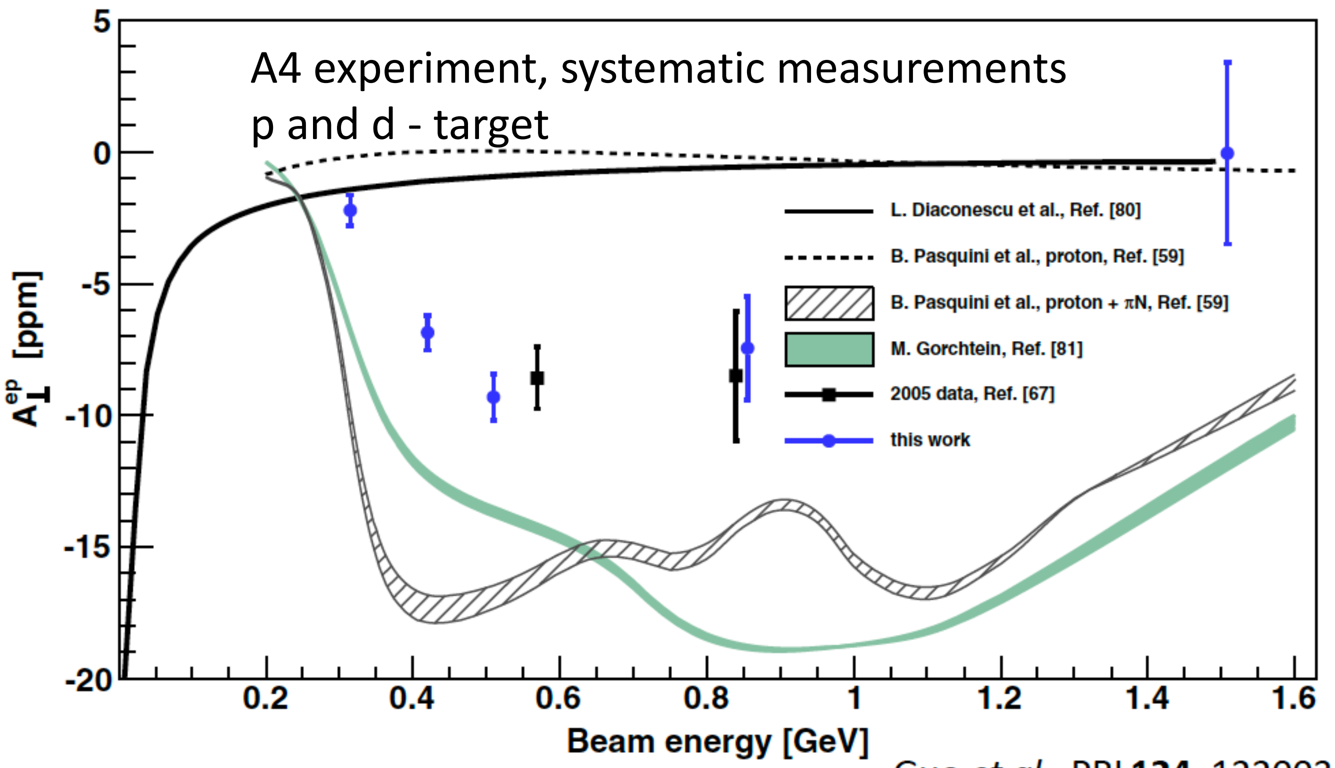
Two photon exchange on elastic electron scattering

two-photon exchange

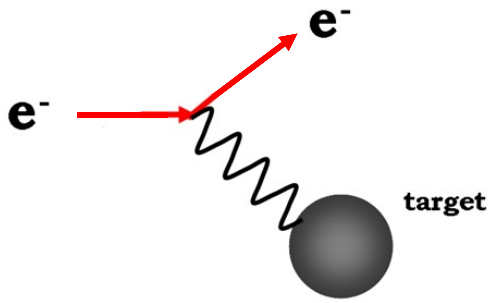


has imaginary part

- Many observables: Target normal spin asymmetry, Beam normal spin asymme
- Different physics for proton target or nu target

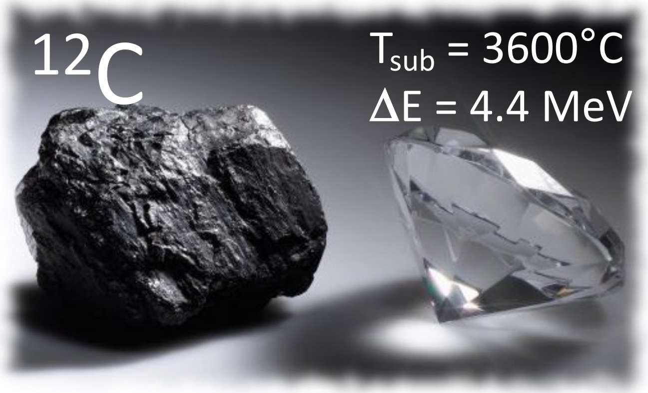


Guo *et al.*, PRL**124**, 122003 (2020)

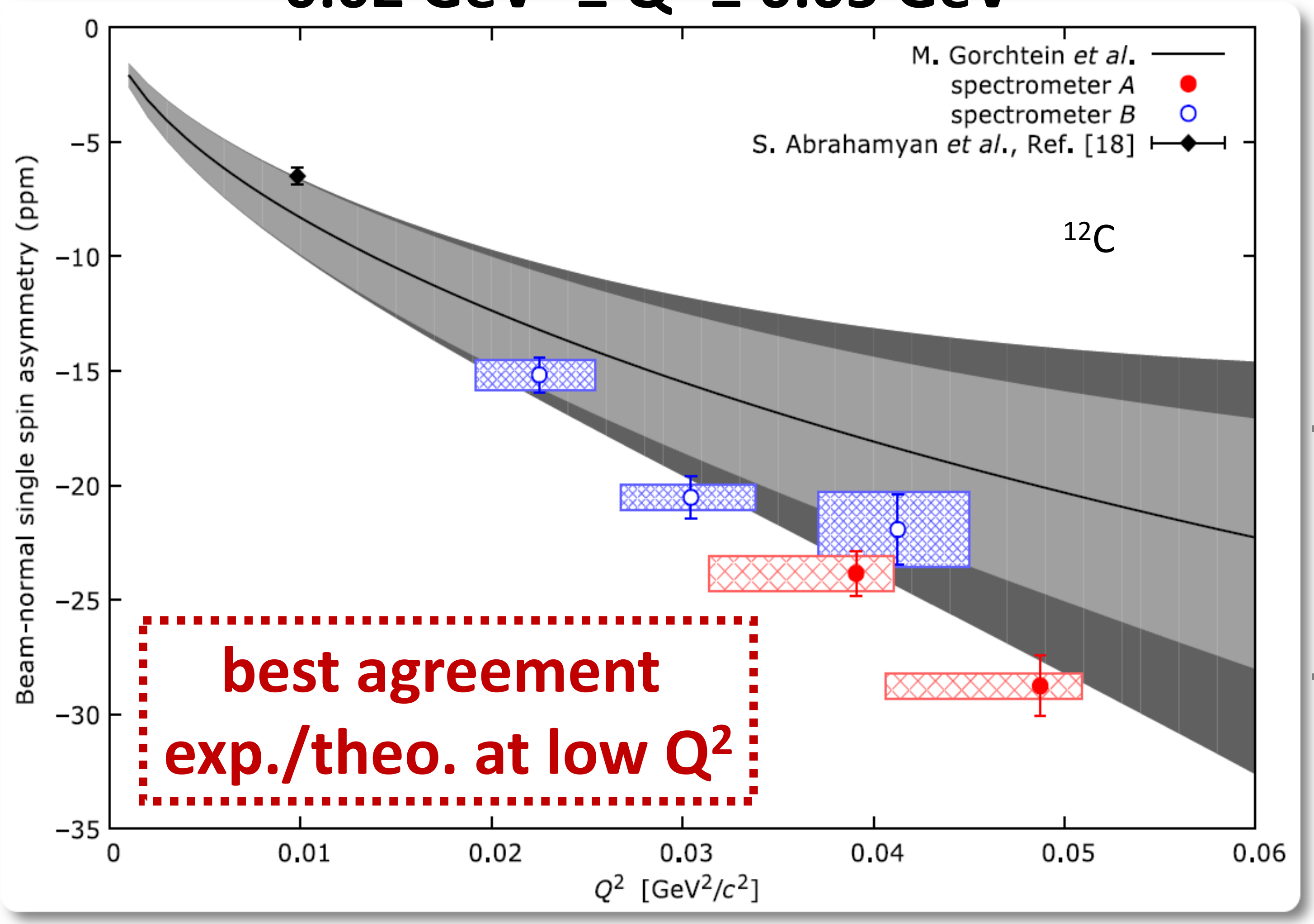


Talk by P. Blunden

results – Q^2 dependence



0.02 GeV² ≤ Q² ≤ 0.05 GeV²



uncertainty of Compton slope parameter:

± 10%

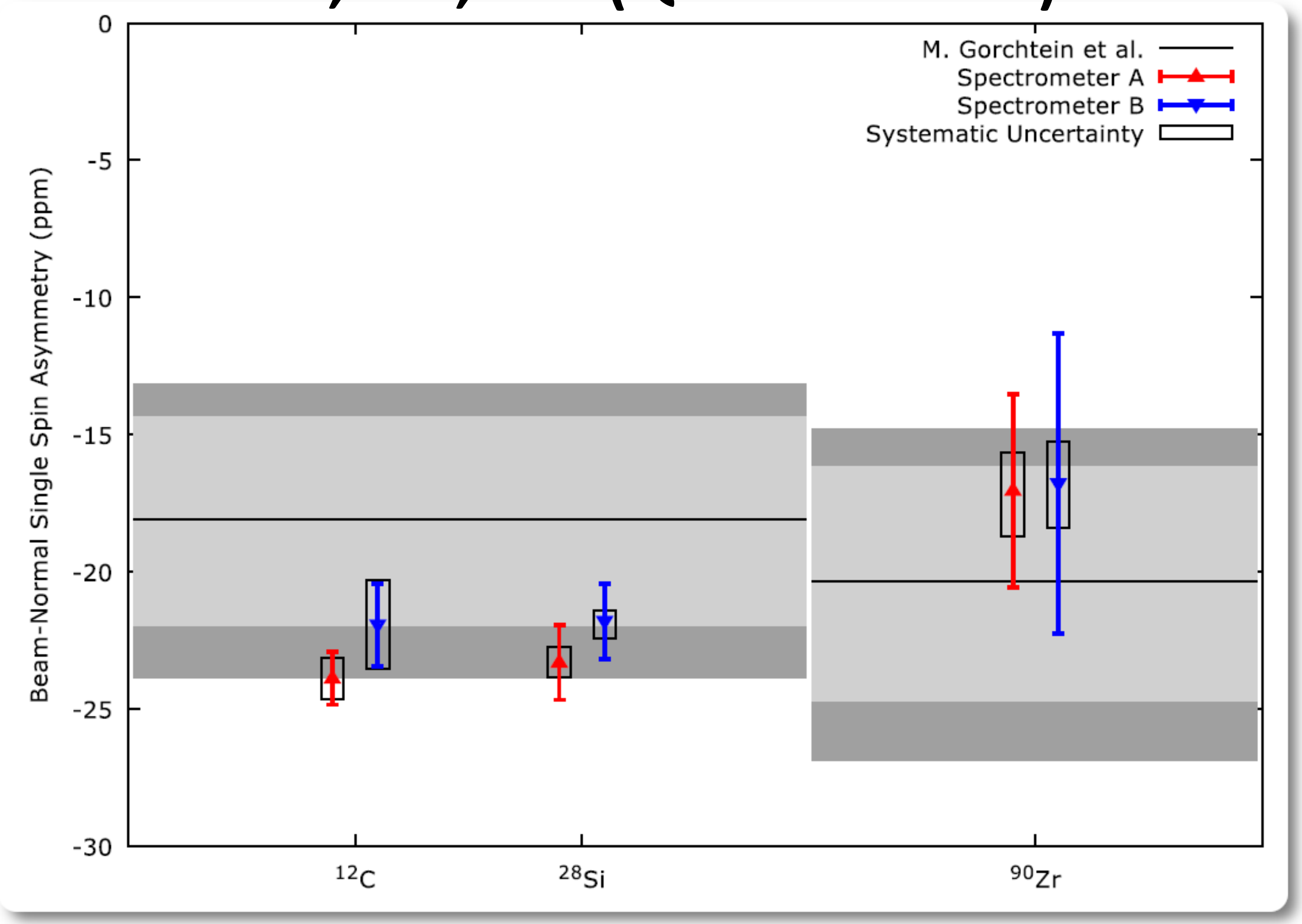
± 20%

A. Esser et al., PRL 121, 022503 (2018)

Talk by M. Thiel

results – A dependence

^{12}C, ^{28}Si, ^{90}Zr (Q^2 = 0.04 GeV^2)



A. Esser et al., PLB 808, 135664 (2020)

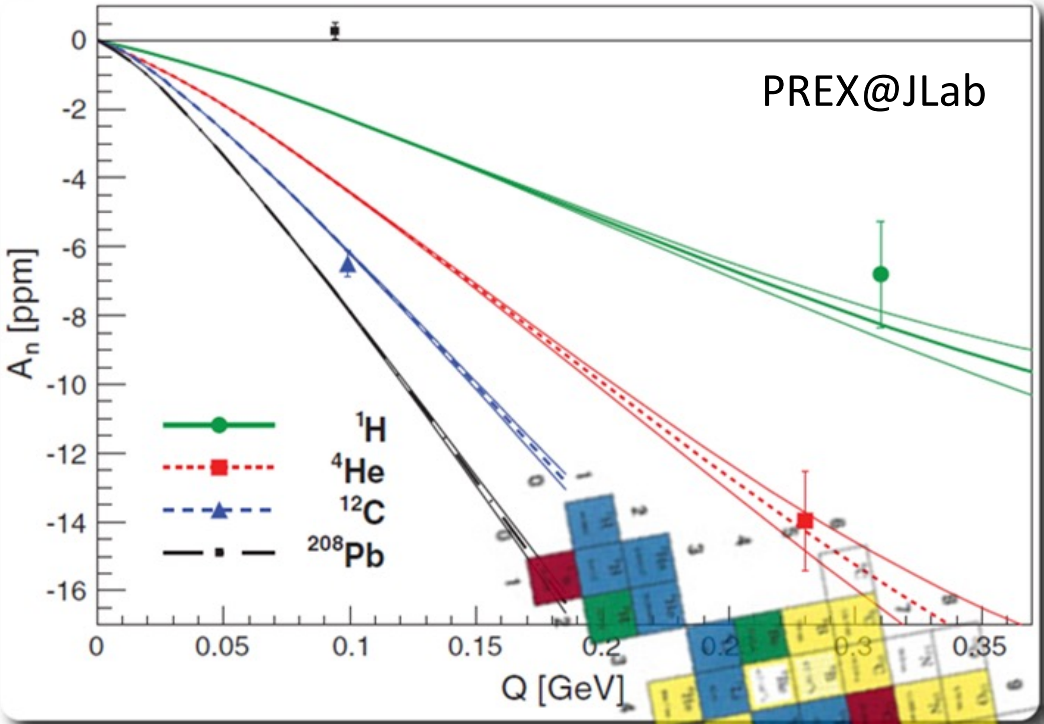
uncertainty of Compton slope parameter:

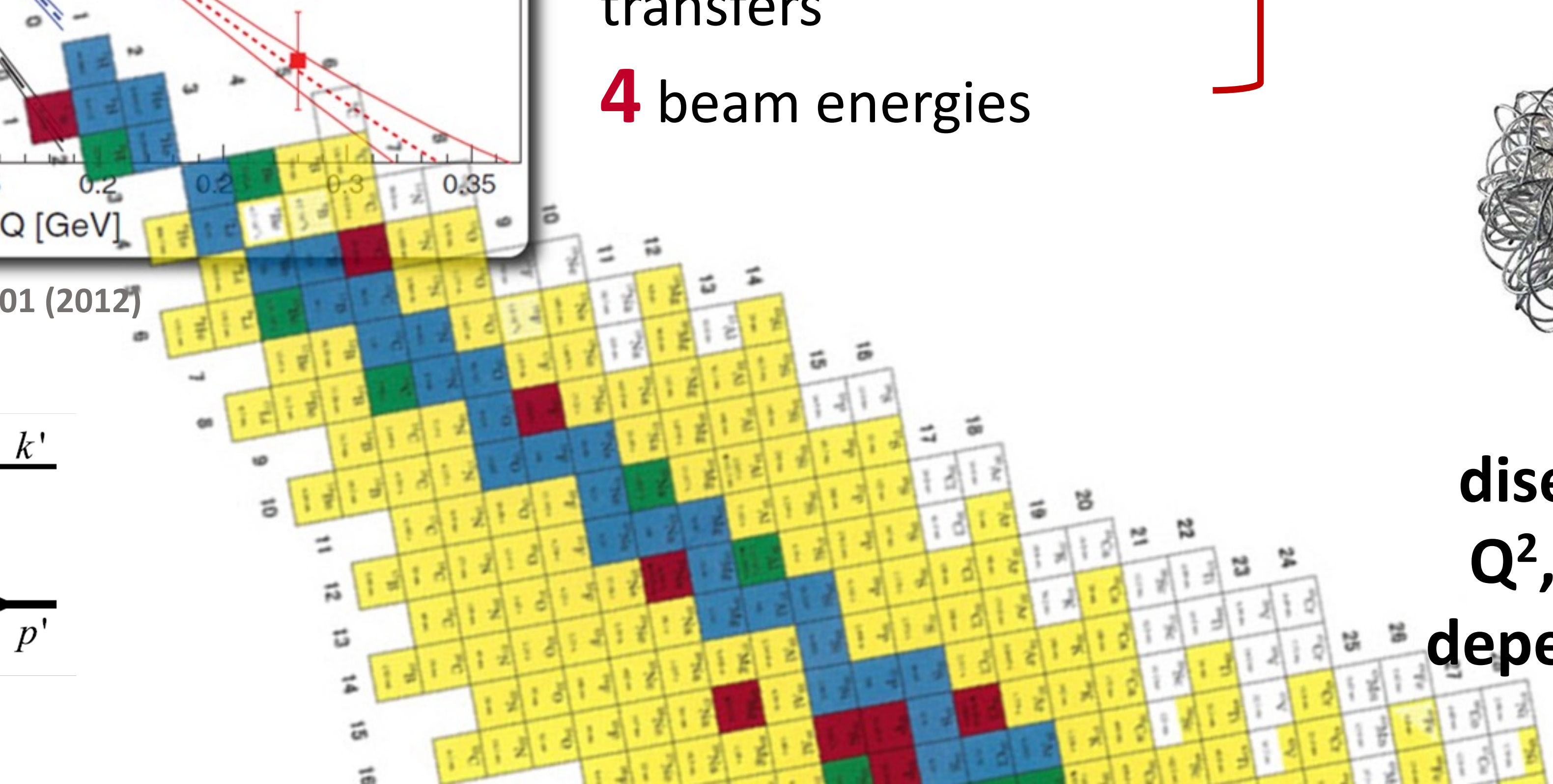
± 10% **± 20%**

Next steps: new DAQ electronics and lead target in A1-Spectrometers at MAMI

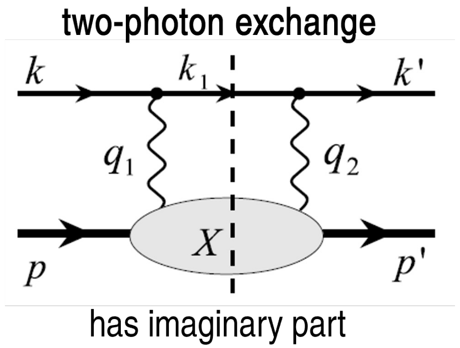
Talk by M. Thiel

the whole nuclear chart in a small band





S. Abrahamyan et al., PRL 109, 192501 (2012)



4 nuclei at:

2 scattering angles

3 four-momentum transfers

4 beam energies

systematic study needed

to disentangle Q^2, Z and E dependencies !

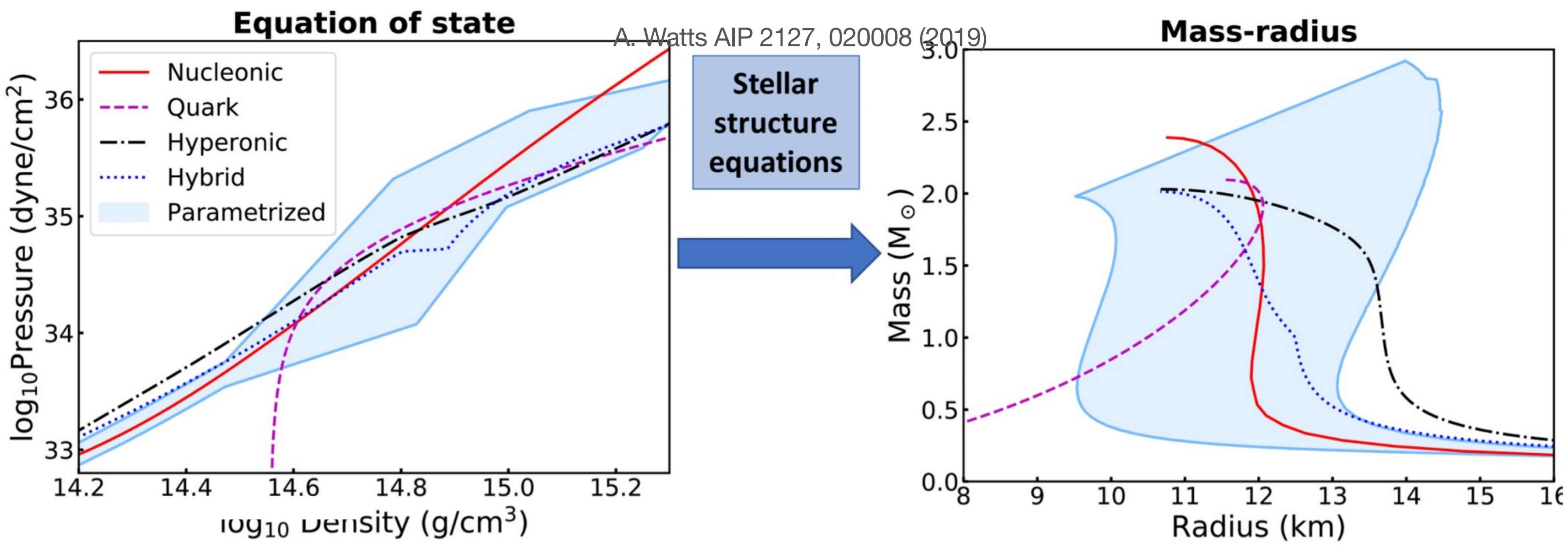
Nuclear physics in P2: Equation of state?

- Neutron Stars are bound by gravity **NOT** by the strong force
- Neutron Stars satisfy the **Tolman-Oppenheimer-Volkoff** equation ($v_{esc}/c \approx 1/2$)

$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2, \quad P = P(\varepsilon) \ \ (\text{EOS})$$

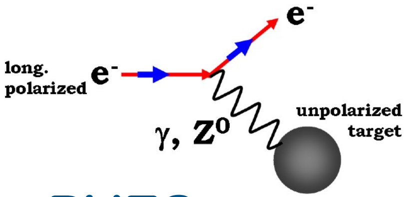
- Only Physics that the TOV equation is sensitive to: **Nuclear equation of State**



A. Watts AIP 2127, 020008 (2019)

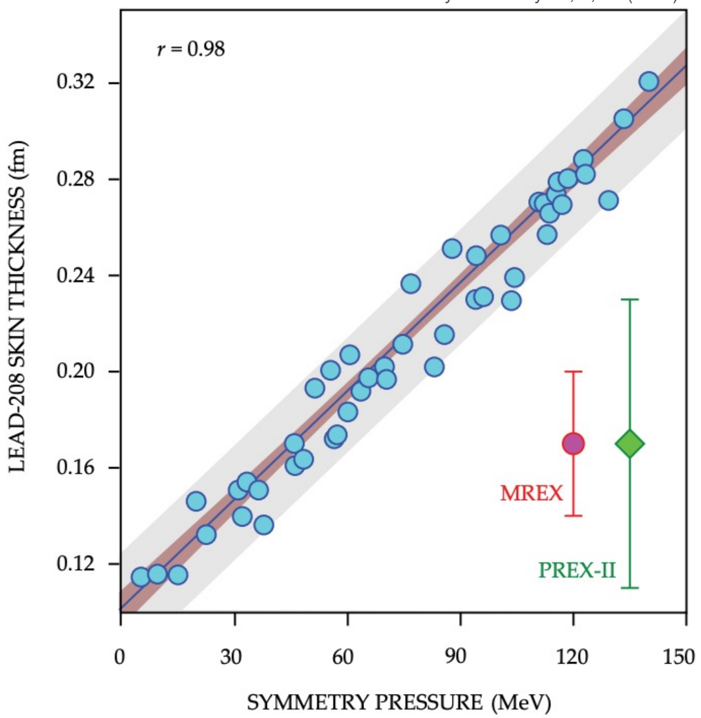
P2-Detector …we call it: MREX

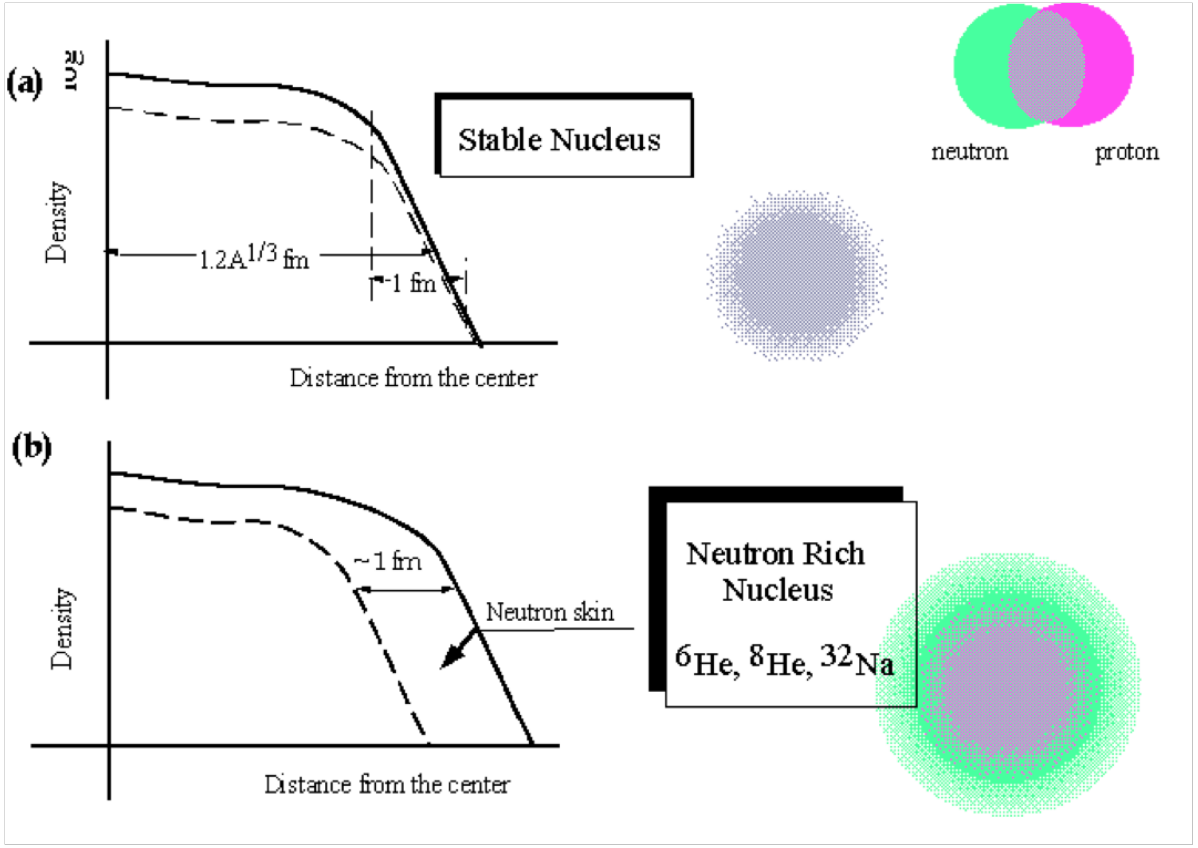
PV-Asymmetry



PVES

Measurement of the neutron disctribution in lead





P2 parity violation experiment in Mainz: program

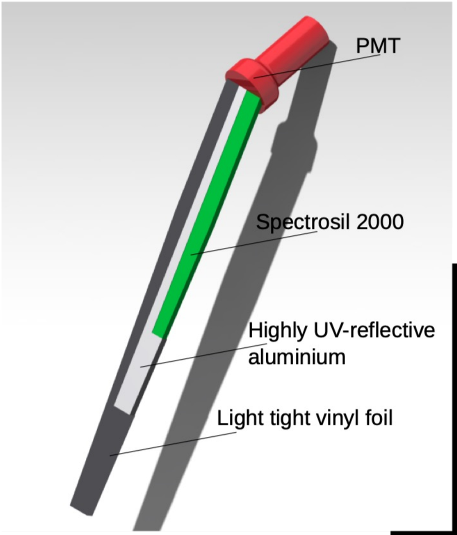
Qweak@Jlab	P2@MESA Hydrogen	P2@MESA Carbon	P2@MESA Calcium,Lead
A_{ep}=-226.5 ppb	A_{ep}=-28 ppb	A_{eC}= 416.3 ppb	A_{ePb}~ 700 ppb
ΔA_{ep}= 9.3 ppb	ΔA_{ep}= 0.5 ppb ppb=1/√N Factor 19 After 11,000 h	ΔA_{ep}^{stat}= 2.7 ppb after 300 h ΔA_{ep}^{stat}= 0.9 ppb after 2500 h	MREX will improve the neutron skin thickness by a factor of two.
$\Delta A_{ep}/A_{ep}$= 4.2 %	$\Delta A_{ep}/A_{ep}$= 1.8 %	$\Delta A_{ep}/A_{ep}^{stat}$= 0.6 % (0.2 %) Polarimetry!	In addition measurements of transverse asymmetries
$\Delta \sin^2 \theta_W / \sin^2 \theta_W$= 0.46 %	$\Delta \sin^2 \theta_W / \sin^2 \theta_W$= 0.15 %	$\Delta \sin^2 \theta_W / \sin^2 \theta_W$= 0.6 % (0.3%)	Two-Photon exchange amplitude
	Aux. measurem. backward angle	Aux. measurem. backward angle	

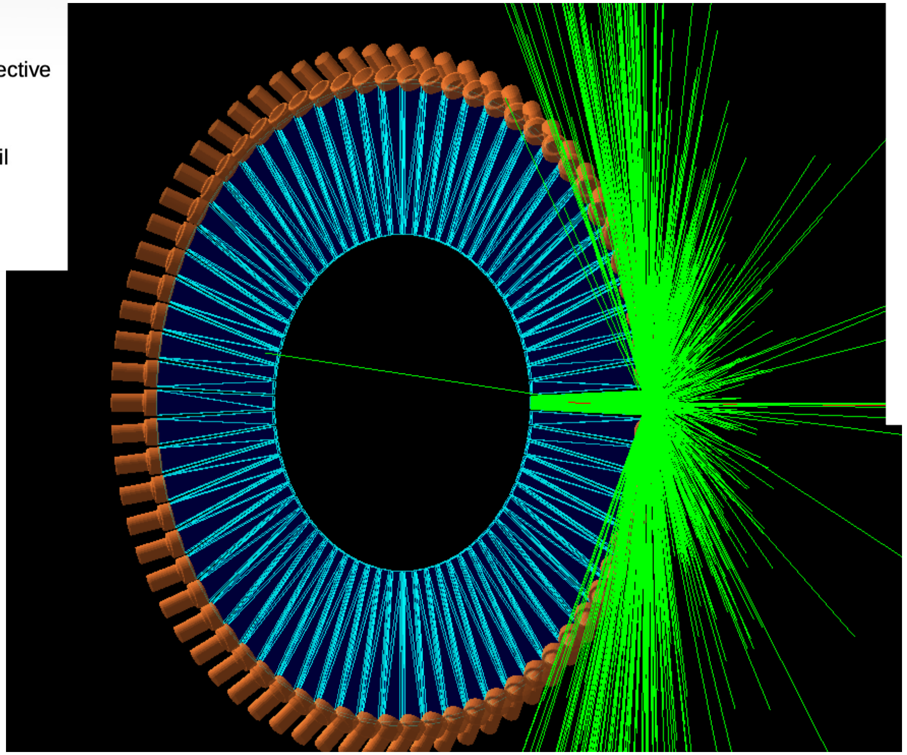
Summary

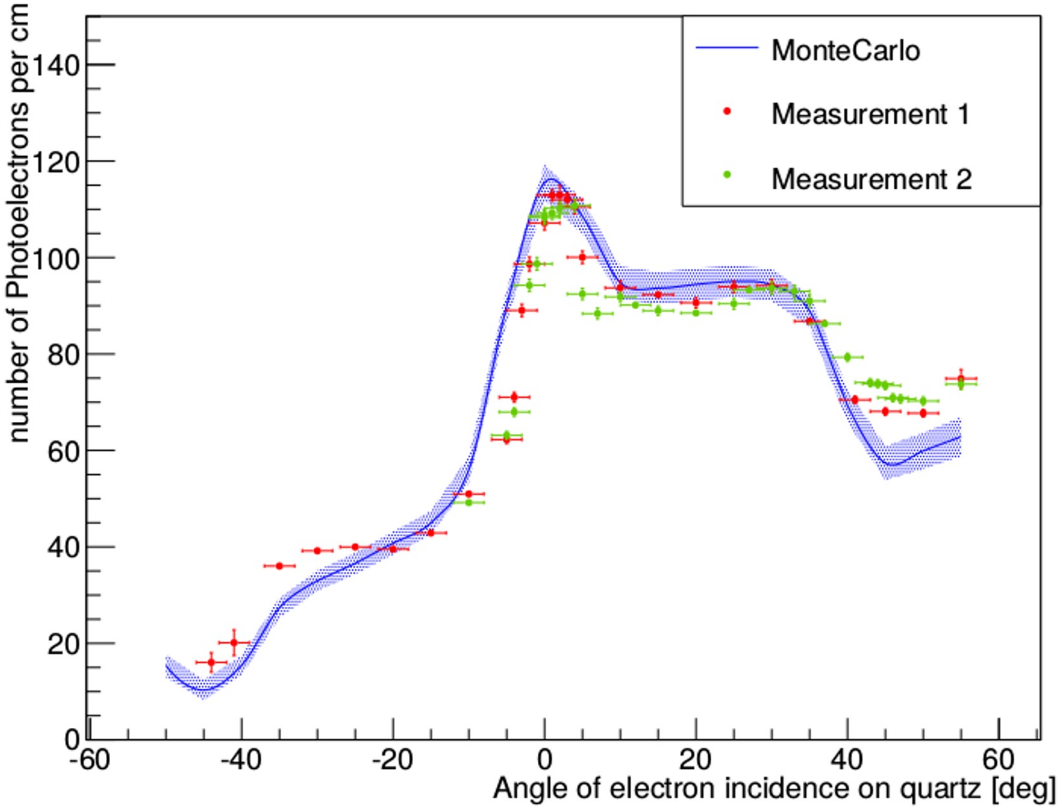
- **Parity violating electron scattering:**
  "Low energy frontier" comprises a sensitive test of the standard model complementary to LHC with a sensitivity to new physics up to 50 TeV
- **Determination of $\sin^2(\theta_W)$ with highest precision 0.15% (similar to Z-pole), test of running of $\sin^2(\theta_W)$**
- **P2-Experiment (proton weak charge) at MESA**
- **Solenoid delivery in October 2024, all critical components delivered, installation of magnet yoke started, start commissioning End of 2025**
- **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 at a scale from 70 MeV up to 50 TeV**
- **Strategic series of measurements from large asymmetries to ultimate precision**
- **Final accuracy corresponds to a factor 3 improvement over Qweak-experiment**
- **Much more physics from P2: Neutron Skin in heavy nuclei, weak charge in light nuclei, Improvement of Vud**

Quartz glas detector concept

- Cherenkov detector ring consisting of **72 fused silica bars**
  - Covering **full azimuth 25° - 45° polar angle**
  - **Integrating detector**

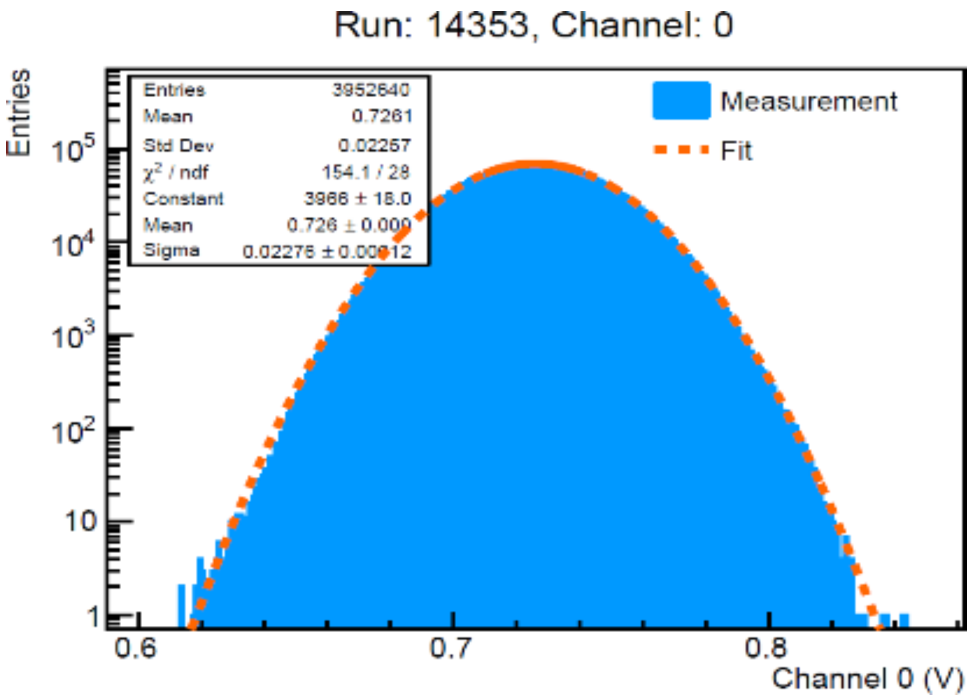


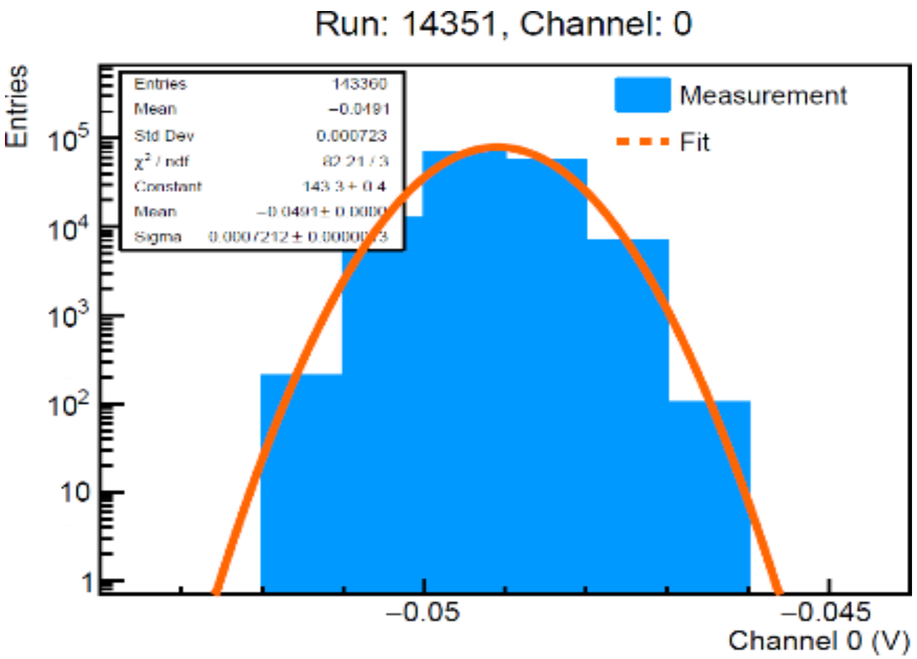




- Extended experimental study
- Quartz glas, PMTs, reflector
- Radiation hardness
- 500 h with MAMI beam

Test of analogue integrating detector and readout

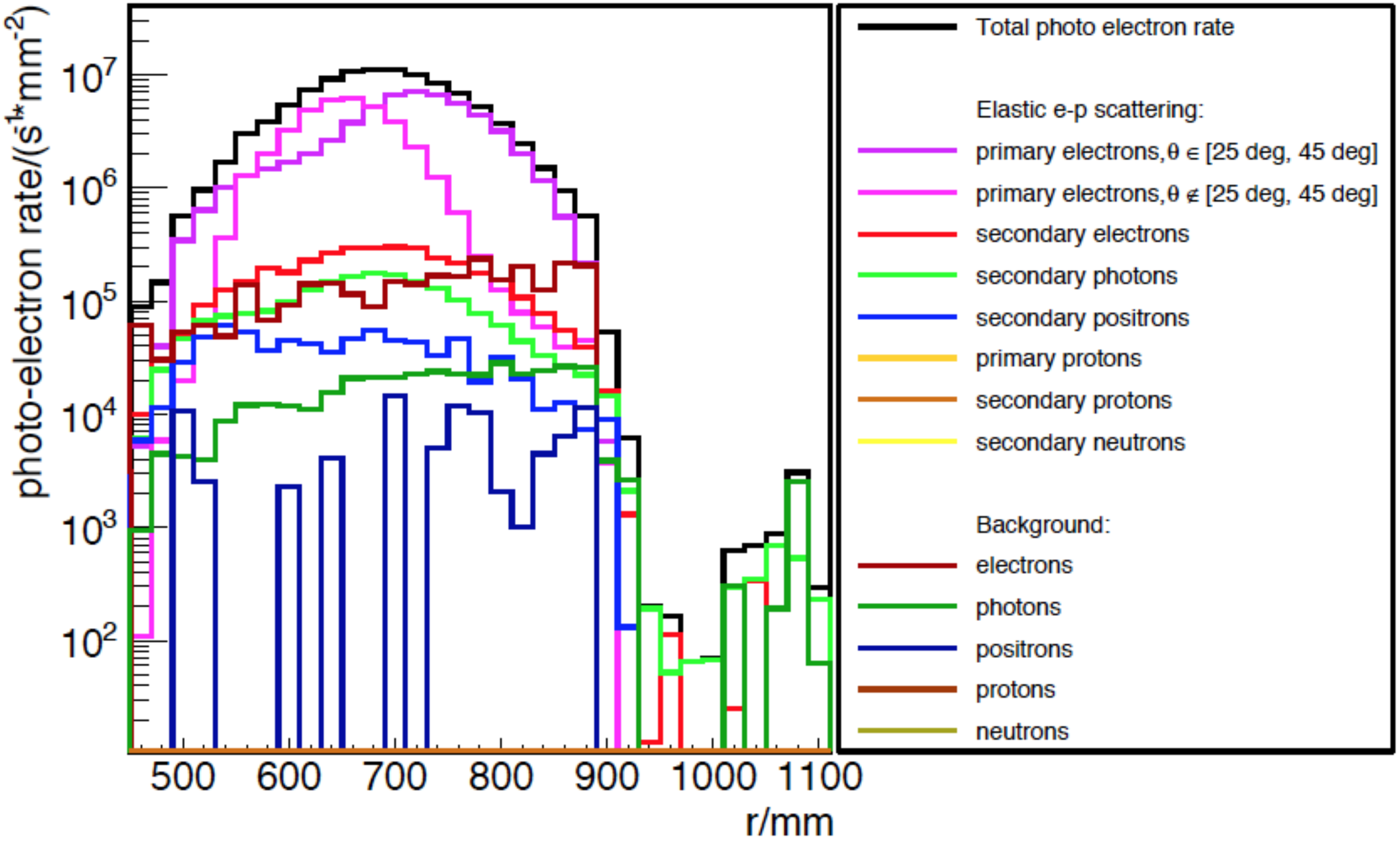




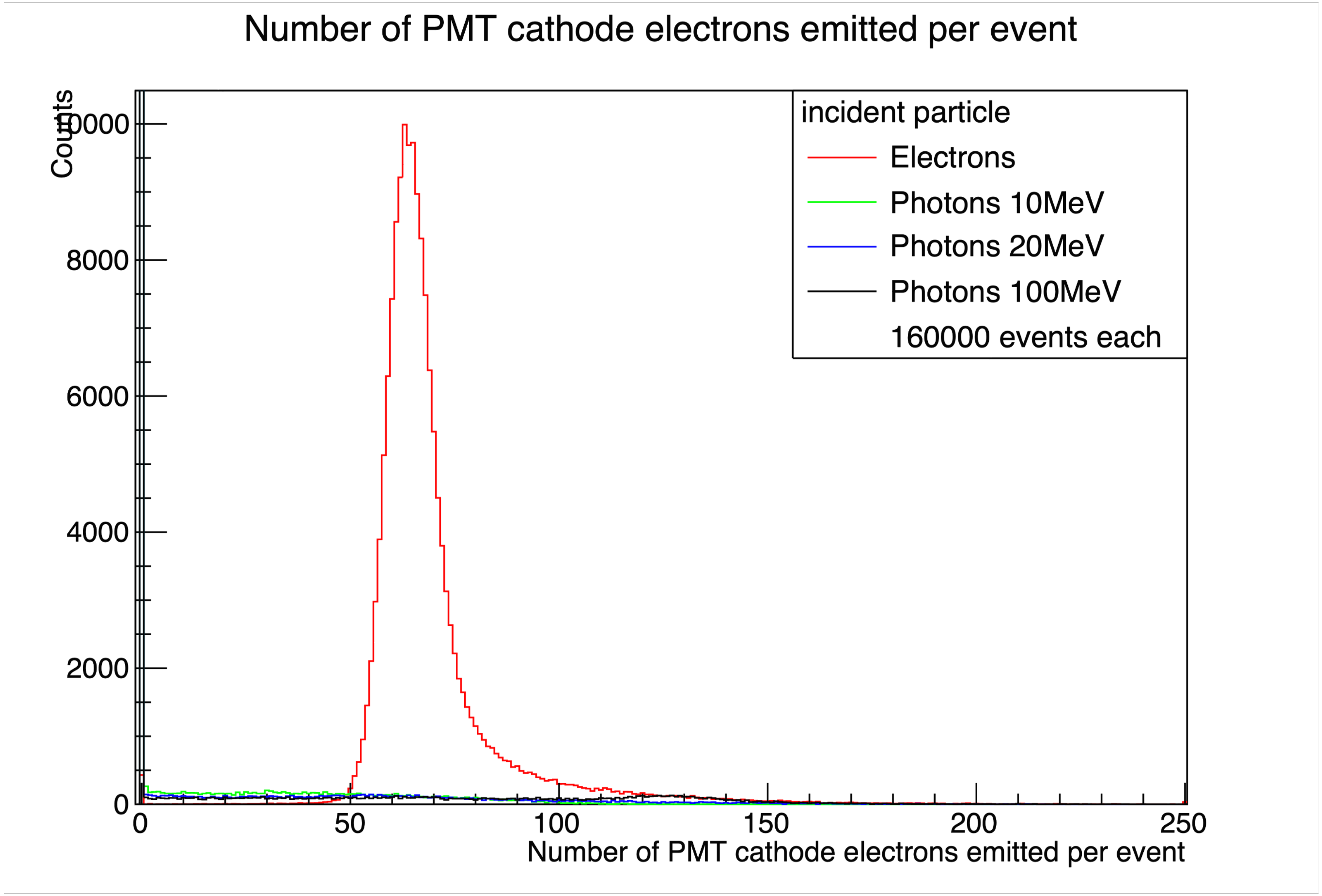
- **Analogue signal from electrons in quartz Cherenkov, 274pA=1.7 GHz electrons on detector**
- **Electronics from U Manitoba**
- **Response of detector and width as expected**
- **System is ready to be used in the experiment**

P2-Detector response

Full GEANT4 simulation

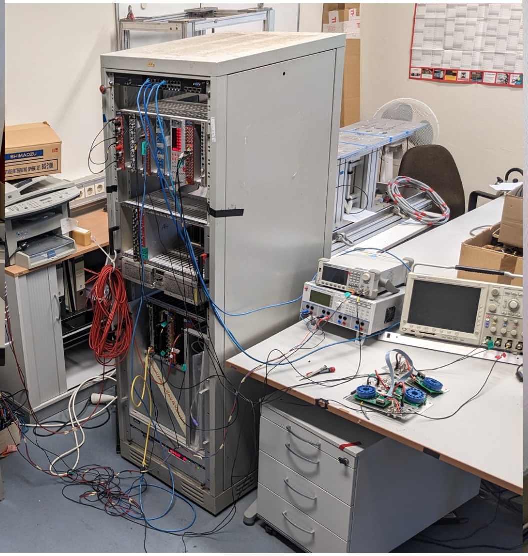


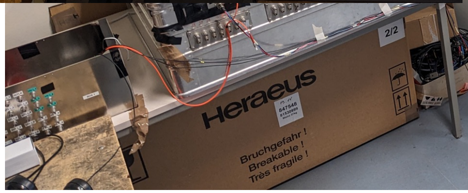
P2-Detector response

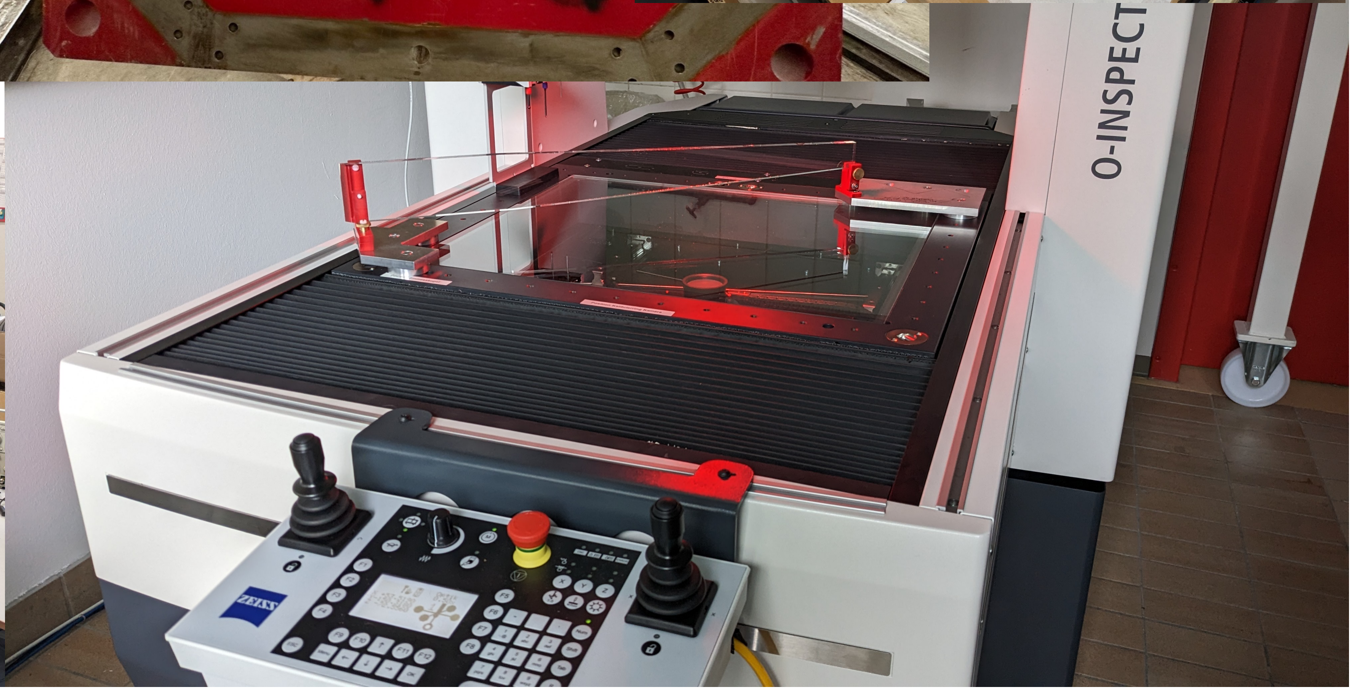


PRiSMA+


Rü oben




Heraeus
Bruchgefahr!
Breakable!
Très fragile!


O-INSPECT
ZEISS