Physics with PERLE

Workshop on electrons for the LHC,
LAL, June 2018

Maarten Boonekamp, IRFU

Some open questions in elastic ep scattering

(personal selection)

- Most demanding objective: precise measurement of the weak mixing angle, $\sin^2\theta_W$
  - Constraints on the design of beam line, target & experiment
  - Standard Model tests and indirect BSM sensitivity
  - Uncertainties in the proton structure

Polarized. beam

Time

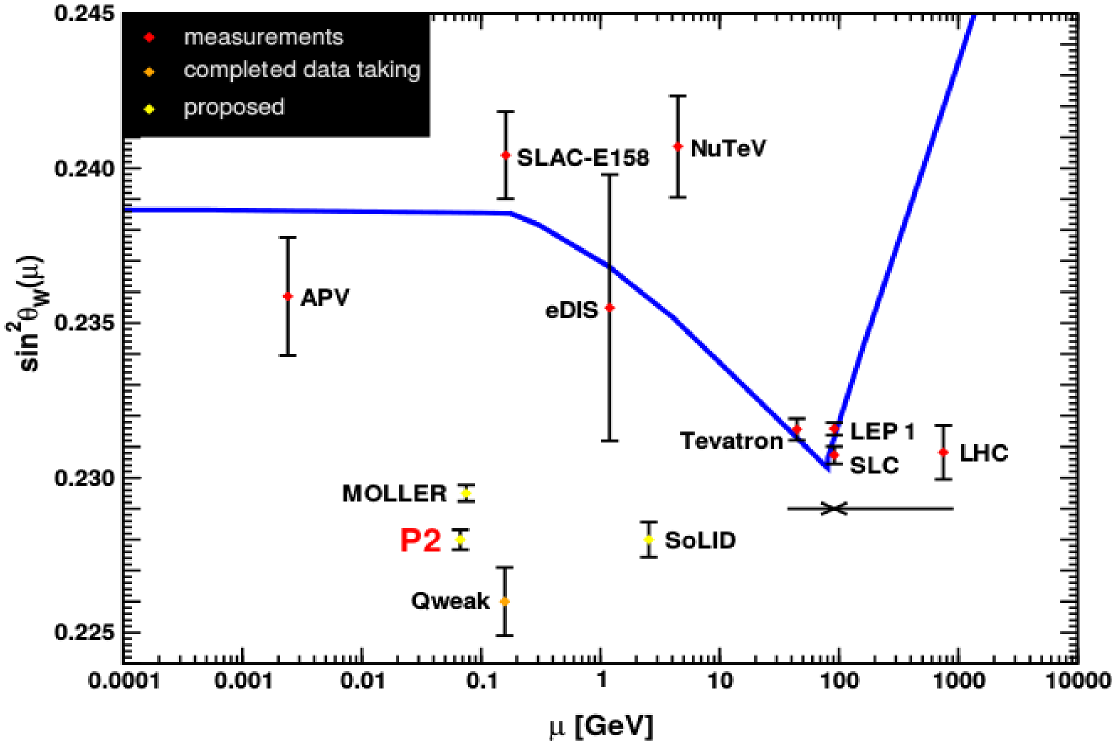
- Related measurements and searches are highly valuable per se
  - Nucleon form factors and $G_{E/M}$; strange form factors
  - Implications for the proton radius
  - Searches for low-mass new particles

Unpol. beam

- Essentially a bibliographical discussion : I start from the CDR, and try to see the implications of the specificities of this experiment, using existing proposals
  - P2 (thanks to F.Maas and collaborators for enlightening discussions!)
  - Various documents and publications from past and present experiments

The weak mixing angle at low Q^2

- Present and future landscape :



- Striking features :
  - Proposed low-Q^2 experiments match the precision of the colliders
  - small uncertainty in the Q^2 evolution, in contrast to α_{QED} :

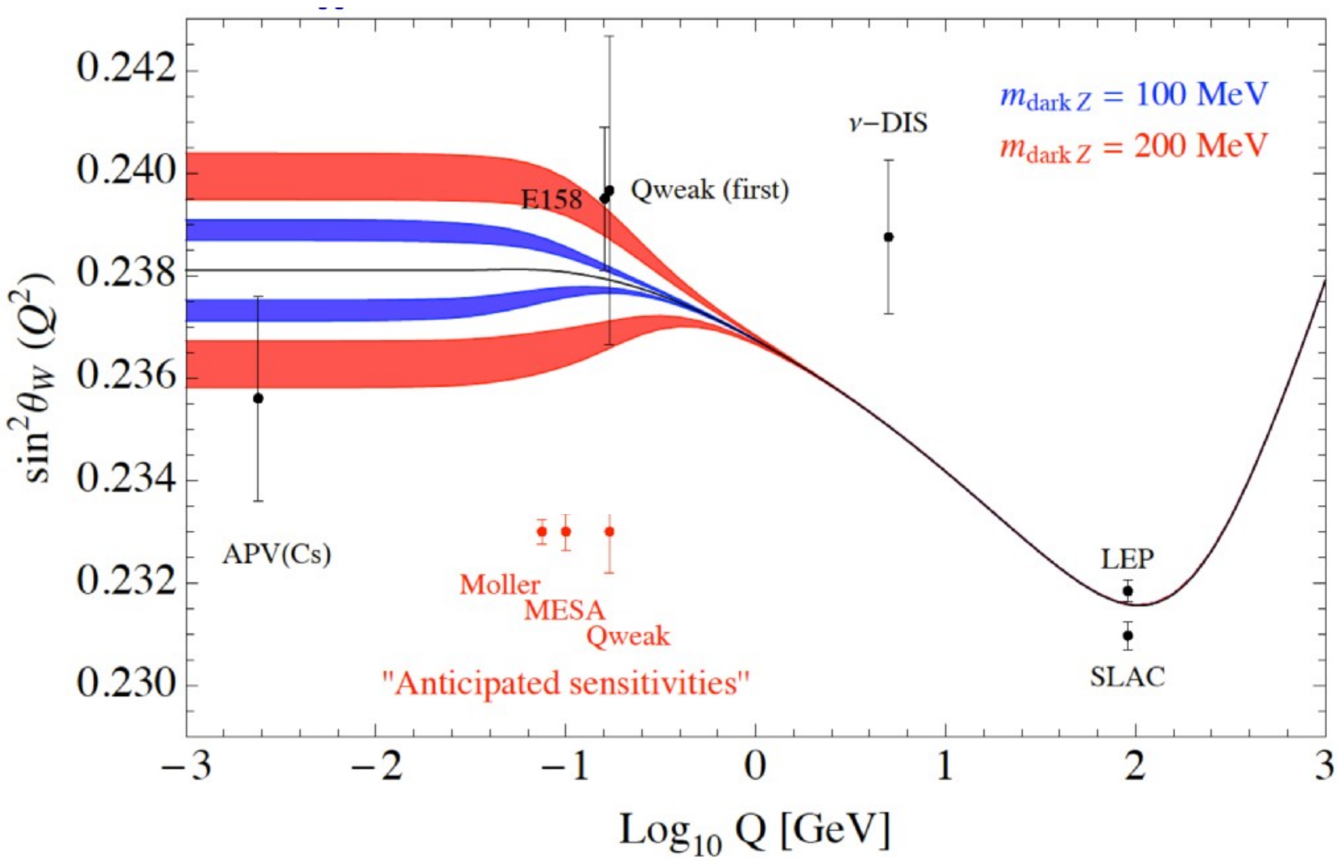
$\sin^2\theta_W = 0.23868 \pm 0.00005$ (EW fit at m_Z) ± 0.00002 (evol.)   (Erler et al, 2018)

Sensitivity to new physics at high scales

	precision	$\Delta \sin^2\overline{\theta}_W(0)$	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

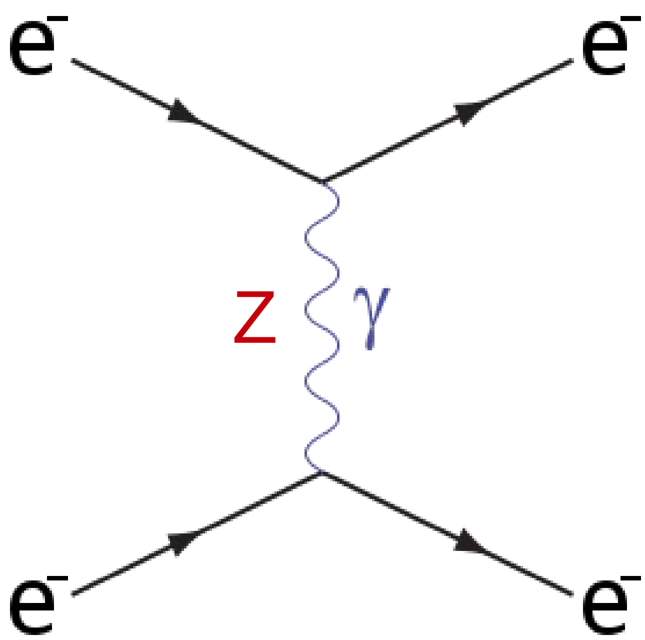
New physics at low energy : “dark” gauge bosons



Bill Marciano

Weak mixing angle with electron beams and hydrogen targets

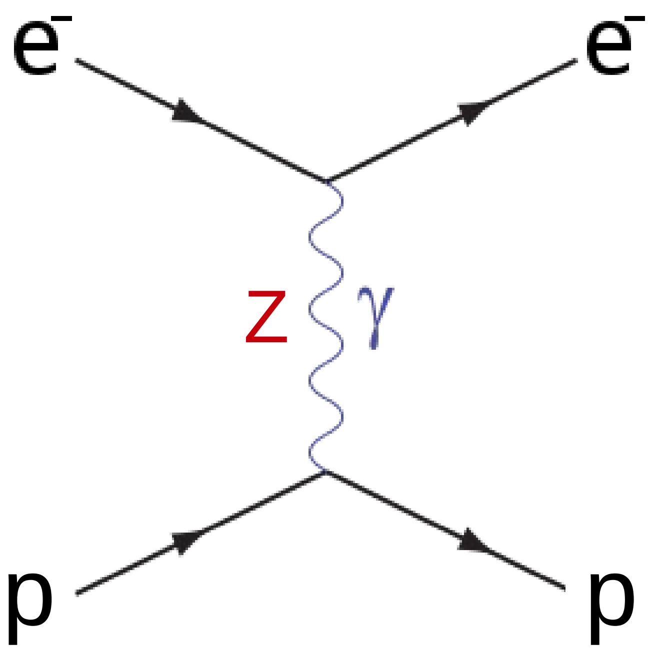
Moller



High energy (multi-GeV),
low angles, (~10-30 mrad),
long flight (~50 m)

E158 (SLAC), MOLLER (JLAB)

Elastic ep



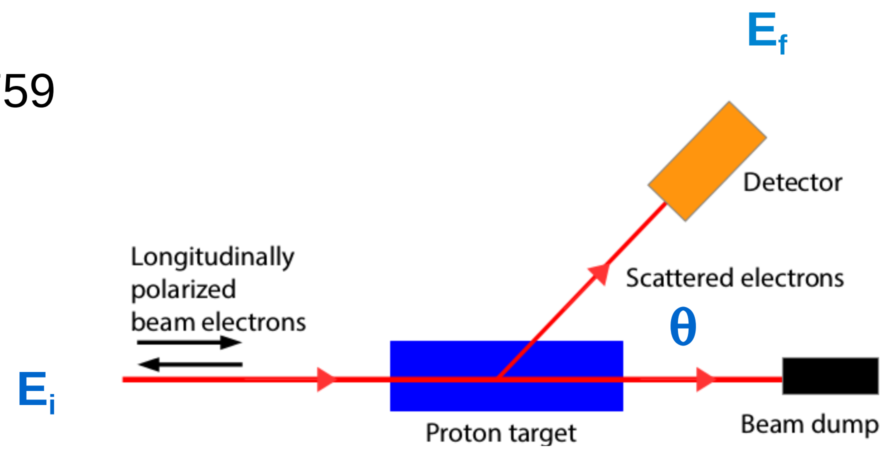
Low energy (<1 GeV),
Large angles (~10-50º)
Short flight (few m)

Qweak (JLAB), P2 (Mainz), PERLE

Sensitivity in ep scattering

- arXiv:1802.04759

- Kinematics :



$$Q^2 \approx 4E_\mathrm{i}E_\mathrm{f}\sin^2(\theta_\mathrm{f}/2)$$

- Parity violating cross section asymmetry : $A^{\mathrm{PV}} = \frac{-G_\mathrm{F}Q^2}{4\pi\alpha_{\mathrm{em}}\sqrt{2}}\left[Q_\mathrm{W}(\mathrm{p}) - F(E_\mathrm{i}, Q^2)\right]$

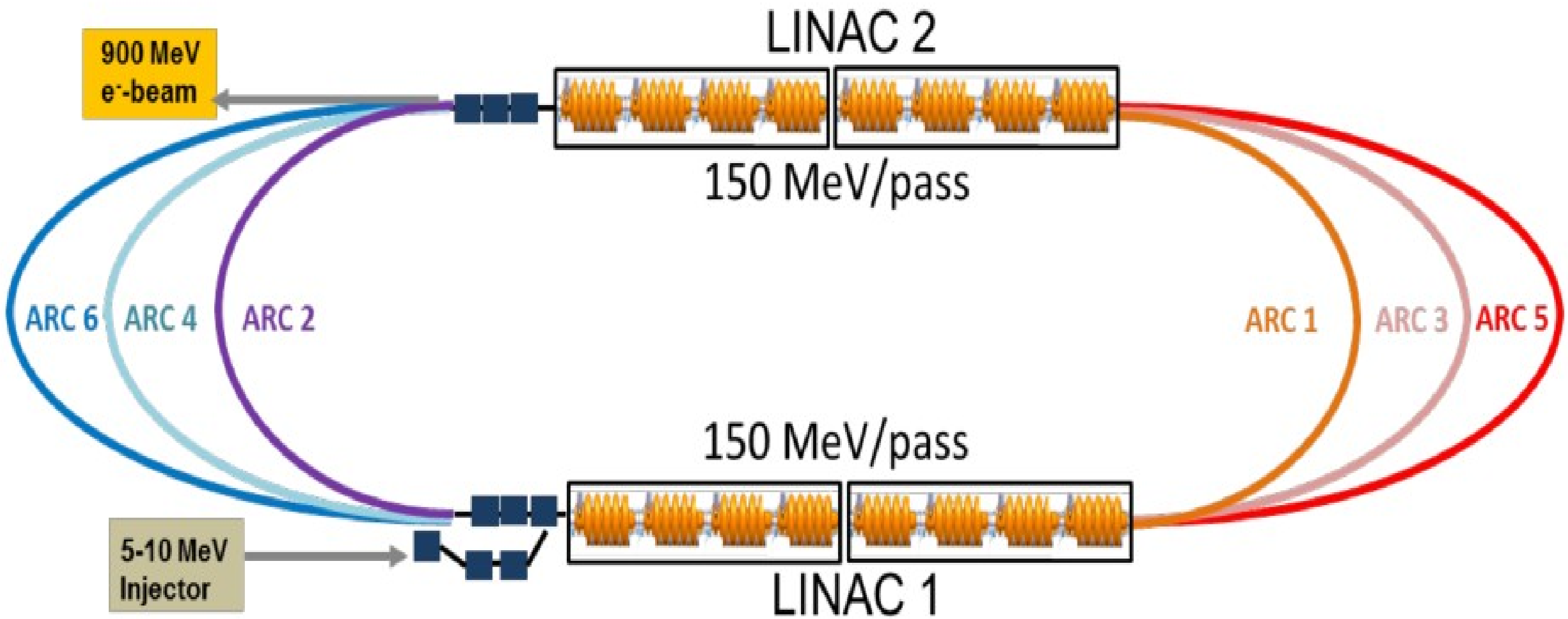
- Sensitivy to $\sin^2\theta_W$: $Q_\mathrm{W}(\mathrm{p}) = 1 - 4\sin^2\theta_\mathrm{W},$

$$\frac{\Delta\sin^2\theta_\mathrm{W}}{\sin^2\theta_\mathrm{W}} = \frac{1-4\sin^2\theta_\mathrm{W}}{4\sin^2\theta_\mathrm{W}} \cdot \frac{\Delta Q_\mathrm{W}(\mathrm{p})}{Q_\mathrm{W}(\mathrm{p})} \approx 0.09 \cdot \frac{\Delta Q_\mathrm{W}(\mathrm{p})}{Q_\mathrm{W}(\mathrm{p})}.$$

- Proton form factors (non-0 for $Q^2>0$): $F(E_\mathrm{i}, Q^2) \equiv F^{\mathrm{EM}}(E_\mathrm{i}, Q^2) + F^{\mathrm{A}}(E_\mathrm{i}, Q^2) + F^{\mathrm{S}}(E_\mathrm{i}, Q^2),$

PERLE settings assumed for this discussion

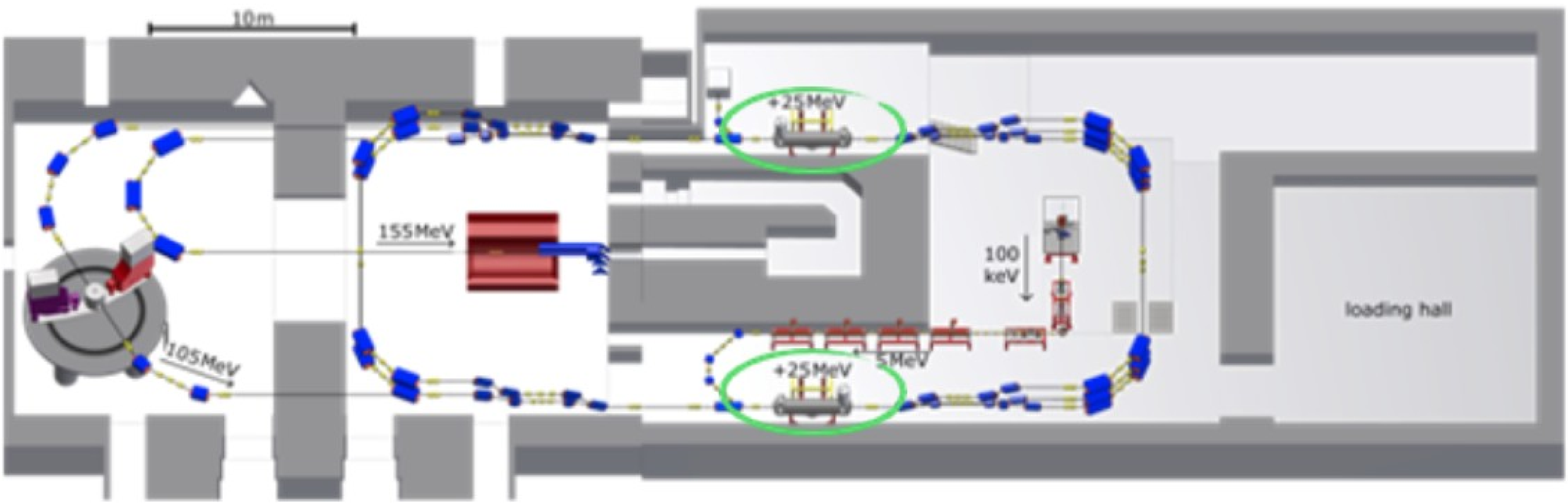
- 5-10 MeV injector
- 300 MeV / turn; up to three turns
- Maximum current ~10 mA



Sensitivity in ep scattering: P2@MESA

Kurt Aulenbacher

MESA — "Mainz Energy-Recovering Superconducting Accelerator

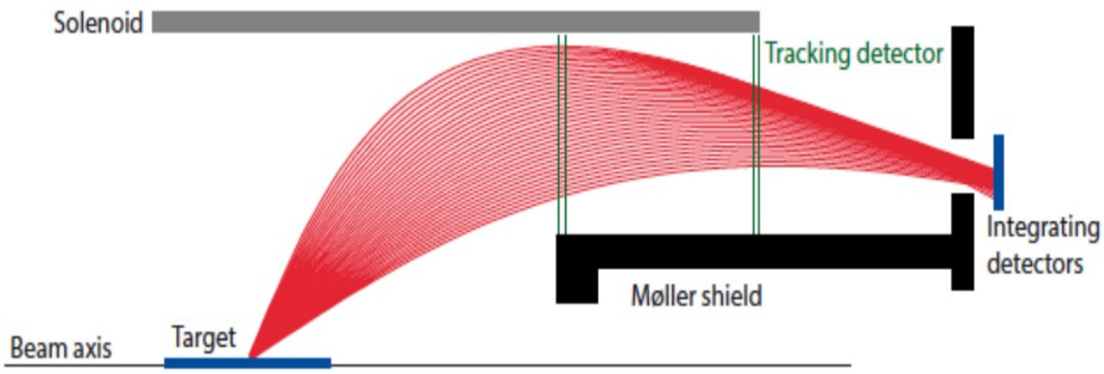


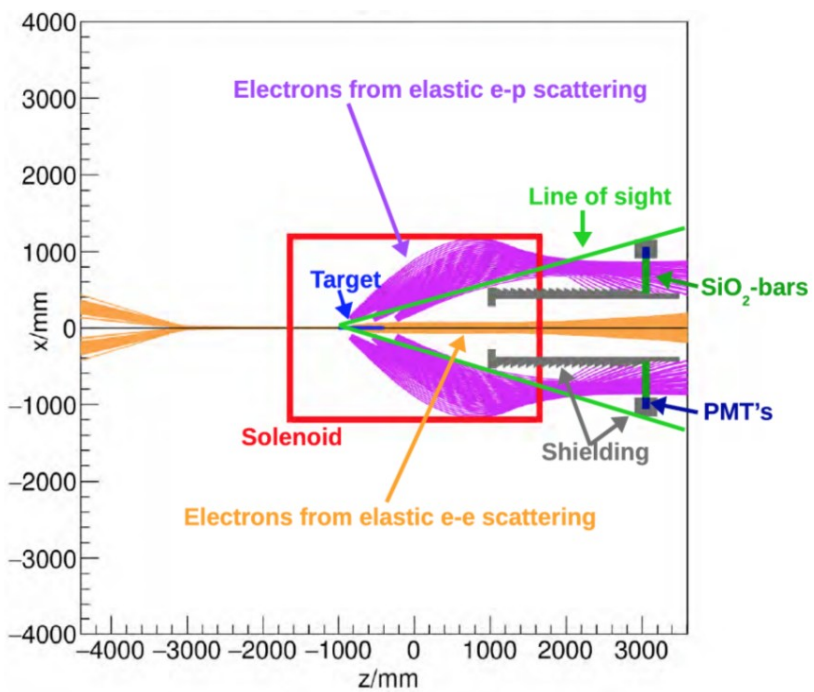
Energy 105 – 155 MeV **Beam current : up to 1-2 mA (in ER mode)**
150 µA (in extraction mode)

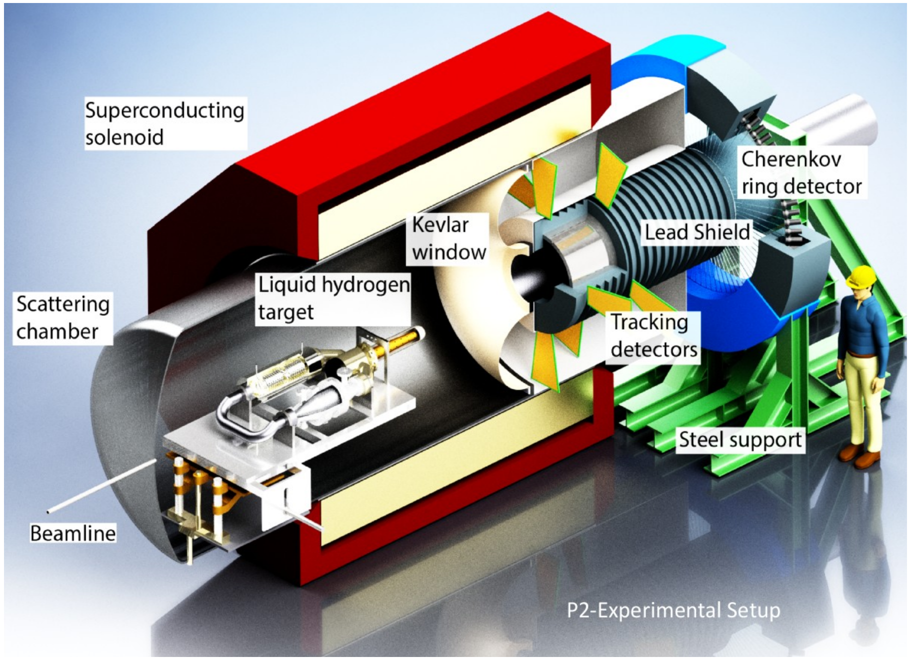
- Completion of construction delayed until middle of 2020
- Allows optimization of research program and of design and delivery contracts

Sensitivity in ep scattering: P2@MESA

- P2 (arXiv:1802.04759)



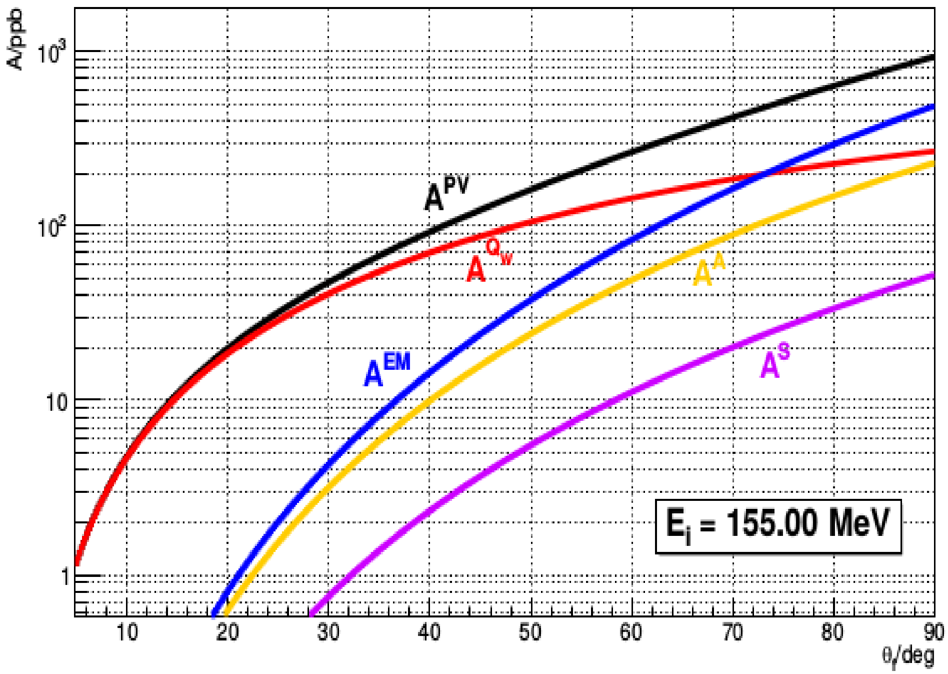




Integrating Cherenkov detectors
(~ 100 GHz impact rate)
Solenoid for measurement of <Q^2>
Moller electrons shielded & confined by a magnetic field, $B_z = 0.6$ T

Sensitivity in ep scattering: P2@MESA

- P2 (arXiv:1802.04759)
- Main experimental parameters and contributions to the polarization asymmetry



λ_l	$\langle\lambda_l\rangle$	$\Delta\lambda_l$
$E_{\rm beam}$	variable	0.13 MeV
$\bar{\theta}_{\rm f}$	variable	$0°$
$\delta\theta_{\rm f}$	variable	$0.1°$
$\delta\phi_{\rm f}$	$360°$	$0°$
I_{beam}	150 µA	0.001 µA
P	0.85	0.00425
L	600 mm	0 mm
T	1×10^4 h	0 h
$A^{\rm app}$	0	0.1 ppb

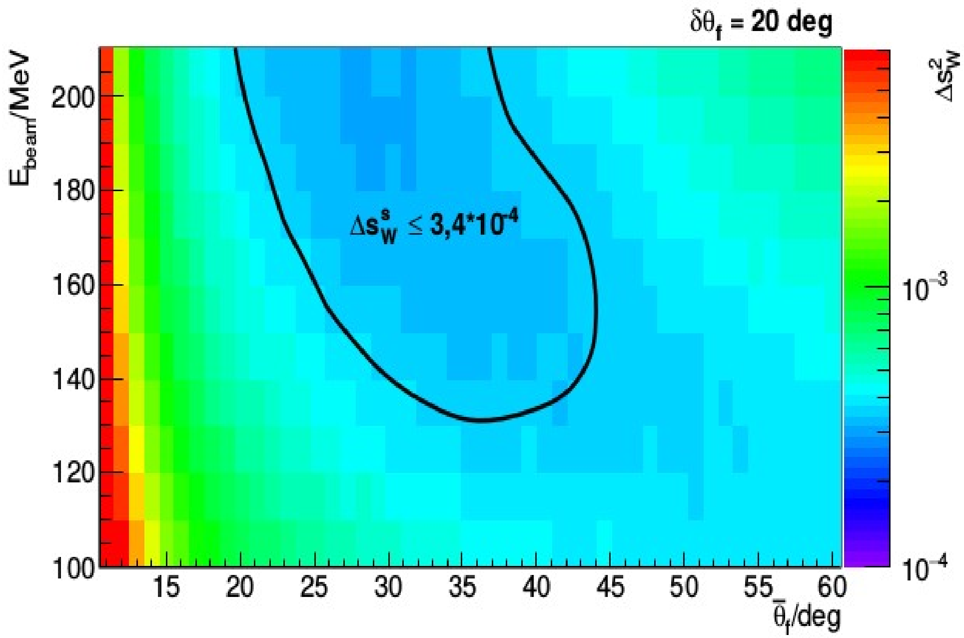
Table 1. Mean values and standard deviations chosen for performing the error propagation calcuations. $\delta\phi_{\rm f}$ denotes the azimuthal acceptance of the detector and T is the measuring time. Parameters for which $\Delta\lambda_l = 0$ is shown have been kept constant during the calculations.

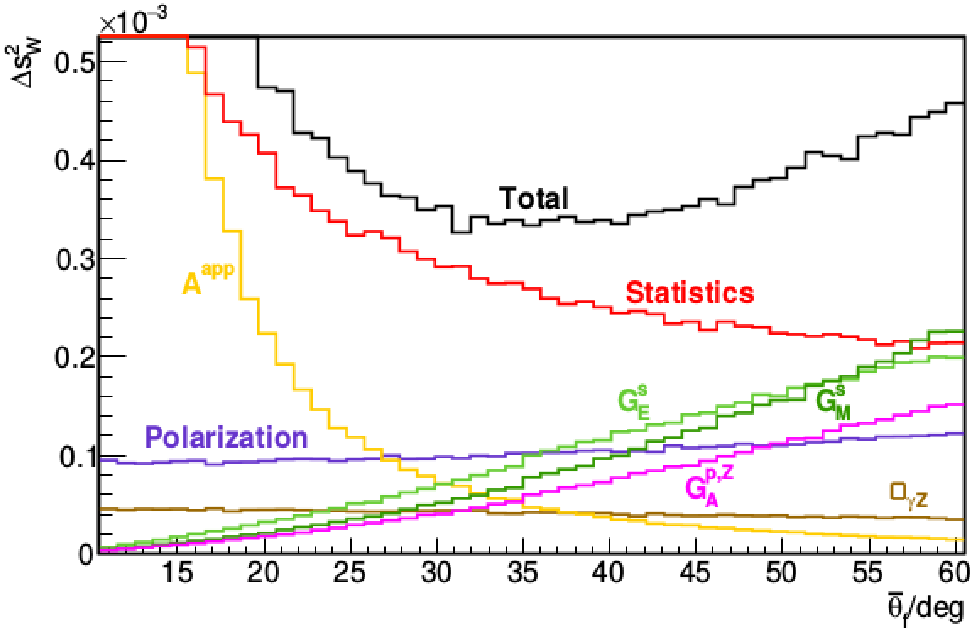
NB : MESA has two operating modes:
"energy recovery" - E = 105 MeV; 1-2 mA, unpolarized
"extracted beam" - E = 155 MeV, 150 µA, polarized → used for physics
(LH_2 target incompatible with ER – electron multiple scattering)

Sensitivity in ep scattering: P2@MESA

- Uncertainty budget vs angle and energy:

arXiv:1802.04759





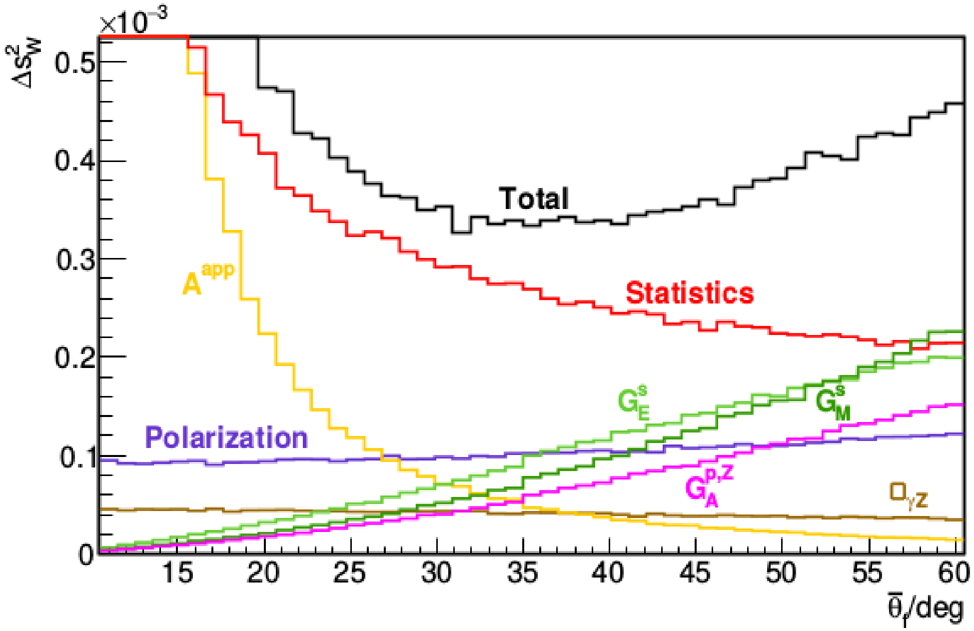
  - Optimum a compromise between sensitivity (prefers larger angle) and form factor uncertainties (prefers smaller)
  - Cross sections increase with beam energy; requires decrease in angle to keep Q^2 constant

Sensitivity in ep scattering: P2@MESA

- Uncertainty budget vs angle and energy:

arXiv:1802.04759

E_{beam}	$155\,\text{MeV}$
$\bar{\theta}_{\text{f}}$	35°
$\delta\theta_{\text{f}}$	20°
$\langle Q^2\rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20^\circ}$	$6\times10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}}\rangle$	$-39.94\,\text{ppb}$
$(\Delta A^{\text{exp}})_{\text{Total}}$	$0.56\,\text{ppb}\ (1.40\,\%)$
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	$0.51\,\text{ppb}\ (1.28\,\%)$
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	$0.21\,\text{ppb}\ (0.53\,\%)$
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	$0.10\,\text{ppb}\ (0.25\,\%)$
$\langle s^2_{\text{W}}\rangle$	$0.231\,16$
$(\Delta s^2_{\text{W}})_{\text{Total}}$	$3.3\times10^{-4}\ (0.14\,\%)$
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	$2.7\times10^{-4}\ (0.12\,\%)$
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	$1.0\times10^{-4}\ (0.04\,\%)$
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	$0.5\times10^{-4}\ (0.02\,\%)$
$(\Delta s^2_{\text{W}})_{\square_{\gamma Z}}$	$0.4\times10^{-4}\ (0.02\,\%)$
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	$1.2\times10^{-4}\ (0.05\,\%)$
$\langle Q^2\rangle_{\text{Cherenkov}}$	$4.57\times10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}}\rangle_{\text{Cherenkov}}$	$-28.77\,\text{ppb}$



PERLE specifics

- Target cooling and stabilization
  - Electron energy loss in target: P = I L ρ dE/dx [W]
    - I = beam current (100 μA – 10 mA), L = target length (10-60 cm),
    - ρ = target density (71 kg/m^3 at 20K), x = target thickness [g/cm2]
  - Past : SAMPLE, G0, E158 targets (1994-2002) → P < 1 kW
  - Present / near future :
    - Qweak@JLAB (2.5 kW, 2010)
    - MØLLER@JLAB (5 kW, ~2020)
    - P2@MESA (4 kW, ~2020) Luminosity ~2 10^{39}
  - PERLE : assume 10 cm LH_2, 1 mA : Luminosity ~3 10^{39}; cooling power ~ 5 kW, scaling with current & target length
    - In this regime, comparable luminosity to MESA; complementary in energy

    Heat load manageable at high luminosity (10 mA ↔ 2 10^{40})? Alternate solutions?

- Separate consideration : for E_{beam} = 900 GeV, $Q^2 = 6.10^{-3}$ is reached for $\theta_{min} = 9^o$

LH2 Targets for Parity Violation

Experiments	p / T / $\dot{m}$ psia / K / kg/s	L cm	P / I W / μA	beam spot mm	$\Delta\rho/\rho$ %	$\delta\rho/\rho$ ppm	E GeV
G0	25 / 19 / 0.3	20	500 / 40-60	2 x 2	1.5	238@15 Hz	3
Q_{weak}	35 / 20 / 1	35	2500 / 180	4 x 4	0.8	46@480 Hz	1
MØLLER		**150**	**5000 / 85**		**<2%**	**<25@960 Hz**	**11**
P2		**60**	**4000 / 150**				**0.2**
IEB		**20**	**7000+ / 1000**		**<4%**	**<30@480 Hz**	**<0.5**

(slide from Silviu Covrig Dusa, JLab)

Constraints on the nucleon form factors

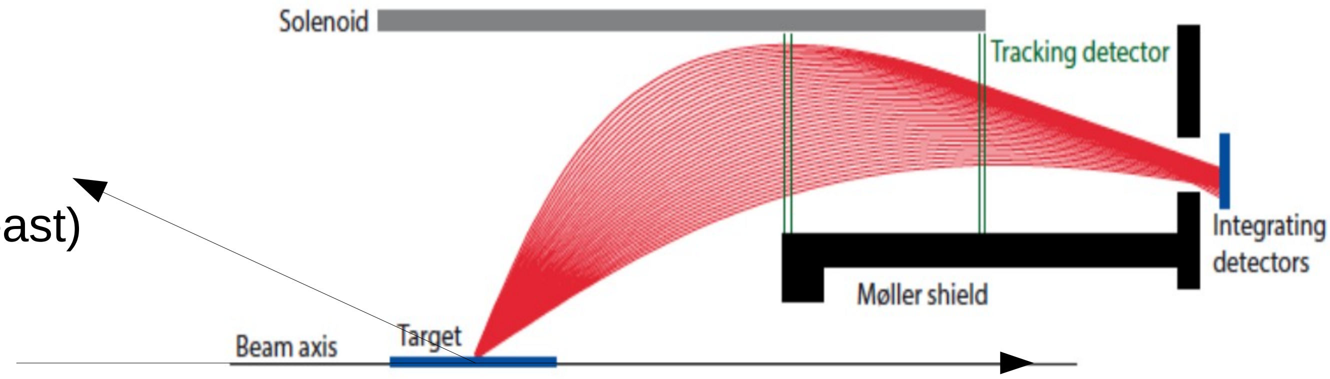
- Prospects shown above assume various factors of improvement:
  - Axial form factor of the proton ($\rightarrow F^A(Q^2)$): $G_A \rightarrow$ **/10**
  - Strange form factors ($\rightarrow F^S(Q^2)$) : $G^s_E \rightarrow$ **/4**; $G^s_M \rightarrow$ **/12**
- Several of these measurements can be performed using dedicated, backward scattering experiments

$$F^{\mathrm{EM}}(E_{\mathrm{i}}, Q^2) \equiv \frac{\epsilon G_{\mathrm{E}}^{\mathrm{p},\gamma} G_{\mathrm{E}}^{\mathrm{n},\gamma} + \tau G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{M}}^{\mathrm{n},\gamma}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}$$

$$F^{\mathrm{A}}(Q^2) \equiv \frac{(1 - 4\sin^2\theta_{\mathrm{W}}) \sqrt{1-\epsilon^2} \sqrt{\tau(1-\tau)} G_{\mathrm{M}}^{\mathrm{p},\gamma} G_{\mathrm{A}}^{\mathrm{p},Z}}{\epsilon (G_{\mathrm{E}}^{\mathrm{p},\gamma})^2 + \tau (G_{\mathrm{M}}^{\mathrm{p},\gamma})^2}.$$

$$\epsilon \equiv \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_{\mathrm{f}}}{2}\right)\right]^{-1}$$

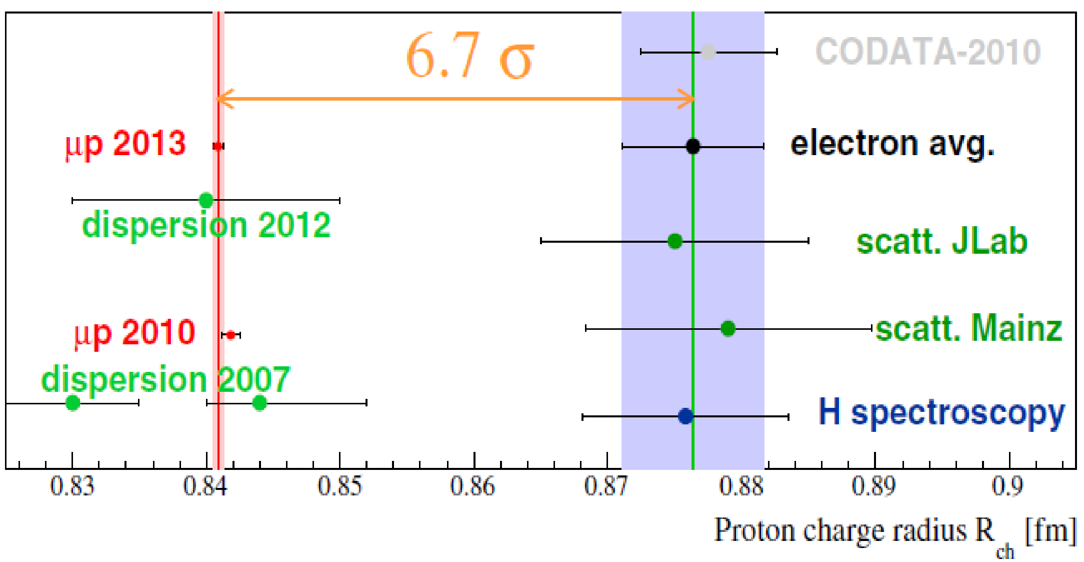
θ ~ 145º
(same Q² as fwd meast)



Impact on the proton radius

arXiv:1706.00696v2

- The proton radius puzzle:
  - Electron measurements : ep scattering; hydrogen spectroscopy
  - Muon measurements : muonic hydrogen spectroscopy – much more sensitive than normal hydrogen, due to larger overlap of muon and proton wave functions



$$\langle r_E^2 \rangle = -\frac{6\hbar^2}{G_E(0)} \frac{dG_E(Q^2)}{dQ^2}\bigg|_{Q^2=0}.$$

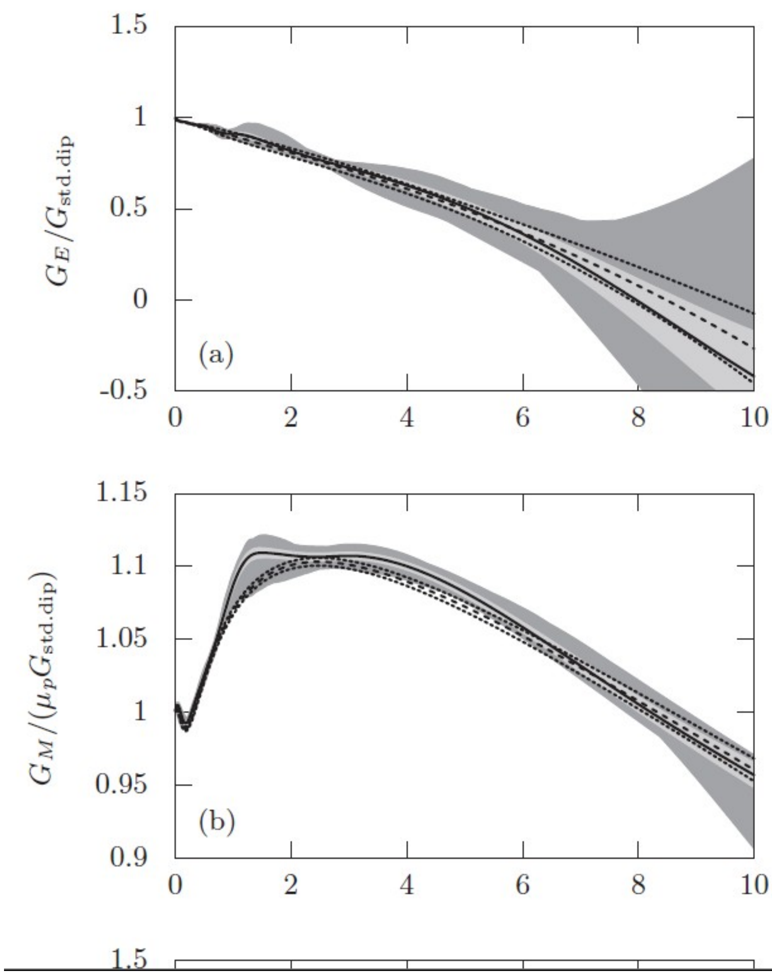
  - ep scattering measurement of radius is limited by the precision of form factor data, which reach Q^2_{min} – 0.003; GeV^2; extrapolation to Q^2=0 is critical
  - To reach this regime, reach low energy and/or small scattering angle

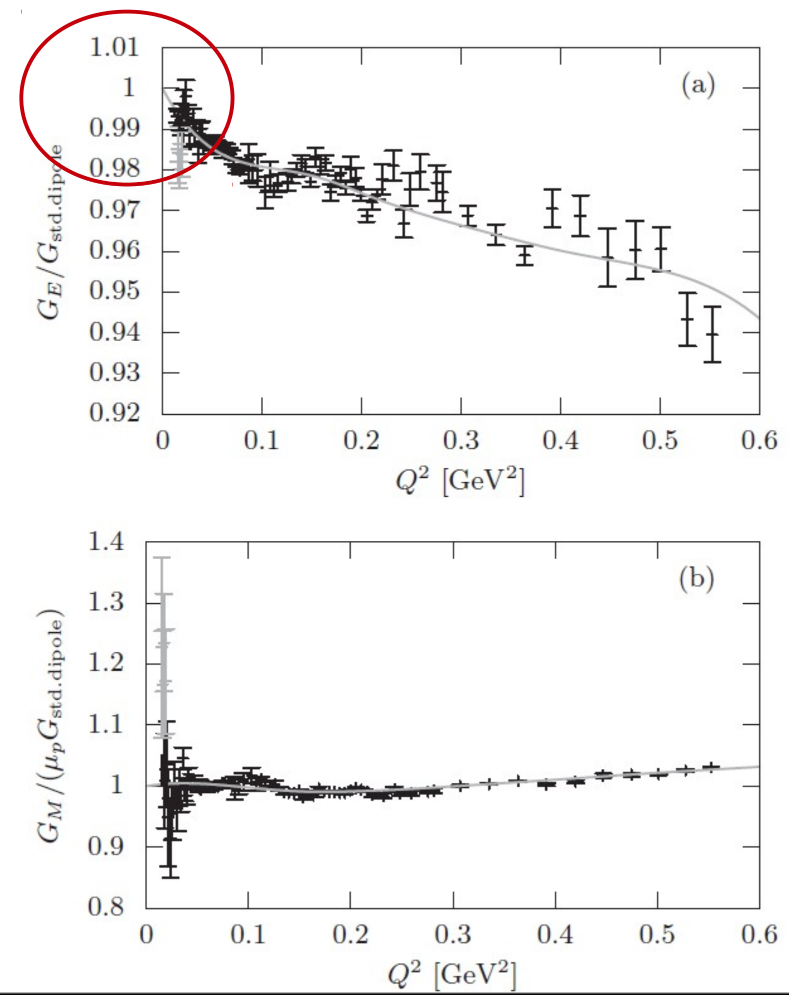
Impact on the proton radius

- Form factors near $Q^2=0$

PHYSICAL REVIEW C 90, 015206 (2014)

$$G_{\text{standard dipole}}(Q^2) = \left(1 + \frac{Q^2}{0.71\ \text{GeV}^2}\right)$$





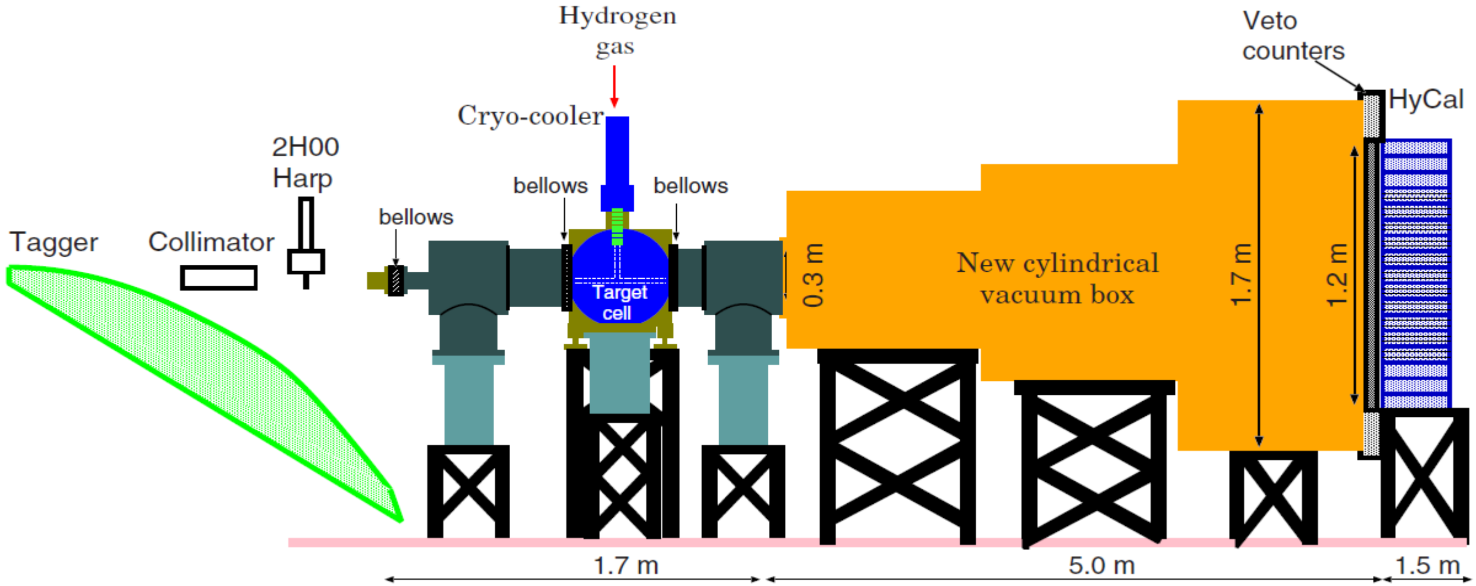
Impact on the proton radius

- Example of the PRad experiment :

http://inspirehep.net/record/1300303

E_{beam} ~ few GeV   Current ~ 10nA   Hydrogen gas target; L ~ 6 10^{28} cm^{-2} s^{-1}

Scattering angle ~ 0.7– 6° → Q^2 ~ 10^{-4} – 10^{-2} GeV^2



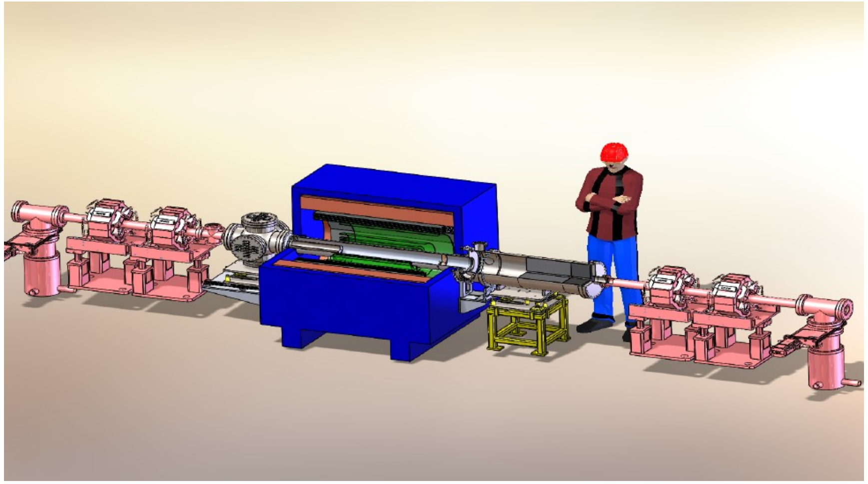
Run time ~15 days; uncertainty on r_E ~ 0.2% (stat) ⊕ 0.4% (exp. syst)

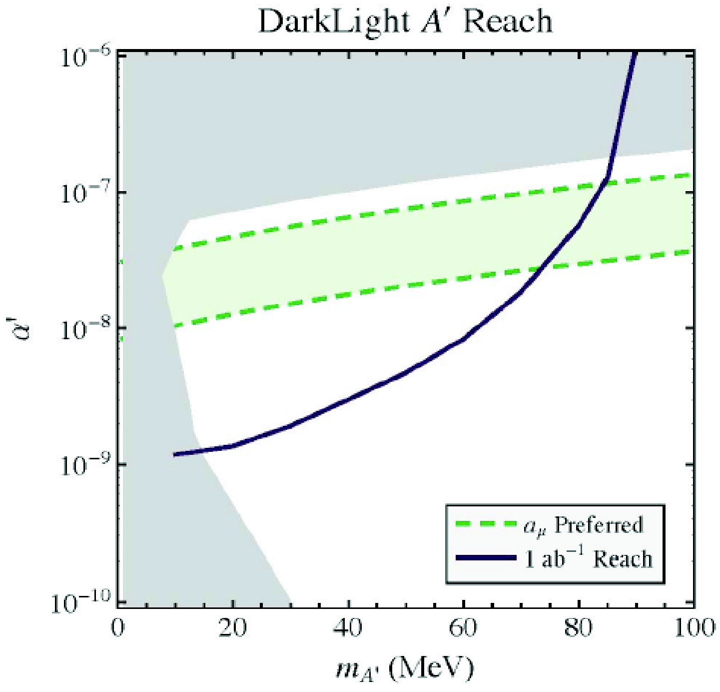
- PERLE could contribute here with increased statistics, if better systematics can be achieved (lower energy → larger angles and better angular measurement)
  - Example : E = 300 MeV (one turn), θ_{min} = 4° → Q^2 ~ 4 10^{-4} GeV^2

Direct detection of dark photons : DarkLight

arXiv:1412.4717

- Motivation for new, light “dark” gauge bosons :
  - positron excess in astrophysical data
  - Candidate to explain a_μ discrepancy, if real
  - Confront with possible deviation observed in the $\sin^2\theta_W$ measurement
- 100 MeV beam, 5 mA; Hydrogen gas target; silicon and gas tracking detectors
- Reconstruct $e^- p \rightarrow e^- p\, e^+ e^-$; final state electrons in the range 10-90 MeV; ~1 MeV mass resolution
- Small scale, short runtime experiment





Conclusions and next steps

- With the extreme luminosities that can be achieved, ep scattering experiments compete with colliders in the measurement of some fundamental electroweak parameters
- Many challenges on the experimental and phenomenological sides
  - Running mode
  - Target cooling & stabilization.
  - Nucleon structure

  for PERLE to maintain its high-luminosity potential for physics
- Measurements of the proton form factors can be brought to a new level of precision. Beyond the weak mixing angle, one direct application is the consolidation of the proton radius measurements using electrons
- The SM prediction of $\sin^2\theta_W$ is unambiguous, and well-motivated extensions of the SM produce visible effects, that can be tested using direct searches

Conclusions and next steps

- Fundamental measurements with different needs : weak mixing angle; proton radius

- Limiting factors
  - Global improvement of proton form factors by a factor ~10, for $Q^2 \leq 10^{-2}$ GeV^2
  - $\sin^2\theta_W$: statistics
    - Beam/target interactions : what heat load can we sustain? To what level can the target noise be maintained?
    - Measurement can not be performed in ER mode; needs beam extraction, and dedicated time. How much can we afford?
  - Proton radius : angular acceptance
    - Dedicated, low-current run (few days beam time should be enough)?
    - How low in angle can we reach (beam backgrounds, …?)

- With answers to these questions we can start thinking more concretely about which experiments are realistic, and the corresponding options for the detectors.

Thank you!

- Max Klein, Boris Militsyn, David Lhuillier, Frank Maas, Kurt Aulenbacher, Hubert Spiessberger, Niklaus Berger

  + many others