Physics at MESA

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JG|U

PRISMA+

Overview

- The future of electron scattering in Mainz:
  The MESA accelerator

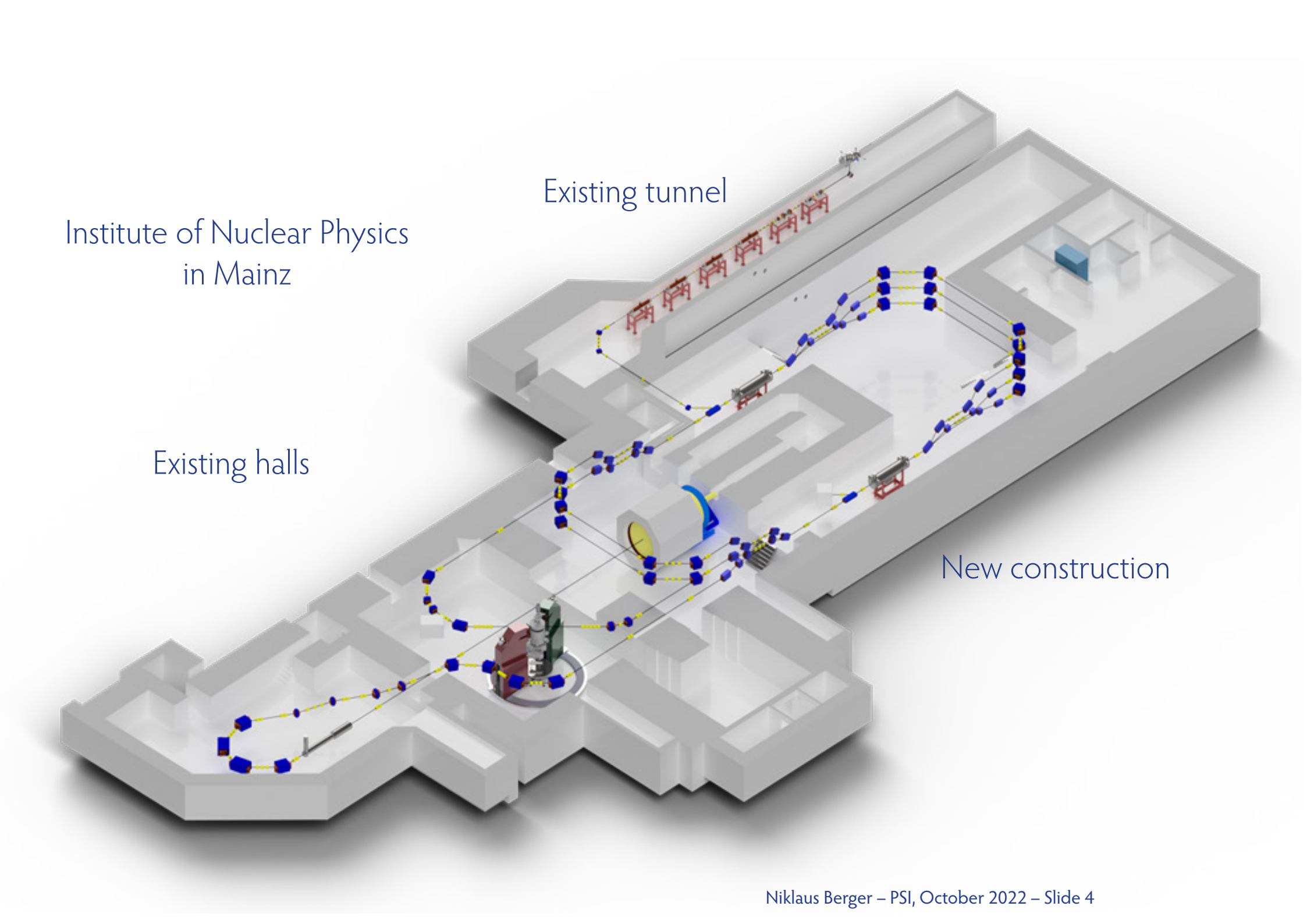
- Parity violation, the weak mixing angle and more:
  The P2 Experiment

- Form factors, few-body systems and nuclear astrophysics
  The MAGIX Spectrometer

- Home-made dark matter
  The DarkMESA beam-dump experiment

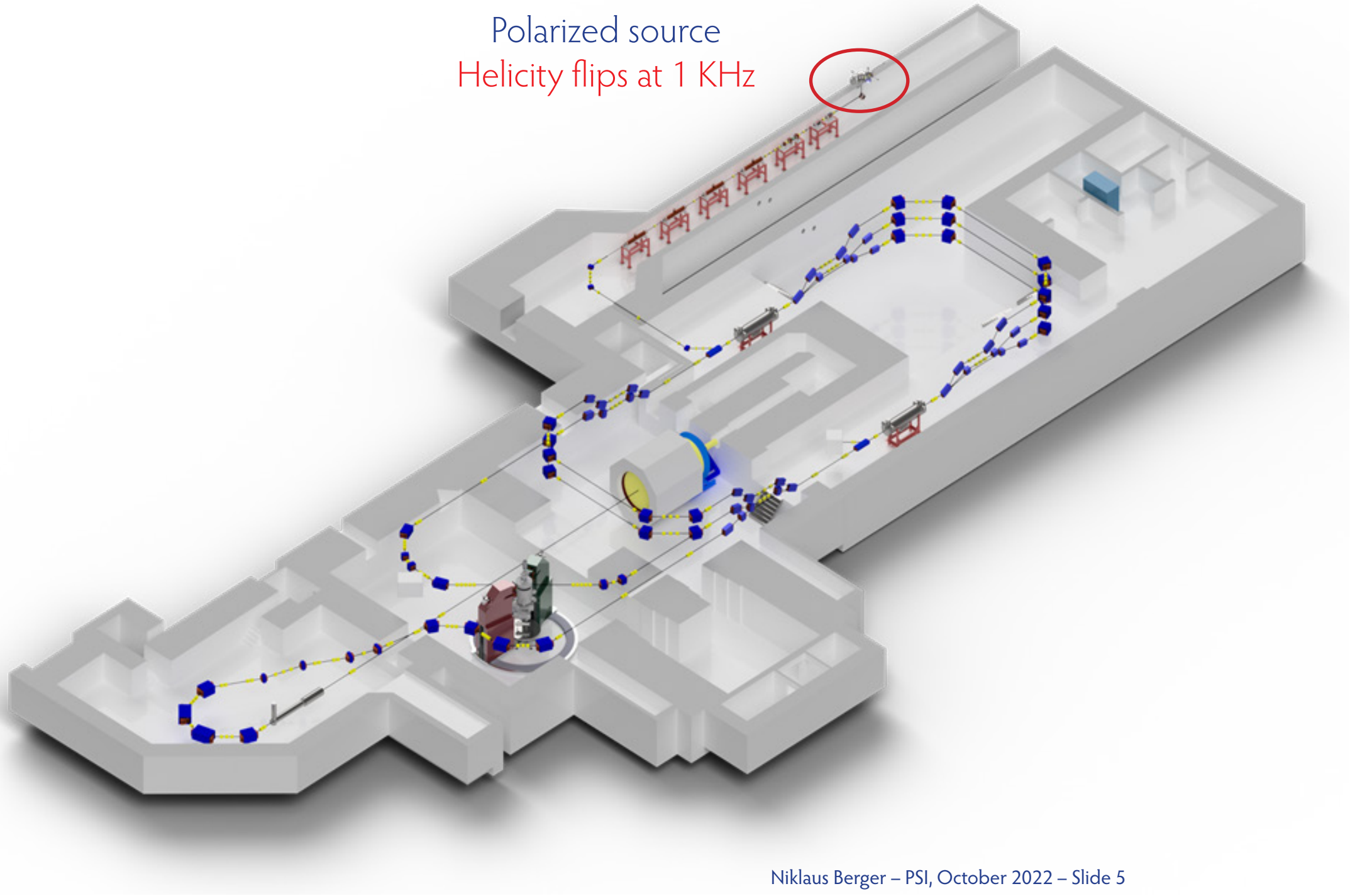
The Mainz Energy-Recovery Supercodcuing Accelerator

(MESA)


Institute of Nuclear Physics
in Mainz
Existing tunnel
Existing halls
New construction

Polarized source

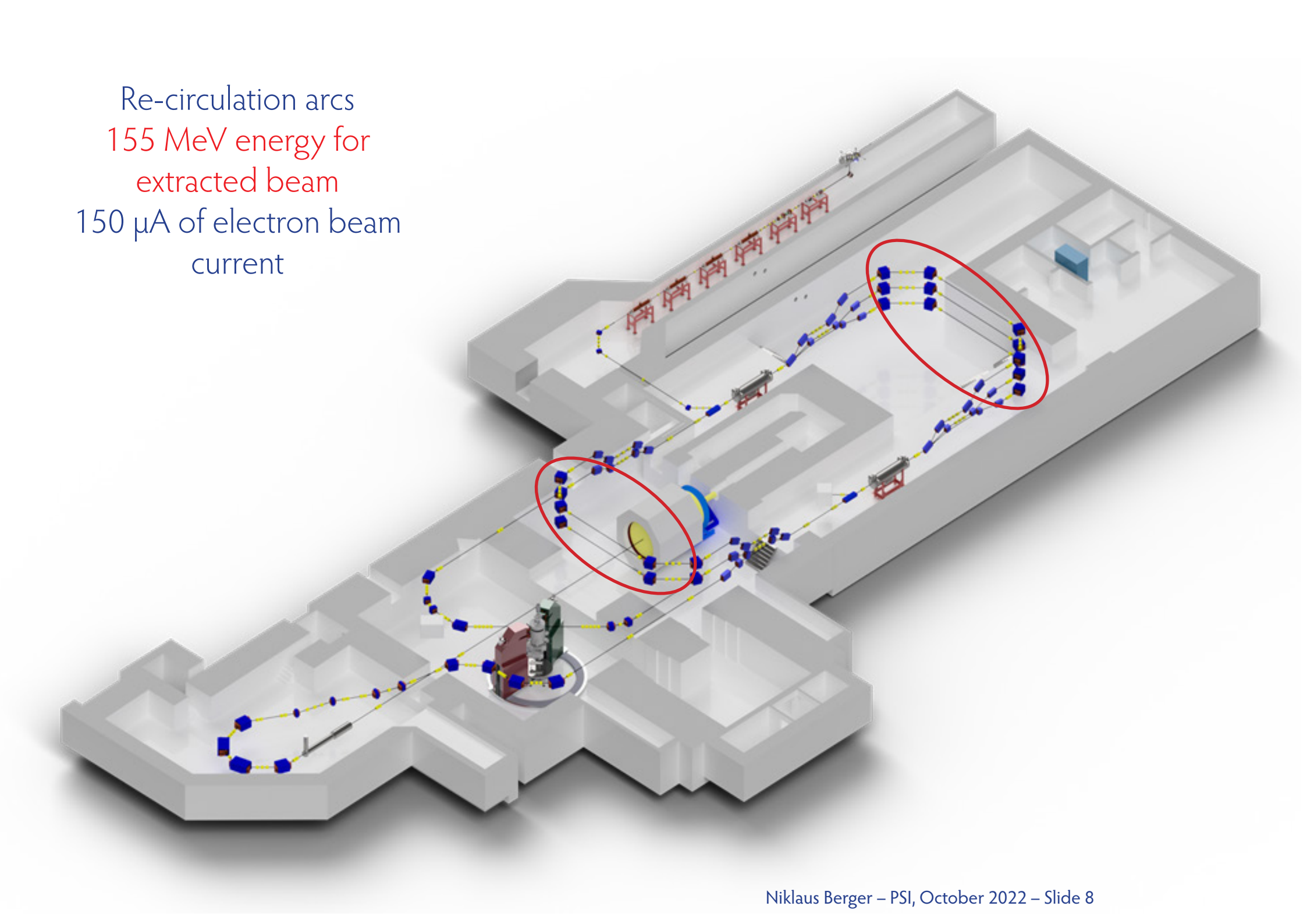
Helicity flips at 1 KHz



Beam preparation and acceleration to 5 MeV

Two superconducting cryomodules
Accelerate beam by 25 MeV per pass

Re-circulation arcs
155 MeV energy for extracted beam
150 µA of electron beam current



Re-circulation arcs

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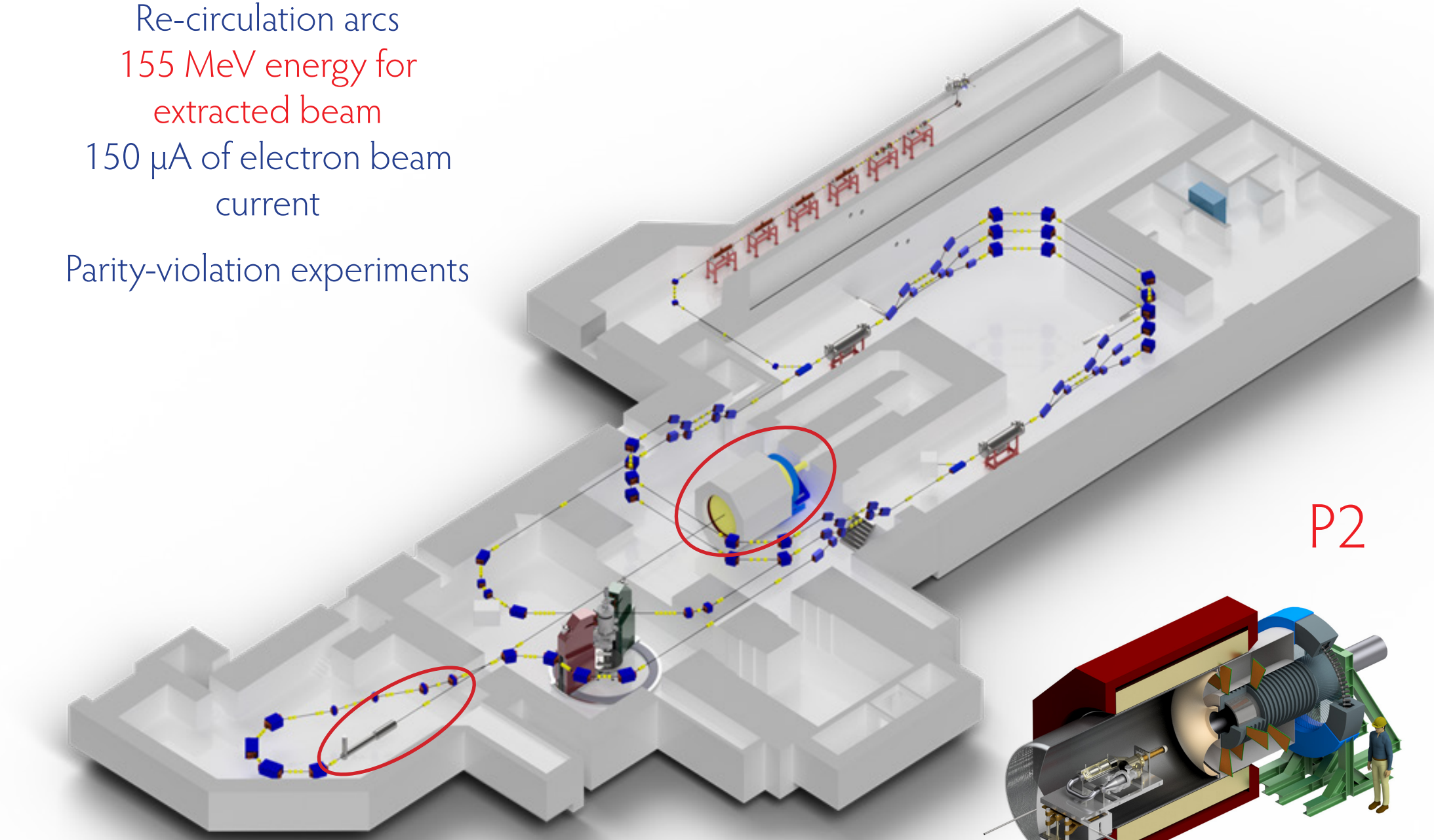
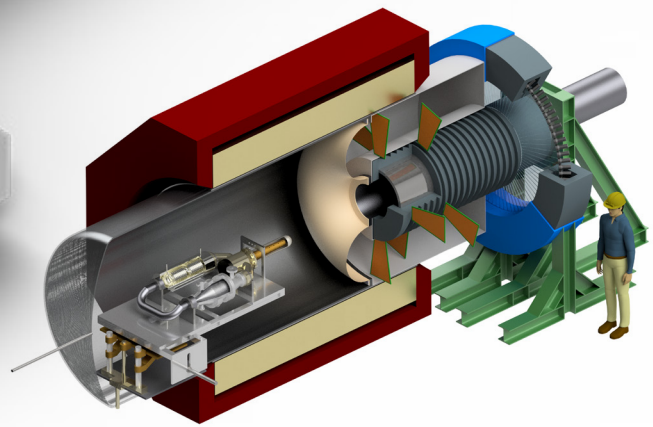
150 μA of electron beam current

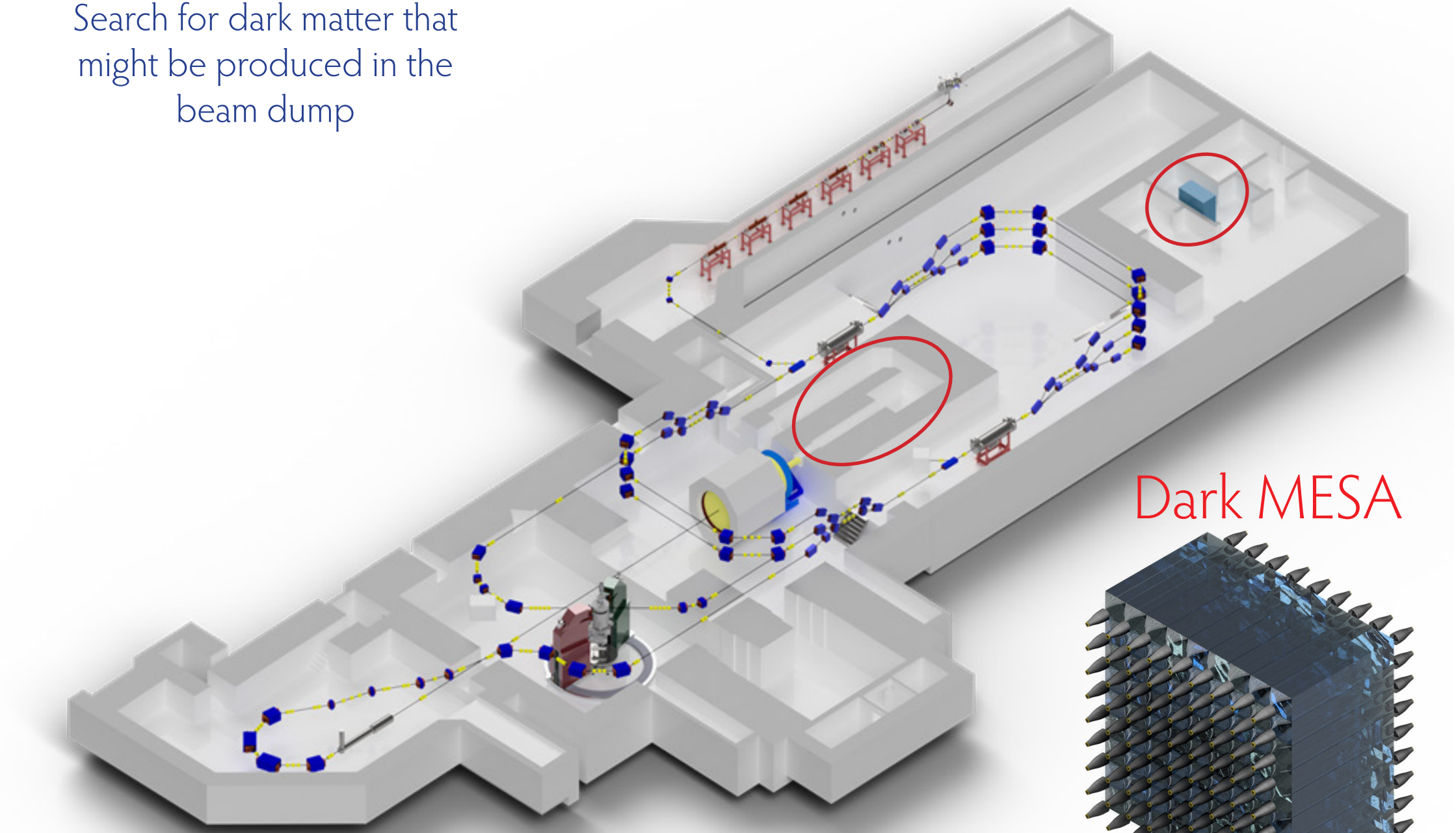
Parity-violation experiments



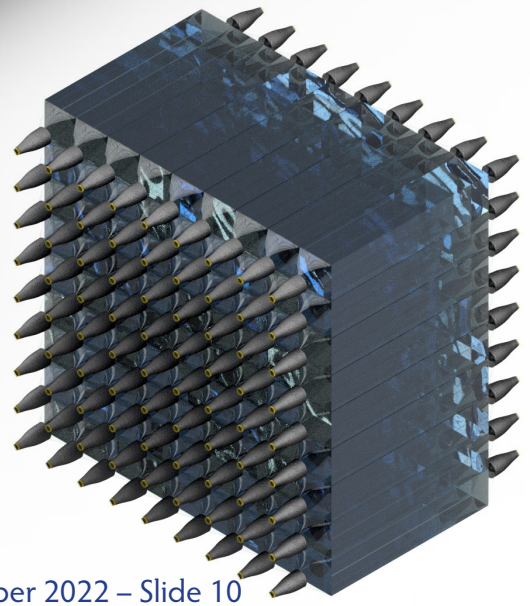
P2



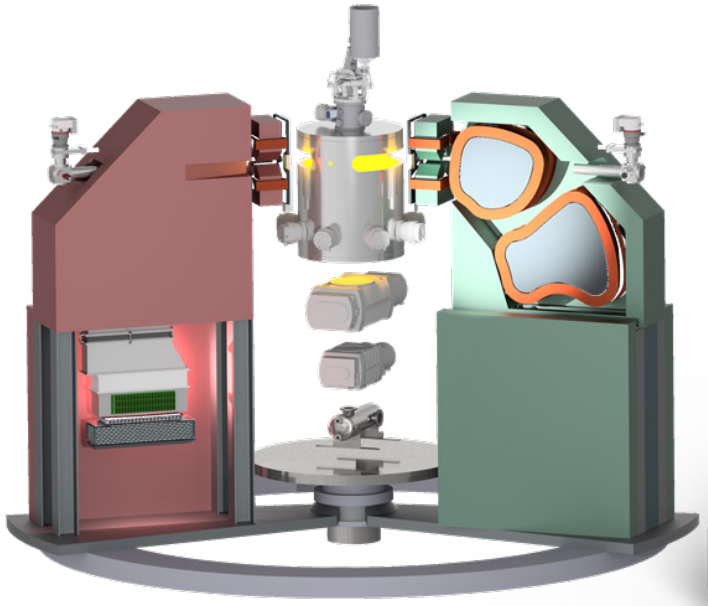
Search for dark matter that might be produced in the beam dump



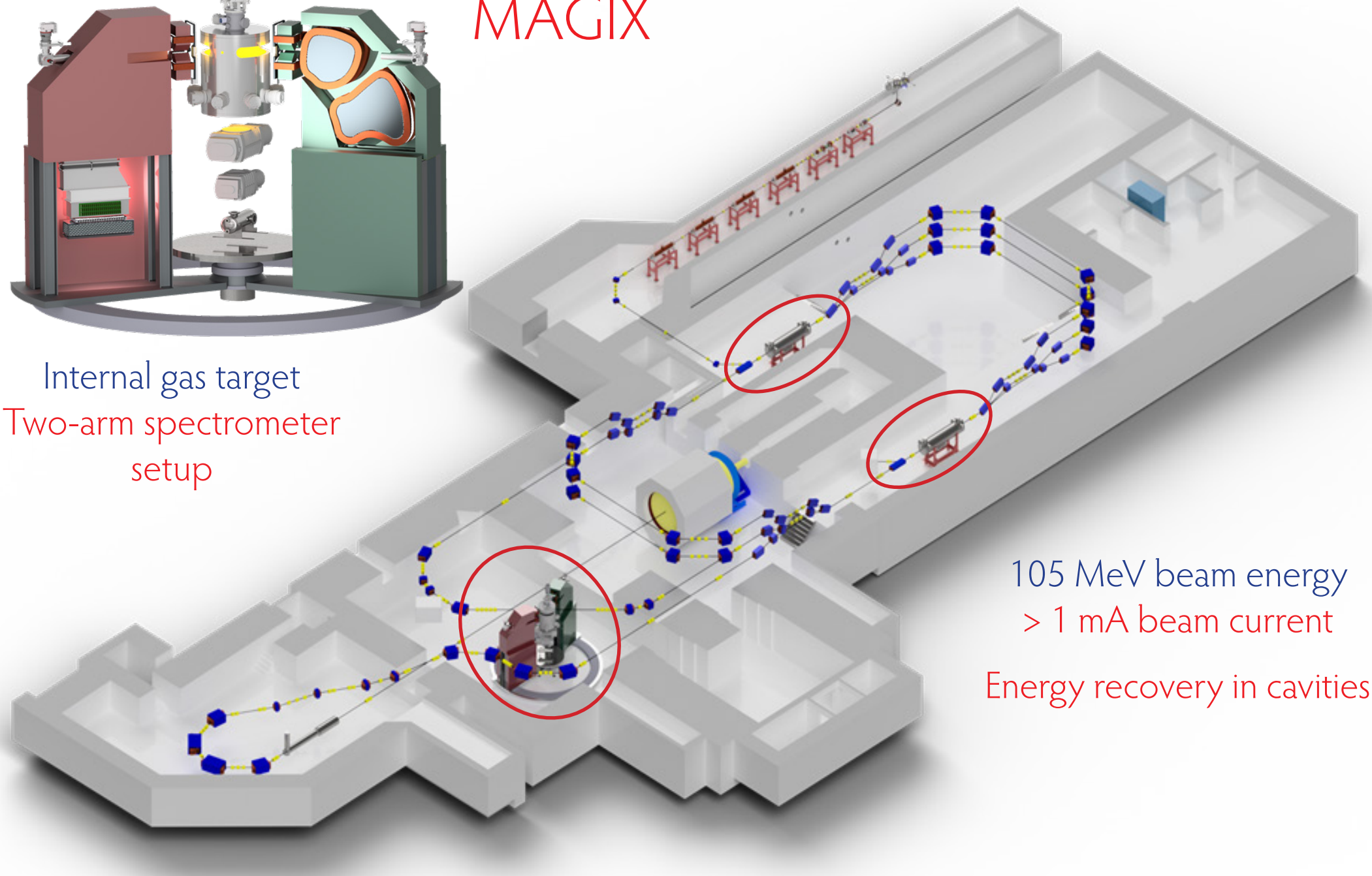
Dark MESA



MAGIX



Internal gas target
Two-arm spectrometer setup



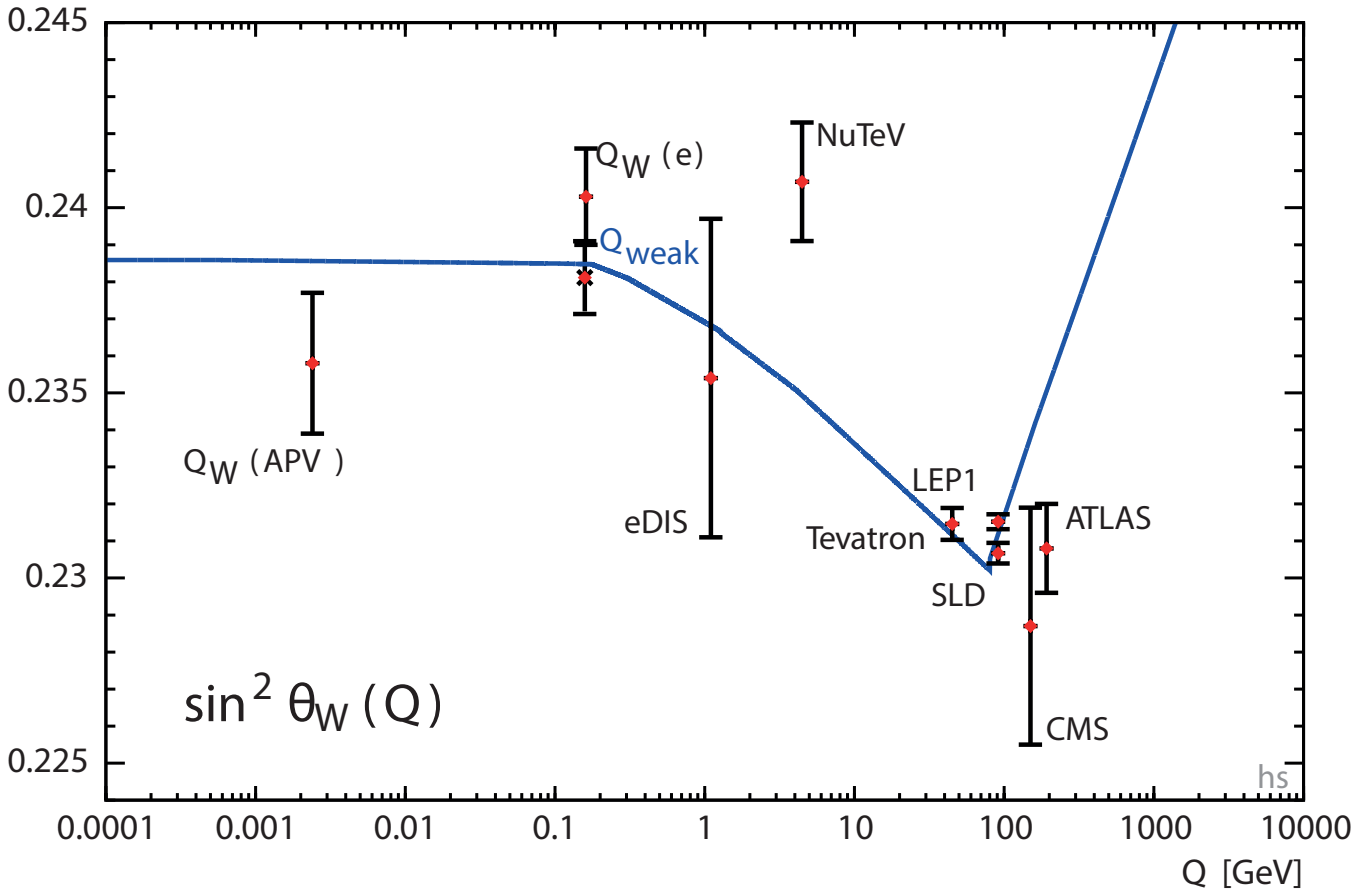
105 MeV beam energy
> 1 mA beam current

Energy recovery in cavities

Studying parity violation with the P2 experiment

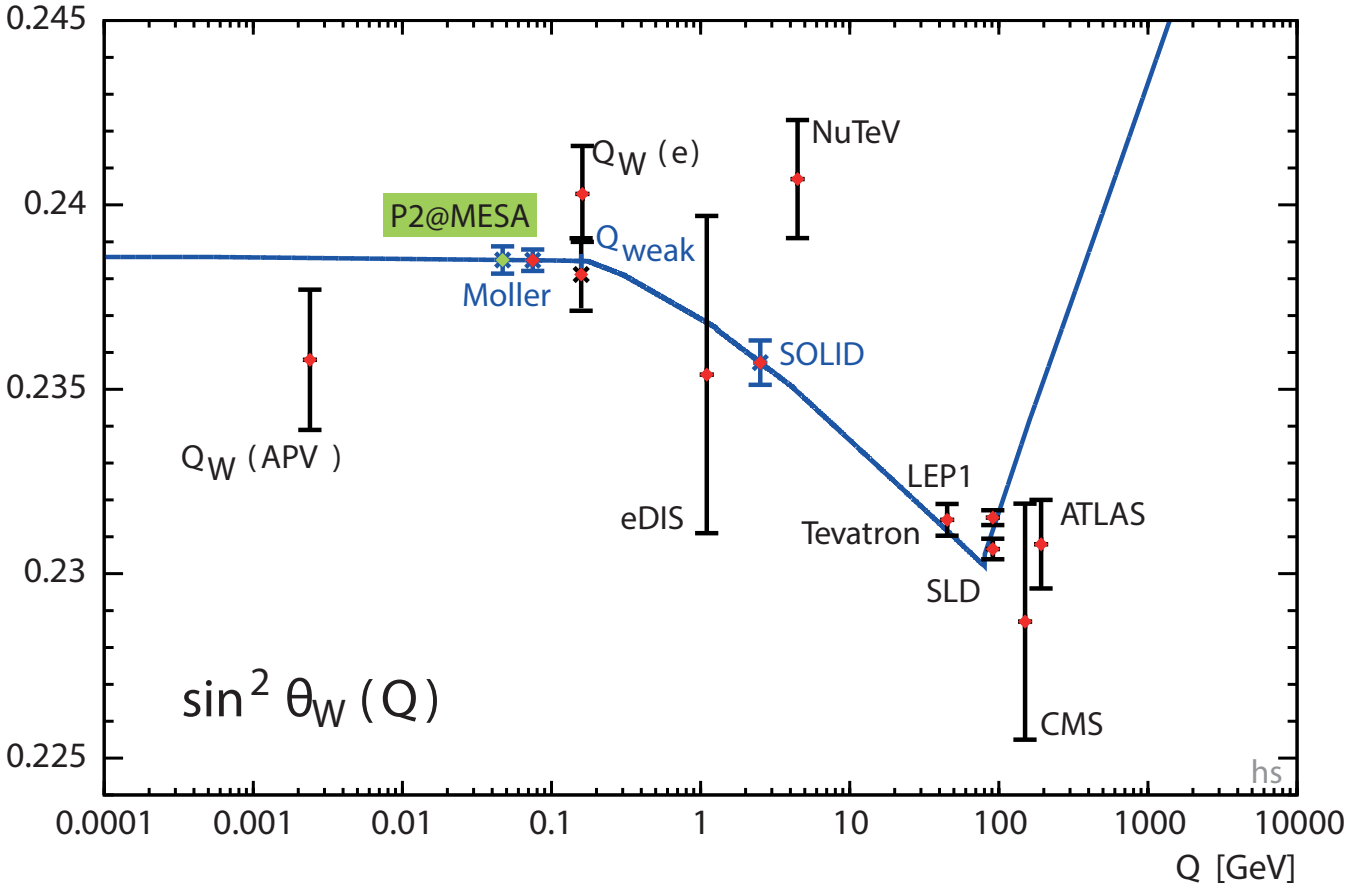
The weak mixing angle $\sin^2\theta_W$

- One of the fundamental parameters of the standard model
  (the two best measurements disagree, should be resolved)
- Value is a free parameter, scale dependence is predicted by theory with exquisite precision

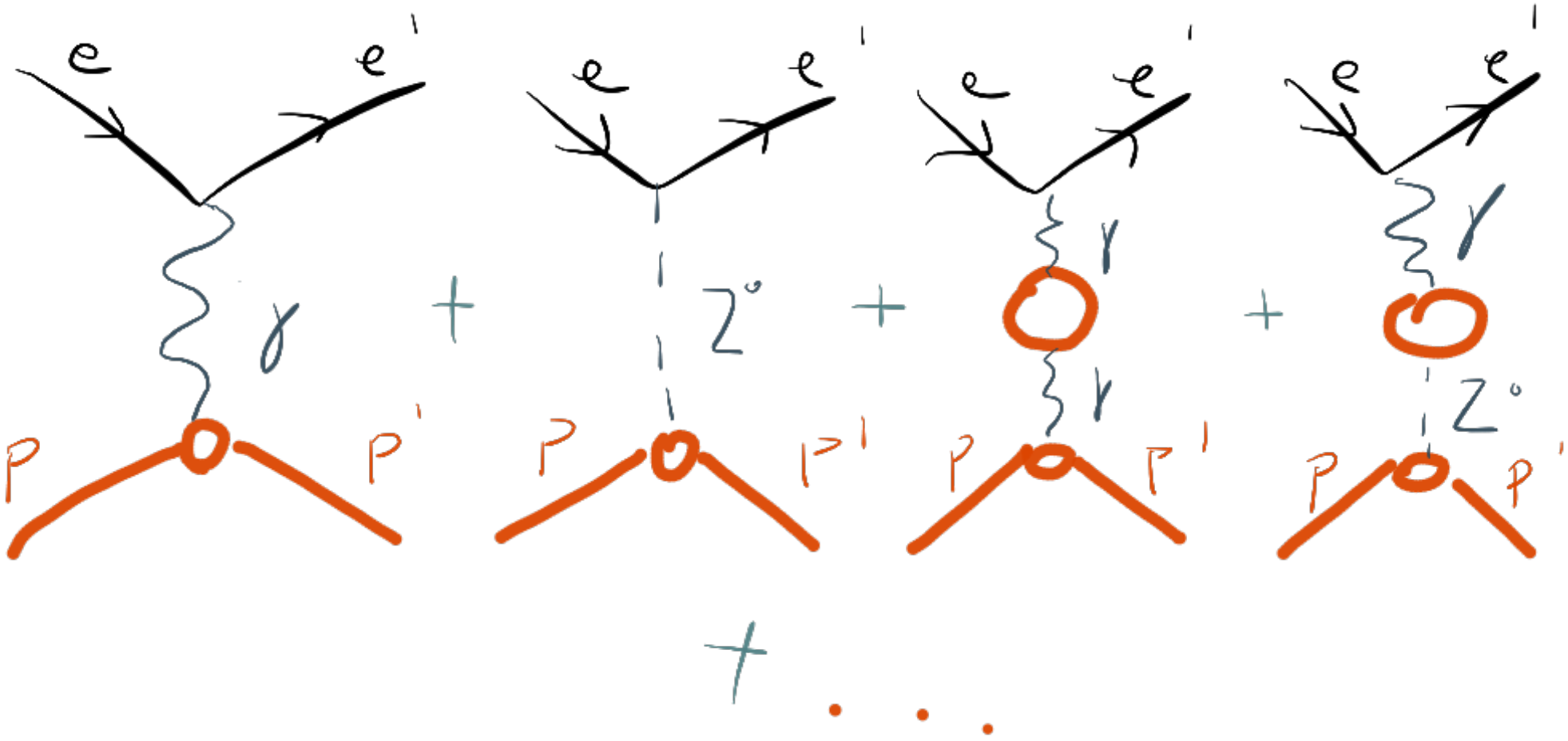


The weak mixing angle $\sin^2\theta_W$

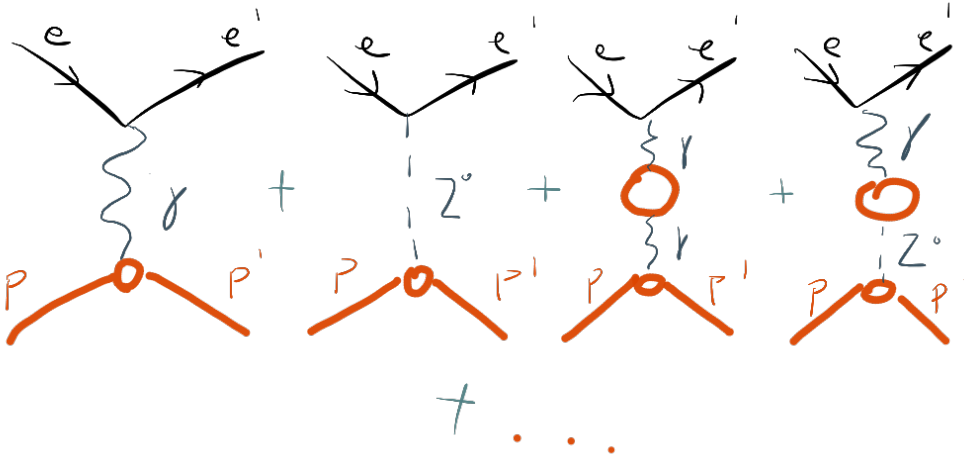
- One of the fundamental parameters of the standard model
  (the two best measurements disagree, should be resolved)
- Value is a free parameter, scale dependence is predicted by theory with exquisite precision
- Aim for a low energy measurement with precision comparable to the LEP/SLD Z-pole measurements

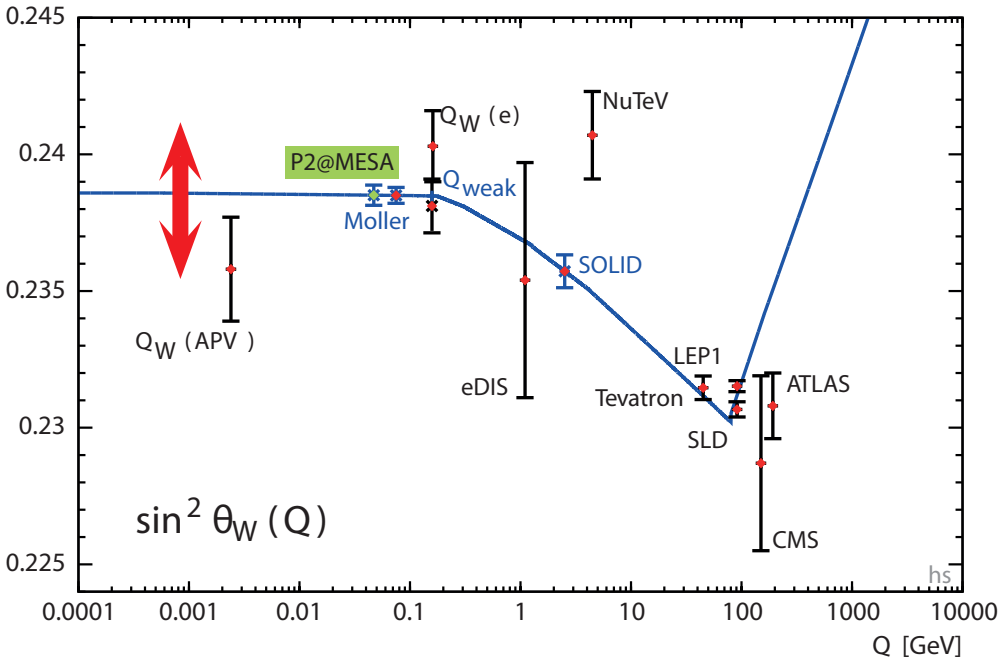


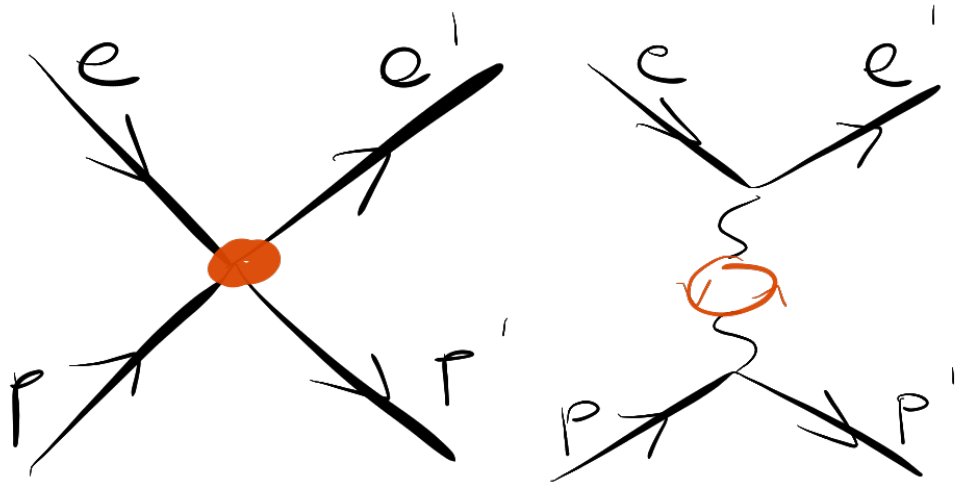
Scale dependence (running) of $\sin^2\theta_W$

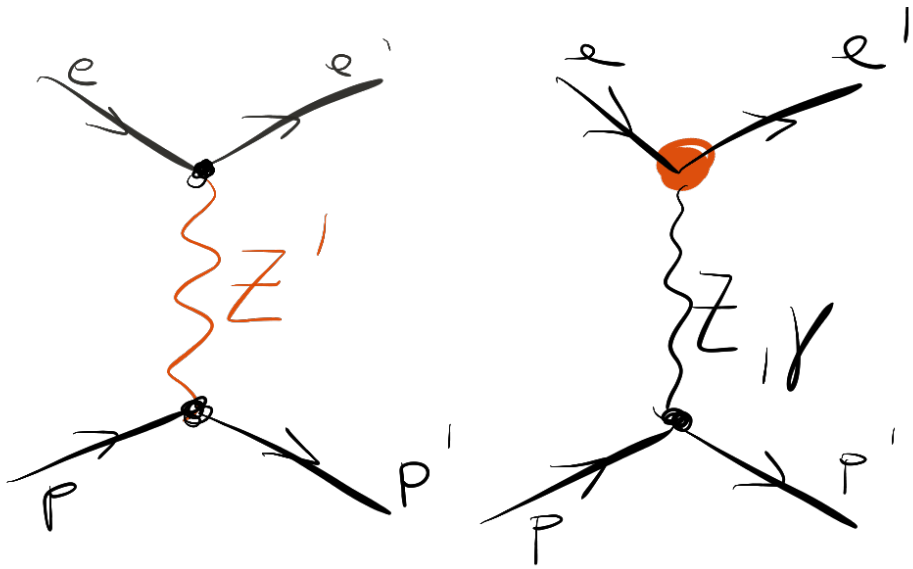


New Physics in the running of $\sin^2\theta_W$

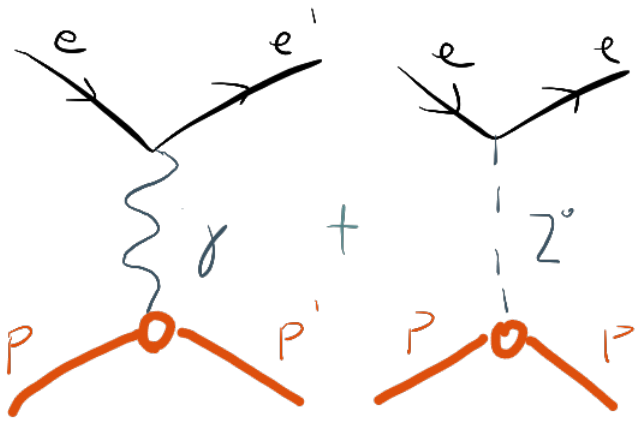


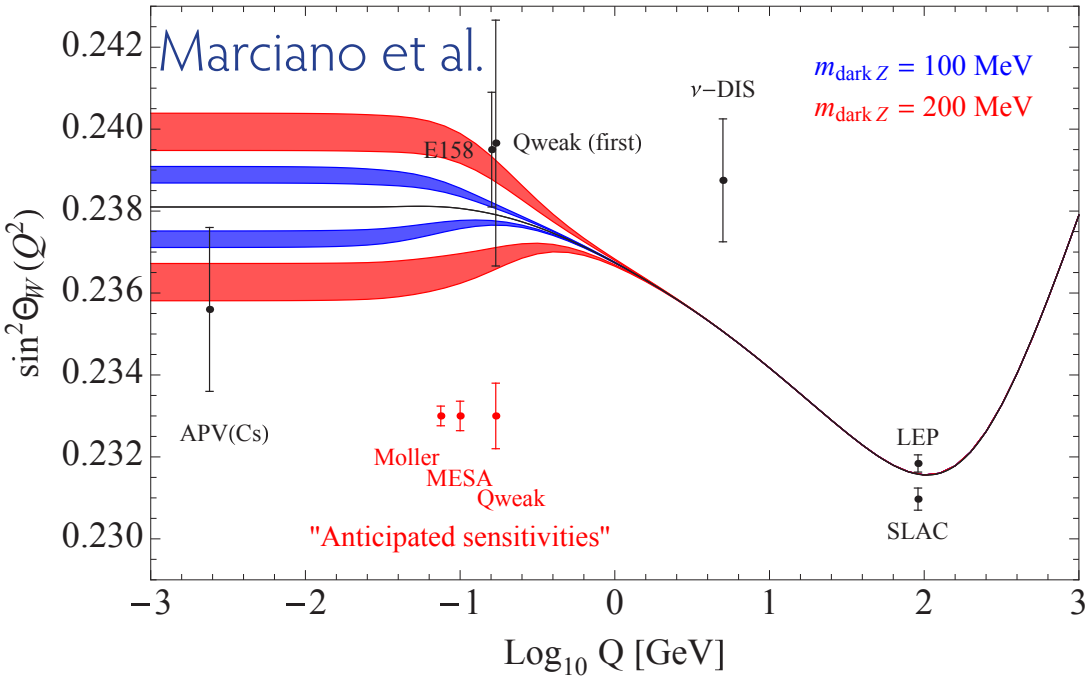


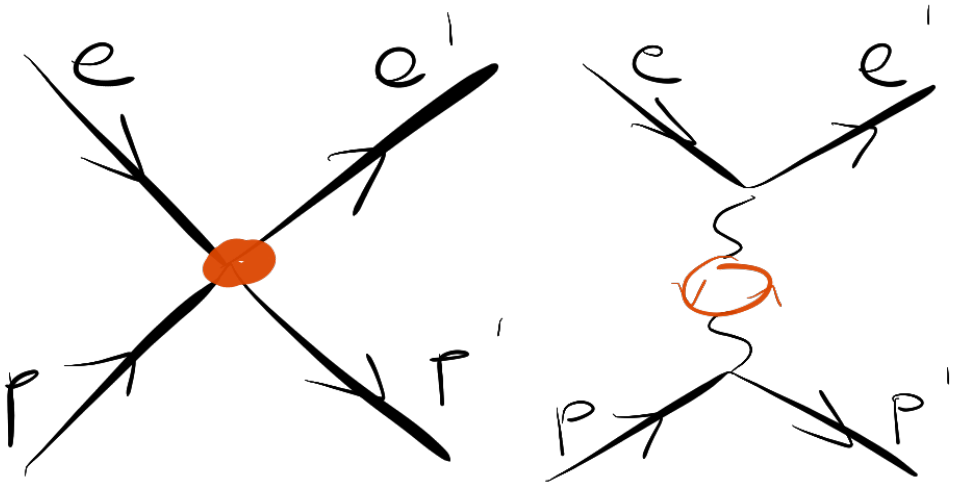




Dark Zs


e
e'
γ
+
e
e
Z'
p
p'
p
p'


Marciano et al.
$m_{\text{dark }Z}$ = 100 MeV
$m_{\text{dark }Z}$ = 200 MeV
ν–DIS
E158
Qweak (first)
APV(Cs)
Moller
MESA
Qweak
"Anticipated sensitivities"
LEP
SLAC
$\sin^2\Theta_W(Q^2)$
Log_{10} Q [GeV]
0.242
0.240
0.238
0.236
0.234
0.232
0.230
−3
−2
−1
0
1
2
3


e
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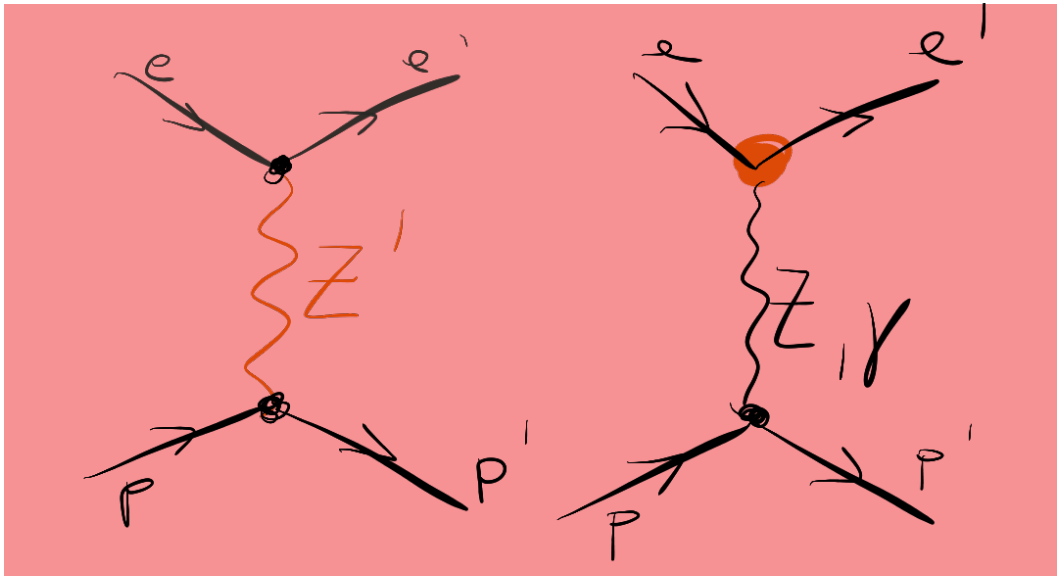
e
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e
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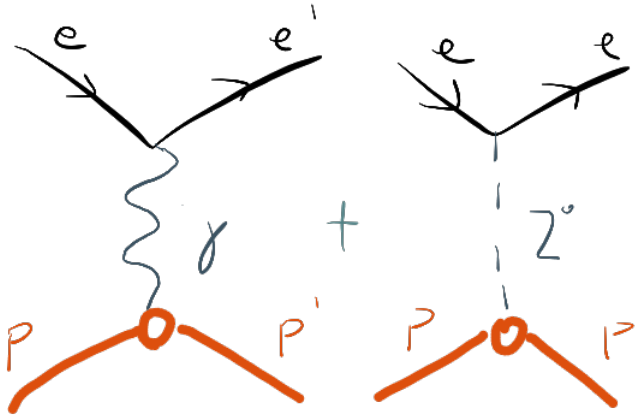
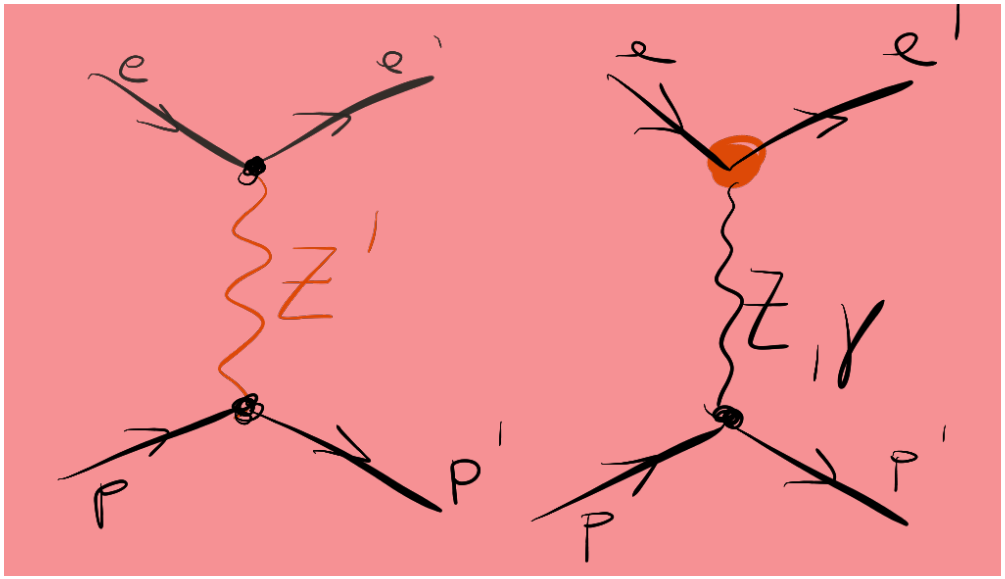
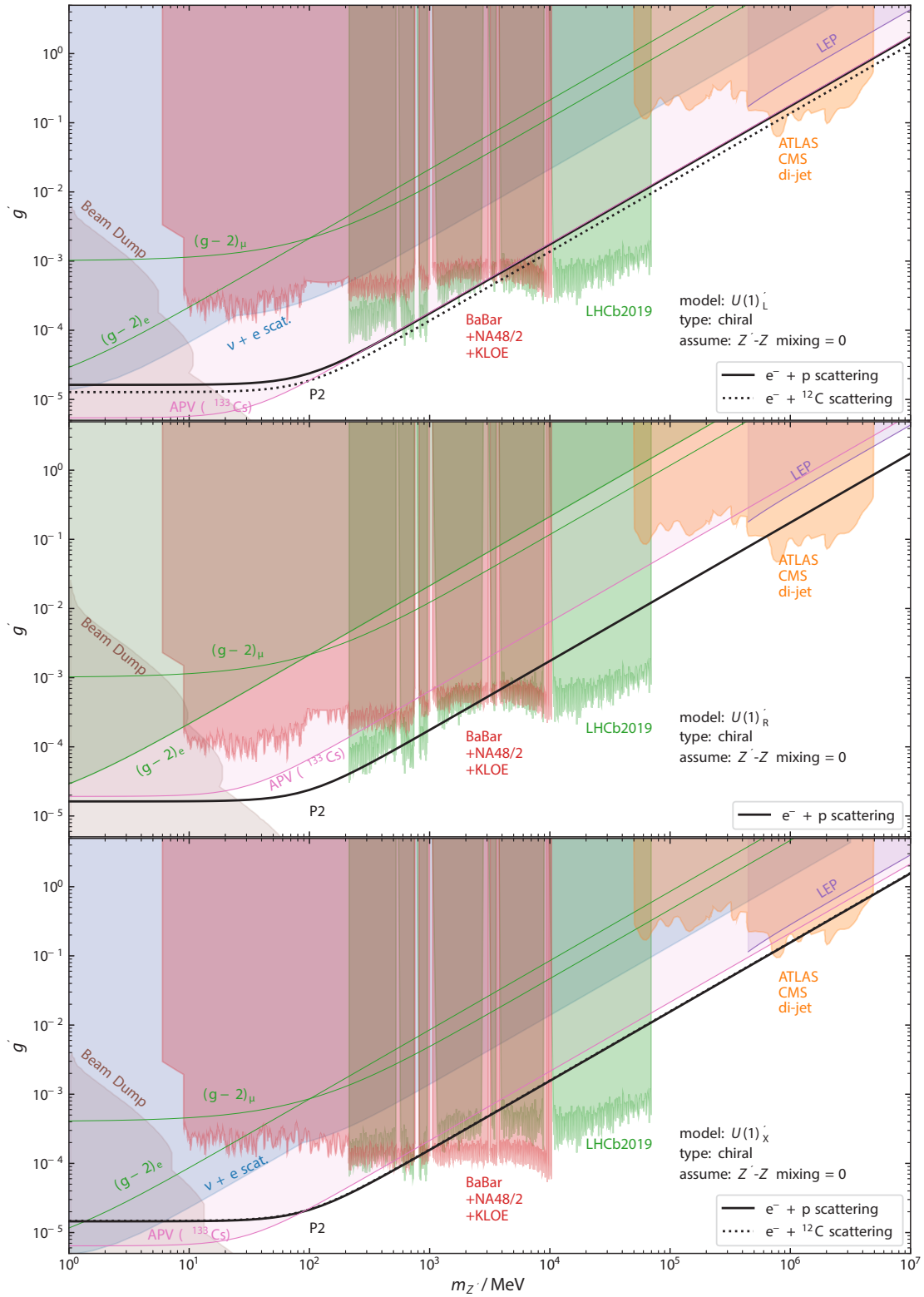
Z
γ
p
p'

Dark Zs

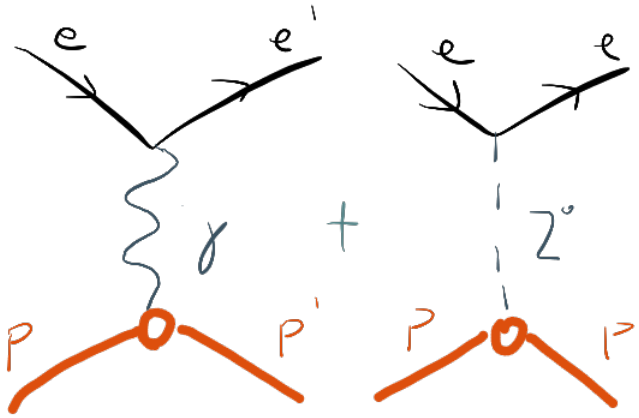


Bhupal Dev, Rodejohann, Xu, Zhang,
arXiv:2103.09067





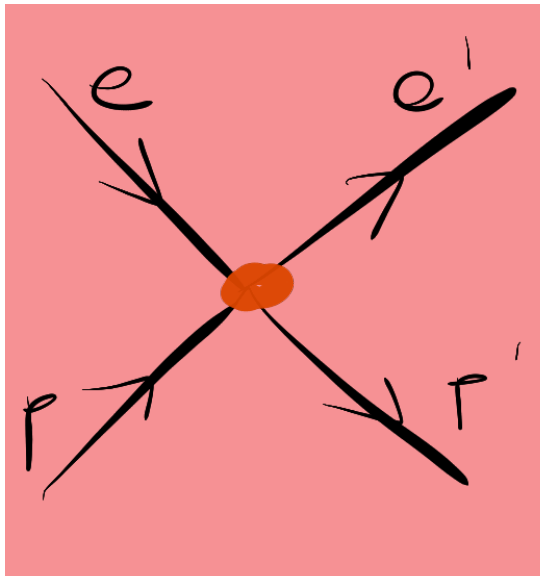
Contact Interactions

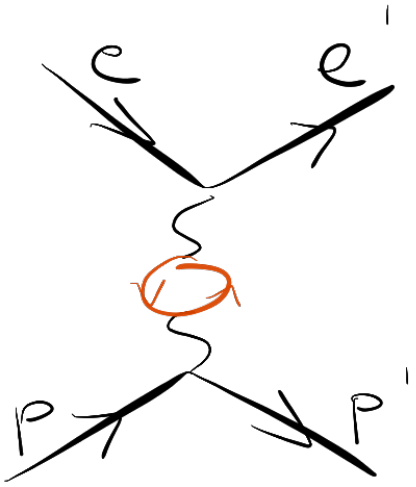


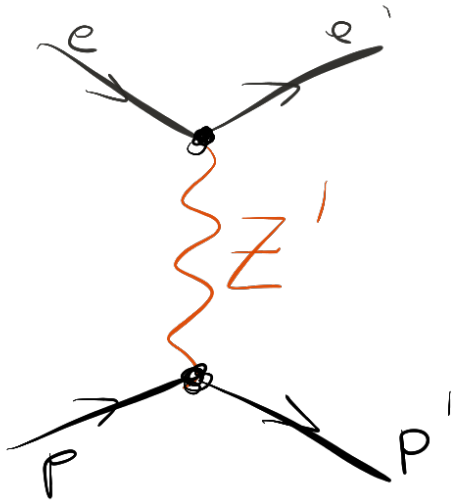
Contact interactions up to

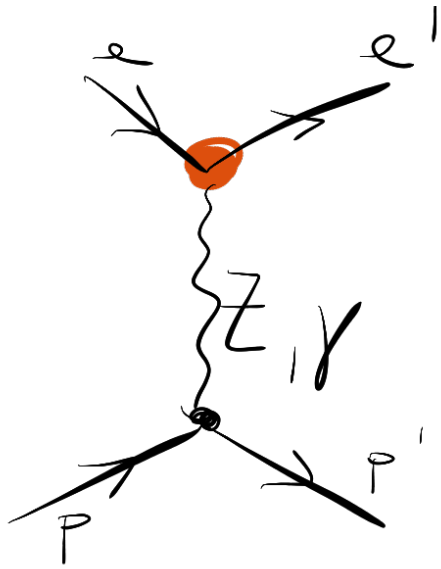
49 TeV

(comparable to LHC at 300 fb^{-1})



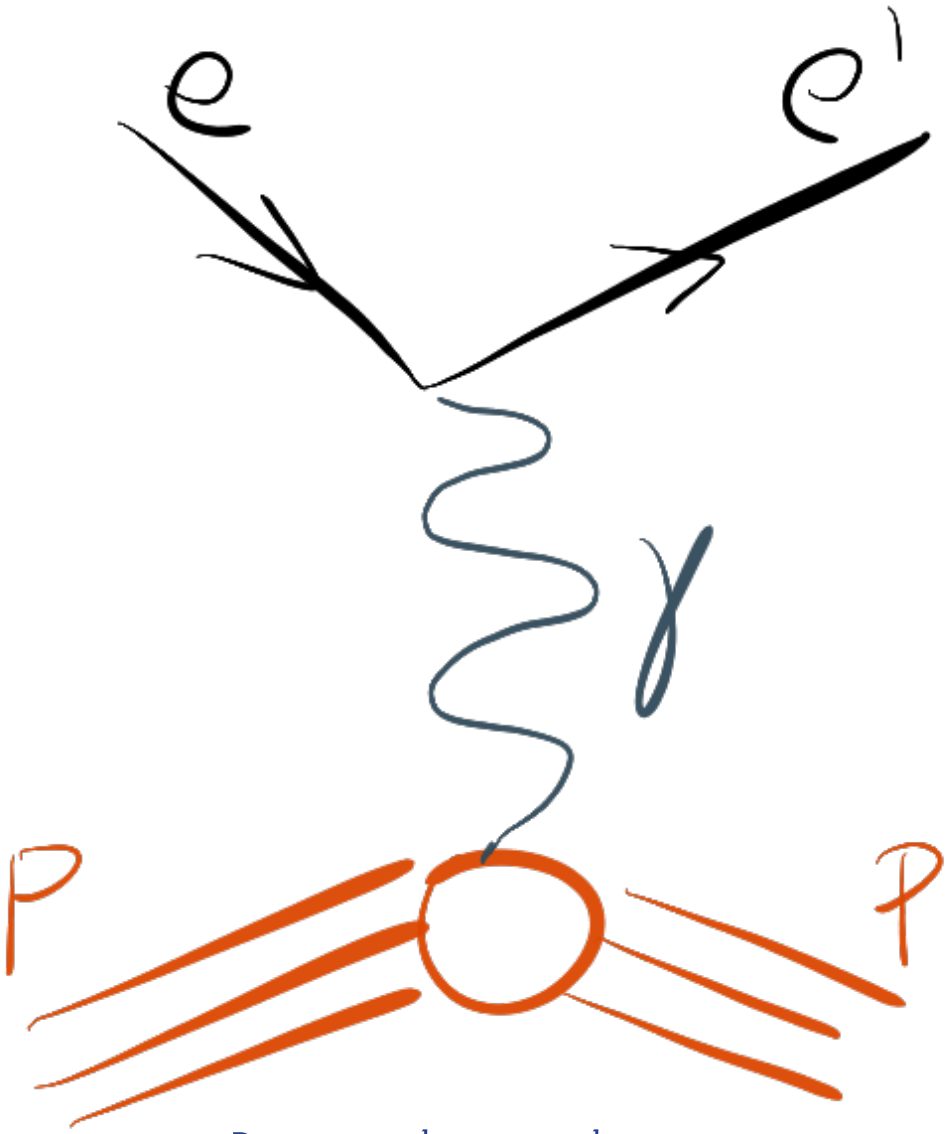






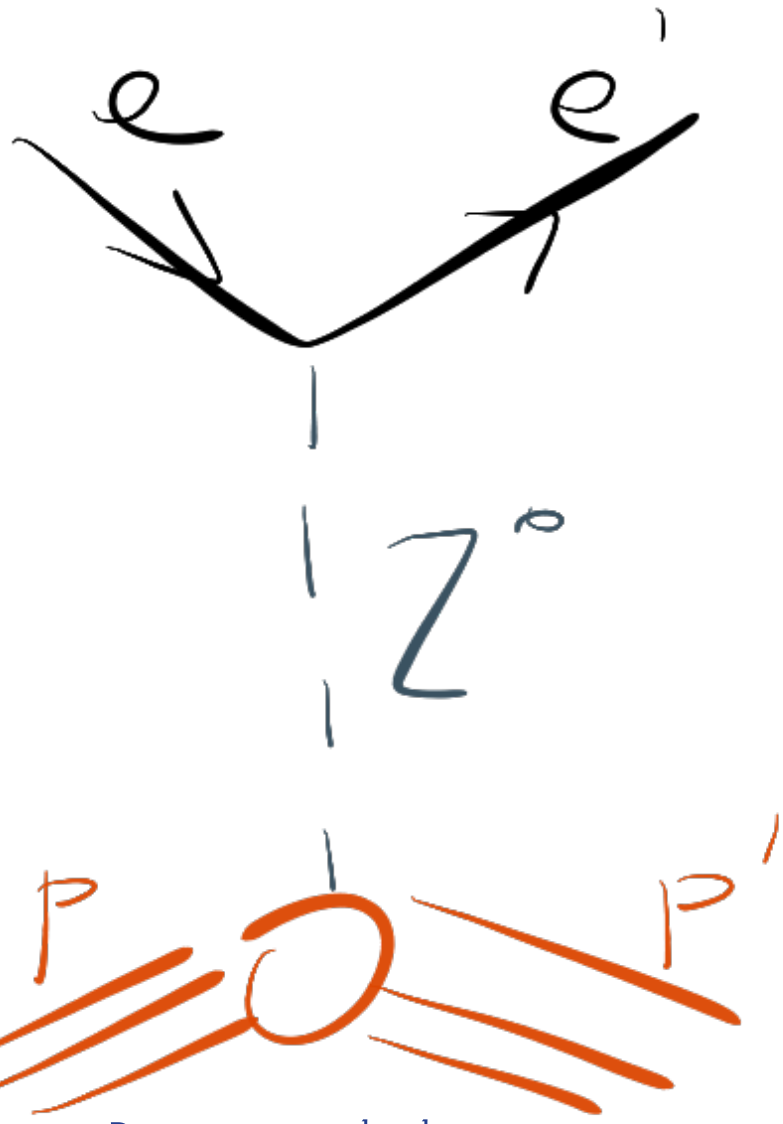
How to measure the weak mixing angle?

Weak mixing angle and charges



Proton electric charge

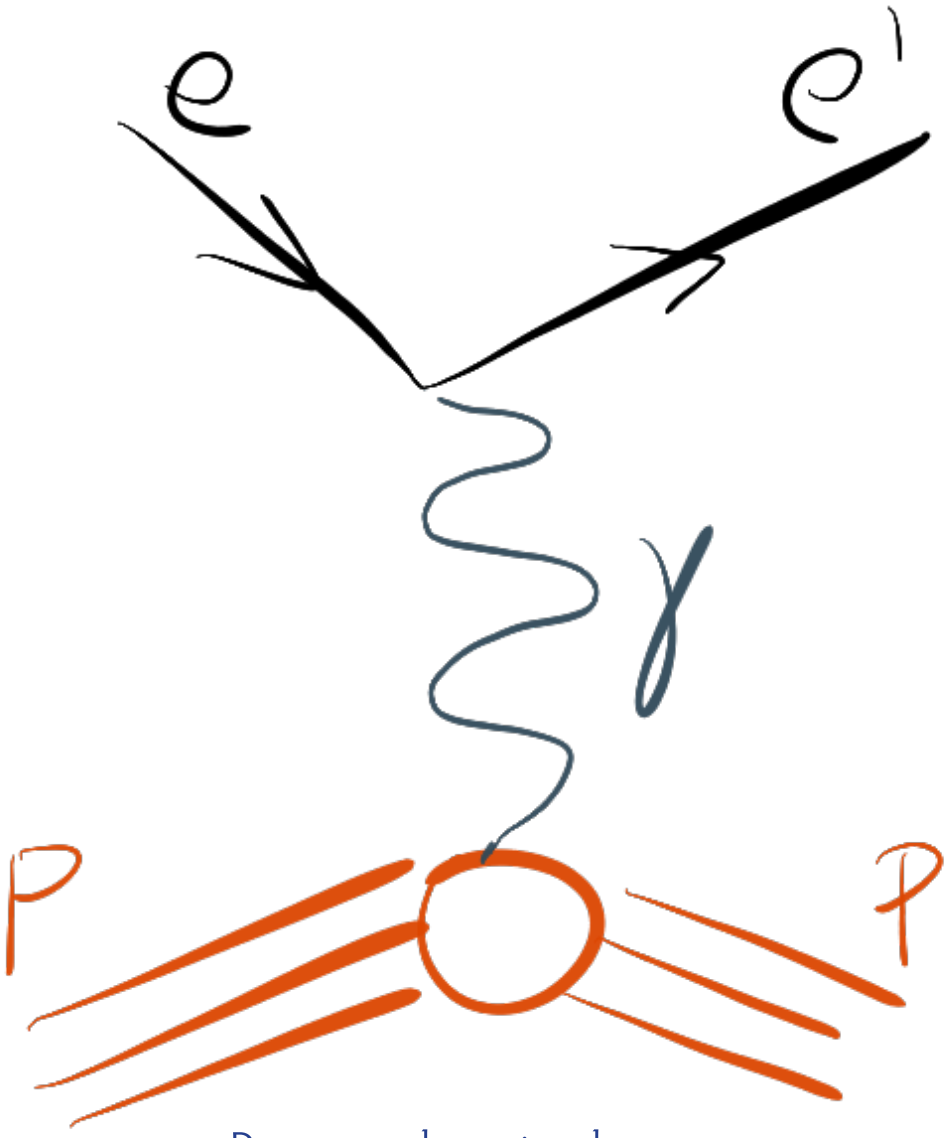
+e



Proton weak charge

$1 - 4 \sin^2\theta_W$

Weak mixing angle and charges



Proton electric charge

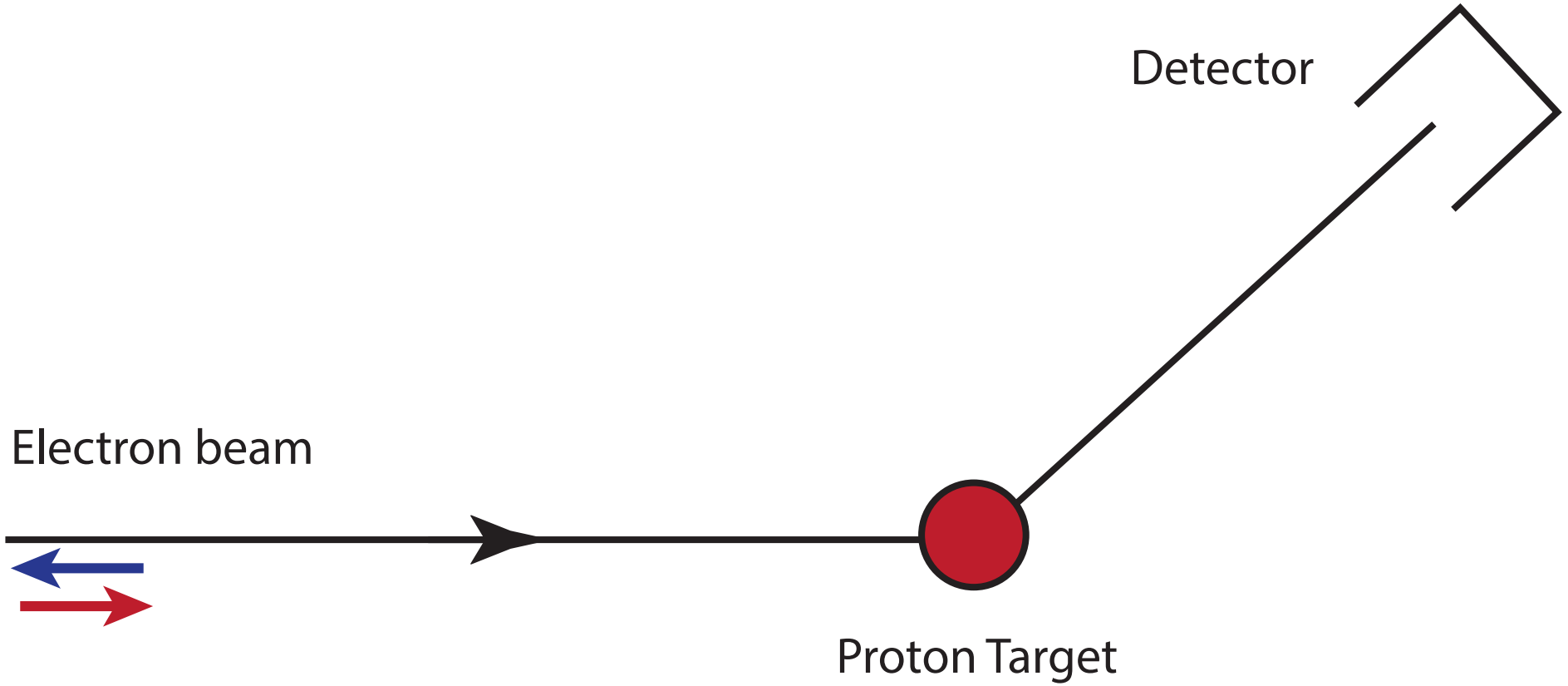
+e

Violates parity!

Proton weak charge

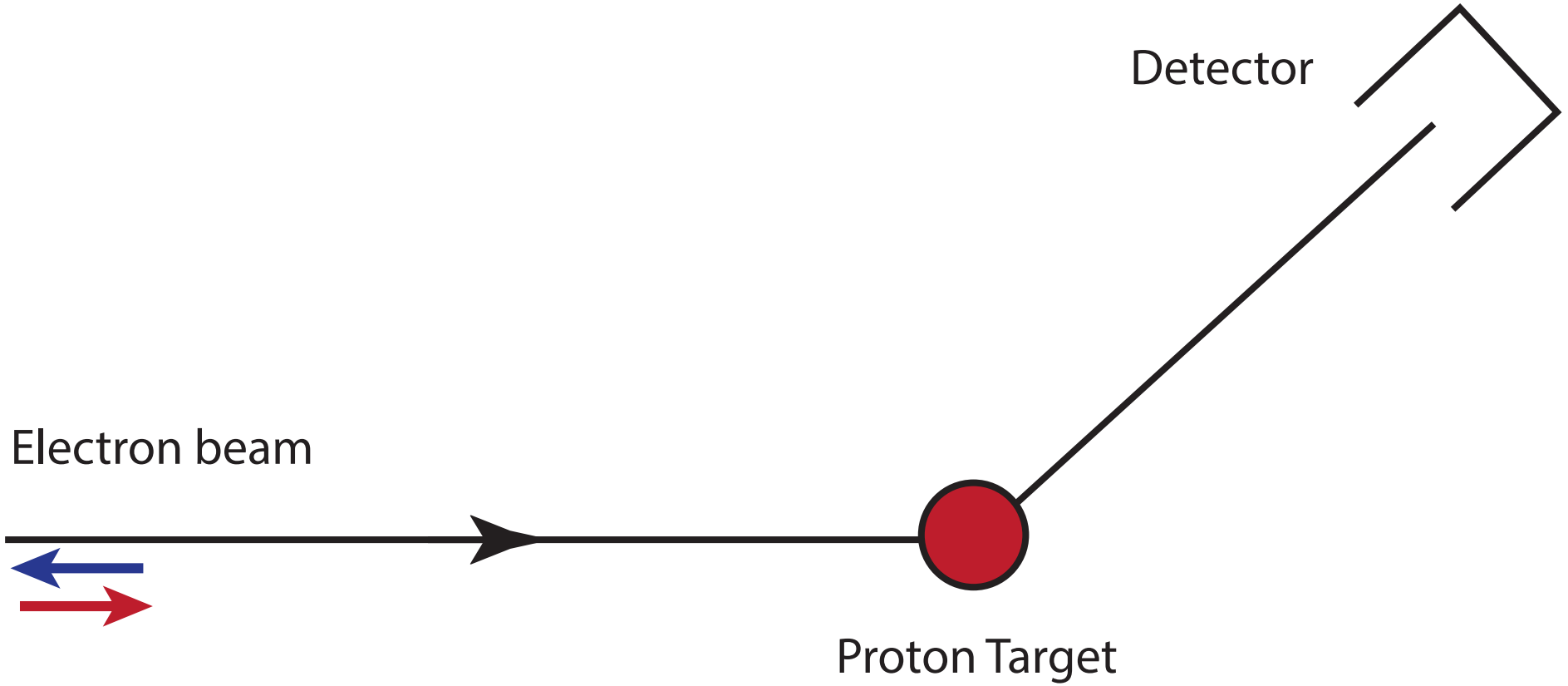
$1 - 4 \sin^2\theta_W$

Parity violating electron scattering



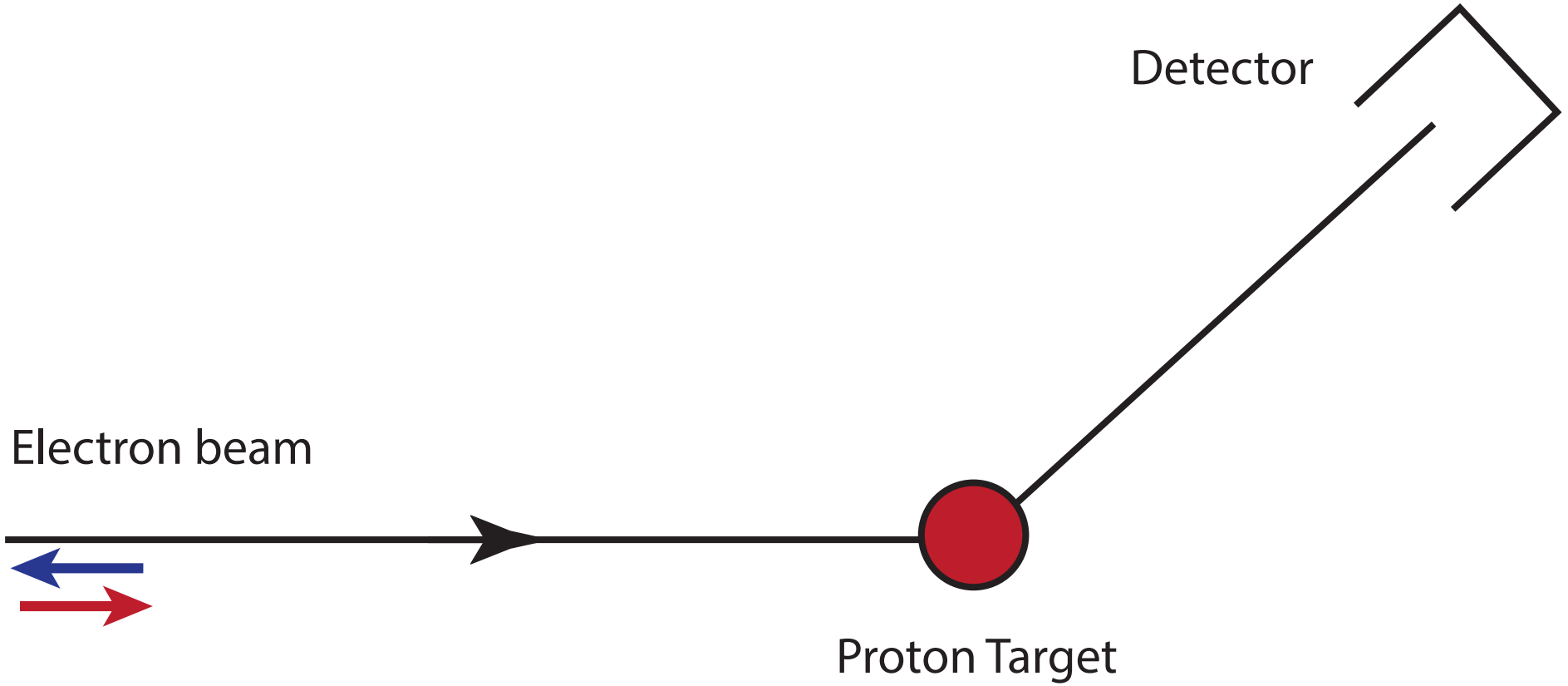
Parity violating electron scattering

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L}$$



Parity violating electron scattering

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}(Q_W - F(Q^2))$$



Parity violating electron scattering

Momentum transfer sets scale

Proton structure - small nuisance if Q^2 small

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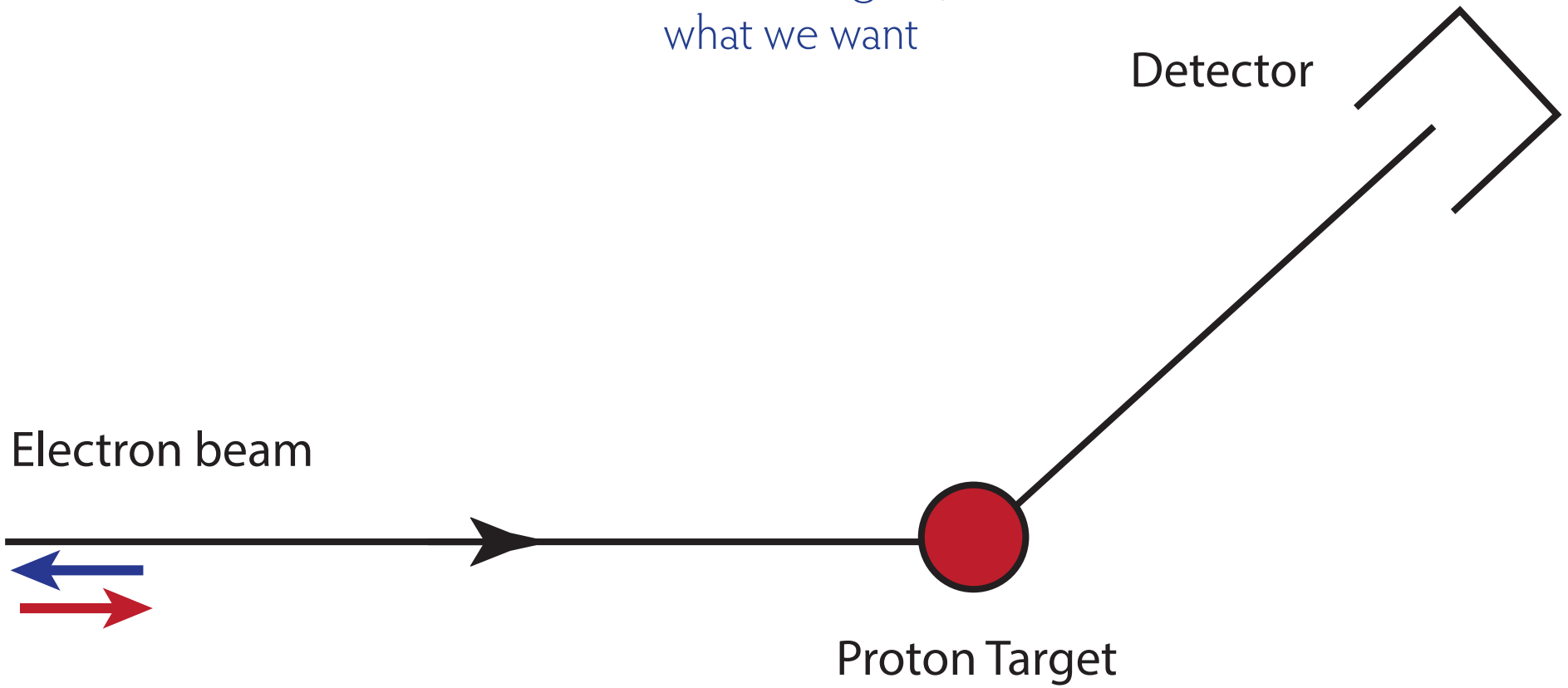
Weak charge - what we want



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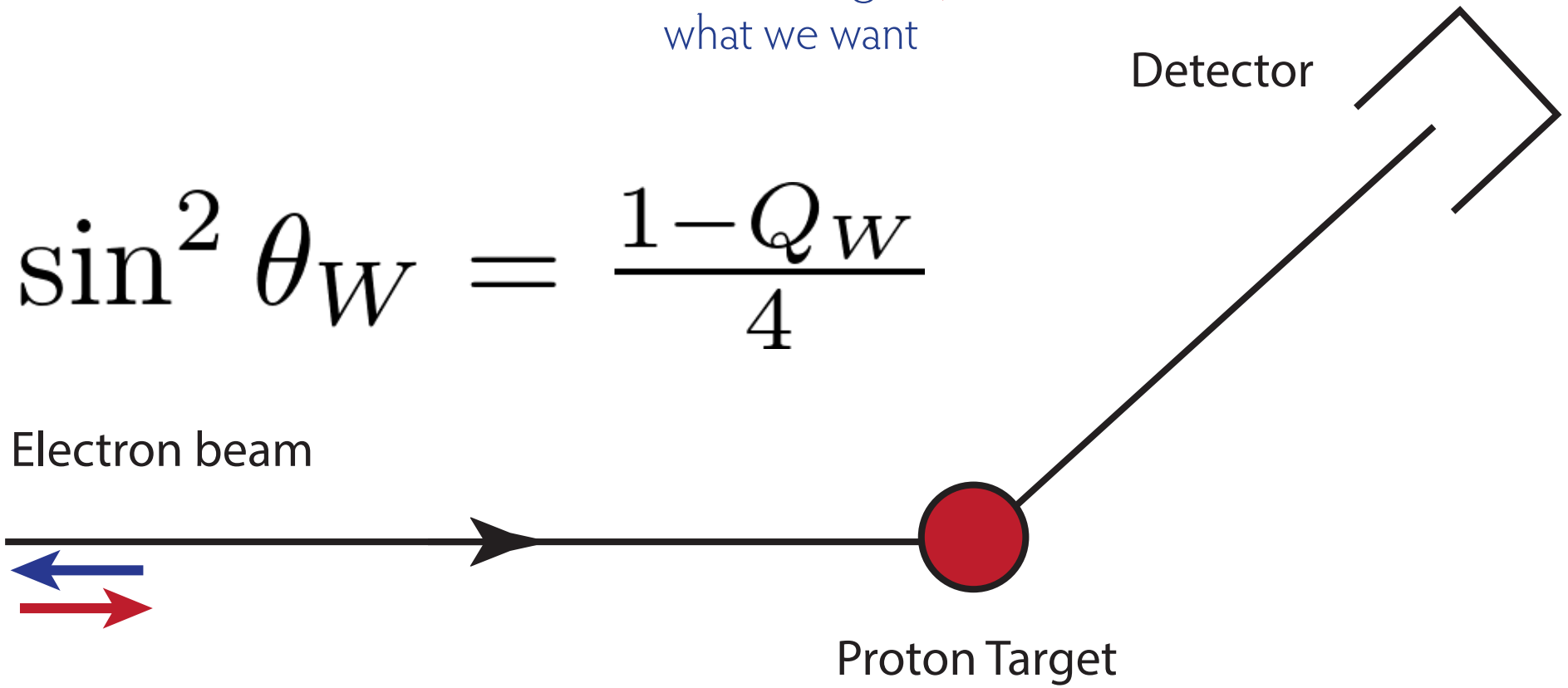
Weak charge - what we want

$$\sin^2\theta_W = \frac{1 - Q_W}{4}$$



Why is this difficult?

- $\sin^2\theta_W \approx 0.25$: Weak charge is tiny

$$Q_W = 1 - 4\sin^2\theta_W$$

- At low Q^2: Asymmetry is tiny (40 parts per billion):
  need very large statistics

$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left(Q_W - F(Q^2)\right)$$

- We are subtracting two huge numbers from each other
  (Not really - subtract many small numbers pair-wise from each other)

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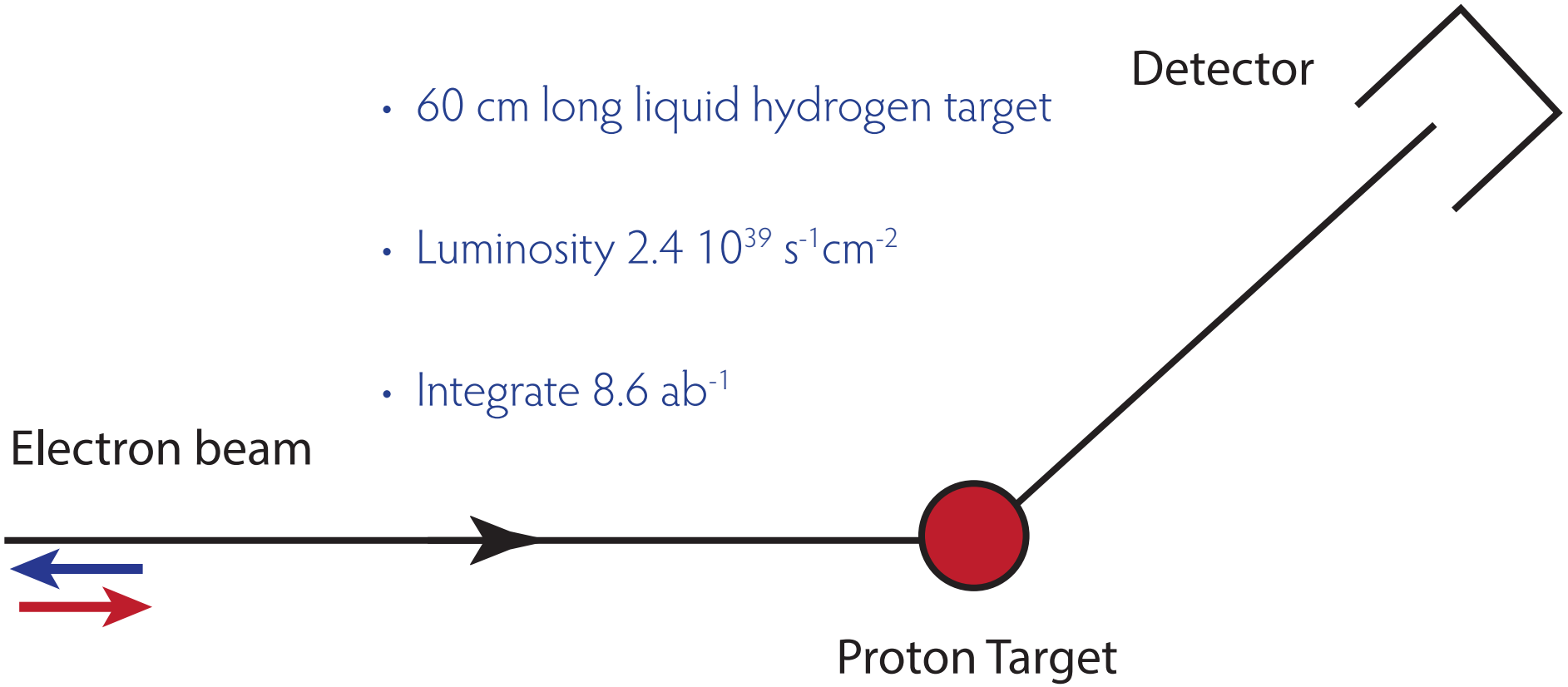
$$A_{PV} = \frac{N_R - N_L}{N_R + N_L} = \frac{G_F Q^2}{4\sqrt{2}\pi\alpha}(Q_W - F(Q^2))$$

- We are subtracting two huge numbers from each other
  (Not really - subtract many small numbers pairwise from each other)
- Want to measure $\sin^2\theta_W$ to 0.13% - Need Q_W at 1.5%
- N a few 10^{18} - Measure 11'000 hours with close to 10^{11} electrons/s - 100 GHz

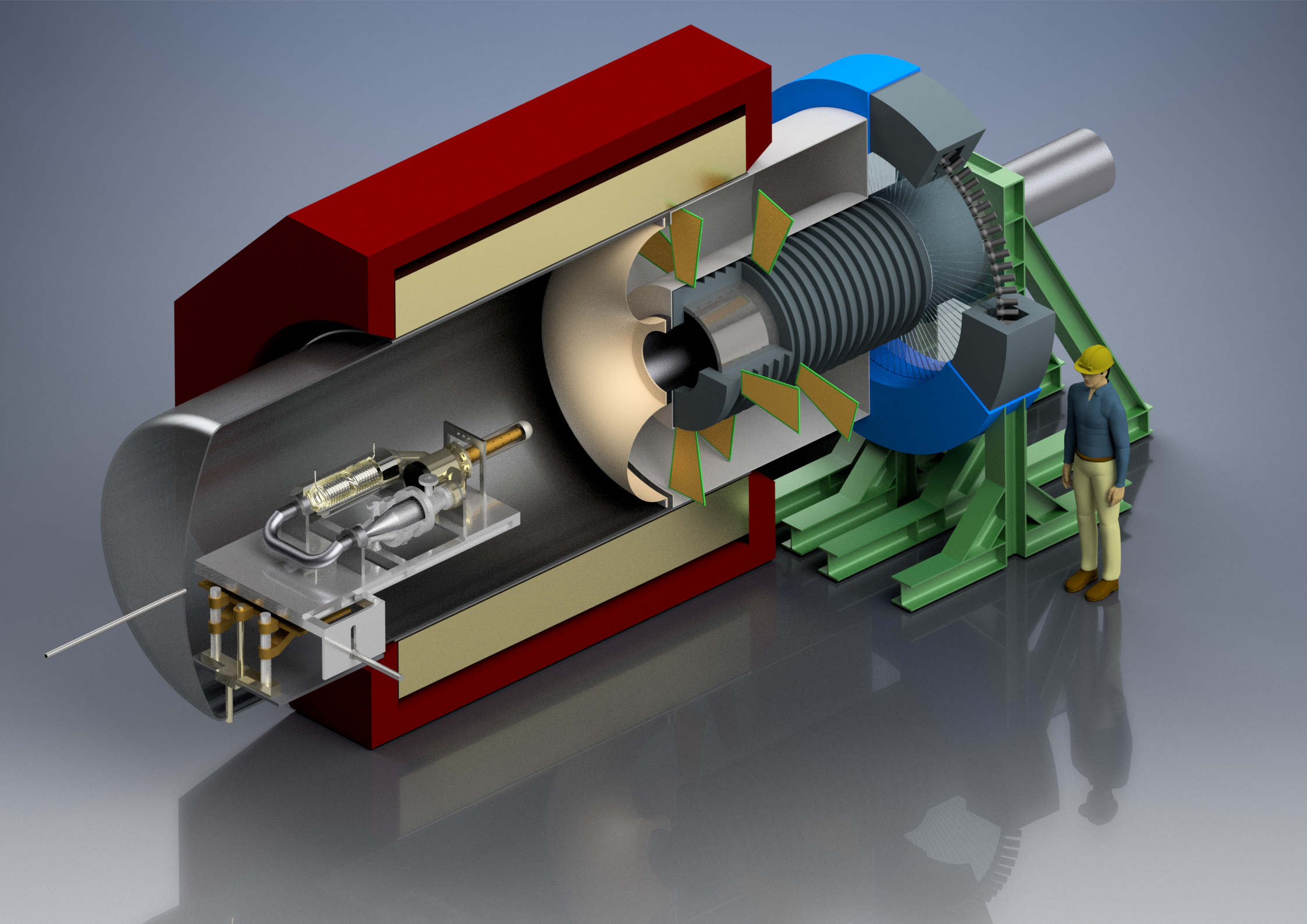
Can we get that rate?

- 150 μA of electron beam current
- 60 cm long liquid hydrogen target
- Luminosity 2.4 10^{39} $s^{-1}cm^{-2}$
- Integrate 8.6 ab^{-1}

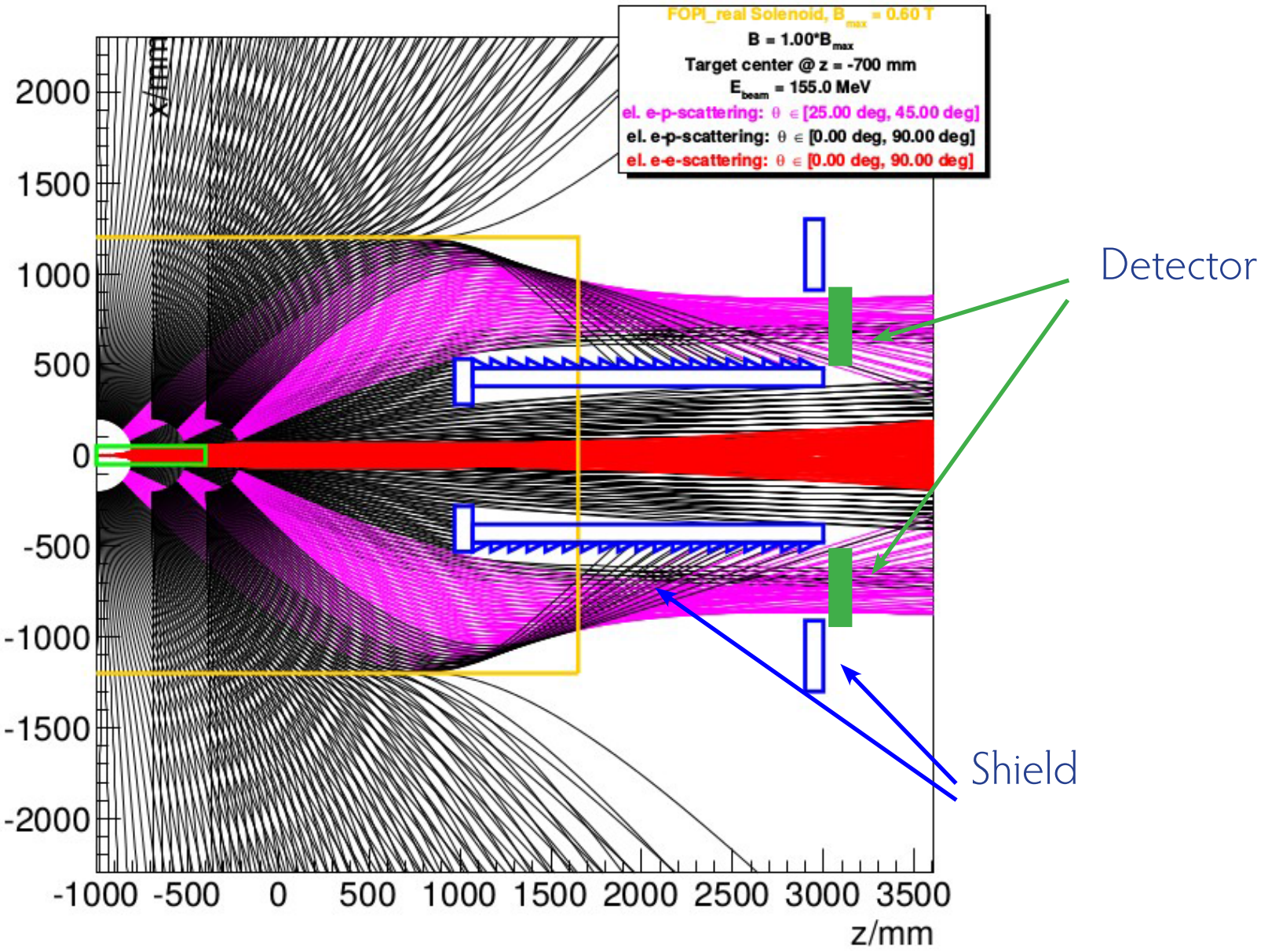


P2:

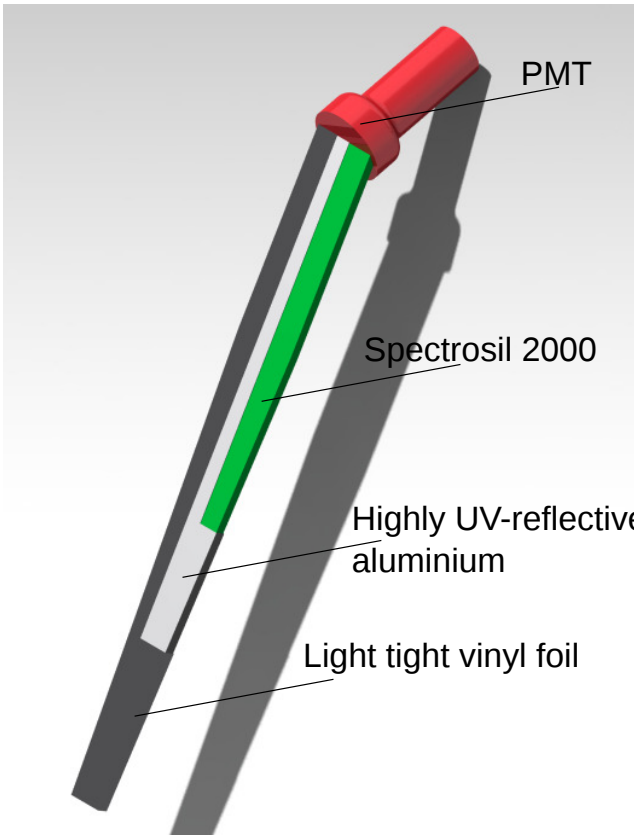
How to detect 100 GHz of (the right) electrons...



Solenoid spectrometer



Integrating detectors



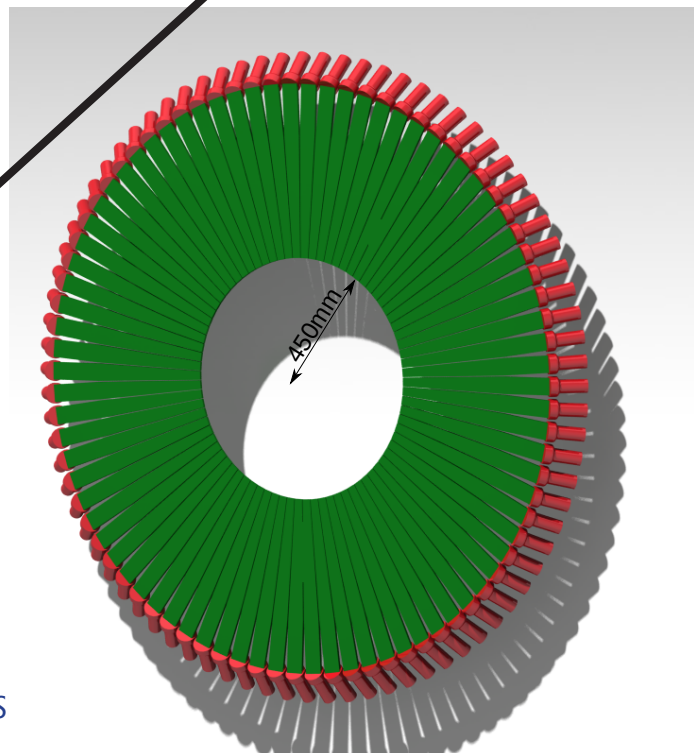
Detect Cherenkov-light created by electrons

Integrate photomultiplier current

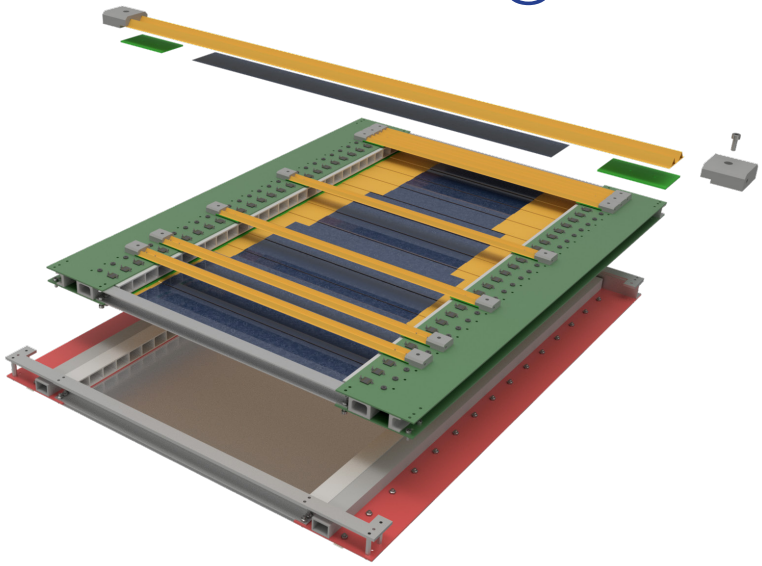
Detector

Electron beam

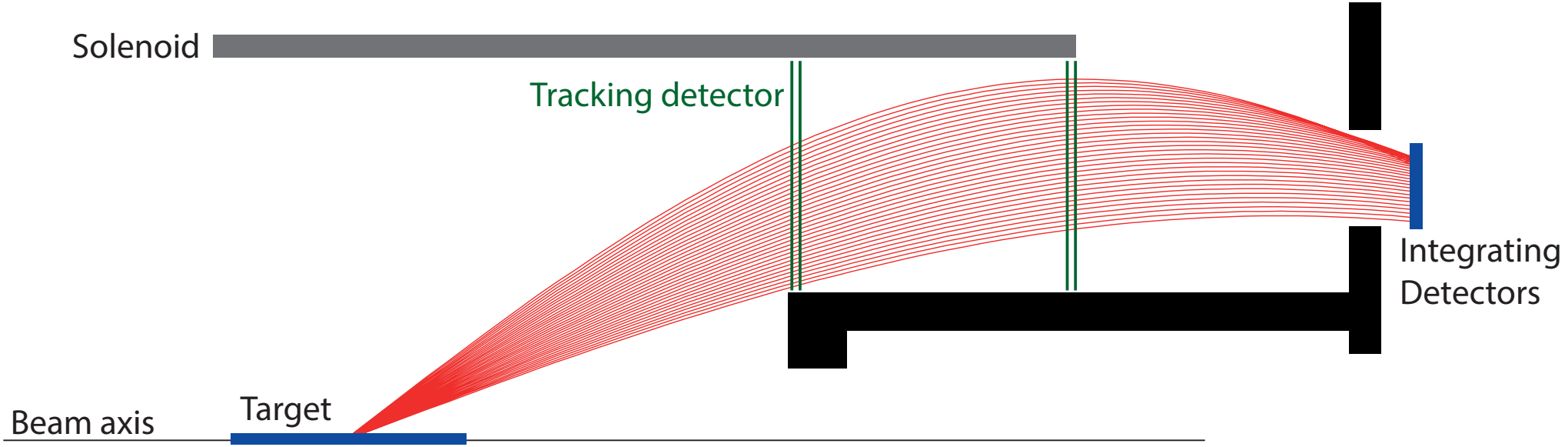
Proton Target



Tracking detector (measuring Q^2)

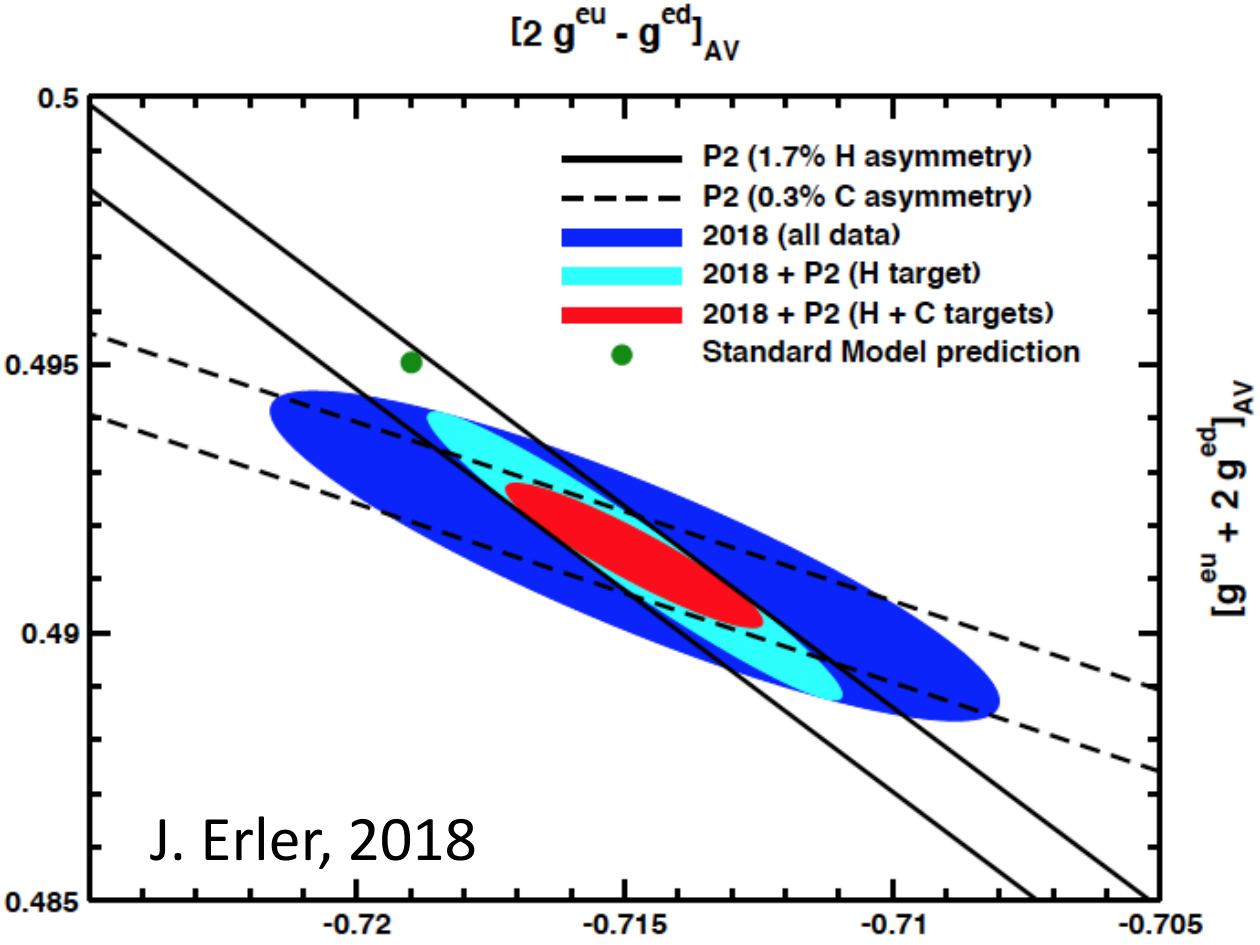


- Low momentum electrons, very high rates:
  Thin, fast, granular detectors
  High-Voltage Monolithic Active Pixel Sensors (see Mu3e)



Can we do more?

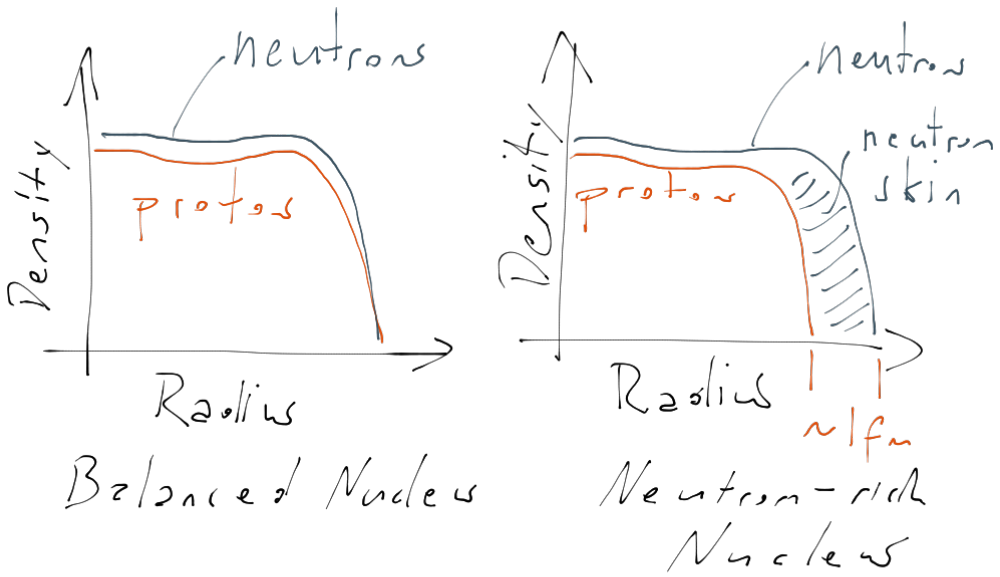
Carbon - Complementary New Physics Search



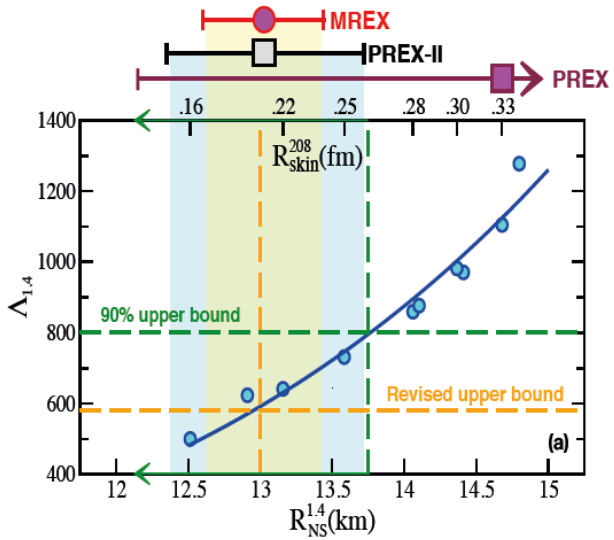
- Same with a ^{12}C target
- Much larger asymmetry
- No 1 - 4 $\sin^2\theta_W$ bonus - not competitive for $\sin^2\theta_W$ (potentially 2nd best measurement on a nucleus)
- But: New direction in isospin space
- Experimentally: Limited by polarimetry, hope to ultimately reach 0.3%
- Best measurement to date: MIT-Bates, ~25%

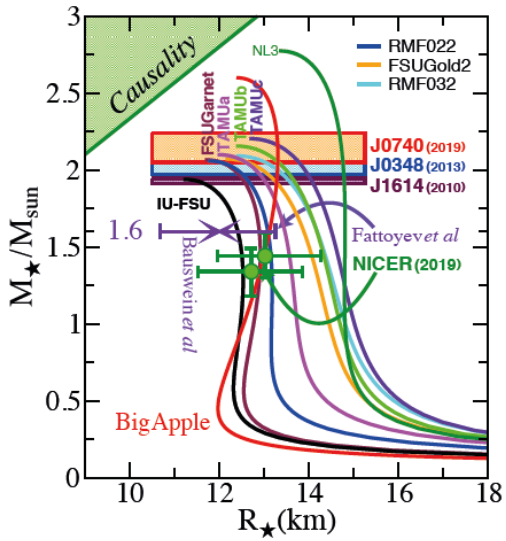
Lead (^{208}Pb) - Neutron Skin

Where are the neutrons in the nucleus?



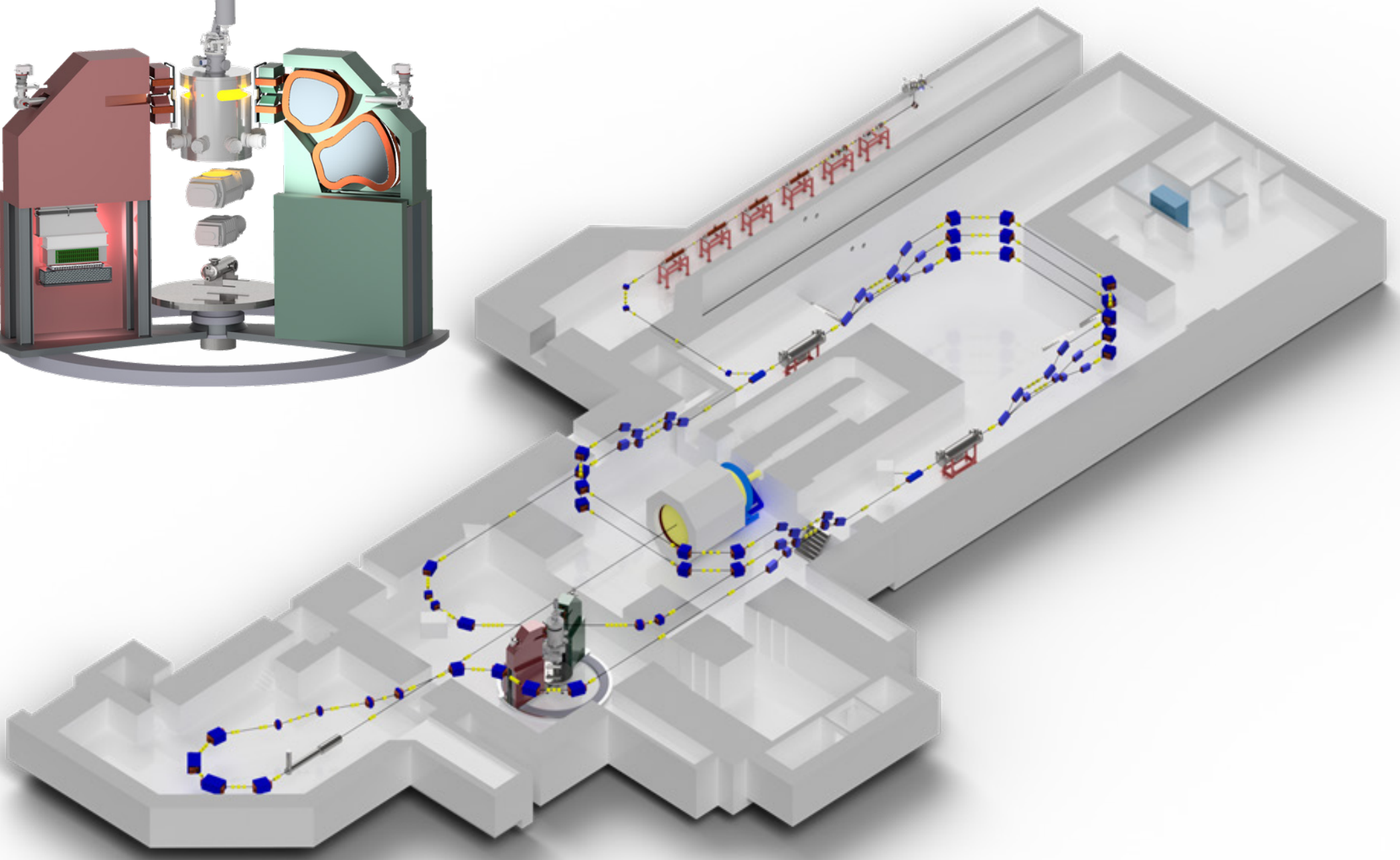
- Parity violating electron scattering gives access to the neutron distribution
- Neutron skin related to the symmetry energy - nuclear Equation of State
- Size of neutron stars





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

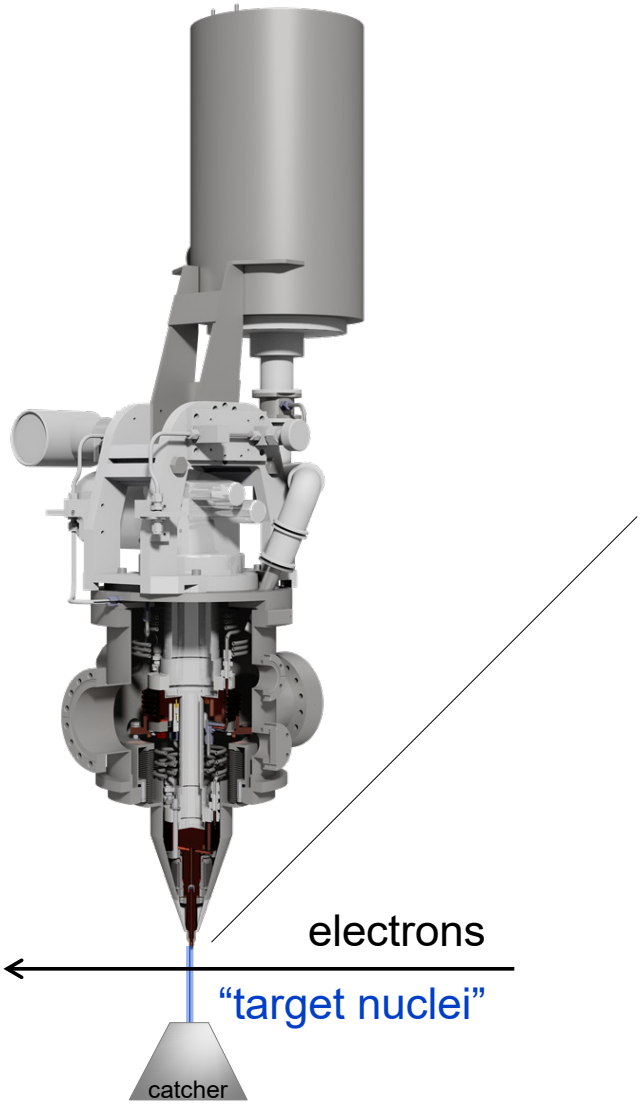
The MAGIX Spectrometers

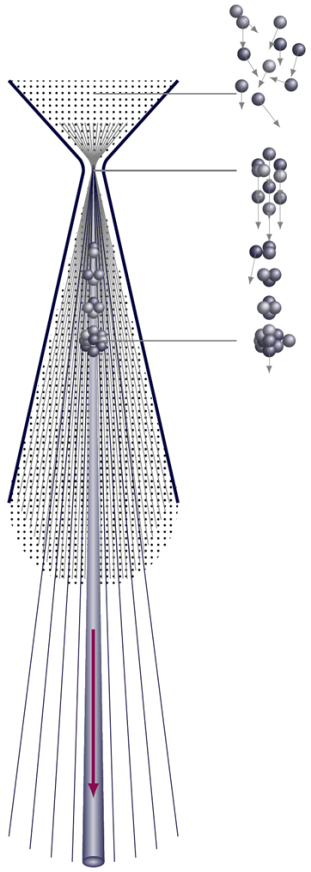


ERL mode: 30-105 MeV, >1000 µA, energy recovered in cavities
MX-EB mode: 20-105 MeV, 10 µA, small beam dump → solid state targets

Gas Jet Target

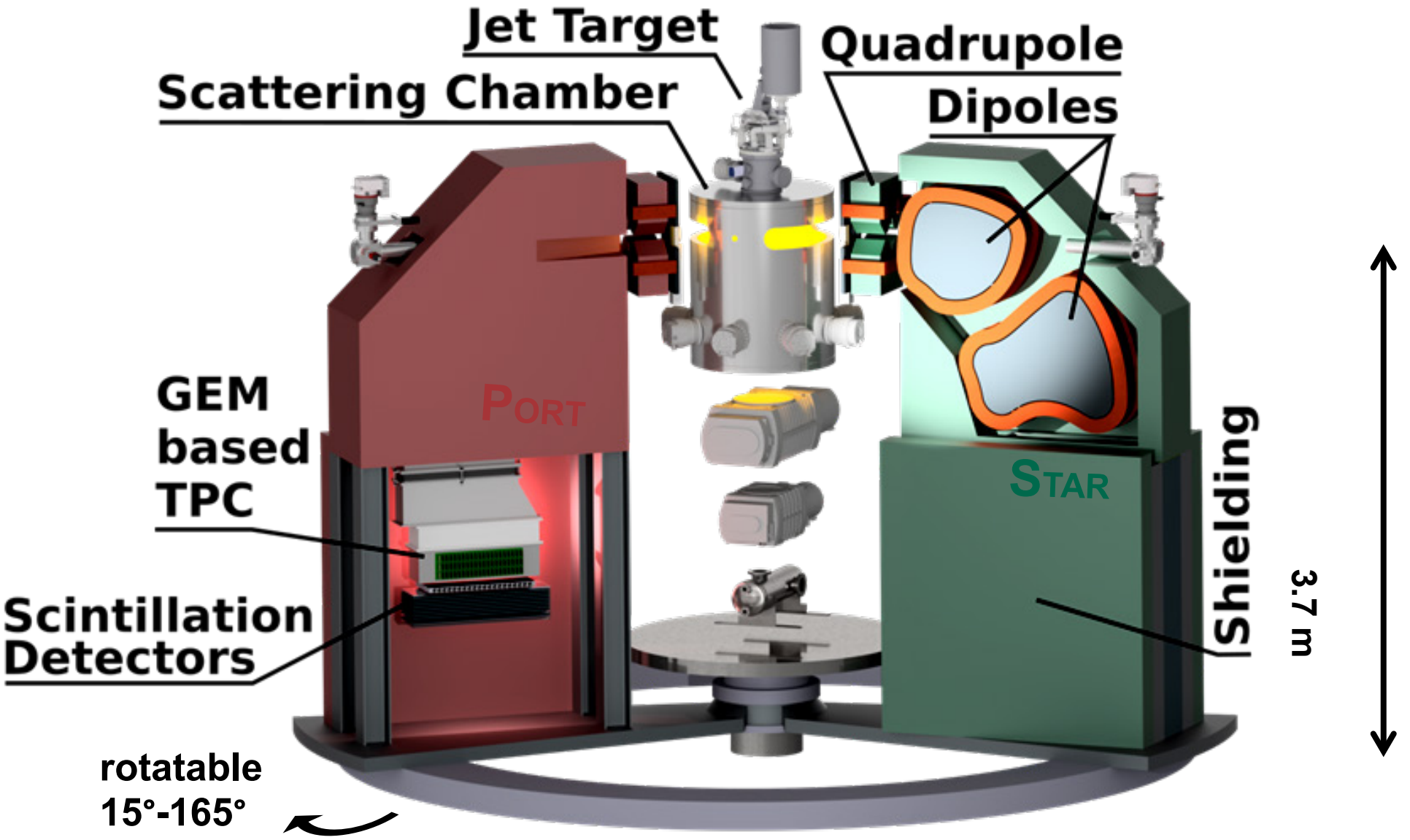
- High resolution of spectrometers easily spoiled by scattering in the target chamber
- Get rid of the target chamber
- Supersonic gas stream shooting into the beam
- Catch most gas below, add differential pumping





- Group of A. Khoukaz, Uni Münster
- Tested in the A1 setup at MAMI

Spectrometers



Physics at MAGIX

Hadron Structure

Topic	Reaction	Jet	Observables
p Formfactor	$H(e,e')p$	H	$G_E(Q^2)$, $G_M(Q^2)$, r_E, r_M
d Formfactor	$D(e,e')d$	D	$A(Q^2)$, $B(Q^2)$, r_d
^{3}He Formfactor	$^3\mathrm{He}(e,e')^3\mathrm{He}$	^{3}He	r_E
^{4}He Formfactor	$^4\mathrm{He}(e,e')^4\mathrm{He}$	^{4}He	r_E

Few-Body Systems

d Breakup	$D(e,e'p)$	D	$\mathrm{d}\sigma/\mathrm{d}\Omega$, polarizabilities
^{3}He inclusive	$^3\mathrm{He}(e,e')$	^{3}He	Structure functions, R_L
^{4}He inclusive	$^4\mathrm{He}(e,e')$	^{4}He	Structure functions, R_L
^{4}He monopole	$^4\mathrm{He}(e,e')^4\mathrm{He}^*$	^{4}He	Transition Formfactors $E(^4\mathrm{He}^*)$, $\Gamma(^4\mathrm{He}^*)$
^{16}O inclusive	$^{16}\mathrm{O}(e,e')$	^{16}O	Structure functions, R_L
^{40}Ar inclusive	$^{40}\mathrm{Ar}(e,e')$	^{40}Ar	Structure functions, R_L
^{3}He exclusive	$^3\mathrm{He}(e,e'p/d)d/p$	^{3}He	$\mathrm{d}\sigma/\mathrm{d}\Omega$
^{4}He exclusive	$^4\mathrm{He}(e,e'p/d)$	^{4}He	$\mathrm{d}\sigma/\mathrm{d}\Omega$

Dark Sector

Leptonic Decay	$Ar(e,A' \rightarrow e^+e^-)$	^{40}Ar, Xe	Lepton pair mass $m_{A'}$ peak search
Invisible Decay	$p(e,e'p)A'$	H	Missing mass $m_{A'}$ peak search

Astrophysical Reactions

S-Factor Phase 1	$^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$	^{16}O	$S_{E1}(E)$, $S_{E2}(E)$
S-Factor Phase 2	$^{16}\mathrm{O}(e,e'\alpha)^{12}\mathrm{C}$	^{16}O	$S_{E1}(E)$, $S_{E2}(E)$

Example: Form factors of the proton

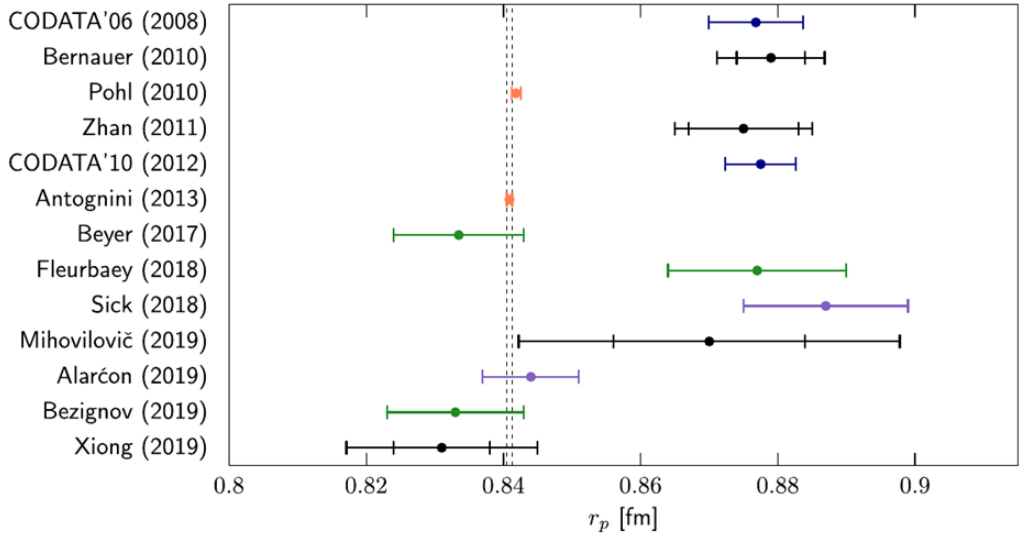
elastic e-p cross section (Rosenbluth formula)

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right) = \left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_e}\right)_{\mathrm{Mott}^*} \cdot \frac{1}{(1+\tau)}\left[G_{\mathrm{E}}^2(Q^2) + \frac{\tau}{\epsilon}G_{\mathrm{M}}^2(Q^2)\right]$$

$$G_{\mathrm{E}}^2(Q^2) \leftrightarrow \text{ charge distribution}$$
$$G_{\mathrm{M}}^2(Q^2) \leftrightarrow \text{ magnetization distribution}$$

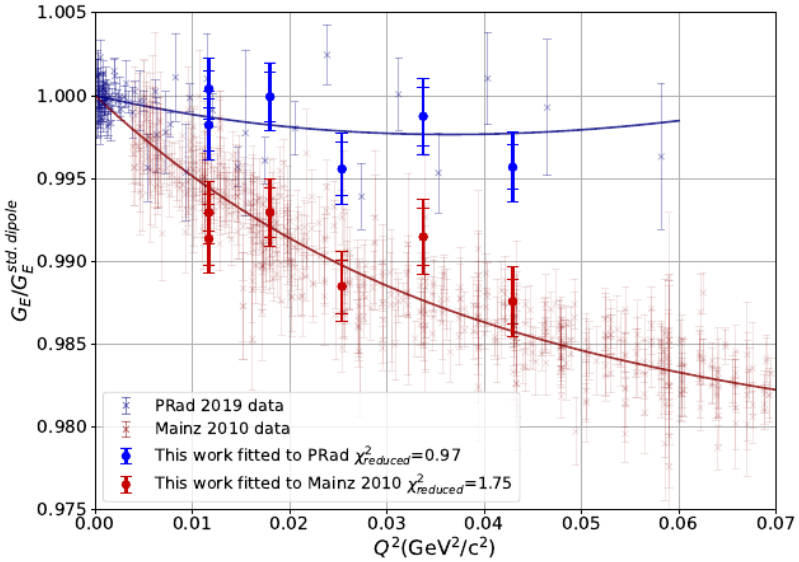
$$\langle r_E^2 \rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_{\mathrm{E}}}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

$$\langle r_M^2 \rangle = -\frac{6}{\mu_p}\hbar^2 \left.\frac{\mathrm{d}G_{\mathrm{M}}}{\mathrm{d}Q^2}\right|_{Q^2=0}$$



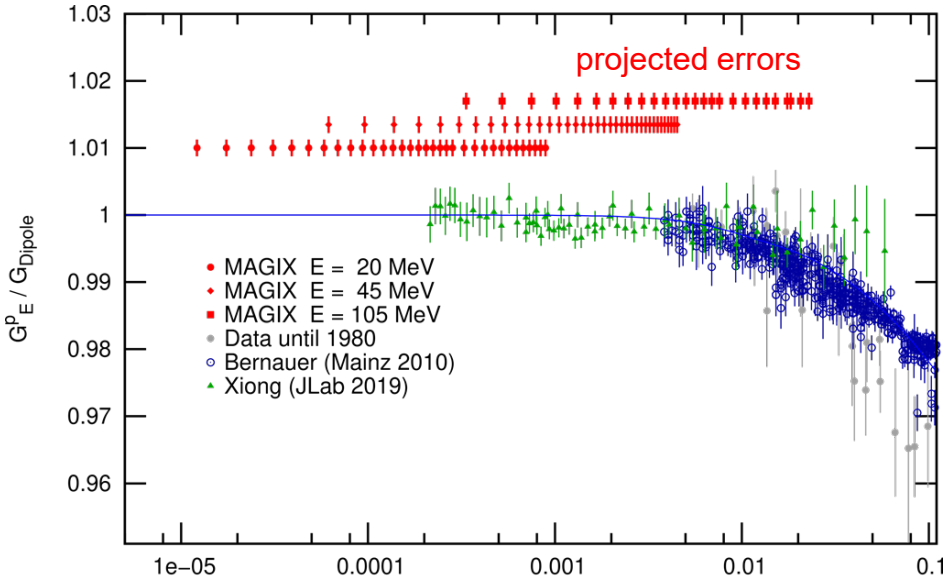
- Elastic e-p scattering gives access to proton form factors
- Starting 2010: Proton radius puzzle e-p scattering and muonic hydrogen give different results
- Now mostly resolved (the proton is small)
- But...

Example: Form factors of the proton

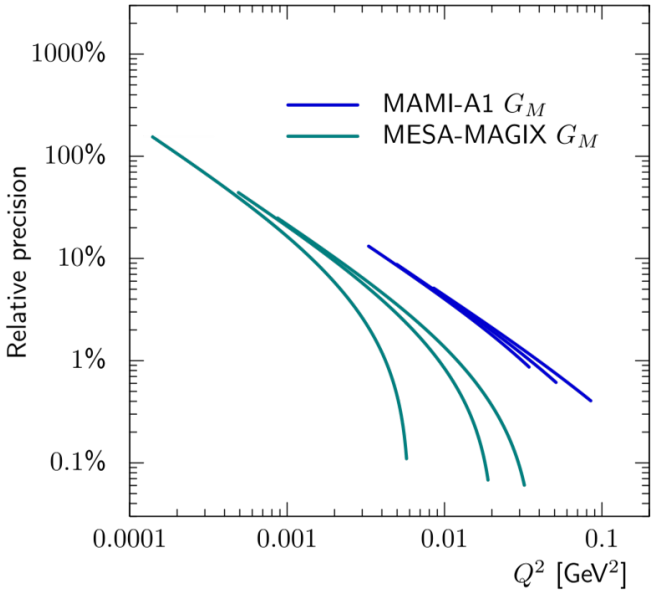


- Mainz A1 and JLab PRAD data are still not consistent
- Form factor puzzle?
- MAGIX:
  Q^2 coverage from 10^{-5} to 0.03 GeV^2

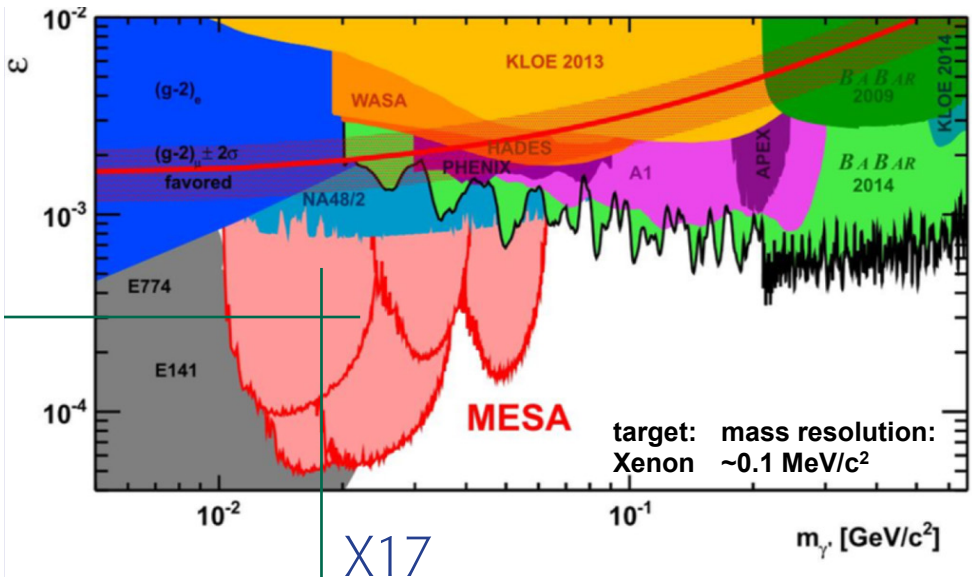
$G_E(Q^2)$



$G_M(Q^2)$

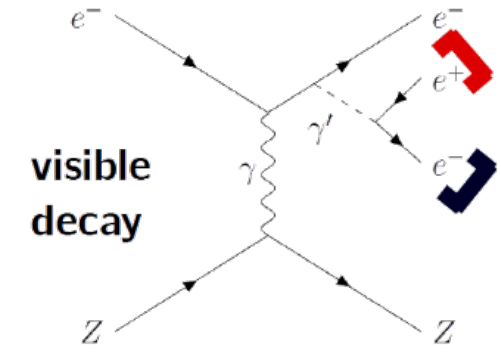


Example: Dark Photons

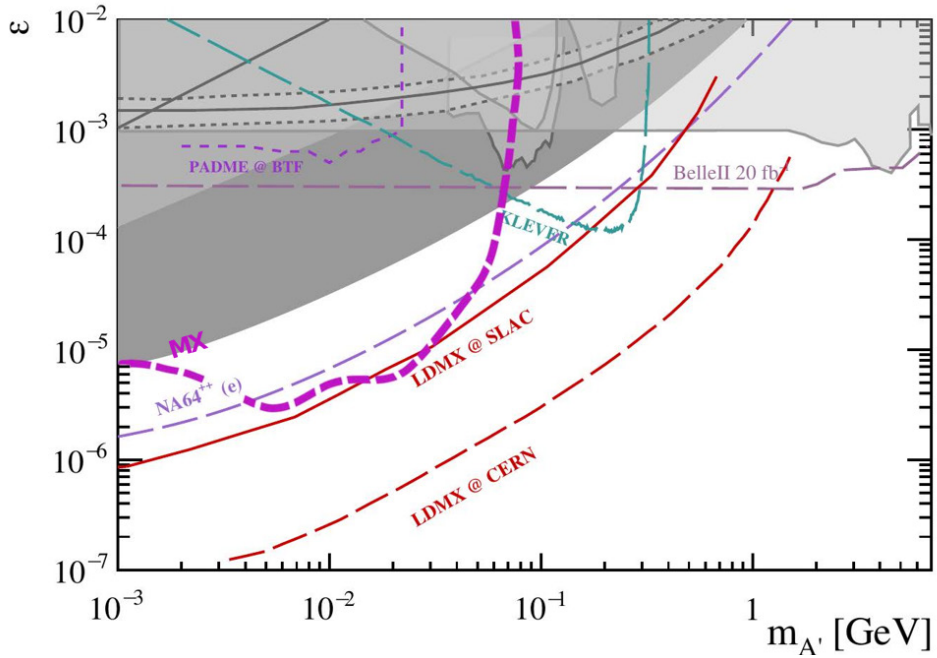


Visible decay to e^+e^-

- Xenon or Argon target, high currents

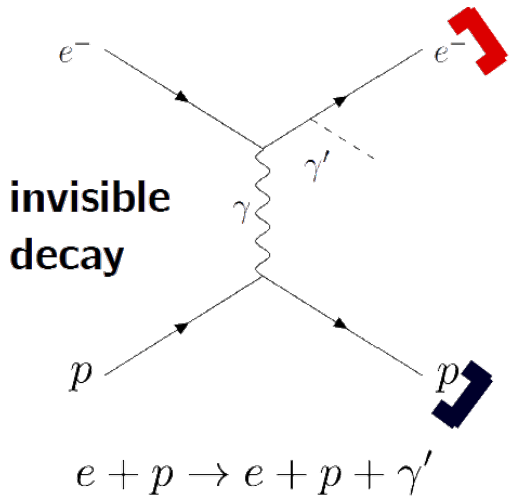


$$e + Z \rightarrow e + Z + \gamma'$$
$$\hookrightarrow e^+ + e^-$$



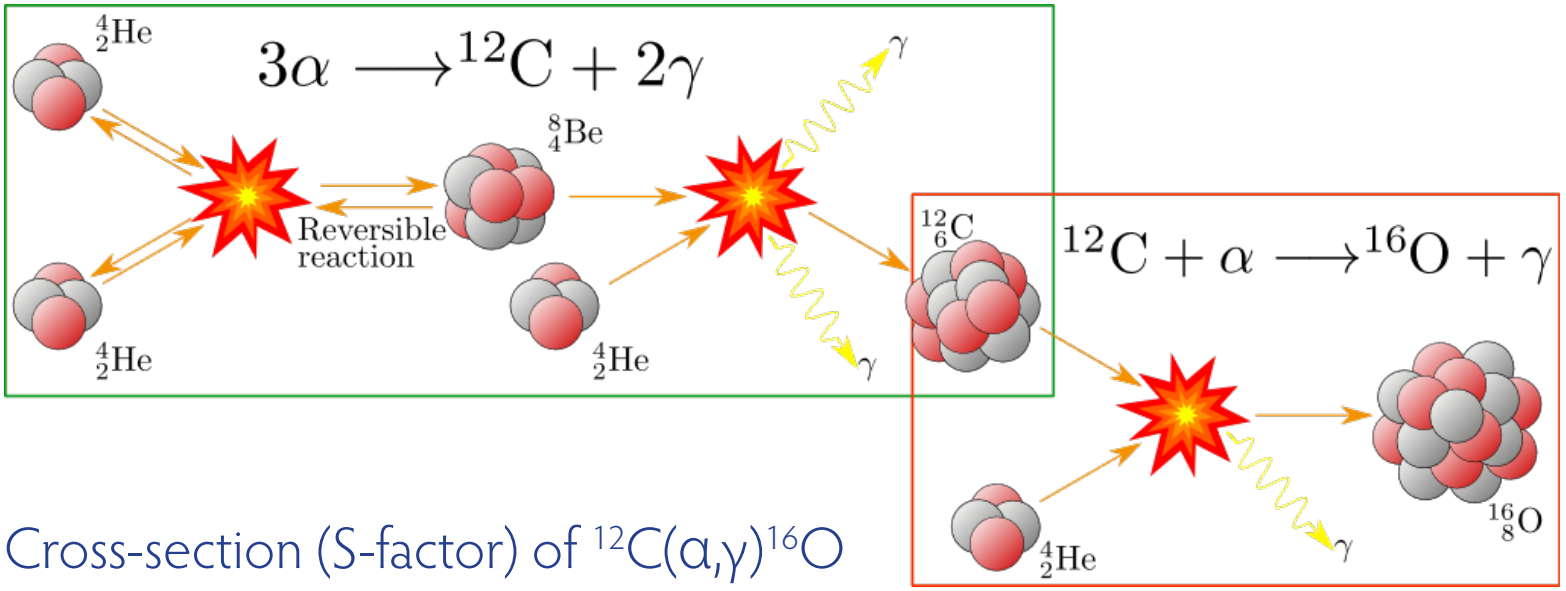
Invisible decays

- Hydrogen target
- Recoil detector
- Limit projection on the way



$$e + p \rightarrow e + p + \gamma'$$

Example: Nuclear astrophysics



Cross-section (S-factor) of $^{12}C(\alpha,\gamma)^{16}O$ very relevant for stellar burning, oxygen abundance and synthesis of heavy elements

C.S. as function of $E_{c.m.}$

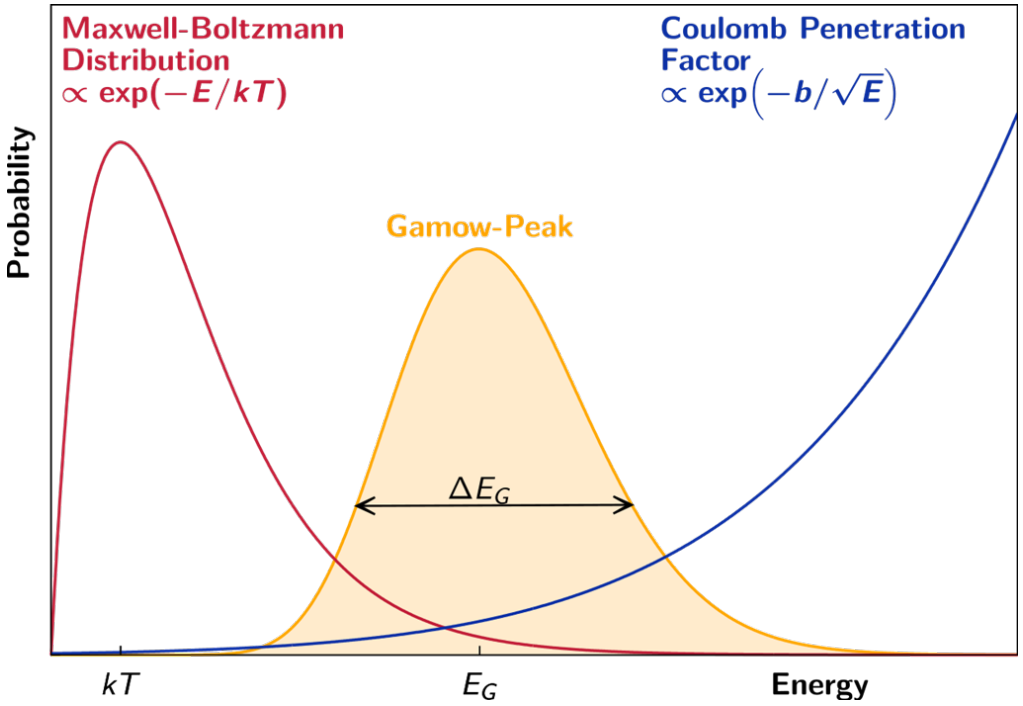
$$\sigma(E) = \frac{1}{E} e^{-\frac{2\pi Z_1 Z_2 \alpha c}{v}} \cdot S(E)$$

"S-factor"
unknown nuclear physics

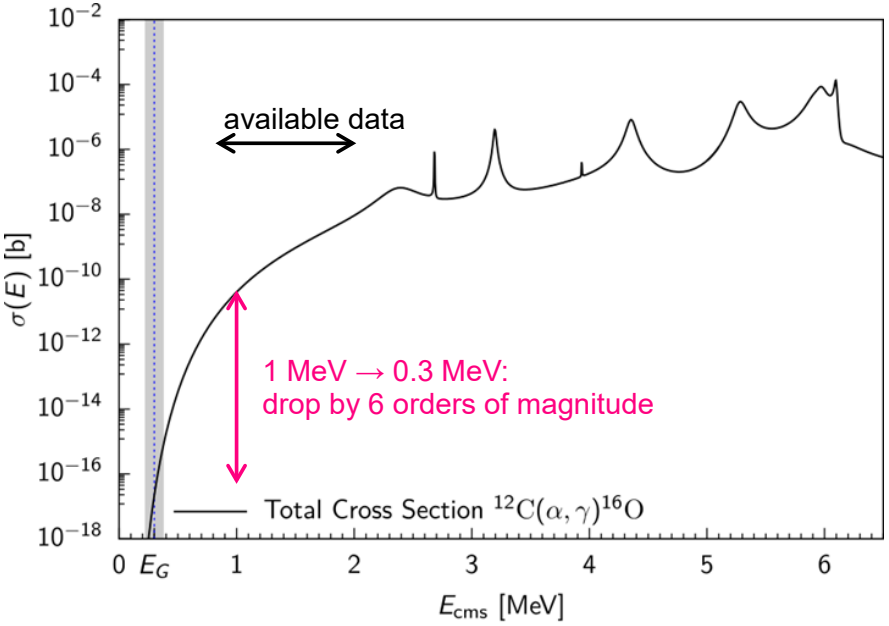
Compton wave length

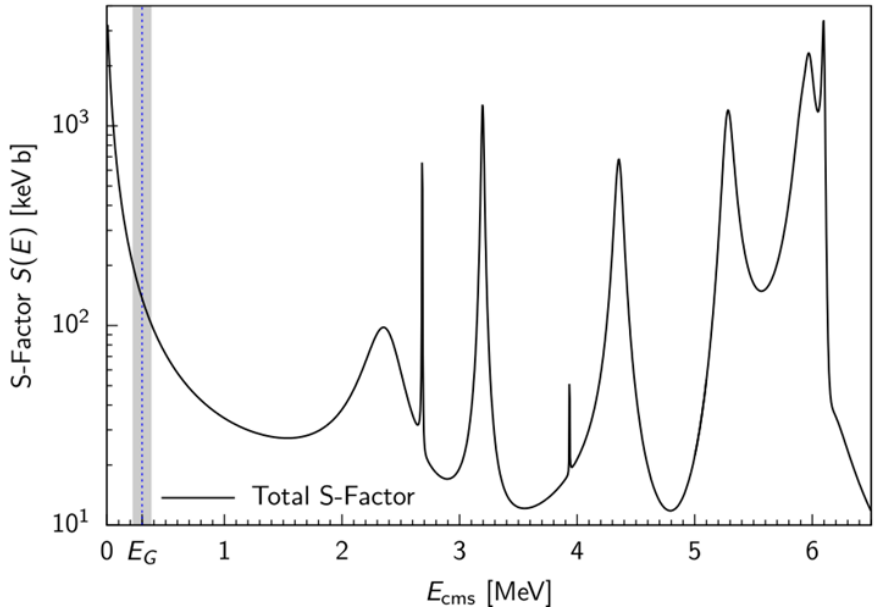
tunneling probability in fusion process

Example: Nuclear astrophysics

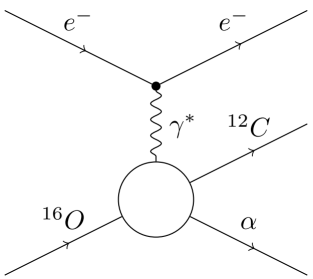


Needed: S-factor at ECM of 300 keV (Gamov-Peak)





Example: Nuclear astrophysics



study $^{12}C(\alpha,\gamma)^{16}O$

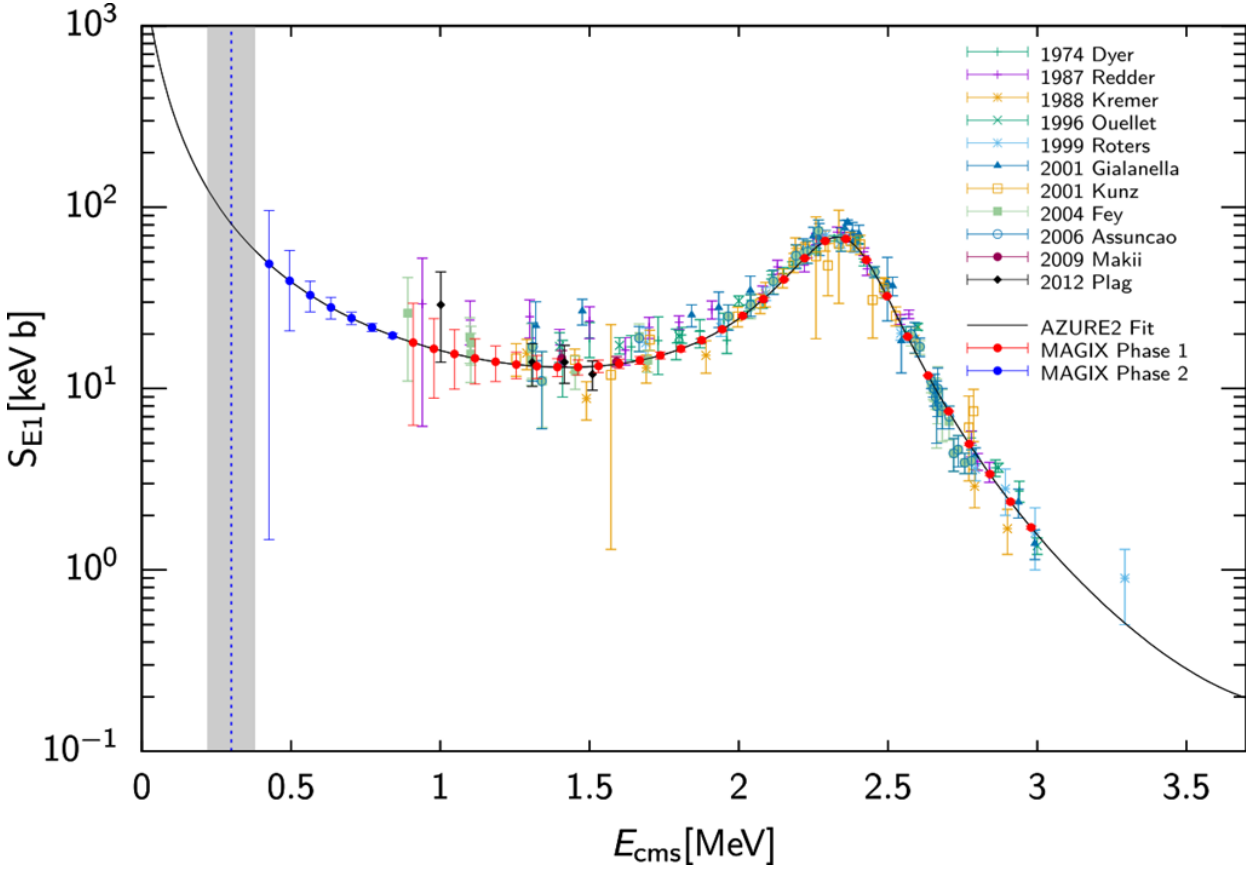
by $^{16}O(\gamma,\alpha)^{12}C$

quasi-real photon, $\gamma^* \approx \gamma$

extract astrophysical S-factor

compare I. Friščić, T. W. Donnelly, R. G. Milner, Phys. Rev. C100, 025804 (2019)

- Phase I: Spectrometers plus recoil detector
- Phase II: Zero-degree detector plus multiple recoil detectors



Dark matter in the beam dump

DarkMESA

DarkMESA

- P2: Several 10^{22} electrons on target
- Dark matter χ, mediator γ'

$$Y_{Prod} \sim \epsilon^2/m_A^2$$

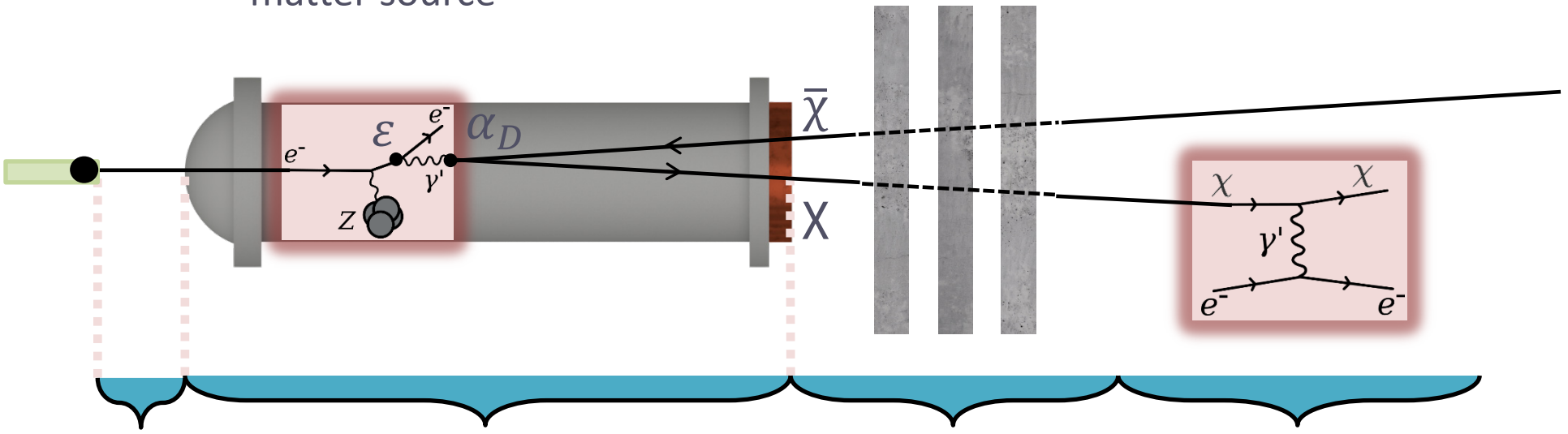
$$Y_{Det} \sim \epsilon^2 \alpha_D/m_A^2$$

P2 target

Beam dump = high energy and high intensity dark matter source

Concrete walls and air

Detector



~ 12 m

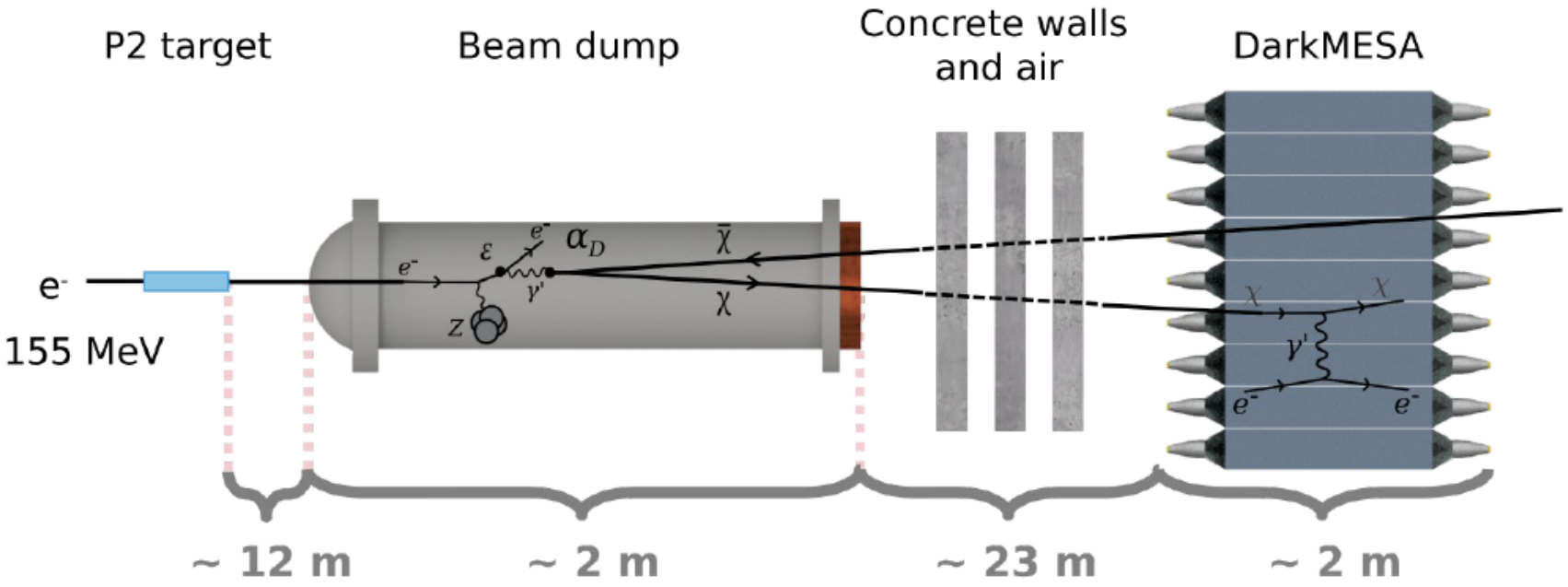
~ 2 m

~ 23 m

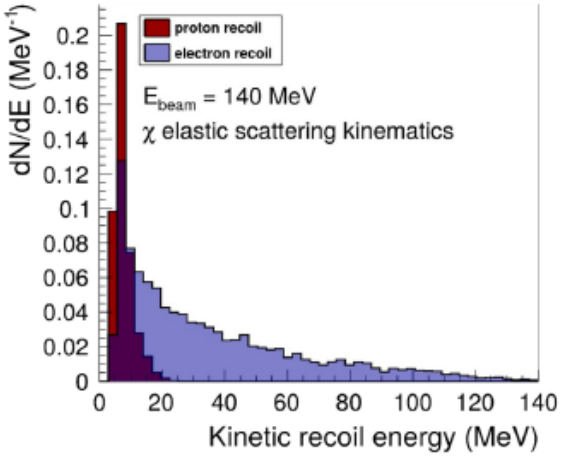
2.4 m

$$Y_{TOT} \sim \epsilon^4 \alpha_D/m_A^4$$

DarkMESA



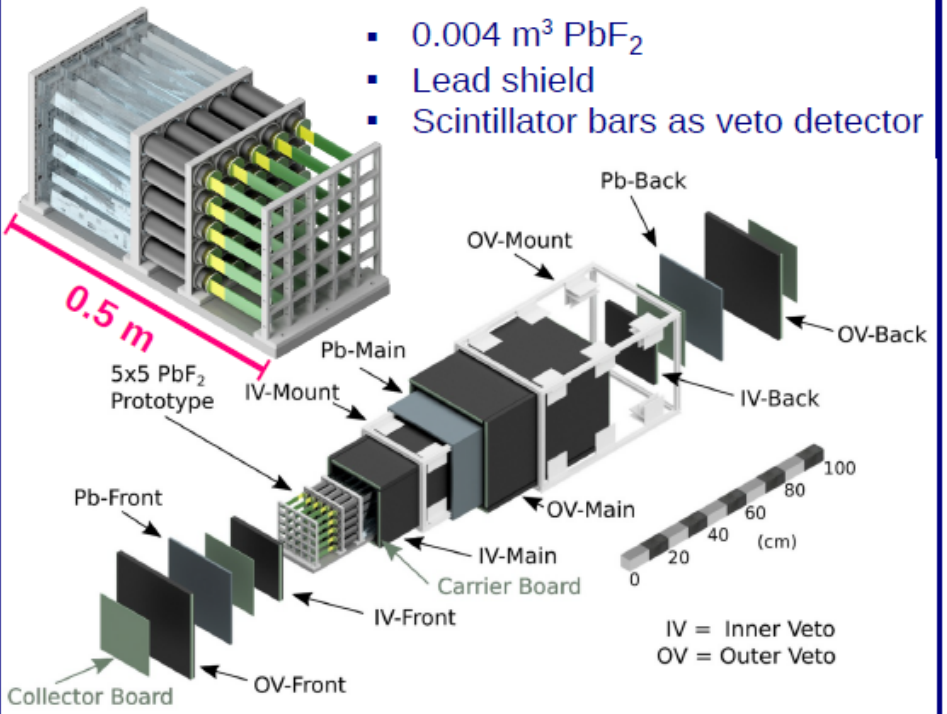
- Detection DM particles
  - enough recoil energy / another DM ↔ SM interaction
- Background
  - Detector well shielded from SM
  - Below π-production threshold
    → no μ, ν produced
  - Cosmogenic background
    - Beam directionality, RF coincidence, beam on / off
    - low neutron sensitivity of detector, active veto detector shield



DarkMESA

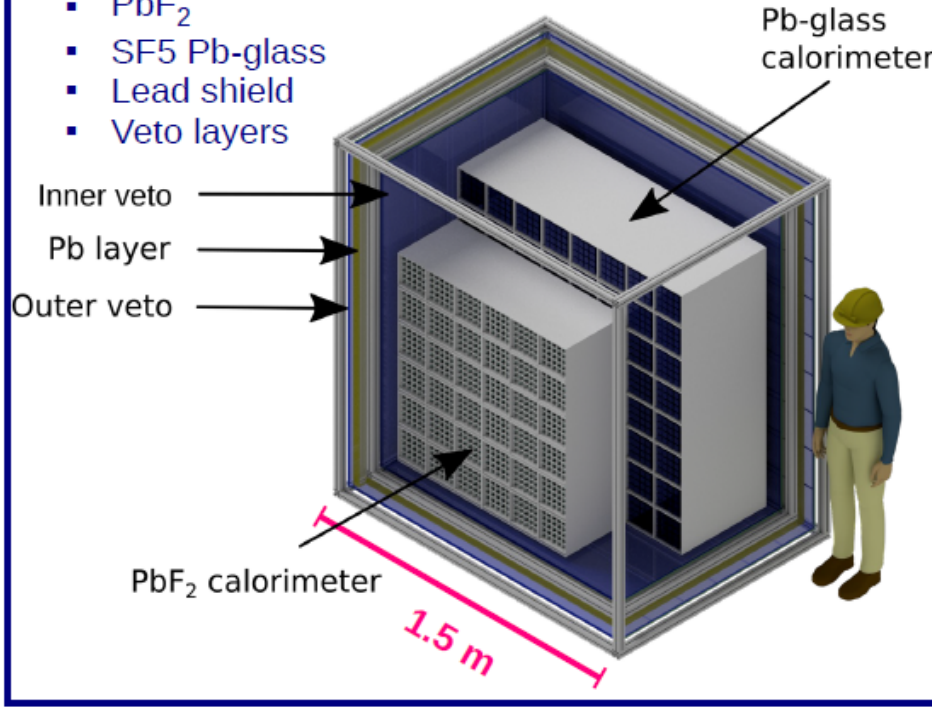
Phase A (prototype)

- 0.004 m³ PbF_2
- Lead shield
- Scintillator bars as veto detector



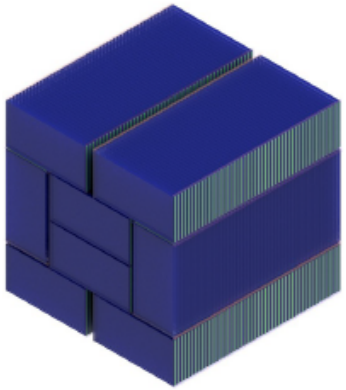
Phase B

- PbF_2
- SF5 Pb-glass
- Lead shield
- Veto layers



Phase C (range extension)

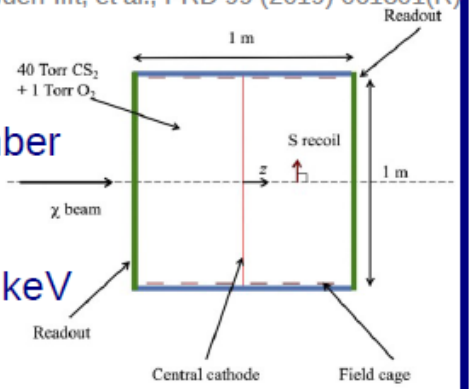
options



Radiation protection glas
e.g., SCHOTT-RD30
Moderate cost: 137 k€ / m³
High density: 3.13 g / cm³

DRIFT -Time Projection Chamber
CS_2 at 50 mbar
~1 m³ active volume
Nuclear recoil threshold: 20 keV

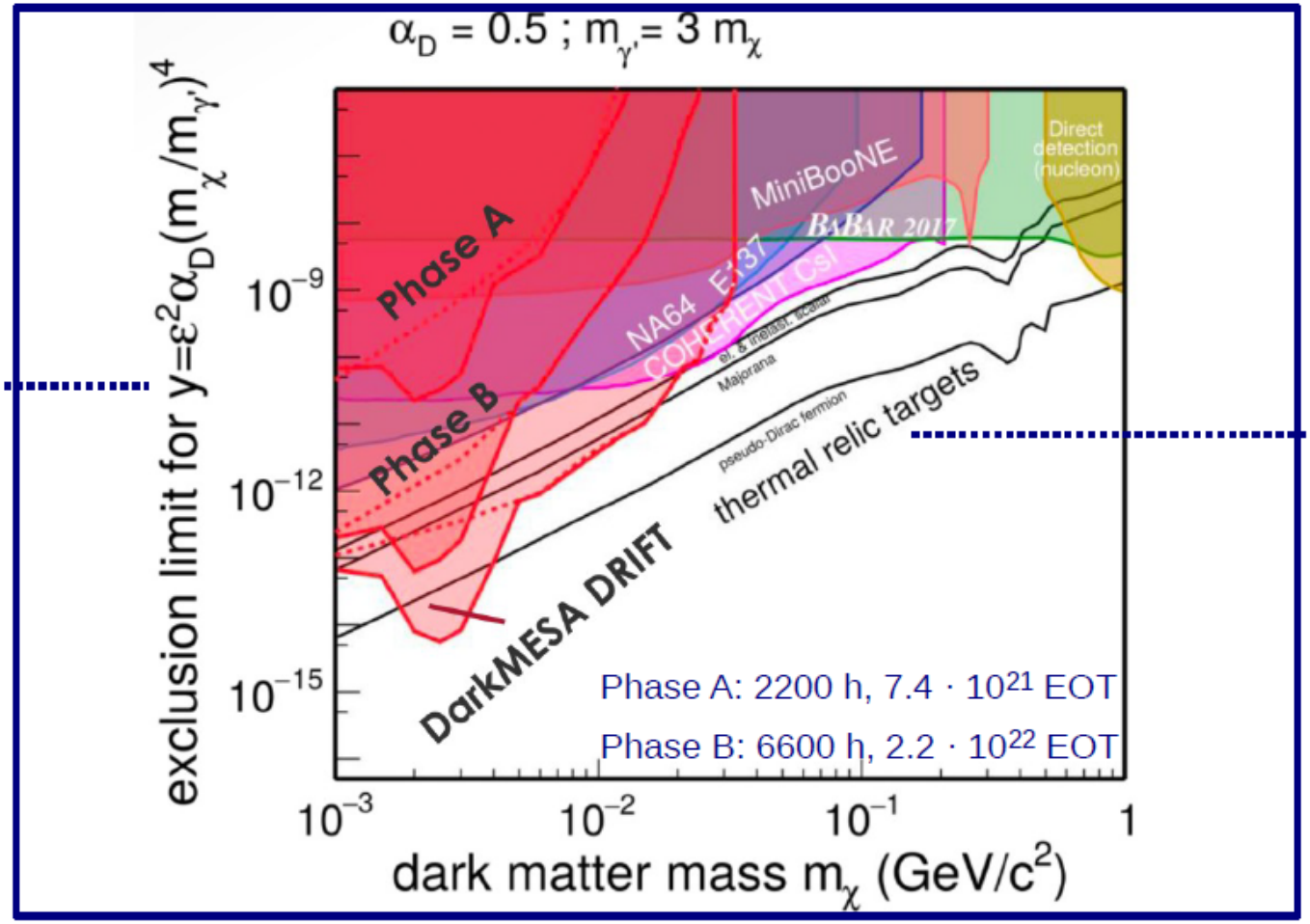
D. P. Snowden-Ifft, et al., PRD 99 (2019) 061301(R)



⇒ Extended parameter space

Sensitivity

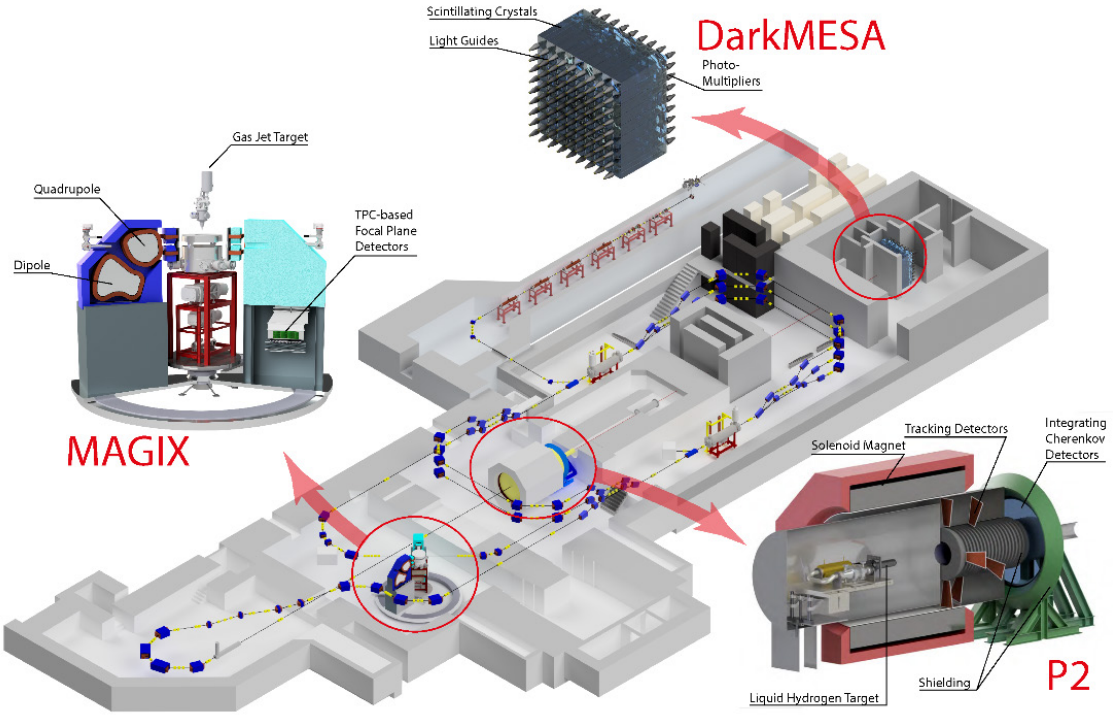
Natural dimensionless interaction strength



Relic density limits for a thermal origin of DM, giving a clear experimental target for possible vector mediators

Outlook

- Civil construction finally coming to a close
- 2023: Setting up the accelerator and experiments (components mostly ready and tested in existing buildings)
- 2024: Accelerator and experiment commissioning, extracted beam, starting at 55 MeV
- 2025++: Full energy, extracted beam data taking, commissioning of energy recovery mode



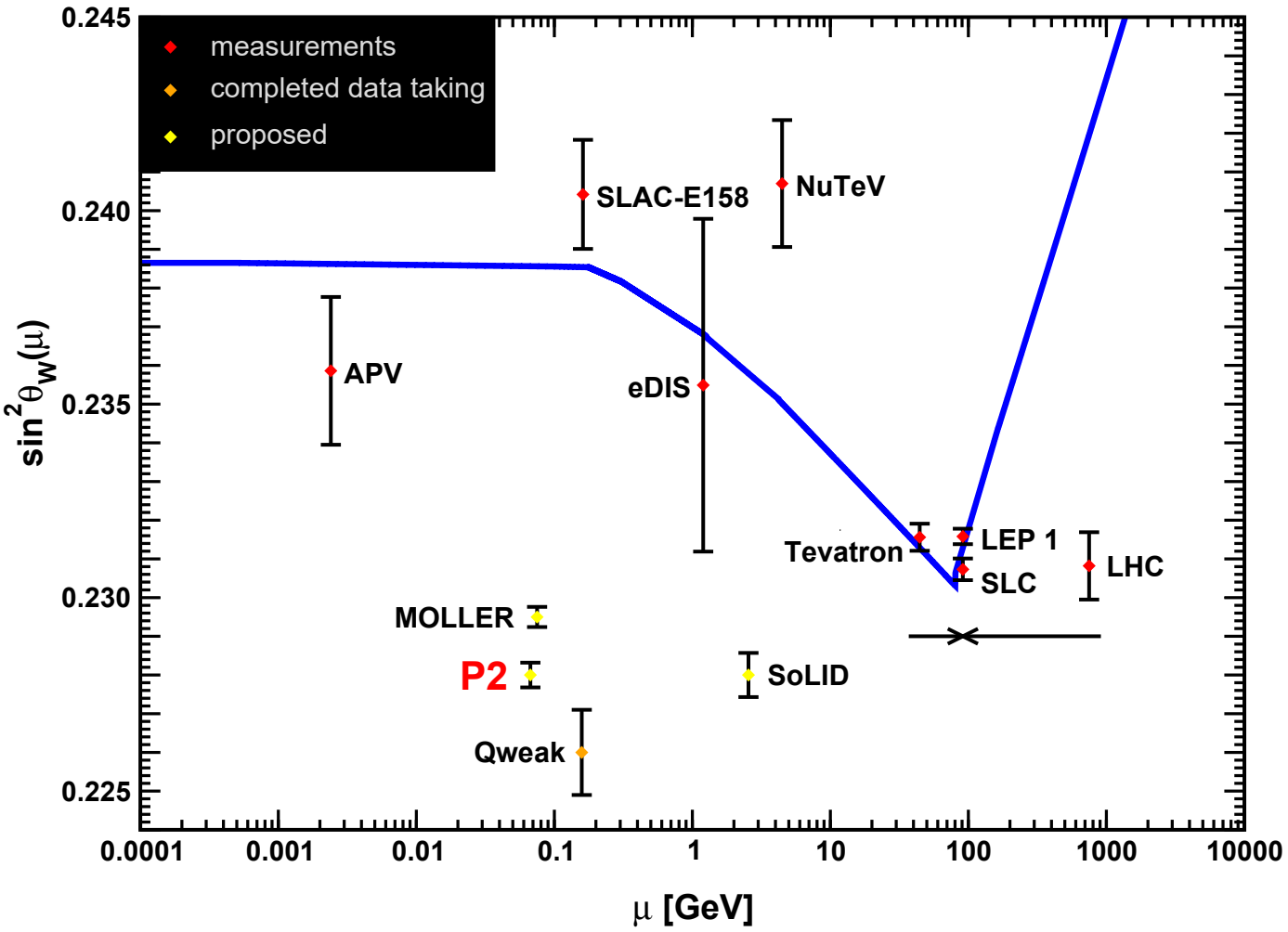
Backup

P2 Error budget

E_{beam}	155 MeV
$\bar{\theta}_{\text{f}}$	35°
$\delta\theta_{\text{f}}$	20°
$\langle Q^2 \rangle_{L=600\,\text{mm},\ \delta\theta_{\text{f}}=20°}$	$6 \times 10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle$	−39.94 ppb
$(\Delta A^{\text{exp}})_{\text{Total}}$	0.56 ppb (1.40 %)
$(\Delta A^{\text{exp}})_{\text{Statistics}}$	0.51 ppb (1.28 %)
$(\Delta A^{\text{exp}})_{\text{Polarization}}$	0.21 ppb (0.53 %)
$(\Delta A^{\text{exp}})_{\text{Apparative}}$	0.10 ppb (0.25 %)

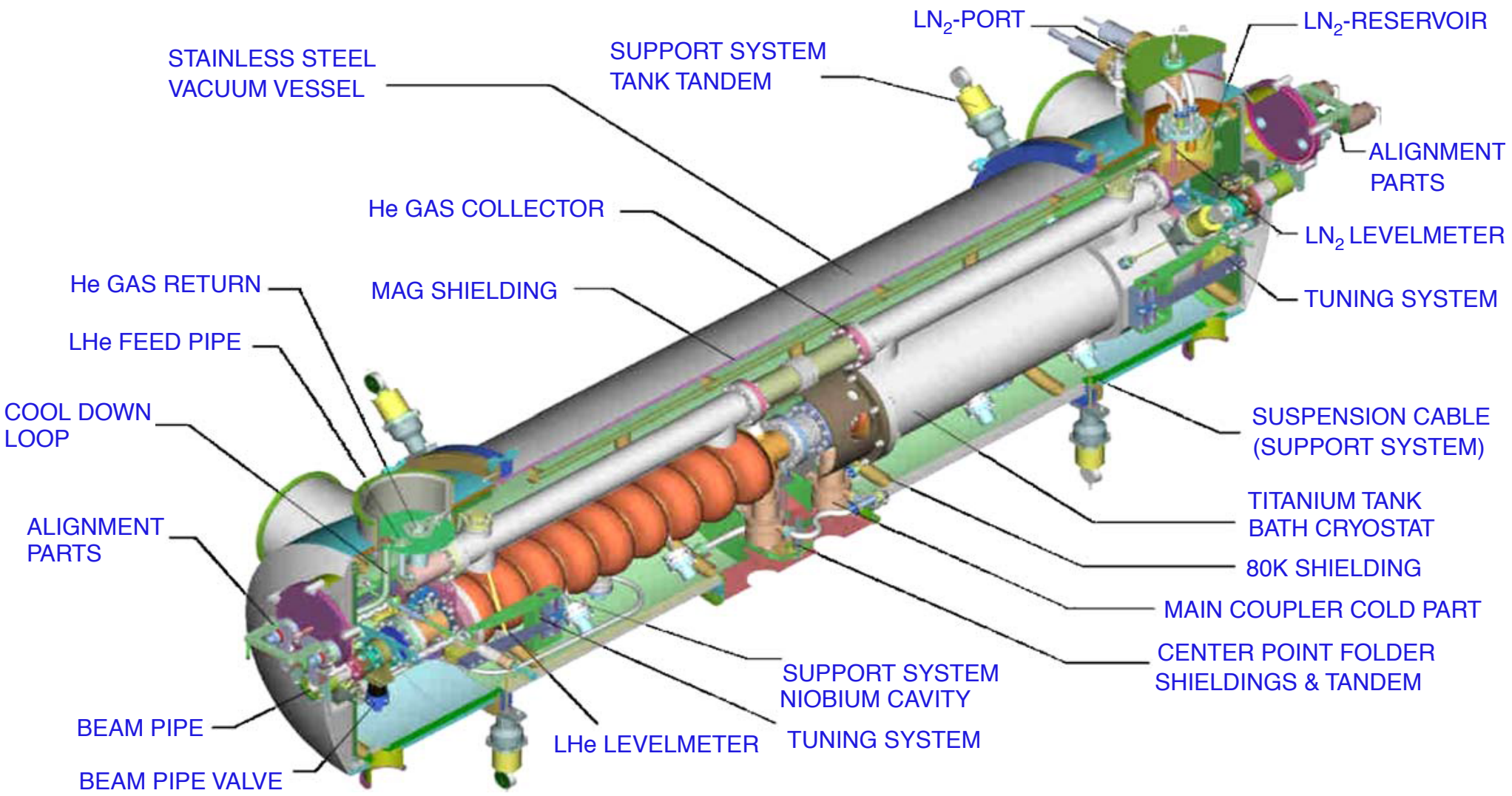
$\langle s^2_{\text{W}} \rangle$	0.231 16
$(\Delta s^2_{\text{W}})_{\text{Total}}$	3.3×10^{-4} (0.14 %)
$(\Delta s^2_{\text{W}})_{\text{Statistics}}$	2.7×10^{-4} (0.12 %)
$(\Delta s^2_{\text{W}})_{\text{Polarization}}$	1.0×10^{-4} (0.04 %)
$(\Delta s^2_{\text{W}})_{\text{Apparative}}$	0.5×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\Box_{\gamma Z}}$	0.4×10^{-4} (0.02 %)
$(\Delta s^2_{\text{W}})_{\text{nucl. FF}}$	1.2×10^{-4} (0.05 %)
$\langle Q^2 \rangle_{\text{Cherenkov}}$	$4.57 \times 10^{-3}\,(\text{GeV/c})^2$
$\langle A^{\text{exp}} \rangle_{\text{Cherenkov}}$	−28.77 ppb

More to come...

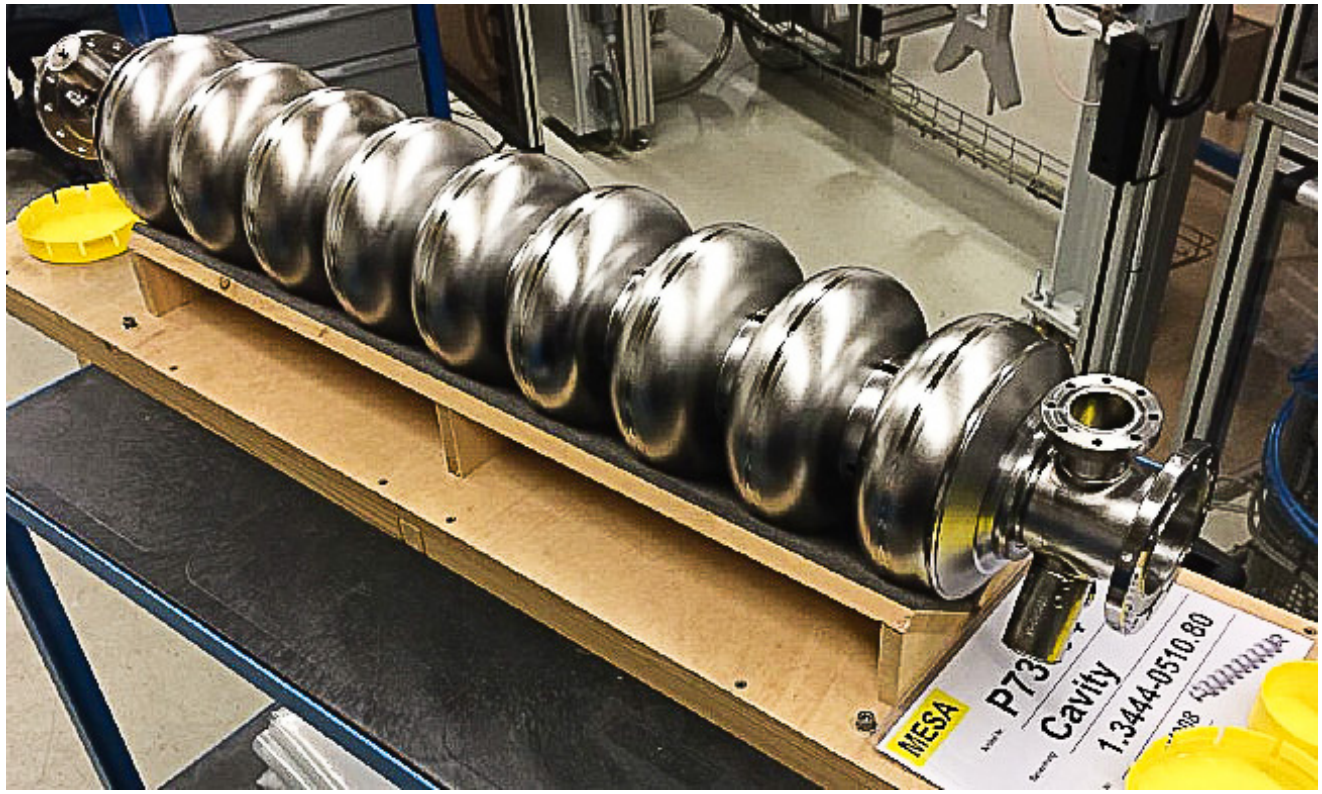


- Atomic parity violation in a single radium ion (Groningen)
- Moller at JLAB e^-e^- scattering
- SoLID: Deep inelastic e-p scattering at JLab
- Much improved LHC measurements at the Z-pole

Superconducting Cryomodules

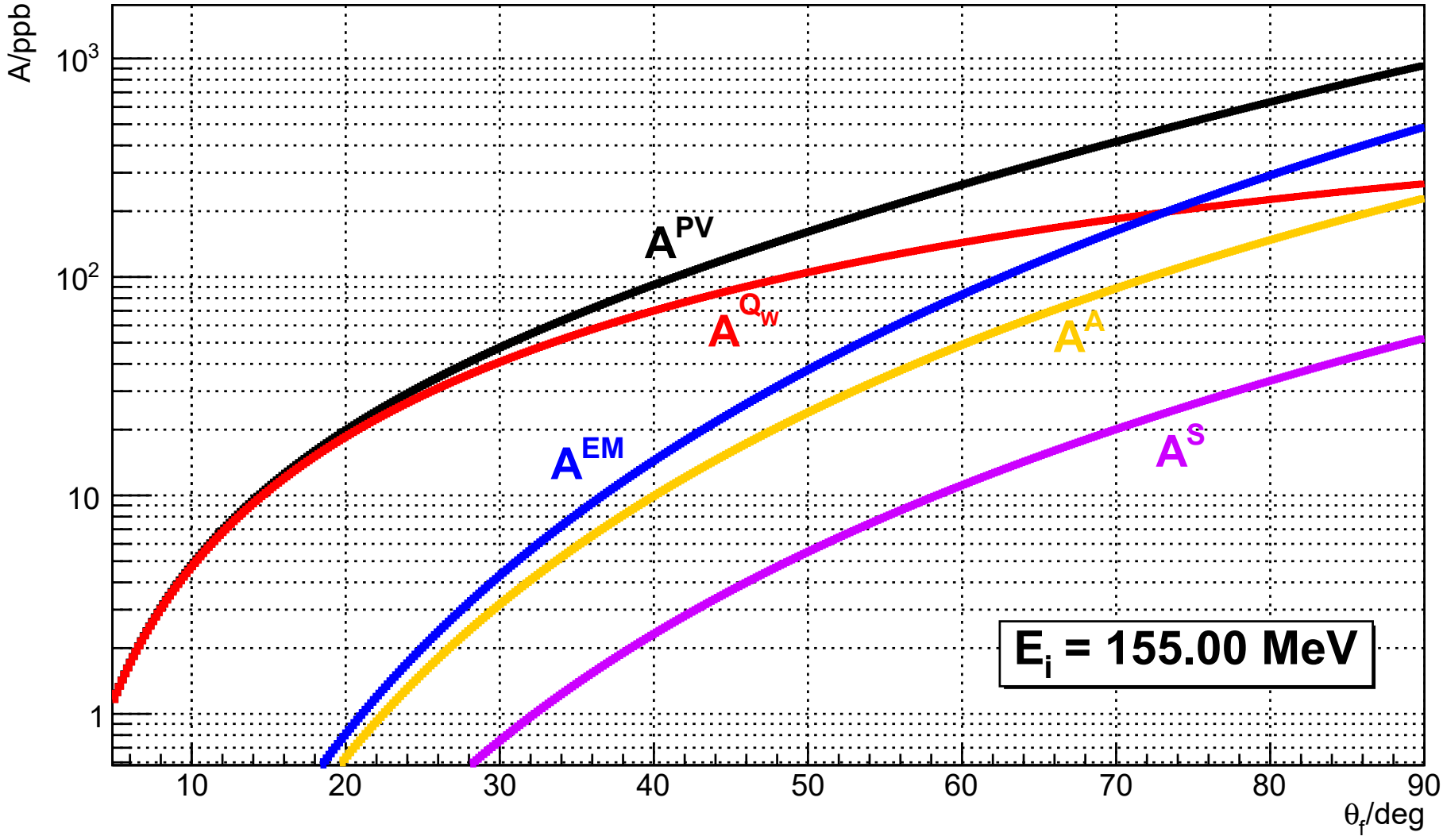


Teichert et al. NIM A 557 (2006) 239

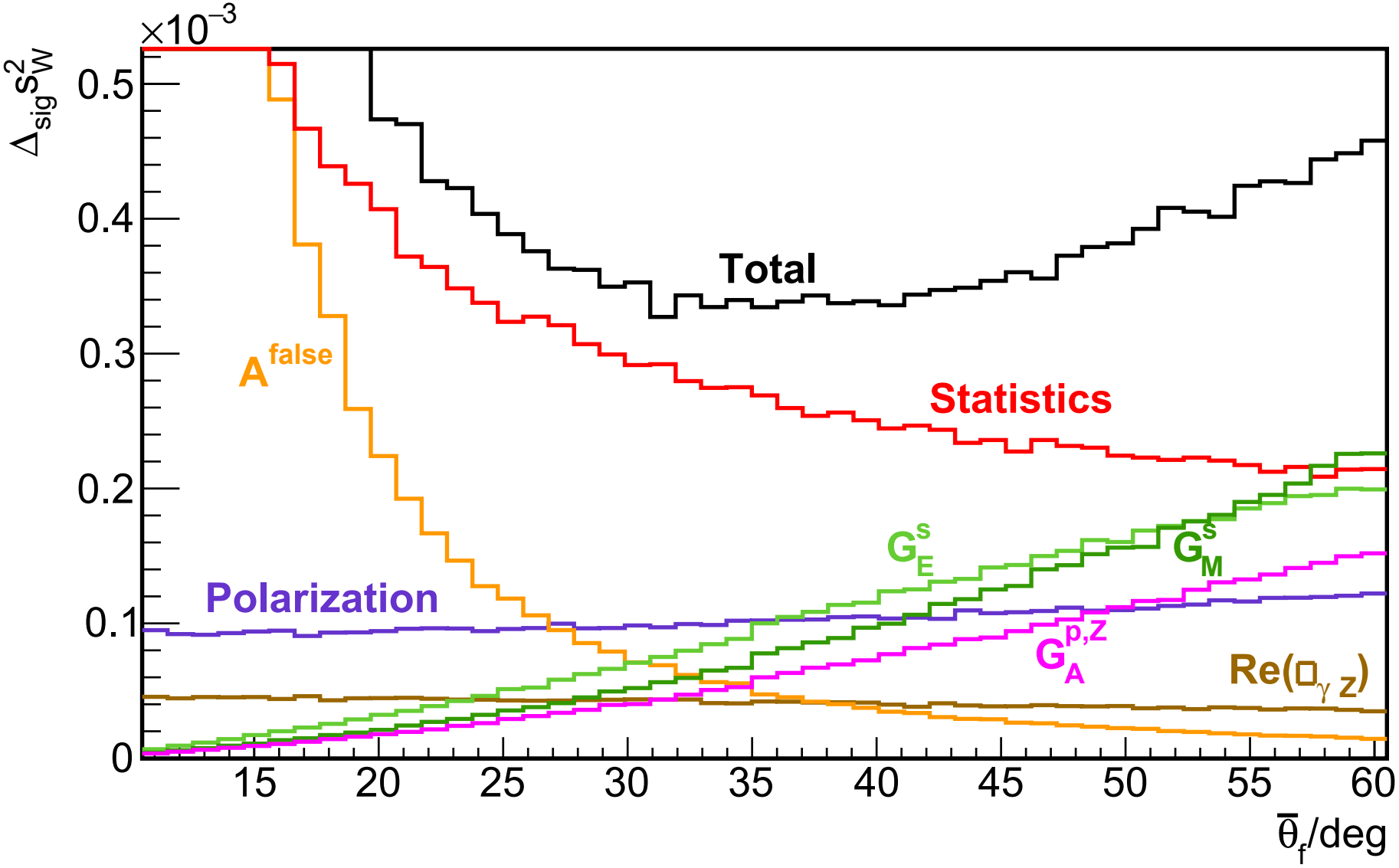

MESA
Cavity
1.3444-0510.80

research
instruments

Choice of scattering angle

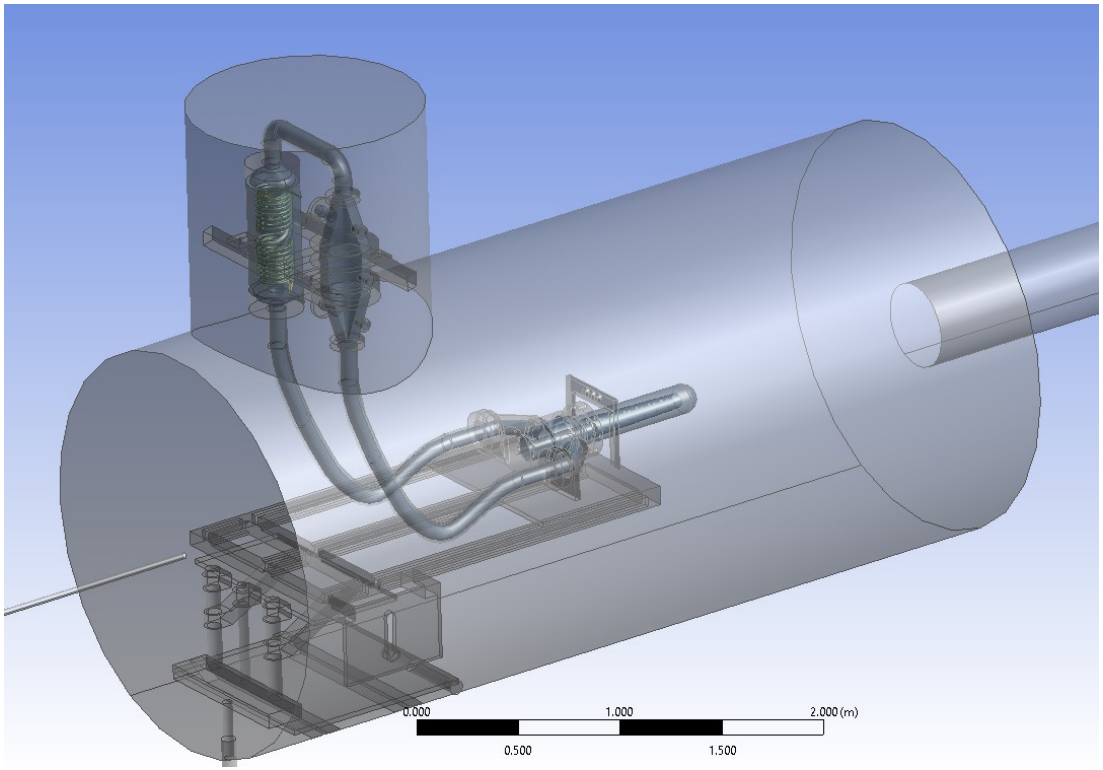


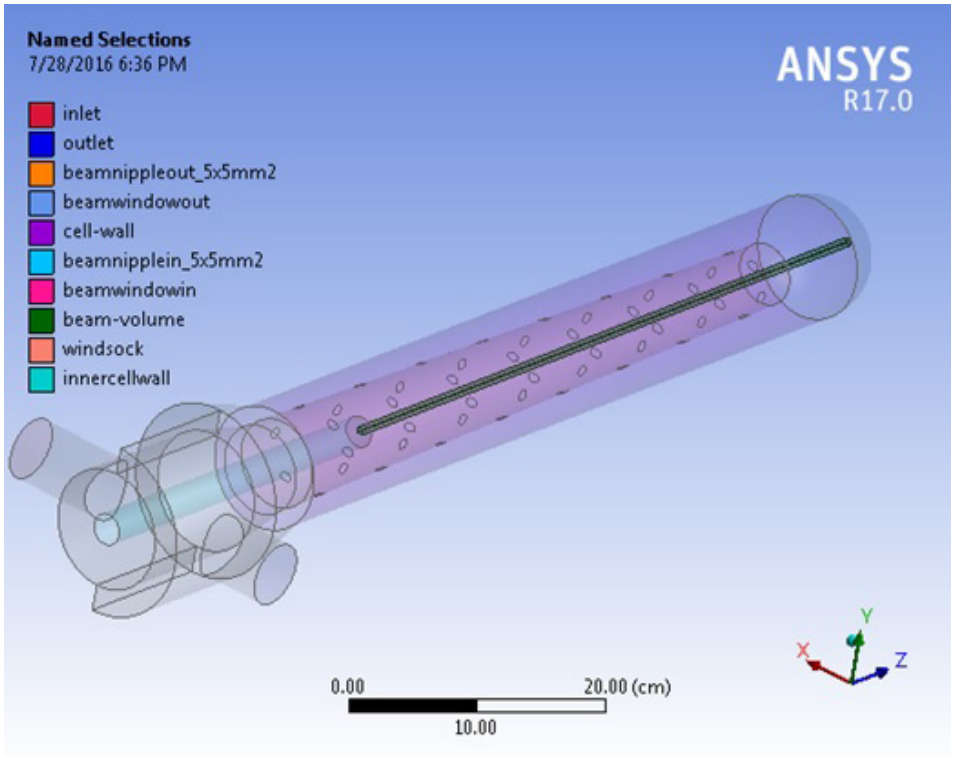
Choice of scattering angle



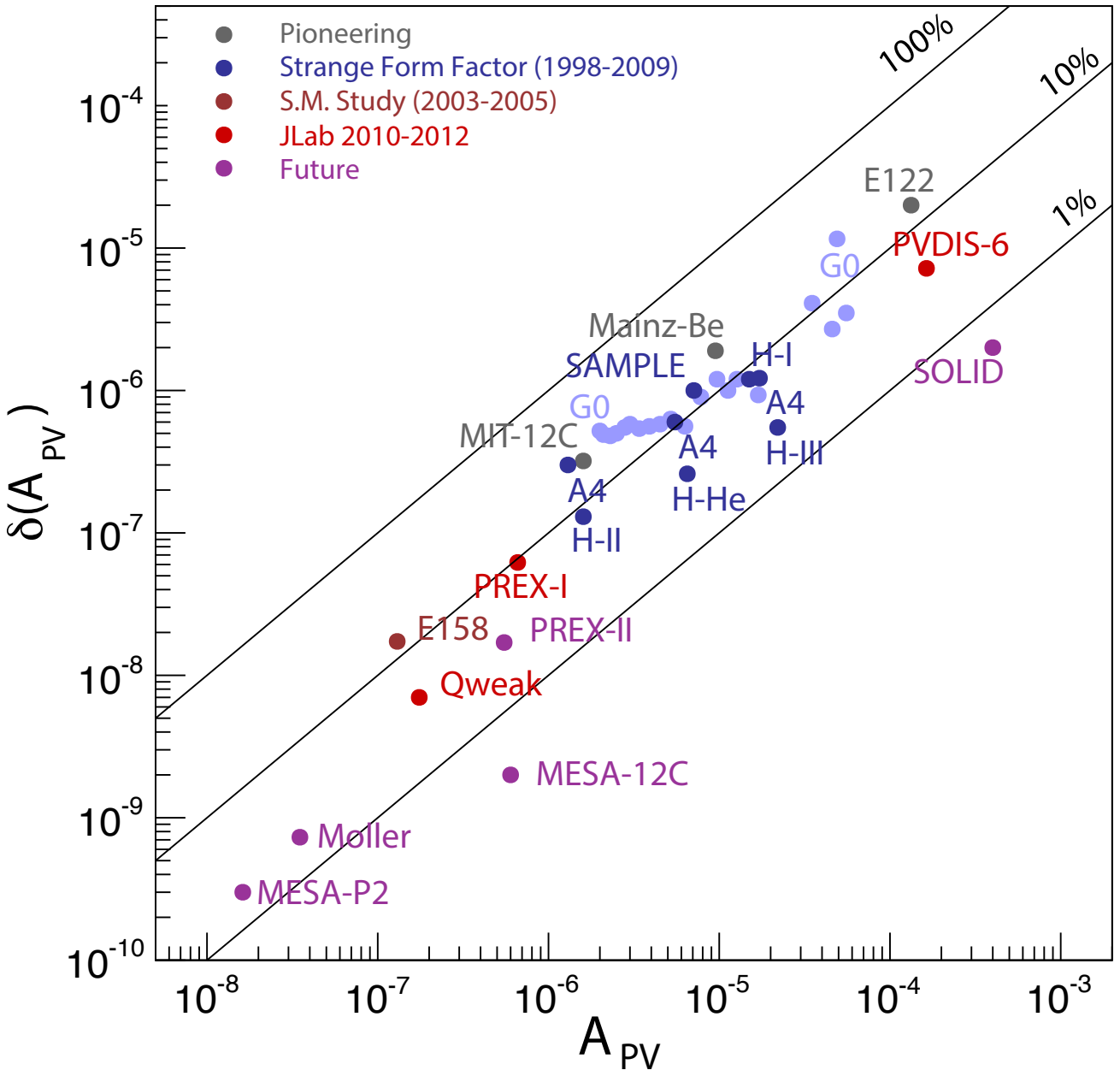
Target

- 60 cm of liquid hydrogen
- 3.1 KW beam power deposited
- Should not boil...
- Challenging design using CFD tools (Silviu Covrig, JLab)

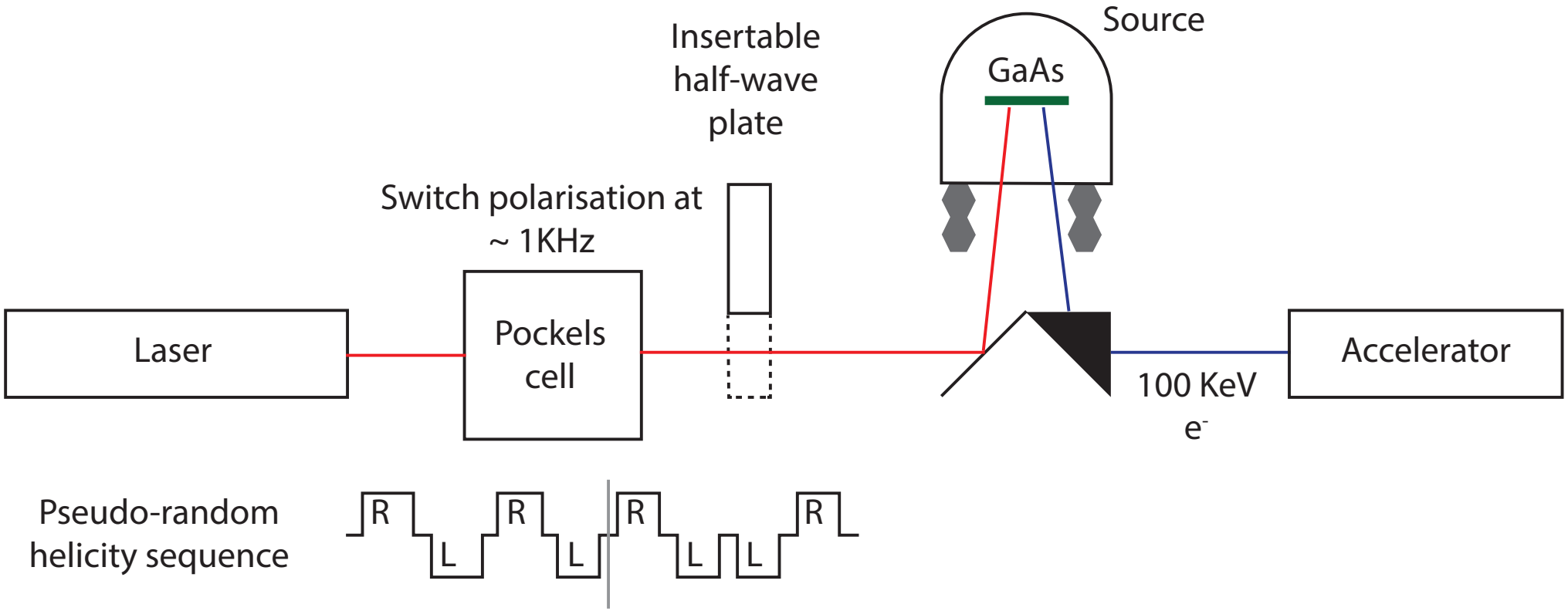




PVeS Experiment Summary



Polarized Source and Helicity Flips



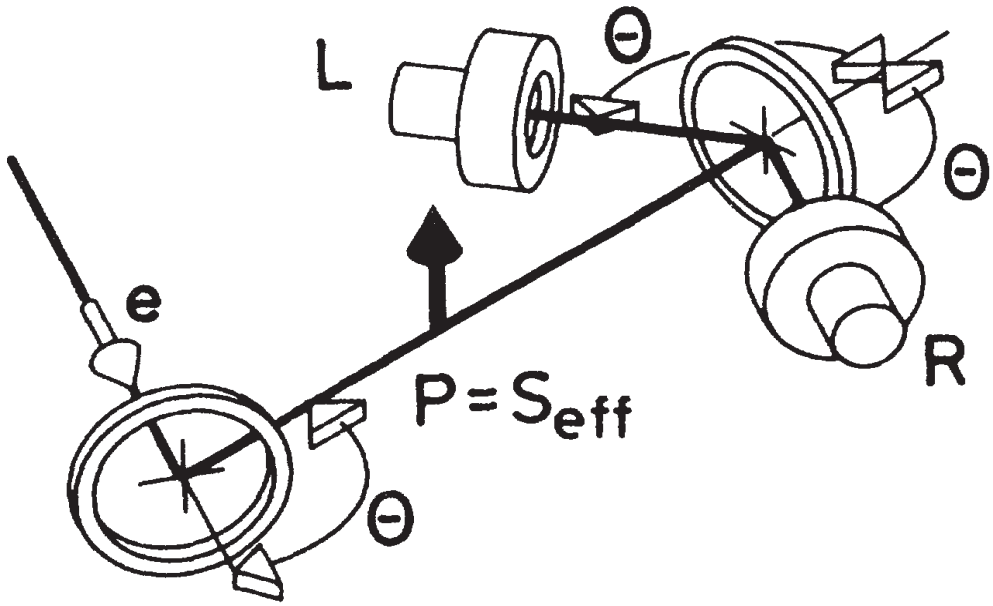
Stability Requirements

The main worry are beam fluctuations correlated with the helicity:

	Achieved at MAMI	$\sin^2\theta_W$ uncertainty	requirement
• Energy fluctuations:	0.04 eV	< 0.1 ppb	ok!
• Position fluctuations	3 nm	5 ppb	0.13 nm
• Angle fluctuations	0.5 nrad	3 ppb	0.06 nrad
• Intensity fluctuations	14 ppb	4 ppb	0.36 ppb

Polarimetry at MESA

Polarimetry: Double Mott Polarimeter



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

Mott Polarimertry:

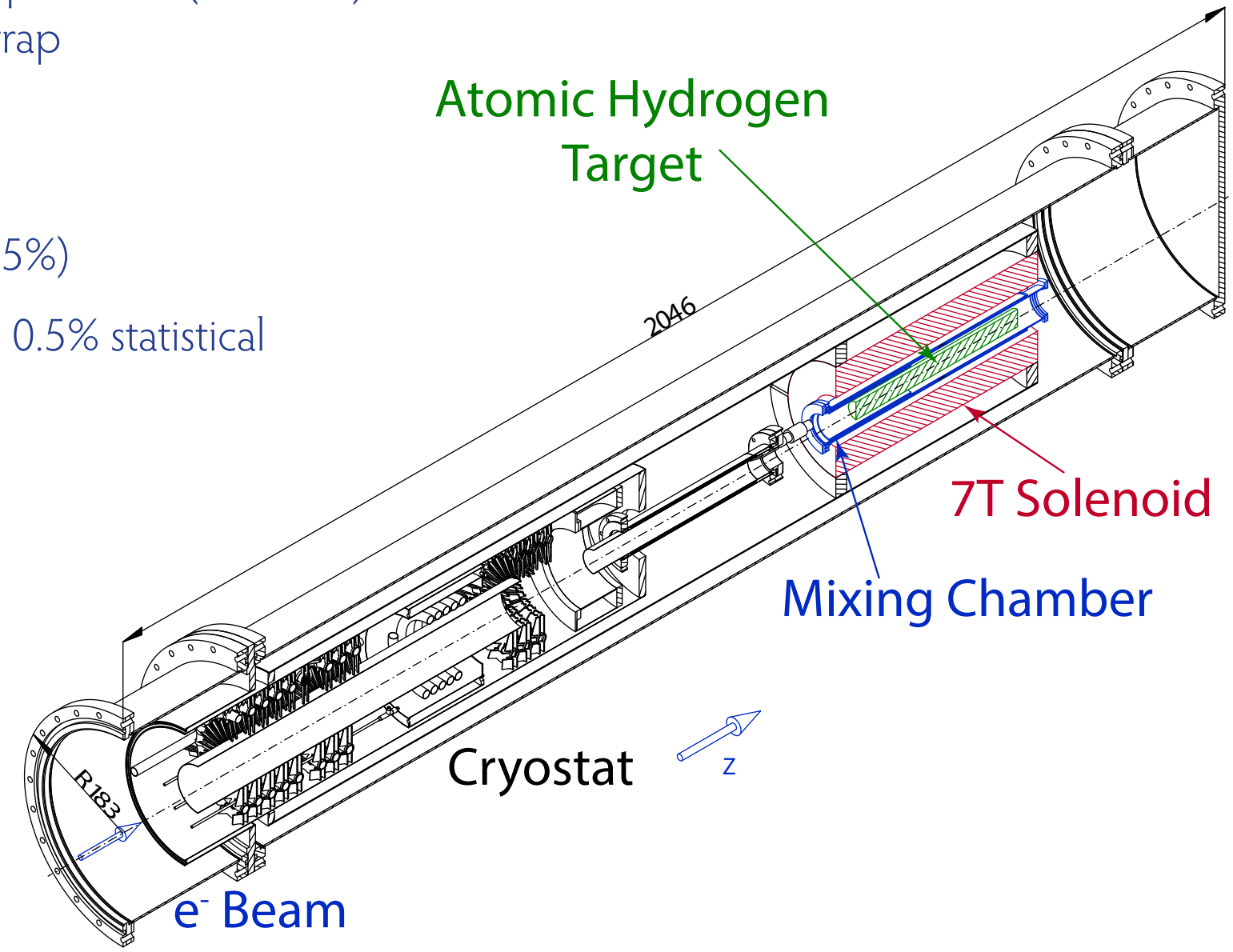
- Measure left/right asymmetry to obtain spin polarisation
- Analysing power of foils needs to be extrapolated

Double Mott Polarimeter:

- Obtain analysing power from measurement
- Precise measurement of spin polarisation

- Invasive measurement at source

Polarimetry: Hydro-Møller Polarimeter

Møller scattering from polarized (8 T field) atomic hydrogen in a trap

- Online capability
- High accuracy (< 0.5%)
- About 2 h to reach 0.5% statistical accuracy