JG|U

SFB 1044 Institut für Kernphysik

Perspectives in parity violating electron scattering

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(Helmholtz Institute Mainz,
Institute for Nuclear Phyiscs,
PRISMA cluster of excellence
Johannes Gutenberg University Mainz)

Kolloquium, Institut of Physics, UNA Mexico, April 4, 2019
The Physics Case of the Weak Charge of Carbon-12

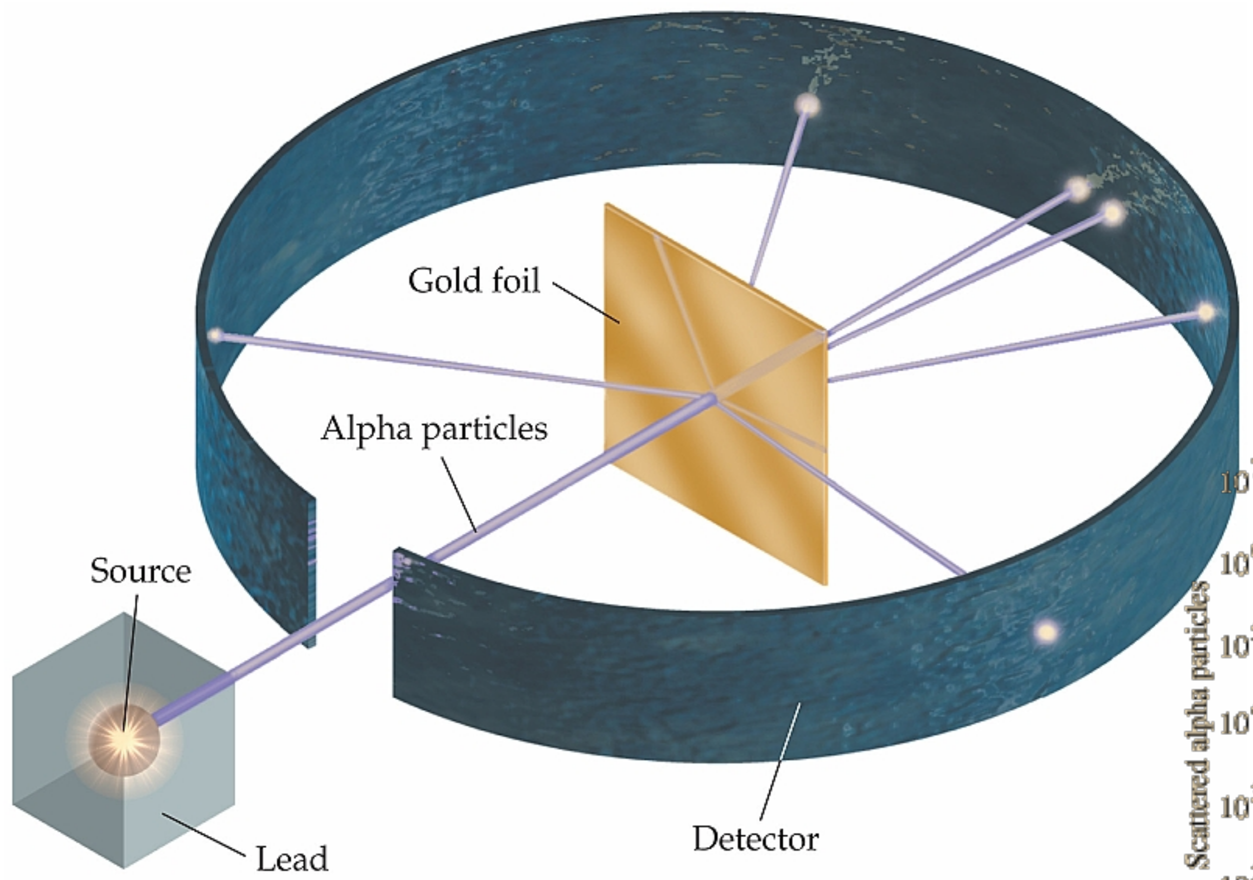
SFB 1044 HIM PRiSMA

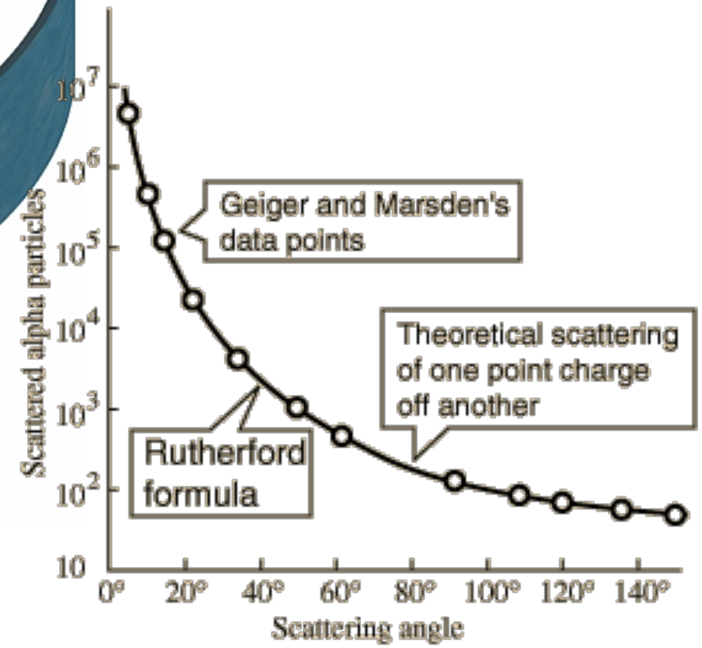
Parity Violating Electron Scattering:

- Electron scattering
- Search for new physics
- Measuring the neutron distribution in nuclei

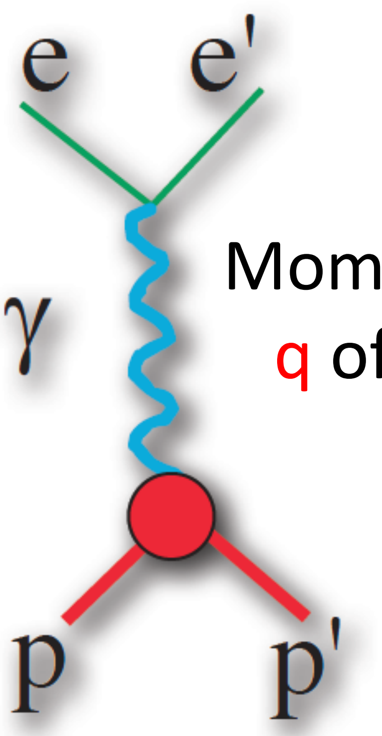
Electron Scattering

Rutherford Scattering (alpha particles):





Elastic electron scattering off nucleons or nuclei:



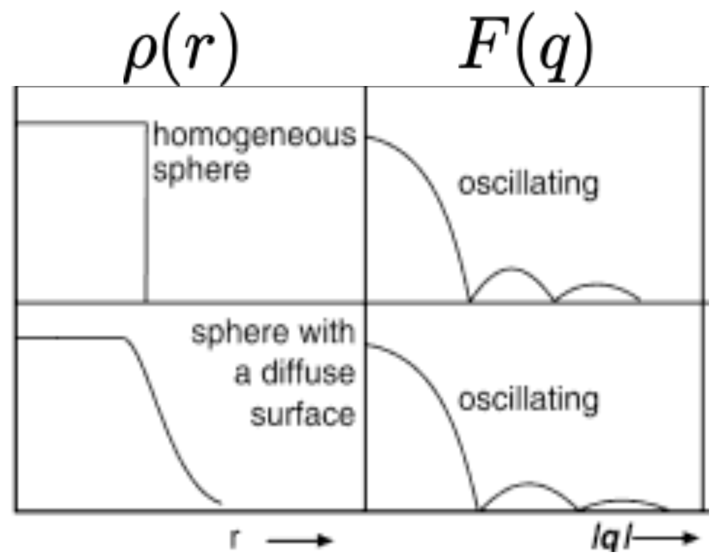
Momentum Tranfer q of the photon

Differential Cross Section

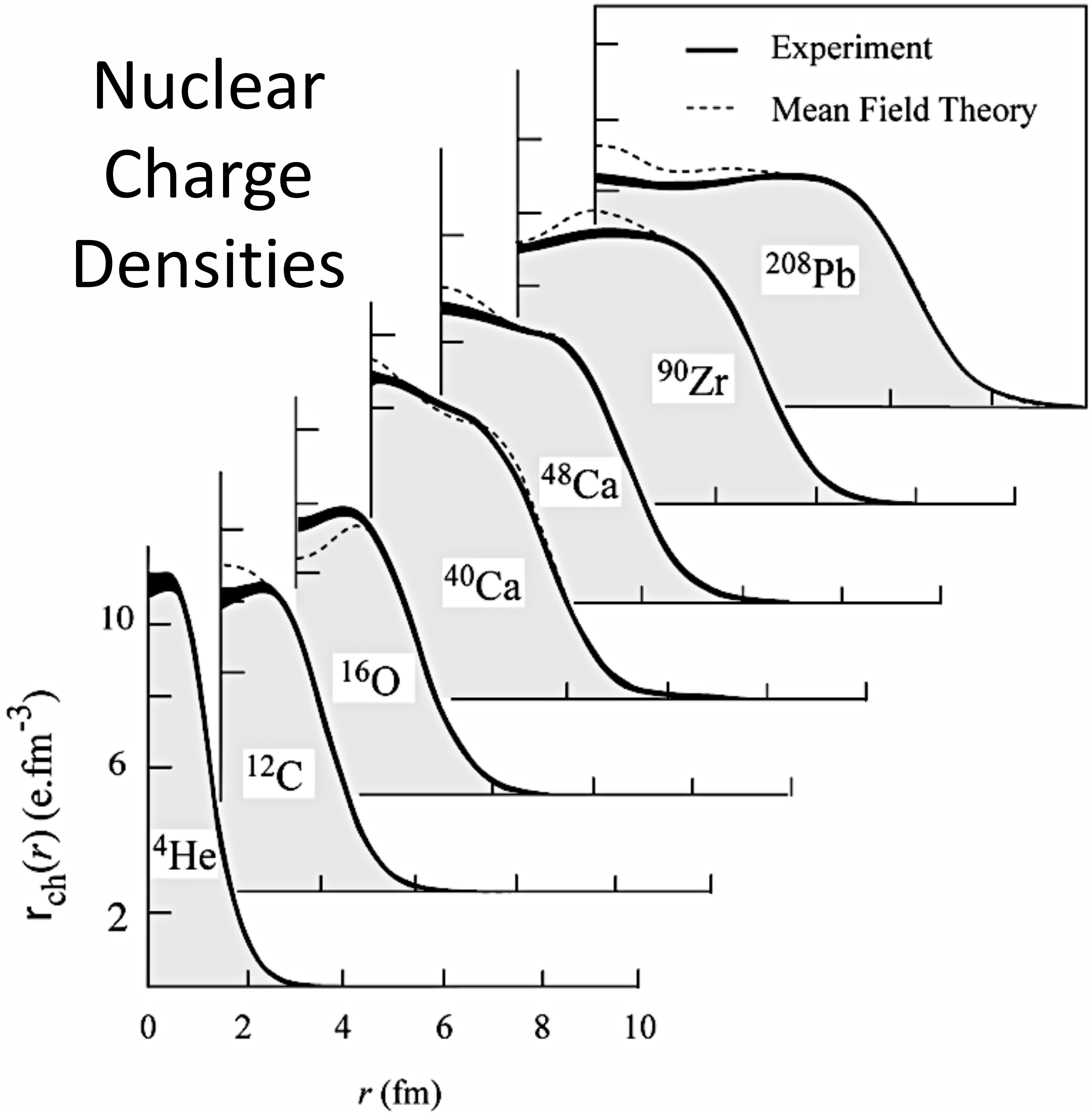
(spin ½ on spinless) :

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \underbrace{\boxed{|F(q)|^2}}_{\text{form factor}}$$

Charge Distribution ρ(r): Fourier transform of form factor



Nuclear Charge Densities



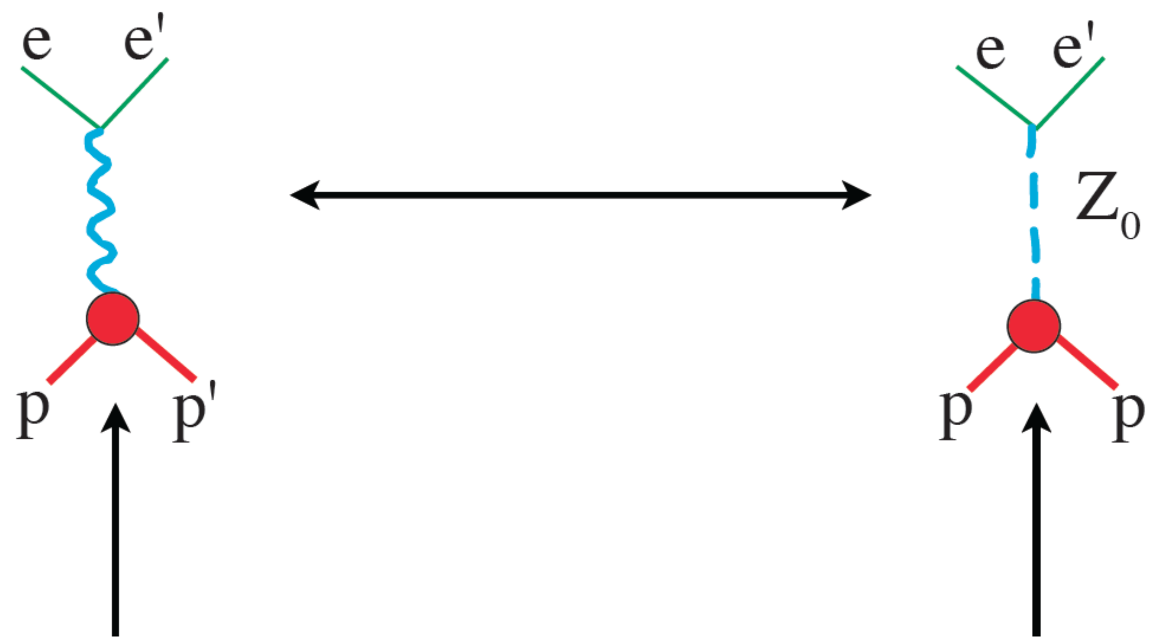
Form Factors:

Proton charge:
form factor
at $q^2 = 0\ (\mathrm{GeV}/c)^2$
$F(q^2=0\ (\mathrm{GeV}/c)^2) = +1e$

Proton radius:
derivative of
Form factor
at $q^2=0\ (\mathrm{GeV}/c)^2$
$\langle r^2 \rangle = -6h^2 dF(q^2)/dq^2$

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
$Q_W(n) = -1$

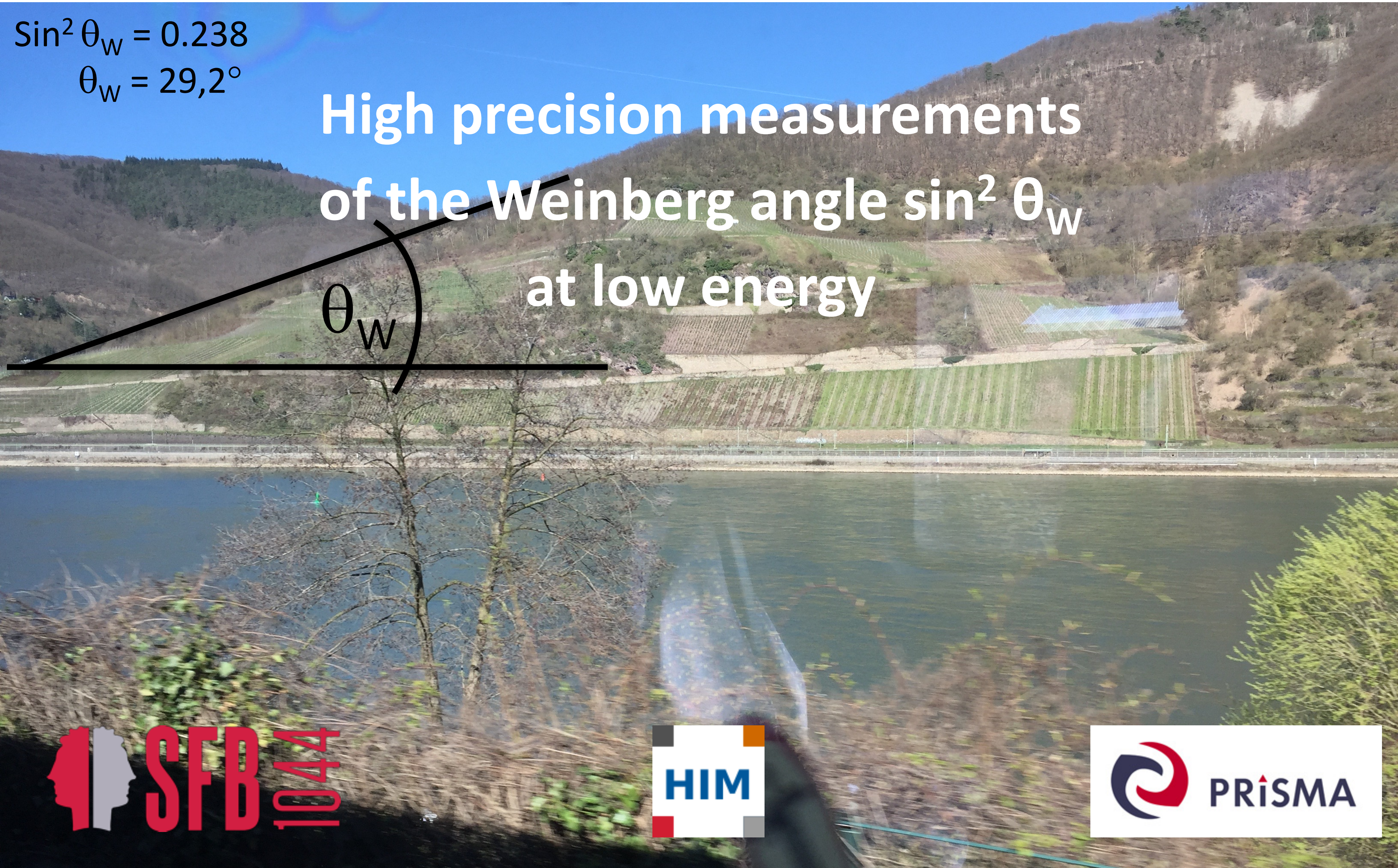
$\sin^2\theta_W$: a central parameter of the standard model

Search for new physics

$\sin^2 \theta_W = 0.238$

$\theta_W = 29{,}2^\circ$

High precision measurements of the Weinberg angle $\sin^2 \theta_W$ at low energy



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HIM

PRISMA

Search for New Physics: Various Methods

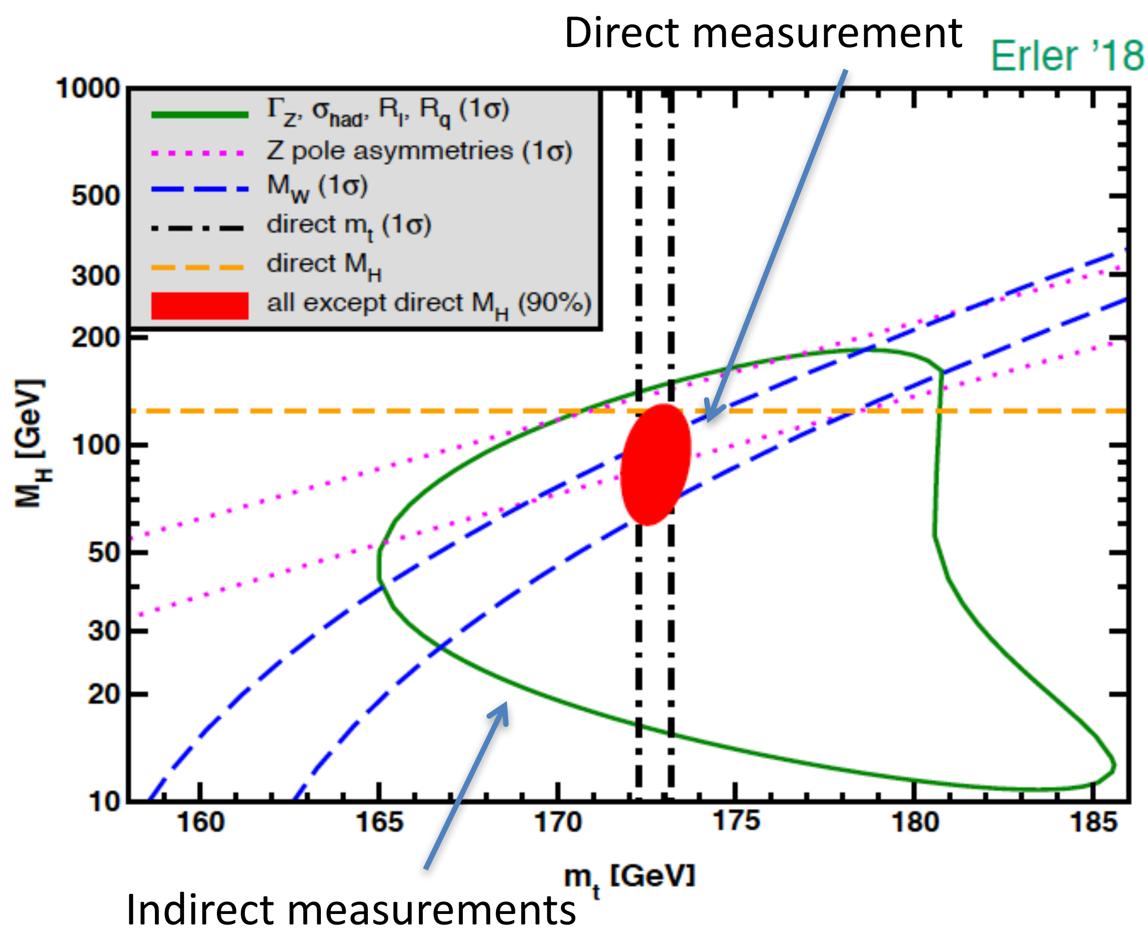
High Energy (LHC)

High Precision
Anom. Mag. Moment
$(g\text{-}2)_{\mu,e}$, EDM, $\sin^2\theta_W$, ...
at low energy

High Intensity
Rare B-decays
R_{D*}

Accurate theory needed

Direct observation versus precision measurements: top-quark, Higgs



Direct measurements:

$$M_H = 125.14 \pm 0.15 \text{ GeV}$$

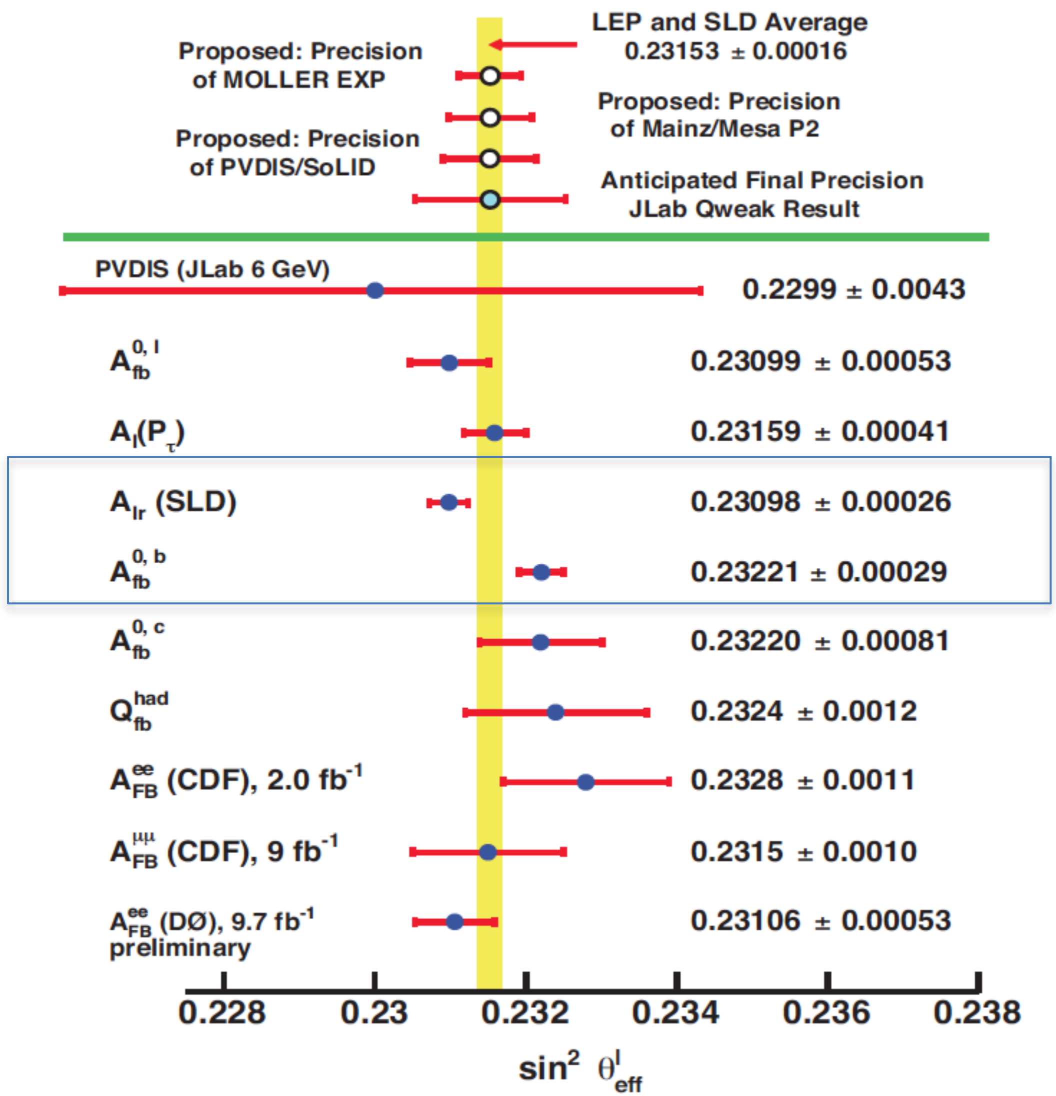
$$m_t = 172.74 \pm 0.46 \text{ GeV}$$

Indirect prediction:

$$M_H = 90^{+17}_{-16} \text{ GeV}$$

$$m_t = 176.4 \pm 1.8 \text{ GeV}$$

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



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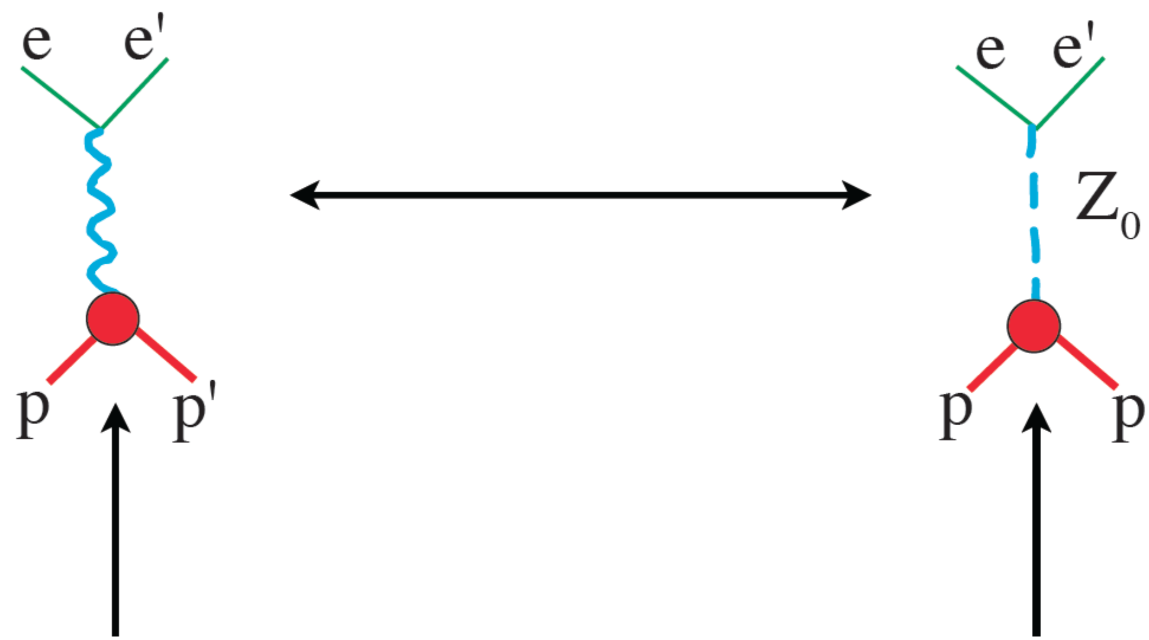

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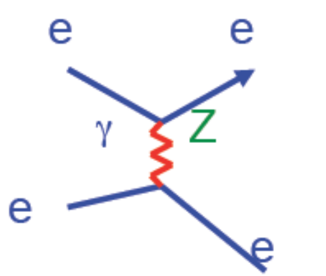
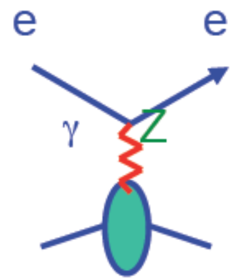
$\sin^2\theta_W$: a central parameter of the standard model

Møller Scattering



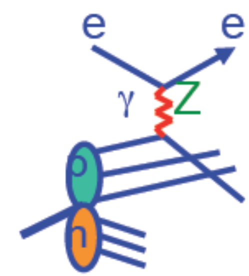
- Purely Leptonic

Q-Weak (JLab)
P2 (Mainz/MESA)



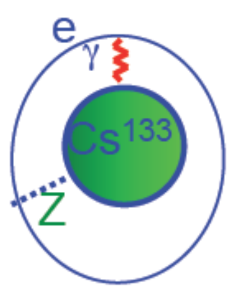
- Coherent quarks in p
- in operation now
- $2(2C_{1u}+C_{1d})$

e-DIS



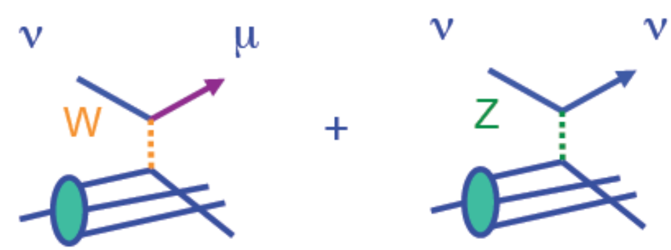
- Isoscaler quark scattering
- $(2C_{1u}-C_{1d})+Y(2C_{2u}-C_{2d})$

Atomic Parity Violation



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

Neutrino Scattering



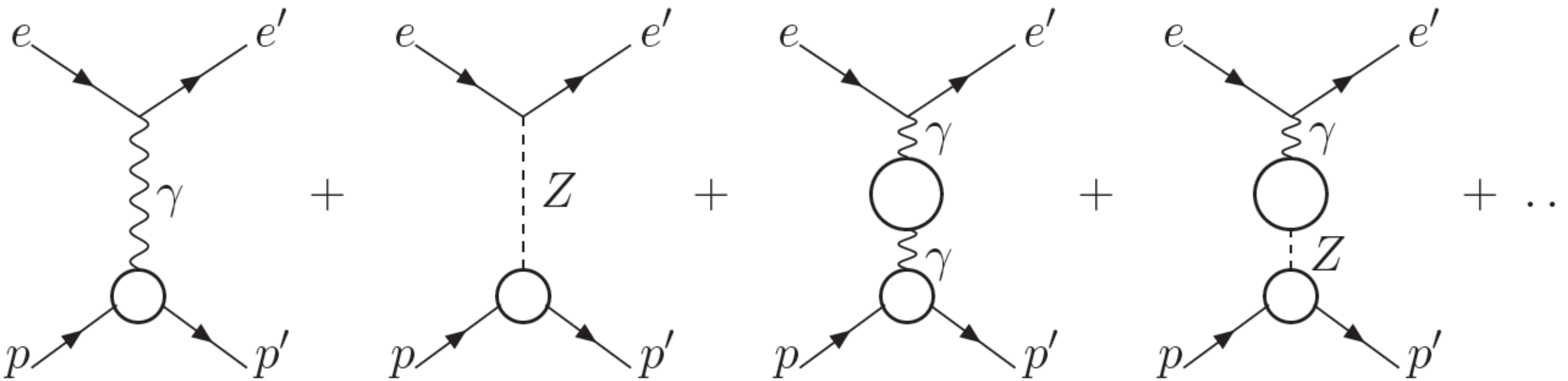
- Quark scattering (from nucleus)
- Weak charged and neutral current difference

S. Su

Courtesy of P. Reimer and R. Arnold

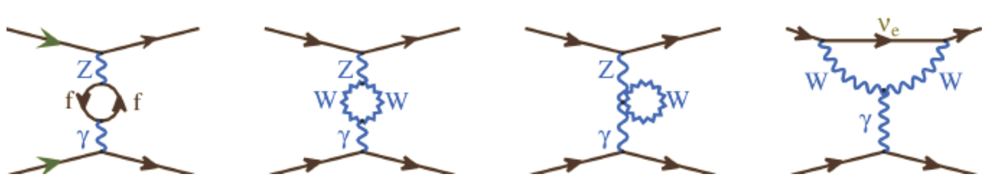
„running“ $\sin^2\theta_{eff}$ or $\sin^2\theta_W(\mu)$

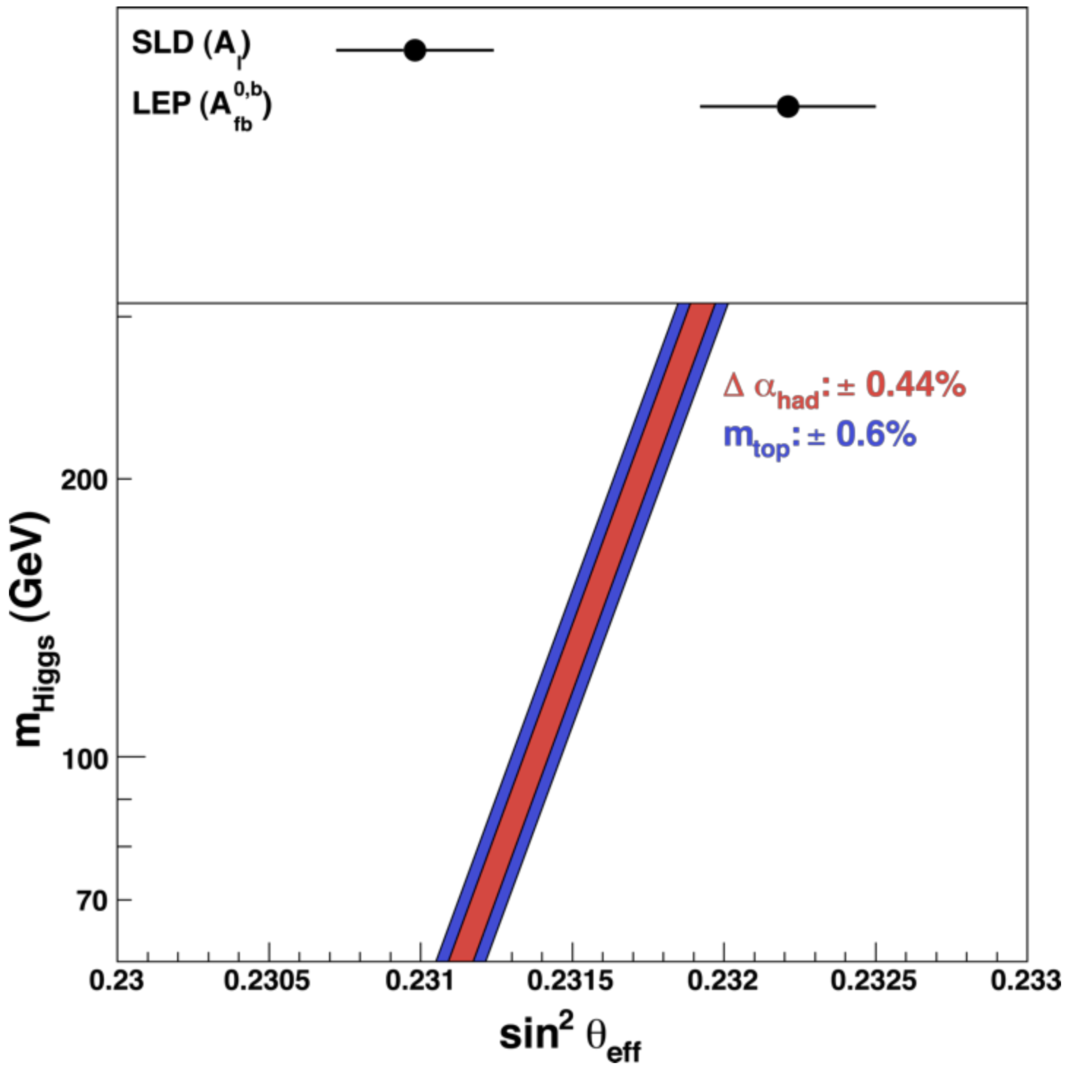
Precision measurements and quantum corrections:

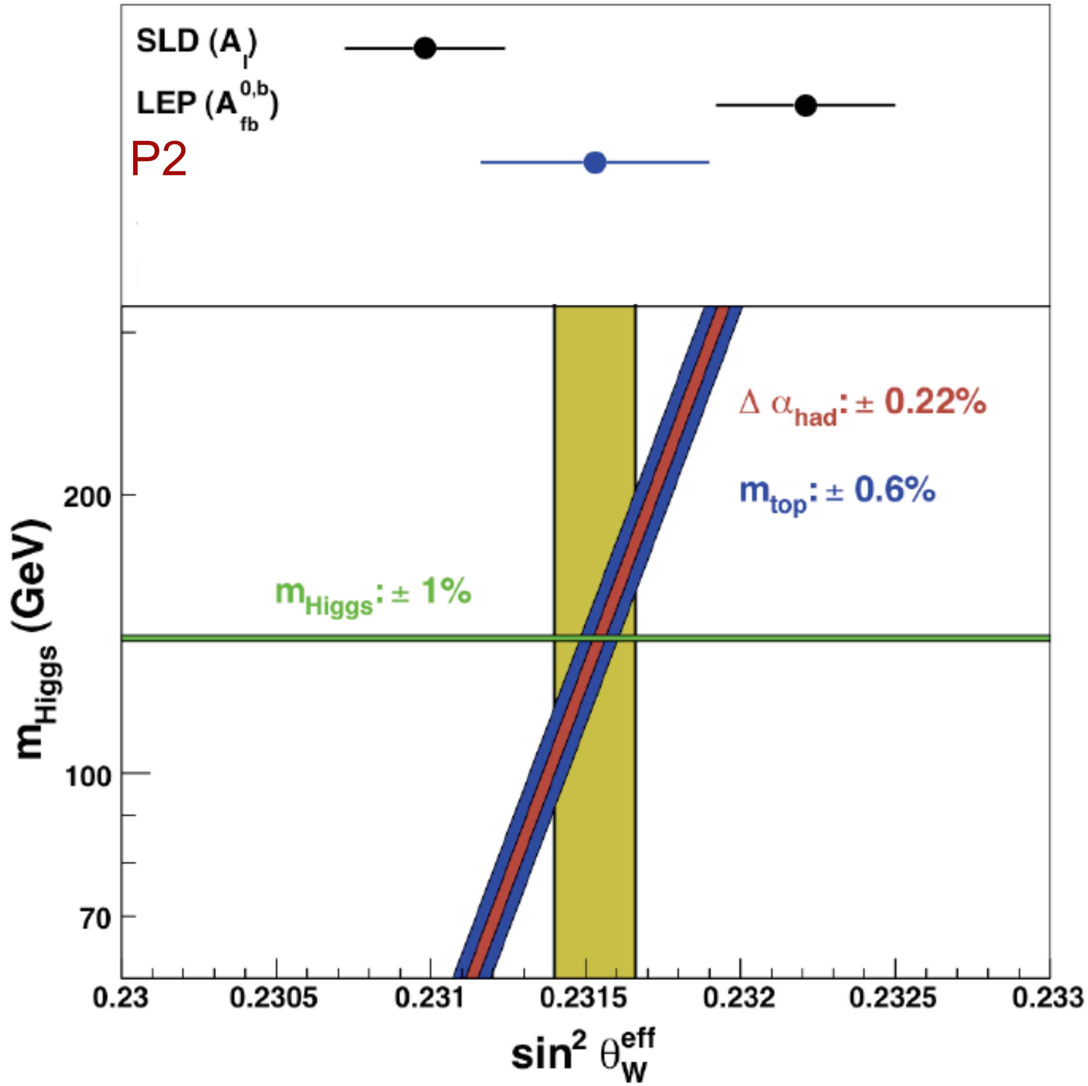


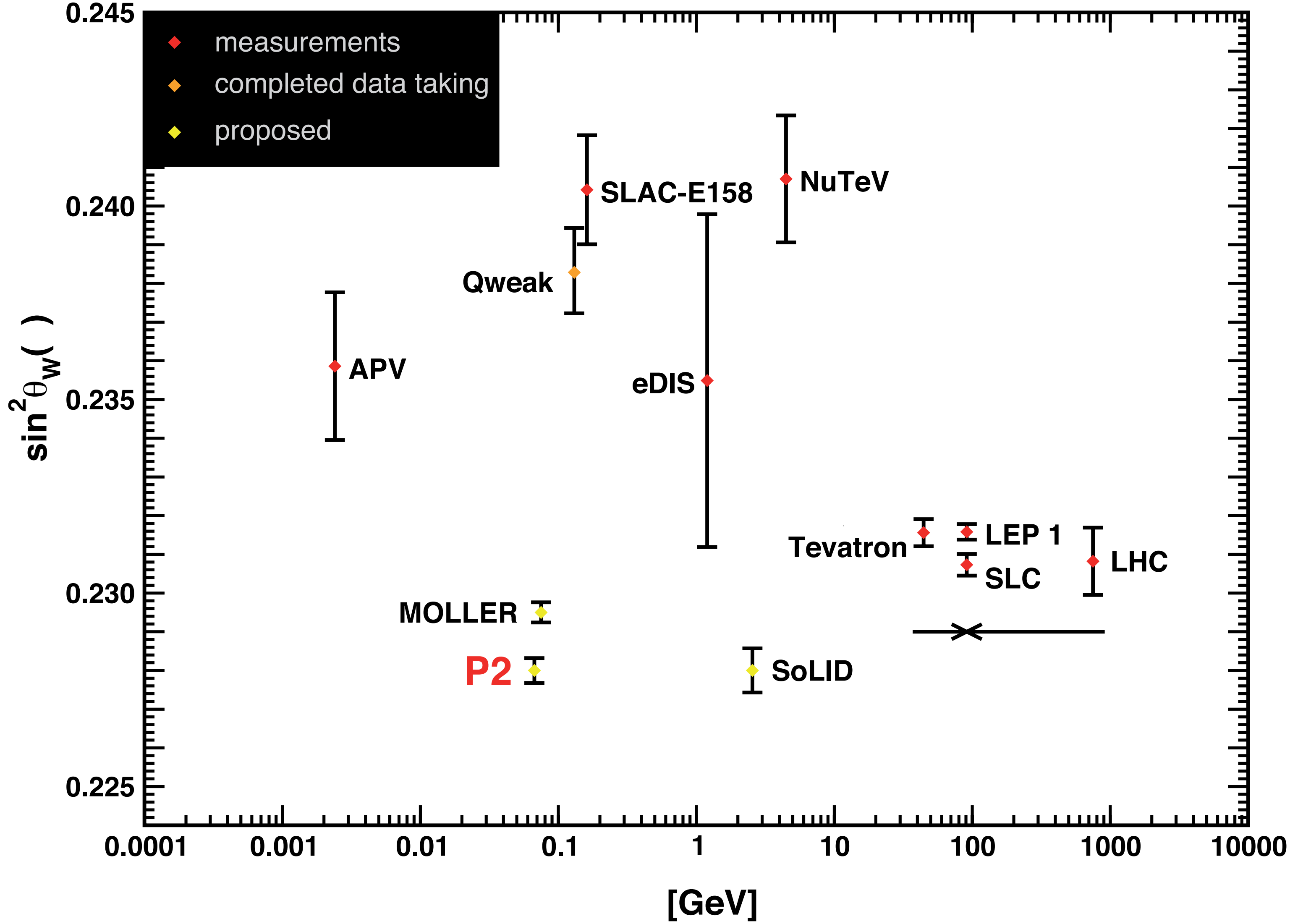
running α running $\sin^2 \theta_W(\mu)$

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




SLD (A_l)
LEP ($A_{fb}^{0,b}$)
$\Delta\ \alpha_{had}$: ± 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
$\sin^2 \theta_{eff}$

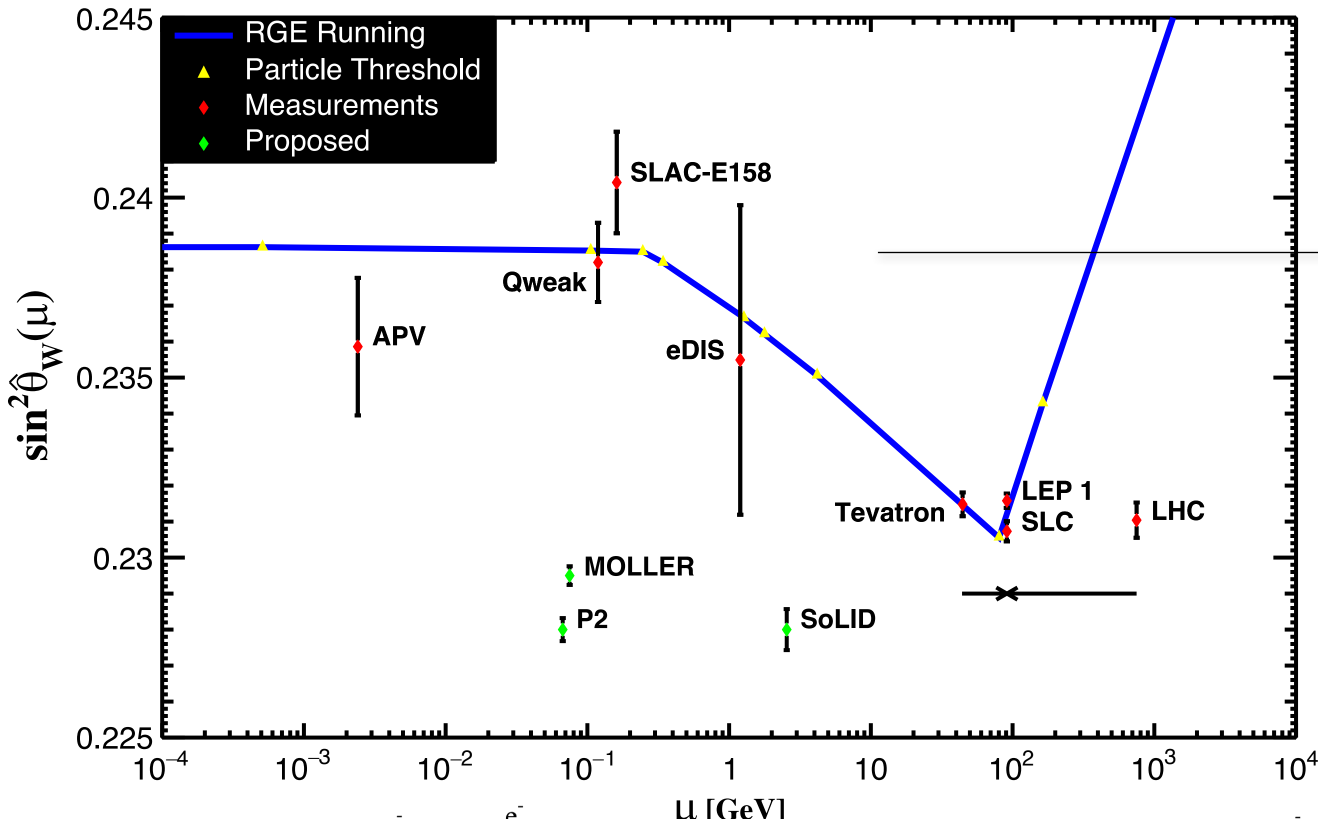

SLD (A_l)
LEP ($A_{fb}^{0,b}$)
P2
$\Delta\,\alpha_{had}$: ± 0.22%
m_{top}: ± 0.6%
m_{Higgs}: ± 1%
m_{Higgs} (GeV)
200
100
70
0.23
0.2305
0.231
0.2315
0.232
0.2325
0.233
$\sin^2\theta_W^{eff}$


measurements
completed data taking
proposed
SLAC-E158
NuTeV
Qweak
APV
eDIS
Tevatron
LEP 1
SLC
LHC
MOLLER
P2
SoLID
0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\ )$
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
[GeV]

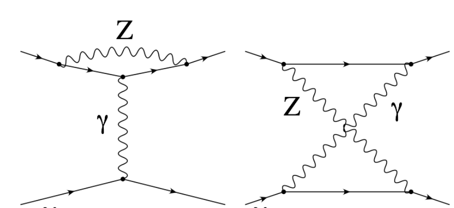
On Z resonance: A_Z is imaginary

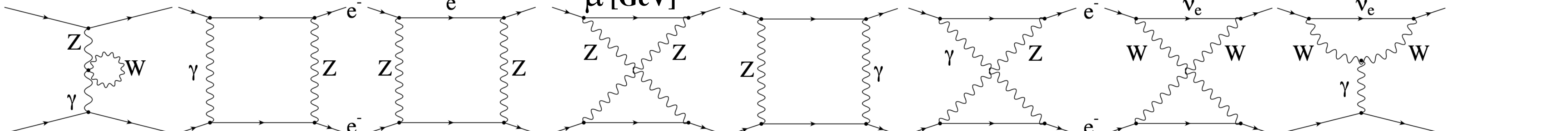
$$\left|\mathbf{A_Z} + \mathbf{A_{new}}\right|^2 \rightarrow \mathbf{A_Z^2}\left[1 + \left(\frac{\mathbf{A_{new}}}{\mathbf{A_Z}}\right)^2\right]$$

No interference term

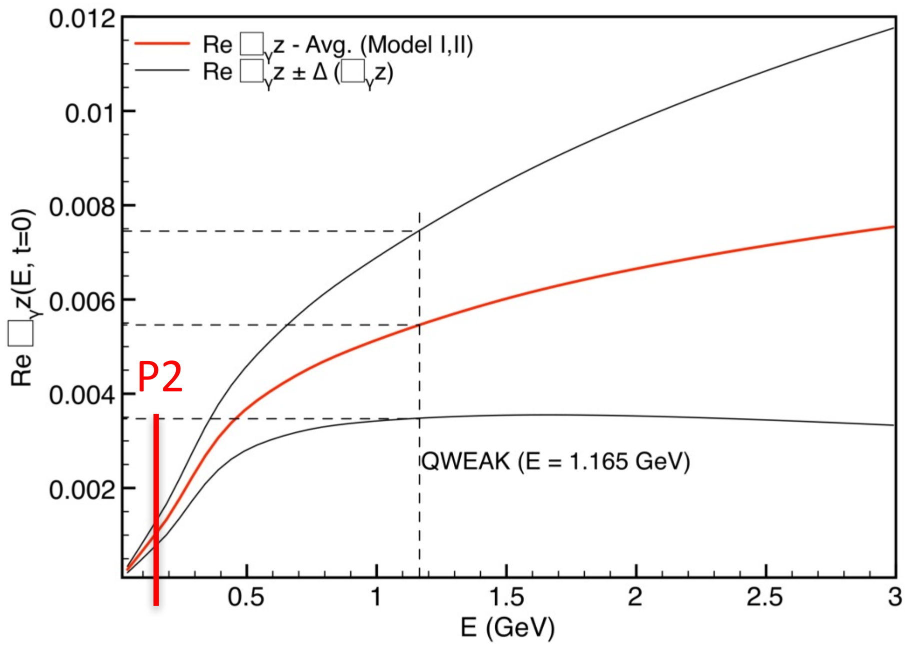


3 %



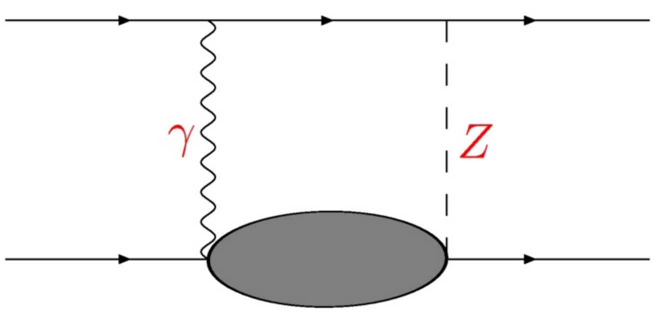


- γZ box graph contributions obtained by modelling hadronic effects:



[Gorchstein, Horowitz & Ramsey-Musolf 2011]

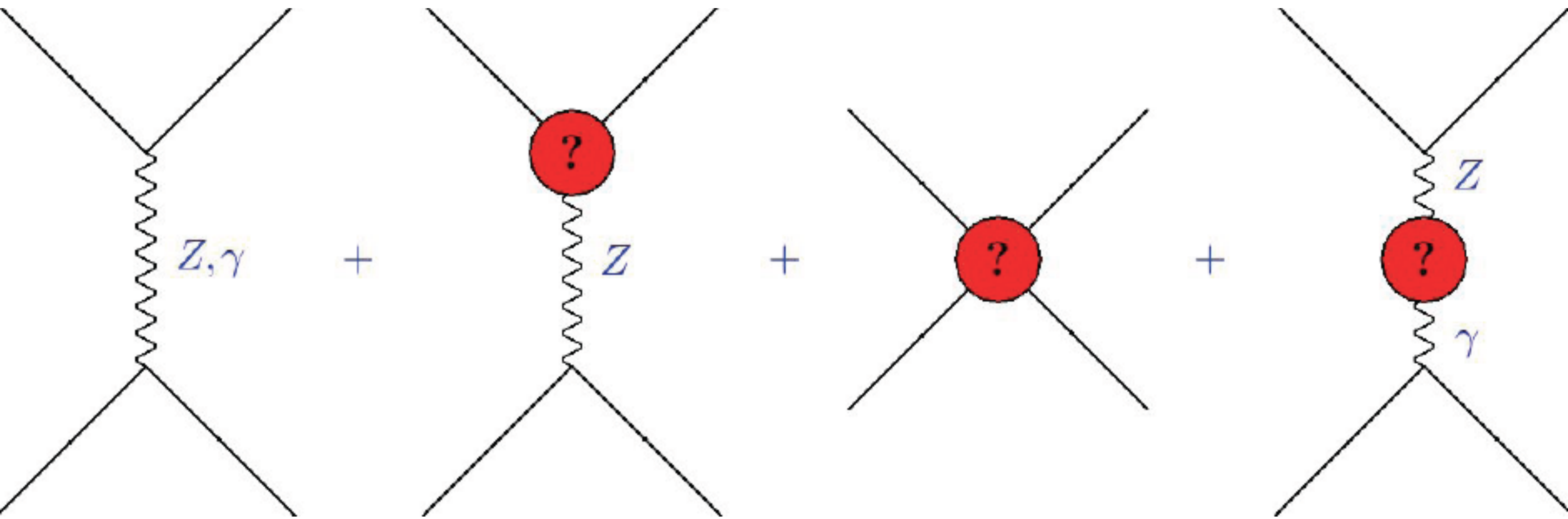
- Hadronic uncertainties suppressed at lower energies
- Low beam energy experiment:
  P2 @ MESA



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

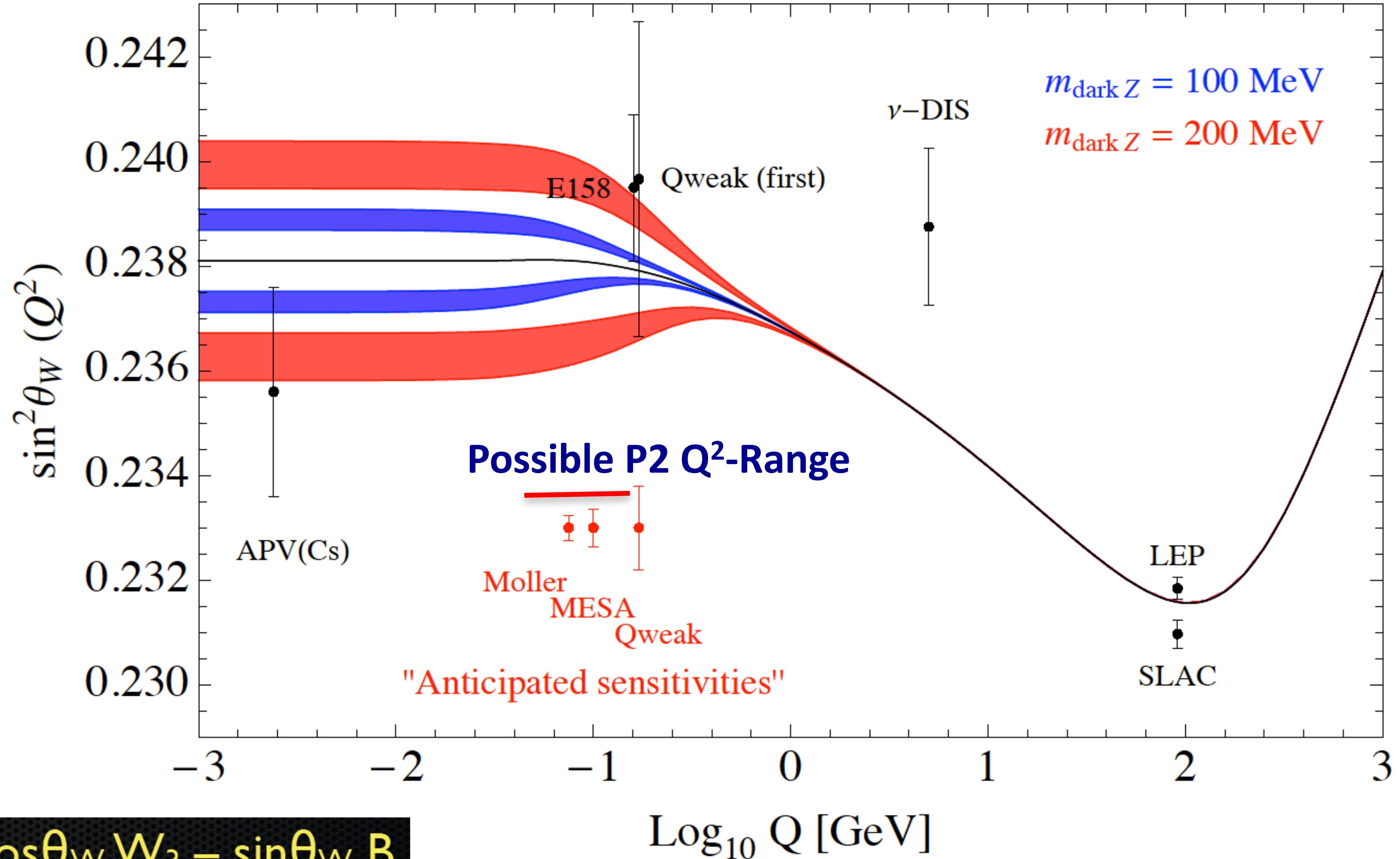
Mixing with Dark photon or Dark Z

Contact interaction

New Fermions

Dark Photon, Z-Boson

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

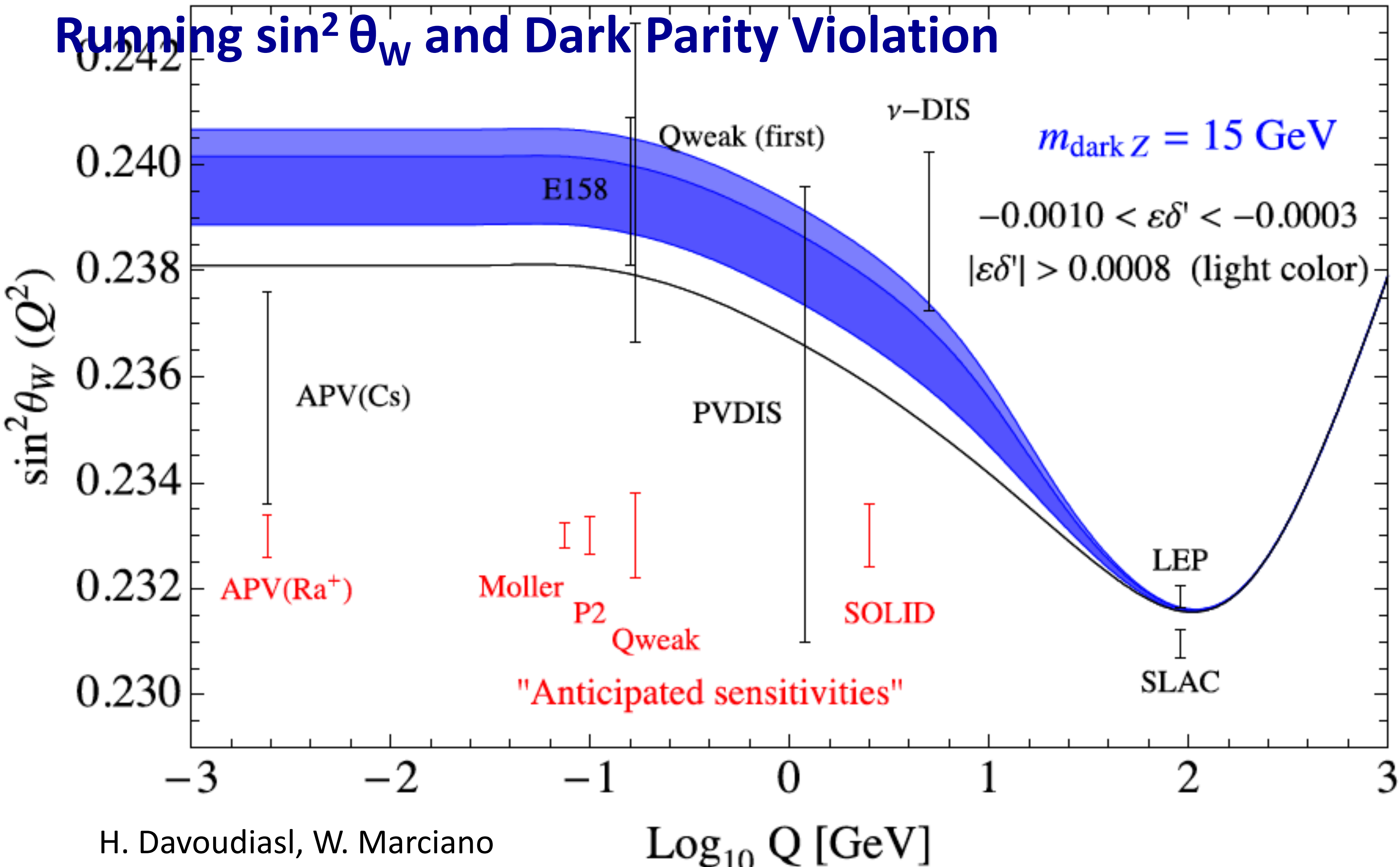


$Z = \cos\theta_W W_3 - \sin\theta_W B$

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

Bill Marciano

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

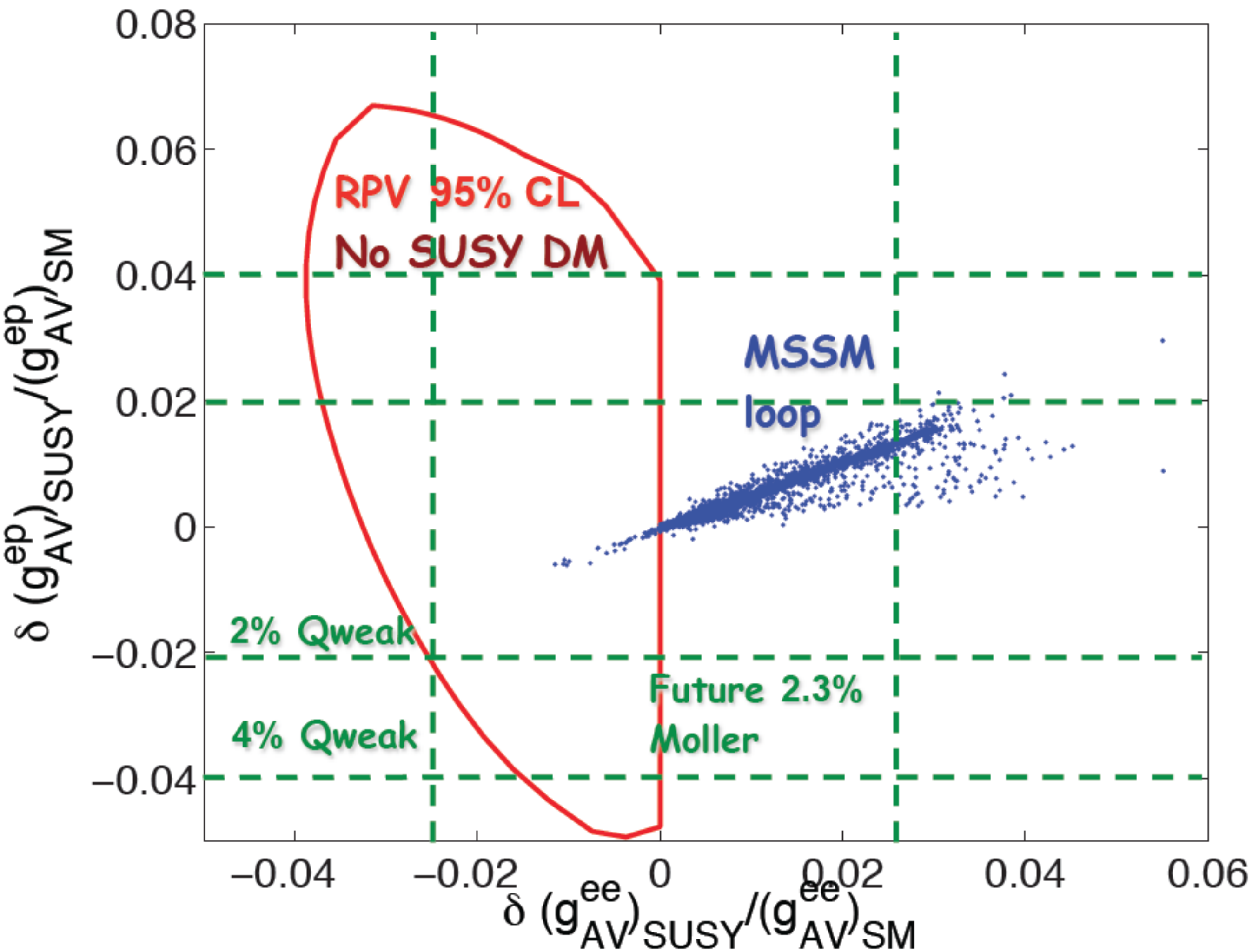


H. Davoudiasl, W. Marciano

Supersymmetry

Example: Supersymmetric standard model extensions

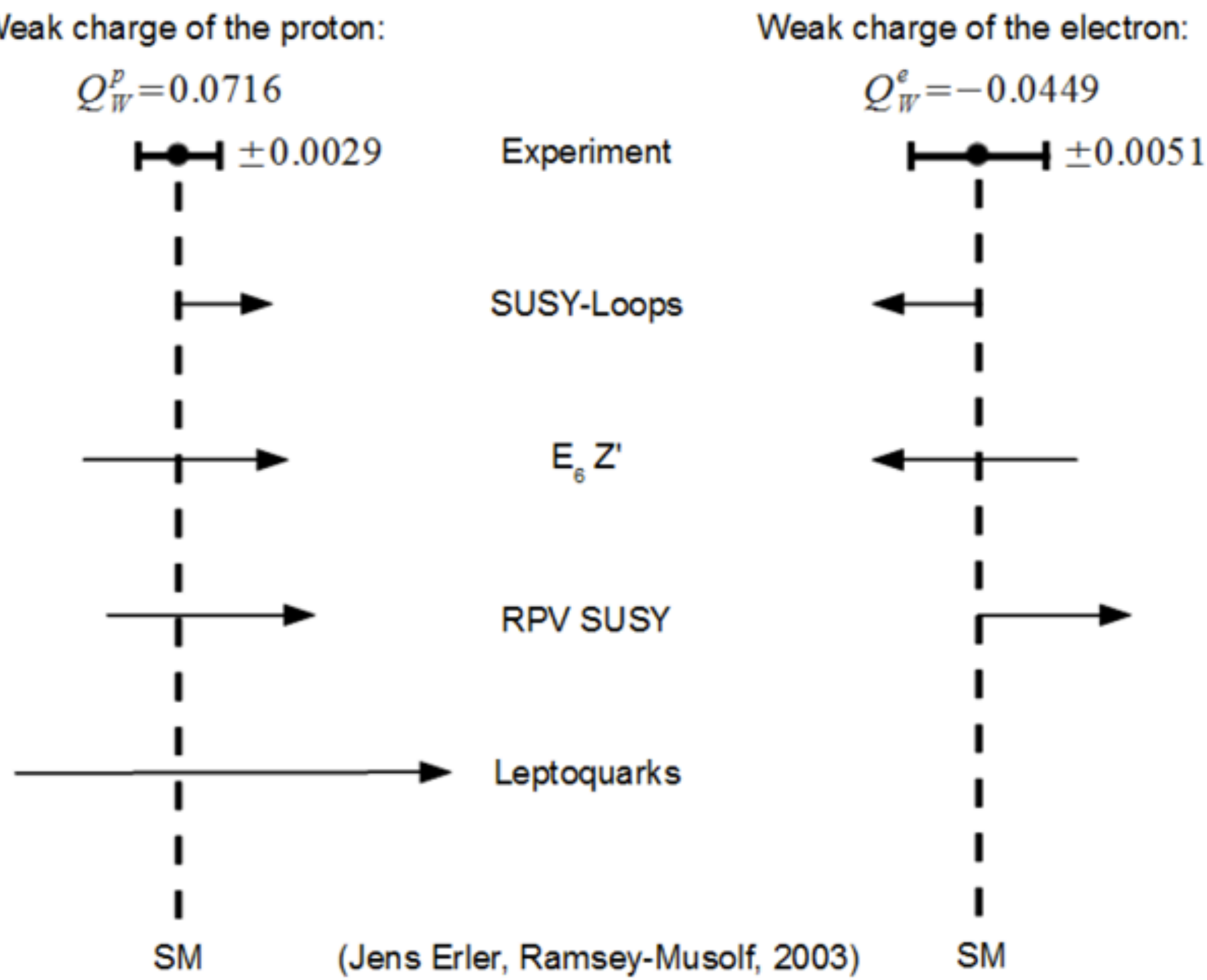
Kurylov, Ramsey-Musolf, Su (2003), updated



After LHC
Run 1

X. Su

- Complementary access by weak charges of proton and electron



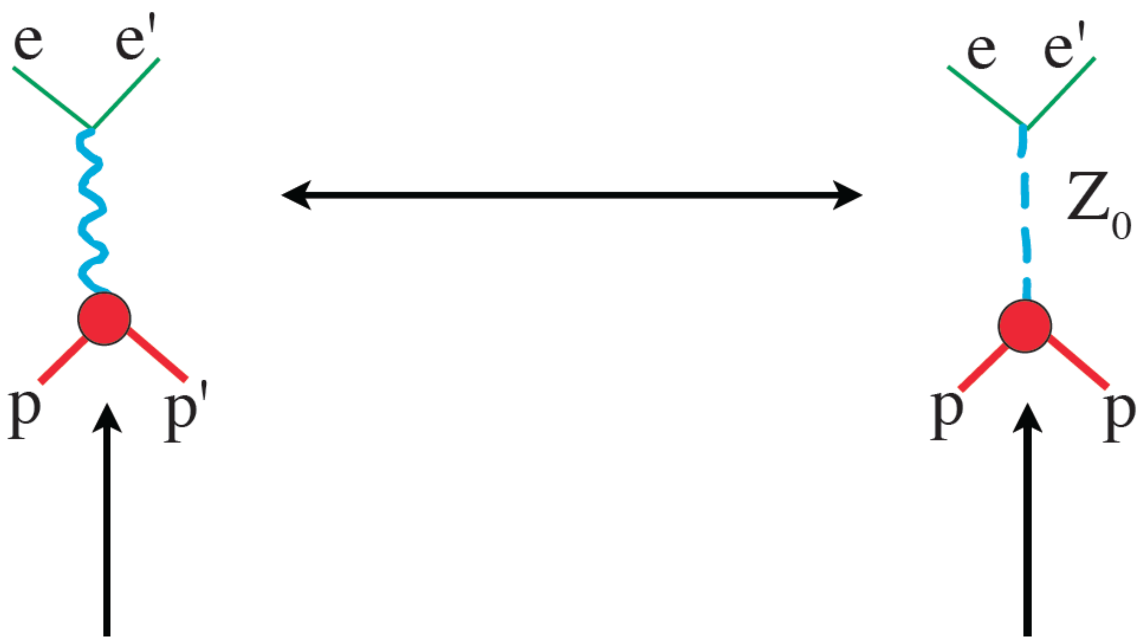
Weak Charge Of Proton: Qweak (Jlab), P2 (MESA)

Weak Charge Of Electron: MOELLER (JLAB)

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

The role of the weak mixing angle

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



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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

Proton: special case

Proton Weak charge:	$Q_W(p)$	=	$1 - 4 \sin^2 \theta_W$
Error:	$\Delta Q_W(p)$	=	$4 \Delta\sin^2 \theta_W$
Rel. error:	$\Delta Q_W(p)/Q_W(p)$	=	$4/((1/\sin^2 \theta_W) - 4)$ $(\Delta\sin^2 \theta_W/\sin^2 \theta_W)$
Rel. error	$\Delta\sin^2 \theta_W/\sin^2 \theta_W$	=	$((1/\sin^2 \theta_W) - 4) /4$ $\Delta Q_W(p)/Q_W(p)$
Example:	$\sin^2 \theta_W$ (50 MeV)	=	0.238
	$4/((1/\sin^2 \theta_W) - 4)$	~	20
	$\Delta Q_W(p)/Q_W(p)$	=	2% from Experiment
	$\Delta\sin^2 \theta_W/\sin^2 \theta_W$	=	0.1 % same precision as LEP, SLAC

Neutron Weak charge:

$\Delta Q_W(p)/Q_W(n)$ = $\Delta\sin^2 \theta_W/\sin^2 \theta_W$

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:

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

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

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

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

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

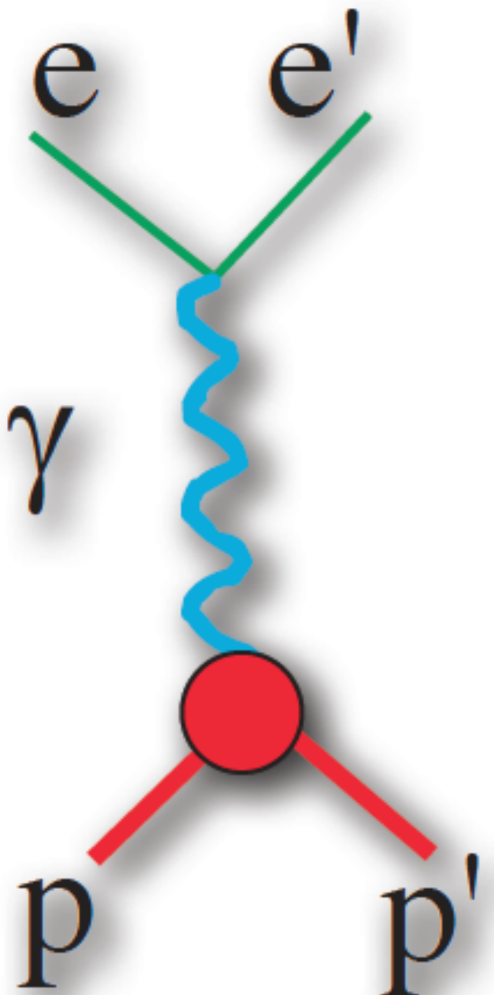
AA, Grilli Di Cortona, Tabrizi
1802.08296

AA, Gonzalez-Alonso
in progress

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

	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

Experimental Method:
Parity Violating Electron Scattering



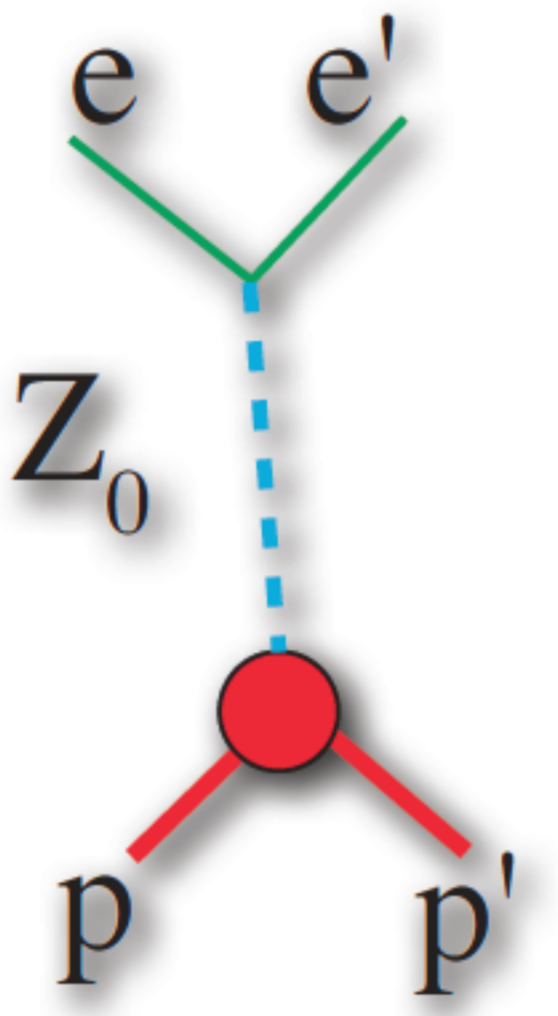
$$\sigma \sim \mathcal{M}\,\mathcal{M}^{*}\ \text{Phasespace}$$

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

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

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

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

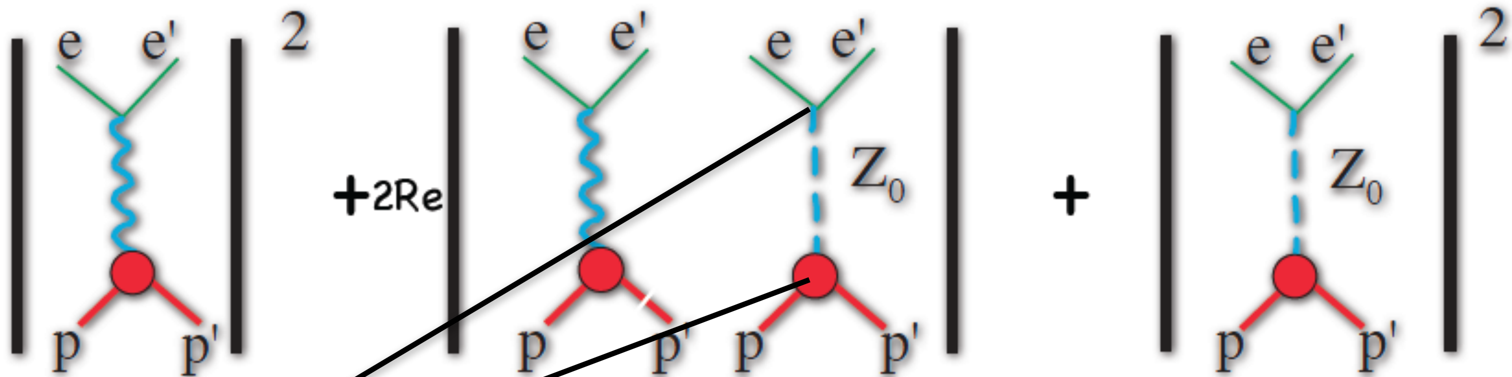


$$\tilde{q}^{d}{}_{V} \quad = \quad \tau_3 - 2q^{d} sin^2(\theta_W)$$

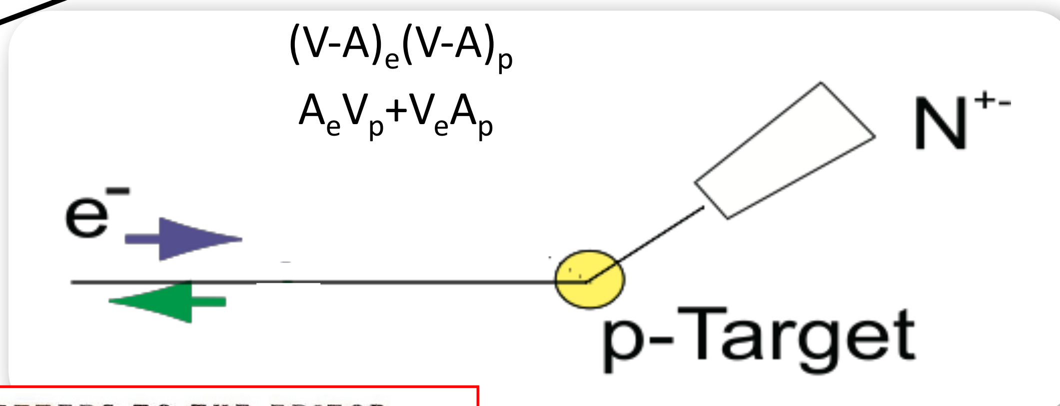
$$\begin{aligned}\tilde{J}^{\mu}_{Z} &\sim \left\langle N|\tilde{q}^{u}\overline{u}\,\gamma_\mu\, u + \tilde{q}^{d}\overline{d}\,\gamma_\mu d + \tilde{q}^{s}\overline{s}\,\gamma_\mu s|N'\right\rangle \\ &= \overline{\mathcal{P}}[\gamma^{\mu}\tilde{F}_1 - i\sigma^{\mu\nu}q_\nu \frac{\kappa_p}{2M_N}\tilde{F}_2]\mathcal{P}\end{aligned}$$

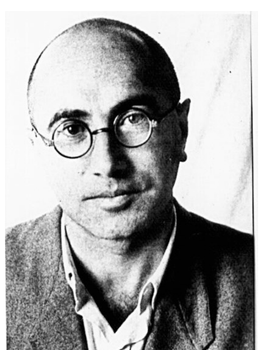
Parity Violating Asymmetry in elastic electron proton scattering

$\sigma \approx$



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





LETTERS TO THE EDITOR

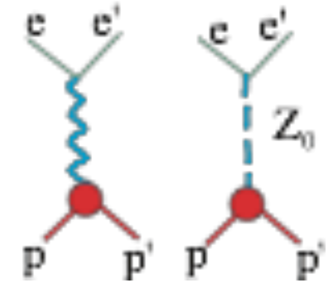
PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) 36, 964-966 (March, 1959)

Parity violating cross section asymmetry



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

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

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

Parity violating cross section asymmetry

tracking system

weak charge

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

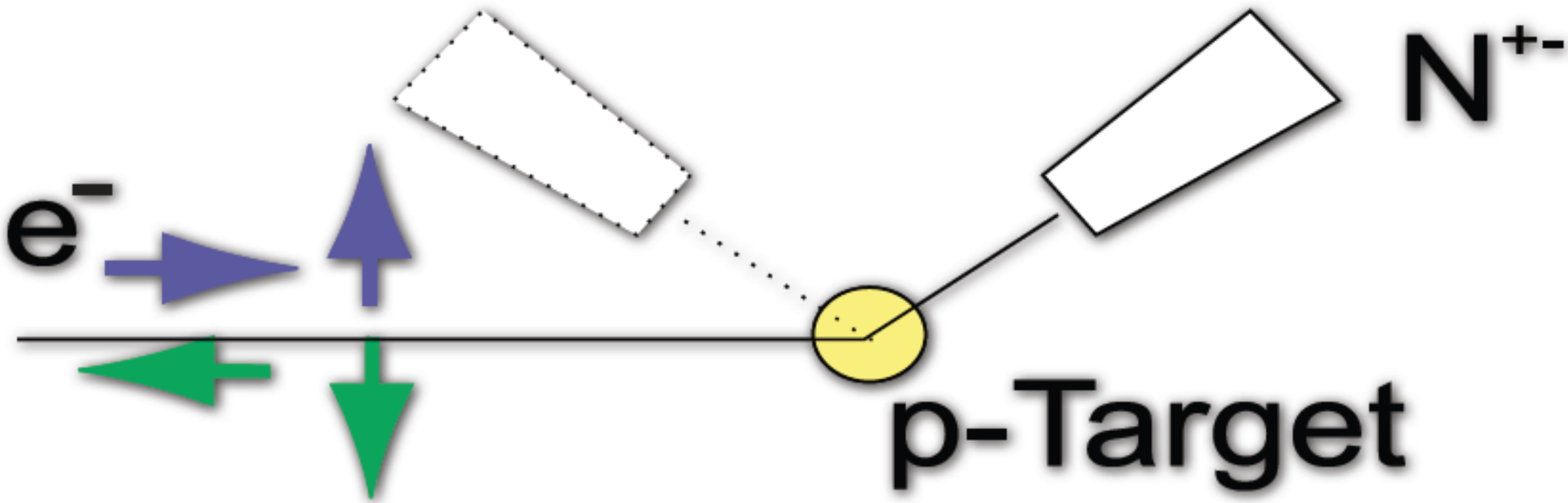
polarisation measurement

hadron structure

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

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

Conceptually very simple experiments



$A = (N^+ - N^-)/(N^+ + N^-)$ $\Delta A = (N^+ + N^-)^{-1/2} = N^{-1/2}$

$A = 20 \times 10^{-9}$ 2% Measurement $N = 6.25 \times 10^{18}$ events

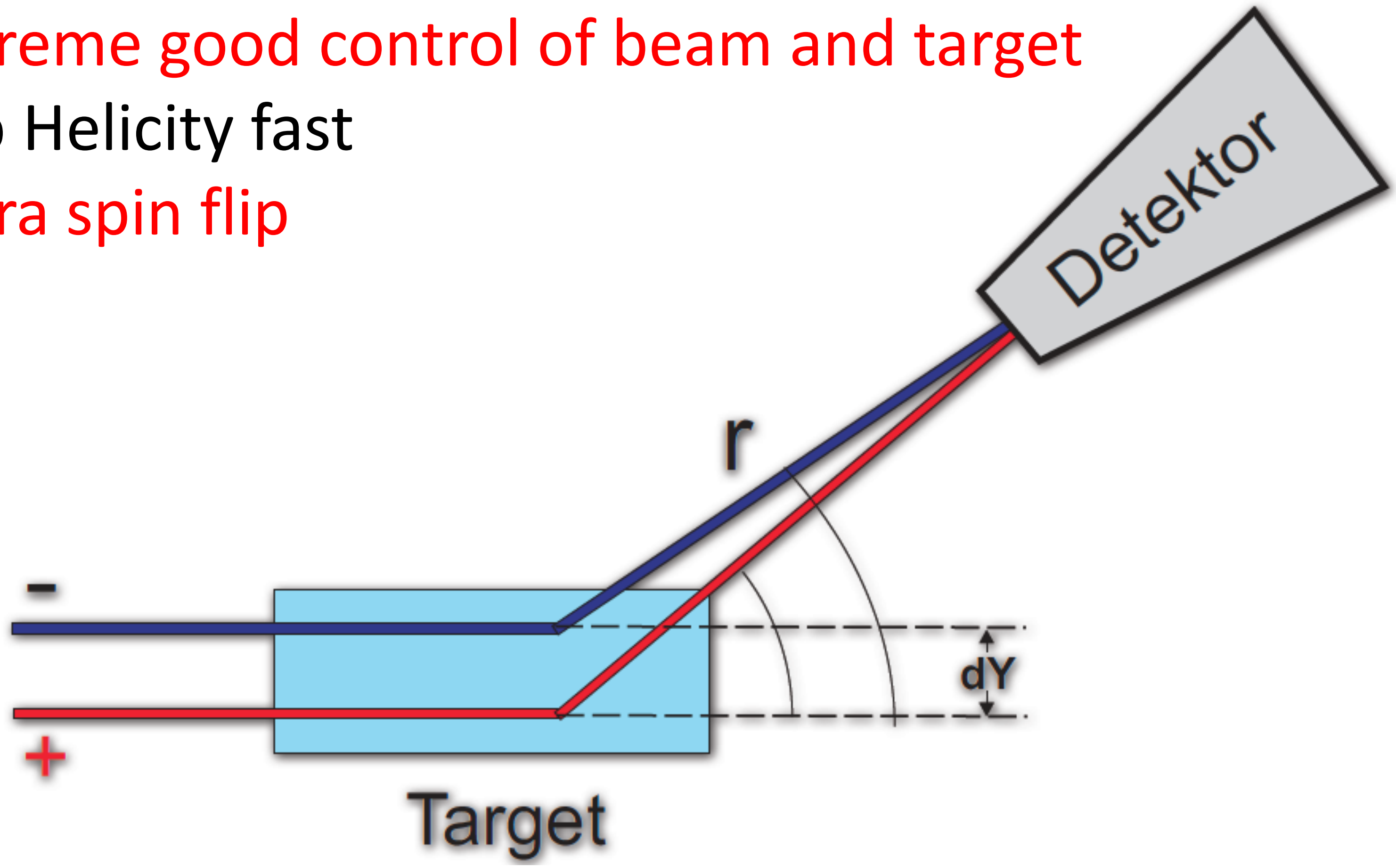
Highest rate, measure Q^2: Large Solid Angle Spectrometers

Systematic effects: detector related (false) asymmetries:

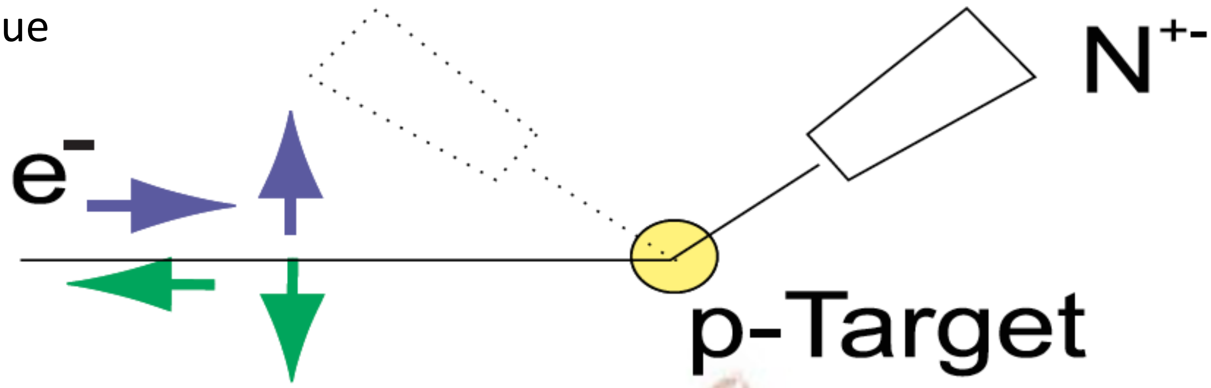
Extreme good control of beam and target

Flip Helicity fast

Extra spin flip

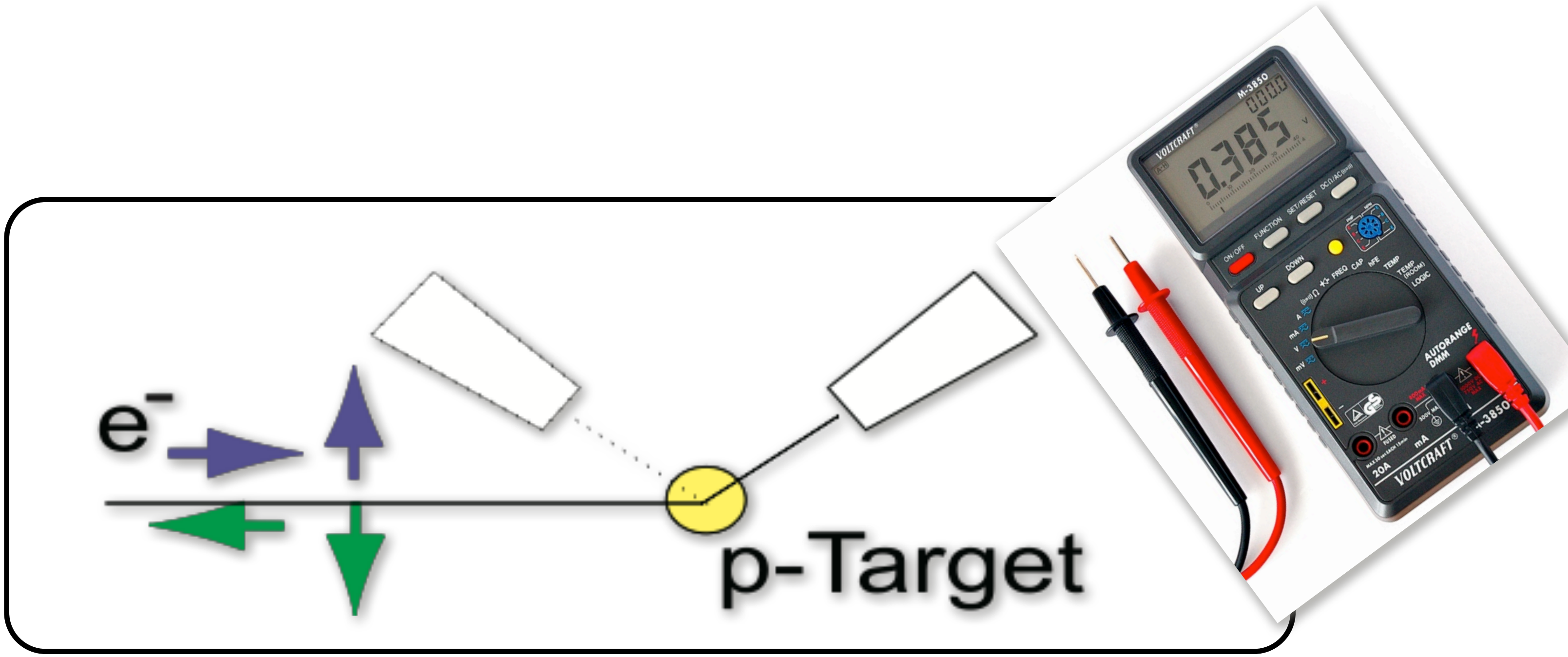


Counting Technique



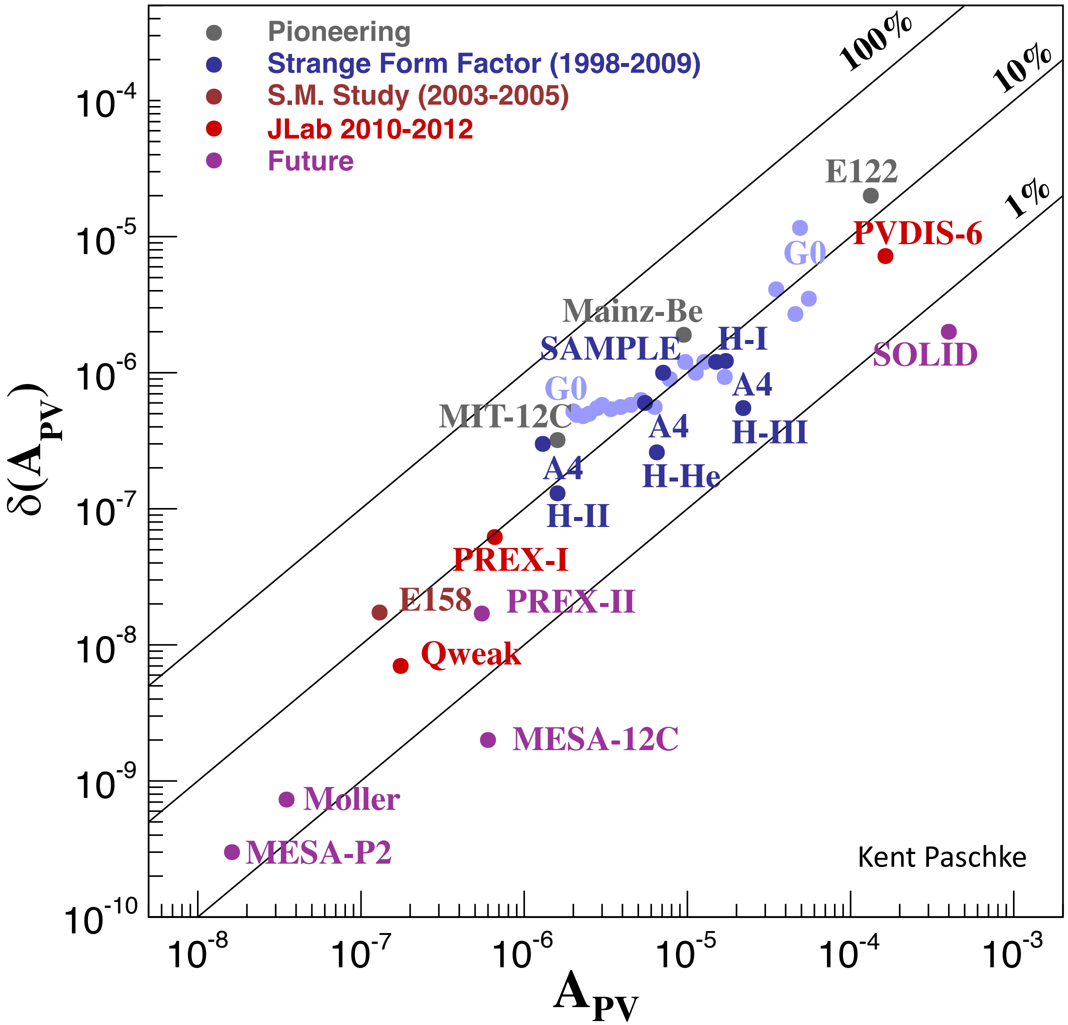
Count scattered electrons:
- pile-up (double count losses)
- Background Asymmetry
- Very Fast Counting (MHz)
- Measure TOF or Energy

Analogue Technique



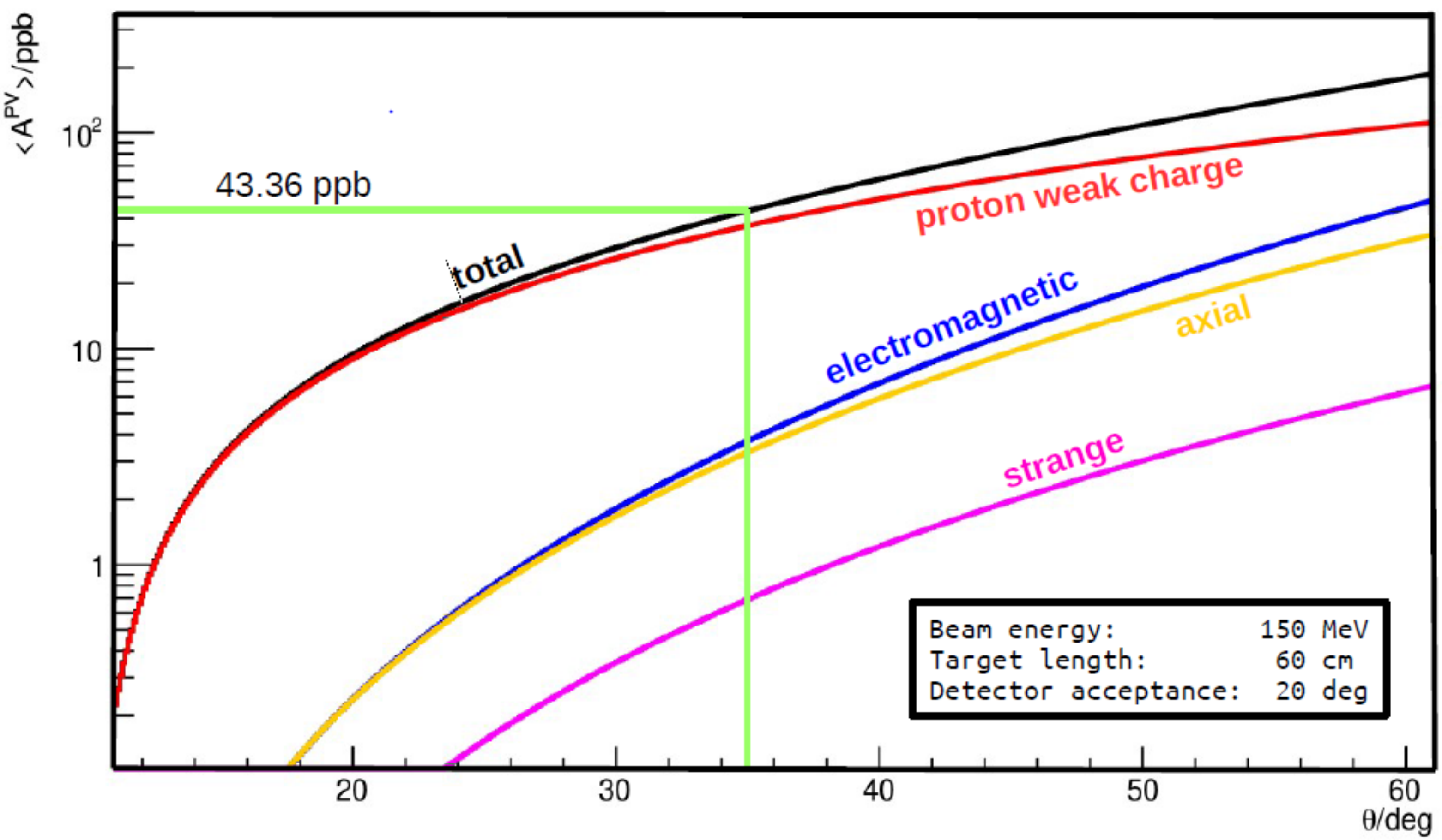
Measure Flux of Scattered electrons:
- no pile-up (double count losses)
- sensitive to small electr. fields.
- no separation of phys. process

PVeS Experiment Summary

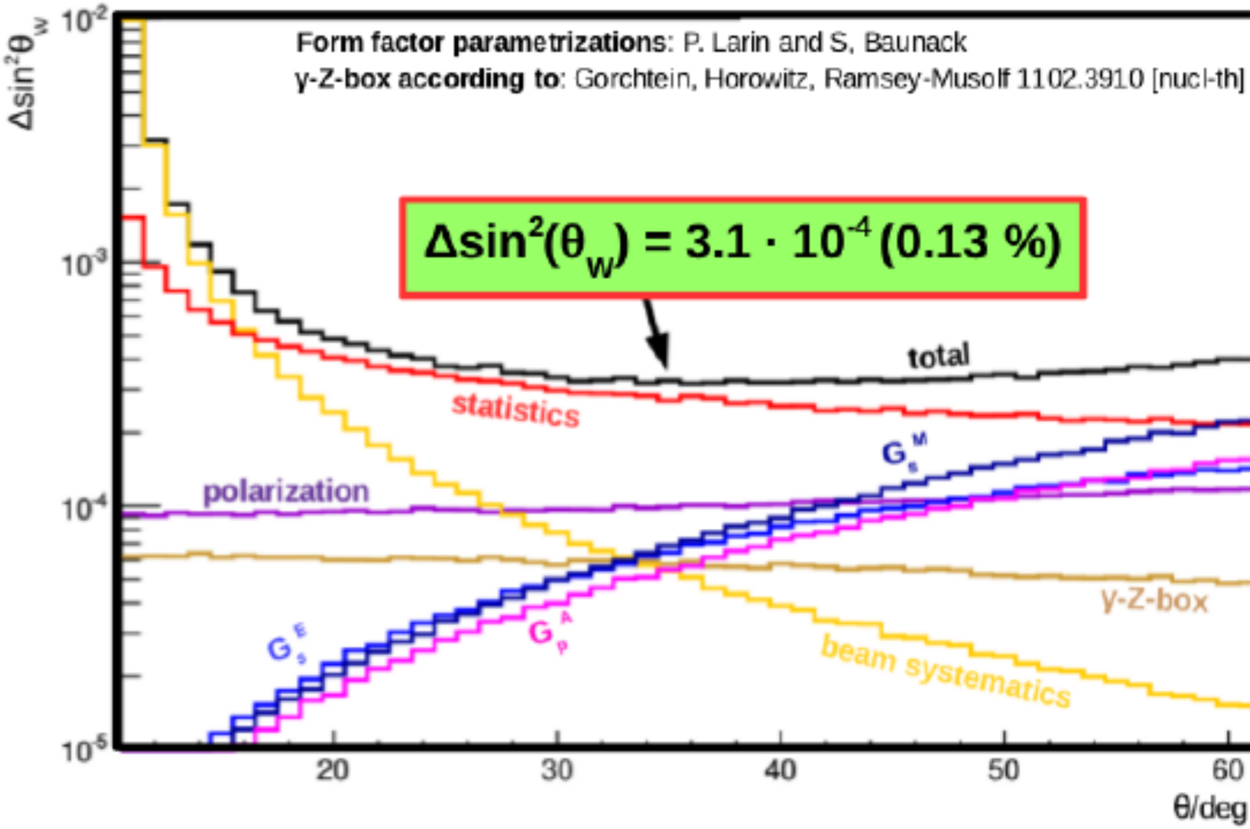


The P2 Experiment at the MESA accelerator in Mainz

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



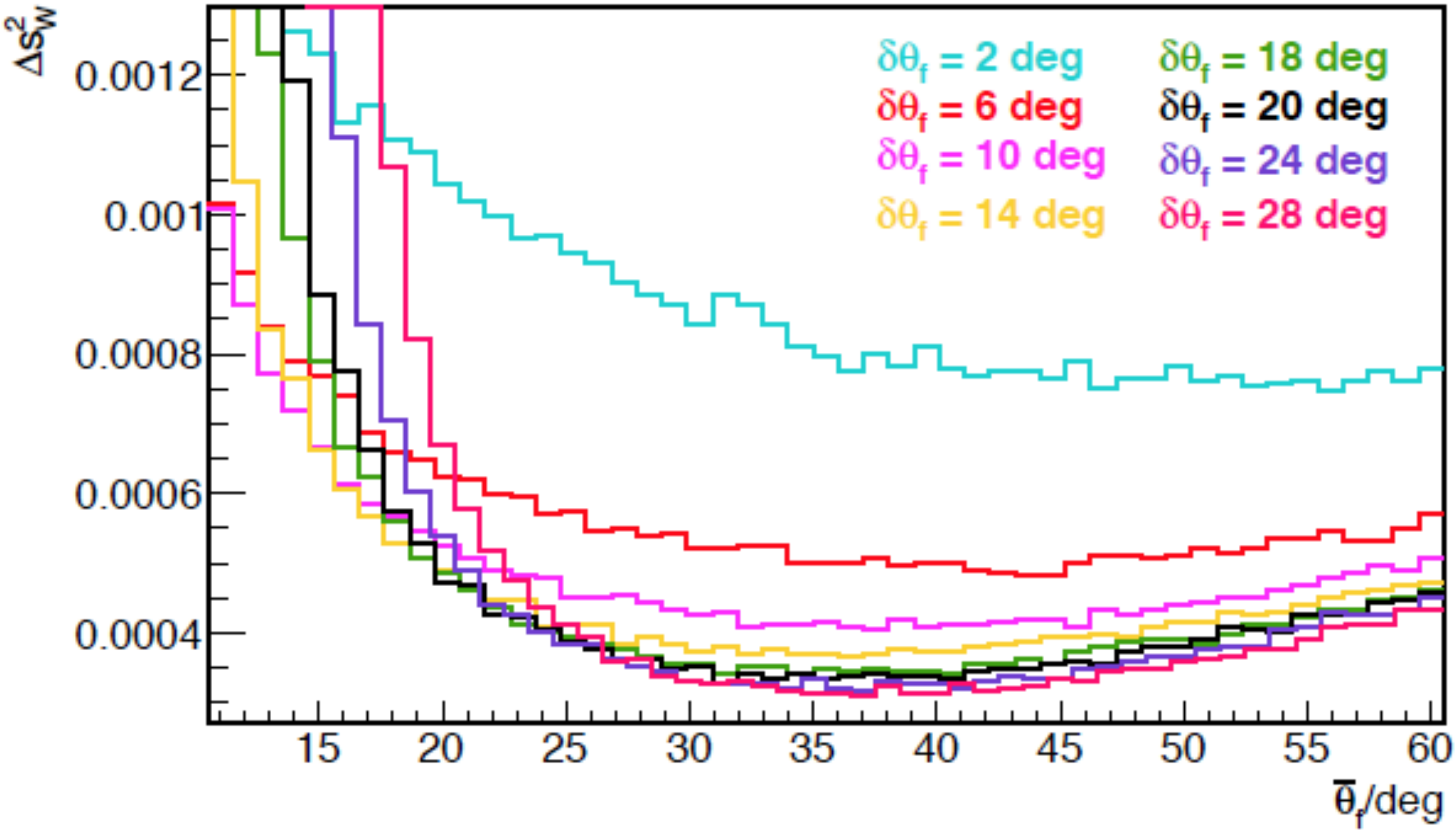
P2-Precision in $\sin^2 \theta_W$



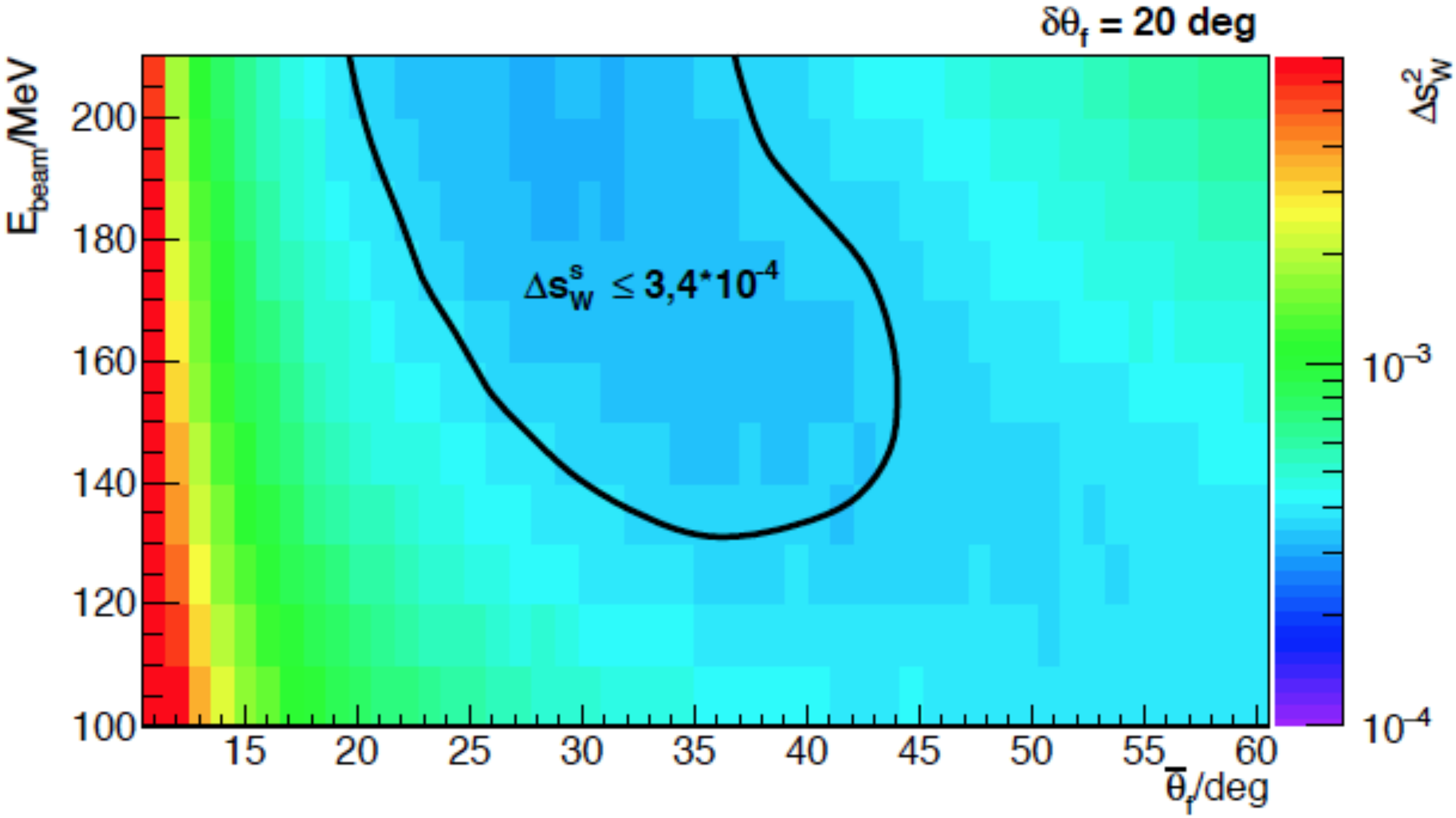
Beam energy:	155 MeV
Beam current:	150 µA
Polarization:	(85±0.5)%
Target:	60 cm lH2
Acceptance:	2π·(35°±10°)
Rate:	0.5 THz
Runtime:	10000 h
ΔA^{app}:	0.1 ppb

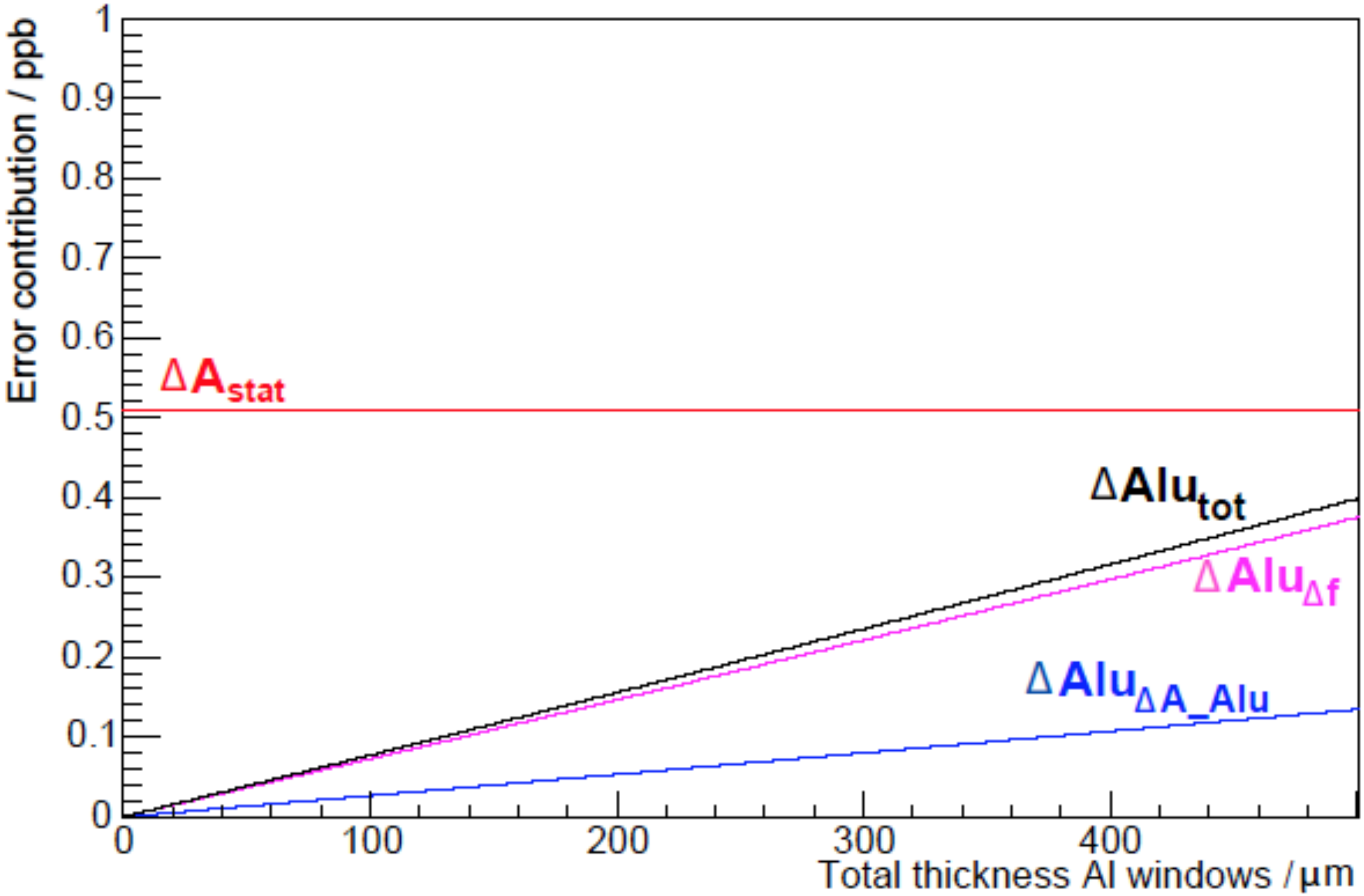
	Total	Statistics	Polarization	Apparative	FF	Re($\square_{\gamma ZA}$)
$\Delta\sin^2(\theta_W)$	3.1e-4 (0.13 %)	2.6e-4 (0.11 %)	9.7e-5 (0.04 %)	7.0e-5 (0.03 %)	1.4e-4 (0.04 %)	6e-5 (0.03 %)
ΔA^{exp}/ppb	0.44 (1.5 %)	0.38 (1.34 %)	0.14 (0.49 %)	0.10 (0.35 %)	0.11 (0.38 %)	0.09 (0.32 %)

Optimization of acceptance in Δθ



Optimization of beam energy and mean scattering angle θ

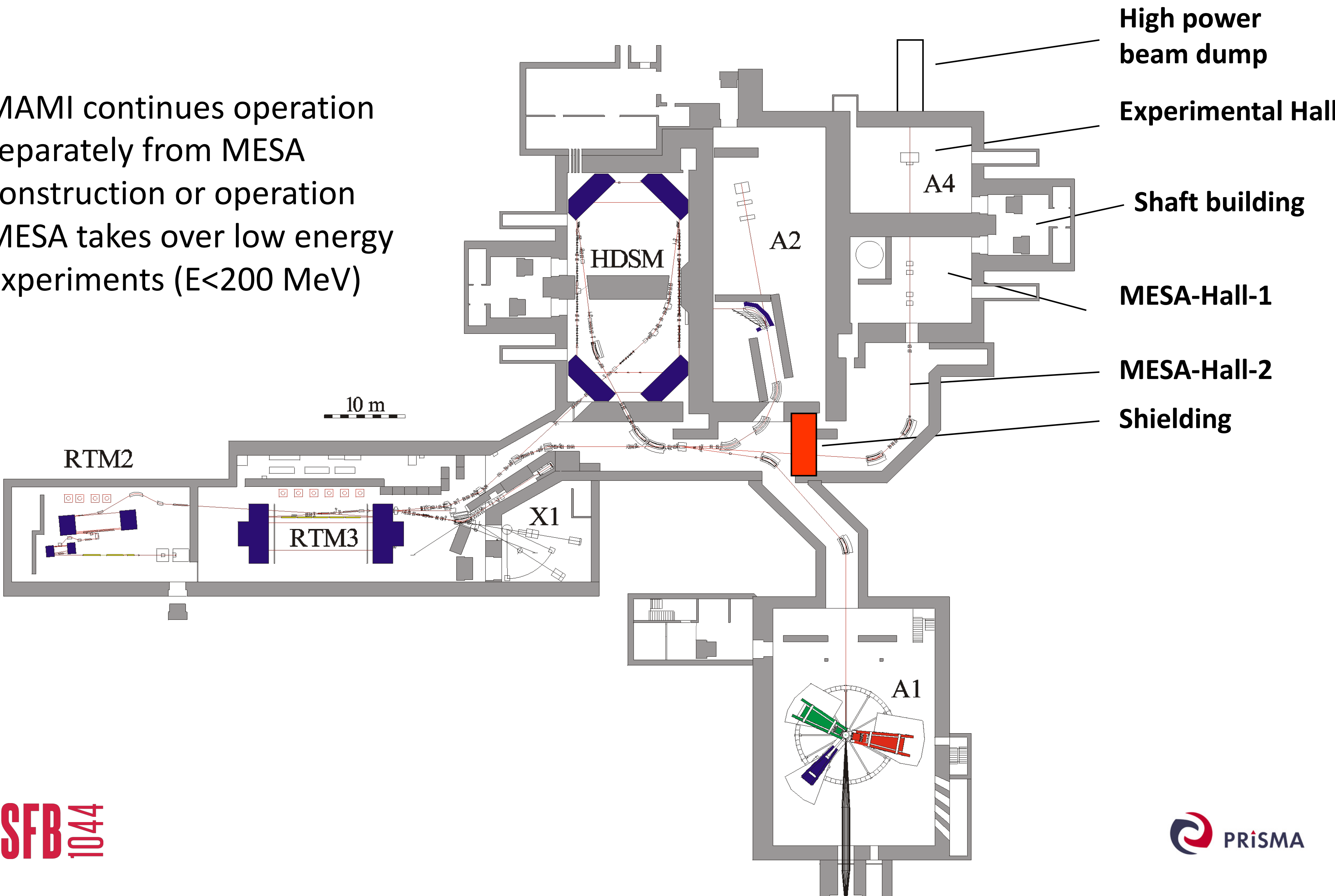




Error contribution / ppb
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ΔA_{stat}
ΔAlu_{tot}
$\Delta Alu_{\Delta f}$
$\Delta Alu_{\Delta A\_Alu}$
0
100
200
300
400
Total thickness Al windows / μm

E_{beam}	155 MeV
$\bar{\theta}_{\mathrm{f}}$	35°
$\delta\theta_{\mathrm{f}}$	20°
$\langle Q^2 \rangle_{L=600\,\mathrm{mm},\ \delta\theta_{\mathrm{f}}=20^\circ}$	$6 \times 10^{-3}\,(\mathrm{GeV/c})^2$
$\langle A^{\mathrm{exp}} \rangle$	$-39.94\,\mathrm{ppb}$
$(\Delta A^{\mathrm{exp}})_{\mathrm{Total}}$	$0.56\,\mathrm{ppb}\ (1.40\,\%)$
$(\Delta A^{\mathrm{exp}})_{\mathrm{Statistics}}$	$0.51\,\mathrm{ppb}\ (1.28\,\%)$
$(\Delta A^{\mathrm{exp}})_{\mathrm{Polarization}}$	$0.21\,\mathrm{ppb}\ (0.53\,\%)$
$(\Delta A^{\mathrm{exp}})_{\mathrm{Apparative}}$	$0.10\,\mathrm{ppb}\ (0.25\,\%)$
$\langle s^2_{\mathrm{W}} \rangle$	$0.231\,16$
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Total}}$	$3.3 \times 10^{-4}\ (0.14\,\%)$
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Statistics}}$	$2.7 \times 10^{-4}\ (0.12\,\%)$
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Polarization}}$	$1.0 \times 10^{-4}\ (0.04\,\%)$
$(\Delta s^2_{\mathrm{W}})_{\mathrm{Apparative}}$	$0.5 \times 10^{-4}\ (0.02\,\%)$
$(\Delta s^2_{\mathrm{W}})_{\square_{\gamma Z}}$	$0.4 \times 10^{-4}\ (0.02\,\%)$
$(\Delta s^2_{\mathrm{W}})_{\mathrm{nucl.\ FF}}$	$1.2 \times 10^{-4}\ (0.05\,\%)$
$\langle Q^2 \rangle_{\mathrm{Cherenkov}}$	$4.57 \times 10^{-3}\,(\mathrm{GeV/c})^2$
$\langle A^{\mathrm{exp}} \rangle_{\mathrm{Cherenkov}}$	$-28.77\,\mathrm{ppb}$

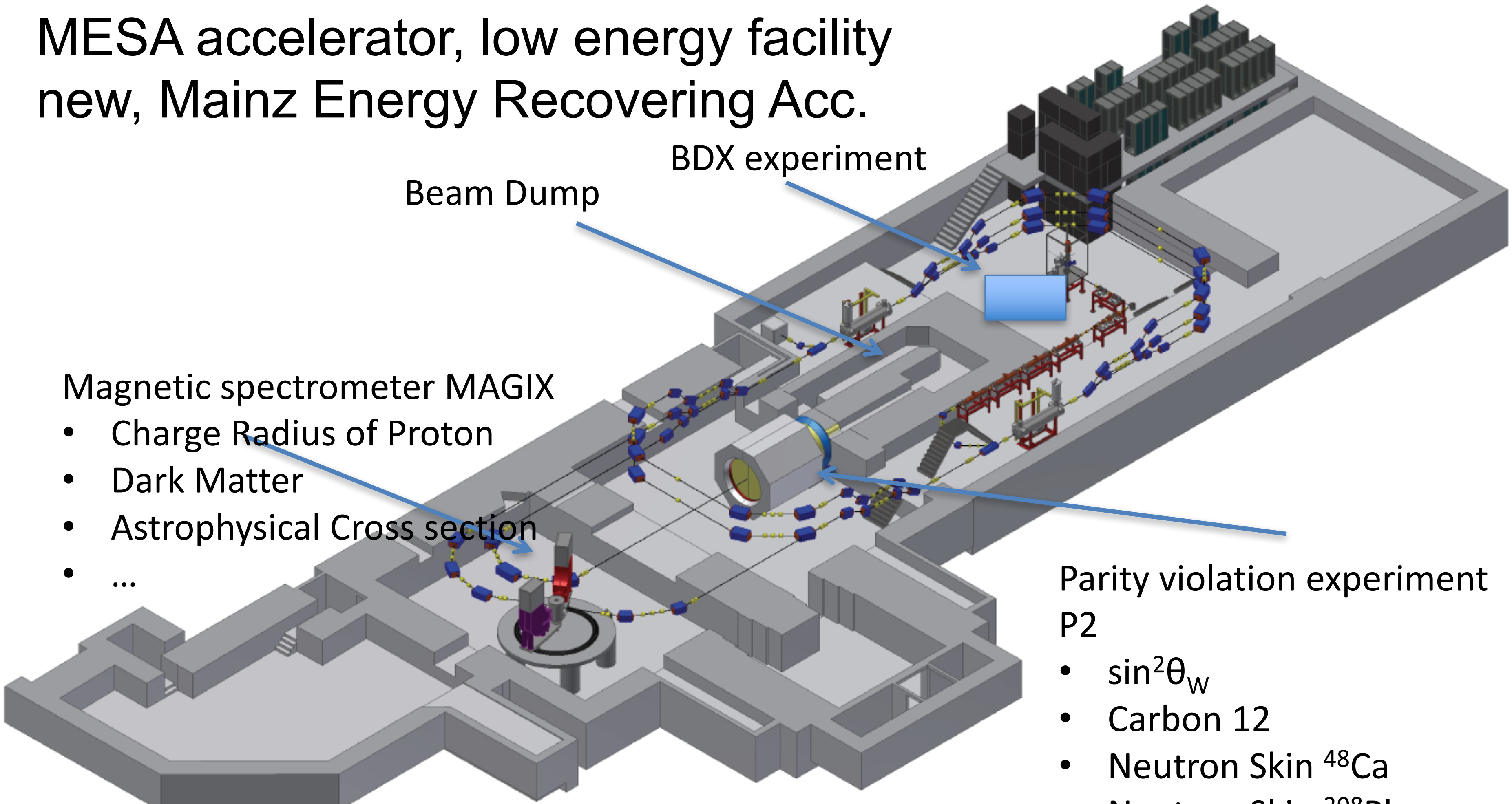
- MAMI continues operation separately from MESA construction or operation
- MESA takes over low energy experiments (E<200 MeV)



JG|U


LEMA
Laboratorio Nacional de Espectrometría
de Masas con Aceleradores

MESA accelerator, low energy facility
new, Mainz Energy Recovering Acc.



Magnetic spectrometer MAGIX

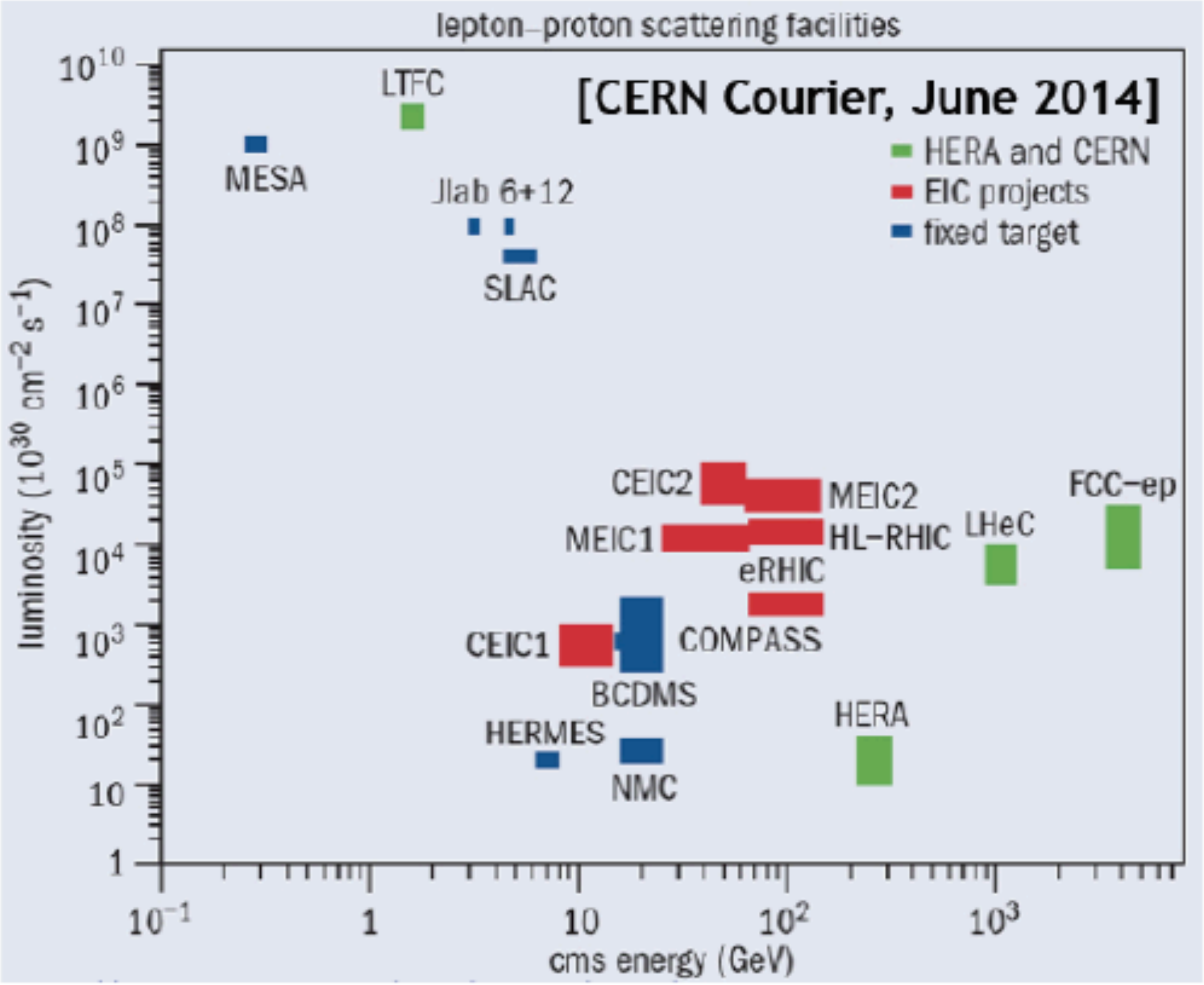
- Charge Radius of Proton
- Dark Matter
- Astrophysical Cross section
- …

Parity violation experiment P2

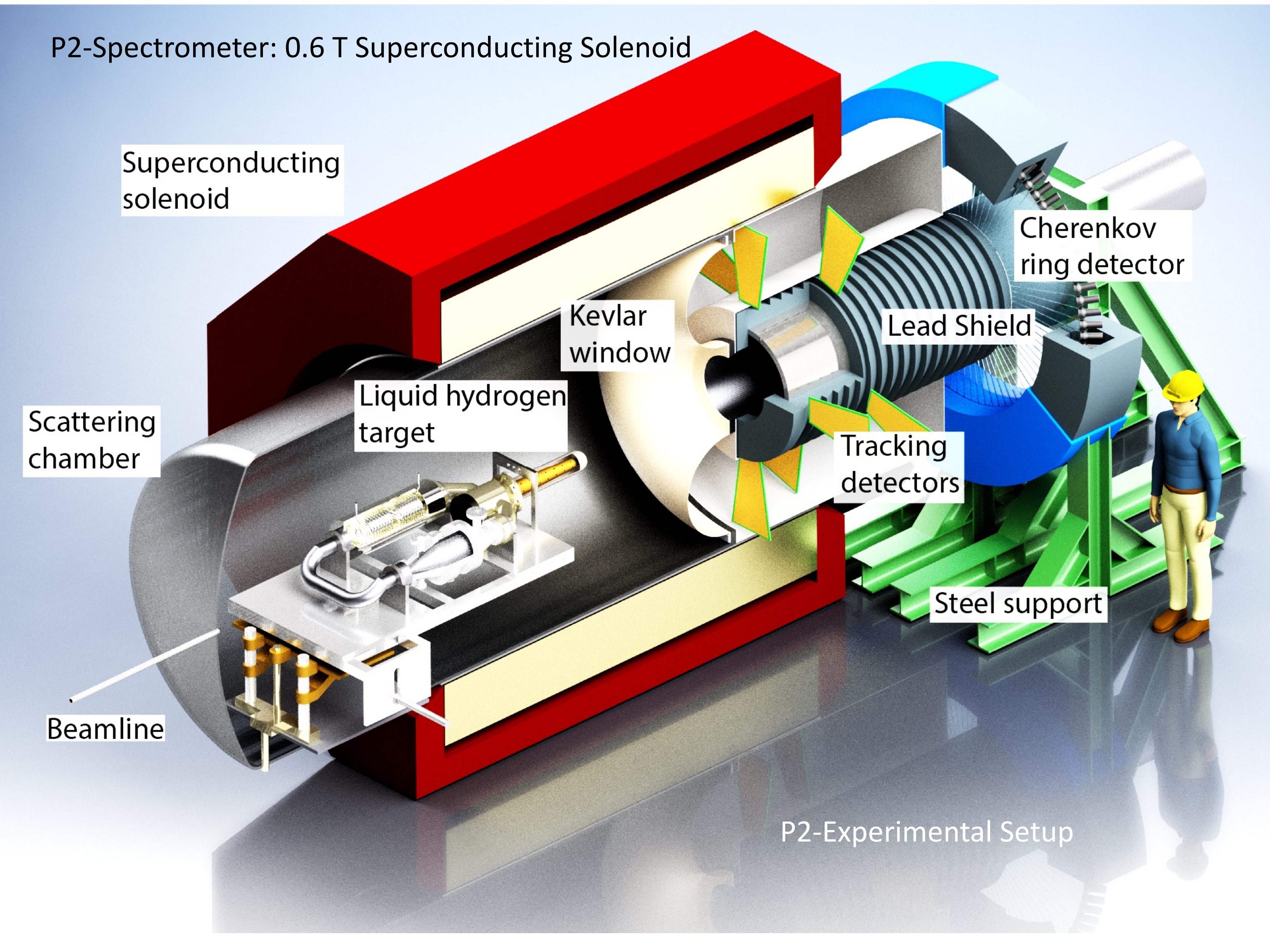
- $\sin^2\theta_W$
- Carbon 12
- Neutron Skin ^{48}Ca
- Neutron Skin ^{208}Pb
- Transverse Beam Spin
- Hadronic Parity Violation

(10,000 h)
data taking ➜

$\int \mathcal{L}dt \simeq 8.6\ \mathrm{ab}^{-1}$



P. Newman


P2-Spectrometer: 0.6 T Superconducting Solenoid
Superconducting solenoid
Cherenkov ring detector
Kevlar window
Lead Shield
Liquid hydrogen target
Scattering chamber
Tracking detectors
Steel support
Beamline
P2-Experimental Setup

P2: International Collaboration

The P2 Experiment

Becker, D., Bucoveanu, R., et al. Eur. Phys. J. A (2018) 54: 208.

A future high-precision measurement of the electroweak mixing angle at low momentum transfer

Dominik Becker[1,2], Razvan Bucoveanu[1,3], Carsten Grzesik[1,2], Ruth Kempf[1,2], Kathrin Imai[1,2], Matthias Molitor[1,2], Alexey Tyukin[1,2], Marco Zimmermann[1,2], David Armstrong[4], Kurt Aulenbacher[1,2,5], Sebastian Baunack[1,2], Rakitha Beminiwattha[6], Niklaus Berger[1,2], Peter Bernhard[1,7], Andrea Brogna[1,7], Luigi Capozza[1,2,5], Silviu Covrig Dusa[8], Wouter Deconinck[4], Jürgen Diefenbach[1,2], James Dunne[17], Jens Erler[9], Ciprian Gal[10], Boris Gläser[1,2], Boxing Gou[1,2,5], Wolfgang Gradl[1,2], Michael Gericke[11], Mikhail Gorchtein[1,2], Yoshio Imai[1,2], Krishna S. Kumar[12], Frank Maas[1,2,5,a], Juliette Mammei[11], Jie Pan[11], Preeti Pandey[11], Kent Paschke[10], Ivan Perić[13], Mark Pitt[14], Sakib Rahman[11], Seamus Riordan[15], David Rodríguez Piñeiro[1,2,5], Concettina Sfienti[1,2,3,7], Iurii Sorokin[1,2], Paul Souder[16], Hubert Spiesberger[1,3], Michaela Thiel[1,2], Valery Tyukin[1,2], and Quirin Weitzel[1,7]

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[2] Institute of Nuclear Physics, Johannes Gutenberg-Universität Mainz, Germany
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[5] Helmholtz Institute Mainz, Johannes Gutenberg-Universität Mainz, Germany
[6] Louisiana Tech University, Ruston, Louisiana, USA
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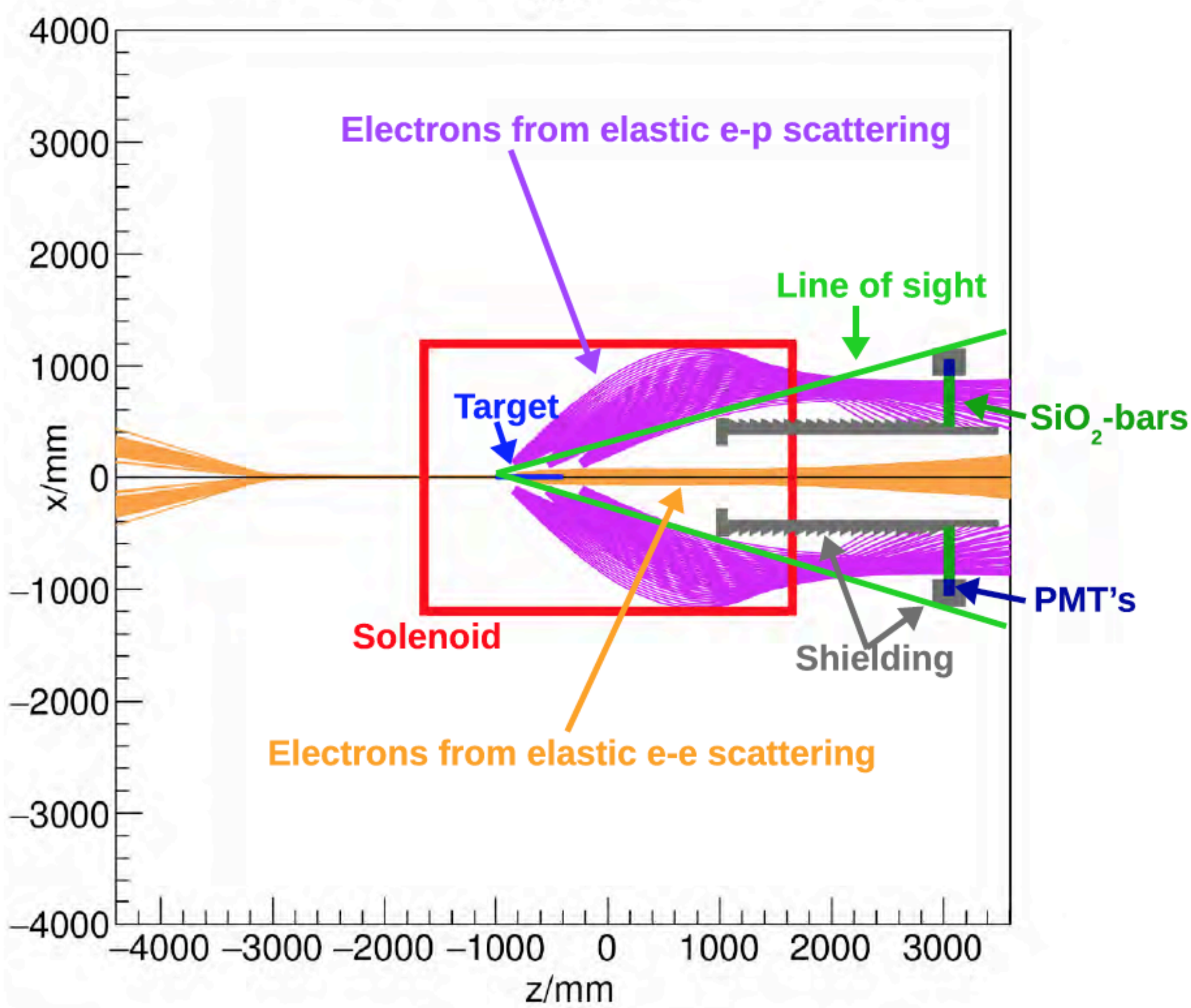
[10] University of Virginia, Charlottesville, Virginia, USA
[11] Department of Physics and Astronomy, University of Manitoba, Winnipeg, Canada
[12] Department of Physics and Astronomy, Stony Brook University, Stony Brook, USA
[13] Institute for Data Processing and Electronics, Karlsruhe Institute of Technology, Karlsruhe, Germany
[14] Virginia Tech University, Blacksburg, Virginia, USA
[15] Physics Division, Argonne National Laboratory, Argonne, USA
[16] Physics Department, Syracuse University, Syracuse, USA
[17] Mississippi State University, Mississippi State, MS, USA

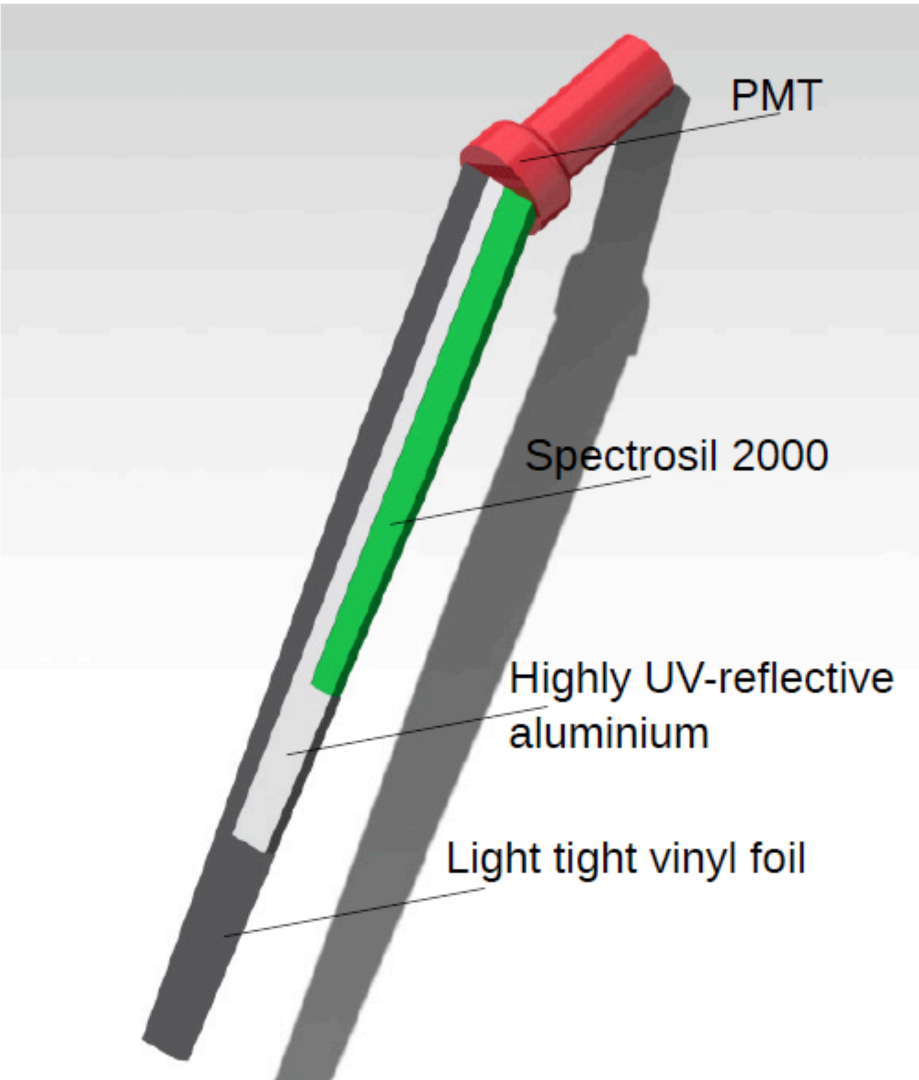
P2-experimental setup

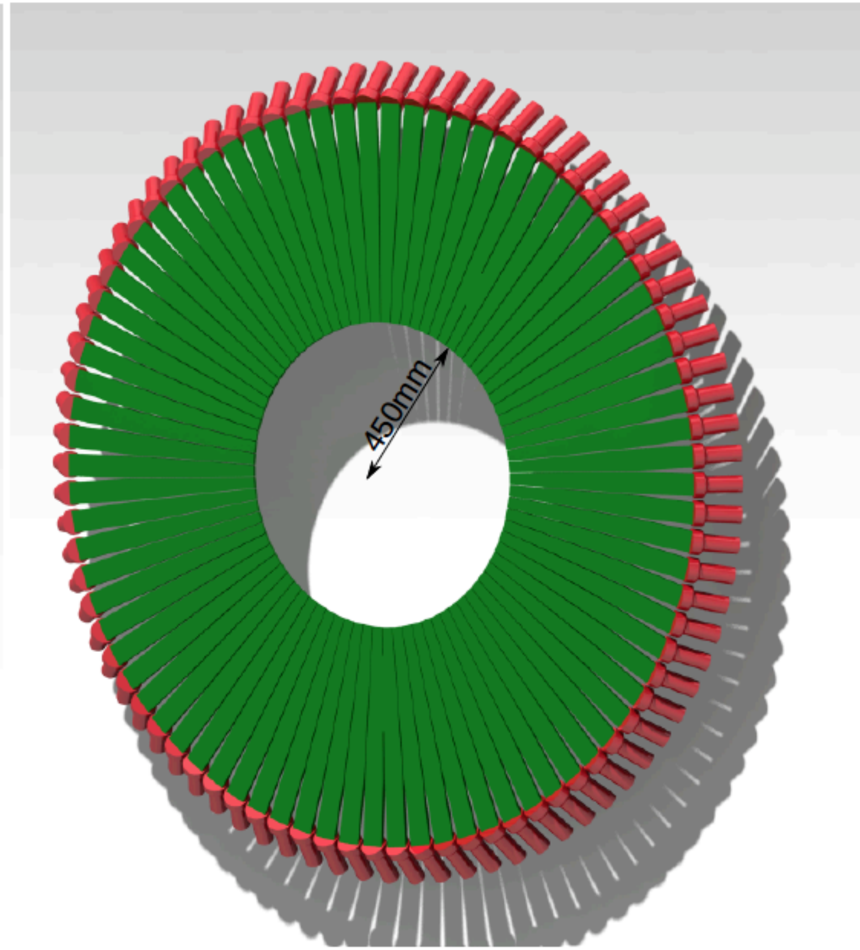
Simple ray-tracing



Cherenkov "Quartz" detectors

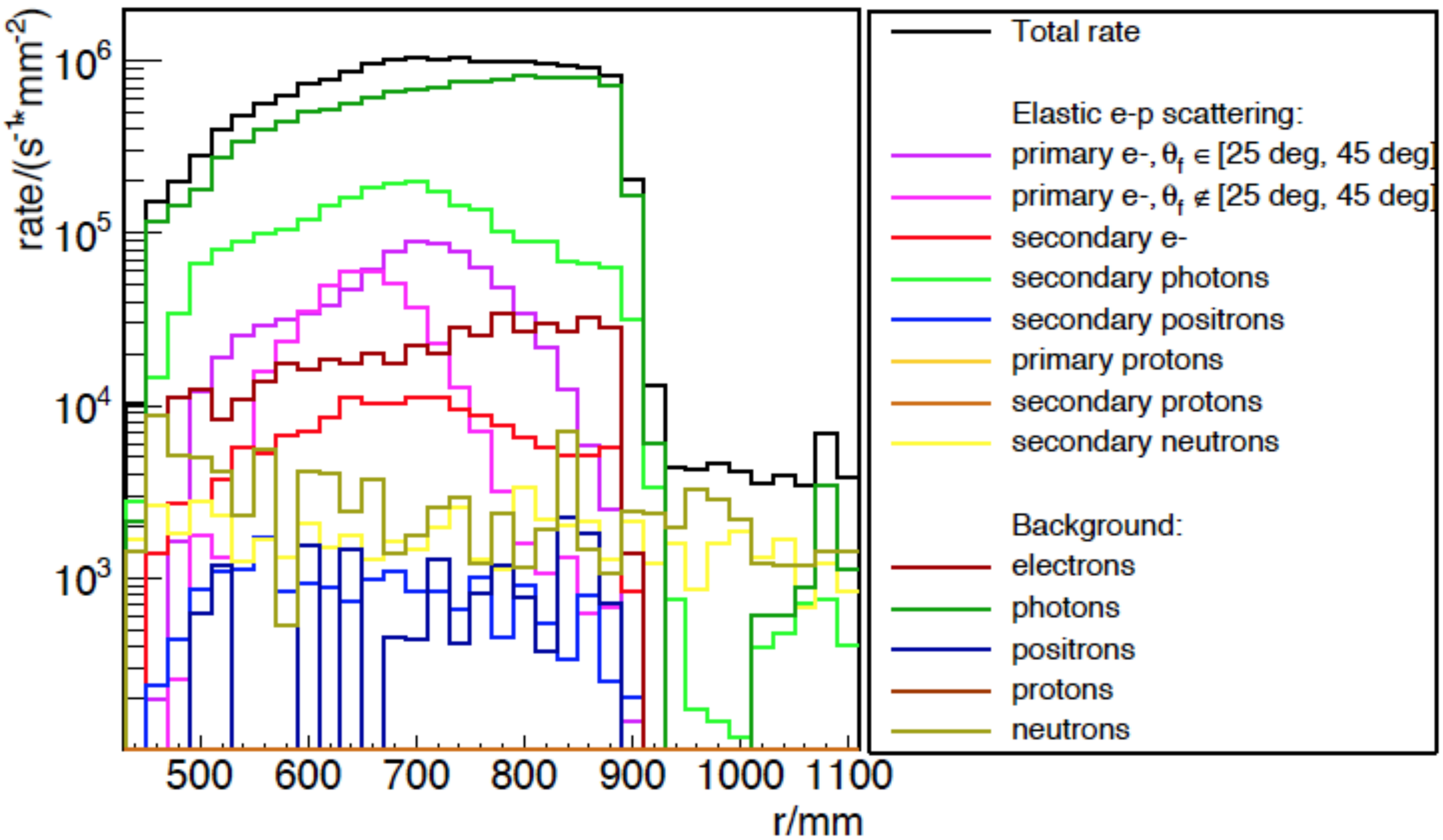
Full GEANT4 simulation





Kathrin Gerz

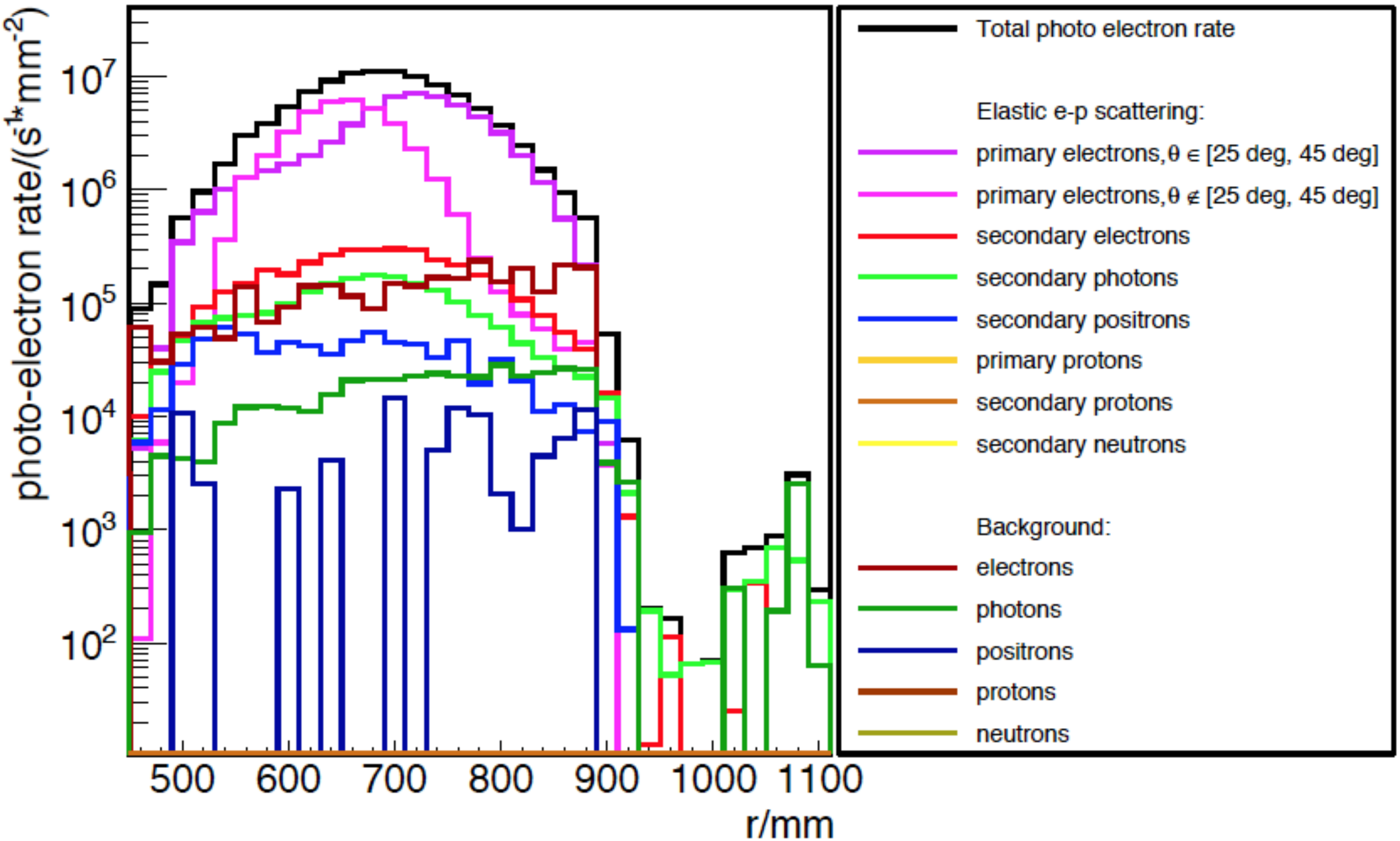
Full GEANT4 simulation



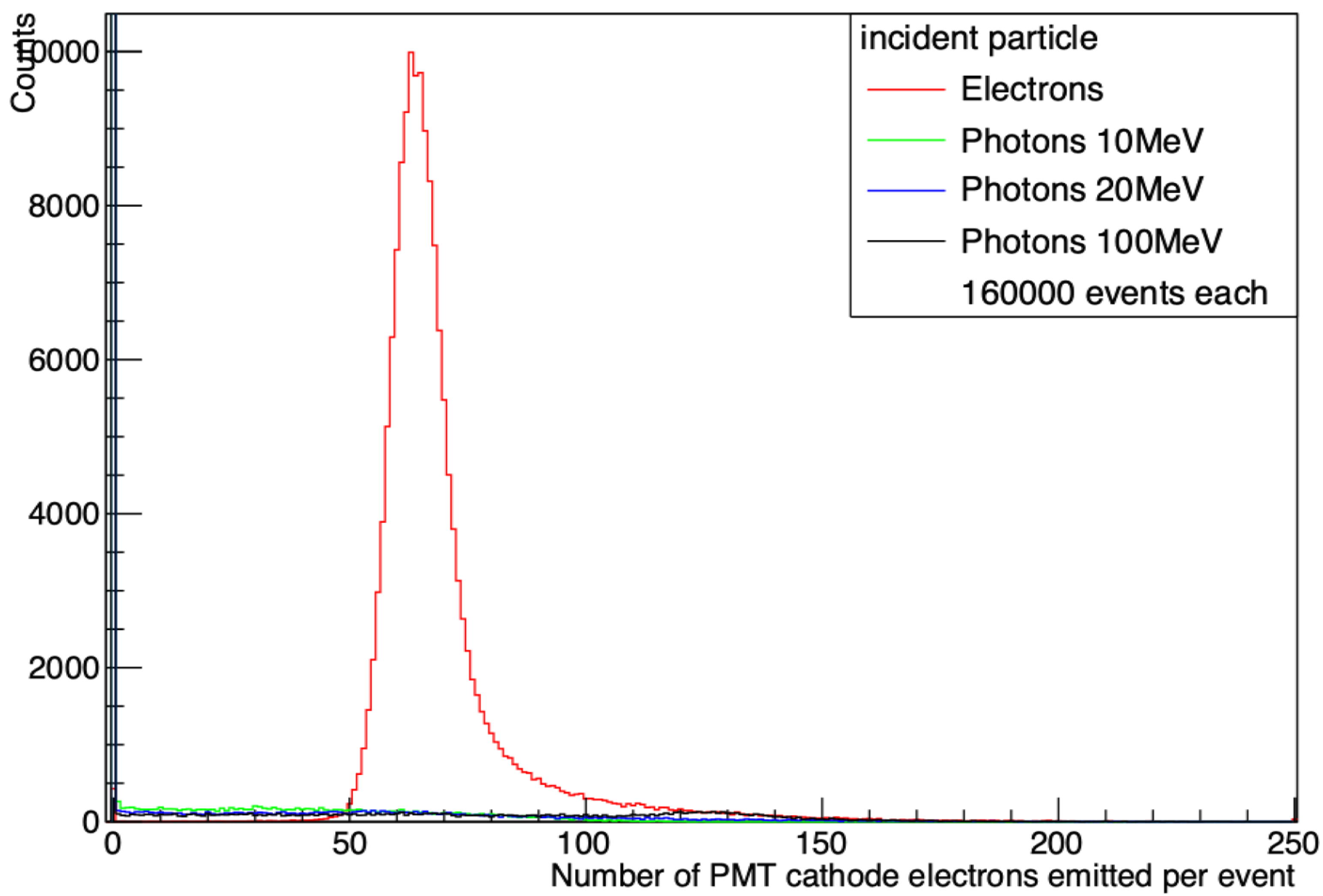
Dominik Becker

P2-Detector response

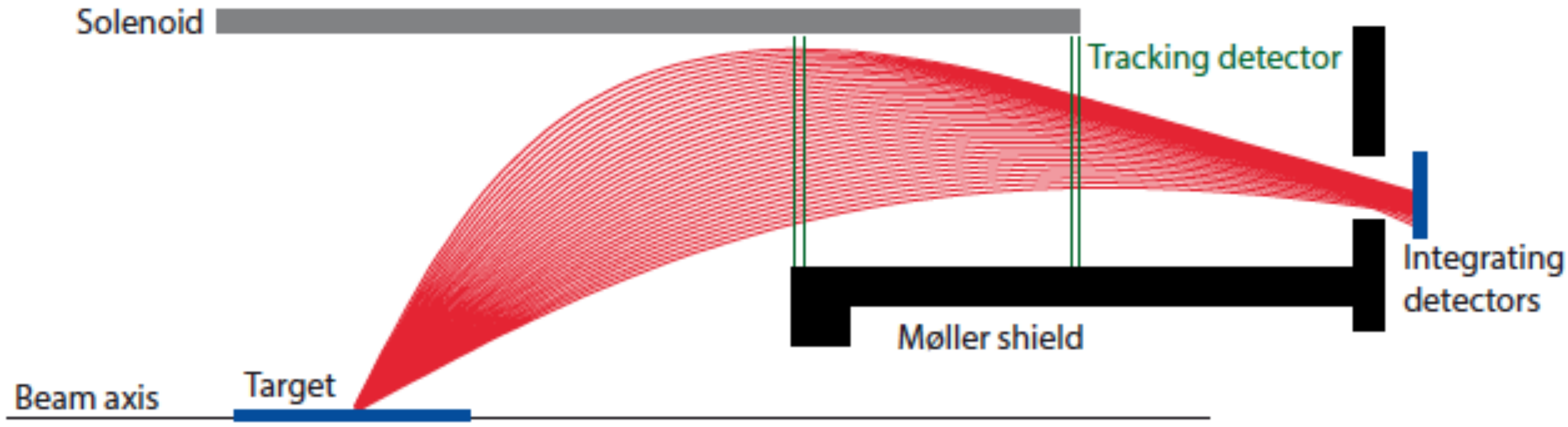
Full GEANT4 simulation

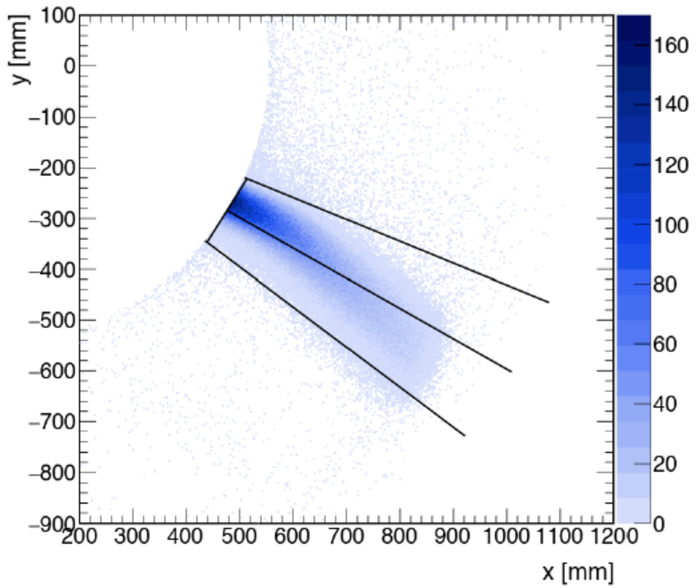


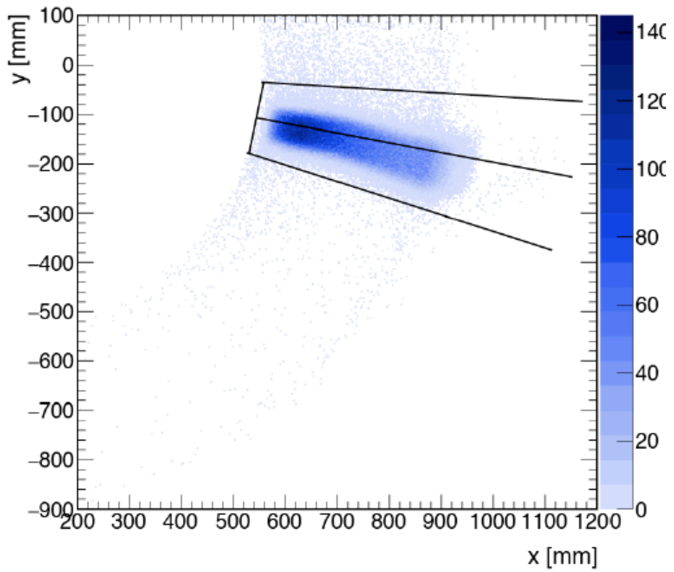
Number of PMT cathode electrons emitted per event

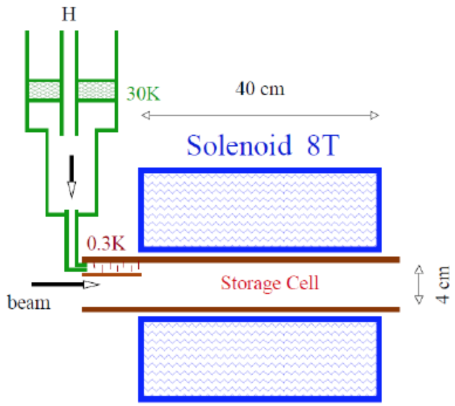


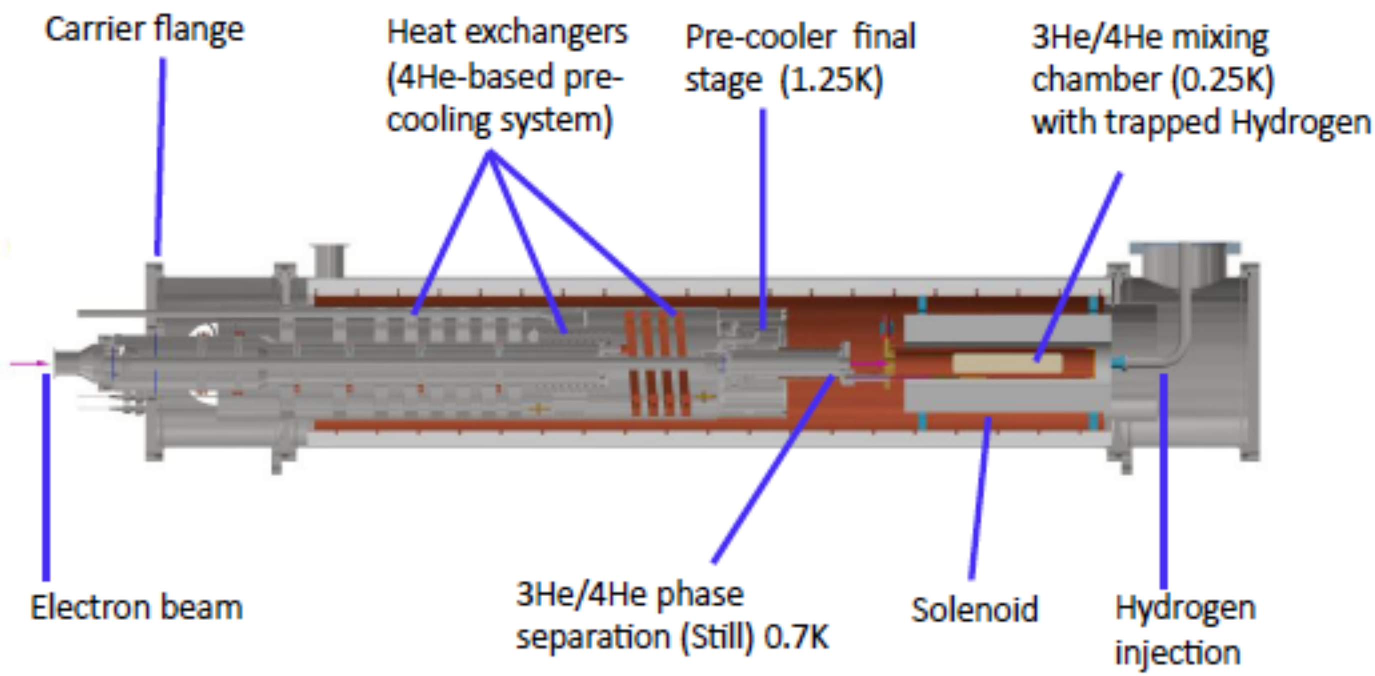
Q^2-Measurement







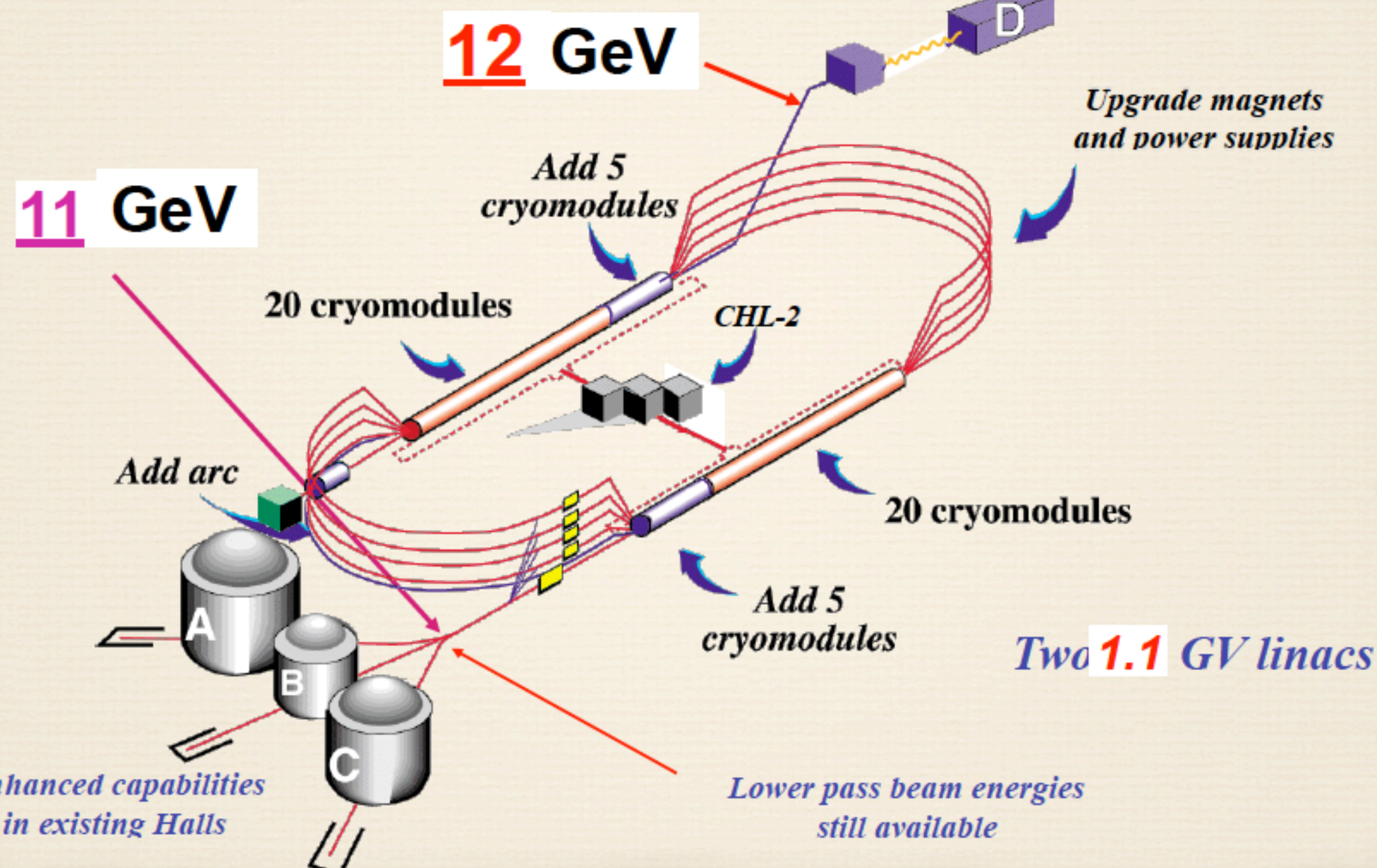

H
30K
40 cm
Solenoid 8T
0.3K
Storage Cell
beam
4 cm


Carrier flange
Heat exchangers (4He-based pre-cooling system)
Pre-cooler final stage (1.25K)
3He/4He mixing chamber (0.25K) with trapped Hydrogen
Electron beam
3He/4He phase separation (Still) 0.7K
Solenoid
Hydrogen injection

The MOLLER Experiment at JLAB

The 12 GeV Upgrade of JLab

First physics beams to Hall A in 2014



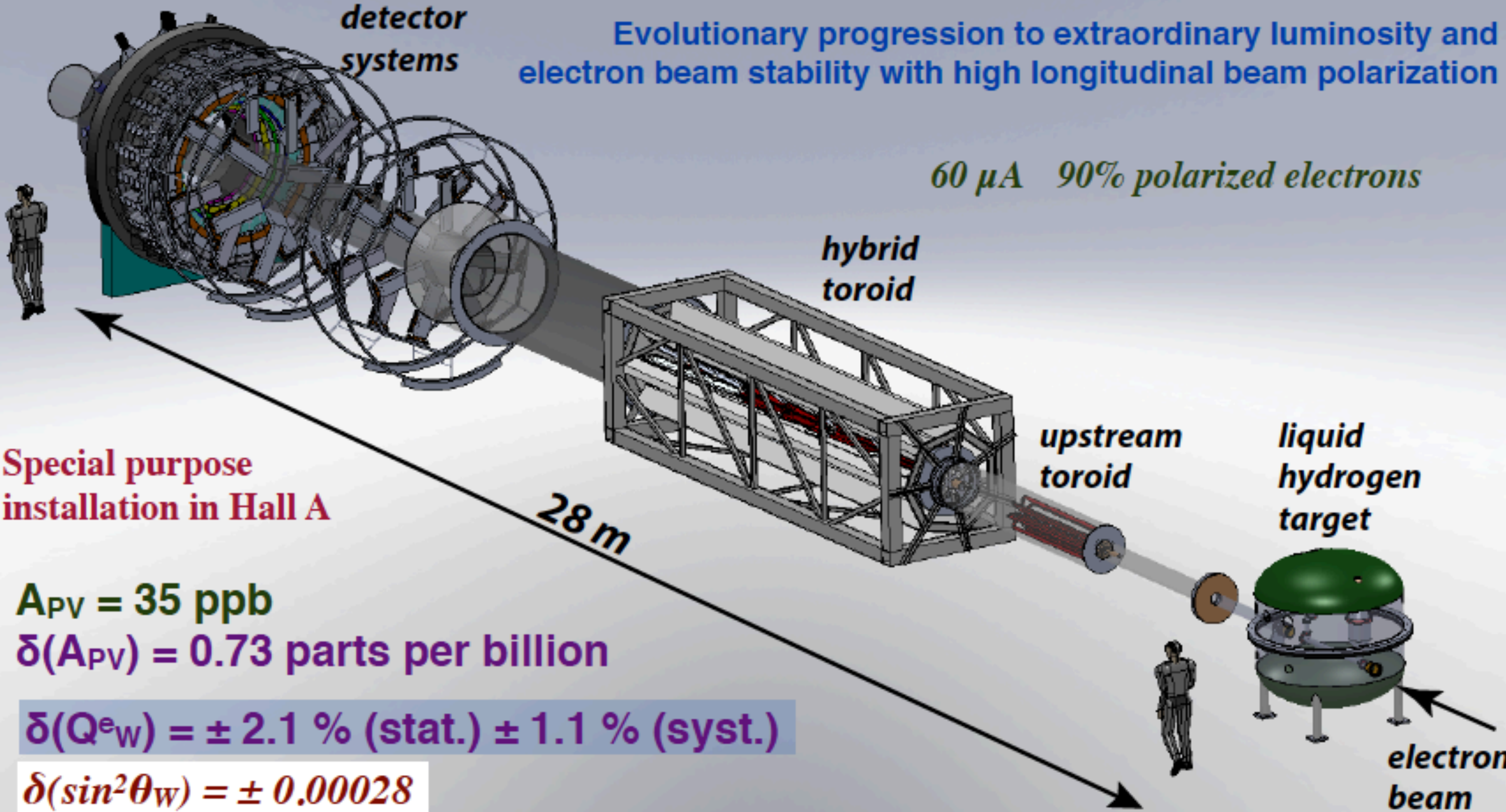
Parity-Violating Fixed Target 11 GeV electron-electron (Møller) scattering

MOLLER at JLab

Unique opportunity leveraging the 12 GeV Upgrade investment

Evolutionary progression to extraordinary luminosity and electron beam stability with high longitudinal beam polarization

60 μA   90% polarized electrons



Special purpose installation in Hall A

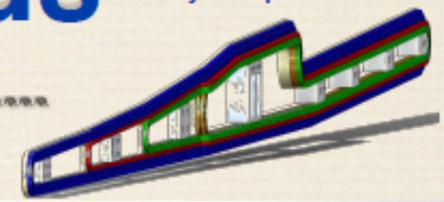
A_{PV} = 35 ppb

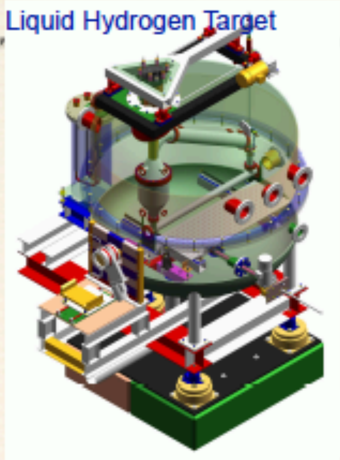
$\delta(A_{PV})$ = 0.73 parts per billion

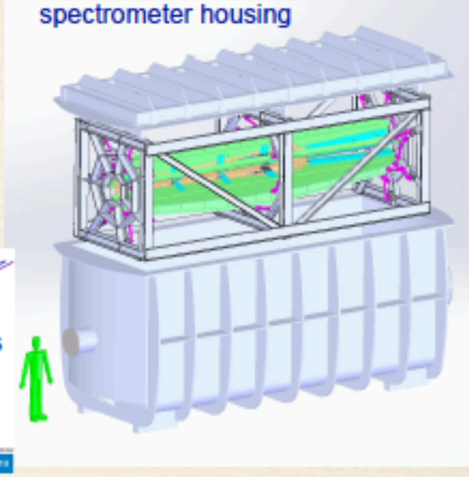
$\delta(Q^e_W) = \pm 2.1\ \%\ \text{(stat.)} \pm 1.1\ \%\ \text{(syst.)}$

$\delta(\sin^2\theta_W) = \pm 0.00028$

MOLLER Apparatus



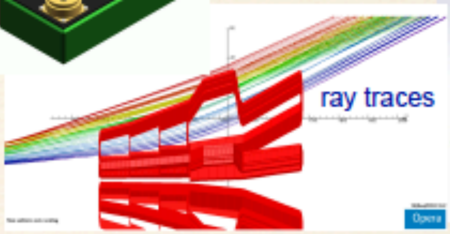


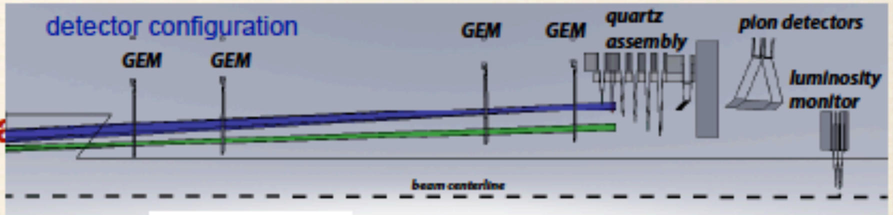


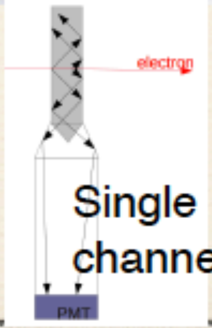
Technical Challenges

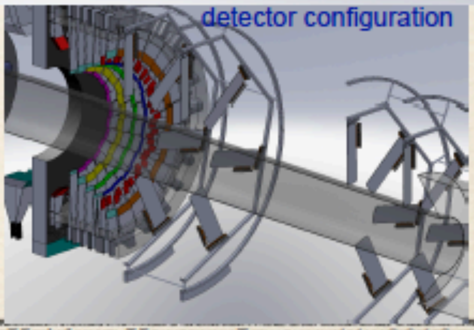
Evolutionary Improvements from Technology of Third Generation Experiments

- ~ 150 GHz scattered electron rate
- 1 nm control of beam centroid on target
- > 10 gm/cm² liquid hydrogen target
  - 1.5 m: ~ 5 kW @ 85 µA
- Full Azimuthal acceptance with θ_{lab} ~ 5 mra
  - novel toroidal spectrometer pair
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry

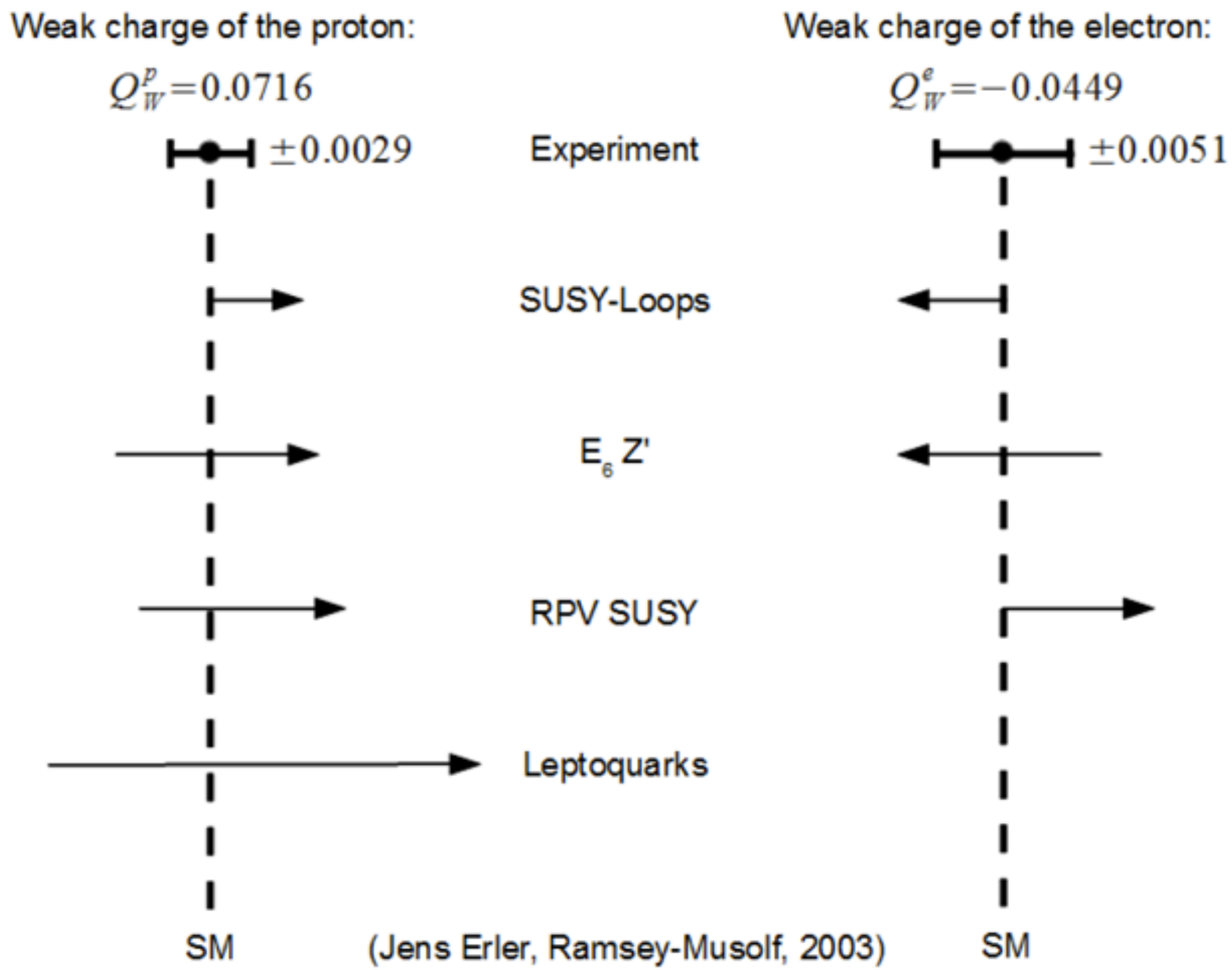








- Complementary access by weak charges of proton and electron



(Jens Erler, Ramsey-Musolf, 2003)

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

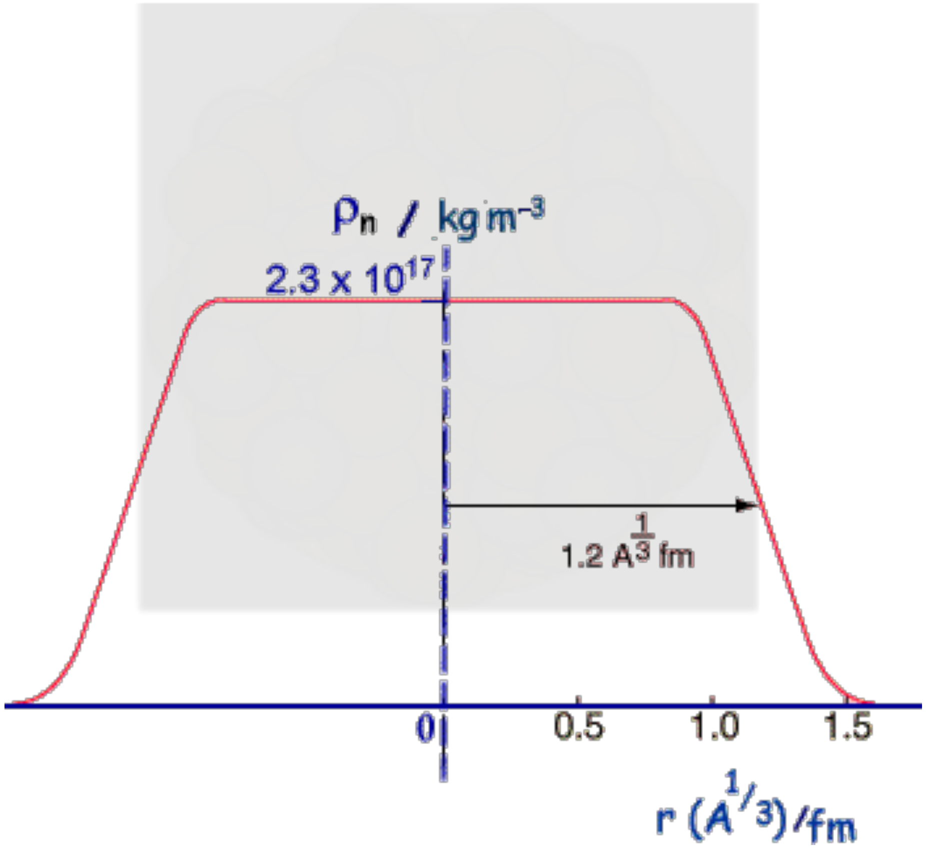
Weak Charge Of Electron: MOELLER (JLAB)

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

Neutron Skin in heavy nuclei:

Neutron Skin for beginner

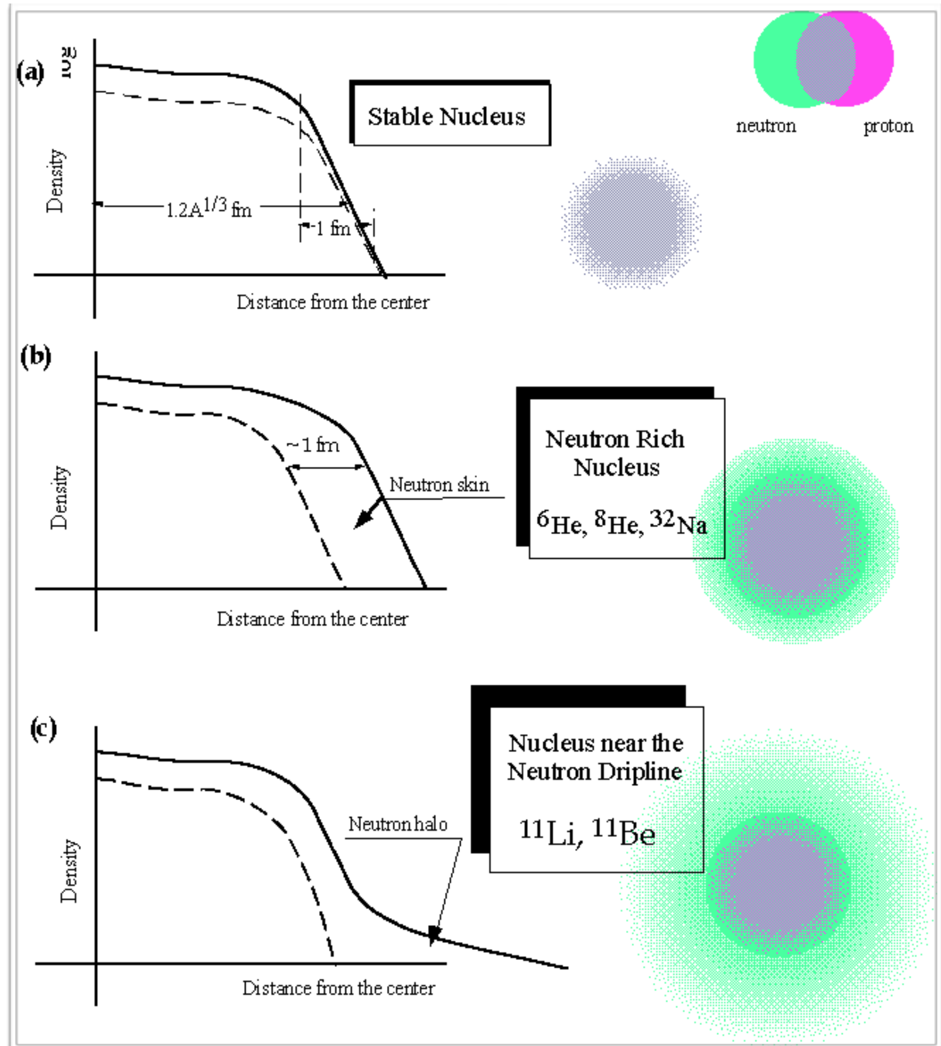
Nuclear charge radii



Where do the neutrons go?

Neutron Skin for beginner

Where do the neutrons go?

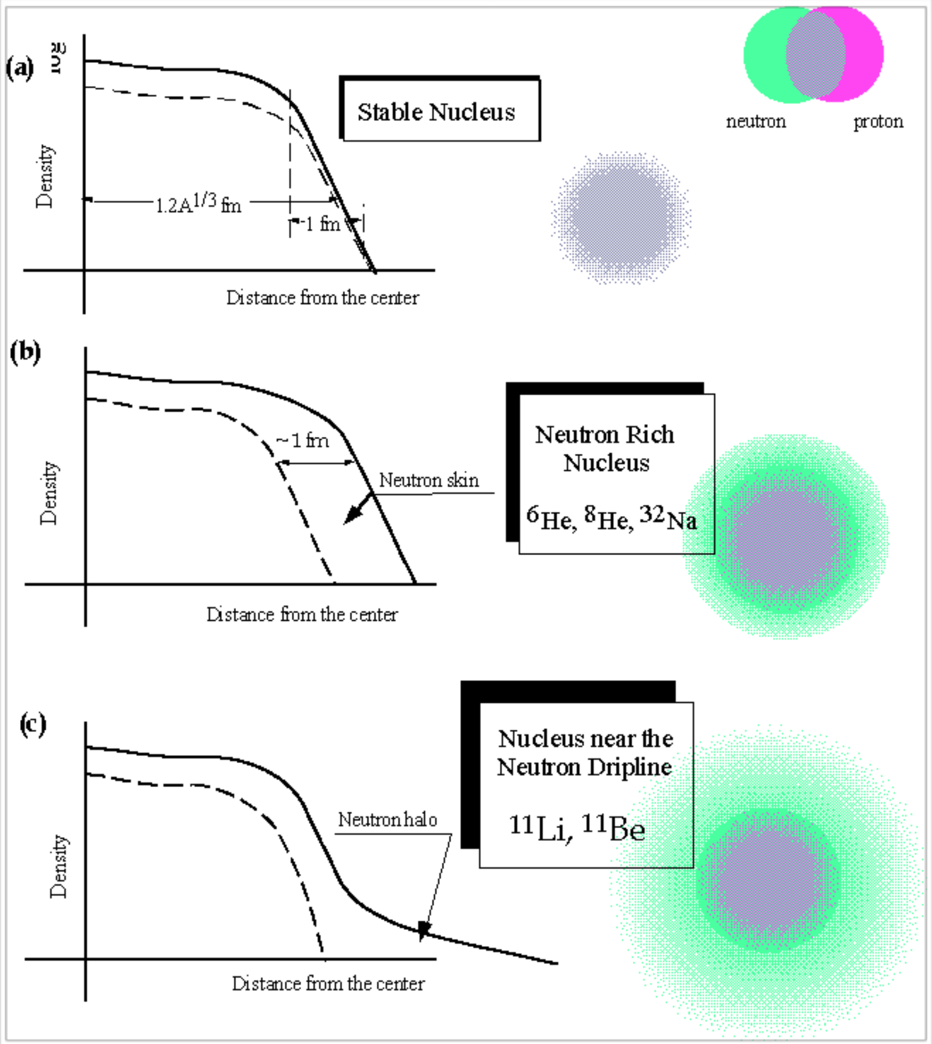


Pressure forces neutrons out against surface tension

→ EOS

Neutron Skin for beginner

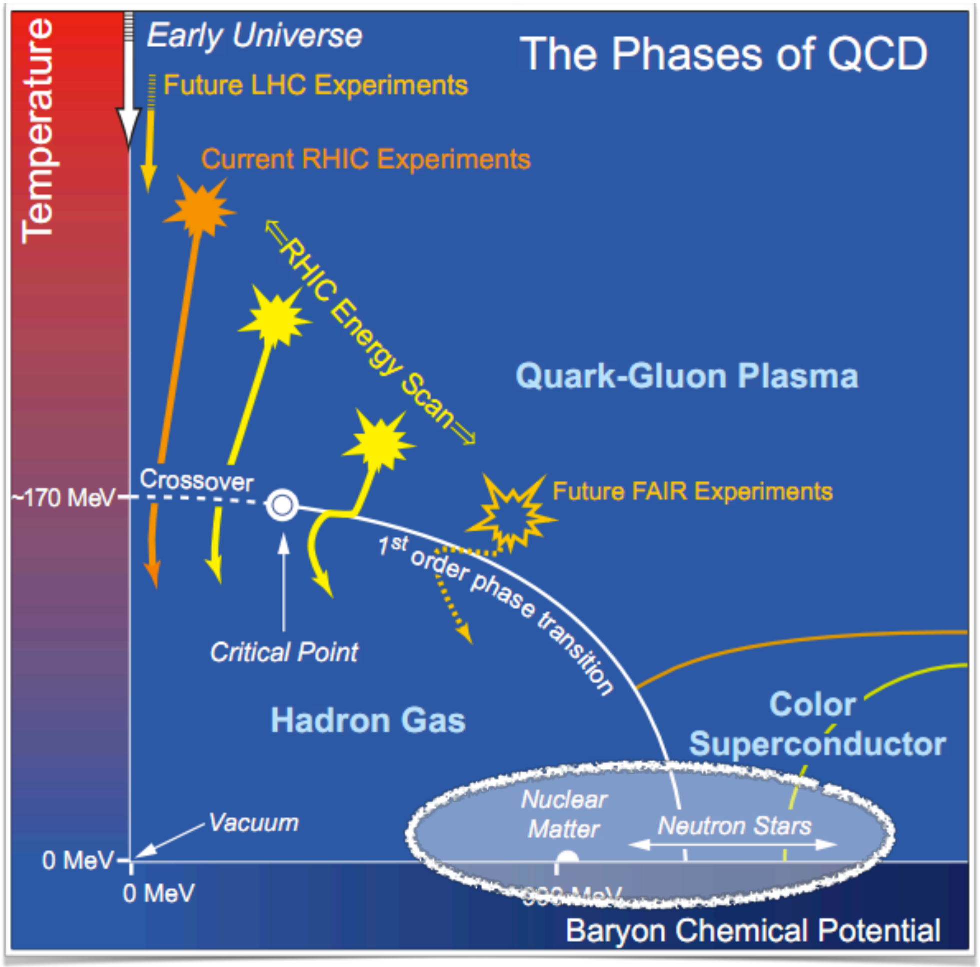
Where do the neutrons go?



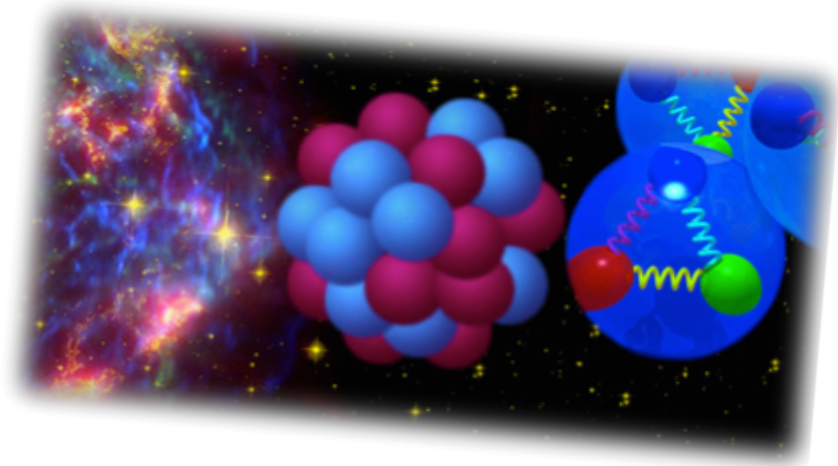
Pressure forces neutrons out against surface tension

→ EOS

Phases of Nuclear Matter



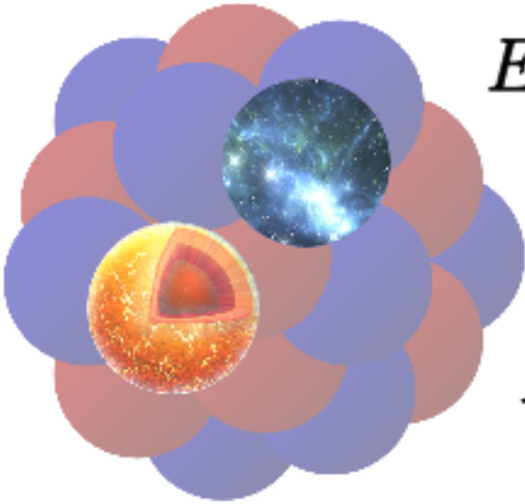
LRP Nuclear Science Advisory Committee(2008)



A heavy nucleus (like ^{208}Pb) is 18 orders of magnitude smaller and 55 orders of magnitude lighter than a neutron star

They are bound by the same EOS

WHY?



$$E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\,\delta^2 + \mathcal{O}(\delta)^4$$

symmetry energy

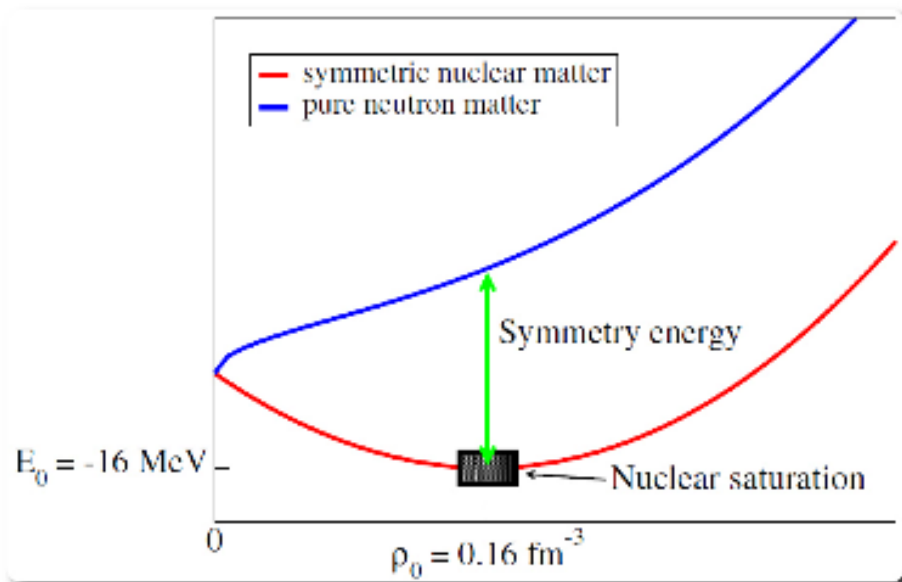
$$E_{sym}(\rho) = \left[S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2\right] + \ldots$$

slope parameter

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

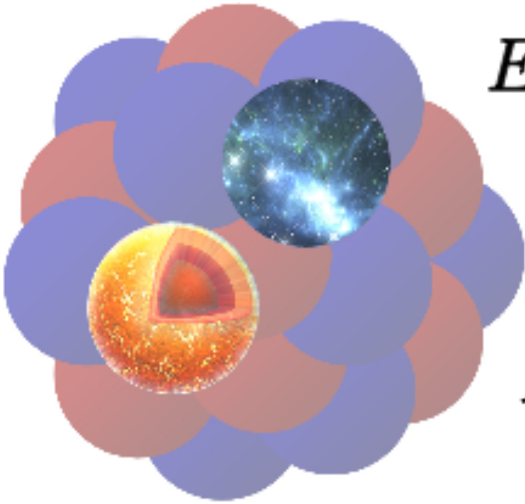
curvature parameter

$$K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho_0}$$



M. Thiel Bormio 2015

WHY?



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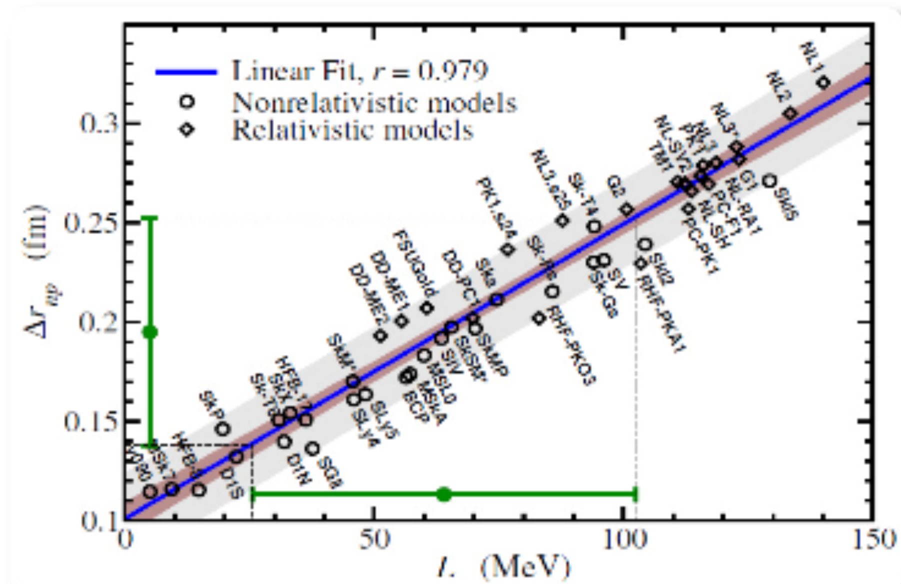
slope parameter

$$L = 3\rho_0 \frac{\partial E_{sym}(\rho)}{\partial \rho}\bigg|_{\rho_0}$$

curvature parameter

$$K_{sym} = 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho_0}$$

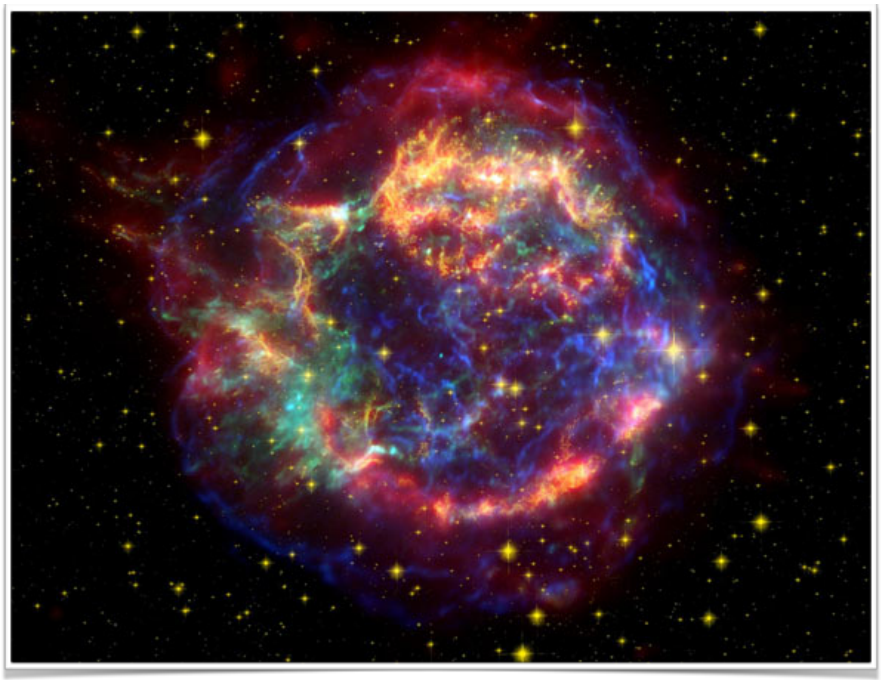


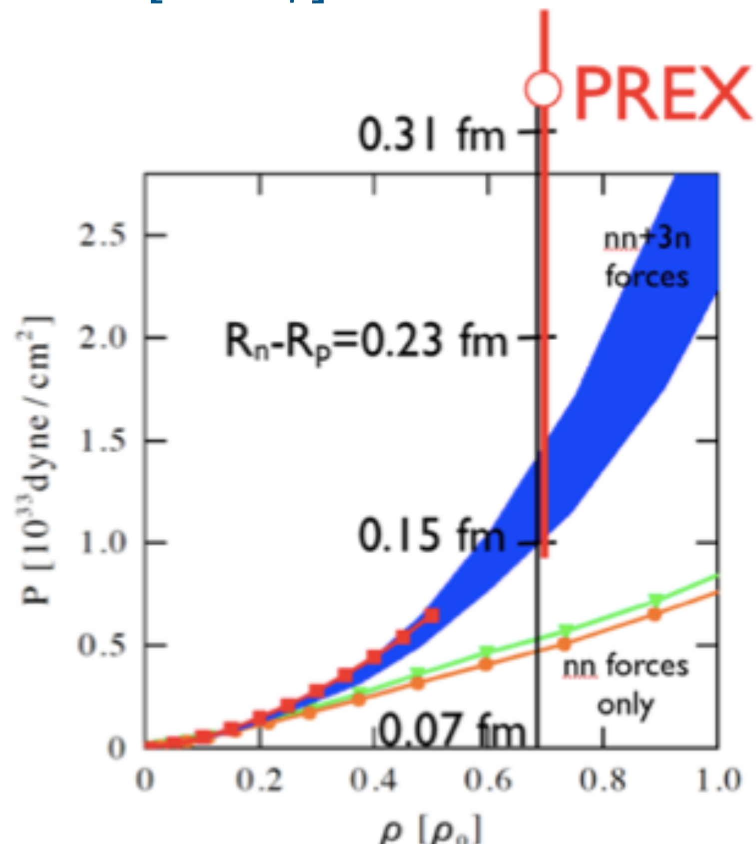
X. Roca-Maza et al., PRL 106 (2011) 252501

M. Thiel

WHY?

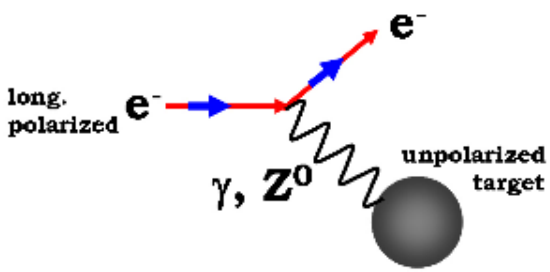
Neutron skins **constraint the EOS**$_{[@\text{low } \rho]}$ **of ...**

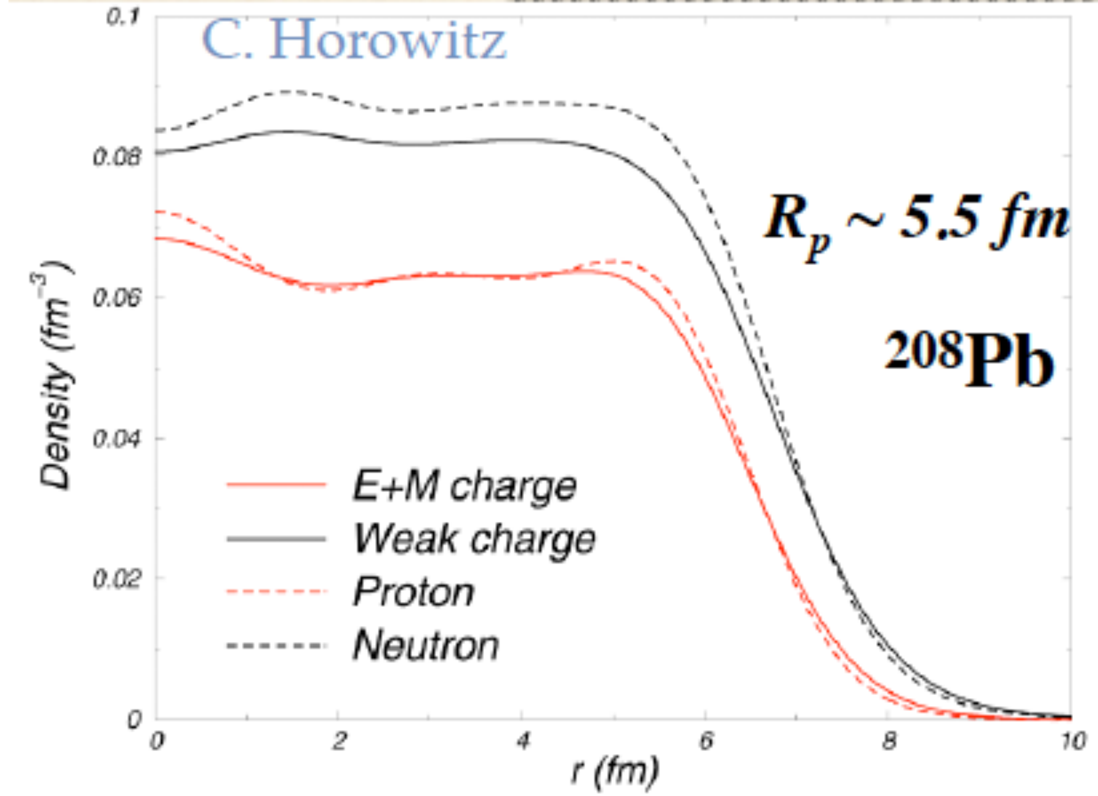




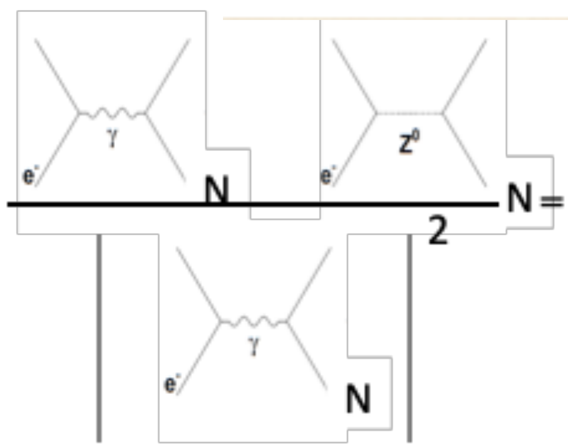
Pressure @ low ρ → Crust thickness

Pressure @ high ρ from mass measurements





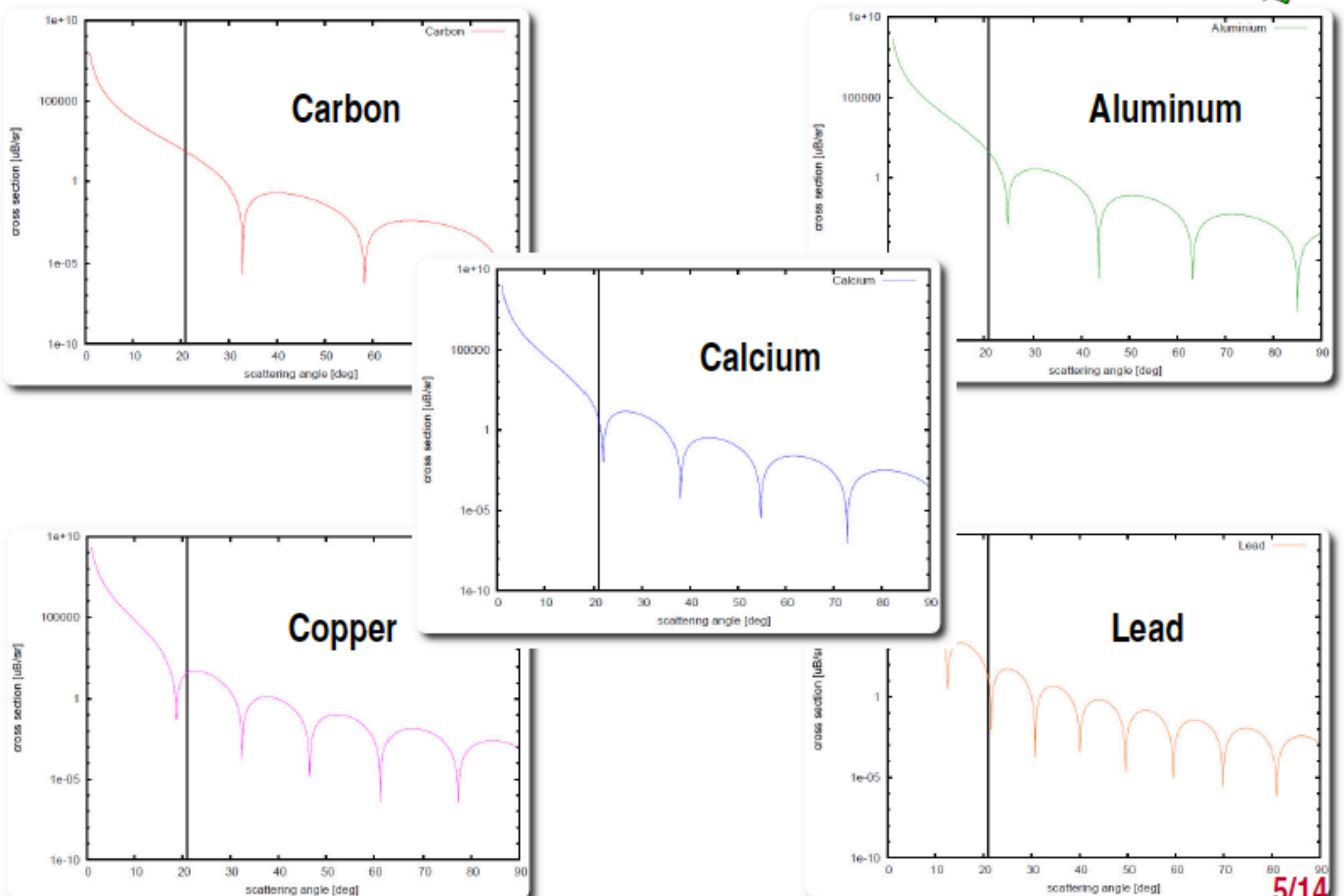
$$A_{PV} = \frac{\left(\frac{d\sigma}{d\Omega}\right)_+ - \left(\frac{d\sigma}{d\Omega}\right)_-}{\left(\frac{d\sigma}{d\Omega}\right)_+ + \left(\frac{d\sigma}{d\Omega}\right)_-} \approx$$



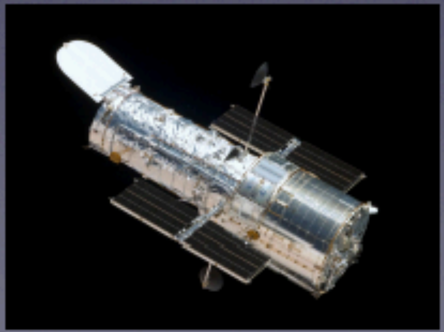
$$= \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{1 - 4\sin^2\theta_W}_{\approx\, 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

$$F_{n,p}(Q^2) = \frac{1}{4\pi}\int d^3r\ j_0(qr)\ \rho_{n,p}(r)$$

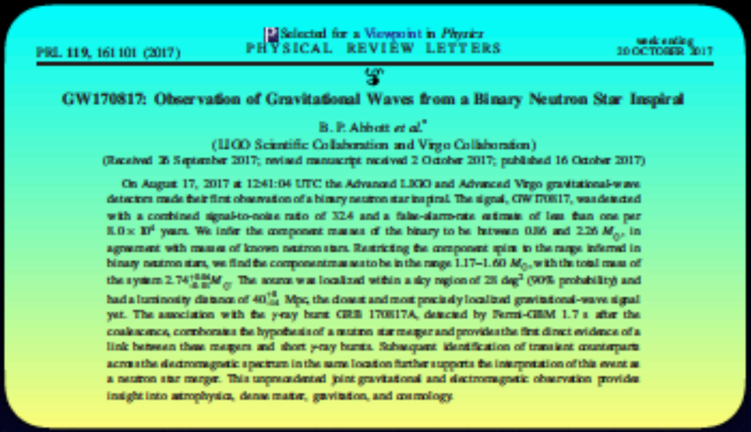
short-range plan: target variety



2017 BREAKTRHOUGH of the YEAR!



Historical first detection of gravitational waves from a binary neutron-star merger



PRL 119, 161101 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

GW170817: A play in three acts

- Act 1: Ligo-Virgo detect GW from BNS merger
  - Source properties inferred from “matched filtering”
  - Extraction of “chirp” mass and “tidal polarizability”

    Stringent limits on the EOS of dense matter
- Act 2: Fermi/Integral detect short γ-ray burst
  - detected ~2 seconds after GW signal
  - Confirms long-held belief of the association between BNS merger and γ-ray bursts
- Act 3: ~70 telescopes tracked the “kilonova”
  - Afterglow of the explosive merger ~11 hours later
  - Powered by the radioactive decay of “r-process” elements

    BNS mergers as a critical site for the r-process!

Neutron-star mergers create gravitational waves, light, and gold!

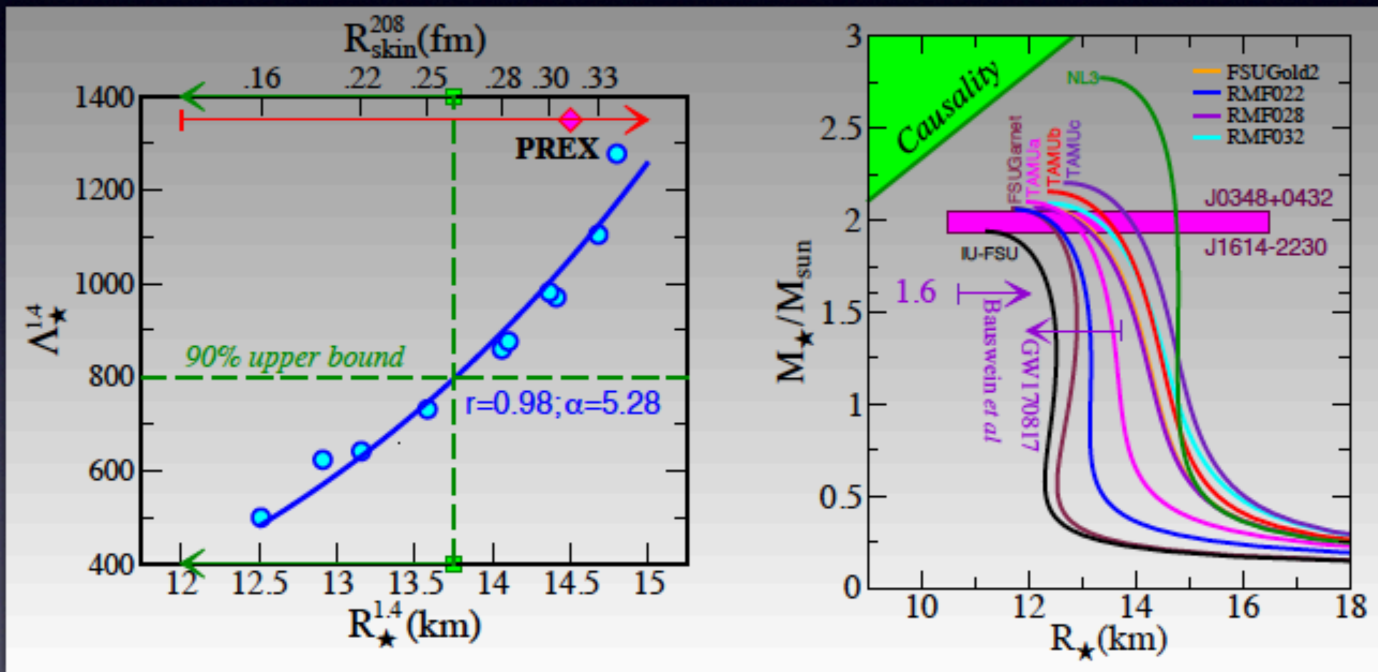
Neutron skins and neutron stars in the multi-messenger era

PHYSICAL REVIEW LETTERS 120, 172702 (2018)

Editors' Suggestion | Featured in Physics

Neutron Skins and Neutron Stars in the Multimessenger Era

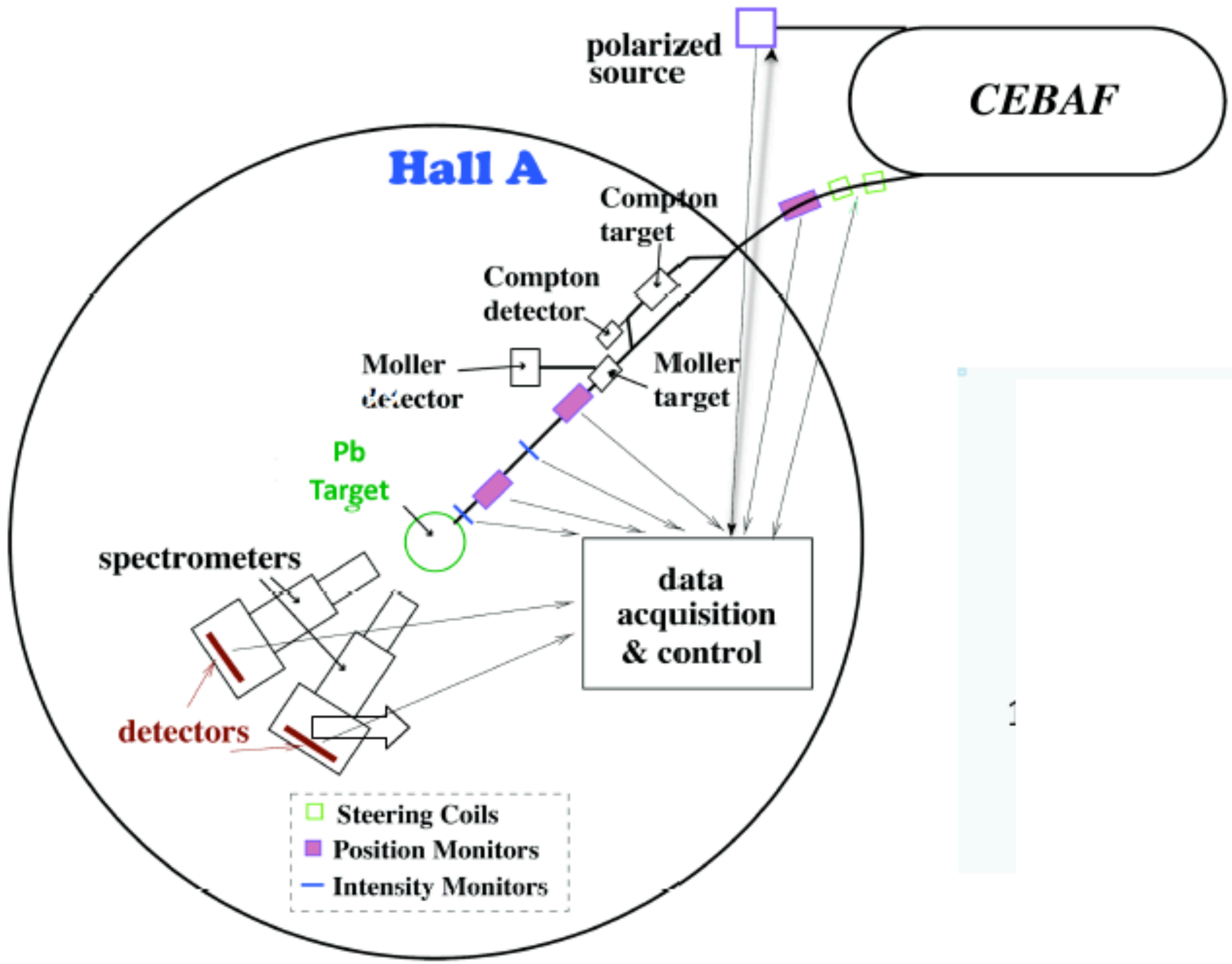
F. J. Fattoyev,[1,*] J. Piekarewicz,[2,†] and C. J. Horowitz[1,‡]
[1]Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA
[2]Department of Physics, Florida State University, Tallahassee, Florida 32306, USA



Exciting possibility: If PREX confirms that Rskin is large and LIGO-Virgo that NS-radius is small, this may be evidence of a softening of the EOS at high densities (phase transition?)

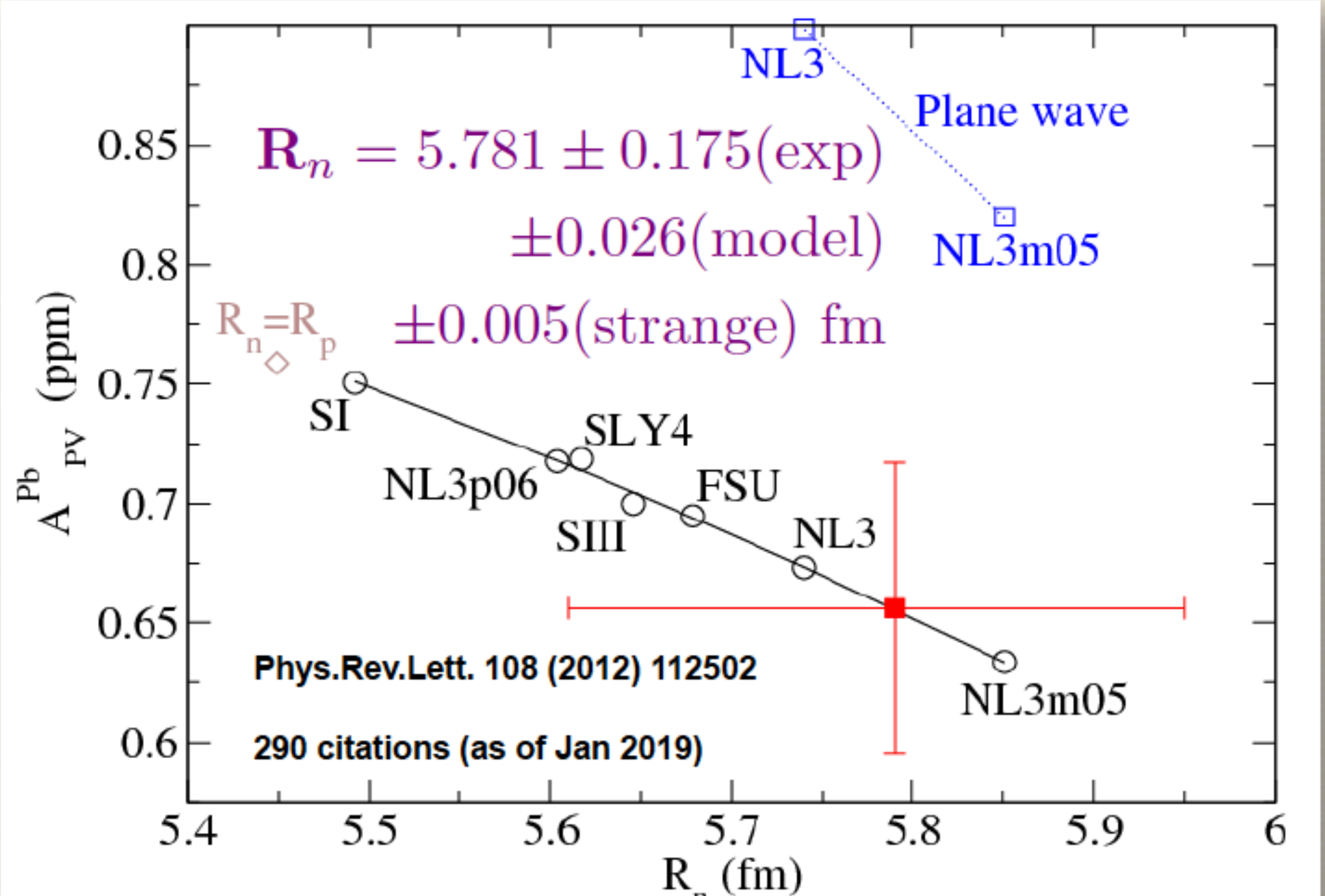
The very first observation of a BNS merger already provides a treasure trove of insights into the nature of dense matter!

PREX @ JLab Hall A: Overview



$$\mathbf{R}_n - \mathbf{R}_p = 0.302 \pm 0.175(\mathrm{exp}) \pm 0.026(\mathrm{model}) \pm 0.005(\mathrm{strange})\ \mathrm{fm}$$

2010 Run: PREX-I Result

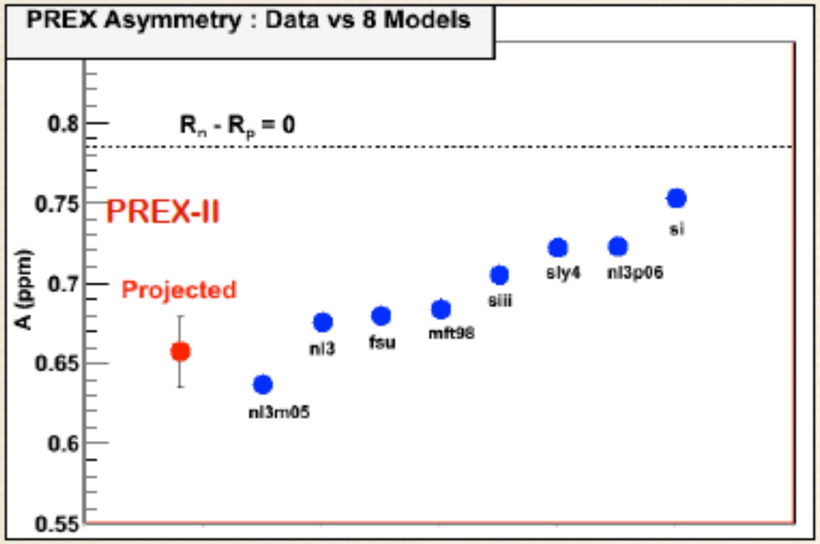


$$A_{PV} = 0.656\ ppm \pm 0.060(stat) \pm 0.014(syst)$$

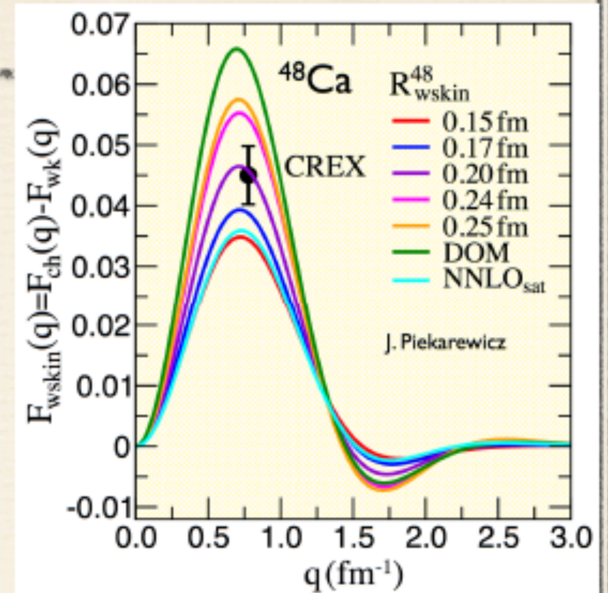
Upcoming: Precise Measurements of both ^{208}Pb and ^{48}Ca

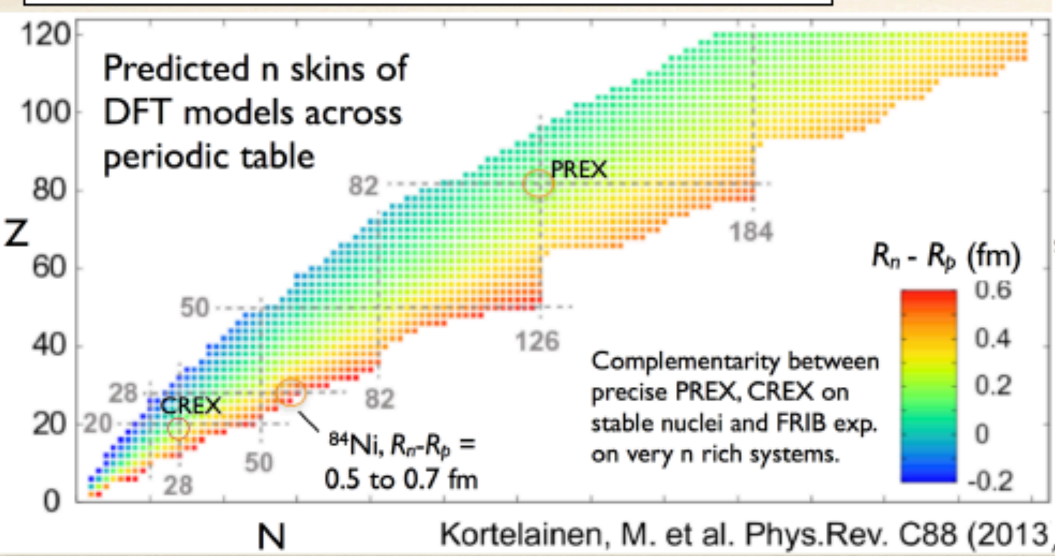
PREX-II and CREX

Summer/Fall 2019

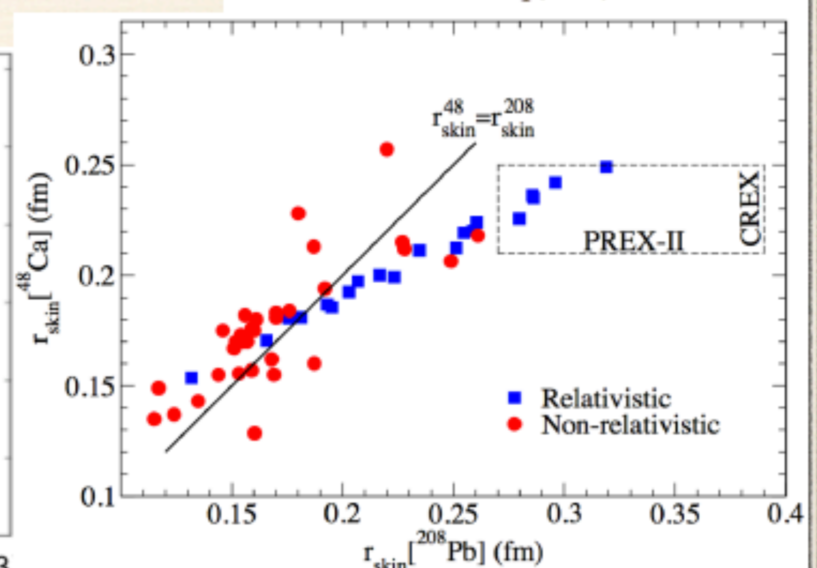


Precise anchors at two ends of the Periodic Table: simultaneously constrain 3-n forces and Nuclear Equation of State



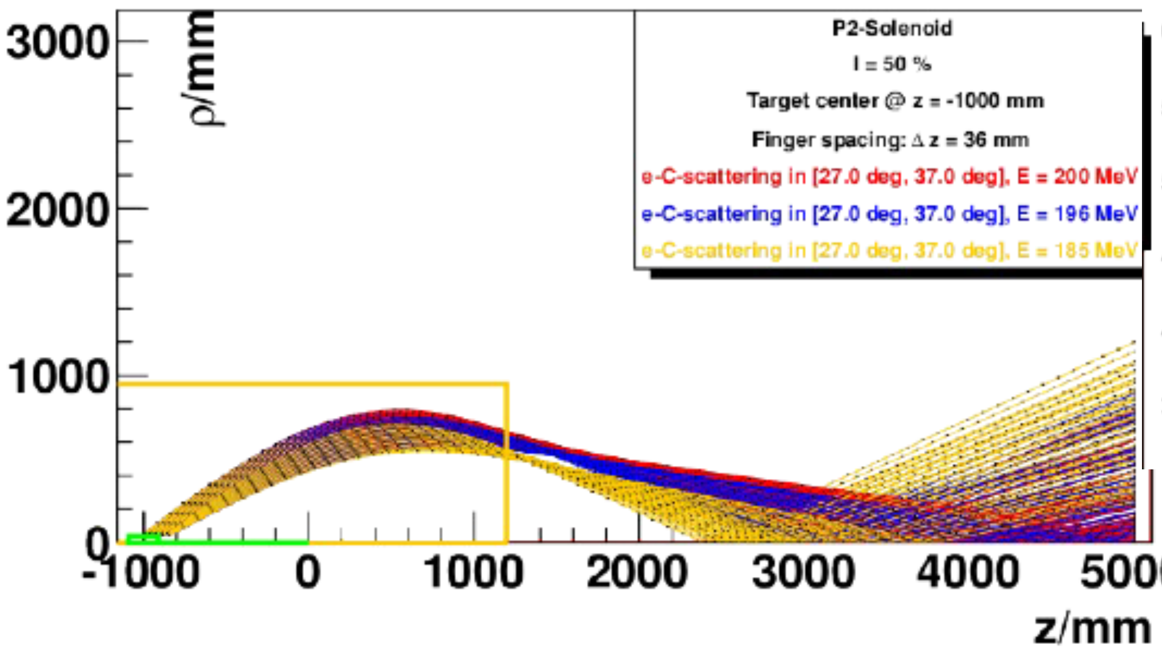


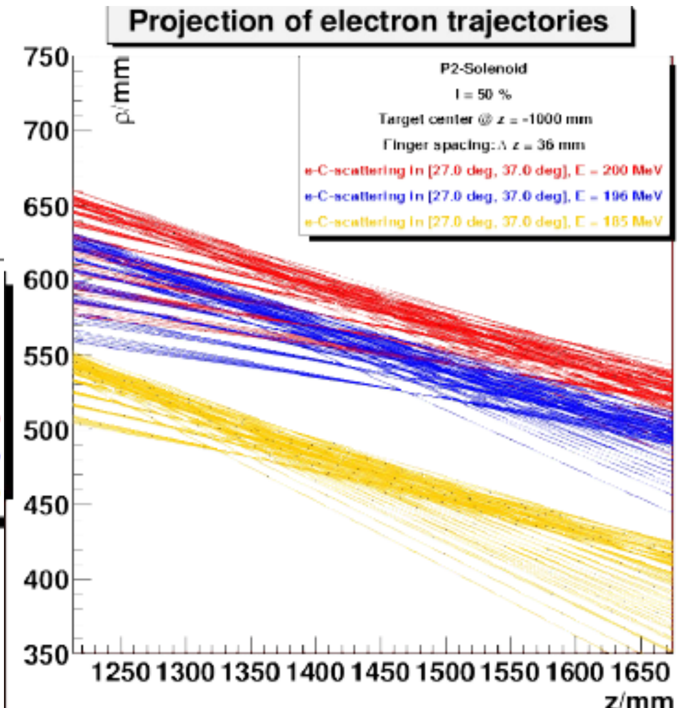
Kortelainen, M. et al. Phys.Rev. C88 (2013,



Neutron skin measurements with P2 at MESA

Separate excited states with magnetic spectrometer:



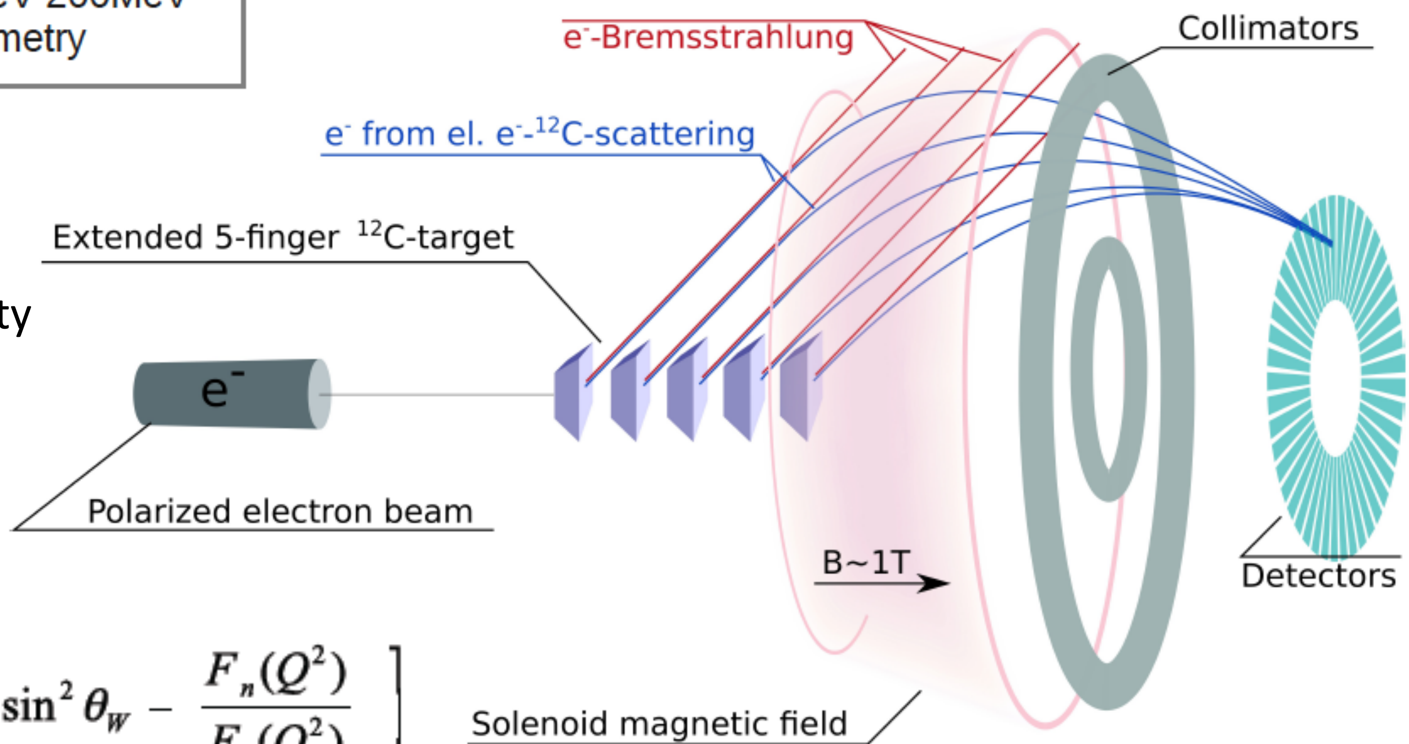


Weak charge in light nuclei (Carbon):

EXPERIMENTAL REALIZATION

MESA:
- 150µA
- 150MeV-200MeV
- Polarimetry

Enhanced sensitivity
To new physics



$$-N = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}}\left[\underbrace{\sin^2\theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)}\right]$$

@ Beam energy $E = 150$MeV
Scattering angle $\Theta = 40° \pm 9°$
Target density $d = 5$g/cm²

Measuring time $t = 2500$h
Beam current $I = 150\mu$A

We can achieve $$\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%$$

$$A_{PV} = \frac{G_F \cdot Q^2}{\sqrt{2}\pi\alpha}\sin^2\Theta_W \longrightarrow$$

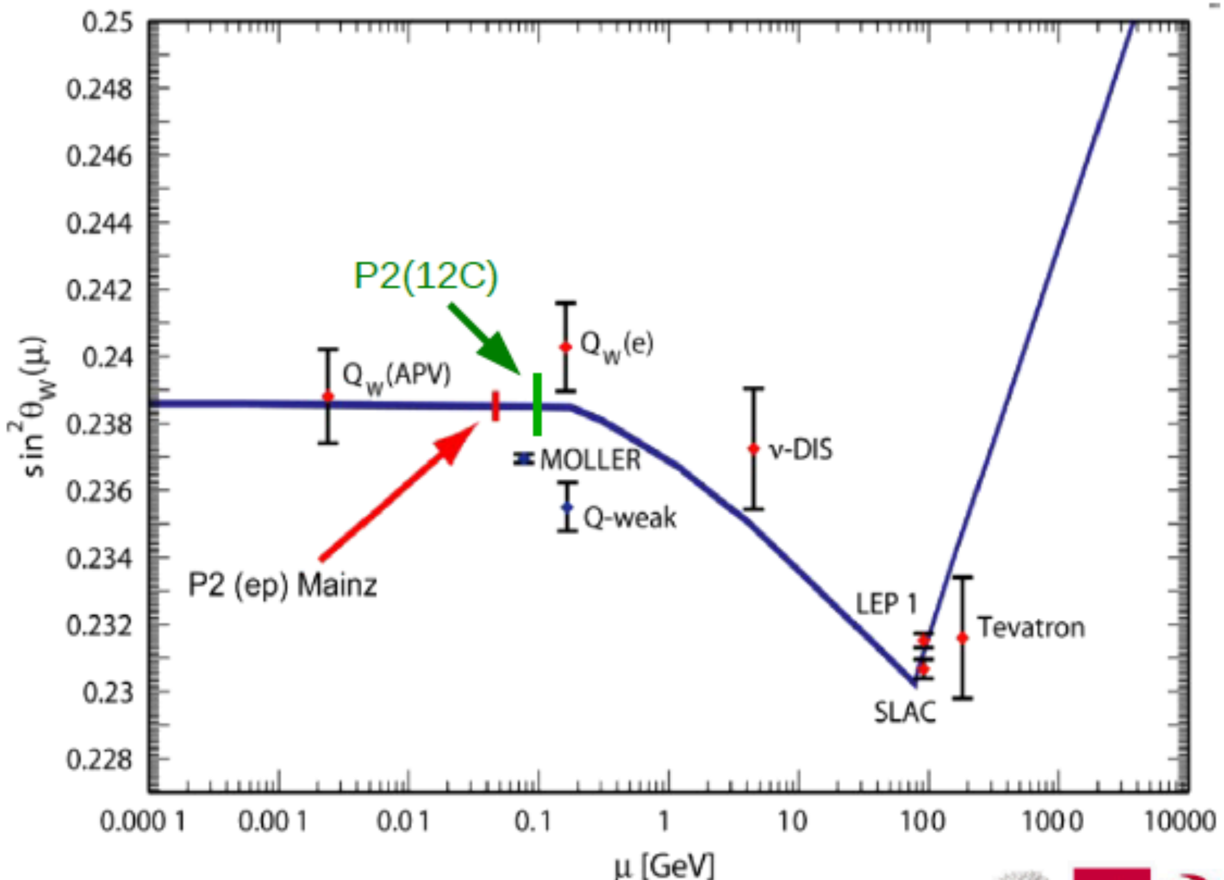
$$Q_W^C = -24\sin^2\Theta_W \longrightarrow$$

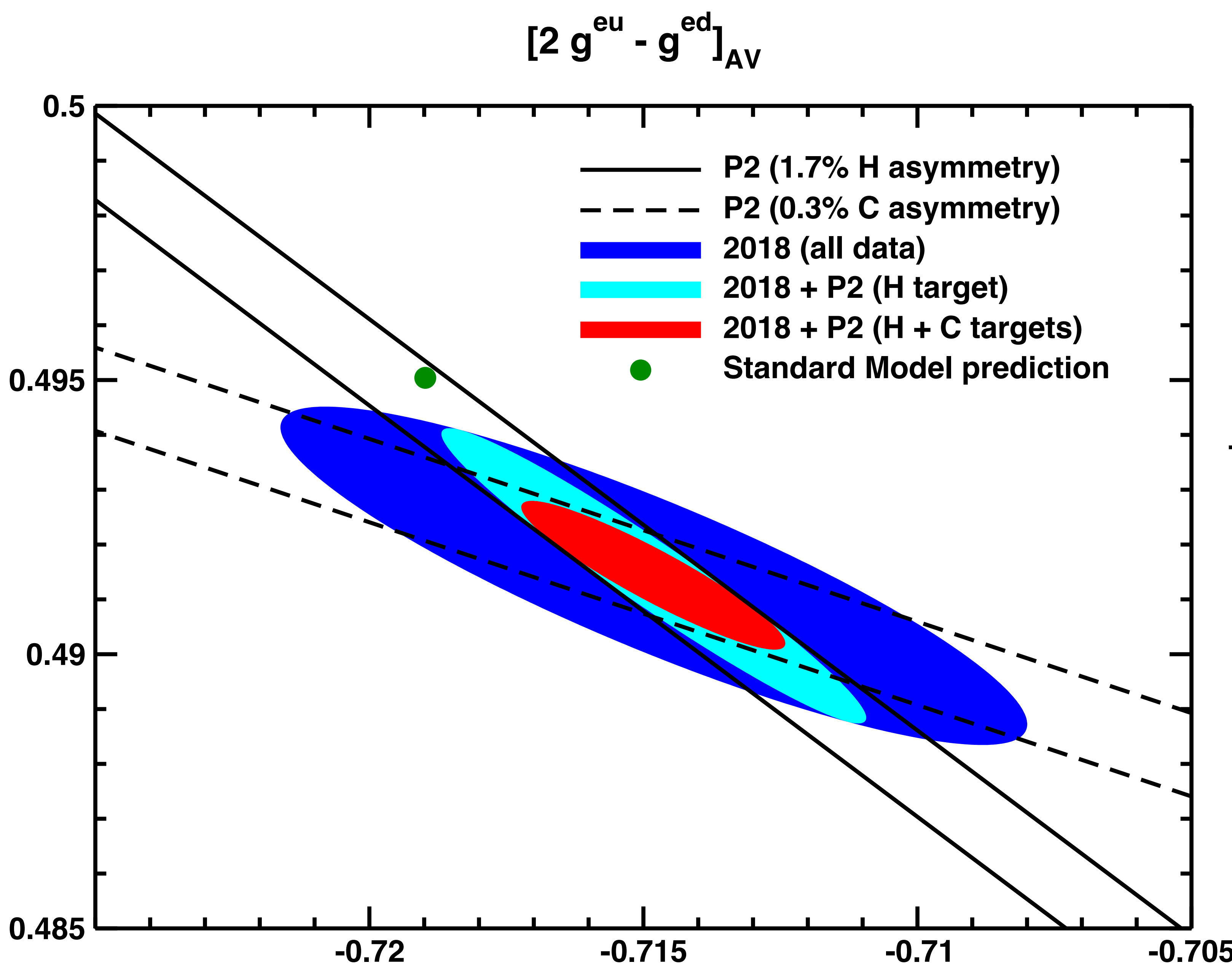
$$\boxed{\frac{\delta A_{PV}}{A_{PV}} = \frac{\delta Q_W^C}{Q_W^C} = \frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.3\%}$$

Reminder: With Hydrogen: $\frac{\delta A_{PV}}{A_{PV}} = 1.7\%$ $\frac{\delta Q_W^H}{Q_W^H} = 2\%$ $\frac{\delta \sin^2\Theta_W}{\sin^2\Theta_W} = 0.15\%$

$$\frac{\delta \sin^2(\Theta_W)}{\sin^2(\Theta_W)} \approx 0.003$$

$$@Q^2 \approx 0.01$$





[2 g^eu - g^ed]_AV
[g^eu + 2 g^ed]_AV
P2 (1.7% H asymmetry)
P2 (0.3% C asymmetry)
2018 (all data)
2018 + P2 (H target)
2018 + P2 (H + C targets)
Standard Model prediction
0.5
0.495
0.49
0.485
-0.72
-0.715
-0.71
-0.705

- **Parity violating electron scattering:**
  "Low energy frontier" comprises a sensitive
  test of the standard model complementary to LHC
- **Determination of $\sin^2(\theta_W)$ with high precision (similar to Z-pole)**
- **P2-Experiment (proton weak charge) at MESA in preparation (2022), MOLLER Experiment at Jlab in preparation**
- **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 up to a scale of 50 MeV up to 50 TeV**
- **Much more physics from PV electron scattering: Neutron Skin in heavy nuclei, weak charge in light nuclei**
- **Together with Moeller@Jlab (electron weak charge) and SOLID@Jlab (quark weak charge) very sensitive test of standard model and possibility to narrow in on Standard Model Extension**