Goals and Status of MOLLER, P2, and SoLID

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Thanks to Frank, KK, Mark, the SoLID collaboration…

Jefferson Lab

U.S. DEPARTMENT OF ENERGY | Office of Science

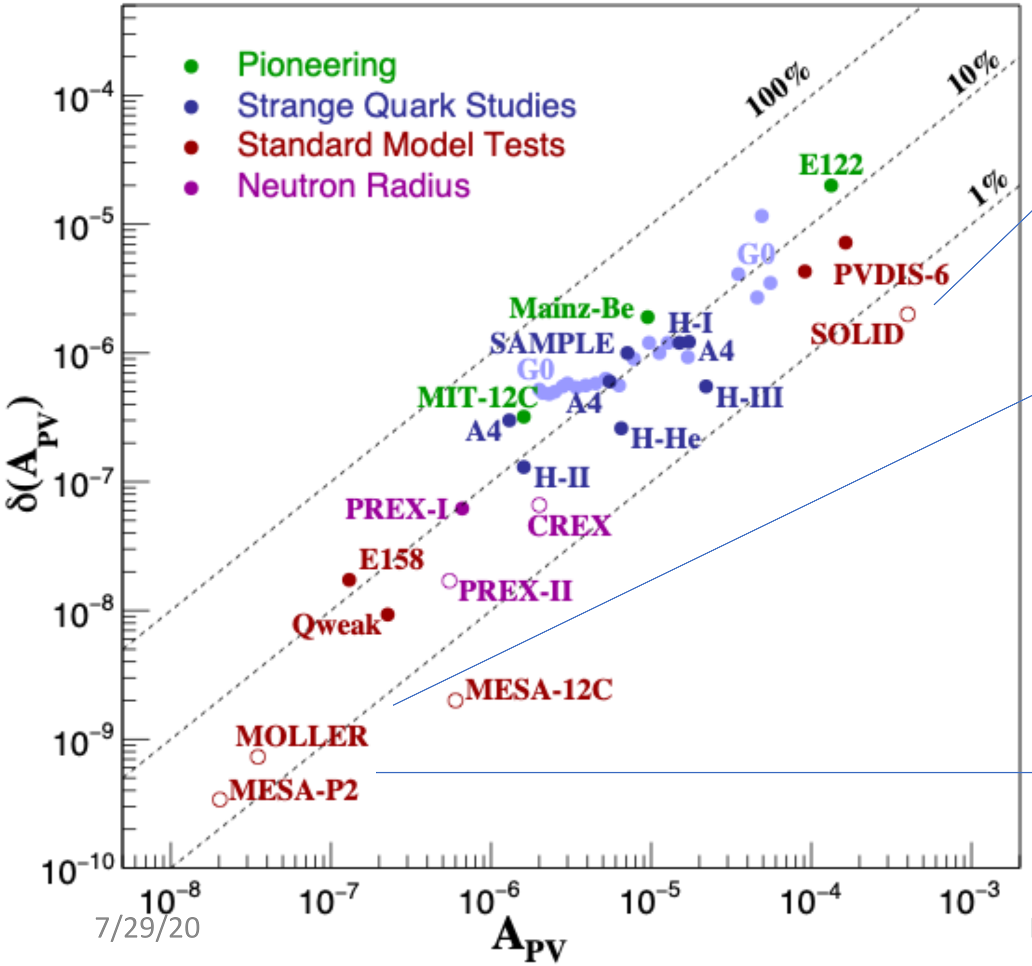
JSA

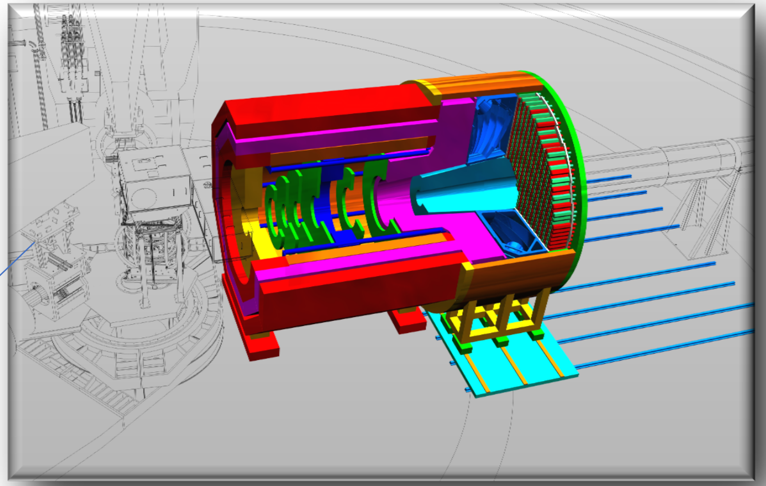
Outline

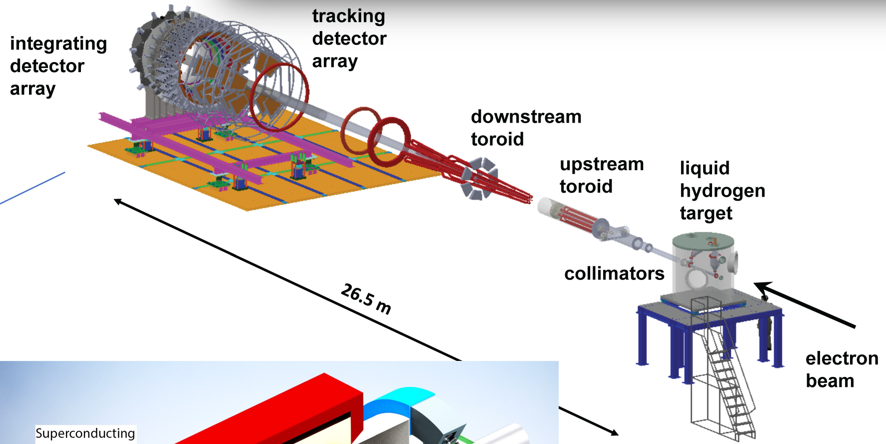
- The experiments
  - MOLLER
  - SoLID
  - P2
- Motivation
  - SMEFT
  - Z_d
  - Leptophobic Z’

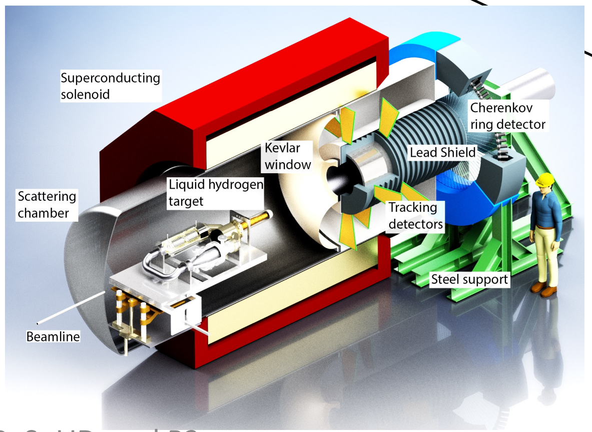
PVES Experiments

MOLLER, SoLID, and P2 all are major extensions in precision









	A	δA
SoLID	500 ppm	3 ppm
MOLLER	35 ppb	0.8 ppb
P2	20 ppb	0.4 ppb

Goal of P2, SoLID, and MOLLER

Measure all the C's

A precisely as possible

$$A_{PV} = Q_W^e \frac{Q^2 G_F}{\sqrt{2}\pi} \left(\frac{1-y}{1+y^4+(1-y)^4} \right)$$

Moller (Simple formula)

$$A_{PV} = \frac{G_F Q^2}{\pi \sqrt{2}} (Q_W^p + A_M + A_s + A_A)$$

P2: eP (Simple formula at low E and θ)

$$A^{PV} = \left(\frac{G_F Q^2}{4\sqrt{2}\pi} \right) (Y_1 a_1 + Y_3 a_3)$$

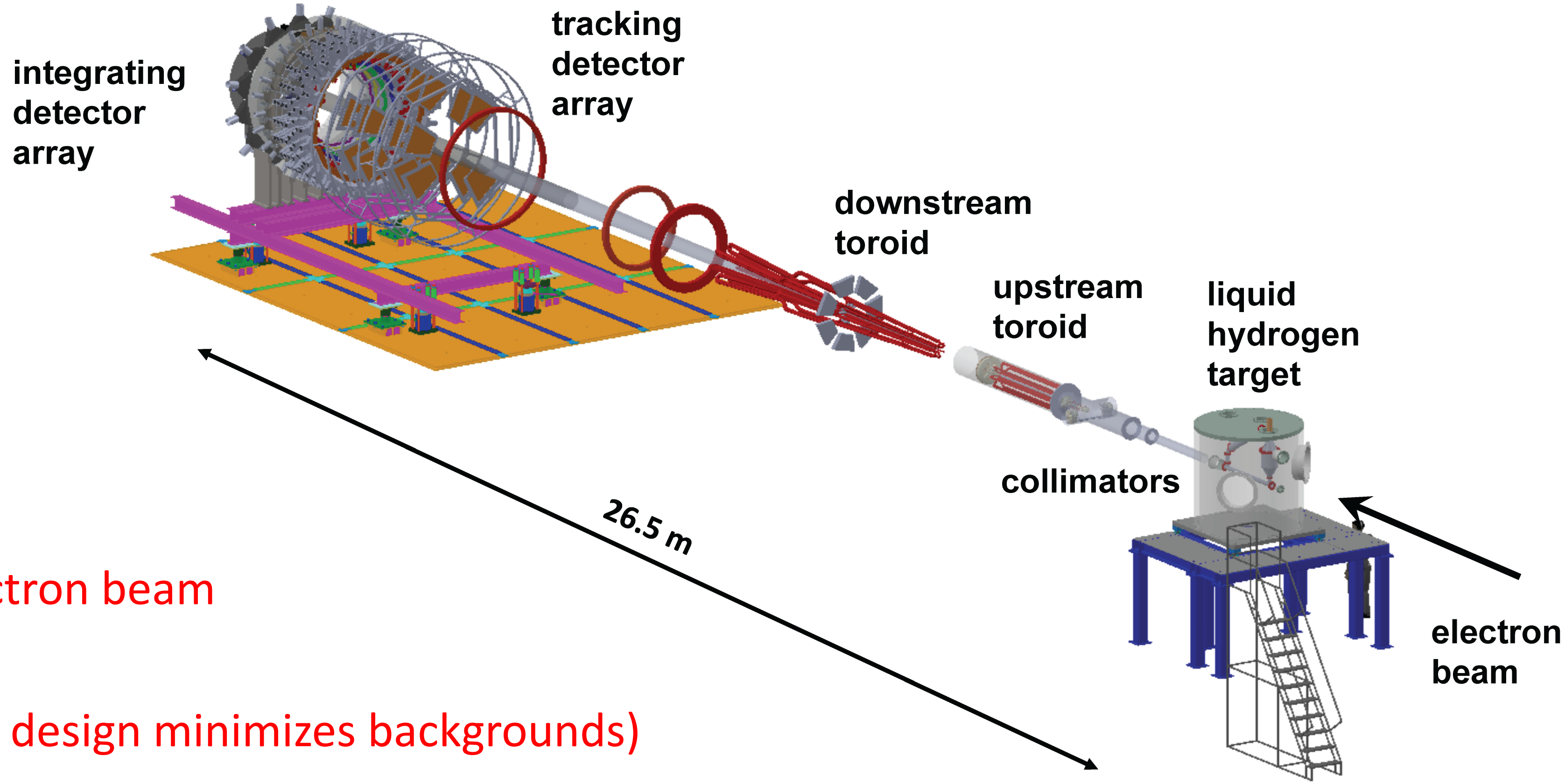
SoLID PVDIS (Simple for d at large E and θ, only way to get C_2's)

$$a_1^d = \frac{6}{5}(2C_{1u} - C_{1d}); \quad a_3^d = \frac{6}{5}(2C_{2u} - C_{2d})$$

$$Q_W(Z,N) = -2[C_{1u}(2Z+N) + C_{1d}(Z+2N)]$$

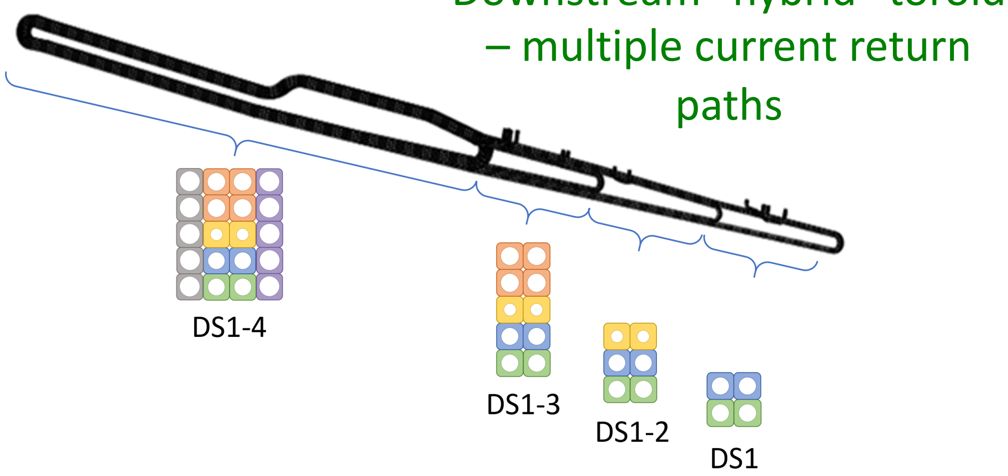
$$Q_W(e) = -2C_{2e}$$

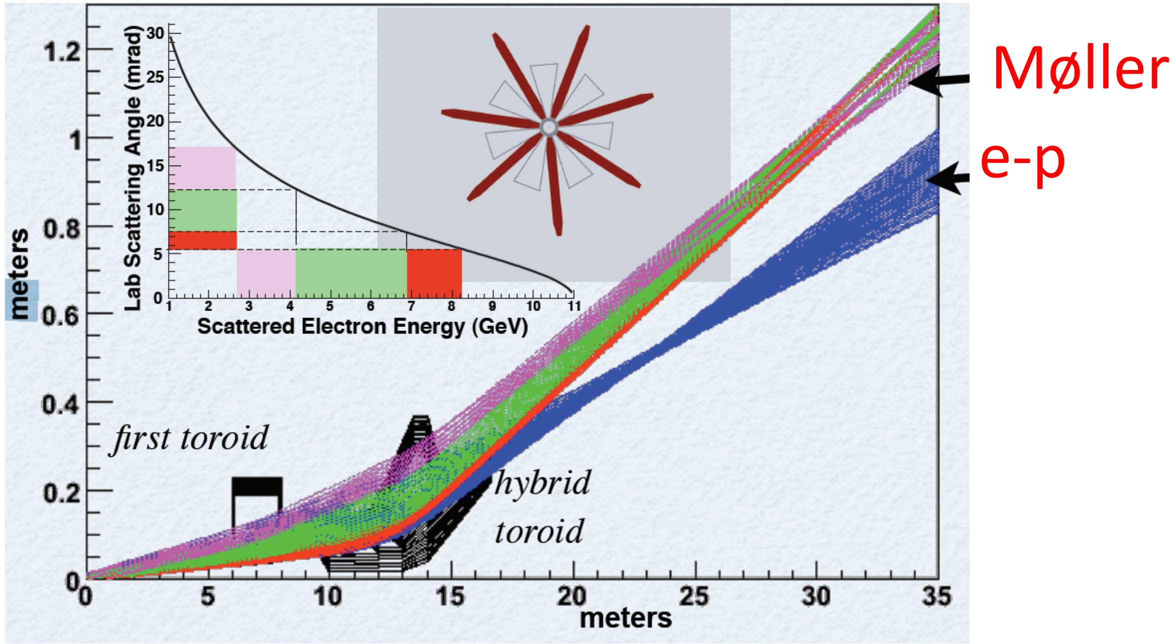
The MOLLER Experiment at JLab



- 11 GeV, 90% polarized, 65 μA electron beam
- 125 cm long, 4 kW LH_2 target
- Precision collimation (“2-bounce” design minimizes backgrounds)
- Novel two (warm) toroid spectrometer
- Variety of integrating and counting detectors for main measurement and backgrounds

MOLLER Spectrometer



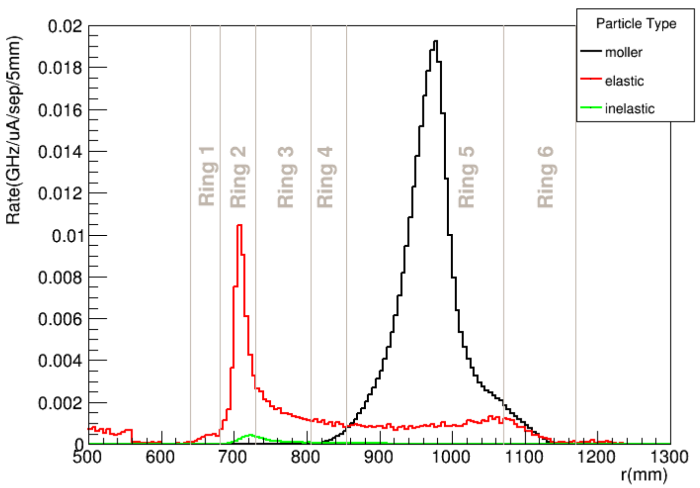


Spectrometer employs a novel two toroid design

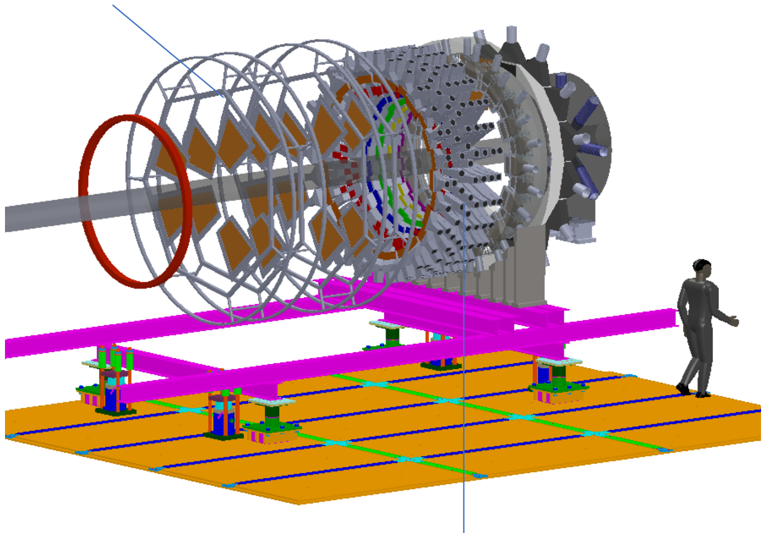
- Upstream toroid has conventional "racetrack" geometry
- **Downstream "hybrid" toroid novel design** inspired by the need to focus Møller electrons with wide scattered energy range E' = 2.0 – 9.0 GeV while separating them from Mott (e-p) scattering background - requires long, skinny magnet with multiple current return paths for needed field integral ~ 1 T-m

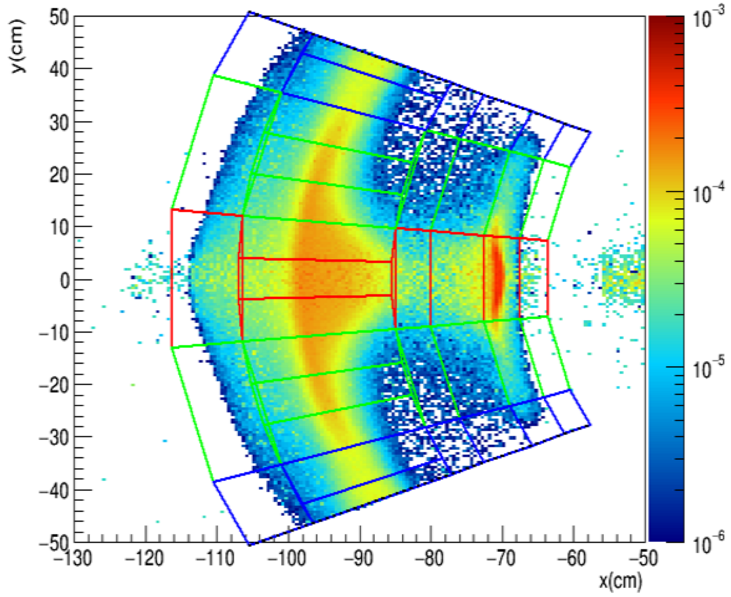
Detector: Rejecting Backgrounds

Radial distribution at detector plane 26.5 m from target



Removable racking detectors for Q^2 measurement





eP and radiative tail

Moller events

Inelastics (with big asymmetries)

Highly segmented detector

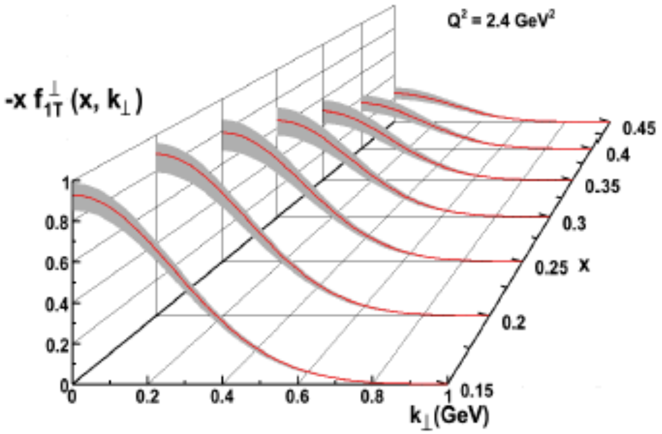
Backgroundshave non-trivial θ and ϕ dependence

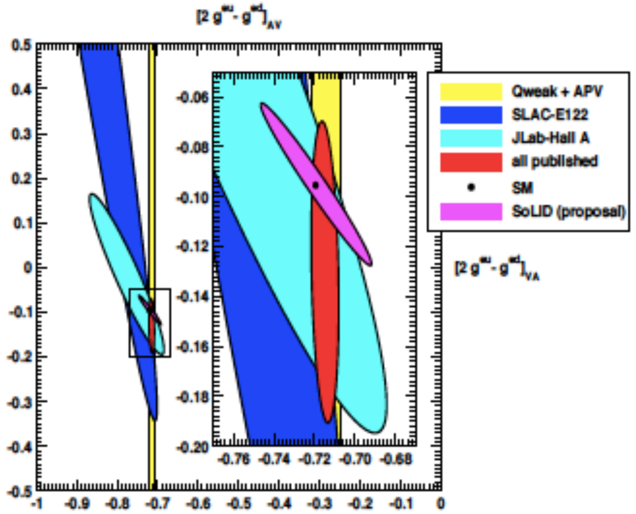
SoLID at JLab: QCD at the Intensity Frontier

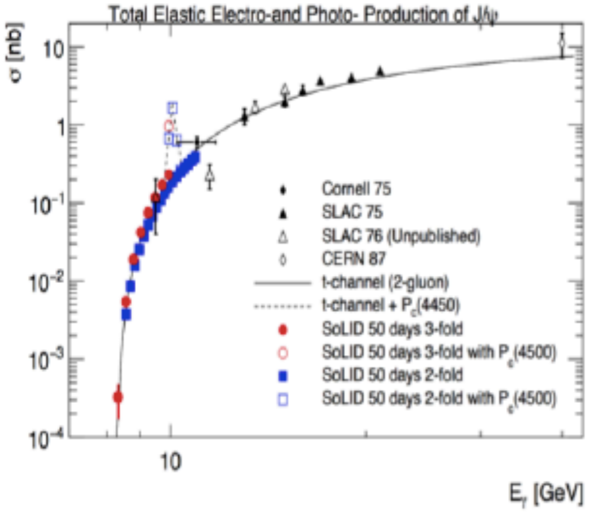
- **Full exploitation of JLab 12 GeV Upgrade to maximize scientific return**

A Large Acceptance Detector AND Can Handle High Luminosity (10^{37}-10^{39})

- SIDIS - reaching ultimate precision for tomography of the nucleon (E12-10-006, E12-11-007, E12-11-108)
- PVDIS in high-x region - providing sensitivity to new physics at 10-20 TeV (E12-10-007)
- Threshold J/ψ - probing strong color fields in the nucleon and the origin of its mass (trace anomaly) (E12-12-006)







- **2015 LRP recommendation IV**

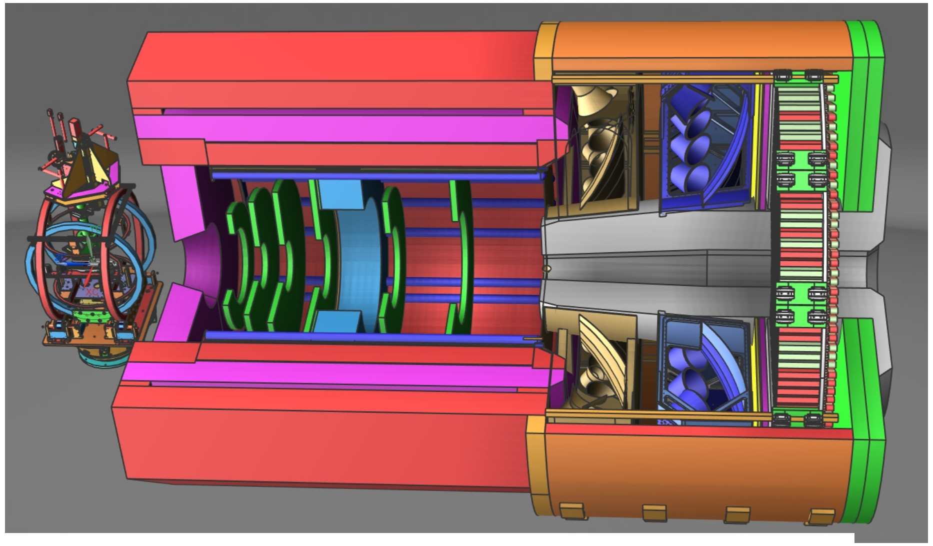
- We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories – **SoLID – mid-scale project**

SoLID Apparatus

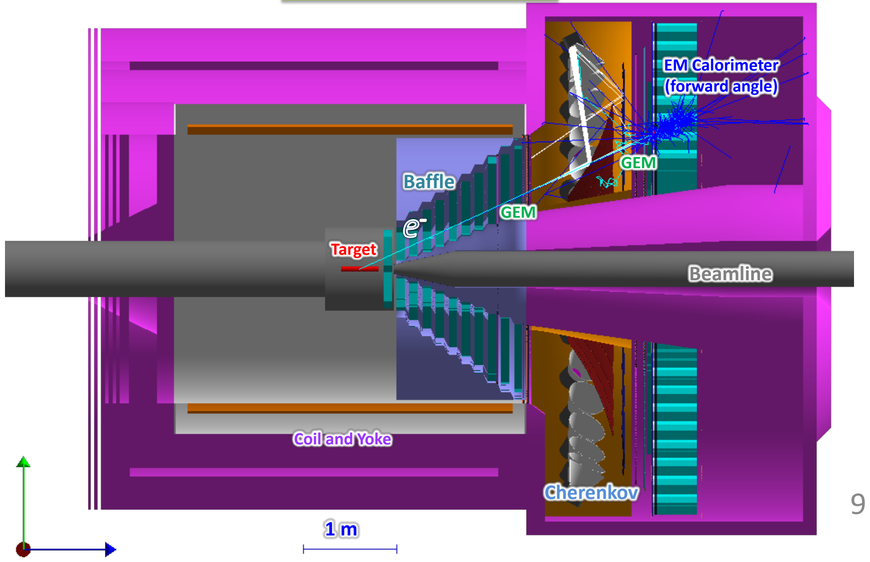
Requirements are Challenging

- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale (Like RHIC)
- New Technologies
  - GEM's
  - Shashlyk Ecal
  - Pipeline DAQ

Polarized ^{3}He (``neutron”) @ SoLID

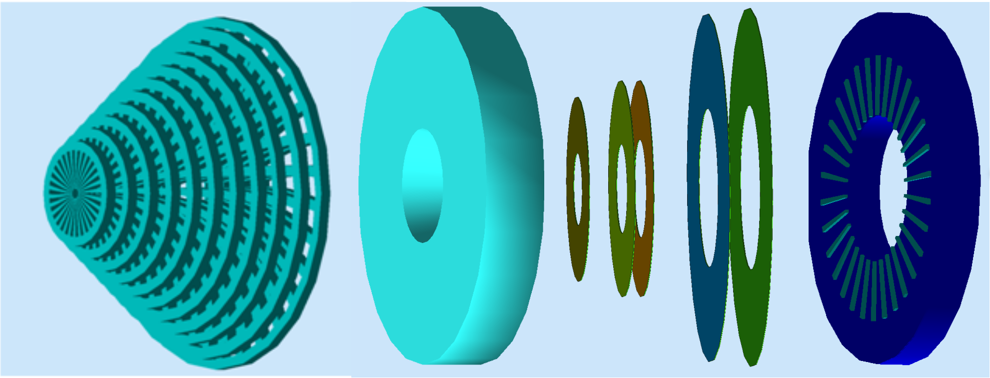


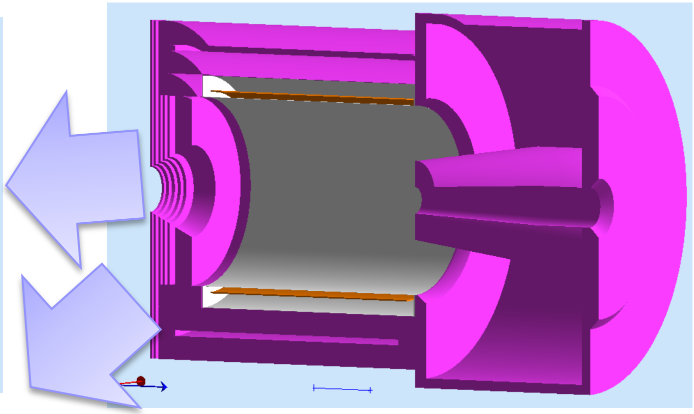
SoLID (PVDIS)



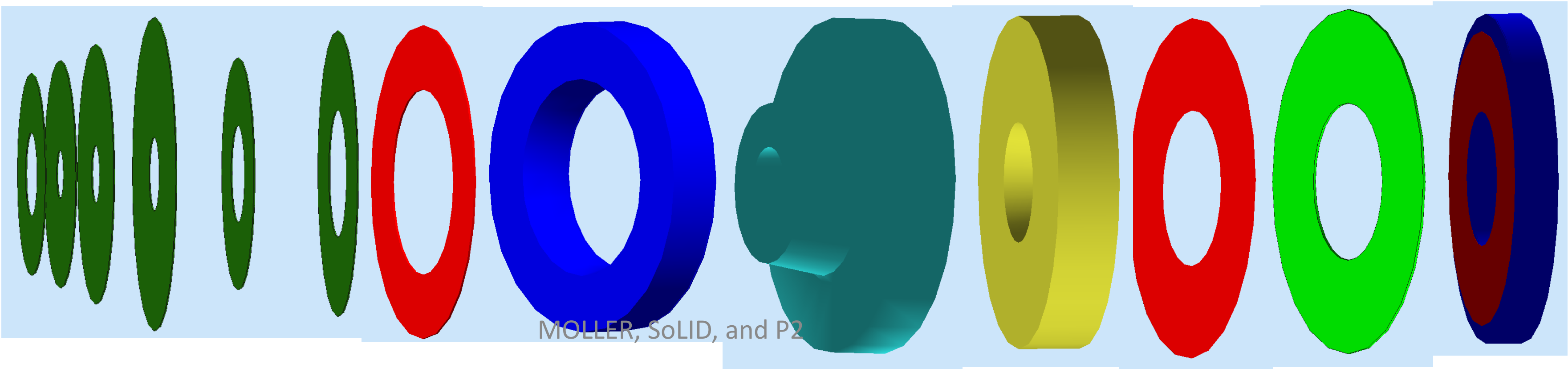
Components of the SoLID Spectrometer

PVDIS: Baffle LGC 5xGEMs EC



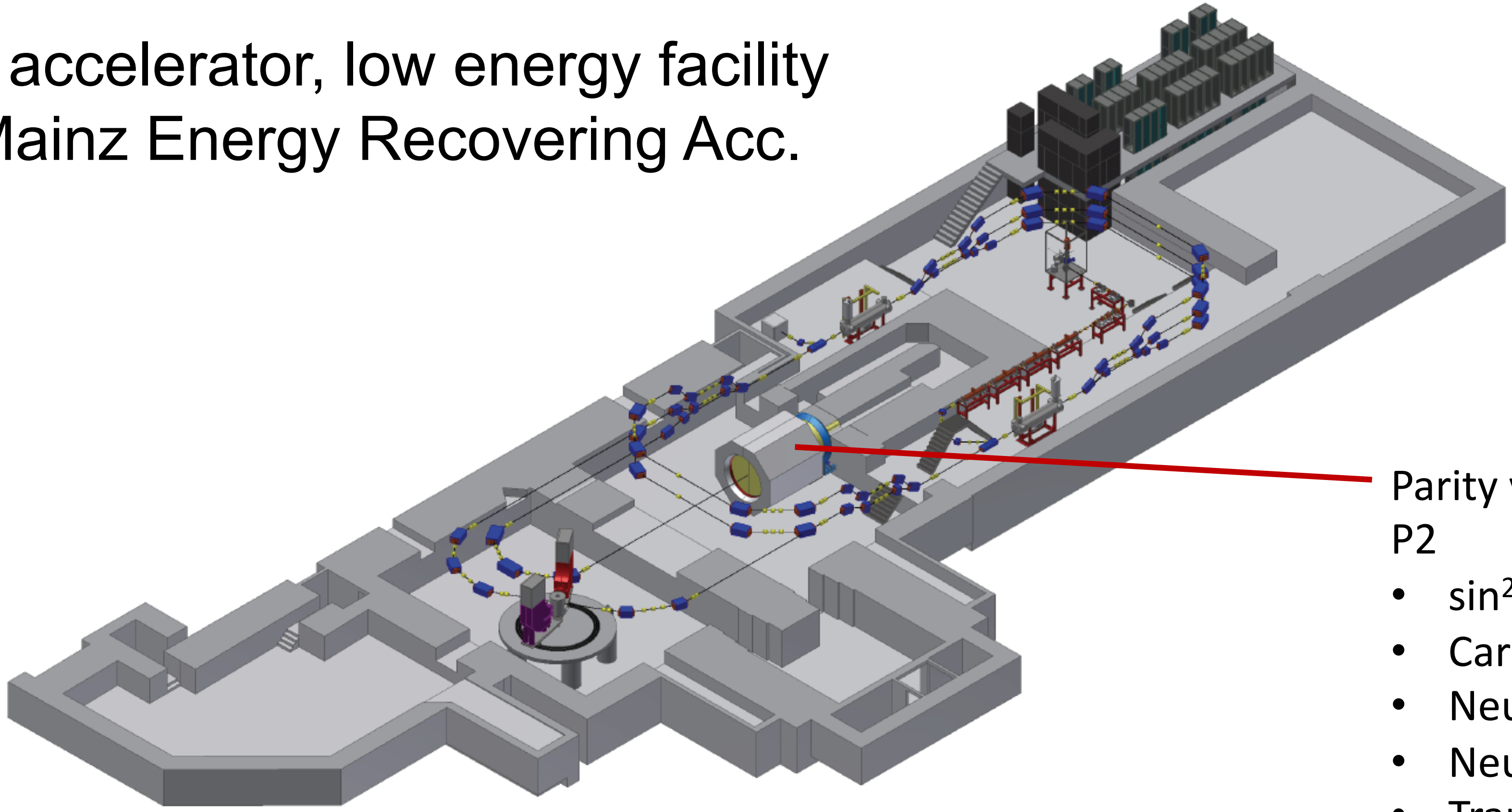


SIDIS&J/Psi:
6xGEMs LASPD LAEC LGC HGC FASPD MRPC FAEC



MESA: New Accelerator at Mainz

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

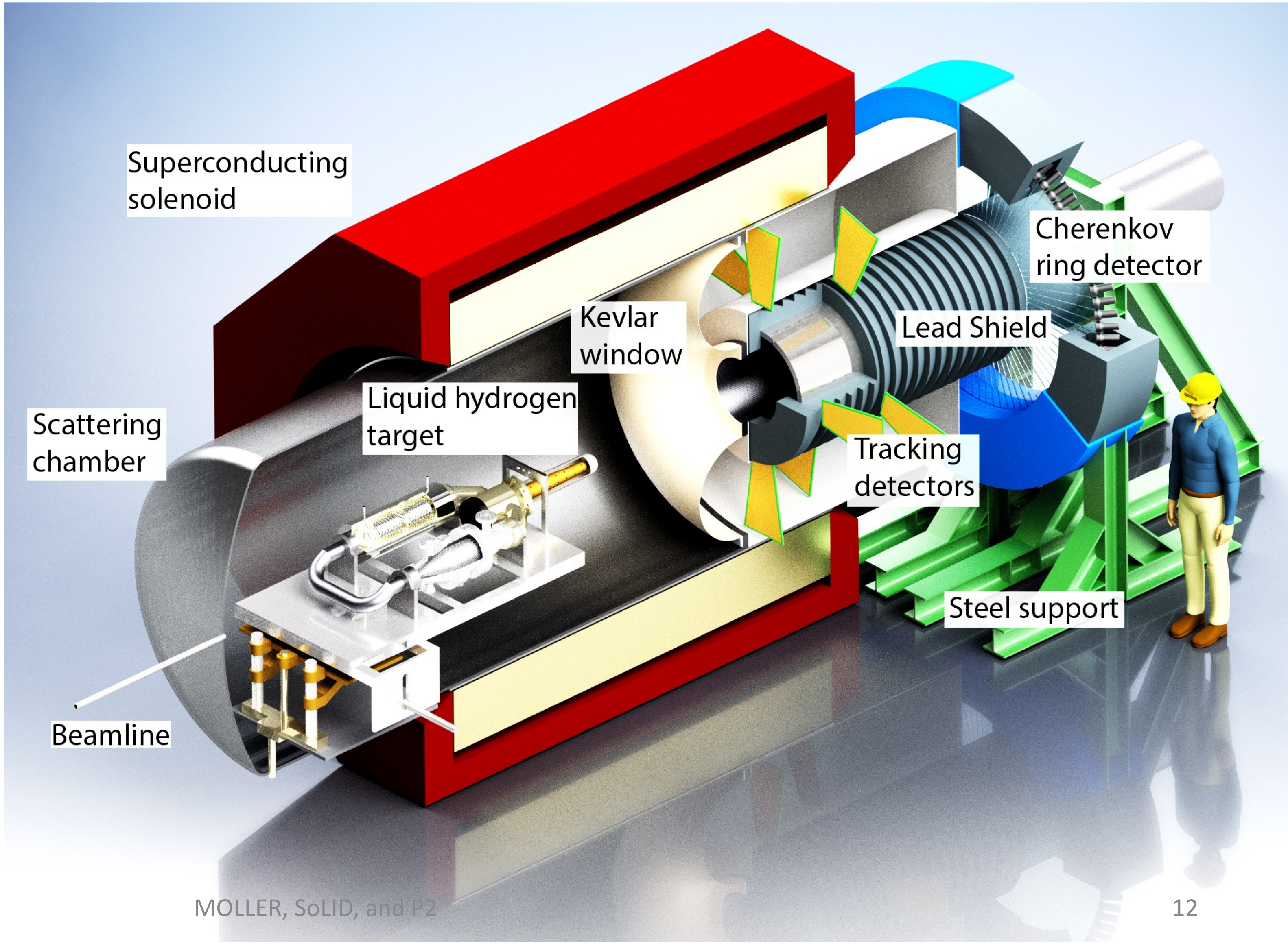


Parity violation experiment P2

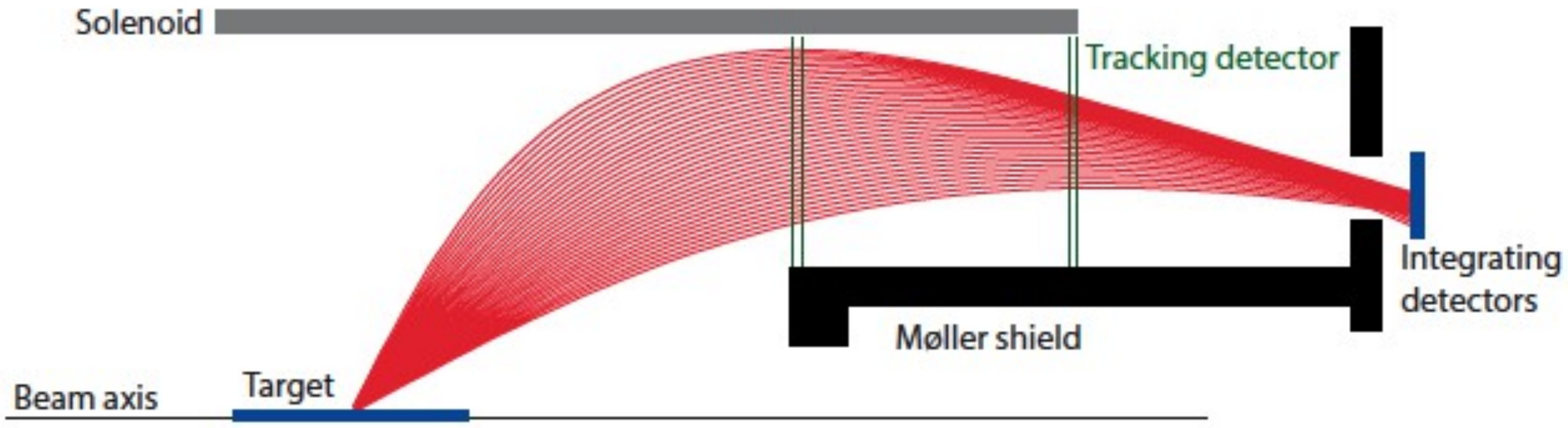
- $\sin^2\theta_W$
- Carbon 12
- Neutron Skin ^{48}Ca
- Neutron Skin ^{208}Pb
- Transverse Beam Spin
- Hadronic Parity Violation

The P2 Spectrometer

Designed to detect elastic eP scattering

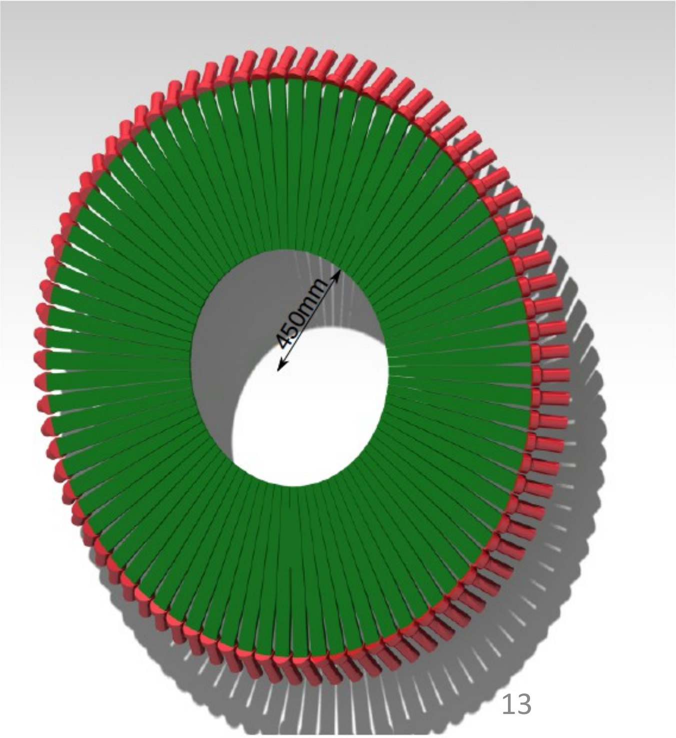


How the P2 Spectrometer Isolates Elastic Events

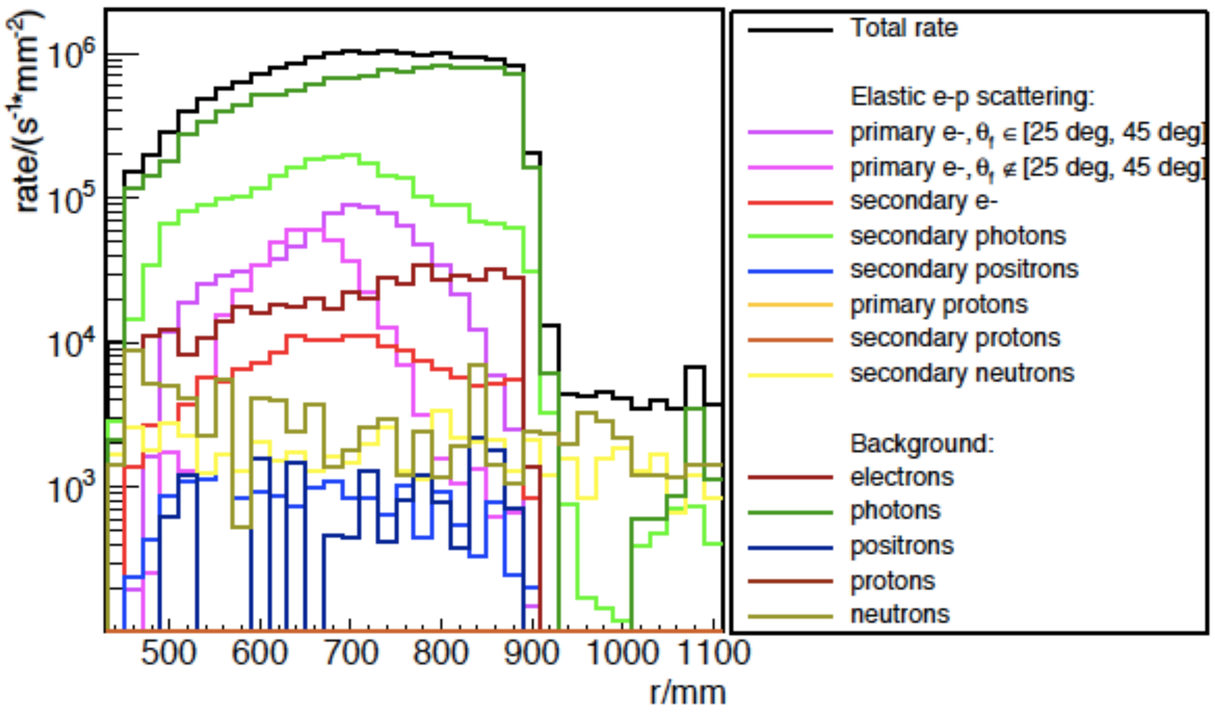


Use solenoid to focus elastic events

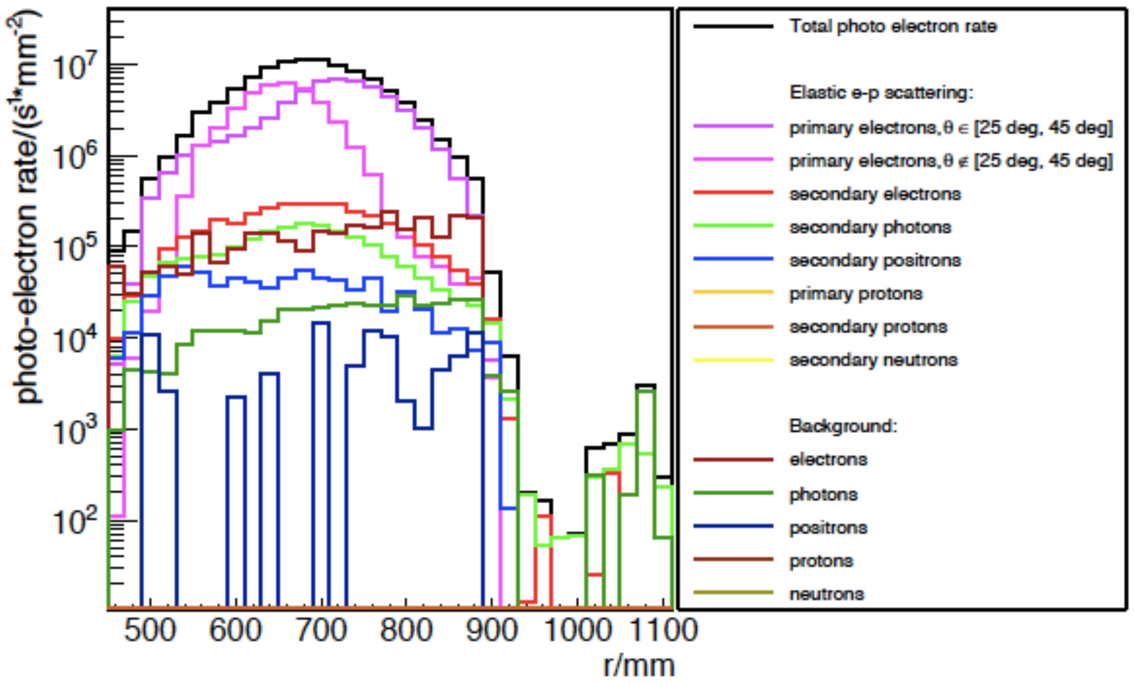
Detect events with quartz bars, which are insensitive to most backgrounds



Background Rejection for P2



Flux of all particles



Sources of PMT current

Moller, SoLID and P2 Schedules

MOLLER

- Approved by Jlab PAC: 2009
- DOE Science Review: 2014
- CD-0 Achieved: 2016
- Directors Cost and schedule review: 2020
- Jim Fast joined Jefferson Lab to lead MOLLER Project
- Preparing for DOE-OPA CD-1 Review: Sept. 2020
- Design and Prototyping: 2021-2022
- Construction: 2023-2025
- First data: 2025

SoLID

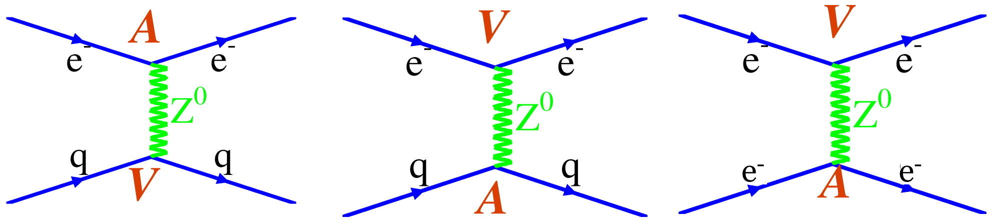
- 5 experiments approved by Jlab PAC: 2010
- Director's Review: 2015
- Directors Cost and schedule review: 2019
- Pre-R&D plan funded: 2020
- SoLID MIE submitted to DOE: 2020
- DOE Science Review, March 8-10, 2021
- CD-0 proposed: 2021
- CD-1 proposed: 2022
- CD-4 (end of construction, commissioning) proposed: 2028

P2

- Delivery of Magnet: Dec. 2021
- Funding for detectors and refrigerator: July: 2020
- Start P2 installation: Dec. 2021
- Start P2 and accelerator commissioning: Dec. 2022
- Start data-taking: July 2023

Most important step for SoLID

PVES Phenomenology

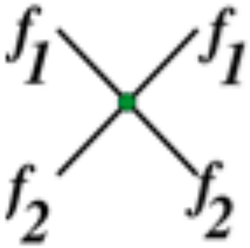


$C_{1i} \equiv 2g_A^e g_V^i$ $\quad C_{2i} \equiv 2g_V^e g_A^i$ $\quad C_{ee} = 2g_V^e g_A^e$

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d)$$
$$+\bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$
$$+C_{ee}(e\gamma^\mu\gamma_5 e\bar{e}\gamma_\mu e)$$

$$\begin{aligned} C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W \approx -0.19 \\ C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W \approx 0.35 \\ C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W \approx -0.04 \\ C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W \approx 0.04 \\ C_{ee} &= \frac{1}{2}-2\sin^2\theta_W \approx 0.02 \end{aligned}$$

+ new physics



$$\mathcal{L}_{eff}^{BSM} = \frac{g^2}{\Lambda^2}\sum_{i,j=L,R}\eta_{ij}^{eff}\bar{e}_i\gamma_\mu e_i\bar{q}_j\gamma^\mu q_j$$
$$= g^2\sum_{i,j=L,R}\left(\frac{1}{\Lambda_{ij}^{ef}}\right)^2\bar{e}_i\gamma_\mu e_i\bar{f}_j\gamma^\mu f_j$$

General Analysis: SMEFT

$$\mathcal{L} = \sum_d \sum_{ij} \frac{C_d^{ij}}{\Lambda^{4-d}} \mathcal{O}_d^{ij}$$

Wilson coefficient (ie. coupling constants)

d = dimension of the operator. SM: d=4, Low energy BSM: d=6, LHC: also d=8

$$\mathcal{O}_d^{ij} = \bar{e}_i \gamma_\mu e_i \overline{f}_j \gamma^\mu f_j$$

e = electron spinor

f = quark spinor

$$e_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi_e$$

$$\mathcal{O}_d^{ij} = LL_f,\ LR_f,\ RL_f,\ RR_f$$

LL_f is shorthand

•*Original work by Eichten, et al., was limited to dimension 6. Phys.Rev.Lett.* 50 (1983) 811-814. (>1000 citations)

Seven Dimension-6 Operators for eN Physics

Warsaw Basis

$$C_{lq}^{(3)}:\ \frac{1}{2}(LL_u - LL_d);\quad C_{lq} = C_{lq}^{(1)}:\ \frac{1}{2}(LL_u + LL_d)$$

$$C_{lu}:\ LR_u;\quad C_{ld}:\ LR_d;\quad C_{eu}:\ RR_u;$$

$$C_{ed}:\ RR_d;\quad C_{eq}:\ RL_u + RL_d$$

•*Boughezal et al., Phys.Rev.D* 101 (2020) 11, 116002 (for EIC)

61 d=6; 993 d=8 independent couplings

$$g_{AV}^{eu} = \frac{1}{2}[C_{lq}^{(3)} - C_{lq} - C_{eu} + C_{eq} + C_{eu}]$$

•S. Alte et al.,e-Print: [2003.11615](https://arxiv.org/abs/2003.11615) [hep-ph]

C_{2u}= $g_{VA}^{eu} = \frac{1}{2}[C_{lq}^{(3)} - C_{lq} + C_{eu} - C_{eq} + C_{eu}]$

Relate Low Energy PVES to LHC Drell-Yan

$$\mathcal{A} = (\mathcal{A}_{SM} + \frac{\mathcal{A}_6}{\Lambda^2} + \frac{\mathcal{A}_8}{\Lambda^4} \ldots)$$

First discussed at 2018 MITP workshop

$$\text{For PVES}: \quad A_{PV} \sim \mathcal{A}_{EM} \times \mathcal{A}$$

- Alioli et al., e-Print: 2003.11615 [hep-ph]

$$\text{For Drell-Yan}: \quad \sigma_{BSM} \sim (\mathcal{A}_6)^2 + \mathcal{A}_{SM} \times \mathcal{A}_8$$

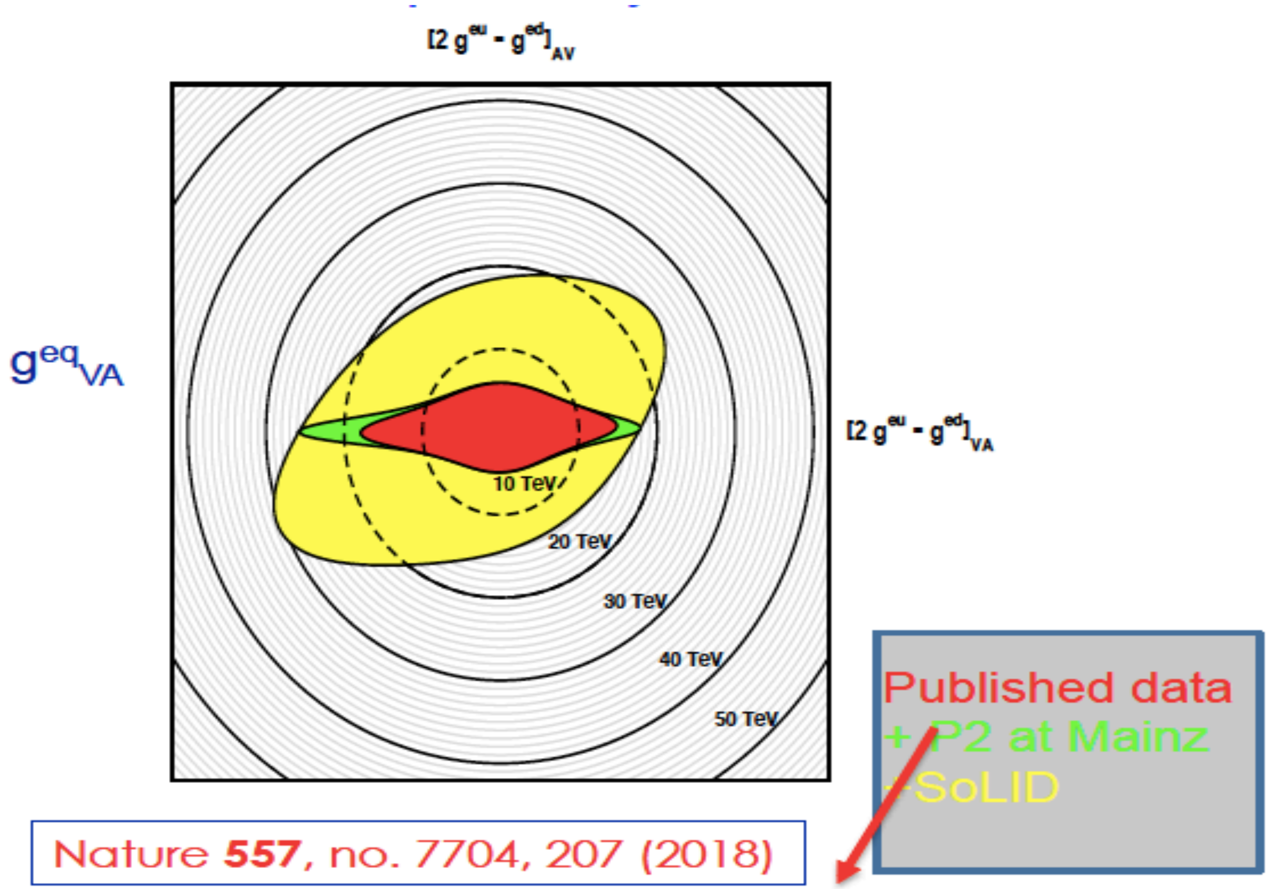
PVES (interference effect) is only sensitive to d=6: $1/\Lambda^2$. LHC (large s) is dominated by $1/\Lambda^4$ term. The $(A_6)^2$ term is the sum of the squares of all the C_{iq} and thus could bound each of the C_{iq}.

Thanks to Vincenzo Cirigliano

However, if one of the dimension-8 operators has a kinematic factor of s, then the A_6^2 and A_8 terms for the LHC data cannot be untangled and there is no bound on C_{iq}.

Λ Plots for P2 and SoLID

P2 and PVDIS have a high-energy reach at the same scale as the LHC, but isolate dimension-6 operators



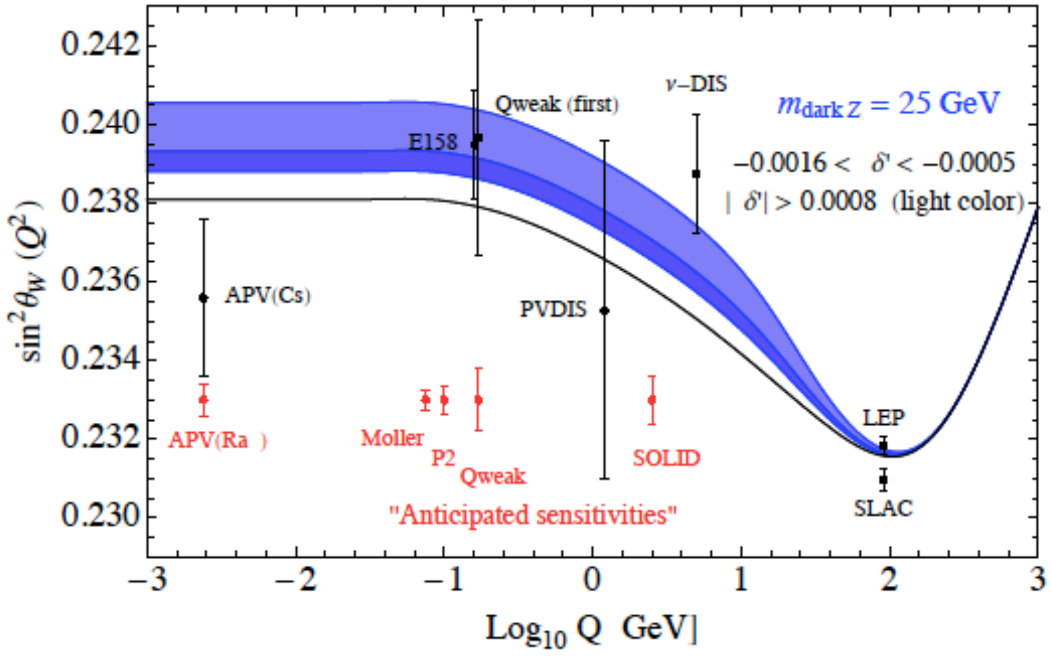
Nature **557**, no. 7704, 207 (2018)

Nature **506**, no. 7486, 67 (2014)

Dark Boson Z_d and $\sin^2\theta_W$

Only effect is to change $\sin^2\theta_W$ at low Q^2

- *Davoudiasl, et al. Phys.Rev.D* 92 (2015) 5, 055005



PVES is the only way to see Z_d if decay is dominated by invisible particles

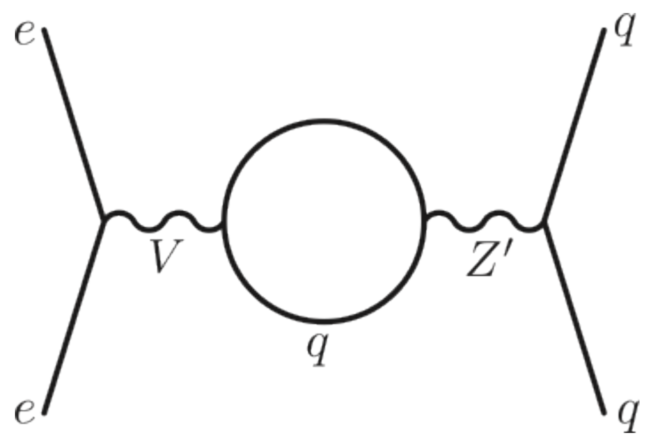
	Precision	$\delta\sin^2\theta_W$	Λ_{new}
APV CS	0.58 %	0.0019	32.3 TeV
E158	14 %	0.0013	17.0 TeV
Qweak	6.3 %	0.0011	26.3 TeV
PVDIS	4.5 %	0.005	7.6 TeV
SoLID	0.6 %	0.0006	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV
ATLAS (2017)			40 TeV

Note poor correlation between $\sin^2\theta_W$ and Λ. This
Is one example of why many experiments are needed.

Leptophobic Z’: 0.1 TEV<M<1 TeV

Phys.Lett. B712 (2012) 261-265

- Contributes to C_{2q}’s
- Z’ decaying primarily to dark matter only accessible to PVDIS, like the Z_d?
- Z-Z’ mixing should be calculated



*Since electron vertex must be vector, the Z’ cannot couple to the C_{1q}’s if there is no electron coupling: can only affect **C_{2q}’s**. Z-Z’ mixing can contribute to the **C_{1q}’s**, but effect is estimated be be small*

Note: $A_Z/A_\gamma \approx Q^2 \; for \; Q^2 \ll MZ$;
: $A_Z/A_\gamma \approx 1 \; for \; Q^2 \gg MZ$

Recent searches at the LHC:
Application of streaming readout

Questions for Theorists for SoLID DOE Review

- What is contribution of Z-Z' mixing for leptophobic Z'?
- Does possibility of leptophobic Z' decays to invisible dark matter particles allow SoLID to evade all collider bounds?
- Is there a dimension-8 operator with the coefficient s?
- What limits are set by low-s LHC data?
- What limits on the C_{iq} are set if A_8 is neglected???

•*Analysis by Boughezal et al., Phys.Rev.D* 101 (2020) 11, 116002 (for EIC) cut on large s LHC data but did not include parity data.

Answers will be featured at the DOE Science review next March.

Summary

- P2 and MOLLER are underway.
- SoLID will be too if it passes the DOE Science Review next March.
- Result: There will be major improvement in precision.
- Will we see BSM physics?