The MOLLER Experiment

Dr. Juliette Mammei

Why parity-violating electron scattering (PVES)?

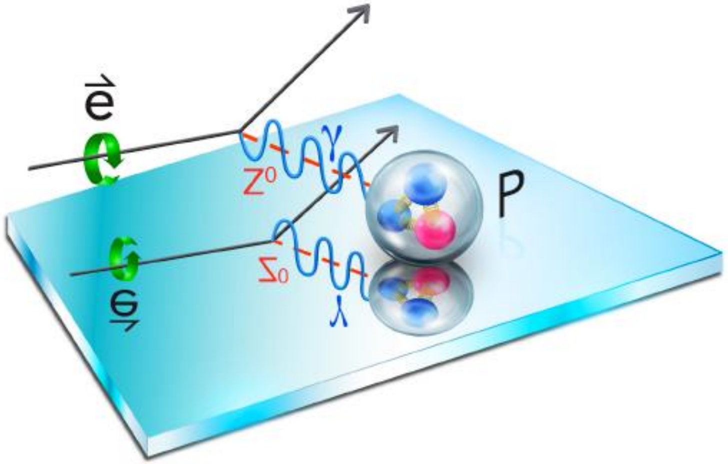
- Search for physics ***Beyond the Standard Model*** (BSM) with low energy ($Q^2 << M^2$) precision tests complementary to high energy measurements

  - ***Neutrino mass and their role in the early universe*** — $0\nu\beta\beta$ *decay*, θ_{13}, β *decay,…*
  - ***Matter-antimatter asymmetry in the present universe*** — *EDM, DM, LFV,* $0\nu\beta\beta$, θ_{13}
  - ***Unseen Forces of the Early Universe*** — *Weak decays,* ***PVES****,* g_μ*-2,…*

- ***LHC new physics signals likely will need additional indirect evidence***

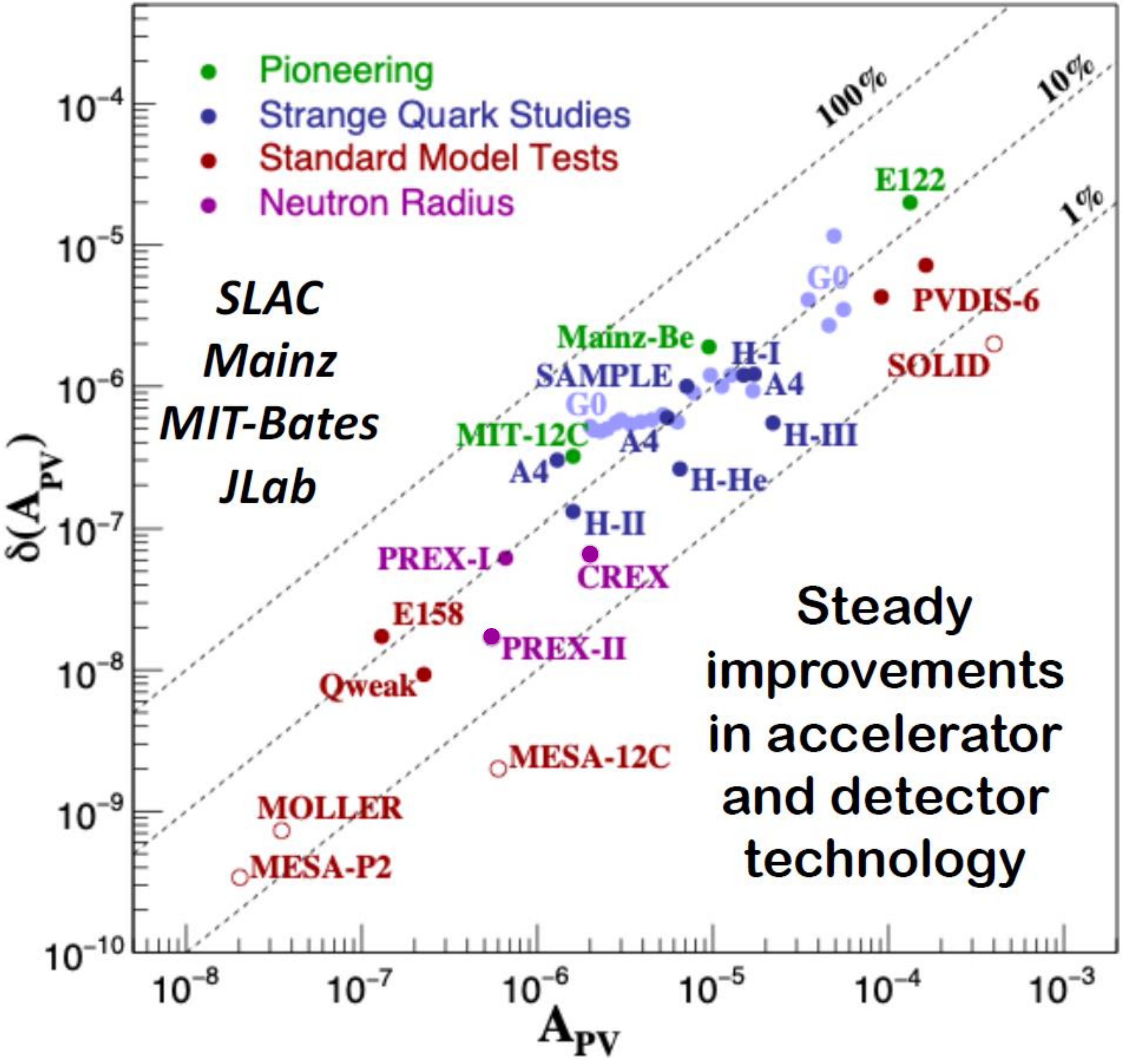
  - ***Neutrons:*** *Lifetime, P- & T-Violating Asymmetries (LANSCE, NIST, SNS...)*
  - ***Muons:*** *Lifetime, Michel parameters, g-2, Mu2e (PSI, TRIUMF, FNAL, J-PARC...)*
  - ***PVES:*** *Low energy weak neutral current couplings, precision weak mixing angle (SLAC, Jefferson Lab, Mainz)*

- Study nuclear and nucleon properties
  - Strange quark content of nucleon
  - Neutron radii of heavy nuclei



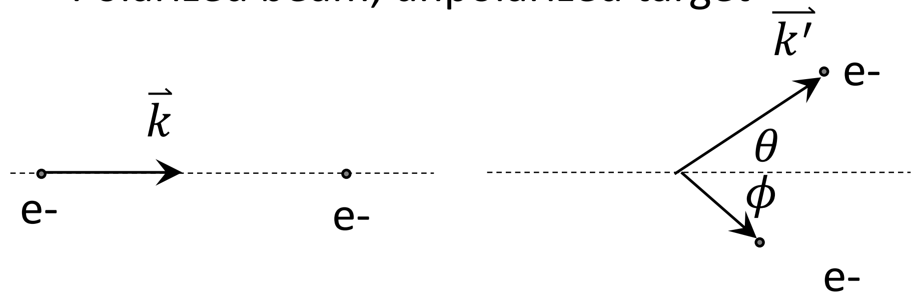
$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

≈ Quantity of interest

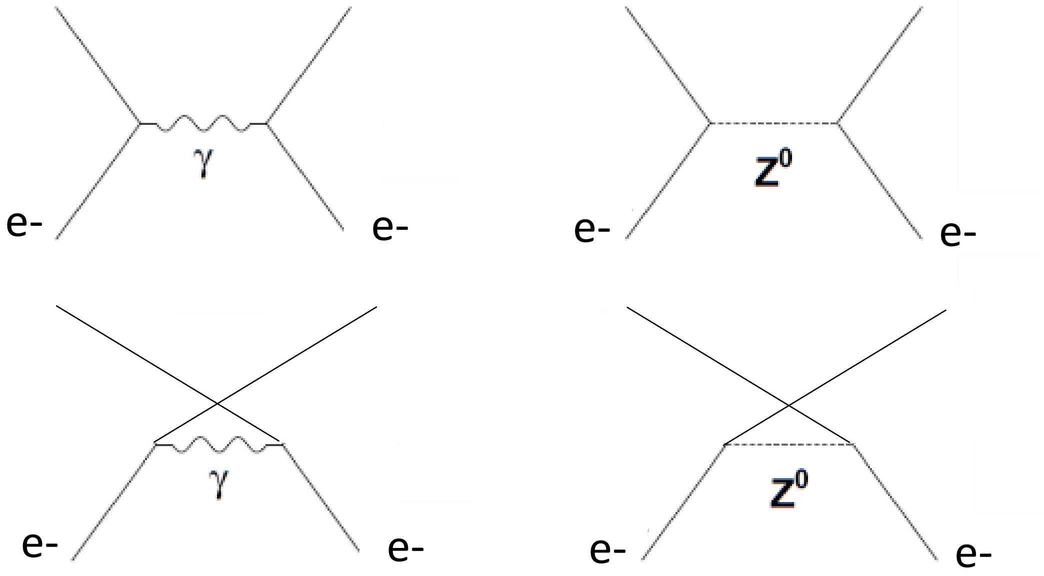


Parity-violating electron scattering

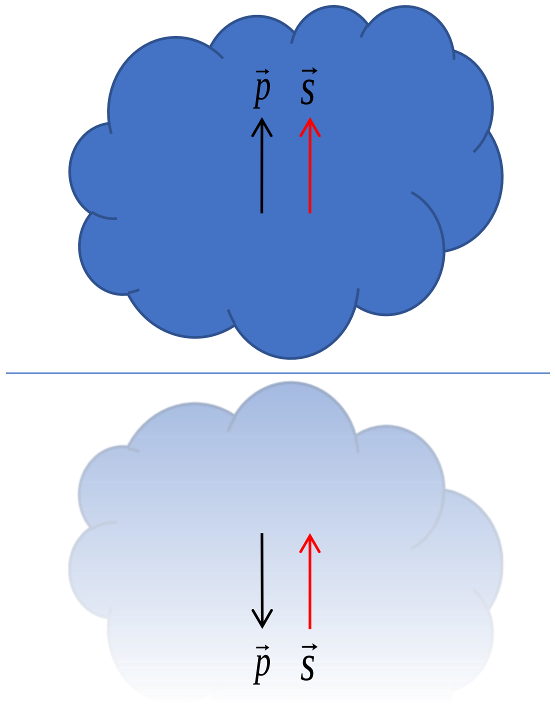
Polarized beam, unpolarized target



Electrons interact via BOTH the E&M and weak forces, and is an example of identical particle scattering ⇒ cross terms

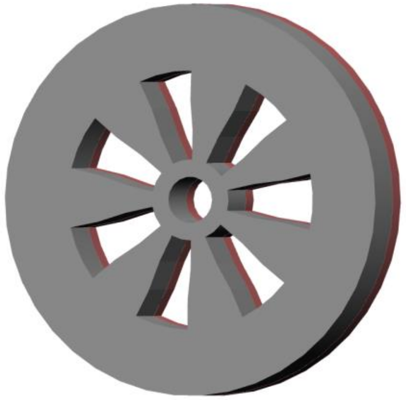


quantum mechanical operator that reverses the spatial sign (P: x -> -x)



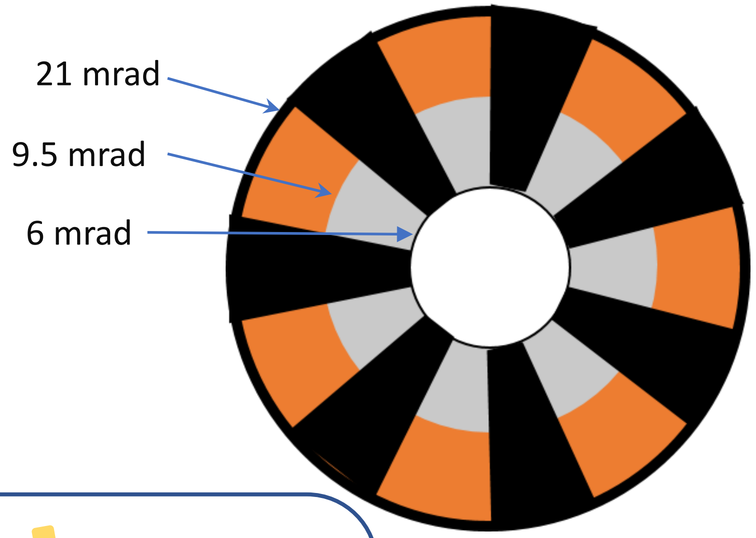
$$h = \frac{\vec{s} \cdot \vec{p}}{|\vec{s} \cdot \vec{p}|}$$

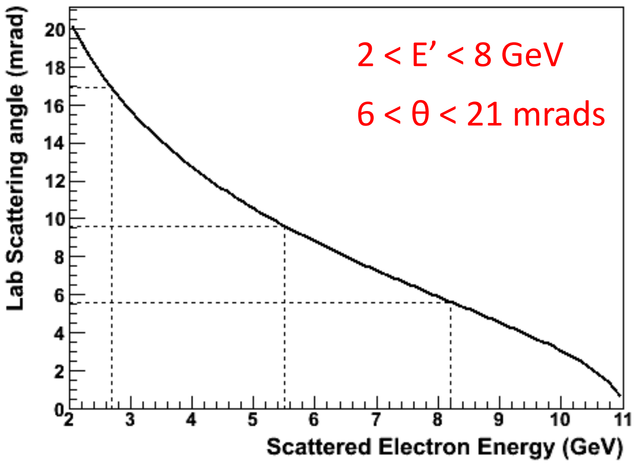
100% Azimuthal acceptance possible



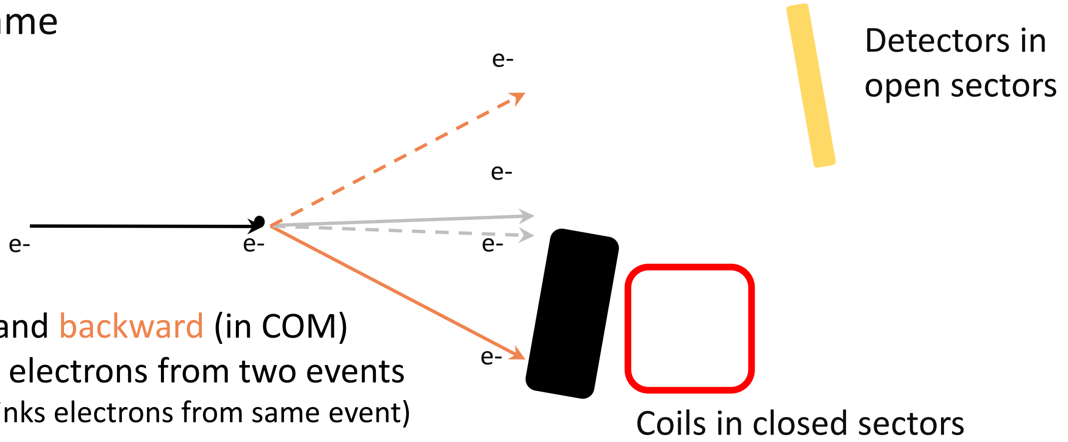
Acceptance defining collimator

- Energy and scattering angle strongly correlated for mollers (eps are all ~11 GeV)
- Maximize azimuthal acceptance
  - identical particle scattering
  - accept COM angles around 90°
- Large energy and angle range to focus



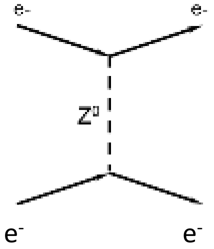


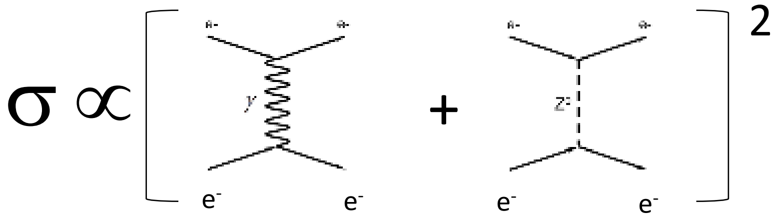
Lab Frame

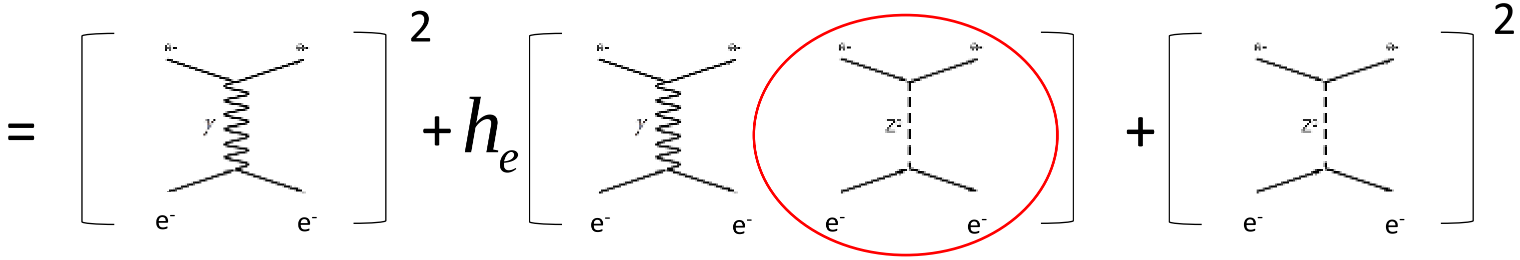


Forward and backward (in COM) scattered electrons from two events (line type links electrons from same event)

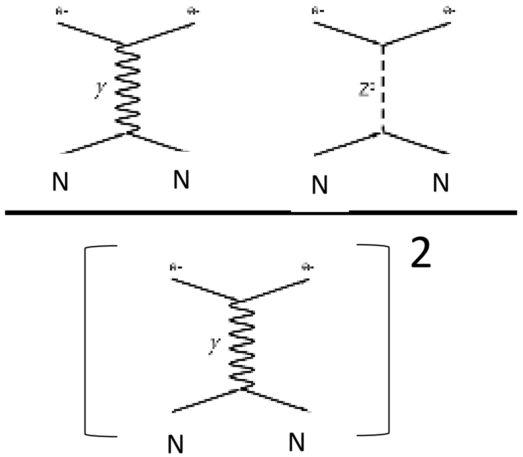
Any odd number of coils will allow for 100% φ acceptance

How does PVES measure  ?





$$A_{PV} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \approx$$



$$= E \frac{G_F}{\sqrt{2}\pi\alpha} \frac{4\sin^2\theta}{(3+cos^2\theta)^2} Q_W^e$$

Measuring the electroweak couplings

The parity-violating (neutral weak) part of the Standard Model Lagrangian is

nucleon target — electron target

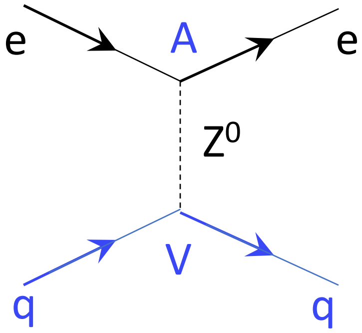
$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^{\mu}\gamma_5 e\left(C_{1u}\bar{u}\gamma_{\mu}u + C_{1d}\bar{d}\gamma_{\mu}d\right) + \bar{e}\gamma^{\mu}e\left(C_{2u}\bar{u}\gamma_{\mu}\gamma_5 u + C_{2d}d\gamma_{\mu}\gamma_5 d\right) + C_{ee}\bar{e}\gamma^{\mu}\gamma_5 e\left(\bar{e}\gamma_{\mu}e\right)\right]$$

EM coupling: $e\gamma^{\mu}$ (not parity violating)

The charged current violates parity maximally: $\frac{g}{2\sqrt{2}}\gamma^{\mu}(1-\gamma^{5})$

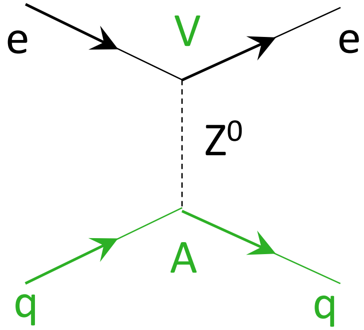
The neutral current coefficients need to be determined:

$$\frac{g}{2cos\theta_W}\left(C_V^f\gamma^{\mu} - C_A^f\gamma^{\mu}\gamma^{5}\right)$$



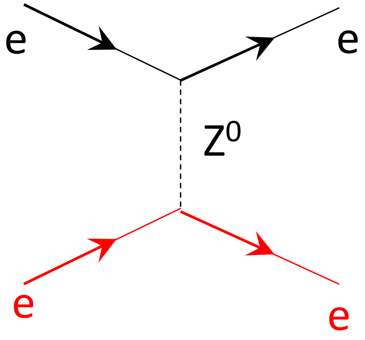
$C_{1q} = 2g_A^e g_V^q$

Small θ



$C_{2q} = 2g_V^e g_A^q$

Large θ

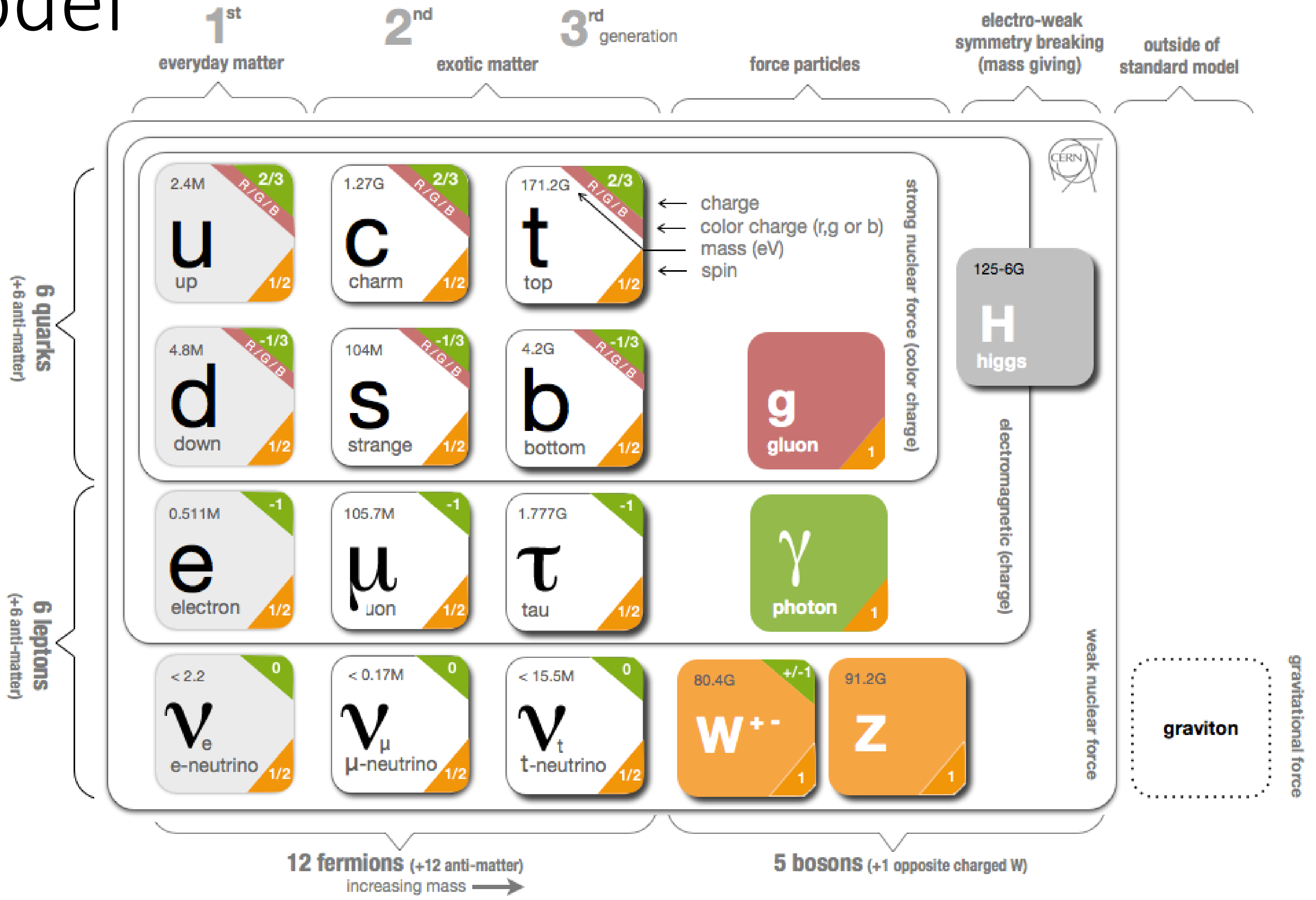


The Standard Model

Summarizes our knowledge of the fundamental particles and the interactions they can undergo

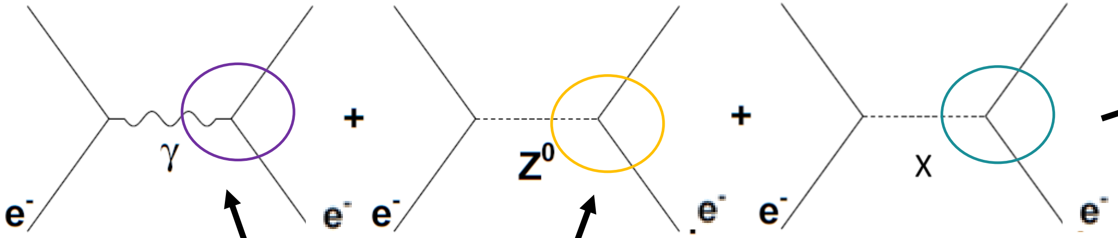
The boxes enclose those particles that interact via a given force through the exchange of the associated boson

Gravity is often mentioned as a fundamental force but is not actually part of the Standard Model



https://webfest.web.cern.ch/content/standard-model-standard-infographic

Testing the Standard Model



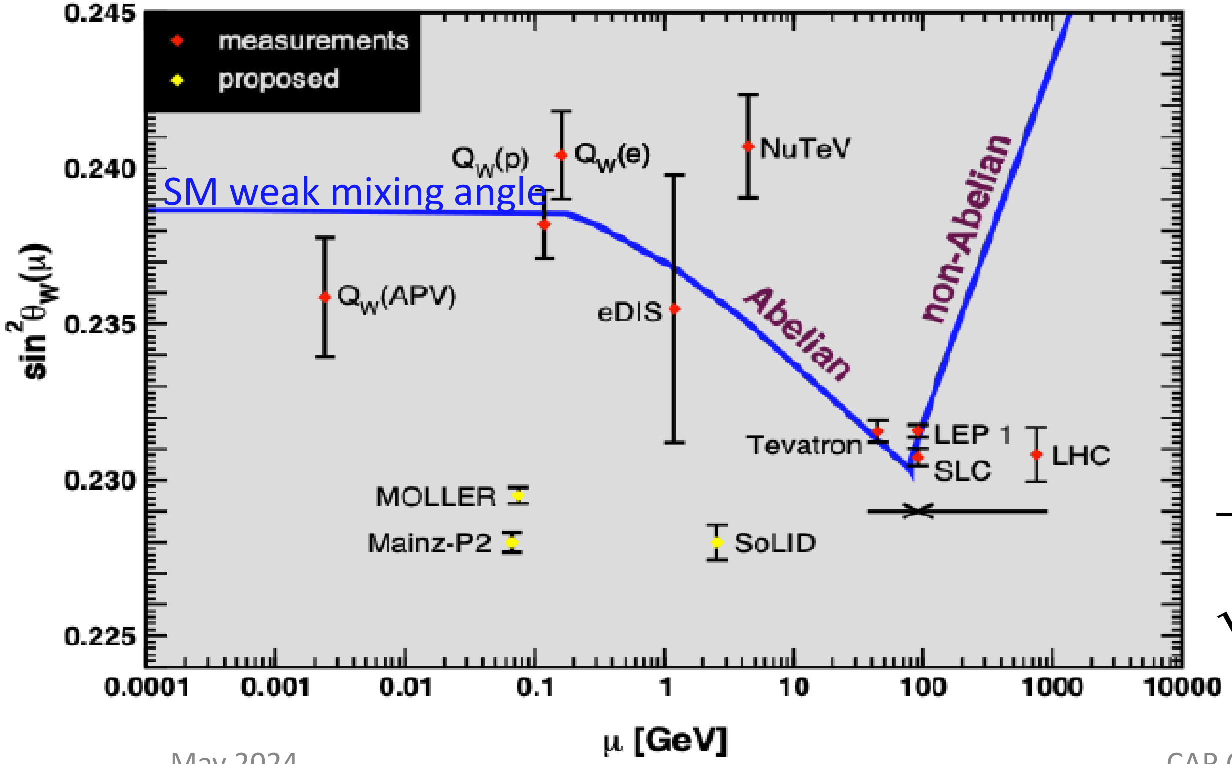
Standard Model processes

Standard Model Test
possible new exchange particle X

$Q^2 \to 0$
measure coupling of new physics to electrons

higher dimensional operators can be systematically classified…

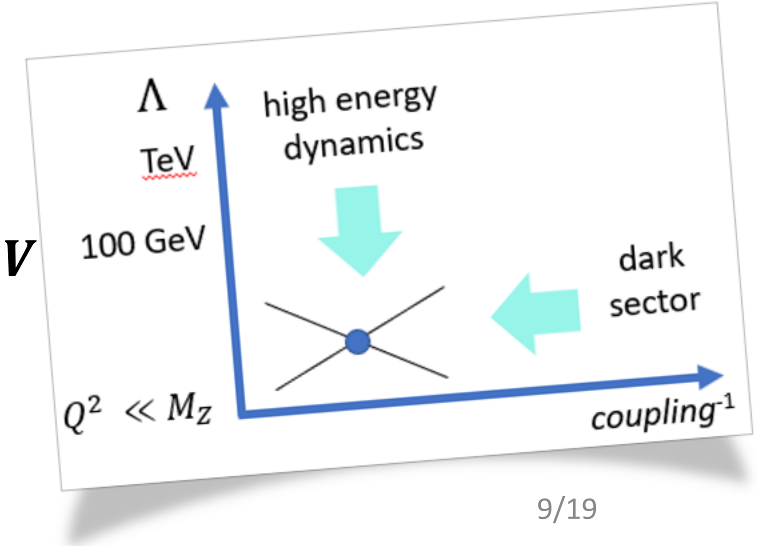
$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$



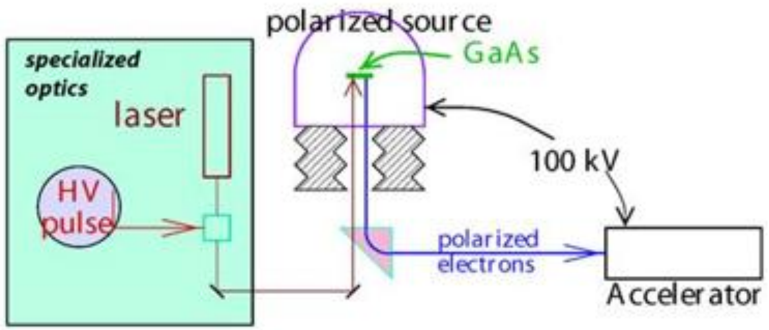
$$\mathcal{L}^{PV}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda_{ij}^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j$$

Parameterize as a 4-fermion contact interaction

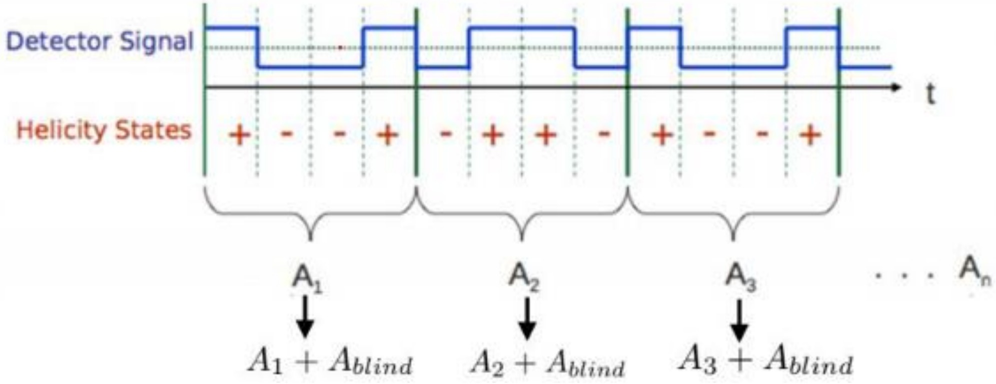
$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \mathbf{7.5\ TeV}$$

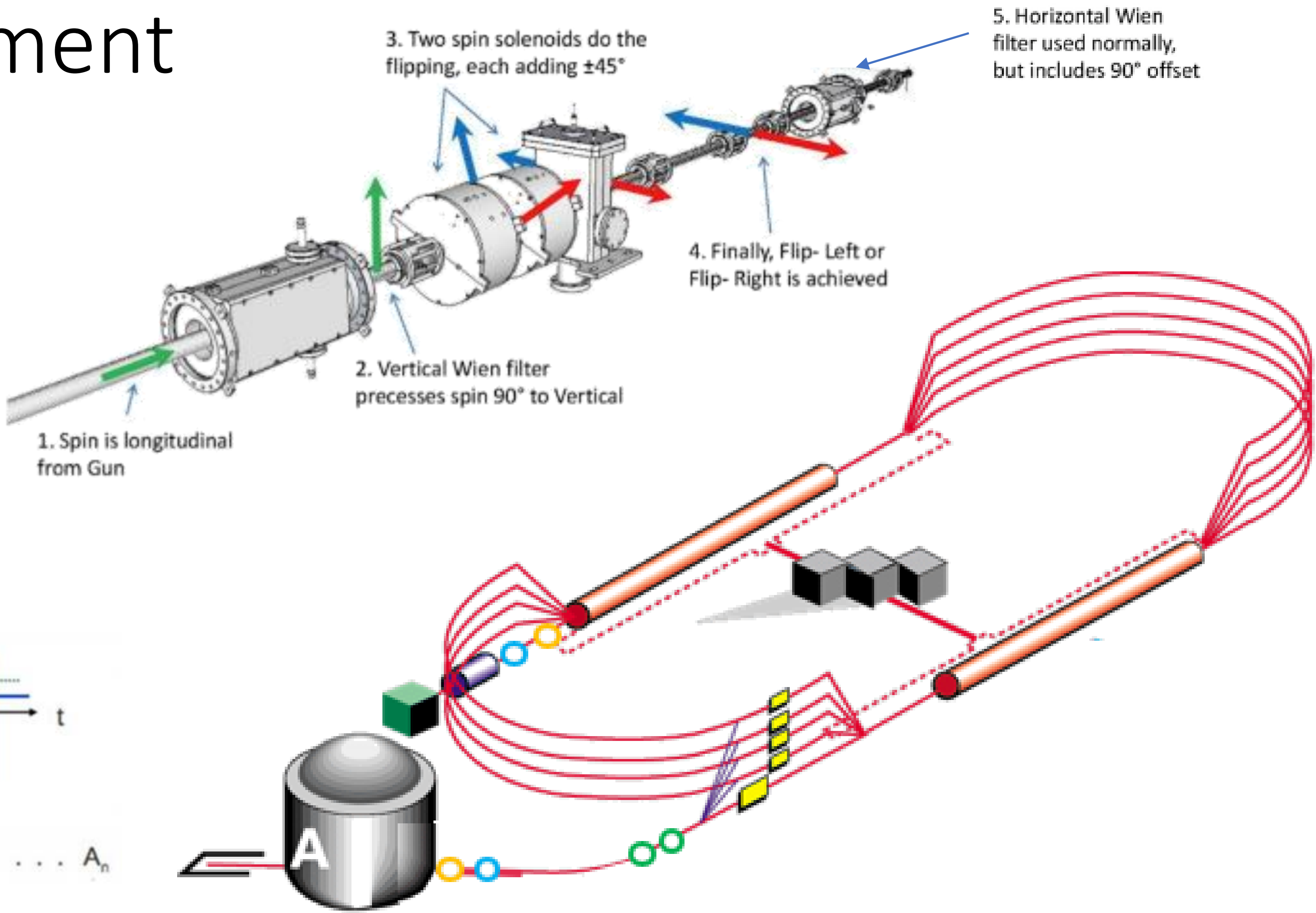


The whole accelerator is part of the experiment

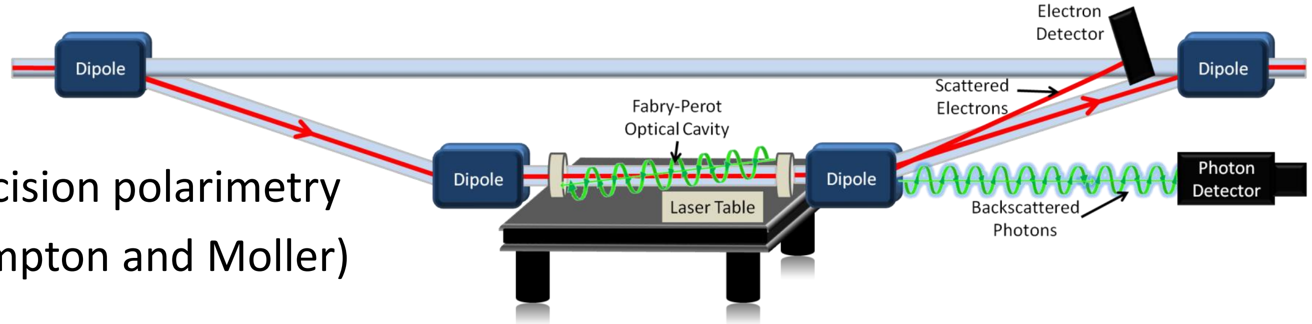


$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$



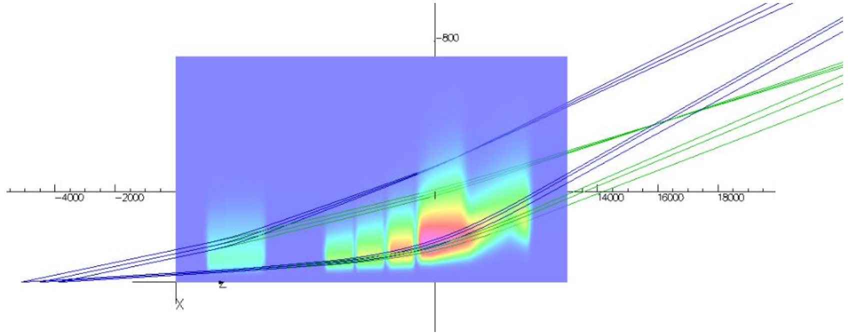


Measuring A_{PV} with ES – "*step by step*"



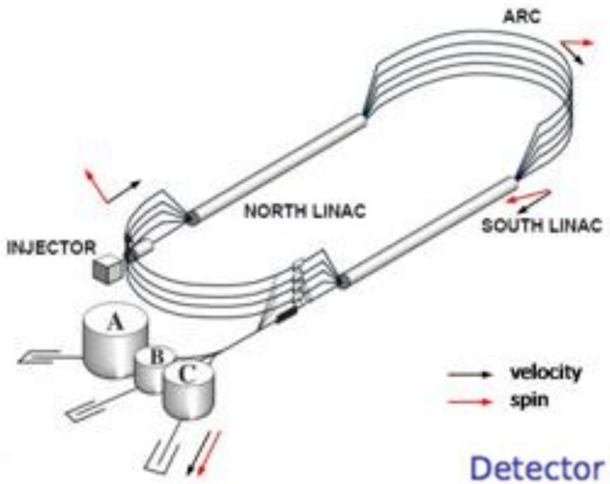
precision polarimetry
(Compton and Moller)

$$A_{PV} = \frac{A_{sig}}{P_{beam}}$$



Spectrometer to kinematically separate scattered electrons

$$A_{sig} = \frac{A_{corr} - A_{back}\ f_{back}}{f_{sig}}$$



beam property monitoring

active feedback to minimize helicity correlations

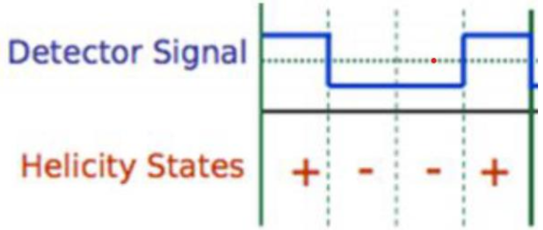
$$A_{corr} = A_{meas} - \sum_{i=1}^{N} \frac{1}{2Y}\left(\frac{\partial Y}{\partial P_i}\right)\Delta P_i$$

where $\Delta P_i = P_+ - P_-$

unpolarized target

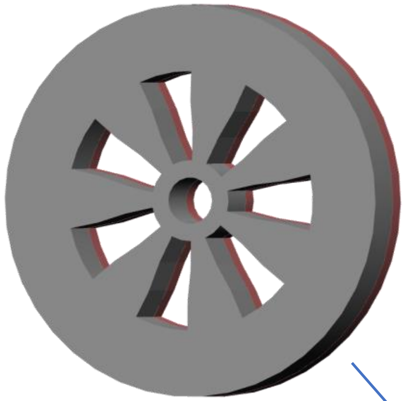
high current, highly polarized beam

both slow and rapid helicity reversals



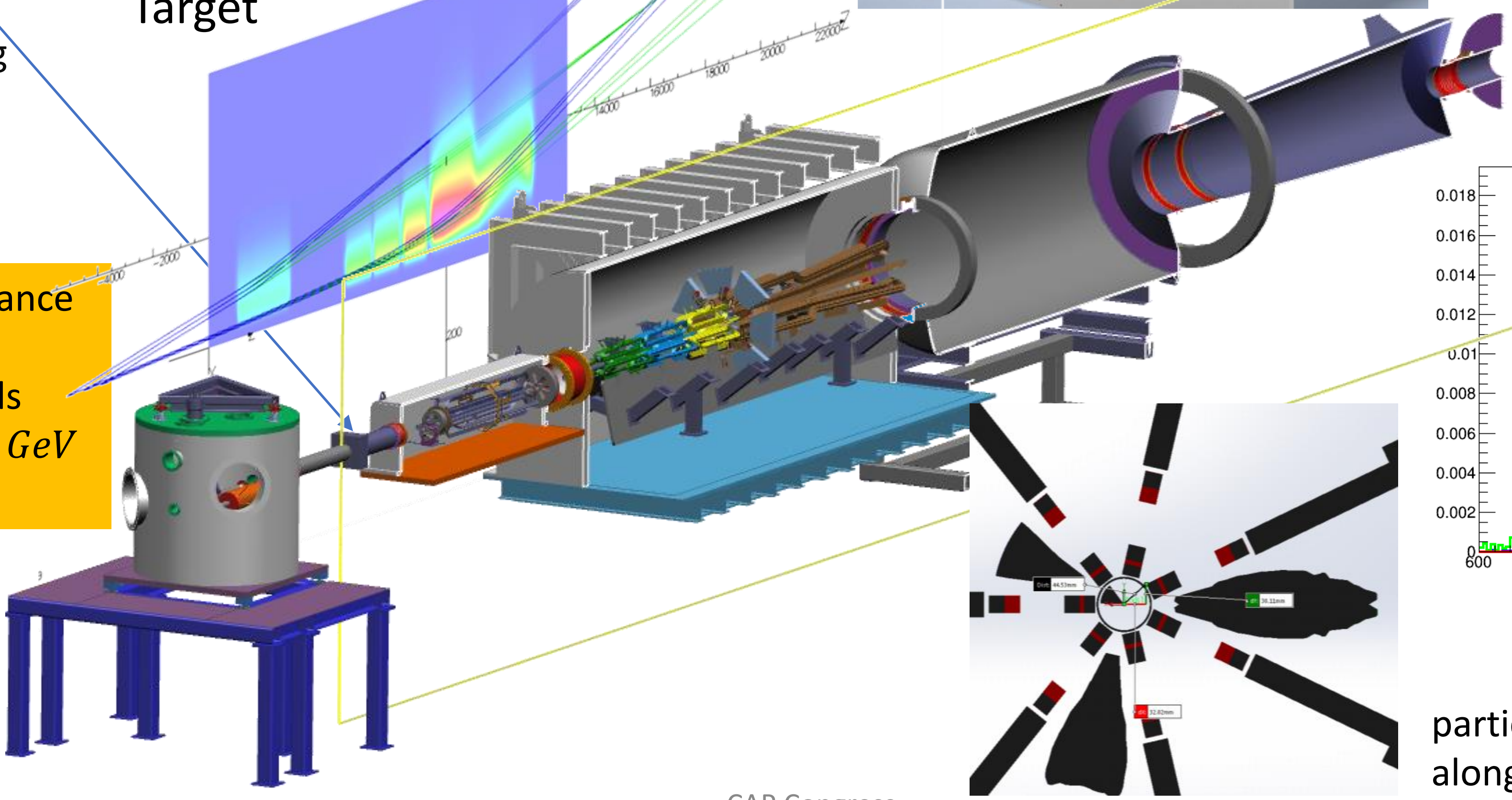
$$A_{meas} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

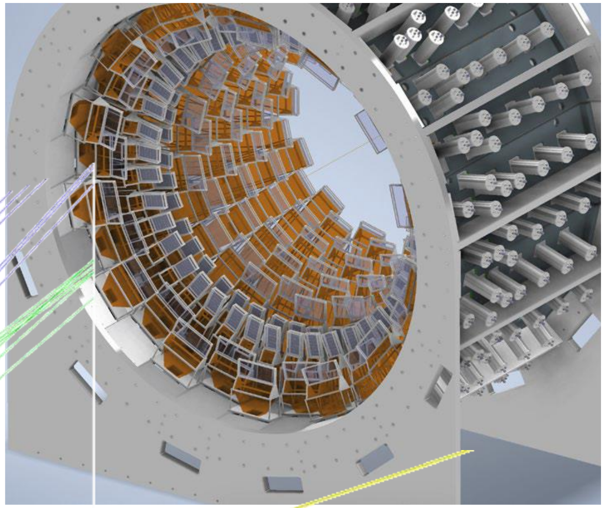
Experimental apparatus



Acceptance defining collimator

Integrating detector array
Tracking detectors
Spectrometer system
Beam monitors
Shielding
Target





$E_{beam} = 11\ GeV$

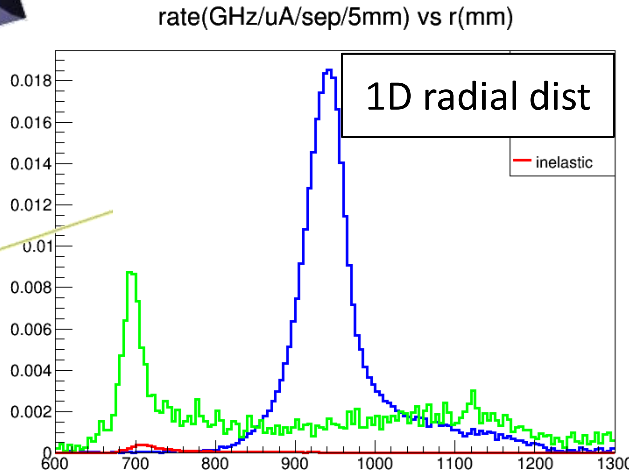
$I_{beam} = 65\ \mu A$

$\mathcal{L} = 3 \times 10^{39}\ cm^{-2} \cdot s^{-1}$

$P_{beam} \geq 90 \pm 0.5\ \%$

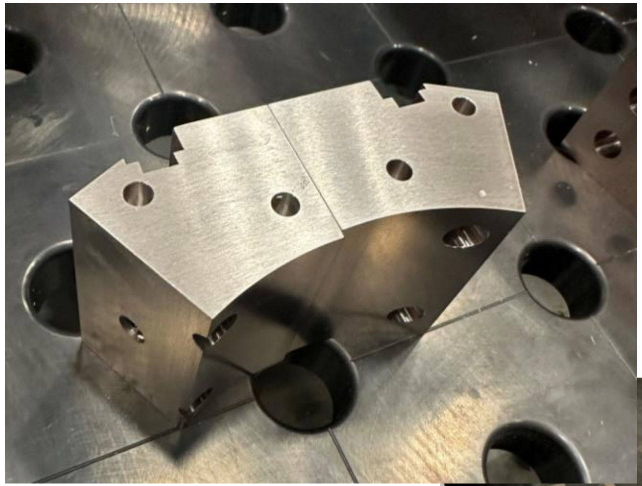
$1.25\ m$ LH_2 target

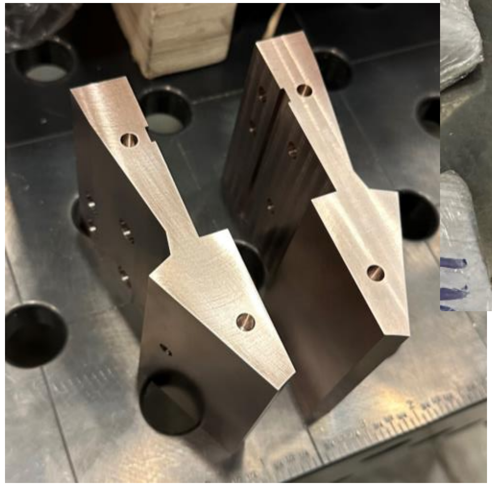
Full azimuthal acceptance for mollers from
$6 < \theta_{lab} < 20$ mrads
$2.75 \leq E_{scat} \leq 8.25\ GeV$

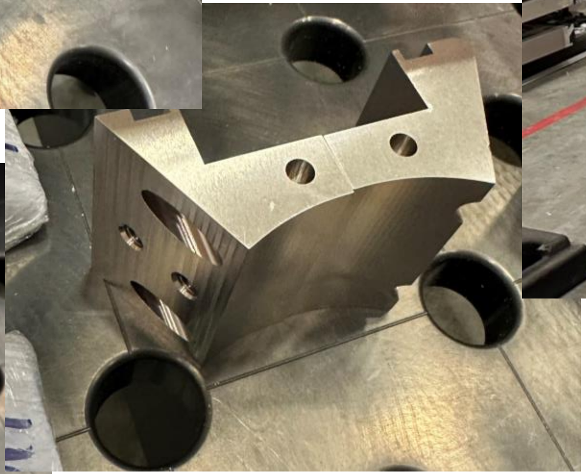


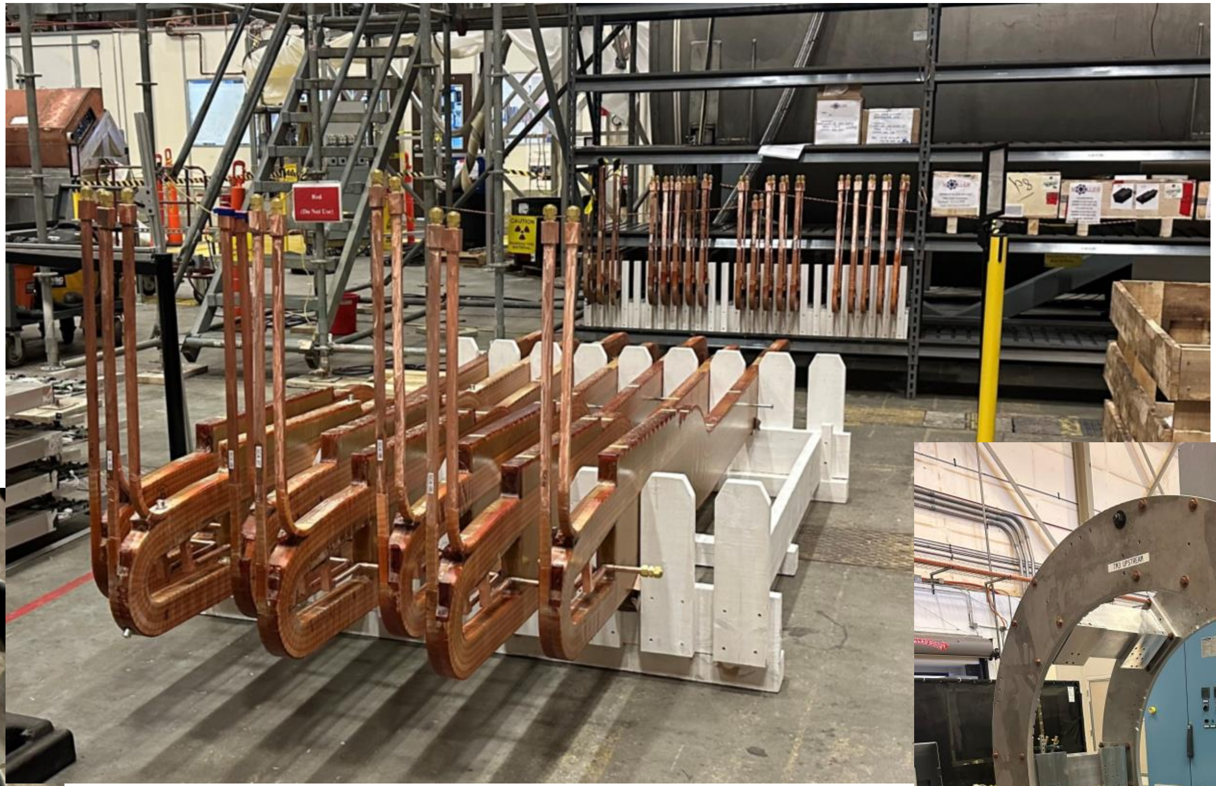
particle envelopes along beamline

Pictures of magnetic spectrometer elements

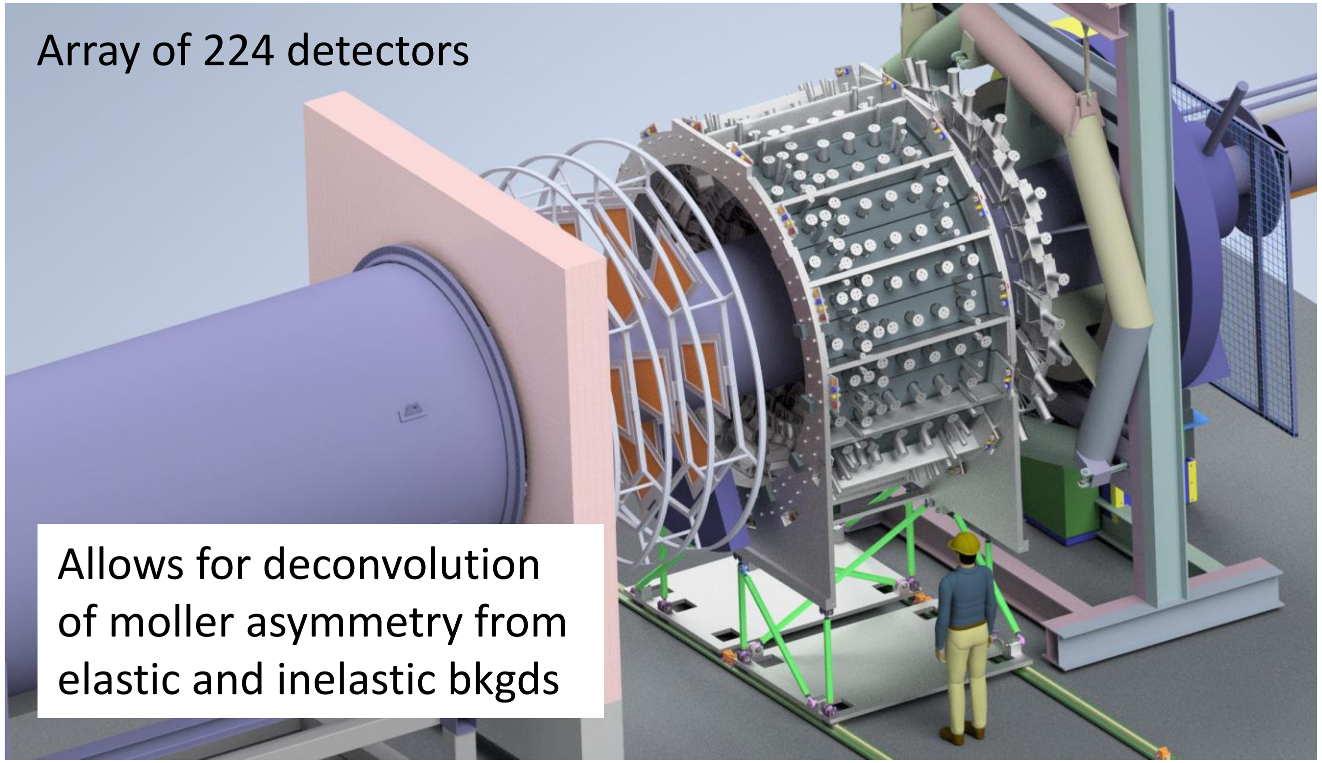


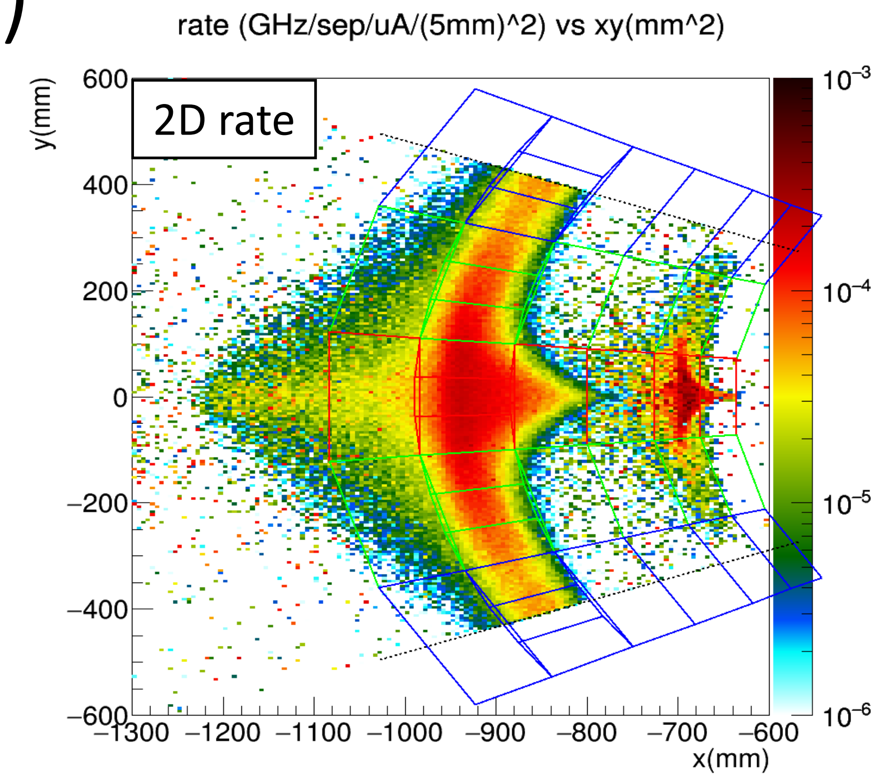


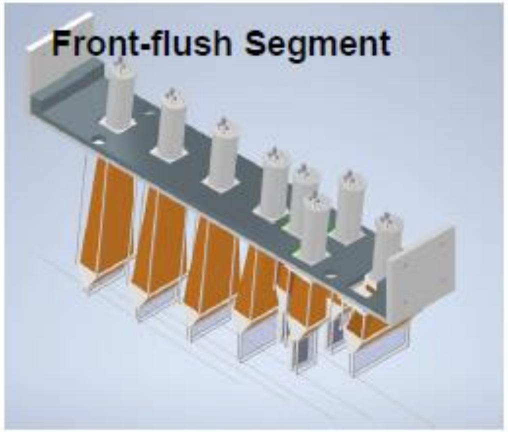


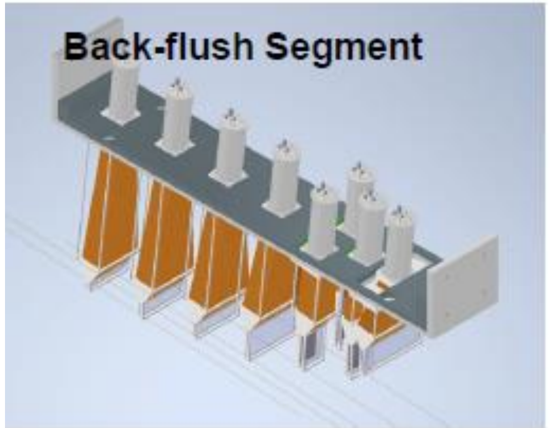


Main detector array (CFI funded)





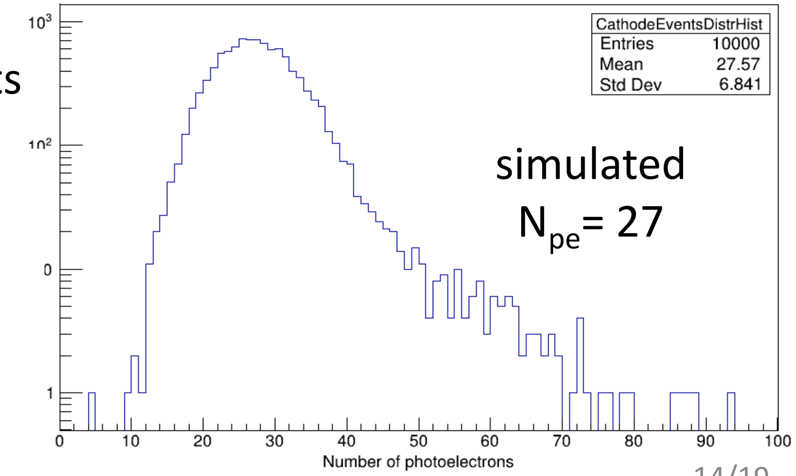




Assembled in segments

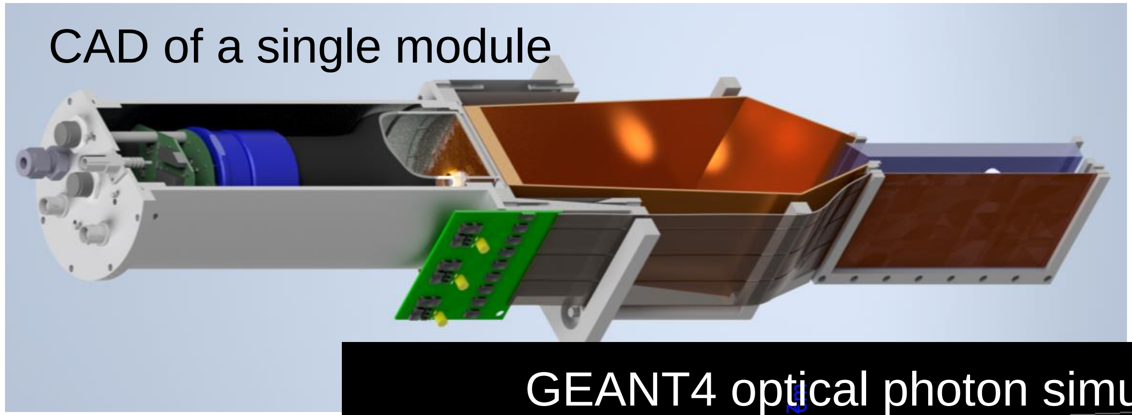
Red – "open"
Blue – closed
Green – transition

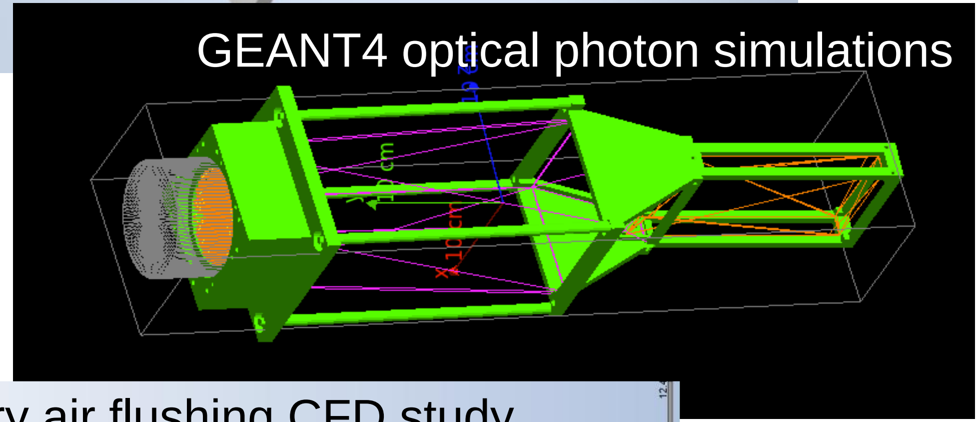
overlap azimuthally

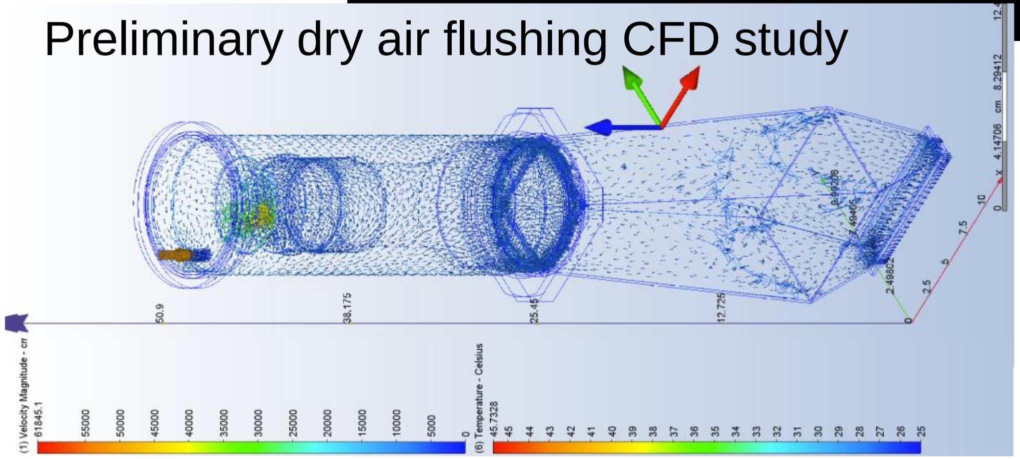


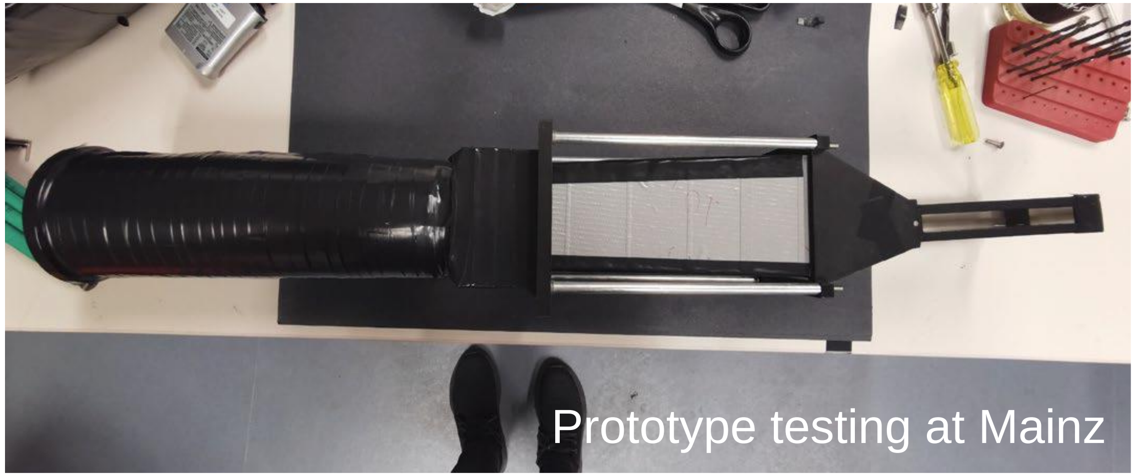
simulated
N_{pe}= 27

Detector prototyping



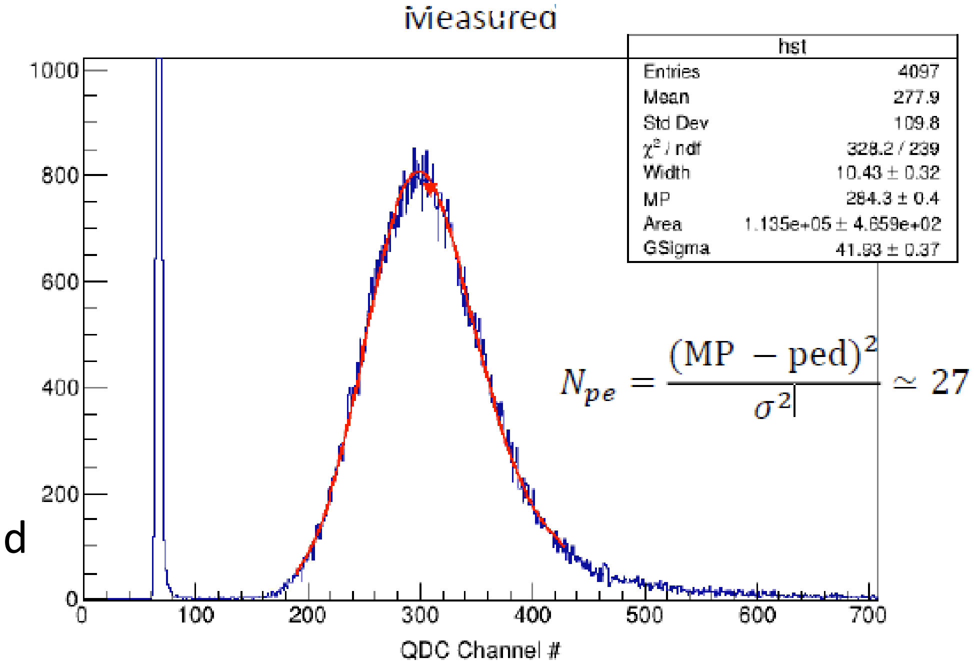






Front-end electronics design is nearly final

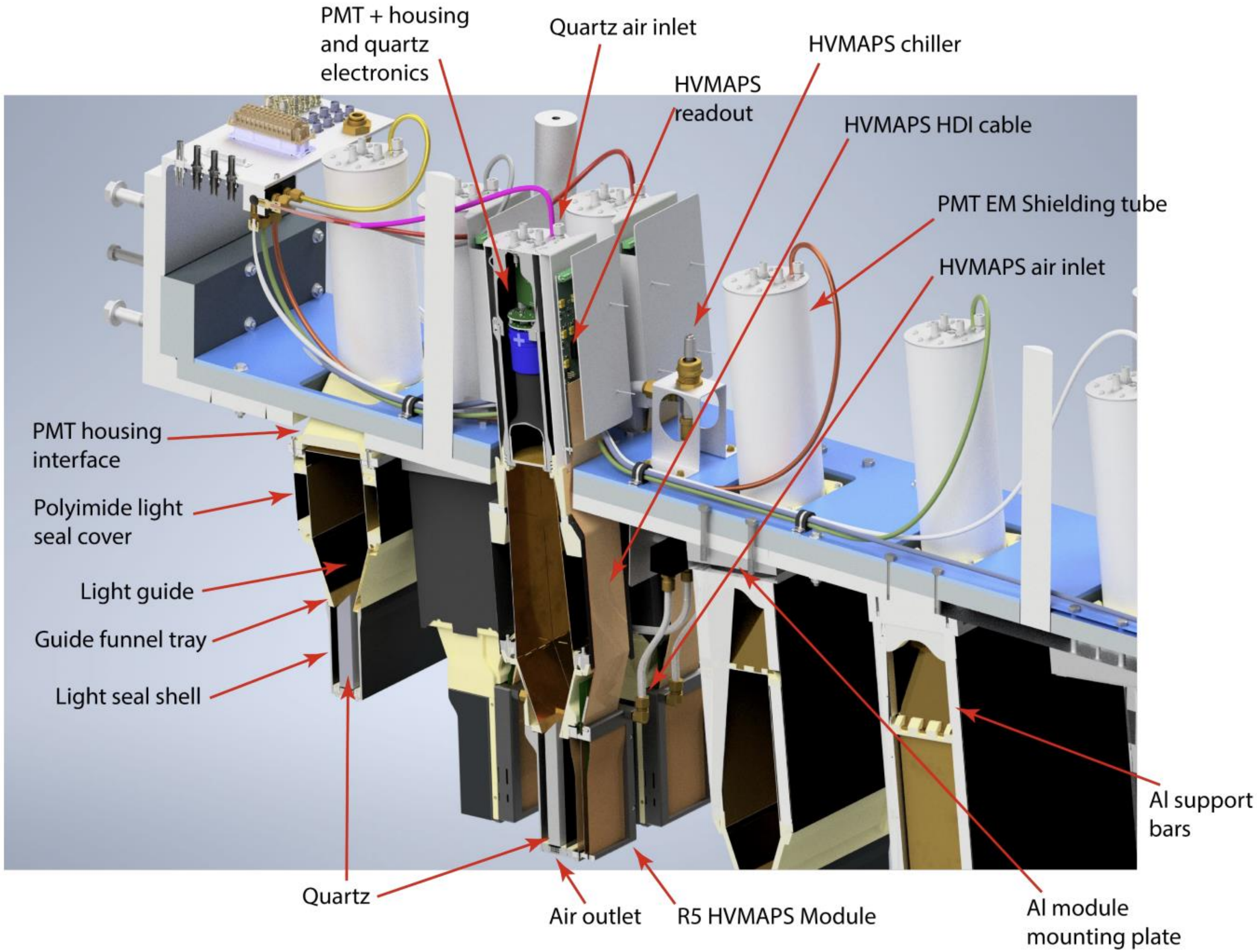
PMT and preamp noise and bandwidth meet goals



Final Main Detector Module Design :

Module parts:

- Fused silica active volume (quartz)
- Air core light guide
- 3D printed housing parts
- Aluminum module structure parts
- PMT
- Front-end electronics
- HVMAPS module (+ readout)
- Light seal cover



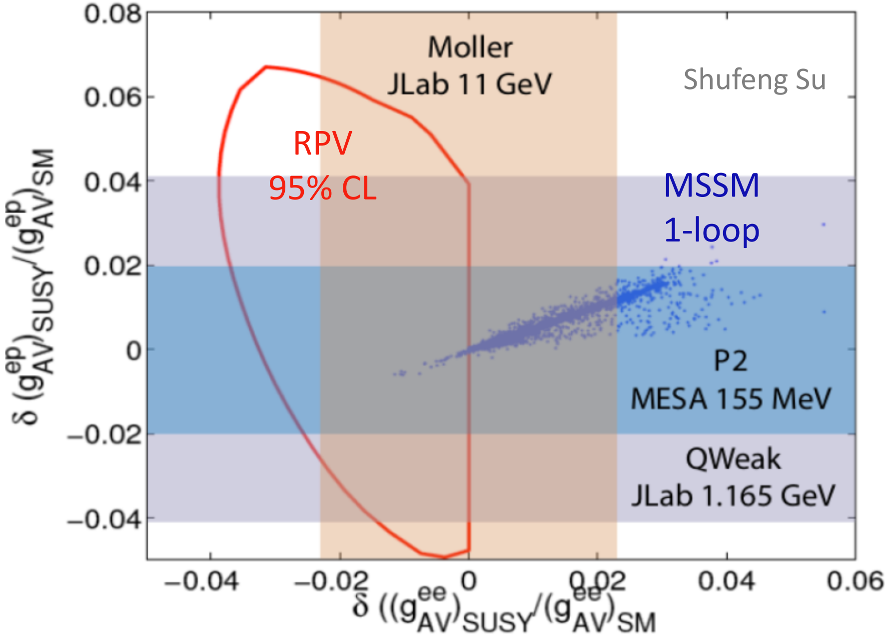
Precision provides physics reach

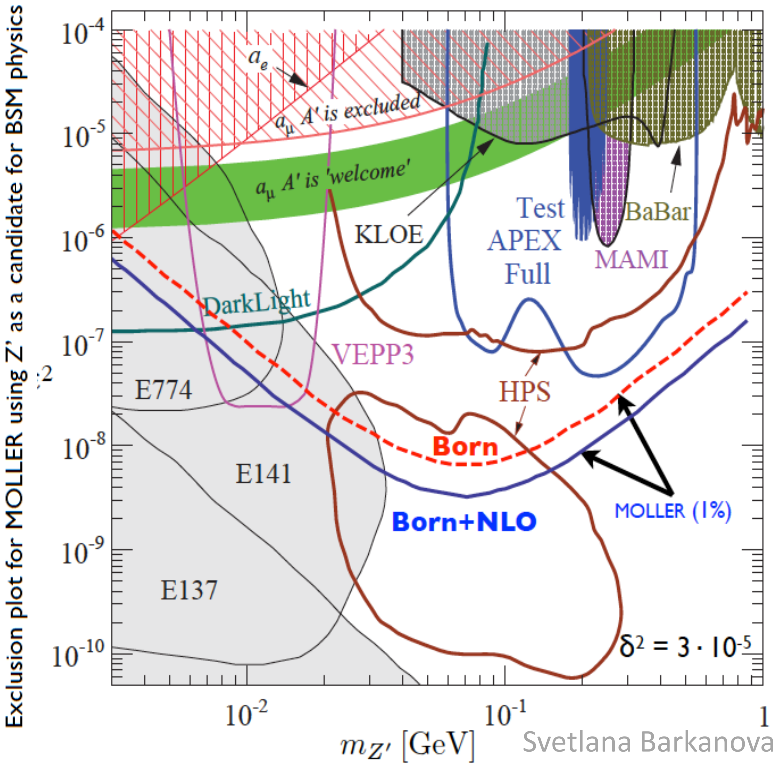
$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} \simeq .05\,\frac{\delta A_{PV}}{A_{PV}} \quad \Rightarrow \quad \delta Q_W^e$$

$$= 2.3\%, \sim 5 \times smaller\ than\ E158$$

2.3% MOLLER uncertainty → mass reach $\mathbf{7.5}$ to $\mathbf{27\ TeV}$

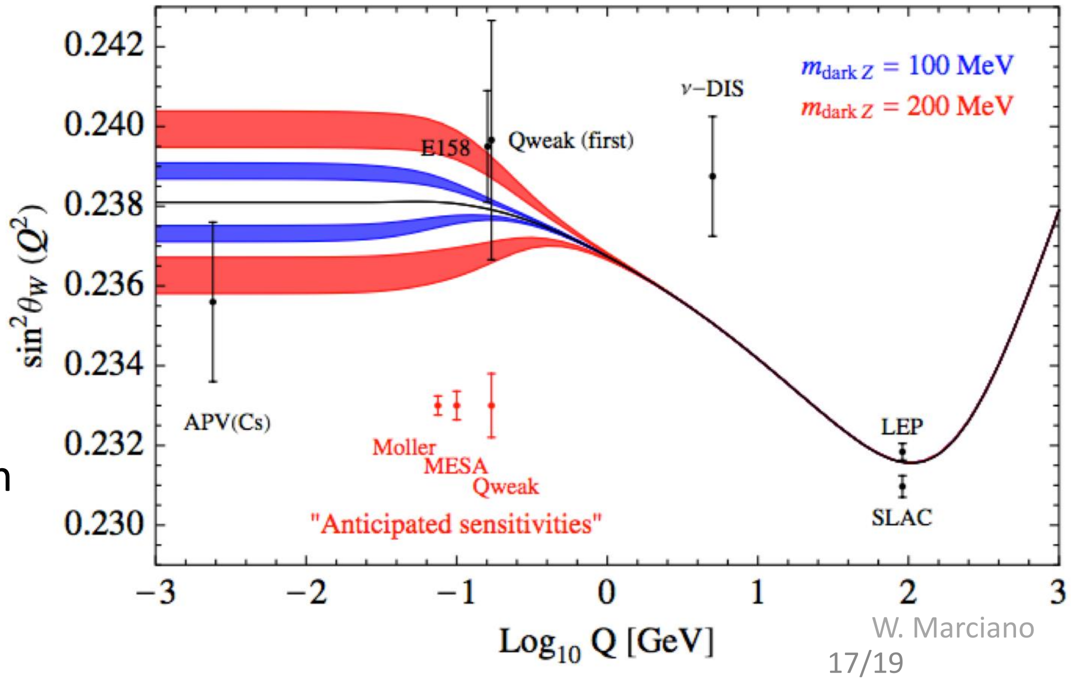
(depending on the model of new physics)



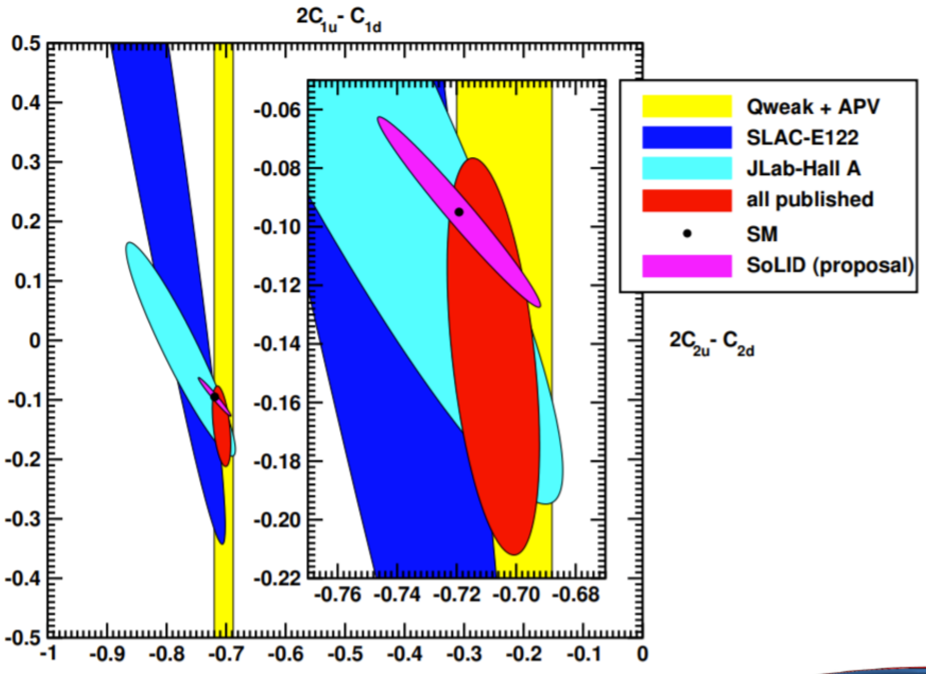


	95% conf. level
LEP200	$\Lambda_{LL}^{ee} \sim 8.3\ TeV$
E158	$\Lambda_{LL}^{ee} \sim 12\ TeV$
MOLLER	$\Lambda_{LL}^{ee} \sim 27\ TeV$

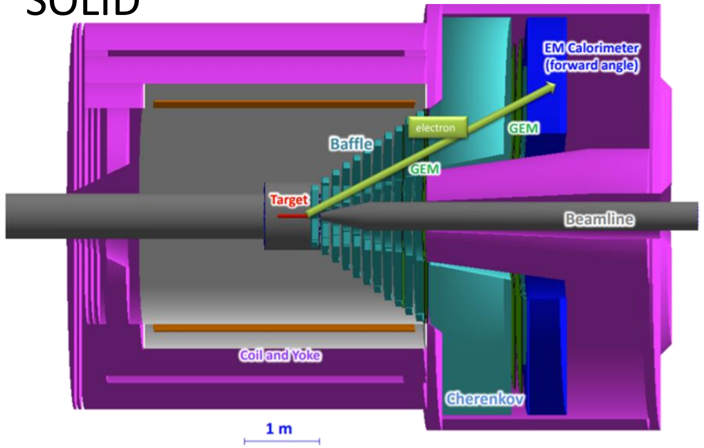
MOLLER is accessing discovery space that cannot be reached until the advent of a new lepton collider or neutrino factory

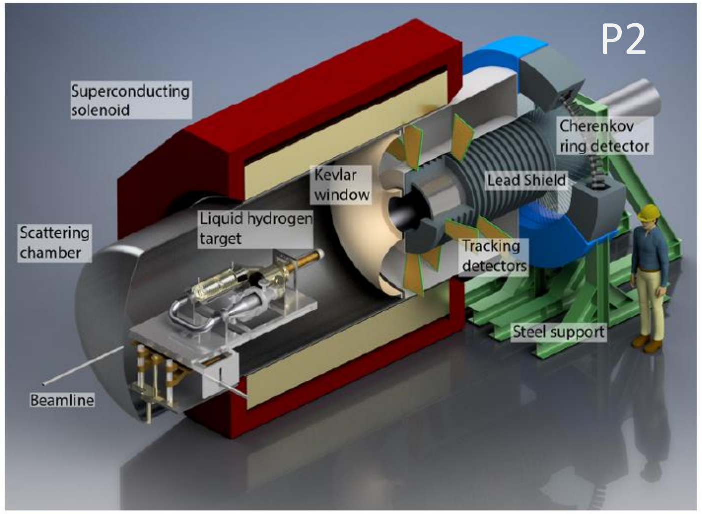


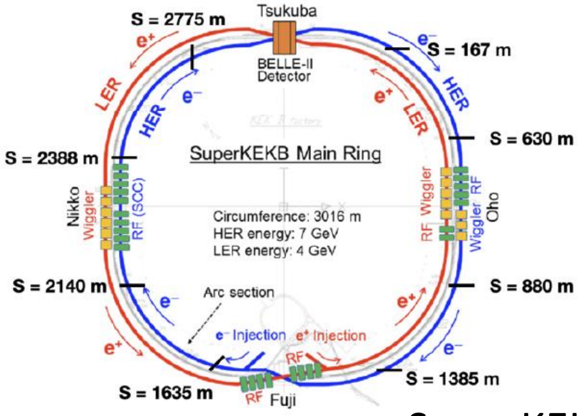
Future – couplings and SM Tests



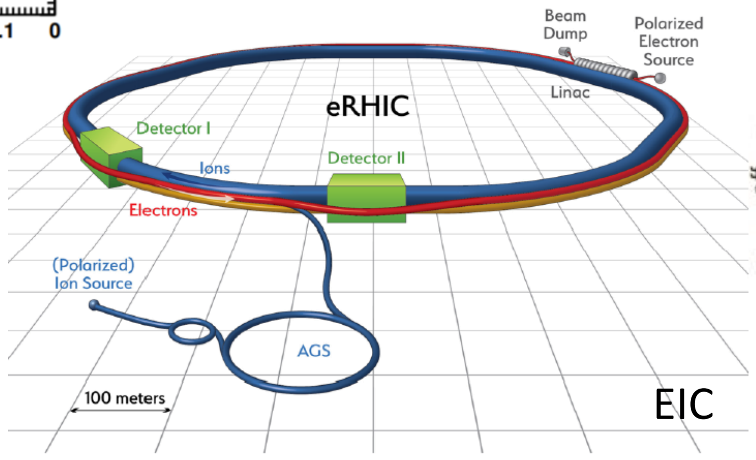
SOLID



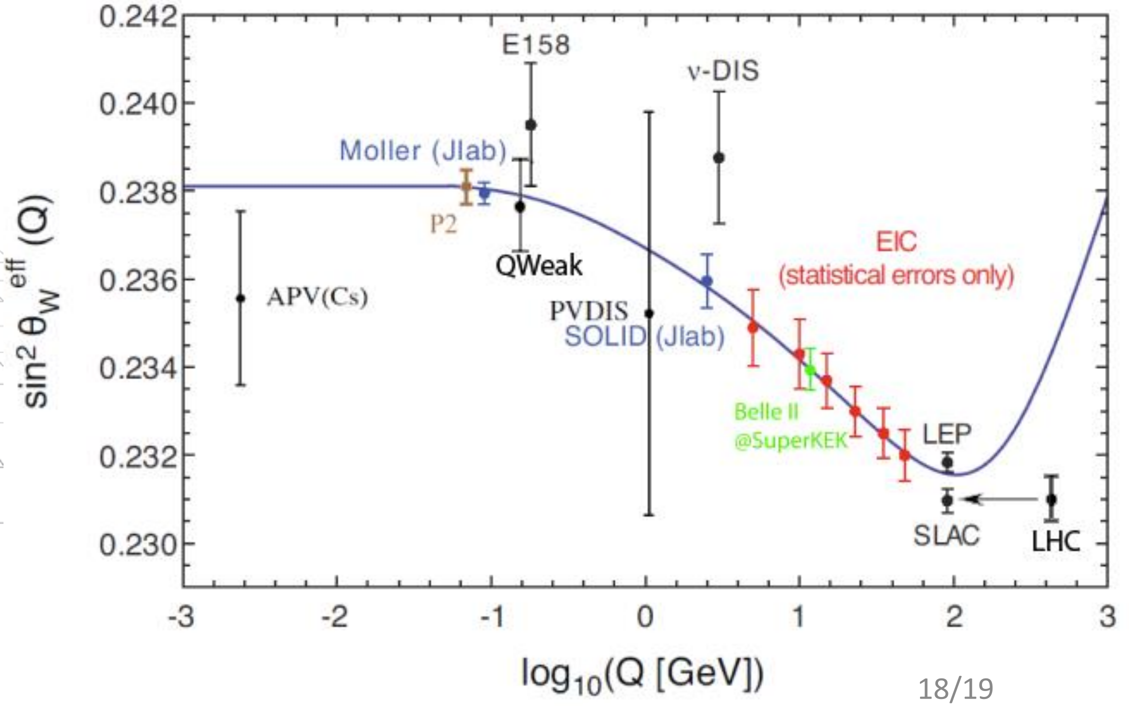




SuperKEKB



EIC



Summary and Outlook – MOLLER

- Fabrication has started for long-lead items
- Fabrication and qualification activity underway at Jlab
- Expect to launch rest of fabrication/procurement with ESAAB review in spring

- Will be ready for assembly mid-2025
- Ready for physics in fall 2026
- With an on-time start, you should expect the first physics publication in mid-2027

- Other experiments will continue to use PVES to "map out" the running of the weak mixing angle

MOLLER Collaboration

~ 160 authors, 37 institutions, 6 countries

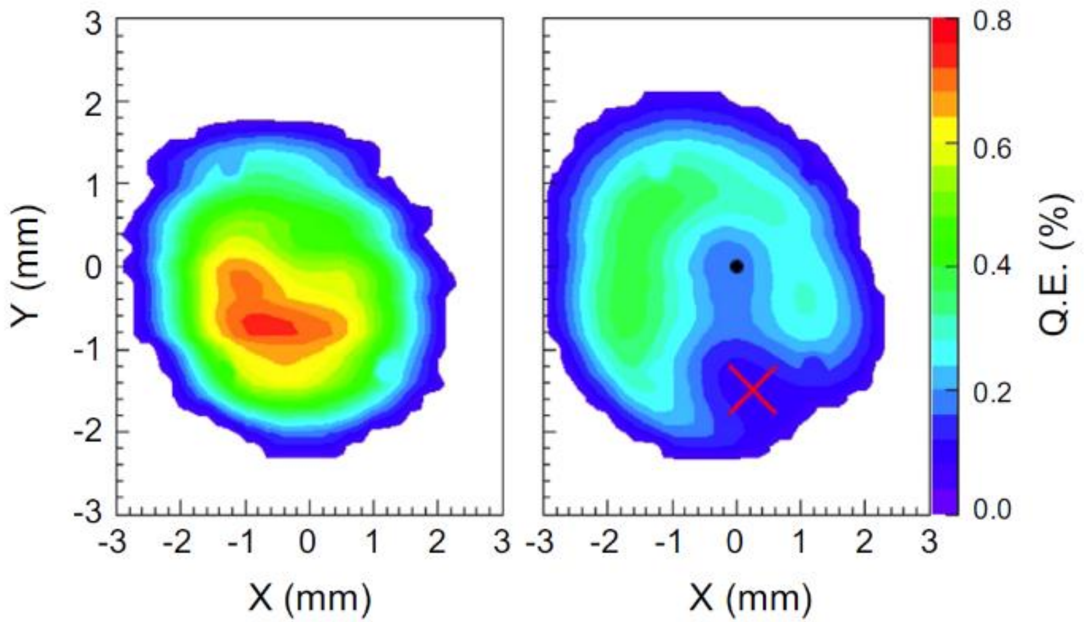
K. Kumar: Spokesperson
R. Fair: Project Manager

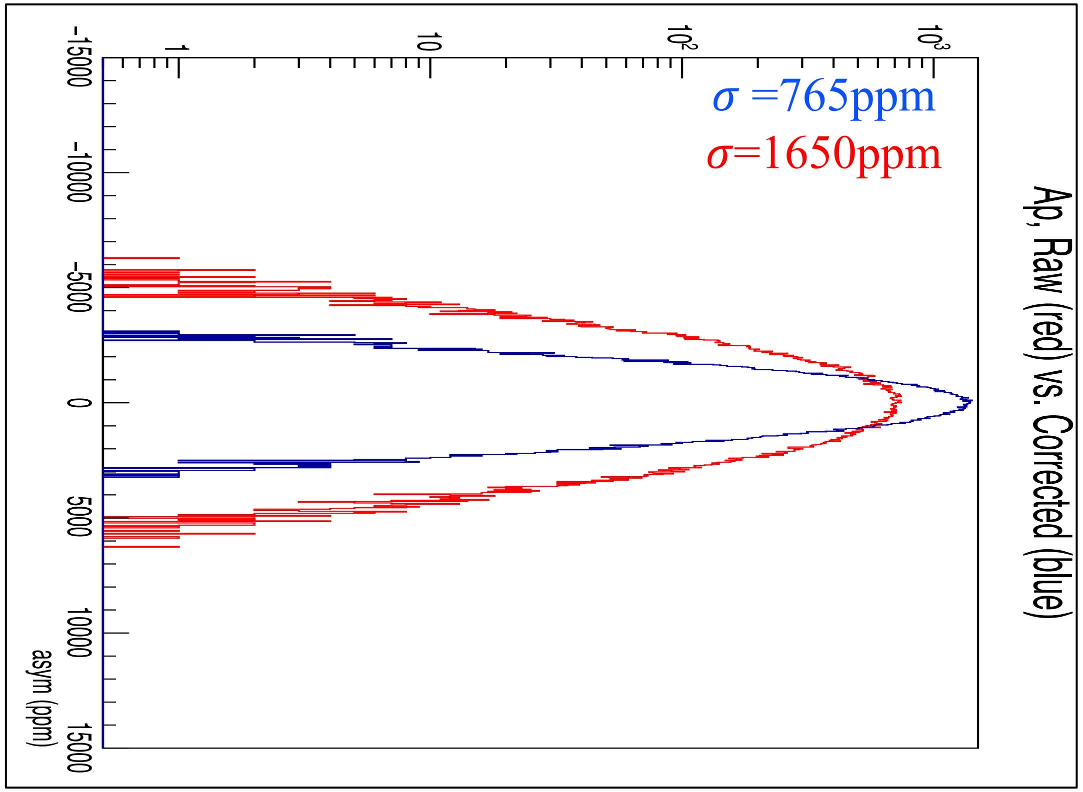
Includes experience from E158, PREX, Qweak, PVDIS, HAPPEX, G-Zero

Current Canadian Group

10 faculty from U. Manitoba, U. Winnipeg, U. Memorial, UNBC
3 postdocs and 8 students

False asymmetries from helicity correlated beam properties





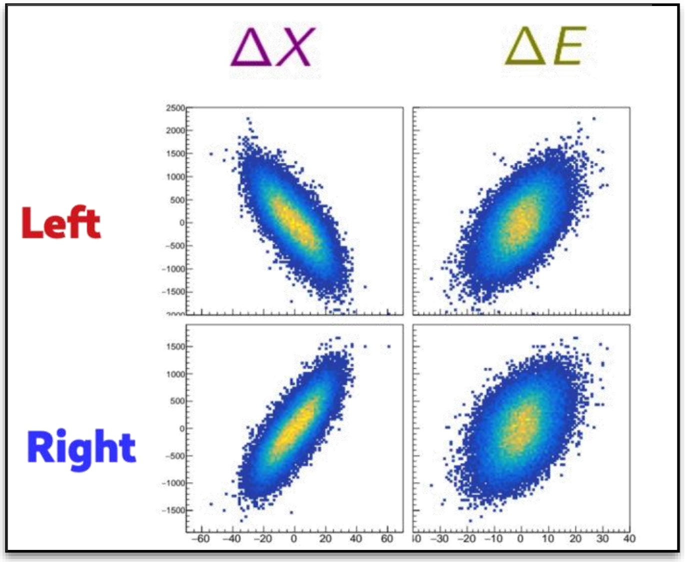
$$A = A_{raw} - A_Q - \sum_i \beta_i \Delta x_i - \beta_E A_E$$

Average position differences at the target controlled to order ~10 nm

The width of human hair is 50,000 nanometers!!!

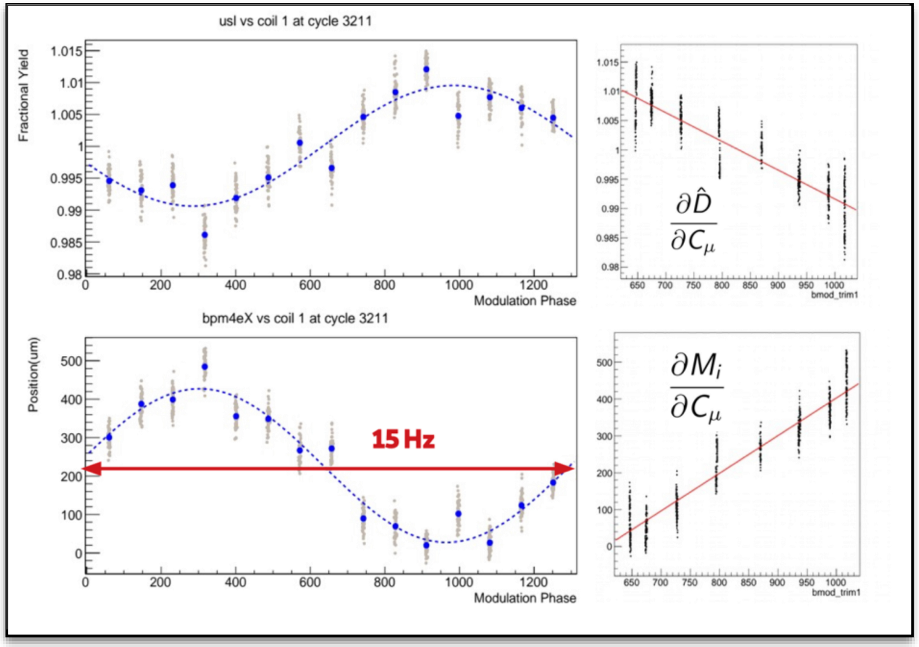
Beam Correction Techniques

Multivariate Regression (A)



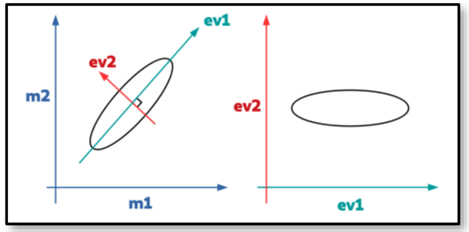
- χ^2 minimization
- Narrowest width
- Best **statistical** precision
- *Slope diluted by monitor resolution*

Beam Modulation (B)

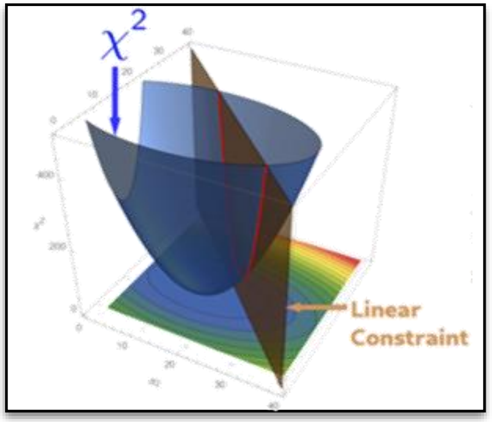


- Spans phase space well
- Constrains sensitivities
- Best **systematic** accuracy
- *Larger widths*

Method of Lagrange Multipliers (C)



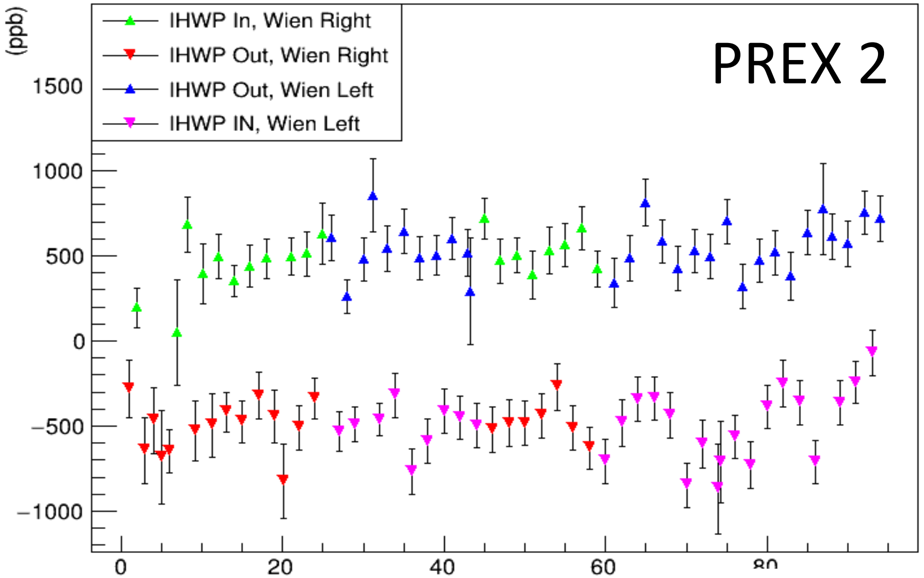
Eigenvector analysis and ranking of beam fluctuations



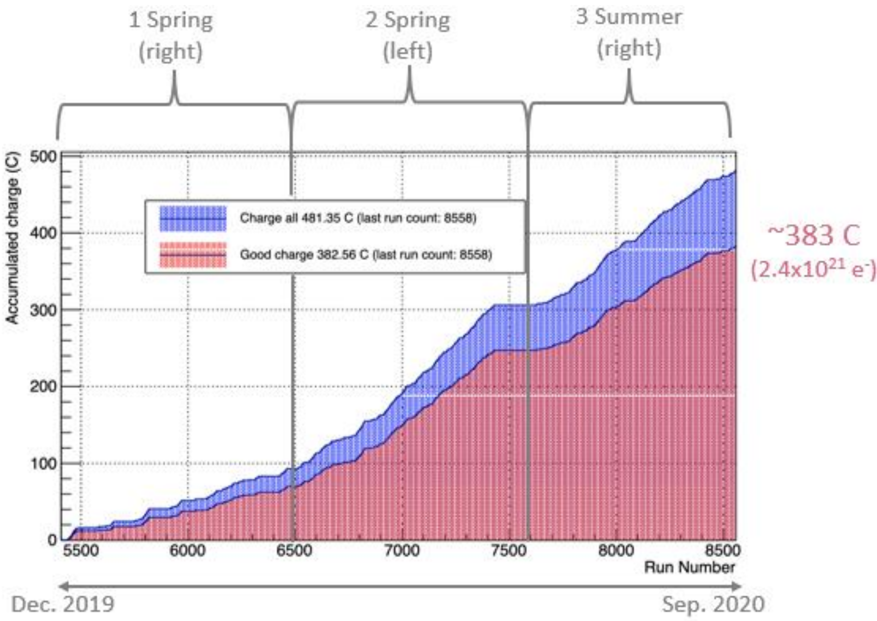
- "Hybrid" of regression and beam modulation techniques
- Best of both worlds
- Best precision given constraints on sensitivities

Data quality

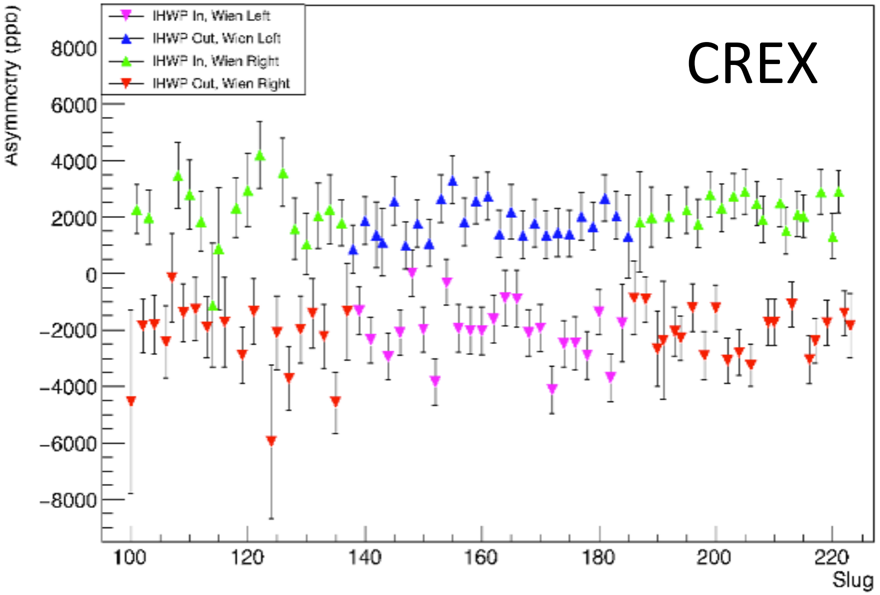
$A_{meas} \Rightarrow A_{corr} \Rightarrow A_{PV} \Rightarrow F_W \Rightarrow F_{W,skin} \Rightarrow r_{skin}$

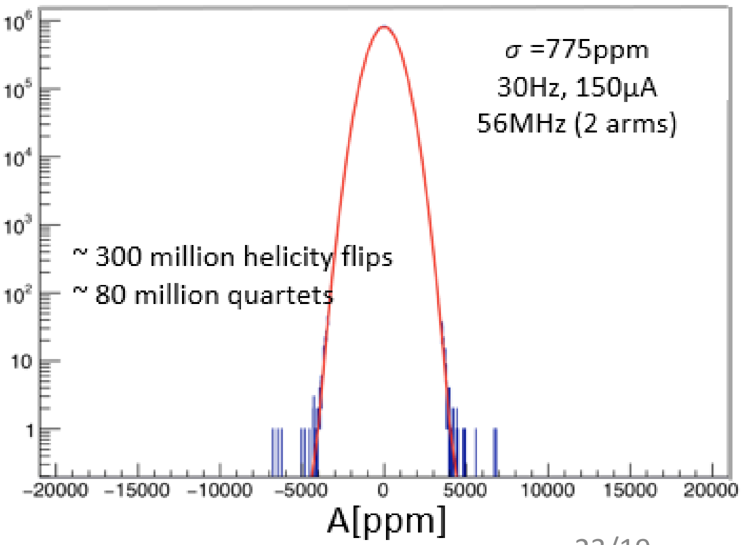


- dominated by counting statistics
- PREX 4GHz, 0.55ppm



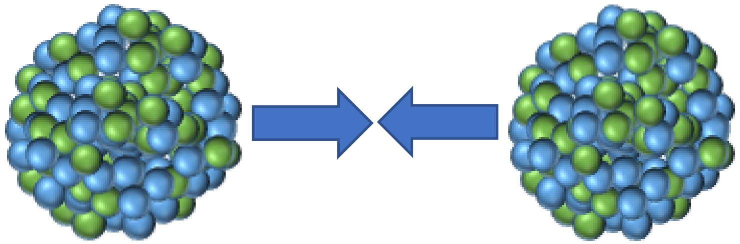
- CREX less challenging
  - 50 MHz (1% PREX)
  - larger asymmetry ~ 2 ppm



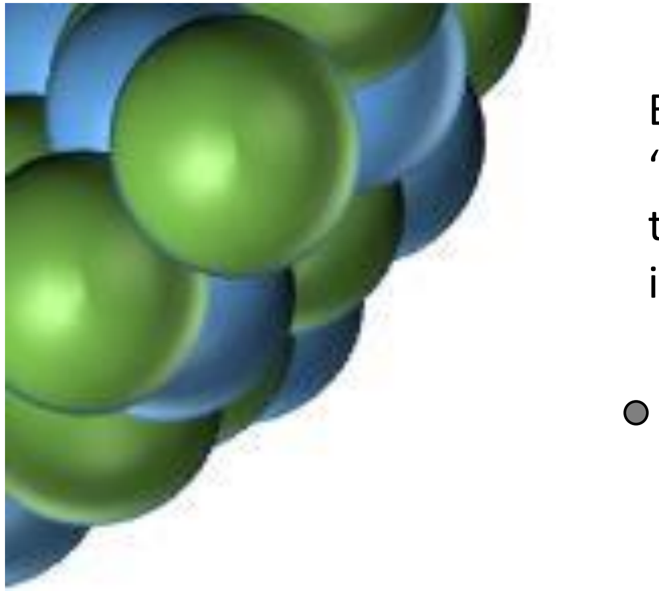


Parity-violating electron scattering

Strong interaction uncertainties in other measurements, like HIC

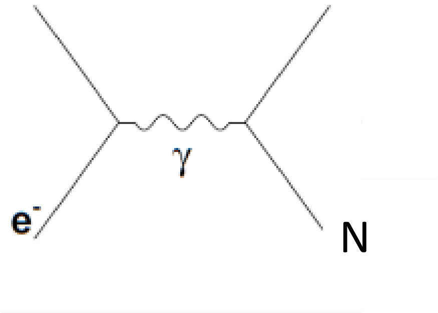


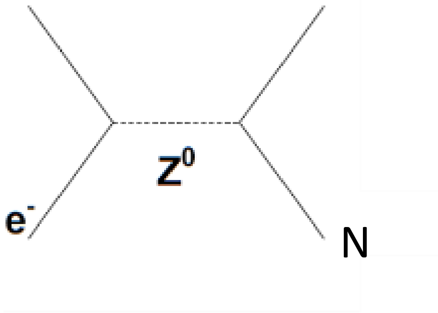
with electron scattering – the probe doesn't interact via the strong force

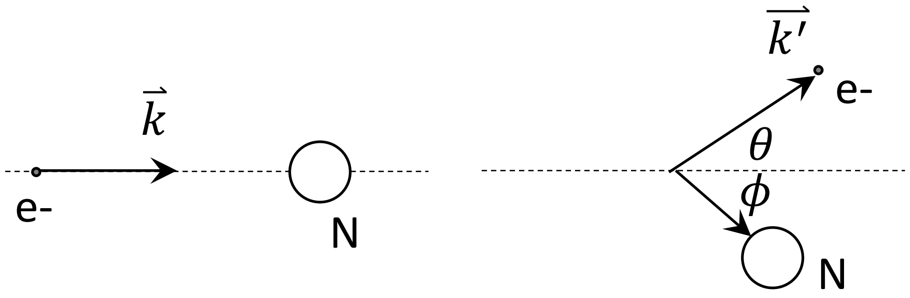


Electrons with different helicities "see" different potentials for the target, N, because of parity-violation in the weak interaction

does interact via BOTH the E&M and weak forces







$$q^2 = (\vec{k'} - \vec{k})^2$$

Elastic scattering

$$\Rightarrow -q^2 = Q^2 = 4EE' \sin^2\theta$$

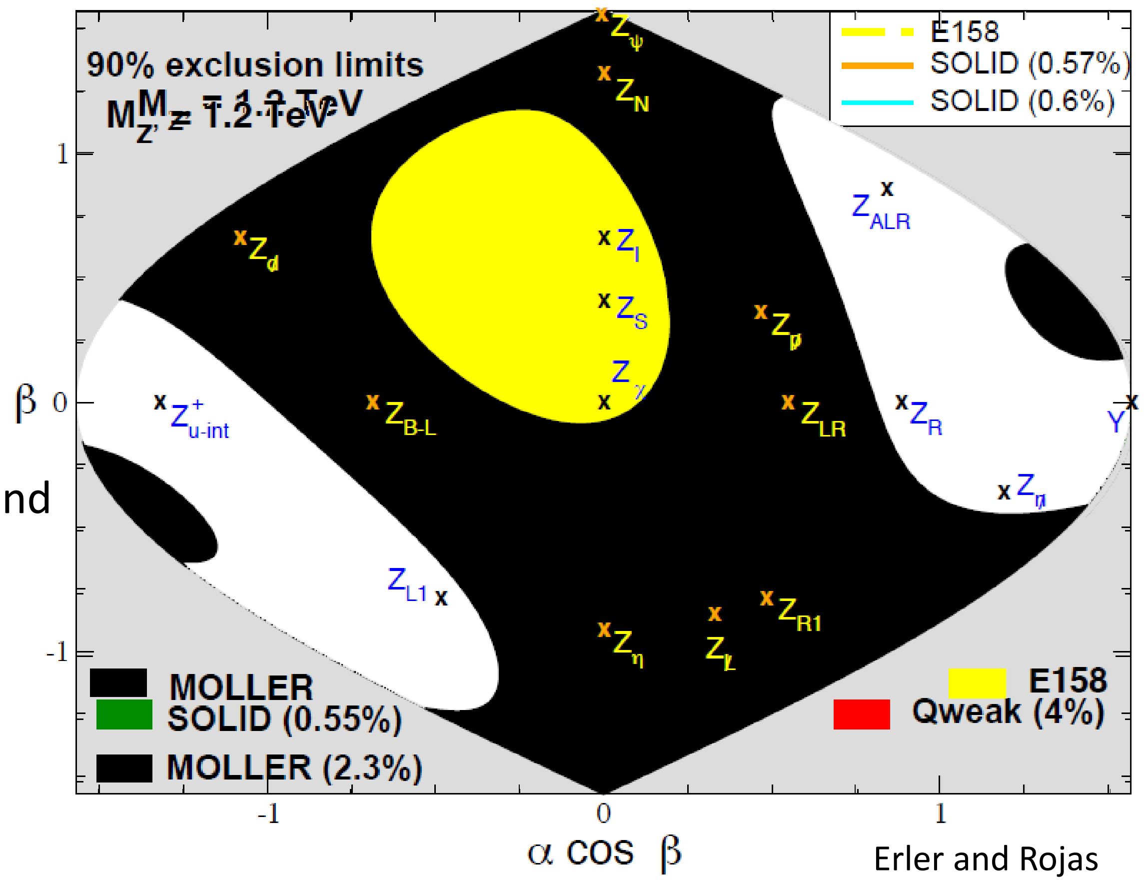
COMPLEMENTARY TO THE LHC - Z′

Assume LHC discovers a new spin 1 gauge boson with M =1.2 TeV

Halfway between SM and E158 central value

If the SM value is measured

MOLLER can distinguish between models



Erler and Rojas

$\alpha = 0 \rightarrow E6\ models, \alpha \neq 0$ describes kinetic mixing

$\beta = 0 \rightarrow SO(10)(including\ those\ based\ on\ LR\ symmetry)$

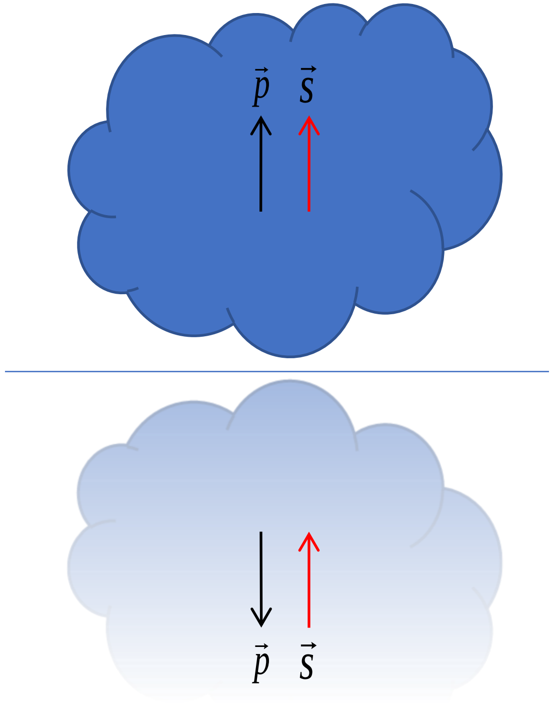
- The MOLLER experiment is a >$40M USD experiment expected to run in 2026. This experiment has a large Canadian contribution, to both the spectrometer and detector systems. The experiment utilizes parity-violation in the weak interaction to measure the asymmetry between longitudinally polarized electrons in the positive and negative helicity states. The electrons scatter from electrons in liquid hydrogen, are collimated and bent through the spectrometer system to the main detector array. There are 224 integrating quartz detectors in the array. In addition there are a set of tracking detectors to study backgrounds and determine the acceptance. In fact, the whole accelerator is part of the experiment, with beam position and charge monitors throughout the beamline serving to study helicity-correlated backgrounds. In this talk I will describe the goals of the MOLLER experiment and its design and provide a status, in particular of the spectrometer and detector systems.

The University of Manitoba campuses are located on original lands of Anishinaabeg, Ininewuk, Anisininewuk, Dakota Oyate and Denesuline, and on the National Homeland of the Red River Métis.

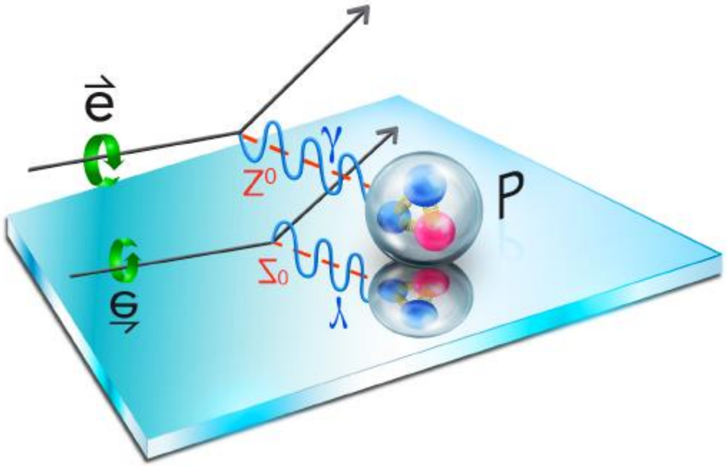
We respect the Treaties that were made on these territories, we acknowledge the harms and mistakes of the past, and we dedicate ourselves to move forward in partnership with Indigenous communities in a spirit of Reconciliation and collaboration.

Parity

quantum mechanical operator that reverses the spatial sign (P: x -> -x)



$$h = \frac{\vec{s}\cdot\vec{p}}{|\vec{s}\cdot\vec{p}|}$$



We describe physical processes as interacting currents by constructing the most general form which is consistent with Lorentz invariance

Terms of the form $\bar{\psi}\,(4\times 4)\,\psi$ where $\gamma^5 \equiv i\gamma^0\gamma^1\gamma^2\gamma^3$

Scalar	$\bar{\psi}\psi$
Pseudoscalar	$\bar{\psi}\gamma^5\psi$
Vector	$\bar{\psi}\gamma^\mu\psi$
Axial Vector	$\bar{\psi}\gamma^\mu\gamma^5\psi$
Tensor	$\bar{\psi}\sigma^{\mu\nu}\psi$

Note:

P (V*V) = +1 P (A*A) = + 1

P (A*V) = -1