2nd Workshop on Nucleon Structure at Low Q and μASTI

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Europe/Athens timezone

Parity Violating Muon Scattering (PVμS)

R Gilman*
Rutgers

Work done / conversations with T Rostomyan (PSI), P Reimer (ANL), A Crivellin (PSI), P Schmidt-Wellenburg (PSI)

1. Why?
2. PVμS is <u>much</u> harder than PVeS
3. How???
4. Conclude

*Supported in part by US NSF PHY 2209348

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2. PVμS is <u>much</u> harder than PVeS
3. How???
4. Conclude

Goals: use no equations, convince you I am not (entirely) crazy

Why?

Why?

PVeS is a mature technology, used to precisely explore nucleon structure, weak coupling coefficients, and new physics.

Why do something that is much harder and will give a worse result?

Why?

PVeS is a mature technology, used to precisely explore nucleon structure, weak coupling coefficients, and new physics.

Why do something that is much harder and will give a worse result?

Novel physics that shows up in μ but not e data.

Many examples of issues with μ's, which so far if resolved have not demonstrated NP (New Physics).

Hints of novel physics in μ sector

LHCb collaboration, *Test of Lepton Universality in beauty-quark decays*, arXiv:2103.11769

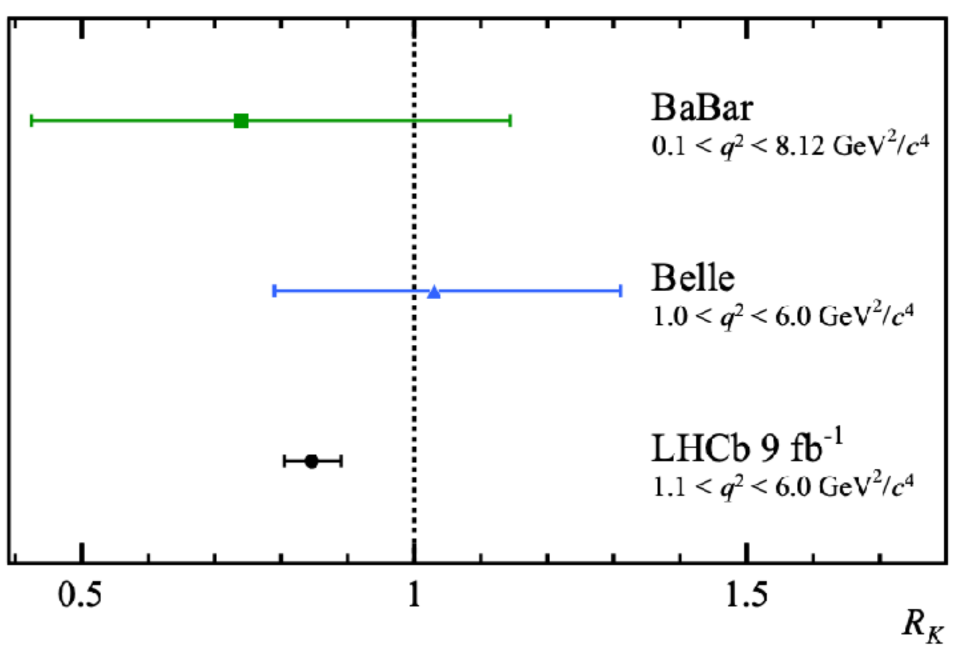

Figure 4: Comparison between R_K measurements. In addition to the LHCb result, the measurements by the BaBar [113] and Belle [114] collaborations, which combine $B^+ \to K^+\ell^+\ell^-$ and $B^0 \to K^0_S\ell^+\ell^-$ decays, are also shown.

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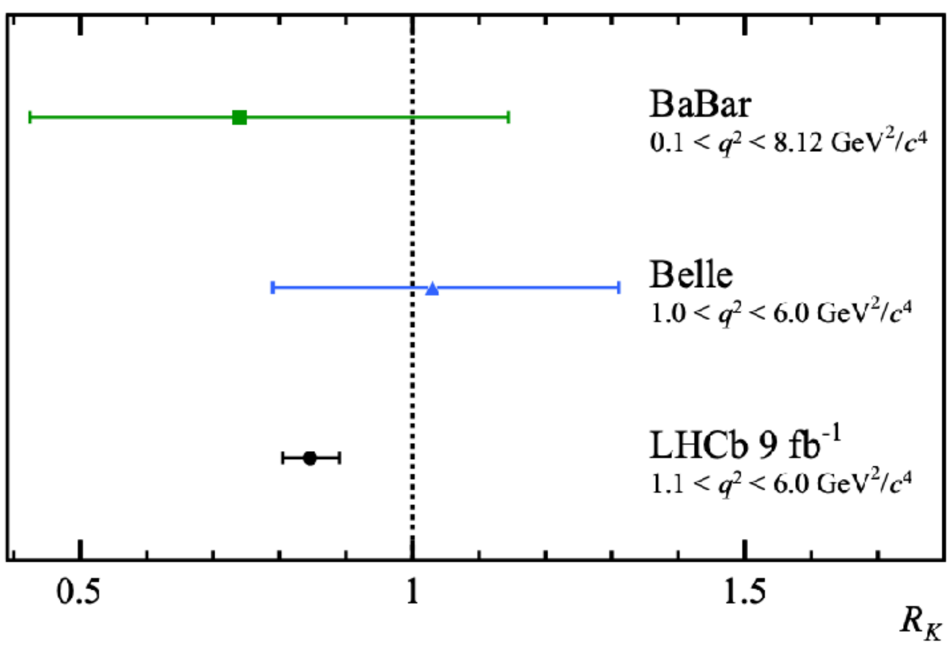

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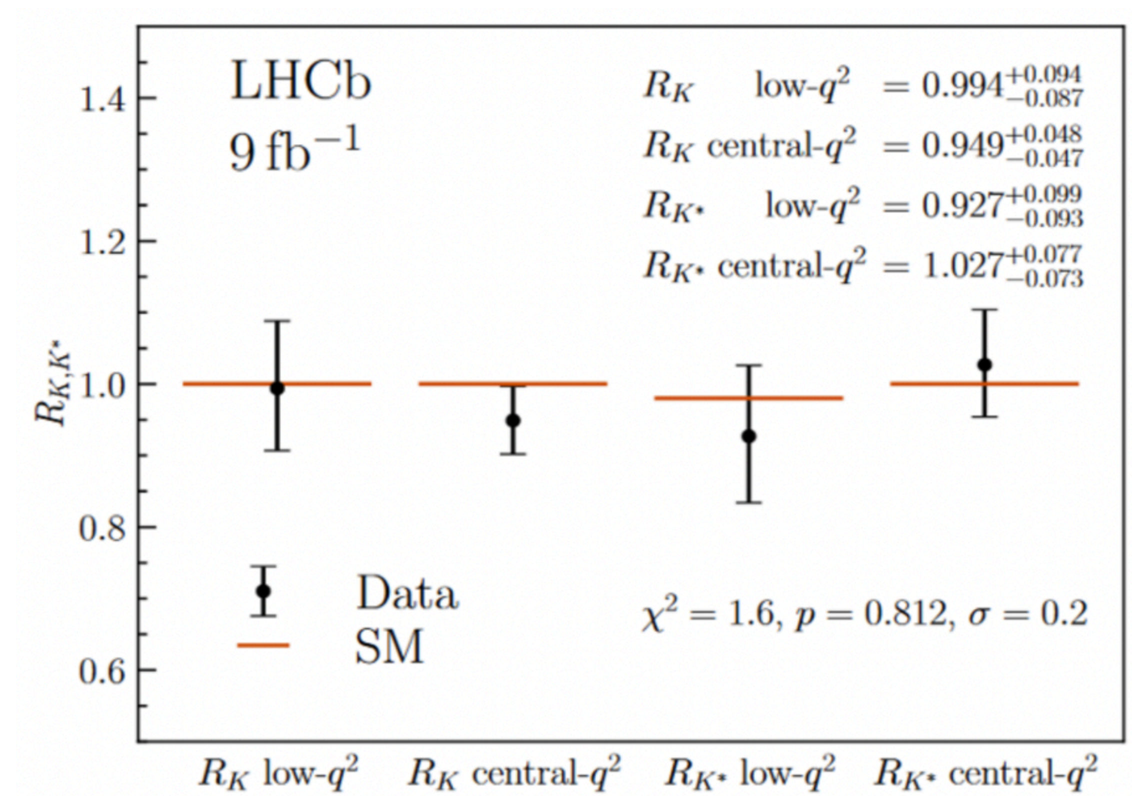
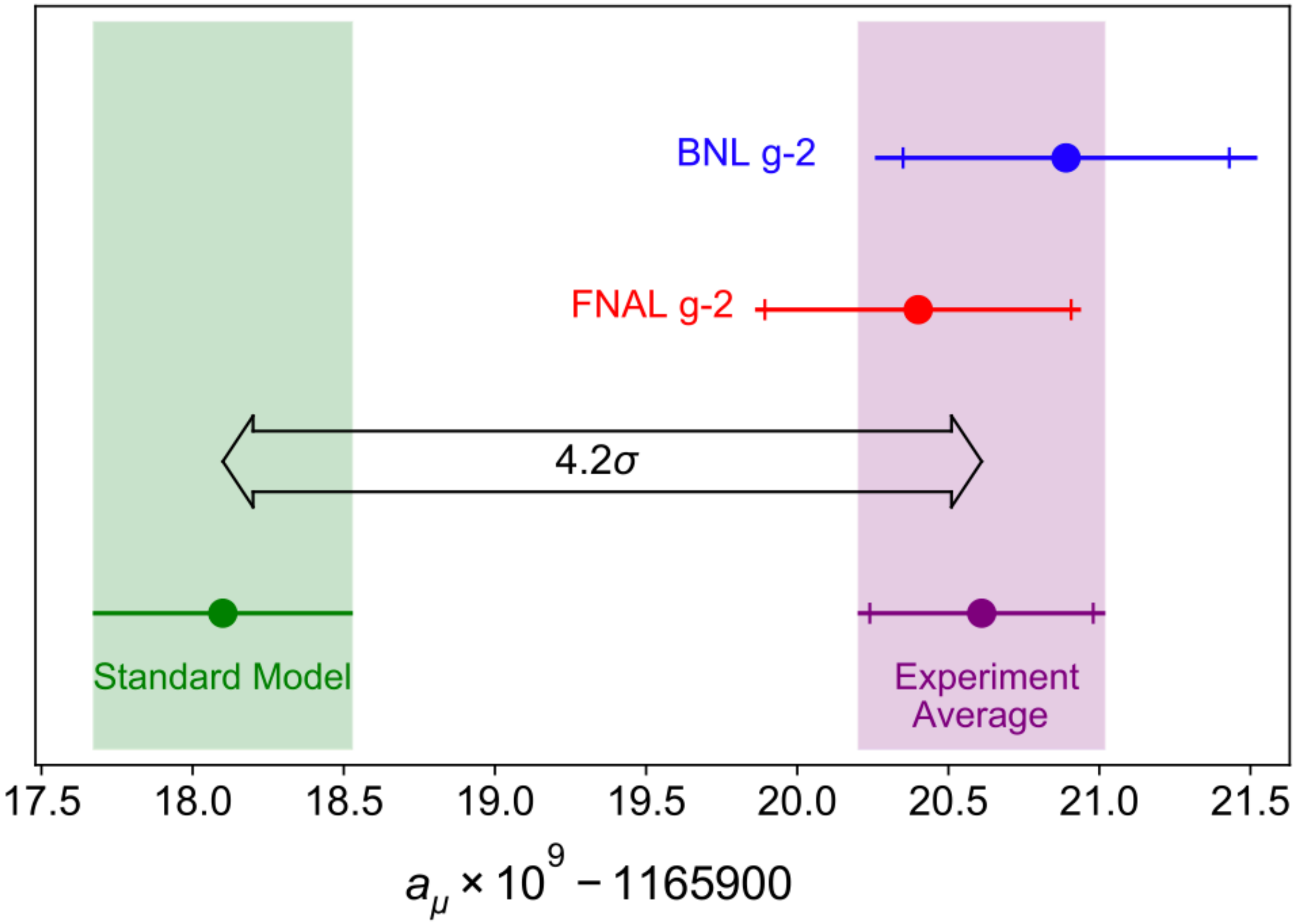
LHCb collaboration, Measurement *of Lepton Universality parameters in* $B^+ \to K^+ l^+ l^-$ *and* $B^0 \to K^{*0} l^+ l^-$ *decays*, arXiv:2212.09153



Hints of novel physics in μ sector

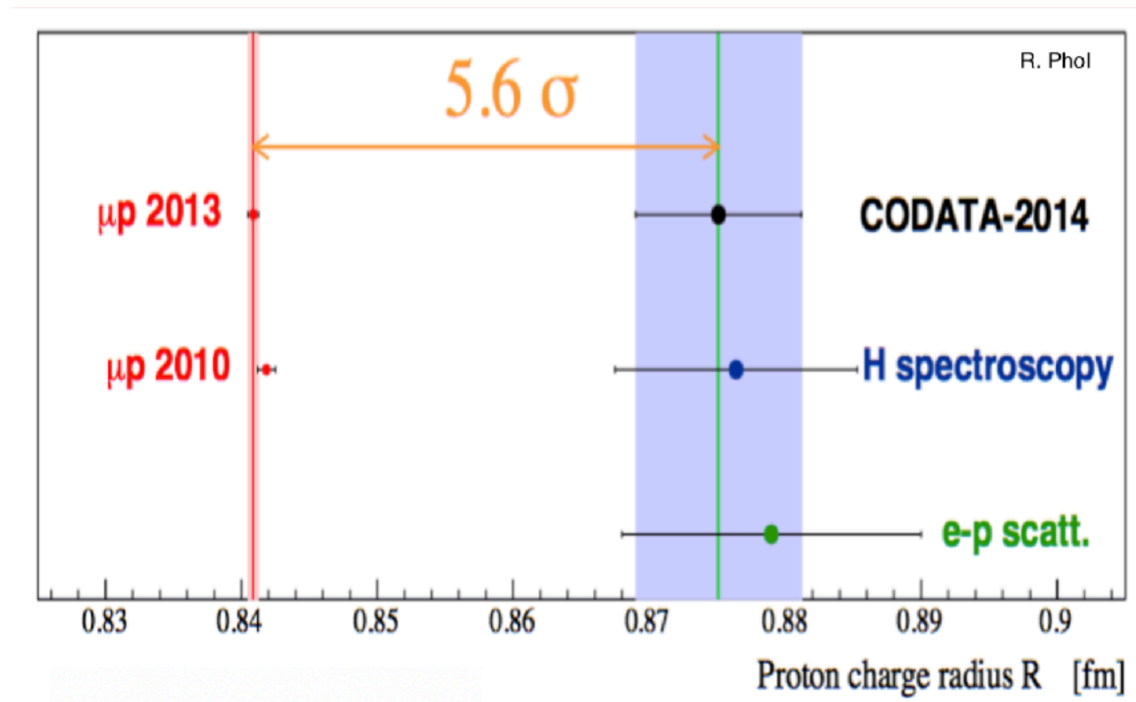
The Muon g - 2 Collaboration, *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, arXiv: 2104.03281



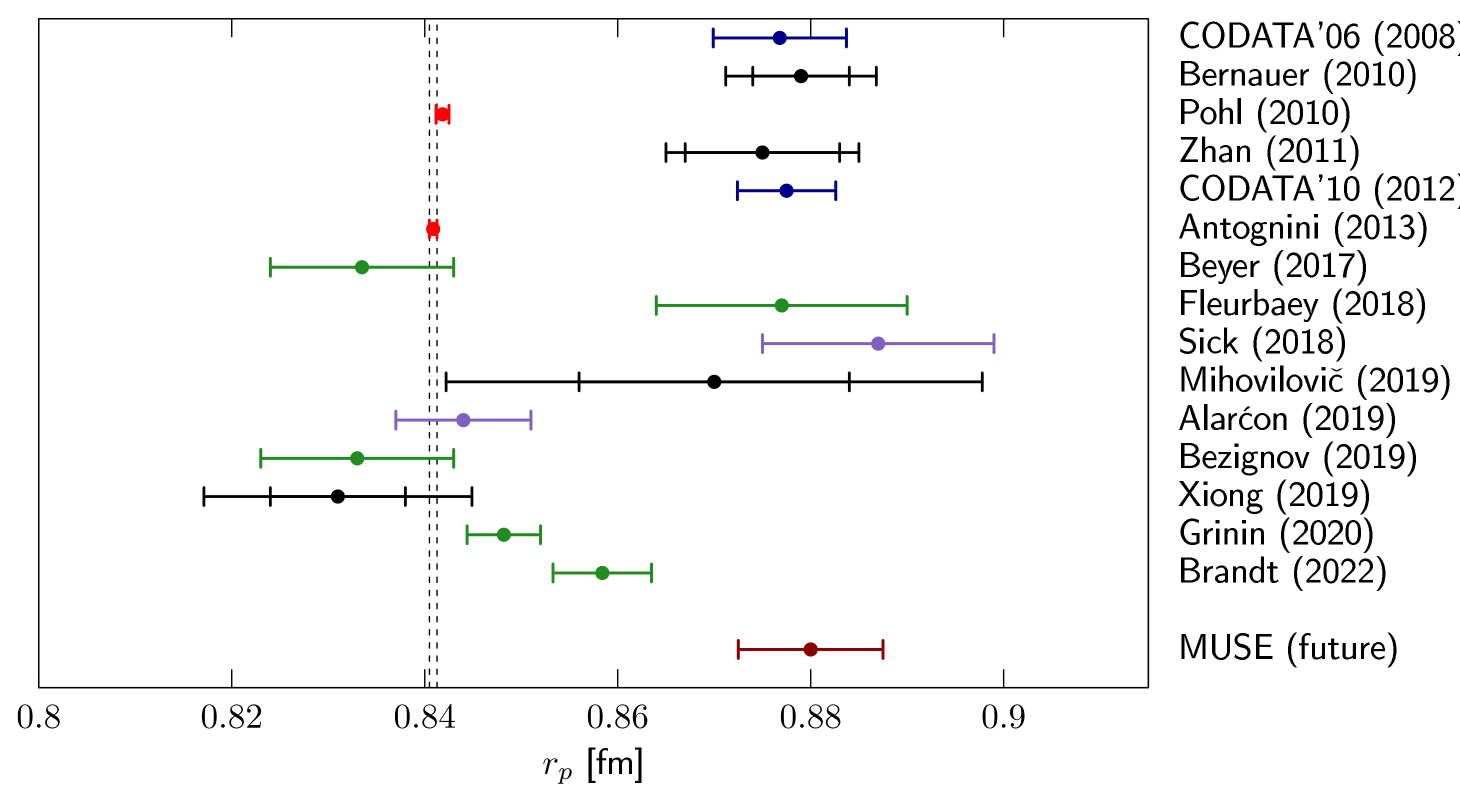
A theory issue?

Hints of novel physics in μ sector

From R Pohl, one of many versions



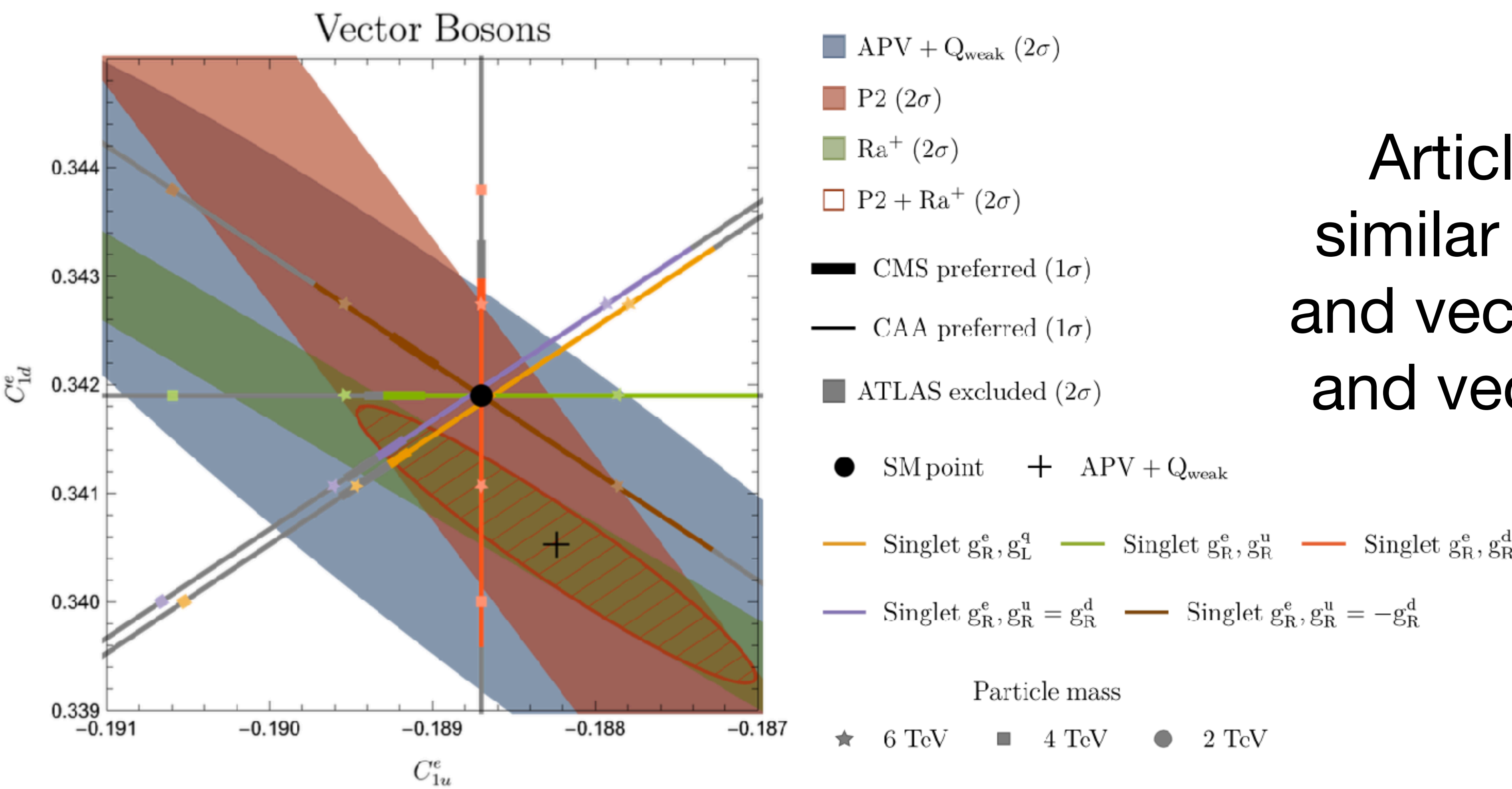
From J Bernauer



Discussed Wednesday

Example of limits on new physics

First-Generation New Physics in Simplified Models: From Low-Energy Parity Violation to the LHC, A Crivellin, M Hoferichter, M Kirk, CA Manzari and L Schnell, arXiv:2107.13569



Article also shows similar plots for scalar and vector leptoquarks, and vector-like quarks

Figure 2. Parametric plot of VB effects in the C^e_{1u}–C^e_{1d} plane, as well as the preferred regions from PV and the corresponding prospects. The gray parts of the lines are excluded by the di-electron searches of ATLAS (95% C.L.) and the preferred regions from CMS and the CAA (both 1σ) are indicated by thick and black lines, respectively. The three different values for the VB masses (6 TeV, 4 TeV, and 2 TeV), setting λ, $\kappa = 1$, are indicated by markers of different shapes, the cross denotes the best-fit point of APV and Q_{weak}, and the black circle the SM point.

Why?

Light NP affecting μ's but not e's is not well constrained by LHC. PVμS might play a role similar to Qweak / APV / …

Also interest in PV with muonic atoms and muonium

Why?

New Parity-Violating Muonic Forces, B Batell, D McKeen, M Pospelov, arXiv:1103.0721

… models with gauged right-handed muon number … new vector and scalar force carriers at the ~100 MeV scale or lighter … consistent with observations … enhancement of the parity-violating asymmetries …

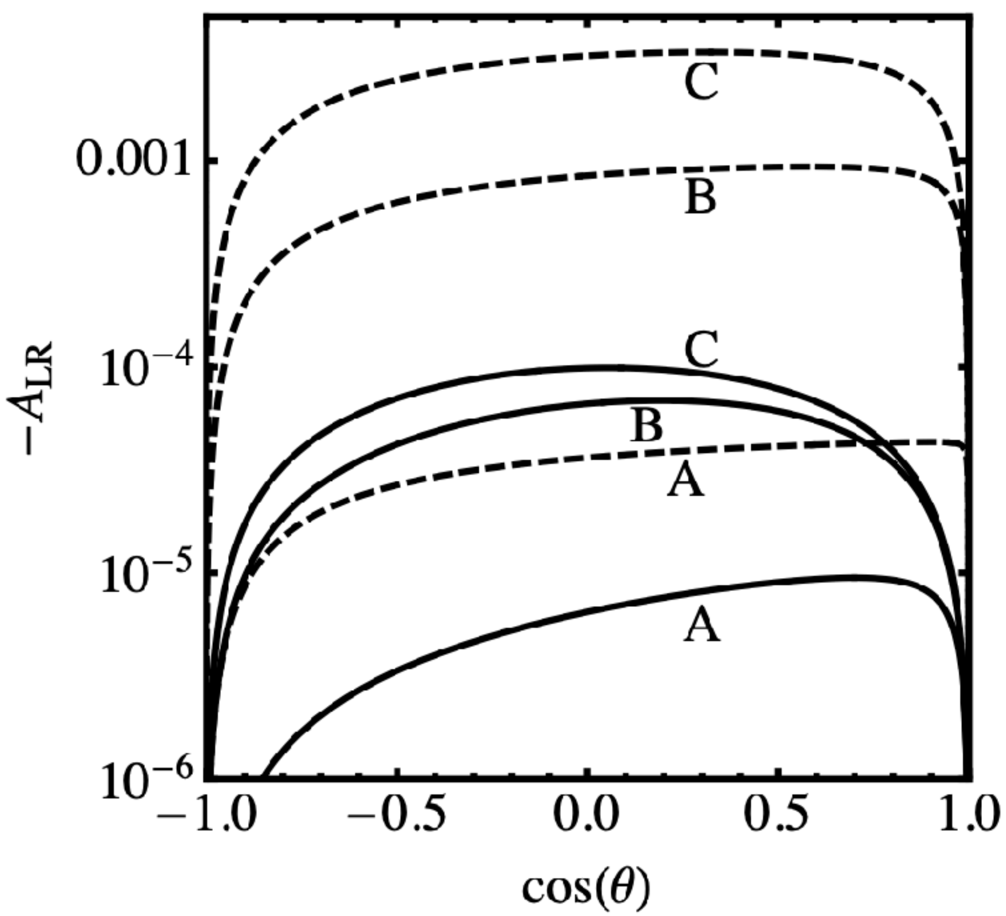


FIG. 1: The asymmetry $A_{\rm LR}(\theta)$ defined in Eq. (13) for the benchmark points labeled A, B, and C in Table I. The solid curves are for $p = 29$ MeV/c and dashed curves for $p = 200$ MeV/c.

Parameter	Point A	Point B	Point C
m_V	10 MeV	50 MeV	100 MeV
m_S	102.84 MeV	90.44 MeV	84.97 MeV
g_R	0.01	0.05	0.07
κ	0.0015	0.0075	0.02
η	2.5×10^{-5}	6.2×10^{-4}	2.3×10^{-3}
v_R	1 GeV	1 GeV	1.4 GeV

TABLE I: Benchmark points for the model that pass all phenomenological constraints.

Note: for high z target

Aside

New Parity-Violating Muonic Forces, B Batell, D McKeen, M Pospelov, arXiv:1103.0721

BMP in fact proposed a theorists' PVμS experiment, suggesting

- d = 10 μm W foil
- full azimuthal coverage 60° - 80°
- 10^8 μ/s beam
- →~ 1 hour for 10^{-4} uncertainty
- "It is thus apparent that the statistical uncertainty will not be a limiting factor in detecting parity violating asymmetries of order 10^{-4}."
- →~ 1 month for 1 ppm uncertainty

Backgrounds / how to measure at 10^5 Hz / systematics are not addressed.

Why?

Light NP affecting μ's but not e's is not well constrained by LHC. PVμS might play a role similar to Qweak / APV / …

In June 2022, Andreas Crivellin (PSI) asked Philipp Schmidt-Wellenburg (PSI) and TR if perhaps MUSE could measure PVμS?

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<u>No.</u>

TR and I did a quick estimate.

MUSE is a counting experiment with O(10 Hz) μ scattering rate. 1 ppm asymmetry error → 10^{12} counts → ~3000 years.

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Also, the μ polarization is small and fixed.

G Miller brought this up years ago …

PVμS is <u>much</u> harder than PVeS

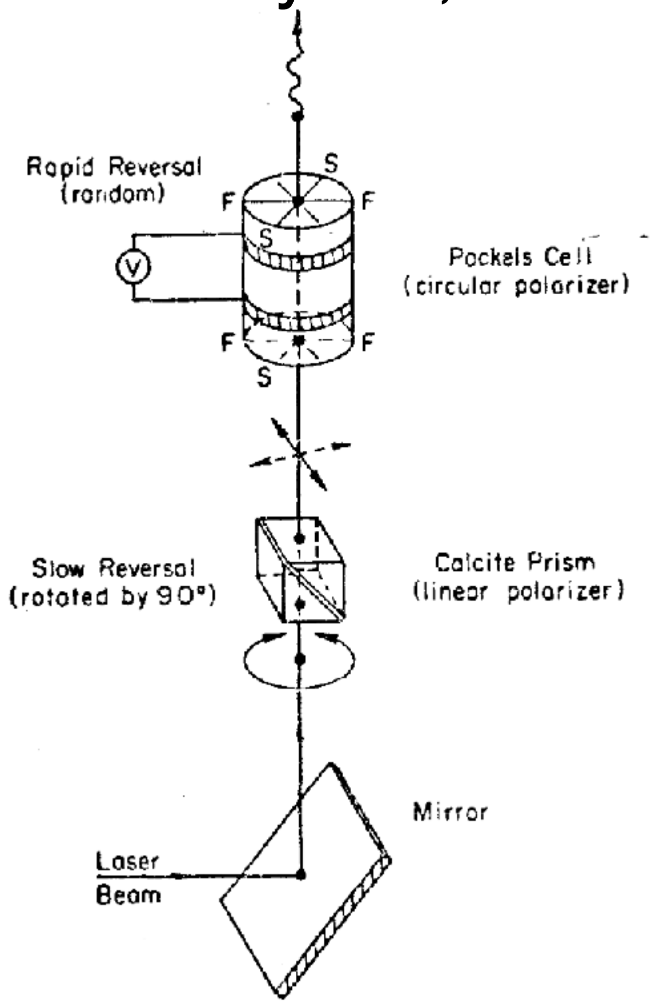
PVeS is a mature technology.

Much of the technology applied to PVeS cannot be easily applied to PVμS.

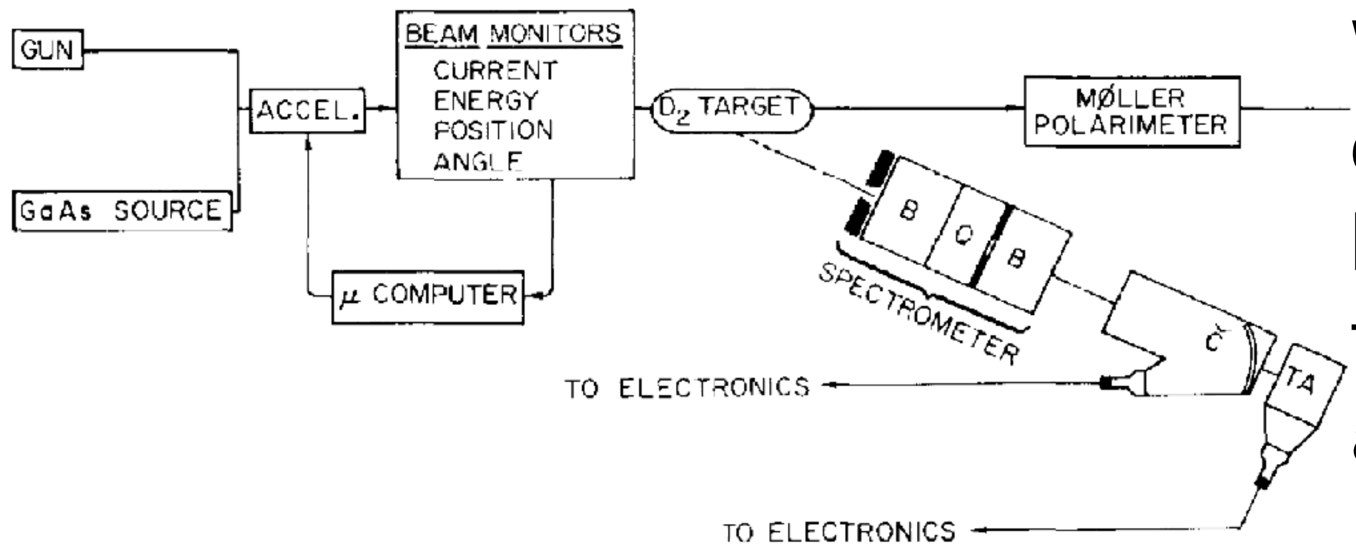
First PV electron scattering

SLAC E122: Prescott et al. PL 77B, pg 347 (1978)

Polarized electron source: Polarized laser on strained GaAs crystal,

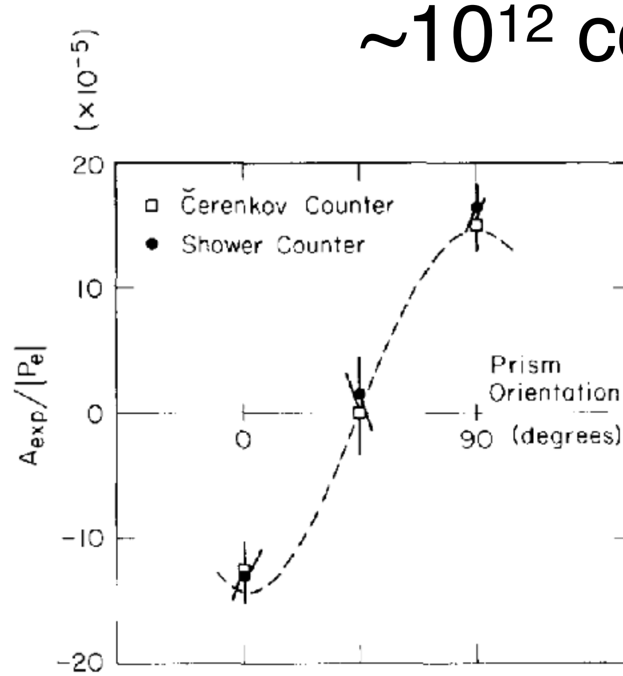


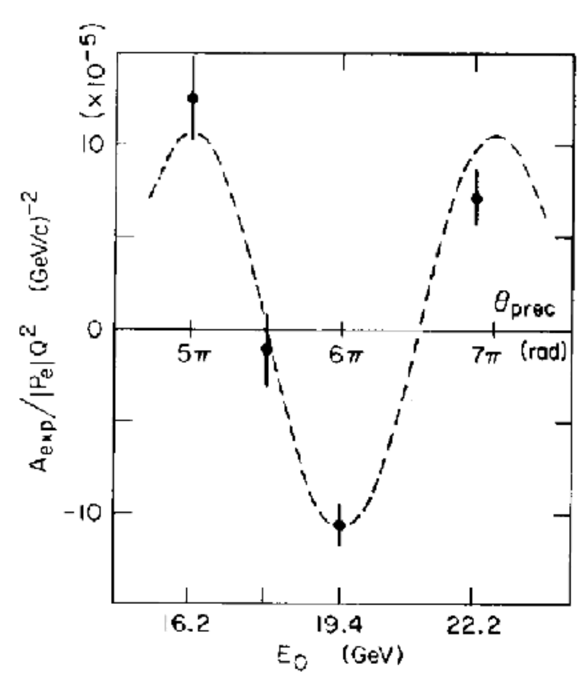
OPTICAL REVERSAL SCHEME
Figure 3



Well-controlled beam, limiting false asymmetries

Deep Inelastic Scattering, 100 ppm asymmetry, ~ ppm uncertainty, requiring ~10^{12} counts





Figures from SLAC-PUB-3506

Extensive, ongoing program

JLab, Mainz

Some features of modern PVeS experiments:

- Clean, intense, precisely controlled, highly-polarized beam
- Fast helicity reversal (pseudo random quads) to cancel drifts
- Polarimetry, spin dances
- False asymmetry checks with transverse polarization
- Spectrometers that provide clean detector region with only events of interest, no background.
- Integrating electronics for high statistics

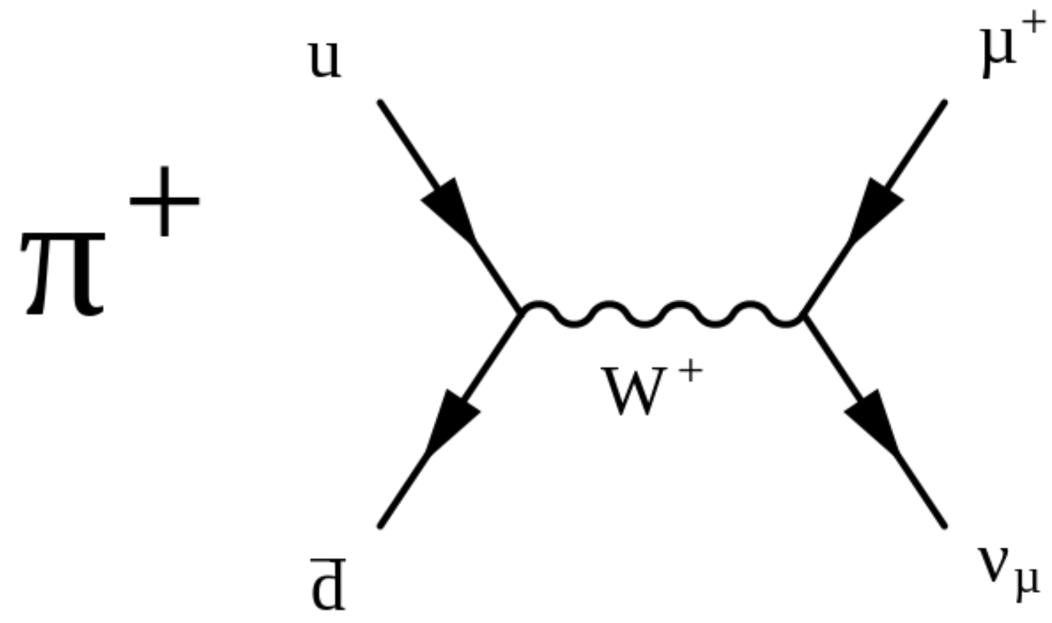
What happens when you go from e’s to μ’s?

PVμS is <u>much</u> harder than PVeS

Property	**e**	**μ**
Clean beam?	✓	secondary beam, also e's and π's
Intense?	✓, 10^{15}/s	up to 10^{8}/s
High polarization?	✓, 90 %	maybe, 0 - 100 %
fast helicity reversal?	✓	no
polarimetry?	Moller, Compton	$\mu \to e\nu\overline{\nu}$ decay is self-analyzing
false asymmetry checks?	✓	perhaps, from backgrounds
integrating electronics for high count rate	✓	cannot use, backgrounds from e's, π's, decays in flight

PVμS is <u>much</u> harder than PVeS

Reminder, on muon production:



$$\pi^+ = u\overline{d} \rightarrow W^+ \rightarrow \mu^+\overline{\nu}$$

π's are spin 0, μ's and ν's are fully polarized in the pion rest frame

Depending on how your beam line selects μ's, they can range from -100 % → 100 % polarized

PVμS is much harder than PVeS

Fundamental issues:

- low μ beam flux → low luminosity
- (Fast) helicity reversals to get cross section difference
- High count rates despite backgrounds being present

PVμS is <u>much</u> harder than PVeS

Fundamental issues:

- low μ beam flux → low luminosity
  - BMP: can be overcome in the right kinematics*
- (Fast) helicity reversals to get cross section difference
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* For a 1 ppm uncertainty experiment,
not to compete with Qweak.

PVμS is <u>much</u> harder than PVeS

Fundamental issues:

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- High count rates despite backgrounds being present

Now I am going to commit PV heresy:

<u>I propose that we do NOT need fast helicity flip.</u>

Fast helicity flip is used to suppress noise and system drifts, equipment response changing with time. It is absolutely needed for integrating systems.

PVμS is <u>much</u> harder than PVeS

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No cryotarget boiling noise with solid target (BMP).

μ decay in flight provide a calibration reaction, determining beam flux, polarization, checking detector response — with a DAQ that can distinguish decay from scattering, we (hope to) continuously calibrate detector response.

Continuous calibration also reduces the sensitivity to helicity-correlated signals in the experiment.

30 MeV/c μ's: ~ 0.5 % decay / m
200 MeV/c μ's: ~ 0.1 % decay / m

PVμS is <u>much</u> harder than PVeS

Fundamental issues:

- low μ beam flux → low luminosity
  - BMP: can be overcome in the right kinematics*
- (Slow) helicity reversals to get cross section difference
- High count rates despite backgrounds being present

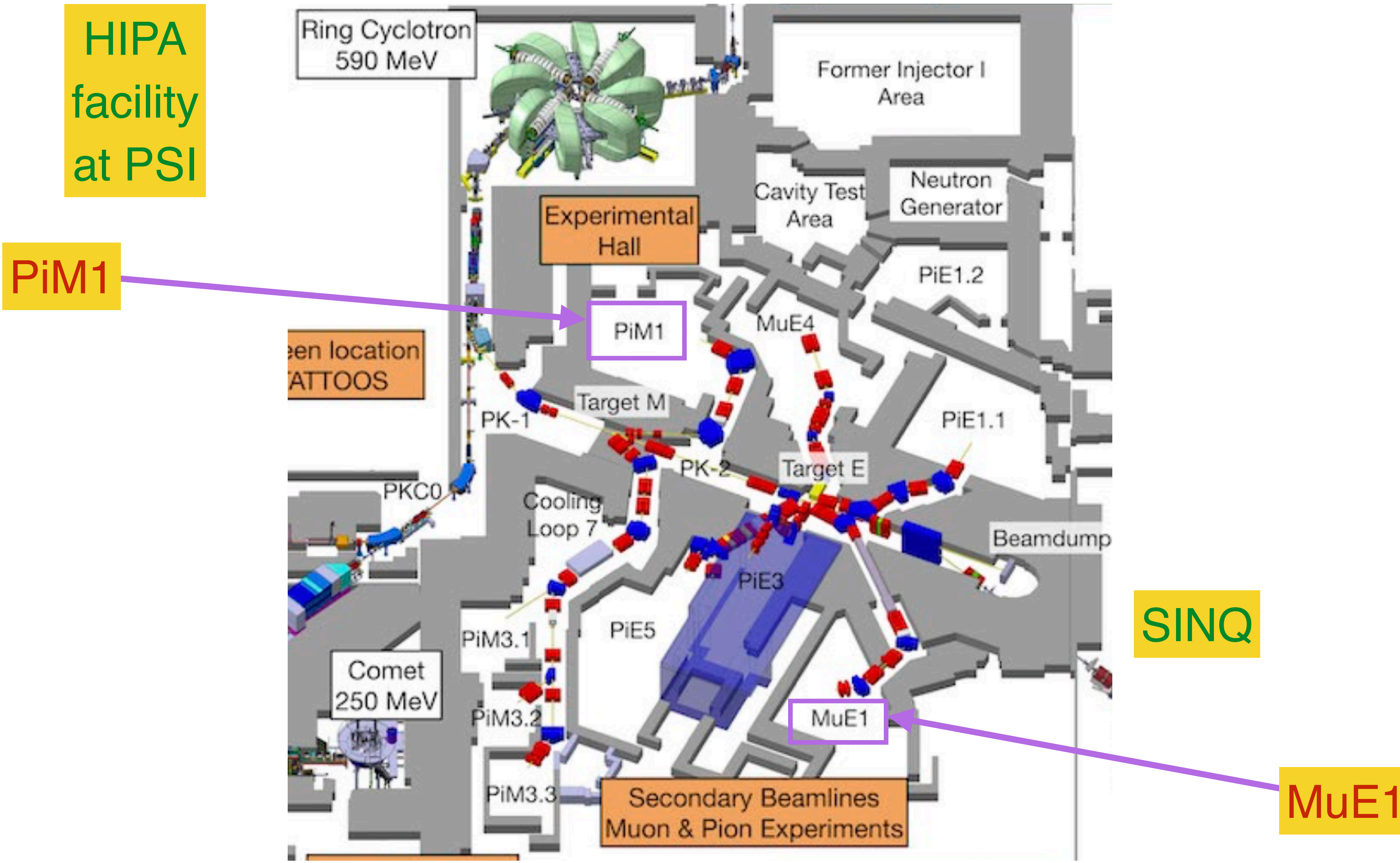
My suggestion:

We need a <u>clean</u> muon beam with at least slow helicity flip.

We need a modern DAQ that can count at high rates, and distinguish scattering from decays in flight.

We need excellent measurements of beam properties, as there are likely helicity correlations of position, etc.

How???
What can be done with existing facilities?



Will only be considering low energy parity violation in this talk.

How???
What can be done with existing facilities?

We cannot do PVμS in PSI PiM1 beam line (MUSE).

What about the existing μE1 beam line?

- Up to 10^8 μ/s, up to 140 MeV/c
- Polarized beams from π decay in flight
  - Can select forward- vs backward-going decays to get both polarization signs
- But:
  - large divergence / emittance, needing collimation
  - e and π backgrounds, asymmetric for + vs - polarization
  - no quick polarization flip
- Not feasible as is

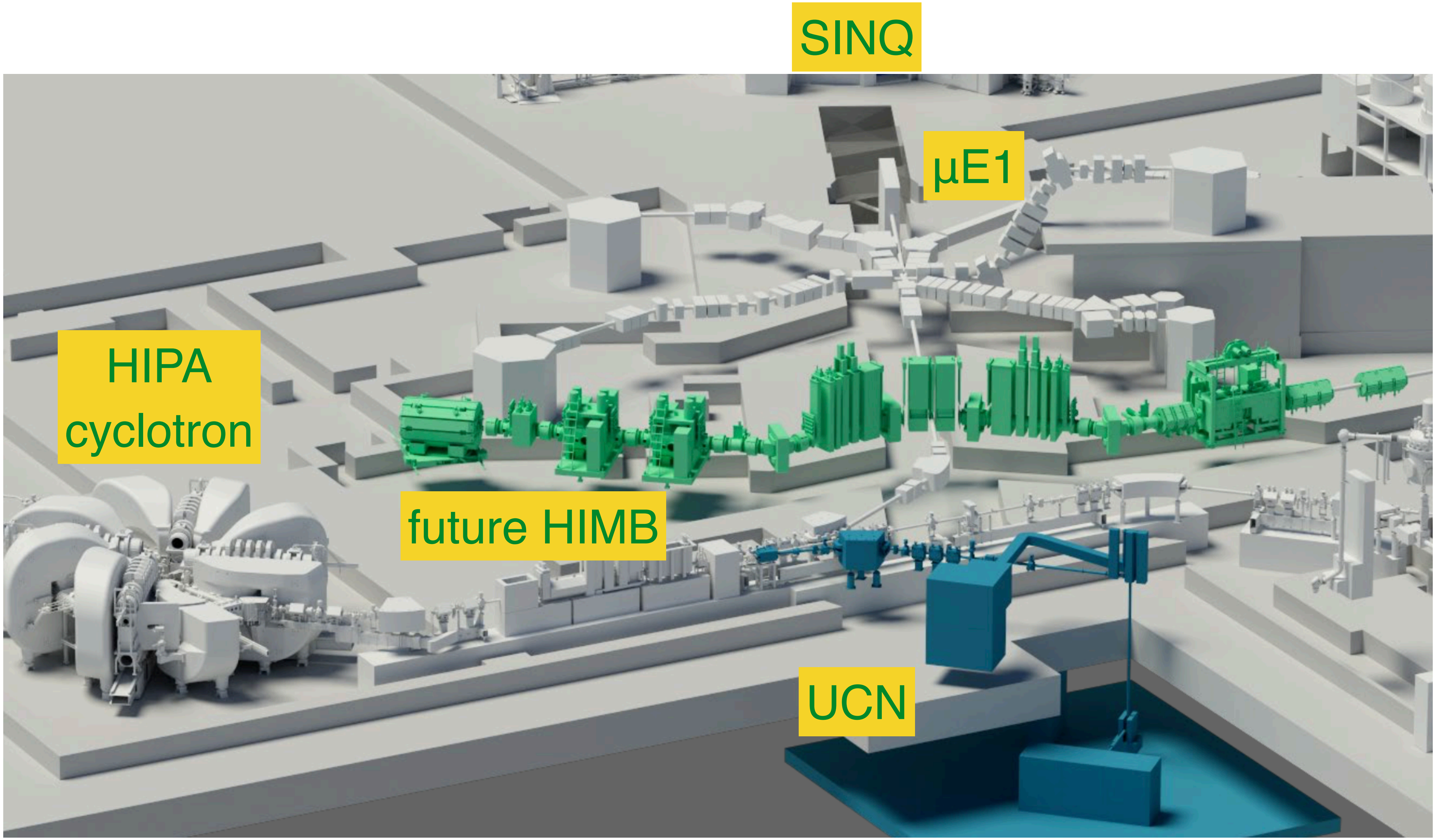
How???
What can be done with future facilities?

We cannot do PVµS in PSI PiM1 beam line (MUSE).
µE1 as is not well suited for PVµS.

One question we briefly thought about but not really explored:

- Can we clean up the µE1 beam?
  - Wien filter? Yes, if space and $.
  - RF separator? Loses flux.

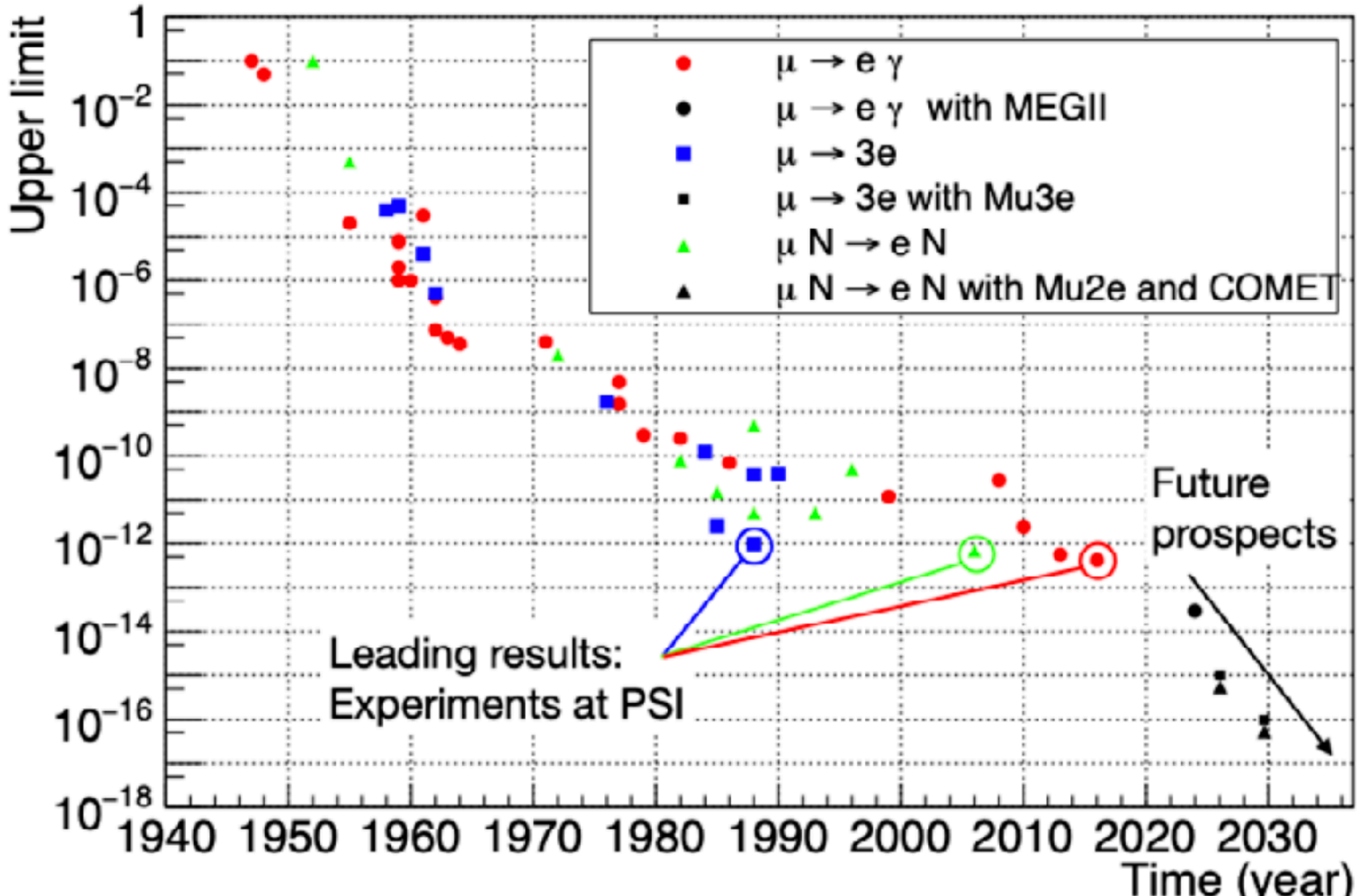
How???
What can be done with future facilities?



HIMB roughly half of the IMPACT project, which totals ~ $80 M

How???
What can be done with future facilities?

Why HIMB? From the CDR…



A physics program that requires μ's with no background. How?

How?
What can be done with future facilities?

Why HIMB? From the CDR…

The new target station will feature an optimized design to maximize the production of low-energy, positive muons ideally suitable for particle physics and condensed matter research. To improve the μ rates available for experiments by up to two orders of magnitude to 10^{10} μ/s, two radiation-hard, large-aperture capture solenoids are located in close proximity on the left and right side of the production target. The following beam transport is based on large-aperture solenoids and dipoles capable of transmitting a large phase space. This combination allows to capture and transport about 10 % of the emitted low-energy μ's to the experimental areas thereby greatly improving on the efficiencies of the current beamlines, which are typically at the per mil level.

How???
What can be done with future facilities?

We cannot do PVμS in PSI PiM1 beam line (MUSE).
μE1 as is not well suited for PVμS.

What about the HIMB beam line?

- Up to 10^{10} μ/s, optimized for 30 MeV/c surface muons, but up to 80 MeV/c
- ``100 %" polarized beam from π decay at rest at 30 MeV/c
  - Requires a "spin rotator" to reverse polarization

How???
What can be done with future facilities?

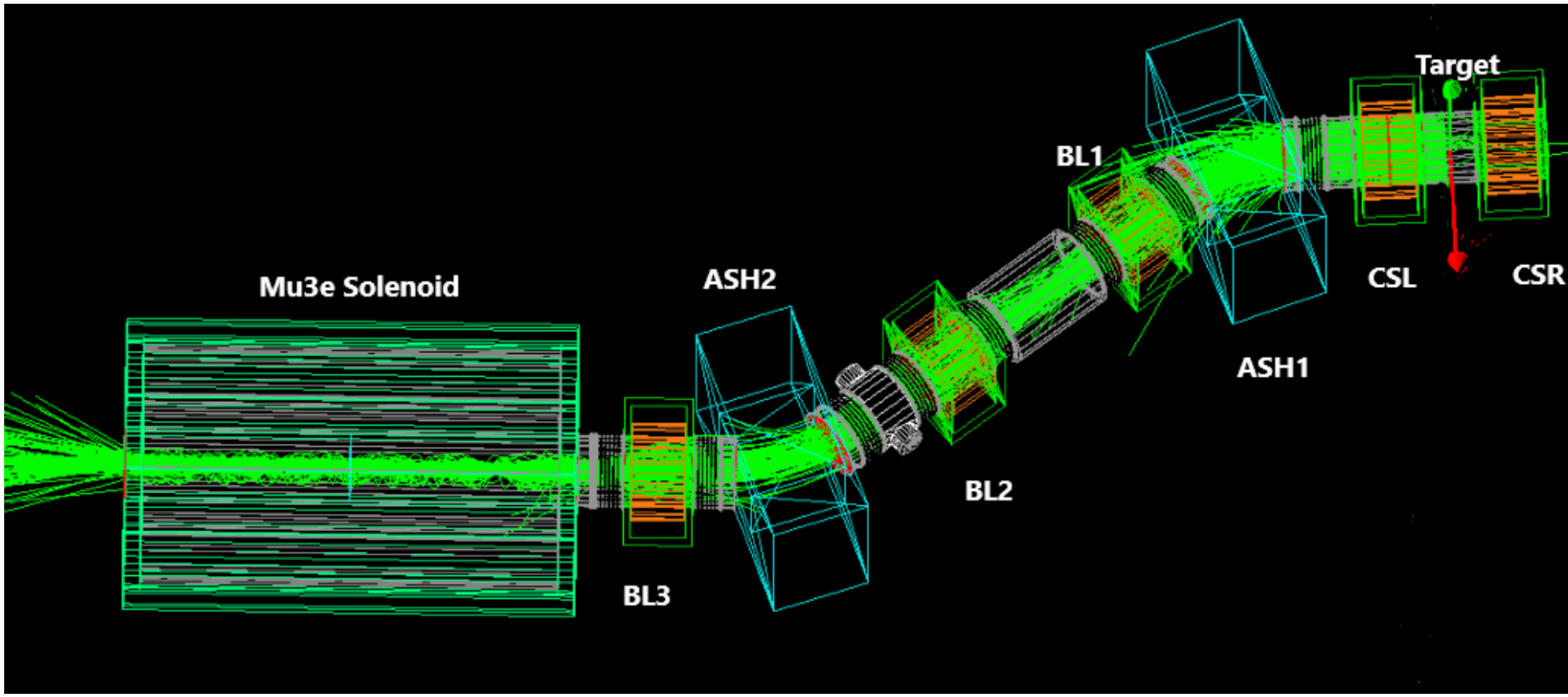


Figure 7.34: Current baseline solution for the MUH2 channel showing the main components, here including the Mu3e solenoid.

A number of tunes developed, all with similar fluxes, sizes, polarizations.
Planning for Wien filter for MUH2, spin rotator for MUH3.

How???

What can be done with future facilities?

Channel Version	Non-Solenoid Final Focus		
	Muon Rates/s at 2.4 mA I_P	spot sizes σ_X/σ_Y mm	Polarization
Short Channel	$1.22\cdot10^{10}$	40/42	-0.95
Baseline All Short Solenoids	$1.19\cdot10^{10}$	38/42	-0.96
All Long Solenoids	$8.2\cdot10^{9}$	45/53	-0.99
Long Capture Solenoids, Short Transport Solenoids	$9.3\cdot10^{9}$	39/42	-0.96

A number of tunes developed, all with similar fluxes, sizes, polarizations.

Planning for Wien filter for MUH2, spin rotator for MUH3.

How???
What can be done with future facilities?

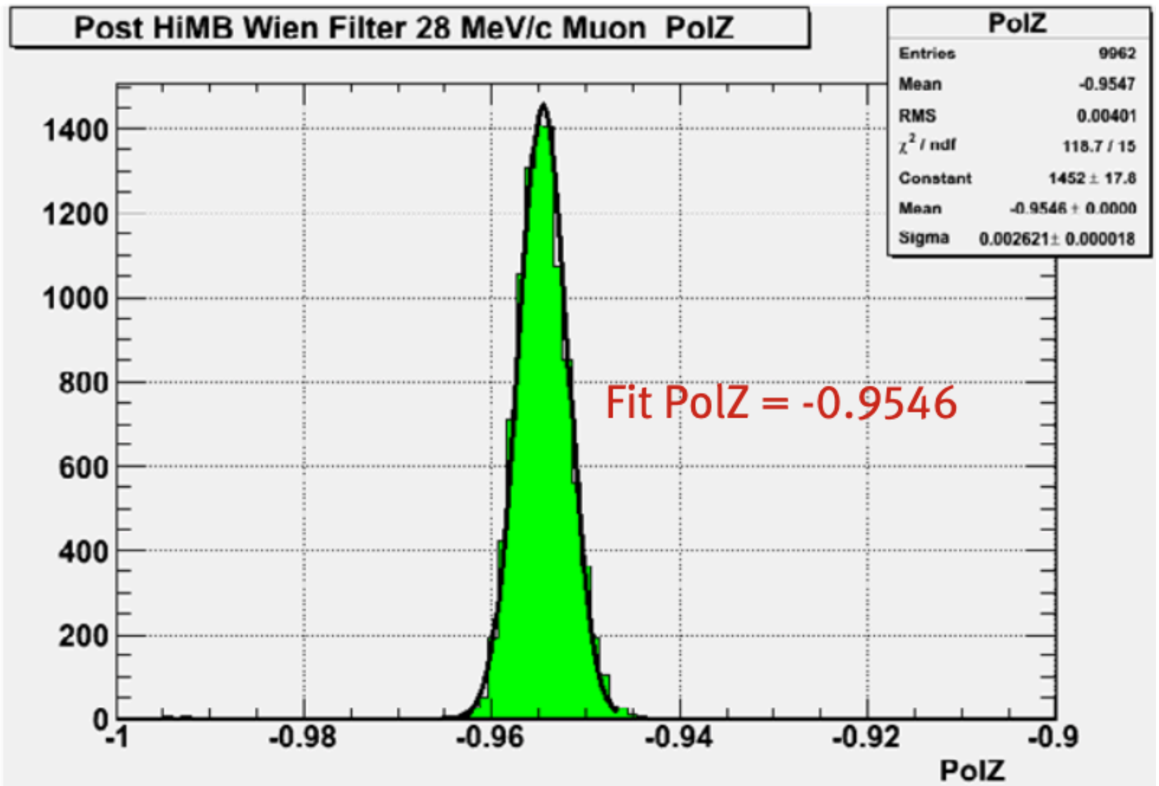


Figure 7.17: Shows a fit to the muon polarization distribution downstream of the Wien-filter for surface muons at 28 MeV/c. The fit results correspond exactly to the calculated rotation effect derived from Eq. 4.

Design parameters for 28 MeV/c	
High voltage separation mode	+/-30 kV
Spin rotation at 60kV	7.7°
High voltage spin rotation mode	+/-275 kV
Spin rotation at 550kV	70.7°
High voltage maximum	+/-300kV
Spin rotation at 600kV	77.1°
Electrode length	300 cm
Gap between electrodes	20 cm
Magnetic field integral	0.12 Tm
Gap between magnet poles	86cm
Beam transmission	70%
High voltage field orientation	vertical
E-field maximum	30 kV/cm
E-field integral at 60 kV	900 cm kV/cm
E-field integral at 550 kV	8250 cm kV/cm
E-field integral at 600 kV	9000 cm kV/cm

Table 7.10: Operational parameters of the existing spin rotator 1 device being operated at the piM3 beamline.

Spin rotator for MUH3 (77° at 28 MeV/c.)

How???
What can be done with future facilities?

Fundamental issues:

- low μ beam flux → low luminosity
  - BMP: can be overcome in the right kinematics*
- (Slow) helicity reversals to get cross section difference
- High count rates despite backgrounds being present

HIMB possible solutions:

- ~ 10^{10} μ/s
- (Slow) helicity changes
  - Will need more complete rotation of polarizations

Note: HIMB uses surface muons, which reduces the RF time structure for the muons — but not for the electrons or pions entering the channels.

Beam flux varies a factor of ~ 2 over 20 ns.

For a “BMP” experiment, we might be better off with an RF time structure, and running electrons at times for systematics checks.

How???
What can be done with future facilities?

Last fundamental issues:

- High count rates despite backgrounds being present

With a clean beam, we need to handle high counting rates with contributions from 2 backgrounds:

- decays in flight
- photons

Decays in flight can be isolated with target-in vs target-out measurements.

Both of these are simpler with an RF structure to the beam and a modern DAQ:

- pixel detectors with ~ ps timing readout
- streaming readout

How???
What can be done with future facilities?

Nice pixel technology is being developed at PSI. From HIMB CDR…

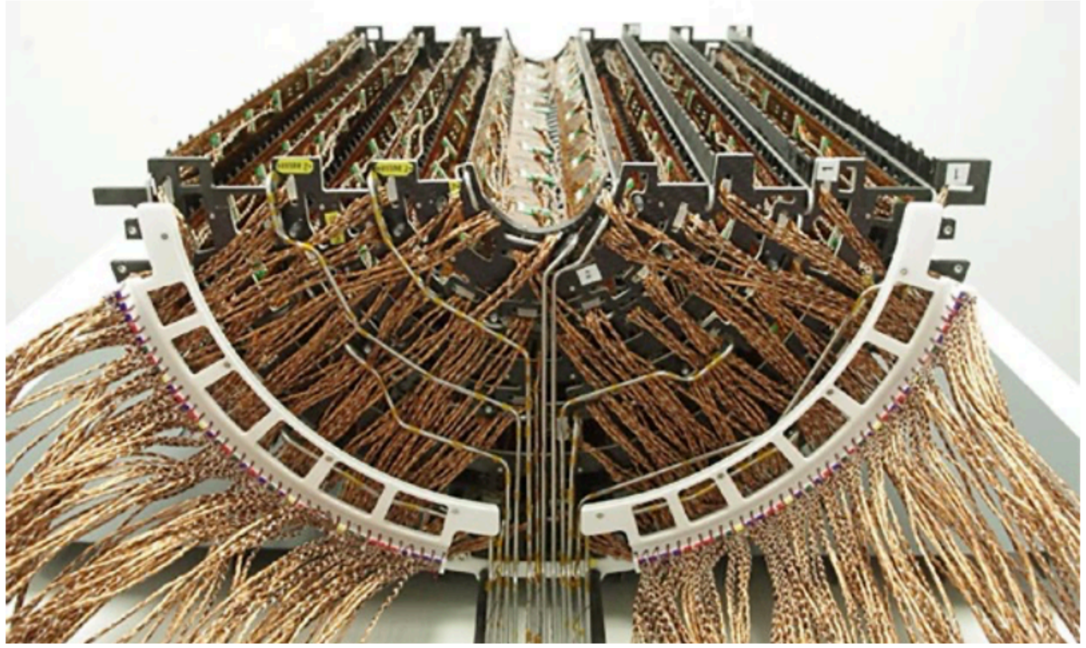


Figure 6.1: Picture of one half of the CMS Phase-1 pixel barrel detector built at PSI in 2017.

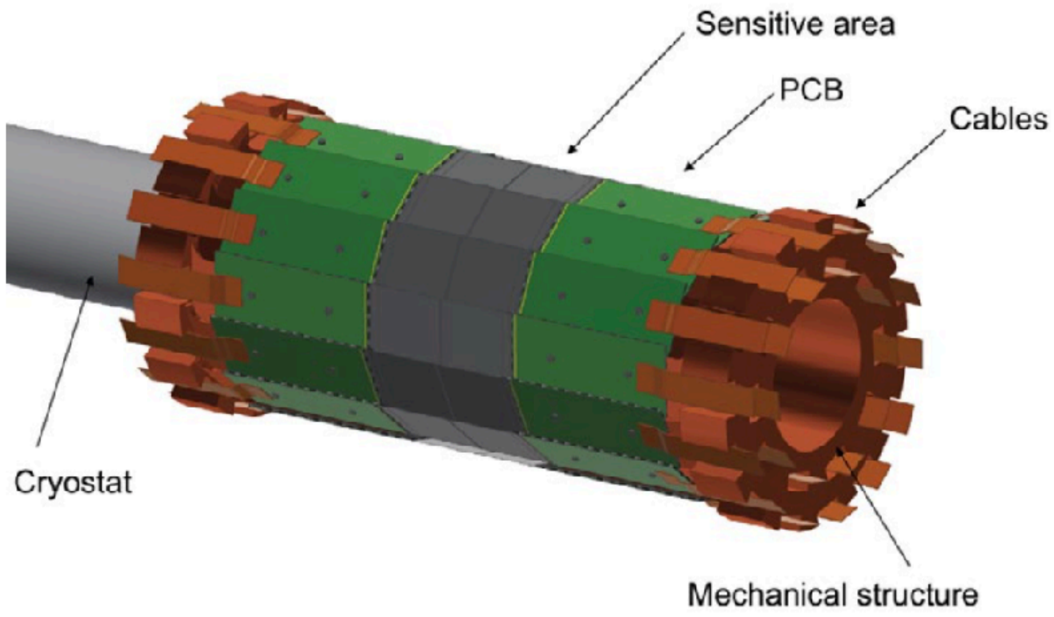


Figure 6.3: Concept of a pixel detector for a muSR instrument.

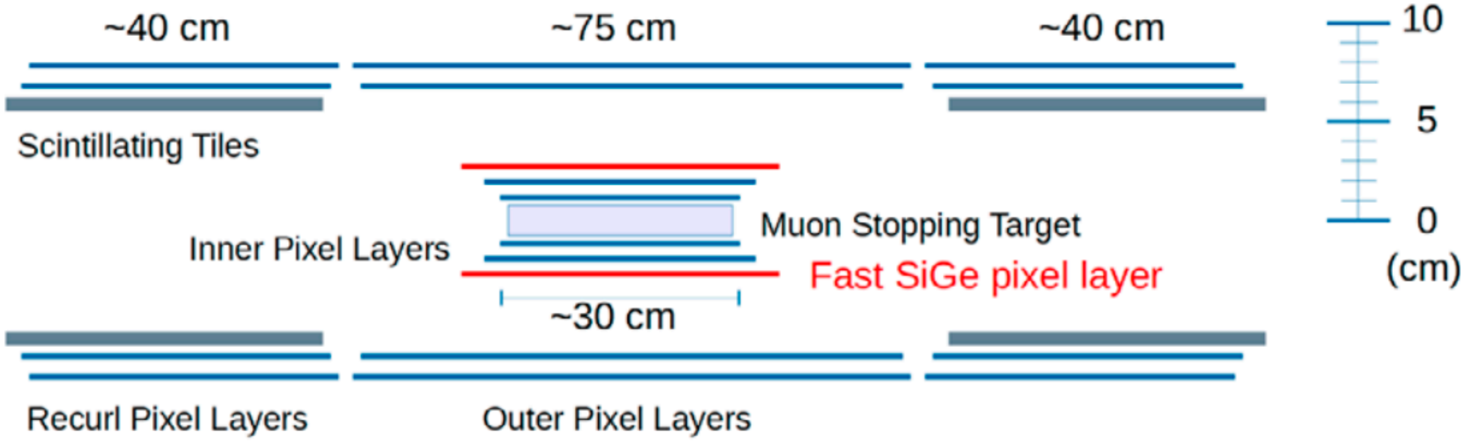
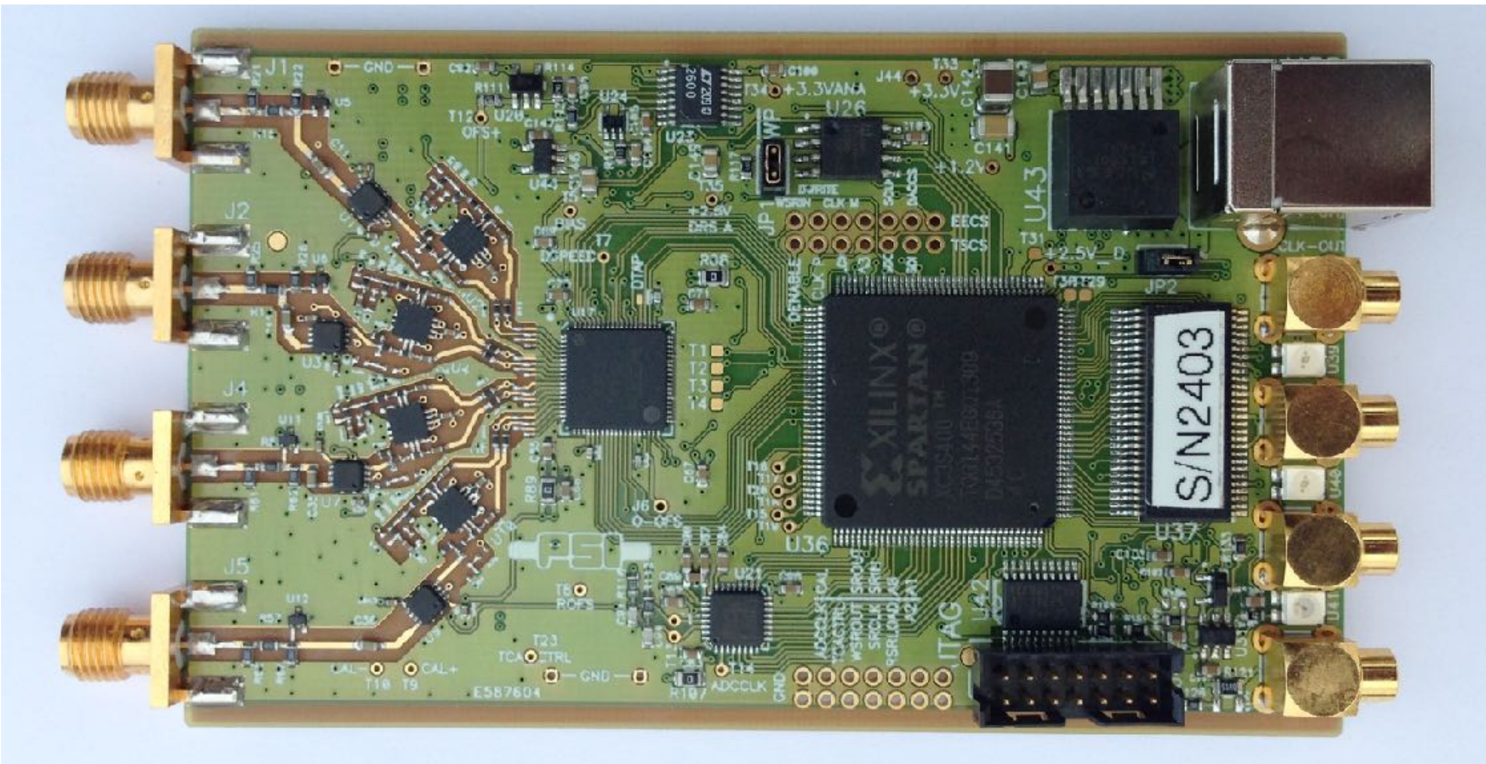


Figure 6.2: Sketch of an elongated detector design for Mu3e Phase-2 at HIMB.

How???
What can be done with future facilities?

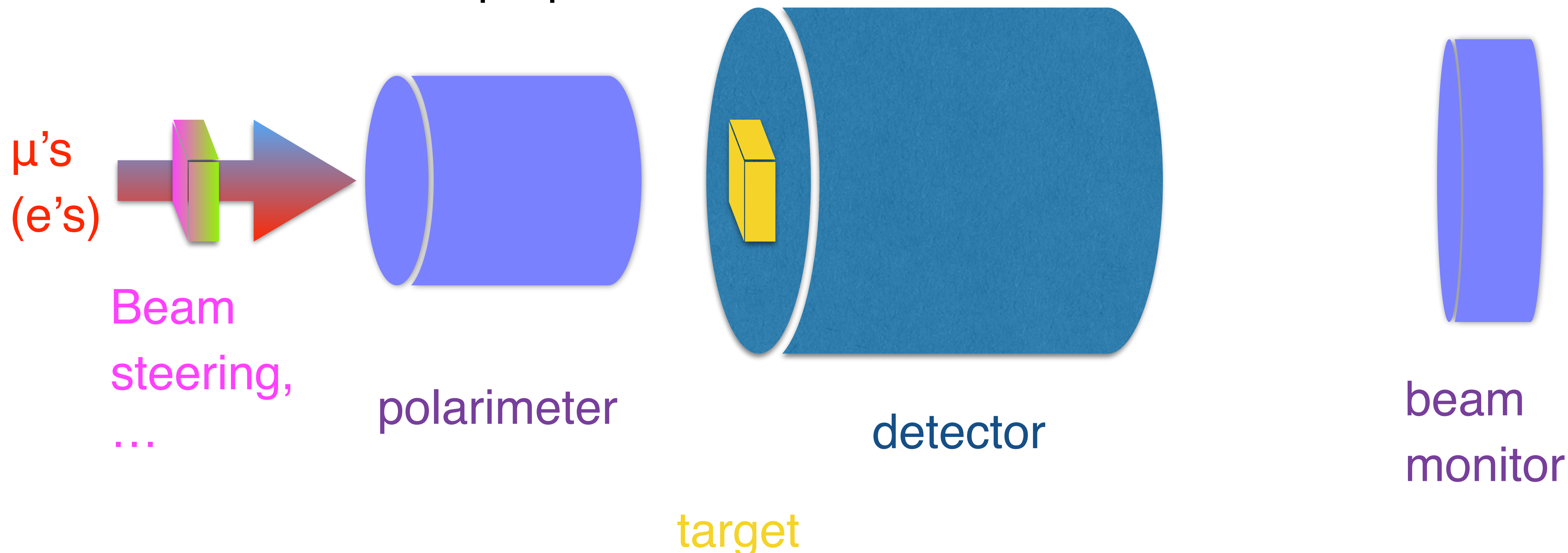
And electronics…



PSI DRS4 evaluation board:
Triggered, 1024 samples at up to 5 GHz, timing as good as 2 ps

How???
What can be done with future facilities?

"Straw" detector proposal



MU3E detector is a good starting point for the muon polarimeter design. Double-barrel for the detector, inner barrel to detect muons, outer barrel to reject electrons.

4. Conclusion / Summary

There are fundamental difficulties in trying to measure PVμS.

- low μ beam flux → low luminosity
- (Fast) helicity reversals to get cross section difference
- High count rates despite backgrounds being present

PVμS will never be as good as PVeS, but it might be good enough.

- Sufficient flux of a clean μ beam for a 1 ppm measurement
- Ability to manipulate spin needed, fast flip is not
  - It appears none of the PSI beam lines as is are quite right
- Need modern detectors with fast readout
- Probably ~ $1 M (?) and 5 years to prototype and test and get started, and ~ $10 M (?) and 10 (?) years to get there, if theory support and all goes well

Thank you

Running of the Weak Coupling Constant

From the Qweak paper (Nature, 2018)

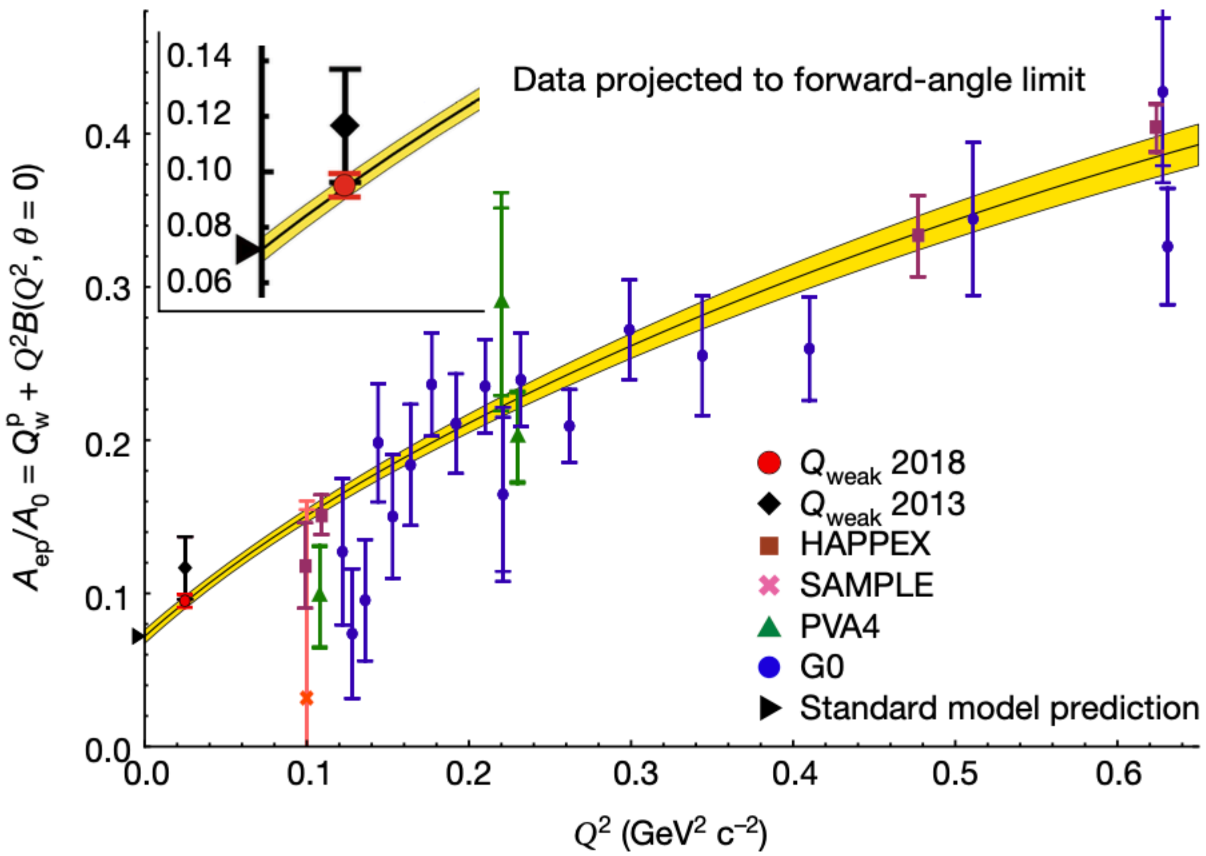
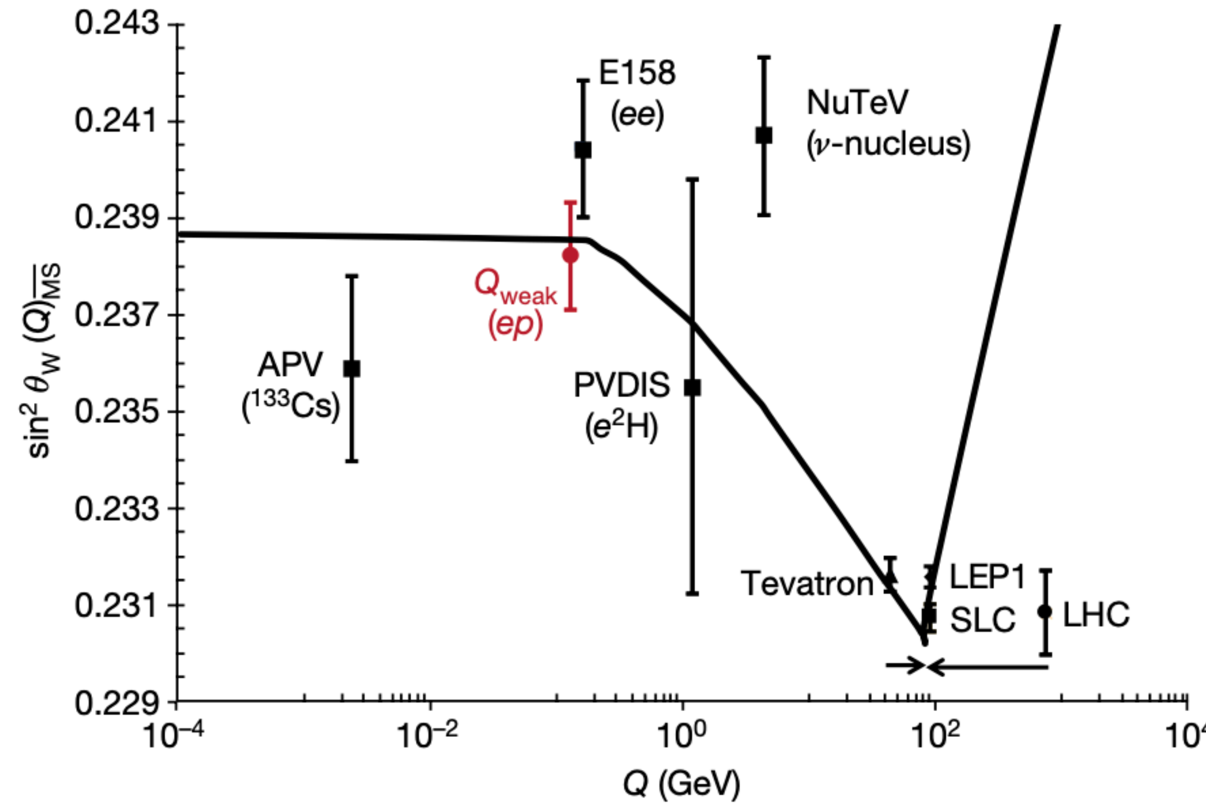


Fig. 2 | The reduced asymmetry $A_{ep}/A_0 = Q_w^p + Q^2B(Q^2, \theta = 0)$ versus Q^2.



PVDIS is the recent JLab measurement, not the original Prescott SLAC measurement

False Asymmetries

Getting the beautiful data and good physics asymmetries with integrating electronics is a problem.

There are lots of false asymmetries.

- Detector response changes with temperature — day/night asymmetries
- Voltages change with time
- 60 Hz electric power noise - cannot operate at multiples of 60 Hz or any other equipment frequencies
- Any helicity correlated signal can induce currents and false asymmetries
- Any helicity correlated beam properties (position, angle, energy) can introduce false asymmetries
- Transverse polarized beam asymmetries of similar magnitude to PV asymmetries — need to align spin to momentum
- …

Paranoia is an asset, if you specialize in PV