PR12-22-005

A Search for a Nonzero Strange Form Factor of the Proton at 2.5 $(GeV/c)^2$

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LaTech, Indiana, UVa, JLab, CUA, INFN - Roma, Temple, Ohio, Syracuse, Glascow, FIU, CNU, Fermilab, UWashington, Tel Aviv U, Hebrew U, W&M, AANL Yerevan, Northern Michigan, UConn, Orsay

Charge symmetry and the nucleon form factors

Charge Symmetry

$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p}$$
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n}$$

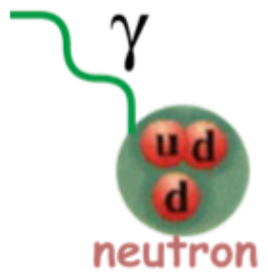
Charge symmetry is assumed for the form factors, $G_E^{u,p} = G_E^{d,n}$, *etc.*
and used to find the flavor separated form-factors,
measuring $G_{E,M}^{p,n}$ to find $G_{E,M}^{u,d}$

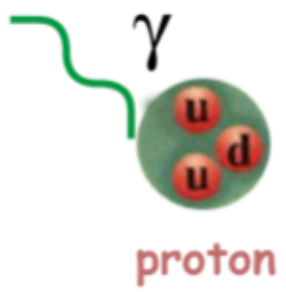
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n} - \frac{1}{3}G_E^s$$

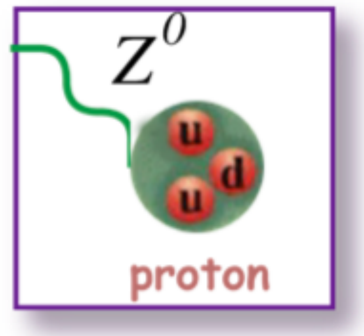
But this can broken! One way is to have a non-zero strange form-factor, which breaks the "2 equations and 2 unknowns" system

The weak form factor provides a third linear combination:

$$G_E^{p,Z} = \left(1 - \frac{8}{3}\sin^2\theta_W\right)G_E^{u,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_E^{d,p} + \left(-1 + \frac{4}{3}\sin^2\theta_W\right)G_E^s$$







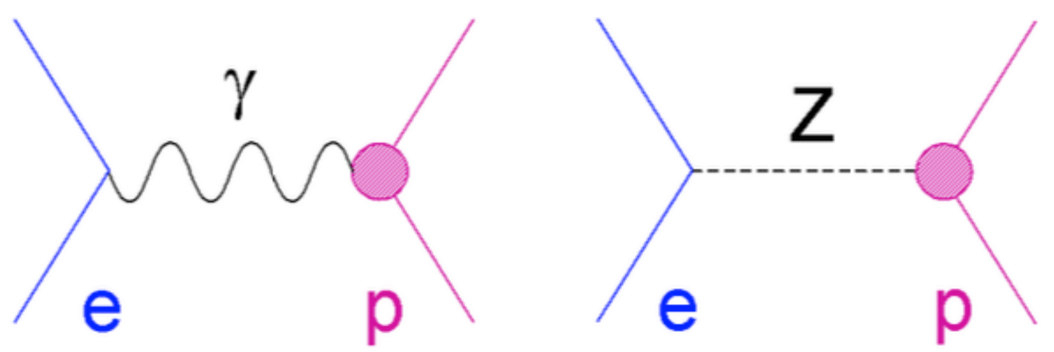
A strange quark form factor would be indistinguishable from a broken charge symmetry in u,d flavors

$$\delta G_E^u \equiv G_E^{u,p} - G_E^{d,n}$$
$$\delta G_E^d \equiv G_E^{d,p} - G_E^{u,n}$$

So, more generally: this experiment tests the assumption of charge symmetry which is crucial to the flavor decomposition of the form factors

Strangeness form factors

Polarized electron beam elastic e-p scattering



$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot [(1-4\sin^2\theta_W) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}$$

$$+ \epsilon'(1-4\sin^2\theta_W)\frac{G_M^p G_A^{Zp}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}]$$

A_{PV} = 150 ppm at θ = 15.5°, Q^2 = 2.5 GeV^2 (for sFF = 0)

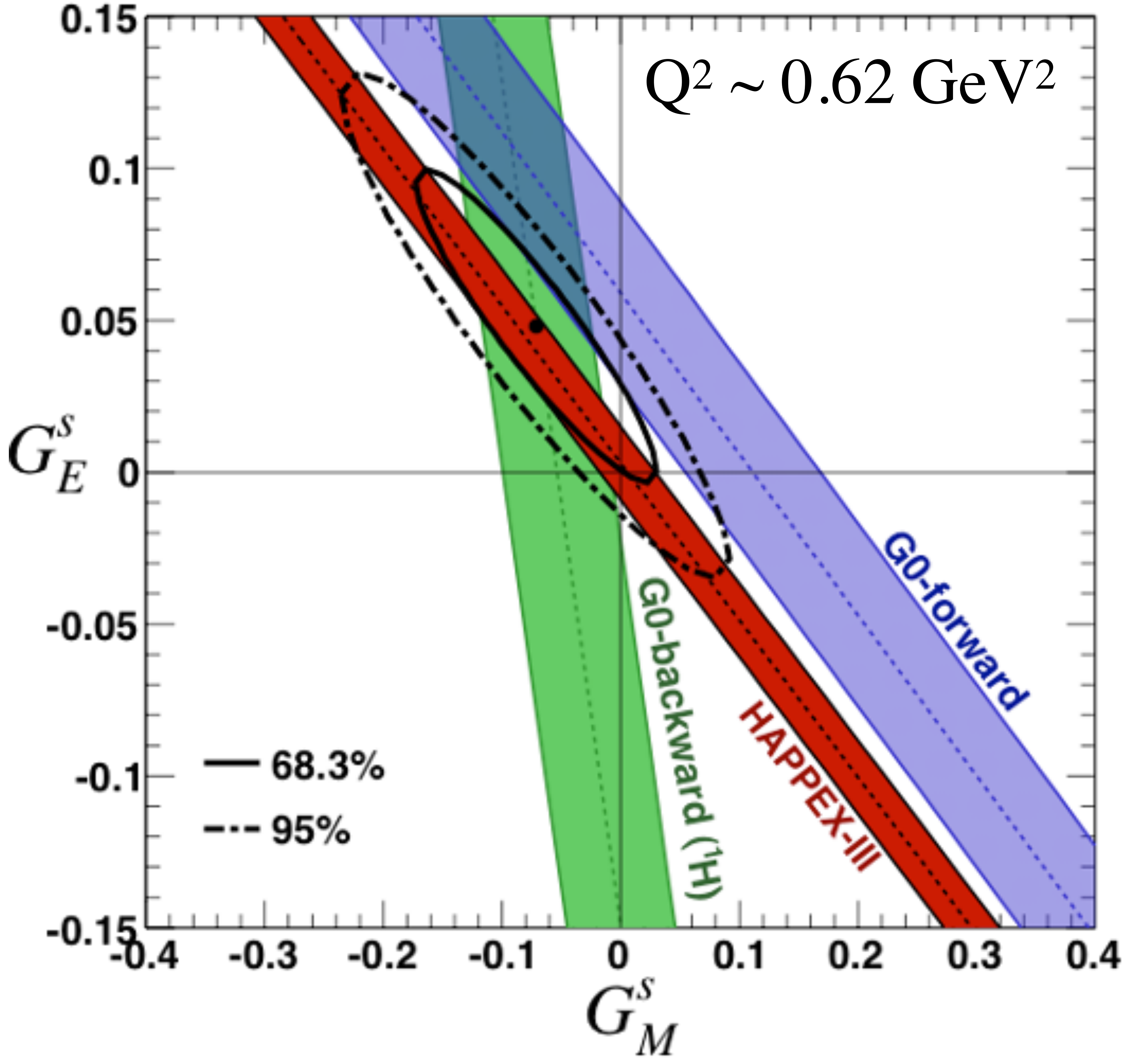
A_{PV} = (-226 ppm) *[0.075 + 0.542 – 6.43*($G_M^s + 0.32\, G_E^s$) + 0.038]

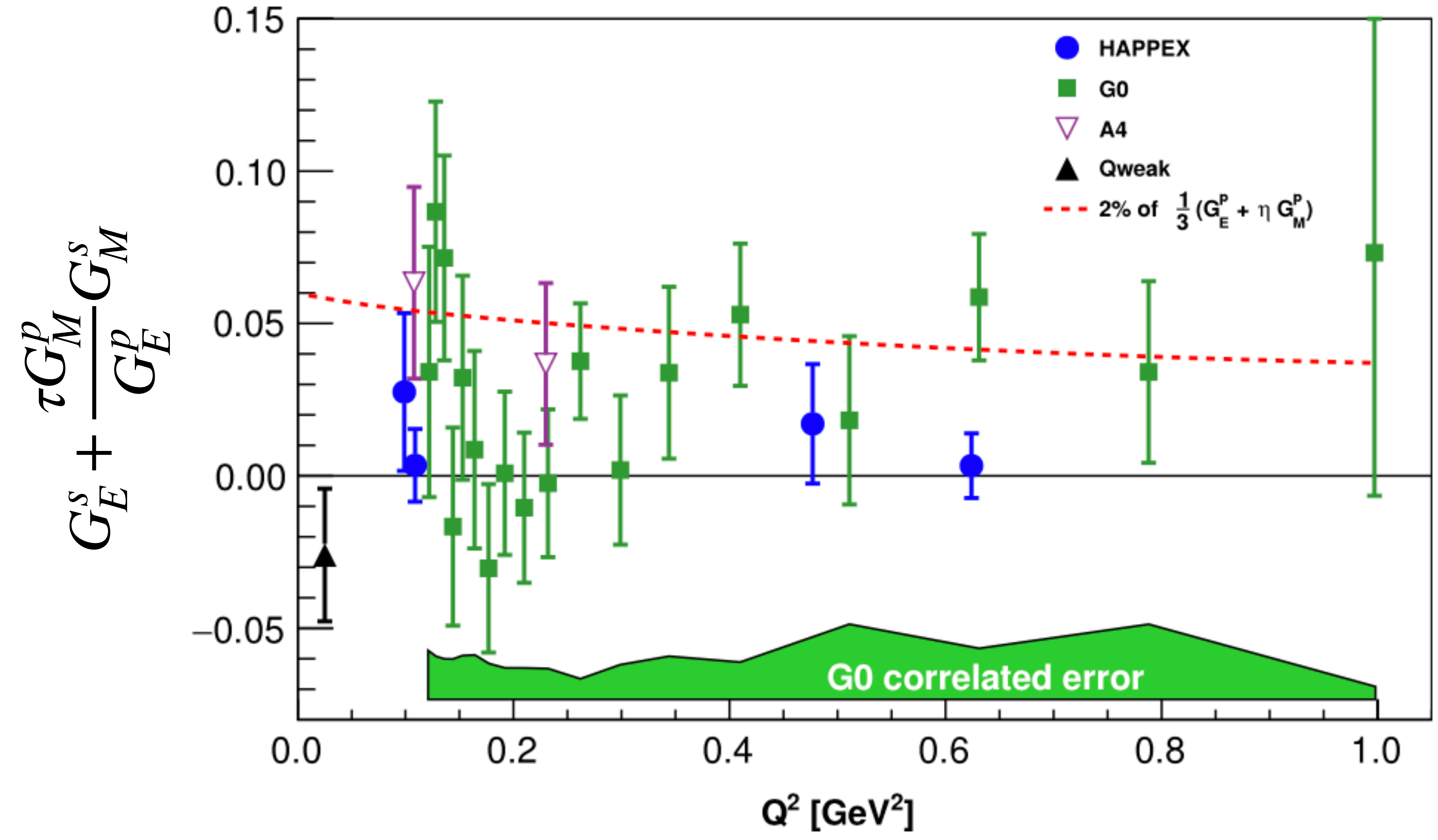
Q_w EMFF axial

strange form-factors

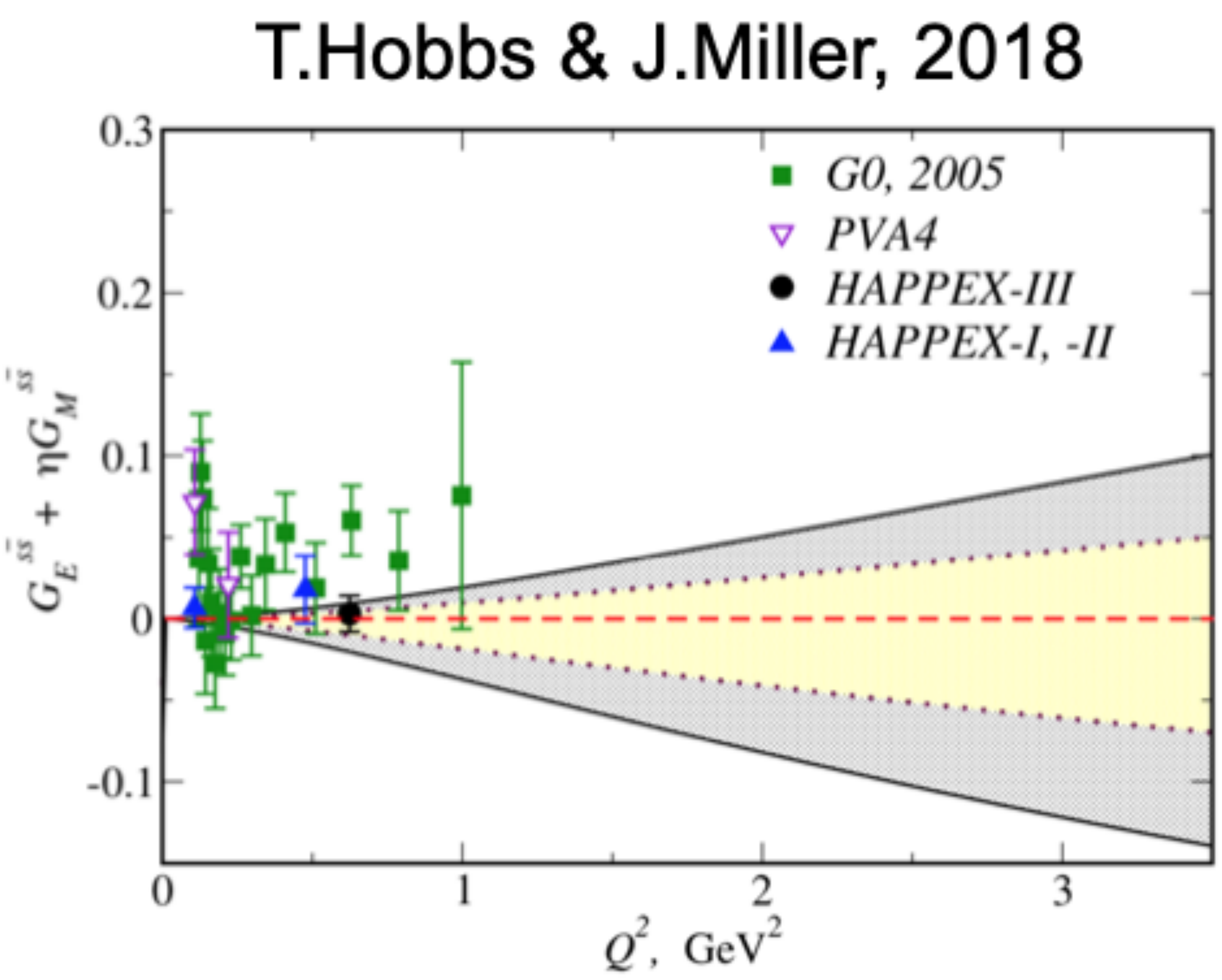
Proton strange form factors via parity violating elastic electron scattering

Strange form factors consistent with zero at low Q^2, but do not rule out non-zero values at higher Q^2, especially for magnetic form factor which is more accessible at higher Q^2





Strange form-factor predictions



Follows work from *Phys.Rev.C* 91 (2015) 3, 035205
(LFWF to tie DIS and elastic measurements in a simple model)

Conclusion: sFF small (but non-zero) at low Q^2, but quite reasonable to think they may grow relatively large at large Q^2

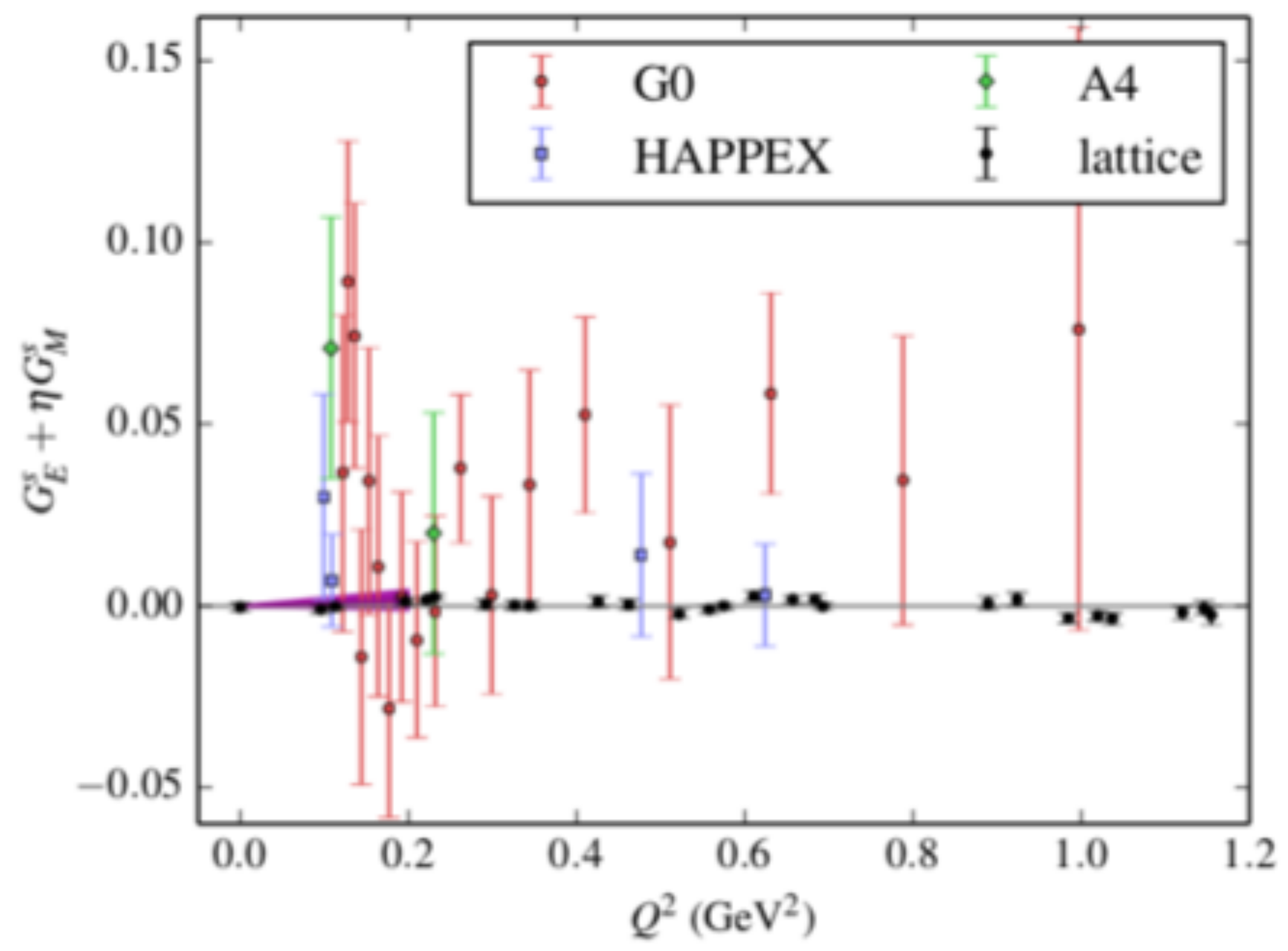
G_D = 0.0477 at 2.5 GeV^2
uncertainty here ranges from (0.036,-0.051)

G_s/G_D ~ 1 is not excluded

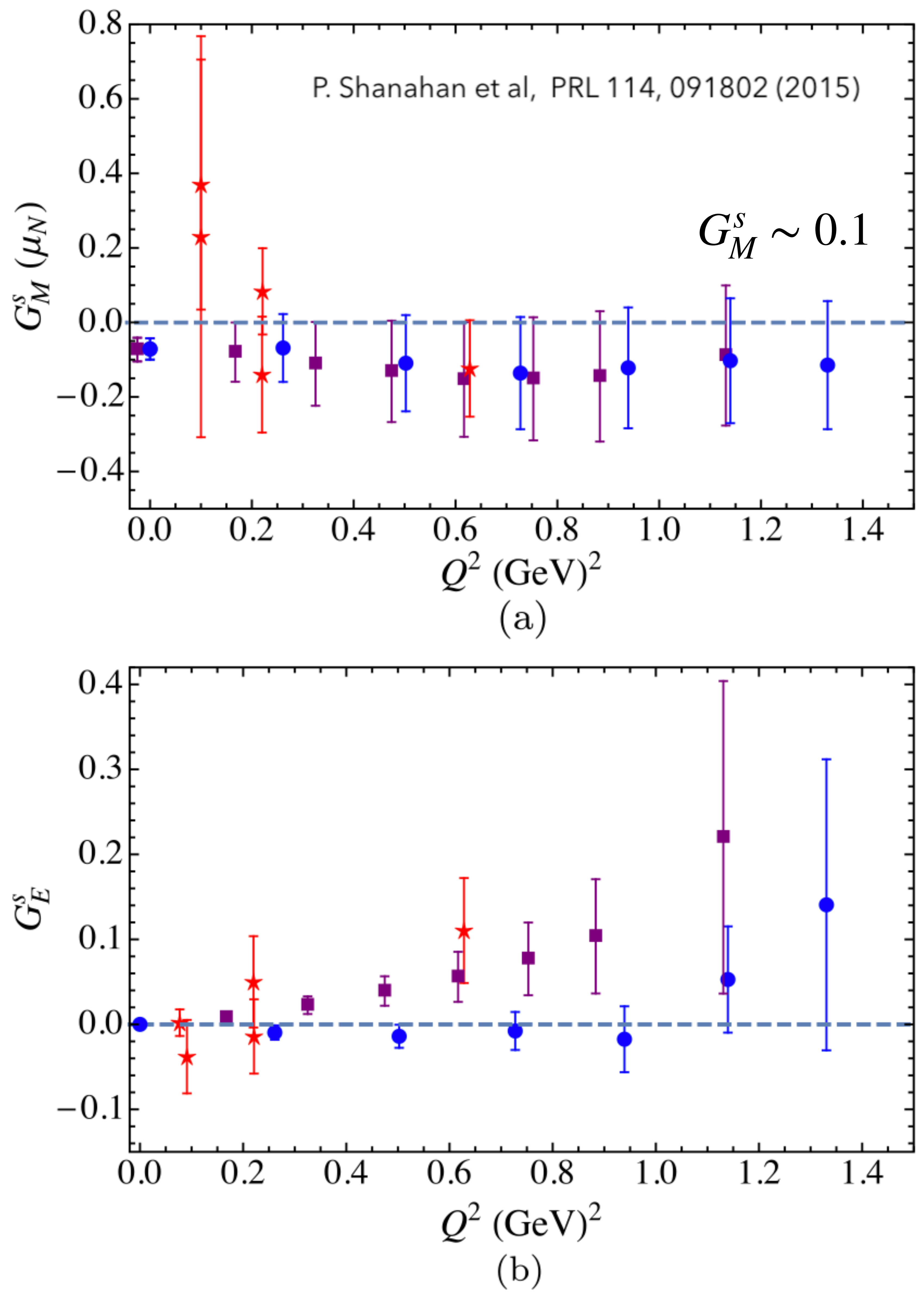
Tim Hobbs and Jerry Miller have both joined the collaboration

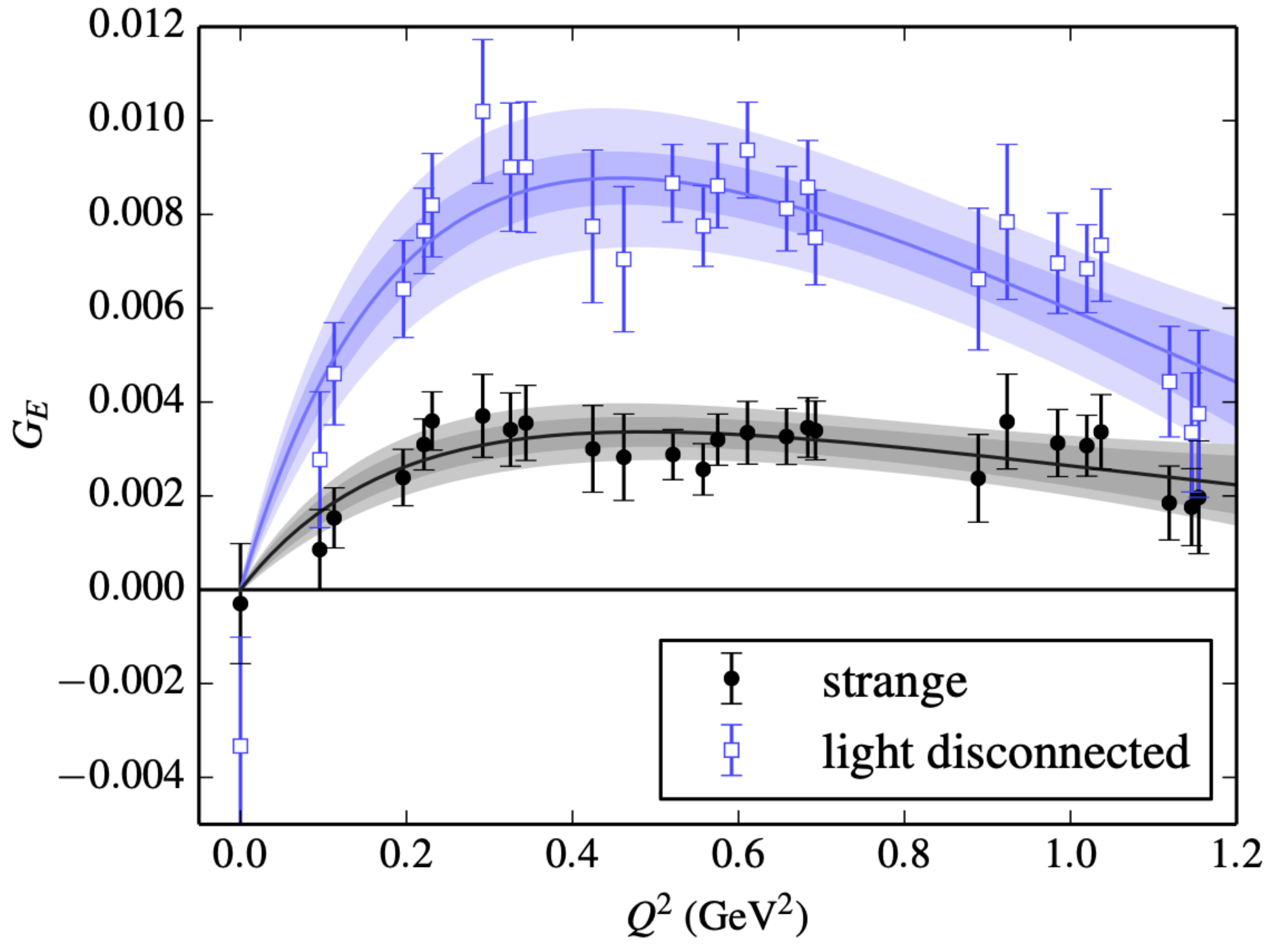
Strange form-factors on the lattice

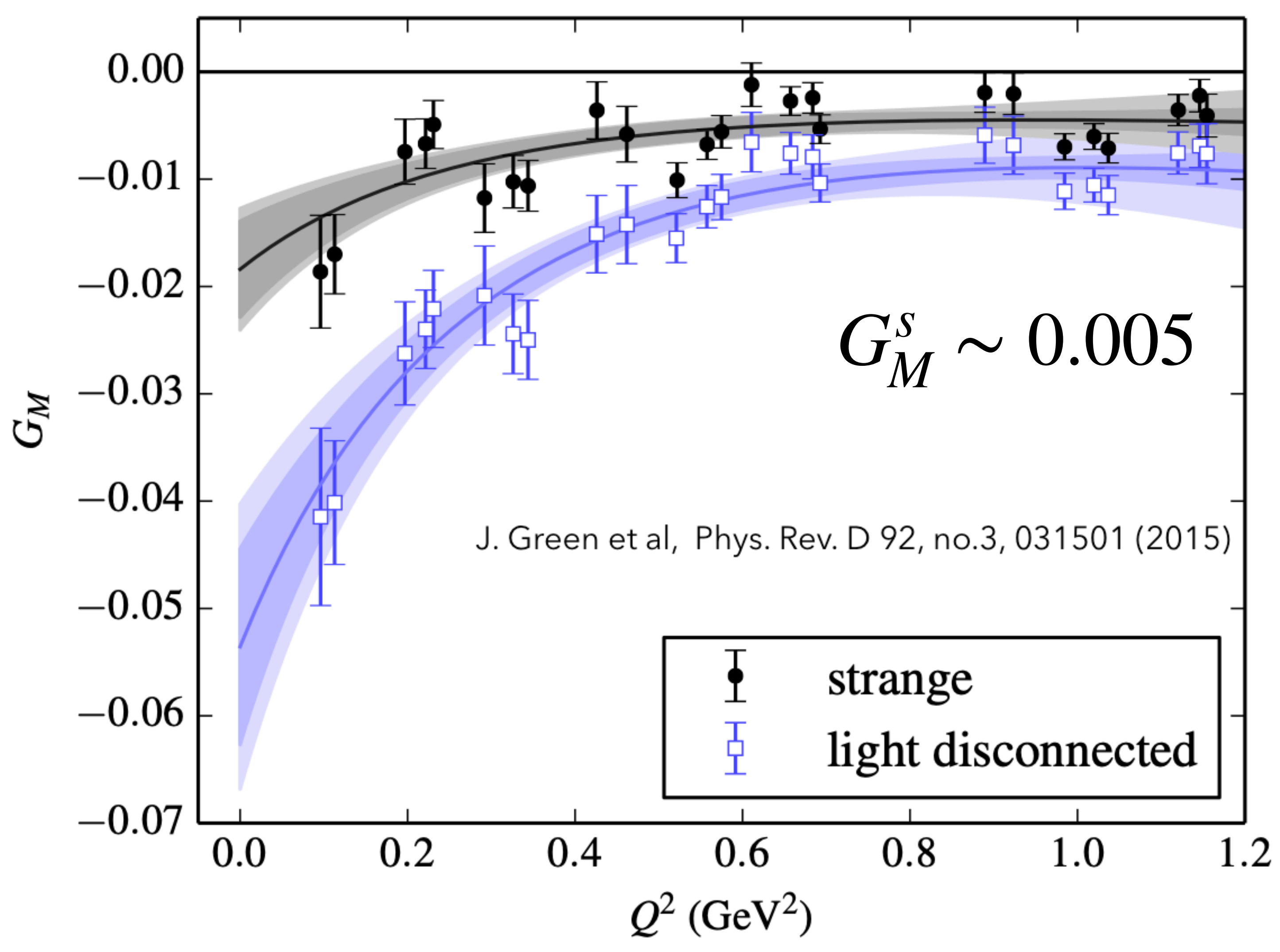
J.Green etal, 2015



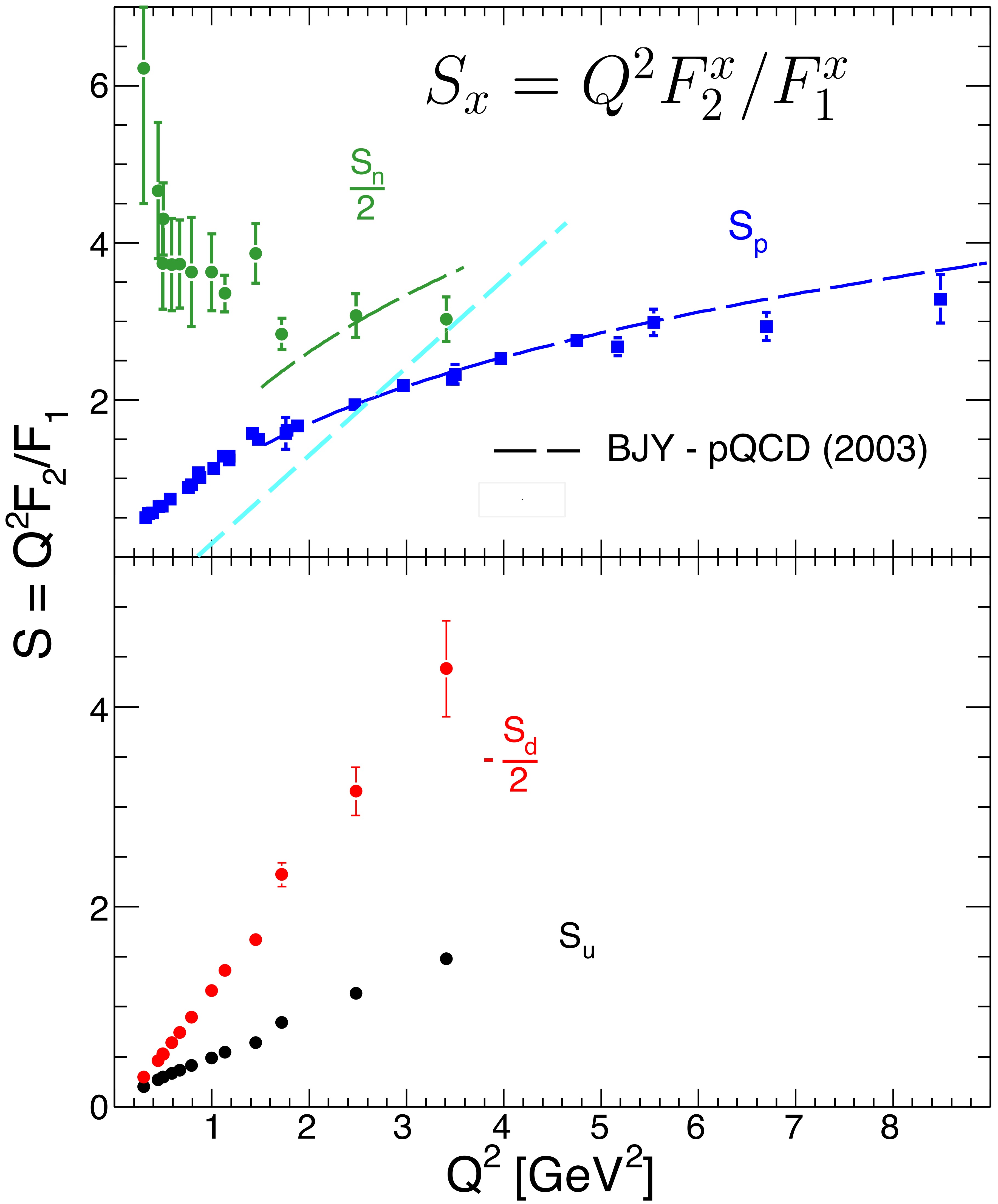
Some lattice calculations predict non-zero central values that would be visible with the proposed precision







Q^2 dependence of F_2/F_1



pQCD prediction for large Q^2: scaling
$$S \to Q^2 F_2/F_1$$

The lines for individual flavor are straight: F_2/F_1 ~ constant

Cates, de Jager, Riordan, Wojtsekowski, Phys.Rev.Lett. 106 (2011) 252003

Q^2 dependence of Q^4F_1

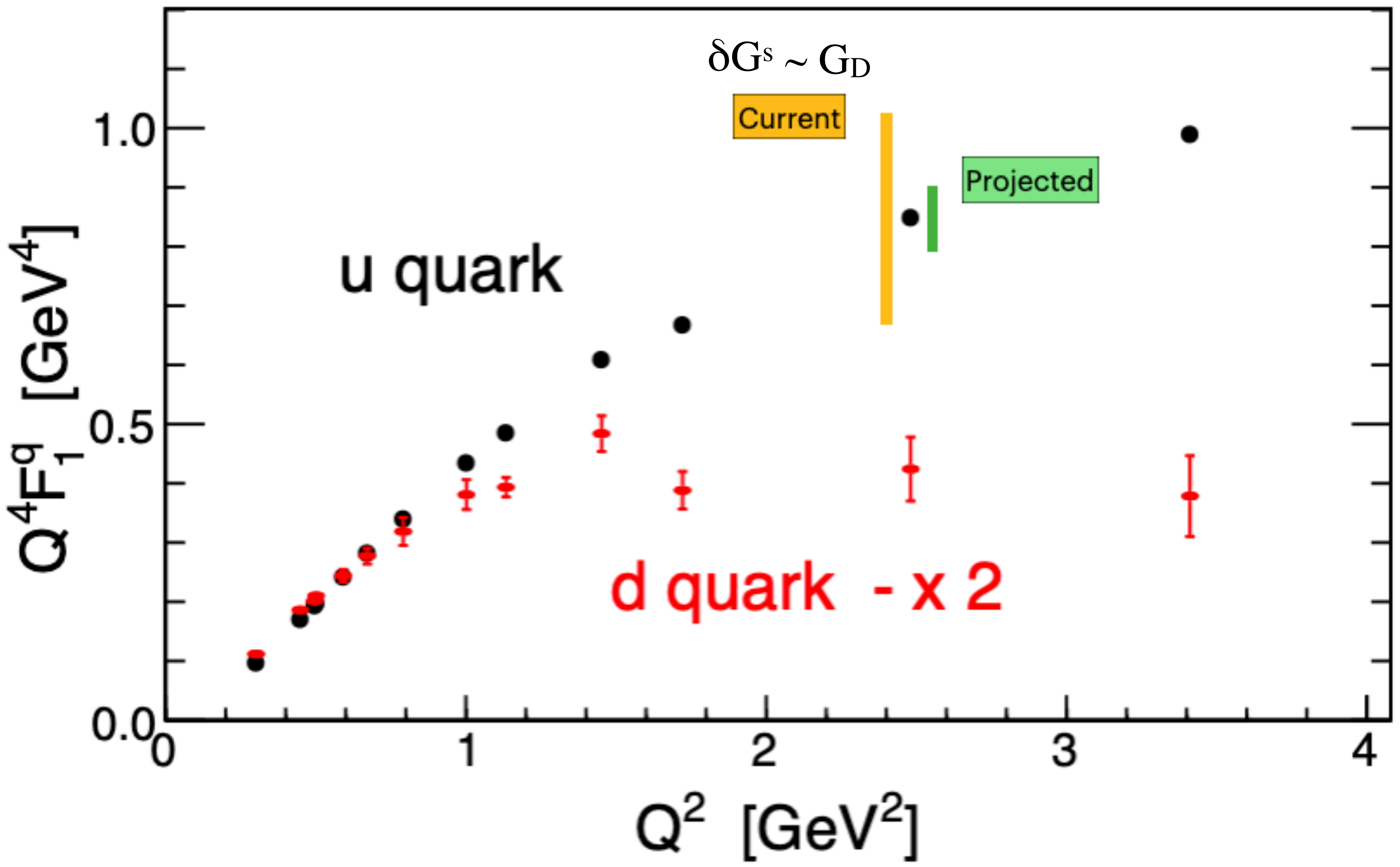
$$F_{1p} = e_u\, F_1^u \; + \, e_d\, F_1^d \; + \, e_s\, F_1^s$$

$$F_{1n} = e_u\, F_1^d \; + \, e_d\, F_1^u \; + \, e_s\, F_1^s$$

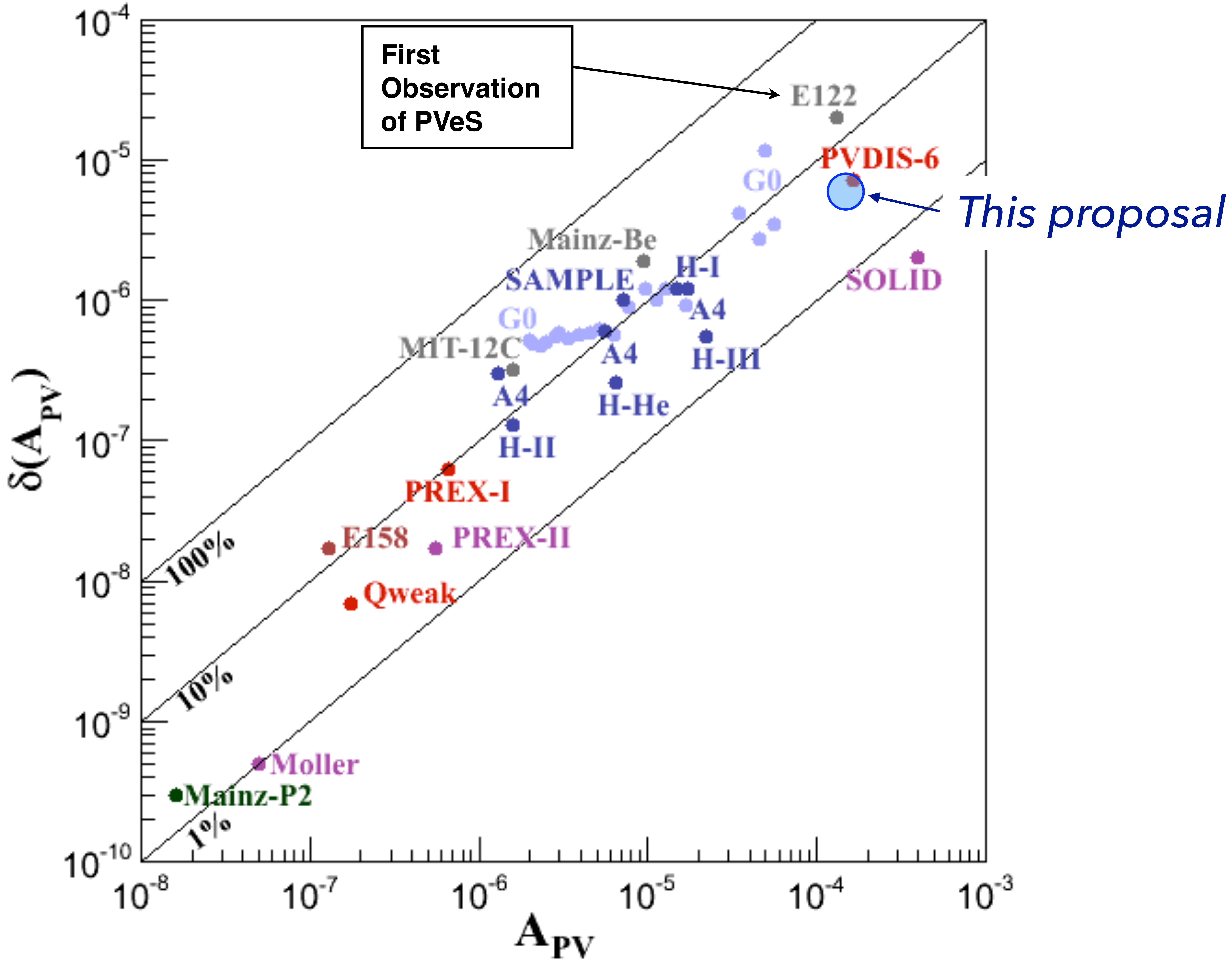
$$F_1^u = 2F_{1p} + F_{1n} - F_1^s \qquad F_1^d = 2F_{1n} + F_{1p} - F_1^s$$

Assuming $\delta G^s_{E,M} \sim G_D \sim 0.048 \longrightarrow \delta(Q^4 F_1^u) \sim \pm\, 0.17$

$$F_1 = \frac{G_E + \tau G_M}{1+\tau} = \frac{G_E + 0.7 G_M}{1.7} \sim \frac{G_D}{1.7}$$



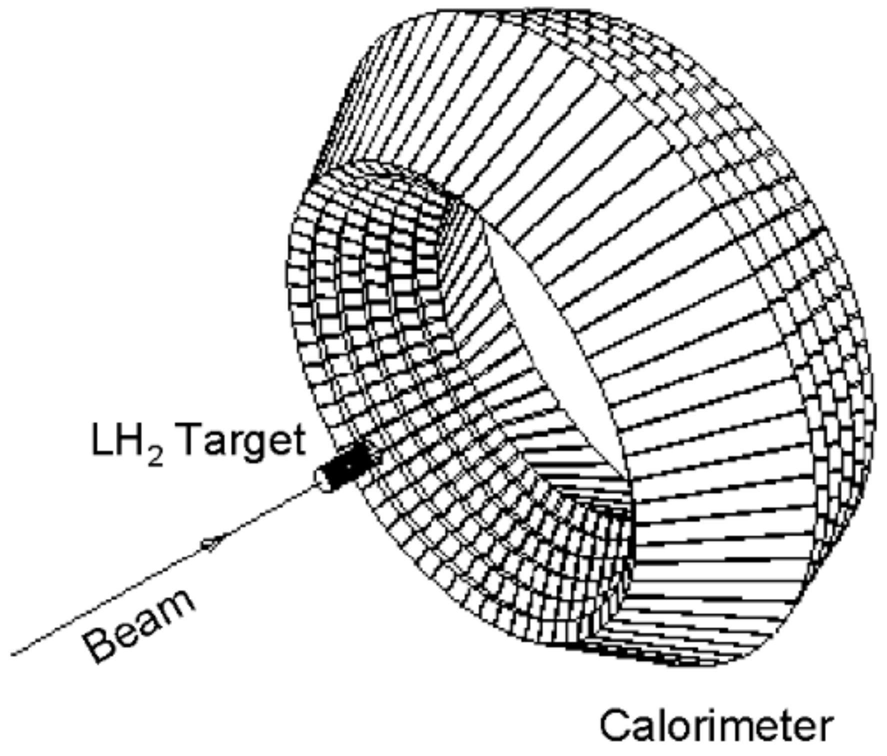
- Form factors are a crucial constraint on GPDs, and the flavor content must be understood
- Whatever future data informs GPDs and the nucleon femtography project, form-factors will remain an important constraint
- The quark flavor content of the form-factor must be known for this purpose!

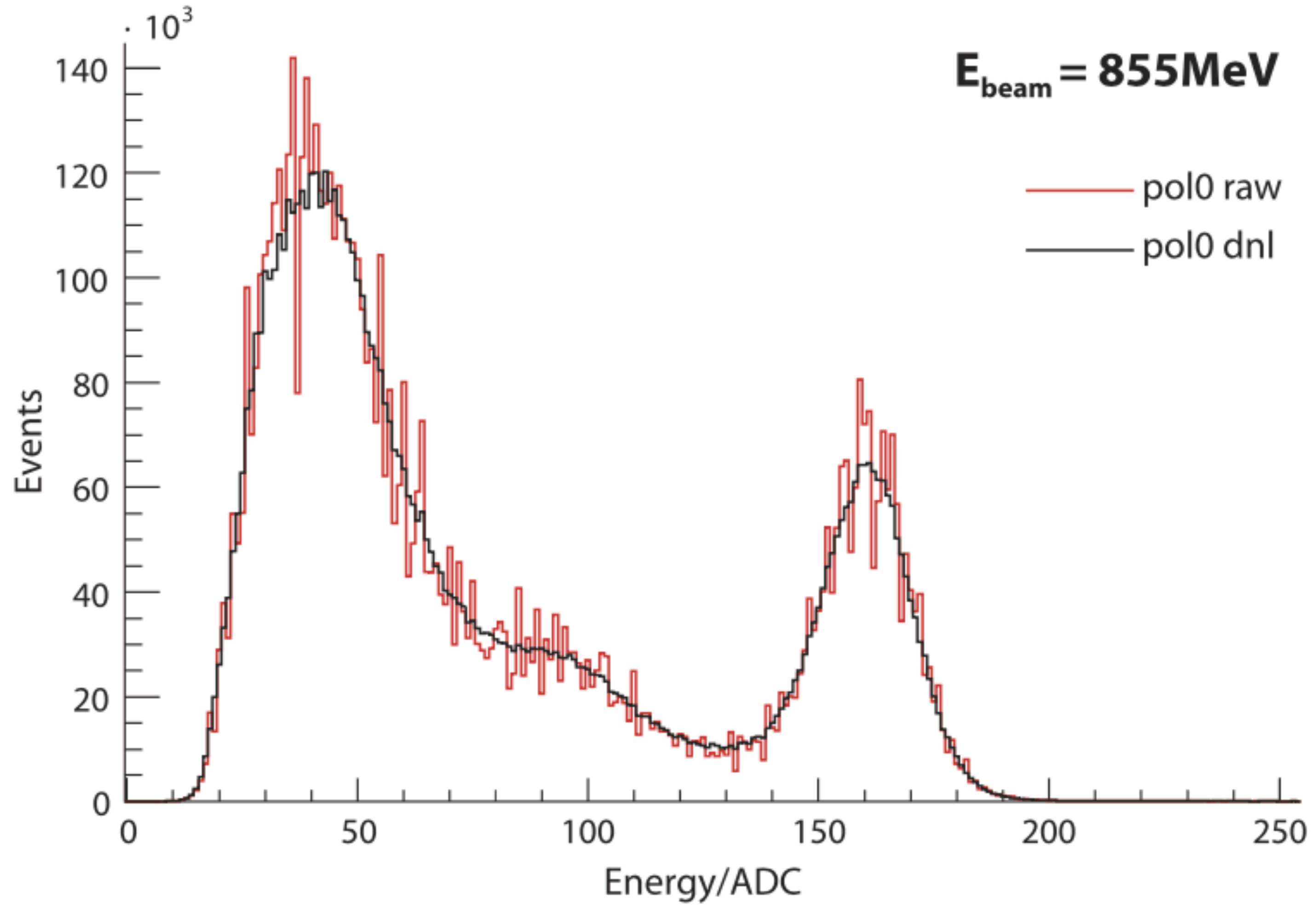


First Observation of PVeS
E122
PVDIS-6
This proposal
G0
Mainz-Be
SAMPLE
H-I
SOLID
G0
A4
MIT-12C
A4
H-III
A4
H-He
H-II
PREX-I
E158
PREX-II
100%
Qweak
10%
Moller
Mainz-P2
1%
$\delta(A_{PV})$
A_{PV}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}

PVES "counting" experiments

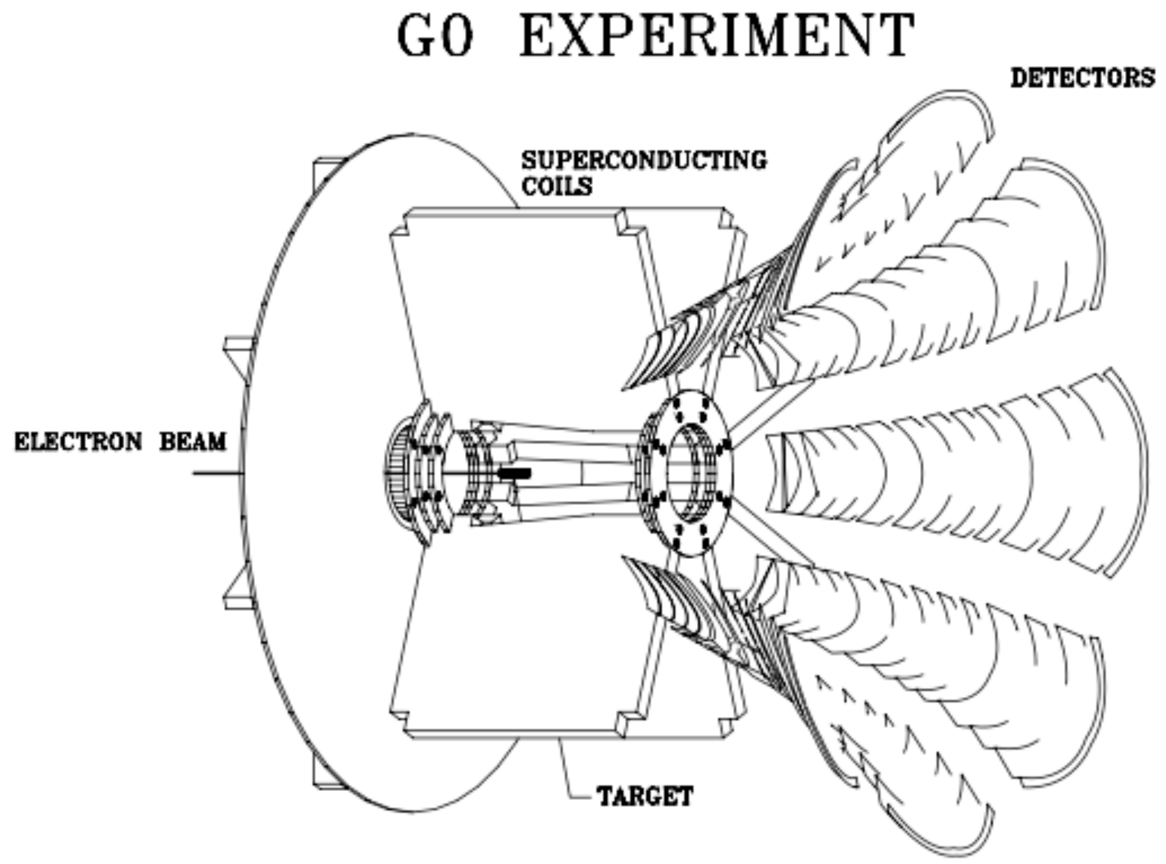
Mainz A4

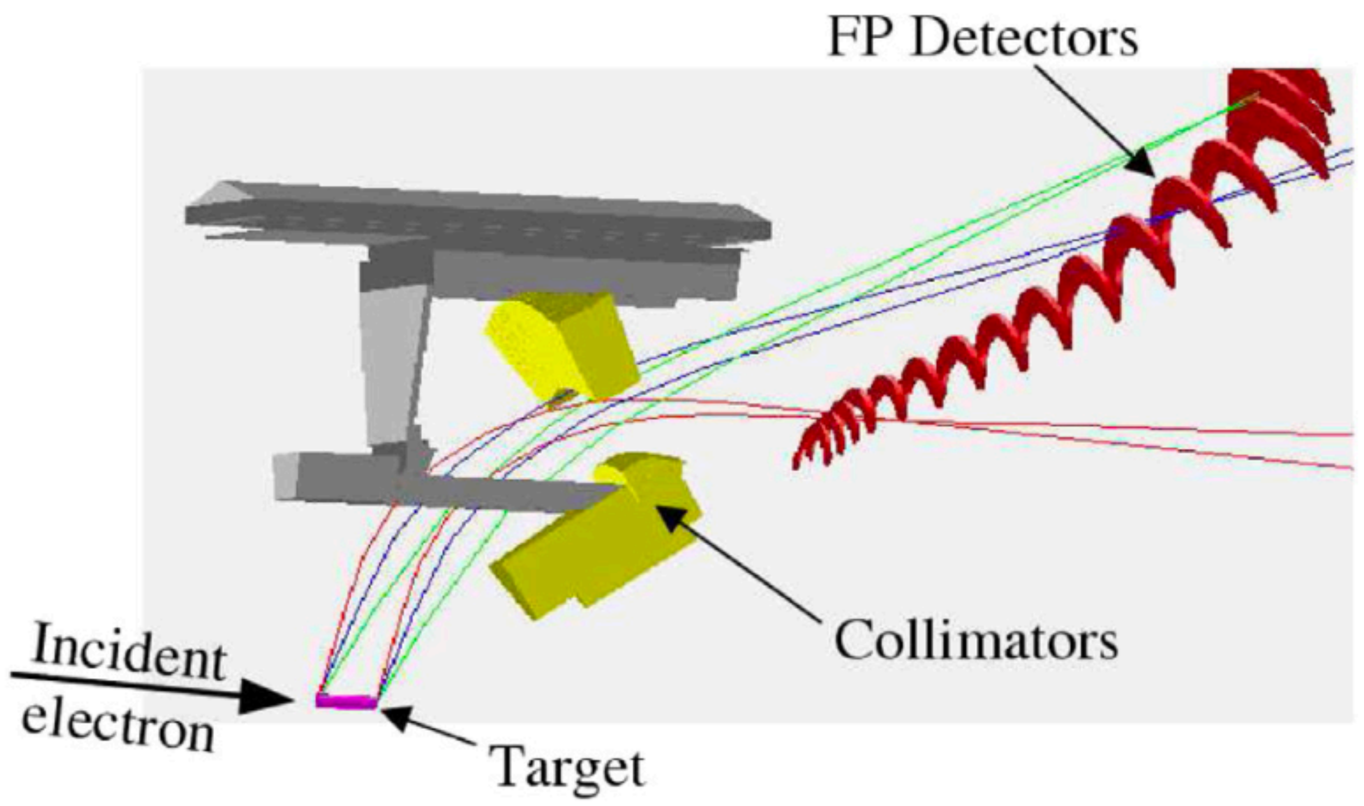




Total energy of electron

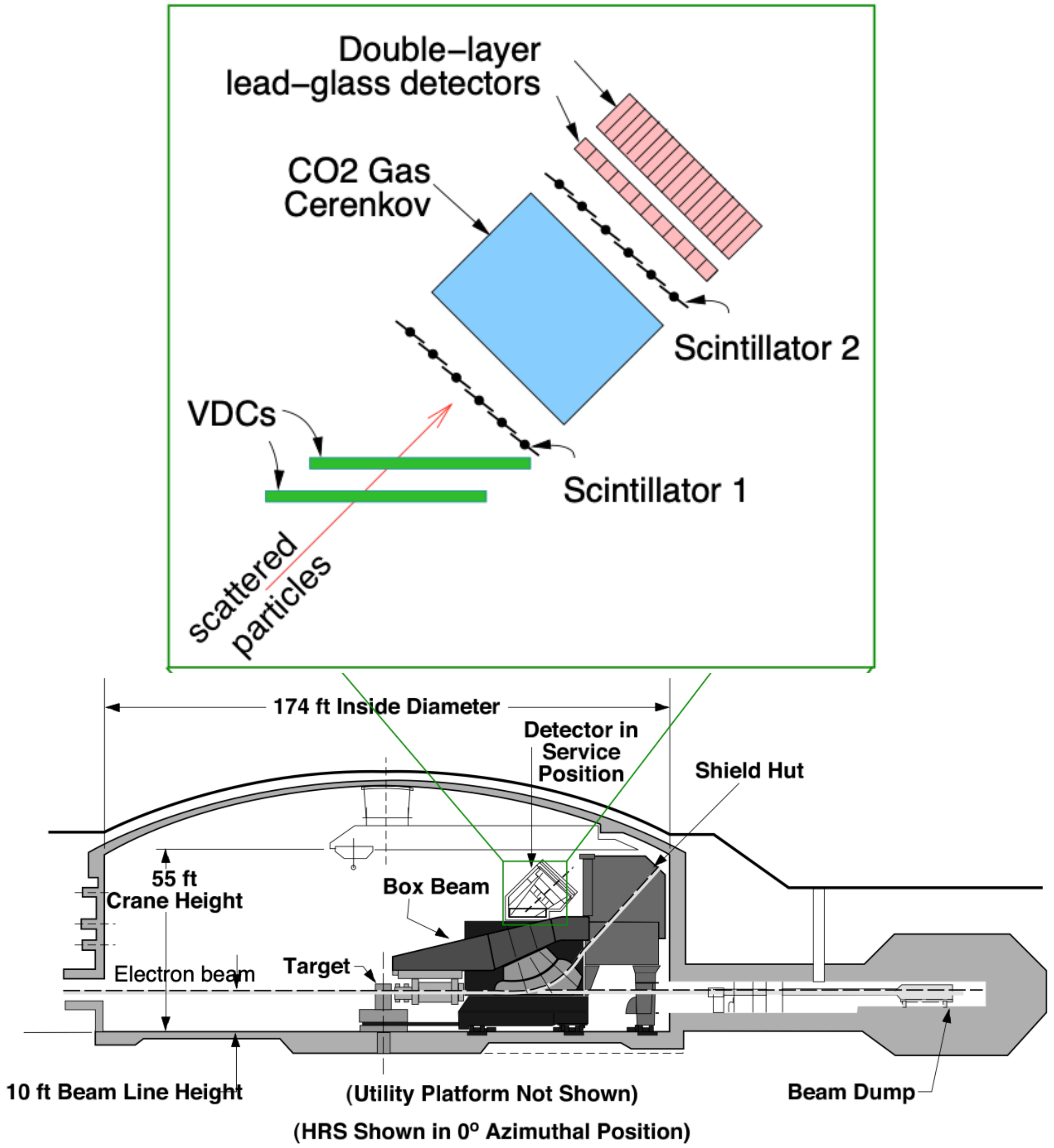
G0





Time of flight of recoil proton

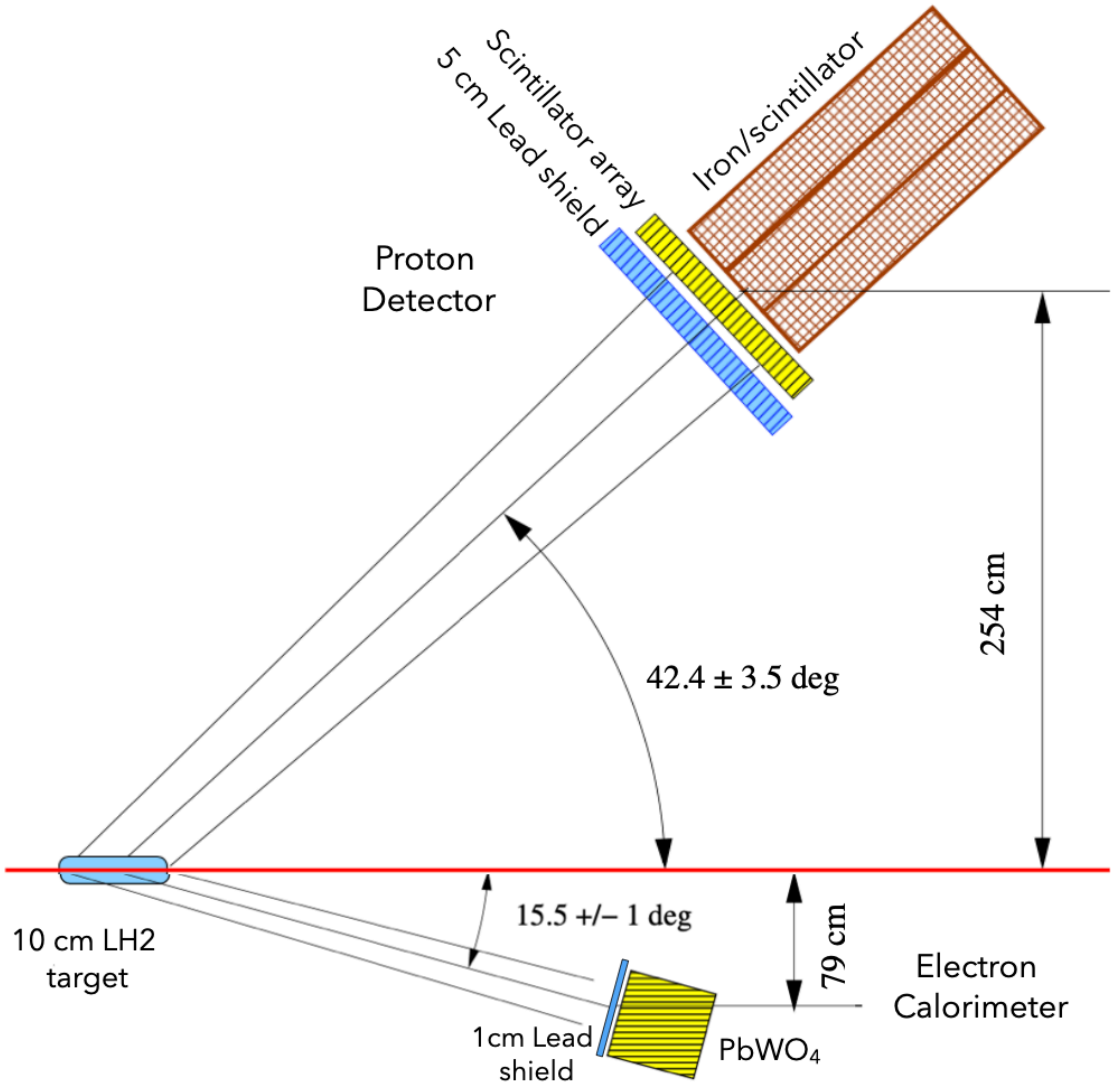
PVDIS-6



Calorimetry + Cerenkov PID

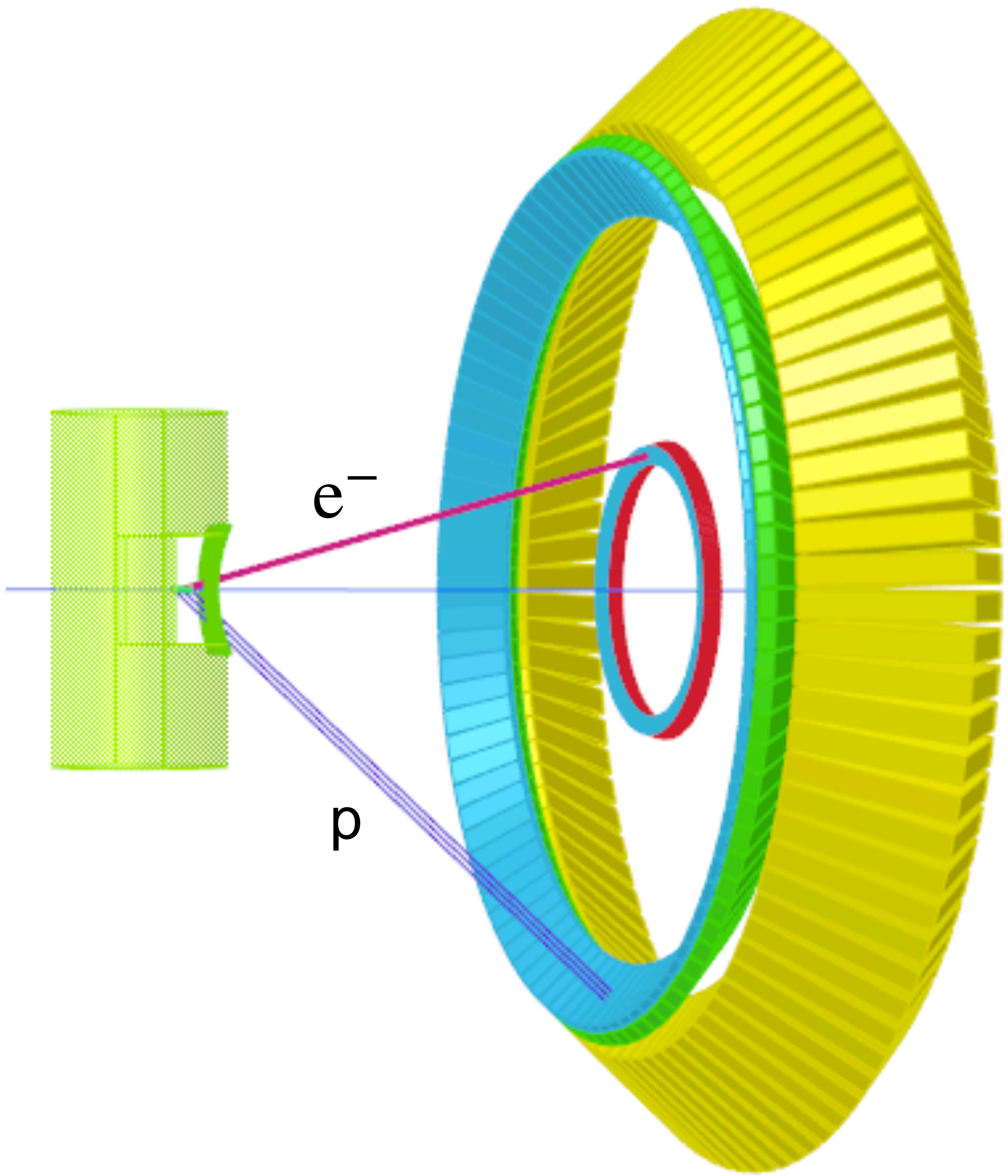
Experimental concept

- Elastic kinematics between electron and proton
- Full azimuthal coverage, ~42 msr
- High resolution calorimeter for electron arm
- Angular correlation e-p
  - Scattered electron at 15.5 degrees
  - Scattered proton at 42.4 degrees

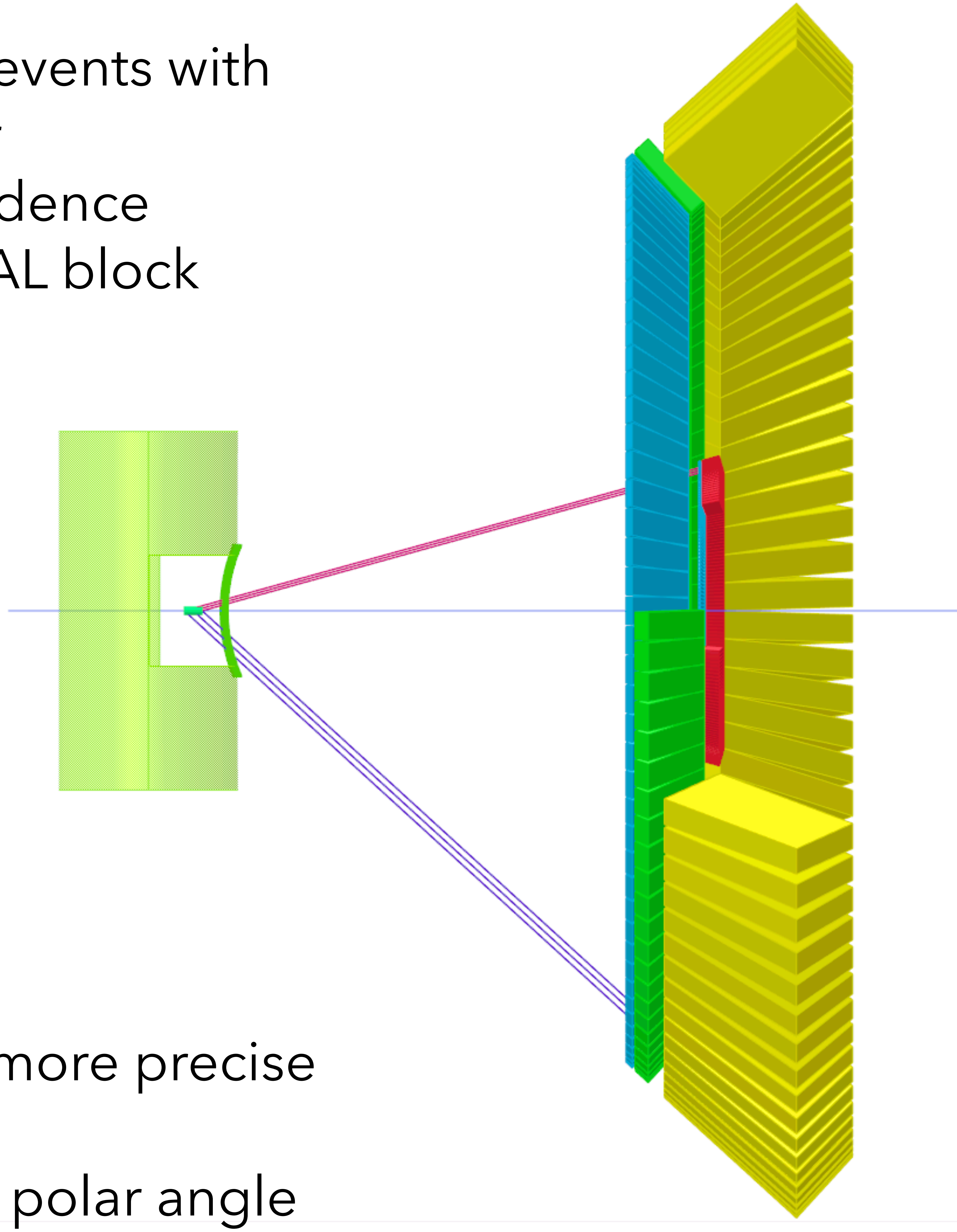


- 6.6 GeV beam
- 10 cm LH_2 target, 65 μA, $\mathcal{L} = 1.7 \times 10^{38}$ cm^{-2}/s

Experimental concept

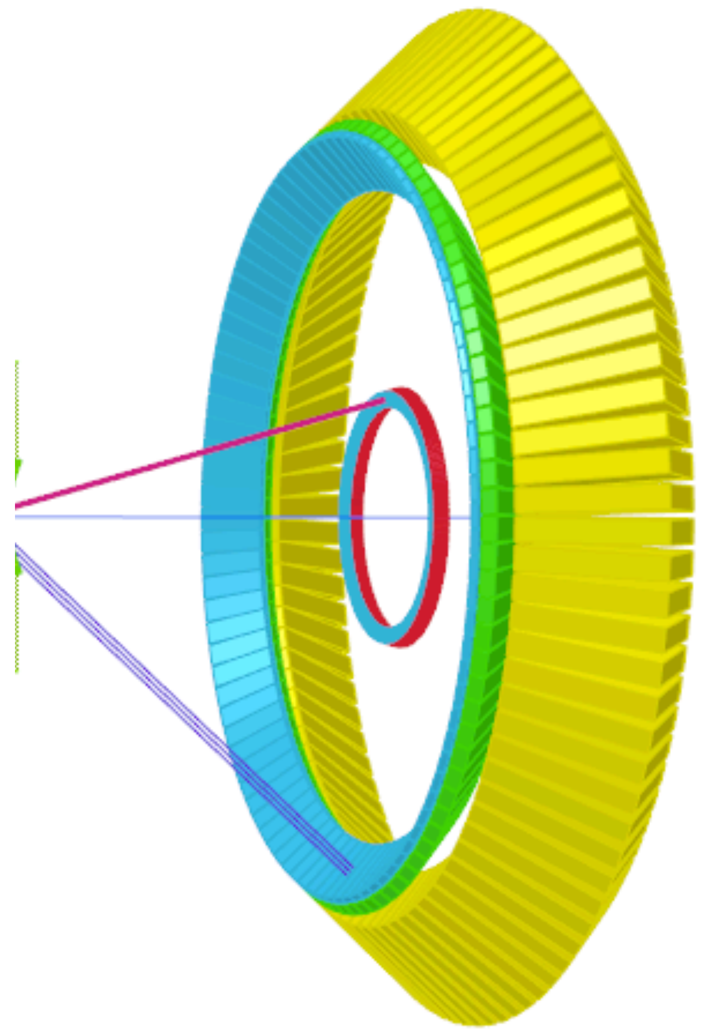


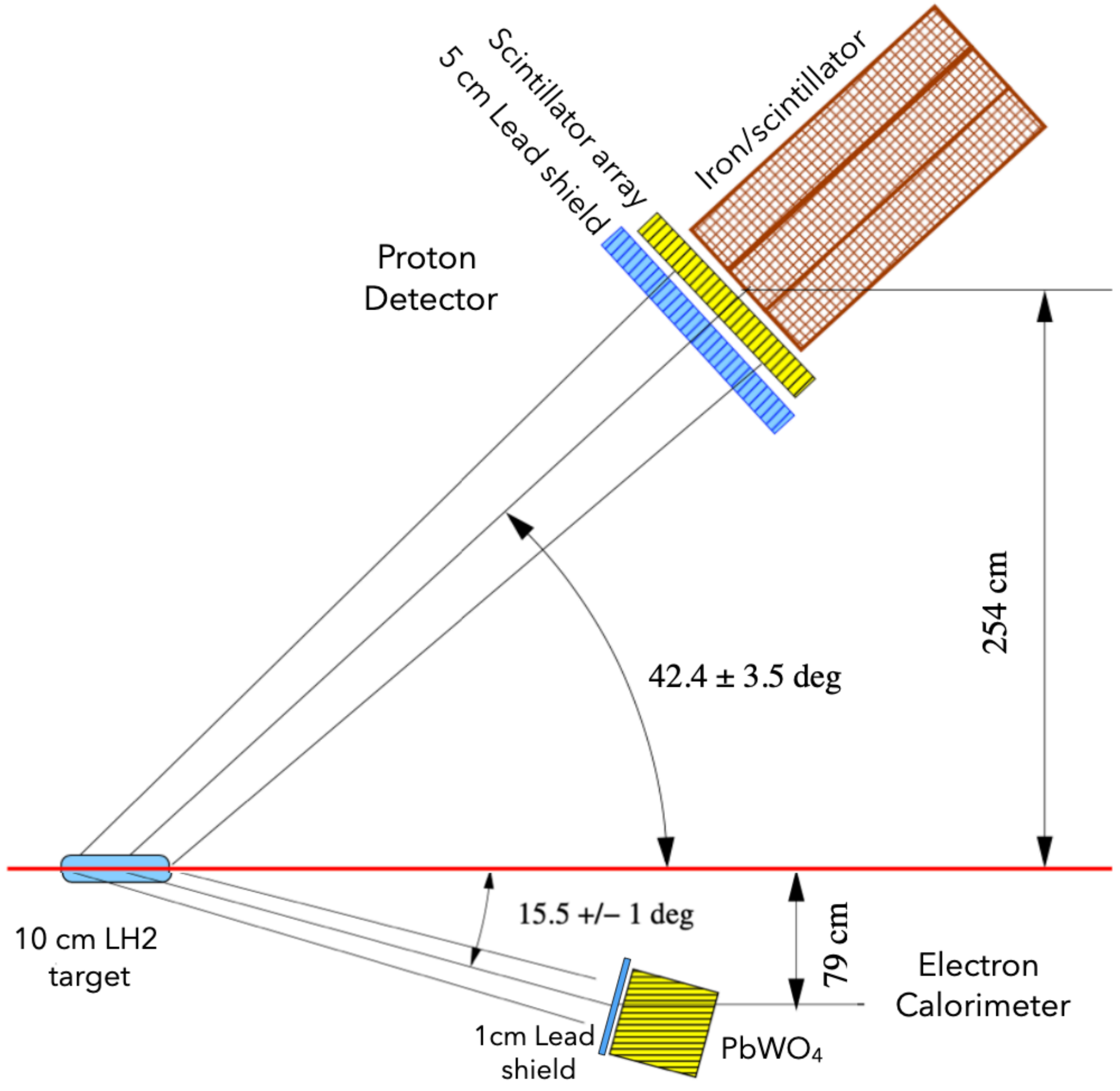
Streaming readout, recording events with
- E>threshold in calorimeter
- polar and azimuthal coincidence
- ECAL cluster center vs HCAL block matches ep elastic



Off-line analysis
- pixel hodoscope adds more precise proton position
- Tighten cuts, especially polar angle

Detector System





HCAL - hadron calorimeter

- Reassembled from detector elements from the SBS HCAL
- 288 blocks, each 15.5 x 15.5 x 100 cm^3
- iron/scintillator sandwich with wavelength shifting fiber readout

ECAL - electron calorimeter

- Reassembled from detector elements from the NPS calorimeter
- 1200 blocks, each 2 x 2 x 20 cm^3
- $PbWO_4$ scintillator
- 1 cm lead shield

Scintillator array

- New detector, requires construction
- Used for improved position resolution in front of HCAL
- Not used to form trigger
- 7200 blocks, each 3 x 3 x 10 cm^3
- Lead shield in front (thickness to be optimized) to reduce photon load

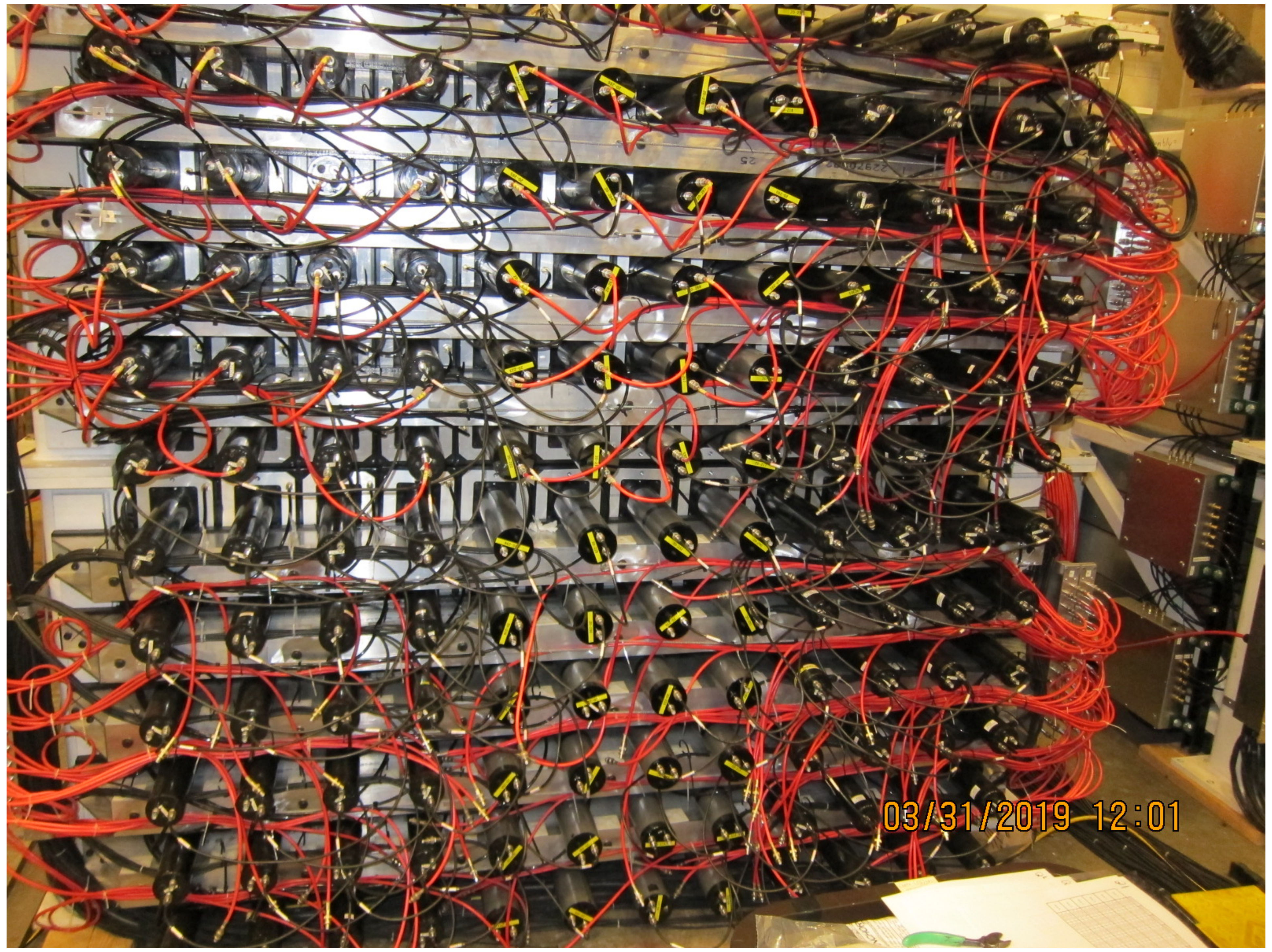
Calorimeters reusing components

NPS electromagnetic calorimeter

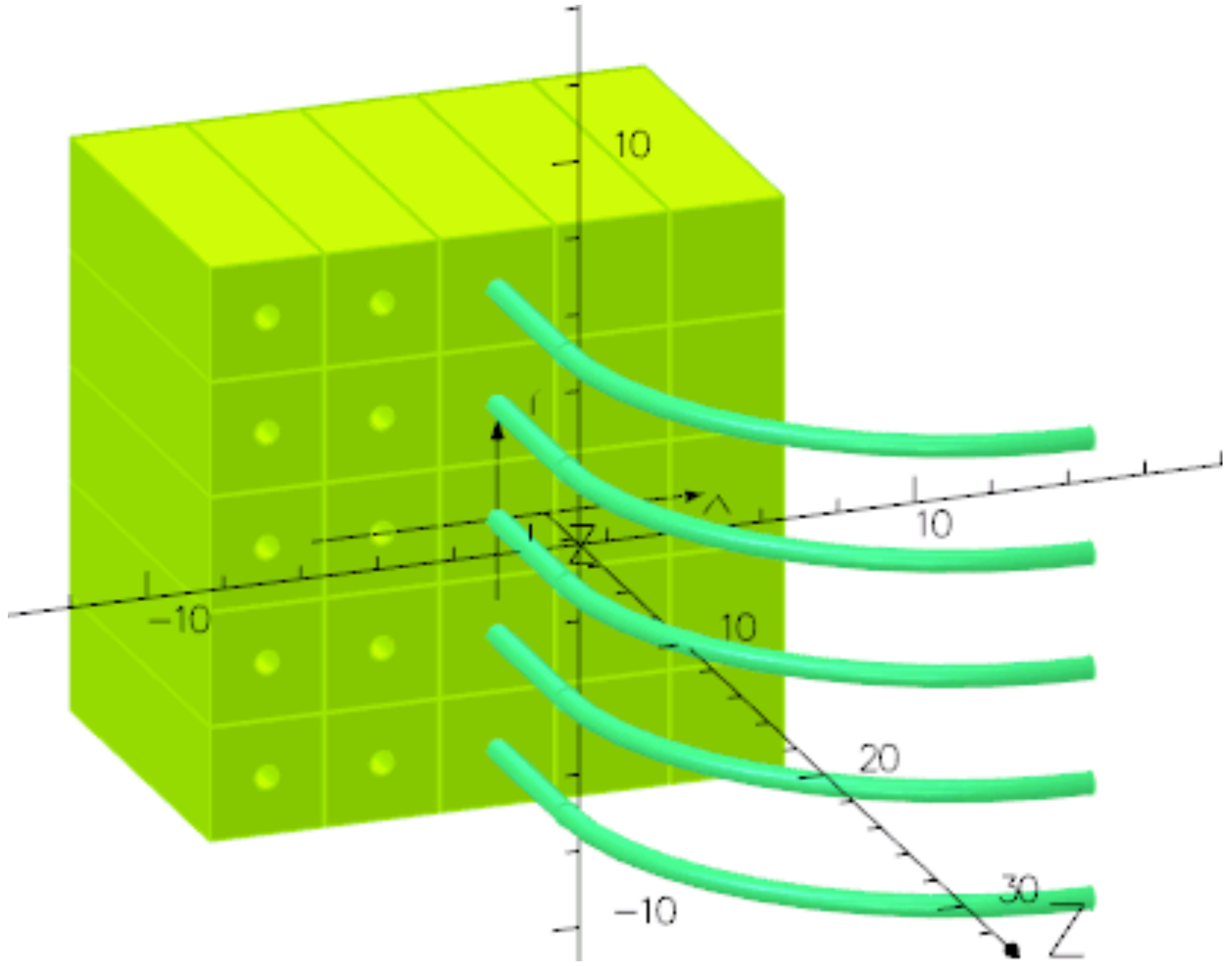
- 1080 $PBWO_4$ scintillators, PMTs + bases
- will run in future NPS experiment

SBS hadronic calorimeter

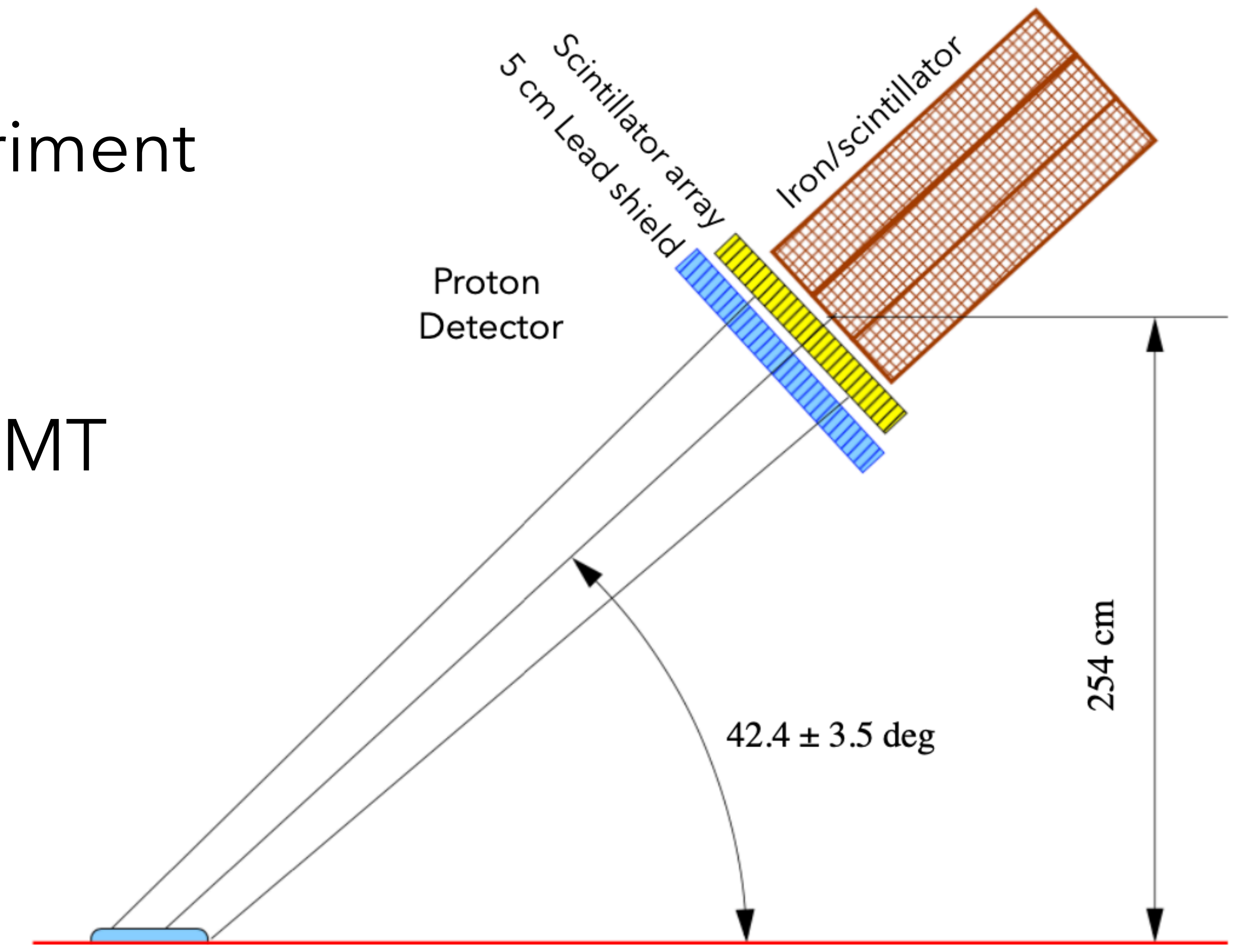
- 288 iron/scintillator detectors, PMTs + bases
- Already in use with SBS



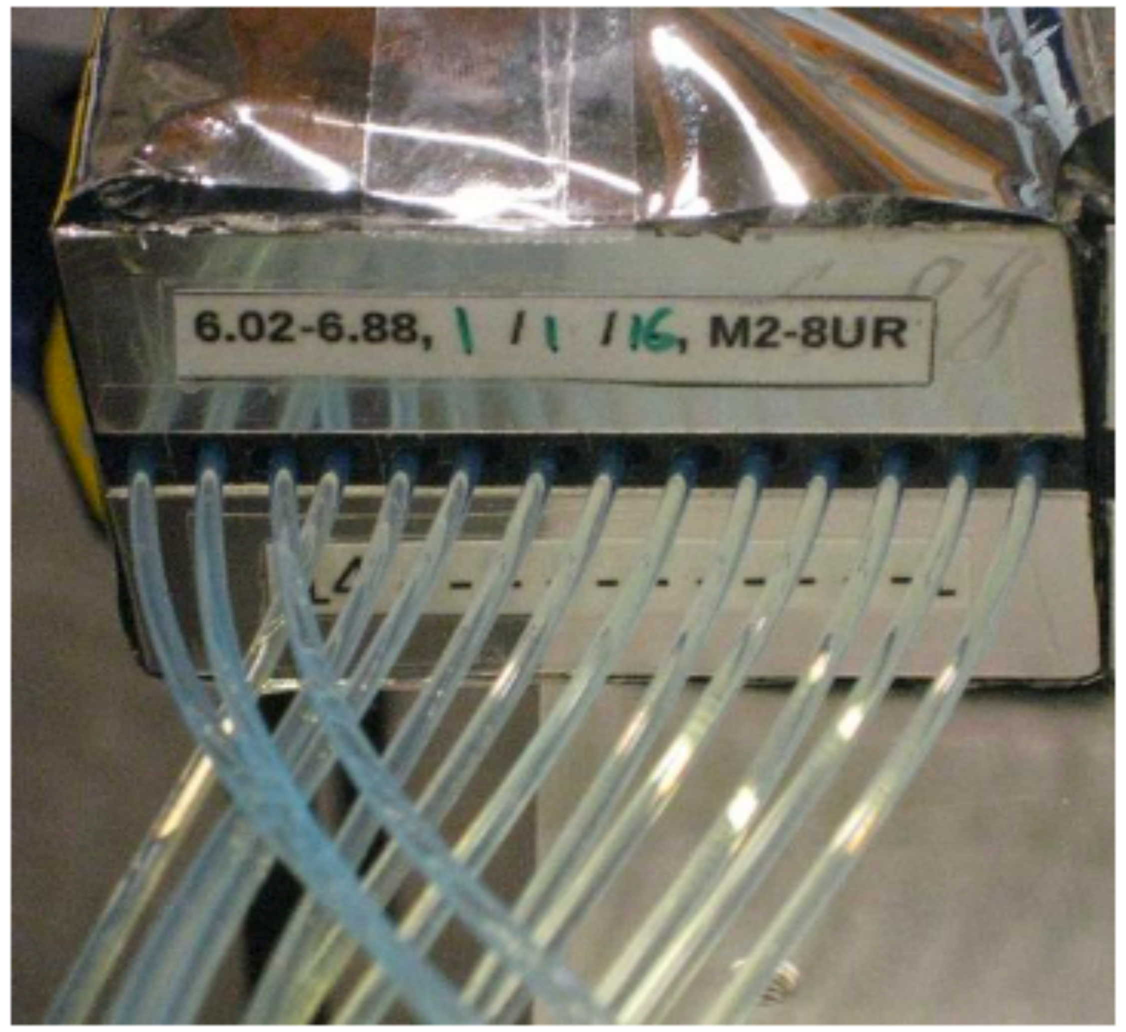
Scintillator Array

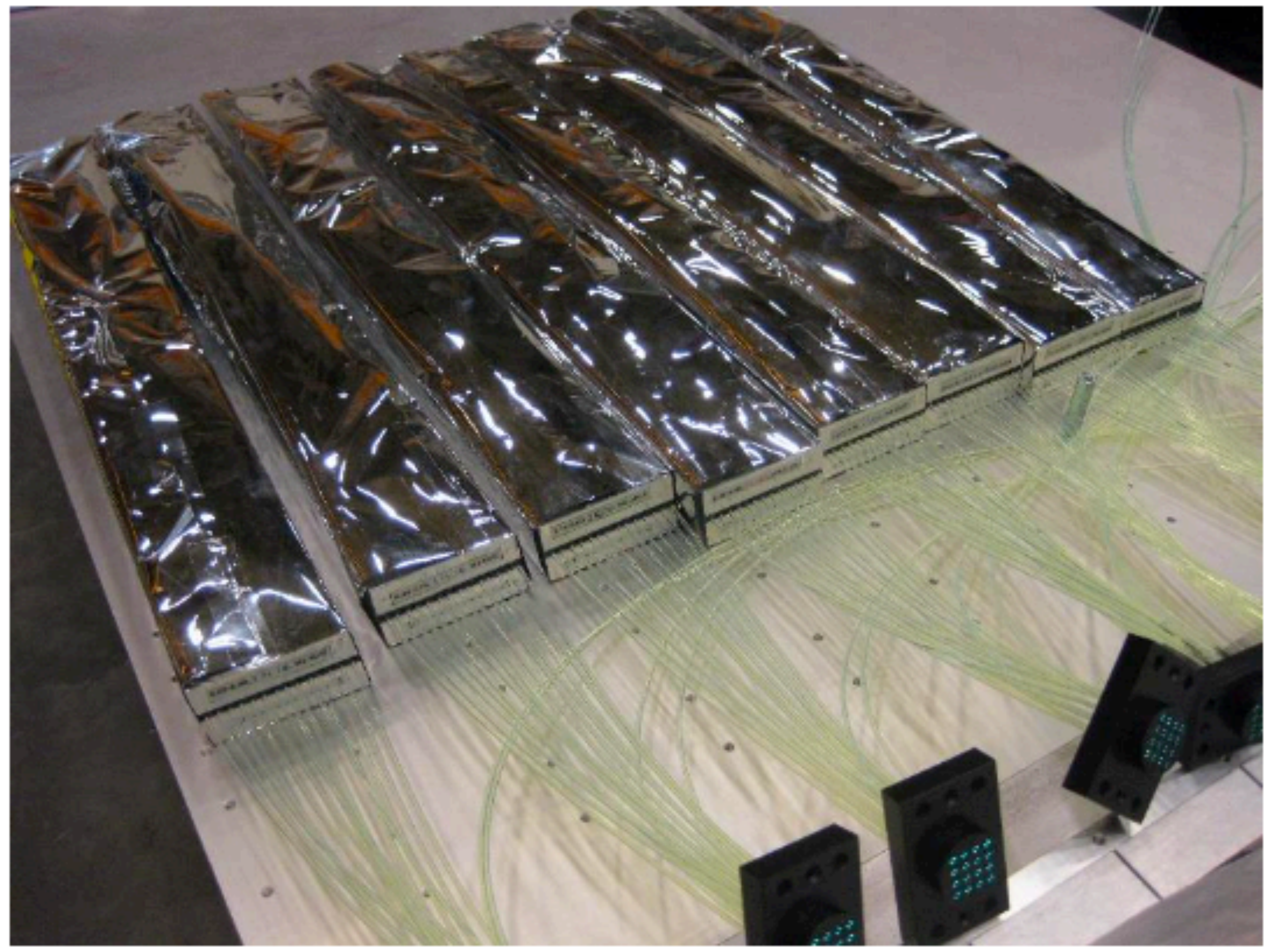


- New detector, must be built for this experiment
- Extruded plastic scintillator block
- Readout with wavelength-shifting fiber
- Each fiber read by pixel on multi-anode PMT
- 7200 blocks, each 3 x 3 x 10 cm^3



Design matches scintillator array built for GEP
- 2400 elements, 0.5 x 4 x 50 cm^3
- Already built, will run next year

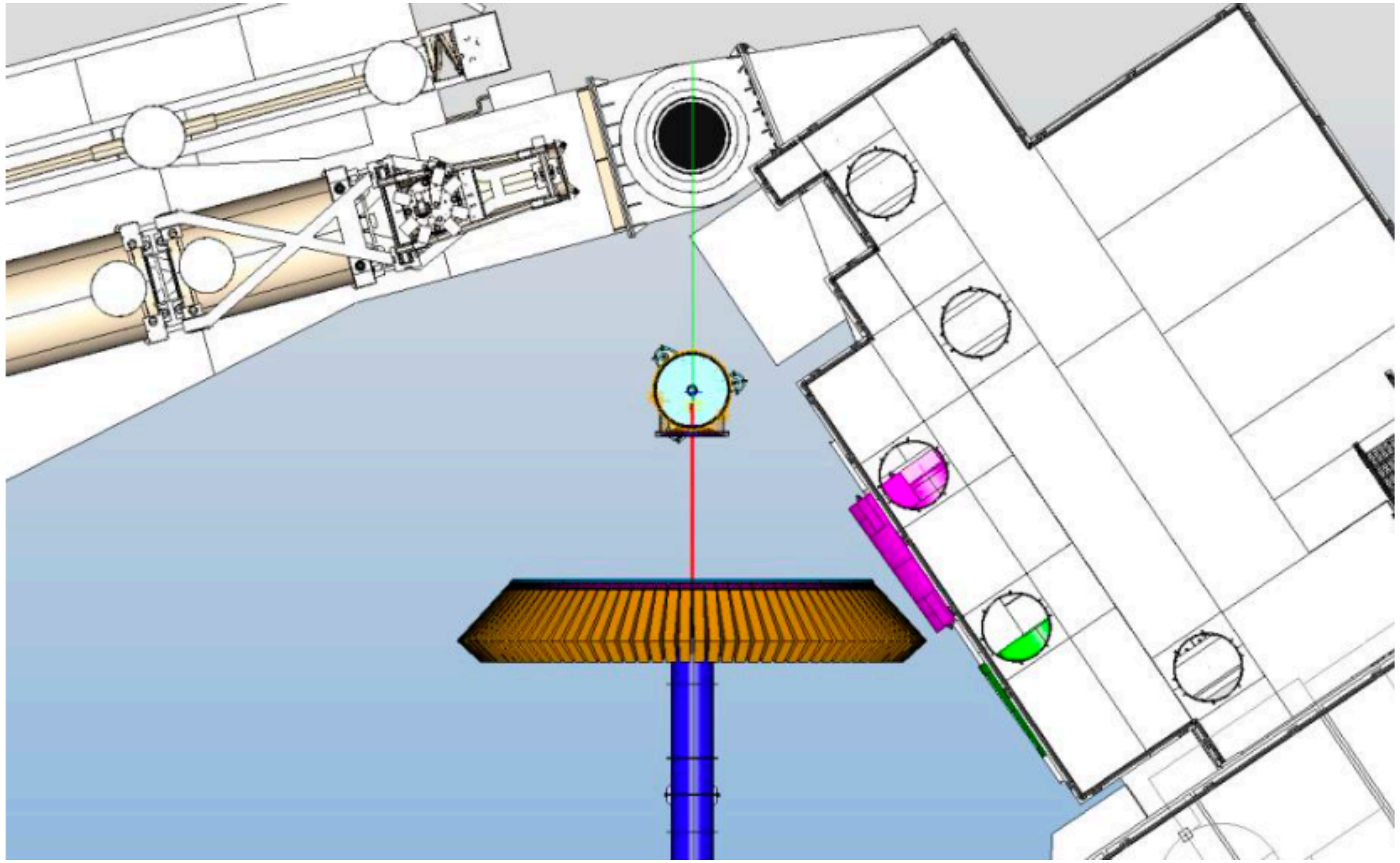


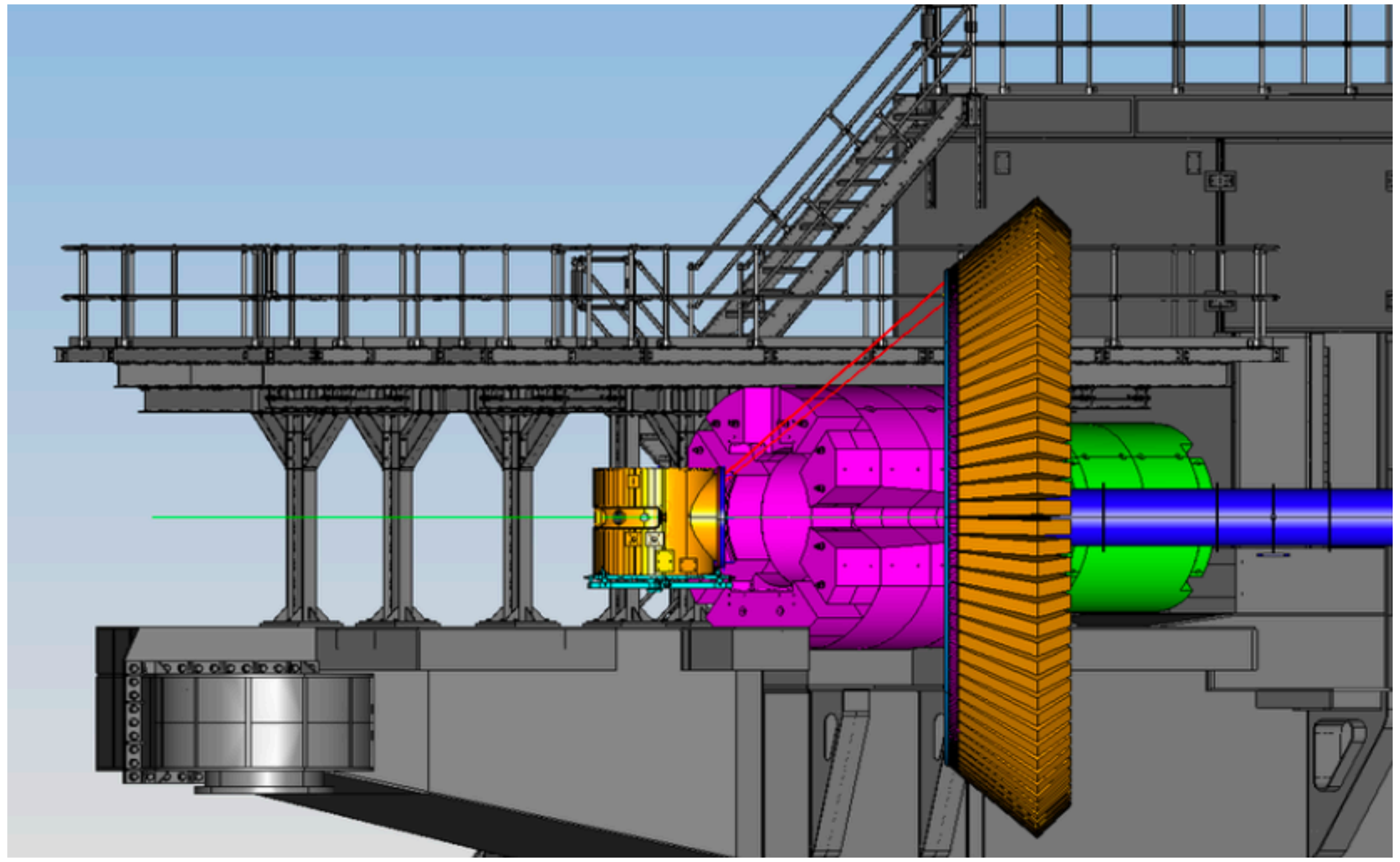


Installation in Hall C

3.5 m target shift downstream from pivot due to space limitation on the SHMS side

Will need a very substantial frame to support HCAL

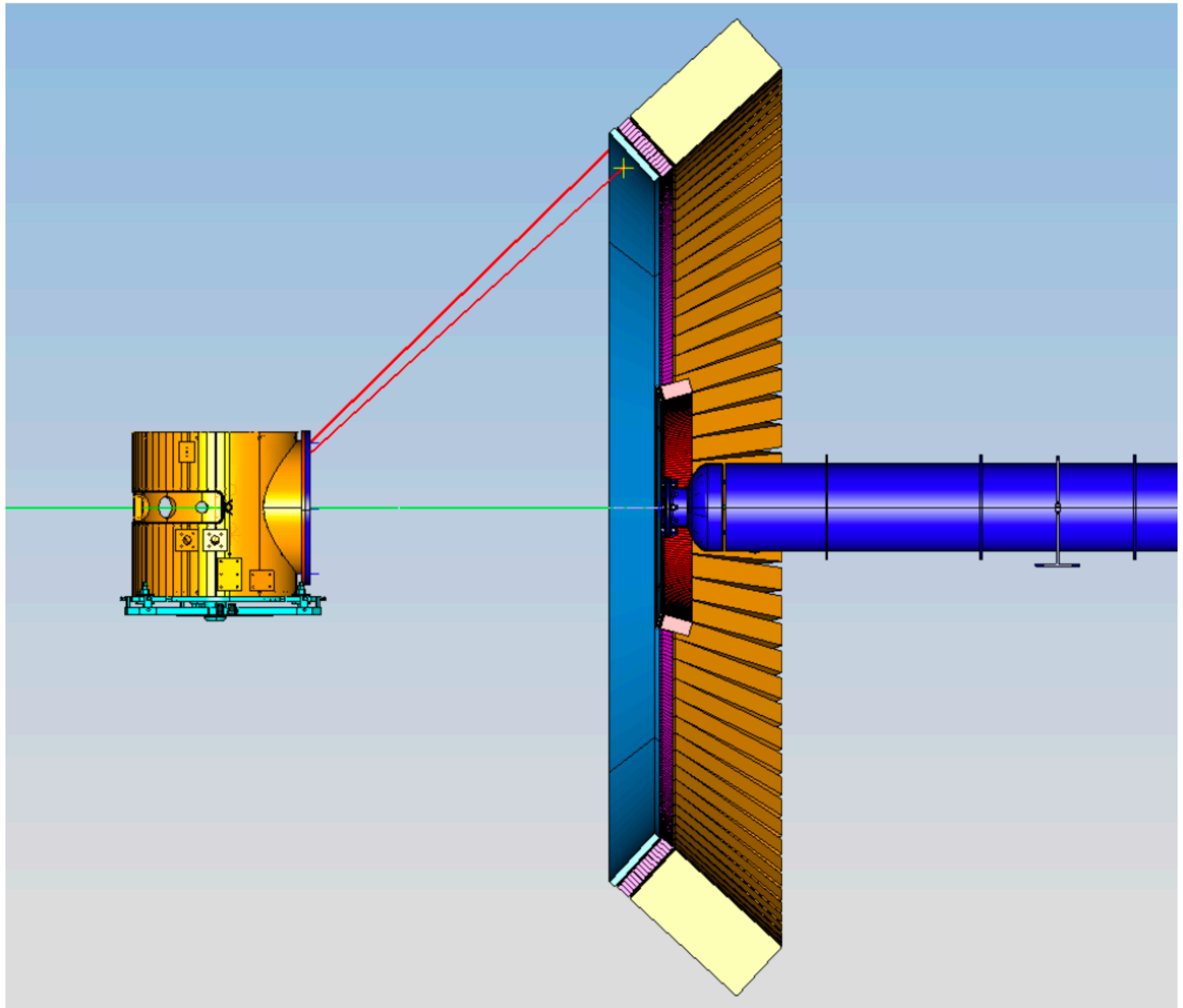


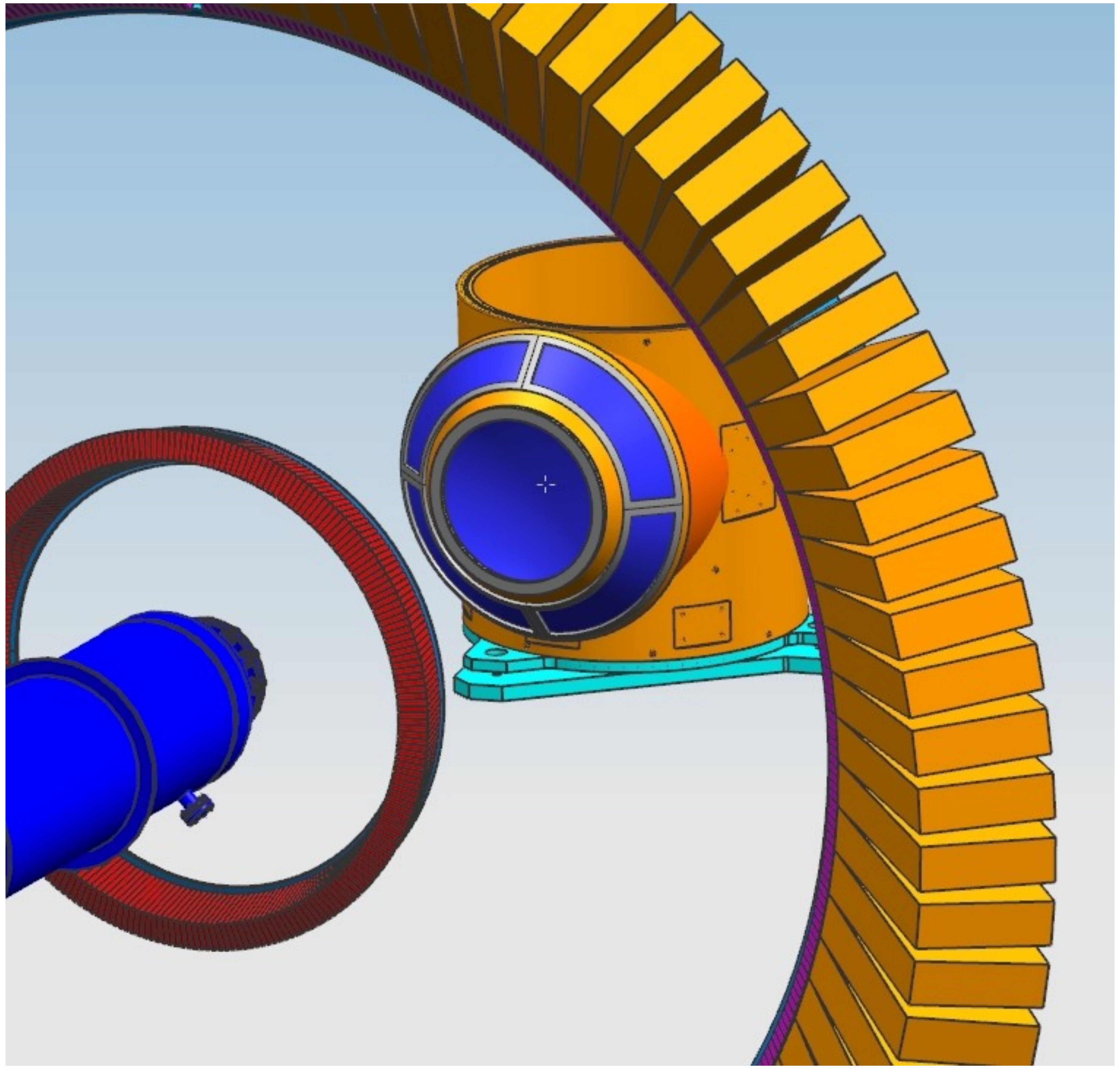


Scattering chamber

Cylindrical scattering chamber with large Al window to pass 15° electrons and 45° protons

Design uses a cone with “ribs”, plus an inverted hemisphere center, windows could be as thin as 0.5mm





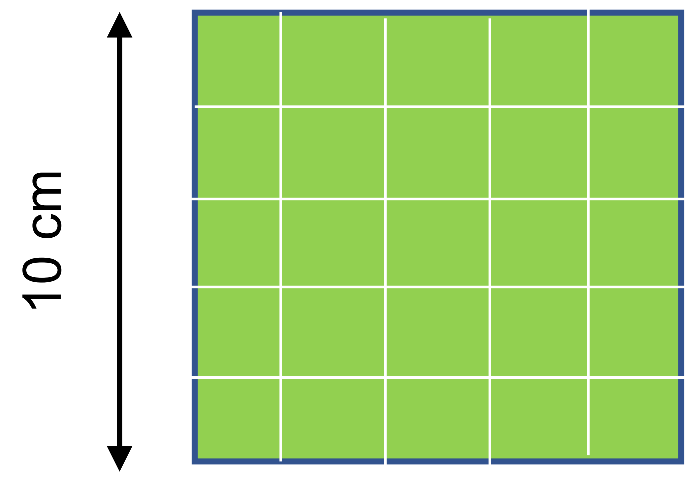
Requires air gap - will use He bag (not shown) to transport beam, so open air gap is only ~50cm

Triggering

Grouping into "subsystems" for energy threshold and coincidence triggering of event record

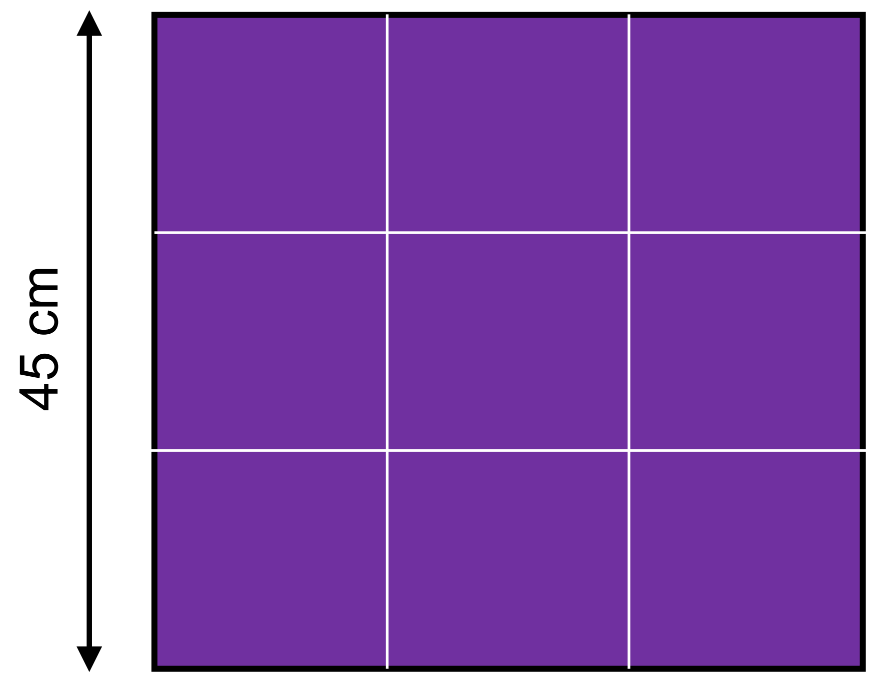
- each polar column of detectors, overlapping with neighbors
- sum amplitude with conservative coincidence timing window
- compare to conservative energy threshold
- trigger when complementary (ECAL and HCAL) subsystems are both above threshold

Electron subsystems



- 1200 $PbWO_4$ crystals
- 2x2x20 cm^3
- 5x5 grouping for subsystem
- 240 overlapping subsystems

Proton subsystems

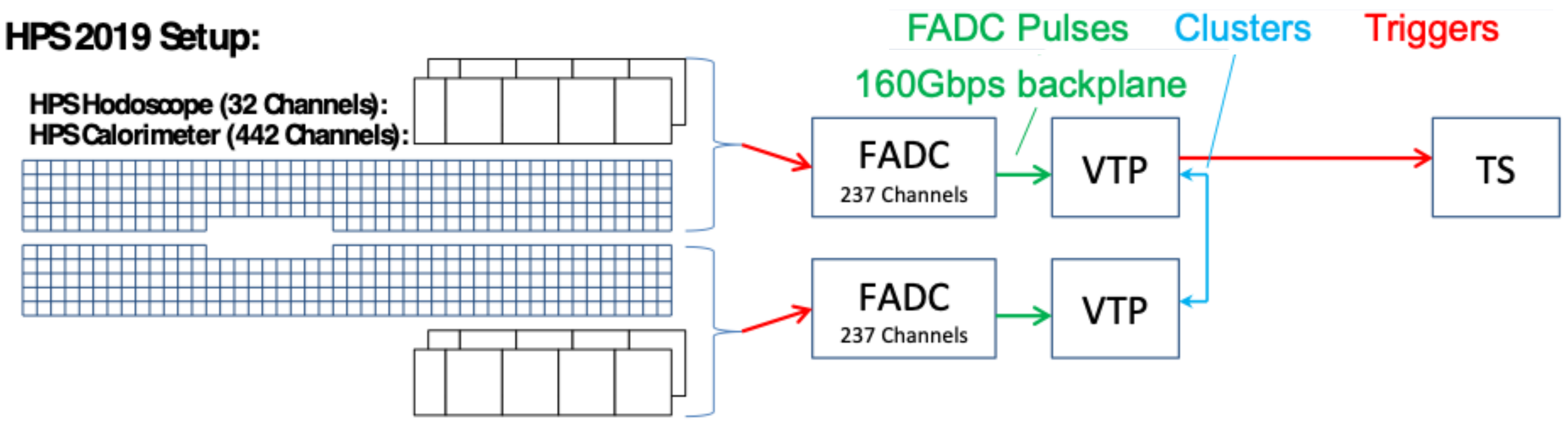


- 288 iron/scintillators
- 15.5x15.5x100 cm^3
- 3x3 grouping for subsystem
- 96 overlapping subsystems

Fast Counting DAQ

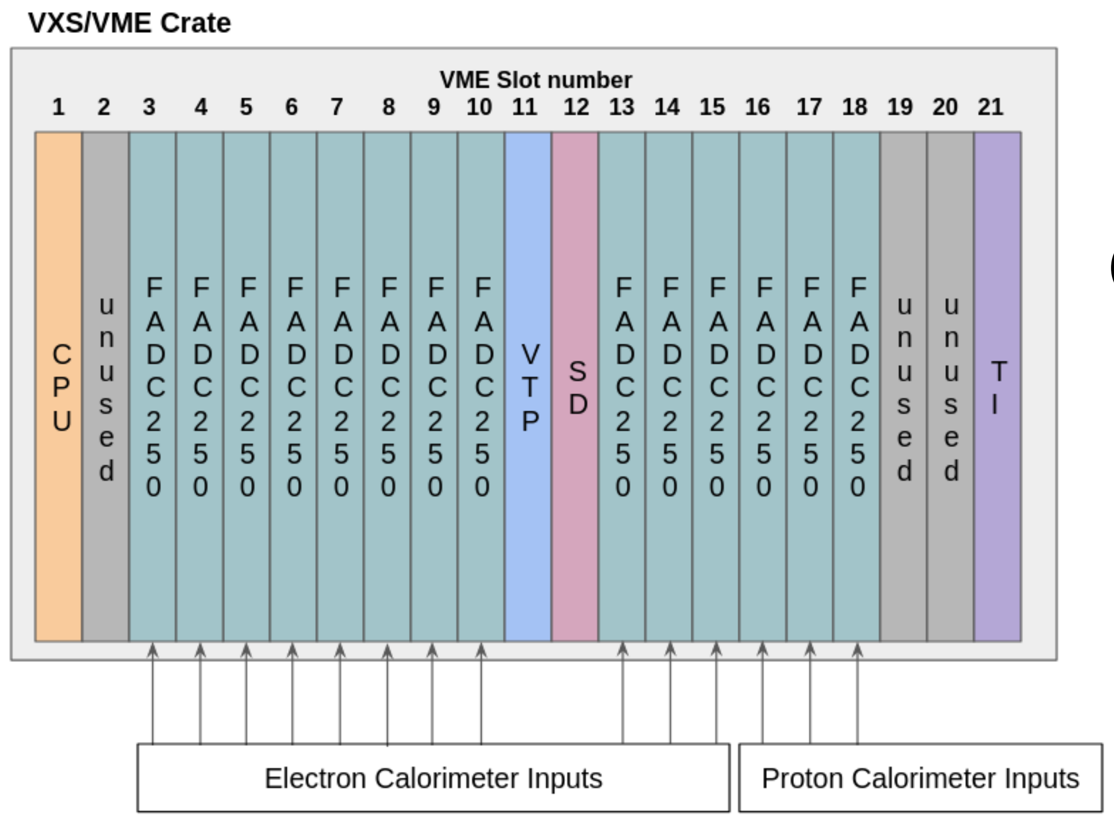
Readout for fast counting is now very common challenge and enabled by new, and now common, technologies. In particular, SOLID will face this challenge in measurement of PV-DIS, and this experiment will be an important testing ground for precise asymmetry measurements.

Concept very similar to the HPS DAQ, used in 2019 or NPS DAQ:



JLab **FADC250** for HCAL and ECAL readout
Provides the pulse information for a fast, "deadtime-less" trigger

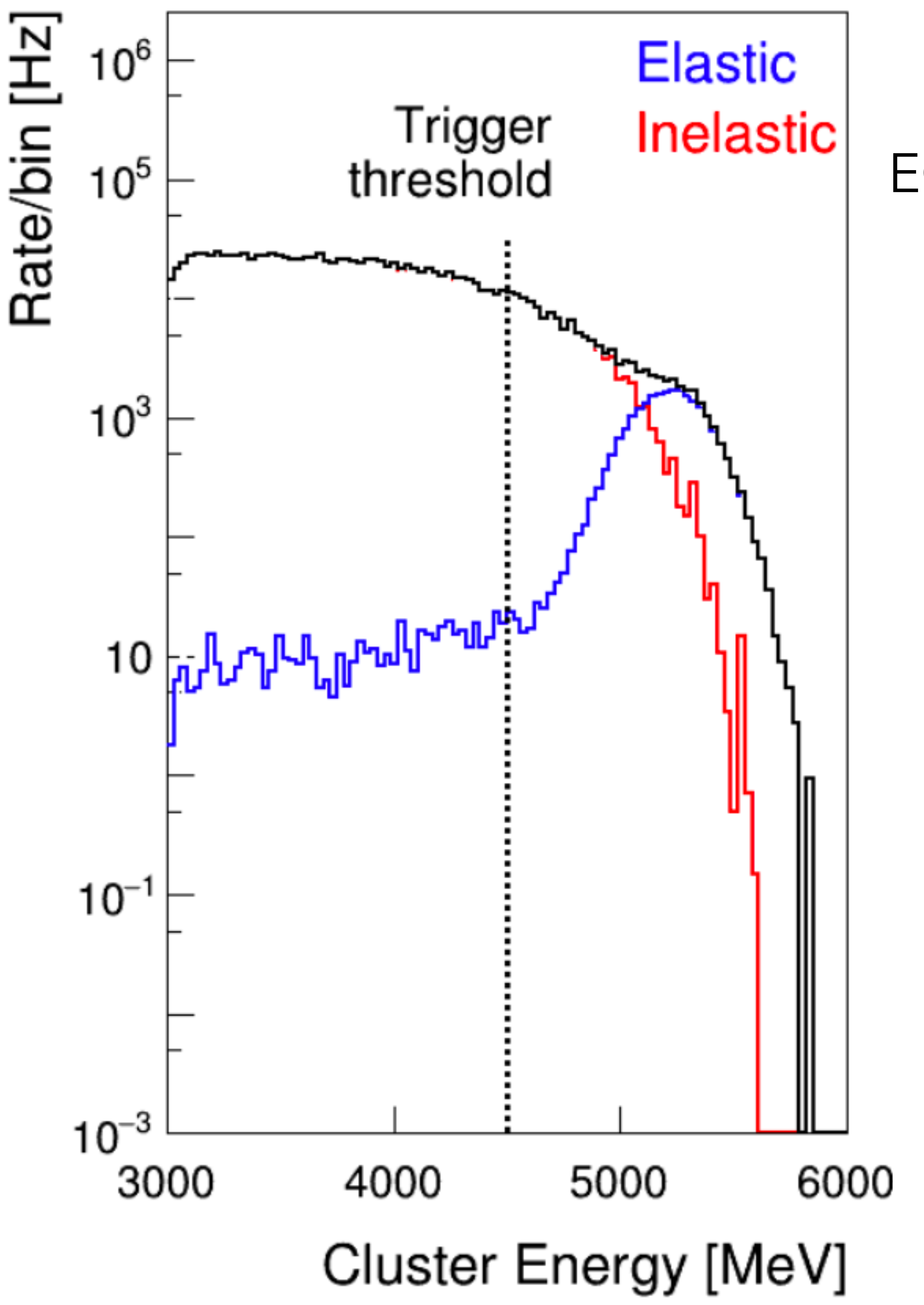
VTP (VXS Trigger Processor)
Clusters in time, sums over subsystems, finds ECAL+HCAL coincidence



One VXS crate will handle one sixth of ECAL + HCAL, also provide external trigger for ScintArray pipelineTDC readout

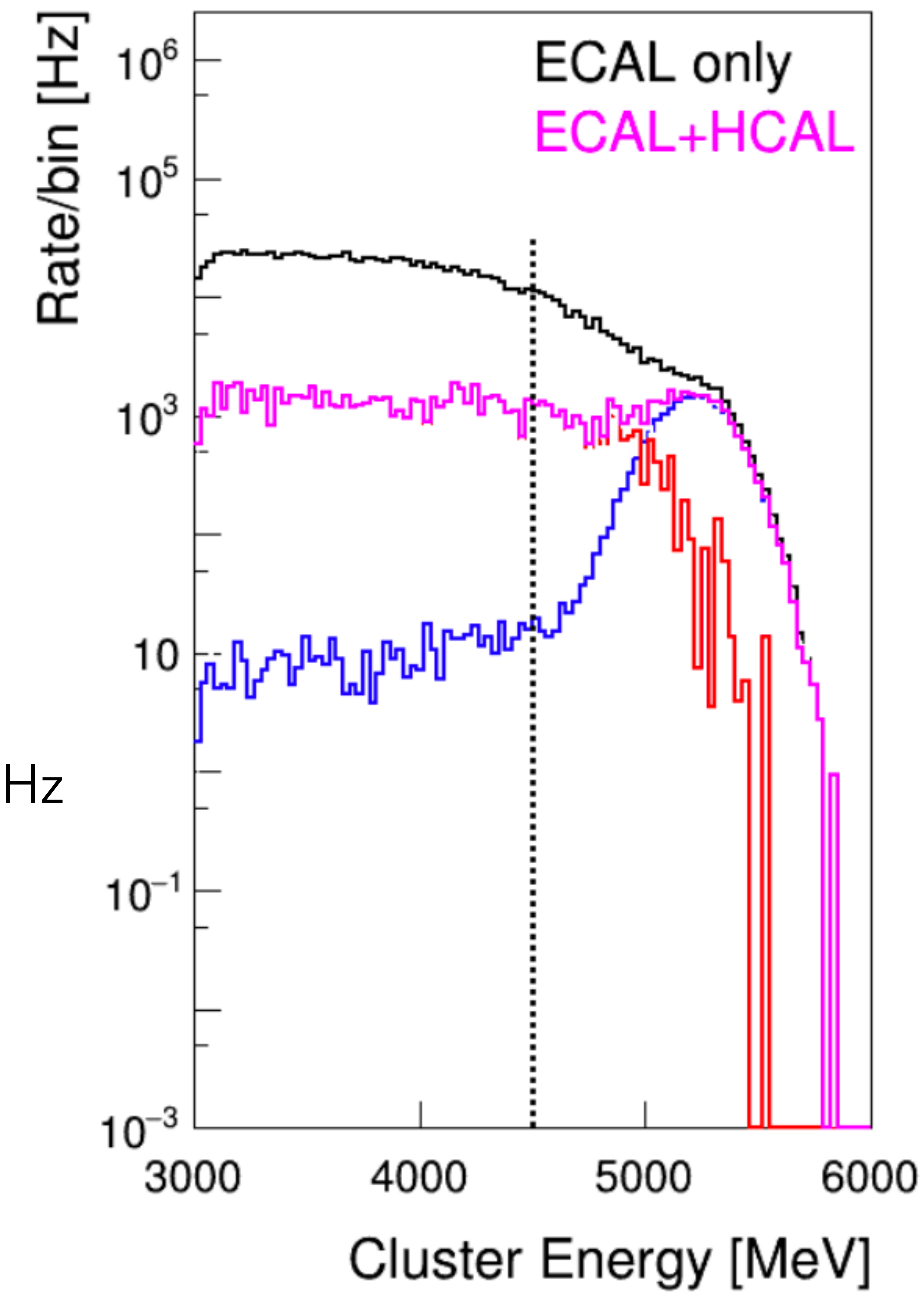
Expect ~50kHz total, ~250 Mb/s data rate, distributed over 6 separate crates

ECAL cluster rates



ECAL > 4.5 GeV : 153 kHz

ECAL > 4.5 GeV & HCAL > 50 MeV : 35 kHz



Rates and Precision

Beam and target: 60 uA on 10 cm LH_2 => luminosity is 1.6×10^{38} cm^{-2}/s

Trigger (online)

- Elastic coincidence 18 kHz signal in full detector
- Inelastic (pion production) coincidence trigger rate ~16 kHz
- Accidental coincidence rate < 0.2 kHz
  - ~150 kHz total singles rate in ECAL > 4.5 GeV energy threshold, 200/5 unique subsystems
  - ~19 MHz total singles rate in HCAL > 50 MeV energy threshold, 96/3 unique subsystems
  - Temporal coincidence cut 40ns
- ~35 kHz total coincidence trigger rate

Offline analysis

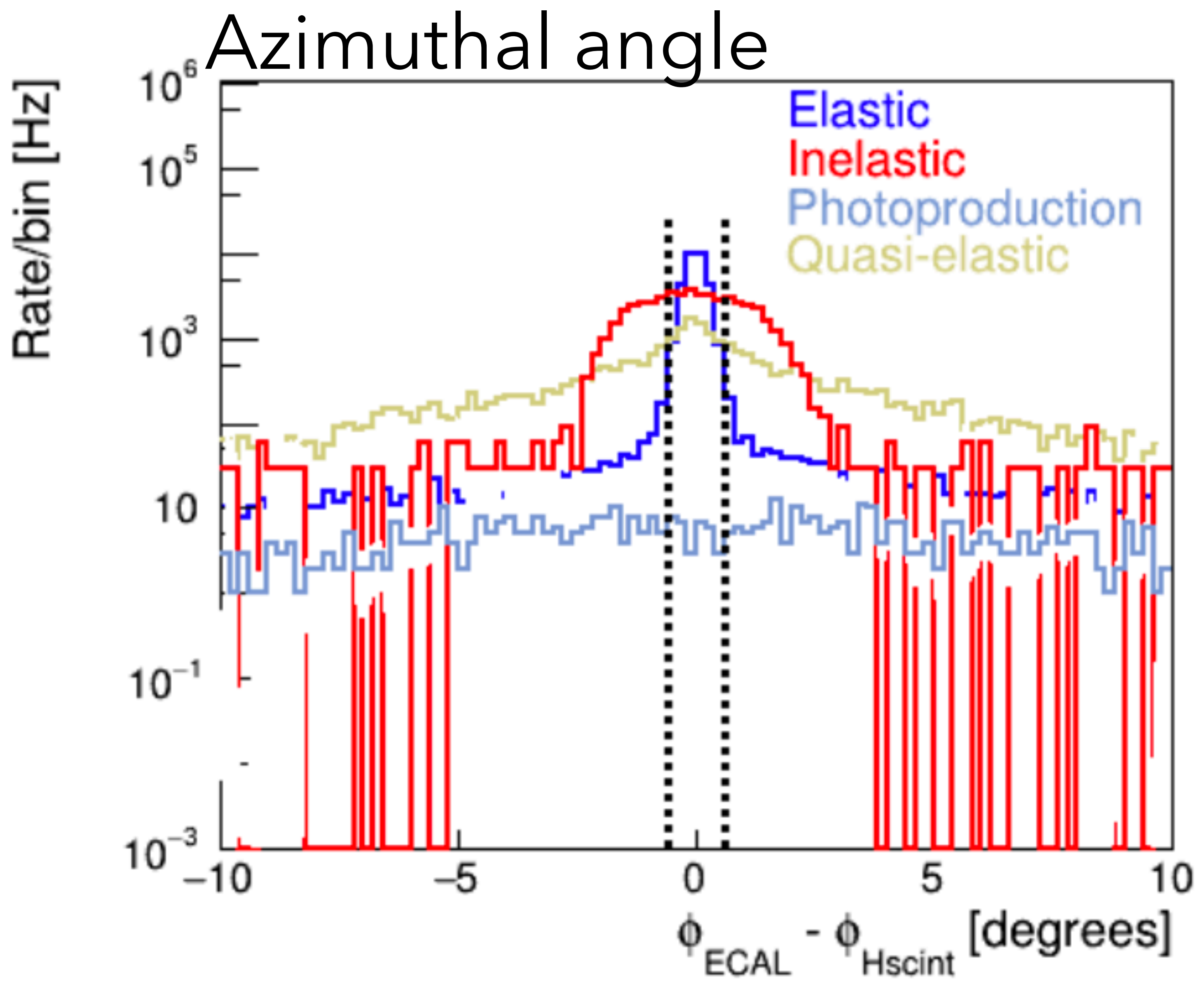
- clustering, scintillator array to improve geometric cuts, tighter acceptance and ECAL cut, 4 ns timing
- Accepted elastic signal reduced to 13 kHz - production statistics
- Inelastic (pion production) <0.5%, accidentals $<1 \times 10^{-5}$ due to angular precision and higher E cut

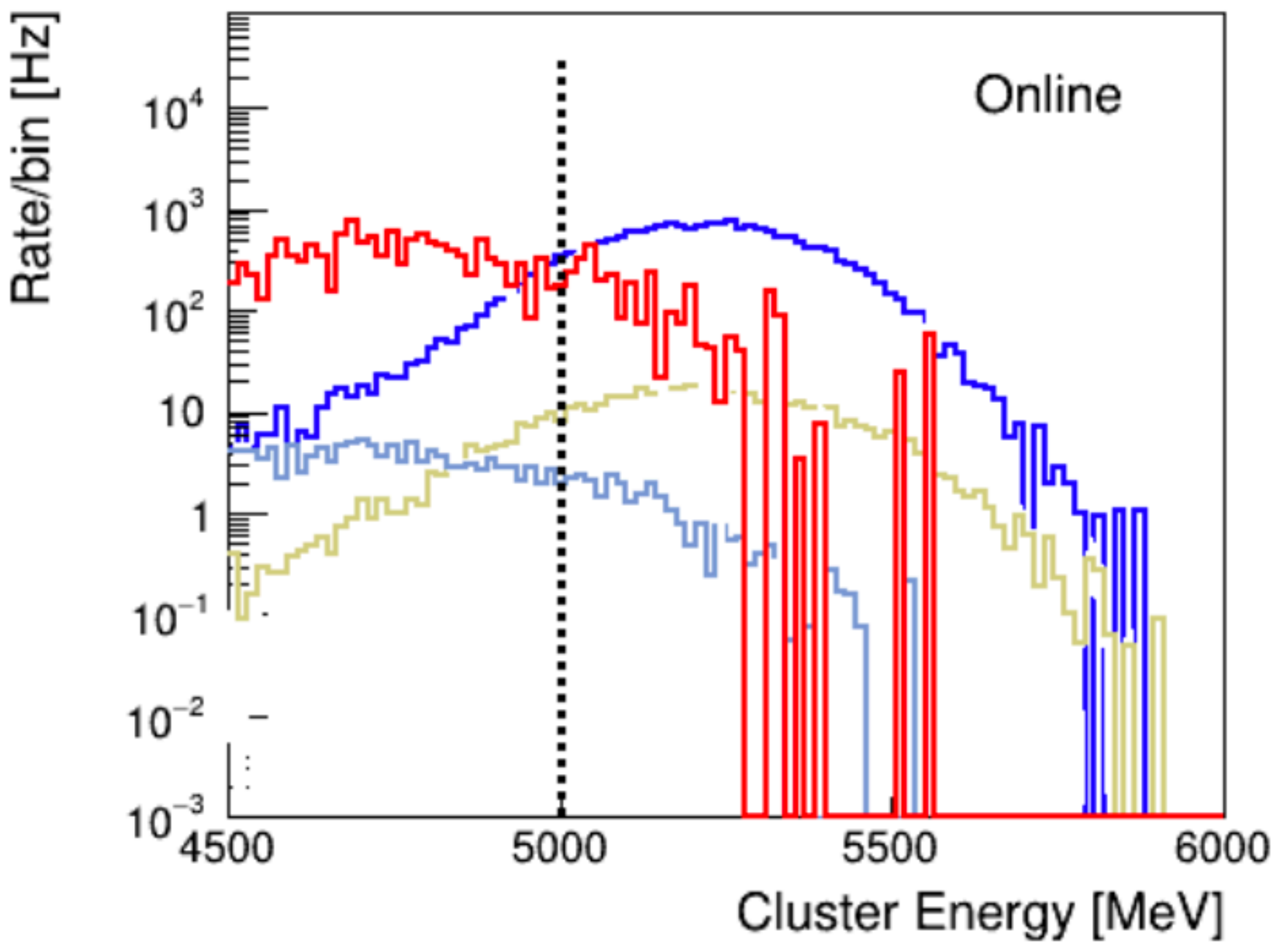
Beam polarization 85%

40 days production runtime ⟶ Raw asymmetry statistical precision $\delta(A_{raw}) \sim 5$ ppm

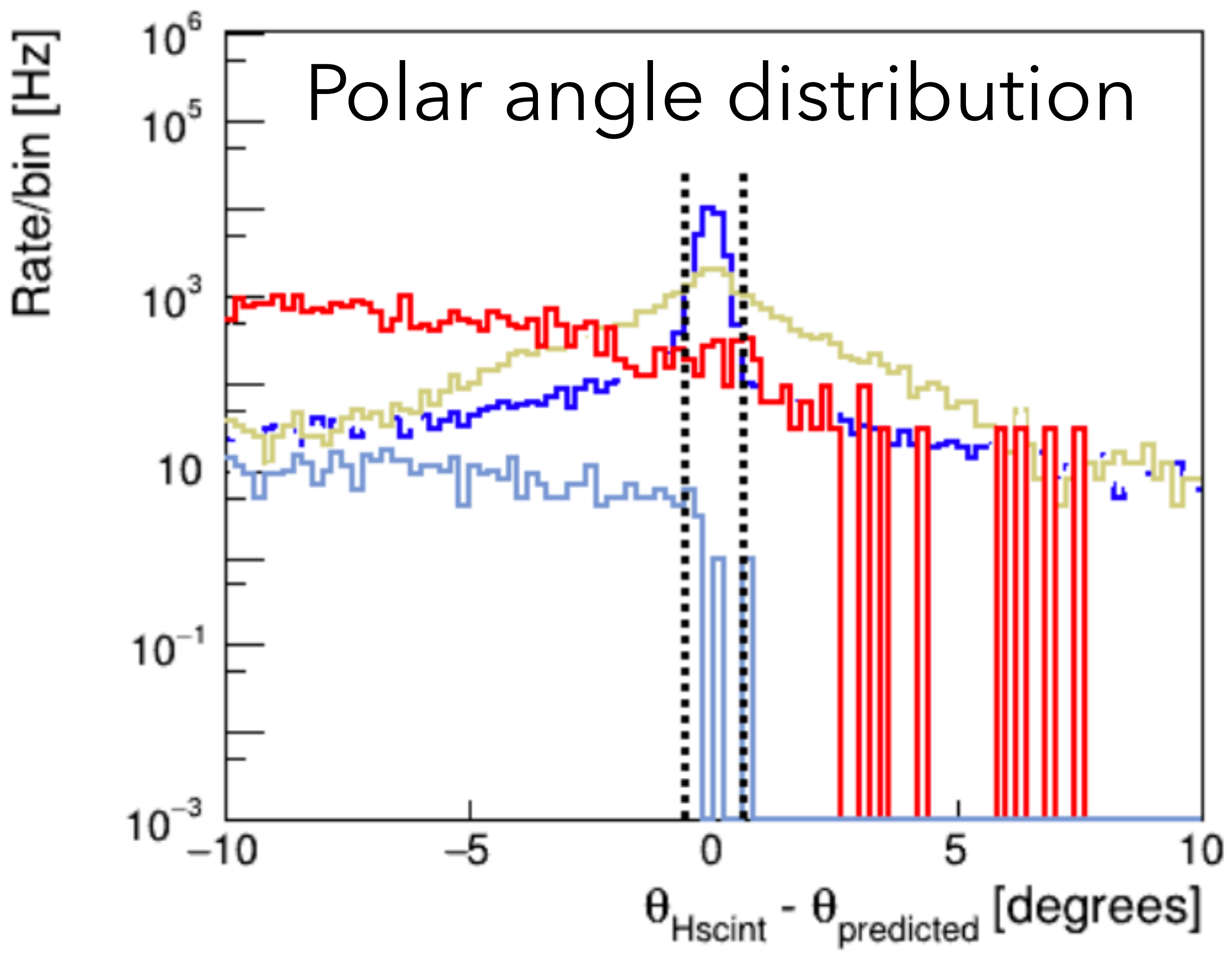
⟶ $A_{PV} = -150 \pm 6.2$ ppm

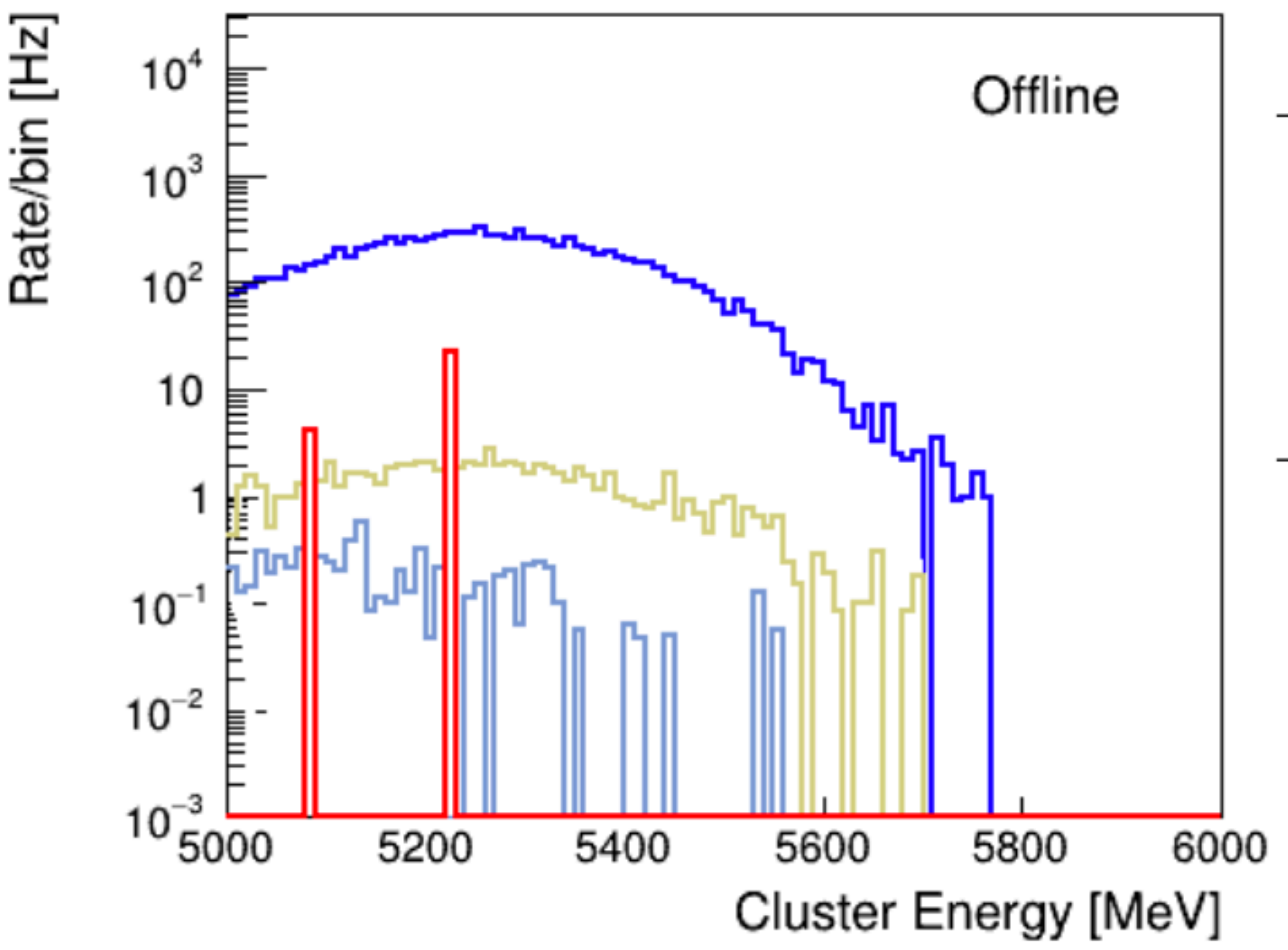
Elastic event discrimination





dashed lines = offline cuts





Fraction of total by event type	Online	Offline
Elastic scattering	0.531	0.989
Inelastic (pion electro-production)	0.450	0.002
Quasi-elastic scattering (target windows)	0.015	0.008
π^0 photo-production	0.004	0.001

"sideband" analyses will help verify QE and inelastic asymmetries

Error budget

quantity	value	contributed uncertainty
Beam polarization	85% ± 1%	1.2%
Beam energy	6.6 + / − 0.003 GeV	0.1%
Scattering angle	$15.5^\circ \pm 0.03^\circ$	0.4%
Beam intensity	<100 nm,<10 ppm	0.2%
Backgrounds	< 0.2 ppm	0.2%
G_E^n/G_M^n	-0.2122 ± 0.017	0.9%
G_E^p/G_M^p	0.246 ± 0.0016	0.1%
σ_n/σ_p	0.402 ± 0.012	1.2%
$G_A^{Zp}/G_{\text{Dipole}}$	-0.15 ± 0.02	0.9%
Total systematic uncertainty:		2.2%

or 3.3 ppm

Statistical precision for A_{PV}: 6.2 ppm (4.1%)

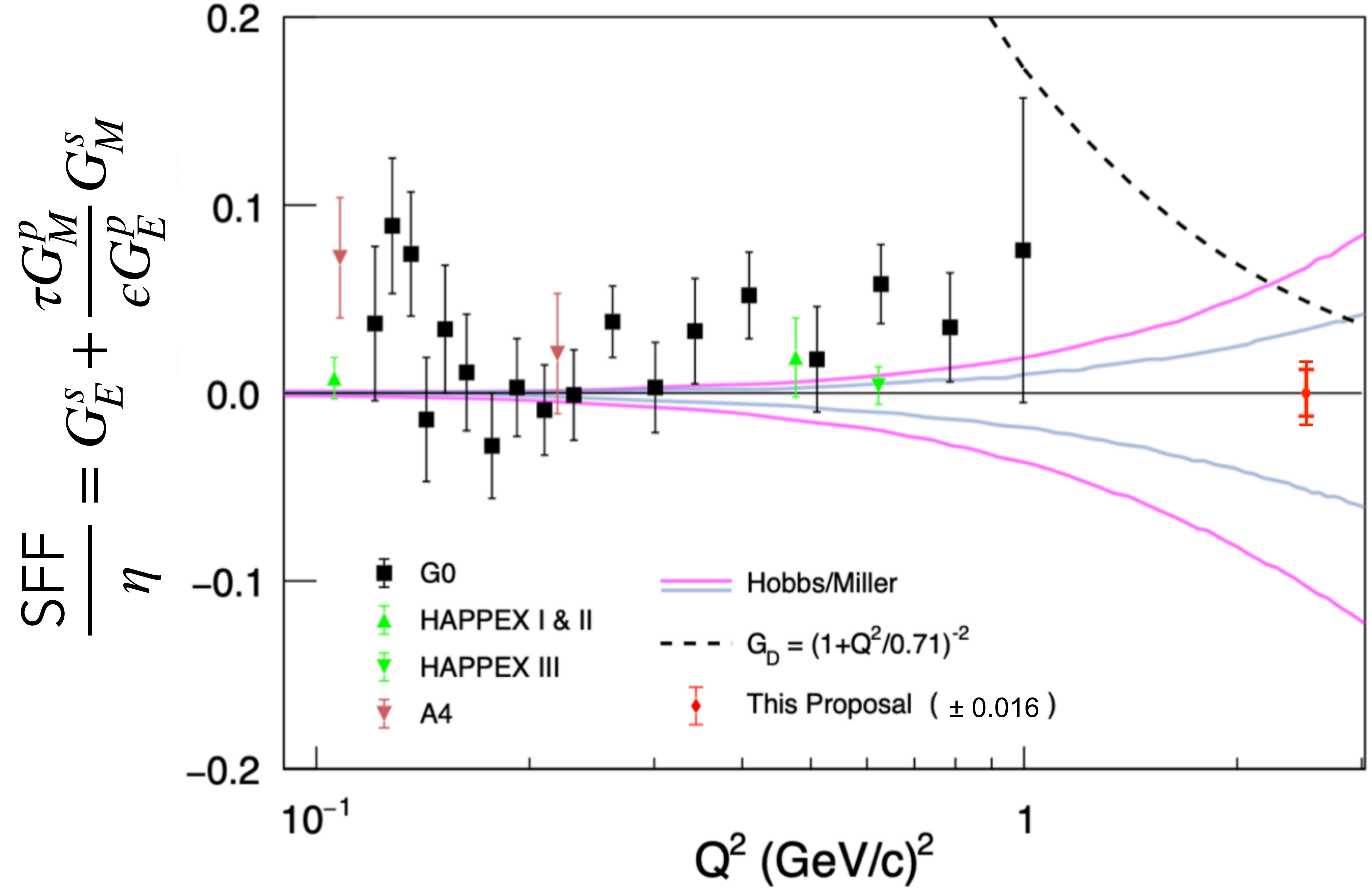
There is also an uncertainty from radiative correction, is small except for a dominant "anapole" piece.

If the anapole uncertainty is not improved, this would contribute at additional 4.1 ppm (2.7%) uncertainty

Projected result

δ A_{PV} = ± 6.2 (stat) ± 4.5 (syst)

$\delta\left(G_E^s + 3.1 G_M^s\right)$ = ± 0.013 (stat) ± 0.010 (syst) = 0.016 (total)



If $G_M^s = 0$, $\delta G_E^s \sim 0.016$, (about 34% of G_D)

If $G_E^s = 0$, $\delta G_M^s \sim 0.0052$, (about 11% of G_D)

The proposed measurement is especially sensitive to G_M^s

The proposed error bar reaches the range of lattice predictions, and the empirically unknown range is much larger.

Summary

Configuration #	Procedure	Beam current, μA	time, days
C1	Beam parameters	1-70	1
C2	Detector calibration	10	2/3
C3	Dummy target data	20	1/3
C4	Moller polarimetery	1-5	3
C5	A_{PV} data taking	60	40
	Total requested time		45

- 10+ years after the last sFF searches were performed, a new experiment is proposed for much higher Q^2, motivated by interest in flavor decomposition of electromagnetic form factors
- Projected accuracy at 11% of the dipole value allows high sensitivity search for non-zero strange form factor.
- The proposed error bar is in the range possibly suggested by lattice predictions, and significantly inside the range from the simple extrapolation from previous data
- These results will be crucial to support the interpretation of the nucleon form-factors as constraints on GPDs
- We are requesting PAC approval of 45 days of beam time (65 uA on 10 cm long LH2 target).

Backup slides

Helicity-correlated Beam Asymmetries

Position differences (like angle, but angle ~10x smaller):
APV roughly proportional to Q^3 , so sensitivity $\delta A / \delta\theta \sim 3\, \delta\theta / \theta$

Assume very large (by today's standards) position difference of 200 nm, to be compared to 64cm radius of ECAL

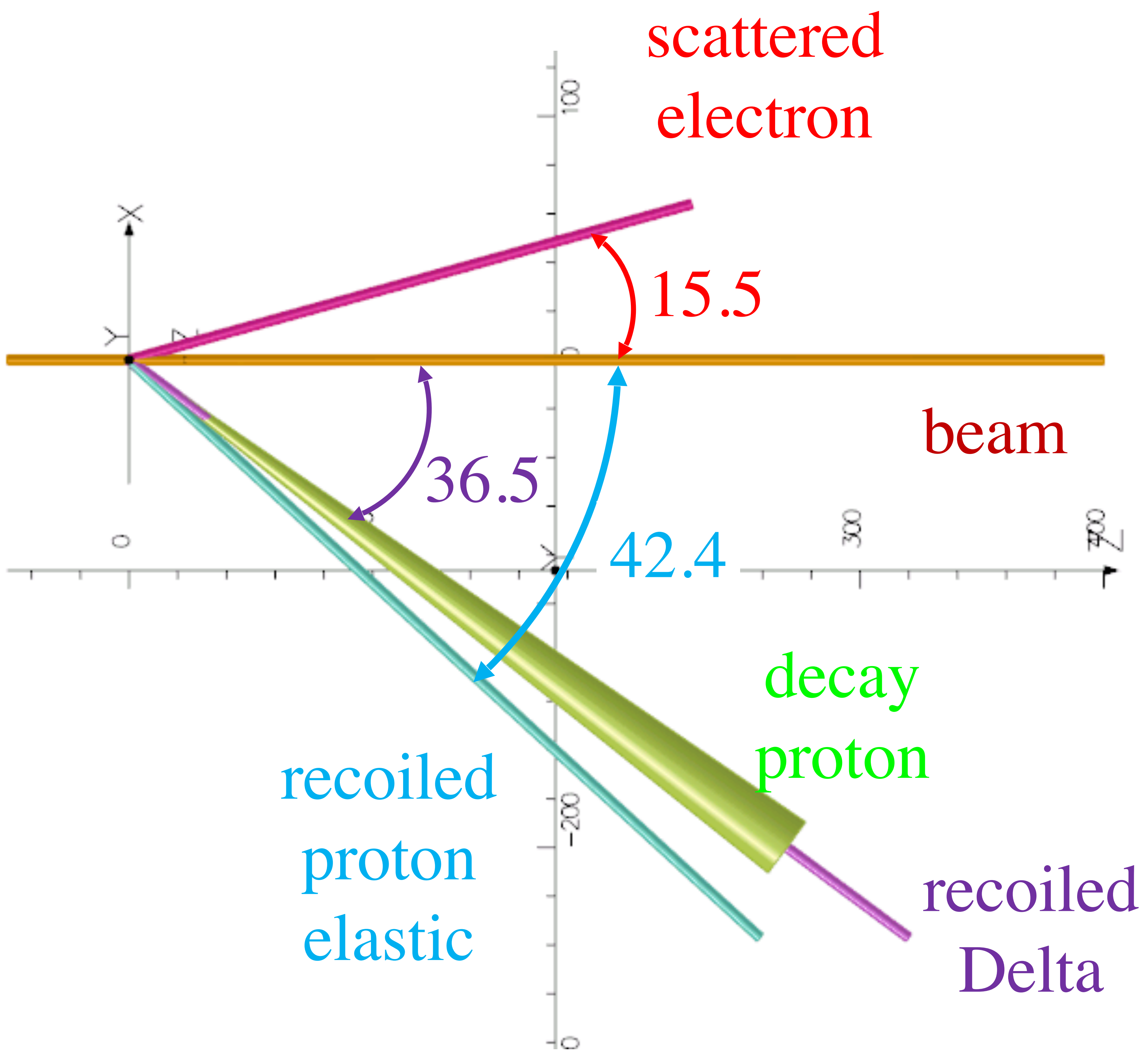
200nm / 64 cm ~ 0.3 ppm, or 0.2%

Similarly, energy, assuming 200 nm in dispersive bpm (~1m dispersion)$\longrightarrow$ 0.2 ppm, or 0.15%

Azimuthal symmetry leads to excellent cancellation, so the net effects will be very small. Can be checked with regression

Charge asymmetry
Using feedback, <10ppm easily achievable. 1% calibration $\longrightarrow$ 0.1ppm systematic, 0.06%

Pion electro-production contribution



Pion production rate
above offline ECAL threshold ~ 3 kHz

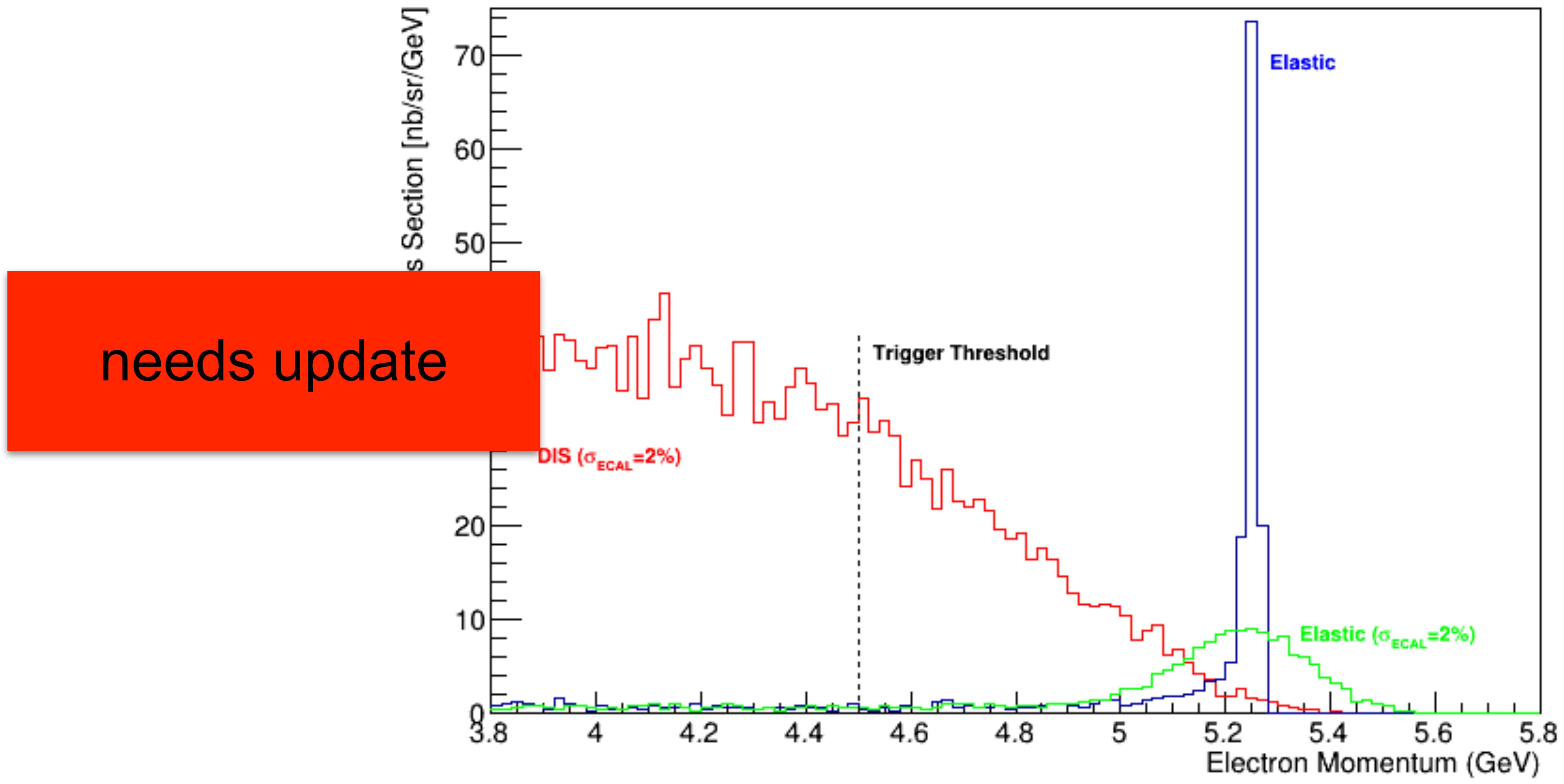
Angular separation:
6° (at Δ peak)
2.8° (at π threshold)

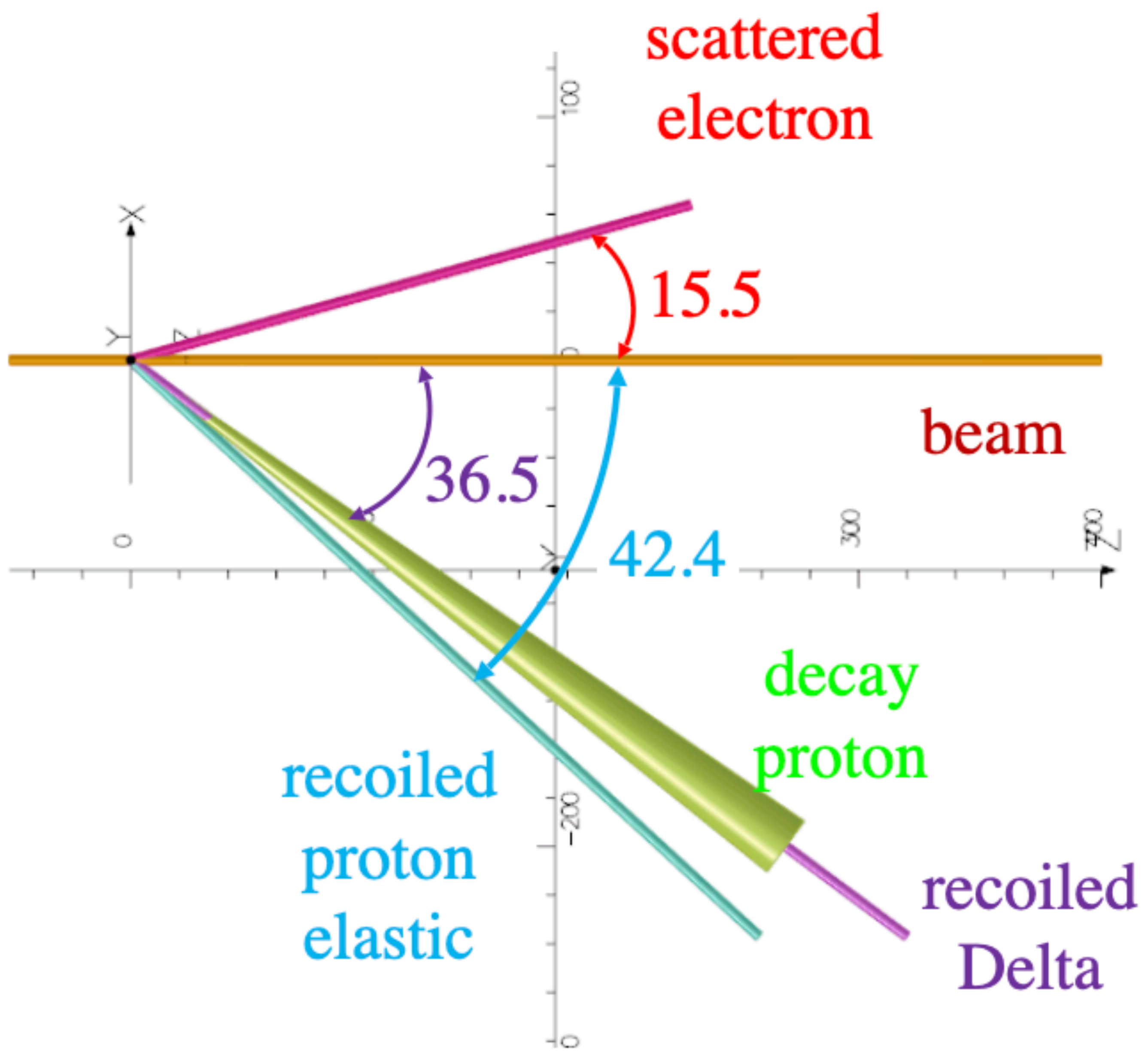
Angular resolution ~0.6° (polar)

Proton cone around Δ recoil, projected to polar angle:
RMS = 2° (so, 2.5σ separation for Δ)

Fraction to elastic rate < 0.3%

Pion-production background rate calculation





Online:
Electron arm single rate for $E_{e'}$ > 5 GeV is ~18 kHz
about 50% enters HCAL acceptance as coincidence, so ~10kHz

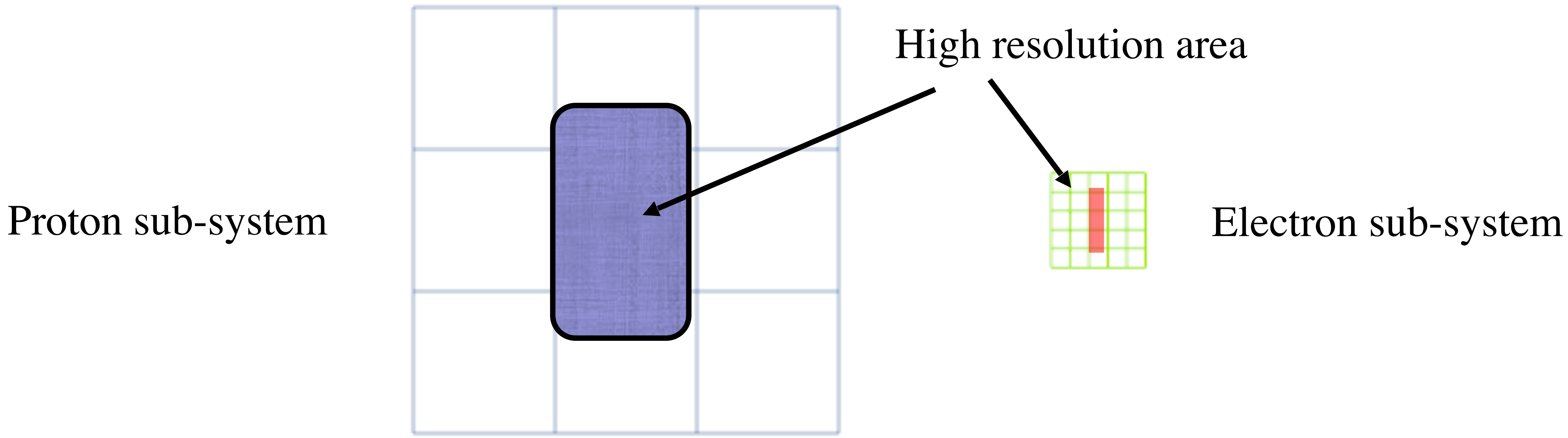
Offline:
electron arm single rate for E> 5.2 GeV is ~3 kHz
high angular resolution excludes >99%

Accidental background coincidence calculation

Online:
Electron arm single rate for $E_{e'}$ > 5 GeV is ~18 kHz : 18 Hz/detector, 450 Hz/subsystem
Proton arm single rate 1.2 MHz : 36 kHz/subsystem
Time window in the trigger 40 ns -> total accidental coincidence rate ~ 0.2 kHz

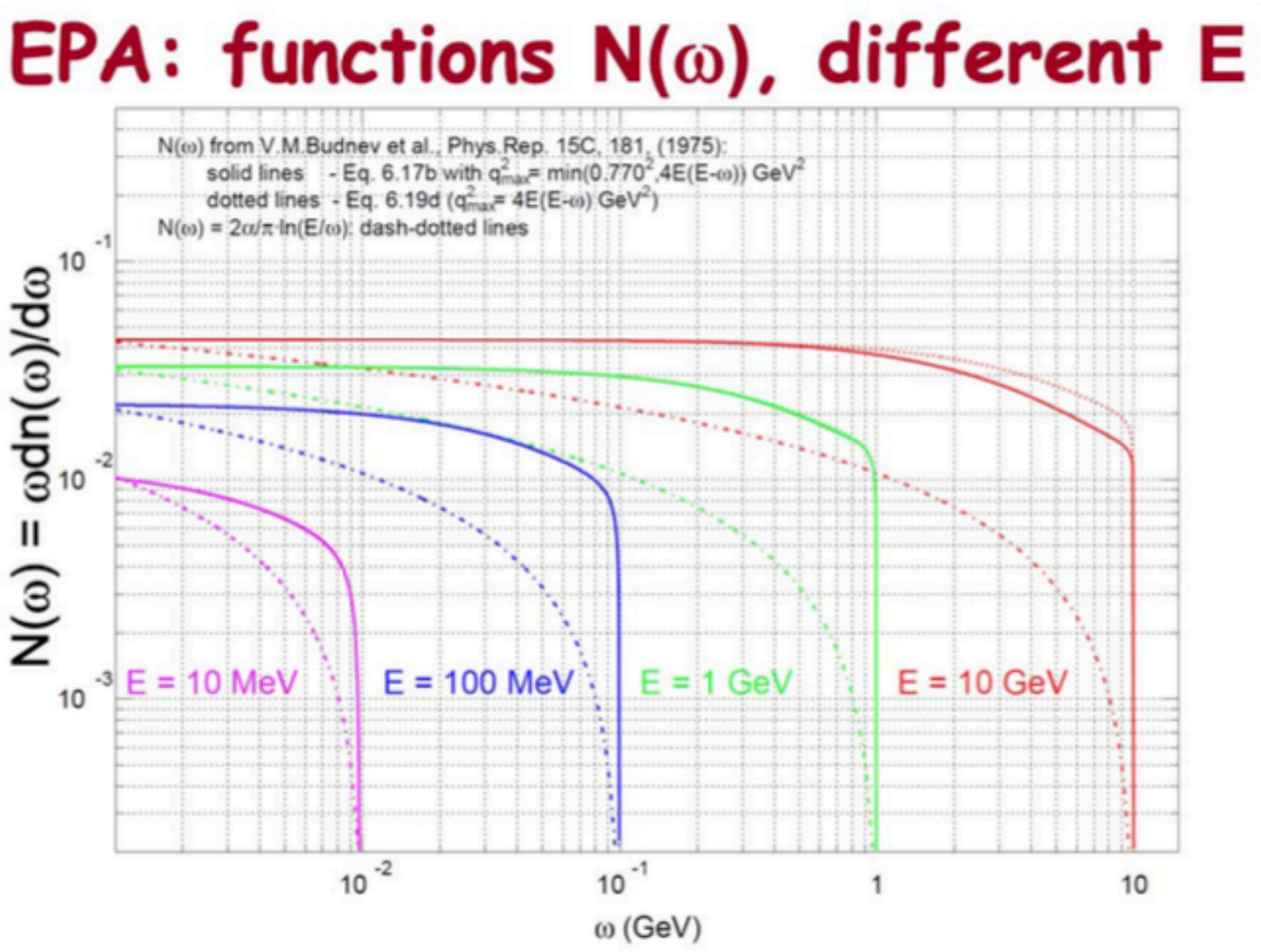
Offline:
Time window in analysis 4 ns
Accidental rate is 0.02 Hz in high resolution part of solid angle
of sub-system where elastic rate is 70 Hz.

Next reduction due to higher threshold in offline analysis:
electron arm single rate for E> 5.2 GeV is 3 kHz-> extra factor of 5



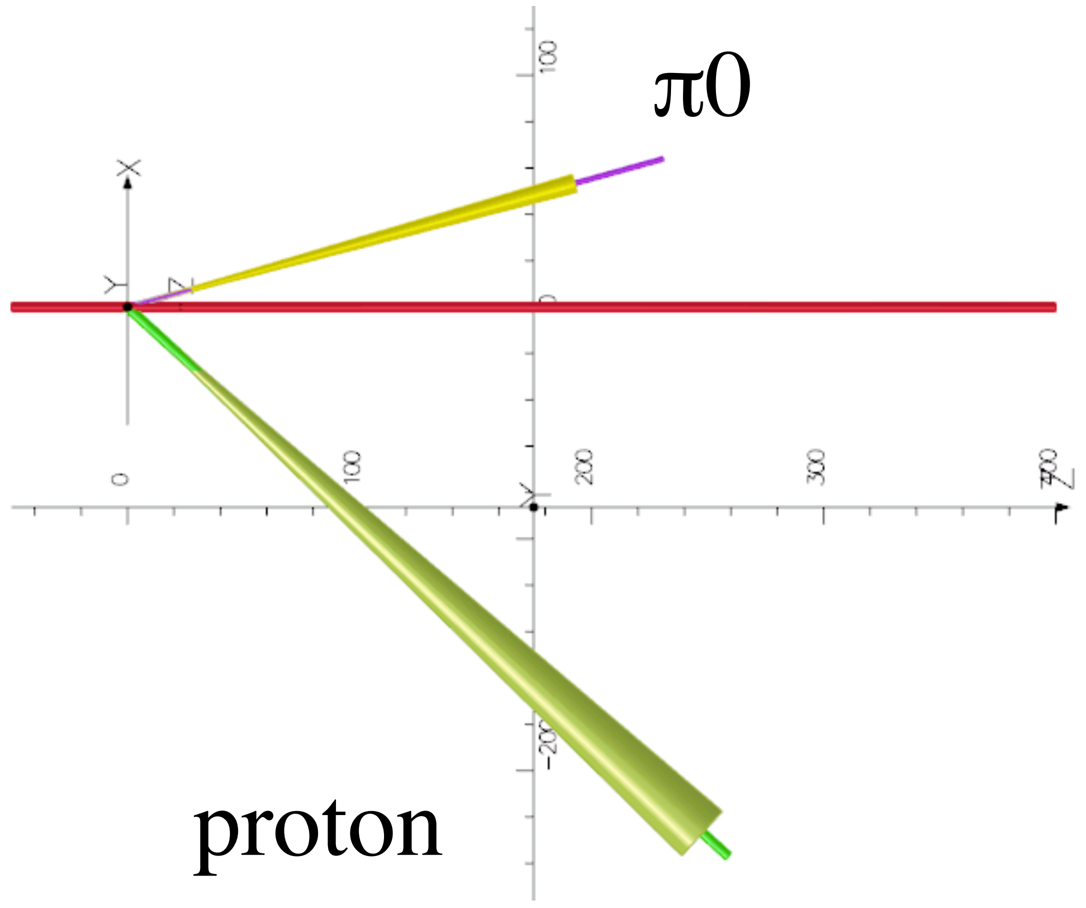
Single pion photo-production contribution

pion (ECAL) - proton (HCAL) coincidence



$$\frac{d\sigma}{dt}_{\gamma n\to\pi^- p} = 1.7\times 0.83\times\left(\frac{10}{s\,[\mathrm{GeV}^2]}\right)^7 (1-z)^{-5}(1+z)^{-4}\ \ (\mathrm{nb/GeV}^2)\,,$$

$$N_{\pi^- p} = \frac{d\sigma}{dt}_{\pi^- p}\frac{p_{\pi^-}^2}{\pi}\Delta\Omega_{\pi^-} f_{\pi^- p}\left[\frac{\Delta E_\gamma}{E_\gamma}\frac{t_{rad}}{X_o}\mathcal{L}_{en}\right]$$



Near the end point the photon yield is going down ⟶ reduction in factor t_{rad}/X_0

$f_{\pi-p}$ takes care of the cuts on angular correlation/resolution

Remaining single pion events < 0.2% of elastic rate

Background events from Al

- assumed 5 mils target cell windows, ~5% nucleon
- Fermi energy smears quasi-elastic scattering distribution, about 80x suppression
- B/S < 0.1%
- a dummy target will be used to check accepted rate

Anapole Moment

In the context of a very large discrepancy from SAMPLE, the anapole radiative correction was investigated as a possible cause

$$\tilde{G}_A^e(Q^2) = \left[\tau_3 g_A(1 + R_A^{(T=1)}) + \frac{3F - D}{2} R_A^{(T=0)} + (1 + R_A^{(0)})\Delta s\right] G_A^D(Q^2)$$

The 1-quark and many-quark corrections to the axial charges in the $\overline{MS}$ renormalization scheme.

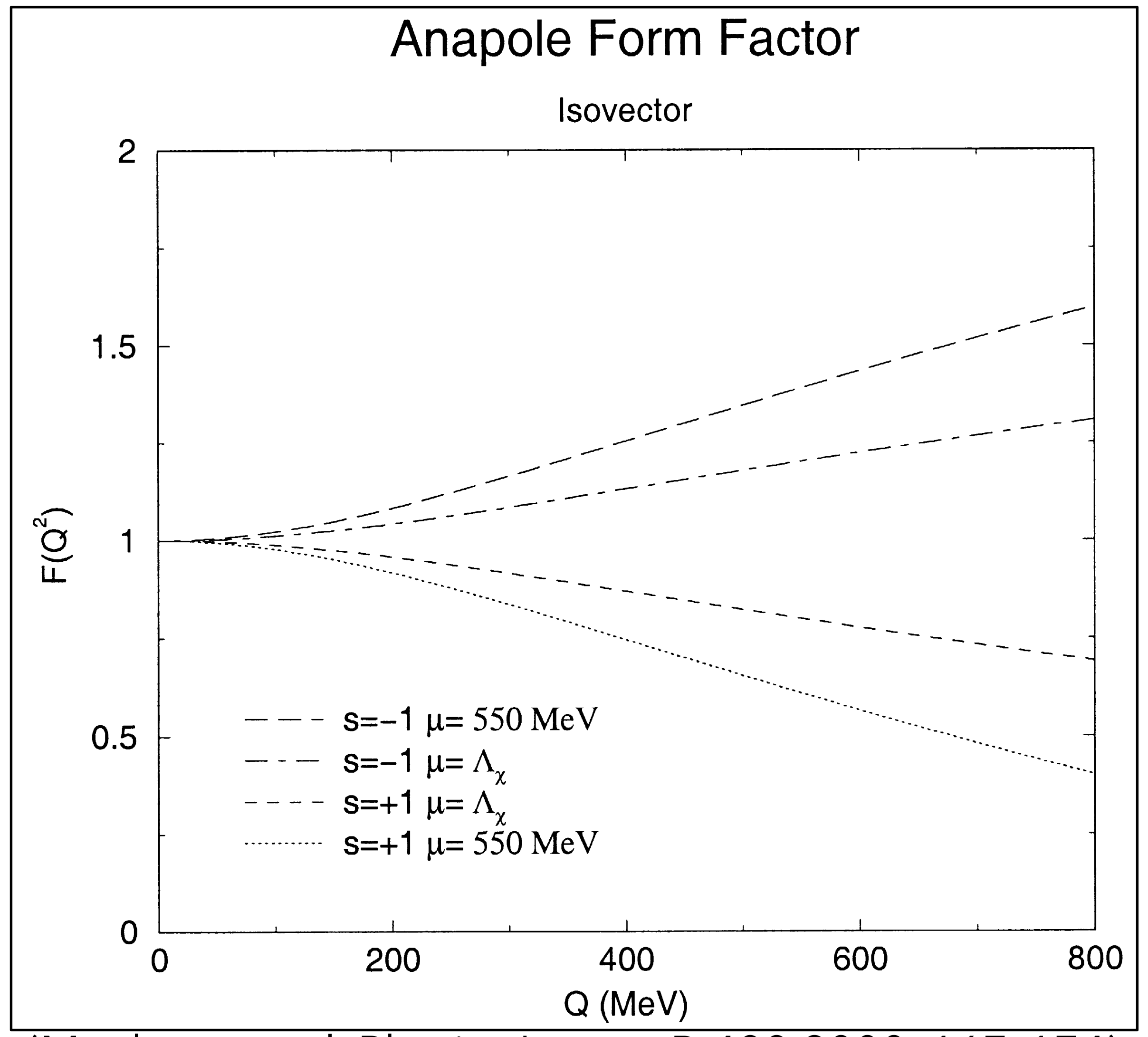
	$R_A^{(T=1)}$	$R_A^{(T=0)}$	$R_A^{(0)}$
1-quark	−0.172	−0.253	−0.551
Many-quark	−0.086(0.34)	0.014(0.19)	–
Total	−0.258(0.34)	−0.239(0.20)	−0.551

values from Shi-Lin Zhu, S.J. Puglia, Barry R. Holstein, M.J. Ramsey-Musolf, Phys. Rev. D 62 (2000) 033008.

Suggests a coefficient on the axial term at $Q^2 = 0$:

$$(1 + R_A^{(T=1)}) = 0.74 \pm 0.34$$

Without improvement, this would correspond to 4.1ppb, or 2.7% of A_{PV}

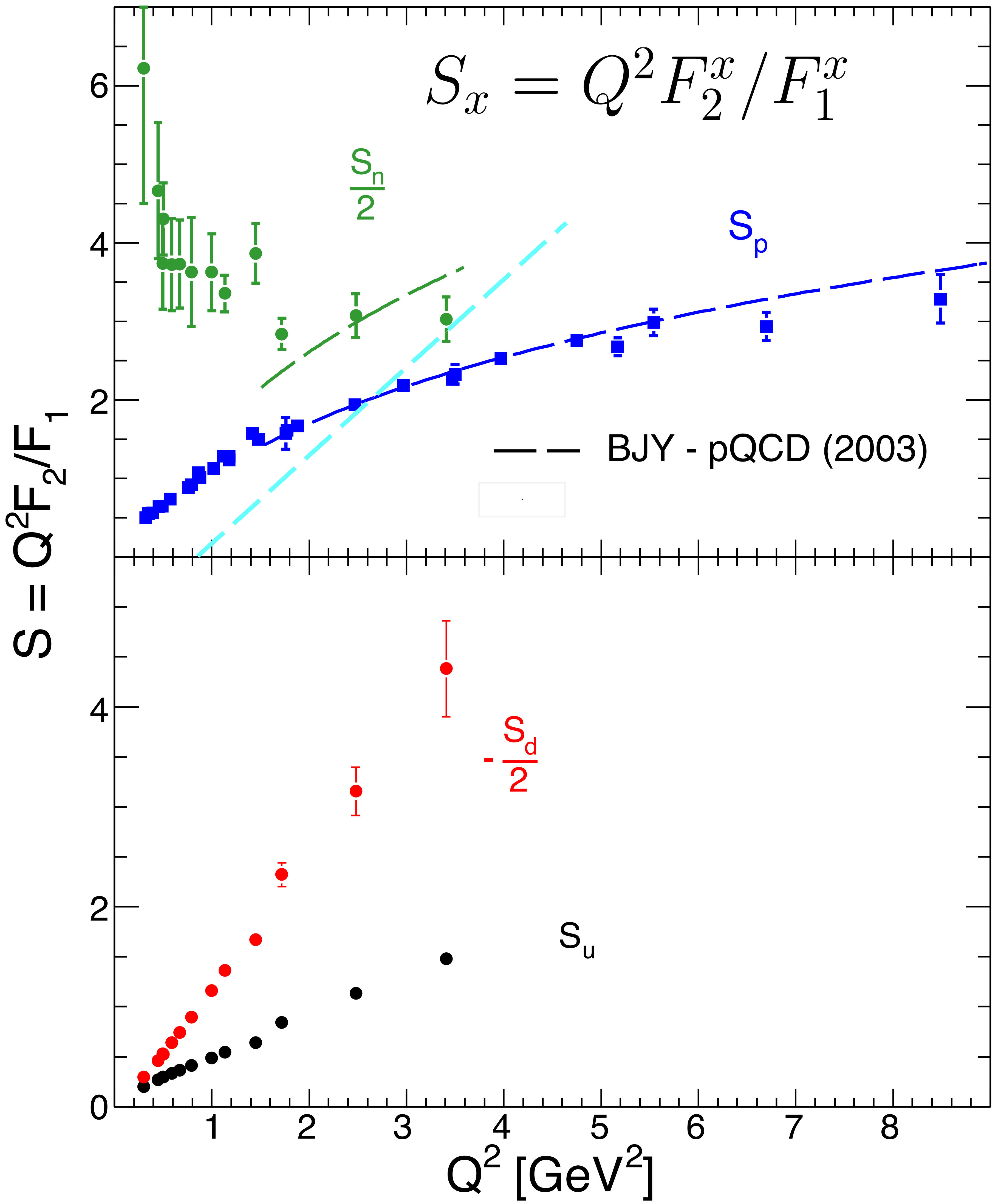


(Maekawa et al, Physics Letters B 488 2000. 167–174)

Q^2 dependence was explored at that time - suggested that it may be significant, but hasn't been evaluated since, or to high Q^2.

(Here, I believe this $F(Q^2)$ multiplies only the many-quark $R_A^{(T=1)}$= -0.086 contribution.)

Q^2 dependence of F_2/F_1



Cates, de Jager, Riordan, Wojtsekowski, Phys.Rev.Lett. 106 (2011) 252003

pQCD prediction for large Q^2: scaling

$$S \to Q^2 F_2/F_1$$

pQCD updated prediction:

$$S \to \left[Q^2/\ln^2(Q^2/\Lambda^2)\right] F_2/F_1$$

The lines for individual flavor are straight: F_2/F_1 ~ constant

Gamma-Z Box

Additional radiative correction to Q_W

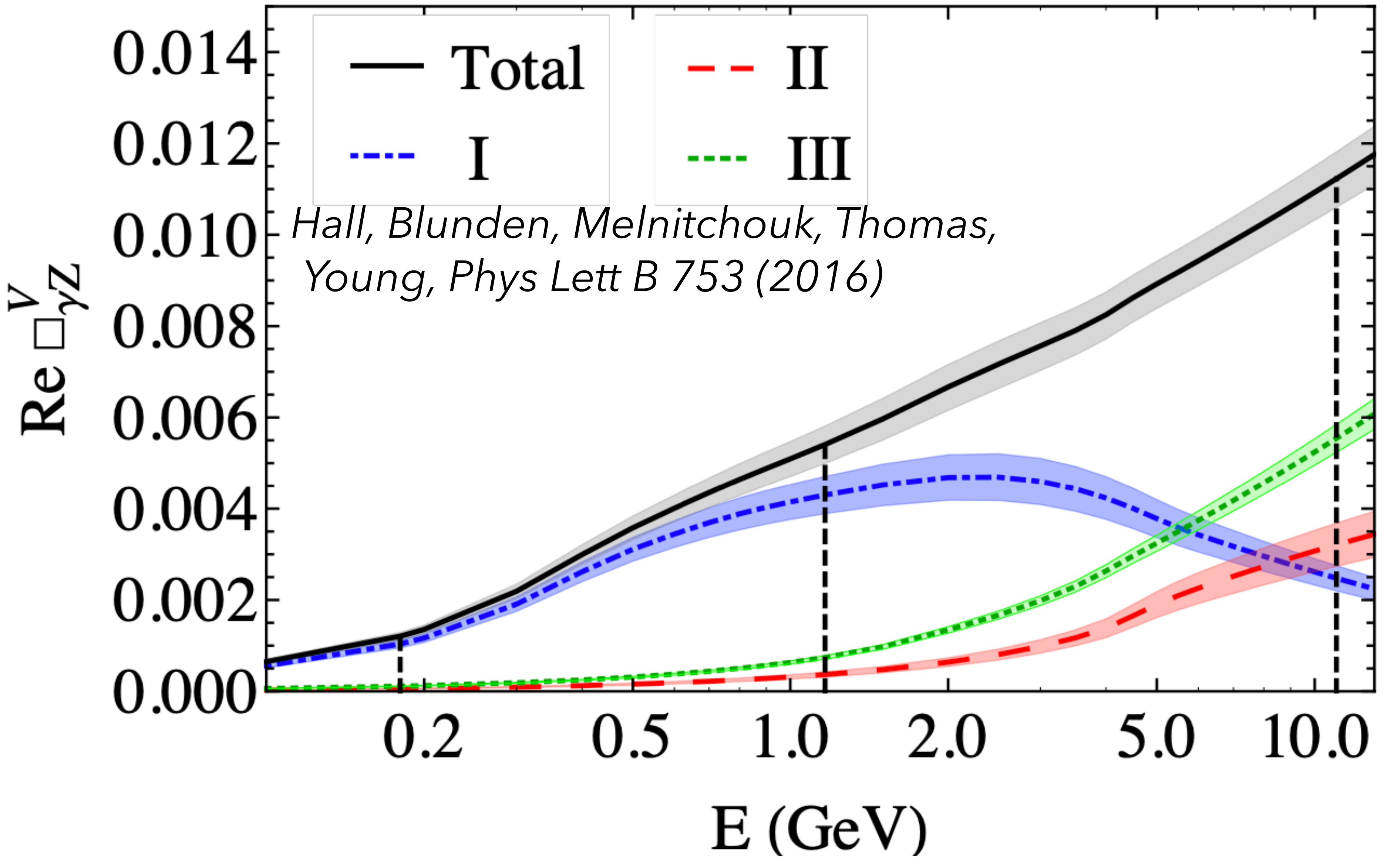
$$Q_W^p = (1 + \Delta\rho + \Delta_e)\left(1 - 4\sin^2\theta_W(0) + \Delta_e'\right) + \Box_{WW} + \Box_{ZZ} + \Box_{\gamma Z}(0)$$

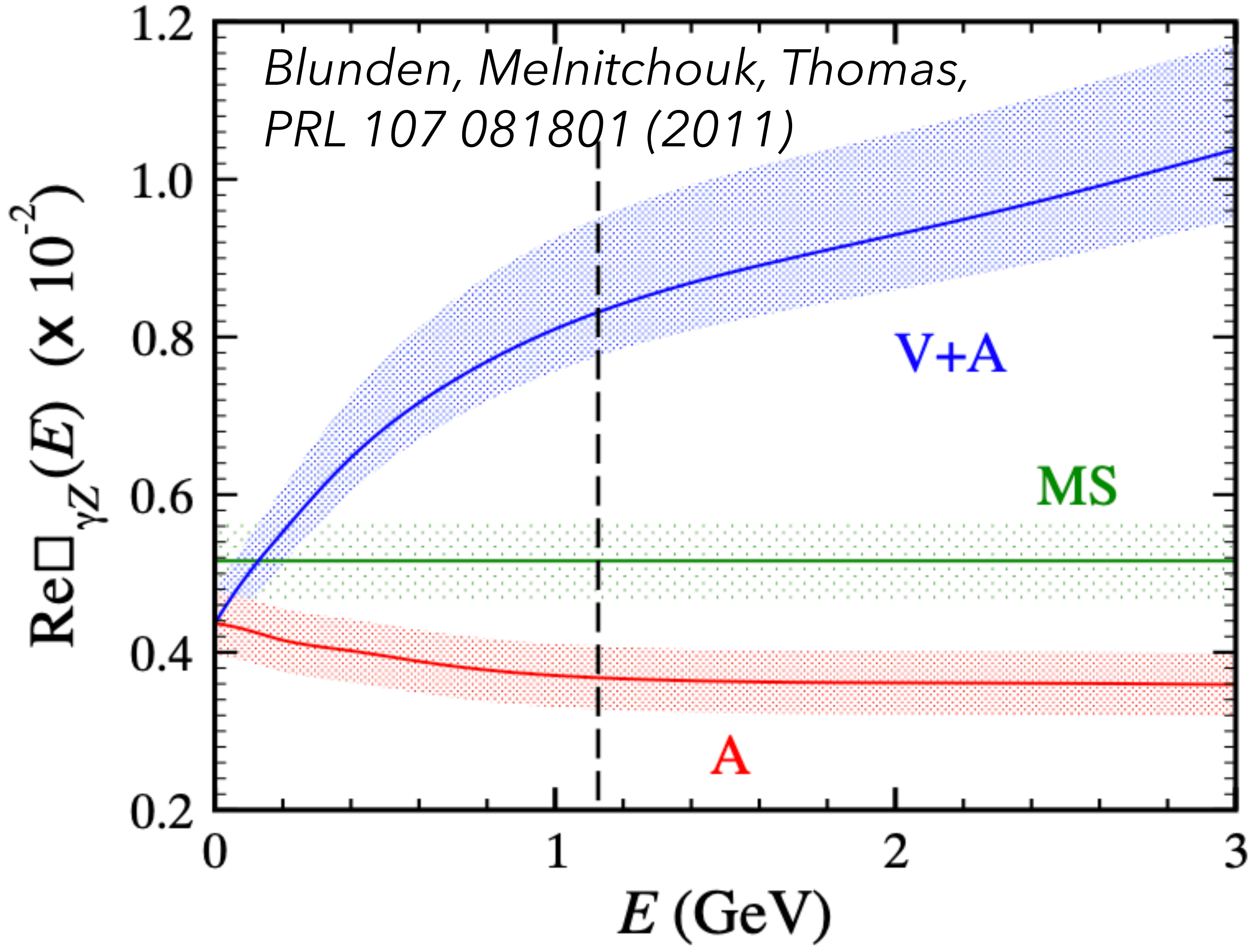
For Qweak, added ~0.5% uncertainty

Here, $\Box^{\mathrm{v}}_{\gamma Z}(0)$ = 0.0095 ± 0.0005 and $\Box^{\mathrm{a}}_{\gamma Z}(0)$ = -0.0036 ± 0.0004 which together is about 1.33±0.14 ppm (0.9±0.1%)

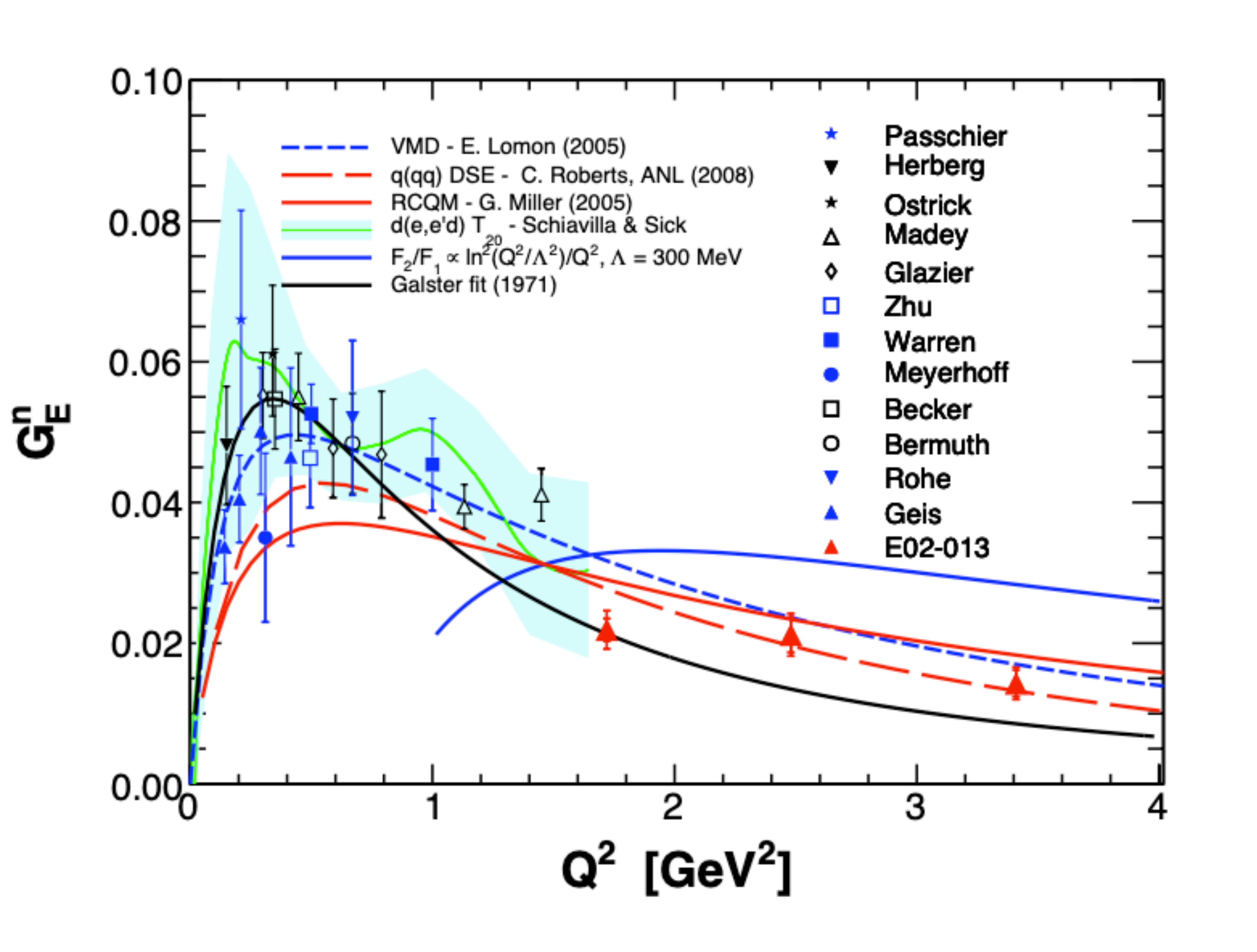
Caveat: this calculation is for forward direction. Off-forward expected to be greatly reduced (but this is also model dependent).

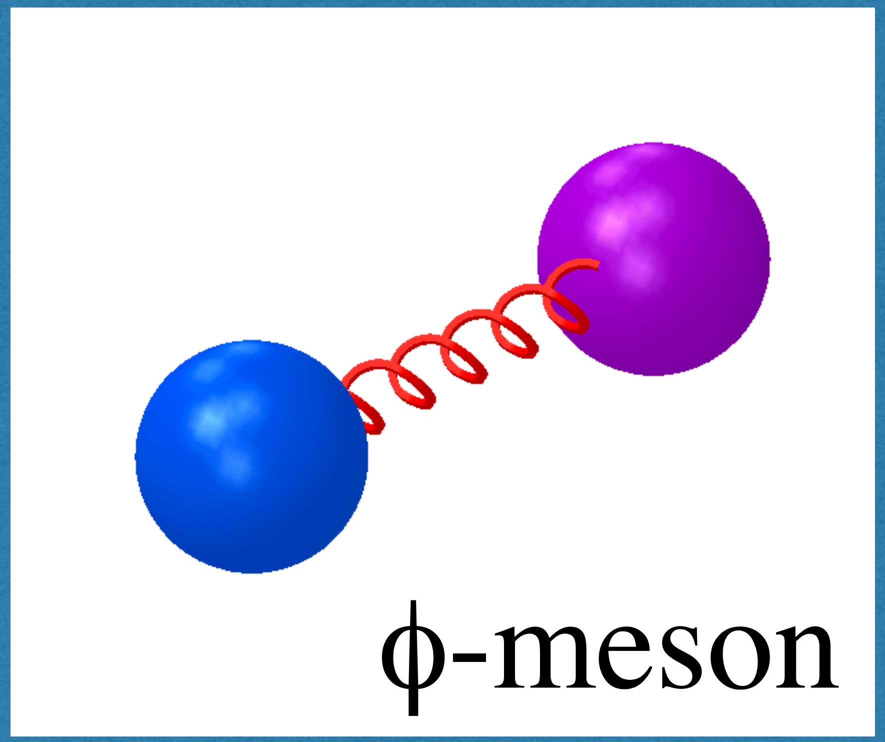
Axial piece smaller, didn't receive as much recent attention/update, seems stable with energy





Why search at high Q2?





PARAMETER β IN $\phi \to \pi^0 e^+ e^-$ DECAY

VALUE (GeV^{-2})	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
2.02±0.11	9.5k	[1] ANASTASI	16B	KLOE	1.02 $e^+e^- \to \pi^0 e^+ e^-$

This combined phi-pi radius ~ 0.69 fm
with a pi-0 radius of ~ 0.64 fm and
a ϕ-meson radius of ~ 0.26 fm