Measurement of the weak neutral form-factor of the proton at high momentum transfer

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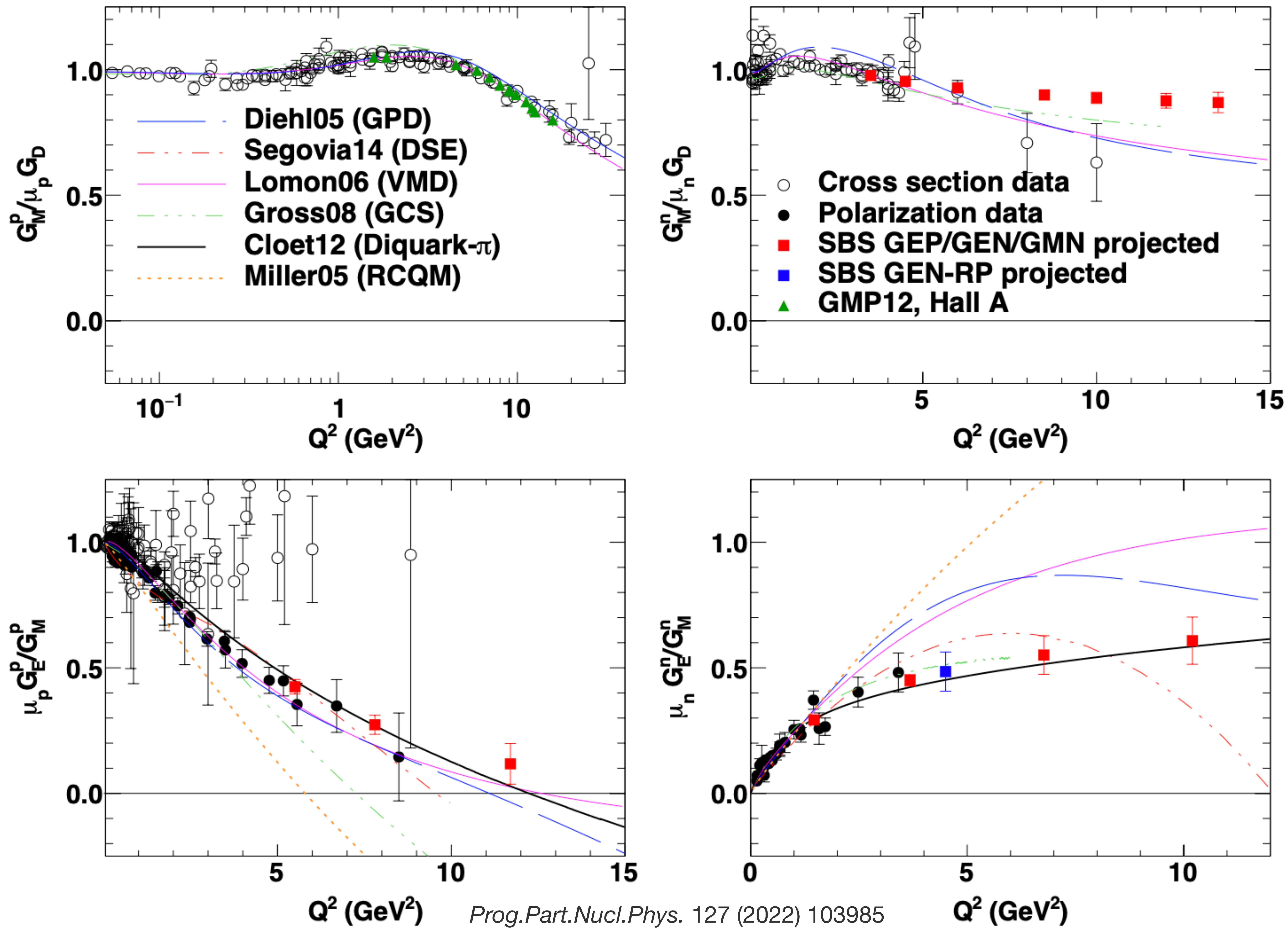
LaTech, Glascow, Indiana, UVa, JLab, CUA, INFN - Roma, Temple, Ohio, Syracuse, FIU, CNU, Fermilab, UWashington, Tel Aviv U, Hebrew U, W&M, AANL Yerevan, Northern Michigan, UConn, Orsay

Nucleon Form Factors at High Q^2



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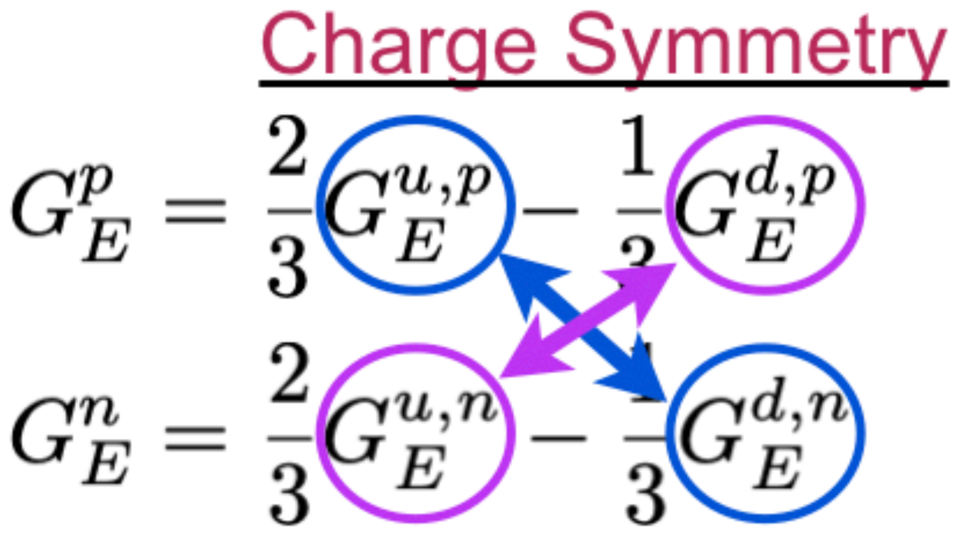
- One might expect a transition to perturbatively dominated mechanisms
- Other degrees of freedom might become evident, such as orbital angular momentum or diquark structure
- Part of the 3D mapping of nucleon structure as the first moment of GPDs at $\xi = 0$

$$\int_{-1}^{+1} dx\, H^q(x,0,Q^2) = F_1^q(Q^2)$$

$$\int_{-1}^{+1} dx\, E^q(x,0,Q^2) = F_2^q(Q^2)$$

These implications rely on extracting the independent quark contributions

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 $G_{E,M}^{u,d}$

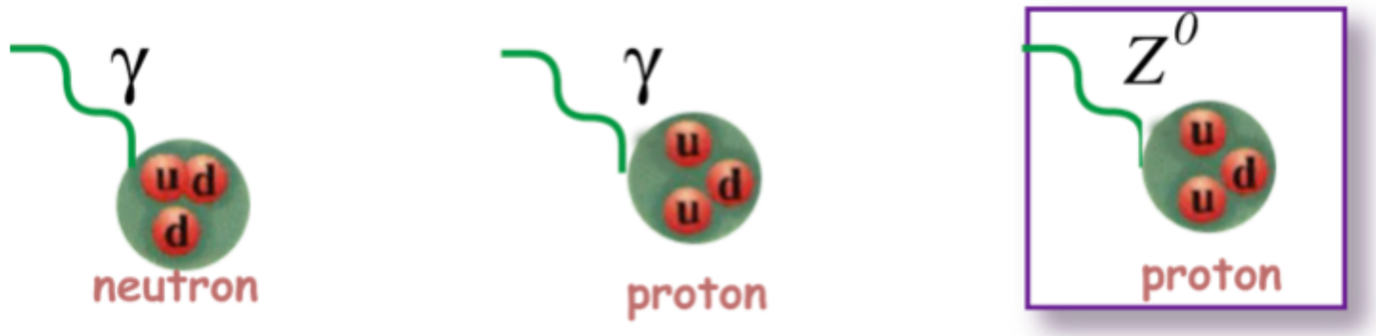
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$

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

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: the assumption of charge symmetry is crucial to the flavor decomposition of the form factors

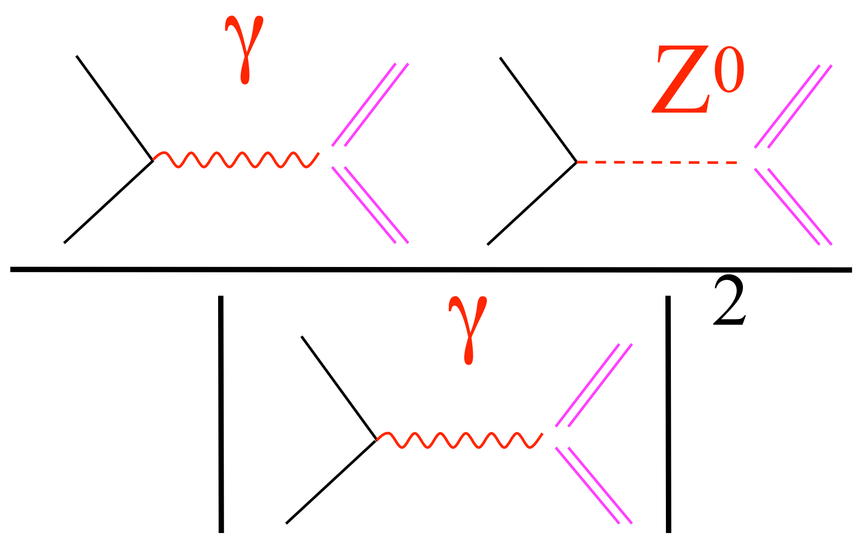
Parity Violating Electron Scattering

Elastic e-p scattering with longitudinally polarized beam and unpolarized target:

Weak and EM amplitudes interfere:

$$\boxed{\sigma = |\mathcal{M}_\gamma + \mathcal{M}_Z|^2}$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim$$



$$\approx \frac{|\mathcal{M}_Z|}{|\mathcal{M}_\gamma|}$$

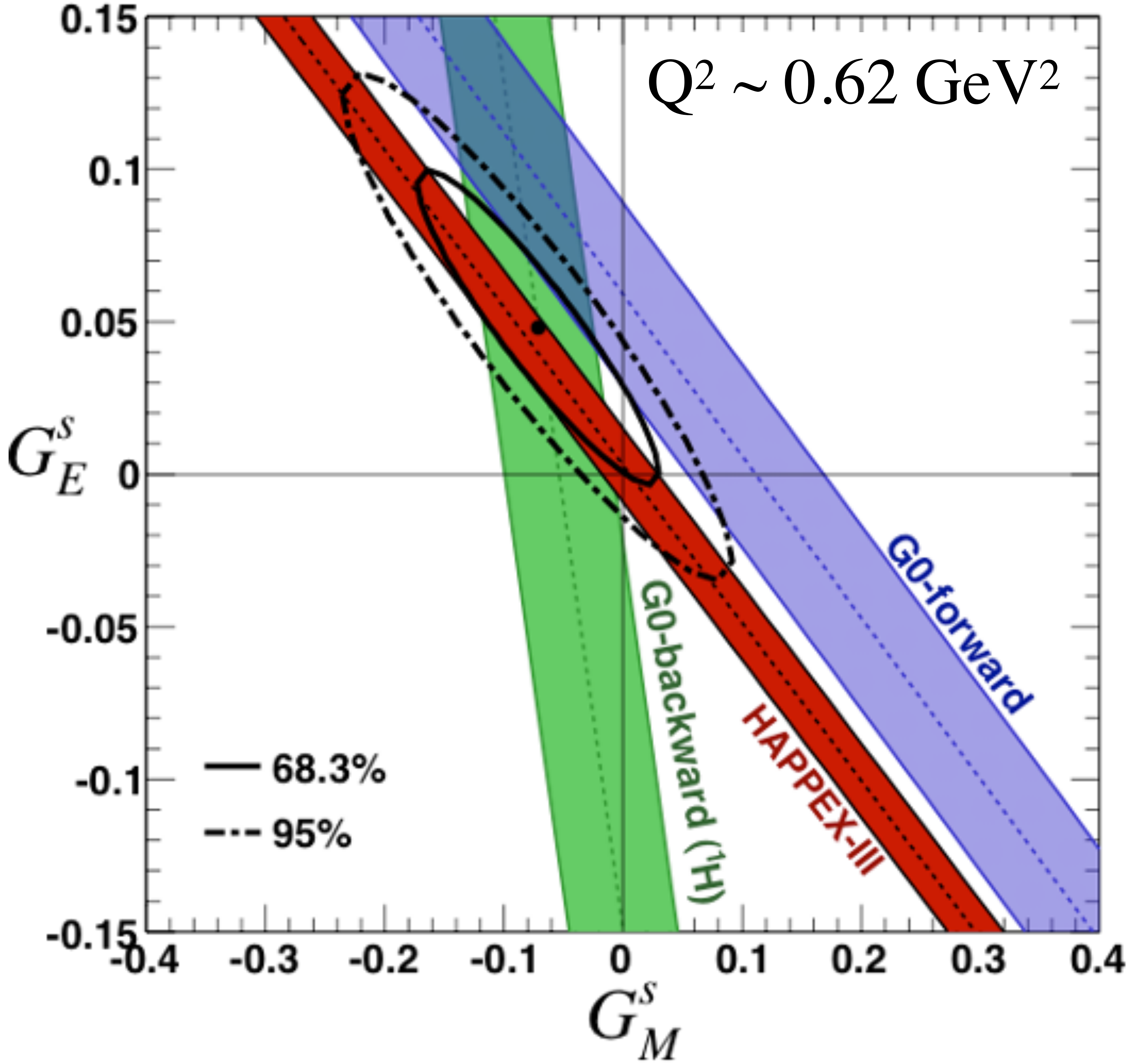
Expressing A_{PV} for e-p scattering, with proton and neutron EM form-factors plus strange form factors:

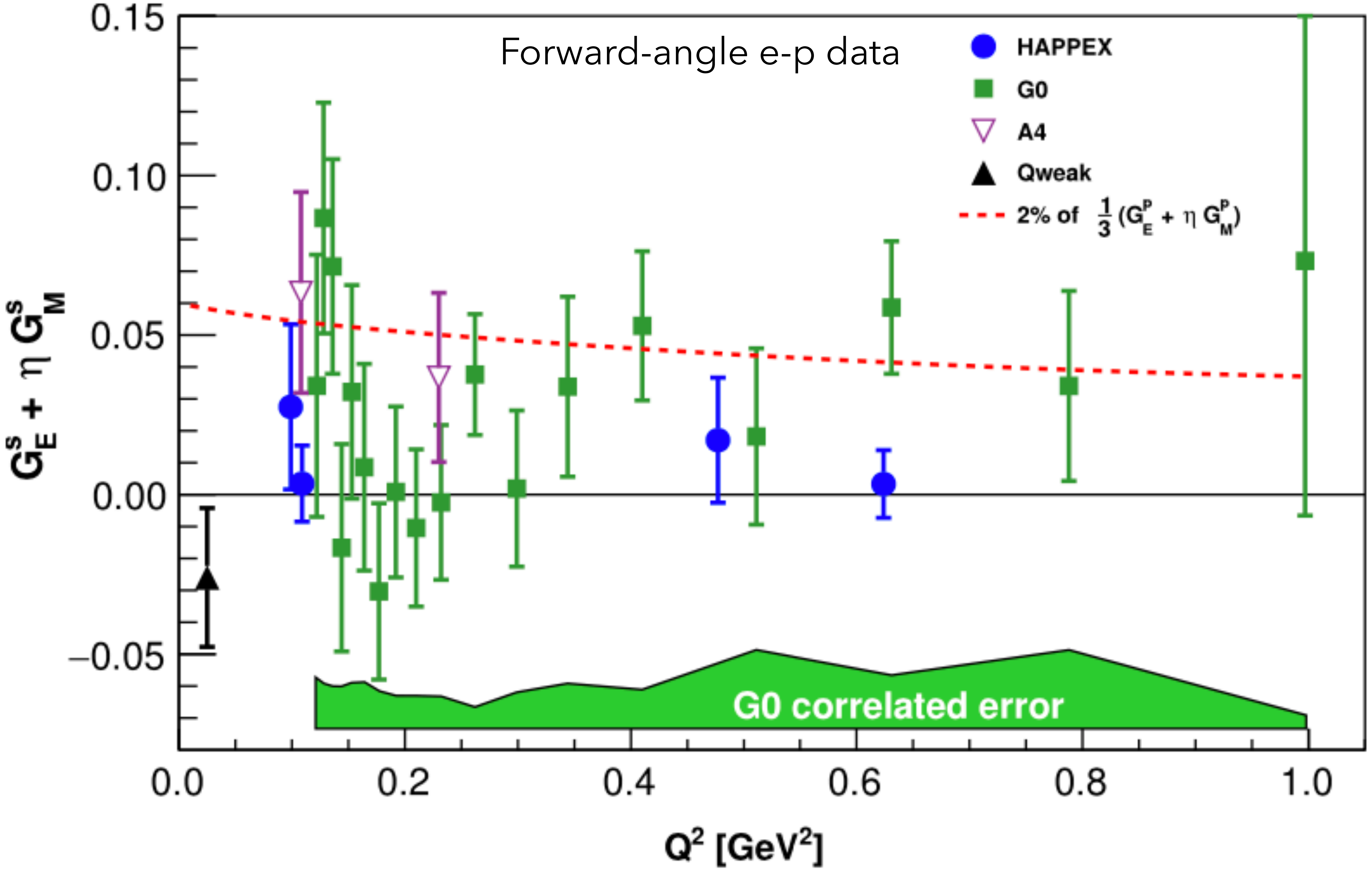
$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot [(1-4\sin^2\theta_W) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p \boxed{G_E^s} + \tau G_M^p \boxed{G_M^s}}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}$$
$$+\epsilon'(1-4\sin^2\theta_W)\frac{G_M^p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

This technique was used to hunt for indications of strange quark contributions in the nucleon, particularly in the *static* (*i.e.* $Q^2 \rightarrow 0$) properties: a strange charge radius or strange magnetic moment

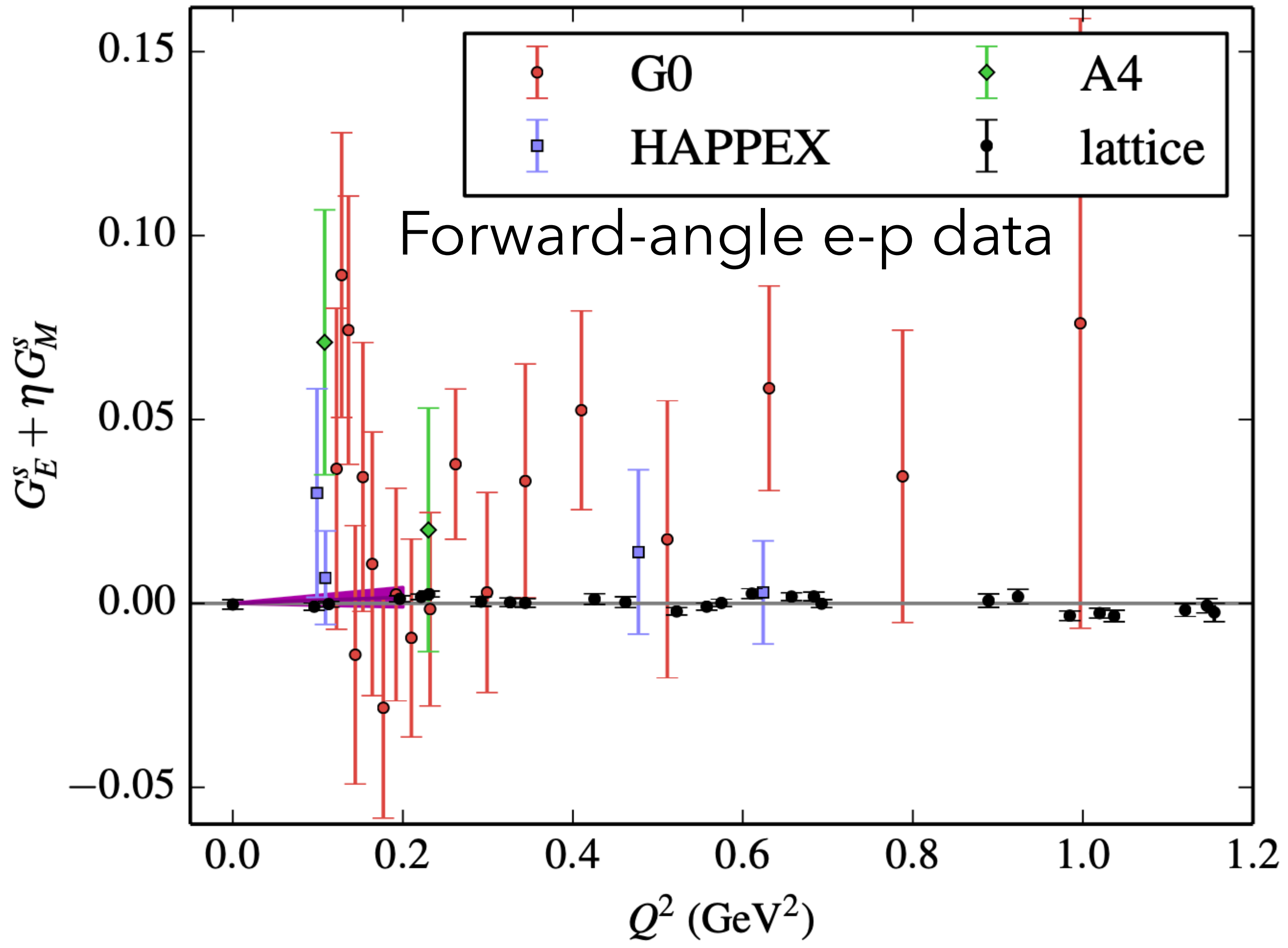
Proton strange form factors via parity violating elastic electron scattering

Strange form factors are measured to be 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





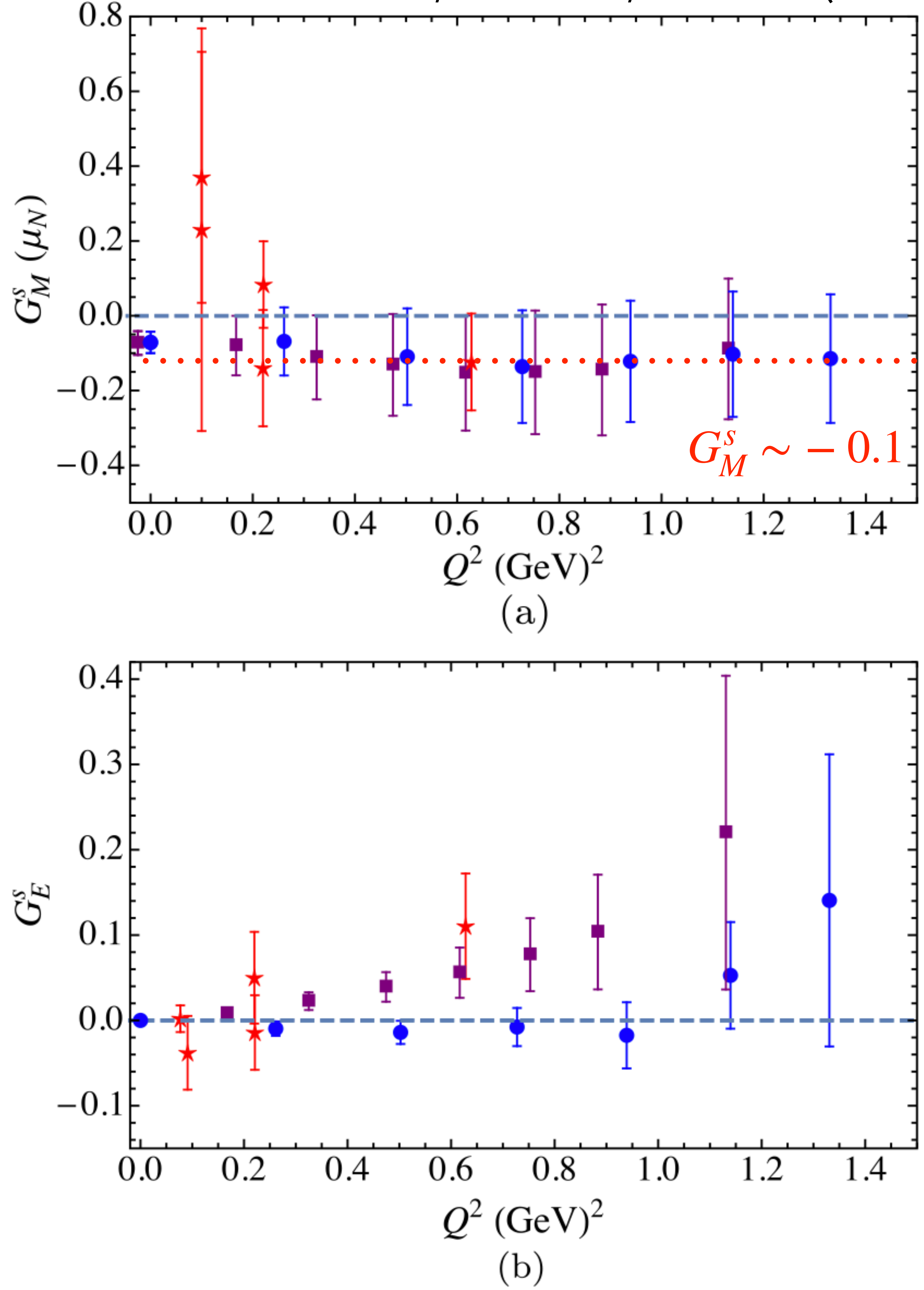
Strange form-factors on the lattice



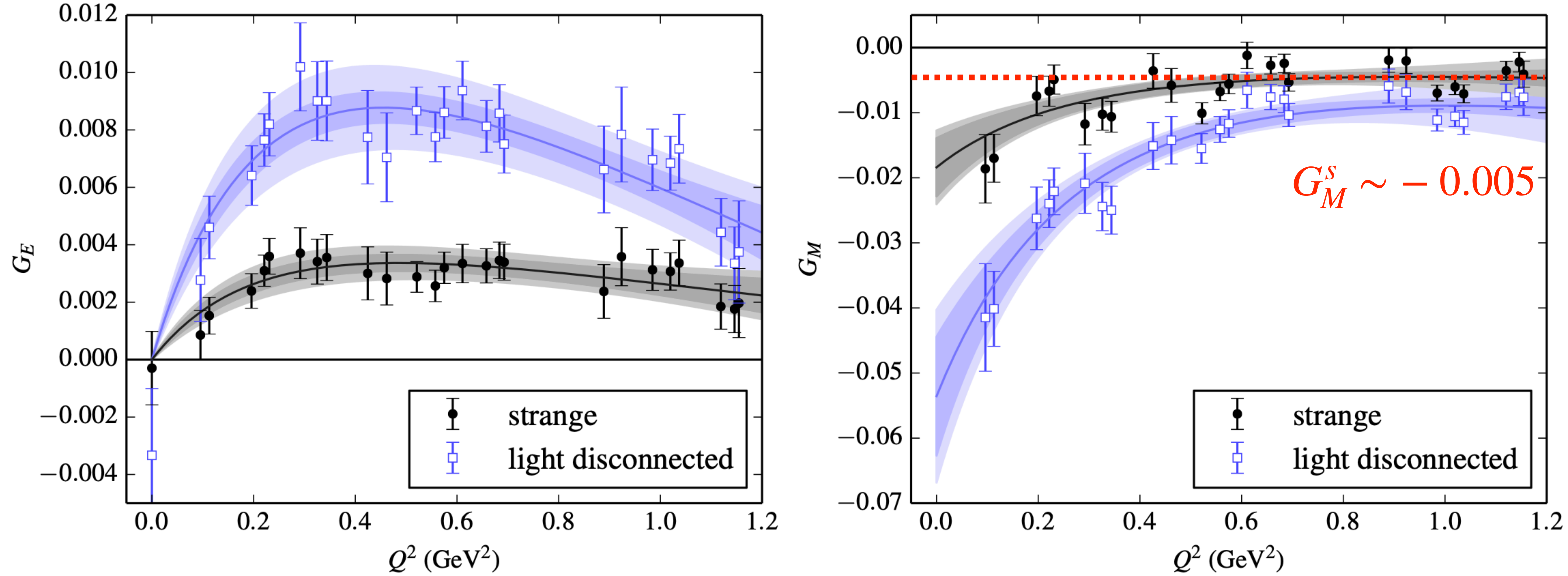
Some lattice calculations predict central values which are small, 10x below the limit of low Q^2 studies.

But they do not apparently fall with Q^2. **These values would be significant contributions at high Q^2**

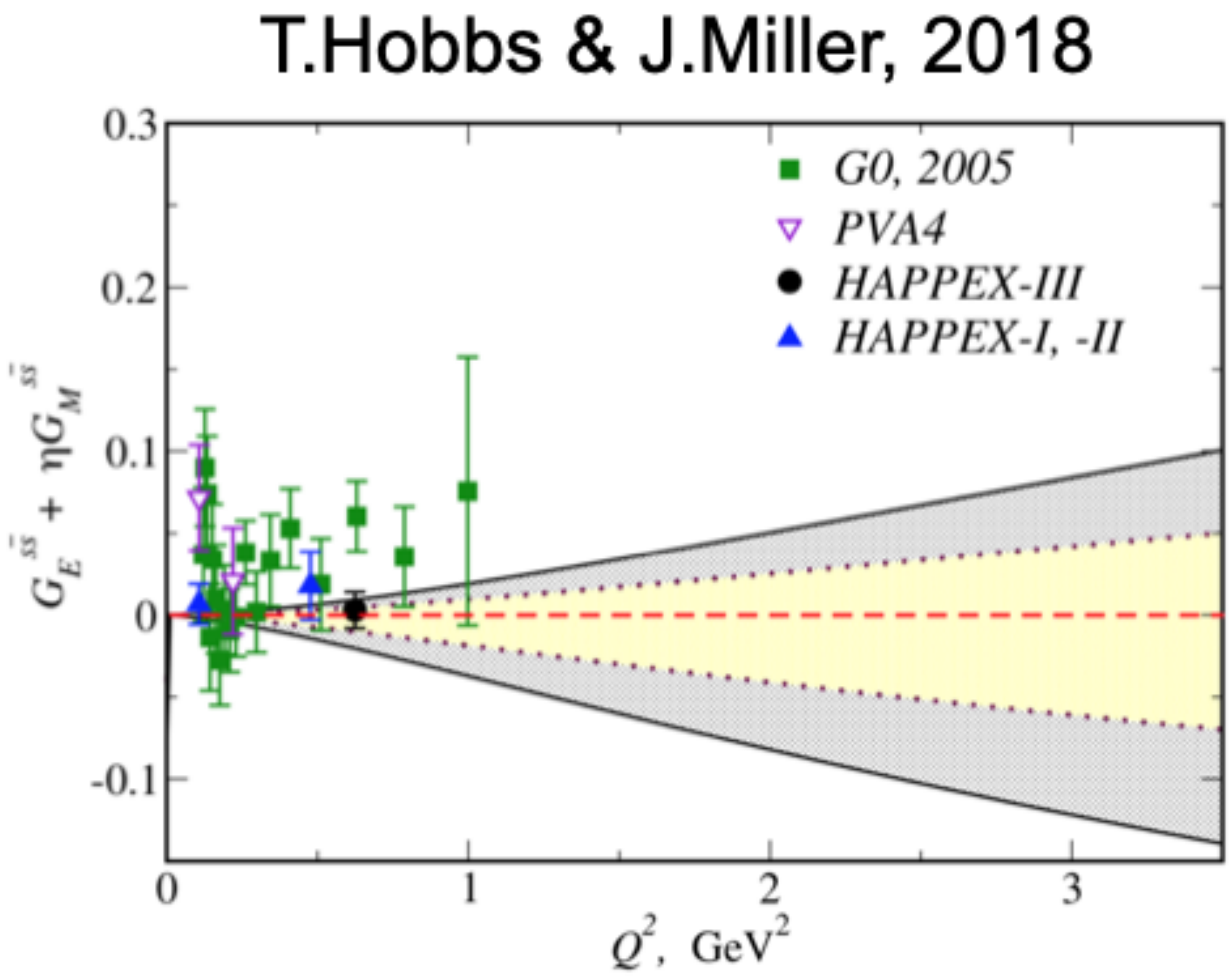
P. Shanahan *et al.*, PRL 114, 091802 (2015)



J. Green *et al.*, Phys. Rev. D 92, 031501 (2015)



Strange form-factor predictions


T.Hobbs & J.Miller, 2018

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 within constraints from data to think that they may grow relatively large at large Q^2

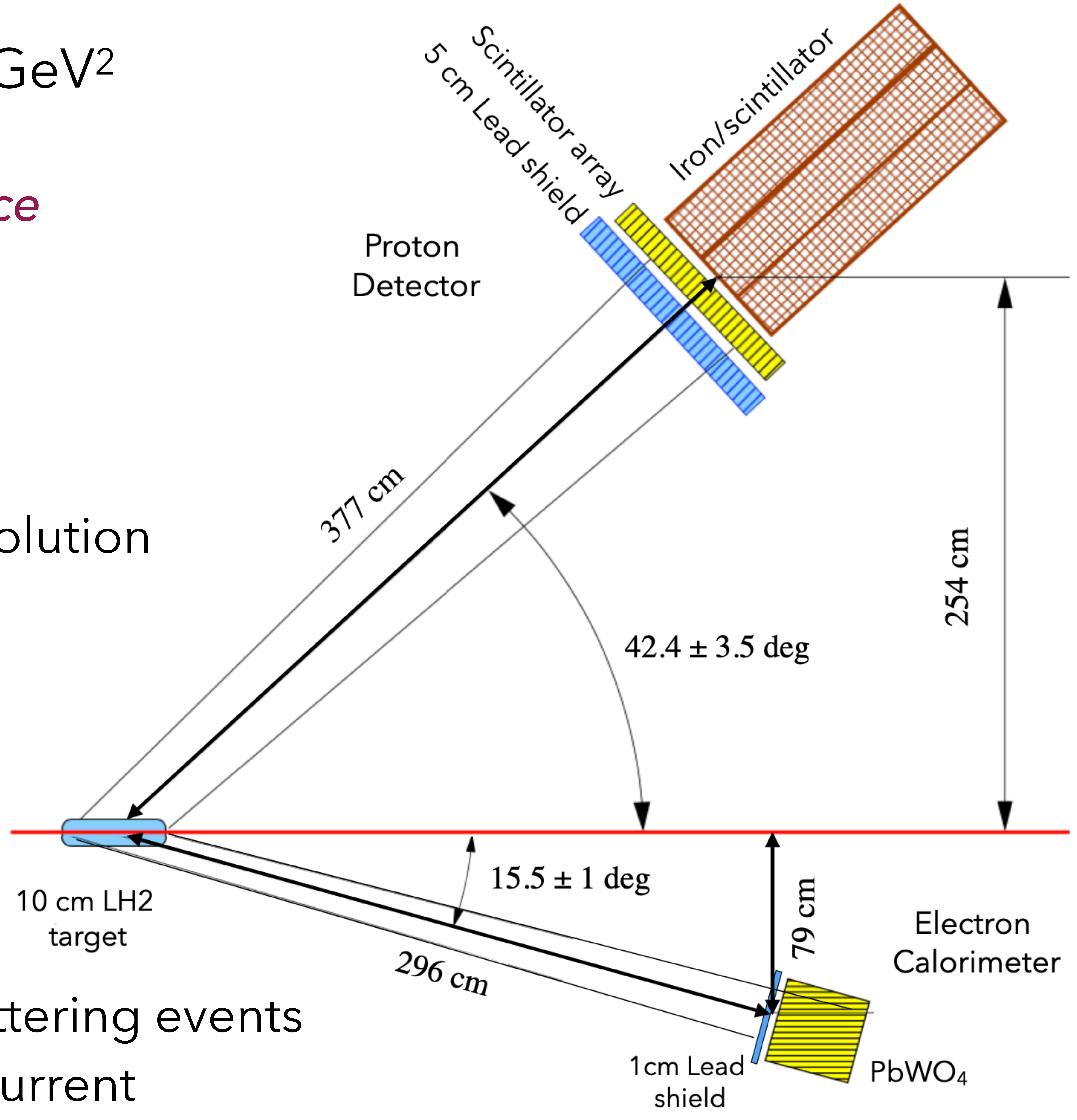
To set the scale of the data constraints: the width of the uncertainty band at $Q^2 = 2.5$ GeV^2 is approximately the size of the dipole form-factor parameterization G_D

G_s/G_D ~ 1 is not excluded

Such a large SFF could be huge in a proton PV measurement
δA_{PV} ~ ±22 ppm, ~±15% of A_{PV}^{ns}

The planned measurement

Aim for $Q^2 = 2.5\ \text{GeV}^2$



Identify elastic kinematics with electron-proton coincidence

- Angular e-p correlation, 6.6 GeV beam energy
  (electron at 15.5 degrees, proton at 42.4 degrees)
- High resolution calorimeter trigger for electron arm
- Calorimeter trigger for proton arm
- Scintillator array on proton arm, to improve position resolution

- APV = 150 ppm, 4% precision goal, so $3\text{x}10^{10}$ elastic scattering events
- $\mathcal{L} = 1.7 \text{ x } 10^{38}\ \text{cm}^{-2}/\text{s}$, 10 cm LH_2 target and 65 μA beam current
- Full azimuthal coverage, ~42 msr

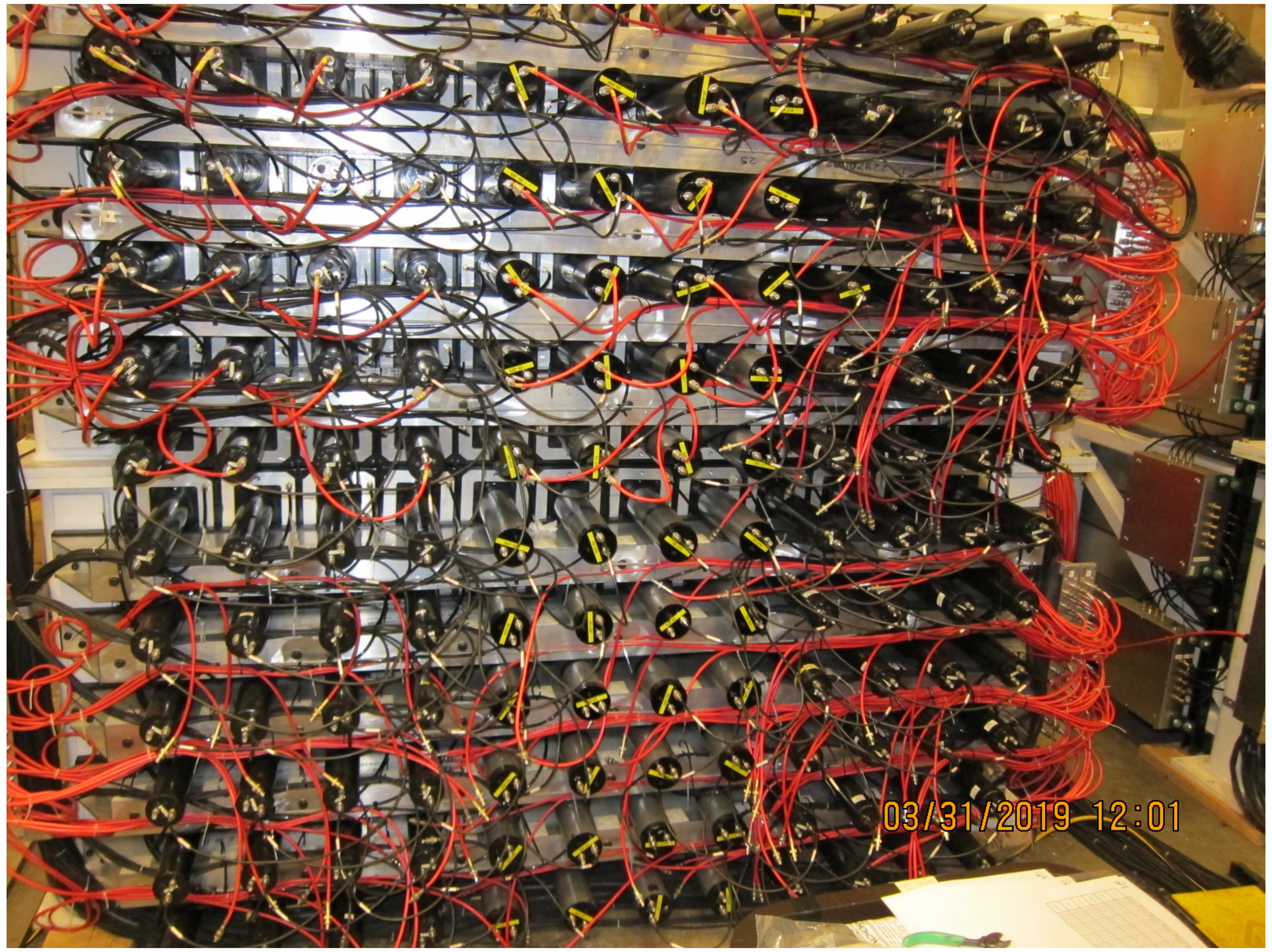
Calorimeters reusing components

NPS electromagnetic calorimeter

- 1200 $PBWO_4$ scintillators, PMTs + bases

SBS hadronic calorimeter

- 288 iron/scintillator detectors, PMTs + bases



Detector System

HCAL - hadron calorimeter

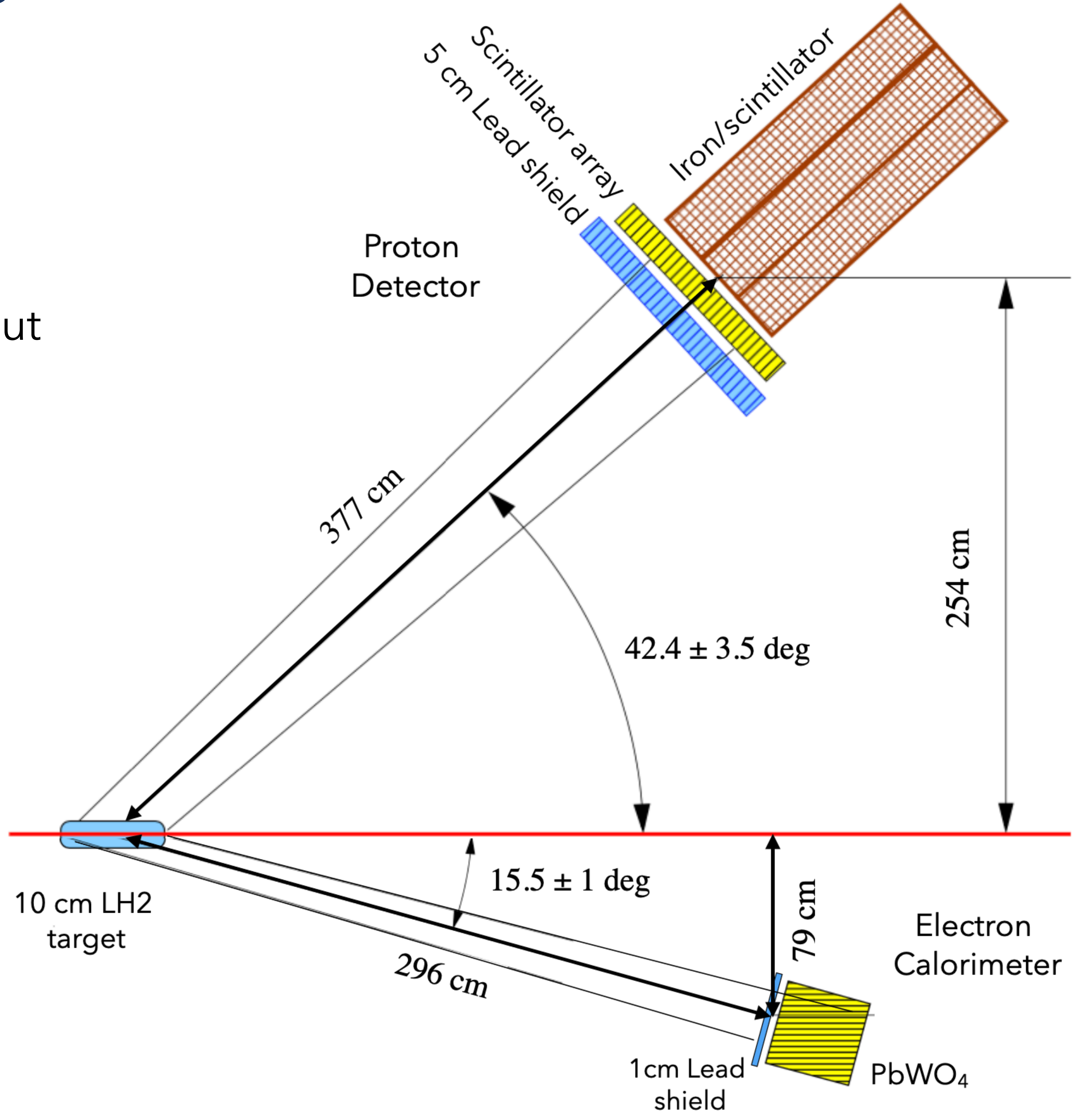
- Detector elements from the SBS HCAL
- 288 blocks, each 15.5 x 15.5 x 100 cm^3
- iron/scintillator sandwich with wavelength shifting fiber readout

ECAL - electron calorimeter

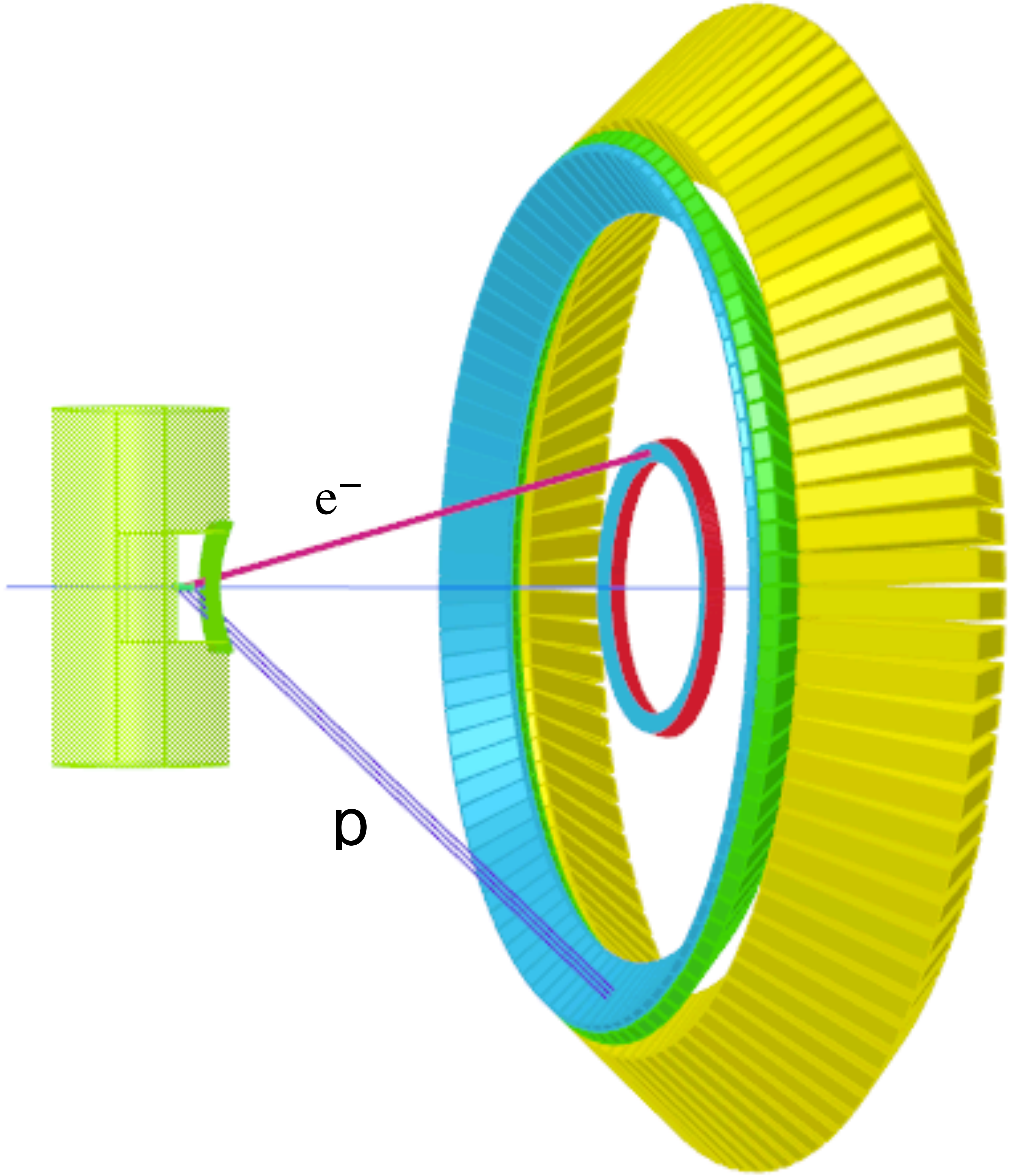
- Detector elements from the NPS calorimeter
- 1200 blocks, each 2 x 2 x 20 cm^3
- $PbWO_4$ scintillator

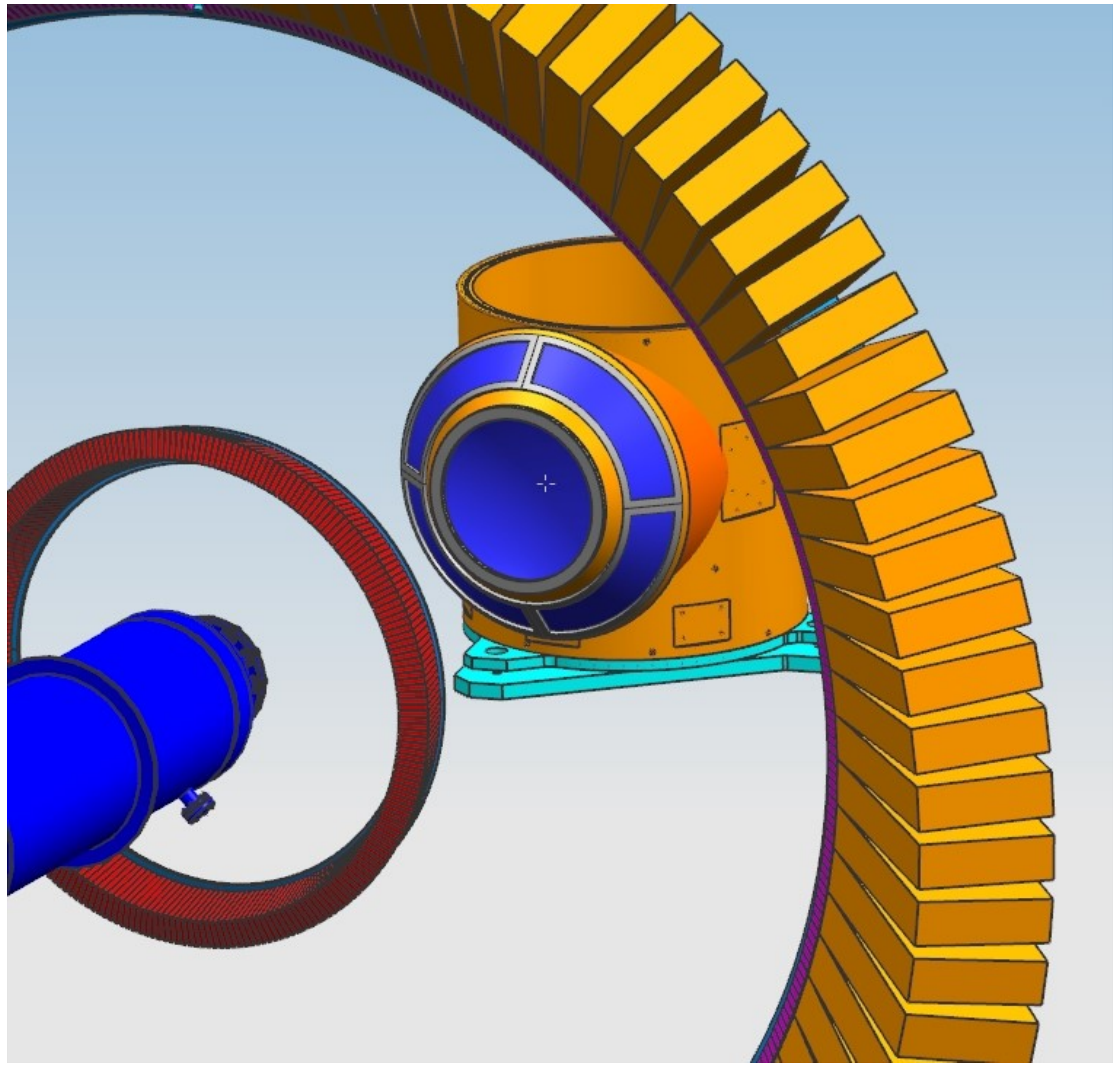
Scintillator array

- 7200 plastic scintillators, each 3 x 3 x 10 cm^3
- Wavelength shifting fiber to MA-PMT
- Used for position resolution in front of HCAL



Experimental concept

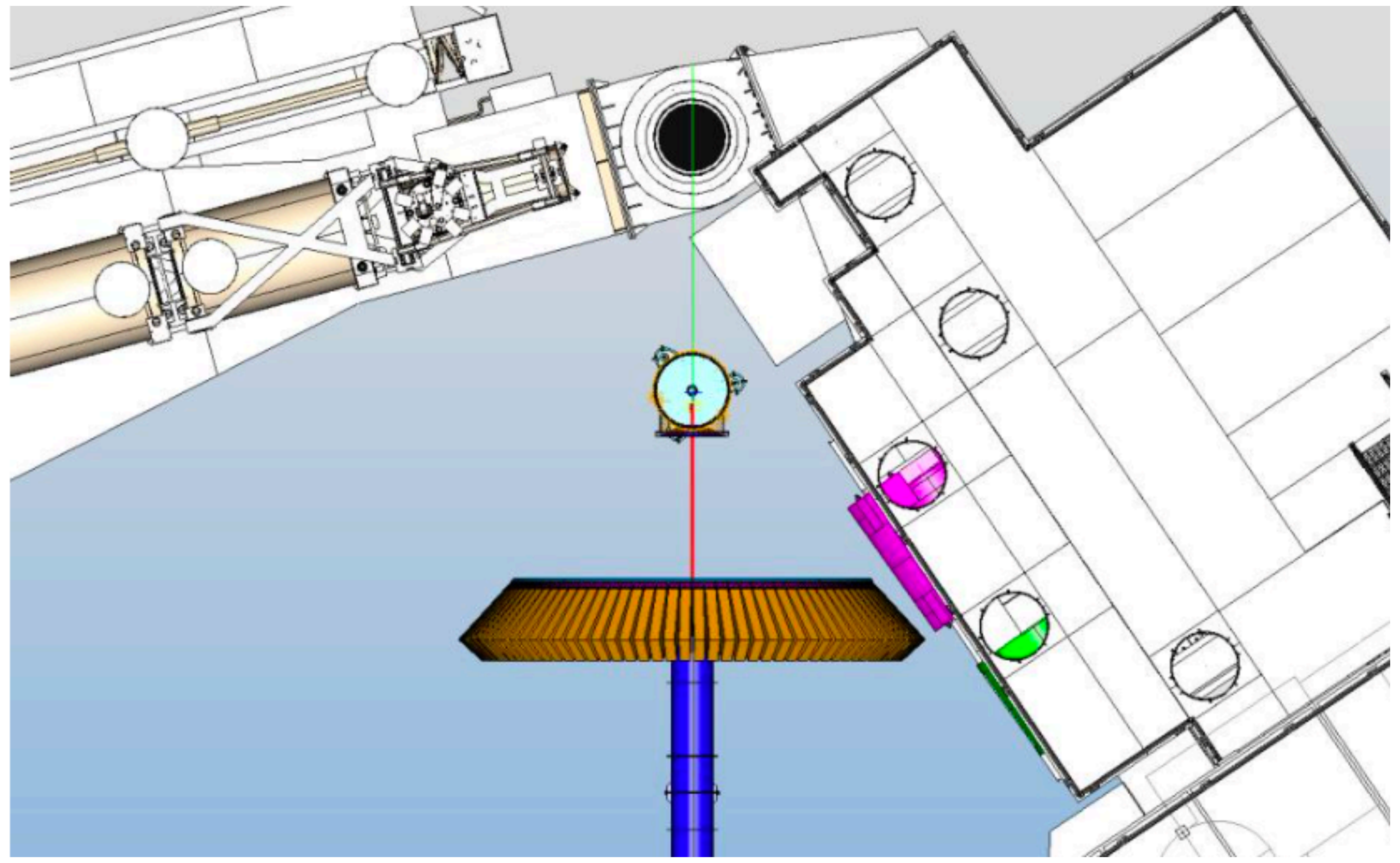


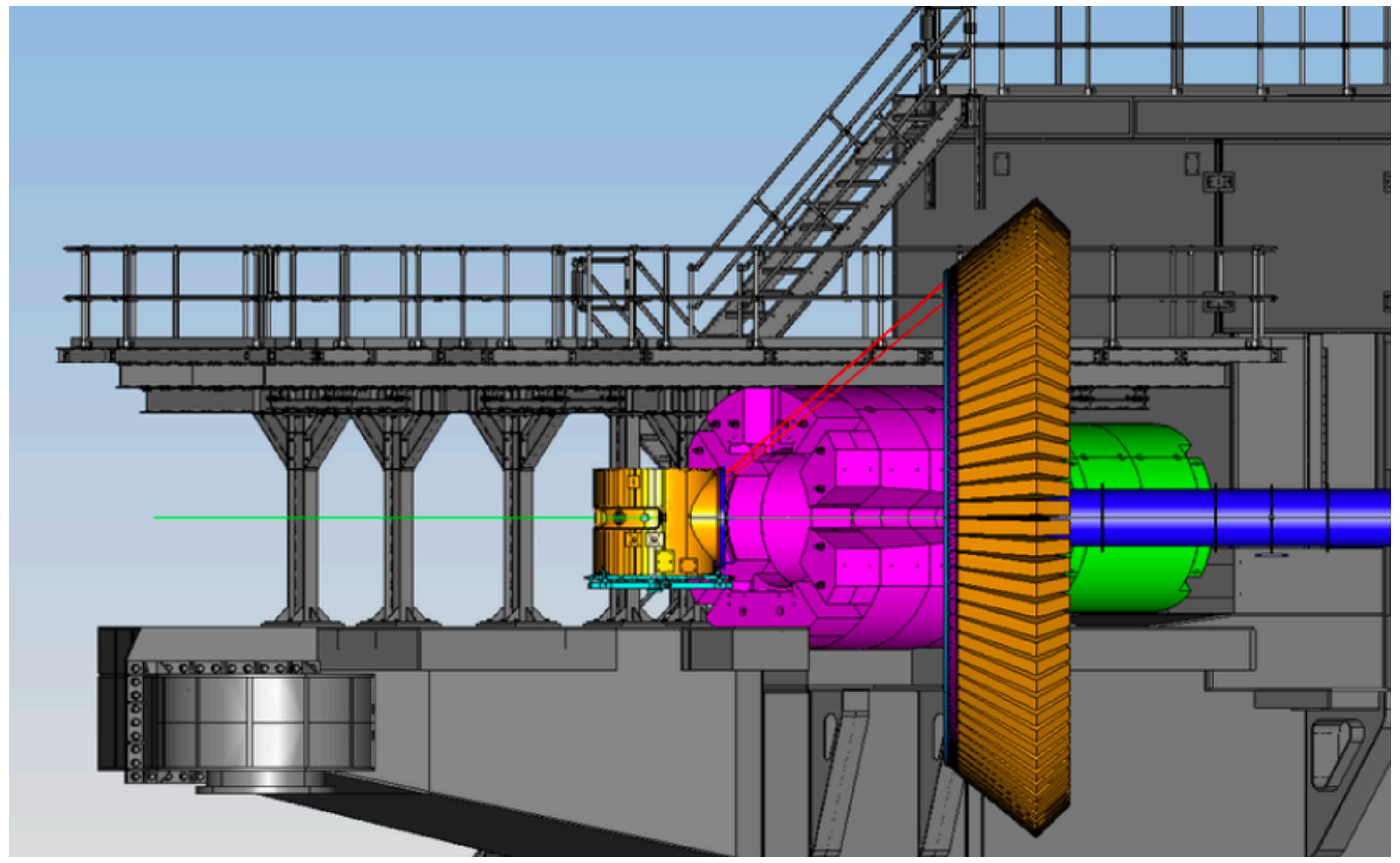


Preliminary design of scattering chamber

He bag will reduce backgrounds between target chamber and exit beampipe

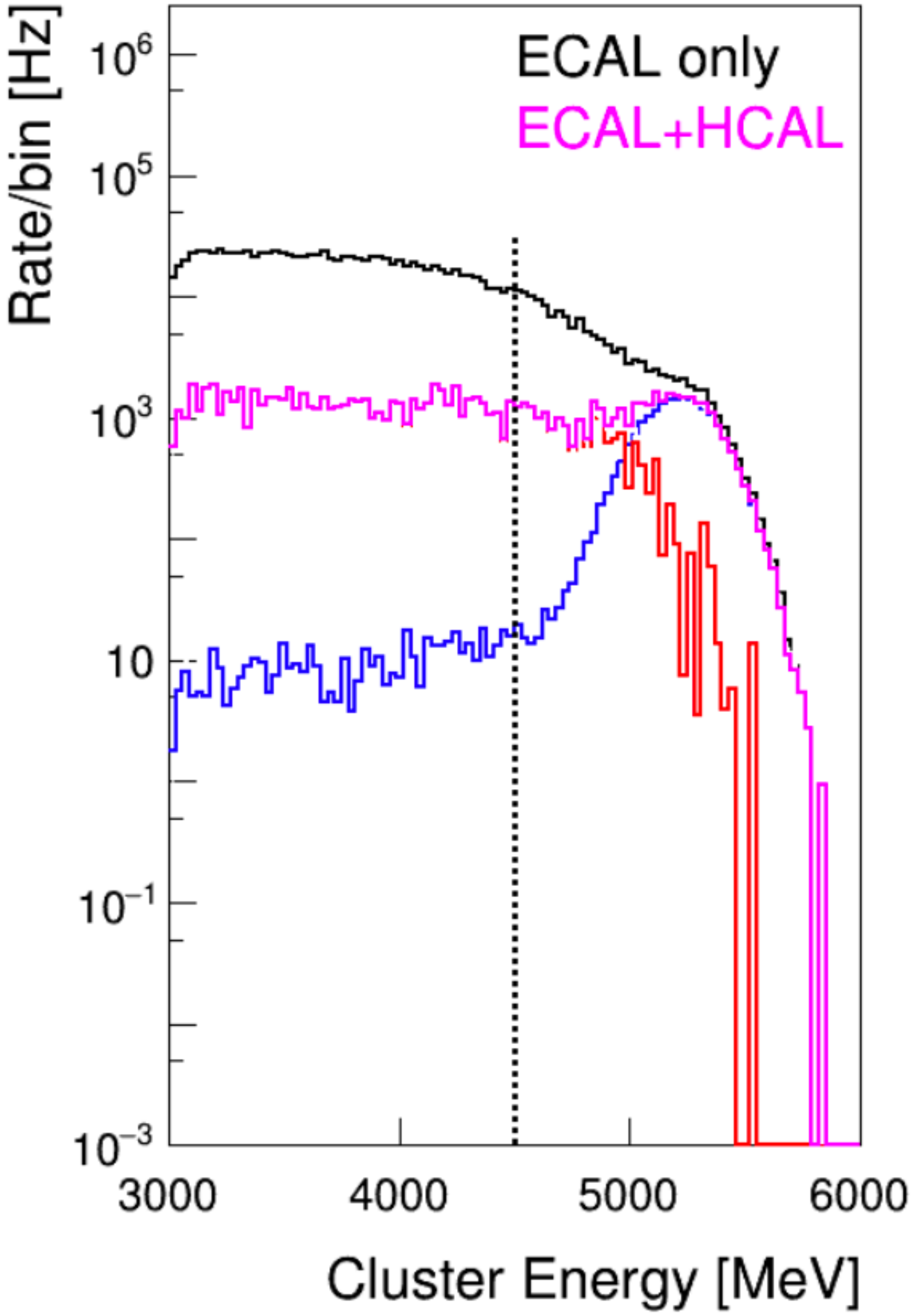
This fits in Hall C (but it's tight)





Trigger: calorimeters, with geometric coincidence

A relatively high ECAL cut (~66% of beam energy) and loose e-p coincidence cut provides high efficiency and manageable data rate



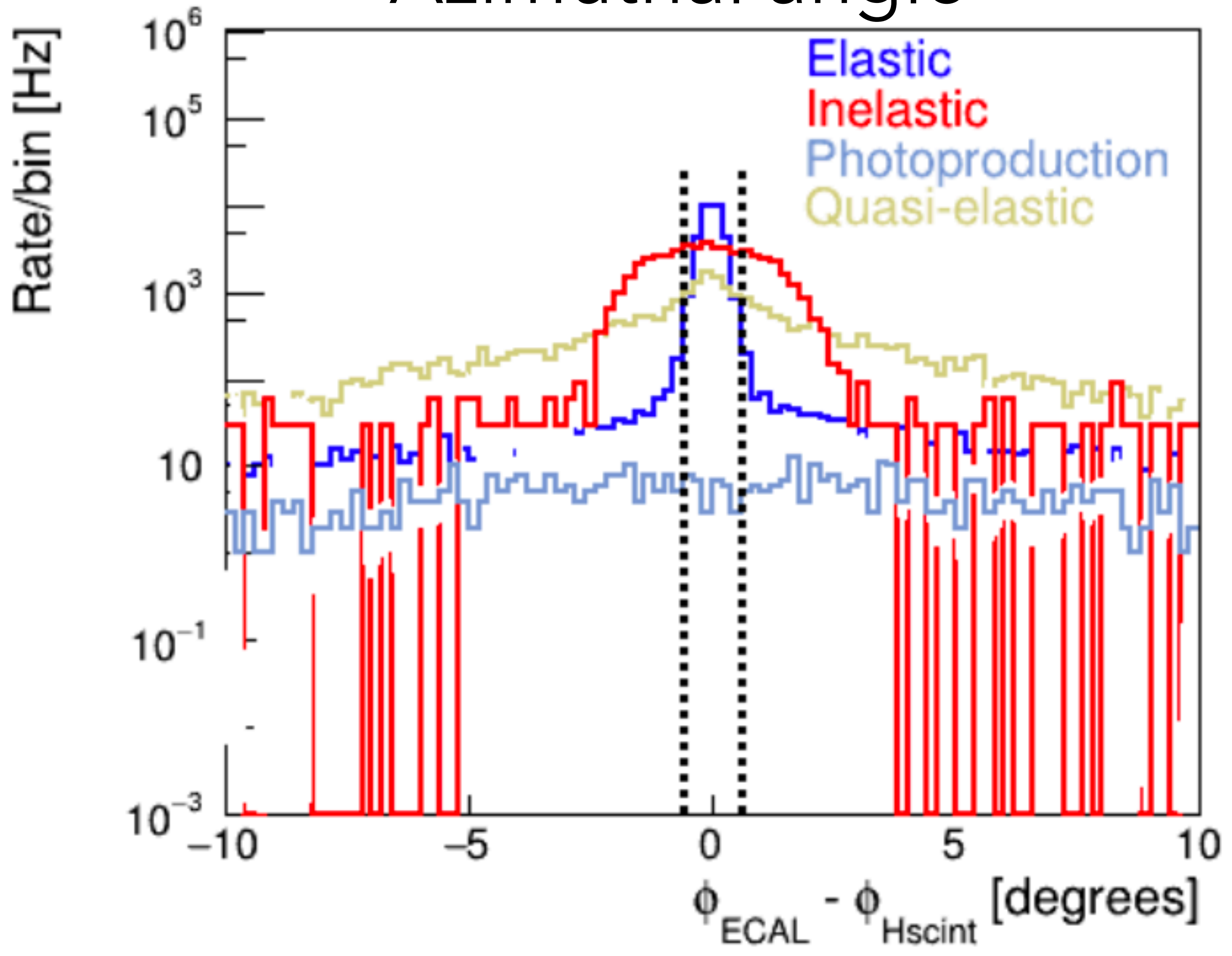
ECAL > 4.5 GeV: 150 kHz

ECAL + HCAL in coincidence: 35 kHz

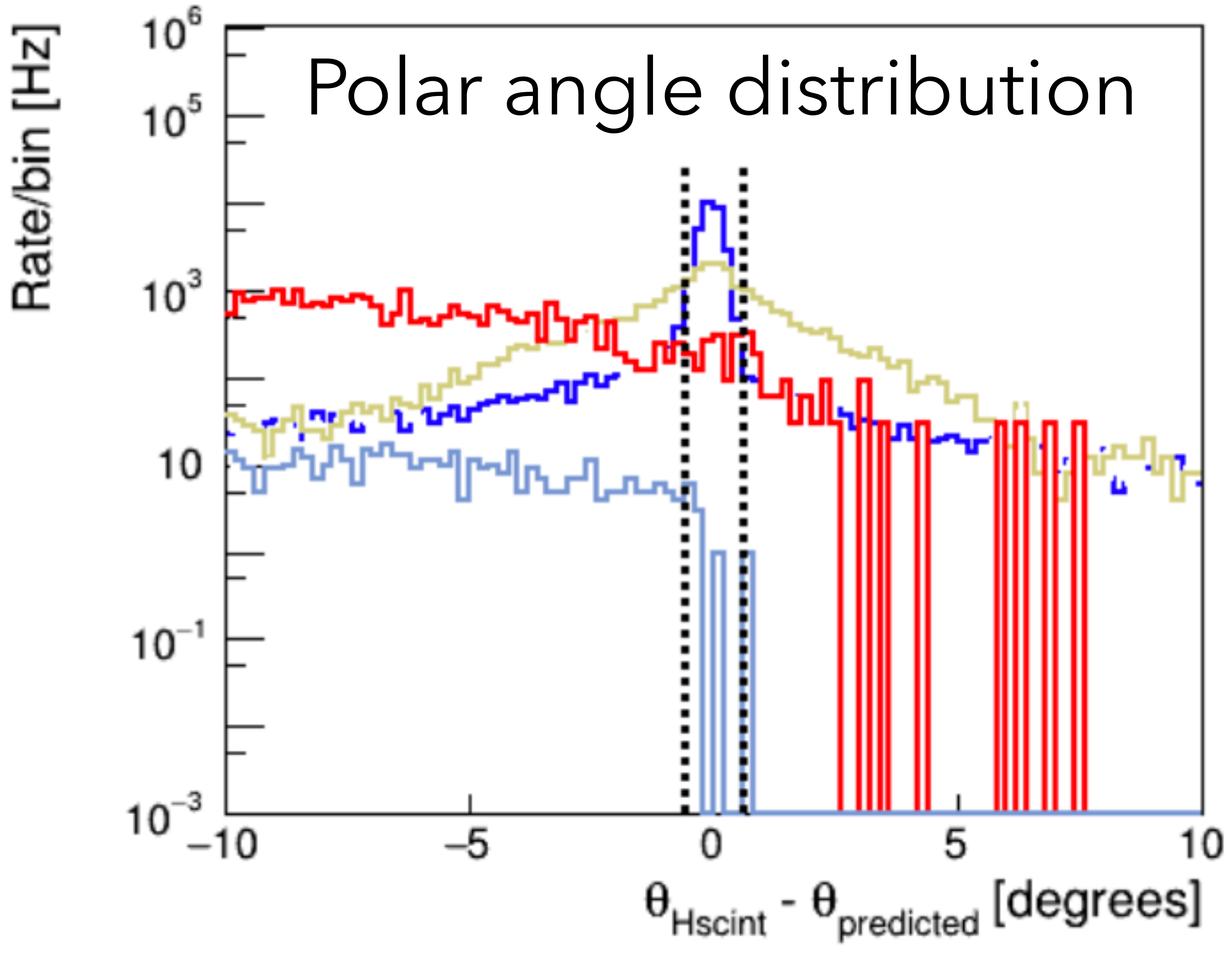
Fraction of total by event type	Online
Elastic scattering	0.531
Inelastic (pion electro-production)	0.450
Quasi-elastic scattering (target windows)	0.015
π^0 photo-production	0.004

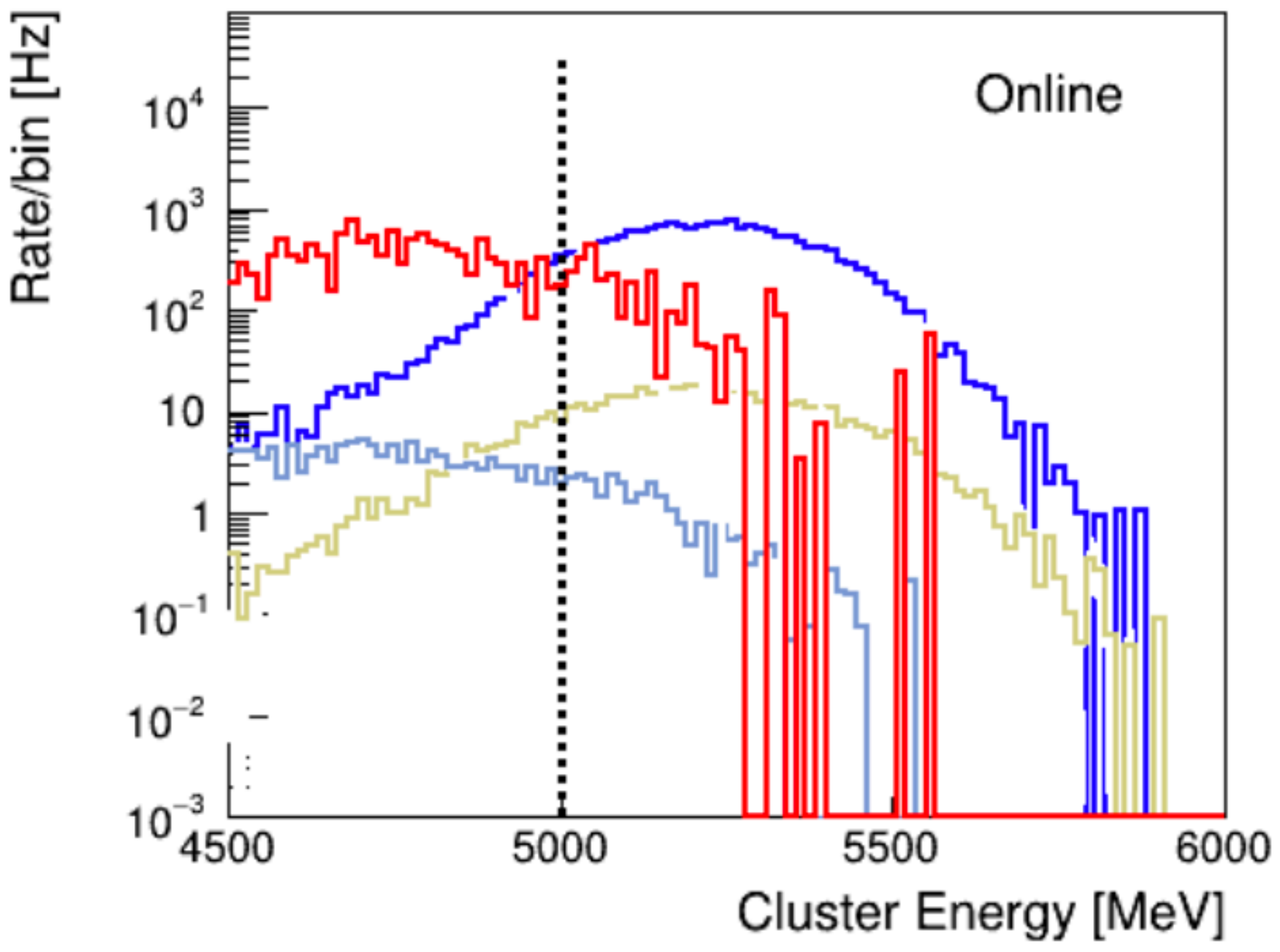
Elastic event discrimination

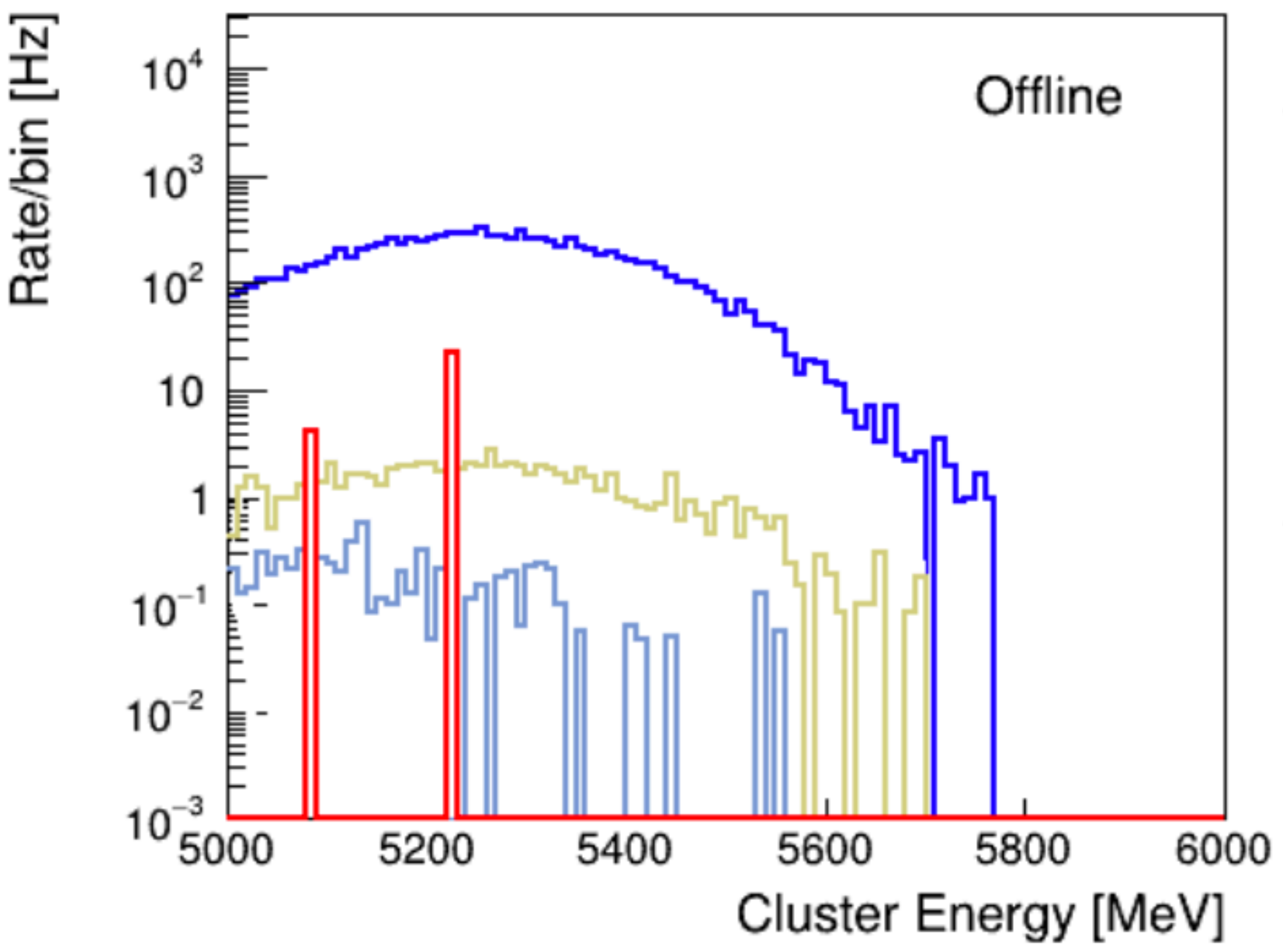
Azimuthal angle



dashed lines = offline cuts


Polar angle distribution





Offline: tighten geometric cut with pixel hodoscope and ECAL cluster center

Exclude inelastic background to ~0.2%

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

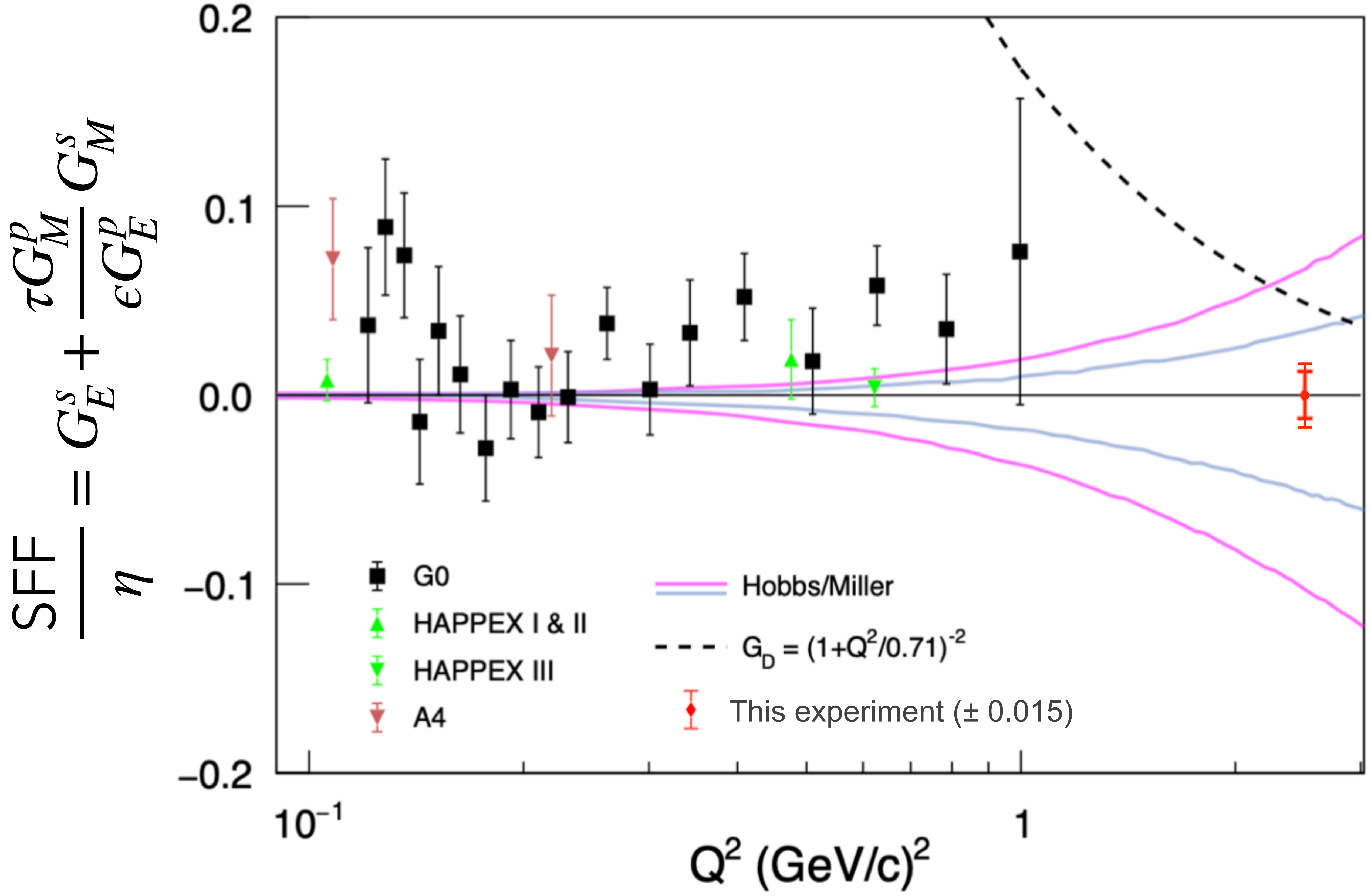
“sideband” analyses will help verify QE and inelastic asymmetries

Projected result

A_{PV} = 150 ppm (if no strange FF)

δ A_{PV} = ± 6.2 (stat) ± 3.3 (syst) (δA/A = ± 4% ± 2%)

$$\delta\left(G_E^s + 3.1 G_M^s\right) = \pm\ 0.013\ \text{(stat)}\ \pm\ 0.007\ \text{(syst)} = 0.015\ \text{(total)}$$



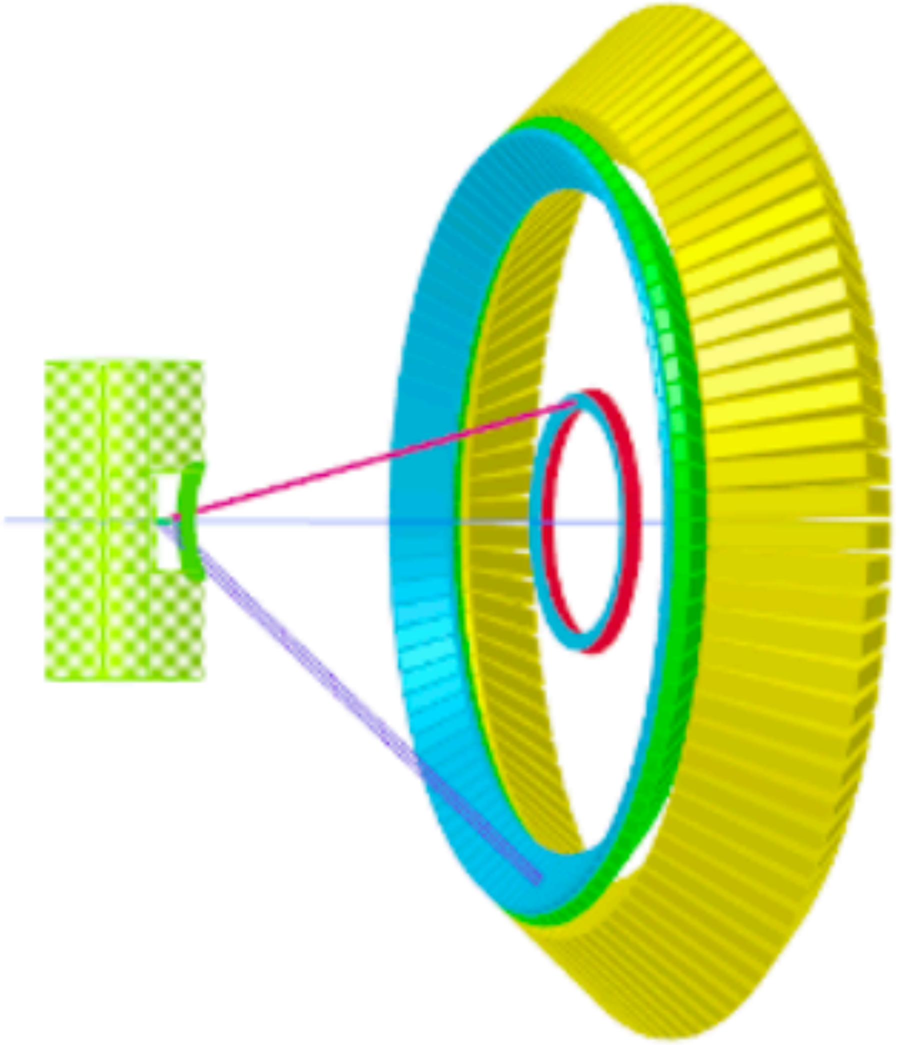
If $G_M^s = 0,\ \ \delta G_E^s \sim 0.015,$ (about 34% of G_D)

If $G_E^s = 0,\ \ \delta G_M^s \sim 0.005,$ (about 11% of G_D)

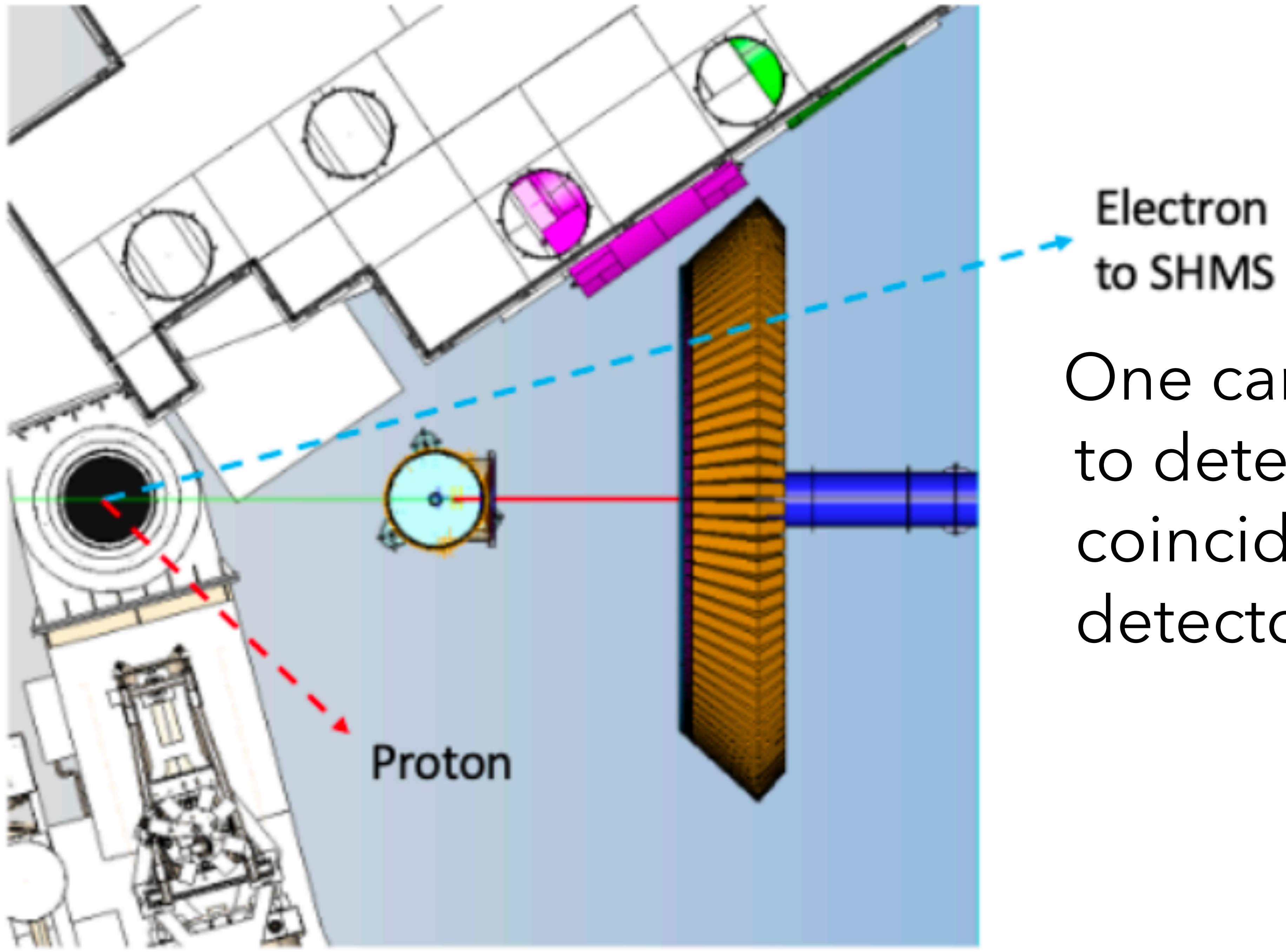
The proposed measurement is especially sensitive to G_M^s

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

Next Step - Test Performance of Detector Concept



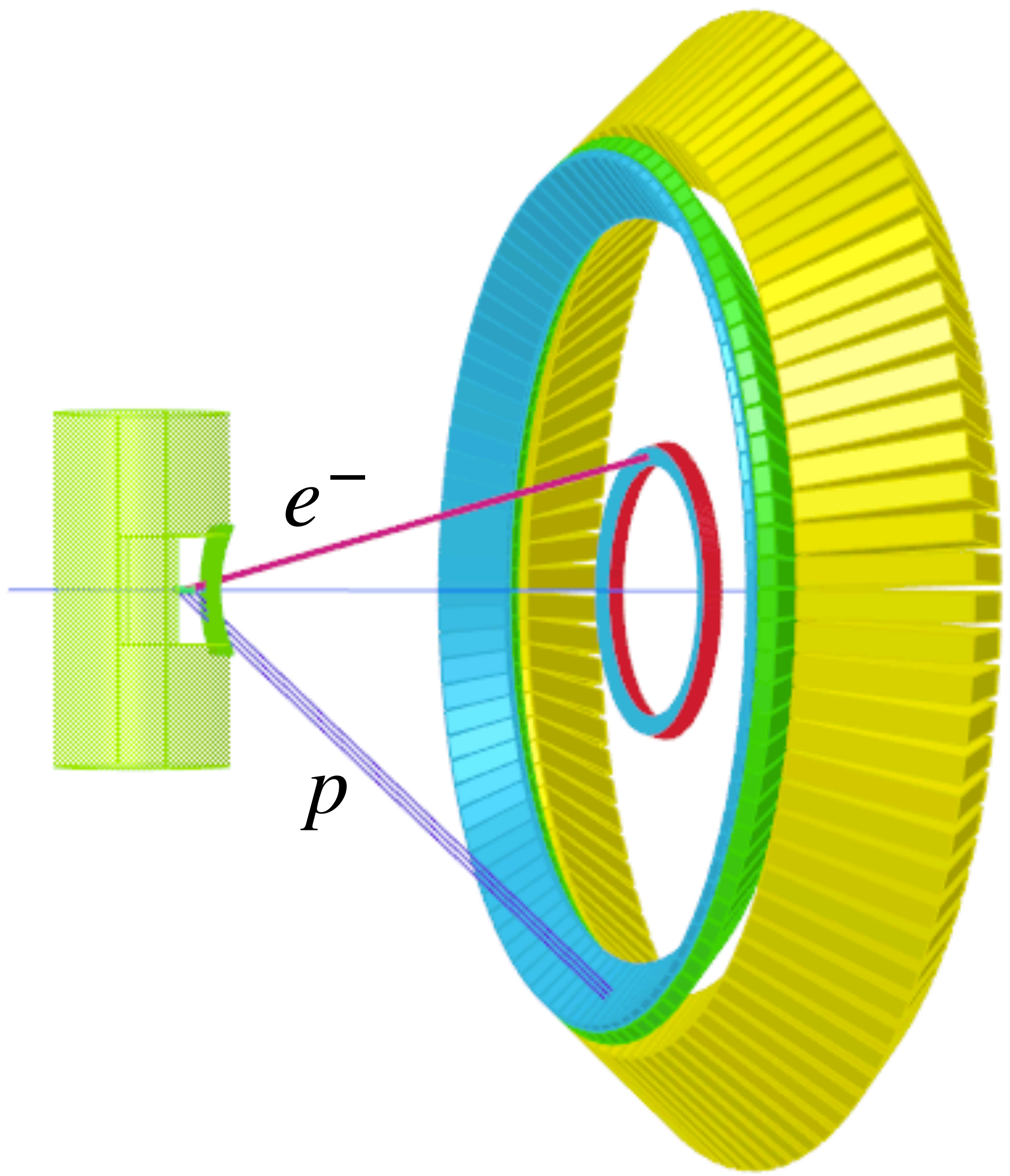
electron angle 15.5°
proton angle 42.4°

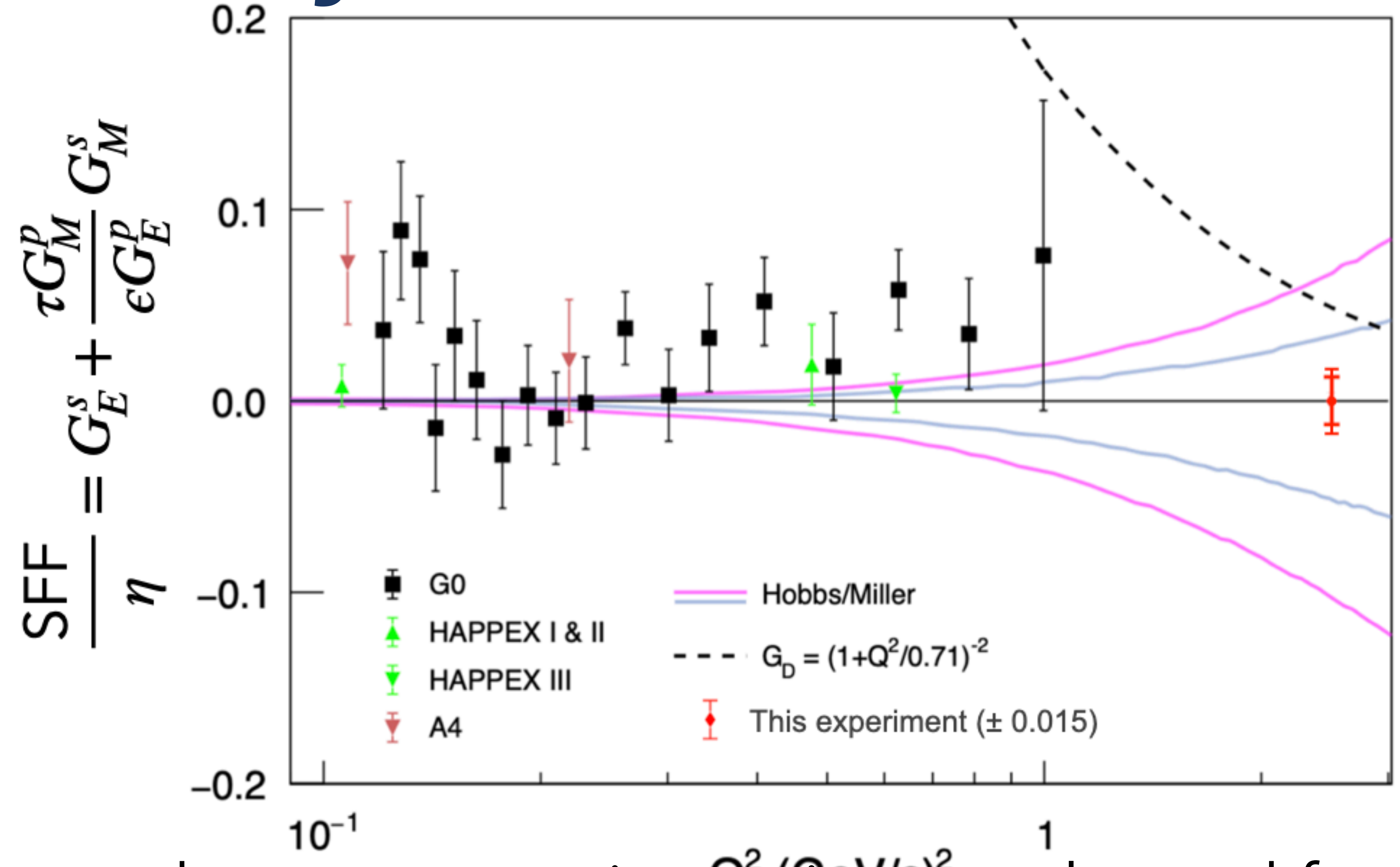


One can position the SHMS to 15.5° to detect electrons, measured in coincidence with a prototype proton detector at 42.4°

Prototype proton detector:
- pixel array of 32 small scintillators with MA-PMT readout with 6 SBS HCAL blocks
- NINO card front-end, FADC readout
- 50uA on 15cm Hydrogen target at 6.6 GeV, about 2kHz rate into detector
- test elastic identification and background rate

Summary





- 10+ years after the last sFF searches were performed, a new experiment is now planned 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 smaller than the uncertainty range in the extrapolation from previous strange form-factor data
- PAC approved, but needs funding and devlopment. Schedule is as yet uncertain, but the path forward is clear.