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

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Nucleon Elastic Form-factors

Elastic form factors describe the deviation of the cross section from that of a point-like target

Fixed-target elastic electron-nucleon scattering

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\mathrm{Mott}} \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}$$

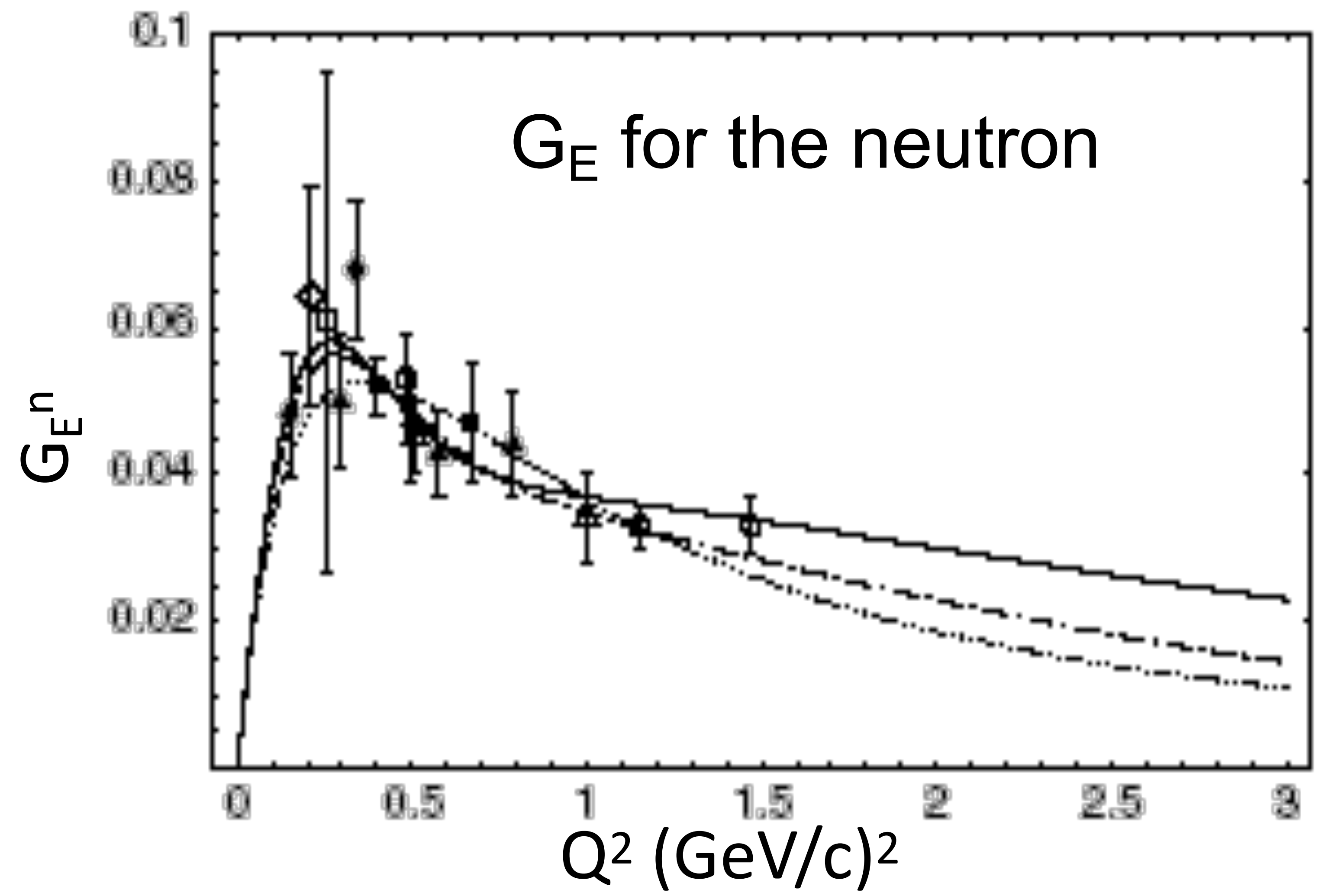
$$\tau = \frac{Q^2}{4M^2} \quad \epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

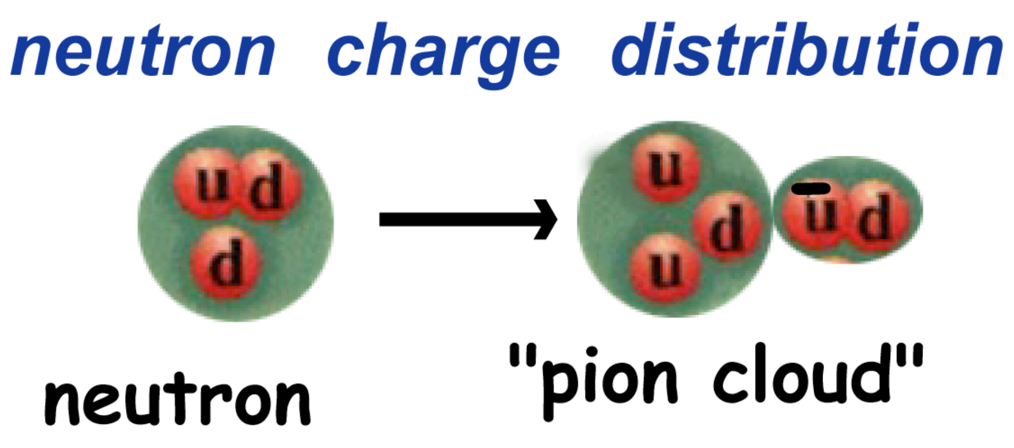
Alternative expression: Dirac (F_1) and Pauli (F_2) form factors instead of Sachs (G_E, G_M)

$$G_E = F_1 - \tau F_2$$

$$G_M = F_1 + F_2$$

At low Q^2, (non-relativistic recoil) G_E and G_M are the Fourier transforms of the charge and magnetization distributions





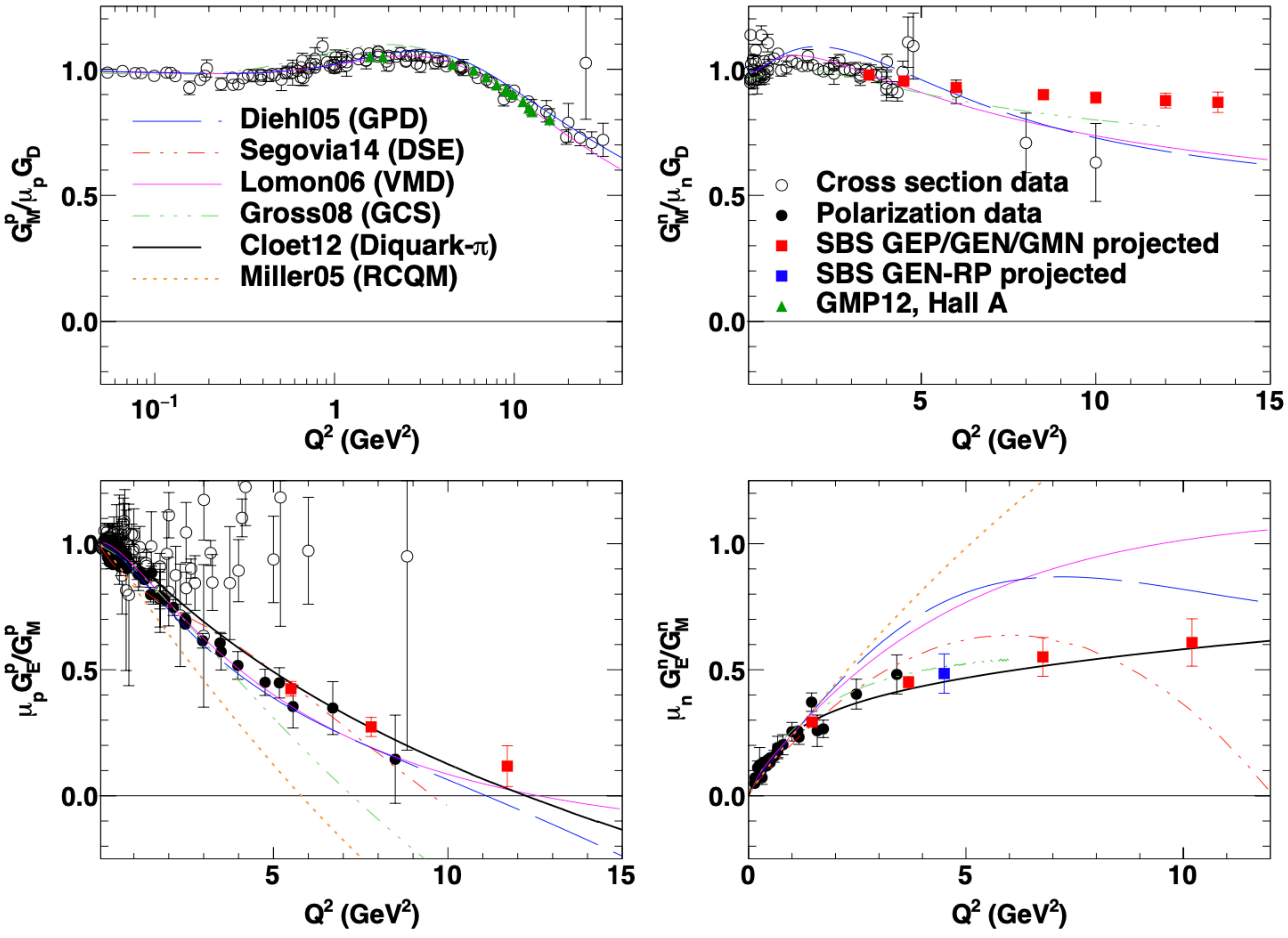
At $Q^2 = 0$, the form factor represents an integral over the nucleon

	G_E	G_M
proton	1	2.79
neutron	0	-1.91

magnetic moment

charge

Nucleon Form Factors at High Q^2



Prog.Part.Nucl.Phys. 127 (2022) 103985

- 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 $\xi = 0$

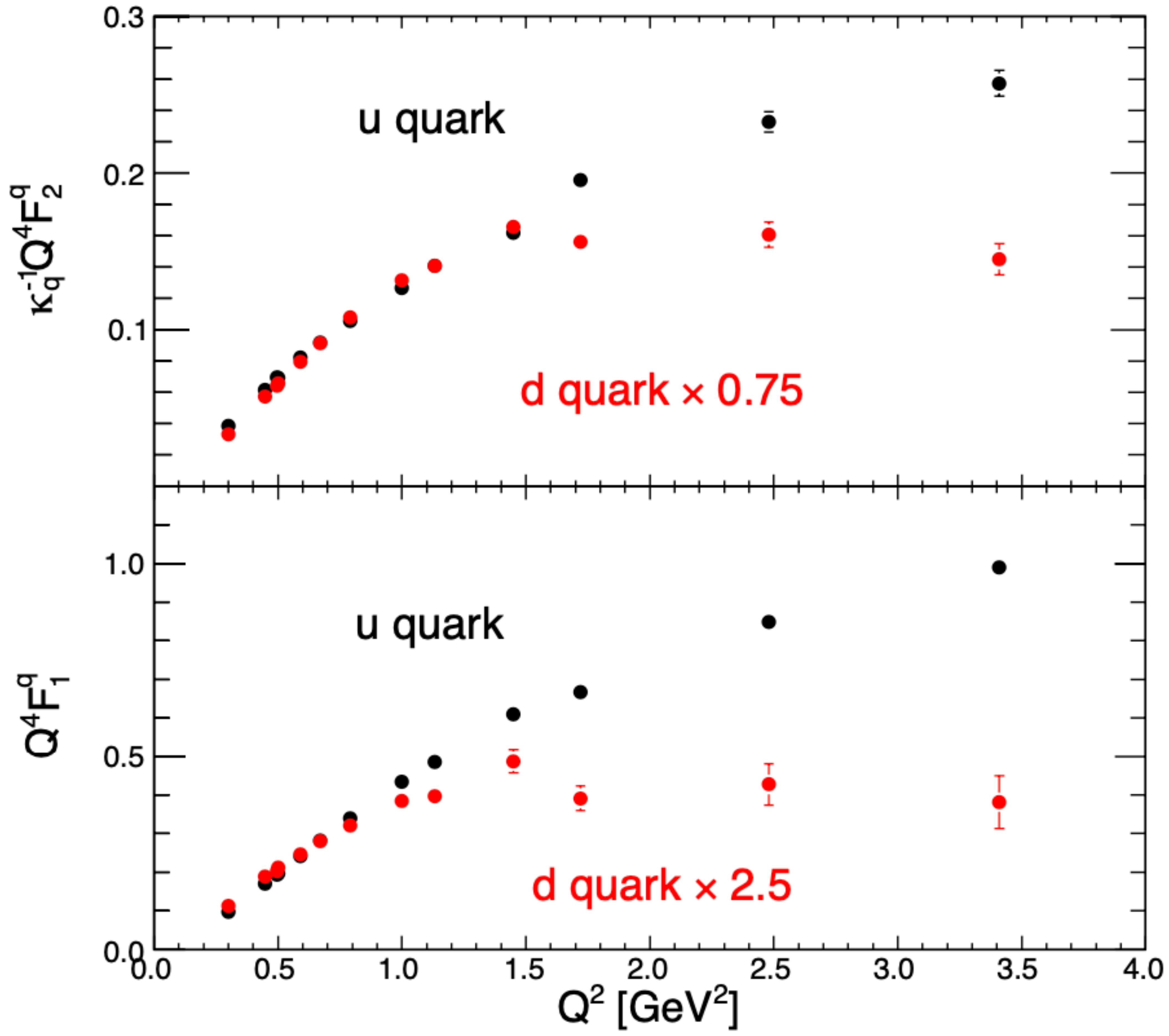
$$\int_{-1}^{+1} dx\, H^q(x,0,Q^2) \;=\; F_1^q(Q^2)$$

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

Flavor Separation of Nucleon Form Factors

These implications rely on extracting the independent quark contributions

$$F^u_{1(2)} = 2\,F^p_{1(2)} + F^n_{1(2)} \quad \text{and} \quad F^d_{1(2)} = 2\,F^n_{1(2)} + F^p_{1(2)}$$



G. Cates et al. Phys. Rev Lett. 106 (2011)

For example: the apparent onset of Q^4 scaling for d-quark form-factors has been suggested to be consistent with the emergence of perturbative behavior in scattering and with the minority quark tied up in a diquark structure

This is speculative, but there is a strong effort to extend this data to higher Q^2

Charge symmetry and the nucleon form factors

Charge Symmetry

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

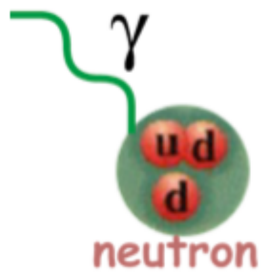
Charge symmetry is assumed for the form factors, $G_E^{u,p} = G_E^{d,n}$, *etc.* and used to find the flavor separated form-factors, measuring $G_{E,M}^{p,n}$ to find $G_{E,M}^{u,d}$

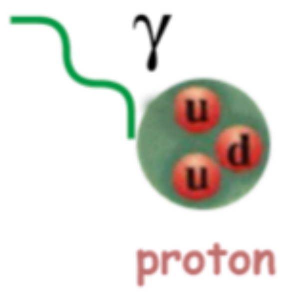
$$G_E^p = \frac{2}{3}G_E^{u,p} - \frac{1}{3}G_E^{d,p} - \frac{1}{3}G_E^s$$
$$G_E^n = \frac{2}{3}G_E^{u,n} - \frac{1}{3}G_E^{d,n} - \frac{1}{3}G_E^s$$

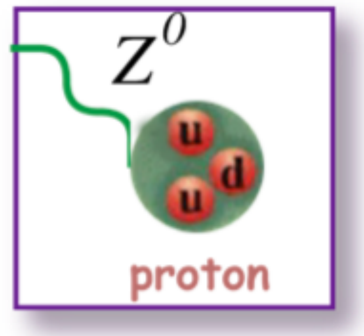
But this can broken! One way is to have a non-zero strange form-factor, which breaks the "2 equations and 2 unknowns" system

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

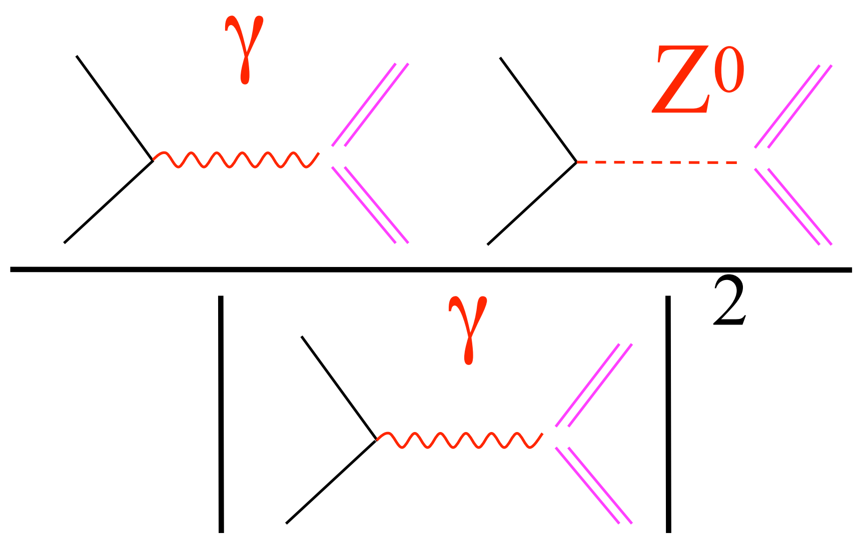
Parity Violating Electron Scattering

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

Weak and EM amplitudes interfere:

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

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



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

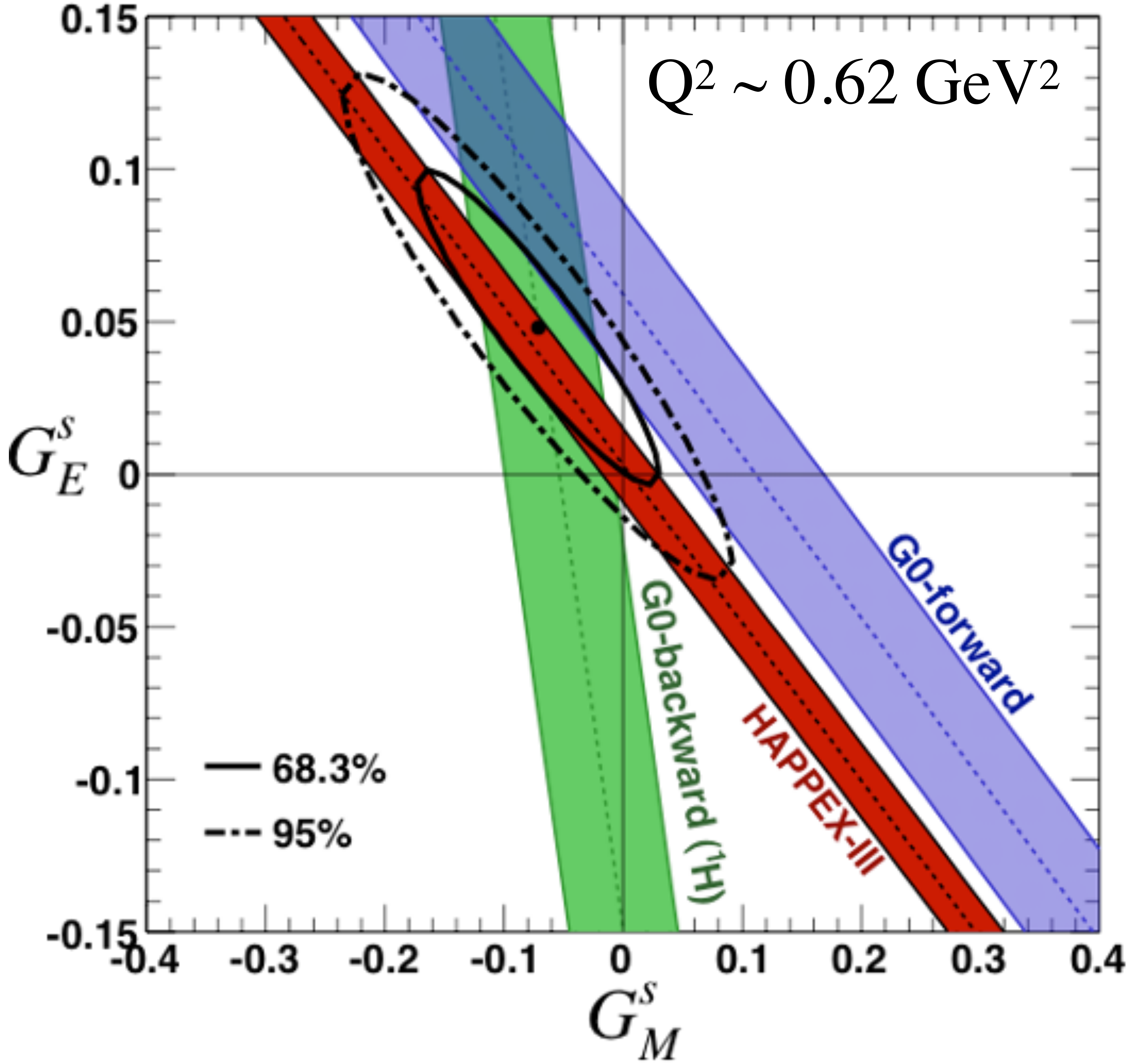
Expressing A_{PV} for e-p scattering, with proton and neutron EM form-factors plus strange form factors:

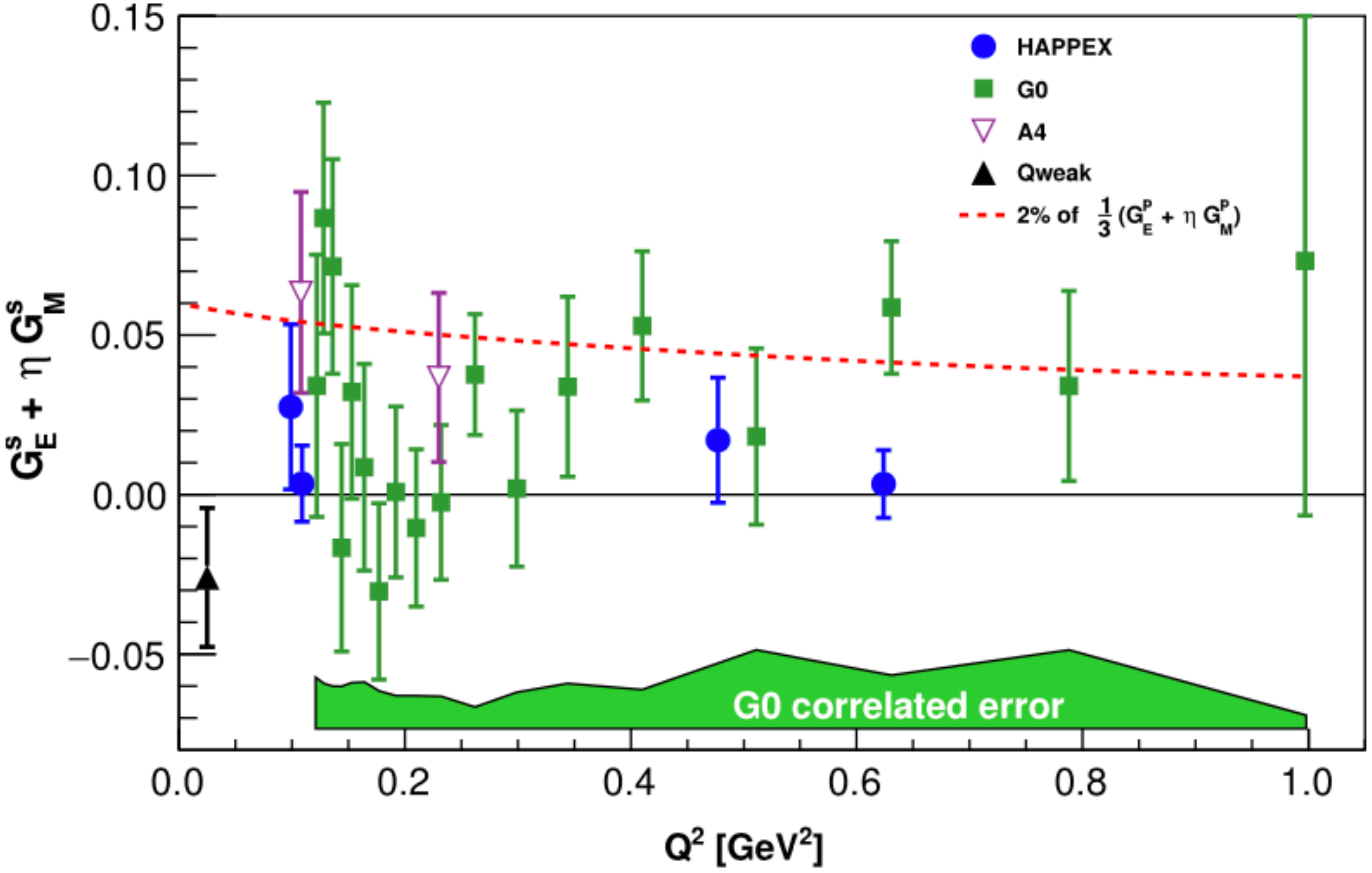
$$A_{PV} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \cdot [(1-4\sin^2\theta_W) - \frac{\epsilon G_E^p G_E^n + \tau G_M^p G_M^n}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2} - \frac{\epsilon G_E^p G_E^s + \tau G_M^p G_M^s}{\epsilon (G_E^p)^2 + \tau (G_M^p)^2}$$
$$+ \epsilon'(1-4\sin^2\theta_W)\frac{G_M^p G_A^{Zp}}{\epsilon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

This technique was used to hunt for indications of strange quark contributions in the nucleon, particularly in the static properties: a strange charge radius or strange magnetic moment

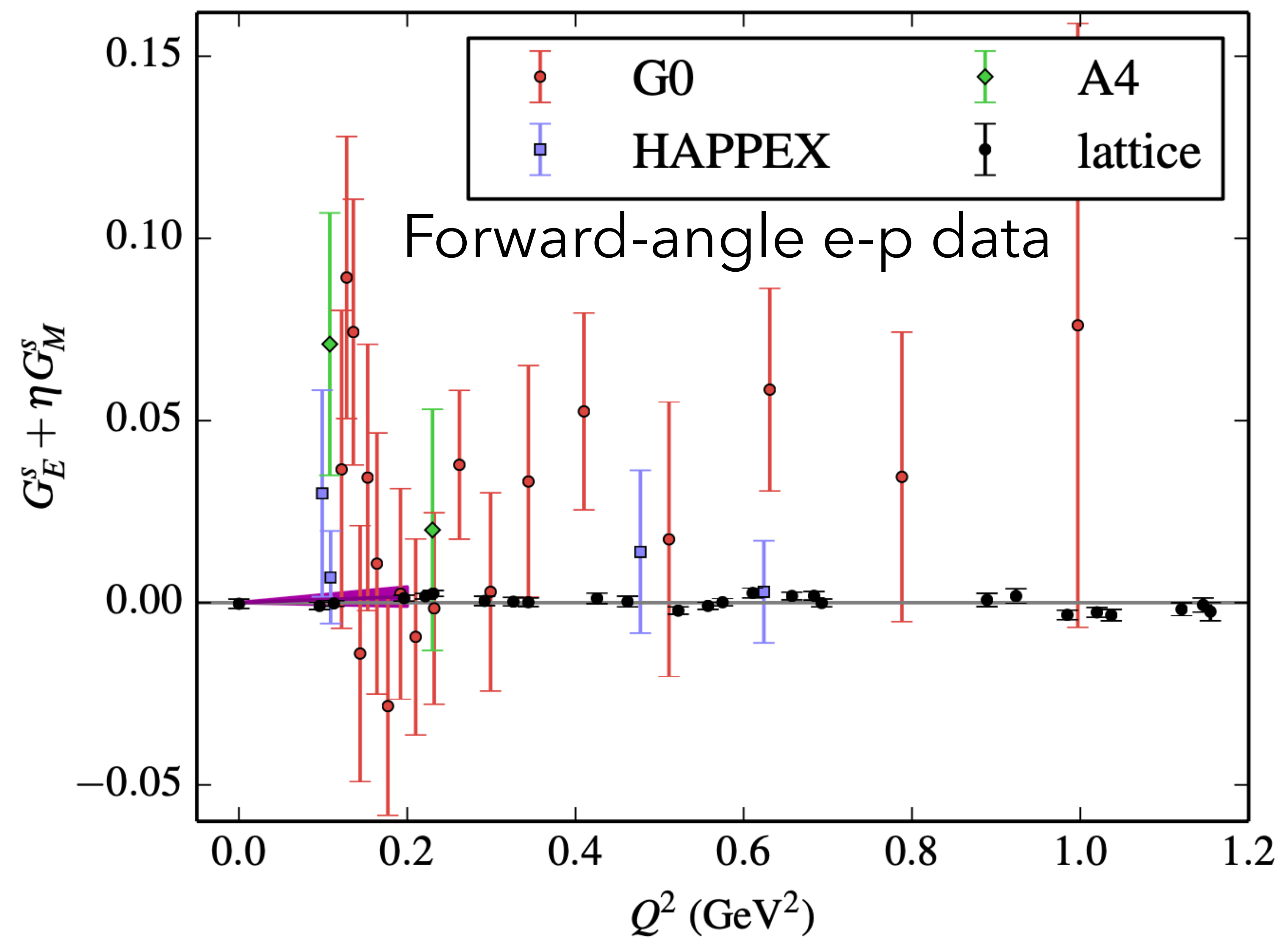
Proton strange form factors via parity violating elastic electron scattering

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





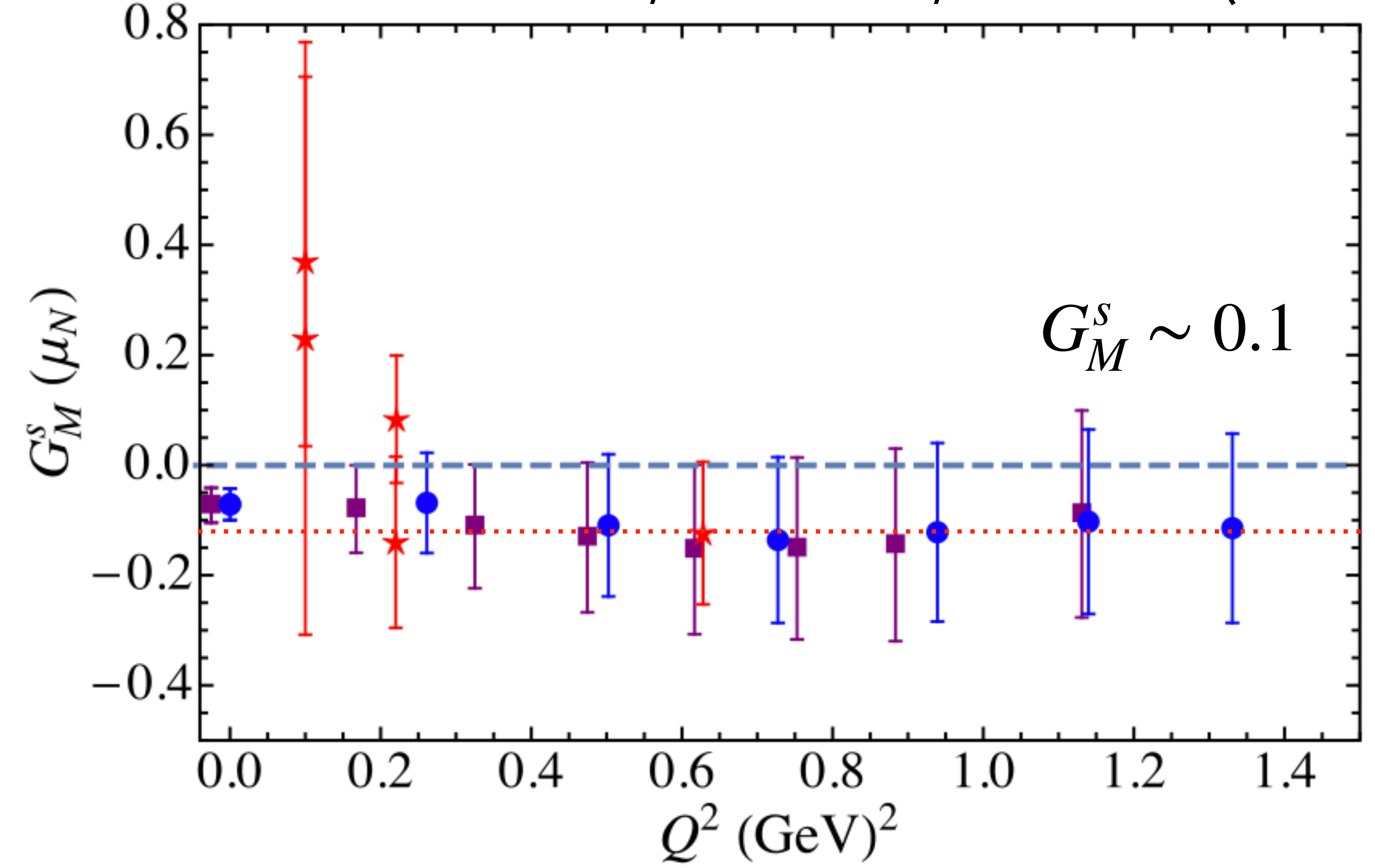
Strange form-factors on the lattice



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

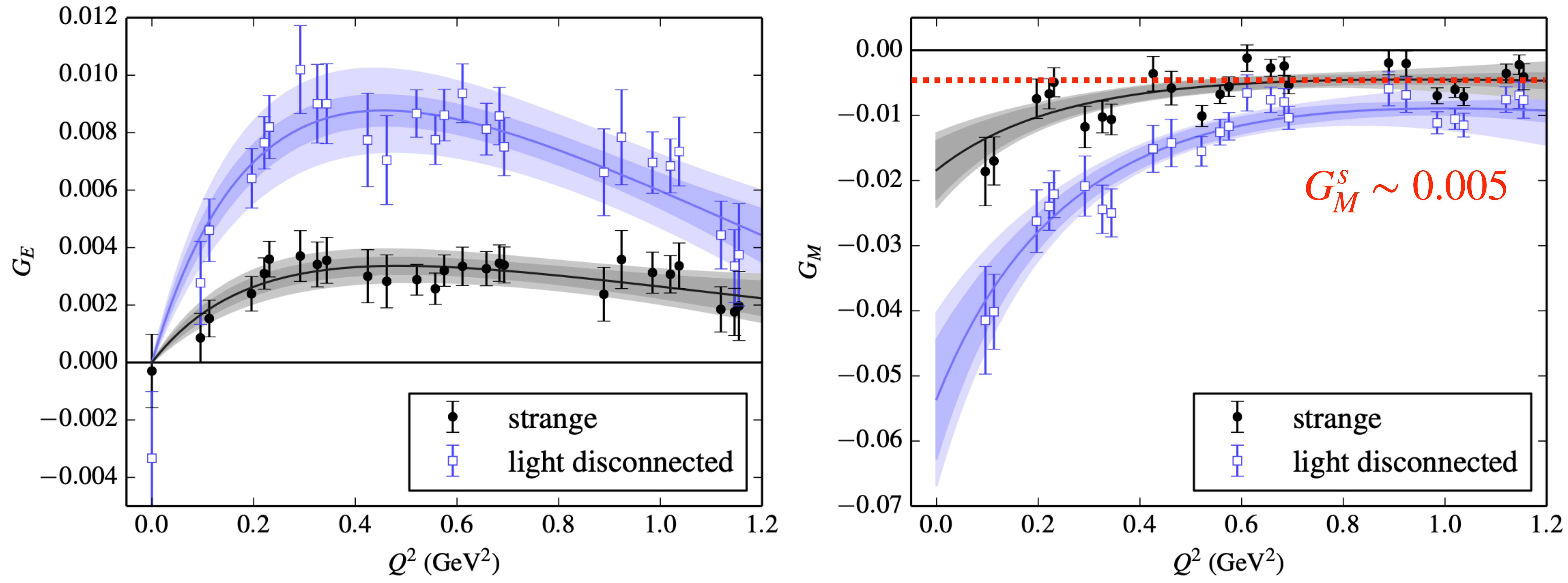
But they do not apparently fall with Q^2. **These values would be significant contributions at high Q^2**

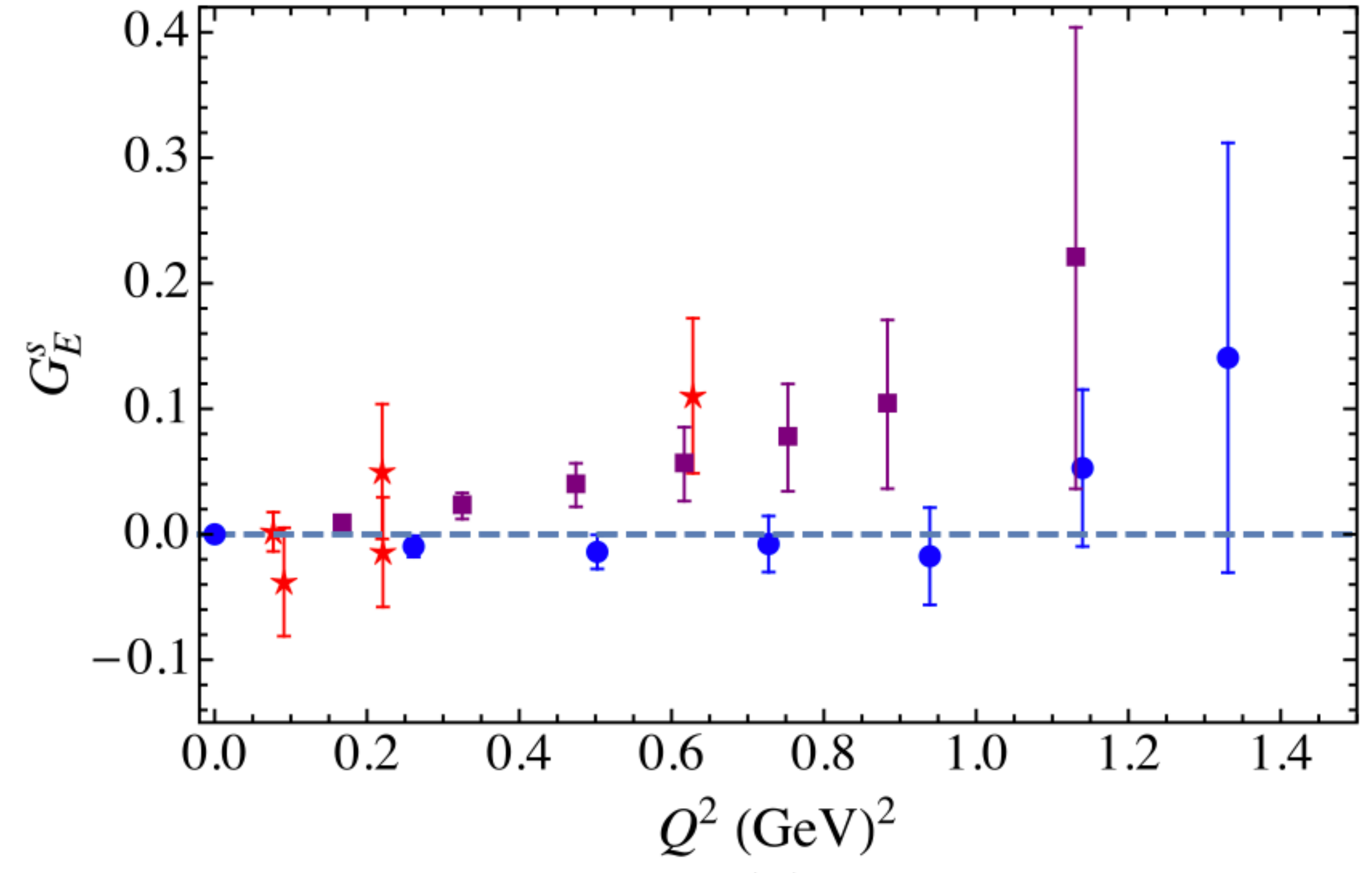
P. Shanahan *et al.*, PRL 114, 091802 (2015)



(a)

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

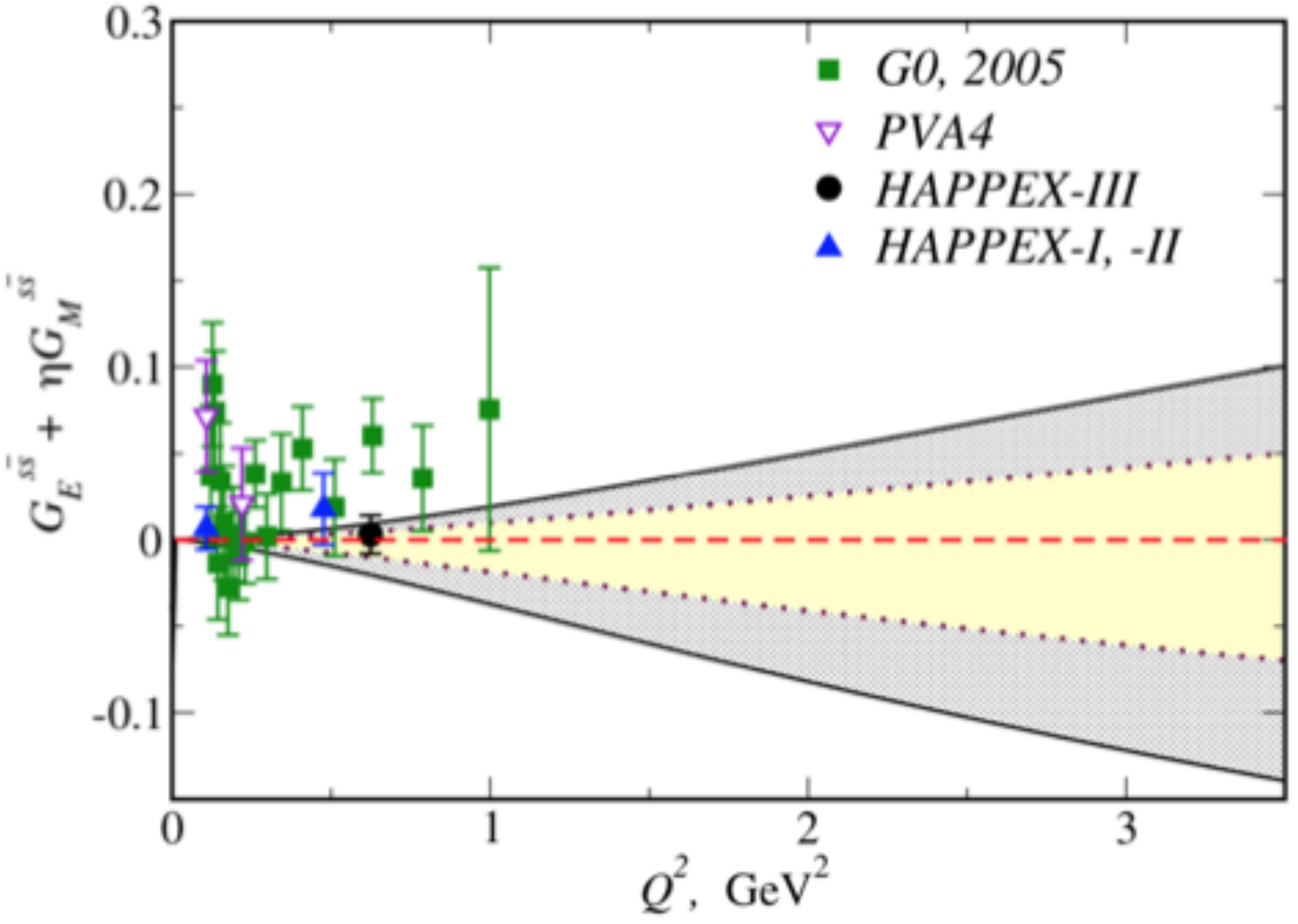




(b)

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

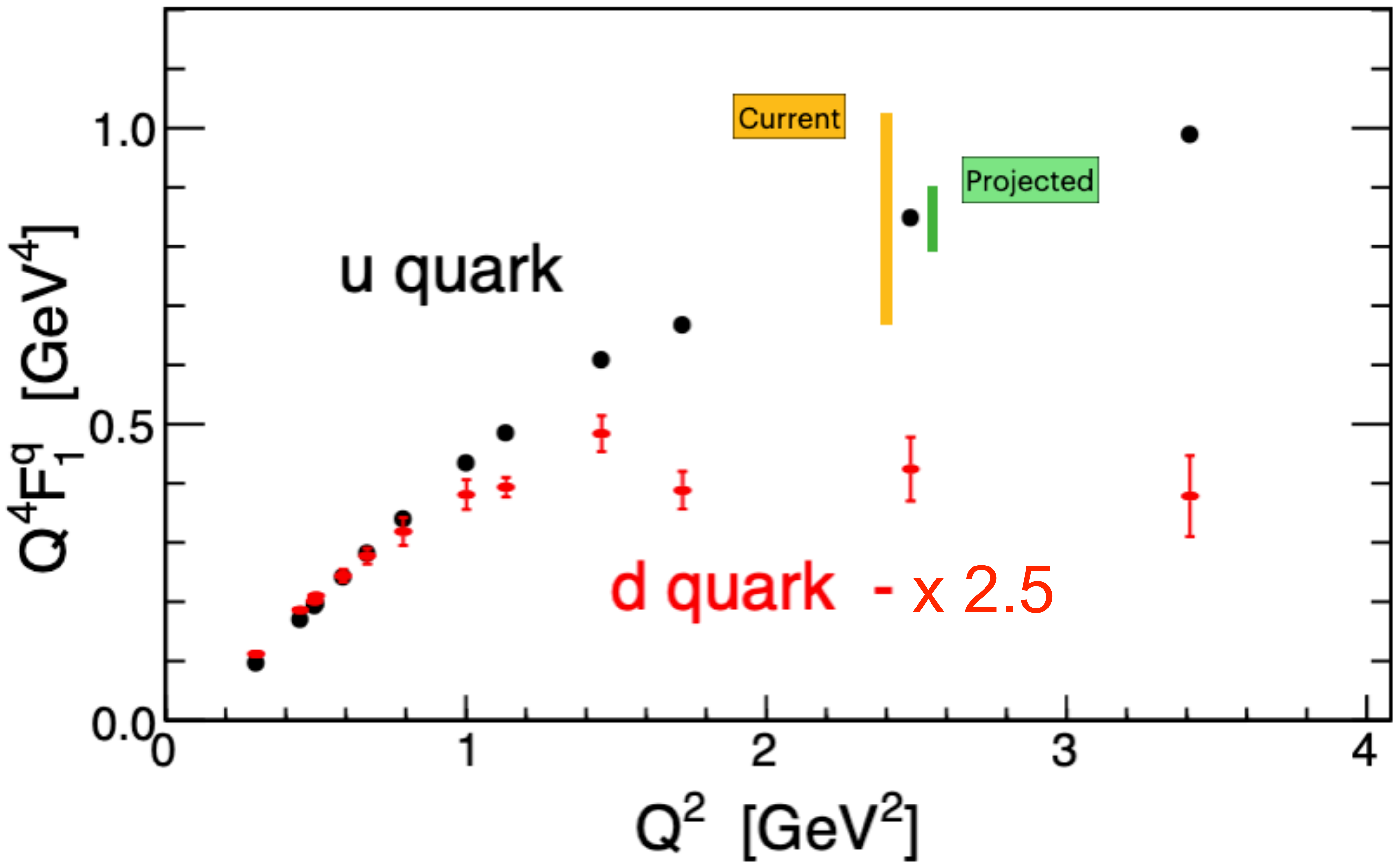
To set the scale of the data constraints: the width of the uncertainty band at Q^2 = 2.5 GeV^2 is approximately the size of the dipole form-factor parameterization G_D

G_s/G_D ~ 1 is not excluded

Q^2 dependence of Q^4F_1

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

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



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

- Flavor separated form factors are a crucial piece of information for GPDs / nuclear femtography.
- So far, these have relied on poorly tested assumptions of strange quark contributions.
- Experimentally not ruled out (at level of yellow band) and lattice calculations do not rule out significant contributions (at level of 1x-2x the green band)

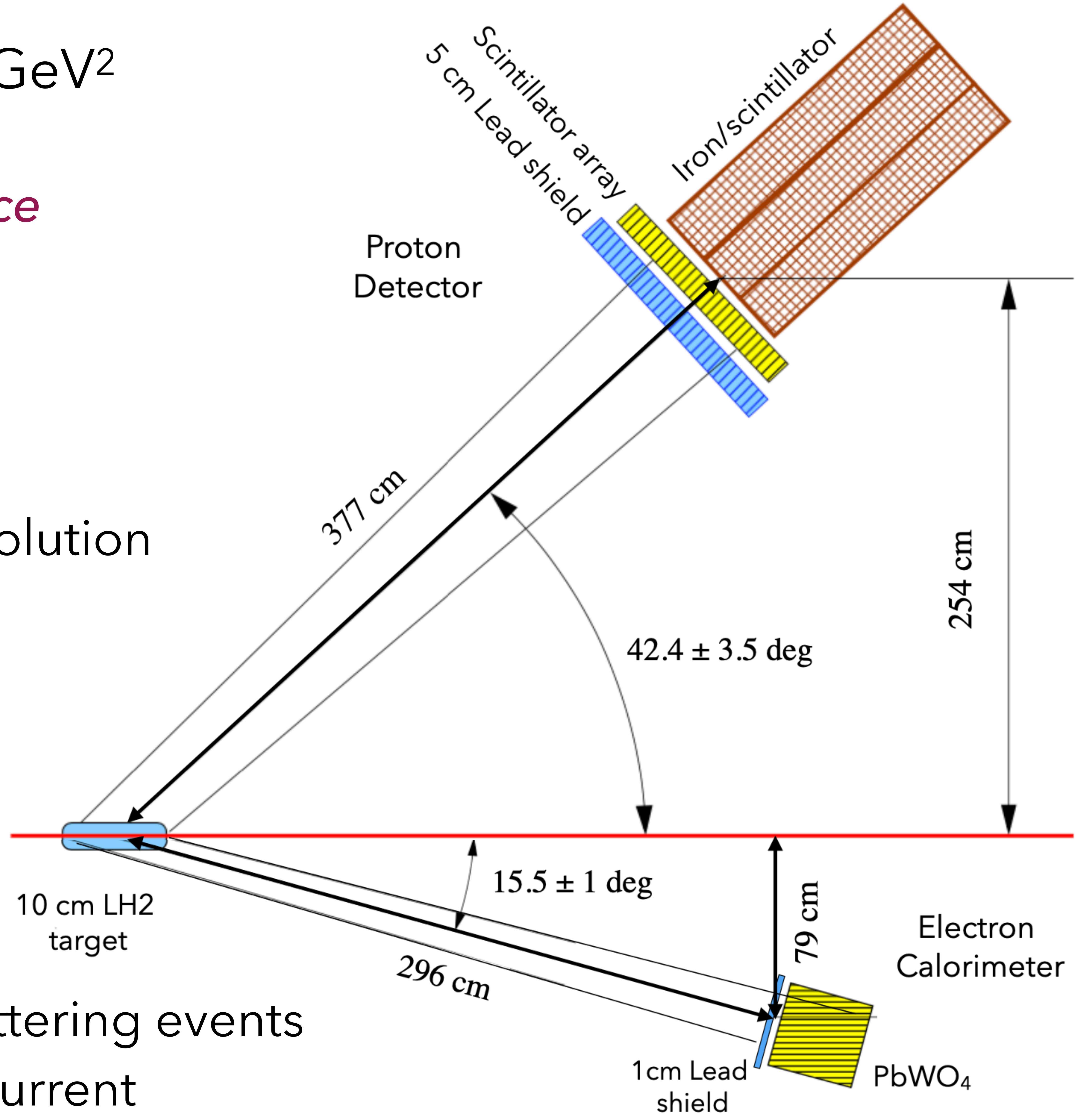
A measurement is needed

The planned measurement

Aim for $Q^2 = 2.5\ GeV^2$

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 3×10^{10} elastic scattering events
- $\mathcal{L} = 1.7 \times 10^{38}\ cm^{-2}/s$, 10 cm LH_2 target and 65 μA beam current
- Full azimuthal coverage, ~42 msr

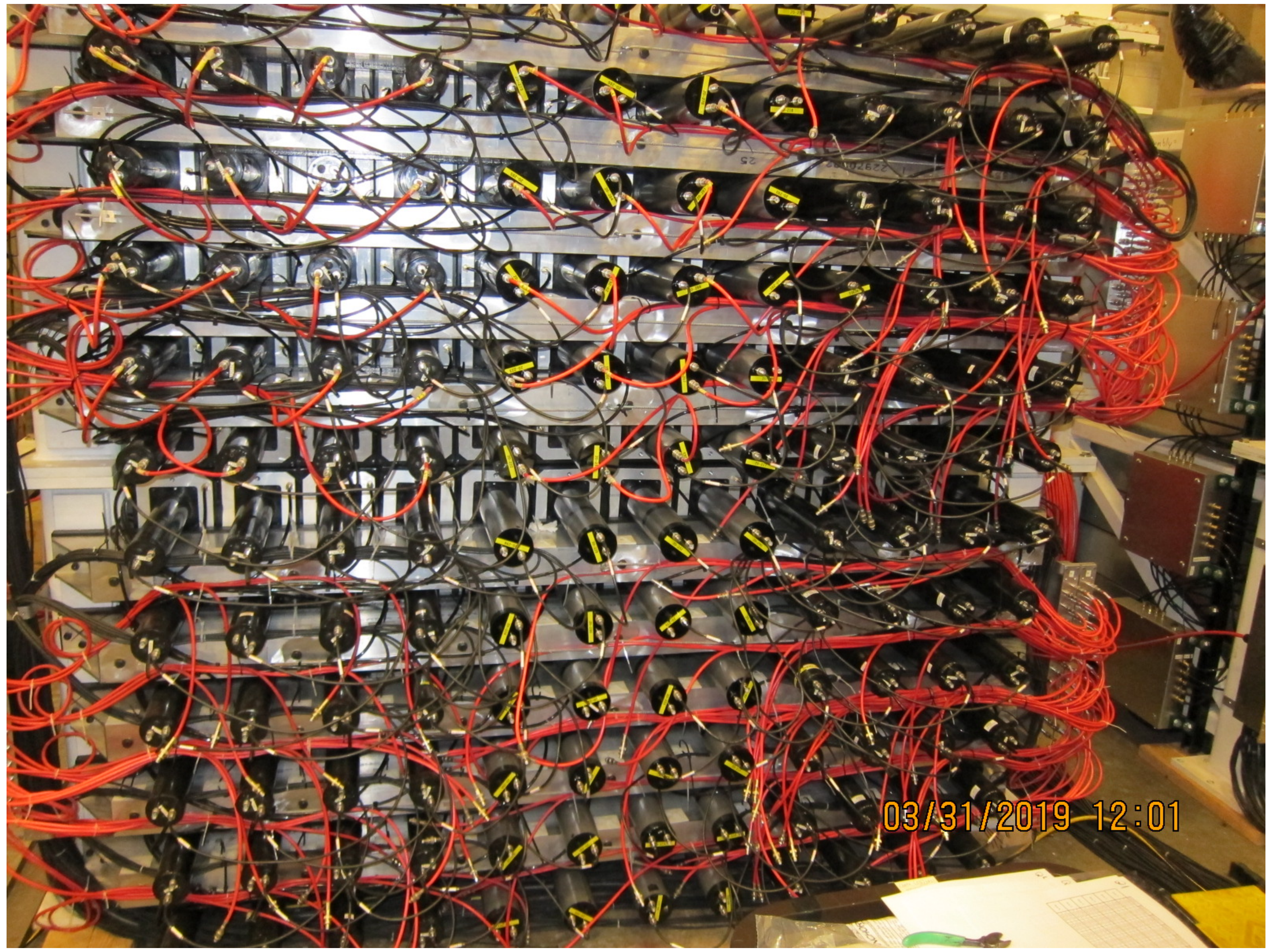
Calorimeters reusing components

NPS electromagnetic calorimeter

- 1200 $PbWO_4$ scintillators, PMTs + bases

SBS hadronic calorimeter

- 288 iron/scintillator detectors, PMTs + bases



Detector System

HCAL - hadron calorimeter

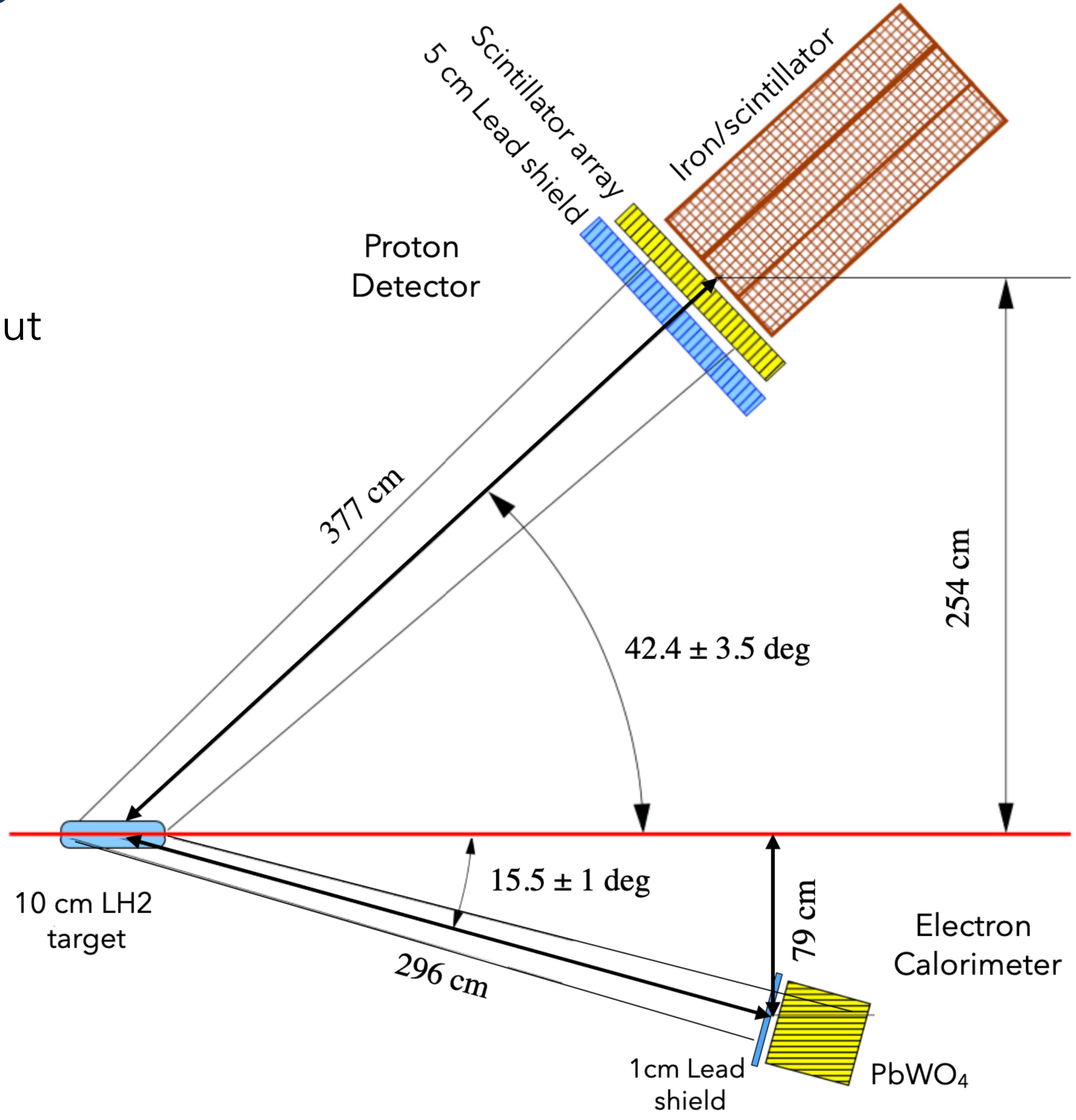
- Detector elements from the SBS HCAL
- 288 blocks, each 15.5 x 15.5 x 100 cm^3
- iron/scintillator sandwich with wavelength shifting fiber readout

ECAL - electron calorimeter

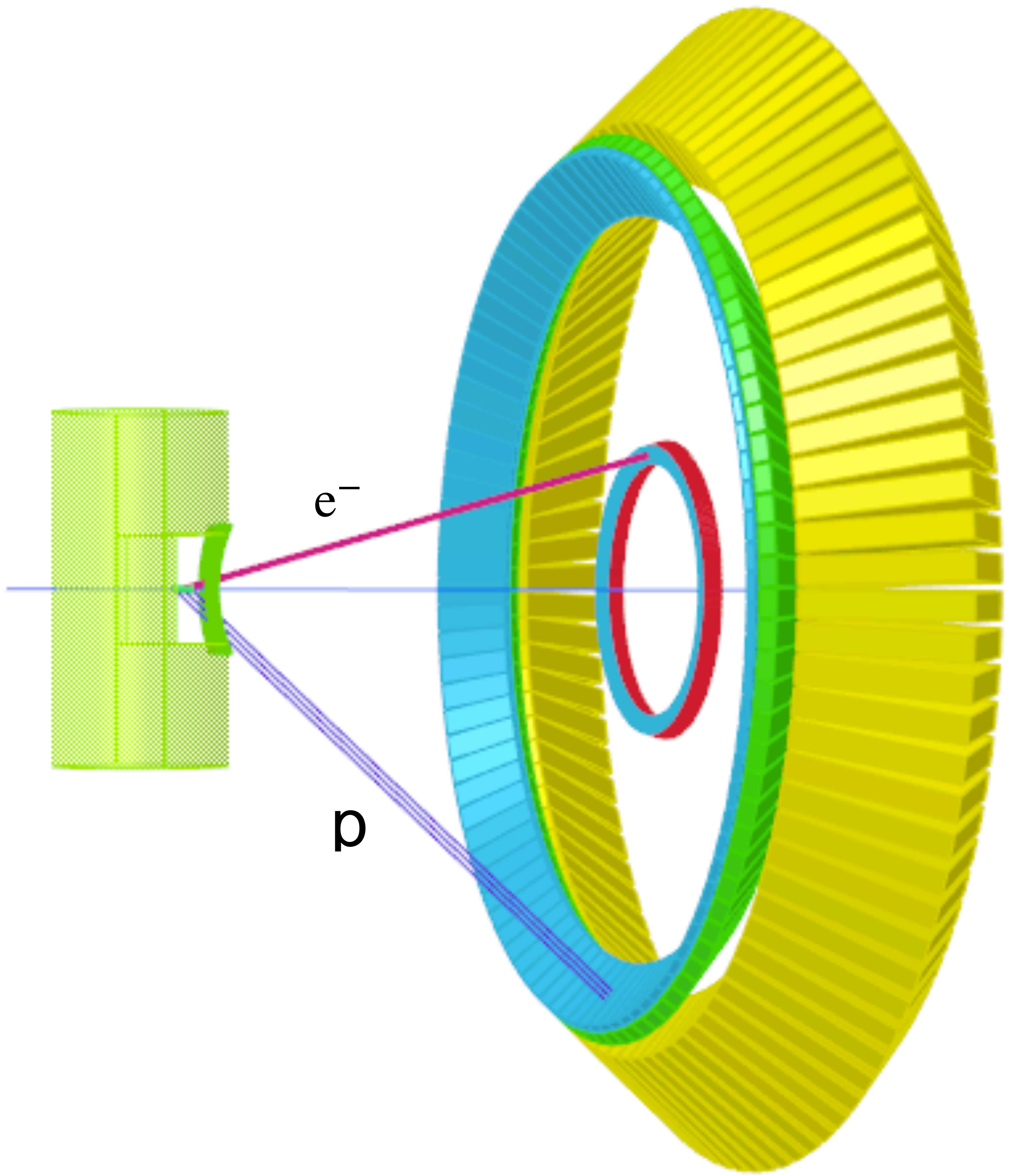
- Detector elements from the NPS calorimeter
- 1200 blocks, each 2 x 2 x 20 cm^3
- $PbWO_4$ scintillator

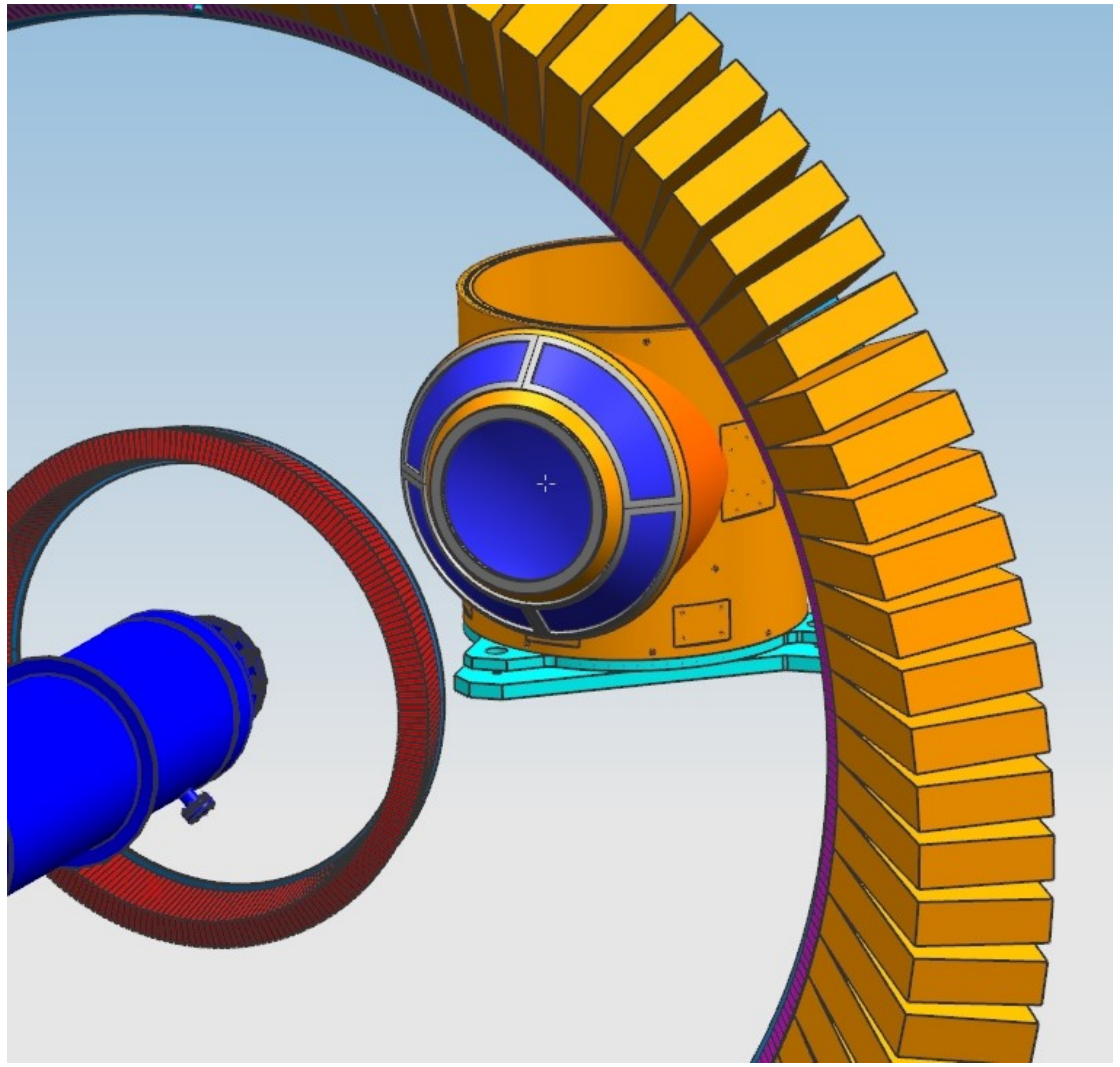
Scintillator array

- 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

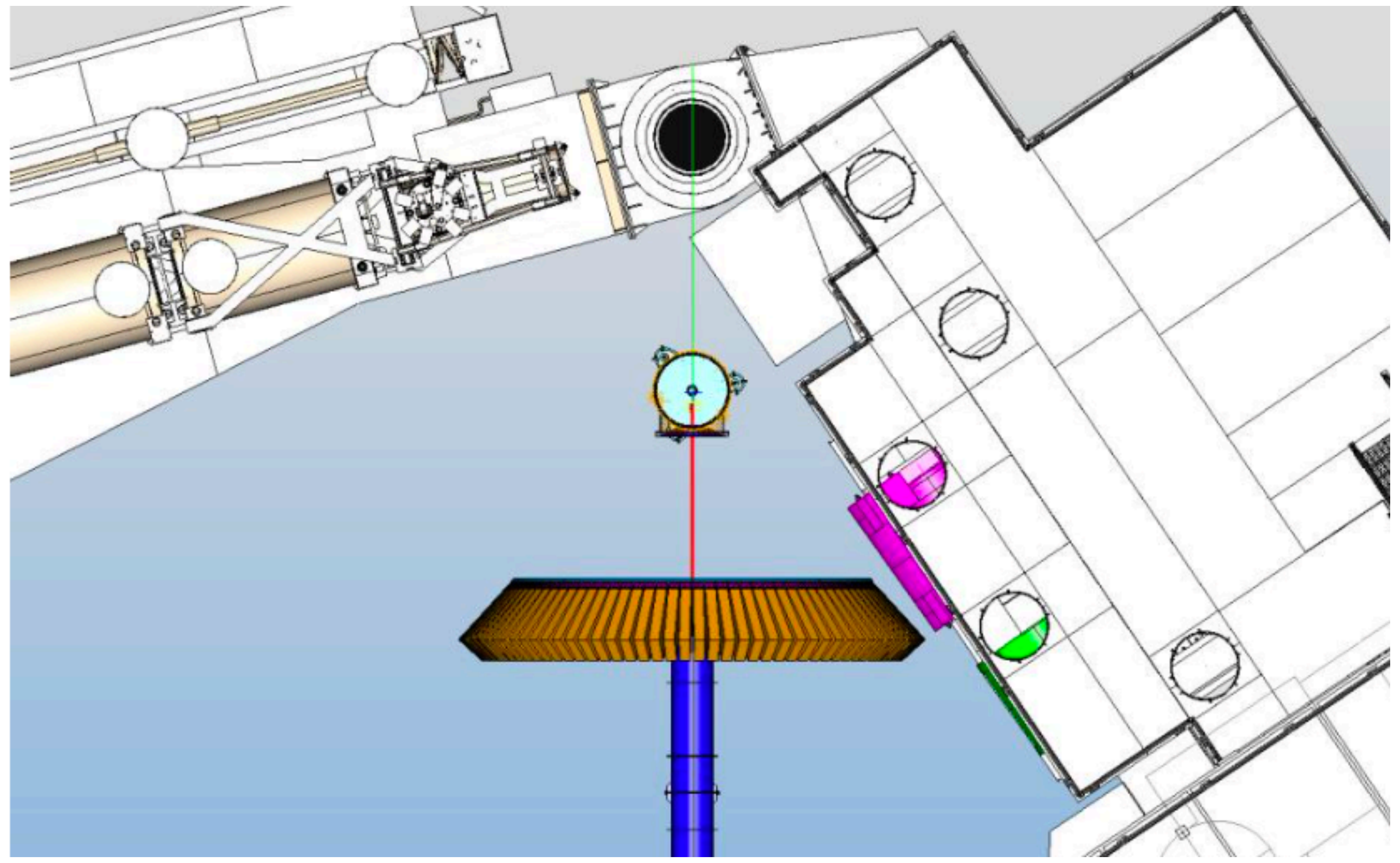


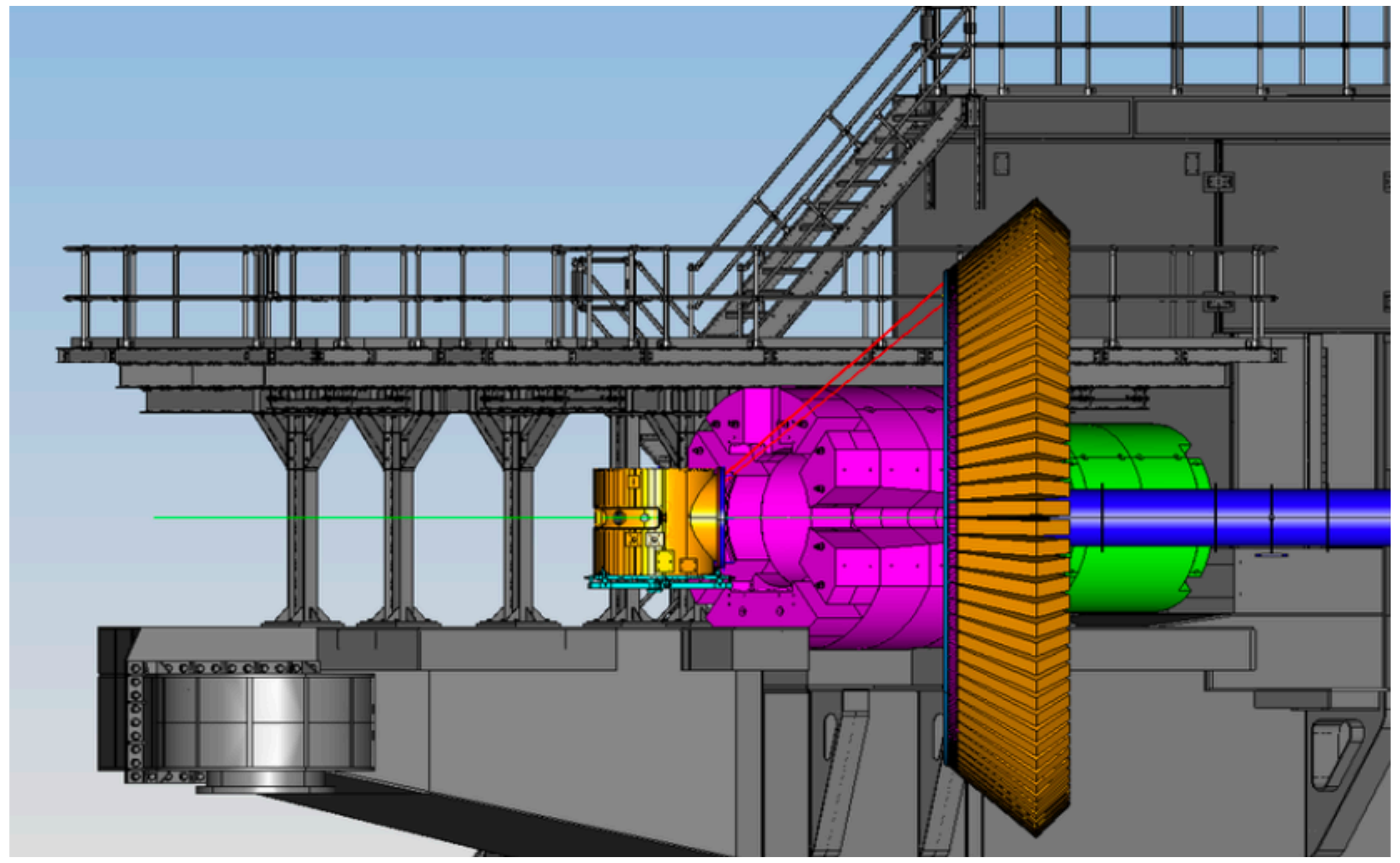


Preliminary design of scattering chamber

He bag will reduce backgrounds between target chamber and exit beampipe

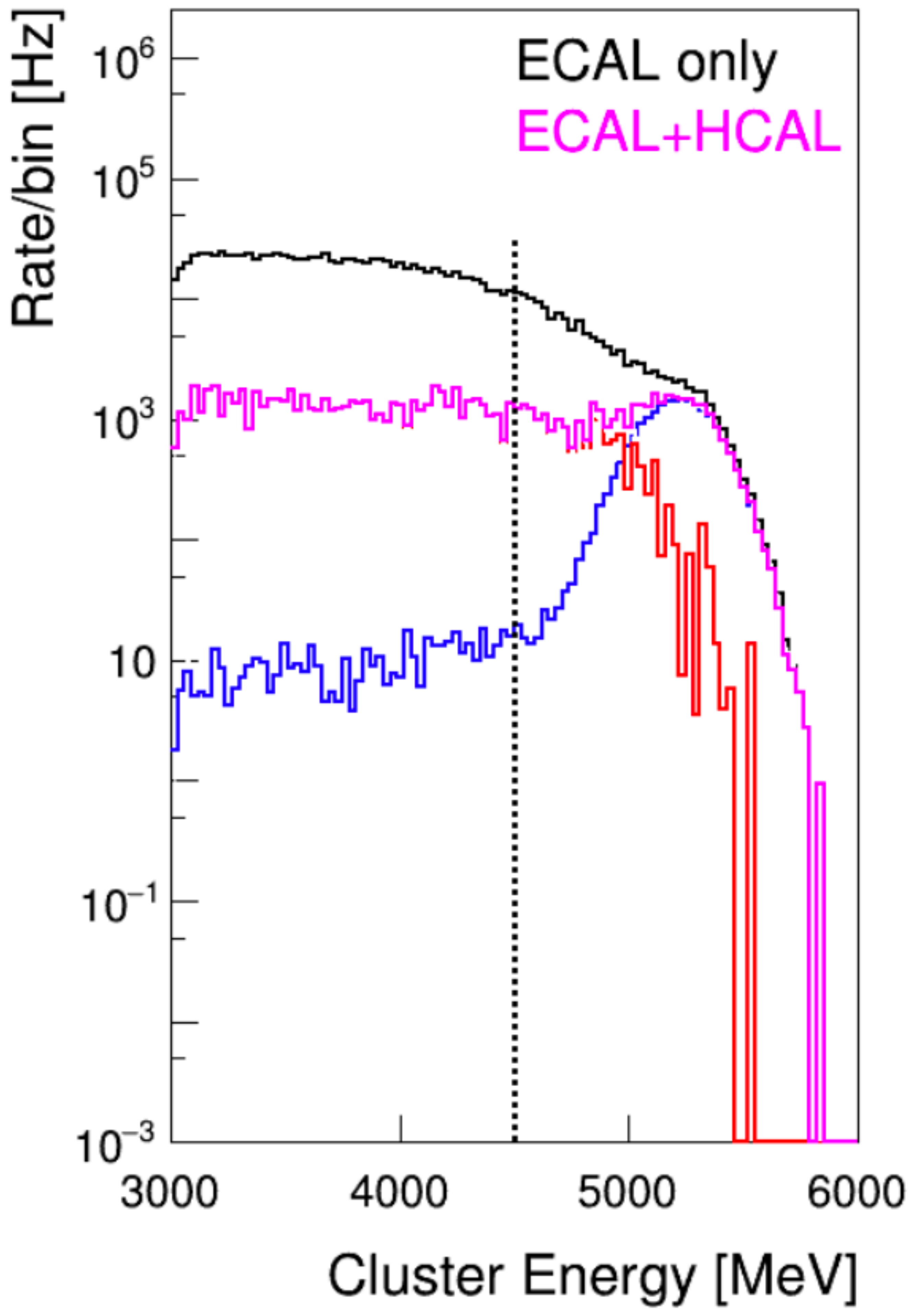
This fits in Hall C (but it's tight)





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



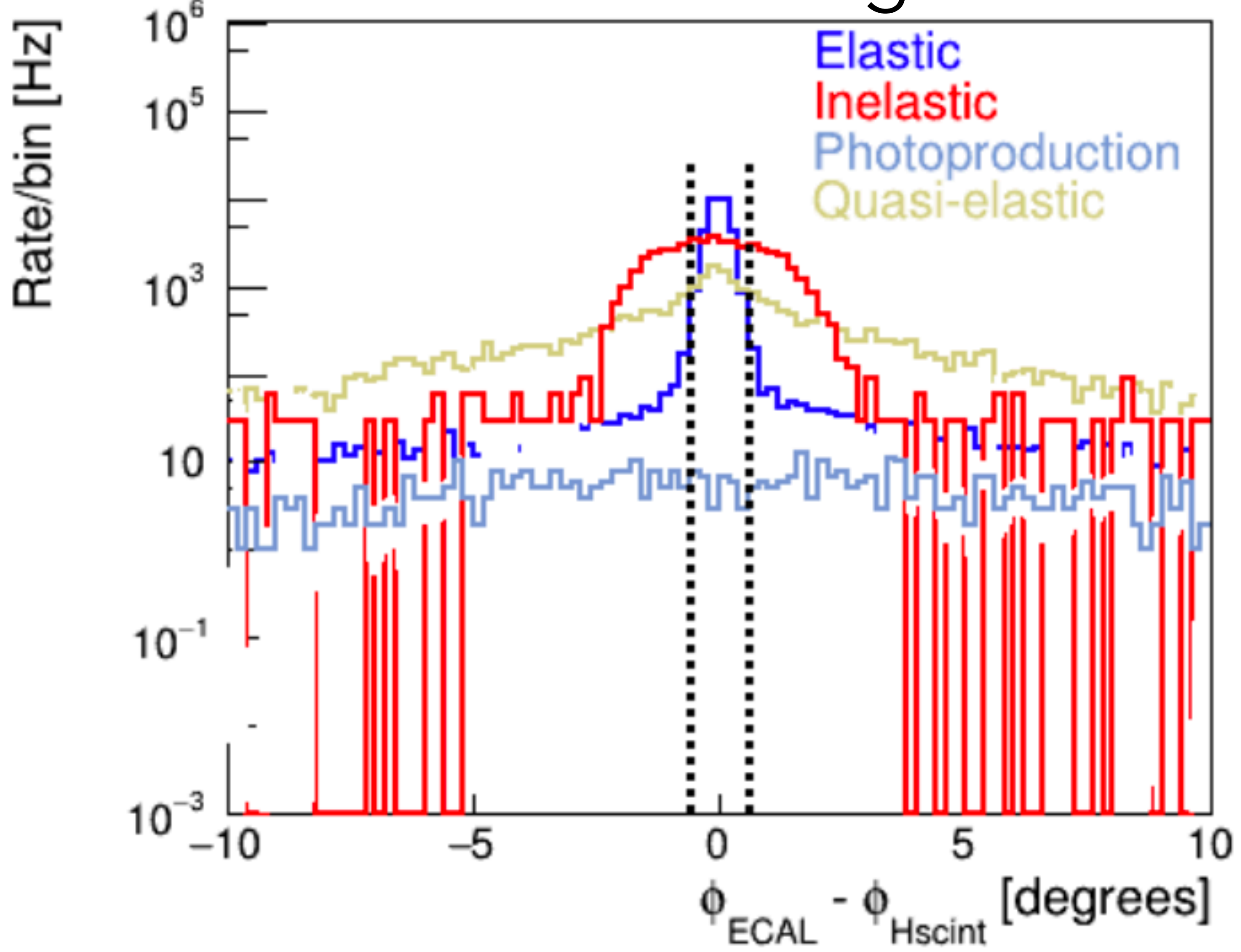
ECAL > 4.5 GeV: 150 kHz

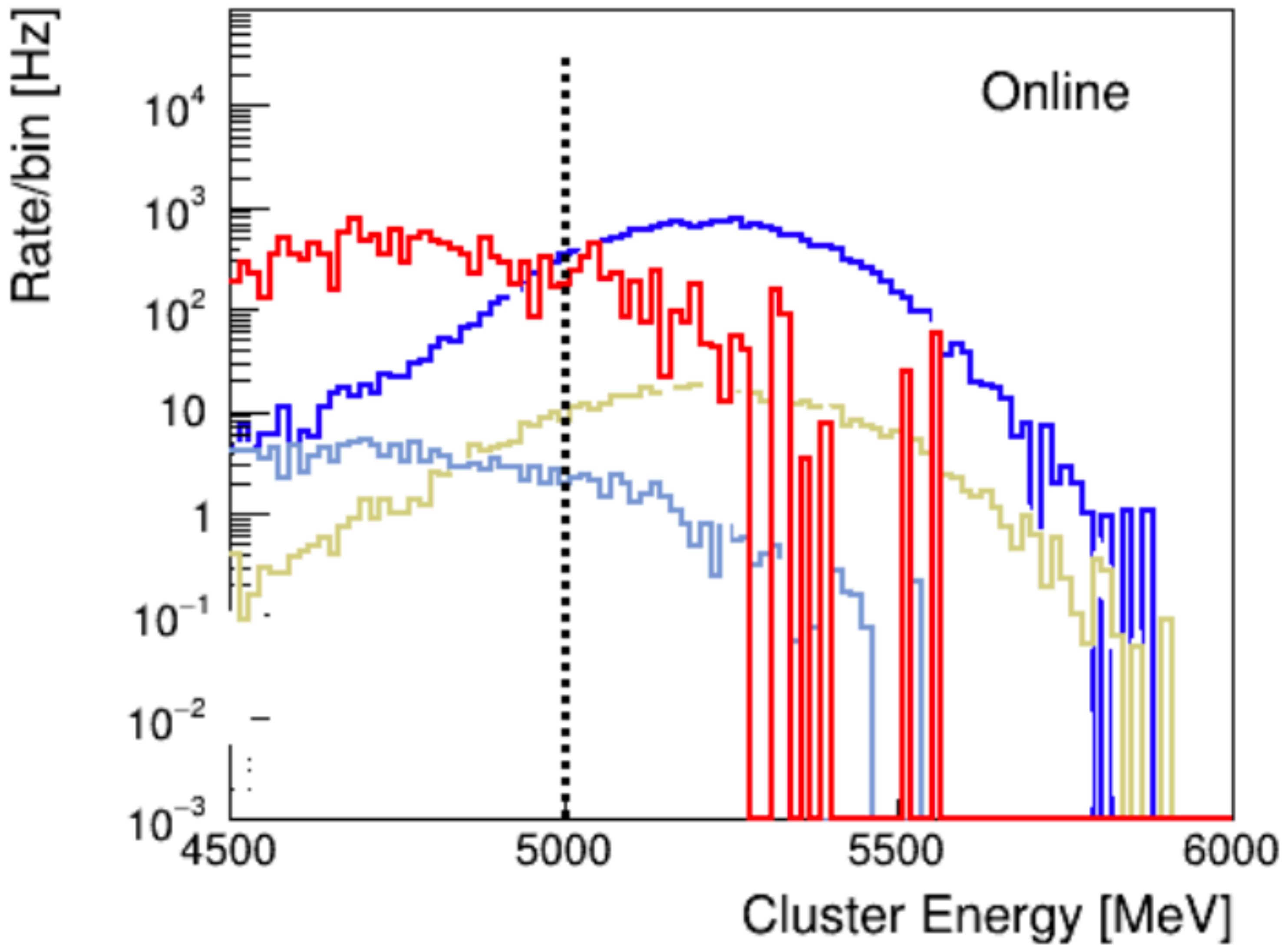
ECAL + HCAL in coincidence: 35 kHz

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

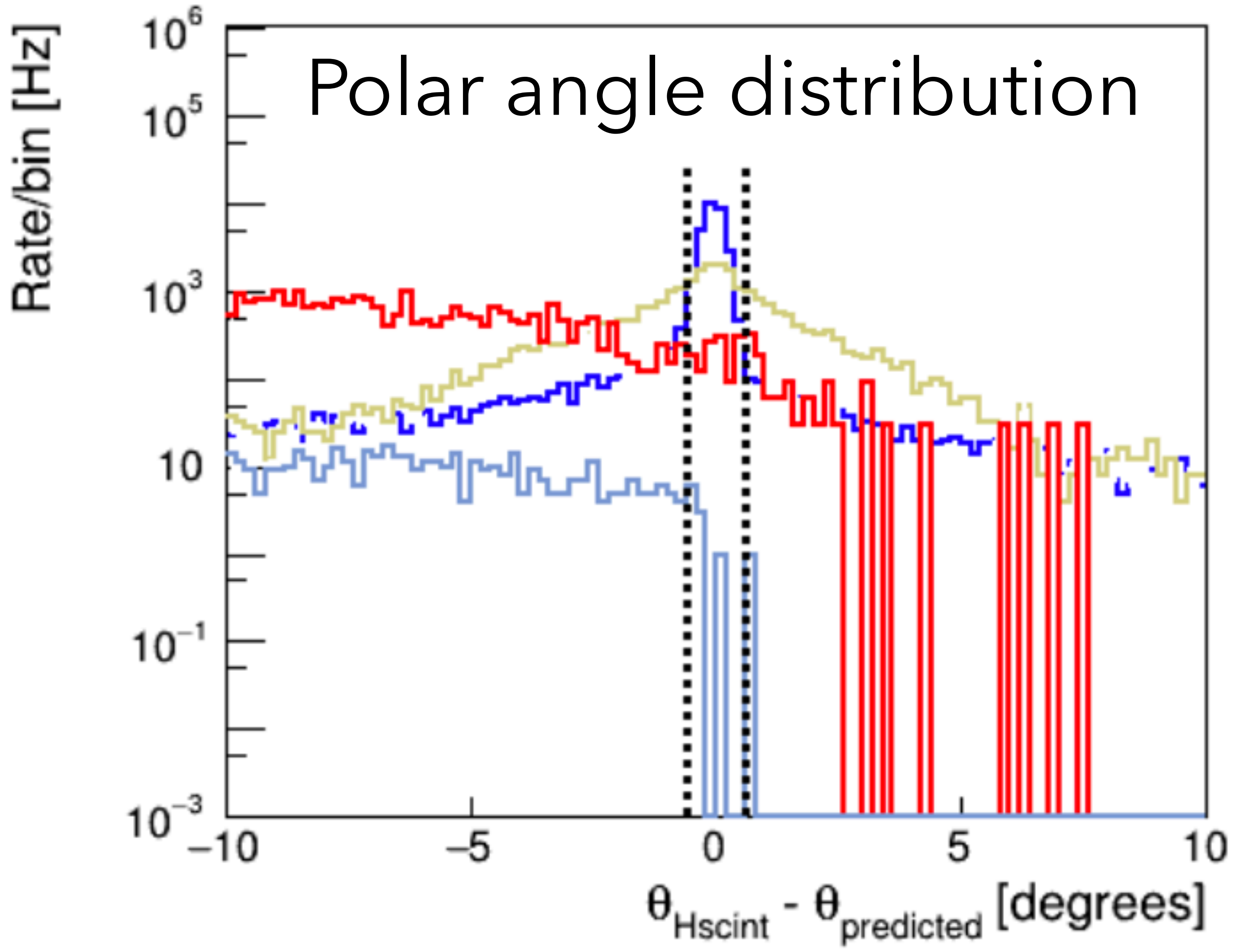


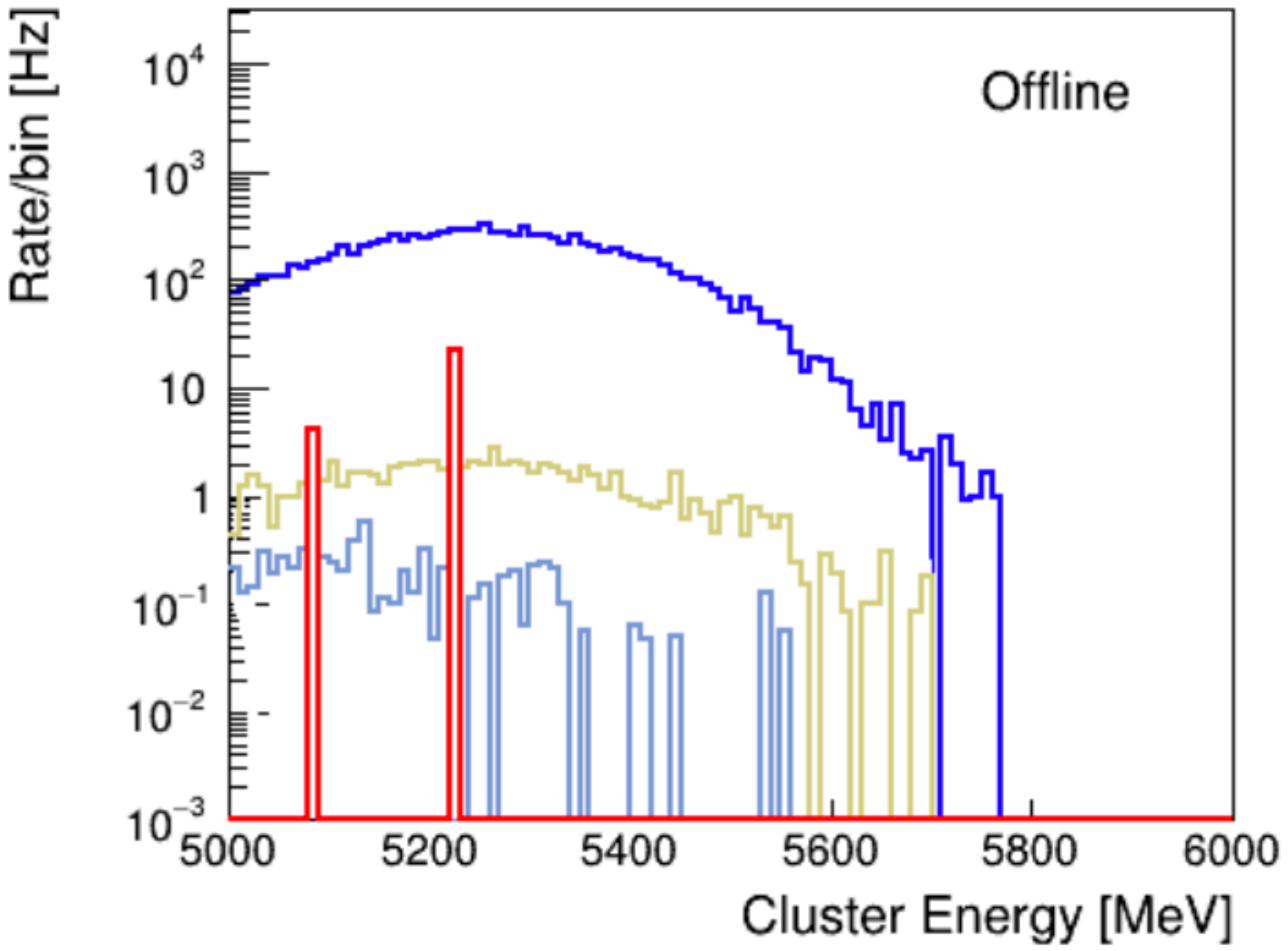


Offline: tighten geometric cut with pixel hodoscope and ECAL cluster center

Exclude inelastic background to ~0.2%

dashed lines = offline cuts





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

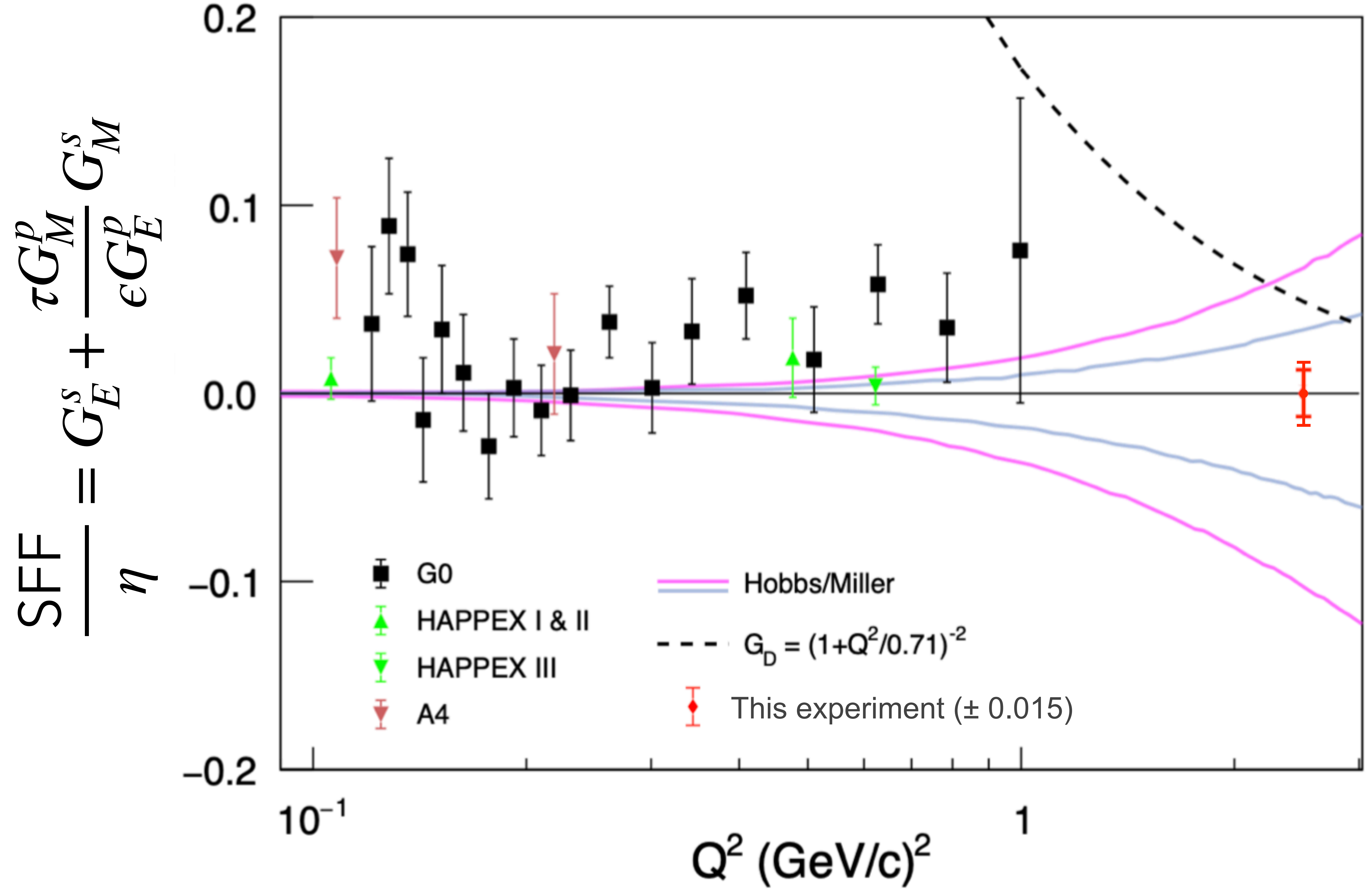
"sideband" analyses will help verify QE and inelastic asymmetries

Projected result

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

δA_{PV} = ± 6.2 (stat) ± 3.3 (syst) ($\delta A/A$ = ± 4% ± 2%)

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



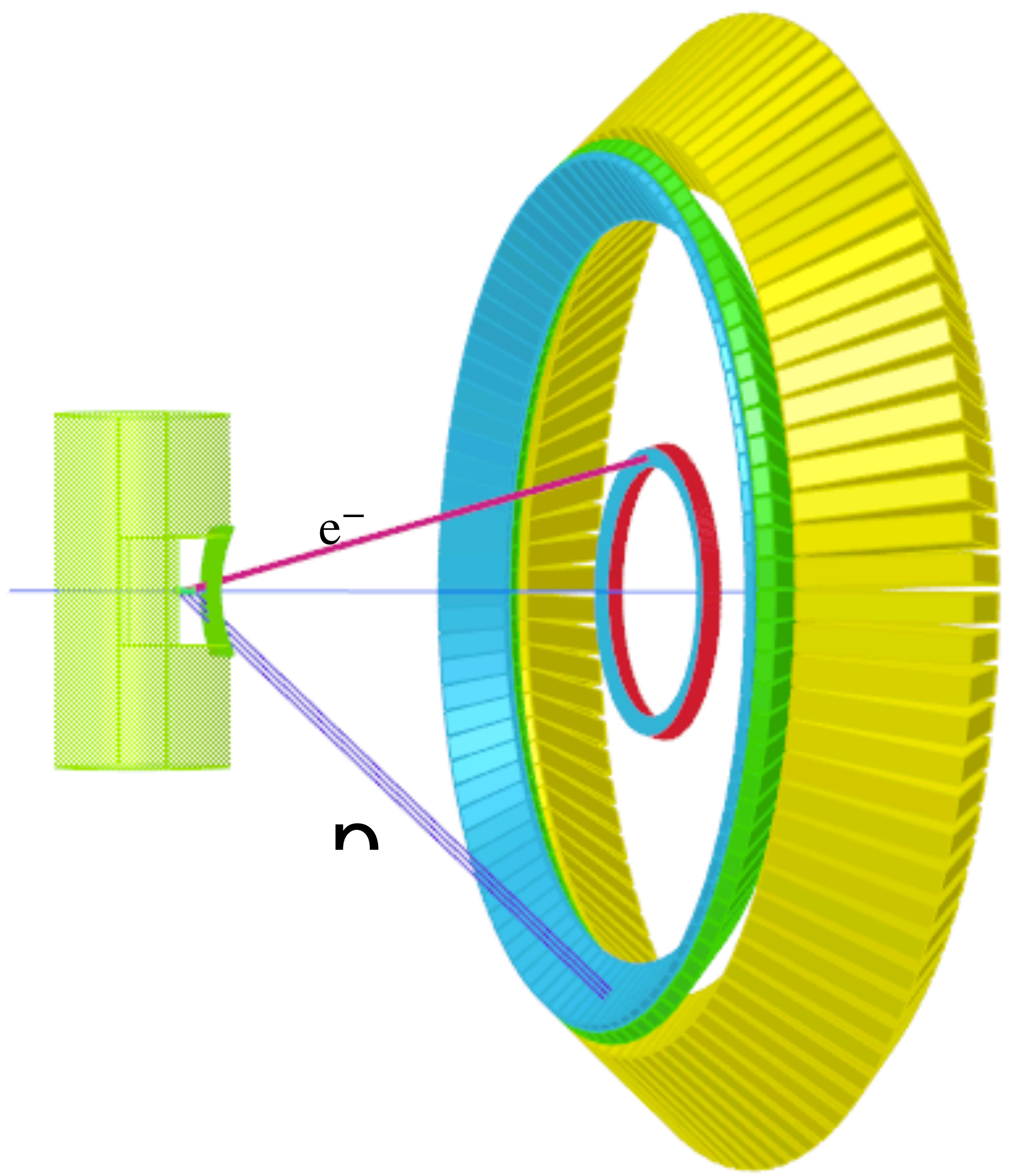
If $G_M^s = 0$, $\delta G_E^s \sim 0.015$, (about 34% of G_D)

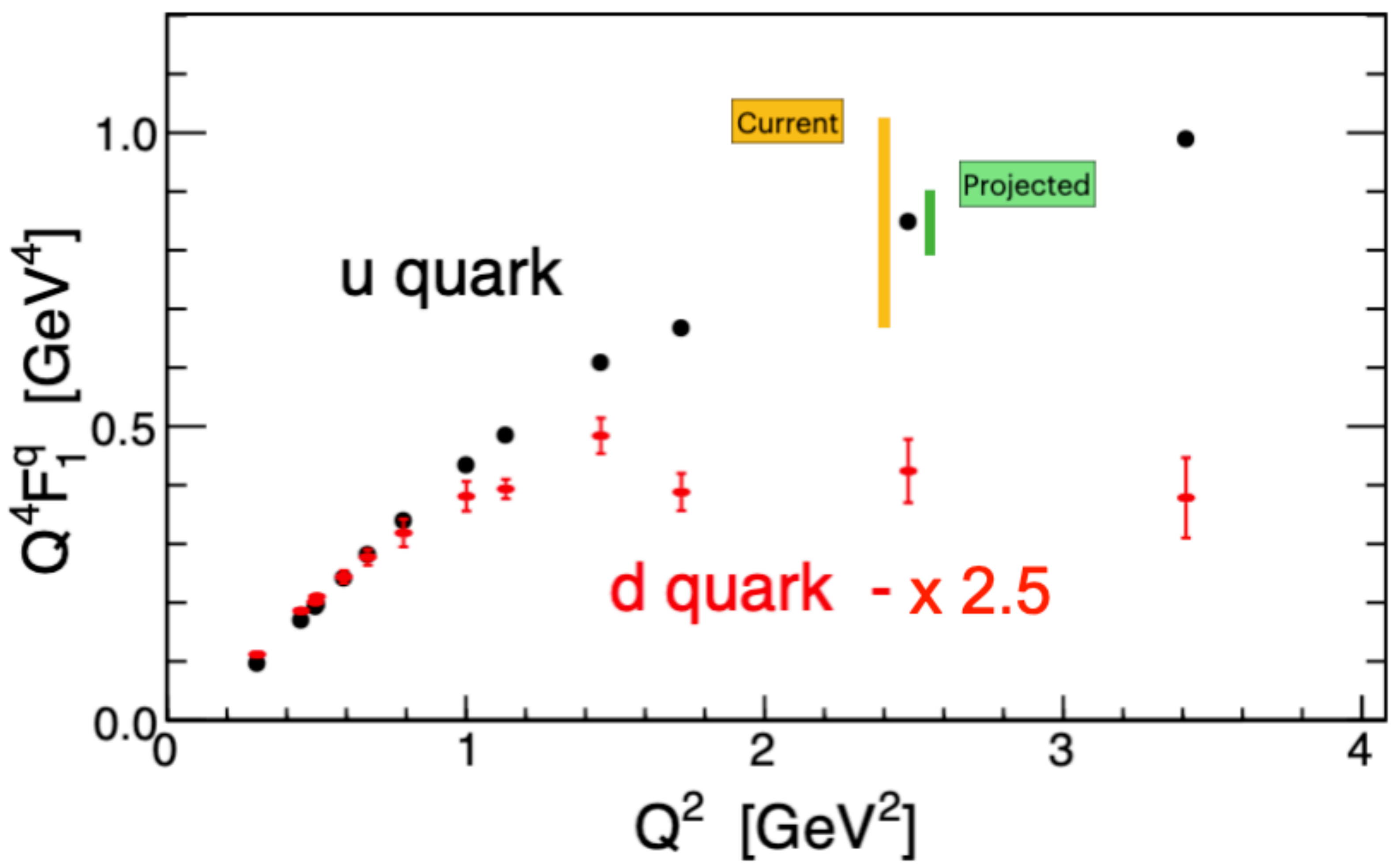
If $G_E^s = 0$, $\delta G_M^s \sim 0.005$, (about 11% of G_D)

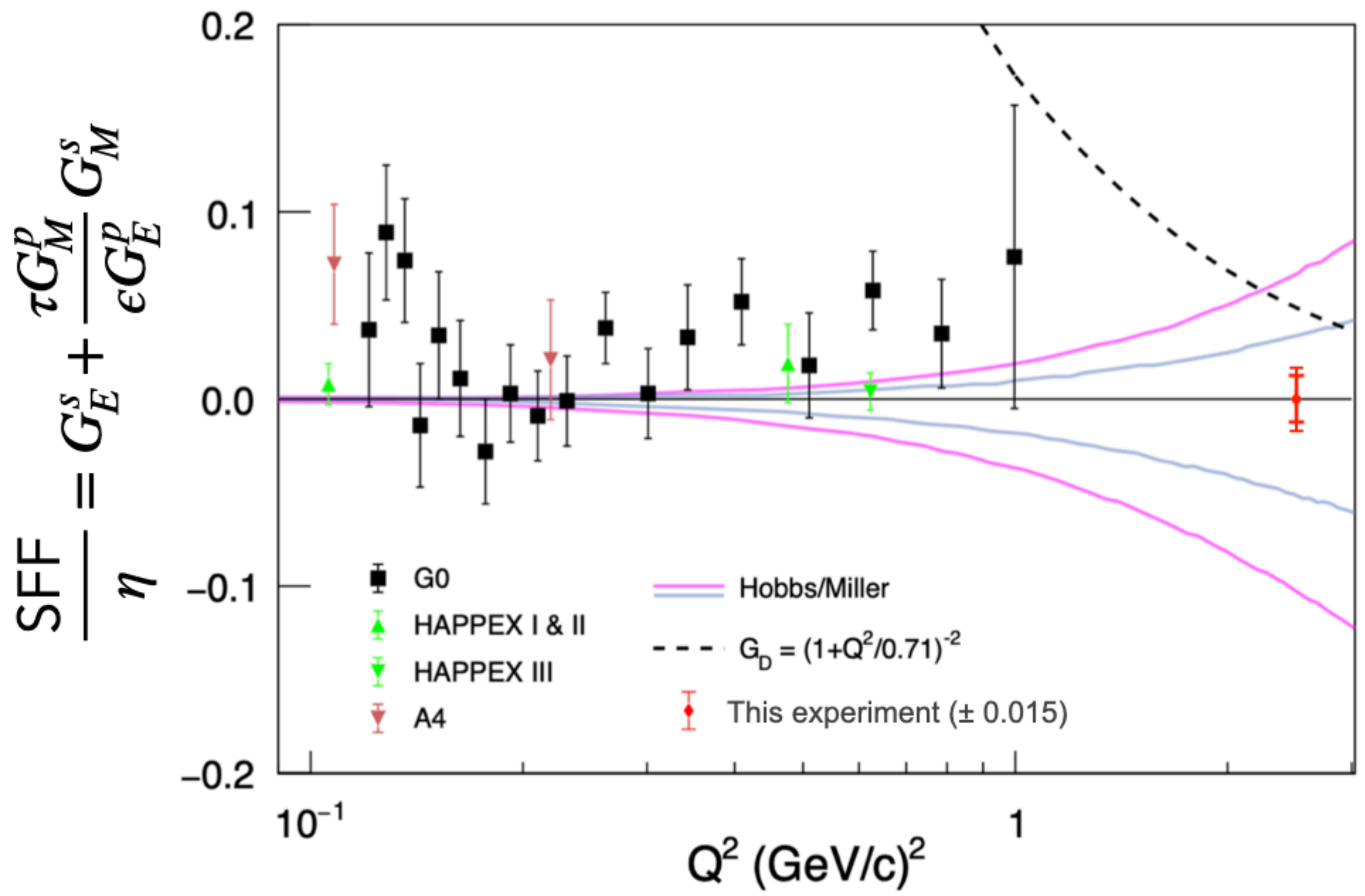
The proposed measurement is especially sensitive to G_M^s

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

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 inside the range from the simple extrapolation from previous data
- Recently approved. Schedule is as yet uncertain, but the path forward is clear.

Backup slides

Error budget

quantity	value	contributed uncertainty
Beam polarization	$85\% \pm 1\%$	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%
$G_A^{Zp}/G_{\mathrm{Dipole}}$	-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%)

Radiative correction uncertainties are small; theoretical correction uncertainty lies in the proton "anapole" moment

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