Extracting Q-weak from PVES

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γZ box(ing): Radiative corrections to parity-violating electron scattering
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Proton Asymmetry

- Leading-order asymmetry (one-boson exchange)

$$A_{LR}(\vec{e}p) = -\frac{G_\mu Q^2}{4\pi\alpha\sqrt{2}} \left[\frac{g_A^e \left(\epsilon G_{Ep}^\gamma G_{Ep}^Z + \tau G_{Mp}^\gamma G_{Mp}^Z \right) + g_V^e \epsilon' G_{Mp}^\gamma \widetilde{G}_{Ap}}{\epsilon (G_{Ep}^\gamma)^2 + \tau (G_{Mp}^\gamma)^2} \right]$$

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

$$\epsilon' = \sqrt{(1-\epsilon^2)\tau(1+\tau)}$$

- Reduced asymmetry

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Weak charge

- Take the momentum transfer to zero for forward scattering

$$Q^2 \to 0, \quad \epsilon \to 1$$

- Reduced asymmetry is just the weak charge (tree level for now)

$$\overline{A^p_{LR}} \to g^e_A G^Z_{Ep}$$

- Of course there are corrections at physical kinematics: $\text{small } Q^2, \ \text{small } \theta$

$$\begin{aligned}\overline{A^p_{RL}} = {} & g^e_A g^{Z(p)}_E \\ & + Q^2 \frac{1}{12M_p^2}\left[3g^e_A \mu_p \mu^Z_p + g^e_A g^{Z(p)}_E \left(2M_p^2(\langle r^2\rangle^\gamma_{Ep} - \langle r^2\rangle^Z_{Ep}) - 3\mu_p^2\right)\right] \\ & + |Q|\theta \frac{g^e_v}{2M_p}\mu_p \widetilde{G}^p_A + \mathcal{O}\left(|Q|^3, \theta^2\right)\end{aligned}$$

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axial + anapole

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note: expansion is just for illustration

Proton asymmetry

- Full expression

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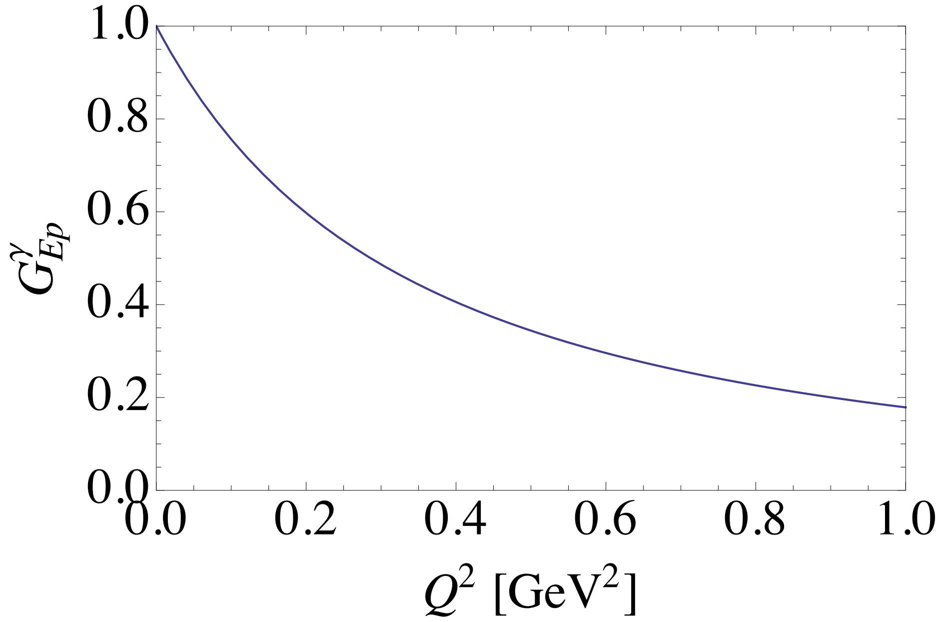
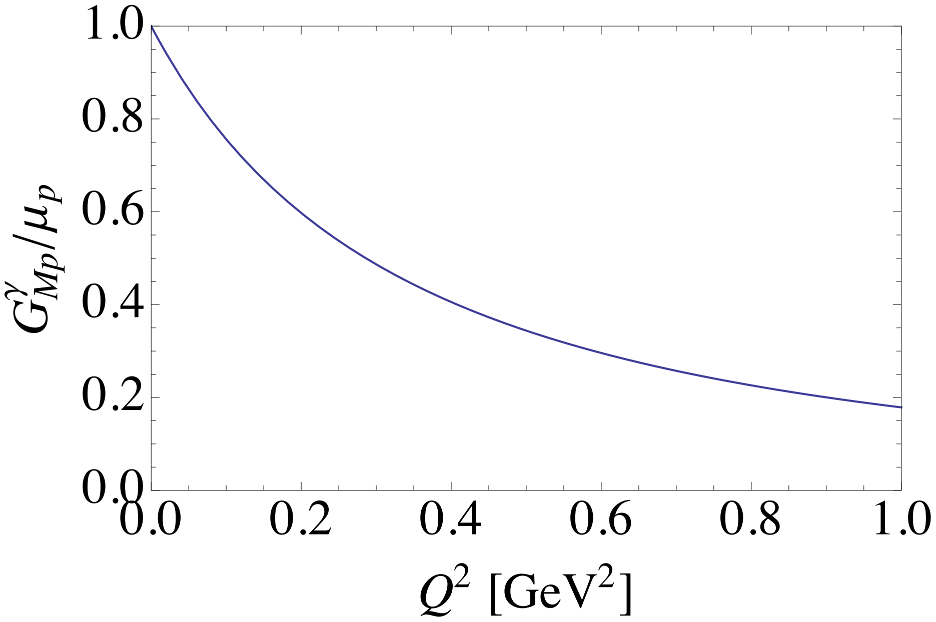
electromagnetic form factors

The easy part

- Electromagnetic form factors $G^{\gamma}_{Ep}, \ G^{\gamma}_{Mp}$

- Kelly parameterisation





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electroweak form factors

Electroweak form factors

- *Z* boson couples differently to electromagnetic currents
  - Break down EM form factors into individual quark contributions

$$G^Z_{Ep} = g^u_V G^u_{Ep} + g^d_V G^d_{Ep} + g^s_V G^s_{Ep}$$

  - compare usual electromagnetic

$$G^\gamma_{Ep} = \frac{2}{3} G^u_{Ep} - \frac{1}{3} G^d_{Ep} - \frac{1}{3} G^s_{Ep}$$

proton

$$G^\gamma_{En} = -\frac{1}{3} G^d_{En} + \frac{2}{3} G^u_{En} - \frac{1}{3} G^s_{En}$$

neutron

Electroweak form factors

$$G_{En}^{d} = G_{Ep}^{u} - G_{E}^{\delta u}$$

$$G_{En}^{u} = G_{Ep}^{d} - G_{E}^{\delta d}$$

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Electroweak form factors

- Charge symmetry: Protons are like neutrons

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charge symmetry violation:
expected to be small

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charge symmetry violation: expected to be small

- We can then rewrite the neutral form factor as

$$G_{Ep}^{Z} = (1 - 4\sin^2\theta_W)G_{Ep}^{\gamma} - G_{En}^{\gamma} - \left[G_{Ep}^{s} - \frac{1}{3}\left(G_{E}^{\delta u} + G_{E}^{\delta s} - 2G_{E}^{\delta d}\right)\right]$$

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we will just parameterise our ignorance

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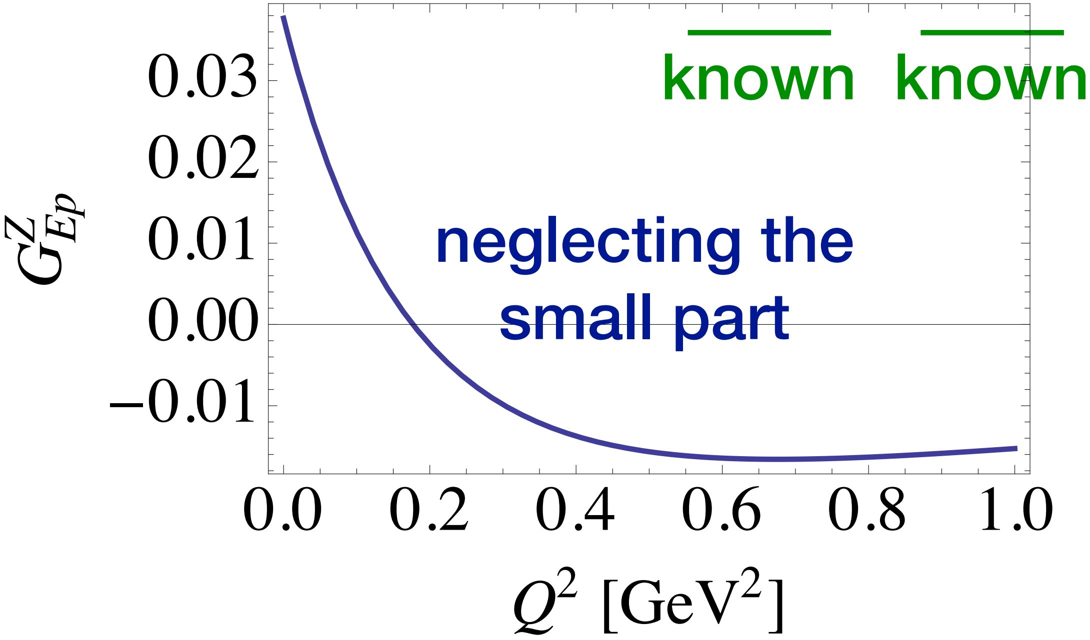

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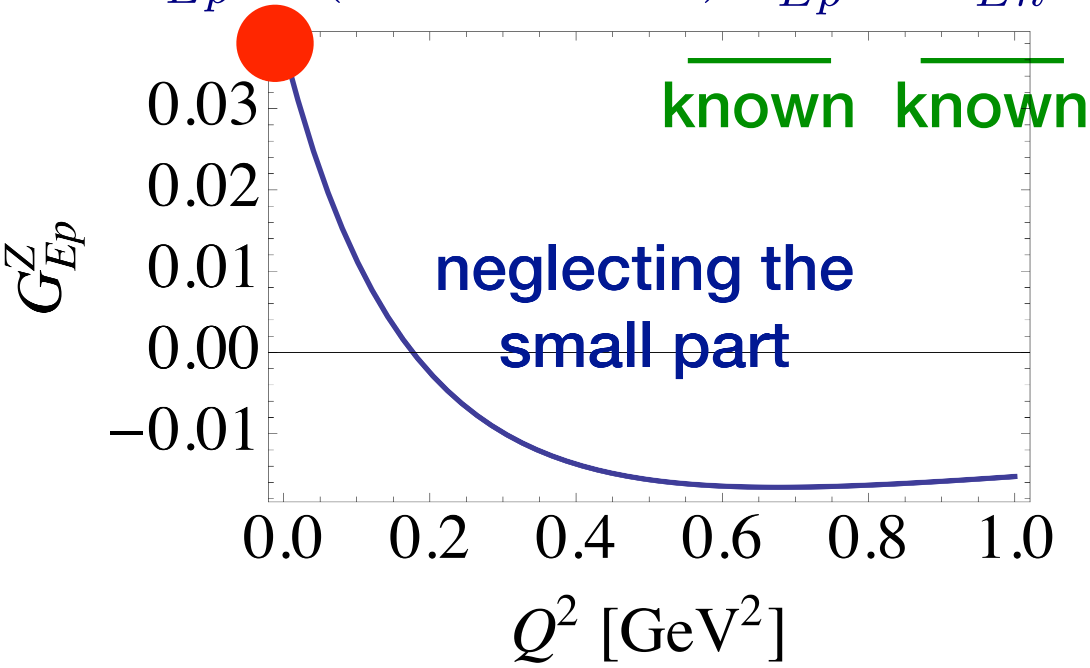

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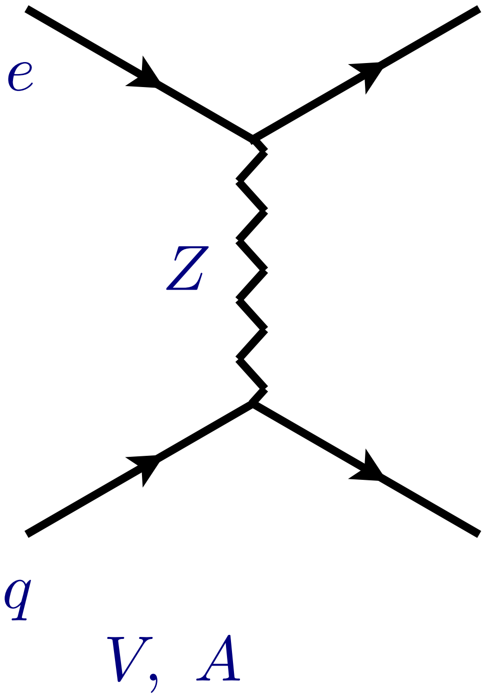
Radiative corrections

- Neutral current processes at the *Z*-pole

$Q^2 \sim M_Z^2$



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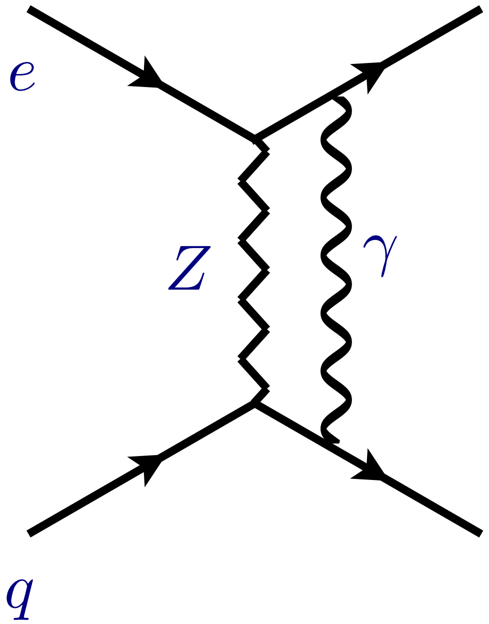

$$V, \; A$$

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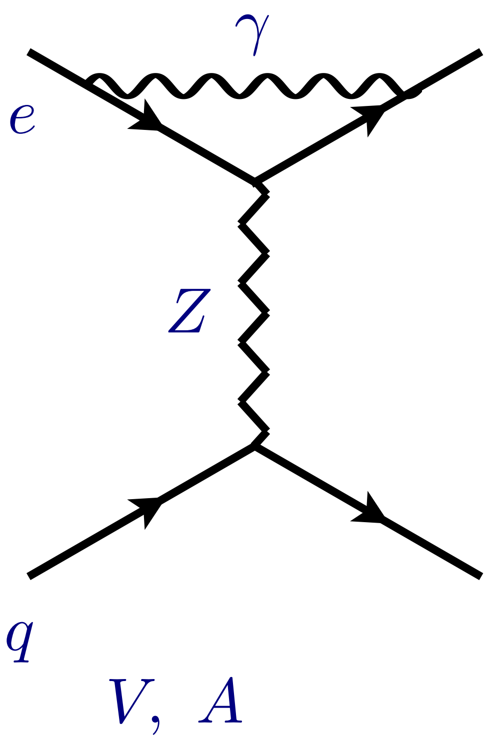

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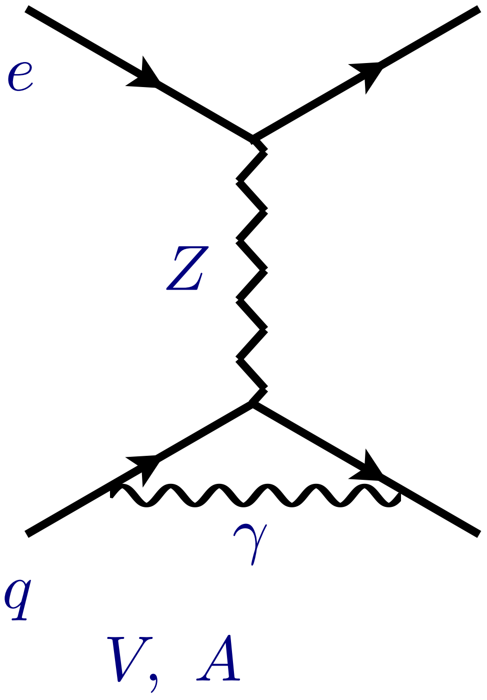

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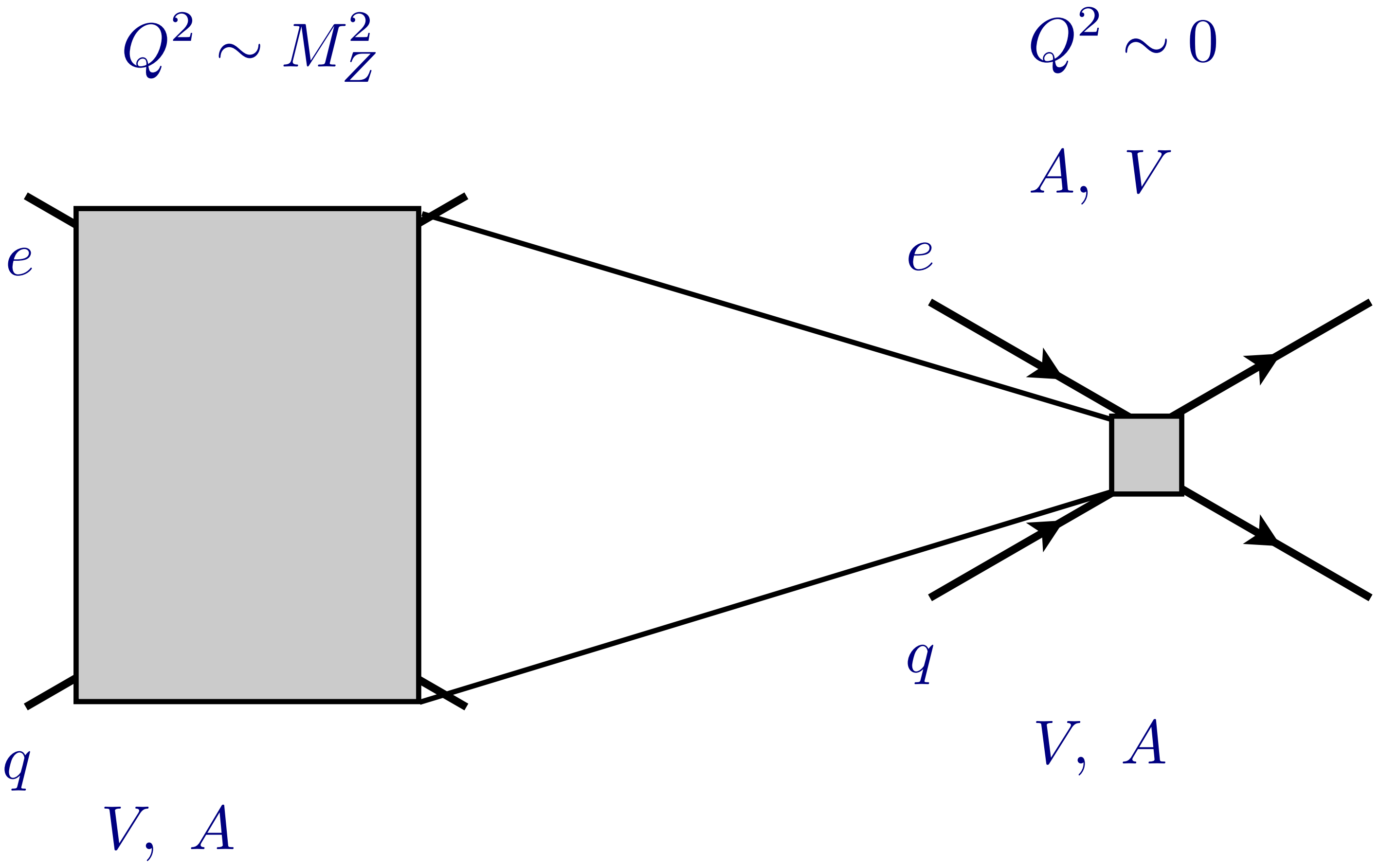

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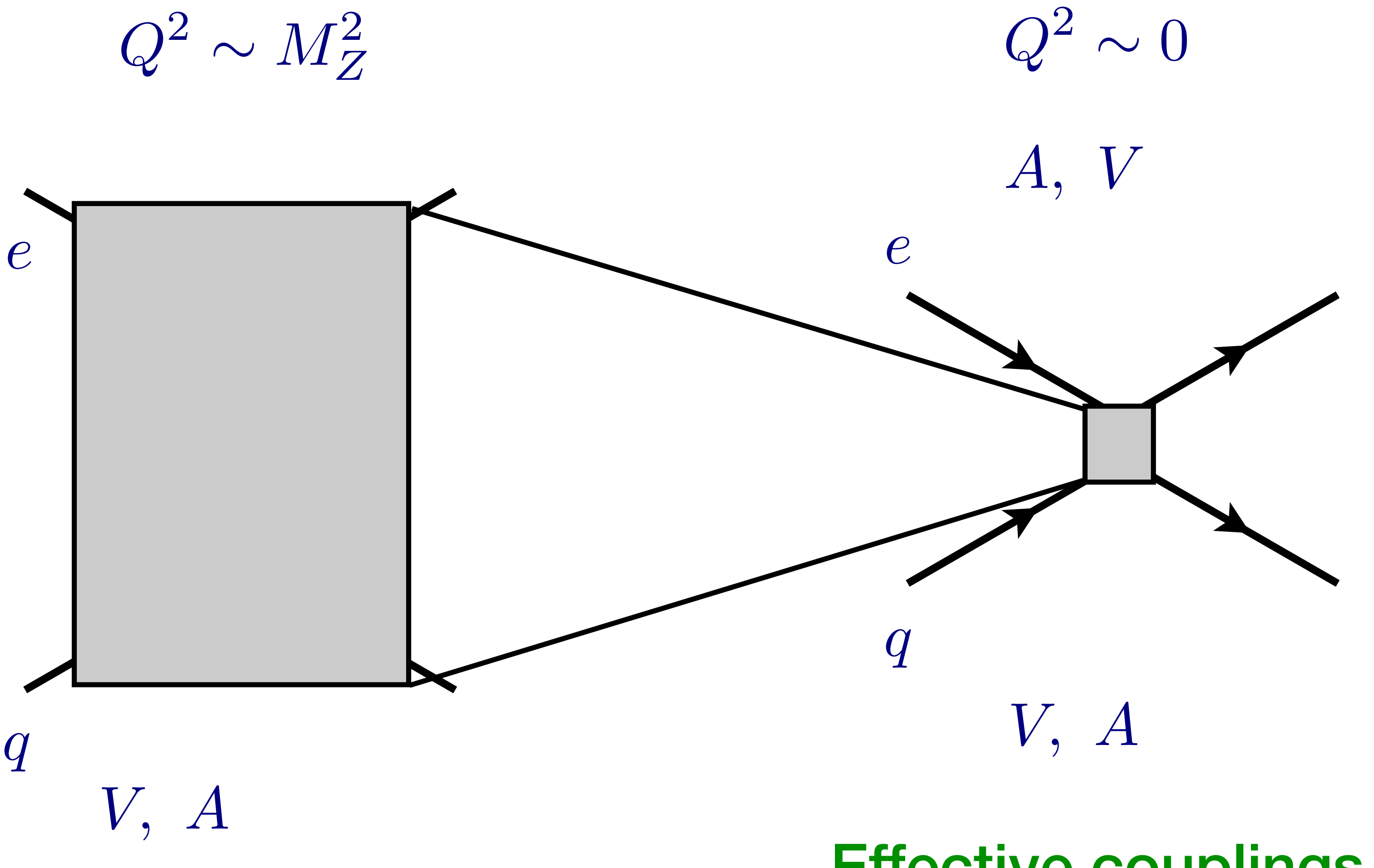


Effective couplings

$C_{1q},\ C_{2q}$

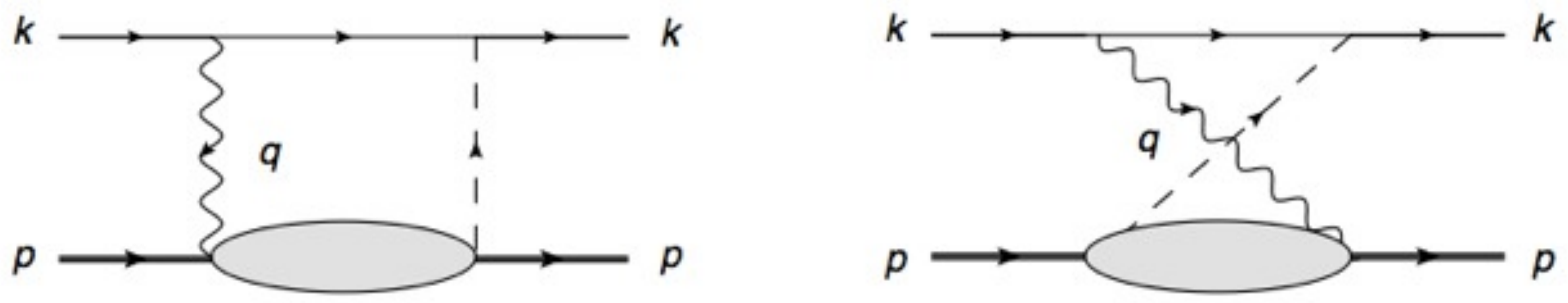
Radiative corrections

- Absorb electron coupling; and full evolution down to low scale

$$g_A^e G_{Ep}^Z = -2(2C_{1u} + C_{1d})G_{Ep}^\gamma - 2(C_{1u} + 2C_{1d})G_{En}^\gamma + \xi_V^{(0)} G_E^s$$

Radiative corrections: γZ box

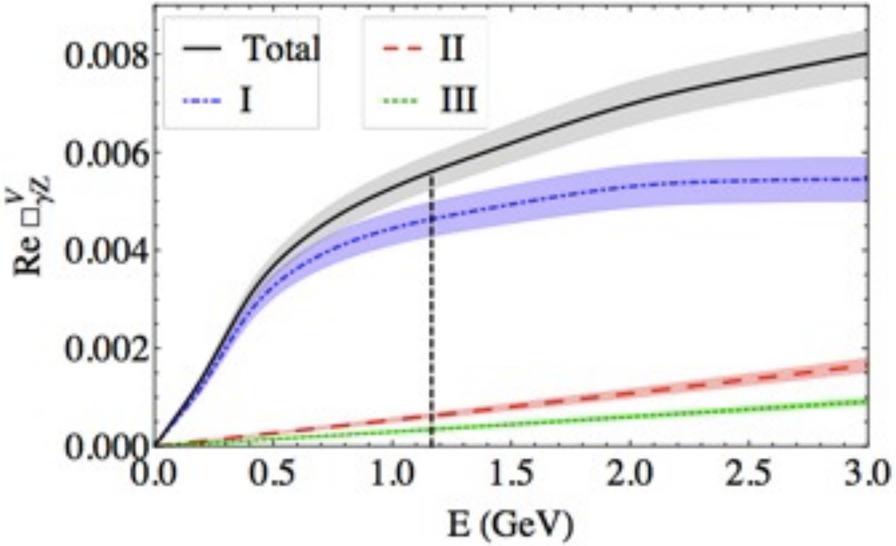
- Significant **energy-dependent** correction from inelastic hadronic states identified by Gorchtein & Horowitz PRL(2009)



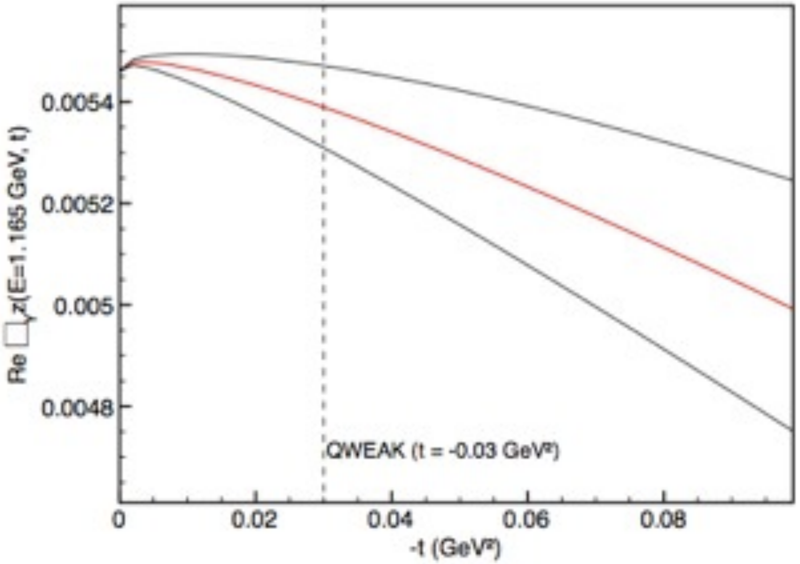
- Forward scattering limit evaluated through dispersion relation

Radiative corrections: γZ box

- Energy dependence: Hall, Melnitchouk *et al.* (AJM Model), PRD(2013)



- Q^2-dependence: Gorchtein *et al*. (GHRM), PRC(2011)



Radiative corrections: γZ box

- Also used for large-angle results!!
  - dispersive treatment breaks down
- *For now*: all data points >20 degrees
  - Use same calculation, but assign 100% uncertainty
    - Current analysis $\Delta Q_W^p \lesssim \pm 0.0006$
    - cf. $\Delta Q_W^p \sim \pm 0.012$

Proton asymmetry

- Full expression

$$\overline{A^p_{LR}} = \frac{A^p_{LR}}{A_0} = \frac{g^e_A \left(\epsilon G^\gamma_{Ep} G^Z_{Ep} + \tau G^\gamma_{Mp} G^Z_{Mp}\right) + g^e_V \epsilon' G^\gamma_{Mp} \widetilde{G}_{Ap}}{\epsilon (G^\gamma_{Ep})^2 + \tau (G^\gamma_{Mp})^2}$$

axial + anapole form factor

- Forward angles $\epsilon' \sim 0$
- Significant nonperturbative radiative corrections
  - For those familiar:

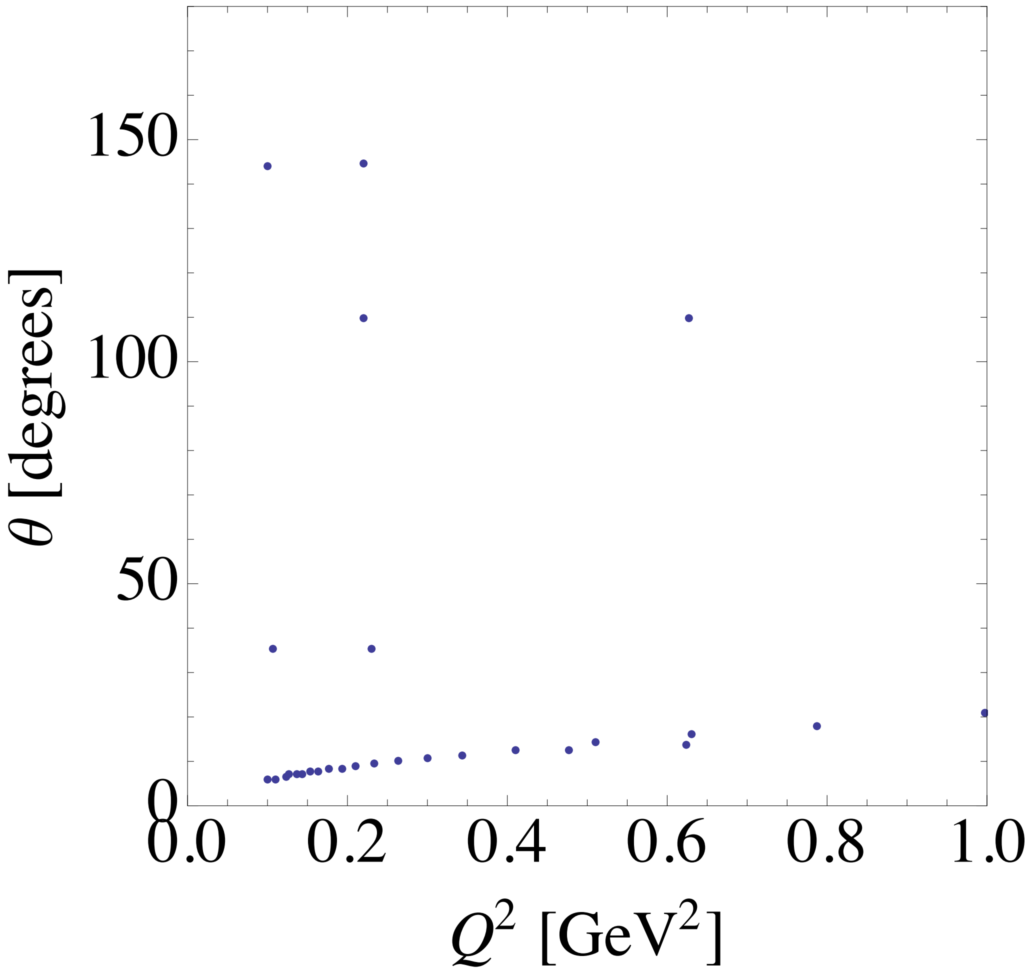
$$\widetilde{G}^{T=1}_A \ : \ \text{dipole form (1 GeV), normalisation } \textit{fit} \text{ to data}$$

$$\widetilde{G}^{T=0}_A \ : \ \text{dipole form (1 GeV), normalisation } \textit{constrained} \text{ to theory}$$

based upon **Zhu et al. PRD(2000)**

Proton asymmetry measurements

- Kinematic coverage



- Note also, He-4 and Deuteron measurements also included in data ensemble

Proton asymmetry measurements

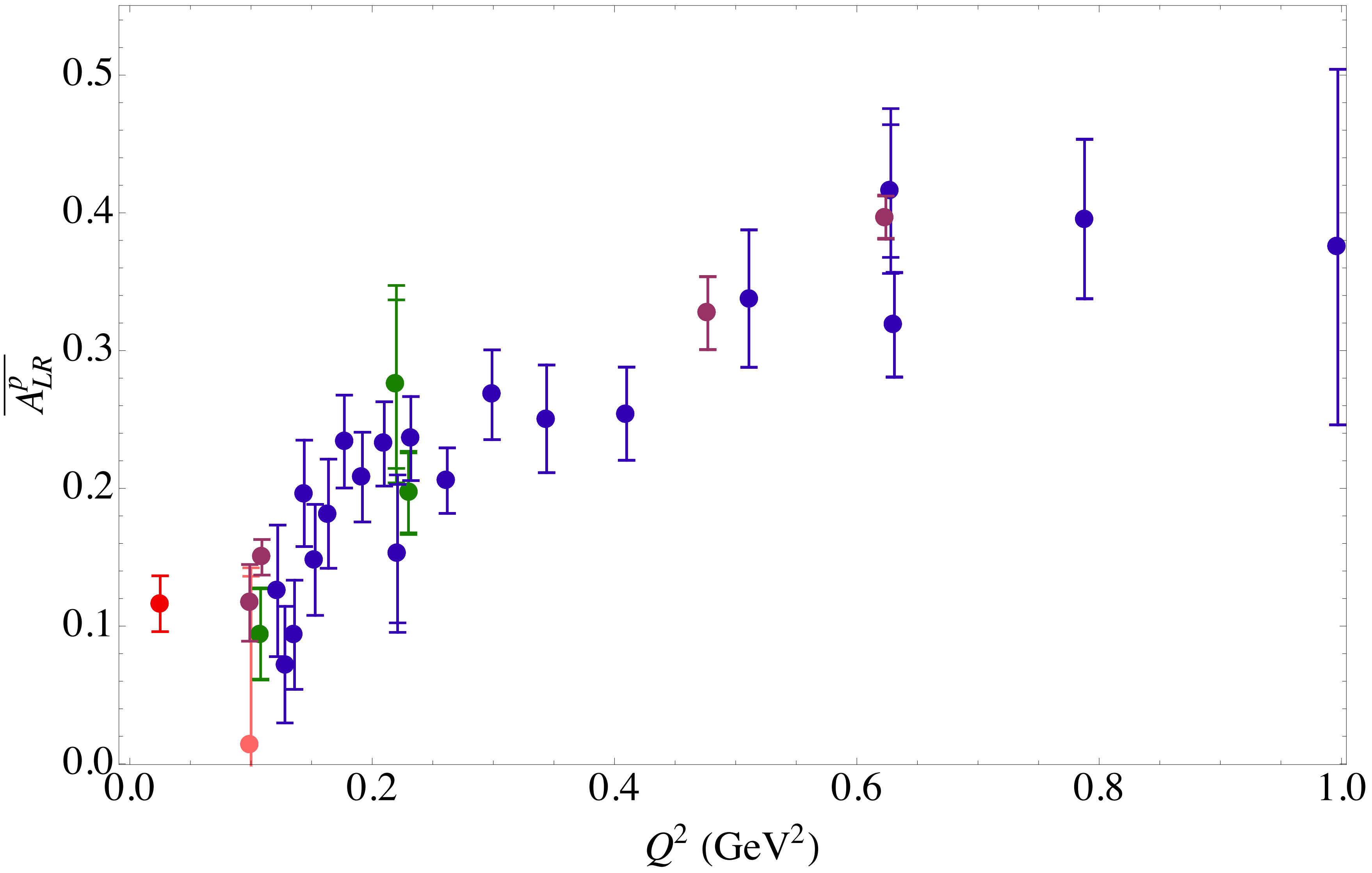
- Even for proton alone, very hard to represent points on a single plot
  - I’ve not shown any fits yet; but let’s look at all points projected onto

$$\epsilon \to 1 \quad (\text{or } \theta \to 0)$$

$$\overline{A^p_{LR}}^{data}(\theta = 0, Q^2) = \overline{A^p_{LR}}^{data}(\theta^{data}, Q^2) - \left[\overline{A^p_{LR}}^{fit}(\theta^{data}, Q^2) - \overline{A^p_{LR}}^{fit}(\theta = 0, Q^2)\right]$$

Proton asymmetry measurements

- Forward scattering projection



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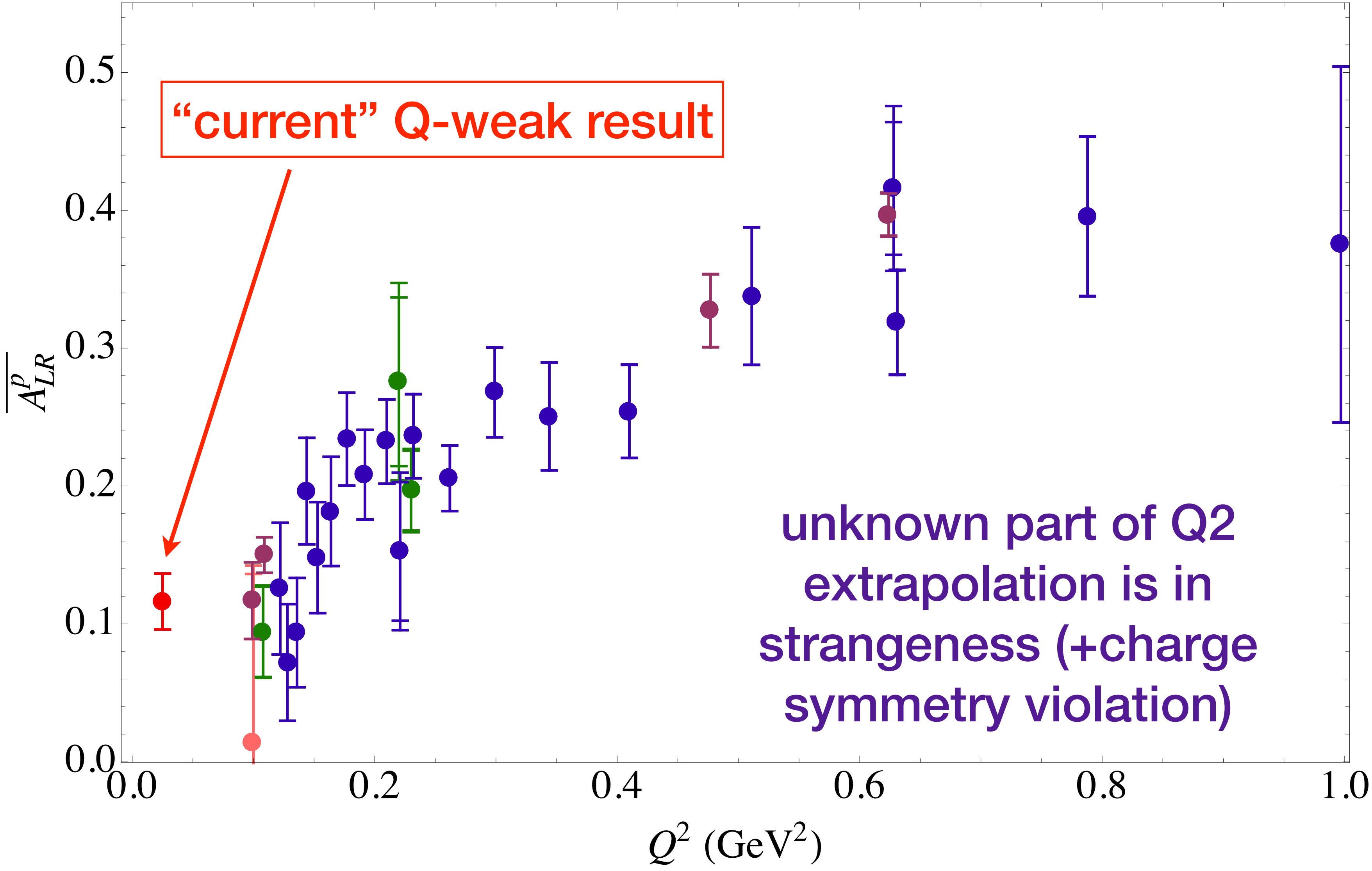

"current" Q-weak result

unknown part of Q2 extrapolation is in strangeness (+charge symmetry violation)

Strangeness parameterisation

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- Taylor expansion

$$G_E^s = \rho^s Q^2 + \rho_2^s Q^4 + \dots$$

$$G_M^s = \mu^s + \mu_2^s Q^2 + \dots$$

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“leading-order polynomial”

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“leading-order polynomial”

“second-order polynomial”

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$$

“leading-order polynomial”

“second-order polynomial”

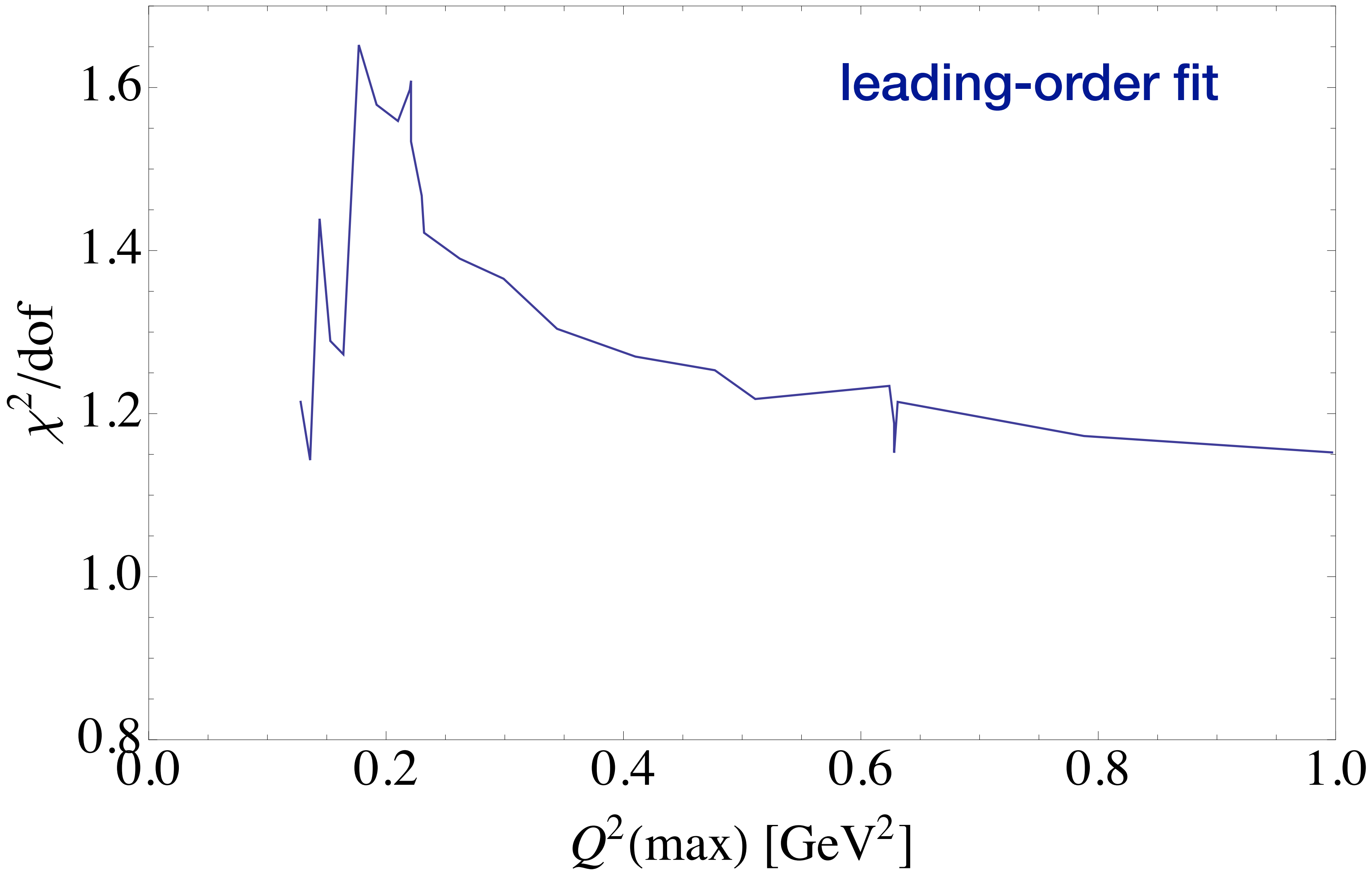
- OR I’ll talk about a “dipole” form

$$G_E^s = \rho^s Q^2 \left(\frac{1}{1 + Q^2/\Lambda^2} \right)^2$$

$$G_M^s = \mu^s \left(\frac{1}{1 + Q^2/\Lambda^2} \right)^2$$

Fits to full data ensemble (truncated in Q^2)

- Taylor expansions



Fits to full data ensemble (truncated in Q^2)

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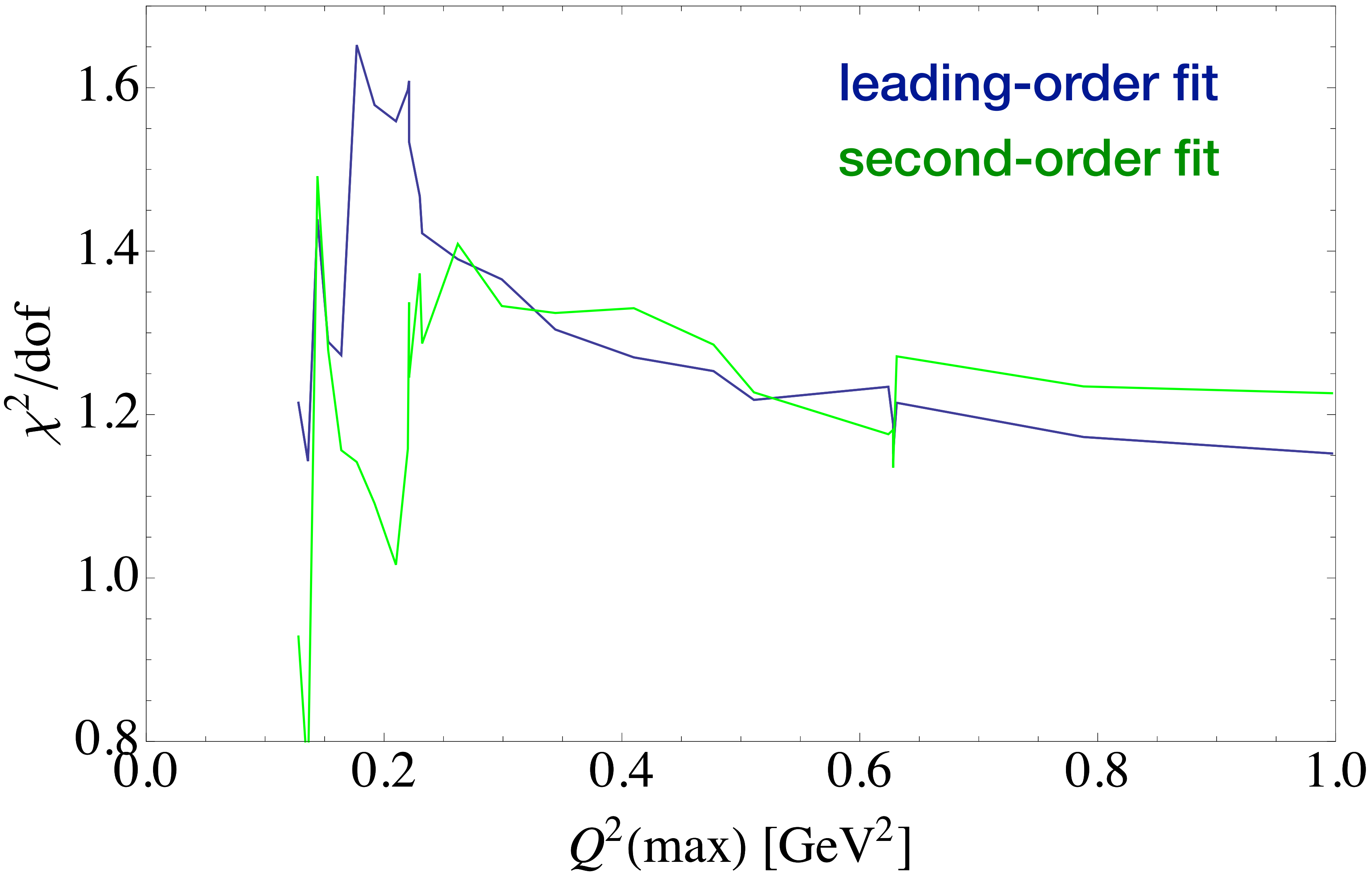

Fits to full data ensemble (truncated in Q^2)

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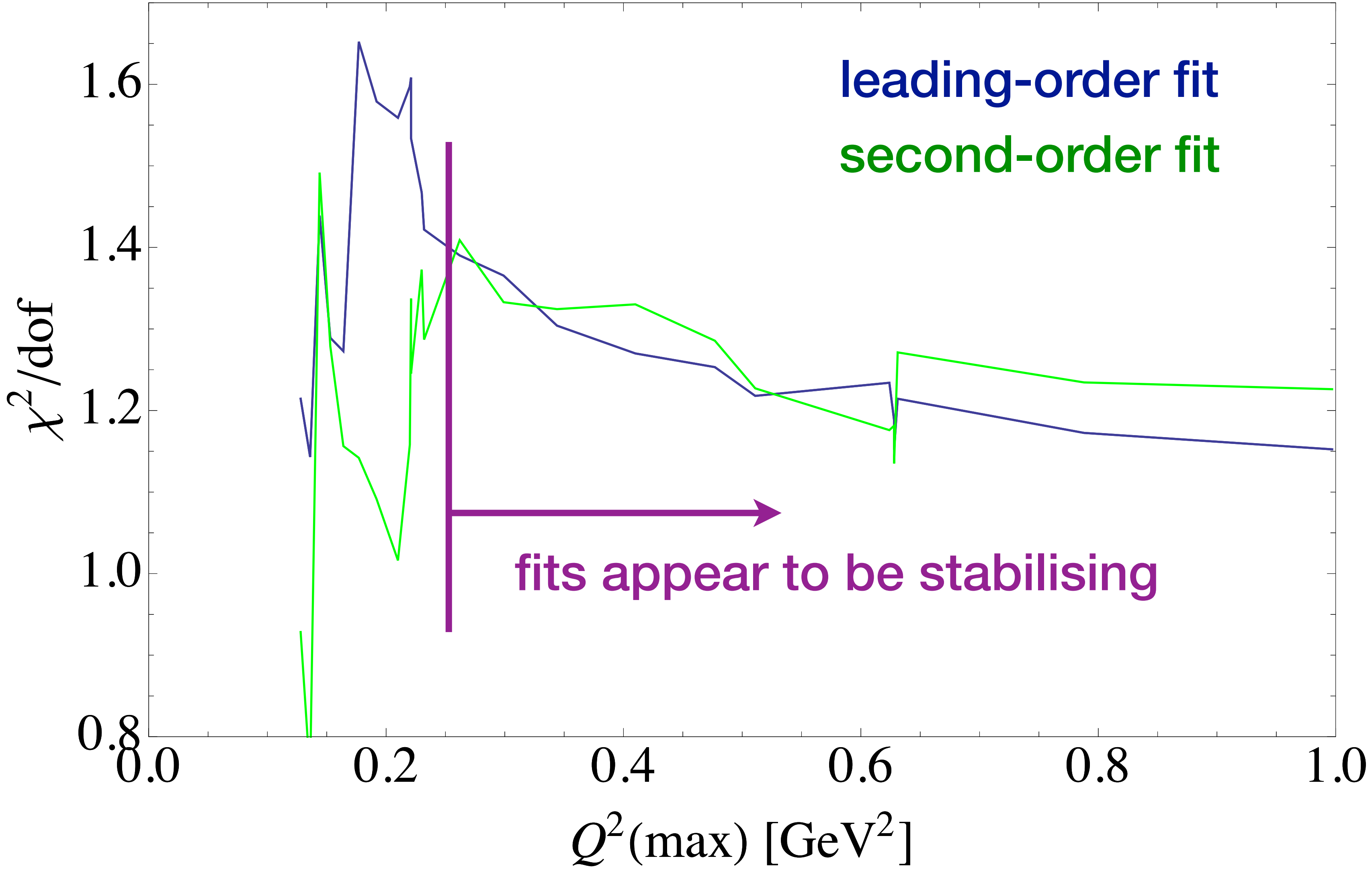
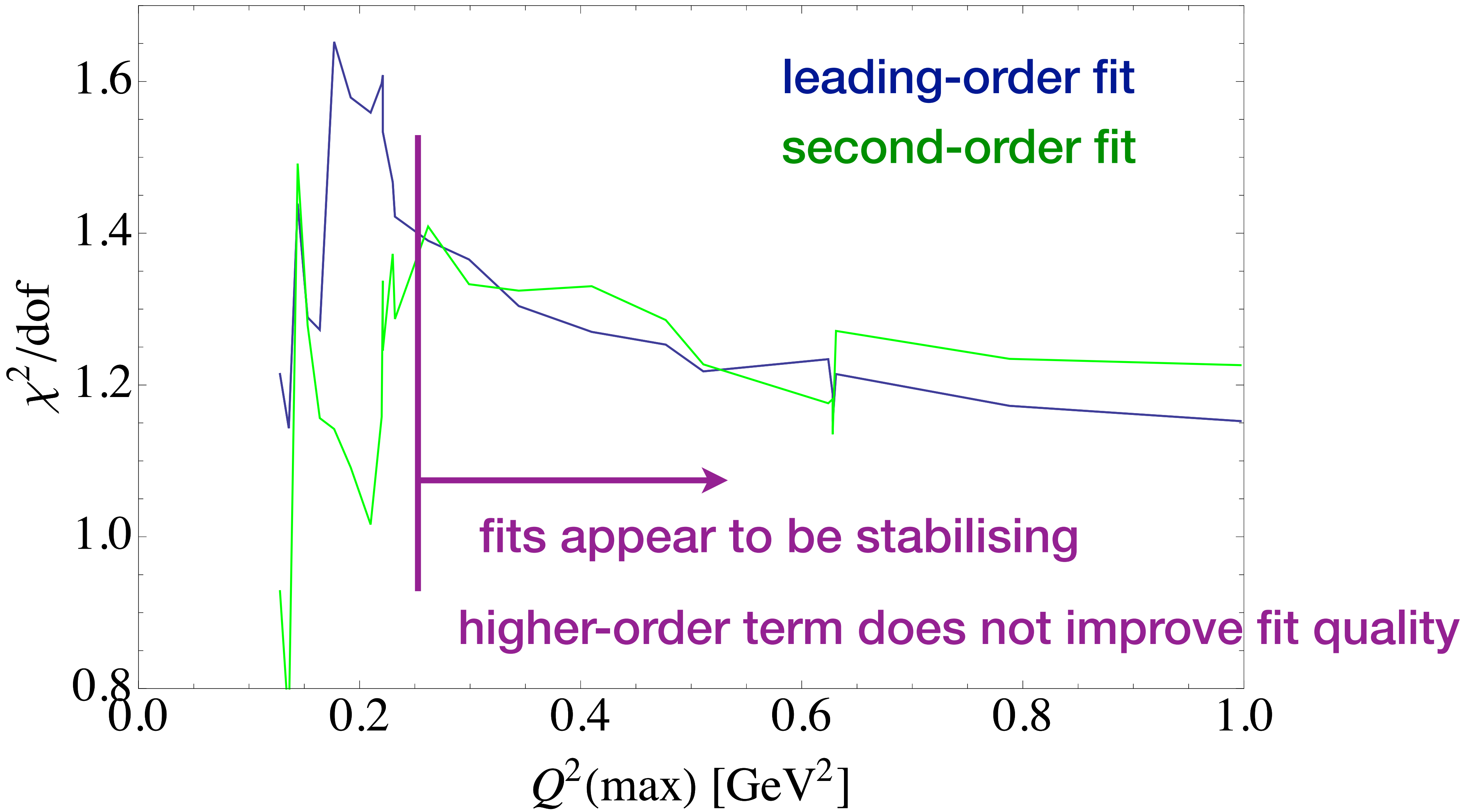


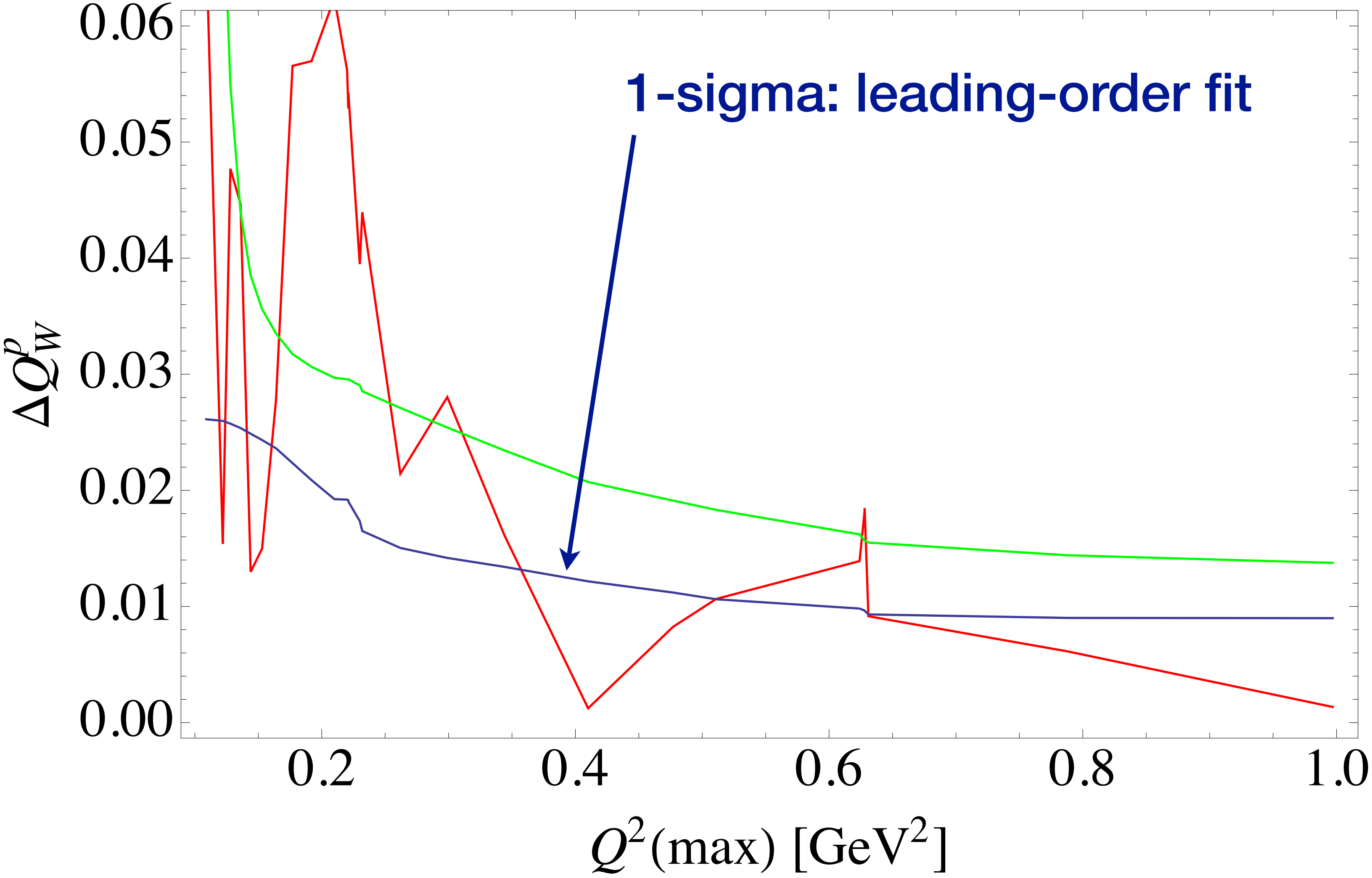
Fits to full data ensemble (truncated in Q^2)

- Taylor expansions



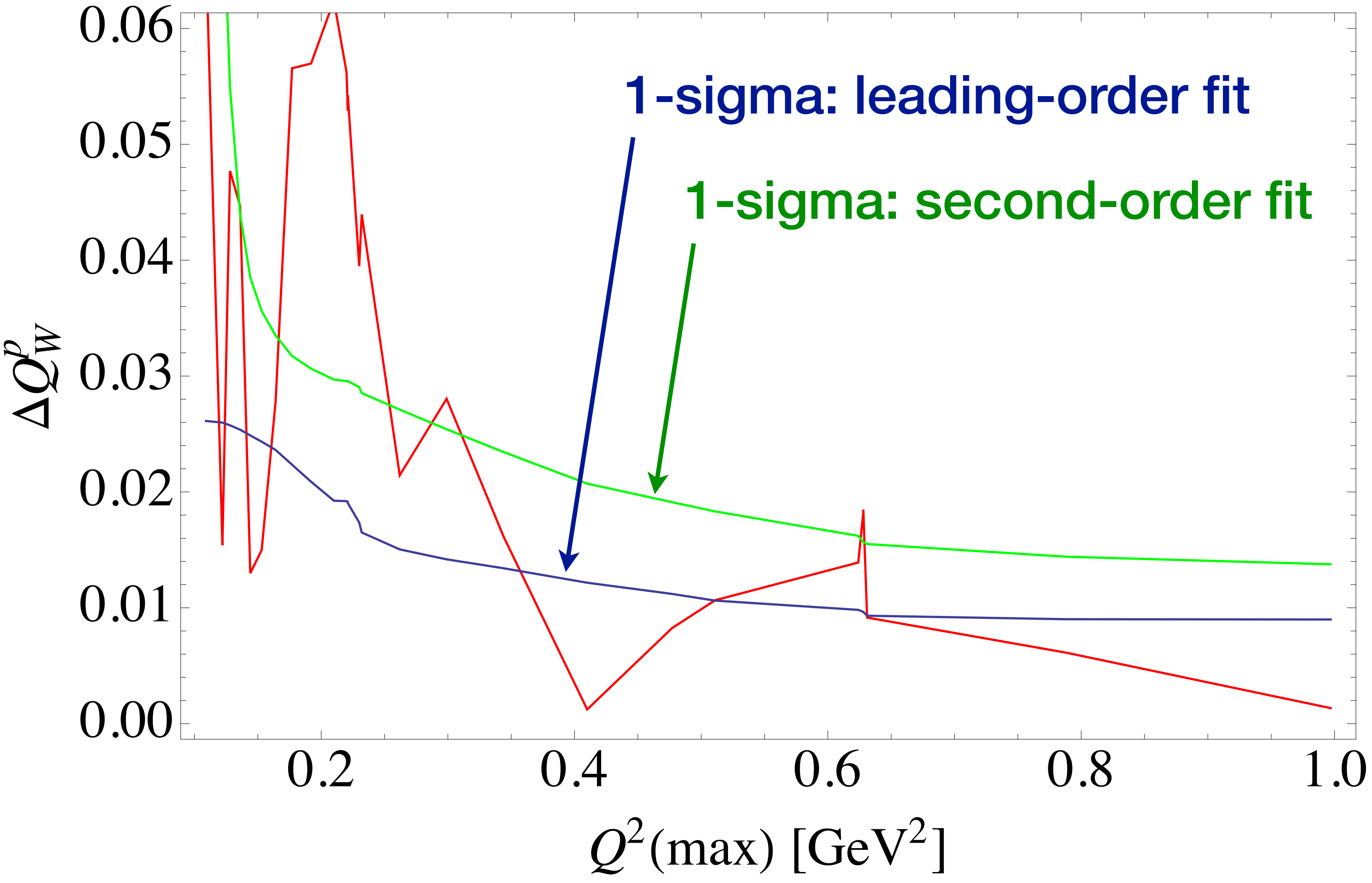
Q-weak precision

- Taylor expansions



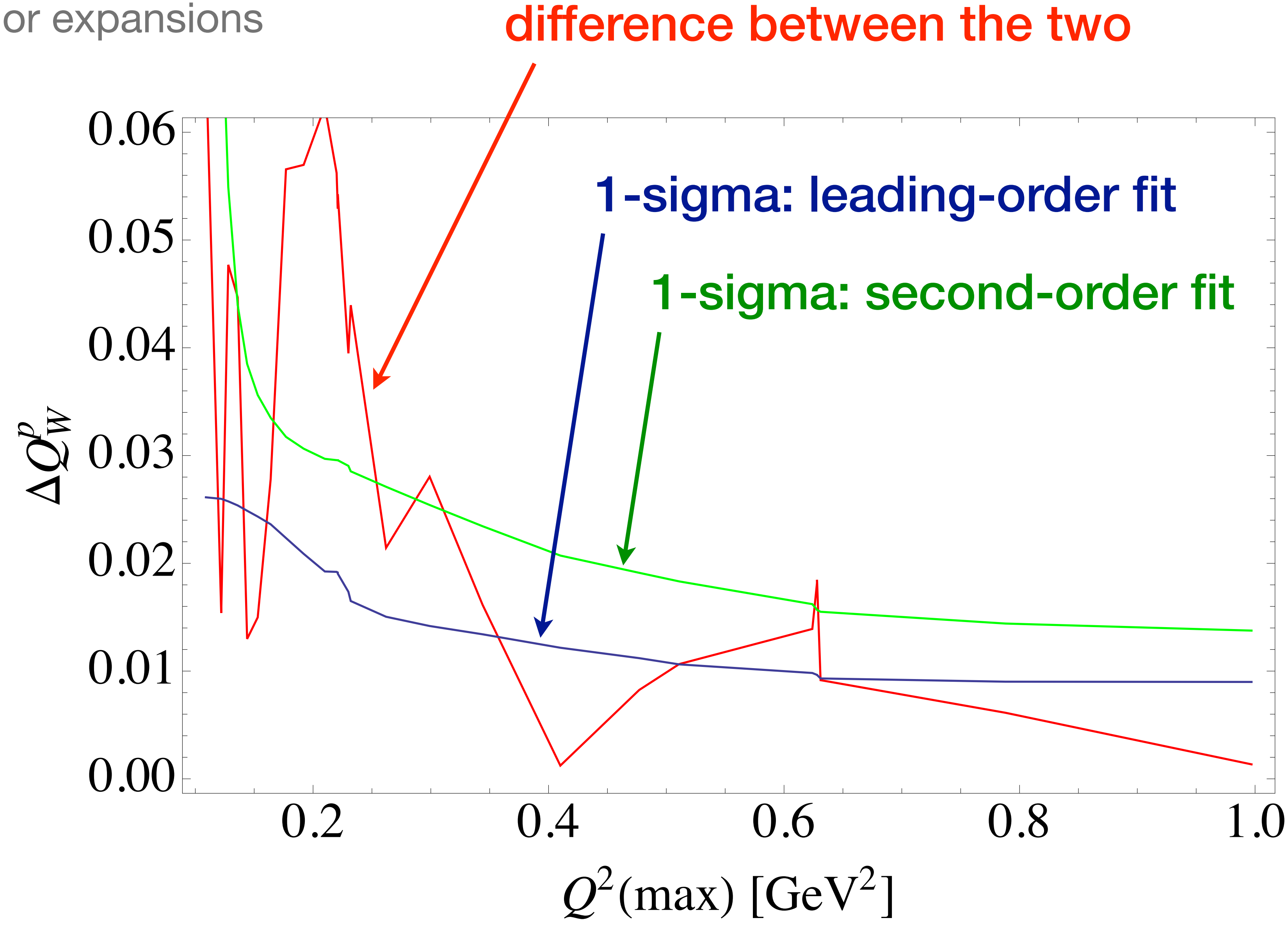
Q-weak precision

- Taylor expansions

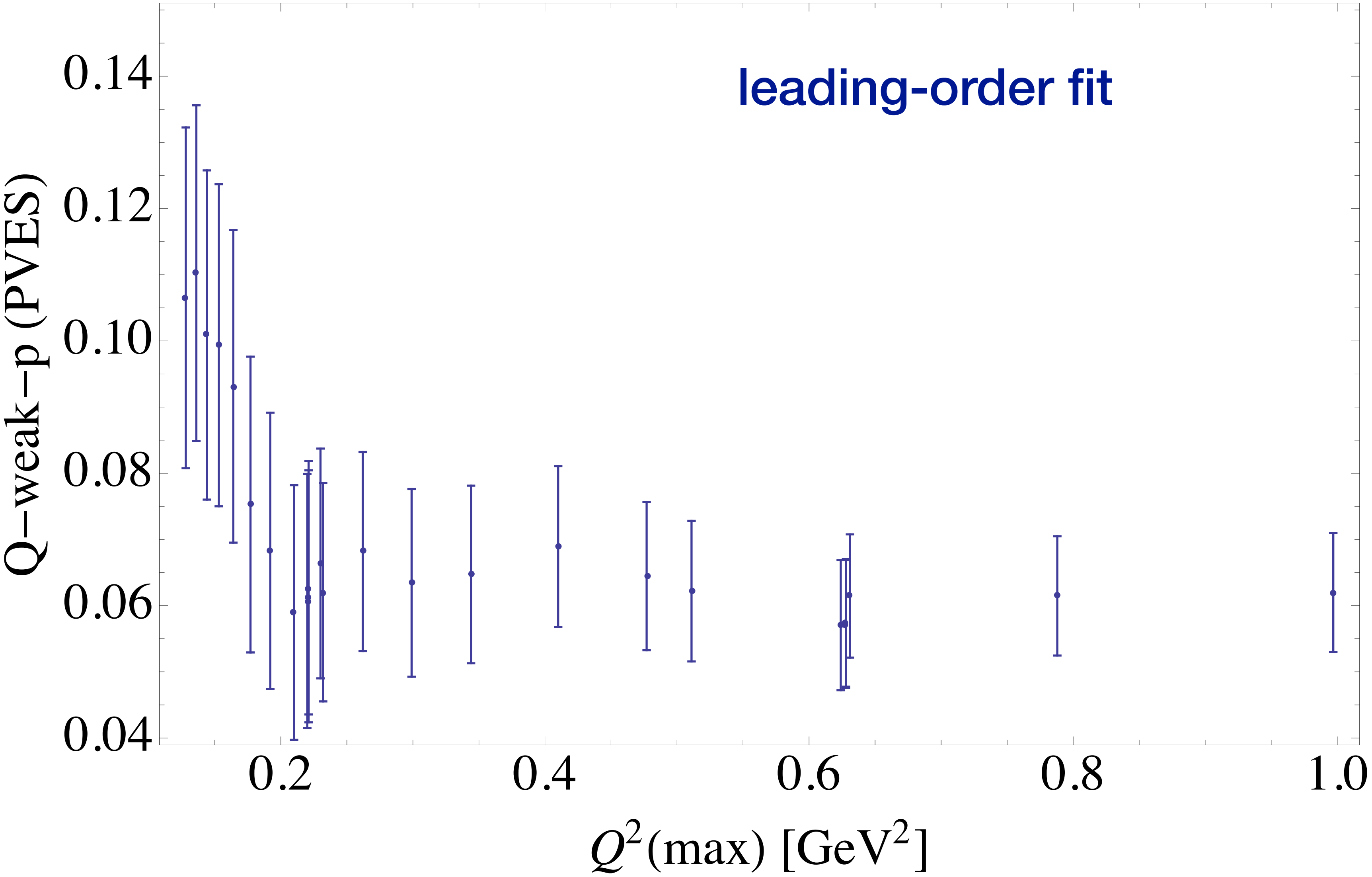


Q-weak precision

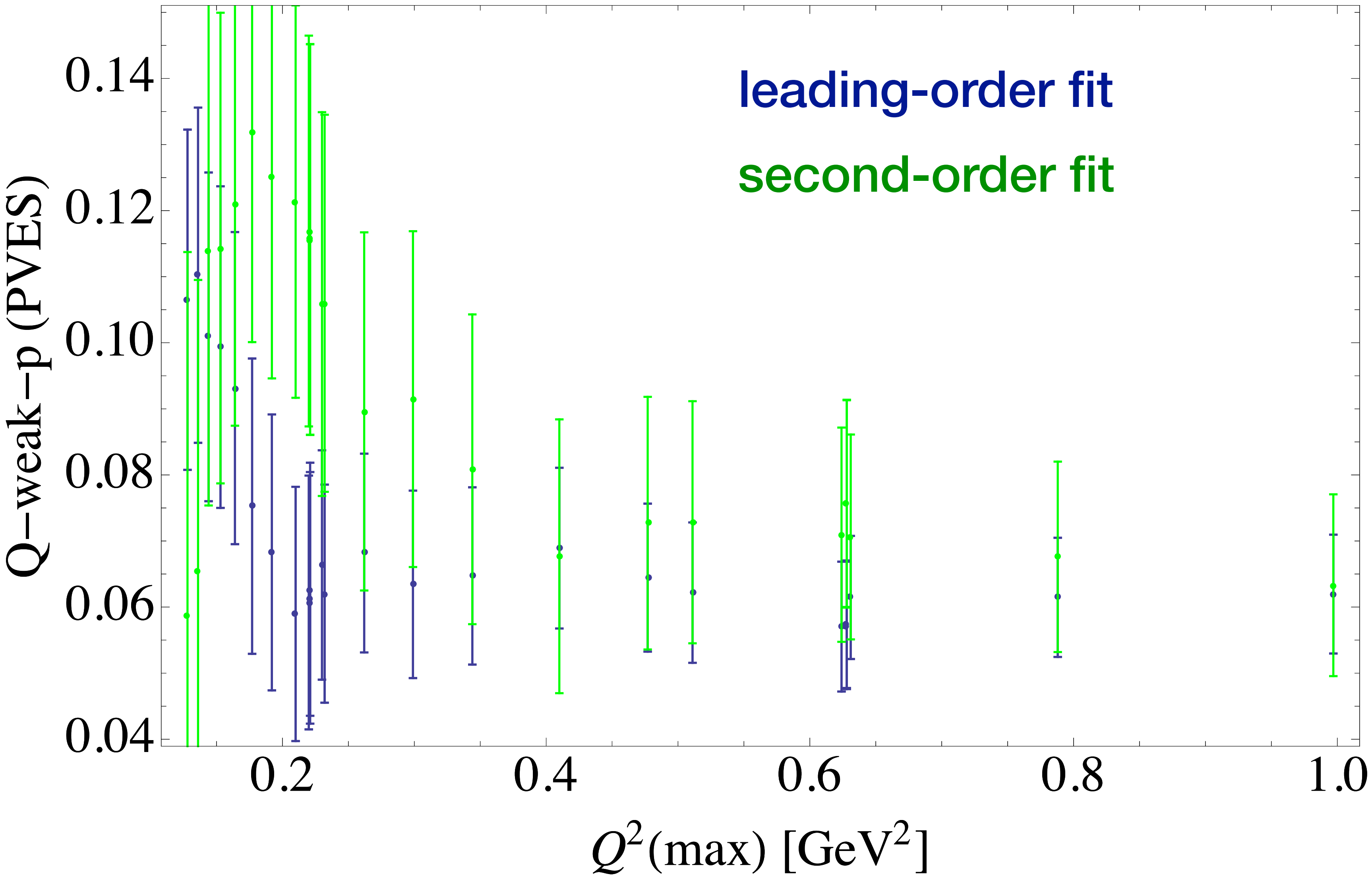
- Taylor expansions



Q-weak determination



Q-weak determination



Just leading order?

- **You might be nervous about using the leading Taylor expansion over such a wide range**

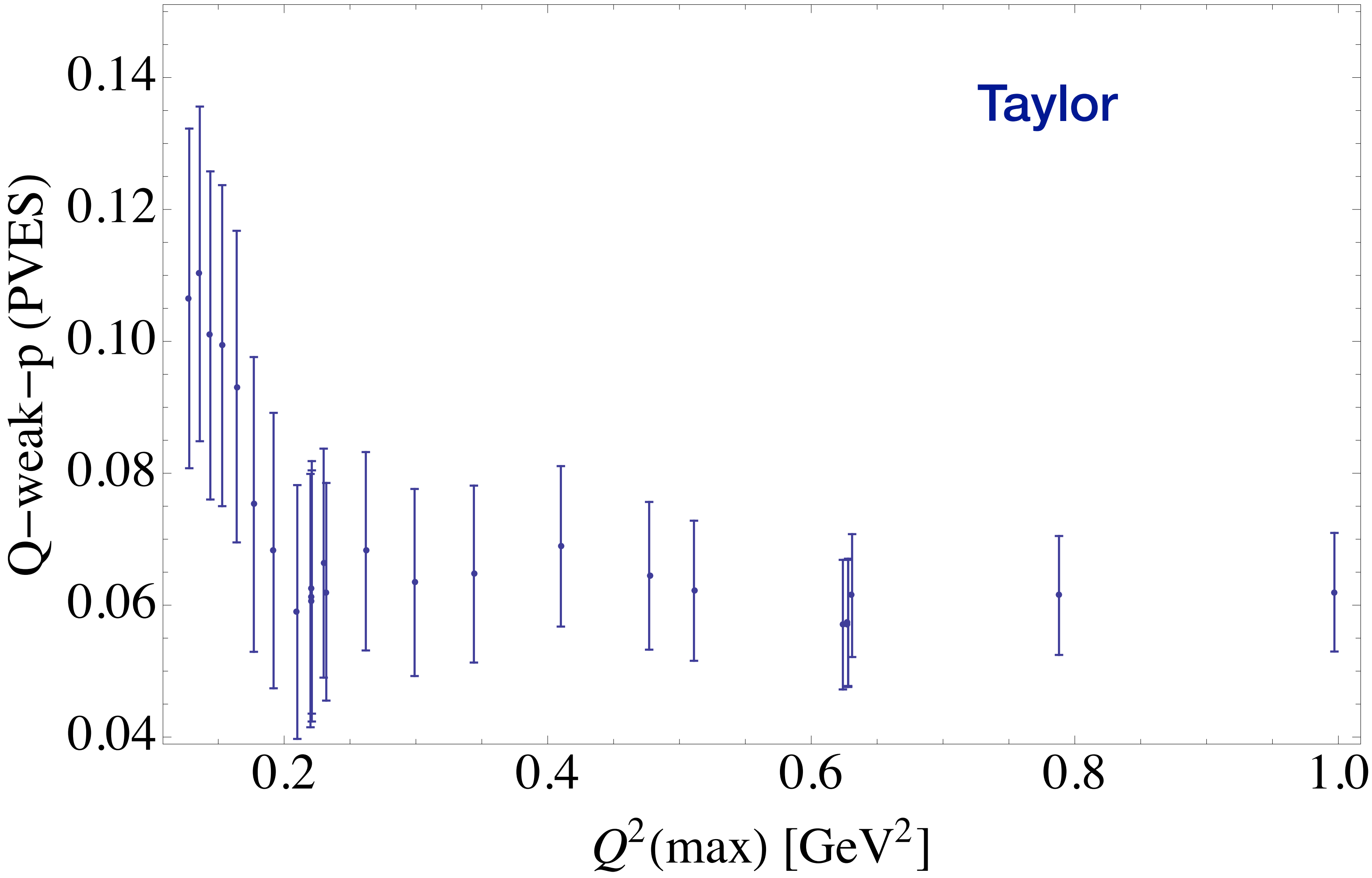
- What about dipole-type forms?
    - Physically, strangeness would have a characteristic mass scale set by the phi meson

$$\Lambda^2 \sim 1\,\mathrm{GeV}^2$$

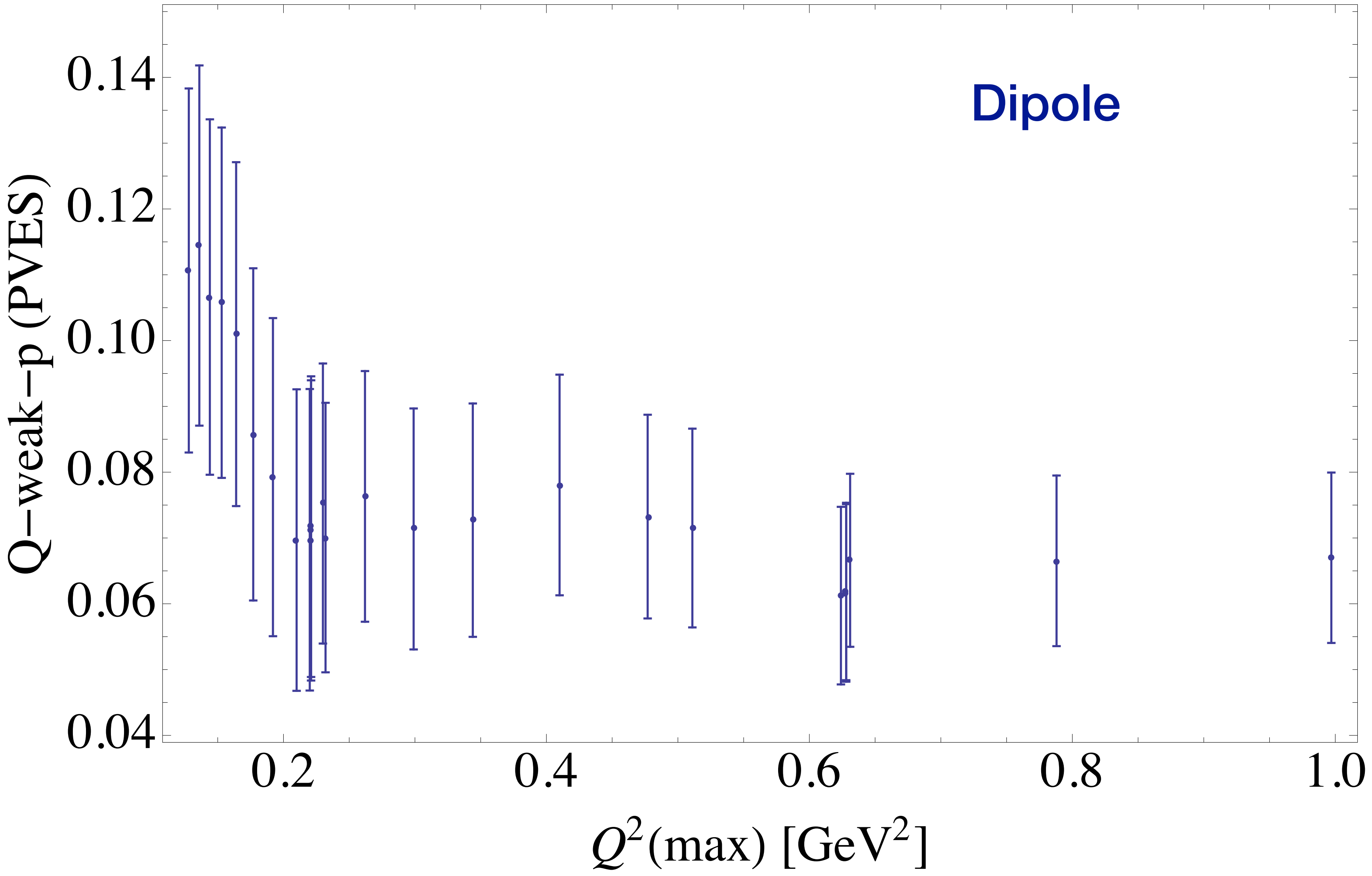
    - But a more extreme limit would be “light-quark” mass

$$\Lambda^2 \sim 0.71\,\mathrm{GeV}^2$$

Dipole form $\Lambda^2 \sim 0.71\,\mathrm{GeV}^2$



Dipole form $\Lambda^2 \sim 0.71\,\mathrm{GeV}^2$



Let’s see what we get for the fit

- Take 1 GeV Lambda as a “central” value

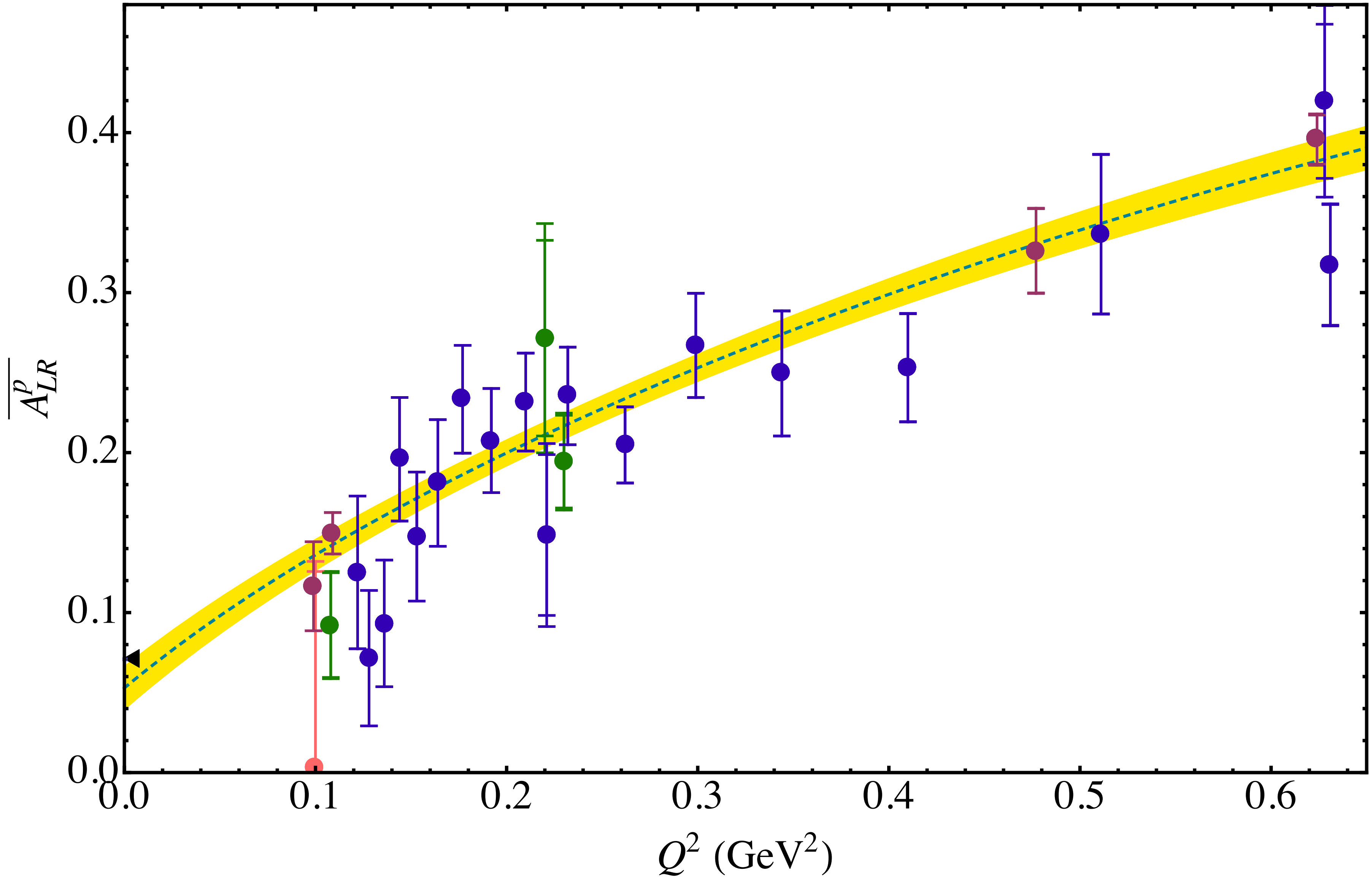
$$0.71\,\mathrm{GeV}^2 < \Lambda^2 = 1\,\mathrm{GeV}^2 < \infty$$

light-quark radii **Taylor expansion**

  - Difference between bounds gives model-dependence uncertainty
- And let’s be ambitious and use all data up to $Q^2 \sim 0.63\,\mathrm{GeV}^2$

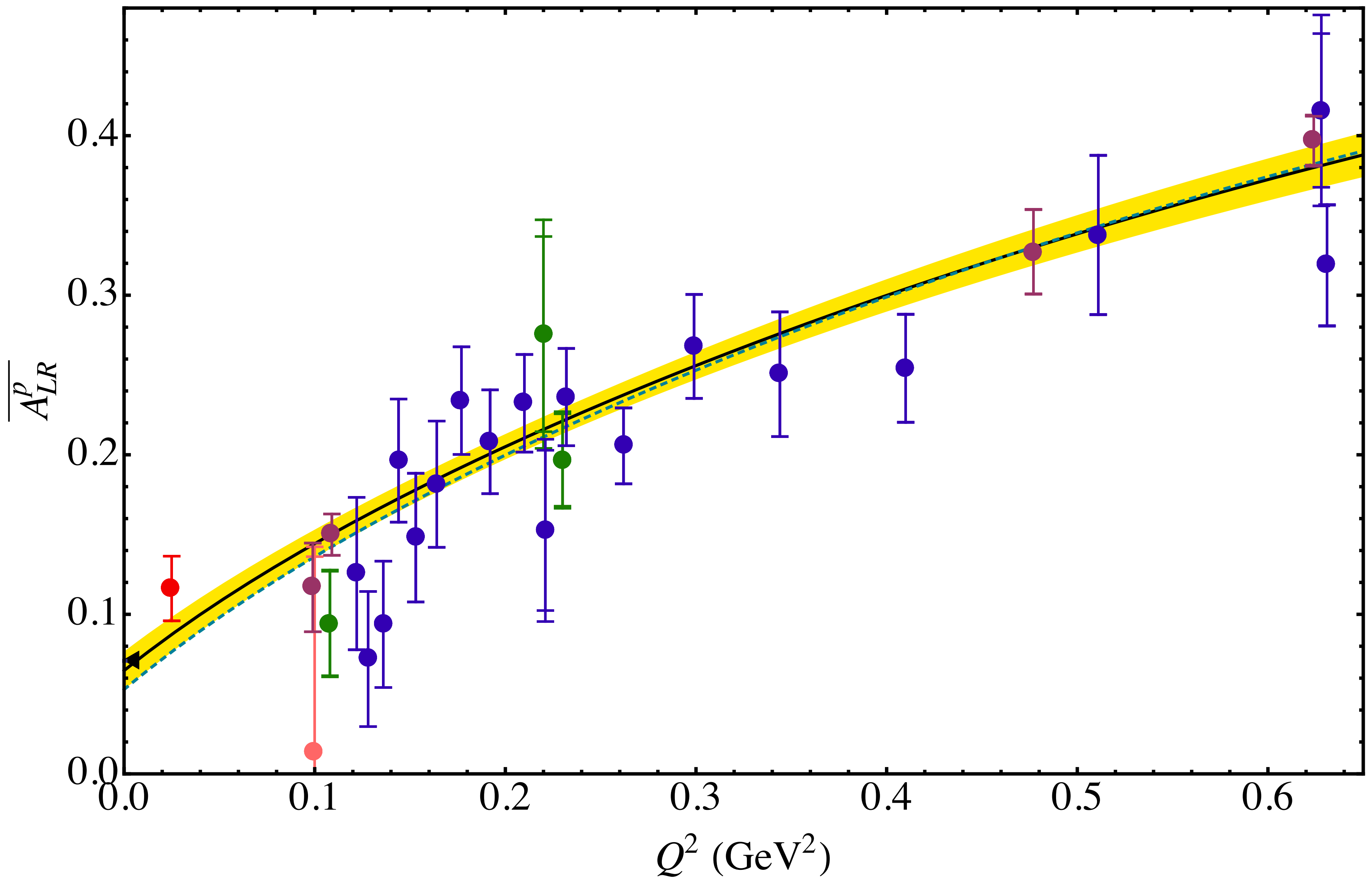
“B-term” plot

- Without Q-weak



“B-term” plot

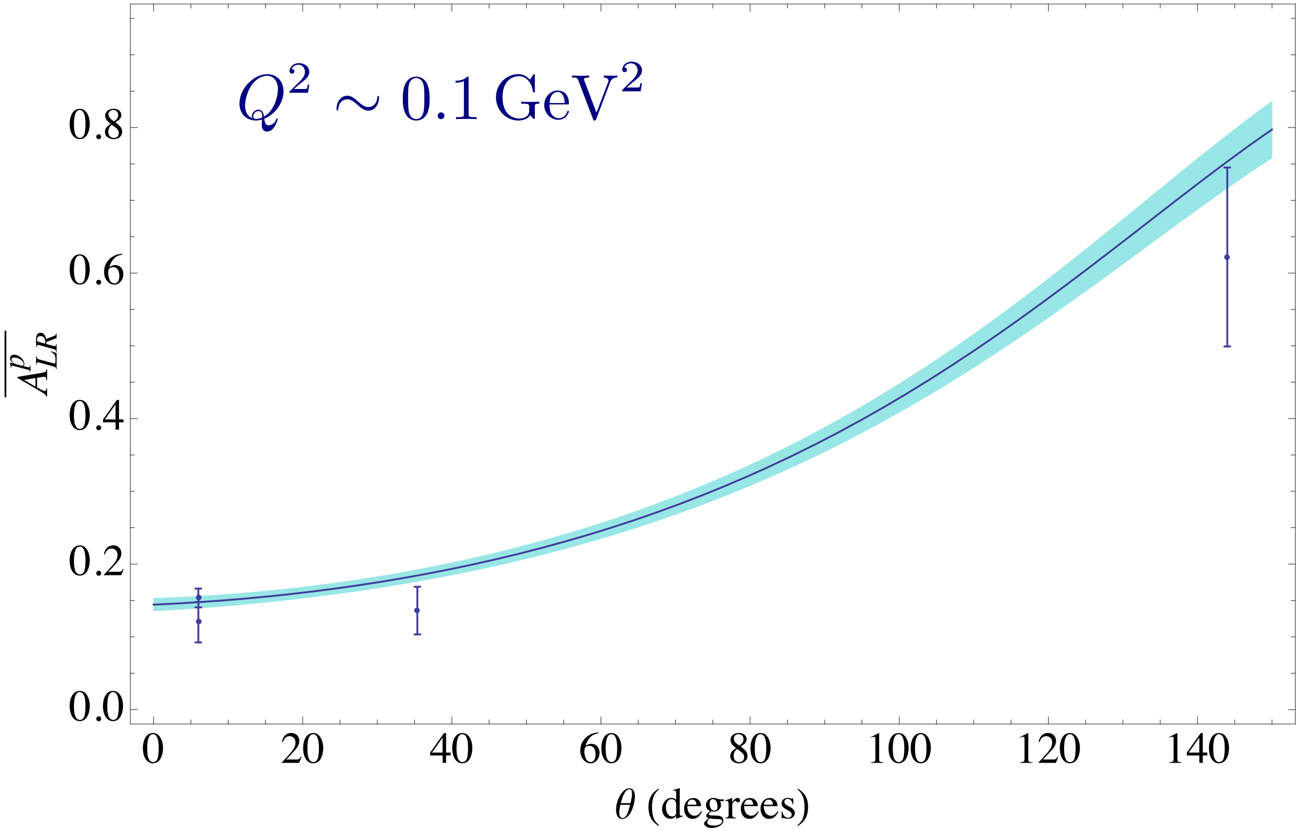
- WITH Q-weak



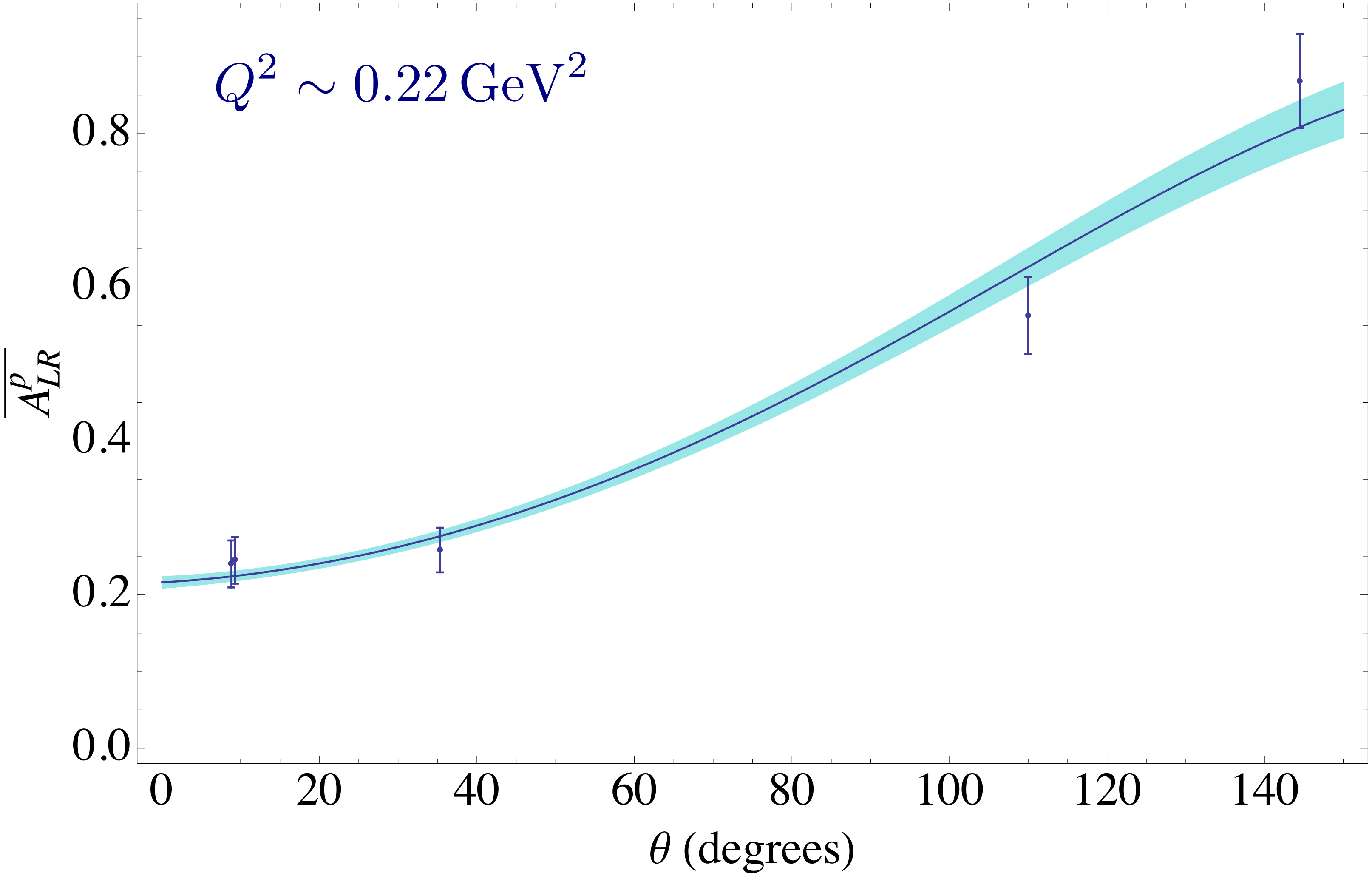
Forward rotation

- Shifted data points

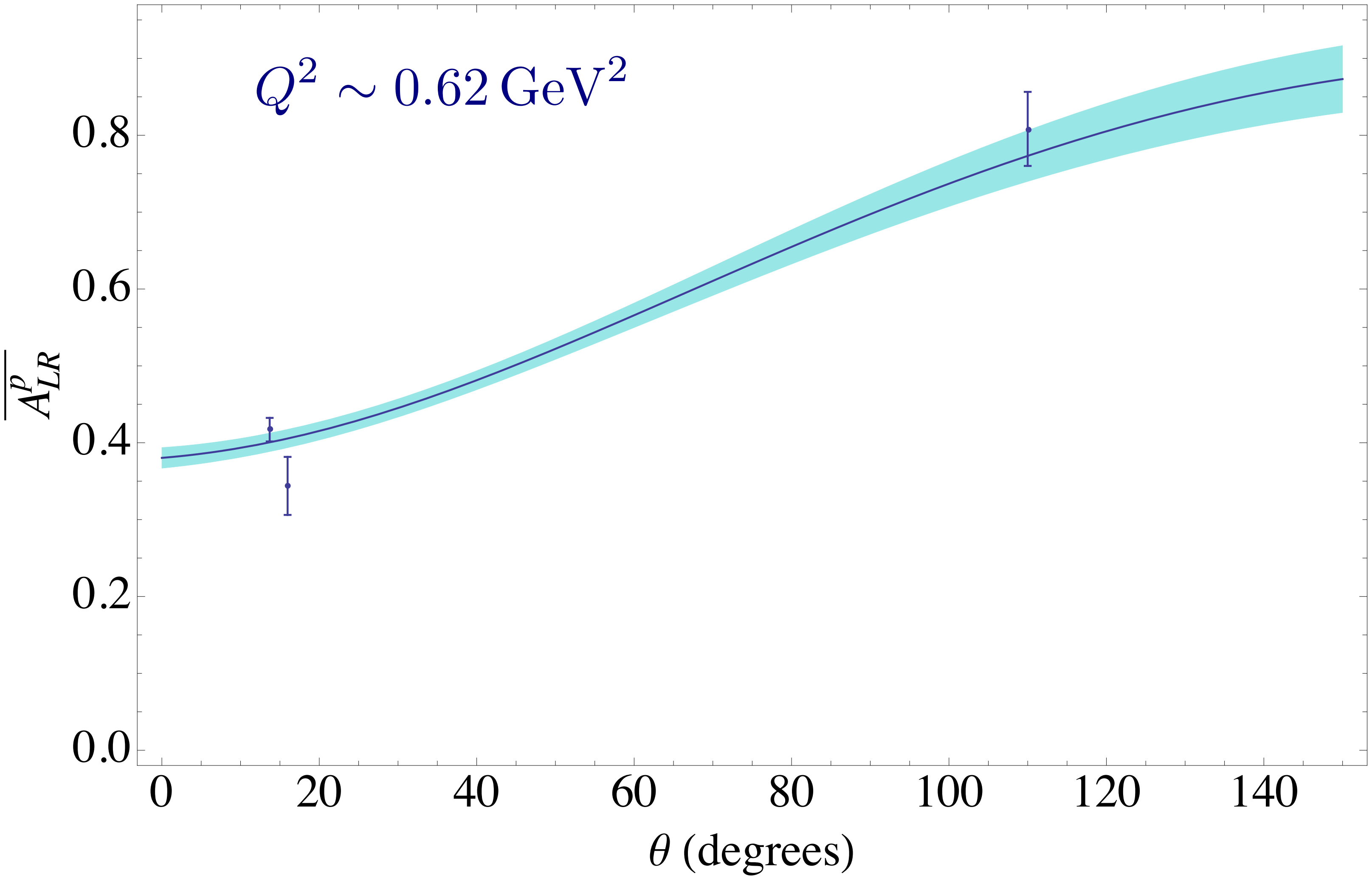
$$\overline{A^p_{LR}}^{data}(\theta = 0, Q^2) = \overline{A^p_{LR}}^{data}(\theta^{data}, Q^2) - \left[\overline{A^p_{LR}}^{fit}(\theta^{data}, Q^2) - \overline{A^p_{LR}}^{fit}(\theta = 0, Q^2)\right]$$



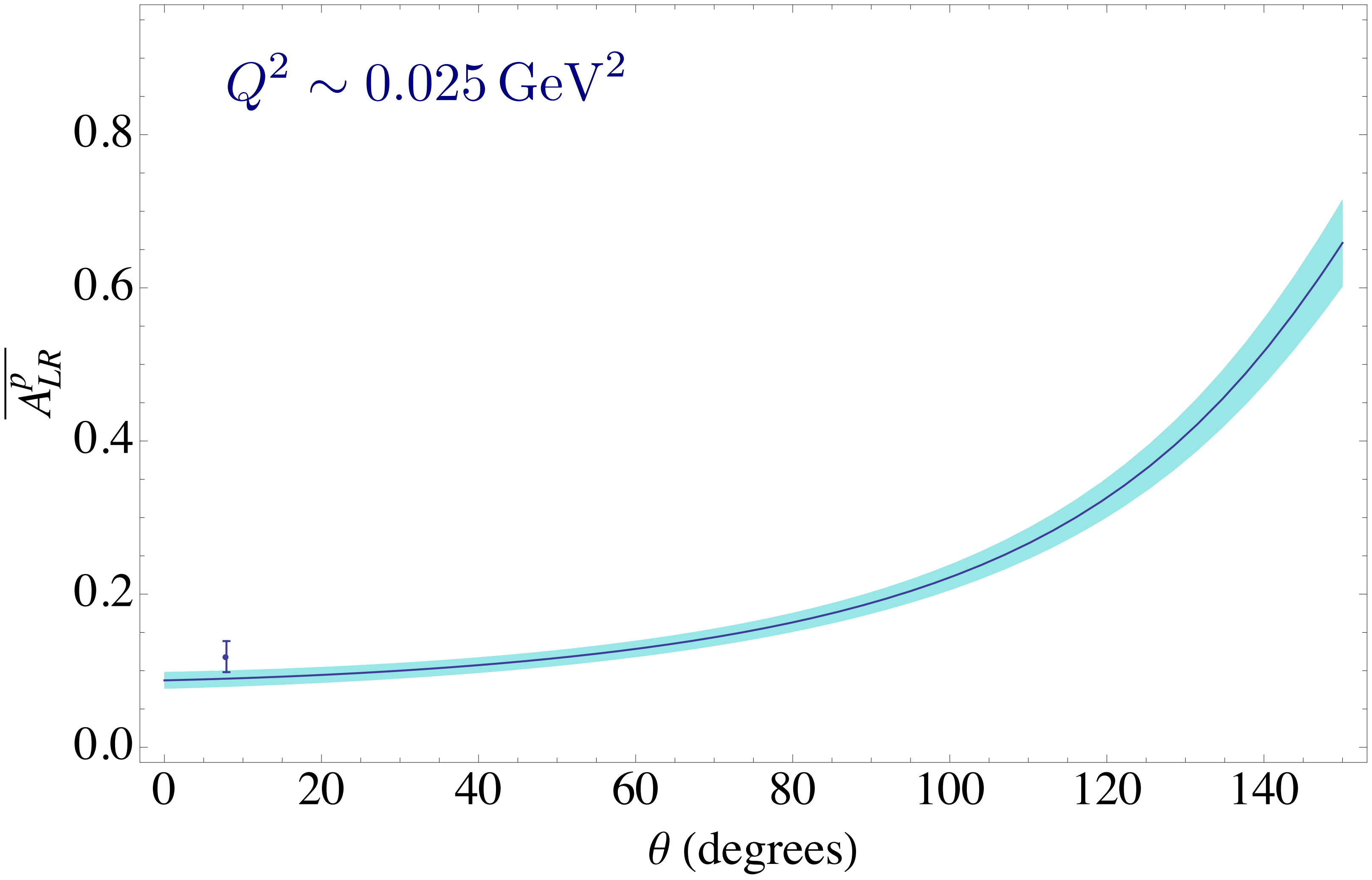
Forward rotation



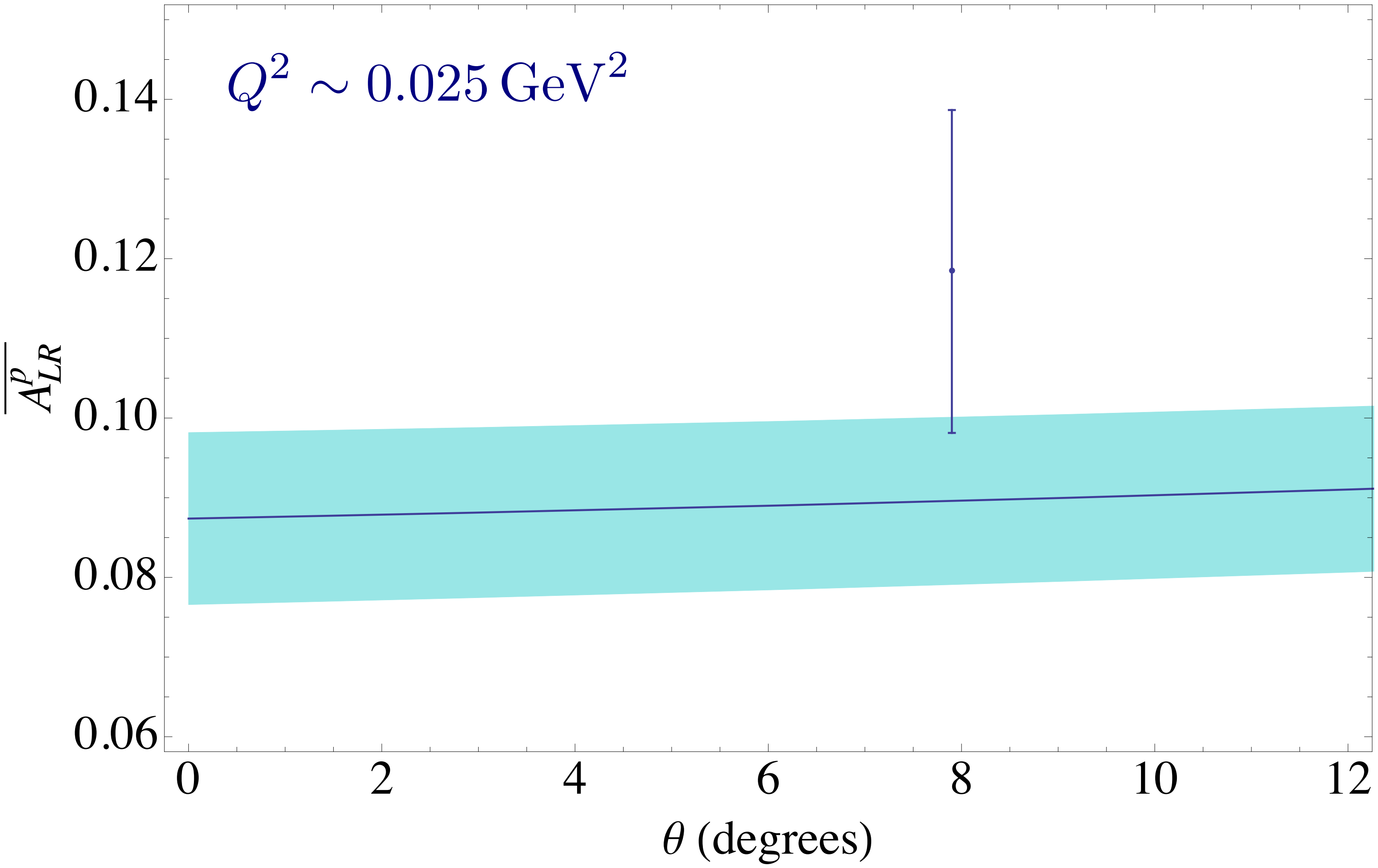
Forward rotation



Forward rotation - Q-weak

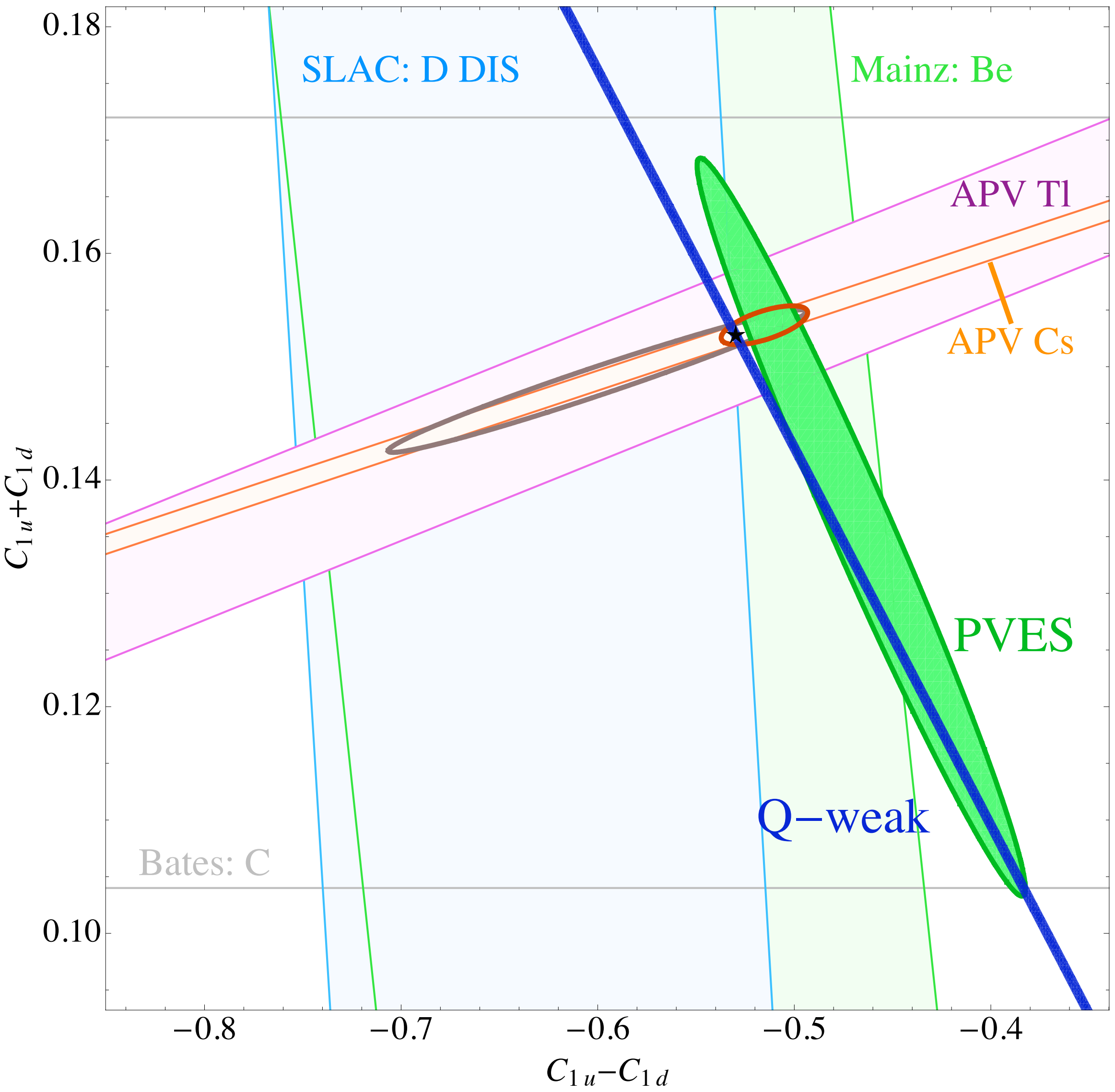


Forward rotation - Q-weak - close-up

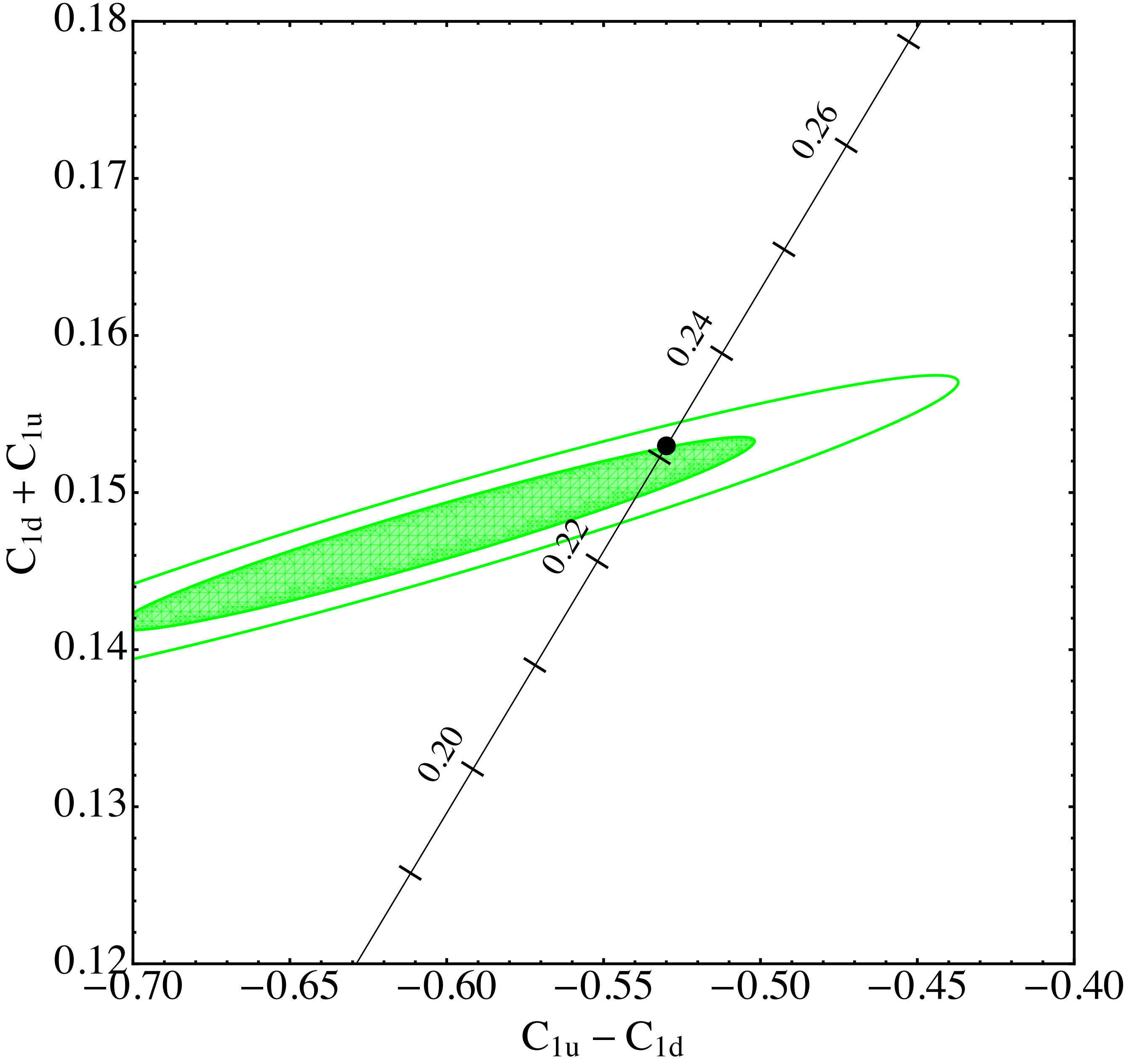


Weak charges

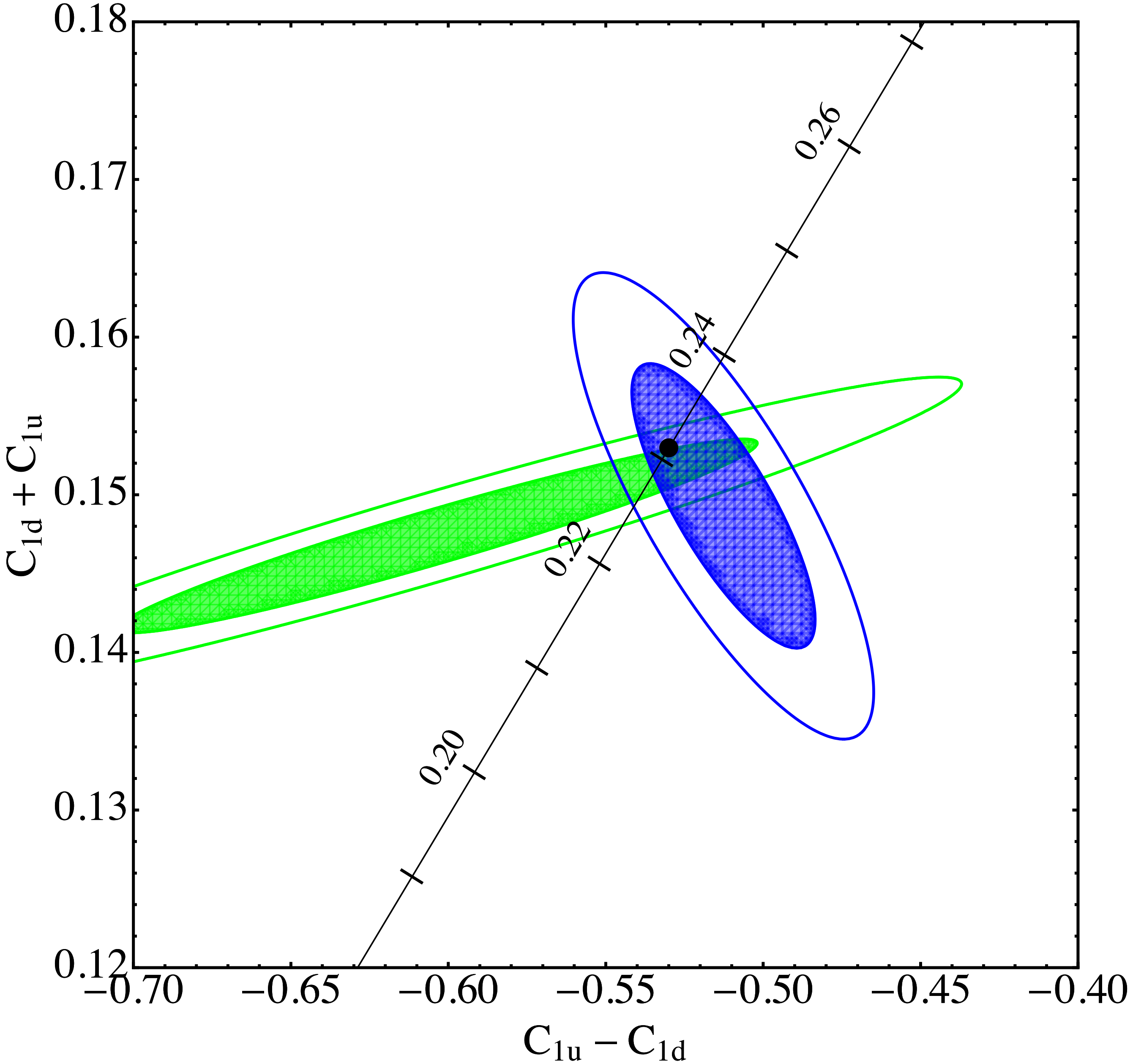
- Remember the old status



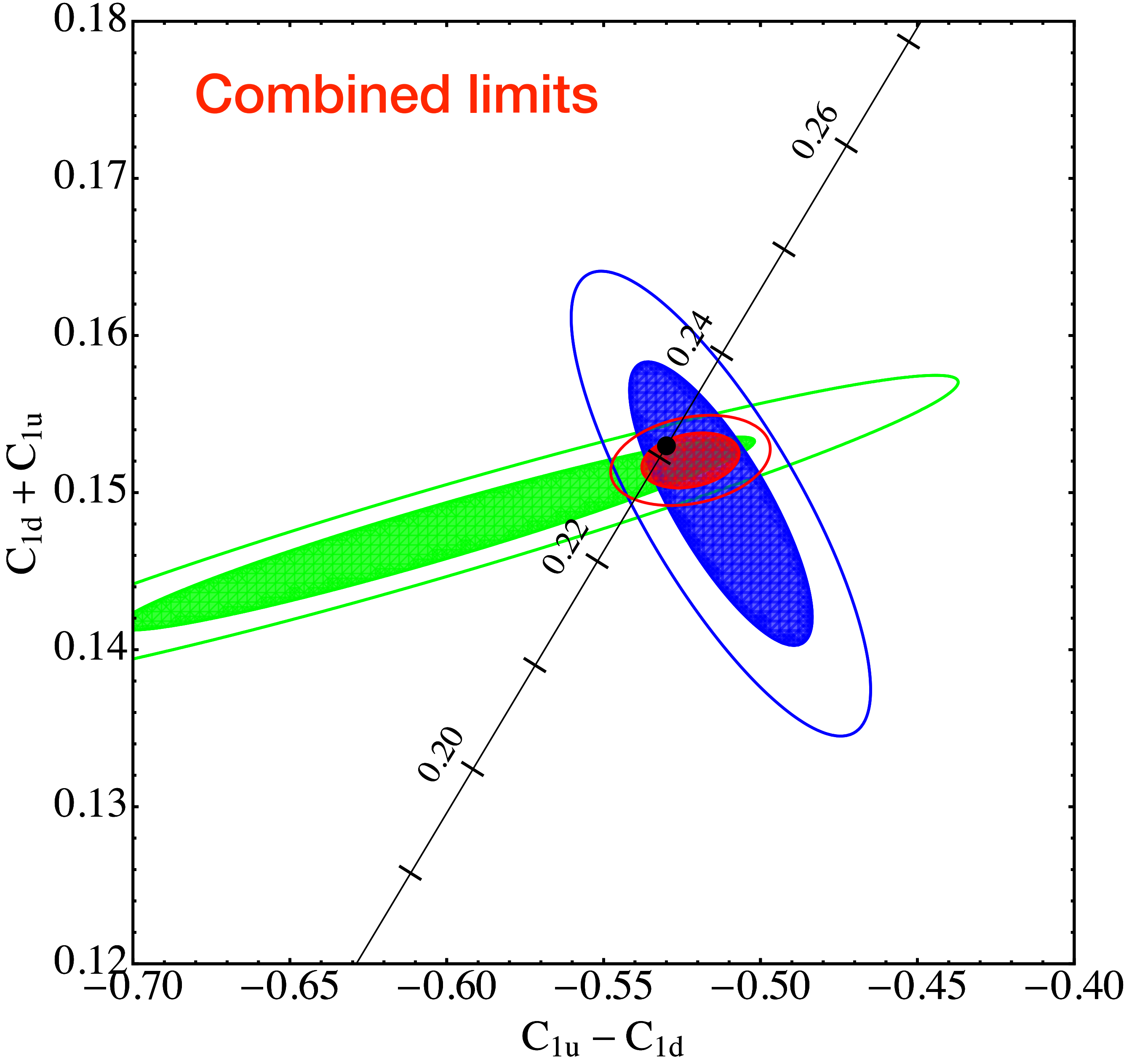
Weak charges



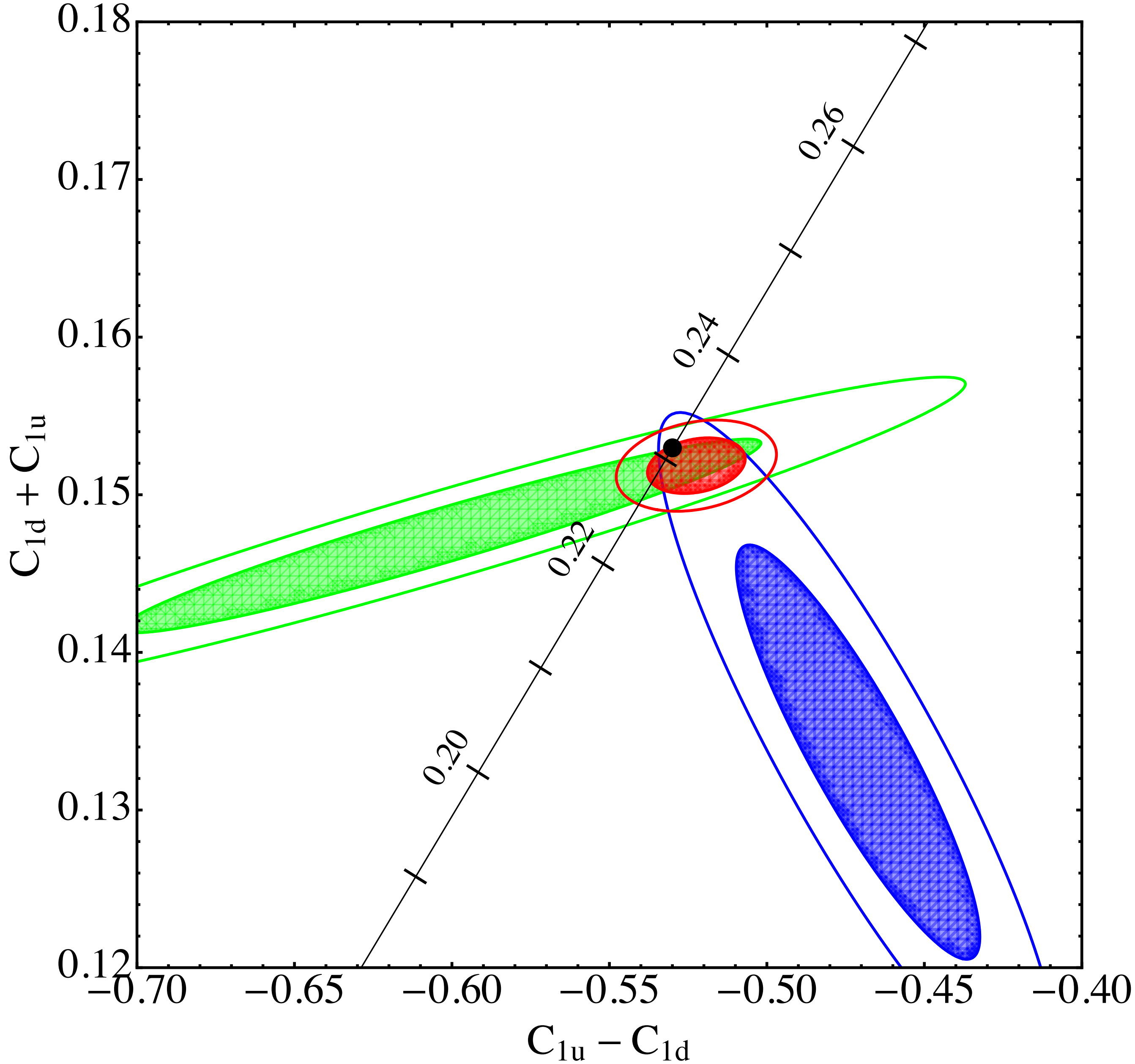
Weak charges



Weak charges

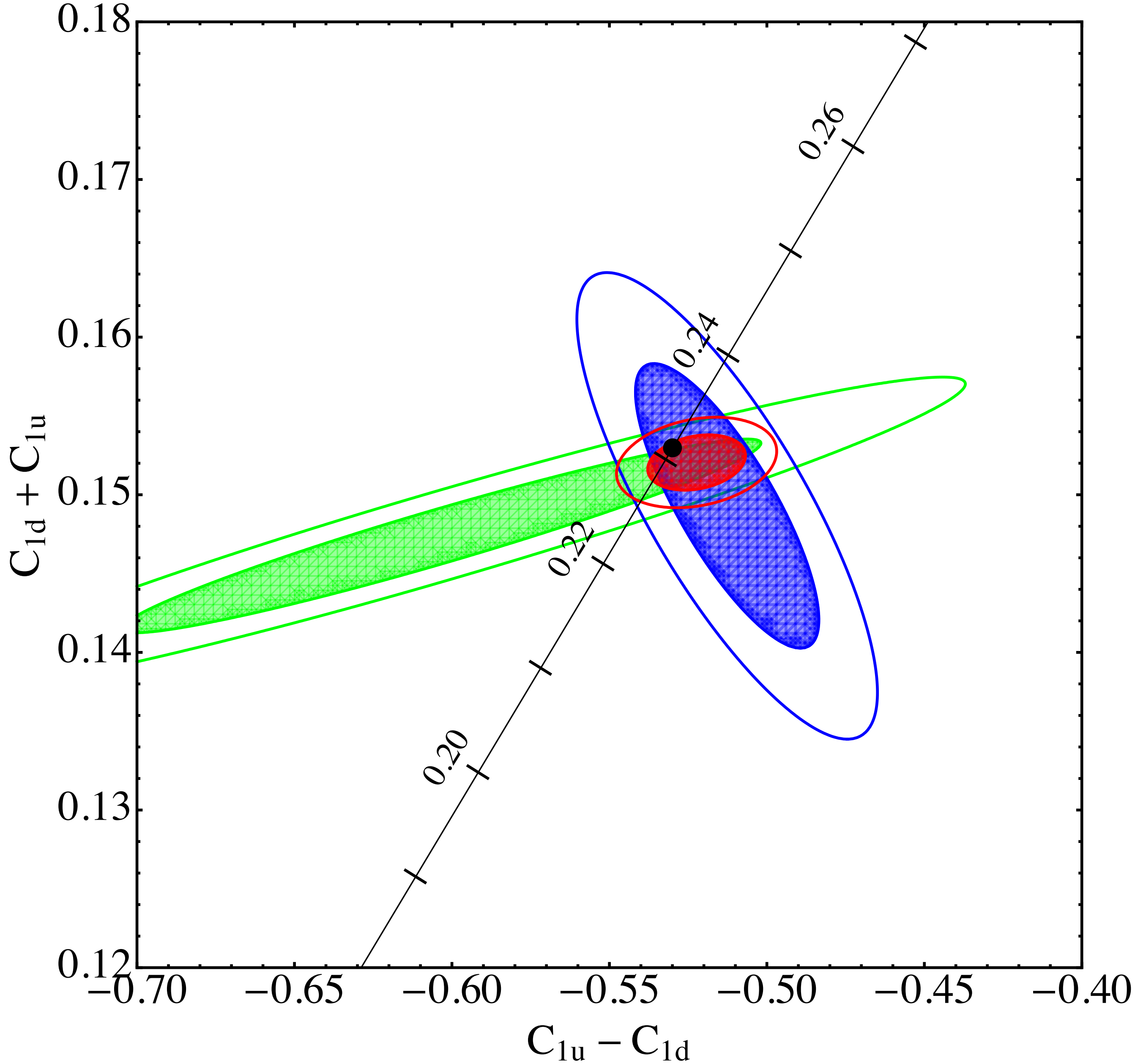


Weak charges



Isoscalar Zhu
- WITHOUT

Weak charges



Isoscalar Zhu
- WITH

Dipole and Taylor

Dipole and Taylor

- **You still might be nervous about using the a constrained functional form over such a wide range**

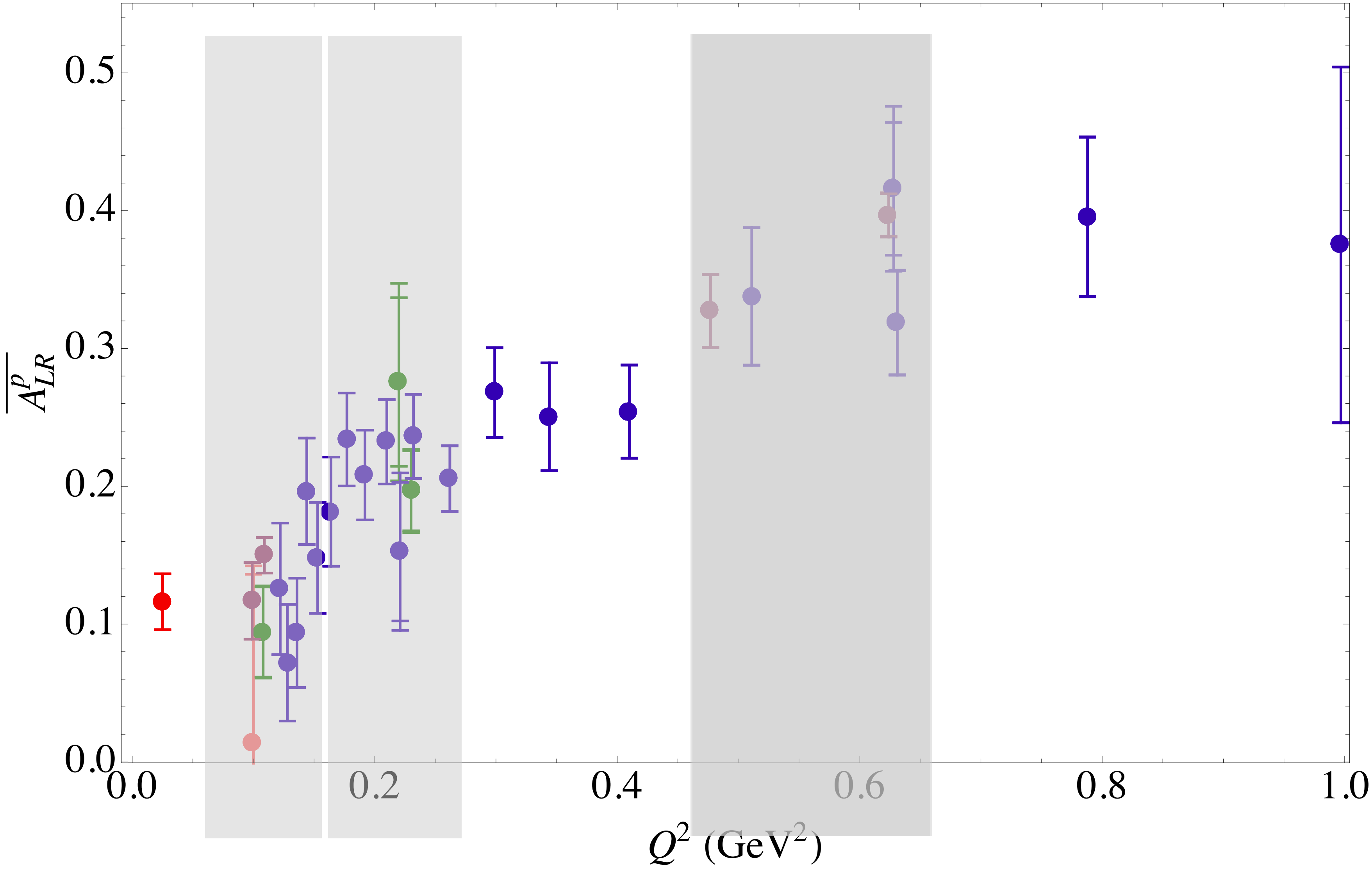
Dipole and Taylor

- **You still might be nervous about using the a constrained functional form over such a wide range**

- How about a way of resolving how sensitive we are to this parameterisation?

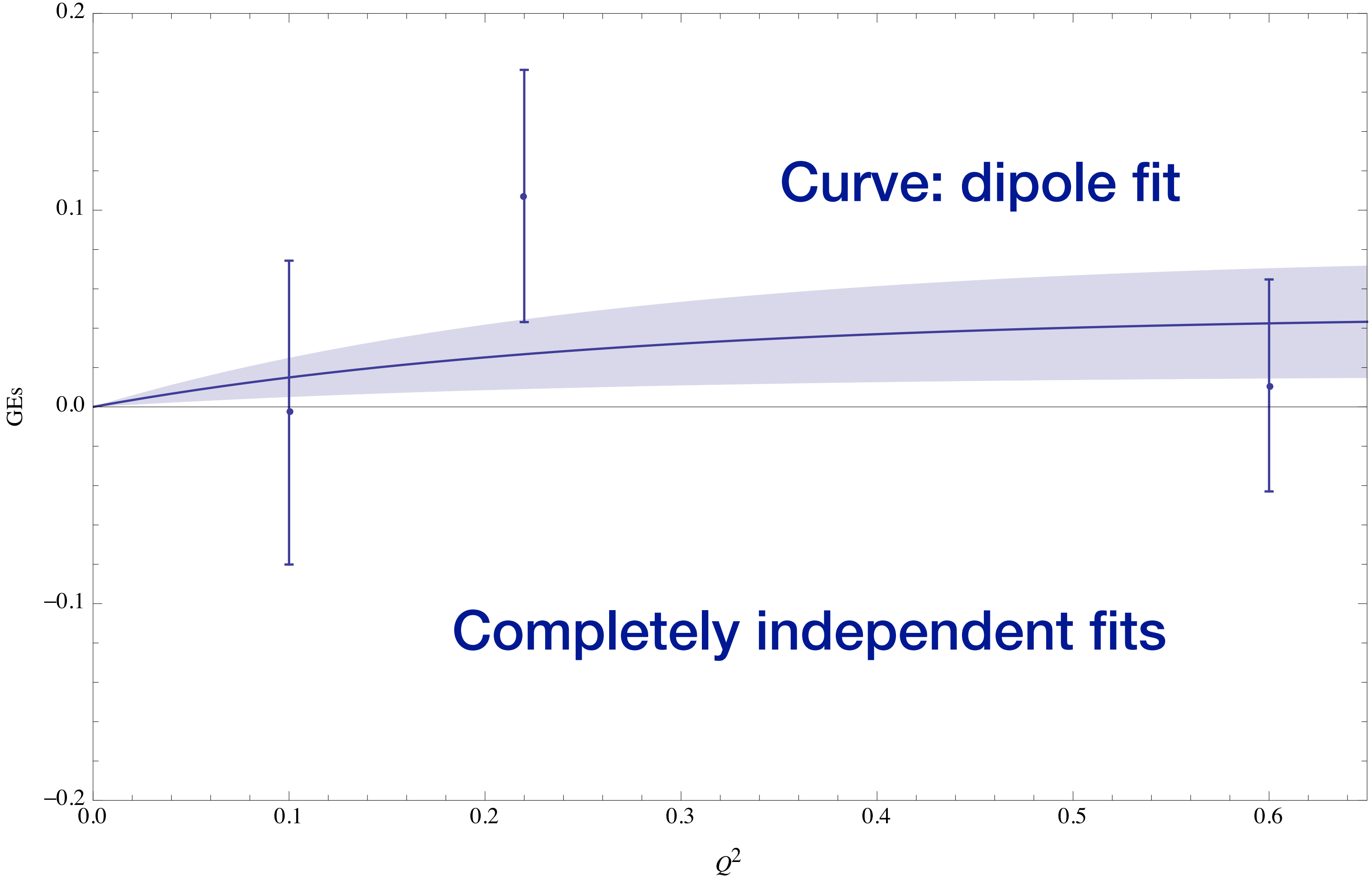
Fit clusters of Q^2

- Grab local bins of the data



Fit clusters of Q^2

- Strangeness electric form factor

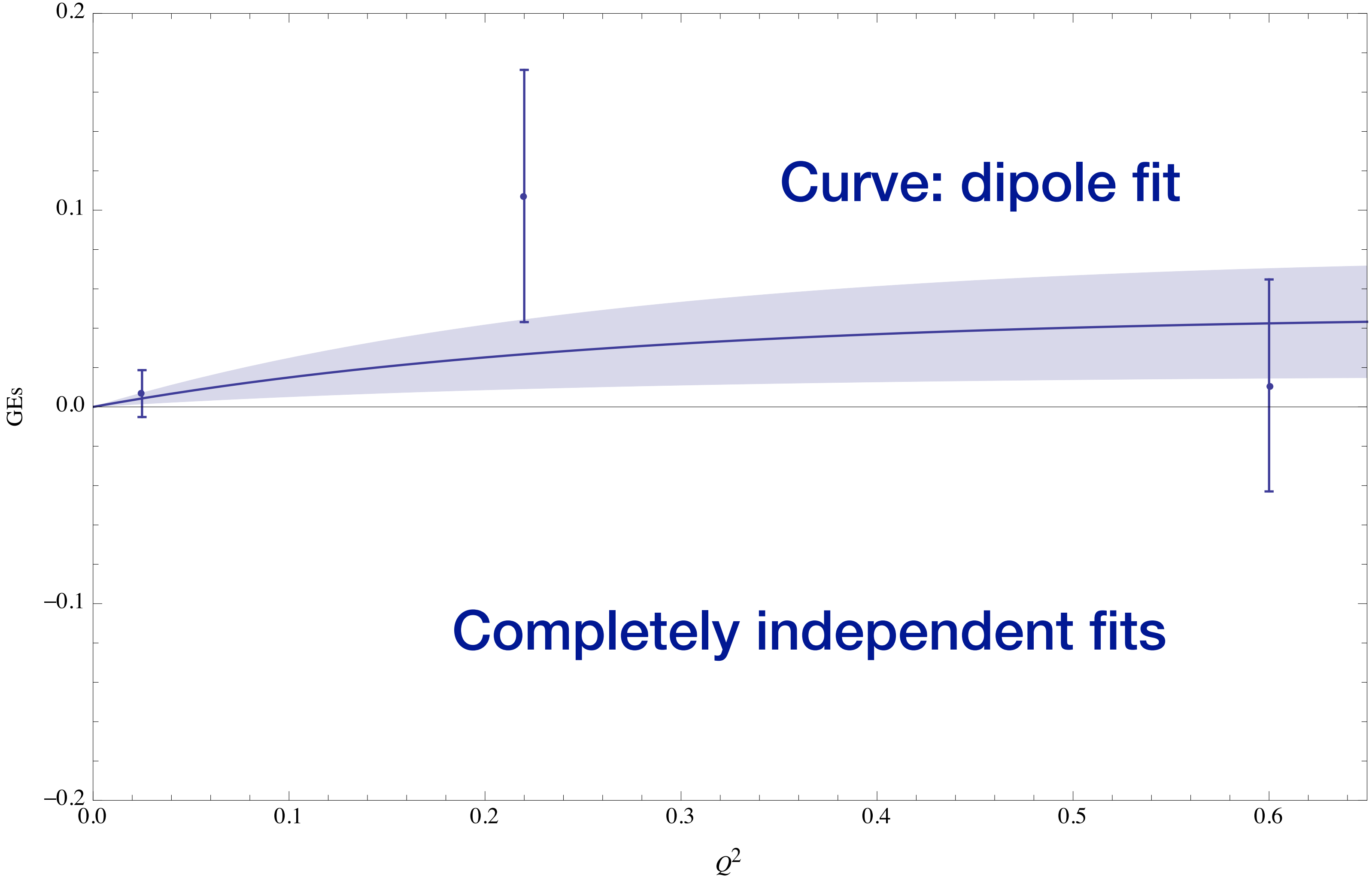


Curve: dipole fit

Completely independent fits

Fit clusters of Q^2

- Strangeness electric form factor - with Q-weak point

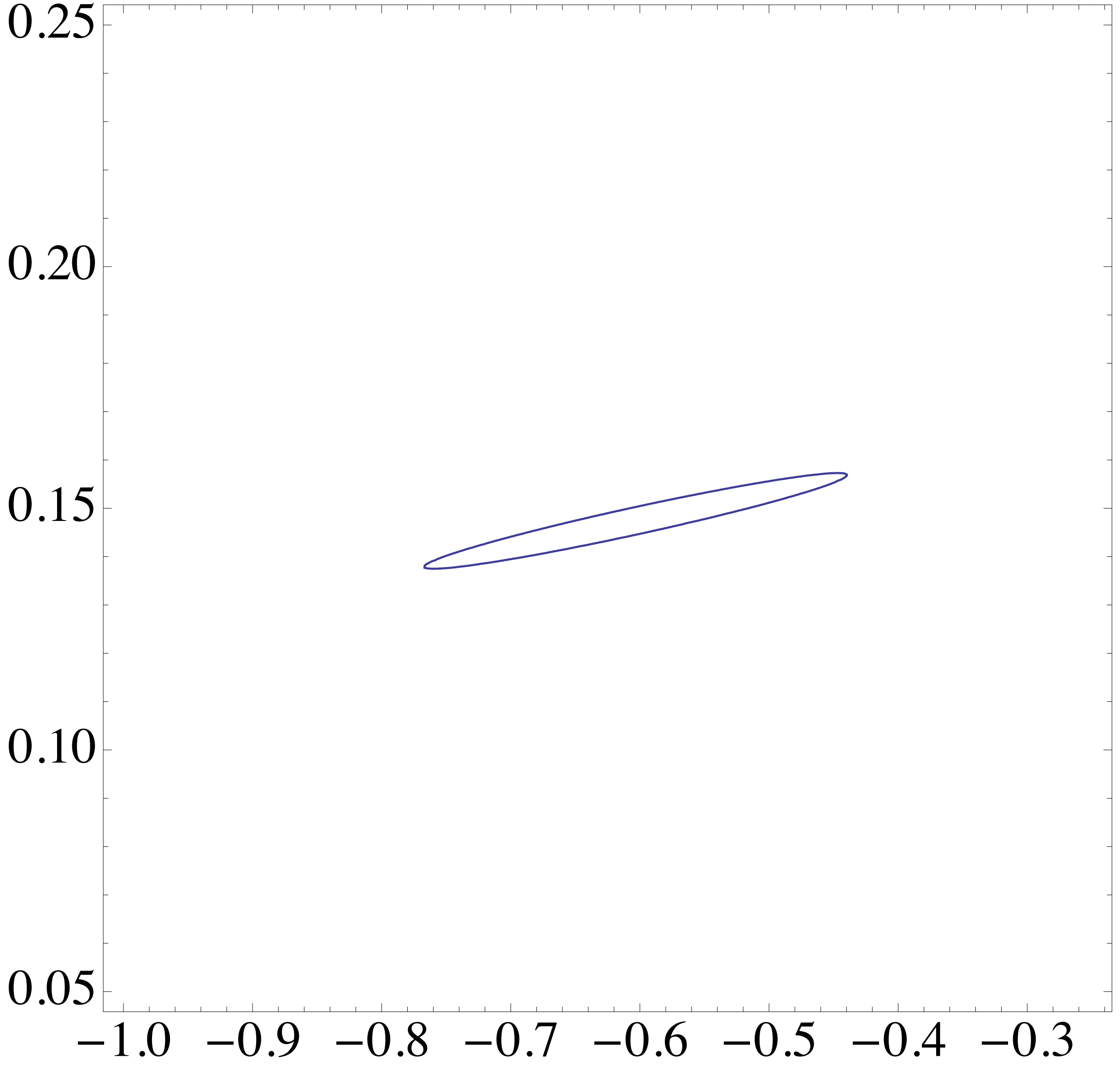


Curve: dipole fit

Completely independent fits

Fit clusters of Q^2

- Weak charges from independent fits



APV

Q2~0.1

Q2~0.22

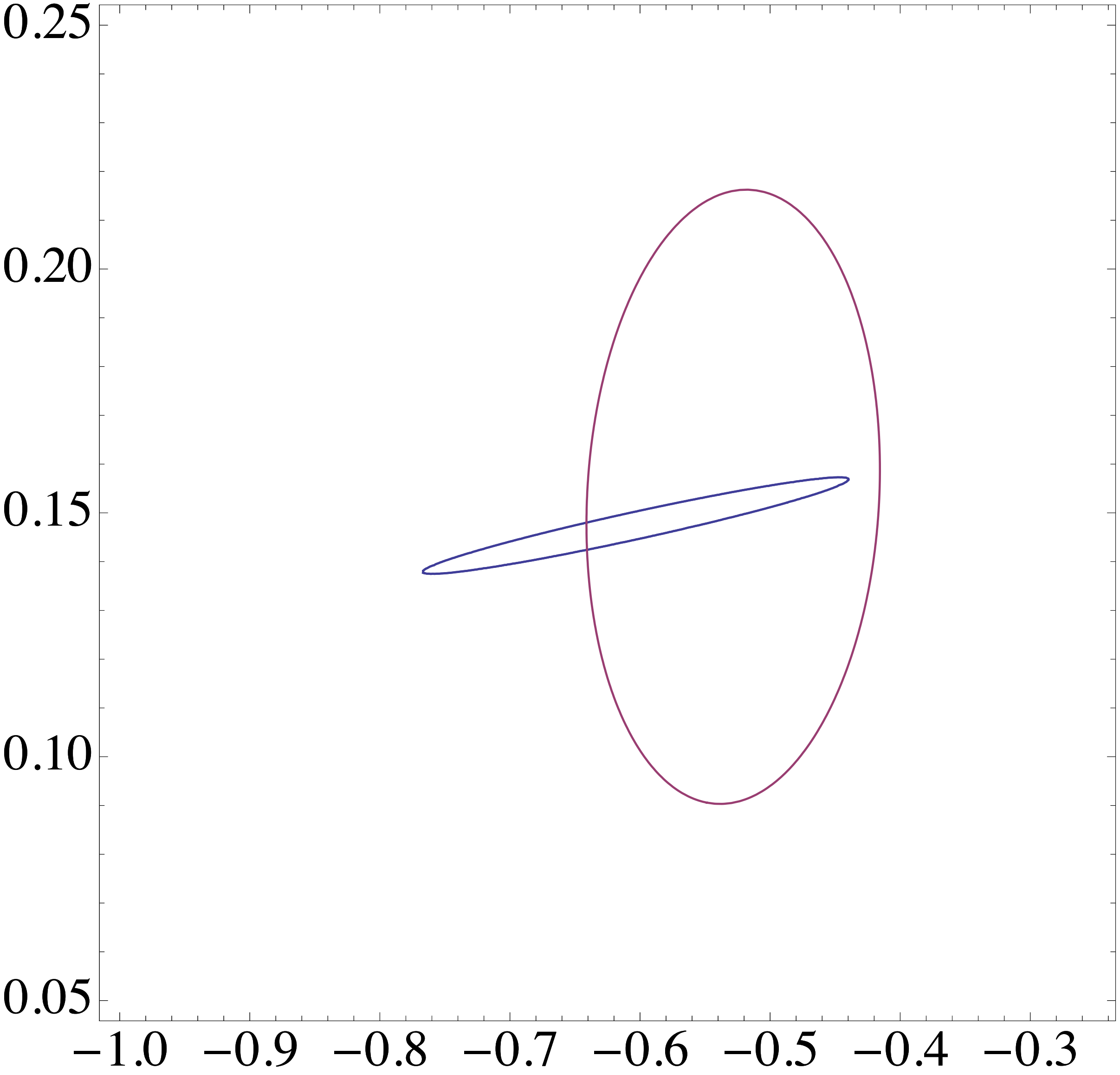
Q2~0.6

Q2~0.1+Qweak

Combined

Fit clusters of Q^2

- Weak charges from independent fits



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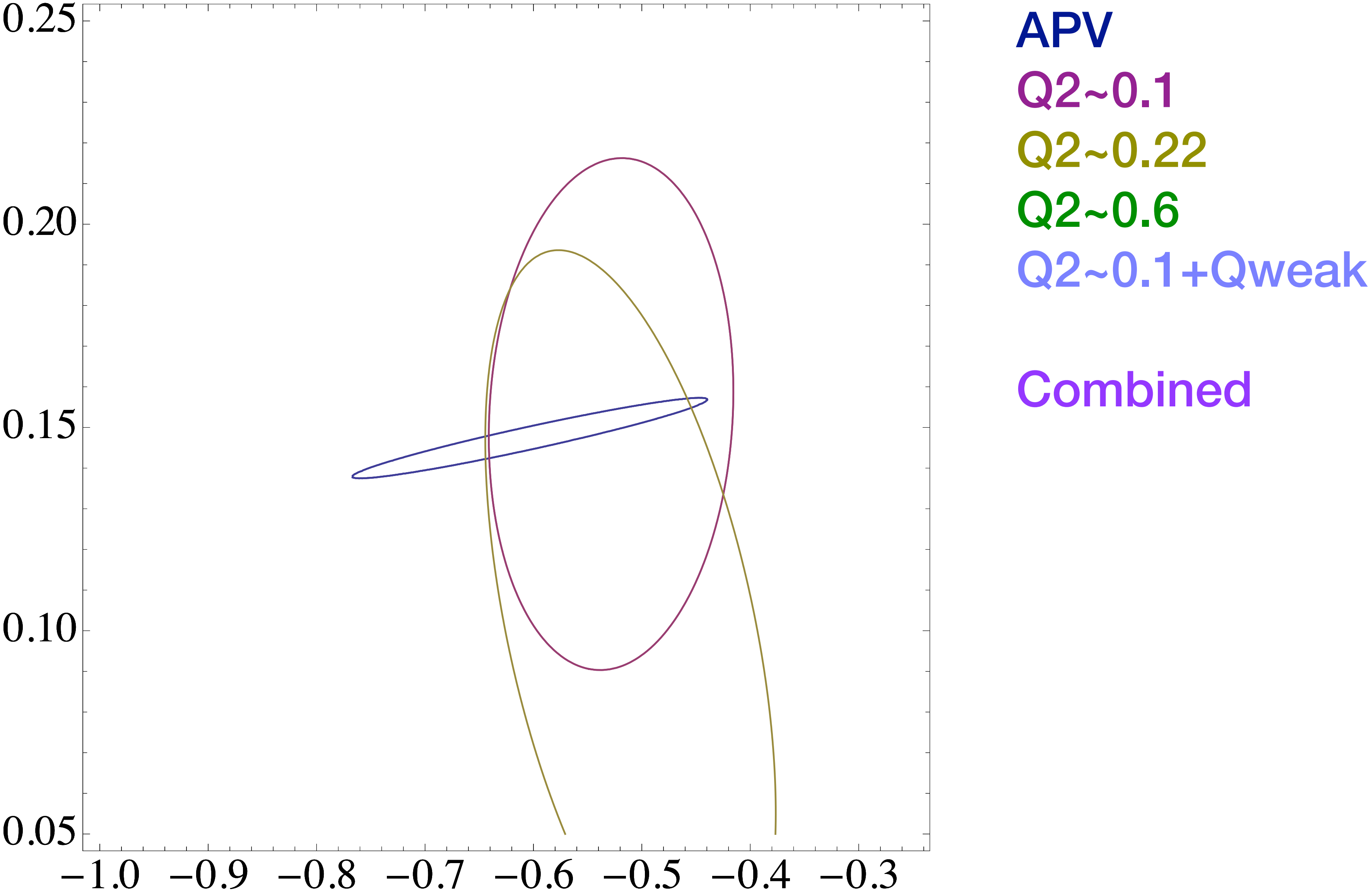
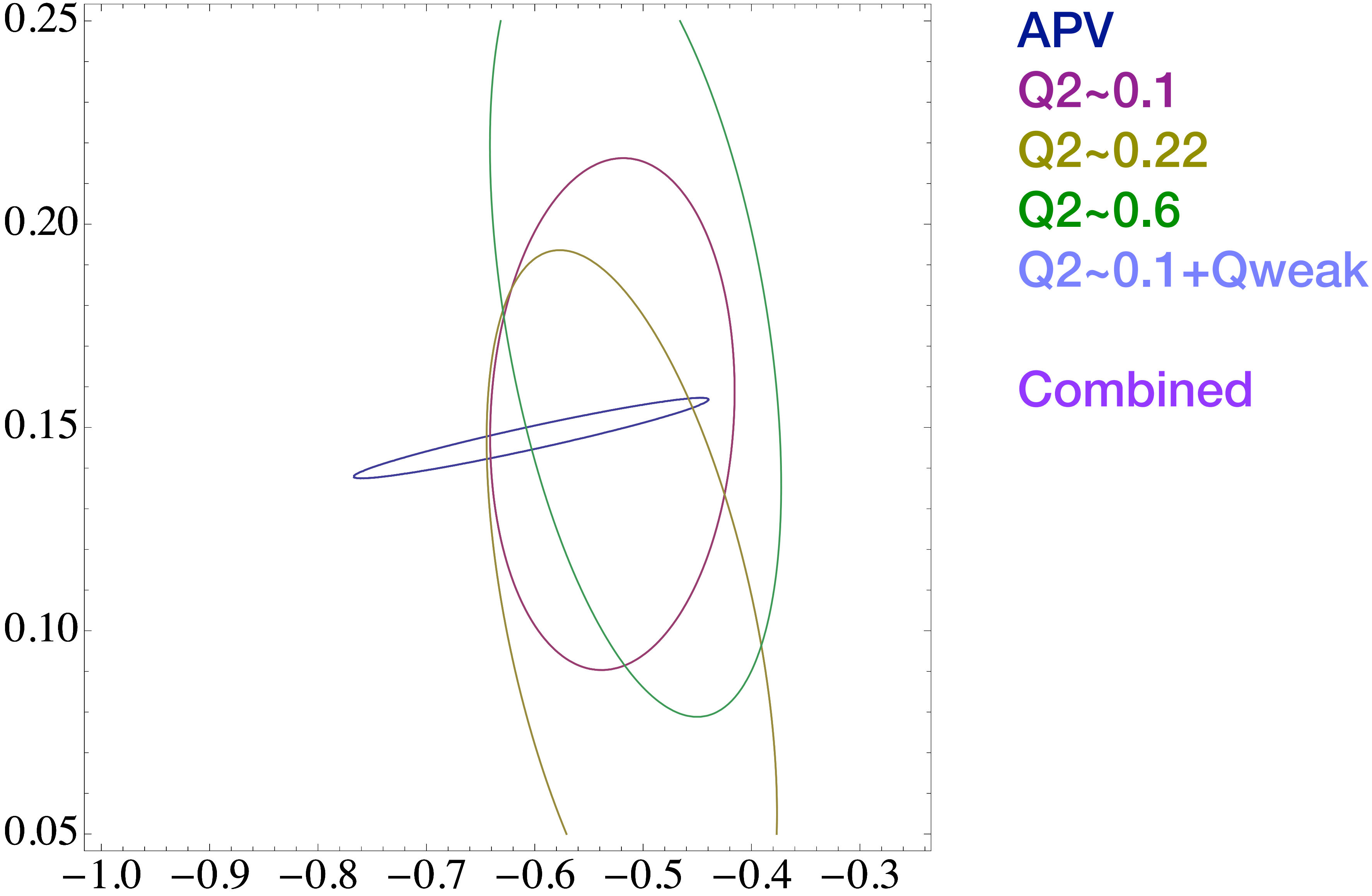


Fit clusters of Q^2

- Weak charges from independent fits



Fit clusters of Q^2

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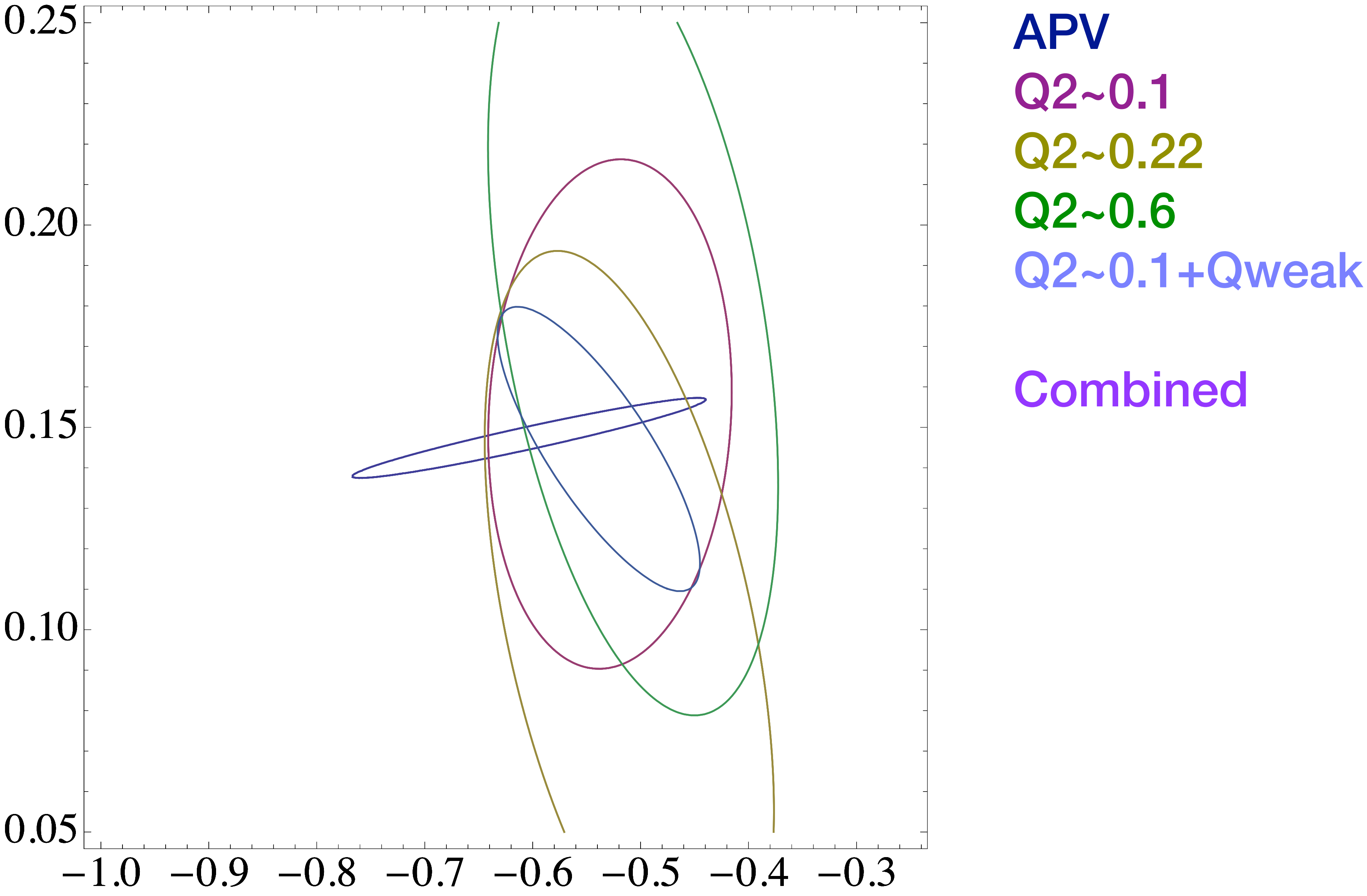
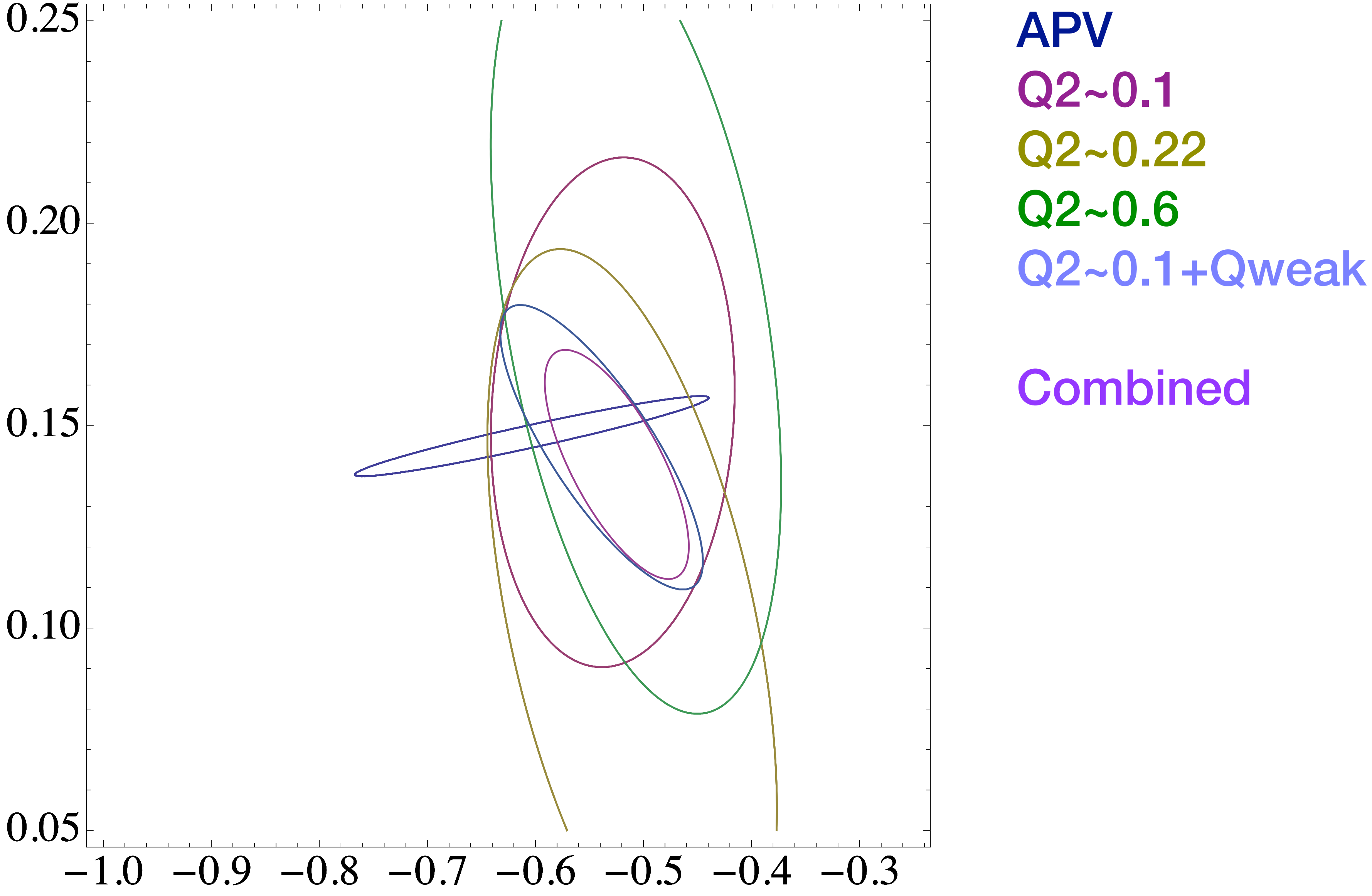


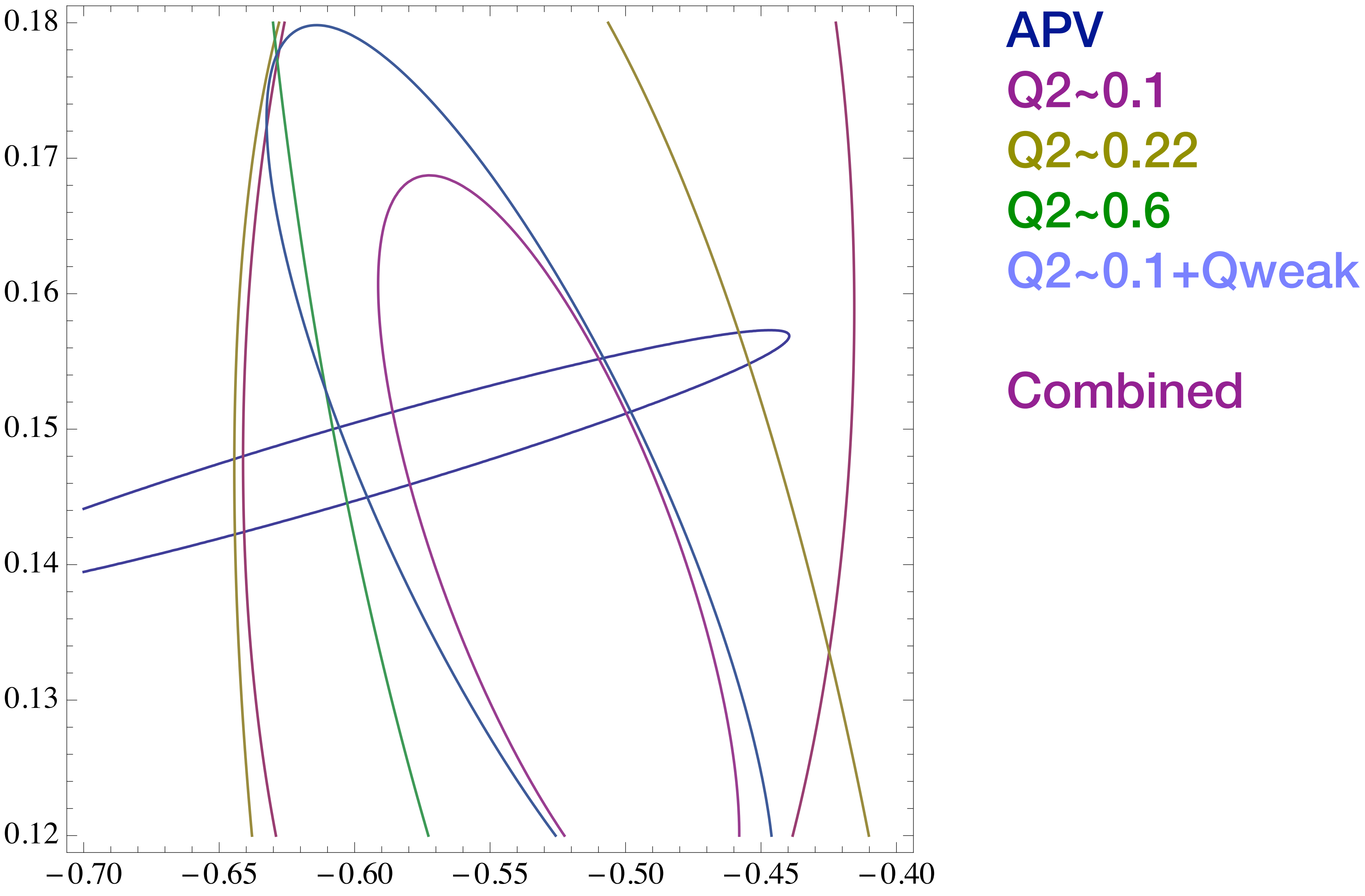
Fit clusters of Q^2

- Weak charges from independent fits



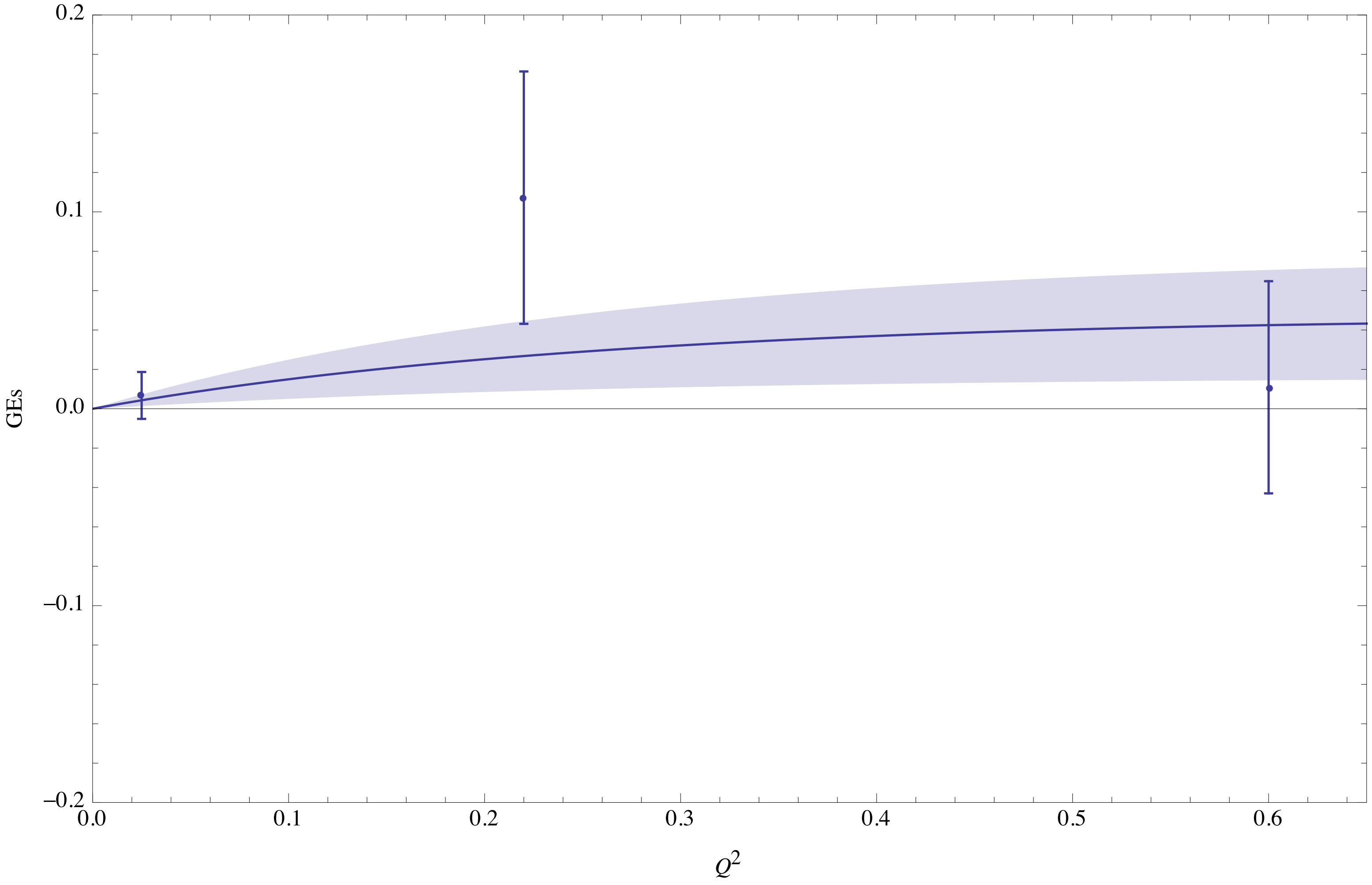
Fit clusters of Q^2

- Weak charges from independent fits - close-up

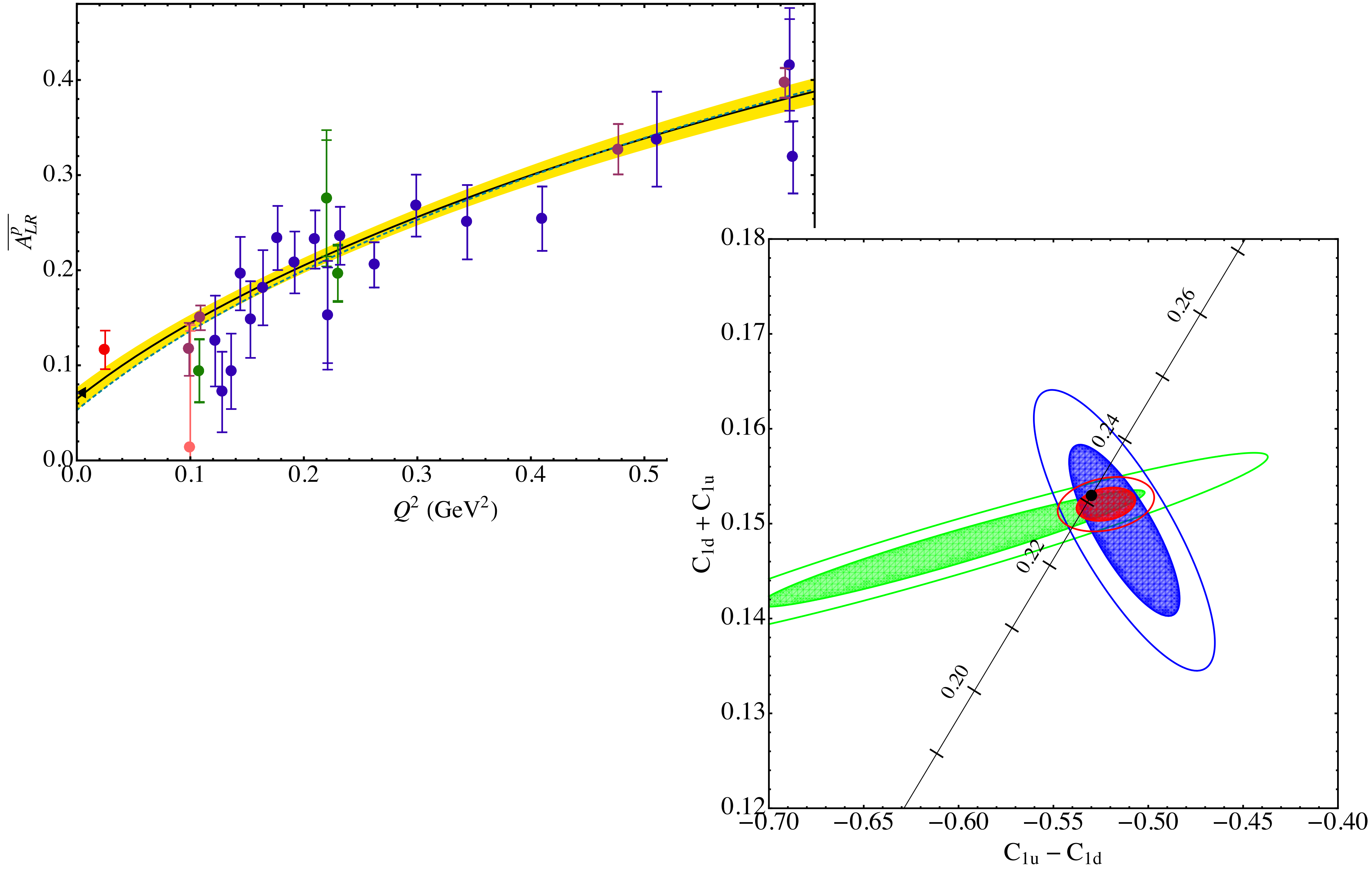


Fit clusters of Q^2

- It appears that the parameterisation of the strangeness form factors over the full range is not overly ambitious



Current status



Future

- Shopping list
  - Charge symmetry violation (deuteron & Helium-4)
  - Uncertainties on EM form factors
    - already implemented MC sampling over Kelly fit parameters
    - new data(?)
  - Gamma-Z box
    - E **and** Q^2 dependence
    - (quasi-elastic) deuteron & (elastic) Helium-4