Power corrections in PV-DIS

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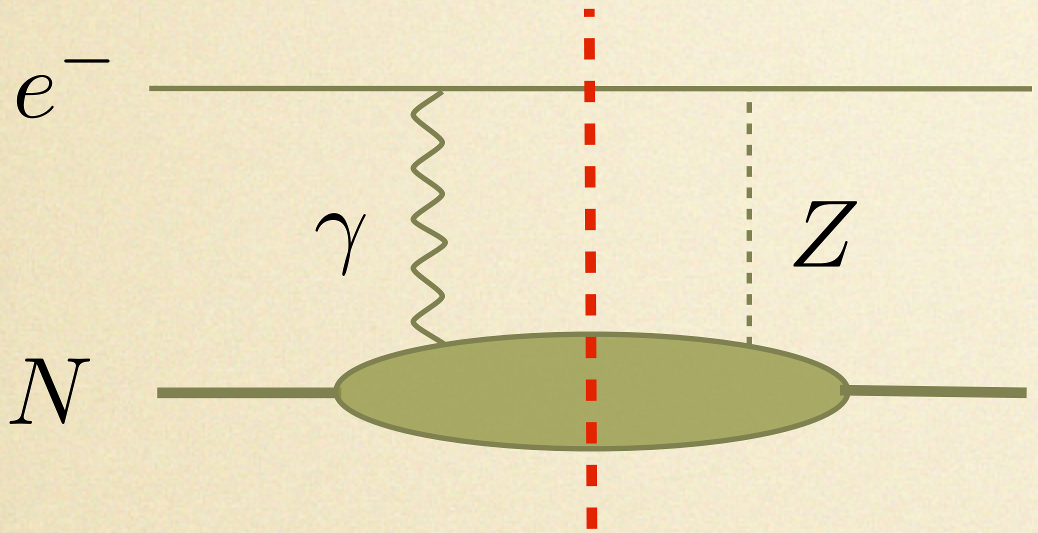
Based on arXiv:1104.0511 [hep-ph]
with A. Schaefer and A. Manashov

Outline

- PV DIS
- Cahn-Gilman asymmetry
- Corrections to CG
- Twist-4
- Nucleon light-cone wave functions
- Estimates

PV-DIS

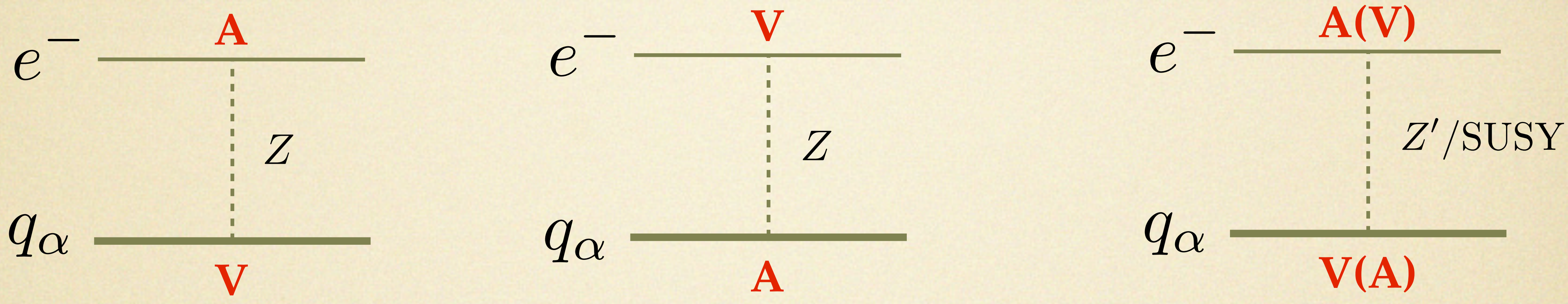


Prescott et al.' 77

$\sin^2\theta_W = 0.20 \pm 0.03$

- Probe of PV weak neutral current in SM
- Precise measurement of the Weinberg angle
- Tool to measure flavor and isospin dependence of nucleon PDFs
- Access New Physics (NP)

Standard and New Physics



$C_{1\alpha} = 2g_A^e g_V^\alpha$ $\quad$ $C_{2\alpha} = 2g_V^e g_A^\alpha$ $\quad$ $\delta C_{j\alpha}$

$$\mathcal{L}_{\rm PV} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^\mu\gamma_5 e\left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right) + \bar{e}\gamma^\mu e\left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\right)\right]$$

- Measurement of weak charges

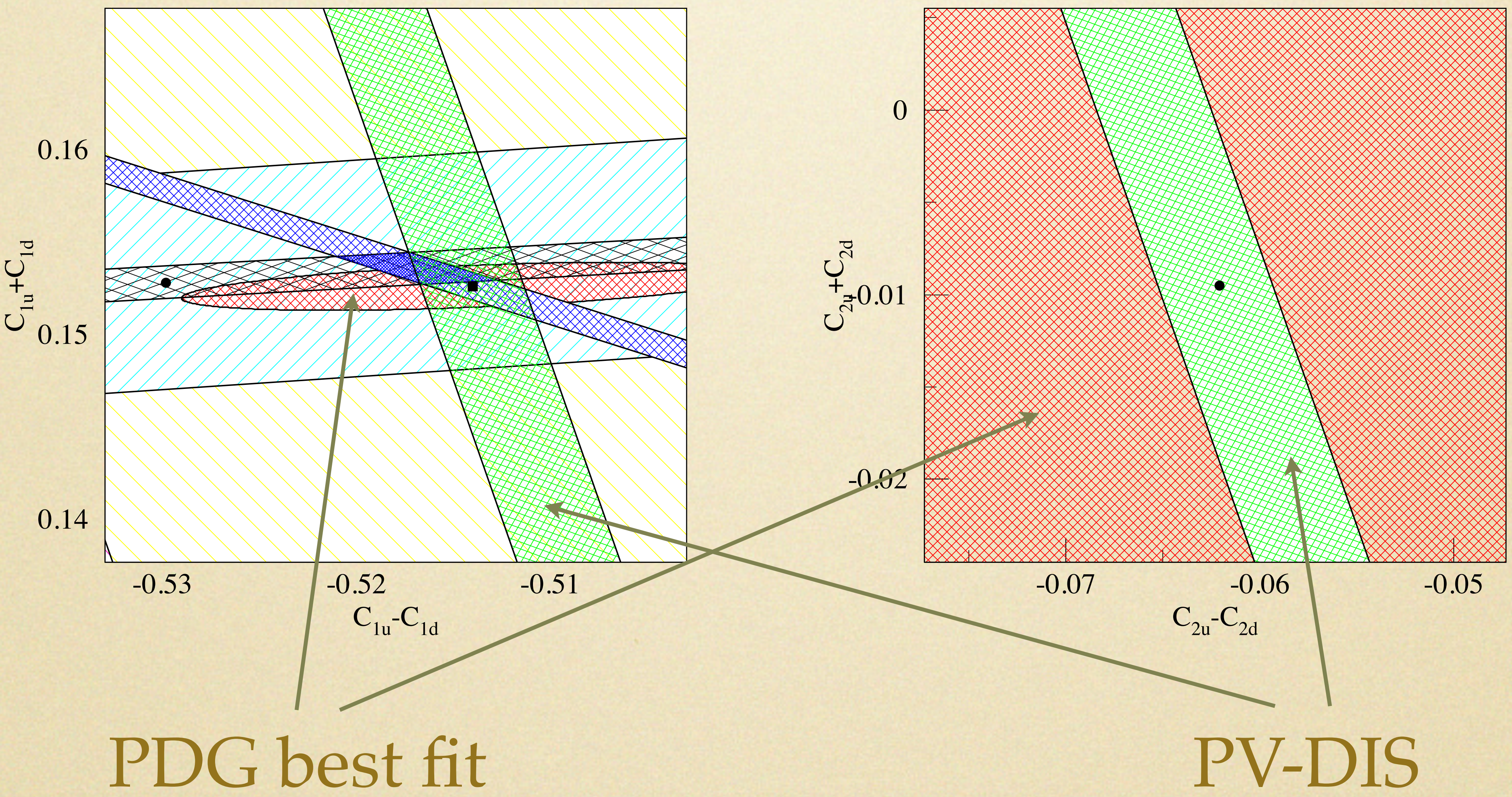
$$g_{V,A}^f = Q_{wf}^L \pm Q_{wf}^R \qquad Q_{w,f}^\alpha = T_3(f_\alpha) - Q(f)\sin^2\theta_W$$

- And their deviation due to New Physics

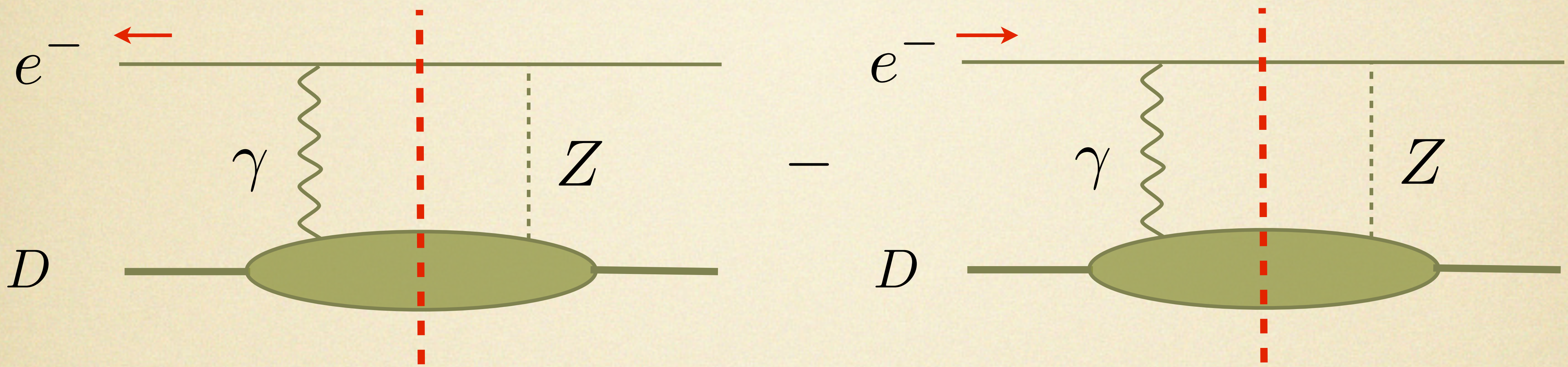
$$C_{1\alpha} = 2g_A^e g_V^\alpha + \delta C_{1\alpha} \qquad C_{2\alpha} = 2g_V^e g_A^\alpha + \delta C_{2\alpha}$$

Current info on Cs

from Reimer '10 (DIS 2010)



Cahn-Gilman asymmetry



$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

- All hadronic effects cancel in the asymmetry on deuteron (parton model = twist-two):

$$A_{LR} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{3}{5}\left[(2C_{1u} - C_{1d}) + (2C_{2u} - C_{2d})\frac{1-(1-y)^2}{1+(1-y)^2}\right] \quad \simeq 10^{-4} Q^2 [\mathrm{GeV}^2]$$

- Hadronic effects manifest themselves as small corrections to the Cahn-Gilam formula

Correcting CG asymmetry

$$A_{LR} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{3}{5}\left[\tilde{a}_1 + \tilde{a}_2 \frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\tilde{a}_k = -(2C_{ku} - C_{kd})\left[1 + R_j(\mathrm{NP}) + R_j(\mathrm{CSV}) + R_j(\mathrm{TMC}) + R_j(\mathrm{HT})\right]$$

- In attempt to measure NP, all other corrections to CG have to be under theoretical control
- Alternatively, precision PV-DIS can be used to probe subtle hadronic physics effects
- Precision measurements over wide range of kinematics could potentially disentangle different effects

Asymmetry: exactly

$$A_{LR} = -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e Y_3 \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$2C_{2u} - C_{2d} \simeq 0.04$

leading — suppressed

- Sources of hadronic and perturbative effects:

$$Y_1 = \left(\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right)\frac{1+(1-y)^2 - y^2\left[1-r^2/(1+R^{\gamma Z})\right] - 2xyM/E}{1+(1-y)^2 - y^2\left[1-r^2/(1+R^{\gamma})\right] - 2xyM/E} \xrightarrow{\text{CG}} 1$$

$$Y_3 = \left(\frac{r^2}{1+R^{\gamma}}\right)\frac{1-(1-y)^2}{1+(1-y)^2 - y^2\left[1-r^2/(1+R^{\gamma})\right] - 2xyM/E} \qquad \frac{1-(1-y)^2}{1+(1-y)^2}$$

$$R^{\gamma(\gamma Z)} = \left(1+\frac{4x^2M^2}{Q^2}\right)\frac{F_2^{\gamma(\gamma Z)}}{2xF_1^{\gamma(\gamma Z)}} - 1 \xrightarrow{\text{CG}} \frac{4x^2M^2}{Q^2}$$

- CG (=parton-model) limit yields hadronic-free result

$$\frac{F_1^{\gamma Z}}{F_1^{\gamma}} \to -\frac{3}{5}\left(2C_{1u} - C_{1d}\right)$$

Strong corrections

- Higher order correction in strong coupling

$$R^{\gamma(\gamma Z)} \sim O(\alpha_s)$$

- Target mass effects (important at large-x)

$$\xi = 2x/\left(1+\sqrt{1+4x^2M^2/Q^2}\right)$$

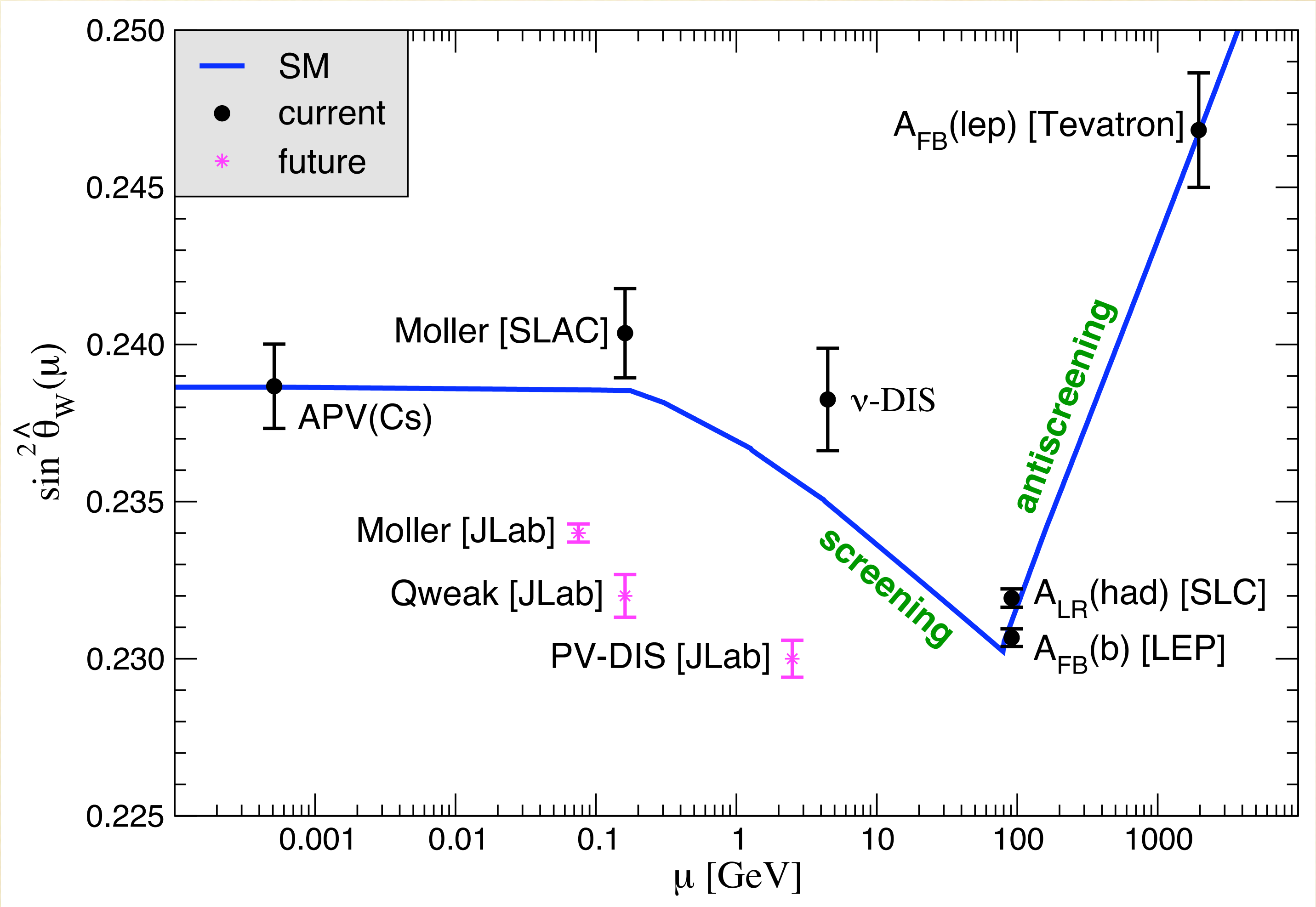
- Charge-symmetry violation (x-dep., Q^2-indep.)

$$\delta u = u_p - d_n \qquad \delta d = d_p - u_n$$

- Dynamical higher twists (x-dep., Q^2-dep.)

JLab precision measurements

Focus: detection of physics beyond Standard Model



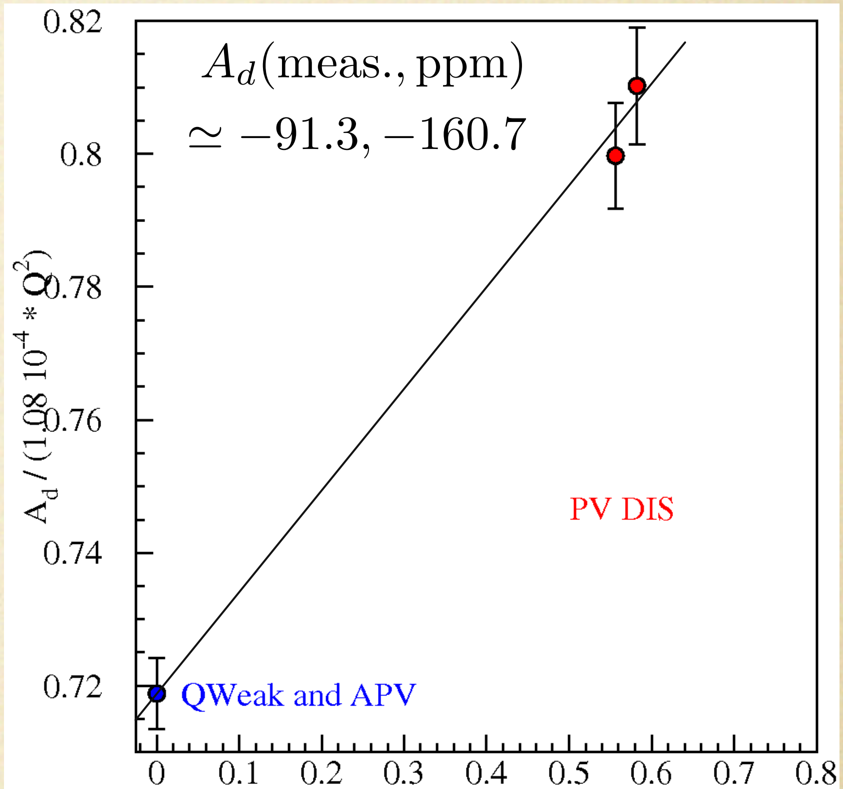
- PV program:
  - Moller
  - QWeak (elastic scattering): C_{1q}
  - Hall C (baseline equipment): C_{2q}
  - SoLID (Solenoidal Large Intensity Device) PV-DIS: C_{2q}

JLab PV-DIS experiments

- HallA@6GeV [PR-08-011]
  - Kinematics:

    $Q^2 = 1.1,\ 1.9\ \mathrm{GeV}^2 \qquad \langle x \rangle = 0.3$
  - Accuracy:

    $\delta A_d / A_d = 2.52\%(2.11\%)\ [\mathrm{tot.(stat.)}]$



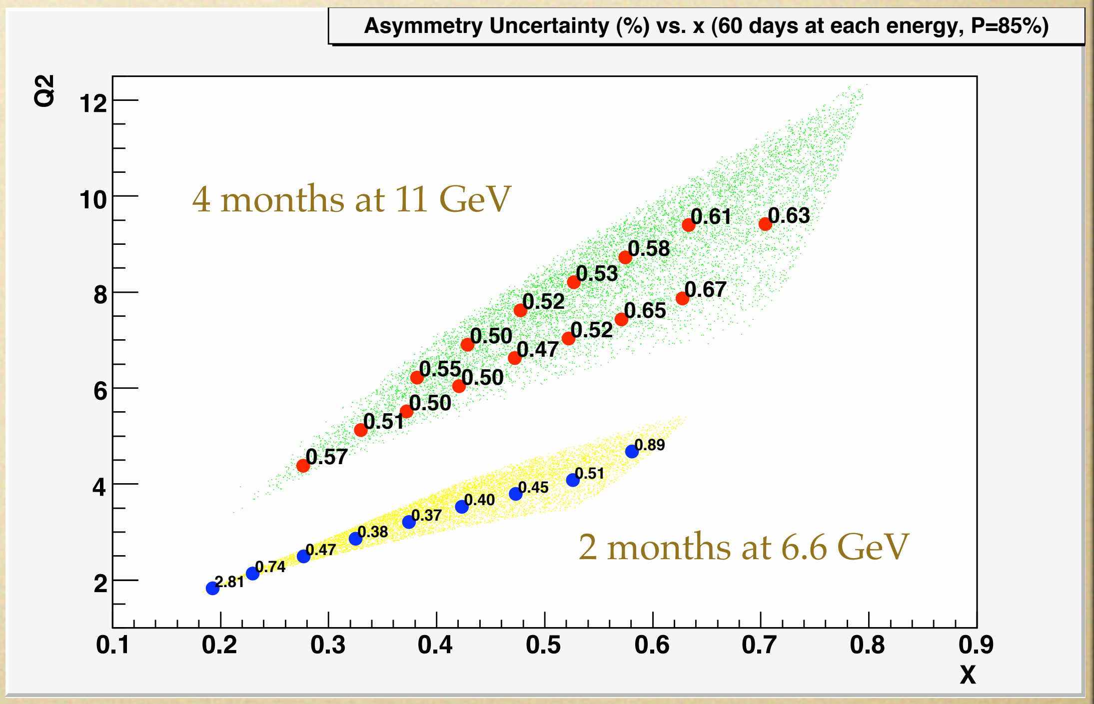
$A_d \propto 2C_{1u} - C_{1d} + Y\,(2C_{2u} - C_{2d})$

from Reimer '08

- HallC@12GeV [PR12-07-102]
  - Kinematics:

    $Q^2 = 3.3\,\mathrm{GeV}^2, \quad \langle x \rangle = 0.34$
  - Accuracy:

    $\delta A_d / A_d = 0.5\%(0.6\%)\ [\mathrm{stat.(sys.)}]$
- HallA-SoLID @ 12GeV ⟶



Kummer & Souder '08

Twist-four corrections

$$\sigma_L - \sigma_R \sim W_{ud}$$

Bjorken '78

Wolfenstein '78

Asymmetry is determined by the hadronic tensor

$$W^{\mu\nu}_{ud}(p,q) = \mathrm{Im}\Big[\frac{i}{4\pi M_D}\int d^4z\, e^{iq\cdot z}\langle D(p)|T\{\bar u(z)\gamma^\mu u(z)\,\bar d(0)\gamma^\nu d(0) + (u\leftrightarrow d)\}|D(p)\rangle\Big]$$

LC OPE starts at twist-four

Balitsky & Braun '89

$$T\Big\{\bar u(z)\gamma_\mu u(z)\,\bar d(-z)\gamma_\nu d(-z) + (u\leftrightarrow d)\Big\}^{\mathrm{tw-4}} = \frac{\alpha_s}{16\pi i}\Big\{-\log z^2\partial_\mu\partial_\nu\int_0^1 du\frac{\bar u}{u^2}\mathcal{Q}(uz) + \frac{1}{z^2}S_{\mu\alpha\nu\beta}z^\alpha\partial^\beta\int_0^1\frac{du}{u}\mathcal{Q}(uz)\Big\}$$

$$\mathcal{Q}_A(a) = \Big(\bar u(a_1 z)t^a \not{z}\gamma_5 u(a_2 z)\Big)\Big(\bar d(a_3 z)t^a \not{z}\gamma_5 d(a_4 z)\Big)$$

$$\mathcal{Q}_V(a) = \Big(\bar u(a_1 z)t^a \not{z} u(a_2 z)\Big)\Big(\bar d(a_3 z)t^a \not{z} d(a_4 z)\Big)$$

Twist-four correction to CG asymmetry

$$R_1^{\mathrm{tw-4}} = \frac{1}{Q^2}\frac{\alpha_s\pi}{5(1-\frac{20}{9}\sin^2\theta_W)}\frac{x\,\widetilde{\mathcal{Q}}_D(x)}{u_D(x)+d_D(x)}$$

with twist-four "distribution"

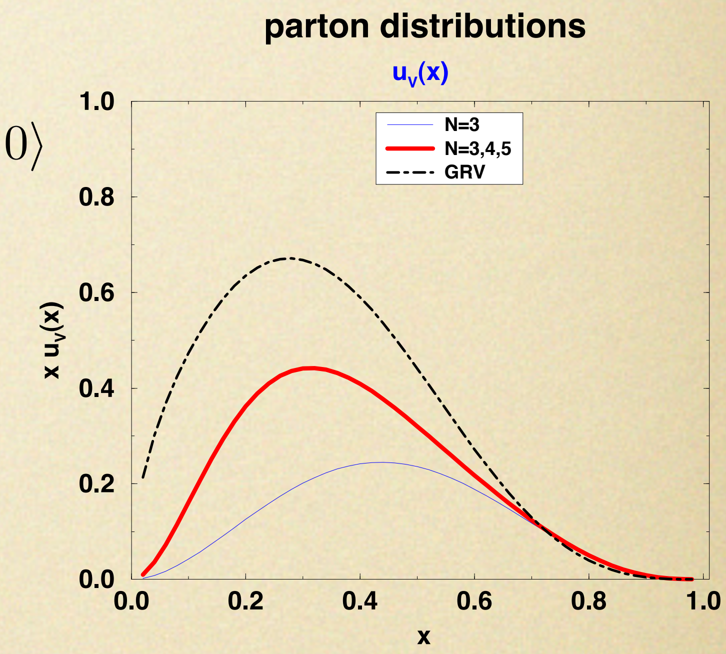
$$\langle D|\mathcal{Q}(z)|D\rangle = i\int_{-1}^1 dx\, e^{2i(p\cdot z)x}\,\widetilde{\mathcal{Q}}_D(x)$$

LCWF

$$|p,+\rangle = |p,+\rangle_{uud} + |p,+\rangle_{uudg} + \ldots$$

- Three-quark (qqq) component

$$|p,+\rangle_{3q} = -\frac{\epsilon^{ijk}}{\sqrt{6}} \int [\mathcal{D}X]_3 \Psi^{(0)}_{123}(X) \times \Big(u^\dagger_{i\uparrow}(1) u^\dagger_{j\downarrow}(2) d^\dagger_{k\uparrow}(3) - u^\dagger_{i\uparrow}(1) d^\dagger_{j\downarrow}(2) u^\dagger_{k\uparrow}(3) \Big) |0\rangle$$



Bolz-Kroll form:

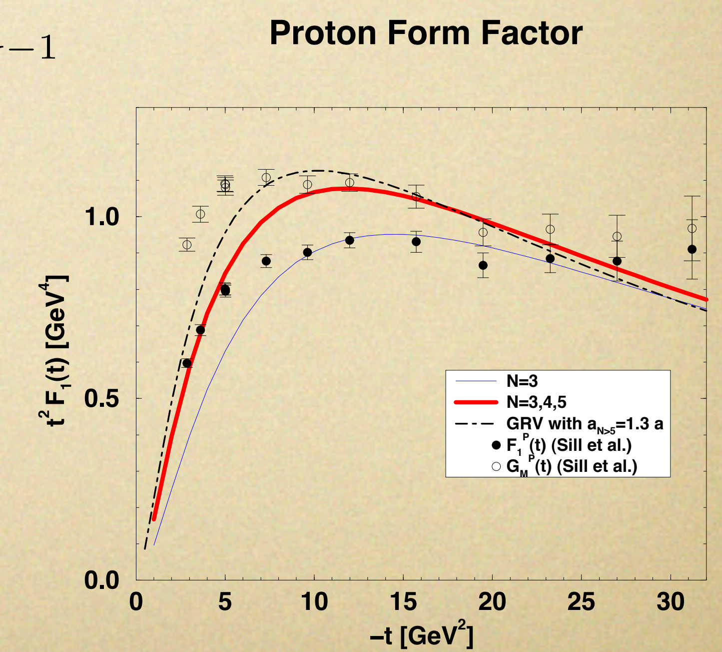
$$\Psi^{(0)}_{123} = \frac{f_N}{4\sqrt{6}} \phi(x_1, x_2, x_3)\, \Omega_3(a_3, x_i, \boldsymbol{k}_{\perp i})$$

Diehl et al.'98

$$\Omega_N(a_N, x_i, \boldsymbol{k}_{\perp i}) = \frac{(16\pi^2 a_N^2)^{N-1}}{x_1 x_2 \ldots x_N} \exp\left[-a_N^2 \sum_i \boldsymbol{k}^2_{\perp i}/x_i \right]$$

$$\langle \boldsymbol{k}_\perp \rangle = 411\,\mathrm{MeV}$$

$$a_3 = 0.75\,\mathrm{GeV}^{-1}$$



$$\Phi_3(x) = 60\, x_1 x_2 x_3\, (1 + 3x_1)$$

Probability of $3q$ state in the nucleon:

$$P_{3q} = \frac{435}{112} f_N^2 \rho_3 \simeq 0.17$$

LCWF (cont'd)

- Three-quark-gluon (*qqqG*) component

$$|p,+\rangle_{uudg_\downarrow} = \epsilon^{ijk}\int [\mathcal{D}X]_4\, \Psi^{\downarrow}_{1234}(X)\, a^{a,\dagger}_{\downarrow}(4)\, [t^a u_\uparrow(1)]^\dagger_i\, u^\dagger_{j\uparrow}(2))\, d^\dagger_{k\uparrow}(3)|0\rangle$$

$$|p,+\rangle_{uudg^\uparrow} = \epsilon^{ijk}\int [\mathcal{D}X]_4 \Big\{ \Psi^{\uparrow(1)}_{1234}(X)\, [t^a u_\downarrow(1)]^\dagger_i \Big(u^\dagger_{j\uparrow}(2) d^\dagger_{k\downarrow}(3) - d^\dagger_{j\uparrow}(2) u^\dagger_{k\downarrow}(3)\Big) a^{a,\dagger}_\uparrow(4)$$
$$+\Psi^{\uparrow(2)}_{1234}(X) u^\dagger_{i\downarrow}(1)\Big([t^a u_\downarrow(2)]^\dagger_j\, d^\dagger_{k\uparrow}(3) - [t^a d_\downarrow(2)]^\dagger_j\, u^\dagger_{k\uparrow}(3)\Big) a^{a,\dagger}_\uparrow(4)\Big\}|0\rangle$$

Bolz-Kroll form:

$$\Psi_{1234} = \frac{1}{\sqrt{2x_4}}\psi_g(x_1,x_2,x_3,x_4)\Omega_4(a_g,x_i,\boldsymbol{k}_{\perp i})$$

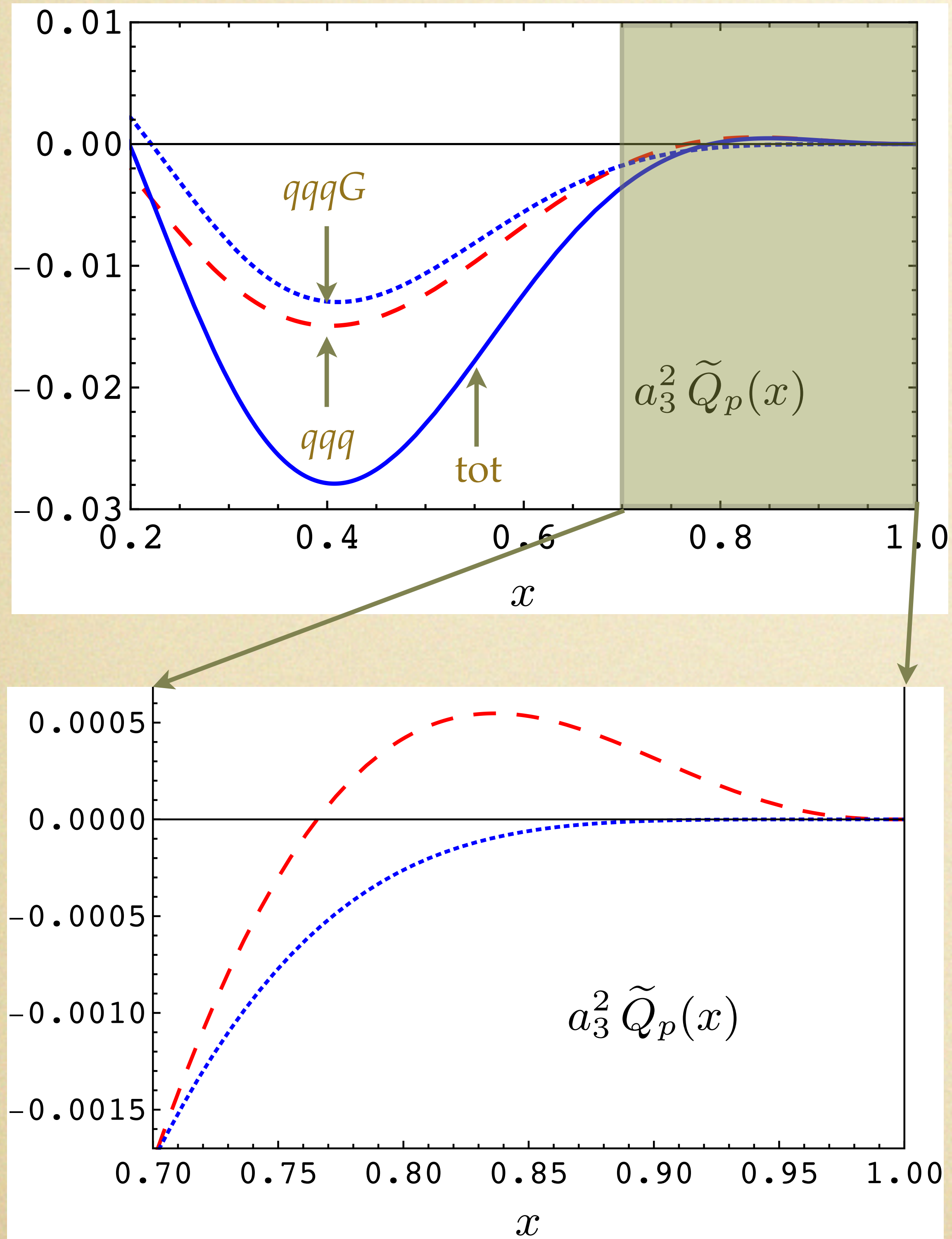
Models (leading conformal wave only):

$$g\phi_g(x_1,x_2,x_3,x_4) = -210 m_N \lambda^g_1\, x_1x_2x_3x_4^2$$
$$g\psi^{(i)}_g(x_1,x_2,x_3,x_4) = -105 m_N(\lambda^g_2 \pm \lambda^g_3)\, x_1x_2x_3x_4^2$$

Probabilities of *3qG* state in the nucleon:

$$P_{g^\downarrow} = \frac{35}{8g^2} m_N^2 \rho_4 (\lambda^g_1)^2 \simeq 0.15 \qquad P_{g^\uparrow} = \frac{105}{16g^2} m_N^2 \rho_4 \Big[(\lambda^g_2)^2 + (\lambda^g_3)^2\Big] \simeq 0.185$$

Twist-four corrections

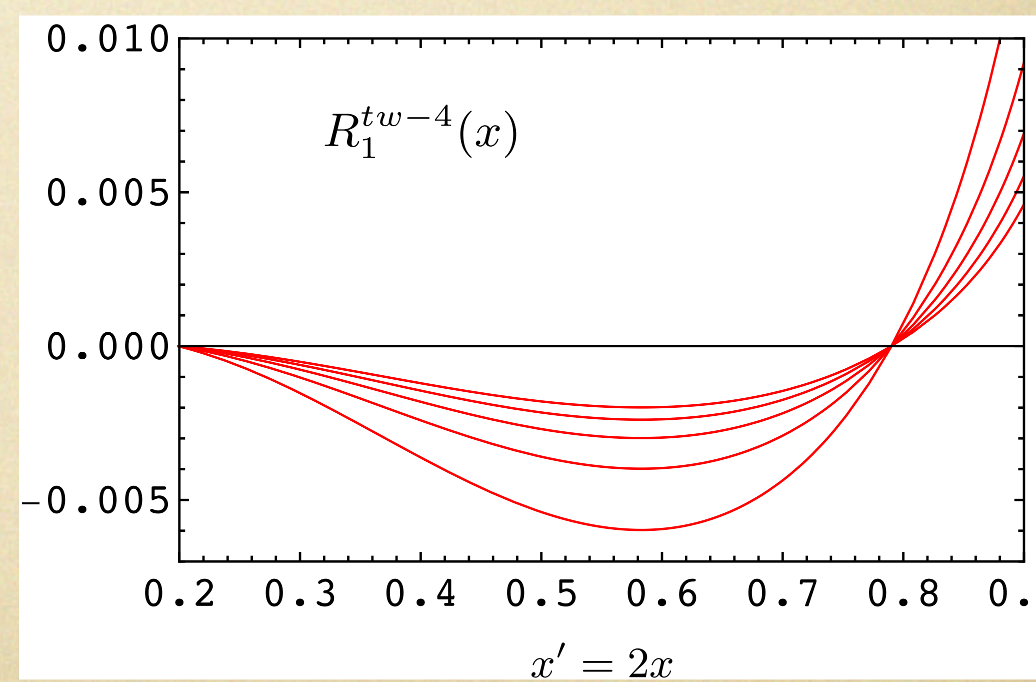


- *qqqG / qqq*:

$$[\widetilde{Q}_p(x)]_{\rm tot}/[\widetilde{Q}_p(x)]_{qqq} \sim (1-x)^3$$

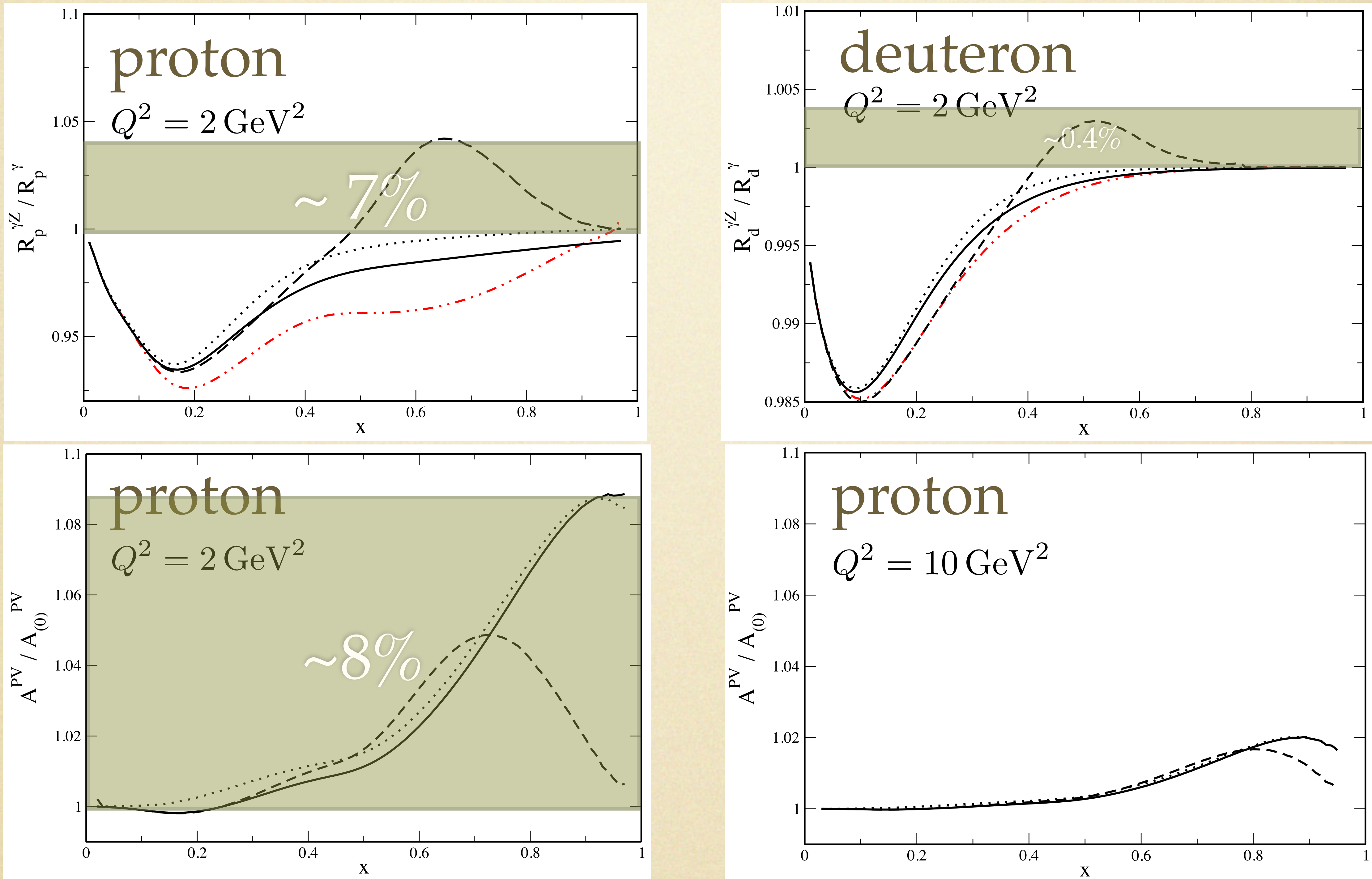
- Large-x behavior:

$$[\widetilde{Q}_p(x)]_{\rm tot}/u_p(x)\Big|_{x\to 1} \sim \log(1-x)$$



Target mass effects

Hobbs & Melnitchouk'08

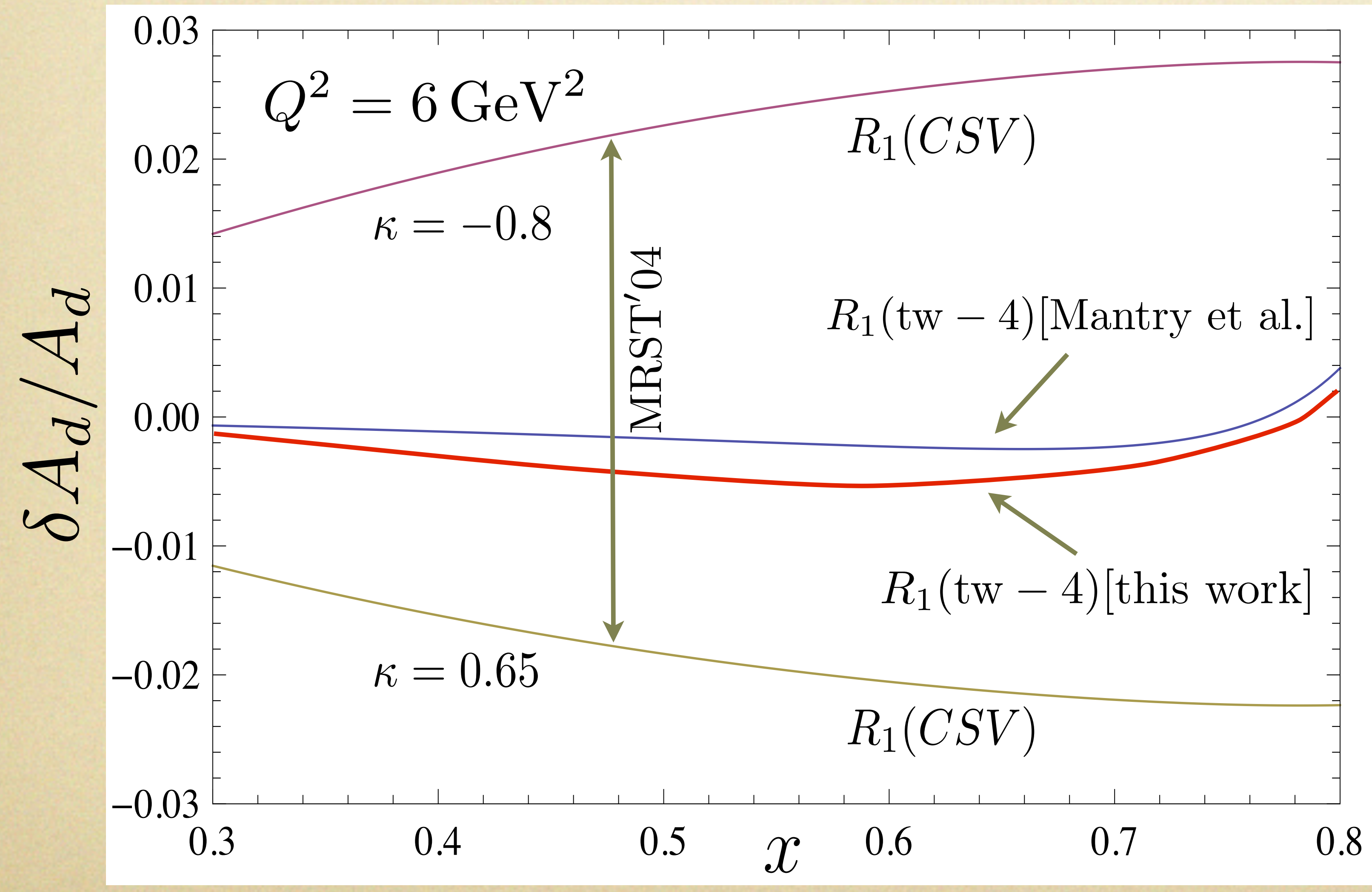


- Proton asymmetry is enhanced by ~8%
- Less then 1% effect on deuteron asymmetry

Charge-symmetry violation

- Sensitivity to CSV $\tilde{a}_1 = \tilde{a}_1^{(0)} + \delta^{\mathrm{CSV}}\tilde{a}_1$

$$\frac{\delta^{\mathrm{CSV}}\tilde{a}_1}{\tilde{a}_1^{(0)}} = \left(-\frac{3}{10} + \frac{1}{2}\frac{2C_{1u}+C_{1d}}{2C_{1u}-C_{1d}}\right)\frac{\delta u - \delta d}{u+d}$$



MRST'04

$$\delta u - \delta d \simeq 2\kappa(1-x)^4\sqrt{x}$$

from Mantry, Ramsey-Musolf '11

see also Hobbs & Melnitchouk'08

Conclusions

- PV-DIS on deuteron is arguably a clean(er) probe for NP
- Future experimental capabilities will hopefully allow to disentangle various effects
- LR asymmetry on deuteron is sensitive to single twist-4 quark matrix element
- LCWF estimates demonstrate boarderline effect: it has to be included to improve sensitivity to NP