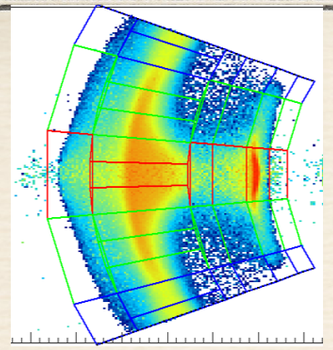
Higher Twist Effects in PVDIS

Sonny Mantry
University of North Georgia

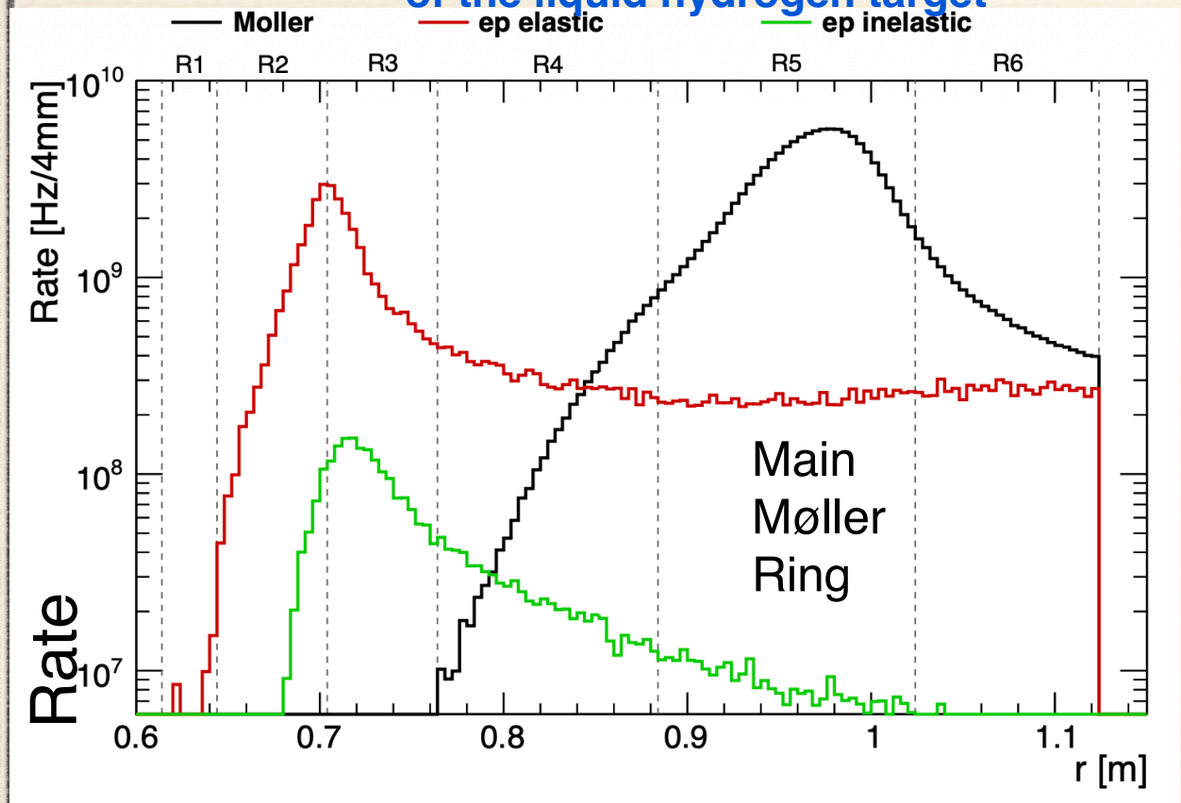
Precision Physics with MOLLER, Workshop 2026
November 5th-6th, 2026



Inclusive Electron Rate Distributions

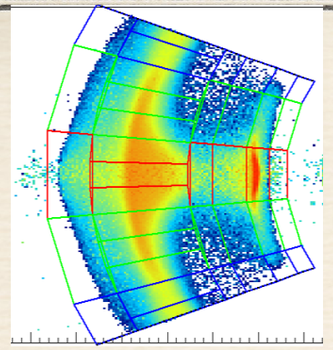
Inclusive 11 GeV electron scattering off hydrogen

Radial distributions 26.5 m downstream of the liquid hydrogen target



- Black: e-e scattering
- Red: elastic e-p scattering
- Green: inelastic e-p scattering

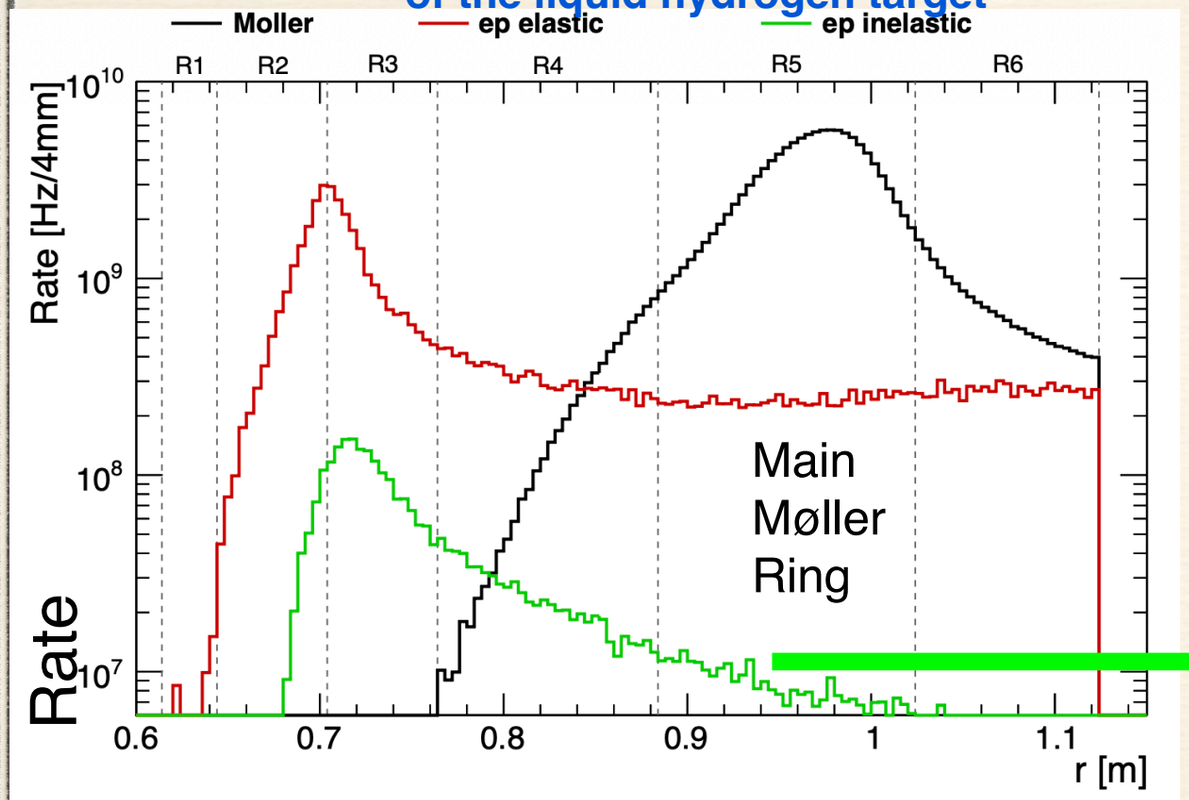
Slide from K.Kumar's Talk

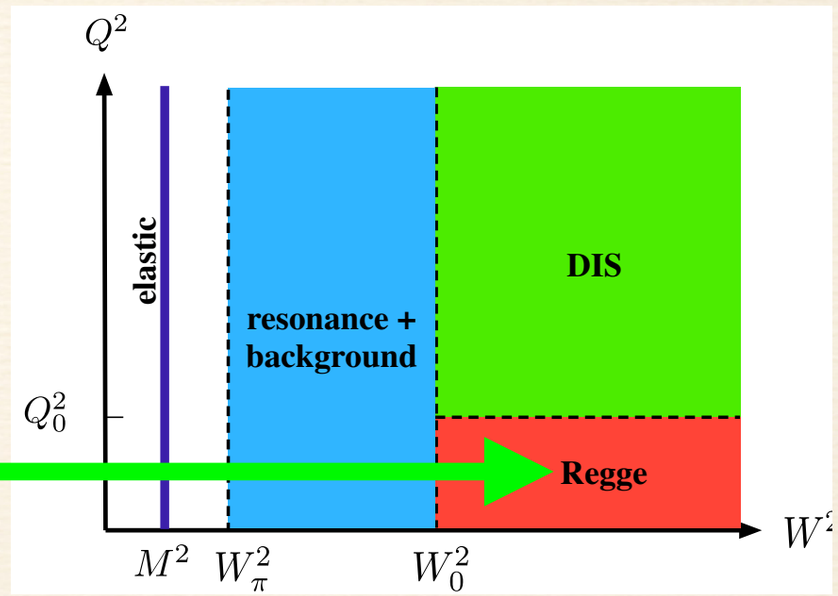


Inclusive Electron Rate Distributions

Inclusive 11 GeV electron scattering off hydrogen

Radial distributions 26.5 m downstream of the liquid hydrogen target





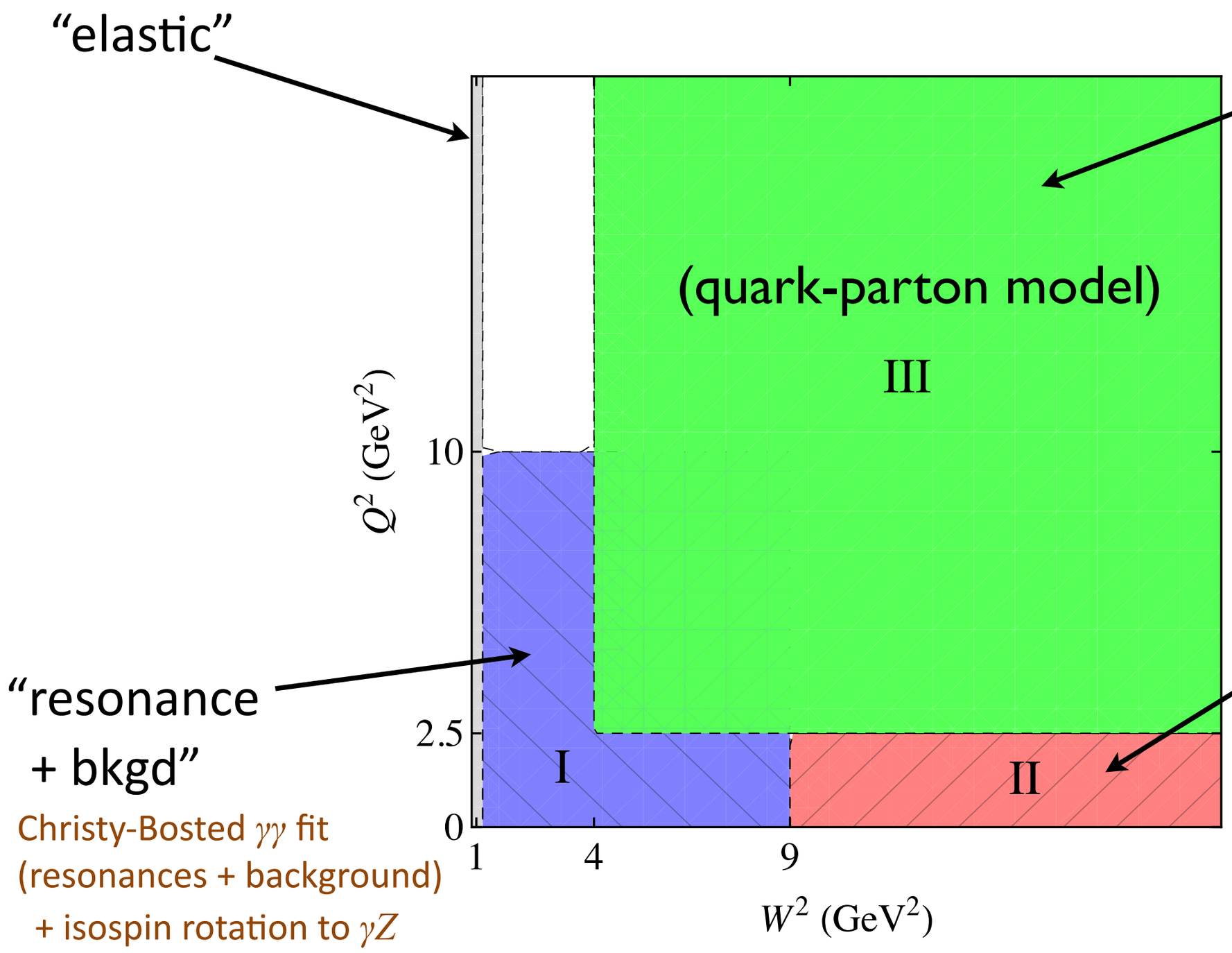
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From P. Blunden's Talk

Slide from P. Blunden's Talk

Structure function map: 3 distinct regions

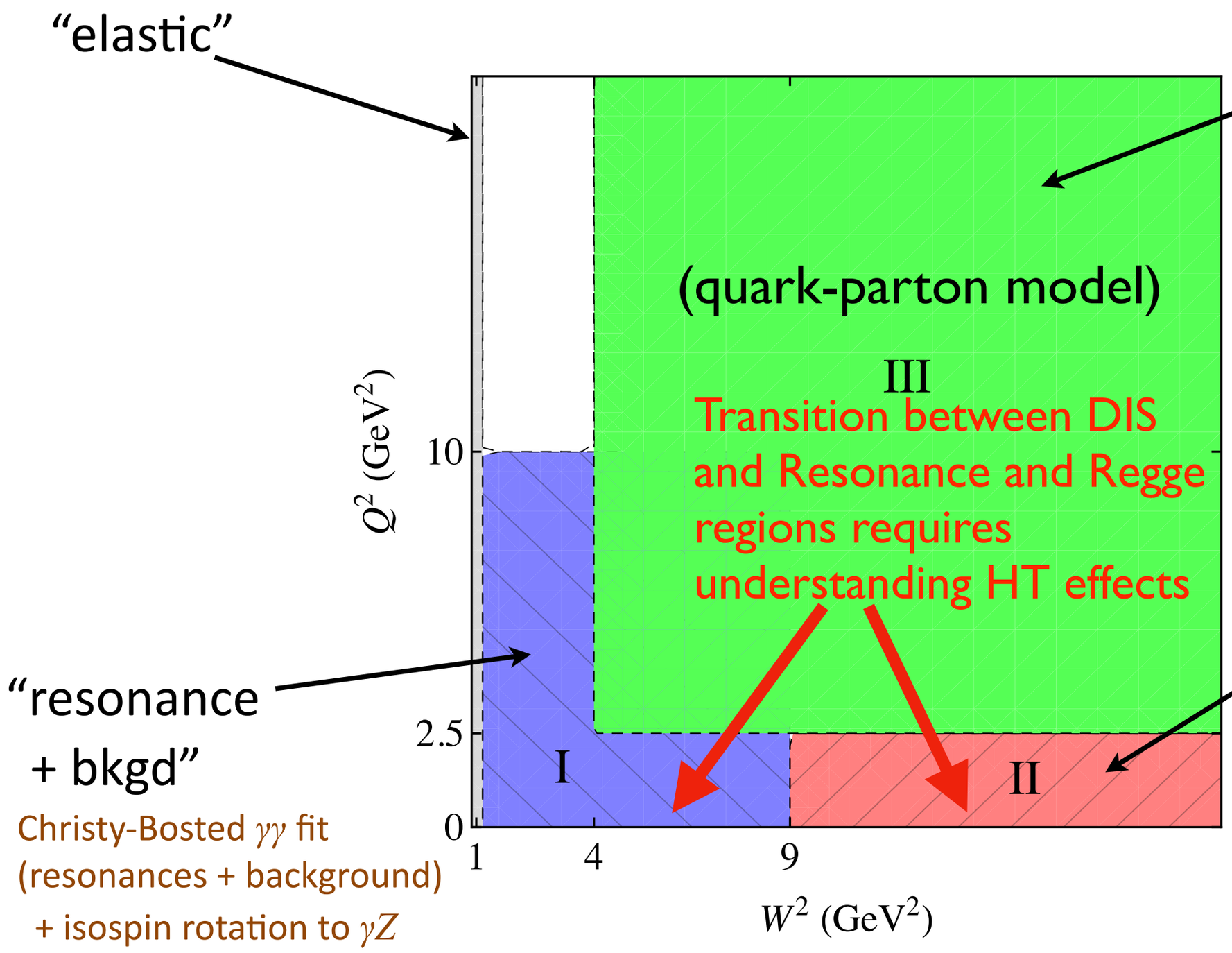
Need structure functions for $A_e \times V_h$ $(F_{1,2}^{\gamma Z})$ and $V_e \times A_h$ $(F_3^{\gamma Z})$



Slide from P. Blunden's Talk

Structure function map: 3 distinct regions

Need structure functions for $A_e \times V_h$ $(F_{1,2}^{\gamma Z})$ and $V_e \times A_h$ $(F_3^{\gamma Z})$



Slide from K.Kumar's Talk

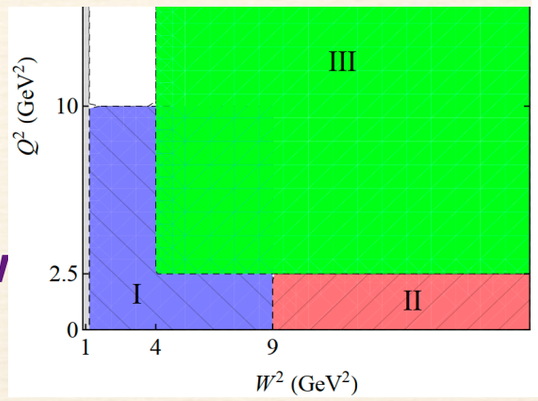
PV Electron-Proton Inelastic Scattering

MOLLER kinematics:	**E_{beam} = 11 GeV, $6 < \theta_{lab} < 20$ mrad, E' = 3 to 8 GeV** **$Q^2 \sim 0.001$ - 0.02 GeV^2, W^2 from 1 to 20 GeV^2**	**Diffractive Regime (VMD/Pomeron Physics)**

first principles: using electroweak neutral current structure functions

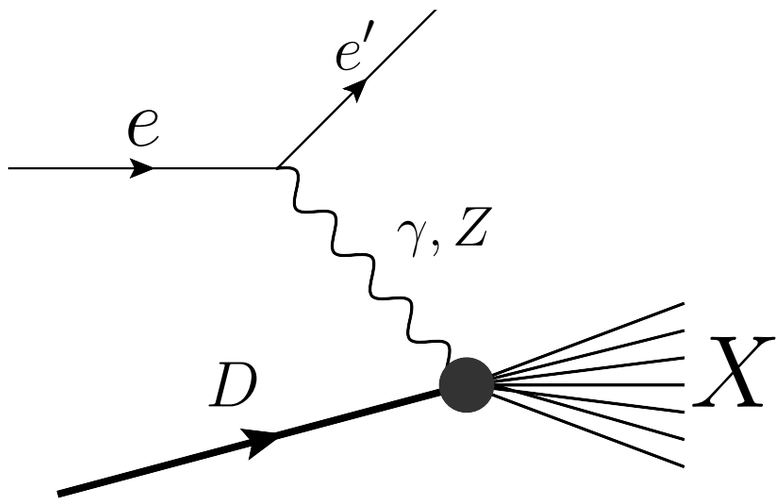
$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right] \Rightarrow A_{PV} \approx \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}}$$

At high Q^2, one can use quark pdf's and standard model couplings. At forward angles, the prediction is $A_{PV}/Q^2 \sim 8.5 \times 10^{-5}$. However, for very low Q^2, one needs a model as a function of W.



Models in the resonance and Regge regions must smoothly interpolate with DIS region, going across the region where HT effects are important

Electron-Deuteron Asymmetry



- Parity Violating asymmetry

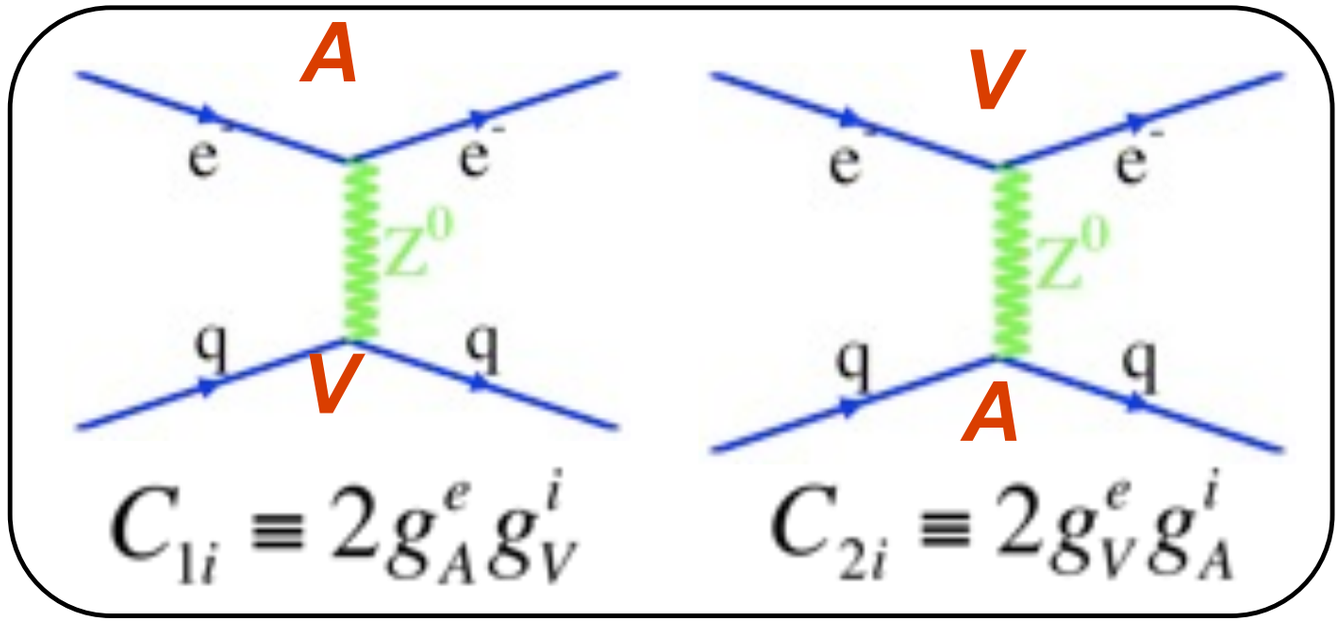
$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

- Probe of the parity-violating Weak Neutral Current (WNC) in the Standard Model (SM).

- Led to a spectacular confirmation of WNC theory of the SM in 1978 (SLAC).

- Gave one of the first precise measurements of the weak mixing angle to within 10%.

Electron-Deuteron Asymmetry



- Probe of parity-violating interactions in the Standard Model.

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

- Led to one of the first measurements of the weak mixing angle

$$C_{1u}^{\text{tree}} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W, \qquad C_{1d}^{\text{tree}} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W,$$
$$C_{2u}^{\text{tree}} = -\frac{1}{2} + 2\sin^2\theta_W, \qquad C_{2d}^{\text{tree}} = \frac{1}{2} - 2\sin^2\theta_W \quad .$$

Electron-Deuteron Asymmetry

- All hadronic effects cancel in the asymmetry to first approximation; Cahn-Gilman (CG) formula:

$$A_{\rm CG}^{RL} \;=\; -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\Big[\big(1-\frac{20}{9}\sin^2\theta_W\big)+\big(1-4\sin^2\theta_W\big)\frac{1-(1-y)^2}{1+(1-y)^2}\Big]$$

All hadronic effects cancel! → Clean probe of WNC

- Hadronic effects appear as small corrections to the CG formula.

Corrections to Cahn-Gilman

- In the precision era, all corrections to CG must be under control

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\tilde{a}_1 + \tilde{a}_2\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\tilde{a}_j = -\frac{2}{3}\left(2C_{ju} - C_{jd}\right)\left[1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})\right]$$

New physics

Sea quarks

Charge symmetry violation

Target mass

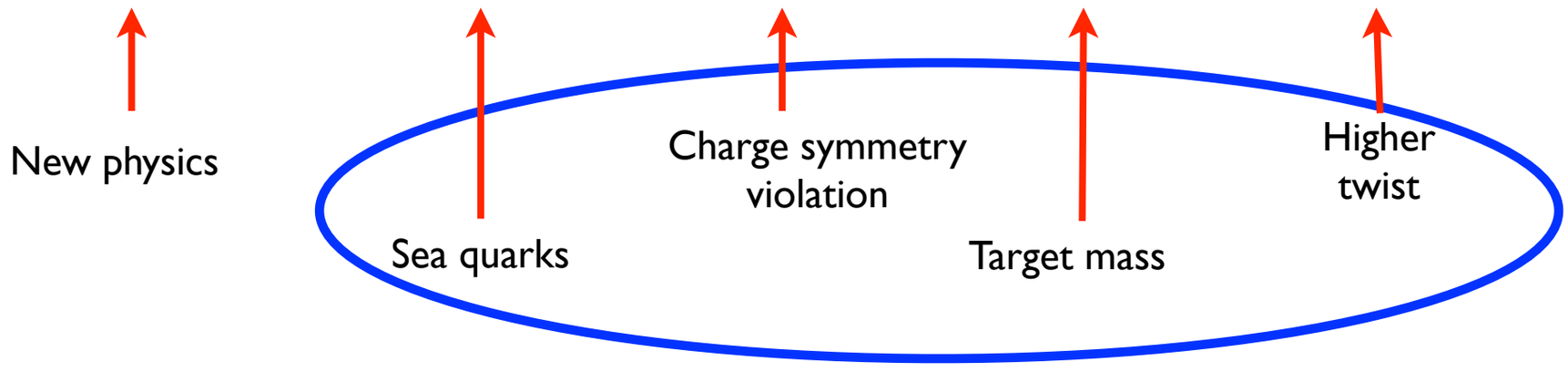
Higher twist

- Hadronic and electroweak effects must be well understood before any claim for evidence of new physics can be made.

Asymmetry as a Probe of Hadronic Physics

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\tilde{a}_1 + \tilde{a}_2\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\tilde{a}_j = -\frac{2}{3}\left(2C_{ju} - C_{jd}\right)\left[1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})\right]$$

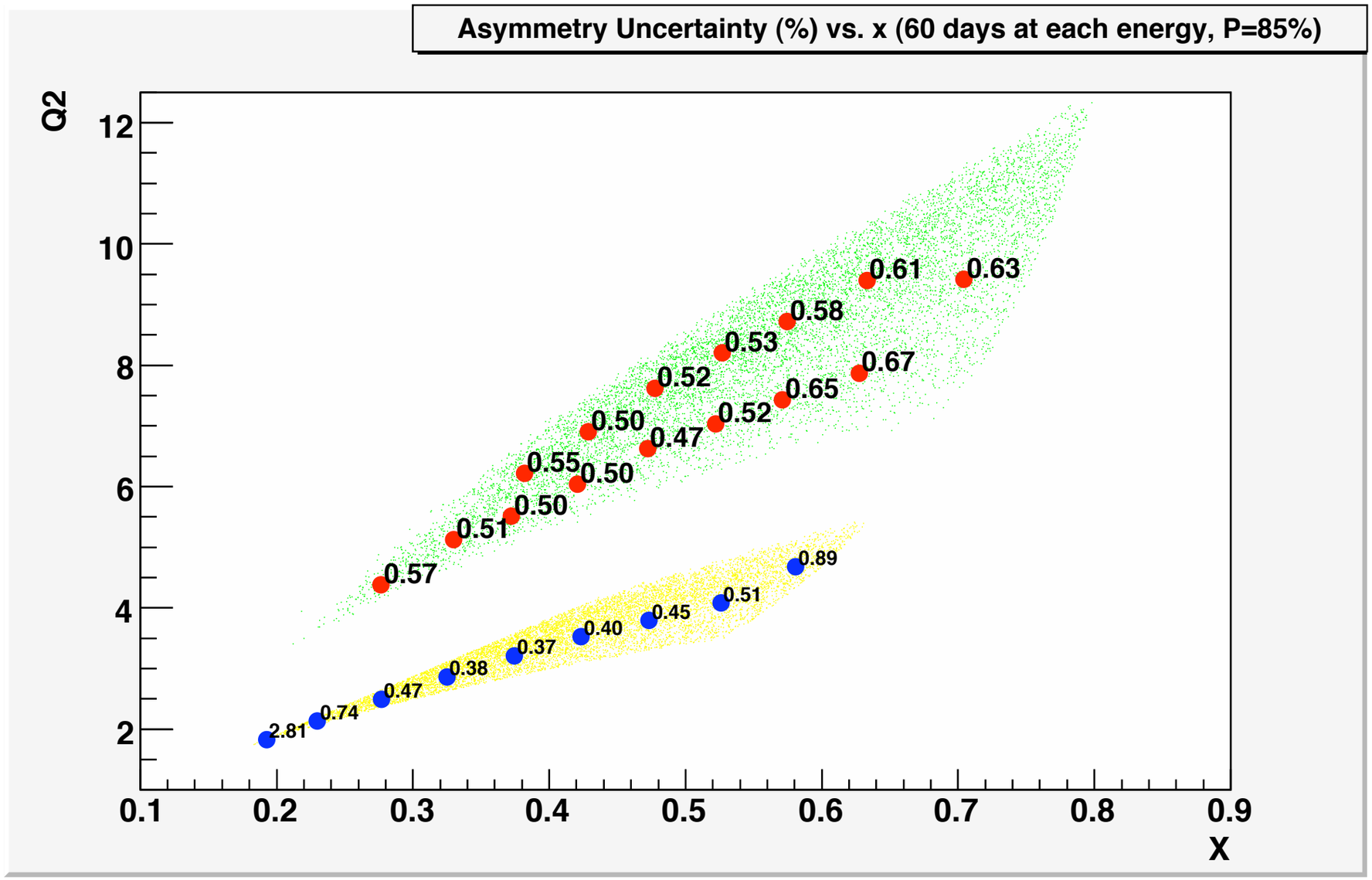


- Alternatively, precision PV DIS can be viewed as a probe of hadronic physics.

- Precision measurements over wide kinematic range can disentangle various effects.

SOLID

- SOLID plans to measure the asymmetry at the percent level over a wide kinematic range:

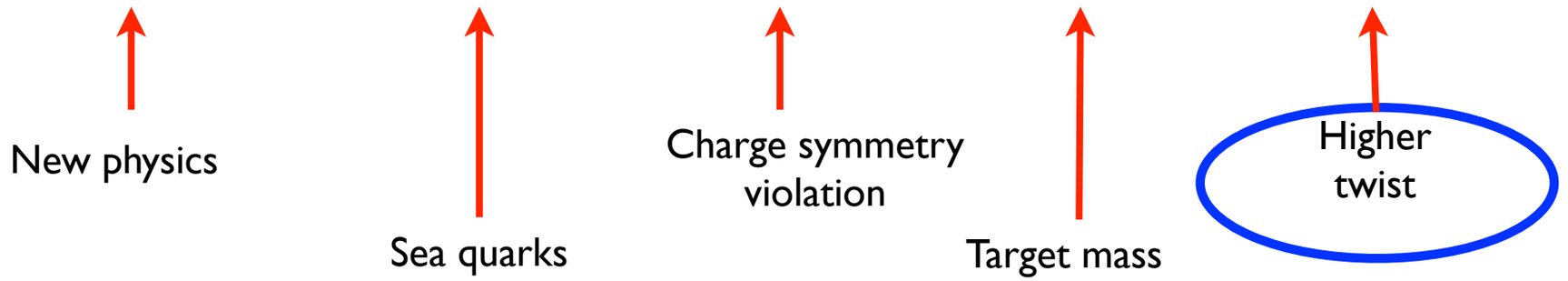


Projected data with errors for SOLID
(K.Kumar, P. Souder)

Asymmetry as a Probe of Higher Twist

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\tilde{a}_1 + \tilde{a}_2\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\tilde{a}_j = -\frac{2}{3}\left(2C_{ju} - C_{jd}\right)\left[1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})\right]$$

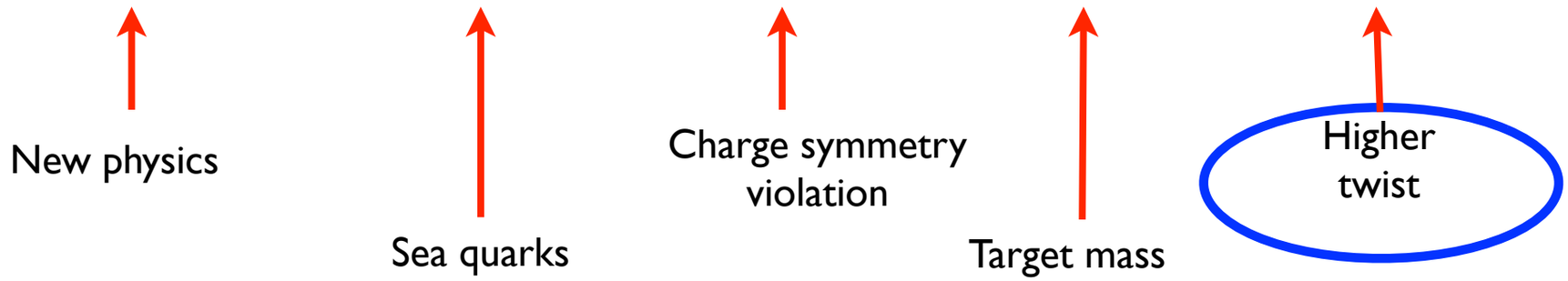


- Precision PV DIS can be a probe of higher twist correlations.

Asymmetry as a Probe of Higher Twist

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\tilde{a}_1 + \tilde{a}_2\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$\tilde{a}_j = -\frac{2}{3}\left(2C_{ju} - C_{jd}\right)\left[1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})\right]$$



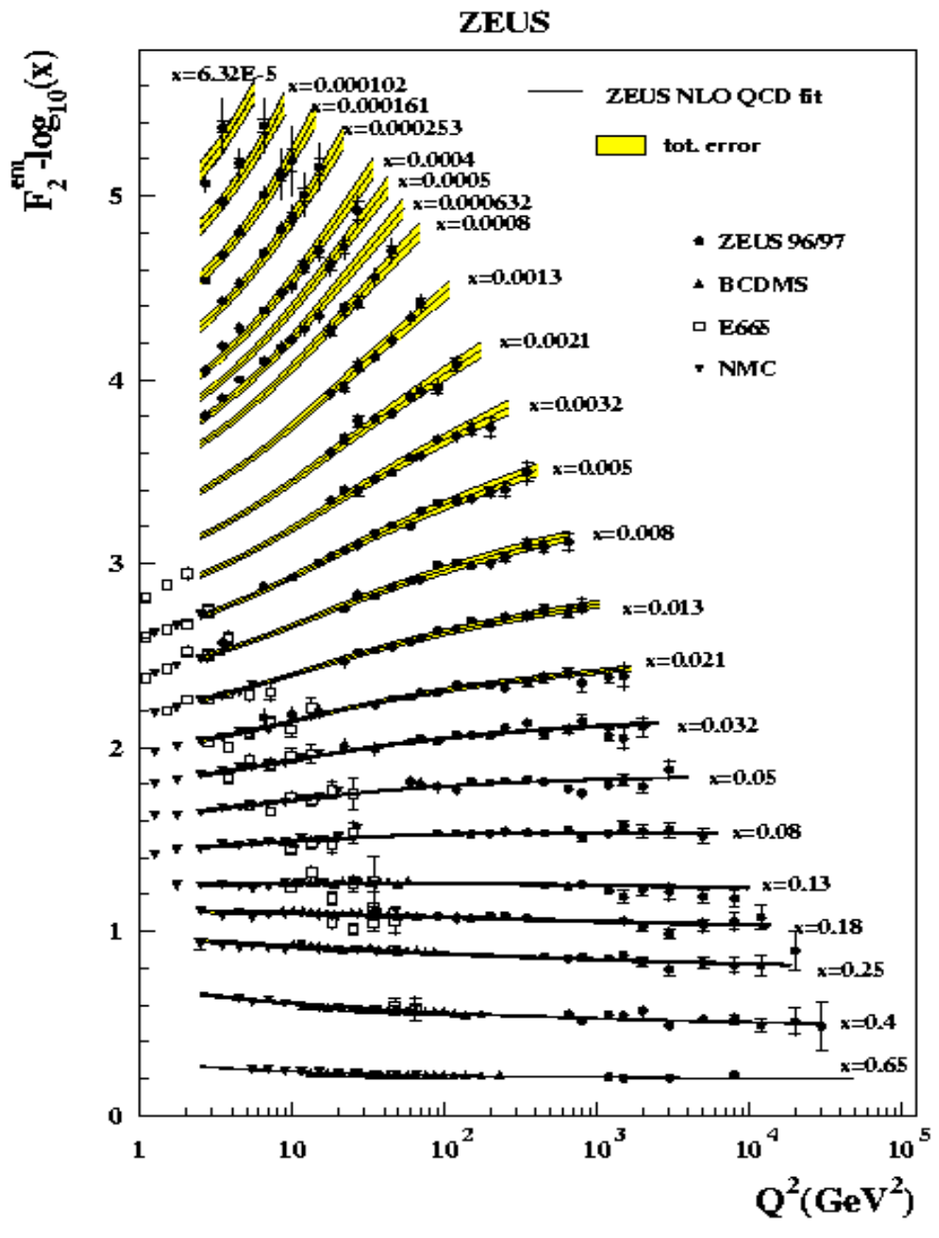
- Precision PV DIS can be a probe of higher twist correlations.

- Can probe a single four-quark matrix element which encodes quark-quark correlations. (Bjorken, Wolfenstein)

Higher Twist

Parton Model and Bjorken Scaling

- Bjorken limit: high Q^2 at fixed Bjorken-x.

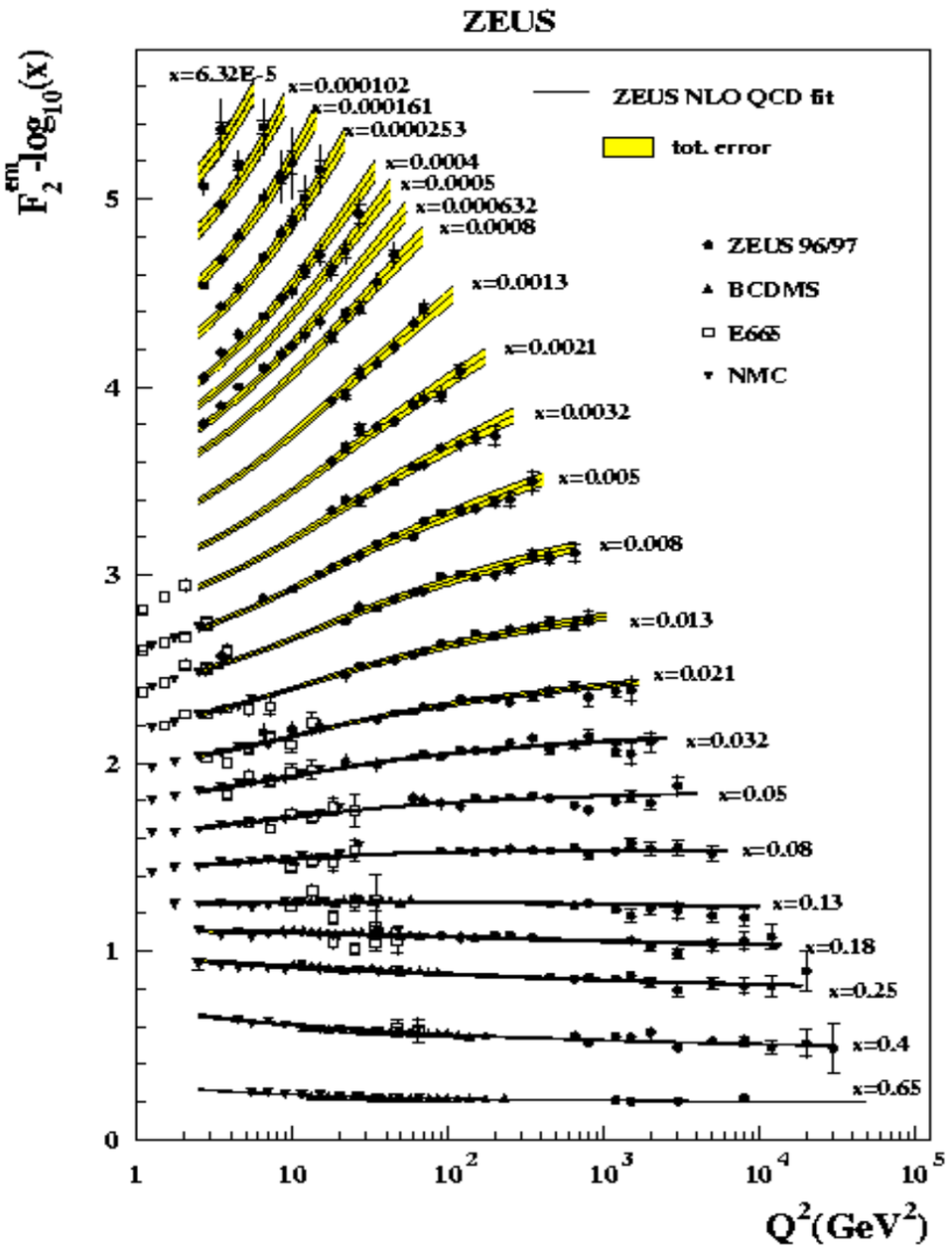


- Structure functions independent of Q^2 up to logarithmic deviations.

- Nucleon is a collection of "almost free quarks".

Parton Model and Bjorken Scaling

- Bjorken limit: high Q^2 at fixed Bjorken-x.

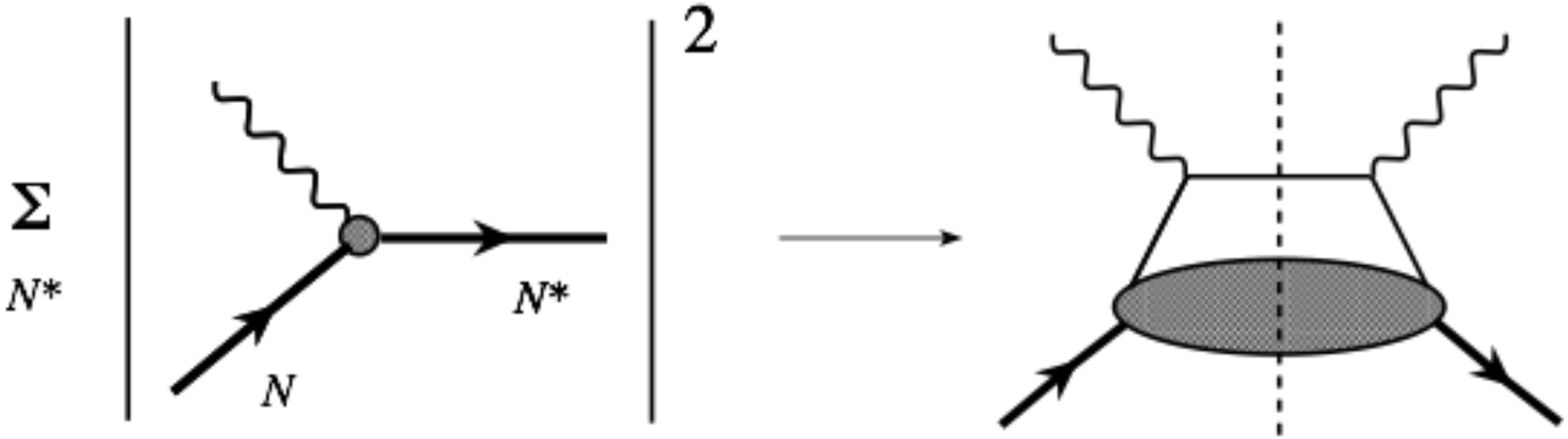


- Structure functions independent of Q^2 up to logarithmic deviations.

- Nucleon is a collection of "almost free quarks".

Long range quark and gluon correlations?

Operator Product expansion



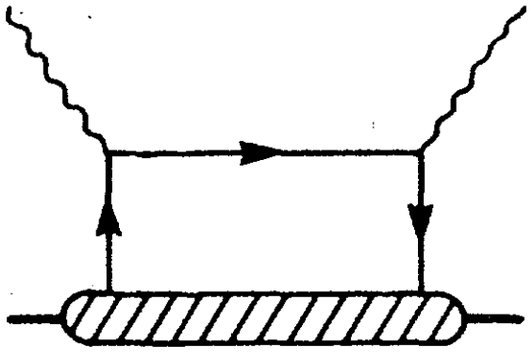
Optical Theorem

- Twist expansion:

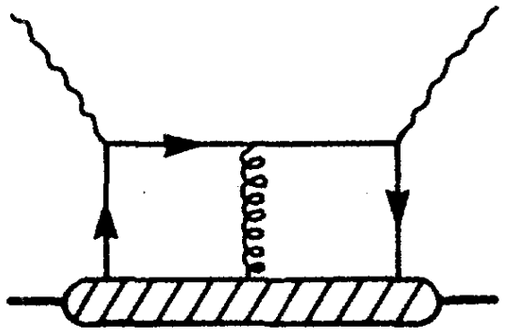
$$i\int d^4z\, e^{iq\cdot z} T\Big[J_\mu(z)J_\nu(0)\Big] = \sum_{n,\tau} C_{\mu\nu}^{(n,\tau)}(q,\mu)\, O^{(n,\tau)}(\mu)$$

- Leading twist gives the parton model.
- Correlation matrix elements beyond parton model suppressed by powers of 1/Q^2: Higher Twist Terms

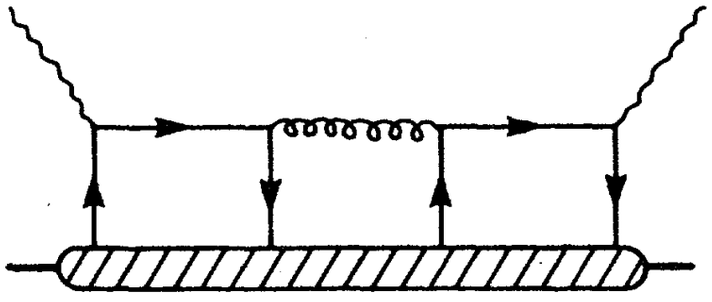
Operator Product Expansion



Twist-2 ⟶ Bjorken scaling



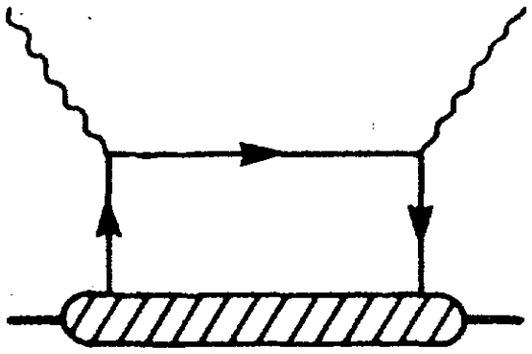
Quark-gluon correlation (Twist-4)



Power corrections

Quark-quark correlation(Twist-4)

Operator Product Expansion

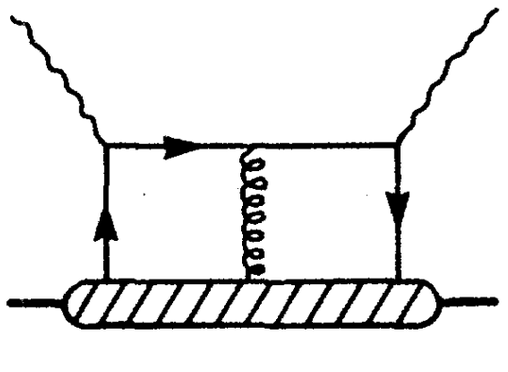


Twist-2

$$\mathcal{O}^{\rm NS}_{q;\mu_1\ldots\mu_n} = i^{n-1}\mathbf{S}\left[\bar{\psi}_f\,\gamma_{\mu_1}D_{\mu_2}\ldots D_{\mu_n}\frac{\lambda_a}{2}\,\psi_f\right] - \text{trace terms}$$

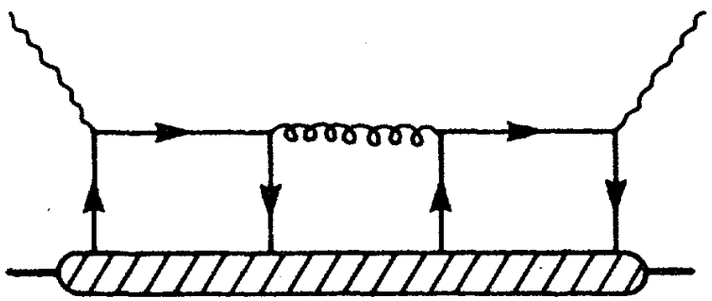
$$\mathcal{O}^{\rm S}_{q;\mu_1\ldots\mu_n} = i^{N-1}\mathbf{S}\left[\bar{\psi}_f\,\gamma_{\mu_1}D_{\mu_2}\ldots D_{\mu_n}\,\psi_f\right] - \text{trace terms},$$

$$\mathcal{O}^{\rm S}_{G;\mu_1\ldots\mu_n} = 2i^{N-2}\mathbf{S}\left[F^a_{\mu_1\alpha}D_{\mu_2}\ldots D_{\mu_{n-1}}F^{\alpha,a}_{\mu_n}\right] - \text{trace terms}$$



Quark-gluon correlation (Twist-4)

$$\Delta\cdot O^{G1}_n = \mathrm{Tr}[F^{\alpha\beta}\,\vec{d}^{\,n}\,F_{\alpha\beta}]$$



$$\Delta\cdot O^{G2(k,\ell)}_n = \mathrm{Tr}[f_\alpha\vec{d}^{\,n-4-k-\ell}\,f^\alpha\,\vec{d}^{\,k}\,f_\beta\vec{d}^{\,\ell}\,f^\beta]$$
$$\Delta\cdot O^{G3(k,\ell)}_n = \mathrm{Tr}[f_\alpha\vec{d}^{\,n-4-k-\ell}\,f^\beta\vec{d}^{\,k}\,f_\alpha\vec{d}^{\,\ell}\,f^\beta]$$
$$\Delta\cdot O^{G4(k,\ell)}_n = \mathrm{Tr}[f_\alpha\vec{d}^{\,n-4-k-\ell}\,f^\beta\vec{d}^{\,k}\,f_\beta\vec{d}^{\,\ell}\,f^\alpha]$$
$$\Delta\cdot O^{G5(\ell)}_n = \mathrm{Tr}[f_\alpha\vec{d}^{\,n-2-\ell}\,F_{\alpha\beta}\,\vec{d}^{\,\ell}\,f^\beta]$$

Quark-quark correlation(Twist-4)

$$\Delta\cdot Q^{1(k,\ell)}_n = g\bar{\psi}_R\not{\Delta}\overleftarrow{d}^{\ell}\vec{d}^{\,k}\psi_R\,\bar{\psi}_R\not{\Delta}\vec{d}^{\,n-2-k-\ell}\psi_R,$$
$$\Delta\cdot Q^{2(k,\ell)}_n = g\bar{\psi}_R\tau_a\not{\Delta}\overleftarrow{d}^{\ell}\vec{d}^{\,k}\psi_R\,\bar{\psi}_R\not{\Delta}\vec{d}^{\,n-2-k-\ell}\tau_a\psi_R,$$
$$\Delta\cdot Q^{3(k,\ell)}_n = g\bar{\psi}_R\not{\Delta}\overleftarrow{d}^{\ell}\vec{d}^{\,k}\psi_R\,\bar{\psi}_L\not{\Delta}\vec{d}^{\,n-2-k-\ell}\psi_L,$$
$$\Delta\cdot Q^{4(k,\ell)}_n = g\bar{\psi}_R\tau_a\not{\Delta}\overleftarrow{d}^{\ell}\vec{d}^{\,k}\psi_R\,\bar{\psi}_L\not{\Delta}\vec{d}^{\,n-2-k-\ell}\tau_a\psi_L,$$
$$\Delta\cdot Q^{5(k,\ell)}_n = g\bar{\psi}_L\not{\Delta}\overleftarrow{d}^{\ell}\vec{d}^{\,k}\psi_L\,\bar{\psi}_L\not{\Delta}\vec{d}^{\,n-2-k-\ell}\psi_L,$$
$$\Delta\cdot Q^{6(k,\ell)}_n = g\bar{\psi}_L\tau_a\not{\Delta}\overleftarrow{d}^{\ell}\vec{d}^{\,k}\psi_L\,\bar{\psi}_L\not{\Delta}\vec{d}^{\,n-2-k-\ell}\tau_a\psi_L,$$
$$\Delta\cdot Q^{7(k)}_n = \bar{\psi}\,\overleftarrow{d}^{\,k}\not{f}\gamma_5\vec{d}^{\,n-1-k}\psi,$$
$$\Delta\cdot Q^{8(k)}_n = i\bar{\psi}\not{\Delta}\overleftarrow{d}^{\,k}\not{f}\,\vec{d}^{\,n-1-k}\psi,$$

- The nucleon matrix elements in the twist expansion can be accessed via moments of the structure functions:

$$M_2^{(n)}(Q^2) = \int_0^1 dx\, x^{n-2} F_2(x, Q^2)$$

$$M_2^{(n)}(Q^2) = \sum_i \sum_{\tau=2k}^{\infty} \left(\frac{\Lambda^2}{Q^2}\right)^{\frac{\tau-2}{2}} C^i_{n\tau}(\mu, Q^2) \quad \frac{\langle \mathcal{O}^i_{n\tau} \rangle}{\Lambda^{\tau-2}}.$$

- The large number of operators at higher twist require phenomenological parameterizations:

$$F_i(x_B, Q^2) = F_i^{\text{LT+TMC}}(x_B, Q^2) + \frac{H_i(x_B)}{Q^2}$$

$$F_i(x_B, Q^2) = F_i^{\text{LT+TMC}}(x_B, Q^2)\left[1 + \frac{C_i(x_B)}{Q^2}\right]$$

(see recent review by W. Melnitchouk, arXiv: 2609.19620)

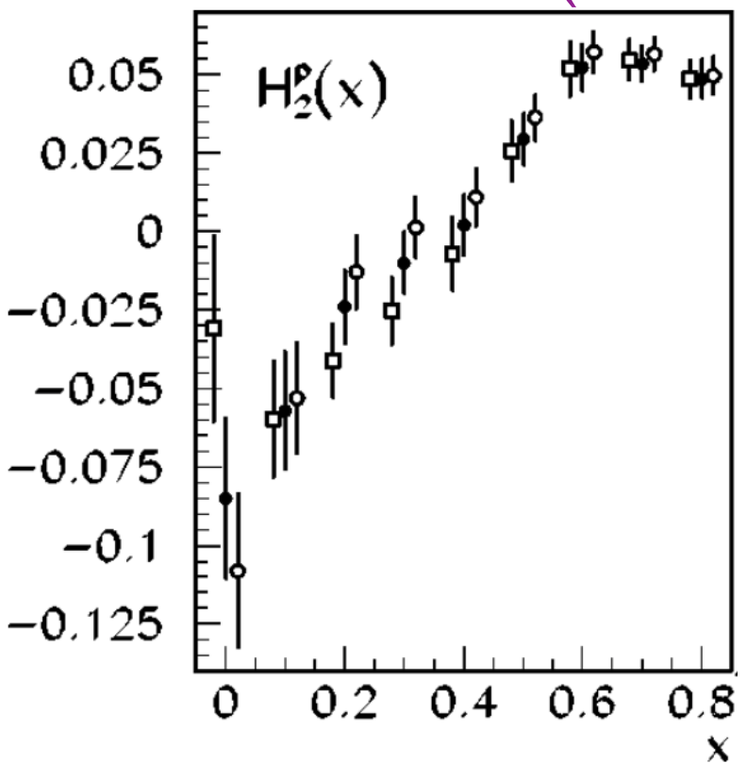
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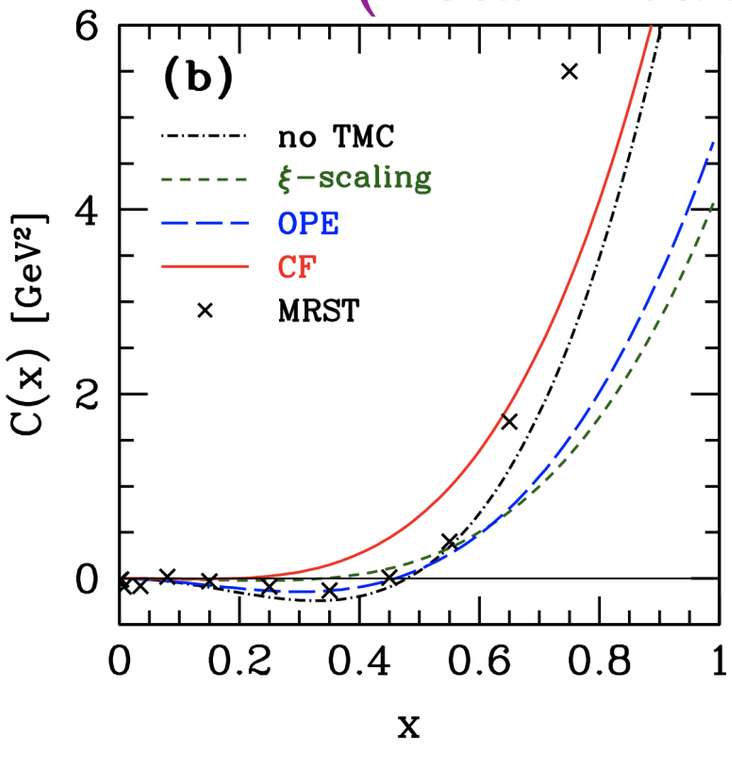
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$$F_i(x_B, Q^2) = F_i^{\mathrm{LT+TMC}}(x_B, Q^2)\left[1 + \frac{C_i(x_B)}{Q^2}\right]$$

(Alekhin 2001)

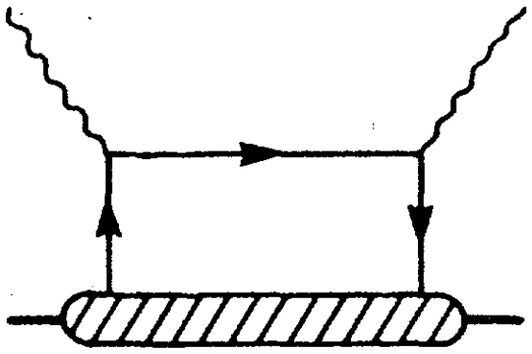


(Accardi et. al. 2010)

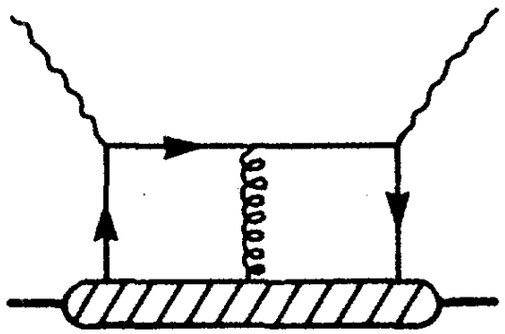


Leading twist and target mass corrections are not sufficient to describe data at high precision. Higher twist effects must be incorporated.

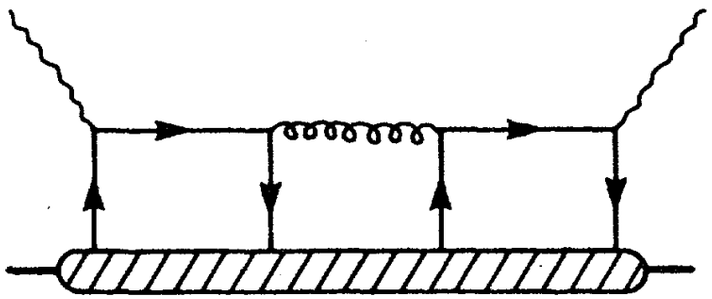
Operator Product Expansion



Twist-2



Quark-gluon correlation (Twist-4)



Quark-quark correlation(Twist-4)

Isolated in e-D asymmetry

$$\mathcal{O}^{\mu\nu}_{ud}(x) = \frac{1}{2}[\bar{u}(x)\gamma^{\mu}u(x)d(0)\gamma^{\nu}d(0) + (u \leftrightarrow d)]$$

Key features of the Asymmetry Terms

- Asymmetry can be brought into the form:

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

- Dominant term in asymmetry
- Can in principle be kinematically distinguished from second term (independent of y)
- Can be sensitive to only quark-quark correlations
- A single twist-4 matrix element determines quark-quark correlations.

- suppressed by small electron vector coupling
- Can be kinematically distinguished from second term(dependent on y)
- Can be sensitive to quark-quark and quark-gluon correlations
- Multiple twist-4 matrix elements determine correlations
- Can be extracted from neutrino scattering data

Key features of the Asymmetry Terms

- Asymmetry can be brought into the form:

Focus of this talk

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

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Some Definitions and Notation

- Asymmetry can be brought into the form:

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

- The Y_1 factor has the form:

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

- The Y_3 factor has the form:

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

- We have used the definitions:

$$R^{\gamma(\gamma Z)} \equiv \frac{\sigma_L^{\gamma(\gamma Z)}}{\sigma_T^{\gamma(\gamma Z)}} = r^2 \frac{F_2^{\gamma(\gamma Z)}}{2xF_1^{\gamma(\gamma Z)}} - 1, \qquad r^2 = 1 + \frac{4M^2x^2}{Q^2}$$

Cahn-Gilman Limit

- Cahn-Gilman limit:

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

$$R^\gamma = R^{\gamma Z} = r^2 - 1,$$

$$Y_1 = 1$$

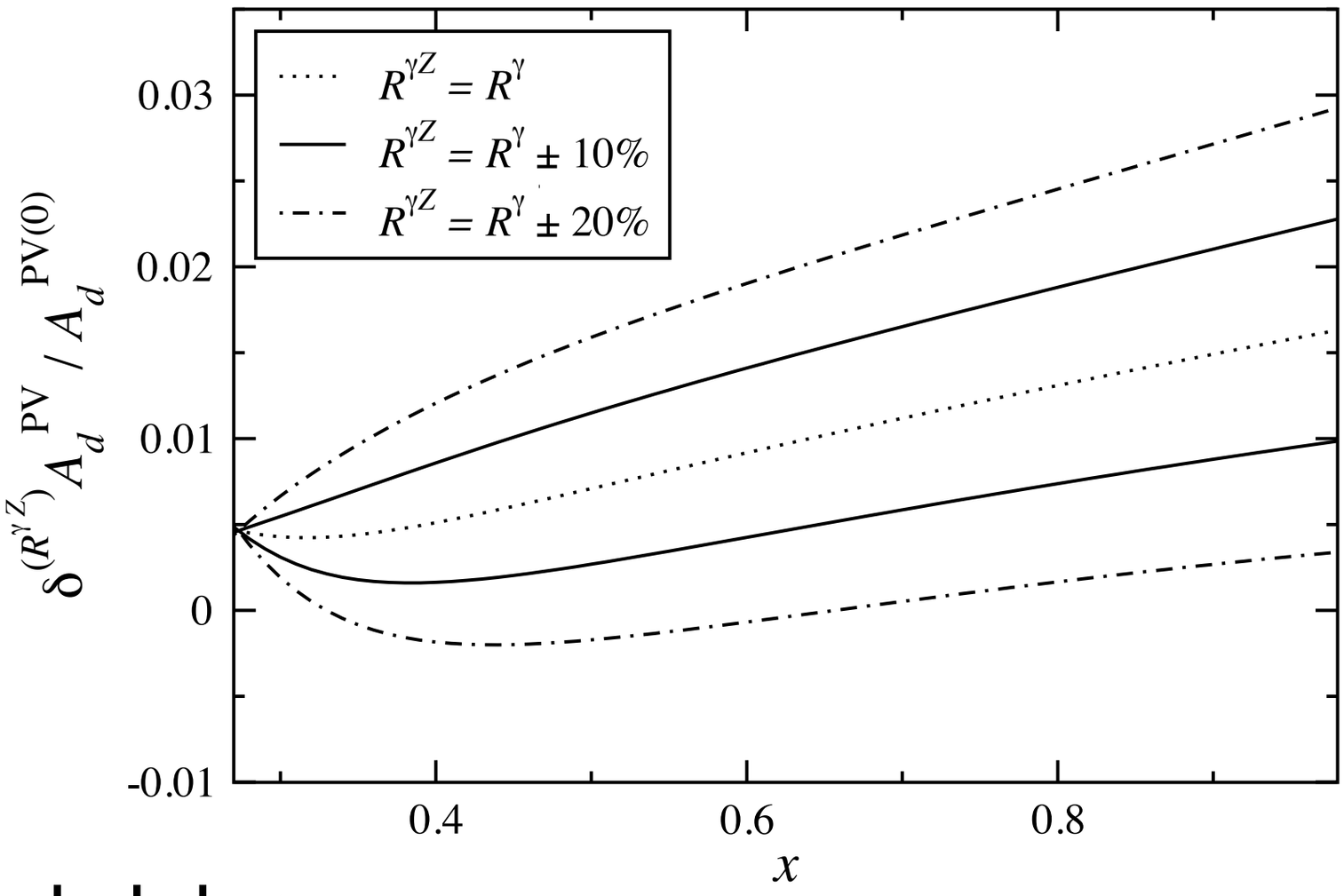
$$\left[\frac{F_1^{\gamma Z}}{F_1^\gamma}\right]_{\rm CG} = \frac{9}{10}(1 - \frac{20}{9}\sin^2\theta_W)$$

- Higher twist effects can modify these relations.

Hobbs/Melnitchouck Analysis

- Considered the possibility that higher twist effects arise entirely through the relation:

$$R^{\gamma} \neq R^{\gamma Z}$$



- Concluded that:

  -20% difference gives a 1% effect in asymmetry

  -Could interfere with extraction of CSV effects

More Recent Analysis

(SM, M.Ramsey-Musolf, G.Sacco)

- Our conclusions based on the Bjorken/Wolfenstein argument:

-Twist-4 effects in vector WNC term come only from quark-quark correlations.
-A single 4-quark twist-4 matrix element contributes to the vector WNC term.
- The relation $R^{\gamma Z} = R^{\gamma}$ holds true at twist-4 up to perturbative corrections.

Only quark-quark correlations given by a single matrix element

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

$Y_1 = 1$

Twist-4 effects reside in ratio of form factors

Bjorken-Wolfenstein Argument

- Isospin decomposition of electromagnetic and vector neutral currents:

$$J_\gamma^\mu \;=\; v_\mu + \frac{1}{3}s_\mu - \frac{1}{3}\lambda_\mu$$

$$J_Z^{V\mu} \;=\; 2\big[(1-2\sin^2\theta)v_\mu - \frac{2}{3}\sin^2\theta s_\mu - (\frac{1}{2}-\frac{2}{3}\sin^2\theta)\lambda_\mu\big]$$

$$v_\mu = \frac{1}{2}(\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d), \qquad s_\mu = \frac{1}{2}(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d), \qquad \lambda_\mu = \bar{s}\gamma_\mu s$$

- Isospin decomposition of electromagnetic and interference hadronic tensors

$$W_{\mu\nu}^{\gamma} \;=\; W_{\mu\nu}^{vv} + \frac{1}{9}W_{\mu\nu}^{ss}\,.$$

$$W_{\mu\nu}^{V;\gamma Z} \;=\; 2(1-2\sin^2\theta)W_{\mu\nu}^{vv} - \frac{4}{9}\sin^2\theta W_{\mu\nu}^{ss}$$

Bjorken-Wolfenstein Argument

- Isospin decomposed hadronic tensors:

$$W^{vv}_{\mu\nu} = \frac{1}{2\pi M}\int d^4x\, e^{iq\cdot x}\langle D(P)|v_\mu(x)v_\nu(0)|D(P)\rangle$$

$$W^{ss}_{\mu\nu} = \frac{1}{2\pi M}\int d^4x\, e^{iq\cdot x}\langle D(P)|s_\mu(x)s_\nu(0)|D(P)\rangle$$

- Twist-4 quark-quark correlation hadronic tensor:

$$W^{du}_{\mu\nu} = W^{ss}_{\mu\nu} - W^{vv}_{\mu\nu},$$

$$= \frac{1}{2\pi M}\int d^4x\, e^{iq\cdot x}\langle D(P)|\frac{1}{2}\{\bar{d}(x)\gamma_\mu d(x)\;\bar{u}(0)\gamma_\nu u(0) + (u\leftrightarrow d)\}|D(P)\rangle$$

- Structure Function definitions

$$W^{vv,ss,du}_{\mu\nu} = \big(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\big)\frac{F_1^{vv,ss,du}}{M} + \big(P_\mu - \frac{P\cdot q}{q^2}q_\mu\big)\big(P_\nu - \frac{P\cdot q}{q^2}q_\nu\big)\frac{F_2^{vv,ss,du}}{MP\cdot q}$$

$$F^{vv}_{1,2} = F^{ss}_{1,2} - F^{du}_{1,2}$$

Bjorken-Wolfenstein Argument

- Original structure functions can be written as:

$$F_{1,2}^{\gamma} = \frac{10}{9} F_{1,2}^{ss} - F_{1,2}^{du}$$

$$F_{1,2}^{\gamma Z} = 2(1 - \frac{20}{9}\sin^2\theta) F_{1,2}^{ss} - 2(1 - 2\sin^2\theta) F_{1,2}^{du}$$

- Asymmetry in terms of original structure functions:

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

- Y_1 term:

$$A_{RL}^V = -\frac{9}{10}\left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right) g_A^e \left\{\left(1 - \frac{20}{9}\sin^2\theta\right) - \frac{1}{10}\frac{F_1^{du}}{F_{1;LT}^{ss}} + \cdots\right\}$$

Form of twist-4 correction

- Y1 term:

$$A_{RL}^{V} = -\frac{9}{10}\left(\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\right) g_A^e \left\{ \left(1 - \frac{20}{9}\sin^2\theta\right) - \frac{1}{10}\frac{F_1^{du}}{F_{1;LT}^{ss}} + \cdots \right\}$$

- Twist-4 correction given by:

$$R_1(\mathrm{HT}) = \left[\frac{-4}{5(1-\frac{20}{9}\sin^2\theta_W)}\right]\frac{F_1^{du}}{u_p(x)+d_p(x)}.$$

$$R^{\gamma Z} \;=\; R^{\gamma}$$

- Quark-quark correlation twist-4 operator matrix element:

twist-4 structure functions

$$\frac{1+R^{\gamma Z}}{1+R^{\gamma}} \;=\; 1+\frac{(F_2^{du}-2xF_1^{du})}{2xF_{1;LT}^{ss}}\left[\frac{9}{10}-\frac{1-2\sin^2\theta}{1-\frac{20}{9}\sin^2\theta}\right]$$

twist-2 structure function

- Using the Callan-Gross relation at tree level we get:

$$F_2^{du} \;=\; 2xF_1^{du} \longrightarrow \frac{1+R^{\gamma Z}}{1+R^{\gamma}} \;=\; 1$$

(R.Ellis, W.Furmanski, R.Petronzio; X.Ji; J.Qiu)

- We also give an effective field theory (SCET) argument

(SM, M. Ramsey-Musolf, G.Sacco)

$$R^{\gamma Z} \;=\; R^{\gamma}$$

$$\frac{1+R^{\gamma Z}}{1+R^{\gamma}} \;=\; 1$$

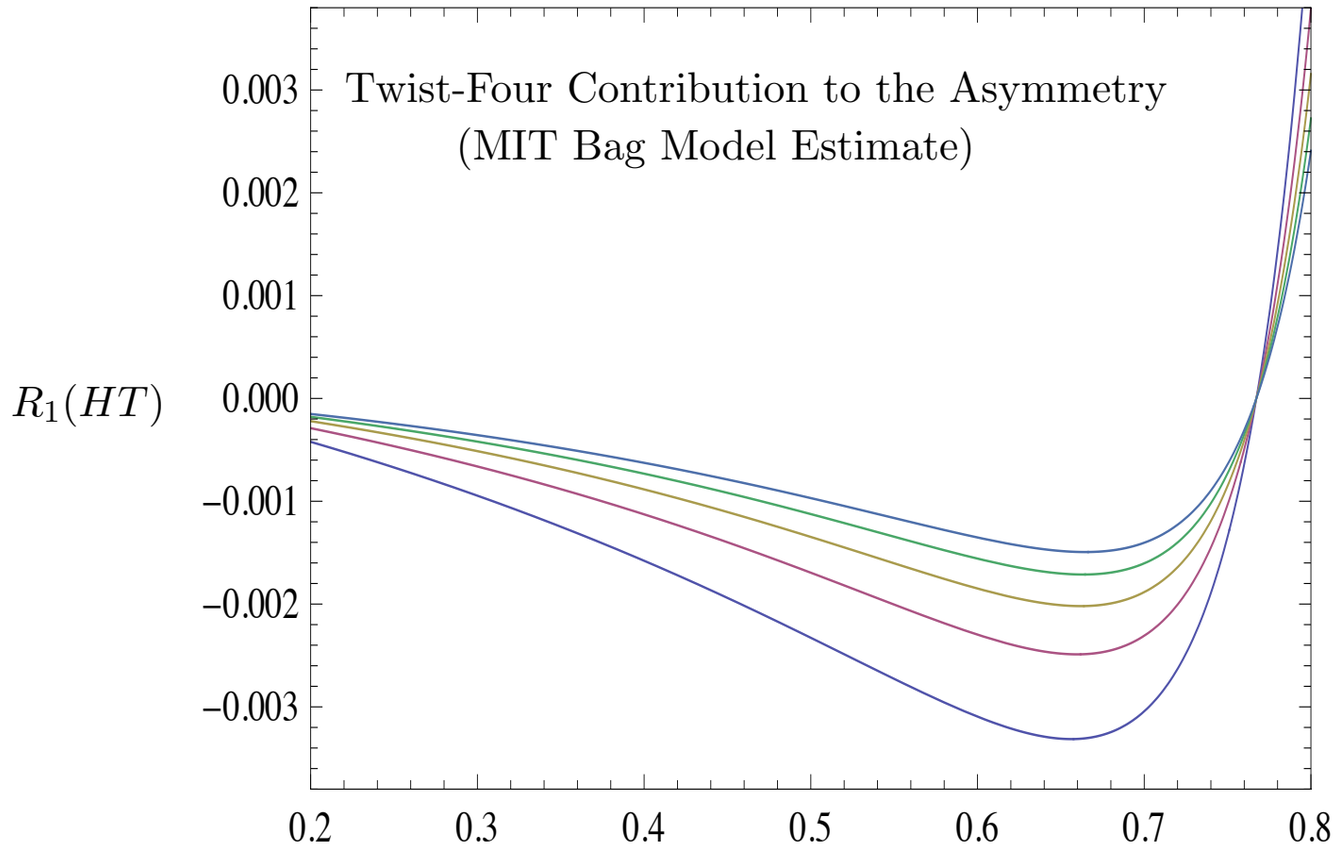
- Using the Callan-Gross relation at tree level we get:

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

free of twist-4 effects

twist-4 quark-quark correlations reside in ratio of structure functions

Form of twist-4 correction

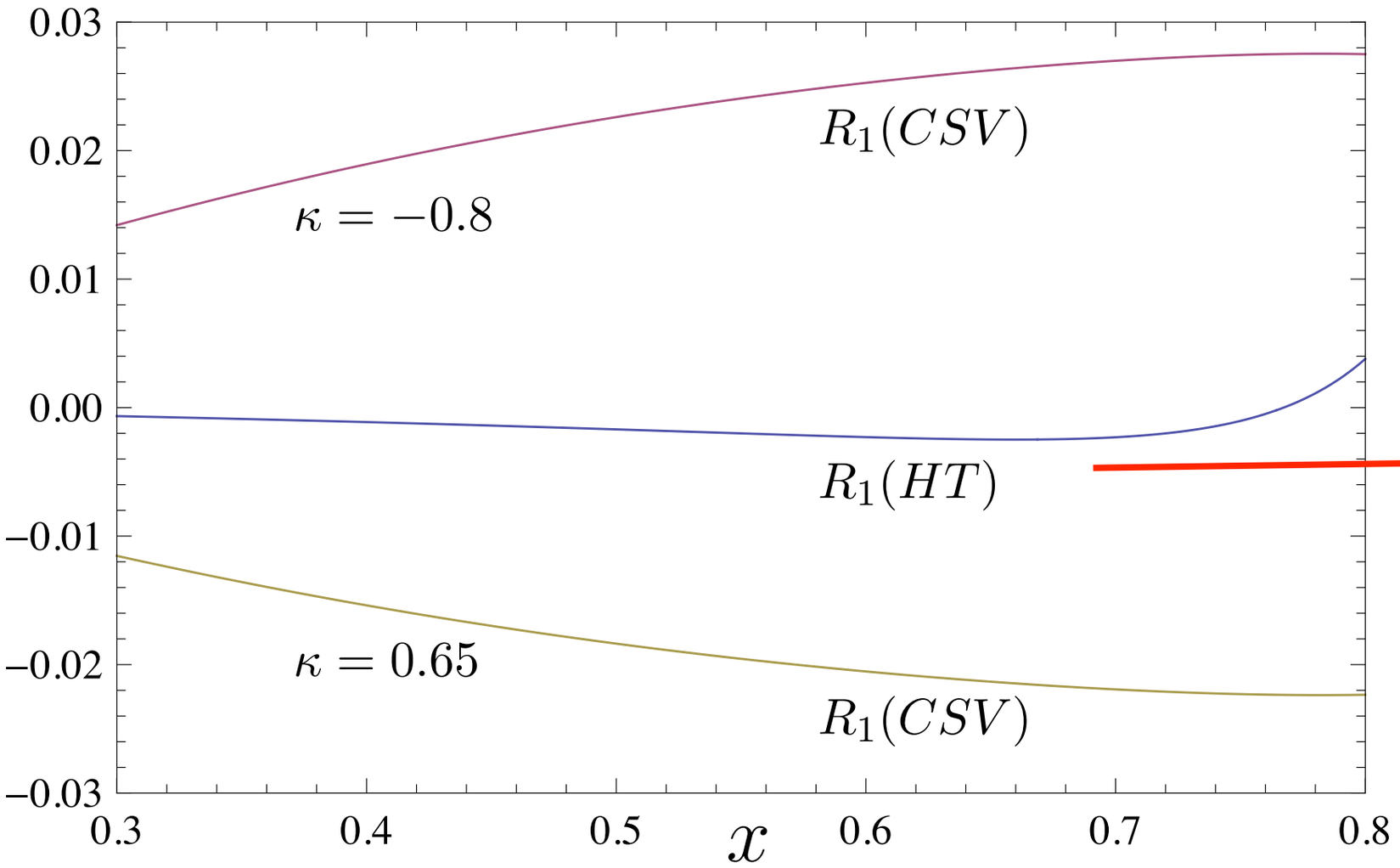


$$R_1(\mathrm{HT}) \;=\; \left[\frac{-4}{5(1-\frac{20}{9}\sin^2\theta_W)}\right]\frac{F_1^{du}}{u_p(x)+d_p(x)}.$$

- Bag model estimate of quark-quark correlation is below the half-percent level.

- Estimates using multi-parton nucleon light-cone wave functions, found an effect twice as big. (Belitsky, Manashov, Schafer)

CSV vs Higher Twist



Bag model estimate of higher twist

$$\delta u - \delta d \;=\; 2\kappa f(x), \qquad f(x) \;=\; x^{-1/2}(1-x)^4(x-0.0909)$$

- Negligible higher twist effects can allow for a cleaner extraction of CSV or new physics effects.

Conclusions

- PV DIS can be a powerful probe of hadronic physics beyond the parton model.
- The precision and wide kinematic reach of 12 GeV Upgrade at JLAB can in principle disentangle various hadronic effects such as sea quarks, CSV, and higher twist.
- PV DIS can probe a `single' twist-4 quark-quark correlation matrix element and is the only known observable with this property.
- Uncertainties in $R_{\gamma Z}$ appear to have only a small effect on higher twist effects.
- Could understanding HT effects provide useful constraints on models of structure functions in the Regge region, of relevance to MOLLER?