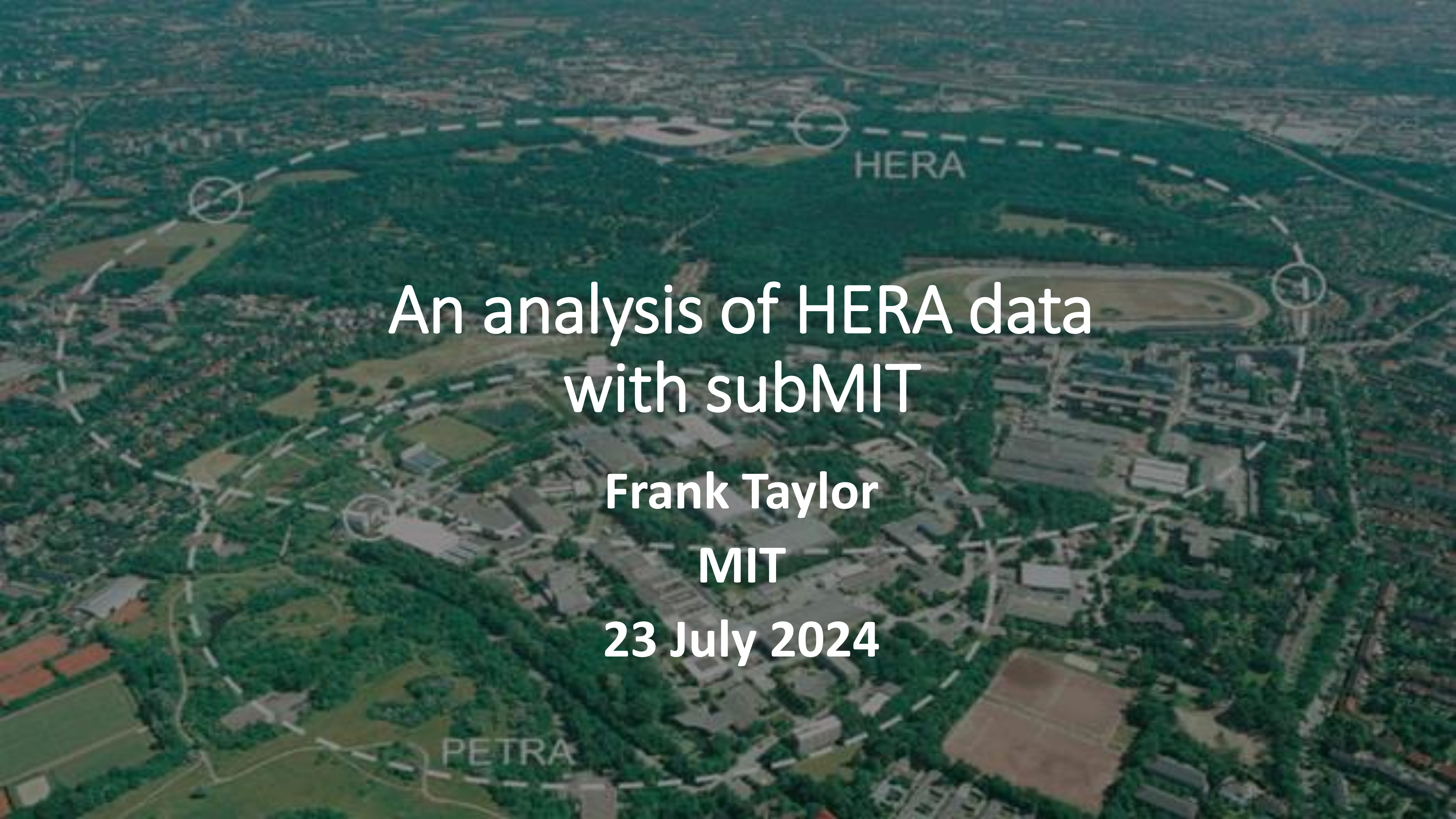

An analysis of HERA data with subMIT

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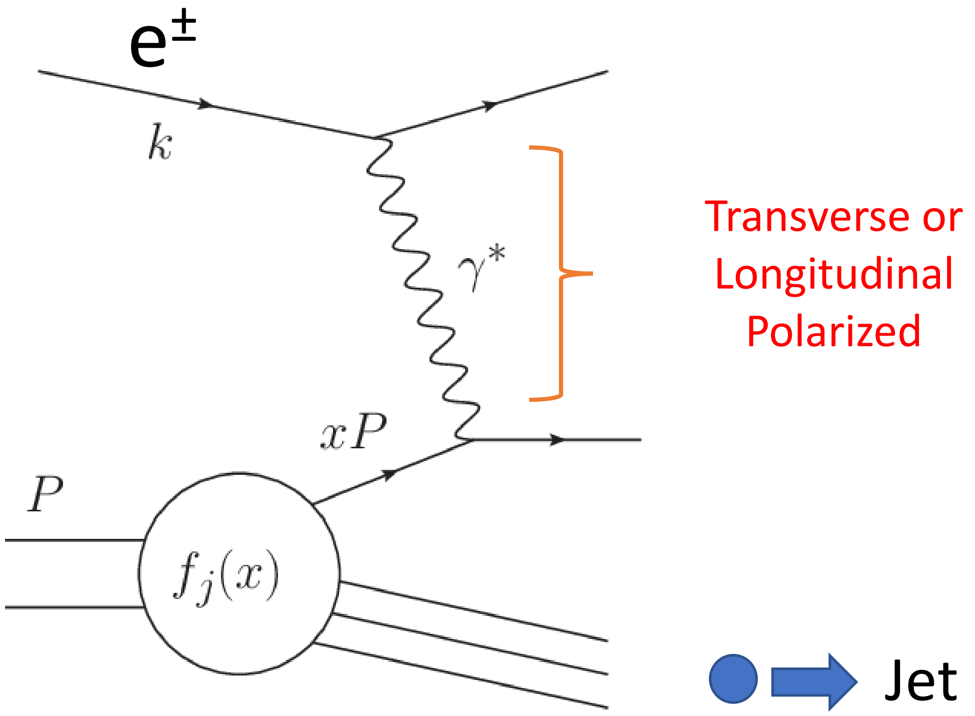
Lived the 'good' life at the top of the 'food chain'

- I analyzed the H1 & ZEUS combined NC DIS data posted on HEPData
  - https://www.hepdata.net/record/ins1377206
- Used ROOT to determine the Longitudinal Structure Function F_L
  - Minimum χ^2 fits using MINUIT
  - Single variable numerical integrations
  - Various numerical tests & 'tabletop' calculations
- My paper posted on arXiv
  - "A determination of F_L at $x=Q^2/s$ with HERA data"
  - https://arxiv.org/abs/2406.19970

Electron-Proton Scattering – DNA of MITLNS

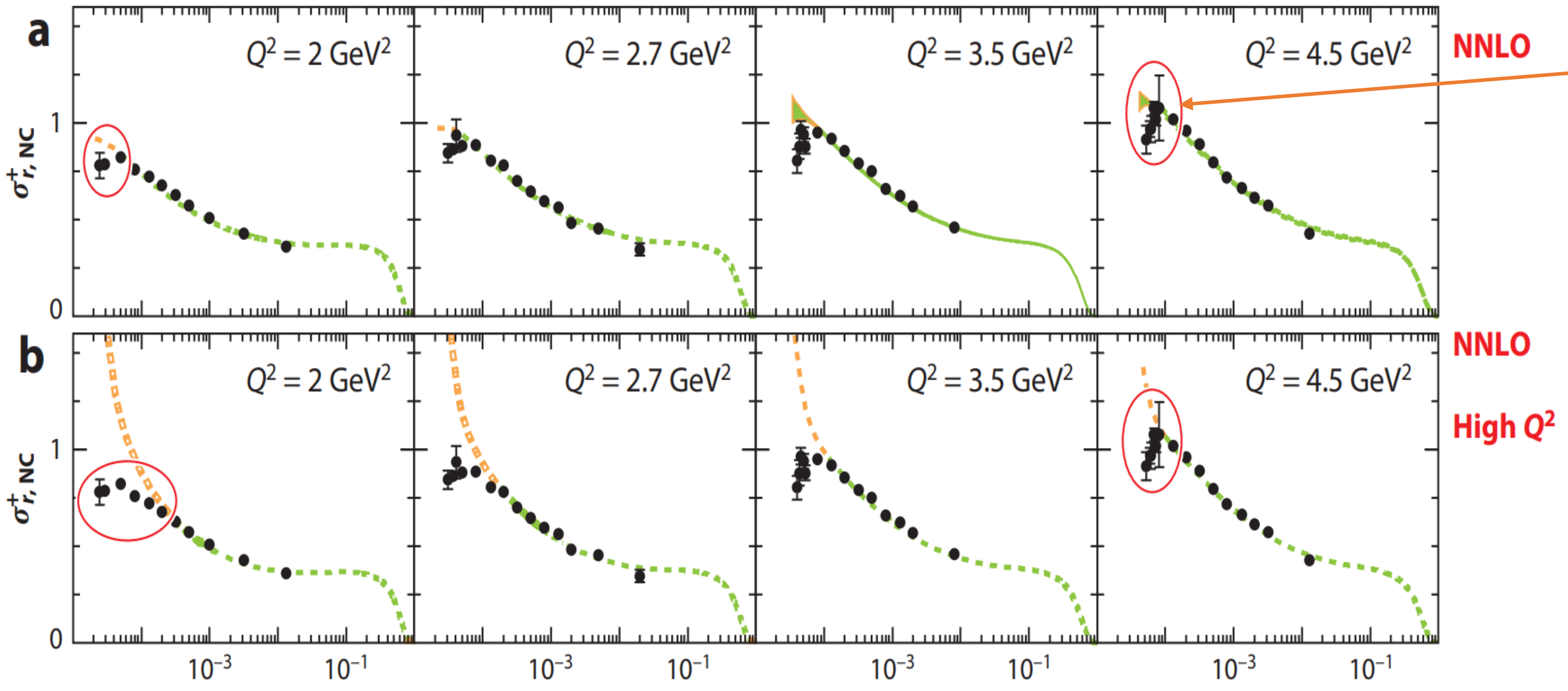
- For NC DIS (inclusive electron) the basic measurements are
  - Scattered electron energy E_e'
  - Scattered electron angle θ
- Determines
  - Four-momentum transfer to quark Q
  - The quark momentum fraction x
  - The inelasticity y
  - Reduced cross section σ_r



$$\sigma_r\left(x,Q^2,s\right)=\frac{d^2\sigma(e^\pm p)}{dQ^2dx}\left[\frac{Q^4}{2\pi\alpha_e^2}\frac{x}{Y_+}\right]=F_2-\left(\frac{y^2}{1+(1-y)^2}\right)F_L=2xF_1+\left(\frac{2(1-y)}{1+(1-y)^2}\right)F_L$$

A puzzling feature of HERA data

- At very low x the cross section is smaller than expectation – it turns over
  - Does not agree with NNLO calculations based on global fits to data – Why?



HERAPDF2.0
Q^2_{min}= 3.5 GeV^2

HERAPDF2.0HiQ2
Q^2_{min}= 10.0 GeV^2

I. Abt, Ann. Rev.

The longitudinal SF F_L controls σ_r turn-over at small x

- The Physics
  - Virtual photon off the mass shell → both transverse and longitudinal polarization
  - Longitudinal photons can not directly interact with spin ½ partons => σ_r becomes smaller at low x
- The reduction of cross section at $x_{min} = Q^2/s$ (y=1) for fixed Q^2 in SM is:

$$\lim_{y\to 1}\left[\sigma_r\left(x,Q^2,s\right)\right]=F_2(Q^2/s,Q^2)-F_L(Q^2/s,Q^2)=2xF_1\left(Q^2/s,Q^2\right)$$

- Therefore, at x_{min} a measurement of F_2 and $2xF_1$ determines $F_L = F_2-2xF_1$

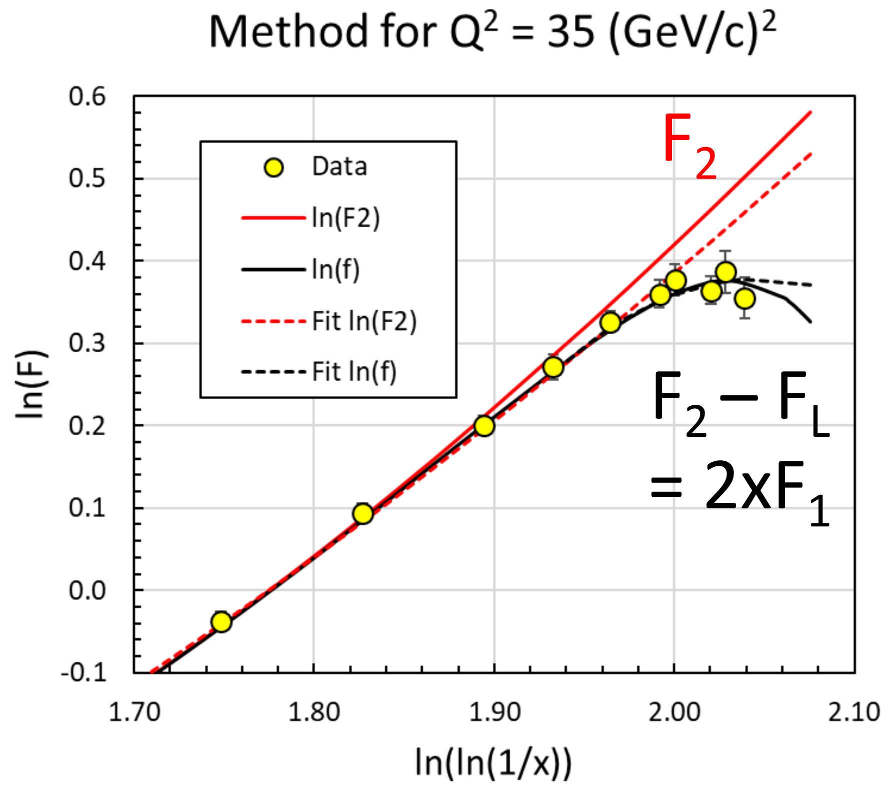
VERY SIMPLE – but results in F_2 and F_L only along the line $x_{min} = Q^2/s$

Determine $F_2(x_{min})$ & $2xF_1(x_{min})$ from one distribution

- $d^2\sigma_r/dxdQ^2$ at x_{min} can not be measured directly
  - The electron backscatters $\theta = \pi$ into incoming beam
  - Have to determine cross section components at this point numerically
- To determine values at x_{min} perform two fits on one distribution of form:

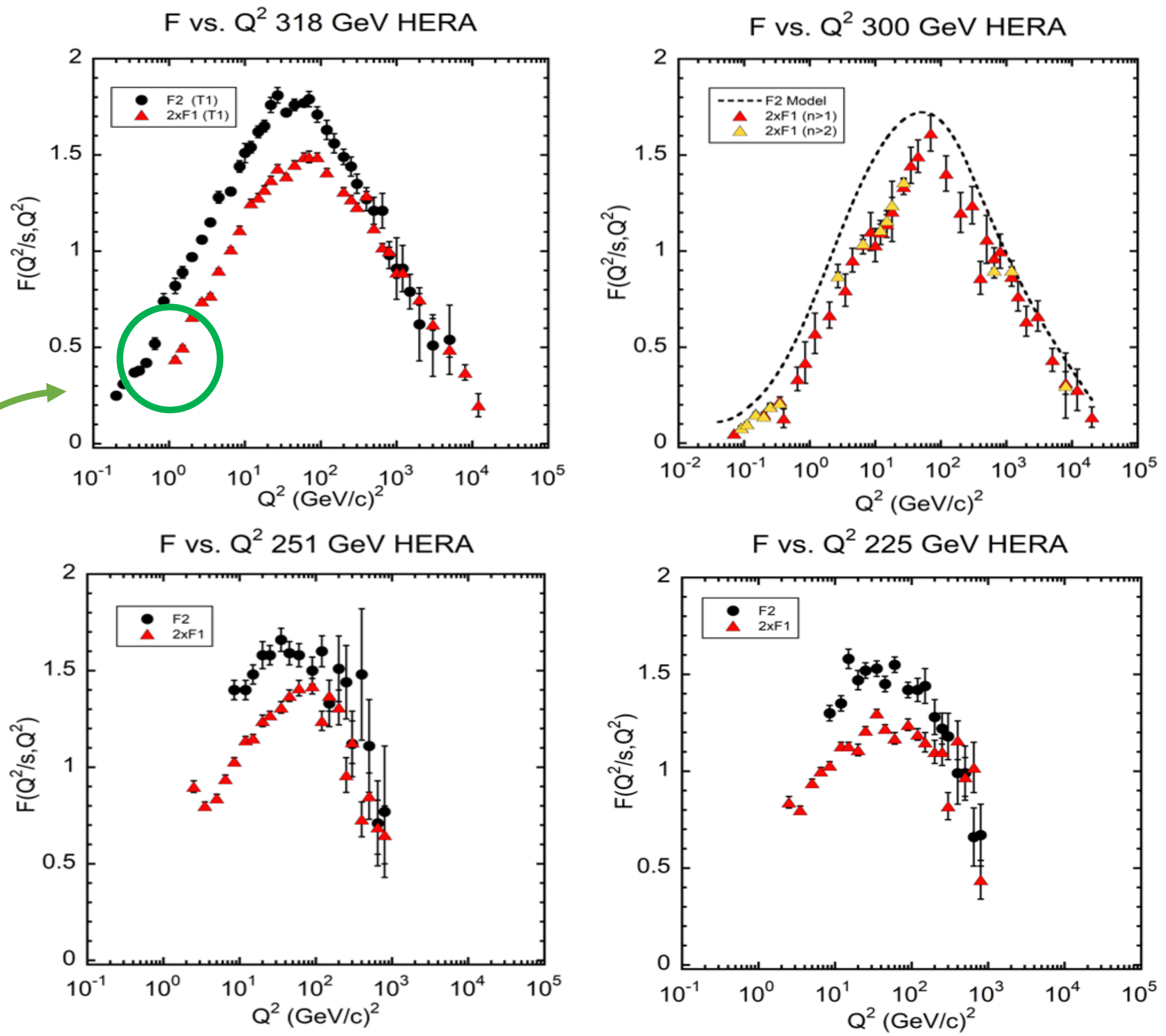
$$\ln\left[F_2 - \frac{y^2}{Y_+}F_L\right] = P_n\left[\ln\left(\ln\left(1/x\right)\right)\right]$$

  - Polynomial order n = 2 or 3
  - $y \leq 0.3$ for F_2 and $y \geq 0.3$ for $F_2 - F_L = 2xF_1$

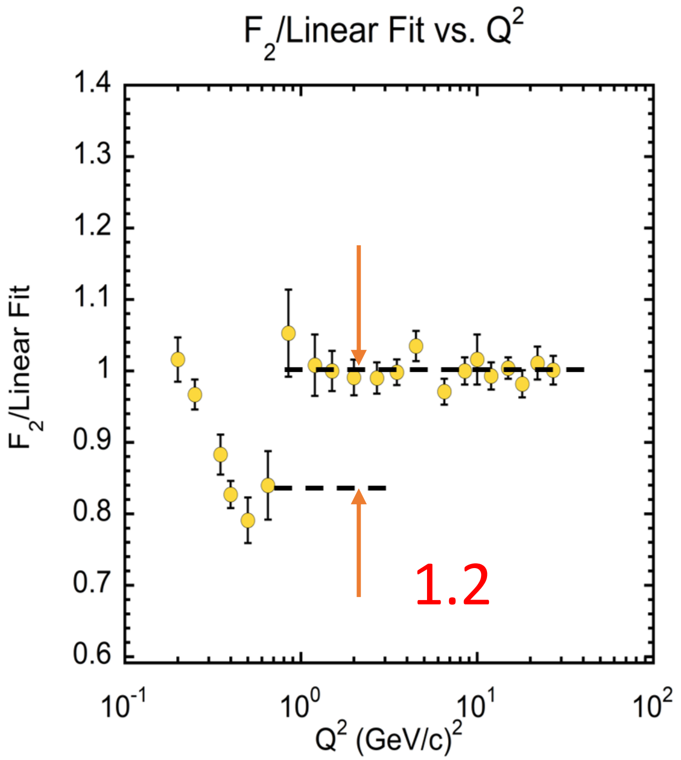


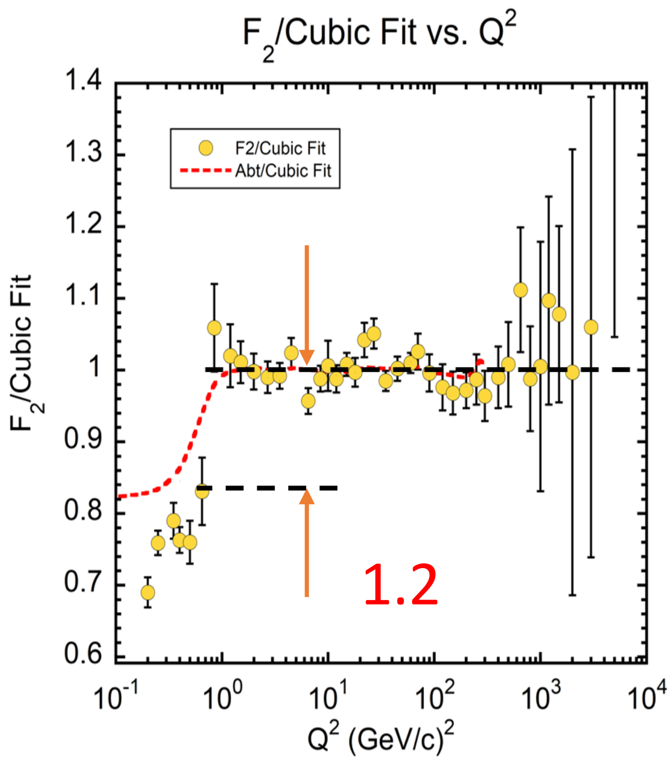
The HERA F_2 and F_2-F_L at x_{min}

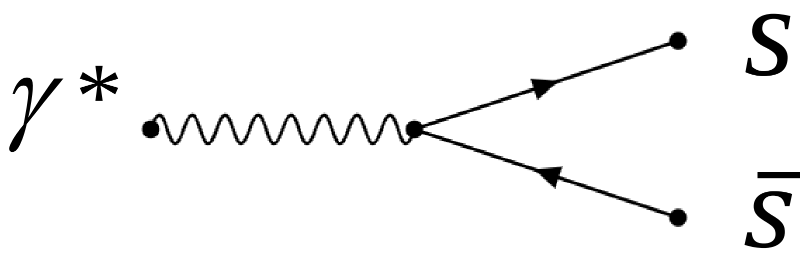
- This is the first time that F_2 and F_2-F_L have been measured at $x_{min} = Q^2/s$
  - Structure functions at x_{min} are sensitive to heavy quark thresholds
  - Observe the strange quark-antiquark threshold for √s = 318 GeV data
- The difference between black and red points is F_L at x_{min}



The strange quark threshold in $F_2(Q^2/s)$







Size of anomaly jump 1.2 ± 0.07

$$\frac{F_2(Q^2 > 1\ (GeV/c)^2)}{F_2(Q^2 < 1\ (GeV/c)^2)} \approx \frac{\sum_{i=1}^{6} e_i^2}{\sum_{i=1}^{4} e_i^2} = 1.2$$

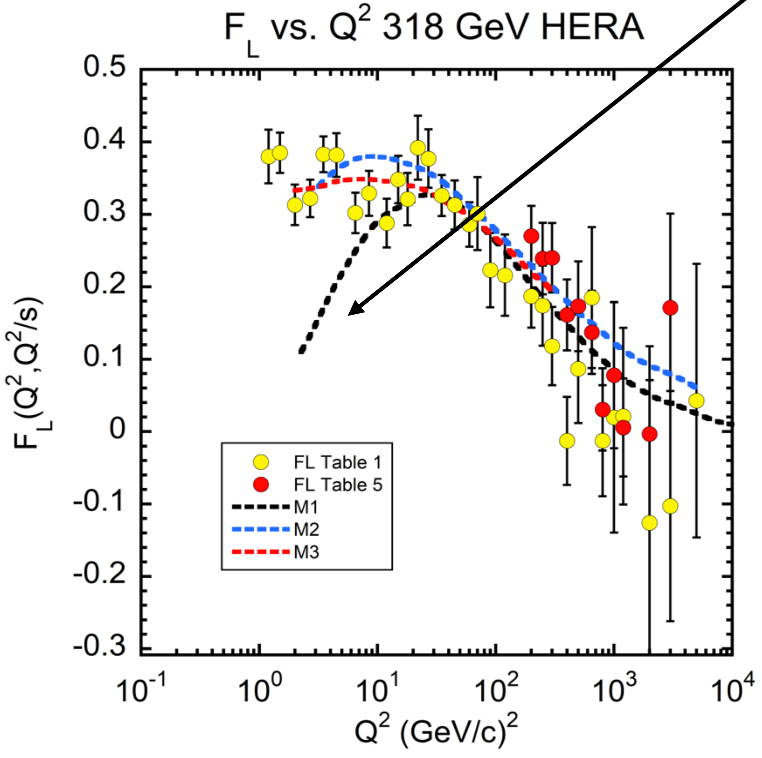
Assuming:

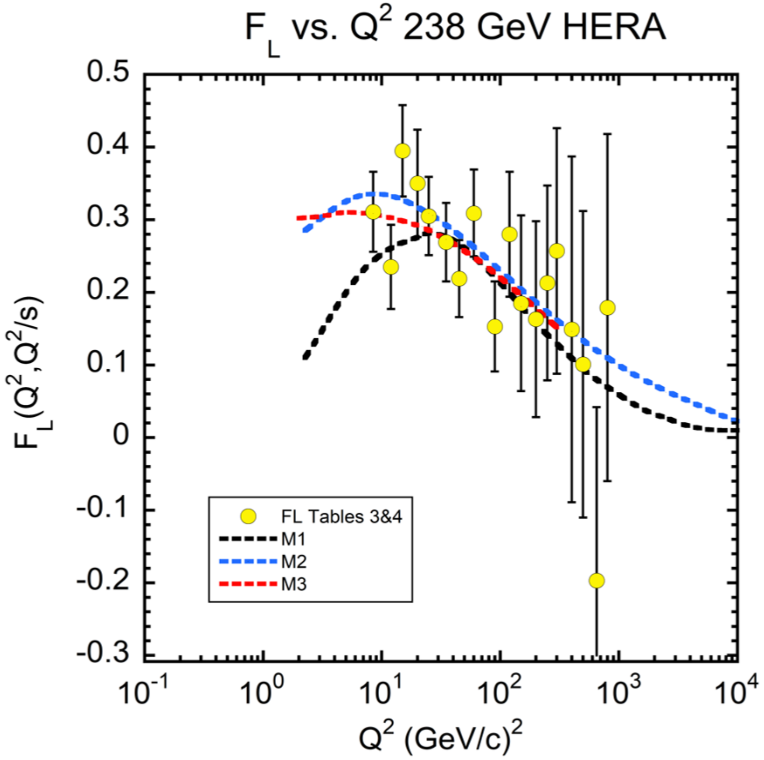
$$x\bar{u}(x) = x\bar{d}(x) = xs(x) = x\bar{s}(x)$$

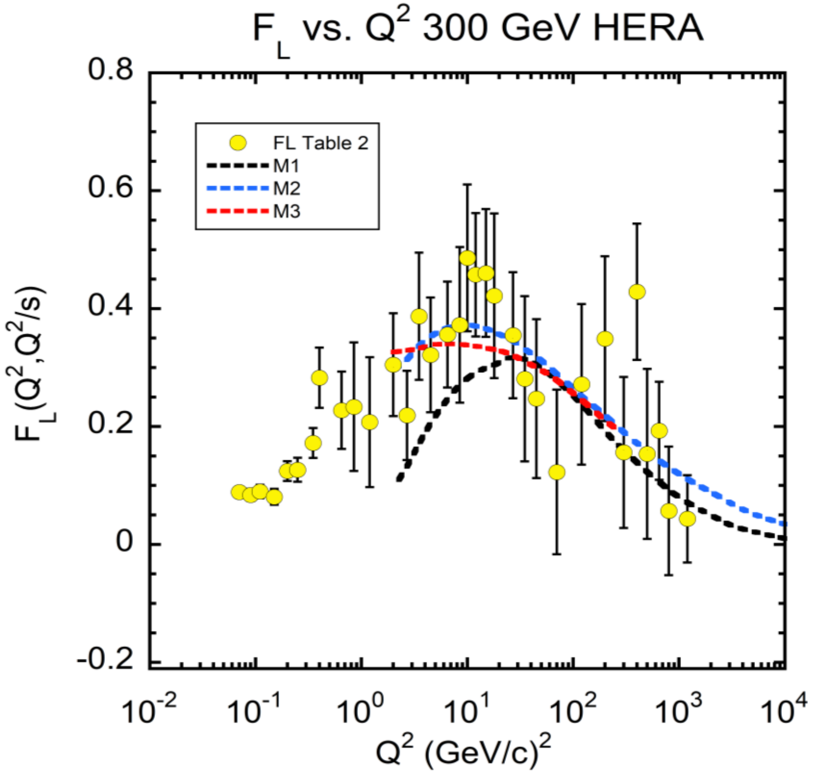
F_L has 2 parts: quark-antiquark (F_2) and gluon (xG)

At x_{min} the virtual photon is transversely polarized implying that gluon component is strongly suppressed by theory. But F_L is larger than expected. In fact, F_L is consistent with an enhanced (4.7± 0.5) F_2 part with gluon part = 0. The turn-over at low x is due to enhanced F_2 part.

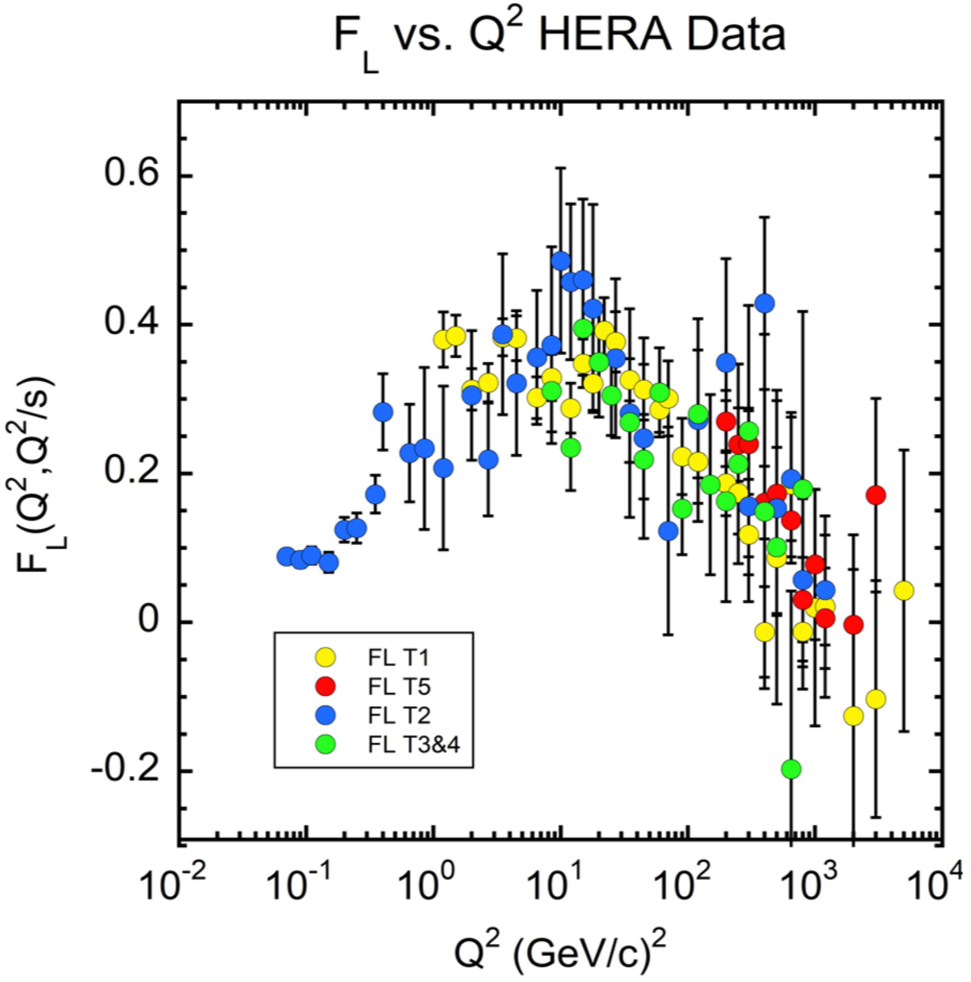
SM Gluon disfavored

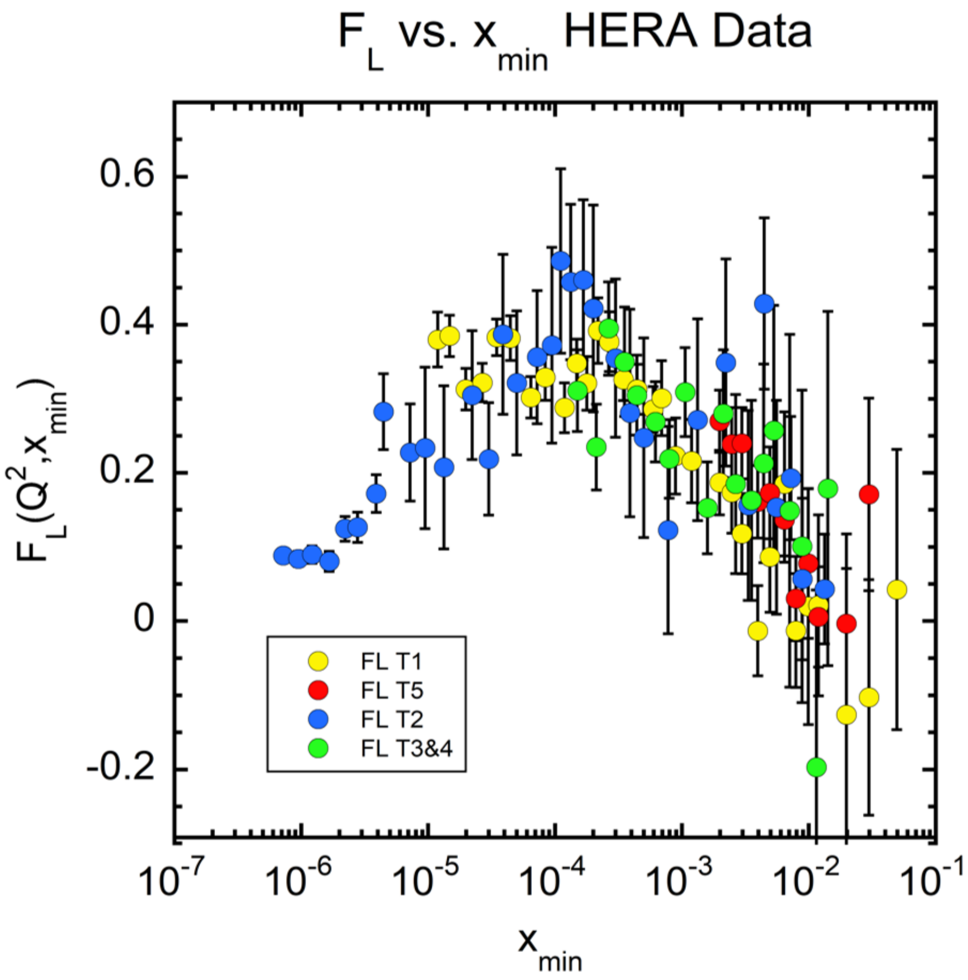






All HERA data together 225 ≤ √s ≤ 318 GeV

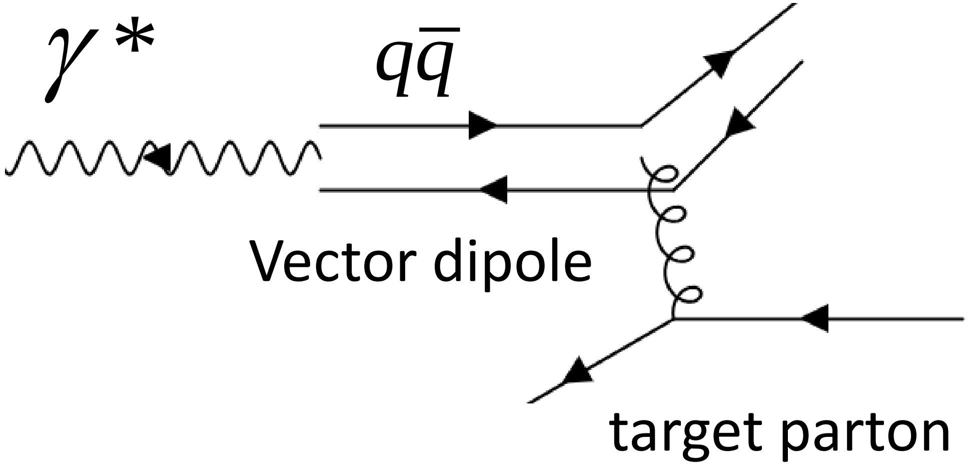




Conclusions – F_L in transverse polarization limit

- At x_{min} γ^* is transversely polarized thus only interacts with spin ½ partons.
- The following are consistent
  - Observe strange quark threshold in F_2 at Q ≈ 1 GeV/c in √s = 318 GeV data
  - The ratio $2xF_1/F_2$ is consistent with suppressed gluons – enhanced quarks
  - F_L (Q > 1.4 GeV/c) appears to be consistent with an enhanced quark term by 4.7 ± 0.5 not SM gluon term (0)
- Data favors the Dipole Model
  - Another interaction channel in NC DIS

Dipole interaction



J. Bartels, K.Golec-Biernat and H. Kowalski, Phys.Rev. D66, (2002) 19

Extras

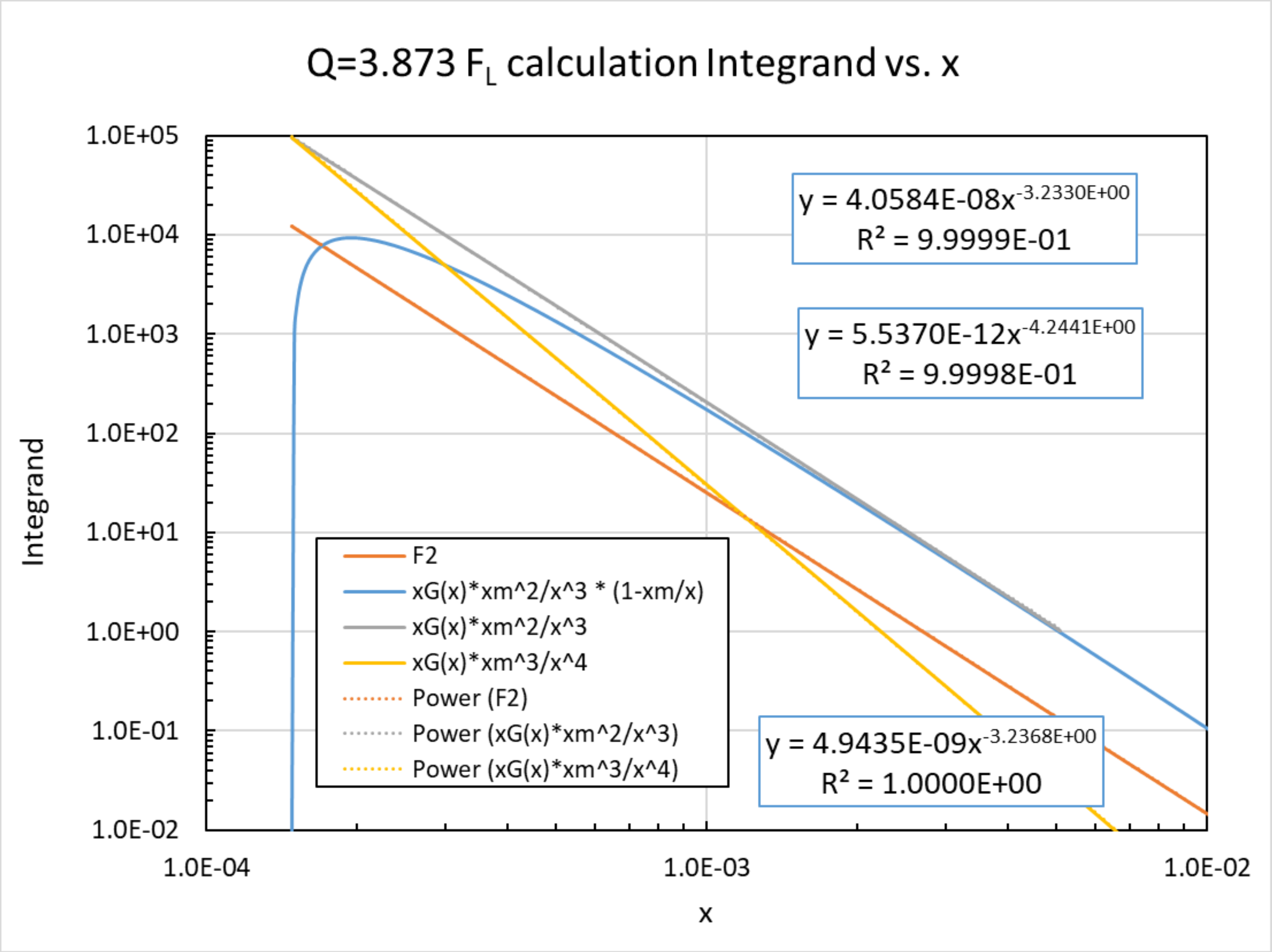
Theory of F_L in parton SM

- F_L has an F_2 (quark-antiquark) and a dominant xG (gluon) component
  - F_L is proportional to the strong coupling constant $\alpha_s(Q^2)$

$$F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{\pi}\left[\frac{4}{3}\int_x^1 \frac{dy}{y}\left(\frac{x}{y}\right)^2 F_2(y,Q^2) + 2\sum e_q^2 \int_x^1 \frac{dy}{y}\left(\frac{x}{y}\right)^2\left(1-\frac{x}{y}\right) yG(y,Q^2)\right]$$

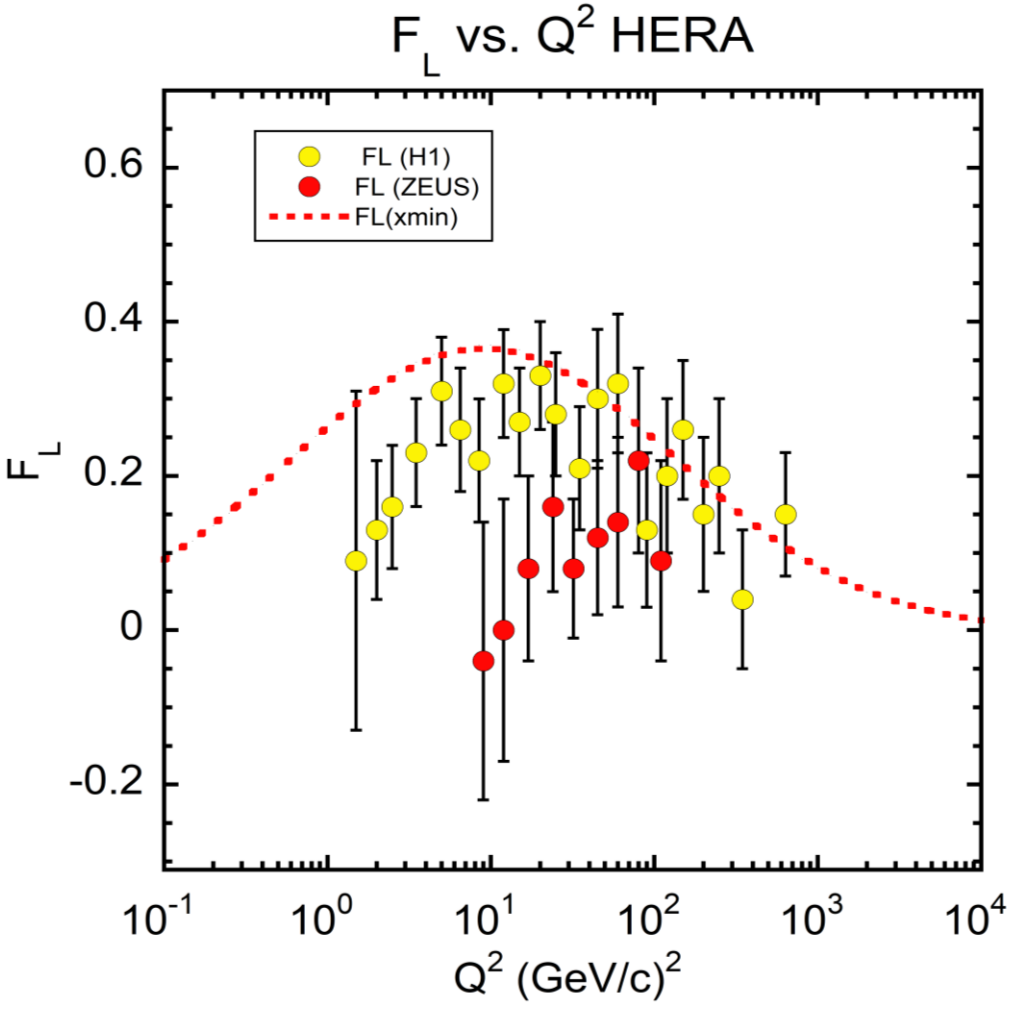
- Three integrals evaluated numerically with many checks
  - Used CTEQ10 PDF and parameterization of Abt, et al.
  - Tuned xG to agree with high Q^2 data, checked F_2 with data
  - Found that each of the three integrands are power laws in 1/x for small x
  - Knowing the powers of the power laws can estimate the integrals by hand!

Check of F_L integration by power law

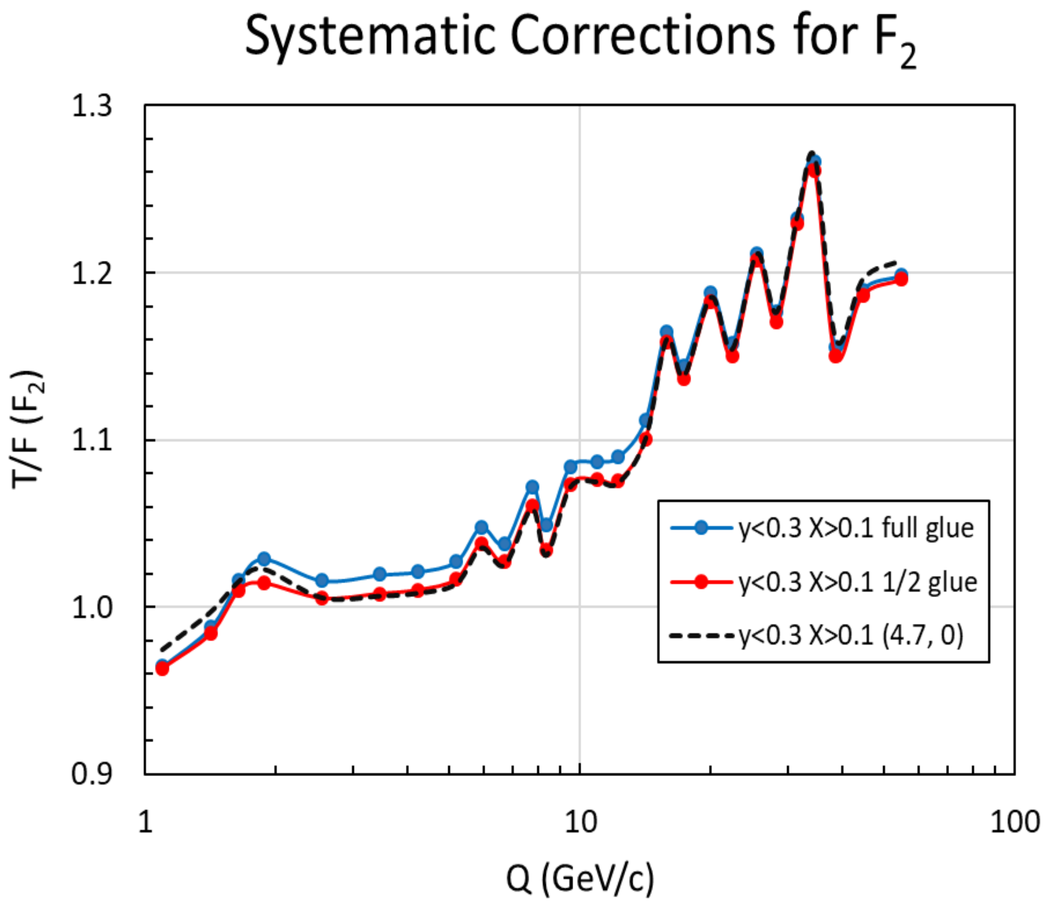


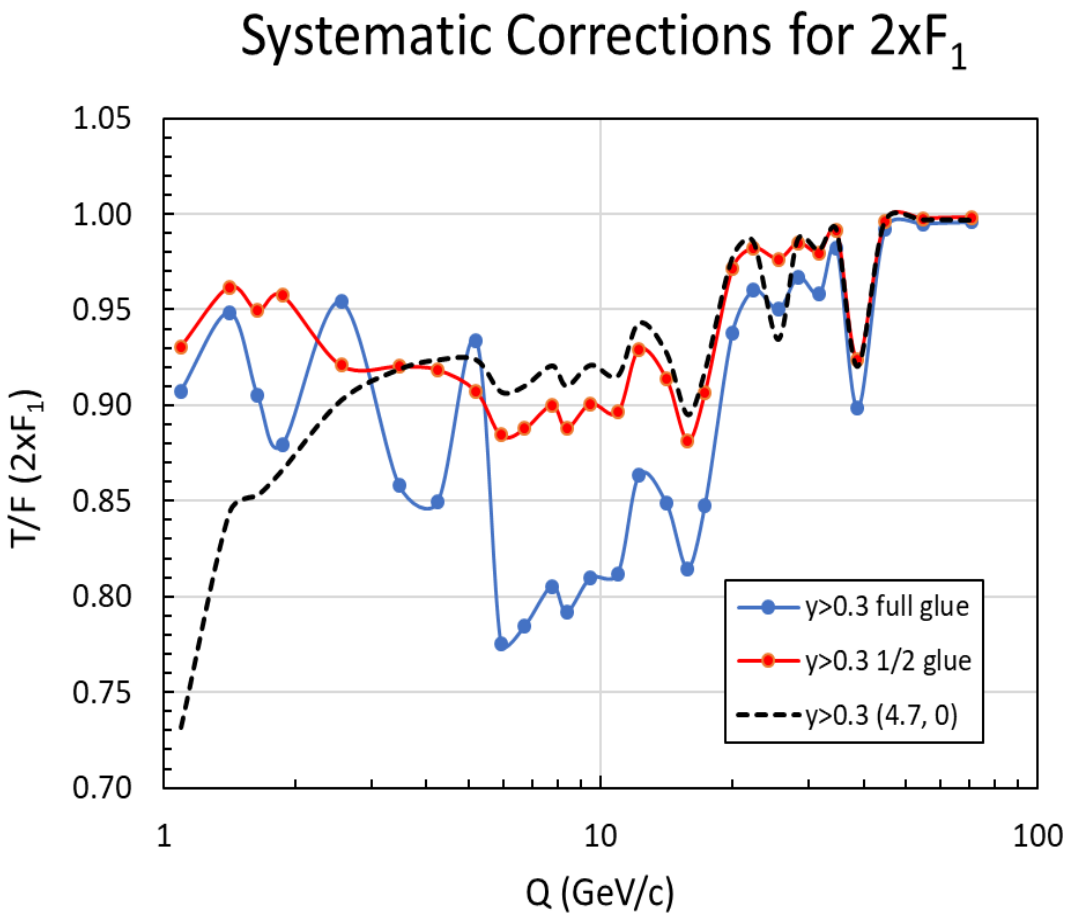
F_L measured by H1 and ZEUS

- The analysis performed by Rosenbluth method
  - Used the y-dependence for fixed x and Q^2 to allow determinations of both F_2 and F_L
  - Analysis included longitudinally polarized virtual photons
  - Different from my determination of F_L in the transverse polarization limit at x_{min}

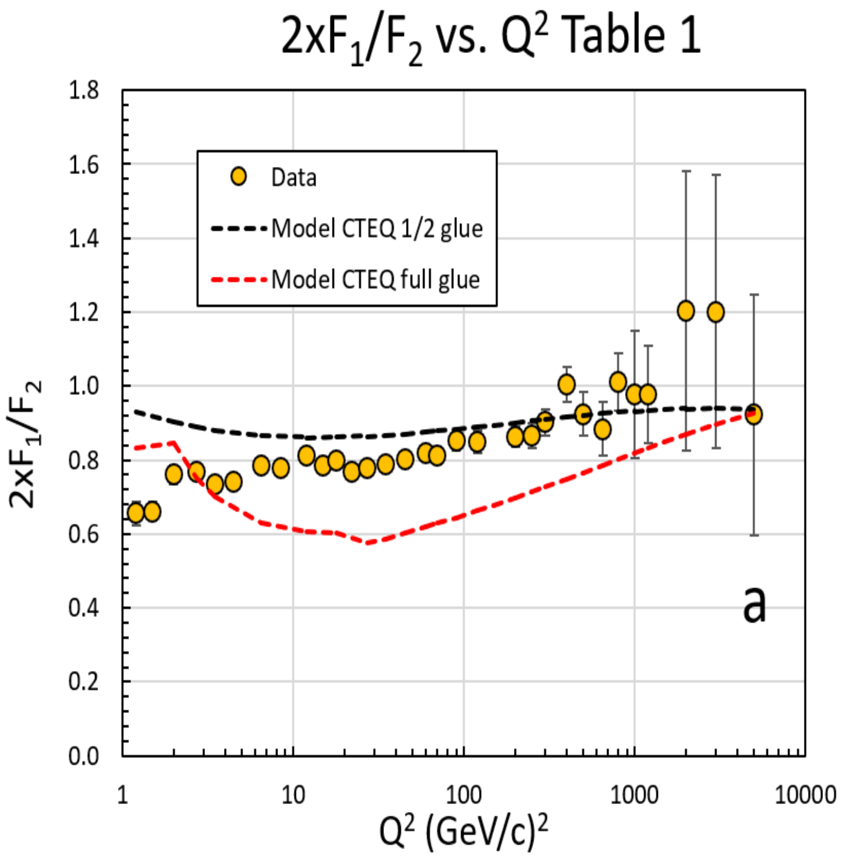


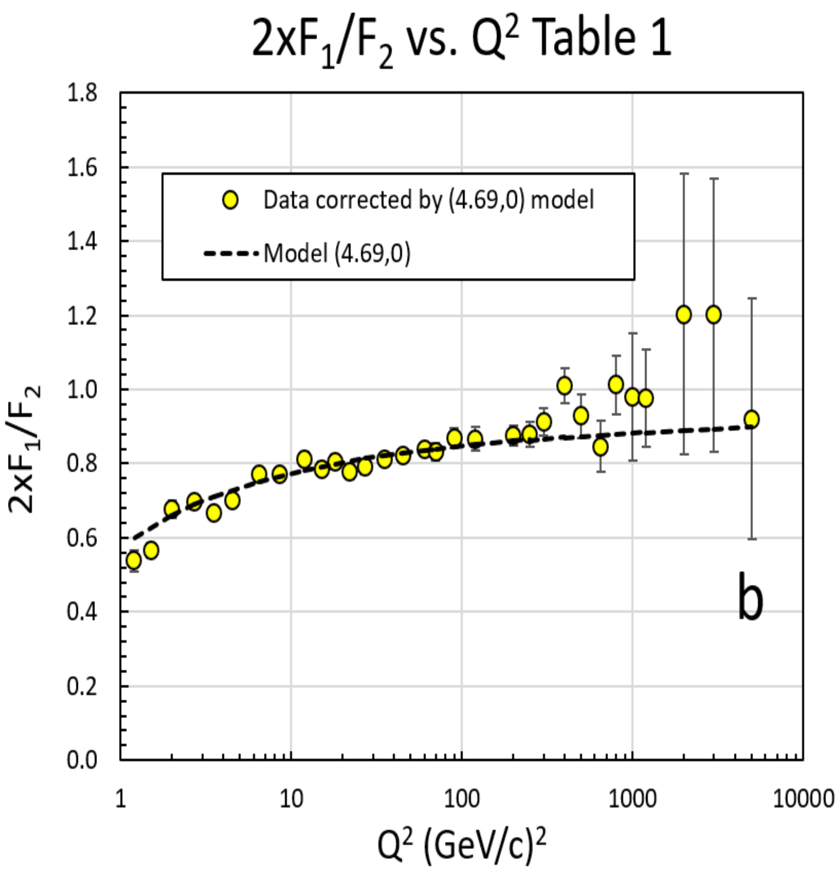
Fitting corrections

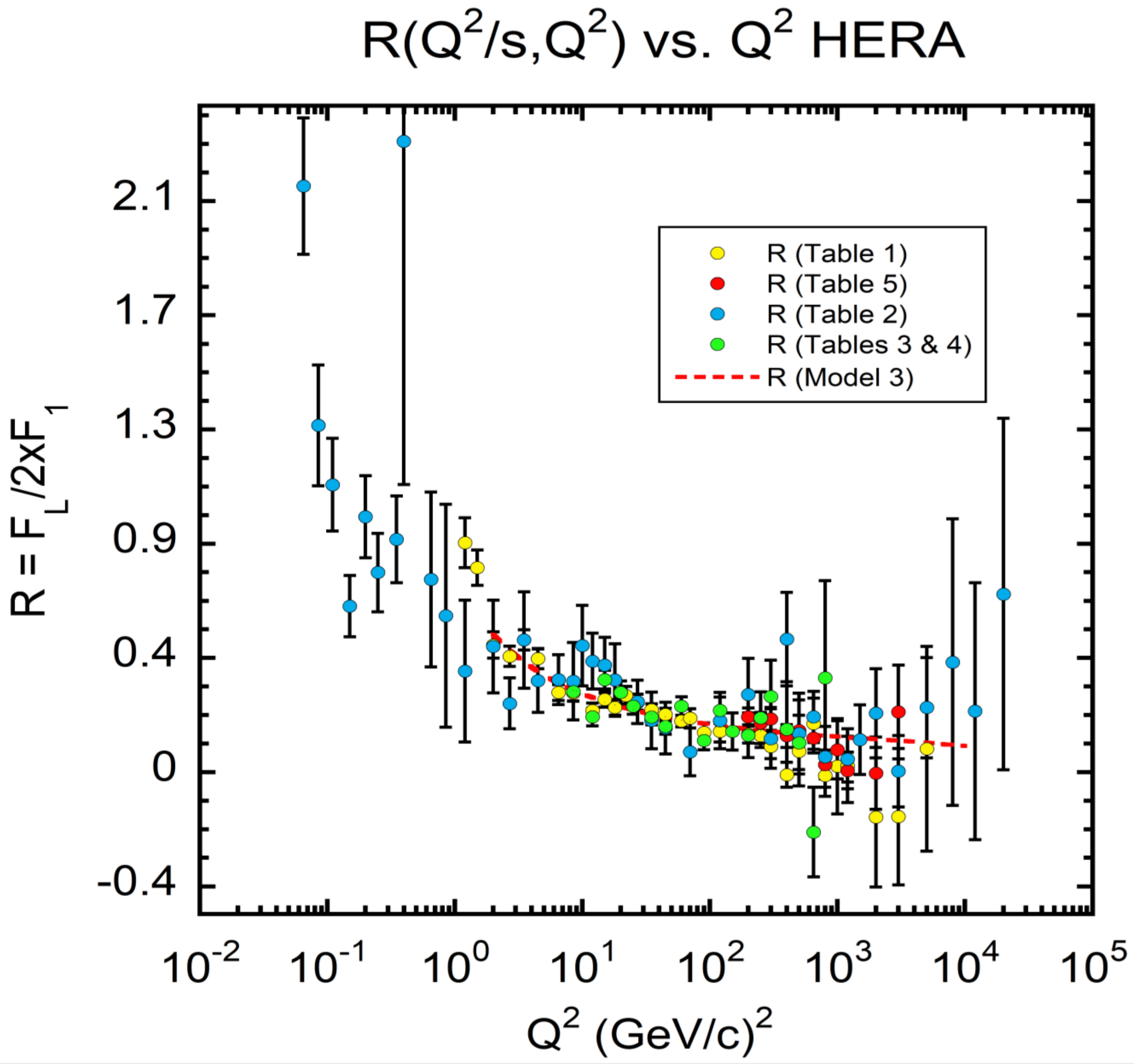




Ratio showing xG contribution disfavored







R(Q²/s,Q²) vs. Q² HERA
R = F_L/2xF_1
2.1
1.7
1.3
0.9
0.4
0
-0.4
R (Table 1)
R (Table 5)
R (Table 2)
R (Tables 3 & 4)
R (Model 3)
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
Q² (GeV/c)²