New developments in extracting parton densities and beyond

Nobuo Sato

Director's seminar, December 2nd 2015

About Me

Education

Florida State University, Tallahassee, FL, USA (2008-2014)

- Ph.D. program in Theoretical High Energy Physics, 2010-2014
- Thesis Topic: *Threshold resummation in direct photon production at NLO+NLL.*
- Advisor: J. F. Owens.

Universidad del Valle, Cali, Colombia (2002-2007)

- B.S. Physics,
- Thesis Topic: *Tachyon field as source of dark energy.*
- Advisor: N. Granda

Research topics

- PDFs, TMDs, threshold resummation, collider phenomenology

Projects @ JLab (fall 2014 - present)

JAM

- Inclusion of all 6GeV JLab data (eg1b-dvcs, eg1b, Hall A)
- New MC methodology to extract spin-dependent PDFs
- Constraints on higher twist distributions $\rightarrow$ d_2
- Extraction of Δg (JAM16)
- New software to perform global analysis
- Collaborators: A. Accardi, J. Ethier, W. Melnitchouk, S. Kuhn.

TMD

- New methodology to describe transverse dependent observables at low momentum transfer (SIDIS data from COMPASS, HERMES)
- New software for TMD analysis.
- Collaborators: T. Rogers, B. Wang, A. Prokudin, L. Gamberg, D. B.Clark.

Pions and nucleon structure

- Extraction of pion structure function from HERA leading neutron data and E866 $\bar{d} - \bar{u}$ asymmetry data.
- Collaborators: J. McKenney, W. Melnitchouk, C. R. Ji

JAM: Motivations

Spin structure of nucleons

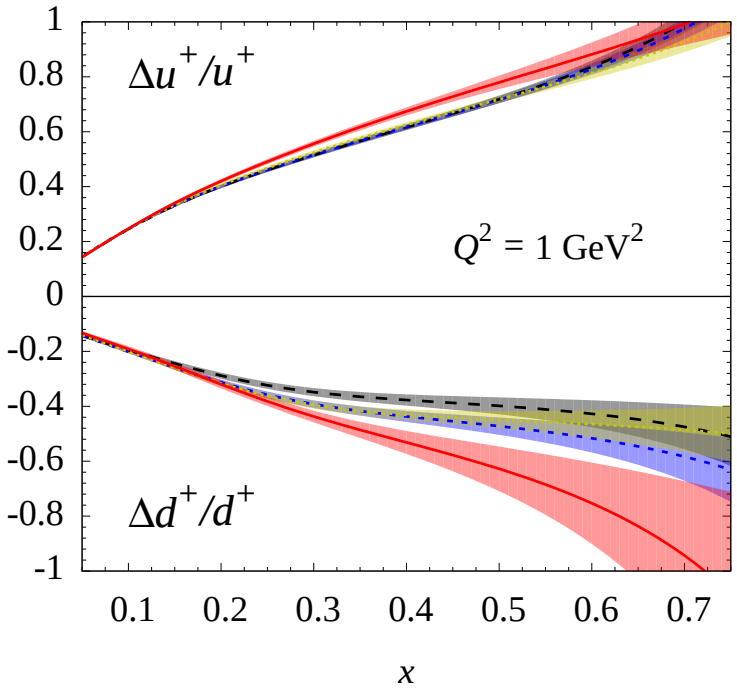
- Spin sum rule $\rightarrow \frac{1}{2} = \frac{1}{2}\Delta\Sigma^{(1)} + \Delta g^{(1)} + \mathcal{L}$
- The spin contribution from quarks: $\rightarrow \Delta\Sigma^{(1)} = \Delta u_+^{(1)} + \Delta d_+^{(1)} + \Delta s_+^{(1)}$
- From existing global analysis $\rightarrow \Delta\Sigma^{(1)}_{[10^{-3},1]} \sim 0.3, \quad \Delta g^{(1)}_{[0.05,0.2]} \sim 0.1$

Higher twists

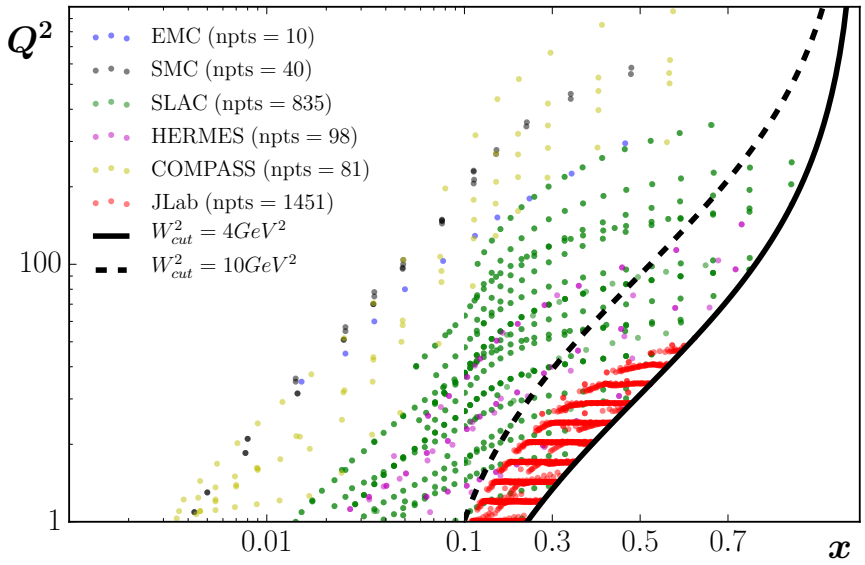
- d_2 matrix element
  $\rightarrow d_2 = 2g_1^{(3)}(Q^2) + 3g_2^{(3)}(Q^2)$
- Color forces experienced by struck quarks
  $\rightarrow \tilde{F}_E = 2d_2 + f_2, \quad \tilde{F}_B = 4d_2 - f_2$
- Dedicated global QCD anlysis is required

High x

- $SU(6)$ spin-flavor symmetry:
  $\rightarrow \Delta u/u \rightarrow 2/3, \quad \Delta d/d \rightarrow -1/3$
- pQCD $\rightarrow \Delta q/q \rightarrow 1$



JAM: Global Analysis



Data

- ✓ Polarized DIS $\rightarrow \Delta u, \Delta d$
- Polarized SIDIS: $\rightarrow \Delta\bar{d}, \Delta\bar{u}, \Delta s$
- Inclusive Jets/π^0 : $\rightarrow \Delta g$
- W production $\rightarrow \Delta\bar{d}, \Delta\bar{u}$

Theory

- ✓ Target mass corrections
- ✓ Twist-3 and twist-4 contributions in polarized structure functions
- ✓ Nuclear corrections for ^{3}He and deuteron targets
- Threshold resummation $\rightarrow (\alpha_S^m \log(1-x)^n)$

Tools

- ✓ Numerical codes developed within python framework
- ✓ Development of DGLAP evolution equations in Mellin space
- ✓ Fast calculation of observables $\rightarrow$ Mellin space techniques

JAM: Polarized DIS

Asymmetries

$$A_{||} = \frac{\sigma^{\uparrow\Downarrow} - \sigma^{\downarrow\Downarrow}}{\sigma^{\uparrow\Downarrow} + \sigma^{\downarrow\Downarrow}} = D(A_1 + \eta A_2)$$

$$A_{\perp} = \frac{\sigma^{\uparrow\Rightarrow} - \sigma^{\downarrow\Rightarrow}}{\sigma^{\uparrow\Rightarrow} + \sigma^{\downarrow\Rightarrow}} = d(A_2 - \xi A_1)$$

$$A_1 = \frac{(g_1 - \gamma^2 g_2)}{F_1} \qquad A_2 = \gamma \frac{(g_1 + g_2)}{F_1} \qquad \gamma^2 = \frac{4M^2x^2}{Q^2}$$

Theory

$$g_1(x, Q^2) = g_1^{LT+TMC}(\Delta u^+, \Delta d^+, \Delta g, \ldots) + g_1^{T3+TMC}(D_u, D_d) + g_1^{T4}(H_{p,n})$$

$$g_2(x, Q^2) = g_2^{LT+TMC}(\Delta u^+, \Delta d^+, \Delta g, \ldots) + g_2^{T3+TMC}(D_u, D_d)$$

JAM: Fitting strategy

Parametrization

- $xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$
- LT quark distributions $\rightarrow \Delta u^+, \Delta d^+, \Delta s^+, \Delta g$
- T3 quark distributions $\rightarrow D_u, D_d$
- T4 structure functions $\rightarrow H_p, H_n$

Chi-squared minimization $\rightarrow$ with correlated systematic uncertainties

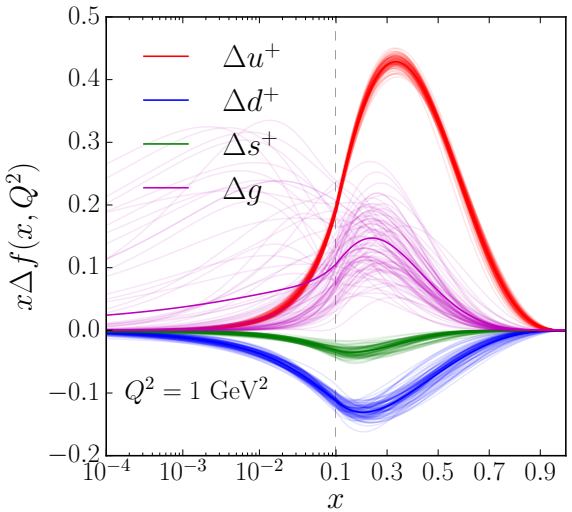
$$\chi^2 = \sum_i \left(\frac{D_i - T_i(1 - \sum_k r^k \beta_i^k / D_i)^{-1}}{\alpha_i} \right)^2 + \sum_k (r^k)^2$$

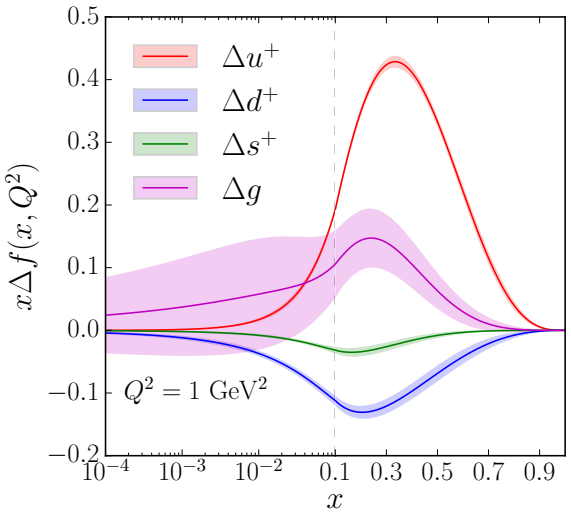
Issues

- Stability in the moments (e.g. $\Delta\Sigma^{(1)}$)
- Is the solution given by a single fit unique? $\rightarrow$ False minima
- Is over-fitting present in our fits?
- Which parameters should be fixed and at which value?
- Determination of uncertainty bands.

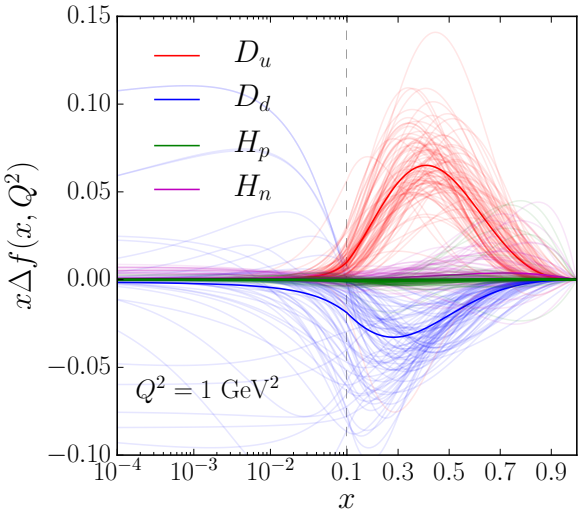
Solution $\rightarrow$ MC approach

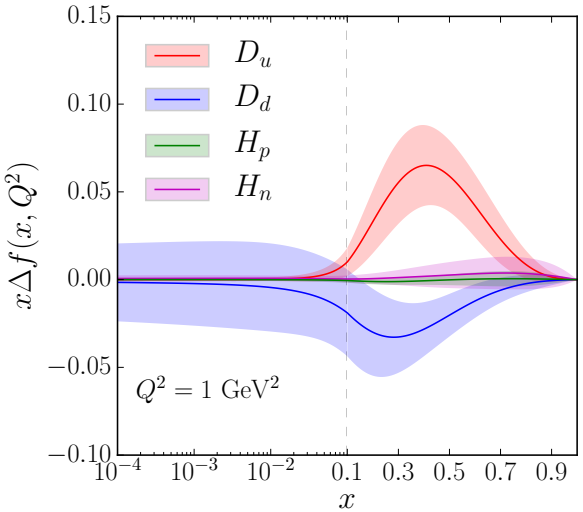
JAM: results (fitted distributions)





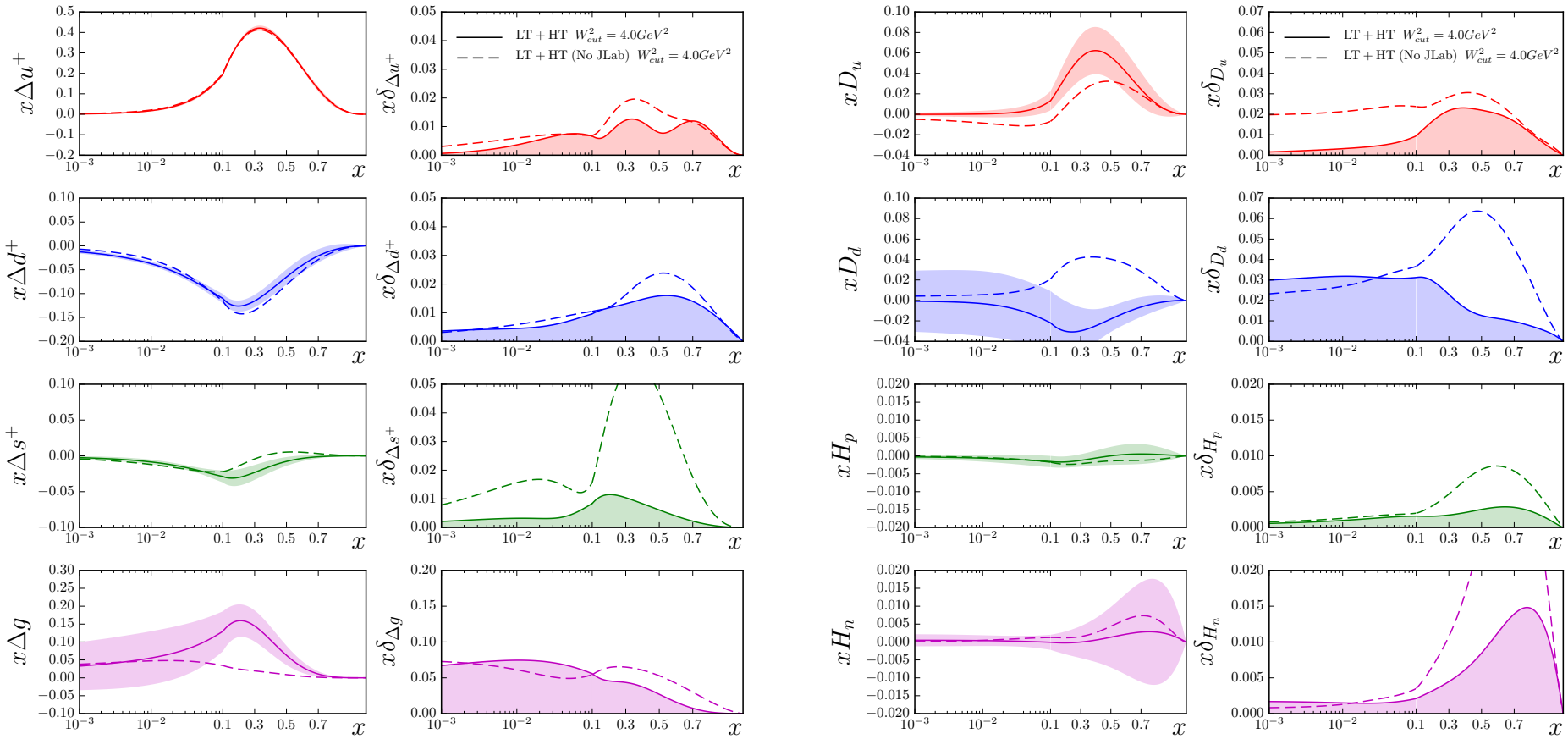
- Large uncertainties for small-x gluons $\rightarrow$ need jet data
- Constraints on strange $\rightarrow$ weak baryon decay constants





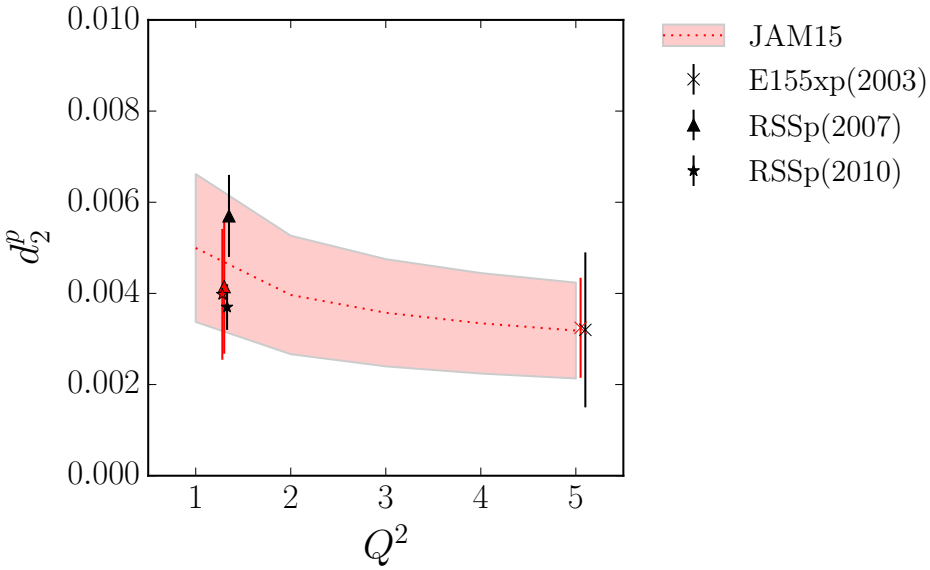
- Non-vanishing signal of T3 distributions
- Large D_d uncertainties $\rightarrow$ need more data
- T4 distributions are consistent with zero

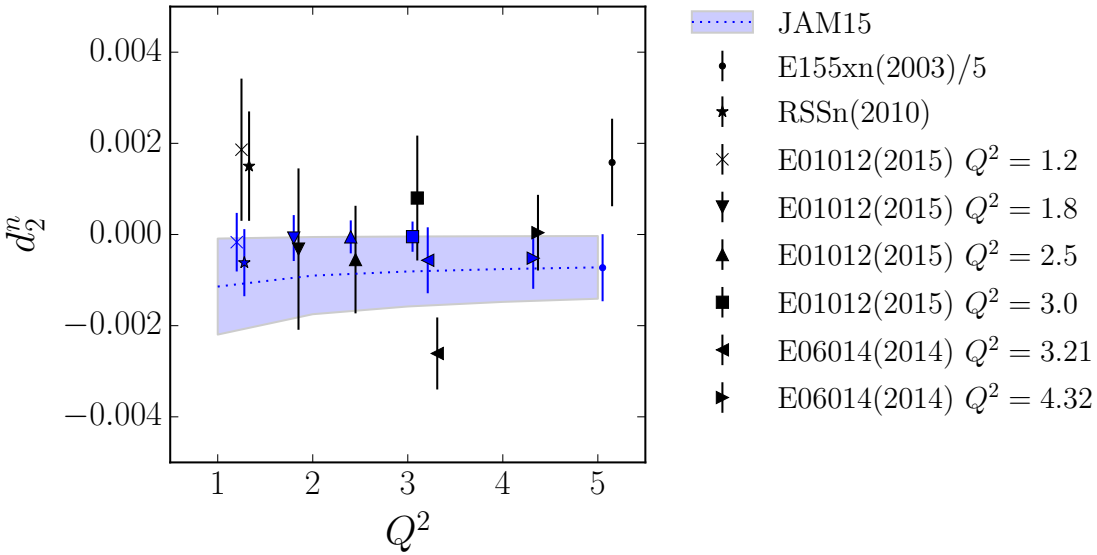
JAM: results (impact of JLab data)

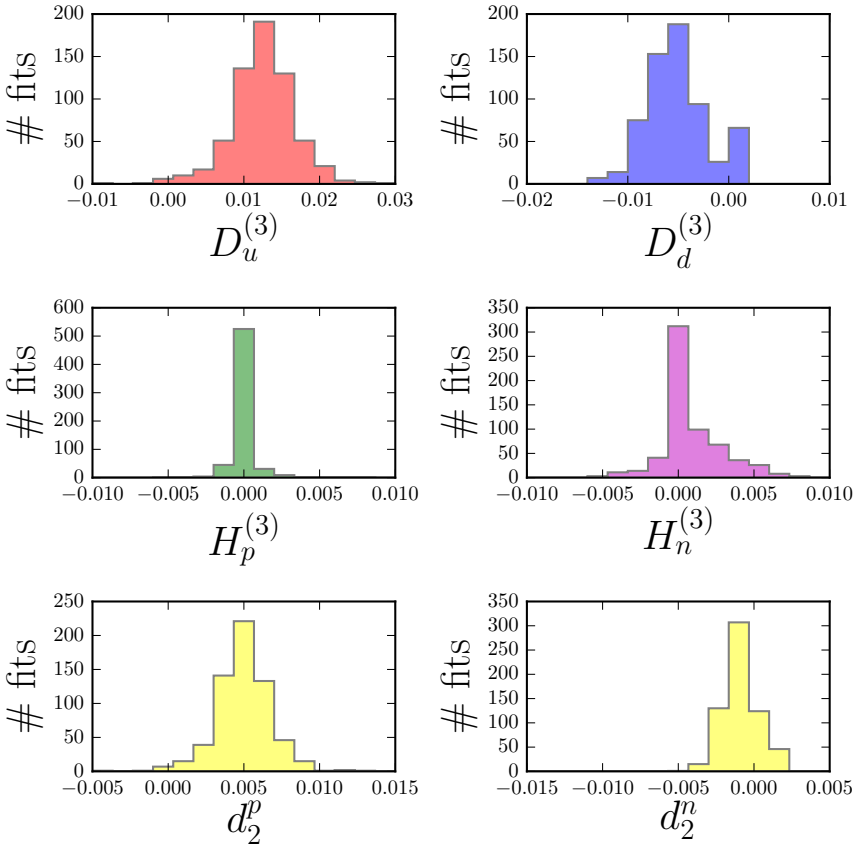


- **Significant** reduction of the uncertainties in the LT & HT distributions
- Sizable modifications to the gluon $\rightarrow$ QCD evolution
- Constraints on HT distributions $\rightarrow$ impact on d_2 matrix element
- In DSSV, strange is positive at the high x region

JAM: results (moments)







- First extraction of d_2 matrix element in global QCD analysis
- Confirmation of duality in d_2 down to $Q^2 \sim 2\ \mathrm{GeV}^2$

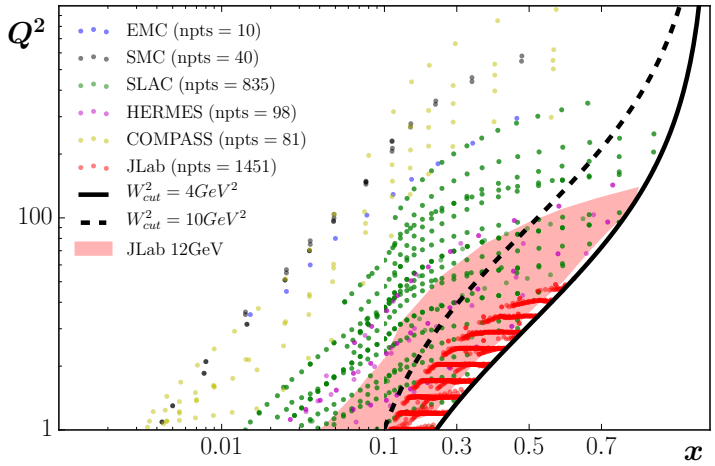
JAM: Outlook

JAM

- ✓ New JAM15 analysis to study impact of all JLab 6 GeV inclusive DIS data at low W and high x
- ✓ New extraction of LT & HT distributions
- Upcoming JAM16 analysis to study polarization of sea quarks & gluons.
  - SIDIS for flavor separation.
  - polarized pp cross sections (inclusive jet & π production) for Δg
  - W boson asymmetries
  - Threshold resummation impacts on large x
- Combined analysis of all inclusive (un)polarized DIS data
- Fits to helicity distributions

JLab 12

- Measurements at high-x $\rightarrow$ $\Delta q/q$
- Wider coverage in Q^2 $\rightarrow$ Δg
- Determination of pure twist-3 d_2 in DIS



Backup

JAM: Polarized DIS

$\rightarrow \xi = \frac{2x}{1+(1+4\mu^2x^2)^{1/2}}$
$\rightarrow \mu^2 = M^2/Q^2$

Leading twist structure functions:

$$g_1^{LT+TMC}(x,Q^2) = \frac{x}{\xi}\frac{g_1^{LT}(\xi)}{(1+4\mu^2x^2)^{3/2}} + 4\mu^2x^2\frac{x+\xi}{\xi(1+4\mu^2x^2)^2}\int_\xi^1 \frac{dz}{z} g_1^{LT}(z)$$
$$- 4\mu^2x^2\frac{2-4\mu^2x^2}{2(1+4\mu^2x^2)^{5/2}}\int_\xi^1 \frac{dz}{z}\int_{z'}^1 \frac{dz'}{z'} g_1^{LT}(z')$$

$$g_2^{LT+TMC}(x,Q^2) = -\frac{x}{\xi}\frac{g_1^{LT}(\xi)}{(1+4\mu^2x^2)^{3/2}} + \frac{x}{\xi}\frac{(1-4\mu^2x\xi)}{(1+4\mu^2x^2)^2}\int_\xi^1 \frac{dz}{z} g_1^{LT}(z)$$
$$+ \frac{3}{2}\frac{4\mu^2x^2}{(1+4\mu^2x^2)^{5/2}}\int_\xi^1 \frac{dz}{z}\int_{z'}^1 \frac{dz'}{z'} g_1^{LT}(z')$$

In the Bjorken limit $(Q^2 \to \infty)$:

$$g_1^{LT+TMC}(x,Q^2) \simeq g_1^{LT}(x), \quad g_2^{LT+TMC}(x,Q^2) \simeq -g_1^{LT}(x) + \int_\xi^1 \frac{dz}{z} g_1^{LT}(z)$$

Leading twist quark distributions:

$$g_1^{LT}(x) = \frac{1}{2}\sum_q e_q^2 \left[\Delta C_{qq} \otimes \Delta q(x) + \Delta C_{qg} \otimes \Delta g(x)\right]$$

JAM: Polarized DIS

Twist-3 structure functions:

$$g_1^{T3+TMC}(x,Q^2) = 4\mu^2x^2\frac{D(\xi)}{(1+4\mu^2x^2)^{3/2}} - 4\mu^2x^2\frac{3}{(1+4\mu^2x^2)^2}\int_\xi^1\frac{dz}{z}D(z)$$
$$+ 4\mu^2x^2\frac{2-4\mu^2x^2}{(1+4\mu^2x^2)^{5/2}}\int_\xi^1\frac{dz}{z}\int_{z'}^1\frac{dz'}{z'}D(z')$$
$$g_2^{T3+TMC}(x,Q^2) = \frac{D(\xi)}{(1+4\mu^2x^2)^{3/2}} - \frac{1-8\mu^2x^2}{(1+4\mu^2x^2)^2}\int_\xi^1\frac{dz}{z}D(z)$$
$$- \frac{12\mu^2x^2}{(1+4\mu^2x^2)^{5/2}}\int_\xi^1\frac{dz}{z}\int_{z'}^1\frac{dz'}{z'}D(z')$$

Bjorken limit$(Q^2 \to \infty)$:

$$g_1^{T3+TMC}(x,Q^2) \simeq 0 \qquad g_2^{T3+TMC}(x,Q^2) \simeq D(x) - \int_\xi^1\frac{dz}{z}D(z)$$

Twist-3 quark distributions:

$$D(x,Q^2) = \frac{4}{9}D_u(x,Q^2) + \frac{1}{9}D_d(x,Q^2)$$

JAM: Polarized DIS

Twist-4 structure function:

$$g_1^{T4(p,n)}(x,Q^2) = H^{(p,n)}(x)/Q^2$$

Nuclear corrections: $\rightarrow$ nuclear smearing functions

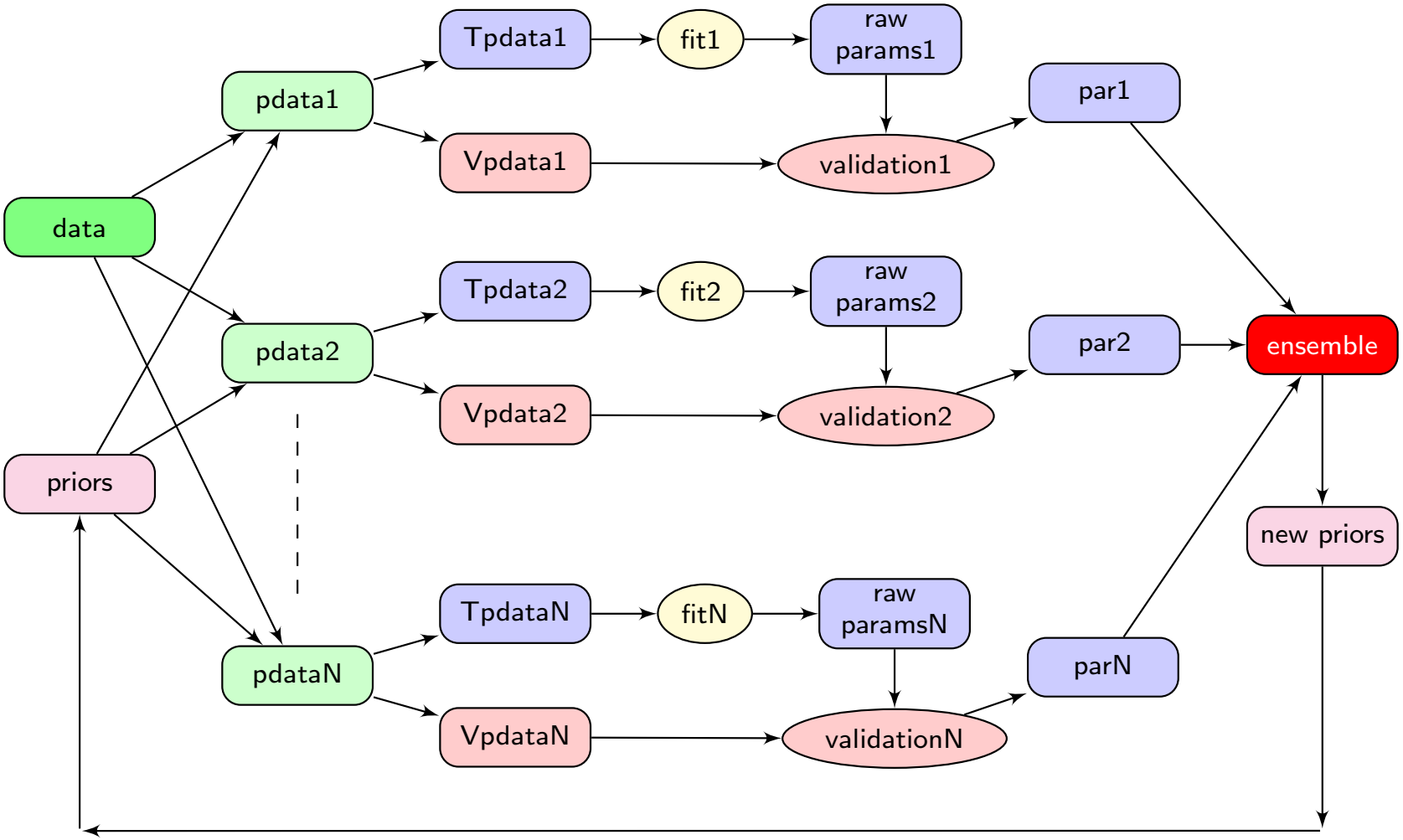
$$g_i^A(x,Q^2) = \sum_N \int \frac{dy}{y} f_{ij}^N(y,\gamma) g_j^N(x/y,Q^2)$$

Curse of dimensionality $\rightarrow$ Mellin trick (Stratmann, Vogelsang)

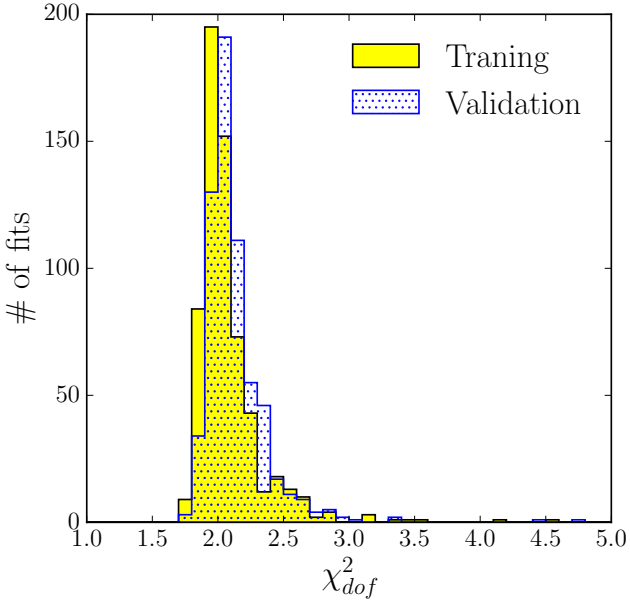
$$\begin{aligned}
I(x) &= \int_x^1 \frac{dy}{y} f(y) \int_y^1 \frac{dz}{z} g\left(\frac{x}{yz}\right) \qquad \leftarrow \qquad g(\xi) = \frac{1}{2\pi i}\int dN \xi^{-N} g_N \\
&= \frac{1}{2\pi i}\int dN g_N \left[\int_x^1 \frac{dy}{y} f(y) \int_y^1 \frac{dz}{z} \left(\frac{x}{yz}\right)^{-N}\right] \\
&= \frac{1}{2\pi i}\int dN g_N \mathcal{M}_N \\
&= \sum_{i,k} w_i^k j^k \mathrm{Im}\left(e^{i\phi} g_{N_j^k} \mathcal{M}_{N_j^k}\right) \qquad \leftarrow \qquad \text{Gaussian quadrature}
\end{aligned}$$

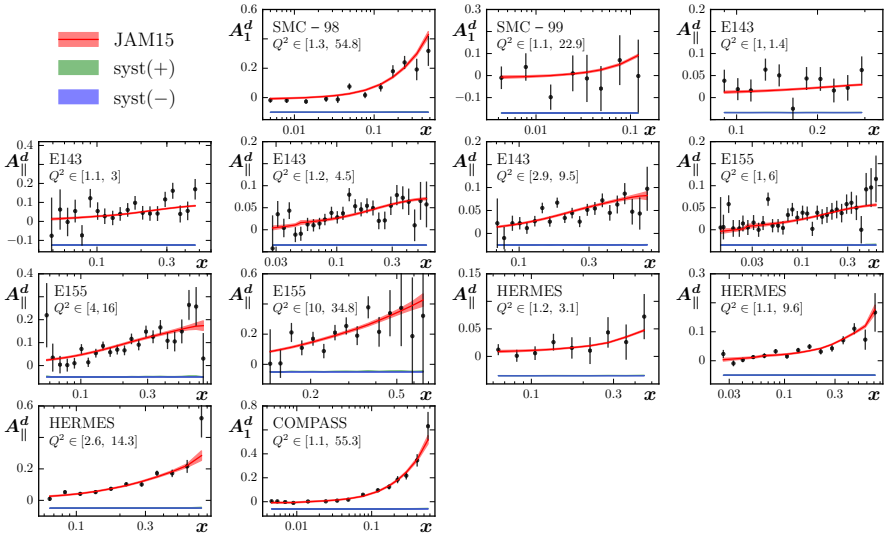
$\rightarrow$ time consuming part can be precalculated prior to the fit

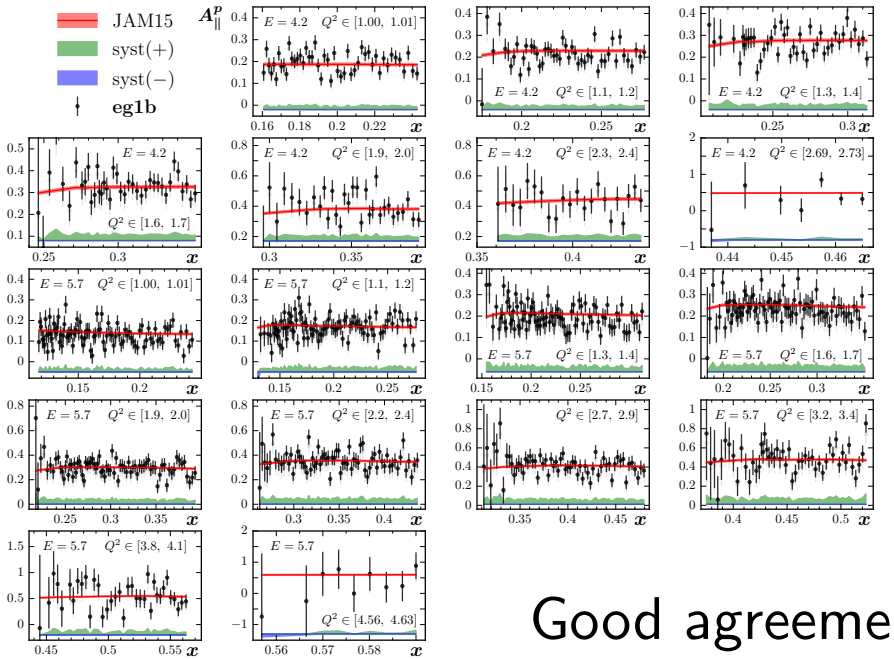
JAM: Iterative MC fitting strategy

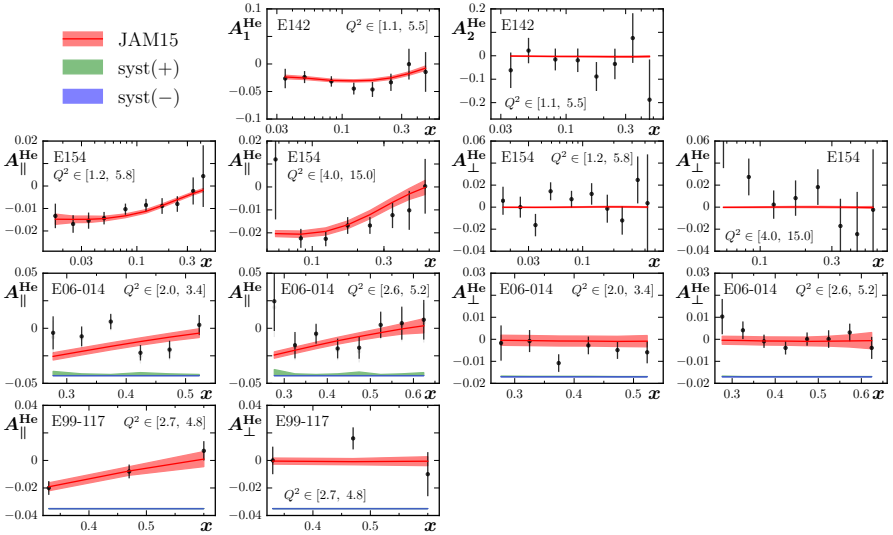


JAM: results (data vs. theory)



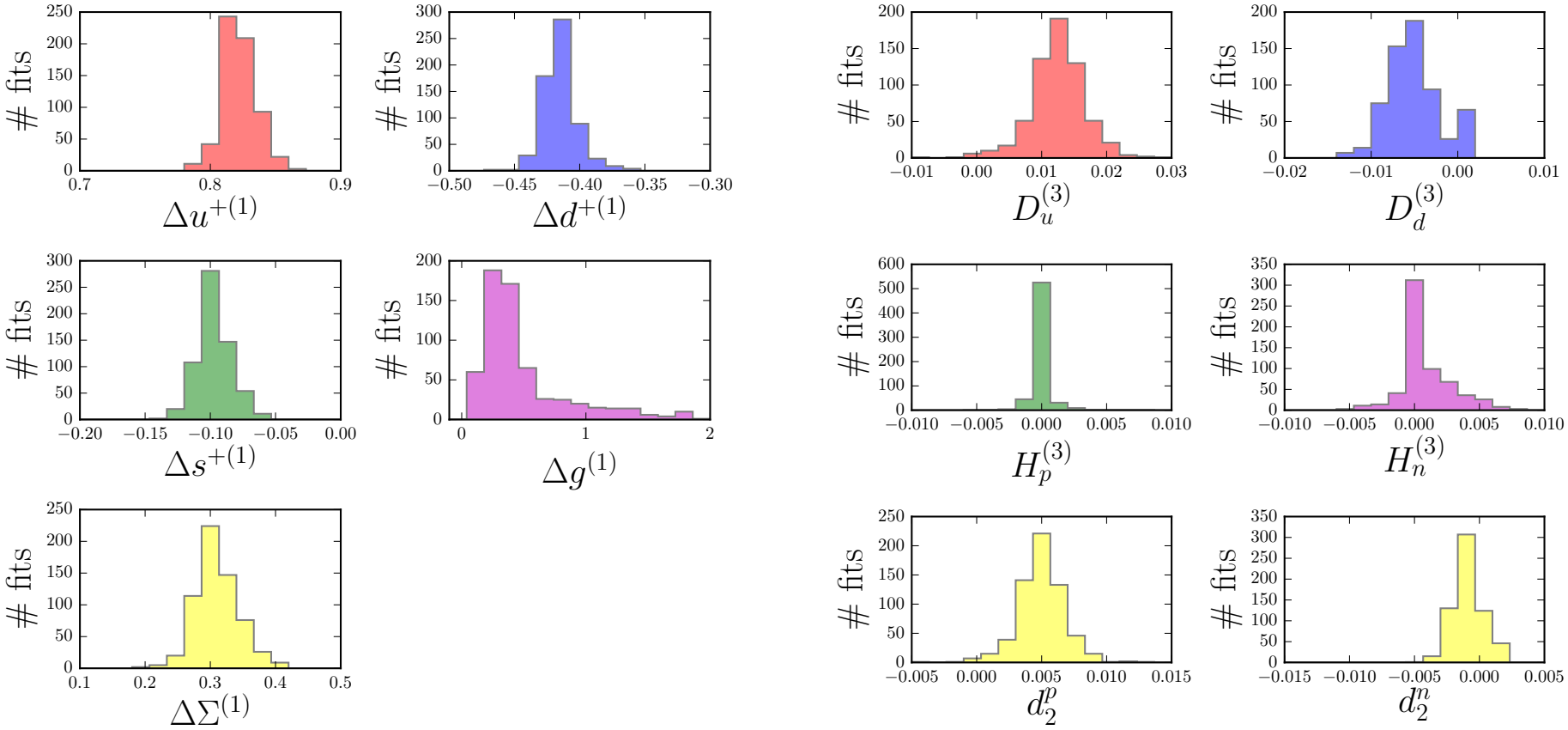






Good agreement between theory and data.

JAM: results (moments)



- **New** extraction of $\Delta\Sigma^{(1)} = 0.31 \pm 0.03$ (Only truncated moments are shown $x \in [10^{-3}, 0.8]$)
- First extraction of d_2 matrix element in global QCD analysis
- **JAM16**: reduction of gluon uncertainties (jet data)

TMD: Summary

At present

- TMD factorization formalism exists $\rightarrow$ difficult to implement @ low Q^2
- Current description of HERMES and COMPASS data $\rightarrow$ *Gaussian models*
- Gaussian models are approximate description data.
- Need to address these issues to describe 12GeV JLab data

✓ New framework to describe transverse dependent observables at small momentum transfer $\rightarrow$ **(see talk by BW)**

✓ Numerical tools to analyze data $\rightarrow$ extraction of non-perturbative quantities (TMD)

Future

- Higher order pQCD corrections
- Fracture functions
- Higher twist
- Target mass corrections
- Treatment of heavy quark contributions
- Development of TMD event generators

Pions and nucleon structure: Summary

Goals

- Study the role of pions in connection with $\bar{d} - \bar{u}$ asymmetry in the proton (E866 DY)
- Asymmetry described within effective chiral framework $\rightarrow \bar{d} - \bar{u} = f_{\pi/N} \otimes \bar{q}_v^{\pi}$
- Analyze recent ZEUS and H1 measurements on SIDIS leading neutron cross sections: $ep \rightarrow enX$

$$\frac{d^3\tilde{\sigma}^{\mathrm{LN}}}{dx dQ^2 dy} = f_{\pi/N}(y) F_2^{\pi}(x/y, Q^2)$$

- HERA data probes F_2^{π} for down to $x_{\pi} = x/y \sim 10^{-4}$

Results

- HERA data alone **cannot** constrain F_2^{π}
- New analysis of combined E866 & HERA data $\rightarrow$ constraints on F_2^{π} and $f_{\pi/N}$
- Predictions made for 12GeV Tagged DIS experiment JLab