Partonic Hadron Structure III

Paul E Reimer

Physics Division

Argonne National Laboratory

July 2017

I. Where are we now?
II. Spin
III. π structure
IV. Generalized Parton Distributions

This work is supported in part by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

Review Partonic Hadron Structure I & II

- **Data** looks like scattering from many point particles (partons)
  - These distributions are universal and process independent
- **Data** allows the determination of the distributions of partons
  - But having the correct assumptions in interpreting data is critical!

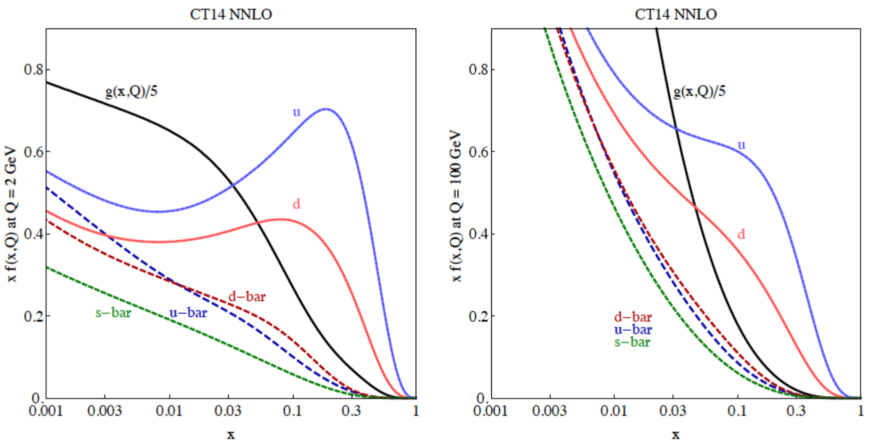
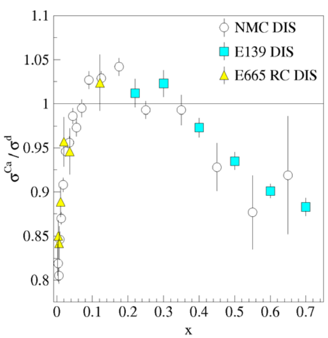
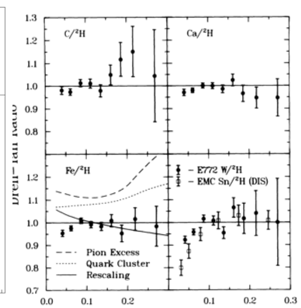


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \overline{u}, d, \overline{d}, s = \overline{s}$, and g.





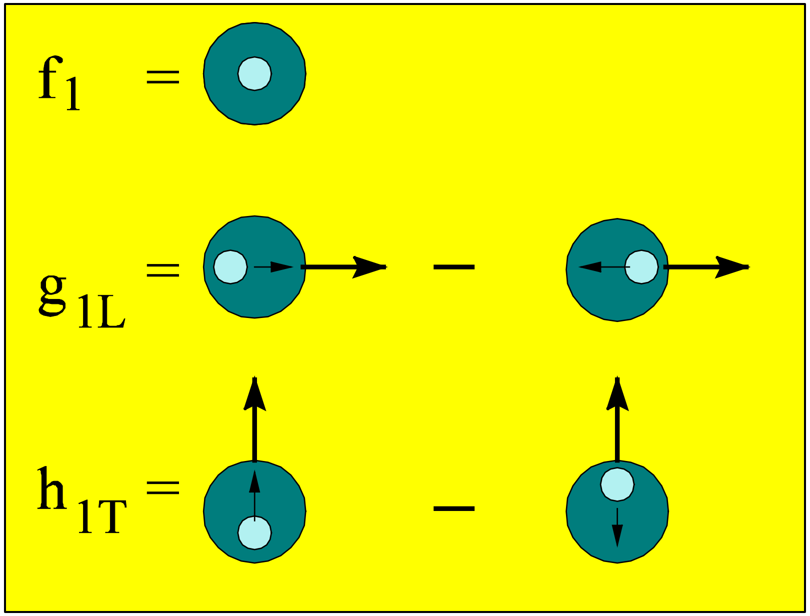
- **Data** shows that these distributions change when the proton is contained in a nucleus
  - Models of these effects are not satisfactory

- The proton’s spin is not where we are looking, but the options are narrowing

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G \qquad \frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

The proton in terms of all parton distributions

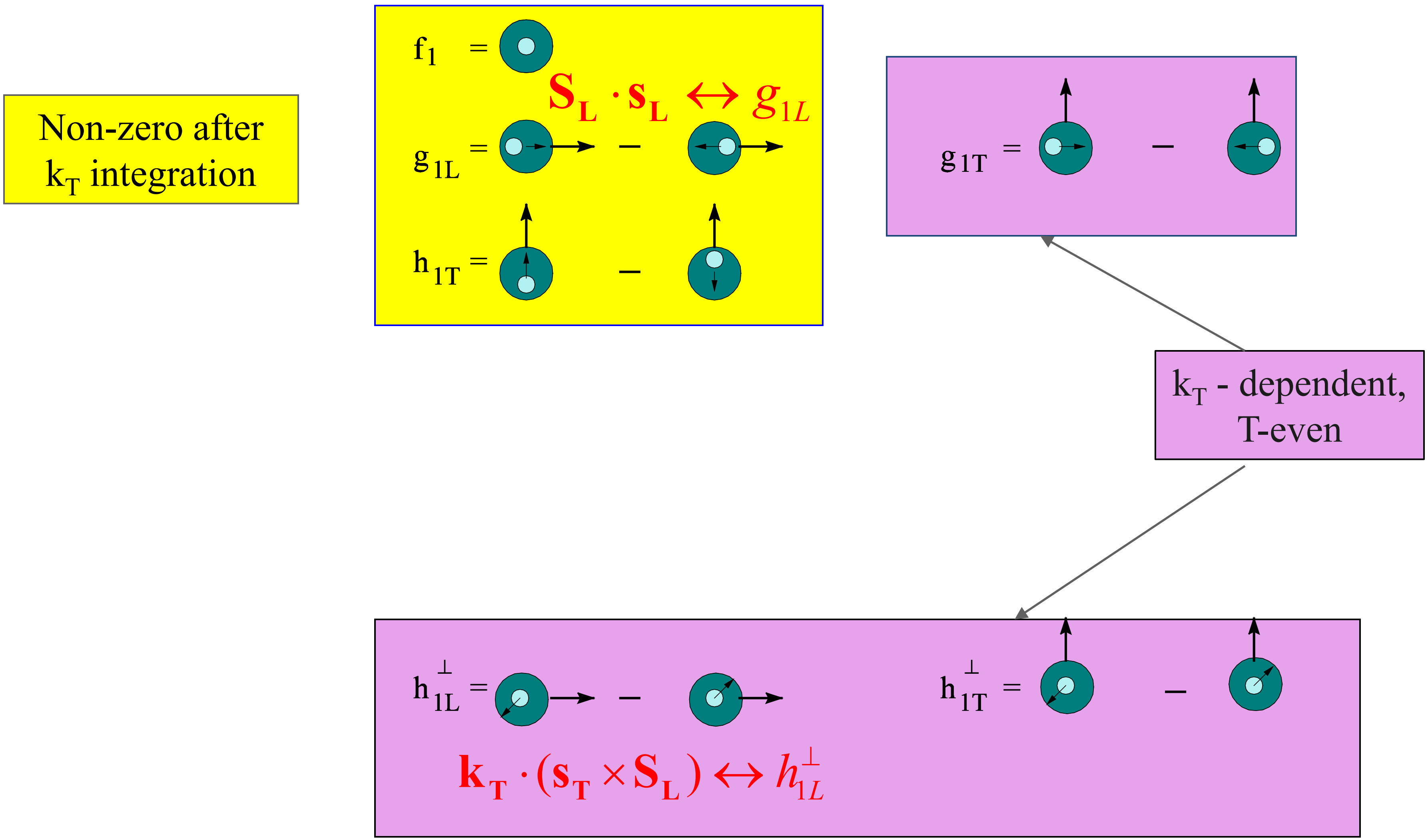
Non-zero after k_T integration



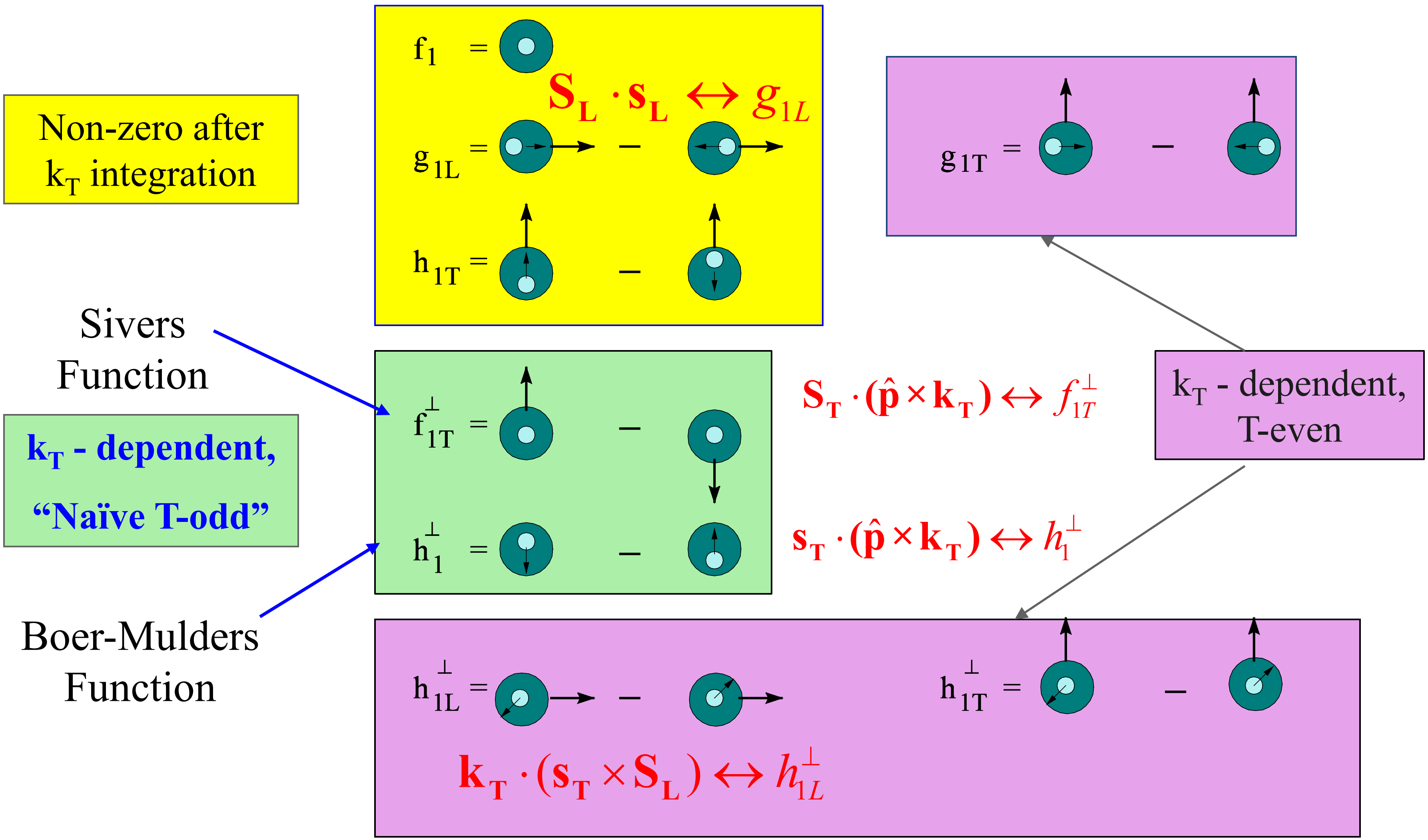
$S_L \cdot s_L \leftrightarrow g_{1L}$

k_T intrinsic transverse motion of the parton inside the nucleon

Transverse Momentum Distributions: Introduction



Transverse Momentum Distributions: Introduction

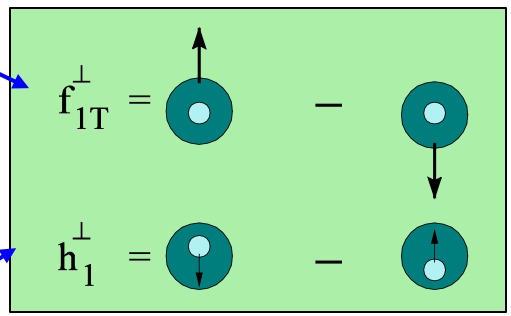


Transverse Momentum Distributions: Introduction

Sivers Function

k_T - dependent,

“Naïve T-odd”



Boer-Mulders Function

Transverse Momentum Distributions: Introduction

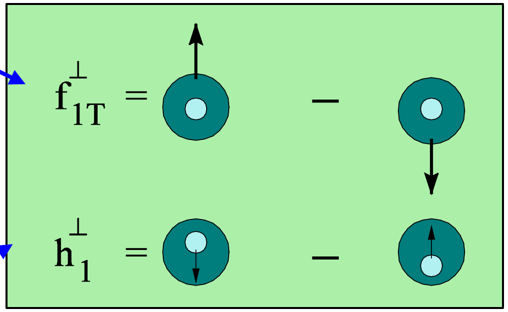
- Sivers Function
  - a correlation between the proton's transverse spin and the motion of an **unpolarized** quark.
  - "Naively" time reversal odd

  - **In the absence of initial- and final-state interactions this should be identically 0. (Proof by Collins)**

Sivers Function

k_T - dependent,

"Naïve T-odd"



$$\mathbf{S}_\mathbf{T} \cdot (\hat{\mathbf{p}} \times \mathbf{k}_\mathbf{T}) \leftrightarrow f_{1T}^{\perp}$$

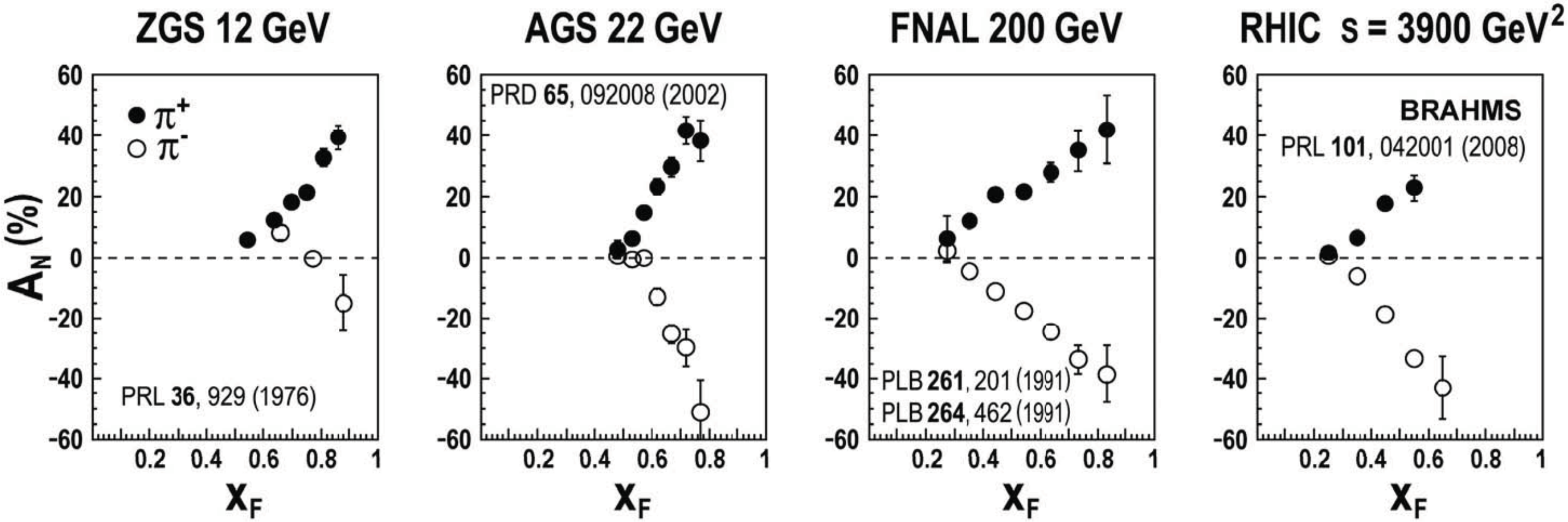
$$\mathbf{s}_\mathbf{T} \cdot (\hat{\mathbf{p}} \times \mathbf{k}_\mathbf{T}) \leftrightarrow h_1^{\perp}$$

Boer-Mulders Function

Immediate reaction:

How can a parton distribution depend on initial and final state interactions?

Single Spin Asymmetries (SSA)



C. Aidala SPIN 2008 Proceeding and CERN Courier June 2009

- Single spin asymmetries in hadron-hadron interactions have been observed over a wide range of center-of-mass energies
- Explanations:
  - k_T dependent fragmentation function in hadronization of quarks

    Collins Fragmentation Function, $H_{1T}^{\perp,q\rightarrow H}(k_T,x,Q^2)$
  - k_T dependent parton distribution in transversely polarized nucleon

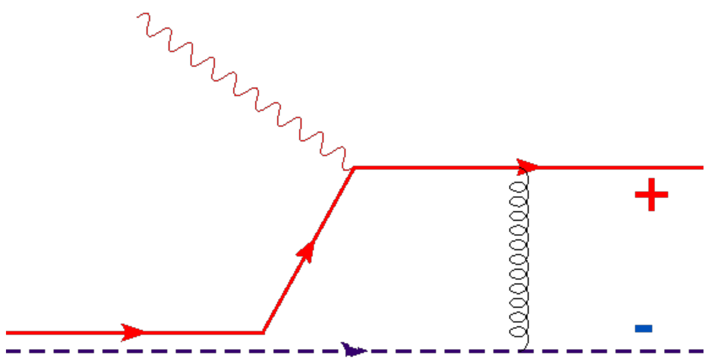
    Sivers Distribution Function, $F_{1T}^{\perp}(k_T,x,Q^2)$

    Apparently T-Odd—but not really!

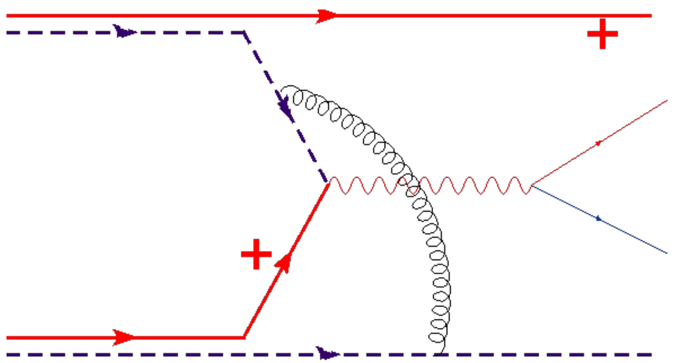
Sivers Function and gauge invariance

- Colored objects are surrounded by gluons, a consequence of gauge invariance by Wilson lines.
- Wilson lines can couple either after (DIS) or before (Drell-Yan) the quark annihilation
- Sivers function has opposite sign

Space-like (DIS) virtual photon



Time-like (Drell-Yan)



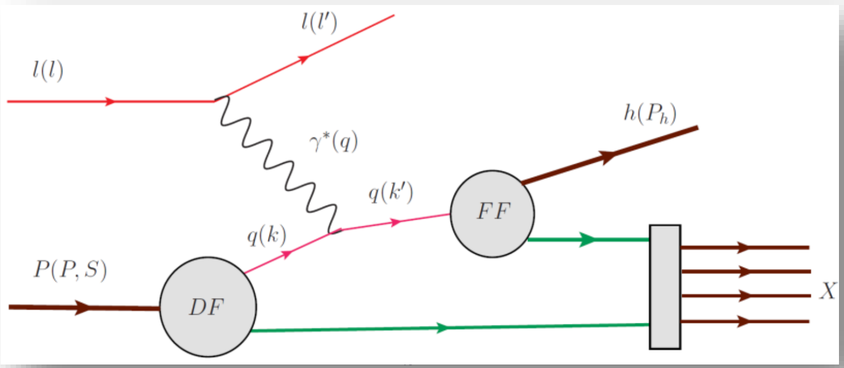
Alexei Prokudin

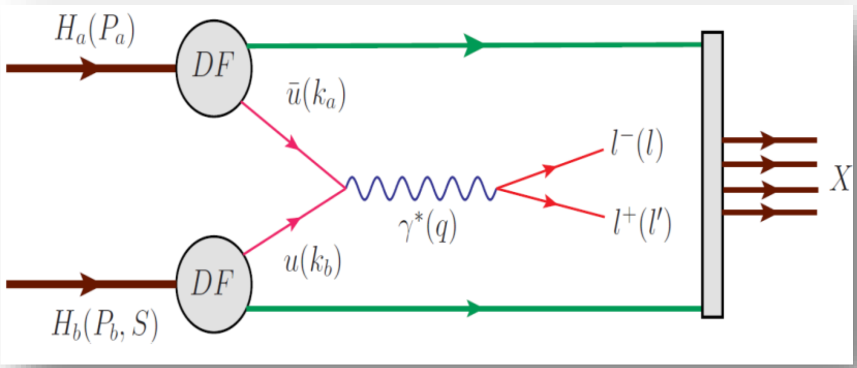
$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = - f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

Sivers Function and gauge invariance

- Rotation from a space-like to a time-like virtual photon changes the interference of the soft gluon gauge links.
- **Path integrals not invariant under this rotation**

Space-like (DIS) virtual photon **Time-like (Drell-Yan)**





A. Kotzinian, DY workshop, CERN, 4/10

$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

Sivers function classical picture

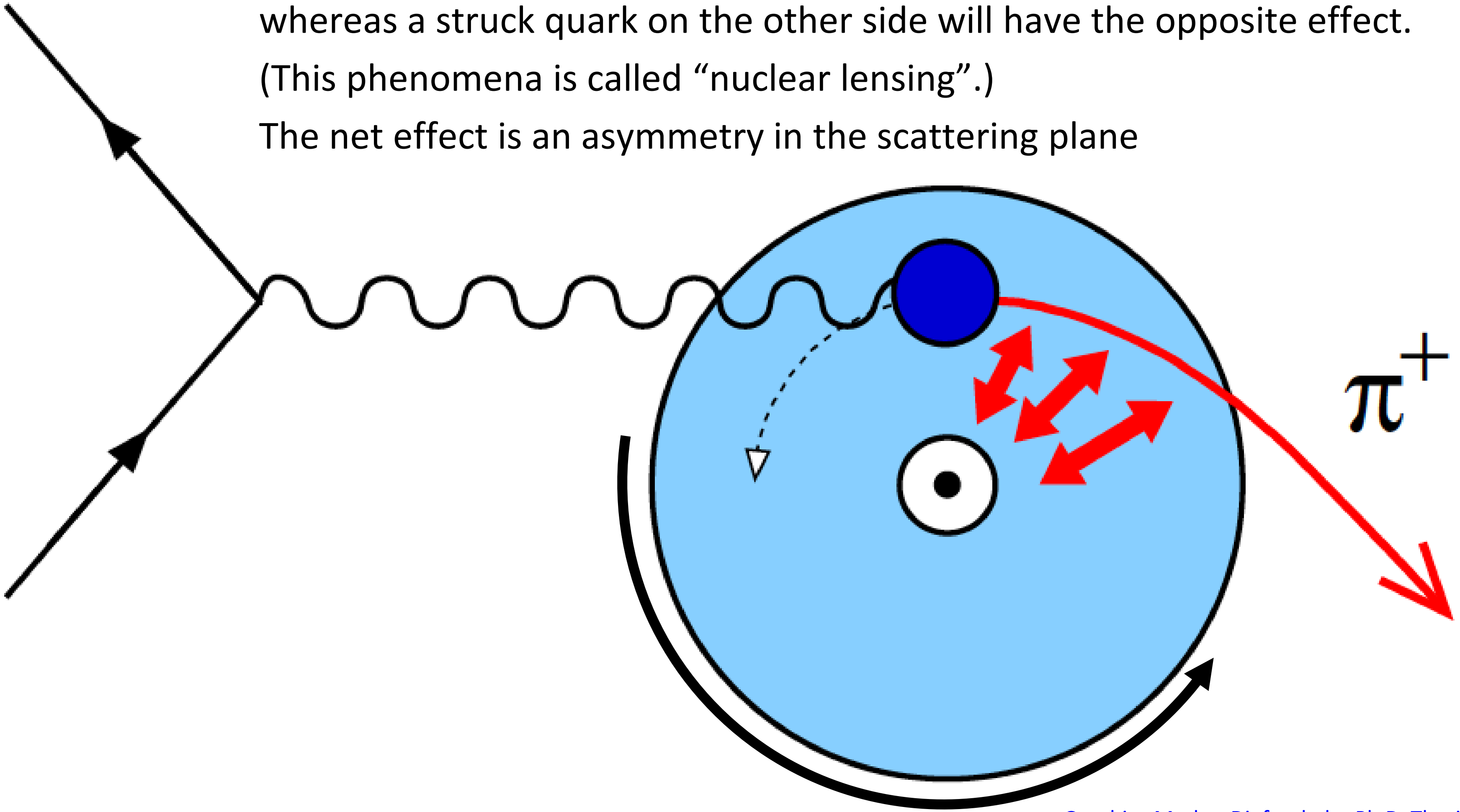
Consider a nucleon that is polarized with spin out of the page

A struck quark on one side will be pulled back into the nucleon remnant,

whereas a struck quark on the other side will have the opposite effect.

(This phenomena is called "nuclear lensing".)

The net effect is an asymmetry in the scattering plane



Graphic: Markus Diefenthaler Ph.D. Thesis

Sivers function classical picture

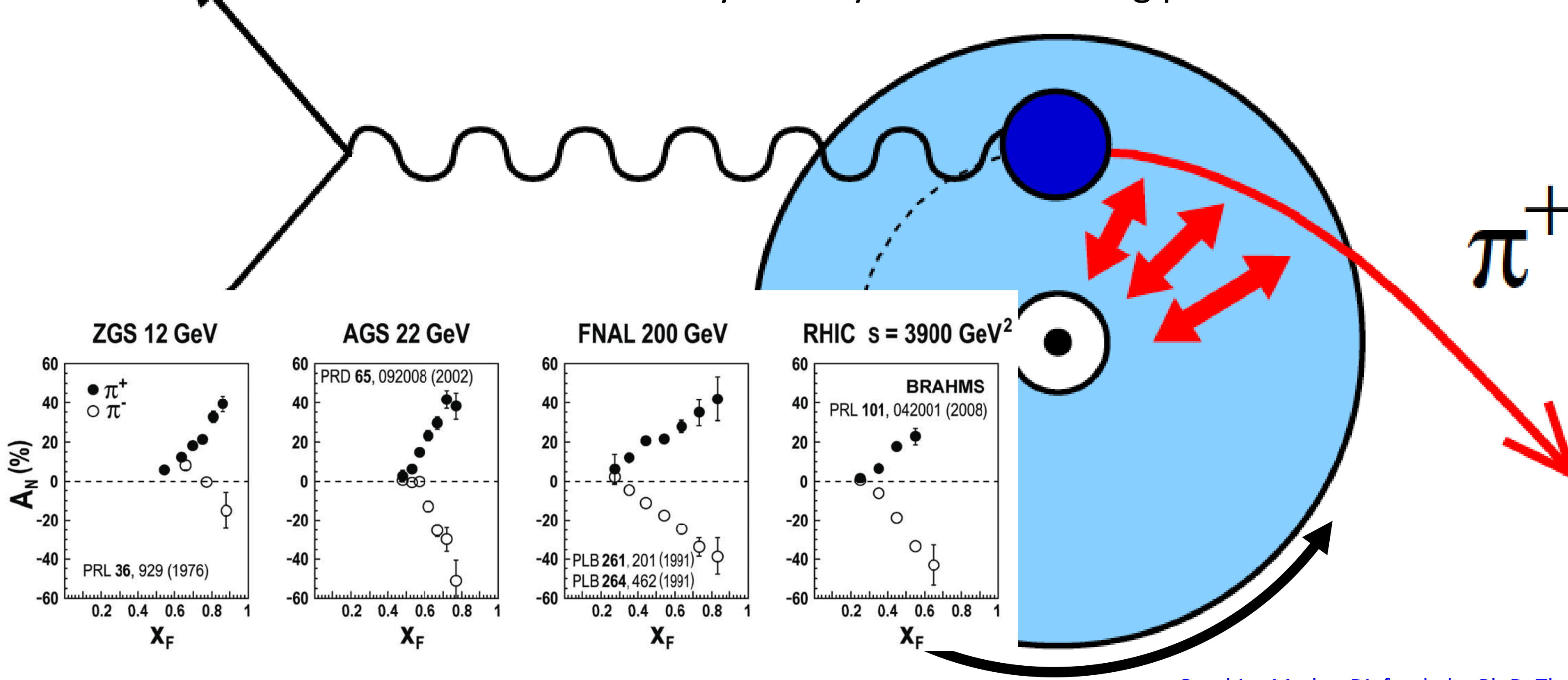
Consider a nucleon that is polarized with spin out of the page

A struck quark on one side will be pulled back into the nucleon remnant,

whereas a struck quark on the other side will have the opposite effect.

(This phenomena is called “nuclear lensing”.)

The net effect is an asymmetry in the scattering plane



Graphic: Markus Diefenthaler Ph.D. Thesis

Sivers function classical picture

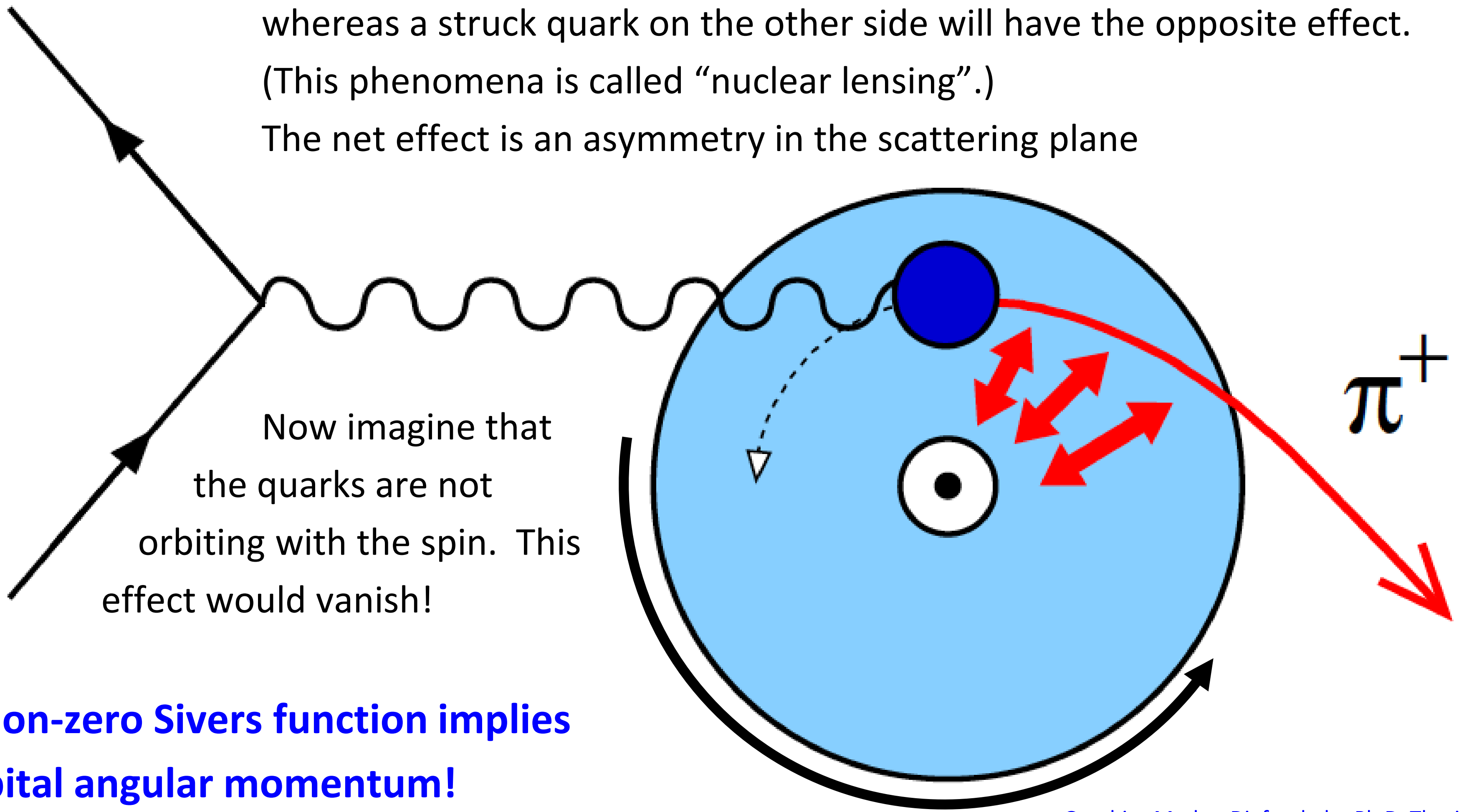
Consider a nucleon that is polarized with spin out of the page

A struck quark on one side will be pulled back into the nucleon remnant,

whereas a struck quark on the other side will have the opposite effect.

(This phenomena is called “nuclear lensing”.)

The net effect is an asymmetry in the scattering plane

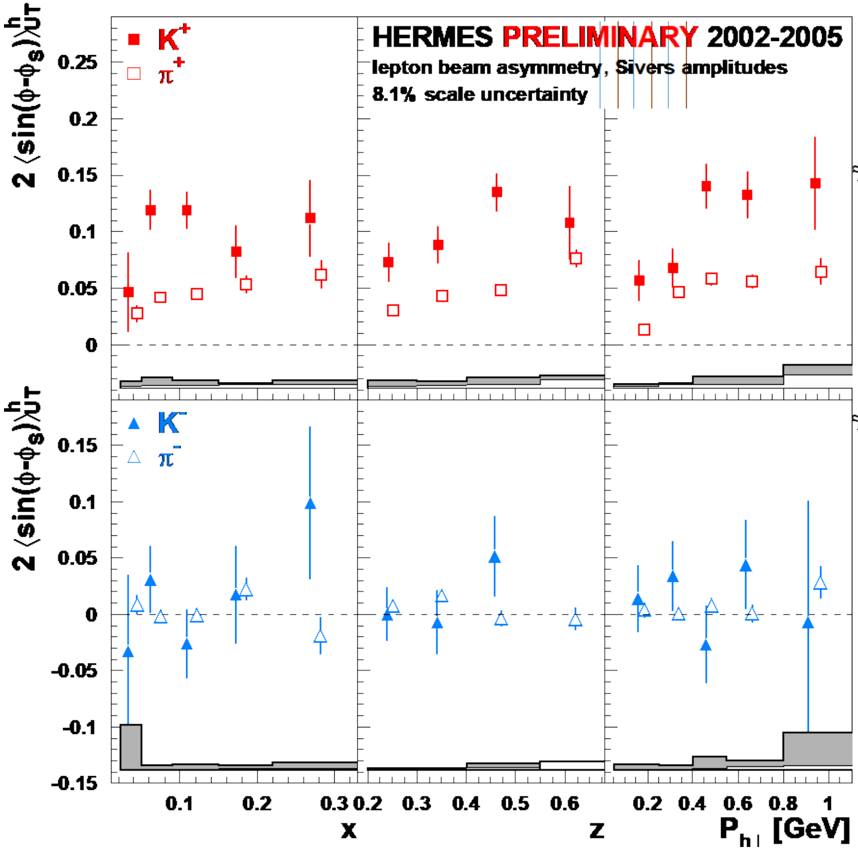


Now imagine that the quarks are not orbiting with the spin. This effect would vanish!

A non-zero Sivers function implies orbital angular momentum!

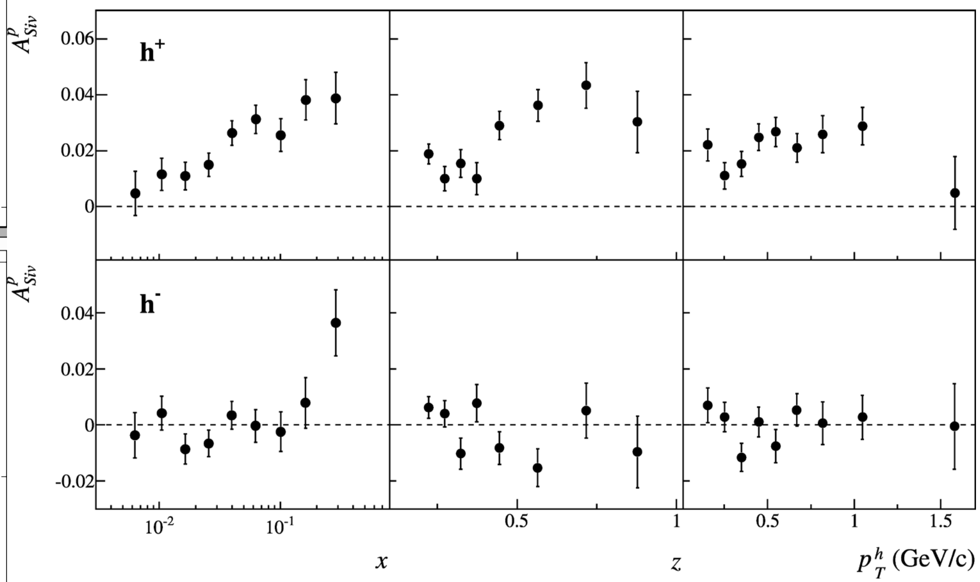
Graphic: Markus Diefenthaler Ph.D. Thesis

SIDIS Sivers' measurements



HERMES, Airapetian *et al.* Phys. Rev. Lett. 103, 152002

COMPASS, Adloph *et al.* Phys Lett. B, 717, 383



- Global fit to $\sin(\phi_h - \phi_S)$ asymmetry in SIDIS from HERMES, and COMPASS

Fits of Sivers asymmetries

- Data fit to extract Sivers distributions
- Shown at left are the 1st moments

The Sivers function is non-zero

Quarks have orbital angular momentum!

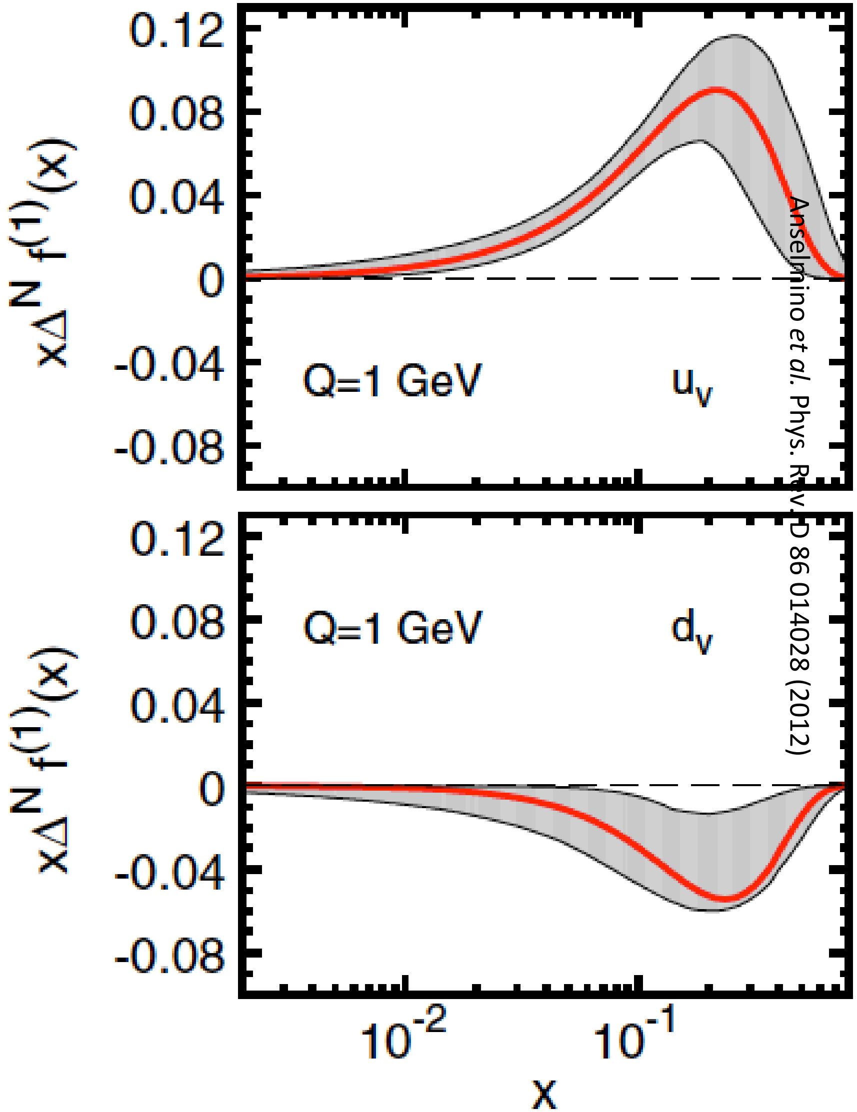
But . . .

While it can be shown rigorously that a non-zero Sivers function implies orbital angular momentum,

There is not yet a rigorous method to quantitatively extract L_q from , $F_{1T}^{\perp}$

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

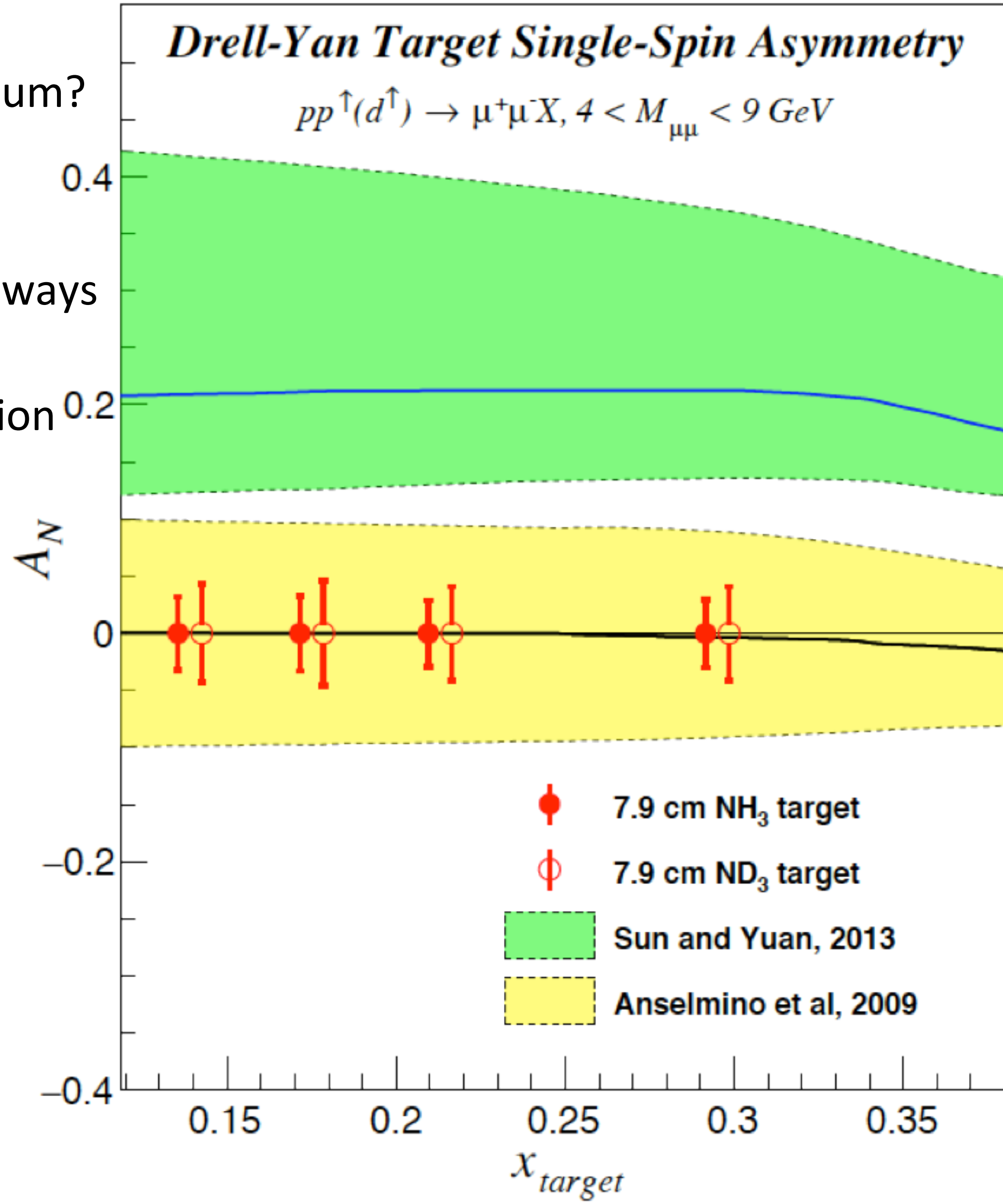
$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\% \quad L_q \neq 0$$



Anselmino *et al.* Phys. Rev. D 86 014028 (2012)

Sivers asymmetries for the sea?

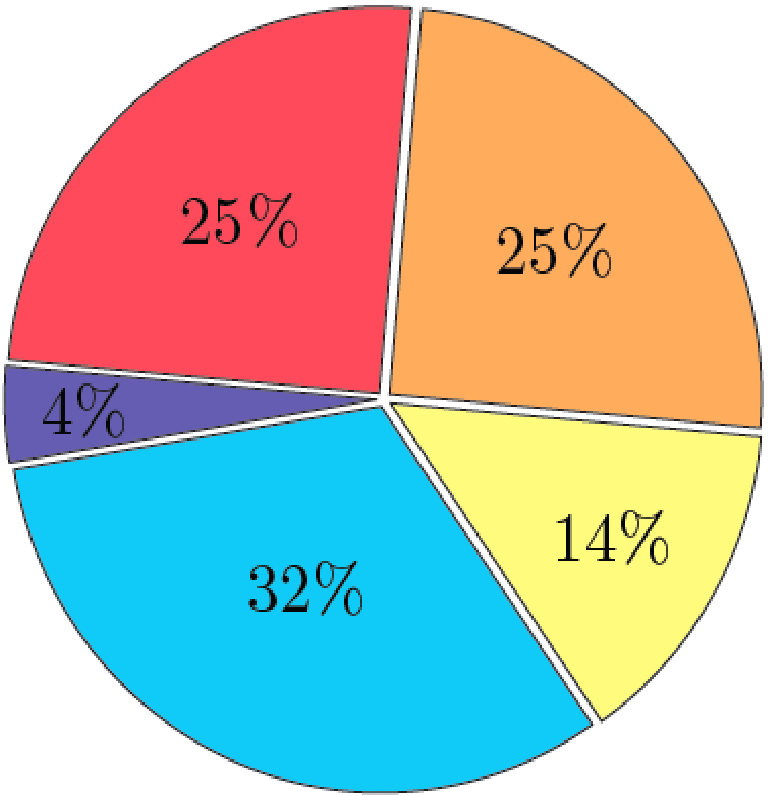
- Does the sea have orbital angular momentum?
  - Macroscopic properties seem to be Valence
- Past assumptions about the sea seem to always turn out to be wrong, e.g.:
  - The sea is solely created by QCD evolution
  - If not that, then at least $\bar{d}(x) = \bar{u}(x)$
- Polarized target Drell-Yan
  - Fermilab E1039
  - Both Fermilab and DOE/Nuclear Physics are interested, but. . .



Final comment on angular momentum: Lattice

Lattice calculation of the spin budget

K.-F. Liu *et al* arXiv:1203.6388



- L^{u+d}
- $L^{\bar{u}+\bar{d}}$
- $L^{s+\bar{s}}$
- J^{g}
- $\frac{\Delta\Sigma}{2}|^{u+d+s}$

$$\Delta\Sigma \approx 25\%$$

$$2L_q^{\mathrm{Valence}} \approx 5\%$$

$$2L_q^{\mathrm{Sea}} \approx 45\%$$

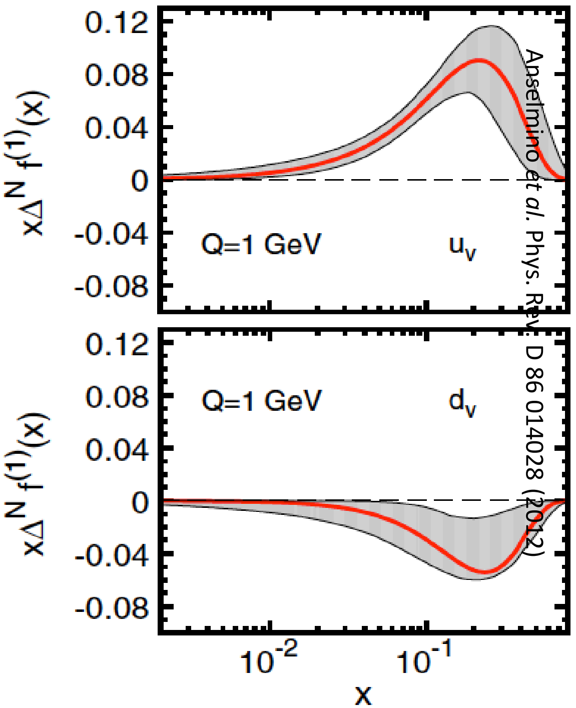
$$2J_g \approx 25\%$$

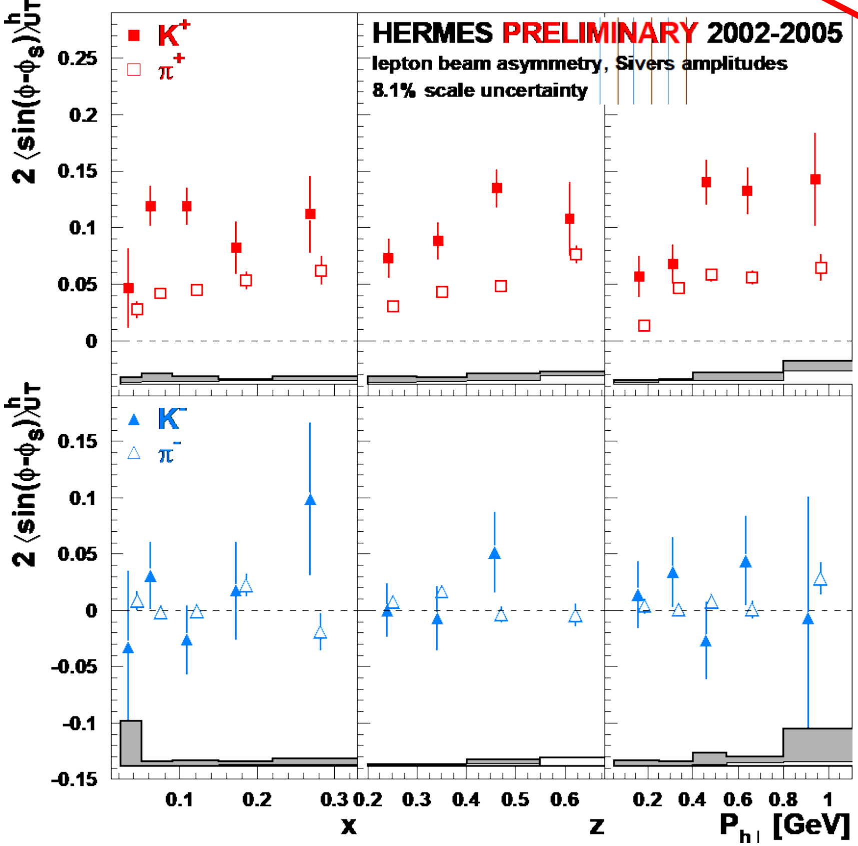

Becky: Happy!


Dusty:
Not so happy

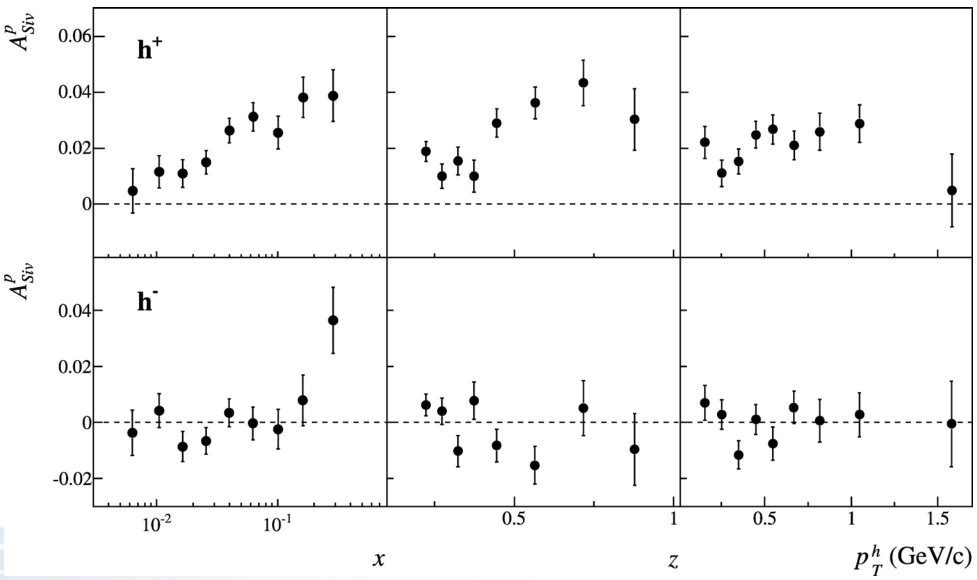
What about gauge invariance?

$$\boxed{f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}}} = -\, f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$





COMPASS

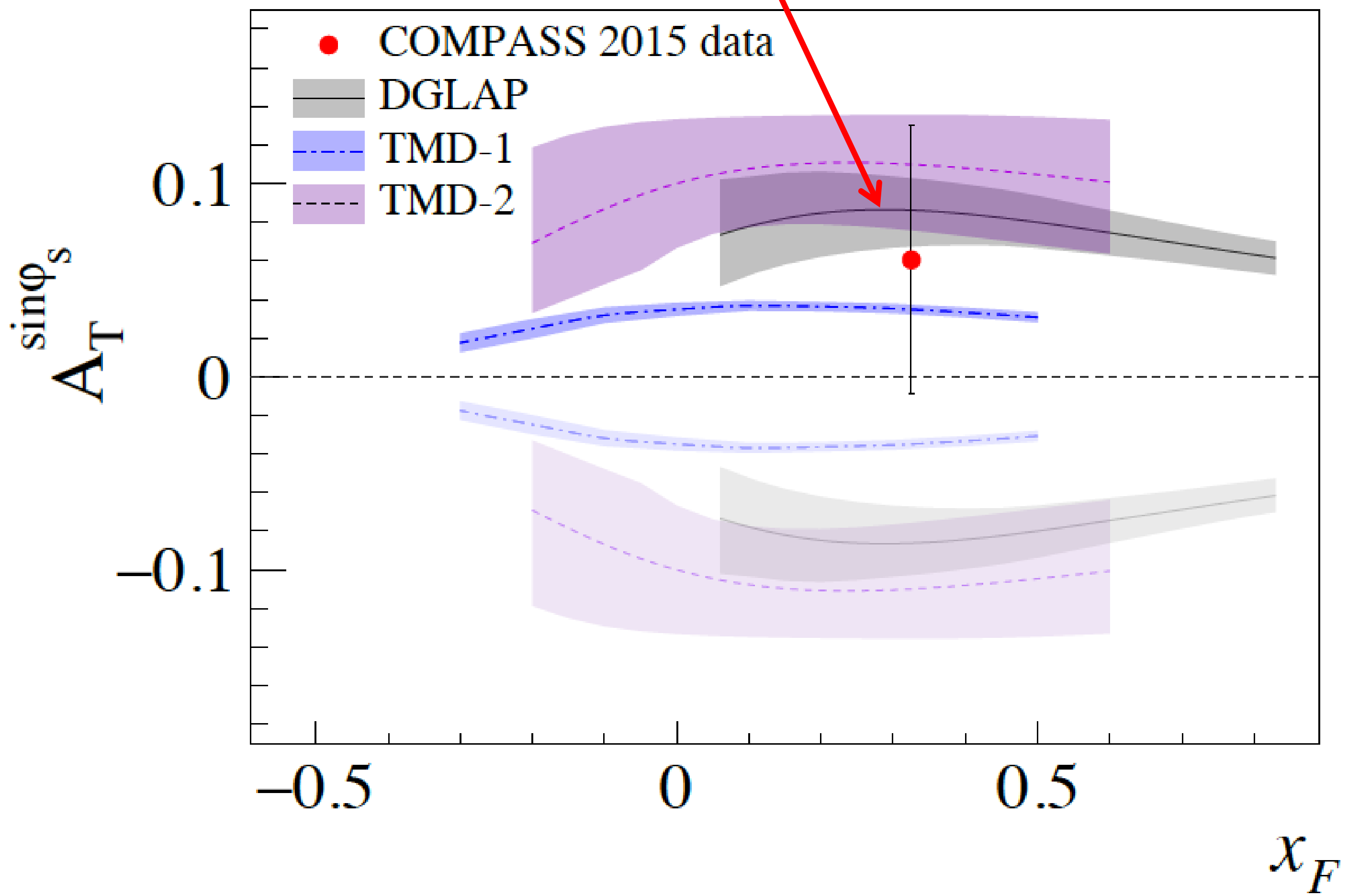


What about gauge invariance?

$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = - f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

What about gauge invariance?

$$f_{1T}^{\perp}\Big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\Big|_{\mathrm{DY}}$$

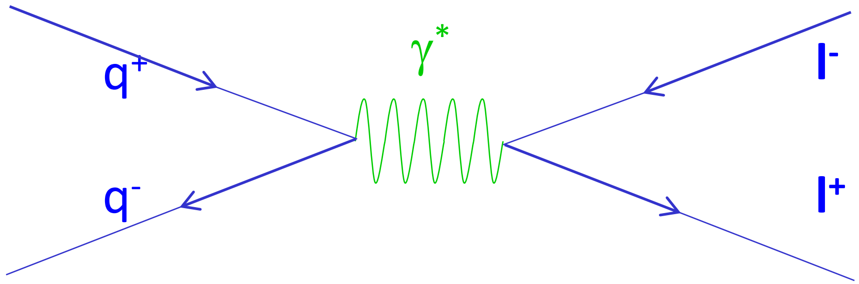


What about gauge invariance?

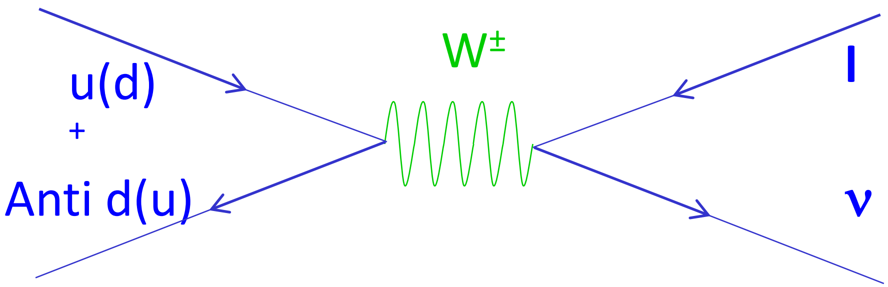
$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

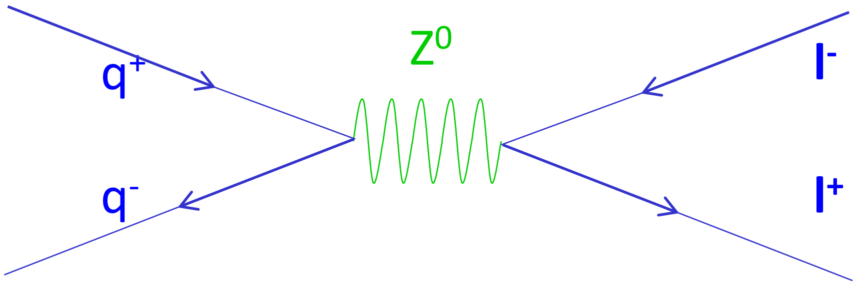
STAR

Drell-Yan



Pseudo Drell-Yan

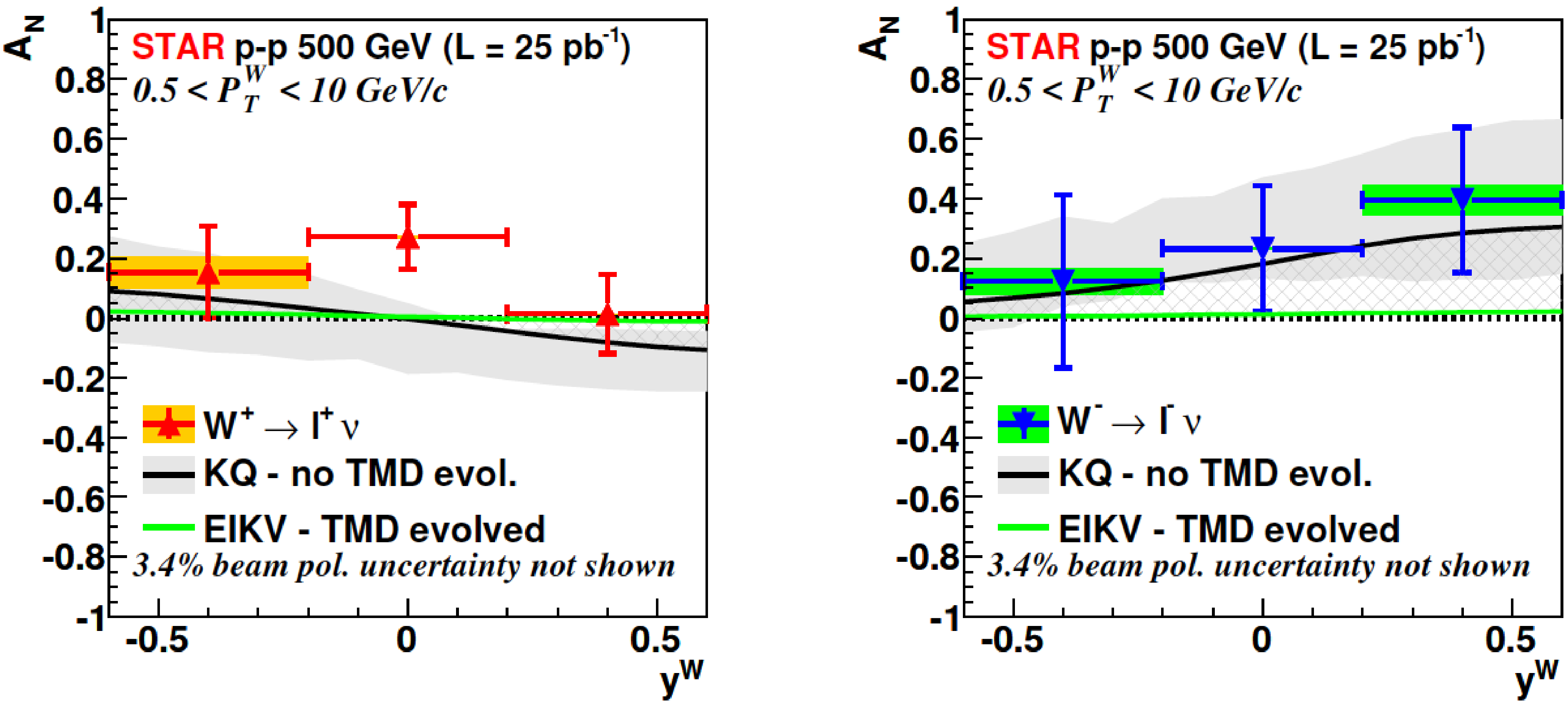




What about gauge invariance?

$$f_{1T}^{\perp}\big|_{\mathrm{SIDIS}} = -\, f_{1T}^{\perp}\big|_{\mathrm{DY}}$$

STAR

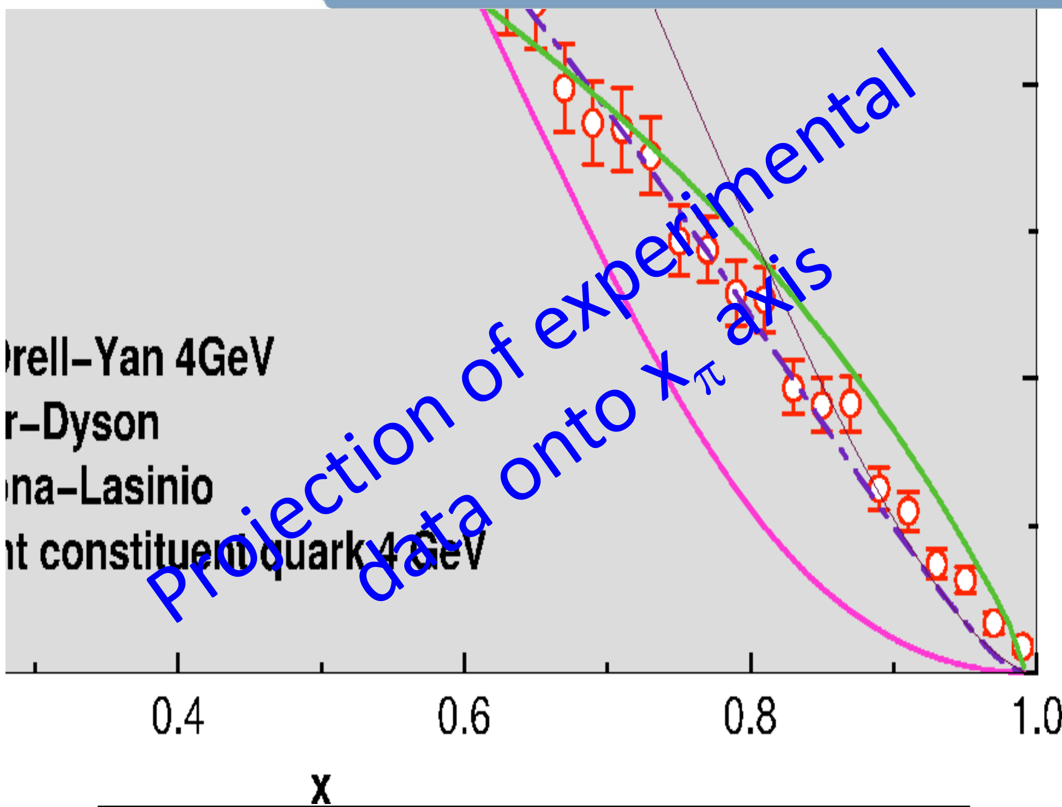


Partonic structure of mesons

Models of the Pion

- Nambu and Jona-Lasinio Model:
  - R. Davidson, E. Arriola, PLB (1995)
  - J.T. Londergan *et al.* PLB (1994).
  - T. Shigetani *et al.* PLB (1993).
- Dyson Schwinger Equation:
  - M. Hecht *et al.* PRD (2001).
- Chiral Quark Model:
  - K. Suzuki, W. Weise, NPA (1998).
  - D. Arndt, M. Savage, nucl-th (2001).
- Light-front constituent quark models:
  - G. Miller,
  - *et al.* (too many to list).
- Instanton Model:
  - A. Dorokhov, L. Tomio, PRD (2000).
- QCD Sum Rule Calculations
  - A. Bakulev *et al.* PLB (2001).
- Lattice Gauge
  - C. Best *et al.* PRD (1997).

and more



At some base q_0

NJL: $xq(x) \sim (1-x)^\beta$ $\beta = 1$

pQCD: $xq(x) \sim (1-x)^\beta$ $\beta = 2$

DSE: $xq(x) \sim (1-x)^\beta$ $\beta \approx 1.9$

Evolution to experimental Q increases β.

Consider the Available Data

No on-mass pion targets—only pion-hadron data

- Direct photos in πp interactions
- Drell-Yan πA interaction
  - π^+/π^- ratios
  - Absolute πA cross sections
- Virtual π cloud—Sullivan effect

Experimental tools for π structure

- Direct photos in πp interactions
  - Sensitive to gluon distributions.

    [CERN WA 70, Z. Phys. **C37** 535 (1988)]

Assume parameterization

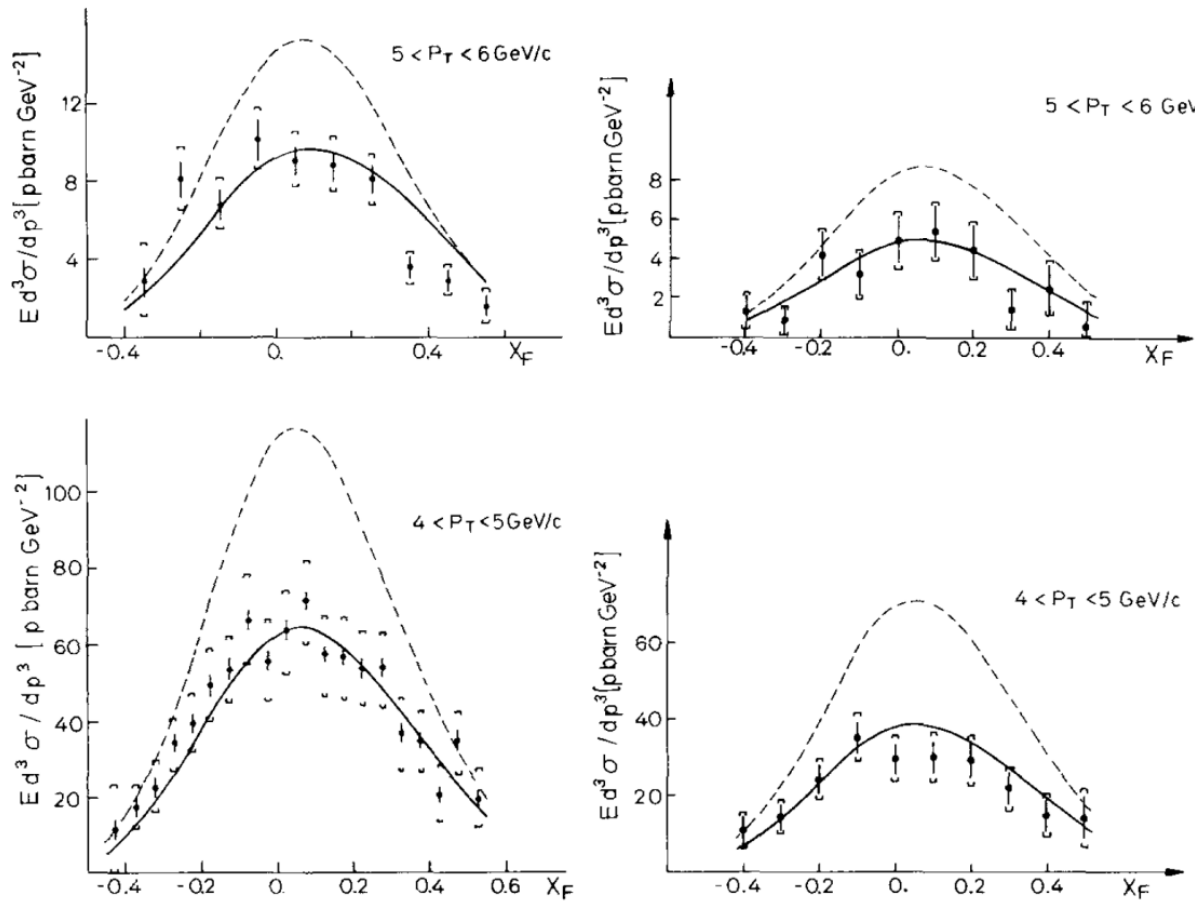
SMRS, PR**D45** 2349 (1992)

$$xg_\pi(x) = A_\pi^g (1-x)^\eta$$

$$\eta \approx 2.1$$

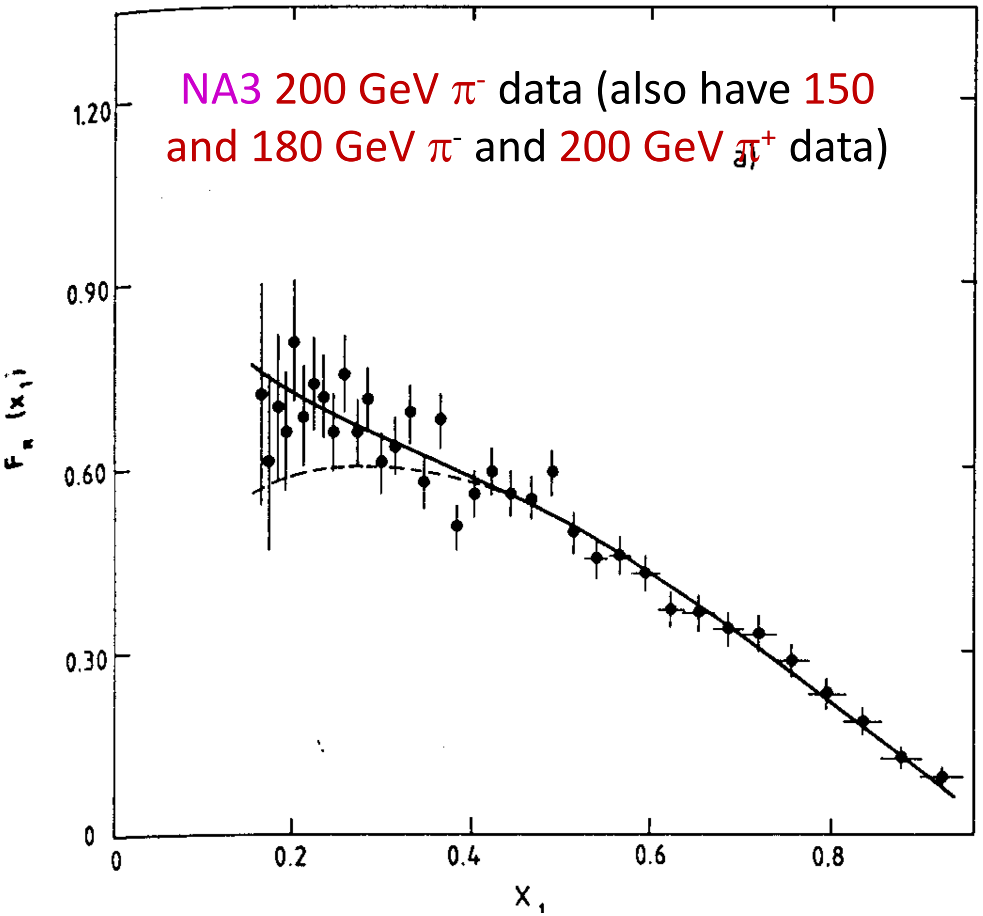
$$G_\pi \equiv \int_0^1 xg_\pi(x)dx = 0.4$$

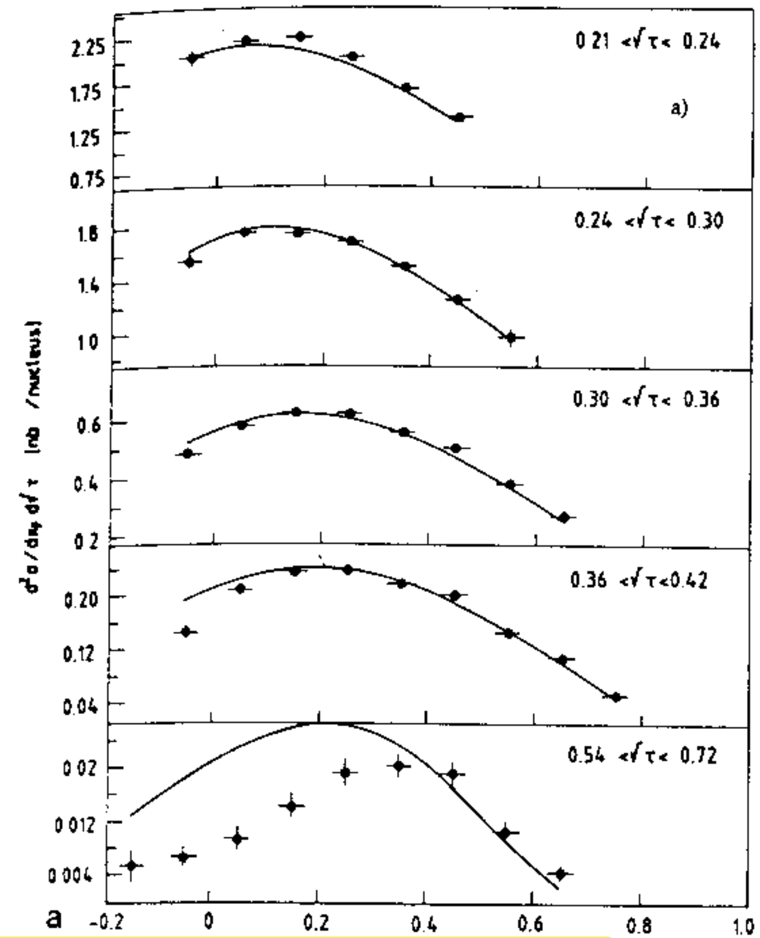
Half of pion's momentum is carried by glue



Pion Drell-Yan Data: CERN NA3 ($\pi^{\pm}$) NA10 (π^{-})

NA3 200 GeV π^- data (also have 150 and 180 GeV π^- and 200 GeV π^+ data)





NA10 194 GeV π^- data

$$Q_\pi^{\text{sea}} \equiv \int_0^1 x q_\pi^{\text{sea}}(x)\,dx = 0.01$$

Very small quark sea in the pion

Experimental Tools for π structure

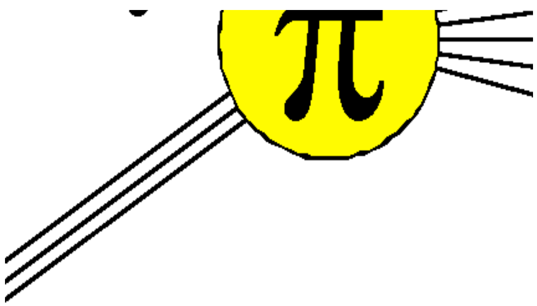
- Deeply Inelastic Scattering:

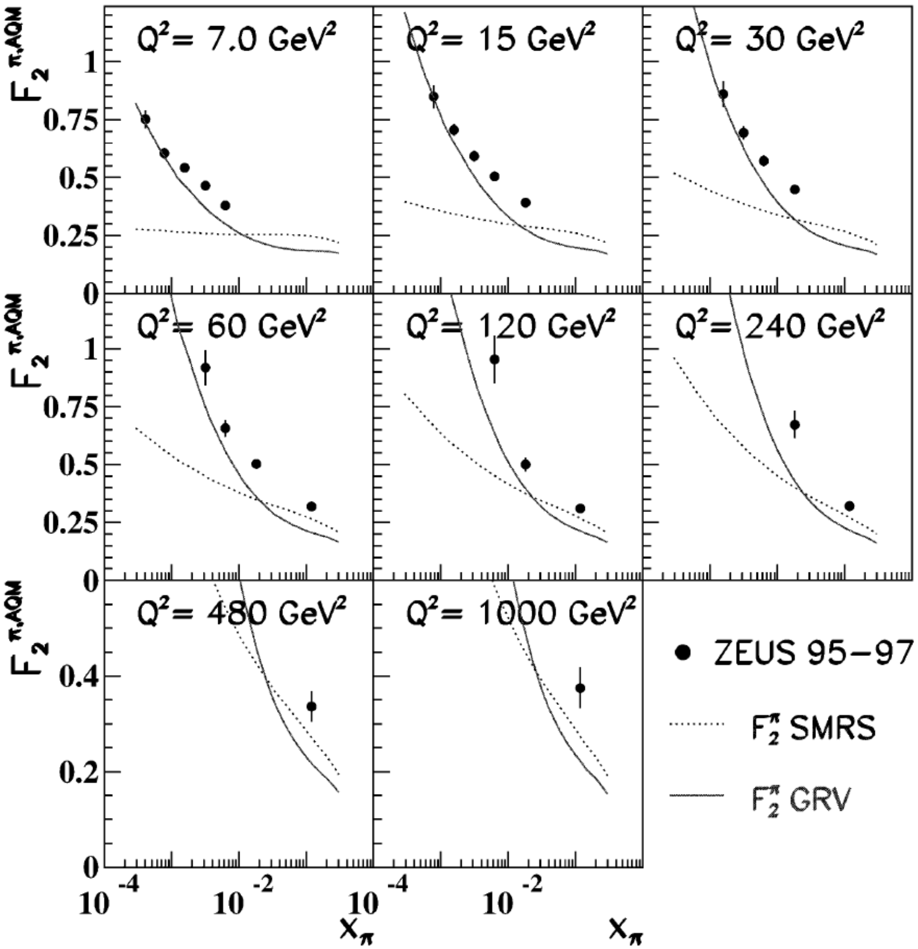
  “pion targets are not abundant” Hecht

  – DIS on virtual pions:

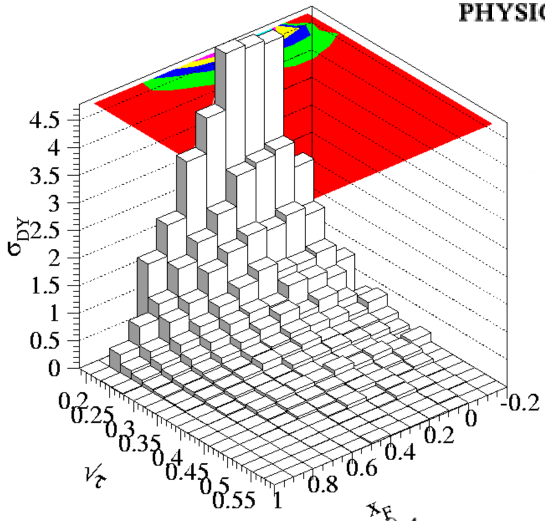
    ep→eNx HERA data [ZEUS, NPB637 3 (2002)]

    Possible JLab and EIC.





Pion Drell-Yan Data: Fermilab E615



PHYSICAL REVIEW D VOLUME 39, NUMBER 1 1 JANUARY 1989

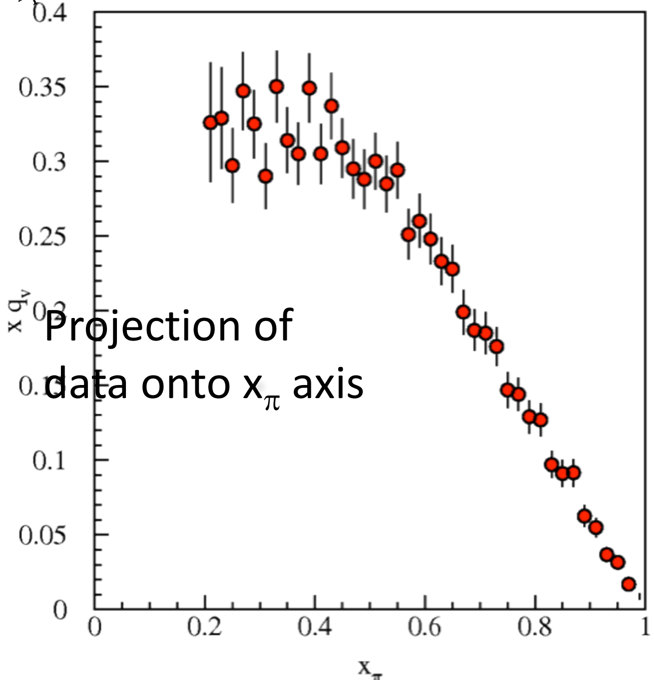
Experimental study of muon pairs produced by 252-GeV pions on tungsten

J. S. Conway,* C. E. Adolphsen,† J. P. Alexander,‡ K. J. Anderson, J. G. Heinrich, J. E. Pilcher, and A. Possoz
Enrico Fermi Institute and Department of Physics, The University of Chicago, Chicago, Illinois 60637

E. I. Rosenberg
Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011

C. Biino,§ J. F. Greenhalgh,** W. C. Louis,†† K. T. McDonald, S. Palestini,§ F. C. Shoemaker, and A. J. S. Smith
Joseph Henry Laboratories, Department of Physics, Princeton University, Princeton, New Jersey 08544

(Received 8 July 1988)

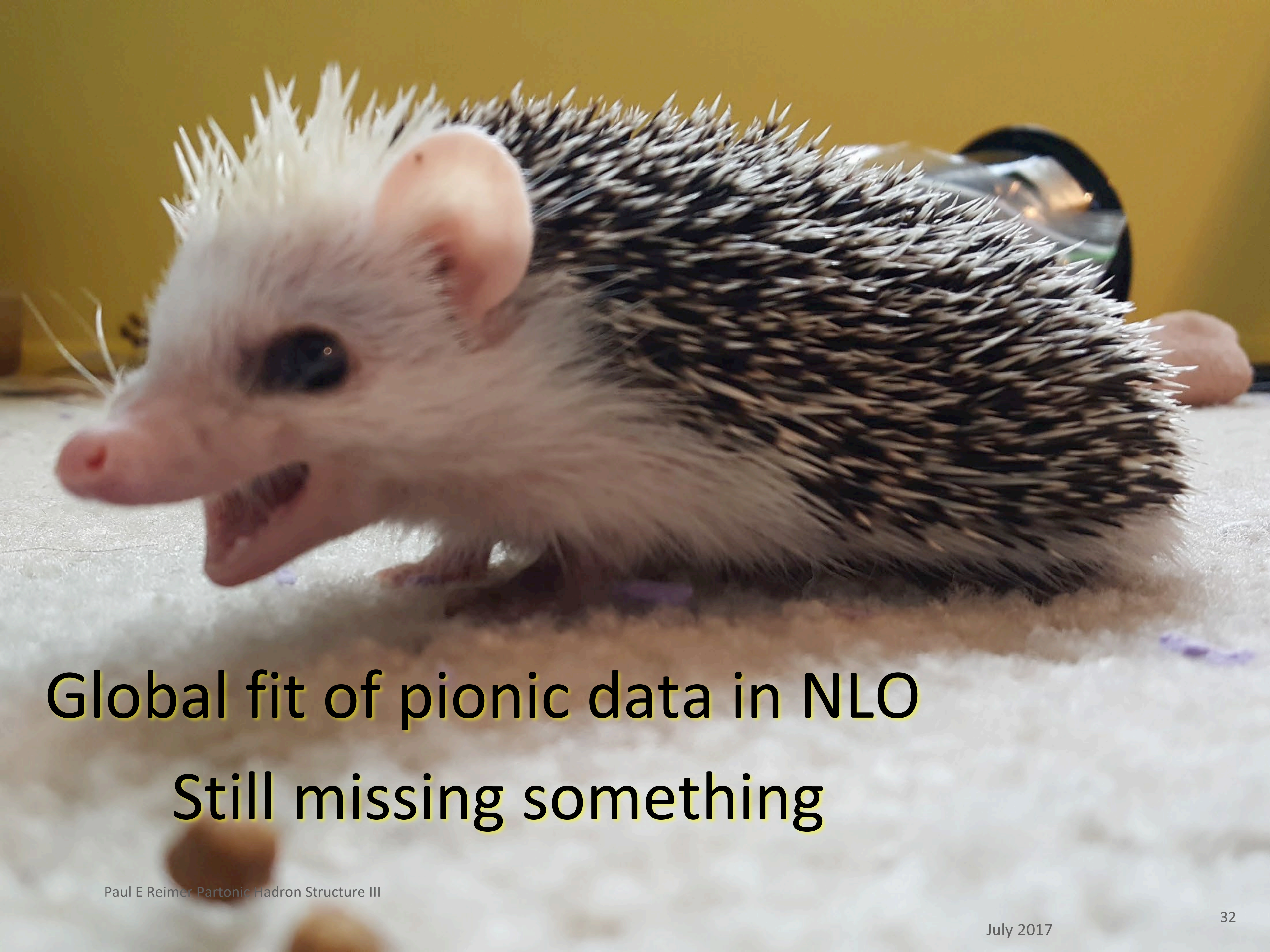


Projection of data onto x_π axis

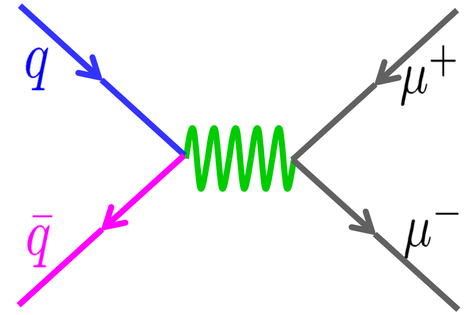
Fermilab E615

- 252 GeV π^-W Drell-Yan
- Projected each data point onto x_π axis (diagonal)
- Valence quark distributions extracted assuming

$xq(x) = A\, x^\alpha (1-x)^\beta$


Global fit of pionic data in NLO
Still missing something

Soft Gluon Resummation



$$\frac{d\sigma}{dQ^2 d\eta} = \sigma_0 \sum_{a,b} \int_{x_1^0}^{1} \frac{dx_1}{x_1} \int_{x_2^0}^{1} \frac{dx_2}{x_2} \left[q_a^\pi(x_1) q_b^p(x_2) \right.$$
$$\left. \times\, \omega_{ab}\left(x_1, x_1^0, x_2, x_2^0, Q/\mu\right)\right]$$

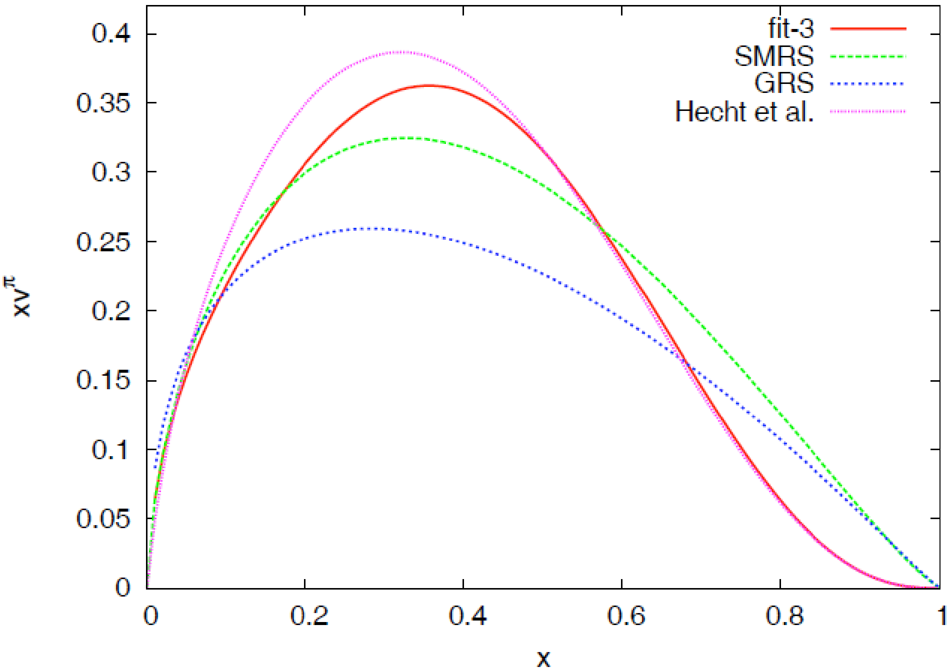
- ω_{ab} is hard scattering function

- Resum large logarithmic "soft" gluon contributions which arise as

$$z = \frac{Q^2}{\hat{s}} = \frac{\tau}{x_1 x_2} \to 1$$

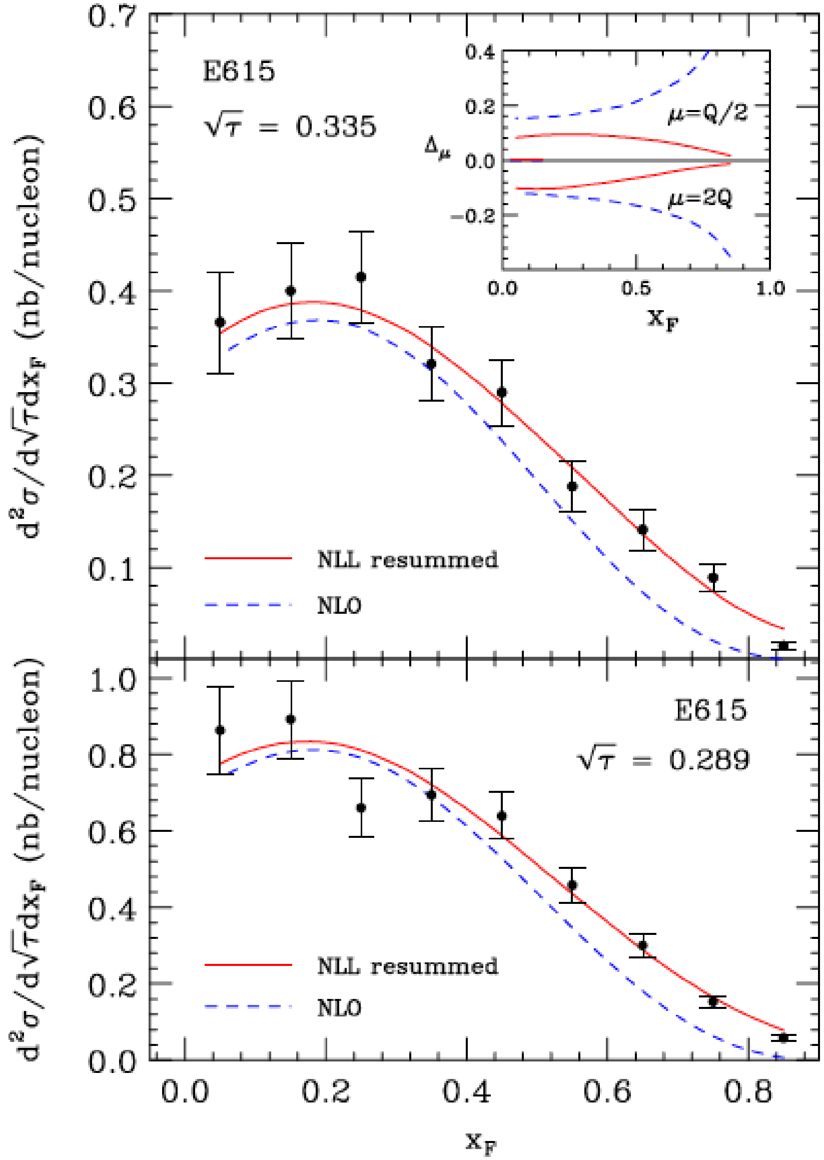
- Accomplished with combined Mellin and Fourier transform of the cross section
  Aicher, Schäfer and Vogelsang, Phys. Rev. Lett. **105**, 252003 (2010)
- Refit of pion Drell-Yan data

Soft Gluon Resummation



$$xq_V^\pi(x) = A_V^\pi x^\alpha (1-x)^\beta \left(1+\gamma x^\delta\right)$$

β = 2.03 ±0.06

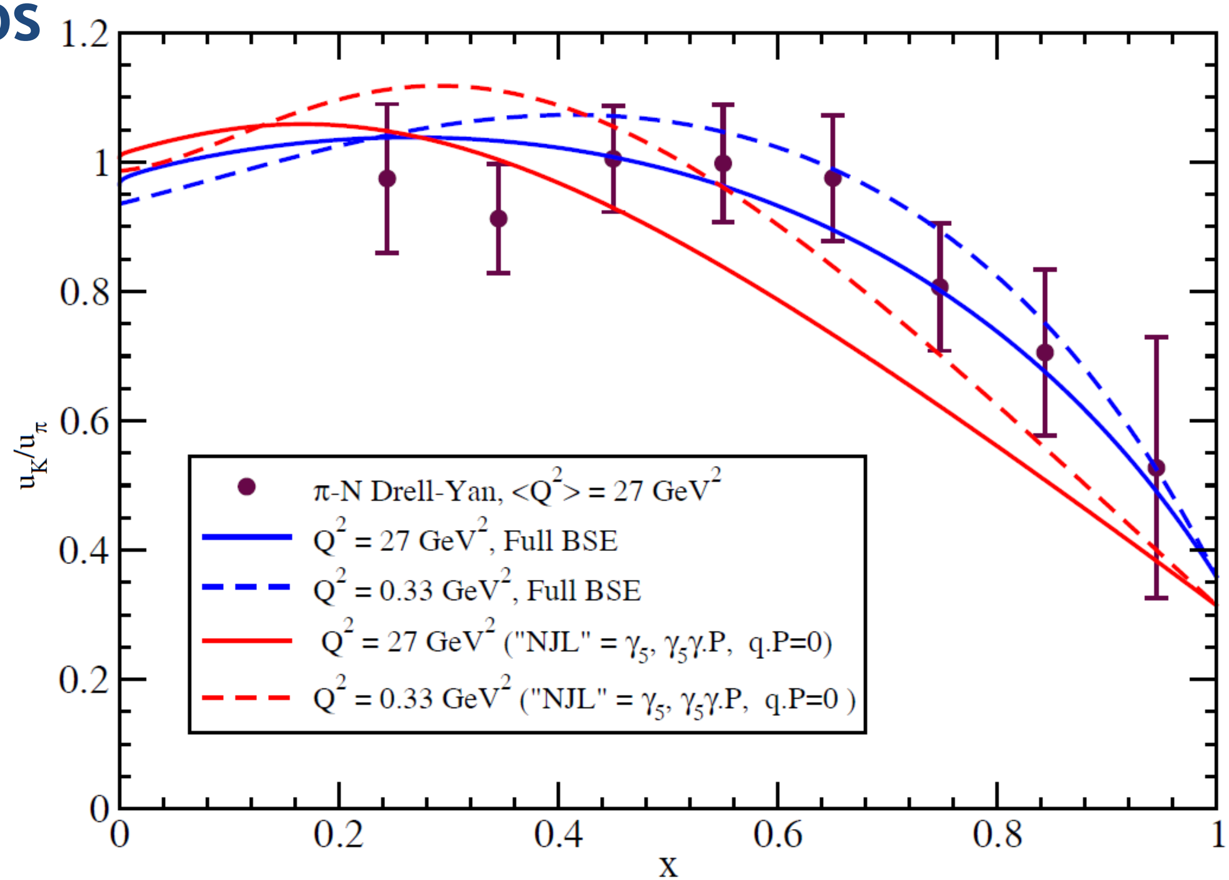


QCD and Dyson-Schwinger survive!
pQCD: $xq(x)/ (1-x)^\beta$ $\beta = 2$
DSE: $xq(x)/ (1-x)^\beta$ $\beta \approx 1.9$

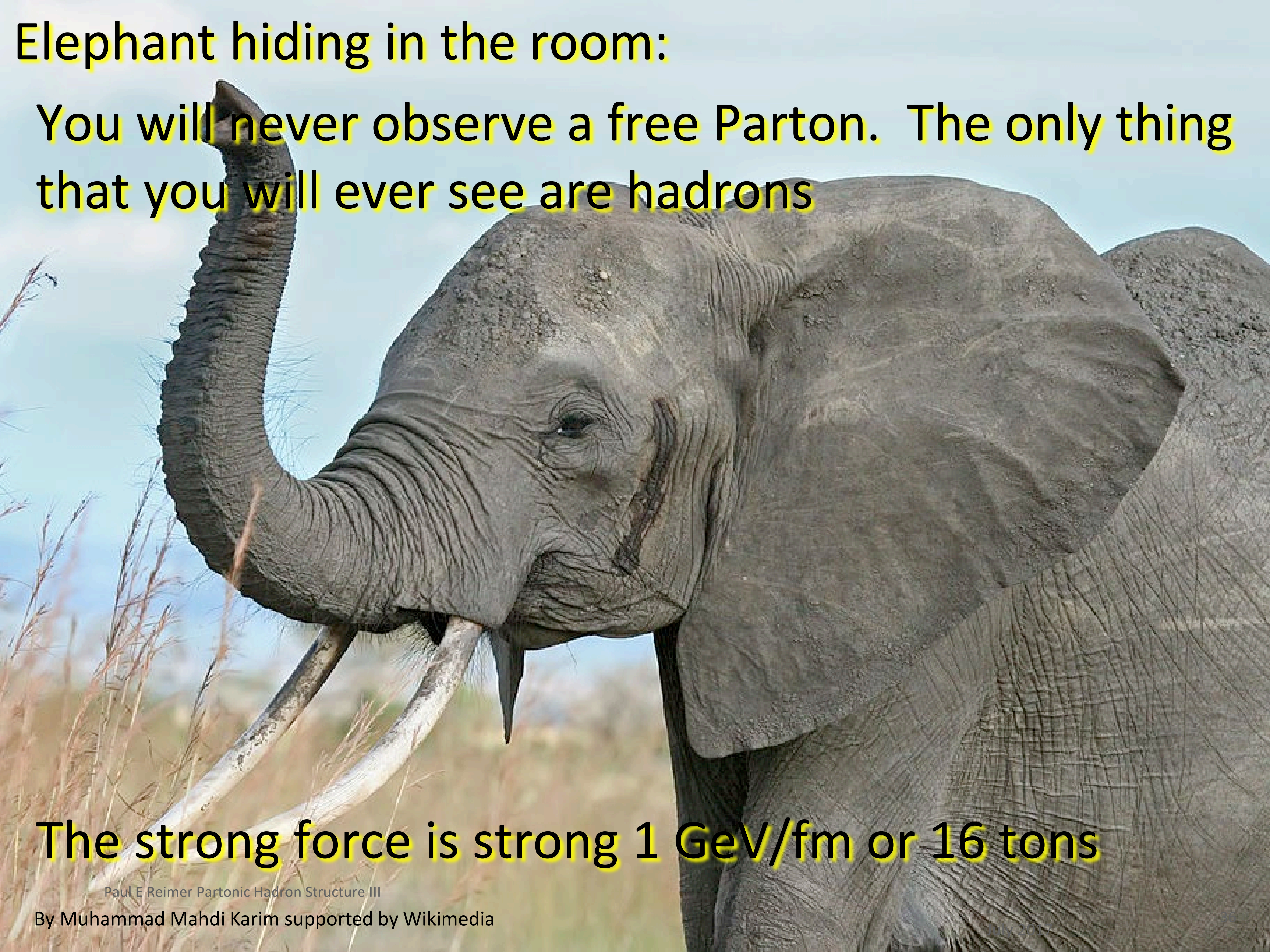
K/π Drell-Yan Ratios

More recent developments:

- Predictions of the K/π Drell-Yan ratio based on Bethe-Salpeter Equations (BSE)
- Can we get a Kaon beam to test this high-x_{Bj} structure of the Kaon?
  - This might be possible in the next incarnation of COMPASS



A. Bashir, T. Nguyen, C.D. Roberts and P.C. Tandy Phys.Rev. C83 (2011) 062201
Data: Badier *et al.* Phys. Lett. **B93** 354 (1980)



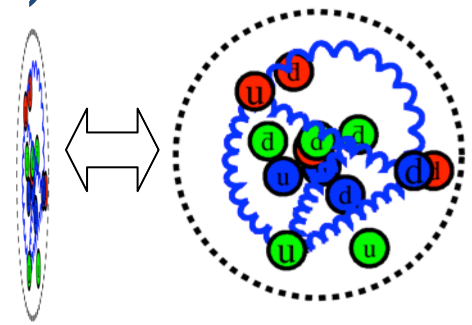
Elephant hiding in the room:

You will never observe a free Parton. The only thing that you will ever see are hadrons

The strong force is strong 1 GeV/fm or 16 tons

By Muhammad Mahdi Karim supported by Wikimedia

Generalized Parton Distributions (GPDs)



PDF's discussed so far are completely in momentum space

$$f = f\left(x, k_T, Q^2\right)$$

No spatial information is encoded

Problems with adding spatial information:

- Heisenberg

$$\delta x\ \delta p \geq \frac{\hbar}{2}$$

- Infinite momentum vs. rest frame:
  - PDFs in the infinite momentum frame Lorenz contract the proton, removing the information that we wish to know.

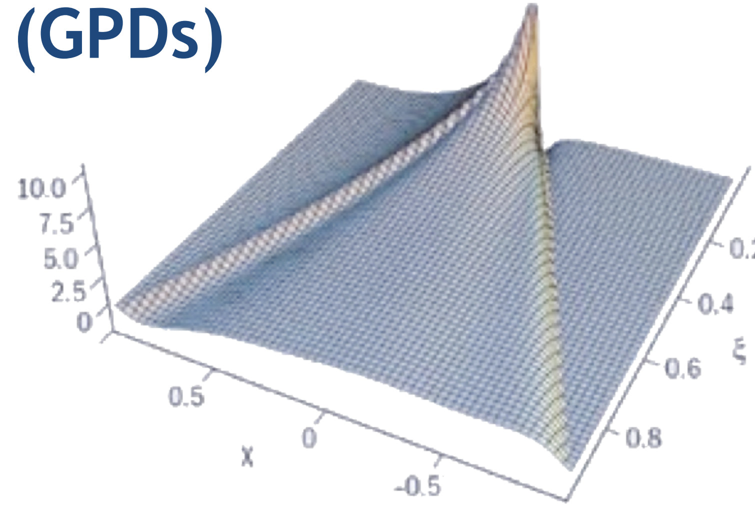
Wigner distributions and quantum phase space

$$\widehat{\mathcal{W}}\left(\vec{r}, k\right) = \int d^4\eta e^{ik\cdot\eta}\bar{\Psi}\left(\vec{r} - \frac{\eta}{2}\right)\Gamma\Psi\left(\vec{r} + \frac{\eta}{2}\right)$$

$$W_\Gamma\left(\vec{r}, k\right) = \frac{1}{2}\int \frac{d^3\vec{q}}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} \left\langle \frac{\vec{q}}{2}\middle|\widehat{\mathcal{W}}\left(0, k\right)\middle|\frac{-q}{2}\right\rangle$$

And now there is a lot of math: see **Xiangdong Ji, Annu. Rev. Nucl. Part. Sci. 2004. 54:413–50**

Generalized Parton Distributions (GPDs)



8 GPDs per flavor

$$H\,(x,\xi,t) \quad E\,(x,\xi,t) \quad H_T\,(x,\xi,t) \quad E_T\,(x,\xi,t)$$
$$\widetilde{H}\,(x,\xi,t) \quad \widetilde{E}\,(x,\xi,t) \quad \widetilde{H}_T\,(x,\xi,t) \quad \widetilde{E}_T\,(x,\xi,t)$$

Now things get interesting **(stating without justification)**

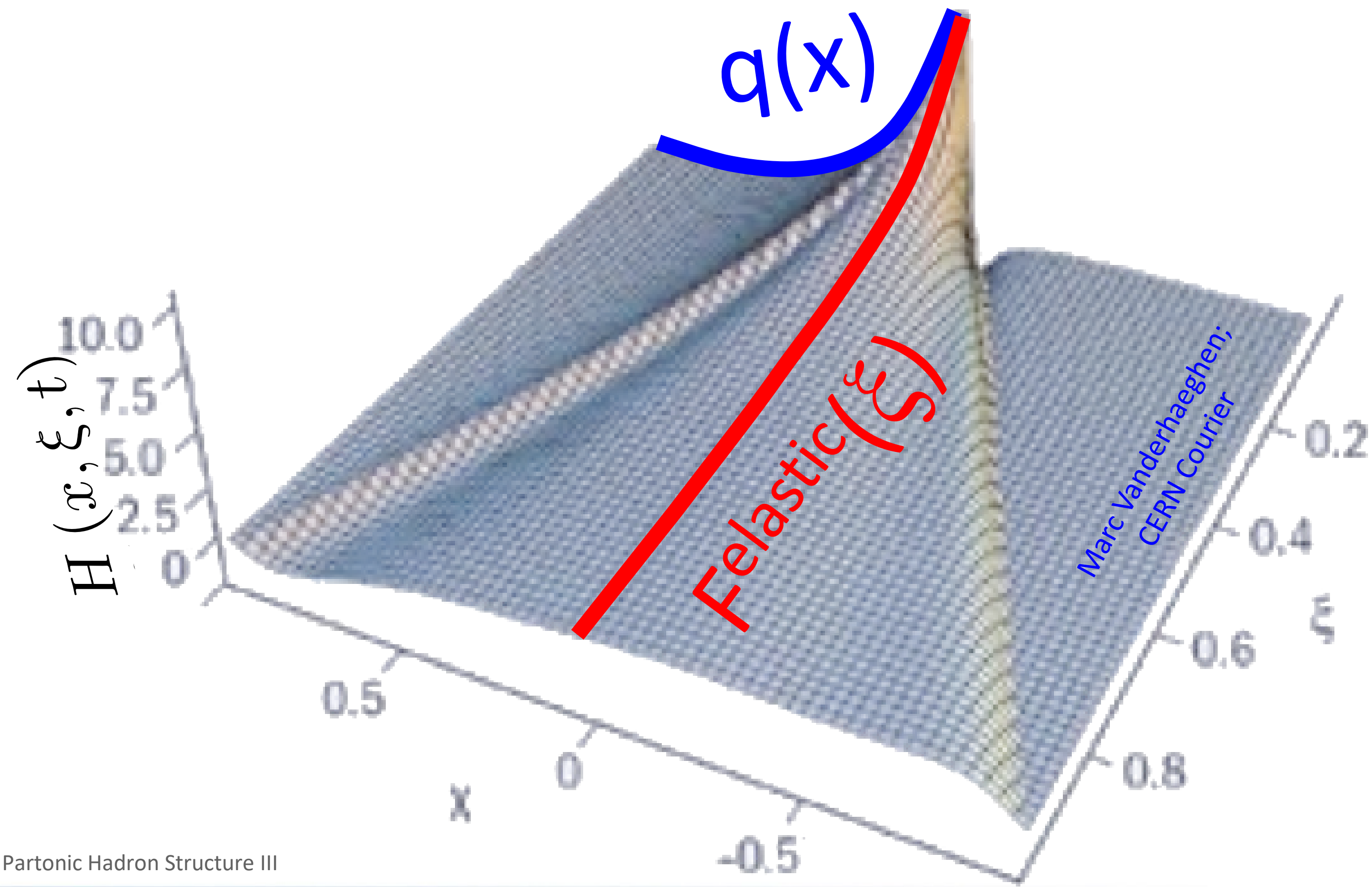
$$\left.\begin{aligned} H_q(x,0,0) &\equiv q(x) \\ \widetilde{H}_q(x,0,0) &= \Delta q(x) \end{aligned}\right\} \text{Longitudinal parton distributions}$$

$$\left.\begin{aligned} \int_{-1}^{1} dx H_q(x,\xi,t) = F_1(t) \qquad \int_{-1}^{1} dx E_q(x,\xi,t) = F_2(t) \\ \int_{-1}^{1} dx \widetilde{H}_q(x,\xi,t) = G_A(t) \qquad \int_{-1}^{1} dx \widetilde{E}_q(x,\xi,t) = G_P(t) \end{aligned}\right\} \text{Elastic form factors}$$

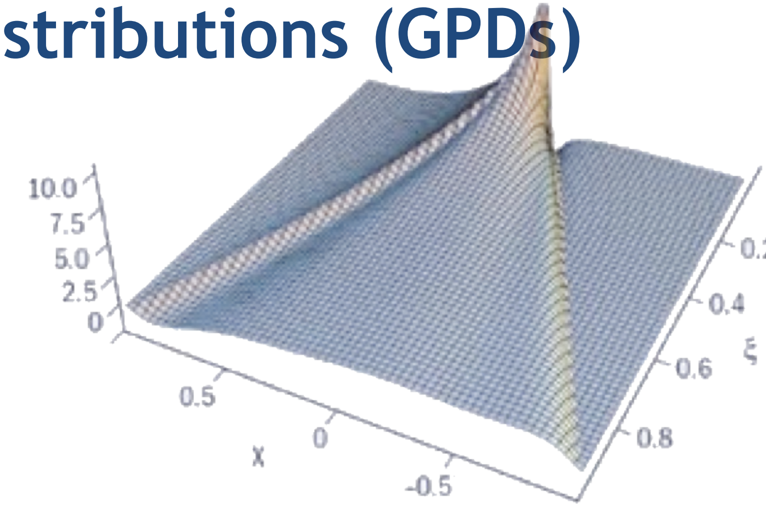
Generalized Parton Distributions (GPDs)

8 GPDs per flavor

$$H(x,\xi,t) \quad E(x,\xi,t) \quad H_T(x,\xi,t) \quad E_T(x,\xi,t)$$
$$\widetilde{H}(x,\xi,t) \quad \widetilde{E}(x,\xi,t) \quad \widetilde{H}_T(x,\xi,t) \quad \widetilde{E}_T(x,\xi,t)$$



Measuring Generalized Parton Distributions (GPDs)



8 GPDs per flavor

$$
\begin{array}{llll}
H(x,\xi,t) & E(x,\xi,t) & H_T(x,\xi,t) & E_T(x,\xi,t) \\
\widetilde{H}(x,\xi,t) & \widetilde{E}(x,\xi,t) & \widetilde{H}_T(x,\xi,t) & \widetilde{E}_T(x,\xi,t)
\end{array}
$$

Now things get interesting **(stating without justification)**

$$
\left.\begin{array}{l}
H_q(x,0,0) \equiv q(x) \\
\widetilde{H}_q(x,0,0) = \Delta q(x)
\end{array}\right\} \text{Longitudinal parton distributions}
$$

$$
\left.\begin{array}{ll}
\int_{-1}^{1} dx H_q(x,\xi,t) = F_1(t) & \int_{-1}^{1} dx E_q(x,\xi,t) = F_2(t) \\
\int_{-1}^{1} dx \widetilde{H}_q(x,\xi,t) = G_A(t) & \int_{-1}^{1} dx \widetilde{E}_q(x,\xi,t) = G_P(t)
\end{array}\right\} \text{Elastic form factors}
$$

$$
\rho_+(\vec{r},x) = \int \frac{d^3\vec{q}}{(2\pi)^3} e^{-I\vec{q}\cdot\vec{r}} \left[H(x,\xi,t) + E(x,\xi,t)\right]
$$

Charge density

$$
J_{q(g)} = \frac{1}{2}\int_{-1}^{1} dx\ x\left[H_{q(g)}(x,\xi,0) + E_{q(g)}(x,\xi,0)\right]
$$

Spin

$$
\boxed{J_q = \frac{1}{2}\Delta\Sigma + L_q}
$$

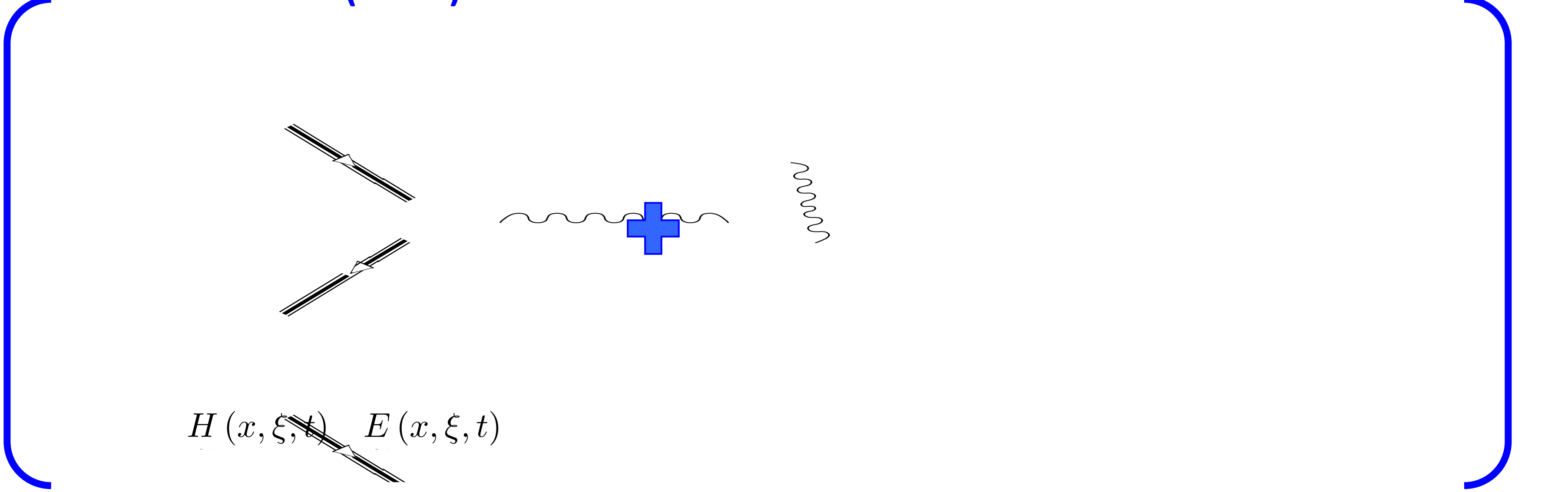
Measurement of GPDs

More difficult measurements

1. Can't blow the nucleon apart
2. More final state particles that must be detected
3. Interference from processes with the same signature

Deep Virtual Compton Scattering (DVCS)

Bethe-Heitler



There already is some data form HERMES (DESY), COMPASS (CERN) and JLab.

Expect more data from JLab 12 GeV CEBAF

What have we learned?

What have we learned?

- **Data** looks like scattering from many point particles (partons)
  - These distributions are universal and process independent
- **Data** allows the determination of the distributions of partons

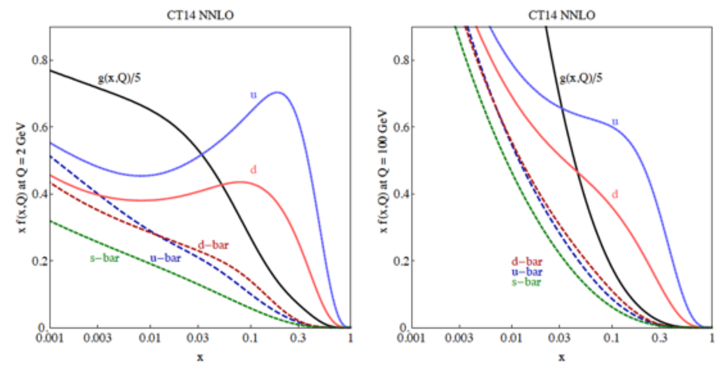
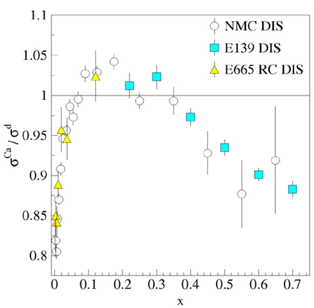
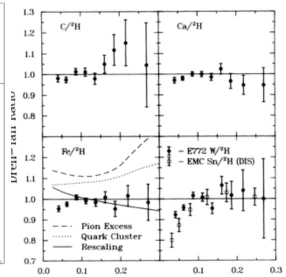


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \overline{u}, d, \overline{d}, s = \overline{s}$, and g.





- **Data** says that these distributions change when the proton is contained in a nucleus
- **Data** shows proton's spin is not where we expected, but the options are narrowing

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

What have we learned?

- **Data** looks like scattering from many point particles (partons)
  - These distributions are universal and process independent
- **Data** allows the determination of the distributions of partons

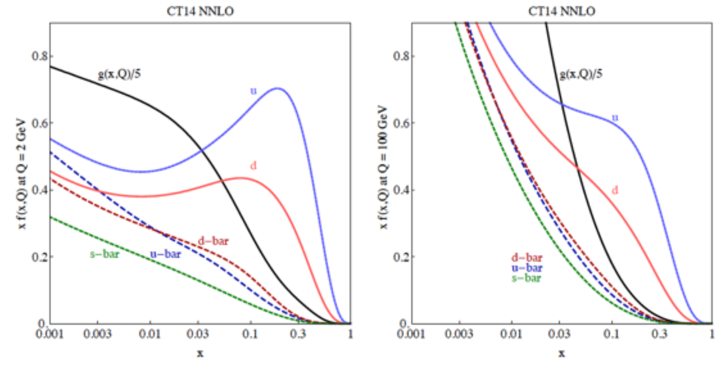
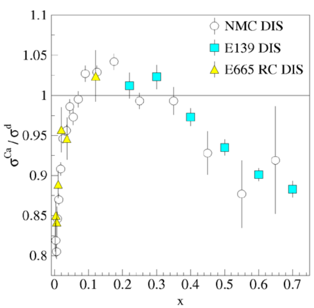
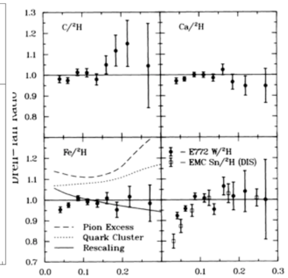


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \bar{u}, d, \bar{d}, s = \bar{s}$, and g.





- **Data** says that these distributions change when the proton is contained in a nucleus
- **Data** shows proton's spin is not where we expected, but the options are narrowing

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

- But, none of the data would be interesting without a frame work in which to view what is measured!
- How would we even know what is interesting to investigate?

Theory

What have we learned?

- **Data** looks like scattering from many point particles (partons)
  - These distributions are universal and process independent
- **Data** allows the determination of the distributions of partons

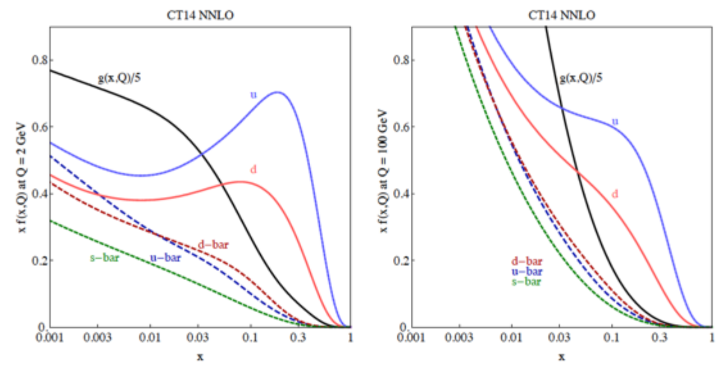
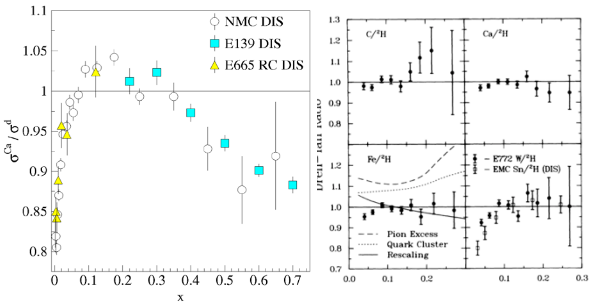


FIG. 5: The CT14 parton distribution functions at $Q = 2$ GeV and $Q = 100$ GeV for $u, \bar{u}, d, \bar{d}, s = \bar{s}$, and g.



- **Data** says that these distributions change when the proton is contained in a nucleus
- **Data** shows proton's spin is not where we expected, but the options are narrowing

Episode IV

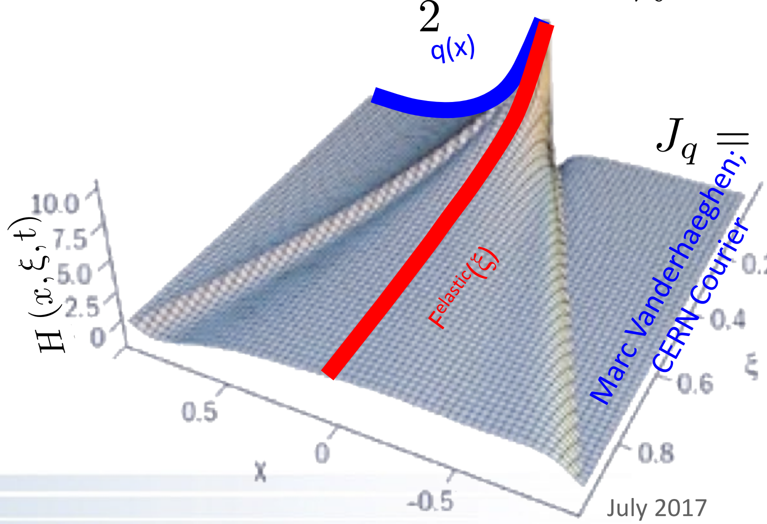
A New Hope

In a laboratory far away, rebel physicist are attempting their most daring mission so far. Secret plans to the structure of the proton have been hidden within ***Generalized Parton distributions****. The rebels must find a way to unlock these plans before it is too late.* ***Data*** *is needed to lead the way*

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G$$

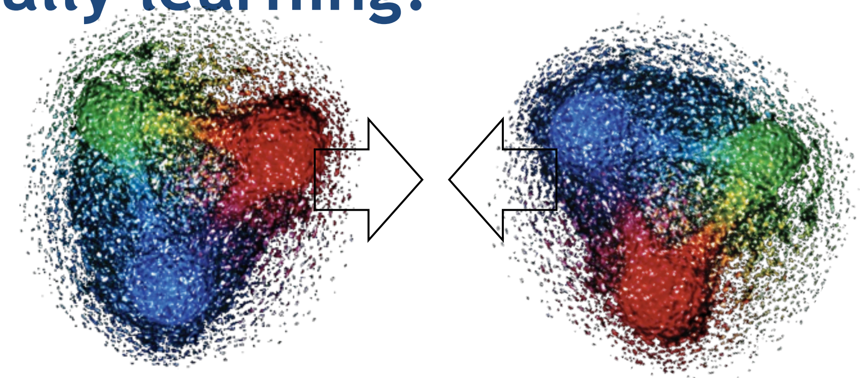
$$\frac{1}{2}\Delta\Sigma \approx 25\% \quad \Delta G \approx 0 - 15\%$$

$$J_q = \frac{1}{2}\Delta\Sigma + L_q$$

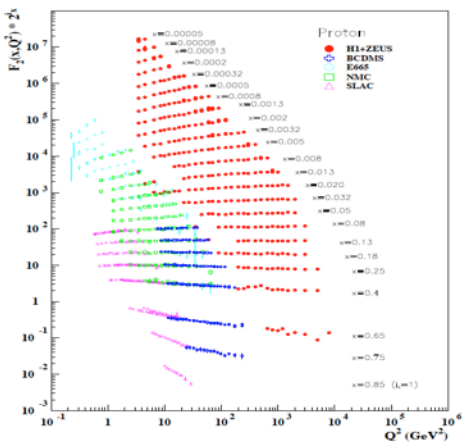


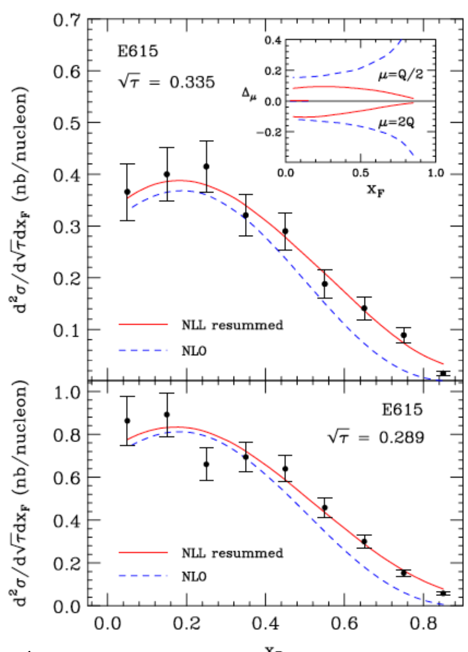
Epilog: Goals—What are we really learning?

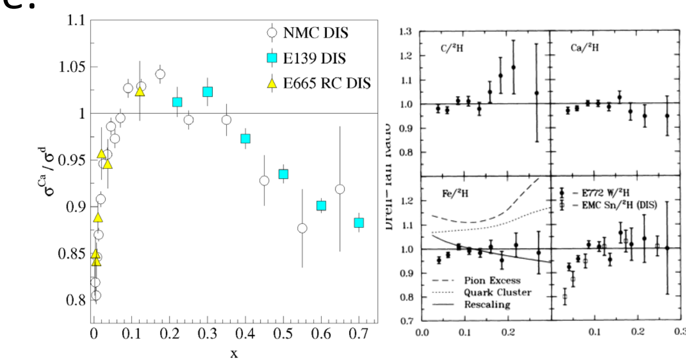
- LHC/HEP view—colliding bags of quarks

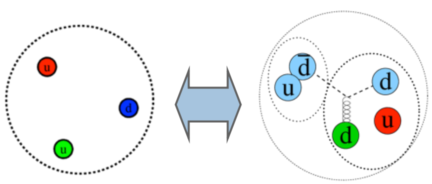


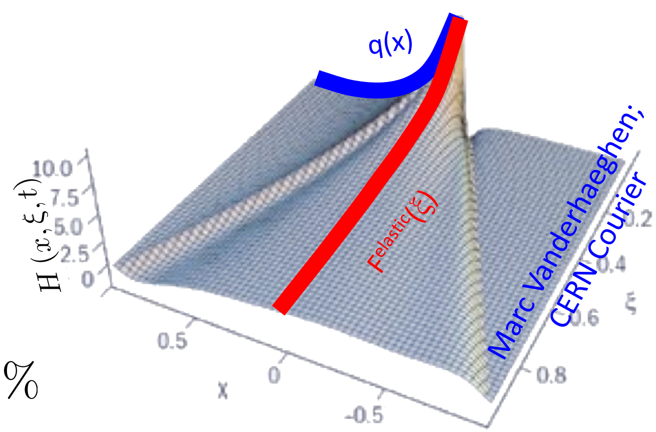
- Nuclear Physics: Revealing the nature of the strong force:











$$\frac{1}{2}=\frac{1}{2}\Delta\Sigma+L_q+\Delta G$$

$$\frac{1}{2}\Delta\Sigma\approx 25\%\quad \Delta G\approx 0-15\%$$


All the pets are happy!
Structure III