Transverse Momentum Dependent Distributions: Jefferson Lab 12 and beyond

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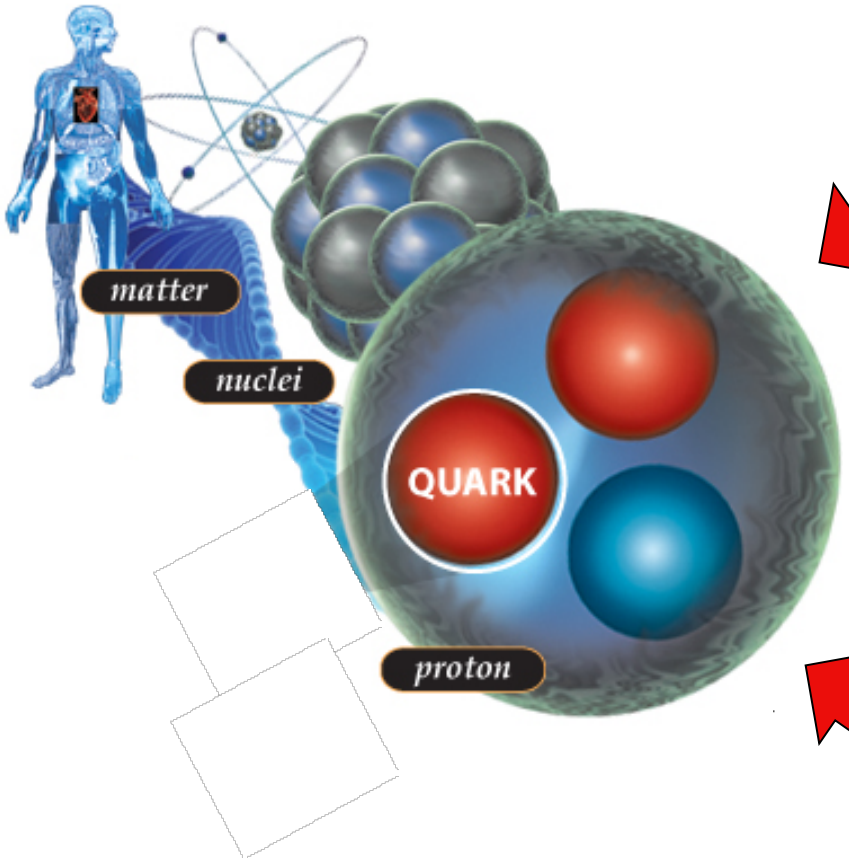
February 17, 2014

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Exploring the nucleon: a fundamental quest



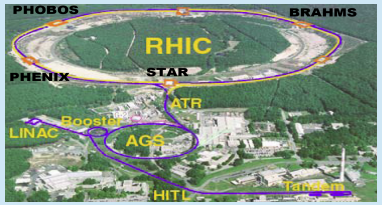
Know what we are made of !

Understand the strong force: "QCD"

Use protons as tool for discovery (e.g. LHC)

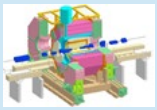
Hadron structure

BNL: RHIC, PHENIX, STAR

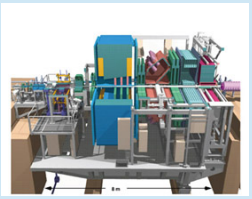


CERN: LHC, COMPASS

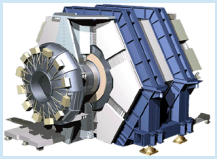
KEK: BELLE



DESY: HERMES, ZEUS, H1



SLAC: BaBar

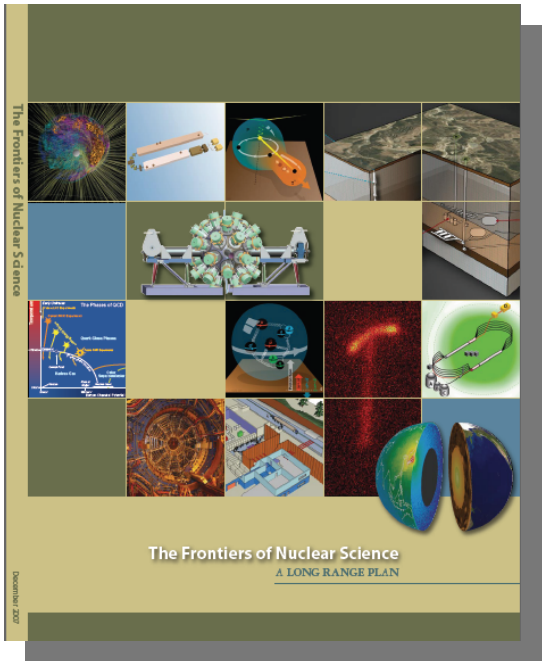


FERMILAB: SeaQuest etc

Many other facilities utilizing other processes

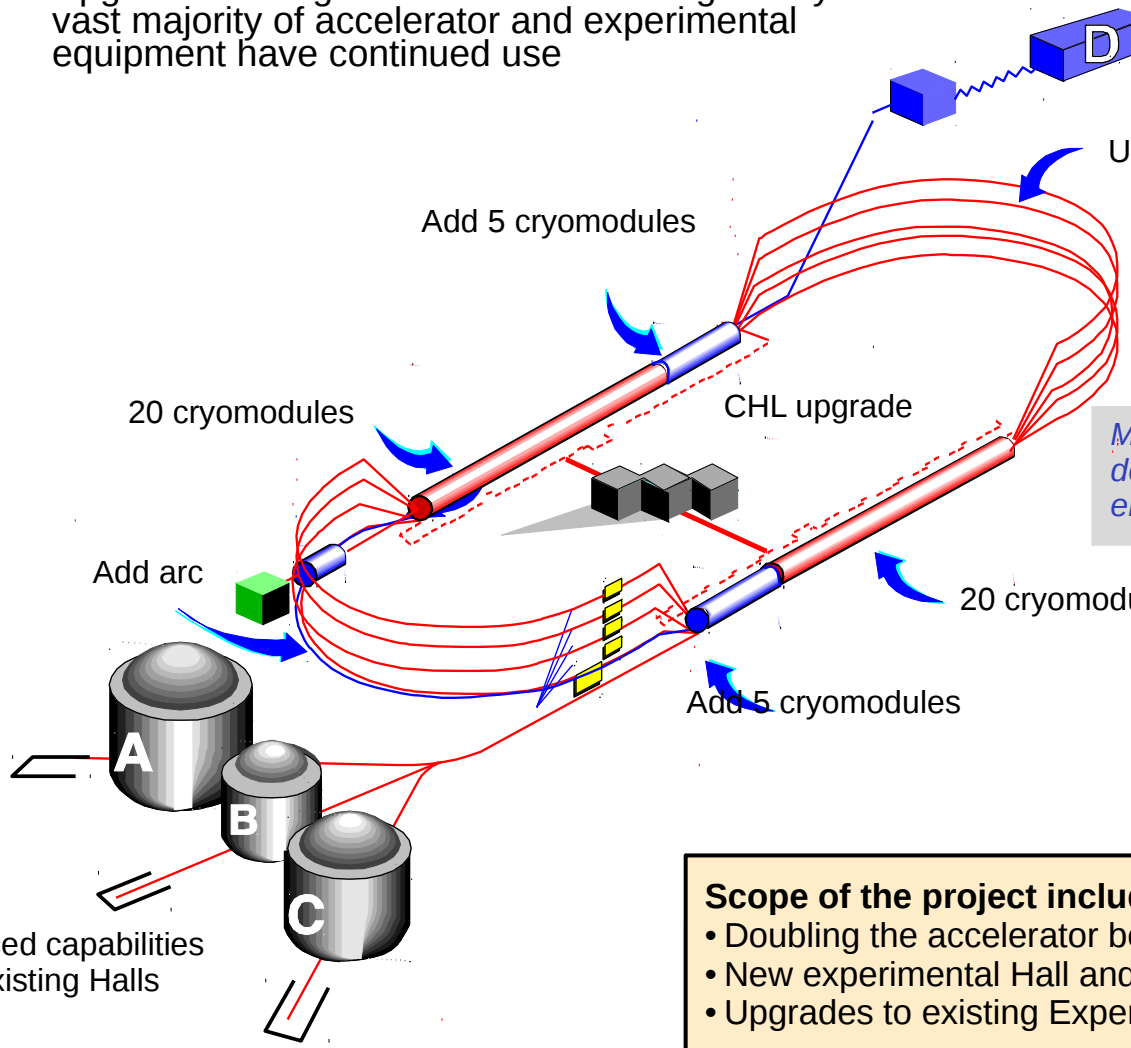
JLAB: HALL A,B,C

12 GeV Upgrade Project



The completion of the 12 GeV Upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan.

Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use



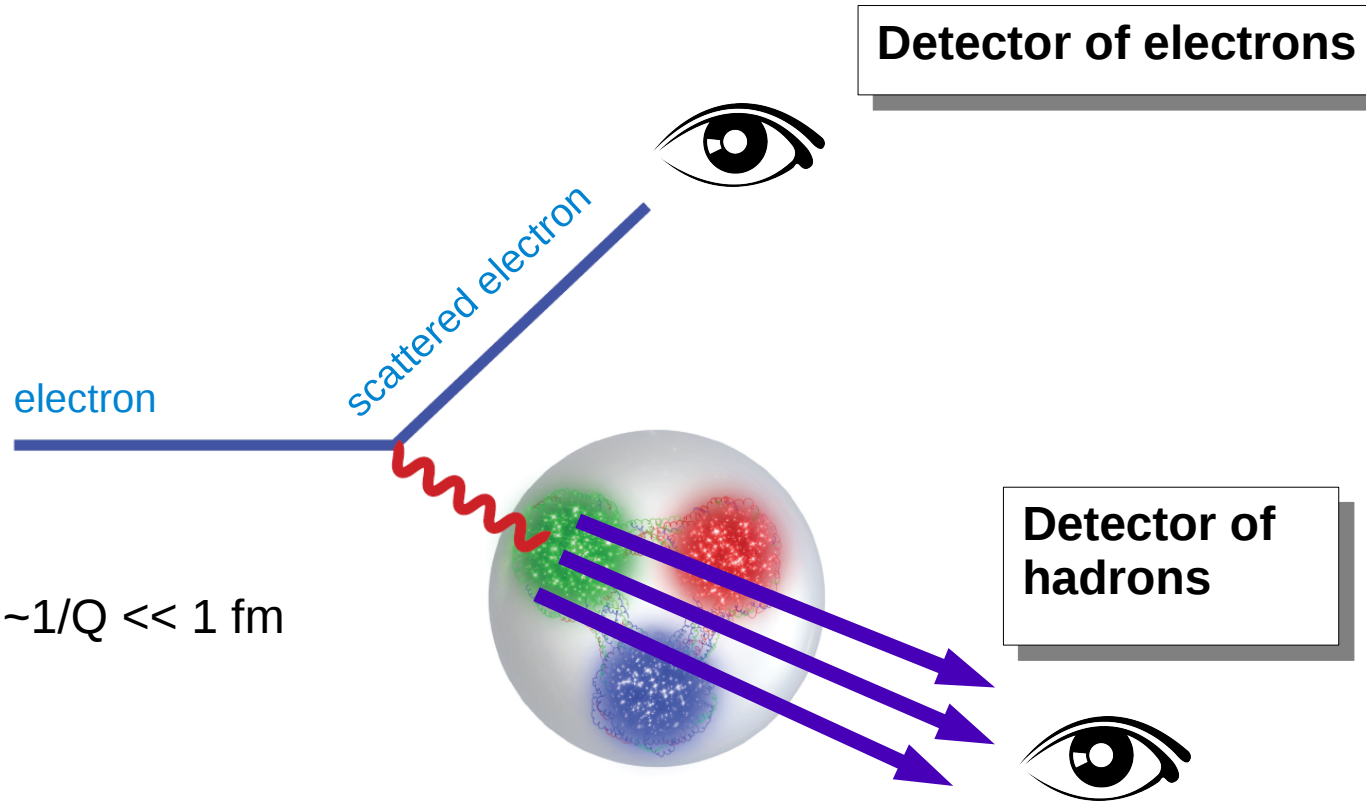
Maintain capability to deliver lower pass beam energies: ***2.2, 4.4, 6.6….***

Scope of the project includes:
- Doubling the accelerator beam energy
- New experimental Hall and beamline
- Upgrades to existing Experimental Halls

How Jefferson Lab does it?

$$q^2 = -Q^2$$

virtuality of the photon



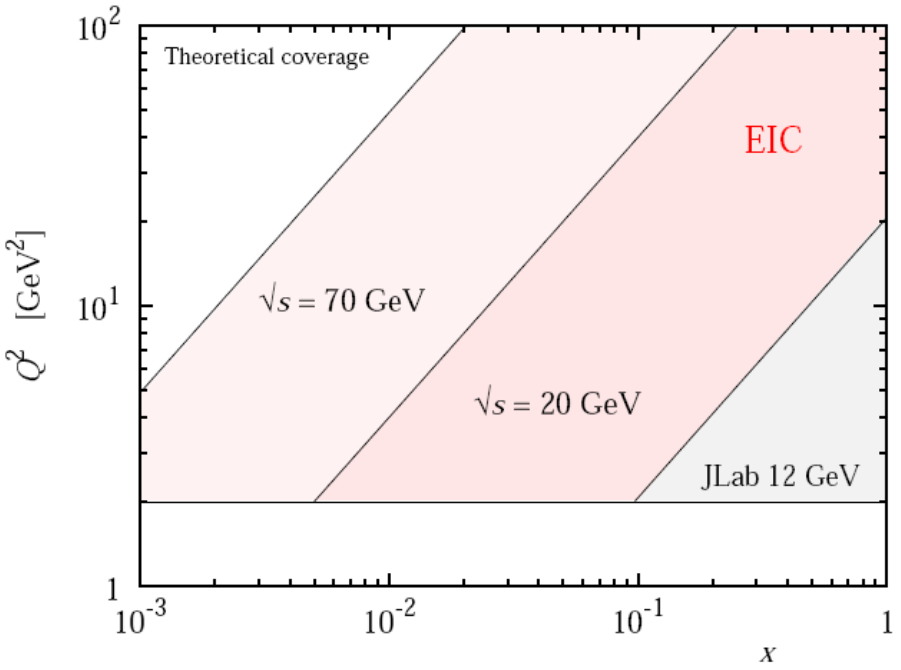
Photon probes
transverse distance of ~1/Q << 1 fm
inside of the proton

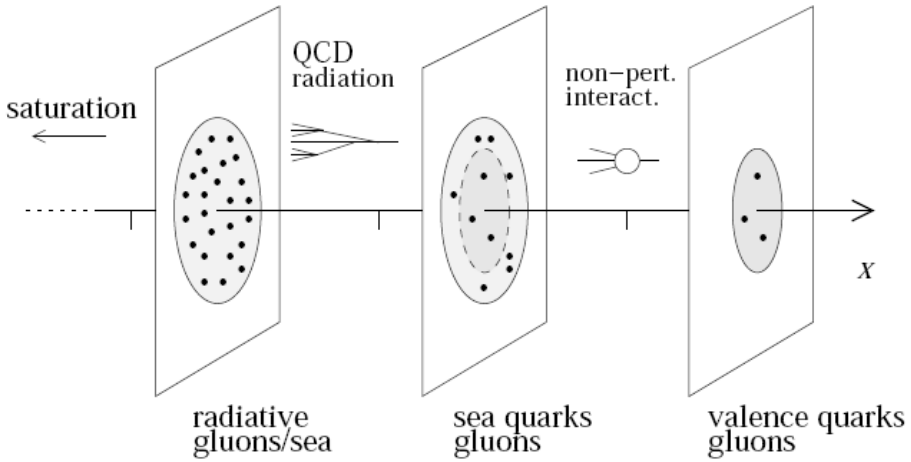
Photon scatters off a parton: quark
or anti-quark

Bjorken variable gives fraction of longitudinal momentum
of the proton carried by the parton

$$x = \frac{Q^2}{2P \cdot q}$$

Nucleon landscape





Nucleon is a many body dynamical system of quarks and gluons

Changing x we probe different aspects of nucleon wave function

How **partons move** and how they are distributed in **space** is one of the future directions of development of nuclear physics

Technically such information is encoded in Generalised Parton Distributions and Transverse Momentum Dependent distributions

These distributions are also referred to as **3D (three-dimensional) distributions**

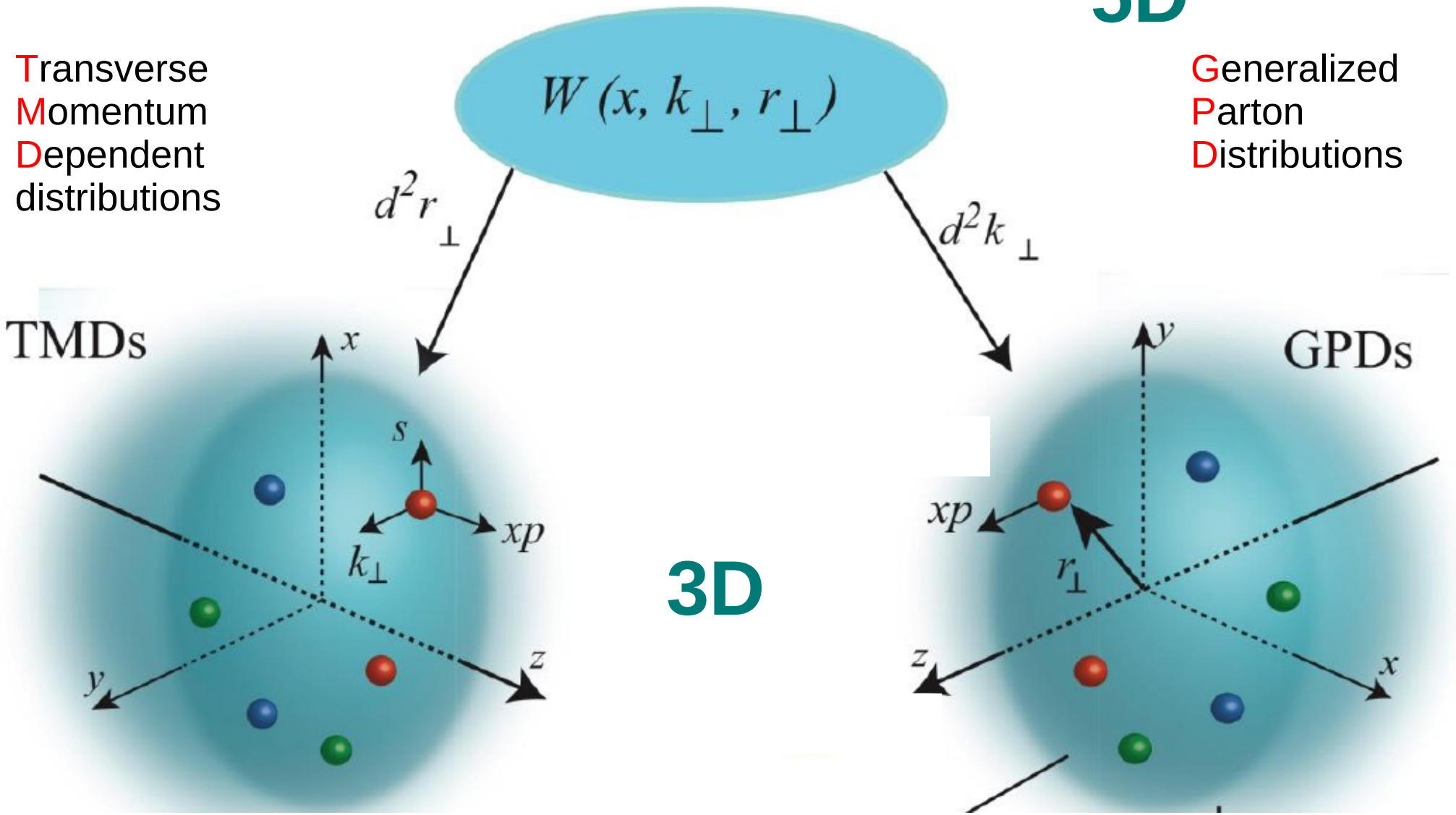
Unified View of Nucleon Structure

Wigner function

5D

Transverse
Momentum
Dependent
distributions

Generalized
Parton
Distributions



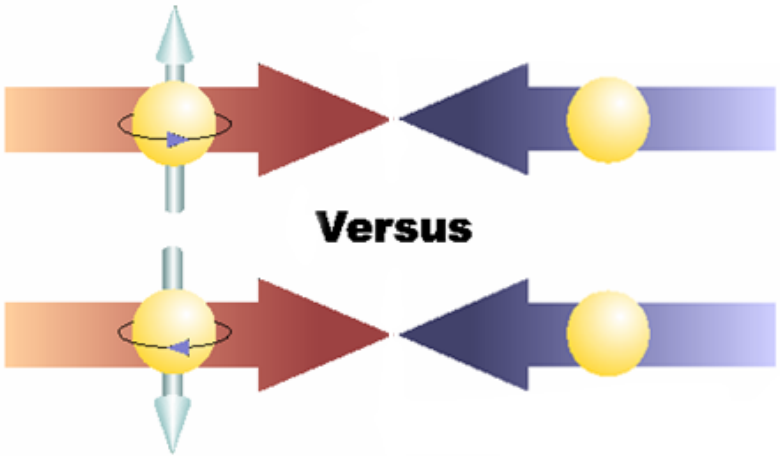
3D

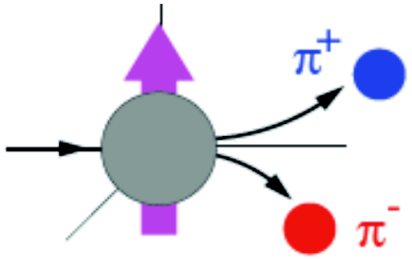
Particular processes to study. Polarization is required!

"Polarisation data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection."

J. D. Bjorken, Proc. Adv. Research Workshop on QCD Hadronic Processes, St. Croix, Virgin Islands (1987).

Consider A_N in hadron hadron collision:



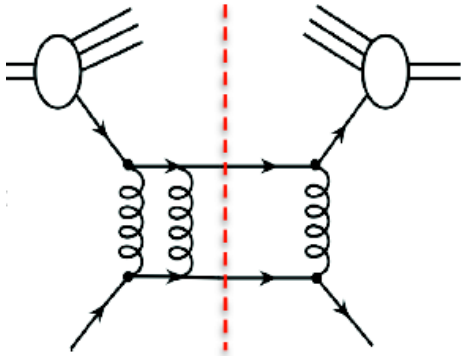


$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

Spin and QCD

QCD had a very simple prediction:

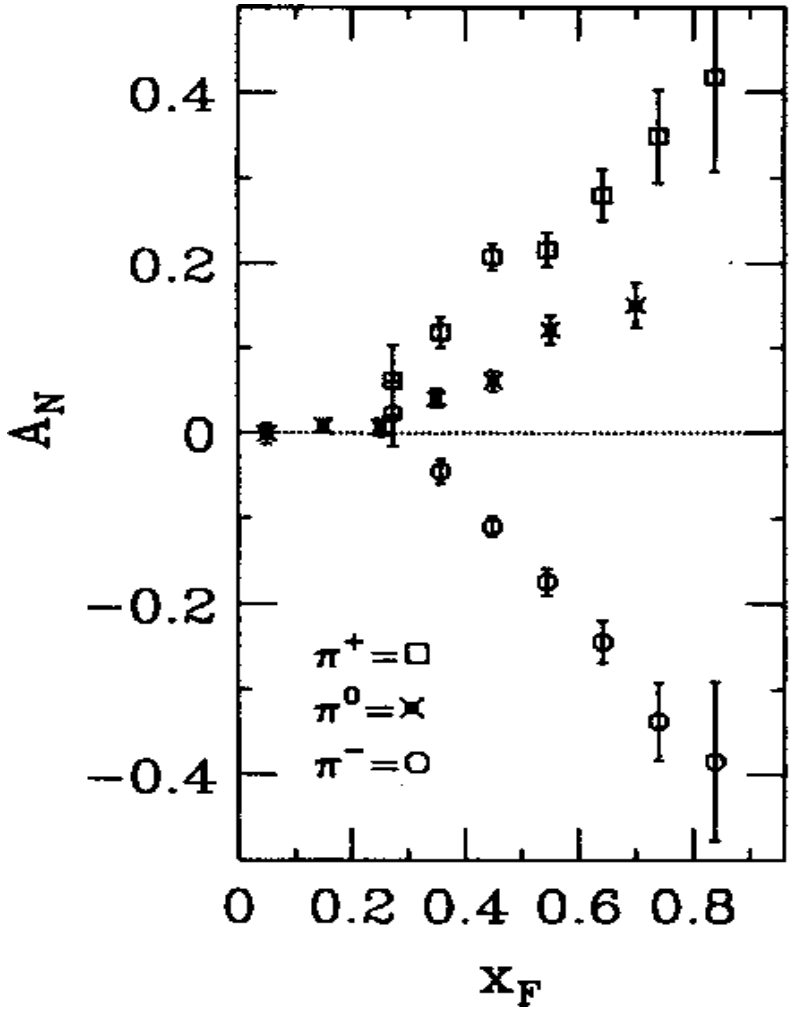
If we try to generate asymmetry on the quark interaction level the result is very small



$$\propto \alpha_s \frac{m_q}{p_T} \qquad A_N \simeq 0.001$$

Kane, Pumplin and Repko (1978)

Experiment proved this prediction wrong

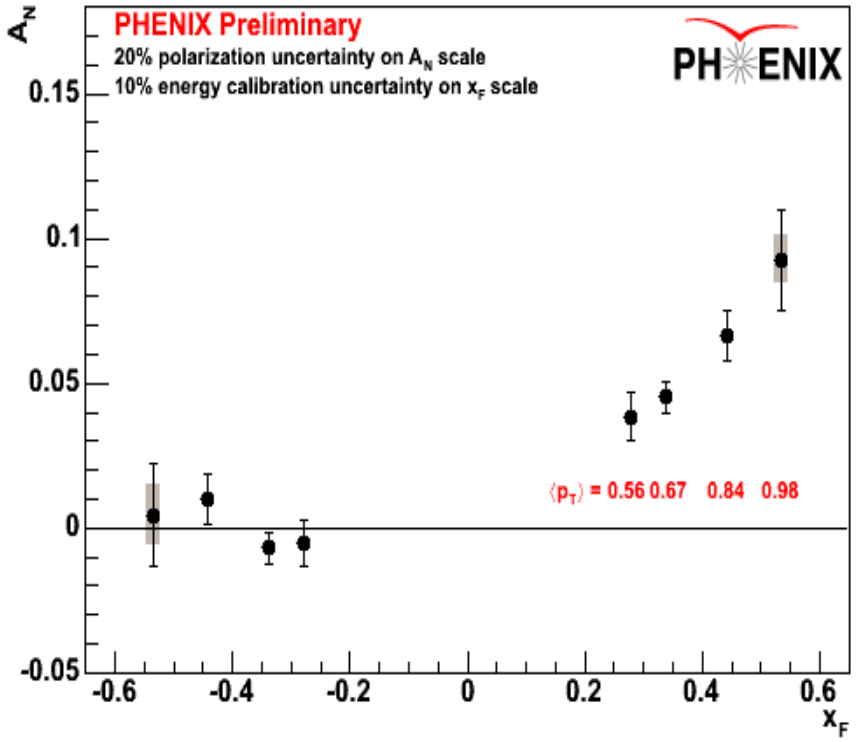


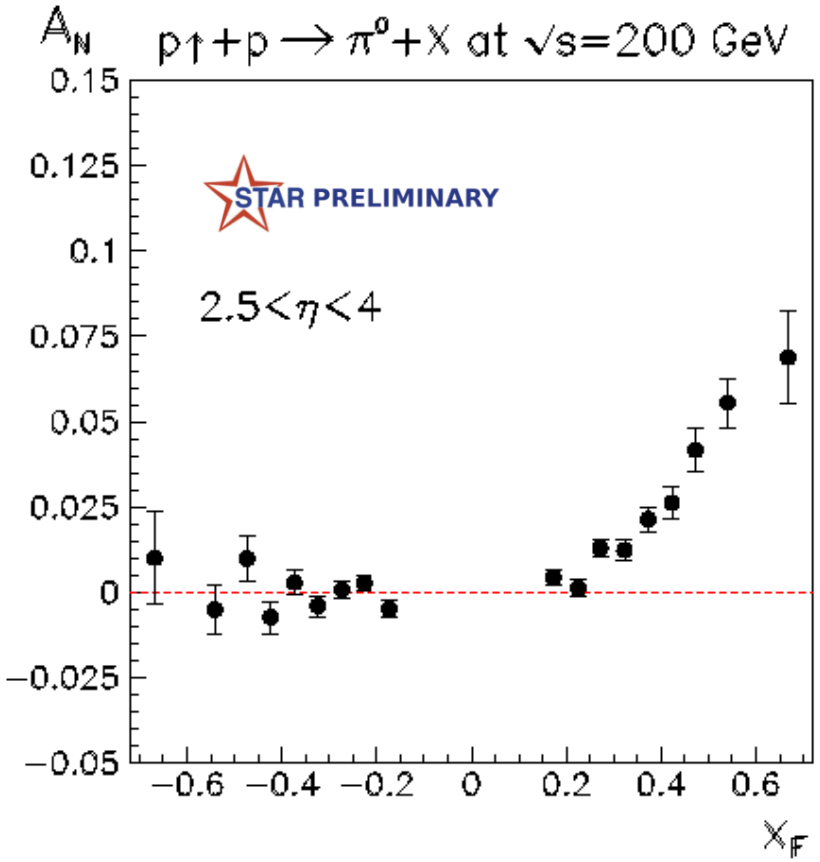
FNAL-E704 Collaboration, Adams (1991)

$$A_N \simeq 40\%$$

Asymmetry survives with energy in PP

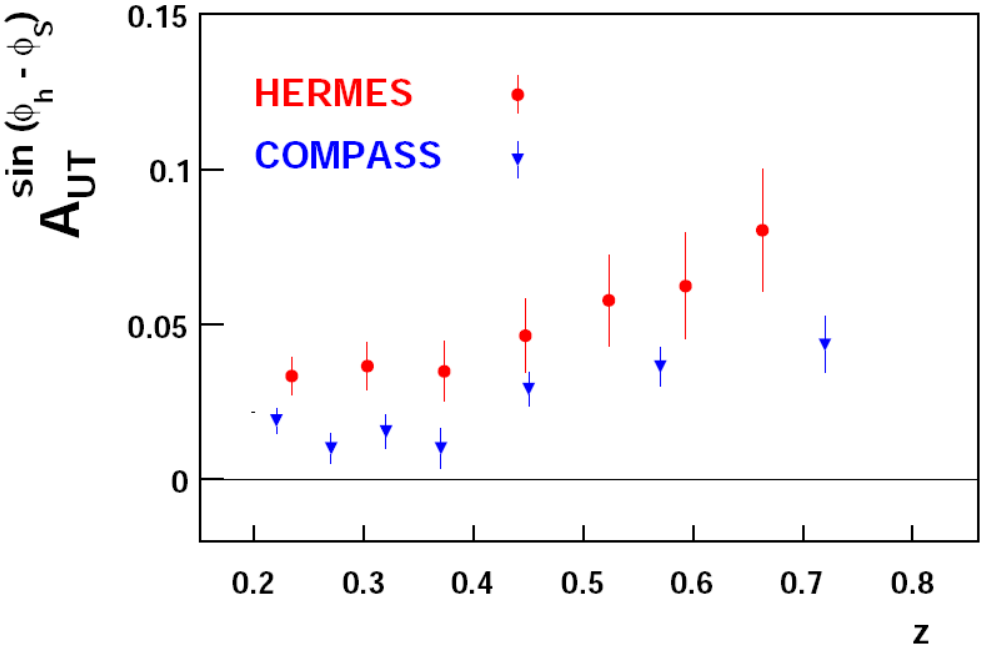
$$\sqrt{s} = 62\ \mathrm{GeV}$$

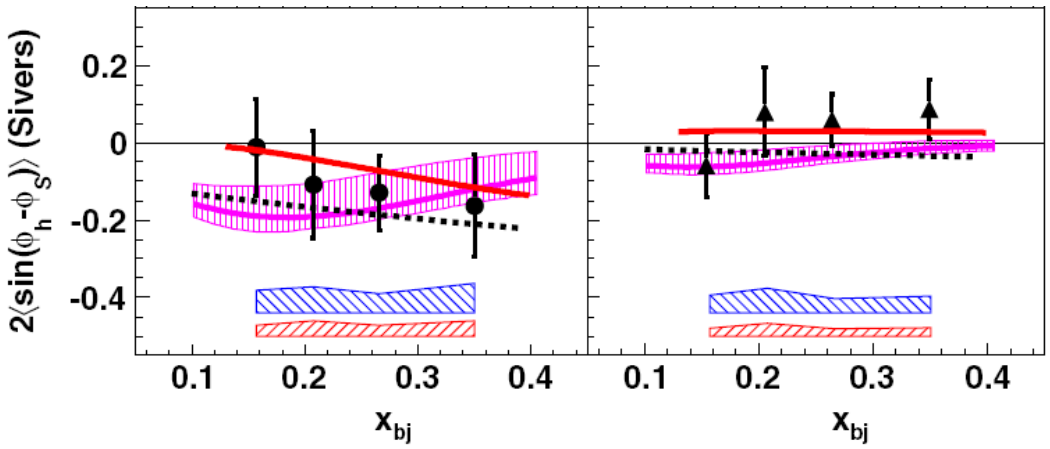




RHIC: PHENIX and STAR

Asymmetry survives with energy in SIDIS





HERMES, COMPASS

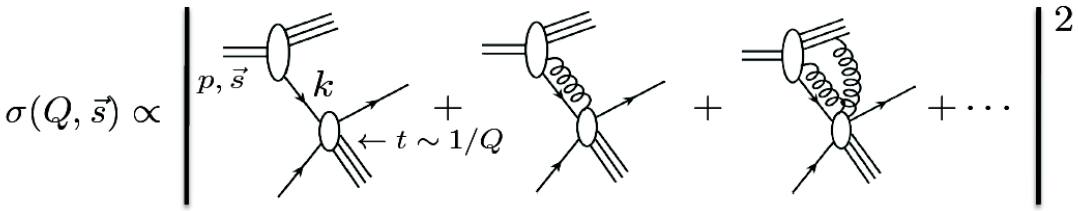
JLab

Failure of QCD?

Not at all: better understanding of QCD

Better understanding of QCD

Multy parton correlations contribute to the cross section and may dominate asymmetries



Efremov Teryaev (1982),
Qiu, Sterman (1991)

These correlations are called
Efremov-Teryaev-Qiu-Sterman matrix elements,
They appear at twist-3 level in cross section.

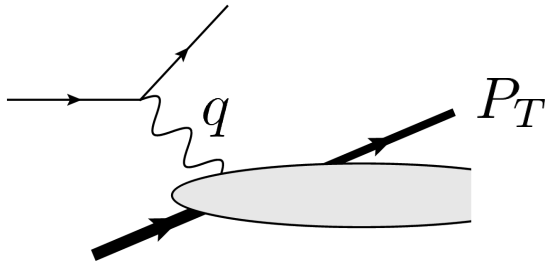
Parton intrinsic motion can be correlated with spin of the nucleon
and generate asymmetries – corresponding distributions are called
Transverse Momentum Dependent distributions

Mulders, Tangerman 1995
Boer, Mulders 1998, Collins 2011

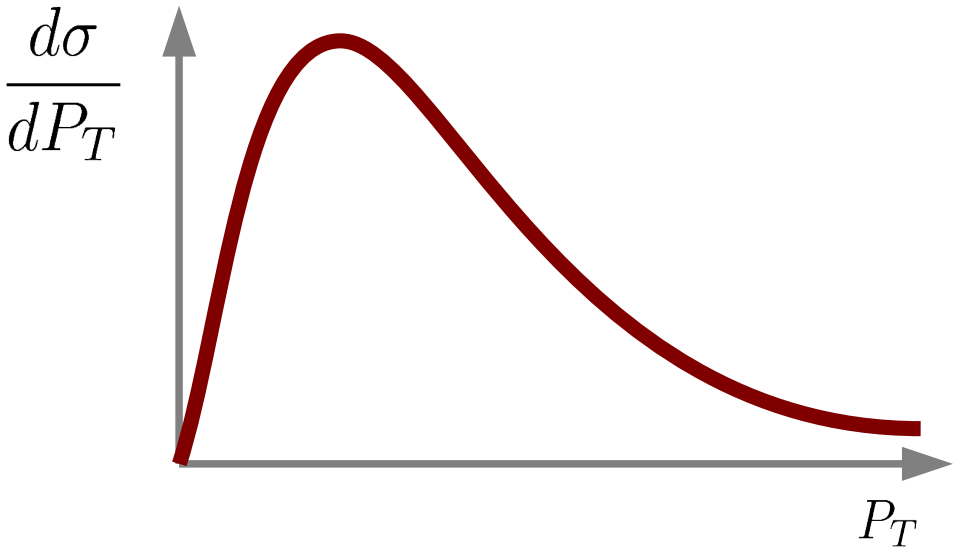
Two scale problem in QCD

Consider Semi Inclusive Deep Inelastic Scattering:

There are two measured scales P_T, Q



$$\ell + P \to \ell' + h + X$$



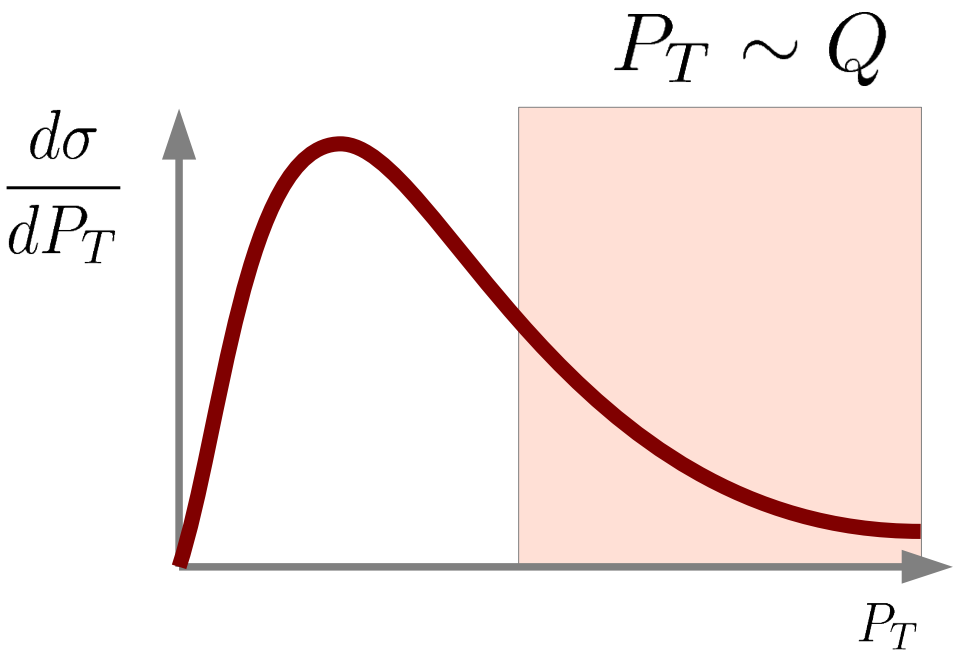
Two scale problem in QCD

Consider Semi Inclusive Deep Inelastic Scattering:

There are two measured scales P_T, Q

One scale problem, $P_T, Q \gg \Lambda_{QCD}$

The treatment is referred to as “collinear”.
One neglects transverse motion of partons.
Observed momentum is generated by gluon radiation.



$f(x; Q^2)$

Beyond leading twist:
Twist-3 matrix elements – dominate asymmetries
Efremov Teryaev (1982), Qiu, Sterman (1991)

Two scale problem in QCD

Consider Semi Inclusive Deep Inelastic Scattering:

There are two measured scales P_T, Q

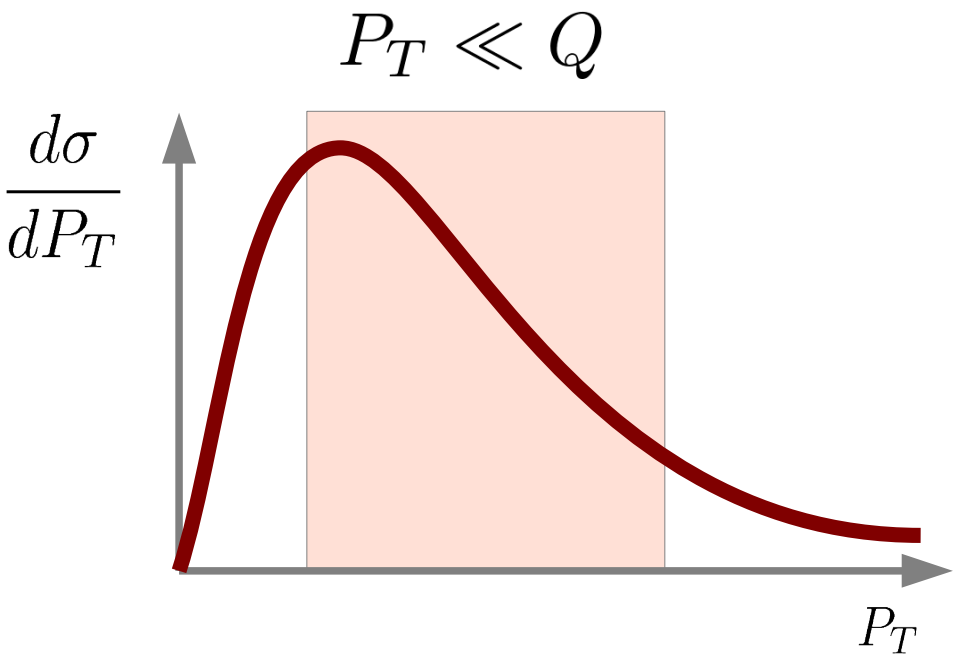
Two scale problem, $P_T \gg \Lambda_{QCD}$

Collinear treatment is still possible, but large logs should be resummed to all orders

$$\alpha_s^n \ln^{2n}\left(Q^2/P_T^2\right)$$

So-called Collins-Soper-Sterman resummation

Collins, Soper, Sterman 1985



Two scale problem in QCD

Consider Semi Inclusive Deep Inelastic Scattering:

There are two measured scales P_T, Q

Two scale problem, $P_T \sim \Lambda_{QCD}$

One cannot neglect transverse motion of partons

Large logs should be resummed to all orders

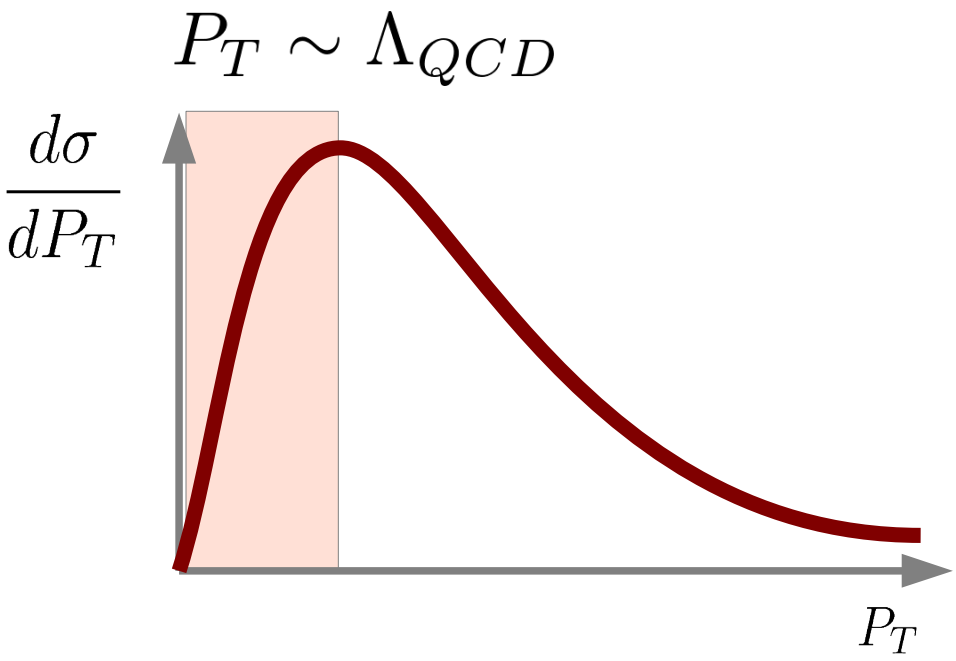
$$\alpha_s^n \ln^{2n}\left(Q^2/P_T^2\right)$$

So-called TMD factorization

Mulders, Tangerman 1995

Ji, Ma, Yuan 2004

Boer, Mulders 1998, Collins 2011

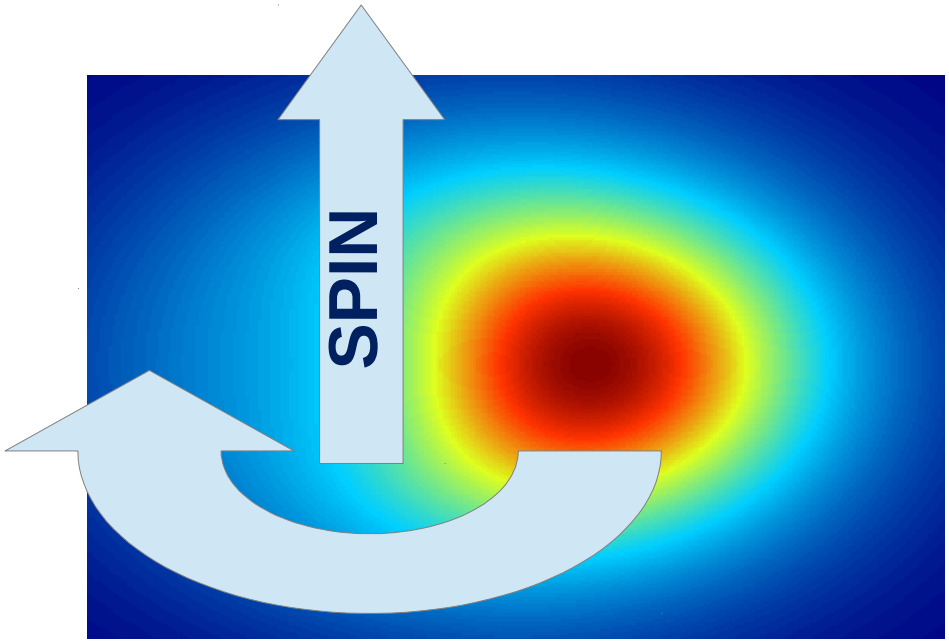


$$f(x, k_\perp; Q^2)$$

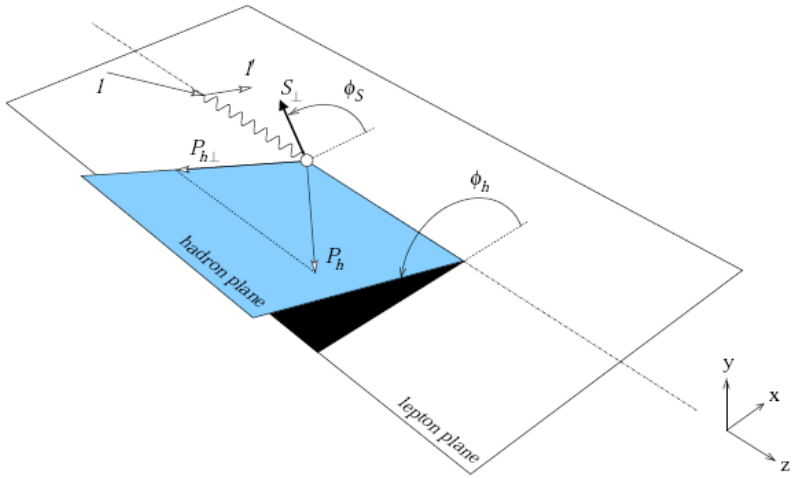
TMD functions

Jefferson Lab kinematics is dominated by this region

My scientific interests



Transverse Momentum Dependent distributions



$$\mathbf{l} + \mathbf{P} \rightarrow \mathbf{l}' + \mathbf{h} + \mathbf{X}$$

If produced hadron has low transverse momentum

$$\Lambda_{QCD} \sim P_T << Q$$

it will be sensitive to quark transverse $k_\perp$ momentum

TMD factorization proven in QCD

Ji, Ma, Yuan (2004)

Collins (2011)

For processes with two hadrons

SIDIS, DY, e+e-

Cross-section formula contains structure functions – Convolutions of TMDs

Mulders, Tangerman (1995),

Boer, Mulders (1998)

Bacchetta et al (2007)

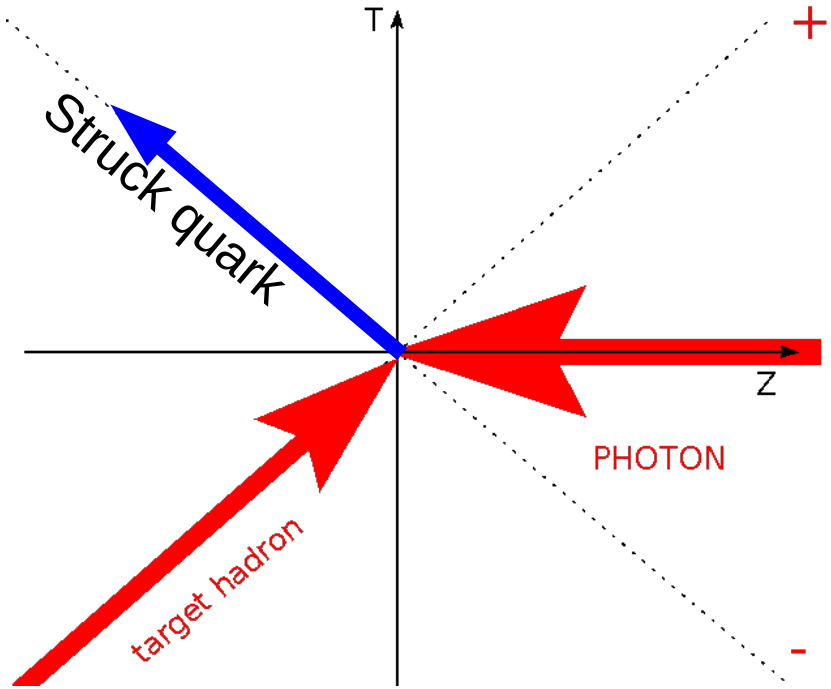
Anselmino et al (2011)

$$\Phi_{ij}(x, \mathbf{k}_\perp) = \int \frac{d\xi^-}{(2\pi)} \frac{d^2\xi_\perp}{(2\pi)^2} e^{ixP^+\xi^- - i\mathbf{k}_\perp\xi_\perp} \langle P, S_P|\bar{\psi}_j(0)\mathcal{U}(\mathbf{0}, \xi)\psi_i(\xi)|P, S_P\rangle$$

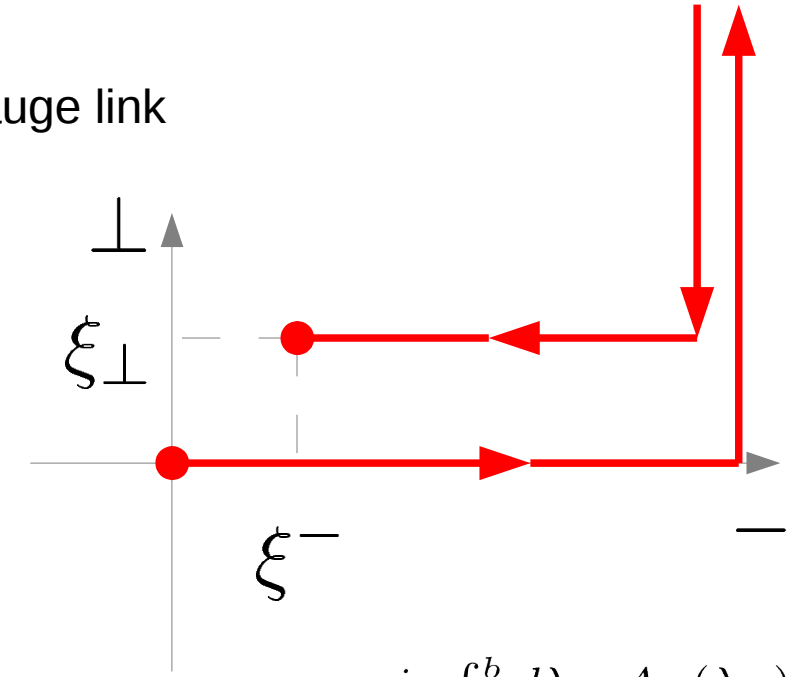
Transverse Momentum Dependent distributions

$$\Phi_{ij}(x,\mathbf{k}_\perp) = \int \frac{d\xi^-}{(2\pi)} \frac{d^2\xi_\perp}{(2\pi)^2} e^{ixP^+\xi^- - i\mathbf{k}_\perp\xi_\perp} \langle P,S_P|\bar{\psi}_j(0)\mathcal{U}(\mathbf{0},\xi)\psi_i(\xi)|P,S_P\rangle|_{\xi^+=0}$$

SIDIS in IMF:



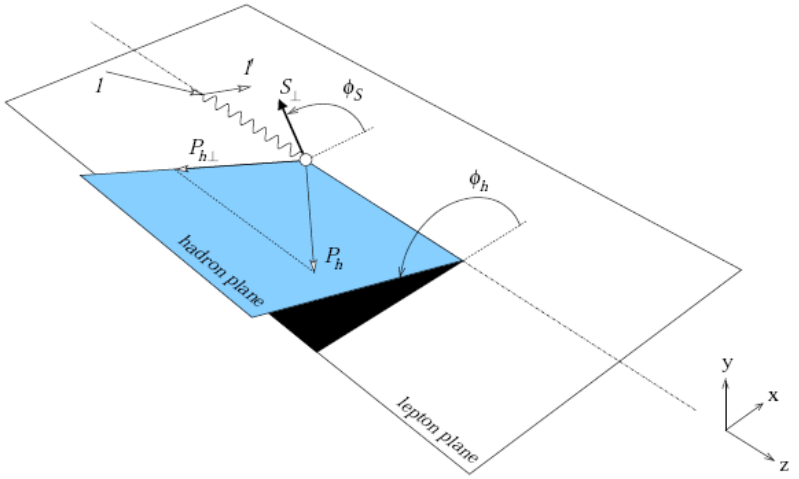
Gauge link



$$\mathcal{U}(a,b;n) = e^{-ig\int_a^b d\lambda n\cdot A_\alpha(\lambda n)t_\alpha}$$

Ensures gauge invariance of the distribution, cannot be canceled by gauge choice

Semi Inclusive Deep Inelastic scattering



One can rewrite the cross-section in terms of **18** structure functions

Each structure function encodes parton dynamics via convolutions of TMDs when factorization is applicable

Mulders, Tangerman (1995),
Boer, Mulders (1998)
Bacchetta et al (2007)

$$F_{UU,T} = \int \mathrm{d}^2 k_\perp \mathrm{d}^2 p_\perp \delta^{(2)}(\mathbf{P}_{h\perp} - z\mathbf{k}_\perp - \mathbf{p}_\perp) f(x, k_\perp^2) D(z, p_\perp^2)$$

$$\frac{d\sigma}{dx\, dy\, d\psi\, dz\, d\phi_h\, dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\, F_{UU}^{\cos\phi_h}$$

$$+ \varepsilon\cos(2\phi_h)\, F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\, F_{LU}^{\sin\phi_h} + \ldots$$

TMDs

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

8 functions in total (at leading twist)

Each represents different aspect of partonic structure

Each function is to be studied

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998)

Distributions

Unpolarised distributions

$$f_1(x) \propto \langle P, S_P | \bar{\psi}(0) \frac{\gamma^+}{2} \psi(\xi) | P, S_P \rangle$$

Distribution of unpolarised quarks inside unpolarised nucleon

Polarised distributions

$$g_1(x) \propto \langle P, S_L | \bar{\psi}(0) \frac{\gamma^+ \gamma_5}{2} \psi(\xi) | P, S_L \rangle$$

Helicity distribution – distribution of longitudinally polarised quarks inside longitudinally polarised nucleon

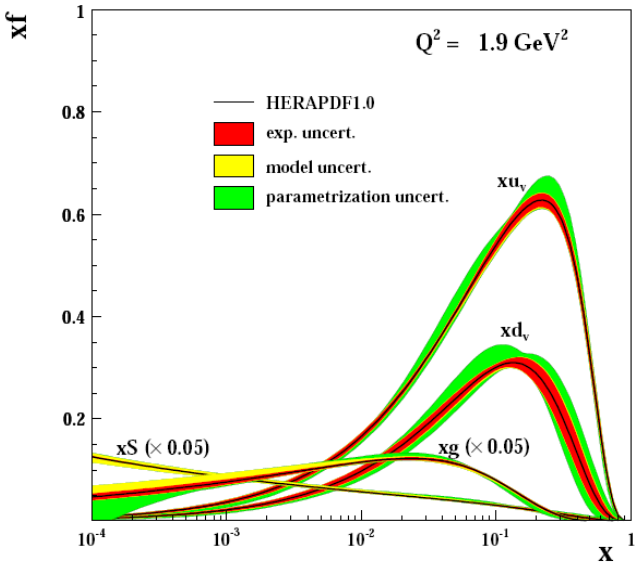
$$h_1(x) \propto \langle P, S_{T1} | \bar{\psi}(0) \frac{\gamma^+ \gamma^1 \gamma_5}{2} \psi(\xi) | P, S_{T1} \rangle$$

Transversity distribution – distribution of transversely polarised quarks inside transversely polarised nucleon

Kotzinian (1995), Mulders, Tangerman (1995), Boer, Mulders (1998), Collins (2011)

TMDs

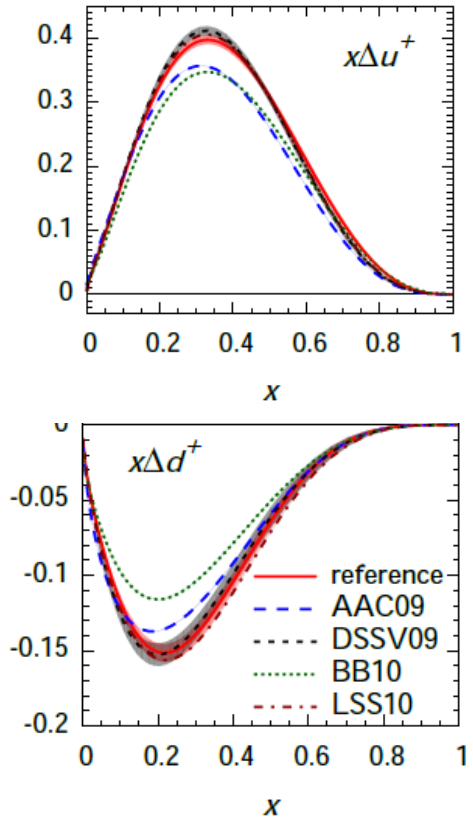
Good knowledge of f1



CTEQ, NNPDF, etc

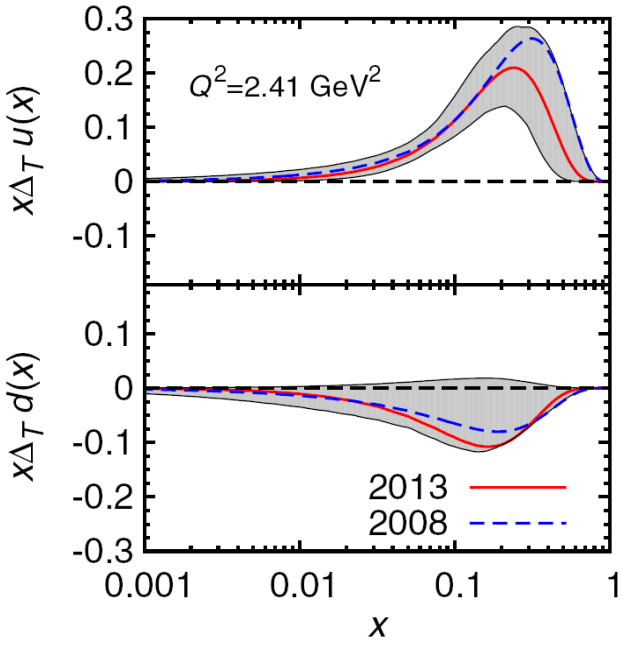
From fixed targets to HERA to LHC

Relatively good knowledge of g1



DSSV, LSS, JAM, etc
Fixed target experiments, HERMES, COMPASS, JLAB

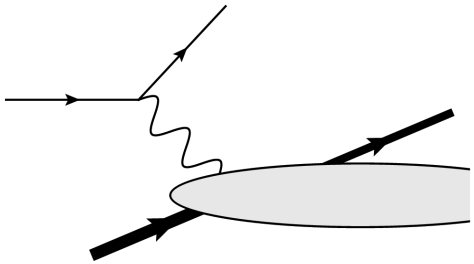
First results on h1



Anselmino et al, Bacchetta et al
HERMES, COMPASS, JLAB, BELLE, BABAR

Complementarity of SIDIS,e+e- and Drell-Yan

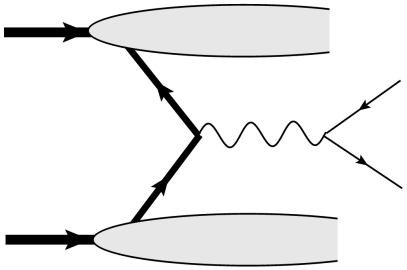
Various processes allow study and test of evolution, universality and extractions of distribution and fragmentation functions. We need information from all of them



$$f(x) \otimes D(z)$$

Semi Inclusive DIS – convolution of distribution functions and fragmentation functions

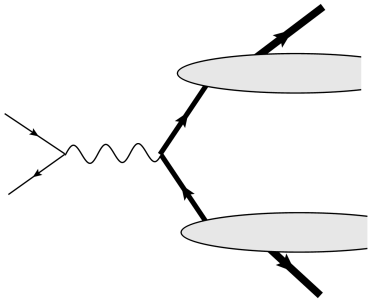
$$\ell + P \to \ell' + h + X$$



$$f(x_1) \otimes f(x_2)$$

Drell-Yan – convolution of distribution functions

$$P_1 + P_2 \to \bar{\ell}\ell + X$$



$$D(z_1) \otimes D(z_2)$$

e+ e- annihilation – convolution of fragmentation functions

$$\bar{\ell} + \ell \to h_1 + h_2 + X$$

Combining measurements from all above is important

What do we learn from TMDs?

Can transverse motion of partons be correlated with the spin of the proton?

What do we learn from TMDs?

Let us consider distribution of unpolarised quarks inside of unpolarised nucleon

by using vector projection γ^+

$$f(x, \mathbf{k}_\perp, \mathbf{S}_\perp) = f_1(x, \mathbf{k}_\perp^2) - f_{1T}^\perp(x, \mathbf{k}_\perp^2) \frac{\epsilon_T^{ij} \mathbf{k}_{\perp i} \mathbf{S}_{\perp j}}{M}$$

Sivers function

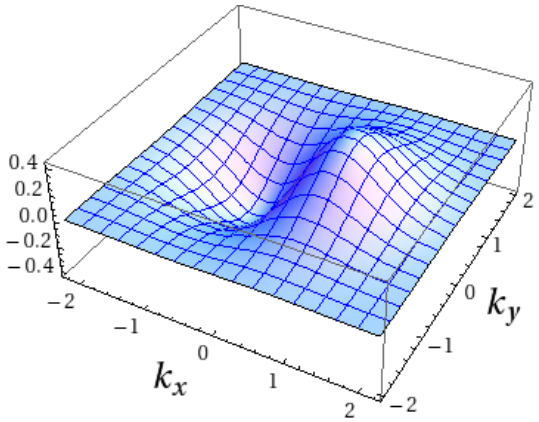
What do we learn from TMDs?

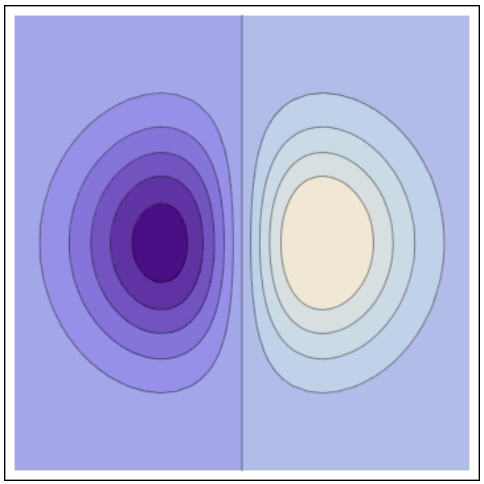
$$f(x, \mathbf{k}_\perp, \mathbf{S}_\perp) = f_1(x, \mathbf{k}_\perp^2) - f_{1T}^\perp(x, \mathbf{k}_\perp^2)\frac{\mathbf{k_x}}{M}$$

Suppose the spin is along Y direction: $S_\perp = (0, 1)$

Deformation in momentum space is: $x \cdot f(x^2 + y^2)$

This is so-called “dipole” deformation





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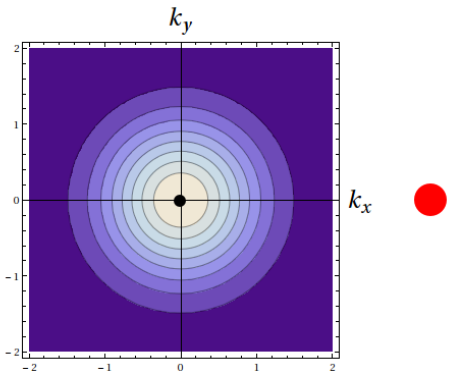
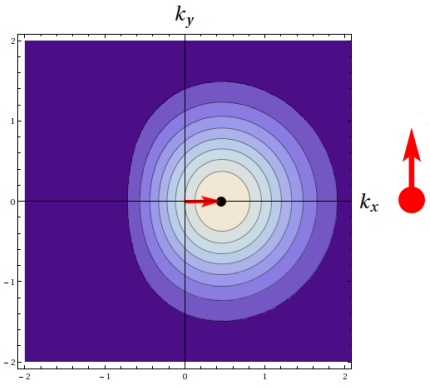
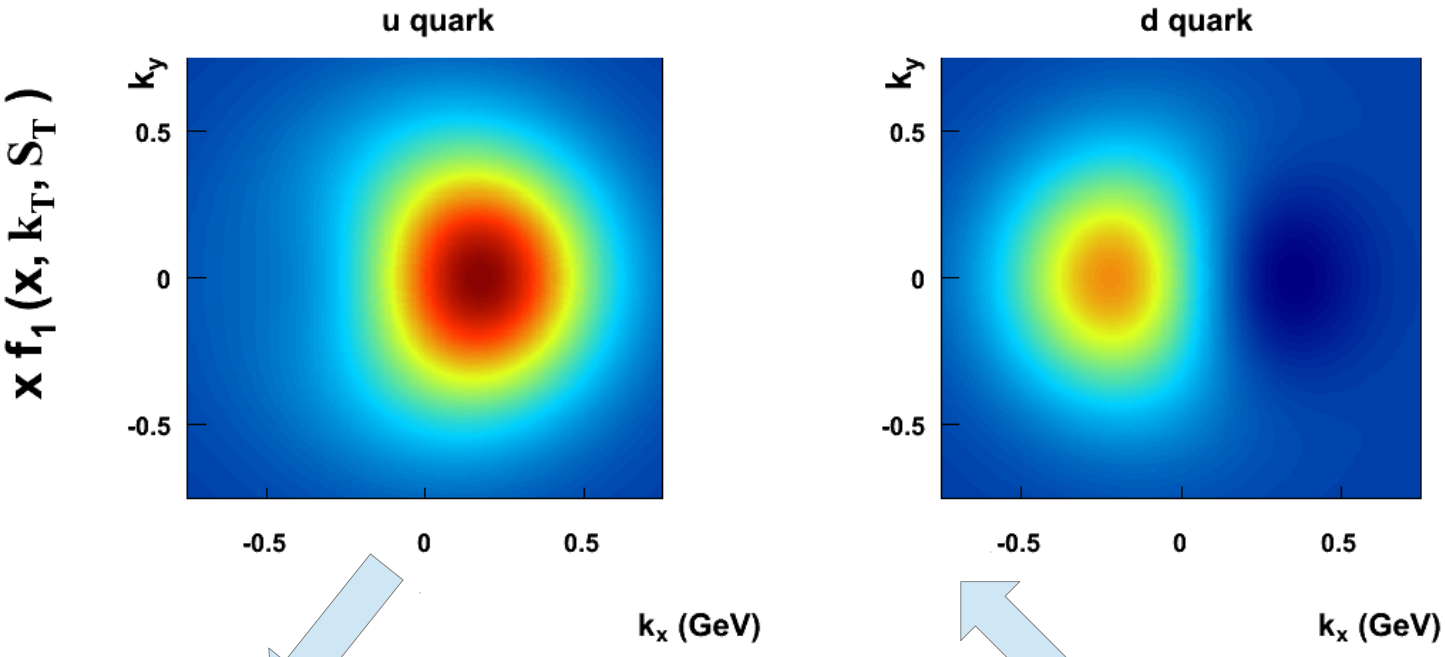
No correlation:



Correlation:



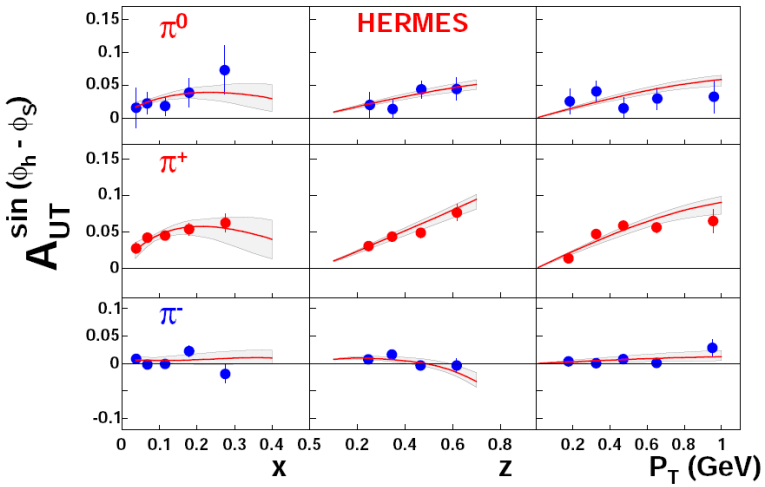
Tomographic scan of the nucleon



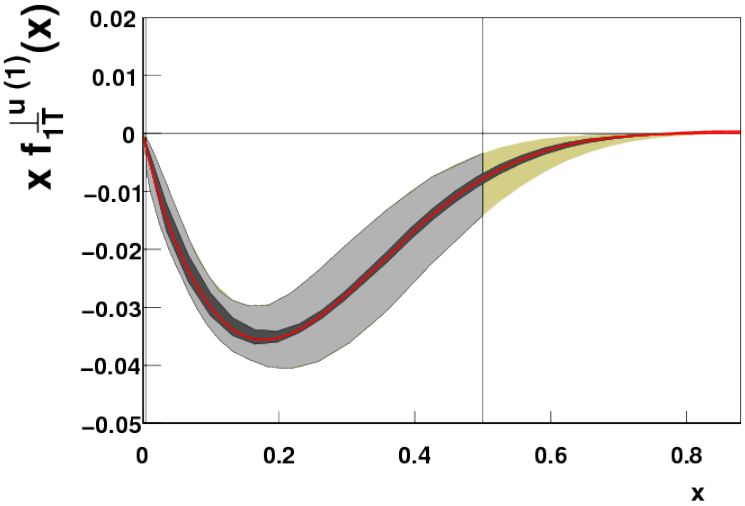
AP 2012

Data

Results

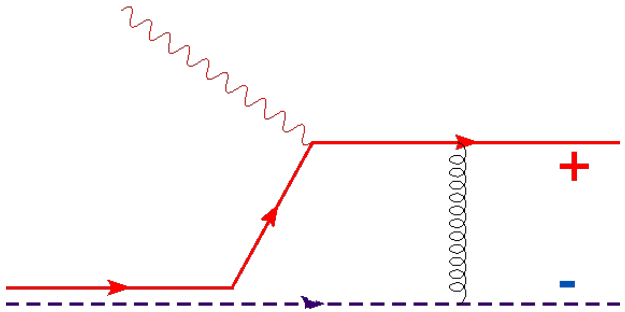


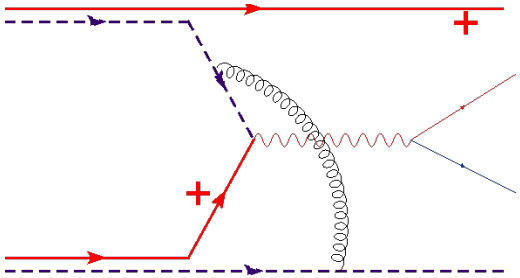
Global analysis of the data



Physics of gauge links

Colored objects are surrounded by gluons, profound consequence of gauge invariance.
Sivers function has opposite sign when gluon couple after quark scatters (SIDIS) or before quark annihilates (Drell-Yan)





Brodsky,Hwang, Schmidt
Belitsky,Ji,Yuan
Collins
Boer,Mulders,Pijlman, etc

$$f_{1T}^{\perp SIDIS} = -f_{1T}^{\perp DY}$$

One of the main goals is to verify this relation.
It goes beyond “just” check of TMD factorization.
Motivates Drell-Yan experiments

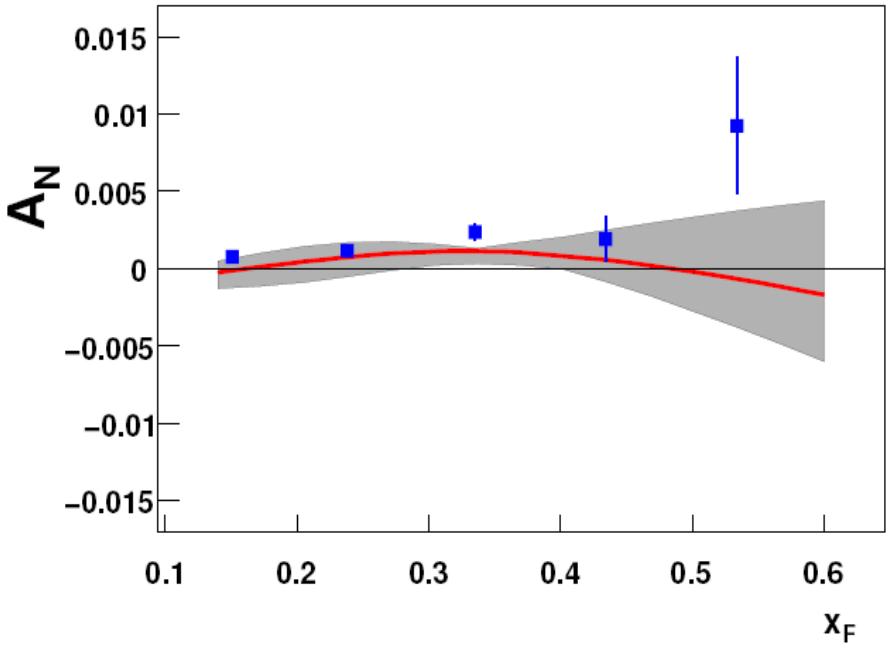
COMPASS, RHIC, FERMILAB, JPARC, PAX etc
Barone et al., Anselmino et al., Yuan,Vogelsang, Schlegel et al., Kang,Qiu, Metz,Zhou

First indication that this relation is correct comes from RHIC, data of AnDY experiment
Contains both initial and final state interactions

Gamberg, Kang, AP PRL 110 (2013)

$$P^{\uparrow}P \to JetX$$

AnDY Collaboration (2013)



We took into account both initial and final state interactions

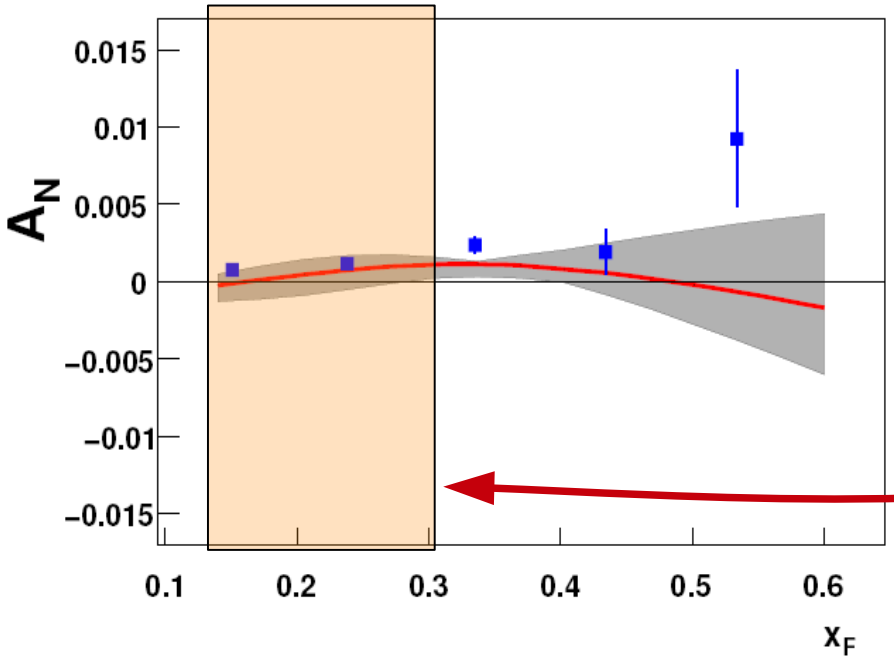
Not a fit of the data, just prediction based on Sivers function from SIDIS

$$\langle y \rangle = 3.25,\ \sqrt{s} = 500(GeV)$$

First indication that this relation is correct comes from RHIC, data of AnDY experiment
Contains both initial and final state interactions

$$P^{\uparrow}P \to JetX$$

Gamberg, Kang, AP PRL 110 (2013)



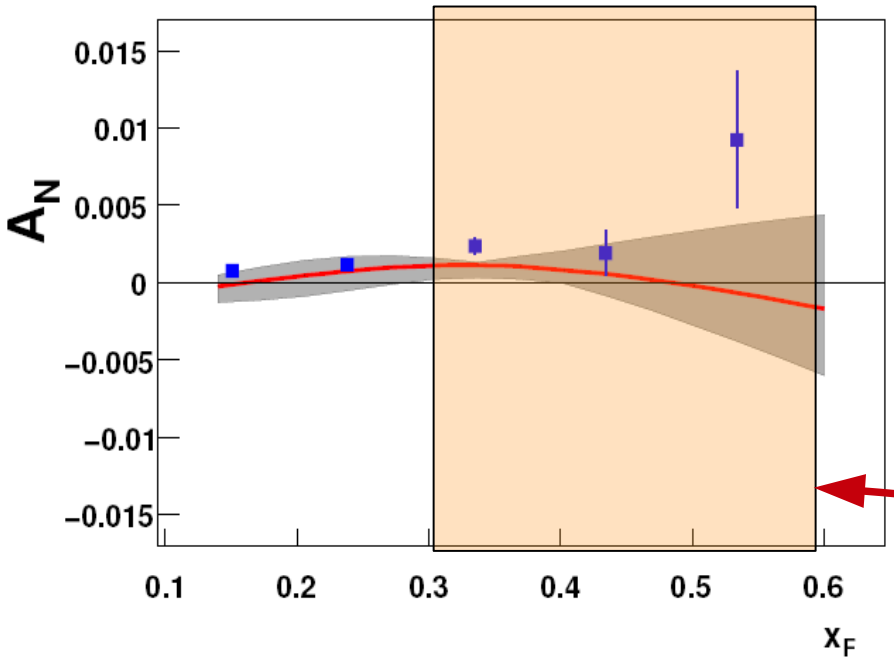
This region corresponds to SIDIS kinematics
agreement is very encouraging

$$\langle y \rangle = 3.25,\ \sqrt{s} = 500(GeV)$$

First indication that this relation is correct comes from RHIC, data of AnDY experiment
Contains both initial and final state interactions

$$P^{\uparrow}P \to JetX$$

Gamberg, Kang, AP PRL 110 (2013)



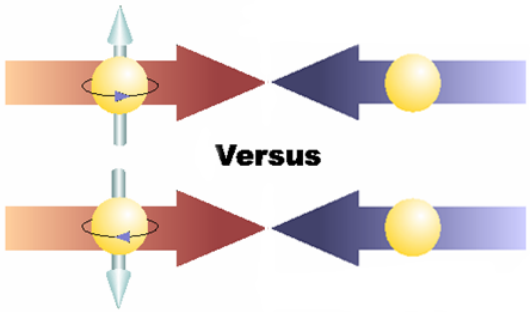
Region of high-x is still unexplored. JLab 12 data will be very important

$$\langle y \rangle = 3.25,\ \sqrt{s} = 500(GeV)$$

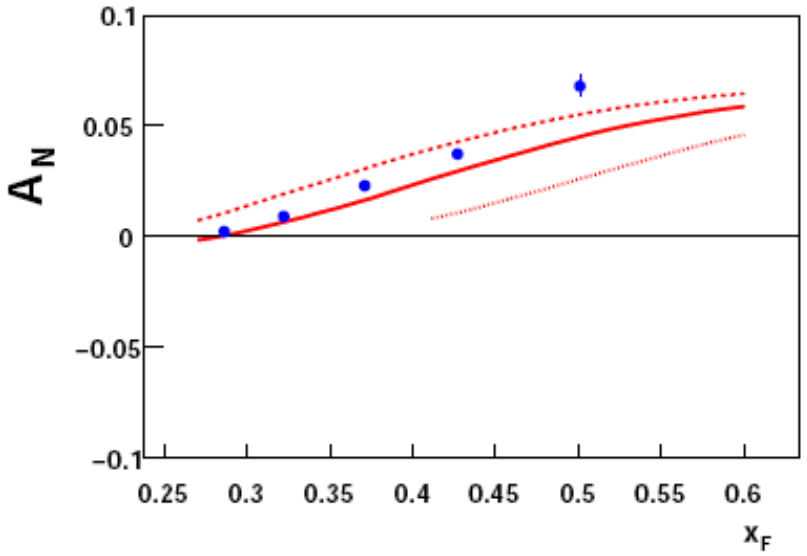
P P data from RHIC

RHIC has produced a lot of data on left-right asymmetries.
The data are to be integrated into the common framework

$$P^{\uparrow} P \to \pi^0 X$$



STAR data,
Abelev STAR coll (2008)



Results are promising,
More work is needed to accommodate all data

Kang, AP (2011)

$$\langle y \rangle = 3.7,\ \sqrt{s} = 200(GeV)$$

Phenomenology

It is extremely important to test our knowledge by **predicting** results of future measurements

Phenomenology

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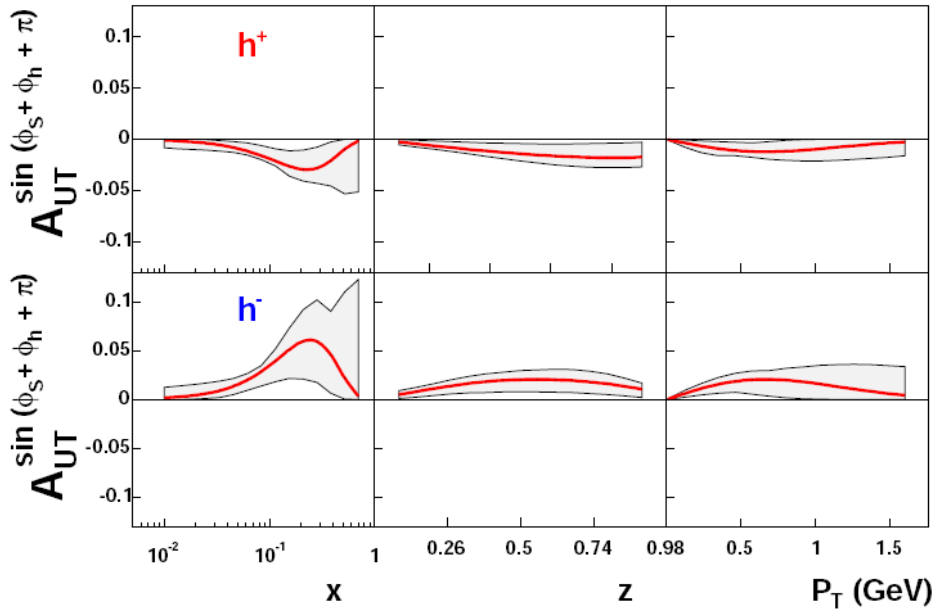

Prediction
Anselmino, Boglione,
D'Alesio, Kotzinian, Murgia, **AP**, Turk
PRD75 (**2007**) 054032

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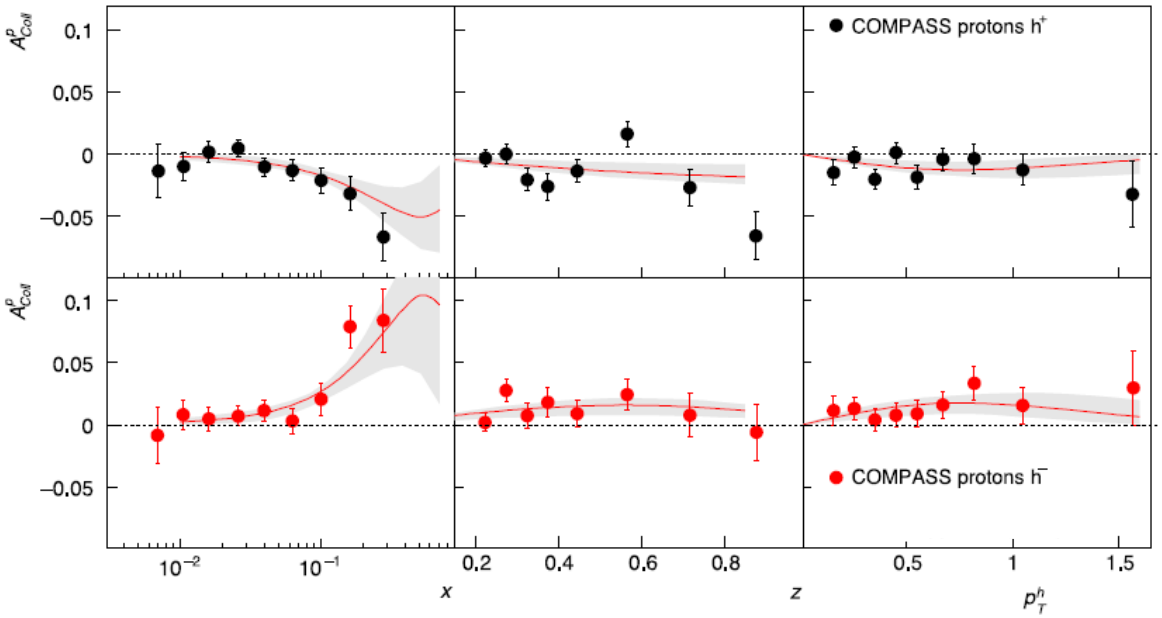

Prediction
Anselmino, Boglione,
D'Alesio, Kotzinian, Murgia, **AP**, Turk
PRD75 (**2007**) 054032

Measurement
COMPASS Collaboration CERN
PLB717 (**2012**) 376-382

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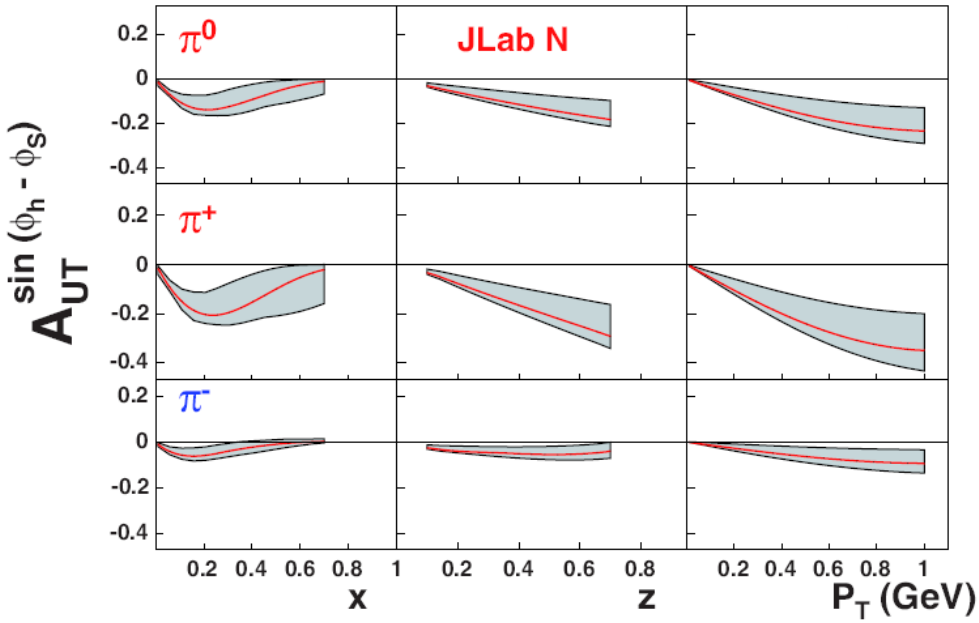

Prediction
Anselmino, Boglione,
D'Alesio, Kotzinian, Murgia, Melis,
AP, Turk
EPJA 39 (**2009**) 89-100

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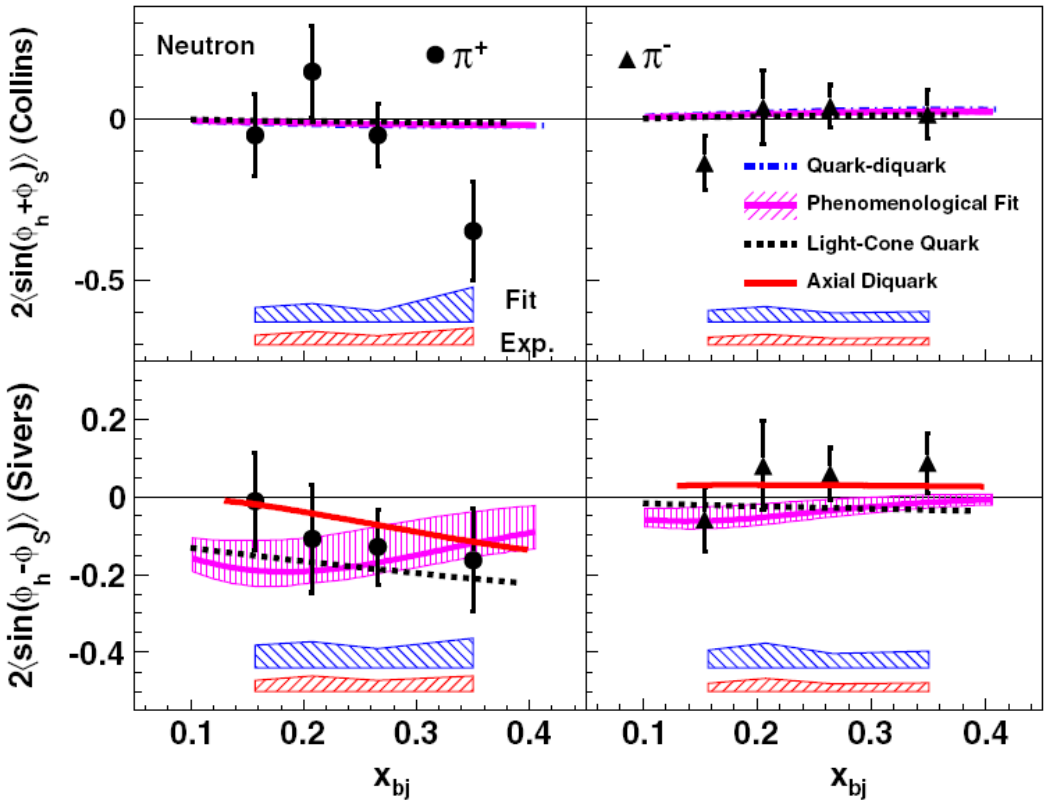

Prediction
Anselmino, Boglione,
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AP, Turk
EPJA 39 (**2009**) 89-100

Measurement
X. Qian et all (JLab HALL A Coll)
PRL 107 (**2011**) 072003

Phenomenology

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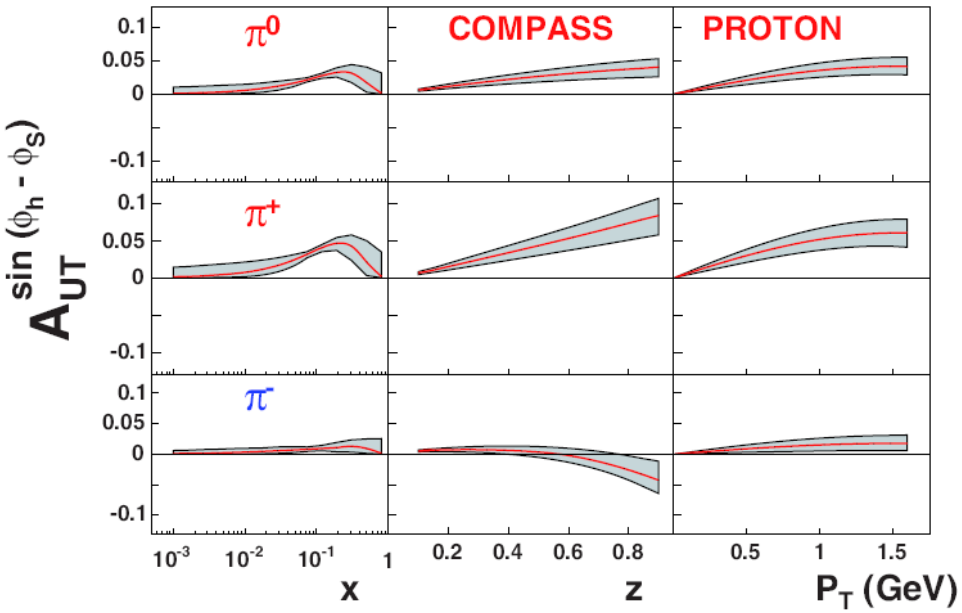

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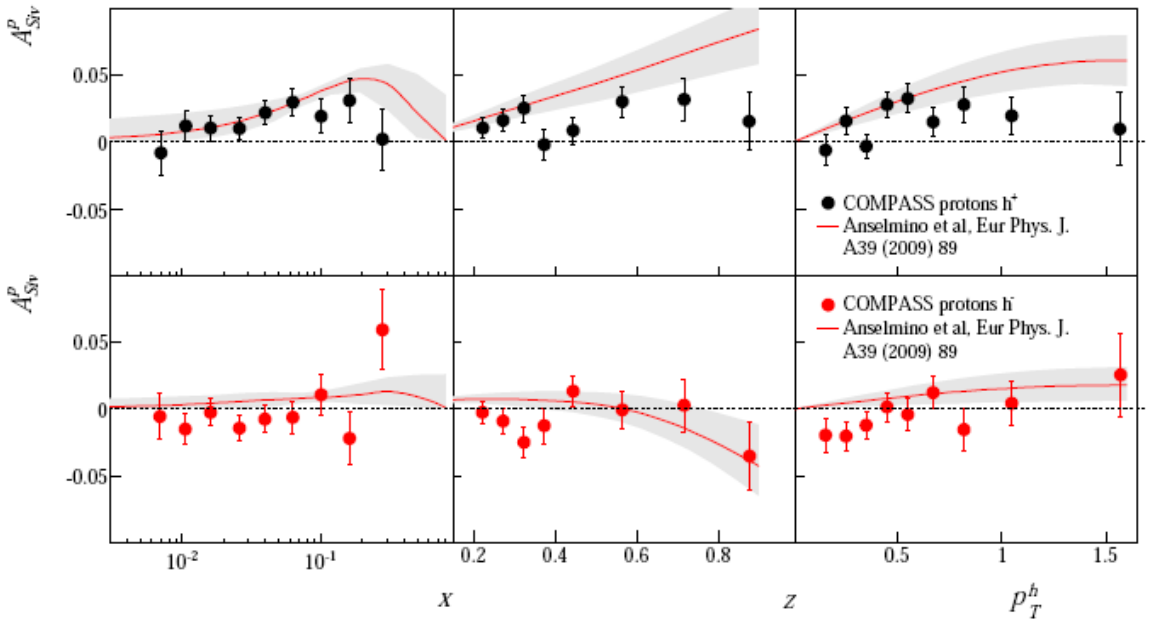

Prediction
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D'Alesio, Kotzinian, Murgia, Melis,
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EPJA 39 (**2009**) 89-100

Measurement
Compass Collaboration
Fizika B20 (**2011**) 93-106

Phenomenology

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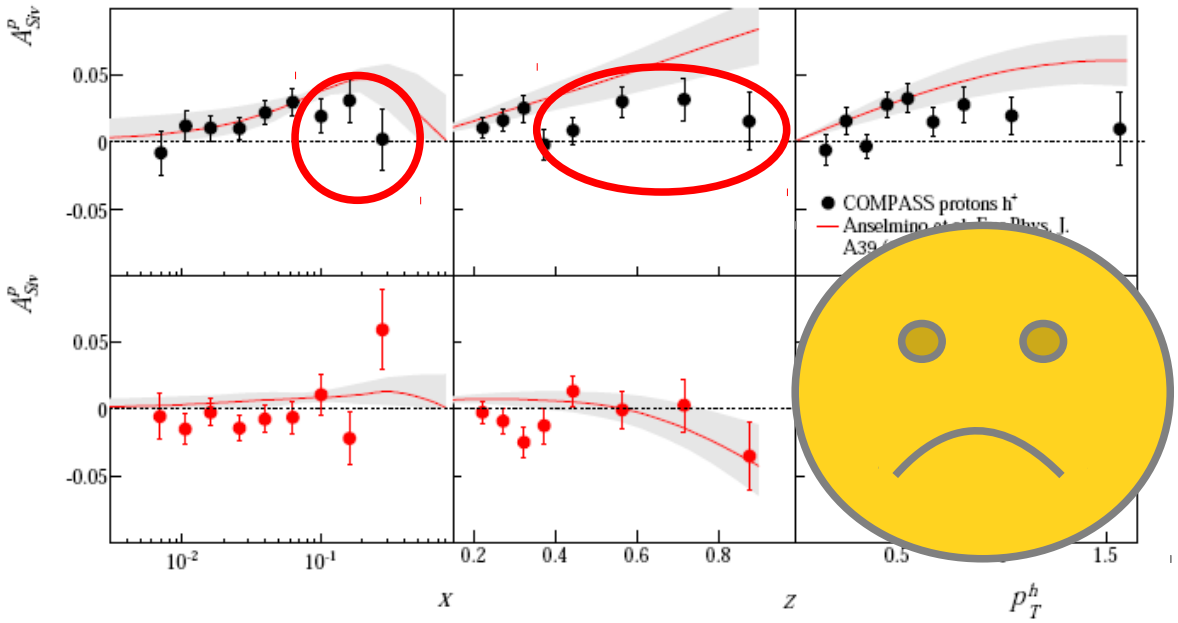

Prediction
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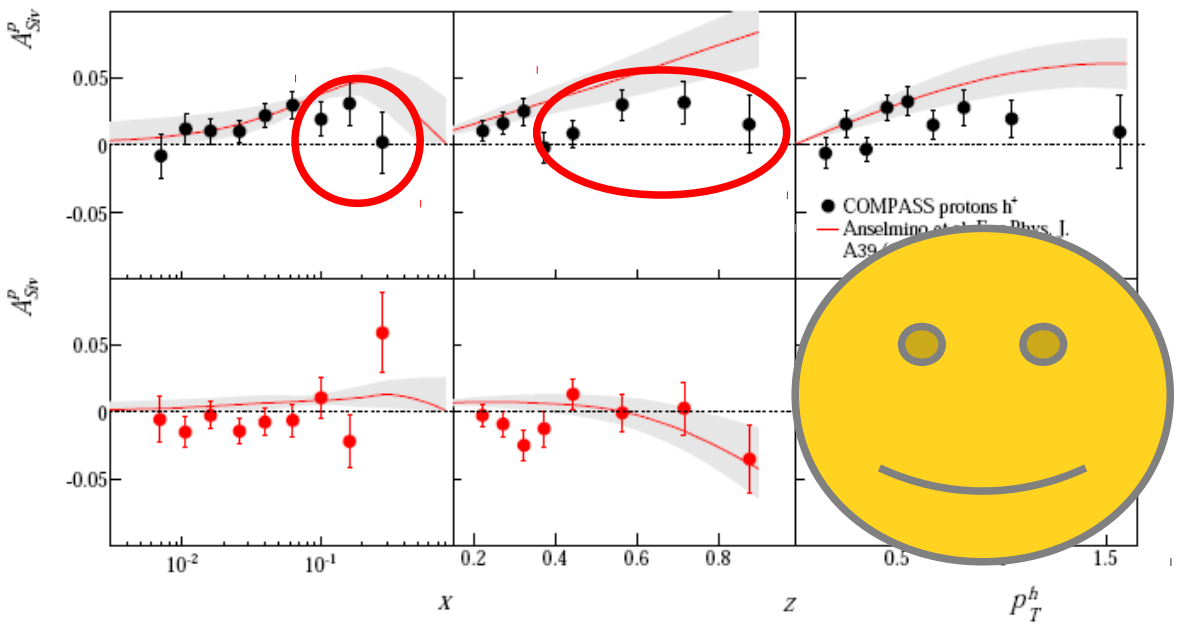


Prediction
Anselmino, Boglione,
D'Alesio, Kotzinian, Murgia, Melis,
AP, Turk
EPJA 39 (**2009**) 89-100

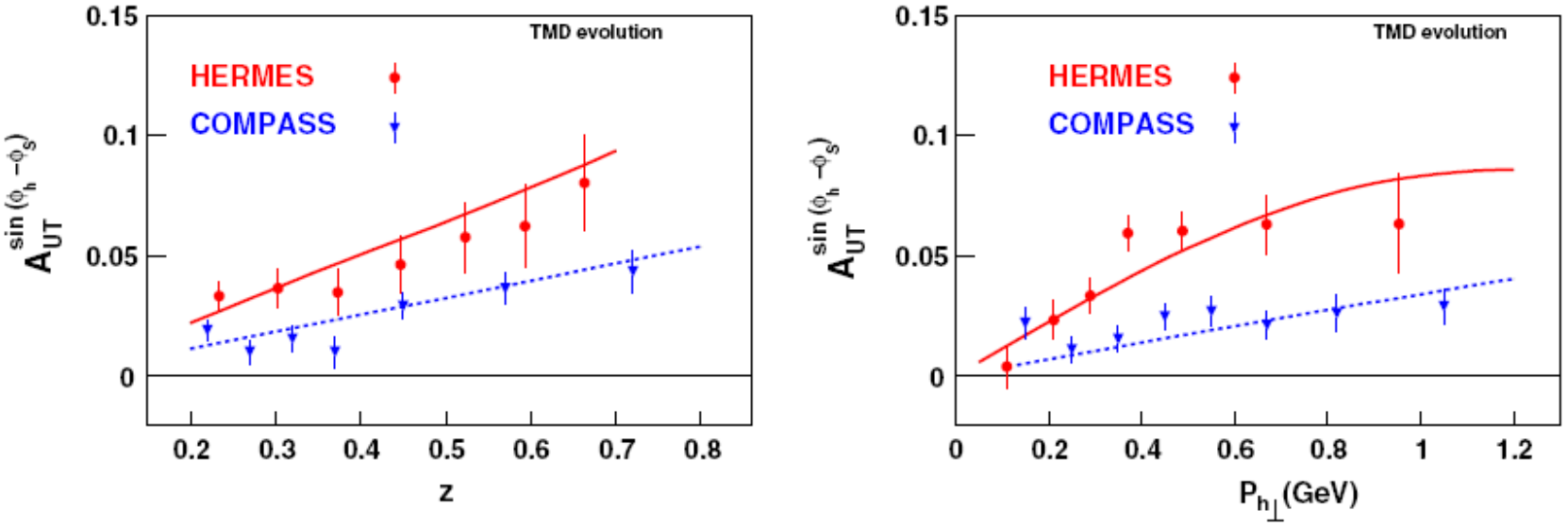
Measurement
Compass Collaboration
Fizika B20 (**2011**) 93-106

This is a chance to learn something new!

Phenomenology

It is extremely important to test our knowledge
by **explaining** results of future measurements

TMD evolution taken into account:



Aybat, **AP**, Rogers, PRL 108 (**2012**) 242003

This is a chance to learn something new!

What do we know about evolution?

TMD evolution: helicity and transversity

At small values of b_T (Fourier conjugate to $k_\perp$)TMDS are related to collinear distribution

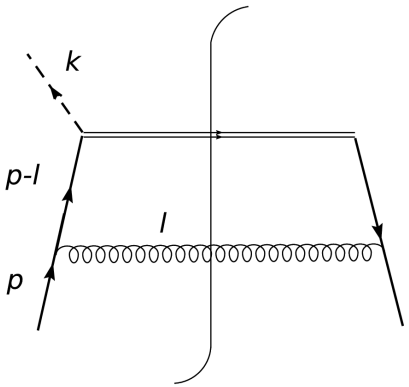
Collins, Soper, Sterman 1985
Ji, Ma, Yuan 2004
Collins 2011

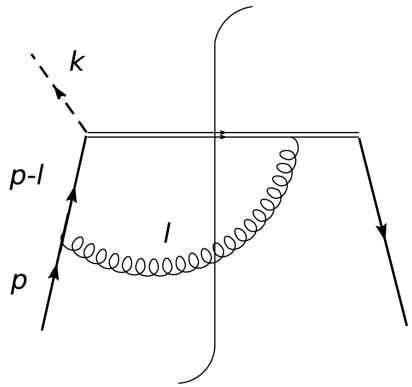
$$\tilde{f}^f(x, b_T; \mu, \zeta_F) \simeq \sum_i \int_x^1 \frac{d\hat{x}}{\hat{x}} \tilde{C}_{f/i}(x/\hat{x}, b_T; \mu, \zeta_F) f^i(\hat{x}, \mu)$$

Coefficient functions

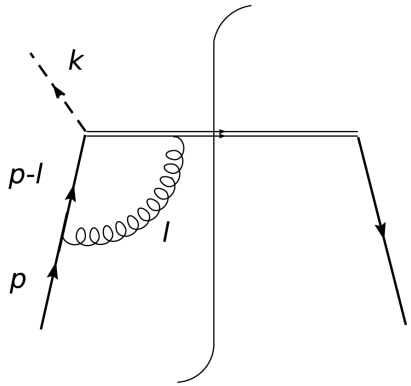
Calculate coefficient functions:

A. Bacchetta, AP, 2013





Real gluon emissions



Virtual gluon emissions

TMD evolution: helicity and transversity

A. Bacchetta, AP, 2013

Calculate everything at α_s:

Unpolarised

$$\tilde{C}_{j'/j}(x,\boldsymbol{b}_T;\mu;\zeta_F/\mu^2) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{\pi}\left\{ \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\left(\frac{1+x^2}{1-x}\right)_+ + \frac{1}{2}(1-x)+ \right.$$
$$\left. + \delta(1-x)\left[-\ln^2\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right) + \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\ln\left(\frac{\zeta_F}{\mu^2}\right)\right]\right\} + \mathcal{O}(\alpha_s^2)\,,$$

Helicity

$$\Delta\tilde{C}_{j'/j}(x,\boldsymbol{b}_T;\mu;\zeta_F/\mu^2) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{\pi}\left\{ \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\left(\frac{1+x^2}{1-x}\right)_+ + \frac{1}{2}(1-x)+ \right.$$
$$\left. + \delta(1-x)\left[-\ln^2\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right) + \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\ln\left(\frac{\zeta_F}{\mu^2}\right)\right]\right\} + \mathcal{O}(\alpha_s^2)\,,$$

Transversity

$$\delta\tilde{C}_{j'/j}(x,\boldsymbol{b}_T;\mu;\zeta_F/\mu^2) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{\pi}\left\{ \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\left(\frac{2x}{1-x}\right)_+ + \right.$$
$$\left. + \delta(1-x)\left[-\ln^2\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right) + \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\ln\left(\frac{\zeta_F}{\mu^2}\right)\right]\right\} + \mathcal{O}(\alpha_s^2)\,.$$

TMD evolution: helicity and transversity

A. Bacchetta, AP, 2013

Calculate everything at α_s:

$$\tilde{C}_{j'/j}(x,\boldsymbol{b}_T;\mu;\zeta_F/\mu^2) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{\pi}\left\{ \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\left(\frac{1+x^2}{1-x}\right)_+ + \frac{1}{2}(1-x)+ \right.$$

Unpolarised

$$\left. + \delta(1-x)\left[-\ln^2\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right) + \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\ln\left(\frac{\zeta_F}{\mu^2}\right)\right]\right\} + \mathcal{O}(\alpha_s^2)\,,$$

$$\Delta\tilde{C}_{j'/j}(x,\boldsymbol{b}_T;\mu;\zeta_F/\mu^2) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{\pi}\left\{ \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\left(\frac{1+x^2}{1-x}\right)_+ + \frac{1}{2}(1-x)+ \right.$$

Helicity

$$\left. + \delta(1-x)\left[-\ln^2\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right) + \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\ln\left(\frac{\zeta_F}{\mu^2}\right)\right]\right\} + \mathcal{O}(\alpha_s^2)\,,$$

$$\delta\tilde{C}_{j'/j}(x,\boldsymbol{b}_T;\mu;\zeta_F/\mu^2) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{\pi}\left\{ \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\left(\frac{2x}{1-x}\right)_+ + \right.$$

Transversity

$$\left. + \delta(1-x)\left[-\ln^2\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right) + \ln\left(\frac{2e^{-\gamma_E}}{\mu b_T}\right)\ln\left(\frac{\zeta_F}{\mu^2}\right)\right]\right\} + \mathcal{O}(\alpha_s^2)\,.$$

Connection to DGLAP! Collinear splitting functions

TMD evolution:helicity and transversity

A. Bacchetta, AP, 2013

Optimize by smart choice of the scale:

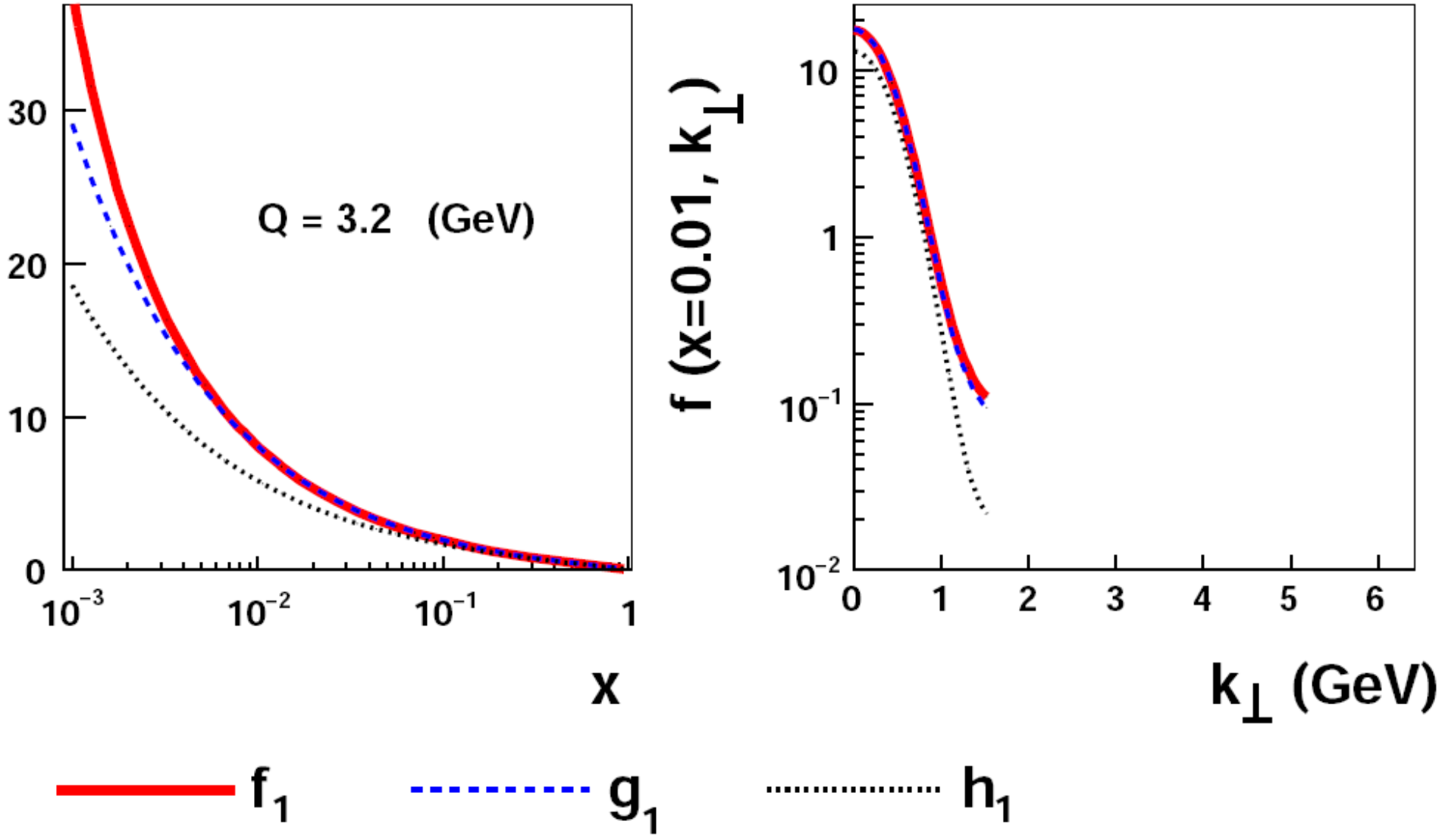
$$\tilde{C}_{j'/j}(x, b_*; \mu_b) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{2\pi}(1-x) + \mathcal{O}(\alpha_s^2),$$

$$\Delta\tilde{C}_{j'/j}(x, b_*; \mu_b) = \delta_{j'j}\delta(1-x) + \delta_{j'j}\frac{\alpha_s C_F}{2\pi}(1-x) + \mathcal{O}(\alpha_s^2),$$

$$\delta\tilde{C}_{j'/j}(x, b_*; \mu_b) = \delta_{j'j}\delta(1-x) + \mathcal{O}(\alpha_s^2).$$

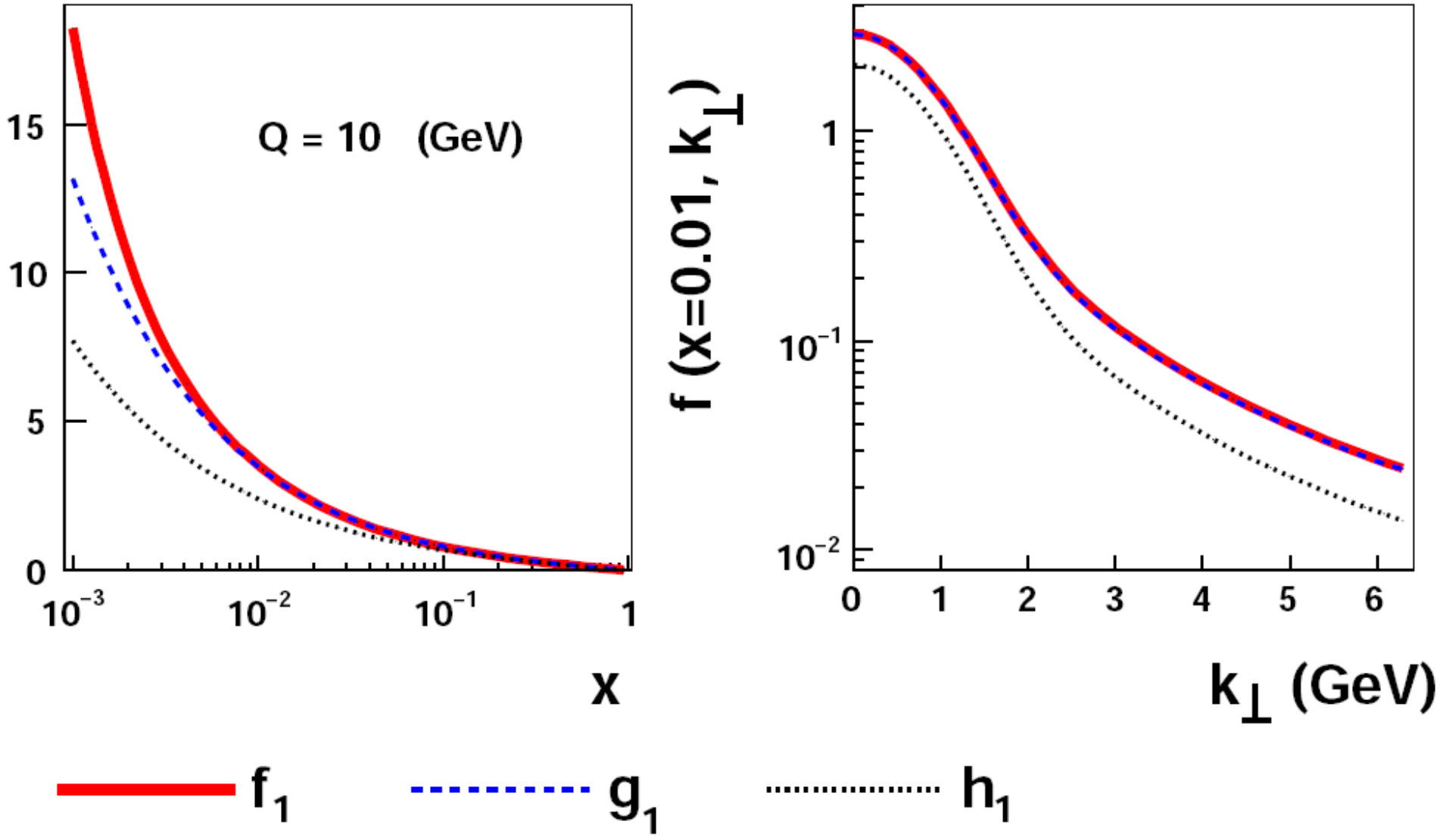
Phenomenology

A. Bacchetta, AP, 2013



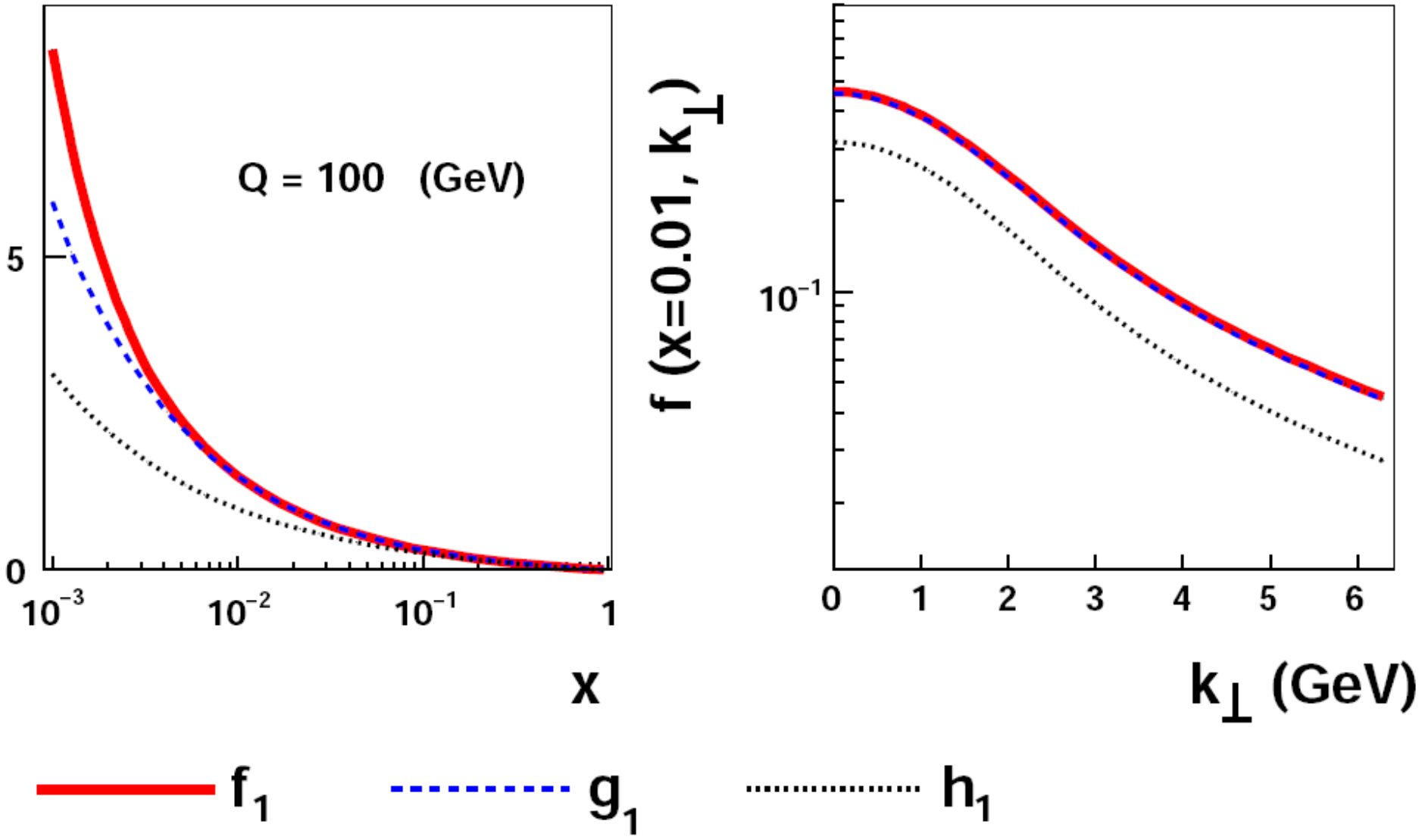
Phenomenology

A. Bacchetta, AP, 2013



Phenomenology

A. Bacchetta, AP, 2013



What do we expect from Jefferson Lab?

Tensor charge

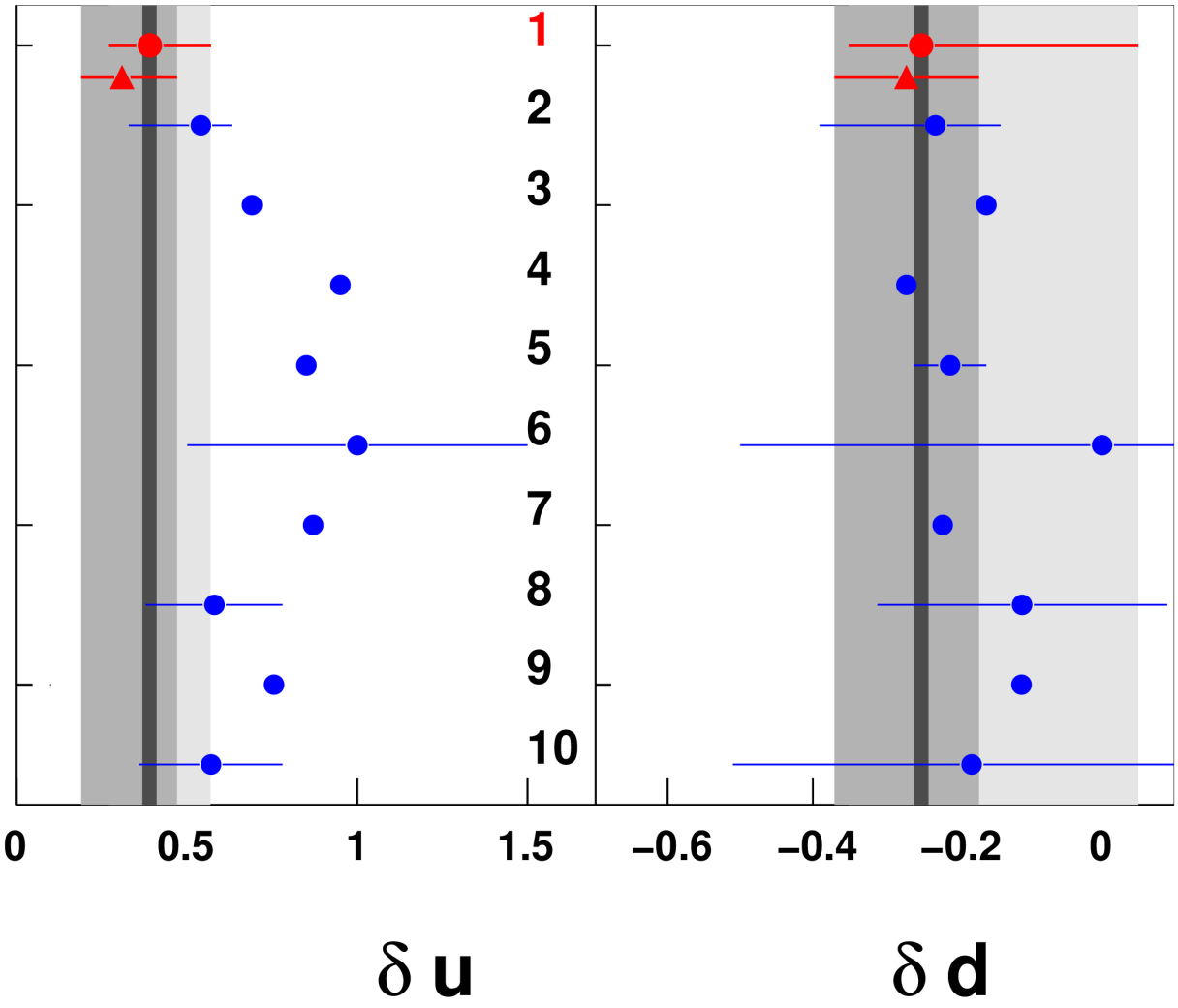
Anselmino et al (2013)

1 – Anselmino et al (2013)
2 – Anselmino et al., Nucl. Phys. Proc. Suppl. (2009)
3 – Cloet, Bentz and Thomas, Phys. Lett. B (2008)
4 – Wakamatsu, Phys. Lett. B (2007)
5 – Gockeler et al., Phys. Lett. B (2005)
6 – He and Ji, Phys. Rev. D (1995)
7 – Pasquini et al, Phys. Rev. D (2007)
8 – Gamberg and Goldstein, Phys. Rev. Lett. (2001)
9 – Hecht, Roberts and Schmidt, Phys. Rev. C (2001)
10 – Bacchetta, Courtoy, Radici, arXiv:1212.3568

$$\delta q = \int_0^1 dx \, (h_1^q(x) - h_1^{\bar{q}}(x))$$

● $\delta u = 0.39^{+0.18}_{-0.12}$, $\delta d = -0.25^{+0.3}_{-0.1}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$, $\delta d = -0.27^{+0.1}_{-0.1}$



JLab 12 data is going to improve our knowledge of tensor charge

Future beyond Jefferson Lab 12

Electron Ion Collider

Study sea quarks and gluons

Spin and 3D quark/gluon structure of the hadron

Dynamics of color fields in nuclei

Emergence of hadrons from color charge

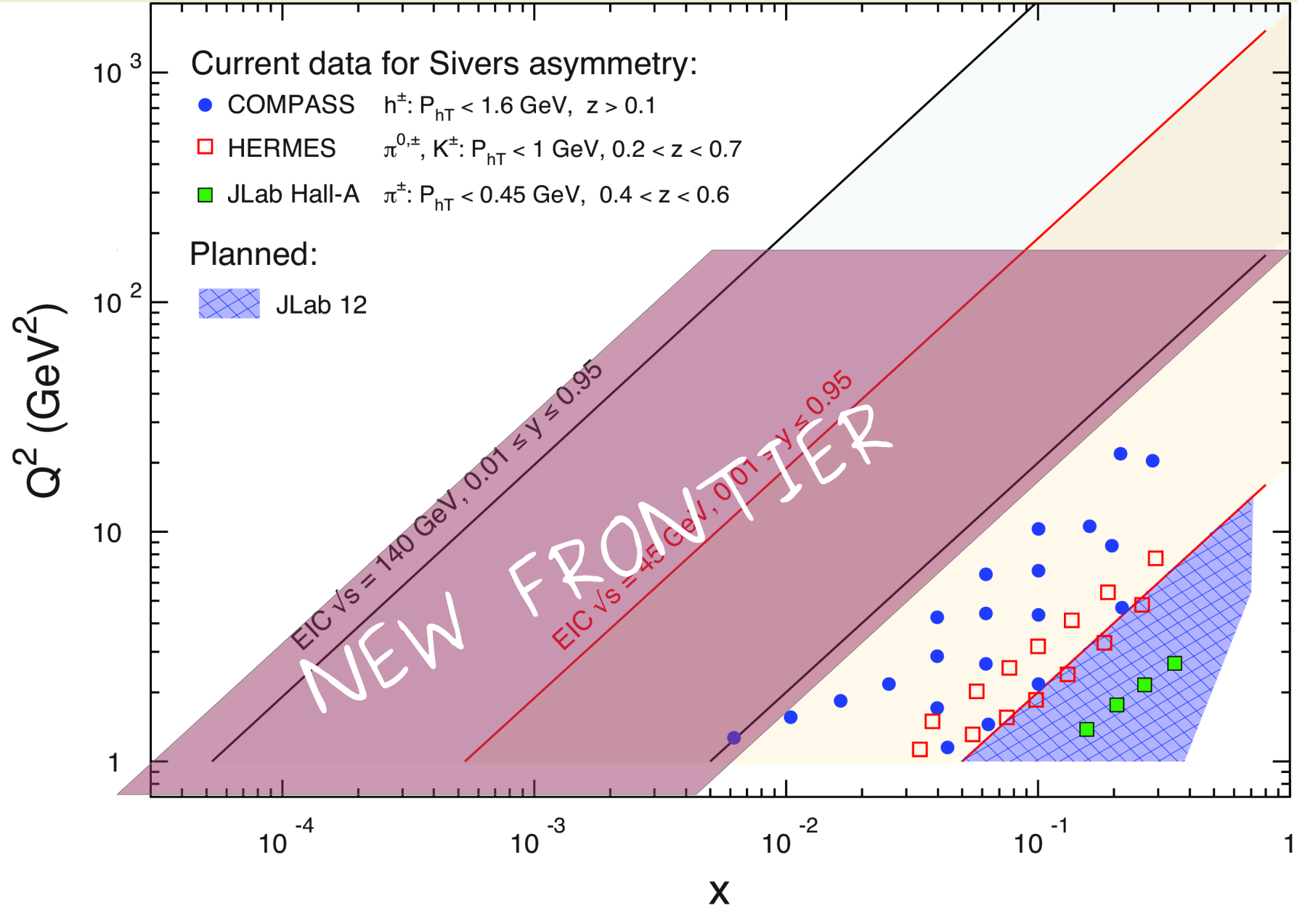
etc

Concept

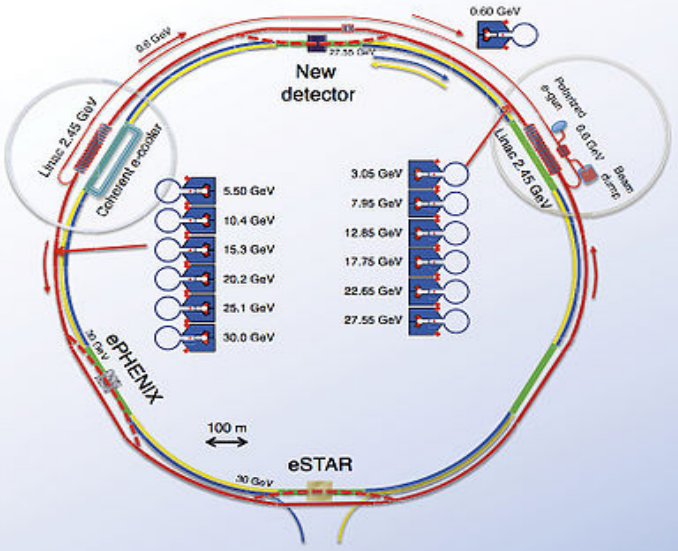
Energy from a few 100 to a few 1000 (GeV^2)
ep/eA collider
fully-polarized, longitudinal and transverse
luminosity: few x 10^{34} e-nucleons cm^{-2} s^{-1}

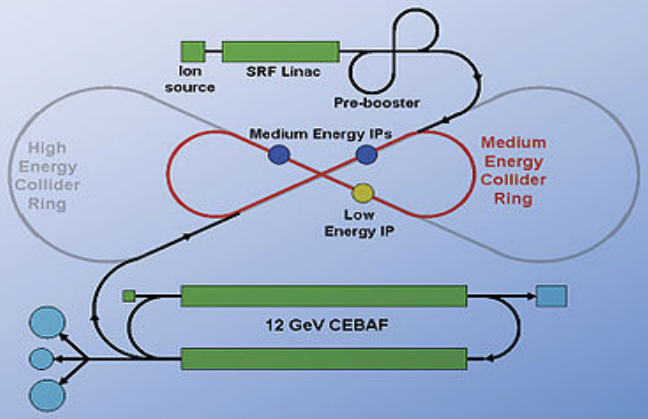
Upgradable to higher energies

Into the “sea”: Electron Ion Collider



Electron Ion Collider





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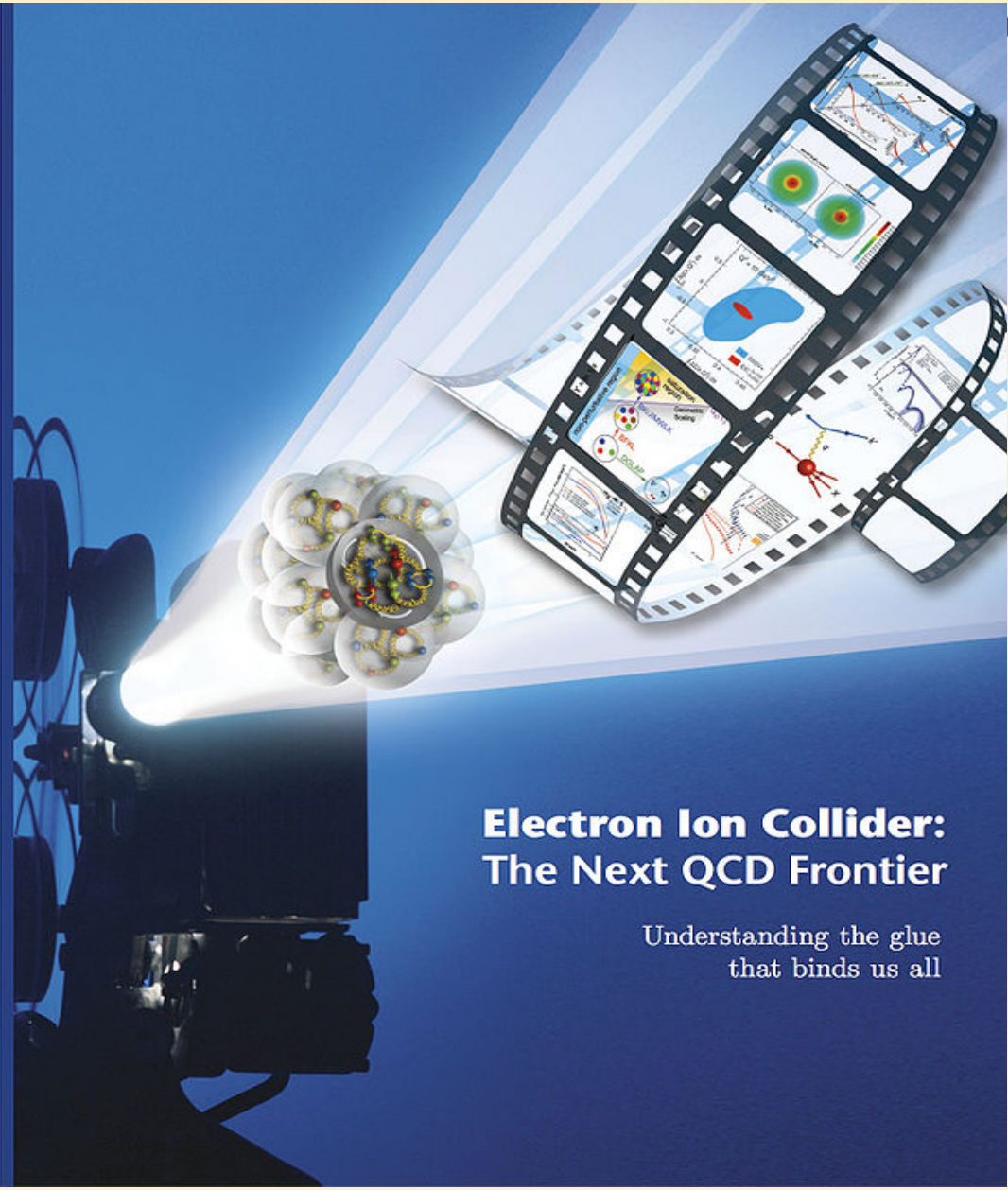
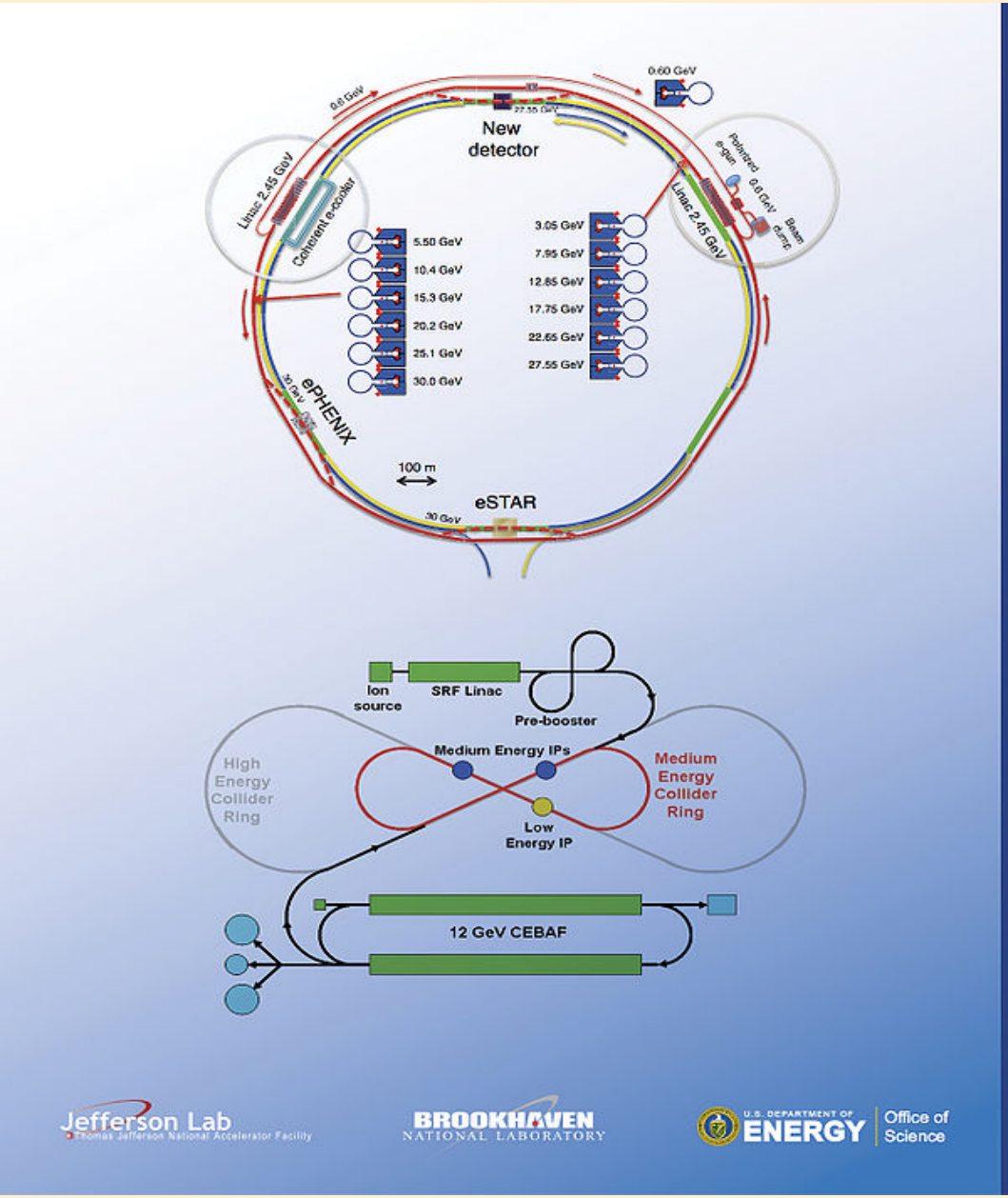
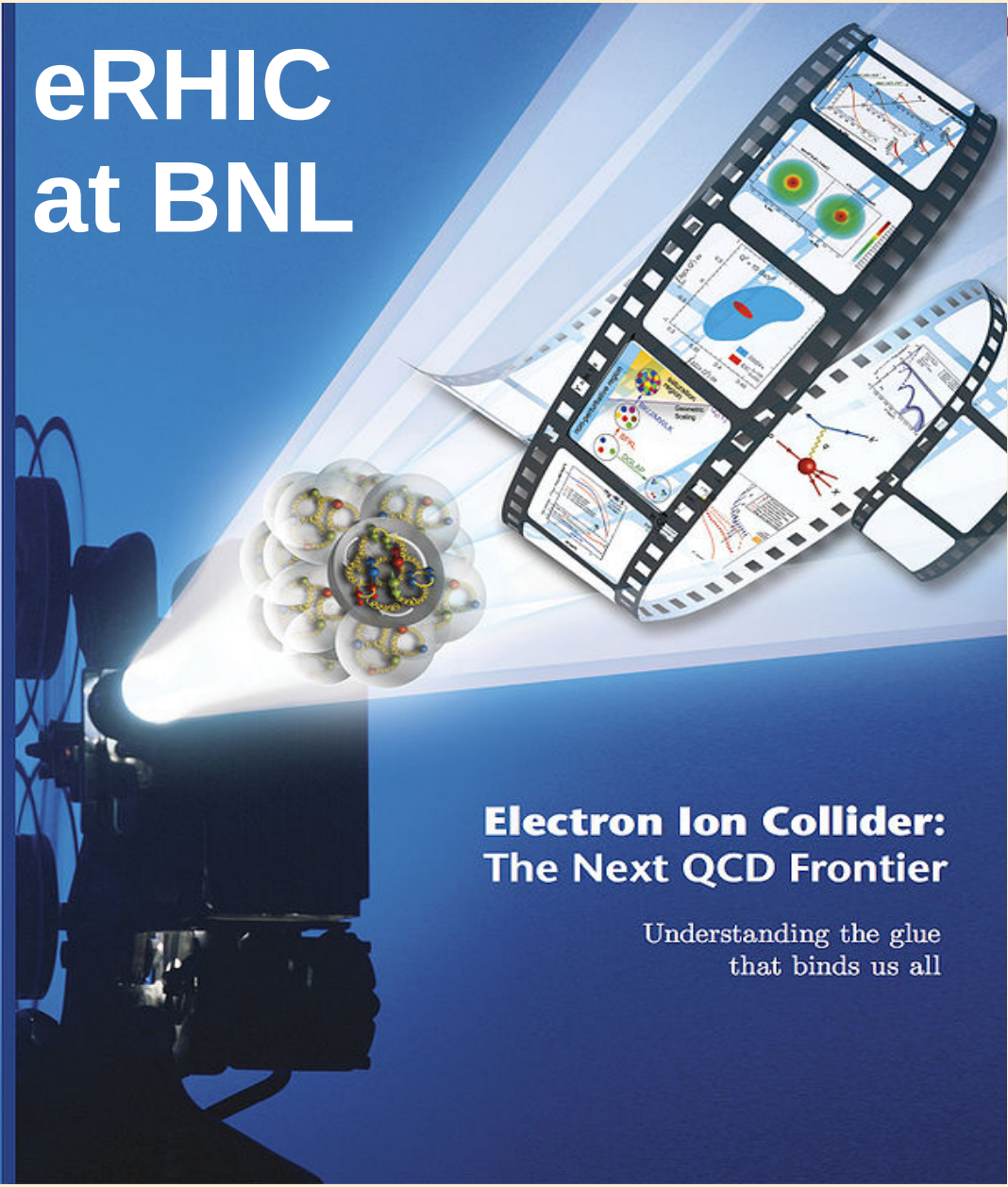
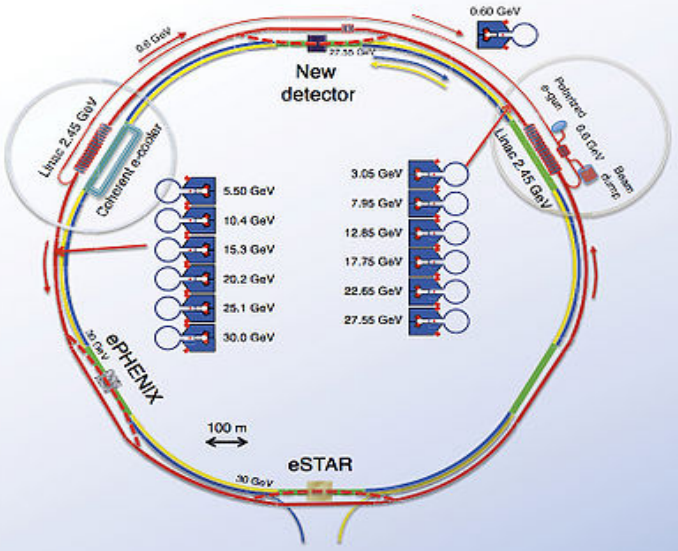


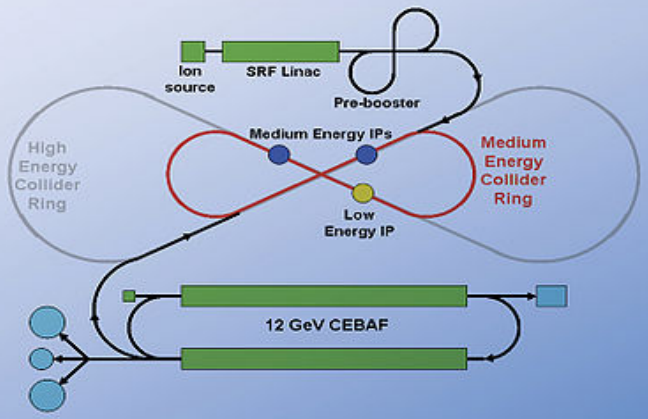
Electron Ion Collider





Electron Ion Collider





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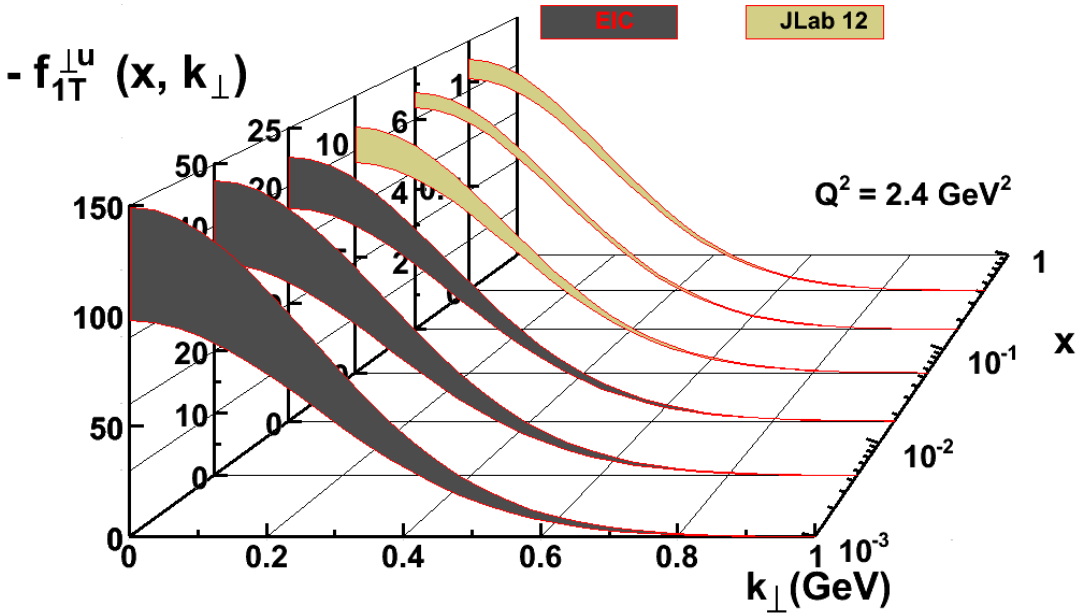
MEIC at JLAB

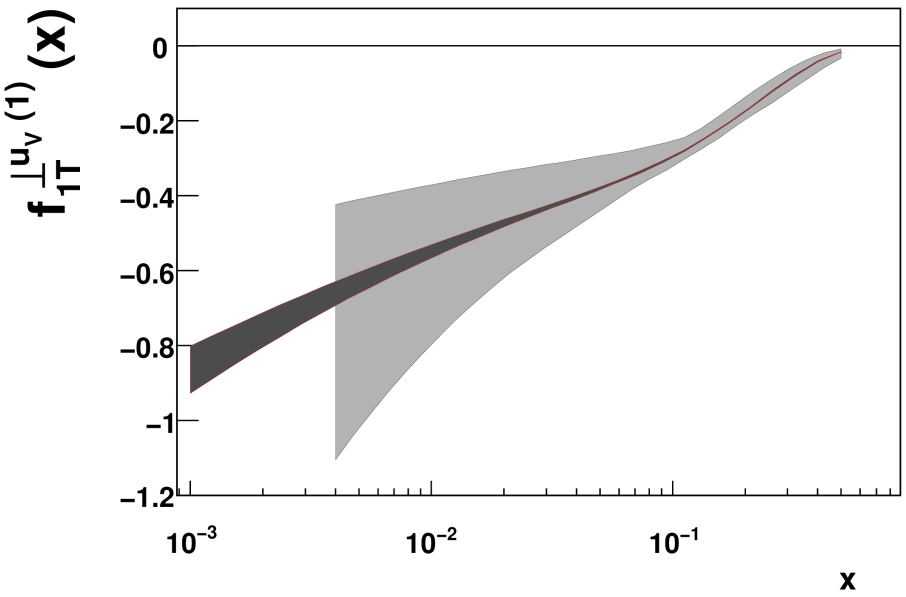
Electron Ion Collider: The Next QCD Frontier

Understanding the glue that binds us all

What will be achieved? Example:

Expected result for an individual function:

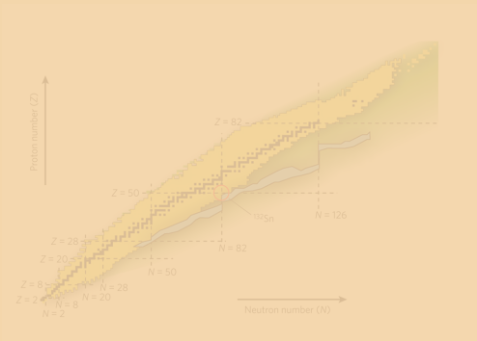


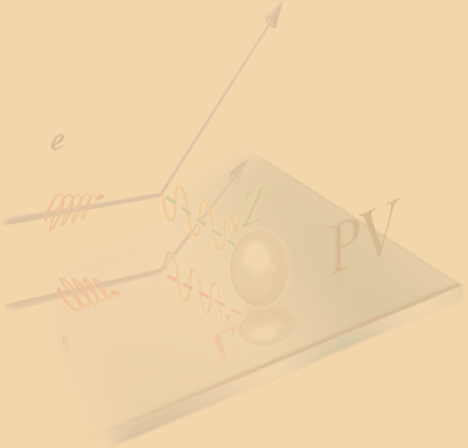


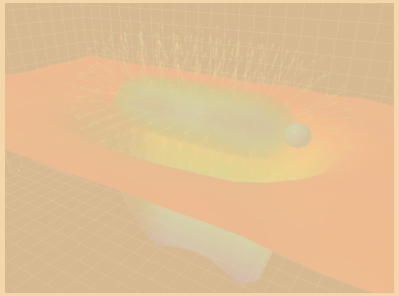
Expected accuracy of TMD profile

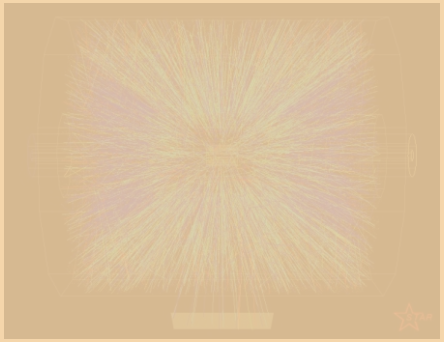
A. Prokudin (2012) contribution to EIC white paper

Conclusions









Very quickly developing field

PDFs

GPDs

TMDs

Experiment

We started here...

We have become this...