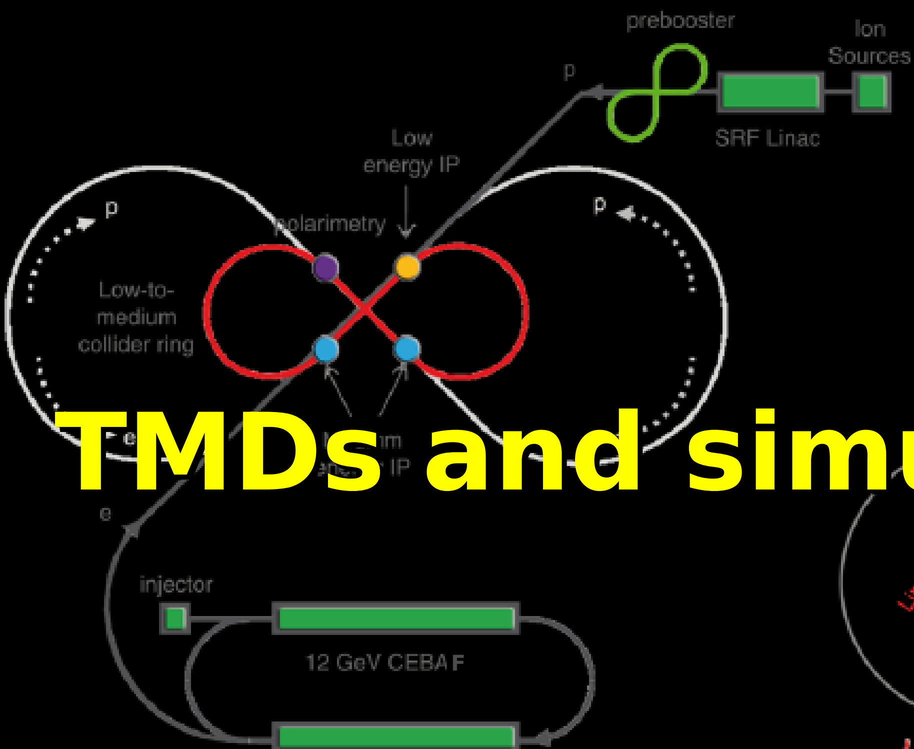
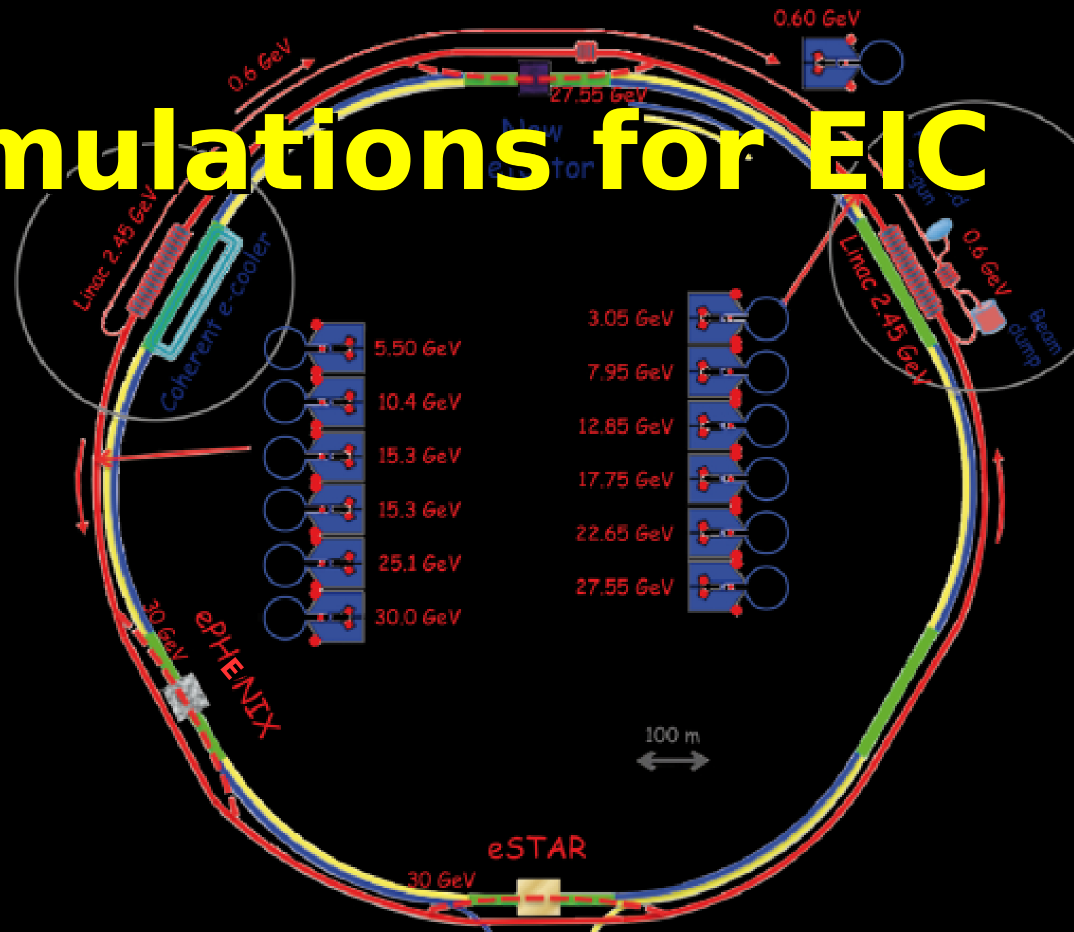
Alexei Prokudin Jefferson Lab

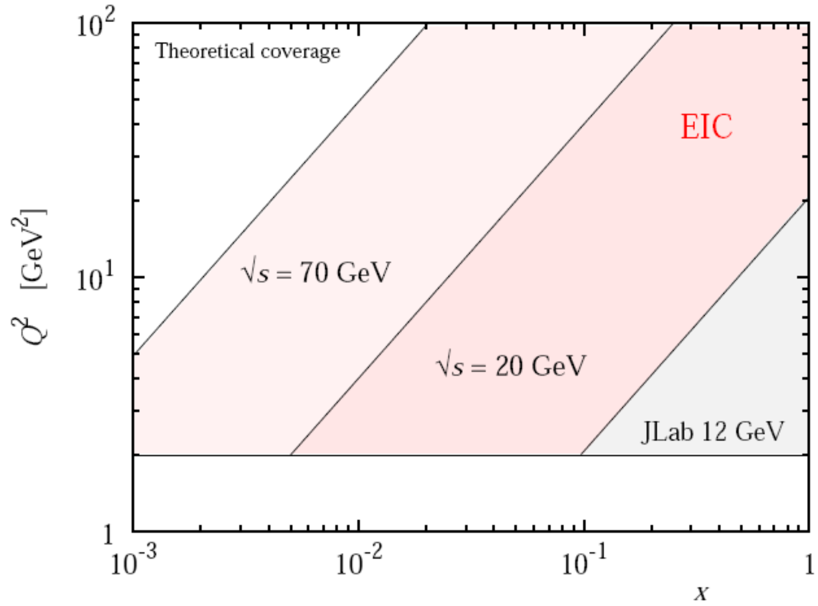


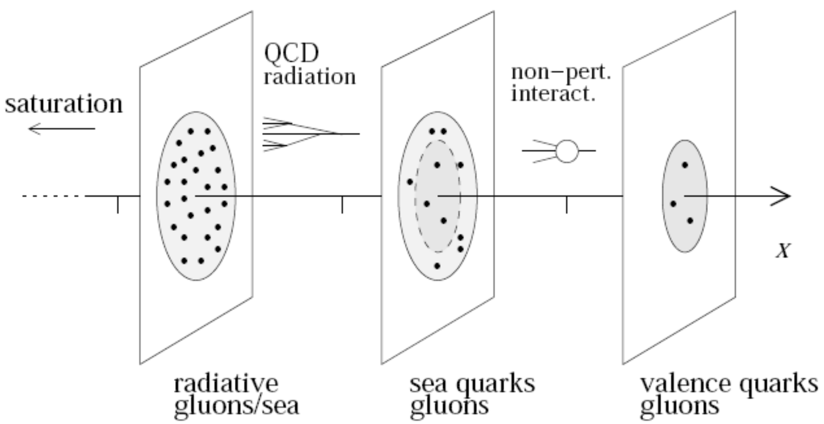
From: Nuclear physics with a medium-energy Electron-Ion Collider by A. Accardi et al.

TMDs and simulations for EIC



Nucleon landscape





Plot courtesy of Christian Weiss

Nucleon is a many body dynamical system of quarks and gluons

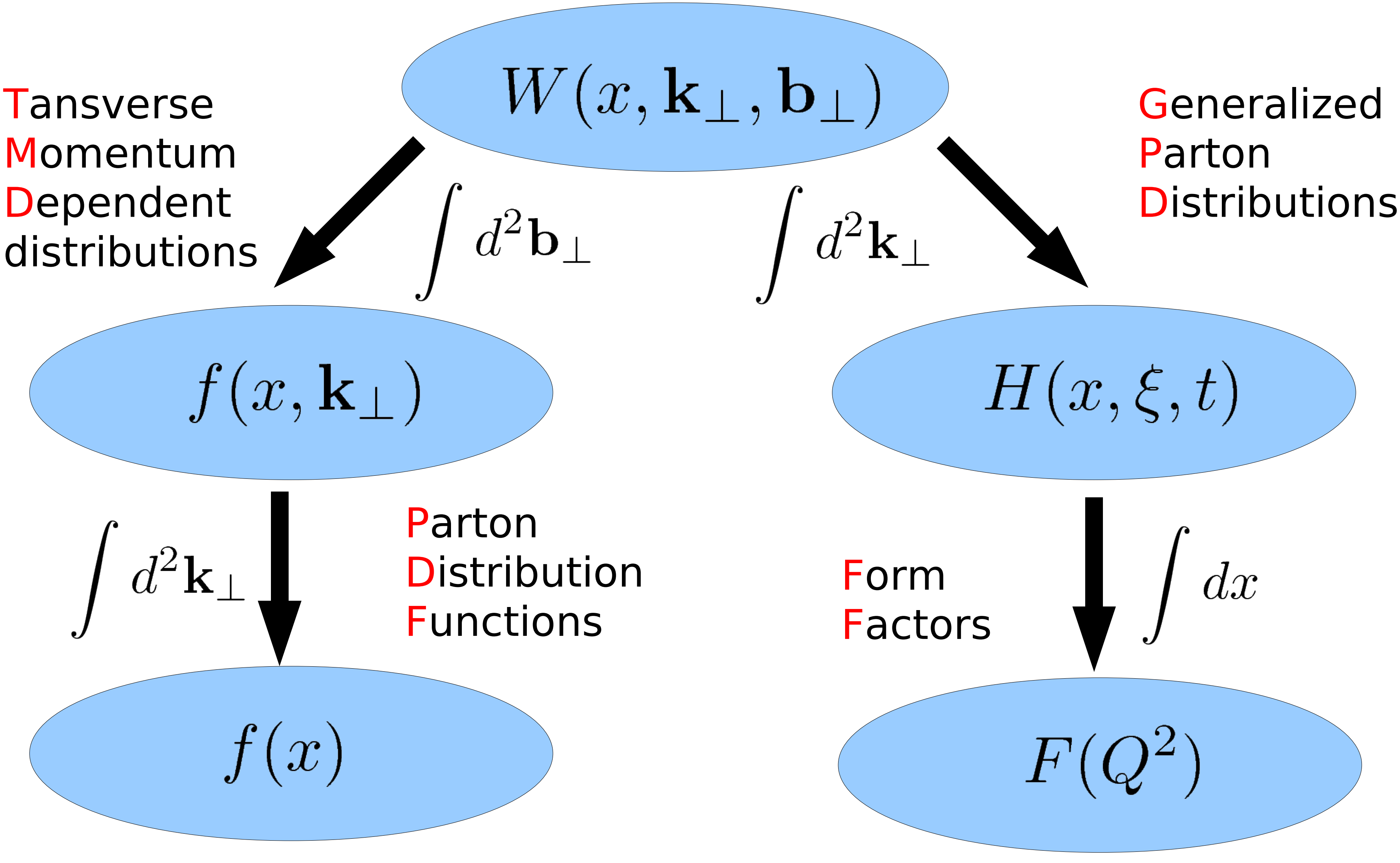
Changing x we probe different aspects of nucleon wave function

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 into Generalised Parton Distributions and Transverse Momentum Dependent distributions
See talks by Christian Weiss, Jianwei Qiu, Marc Schlegel, ...

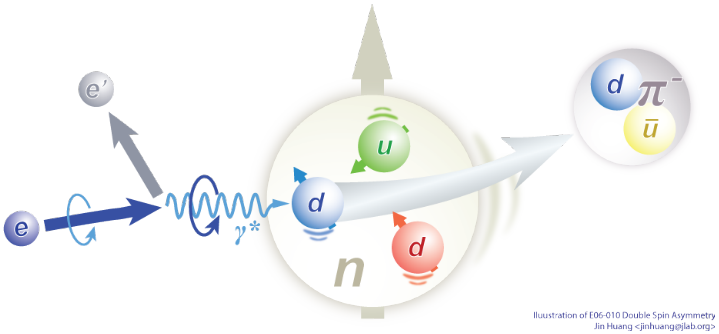
These distributions are also referred to as 3D (three-dimensional) distributions

Wigner distribution



Transverse Momentum Dependent distributions

SIDIS



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

If produced hadron has low transverse momentum

$$P_{hT} \sim \Lambda_{QCD} << Q$$

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

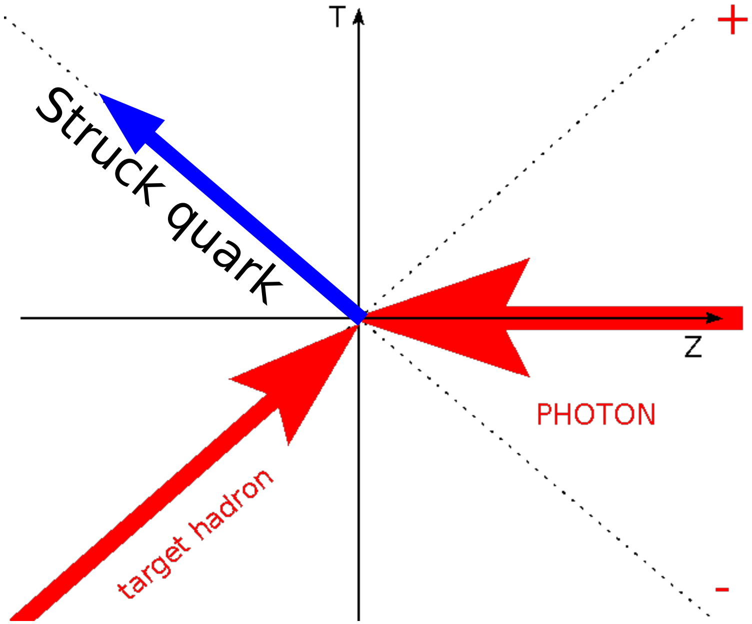
TMD factorization proven in QCD
Ji, Ma, Yuan (2002)
Collins (2011)

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

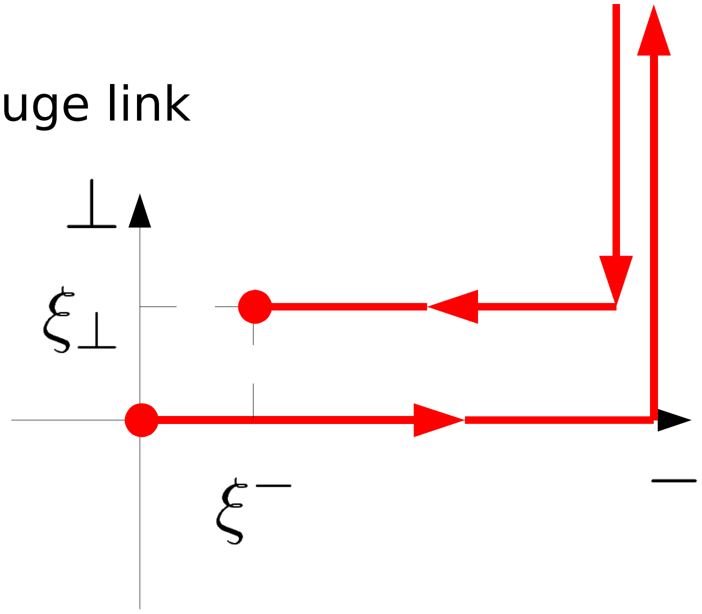
Transverse Momentum Dependent distributions

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

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

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 aspects of partonic structure

Each function is to be studied

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

Correlation of transverse quark motion and the nucleon spin – Sivers function

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

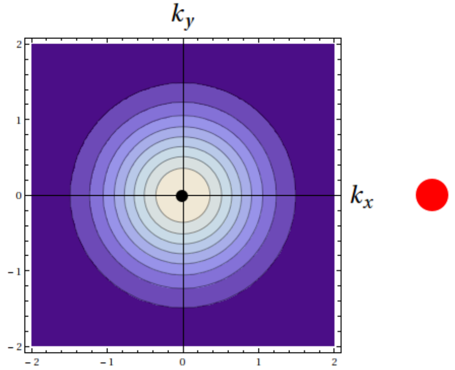
This function gives access to 3D imaging

Spin-orbit correlation

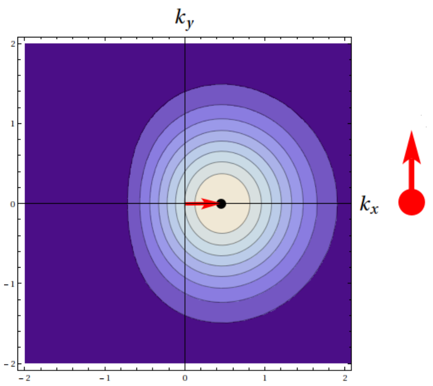
Physics of gauge links is represented

Requires Orbital Angular Momentum

No polarisation:



Polarisation:



EIC report, Boer, Diehl, Milner, Venugopalan,Vogelsang et al , 2011;
Duke workshop report: Anselmino et al Eur.Phys.J.A47:35,2011
EIC Whitepaper

What do we know about ~~TMDs~~

Sivers function

HERMES, COMPASS, RHIC, BELLE, BABAR and JLab
are sources of experimental information for TMD physics

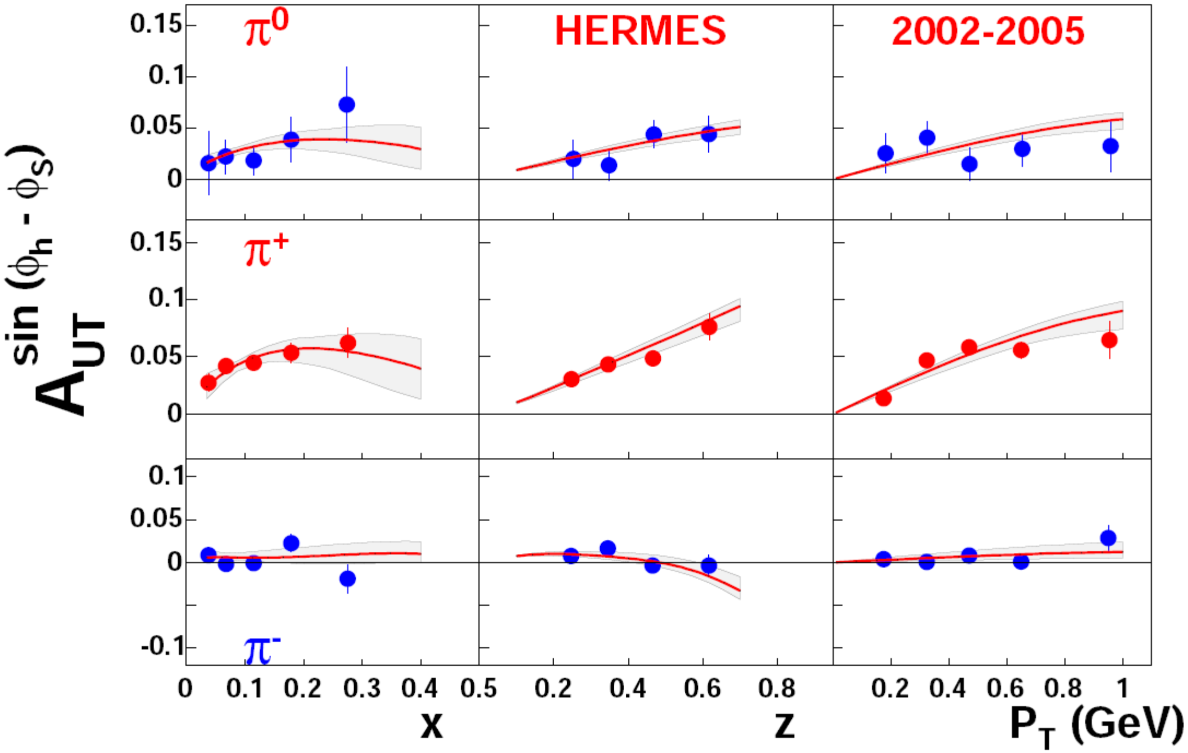
Hundreds of experimental points on Sivers function

There exists a number of extractions

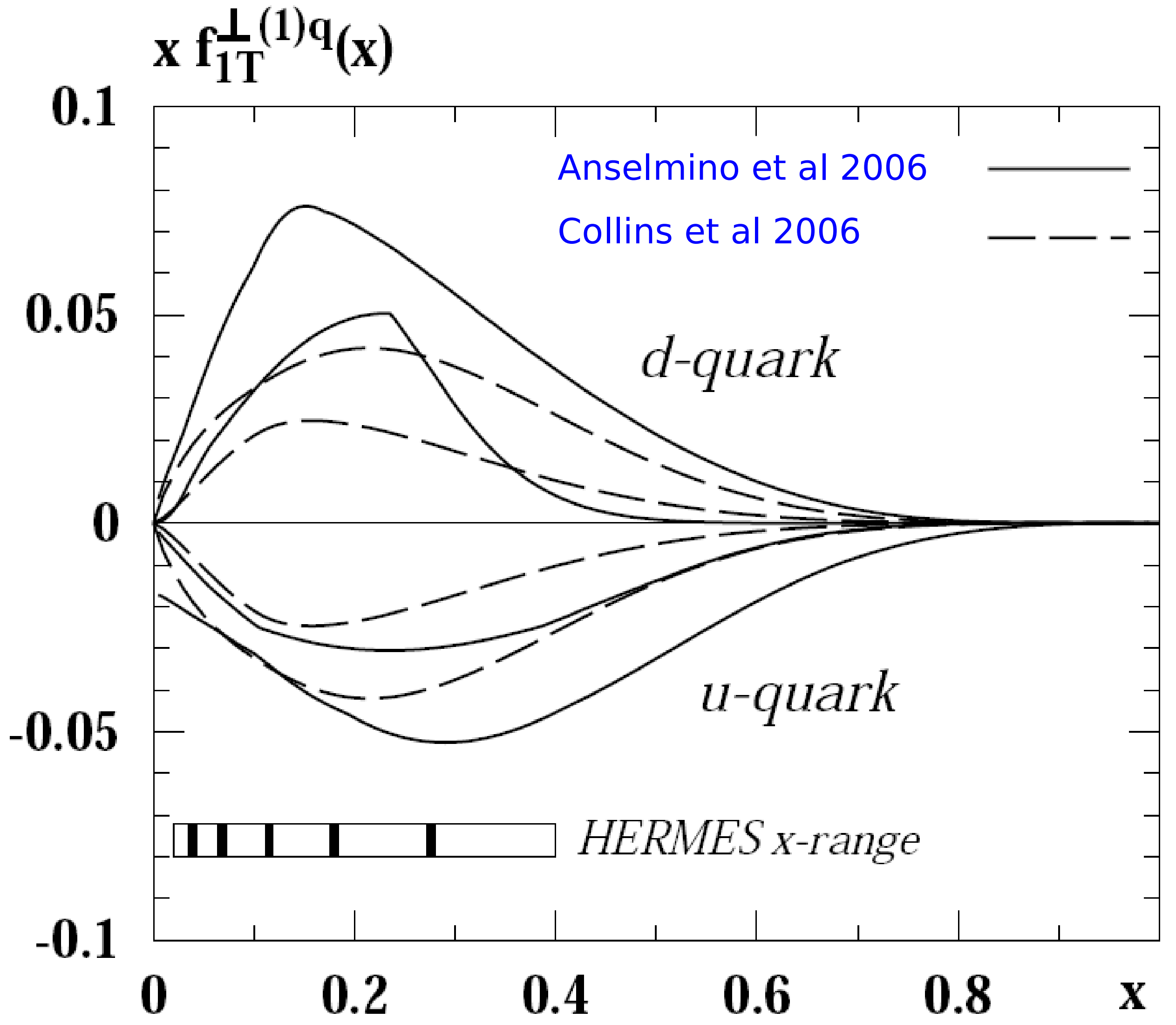
HERMES 02 -
COMPASS 04 -
JLAB 11 -

Vogelsang, Yuan 05
Collins et al 06
Anselmino et al 06-09
Bacchetta, Radici 11

Anselmino et al 2009

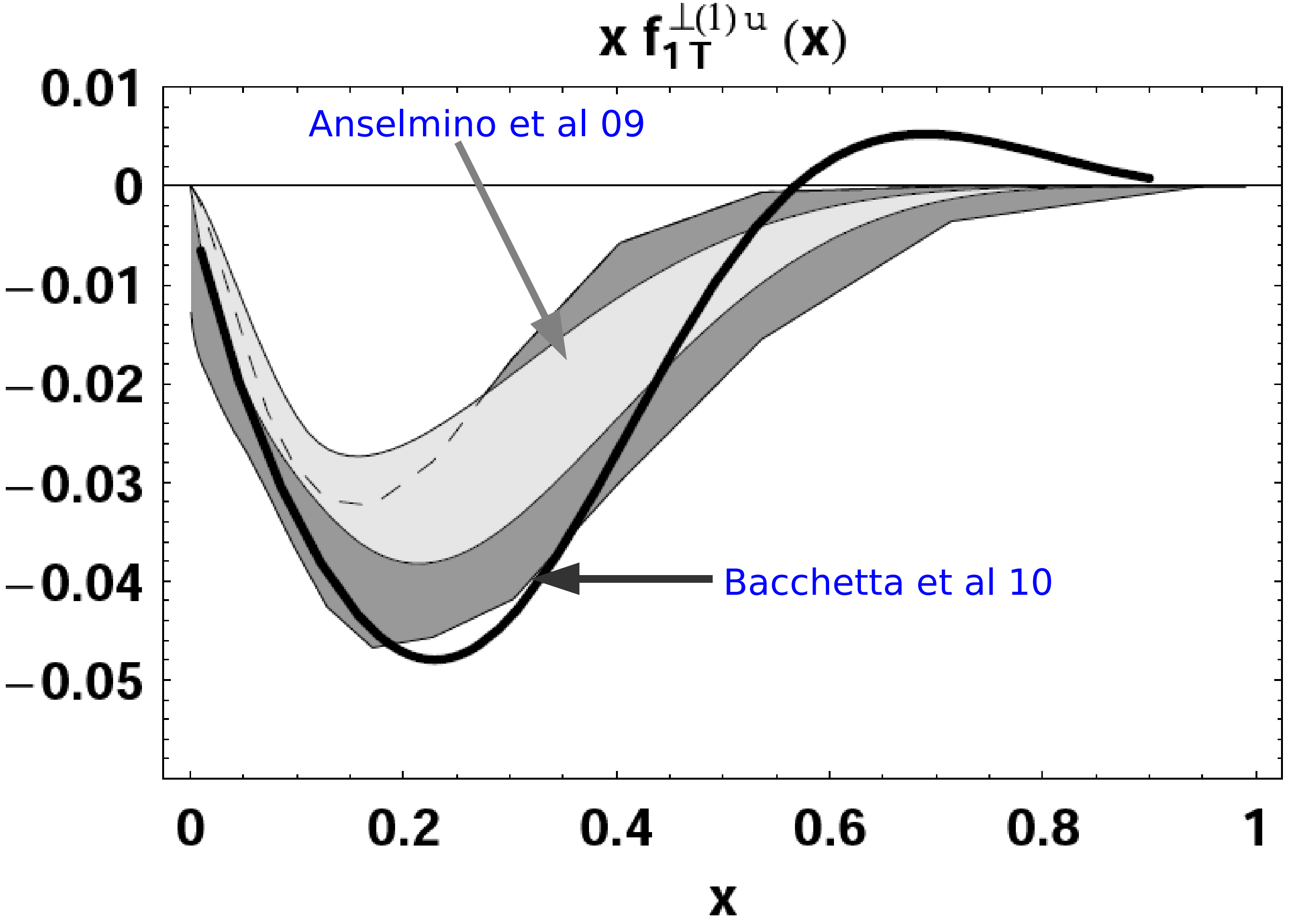


Extractions compare well with each other



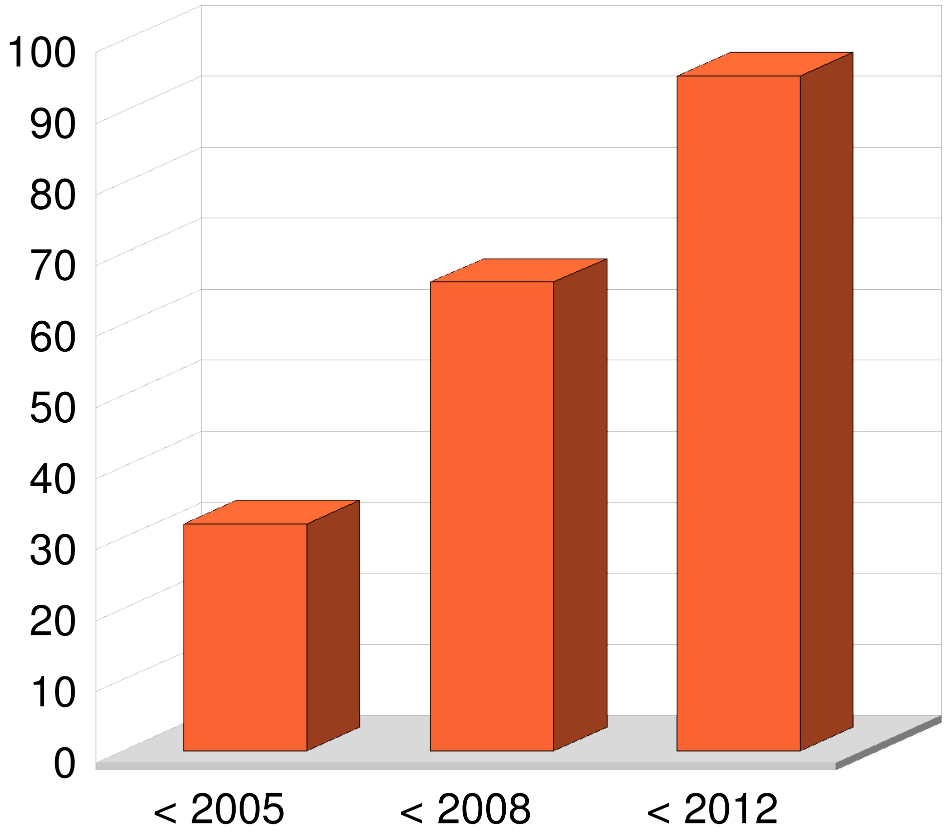
Extractions compare well with models

MIT bag model	Yuan 03
Quark-diquark model	Gamberg, Goldstein, Schlegel 08
LCWF	Yuan, Pasquini 10
Quark-diquark model	Bacchetta et al 10
MIT bag model	Avakian et al 10 etc



Steady growth of interest

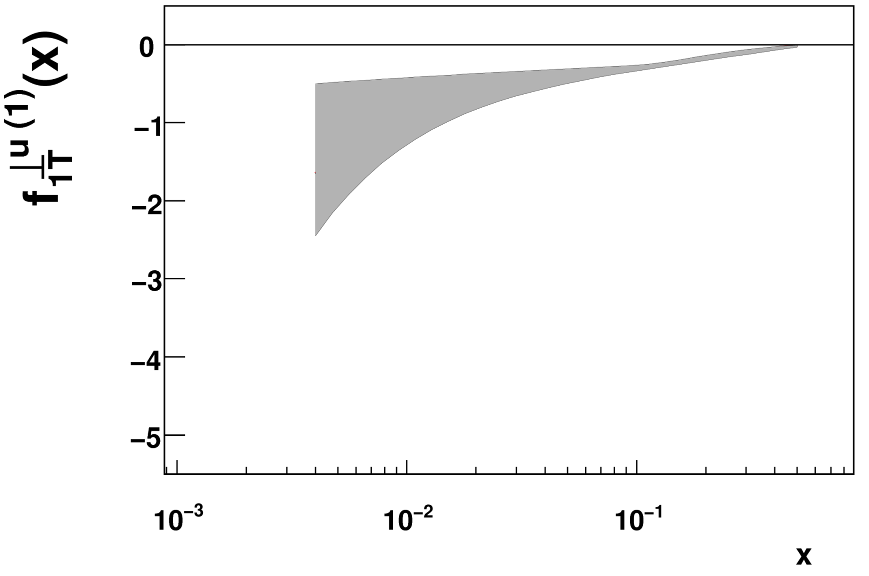
Title "Sivers"
in the literature



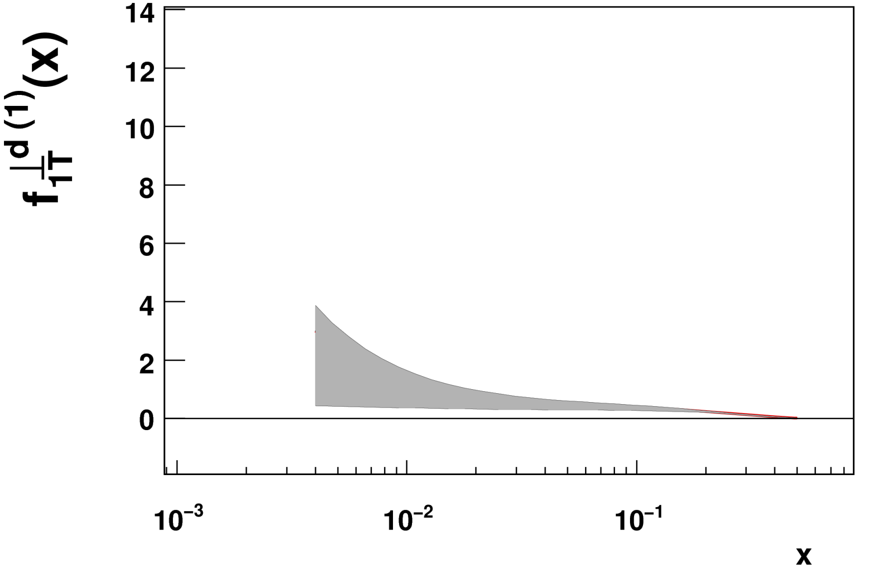
Estimate of current uncertainty

Based on Anselmino et al 09

Up quark

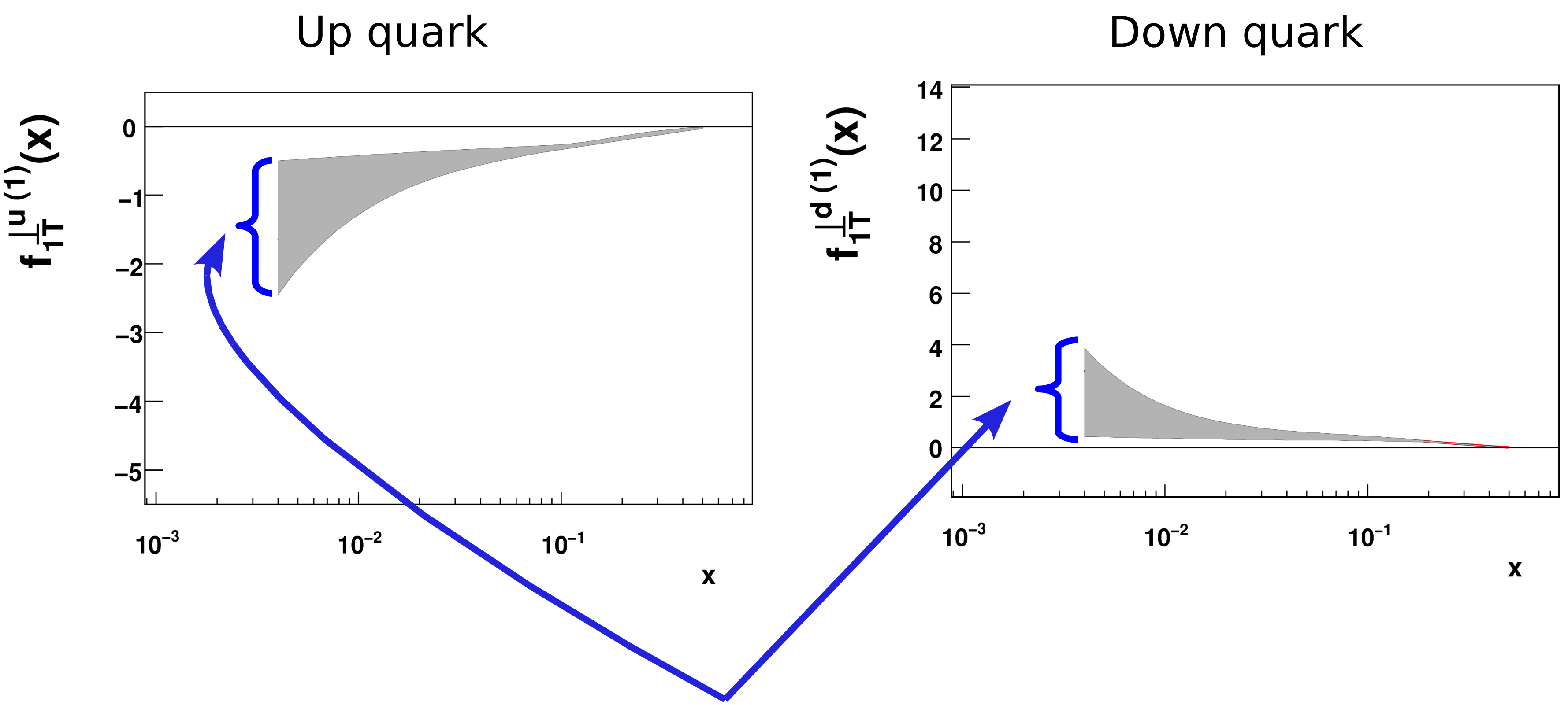


Down quark



Estimate of current uncertainty

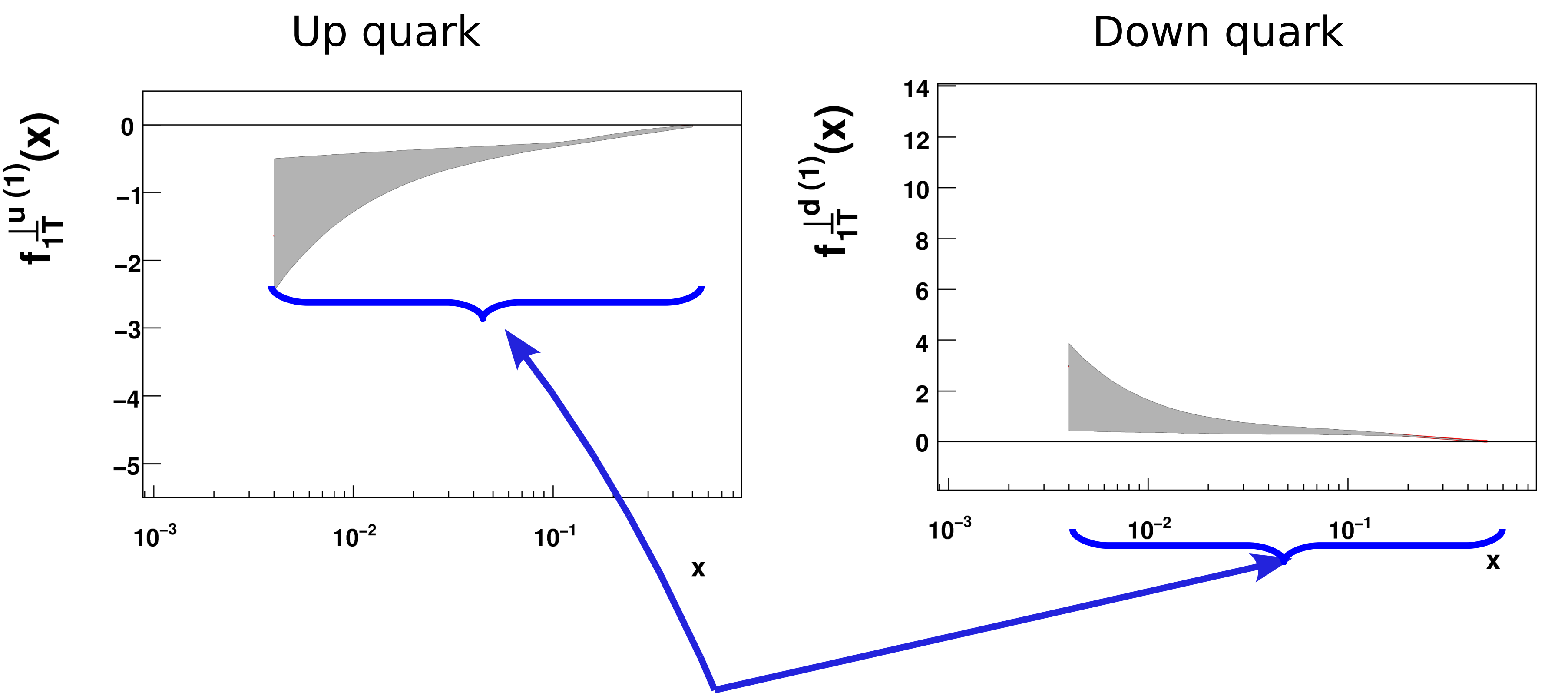
Based on Anselmino et al 09



Current uncertainty in low x region

Estimate of current uncertainty

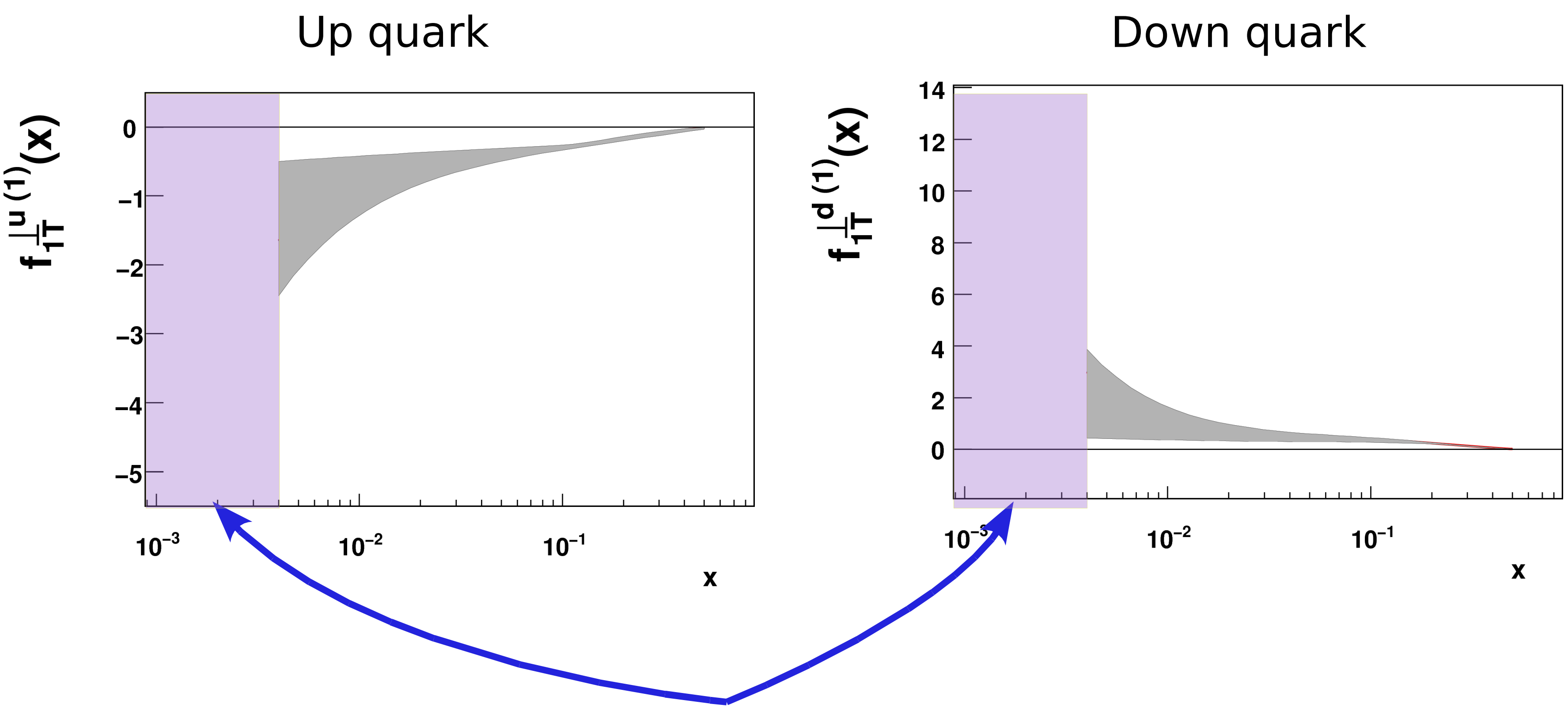
Based on Anselmino et al 09



Region of x covered by existing data

Estimate of current uncertainty

Based on Anselmino et al 09

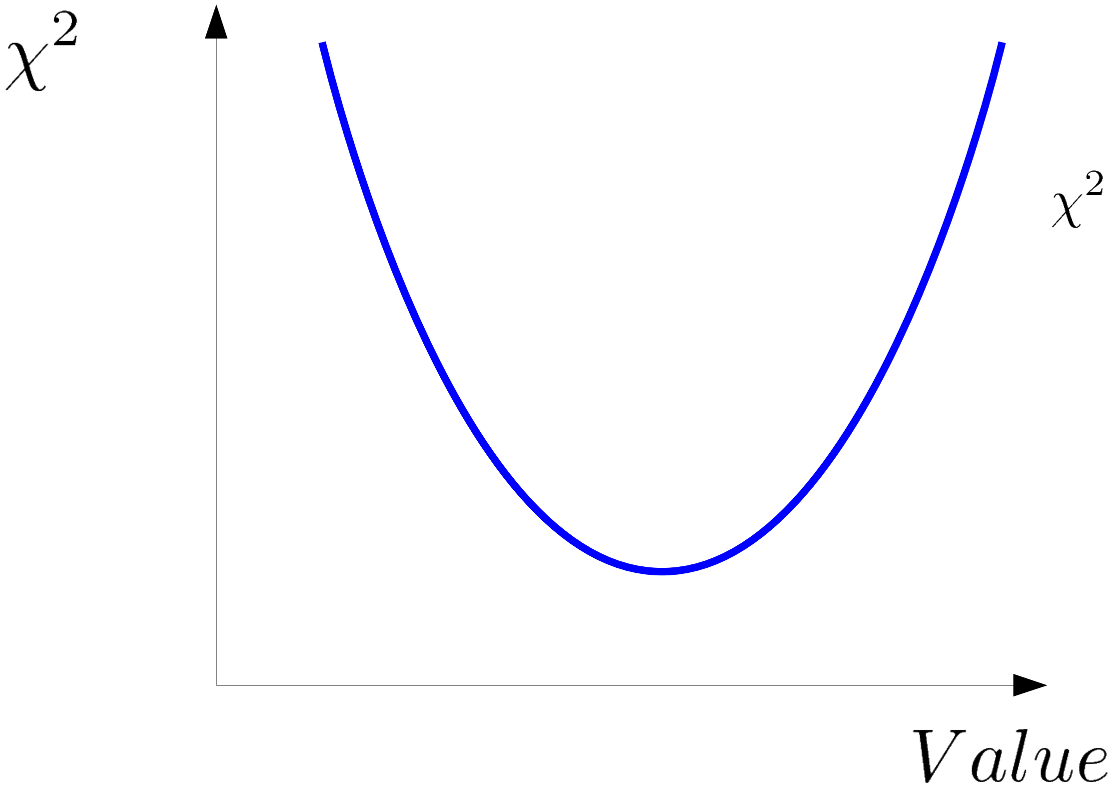


EIC can reach here

Estimate of current uncertainty

Based on Anselmino et al 09

Estimate of uncertainty is based on Monte Carlo method

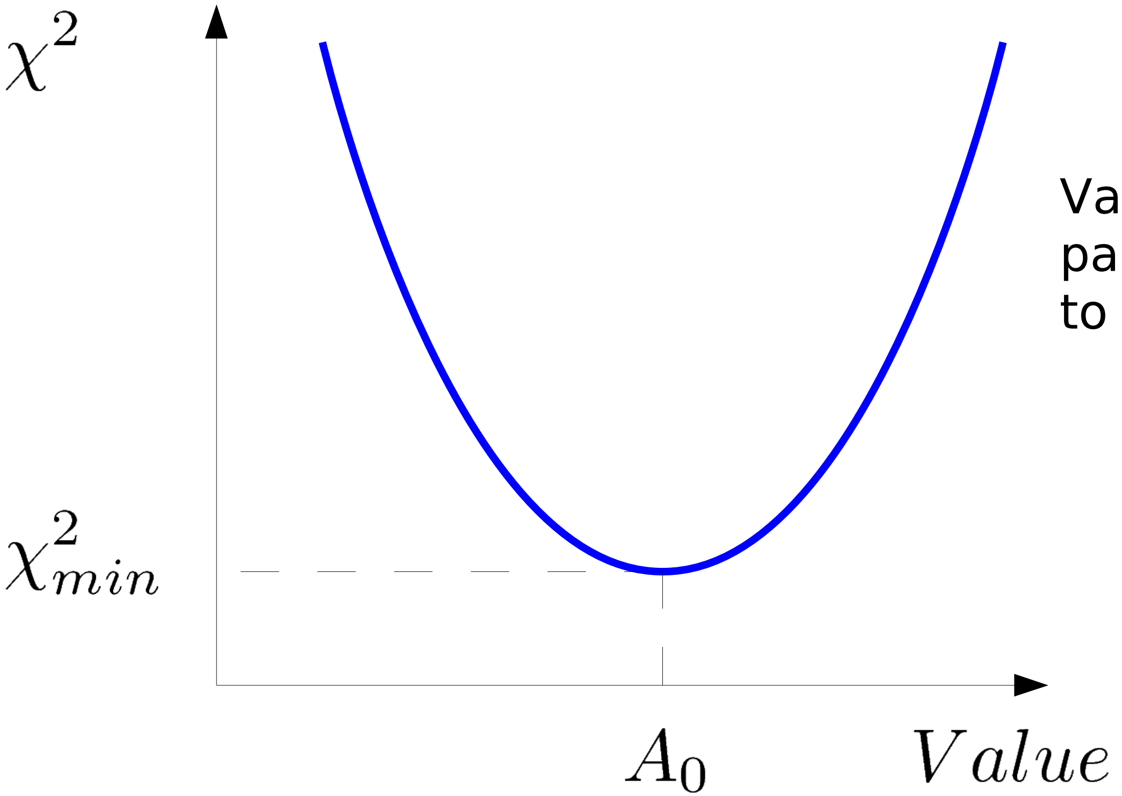


$$\chi^2 = \sum_{n=1}^{N_{tot}} \left(\frac{\sigma_n^{theor} - \sigma_n^{exp}}{\Delta \sigma_n^{exp}} \right)^2$$

Estimate of current uncertainty

Based on Anselmino et al 09

Estimate of uncertainty is based on Monte Carlo method

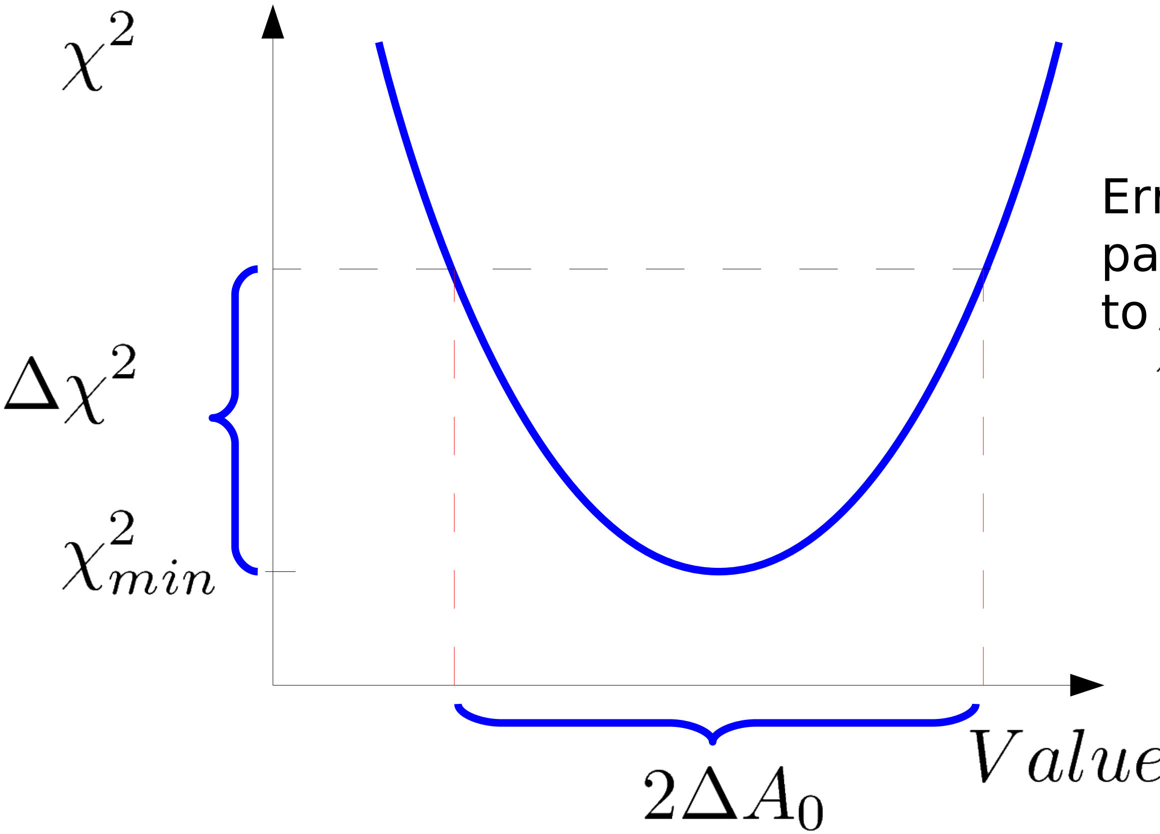


Value A_0 of parameter corresponds to the minimum of χ^2

Estimate of current uncertainty

Based on Anselmino et al 09

Estimate of uncertainty is based on Monte Carlo method

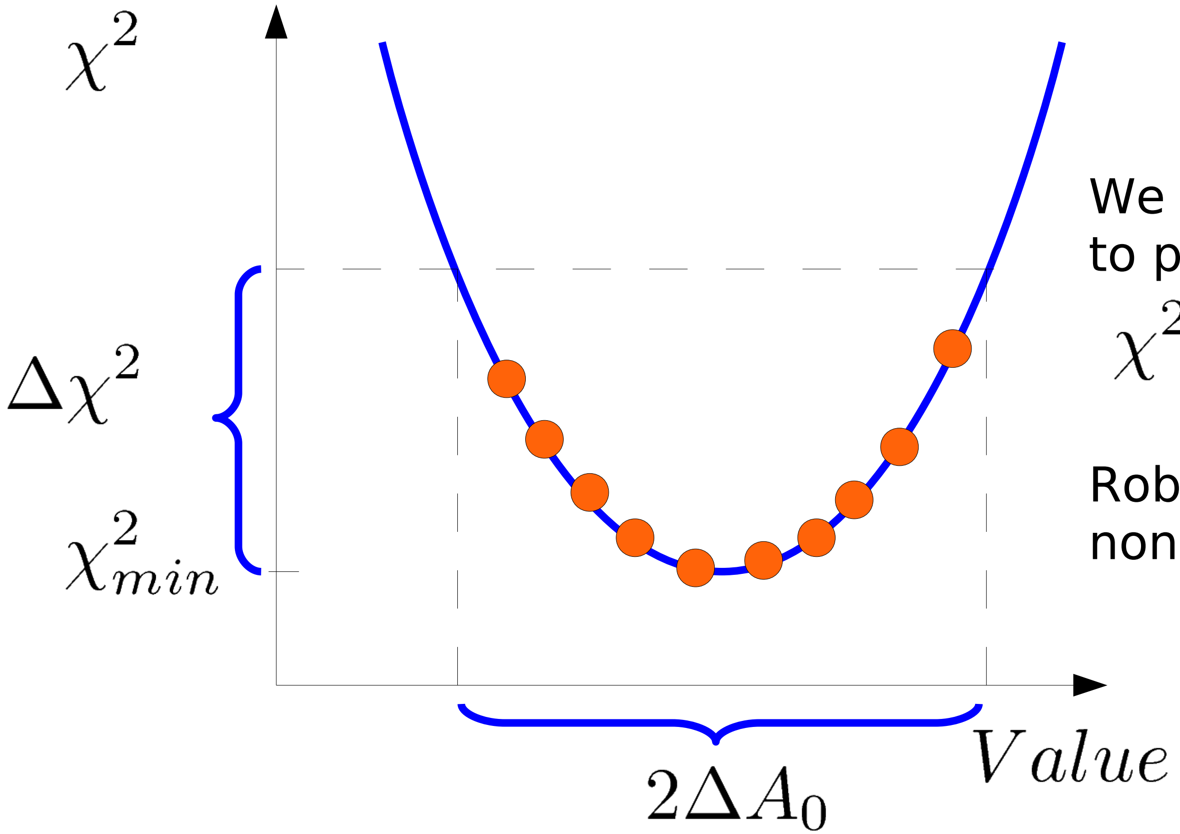


Error ΔA_0 of parameter corresponds to $\chi^2 = \chi^2_{min} + \Delta\chi^2$

Estimate of current uncertainty

Based on Anselmino et al 09

Estimate of uncertainty is based on Monte Carlo method



We use Monte Carlo to populate

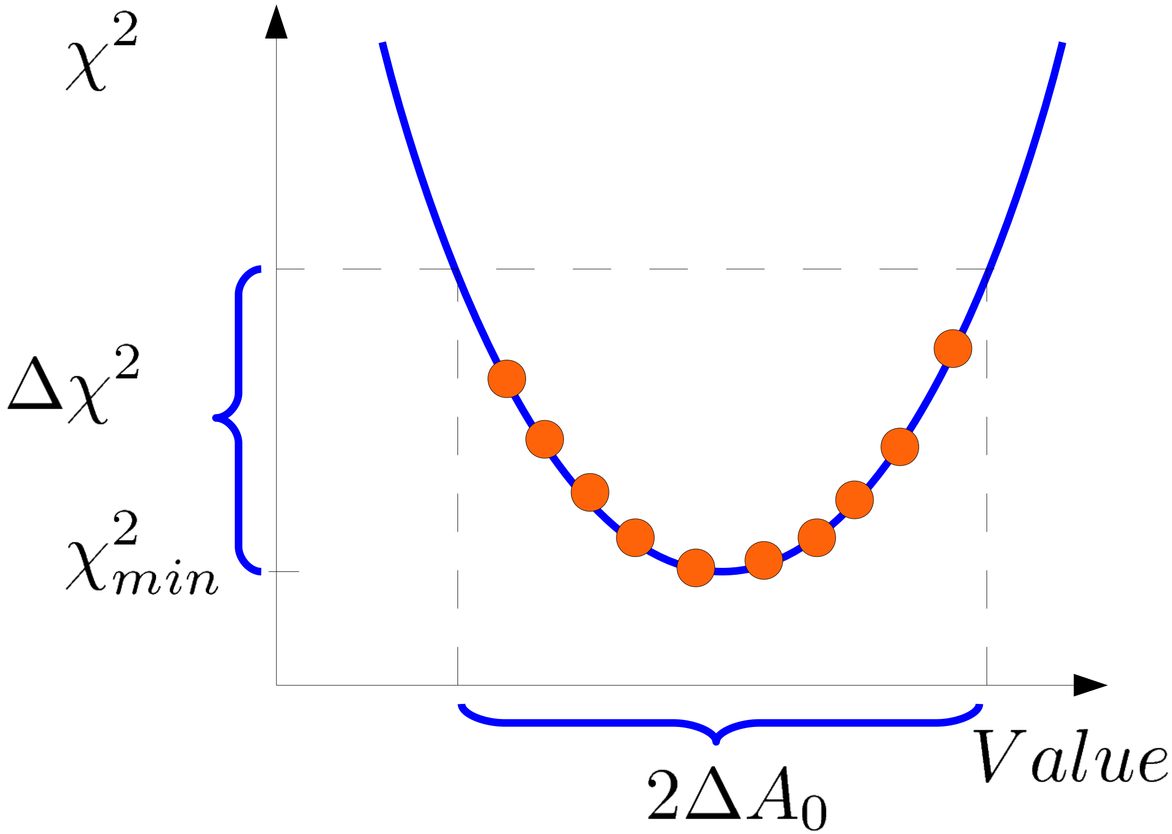
$$\chi^2 = \chi^2_{min} + \Delta\chi^2$$

Robust in case of non symmetric errors

Estimate of current uncertainty

Based on Anselmino et al 09

Estimate of uncertainty is based on Monte Carlo method



Choice of $\Delta\chi^2$ is important

$$\Delta\chi^2 = 1$$

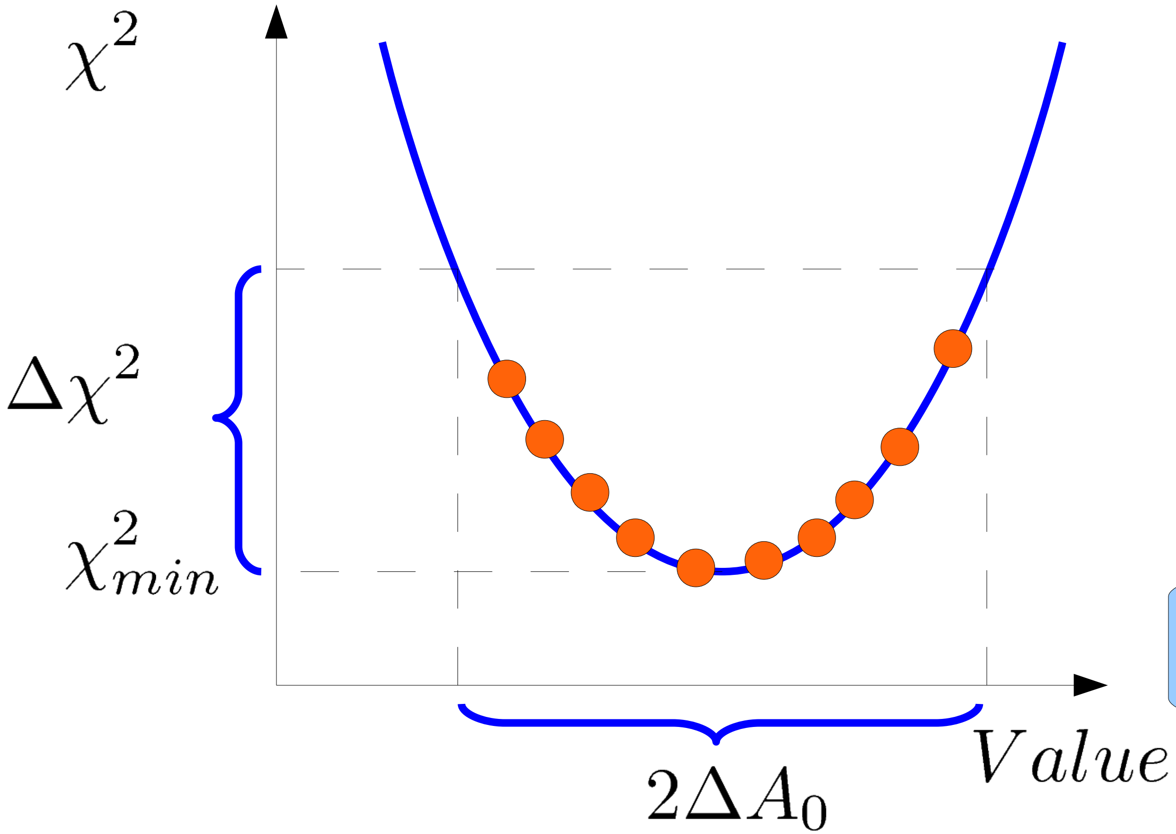
$$\Delta\chi^2 = 3\%\chi^2$$

$$\Delta\chi^2 = f(N_{par})$$

Estimate of current uncertainty

Based on Anselmino et al 09

Estimate of uncertainty is based on Monte Carlo method



Choice of $\Delta\chi^2$ is important

$\Delta\chi^2 = 1$

$\Delta\chi^2 = 3\%\chi^2$

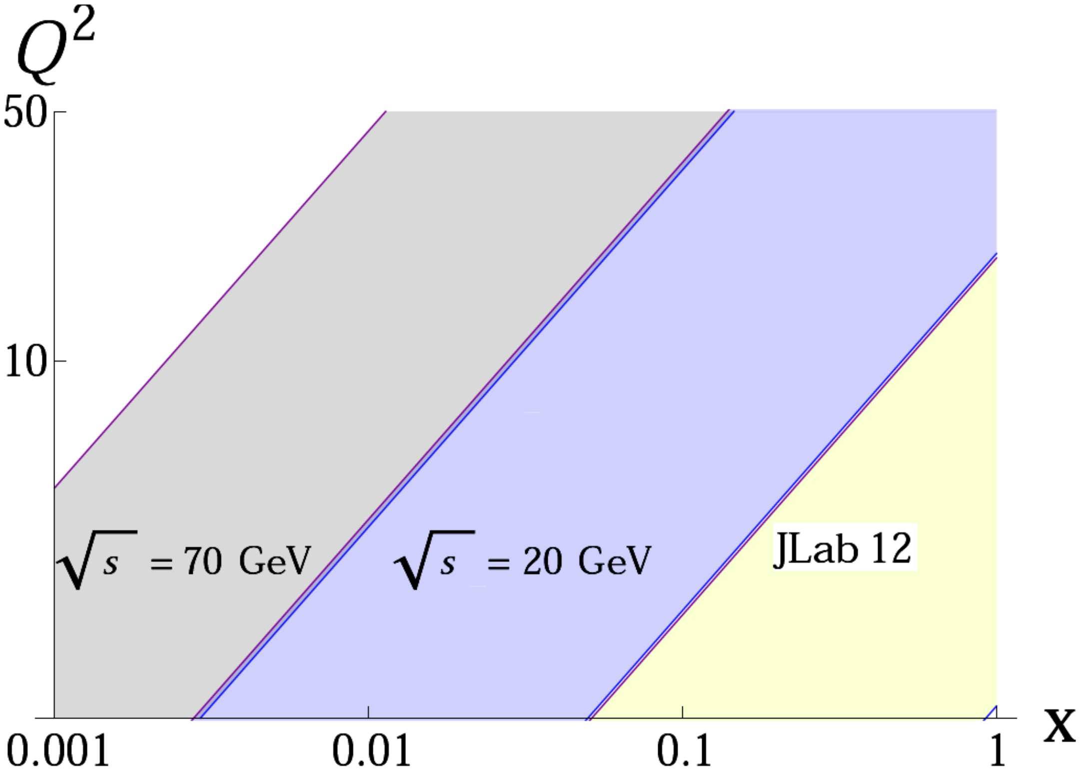
$\Delta\chi^2 = f(N_{par})$

Anselmino et al 09

What do we expect from EIC?

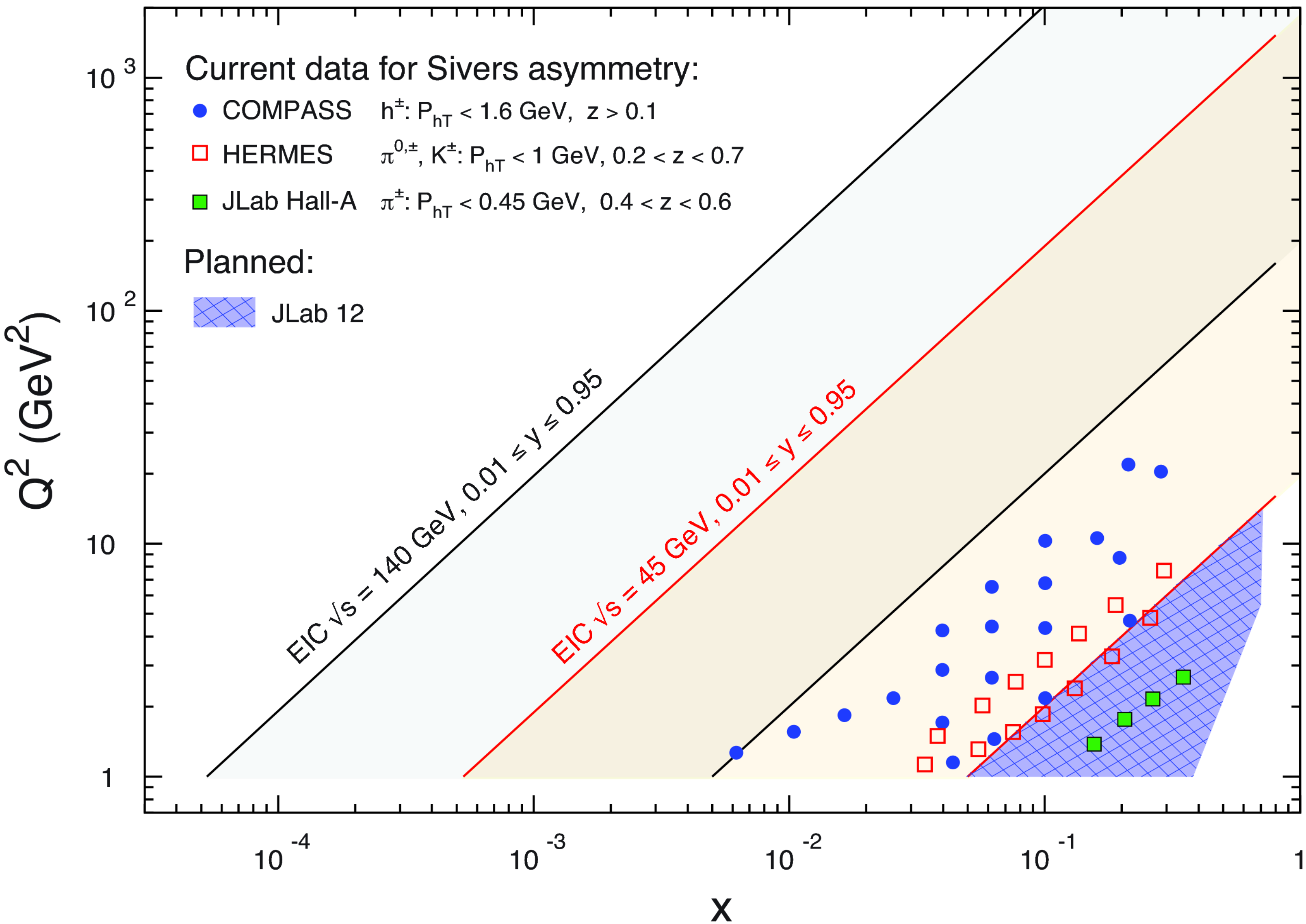
Kinematics

Kinematics $Q^2 \simeq sxy$



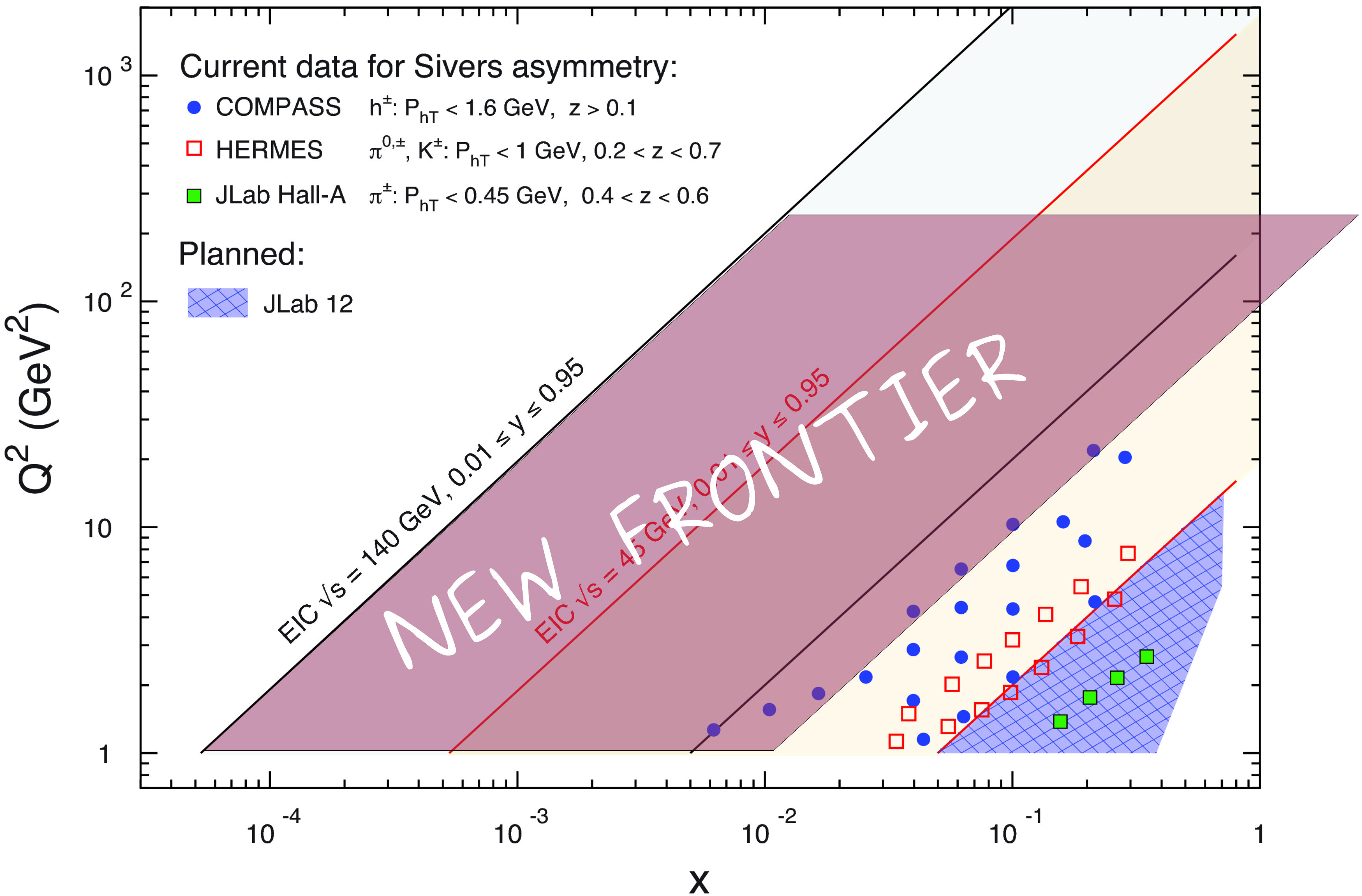
JLab 12 and future Electron Ion Collider are complimentary

Kinematics and existing data



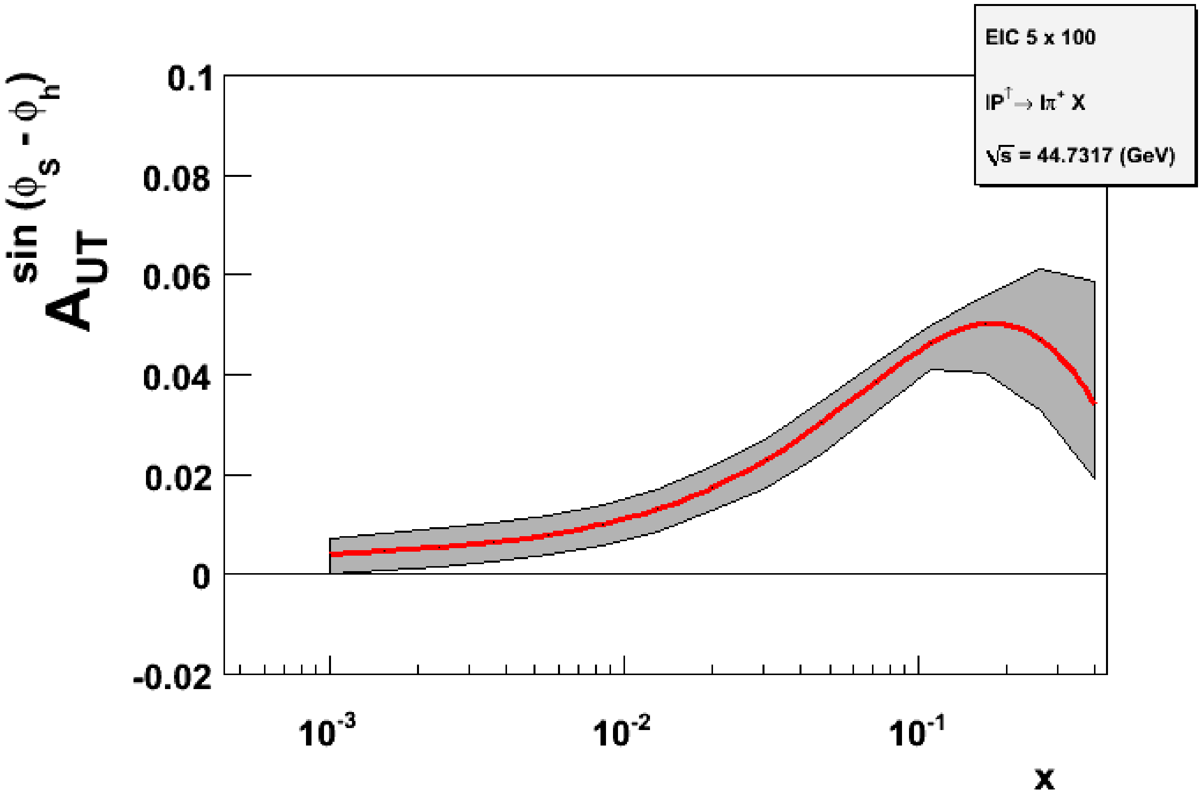
Alexei Prokudin

Kinematics and existing data



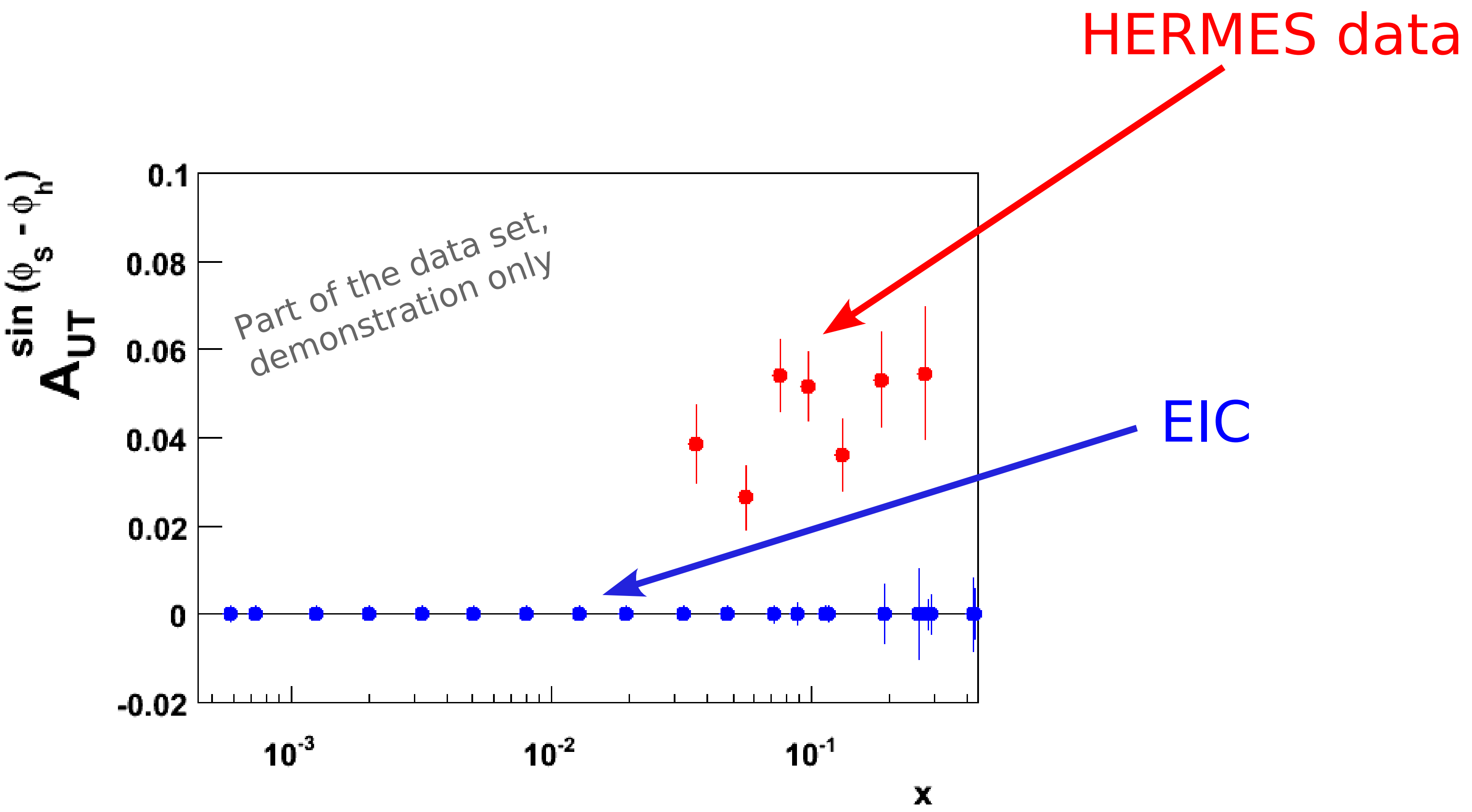
Alexei Prokudin

What do we expect at EIC?



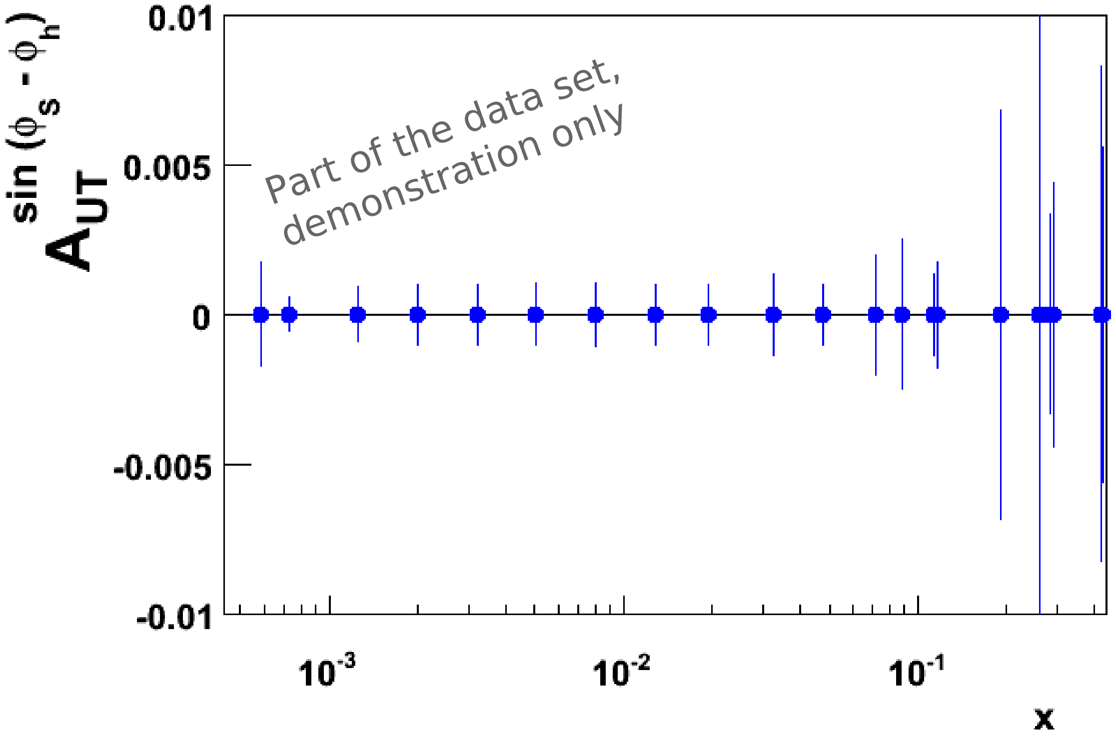
Prediction for EIC 5x100 kinematics based on Anselmino et al 09

What do we expect at EIC?



Estimates of experimental error for EIC at 10/fb

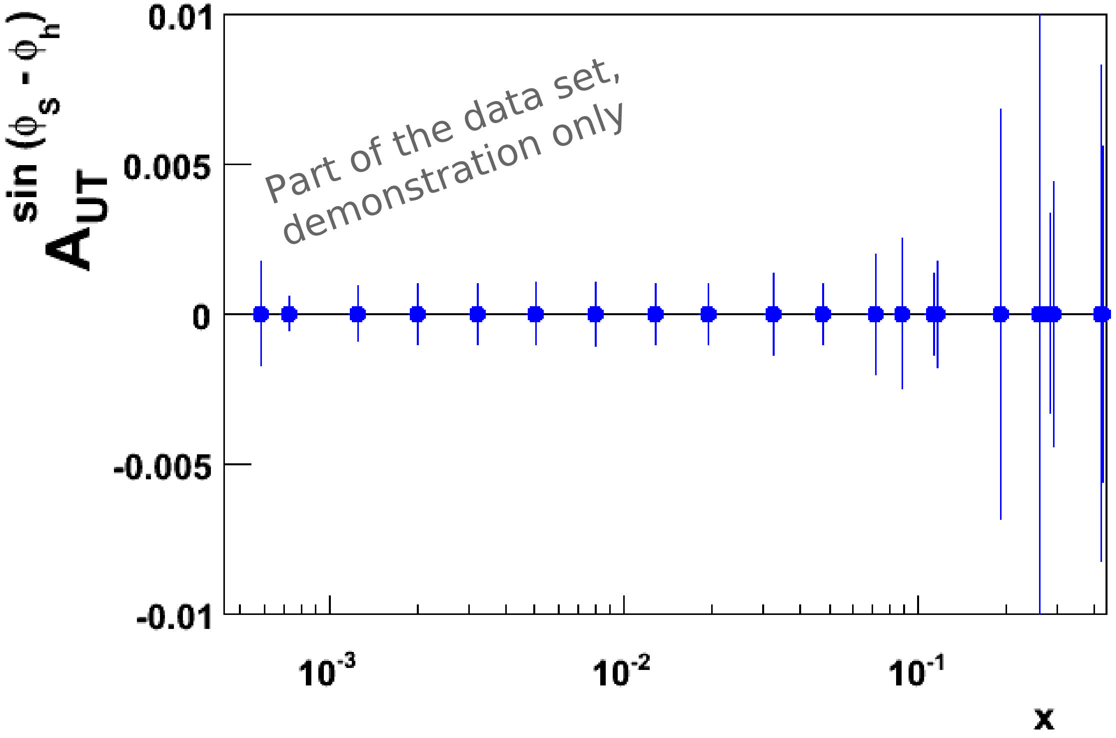
What do we expect at EIC?



Very small error in low-x region

Estimates of experimental error for EIC at 10/fb

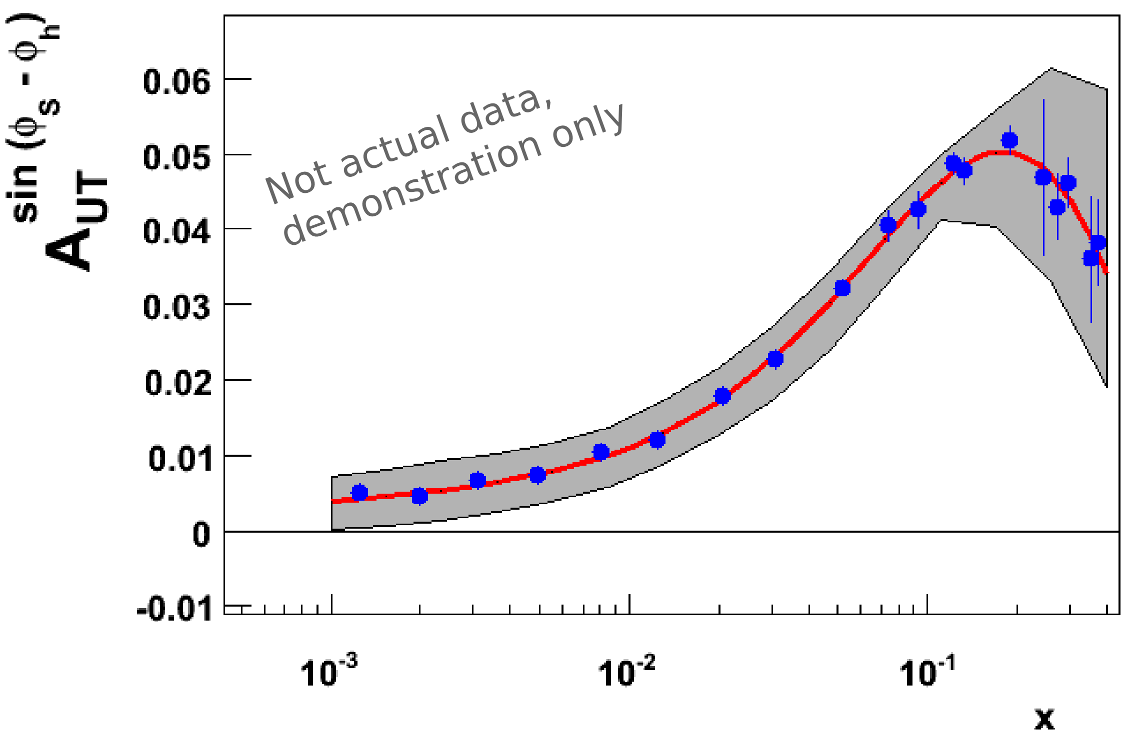
Generate pseudo-data



Generate pseudodata around our predictions

Estimates of experimental error for EIC at 10/fb

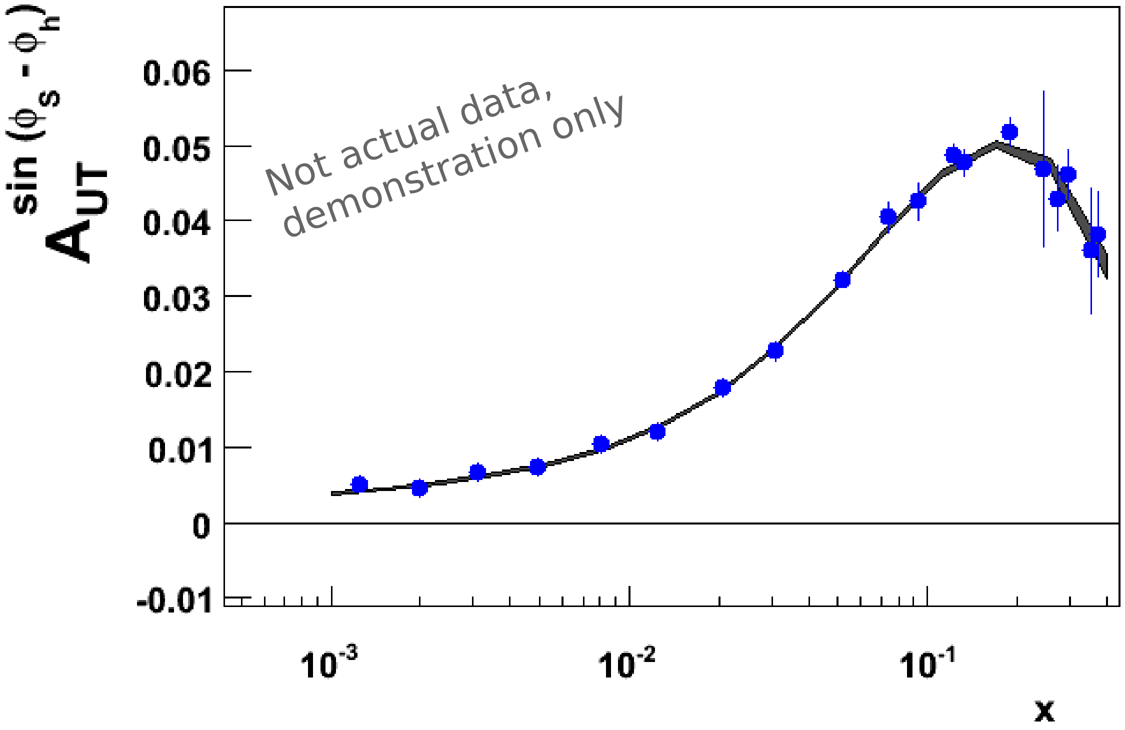
Generate pseudo-data



Generate
pseudodata
1-σ around our
predictions

Based on Anselmino et al 09

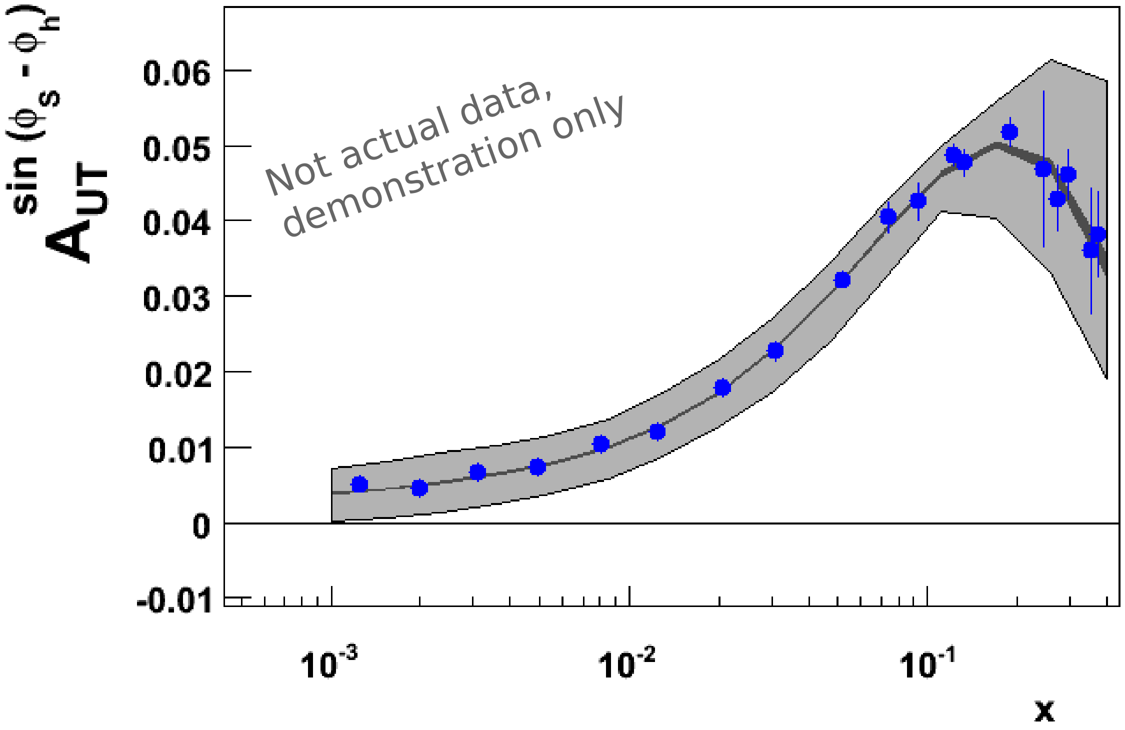
Fit the pseudo-data



Fit the pseudodata and estimate the error

Based on Anselmino et al 09

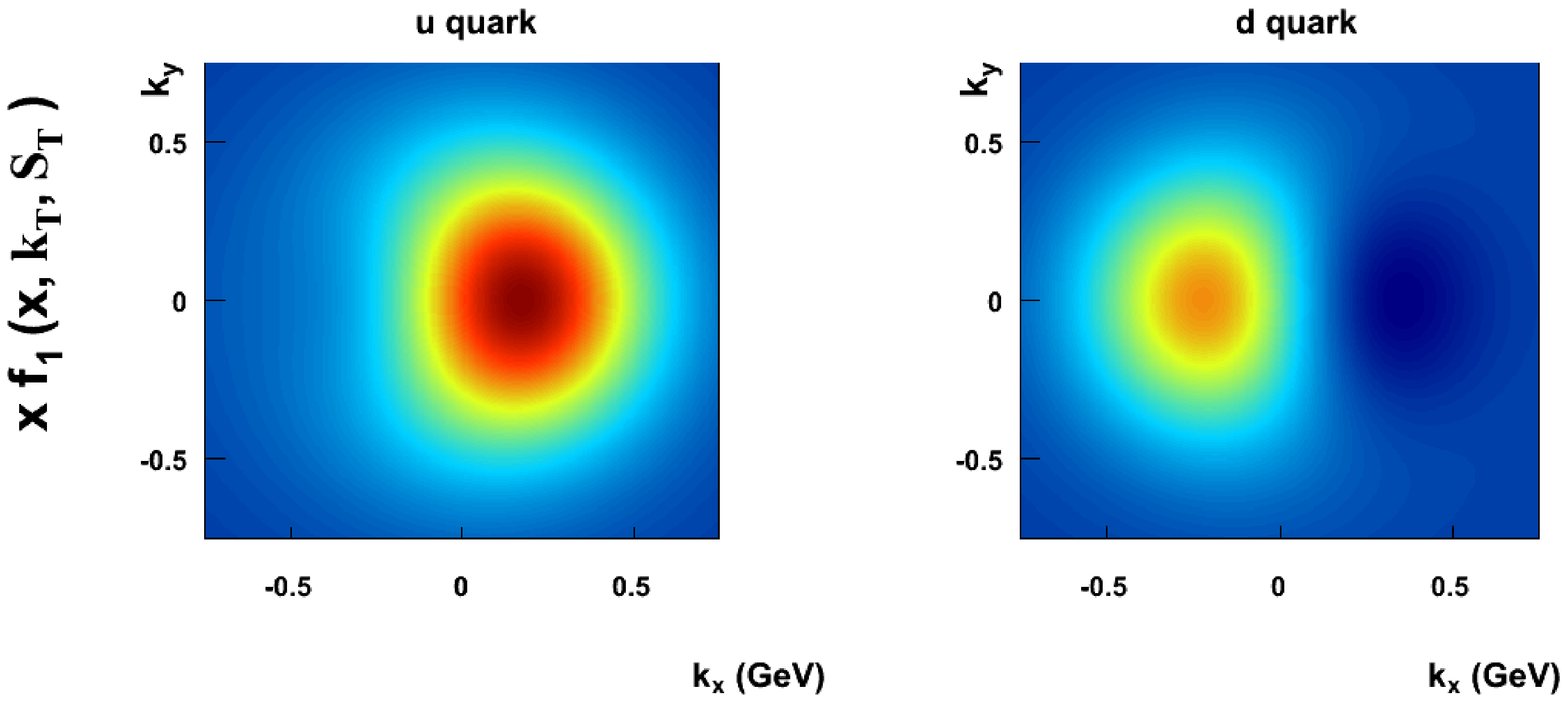
Generate pseudo-data



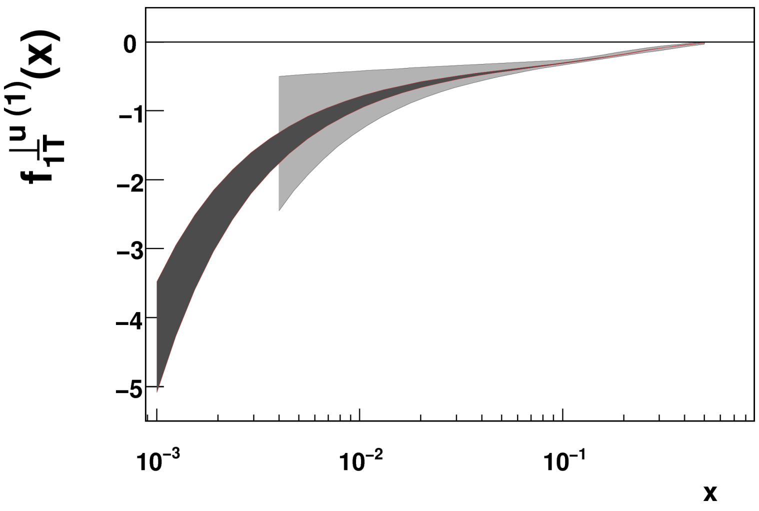
Compare the error to the existing one

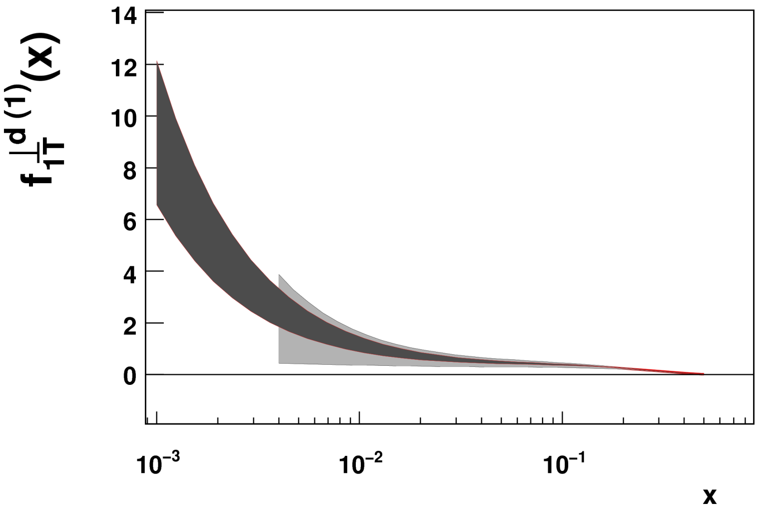
Based on Anselmino et al 09

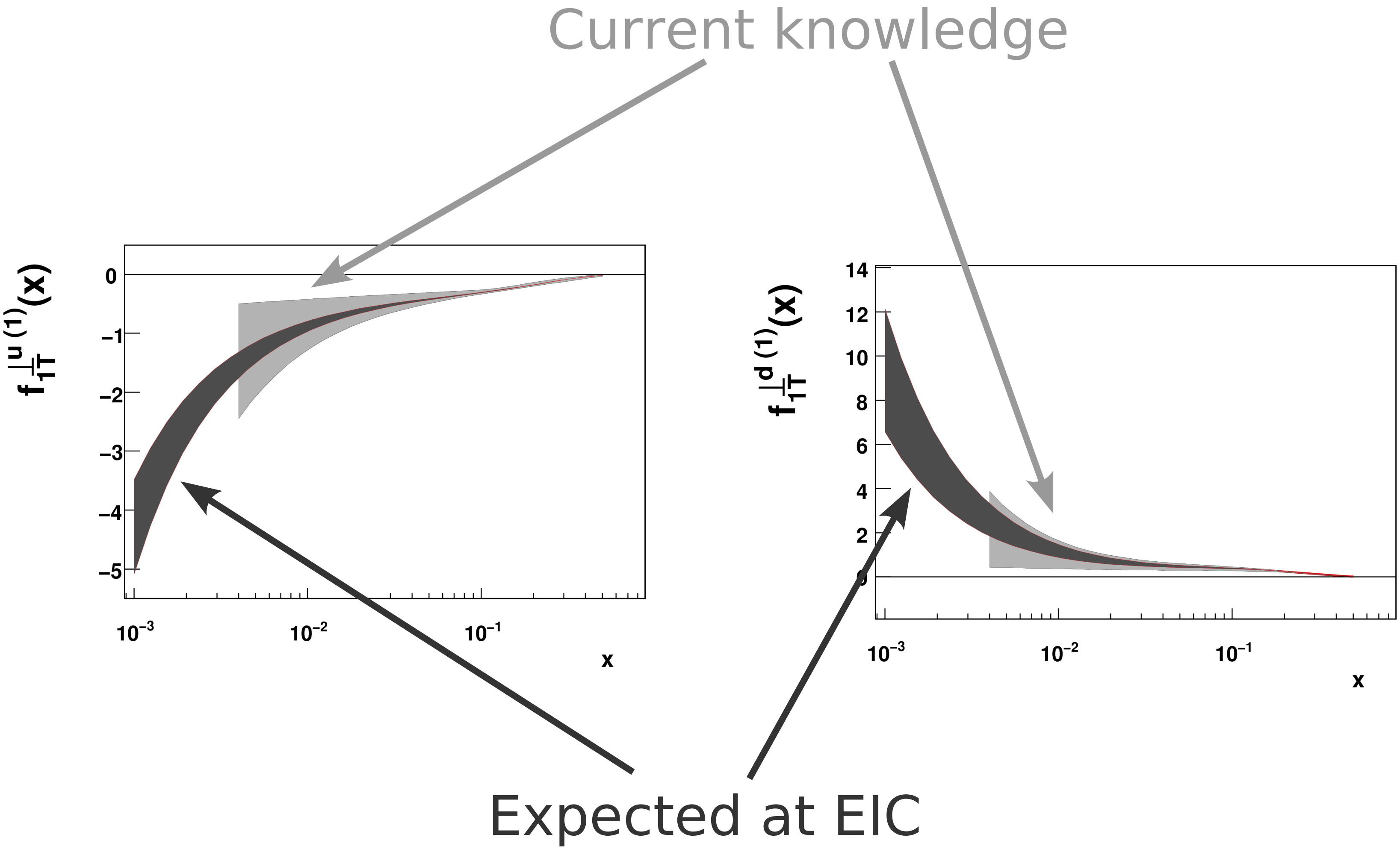
Tomographic scan of the nucleon



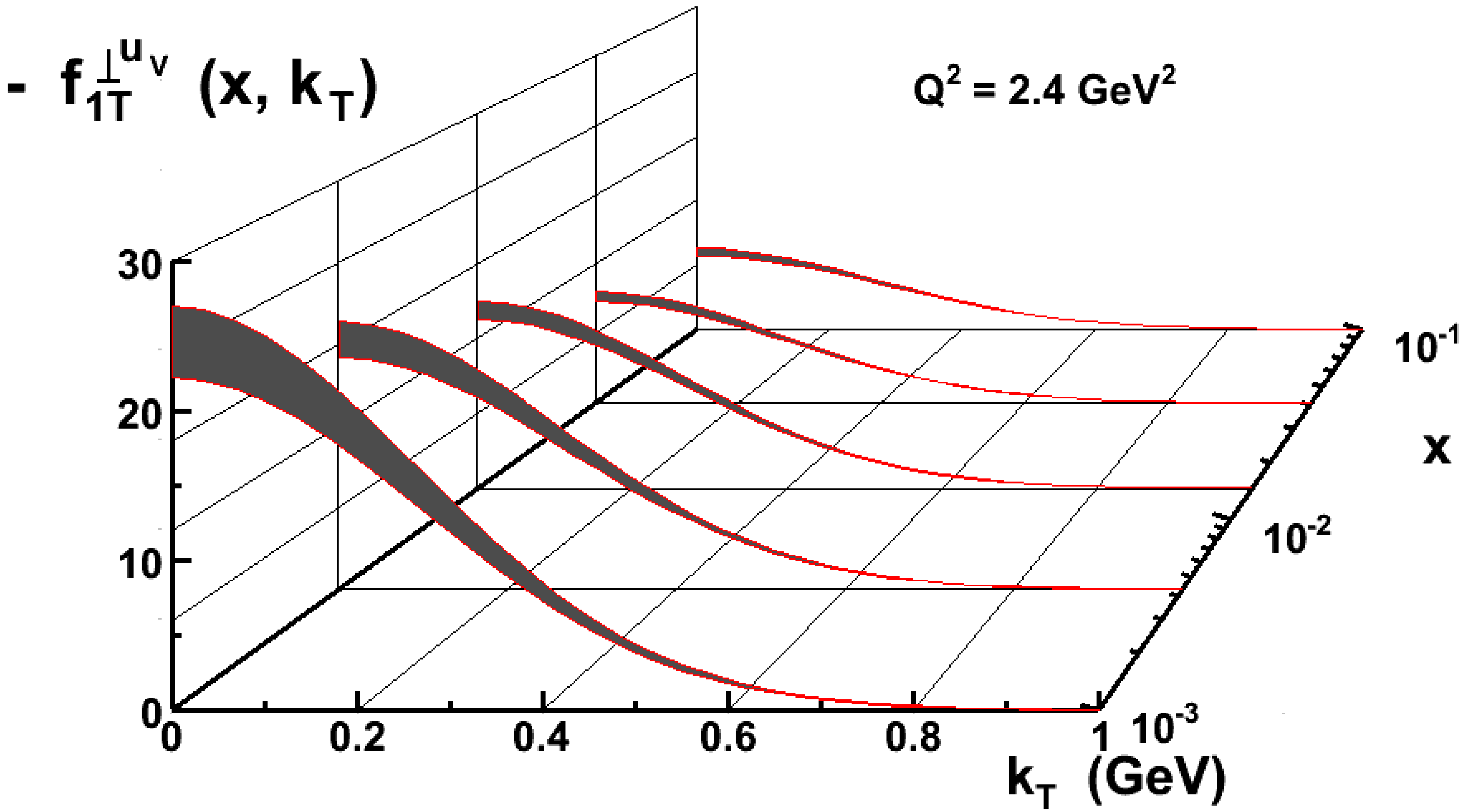
Results


$f_{1T}^{\perp u\,(1)}(x)$
0
−1
−2
−3
−4
−5
10^{-3}
10^{-2}
10^{-1}
x


$f_{1T}^{\perp d\,(1)}(x)$
14
12
10
8
6
4
2
0
10^{-3}
10^{-2}
10^{-1}
x

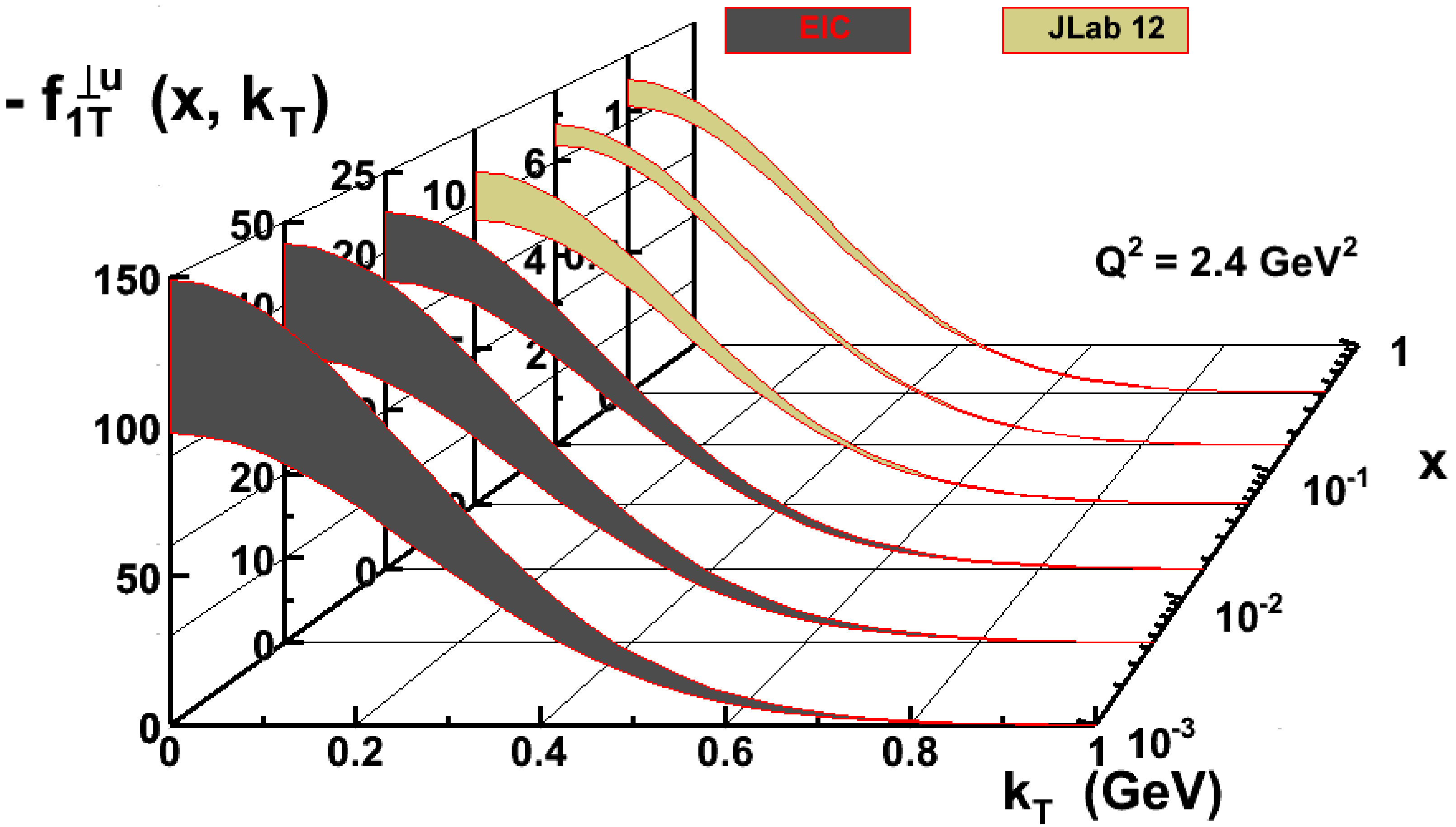

Current knowledge
$f_{1T}^{\perp u\,(1)}(x)$
0
−1
−2
−3
−4
−5
10^{-3}
10^{-2}
10^{-1}
x
$f_{1T}^{\perp d\,(1)}(x)$
14
12
10
8
6
4
2
0
10^{-3}
10^{-2}
10^{-1}
x
Expected at EIC

Results



$- f_{1T}^{\perp u_v}(x, k_T)$
$Q^2 = 2.4\ GeV^2$
30
20
10
0
0
0.2
0.4
0.6
0.8
1
k_T (GeV)
10^{-1}
x
10^{-2}
10^{-3}

Results


EIC
JLab 12
$- f_{1T}^{\perp u}\ (x, k_T)$
$Q^2 = 2.4\ GeV^2$
x
k_T (GeV)
0
0.2
0.4
0.6
0.8
1
10^{-3}
10^{-2}
10^{-1}
1
150
100
50
0
50
20
10
0
25
20
0
10
6
4
2
1

Drawbacks

- The estimate is pure **statistical**
- No control over “**systematical”** theoretical error, such as dependence on functional form, higher twist contributions, evolution etc
- Note that generated pseuododata does not have estimate on **systematical** errors either
- No error propagation due to the use of existing PDFs and FFs (those have substantial uncertainty)
- Given all this one should comment results carefully

Advantages

Conclusions

- The estimate of the error uses **the same** method as the estimate of current error
- Thus the comparison of existing uncertainty and the projected one at EIC is trustworthy
- Some of theoretical uncertainties such as evolution can be controlled
- There is no doubt that EIC precision in TMD measurements is going to be great!

Thanks to
Xin Qian (CALTECH)
Tom Burton (BNL)
Min Huang (JLab)
for their contribution
to the analysis