Open TH questions : Nucleon Structure

Daniel de Florian
Dpto. de Física - FCEyN
Universidad de Buenos Aires

Workshop on Electron-Ion Colliders

Milos, September 27 2009

Departamento de Física Juan José Giambiagi
Facultad de Ciencias Exactas y Naturales Universidad de Buenos Aires

Several aspects of ep/eA colliders

- Precision Physics (QCD)
- Nucleon Structure
- Nuclear Structure

Precision Physics (QCD)

In last 10 years QCD in the precision era : combination of Exp. and TH effort

Why TH effort?

Fixed order expansion $$\sigma = \sigma^{(LO)} + \alpha_s\,\sigma^{(NLO)} + \alpha_s^2\,\sigma^{(NNLO)} + \dots$$

$\alpha_s(Q^2 = 10) \sim 0.2$ Corrections are usually sizable

Renormalization and Factorization introduce dependence on unphysical scales: cancels only to all orders!

QCD calculations produce quantitative predictions from NLO

Standard: NLO 'automatic' and many legs

NNLO available for some processes, more coming very difficult but doable!

Resummation of dominant logs up to NNLL essential in some kinematical regimes

Precise measurements and calculations allow extraction of pdfs

NNLO splitting functions Moch, Vermaseren, Vogt

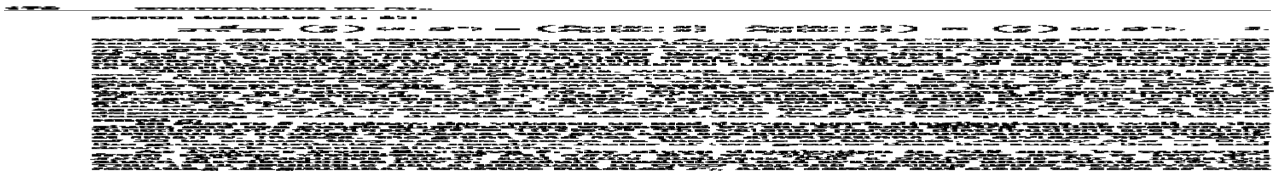
Nucleon Structure

Parton distributions

Probability of finding a parton “a” in the nucleon carrying a momentum fraction “x”

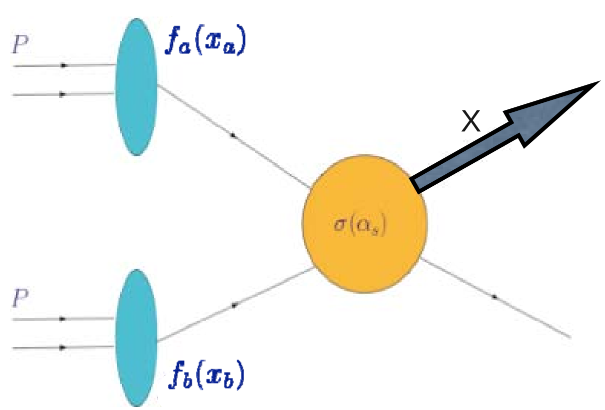
Non-perturbative but UNIVERSAL (factorization)

Scale dependence given by DGLAP equations



i. Main ingredient in the parton model to compute cross-sections

$$d\sigma = \sum_{ab} \int dx_a \int dx_b \, f_a(x_a, Q^2) \, f_b(x_b, Q^2) \times \hat{\sigma}_{ab}(x_a, x_b, Q^2, \alpha_s(Q^2))$$



ii.Direct information on the non-perturbative structure of the nucleon

$$\int_0^1 dx\, x^{n-1} f_a(x,Q^2) \sim < P|O_a^{(n)}|P >$$

codify some information about wave function $|P >$

n=1 : "number" of partons

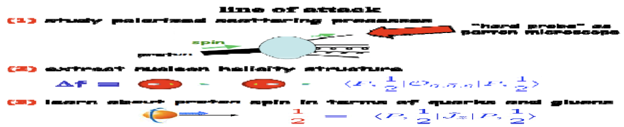
$$\int_0^1 dx\,[u(x,Q^2) - \bar{u}(x,Q^2)] \sim 2 \qquad \int_0^1 dx\,[d(x,Q^2) - \bar{d}(x,Q^2)] \sim 1$$

n=2 : "momentum" of partons

$$\sum_i \int_0^1 dx\; q_i(x,Q^2) \sim \int_0^1 dx\; g(x,Q^2)$$

n=1 polarized : "spin" of partons

$$\Delta f_j(x,Q^2) \equiv f_j^+(x,Q^2) - f_j^-(x,Q^2)$$



$$\sum_i \int_0^1 dx\; \Delta q_i(x,Q^2) \ll 1$$

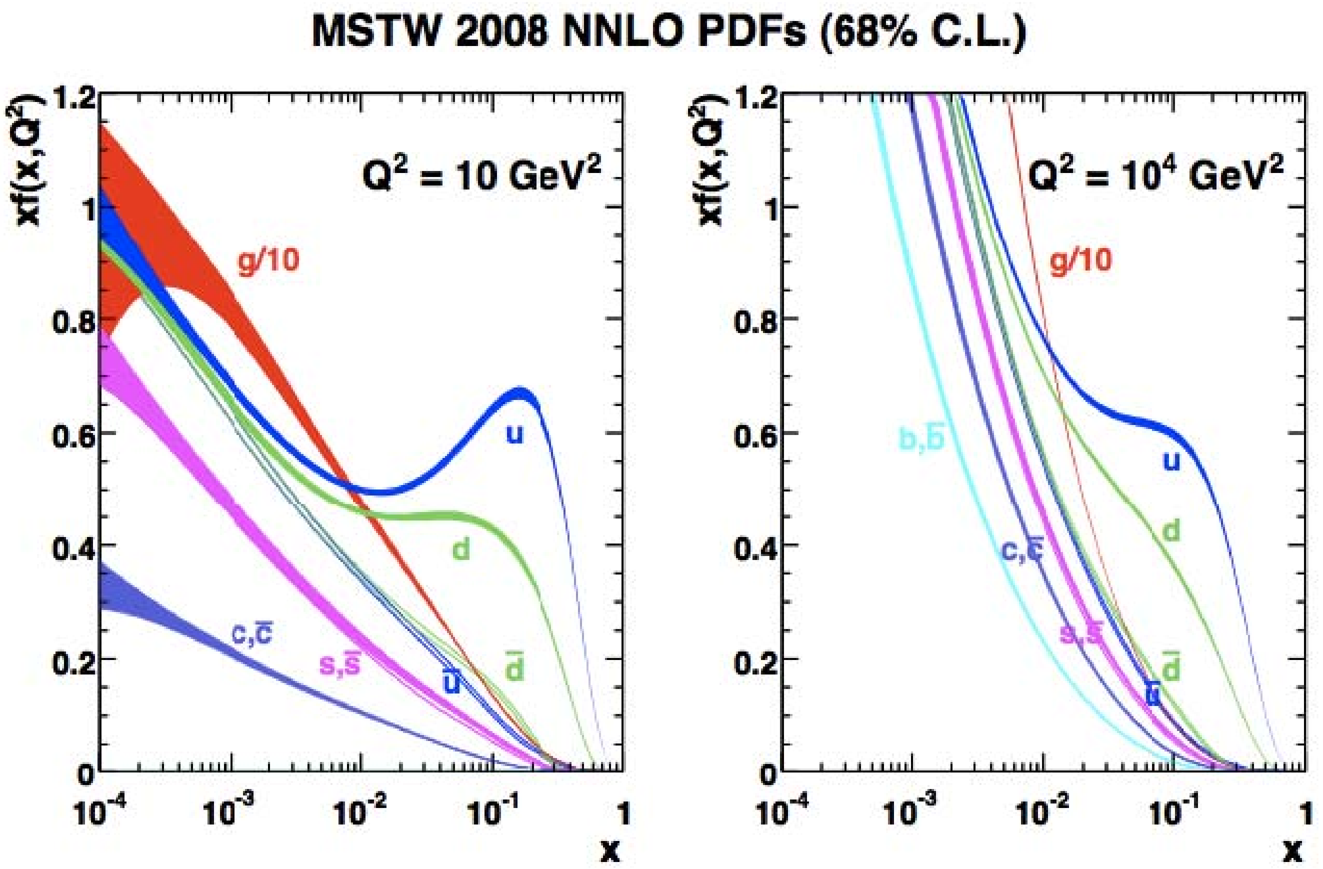
more information about wave function in 'less inclusive' distributions: GPD/TMD

Global Fits: Several groups MSTW and CTEQ

State of the art in the unpolarized case: MSTW2008 Martin, Stirling, Thorne, Watt

- NNLO accuracy
- pdfs uncertainties
- α_s uncertainties (new!)

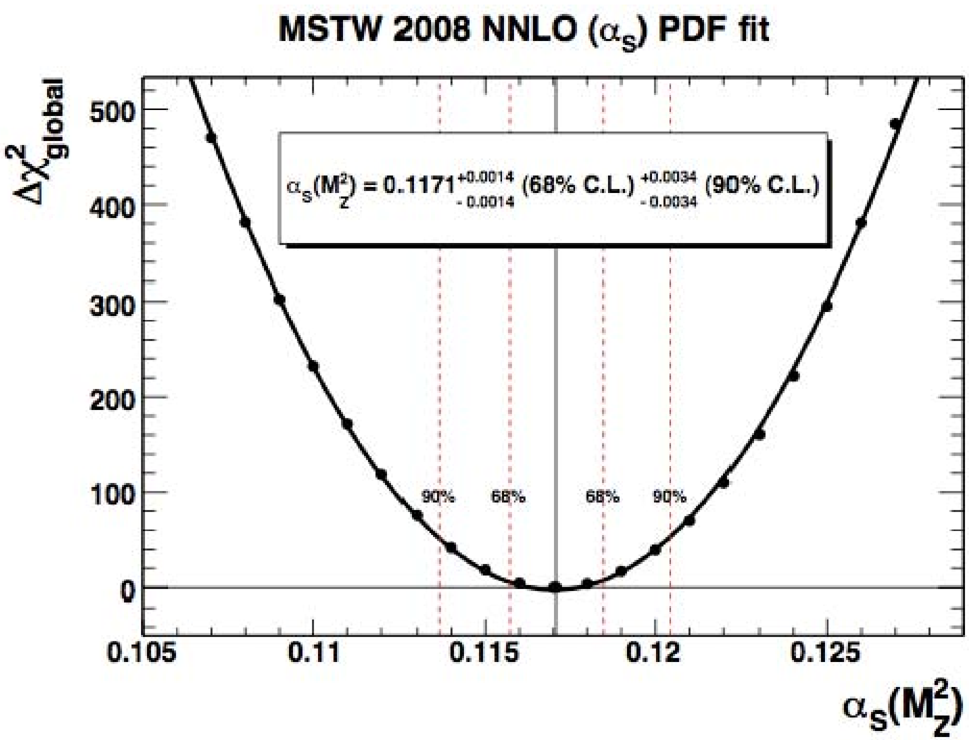
considerably reduce TH uncertainty

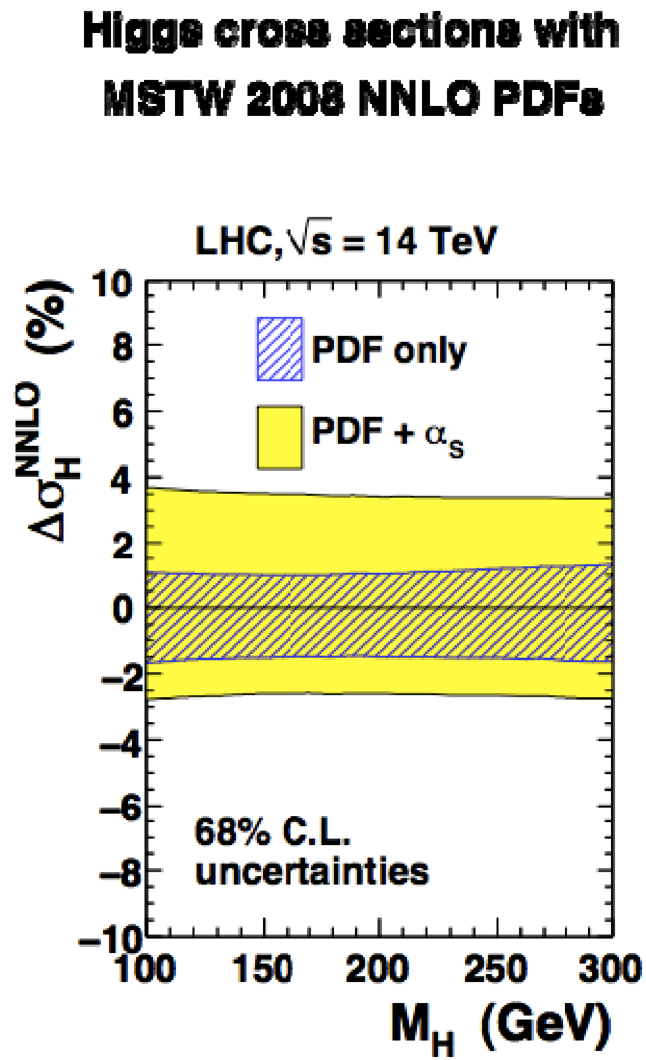


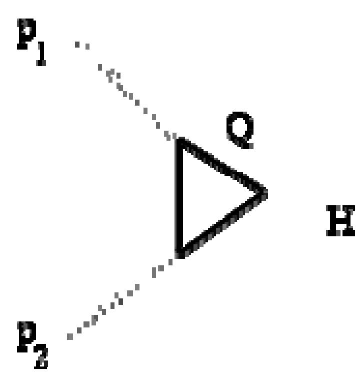
QCD in the precision era : pdfs + partonic cross-sections (NLO/NNLO)

Nuclear structure fundamental for precise QCD

I.Main ingredient in the parton model to compute cross-sections







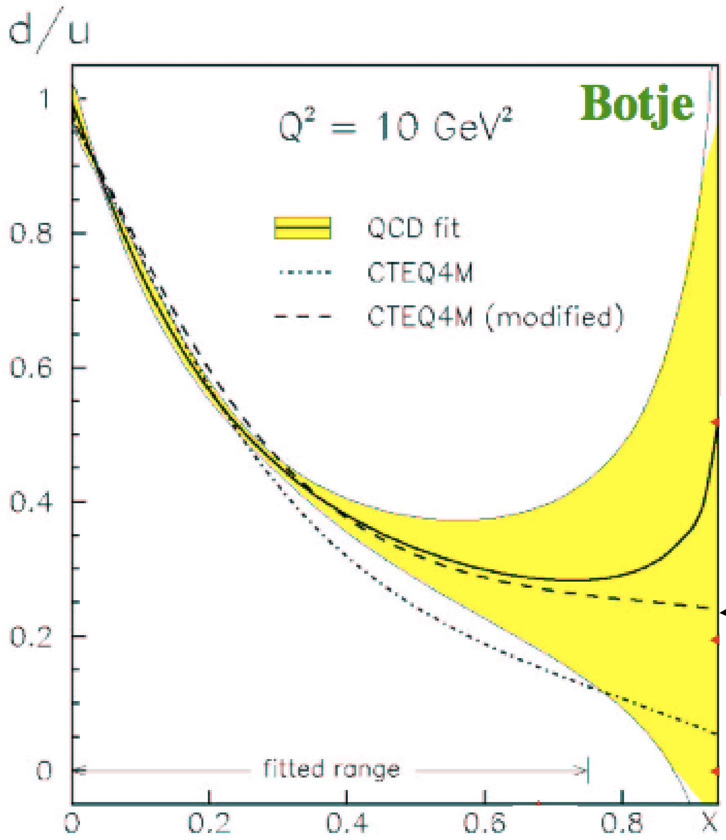
Precise enough for LHC

at 90% C.L. ~7%

DdeF. M.Grazzini

Not negligible uncertainties for some distributions at extreme kinematics

relevant for nucleon structure/QCD



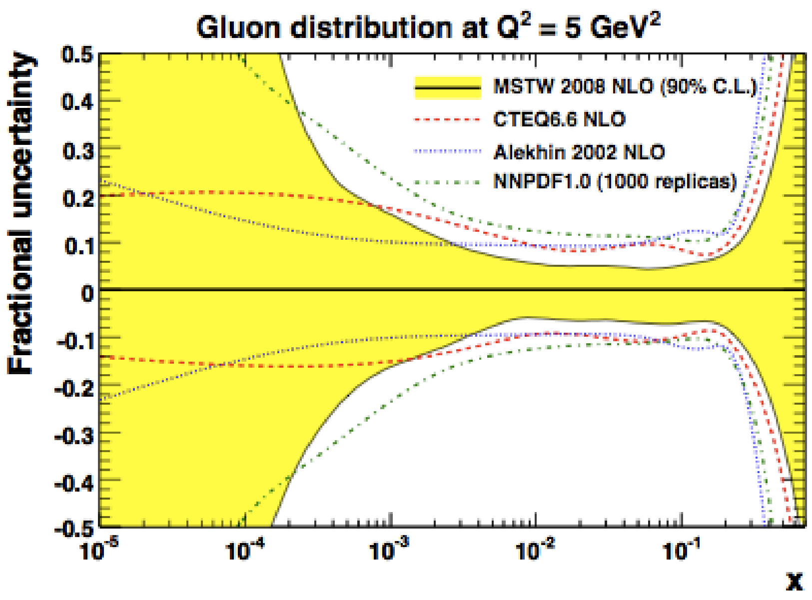
Nucleon models : valence region
(constant, rise,0?)

large uncertainties at large x

‘Low’ energy/High Luminosity ep collider
can help a lot!

Not negligible uncertainties for some distributions at extreme kinematics

relevant for nucleon structure/QCD

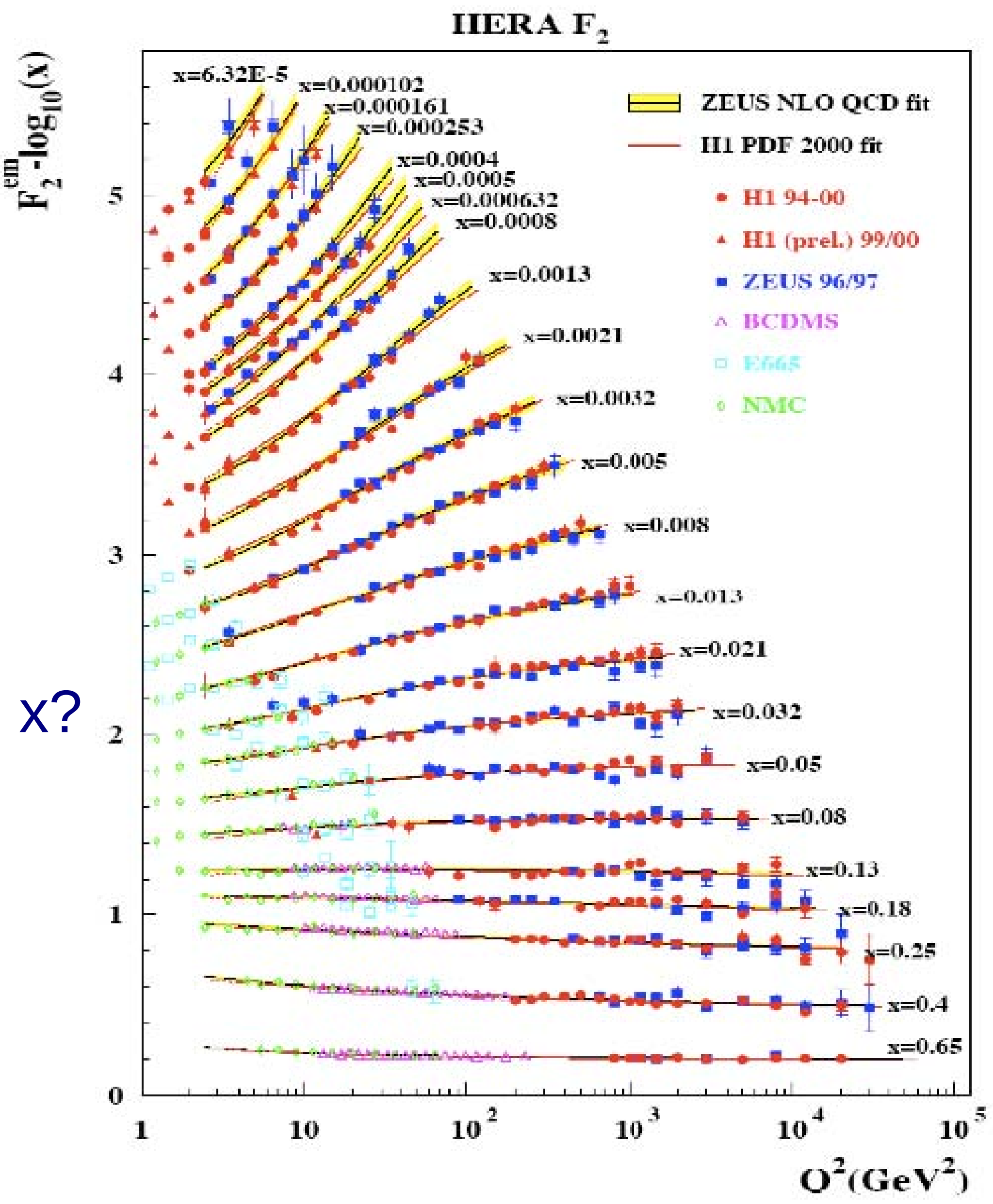


large uncertainties at small x

Saturation of the gluon density at small x?
Not seen at HERA

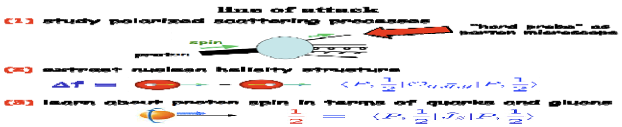
Where is BFKL?

Precision QCD at small x LHeC



Spin Structure : Polarized PDFs

$$\Delta f_i(x,Q^2) \equiv f_i^{\uparrow}(x,Q^2) - f_i^{\downarrow}(x,Q^2)$$



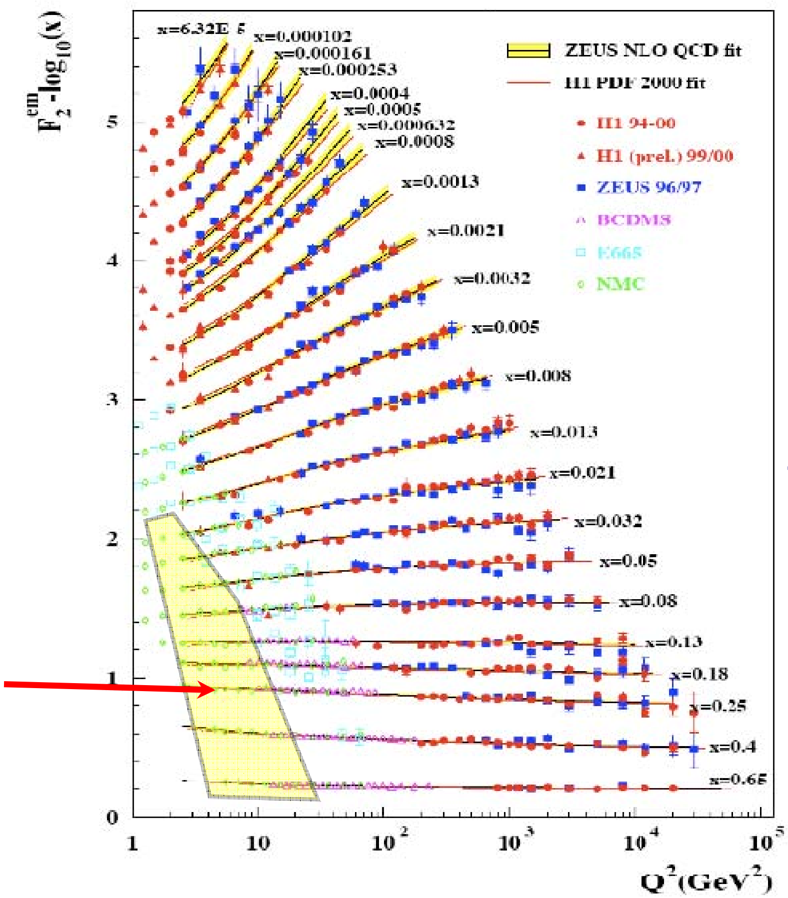
Longitudinal

$$\Delta\Sigma = \sum_i \int_0^1 \Delta q_i(x,Q^2)\,dx \qquad \Delta G = \int_0^1 \Delta g(x,Q^2)\,dx$$

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

Spin sum rule

Exp. data: DIS only fixed target



Polarize
d DIS

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2\left[\Delta q(x,Q^2) + \Delta\bar{q}(x,Q^2)\right]$$

not enough to determine gluon

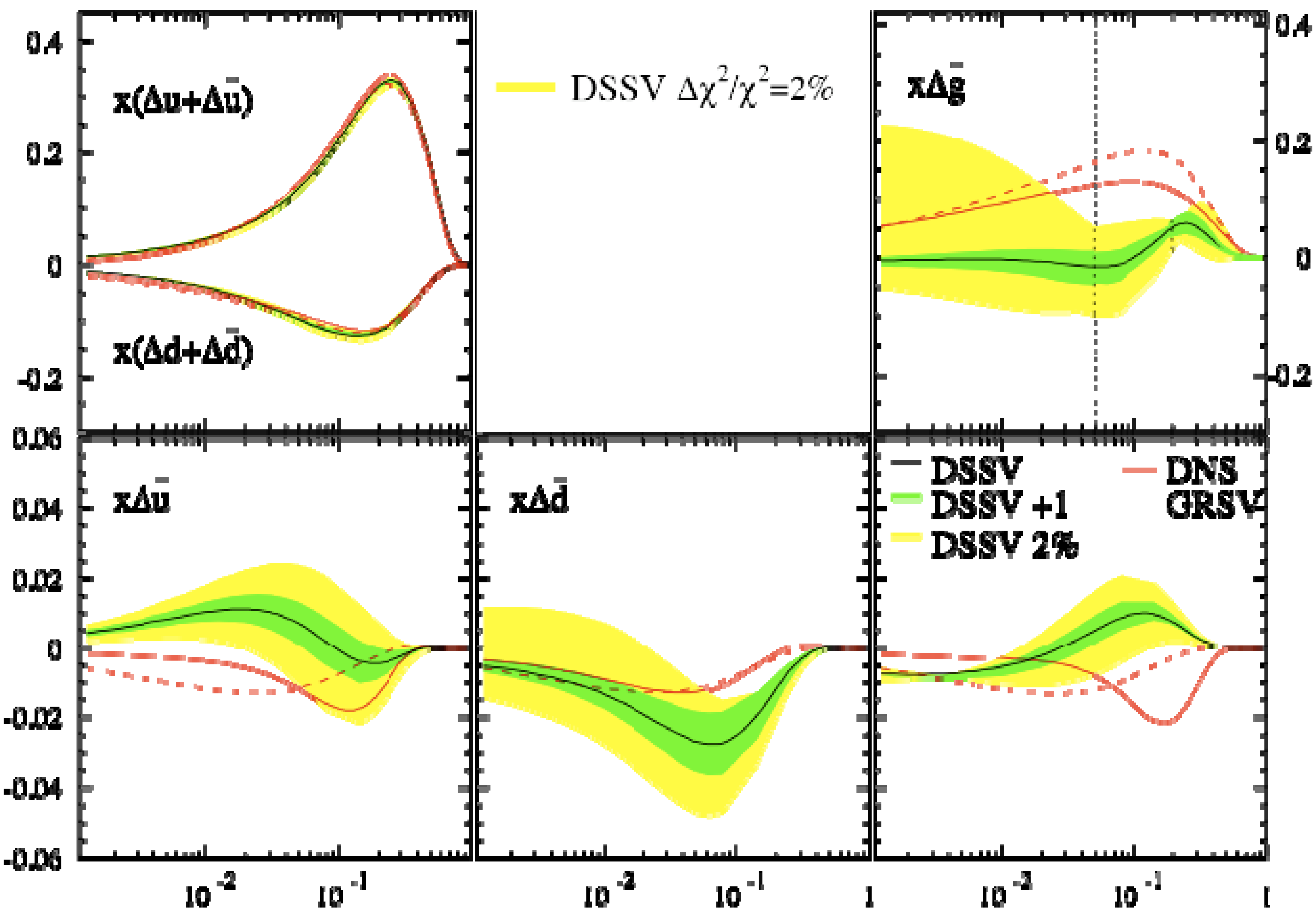
~ 100 different sets of pdf over the last decad

Global analysis of DIS, SIDIS and RHIC (pion and jet) data

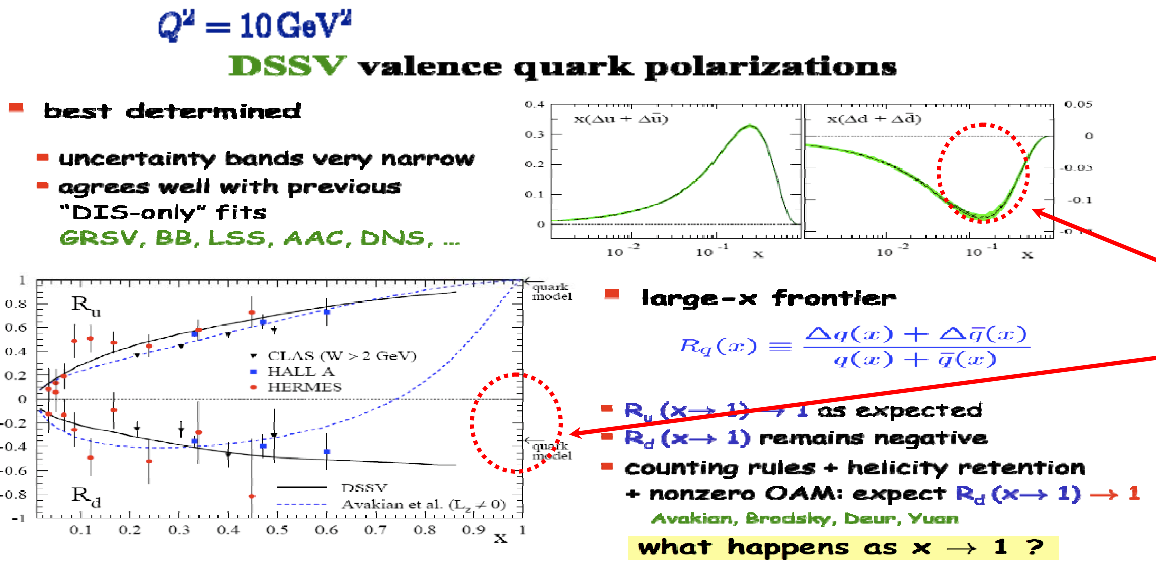
q+qbar sea/flavor gluon

DSSV (deF, Sassot, Stratmann, Vogelsan

PDFs + uncertainties

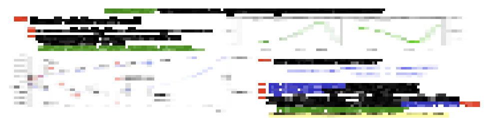


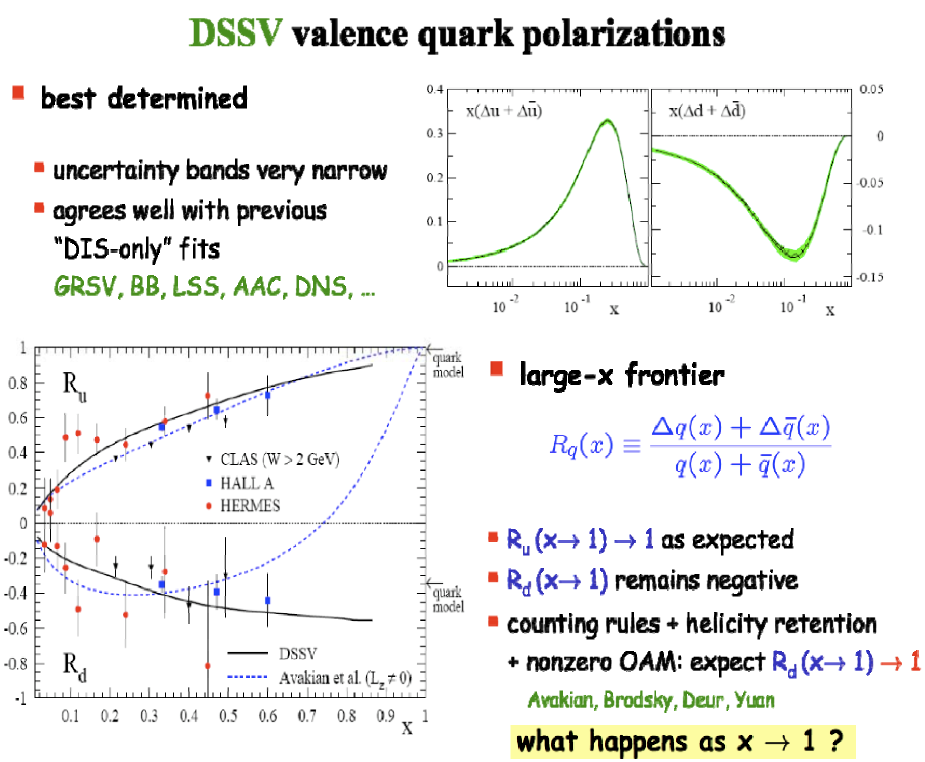
Polarized Quarks



'total' u and d distributions well determined

but large x hardly constrained by data



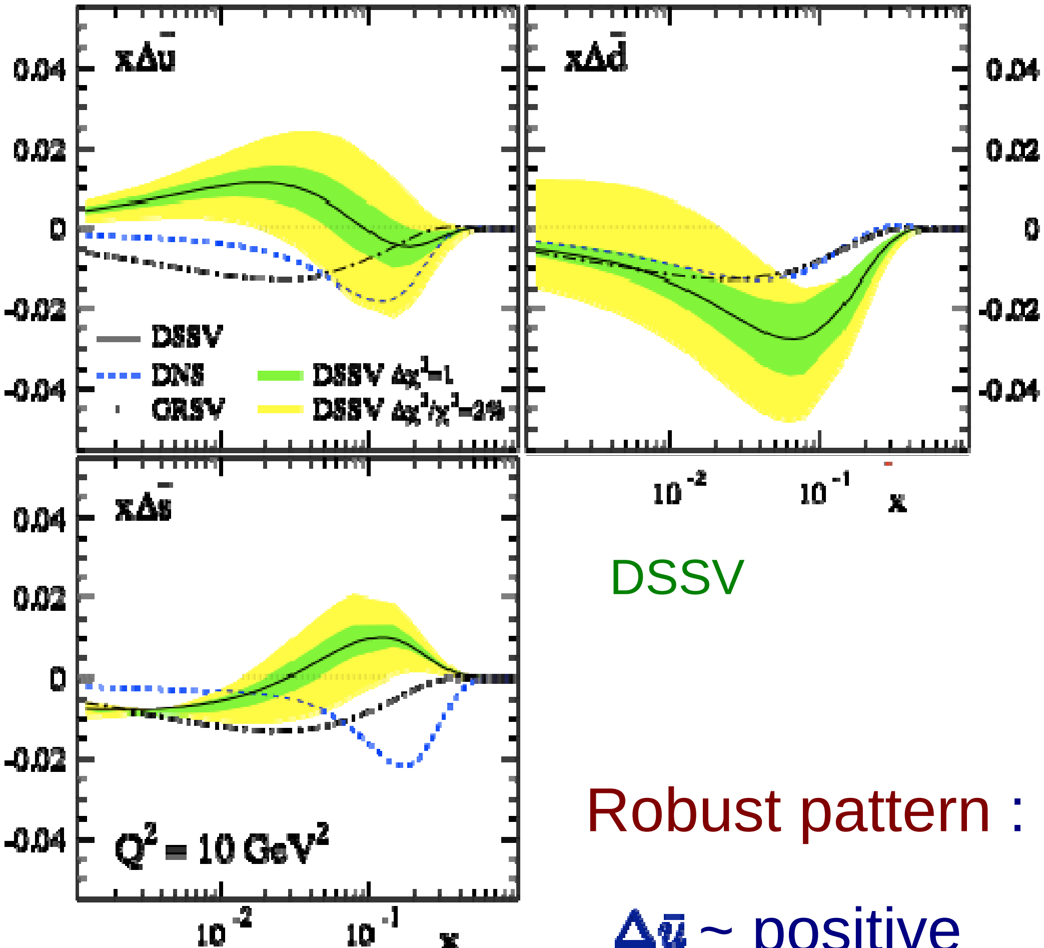


Constituent Model predicts negative d
but QCD power counting (with Lz) positive

H.Avakian et al

possible change of sign at large x?
Not evident from data

Polarized Sea



DSSV

Moments $Q^2 = 10\ \mathrm{GeV}^2$

$$\int_0^1 dx\, f(x) \qquad \int_{x_{min}}^1 dx\, f(x)$$

	$x_{min} = 0$ best fit	$x_{min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

small x extrapolation
sizable

Robust pattern : ~~SU~~(3) sea

$\Delta\bar{u}$ ~ positive

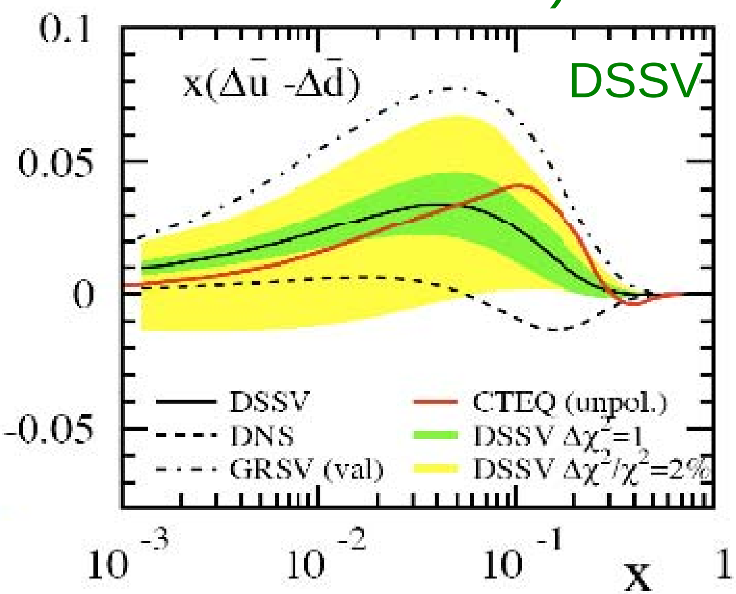
$\Delta\bar{d}$: negative

$\Delta\bar{s}$ SIDIS requires positive (HERMES)
but first moment negative (DIS)

Polarized Sea

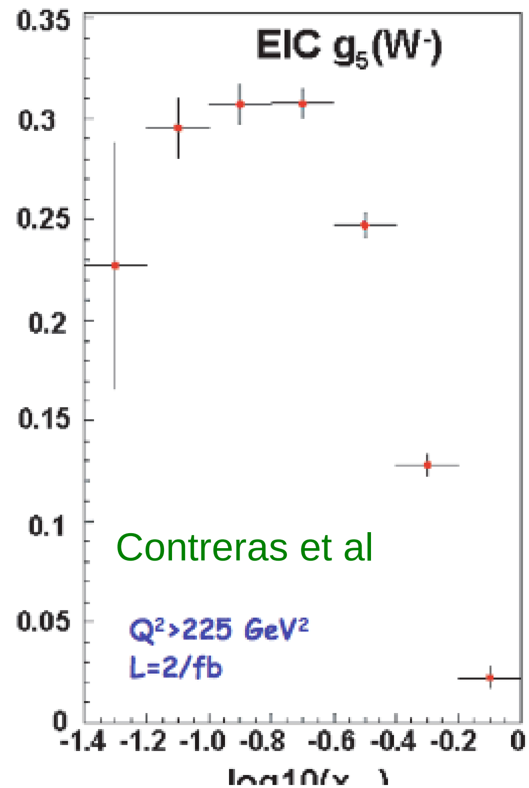
Sea-Flavor separation

Driven by SIDIS (DSS, reliable?)

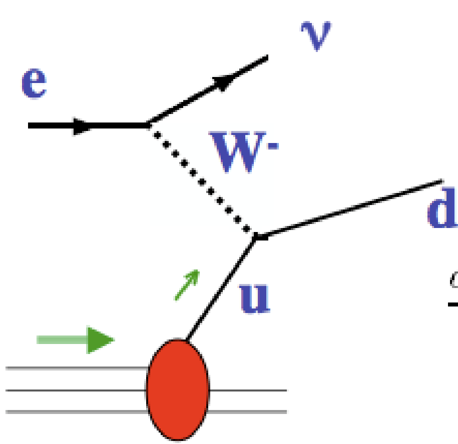


More SIDIS cross-section and asymmetries

Fragmentation functions @ ep



More information from W@RHIC



Weak structure functions @ ep

$$\frac{d^2\sigma^{\lambda,\Rightarrow}}{dx dQ^2} - \frac{d^2\sigma^{\lambda,\Leftarrow}}{dx dQ^2} \propto C(G_v, G_a, \lambda)\left[\lambda x y(2-y)\, g_1 + (1-y)\, g_4 + x y^2\, g_5\right]$$

$$g_1^{W^-}(x) = \Delta u(x) + \Delta\bar{d}(x) + \Delta\bar{s}(x) \qquad g_5^{W^-}(x) = \Delta u(x) - \Delta\bar{d}(x) - \Delta\bar{s}(x)$$

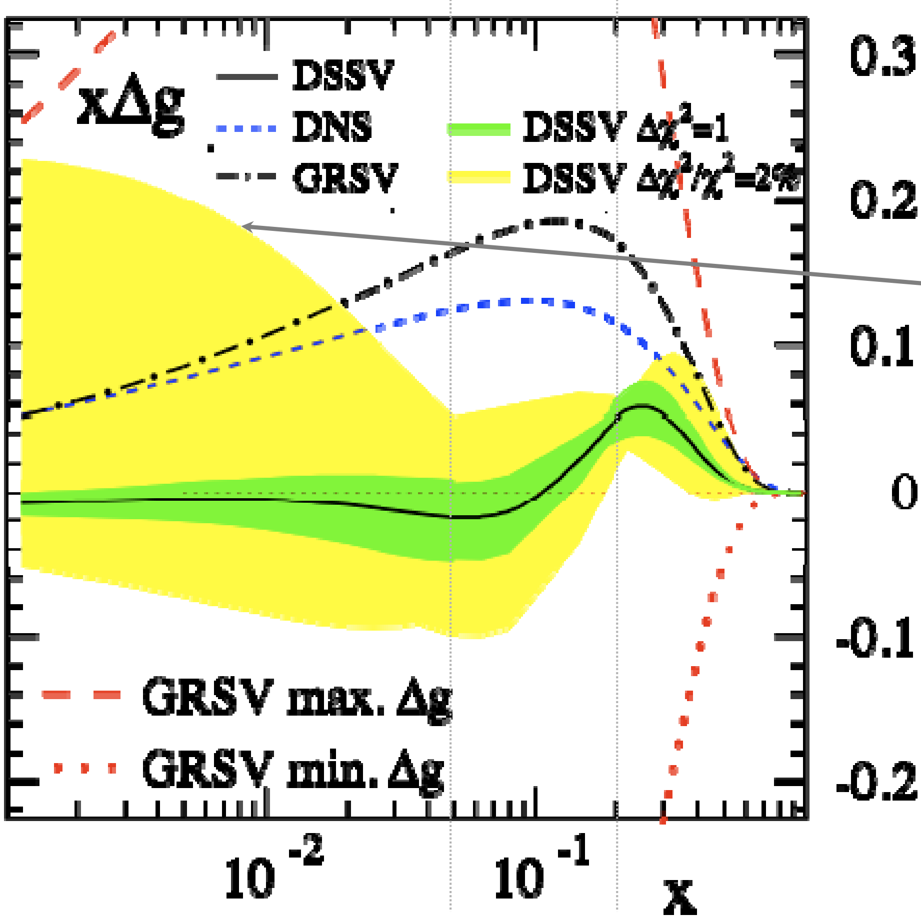
Polarized Gluons

Moments $Q^2 = 10\,\mathrm{GeV}^2$

	$x_{min} = 0$	$x_{min} = 0.001$	
	best fit	$\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
Δg	-0.084	$0.013^{+0.106}_{-0.120}$	$0.013^{+0.702}_{-0.314}$

Best fit : small first moment ... but..

DSSV



No clear statement possible for First moment : ~0 but huge uncertainty at small x

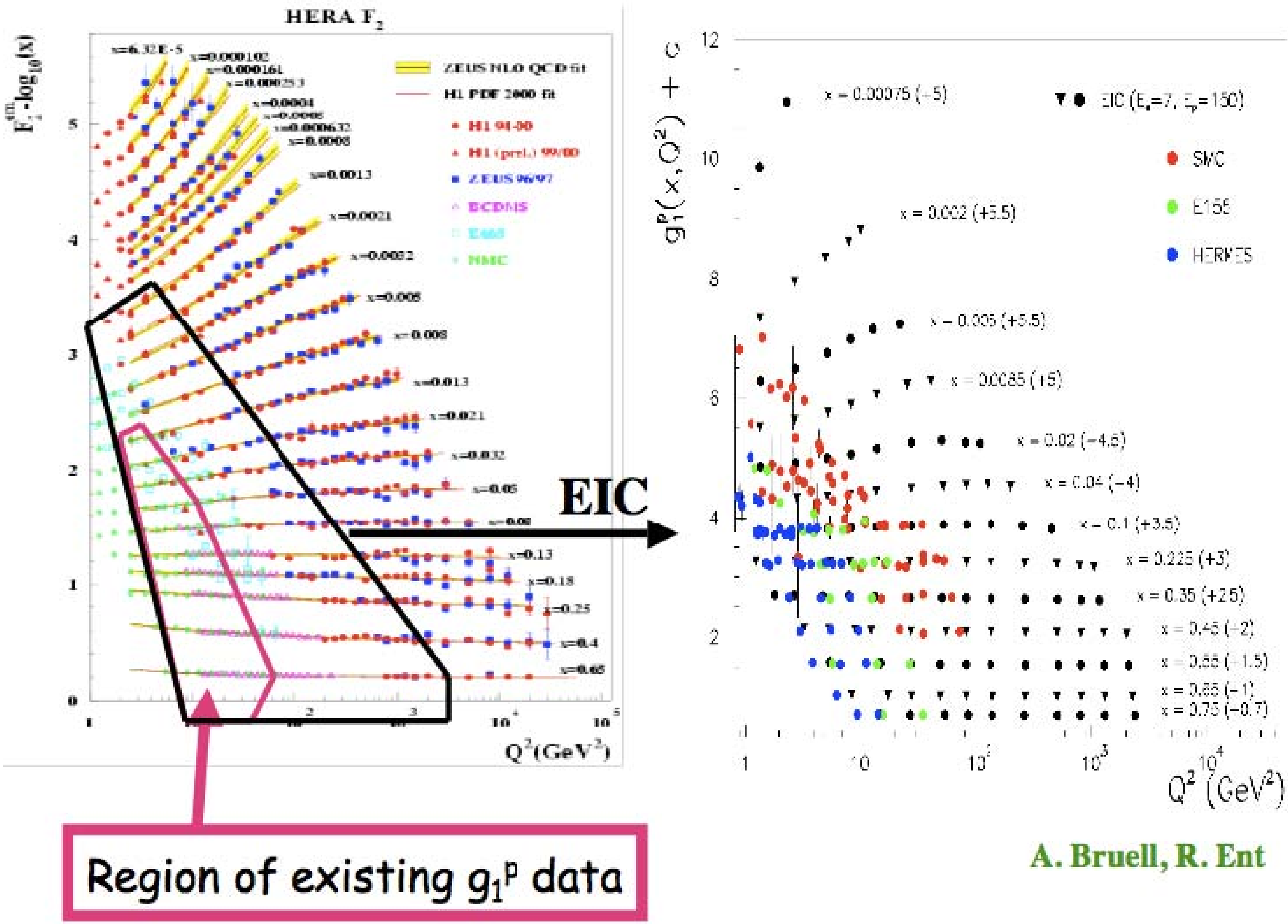
Any small x extrapolation for gluon is unreliable

polarized gluon rather small even moderate estimates (DNS/GRSV) ruled out

Gluon distribution at small x : DIS and evolution

$$\int_{0}^{1} \Delta g(x, Q^2)\, dx \qquad (0 \to \sim 10^{-3})$$

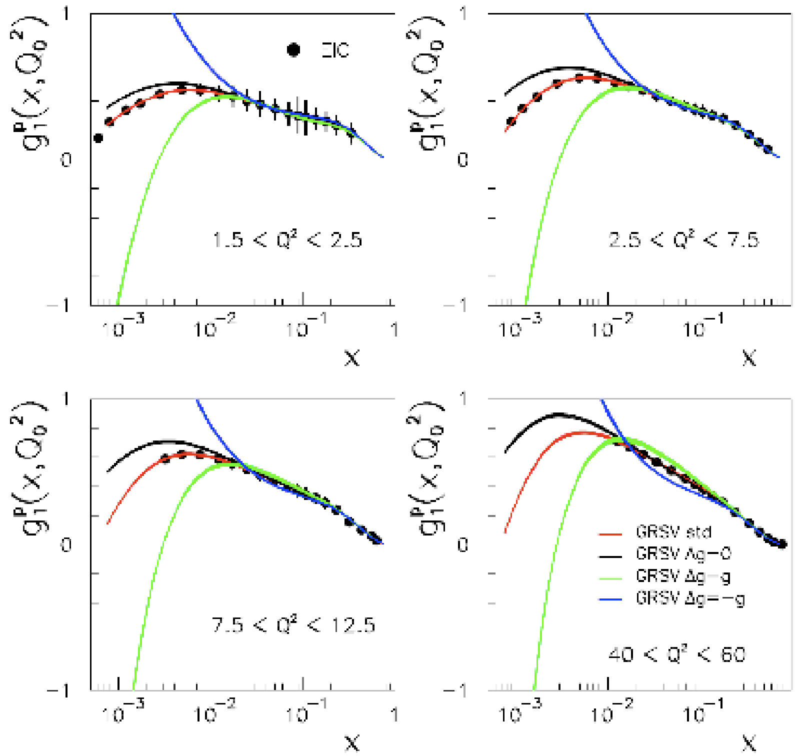
$$\frac{d\, g_1}{d \log(Q^2)} \propto -\Delta g(x, Q^2) \qquad \text{at small } x$$



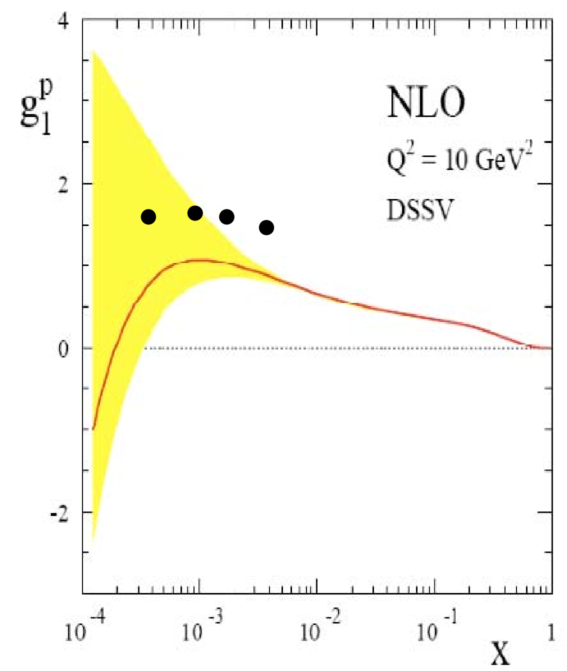
To settle down gluon contribution at small x : high energy polarized ep collider

Play the role of HERA for spin dependent

A. Bruell, R. Ent $E_e=7$, $E_p=150$ at $L=10^{33}$



small x uncertainty in DSSV



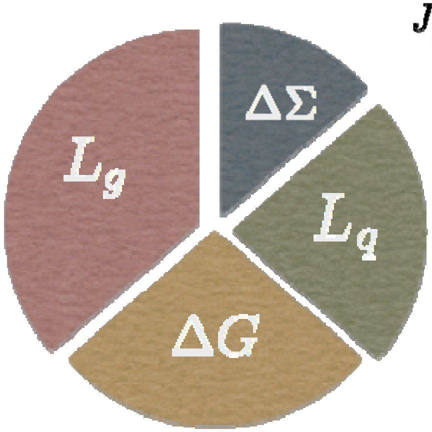
Small x allow to check sum rules (Bjorken) with much better accuracy

$\int_0^1 dx\, g_1^{ep-en}(x, Q^2$ from 10% to 1-2% ?

Without polarized ep collider : spin ‘crisis’ has NO solution

SPIN SUM RULES

Jaffe, Manohar



$J_g \neq L_g + \Delta G$

$L_q \neq L'_q$

Partonic interpretation
local operator only in
light cone gauge

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

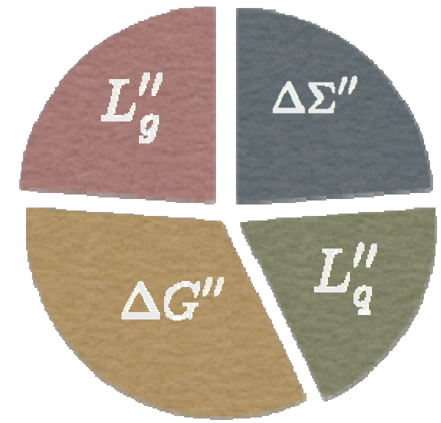
~ 0.12 small? (-0.084) must be sizable

Ji

Gauge invariant
Lattice and GPDs
Contains interactions

$$\frac{1}{2}\Delta\Sigma + L'_q + J_g = \frac{1}{2}$$

Chen, Lu, Sun, Wang, Goldman



Gauge invariant
physical interpretation
?
related to new pdfs ?

$$\frac{1}{2}\Delta\Sigma'' + \Delta G'' + L''_q + L''_g = \frac{1}{2}$$

Possible scenario : most of spin by OAM
?

TH work needed to relate different approaches and find how to measure OAM

Experimental activity triggers TH!

RHIC can provide more information about gluons

- 500 GeV to smaller x (x>0.01)

- New pp observables can give complementary information

  Prompt photons
  Heavy quarks

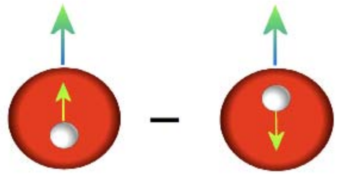
- More exclusive observables

  Dijets (Star)
  Jet + pion (Star)
  pion + photon (Phenix)

- More exclusive allows to perform a more detailed selection

  Cuts to enhance some partonic channel
  Plot data in term of other variables (enhance sensitivity)

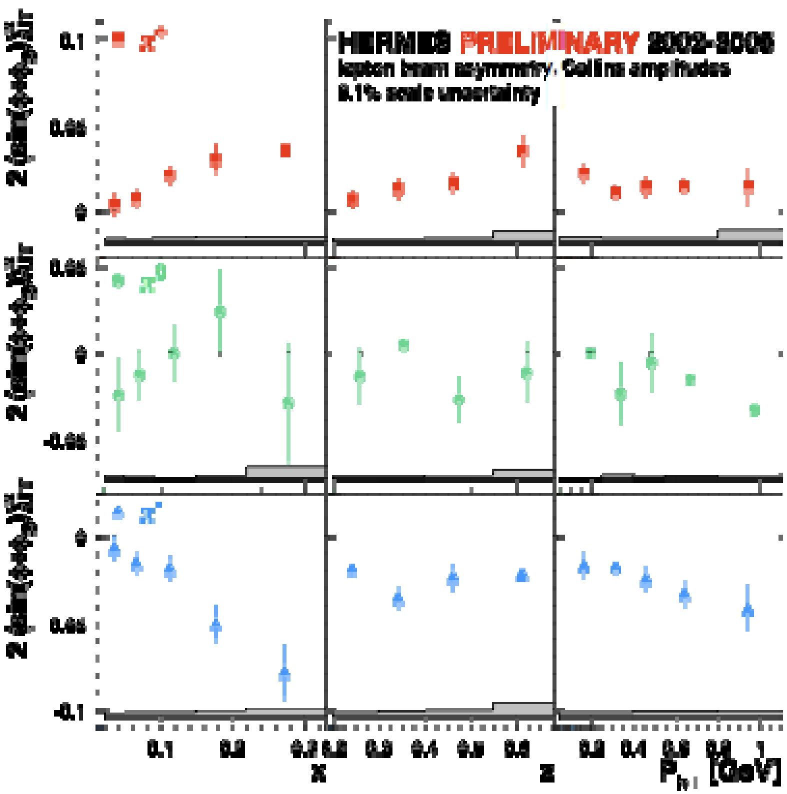
Transversity

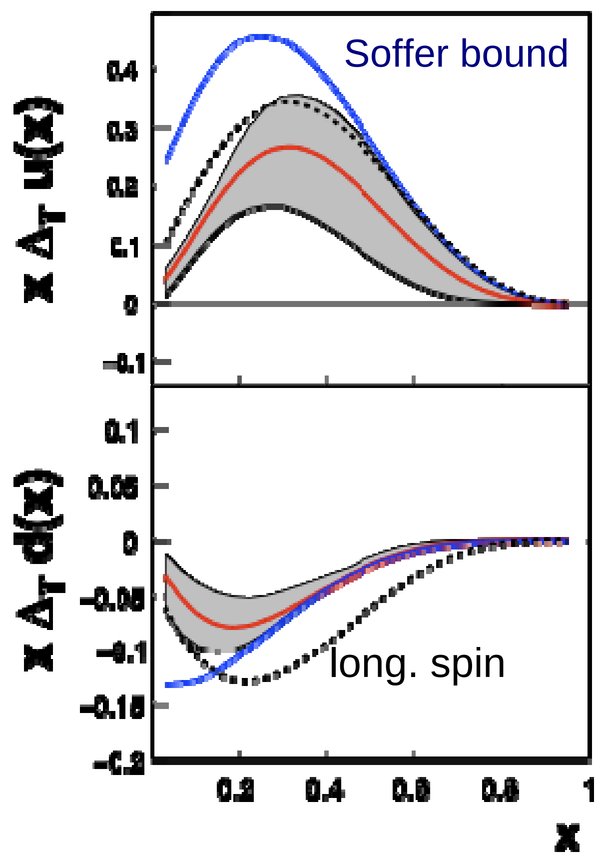
$\delta q(x) =$  measurement of quark transversity not easy: odd chiralit

in pp: small (DY) or SSA

Need SIDIS + Collins fragmentation (transverse momentum FFs from e+e-)

azimuthal asymmetries in $e\,p^{\uparrow} \rightarrow e\,\pi\,X$





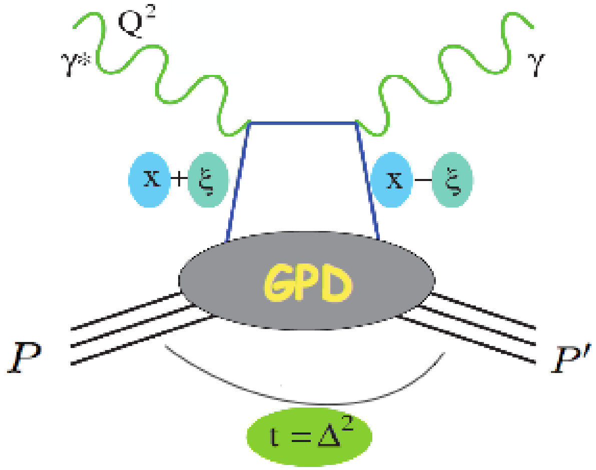
Anselmino et al

large uncertainties but sizable

- Repeat longitudinal spin programme
- Study Transverse spin sum rule

More powerful description of nucleon structure

Generalized Parton Distributions



- x: average quark momentum frac
- ξ: "skewing parameter" $= x_1 - x_2$
- t: 4-momentum transfer²

Burkardt; Ji

Off-forward distributions: require exclusive measurements

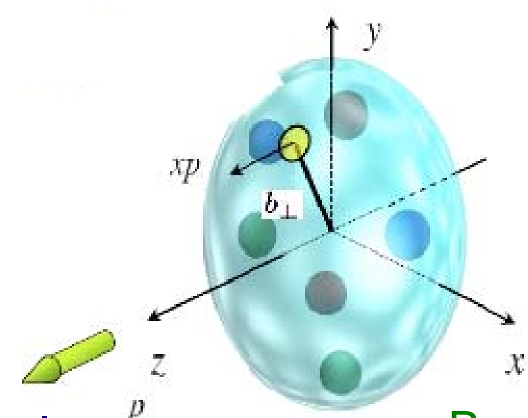
'forward limit'

Fourier transform of impact parameter PDFs

$$\int d^2\boldsymbol{\Delta}_\perp \, e^{-i\boldsymbol{\Delta}_\perp \cdot \mathbf{b}_\perp} H_q(x, \xi = 0, -\boldsymbol{\Delta}_\perp^2) \;=\; q(x, b_\perp)$$

quark with fraction x
and transverse
distance b from center

transverse profile of the nucleon

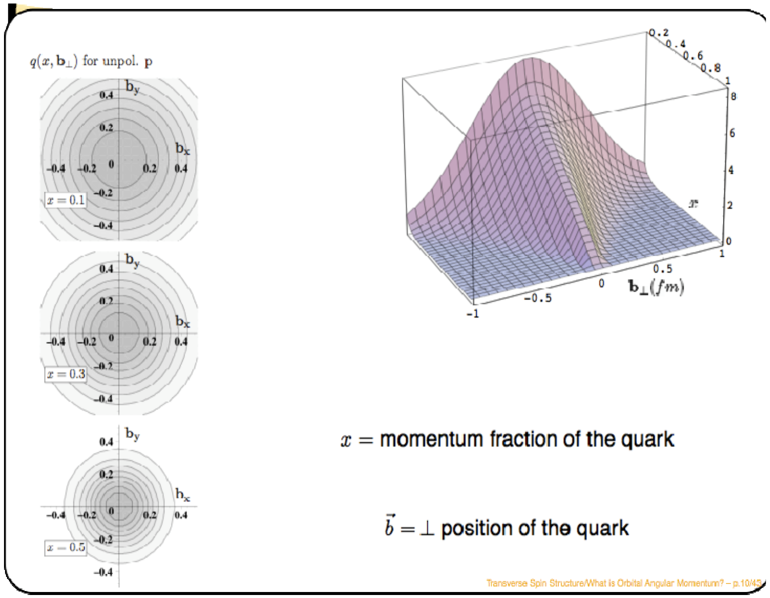


Burkardt; Ji

GPDs can provide a transverse profile of the nucleon

Burkardt; Ji

Position space distribution of partons : Tomographic images of nucleon



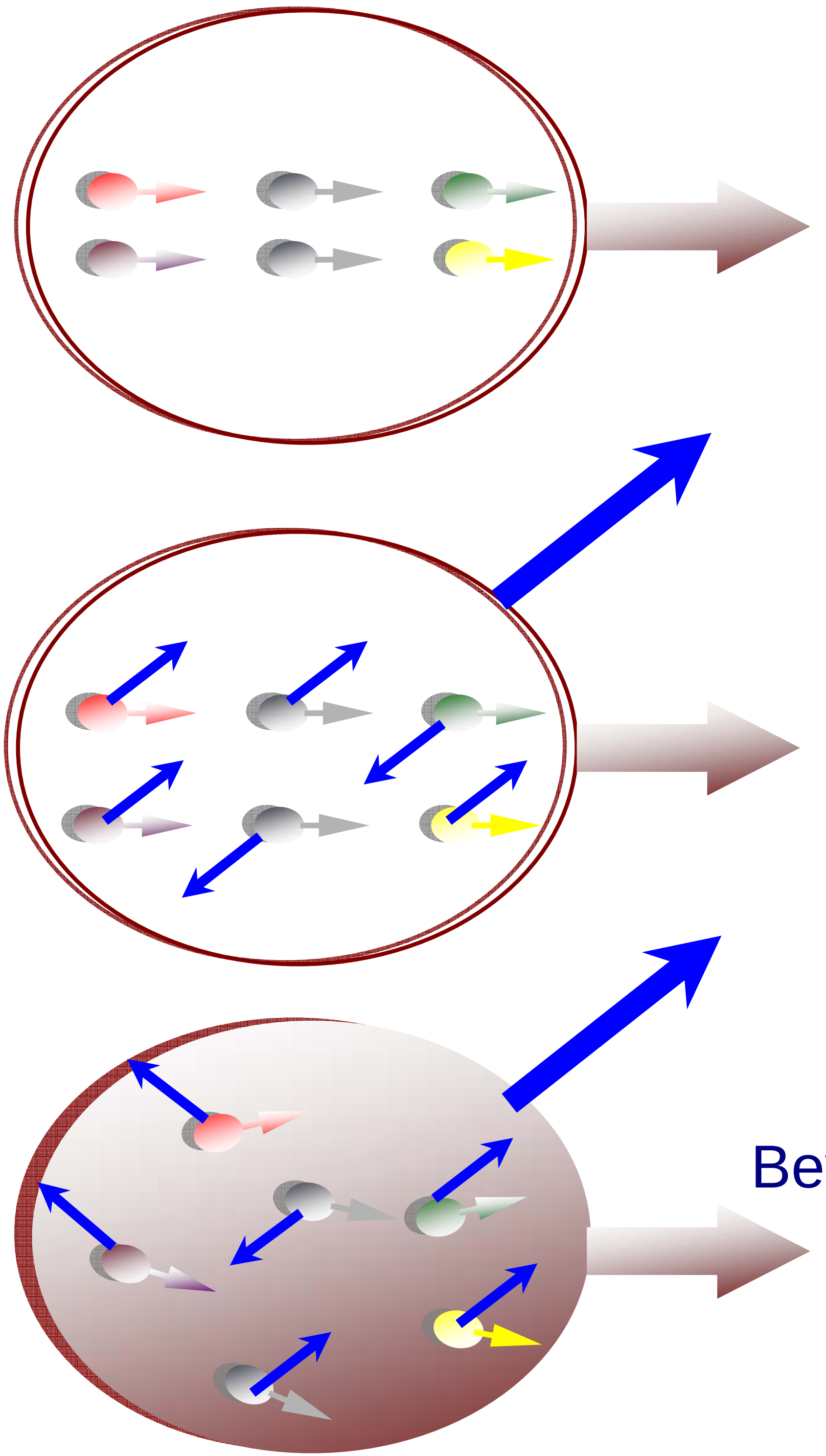
Related to total quark angular momentum Ji

measurable in DVCS
computable in lattice

$$J_q = \frac{1}{2} \lim_{t \to 0} \int dx\, x \left[H_q(x,\xi,t) + E_q(x,\xi,t) \right] = \frac{1}{2}\Delta q + L_q$$

But still measuring OAM not that clear in a model independent way

GPDs can open a new window on the nucleon structure



Collinear Parton Model (unpolarized)

We know quite a lot

$$\sum_{spin} \int dPS_{all\ partons\ but\ 1} \, | \, \mathbf{P} \rangle$$

$$q(x, Q^2)\ ,\ \ g(x, Q^2)$$

Collinear Parton Model (polarized)

We know a bit about long. pol.

$$\int dPS_{all\ partons\ but\ 1} \, | \, \mathbf{P} \rangle$$

$$\Delta q(x, Q^2)\ ,\ \ \Delta g(x, Q^2)$$

Beyond collinear approximation /fully inclusive

we know very little!

GPDs

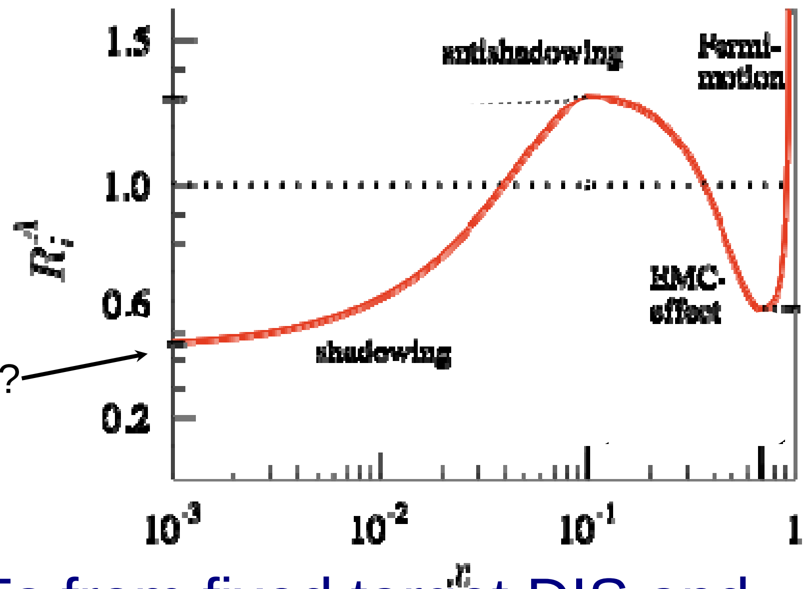
Nuclear PDFs

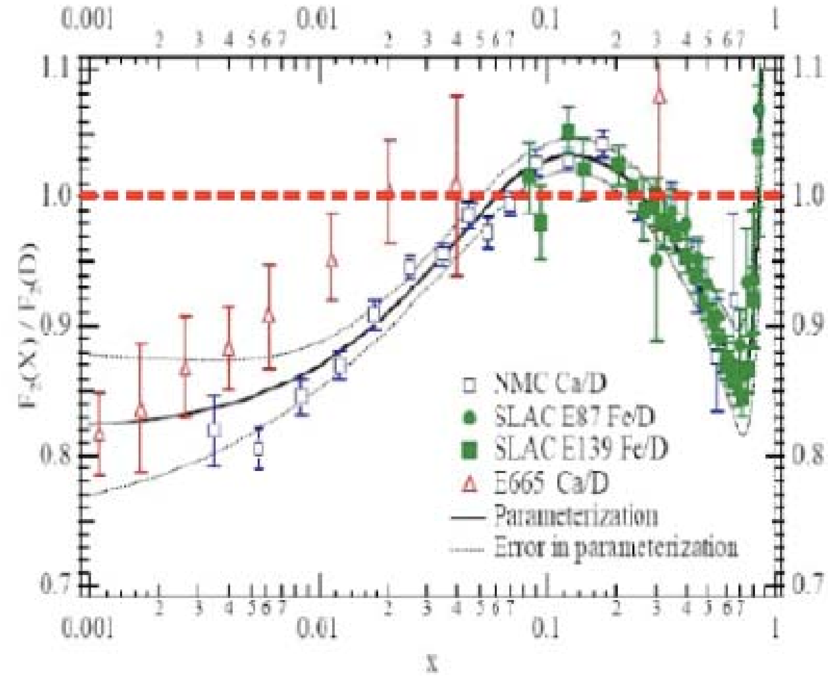
Modification of parton distributions on bound nucleons : larger than expected

$$F_2^A = \frac{1}{A}\left[Z\,F_2^p + (A-Z)\,F_2^n\right]$$

$$R^A = \frac{F_2^A}{F_2^D}$$

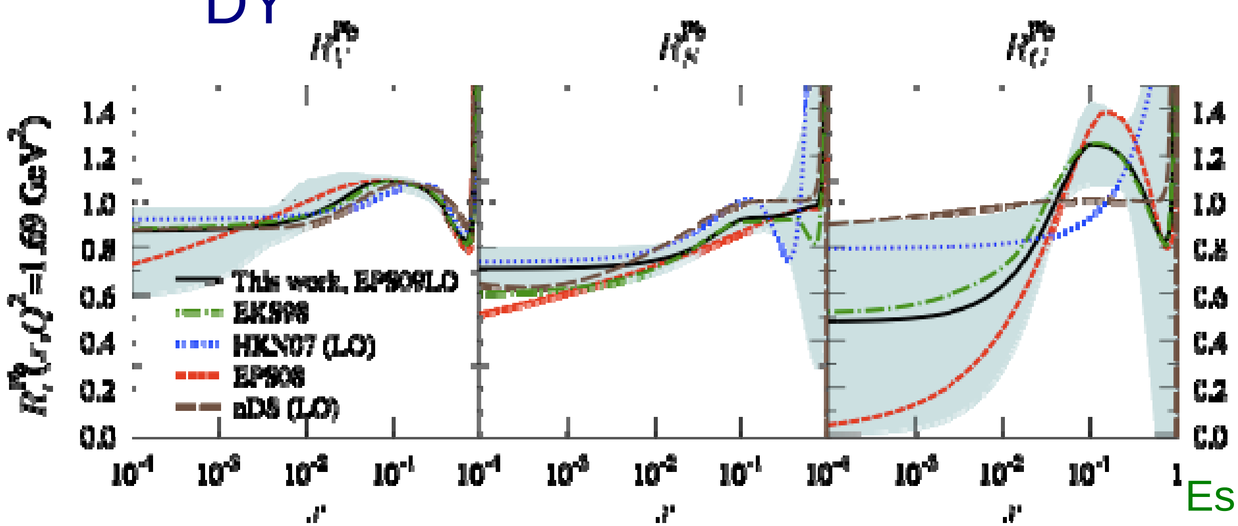
saturation?





nPDFs from fixed target DIS and DY

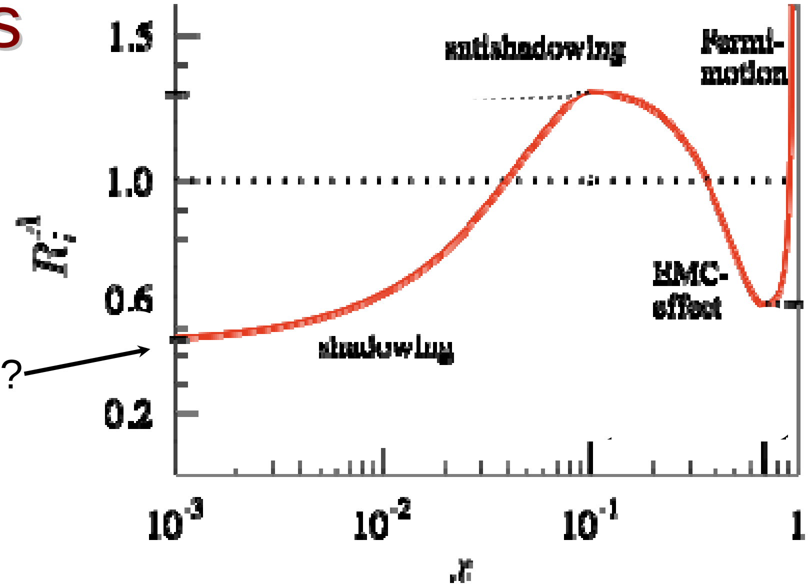
$$R_i^A = \frac{f_i^A}{f_i^D}$$



Eskola, Paukkunen, Salgado

Nuclear PDFs

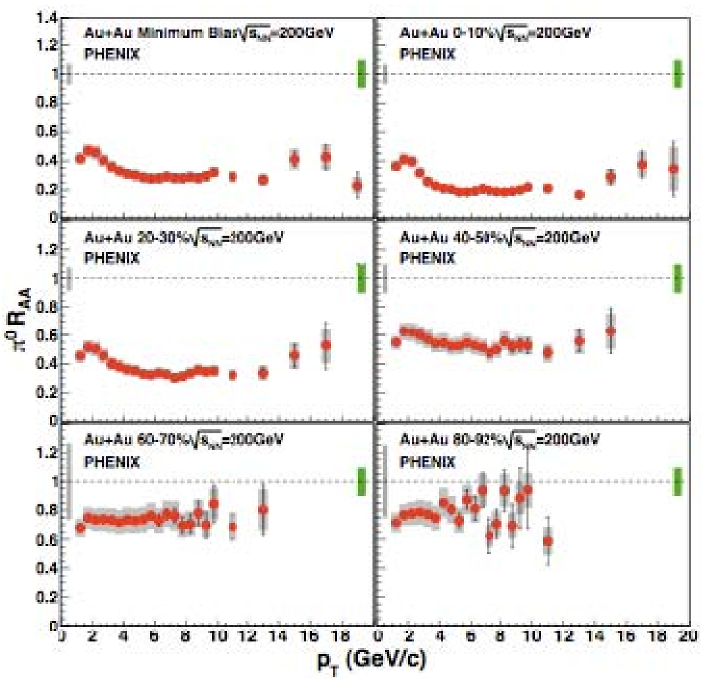
Large uncertainties in the gluon ratio



Several models predict saturation in hadowing : need small x and large Q

Only EIC can look at that region $\frac{\partial F_2^A / F_2^D}{\partial \ln Q^2} \sim R_g^A$ + recombination term?

What about pA / AA collisions?



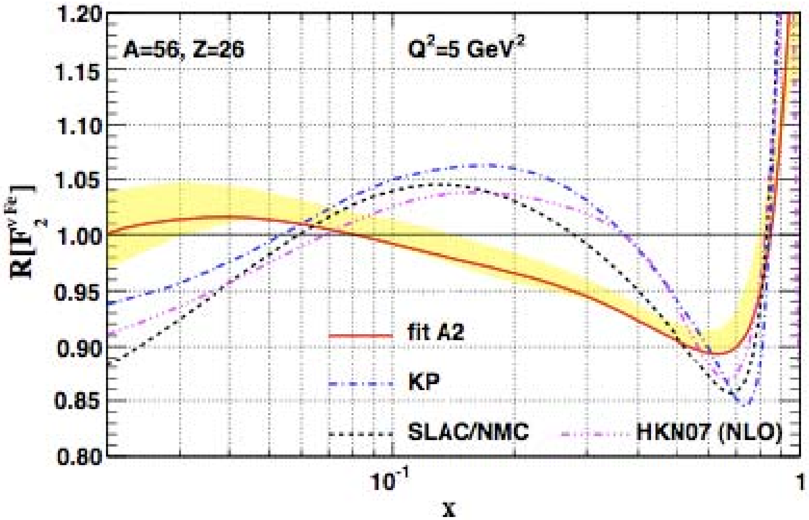
At medium x complementary measurements eA/pA

R is 'background' for new state of matter (QGP)

Nuclear PDFs

New: nuclear effects with neutrino data (Fe and Pb) Schienbein et al

$R^e \neq R^\nu$?



Can they be understood together (artifact of analysis?) or true effect (difference of propagation of photon and W through dense nuclear matter?)

Assumed to be equal for pdf extraction! strange distribution affected? $\nu_\mu N \to \mu^+ \mu^- X$

NuTeV anomaly in $\sin^2\theta_W$?

EIC can scan over different nuclei with photon and W exchange

Summary

QCD in the precision era → New insight on nucleon structure

✓ Unpolarized PDFs : OK for LHC but some kinematical regions uncovered

small x : Saturation?

large x : nucleon models

✓ Polarization : where is the spin of the proton?

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

Gluonic contribution requires small x : only possible at high energy ep collider $\int_0^1 \Delta g(x, Q^2)\, dx$

Without polarized ep collider : spin ‘crisis’ has NO solution

✓ Generalized Parton Distributions : Powerful description of nucleon structure

Tomographic images of nucleon
Orbital Angular Momentum ?

✓ eA collisions : nuclear modified pdfs

large uncertainties at present
complementary measurements with pA/AA
“Background” for QGP

Thanks