New statistical PDF: predictions and tests up to LHC energies

Jacques Soffer

Department of Physics, Temple University, Philadelphia, PA 19122-6082, USA

Outline

- Basic procedure to construct the statistical polarized parton distributions
- Essential features from unpolarized and polarized Deep Inelastic Scattering data
- New results using a much broader DIS data set
- The multi TeV energy range: single-jet, $W^\pm$, Drell-Yan
- Conclusions

Collaboration with Claude Bourrely and Franco Buccella

- A Statistical Approach for Polarized Parton Distributions
  Euro. Phys. J. C23, 487 (2002)
- Recent Tests for the Statistical Parton Distributions
  Mod. Phys. Letters A18, 771 (2003)
- The Statistical Parton Distributions: status and prospects
  Euro. Phys. J. C41, 327 (2005)
- The extension to the transverse momemtum of the statistical parton distributions
  Mod. Phys. Letters A21, 143 (2006)
- Strangeness asymmetry of the nucleon in the statistical parton model
  Phys. Lett. B648, 39 (2007)
- How is transversity related to helicity for quarks and antiquarks in a proton?
  Mod. Phys. Letters A24, 1889 (2009)
- Semiinclusive DIS cross sections and spin asymmetries in the quantum statistical parton distributions approach, Phys. Rev. D83, 074008 (2011)
- The transverse momentum dependent statistical parton distributions revisited
  Int. Journal of Mod. Phys. A28, 1350026 (2013)

- $W^{\pm}$ bosons production in the quantum statistical parton distributions approach
  Phys. Lett. B726, 296 (2013)
- Statistical description of the proton spin with a large gluon helicity distribution
  Phys. Lett. B740, 168 (2015)
- New developments in the statistical approach of parton distributions: tests and predictions up to LHC energies
  arxiv:1502.02517v1 [hep-ph]

Our motivation and goals

- Will propose a quantum statistical approach of the nucleon viewed as a gas of massless partons in equilibrium at a given temperature in a finite size volume.
- Will incorporate some well known phenomenological facts and some QCD features

Our motivation and goals

- Will propose a quantum statistical approach of the nucleon viewed as a gas of massless partons in equilibrium at a given temperature in a finite size volume.
- Will incorporate some well known phenomenological facts and some QCD features
- Will parametrize our PDF in terms of a rather small number of physical parameters, at variance with standard polynomial type parametrizations
- Will be able to construct simultaneously unpolarized and polarized PDF: A UNIQUE CASE ON THE MARKET!
- Will be able to describe physical observables both in DIS and hadronic collisions
- Will make some very specific challenging predictions, from the behavior of unpolarized and polarized PDF, either in the sea quark region or in the valence region
- Will present new tests and predictions up to LHC energies

Basic procedure

Use a simple description of the PDF, at input scale Q_0^2, proportional to $[\exp[(x - X_{0p})/\bar{x}] \pm 1]^{-1}$, *plus* sign for quarks and antiquarks, corresponds to a Fermi-Dirac distribution and *minus* sign for gluons, corresponds to a Bose-Einstein distribution. X_{0p} is a constant which plays the role of the *thermodynamical potential* of the parton *p* and $\bar{x}$ is the *universal temperature*, which is the same for all partons.

NOTE: x is indeed the natural variable, since all the sum rules we will use are expressed in terms of x

Basic procedure

Use a simple description of the PDF, at input scale Q_0^2, proportional to $[\exp[(x - X_{0p})/\bar{x}] \pm 1]^{-1}$, *plus* sign for quarks and antiquarks, corresponds to a Fermi-Dirac distribution and *minus* sign for gluons, corresponds to a Bose-Einstein distribution. X_{0p} is a constant which plays the role of the *thermodynamical potential* of the parton *p* and $\bar{x}$ is the *universal temperature*, which is the same for all partons.

NOTE: x is indeed the natural variable, since all the sum rules we will use are expressed in terms of x

From the chiral structure of QCD, we have two important properties, allowing to RELATE quark and antiquark distributions and to RESTRICT the gluon distribution:
- Potential of a quark q^h of helicity *h* is opposite to the potential of the corresponding antiquark $\bar{q}^{-h}$ of helicity *-h*, $X_{0q}^h = -X_{0\bar{q}}^{-h}$.
- Potential of the gluon G is zero, $X_{0G} = 0$.

The polarized PDF $q^{\pm}(x, Q_0^2)$ at initial scale Q_0^2

For light quarks $q = u, d$ of helicity $h = \pm$, we take

$$xq^{(h)}(x, Q_0^2) = \frac{A X_{0q}^{h} x^b}{\exp[(x - X_{0q}^{h})/\bar{x}] + 1} + \frac{\tilde{A} x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} ,$$

consequently for antiquarks of helicity $h = \mp$

$$x\bar{q}^{(-h)}(x, Q_0^2) = \frac{\bar{A} (X_{0q}^{h})^{-1} x^{\bar{b}}}{\exp[(x + X_{0q}^{h})/\bar{x}] + 1} + \frac{\tilde{A} x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} .$$

Note: $q = q^+ + q^-$ and $\Delta q = q^+ - q^-$ (idem for $\bar{q}$).
Extra term is absent in Δq and q_v also in $u - d$ or $\bar{u} - \bar{d}$.
The additional factors X_{0q}^{h} and $(X_{0q}^{h})^{-1}$ are coming from TMD

The polarized PDF $q^{\pm}(x, Q_0^2)$ at initial scale Q_0^2

For light quarks $q = u, d$ of helicity $h = \pm$, we take

$$xq^{(h)}(x, Q_0^2) = \frac{AX_{0q}^h x^b}{\exp[(x - X_{0q}^h)/\bar{x}] + 1} + \frac{\tilde{A}x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} ,$$

consequently for antiquarks of helicity $h = \mp$

$$x\bar{q}^{(-h)}(x, Q_0^2) = \frac{\bar{A}(X_{0q}^h)^{-1} x^{\bar{b}}}{\exp[(x + X_{0q}^h)/\bar{x}] + 1} + \frac{\tilde{A}x^{\tilde{b}}}{\exp(x/\bar{x}) + 1} .$$

Note: $q = q^+ + q^-$ and $\Delta q = q^+ - q^-$ (idem for $\bar{q}$).
Extra term is absent in Δq and q_v also in $u - d$ or $\bar{u} - \bar{d}$.
The additional factors X_{0q}^h and $(X_{0q}^h)^{-1}$ are coming from TMD
For strange quarks and antiquarks, s and $\bar{s}$, use the same procedure which leads to $xs(x, Q_0^2) \neq x\bar{s}(x, Q_0^2)$ and $x\Delta s(x, Q_0^2) \neq x\Delta\bar{s}(x, Q_0^2)$, but involve the same number of free parameters as for light quarks
For gluons we use a Bose-Einstein expression given by $xG(x, Q_0^2) = \frac{A_G x^{b_G}}{\exp(x/\bar{x}) - 1}$, with a vanishing potential and the same temperature $\bar{x}$. For the polarized gluon distribution $x\Delta G(x, Q_0^2)$ we take a similar expression at initial scale (positive for all x)

Essential features from the DIS data

From well established features of u and d extracted from DIS data, we anticipate some simple relations between the potentials:

- $u(x)$ dominates over $d(x)$, so we should have $X^{+}_{0u} + X^{-}_{0u} > X^{+}_{0d} + X^{-}_{0d}$
- $\Delta u(x) > 0$, therefore $X^{+}_{0u} > X^{-}_{0u}$
- $\Delta d(x) < 0$, therefore $X^{-}_{0d} > X^{+}_{0d}$.

Essential features from the DIS data

From well established features of u and d extracted from DIS data, we anticipate some simple relations between the potentials:

- $u(x)$ dominates over $d(x)$, so we should have $X_{0u}^{+} + X_{0u}^{-} > X_{0d}^{+} + X_{0d}^{-}$
- $\Delta u(x) > 0$, therefore $X_{0u}^{+} > X_{0u}^{-}$
- $\Delta d(x) < 0$, therefore $X_{0d}^{-} > X_{0d}^{+}$.

So we expect X_{0u}^{+} to be the largest potential and X_{0d}^{+} the smallest one. In fact, from our fit we have obtained the following ordering

$$X_{0u}^{+} > X_{0d}^{-} \sim X_{0u}^{-} > X_{0d}^{+} \, .$$

This ordering has important consequences for $\bar{u}$ and $\bar{d}$, namely

Essential features from DIS data

- $\bar{d}(x) > \bar{u}(x)$, flavor symmetry breaking expected from Pauli exclusion principle. This was already confirmed by the violation of the Gottfried sum rule (NMC).
- $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$, a PREDICTION from 2002, in agreement with polarized DIS (see below) and has been more precisely checked at RHIC-BNL from $W^{\pm}$ production, already in active running phase (see PLB726, 296,(2013)).

Essential features from DIS data

- $\bar{d}(x) > \bar{u}(x)$, flavor symmetry breaking expected from Pauli exclusion principle. This was already confirmed by the violation of the Gottfried sum rule (NMC).
- $\Delta\bar{u}(x) > 0$ and $\Delta\bar{d}(x) < 0$, a PREDICTION from 2002, in agreement with polarized DIS (see below) and has been more precisely checked at RHIC-BNL from $W^{\pm}$ production, already in active running phase (see PLB726, 296,(2013)).
- Note that since $u^{-}(x) \sim d^{-}(x)$, it follows that $\bar{u}^{+}(x) \sim \bar{d}^{+}(x)$, so we have

$$\Delta\bar{u}(x) - \Delta\bar{d}(x) \sim \bar{d}(x) - \bar{u}(x) ,$$

i.e. the flavor symmetry breaking is almost the same for unpolarized and polarized distributions ($\Delta\bar{u}$ and $\Delta\bar{d}$ contribute to about 10% to the Bjorken sum rule).

Very few free parameters

By performing a NLO QCD evolution of these PDF, we were able to obtain a good description of a large set of very precise data on $F_2^p(x,Q^2), F_2^n(x,Q^2), xF_3^{\nu N}(x,Q^2)$ and $g_1^{p,d,n}(x,Q^2)$, in correspondance with ten free parameters for the light quark sector with some physical significance:

* the four potentials $X_{0u}^+,\ X_{0u}^-,\ X_{0d}^-,\ X_{0d}^+,$
* the universal temperature $\bar{x}$,
* and $b,\ \bar{b},\ \tilde{b},\ b_G,\ \tilde{A}.$

Very few free parameters

By performing a NLO QCD evolution of these PDF, we were able to obtain a good description of a large set of very precise data on $F_2^p(x, Q^2), F_2^n(x, Q^2), xF_3^{\nu N}(x, Q^2)$ and $g_1^{p,d,n}(x, Q^2)$, in correspondance with ten free parameters for the light quark sector with some physical significance:

* the four potentials $X_{0u}^+, \; X_{0u}^-, \; X_{0d}^-, \; X_{0d}^+$,

* the universal temperature $\bar{x}$,

* and $b, \; \bar{b}, \; \tilde{b}, \; b_G, \; \tilde{A}$.

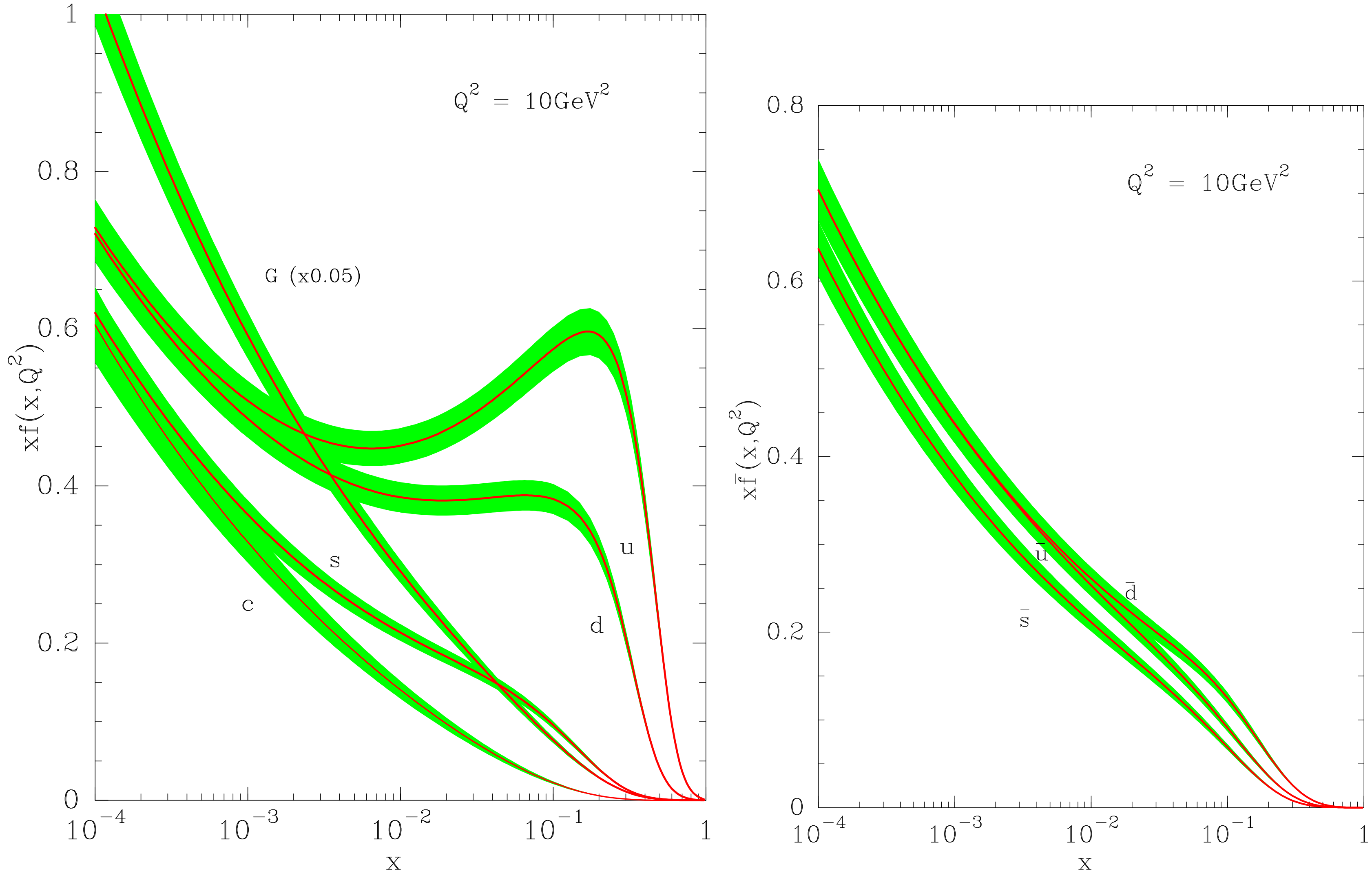
We also have three additional parameters, $A, \; \bar{A}, \; A_G$, which are fixed by 3 normalization conditions .

$$u - \bar{u} = 2, \;\; d - \bar{d} = 1$$

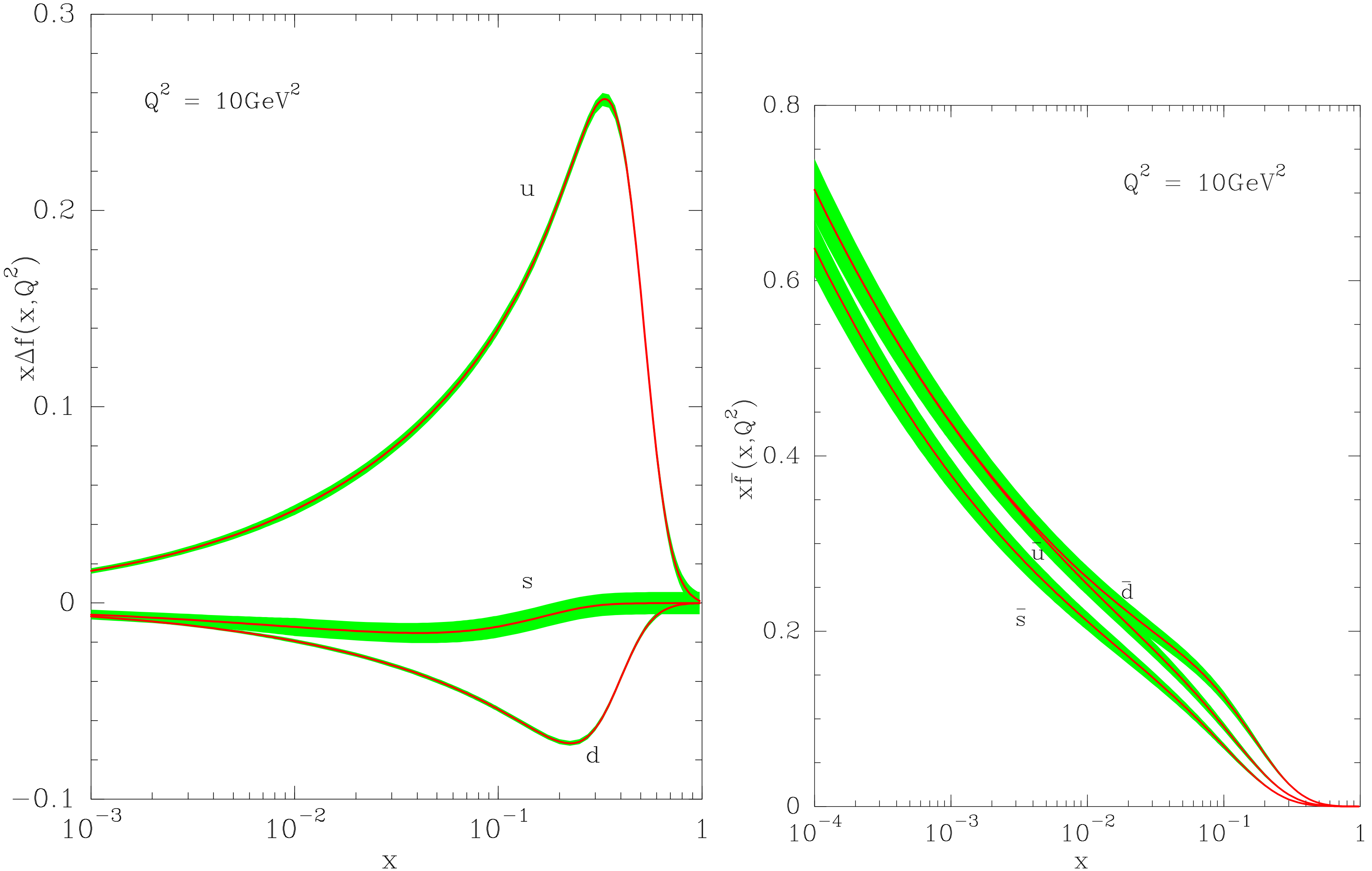
and the momentum sum rule.

There are several additional parameters to describe the strange quark-antiquark sector and for the gluon polarization. We use the constraint $s - \bar{s} = 0$.
We note that potentials become smaller for heaviest quarks and since $X_{0s}^- > X_{0s}^+$, we will have $\Delta s < 0$ like for d-quarks.

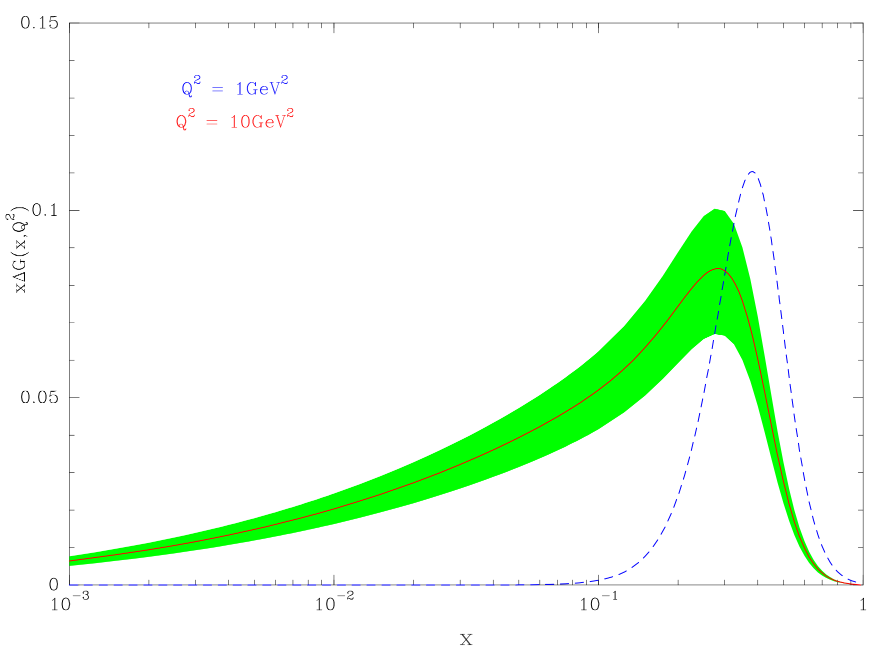
Resulting quark (antiquark) unpolarized distributions

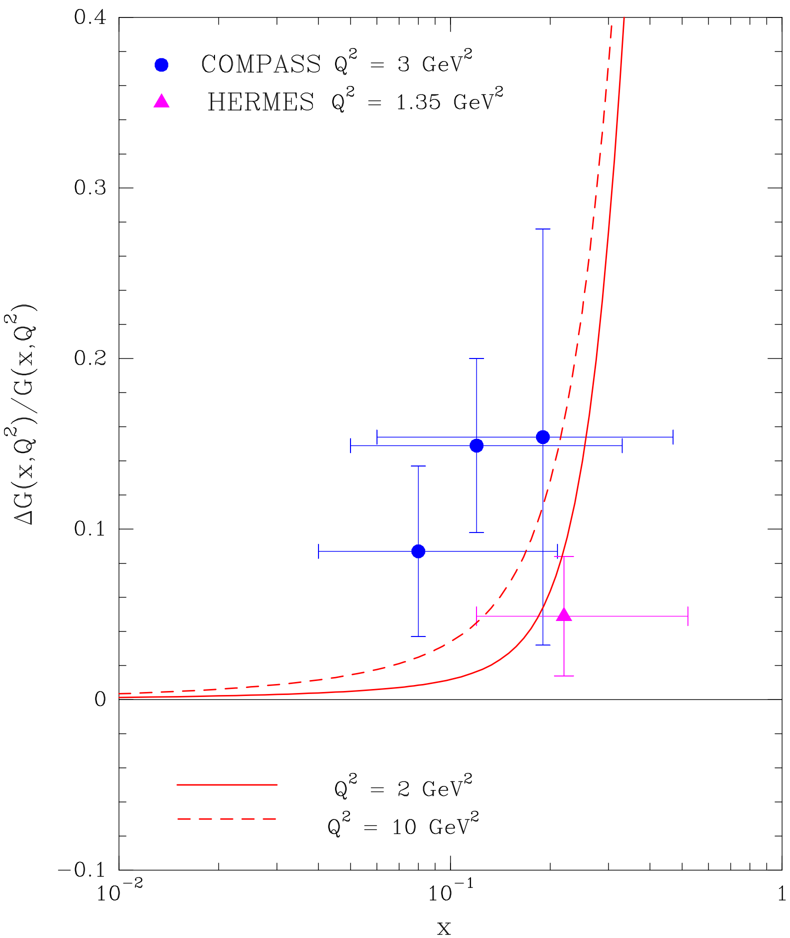


Resulting quark (antiquark) helicity distributions

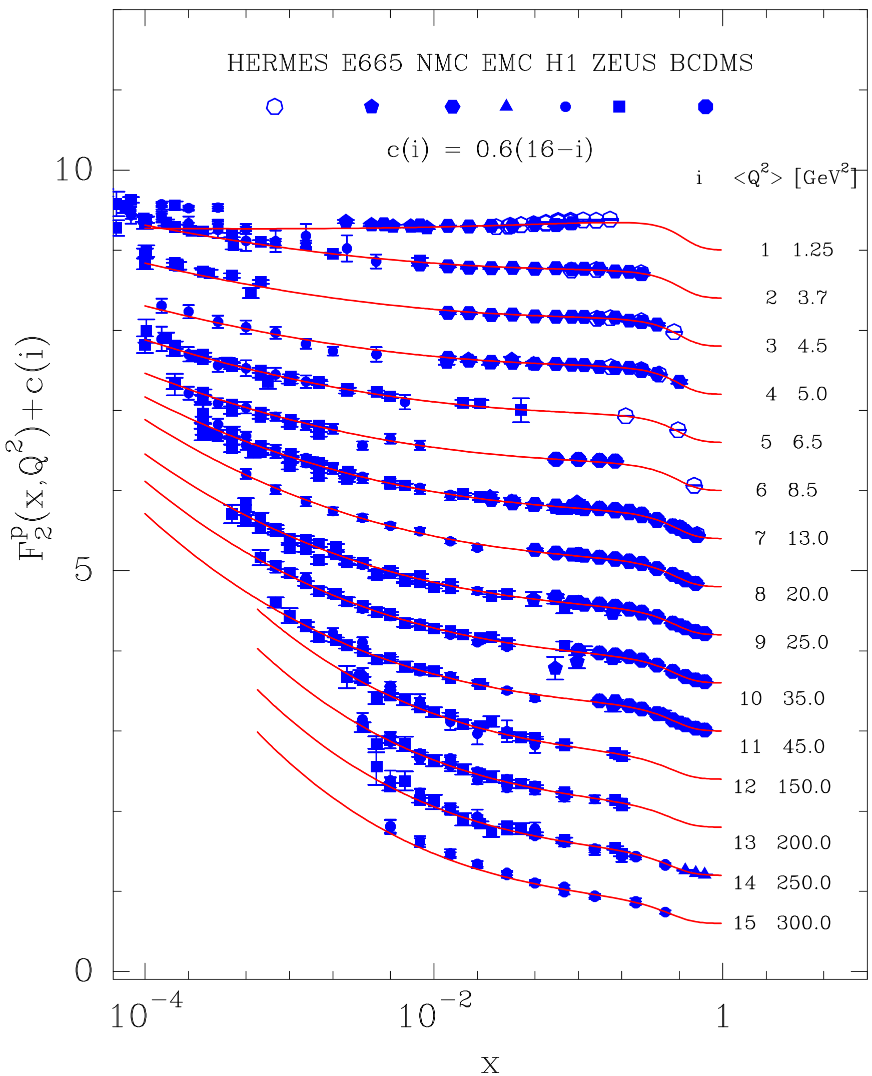


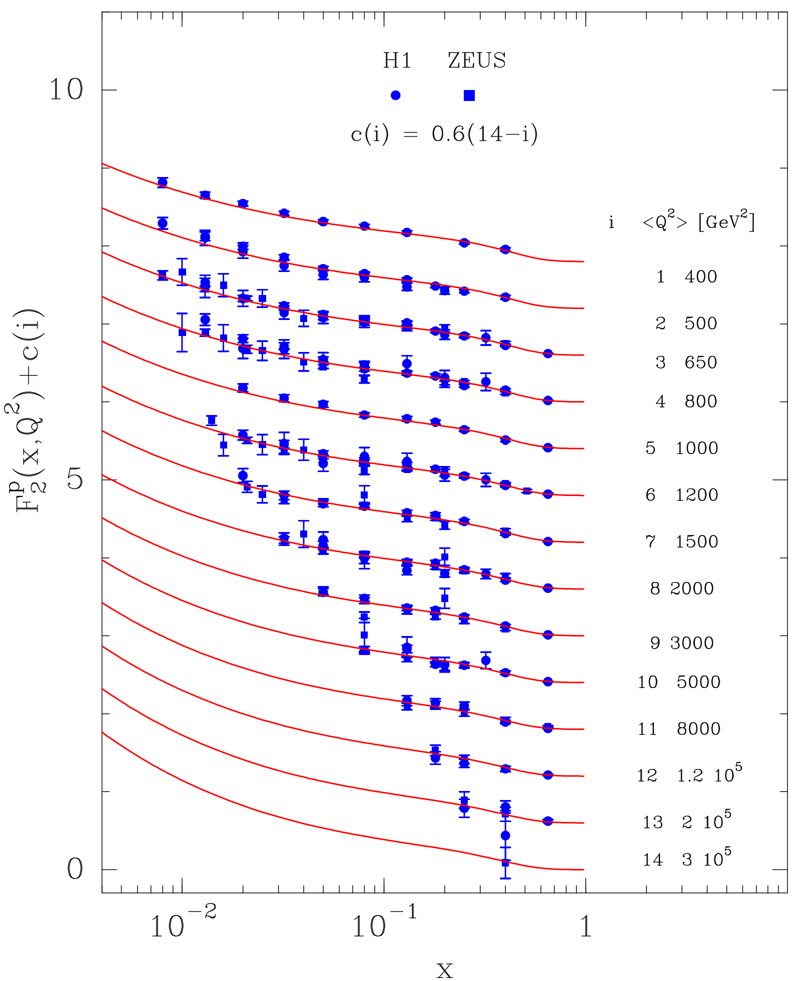
Resulting gluon helicity distribution



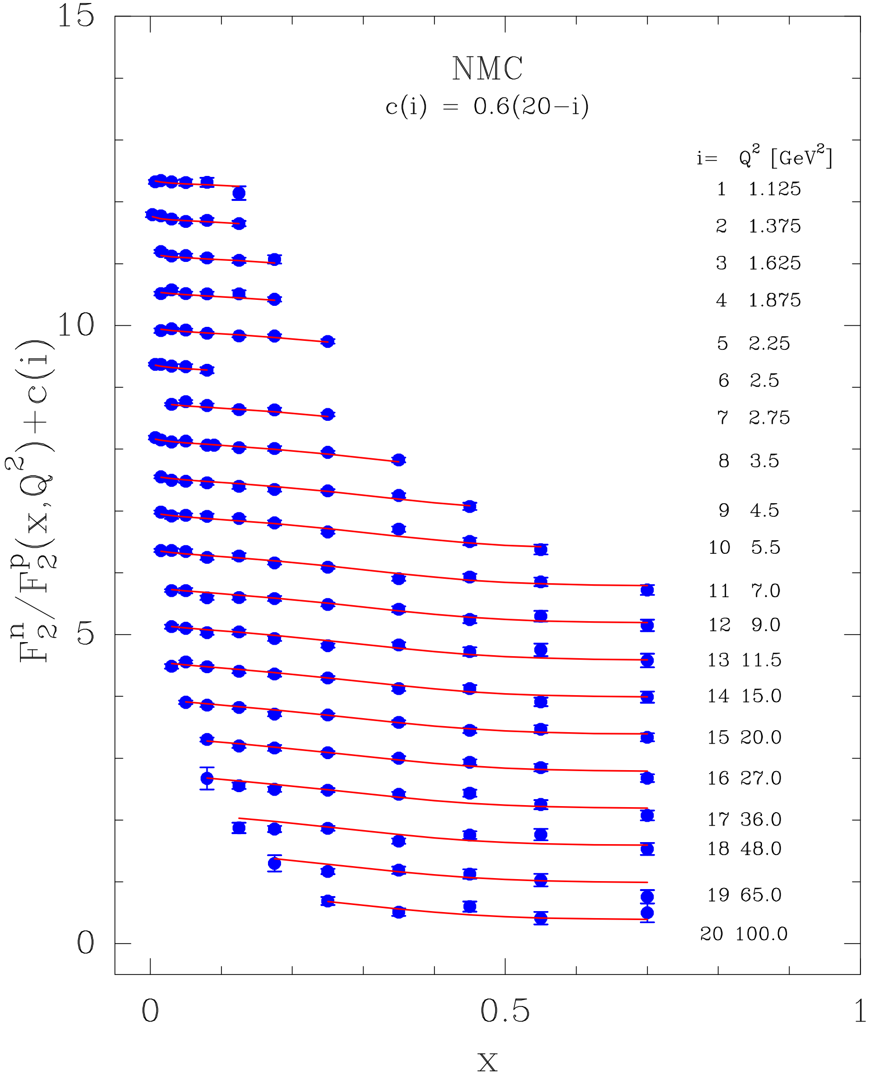


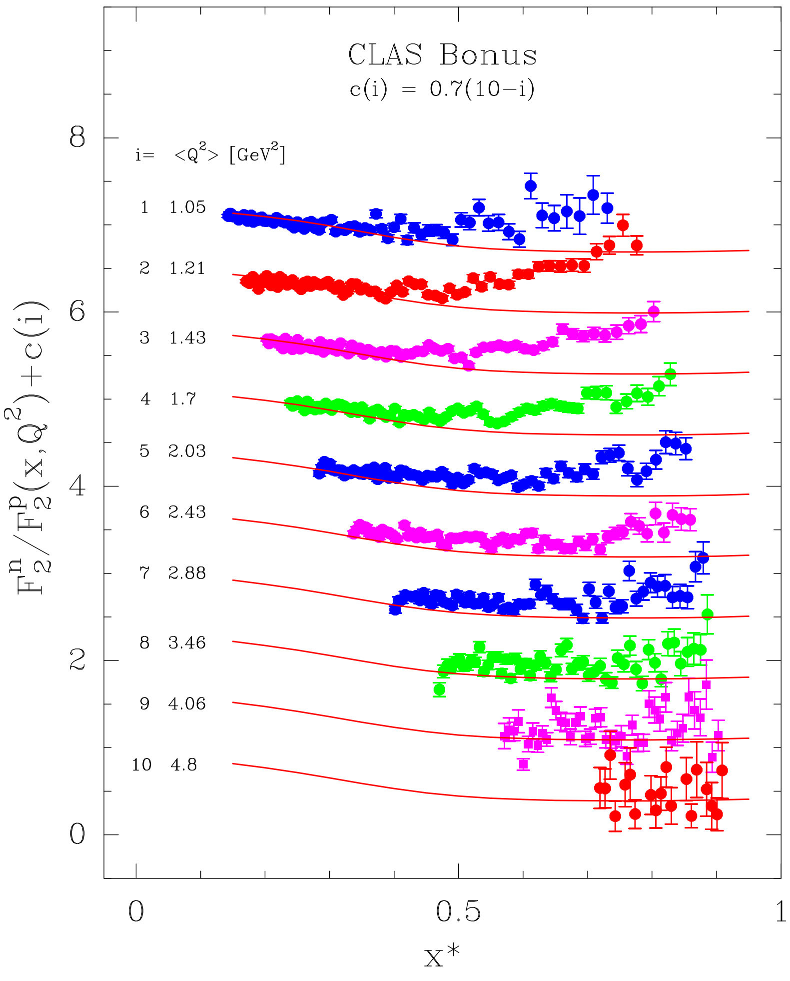
Some data on $F_2^p(x, Q^2)$



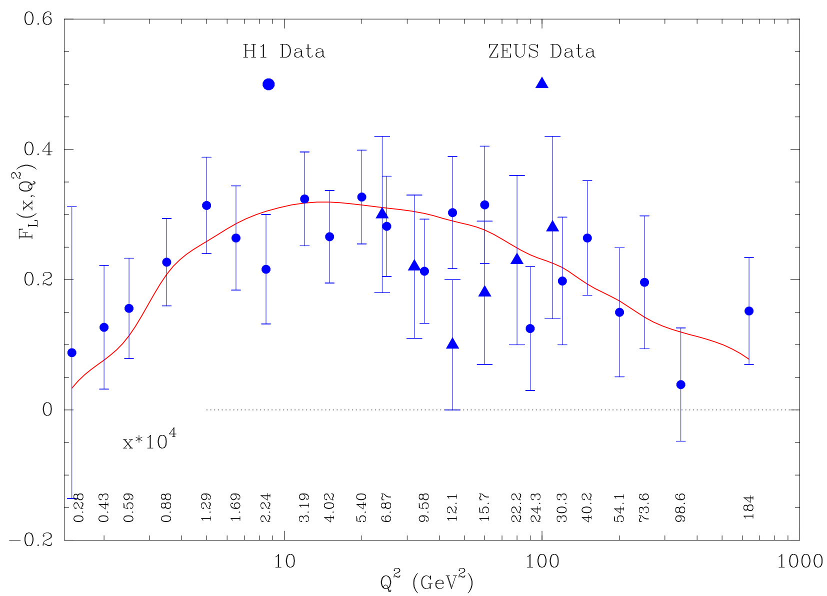


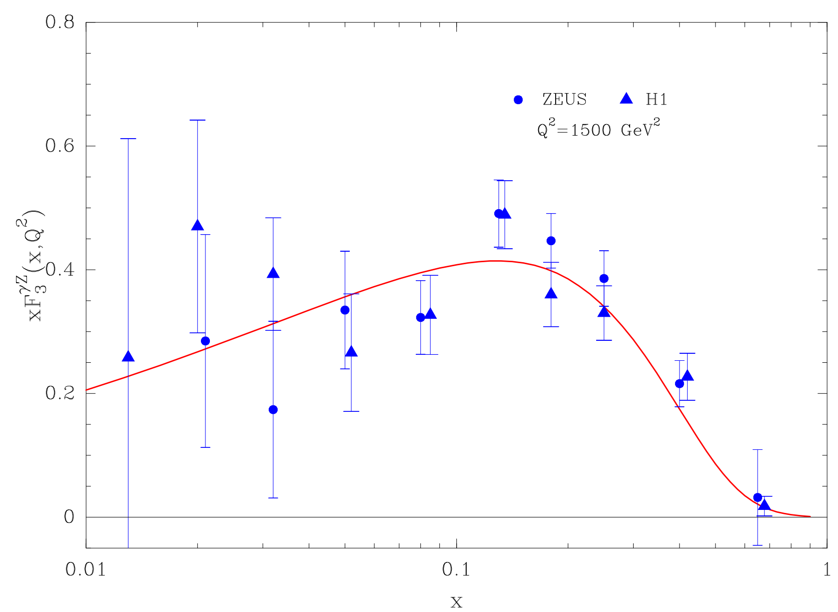
Some data on $F_2^n(x,Q^2)/F_2^p(x,Q^2)$



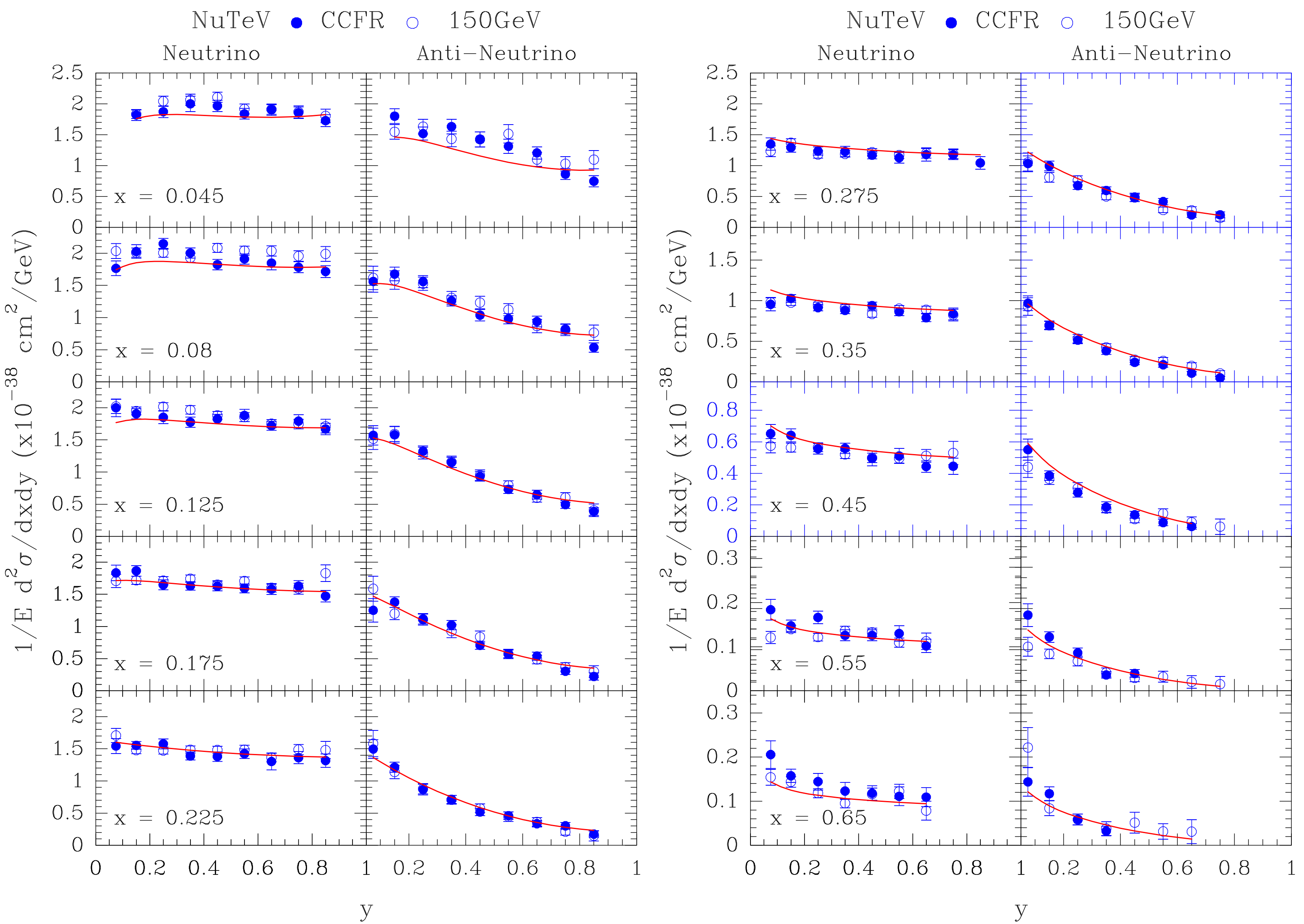


Some data on $F_L(x, Q^2)$ and $xF_3^{\gamma Z}(x, Q^2)$

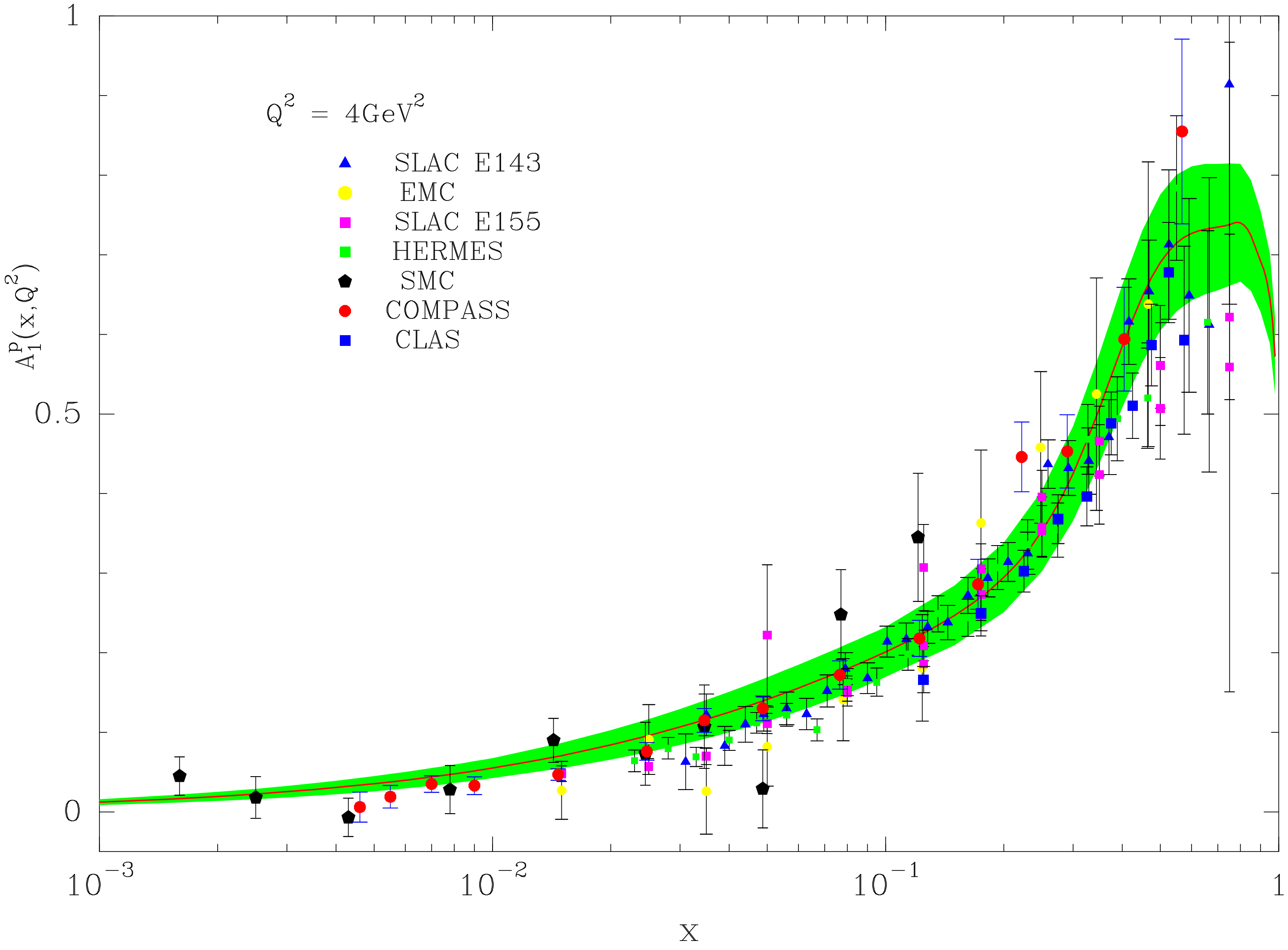




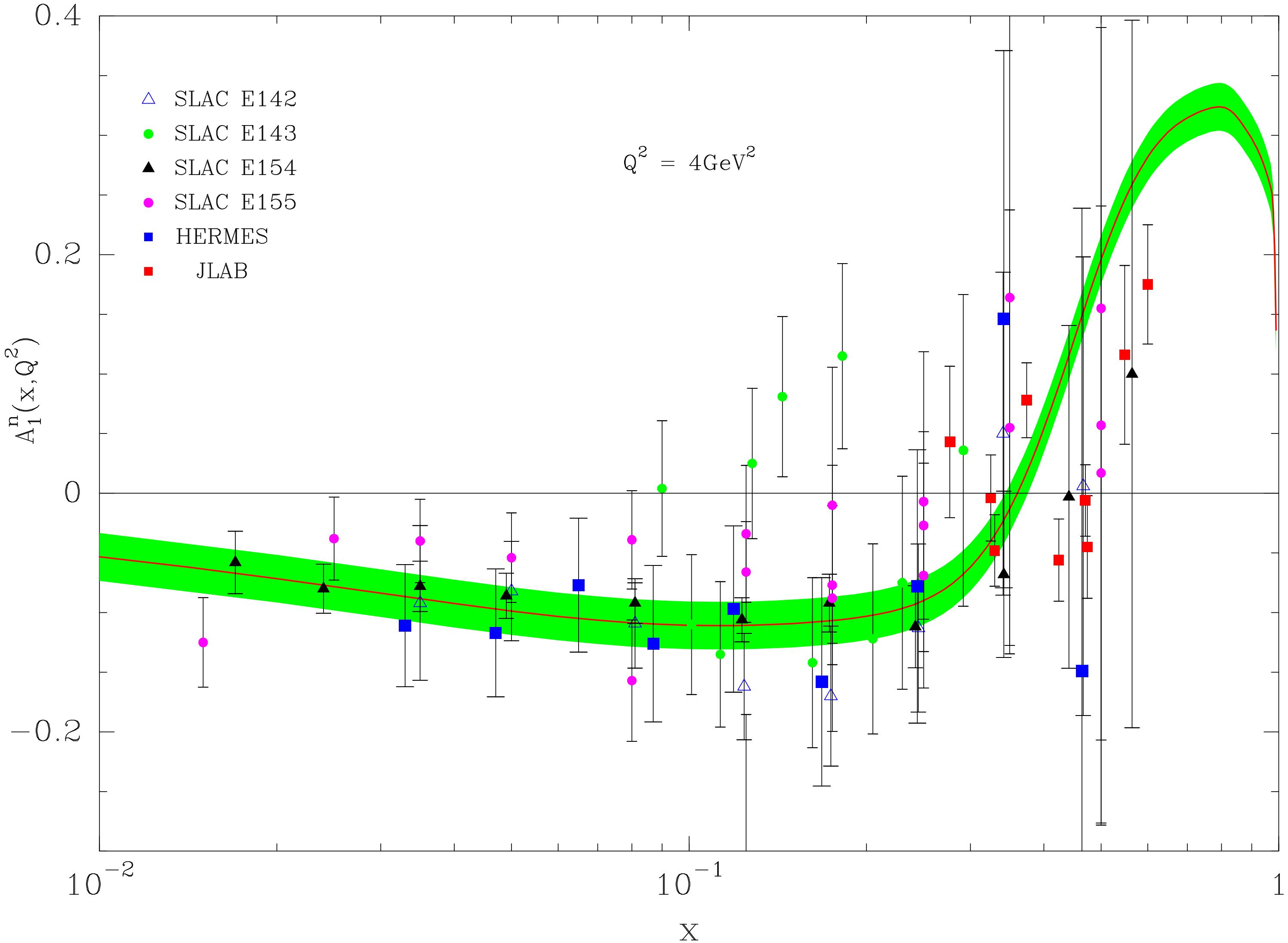
Some data on neutrino-antineutrino cross sections



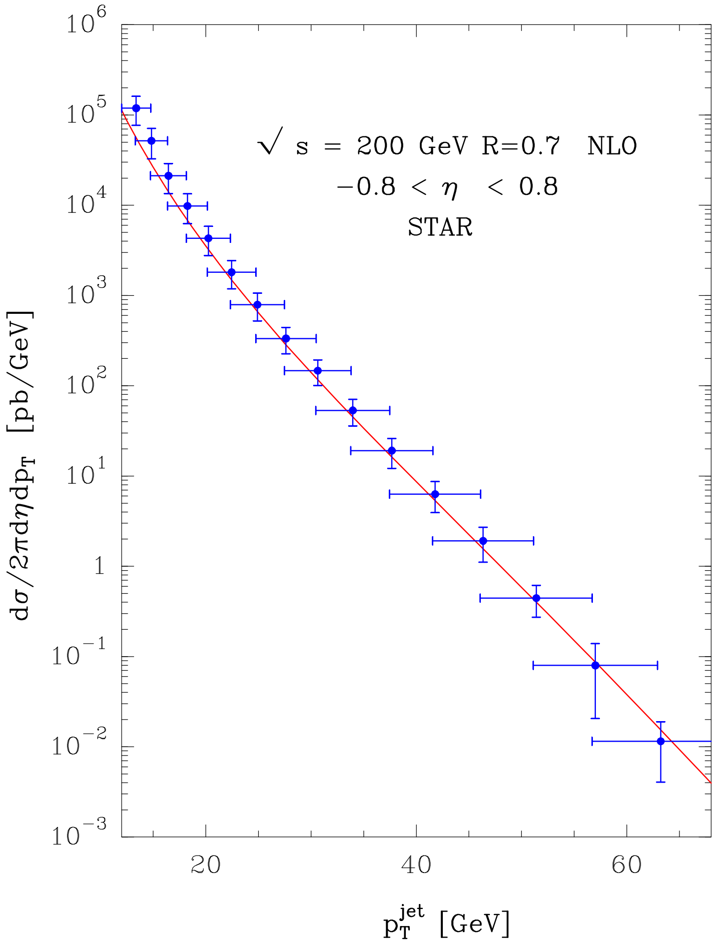
Polarized DIS - A compilation of data on $A_1^p(x, Q^2)$

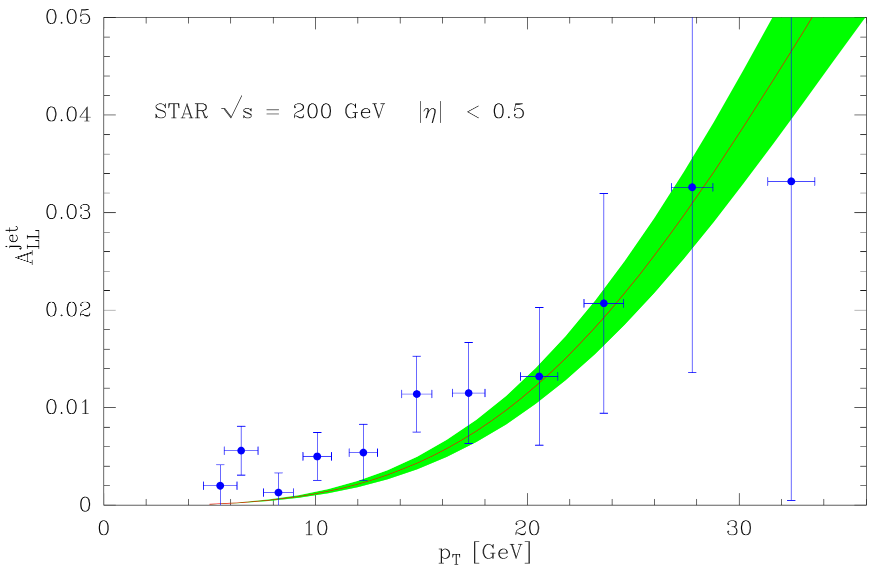


Polarized DIS - A compilation of data on $A_1^n(x, Q^2)$

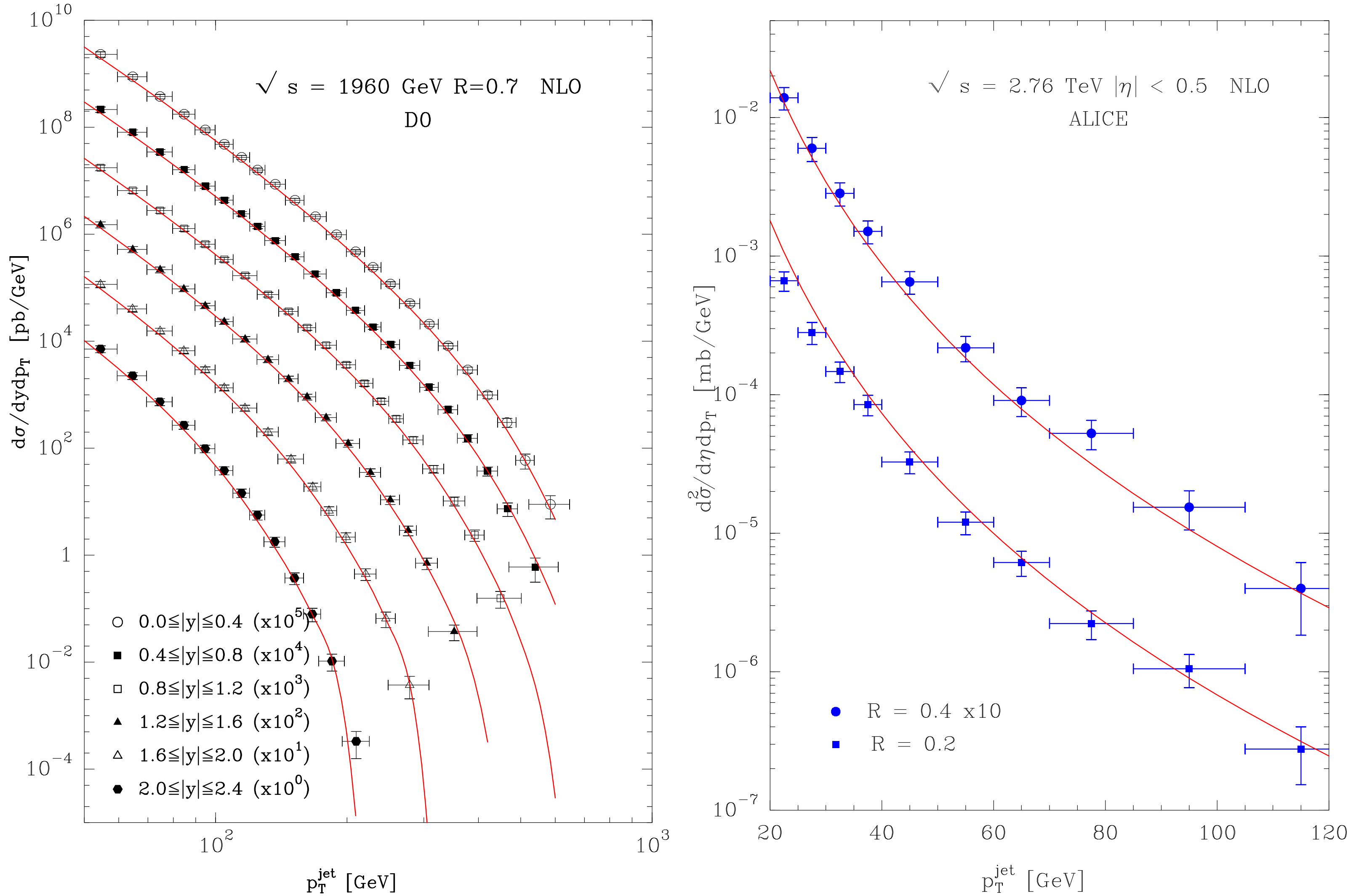


Single-jet production at RHIC: cross section and double helicity asymmetry

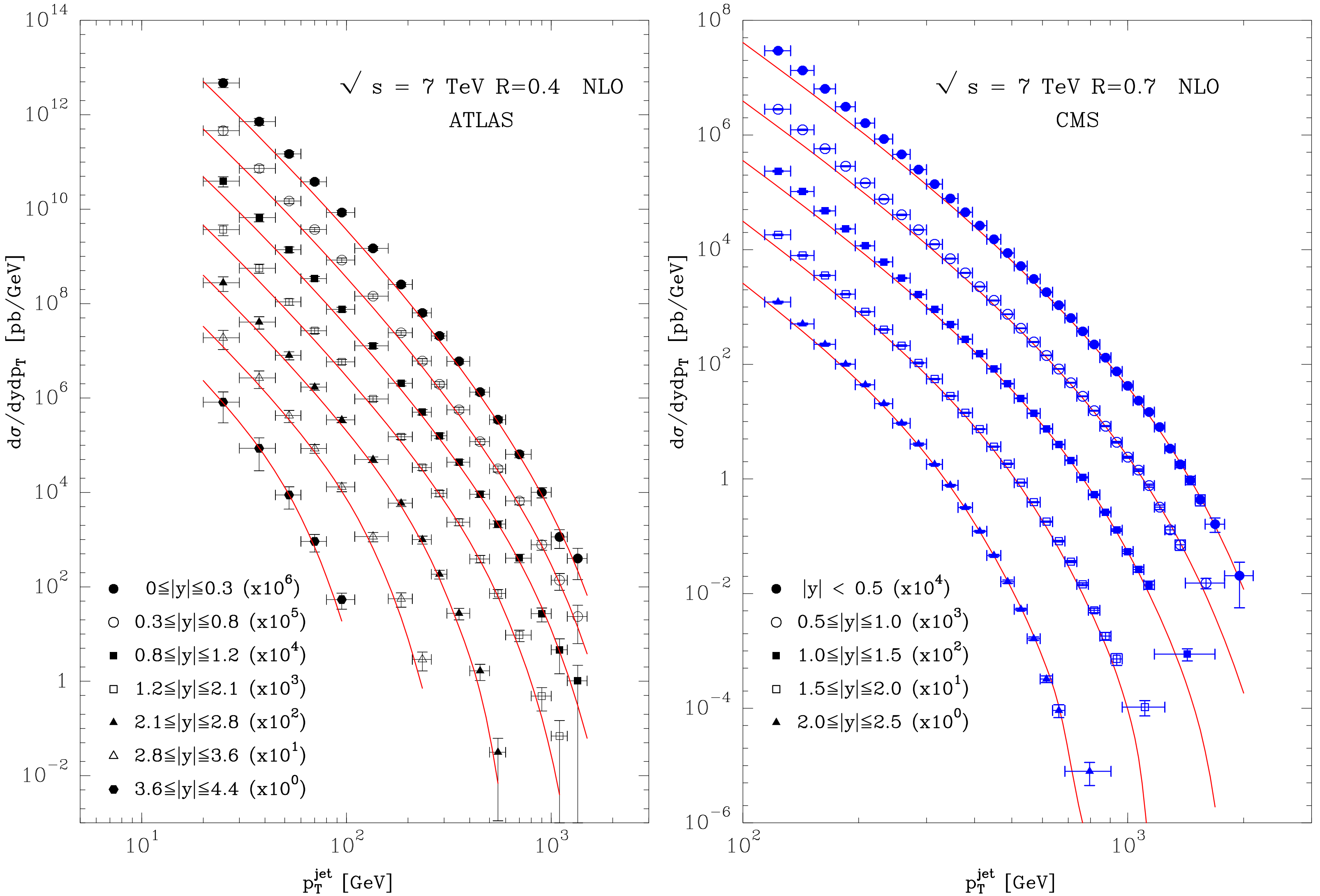




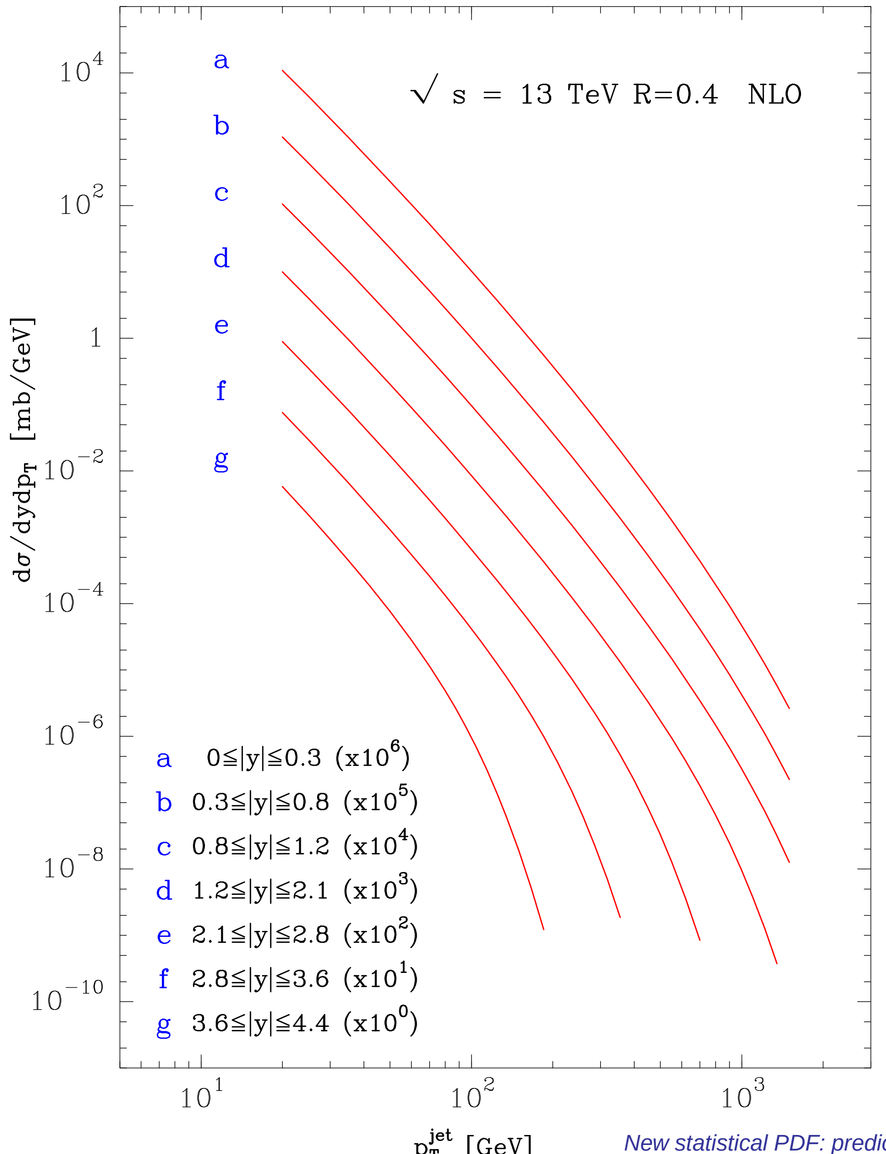
Single-jet production at Tevatron and ALICE



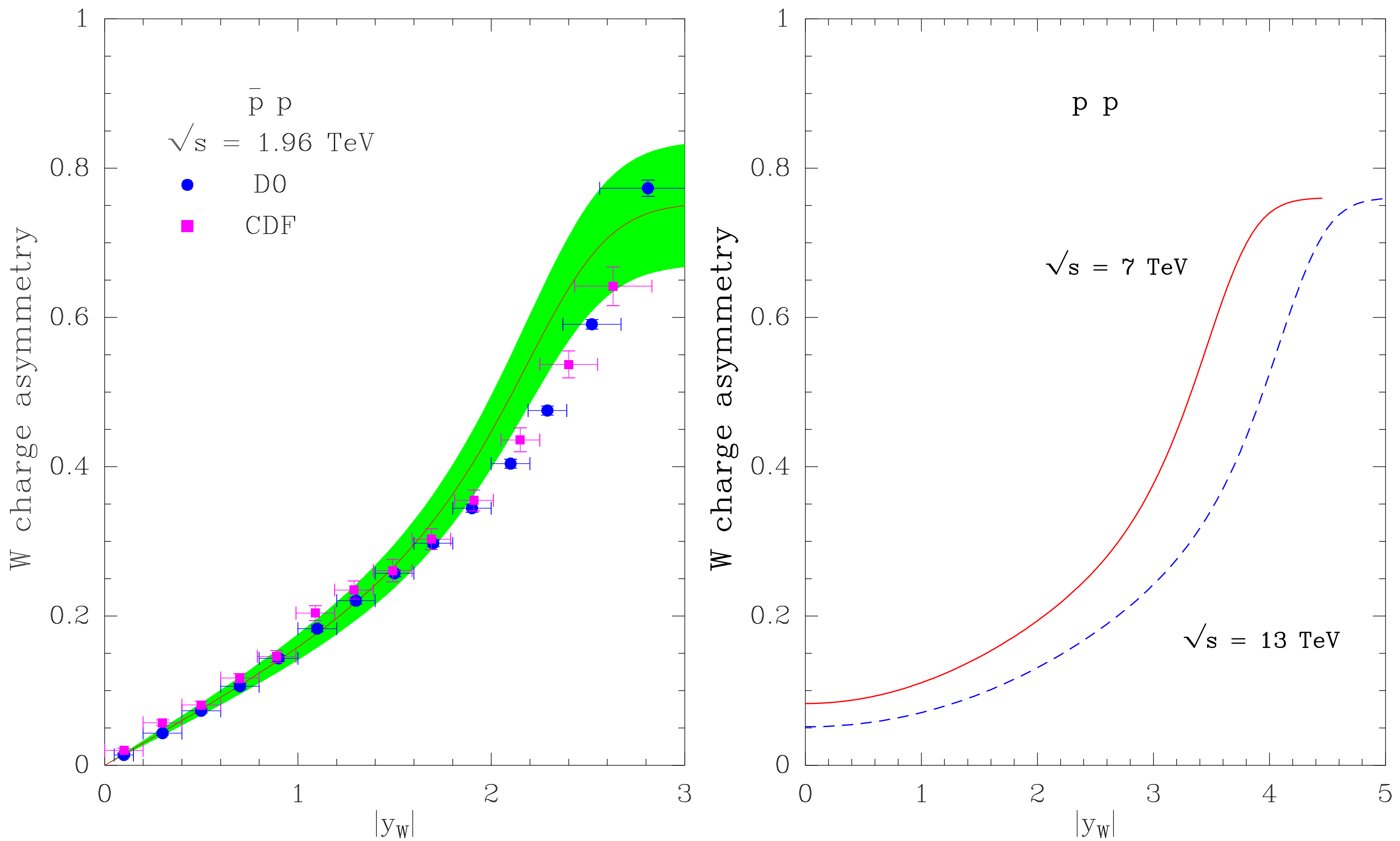
Single-jet production at ATLAS and CMS



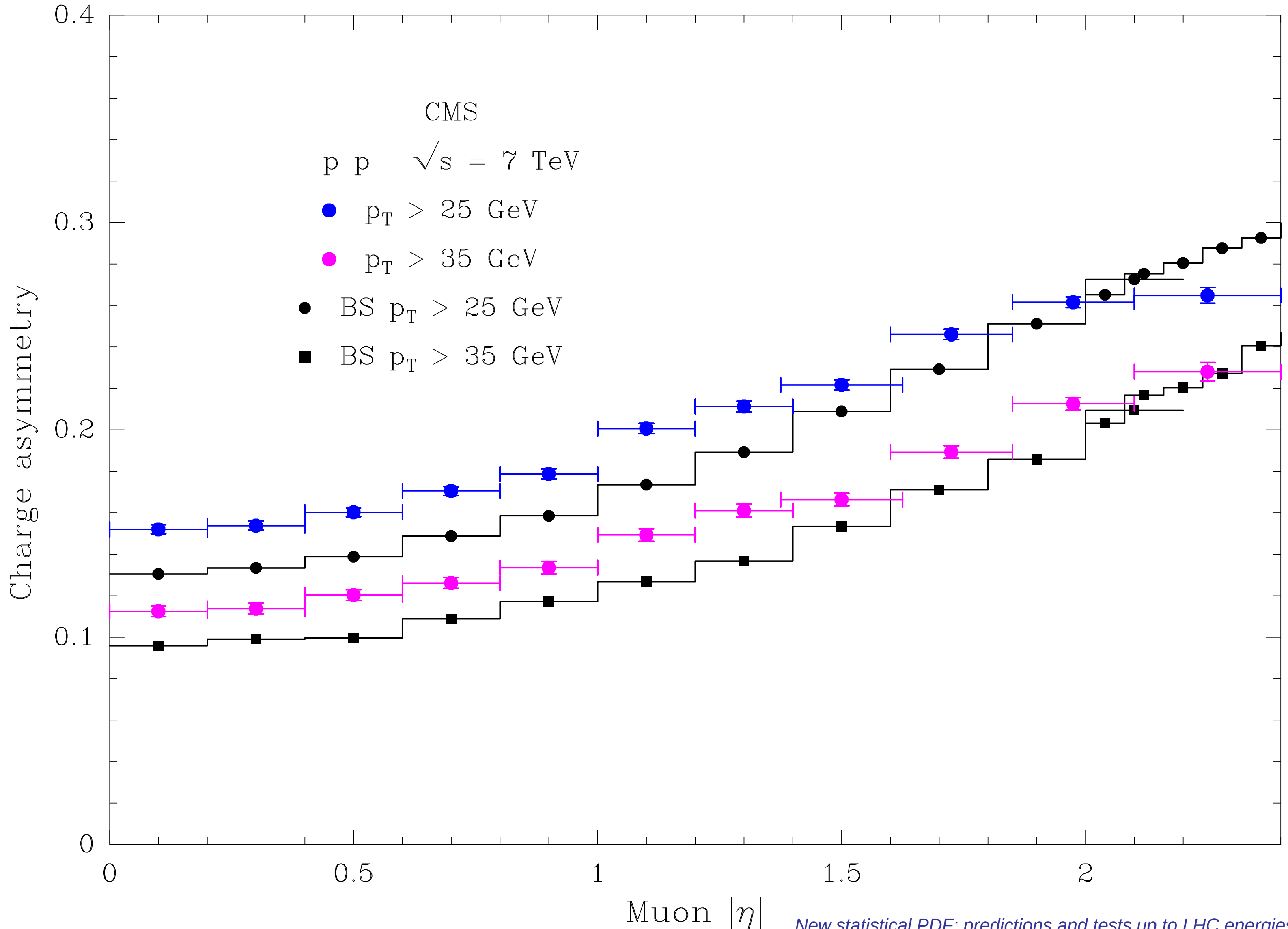
Single-jet production at LHC 13TeV (run 2)



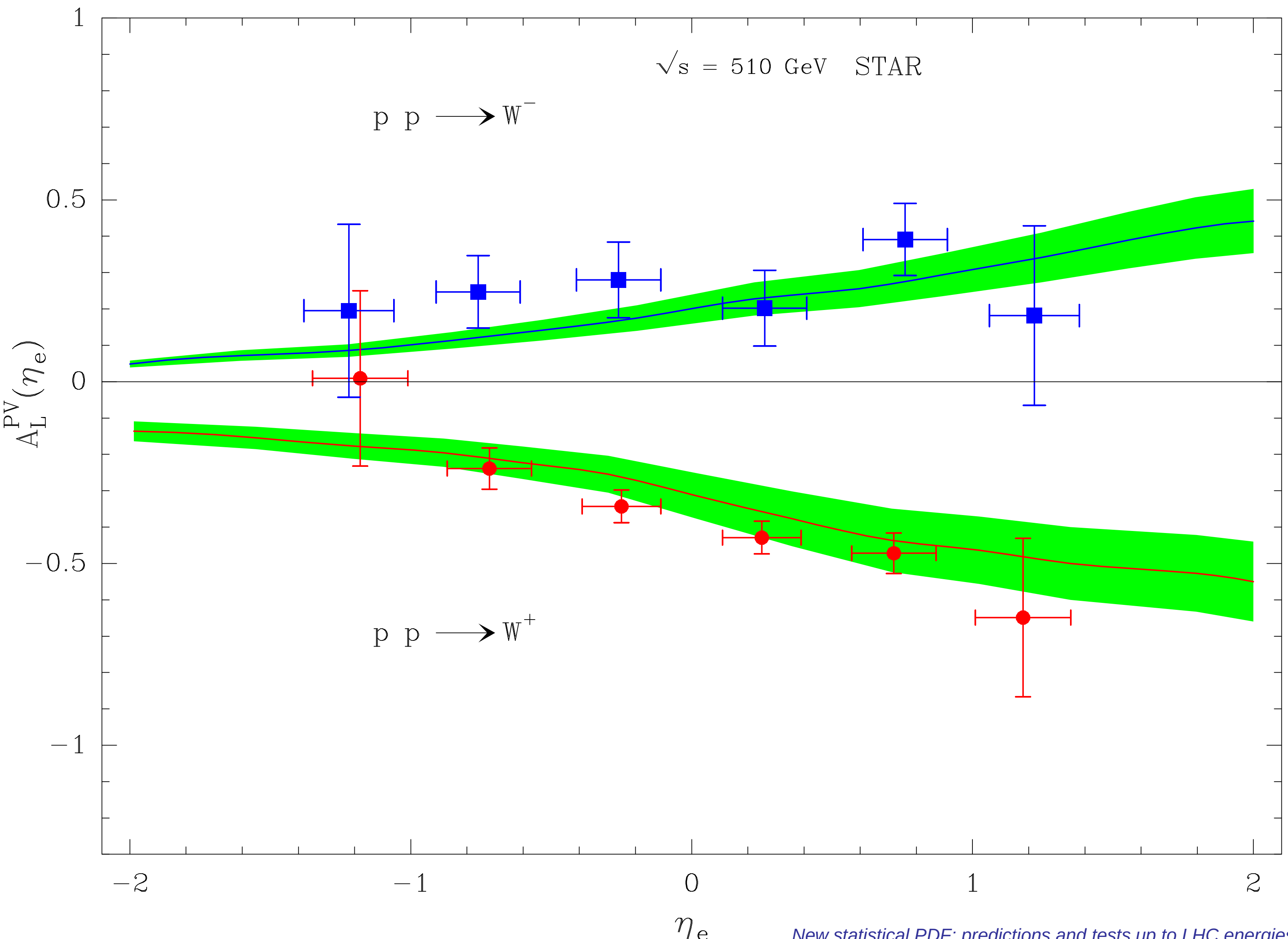
Charge asymmetry in $W^{\pm}$ production at Tevatron versus the W rapidity and prediction for LHC



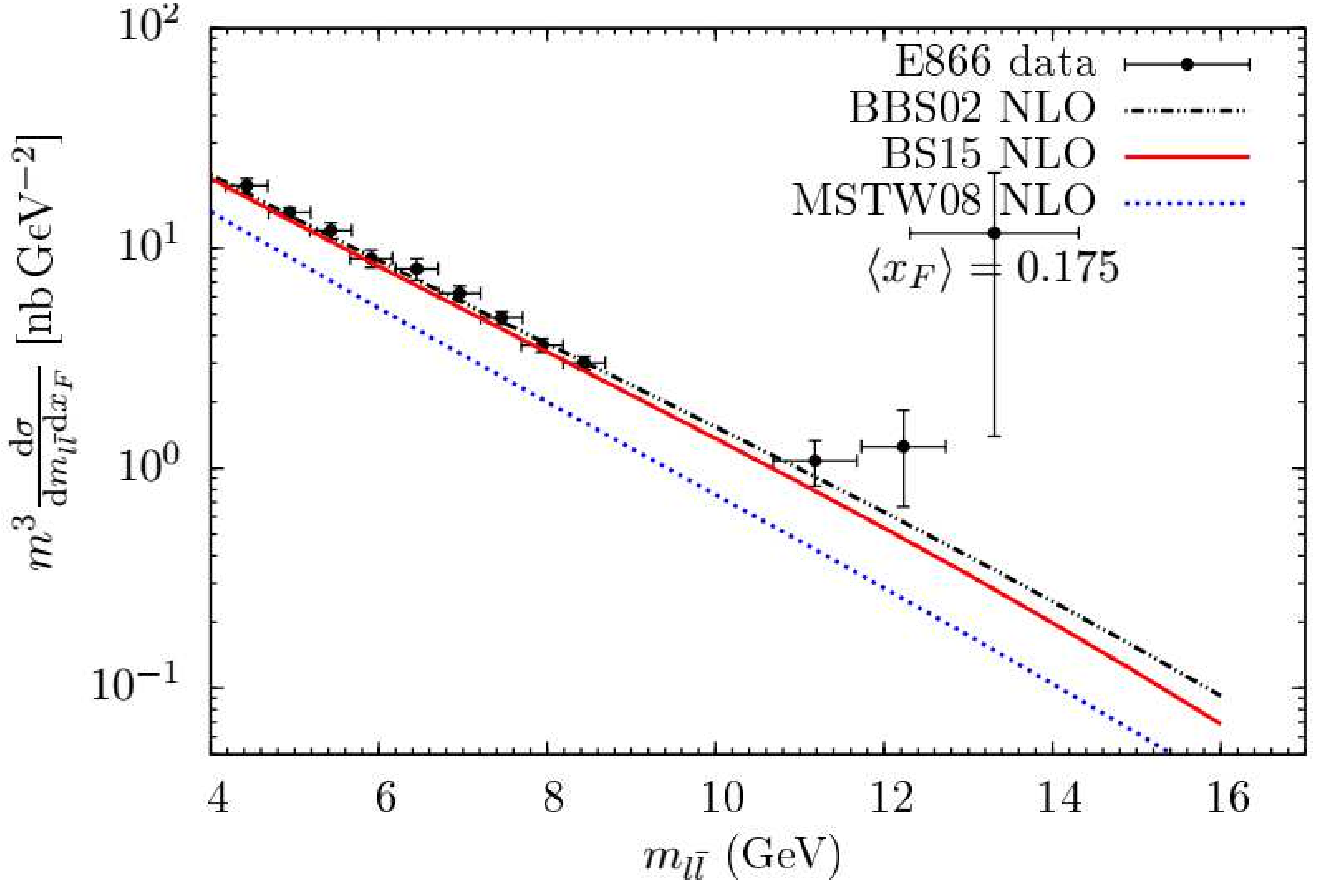
Charge asymmetry in $W^{\pm}$ production at LHC versus the charge lepton rapidity



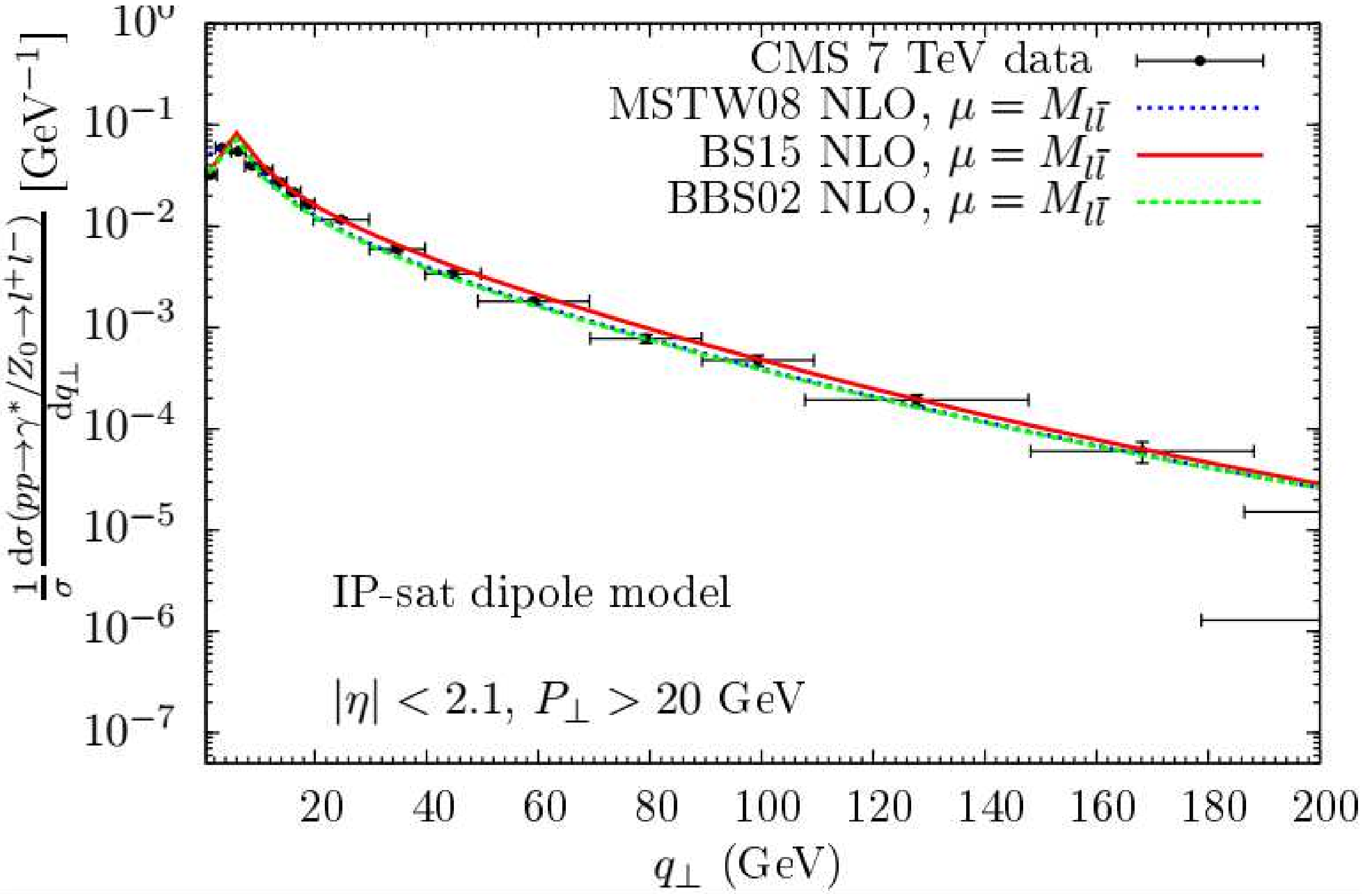
The parity-violating helicity asymmetry for $W^{\pm}$ production versus the charged-lepton rapidity



Drell-Yan process (Work in progress with R. Pasechnik and E. Basso)



Drell-Yan process (Work in progress with R. Pasechnik and E. Basso)



Conclusions

- A new set of PDF is constructed in the framework of a statistical approach of the nucleon.
- All unpolarized and polarized distributions depend upon a small number of free parameters, with some physical meaning.
- New tests against experiments in particular, for unpolarized and polarized sea distributions, are very satisfactory.
- A large positive gluon helicity distribution emerges concentrated in the medium x-region

  NEED TO BE CONFIRMED
- This statistical approach has a good predictive power up to LHC energies
- Future tests will be very challenging