New statistical PDF: predictions and tests up to LHC energies

Jacques Soffer

Department of Physics, Temple University, Philadelphia, PA, 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:
  Find a new gluon helicity distribution (to be confirmed)
- Predictions for hadron colliders up to LHC energy:
  The structure of the nucleon light sea a new challenge
  Cross sections and Helicity asymmetries for single-jet and $W^{\pm}$ production
- 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)

- $W^{\pm}$ 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
Nucl. Phys. A941, 307 (2015)
- The Drell-Yan process as a testing ground for parton distributions up to LHC
Nucl. Phys. A948, 63 (2016) (with Eduardo Basso and Roman Pasechnik)

Hadron production using statistical models is an old story

- E. Fermi, Phys. Rev. 92, 452 (1953)
- I. Ya. Pomeranchuk, Izv. Dokl. Akad. Nauk Ser.Fiz. 78, 889 (1951)
- L.D. Landau, Izv. Akad. Nauk Ser. Fiz. 17, 51 (1953)
- R. Hagedorn, Supple. al Nuovo Cimento III, 147 (1965)
- R. Hagedorn, Nuovo Cimento 35, 395 (1965)
- R. Hagedorn, Nuovo Cimento A 56, 1027 (1968)

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 also consider the case of the elusive gluon helicity distribution

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

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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 (see below)

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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 $x\Delta s(x, Q_0^2) \neq x\Delta\bar{s}(x, Q_0^2)$ (Phys. Lett. B648, 39 (2007)).

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

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- $u(x)$ 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 below).

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- 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).

This is a very important prediction of the statistical approach resulting from the SIMULTANEOUS fitting of unpolarized and polarized DIS data

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 $b,\ \bar{b},\ \tilde{b},\ b_G,\ \tilde{A}$.

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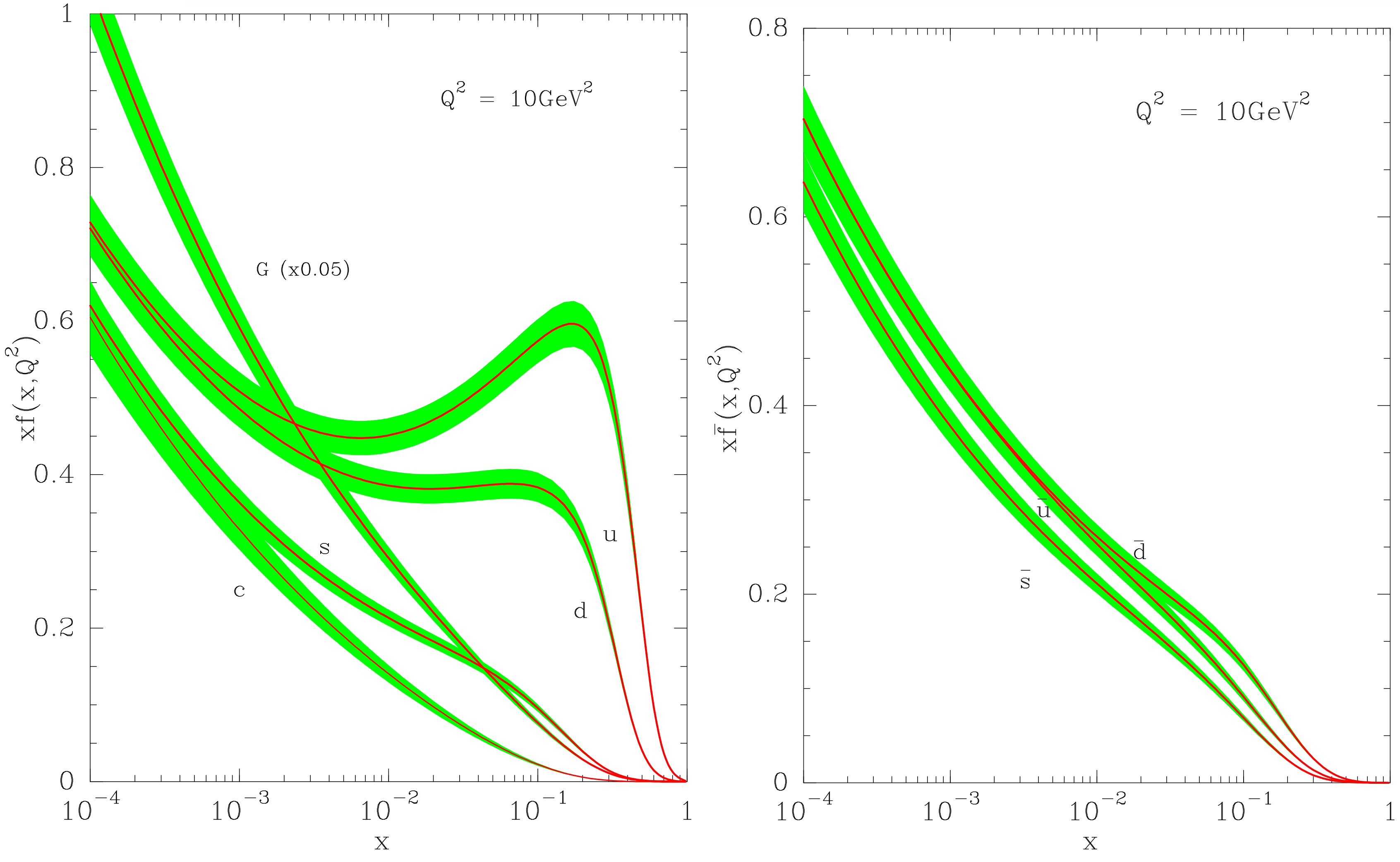
We also have three additional parameters, $A,\ \bar{A},\ A_G$, which are fixed by 3 normalization conditions .

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

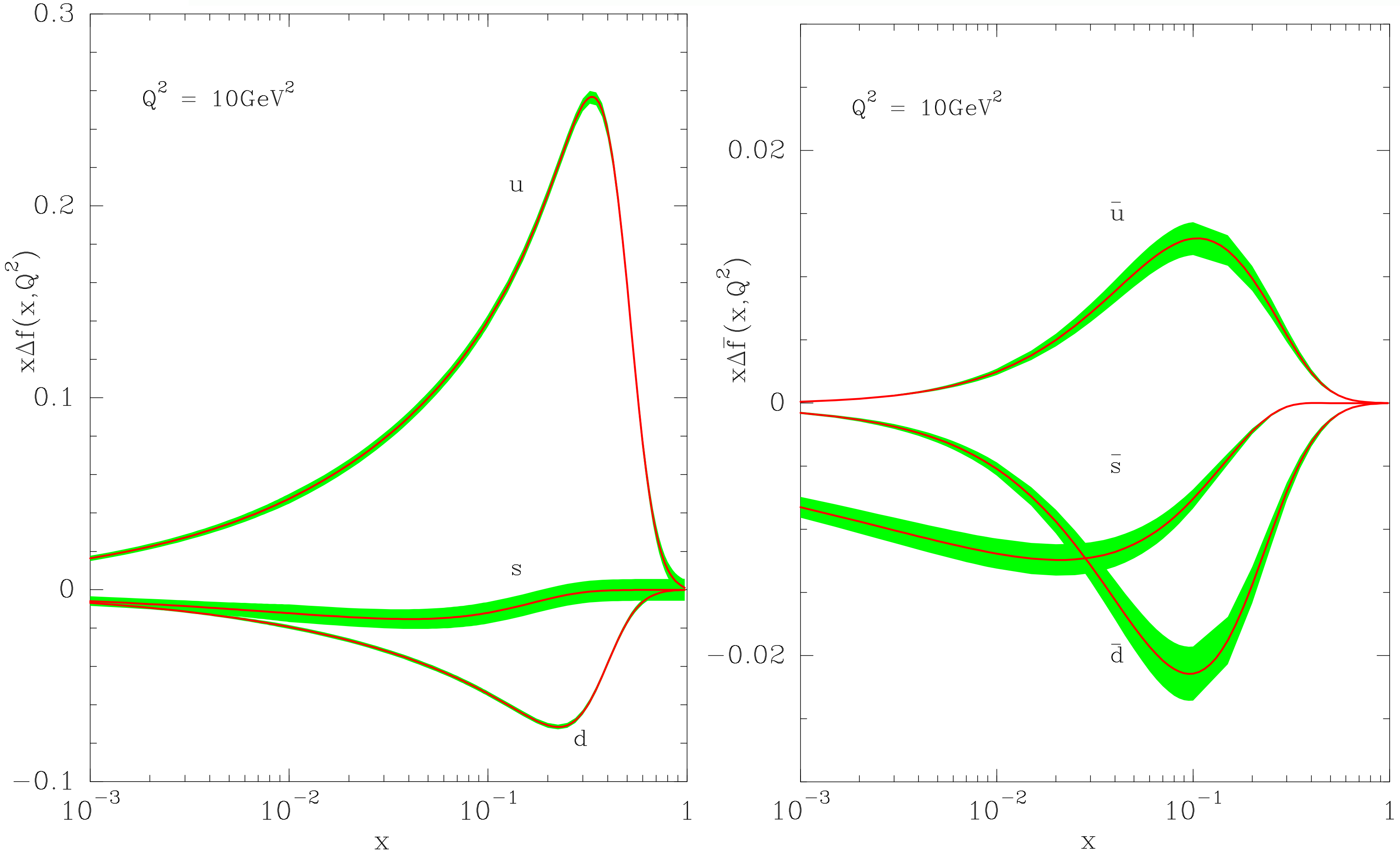
and the momentum sum rule.

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.

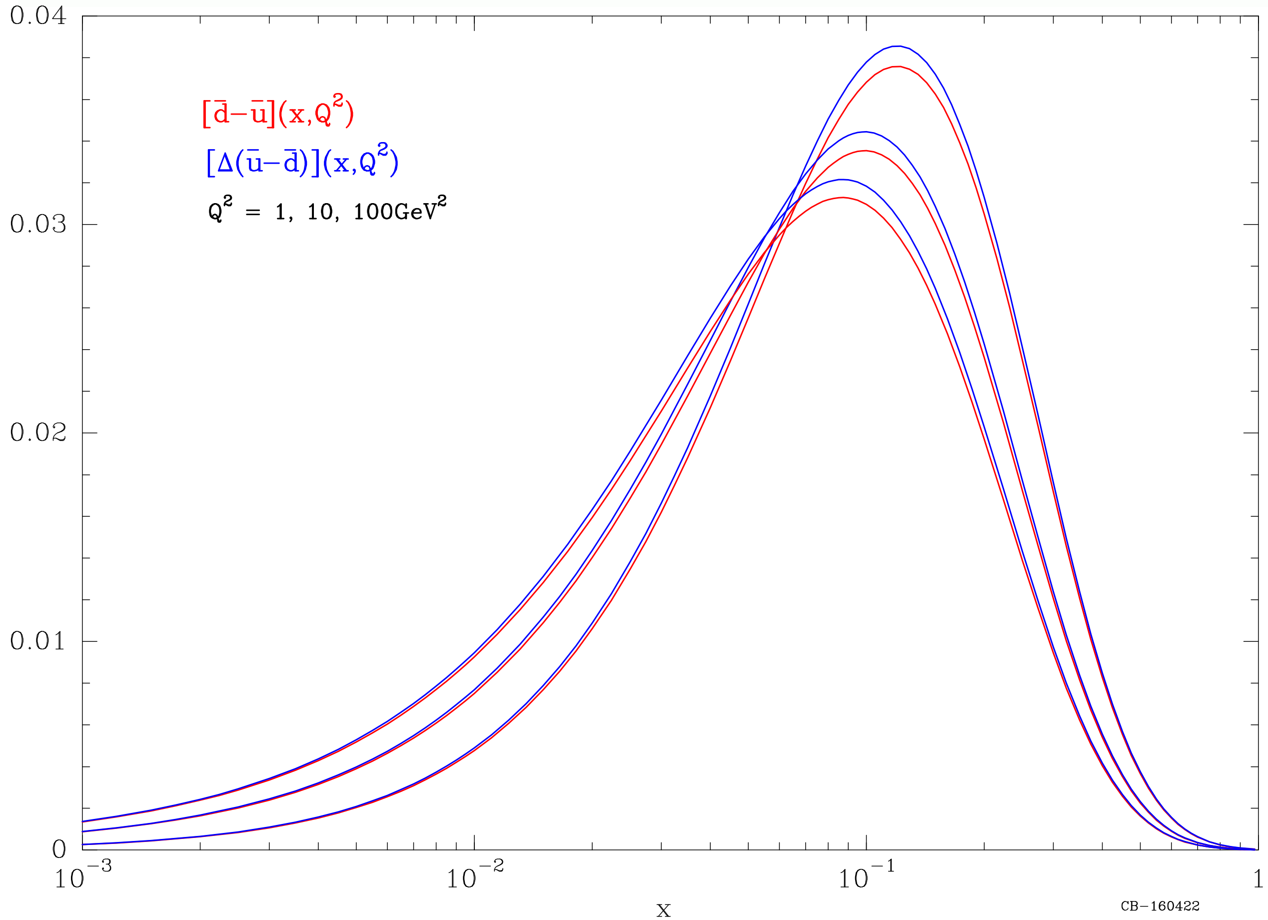
A global view of the unpolarized parton distributions



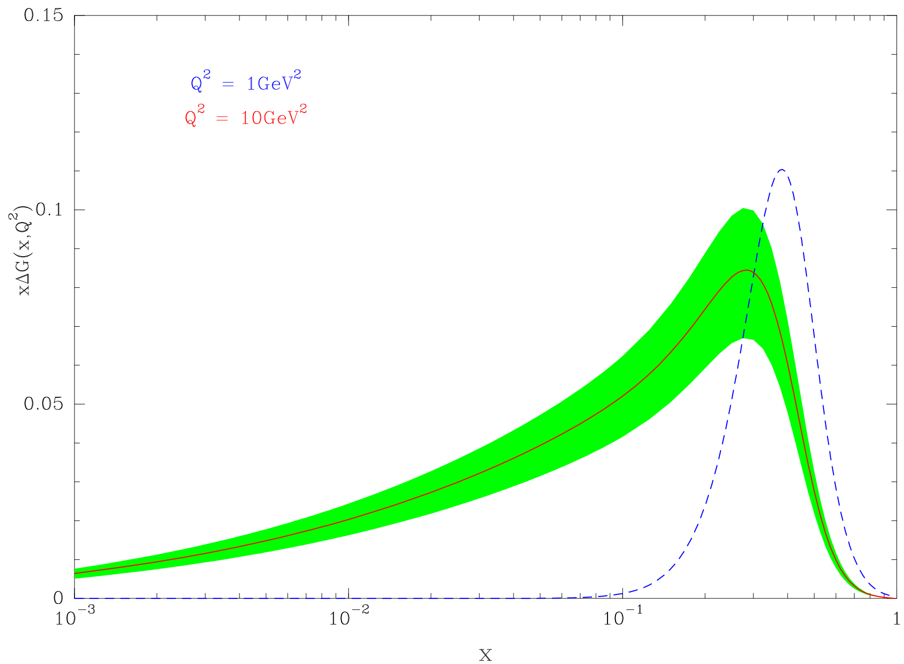
A global view of the quark (antiquark) helicity distributions

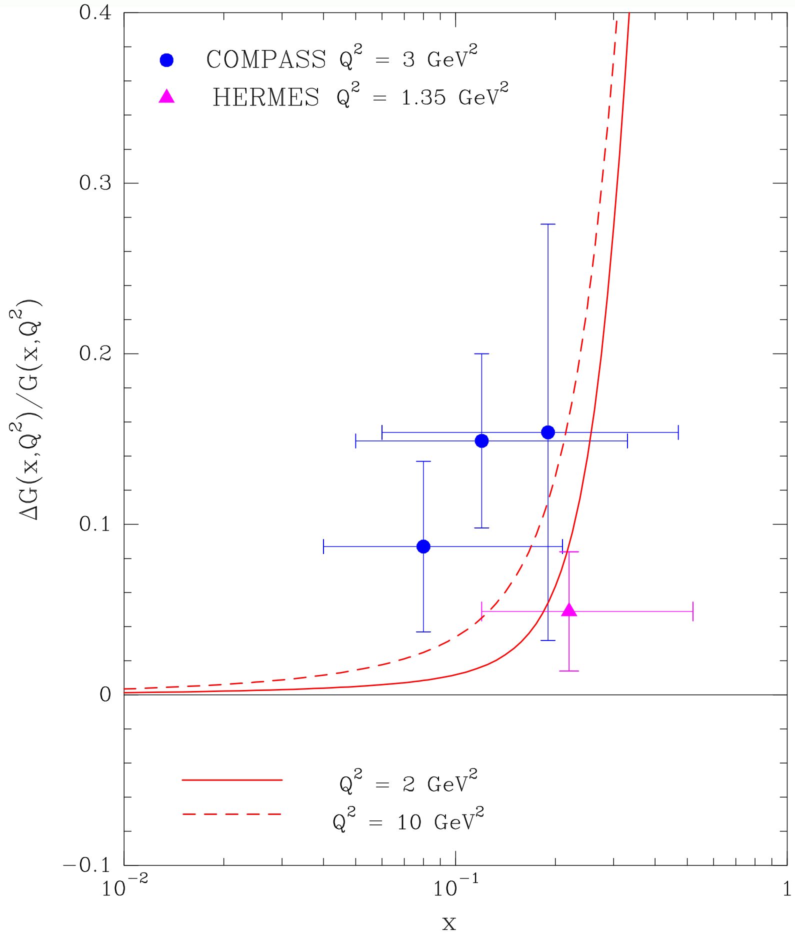


Sea quark flavor asymmetry



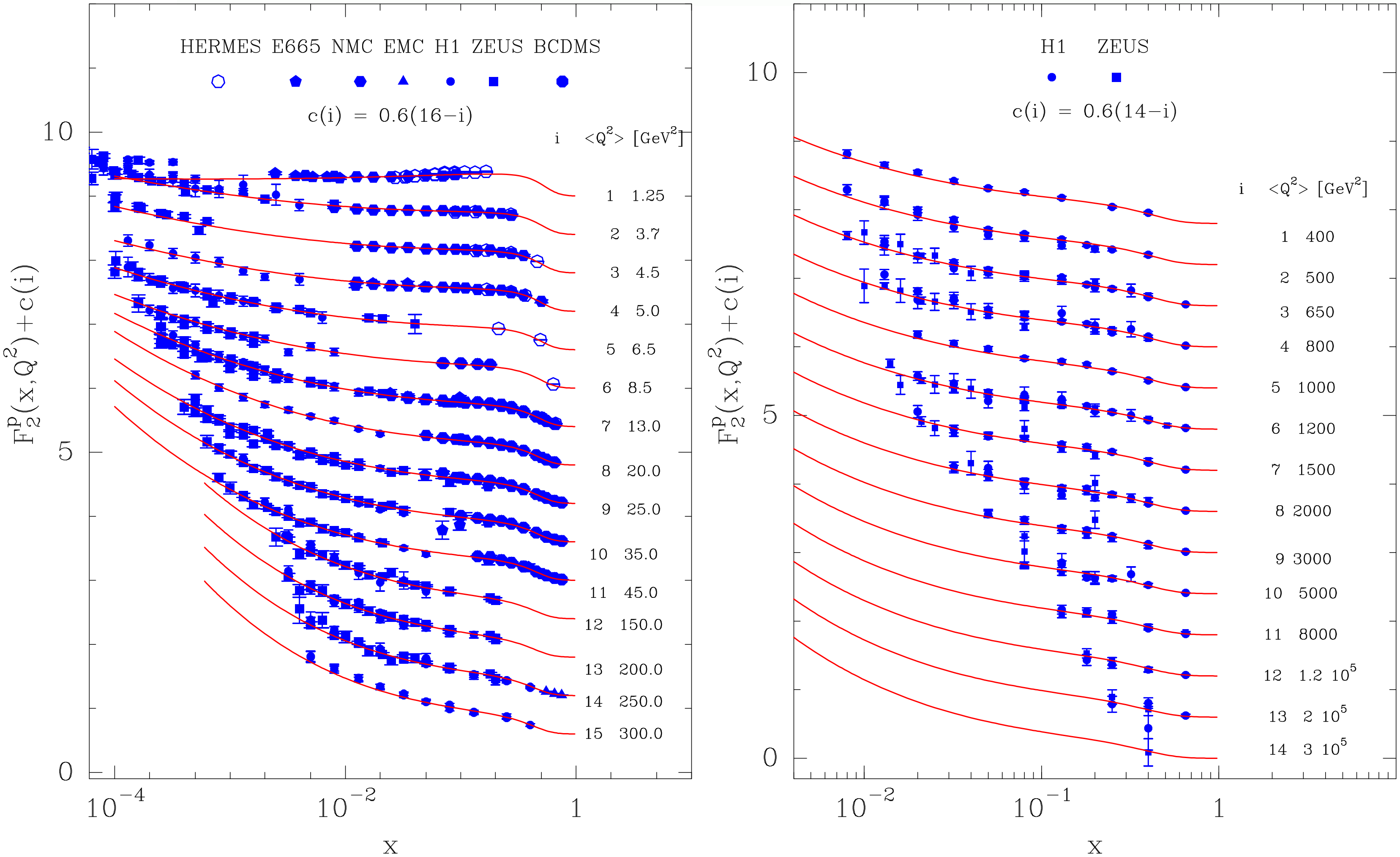
The resulting gluon helicity distribution



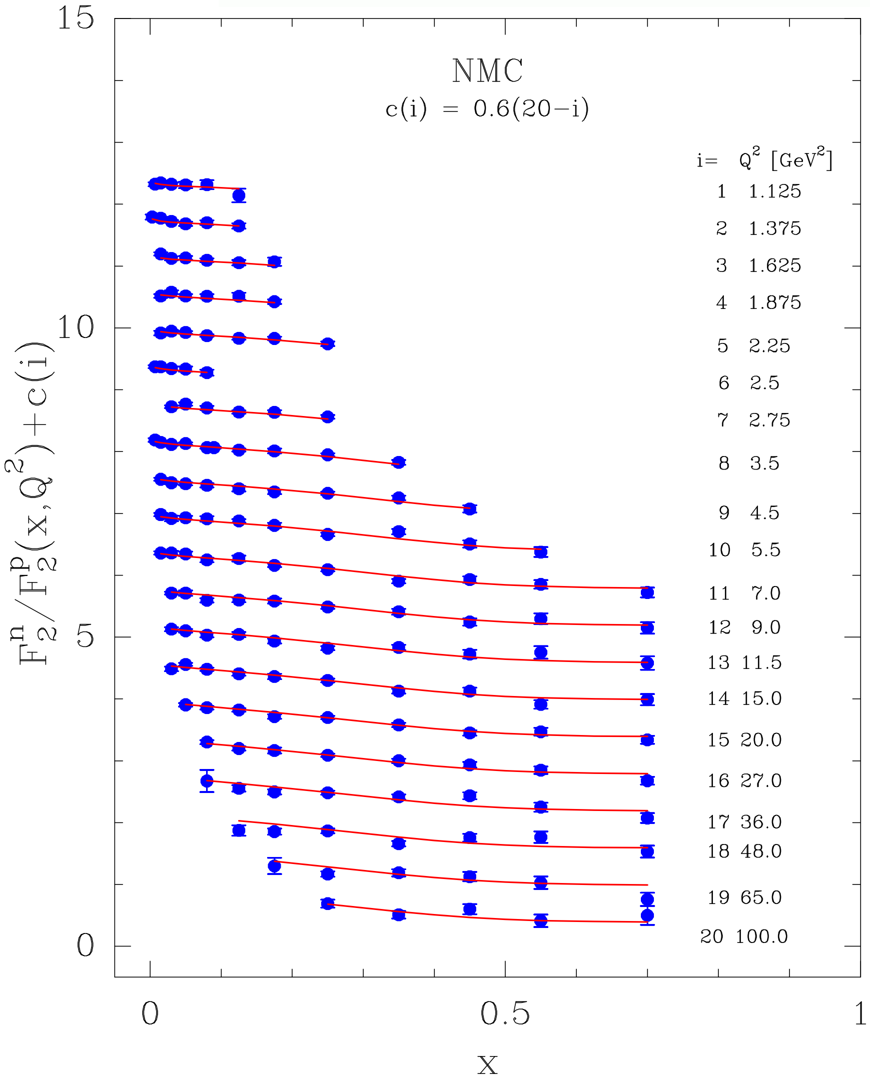


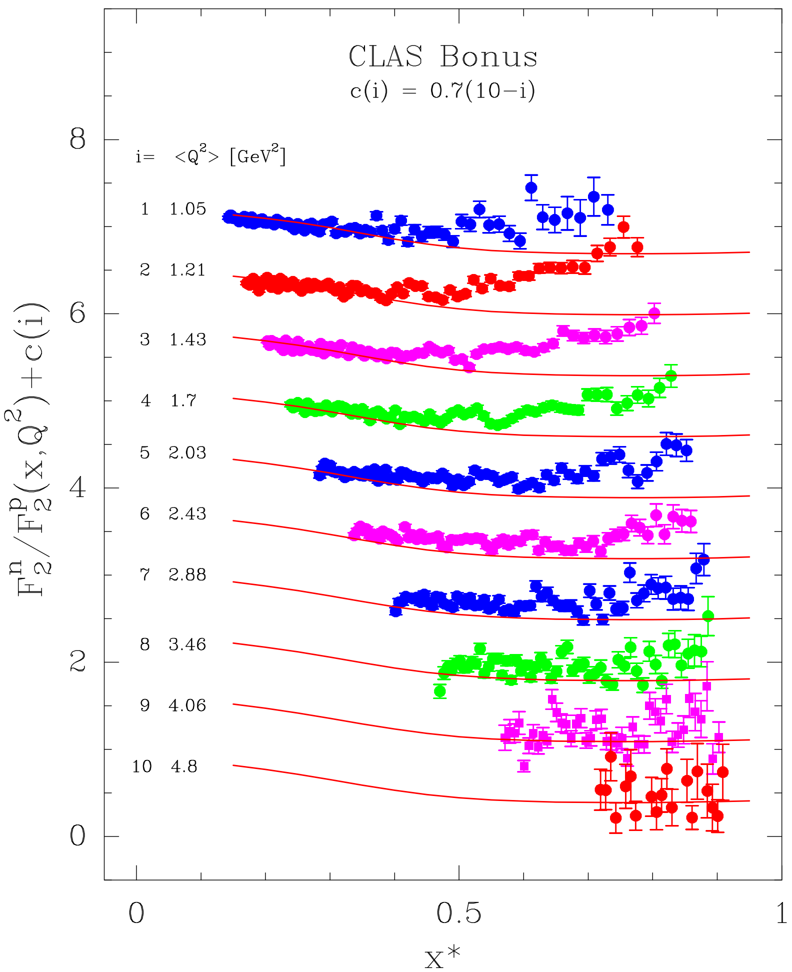
It is concentrated in the medium x-region. We show a comparison with COMPASS data STAR and PHENIX at BNL-RHIC can check it

A compilation of data on $F_2^p(x, Q^2)$ in DIS

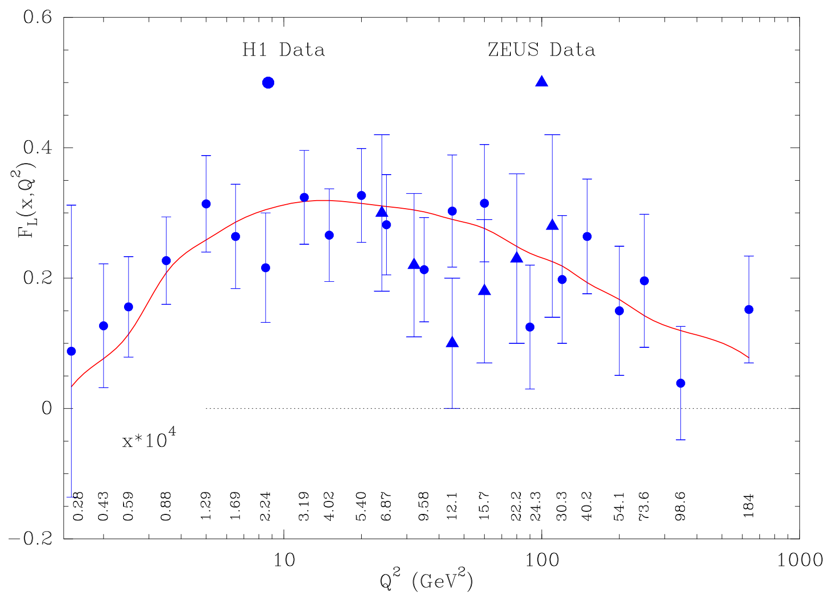


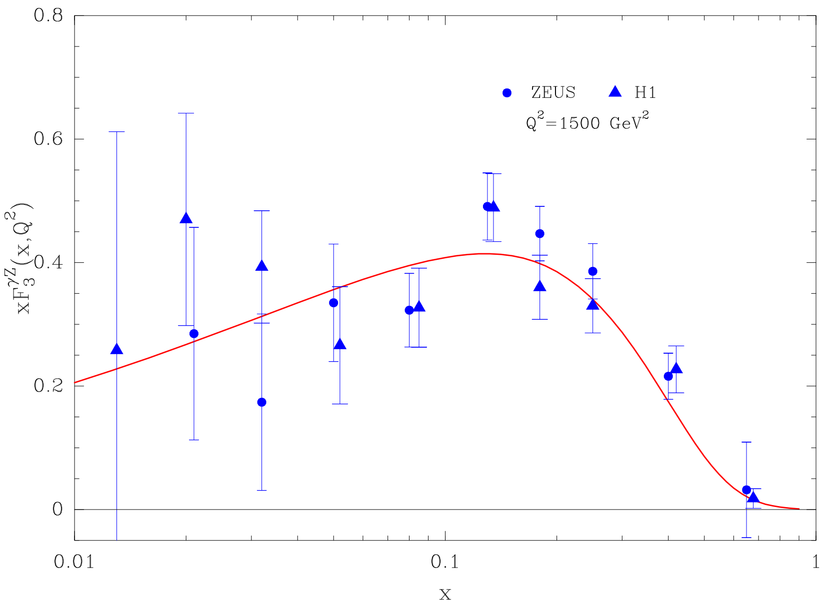
Some data on $F_2^n(x,Q^2)/F_2^p(x,Q^2)$



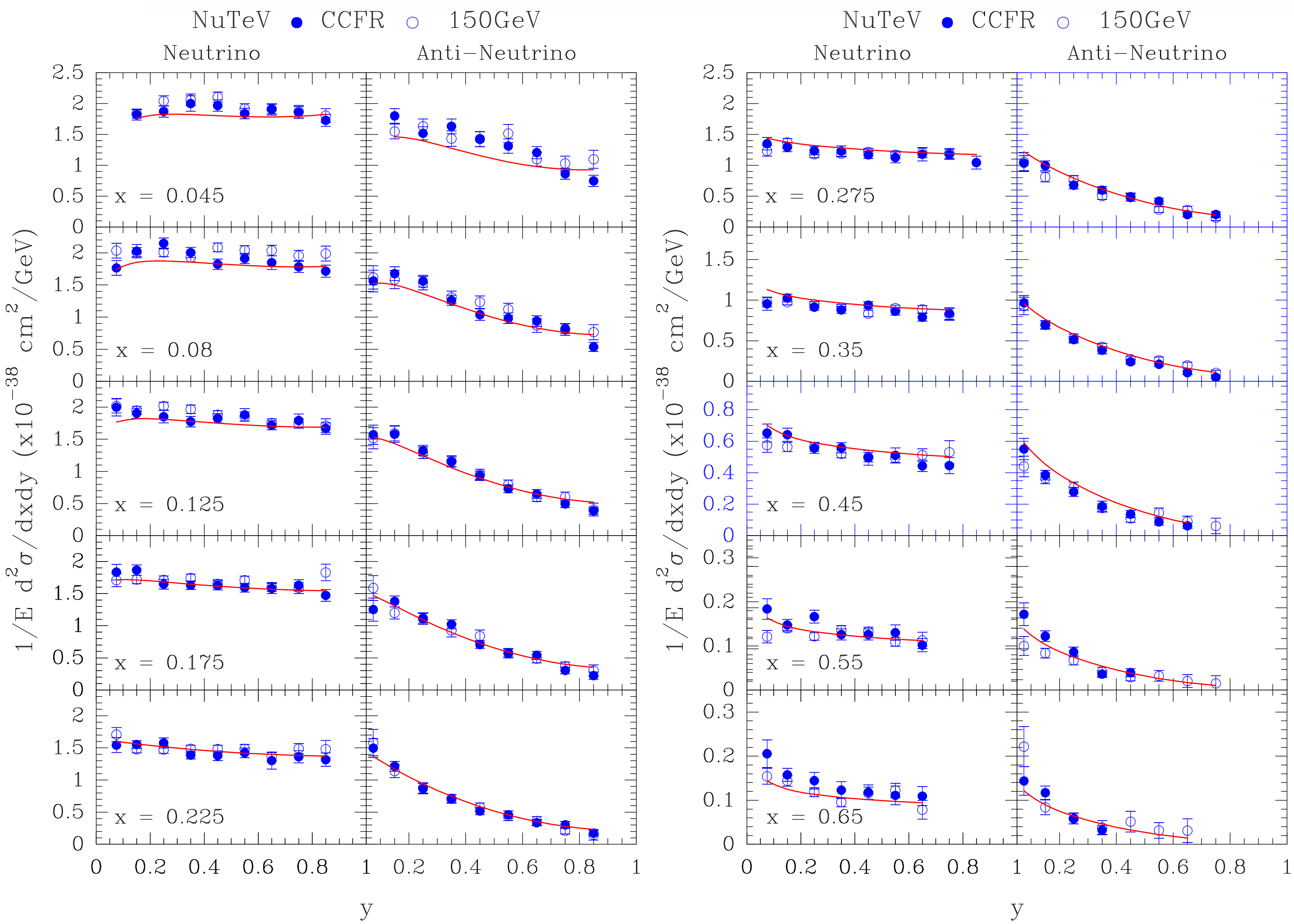


Some data on $F_L(x,Q^2)$ and $xF_3^{\gamma Z}(x,Q^2)$

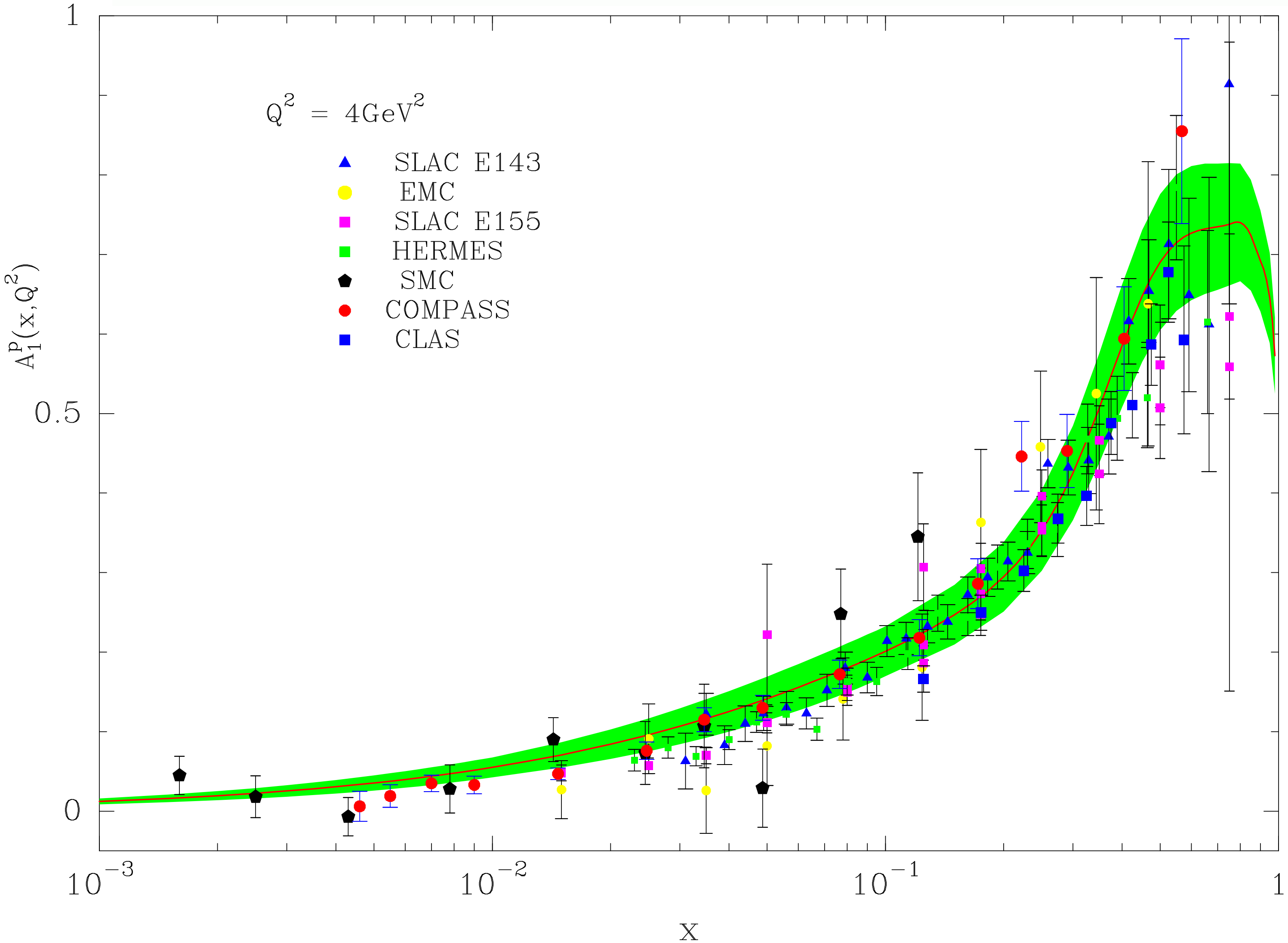




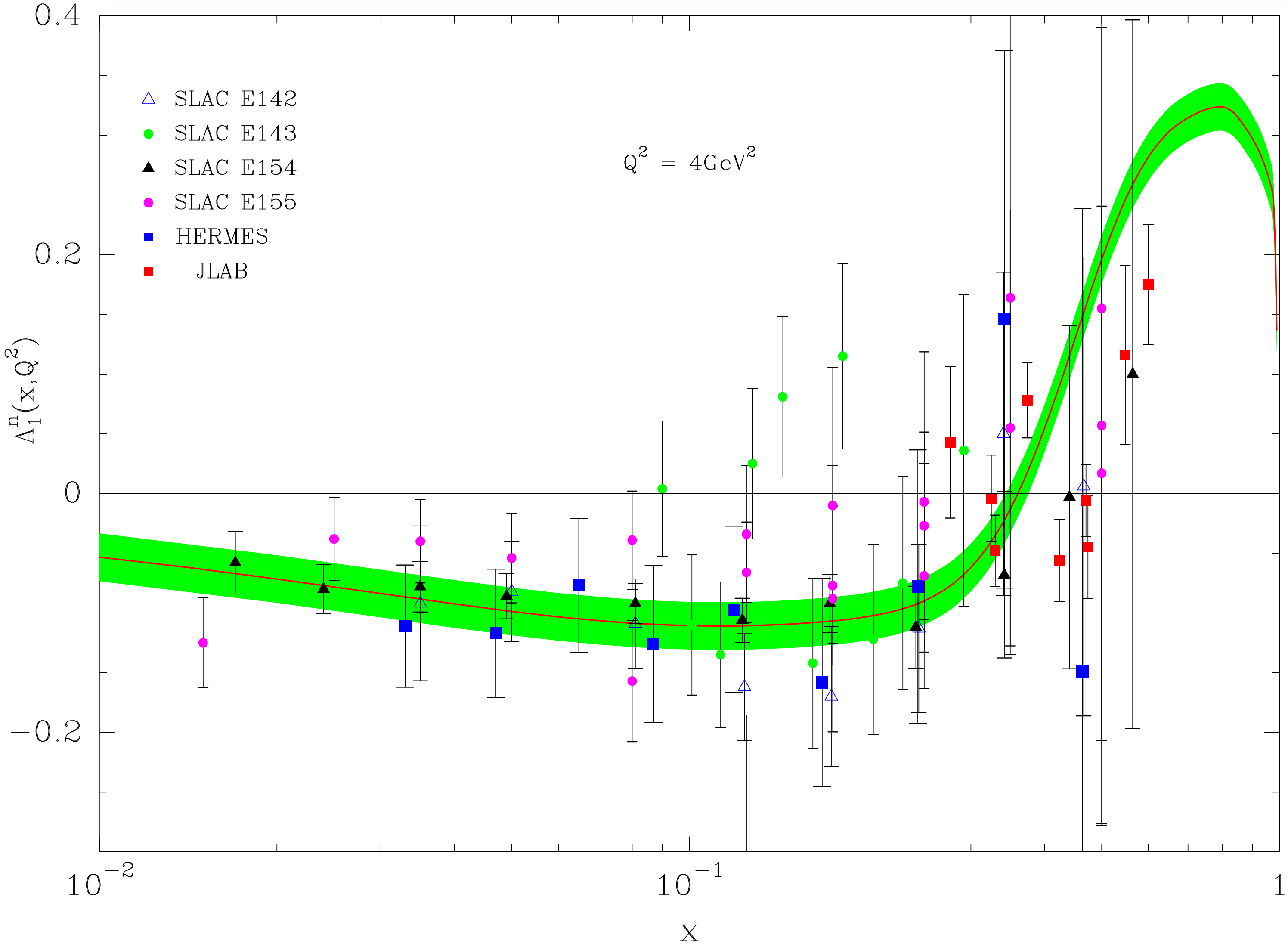
Some data on neutrino-antineutrino cross sections



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



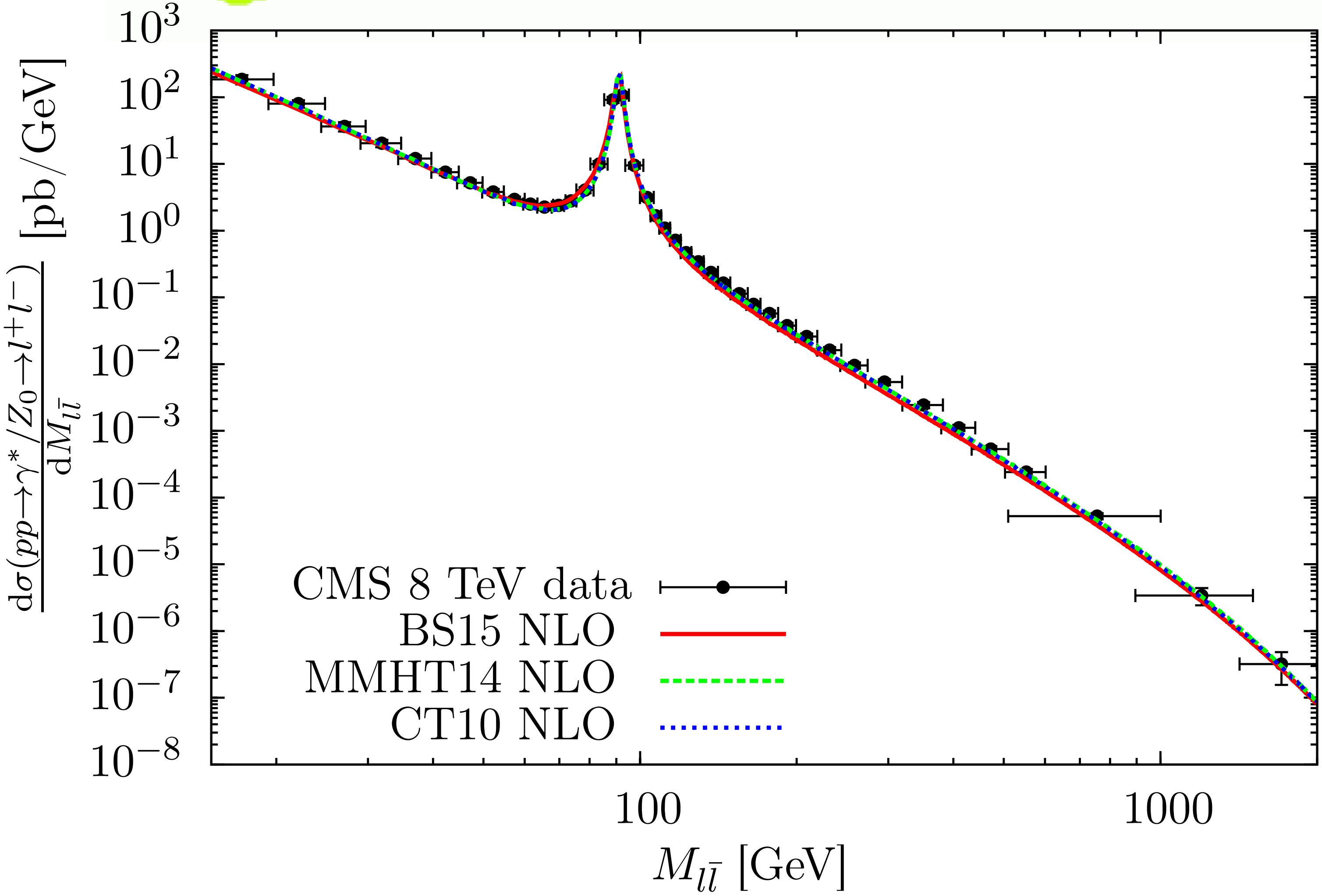
A compilation of data on $A_1^n(x, Q^2)$ in DIS



No more DIS fitting results

Let us now turn to PREDICTIONS

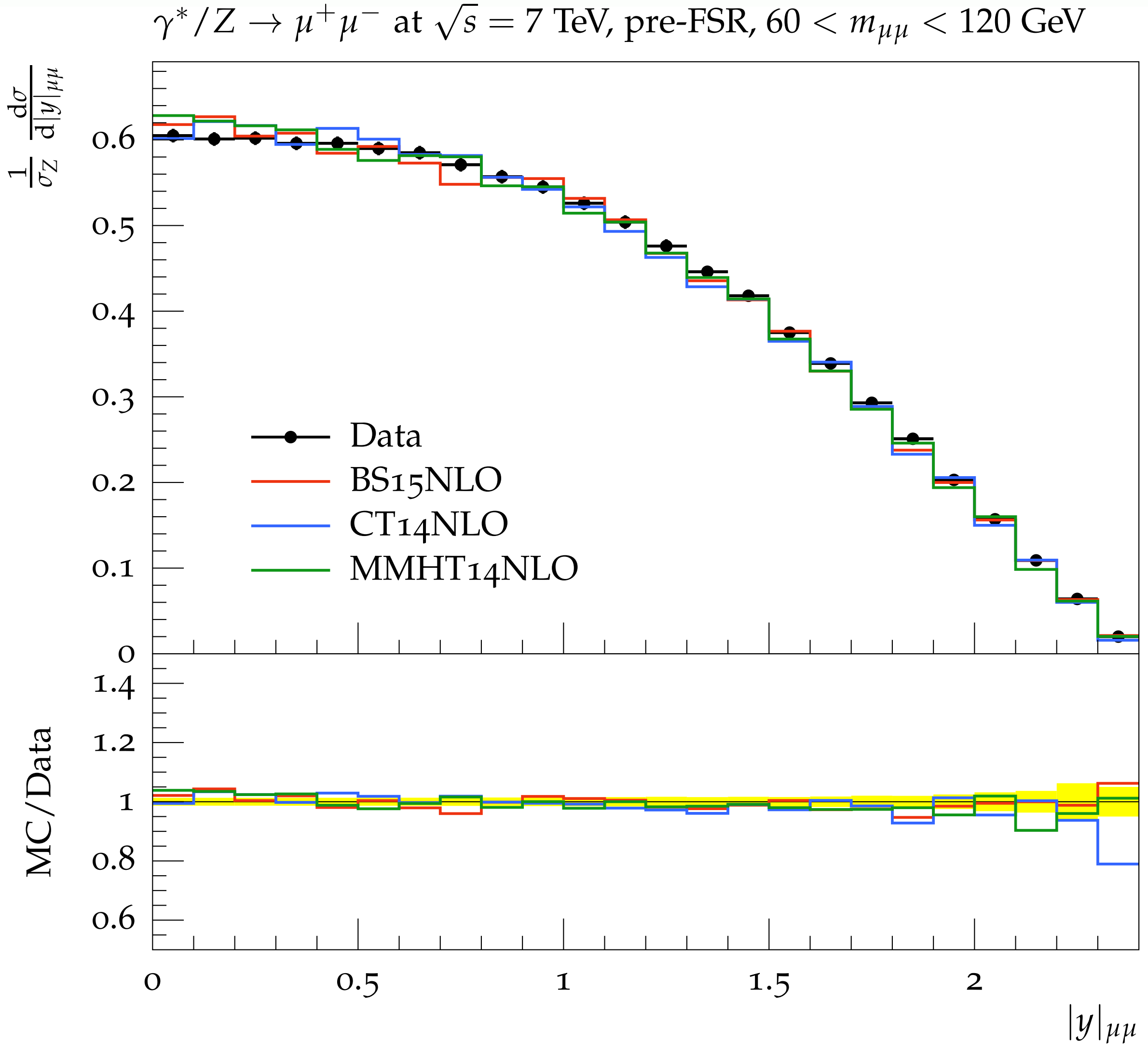
A remarkable simple process: Drell-Yan



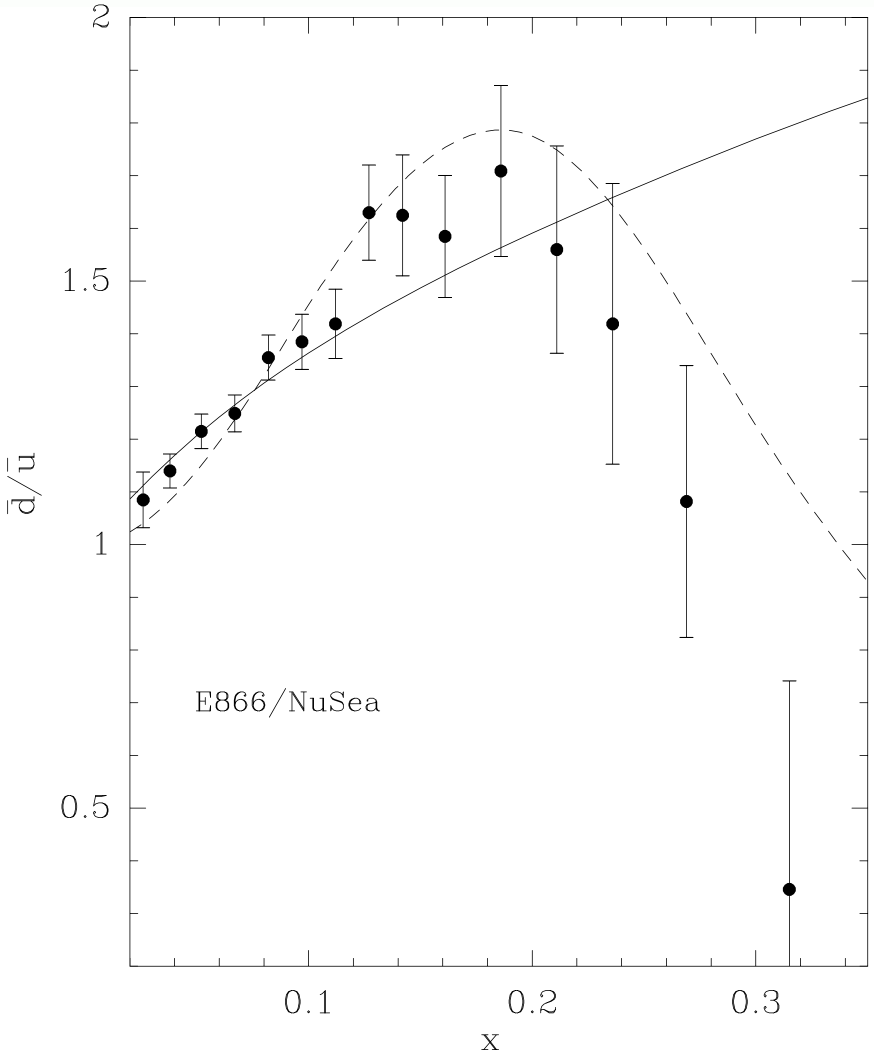
Excellent agreement at LHC up to very high dimuon masses

No way to discriminate between different PDF sets

Rapidity distribution for DY from CMS



Important issue: $\bar{d}/\bar{u}$ *at large* x *and high* Q^2



We look forward to the results of E906 at FNAL (See below SeaQuest)

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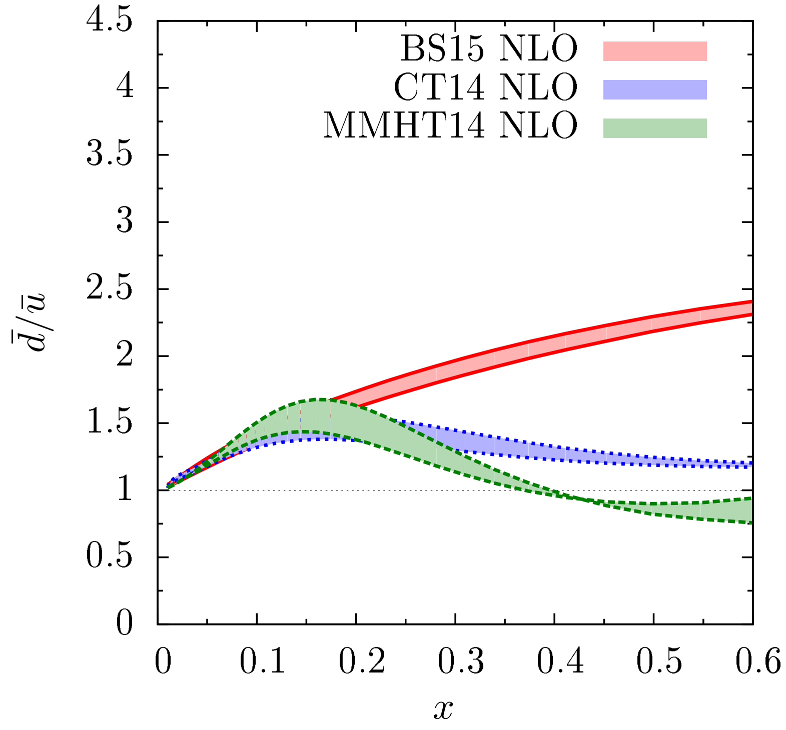

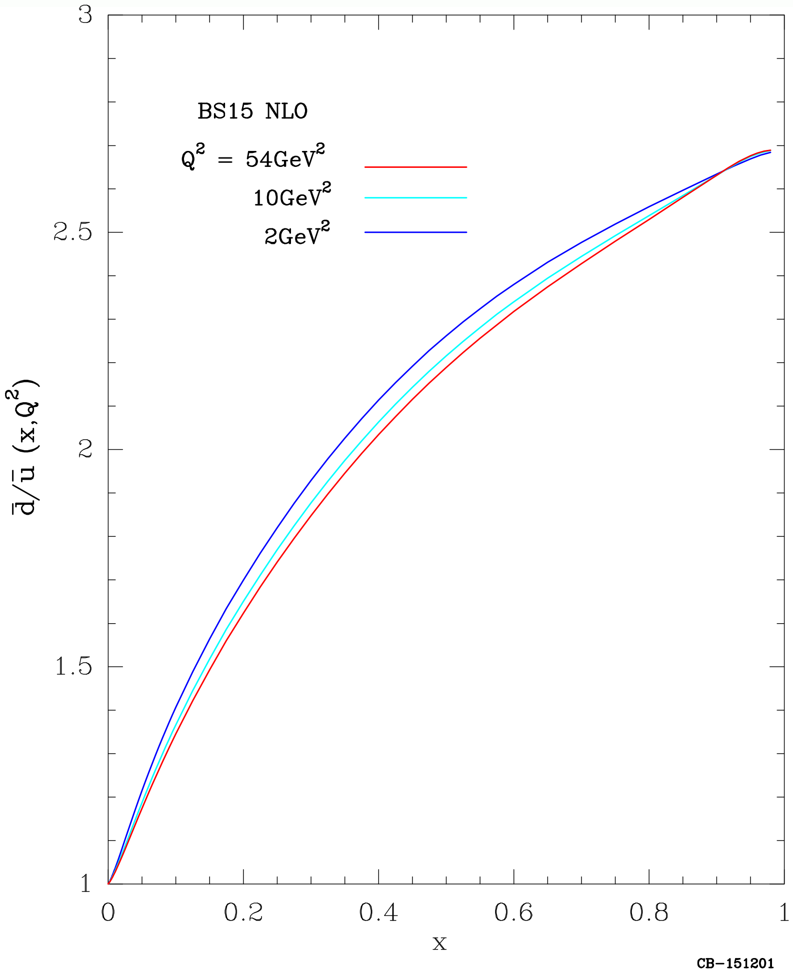

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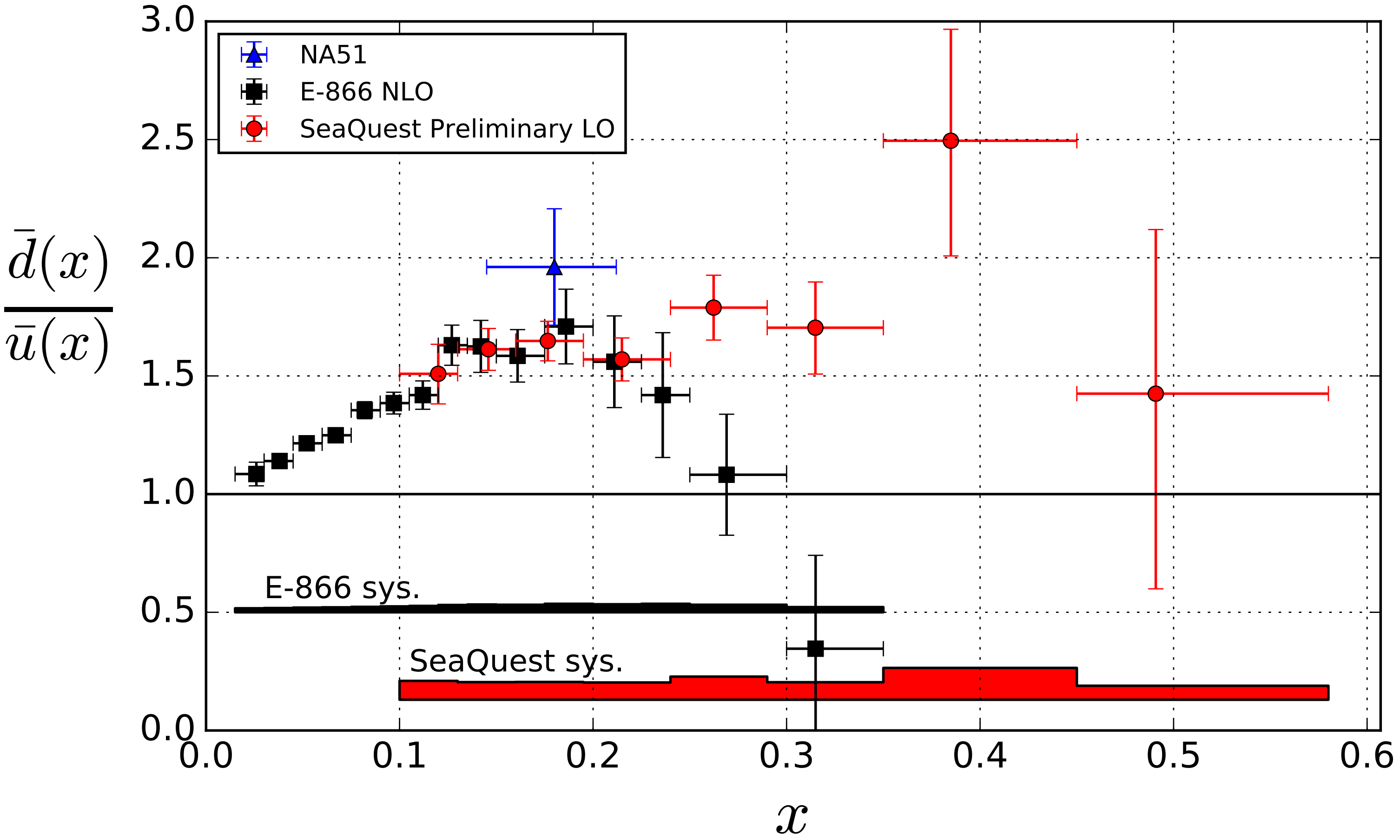
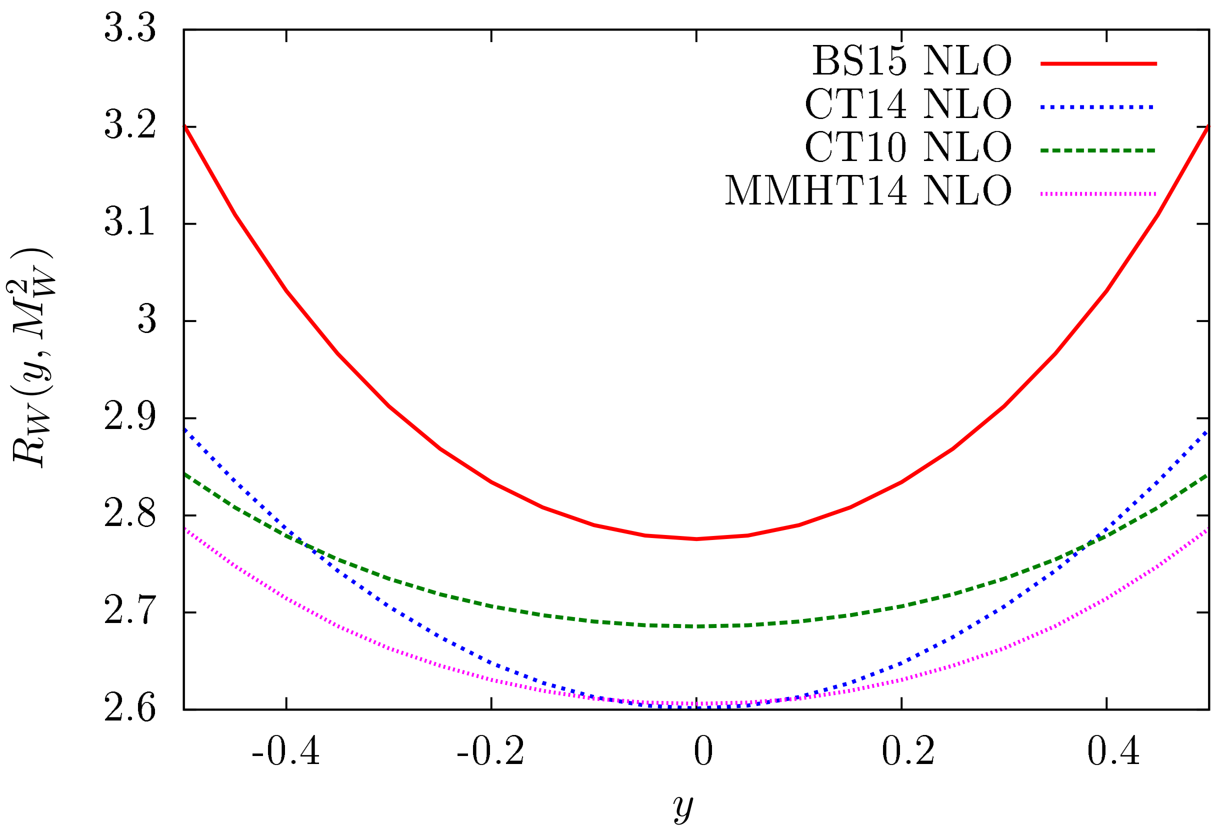


Got special permission to show that. Thanks to Markus Diefenthaler

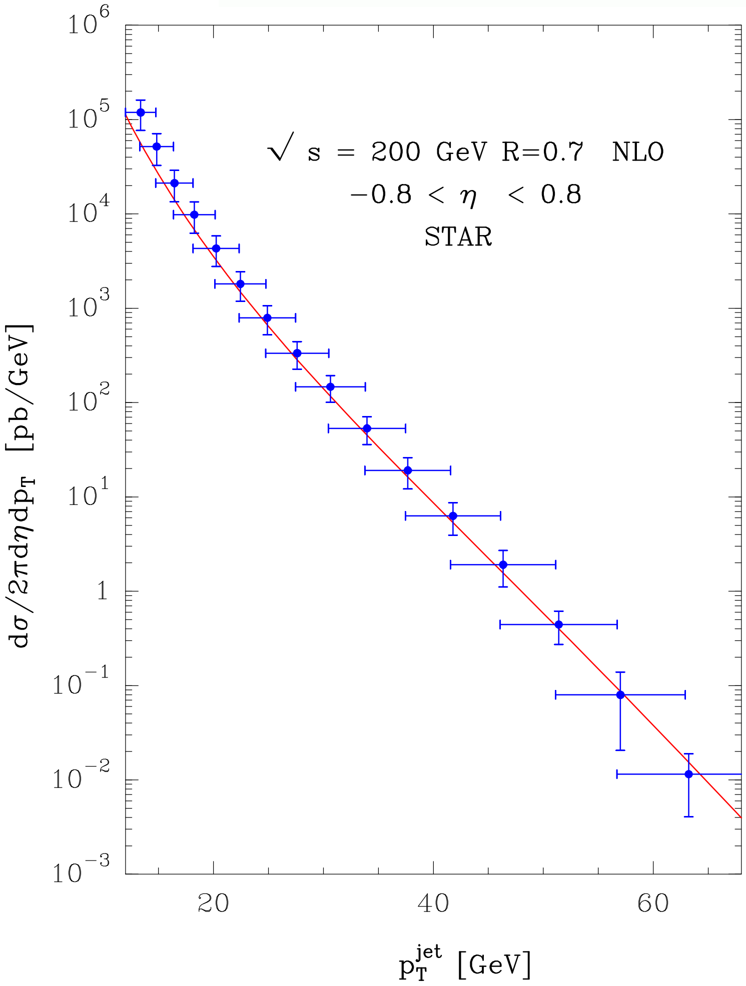
Ratio of $W^{\pm}$ cross sections

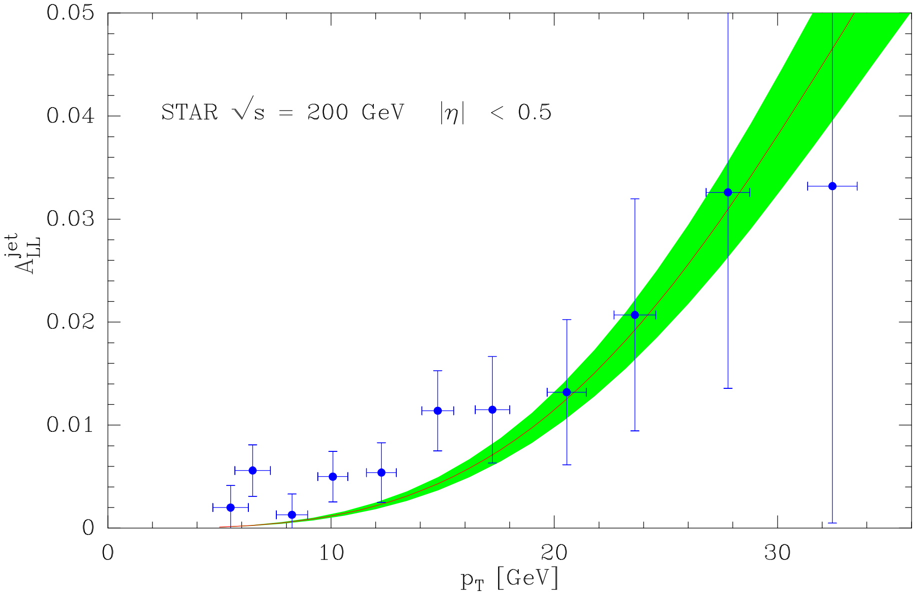
Another possible way to access it



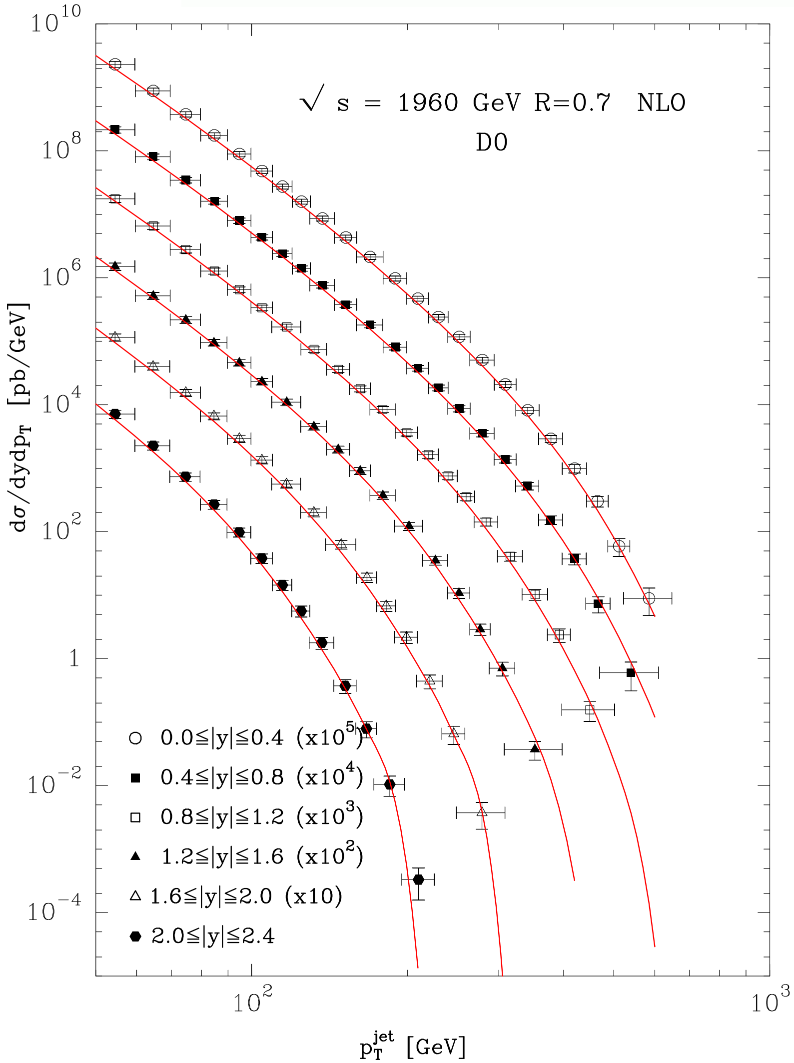
Ratio of $W^{\pm}$ cross sections at $\sqrt{s} = 510 GeV$: comparison of different predictions

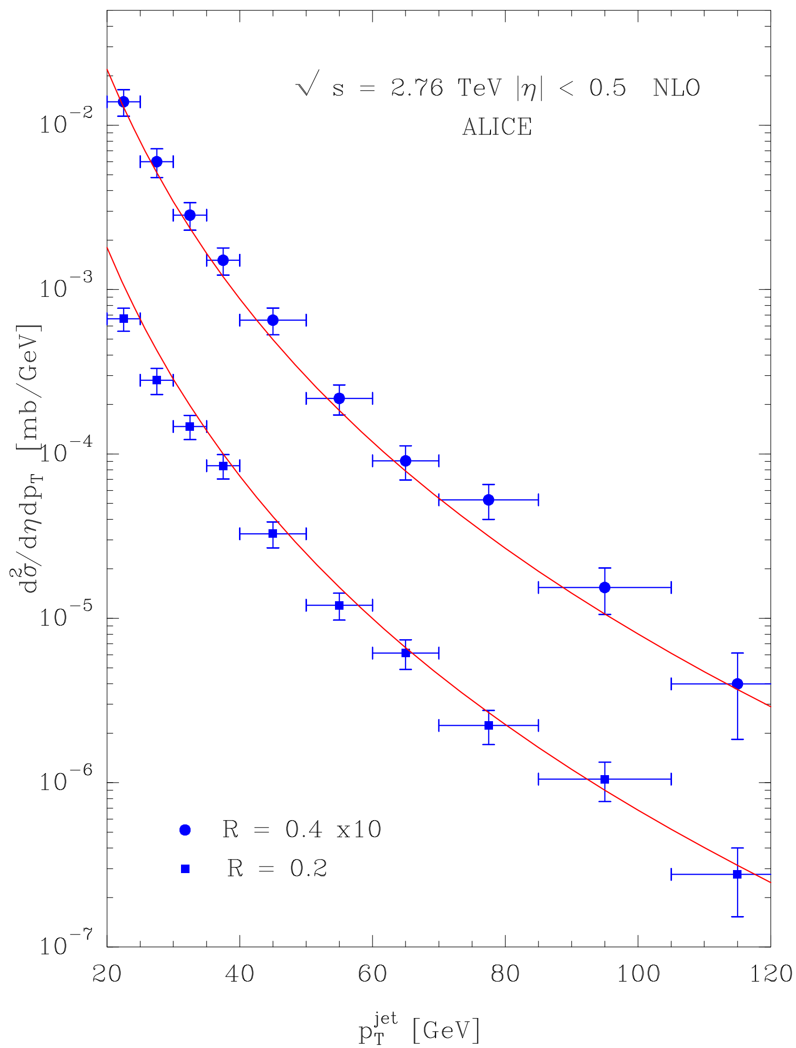
Single-jet production at RHIC: cross section and double helicity asymmetry



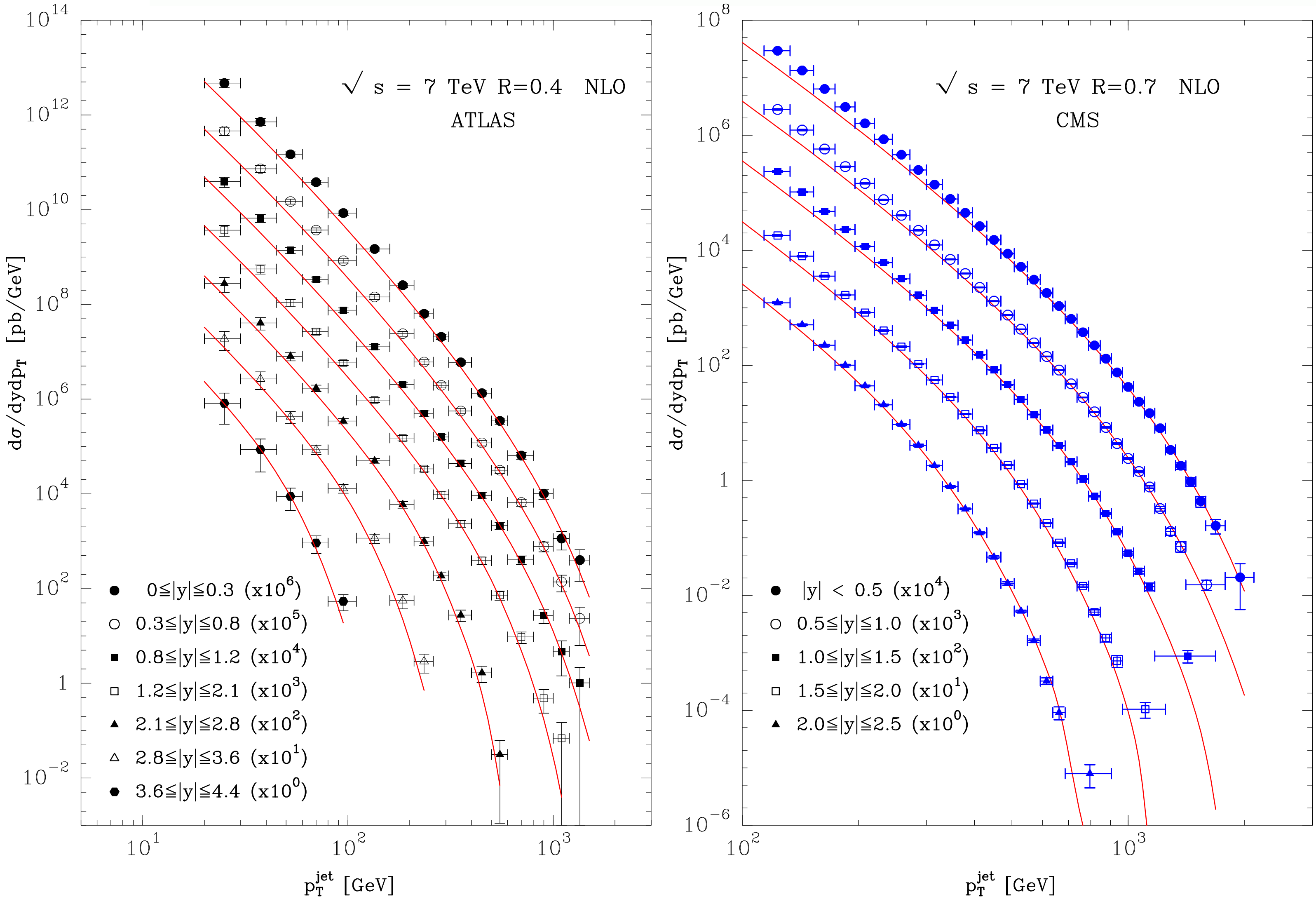


Single-jet production at Tevatron and ALICE

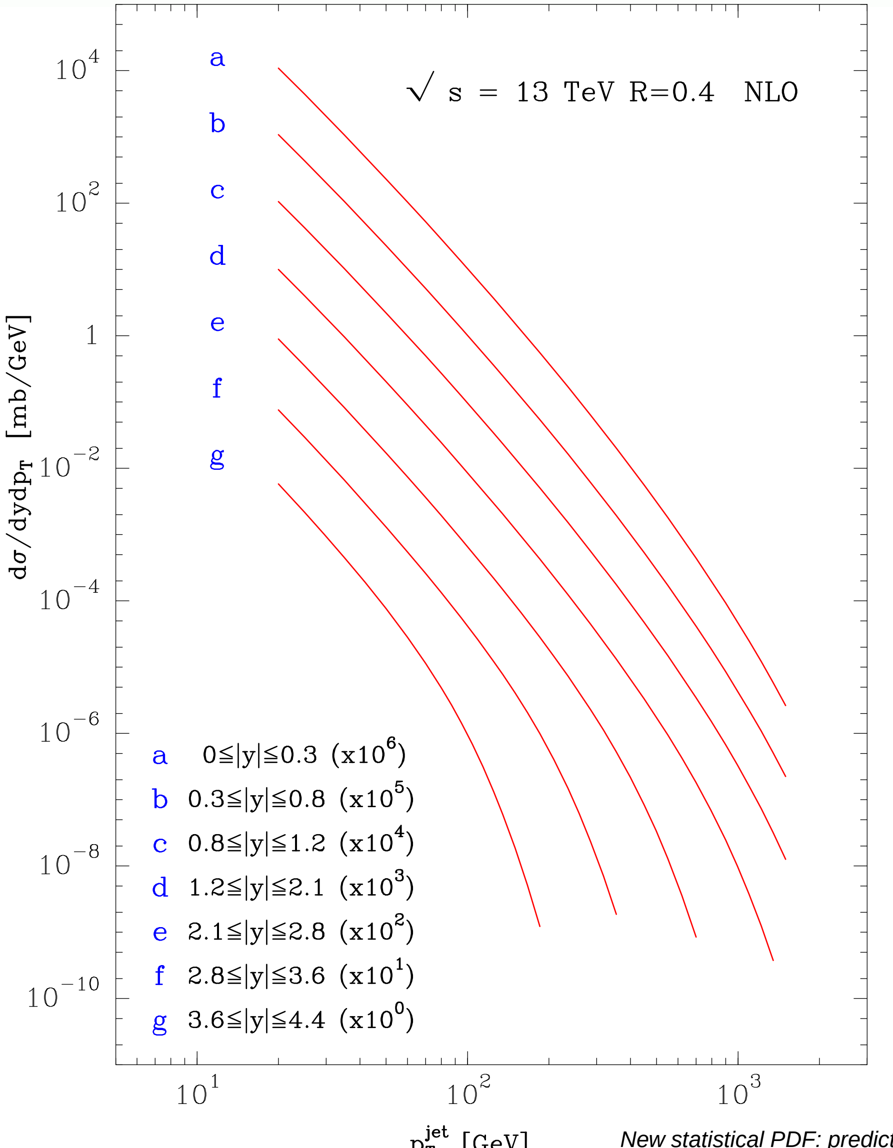




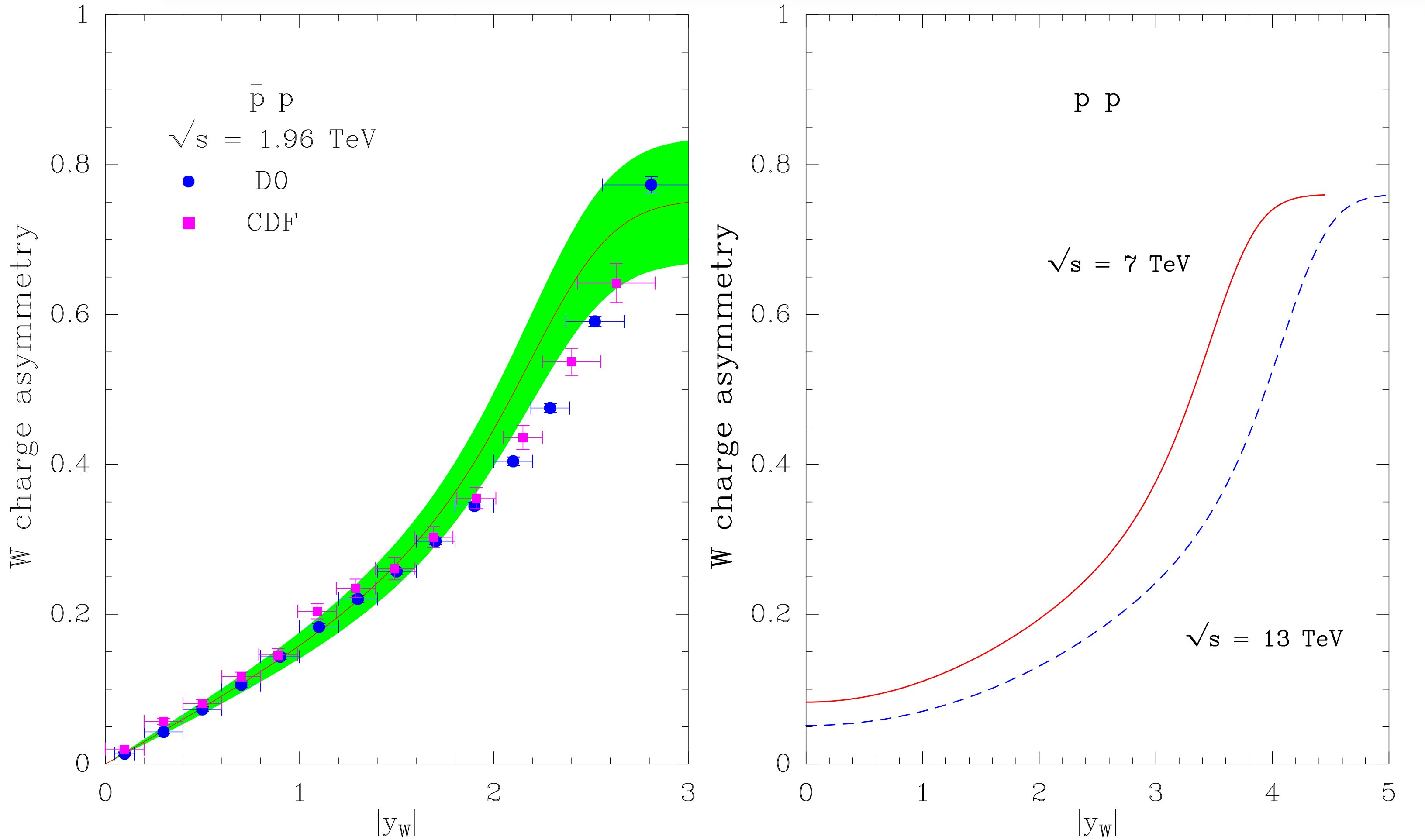
Single-jet production at ATLAS and CMS



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

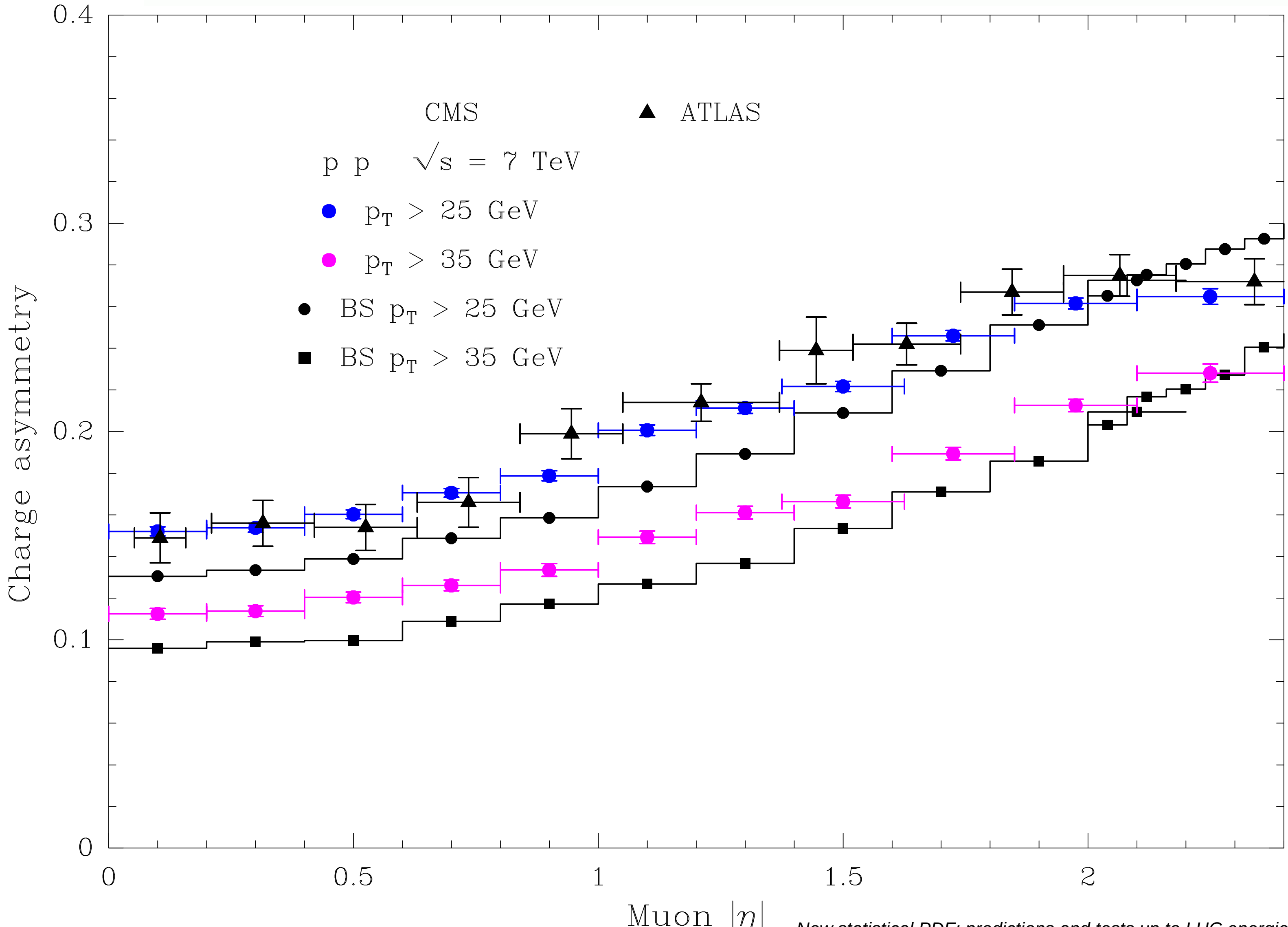


Charge asymmetry in $W^{\pm}$ production at Tevatron versus the W rapidity and prediction for LHC



It is sensitive to the ratio d/u

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



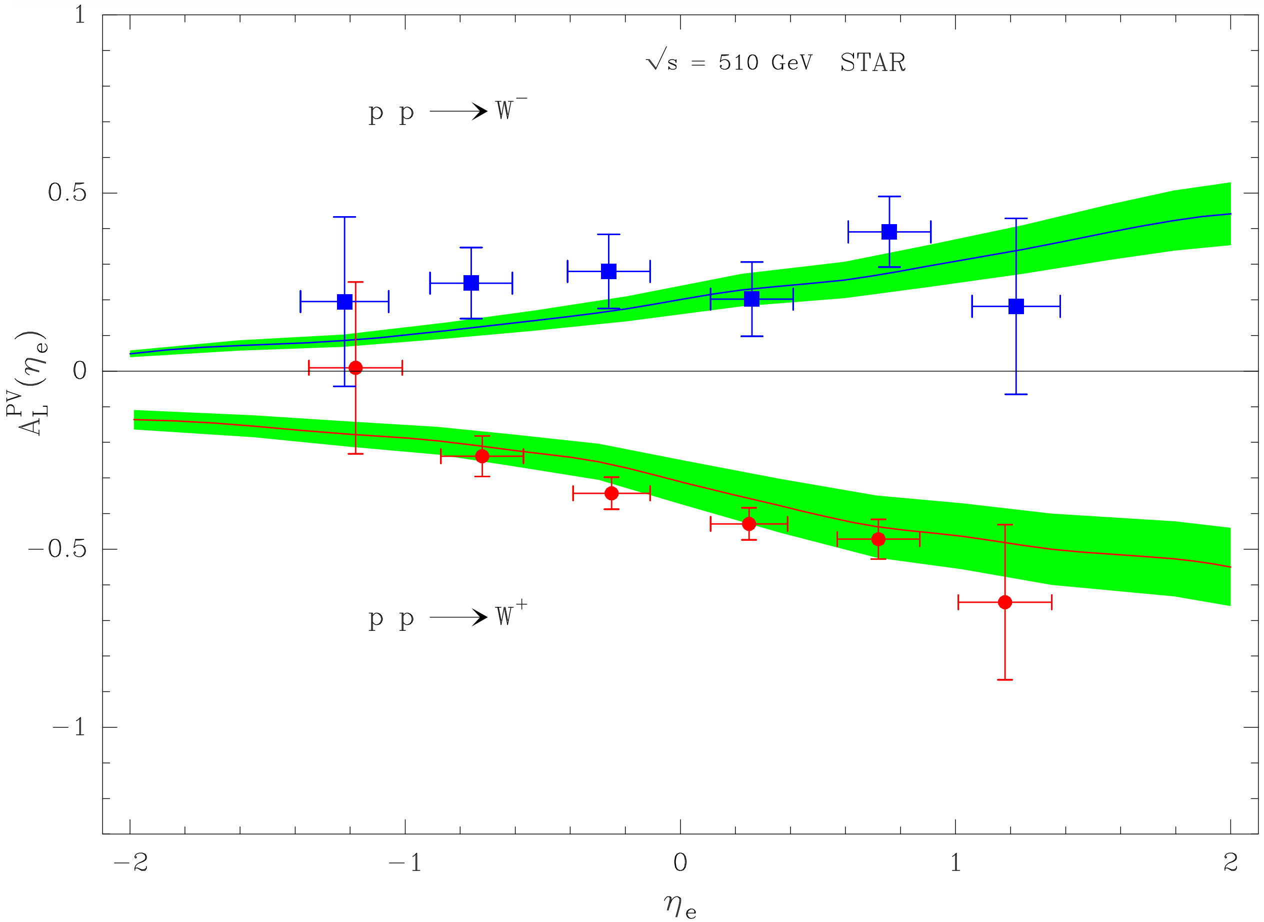
Helicity asymmetry in $W^{\pm}$ production at BNL-RHIC

Consider the processes $\overrightarrow{p}p \to W^{\pm} + X \to e^{\pm} + X$, where the arrow denotes a longitudinally polarized proton and the outgoing $e^{\pm}$ have been produced by the leptonic decay of the $W^{\pm}$ boson. The helicity asymmetry is defined as $A_L = \frac{d\sigma_+ - d\sigma_-}{d\sigma_+ + d\sigma_-}$.
Here σ_h denotes the cross section where the initial proton has helicity h.
For W^- production, the numerator of the asymmetry is found to be proportional to

$$\Delta\bar{u}(x_1, M_W^2)d(x_2, M_W^2)(1 - \cos\theta)^2 - \Delta d(x_1, M_W^2)\bar{u}(x_2, M_W^2)(1 + \cos\theta)^2 ,$$

where θ is the polar angle of the electron in the $c.m.s.$, with $\theta = 0$ in the forward direction of the polarized parton. The denominator of the asymmetry has a similar form, with a plus sign between the two terms of the above expression. For W^+ production, the asymmetry is obtained by interchanging the quark flavors ($u \leftrightarrow d$).
We first show below the results of the calculations of the helicity asymmetries, versus the charged-lepton pseudo-rapidity and for a clear interpretation some explanations are required. At high negative η_e, one has $x_2 >> x_1$ and $\theta >> \pi/2$, so the first term above dominates and the asymmetry generated by the W^- production is driven by $\Delta\bar{u}(x_1)/\bar{u}(x_1)$, for medium values of x_1. Similarly for high positive η_e, the second term dominates and now the asymmetry is driven by $-\Delta d(x_1)/d(x_1)$, for large values of x_1. So we have a clear separation between these two contributions.

The parity-violating helicity asymmetry for $W^{\pm}$ production



Statistical prediction compared with STAR data (2014)

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.
- Gluon helicity distribution is concentrated in the medium x-region.
  A real challenge
- Another challenge is the ratio $\bar{d}/\bar{u}$ in the high x-region.
  Data seem to confirm the predicted rising behavior.
- This statistical approach has a good predictive power up to LHC energies