Global QCD Analysis of Nucleon Structure: Progress and Prospects

- Recent Past (say, up to DIS2002):
  - Experiment: More precision DIS measurements (mainly HERA) and Tevatron inclusive jet production (CDF, D0);
  - Advances in PDF Analysis: better ***gluon determination***; more systematic ***Uncertainty Analysis*** (Hessian, Lagrangian methods)
- Current:
  - Experiment: Extensive Drell-Yan p-p and p-d Expt. (E866); Charm production in Neutrino Scattering (CCFR, NuTeV) … etc.
  - Expected Advances in PDF analysis: more reliable quark ***flavor differentiation***: $u_v,\ d_v,\ s,\ \bar{u},\ \bar{d},\ \bar{s},\ c,\ b, \ldots$
- Near Future (Tevatron Run II, HERA II, and LHC)

  What can we predict? What measurements at the new colliders can advance our knowledge of the parton structure of the nucleon?

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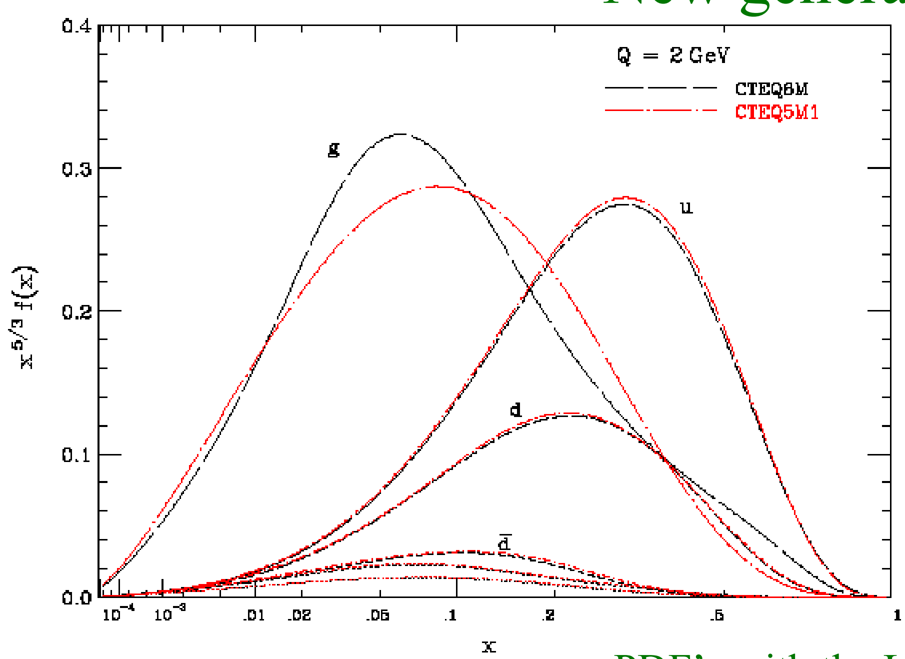
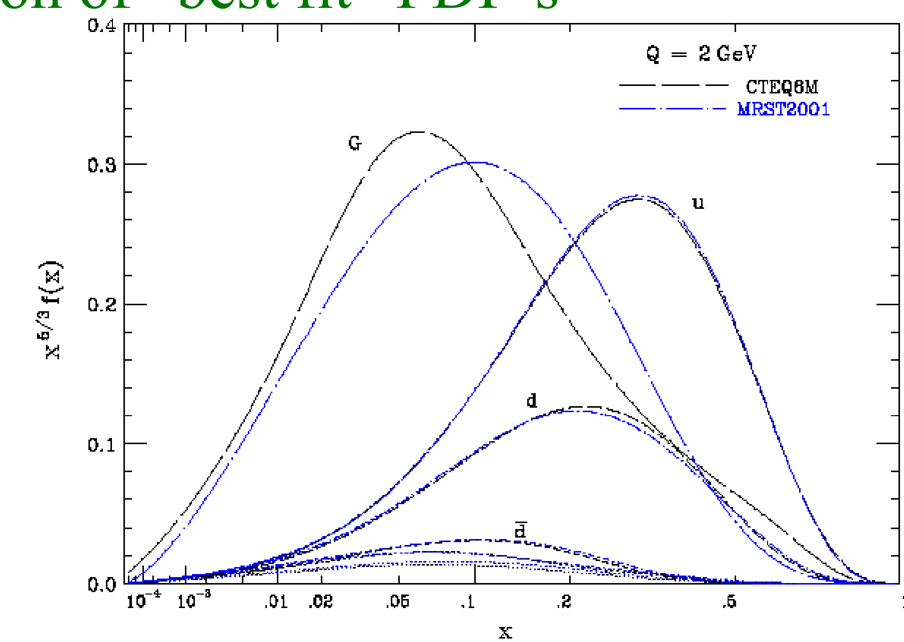
Recent Advances (say, to DIS2002) I

- More precise HERA DIS and Tevatron inclusive jet (D0) led to better determination of quark and gluon PDFs:
- More DIS based PDF analyses: H1, ZEUS, Alekhin
- More Global PDF analyses: MRST2001, CTEQ6, … etc.

This talk will focus on the global analyses.

New generation of “best fit” PDF’s





PDF’s with the Les Houches interface: http://vircol.fnal.gov/index.html

Main difference is in the gluon distribution.

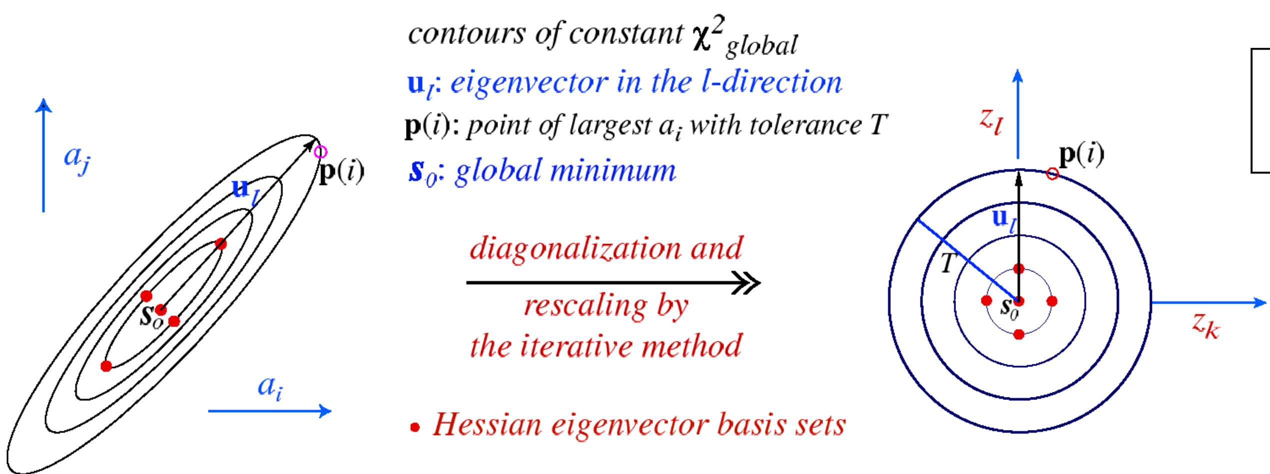
Recent Advances II: quantifying uncertainties
systematic error propagation and uncertainty studies:

- Expt. pioneers: H1 and ZEUS (Pascaud, Zomer; Botje; …);
- Theory pioneers: Alekhin, Giele et.al.

– Effective (Hessian and Lagrangian) methods in the Global Analysis context developed by Pumplin, Stump, et.al. (CTEQ): These were first applied to the CTEQ5/6 analyses (2001/2002);

– They have now also been adopted by the MRST2002 analysis.

2-dim (i,j) rendition of d-dim (~20) PDF parameter space



(a)
Original parameter basis

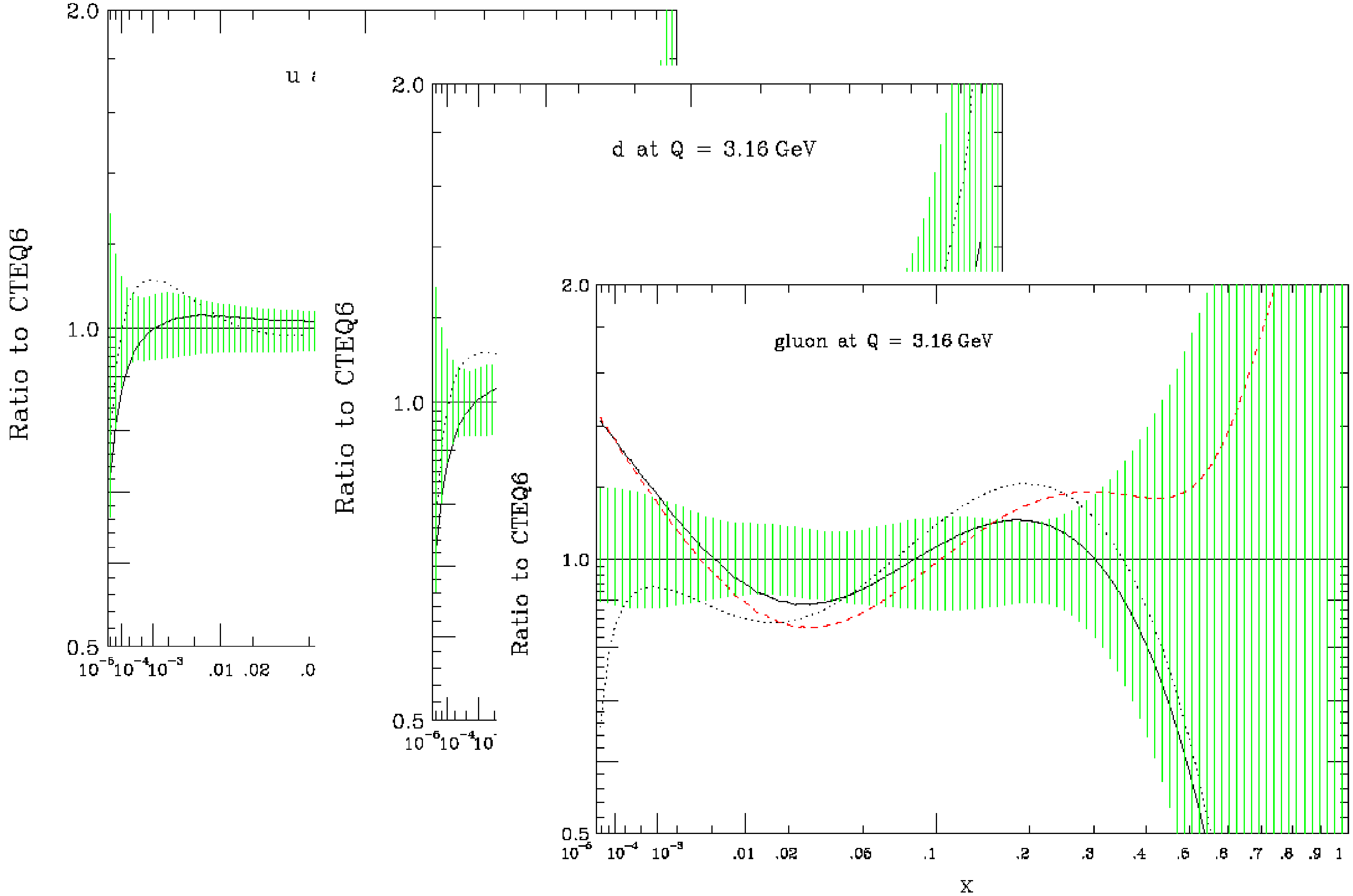
(b)
Orthonormal eigenvector basis

CTEQ: JHEP 2002 0207:012

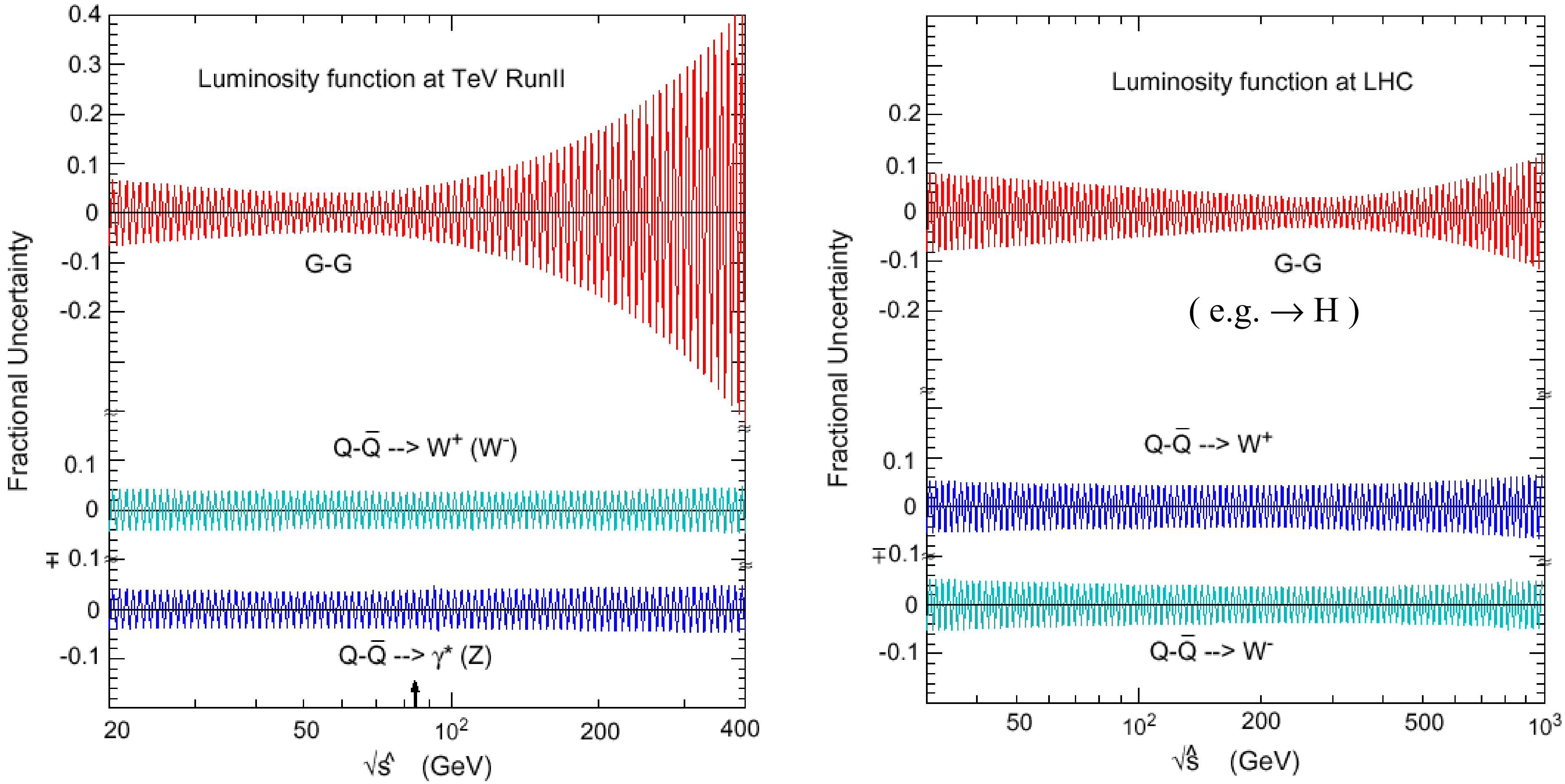
MRST: hep- ph/ 0211080

HEPDATA: http://durpdg.dur.ac.uk/hepdata/pdf3.html

Uncertainties of PDFs: CTEQ6

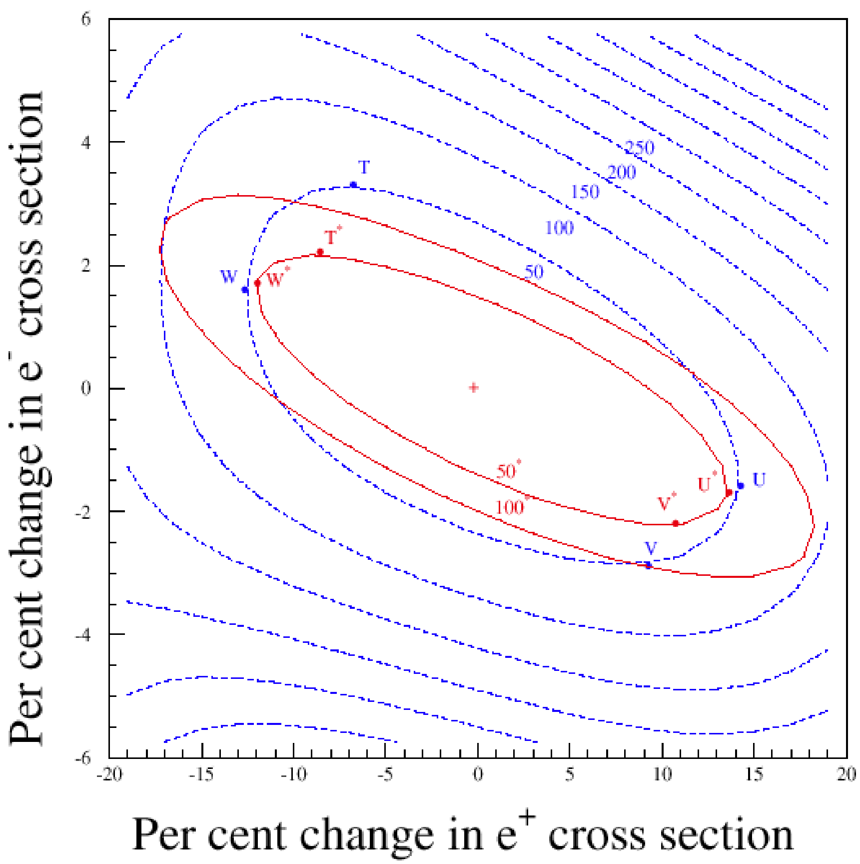


Uncertainties of observables: CTEQ6

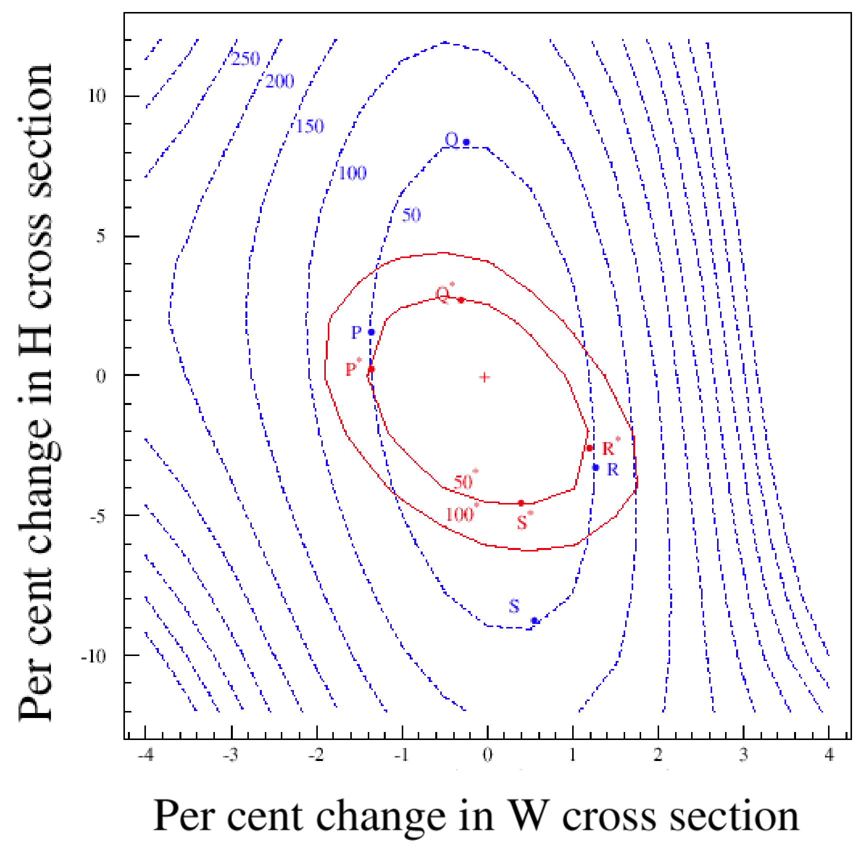


Uncertainties: (from MRST2002)

errors on $F_2^{CC}(e^{\pm}p)$ HERA



Errors on σ_H/σ_W at the Tevatron



* Contours of equal $\Delta\chi^2$ = 50, 100, … around the global minimum

Current Developments

- More refined treatment of precision DIS data (HERA), including charm quark mass effect: CTEQ6HQ
- Detailed analysis of gluon uncertainties, jet cross-sections, and probing New Physics at the shortest distance scale.
- New extensive DY data (E866), u/d differences, and large-x behavior of u/d quark PDFs;
- First global analysis including dimuon data (charm production) in neutrino and anti-neutrino scattering experiments (CCFR and NuTeV): new constraints on the strange and anti-strange quark distributions.
- More refined study of experimental and theoretical uncertainties on global analysis

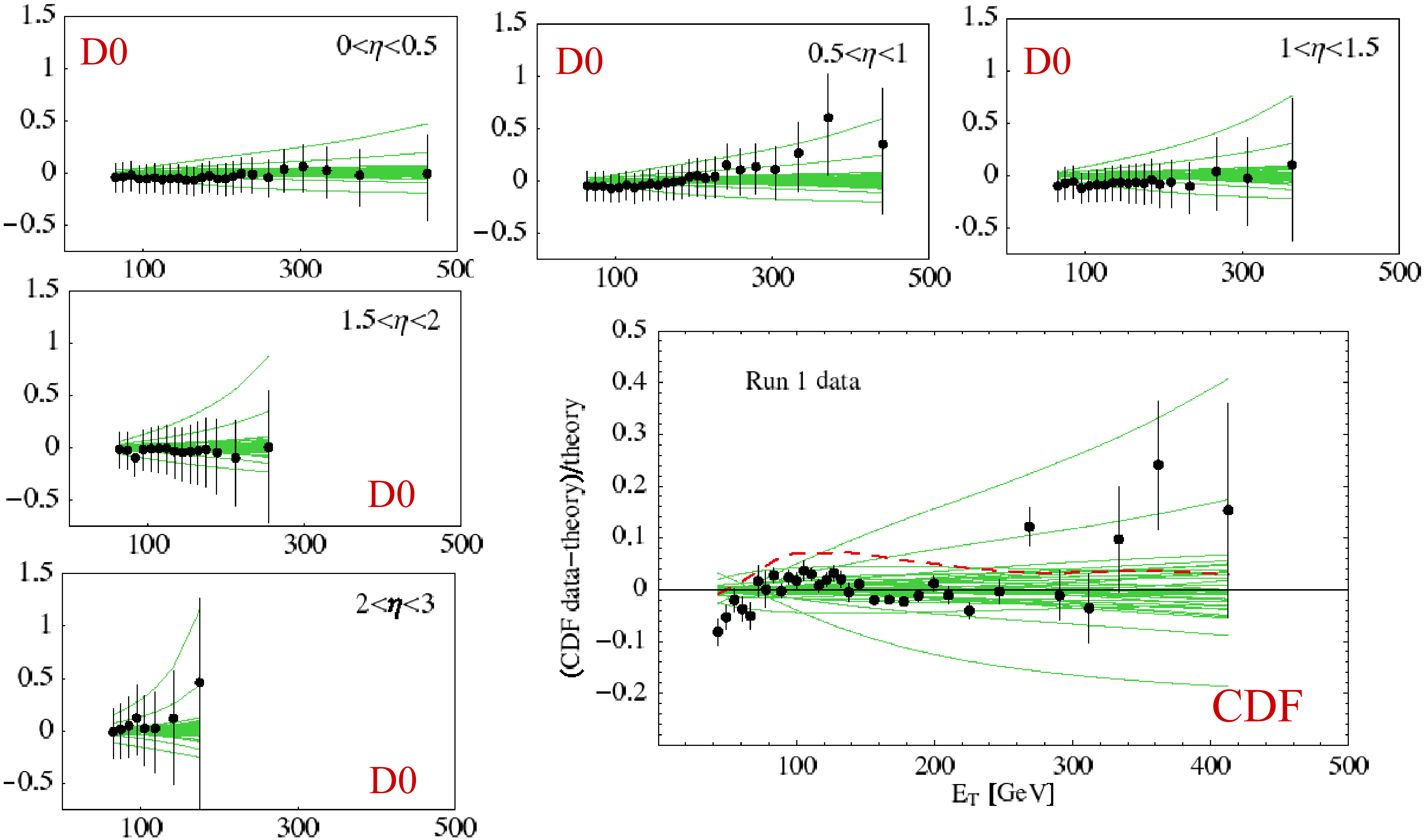
Various applications to SM (t-, H-, …) and beyond SM processes:

Cacciari etal, (t) hep-ph/0303085; Nadolsky etal. (Q) ph/0111358; (H) ph/0110378

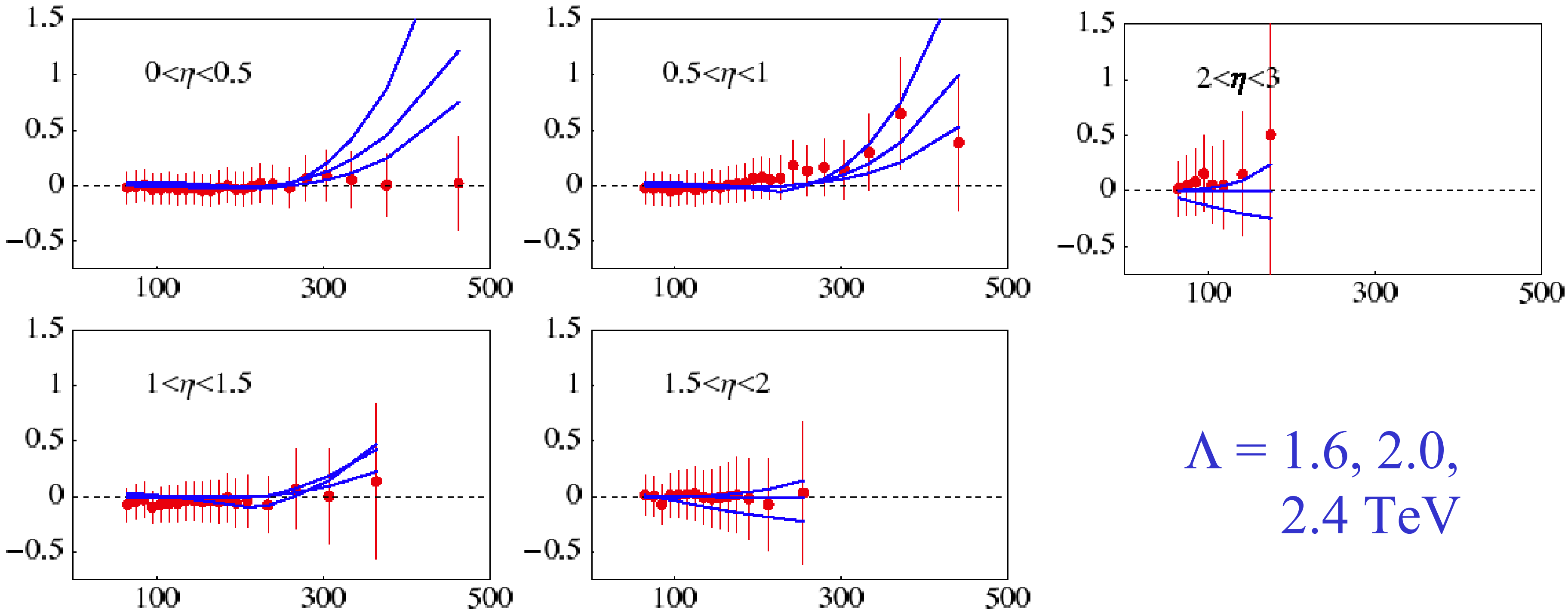
New CTEQ study of Jet Production, Gluons, and Probing new physics at short distances: arXive: hep- ph/ 0303013

- Jet production cross-sections at hadron colliders probe the shortest distances available in the laboratories;
- Jet X-section is sensitive to Gluon distribution at large x;
- Better determination of G(x,Q) provides better predictions of many new physics processes at higher energies.
- Any deviation from QCD predictions at high energies can indicate signals for new physics.

Current Hadronic inclusive jet cross-section (Tevatron Run I) and Parton uncertainties (CTEQ6)



Limits on New Physics



Λ = 1.6, 2.0, 2.4 TeV

Curves: New Physics with (effective) contact term interactions.

$$\mathcal{L}_{qq} = A(2\pi/\Lambda^2)(\overline{q}_L\gamma^\mu q_L)(\overline{q}_L\gamma_\mu q_L) \qquad \text{where} \qquad A = \pm 1.$$

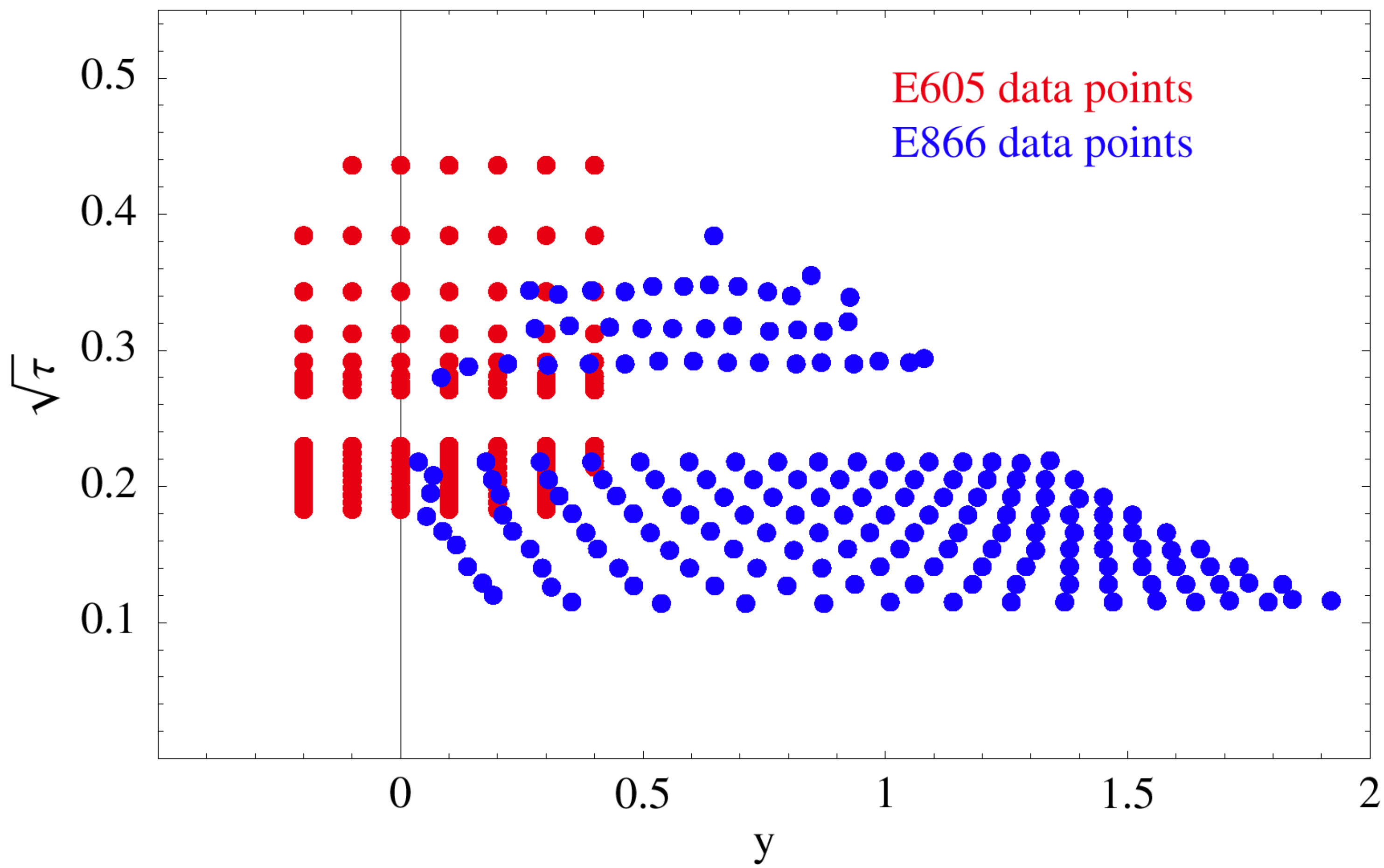
Calculation involves re-doing the global fits with the new interaction

More extensive constraints provided by the new E866 data
Drell-Yan process (continuum e^+e^- or $\mu^+\mu^-$ in hadron collisions)

- Cross-section is *multiplicatively dependent on anti-quarks*, i.e. $u\cdot\bar{u}$, $d\cdot\bar{d}$, …compared to *additively dependent*, i.e. $u+d+\bar{u}+\bar{d}$ … in DIS.
- E605 (~1989, *pA* collision) has been the main source of experimental input to global analysis;
- ***pp/pd*** measurement of NA51 and E866 revolutionized the determination of ***d/u*** quark distribution ratio several years ago.
- Recent E866 data on separate ***pp*** and ***pd*** cross-sections will make the ***d/u*** discrimination much more quantitative.

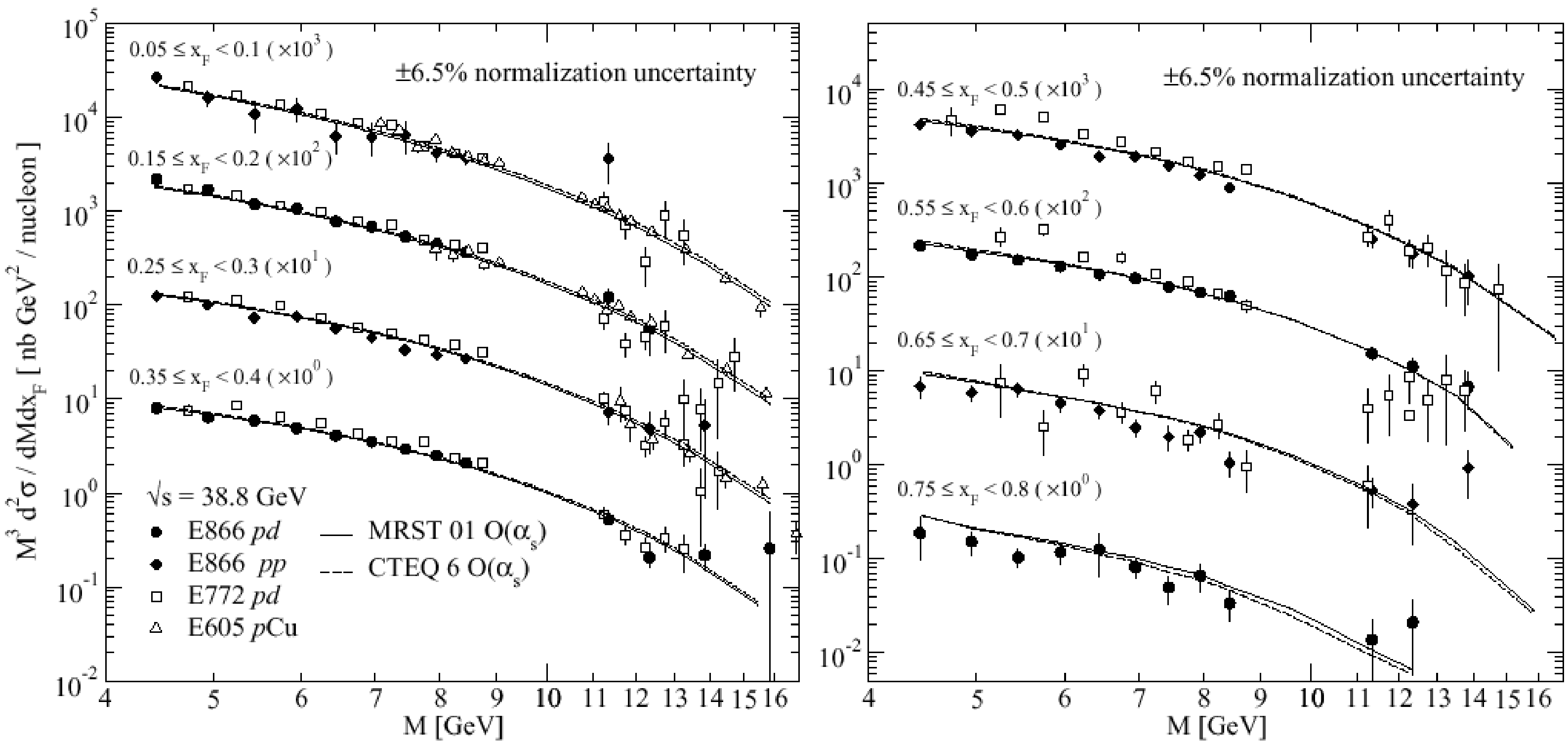
The *d/u* ratio at large *x* is more directly probed by the CC e^+p / e^-p (and ep / ed) measurements at HERA.

Comparison of the kinematic ranges of the Drell-Yan exptl data sets: the previous E605 and the new E866



Comparison of data with current PDFs

E866 paper

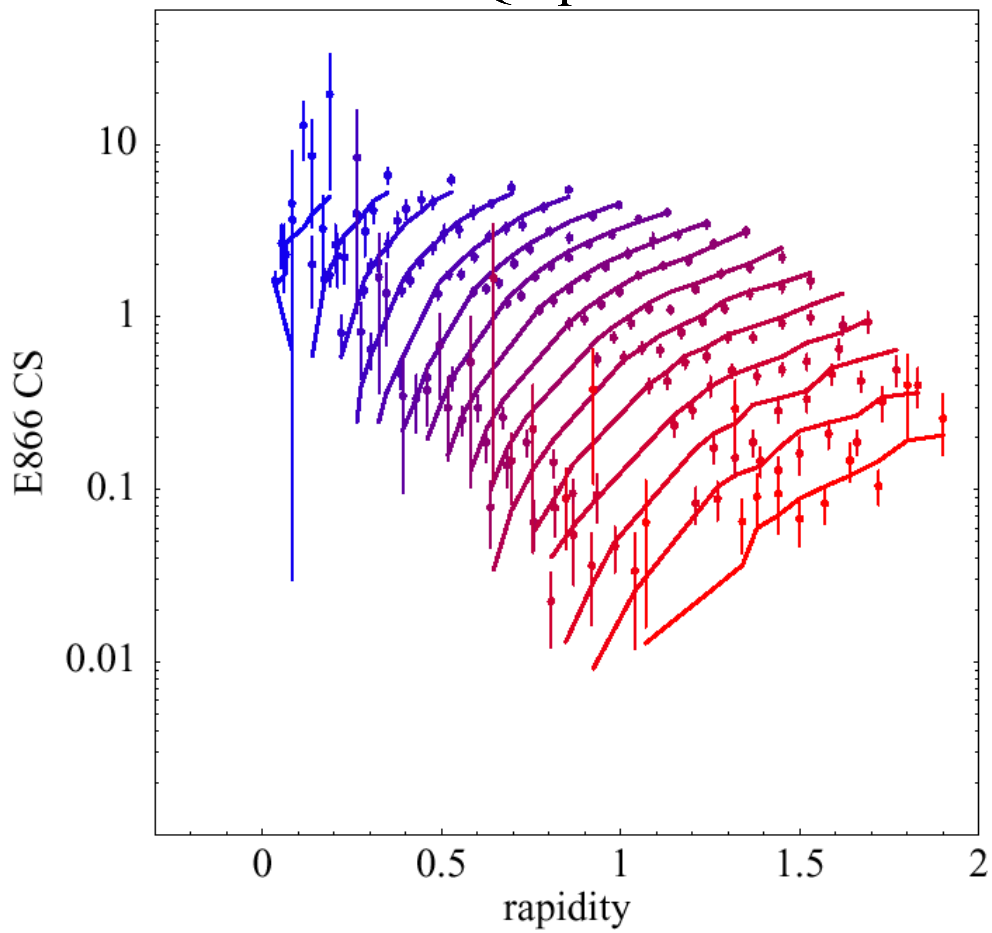


PDF	K'_{pp}	χ^2/dof	K'_{pd}	χ^2/dof
CTEQ5 [3]	0.976	1.42	0.963	2.51
CTEQ6 [4]	1.016	1.39	1.001	2.56
MRST98 [5]	0.973	1.38	0.960	2.37
MRST2001 [6]	0.980	1.45	0.966	2.44

Impact of E866 data on current global analysis

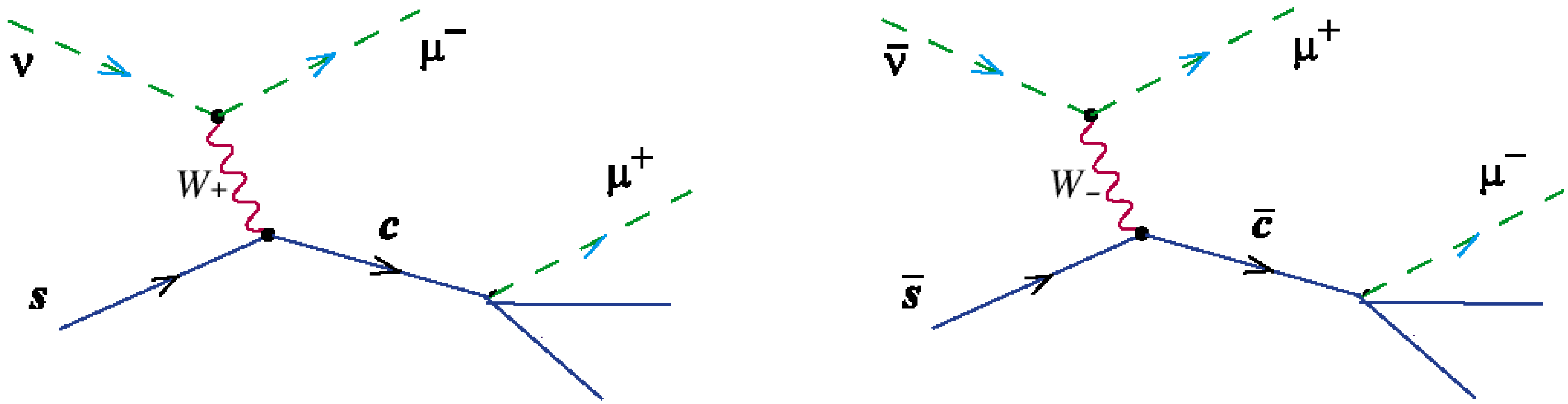
- Data and predictions in general agreement;
- The χ^2 can be substantially improved by including these data in the fit; this is underway.
- The determination of *u* and *d* quark distributions will be much improved.
- Very complementary with HERA CC and *ep* / *ed* (HERA III) measurements.

Comparison with existing CTEQ6 prediction



Dimuon Neutrino Sc. Data and the Strange Quarks

Most direct source of information on the strange quarks.



New data: CCFR + NuTeV

Physics issues:

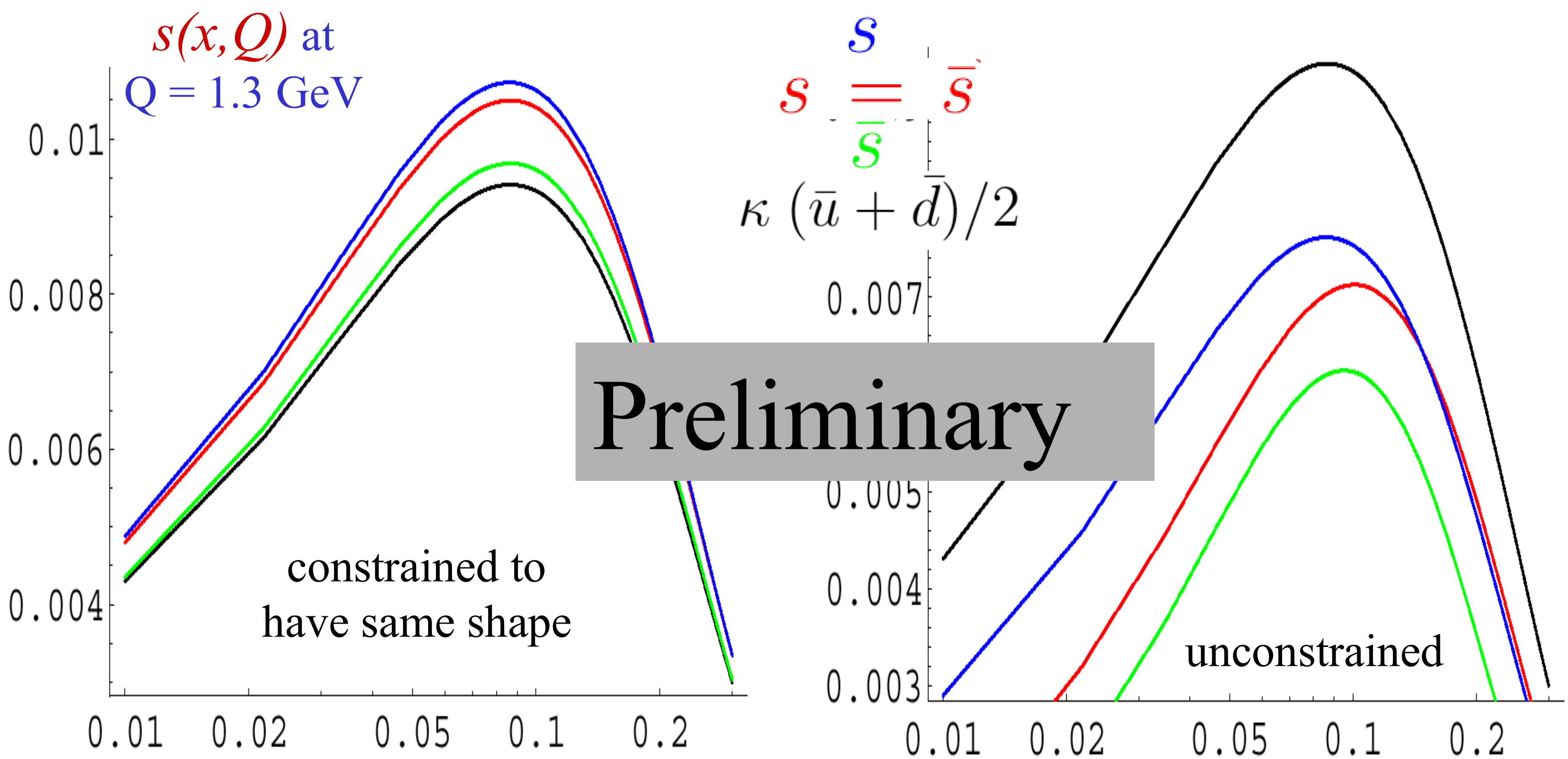
What is the ratio of strange/non-strange– $\kappa = \frac{s+\bar{s}}{\bar{u}+\bar{d}}$?

Is the shape of $s(x,Q)$the same as $(\bar{u}+\bar{d})$?

Are $s(x,Q)$and $\bar{s}(x,Q)$ the same, or different?

(relevant to the NuTeV anomaly)

First Dimuon Neutrino Sc. Data studied in the global QCD analysis context (very preliminary analysis)



κ factor at Q=1.3 GeV is about 1/4; $s(x,Q)$ and $\bar{s}(x,Q)$

prefer to be somewhat different in magnitude and in shape (?)

Looking forward to Tevatron Run II and LHC physics

- What can PQCD and PDFs do for Tevatron Run II and LHC?

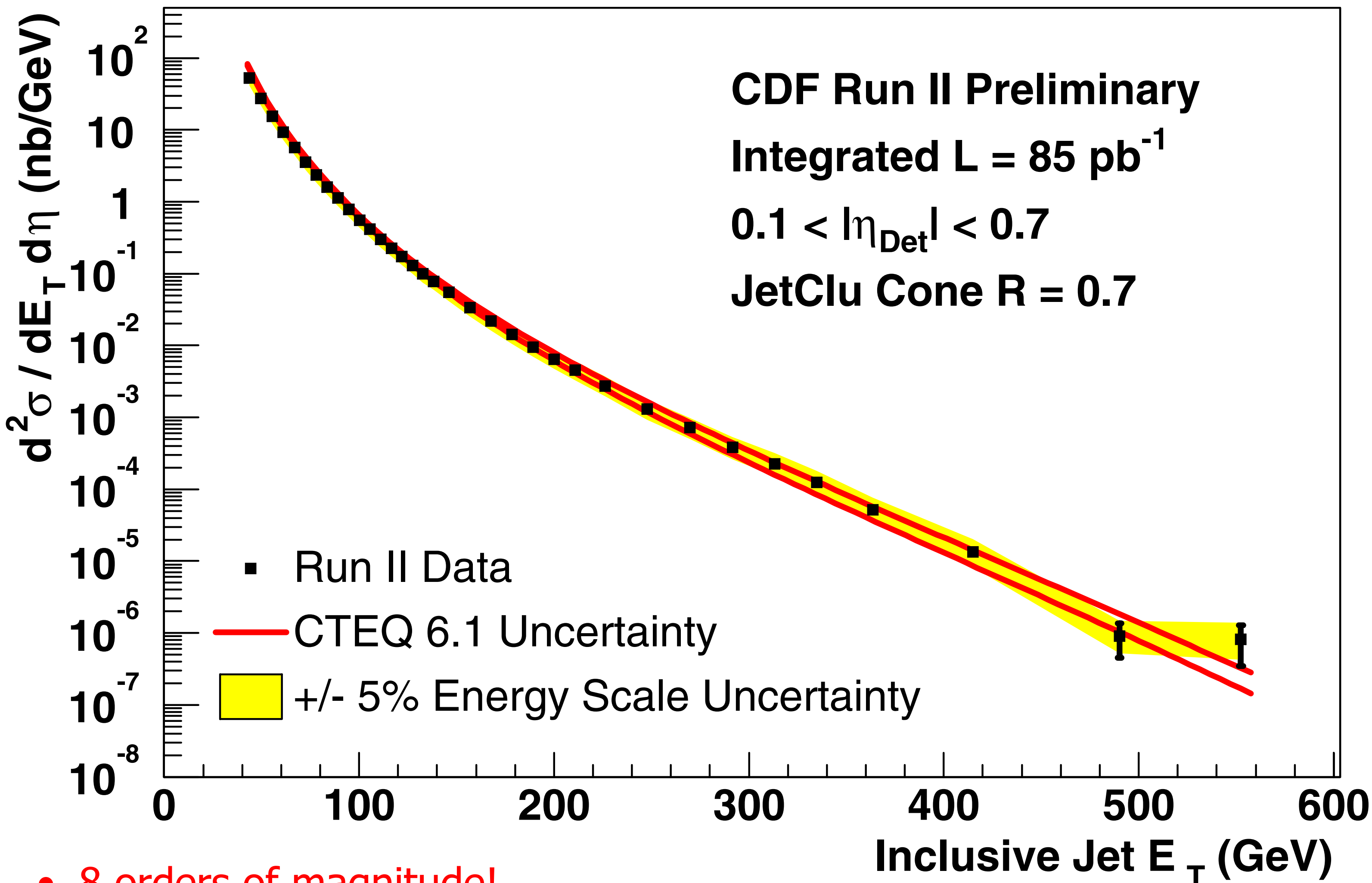
  - o Luminocity Standard (related to uncertainties on W/Z cross-sections due to PDFs

  - o Quantifying the uncertainty of the W-mass measurement due to PDFs.

  - o Predicting signals and backgrounds for SM and new physics searches

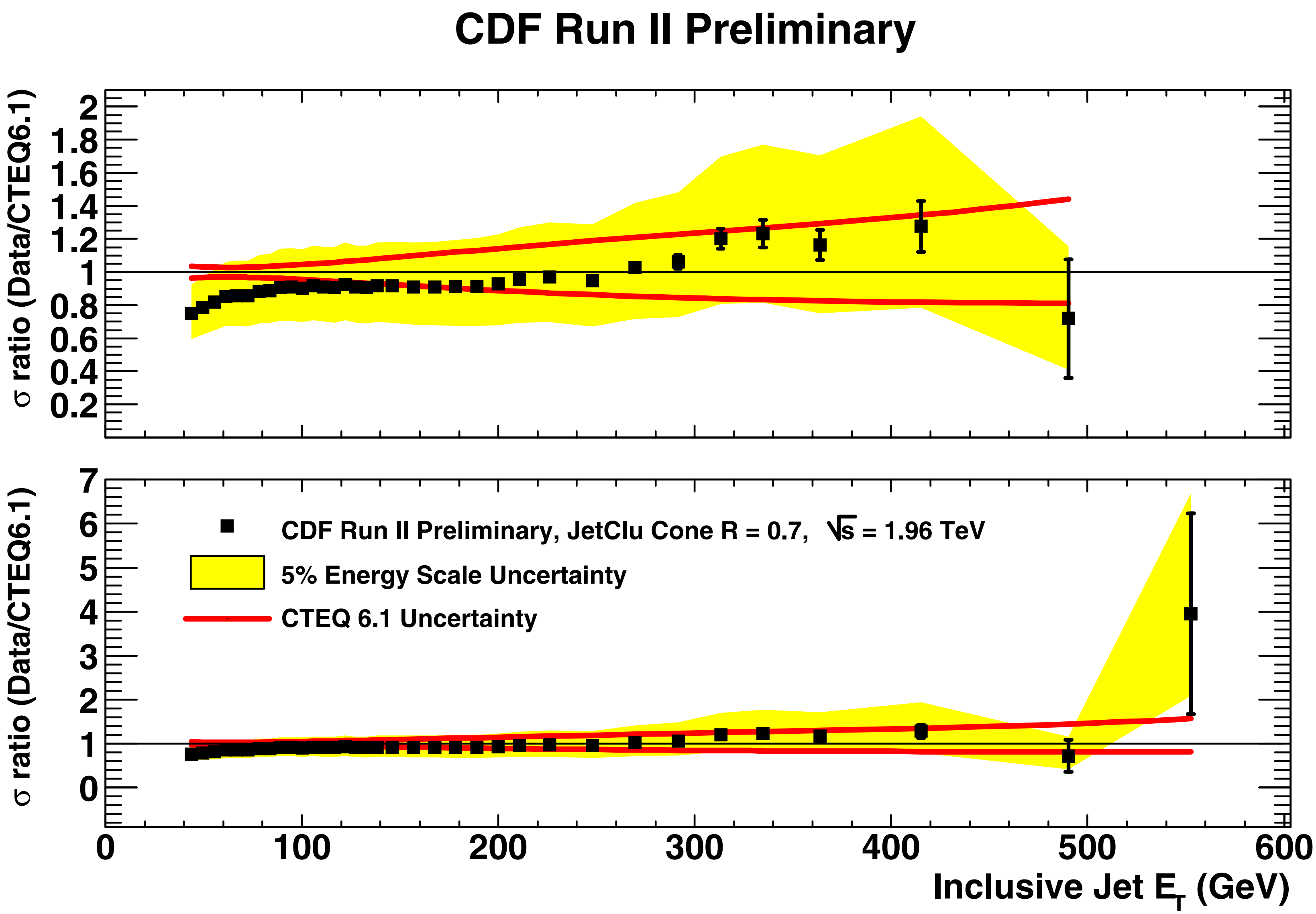
  - o Estimating the uncertainties of the above

Comparison: prediction vs. first data from Tevatron
IICDF – La Thuile and Moriond



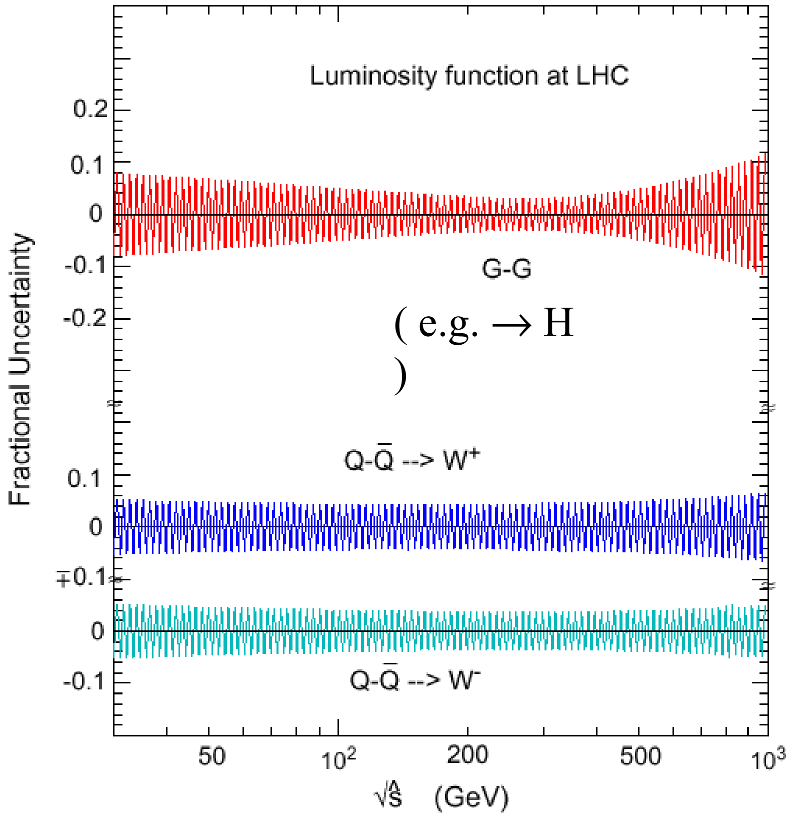
- 8 orders of magnitude!
- Highest E_T jets ever!

Comparison: prediction vs. preliminary data -- linear plot



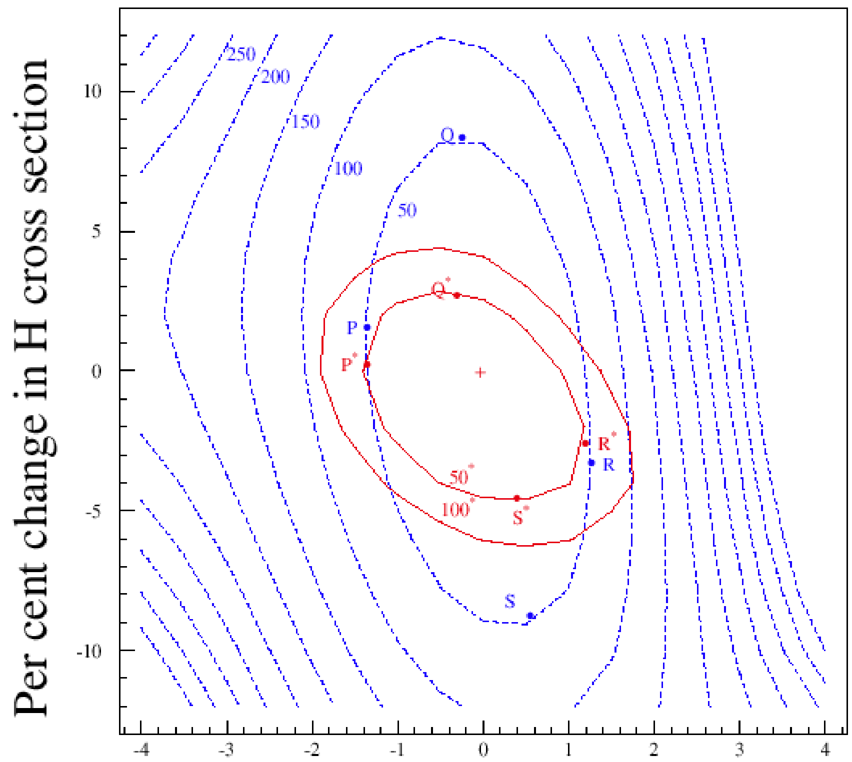
Good agreement (within uncertainties)

Some Predictions for LHC



(e.g. → H)

Errors on σ_H/σ_W at the Tevatron



What can Tevatron Run II and LHC do for PDFs?

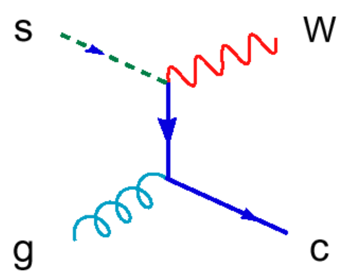
a lot ! — next generation hadron colliders are W/Z factories.

- Precision PQCD phenomenology–”DIS expts” of the 2000’s?.
  - W/Z/lepton-pair (various differential distributions)
  - Inclusive jets, W/Z + jets, ….
  - Direct photons, heavy quarks, …
- Lots of handles on quarks and gluons;
- Some unique probes for s/c/b quarks?

Probing the Sea Quark PDFs: s, c, b
using tagged final states $W/Z/\gamma + c/b$?

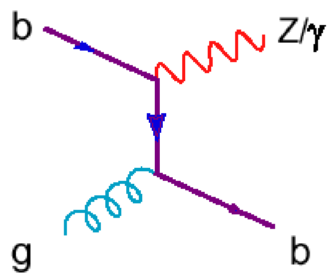
$s(x, Q)$:

$g + s \to W + c$



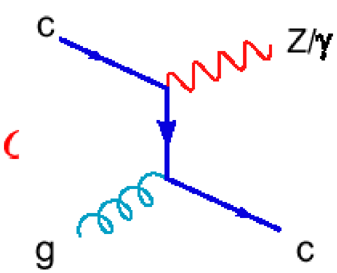
$b(x, Q)$:

$g + b \to Z/\gamma +$

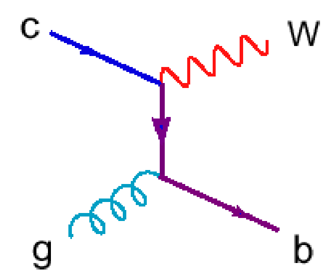


$c(x, Q)$:

$g + c \to Z/\gamma +$



$g + c \to W + b$



Parton Structure of the Nucleon, DIS, and HERA

- The *ep* and *ed* DIS expts at SLAC in the late 1960's and the neutrino expts. of the early 70's laid the foundation of PQCD, the parton model picture of high energy interactions, and the entire language of modern particle physics.
- High energy muon and neutrino scattering on nucleons and nuclei in the 70's and 80's expanded the kinematic range of DIS, and along with DY and other hard scattering processes, allowed the quantitative global QCD analyses of PDFs of the nucleon.
- The HERA experiments expanded the kinematic range into the small-x and high Q region by orders of magnitudes, and pushed the accuracy to unprecedented levels.
- HERA II (and III) can complete this remarkable journey of discovery on studying the fundamental structure of matter by measuring $e^{\pm}p$ and $e^{\pm}d$ scattering at even higher accuracy, including the yet unmeasured (but fundamental) F_L structure function, over the *entire kinematic range* available.