Summary of Working Group I

Parton Density Functions

Convenors

M. Dittmar (CMS) S. Forte (Milan) A. Glazov (H1) S. Moch (DESY)

– Workshop HERA and the LHC, DESY, Hamburg, Mar 16, 2007 –

Plan

- Theory developments
  - progress on theoretical accuracy at higher orders in QCD
- Parton density functions
  - structure functions analysis and new global fits

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- Future prospects (theory and experiment) **S. Forte**

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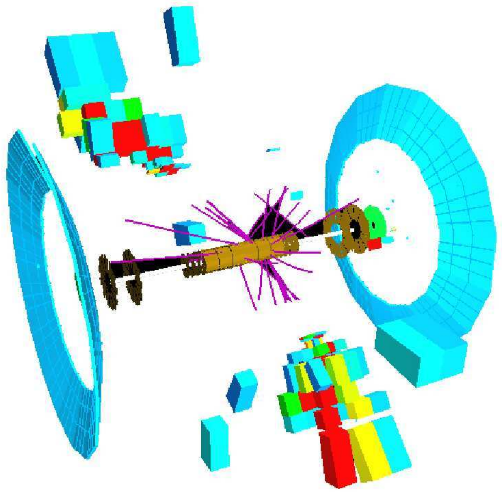
My comments in red boxes

Theory developments

Jet production

Daleo

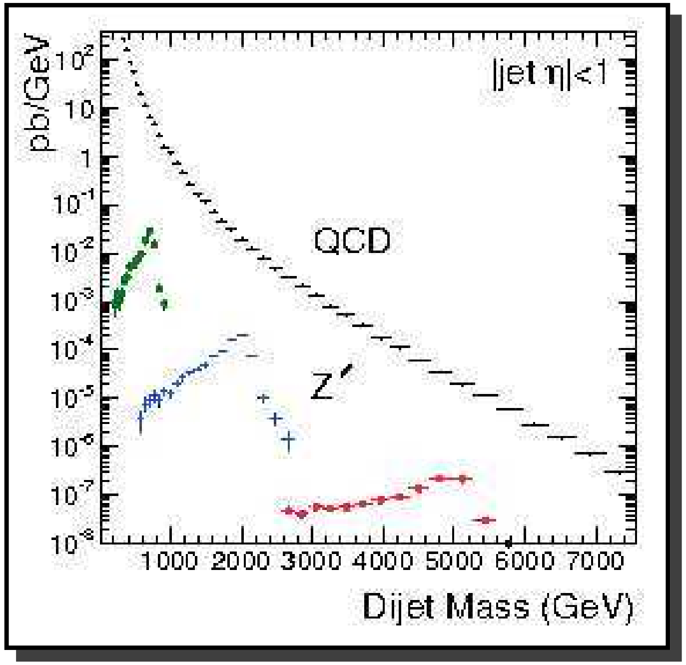
- dominat hard scattering process at LHC
- important input to constrain gluon PDFs and α_s
- rich in potential signals of new physics:
  - composite quarks
  - SUSY
  - extra gauge bosons, Z' and W'
  - Randall-Sundrum models (extra dimensions)



Hadronic di-jets at NNLO

- new physics (di-jet angular correlations)
- gluon jets for PDF at medium/large x

Higher precision: technological challenge



Production rates at NNLO

Somogyi

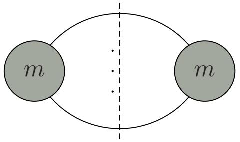
- The formal loop expansion for a producution rate to NNLO accuracy reads

$$\sigma = \sigma^{\rm LO} + \sigma^{\rm NLO} + \sigma^{\rm NNLO} + \ldots$$

- Consider m-jet production

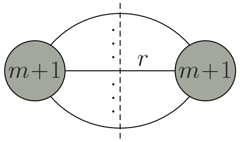
Ground breaking work
Theory prerequisites for NNLO jet programs
Subtraction schemes Daleo, Somogyi

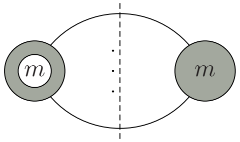
☐ LO



$$\sigma^{\rm LO} = \sigma^{\rm B}_m = \int {\rm d}\phi_m |\mathcal{M}^{(0)}_m|^2 J_m$$

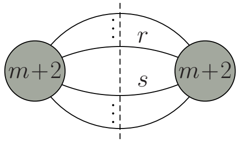
☐ NLO

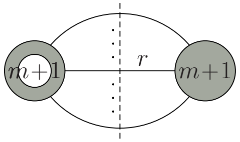


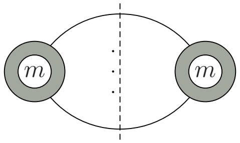


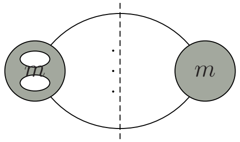
$$\sigma^{\rm NLO} = \sigma^{\rm R}_{m+1} + \sigma^{\rm V}_m = \int {\rm d}\phi_{m+1} |\mathcal{M}^{(0)}_{m+1}|^2 J_{m+1} + \int {\rm d}\phi_m 2{\rm Re}\langle \mathcal{M}^{(0)}_m | \mathcal{M}^{(1)}_m \rangle J_m$$

☐ NNLO









$$\sigma^{\rm NNLO} = \sigma^{\rm RR}_{m+2} + \sigma^{\rm RV}_{m+1} + \sigma^{\rm VV}_m = \int {\rm d}\phi_{m+2} |\mathcal{M}^{(0)}_{m+2}|^2 J_{m+2} +$$

$$+ \int {\rm d}\phi_{m+1} 2{\rm Re}\langle \mathcal{M}^{(0)}_{m+1} | \mathcal{M}^{(1)}_{m+1} \rangle J_{m+1} + \int {\rm d}\phi_m \left[|\mathcal{M}^{(1)}_m|^2 + 2{\rm Re}\langle \mathcal{M}^{(0)}_m | \mathcal{M}^{(2)}_m \rangle \right] J_m$$

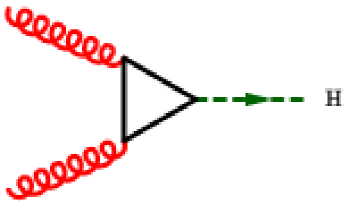
Del Duca

Review of Higgs production with emphasis on final state characteristics

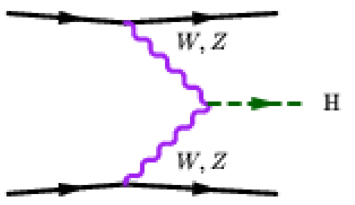
HIGGS PRODUCTION MODES AT LHC

In proton collisions at 14 TeV, and for $M_H > 100$ GeV the Higgs is produced mostly via

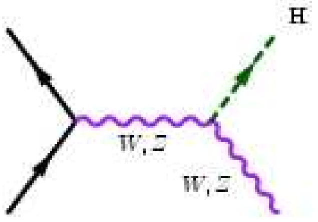
- gluon fusion $gg \to H$
  - largest rate for all M_H
  - proportional to the top Yukawa coupling y_t



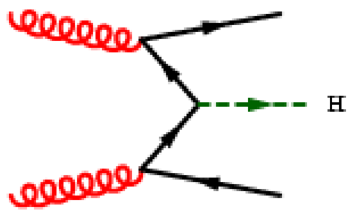
- weak-boson fusion (WBF) $qq \to qqH$
  - second largest rate (mostly $u\,d$ initial state)
  - proportional to the WWH coupling



- Higgs-strahlung $q\bar{q} \to W(Z)H$
  - third largest rate
  - same coupling as in WBF



- $t\bar{t}(b\bar{b})H$ associated production
  - same initial state as in gluon fusion, but higher x range
  - proportional to the heavy-quark Yukawa coupling y_Q

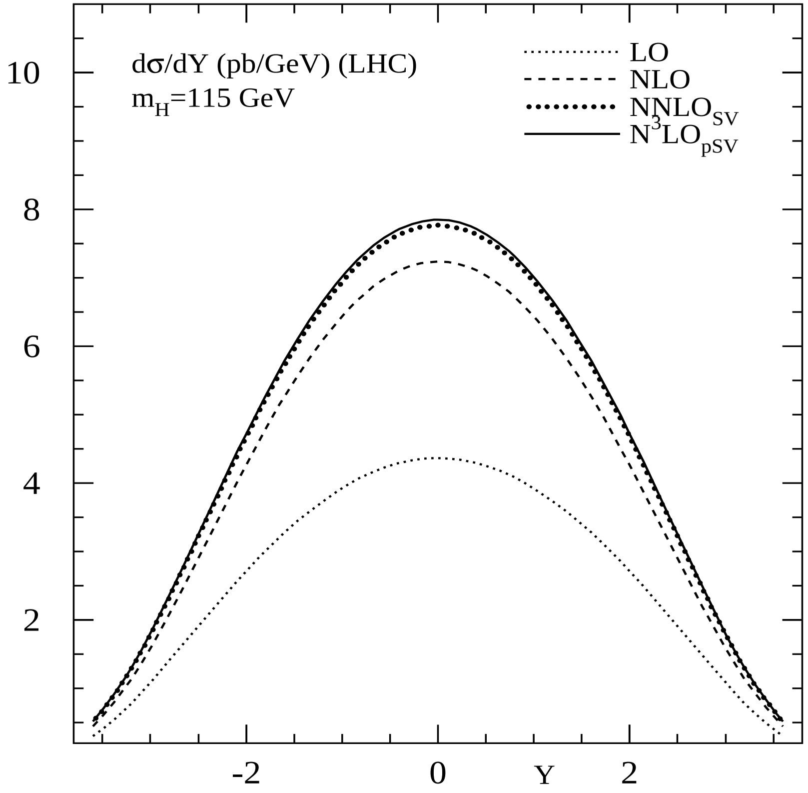


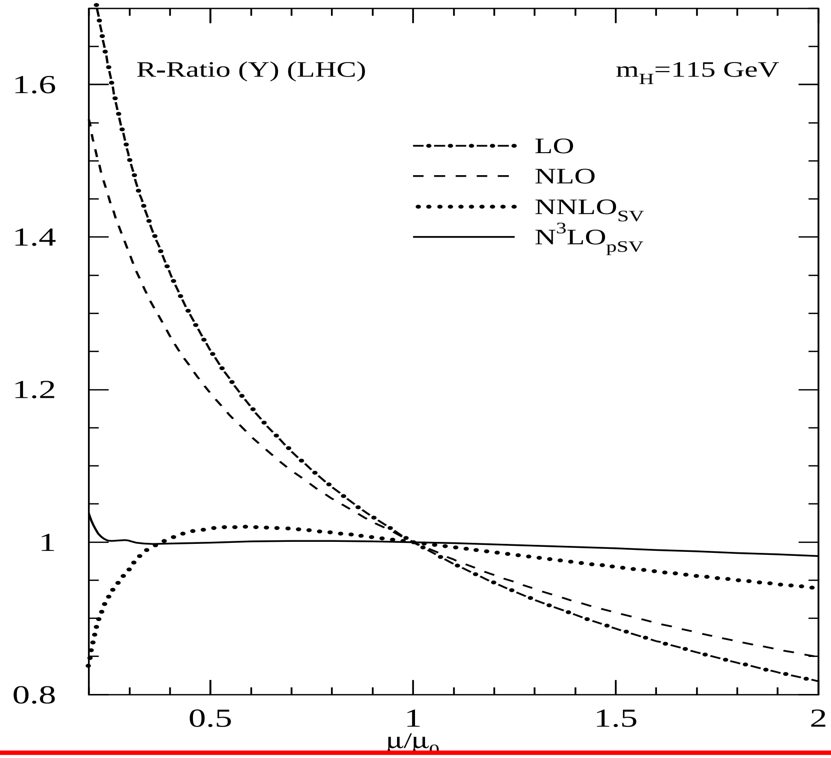
Rapidity distribution $d\sigma/dy$ of Higgs at N^3LO_{pSV}

J.Smith, W. van Neerven, V. Ravindran

Smith

$$R = \frac{\sigma_{N^iLO}(\mu)}{\sigma_{N^iLO}(\mu_0)}$$





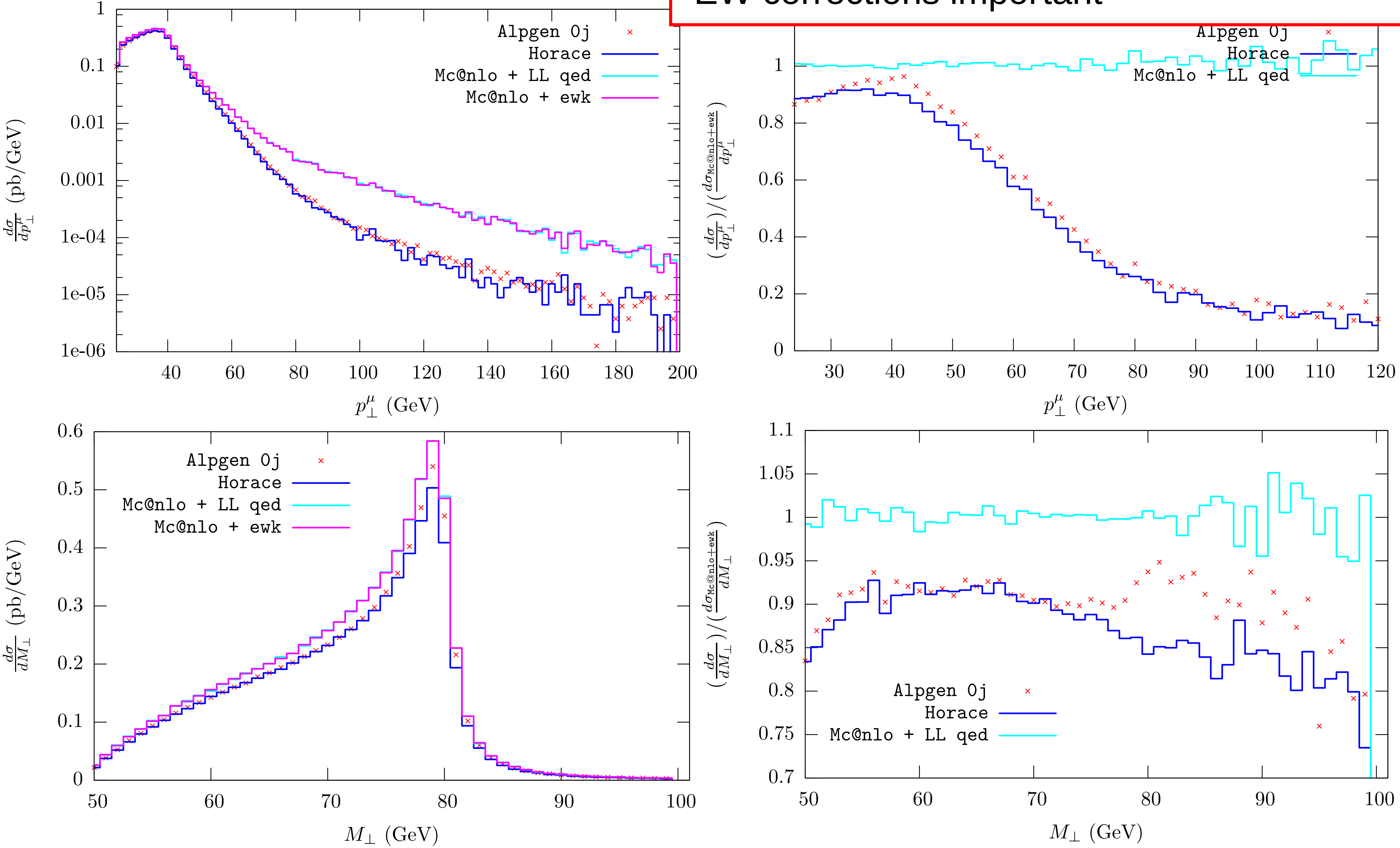
- Scale uncertainity improves a lot
- Perturbative QCD works at LHC

Soft+virtual QCD corrections at N^3LO (large x)
Good approximation for gg → Higgs
Very small residual scale dependence

QCD $\oplus$ EW: Lepton $p_\perp$ and $M_\perp$

Piccinini

QCD $\oplus$ EW for Drell-Yan distributions at LHC
EW corrections important

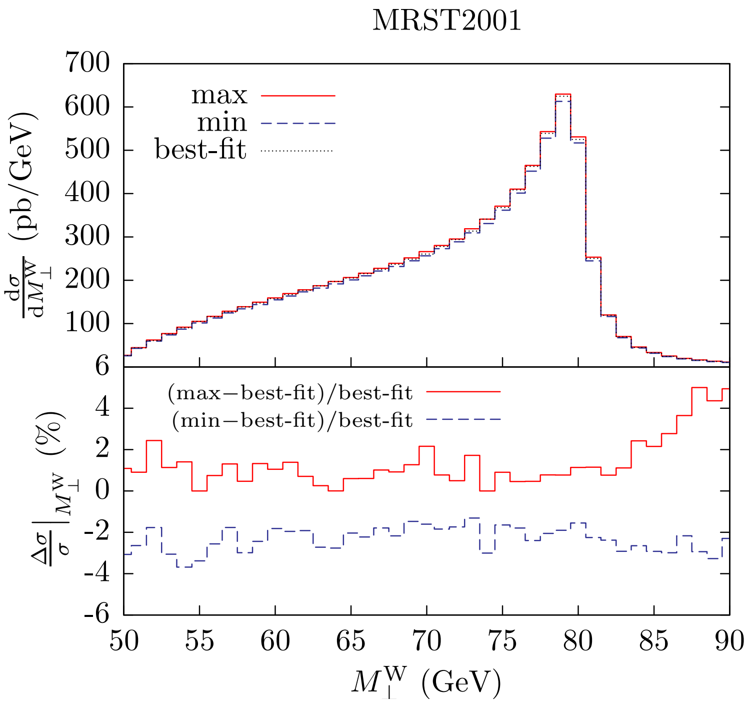


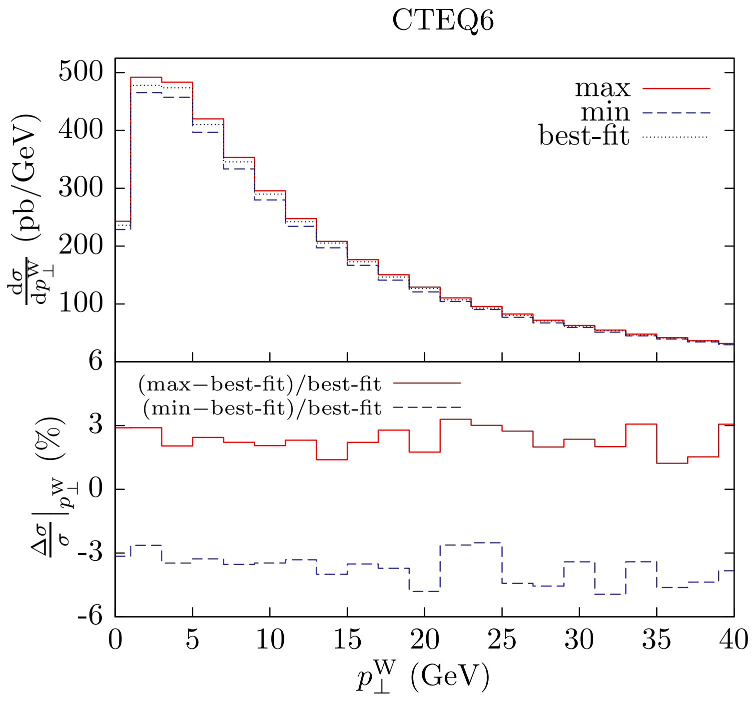
PDF's uncertainties

Piccinini

PDF uncertainties included in studies

- For precision predictions for D-Y, PDF's uncertainties need to be estimated
- We are studying them within the context of LHAPDF with error estimates (reflecting only the errors of exp. origin in the PDF parameters)





Ward

QED⊗QCD Threshold Corrections

,Shower/ME Matching & IRI-DGLAP Theory at the LHC

We shall apply the new simultaneous QED⊗QCD exponentiation calculus to the sinlge Z production with leptonic decay at the LHC (and at FNAL) to focus on the ISR alone, for definiteness. See also the work of Baur *et al.*, **Dittmaier and Kramer, Zykunov for exact $\mathcal{O}(\alpha)$ results and Hamberg** *et al.*, **van Neerven and Matsuura and Anastasiou** *et* **for exact $\mathcal{O}(\alpha_s^2)$ results.**

Further improvement for QCD ⊕ QED through exponentiation

or the basic formula

$$\sigma_{exp}(pp \to V + X \to \bar{\ell}\ell' + X') = \sum_{i,j} \int dx_i dx_j F_i(x_i) F_j(x_j) d\hat{\sigma}_{exp}(x_i x_j s), \tag{8}$$

we use the result in (6) here with semi-analytical methods and structure functions from Martin *et al.*.

A MC realization will appear elsewhere.

Results

Moch

$$
\begin{aligned}
C^{\mathrm{ns}}_{3,10} \; = \;& \\
& 1 + a_s C_F \frac{1953379}{138600} + a_s^2 C_F n_f \left(-\frac{537659500957277}{15975002736000} \right) + a_s^2 {C_F}^2 \left(\frac{5973994463755 24589}{14760902528064000} \right. \\
& \left. + \frac{7202}{105} \zeta_3 \right) + a_s^2 C_A C_F \left(\frac{583260205812 2267}{29045459520000} - \frac{99886}{1155} \zeta_3 \right) \\
& + a_s^3 C_F {n_f}^2 \left(\frac{5133975667319 4617191}{99636092064432 0000} + \frac{48220}{18711} \zeta_3 \right) + a_s^3 {C_F}^2 n_f \left(-\frac{1254838179460551 21351353}{209235793335307 200000} \right. \\
& \left. - \frac{59829376}{3274425} \zeta_3 + \frac{24110}{693} \zeta_4 \right) + a_s^3 {C_F}^3 \left(-\frac{744474223606695878525401307}{70889086782002079360 00000} + \frac{28630985464358}{24960941775} \zeta_3 \right. \\
& \left. + \frac{151796299}{8004150} \zeta_4 - \frac{53708}{99} \zeta_5 \right) + a_s^3 C_A C_F n_f \left(-\frac{185221350045507487753}{2264456637828 00000} + \frac{8071097}{39690} \zeta_3 \right. \\
& \left. - \frac{24110}{693} \zeta_4 \right) + a_s^3 C_A {C_F}^2 \left(\frac{197700787293386077320 75449}{83694317334122880 00000} - \frac{619383700181}{5546875950} \zeta_3 \right. \\
& \left. - \frac{151796299}{5336100} \zeta_4 - \frac{37322}{99} \zeta_5 \right) + a_s^3 {C_A}^2 C_F \left(\frac{937987196390566481 25143}{362313062052480000 00} - \frac{43202630363}{20582100} \zeta_3 \right. \\
& \left. + \frac{151796299}{16008300} \zeta_4 + \frac{195422}{231} \zeta_5 \right)
\end{aligned}
$$

New QCD results at N^{3}LO for DIS structure functions $F_{2,L}^{\nu p-\bar{\nu} p}$ and $F_3^{\nu p-\bar{\nu} p}$ (Mellin moments)

Summary

Theory developments

- Technological challenges tackled for NNLO jet cross sections
  - subtraction schemes for real emission
- Perturbative QCD predictions for Higgs production
  - perturbation theory in good shape
- QCD $\oplus$ EW corrections for Drell-Yan process
  - EW corrections do matter
  - improvements through exponentiation
- Continous improvements on QCD corrections to DIS structure functions

Parton density functions

Can produce full NNLO predictions for charm with discontinuous partons, but continuous $F^H(x,Q^2)$.

Approximation in $\mathcal{O}(\alpha_S^3)$ heavy flavour coefficient functions for $Q^2 \leq m_H^2$ and frozen for $Q^2 > m_H^2$.

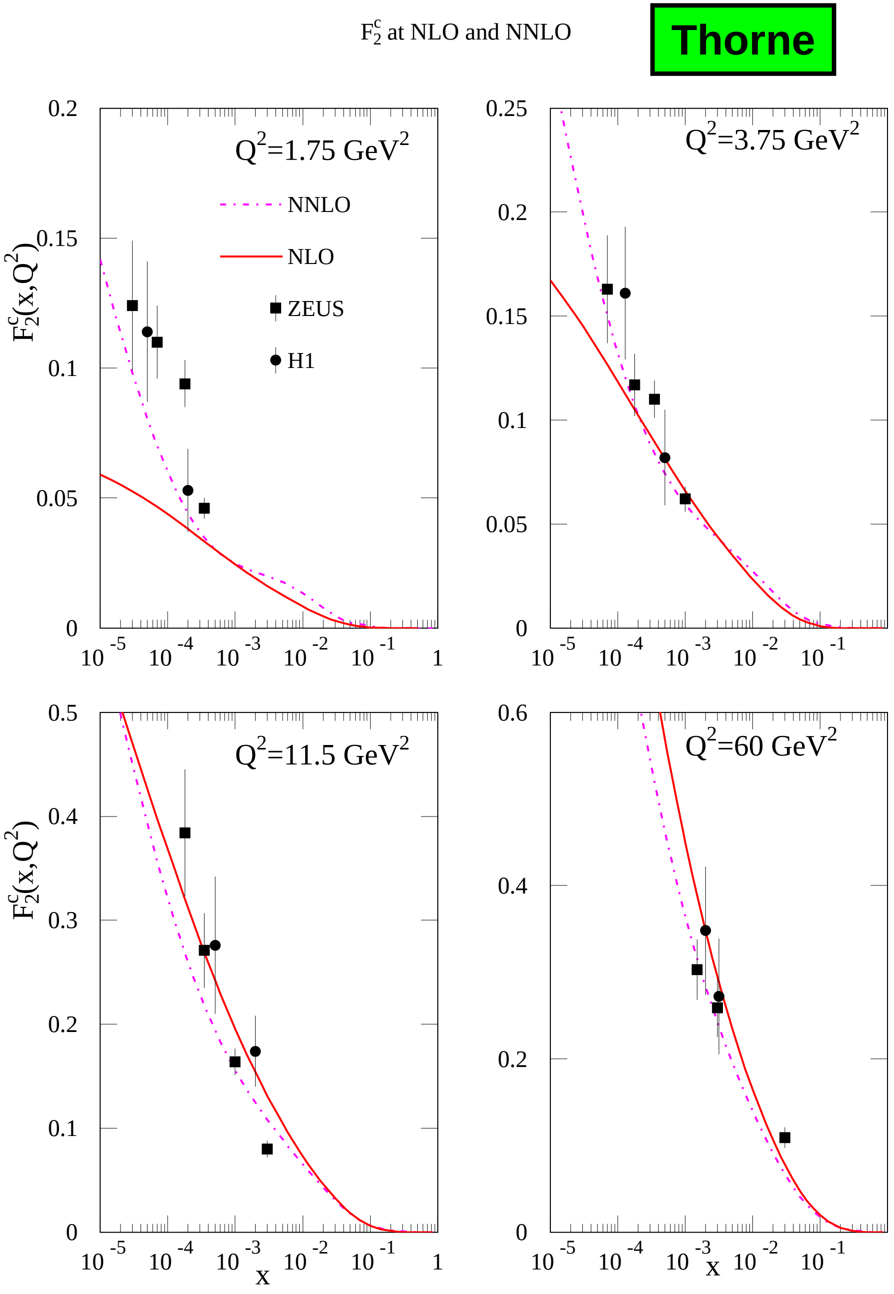
Results not very sensitive to choices in this, within sensible range.

Clearly improves match to lowest Q^2 data, where NLO always too low.

Have $\chi^2 = 97/78$ at NLO for all HERA data with $Q^2 \geq 2\mathrm{GeV}^2$.

$\rightarrow \chi^2 = 90/78$ at NNLO. Improvement at lowest Q^2, but generally changed shape.

Thorne



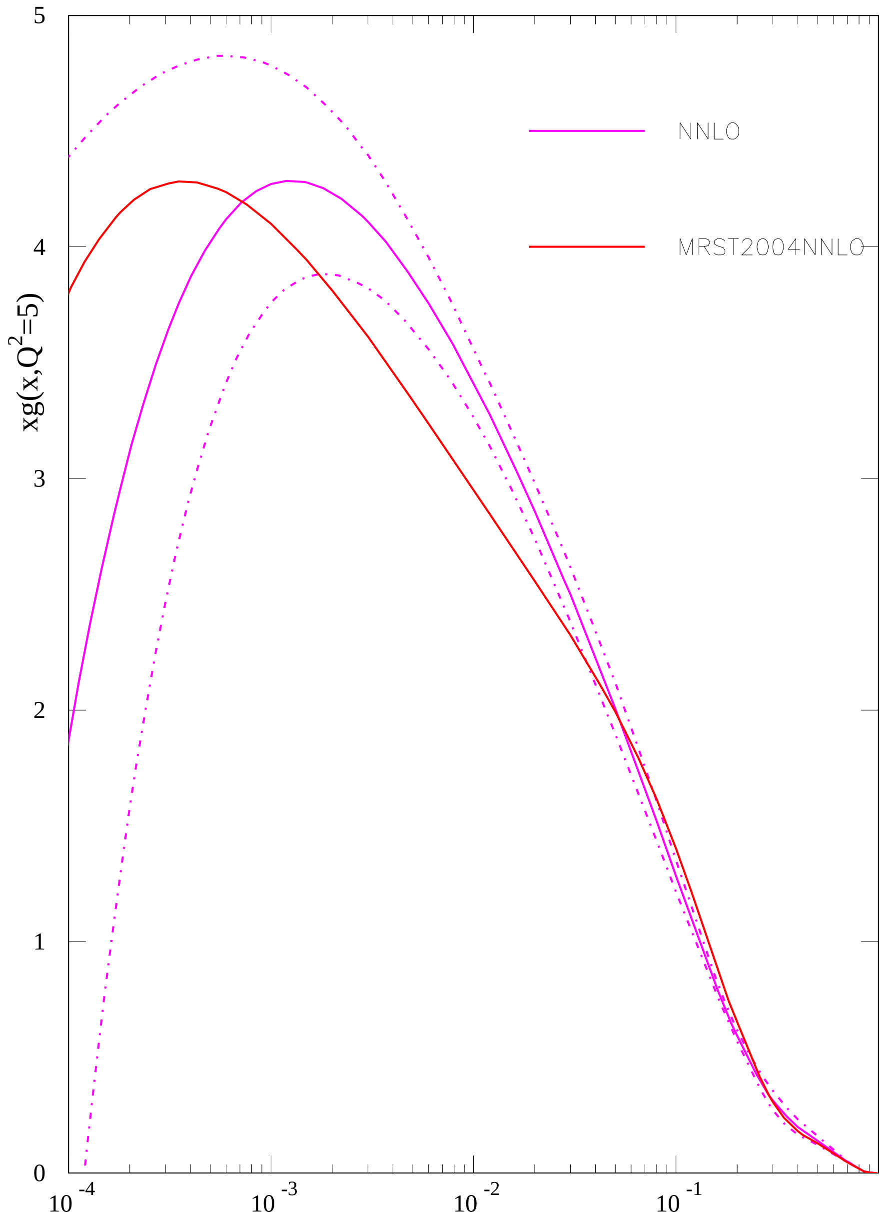
Treatment of heavy quarks
(fully consistent through NNLO)

Difference in charm procedure affects gluon compared to approx MRST2004 NNLO fit.

Change greater than uncertainty in some places. Correct heavy flavour treatment vital.

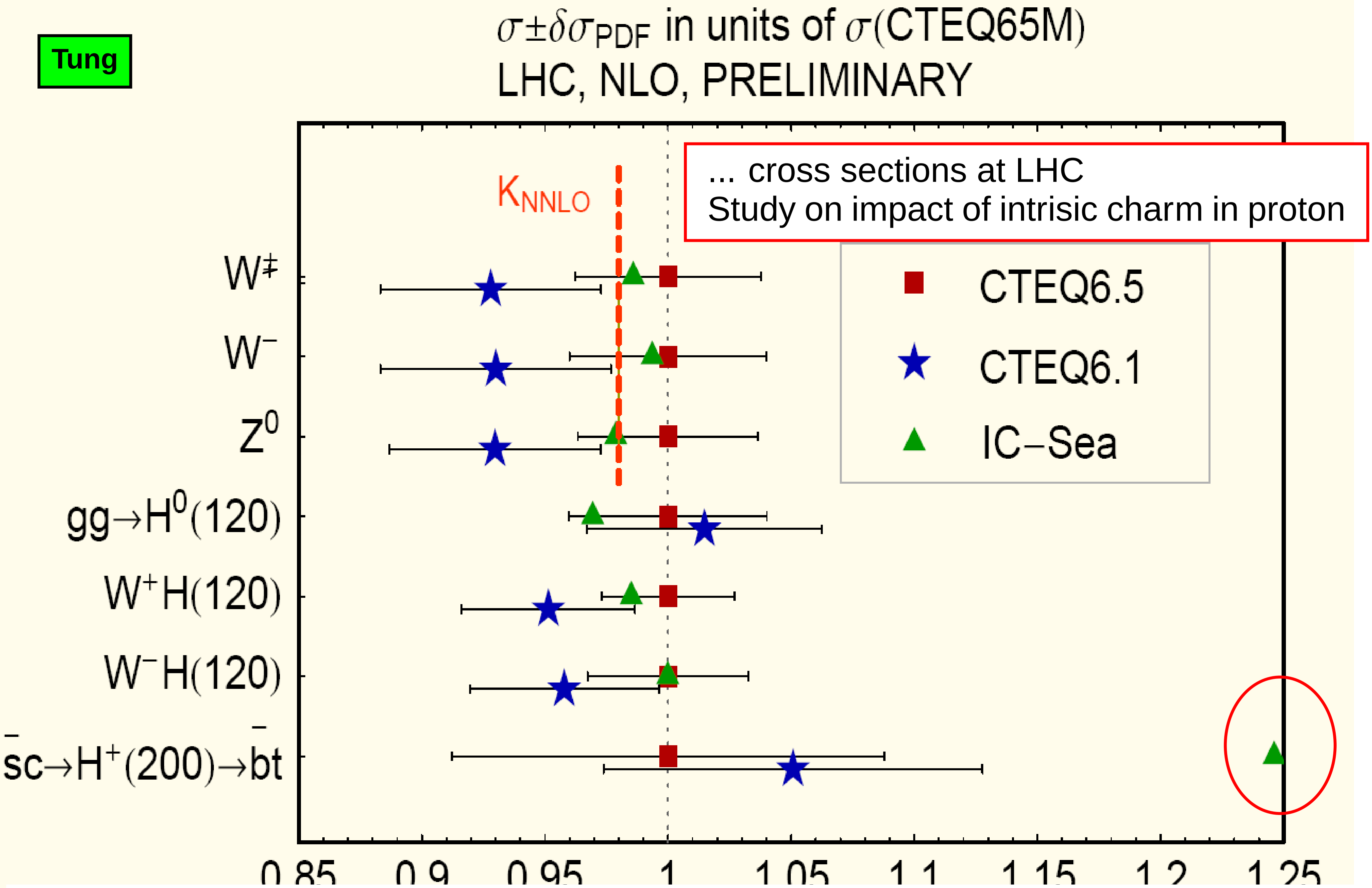
Prescription on charm (beauty) affects other parton densities e.g. gluon ...
MRST2004 vs. MSTW

Thorne



Impact of CTEQ6.5M,S,C PDF's on σ_{tot}'s at LHC

Tung



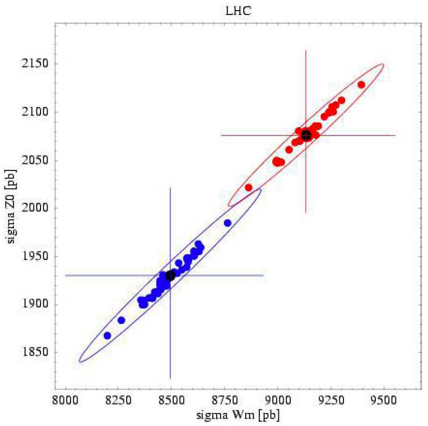
... cross sections at LHC
Study on impact of intrisic charm in proton

Huston

Summary on CTEQ6.5
Large shift in LHC cross sections (comparison CTEQ6.1 vs. CTEQ6.5)

Conclusions on CTEQ6.5

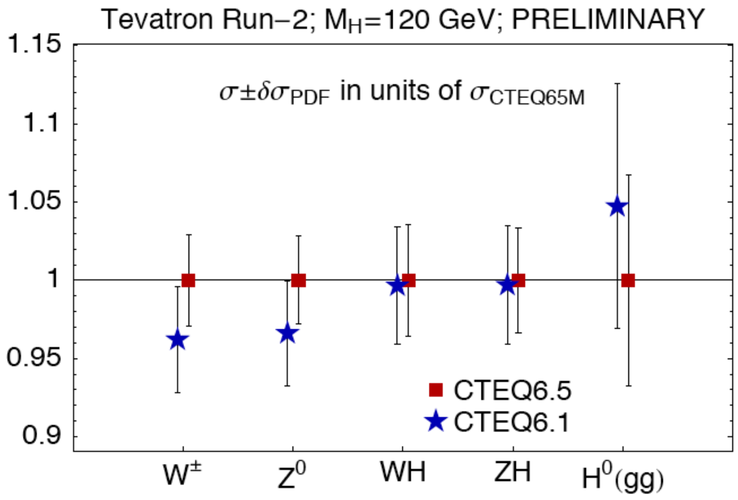
1. Improved Input
   - HQ formalism implemented
   - Use HERA measured cross sections directly
   - Include HERA CC data and NuTeV dimuon data (weight=2.0)
2. Gives better fit (χ^2 lower by ~ 200), suggesting that the physics is better! :)
3. CTEQ6.1 uncertainties were not unreasonable
4. Little or no decrease in estimated uncertainty – though the agreement with CTEQ6.1 (except where difference is expected) inspires increased confidence.
5. Larger q and $\bar{q}$ distributions at $x \sim 10^{-3}$ from correcting the former ZM approximation implies larger cross sections at LHC.

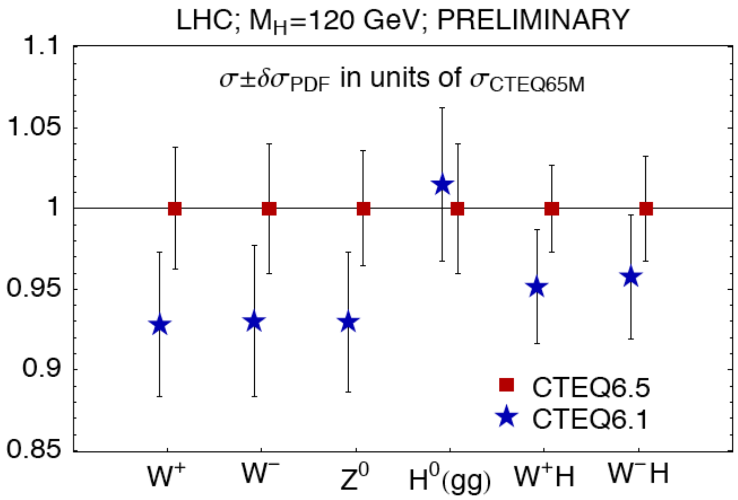


LHC

W- and Z0 cross sections for CTEQ6.1 (Blue) and CTEQ6.5 (Red)

Uncorrelated uncertainties and correlated error ellipses.



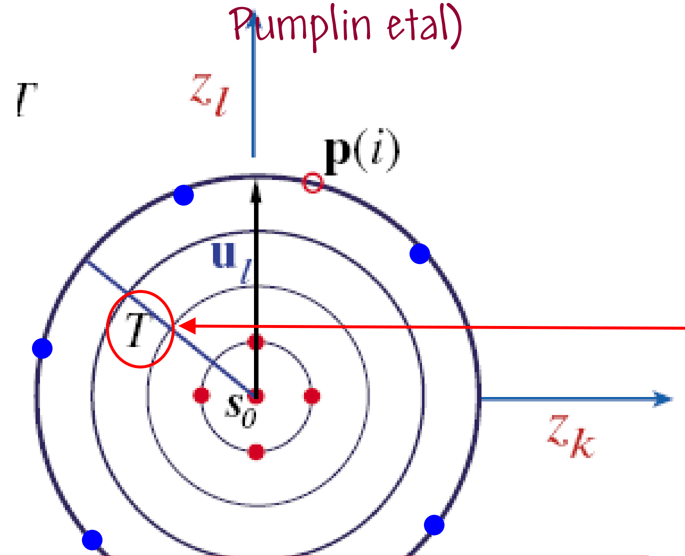


The iterative procedure: self-consistent case

Tung

$$\chi^2_{\text{global}}(a) = \sum_n \boxed{w_n} \chi^2_n(a)$$

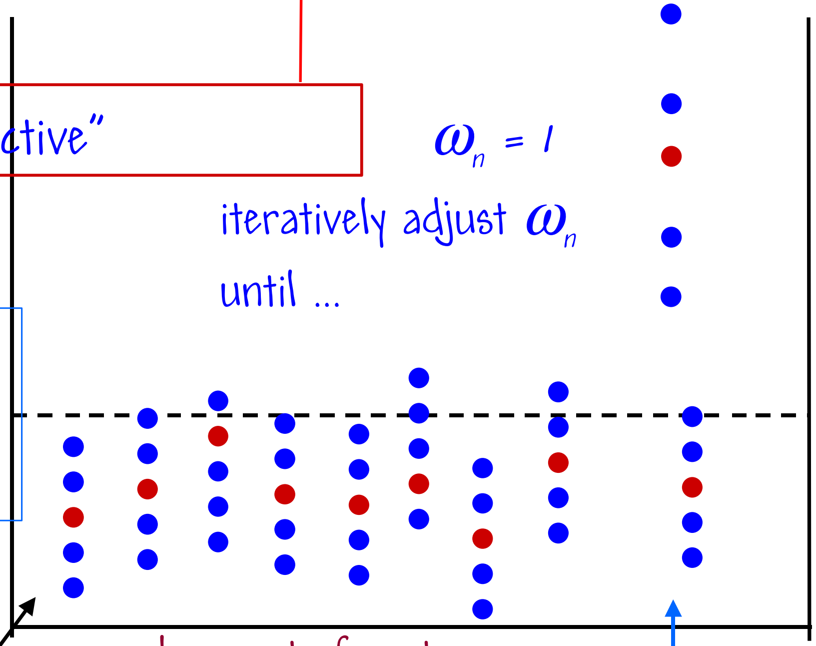
Parton parameter space (eigenvector basis of Pumplin etal)



Goodness-of-fit of individual expts.
(e.g. χ^2/dof, C.L., ... etc.)

bad fit

"arbitrary", "subjective"



$\omega_n = 1$

iteratively adjust ω_n
until ...

a priori acceptable
fit
(e.g. 90 % CL)

perfect fit

base set of expts
(e.g. DIS + ...)

new expt. sensitive to new parton
degrees of freedom

Reweighting
inconsistent data sets

iterations

ω_n

χ^2_{global}

T: tolerance for Hessian eigenvector sets

Remarks

Tung

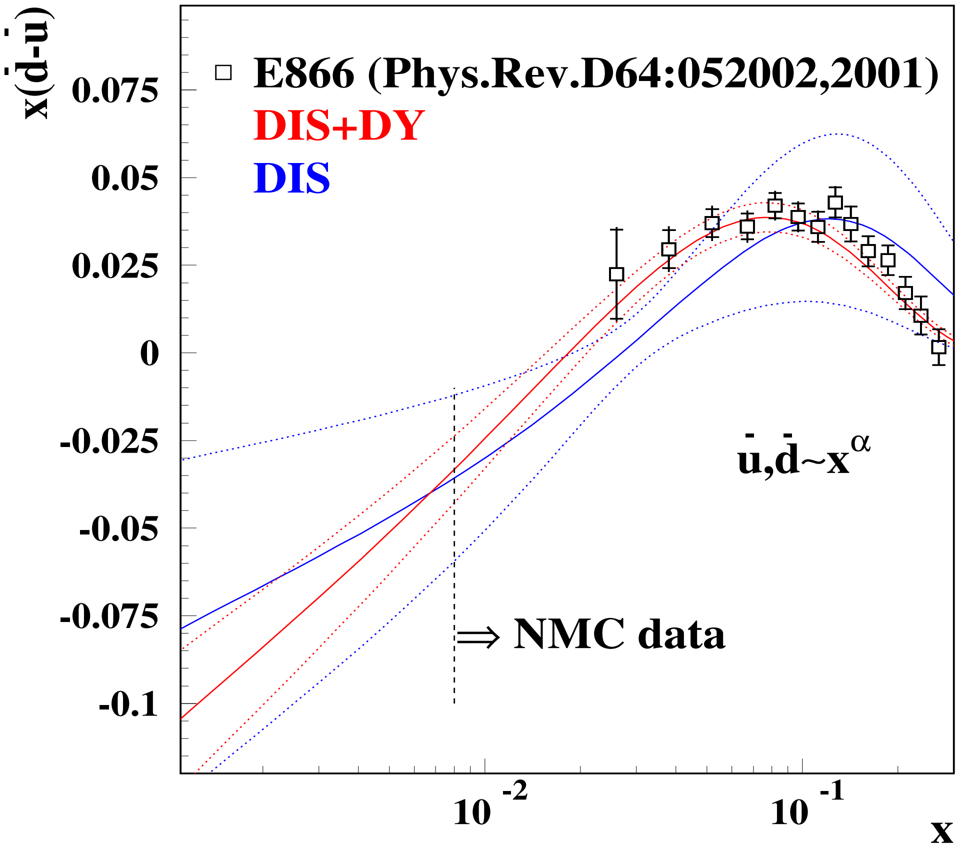
- This is a self-consistent procedure, since the proper weights and the tolerance for uncertainties in parton parameter space are not chosen a priori, but they are generated iteratively;
- The main goodness-of-fit criterion (e.g. 90% CL), although not unique, is used consistently throughout.
- This procedure is still *not statistically rigorous*; neither is it "*rocket science*". However,
  - It is a great deal *more objective* than before;
  - Because the procedure is *self-consistent* (*iterative*), the PDFs and their uncertainties obtained with it is much more *stable* and *robust* than before.

Differences in basic approach:
χ^2 reweighting (final fit sets weights $\omega = 1$) CTEQ
vs. discarding data sets Alekhin

Determination of isospin asymmetric sea
Problems with inconsistent fixed target data
in some kinematic regions (e.g. E772)

Alekhin

Isospin asymmetry of the nucleon sea



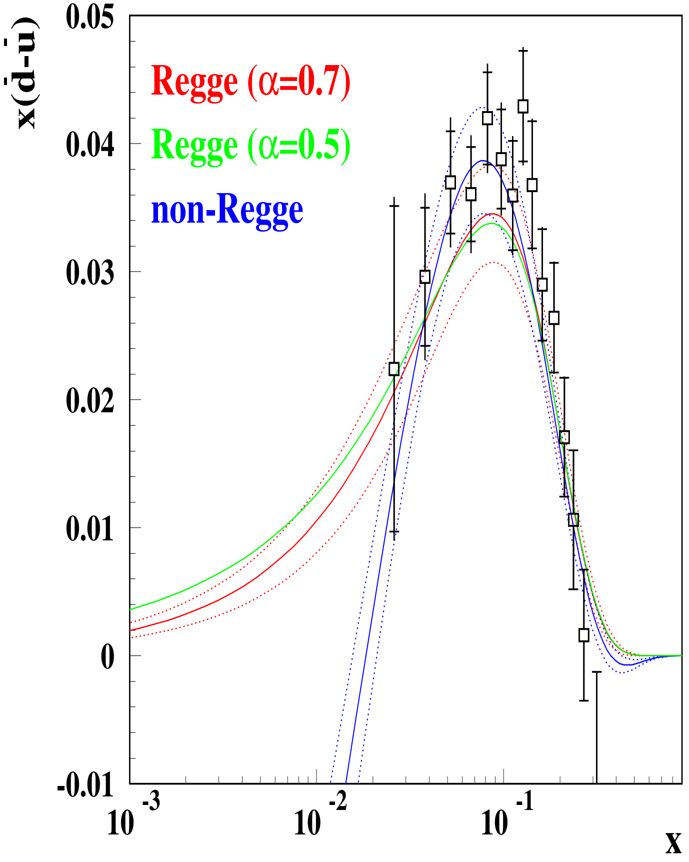
The DY data constrain $(\overline{d}-\overline{u})$ at large x, but do not help at $x < 0.01$; in this region its value is rather constrained by the functional form of the sea distributions (compare with the neural network determination of $(\overline{d}-\overline{u})$ by NNPDF collaboration)

Unconstrained region of small x

Impact on lepton charge asymmetry from $W^{\pm}$ production

Alekhin

Regge constraint on $(\bar{d} - \bar{u})$



For the shape like $x(\bar{d} - \bar{u}) \sim x^{\alpha}$ at small x uncertainty in $(\bar{d} - \bar{u})$ at $x \lesssim 0.01$ is suppressed. The price is some deterioration of the fit quality and stronger model dependence. The value of the low-x exponent for $x(\bar{d} - \bar{u})$ is uncertain (0.5 from the meson trajectories intercepts, 0.7 for the fitted valence quark distributions, and about 0.9 for the neutrino structure function xF_3)

Strange parton content of the nucleon

- Surprisingly little is known so far about the strangeness sector of the parton structure of the nucleon:
  - generally assume $s(x) = \bar{s}(x) = r(\bar{u}(x) + \bar{d}(x))/2$
  - it is known that $r \sim 0.5$, with large uncertainties.

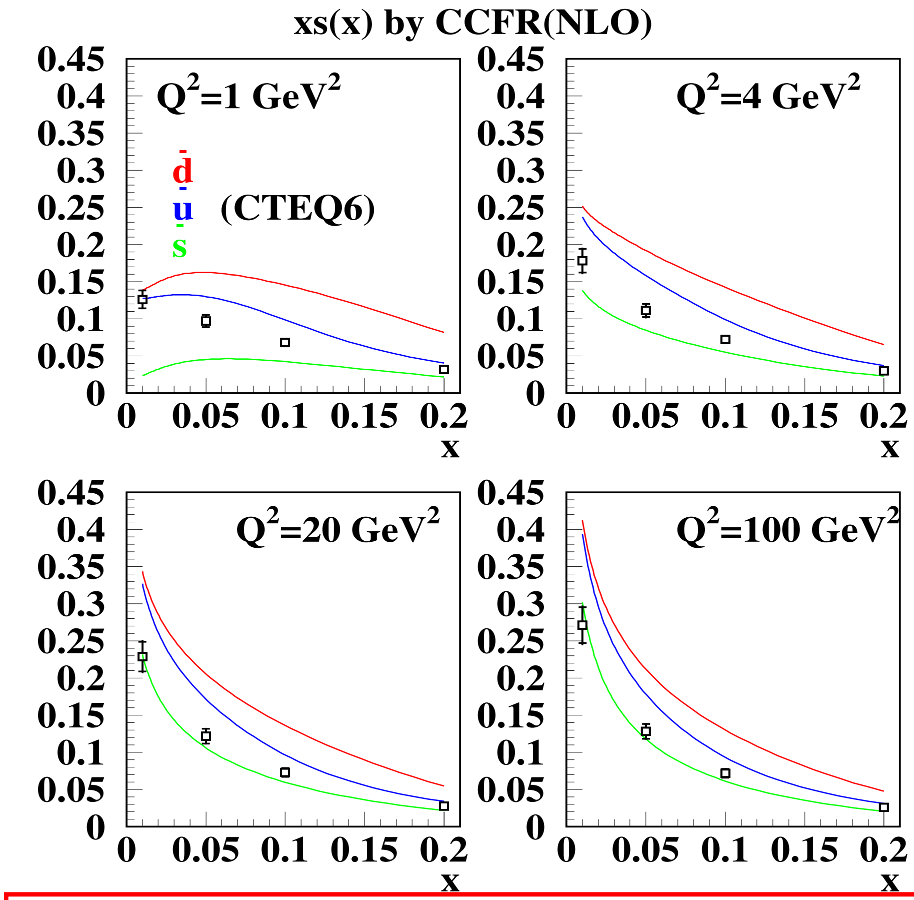
Tung

- Inputs that can improve our knowledge of this sector:
  - NuTeV CC dimuon prod. data (sensitive to s + W → c);
  - More precise GM QCD calculation of HQ processes.

- dedicated study of the strangeness sector: CTEQ6.5S:
  - Can $s_+(x) = s(x) + \bar{s}(x)$ w be determined? What is it like?
  - What can we say about the strangeness asymmetry $s_-(x) = s(x) - \bar{s}(x)$

Handle on strange density from neutrino(ν)-nucleon DIS data

Strange sea distribution in the global fits



- The sea is not SU(3) symmetric
- The CCFR determination is not consistent with the QCD evolution
- The existing data on s(x) cover the region of $x = 0.01 \div 0.2$ only

Still poor constraints on strange sea especially at small x (under further study)

Alekhin

Fitting to strange from NUTEV dimuon data affects uncertainties on partons other than strange.

Previously for us (and everyone else) strange a fixed proportion of total sea in global fit.

Genuine *larger* uncertainty on $s(x)$– feeds into that on $\bar{u}$ and $\bar{d}$ quarks.

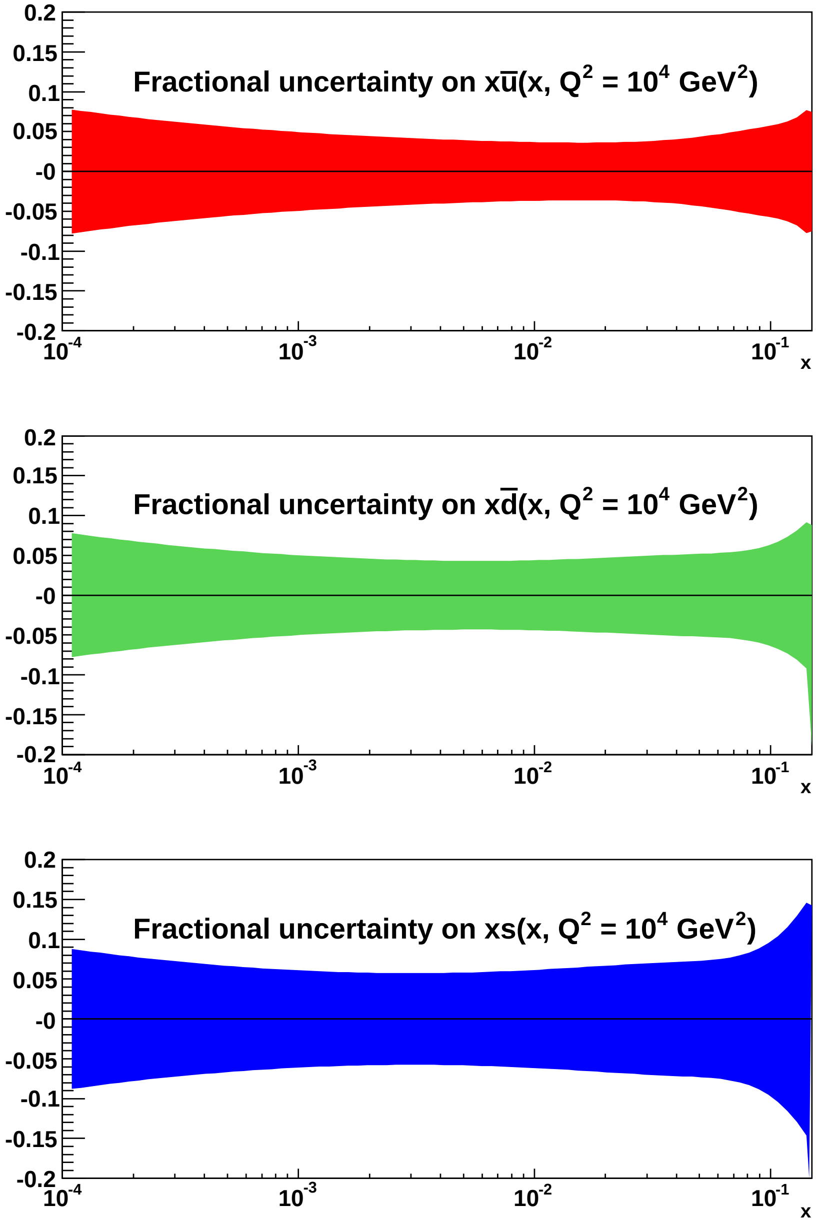
Low x data on $F_2(x,Q^2)$ constrains sum $4/9(u+\bar{u})+1/9(d+\bar{d}+s+\bar{s})$.

Changes in fraction of $s+\bar{s}$ affects size of $\bar{u}$ and $\bar{d}$ at input.

The size of the uncertainty on the small x anti-quarks roughly doubles – $\sim 1.5\% \rightarrow \sim 3\%$. (Remember uncertainties quoted as 90% confidence limits.)

PDF errors will get larger

MSTW 2007 NLO PDFs (preliminary)

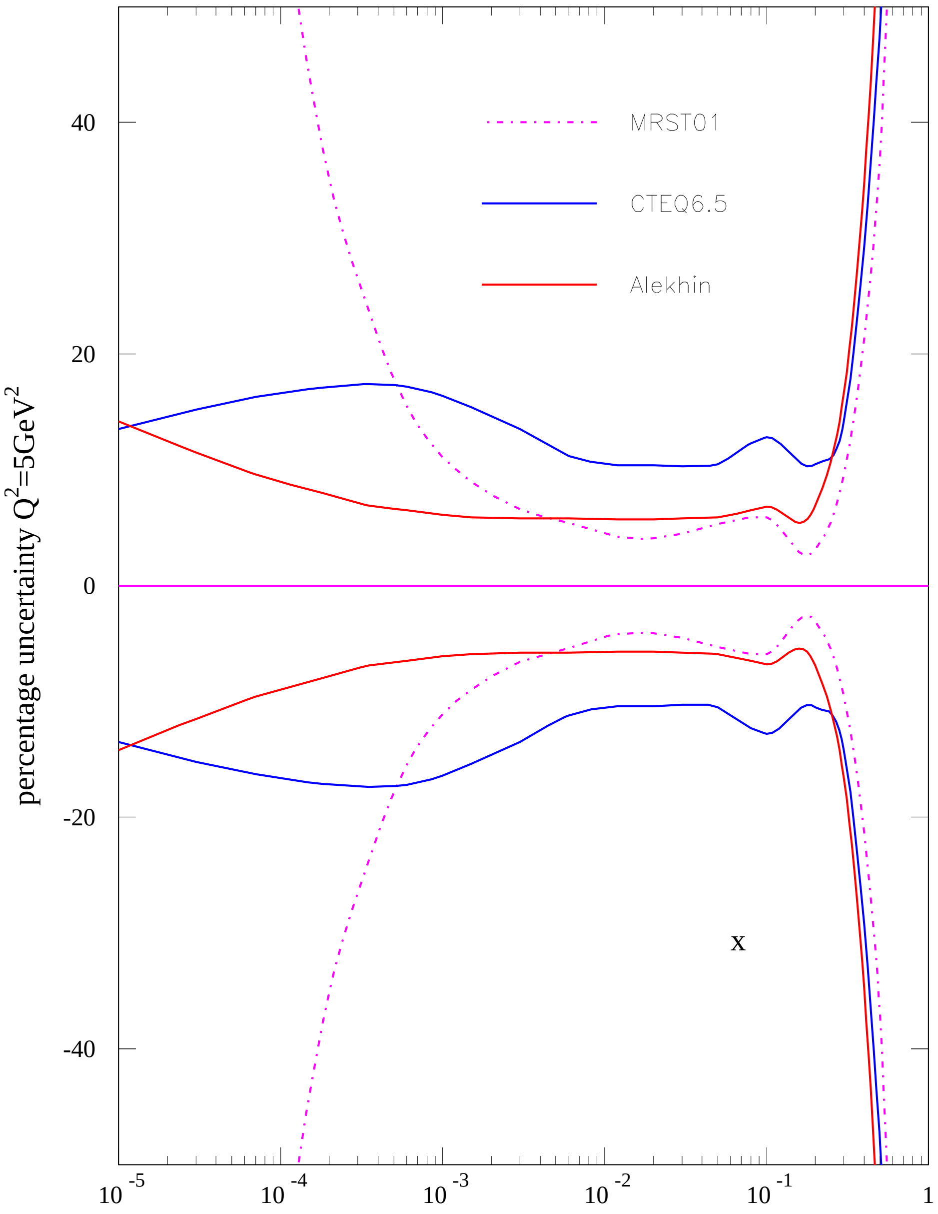


Thorne

MRST uncertainty blows up for very small x, whereas Alekhin (and ZEUS and H1) gets slowly bigger, and CTEQ saturates (or even decreases).

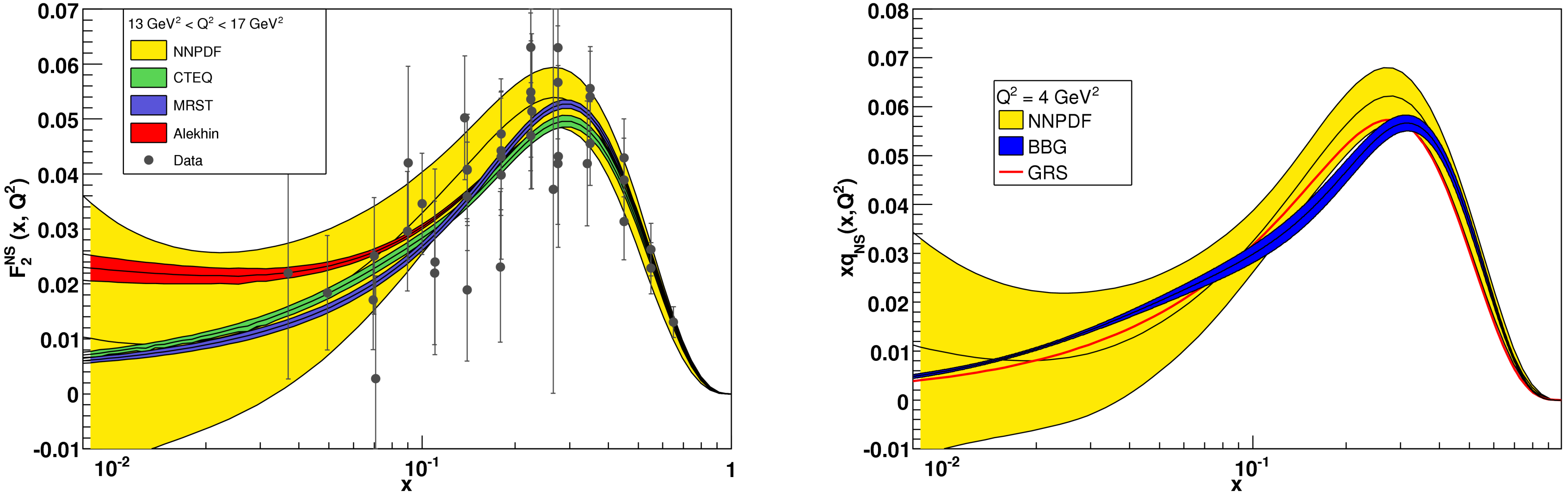
Related to input forms and scales.

Thorne



Error on gluon density at $x = 10^{-5}$ largely due to parametrization bias

Neural network analysis without parametrization bias
First neural PDF set announced for summer 2008



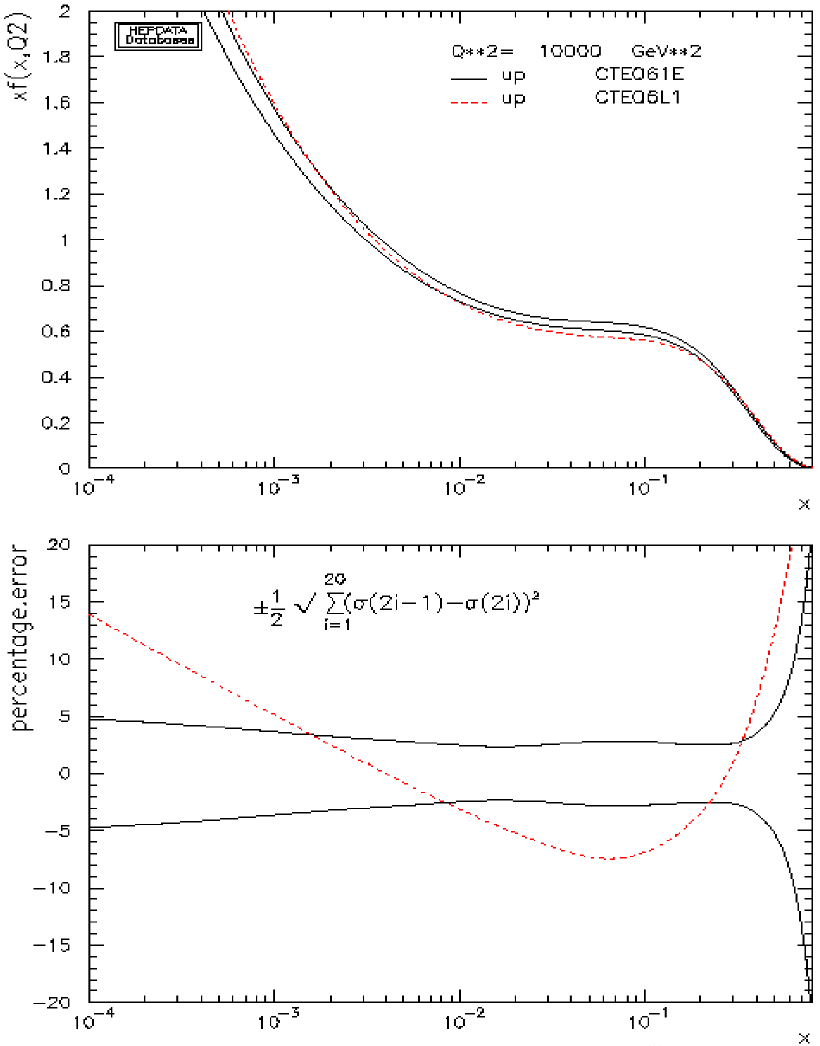
Rojo

1. Compatibility with existing fits (both global and NS)
2. Larger uncertainties both in data and in extrapolation region (same effect in pure NS fits)
3. Clear effect of error increase in extrapolation region.

…which brings me to: LO vs NLO pdf’s for parton shower MC’s

Huston

- For NLO calculations, use NLO pdf’s (duh)
- What about for parton shower Monte Carlos?
    - somewhat arbitrary assumptions (for example fixing Drell-Yan normalization) have to be made in LO pdf fits
    - DIS data in global fits affect LO pdf’s in ways that may not directly transfer to LO hadron collider predictions
    - LO pdf’s for the most part are outside the NLO pdf error band
    - LO matrix elements for many of the processes that we want to calculate are not so different from NLO matrix elements
    - by adding parton showers, we are partway towards NLO anyway
    - any error is formally of NLO
- (my recommendation) use NLO pdf’s
    - pdf’s must be + definite in regions of application (CTEQ is so by def’n)
- Note that this has implications for MC tuning, i.e. Tune A uses CTEQ5L
    - need tunes for NLO pdf’s



. . . but at the end of the day this is still LO physics; There’s no substitute for honest-to-god NLO.

Huston

Dedicated study program under way including MC showers

- We are carrying out a systematic study of the impact of the use of NLO pdf's for LO parton shower predictions

Torbjorn Sjostrand

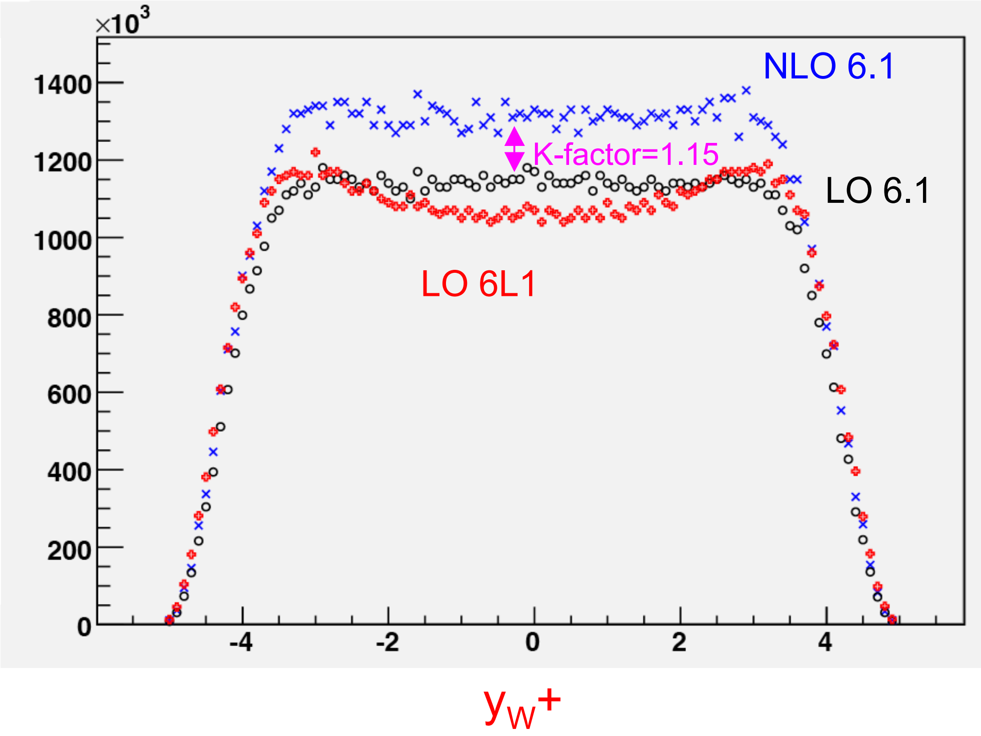
The proof of the pudding . . .

Assume the best description of physics is obtained with
(a) $\hat{\sigma}(\mathrm{NLO}) \otimes \mathrm{PDF}(\mathrm{NLO})$.

Interesting comparisons would then be with the scenarios:
(b) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{LO})$.
(c) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{LO}) \otimes$ showers.
(d) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{NLO})$.
(e) $\hat{\sigma}(\mathrm{LO}) \otimes \mathrm{PDF}(\mathrm{NLO}) \otimes$ showers.
Only if (e) is a better approximation to (a) than is (c) would the use of NLO PDF's be motivated in a general-purpose generator.

Technical aside:
(a) = external NLO program.
(c), (e) = PYTHIA/HERWIG/. . . without primordial $k_\perp$, MI or hadronization.
(b), (d) = ditto, also without ISR and FSR showers.

W⁺ rapidity distribution at LHC



- One possibility
  - use CTEQ5L for UE but NLO pdf's for matrix element evaluation
- Answers by/at Les Houches 2007

For example, the shape of the W⁺ rapidity distribution is significantly different than the NLO result if the LO pdf is used, but very similar if the NLO pdf is used.

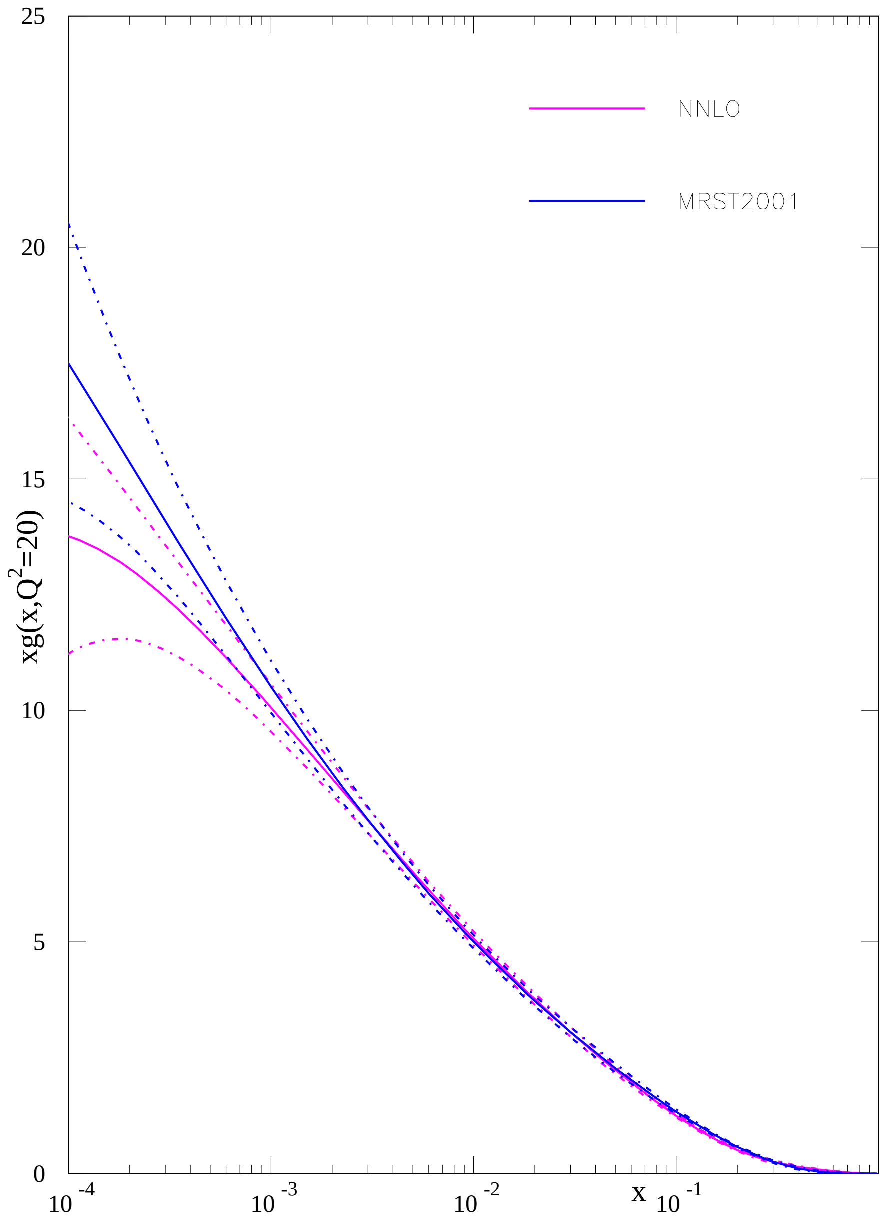
At small x effect of splitting functions particularly $P^2_{qg}(x,Q^2)$ important.

Positive $\ln(1/x)/x$ contribution at low x.

Affects gluon by fitting $dF_2(x,Q^2)/d\ln Q^2$.

Smaller at very low x.

NNLO coefficient functions very important for $F_L(x,Q^2)$.



Thorne

Higher orders resolve more features of theory e.g. q^s, q^v, q^-
all evolve with different kernels
at NNLO

At large x coefficient functions important again,

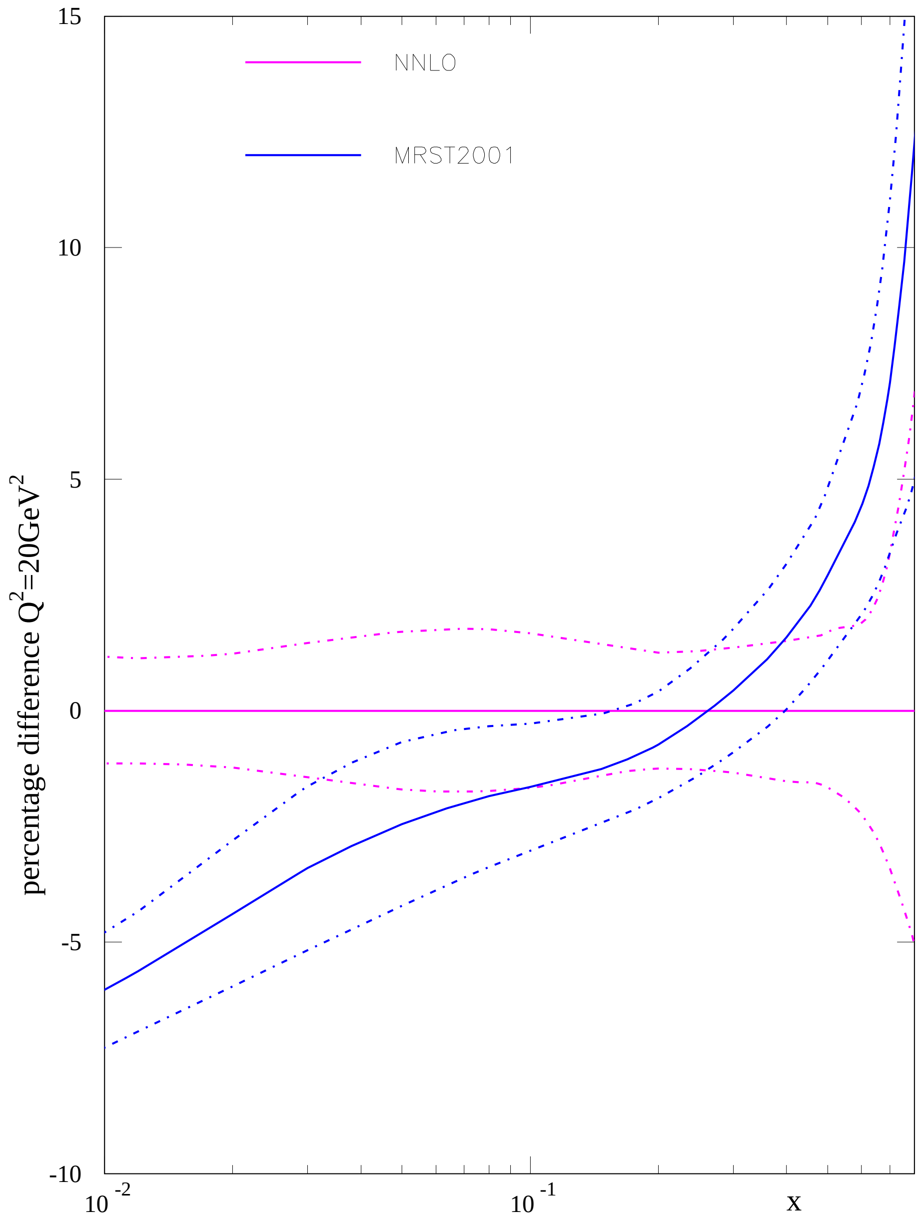
$$C^2_{2,q}(x) \sim \left(\frac{\ln^3(1-x)}{1-x}\right)_+$$

Change from NLO to NNLO again larger than uncertainty in each.

No real change from MRST2004NNLO partons.

Thorne

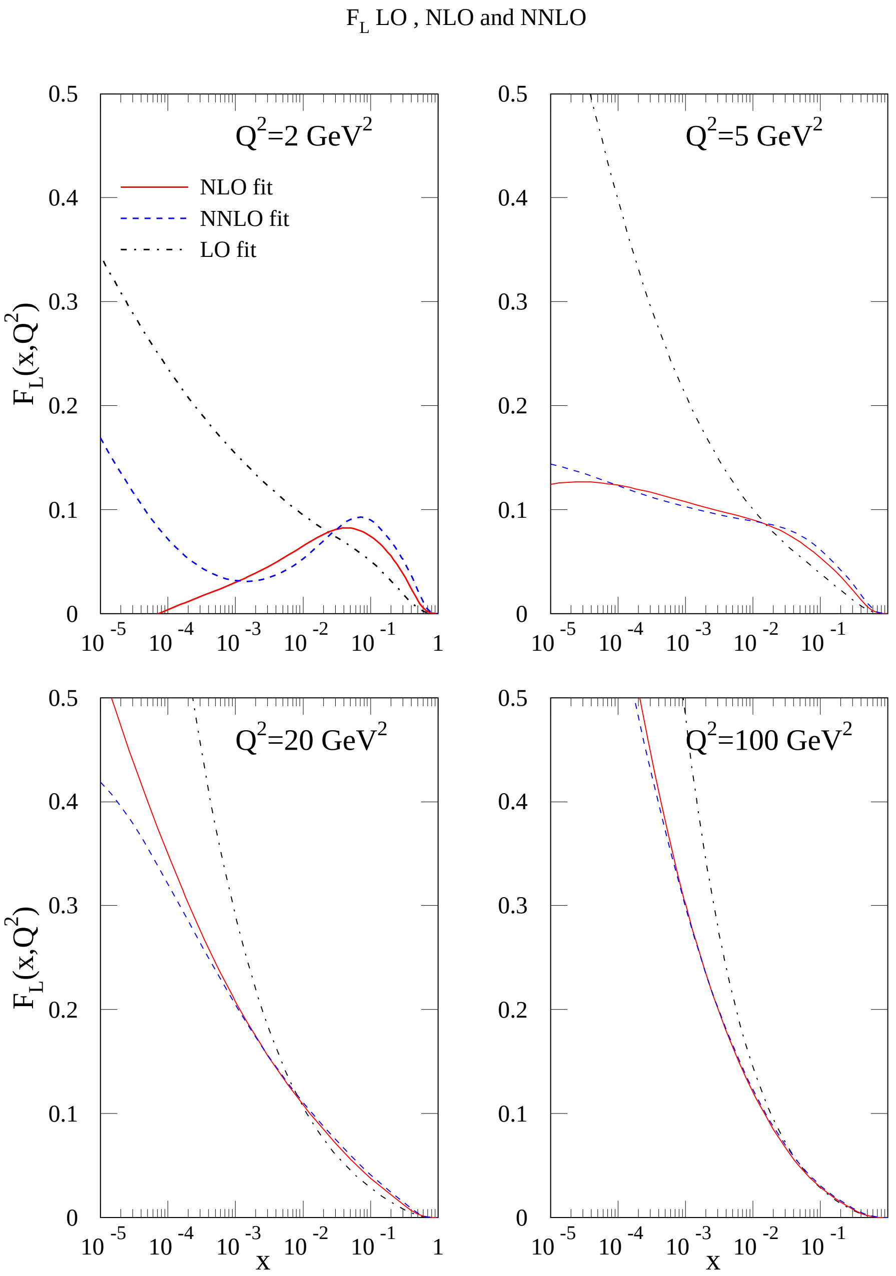
Impact of higher order QCD corrections



$F_L(x,Q^2)$ predicted from the global fit at LO, NLO and NNLO.

NNLO coefficient function more than compensates decrease in NNLO gluon.

Thorne



Problem with positivity of F_L resolved

Summary

Quality of full fit at NLO and at NNLO.

Thorne

NNLO fairly consistently better than NLO.

Definite tendency for $\alpha_S(M_Z^2)$ to go up with all changes.

At NLO $\alpha_S(M_Z^2) = 0.121$.

At NNLO $\alpha_S(M_Z^2) = 0.119$.

Pull for high $\alpha_S(M_Z^2)$ at NLO from NMC data, SLAC data, Tevatron jets (indirectly) and $F_L(x, Q^2)$ data (against from BCDMS data).

Generally naturally improved by NNLO fit.

Some room for improvement.

α_s from PDF fits getting larger again

Summary

Parton density functions

- Heavy quark prescriptions important
  - matters for PDF uncertainties at the per cent level
- Handling of inconsistent data sets
  - reweighting vs. discarding data sets
- New issues with impact on LHC cross sections
  - determination of isospin sea asymmetry $\bar{u} - \bar{d}$
  - stange sea parametrizations considered by all groups now
- Removing assumptions on flavor composition
  - larger PDF errors
- LO PDFs vs. NLO PDFs vs. NNLO PDFs
  - largely depended on observable (K-factor philosophy)