Dynamical parton distributions

and Weak Gauge and Higgs Boson Production

at Hadron Colliders at NNLO of QCD

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DIS2010

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The dynamical approach

Global NNLO analysis and the determination of $\alpha_s(M_Z^2)$

The longitudinal structure function

The treatment of heavy quarks

Weak-gauge and Higgs boson production at hadron colliders

The dynamical approach

Idea: at low-enough Q^2 only "valence" partons would be "resolved"

$\longrightarrow$ *structure at higher Q^2 appears* ***radiatively*** *(i.e. due to QCD* ***dynamics****)*

DYNAMICAL:

$Q_0^2 < 1\,\mathrm{GeV}^2$ optimally **determined**

$\mathbf{a} > 0$ *"valence-like"*

"STANDARD":

$Q_0^2 = 2\,\mathrm{GeV}^2$ arbitrarily **fixed**

Unrestricted parameters

$$xf(x, Q_0^2) = N\,x^{\mathbf{a}}(1-x)^b(1 + A\sqrt{x} + Bx)$$

Positive definite input distributions	Arbitrary fine tunning ($g < 0!$)
QCD **predictions** for $x \lesssim 10^{-2}$	**Extrapolations** to unmeasured region
More restrictive, **less uncertainties**	Less restrictive, *marginally* smaller χ^2

Physical aid for determining **CC for DGLAP $\neq$ NP structure** of the nucleon

Brief history of the dynamical distributions

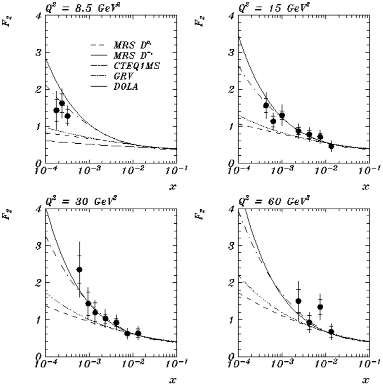
Dynamical assumption [Altarelli, Cabibbo, Maiani, Petronzio 74], [Parisi, Petronzio 76], [Novikov 76], [Glück, Reya 77] in connexion with the *constituent quark model*: only valence quarks

First dynamical determination of parton distributions [Glück, Reya 77]

Used in the 80’s: e.g. for the discovery of W and Z bosons (SPS, CERN)

Extended to include **light sea** [Glück, Reya, Vogt 90] and **gluon** [Glück, Reya, Vogt 92] **valence-like input**
⟶ **steep gluon and sea at small-x!!**

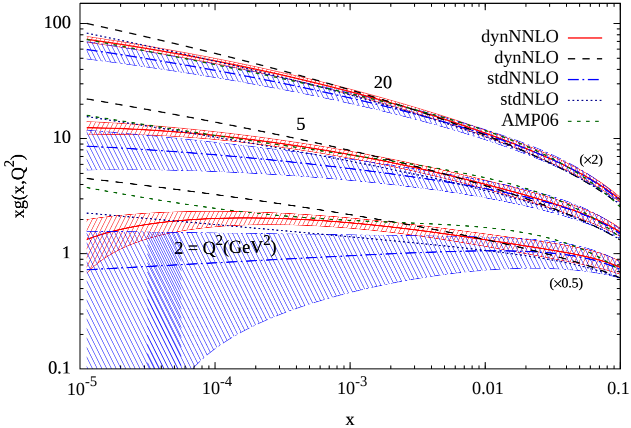
Confirmed by first HERA $F_2(x,Q^2)$ data [H1, ZEUS 93]



GRV95 and GRV98 contributed greatly in the 90’s and beginning of the 00’s

New **improved** **generation** (GJR08, JR09):
$\overline{\text{MS}}$ + DIS factorization schemes, NNLO, error analysis, FFNS+VFNS, **new data**

Dynamical vs standard distributions: gluon



Uncertainties decrease as Q^2 increase: *pQCD evolution*

Valence-like input, i.e., *larger "evolution* distance" ⇒ **less uncertainties**

Q_0^2 also play another role ⇒ standard gluons fall below dynamical

Smaller effect for the sea: rather flat dynamical input

Global NNLO analysis

Only DIS (1178) and DY (390) data included at NNLO for **consistency**

Drell-Yan data instrumental in fixing non-singlet distributions ($u_v, d_v, \bar{d} - \bar{u}$)

Excellent agreement with data:

dynamical: $\chi^2_{\rm DIS} = 0.90$

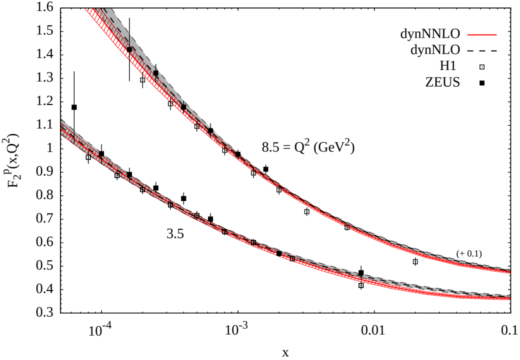
“standard”: $\chi^2_{\rm DIS} = 0.87$

(fine tunning marginal)

NNLO effects small (few %):

$$\chi^2_{\rm NNLO} \simeq 0.9 \chi^2_{\rm NLO}$$

with (not much) reduced errors



Other effects (*QED*, factorization schemes, ...) comparable

Determination of $\alpha_s(M_Z^2)$

Consistent determination *together with the distributions*

General *agreement* but DIS-dominated fits usually yield smaller values

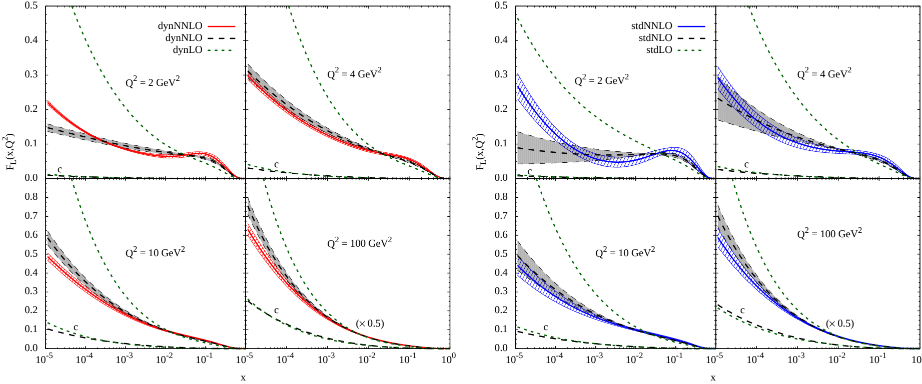
	dynamical	**"standard"**
NNLO	0.1124 ± 0.0020	0.1158 ± 0.0035
NLO	0.1145 ± 0.0018	0.1178 ± 0.0021
LO	0.1263 ± 0.0015	0.1339 ± 0.0030

Dynamical constraints reduce the uncertainty! (in particular at NNLO)

Dynamical results are smaller: larger "evolution distance" ($Q_0^2 < 1\,\mathrm{GeV}^2$)

Other groups are either close to the dynamical or to the "standard" results

The perturbative stability of F_L



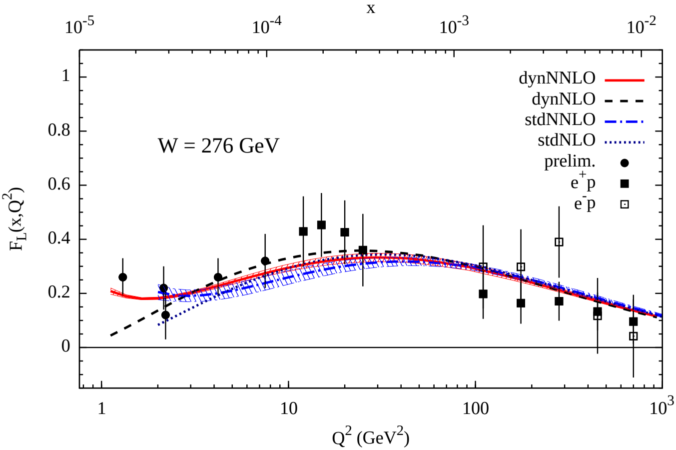
Both dynamical *and* standard results manifestly **positive** at all orders

Dynamical predictions **stable** already at $Q^2 \gtrsim 2$ GeV^2

Standard differ more but less distinguishable due to the **larger error bands**

Observed [M(R)ST(W)] instabilities *unphysical*: **artefact** of negative gluons

Confronting results with data



Positive and in complete **agreement** with measurements

Dynamical predictions more tightly constrained

Higher-twist effects may contribute for $Q^2 \leq 2$ GeV^2

Heavy-quark contributions: FFNS

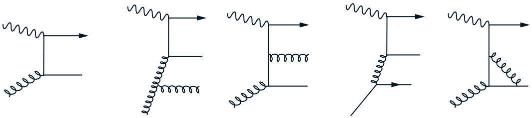
HQ generated in hard collisions: not collinearlly, short “lifetime” ($\neq$ parton)

Experiment: **No intrinsic heavy-quark** (c,b,t) content in the nucleon

FFNS $\equiv$ **FOPT** initiated by gluons and light (u,d,s) quarks

$\longrightarrow$ **final state** $\equiv$ **extrinsic heavy-quark** content

HQ contributions to DIS:



$$
\begin{aligned}
F^h_{k=2,L}(x,Q^2,m^2) = \frac{Q^2\alpha_s(\mu^2)}{4\pi^2 m^2}\int_x^{\frac{Q^2}{Q^2+4m^2}} \frac{dz}{z}\Bigg\{ & e_h^2\, c^{(0)}_{k,g}(\eta,\xi)\, g\left(\tfrac{x}{z},\mu^2\right) \\
& +4\pi\alpha_s(\mu^2)\left[e_h^2\left(c^{(1)}_{k,g}(\eta,\xi)+\bar{c}^{(1)}_{k,g}(\eta,\xi)\ln\frac{\mu^2}{m^2}\right) g\left(\tfrac{x}{z},\mu^2\right) + \right. \\
\sum_q \left(e_h^2\left(c^{(1)}_{k,q}(\eta,\xi)+\bar{c}^{(1)}_{k,q}(\eta,\xi)\ln\frac{\mu^2}{m^2}\right) q\left(\tfrac{x}{z},\mu^2\right) \right. & \left.\left. +e_q^2\left(d^{(1)}_{k,q}(\eta,\xi)+\bar{d}^{(1)}_{k,q}(\eta,\xi)\ln\frac{\mu^2}{m^2}\right) q\left(\tfrac{x}{z},\mu^2\right)\right)\right]\Bigg\},
\end{aligned}
$$

$\ln\frac{\mu^2}{m^2}$ are **not (mass) divergences**: **FFNS gets trough *all* “stability tests”!!**

Only **drawback**: calculational difficulty

Effective heavy-quark PDFs: VFNS

Idea: Resum (RGE) the $\ln\frac{\mu^2}{m^2}$ *to gain calculational power*

Asymptotically ($Q^2 \gg m^2$):

$$H\left(\frac{Q^2}{\mu^2},\frac{\mu^2}{m^2}\right) \longrightarrow A\left(\frac{\mu^2}{m^2}\right)\otimes C\left(\frac{Q^2}{\mu^2}\right)$$

A's=massive OME's, **process independent!!**

C's=light-parton coefficient functions

Light-parton PDFs $\xrightarrow{A\text{'s}}$ effective HQ-PDFs

assumed to be correct **asymptotically**

Ressumation of **final-state** contributions

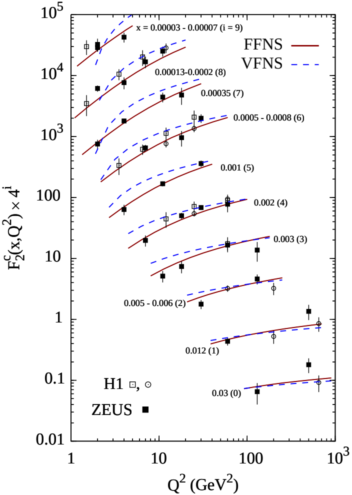
($\neq$ intrinsic heavy-quark content)

In practice: **massless evolution** increasing n_f

at unphysical "thresholds" $\mu^2 \simeq m^2$ (not $\hat{s} \gtrsim 4m^2$)

Input determined always in the FFNS!!

(most data in threshold region)



VFNS HQ-PDFs generated **from FFNS** **preserving universality**

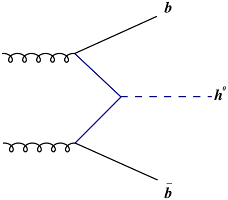
FFNS vs VFNS: Examples

VFNS reliable for large invariant mass of the produced system: $W^2 \gg m^2$

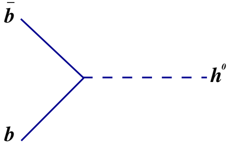
$\longrightarrow$ *non-relativistic* ($\beta_h \lesssim 0.9$) *threshold effects supressed*

Example: Higgs produced in $b\bar{b}$ fusion: $\frac{W_{\text{th}}}{m_b} = \frac{2m_b + m_H}{m_b} \simeq \frac{M_H}{m_b} \gg 1$

FFNS: $g\,g \to b\,\bar{b}\,H$



VFNS: $b\,\bar{b} \to H$



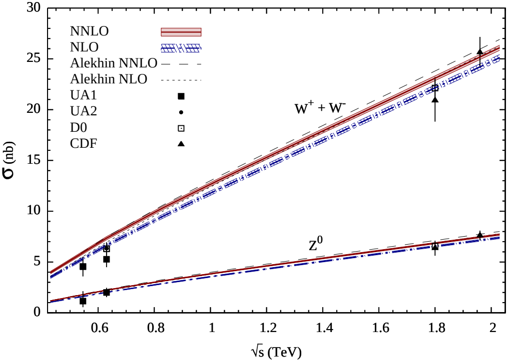
Uncertainties from choices of factorization scheme typically **important!**

Example: $W^{\pm}$ production at *LHC*:

$$\sigma^{\text{NLO}} = \begin{cases} 186.5 \pm 4.9_{\text{pdf}}\ {}^{+4.8}_{-5.5}\,|_{\text{scale}}\ \text{nb} & \text{(VFNS)} \\ 192.7 \pm 4.7_{\text{pdf}}\ {}^{+3.8}_{-4.8}\,|_{\text{scale}}\ \text{nb} & \text{(FFNS)} \end{cases}$$

VFNS sufficiently reliable for LHC and Tevatron energies.

Weak gauge boson production rates



NNLO typically larger but stable; scale uncertainty greatly (%4) reduced

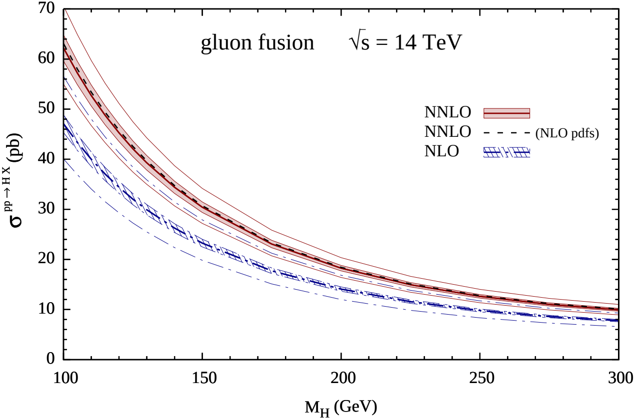
Results from different groups **within experimental uncertainty at Tevatron**

NNLO expectations for **LHC ($\approx 5\%$ accuracy)**:

$$\sigma^W = 190.2 \pm 5.6_{\text{pdf}}\ {}^{+1.6}_{-1.2}|_{\text{scale}}\ \text{nb}, \qquad \sigma^Z = 55.7 \pm 1.5_{\text{pdf}}\ {}^{+0.6}_{-0.3}|_{\text{scale}}\text{nb}$$

MSTW08 and ABKM09 some **5–10% higher at LHC**

Higgs boson production



NNLO rather (20%) larger than NLO but *total* uncertainty bands overlap

Not *very* dependent on PDFs. Similar (within 10%) to other groups

Total **accuracy at NNLO of about 10% at LHC**

Tevatron: *Similar* features although *uncertainty almost doubles*

Conclusions

New generation of **dynamical parton distributions** available up to NNLO

Dynamical approach: more **predictive** and **smaller uncertainties**

Consistent determination of $\alpha_s(M_Z^2)$ together with the distributions

Positive distributions and cross-sections (F_L) in **agreement with all data**

FFNS reliable: no need for "resummation" (heavy-quark distributions)

Effective (VFNS) "heavy" quark distributions **reliable** for **Tevatron** and **LHC**

Total accuracy at **LHC**: $\approx 5\%$ **for gauge-boson production rates**
$\approx 10\%$ **for Higgs production**

(Dis)agreement with ABKM09 and MSTW08 at the **level of 10%** at LHC