Dynamical Parton Distribution Functions

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[with E. Reya and M. Glück]

PSI Particle Theory Seminar

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technische universität dortmund

f(p) fakultät physik

A next step in the adventure of Physics:

LHC: 14 TeV p-p collider:

No Higgs?

Higgs?

Grand Unification?

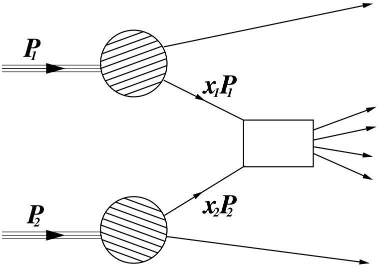
Supersymmetry?

Extra dimensions?

Mini black holes?

Strings?

...? *... starting soon!*



$$\sigma(P_1,P_2) = \sum_{i,j} \int dx_1\, dx_2\, \hat{\sigma}_{ij}\Big(x_1, x_2, \ln\frac{M^2}{\mu^2}, a_s(\mu^2)\Big) f_i(x_1,\mu^2) f_j(x_2,\mu^2)$$

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- Factorization and the parton picture
- Global QCD analysis
- Estimation of uncertainties
- The dynamical/radiative model

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- Dimuon production
- Fitting the data
- The strangeness asymmetry

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Overview of perturbative QCD

Renormalization: $\alpha_s(Q^2)$ small for large Q^2 (*asymptotic freedom*)

$\longrightarrow$ **perturbative expansions**

Factorization: (universal) **parton distribution functions**
Universality + *experiment*:

$$\text{Input PDFs } xf(x,Q_0^2) \xrightarrow{\text{DGLAP}} xf(x,Q^2)$$

Infrared safety: inclusive σ's, *BR*, jet production, event shapes, ...

(Models for) *hadronization* $\rightarrow$ comparisons to experiment

Predictions + experiment $\rightarrow$ Further development: SM, new physics ...

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Factorization and the parton picture

(QCD improved) parton picture of hadrons $\equiv$ cloud of partons being emited and absorved constantly by one another

Proving with a "wavelength" μ^{-1} a parton **is** ("resolved") if:

$$\frac{t_{\text{form}}}{t_{\text{hadr}}} \propto \frac{\mu^2}{k_T^2} \ll 1, \qquad \mu \gtrsim M \equiv m_{\text{const}} \approx m_{\text{hadr}} \approx \text{some hundred MeV}$$

[Dokshitzer et al.'s book]

Collinear ($k_T \to 0$, $m = 0$) phase-space regions?

(NP physics) "absorved" in the hadron structure $\longrightarrow$ **Factorization**

$$q(x,\mu^2) \equiv q^{\text{bare}}(x) + \Delta q(x,\mu^2)$$

Logarithmic dependence: $\int^{\mu^2} \frac{dk_T^2}{k_T^2}\alpha_s \to \alpha_s \ln \mu^2 \longrightarrow$ Evolution equations ($RGE \equiv DGLAP$)

Universality: Collinear/mass singularities **independent** of the hard process

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Global QCD analysis

Determination of NP information: **input distributions** $xf(x,Q_0^2)$

for light quarks + gluon: $f = u, d, \bar{u}, \bar{d}, \bar{s}$ and g (*no heavy-quark PDFs!*)

Selected **experiment**al information + **parametrizations** (BIAS)

Nucleon structure Functions

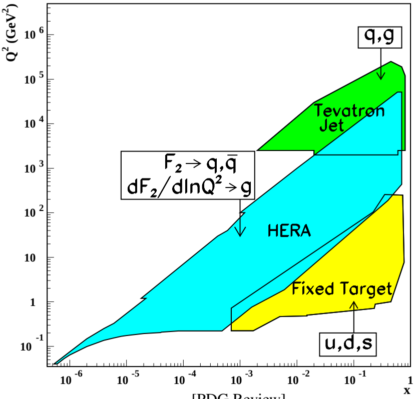
Jets from Tevatron (up to NLO)

Drell-Yan pp + pn (or neutrino DIS) data needed for $\bar{d} \neq \bar{u}$

Strange symmetric input $s \equiv \bar{s} = 0$
(or asymmetric, discussed later)

Chi-square method:

$$\chi^2(p) \equiv \sum_{i=1}^{N} \left(\frac{\text{data}(i) - \text{theory}(i,p)}{\text{error}(i)} \right)^2$$



[PDG Review]

Estimation of uncertainties

Propagation of **experimental** errors (only!) into the PDFs

Hessian method: quadratic expansion around the global minimum

$$\Delta\chi^2 = \chi^2 - \chi_0^2 \simeq \frac{1}{2}\sum_{i,j=1}^{d} H_{ij}(a_i - a_i^0)(a_j - a_j^0) \leq T^2$$

Tolerance parameter: $T^2 = T_{1\sigma}^2 = \sqrt{2N}/(1.65)^2 \Rightarrow \mathbf{T \simeq 5}$

diagonalization of $H_{ij} \longrightarrow$ (rescaled) eigenvector matrix M_{ij}

"Eigenvector sets": $\quad a_i^{\pm j} = a_i^0 \pm T M_{ij}$

Calculation of a quantity $X \pm \Delta X$:

$$X = X(a^0), \qquad \Delta X = \frac{1}{2}\sum_{j=1}^{d}\sqrt{\left(X(a^{+j}) - X(a^{-j})\right)^2}$$

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The dynamical/radiative model

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**)*

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

DYNAMICAL:

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

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

Positive definite input distributions

QCD *predictions* for $x \lesssim 10^{-2}$

More restrictive, *less uncertainties*

"STANDARD":

Unrestricted parameters

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

Arbitrary fine tunning ($g < 0$!)

Extrapolations to unmeasured region

Less restrictive, *marginally smaller* χ^2

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

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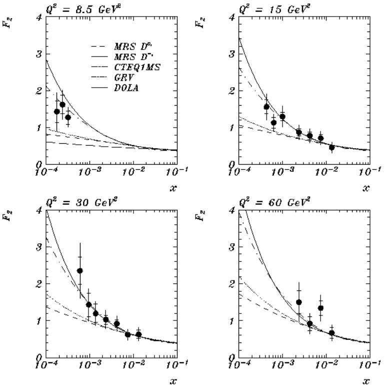
Lepton asymmetry and the new D0 data (preliminary)

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)



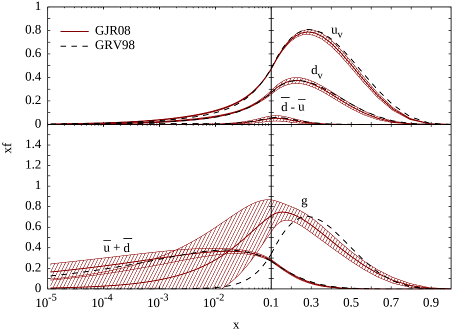
Extended to include *light sea* [Glück, Reya, Vogt 90] and *gluon* [Glück, Reya, Vogt 92] **valence-like input**
$\longrightarrow$ **steep gluon and sea at small-x**

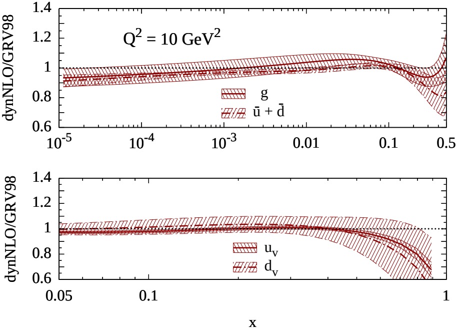
Confirmed by first HERA $F_2(x, Q^2)$ data [H1, ZEUS 93]

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

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

Comparison with GRV98





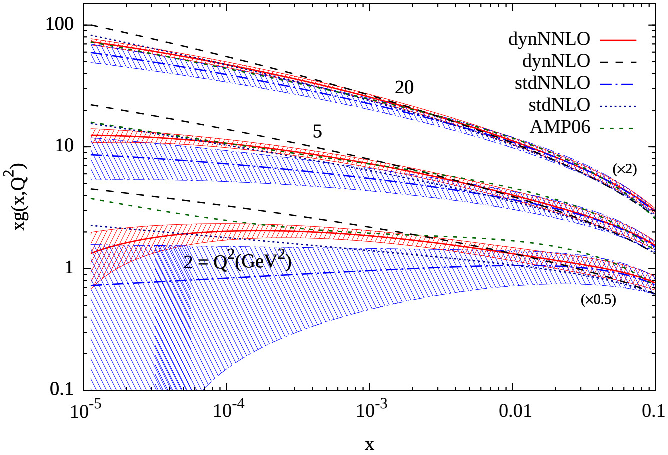
Very **similar** to the previous *dynamical* (input) distributios **GRV98** [up to NLO]

All quark distributions *within error* estimates [note the flat sea (for later)]

Similar gluon as well: peaks at slightly different x but within 2σ

Stable after evolution, less than $10-20\%$ of “acceptable” (1σ) difference

Dynamical vs standard distributions: gluon



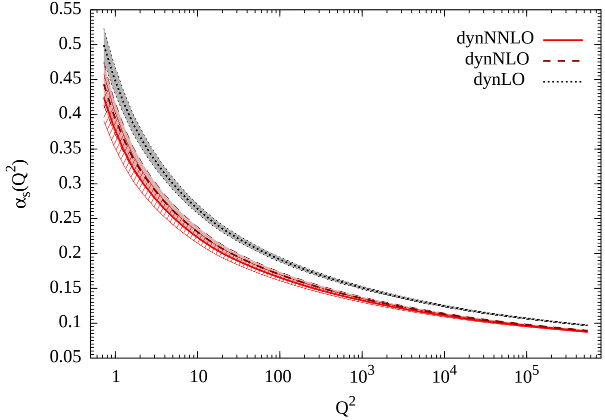
Uncertainties decrease as Q^2 increase: *pQCD evolution*

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

Determination of $\alpha_s(M_Z^2)$

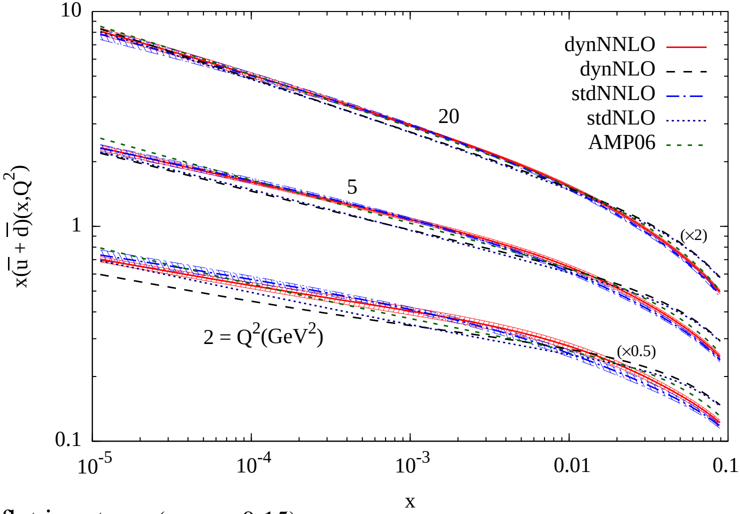
Only free parameter (besides masses) in *QCD*: *acceptable agreement*

However "dispersion" > uncertainties: global fits (*DIS*) yield smaller values



Our NNLO result: $\begin{cases} \text{dynamical: } 0.1124 \pm 0.0020 \\ \text{standard: } 0.1158 \pm 0.0035 \quad (\textit{larger error}) \end{cases}$

Dynamical vs standard distributions: sea



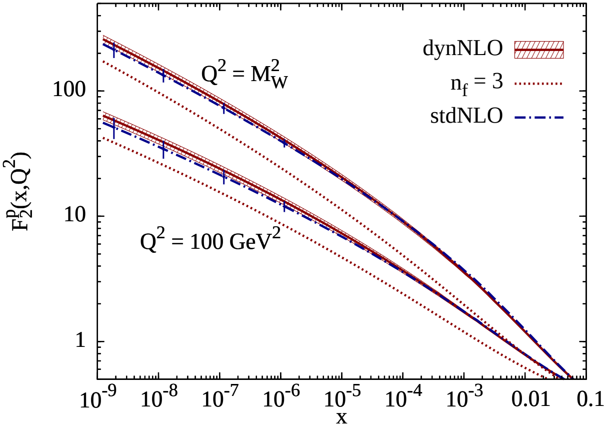
Rather flat input sea ($a_{\bar{u}+\bar{d}} \simeq 0.15$) ⇒

equally increasing down to $x \simeq 10^{-2}$ ⇒ **marginally smaller** errors

Extremely small-x: astrophysical relevance

More sensible for astrophysics: ultrahigh energy ($E_\nu \simeq 10^{12}$GeV) ν-N scattering

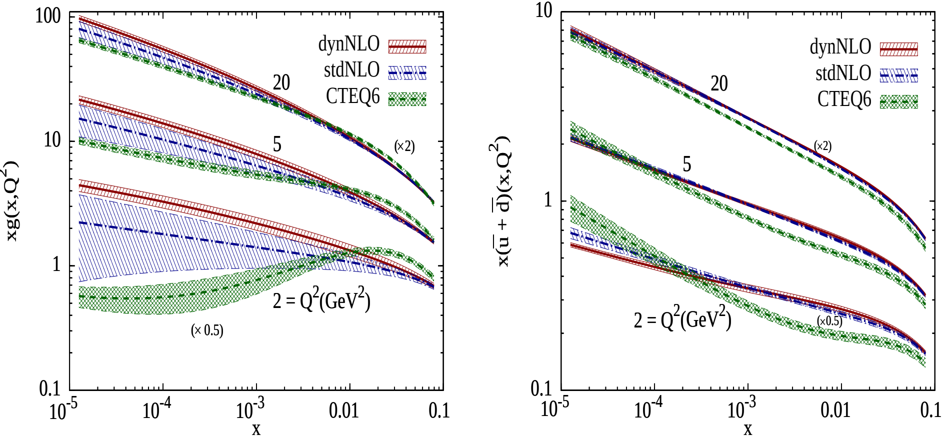
$\longrightarrow$ **sea dominated** as F_2^p for small x



For $x \lesssim 10^{-2}$ parameter free dynamical predictions $\Rightarrow$ 10% accuracy

Uncertainties on the "standard" extrapolations are twice as large

Comparison with other groups: CTEQ



CTEQ6 has a **valence-like gluon** at $Q_0^2 = m_c^2 \simeq 1.7\,\mathrm{GeV}^2$!!

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

Non-valencelike sea ⇒ larger uncertainties

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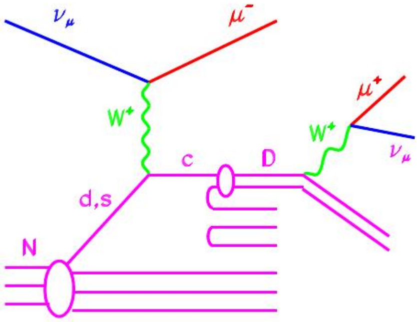
Dimuon production

$$\frac{d\sigma^+}{dxdy}\left(x,y,E_{\nu(\bar{\nu})}\right) = \frac{G_F^2 M E_{\nu(\bar{\nu})}}{\pi} B_c \mathscr{A}\left(x,y,E_{\nu(\bar{\nu})}\right) \frac{d\sigma^{\nu(\bar{\nu})}}{dxdy}\left(x,y,E_{\nu(\bar{\nu})}\right)$$



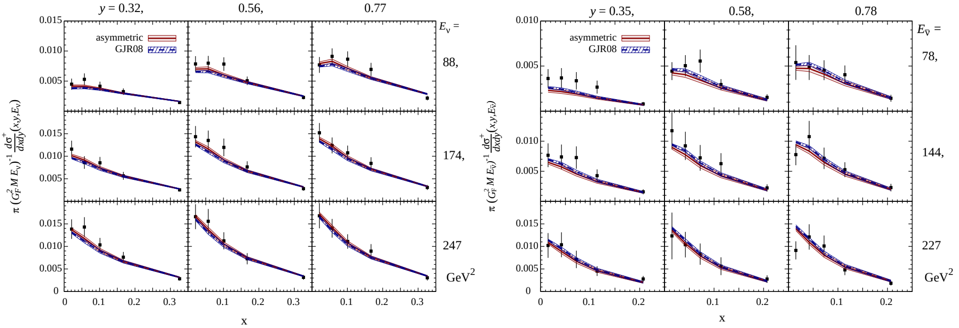
[NuTeV Coll. PRD64 (2001) 112006]

Signature: Two muons of different sign

Directly related to **charged current charm production** $\propto s(x,Q^2)$

Sensitive to differences between s and $\bar{s}$

Fitting the data



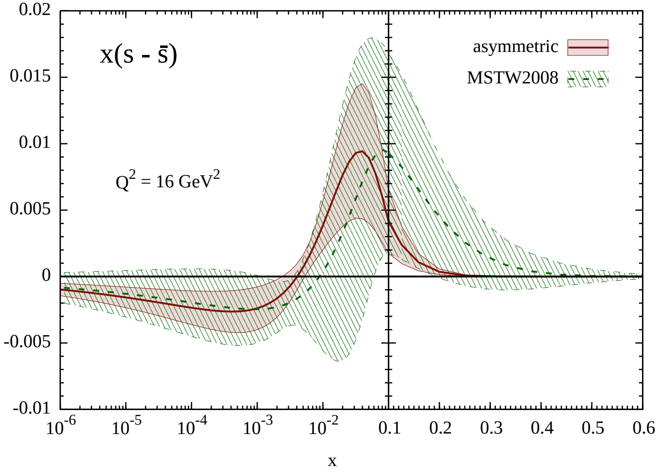
Already **well described by GJR08**: $\chi^2 = 65$ for 90 data points (1σ)

$\Rightarrow$ radiatively generated strangeness plausible: $s^+(x, Q_0^2) = 0$

Introducing an asymmetry ($s^-(x, Q_0^2) \neq 0$) χ^2 goes down to 60

Neutrino increases, antineutrino decreases $\Rightarrow$ **“positive” asymmetry**

The strangeness asymmetry



Compatible with previous determinations but smaller uncertainties

Very small effect, irrelevant for most applications

Important for dedicated experiments (e.g. NuTeV anomaly)

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DIS "reduced" cross-section

$$\sigma_r^{NC} \equiv \left(\frac{2\pi\alpha^2}{xyQ^2}Y_+\right)^{-1}\frac{d^2\sigma^{NC}}{dx\,dy} = F_2^{NC} - \frac{y^2}{Y_+}F_L^{NC} \mp \frac{Y_-}{Y_+}xF_3^{NC}$$

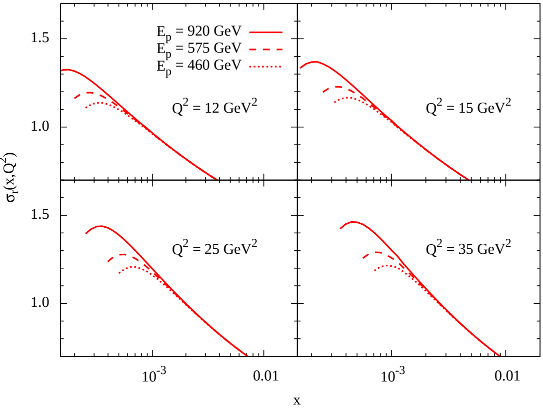
Usually dominated by F_2^γ

$$y = \frac{Q^2}{s}\frac{1}{x}$$

for fixed Q^2 (and s)
F_L relevant with increasing y

$\rightarrow$ *turnover* at small x

$\Rightarrow$ F_L **positive**



gluon dominated in the small-x region $\Rightarrow$ **positive gluon** (also beyond LO!)

DIS "reduced" cross-section

$$\sigma_r^{NC} \equiv \left(\frac{2\pi\alpha^2}{xyQ^2}Y_+\right)^{-1}\frac{d^2\sigma^{NC}}{dx\,dy} = F_2^{NC} - \frac{y^2}{Y_+}F_L^{NC} \mp \frac{Y_-}{Y_+}xF_3^{NC}$$

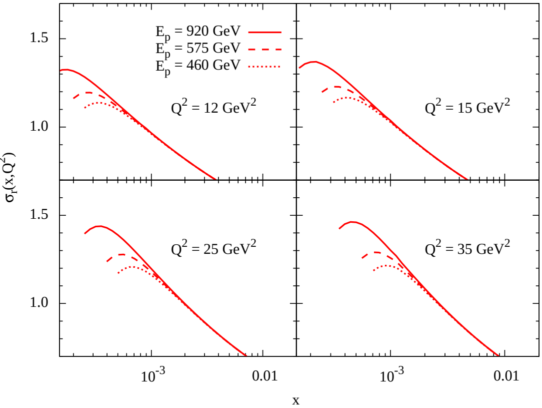
Usually dominated by F_2^γ

$$y = \frac{Q^2}{s}\frac{1}{x}$$

for fixed Q^2 (and s)
F_L relevant with increasing y

$\rightarrow$ *turnover* at small x

$\Rightarrow$ F_L **positive**



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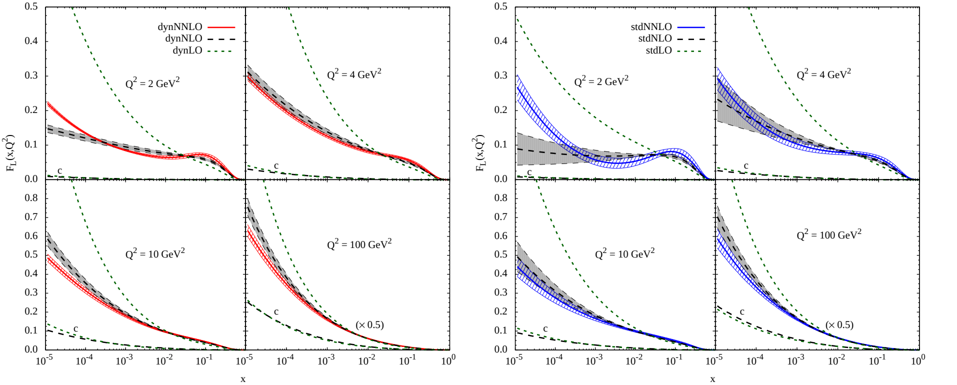
The perturbative stability of F_L



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

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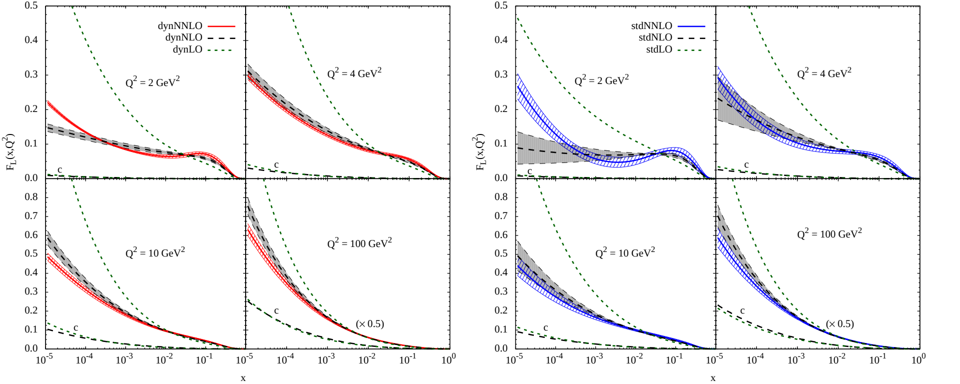

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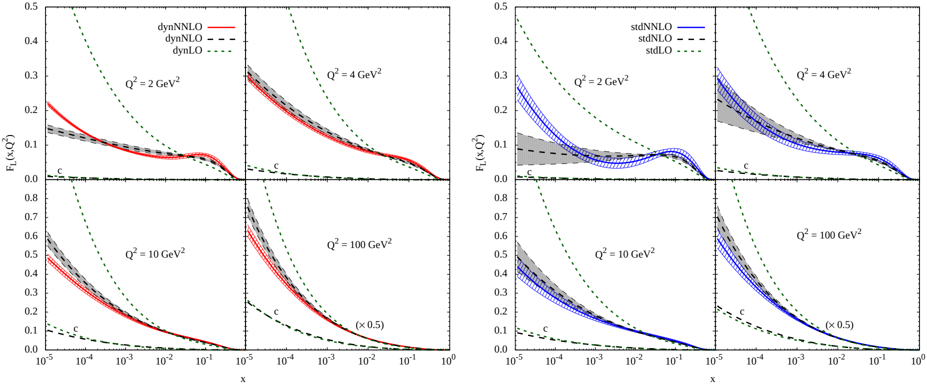

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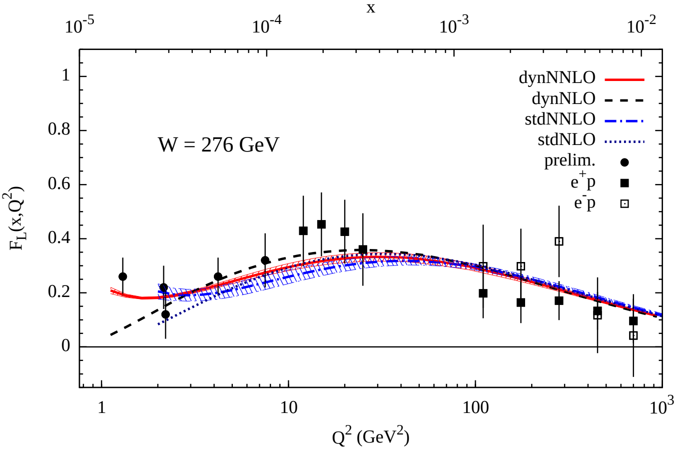
Confronting results with data



Positive and in complete **agreement** with measurements

Dynamical predictions more tightly constrained

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

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Heavy-quark contributions: FFNS

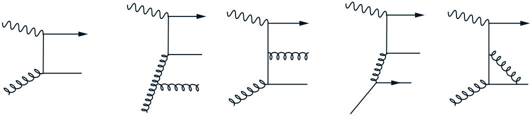
Experiment: **No intrinsic** heavy-quark (c,b,t) content in the nucleon

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

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

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

HQ contributions to DIS:



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

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

Only *drawback*: calculational difficulty

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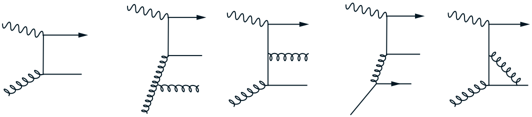

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Effective heavy-quark PDFs: VFNS

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

Asymptotically:

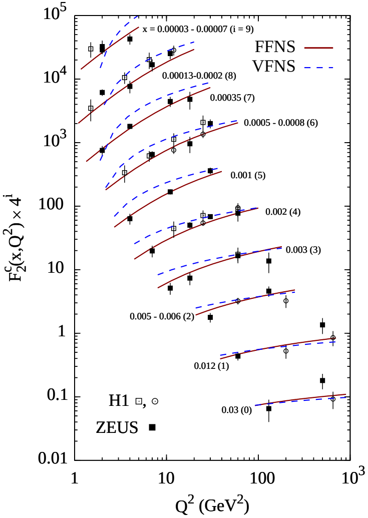
$$H^{Q^2 \gg m^2}\left(\frac{Q^2}{\mu^2}, \frac{\mu^2}{m^2}\right) = A\left(\frac{\mu^2}{m^2}\right) \otimes C\left(\frac{Q^2}{\mu^2}\right)$$

A's=massive OME's $\longrightarrow$ **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 quark content

In practice: **massless evolution** with increasing n_f at unphysical "thresholds" $\mu^2 \simeq m^2$
(not $\hat{s} \gtrsim 4m^2$)



VFNS HQ-PDFs generated from FFNS preserving universality

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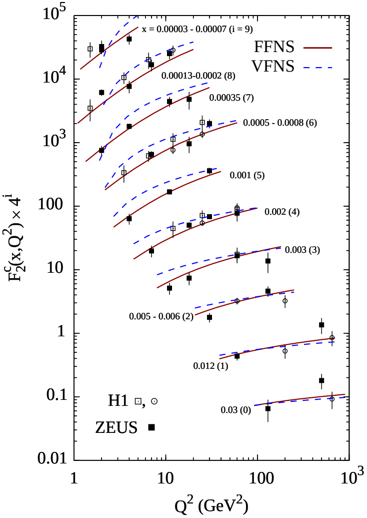


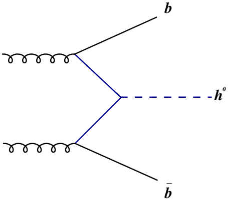
VFNS HQ-PDFs generated from **FFNS** **preserving universality**

Examples: W and Higgs production

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*

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



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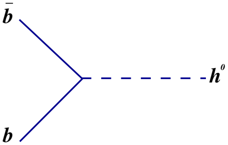

Condition for Higgs produced in $b\bar{b}$ fusion: $\frac{W_{\rm th}}{m_b} = \frac{2m_b + m_H}{m_b} \simeq \frac{M_H}{m_b} \gg 1$

Input determined always in the FFNS!! (most data in threshold region)

Example, W production at *LHC*:

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

VFNS sufficiently accurate ($\approx 10\%$) for LHC and Tevatron energies.

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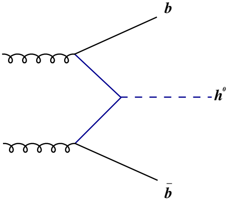

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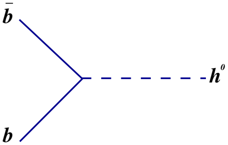

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Example, W production at LHC:

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Comments on GM-VFNS

Idea: Interpolation between FFNS and VFNS: **reshuffle** of mass-dependent terms
$\longrightarrow$ **models** [Aivazis, Collins, Olness, Tung], [Buza, Matiounine, Smith, van Neerven], [Roberts, Thorne] + variations

Constructed [as the VFNS] over the FFNS: **no new information** +
new model uncertainties

DIS mass deppendences absorved in PDFs: **process-dependent distributions!**
(plausible only for DIS)

What happened with **Universality**?

Unnecesary for *HERA* (fits, FFNS) *and* for *Tevatron* or *LHC* (VFNS)

Further: (partonic) cross-sections are not modified (to compensate):
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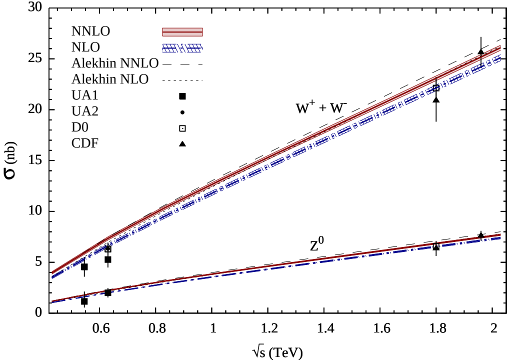
Weak gauge boson production rates



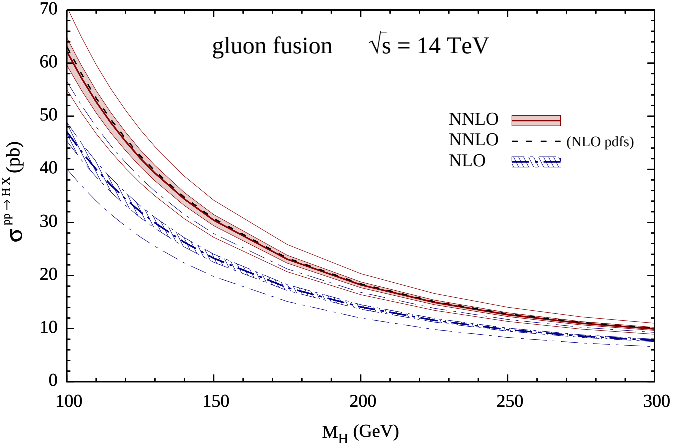
NNLO typically larger but stable; scale uncertainty greatly (%4) reduced

Results from different groups **within experimental** uncertainty

NNLO expectations for LHC (≈ 5% accuracy):

$$\sigma(pp \to W^+ + W^- + X) = 190.2 \pm 5.6_{\text{pdf}} \; {}^{+1.6}_{-1.2}|_{\text{scale}} \; nb$$
$$\sigma(pp \to Z^0 + X) = 55.7 \pm 1.5_{\text{pdf}} \; {}^{+0.6}_{-0.3}|_{\text{scale}} \; nb$$

Higgs boson production at LHC

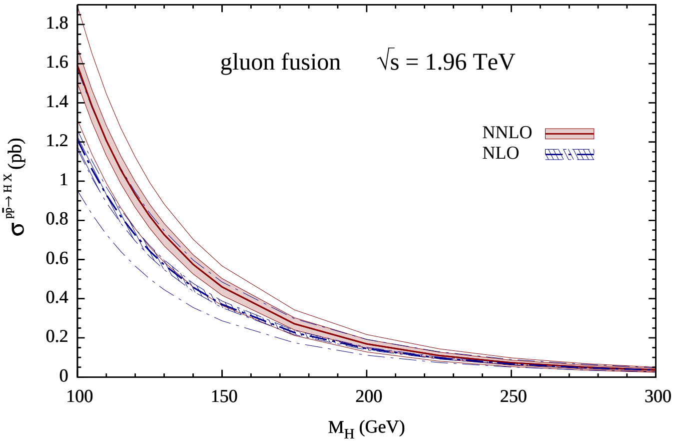


NNLO rather (20%) larger than NLO but *total* uncertainty bands overlap

Similar (within 10%) to other groups, not *very* dependent on PDFs

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

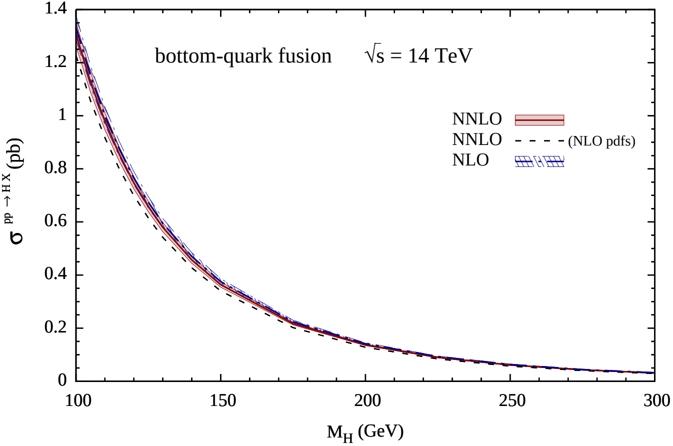
Higgs boson production at Tevatron



Similar features

Larger (factor of 2) uncertainty bands

Higgs production via $b\bar{b}$ fusion



Subdominant contribution with rather *different* features:

- *marginal scale dependence* (here the appropriate scale is $\frac{M_H}{4}$)
- *small K-factor*: NLO/NNLO almost coincide
- Correct choice of NNLO PDFs important

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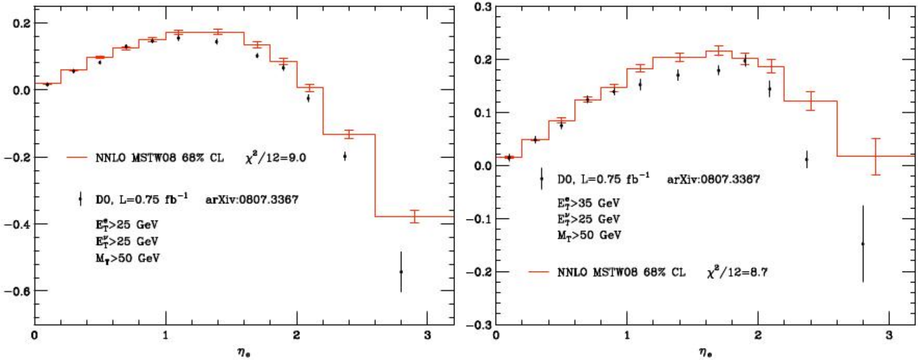
D0 lepton asymmetry with MSTW2008

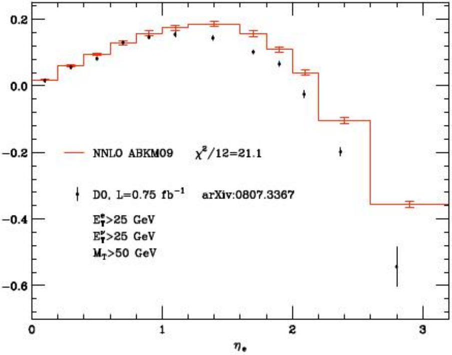
Preliminary

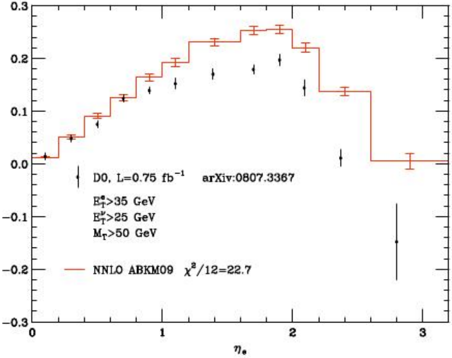


[M. Grazzini *et al.*, arXiv:1002.3115]

D0 lepton asymmetry with ABKM09

Preliminary

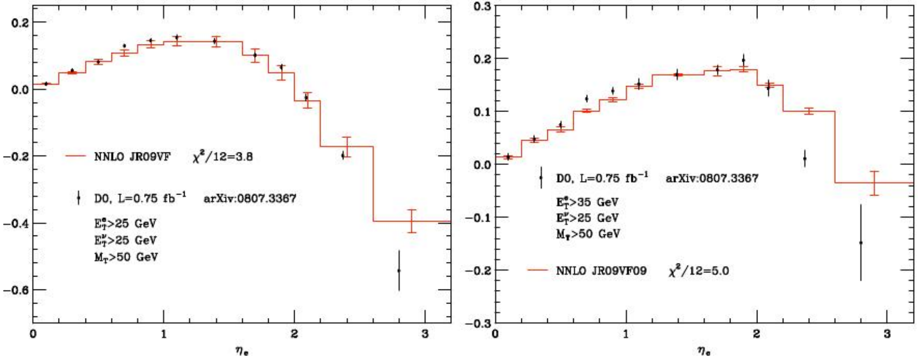




[M. Grazzini *et al.*, arXiv:1002.3115]

D0 lepton asymmetry with JR09VFNS

Preliminary



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The End

Dynamical LO and NLO PDFs **updated**: Compatible with **GRV98**

Analyses **extended**: new data, NNLO, errors ...

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

Strangeness asymmetry **precisely** determined: small and positive

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**.