CT14 Intrinsic Charm PDFs from CTEQ-TEA Global Analysis

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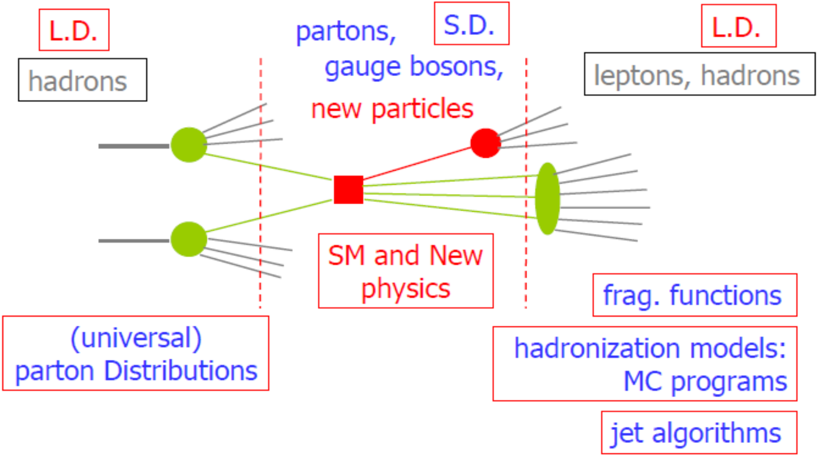
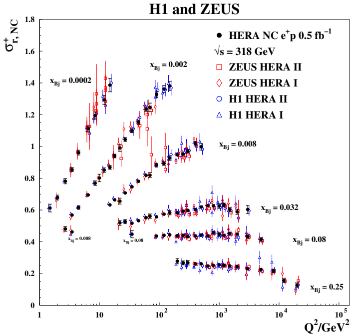
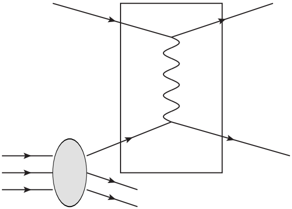
Hadron Collider Physics



PDF is determined by comparing data and hard cross section

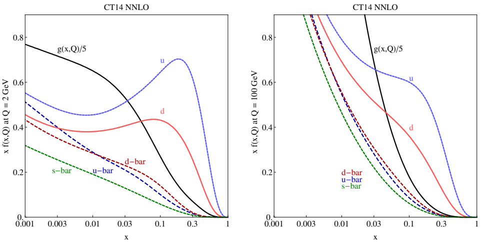
$$\sigma = f(x, Q^2, \{a\}) \otimes \hat{\sigma}$$

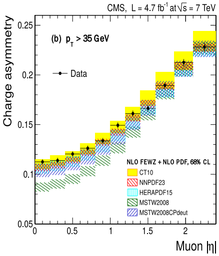


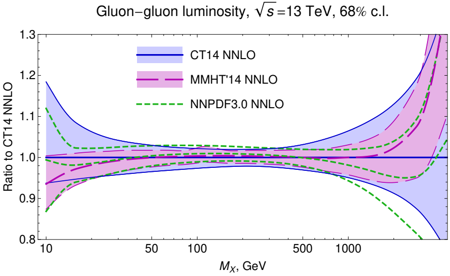


PDF	Hard part
LO	LO
NLO	NLO
NNLO	NNLO

PDF will then contribute to the precision measurment and search for new physics.







Is there a (sizable) non-perturbative contribution to charm PDF?

Which physics effects can lead to a non-zero fitted $c(x, Q = m_c)$?

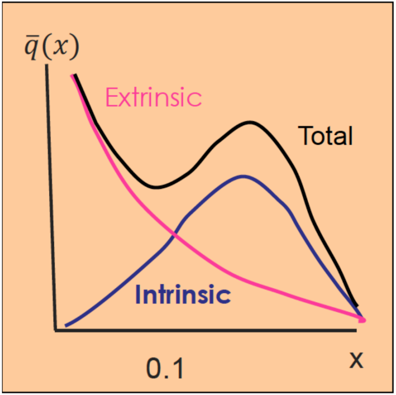
$$
\begin{aligned}
\text{Fitted charm} &= \text{Intrinsic charm(nonperturbative)} \\
&+ \text{other(possibly not universal)} \\
&\quad \text{higher"}O(\alpha_s)/\text{Higher power terms}
\end{aligned}
$$

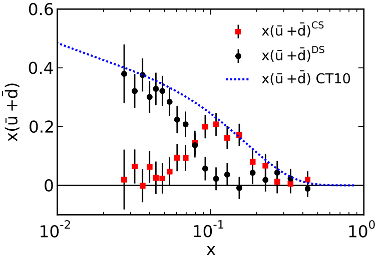
QCD factorization theorem for DIS structure function $F(x,Q)$ [Collins, 1998]:

$$F(x,Q) = \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha_s(\mu)\right) f_{a/p}(\xi,\mu) + \mathcal{O}(\Lambda^2/m_c^2, \Lambda^2/Q^2).$$

The PDF fits implement this formula up to (N)NNLO ($N_{ord} = 1$ or 2):

$$F(x,Q) \;\; = \;\; \sum_{a=0}^{N_f} \int_x^1 \frac{d\xi}{\xi} \mathcal{C}_a^{(N_{ord})}\left(\frac{x}{\xi}, \frac{Q}{\mu}, \frac{m_c}{\mu}; \alpha_s(\mu)\right) f_{a/p}^{(N_{ord})}(\xi,\mu)$$





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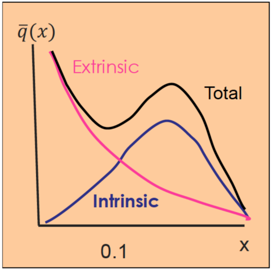
Instead of parametrize the charm as strange in the usual way, we concern the possibility of **valence-like**(intrinsic) and **sea-like**(extrinsic) component of charm.

1.The Sea-like(extrinsic) component:

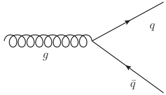


- Monotonic in x, satisfies

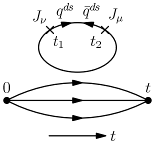
$$q(x) \propto x^{-1}, \text{ for } x \to 0$$

- May be generate in several ways, e.g.

  In PQCD, from gluon splittings



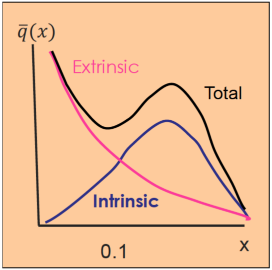
  In Lattice QCD, from disconnected diagrams



2.Valence-like (intrinsic) component:

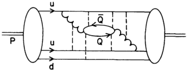
- peaks in x, satisfies

$$q(x) \propto x^{-1/2}, \text{ for } x \to 0$$

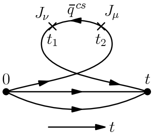


- May be generate in several ways, e.g.

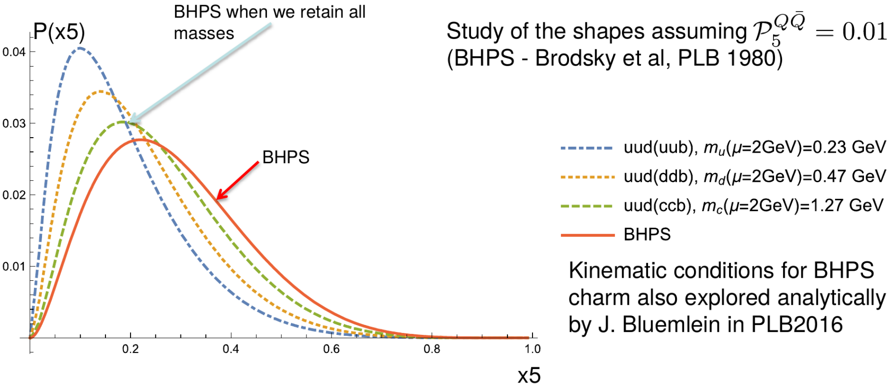
  For all flaovers, nonperturbatively from a $|uudQ\bar{Q}>$ Fock state: (Brodsky, Peterson, Sakai, PRD 1981)



  In Lattice QCD, from connected diagrams



Brodsky-Hoyer-Peterson-Sakai model: valence-like PDF from kinematic dependence



Study of the shapes assuming $\mathcal{P}_5^{Q\bar{Q}} = 0.01$ (BHPS - Brodsky et al, PLB 1980)

Kinematic conditions for BHPS charm also explored analytically by J. Bluemlein in PLB2016

$$P(x_5) = \int_0^1 dx_1 \ldots dx_4\, \delta(1 - \sum_{i=1}^{5} x_i) \frac{1}{\left[M_p^2 - \sum_{i=1}^{5} \frac{m_i^2}{x_i^2}\right]^2},\ M_p = 1\text{GeV}$$

Parametrizations for BHPS and SEA models

- ”Valence-like” charm quark PDF according to the BHPS model (scale is unknown in this model):

$$c(x) = \bar{c}(x) = \frac{1}{2} A\, x^2 \left[\frac{1}{3}(1-x)(1+10x+x^2) - 2x(1+x)\ln(1/x) \right].$$

- ”BHPS3” model: we include intrinsic $u\bar{u}$, $d\bar{d}$ and $c\bar{c}$ with **numerical** solutions for the BHPS model.
- ”Sea-like” charm quark distribution, similar to that of the light flavor sea quarks:

$$c(x) = \bar{c}(x) = A \left[\bar{d}(x, Q_0) + \bar{u}(x, Q_0) \right]$$

- We characterize the magnitude of IC by the momentum fraction carried by charm at starting scale $Q_0 = 1.3$ GeV

$$\langle x \rangle_{\text{IC}} = \langle x \rangle_{c+\bar{c}}(Q = Q_0) = \int_0^1 x\,[c(x) + \bar{c}(x)]\,dx$$

Setup for the global analysis for CT14 and CT14HERA2:

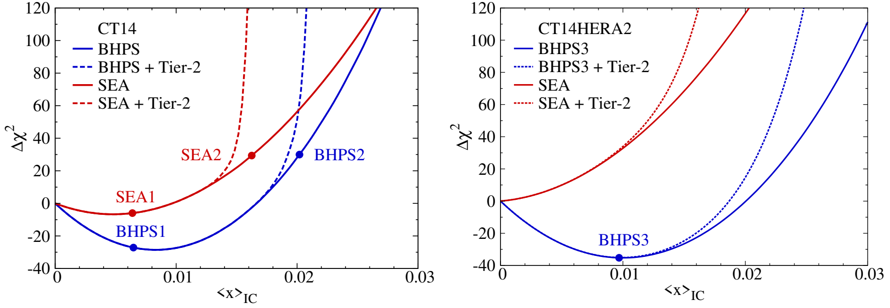
- $\alpha_s(M_Z) = 0.118$, compatable with the world average value $\alpha_s(M_Z) = 0.1184 \pm 0.0007$; the default value for recent CT PDF fits. Different value of $\alpha_s(M_Z)$ yields different PDFs.

- HOPPET - evolution code used to include nonperturbative charm model with NNLO matching, and to evolve the PDF at NNLO.

- Partons are parametrized at the initial energy scale $Q_0 = 1.295$GeV, which is slightly lower than the default charm quark mass $m_c^{pole} = 1.3GeV$.
- Choose experimental data with $Q^2 > 4$ GeV^2 and $W^2 > 12.6$GeV^2 to minimize high-twist, nuclear correction, etc., and focus on perturbative QCD predictions.

Difference in CT14HERA2 from CT14:

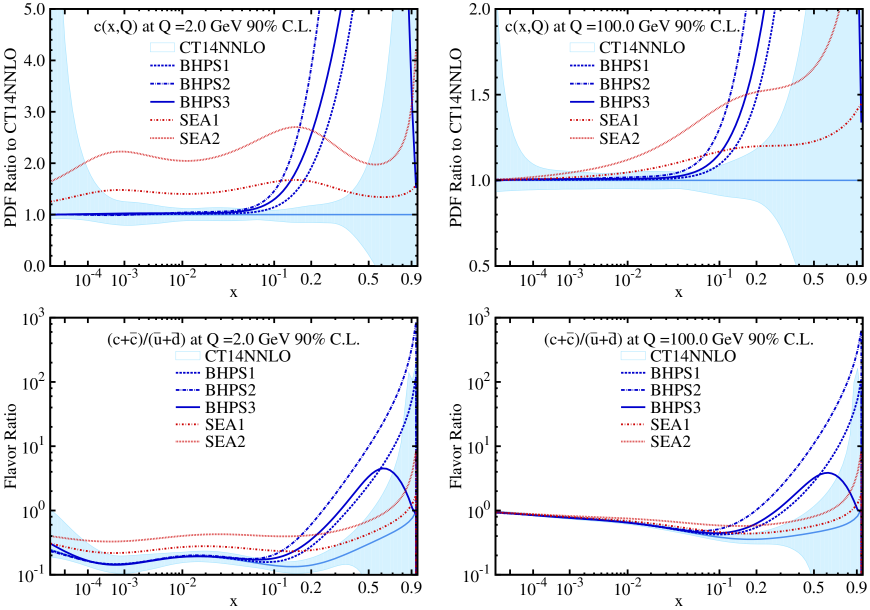
- Combined HERA Run I+II data were used in place of the HERA Run I data in CT14.
- One of the poorly fit NMC data were drop in CT14HERA2.
- Strange quark no longer bound with $\bar{u}$ and $\bar{d}$. Smaller strangeness is prefer than CT14.
- More geneal model BHPS3 use the setup of CT14HERA2.

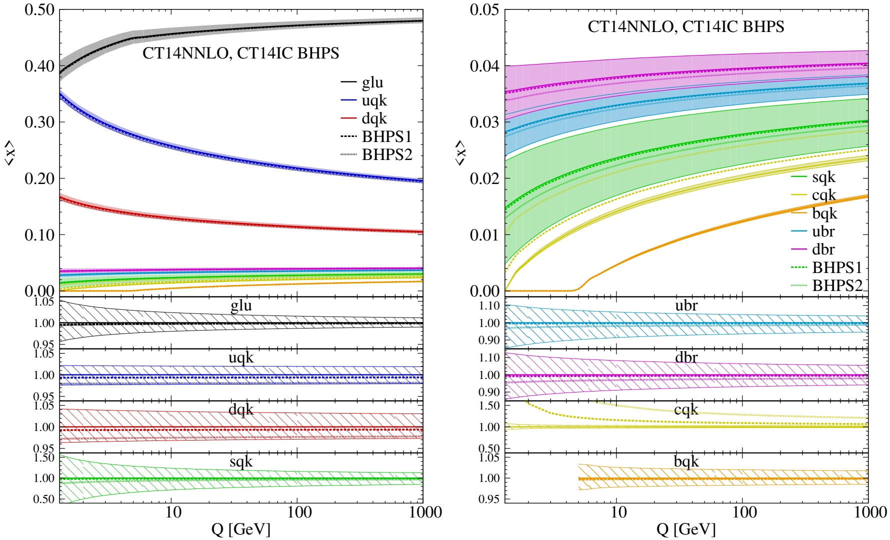


The dotted curves show $\Delta\chi^2 + T_2$ versus $< x >_{IC}$ for the two models of IC.

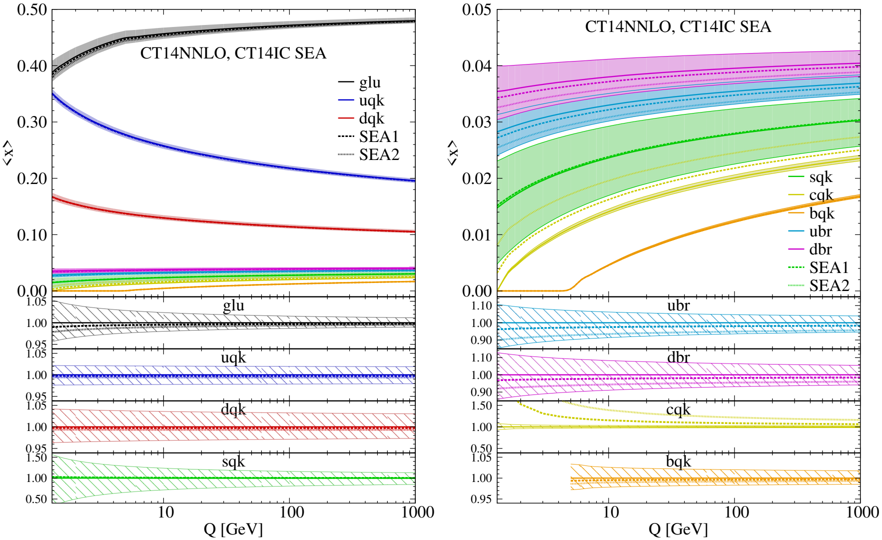
$$\begin{aligned} \langle x \rangle_{\text{IC}} &\lesssim 0.021 \text{ for CT14 BHPS}, \\ \langle x \rangle_{\text{IC}} &\lesssim 0.024 \text{ for CT14HERA2 BHPS}, \\ \langle x \rangle_{\text{IC}} &\lesssim 0.016 \text{ for CT14 and CT14HERA2 SEA}. \end{aligned} \tag{1}$$

Impact of IC on the PDFs and their ratios



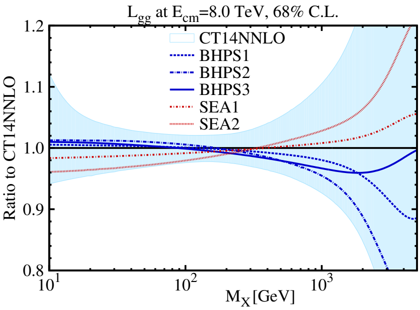


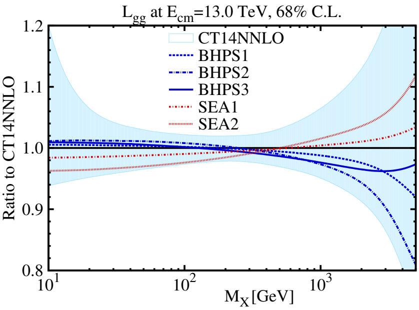
CT14NNLO, CT14IC BHPS
glu
uqk
dqk
BHPS1
BHPS2
<x>
Q [GeV]
sqk
cqk
bqk
ubr
dbr



CT14NNLO, CT14IC SEA
glu
uqk
dqk
SEA1
SEA2
<x>
Q [GeV]
sqk
cqk
bqk
ubr
dbr

Impact of IC on luminosities

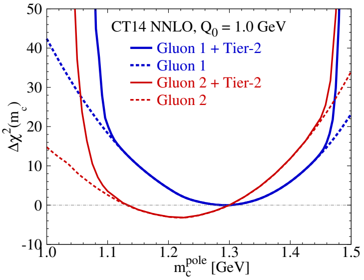




At $\sqrt{s} = 8$ TeV the most prominent distortions are from the SEA2 model which is suppressed at lower MX and is notably larger than CT14 for M_X in the TeV range. The BHPS models are almost coincident with CT14 for $M_X < 200$ GeV: BHPS1 and BHPS2 are highly suppressed above $M_X > 300$ GeV, while BHPS3 is suppressed for $0.3 < M_X < 3$ TeV and enhanced above this energy by approximately 3%. The impact on the Higgs cross section is small, with sizable impacts on the high mass gg PDF luminosities, but still within uncertainties.

Will the intrinsic charm affect by the choice of m_c? How much?

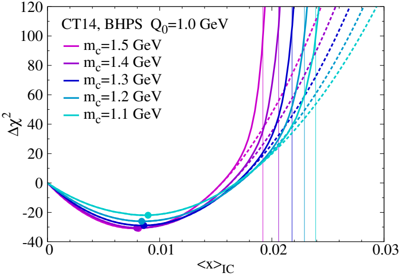
m_c^{pole} scan

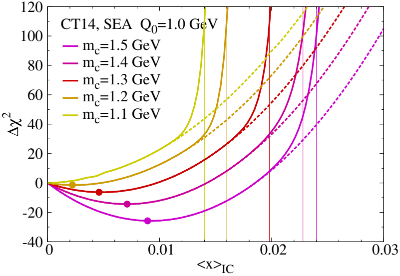


$Q_0 = 1.0$GeV for the study of m_c.
In "gluon-2", gluon is allowed to be negative at small x and Q, which does not lead to unphysical predictions. The "gluon-2" has minimal χ^2 at $m_c^{pole} = 1.22$ GeV.

DEPENDENCE OF FIT ON THE CHARM-QUARK MASS

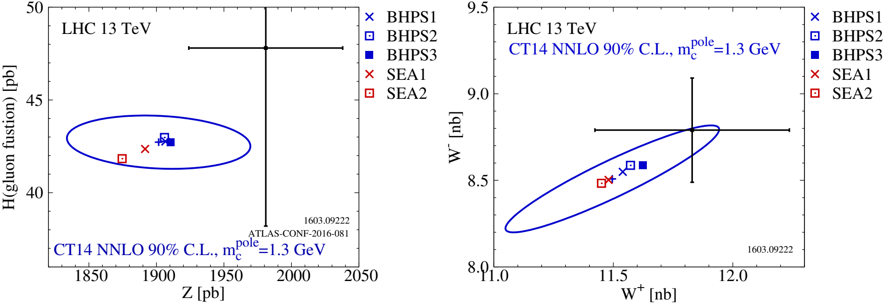
The combined HERA charm production and inclusive DIS data play an important role in the description of the goodness of fit. mc is a key input scale.





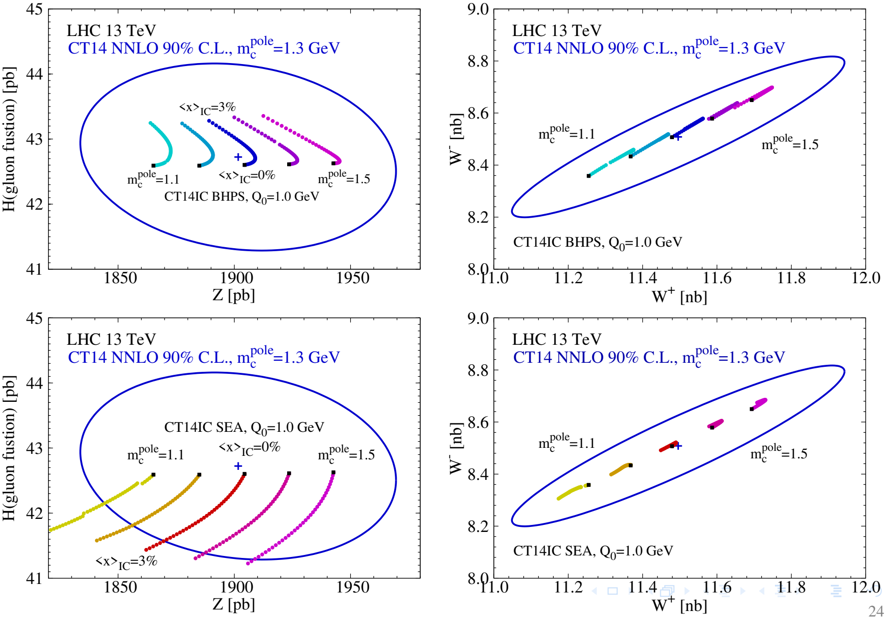
BHPS model: the position of the minimum is relatively stable as mc is varied, while the upper limit on the amount of IC decreases to 1.7%. BHPS model is not dramatically affected by variations of m_c

SEA model: limits on the amount of IC allowable are shifted towards higher values. ubar and dbar are well constrained by data (vector boson production in pp and pbar p) in the intermediate/small x region, and cannot change too much

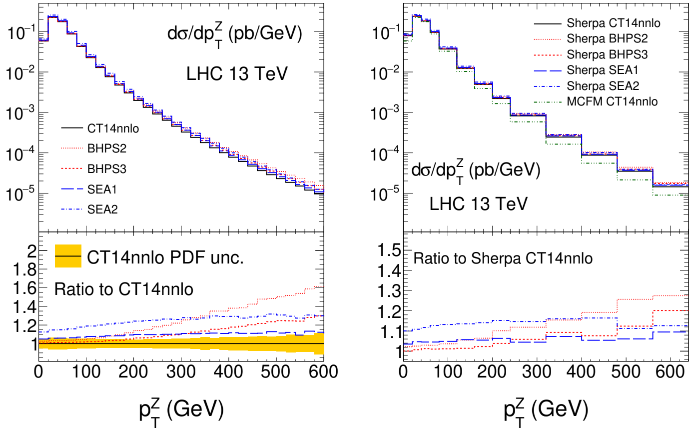


The W and Z inclusive cross section are calculated by using Vrap 0.9 at NNLO in QCD with μ_R and μ_f set equal to the invariant mass of the vector boson. The Higgs boson cross section via gluon-gluon fusion are calculated at NNLO in QCD by using iHix1.3 with the QCD scale set equal to the invariant mass of the Higgs boson.

NNLO Total inclusive electroweak boson production cross sections $\sigma_{tot}(ppVX)$



Z+c NLO LHC 13 TeV



The parton shower has the most significant effect in dampening the hard $p_T(Z)$ tail especially for BHPS fits. Sherpa predictions include HO tree-level MEs compared to MCFM and therefore show enhancements in the harder $p_T(Z)$ region compared to MCFM, but the relative change due to the IC models on top of the default (CT14) turns out to be as already predicted by MCFM. Similarly increasing or decreasing the number of multileg MEs in the merging changes the absolute level of p_T hardness but again the relative changes due to the IC models stay the same.

Summary

- We estimated the magnitude of a nonperturbative contribution to charm PDF, assuming that factorization for such contributions exists.
- We have determined the magnitude of the IC component of the proton that is consistent with the CT14 global QCD analysis of hard scattering data: $\langle x \rangle < 2\%$ for BHPS IC and $\langle x \rangle < 1.6\%$ for SEA IC at 90% C.L..
- The allowed IC momentum fraction value increased for BHPS, and decreased for SEA model when we use the CT14HERA2 setup.
- We analyzed implication of IC in charm-sensitive processes at the LHC with parton shower: most significant effect of the shower is to dampen the hard $p_T(Z)$ tail especially for BHPS fits.
- Experimental confirmation still missing: data from more sensitive measurements required; high energy and high luminosity fixed-target experiment (EIC) will be ideal.

Thank you very much for your attension!

BACKUP

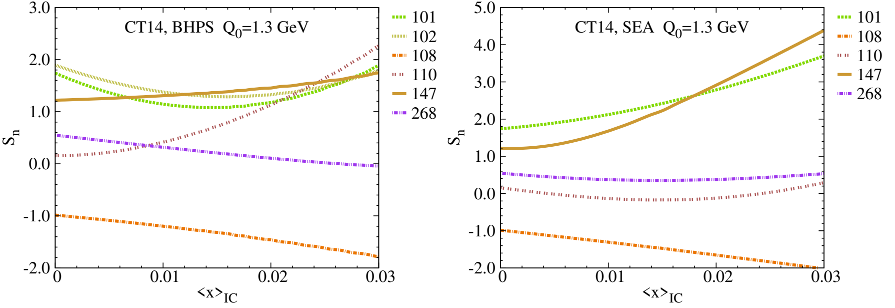
Why this is important

If an intrinsic charm component (IC) is present at a low energy scale, it will participate fully in QCD dynamics and evolve along with the other partons as the energy scale increases:

- observable consequences on physically interesting processes at high energies and short distances.
- Precision PDFs is required for precision determinations of key observables at the LHC sensitive to charm
- the c and cbar PDFs will be relevant to some important LHC measurements: production of W and Z0 involves cd, cs, dc, sc and cc contributions.
- charmed particle production at the LHC, which will depend quite directly on the c and cbar partons
- Implications on New Physics Searches
- Important to understand the flavor content of the nucleon sea:
    - observation of the light-quark sea difference between $\bar{d}$ and $\bar{u}$ in DIS and Drell-Yan
    - extraction of strange quark content s+sb from semi-inclusive DIS
    - lattice QCD calculations of sea quark contributions

Impact from data: analysis using an effective gaussian χ^2 variable

$-1 < S_n < 1$ reasonable fit, i.e. within the errors; $S_n > 3$ poor fit. $S_n < -3$ better than one would expect from normal statistical analysis.



The CCFR structure function data (ID 110) is most sensitive to the BHPS model. And thus the upper limit on the $< x >_{IC}$ value for BHPS model comes from the CCFR structure function data.

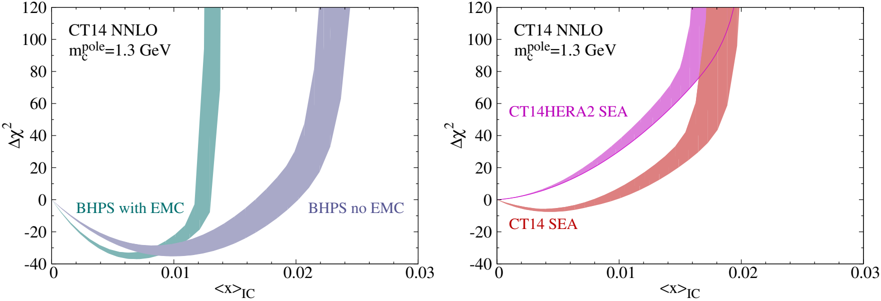
The HERA combined charm data (ID 147) is most sensitive to the SEA model. Which means the HERA combined charm data sets the upper limit on $< x >_{IC}$ for the SEA model.

European Muon Collaboration (EMC)
semi-inclusive dimuon and trimuon production in DIS on an iron target

- Excess in a few high-x bins of the $F_{2c}(x,Q)$
- No systematic error.
- Analysis done at the leading order of QCD.
- Tension with various inclusive and semi-inclusive DIS data.

J. J. Aubert et al. (European Muon Collaboration), Nucl. Phys. B213, 31 (1983).

In-depth study of CT14 IC fits



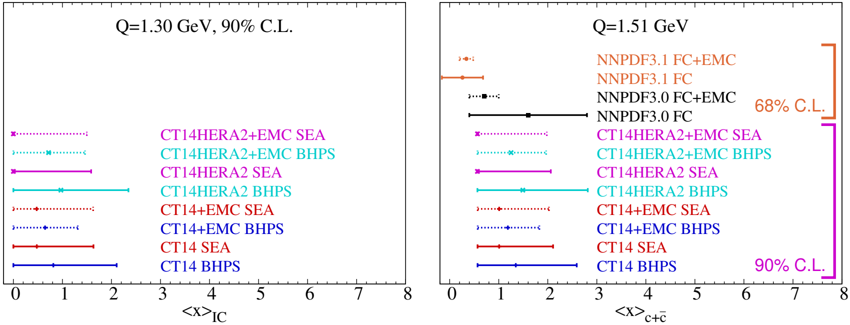
χ^2 as function of $< x >_{IC}$ in fits with and without the EMC data for both the BHPS and SEA models for $m_c = 1.3$ GeV. For the BHPS model (left), the two distinct behaviors are from fits with and without the EMC data. For the SEA model (right) the two distinct behaviors are from different parametrizations in the CT14 and CT14HERA2 fits.

χ^2 values for CT14 CT14HERA2 fits with and without EMC data

Candidate NNLO PDF fits	χ^2/N_{pts}			
	All Expt.	HERA inc. DIS	HERA $c\bar{c}$ SIDIS	EMC $c\bar{c}$ SIDIS
CT14 + EMC (weight=0), no IC	1.10	1.02	1.26	3.48
CT14 + EMC (weight=10), no IC	1.14	1.06	1.18	2.32
CT14 + EMC in BHPS model	1.11	1.02	1.25	2.94
CT14 + EMC in SEA model	1.12	1.02	1.28	3.46
CT14 HERA2 + EMC (weight=0), no IC	1.09	1.25	1.22	3.49
CT14 HERA2 + EMC (weight=10), no IC	1.12	1.28	1.16	2.35
CT14 HERA2 + EMC in BHPS model	1.09	1.25	1.22	3.05
CT14 HERA2 + EMC in SEA model	1.11	1.26	1.26	3.48

The EMC data (1983), do not satisfy the stringent criteria on systematic uncertainties required in more recent experimental analyses. This is one of the reasons why these measurements are not included in CTEQ PDF analyses, whose policy is to include only data with trusted systematic errors. However, it is still useful to examine how the EMC measurements of the heavy-flavor F2c structure function could possibly affect the amount of IC.

Allowed ranges of $c + \bar{c}$ momentum fractions



CT14: $90\% c.l., Q_0 = m_c^{pole} = 1.3 GeV$
NNPDF: $68\% c.l., Q_0 = m_c^{pole} = 1.51 GeV$

LHC searches for intrinsic charm

Z+c NLO computation with various models, without (left) and with parton shower (right)