Fitted charm, intrinsic charm…

in CTEQ-TEA parton distributions

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CTEQ-TEA (Tung et al.) working group

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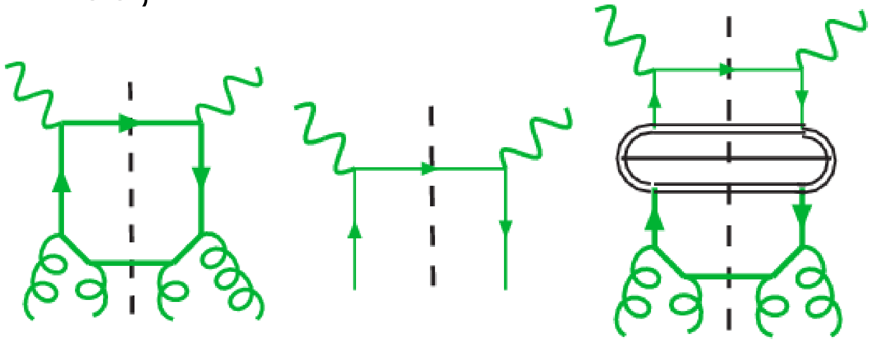
Southern Methodist University: T.-J. Hou, P. Nadolsky, B. T. Wang, K. P. Xie

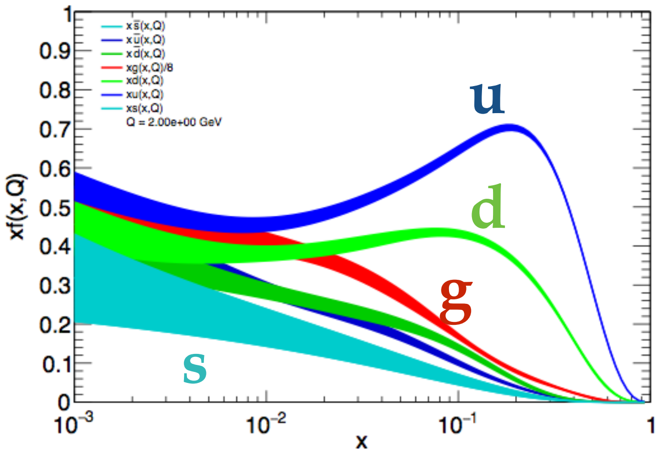
Xinjiang University: S. Dulat



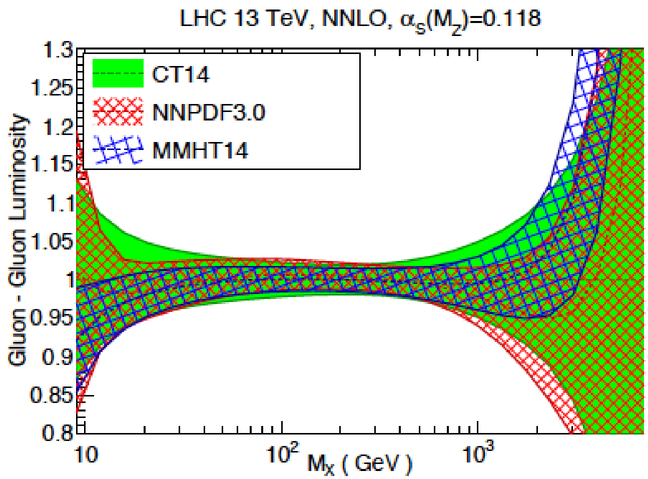
CT14 Parton distributions

- 2015 major release on general-purpose PDFs, CT14 NNLO/NLO sets including alternative α_s series and $N_f = 3,4,6$ **[1506.07443]**

CT14 NNLO PDFs



gluon-gluon luminosity



- combined HERA charm production, H1 FL data in NC DIS
- early LHC Run I data on W/Z charged lepton rapidity and asymmetry data;
- old D0 W-electron asymmetry data superseded by the new one with full luminosity;
- inclusive jet production from ATLAS and CMS

- more flexible parametrization for gluon, d/u at large-x, both d/u and dbar/ubar at small-x, 28 eigenvectors comparing to 25 for CT10

http://hep.pa.msu.edu/cteq/public/index.html

Beyond CT14 parton distributions

Progress is made towards the new CT17 family of PDFs with LHC data, and in development of specialized post-CT14 PDF sets

- **CT17 preliminary fits: [Jun Gao, DIS'2017 workshop, April 2017]**
- **CT14 QEDinc PDFs**: constraints on photon PDFs in the nucleon **[1509.02905]**
- **CT14 MC PDFs:** Monte-Carlo replicas for certain applications **[1607.06066]**
- **CT14 HERA2 PDFs:** effects of combined HERA1+2 data **[1609.07968]**
- **CT14 IC PDFs:** intrinsic/fitted charm component, **[1706.xxxxx]**

A year-long investigation by CT group (T.-J. Hou, M. Guzzi, J. Winter, K. Xie, J. Gao,…), with valuable insights from CTEQ colleagues (J. Collins, D. Soper, F. Olness,…) and discussions with S. Alekhin, L. Del Debbio, J. Rojo, M. Ubiali, T. Hobbs, W. Melnitchouk, K.-F. Liu, …

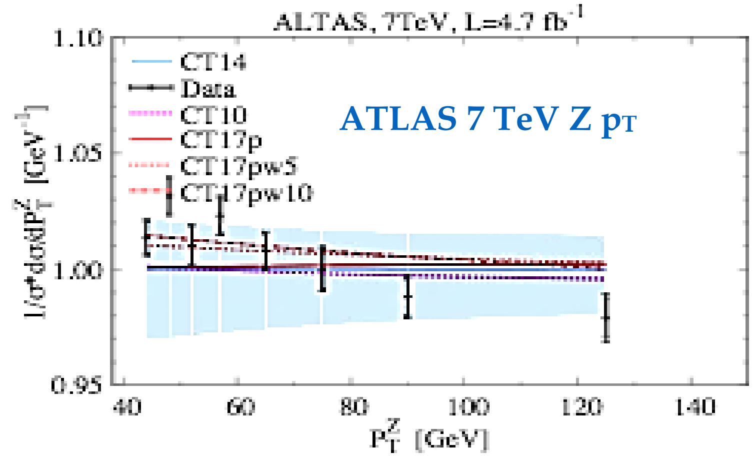
CT17p: preliminary PDFs with new LHC data

Included experiments:

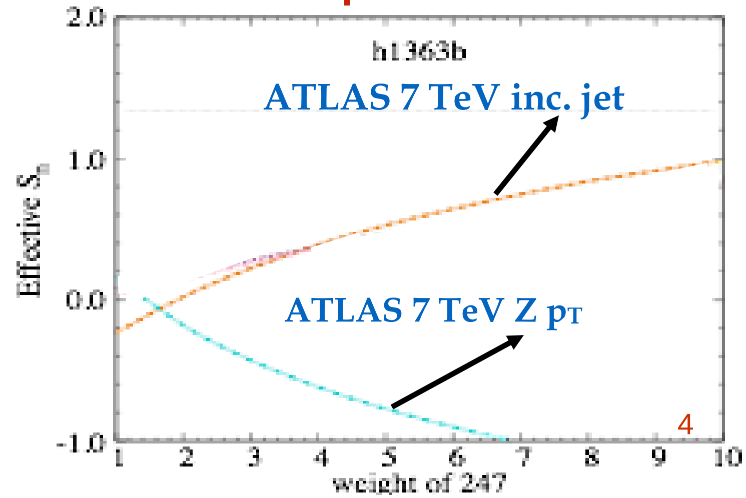
- Combined HERA1+2 DIS
- LHCb 7 TeV Z, W muon rapidity dist.
- LHCb 8 TeV Z rapidity dist.
- ATLAS 7 TeV inclusive jet
- CMS 7 TeV inclusive jet (extended y range)
- ATLAS 7 TeV Z pT dist.
- LHCb 13 TeV Z rapidity dist.
- CMS 8 TeV Z pT and rapidity dist. (double diff.)
- CMS 8 TeV W, muon asymmetry dist.
- ATLAS 7 TeV W/Z, lepton(s) rapidity dist.
- CMS 7,8 TeV tT differential dist.
- ATLAS 7,8 TeV tT differential dist.

Are twist-2 NNLO contributions sufficient for describing the most precise experiments?

Predictions vs. LHC data

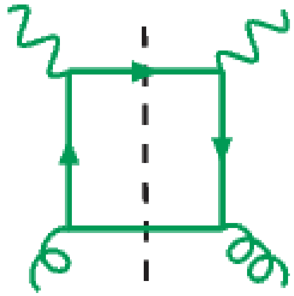


Study agreement between the LHC experiments

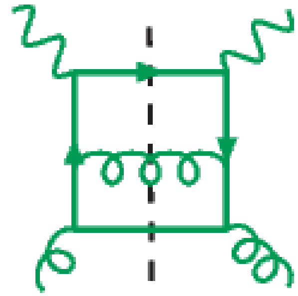


A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")

Twist-2
$\gamma^* g \to c\bar{c}$



Order $\alpha_s(Q)$

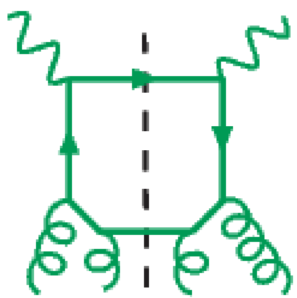


$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

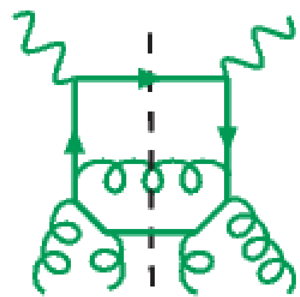
Must be resummed in $c(x, Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

Twist-4
$\gamma^*(gg) \to c\bar{c}$

$\Lambda \lesssim 1$ GeV



$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$

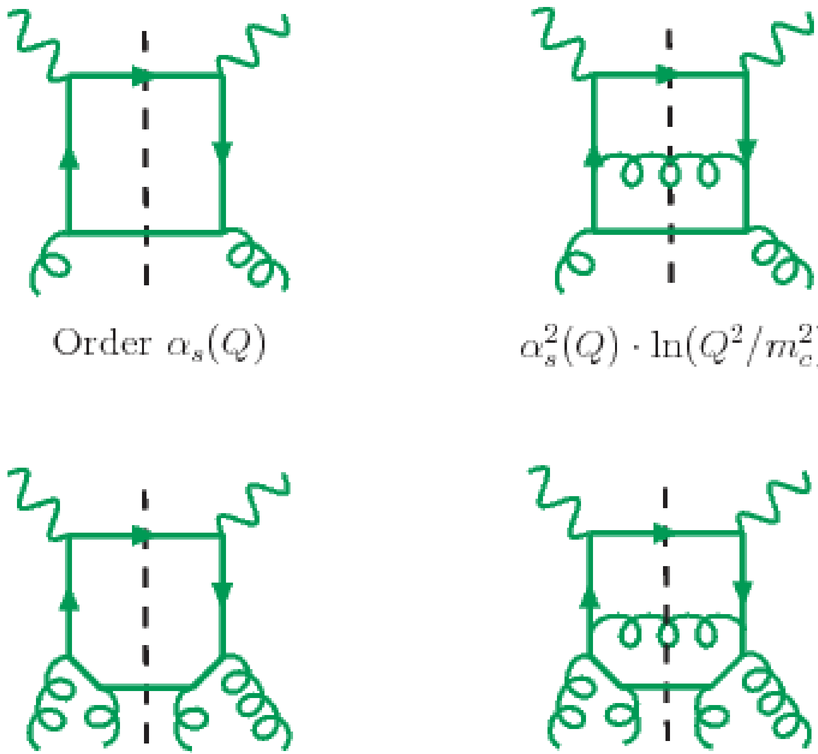


$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")

Twist-2
$\gamma^* g \to c\bar{c}$

Twist-4
$\gamma^* (gg) \to c\bar{c}$



Order $\alpha_s(Q)$

$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

Must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

$\Lambda \lesssim 1$ GeV

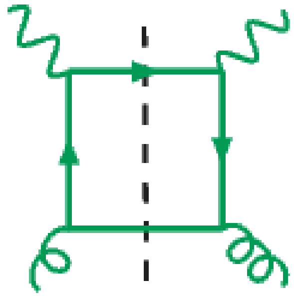
$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$

$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

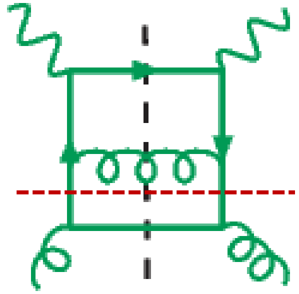
Can be of order 10% of the twist-2 α_s^2 term

A twist-4 contribution in HERA DIS charm production ($\subset$ "intrinsic charm")

Twist-2
$\gamma^* g \to c\bar{c}$



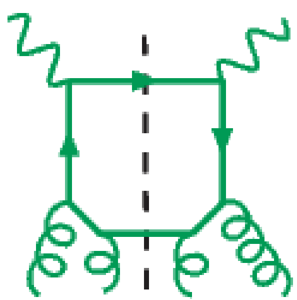
Order $\alpha_s(Q)$



$\alpha_s^2(Q) \cdot \ln(Q^2/m_c^2)$

Must be resummed in $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2$; e.g., in the ACOT scheme

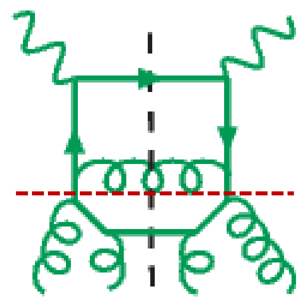
Twist-4
$\gamma^*(gg) \to c\bar{c}$



$\Lambda \lesssim 1$ GeV

$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$

Can be of order ~10% of the twist-2 α_s^2 term



$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

The "twist-2" subgraphs can be resummed as a part of $c(x,Q)$ in the $N_f = 4$ scheme at $Q^2 \gg m_c^2 > \Lambda^2$;

contributes to the boundary condition for $c(x,Q_0)$ at $Q_0 \approx m_c$;

obeys twist-2 DGLAP equations.

CT14 IC study: answers to important questions

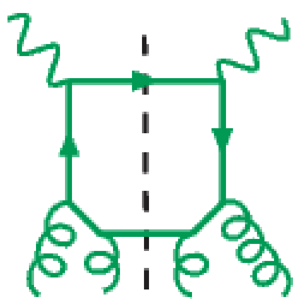
What are phenomenological constraints on the "intrinsic charm" from the global QCD data?

⇒ The CT14 charm PDFs can include an "intrinsic", or "nonperturbative", component carrying a total momentum fraction of $\sim 1\%$ in DIS at $Q \approx m_c$.

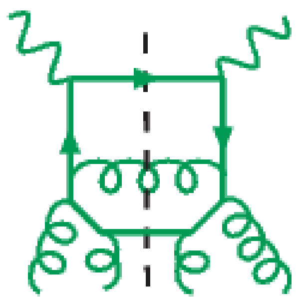
Can we predict its impact on the LHC predictions?

Yes, based on the simplest approximation of the "nonperturbative" charm contribution. The estimated impact is less than the net CT14 PDF uncertainty.

Twist-4
$\gamma^*(gg) \to c\bar{c}$



$\alpha_s^2(Q) \cdot (\Lambda^2/Q^2)$
or $\alpha_s^2(Q) \cdot (\Lambda^2/m_c^2)$



$\alpha_s^3(Q) \cdot (\Lambda^2/m_c^2) \ln(Q^2/m_c^2)$

Note:
"intrinsic charm" ≠ "fitted charm"

PDF fits may include a ``fitted charm'' PDF

``Fitted charm'' = ``nonperturbative charm''
+ other (possibly not universal)
higher O(α_s) / higher power terms

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

All α_s orders:

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

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

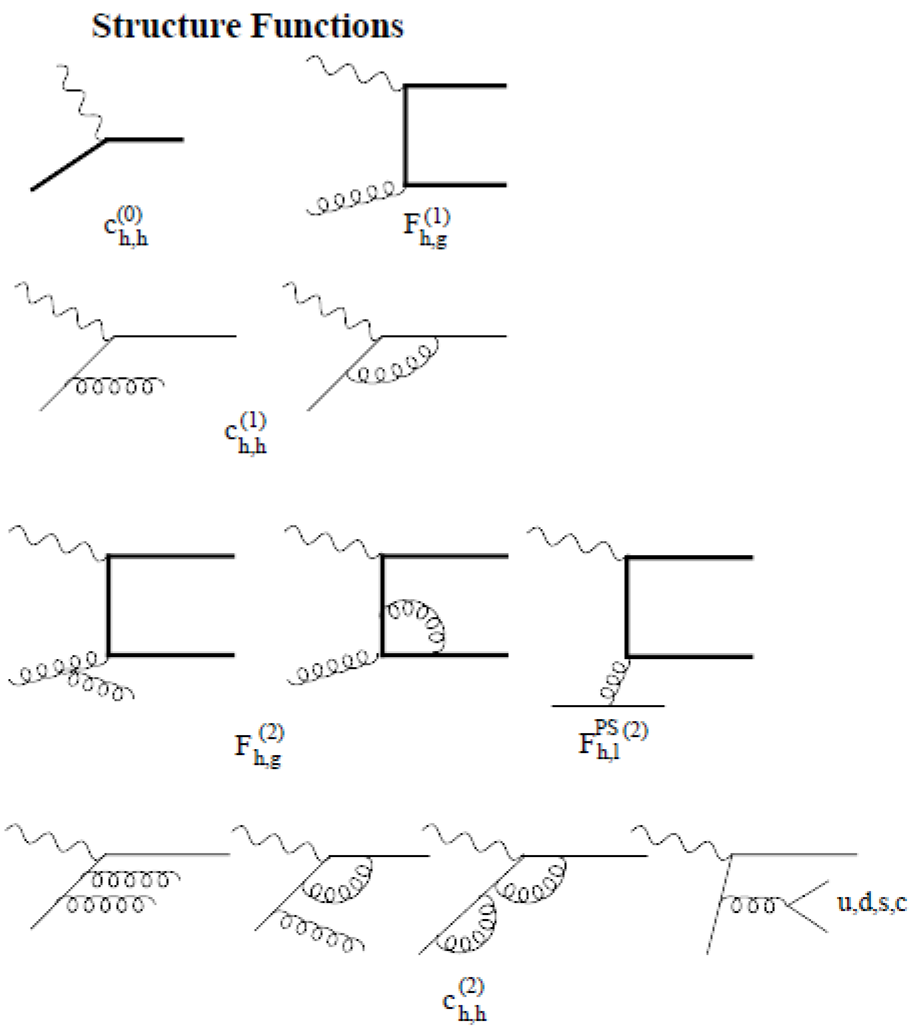
PDF fits:

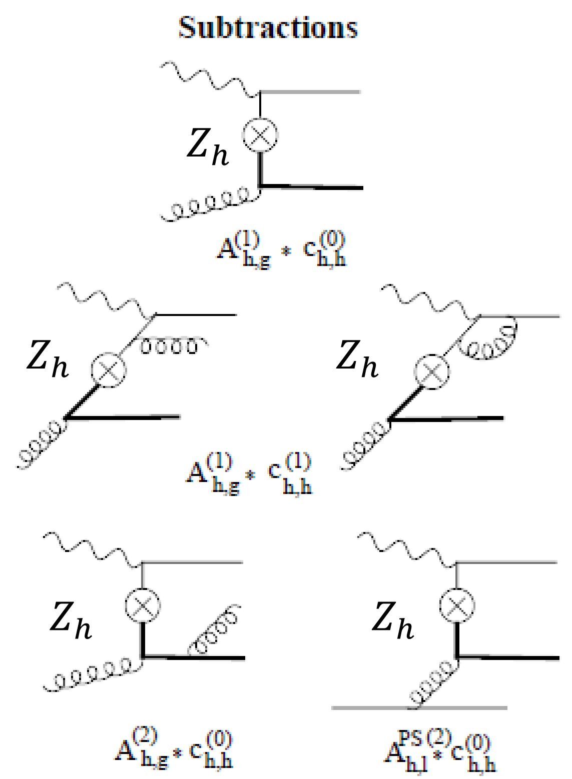
$$F(x,Q)=\sum_{a=0}^{N_f}\int_x^1\frac{d\xi}{\xi}\mathcal{C}_a^{(N_{ord})}\left(\frac{x}{\xi},\frac{Q}{\mu},\frac{m_c}{\mu};\alpha(\mu)\right)f_{a/p}^{(N_{ord})}(\xi,\mu).$$

The perturbative charm PDF component cancels at $Q\approx m_c$ up to a higher order

The 'fitted charm component' may approximate for missing terms of orders α_s^p with $p>N_{ord}$, or Λ^2/m_c^2, or Λ^2/Q^2

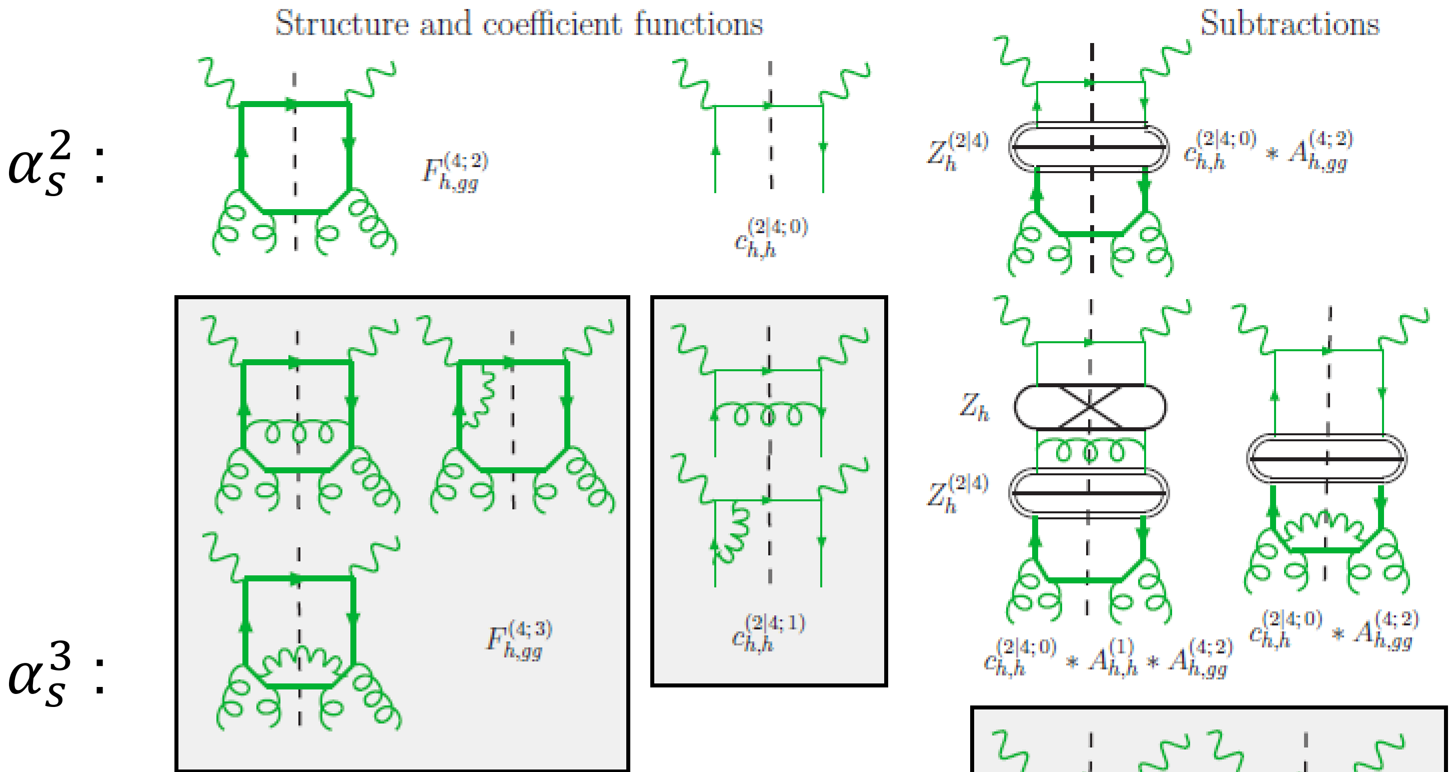
Twist-2: factorization for DIS in S-ACOT-χ scheme up to NNLO



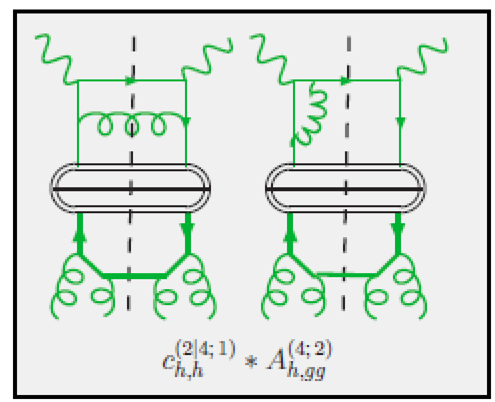


Leading-power radiative contributions to neutral-current DIS charm production in the CTEQ-TEA NNLO analysis,
from Guzzi et al., arXiv:1108.5112

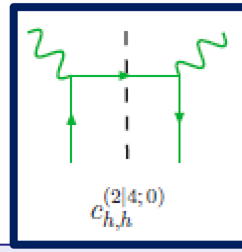
ACOT-like factorization for twist-4 charm contributions (an example)



Many novel terms arise, involving twist-4 nonperturbative functions!



Intrinsic charm contributions, practical implementation



In the absence of full computation, we (and other groups) make the simplest approximation:

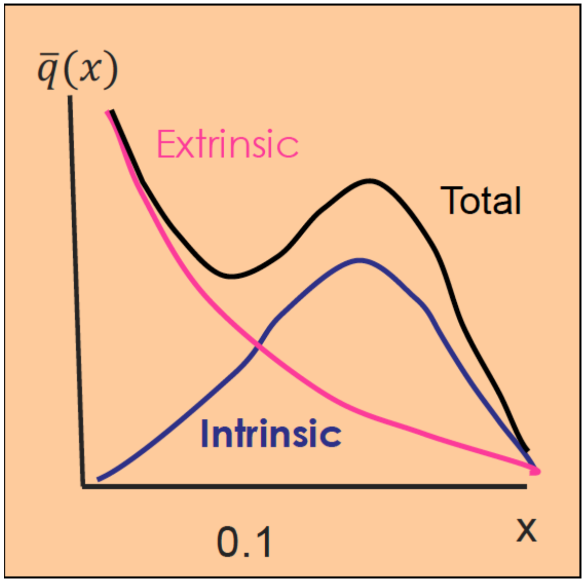
$$F_{IC}(x, Q_0) = [c_{h,h}^{(2|4;0)} \otimes f_{c/p}^{IC}](x, Q_0)$$

$\boldsymbol{c_{h,h}^{(2|4;0)}}$ **is the twist-2 charm DIS coefficient function** introduced to factorize the $O(\alpha_s^0)$ twist-4 term; depends on the heavy-quark scheme

CT14 IC: $c_{h,h}^{(2|4;0)}$ is defined to be equal to $c_{h,h}^{(0)}$ in the S-ACOT-χ scheme

$\boldsymbol{f_{c/p}^{IC}(\xi, Q_0)}$ **is a nonperturbative charm parametrization**:
CT14 IC: $f_{c/p}^{IC}(\xi, Q_0)$ is a "**valence-like**" or a "**sea-like**" function, combined with the to the perturbative charm $f_{c/p}^{pert}$ from $g \to c\bar{c}$ splittings

Sea-like and valence-like PDFs



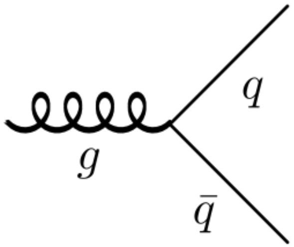
A simple model for a quark PDF at Q_0 consists of two components:

1. Sea-like ("extrinsic") component:

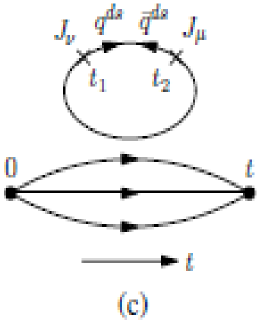
- monotonic in *x*, satisfies

$$q(x) \propto x^{-1} \quad x \to 0$$

- may be generated in several ways, e.g.,
  - in perturbative QCD from gluon splittings

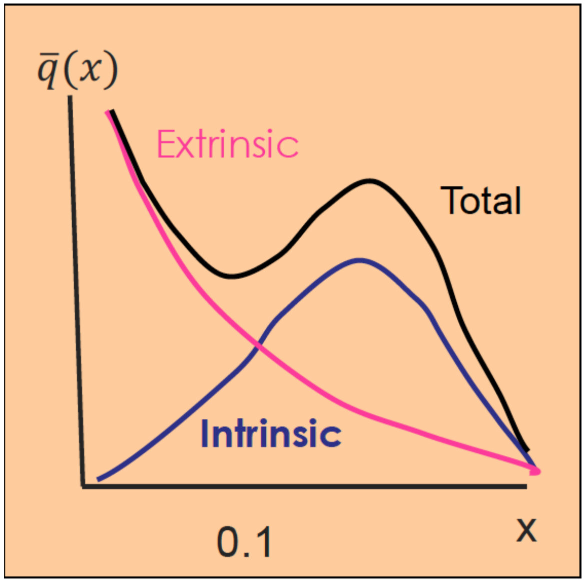


  - in lattice QCD from disconnected diagrams



[K.-F. Liu et al., 1206.4339]

Sea-like and valence-like PDFs

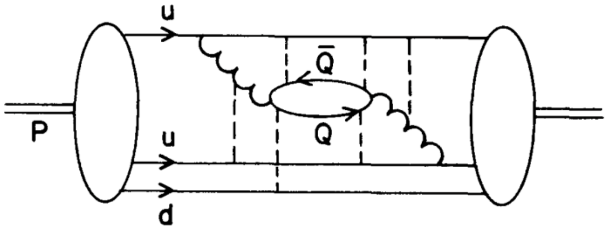


A simple model for a quark PDF at Q_0 consists of two components:

2. Valence-like ("intrinsic") component peaks in *x*, satisfies

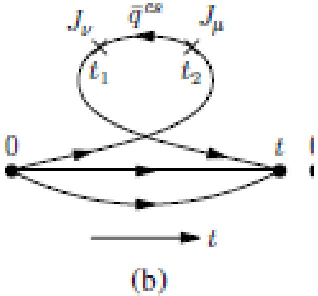
$$q(x) \propto x^{-1/2} \quad x \to 0$$

- may be generated in several ways, e.g.,
  - for all flavors, nonperturbatively from a $uudQ\bar{Q}$ Fock state:

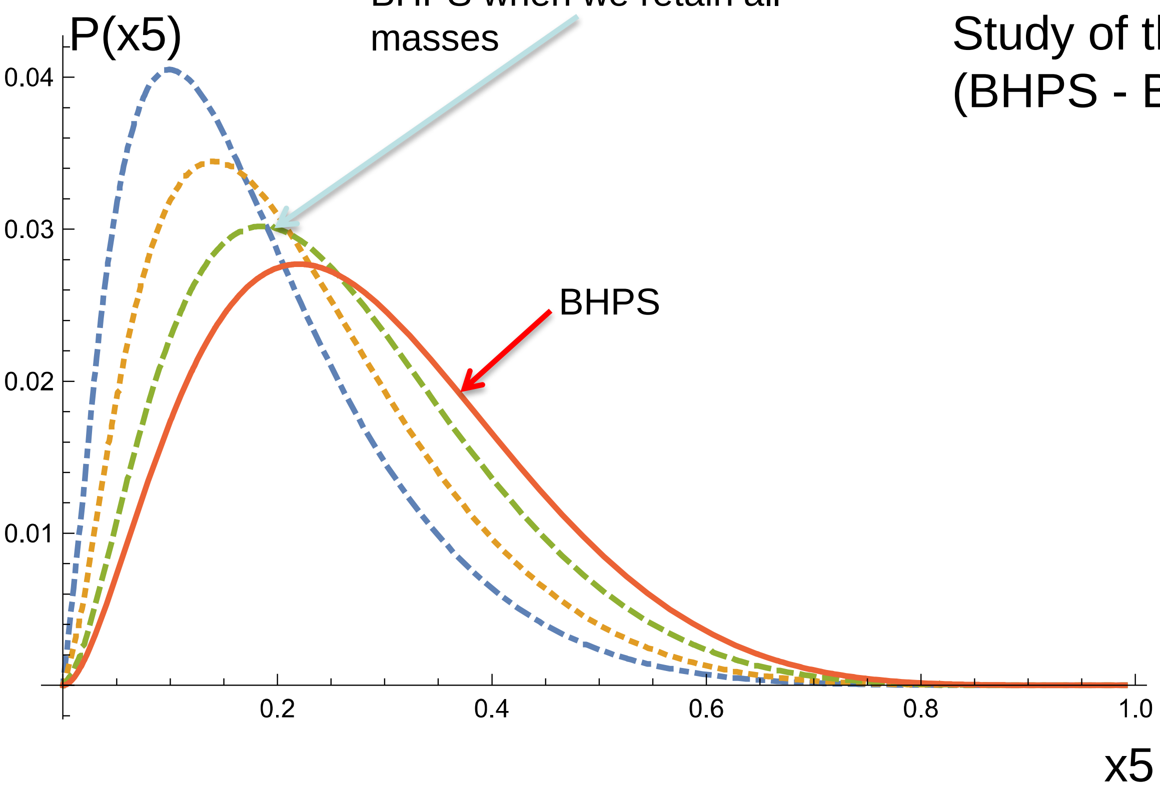


Brodsky, Peterson, Sakai, PRD 1981

- for ubar and dbar, in lattice QCD from connected diagrams **[1206.4339]**



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

Mp=1 GeV

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

x-dependence distribution for intrinsic charm in the BHPS model with all masses kept

Parametrizations for BHPS and SEA models

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

Brodsky et al PLB 1980

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

- "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**:

$$\langle x \rangle_{c+\bar{c}} = \int_0^1 x \left[c(x) + \bar{c}(x) \right] dx$$

SET UP FOR THE GLOBAL ANALYSIS for CT14 and CT14HERA2:
We mainly focus on the CT14 analysis, CT14HERA2 gives similar results

For all three models:

- $\alpha_s(M_Z) = 0.118$, compatible with the world average value $\alpha_s(M_Z) = 0.1184 \pm 0.0007$; the default value for recent CT PDF fits.

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

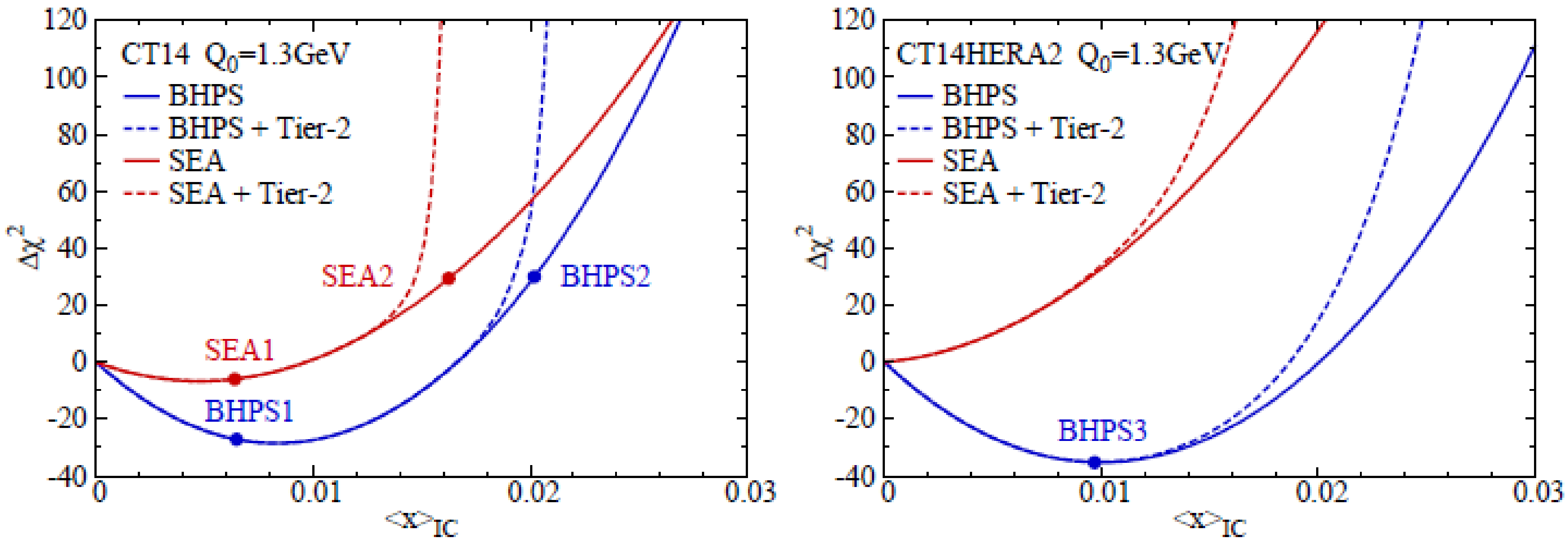
- S-ACOT-χ at NNLO --- CT GM-VFN default scheme for heavy-flavour treatment in the inclusive DIS structure functions.
  Differences between ACOT vs S-ACOT-χ for IC contr. are $\mathcal{O}\left(\Lambda^2/Q^2\right)$

- Production threshold kinematics are accounted for by using the χ convention. The other partons are parametrized at an initial scale $Q_0 = 1.295$ GeV, as in the CT14 analysis.

- The default charm-quark mass, $m_c^{pole} = 1.3$ GeV, is varied as a part of the analysis

Best fit for different IC choices

PRELIMINARY

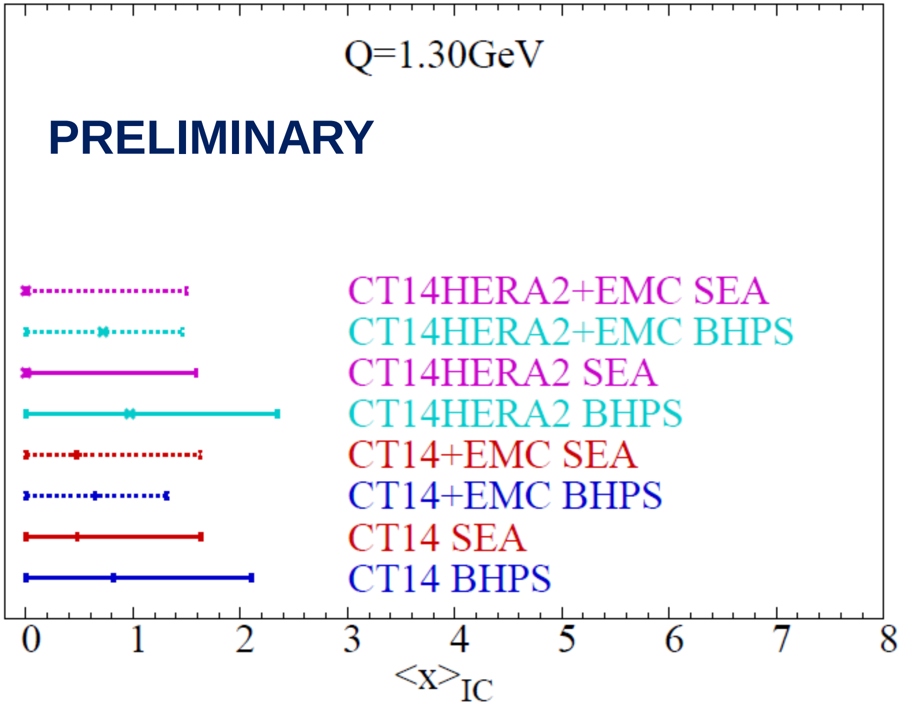


The dotted curves show $\Delta\chi^2 + T_2$ versus $\langle x \rangle_{\rm IC}$ for the two models of IC.

New upper limits on $\langle x \rangle_{IC}$ for CT14 and CT14HERA2 at $Q_0 = 1.3$ GeV, 90% C.L.

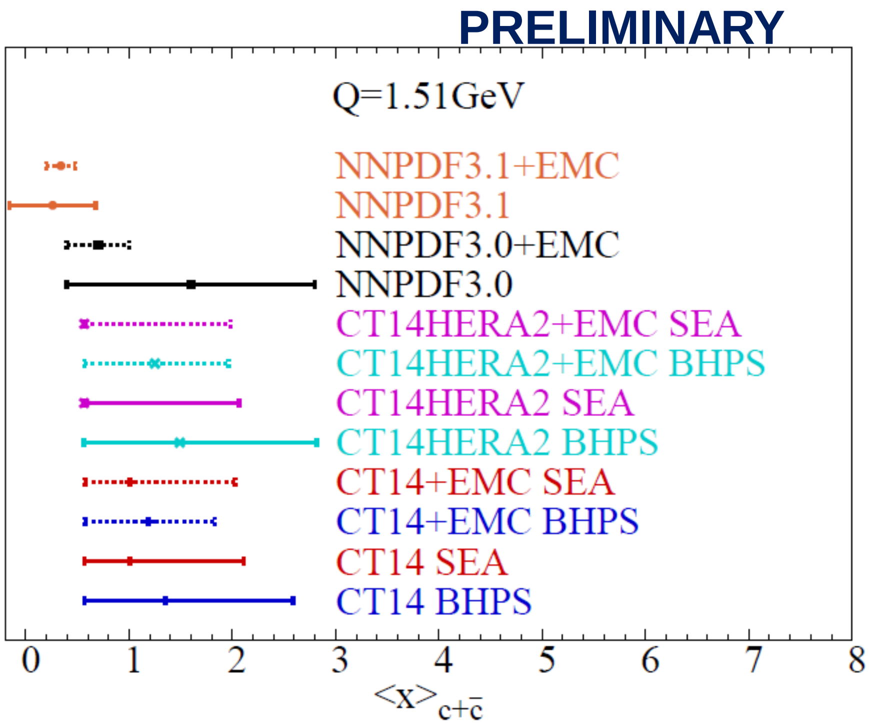
$$\langle x \rangle_{\rm IC} \lesssim 0.021 \quad \text{BHPS for CT14},$$
$$\langle x \rangle_{\rm IC} \lesssim 0.024 \quad \text{BHPS for CT14HERA2},$$
$$\langle x \rangle_{\rm IC} \lesssim 0.016 \quad \text{SEA for CT14 and CT14HERA2}.$$

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



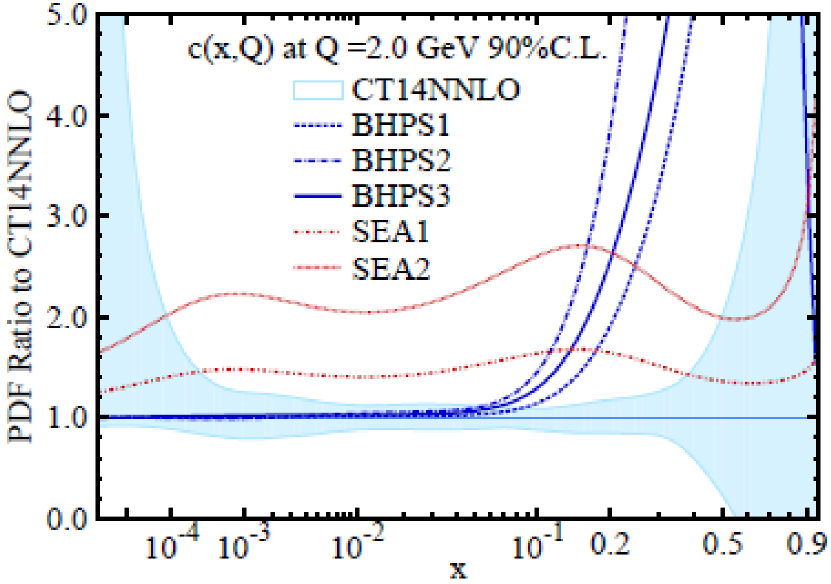
CT14: 90% c.l., $Q_0 = m_c^{pole} = 1.3$ GeV

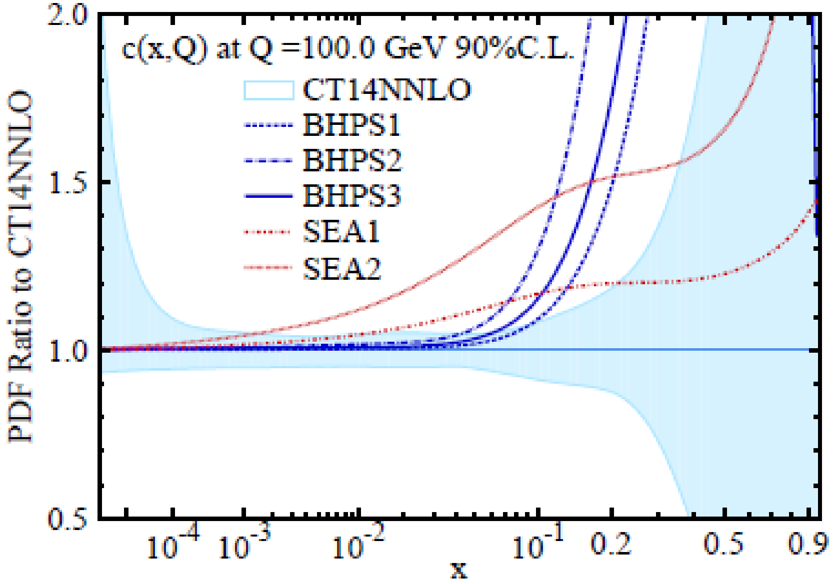
NNPDF: 68% c.l., $Q_0 = m_c^{pole} = 1.51$ GeV



Impact of IC on the PDFs and their ratios

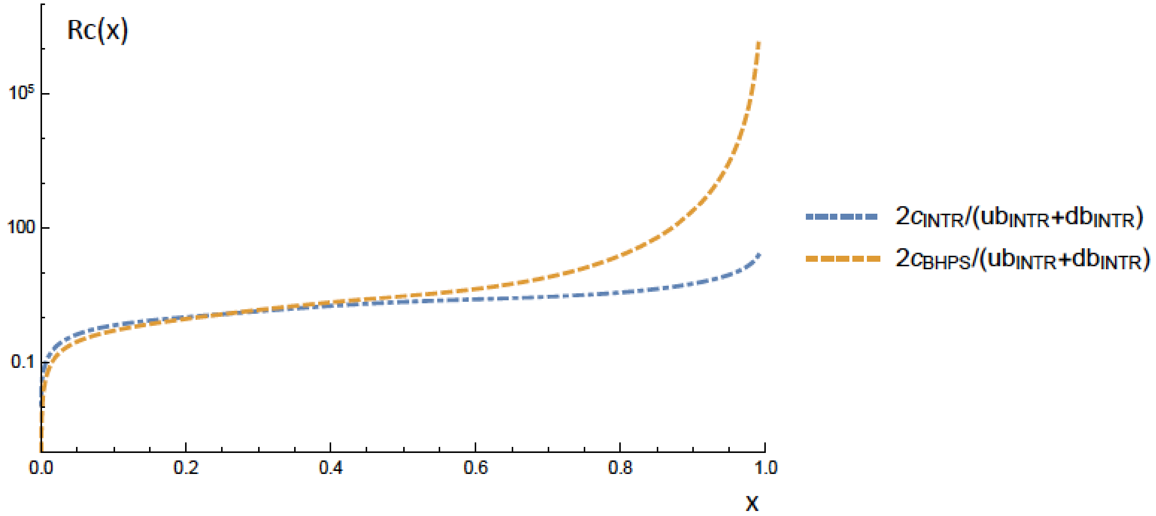
PRELIMINARY

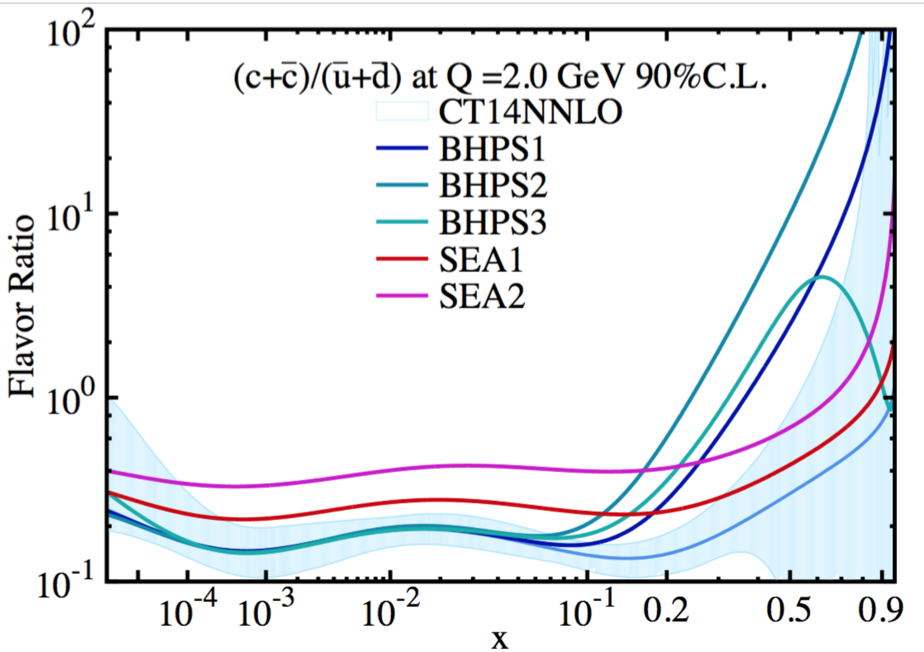


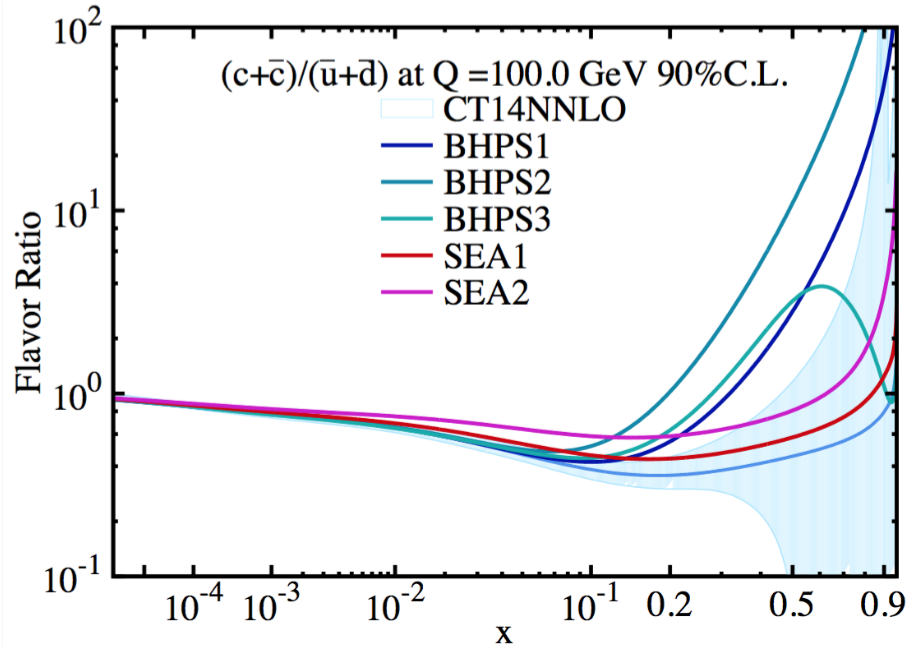


Study of Rc =(c+cbar)/(ubar+dbar) suppression ratio

PRELIMINARY

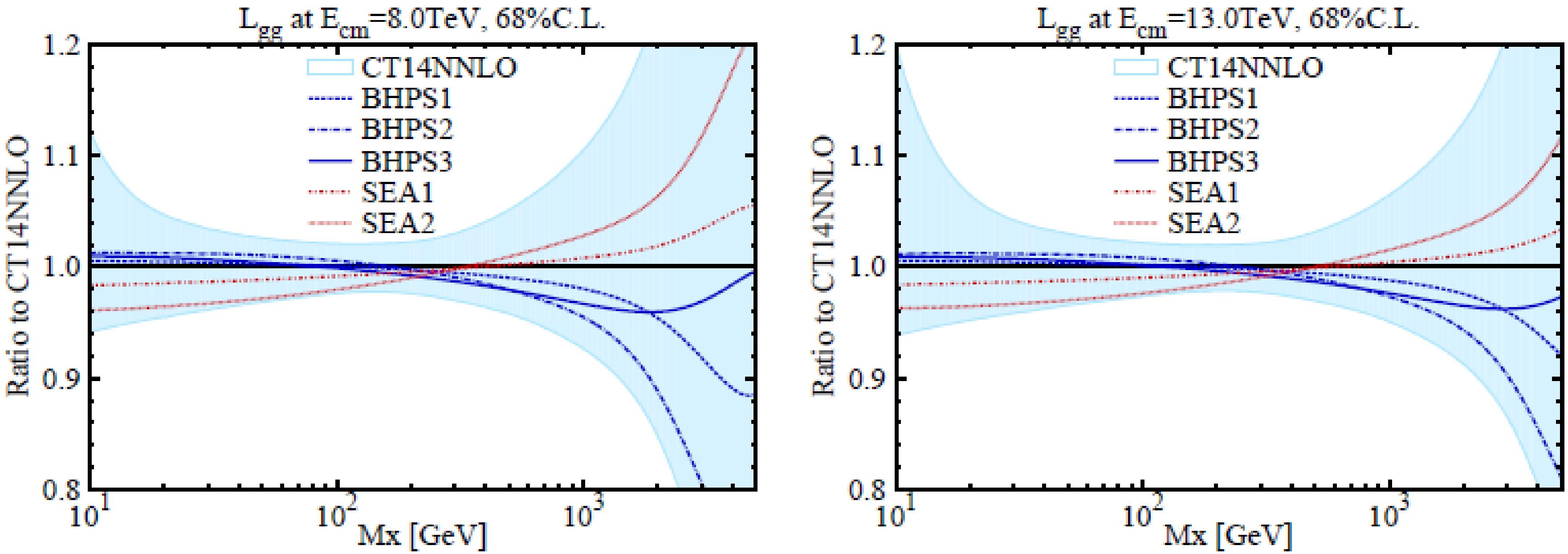






Impact of IC on gg luminosities

PRELIMINARY



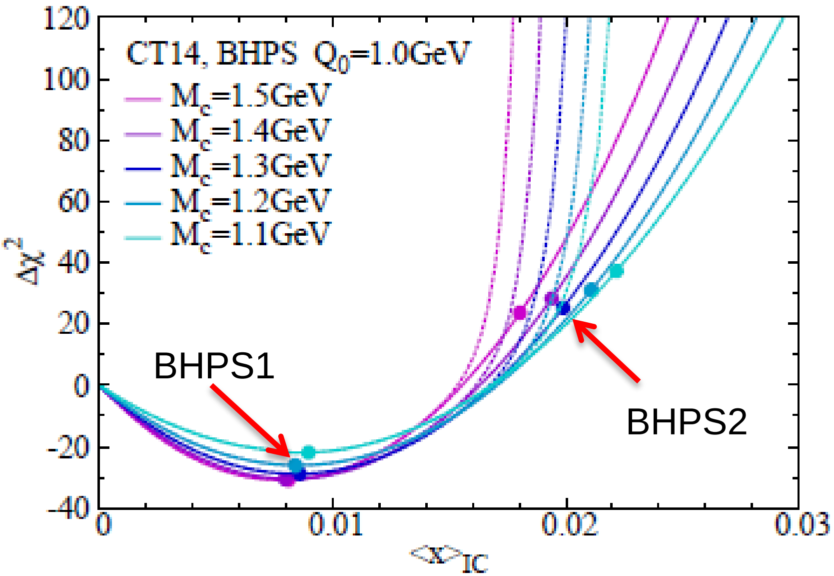
At $\sqrt{s}$ = 8 TeV the most prominent distortions are from the SEA2 model which is suppressed at lower MX and is notably larger than CT14 for MX in the TeV range. The BHPS models are almost coincident with CT14 for MX < 200 GeV: BHPS1 and BHPS2 are suppressed above MX > 300 GeV, while BHPS3 is suppressed for 0.3 <MX < 3 TeV and enhanced above this energy by approximately 3%.

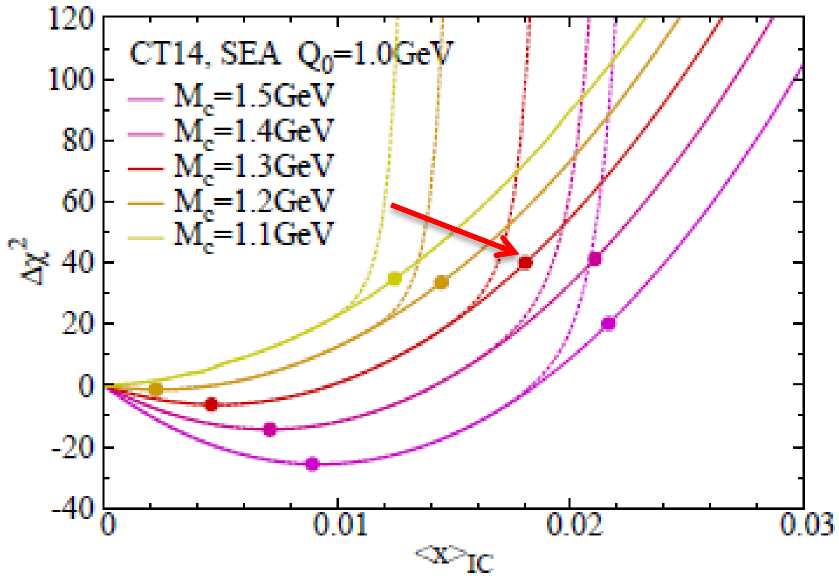
The impact on the Higgs cross section is small, with sizable impacts on the high mass gg PDF luminosities, but still within uncertainties.

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.

PRELIMINARY





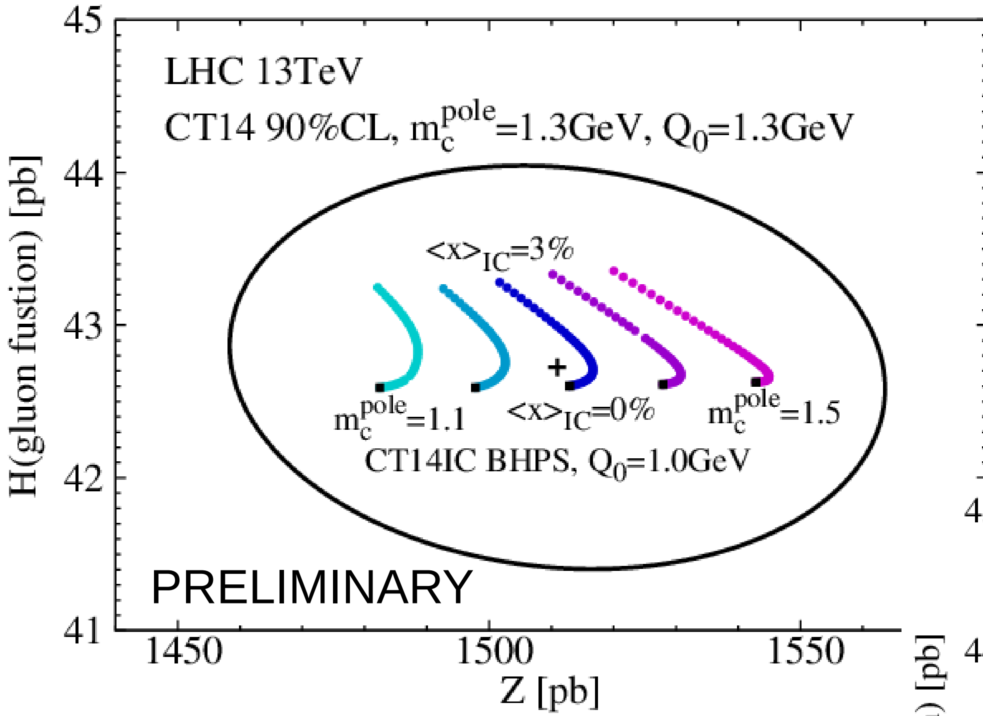
BHPS model: the position of the χ^2 minimum is relatively stable as mc is varied, while the upper limit on the amount of IC decreases to 1.7%. BHPS model is not dramatically affected by variations of mc

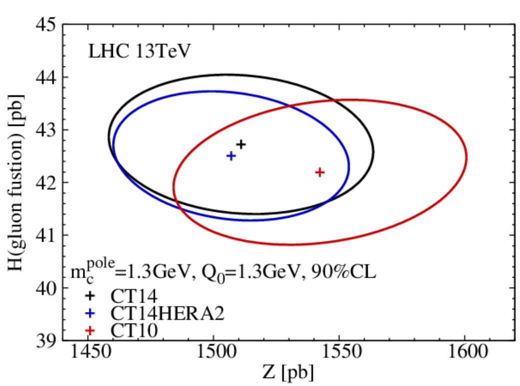
SEA model: limits on the amount of IC allowable are shifted towards higher values.
ubar and dbar are well constrained by data (vector boson production in pp and pbar p) in the intermediate/small x region, and cannot change too much

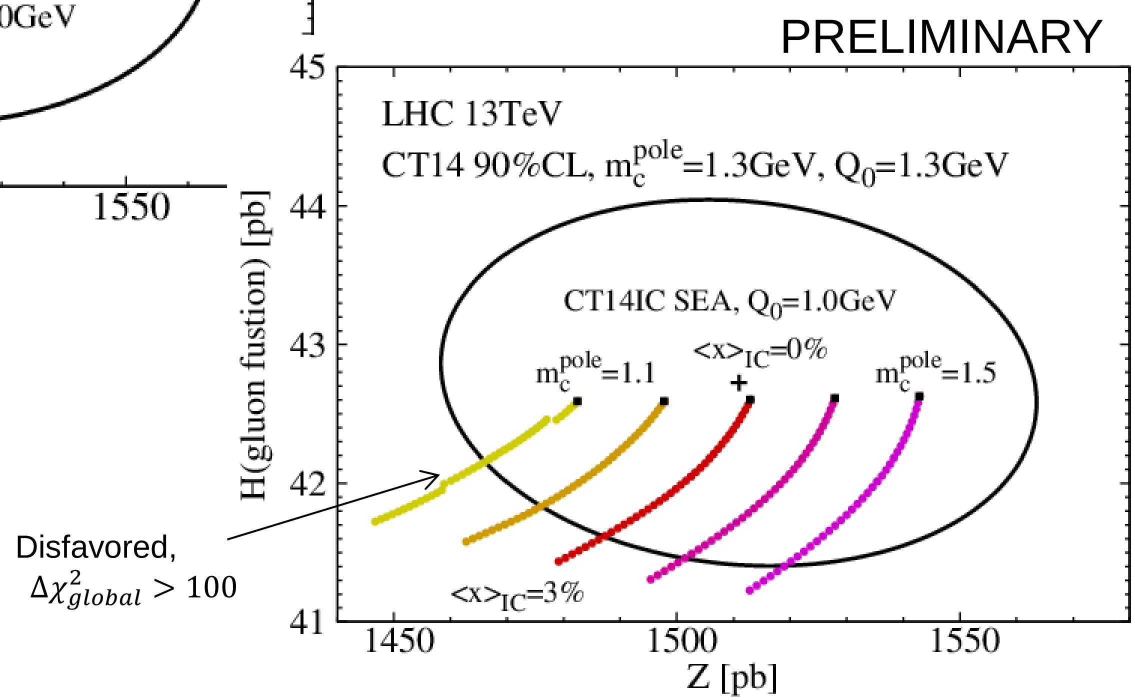
Impact of IC on key LHC observables is mild

[Our estimates assume that the IC PDF component does not depend on the hard process.]

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

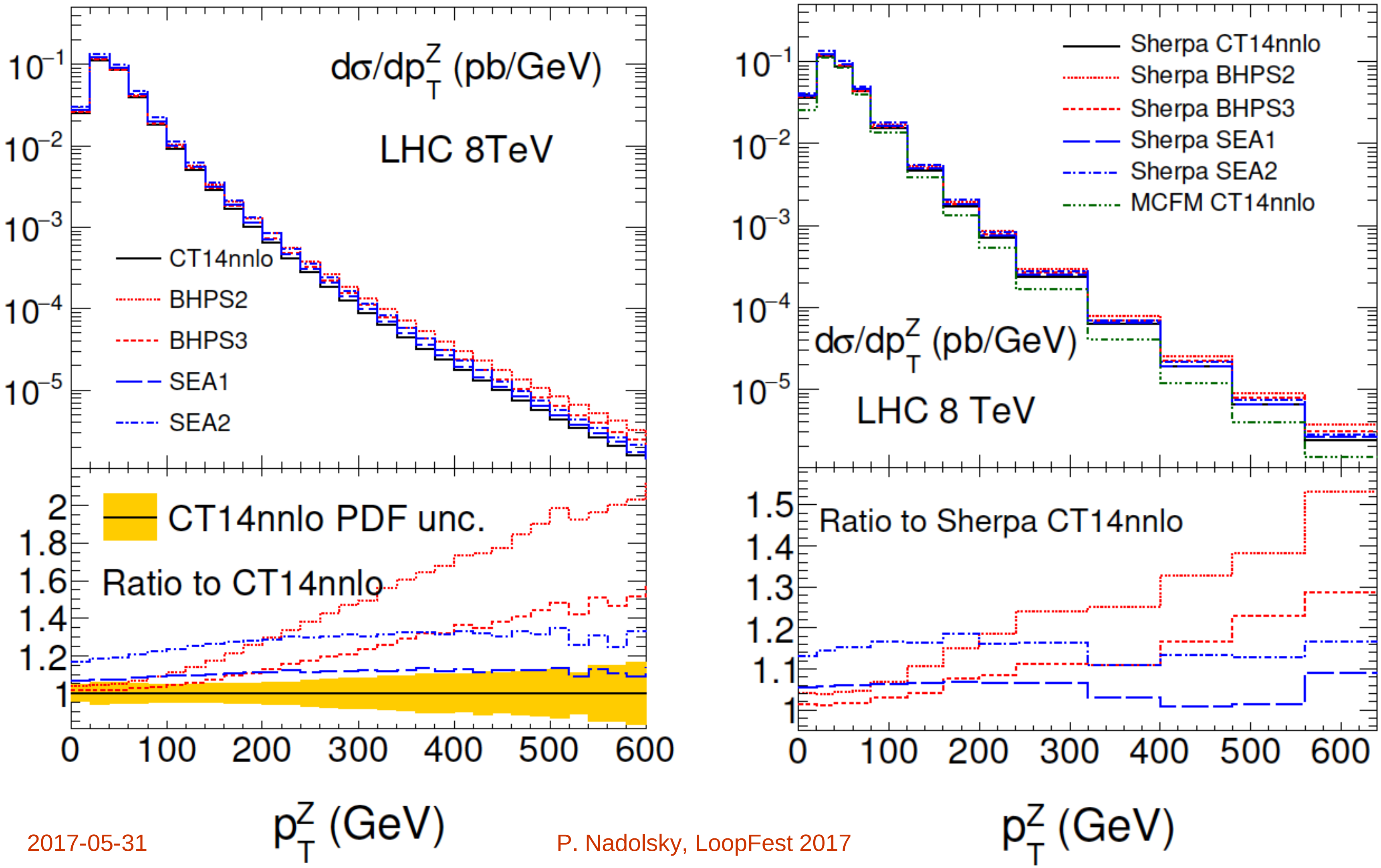






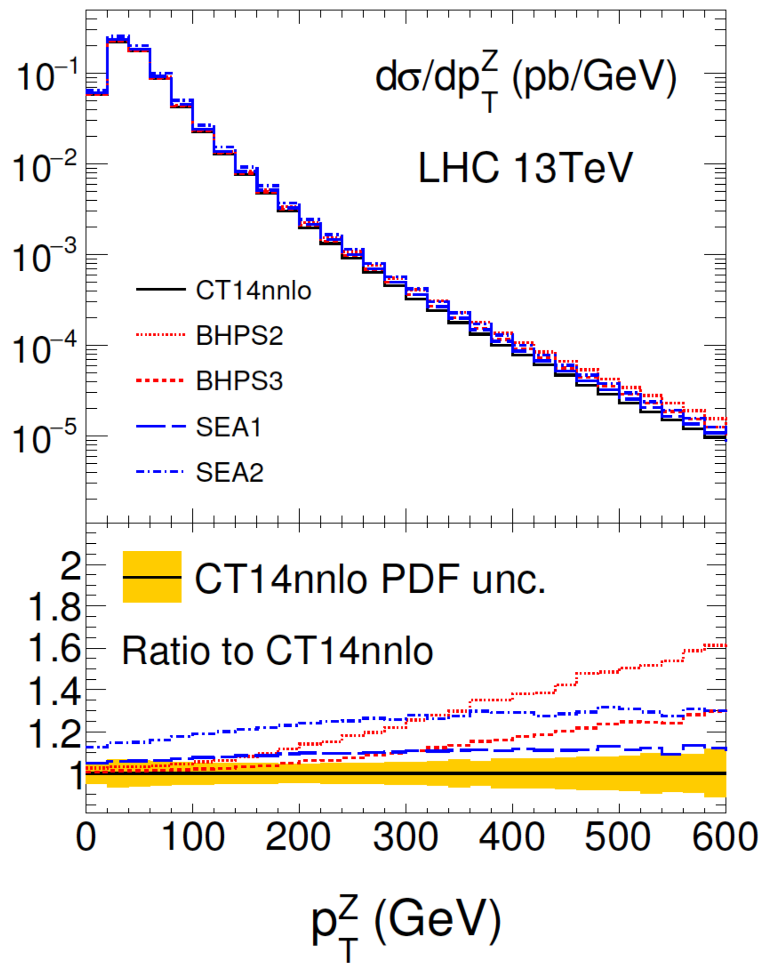
LHC searches for intrinsic charm

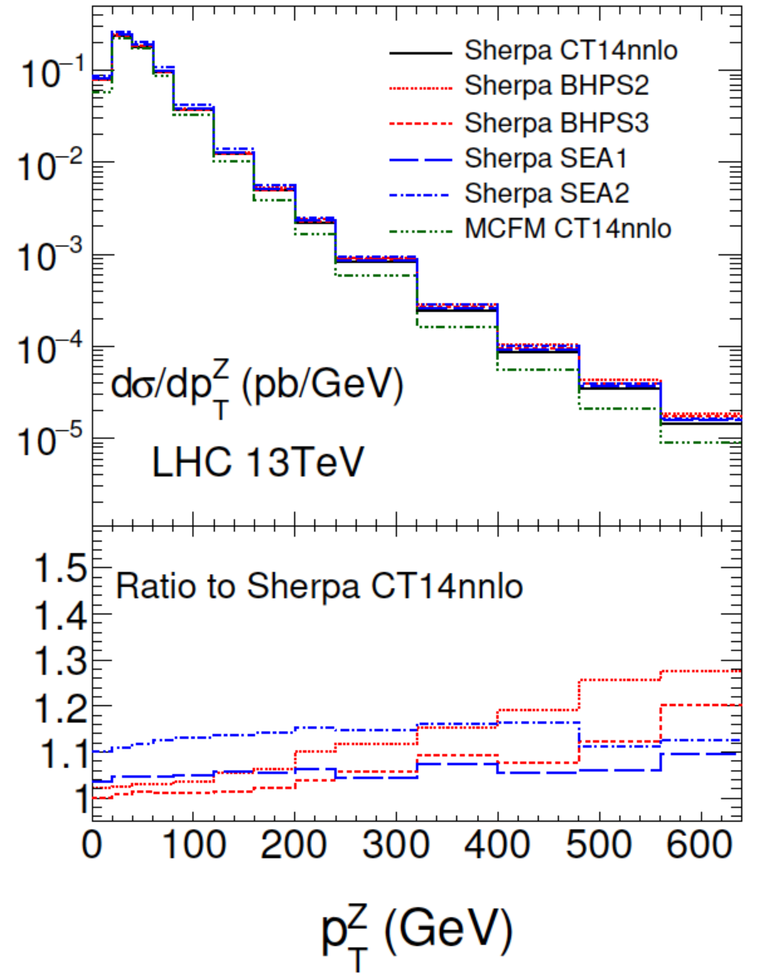
Z+c NLO computation with various models, without (left) and with parton shower (right)



Z+c NLO LHC 13 TeV

PRELIMINARY





The parton shower has the most significant effect in dampening the hard pT(Z) tail especially for BHPS fits. Sherpa predictions include HO tree-level MEs compared to MCFM and therefore show enhancements in the harder pT(Z) region compared to MCFM. Similarly increasing or decreasing the number of multileg MEs in the merging changes the absolute level of pT.

Conclusions

- We estimated the magnitude of a nonperturbative contribution to charm PDF in DIS processes at NNLO QCD
- The magnitude of the IC component of the proton is consistent with the CT14 global QCD analysis of hard scattering data: $\langle x \rangle_{IC} < 2\%$ for BHPS IC and $\langle x \rangle_{IC} < 1.6\%$ for SEA IC at 90% C.L.
- The final HERA I+II DIS data prefer a slighly higher (lower) IC momentum fraction value for the BHPS (SEA model), compared to CT10 NNLO
- We analyzed the impact of EMC data: the allowed IC momentum fraction value decreases for BHPS model in fits with EMC data (but no control of systematic errors)
- The impact of IC on the LHC predictions is within the standard CT14 NNLO uncertainty, assuming the CT14 IC component is universal. Parton showering in $Z + c$ production dampens the enhancement at high $p_T(Z)$ observed with the BHPS model
- **Experimental confirmation of the IC contributions is still missing:** data from more sensitive measurements required; high energy and high luminosity fixed-target experiment (EIC) will be ideal.

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**

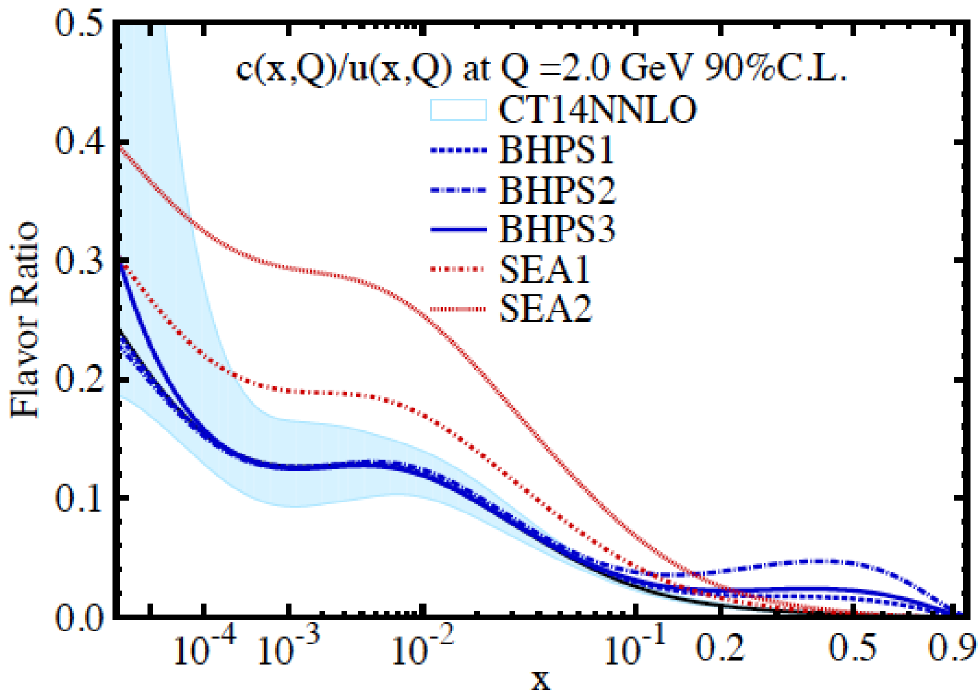
- ❖ **the c and cbar PDFs will be relevant to some important LHC measurements: production of W± and Z0 involves cd, cs, dc, sc and cc contributions.**

- ❖ **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 db and ub in DIS and Drell-Yan
- extraction of strange quark content s+sb from semi-inclusive DIS
- lattice QCD calculations of sea quark contributions



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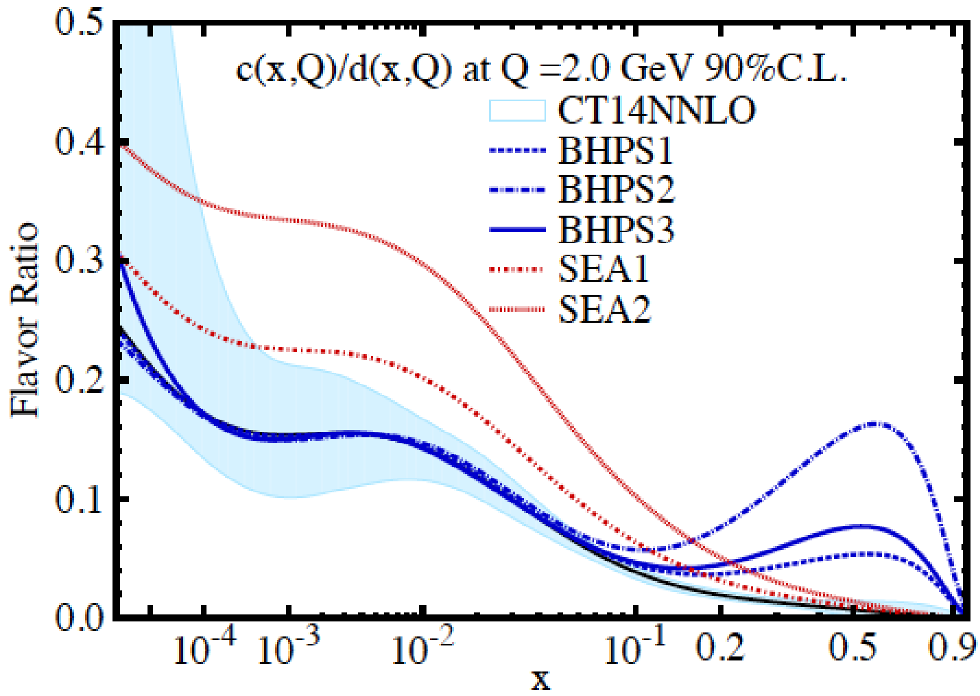
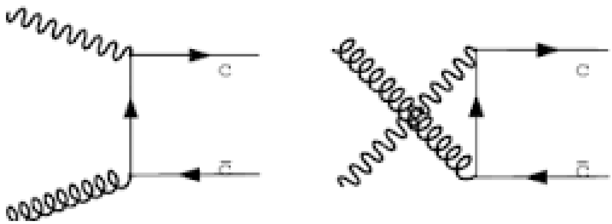


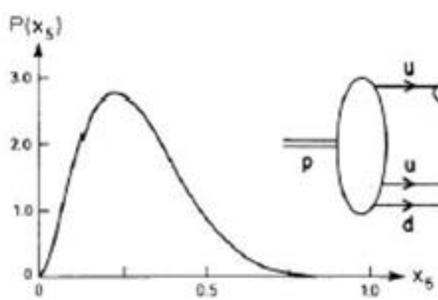
Three types of charm content in the proton

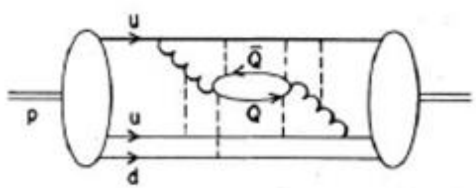
1. Perturbative charm CT14:

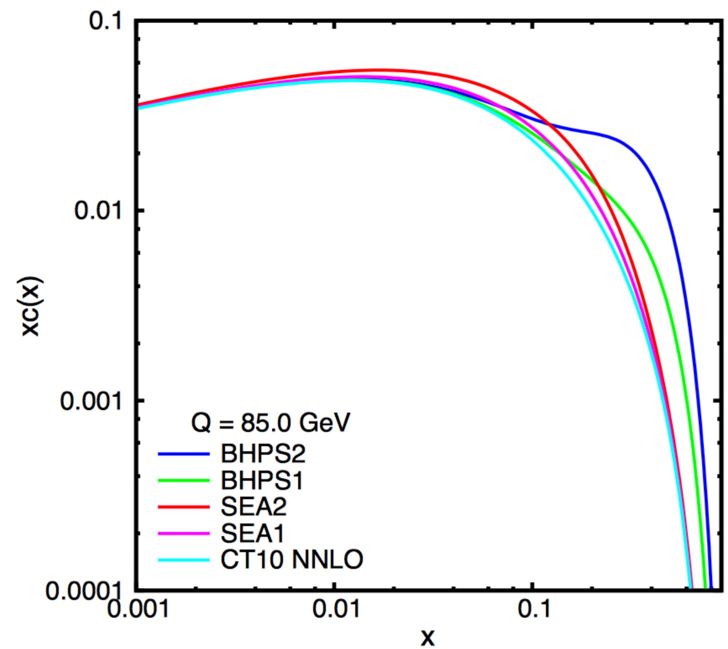
$$c(x, Q_0) = 0 \quad \text{at} \quad \mu = \mathrm{Q}_0 = \mathrm{m_c}$$



2. Intrinsic ``valence like" charm:







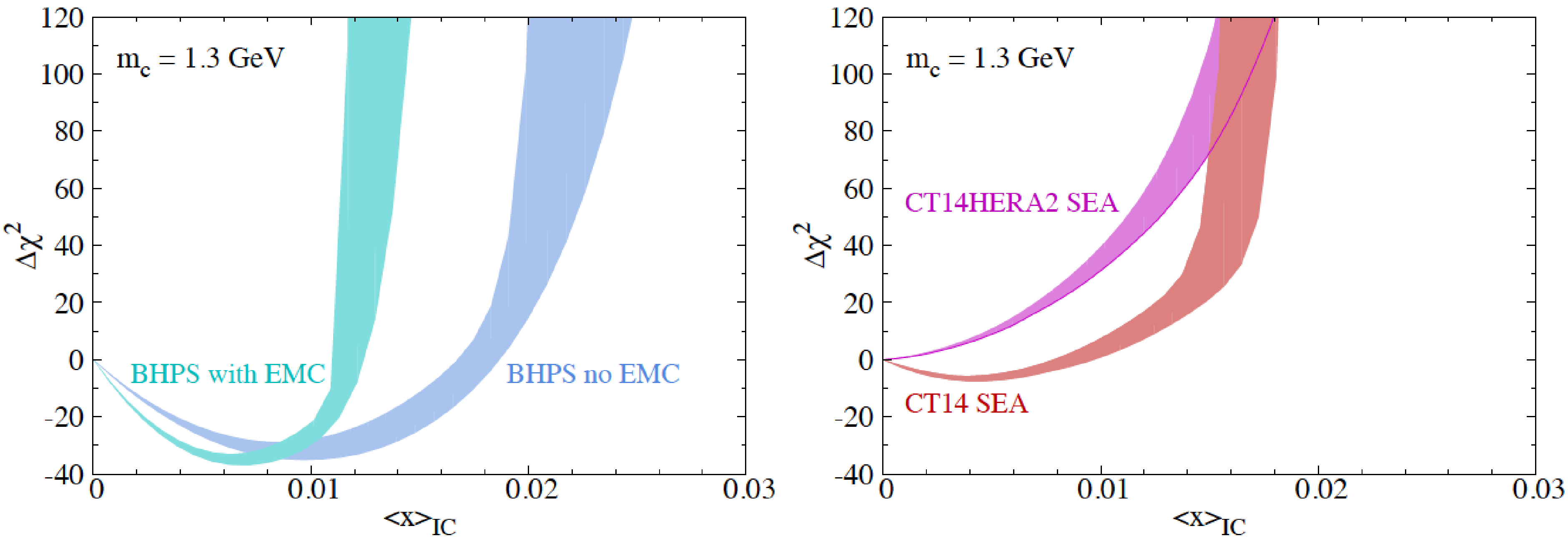
Light cone models BHPS (Brodsky et al 1980) (see also 1504.06287 by Brodsky, Kusina, Lyonnet, Schienbein, Spiesberger, Vogt)

3. ``sea-like" charm:

a purely phenomenological scenario in which the shape of the charm distribution is sea-like—i.e., similar to that of the light flavor sea quarks, except for an overall mass-suppression.

In-depth study of CT14 IC fits (T.-J. Hou)

PRELIMINARY



χ^2 as function of $\langle x\rangle_{IC}$ in fits with and without the EMC data for both the BHPS and SEA models for mc = 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 and CT14HERA2 fits with and without EMC data

PRELIMINARY

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

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.