CTEQ distributions with intrinsic charm

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C T E Q

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Problem

the charm PDF in most of the QCD global analyses of world data is calculated and not fitted, with boundary condition for DGLAP evolution calculated perturbatively (matching condition when switching from nf=3 to nf=4 flavours) c(x,Q=mc) = 0

is this sufficient?

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

What physics effects can lead to a non-zero fitted c(x, Q=mc)?

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

``Fitted charm'' = ``nonperturbative charm''

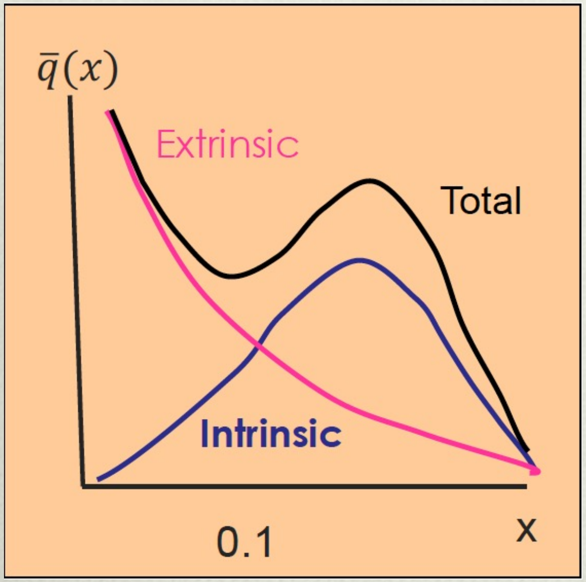
+ other (possibly not universal)

higher O(αs) / Higher power terms

The perturbative charm PDF component cancels near the threshold up to a higher order

The 'fitted charm component' may approximate for a missing higher-order term or a power-suppressed component of a 'sea-like'or 'valence-like' type

Sea-like and valence-like PDFs



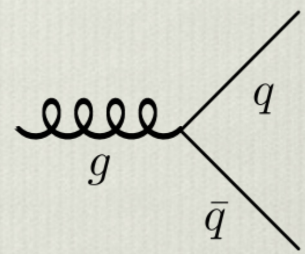
A simple model for a quark PDF at Q0 consists of two components:

1. Sea-like (”extrinsic”) component:

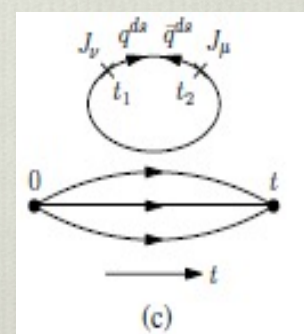
- monotonic in *x*, satisfies

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

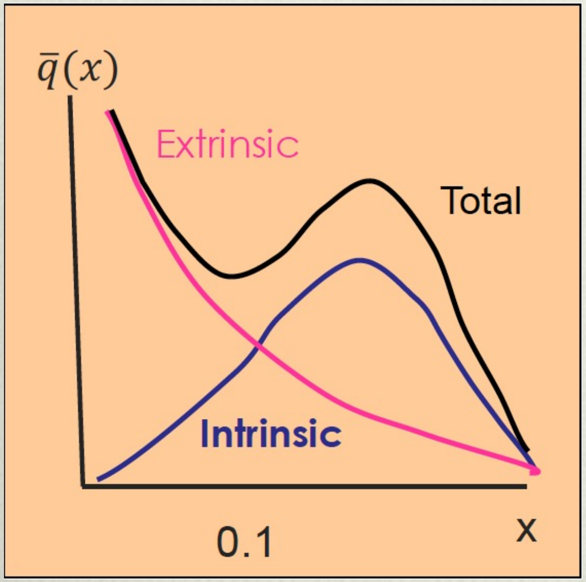
- may be generated in several ways, e.g.,
  - in perturbative QCD from gluon splittings



  - in lattice QCD from disconnected diagrams



Sea-like and valence-like PDFs

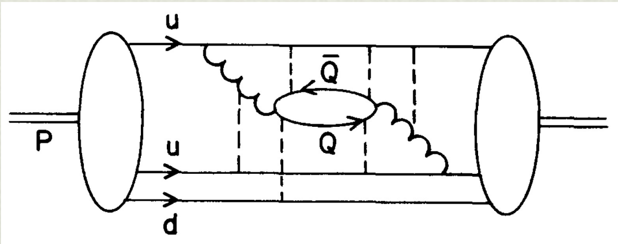


A simple model for a quark PDF at Q0 consits of two components:

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

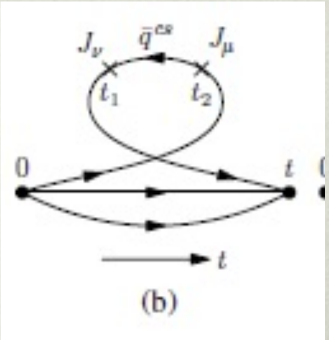
$$q(x) \propto x^{-1/2} \quad x \to 0$$

- may be generated in several ways, e.g.,
  - for all flavors, nonperturbatively from a uudQQbar Fock state:



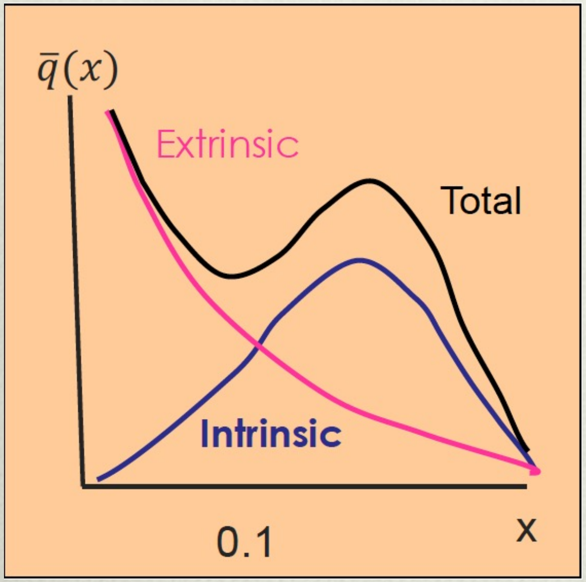
Brodsky, Peterson, Sakai, PRD 1981

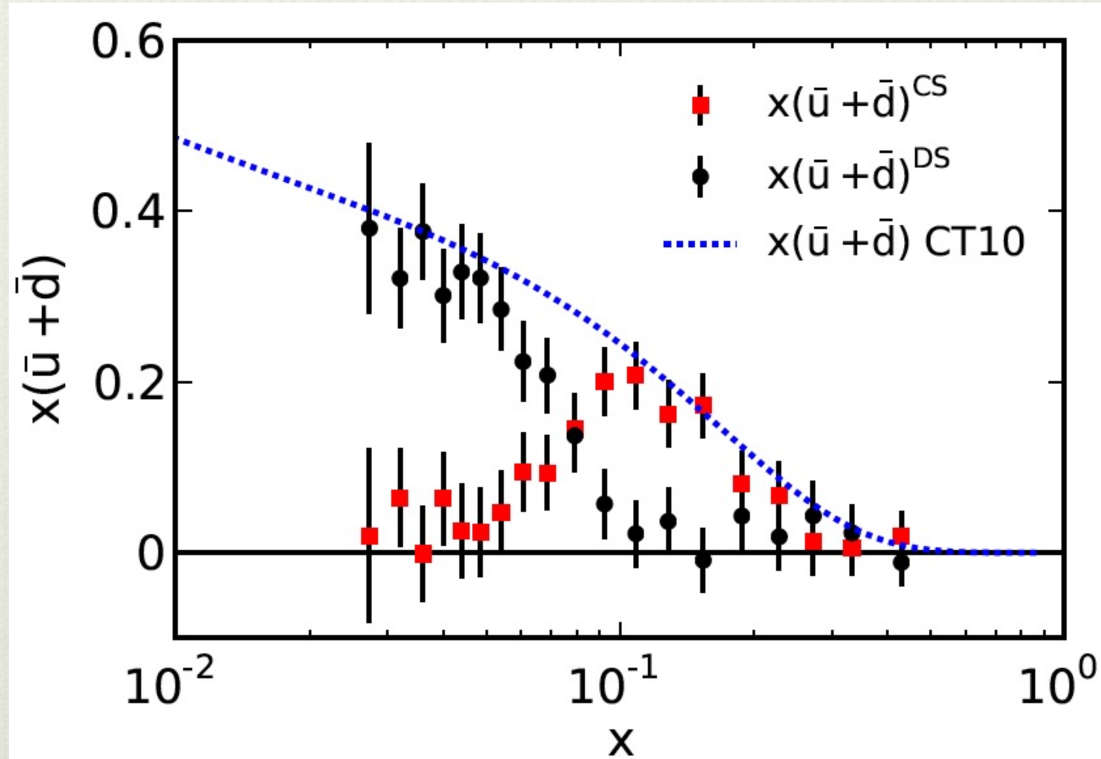
- for ubar and dbar, in lattice QCD from connected diagrams



ubar and dbar PDFs, deconstruction

Smooth ubar+dbar parametrizations can hide existence of two components





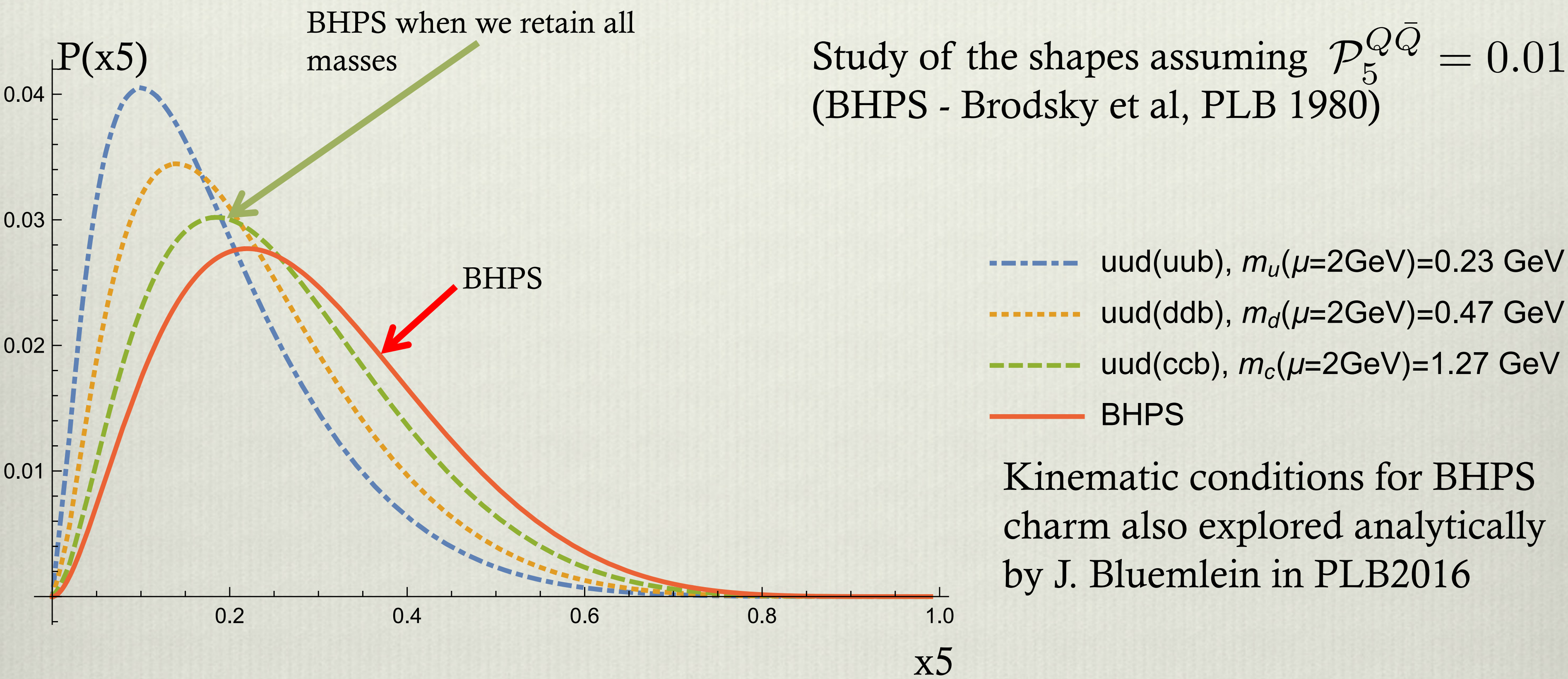
$$x(\bar{u}+\bar{d})^{CS}$$

$$x(\bar{u}+\bar{d})^{DS}$$

CS (connected Sea) and DS (Disconnected Sea) are related to intrinsic and extrinsic components respectively according to the short-distance expansion of the hadronic tensor in lattice QCD.

Liu, Chang, Cheng, Peng, PRL(2012) 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

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

``Fitted charm'' = ``intrinsic charm''

+ other (possibly not universal)

higher O(αs) / Higher power terms

We don't have an agreed definition/framework to factorize intrinsic charm contributions.

DIS HQ factorization by Collins PRD(1998) was proved only for radiative charm

IC is a correction that scales like $\frac{\Lambda^2_{QCD}}{m_c^2} \ln\left(\frac{Q^2}{\mu^2}\right)$

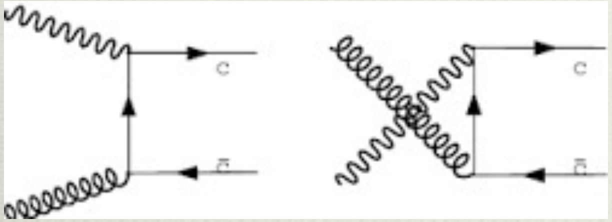
There is no consensus on how to factorize these contributions in DIS

But assuming that factorization exists for IC we can perform phenomenological studies to estimate the impact of IC on the CT global analysis of PDFs at NNLO.

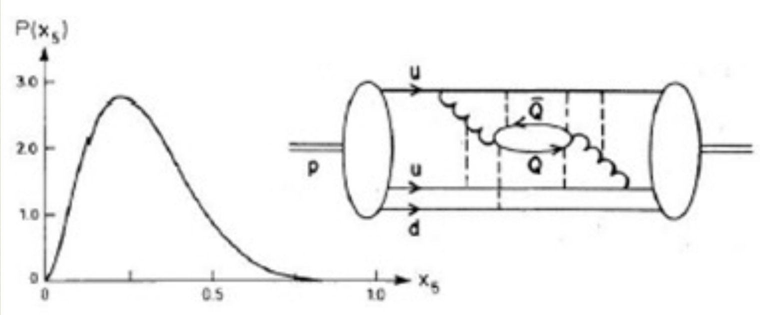
Three types of charm content in the proton

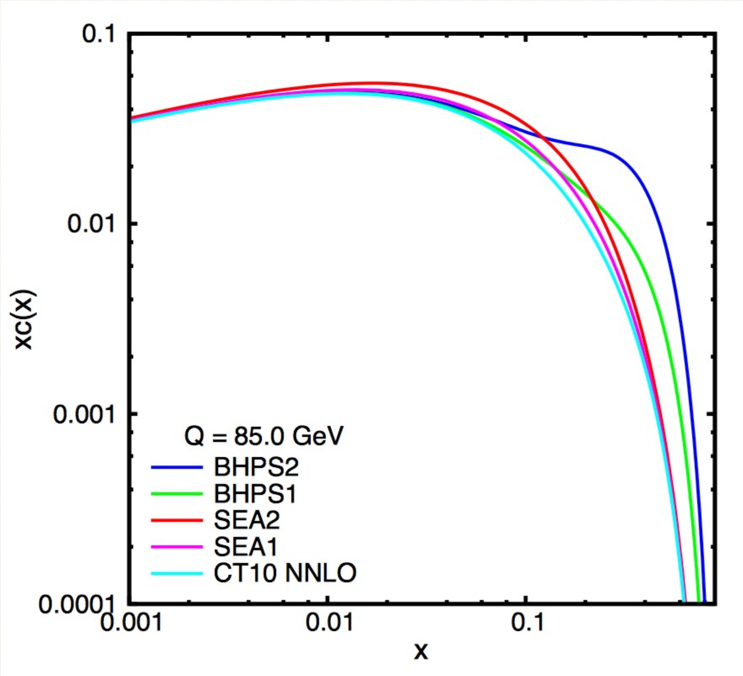
1. Perturbative charm CT analyses:

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



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.

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 uubar, ddbar and ccbar with numeric solutions for the BHPS model.

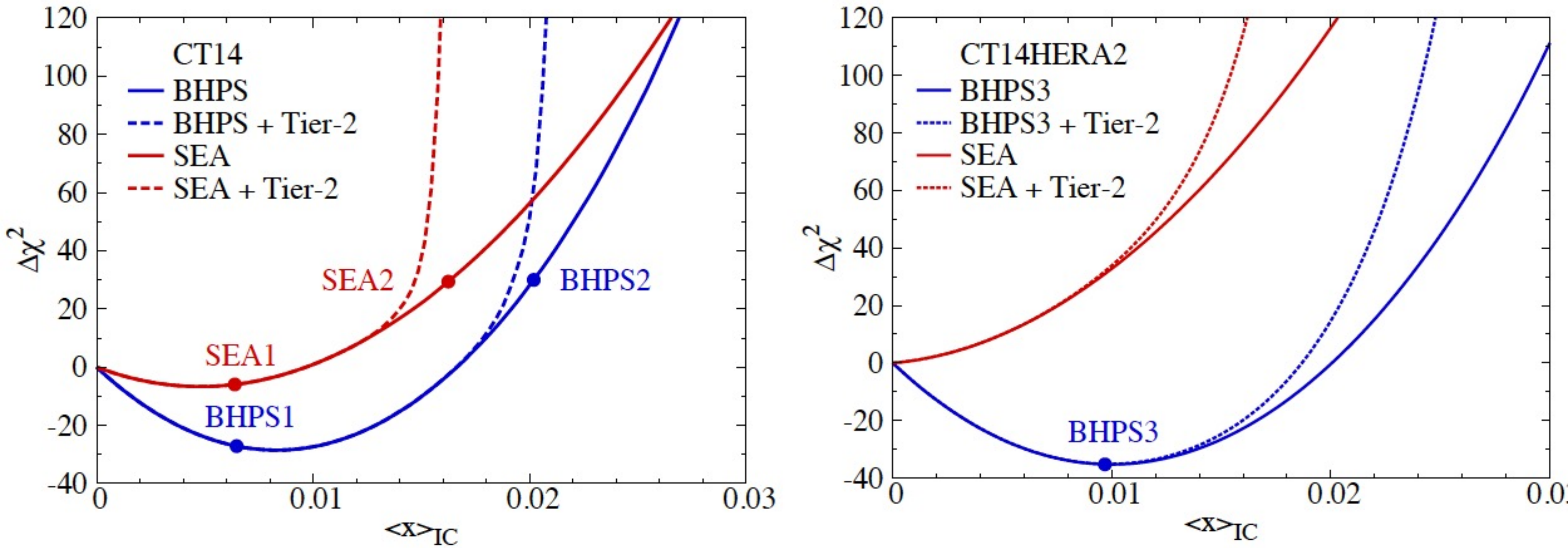
- ``Sea-like'' charm quark distribution, similar to that of the light flavor sea quarks:

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

❖ We characterize the magnitude of IC by the momentum fraction carried by **charm at starting scale Q0=1.3 GeV**:

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

Best fit for different IC choices



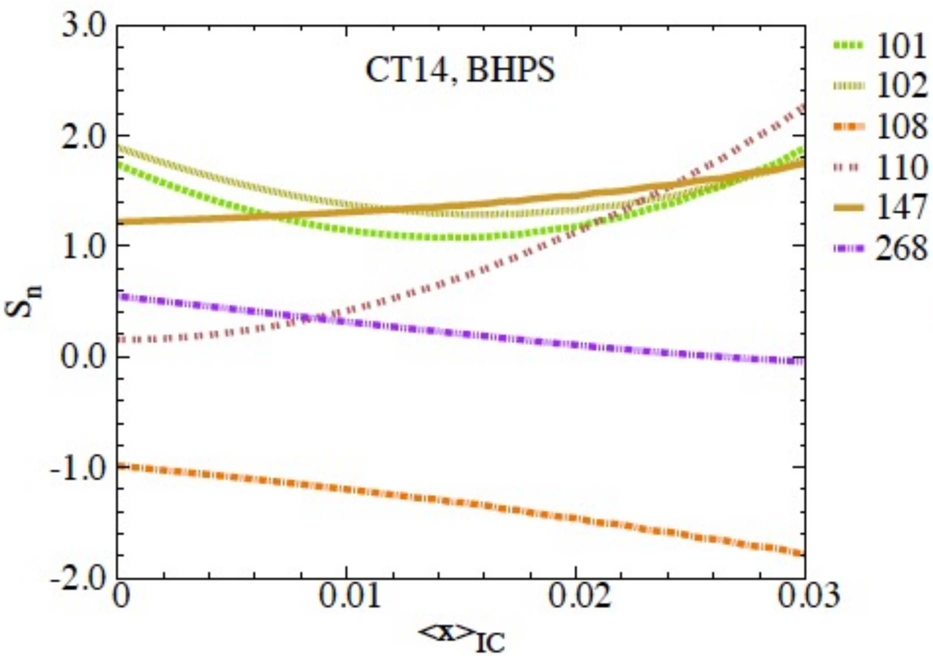
The dotted curves show $\Delta\chi^2 + T_2$ versus $\langle x \rangle_{\rm IC}$ for the two models of IC.

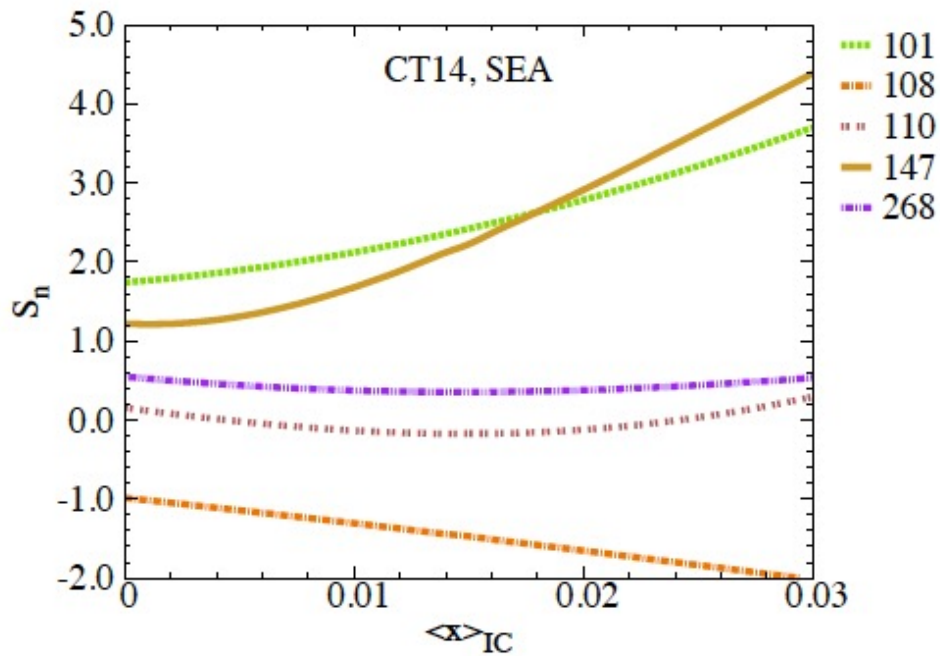
New upper limits on <x>IC for CT14 and CT14HERA2 at the 90% C.L.

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

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

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





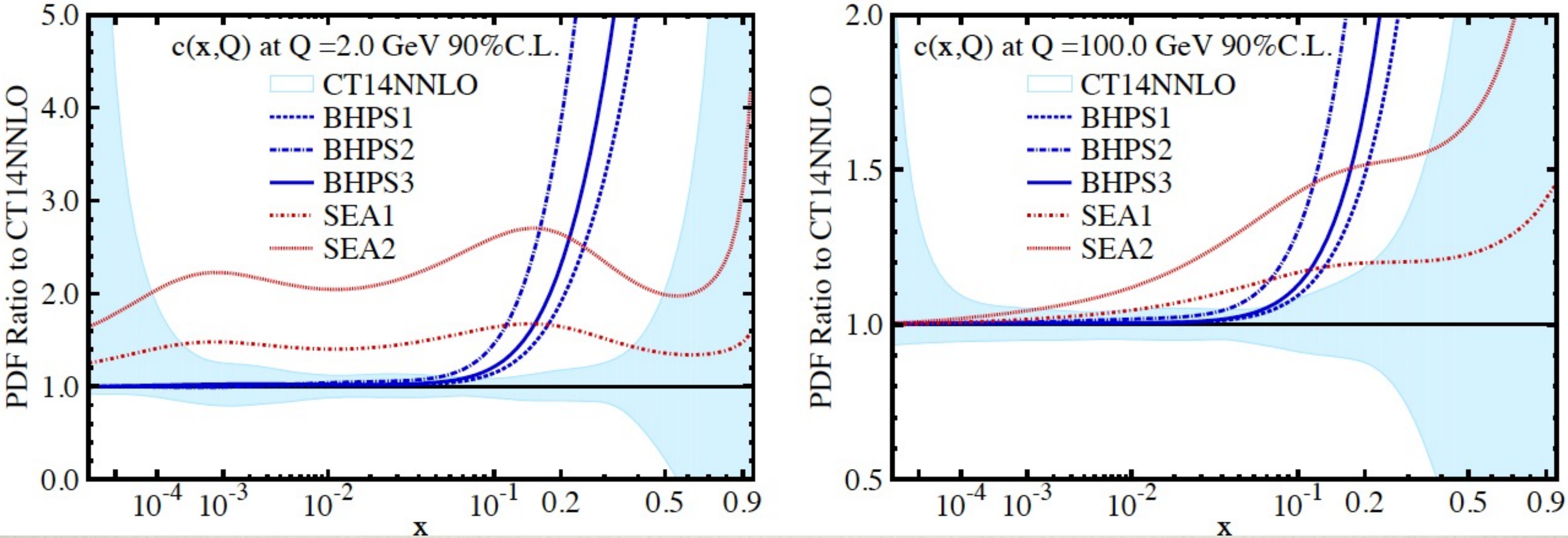
The CCFR structure function data (ID 110) is most sensitive to the BHPS model. And thus the upper limit on the $\langle x \rangle_{\rm IC}$ value for BHPS model comes from the CCFR structure function data.

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 $\langle x \rangle_{\rm IC}$ for the SEA model.

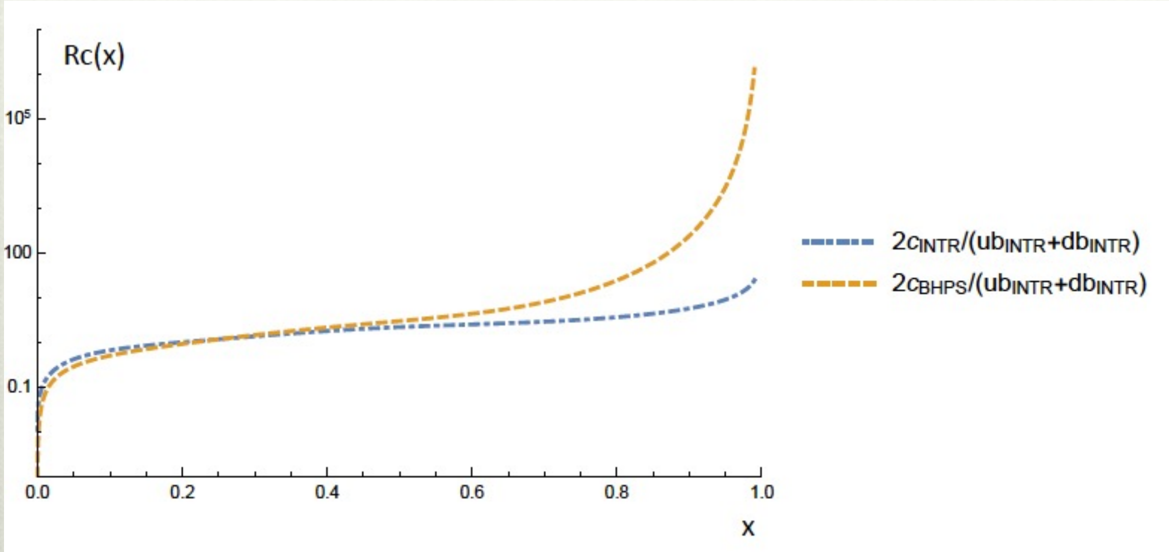
Insights from FPF and EIC

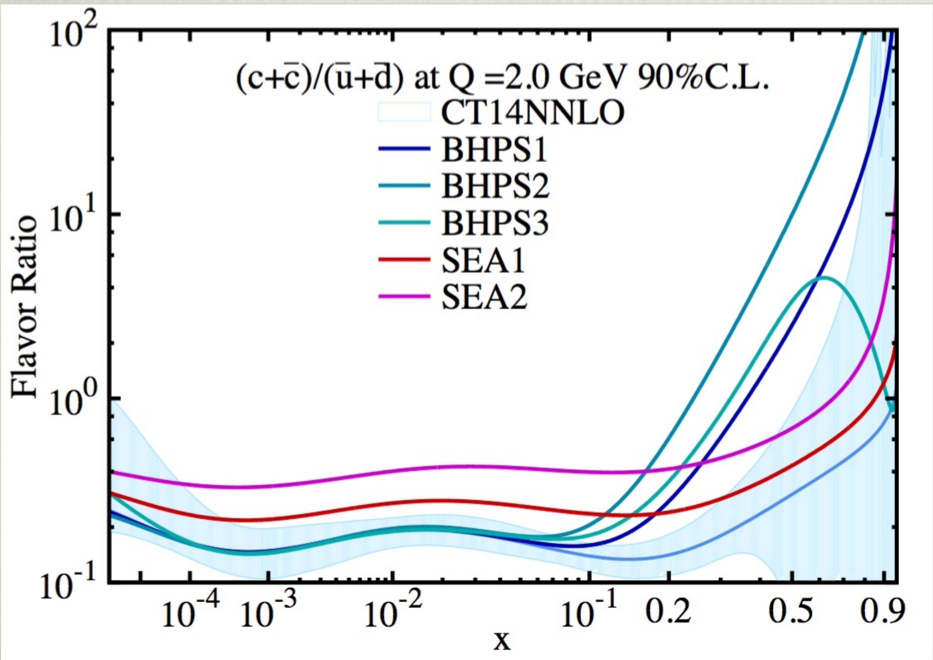
- The FPF detector will use a tungsten fixed target.
- Knowledge of nuclear PDFs is necessary. The detection is like the NuTeV experiment at higher neutrino energies.
- The preliminary studies by the UC Irvine indicate that the inclusive CC DIS cross sections in FPF are described well by nuclear PDFs (just like inclusive CC DIS at NuTeV).
- On other hand, the dimuon CC SIDIS at FPF will be sensitive to strangeness and potentially IC PDFs for tungsten.
- EIC will allow us to get orders-of-magnitude more events to probe IC models: it can replace most of fixed-target and nuclear-target measurements constraining proton PDFs at large x. It will systematically study PDFs for heavy nuclei

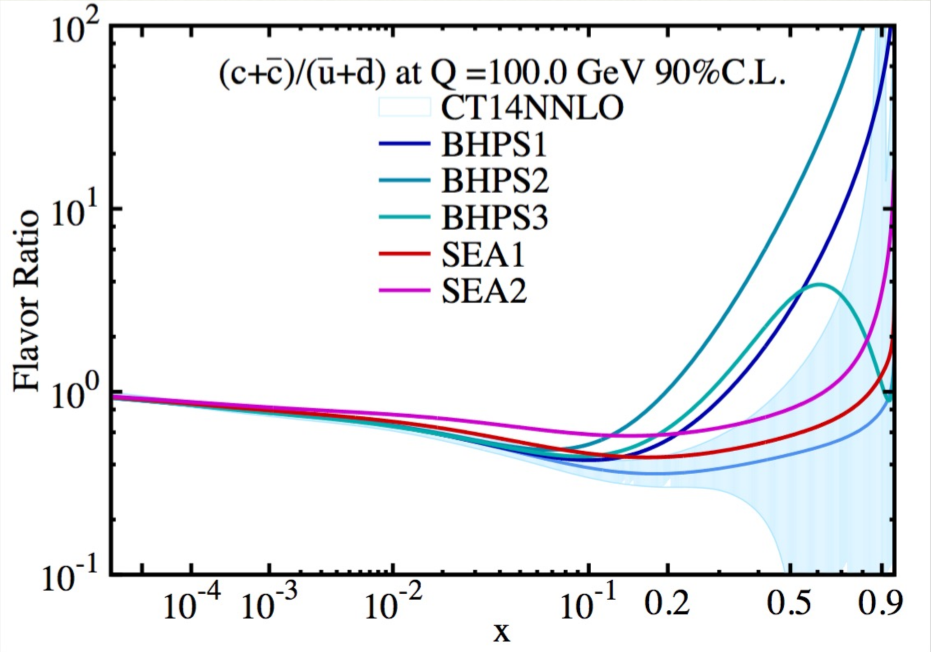
Impact of IC on the PDFs and their ratios



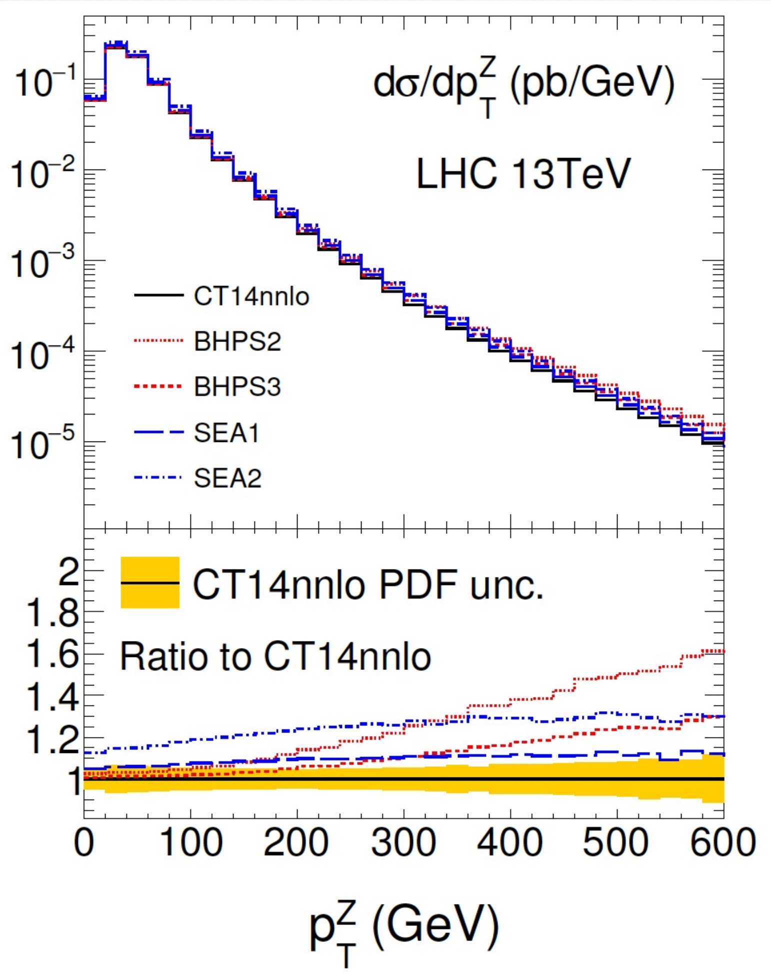
Study of Rc =(c+cbar)/(ubar+dbar) suppression ratio

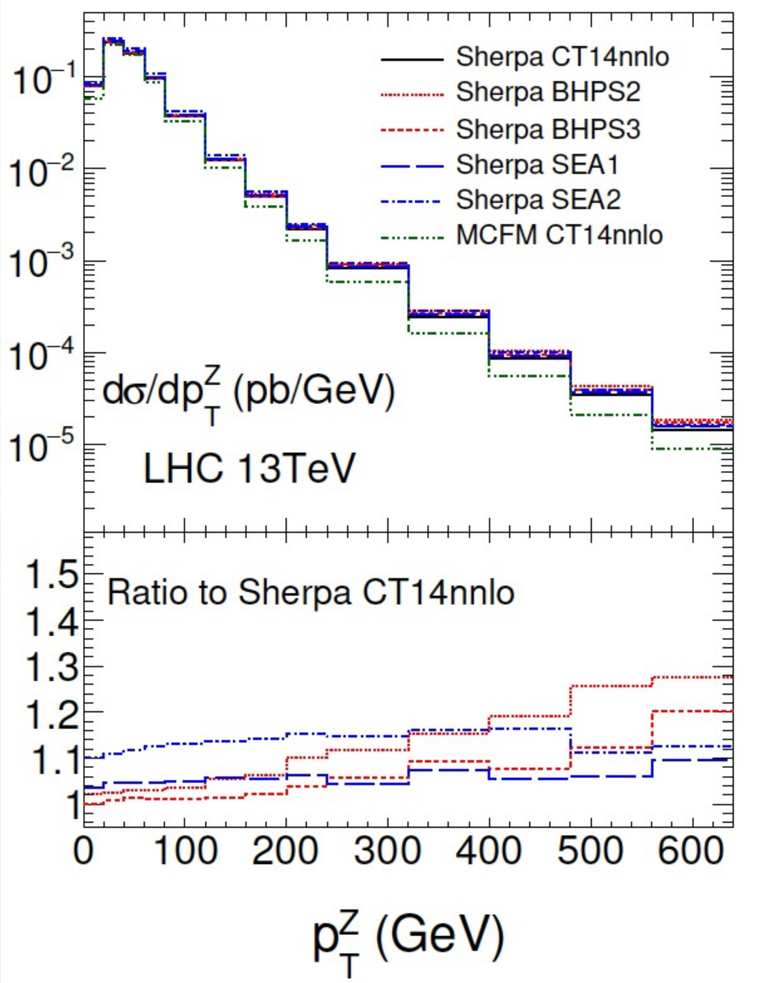






Z+c NLO LHC 13 TeV





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 explored the possibility of sizeable 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: <x> < 2% for BHPS IC and <x> <1.6% for SEA IC at 90% C.L..

- We analyzed implication of IC in charm-sensitive processes at the LHC with parton shower: most significant effect in dampening the hard pT(Z) tail especially for BHPS fits.

- **Experimental confirmation still missing:** data from more sensitive measurements required; high energy and high luminosity fixed-target experiment needed. Constraining power of current data still not sufficient.

- Forward Physics Facilities will play a crucial role in the discrimination/validation of IC models, and we will rely on new high-precision measurements from these future facilities

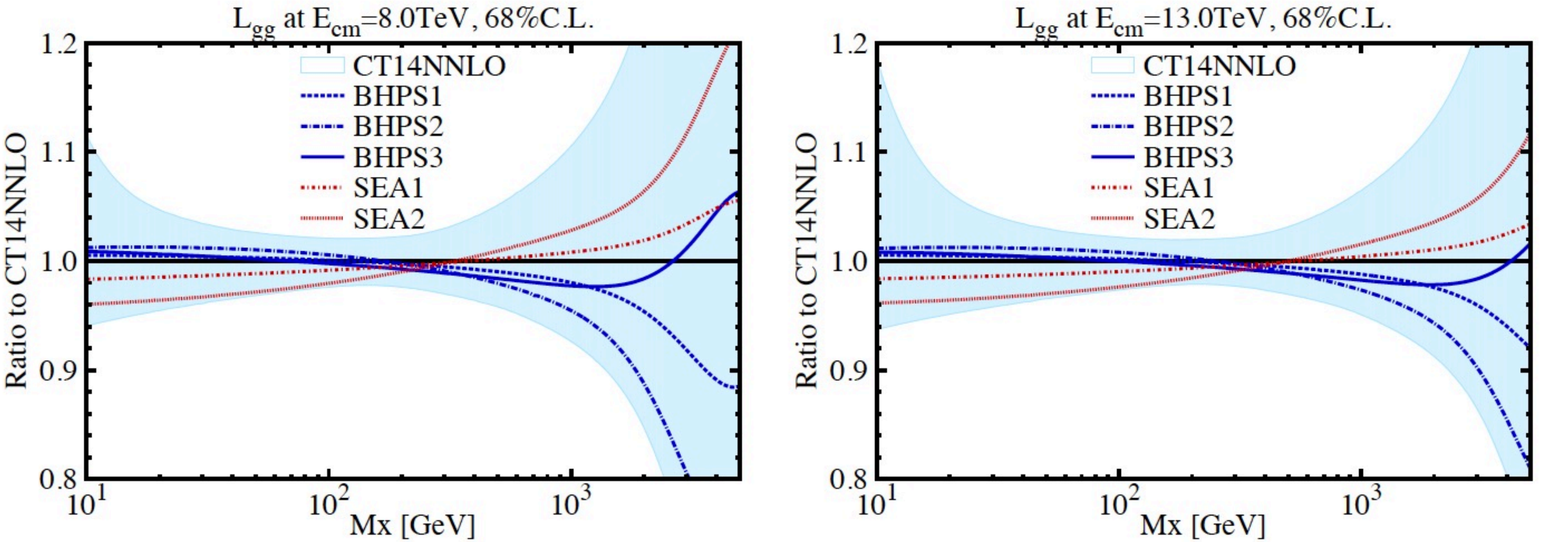
BACKUP

SET UP FOR THE GLOBAL CTEQ ANALYSIS:
We mainly focus on the CT14/CT14HERA2 analysis, CT18 in progress.

For all three models:

- $\alpha_s(M_Z) = 0.118$, compatible with the world average value $\alpha_s(M_Z) = 0.1184 \pm 0.0007$, and the standard 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-χNNLO --- CT GMVFN default scheme for heavy-flavour treatment in the inclusive DIS structure functions.
  Differences between ACOT-χ 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 CT analyses.
- The charm-quark mass, $m_c = 1.3$ GeV, is in the pole mass scheme unless otherwise specified.

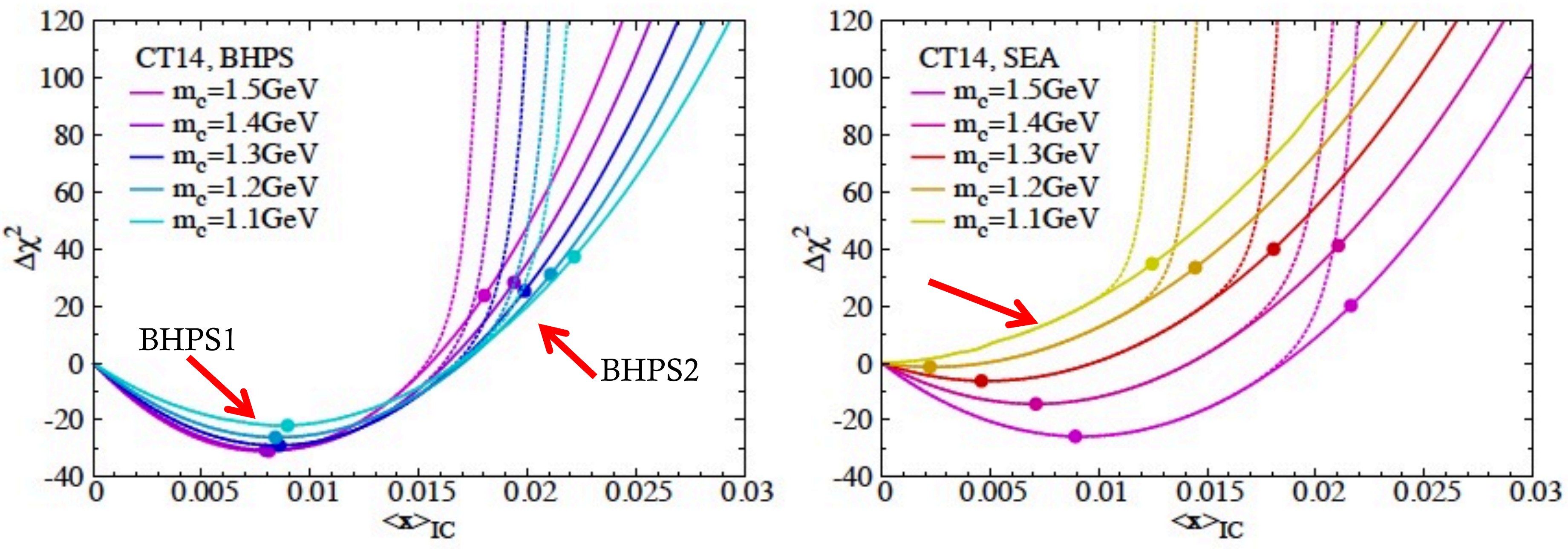
Impact of IC on luminosities



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 MX in the TeV range.
The BHPS models are almost coincident with CT14 for MX < 200 GeV: BHPS1 and BHPS2 are highly 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

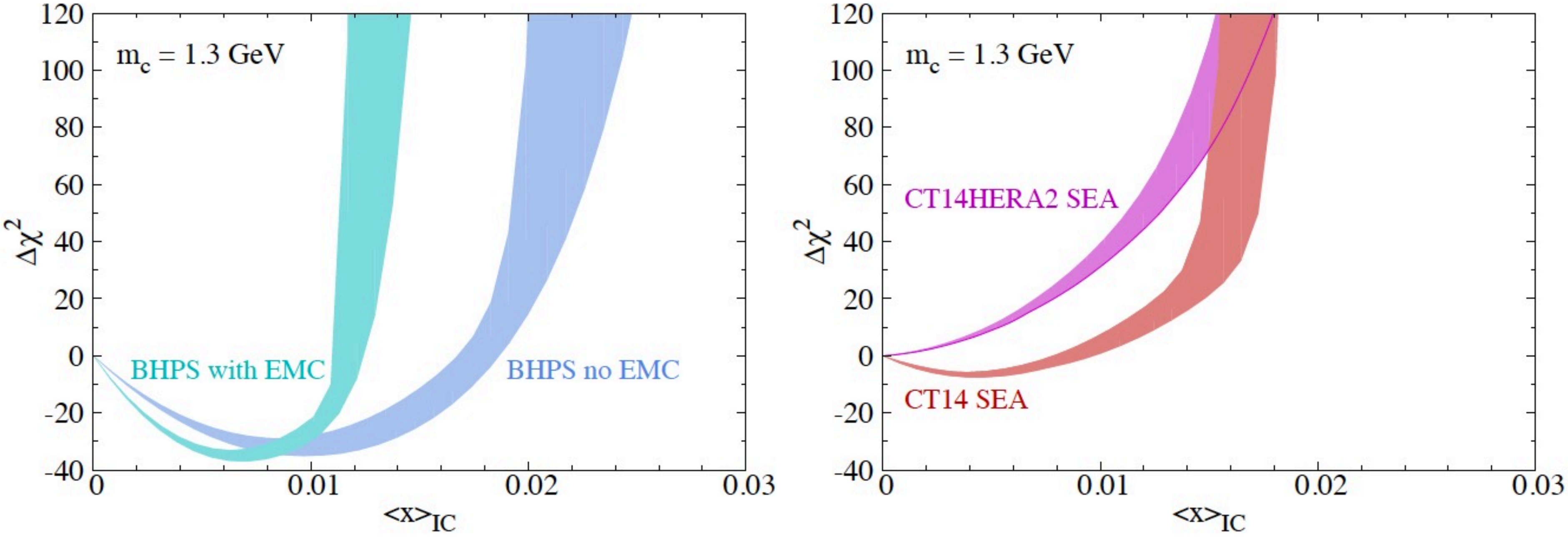
The combined HERA charm production and inclusive DIS data play an important role in the description of the goodness of fit. mc is a key input scale.



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

In-depth study of CT14 IC fits



χ^2 as function of $\langle x \rangle_{\rm IC}$ 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.

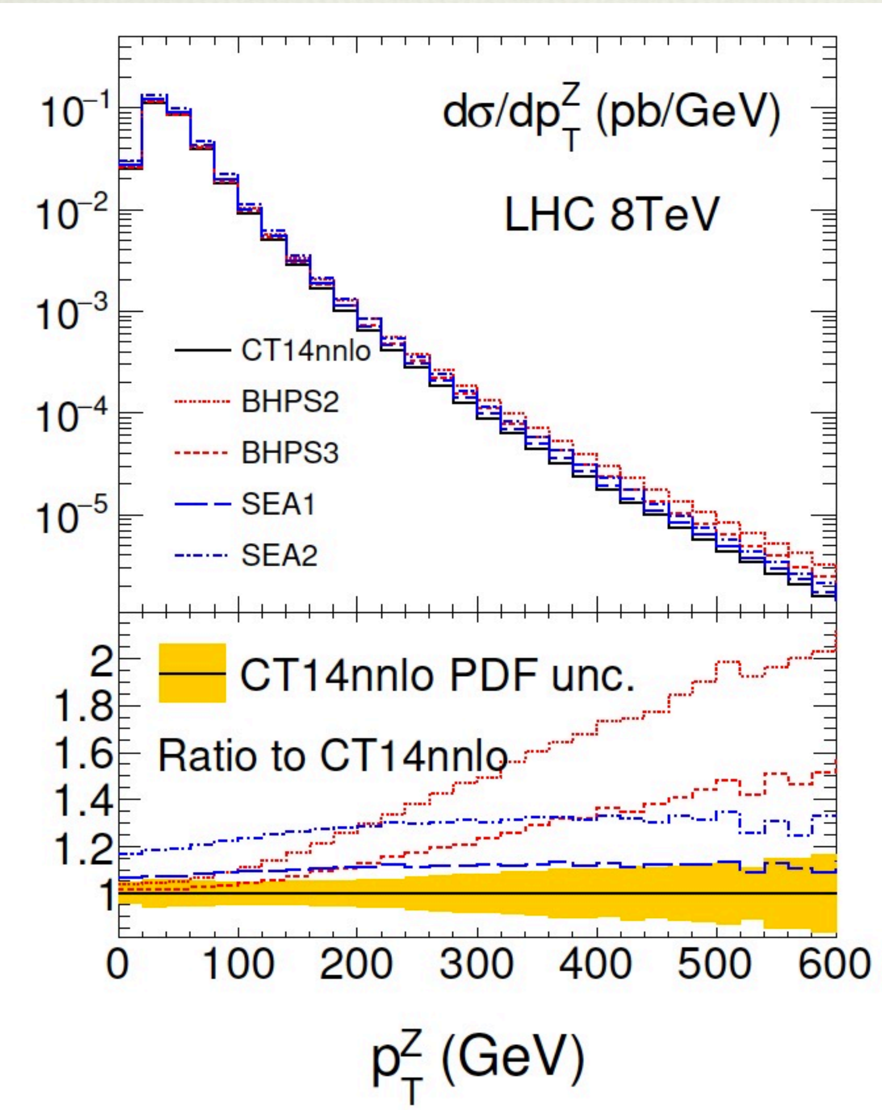
χ^2 values for CT14 and CT14HERA2 fits with and without EMC data

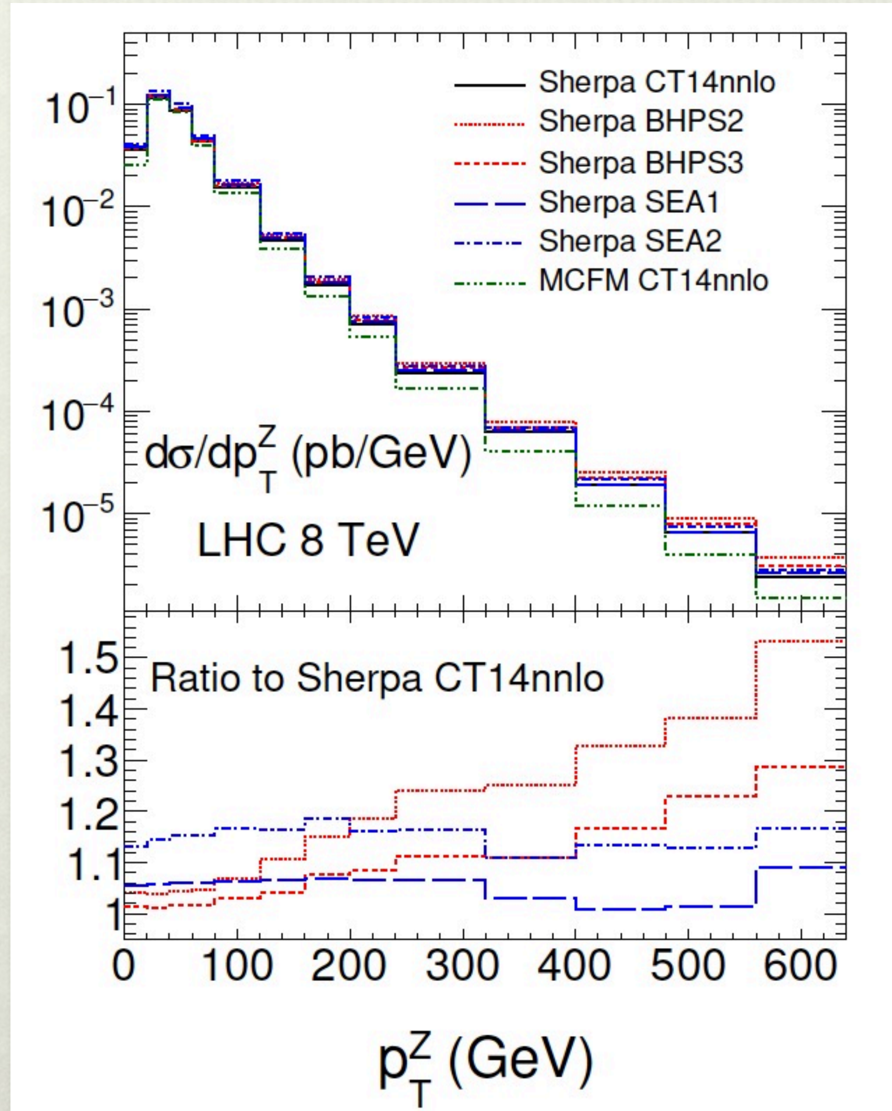
Candidate NNLO PDF fits	χ^2/N_{pts}		
	All Experiments	HERA inc. DIS	HERA $c\bar{c}$ SIDIS
CT14 + EMC (weight=0), no IC	1.10	1.02	1.26
CT14 + EMC (weight=10), no IC	1.14	1.06	1.18
CT14 + EMC BHPS	1.11	1.02	1.25
CT14 + EMC SEA	1.12	1.02	1.28
CT14 HERA2 + EMC (weight=0), no IC	1.09	1.25	1.22
CT14 HERA2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

LHC searches for intrinsic charm

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





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 sensitive to charm at hadron colliders**

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

- ❖ **charmed particle production at the LHC and future facilities, 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 to nucleon orbital angular momenta.