CT14 Intrinsic Charm Parton Distribution Functions from CTEQ-TEA Global Analysis

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On behalf of the CTEQ-TEA collaboration

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CTEQ-TEA collaboration

CTEQ (Coordinate Theoretical-Experimental Project on QCD)

- **CTEQ – Tung et al. (TEA)**

  in memory of Prof. Wu-Ki Tung,
  who established **CTEQ** Collaboration in early 90's

- **Current members:**

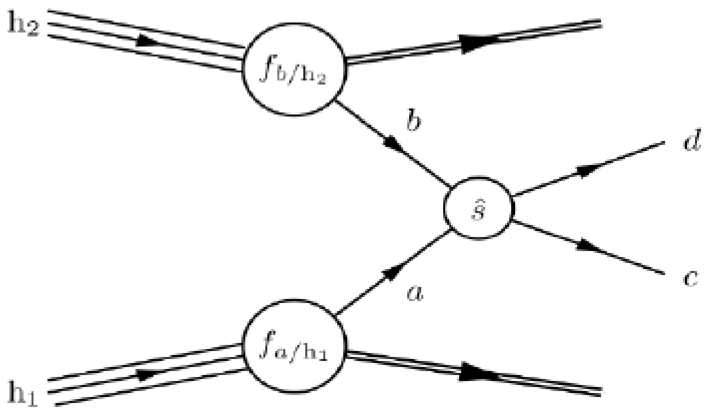
  Sayipjamal Dulat (Xinjiang University),
  Tie-Jiun Hou, Keping Xie, Pavel Nadolsky (Southern Methodist Univ.),
  Jun Gao (Shanghai Jiaotong Univ.),
  Marco Guzzi (Univ. of Manchester),
  Joey Huston, Jon Pumplin, Daniel Stump, Carl Schmidt, Jan Winter,
  and C.- P.Yuan (Michigan State Univ.)

Parton distribution functions(PDFs)

Cross section for some hard process in hadron-hadron collisions:

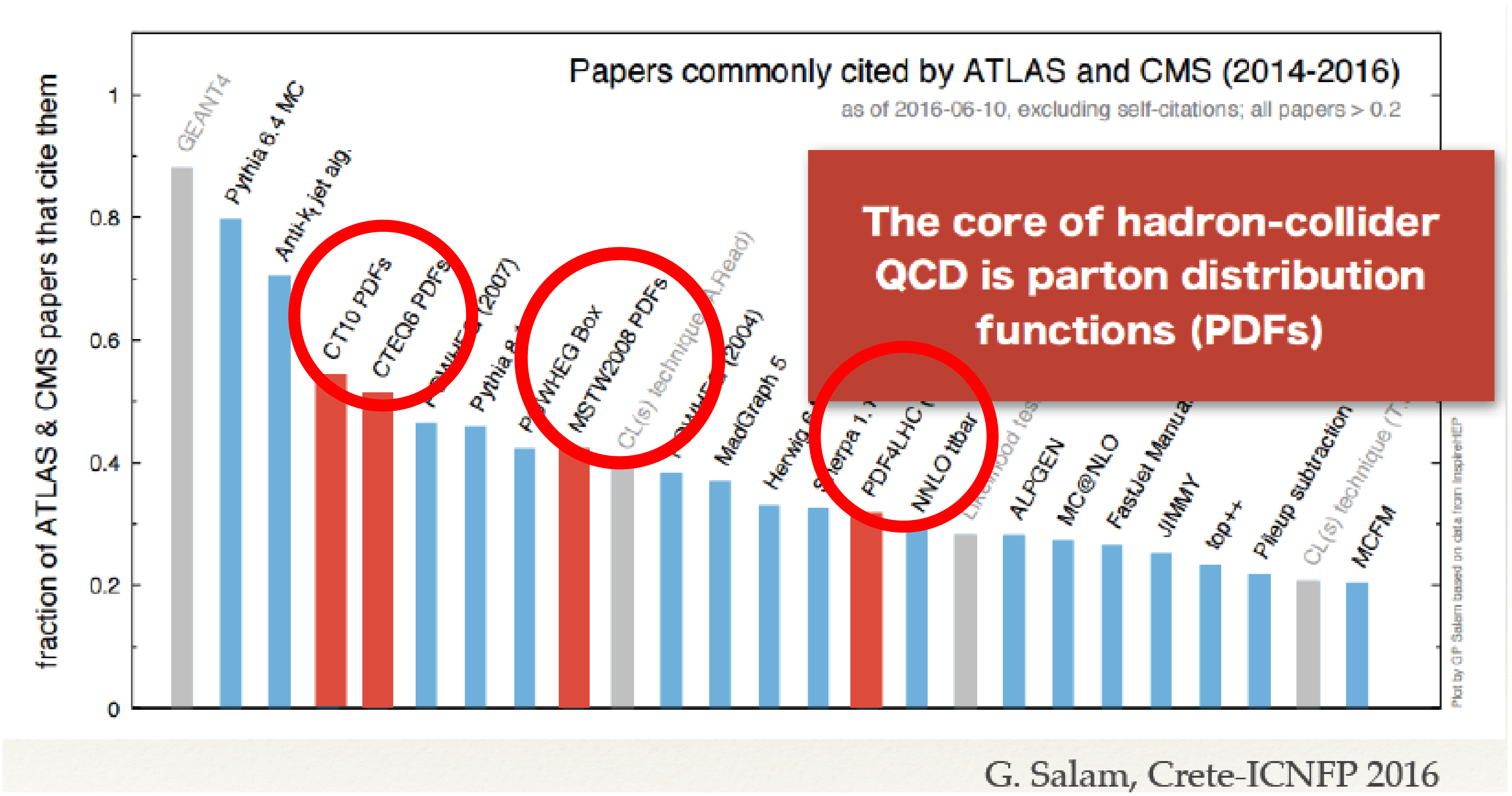
$$d\sigma^{h_1 h_2 \to cd} = \int_0^1 dx_1 \int_0^1 dx_2 \sum_{a,b} f_{a/h_1}(x_1, \mu_F^2) f_{b/h_2}(x_2, \mu_F^2) d\hat{\sigma}^{ab\to cd}(Q^2, \mu_F^2)$$

- $f_{a/hi}(x_i)$: parton distribution function: probability of finding a parton of type a with momentum fraction x_i in the hadron h_i
  - process-independent but not calculable in perturbation theory
  - needs to be determined from data
  - contains all unresolved emission below factorization scale μ_F
- $\sigma^{ab\to cd}$: parton-level hard scattering cross section
  - calculable in perturbative QCD as series expansion in α_s
  - contains only hard emissions above factorization scale μ_F



Calculation of cross section at the LHC relies on PDFs.

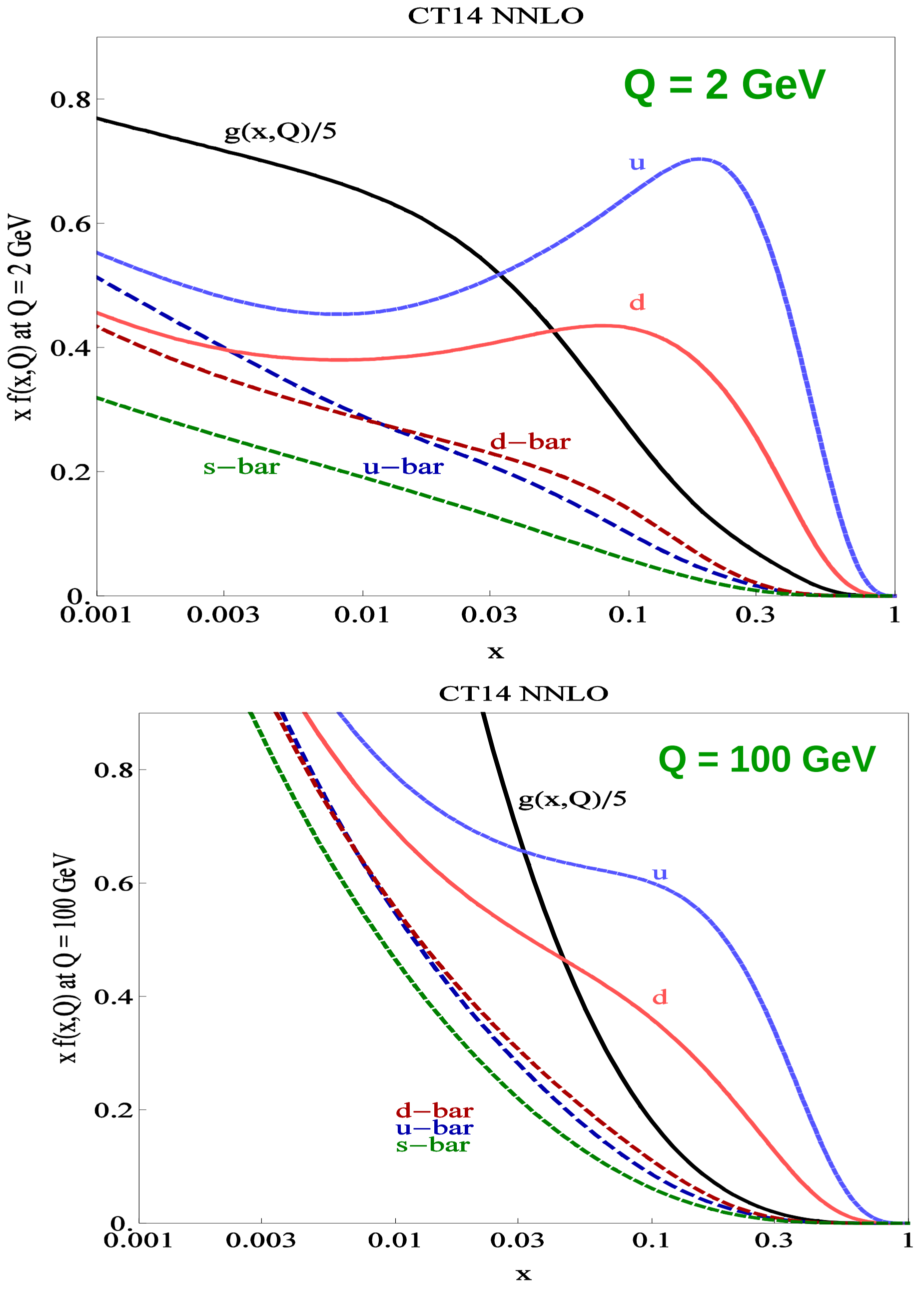
PDFs are important



How can one determine the PDFs?

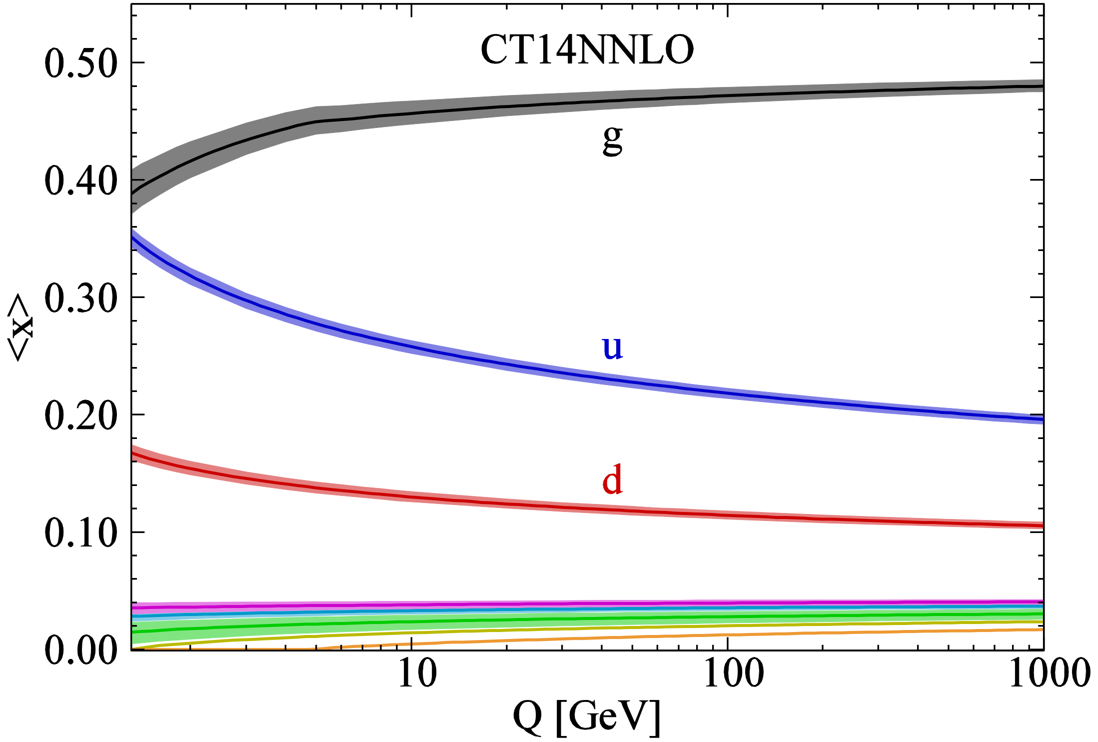
- PDFs are determined by global QCD analyses of data from DIS, DY and jet production…now adding additional LHC processes such as ttbar production, W/Z/photon +charm, etc.

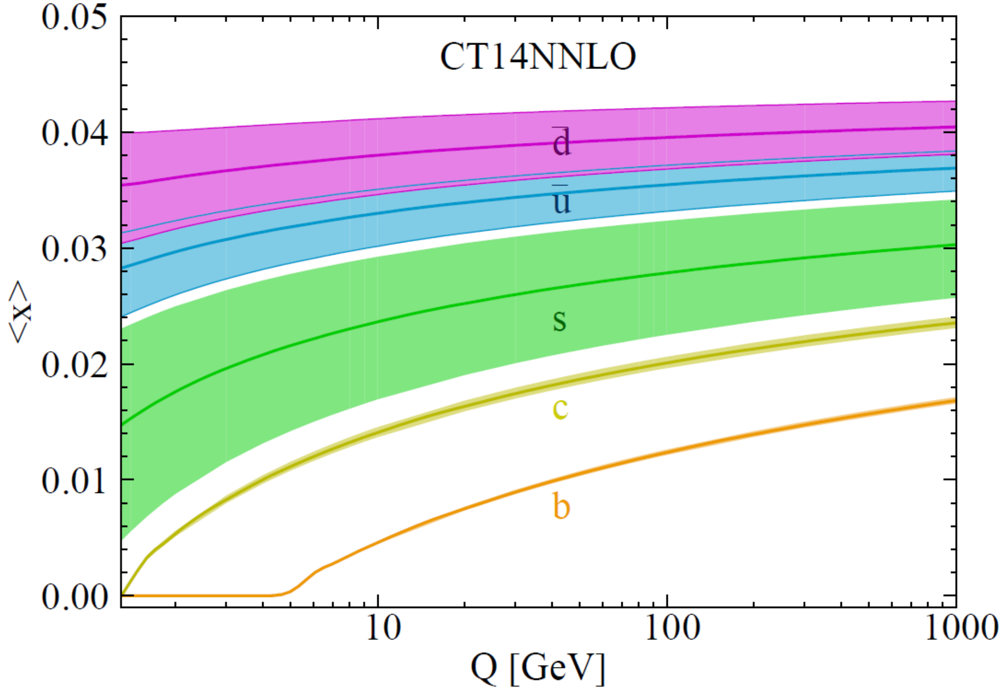
- PDF fitting groups come out with new PDF sets as new data/technology warrants, at LO, NLO and NNLO:
  - *ABM12*
  - *CT14 – our group*
  - *HERAPDF2.0*
  - *MMHT2014*
  - *NNPDF3.0*



Figs. show an overview of the CT14 PDFs for Q = 2 and 100 GeV.

Momentum carried by partons





The PDFs for u, d, s (anti) quarks and the gluon are parametrized at an initial scale.
PDFs for heavy (charm, bottom and top) quarks are generated perturbatively through gluon radiation. So normally no heavy quarks at an initial scale.

CT14 NNLO PDFs with IC

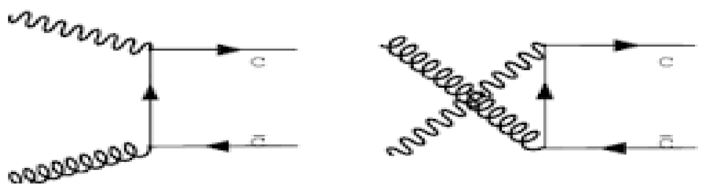
Explore stability of CT14 IC PDFs released in PoS DIS2015 (2015) 166.
The ongoing study examines:

- effect of legacy HERA data (minor)
- dependence on initial scale Q_0, charm mass M_c,
- parametrization form dependence (moderate)
- effect of including 1983 EMC charm structure function F_2^c data (minor, questions about EMC F_2^c data systematic effects)
- two best-fit IC parametrizations: **CT14 BHPS1, SEA1**
- two extreme IC parametrizations: **CT14 BHPS2, SEA2**

Three types of charm distributions

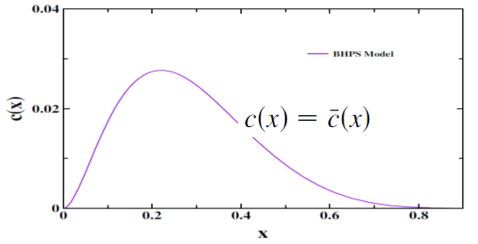
1. **CT14 Perturbative** charm:

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

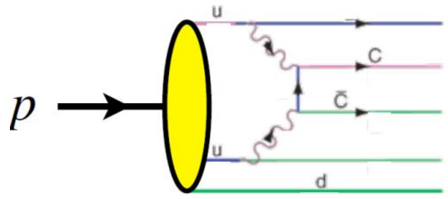


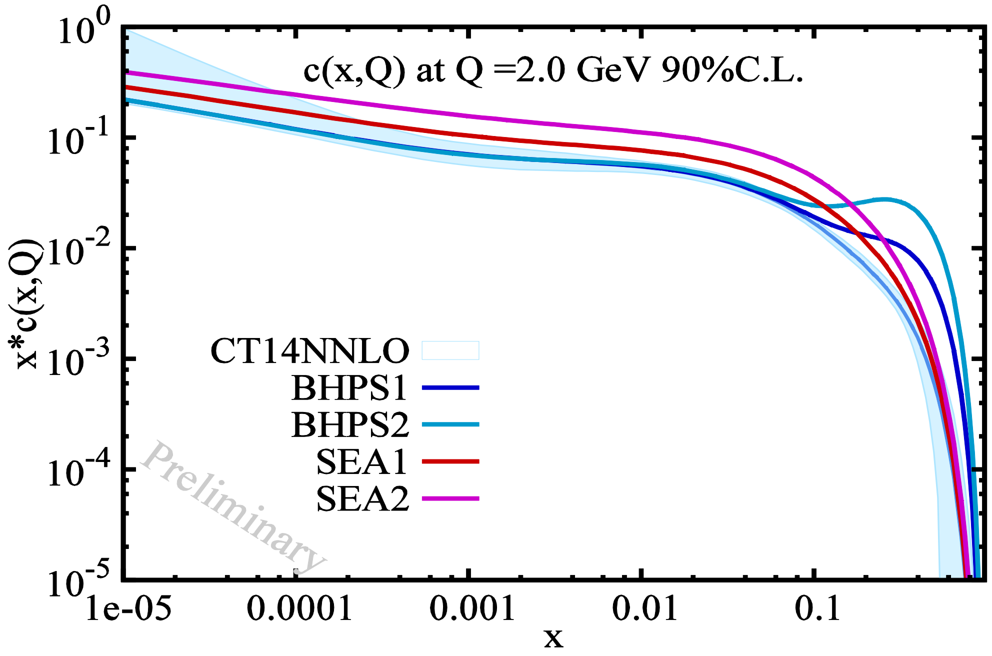
2. **BHPS: Intrinsic** valence-like charm(large-x)

(Brodsky, Hoyer, Peterson, Sakai, **PLB93 (1980) 451**)



The x-dependency of the intrinsic charm distribution $c(x)$ in the five-quark state $|uudc\bar{c}\rangle$ from the BHPS model.





Charm quark distribution from the BHPS1 and BHPS2 (which have 0.6% and 2%); From SEA1 and SEA2 (0.6% and 1.6%) ; the central value and uncertainty from CT14 which have no IC.

3. **SEA**: sea-like (small-x)

If IC component is present at a low energy Q_0, it will evolve along with the other partons and lead to observable consequences at high Q.

Parametrizations for BHPS and SEA models

- **According to the BHPS model the probability distribution of the IC within the proton at the starting scale as a function of x has the following form:**

$$c(x) = \bar{c}(x) = A\,x^2\,\left[6\,x\,(1+x)\,\ln x\; +\; (1-x)(1+10x+x^2)\right]$$

- **We also examine a purely phenomenological model in which the shape of the charm distribution is SEA-like --- i.e. the x-dependence similar to that of the light flavor sea quarks:**

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

Here A is the normalization constant, that controls the magnitude of IC， and it is treated as variable parameter.

- **We characterize the magnitude of IC by the mean momentum fraction carried by charm at starting scale:**

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

CT14 IC fit set up

For the **CT14 IC,** we use the same **experimental input data sets and theoretical framework** as the **CT14 analysis**.

Data Sets for CT14

- **Based on CT10 data sets, we include some new data sets in CT14 :**
- **HERA longitudinal structure function F_L;**
- **HERA charm production cross sections;**
- **TEVATRON data:**
- **Tevetron Run 1 CDF and D0 inclusive jet data are dropped;**
- **old D0 data (0.75 1/fb) replaced by the new D0 (9.7 1/fb) W-electron rapidity asymmetry data.**
- **LHC 7 TeV Run 1 data :**
- **ATLAS and LHCb W/Z production;**
- **ATLAS, CMS and LHCb W-lepton charge asymmetry;**
- **ATLAS and CMS inclusive jet data.**

The experimental data sets that are included in the CT14 global analysis are:

ID#	Experimental data set	N_{pt}	χ_e^2	χ_e^2/N_{pt}	S_n
101	BCDMS F_2^p	337	384	1.14	1.74
102	BCDMS F_2^d	250	294	1.18	1.89
104	NMC F_2^d/F_2^p	123	133	1.08	0.68
106	NMC σ_{red}^p	201	372	1.85	6.89
108	CDHSW F_2^p	85	72	0.85	-0.99
109	CDHSW F_3^p	96	80	0.83	-1.18
110	CCFR F_2^p	69	70	1.02	0.15
111	CCFR xF_3^p	86	31	0.36	-5.73
124	NuTeV $\nu\mu\mu$ SIDIS	38	24	0.62	-1.83
125	NuTeV $\bar{\nu}\mu\mu$ SIDIS	33	39	1.18	0.78
126	CCFR $\nu\mu\mu$ SIDIS	40	29	0.72	-1.32
127	CCFR $\bar{\nu}\mu\mu$ SIDIS	38	20	0.53	-2.46
145	H1 σ_r^b	10	6.8	0.68	-0.67
147	Combined HERA charm production	47	59	1.26	1.22
159	HERA1 Combined NC and CC DIS	579	591	1.02	0.37
169	H1 F_L	9	17	1.92	1.7

Very important for PDF determination

The experimental data sets that are included in the CT14 global analysis are:

ID#	Experimental data set	N_{pt}	χ^2_e	χ^2_e/N_{pt}	S_n
201	E605 Drell-Yan process	119	116	0.98	-0.15
203	E866 Drell-Yan process, $\sigma_{pd}/(2\sigma_{pp})$	15	13	0.87	-0.25
204	E866 Drell-Yan process, $Q^3 d^2\sigma_{pp}/(dQdx_F)$	184	252	1.37	3.19
225	CDF Run-1 electron A_{ch}, $p_{T\ell} > 25$ GeV	11	8.9	0.81	-0.32
227	CDF Run-2 electron A_{ch}, $p_{T\ell} > 25$ GeV	11	14	1.24	0.67
234	DØ Run-2 muon A_{ch}, $p_{T\ell} > 20$ GeV	9	8.3	0.92	-0.02
240	LHCb 7 TeV 35 pb^{-1} W/Z $d\sigma/dy_\ell$	14	9.9	0.71	-0.73
241	LHCb 7 TeV 35 pb^{-1} A_{ch}, $p_{T\ell} > 20$ GeV	5	5.3	1.06	0.30
260	DØ Run-2 Z rapidity	28	17	0.59	-1.71
261	CDF Run-2 Z rapidity	29	48	1.64	2.13
266	CMS 7 TeV 4.7 fb^{-1}, muon A_{ch}, $p_{T\ell} > 35$ GeV	11	12.1	1.10	0.37
267	CMS 7 TeV 840 pb^{-1}, elec. A_{ch}, $p_{T\ell} > 35$ GeV	11	10.1	0.92	-0.06
268	ATLAS 7 TeV 35 pb^{-1} W/Z cross sec., A_{ch}	41	51	1.25	1.11
281	DØ Run-2 9.7 fb^{-1} elec. A_{ch}, $p_{T\ell} > 25$ GeV	13	35	2.67	3.11
504	CDF Run-2 inclusive jet production	72	105	1.45	2.45
514	DØ Run-2 inclusive jet production	110	120	1.09	0.67
535	ATLAS 7 TeV 35 pb^{-1} incl. jet production	90	50	0.55	-3.59
538	CMS 7 TeV 5 fb^{-1} incl. jet production	133	177	1.33	2.51

Theoretical framework in CT14

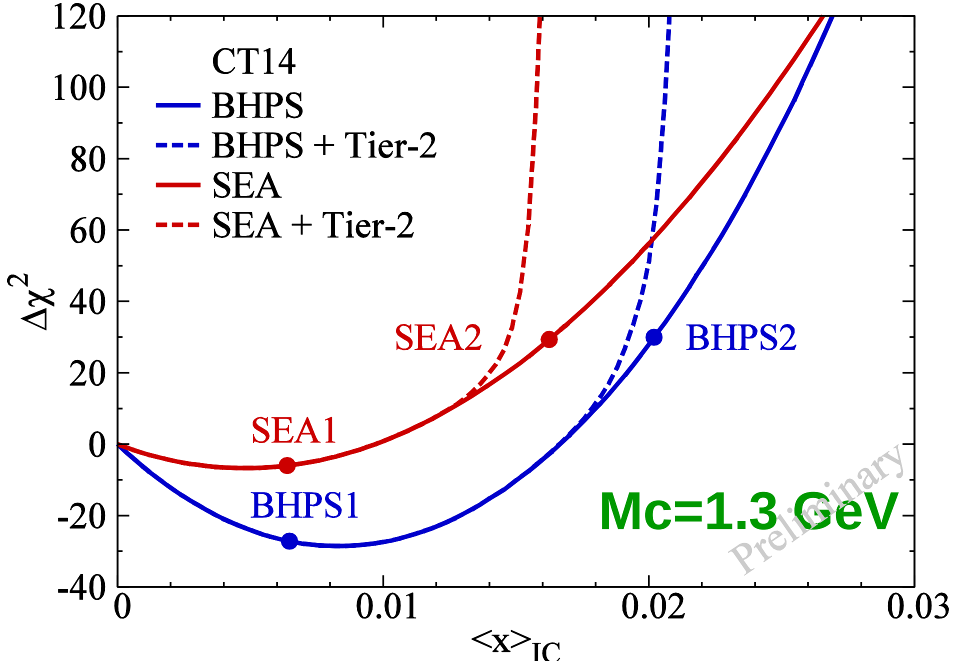
- CT14 contains 28 shape parameters, and CT10 has 25.
- The light quarks and gluon PDFs are parameterized at an initial scale Q=1.3 GeV. PDFs at any other scale can be obtained from pQCD via DGLAP evolution.
- When we perform a global fit we choose data with $Q^2 > 4$ GeV^2 and $W^2 > 12.5$ GeV^2 , namely, large-x data are not included to avoid large non-perturbative contributions.
- CT14 has more flexible parameterizations for gluon, d/u at large-x, both d/u and dbar/ubar at small x, and strangeness (s = sb) PDFs. The non-perturbative parameterization form:

$$x\, f_a(x) = x^{a_1}\, (1-x)^{a_2}\, P_a(x)$$

  where $P_a(x)$ is expressed as a linear combination of Bernstein polynomials.
- To deal with the heavy quark partons we use s-ACOT-χ prescription.

- In our global fit we have taken NNLO calculations for DIS, DY, W, Z cross sections, but for the jet cross sections we only use the NLO calculation but with NNLO PDF.

Upper limits on the IC from CT14



$\langle x\rangle_{\mathrm{IC}} \leq 2\%$ **for BHPS**

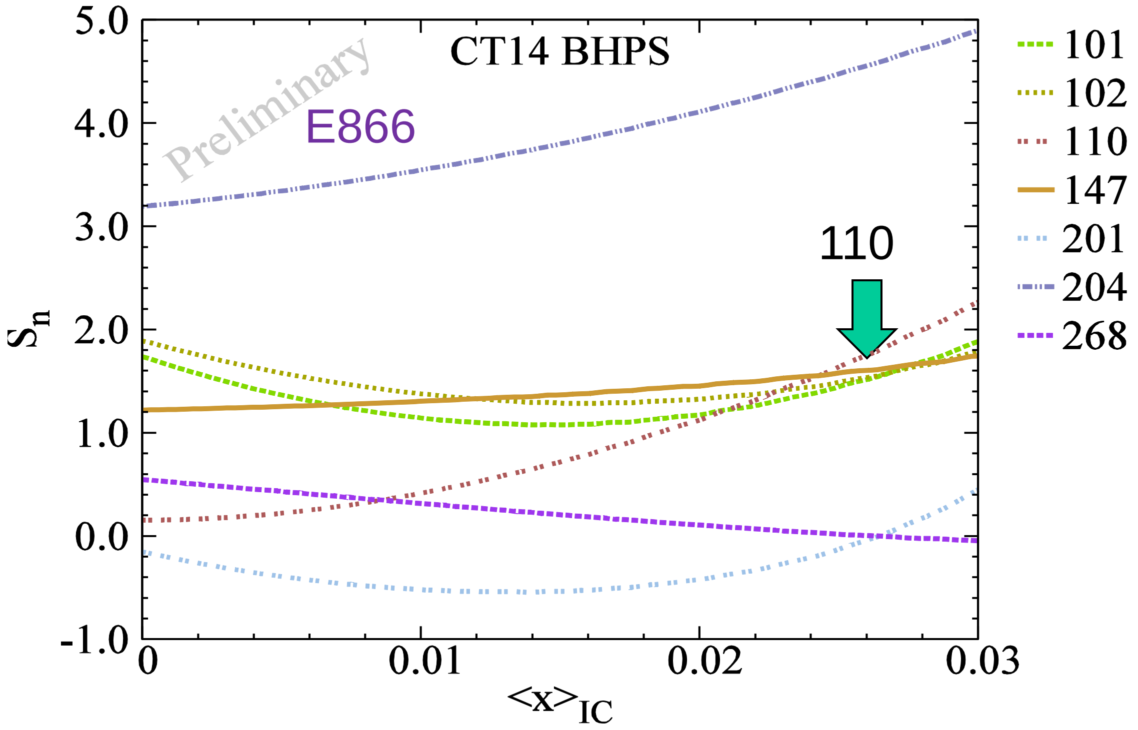
$\langle x\rangle_{\mathrm{IC}} \leq 1.6\%$ **for SEA**

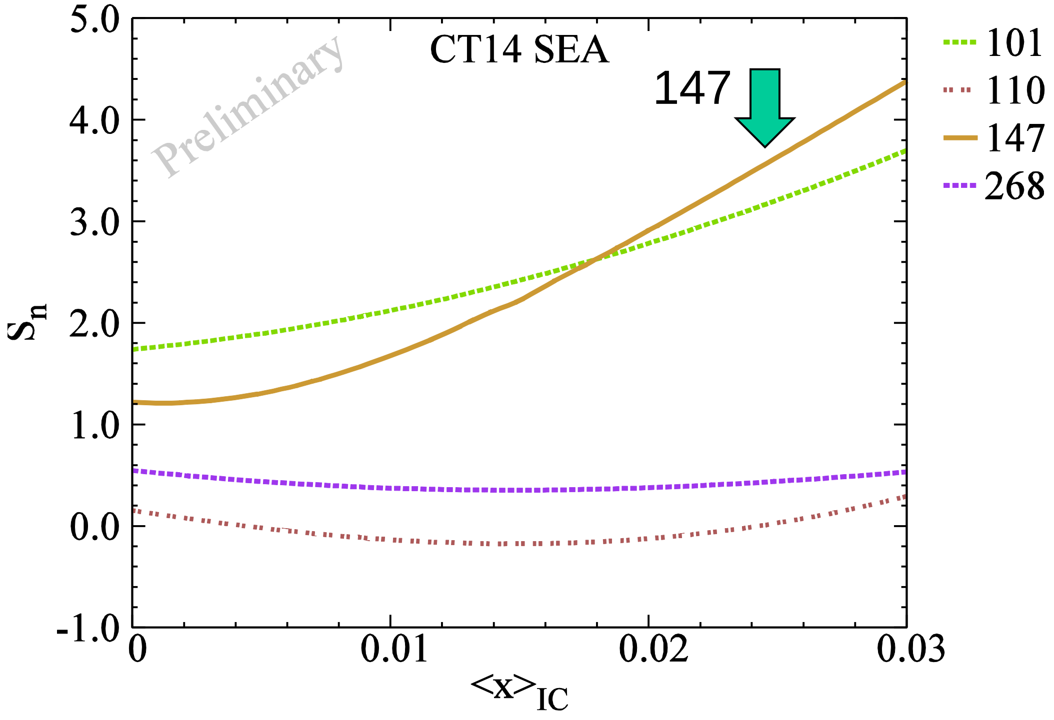
Model	CT14	BHPS1	BHPS2	SEA1	SEA2
$\langle x\rangle_{\mathrm{IC}}$	0%	0.6%	2%	0.6%	1.6%

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

The **dashed-blue** and **dashed-red** curves are obtained by introducing the penalty factor for each experiment, when one or more data sets reach to the boundary of the 90% C.L..

Which of the data sets in the global analyses are most sensitive to IC?





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

The HERA combined charm data (ID 147) is most sensitive to the SEA model. And thus the upper limit on $\langle x \rangle_{IC}$ value comes from the HERA charm data.

The effective Gaussian parameter Sn quantifies the compatibility of any given data with a particular PDF fit.
For a good fit to data, the value of *Sn* should be roughly between -1 and 1.
A fit with *Sn* > 3 should be considered a poor fit to the nth experiment
A fit with Sn < -3 correspond to an unusually good fit to the nth experiment.

PRD D 89, 073004 (2014)

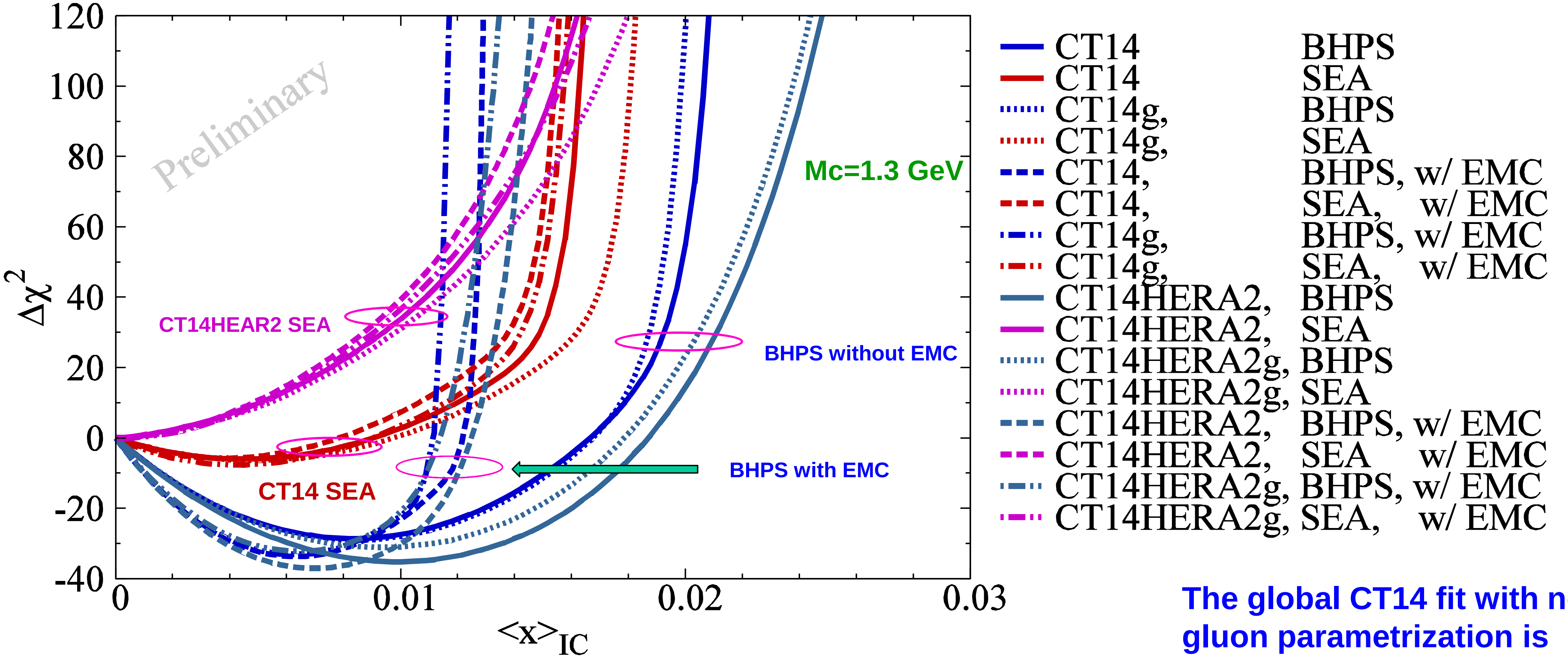
CT14 HERA2 PDFs with IC: χ^2/N_{pt}

Candidate NNLO PDF fits	χ^2/N_{pt} PRELIMINARY			
	All exps	HERA inc. DIS	HERA $c\bar{c}$ SIDIS	EMC F_2^c
CT14 HERA2+EMC (wt=0), no IC	1.09	1.25	1.22	3.49
CT14HERA2+EMC (wt=10), no IC	1.12	1.28	1.16	2.35
CT14HERA2 BHPS+EMC	1.09	1.24	1.22	3.05
CT14HERA2 SEA +EMC	1.11	1.26	1.26	3.48

- **The EMC F_2^c data is not fitted well, has unknown systematic uncertainties.**
- **The quality of agreement with EMC F_2^c data is not improved with the BHPS model .**
- **EMC F_2^c: Nuclear Physics B213 (1983) 1-30.**

- **CT14 HERA2: arXiv:1609.07968**
- **We replace the combined HERA1 data set used in the CT14 PDFs by the combined HERA2 data set.**
- **We use the CT14 parameterization , but adding one more free parameter for strange quark.**

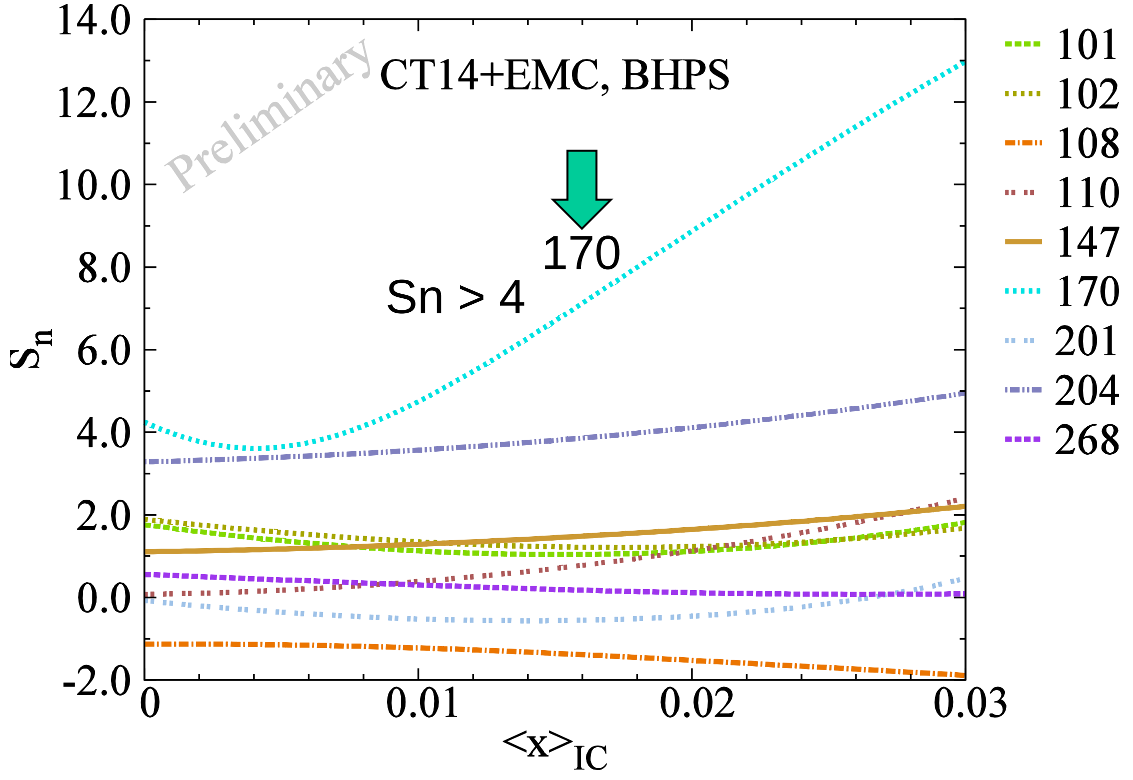
The dependence of the χ^2 on the IC $\langle x \rangle_{IC}$ in the context of the global CT14, CT14g, and CT14HERA2 fits with and without EMC F_2^c measurements:

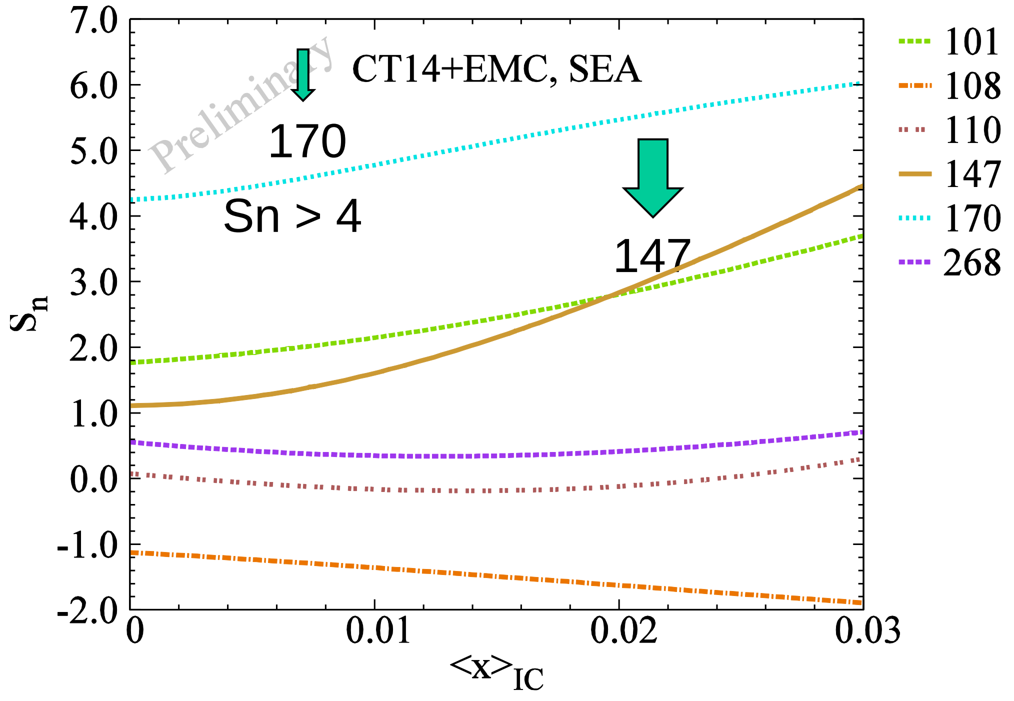


The global CT14 fit with new gluon parametrization is named CT14g.

For the BHPS parametrization, a marginally better χ^2 for IC with $\langle x \rangle_{IC} \approx 1\%$
For SEA parametrization, IC with $\langle x \rangle_{IC} \approx 1.5\%$ is allowed within uncertainty.

Which of the data sets in the global analyses are most sensitive to IC when including the EMC F_2^c data?



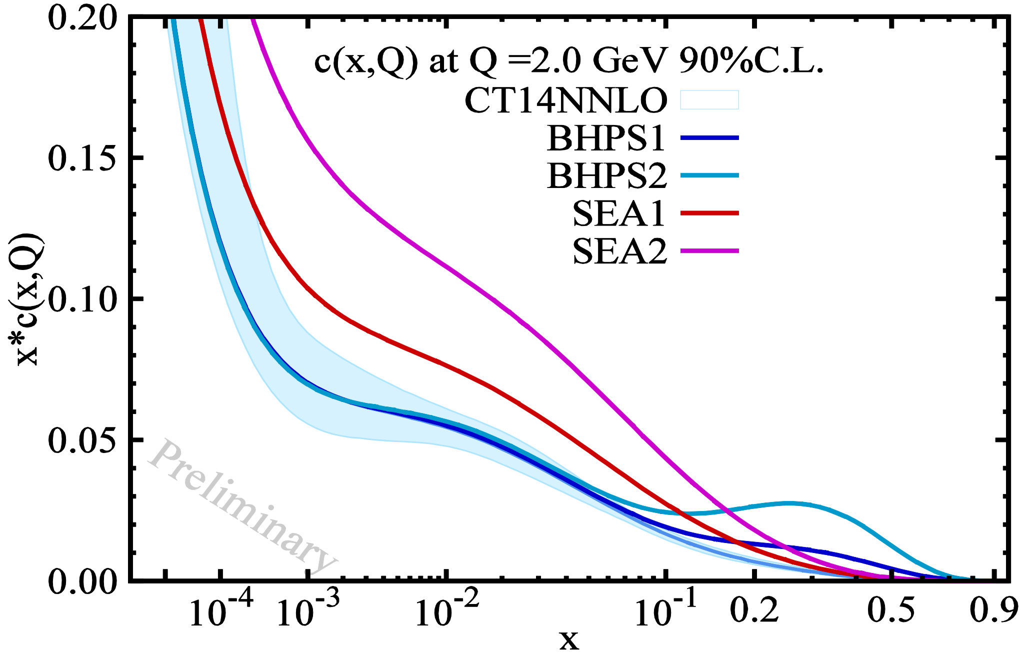


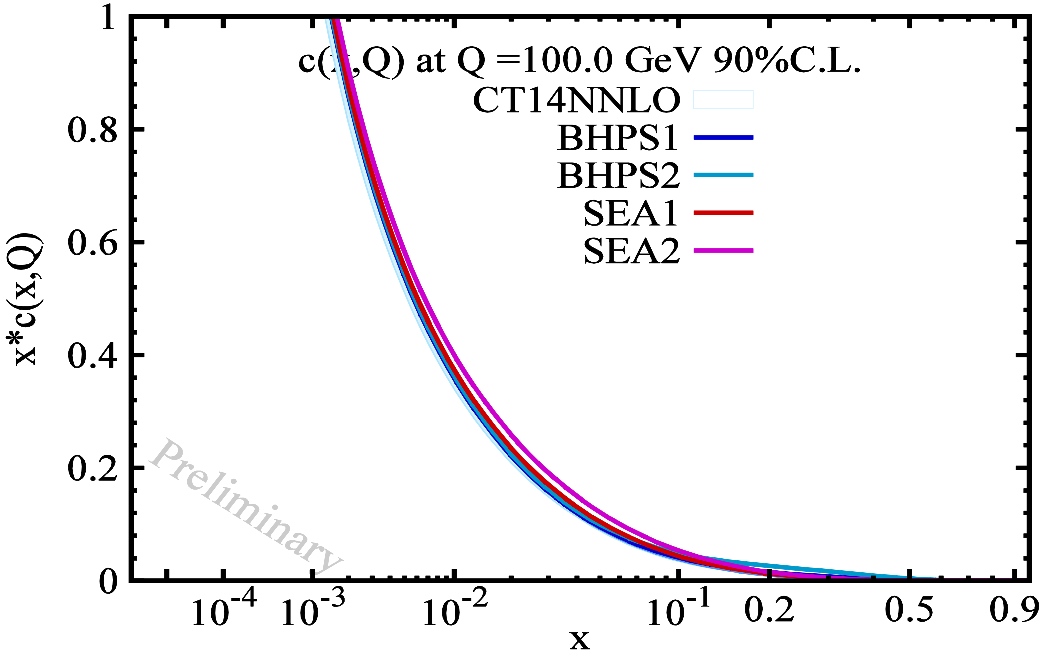
The EMC charm structure function F_2^c data (ID 170) is not fitted well.

It has a large effective Gaussian parameter value Sn both for the BHPS and SEA models.

Impact of IC on the PDFs:

Comparison of charm quark PDFs for the BHPS (BHPS1, BHPS2) and SEA (SEA1, SEA2) models with the CT14 charm PDFs:

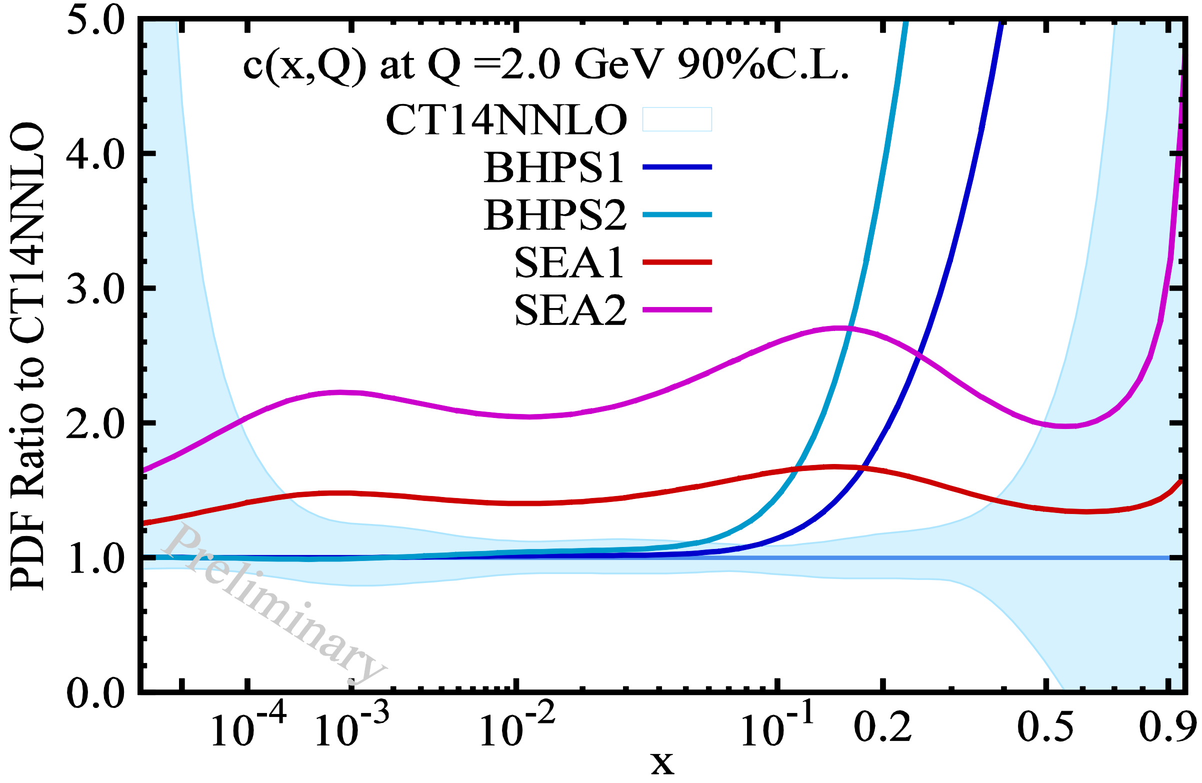


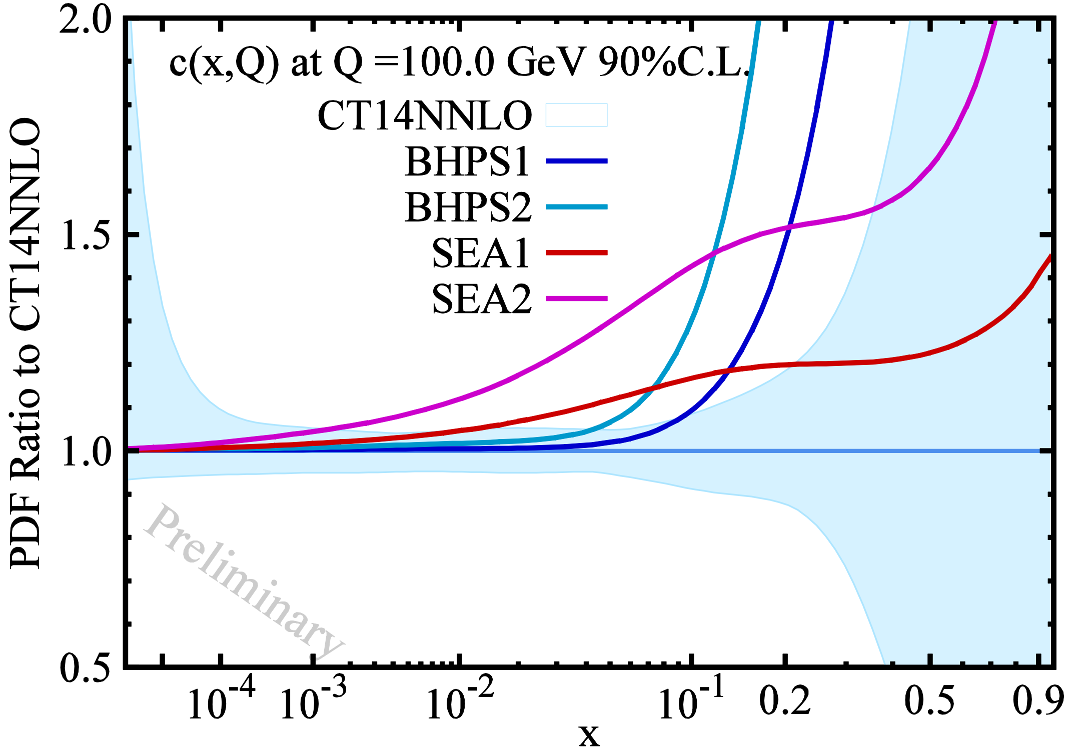


- **At Q=2 GeV and x<0.1: SEA-like charm quark distribution is larger than the CT14 charm PDF.**
- **At Q=2 GeV and x>0.1 BHPS valence like charm quark distribution is larger than the standard CT14 charm PDF .**

- **For Q=100 GeV the evolution effect is dominant small-x.**

The charm quark PDFs for the BHPS (BHPS1, BHPS2) and SEA (SEA1, SEA2) models are normalized to the CT14 charm PDF, that has no IC contribution:

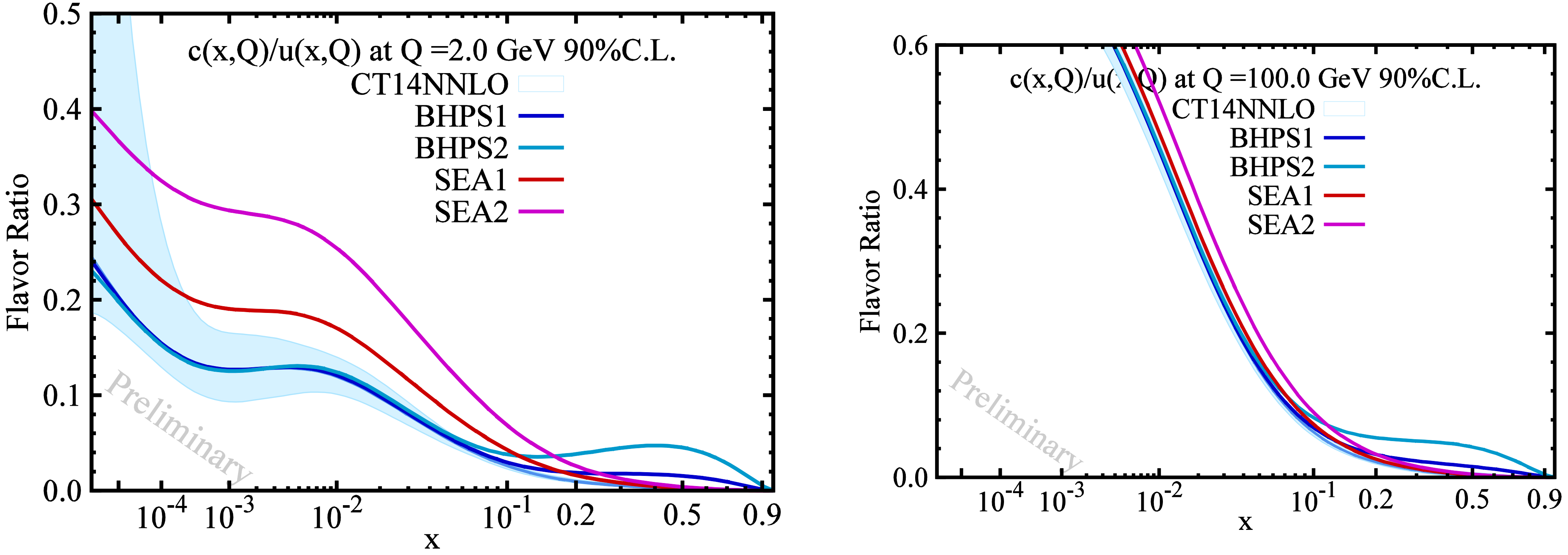




At Q=2GeV, SEA-like charm distribution is dominant at small-x and intermediate region. BHPS valence like charm distribution is dominant at large-x region.

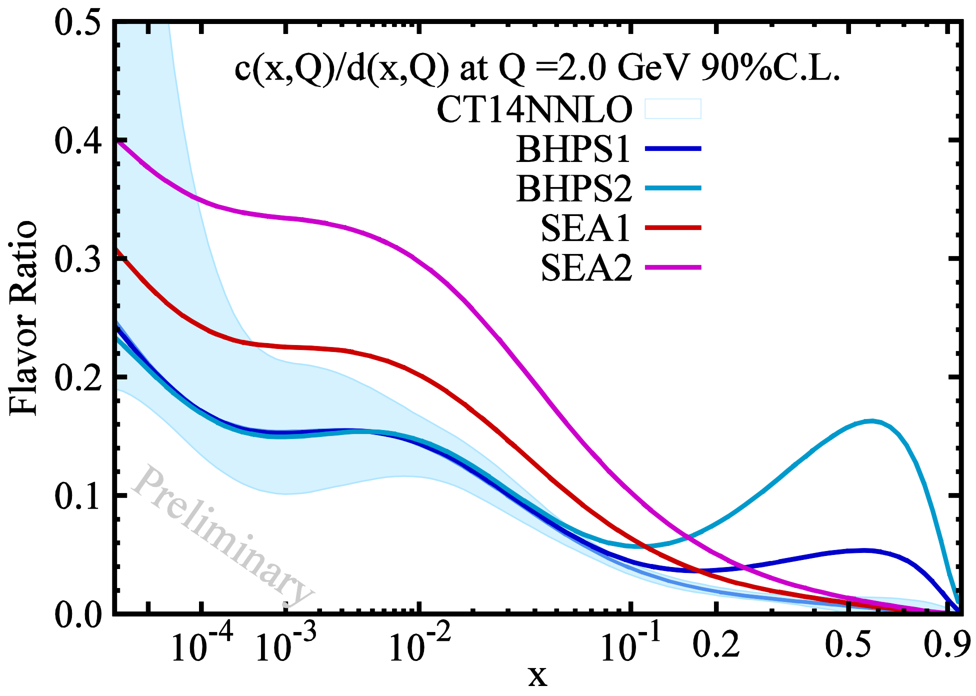
At Q=100 GEV, radiation effect is dominant at small-x.

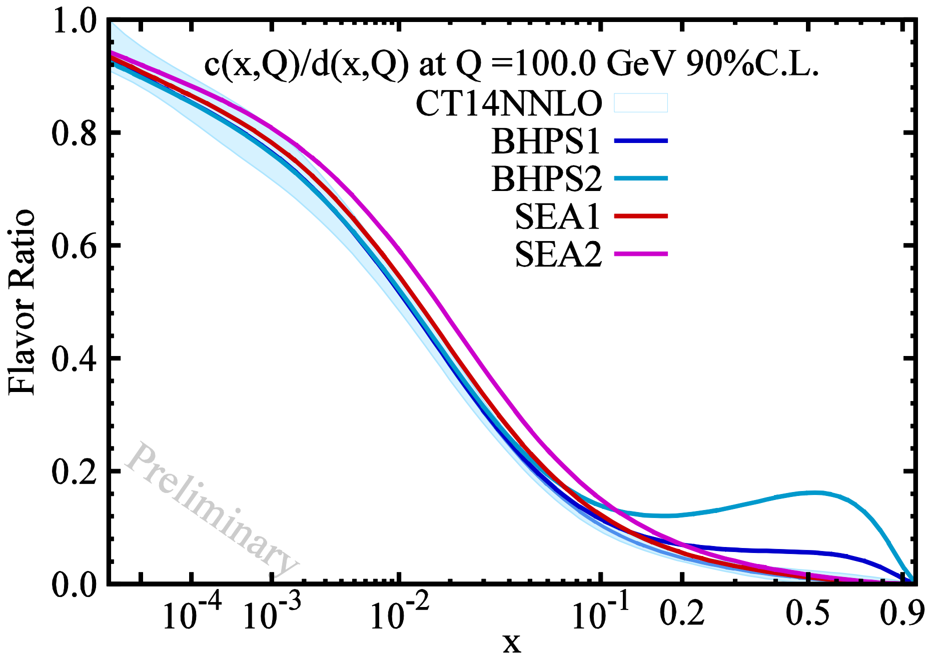
Comparison of c/u PDFs for the BHPS (BHPS1, BHPS2) and SEA (SEA1, SEA2) models with CT14 charm PDFs:



At large-x region the charm quark PDF of BHPS valence-like model is about 5% of u-quark PDF.

Comparison of c/d PDFs for the BHPS (BHPS1, BHPS2) and SEA (SEA1, SEA2) models with CT14 charm PDFs:

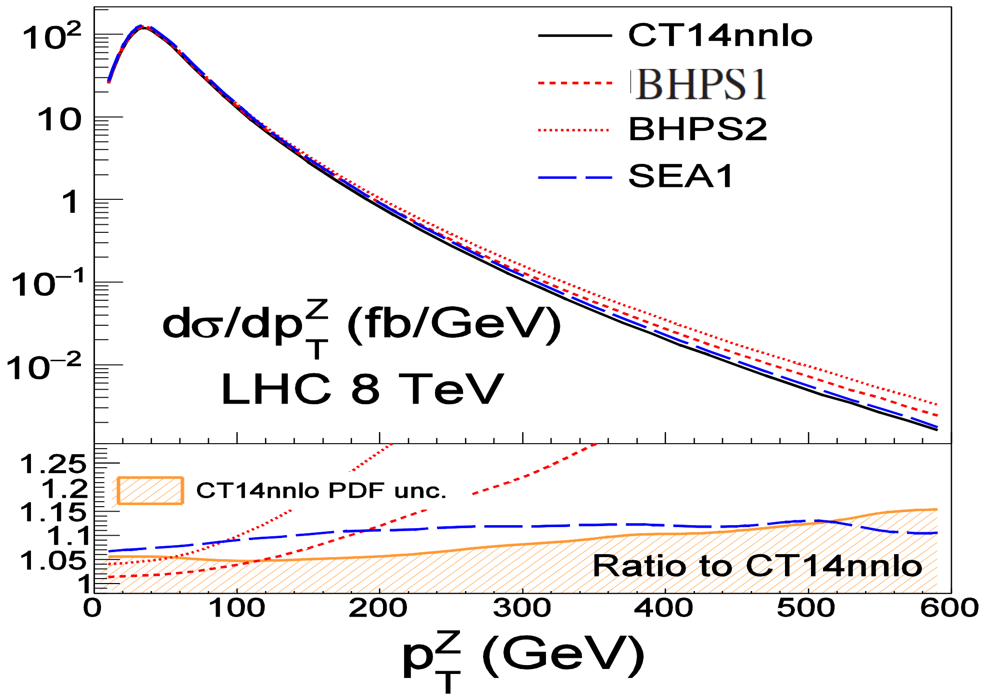


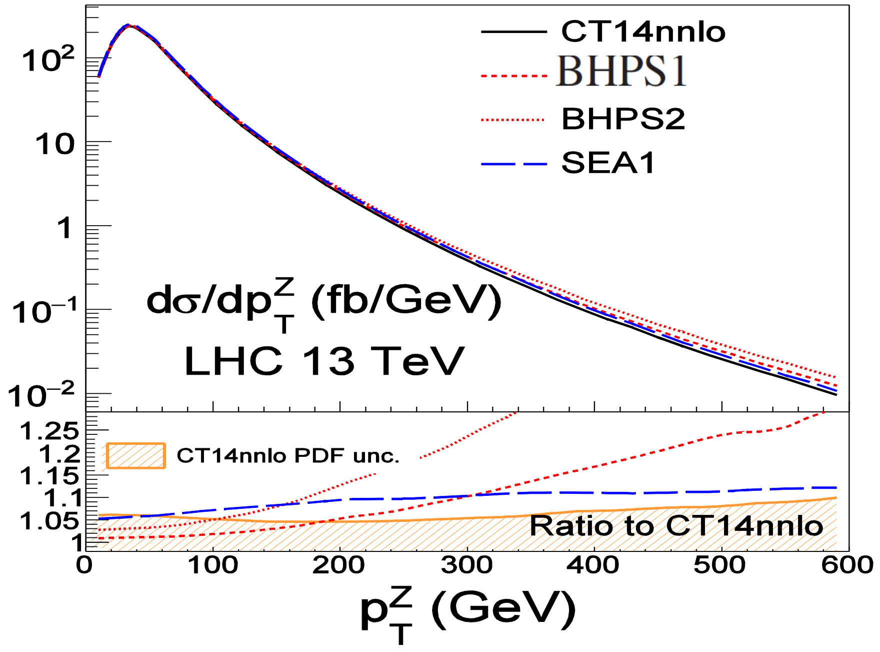


At large-x the charm quark PDF of the BHPS valence–like model is about 18% of d-quark PDF.

$pp \rightarrow ZcX$ with IC PDFs

PRELIMINARY





Predictions from CT14 and CT14IC (BHPS and SEA) models of the differential cross sections as a function of the transverse momentum of an on shell Z production in association with the charm quark at the LHC with C.O.M energy 8 TeV and 13 TeV.

If the IC PDF is universal, it will enhance $Z + c$ production at large $p_T(Z)$, especially with the BHPS model.

Summary

- The range of magnitudes of the IC component of the proton that is consistent with our global QCD analysis fit to hard scattering data:

  <x> < 0.6% for BHPS2 IC and <x> <0.6% for SEA2 IC

  <x> < 2% for BHPS2 IC and <x> <1.6% for SEA2 IC

- NNLO fits with the complete HERA1+2 ensemble prefer a marginally higher value of $\langle x \rangle_{IC}$ with the BHPS model.
- The EMC charm structure function F_2^c data is not fitted well.
- If IC PDFs are universal, they will enhance $Z + c$ production cross sections at the LHC, especially at $p_T(Z) > 200$ GeV with the BHPS1 model.
- The CT14 PDF sets with intrinsic charm are available via the LHAPDF, for use in predicting/analyzing experiments.

Thanks