Special CT14 Parton Distribution Functions

1. **CT14 MC1 and MC2:** Monte Carlo replicas with asymmetric uncertainties and positivity (T.-J. Hou et al., arXiv:1607.06066)
   - Public program **mcgen** to generate such replicas on **metapdf.hepforge.org/mcgen**
2. **CT14 IC (HERA2):** Updated CT14 PDFs with intrinsic charm and legacy HERA data (T.-J. Hou et al., arXiv:1610.xxxxx)

Pavel Nadolsky

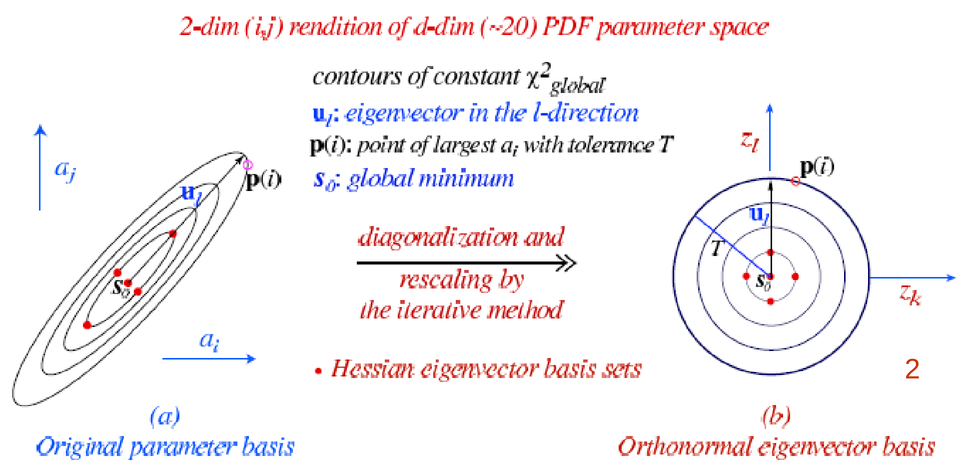
Southern Methodist University, Dallas, TX, USA

On behalf of CTEQ-TEA collaboration

Generation of MC replicas from CT14 Hessian eigenvector sets

MC replicas for PDFs $f_a(x,Q) \equiv f \ldots$

- are constructed from the best-fit (central) PDF values f_0 and 68% c.l. extreme displacements $f_{\pm i}$ along eigenvector directions $\vec{u}_i, i = 1, \ldots, 28$ in parameter space near χ^2 minimum
- retain exact information about boundaries of 68% or 90% probability regions; approximate probability everywhere using Gaussian approximation
- approximate asymmetric Hessian errors using modified standard deviations



CT14 asymmetric PDF errors on X

1. Hessian method

Include diagonal second derivatives for small displacements R_i from the best-fit value $\mathrm{X}(\{0\}\}$ along PDF eigenvector directions i:

$$X(\{R\}) = X(\{0\}) + \sum_{i=1}^{D} \frac{X_{+i} - X_{-i}}{2} R_i + \frac{1}{2} \sum_{i,j=1}^{D} (X_{+i} + X_{-i} - 2X_0) R_i^2$$

X is the PDF or any other function of PDFs (cross sections, etc.).

Each CT14 eigenvector PDF is parametrized to be non-negative in order to return positive QCD cross sections

The Hessian method produces asymmetric master formulas for PDF errors at 68% c.l. *(PN, Sullivan, hep-ph/0110378)*

$$\delta_{68}^{H,>} X = \sqrt{\sum_i (max[X_{+i} - X_0, X_{-i} - X_0, 0])^2}$$

$$\delta_{68}^{H,<} X = \sqrt{\sum_i (max[X_0 - X_{+i}, X_0 - X_{-i}, 0])^2}$$

CT14 asymmetric PDF errors

2. CT14 Monte-Carlo replica ensembles (MC1 and MC2)

N_{rep} Monte-Carlo replicas can be constructed from predictions $X_{\pm i}$ for Hessian eigenvector sets as

$$X^{(k)} = X(\{0\}) + \delta X^{(k)} - \Delta$$

$$\delta X^{(k)} \equiv \sum_{i=1}^{D} \frac{X_{+i} - X_{-i}}{2} R_i^{(k)} + \frac{1}{2} \sum_{i,j=1}^{D} (X_{+i} + X_{-i} - 2X_0) \left(R_i^{(k)}\right)^2$$

Random real values $R_i^{(k)}$ are sampled from the standard normal distribution

There is some freedom in choosing X that is sampled, as long as $X \approx f_a\,(x, Q_0)$ for small uncertainties (in the linear approximation)

CT14 MC1 replicas are constructed from $X = f_a(x, Q_0)$, can be negative
CT14 MC2 replicas are constructed from $X = log\,[f_a/f_{a0}]$, where $f_{a0}(x, Q_0)$ is the central Hessian PDF; **each replica PDF is non-negative**

The MC uncertainties are given by **asymmetric** standard deviations,

$$\delta_{68}^{MC,>} X = \sqrt{\langle (X - \langle X \rangle)^2 \rangle_{X > \langle X \rangle}}$$

$$\delta_{68}^{MC,<} X = \sqrt{\langle (X - \langle X \rangle)^2 \rangle_{X < \langle X \rangle}}$$

f_a/f_{a0} values for individual replicas

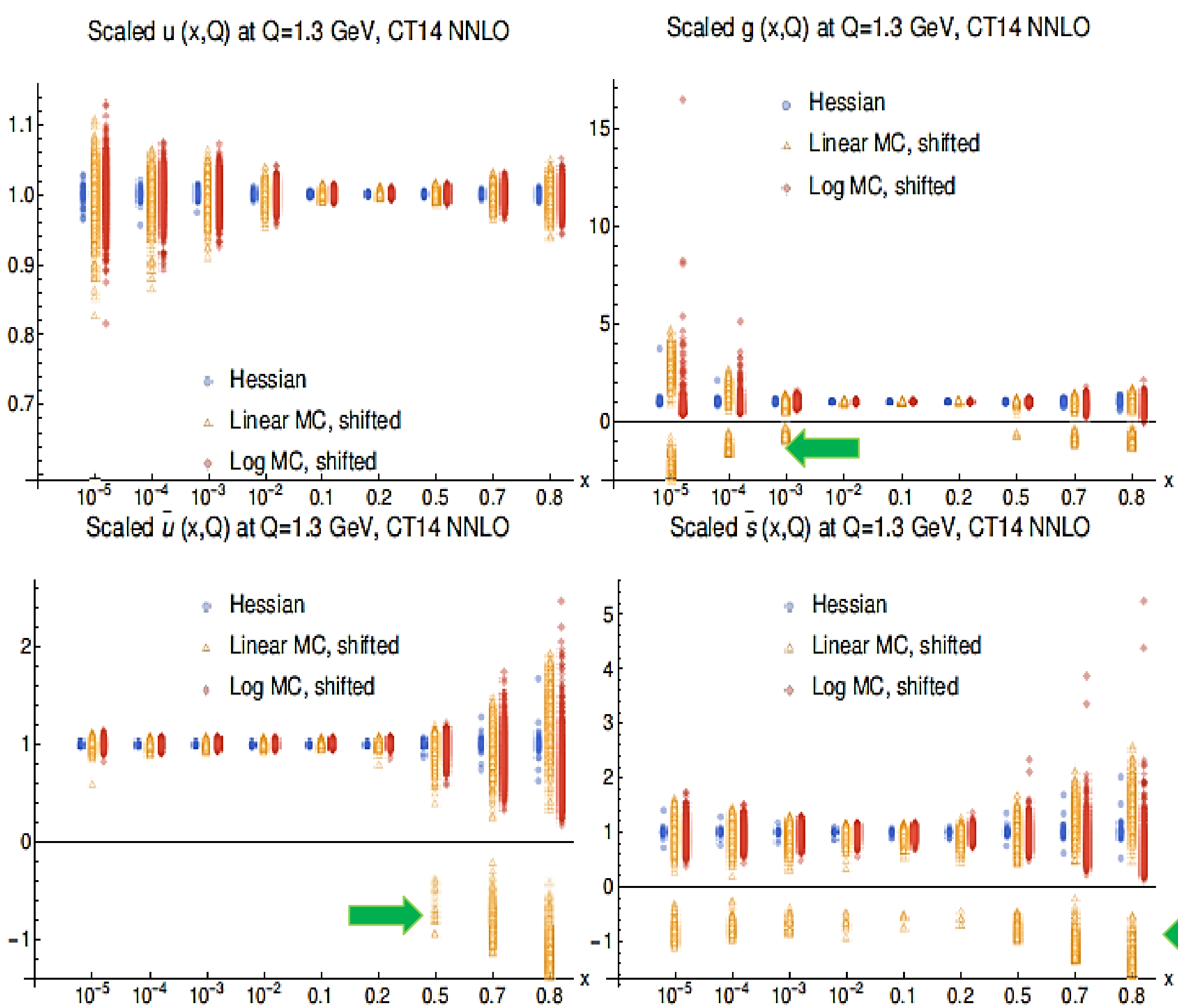


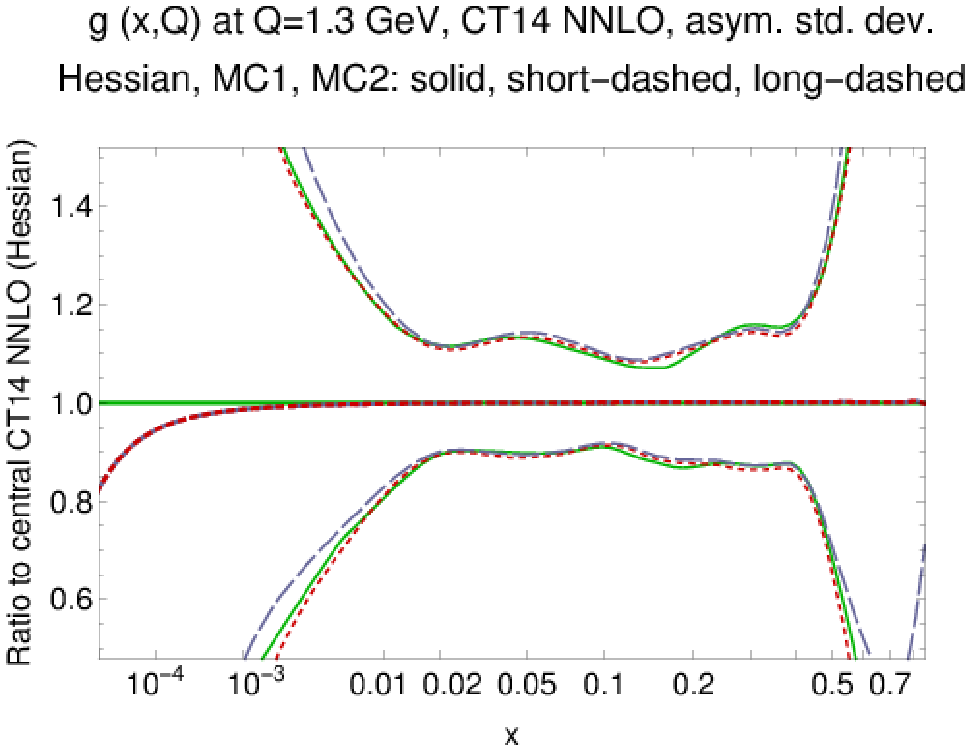
FIG. 2: Distributions of individual replicas for MC1 (linear MC, shifted) and MC2 (log MC, shifted) ensembles.

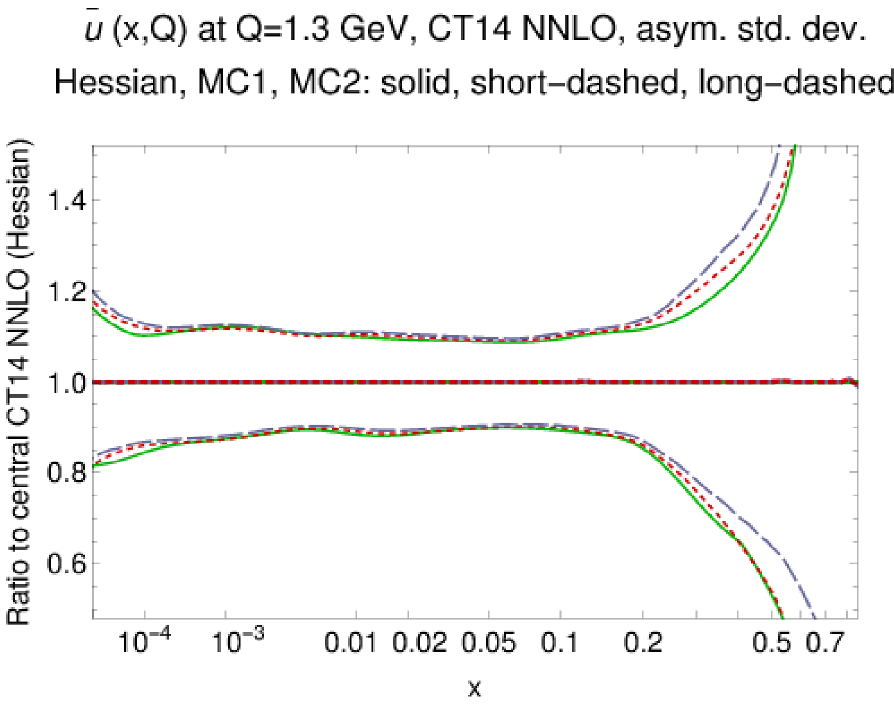
The vertical axes have scale $\left|\frac{f}{f_{a0}}\right|^{0.2} sign(f)$ to visualize relative variations of $\pm$ signs in an extended magnitude range

A fraction of 1000 MC1 replica PDFs can be negative (**green arrows**).

But, all Hessian and MC2 PDFs are positive

Asymmetric standard deviations for PDFs



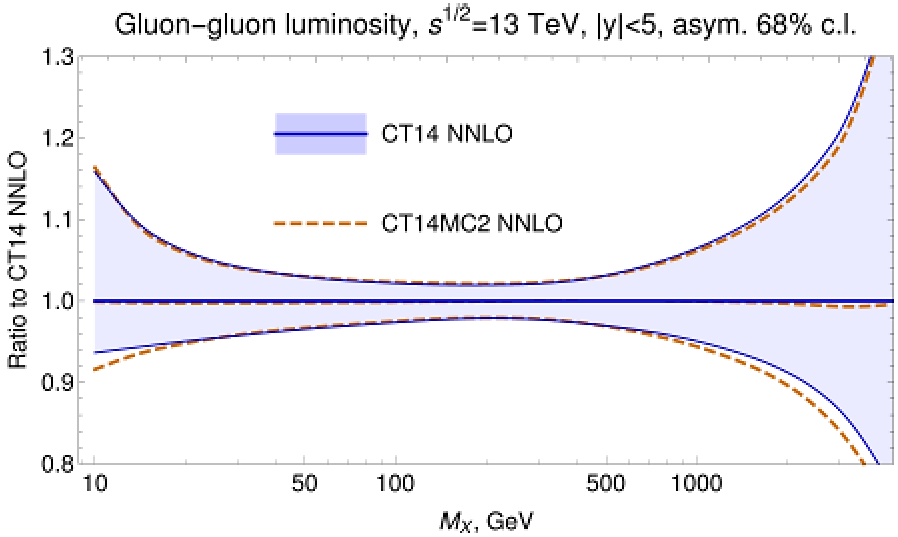


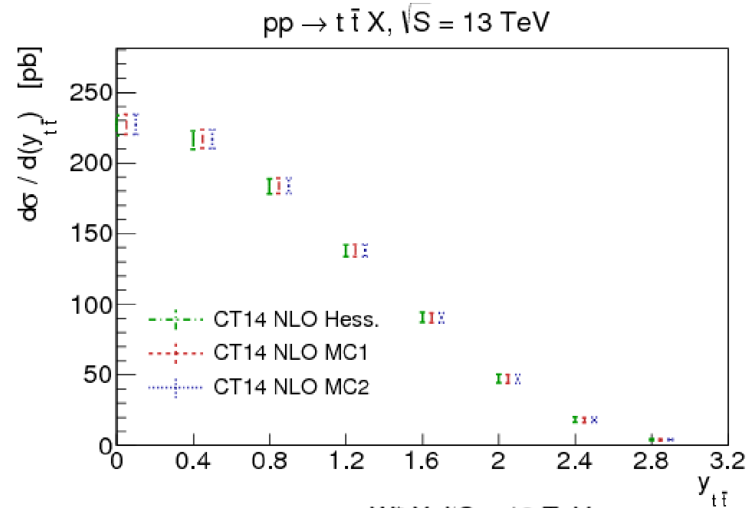
Excellent agreement between the Hessian, MC1, MC2 bands at intermediate x

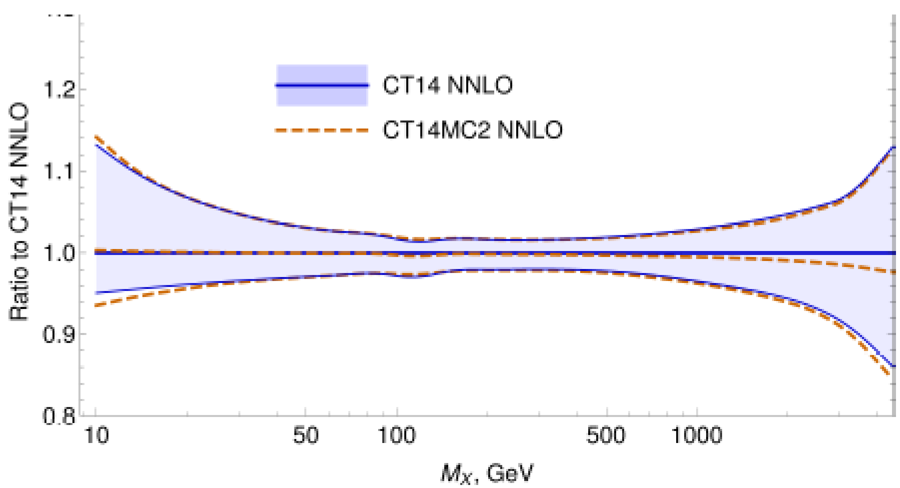
More pronounced differences at small and large x; there are ambiguities in reconstructing MC replicas from the Hessian PDFs when PDF uncertainties are large

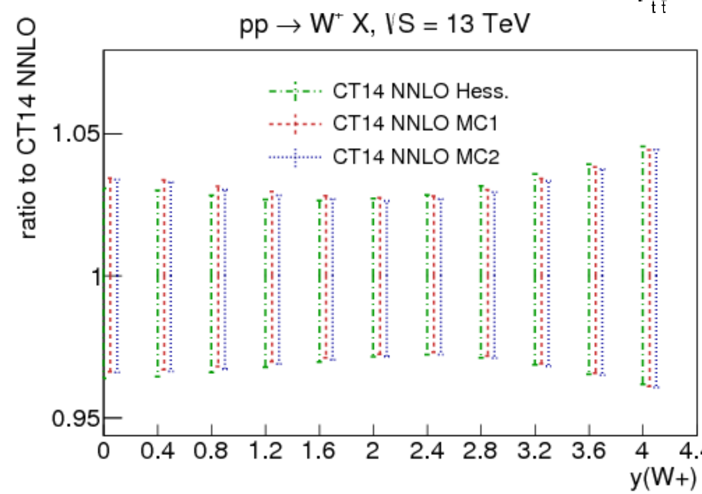
Comparisons for other flavors at
http://hep.pa.msu.edu/cteq/public/ct14/MC/

Asymmetric standard deviations: parton luminosities and LHC cross sections









Excellent agreement between the Hessian, MC1, MC2 uncertainties

Note the $|y| < 5$ constraint on the rapidity of heavy state X to show luminosities in the physical x region

Comparisons for other flavors at
http://hep.pa.msu.edu/cteq/public/ct14/MC/

Comparison with Watt-Thorne algorithm

CT14 algorithm:

$$X^{(k)} = X(\{0\}) + \sum_{i=1}^{D} \frac{X_{+i}-X_{-i}}{2} R_i^{(k)} + \frac{1}{2}\sum_{i,j=1}^{D}(X_{+i} + X_{-i} - 2X_0)\left(R_i^{(k)}\right)^2 - \Delta$$

$$\delta_{68}^{MC,\lessgtr} X = \sqrt{\langle (X - \langle X \rangle)^2 \rangle_{X \gtrless \langle X \rangle}}$$

Recommended

Asymmetric algorithm in Watt, Thorne (arXiv:1205.4024)

$$X^{(k)} = X(\{0\}) + \sum_{i=1}^{D} \frac{\partial X}{\partial R_i} R_i^{(k)}$$

$$\frac{\partial X}{\partial R_i} = \begin{cases} X_{+i} - X_0, & R_i^{(k)} > 0 \\ X_0 - X_{-i}, & R_i^{(k)} < 0 \end{cases}$$

Different from the CT14 algorithm if $R_i^{(k)} \neq \pm 1$

In both methods, separate averaging of positive and negative displacements is most essential for recovering the asymmetry of $\delta^{H,\lessgtr} X$

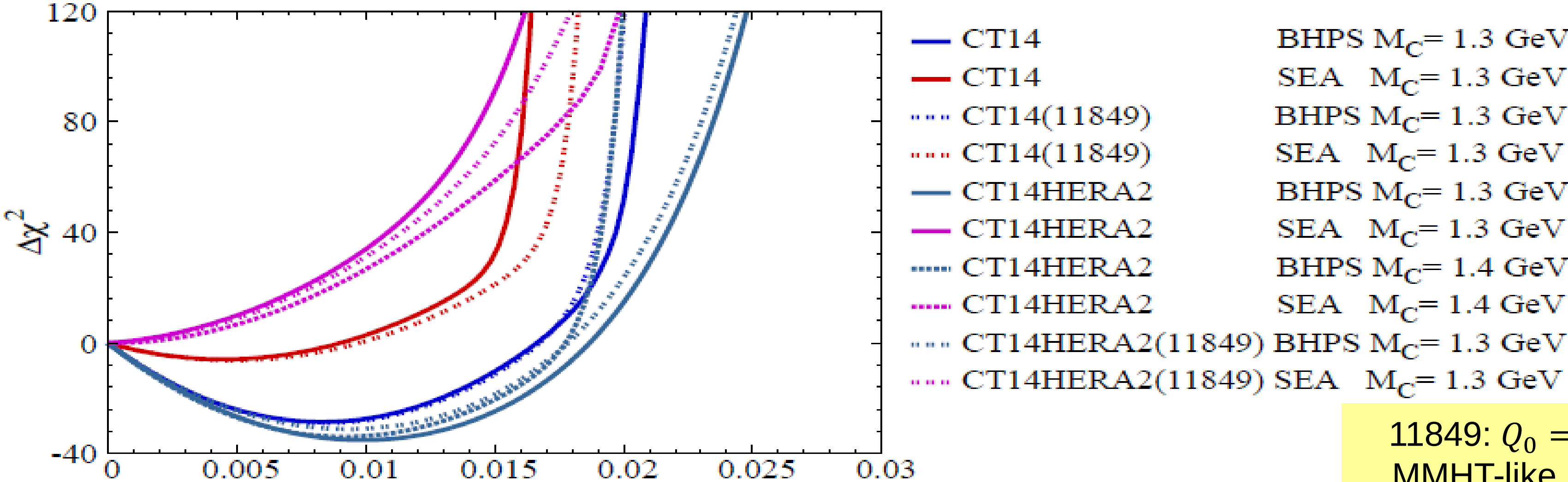
CT14 NNLO PDFs with intrinsic charm (IC)

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

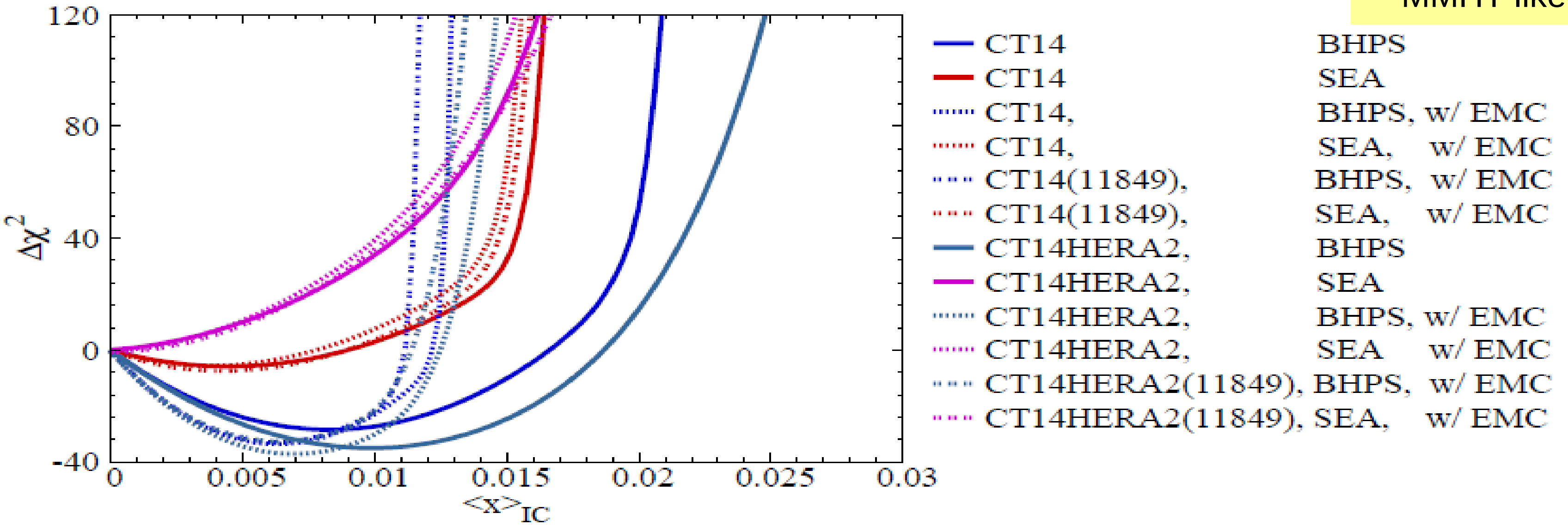
- effect of legacy HERA data (minor)
- dependence on initial scale Q_0, charm mass M_c, parametrization form (moderate)
- effect of including EMC F_{2c} data (minor, tension with other experiments, questions about EMC systematic effects, fiting EMC requires a large normalization shift)

Candidate NNLO PDF fits	χ^2/N_{pt}, **PRELIMINARY**			
	All experiments	HERA inc. DIS	HERA $c\bar{c}$ SIDIS	EMC $F_2^{c\bar{c}}$, δ_{Norm}^{EMC}
CT14 HERA2+EMC (wt=0), no IC	1.09	1.25	1.22	3.49, -3σ
CT14HERA2+EMC (wt=10), no IC	1.08	1.27	1.14	2.39, -2.6σ
CT14HERA2 BHPS+EMC	1.09	1.24	1.22	3.04
CT14HERA2 SEA +EMC	1.13	1.27	1.47	3.94

PRELIMINARY CT14 IC fits (T.-J. Hou)



11849: $Q_0 = 1$ GeV,
MMHT-like $g(x, Q_0)$



For the Brodsky-Hoyer-Peterson-Sakai (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

What is intrinsic charm, according to QCD theory?

The ACOT family of schemes used by CTEQ fits are uniquely suited for establishing physical properties of the "intrinsic charm".

- The FFN scheme and ACOT schemes are proved by the QCD factorization theorem with explicit power counting of scattering contributions at $p^+ \to \infty$
- Factorization for another GM-VFN scheme (FONLL, TR',…) can be demonstrated, e.g., by reducing to a counterpart ACOT scheme order by order in α_s

At $Q^2 \approx m_c^2$, the ACOT $N_f = 4$ scheme reduces to the $N_f = 3$ scheme, order by order in α_s

In the $N_f = 3$ scheme, (Collins 1998) proved that, at $Q^2 \approx m_c^2$,

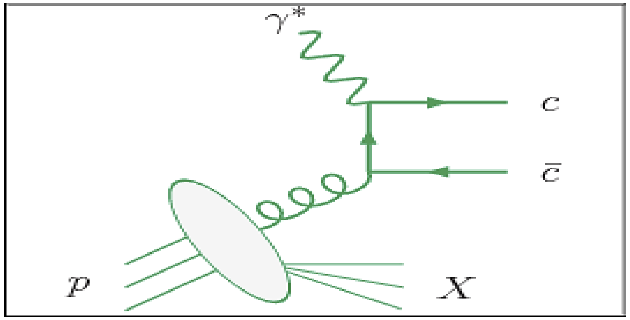
$$F_2(x,Q^2) = \underbrace{\sum_{a=u,d,s,g} \int_x^1 \frac{dz}{z}\, C_a\left(\frac{x}{z}, \frac{m_c^2}{Q^2}, \frac{\mu^2}{Q^2}\right) f_a(z,\mu^2)}_{\text{leading power (l.p.)}} + O(\Lambda^2)$$

- The l.p. term contains charm propagators only in the coefficient functions, sums only over light-flavor PDFs

⇒ **In either the $N_f = 3$ scheme or ACOT scheme at $Q^2 \approx m_c^2$ and $O(\alpha_s^n)$, the phenomenological IC term is composed of $O(\alpha_s^{n+1})$ l.p. terms and $O(\frac{\Lambda^2}{m_c^2})$ terms**

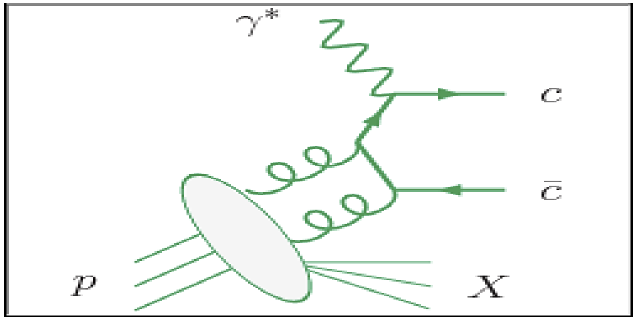
Charm scattering contributions at $Q^2 \approx m_c^2$, sample diagrams

Leading-power charm



- Single-parton scattering
- Of order $\left(\frac{m_c^2}{Q^2}\right)^k$
- All-order $\overline{MS}$ formalism to factorize into hard cross sections and light-parton PDFs
- When matched onto the $N_f = 4$ scheme, gives rise to **process-independent** charm PDFs

Fitted (intrinsic) charm



- Multi-parton scattering
- Of order $(\Lambda^2/m_c^2)^k$
- A power-suppressed correction to the factorized QCD cross section
- Currently not covered by the $\overline{MS}$ factorization theorem; **"IC PDF" can be process-dependent**

Consequences for interpretation of IC PDFs

The phenomenological IC PDF is a model for $O(\alpha_s^{n+1})$ l.p. and $O(\frac{\Lambda^2}{m_c^2})$ scattering terms. The standard formalism does not tell us how to factorize the IC contributions into hard perturbative and universal nonperturbative parts. Nevertheless, the CT14 NNLO IC PDFs can be used for first estimates of sensitivity of LHC cross sections to charm scattering contributions beyond l.p. QCD. **[If used with caution!]**

Thursday, Nov. 17, 2016

A special session on

QCD at the LHC and EIC at 2030 –
Physics opportunities and intersections

During the POETIC'7-CTEQ meeting, Nov. 14-18, 2016
at Temple University, Philadelphia, USA

https://phys.cst.temple.edu/poetic-cteq-2016/

Review talks and panel discussions of…

…synergetic opportunities between physics programs at the LHC and a future ep/eA collider;

…common needs for studies of unpolarized, polarized, and nuclear hadronic matter

…precision targets for successful coordination of hadronic physics studies at the LHC and EIC

…a new generation of QCD calculations and computational tools for precision studies in lepton-hadron scattering

Thank you for your attention!