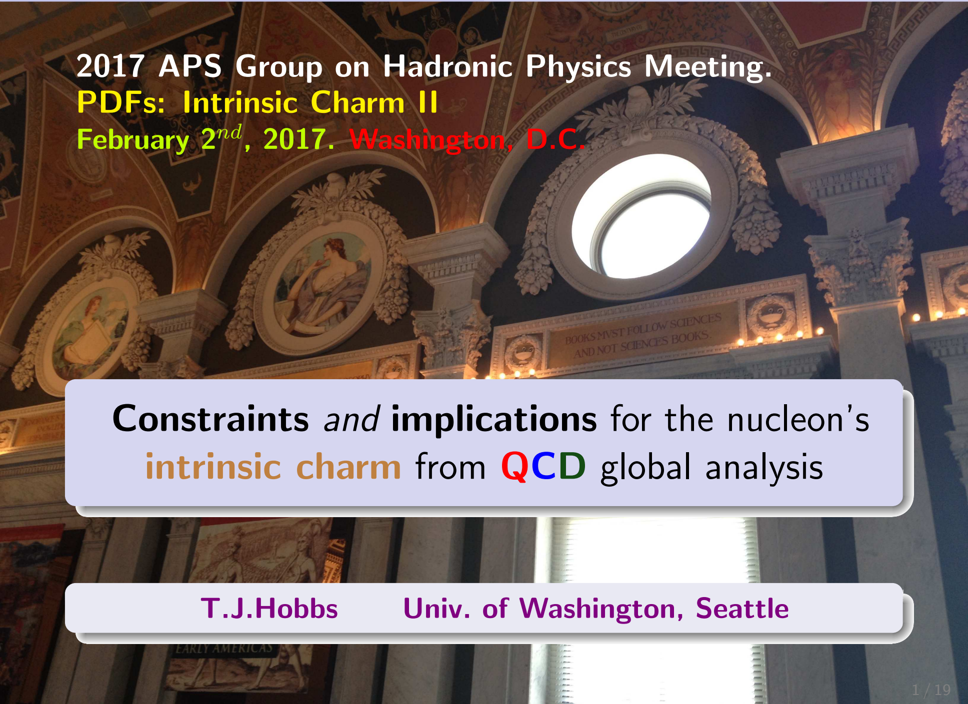

2017 APS Group on Hadronic Physics Meeting.

PDFs: Intrinsic Charm II

February 2^{nd}, 2017. Washington, D.C.

Constraints *and* **implications** for the nucleon's **intrinsic charm** from **QCD** global analysis

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motivation

- though "exotic," **IC** is still **SM** physics, and potentially crucial to **HEP phenomenology**

  → through constraints to **PDF sets** and models,

  → and **background** processes in collider physics

  (*see talk by W. Melnitchouk*)

  → but also studies of hadronic bound-state structure!

- knowledge of charm distributions may influence dynamics in **heavy-ion** physics

  (*see talks in "Onia" I/II*)

  ...*e.g.*, through effects in J/ψ production and decay

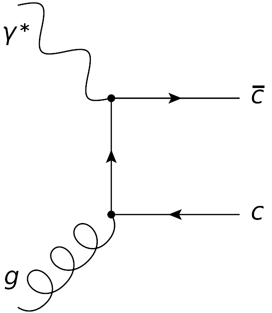
- relevance to searches for **new physics??** (*see talk by S. Gardner*)

  ...i.e., through enhanced BSM cross sections...

  → DM cross sections $\sim \left| m_q \left\langle p \right| \bar{q}q \left| p \right\rangle \right|^2$

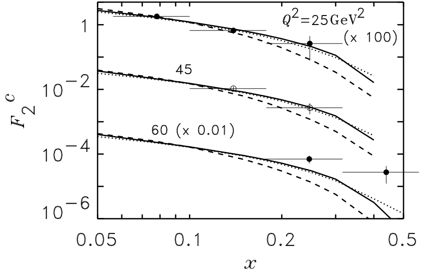
charm in *perturbative* **QCD** (pQCD)

- $c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0$



→

F. M. Steffens, W. Melnitchouk and A. W. Thomas, Eur. Phys. J. C **11**, 673 (1999) [hep-ph/9903441].



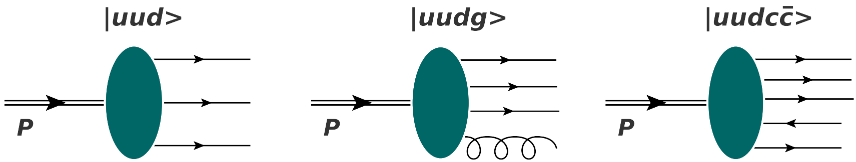
- *intermediate* Q^2:

$$F^c_{2,\ \mathrm{PGF}}(x, Q^2) = \frac{\alpha_s(\mu^2)}{9\pi} \int_x^{z'} \frac{dz}{z}\ C^{\mathrm{PGF}}(z, Q^2, m_c^2) \cdot xg\left(\frac{x}{z}, \mu^2\right)$$

- *high* Q^2:

  massless **DGLAP** (i.e., *variable flavor-number* schemes)

simplest *nonperturbative* **model** calculations



→ original models possessed *scalar* vertices...

- Brodsky et al. (1980):

$$P(p \to uudc\bar{c}) \sim \left[M^2 - \sum_{i=1}^{5} \frac{k_{\perp i}^2 + m_i^2}{x_i}\right]^{-2}$$

→ produces *intrinsic* PDF, $c^{\mathrm{IC}}(x) = \bar{c}^{\mathrm{IC}}(x)$

- Blümlein (2015):

$$\tau_{life} = \frac{1}{\sum_i E_i - E} = \frac{2P}{\left(\sum_{i=1}^{5} \frac{k_{\perp i}^2 + m_i^2}{x_i} - M^2\right)}\Bigg|_{\sum_j x_j = 1} \quad \textbf{vs.} \quad \tau_{int} = \frac{1}{q_0}$$

→ comparison constrains $x - Q^2$ space over which IC is observable

meson-baryon *models* (MBMs)

- we implement a framework which *conserves* **spin/parity**

- **nonperturbative** mechanisms are needed to break
  $c(x, Q^2 \leq m_c^2) = \bar{c}(x, Q^2 \leq m_c^2) = 0!$

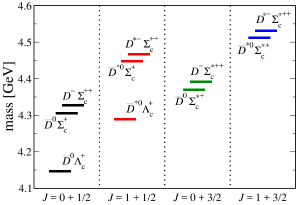
We build an **EFT** which connects IC to properties of the hadronic spectrum: **[TJH, J. T. Londergan and W. Melnitchouk, Phys. Rev. D89, 074008 (2014).]**

- $|N\rangle = \sqrt{Z_2}\,|N\rangle_0 + \sum_{M,B} \int dy\, f_{MB}(y)\, |M(y); B(1-y)\rangle$

$y = k^+/P^+$: k meson, P nucleon

$$c(x) = \sum_{B,M} \left[\int_x^1 \frac{d\bar{y}}{\bar{y}}\, f_{BM}(\bar{y})\, c_B\!\left(\frac{x}{\bar{y}}\right) \right]$$

- a similar *convolution* procedure may be used for $\bar{c}(x)$ ...



amplitudes from hadronic **EFT**

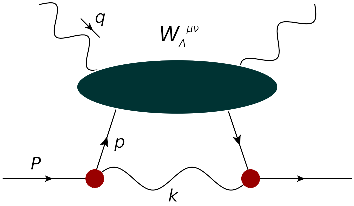
- *e.g.*, for the **dominant** contribution to $c(x)$, i.e., $\boxed{\Lambda_c D^*}$:

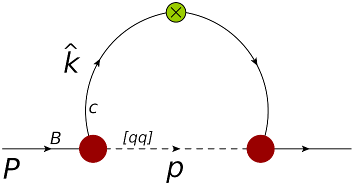
$$c(x) = \int_x^1 \frac{d\bar{y}}{\bar{y}}\, f_{\Lambda D^*}(\bar{y}) \cdot c_\Lambda\left(\frac{x}{\bar{y}}\right):$$

$$\mathcal{L}_{D^*\Lambda N} = g\,\bar{\psi}_N \gamma_\mu\, \psi_\Lambda\, \theta^\mu_{D^*} \;+\; \frac{f}{4M} \bar{\psi}_N \sigma_{\mu\nu} \psi_\Lambda\, F^{\mu\nu}_{D^*} \;+\; \text{h.c.}$$

$$\mathcal{L}_{c[qq]\Lambda} \;=\; g\,\bar{\psi}_\Lambda\, \psi_c\, \phi_{[qq]} \;+\; \text{h.c.}$$

quark model $\rightarrow$ had. g, f



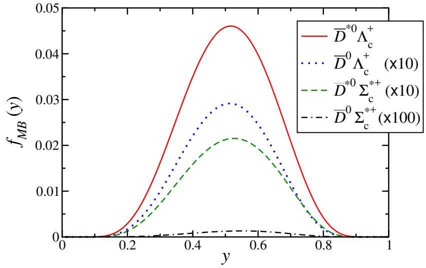


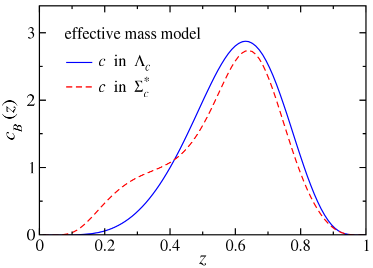
$\rightarrow$ evaluate forward-moving **TOPT** diagrams

hadron/parton **distributions**

$$f_{BD^*}(\bar{y}) = T_B \, \frac{1}{16\pi^2} \int dk_\perp^2 \, \frac{|\mathcal{F}(s_{BM})|^2}{(s_{BM} - M^2)^2} \, \frac{1}{\bar{y}(1-\bar{y})}$$
$$\times \left[g^2 \, G_v(\bar{y}, k_\perp^2) \; + \; \frac{gf}{M} \, G_{vt}(\bar{y}, k_\perp^2) \; + \; \frac{f^2}{M^2} \, G_t(\bar{y}, k_\perp^2) \right]$$

$$c_B(z) = N_B \, \frac{1}{16\pi^2} \int d\hat{k}_\perp^2 \, \frac{1}{z^2(1-z)} \, \frac{|\mathcal{F}(\hat{s})|^2}{(\hat{s} - M_B^2)^2} \left[\hat{k}_\perp^2 + (m_c + z M_B)^2 \right]$$





→ **model dependence** mainly from $\mathcal{F}(s)$,

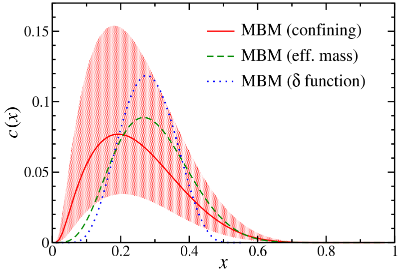
$$s(\bar{y}, k_\perp^2) \; = \; (M_\Lambda^2 + k_\perp^2)/\bar{y} \; + \; (m_D^2 + k_\perp^2)/(1 - \bar{y})$$

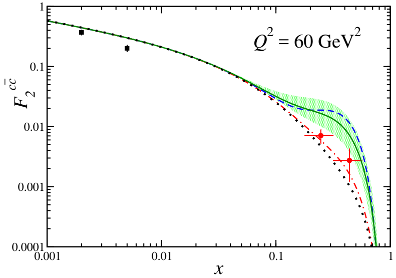
charm in the nucleon

- tune **universal** cutoff $\Lambda = \hat{\Lambda}$ to fit **ISR** $pp \to \Lambda_c X$ collider data

multiplicities, **momentum sum**:

$$\langle n \rangle^{(\text{charm})}_{MB} = 2.40\% \ {}^{+2.47}_{-1.36}; \qquad P_c := \langle x \rangle_{\text{IC}} = 1.34\% \ {}^{+1.35}_{-0.75}$$





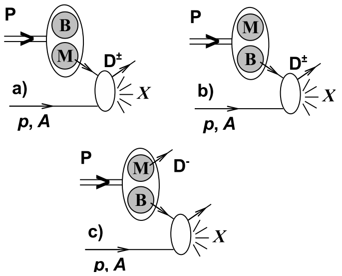
$$F_2^{c\bar{c}}(x, Q^2) = \frac{4x}{9} \left[c(x, Q^2) + \bar{c}(x, Q^2) \right]$$

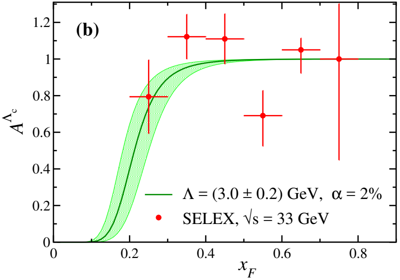
$\to$ evolve to EMC scale, $Q^2 = 60$ GeV^2

low-x H1/ZEUS data check *massless* **DGLAP** evolution

production **asymmetries**?

$$A^{\Lambda_c}(x_F) = \frac{\sigma^{\Lambda_c}(x_F) - \sigma^{\bar{\Lambda}_c}(x_F)}{\sigma^{\Lambda_c}(x_F) + \sigma^{\bar{\Lambda}_c}(x_F)} \qquad (\sigma^{\Lambda_c}(x_F) \equiv d\sigma^{\Lambda_c}/dx_F)$$





$$\frac{d\sigma^{\Lambda_c}}{dx_F} = \frac{d\sigma^{\Lambda_c}_{(\mathrm{val})}}{dx_F} + \frac{d\sigma^{\Lambda_c}_{(\mathrm{sea})}}{dx_F}$$

$$\frac{d\sigma^{\Lambda_c}_{(\mathrm{val})}}{dx_F} \approx \sigma_0 \sum_M f_{\Lambda_c M}(x_F)$$

$$\frac{d\sigma^{\Lambda_c}_{(\mathrm{sea})}}{dx_F} \equiv \frac{d\sigma^{\bar{\Lambda}_c}}{dx_F} \approx \bar{\sigma}_0 (1 - x_F)^{\bar{n}}$$

$$\rightarrow \boxed{A_{\Lambda_c}(x_F) = \frac{\sum_M f_{\Lambda_c M}(x_F)}{\sum_M f_{\Lambda_c M}(x_F) + 2\alpha(1-x_F)^{\bar{n}}}} \qquad (\alpha = \bar{\sigma}_0/\sigma_0,\ \bar{n} = 6.8)$$

systematics of global QCD analysis

extract/constrain quark densities:

$$F^{\gamma}_{qh}(x,Q^2) = \sum_f \int_0^1 \frac{d\xi}{\xi} C_i^{\gamma f}\left(\frac{x}{\xi}, \frac{Q^2}{\mu^2}, \frac{\mu_F^2}{\mu}, \alpha_S(\mu^2)\right) \cdot \phi_{f/h}(\xi, \mu_F^2, \mu^2)$$

- $C_i^{\gamma f}$: pQCD Wilson coefficients
- $\phi_{f/h}(\xi, \mu_F^2, \mu^2)$: *universal* parton distributions

(...here, $\mu_F^2 = 4m_c^2 + Q^2$)

$\Longrightarrow$ exploit properties of QCD to constrain models:

$$\sum_q \int_0^1 dx\, x \cdot \{f_{q+\bar{q}}(x,Q^2) + f_g(x,Q^2)\} \equiv 1 \quad \text{(mom. conserv.)}$$

- DGLAP: **couples** Q^2 evolution of $f_q(x,Q^2)$, $f_g(x,Q^2)$

constraints from **global** fits...

P. Jimenez-Delgado, TJH, J. T. Londergan and W. Melnitchouk; PRL 114, no. 8, 082002 (2015).

26 sets:

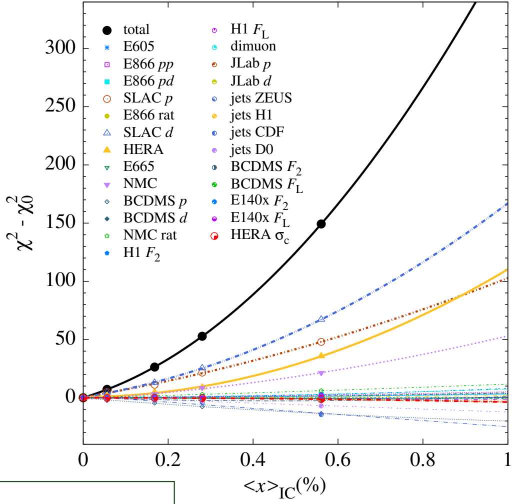
$N_{dat} = 4296$

$Q^2 \geq 1$ GeV^2

$W^2 \geq 3.5$ GeV^2

$\Longrightarrow$

** **HTs, TMCs, smearing...**



- constrain: $$\langle x\rangle_{IC} = \int_0^1 dx\, x \cdot [c+\bar{c}](x)$$ ... '*total* IC momentum'

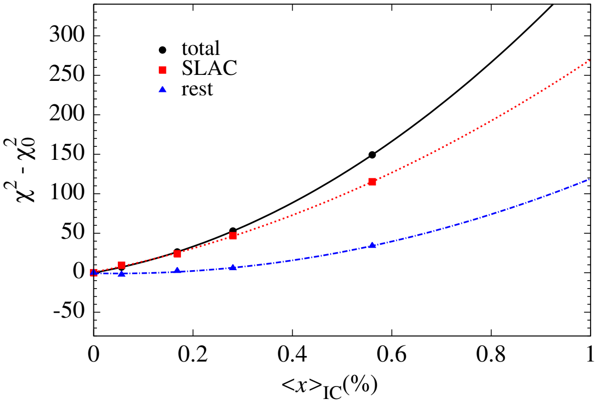
...without **EMC** $F_2^{c\bar{c}}$...

SLAC ep, ed data!

$\langle Q^2 \rangle \sim 15$ GeV^2

$0.06 \leq x \leq 0.9$

$(\chi^2/N_{dat} \sim 1.25)$



'SLAC + REST' $\Longrightarrow$ $\langle x \rangle_{\rm IC} < 0.1\%$; at 5σ !

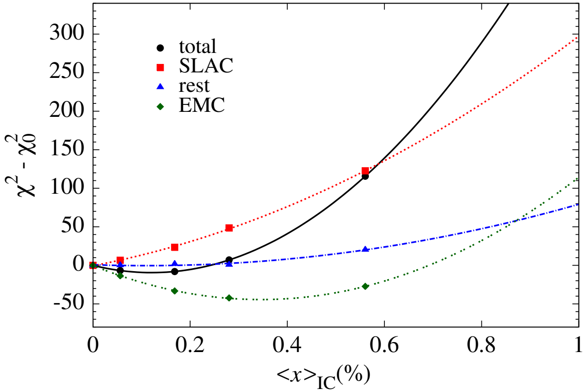
'REST' only $\Longrightarrow$ $\langle x \rangle_{\rm IC} < 0.1\%$; at 1σ

cf., $\langle x \rangle_{\rm IC} \sim 2 - 3\%$

e.g., **[S. Dulat et al., Phys. Rev. D 89, 073004 (2014).]**

N.B.: different *tolerances*: $\Delta\chi^2 = 1$ vs. $\Delta\chi^2_{CT} = 100$

...and constrained by **EMC**



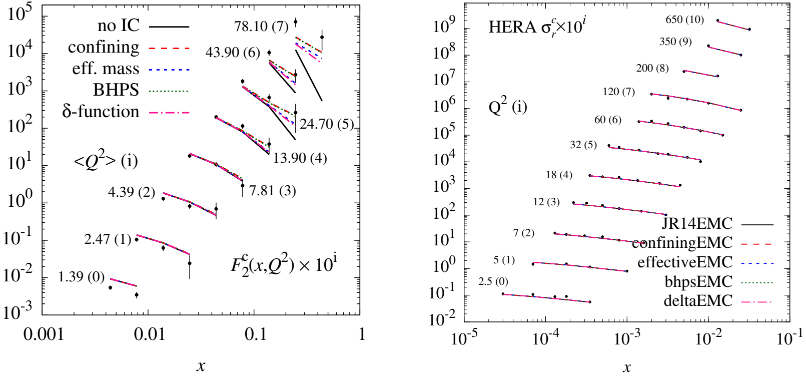
EMC alone: $\langle x \rangle_{\rm IC} = 0.3 - 0.4\%$

+ SLAC/'REST': $\boldsymbol{\langle x \rangle_{\rm IC} = 0.13 \pm 0.04\%}$

...but $F_2^{c\bar{c}}$ poorly fit — $\chi^2 \sim 4.3$ per datum!

data comparisons:

...*full* fits, constrained by EMC $F_2^{c\bar{c}}$ measurements:



- EMC: low-x/low-Q^2 tension with **HERA** σ_r^c
- $\frac{\tau_{life}}{\tau_{int}} = 5 \rightarrow$ for $Q^2 = 170$ GeV^2, EMC sensitive to IC at $x \lesssim 0.01$

$\rightarrow$ **more** $F_2^{c\bar{c}}$ **data** are needed!

new/ongoing global analyses

- **NNPDF3**: <u>not</u> anchored to specific parametrizations/models

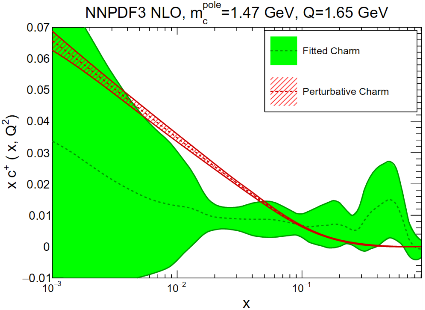
  see: Ball *et al.* Eur. Phys. J. **C76** (2016) no.11, 647

- *included* EMC:

$\langle x \rangle_{\rm IC} = 0.7 \pm 0.3\%$ at $Q \sim 1.5$ GeV

$\rightarrow$ drove a **very** hard $c(x) = \bar{c}(x)$ distribution

- peaked at $x \sim 0.5$
- AND, required a *negative* IC component to describe EMC $F_2^{c\bar{c}}$!



- complementary analyses for possible intrinsic **bottom**

  see: Lyonnet *et al.* JHEP**07** (2015) 141.

$\rightarrow$ would be negligible based on the analysis presented here...

future experimental prospects?

- jet hadroproduction: $pp \to (Zc) + X$ at **LHCb**

  e.g., Boettcher, **Ilten**, Williams, PRD**93**, 074008 (2016).

$\to$ a "direct" measure in the forward region, $2 < \eta < 5$

...sensitive to $c(x)$, $x \sim 1$ for *one* colliding proton

$\to$ can discriminate $\langle x \rangle_{\rm IC} \gtrsim 0.3\%$ ("valencelike"), 1% ("sealike")

- prompt atmospheric neutrinos?

  see: **Laha** & Brodsky, 1607.08240 (2016).

  $\to$ IceCube ν spectra may constrain IC normalization

- possible impact upon hidden charm **pentaquark**, P_c^+?

  e.g., Schmidt & Siddikov, PRD**93**, 094005 (2016).

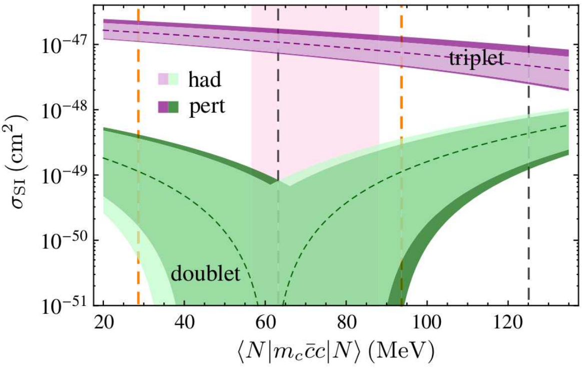
- AFTER@LHC? ... fixed-target pp at $\sqrt{s} = 115$ GeV

  Brodsky *et al.* Adv. High Energy Phys. **2015**, 231547 (2015). **[Signori]**

charm sigma term and DM?

- heavy-particle EFT: after integrating away WIMP scale,
  $\sigma_c = m_c \langle p|\bar{c}c|p\rangle$ dominant DM cross section contribution

  Hill and Solon, Phys. Rev. Lett. **112**, 211602 (2014).



- even with small $F_2^{c\bar{c}}(x, Q^2)$, σ_c may be *non-negligible!*

outlook

- have **model framework** for IC; contacts the $SU(4)$ spectrum

  ...when constrained by $pp \to \Lambda_c X$ data, *overpredicts* $F_2^{c\bar{c}}$

  $\to$ generates "smoking gun" $c(x) \neq \bar{c}(x)$ signal

- modeling necessitated a **QCD global analysis**:

  $\to$ severely limits $\langle x \rangle_{\rm IC} < 0.1\%$, 5σ (without EMC)

  $\to$ with EMC, $\langle x \rangle_{\rm IC} = 0.13 \pm 0.04\%$

  $\to$ improved measurements of $F_2^{c\bar{c}}$ at large x would be **definitive** ... (e.g., by fixed target **EICs**)!

- modeling/numerical analyses have reached an advanced stage

  $\to$ more **experimental information** is required, and diverse channels are available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