INT Heavy Flavor Workshop

Constraints to **nonperturbative** charm in the nucleon

T. Hobbs, NTG

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motivation

- understanding of charm critical to HEP phenomenology

  $\rightarrow$ through constraints to **PDF sets** and models in SM,

  $\rightarrow$ and **background** processes in collider physics

  $\rightarrow$ but also studies of hadronic bound-state structure!

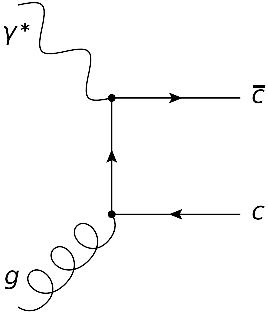
- knowledge of charm distributions may influence dynamics in **heavy-ion** physics

- relevance to searches for **exotic physics??**

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

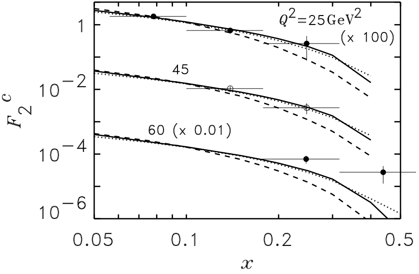
charm in **pQCD**

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



$\rightarrow$

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



- *intermediate* Q^2:

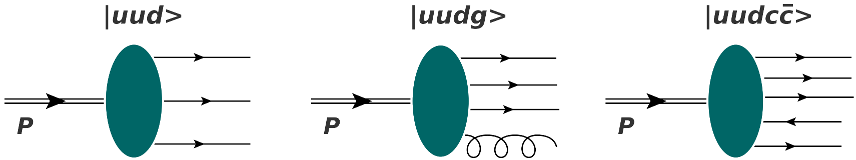
$$F^c_{2,\ \mathrm{PGF}}(x,Q^2) \;=\; \frac{\alpha_s(\mu^2)}{9\pi}\; \int_x^{z'}\; \frac{dz}{z}\; C^{\mathrm{PGF}}(z,Q^2,m_c^2)\cdot xg\left(\frac{x}{z},\mu^2\right)$$

- *high* Q^2:

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

nonperturbative heavy quarks

- a *long-standing* issue...



→ original models possessed *scalar* vertices...

- Brodsky et al. (1980):

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

$$\Longrightarrow P(x) = \frac{N x^2}{2} \left[\frac{(1-x)}{3} \left(1 + 10x + x^2\right) + 2x(1+x)\ln(x) \right]$$

- Pumplin (2006): $dP = \frac{g^2}{(16\pi^2)^{N-1}(N-2)!}$

$$\times \prod_{j=1}^{N} dx_j \, \delta\left(1 - \sum_{j=1}^{N} x_j\right) \int_{s_0}^{\infty} ds \, \frac{(s-s_0)^{N-2}}{(s-m_0^2)^2} \, |F(s)|^2$$

two-body **meson-baryon** models (**MBMs**)

...a **hadronic** effective field theory...

[TH, J. T. Londergan and W. Melnitchouk, Phys. Rev. D89, 074008 (2014).]

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

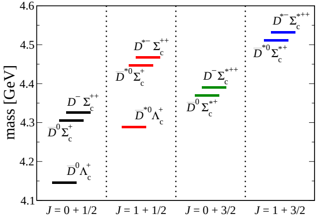
$y = k^+/P^+$: k meson, P nucleon

$$\boldsymbol{f_{MB}(y)} = \int_0^\infty dk_\perp^2\; f_{MB}(y, k_\perp^2) = \boldsymbol{f_{BM}(1 - y := \bar{y})}$$

$\rightarrow$ **convolution model** for $c(x,\mu^2) \neq \bar{c}(x,\mu^2) \neq 0$:

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

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



$f_{MB}(y)$: hadron-level $\qquad \bar{c}_M\left(\frac{x}{y}\right),\; c_B\left(\frac{x}{\bar{y}}\right)$: quark-level

amplitudes from hadronic **EFT**

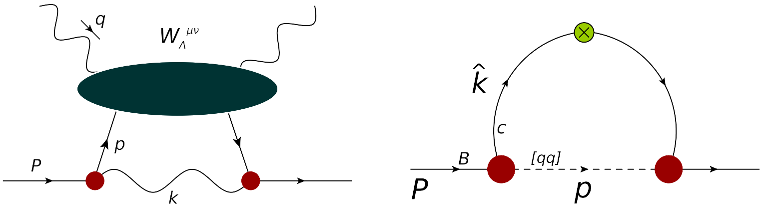
- for the **dominant** contribution to $c(x)$, i.e., $\boxed{\Lambda_c D^*}$:

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

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

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

quark model → had. g, f

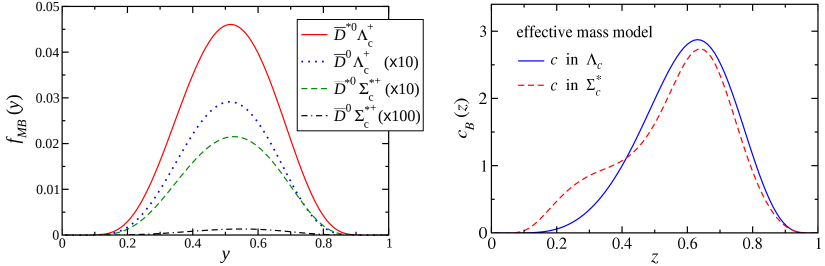


→ evaluate forward-moving **TOPT** diagrams

hadron/parton **distributions**

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

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



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

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

phenomenology of UV **regularization**

hadronic $f_{MB}(y)$ — **s-dependent** form factor, e.g.:

$$\to \boxed{F(s_{MB}) \;=\; \exp[\,-(s_{MB} - M^2)\;/\;\Lambda^2]} \leftarrow \text{used here}$$

or $F(s_{MB}) \;=\; \left(\frac{M^2+\Lambda^2}{M^2+s_{MB}}\right)^n \qquad n \in \{1,2\}$

quark-level $c, \bar{c}(z)$ — more *subtle*:

$$G(\hat{s}) \;=\; \exp\left[-(\hat{s} - m_D^2)/\hat{\Lambda}^2\right]$$
$$\hat{s}(z, \hat{k}_\perp^2) \;=\; (m_{\bar{c}}^2 + \hat{k}_\perp^2)/z \;+\; (m_q^2 + \hat{k}_\perp^2)/(1-z)$$

...but the numerical $\hat{s} = m_H^2$ **pole** must be **controlled**!

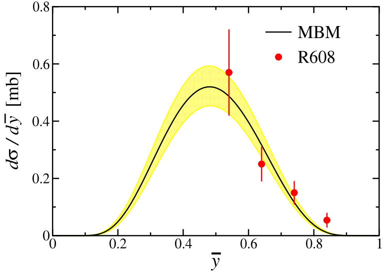
- "effective" mass scheme: $m_{\bar{c}}^{\rm eff} + m_q^{\rm eff} > m_D$
- "confining" prescription:

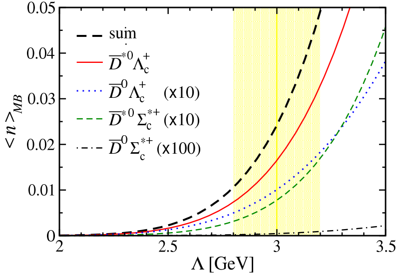
$$G(\hat{s}) \;=\; (\hat{s} - m_D^2)\,\exp\left[-(\hat{s} - m_D^2)/\hat{\Lambda}^2\right]$$

constraints from **hadroproduction**

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

  [*left*] P. Chauvat *et al.*, Phys. Lett. B **199**, 304 (1987).





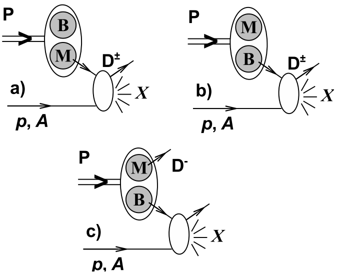
$$\langle n \rangle_{MB} \equiv \mathcal{F}^{(0)}_{MB}; \qquad \mathcal{F}^{(n)}_{MB} = \int_0^1 dy\, y^n\, f_{MB}(y)$$

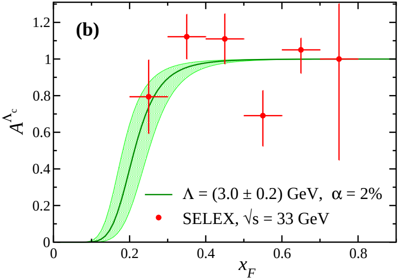
D^* **tensor** interaction $\Longrightarrow$ rapid growth in $\langle n \rangle_{MB}$

...fixes narrow range, $\Lambda = (3.0 \pm 0.2)$ GeV

production **asymmetries**?

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





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

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

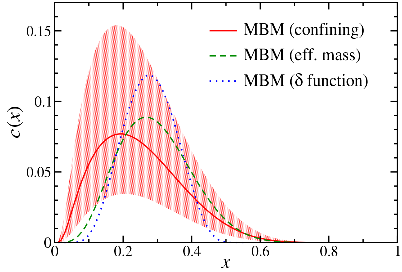
$$\frac{d\sigma^{\Lambda_c}_{(\mathrm{sea})}}{dx_F} \equiv \frac{d\sigma^{\bar{\Lambda}_c}}{dx_F} \approx \bar{\sigma}_0 (1 - x_F)^{\bar{n}}$$

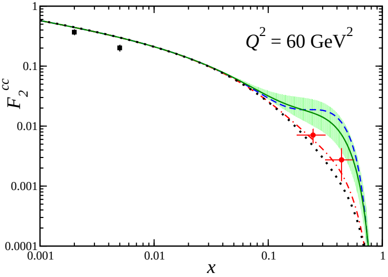
$$\rightarrow \boxed{A_{\Lambda_c}(x_F) = \frac{\sum_M f_{\Lambda_c M}(x_F)}{\sum_M f_{\Lambda_c M}(x_F) + 2\alpha(1-x_F)^{\bar{n}}}} \qquad (\alpha = \bar{\sigma}_0/\sigma_0,\ \bar{n} = 6.8)$$

charm in the nucleon

multiplicities, momentum sum:

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





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

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

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

- Glob. Analysis: P. J. Delgado, TH, J. T. Londergan and W. Melnitchouk, arXiv:1408.1708

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 $f_q(x,Q^2)$, $f_g(x,Q^2)$

quark/target **mass-dependent** PDFs

simple, **three-parameter fits** to MBM...

$$c(x) = C^{(0)}\, A\, x^{\alpha}(1-x)^{\beta}\ , \qquad \bar{c}(x) = C^{(0)}\, \bar{A}\, x^{\bar{\alpha}}(1-x)^{\bar{\beta}}$$

- rescale input PDFs via *modified* Nachtmann variables:

$$c(x) \quad \rightarrow \quad c(\xi_c, \gamma_c) \;=\; c(\xi_c) - \frac{\xi_c}{\gamma_c}\, c(\gamma_c) \quad \Longleftrightarrow \quad \xi_c < \gamma_c$$

$$= 0 \quad \Longleftrightarrow \quad \xi_c \geq \gamma_c$$

$$\xi_c \;=\; \frac{2ax}{\left(1+\sqrt{1+4x^2M^2\big/Q^2}\right)}\ , \qquad a = \frac{1}{2}\left(1+\sqrt{1+4{m_c}^2\big/Q^2}\right)$$

$$\Longrightarrow \xi_c < \gamma_c$$

M: **nucleon**

$$\gamma_c \equiv \xi_c(\hat{x}); \qquad \hat{x} := Q^2\big/(Q^2+4m_c^2+M^2)$$

FFNS in the charm sector

$$F_2 = F_2^{\text{light}} + F_2^{\text{heavy}} \quad \rightarrow \quad F_2^c = F_2^{c\bar{c}} + F_2^{\text{IC}}$$

$$F_2^{c\bar{c}}(x, Q^2, m_c^2) = \frac{Q^2 \alpha_s}{4\pi^2 m_c^2} \sum_q \int \frac{dz}{z} \, \hat{\sigma}_q(\eta, \xi) \cdot f_q\left(\frac{x}{z}, \mu_F\right)$$

- $\hat{\sigma}_q$: hard partonic cross section at **NLO**

$$F_2^{\text{IC}} = \frac{4x^2}{9(1+4x^2M^2/Q^2)^{3/2}} \left\{ \frac{1+4m_c^2/Q^2}{\xi_c} \Big(c(\xi_c, \gamma_c) + \bar{c}(\xi_c, \gamma_c) \Big) + 3\hat{g}(\xi_c, \gamma_c) \right\}$$

$$\hat{g}(\xi_c, \gamma_c) = \frac{2xM^2/Q^2}{(1+4x^2M^2/Q^2)} \int_{\xi_c}^{\gamma_c} \frac{dt}{t} \, (c(t, \gamma_c) + \bar{c}(t, \gamma_c)) \times \left[1 + 2xtM^2/Q^2 + 2xM^2/(tQ^2)\right] \cdot \left(1 - \frac{m_c^2}{t^2 M^2}\right)$$

- compute with ‘confining’ $c(x), \bar{c}(x)$; fit normalization!

constraints from **global** fits...

**[P.Jimenez-Delgado, E. Reya, Phys. Rev. D 89, 074049 (2014)]

26 sets:

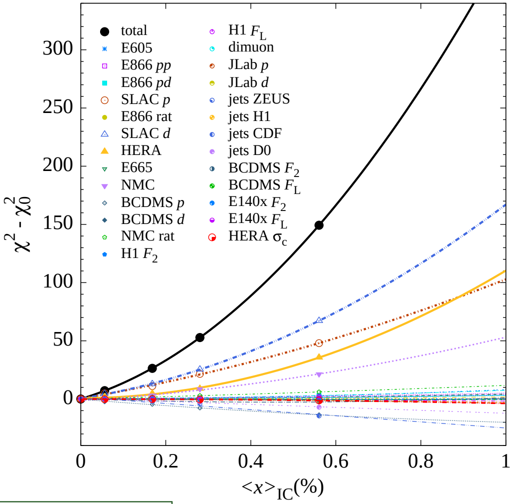
$N_{dat} = 4296$

$Q^2 \geq 1$ GeV^2

$W^2 \geq 3.5$ GeV^2

$\Longrightarrow$

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



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

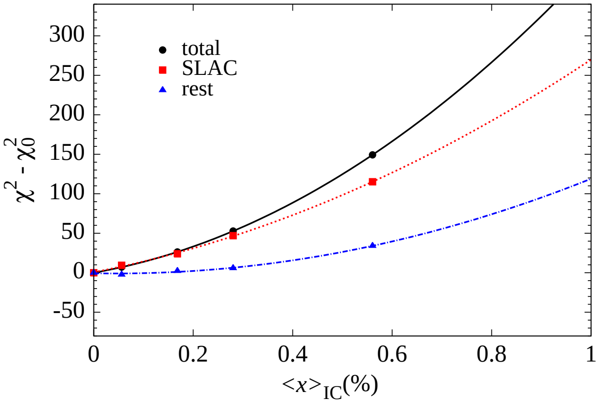
...without EMC $F_2^{c\bar{c}}$...

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 !

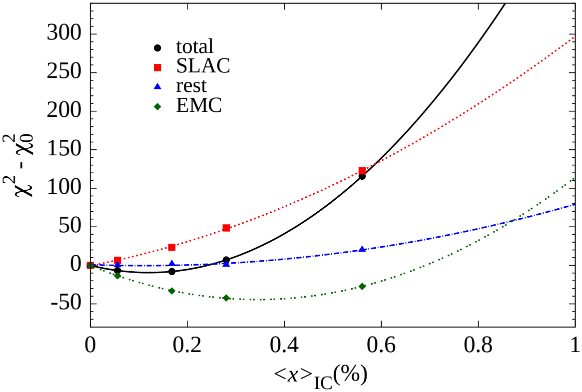
'REST' only $\Longrightarrow$ $\langle x \rangle_{\rm IC} < 0.1\%$; at 1σ

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



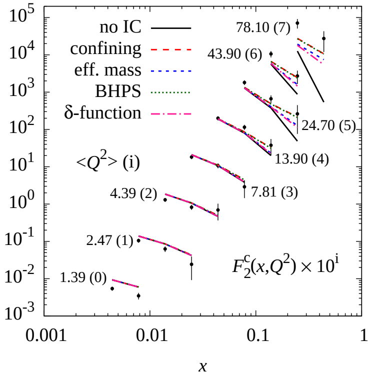
EMC alone: $\langle x \rangle_{\rm IC} = 0.3 - 0.4\%$

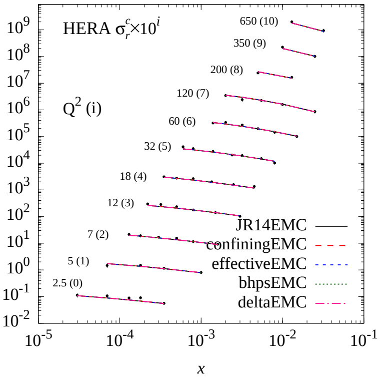
+ **SLAC/'REST':** $\boldsymbol{\langle x \rangle_{\rm IC} = 0.13 \pm 0.04\%}$

...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

  $\Longrightarrow$ many analyses (**CT, NNPDF, ...**) omit F_2^{EMC}

outlook

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

  $\longrightarrow$ portable to other **flavor** sectors (*strangeness*??)

- when constrained by hadroproduction data, overpredicts $F_2^{c\bar{c}}$

  $\longrightarrow$ generates standard $c(x) \neq \bar{c}(x)$ signal

  $\longrightarrow$ other physics at work in $pp \to \Lambda_c X$?

- model incorporated into **global analysis**:

  $\longrightarrow$ severely limits $\langle x \rangle_{\mathrm{IC}} < 0.1\%, \quad 5\sigma$ (without EMC)

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

  $\longrightarrow$ improved measurements at large x would be definitive (e.g., by fixed target **EICs**)!

... thank-you ...