XIIth Confinement and the Hadron Spectrum,
$\Theta\varepsilon\sigma\sigma\alpha\lambda o\nu\iota\kappa\eta$.
Section E; QCD and New Physics
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Recent progress on **intrinsic charm**

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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 by R. Vogt/J. P. Lansberg*)

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

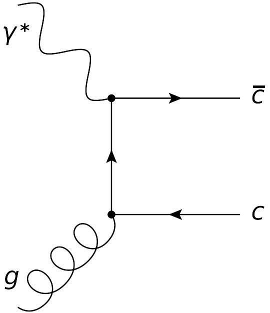
- relevance to searches for **new physics??**

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

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

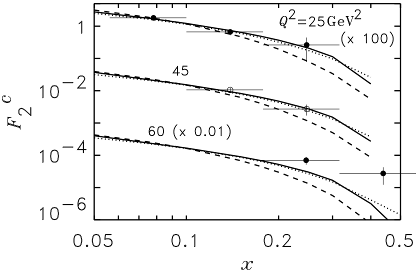
charm in *perturbative* **QCD** (pQCD)

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



→

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



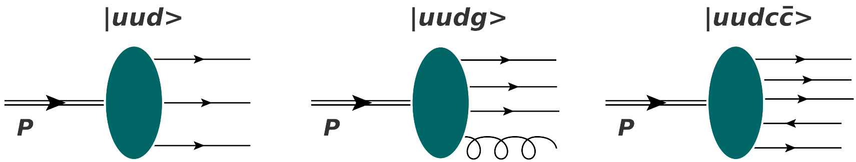
- *intermediate* Q^2:

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

- *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, $c^{\rm IC}(x) = \bar{c}^{\rm IC}(x)$

- 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 <u>break</u>

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

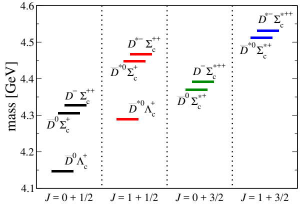
We build an **EFT** which connects IC to properties of the hadronic spectrum: **[TH, J. T. Londergan and W. Melnitchouk, Phys. Rev. D89, 074008 (2014).]**

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

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

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

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



amplitudes from hadronic **EFT**

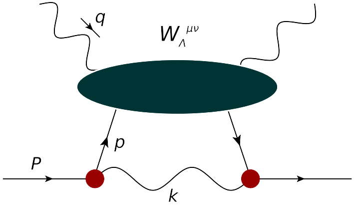
- *e.g.*, for the **dominant** contribution to $c(x)$, i.e., $\boxed{\Lambda_c D^*}$:

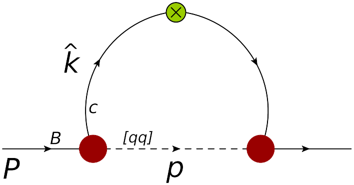
$$c(x) = \int_x^1 \frac{d\bar{y}}{\bar{y}}\, f_{\Lambda D^*}(\bar{y}) \cdot c_\Lambda\left(\frac{x}{\bar{y}}\right):$$

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

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

quark model → had. g, f



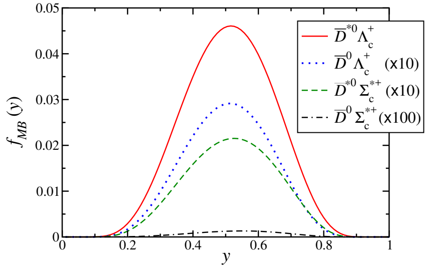


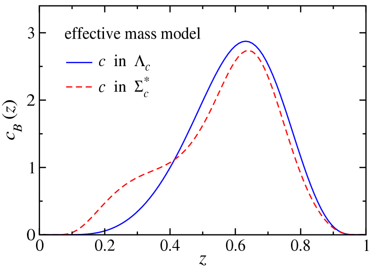
→ evaluate forward-moving **TOPT** diagrams

hadron/parton **distributions**

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

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





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

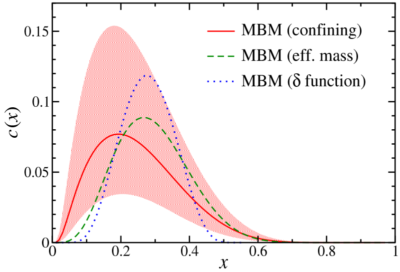
$$s(\bar{y}, k_\perp^2) \;=\; (M_\Lambda^2 + k_\perp^2)/\bar{y} \;+\; (m_D^2 + k_\perp^2)/(1-\bar{y})$$

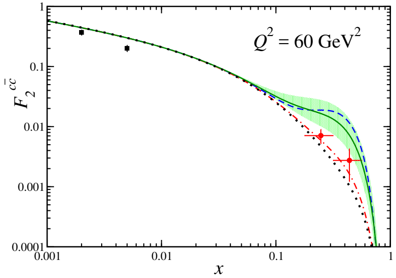
charm in the nucleon

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

multiplicities, **momentum sum**:

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





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

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

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

constraints from **global** fits...

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

26 sets:

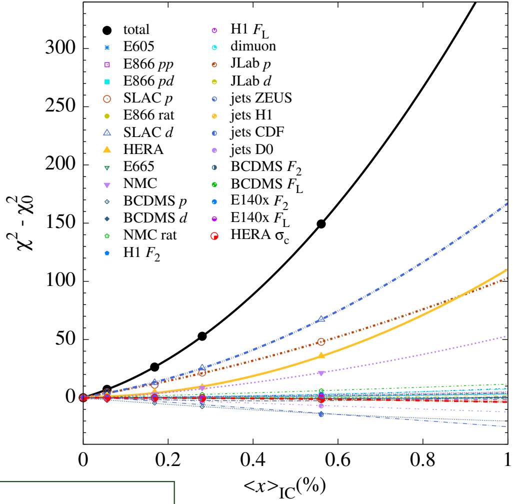
$N_{dat} = 4296$

$Q^2 \geq 1$ GeV^2

$W^2 \geq 3.5$ GeV^2

$\Longrightarrow$

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



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

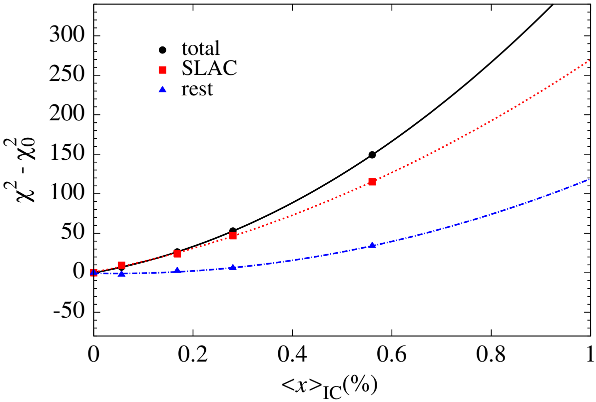
...without **EMC** $F_2^{c\bar{c}}$...

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' $\Longrightarrow$ $\langle x \rangle_{\mathrm{IC}} < 0.1\%$; at 5σ !

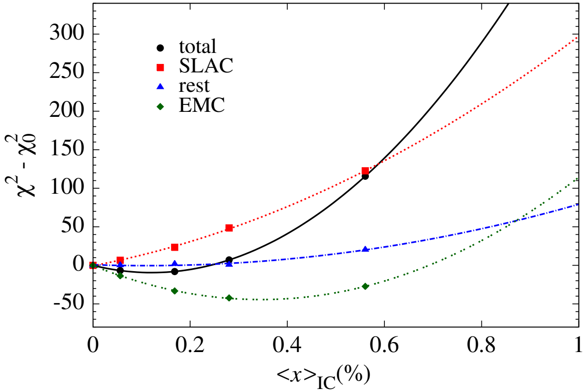
'REST' only $\Longrightarrow$ $\langle x \rangle_{\mathrm{IC}} < 0.1\%$; at 1σ

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

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**



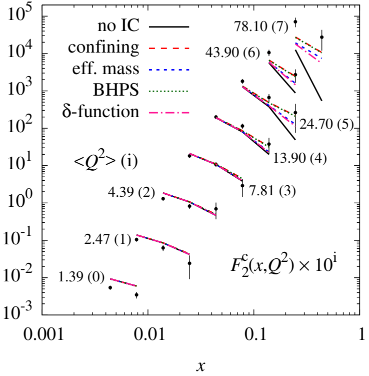
EMC alone: $\langle x \rangle_{\rm IC} = 0.3 - 0.4\%$

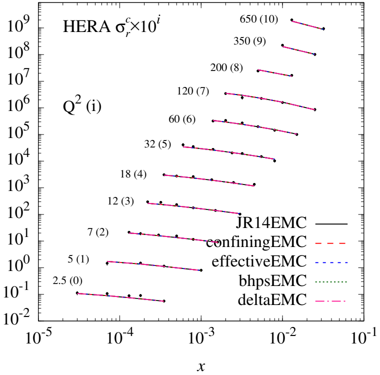
+ **SLAC**/**'REST'**: $\langle x \rangle_{\rm IC} = \mathbf{0.13 \pm 0.04\%}$

...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**: not anchored to specific parametrizations/models

  see: Ball *et al.* 1605.06515

- *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).

outlook

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

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

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

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

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

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

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

- modeling/numerical analyses have reached an advanced stage

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

... thank you ...