CSSM/CoEPP, University of Adelaide
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How much intrinsic charm is there in the nucleon?

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Outline

- Models of intrinsic charm in the nucleon
- Constraints from hadronic reactions
- Limits from global QCD analysis of high-energy data
- Outlook

BHPS model

- Possibility of intrinsic charm (IC) component in nucleon suggested by Brodsky, Hoyer, Peterson, Nakai (BHPS) ~ 35 years ago

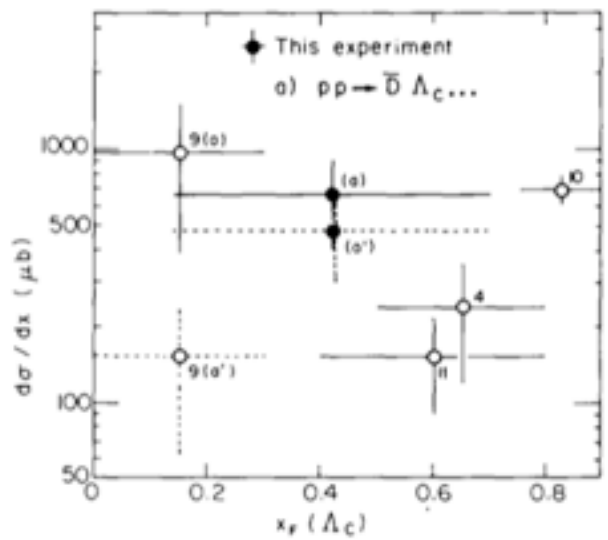
THE INTRINSIC CHARM OF THE PROTON *Phys. Lett.* **93B**, 451 (1980)

S.J. BRODSKY [1]
Stanford Linear Accelerator Center, Stanford, California 94305, USA

and

P. HOYER, C. PETERSON and N. SAKAI [2]
NORDITA, Copenhagen, Denmark

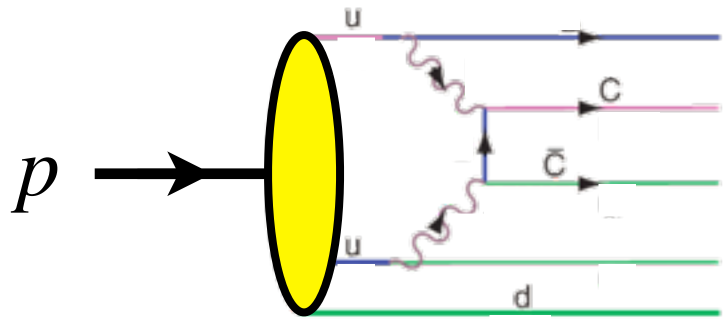
→ inspired by larger than expected production cross sections in *e.g.* $pp \to \overline{D}\Lambda_c X$ at CERN's ISR
(100s μb *cf.* 10s μb)



Phys. Lett. **99B**, 495 (1981)

BHPS model

- Significant (nonperturbative) 5-quark component of nucleon wave function, estimated at "O(1%)", could account for magnitude of new data



- While perturbative gluon radiation + $g \to q\bar{q}$ splitting generally results in symmetric sea quark content, nonperturbatively no reason for $c = \bar{c}$, just as $s \neq \bar{s}$ or $\bar{d} \neq \bar{u}$

BHPS model

- Transition probability (in infinite momentum frame)

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

$i = 4, 5$ for $c, \bar{c}$

- Neglecting transverse momentum and assuming heavy quark limit, $m_{c,\bar{c}} \gg M, m_{1,2,3}$

⟶ probability to produce a single charm quark

$$P(x_5) = \frac{N x_5^2}{2} \left[\frac{(1-x_5)}{3} \left(1 + 10x_5 + x_5^2\right) + 2x_5(1+x_5)\ln(x_5) \right]$$

$N = 3600$

⟶ average momentum fraction $\langle x_5 \rangle = 2/7$
cf. $\langle x_1 \rangle = 1/7$ for light quark distribution

⟶ IC predicted to be at *high* momentum fractions x

Scalar 5-quark model

- Generalisation to include finite size of nucleon

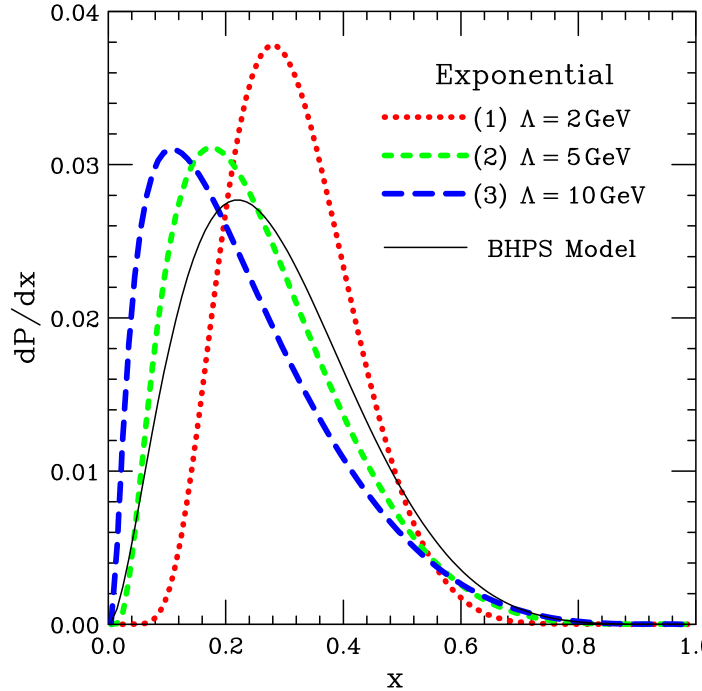
$$dP = \frac{g^2}{(16\pi^2)^{N-1}(N-2)!} \prod_{j=1}^{N} dx_j \, \delta\left(1 - \sum_{j=1}^{N} x_j\right) \int_{s_0}^{\infty} ds \, \frac{(s-s_0)^{N-2}}{(s-m_0^2)^2} |F(s)|^2$$

*Pumplin, PRD **73**, 114015 (2006)*

invariant mass squared $s_0 = \sum_{j=1}^{N} \frac{m_j^2}{x_j}$

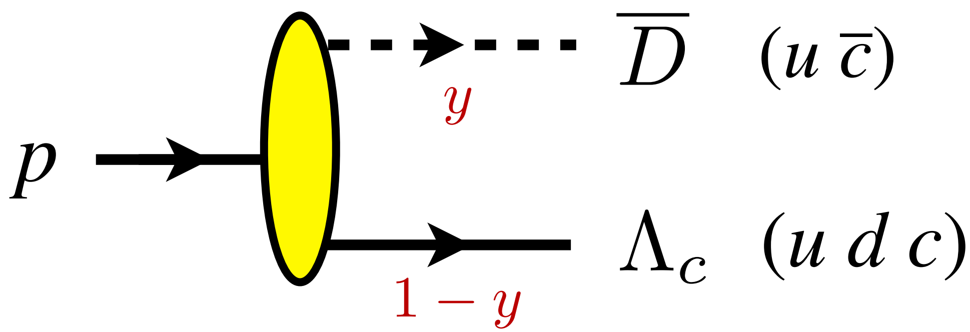
form factor at $N\!-\!qqqc\bar{c}$ vertex

$$|F(s)|^2 = \exp\left[-(s-m_0^2)/\Lambda^2\right]$$



Meson-baryon model

- Fluctuations of nucleon to virtual states with meson & baryon quantum numbers



$$|N\rangle = \sqrt{Z_2}\,|N\rangle_0 + \sum_{M,B}\int dy\, d^2k_\perp\, \phi_{MB}(y,k_\perp^2)\,|M(y,k_\perp);B(1-y,-k_\perp)\rangle$$

wave function renormalization

"bare" 3-quark state

$N \rightarrow M+B$ probability amplitude

longitudinal (or light-cone) momentum fraction

Meson-baryon model

- Charm distributions in nucleon as convolutions of $N \to MB$ splitting functions and distributions inside charmed meson & baryons

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

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

$\longrightarrow$ meson–baryon splitting function

$$f_{MB}(y) = \int_0^\infty d^2k_\perp\, |\phi_{MB}(y, k_\perp^2)|^2 \;=\; f_{BM}(\bar{y})$$

with normalization

$$\langle n \rangle_{MB} = \int_0^1 dy\, f_{MB}(y)$$

Meson-baryon model

- Charm distributions in nucleon as convolutions of $N \to MB$ splitting functions and distributions inside charmed meson & baryons

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

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

$\longrightarrow$ naturally predicts asymmetric charm distributions

$$c(x) \neq \bar{c}(x)$$

Meson-baryon model

- Charm distributions in charmed hadrons, *e.g.* $\bar{c}$ in $\bar{D}$ meson

$$\bar{c}_D(z) = \frac{N_D}{16\pi^2} \int_0^\infty \frac{d\hat{k}_\perp^2}{[z(1-z)]^2} \frac{|G(\hat{s})|^2}{(\hat{s}-m_D^2)^2} \left[\hat{k}_\perp^2 + (z\, m_q + (1-z)\, m_{\bar{c}})^2\right]$$

invariant mass of the $\bar{c}q$ system $\hat{s} = \dfrac{m_{\bar{c}}^2 + \hat{k}_\perp^2}{z} + \dfrac{m_q^2 + \hat{k}_\perp^2}{1-z}$

form factor for $\bar{D}$-$\bar{c}q$ vertex $G(\hat{s})$

→ mass singularity in energy denominator regularized by

- "effective" quark masses such that

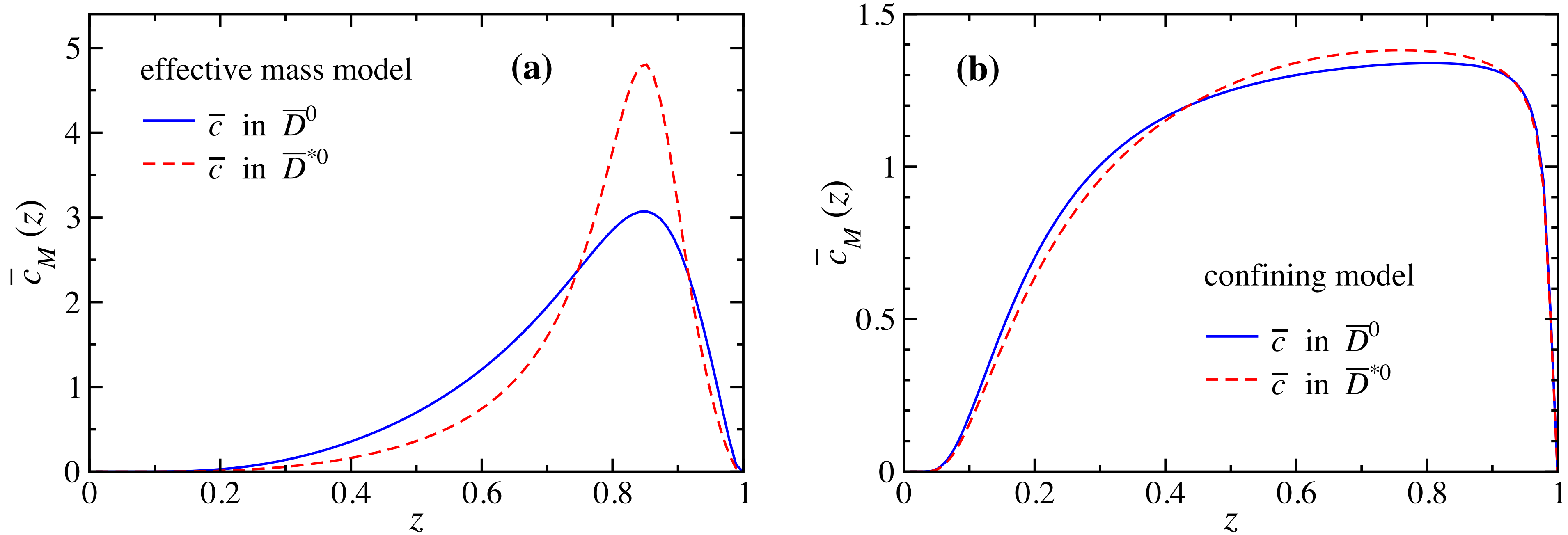
$$m_{\bar{c}}^{\rm eff} + m_q^{\rm eff} > m_D$$

- modeling vertex function such that

$$G(\hat{s}) \propto (\hat{s} - m_D^2)$$

Meson-baryon model

- Charm distributions in charmed hadrons, $e.g.\ \bar{c}$ in $\bar{D}$ meson

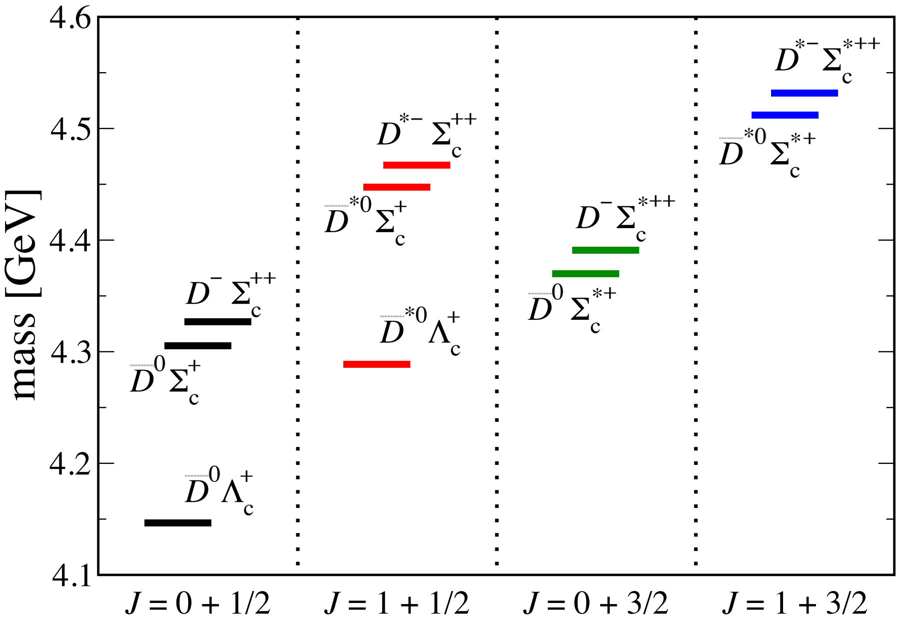


*Hobbs et al., PRD **89**, 074008 (2014)*

→ shape depends somewhat on regularization procedure

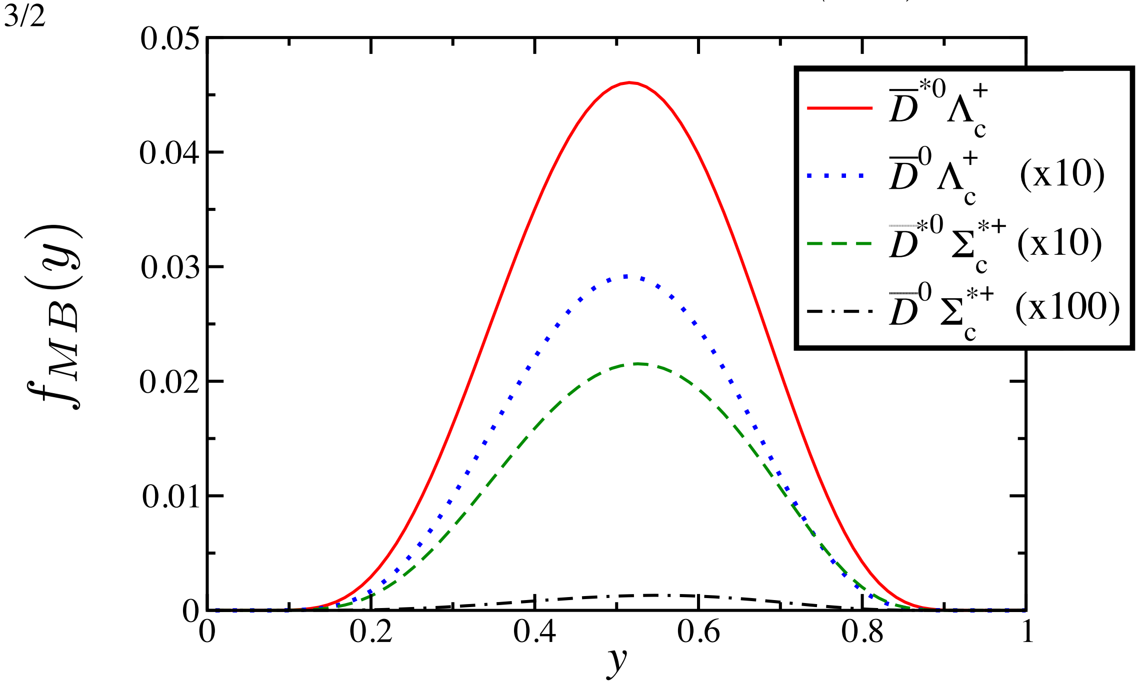
Meson-baryon model

- Including spectrum of lowest-lying charmed states



→ splitting functions for exponential *NMB* form factor with $\Lambda = 3\ \text{GeV}$

*Hobbs et al., PRD **89**, 074008 (2014)*



Constraints from hadronic reactions

- Cutoff parameter fitted to hadronic $p\,p \to \Lambda_c\,X$ data

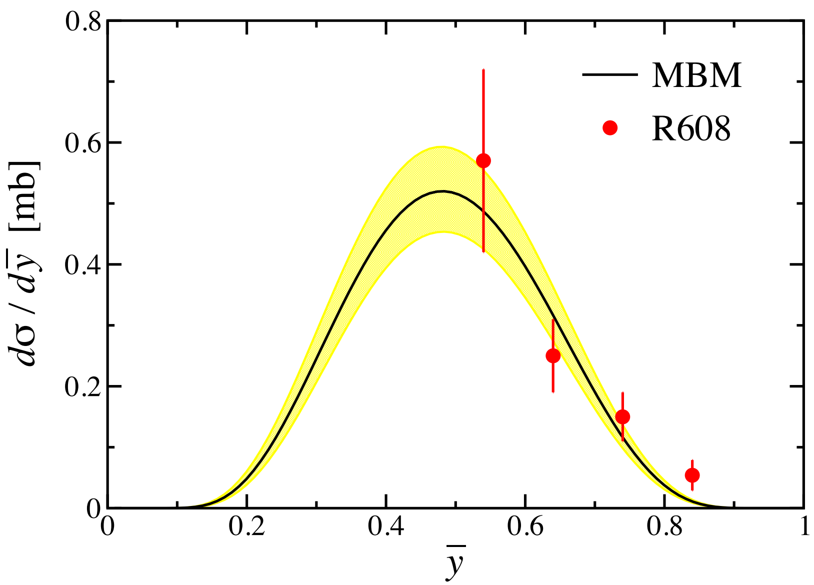
$$E\frac{d^3\sigma}{d^3p} \;=\; \frac{\bar{y}}{\pi}\frac{d^2\sigma}{d\bar{y}\,dk_\perp^2} \;=\; \frac{\bar{y}}{\pi}\sum_M \left|\phi_{BM}(\bar{y},k_\perp^2)\right|^2\,\sigma_{\rm tot}^{Mp}(sy)$$

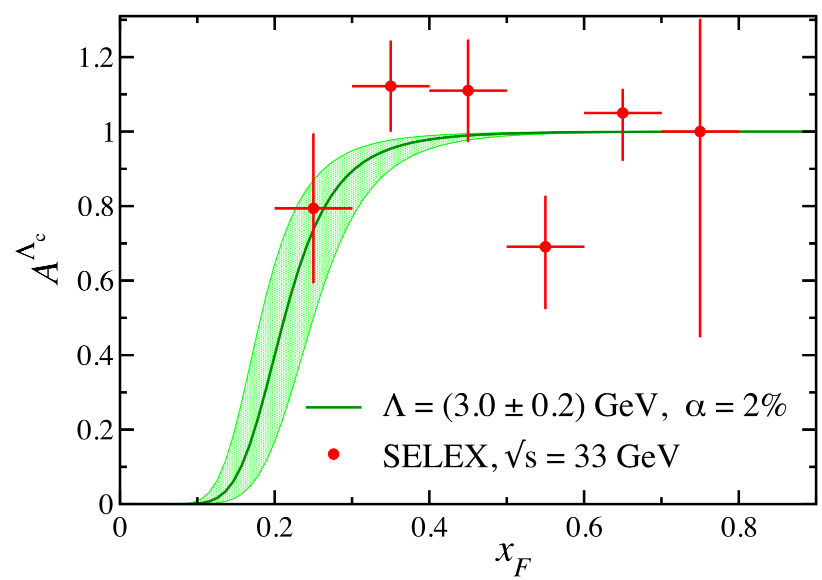
$$\frac{d\sigma}{d\bar{y}} = \sum_{M=D,D^*} f_{\Lambda_c^+ M}(\bar{y})\,\sigma_{\rm tot}^{Mp}(sy)$$

$$A^{\Lambda_c}(x_F) = \frac{\sigma^{\Lambda_c}(x_F) - \sigma^{\bar{\Lambda}_c}(x_F)}{\sigma^{\Lambda_c}(x_F) + \sigma^{\bar{\Lambda}_c}(x_F)}$$

$$\sigma^{\Lambda_c}_{(\rm val)} \approx \sigma_0 \sum_M f_{\Lambda_c M}(x_F)$$

Hobbs et al., PRD ***89****, 074008 (2014)*



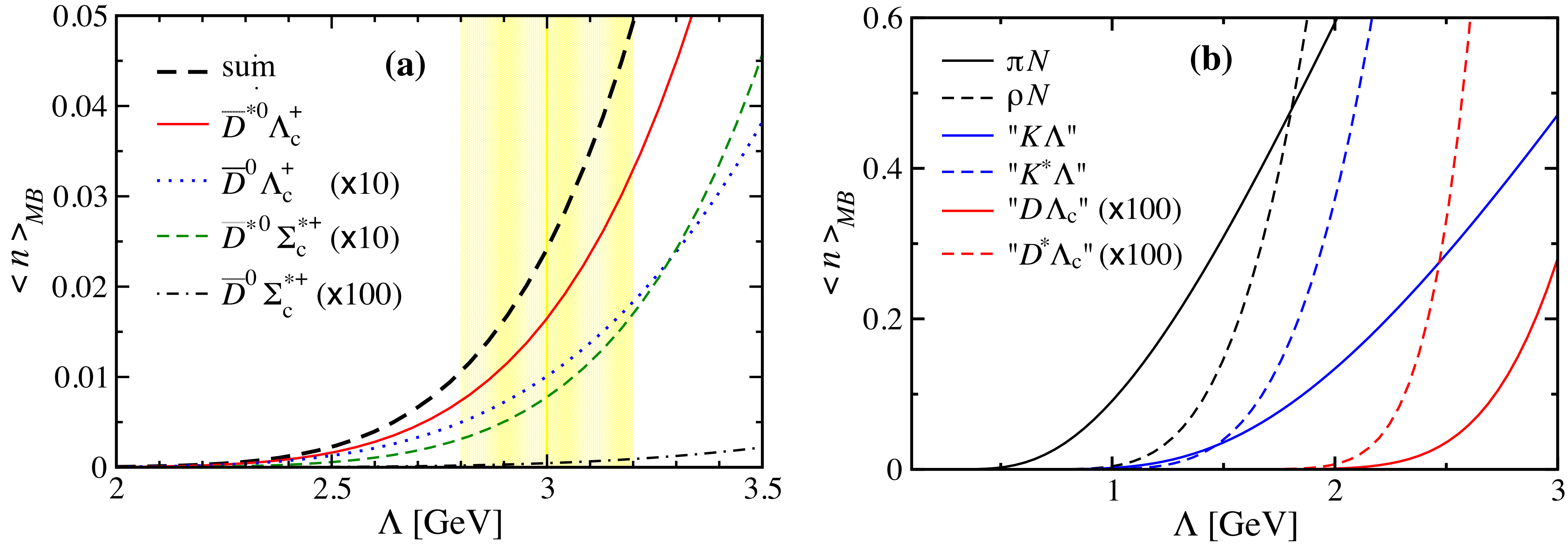


$x_F = 2p^0_\Lambda/\sqrt{s}$

Constraints from hadronic reactions

- Hadronic data prefer relatively large cutoffs ~ 3 GeV, with hadronic couplings from SU(4) symmetry and "typical" charm cross sections

$$\sigma_{\rm tot}^{Dp} \approx \sigma_{\rm tot}^{D^*p} \approx \sigma_{\rm tot}^{\overline{K}p} \approx (20 \pm 10)\ \rm mb$$



$\longrightarrow$ average probability $\langle n \rangle_{MB}^{(\rm charm)} = 2.4\%$ (from ~1% to ~5%)

Intrinsic charm in DIS

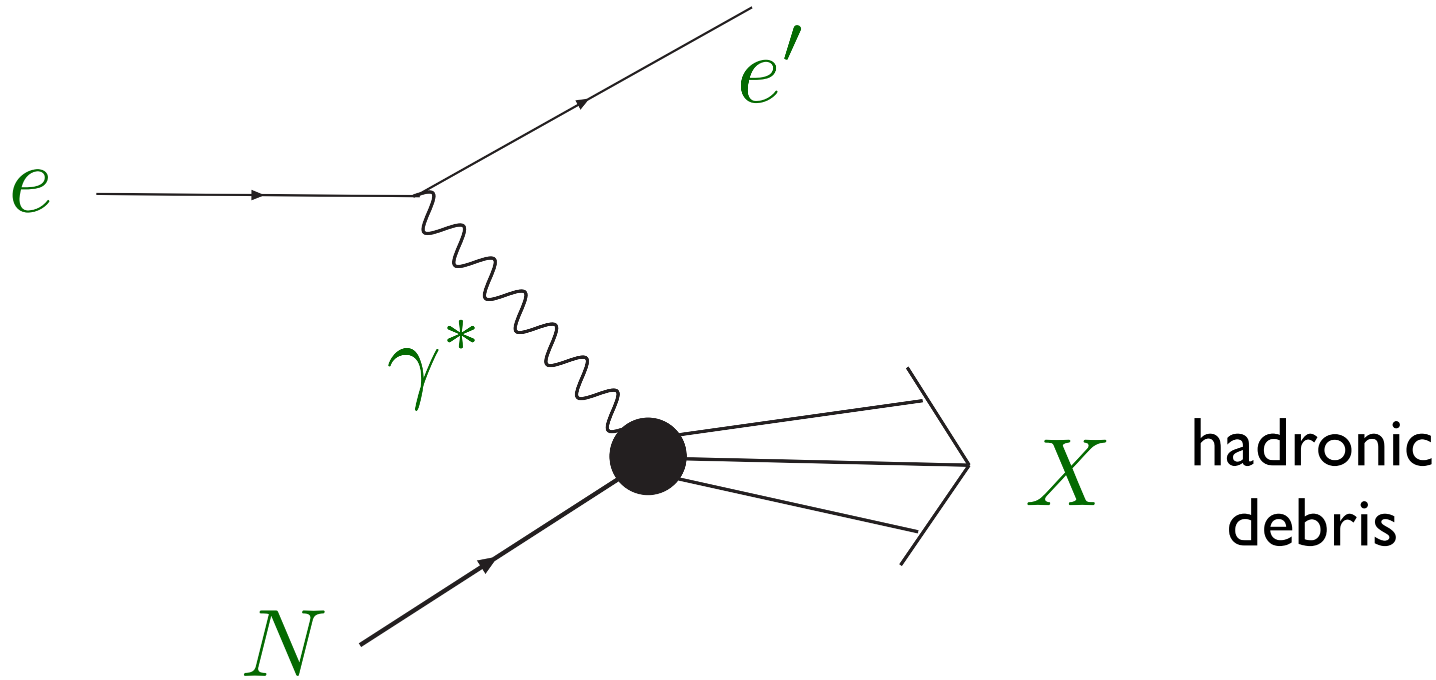
- Cleanest signal of IC may be from charm structure function in deep-inelastic scattering

> “ (b) The most direct test of our ideas would be to study *charm production in deep inelastic ep or μp scattering.* The existence of the uudc$\bar{c}$ component should manifest itself in charm production at large x ”

BHPS, Phys. Lett. ***93B****, 451 (1980)*

Lepton-nucleon deep-inelastic scattering

- Inclusive cross section for $\ell N \to \ell X$

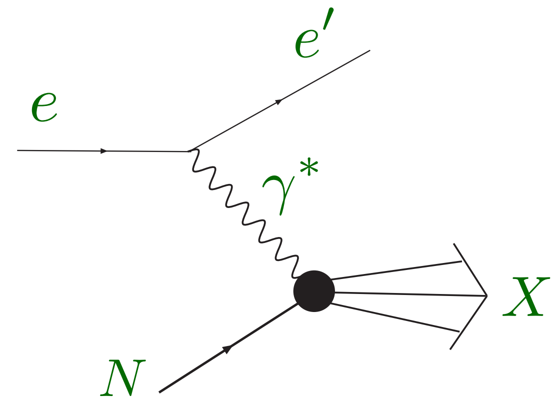


$\longrightarrow$ one-photon exchange approximation

Lepton-nucleon deep-inelastic scattering

- Inclusive cross section for $\ell N \to \ell X$

$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$



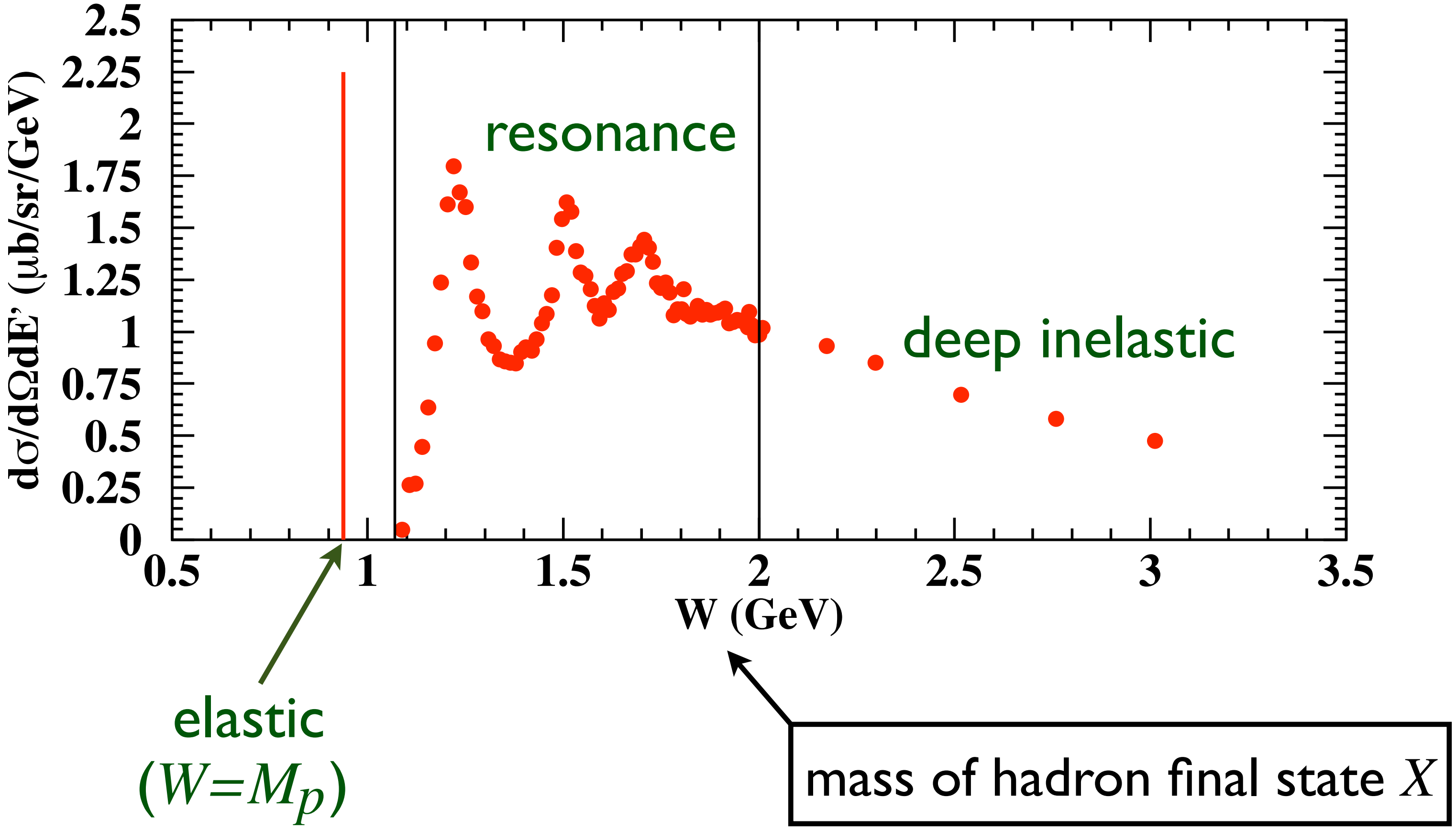
$$\left.\begin{aligned} \nu &= E - E' \\ Q^2 &= \vec{q}^2 - \nu^2 = 4EE'\sin^2\frac{\theta}{2} \end{aligned}\right\} \quad x = \frac{Q^2}{2M\nu}$$

Bjorken scaling variable

- Structure functions F_1, F_2

⟶ contain all information about structure of nucleon
(δ-functions for point-like particles)

Lepton-nucleon deep-inelastic scattering



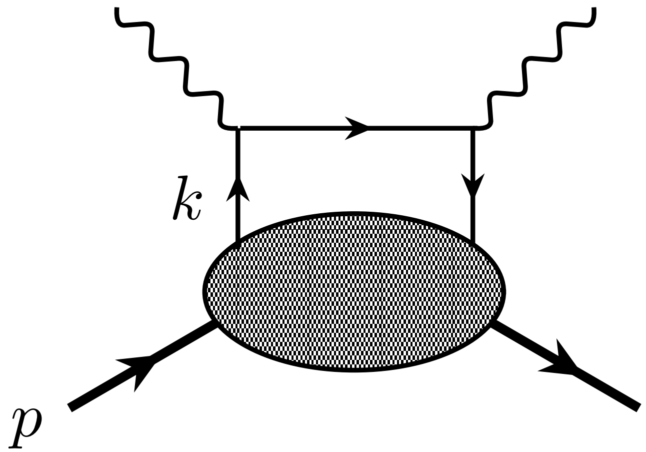
Bjorken variable in terms of Q^2 & W : $x = \dfrac{Q^2}{W^2 - M^2 + Q^2}$

Lepton-nucleon deep-inelastic scattering

Parton model

→ scatter from individual quarks (“*partons*”) in nucleon

$$F_2(x, Q^2) = x \sum e_q^2 \, q(x, Q^2) \qquad (q{=}u,d,s\ldots)$$



→ $q\,(x,Q^2)$ = probability to find quark type “q” in nucleon, carrying (light-cone) momentum fraction x

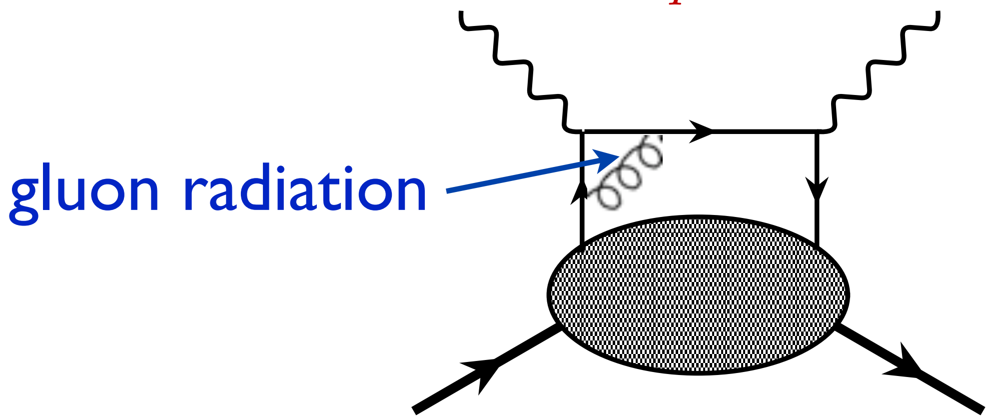
$$x = \frac{k^+}{p^+} = \frac{k^0 + k^z}{p^0 + p^z}$$

Lepton-nucleon deep-inelastic scattering

Parton model

→ scatter from individual quarks ("*partons*") in nucleon

$$F_2(x, Q^2) = x \sum_q e_q^2 \; q(x, Q^2) \qquad (q{=}u{,}d{,}s\ldots)$$



→ at finite energy, Q^2 dependence given by (perturbatively calculable) QCD evolution equations

$$F_2 \to F_2(x, \log Q^2)$$

Intrinsic charm in DIS

- Cleanest signal of IC may be from charm structure function in deep-inelastic scattering

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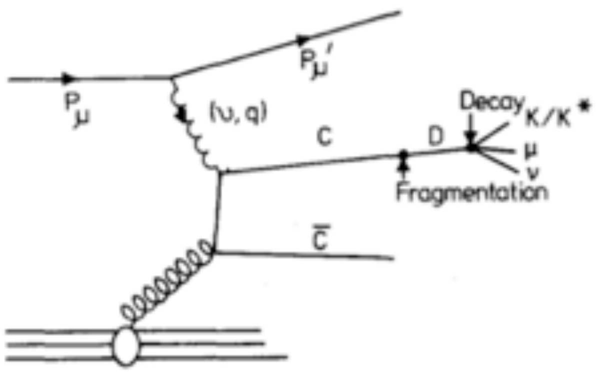
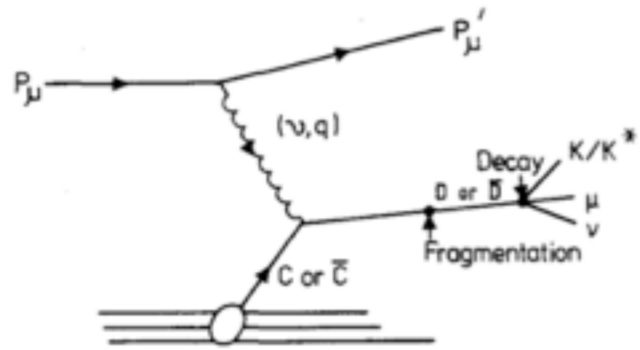
>
> *BHPS, Phys. Lett.* ***93B****, 451 (1980)*

- European Muon Collaboration (EMC) measured open charm production μ “N” $\to \mu\, D\, X$ in early 1980s



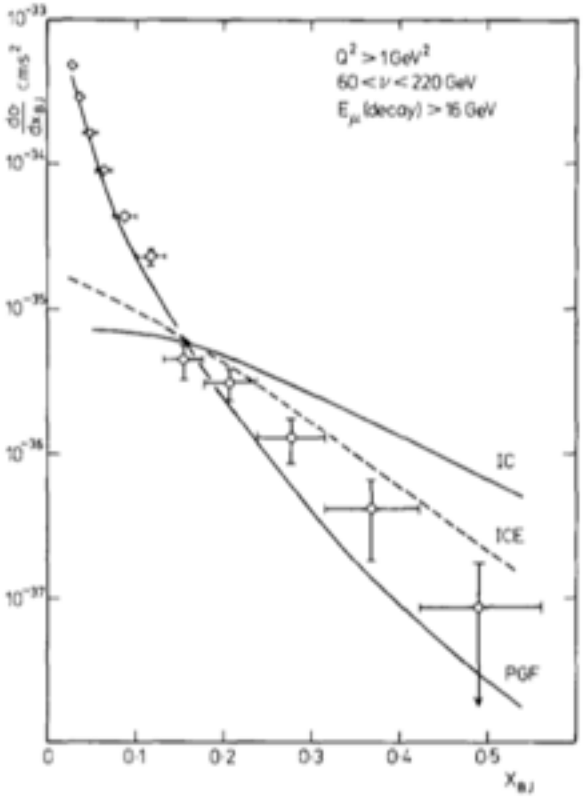


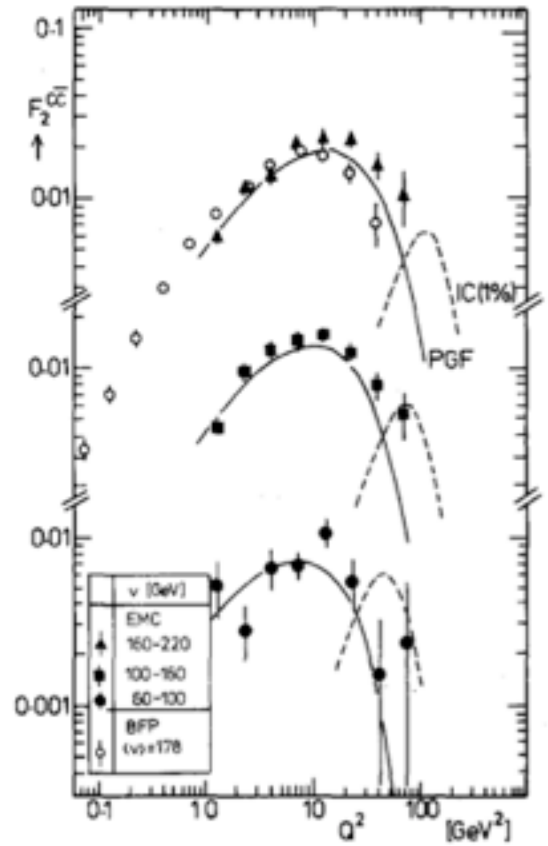
photon–gluon fusion

intrinsic charm

Intrinsic charm in DIS

- EMC data inconclusive





"In conclusion, virtual photoproduction of charm has been studied and is found to be rather well represented by the photon–gluon fusion model (i.e. extrinsic charmed quarks) over the measured range of Bjorken x. The contribution of intrinsic charm as proposed in refs. [4] and [13] is incompatible with the data."

"the data appear to deviate from the PGF model at the highest values of Q^2. This may indicate the onset of an intrinsic charm component with a strong threshold suppression [39]. This suppression is required to be at least of the form $(1 - W_{th}^2/W^2)^7$, where W_{th} is the threshold centre of mass energy"

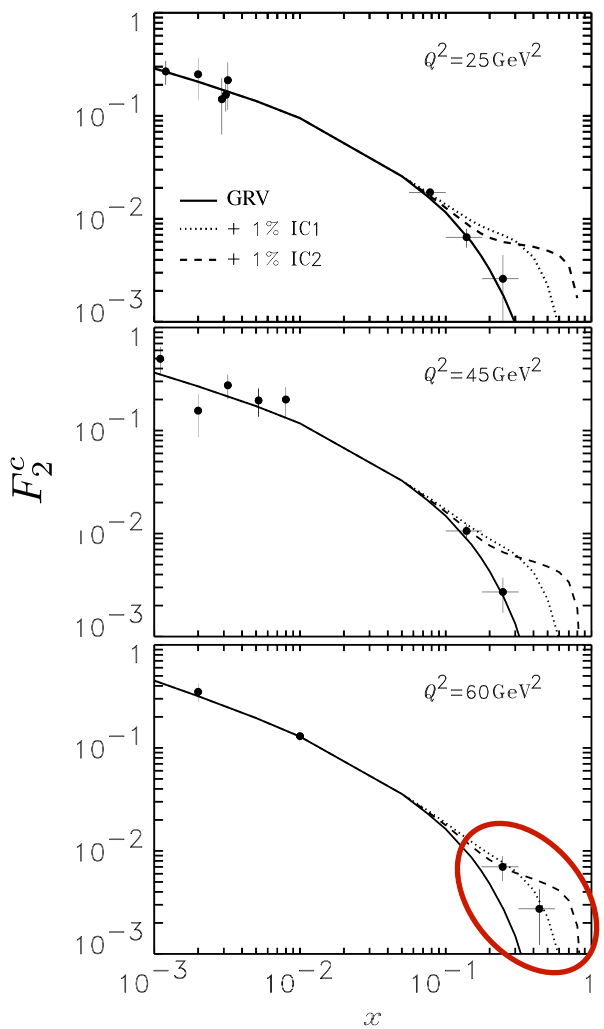
"The effects of an intrinsic charm component of the nucleon are small [6] which implies that either intrinsic charm does not exist at the predicted level or there is strong threshold suppression in the energy range of this experiment."

*EMC, PLB **110**, 73 (1982)*

*EMC, NPB **213**, 31 (1983)*

Intrinsic charm in DIS

- EMC data inconclusive... some hint of excess charm at highest x and Q^2 *cf.* perturbative QCD contribution



Steffens, WM, Thomas
*EPJC **11**, 673 (1999)*

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

at LO in α_s

IC1 = BHPS model

IC2 = meson-baryon model

→ these data frequently cited as evidence for large IC in nucleon

→ definitive study requires systematic global QCD analysis

Global QCD analysis

- Simultaneous QCD−based fit to large array of data from various high-energy processes (DIS; $\mu^+\mu^-$, weak boson & jet production in pp scattering, ...) in terms of set of universal parton distribution functions (PDFs)

$\longrightarrow$ typically parametrised as

$$xf(x,\mu) = Nx^{\alpha}(1-x)^{\beta}\,P(x)$$

with polynomial $e.g.\ P(x) = 1 + \epsilon\sqrt{x} + \eta\, x$

Global QCD analysis

- Simultaneous QCD−based fit to large array of data from various high-energy processes (DIS; $\mu^+\mu^-$, weak boson & jet production in pp scattering, ...) in terms of set of universal parton distribution functions (PDFs)

→ several thousand data points in modern global fits, over large range of x and Q^2

(more if data on nuclear targets $A > 2$ included)

	Experiment	Ref.	# points	χ^2 CJ12min	CJ12mid	CJ12max
DIS F_2	BCDMS (p)	[13]	351	434	436	437
	BCDMS (d)	[13]	254	294	297	302
	NMC (p)	[14]	275	434	432	430
	NMC (d/p)	[15]	189	179	177	182
	SLAC (p)	[16]	565	456	455	456
	SLAC (d)	[16]	582	394	388	396
	JLab (p)	[17]	136	170	169	170
	JLab (d)	[17]	136	124	125	126
DIS σ	HERA (NC e^-)	[18]	145	117	117	118
	HERA (NC e^+)	[18]	384	595	596	596
	HERA (CC e^-)	[18]	34	19	19	19
	HERA (CC e^+)	[18]	34	32	32	32
Drell-Yan	E866 (p)	[19]	184	220	221	221
	E866 (d)	[19]	191	297	307	306
W asymmetry	CDF 1998 (ℓ)	[20]	11	14	16	18
	CDF 2005 (ℓ)	[21]	11	11	11	10
	DØ 2008 (ℓ)	[22]	10	4	4	4
	DØ 2008 (e)	[23]	12	40	36	34
	CDF 2009 (W)	[24]	13	20	25	41
Z rapidity	CDF (Z)	[25]	28	29	27	27
	DØ (Z)	[26]	28	16	16	16
jet	CDF run 1	[27]	33	52	52	52
	CDF run 2	[28]	72	14	14	14
	DØ run 1	[29]	90	21	20	19
	DØ run 2	[30]	90	19	19	20
γ+jet	DØ 1	[31]	16	6	6	6
	DØ 2	[31]	16	13	13	12
	DØ 3	[31]	12	17	17	17
	DØ 4	[31]	12	17	16	17
TOTAL			3958	4059	4055	4096
TOTAL + norm				4075	4074	4117

Global QCD analysis

- Several groups dedicated to global PDF analysis

  - MSTW (Martin-Stirling-Thorne-Watt) — UK-based, LHC focus

  - CTEQ (Coordinate Theoretical-Experimental Project on QCD)
    – CT (CTEQ-Tung et al.) — US-based, LHC focus
    – CJ (CTEQ-JLab) — includes high x, low Q^2
    – nCTEQ — nuclear PDFs

  - ABM (Alekhin-Bluemlein-Moch) — Europe-based, LHC focus

  - HERAPDF — uses only H1 & ZEUS data

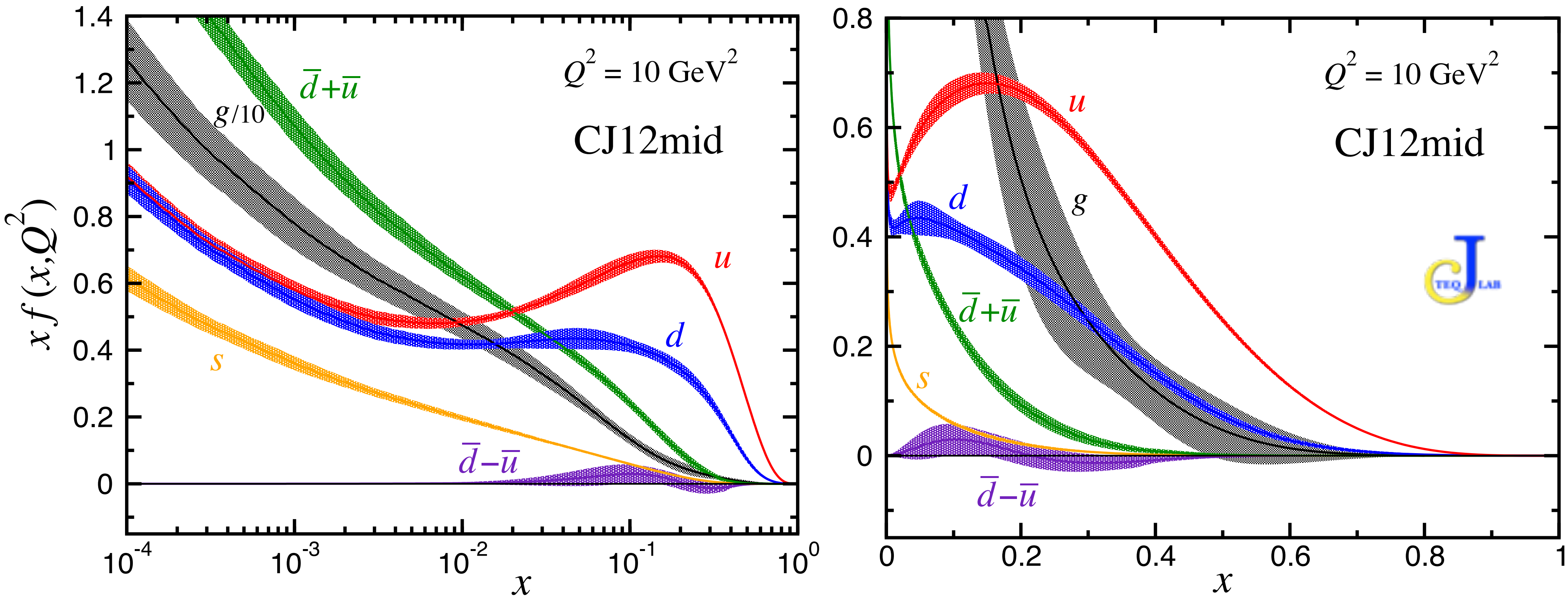
  - JR (Jimenez-Delgado–Reya) — dynamically generated from low Q^2

  - NNPDF — uses "neural networks", strong data cuts

$\longrightarrow$ most use NLO, some use NNLO (partially known)

Global QCD analysis

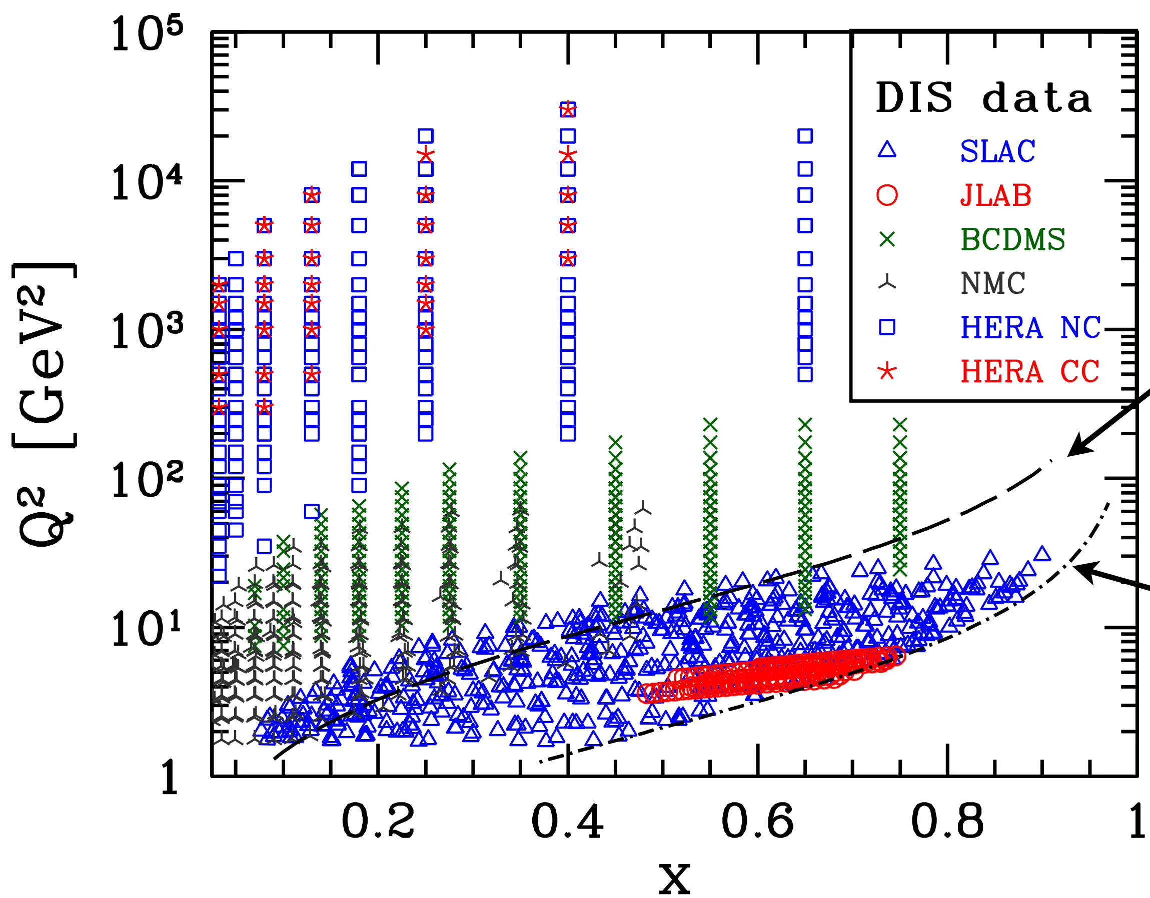
- Example of recent PDFs, from CJ12 analysis



Owens, Accardi, WM
PRD ***87****, 094012 (2013)*

Global QCD analysis

- Kinematic coverage of data in x and Q^2



$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

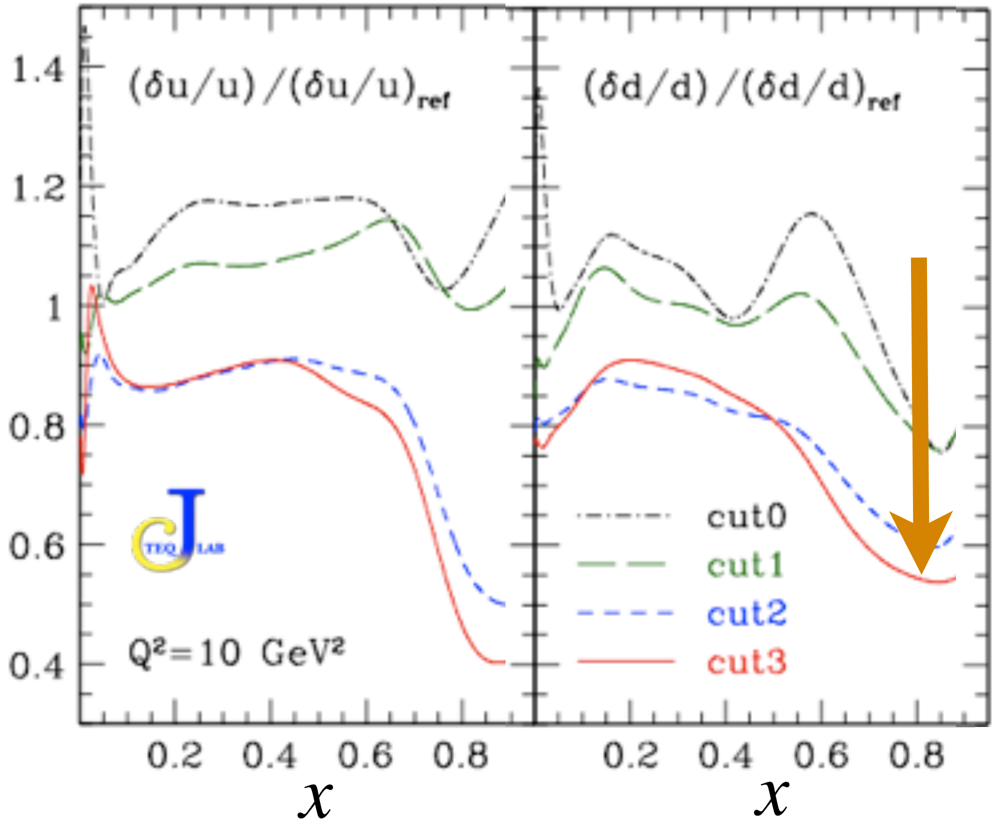
strong cut:
$Q > 2$ GeV, $W > 3.5$ GeV

weak cut:
$Q > 1.3$ GeV , $W > 1.73$ GeV

→ factor 2 increase in # of DIS data points when relax strong cut (excludes most SLAC, all JLab data) → weak cut

Global QCD analysis

- High-x region requires use of data at lower W & Q^2



$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

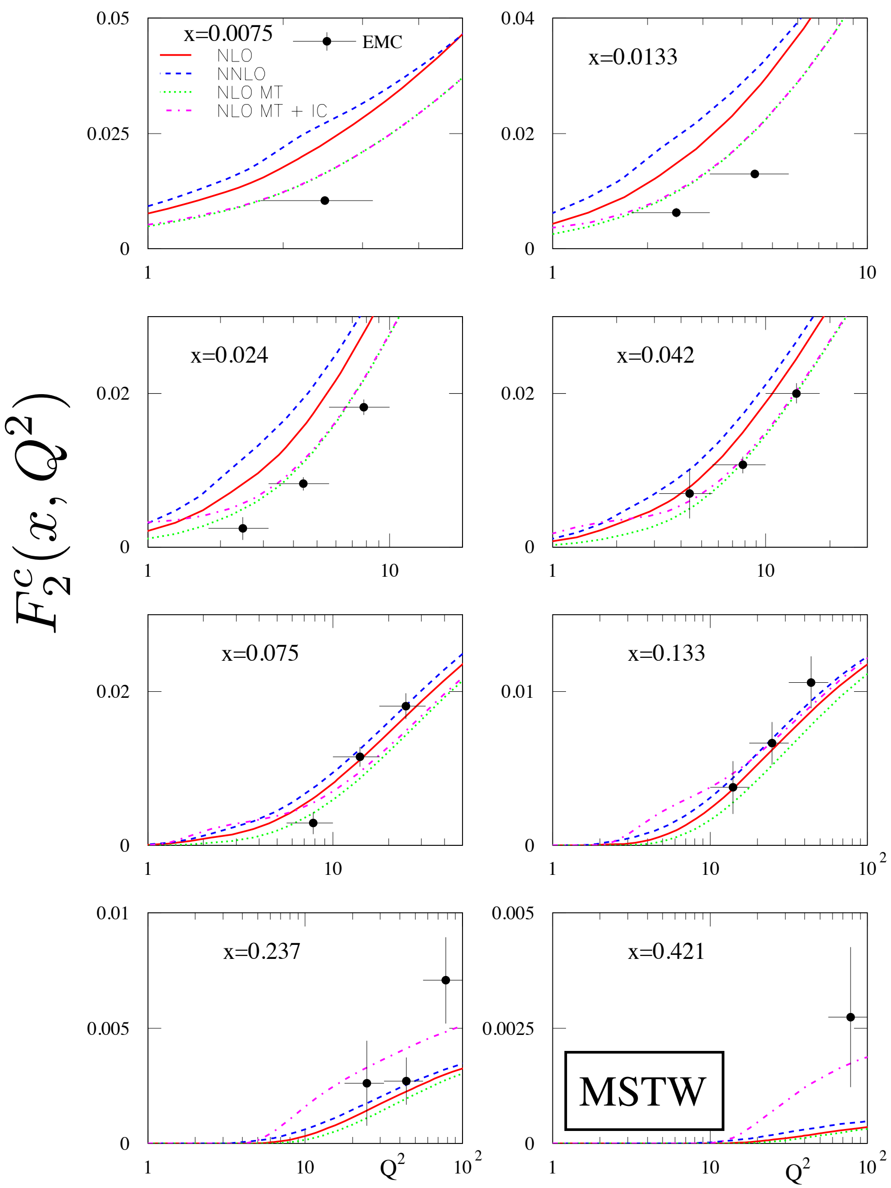
cut0: strong cut

cut3: weak cut

→ significant error reduction when cuts extended to low-W region

Global QCD analysis

- Several previous global analyses have considered possibility of intrinsic charm component



$$m_c^2 \;\rightarrow\; m_c^2(1+\Lambda^2/m_c^2)$$

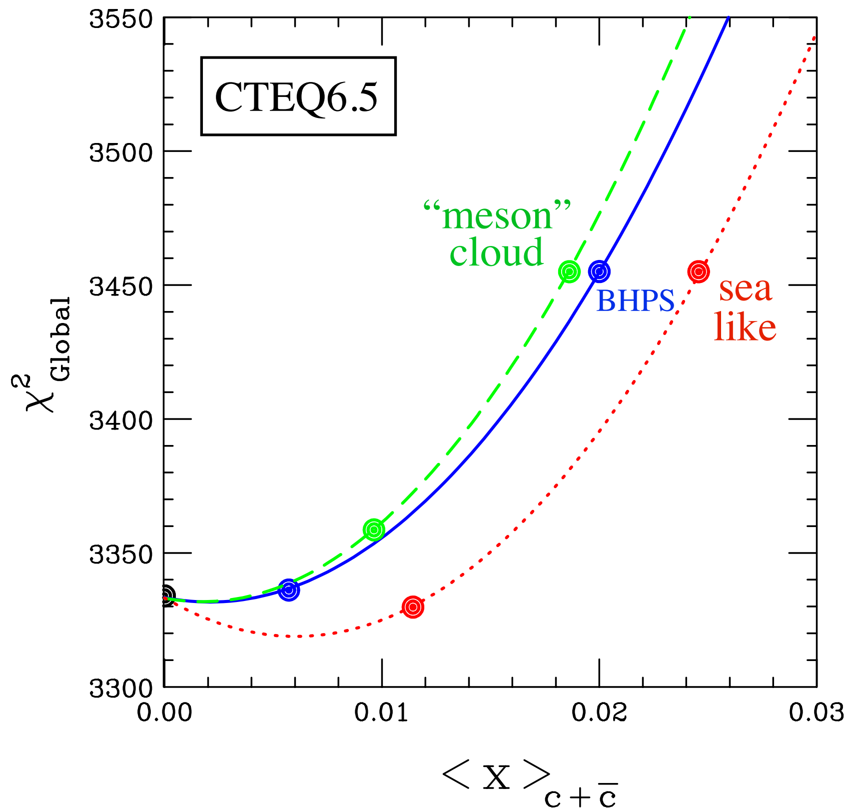
"hadronic threshold" modification

"if the EMC data are to be believed, there is no room for a very sizeable intrinsic charm contribution"

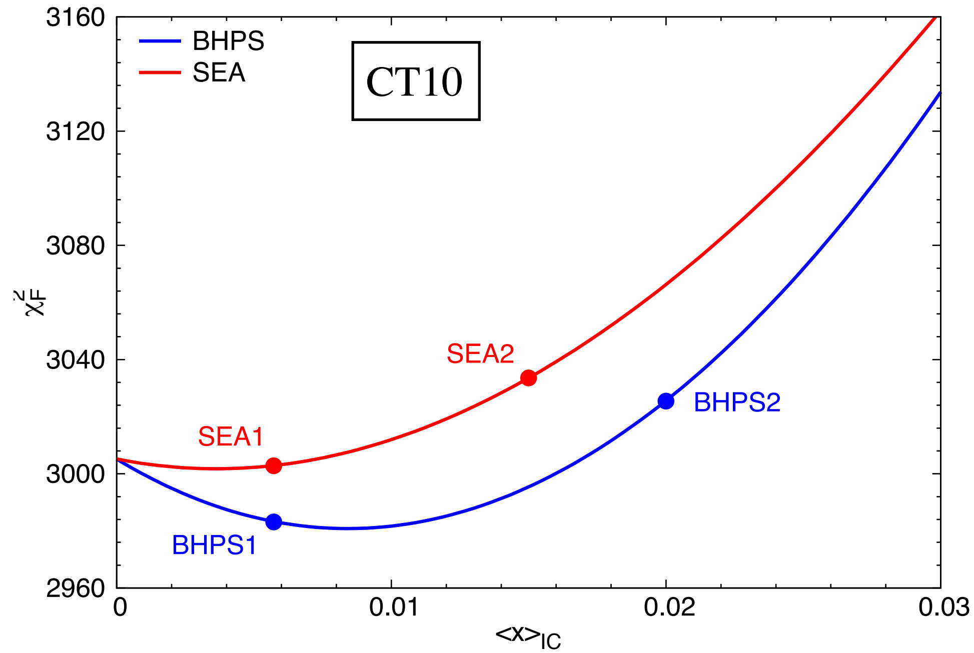
*MSTW, EPJC **63**, 189 (2009)*

Global QCD analysis

- CTEQ *does* find room for ~ few % IC in their analysis



*Pumplin et al., PRD **75**, 054029 (2007)*



*Dulat et al., PRD **89**, 073004 (2014)*

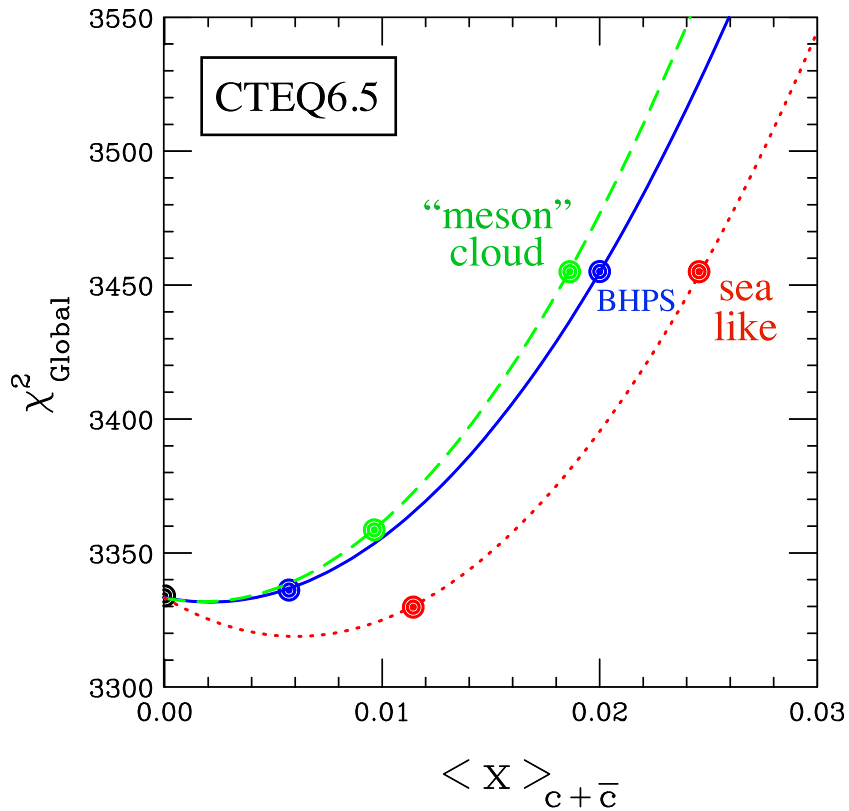
$\langle x \rangle_{\rm IC} \lesssim 0.025$ **at 90% CL**

- “global analysis of hard-scattering data provides no evidence either for or against IC up to 0.01”

- new NNLO analysis, including new HERA data, disfavors “sea-like” IC model, but allows nonzero IC for BHPS model

Global QCD analysis

- CTEQ *does* find room for ~ few % IC in their analysis



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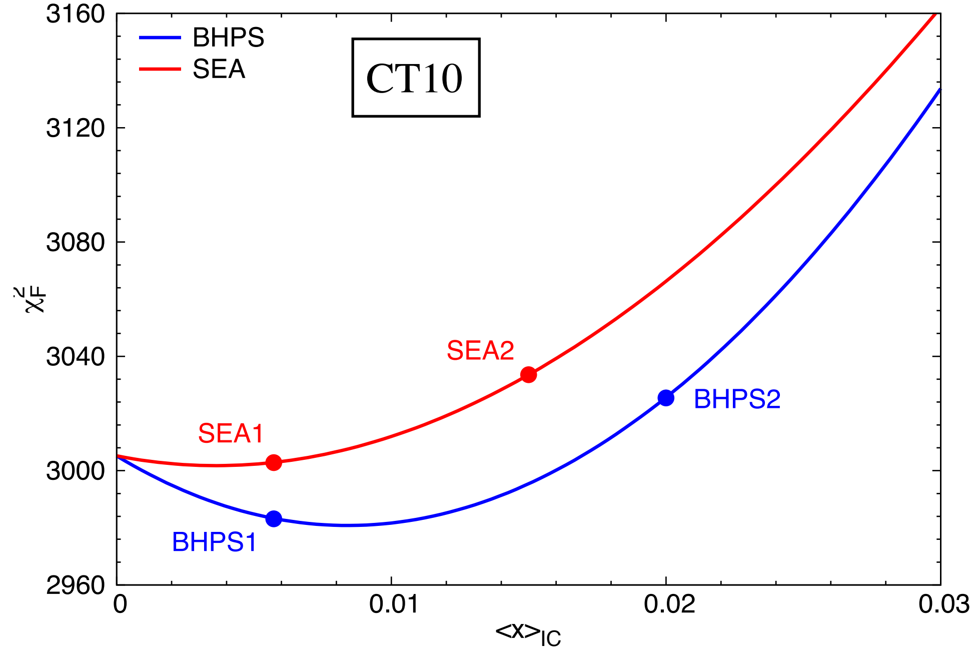


Dulat et al., PRD ***89****, 073004 (2014)*

$\langle x \rangle_{\mathrm{IC}} \lesssim 0.025$ at 90% CL

→ however, CTEQ/CT use rather strong kinematic cuts, excluding much high-x / low-W data

Global QCD analysis

- **Excluding high-x data** (to avoid subleading $1/Q^2$ effects), exclude region where IC expected to be important!

→ several recent analyses (CJ, ABM, JR) have sought better constraints on large-x PDFs by expanding kinematic coverage down to $Q^2 \sim 1\ \mathrm{GeV}^2$ & $W^2 \sim 3.5\ \mathrm{GeV}^2$

→ requires careful treatment of higher twist, target mass, nuclear corrections

→ better constraints on light-quark (u, d) PDFs at large x, which are background on which possible IC sits

recall $F_2^p \sim \frac{4x}{9}(u + \bar{u} + c + \bar{c}) + \frac{x}{9}(d + \bar{d} + s + \bar{s}) + \cdots$

New global QCD analysis

- Using framework of JR14 (NLO) global analysis, most recent analysis has fit all available data for $Q^2 \geqslant 1\ \mathrm{GeV}^2$, $W^2 \geqslant 3.5\ \mathrm{GeV}^2$ allowing for the possibility of IC

Jimenez-Delgado, Reya
*PRD **89**, 074049 (2014)*

$$F_2 = F_2^{u,d,s} + F_2^{c,b}$$

$$F_2^c = F_2^{\mathrm{PGF}} + F_2^{\mathrm{IC}}$$

$\gamma^* g \to c\bar{c}$

- $$F_2^{\mathrm{PGF}}(x, Q^2, m_c^2) = \frac{Q^2 \alpha_s}{4\pi^2 m_c^2} \sum_i \int \frac{dz}{z}\, \hat{\sigma}_i(\eta, \xi)\, f_i\left(\frac{x}{z}, \mu\right)$$

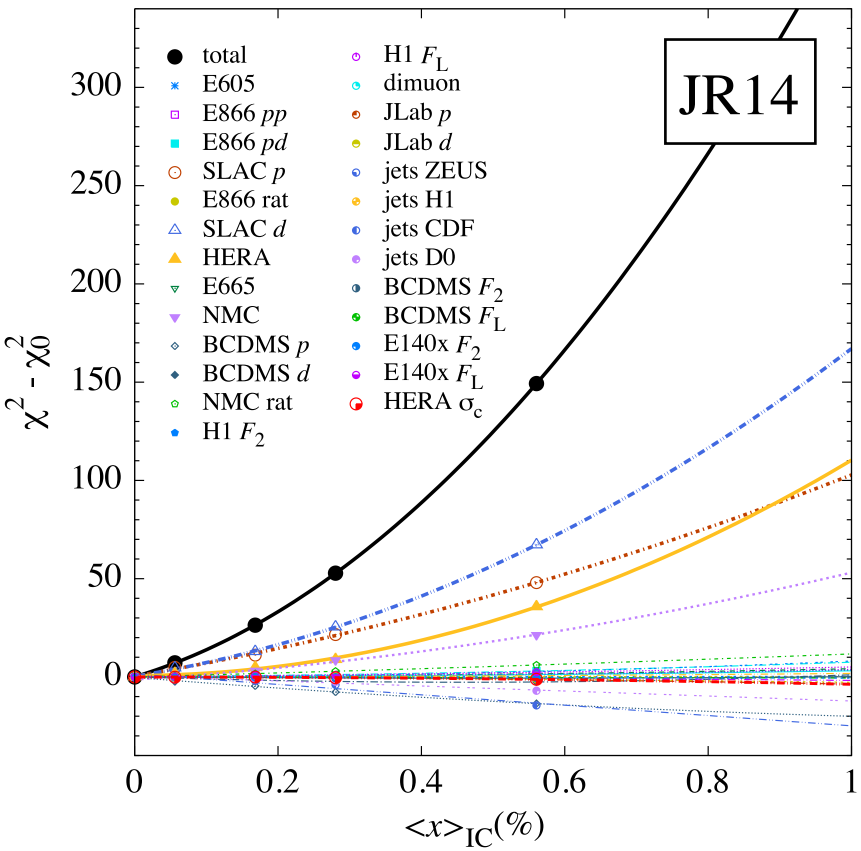
  $\mu^2 = 4m_c^2 + Q^2$

  computed in "fixed-flavor number scheme"

- F_2^{IC} computed from various models (BHPS, MBM)

New global QCD analysis

*Jimenez-Delgado et al., PRL **114**, 082002 (2015)*



$\chi_0^2 = \chi^2$ value for no IC

→ total χ^2 has minimum at zero IC

$\chi^2/N_{\rm dat} = 1.25$ for $N_{\rm dat} = 4296$

and rises rapidly with $\langle x \rangle_{\rm IC}$

→ strongest constraints from SLAC, HERA, NMC data; others have ~ no sensitivity

→ full data set gives $\langle x \rangle_{\rm IC} < 0.1\%$ at 5σ CL for $\Delta\chi^2 = 1$

→ for $\Delta\chi^2 = 100$ (“tolerance”) would have $\langle x \rangle_{\rm IC} \lesssim 0.4\%$

Threshold suppression?

- Significant portion of SLAC data lie *below* partonic charm threshold, $W^2 = 4m_c^2$, so cannot directly constrain IC

→ through Q^2 evolution, stronger constraints on light-quark PDFs at high x influence determination of IC in global fit

→ in fact, partonic threshold is lower than physical charm production threshold, $W^2 \geqslant (M_N + m_{J/\psi})^2 \approx 16\ \mathrm{GeV}^2$

→ various prescriptions to account for mismatch between partonic & hadronic thresholds

- MSTW modified threshold with effective charm mass

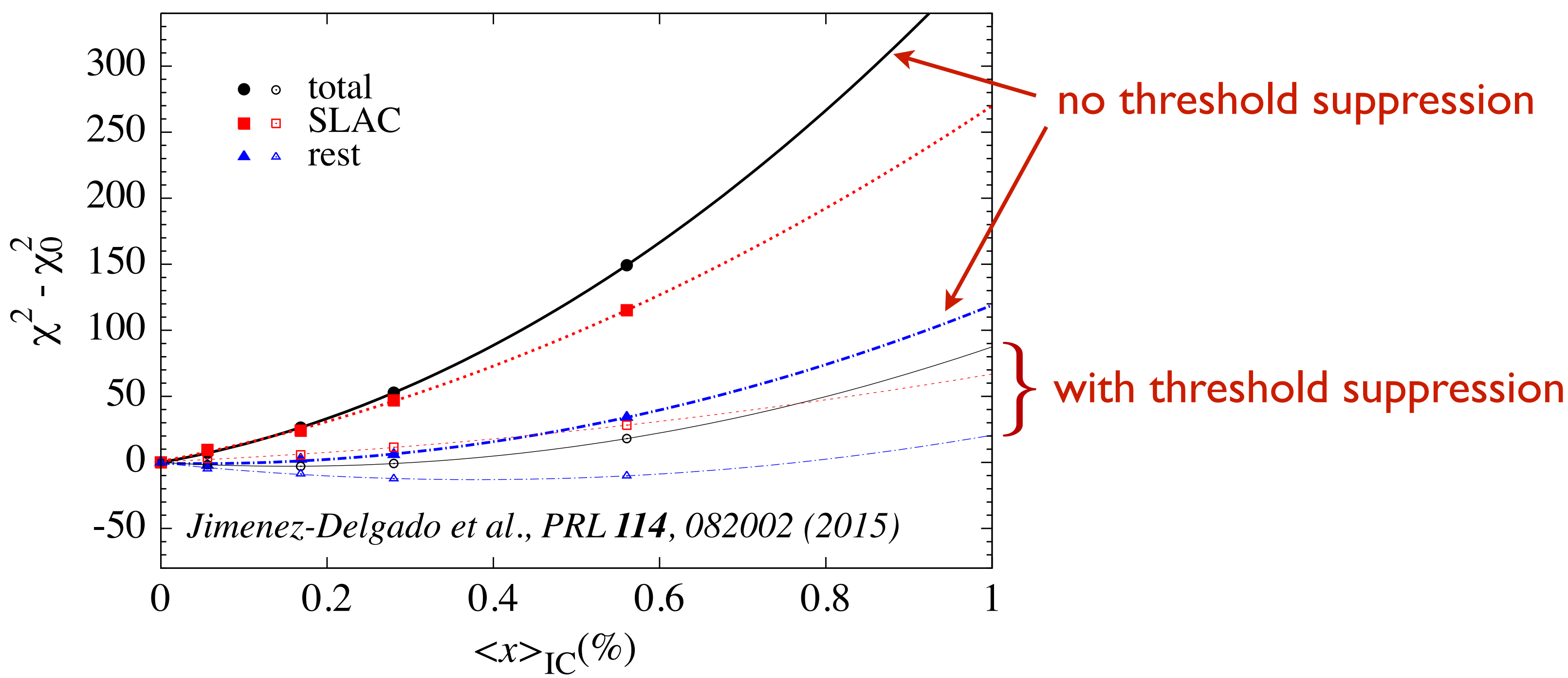
$$m_c^2 \ \to \ m_c^2(1 + \Lambda^2/m_c^2)$$

- threshold suppression factor

$$\theta(W^2 - W_{\mathrm{thr}}^2)(1 - W_{\mathrm{th}}^2/W^2)$$

Threshold suppression?

- Including hadronic suppression factor generally gives shallower χ^2 profile

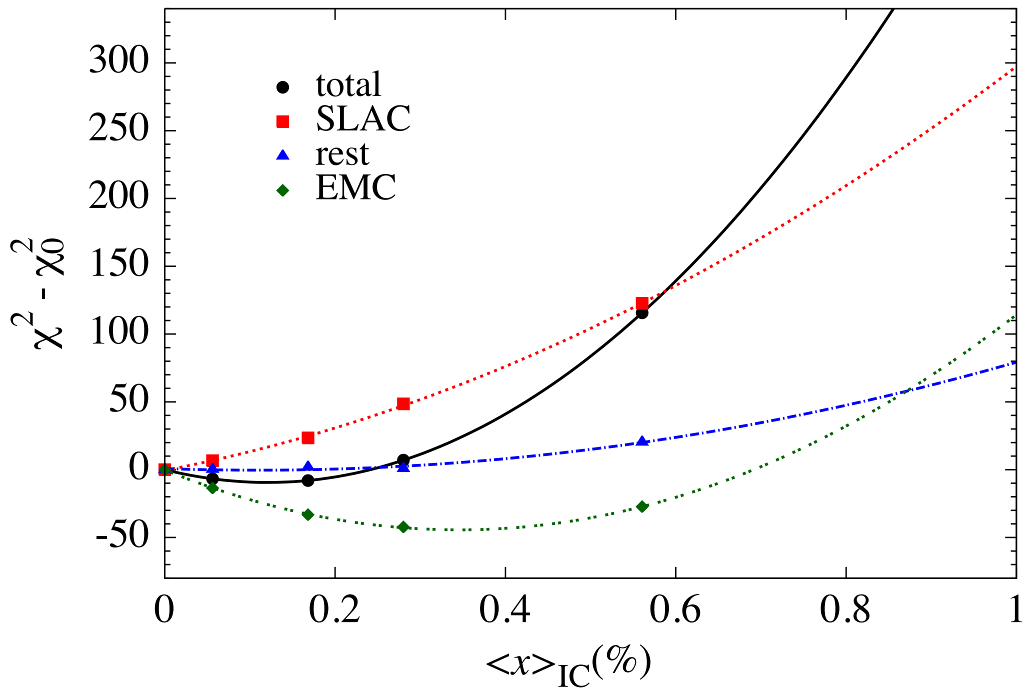


→ minimum χ^2 at $\langle x \rangle_{\rm IC} = (0.15 \pm 0.09)\%$

→ exclusion limit $\langle x \rangle_{\rm IC} \lesssim 0.5\%$ at 4σ CL

Analysis of EMC data

- Including old EMC data on charm structure function favors slightly larger IC

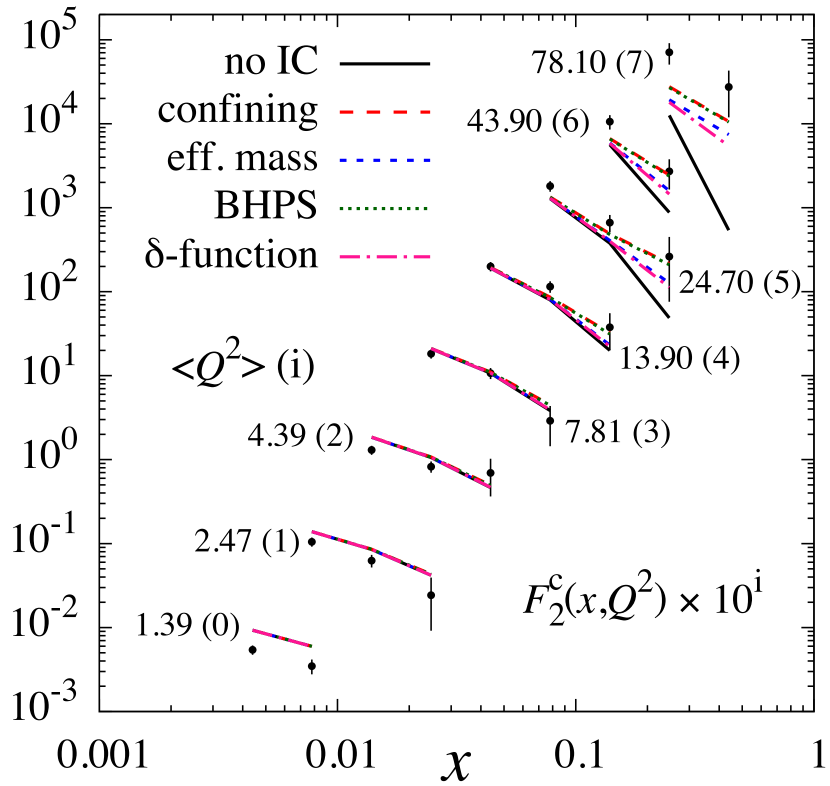


$\longrightarrow$ EMC alone favors $\langle x \rangle_{\rm IC} \approx (0.3 - 0.4)\%$

... but poor description of data, with $\chi^2/N_{\rm EMC} = 4.3$ for $N_{\rm EMC} = 19$

Analysis of EMC data

- Closer look at x dependence of EMC F_2^c data

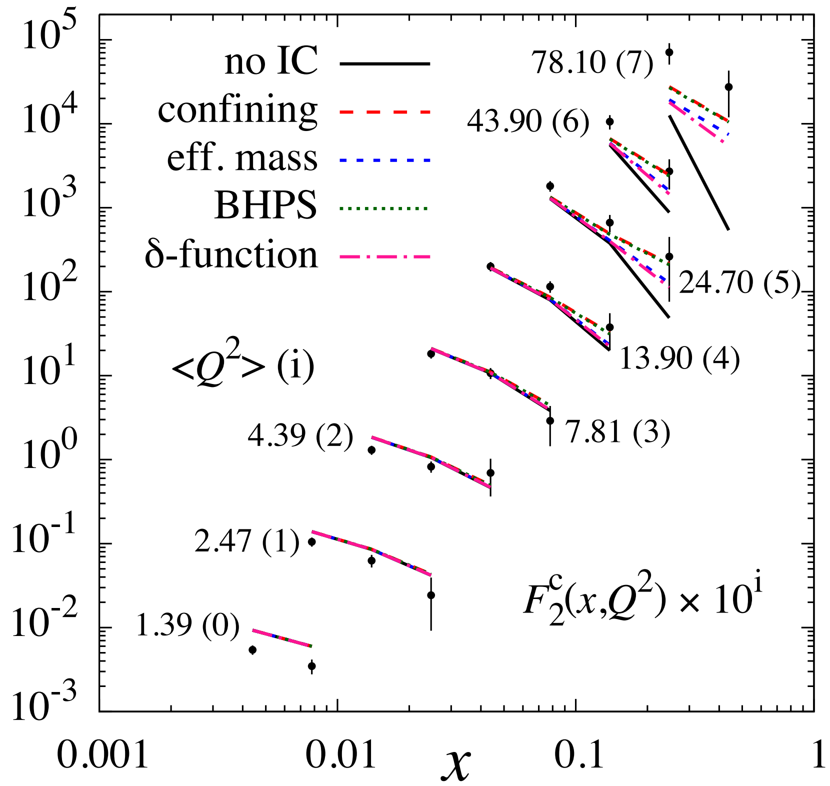


→ at small x ($x \lesssim 0.02$) global fits (constrained by HERA data) overestimate EMC data

→ at largest x ($x \gtrsim 0.2$) fits underestimate EMC data, with or without IC, for all IC models considered

Analysis of EMC data

- Closer look at x dependence of EMC F_2^c data



→ better agreement would require much larger IC at high x <u>and</u> suppression mechanism (negative IC?) at small x

→ because of significant tension with other data sets, IC data usually not included in global PDF analyses

Outlook

- No evidence for large intrinsic charm from global QCD analysis of high-energy data, for large range of IC models

- Small amount of IC not excluded, but more definitive determination requires new data
  (perhaps from future Electron-Ion Collider?)

  $\longrightarrow$ "smoking gun" would be observation of asymmetric distributions $c(x) \neq \bar{c}(x)$

- Study of nonperturbatively generated sea quarks remains exciting subject in QCD

  $\longrightarrow$ novel nonperturbative effects reflected in various asymmetries, $e.g.\ \bar{d} \neq \bar{u}\,,\ s \neq \bar{s}\,,\ \Delta s \neq \Delta\bar{s}\,,\ \ldots$