Limits on Intrinsic Charm in the Nucleon

- Intrinsic vs. Extrinsic sea quark distributions
- Contributions to quark distributions, structure functions

  emphasis on qualitative features of quark PDFs
- Models for intrinsic charm quarks
- Limits on intrinsic charm in the proton

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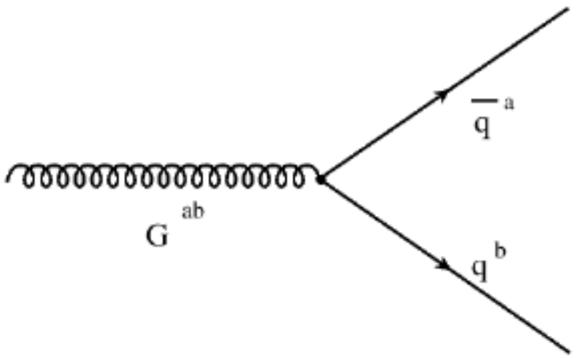
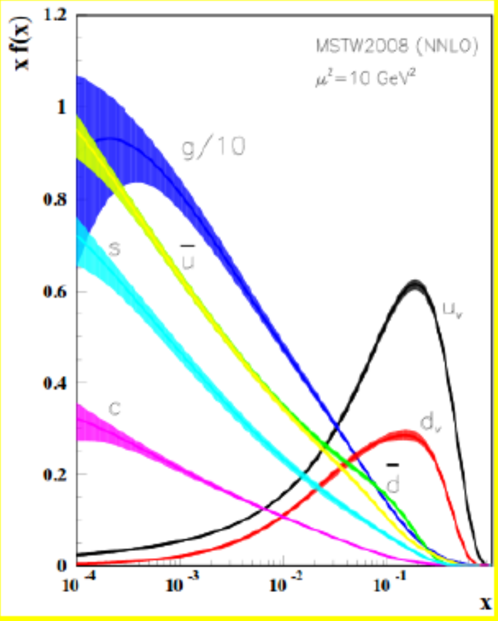
With Tim Hobbs (IU), Wally Melnitchouk & Pedro Jimenez-Delgago (Jlab)

Intrinsic vs. **Extrinsic** Sources of Sea Quarks





Sea quarks in nucleon arise through 2 different mechanisms:

- **Extrinsic:** arises from gluon radiation to q-qbar pairs
  - included in QCD evolution
  - strongly peaked at low x; grows with Q^2
  - extrinsic sea quarks require q = qbar*

* asymmetries (very small, low-x) arise at NNLO order

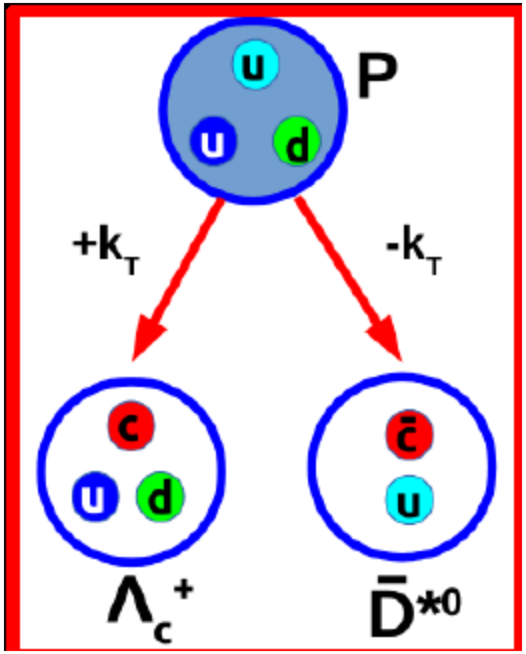
Intrinsic vs. Extrinsic Sources of Sea Quarks

- **Intrinsic:** arises from 4q+qbar fluctuations of N Fock state

- at starting scale, peaked at intermediate x; more "valence-like" than extrinsic

- in general, q ≠ qbar for intrinsic sea

- intrinsic parton distributions move to lower x under QCD evolution



A Simple Model for Intrinsic Sea Quarks:

BHPS *: in IMF, transition probability for p to 5-quark state involves energy denominator of the form:

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

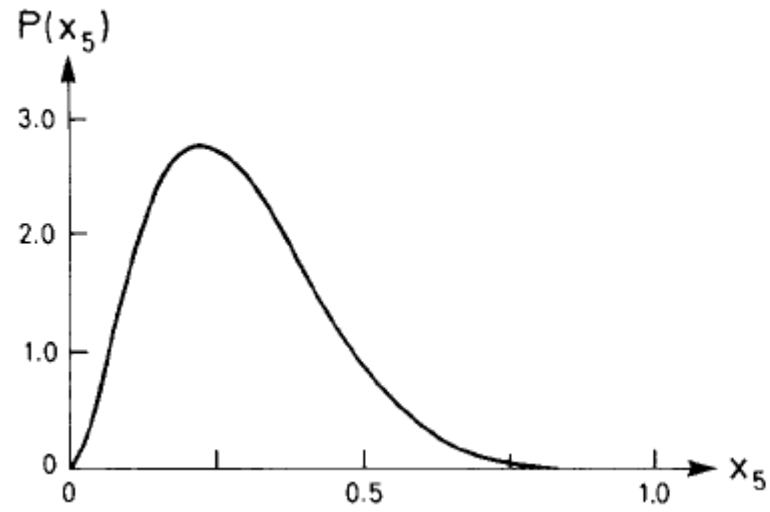
For charm quarks, neglect k_T and assume the charm mass >> all other mass scales → obtain analytic expression for probability of charm quark:

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

* Brodsky, Hoyer, Peterson & Sakai, Phys Lett **B93**, 451 (1980)

BHPS Model for Intrinsic Sea Quarks:

Sea quark PDFs peak at relatively large x values.
Normalize to overall quark probability.
BHPS approximation guarantees c = cbar.



Can calculate for any quark flavor (use Monte Carlo integration)*

"valence-like" PDF at starting scale ($Q \sim m_c$); moves in to smaller x with increasing Q^2 through QCD evolution

Brodsky, Hoyer, Peterson & Sakai, PL **B93**, 451 (1980)

* W-C. Chang and J.C. Peng, PRL **102**, 252002 (2011).

Meson-Baryon Models

"Meson-baryon" models: expand nucleon state in a series of meson-baryon states that include the most important sources of intrinsic quarks:

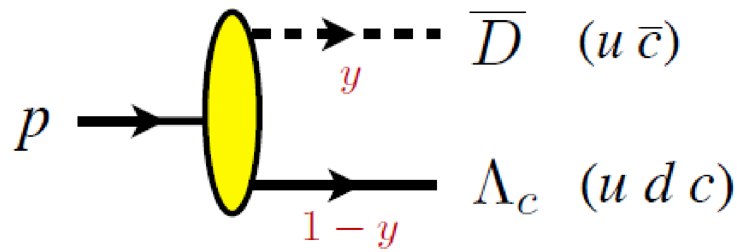
$$|N\rangle = \sqrt{Z}\,|N\rangle_0 + \sum_{M,B}\int dy\, d^2\boldsymbol{k}_\perp\, \phi_{MB}(y,k_\perp^2)\,|M(y,\boldsymbol{k}_\perp); B(1-y,-\boldsymbol{k}_\perp)\rangle$$

wave function renormalization

"bare" 3-quark state

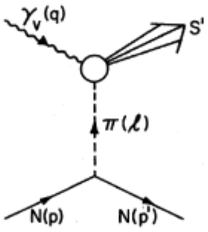
N → M + B Probability amplitude

light-cone momentum fraction



Contribution of a meson-baryon state to parton dist'n function = convolution of splitting function with quark probability in hadron

Meson-Baryon Models



Charm distributions in nucleon given by convolution of
N → MB splitting function, with quark distribution inside charmed meson, baryon

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

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

$$\bar{y} \equiv 1 - y$$

Splitting function = integral of quark probability amplitude over transverse momentum

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

Constraints on Meson-Baryon Models:

Meson-baryon models must satisfy constraints that reflect conservation of charge and momentum. A first and obvious constraint is:

$$f_{MB}(y) = f_{BM}(1-y)$$

If a proton splits into a meson + baryon and the meson carries momentum fraction y, then baryon must carry momentum fraction 1-y. Integrating the splitting function over y gives the charge conservation constraint,

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

The momentum conservation constraint is obtained by multiplying the splitting functions by y and integrating over y,

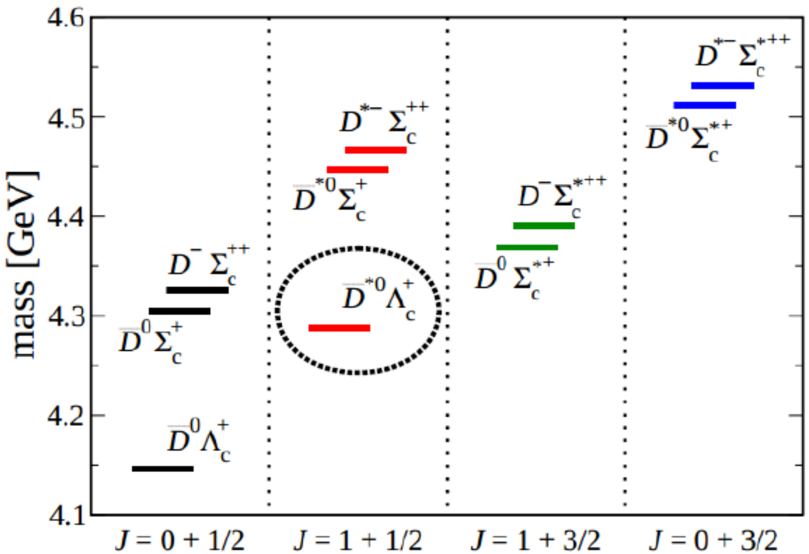
$$\langle y \rangle_{MB} + \langle y \rangle_{BM} = \langle n \rangle_{MB}; \quad \langle y \rangle_{MB} = \int_0^1 f_{MB}(y)ydy$$

Use of IMF kinematics and form factors depending on energy help to ensure that these constraints are satisfied.

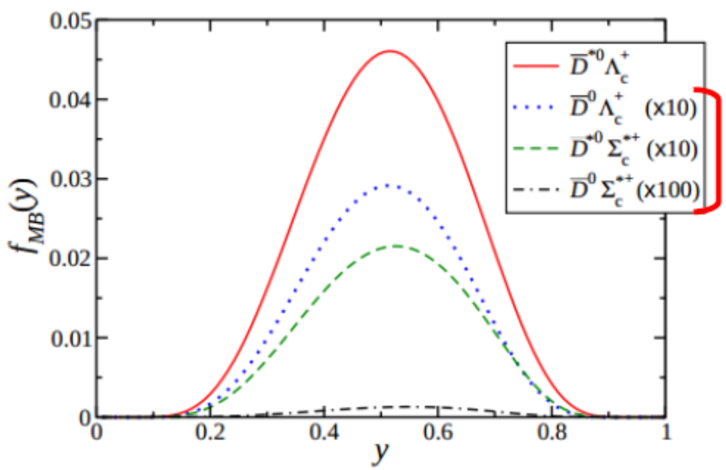
Meson-Baryon Calculation of Intrinsic Charm

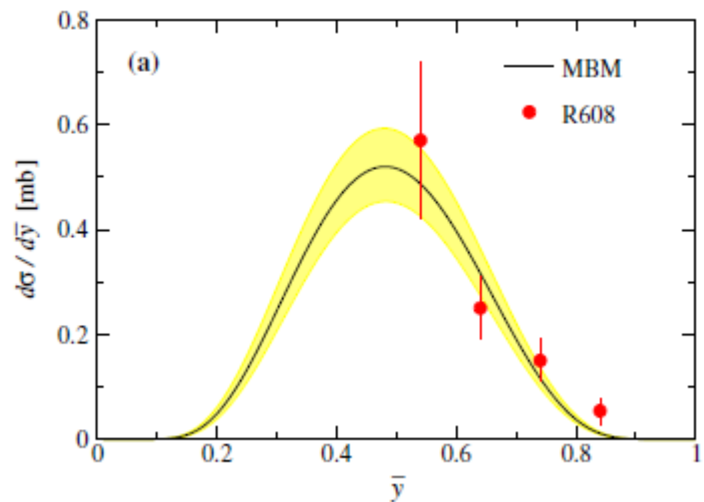
Hobbs/JTL/Melnitchouk, PR**D89**, 074008 (2014)

Expand in series of charmed meson-baryon states
c quark in baryon, cbar in meson
One state is dominant: $p \to \bar{D}^* - \Lambda_c$



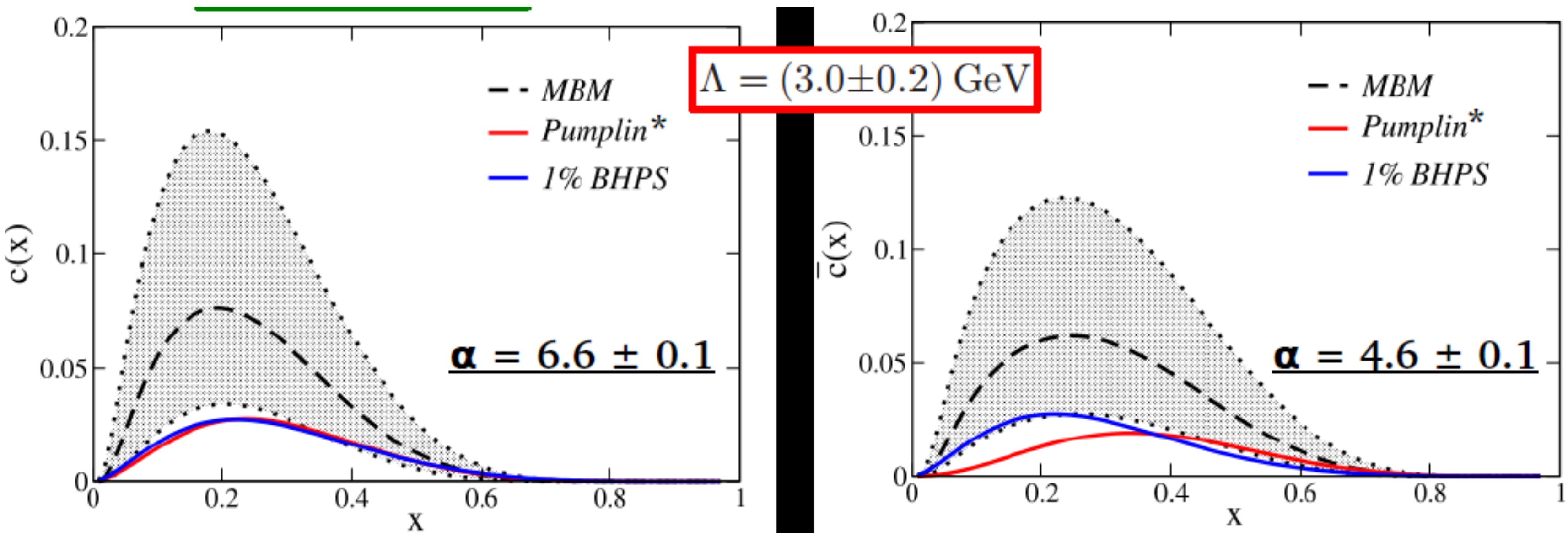
not the lowest-mass state!
Splitting function for this state dominates all others:
Result of large tensor coupling to D*





Strength normalized by fitting to Λ_c inclusive production in pp reactions

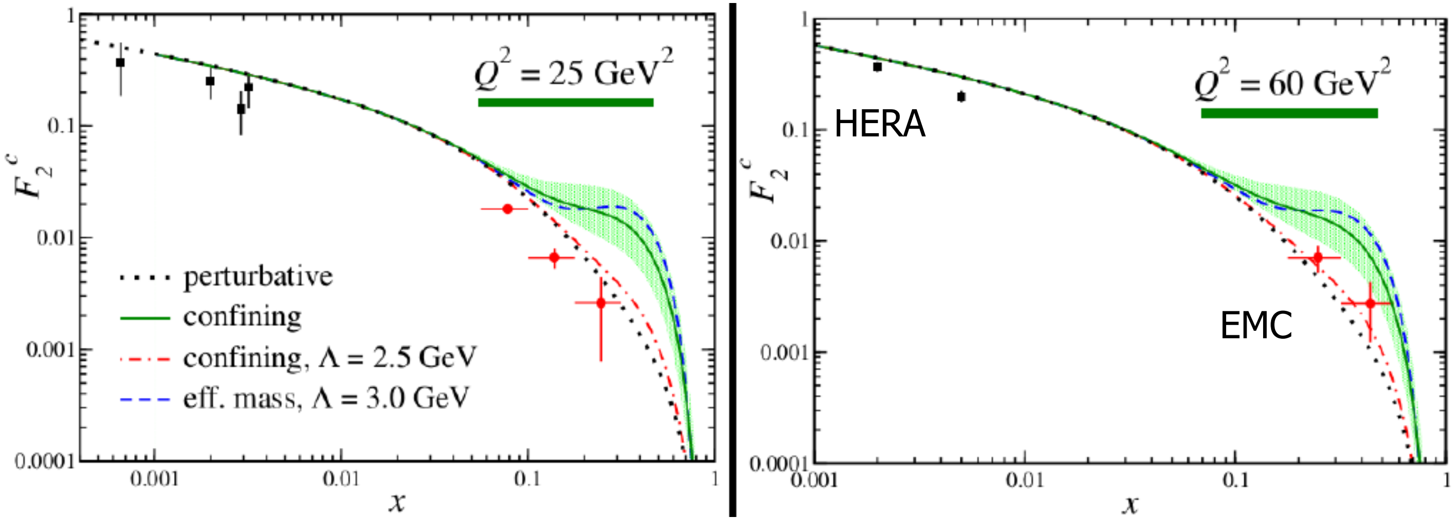
Meson-Baryon Calculation of Intrinsic Charm



Significant uncertainty in intrinsic charm distributions
(due to uncertainty in charm production X-sections)
Our c, cbar PDFs larger than those of BHPS, Pumplin (which are normalized to 1% charm probability – charm carries 0.57% of proton momentum).

Our best fit P_c = 1.34% of proton momentum (~ 2% charm probability).
We obtain cbar harder than c, due to significantly harder distribution of cbar in meson than c in baryon (cbar represents larger fraction of total mass in meson, than c in baryon).

Intrinsic Charm Contribution to Structure Function



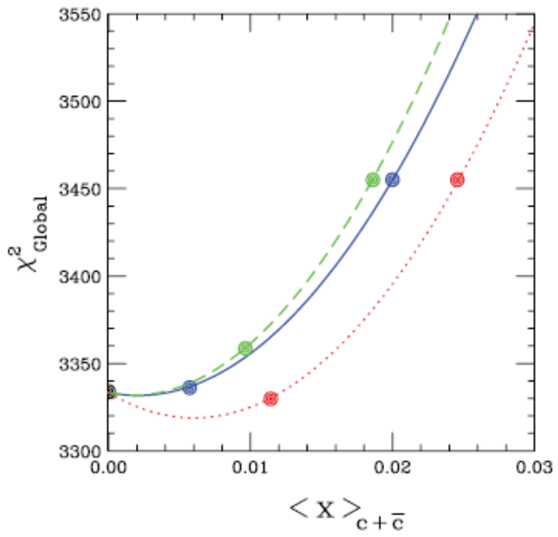
$$F_2^c(x,Q^2) = \frac{4x}{9}\left[c(x,Q^2) + \bar{c}(x,Q^2)\right]$$, to lowest order in α_s

Dotted curve: contribution to F_2^c from extrinsic charm
Shaded curve: our calculation of intrinsic charm (IC) contribution
Black dots: ZEUS data; red squares: EMC charm F_2 data.

1.3% p momentum in IC, would produce a measurable large-x "bump"
[Pumplin, Lai & Tung, PRD75, 054029 (2007)]
IC contribution substantially above EMC data

What Levels of Intrinsic Charm are Allowed by Data?

Pumplin, Lai & Olness, [PRD**75**, 054029 (2007)]: later Dulat [PR**D89**, 0730045 (2014)];
Global fit plus intrinsic charm with shape calculated by Pumplin [PR**D73**, 114015 (2006)],
Magnitude of IC increased until it disagrees with global data.



Global fit can tolerate ~ 2% p momentum in IC
Note: data set does not include EMC charm (the only high-x charm data).

CTEQ, MSTW – global fits focused on PDFs for LHC; strong kinematic cuts remove high-x, low-W^2 data
Note: CTEQ tolerance T^2 = 100 (return later)

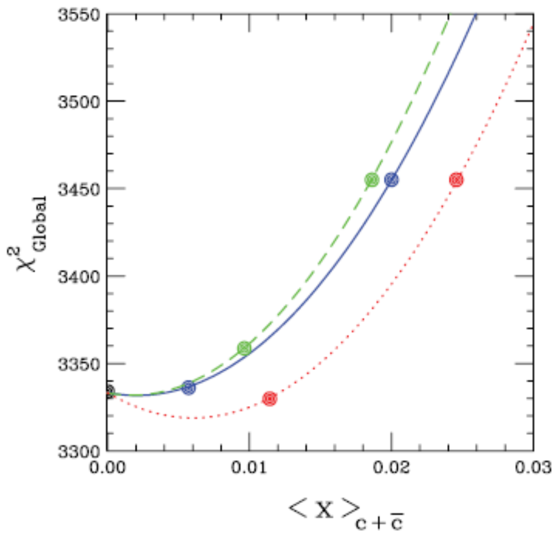
Global QCD Limits on Intrinsic Charm

CTEQ, MSTW: exclude high-x, low-W^2 data (to remove $1/Q^2$ effects)
But, also excludes region where IC is important!

Several recent analyses (CJ, ABM, JR) seek better constraints on large-x PDFs; expand kinematic coverage to $Q^2 \sim 1$ GeV^2, $W^2 \sim 3.5$ GeV^2

Requires careful treatment of higher-twist, target mass, nuclear, …. corrections

→ Stronger constraints on light-quark PDFs at large *x*, which indirectly constrains intrinsic charm PDFs



A New Global QCD Analysis of IC

Jimenez-Delgado, Hobbs, JTL, Melnitchouk
PRL **114**, 082002 (2015)

Use framework of JR-14 (NLO) global analysis
Use all scattering data for $Q^2 \geq 1$ GeV^2, $W^2 \geq 3.5$ GeV^2

Jimenez-Delgado + Reya,
PR **D89**, 074049 (2014)

Includes treatment of higher-twist, target mass, nuclear,
…. corrections

→ Includes intrinsic charm

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

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

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

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

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

F_2^{PGF} computed in "fixed-flavor number scheme"
F_2^{IC} computed from various models (BHPS, MBM)

Re-Analysis of Intrinsic Charm

PJ-D/TH/JTL/WM (PRL **114**, 082002 (2015)):
Global fit (JR-14 fit) plus intrinsic charm with shape from HLM [PRD**89**, 074008 (14)], and strength varied.

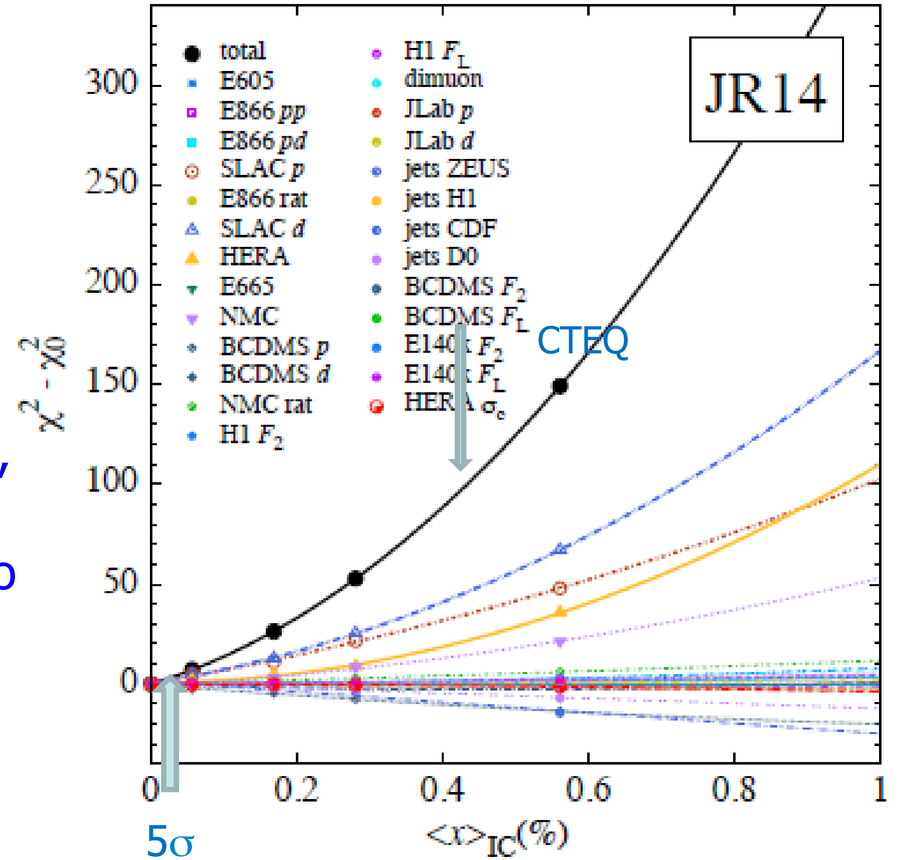
Global fits with, without EMC charm data

Results: 1) intrinsic charm **tiny** – 0.1% IC at 5σ level;

2) Significant discrepancy between EMC charm, HERA + global fit data.

3) χ^2 dominated by SLAC data (HERA, NMC also important)

JR-14 global fit: uses large-x SLAC data on (p,d). Gives **much stronger** upper limit on intrinsic charm than CTEQ, MRST (JR-14 includes low Q^2 data, combined with higher-twist corrections)



Preiiminary

Note: CTEQ uses a looser tolerance criterion
($\Delta\chi^2$ = 100 ~ 0.4% upper limit)

Importance of Threshold Suppression

→ A significant portion of the SLAC data lies below partonic charm threshold $W^2 = 4\ m_c^2$, thus cannot directly constrain intrinsic charm (IC).

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

→ Various prescriptions to account for mismatch between partonic, hadronic charm threshold:

MSTW: use effective charm mass $m_c^2 \to m_c^2 \left(1 + \Lambda^2/m_c^2\right)$

Threshold suppression factor: $\theta(W^2 - W_{thr}^2)\,(1 - W_{thr}^2/W^2)$

Inclusion of Threshold Suppression Factor

Including hadron-threshold suppression factor produces a shallower χ^2 profile.

$$\chi^2_{min} \text{ at } \langle x\rangle_{IC} = 0.15 \pm 0.09\,\%$$

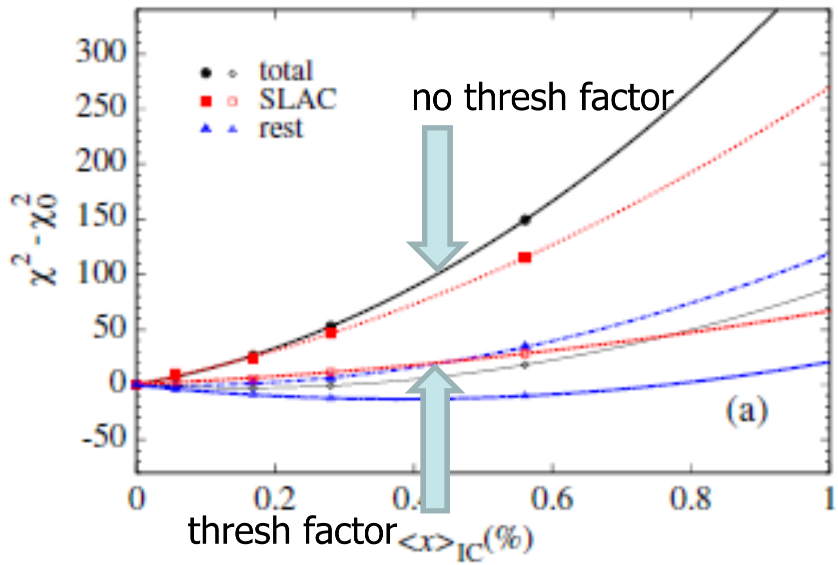
$$\langle x\rangle_{IC} \leq 0.5\,\% \text{ at } 4\sigma \text{ CL}$$

w/suppression factor, allows significantly

larger IC. ☻

SLAC data still dominates;

IC notably smaller if SLAC data included



Why is SLAC data so important?

Most SLAC data below charm prod'n threshold, cannot be directly sensitive to charm PDF; thus can't give strong limits on intrinsic charm probability.

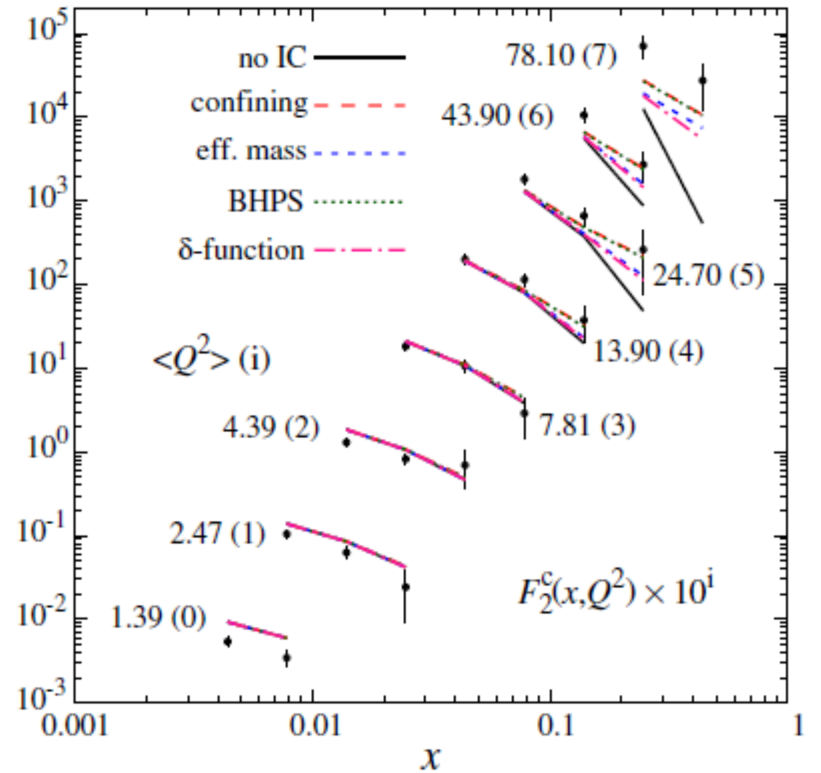
We believe main effect of SLAC data is to pin down up quark PDF at large x; may have strong indirect effect on IC value.

The EMC Charm Data

EMC charm disagrees with HERA charm data

1) At high x, EMC data lie systematically **above** all global fits (only data in high-x region)
2) At low x, EMC data lie **below** global fits, and seriously disagree with HERA measurements

$\chi^2/N = 4.3$ for $N_{EMC} = 19$



Take-away, EMC charm: data show significant inconsistencies with other high-energy data

use with care, if at all

HERA vs. EMC charm data

1) HERA: taken 15 years later than EMC
2) 2 independent expt's (H1, ZEUS)
3) HERA data jointly analyzed; very precise

Criticism of Brodsky & Gardner
[arXiv:1504.00969]

Strong advocates for large intrinsic charm (IC) probability ($\geq 1\%$)

EMC charm measurements seem to support large IC.

1) Much SLAC data below partonic charm threshold $W^2 \sim 4m_c^2$. Should include phase-space suppression factor for below-threshold events.

done

2)We use tolerance criterion $\Delta\chi^2 = 1$. However, our model has ~ 30 parameters. The tolerance criterion $\Delta\chi^2$ needs to be increased, should be proportional to # of parameters in the model -- reference to "Numerical Recipes".

Simply wrong

3)Since much of SLAC data is below charm prod'n threshold, cannot be directly sensitive to charm PDF; thus can't give strong limits on intrinsic charm probability.

SLAC data impacts light quark PDFs

4) Wrong to exclude EMC charm data "on statistical grounds alone".

Large χ^2; use with care

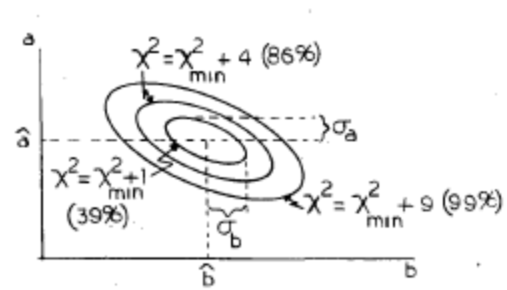
Brodsky/Gardner currently revising critique

Brodsky & Gardner on χ^2

2)We use tolerance criterion $\Delta\chi^2 = 1$. However, our model has ~ 30 parameters. The tolerance criterion $\Delta\chi^2$ needs to be increased, should be proportional to # of parameters in the model -- reference to "Numerical Recipes".

This is completely wrong – BG mistake "# of parameters in fit" with "# of parameters that are simultaneously varied". We are varying 1 parameter (IC probability); thus appropriate statistical tolerance is $\Delta\chi^2 = 1$

Some groups adopt tolerance > 1
(MSTW $T^2 = 50$; CTEQ $T^2 = 100$)
because of tension between data sets
However, this is purely phenomenological, has nothing to do with statistical criterion. Other groups (e.g., ABM, JR, CJ) use $\Delta\chi^2 = 1$
"neural network" fits don't use χ^2 – may help determine sensible errors in PDFs



Lattice Constraints on Intrinsic Charm

Total charm = extrinsic + intrinsic. Intrinsic = small perturbation on extrinsic (but very different x distribution).

Best indicator of intrinsic charm: charm momentum asymmetry

$$C^{-}(x) \equiv \; x[c(x) - \bar{c}(x)]$$

$$C^{-} = \langle C^{-}(x) \rangle$$

No contribution to charm momentum asymmetry from perturbative (extrinsic) charm.

However, expected to be quite small

Experimentally hard to determine

In meson-baryon models, sign of charm momentum asymmetry hard to determine (quite sensitive to type, shape of form factor)

Even sign, approximate magnitude of charm momentum asymmetry from lattice would be useful

Conclusions:

✓ "Meson-baryon" models predict significant "intrinsic" quark probabilities

✓ would make measurable contributions to parton distributions, structure functions

✓ EIC would provide excellent environment for testing intrinsic quark probabilities (s,c,b)

- Intrinsic Charm (IC):
- global fit places **severe** upper limits on IC: P < 0.4%
- EMC charm measurements: strong tension with HERA charm + global data
- large intrinsic charm would produce visible "bump" in high-x X-sections
- possibility to see at LHC
- precise lattice calculations can help pin down c, cbar distributions

Back-Up Slides

"Meson-Baryon" Models of Intrinsic Sea Quarks

Meson-baryon states contribute to the parton distribution function and structure function for a particular quark flavor q_i

$$\delta q(x) = \int_x^1 \frac{dy}{y} f_{MB}(y) q_M(\frac{x}{y}) + \int_x^1 \frac{dy}{y} f_{BM}(y) q_B(\frac{x}{y})$$

$$\delta F_2(x) = \int_x^1 dy f_{MB}(y) F_2^M(\frac{x}{y}) + \int_x^1 dy f_{BM}(y) F_2^B(\frac{x}{y})$$

The Splitting Function in Meson-Baryon Models

The splitting function f_{MB} for nucleon to state with meson M, baryon B is related to the wave function ϕ_{MB} by

$$f_{MB}(y) = \int d^2k_\perp \, |\phi_{MB}(y, m_\perp^2)|^2$$

Calculate in the infinite-momentum frame (IMF), where the wave function is given by

$$\phi_{MB}(y, k_\perp^2) = \frac{1}{2\pi\sqrt{y(1-y)}} \frac{V_\infty(y, k_\perp^2)F(s)}{m_N^2 - s_{MB}}$$

Here V_∞ is the N-MB coupling, F(s) is a form factor to damp out contributions from very large energies, and s_{MB} is the energy in the IMF

$$s_{MB} = \frac{k_\perp^2 + m_M^2}{y} + \frac{k_\perp^2 + m_B^2}{1-y}$$

E.g., V_∞ for N → Nπ,

$$V_\infty(y, k_\perp^2) = \bar{\psi}^N(k')i\gamma_5\phi_\pi(k)\psi^N(p)$$

Quark Distribution in a Meson or Baryon

To obtain the meson-baryon contribution, we need the quark distribution in a meson or baryon. Also working in the IMF, we obtain the quark distribution in a meson, e.g., $D^- = \bar{c}d$

$$\bar{c}(z) = \int dk_\perp^2 \frac{|V_{\bar{c}d}(z, k_\perp^2)|^2 F(s)^2}{4\pi^2 z(1-z)(m_D^2 - s_{\bar{c}d})^2}$$

where the energy s_{cd} is given by

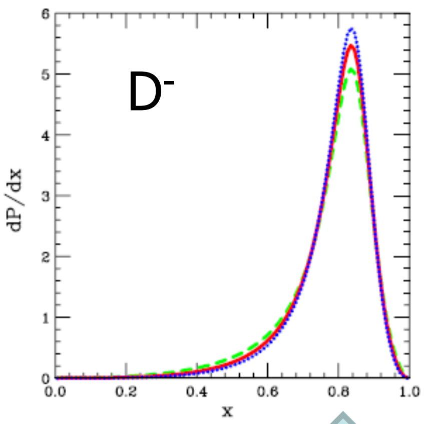
$$s_{\bar{c}d} = \frac{m_c^2 + k_\perp^2}{z} + \frac{m_d^2 + k_\perp^2}{1-z}$$

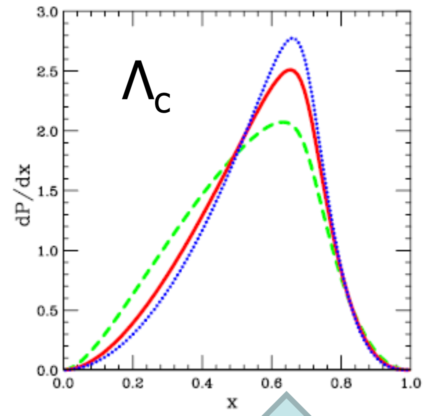
The charm distribution will be peaked at $z \sim \frac{m_c}{m_c + m_d}$ the fraction of the total D mass contributed by the cbar.

We use an analogous argument for the c distribution in $\Lambda_c^+ = (udc)$
In a quark-diquark picture the c distribution should peak at

$$z = \frac{m_c}{m_c + m_d}$$ where m_d is the diquark mass

Examples: Charm, Anticharm Distributions in Hadrons





$$z \sim \frac{m_c}{m_c + m_d}$$

$$z = \frac{m_c}{m_c + m_d}$$

Calculations of charm distributions in hadrons by Pumplin, who used point-like vertices. Left: $\bar{c}$ in $D^- = (\bar{c}d)$. Right: c in $\Lambda_c^+ = (udc)$. The $\bar{c}$ distribution is harder than the c distribution because the $\bar{c}$ is a larger fraction of the D mass than the c quark is of the Λ_c.

Peak shifts and broadening occur when hadron internal structure is included; this approximation works best for heavy quarks (a bad approximation for pion-cloud).

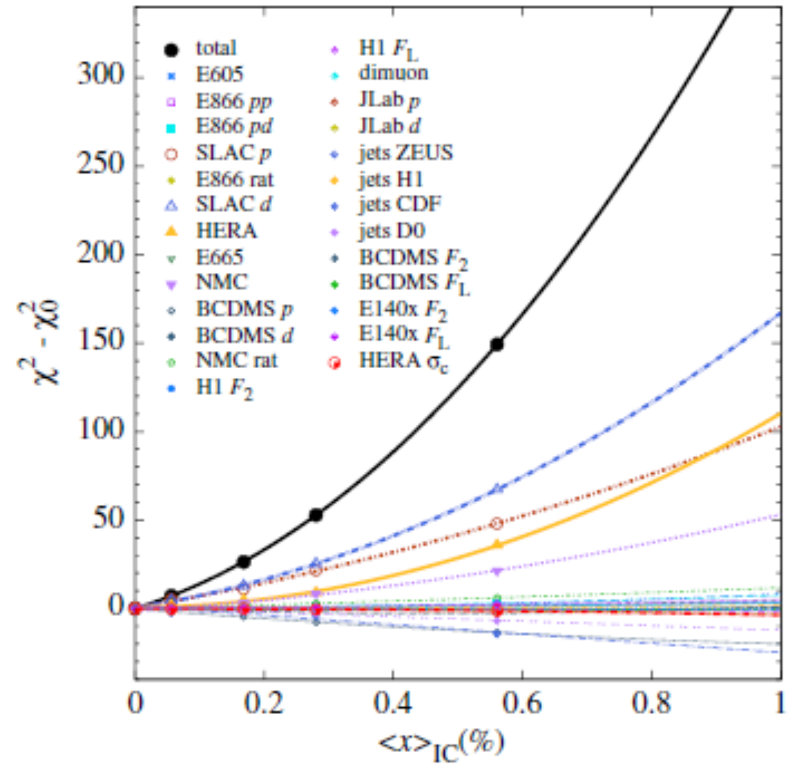
J. Pumplin, PR **D73**, 114015 (2006)

Details of Intrinsic Charm Fit

PJ-D/TH/JTL/WM (PRL **114**, 082002 (2015): Global fit (JR-14 fit) plus intrinsic charm with shape from HLM [PRD**89**, 074008 (14)], and strength varied.

Influence of data sets on intrinsic charm

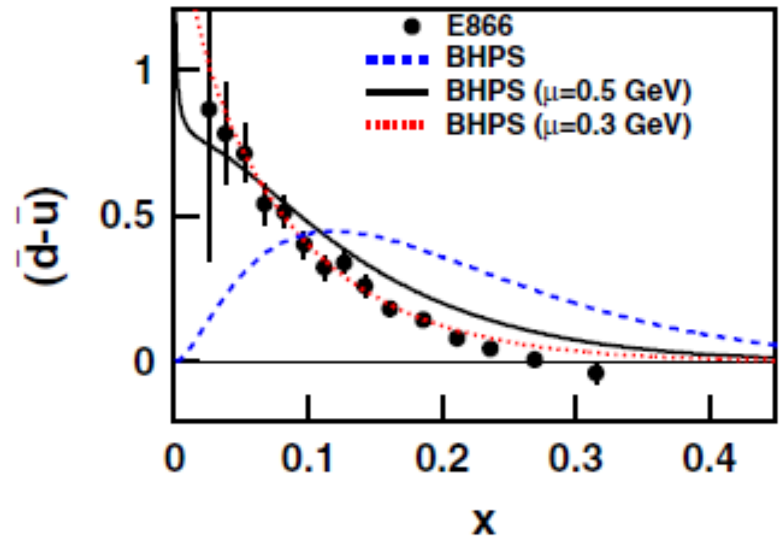
1) SLAC e-d, e-p strongest constraints
2) HERA charm important at small x
3) NMC e-p, e-d at medium x



We carried out 2 fits: 1 without EMC charm data, one including it. EMC charm: significant tension with other data (χ^2/data pt > 4; strong disagreement in shape, magnitude with HERA charm data)

HERA vs. EMC charm: HERA primarily small-x; excellent statistics; combined data from H1, ZEUS; EMC few points, at significantly higher x.

Chang/Peng: BHPS Model for Intrinsic Sea Quarks:



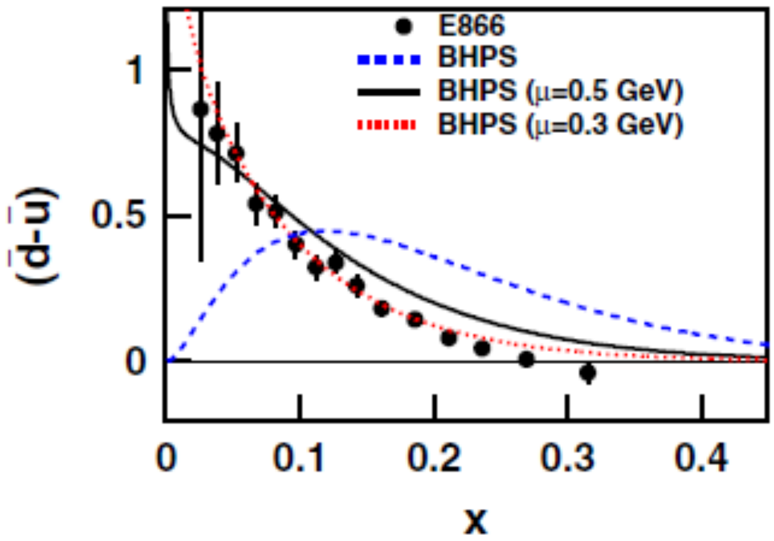
Use BHPS formula for light (u,d) sea quarks, generate dbar – ubar.
Calculate using Monte Carlo integration (Note: extrinsic contrib'n cancels for this combination).
Normalize to overall sea quark probability.
Dashed curve: dbar – ubar at starting scale.
Black curve: QCD evolution from starting scale μ= 0.5 GeV to Q^2 = 54 GeV^2 of E866 exp't.
Red curve: same but with starting scale μ= 0.3 GeV.

$$\int_0^1 [\bar{d}(x) - \bar{u}(x)]dx = 0.118$$ from E866 exp't

W-C Chang and J-C Peng, PRL **106**, 252002 (2011)

Chang/Peng: BHPS Model for Intrinsic Sea Quarks:

Chang/Peng conclusion: the BHPS formula when applied to light sea quarks, gives decent agreement with experimental values for dbar – ubar,
if we normalize to the overall sea quark probabilities as measured by the E866 Collaboration,
and use QCD evolution with starting scale $\mu \sim 0.3$ GeV.



W-C Chang and J-C Peng, PRL **106**, 252002 (2011)

Conclusions (cont’d):

- Strange quarks:
- meson-baryon model predicts large intrinsic strangeness (P ~ 4%)
- normalized to inclusive strange prod’n in pp reactions
- latest HERMES measurements – essentially no s quarks for x > 0.1: would place tight constraints on intrinsic strangeness (multiplicity issues?)
- semi-inclusive measurements (strange particles) at an EIC

- meson-baryon models predict measurable quark-antiquark asymmetry

✓ Strange quarks: dimuon X-sections in neutrino reactions give strange asymmetry – NuTeV/CCFR measurements

✓ Exp’t: strange quarks “harder” than sbar – unusual shape of distribution
✓ meson-baryon models: s- sbar could be either positive or negative
✓ Important to obtain independent replication of strange quark momentum asymmetry