Heavy intrinsic quarks in hadrons: theory, constraints, & consequences

— An Overview —

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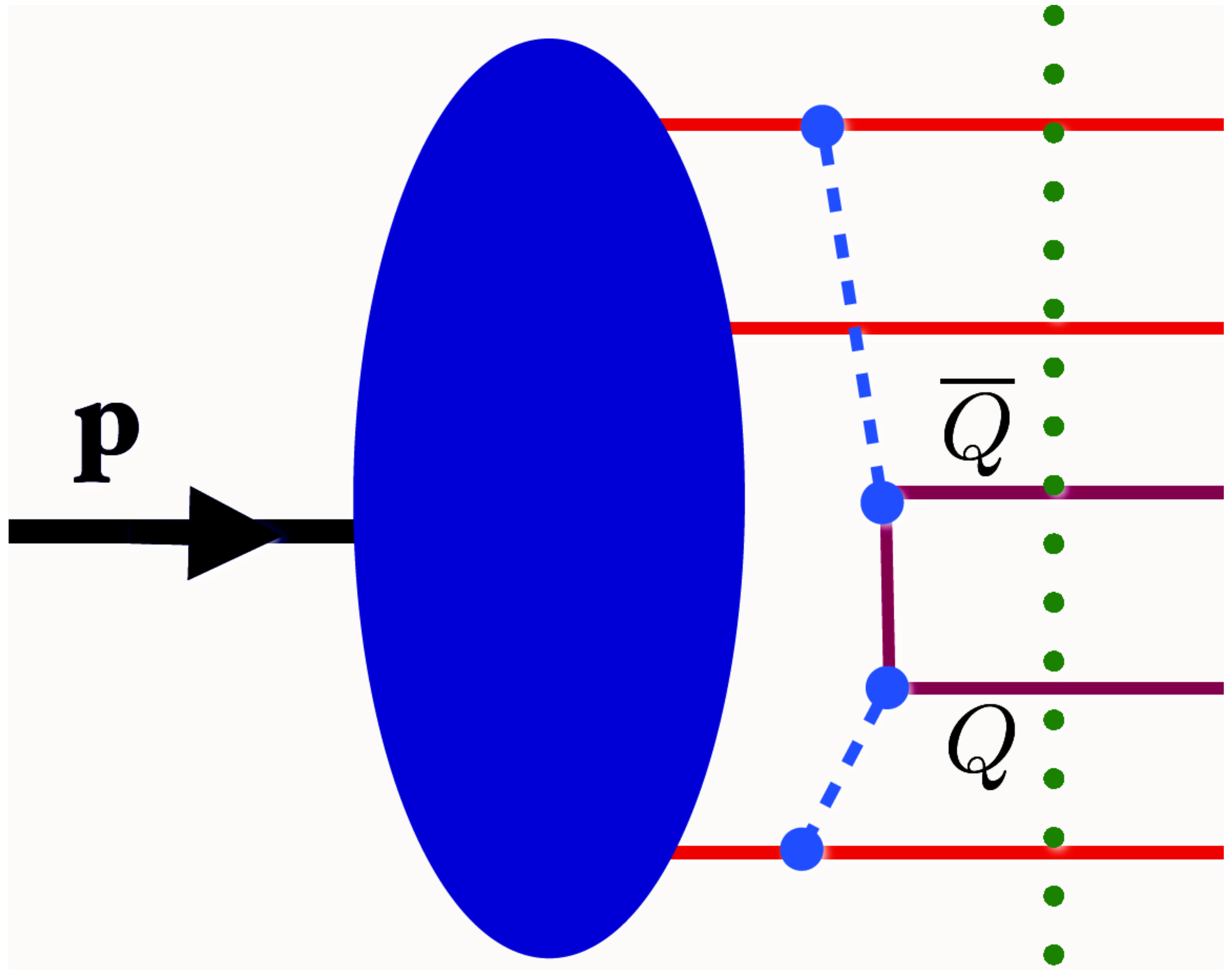
Intrinsic Heavy Quarks

The proton as a bound-state in light-front QCD

The light-front wave function ψ is defined in light-cone quantization at fixed light-front time $\tau^+ = t+z$ via $H_{LC}\,|\psi\rangle = (M^2/P^+)|\psi\rangle$

N.B. a coupled-channel problem in the free Fock-state basis

- Note hadronic "light-by-light" gg $\longrightarrow Q\overline{Q} \longrightarrow$ gg



[Brodsky et al., arXiv: 1504.06287]

"Intrinsic" heavy quarks appear through multiple gluon interactions
Although a rigorous prediction of QCD, they have not been established experimentally

[Brodsky, Hoyer, Peterson, and Sakai (BHPS), 1980; Brodsky, Peterson, Sakai, 1981…]

Intrinsic Heavy Quarks

Appear in the solution of the hadron eigenvalue problem

Dominant configurations thus appear when H_{LC} (“P^-”) is minimized;
in the BHPS model this appears when m_ℓ^2 is minimized

$$\psi_\ell(x_i, \vec{k}_{\perp,i}) = \frac{\Gamma(x_i, \vec{k}_{\perp,i})}{M^2 - m_\ell^2} \qquad m_\ell^2 = \sum_{i=1}^{n} \frac{\hat{m}_i^2}{x_i} \qquad \hat{m}_i^2 = m_i^2 + \langle \vec{k}_{\perp,i}^2 \rangle$$

Or when the parton constituents of Fock state ℓ have equal rapidity

[Brodsky Hoyer, Peterson, and Sakai (BHPS), 1980]

N.B. suitable integrals of $|\psi|^2$ yields the PDFs with $x_{Bj} = x_i$ of the struck parton

[Lepage and Brodsky, 1980]

In contrast, extrinsic quarks are generated by gluon splitting

Intrinsic quarks appear at larger x_{Bj} and are (relatively) of higher twist

[Vogt and Brodsky, 1995]

Intrinsic Heavy Quarks

Enter theoretical models and estimates

An OPE analysis of T^{++} in the proton gives the $1/m_Q^2$ scaling; intrinsic charm carries few x 10^{-3} of the nucleon momentum

[Franz, Polyakov, and Goeke, 2000]

Lattice QCD calculations of $\langle N|c\bar{c}|N\rangle$ also indicate significant intrinsic charm probabilities

[Freeman & Toussaint (MILC), 2013; Gong et al. (χQCD), 2013]

There are different models of the shape of the intrinsic charm PDF; its normalization can then be assessed from fits to DIS data

Since extrinsic heavy quarks appear radiatively, their strength is fixed by the gluon PDF at $Q_0 \simeq m_Q$

An NLO analysis of the EMC data with intrinsic & extrinsic charm also supports intrinsic charm at the ~1% level [Harris, Smith, & Vogt, 1996]

More recent global fits have come to similar conclusions

[Pumplin, Lai, & Tung, 2007, Dulat et al., 2014]

Intrinsic Heavy Quarks

Can engender novel phenomena

They can, e.g., materialize from soft interactions and appear at large x_F

[Brodsky et al., 1985; Brodsky, Hoyer, Mueller, & Tang, 1992]

Its appearance (at expected strength) would be pertinent to many puzzles...

Early evidence for intrinsic charm came from the EMC measurement of the charm structure function F_2^c [Aubert et al., 1983; Hoffman & Moore, 1983]

Also from data on the large x_f production of open charm in hadroproduction (ISR, WA89 and WA92 @ CERN, E791 and SELEX @ Fermilab)

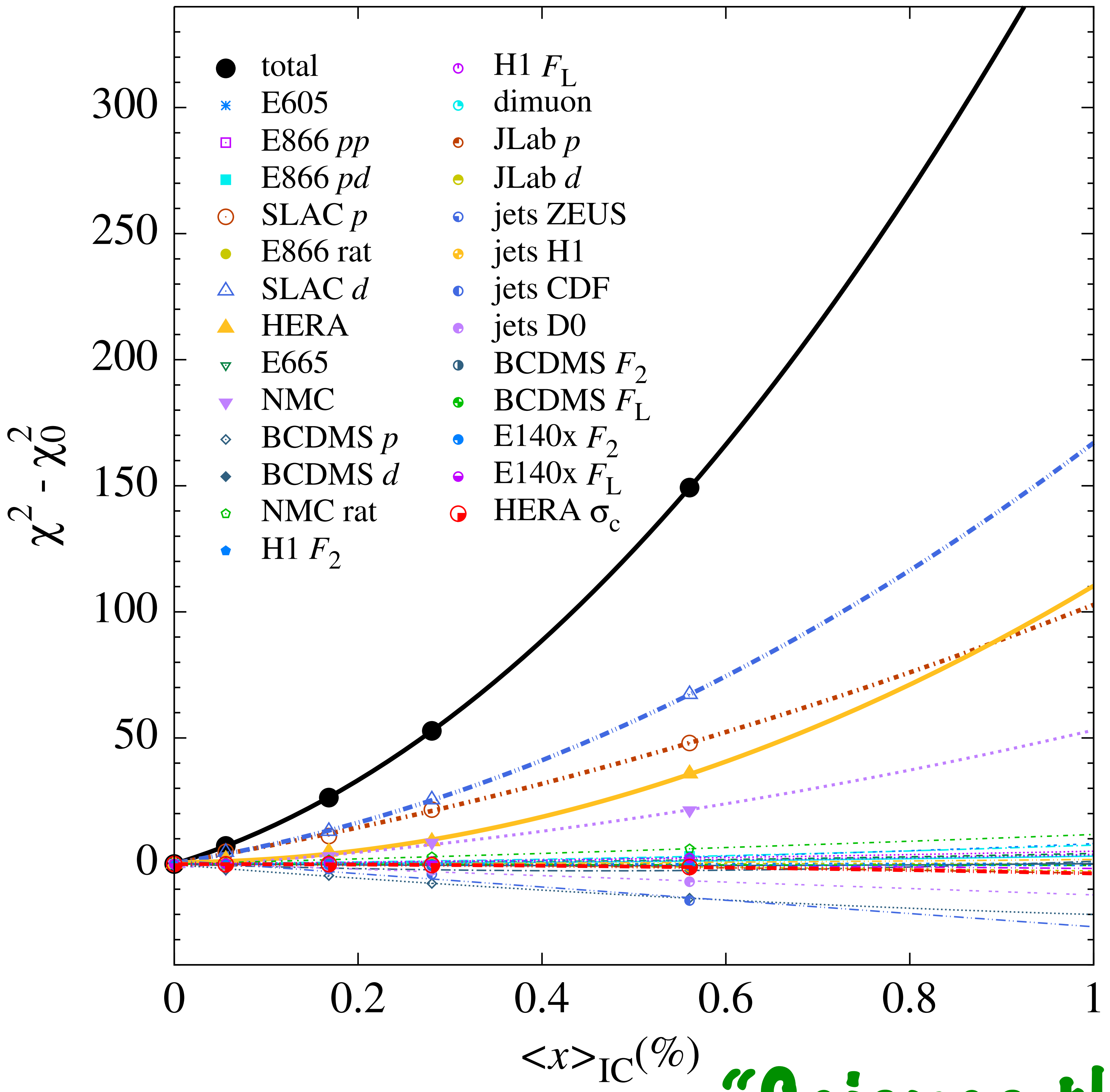
[Gari et al., 1991; Vogt, Brodsky, & Hoyer, 1992; Vogt & Brodsky, 1996; Gutierrez & Vogt, 1999]

Could mimic the effect of "charming penguins" in $B \to \pi K$ decays [Brodsky & SG, 2002]

These examples are not exhaustive — my apologies if your favorites are missing!

Intrinsic Heavy Quarks: Why now?

Different recent global fits have come to differing conclusions...



A new global fit with more low energy data yields $\langle x_{\rm IC} \rangle < 0.1\%$ at 5σ

[Jimenez-Delgado, Hobbs, Londergan, & Melnitchouk, 2015]

Incurring discussion & more work:

[Brodsky & SG, 2016]

We also find some evidence that the charm PDF … has an "intrinsic" component, …, carrying about 1% of the total momentum of the proton.

[NNPDF, Ball et al., arXiv:1605.06515, 2016]

"Science thrives on controversy"

Many new efforts to probe intrinsic heavy quarks are being developed

Intrinsic Charm at the GHP workshop

PDF's — Intrinsic Charm I (this session!)

- *Hadron structure studies with a fixed target experiment at the LHC — AFTER@LHC* [Andrea Signori (JLab)]
- *Intrinsic charm at LHCb* [Philip Ilten (MIT)]

PDF's — Intrinsic Charm II **[16:00 Thurs., Feb. 2 (Coolidge)]**

- *Intrinsic Charm from CTEQ/TEA PDF fits* [Sayipjamal Dulat (Michigan State)]
- *Constraints and implications for the nucleon's intrinsic charm from QCD global analysis* [Timothy Hobbs (Univ. Washington)]
- *IC at IC: IceCube can constrain the intrinsic charm of the proton* [Ranjan Laha (KIPAC, Stanford & SLAC)]
- *Towards combined QCD global analysis of polarized and unpolarized PDFs and fragmentation functions* [Nobu Sato (JLab)]

Unfortunately, NNPDF was unable to send a speaker….

Why do the results differ?

This is more important than the differences themselves!

Some salient points:

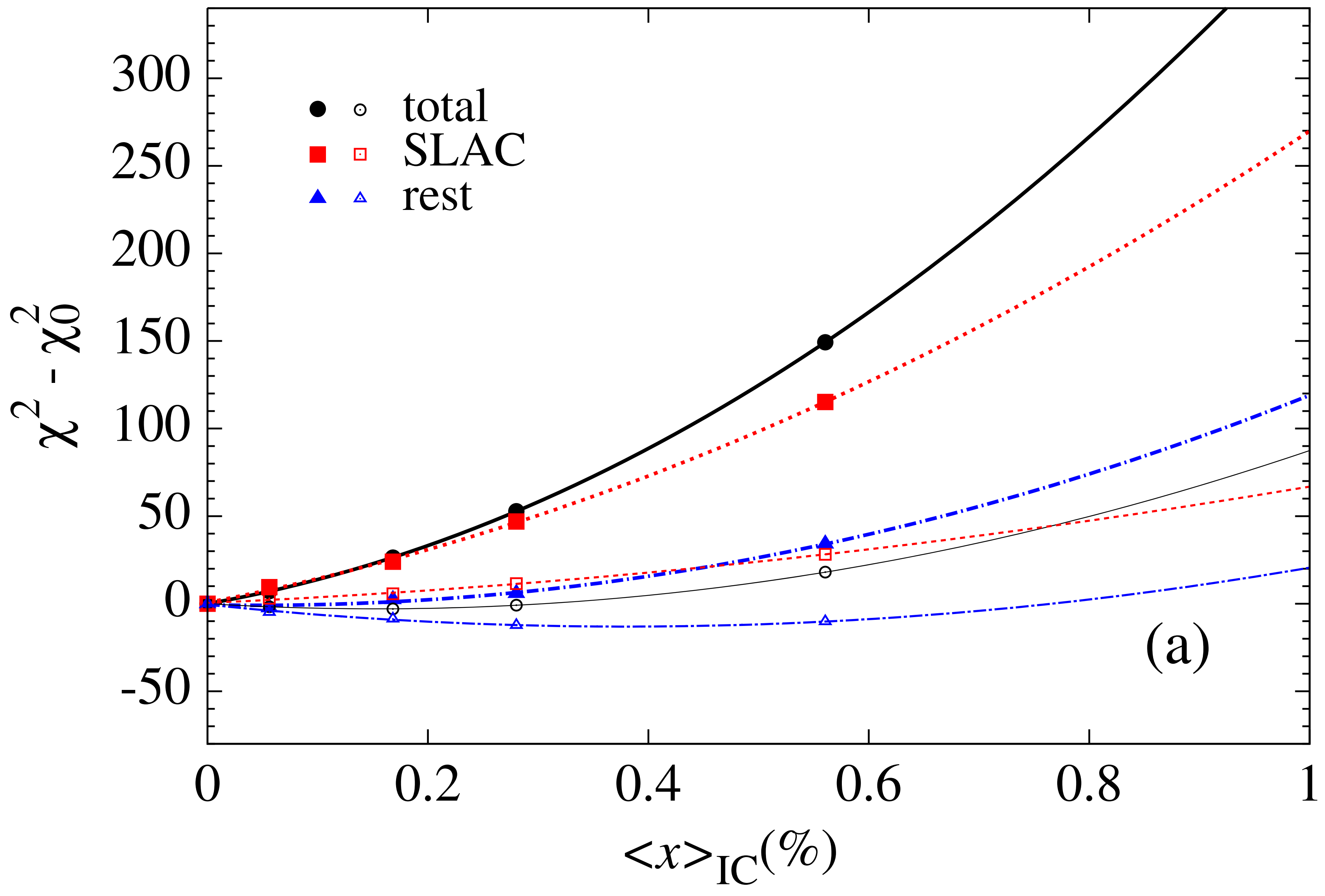
- Unlike other PDF analyses, NNPDF assumes no underlying analytic forms
  This may be particularly pertinent to the study of intrinsic charm, in that its size is better predicted than the shape of its PDF

- At low Q^2 and/or W^2, additional theoretical corrections can appear (due to higher twist and/or heavy quark (meson!) threshold effects)

- In global fits, there can be problems with data set compatibility (e.g., cross section normalizations)

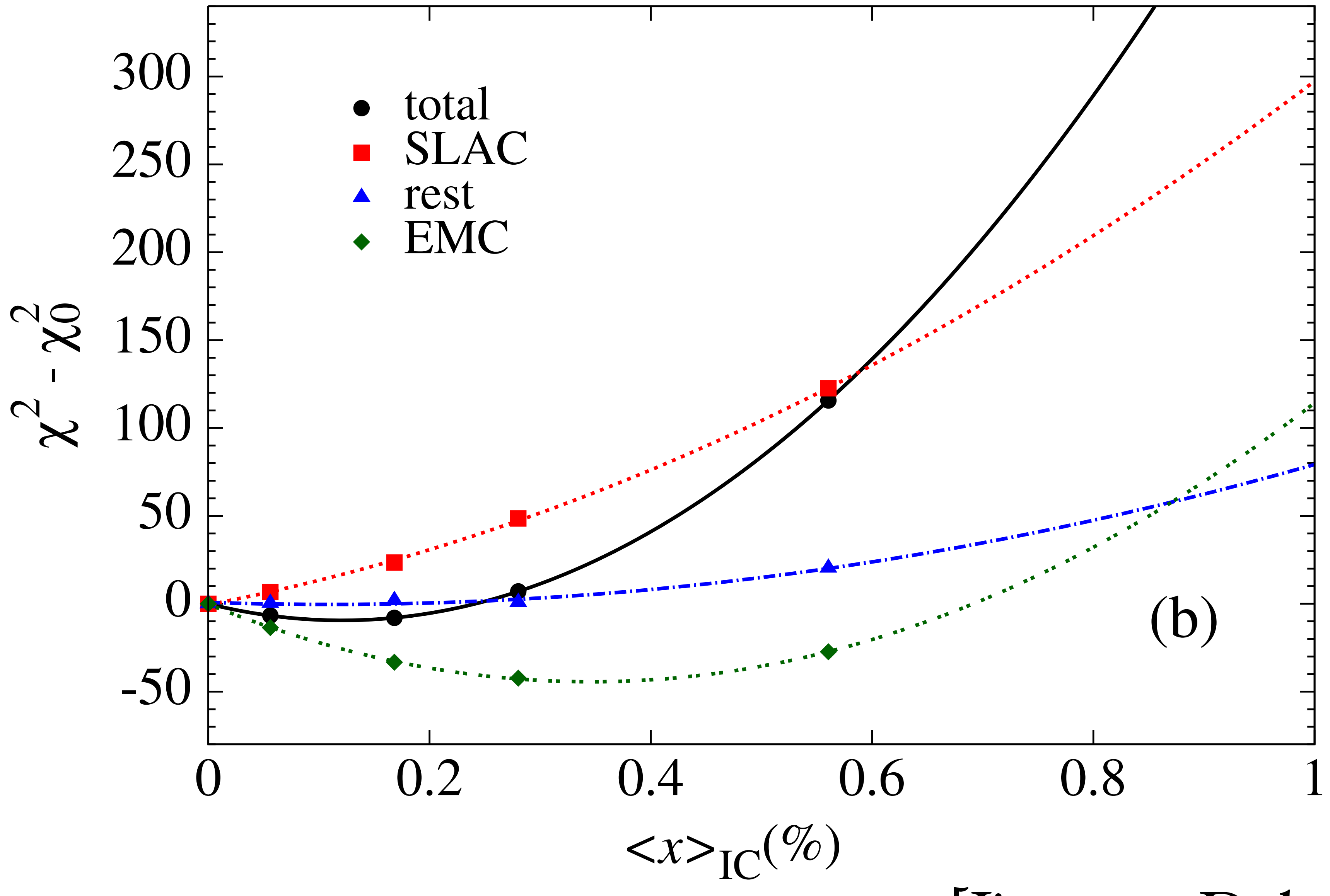
- Associated with this, what is the best statistical way to accept or discard a hypothesis? Altered tolerance criteria have been used in place of scale factors ($\Delta\chi^2=100$ vs. $\Delta\chi^2=1$)

These issues do have impact



Data set not included in other analyses because of low Q^2 and/or W^2

With adjustment for mismatch in charmed parton and hadron mass thresholds



Note result for the EMC data on Fe — a "nuclear" PDF is employed, though NNPDF neglects this

These multiple effects impact conclusions regarding the role of intrinsic charm

[Jimenez-Delgado, Hobbs, Londergan, & Melnitchouk, 2015]

NNPDF and the EMC data

The EMC data provide the only measurement of F_2^c at large x

NNPDF also cannot fit the EMC data with "perturbative charm" only; in their best fit χ^2/N_{dat}=7.3 (the total χ^2 increases by >100)

[NNPDF, Ball et al., arXiv:1605.06515, 2016]

Including "fitted charm" they find χ^2/N_{dat}=1.09

Regarding fitted (intrinsic) charm they note it key to include "massive corrections to the charm-initiated contributions" as well — this has not been done in other fits

N.B. validation of the EMC data possible through LHC measurements, e.g., of Z + c jets at large rapidity, p_T

Summary

Differing results for the intrinsic charm content of the proton has spurred new analyses, both theoretical and experimental

Understanding the origins of the differences is important, for they allow us to probe and refine different global analyses

These new insights will hopefully enable sharpened Standard Model benchmarks for BSM searches at high-energy colliders

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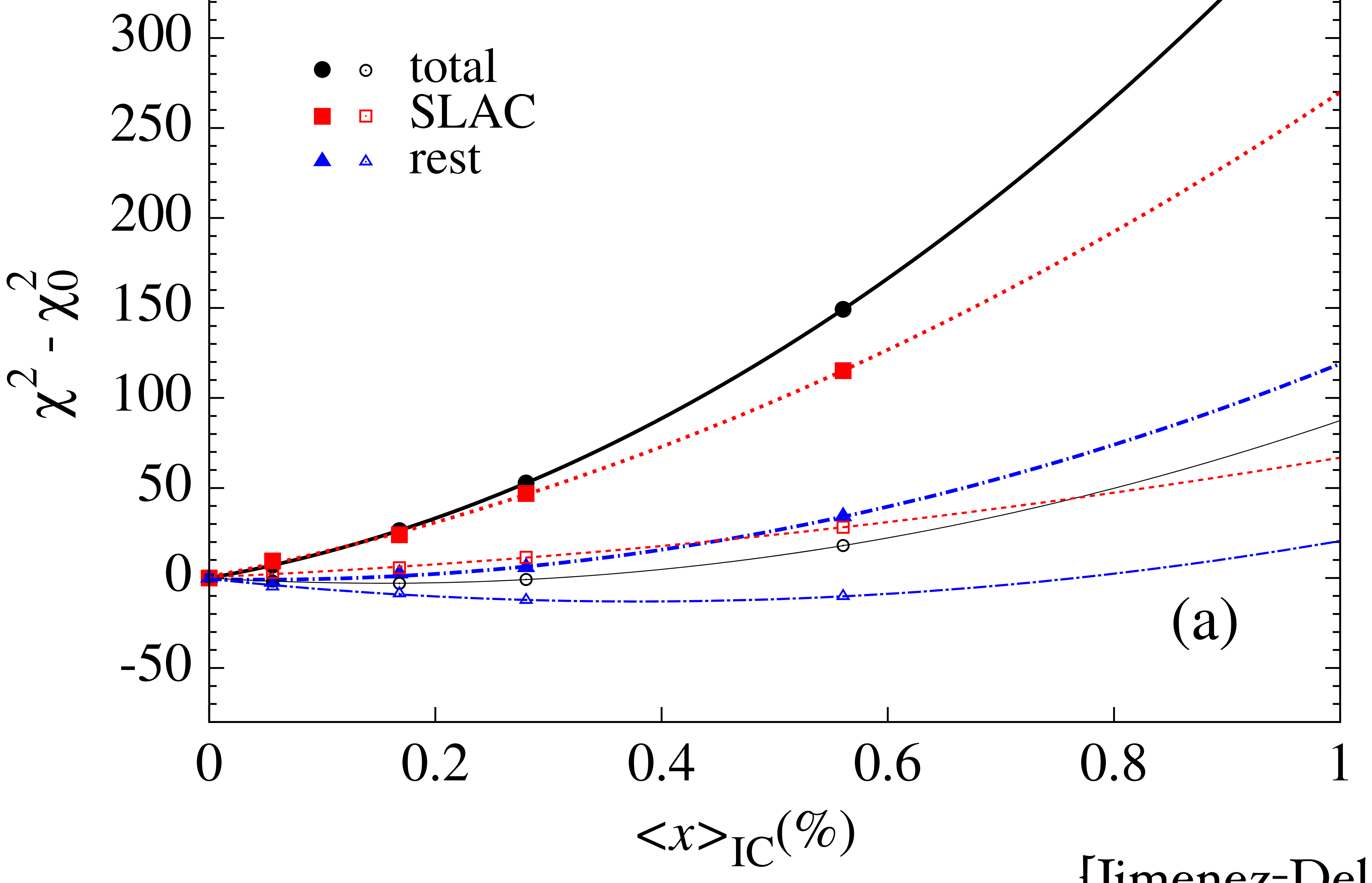
Backup Slides



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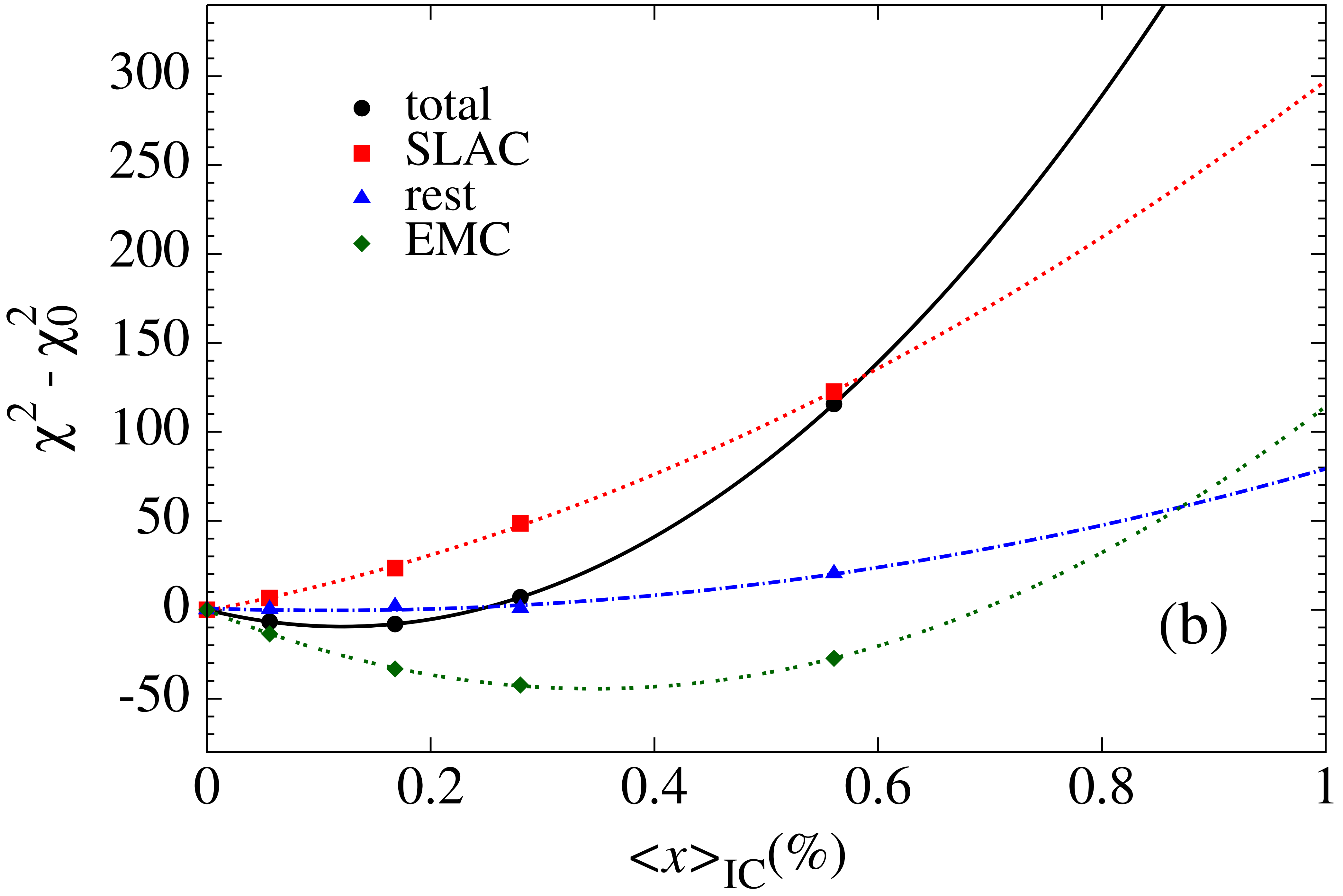

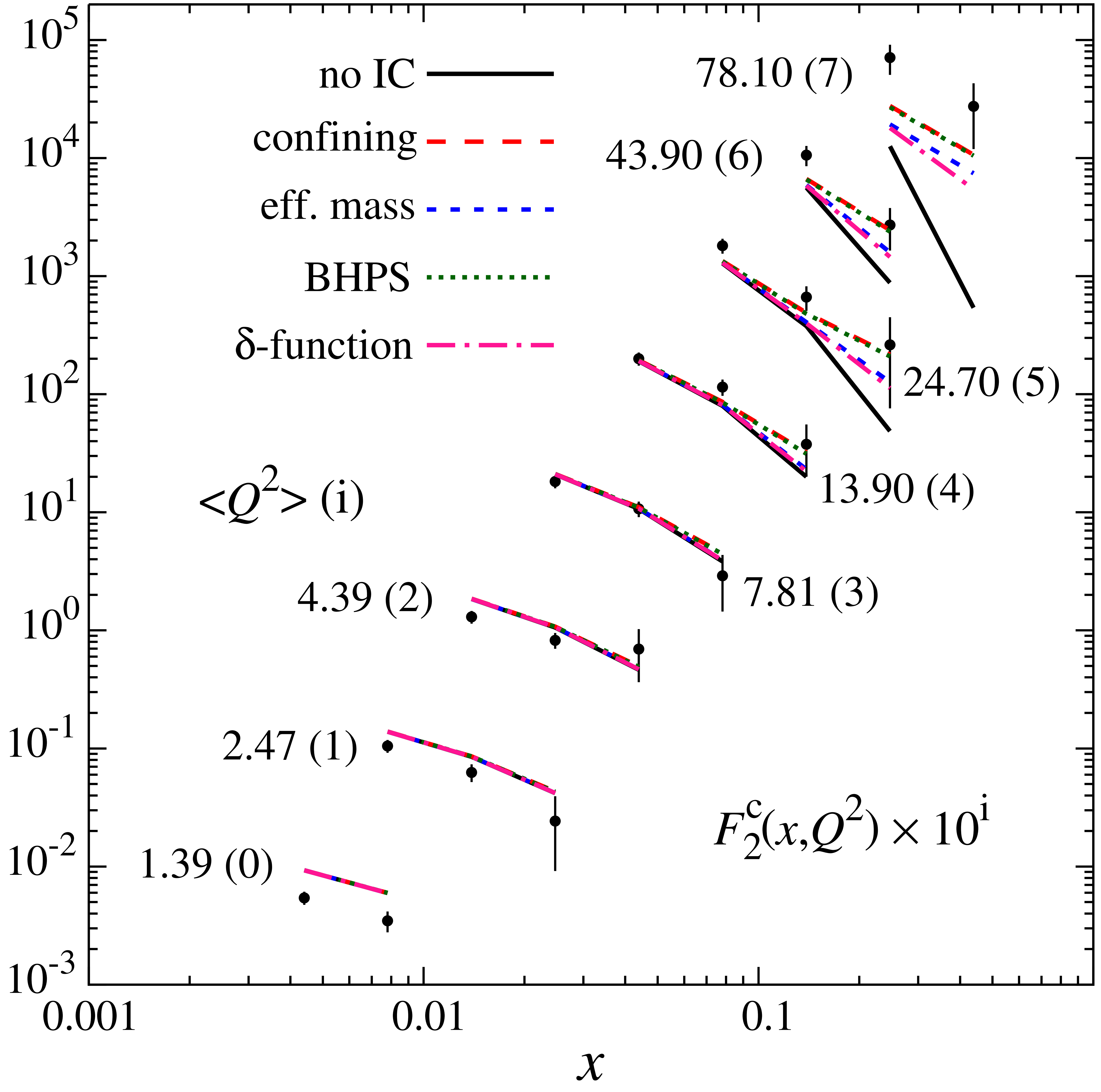

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