Intrinsic Heavy Quarks

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Many thanks to my long term collaborators on heavy quark related topics:
Fred Olness, Aleksander Kusina, Florian Lyonnet,...

and to Pavel Nadolsky for providing some slides

PDF Lattice 2017, Oxford, 23/03/2017

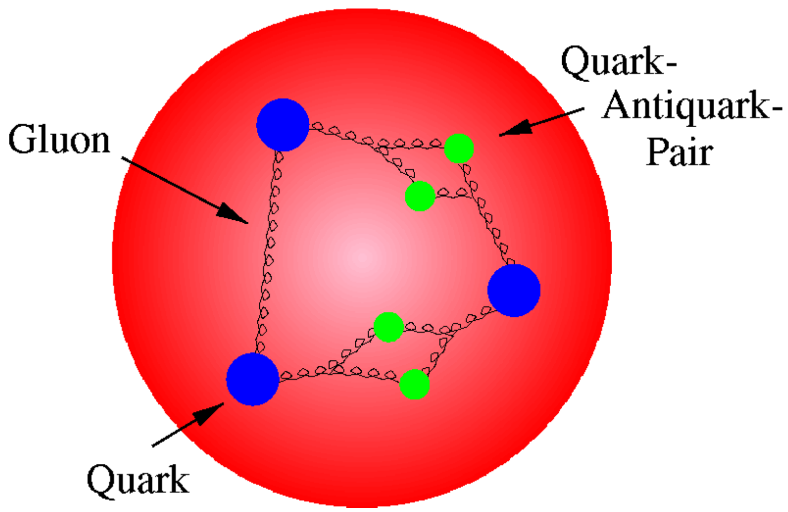
Introduction

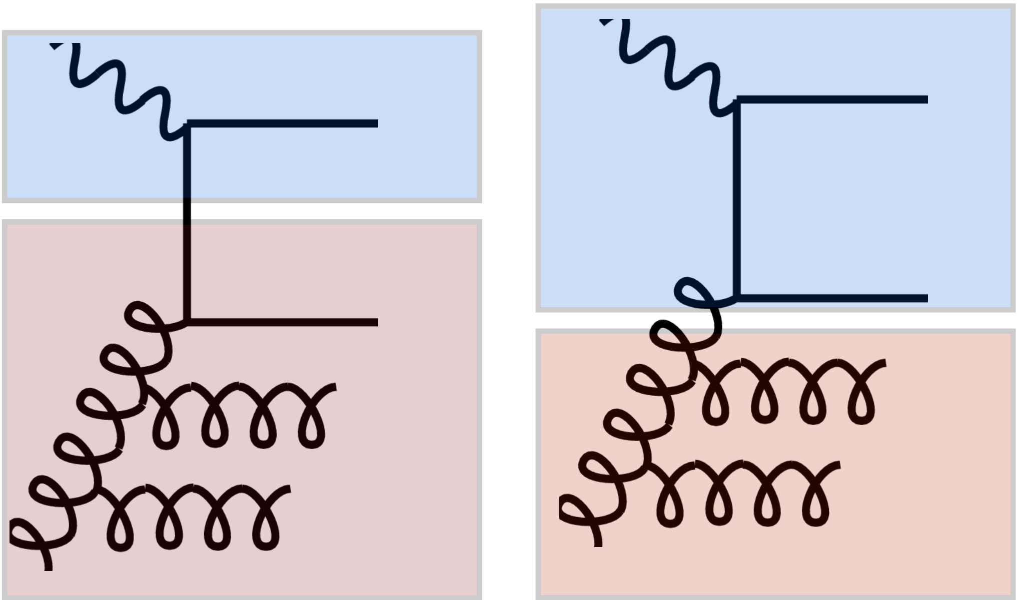
Heavy Quarks

- charm, bottom, top
- $m_h >> \Lambda_{QCD}$, perturbative scale
- Well, charm not so heavy...
- will mostly talk about charm but also a bit about bottom

Is there charm in the nucleon?

- Standard approach: Charm entirely perturbative
- Heavy Flavour Schemes
  - FFNS: charm not in the proton
    keep logs(Q/m) in fixed order
  - VFNS: charm PDF in the proton
    resum logs(Q/m)
- Different Heavy Flavour Schemes = different ways to organize the perturbation series
- What is structure? What is interaction?
  Freedom to choose the factorization scale
- However, charm not so much heavier than Λ_{QCD}
- There could be a non-perturbative intrinsic charm component (added to the VFNS or even FFNS)
- Important to test the charm PDF experimentally





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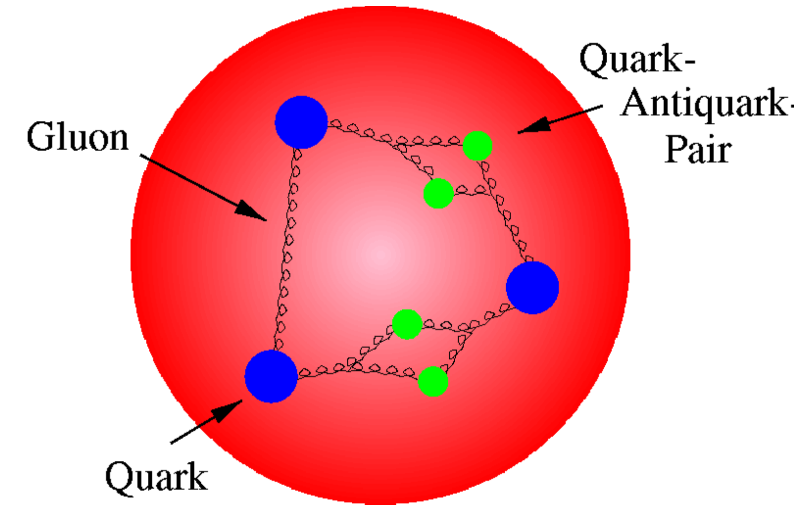
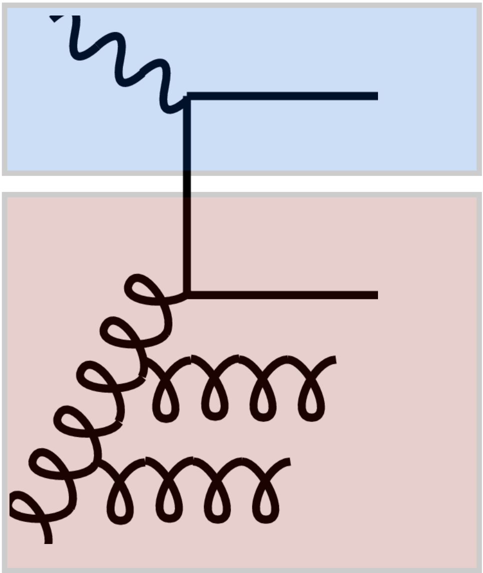
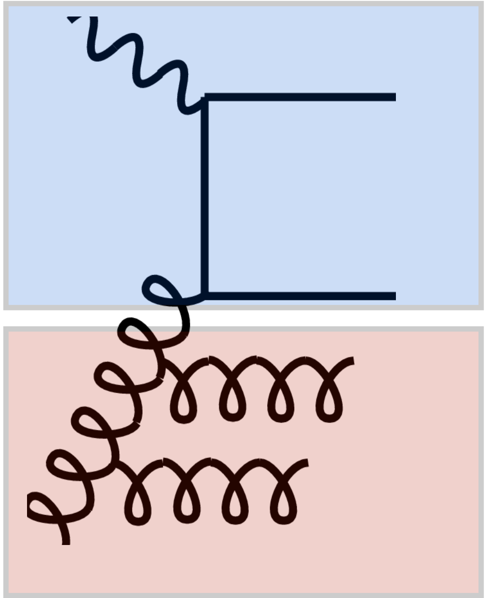






WARNING:
Not sure whether there is consensus on a) whether this is true and b) how it has to be incoprorated in the pQCD formalism

Charm PDFs

- Large majority of global analyses:

  Charm PDF is **calculated**,
  there is no fit parameter!

- Boundary condition for DGLAP evolution calculated perturbatively:

  (matching condition when switching from $n_f=3$ to $n_f=4$ flavours)

  $c(x,Q=m_c) = 0$ @NLO, MSbar

Charm PDFs

- Is there a (sizable) non-perturbative contribution to the twist-2 charm PDF?
- After all, we cannot calculate the strange PDF in perturbation theory and charm is not so heavy.
- **Answers** can come from:
  - global analysis:

    need data sensitive to charm
  - lattice calculations:

    even one or two moments would help

Why do we care?

- **Hadron structure**: (I put it on the 1st place here!)

  Models exist which predict a sizable intrinsic charm component; pheno. consequences for a number of observables;
  searches for BSpQCD (Beyond Standard pQCD) physics

- **LHC**:

  Precision PDFs required as tool,
  there are observables at the LHC sensitive to charm,
  new physics may have couplings ~quark mass!

- **Astroparticle physics**:

  Calculation of neutrino fluxes in the atmosphere depend strongly on the charm PDF

Models predicting intrinsic charm

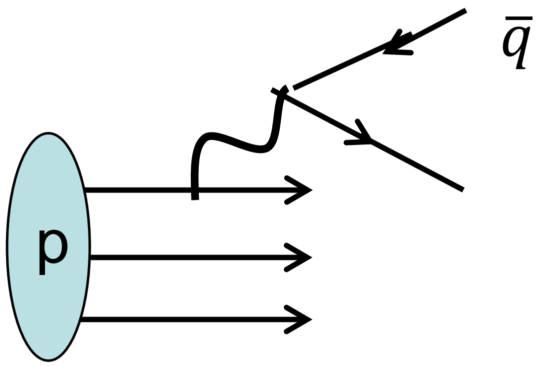
How to define “intrinsic”?

- So far I have only talked about “the charm PDF”
- The question was whether a perturbatively generated charm PDF is sufficient or whether one needs to determine a non-perturbative input distribution from data
- No attempt to split up the charm PDF into something “extrinsic” and “intrinsic” at the end it’s the charm PDF which is needed for collider pheno
- However, for understanding models, the literature need to say precisely what we understand under “intrinsic” and “extrinsic”

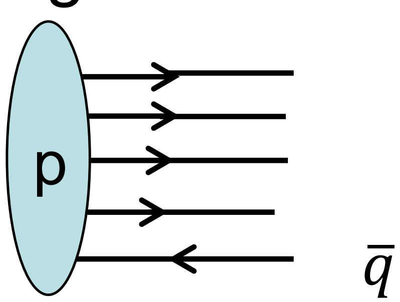
Extrinsic and intrinsic sea PDFs

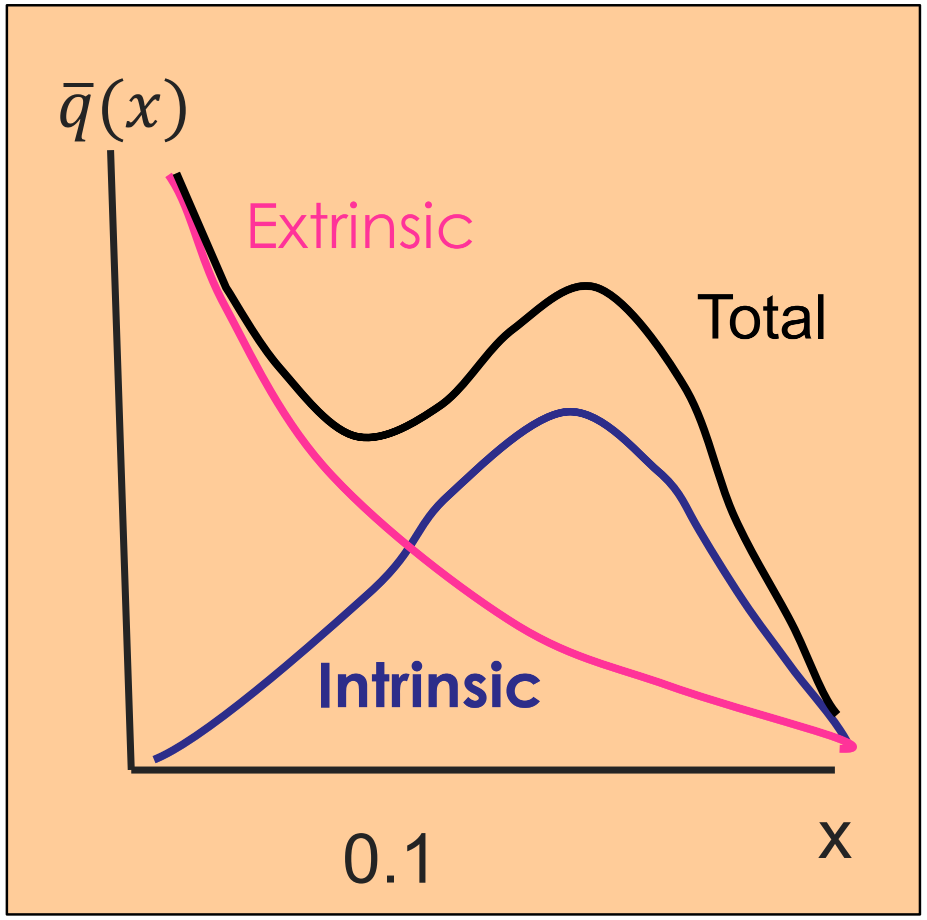
$(\bar{q} = \bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b})$

“Extrinsic” sea
(maps on disconnected diagrams of lattice QCD for both heavy and light flavors?)



“Intrinsic” sea (excited Fock nonpert. states, maps on connected diagrams of lattice QCD?)





(Dis)connected topologies in lattice QCD

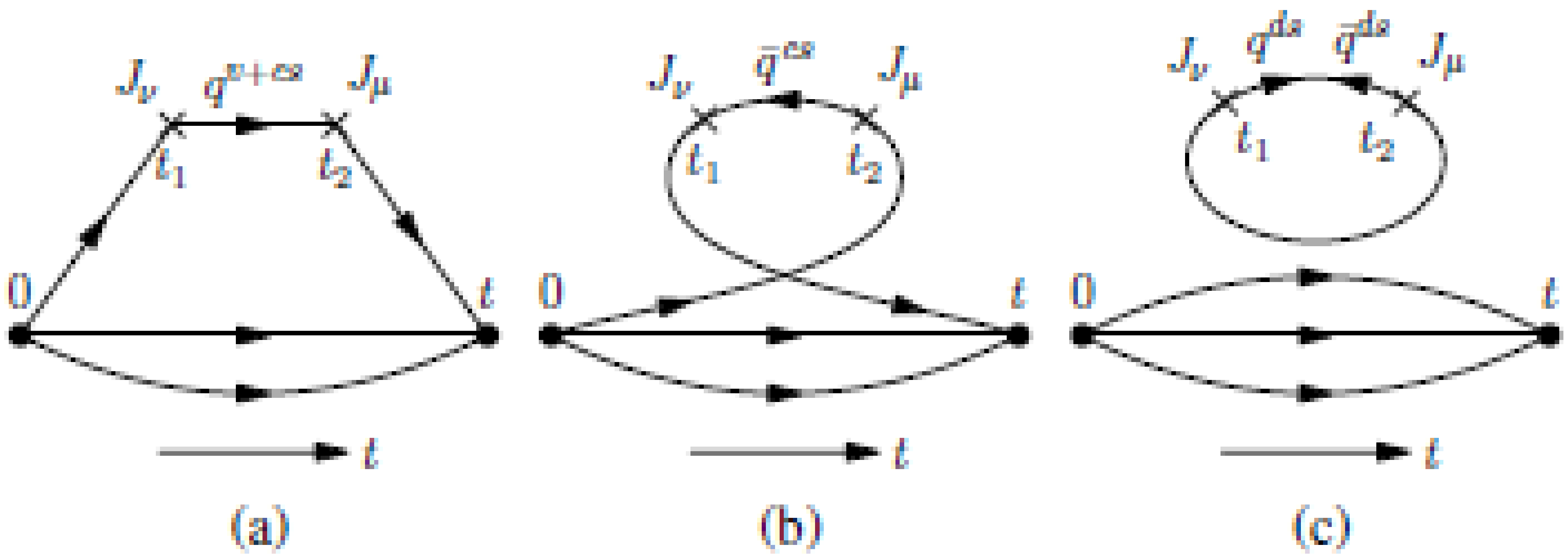


FIG. 1: Three gauge invariant and topologically distinct diagrams in the Euclidean path-integral formalism of the nucleon hadronic tensor in the large momentum frame. In between the currents at t_1 and t_2, the parton degrees of freedom are (a) the valence and CS partons q^{v+cs}, (b) the CS anti-partons $\bar{q}^{cs}$, and (c) the DS partons q^{ds} and anti-partons $\bar{q}^{ds}$ with $q = u, d, s$, and c. Only u and d are present in (a) and (b).

From Pavel's talk in case we want to discuss this

Liu, Chang, Cheng, Peng, 1206.4339

How to define intrinsic heavy quarks?

- For light quarks both mechanisms, "extrinsic" and "intrinsic" are non-perturbative. There is no way to separate the parts, one can only access the full PDF.

- For heavy quarks, one can calculate the "extrinsic" part perturbatively and one can define the "intrinsic part by subtracting the "extrinsic" part from the full result:

  Intrinsic Charm := Charm - Extrinsic Charm

- This definition is to a good accuracy independent of the scale (at least for a large-x intrinsic component) since the intrinsic part decouples from the full evolution equation

- In the following the full charm PDF will also be called "Fitted Charm"

Models

- For a recent review see arXiv:1504.06287
- Most models are concentrated at large x and have a precise x-shape but do not predict the scale (BHPS, Meson cloud models)
- In some models c(x)=cbar(x) in others <u>not</u>
- In global analyses also phenomenological models with a sea-like charm (broad range in x) are analyzed

BHPS model

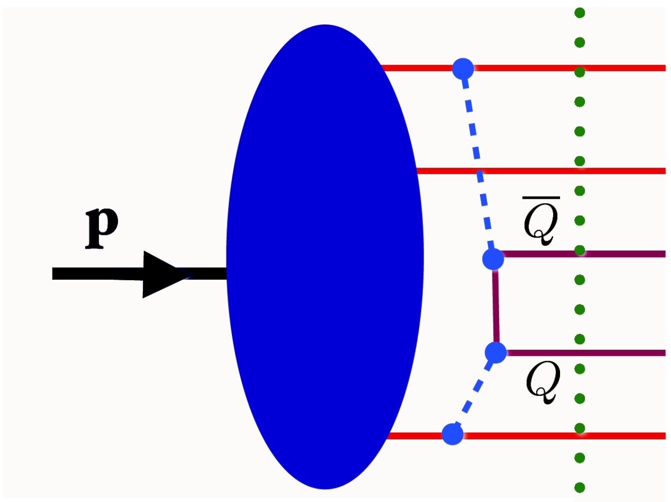


Figure 1: Five-quark Fock state $|uudQ\overline{Q}\rangle$ of the proton and the origin of the intrinsic sea.

- Light cone Fock space picture
- |uudQQbar> state with heavy quarks connected to valence quarks, fundamental property of wave function
- Intrinsic contribution dominant at large x and on the order $O(\Lambda^2/m_Q^2)$
- A finite IC contribution has been extracted from the lattice: Probability for the <N|c cbar|N> ME of 5 to 6% [MILC collab., arXiv:1204.3866]

The x-dependence predicted by the BHPS model, unknown at which scale:

$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

Typical moments;

	$\int_0^1 dx\ c(x)$	$\int_0^1 dx\ x\,[c(x)+\bar{c}(x)] \equiv < x >_{c+\bar{c}}$
CTEQ6.6	0	0
CTEQ6.6c0	0.01	0.0057
CTEQ6.6c1	0.035	0.0200

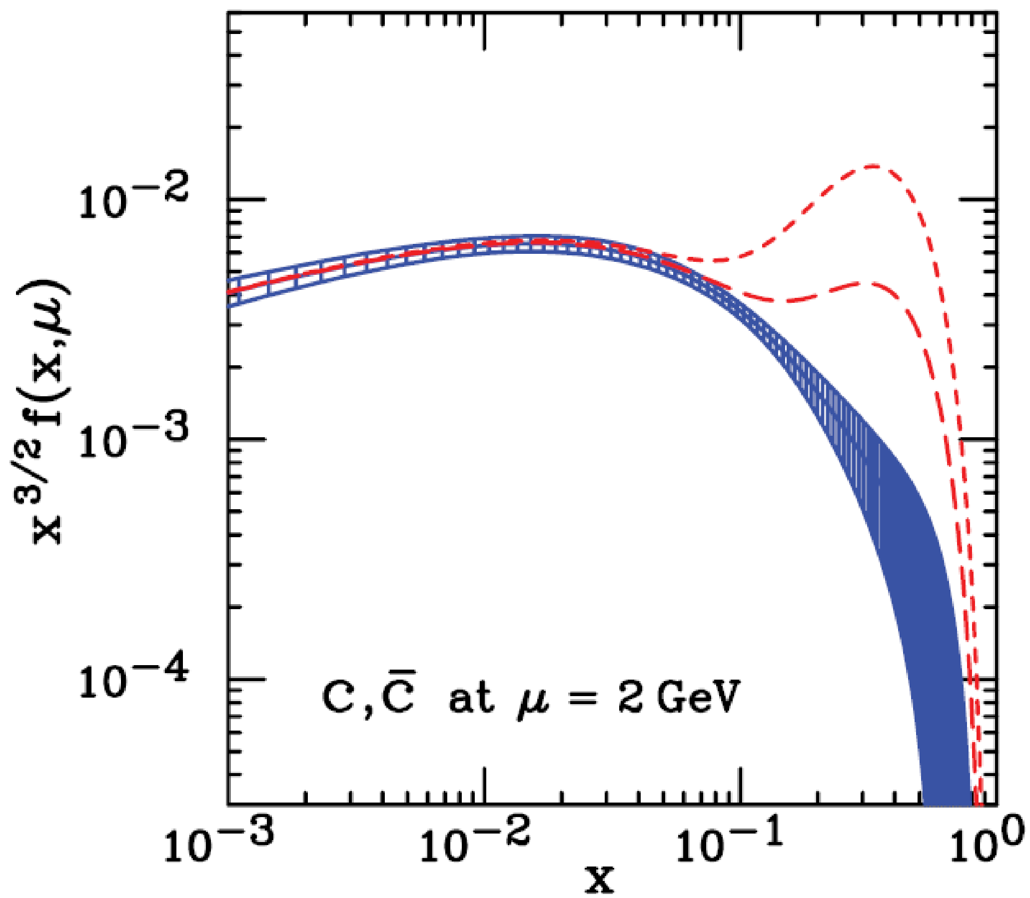
Global anlyses testing intrinsic charm

A global fit by CTEQ to extract IC

PHYSICAL REVIEW D 75, 054029 (2007)

Charm parton content of the nucleon

J. Pumplin,[1,*] H. L. Lai,[1,2,3] and W. K. Tung[1,2]



Blue band corresponds to CTEQ6 best fit, including uncertainty

Red curves include intrinsic charm of 1% and 3% (χ^2 changes only slightly)

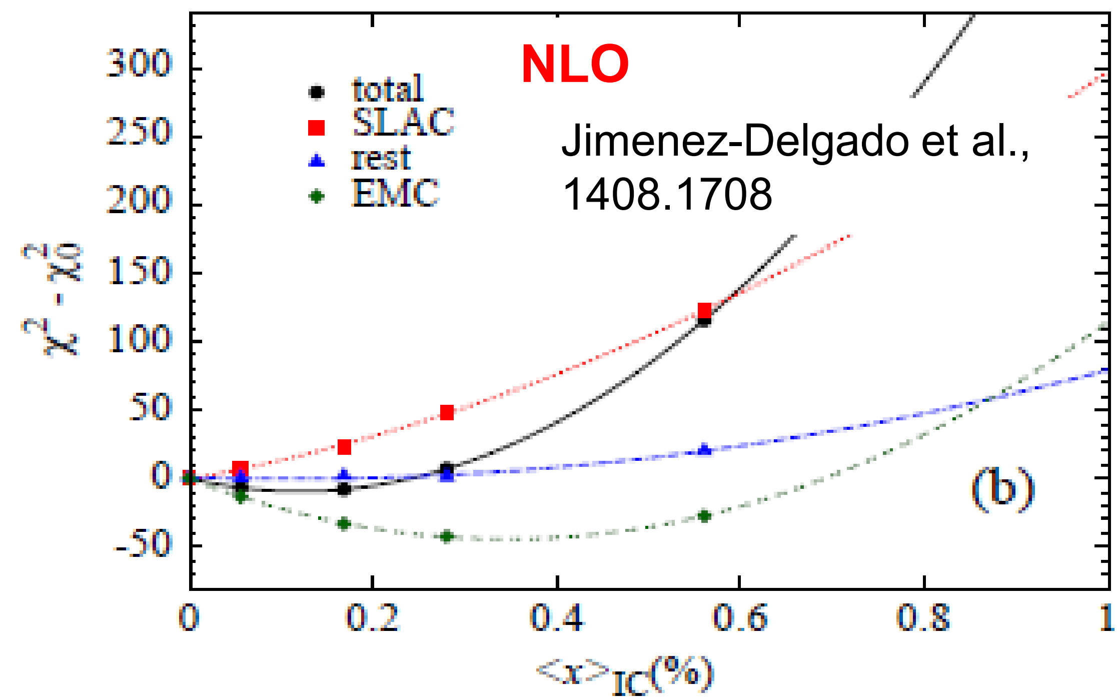
We find that the range of IC is constrained to be from zero (no IC) to a level 2–3 times larger than previous model estimates. The behaviors of typical charm distributions within this range are described, and their implications for hadron collider phenomenology are briefly discussed.

No conclusive evidence for intrinsic-charm

Recent PDFs with fitted charm

Several studies conclude that IC may carry no more than 1% of the proton's momentum

Constraints depend on data selection (e.g., on whether the EMC F_2^c data are included) and methodology (CTEQ vs. NNPDF)



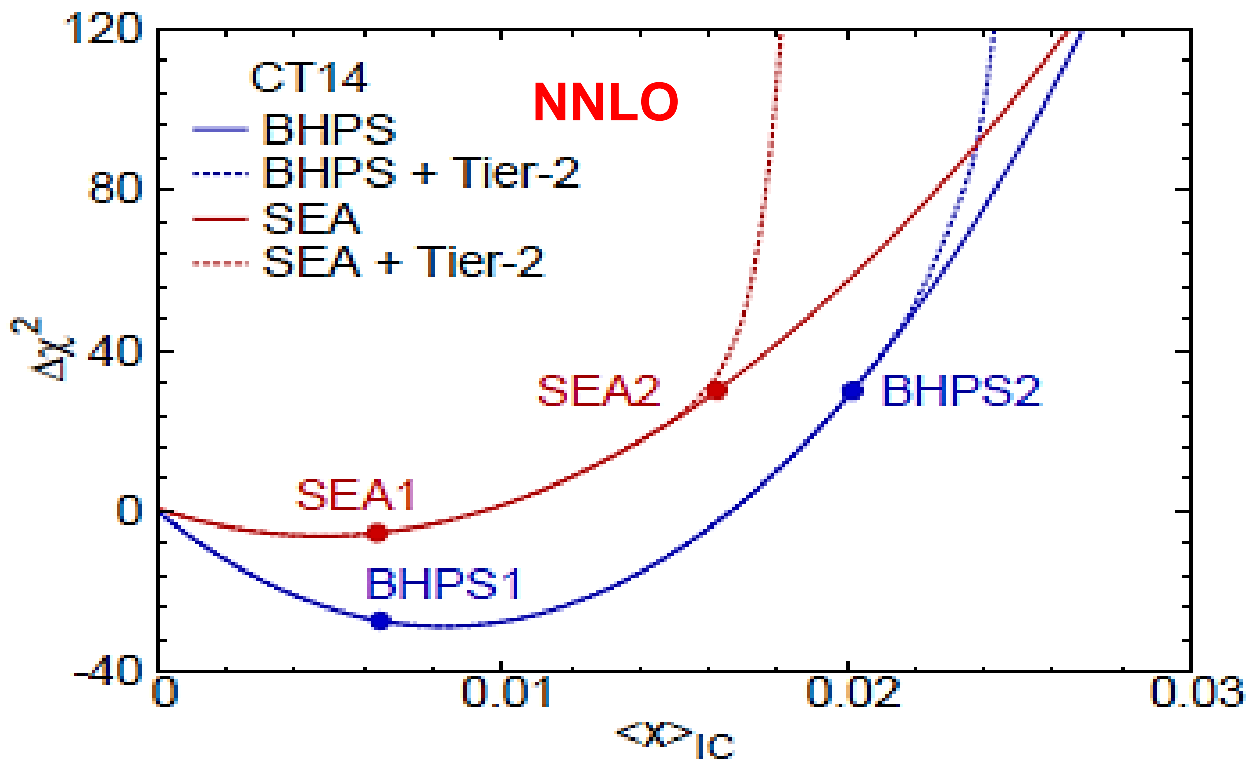
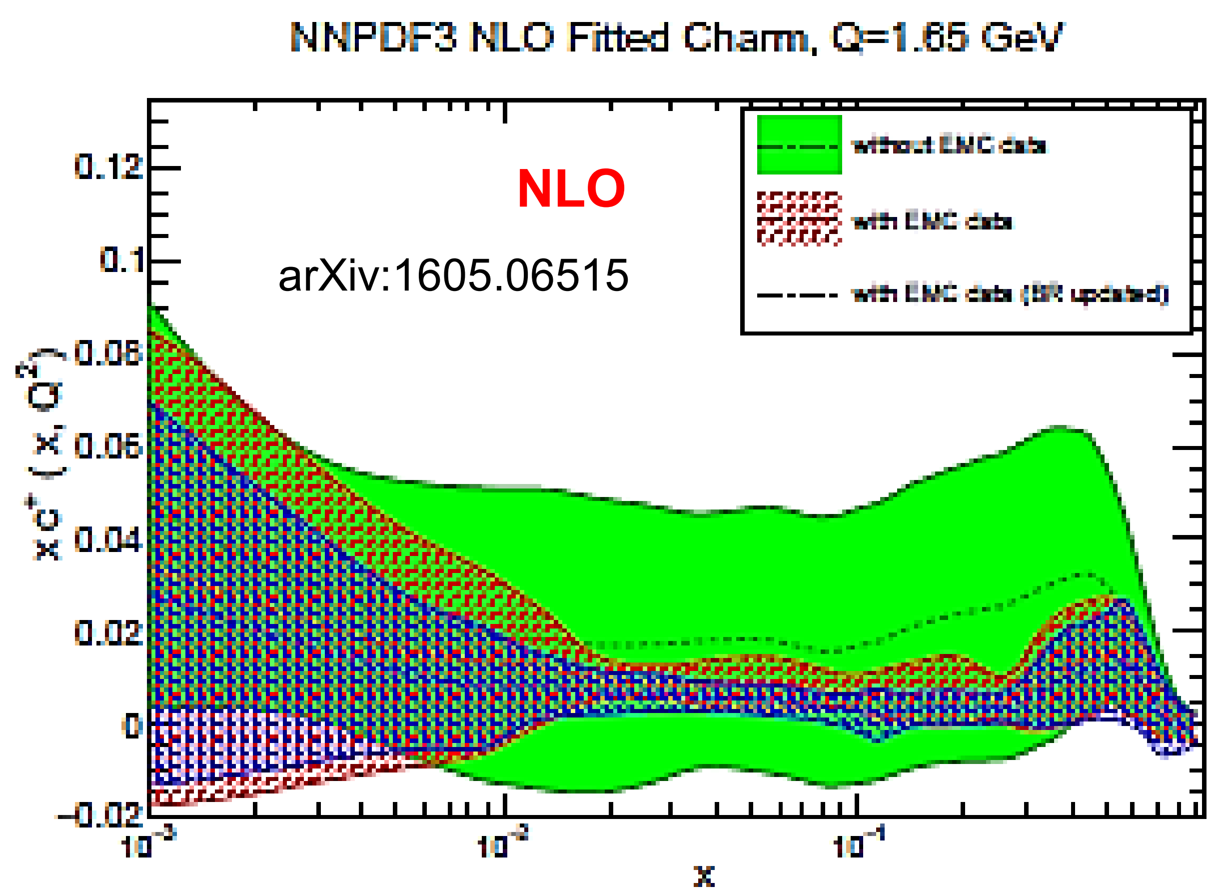
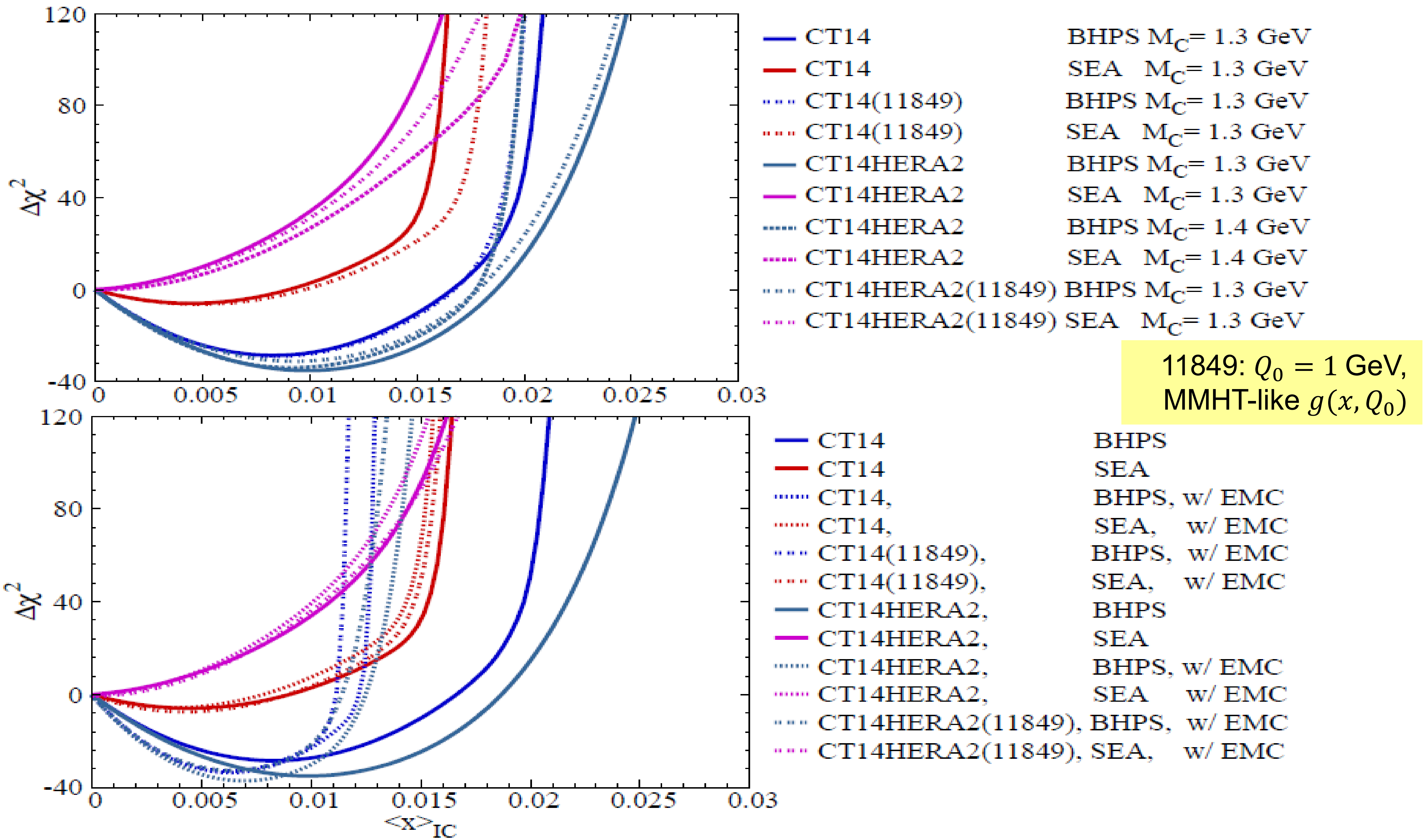


Figure 1: The $\Delta\chi^2$ versus the momentum fraction of charm $\langle x\rangle_{IC}$. **PoS DIS2015 (2015) 166**



CT14 IC fits



For the Brodsky-Hoyer-Peterson-Sakai (BHPS) parametrization,
a **marginally** better χ^2 for IC with $\langle x \rangle_{IC} \approx 1\%$
For SEA parametrization, IC with $\langle x \rangle_{IC} \approx 1.5\%$ is allowed within uncertainty

On the scale evolution of intrinsic heavy quarks

Full set of coupled evolution equations

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q\,,$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q\,,$$
$$\dot{Q} = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q\,.$$

Q is the heavy quark

Writing: Q(x,mu)=Q_0(x,mu)+Q_1(x,mu) where Q_0 is the perturbative piece and Q_1 an intrinsic component with support at large x

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 + \cancel{P_{gQ} \otimes Q_1}\,,$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q_0 + \cancel{P_{qQ} \otimes Q_1}\,,$$
$$\dot{Q}_0 + \dot{Q}_1 = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q_0 + P_{QQ} \otimes Q_1\,.$$

Evolution equation for intrinsic heavy quark

Standard coupled evolution equation without intrinsic heavy quark:

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 \,,$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q_0 \,,$$
$$\dot{Q}_0 = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q_0 \,.$$

Decoupled non-singlet evolution equation for intrinsic component

$$\dot{Q}_1 = P_{QQ} \otimes Q_1 \,.$$

Procedure valid up to small violation of momentum sum rule!
Useful for understanding and phenomenological applications

arXiv:1507.08935

Parton-Parton Luminosities: Charm

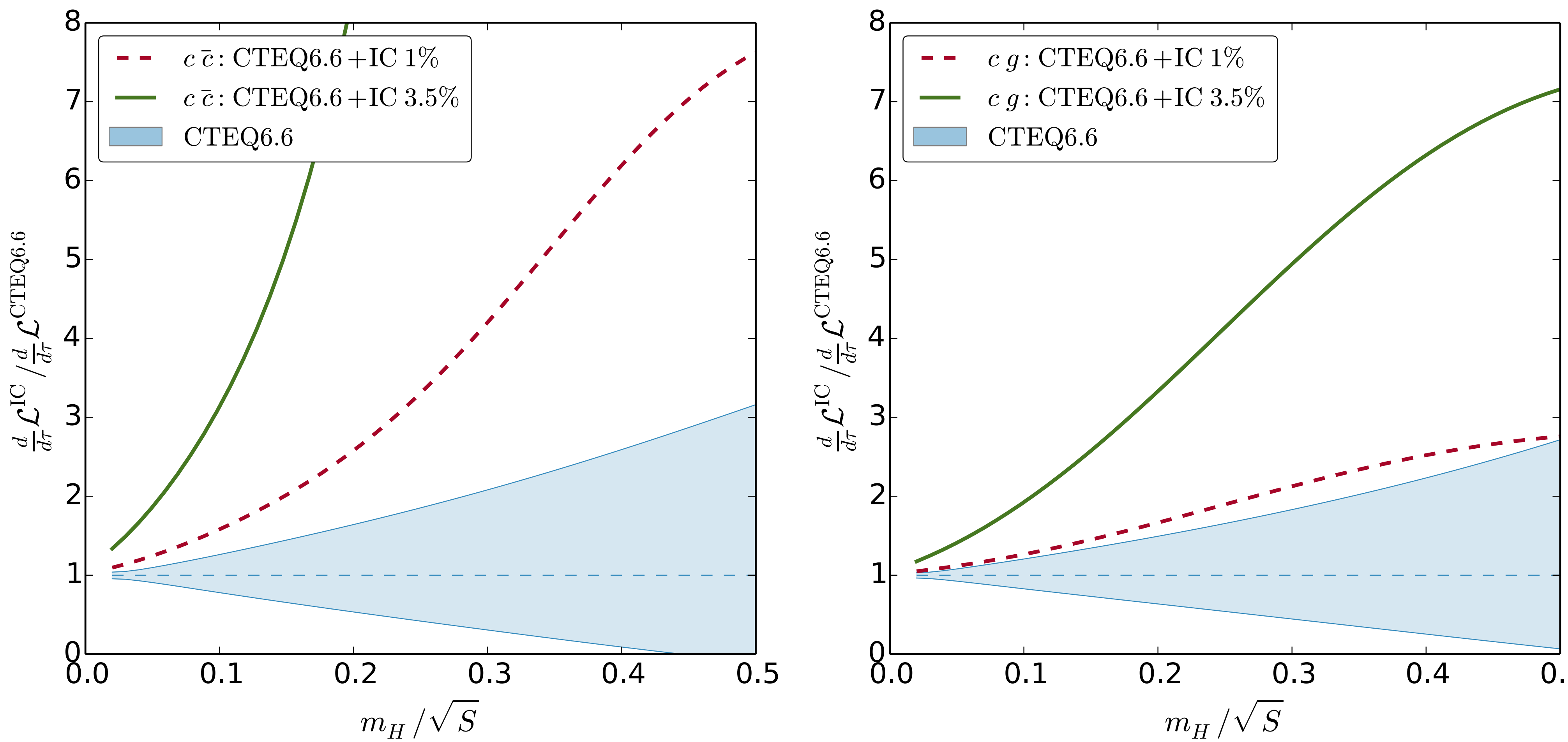
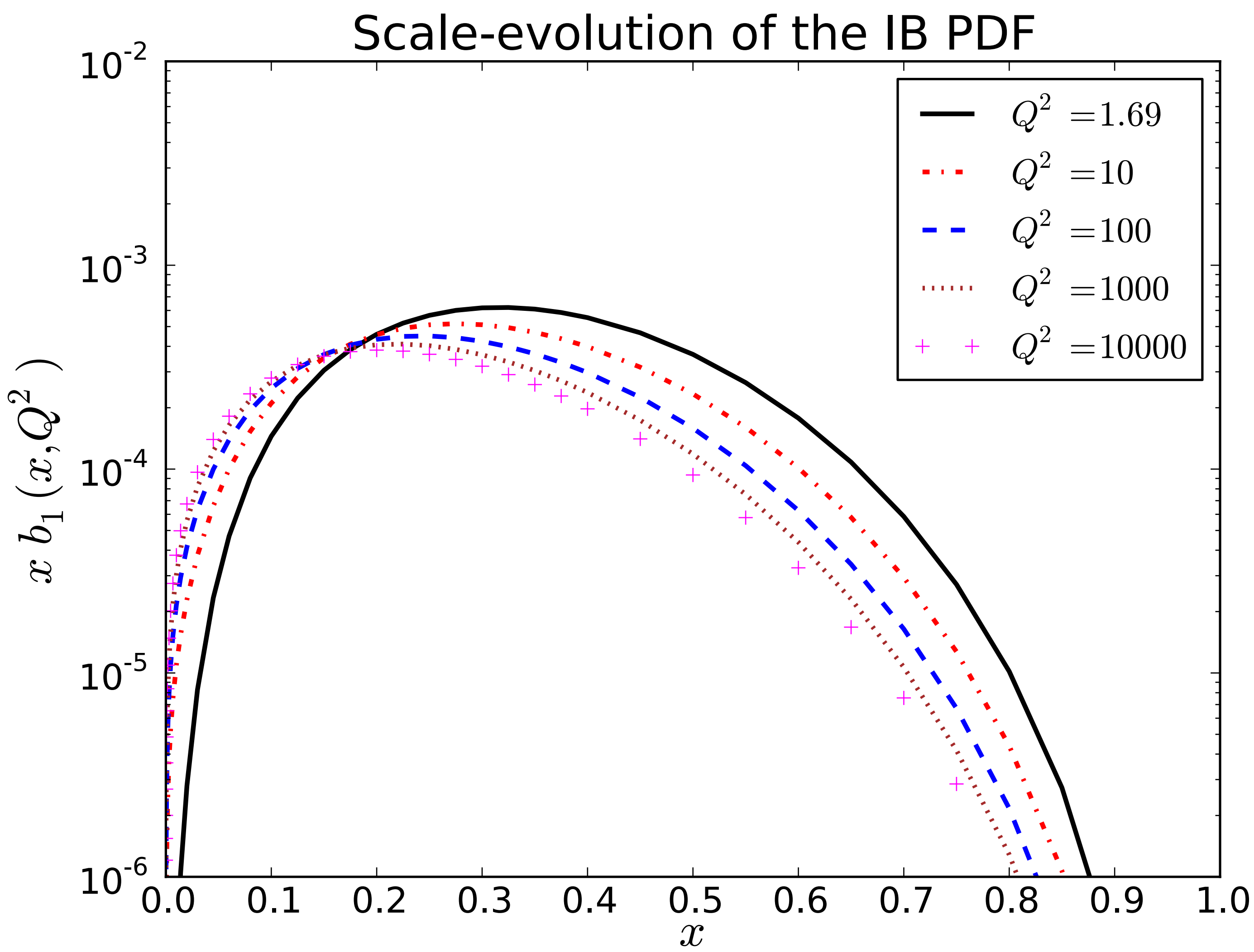


Figure 10. Ratio of $c\bar{c}$ luminosities (left) and cg luminosities (right) at the LHC14 for charm-quark PDF sets with and without an intrinsic component as a function of $\sqrt{\tau} = m_H/\sqrt{S}$. The ratio for the $c\bar{c}$ luminosity (solid, green line) in the left figure reaches values of 50 at $\sqrt{\tau} = 0.5$. In addition to the curves with 1% normalization (red, dashed lines) we include the results for the 3.5% normalization (green, solid lines) which was found to be still compatible with the current data [25].

Scale evolution of IB



Black solid line: BHPS shape

Can add the intrinsic b_1 PDF to the radiatively generated b_0 PDF:
$b(x) = b_0(x) + b_1(x)$

Allows to estimate the effect of IB

Parton-Parton Luminosities: Bottom

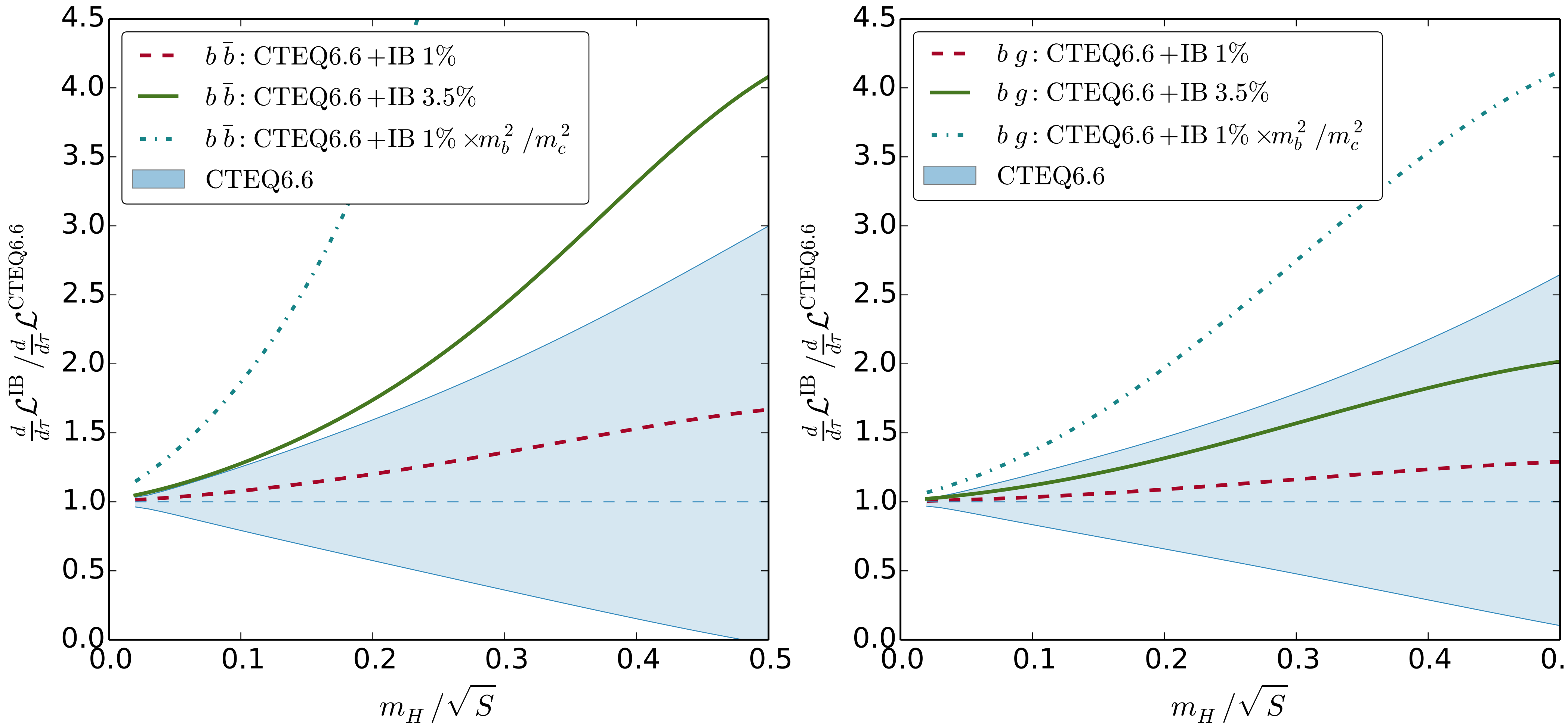
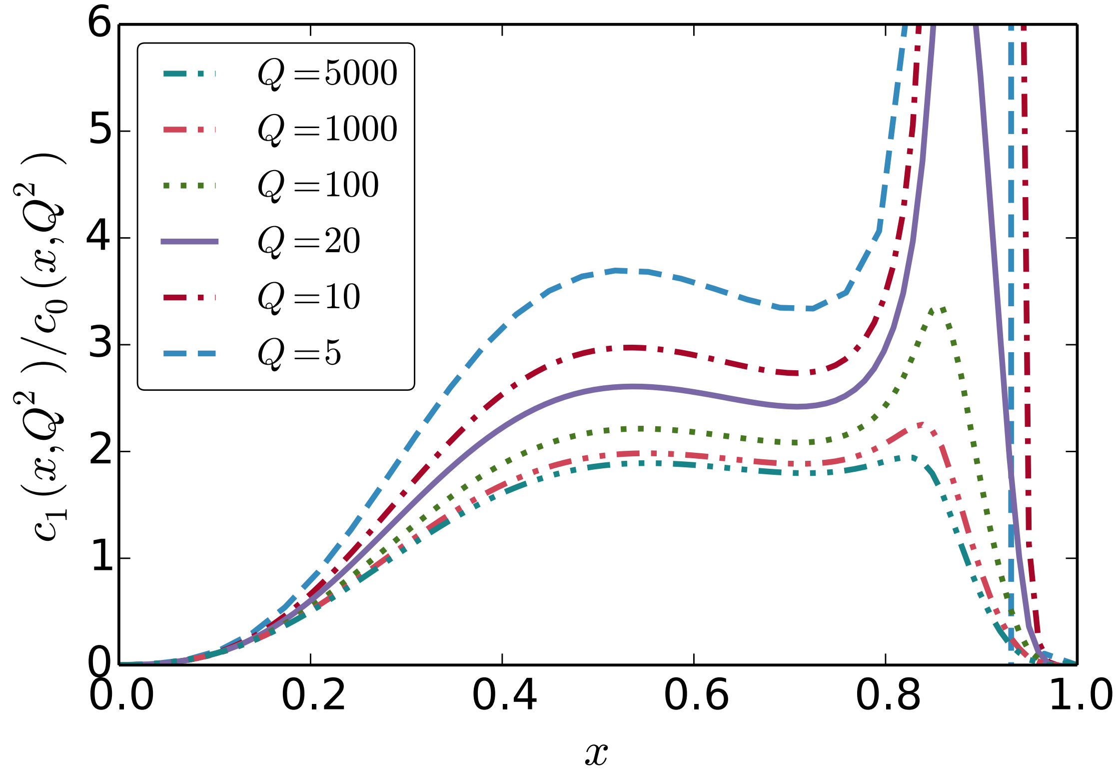
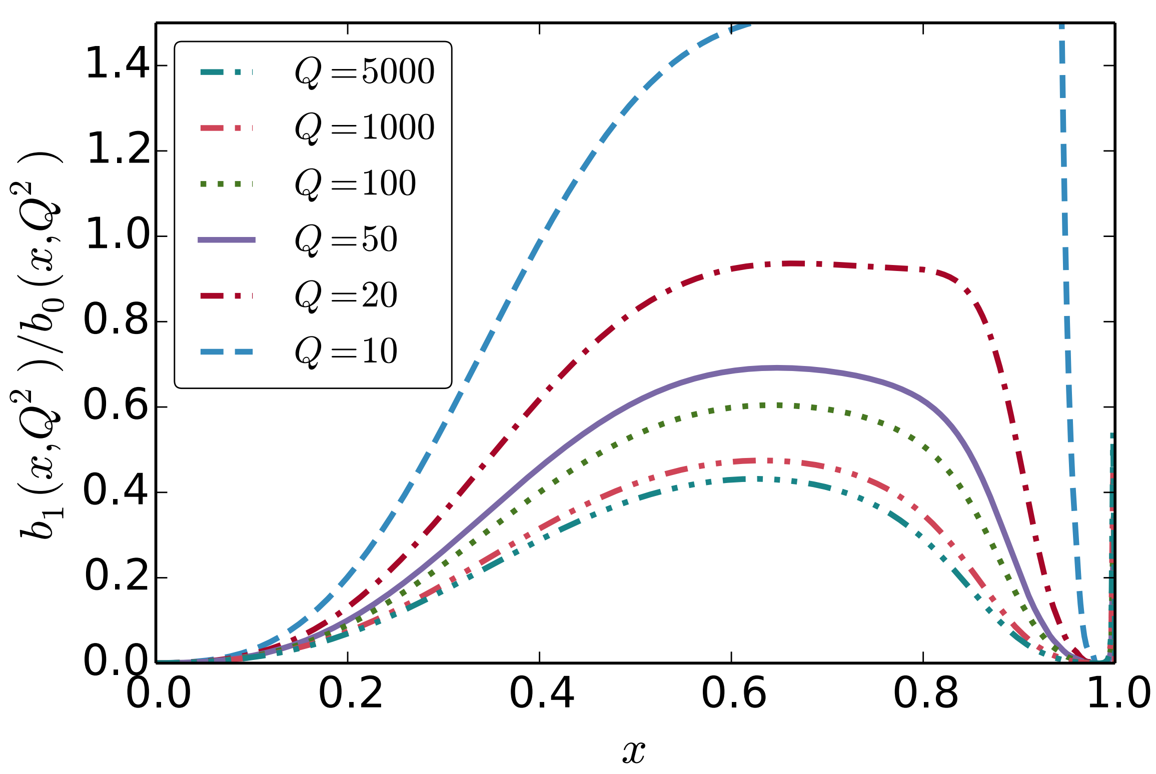


Figure 11. Ratio of luminosities at the LHC14 for bottom-quark PDF sets with different normalizations of the intrinsic bottom component. The plot has been truncated, and the $b\bar{b}$ luminosity in the extreme scenario reaches about 17 at $\sqrt{\tau} = 0.5$.

IC vs IB





- Clearly, $b_1/b_0 << c_1/c_0$ (for the model used)

- Questions:

  What would be the ratio "intrinsic/extrinsic" for the strange sea or the light quark sea at large-x?

  If there is a "bump" due to IC, one can also expect "bumps" for the light sea?

Processes sensitive to heavy quarks

Processes sensitive to the charm PDF

- F_2^c at HERA:

  charm contributes more than 20% to the DIS structure functions

  all charm data at $x<0.1$

- Fixed target DIS:

  the 'controversial' EMC data

  include larger x, new progress in the understanding thanks to recent NNPDF study

Processes sensitive to the charm PDF

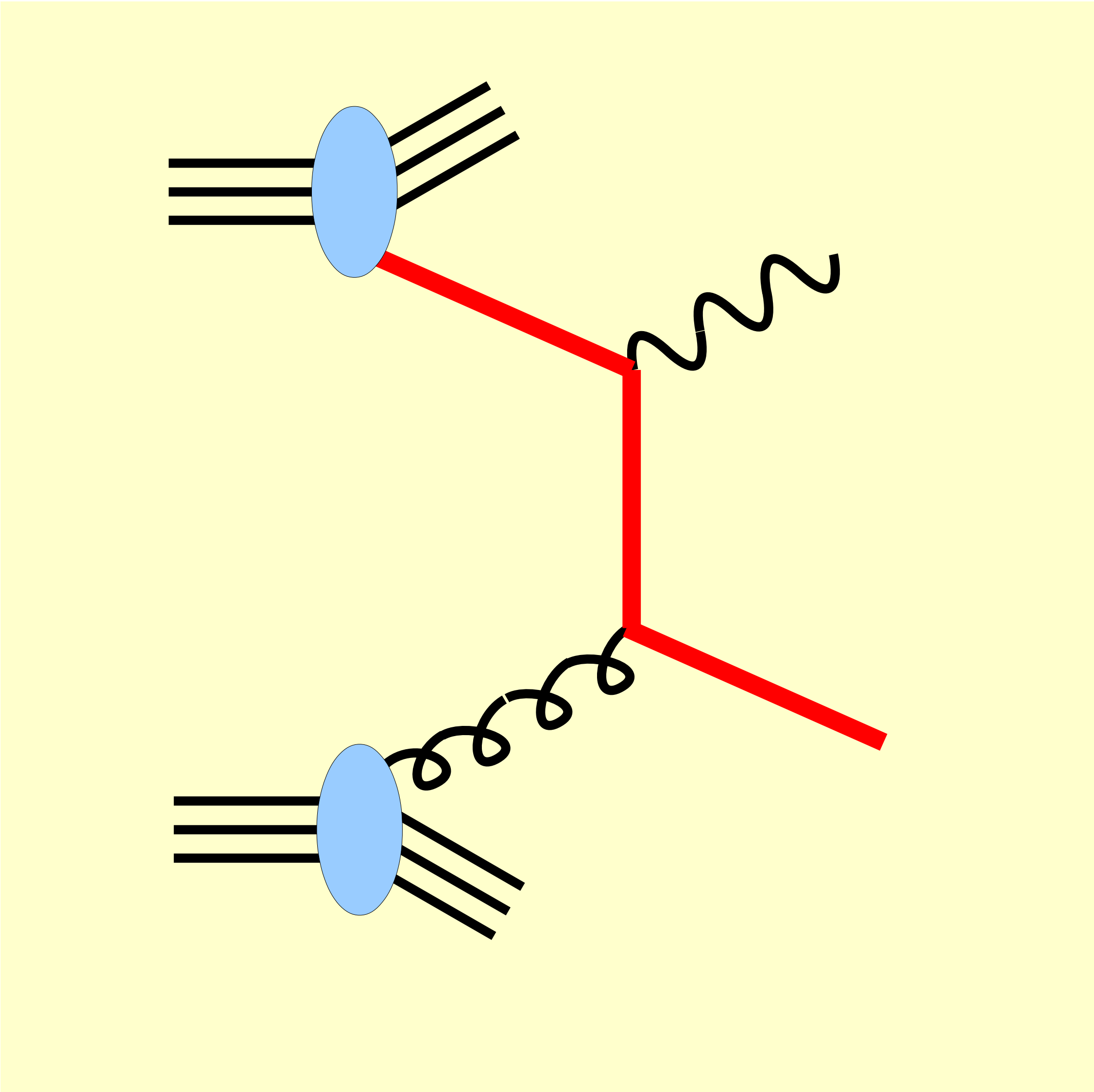
- Drell-Yan production of W/Z has a relevant contribution from the cs-channel at the LHC

- Exclusive processes

  - c+g → c+γ

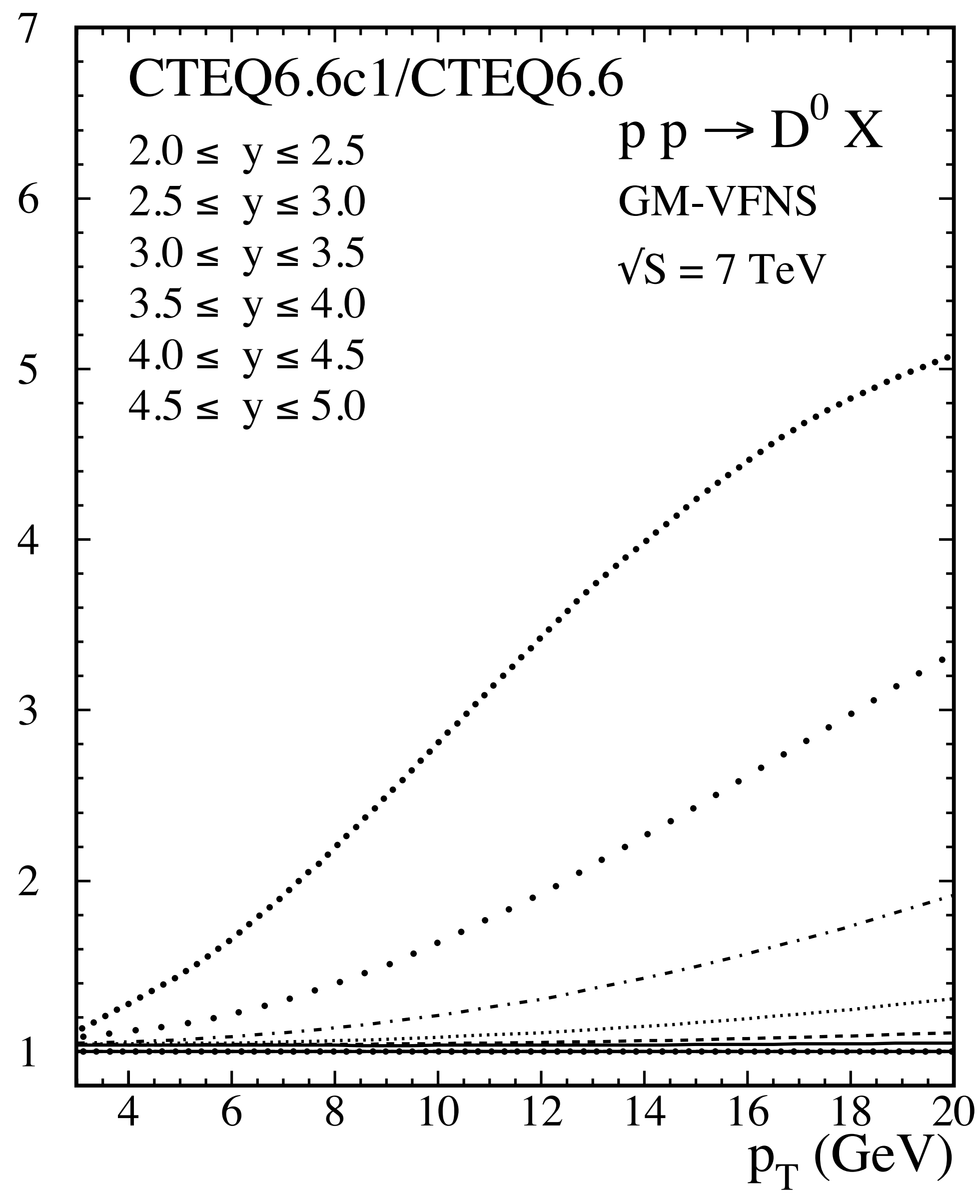
  - c+g → c+Z

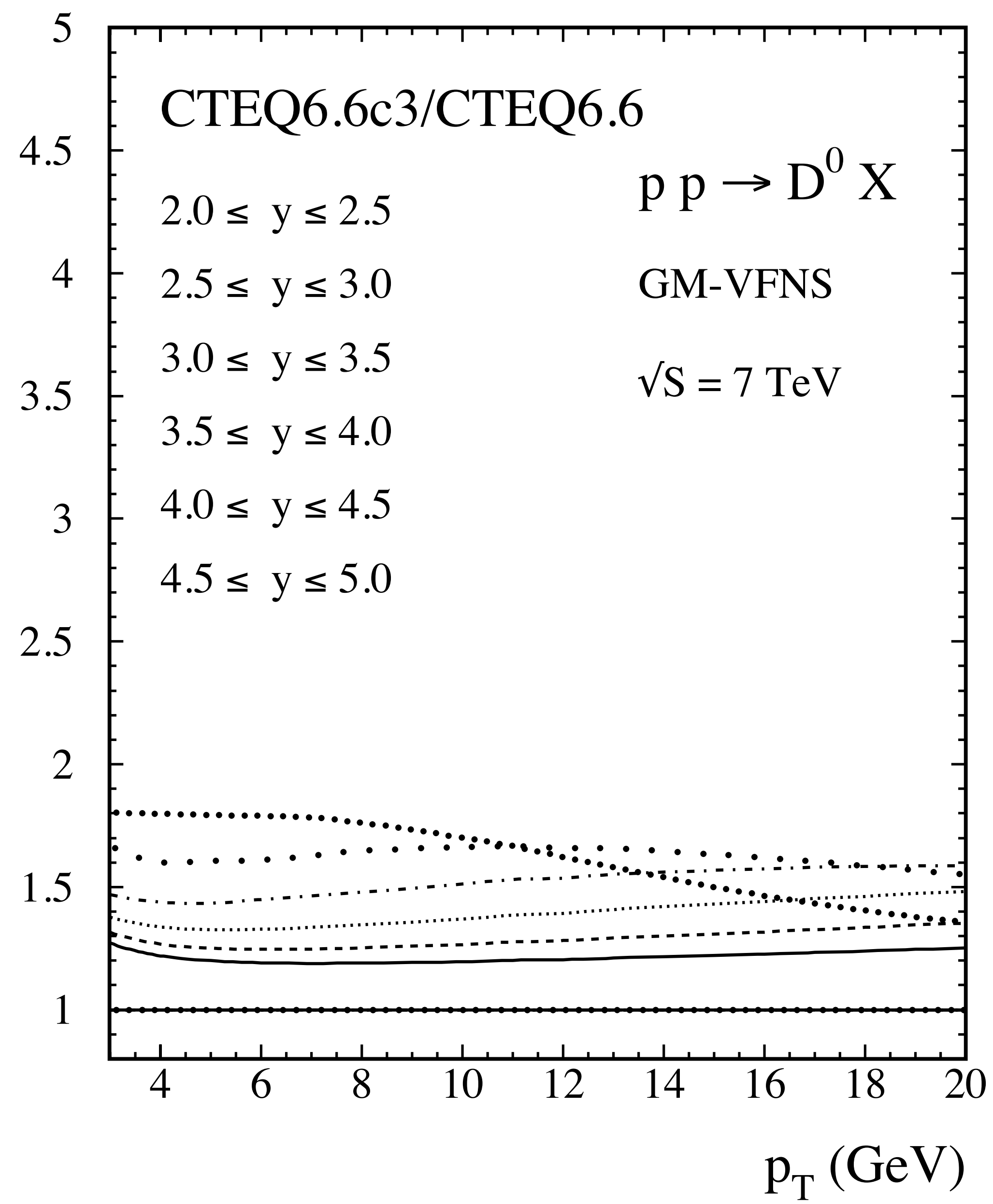
  - c+g → b+W



Inclusive D meson production at LHCb

arXiv:1202.0439,arXiv:0901.4130





CTEQ6.6 updated:

BHPS, 3.5 % $(c + \bar{c})$ at $\mu = 1.3$ GeV

high-strength sea-like charm

➜ large effects expected at large rapidities

Future

- F_2^c at EIC:

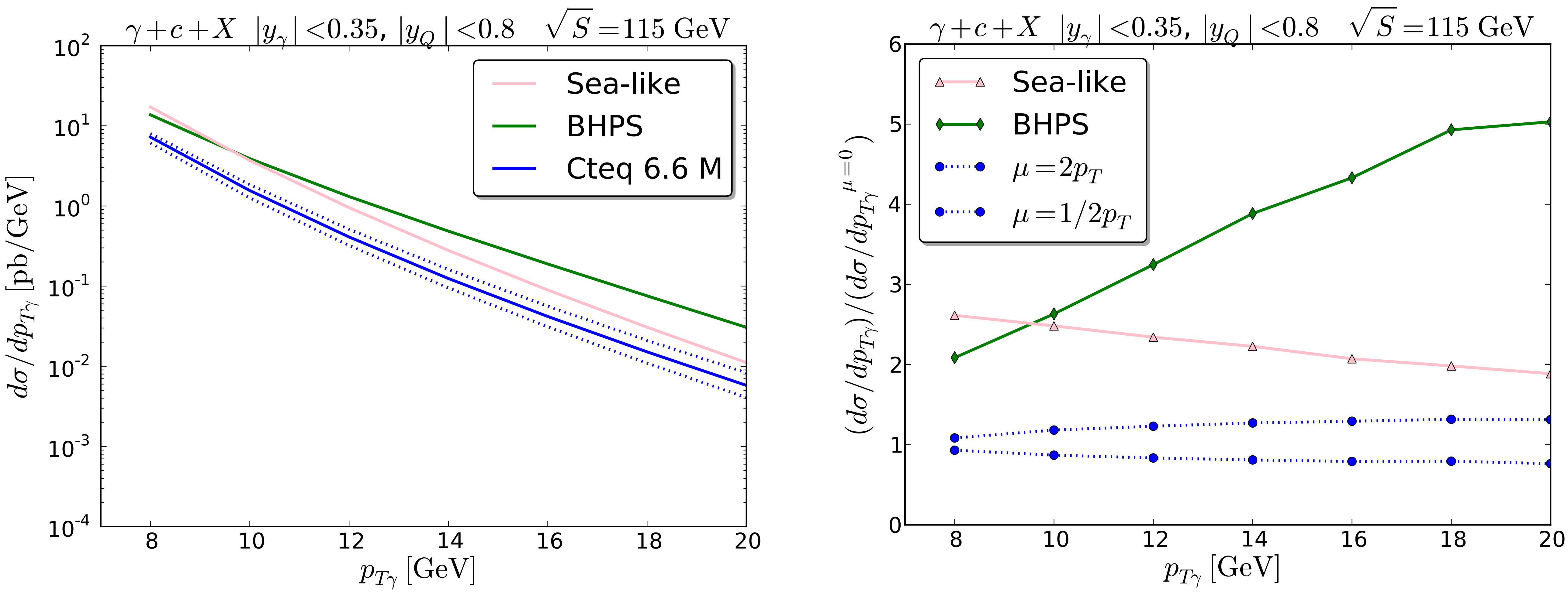
  probing larger x-values ($x \sim 0.3$)

- Fixed target experiments using the LHC beam (AFTER@LHC): $\sqrt{S}=115$ GeV

  would be ideal to probe large-x IC in hadronic collisions

Probing IC in γ+Q production at AFTER@LHC

arXiv:1504.06287



Conclusions

Conclusions

- An intrinsic charm contribution is predicted by QCD.

  "If QCD is right, there has to be IC"

- Open question: "How much IC is there?"
  (If you are believer)

  Normalization is unclear. Typically $\langle x \rangle_{c+cbar} \sim 0.01$

- Need more "DATA" (real or lattice)

- Is it possible to calculate, for example,
  $\langle x \rangle_{c+cbar}$ on the lattice? With which precision?

- c and cbar independently?