Non-perturbative bottom PDF and its possible impact on new physics searches [arXiv:1504.05156]

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Introduction

- *Heavy quark* PDFs (in particular b quark) play an important role in several Standard Model and New Physics processes, e.g.:
  - tW, tH^+ production,
  - associated $b + W/Z/H$ boson production,
  - Hbb production.
- Standard PDF analysis: *Heavy quark* (HQ) PDFs are generated **radiatively** using DGLAP evolution and **perturbatively** calculable boundary conditions.
  - HQ PDFs and their uncertainties are strongly correlated with gluon.
  - They appear only at scales above HQ mass, $\mu \geq m_Q$.
- There are models (light-cone, meson cloud) postulating **non-perturbative**, intrinsic, component of HQ PDFs appearing even below m_Q.

Introduction

- There are global PDF analysis dedicated to **intrinsic charm** (IC) content of the proton [e.g. `hep-ph/0701220`], but there is no analysis that estimates the amount of **intrinsic bottom** (IB).
    - No experimental data allowing for this.
- Nevertheless, it is important to know what would be the impact of **IB** if it existed.
- We proposed [`arXiv:1504.05156`] an approximate method allowing to easily estimate these effects by generating **IB** (and **IC**) PDFs matched to any standard set of perturbative PDFs, where the normalization of IB (IC) can be freely adjusted.

Rest of the talk

1. Explain the method we use for generating matched intrinsic HQ PDFs.
2. Quantify approximation of the method.
3. Show results for luminosities in case of the LHC.

What do we call **intrinsic** bottom (charm)?

○ The intrinsic HQ distribution, Q_1, can be defined at the input scale, μ_0, as the difference of the full boundary condition for the HQ PDF, Q, and the perturbatively calculable (extrinsic) boundary condition Q_0

$$Q_1(x, \mu_0) := Q(x, \mu_0) - Q_0(x, \mu_0)$$

○ Typically $\mu_0 = m_Q$, then in $\overline{\text{MS}}$@NLO $Q_0(x, m_Q) = 0$ and

$$Q(x, \mu_0) = Q_1(x, \mu_0)$$

The method

Scale dependence of PDFs is governed by the DGLAP equations

$$\begin{aligned}\dot{g} &= P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q \\ \dot{q} &= P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q \\ \dot{Q} &= P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q\end{aligned}$$

where $P_{Qg}(x) = P_{qg}(x)$, $P_{QQ}(x) = P_{qq}(x)$, $P_{Qq}(x) = P_{q'q}(x)$ are massless splitting functions.

The method

if we substitute $Q = Q_0 + Q_1$

$$\begin{aligned}
\dot{g} &= P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 + P_{gQ} \otimes Q_1 \\
\dot{q} &= P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q_0 + P_{qQ} \otimes Q_1 \\
\dot{Q}_0 + \dot{Q}_1 &= P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q_0 + P_{QQ} \otimes Q_1
\end{aligned}$$

The method

Intrinsic component will give tiny contribution to the light quarks and gluon evolution we can neglect it.

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 + \cancel{P_{gQ} \otimes Q_1}$$

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Decoupling of the evolution of the intrinsic HQ component:

- standard evolution equation without intrinsic HQ

$$\begin{aligned}\dot{g} &= P_{gg}\otimes g + P_{gq}\otimes q + P_{gQ}\otimes Q_0\\ \dot{q} &= P_{qg}\otimes g + P_{qq}\otimes q + P_{qQ}\otimes Q_0\\ \dot{Q}_0 &= P_{Qg}\otimes g + P_{Qq}\otimes q + P_{QQ}\otimes Q_0\end{aligned}$$

- Standalone non-singlet evolution for intrinsic HQ

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

The method

To fully decouple the evolution of the intrinsic HQ component we need to allow for a small violation of the momentum sum rule.

- Instead of exact

$$\int_0^1 dx\ x\ \left(g + \sum_i (q_i + \bar{q}_i) + Q_0 + \bar{Q}_0 + Q_1 + \bar{Q}_1\right) = 1$$

- we allow for

$$\int_0^1 dx\ x\ \left(g + \sum_i (q_i + \bar{q}_i) + Q_0 + \bar{Q}_0\right) \simeq 1$$

- giving a violation of the order of

$$\int_0^1 dx\ x\ \left(Q_1 + \bar{Q}_1\right)$$

The method

With the this approximation

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

$$\int_0^1 dx\ x\ \left(Q_1 + \bar{Q}_1\right) \quad - \quad \text{small}$$

we can perform a standalone **IB** and **IC** PDF analysis **matched** to any standard (perturbatively generated) PDF set.

Rest of the talk

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Boundary conditions

The BHPS model [PLB 93 (1980) 451] predicts the following x-dependence for the boundary condition of IC PDF:

$$c_1(x, Q_0) = \bar{c}_1(x, Q_0) \propto x^2 \left[6x(1+x)\ln x + (1-x)(1+10x+x^2)\right]$$

- Normalization not predicted.
- $Q_0 \sim m_c$ scale not precisely determined.
- Functional form obtained for $m_c \to \infty$
  - Even better motivated for IB PDF.

In case of bottom we expect its normalization to be suppressed by m_b.

- $b_1(x, m_b) = \frac{m_c^2}{m_b^2}\, c_1(x, m_c)$
- $b_1(x, m_c) = \frac{m_c^2}{m_b^2}\, c_1(x, m_c)$
- No problem in using asymmetric conditions $b_1(x) \neq \bar{b}_1(x)$.

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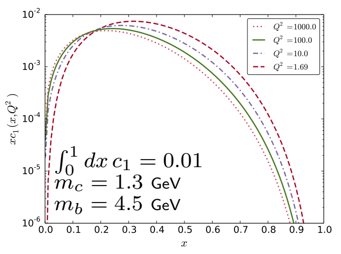
- $b_1(x, m_c) = \frac{m_c^2}{m_b^2} c_1(x, m_c) \quad \to \quad$ our choice
- No problem in using asymmetric conditions $b_1(x) \neq \bar{b}_1(x)$.

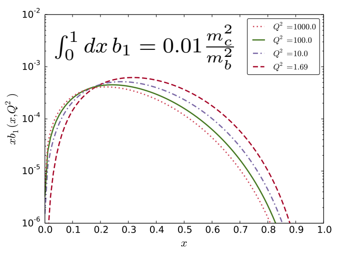
Normalization choice

- We choose two values of IC/IB normalizations that correspond to the choice in CTEQ6.6c global analysis with IC [arXiv:0802.0007]:

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

b_1 normalization is scaled by $m_c^2/m_b^2 \sim 0.083$ factor.

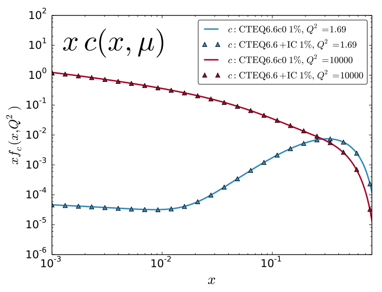


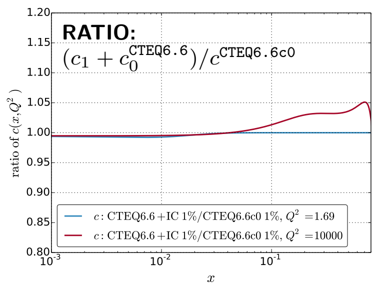


- Normalization can be adjusted by **simple rescaling**.

Quality of the approximation (IC with 1% normalization)

- **Charm distribution** for $\mu = 1.3$ GeV and $\mu = 100$ GeV
  - ▲ – our approximate method
  - solid line – exact (`CTEQ6.6c`)

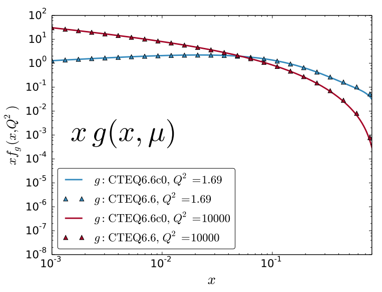


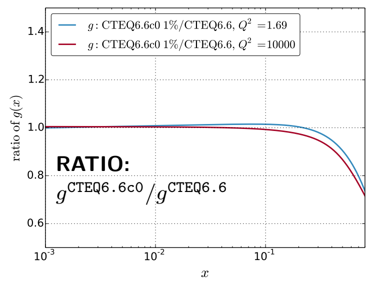


- At high scales the error is still below 5% throughout x range.

Quality of the approximation (IC with 1% normalization)

- **Gluon distribution** for $\mu = 1.3$ GeV and $\mu = 100$ GeV
  - ▲ – our approximate method
  - solid line – exact (`CTEQ6.6c`)





- No effect on low-x gluon.
- Error for gluon at high x is bigger but the gluon PDF at high x is very small and its uncertainty is sizable (40-50%).

Quality of the approximation

- The error of our method is generally smaller then the PDF uncertainties in the corresponding kinematic region.
- The effects will be even smaller (~ 10 times) for the **bottom** distribution (due to additional suppression m_c^2/m_b^2).
- For most applications, adding a standalone intrinsic charm distribution to an existing standard global analysis of PDFs is internally consistent and leads to only a small error.

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Results for LHC at 14 TeV

General estimate of how the nonperturbative **IB** or **IC** can impact LHC observables can be seen looking at parton-parton luminosities.

- In particular we are interested in production of a heavy new particle, with mass m_H, coupling to the Standard Model fermions.

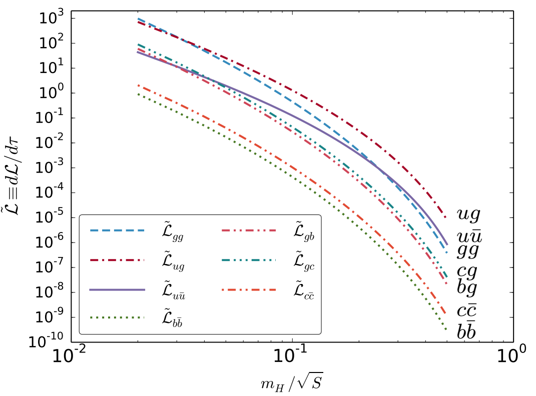
$$\sigma_{pp\to H+X} = \sum_{ij} \int_\tau^1 d\tau \frac{d\mathcal{L}_{ij}}{d\tau} \hat{\sigma}_{ij}(\hat{s})$$

$$\frac{d\mathcal{L}_{ij}}{d\tau}(\tau,\mu) = \frac{1}{1+\delta_{ij}} \frac{1}{\sqrt{S}} \int_\tau^1 \frac{dx}{x} \Big[f_i(x,\mu) f_j(\tau/x,\mu) + f_j(x,\mu) f_i(\tau/x,\mu) \Big]$$

where

- S is the hadronic center of mass energy
- $\hat{s} = x_1 x_2 S = m_H^2$ is partonic CMS
- $\sqrt{\tau} = \sqrt{x_1 x_2} = m_H/\sqrt{S}$

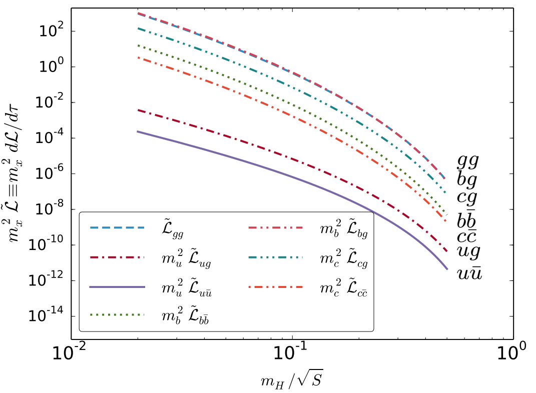
Luminosities for LHC at 14 TeV



- $\sqrt{\tau} \in [0.02, 0.5]$ corresponds to $m_H \in [0.280, 7]$ TeV
- For high m_H mass the heavy quark initiated subprocesses play a minor role.

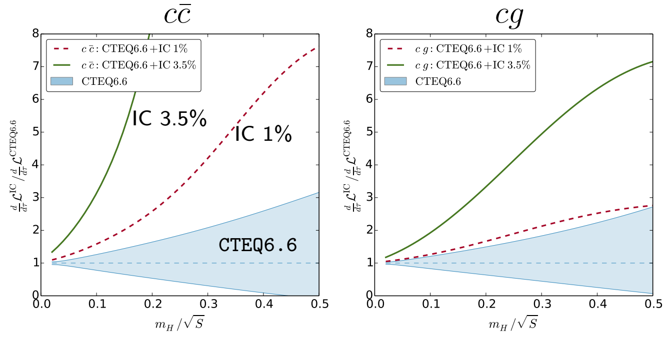
Luminosities for LHC at 14 TeV

- If the produced scalar couplings are proportional to quark masses the hierarchy changes.



Luminosities for LHC14 with IC

$$\frac{d\mathcal{L}^{\mathsf{IC}+\texttt{CTEQ6.6}}}{d\tau} \Bigg/ \frac{d\mathcal{L}^{\texttt{CTEQ6.6}}}{d\tau}$$

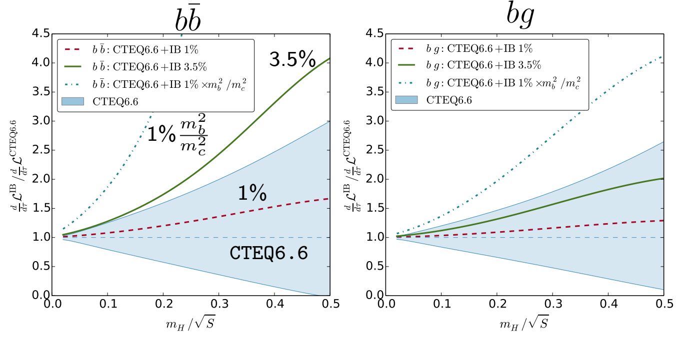


Normalizations:

- 1% : $\int_0^1 dx\, c(x, Q_0) = 0.01$
- 3.5% : $\int_0^1 dx\, c(x, Q_0) = 0.035$

Luminosities for LHC14 with IB

$$\frac{d\mathcal{L}^{\text{IB+}\mathtt{CTEQ6.6}}}{d\tau} \bigg/ \frac{d\mathcal{L}^{\mathtt{CTEQ6.6}}}{d\tau}$$



Normalizations:

- 1% : $\int_0^1 dx\, b(x,Q_0) = 0.01 \times (m_c^2/m_b^2)$
- 3.5% : $\int_0^1 dx\, b(x,Q_0) = 0.035 \times (m_c^2/m_b^2)$
- $1\% \times (m_b^2/m_c^2)$: $\int_0^1 dx\, b(x,Q_0) = 0.01$

Conclusions

- The scale evolution of intrinsic HQ distributions is, to a very good approximation, governed by a non-singlet evolution.
- Therefore, it is possible to perform a standalone analysis of **IB** or **IC** and combine it with **any** standard PDF set
  - with possibility to freely adjust its normalization.

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- Looking at luminosities at 14 TeV LHC we conclude that the impact of **IB** on new physics will be limited, and could show up only in models with highly enhanced $b\bar{b}$ or bg channels.

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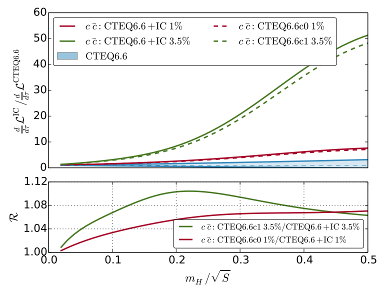
- Looking at luminosities at 14 TeV LHC we conclude that the impact of **IB** on new physics will be limited, and could show up only in models with highly enhanced $b\bar{b}$ or bg channels.
- To search for **IB** a low Q, high-x machine is need, like
  - Electron-Ion Collider (EIC)
  - Large Hadron-Electron collider (LHeC)
  - AFTER@LHC (a fixed target machine with LHC beam)

BACKUP SLIDES

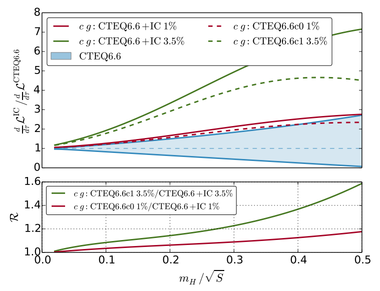
Quality of the approximation: luminosities

- cc and cg luminosities at 14 TeV LHC
  - **solid line** – our approximate method
  - **dashed line** – exact (`CTEQ6.6c`)

$\mathcal{L}_{cc}^{c_1+\texttt{CTEQ6.6}} / \mathcal{L}_{cc}^{\texttt{CTEQ6.6c}}$



$\mathcal{L}_{cg}^{c_1+\texttt{CTEQ6.6}} / \mathcal{L}_{cg}^{\texttt{CTEQ6.6c}}$



Newest IC global analyses

The two latest analyses addressing IC set significantly different limits on the possible intrinsic component.

- CTEQ [PRD 89 (2014) 073004, `arXiv:1309:0025`]

$$\int dx c(x, Q_0) \lesssim 1\%$$

- Jimenez-Delgado et al. [PRL 114 (2015) 082002, `arXiv:1408:1708`]

$$\int dx c(x, Q_0) \lesssim 0.1\%$$