Charm & bottom cross sections in pp, p\bar{p} collisions: data vs NNLO

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Charm & bottom cross sections in pp collisions increase significantly with c.m. energy. At the LHC, they represent ~20%,~1% of $\sigma_{\text{inel}}$.

Experimentally, one measures the c,b-quark fragmentation products (i.e. D,B mesons, $\Lambda$ baryons) plus quarkonia bound states:

Most of total x-sections based on fraction of decay channels + model-dependent extrapolations over ($p_T$, $y$).
Calculation of heavy-Q x-sections in pp, p\bar{p}

- Charm/bottom/top production have intrinsic hard scales $(m_Q \sim 1.7, 4.8, 173 \text{ GeV})$ that allow for application of pQCD framework to compute their cross sections.

- pQCD factorization theorem:

$$
\sigma_{Q+X}[s, m_Q] \sim \sum_{i,j} \int_0^1 dx_i \int_0^1 dx_j \, f^A_i(x_i, \mu_F) f^B_j(x_j, \mu_F) \, \tilde{\sigma}_{ij \rightarrow Q+X}[x_i, x_j, m_Q, \mu_F, \mu_R]
$$

  Sum over active flavours

  Parton densities in proton: Evaluated at momentum fraction $x$ & scale $Q=\mu_F$

  Partonic subprocesses cross sections, expanded in powers of $\alpha_s$:

$$
\tilde{\sigma}_{ij \rightarrow Q+X}[m_Q, \mu_F, \mu_R] = \frac{\alpha_s^2(\mu_R)}{m_Q^2} \left[ \hat{\sigma}_{LO} + \alpha_s(\mu_R) \hat{\sigma}_{NLO} + \alpha_s^2(\mu_R) \hat{\sigma}_{NNLO} + \cdots \right]
$$

- Cross sections clearly dominated by gluon-gluon fusion processes
Heavy-Quark production in pp, pp$\bar{p}$ (LO,NLO)

- **Leading-order (LO) QCD processes:**

- **Next-to-leading-order (NLO) QCD processes:**

  NLO real:

  NLO virtual:

Mangano, Nason, Ridolfi, (MNR) … [1992]
Heavy-Quark production in pp, p\bar{p} (LO,NLO)

- **LO + leading-log (LL) soft gluon resummation QCD processes:**

  - NLO real:
  - NLO virtual:

- **NLO+ next-to-leading-log (NLL) soft gluon resummation QCD:**

  - Mangano, Nason, Ridolfi, Cacciari, (FONLL) Catani, Frixione, Mitov, Czakon, ...
  - [<2012]
Charm & bottom in pp, p\bar{p}: Data vs NLO+NLL

- pQCD predictions at NLO+NLL accuracy (MNR, FONLL) globally Reproduce the data. Better for bottom than for charm (charm measurements are at upper uncertainty band of the predictions):

- pQCD predictions at NLO+NLL accuracy have still very large scale uncertainties: ~60% for ccbar (low \(m_c\sim 1.67\, \text{GeV}\))
  ~35% for b\bar{b} (\(m_b\sim 1.67\, \text{GeV}\))
Heavy-Quark production in pp, p\bar{p} (NNLO)

- LO + leading-log (LL) soft gluon resummation QCD processes:

- NLO+ next-to-leading-log (NLL) soft gluon resummation QCD:
  - NLO real:
  - NLO virtual:

- NNLO+ next-to-leading-log (NLL) soft gluon resummation QCD:
  - Real+Real:
  - Real+Virtual:
  - Virtual+Virtual: Mitov, Czakon (Top++)
    Moch et al. (HATHOR)
    ... [>2013]
Current state-of-the-art NNLO+NNLL calculations for ttbar agree very well with data and have very small scale uncertainties: 5% → 3%

High precision of ttbar data & theory allows for accurate extractions of high-x gluon PDF and of the strong coupling $\alpha_s$.

Use Top++ (NNLO+NNLL) to compute $cc, bb$ total cross sections?
\( \sigma(c\bar{c},b\bar{b}) \) at NNLO. Theoretical setup

- Modified version of Top++:
  - Heavy-quark (pole) masses: \( m_c = 1.67 \text{ GeV}, \; m_b = 4.66 \text{ GeV} \)
  - Active number of flavours: \( N_f = 3 \) (ccbar), 4 (bbbar)

- Model parameters:
  - Default scales: \( \mu_F = \mu_R = 2 \cdot m_{c,b} \) (Uncertainties: \( \mu_F, \mu_R = [1,4] \times m_{c,b} \))
  - QCD coupling (PDF default): \( \alpha_s = 0.118 \)
  - PDFs (3, 4 flavour scheme. Interfaced via LHAPDF v6.1.6):
    - CT14_NNLO (90% CL, 56 eigenvector sets, asymmetric)
    - MMHT14_NNLO (68% CL, 50 eigenvector sets, asymmetric)
    - ABMP16_NNLO (68% CL, 28 eigenvector sets, symmetric)
    - NNPDF3.0_NNLO (68% CL, 100 replicas, symmetric)
  - Pure NNLO. NNLL gluon resummation not included (yet)

- Modified Top++ run for \( \sqrt{s} \) of \( \sim 20 \) existing experimental data sets:
  - Charm: 11 measurements from \( \sqrt{s}=20 \text{ GeV} \) (fixed-target) to 13 TeV (LHC)
  - Bottom: 8 measurements from \( \sqrt{s}=40 \text{ GeV} \) (fixed-target) to 13 TeV (LHC)

[Dd'E 2017, to be submitted]
Large charm & bottom K-factors: $\sigma$(NNLO/NLO)~2 (fixed-target)–1.2 (LHC)

Reduced NLO→NNLO scale uncertainties:

- Charm: NLO→±40%
- Bottom: NLO→±15%
\( \sigma(c\bar{c},b\bar{b}): \text{Data vs. NNLO (CT14 PDF)} \)

- **Charm:** Data \( \times 2 \) theory, but agreement within large uncertainties
- **Bottom:** Very good agreement at all \( \sqrt{s} \) within large uncertainties

- **Charm: Data \( \times 2 \) theory, but agreement within large uncertainties**
  - Fixed-target
  - LHC
  - FCC

- **Bottom: Very good agreement at all \( \sqrt{s} \) within large uncertainties**
  - Fixed-target
  - LHC
  - FCC

**Graphs:**
- Top++ NNLO
- \( pp \rightarrow c\bar{c}+X \) (NNLO, scale unc.)
- PDF=CT14
  - ATLAS (pp)
  - ALICE (pp,pPb)
  - LHCb (pp)
  - STAR (pp)
  - PHENIX (pp)
- HERA-B (pA)
- E653 (pA)
- E743 (pA)
- NA27 (pA)
- NA16 (pA)
- E769 (pA)

- Top++ NNLO
- \( pp \rightarrow b\bar{b}+X \) (NNLO, scale unc.)
- PDF=CT14
  - LHCb (pp)
  - ALICE (pp)
  - CDF (pp)
  - UA1 (pp)
  - PHENIX (pp)
  - HERA-B (pA)
  - E789 (pA)
  - E771 (pA)

**Note:** Large CT14 uncertainties.
σ(c¯c,b¯b): Data vs. NNLO (ABMP16 PDF)

- Charm: Data ×2–5 theory (agreement for LHC within large uncert.)
  - Fixed-target LHC
  - FCC

- Bottom: Very good agreement at all √s within large uncertainties
  - Fixed-target LHC
  - FCC

(tiny AMBP16 uncertainties)
(scale uncertainties)
\( \sigma(\overline{c}c, \overline{b}b) \): Data vs. NNLO (MMHT14 PDF)

- **Charm:** Data \( \times 2.5 \) theory (negative gluon at very low \( x, \sqrt{s}>30 \) TeV)
  - Data \( \times 2.5 \) theory (negative gluon at very low \( x, \sqrt{s}>30 \) TeV)
  - Fixed-target LHC FCC

- **Bottom:** Very good agreement at all \( \sqrt{s} \) within large uncertainties
  - Very good agreement at all \( \sqrt{s} \) within large uncertainties
  - Fixed-target LHC FCC

\[ \sigma_{cc}, \sigma_{bb} \]
σ(c¯c,b¯b): Data vs. NNLO (NNPDF3.0 PDF)

- **Charm**: Data ×2 theory (agreement within uncert. but “kink” at $\sqrt{s}>10$ TeV)

- **Bottom**: Very good agreement at all $\sqrt{s}$ within large uncertainties

### Charm

- Data
- 2 theory
- Agreement within uncert.
- "Kink" at $\sqrt{s}>10$ TeV

### Bottom

- Very good agreement
- At all $\sqrt{s}$
- Within large uncertainties

### Plots

- **Top++ NNLO**
  - PDF=NNPDF3.0
  - $\mu_F=\mu_R=2m_c$

- **ATLAS (pp)**
- **HERA-B (pA)**
- **E653 (pA)**
- **E743 (pA)**
- **NA27 (pA)**
- **NA16 (pA)**
- **E769 (pA)**

- **Bottom++ NNLO**
  - PDF=NNPDF3.0
  - $\mu_F=\mu_R=2m_b$

- **LHCb (pp)**
- **ALICE (pp,pPb)**
- **CDF (pp)**
- **UA1 (pp)**
- **HERA-B (pA)**
- **E789 (pA)**
- **E771 (pA)**

### Ratios

- **Fixed-target**
- **LHC**
- **FCC**

- **Ratio data/NNLO**
- **$\mu_F=\mu_R=2m_c$**

- (large NNPDF3.0 uncertainties)
- (scale uncertainties)
Updated NNPDF3.0 (NLO) low-x gluon

- **Forward D-mesons (LHCb)** probe gluon down to $x \sim 10^{-6}$:

  ![Graph](image1.png)

  [NPB 871 (2013) 1]

  [arXiv: 1510.01707]

- **5,7,13 TeV D-meson data fitted with FONLL calculations (GM-VFN scheme):**

  - Updated analysis based on normalized cross-sections at 5, 7 and 13 TeV and cross-section CoM energy ratios (avoiding double counting)
  - Good description of all datasets, compatible pull on the small-x gluon except the R13/7 ratio
  - The $N^5+N^7+N^{13}$ combination leads to a reduction of the small-x gluon PDF errors by an order of magnitude!

  ![Graph](image2.png)


- **Future NNPDF low-x gluon will cure $\sigma$(cc) high-$\sqrt{s}$ “kink” & reduce uncertainties**
Summary

■ First-ever calculation of NNLO total charm and bottom cross sections in hadronic collisions (using modified version of Top++):
  ✓ Large K-factors: \( \sigma_{\text{NNLO/NLO}} \sim 2(\text{fixed-target})-1.2(\text{LHC}) \)
  ✓ Reduced scale uncertainties:
    Charm: \( \pm (60\%)_{\text{NLO}} \rightarrow \pm (40\%)_{\text{NNLO}} \) Bottom: \( \pm (35\%)_{\text{NLO}} \rightarrow \pm (15\%)_{\text{NNLO}} \)

■ Agreement with data (20 measurements from 20 GeV to 10 TeV), within large (PDF & exp.) uncertainties, though central exp. charm x-section still \( \times 2-3 \) above theory.

■ Very strong sensitivity to low-x gluon PDF (esp. charm). Predictions above LHC have uncontrolled behaviours and/or very large uncertainties:
  – CT14 gluon seems best behaved overall
  – AMBP16 underestimates most low-\( \sqrt{s} \) data.
  – MMHT14 gluon dives to zero above \( \sim 30 \) TeV
  – NNPDF3.0 gluon best agreement w/ data (but unphysical slope change & huge uncertainties at \( \sim 10 \) TeV)

■ At \( \sqrt{s} \sim 300 \) TeV, \( \sigma_{cc} \sim \sigma_{\text{inel}} \); Impact on \( \mu, \nu \) of most energetic cosmic-rays showers
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Bottom x-sections well behaved for all PDFs up to \( \sim 100 \) TeV.
Backup slides