Theoretical aspects of charm and bottom production at the LHC, in view of the most recent results

XII Franco-Italian B physics Workshop:
Tensions in flavour measurements
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Charm-pair production from fixed target to LHC
• why should we even bother discussing a “theory” that has a factor of 10 uncertainty??

• why should experiments even bother doing these measurements? what are they testing? what are we learning?
obvious answer to 2nd bullet ("why measure"):

• expt’s don’t need theorists, they shouldn’t care if there is a theory, they must explore how Nature works, and tell us!

• hvq production plays a key role in addressing a series of fundamental questions, which the LHC was built to address

• studies of the Higgs properties (H identification through its \(bb\) final state is hostage to large QCD \(bb\) bg’s)

• QGP (comparison of hvq production in pp vs pA vs AA)

• CPV (\(pp \rightarrow B^- \neq pp \rightarrow B^+\) pollutes CP asymmetries)

• but also relevant in other fields, e.g. cosmic rays (\(c \rightarrow \nu\) major source of HE vs in ICEcube)

TH is not needed here, the expt’s can figure things out themselves, but it helps (eg export bg estimates from control samples to signal samples)!
As for the first issue (ie, is there a “theory” worth discussing?):
• hint: strong correlation and consistency in $\sigma_{\text{exp}}/\sigma_{\text{TH}}$, over 3 orders of magnitude in $\sqrt{S}$
and, in general, there is a reasonable agreement between data and theory that goes beyond total rates

Exclusive $D^0$ decays

D cross sections well described by pQCD-based models at LHC energies

- FONLL: JHEP, 1210 (2012) 137
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**Semileptonic B decays**

**Cross section measurements**

**Semi-leptonic HF hadron decays**

**Beauty**

Beauty cross sections well described by pQCD-based models at LHC energies

**FONLL:** JHEP, 1210 (2012) 137


**LO $k_T$ fact:** Phys. Rev., D87 (2013) 094022
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Exclusive $B^+ \to J/\psi K^+$ decays
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Inclusive SL b decays

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The systematic uncertainties are dominated by the b-tagging efficiency. Contributions from BR are of the order of 2.5% (an order of magnitude lower than the dominant one). The uncertainty of the b-quark fragmentation is of the order of 4%.
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D\textsuperscript{0} production at forward rapidity

Double differential cross-sections, \(\frac{d^2\sigma_i}{dp_T^2 dy}\), of prompt \(D^0\) vs. \(p_T\).
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Inclusive $B \rightarrow J/\psi \ X$ decays at forward rapidity
the TH challenges

• identify observables that can be reliably predicted, pushing precision to the % level

• identify important measurements that can benefit from increased precision

• contribute to the reduction of systematics, related to production uncertainties, which may influence the precision of flavour-physics measurements

• …. and continue investing in trying to improve !!

ultimately, there is also the pleasure of cracking difficult dynamical problems, at the border between perturbative and non-perturbative QCD, and learning more about the complex underlying mechanisms at play in hadron collisions ....
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- Resummation of small-x logs ($x \sim m^2/S$): at leading order in the early 90’s, NLL+NLO still unavailable, but no evidence from data of a crucial role of these logs (see BFKL vs DGLAP....)
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- NNLO for hvq pair hadroproduction available, also for b and c total rates, but still unsuitable for differential distributions
New opportunities from LHC
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- Measurements at different energies, and over a broad rapidity range, provide an opportunity to constrain gluon PDF in the region of both large and small $x$, with important phenomenological implications.
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• Key ingredient is the **correlation** between theoretical systematics at different beam energies and across the rapidity range:
  • $m_Q$ is obviously fully correlated
  • QCD scale variations: correlated at any given $p_T$ value
  • PDFs: fully correlated, but probing different $x$ at different $\sqrt{S}$
  • BRs, fragmentation fractions and frag functions fully correlated
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- At this time, we need to build confidence that our assumptions about theoretical systematics are robust.
Key references to recent TH work exploring these ideas

• Charm production in the forward region: constraints on the small-x gluon and backgrounds for neutrino astronomy. R. Gauld et al. arXiv:1506.08025

• [CMN] Gluon PDF constraints from the ratio of forward heavy-quark production at the LHC at root(S)=7 and 13 TeV, M. Cacciari M. Mangano and P. Nason, arXiv:1507.06197

• Impact of heavy-flavour production cross sections measured by the LHCb experiment on parton distribution functions at low x, PROSA Collaboration (Zenaiev et al.), arXiv:1503.04581

• Prompt neutrino fluxes in the atmosphere with PROSA parton distribution functions (Garzelli et al), arXiv:1611.03815

• [GR] Precision determination of the small-x gluon from charm production at LHCb, R. Gauld and J. Rojo, arXiv:1610.09373

• [GMS] Lepton fluxes from atmospheric charm revisited, Grazielli, Moch, Stigl, arxiv:1507.01570

• [G] Understanding forward B-hadron production, R. Gauld, arxiv:1703.03636
Sources of TH syst’s for charm XS’s at 13 TeV

Figure 2: Charm quark rapidity distributions at $\sqrt{S} = 13$ TeV.
Rates normalized to central value

Figure 4: Charm quark rapidity distributions at $\sqrt{S} = 13$ TeV, normalised to the central theoretical prediction.
LO vs NLO vs NNLO scale dependence

NNLO scale syst reduction important, but still insufficient for high precision absolute predictions
Systematics of ratio of charm XS's at 13/7 TeV

Immense reduction of scale systematics!!

$\times 10 \Rightarrow \pm 10\%$
Systematics of ratio of charm XS’s at 13/7 TeV, scaled to ratio at $y=0$

=> all that’s left is the PDF systematics!

=> useful probe of PDF behaviour!
Event kinematics

\[ x_{1,2} = \frac{m_T}{E_b} e^{\pm y} \]

Graphs showing the relationship between \( x_1, x_2, \) and \( y \) for different values of \( p_T \). Each graph represents a line with a slope determined by the value of \( y \) and the corresponding \( p_T \) value.
x range covered by gluon PDF

\[ \frac{1}{\sigma} \frac{d\sigma}{d \log x_{1,2}} \]

4 < |y^{charm}| < 5

Solid: \( p_T^{charm} > 0 \)
Dashes: \( p_T^{charm} > 5 \text{ GeV} \)
DotDash: \( p_T^{charm} > 30 \text{ GeV} \)
Figure 5: Bottom quark rapidity distributions at $\sqrt{s} = 13$ TeV, normalised to the central theoretical prediction.
Systematics of ratio of bottom XS's at 13/7 TeV, scaled to ratio at $y=0$
Some PDF sets lead to negative gluons at small $x \Rightarrow$ negative rates at small scales for energies beyond LHC.
The issue shows up dramatically at 100 TeV ....

<table>
<thead>
<tr>
<th>PDF sets</th>
<th>$\sigma(c\bar{c})^{\text{NLO}}$ [mb]</th>
<th>$\sigma(c\bar{c})^{\text{NNLO}}$ [mb]</th>
<th>$\sigma(b\bar{b})^{\text{NLO}}$ [mb]</th>
<th>$\sigma(b\bar{b})^{\text{NNLO}}$ [mb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABM11 [392]</td>
<td>29.5 $\pm$ 2.7</td>
<td>36.6 $\pm$ 2.6</td>
<td>3.57 $\pm$ 0.13</td>
<td>3.06 $\pm$ 0.11</td>
</tr>
<tr>
<td></td>
<td>(54.9 $\pm$ 3.8)</td>
<td></td>
<td>(4.52 $\pm$ 0.18)</td>
<td></td>
</tr>
<tr>
<td>ABM12 [10]</td>
<td>17.3 $\pm$ 2.0</td>
<td>33.2 $\pm$ 2.6</td>
<td>2.36 $\pm$ 0.10</td>
<td>2.97 $\pm$ 0.12</td>
</tr>
<tr>
<td>CJ15 [12]</td>
<td>18.4 $\pm$ 5.3 $\pm$ 2.3</td>
<td>2.67 $\pm$ 0.55 $\pm$ 0.26</td>
<td>3.42 $\pm$ 0.69 $\pm$ 0.31</td>
<td></td>
</tr>
<tr>
<td>CT14 [8]</td>
<td>24.7 $\pm$ 131.5 $\pm$ 3.1</td>
<td>31.8 $\pm$ 671.3 $\pm$ 5.2</td>
<td>3.12 $\pm$ 3.39 $\pm$ 0.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(47.9 $\pm$ 1981.2 $\pm$ 5.2)</td>
<td></td>
<td>(3.91 $\pm$ 6.91 $\pm$ 0.30)</td>
<td></td>
</tr>
<tr>
<td>HERAPDF2.0 [11]</td>
<td>19.0 $\pm$ 3.8 $\pm$ 4.4</td>
<td>3.14 $\pm$ 0.10 $\pm$ 0.13</td>
<td>2.70 $\pm$ 0.21 $\pm$ 0.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(41.5 $\pm$ 5.2 $\pm$ 5.9)</td>
<td></td>
<td>(4.01 $\pm$ 0.13 $\pm$ 0.16)</td>
<td></td>
</tr>
<tr>
<td>JR14 (dyn) [13]</td>
<td>33.6 $\pm$ 0.5</td>
<td>32.7 $\pm$ 0.5</td>
<td>3.17 $\pm$ 0.04</td>
<td>3.08 $\pm$ 0.04</td>
</tr>
<tr>
<td></td>
<td>(58.1 $\pm$ 1.0)</td>
<td></td>
<td>(3.98 $\pm$ 0.06)</td>
<td></td>
</tr>
<tr>
<td>MMHT14 [9]</td>
<td>140.0 $\pm$ 187.0 $\pm$ 104.2</td>
<td>213.9 $\pm$ 271.9 $\pm$ 149.4</td>
<td>4.11 $\pm$ 1.39 $\pm$ 0.90</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(213.9 $\pm$ 271.9 $\pm$ 149.4)</td>
<td></td>
<td>(5.28 $\pm$ 1.77 $\pm$ 1.14)</td>
<td></td>
</tr>
<tr>
<td>NNPDF3.0 [7]</td>
<td>40.5 $\pm$ 62.2</td>
<td>190.3 $\pm$ 547.7 $\pm$ 84.3</td>
<td>2.99 $\pm$ 0.99</td>
<td>4.46 $\pm$ 4.87</td>
</tr>
<tr>
<td></td>
<td>(67.9 $\pm$ 84.3)</td>
<td></td>
<td>(3.82 $\pm$ 1.23)</td>
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</table>

Table 48: The inclusive cross sections for charm- and bottom-quark pair production at NNLO in QCD at $\sqrt{s} = 100$ TeV for $\overline{\text{MS}}$ masses $m_c(m_c) = 1.275$ GeV and $m_b(m_b) = 4.18$ GeV at the nominal scales $\mu_r = \mu_f = 2m_q(m_q)$ for $q = c, b$ with the PDF (and, if available, also $\alpha_s$) uncertainties. The numbers in parenthesis for the cross sections $\sigma(q\bar{q})^{\text{NNLO}}$ have been obtained with NLO PDF sets.
The impact of LHC data
The pedestal subtraction hides that fact that the slope is much bigger at large $y$.

E.g. for $pt=8$ R$\sim3$ @ $y=2-2.5$, and $R=6$ @ $y=4-4.5$

This is the result of the greater sensitivity to small-$x$ and large-$x$ PDFs at large $pt$ and large $y$. 
CMS bottom XS’s at 13 and 7 TeV

CMS, arXiv:1609.00873
Some disturbing issues:

The difference in shape at small-\(\eta\) is a bit worrisome, given the rather sharp TH predictions ....
Nevertheless, the data are sufficient to set new remarkable constraints on the gluon PDF at small-$x$.

Impact of LHCb charm XS measurements at 5, 7 and 13 TeV on gluon PDF [GR]

FIG. 2: The NLO gluon in NNPDF3.0 and for various combinations of LHCb data included, at $Q^2 = 4$ GeV$^2$. 

LHCb arXiv:1610.02230
Impact on XS predictions for 100 TeV pp collider

Gauld, Rojo, Slade, arXiv:1705.04217

<table>
<thead>
<tr>
<th></th>
<th>14 TeV</th>
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<th>100 TeV</th>
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<tbody>
<tr>
<td></td>
<td>No cuts</td>
<td>LHC cuts</td>
<td>No cuts</td>
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</tr>
<tr>
<td>NNPDF3.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W^+$</td>
<td>11.8 (1.9%)</td>
<td>6.4 (2.0%)</td>
<td>73.5 (7.0%)</td>
<td>27.8 (2.9%)</td>
</tr>
<tr>
<td>$W^-$</td>
<td>8.8 (1.8%)</td>
<td>4.7 (1.4%)</td>
<td>61.9 (5.5%)</td>
<td>26.0 (3.0%)</td>
</tr>
<tr>
<td>$Z$</td>
<td>2.0 (1.7%)</td>
<td>1.5 (1.8%)</td>
<td>14.1 (5.1%)</td>
<td>7.9 (3.2%)</td>
</tr>
<tr>
<td>NNPDF3.0+LHCb</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W^+$</td>
<td>12.2 (1.6%)</td>
<td>6.6 (1.7%)</td>
<td>73.4 (3.0%)</td>
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Cross-sections at 100 TeV normalised to NNPDF3.0 + $N_5 + N_7 + N_{13}$ with FCC cuts

Cross-sections at 100 TeV normalised to NNPDF3.0 + $N_5 + N_7 + N_{13}$ with improved LHCb cuts
Impact of “charm-XS-improved” gluon PDF on $\sigma_{VN}$ at high energy
Bgs to cosmogenic $\nu$'s: HE $\nu$'s from decays of charm produced in cosmic ray showers

Reduction in QCD systematics is needed to properly assess bgs, and possibly learn about CR syst's
Next steps

• Wait for a final round of measurements of c and b production at 13 TeV, and updated XS ratio measurements

• Assess global consistency of interpretation of both c and b data (e.g. do they lead to the same gluon PDF constraints?)

• Important deviations from the precise predictions of XS ratios could point to onset of new dynamical effects (e.g. role of small-x resummation) … but this is not true of any deviation, for a large kinematic range these TH predictions are robust

• Match xs’s at the ATLAS/CMS-LHCb boundary, η~2-2.5, to give further robustness to the overall picture

• Push the kinematic reach of measurements (e.g. high-\(E_T\) b’s and b-jets)

• Test fragmentation function universality in the hadronic environment

• Look forward to availability of full NNLO differential distributions
$\psi$ & $\psi'$ production, pt spectra

Data vs NLO NRQCD

\[ \sqrt{s} = 0.2 \text{ TeV for RHIC} \]

\[ \sqrt{s} = 7 \text{ TeV for LHC} \]
Significant dependence on fits NRQCD long distance matrix elements (LDME), arising from set of ops considered, pert order, and pt range used in the fits.

\[ \langle O^{J/\psi}(^3S_1^{[1]}) \rangle = 1.32 \text{ GeV}^3 \]
\[ \langle O^{J/\psi}(^1S_0^{[8]}) \rangle = 0.0497 \text{ GeV}^3 \]
\[ \langle O^{J/\psi}(^3S_1^{[8]}) \rangle = 0.0022 \text{ GeV}^3 \]
\[ \langle O^{J/\psi}(^3P_0^{[8]}) \rangle = -0.0161 \text{ GeV}^5 \]
Upsilon production, pt spectra

Data vs NLO NRQCD

Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang, arxiv:1305.0748
Upsilon production, polarization

Data vs NLO NRQCD

Bin Gong, Lu-Ping Wan, Jian-Xiong Wang and Hong-Fei Zhang, arxiv:1305.0748

* $\lambda = 0, +1, -1 \Rightarrow \text{nopol, } \perp \text{ pol, } // \text{ pol}
Remark: NRQCD-based production description in default Pythia is rather naive, and a discrepancy with a theoretically more robust calculation was first noticed in Bain et al, arXiv:1603.06981
So this comparison is not very compelling in terms of assessing the reliability of NRQCD.
First-principle NRQCD predictions

B&K
\(\sqrt{s} = 13 \text{ TeV}\)

GFIP
FJF

Chao et al.
\(\sqrt{s} = 13 \text{ TeV}\)

GFIP
FJF

Bodwin et al.
\(\sqrt{s} = 13 \text{ TeV}\)

GFIP
FJF

Bain et al, arxiv:1702.05525
See also
Baumgart et al, arXiv:1406.2295
Bain et al, arXiv:1603.06981

FJF: fragmenting jet functions
GFIP: gluon-fragmentation improved Pythia

BK, Chao et al, Bodwin et al: different fits of NRQCD LDME
• Given the complexity of the problem of describing onium production, I believe NRQCD is in good shape

• $p_T$ spectra, across multitude production environments (HERA, Tevatron, LHC) are rather well accounted for

• The situation of polarization is complicated by existing internal discrepancies between various measurements at Tevatron and LHC, as well as by the role of feeddown and of different contributions by various states

• Fragmentation function is ok, in my view ….
More avenues
Collective effects in pp collisions?

Multiplicity dependence

- pp data at $\sqrt{s}=13$ TeV allow us to extend the $J/\psi$ measurement to higher multiplicity (x2)
- Faster than linear increase
- No visible $\sqrt{s}$ dependence for $J/\psi$
- Similar behavior for $D$ and $J/\psi$ (caveat: different $p_T$ and $\eta$ regions)
  - acts on the HQ production (rather than hadronisation)

normalized yields

ALICE, pp

$J/\psi \rightarrow e^+e^-$, $|y|<0.9$
$E=7$ TeV, [PLB 712 (2012) 165]

$D$, $|y|<0.5$, $2<p_T<4$ GeV/c
$E=7$ TeV, [JHEP 09 (2015) 148]
$N_{\text{track}}$ dependence not explained by standard MCs

**Model comparison**

**J/$\psi$**

**Percolation Model**
Mimic MPI via interactions of color sources with finite spatial extension

**EPOS 3 for D** (with Hydro)
Parton based Gribov-Regge formalism, MPI proportional to multiplicity

**PYTHIA 8**
Hard processes in MPI (new w.r.t. PYTHIA6)

**Kopeliovich et al.**
[Phys. Rev. D 88, 116002 (2013)]
High multiplicities reached by contributions of higher Fock states

Models reproduce the data at low multiplicity while deviate at high multiplicity

**Important role of MPI at high multiplicity in hadronic collisions**
Recent ALICE data on the relative production rate of strange hadrons show an increase with final-state event multiplicity. This is not predicted by standard QCD MCs. It would be interesting to search for a similar effect in $f_s/f_d$ vs $dN_{ch}/d\eta$. 

Signs of QGP in high-multiplicity $pp$ collisions? If not, what else? A whole new game!
Overall conclusions

- HVQ production at LHC remains a highly interesting topic
- Flexibility of LHC operations (different $E_{\text{beam}}$) and of detectors ($\eta$ range, $p_T$ range, production modes, etc) opens new opportunities for incisive measurements
- TH is slowly but steadily improving, and a set of precise predictions (eg for XS ratios) is available
- The outcome of these measurements has important consequences for a wide array of applications, from PDF fits, low-$x$ gluons, extrapolations to the highest energies, better bg estimates for the study of Higgs properties, new physics searches, CR physics, collective phenomena …