Theory of heavy flavor and onia production

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Heavy quarks are very special, both experimentally and theoretically. Since they can only decay via weak interaction, they are long lived, giving rise to displaced vertices. The fact that they are much heavier than \( \Lambda_{\text{QCD}} \) means that the non-perturbative structure of heavy quarks is much different than that of light quarks.

Mass of heavy mesons mostly determined by heavy quark mass. Non non-perturbative information about heavy quark in proton.
This talk will give a very selective overview of recent progress in heavy quark and quarkonium production

- Heavy quarkonium production
- Open heavy flavor production
- Outlook and conclusions
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Quarkonium production has a rich history theoretically.

Early attempts at quarkonium production relied on the production of two heavy quark in a color singlet configuration.

This under predicted data at the Tevatron in a spectacular fashion.

In 1994 Fleming and Braaten showed that color octet contributions can explain the CDF data.

Fleming, Braaten (’95)
To describe the production of quarkonia, rely on factorization of perturbative and non-perturbative physics using NRQCD

\[ d\sigma(p p \to \Psi) = f_{k/p} \otimes f_{l/p} \otimes d\sigma(kl \to cc[n]) \langle O_\Psi^{[n]} \rangle \]

Bodwin, Braaten, Lepage (’94)
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partonic x-section

parton distribution function

non-perturbative matrix element

Similar formulas for photo-production and $e^+e^-$ scattering

Non-perturbative matrix elements are process independent, but have to be extracted from data
Three matrix elements are required to describe a large data set from many processes

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>PRD 79, 071101 (2009)</td>
</tr>
<tr>
<td>PHENIX</td>
<td>PRD 82, 012001(2010)</td>
</tr>
<tr>
<td>HI (Run I)</td>
<td>EPJ C25, 25 (2002)</td>
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<tr>
<td>H1 (Run II)</td>
<td>EPJ C68, 401 (2010)</td>
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<tr>
<td>ZEUS (Run I)</td>
<td>EPJ C27, 173 (2003)</td>
</tr>
<tr>
<td>CDF (Run I)</td>
<td>PRL 79, 572, 578 (1997)</td>
</tr>
<tr>
<td>CDF (Run II)</td>
<td>PRD 71 032001 (2005)</td>
</tr>
<tr>
<td>CMS</td>
<td>EPJ C71, 1575 (2011)</td>
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<tr>
<td>ATLAS</td>
<td>ATLAS-CONF 2010-062</td>
</tr>
<tr>
<td>ALICE</td>
<td>1203.3641</td>
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<tr>
<td>LHCb</td>
<td>EPJ C71, 1645 (2011)</td>
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</tbody>
</table>
A global fit to all data has been performed recently, with reasonable, and all data is described reasonably well.

Kniehl, Butenschön ('12)
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\begin{center}
\begin{tabular}{|c|c|}
\hline
\langle O^{J/\psi} (1S_0^{[8]} ) \rangle & \langle O^{J/\psi} (3S_1^{[8]} ) \rangle \\
(4.97 \pm 0.44) \times 10^{-2} \text{ GeV}^3 & (2.24 \pm 0.59) \times 10^{-3} \text{ GeV}^3 \\
\langle O^{J/\psi} (3P_0^{[8]} ) \rangle & \langle O^{J/\psi} (3P_1^{[8]} ) \rangle \\
(-1.61 \pm 0.20) \times 10^{-2} \text{ GeV}^5 & \\
\hline
\end{tabular}
\end{center}

\[ \chi^2_{\text{dof}} = 4.42 \]

Size consistent with NRQCD velocity scaling rules

(v^4 relative to color singlet matrix element)

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Given this fit, one can make a zero-parameter prediction of the polarization of the $J/\Psi$

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While the predictions form ALICE are reproduced, the results from CDF are not
Values of NRQCD matrix elements can be obtained that fit the polarization data, but they are not compatible with HERA data.
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Feed-down from higher Ψ resonances is considerable and can affect the polarization prediction.

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Gong, Wan, Wang, Zhan (’12)
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But again possible issue with HERA data
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But again possible issue with HERA data

Need new data from LHC to settle this issue
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There are many schemes used to make theoretical predictions. What do they all mean?
In heavy quark production, there are typically two scales that can arise: $m_Q$ and $p_T$. This gives rise to large logarithms

A fixed order calculation has a complicated dependence on both scales

$$\frac{d\sigma}{dp_T} = \alpha_s^2 \sum_{k=0}^{\infty} \alpha_s^k a_k(m_Q, p_T)$$

with

$$a_k(m_Q, p_T) = \sum_{n=0}^{k} g_{k,i}(m_Q, p_T) \log^n \left( \frac{m_Q}{p_T} \right)$$

The appearance of extra powers of logarithms at each order in perturbation theory is a very general feature.
Usual fixed order calculation (typically up to \( k=1 \)) keeps the full dependence on mass in functions \( a_k(m_Q, p_T) \)

\[
\frac{d\sigma}{dp_T} = \alpha_s^2 \sum_{k=0}^{\infty} \alpha_s^k a_k(m_Q, p_T) \quad a_k(m_Q, p_T) = \sum_{n=0}^{k} g_{k,i}(m_Q, p_T) \log^n \left( \frac{m_Q}{p_T} \right)
\]

These calculations use that \( m_Q \gg \Lambda_{\text{QCD}} \) and therefore have no heavy quarks in initial states (part of the protons)

\[
\frac{d\sigma}{dp_T} = f_{l_1/p} \otimes f_{l_2/p} \otimes h(l_1l_2 \rightarrow h(p_T)\bar{h} + X)
\]

Such calculation are said to be in the “massive” or “4FNS” scheme

They assume that the logarithm of \( m_Q/p_T \) is not large
Fixed order calculations can be combined with a parton shower to produce exclusive events

$$\frac{d\sigma}{dp_T} = \alpha_s^2 \sum_{k=0}^{\infty} \alpha_s^k a_k(m_Q, p_T) \quad a_k(m_Q, p_T) = \sum_{n=0}^{k} g_{k, i}(m_Q, p_T) \log^n \left( \frac{m_Q}{p_T} \right)$$

Exclusive final state allows for more direct implementation of experimental acceptances and efficiencies

Several important processes implemented in both POWHEG and MC@NLO
In the limit $p_T \gg m_Q$ the logarithms in the perturbative expansion can spoil the accuracy of the prediction

$$\frac{d\sigma}{dp_T} = \alpha_s^2 \sum_{k=0}^{\infty} \alpha_s^k a_k(m_Q, p_T) \quad a_k(m_Q, p_T) = \sum_{n=0}^{k} g_{k,i}(m_Q, p_T) \log^n \left( \frac{m_Q}{p_T} \right)$$

Introduce parton distribution and fragmentation functions, and resum through evolution (get only $k=n, n-1$)

$$\frac{d\sigma}{dp_T} = f_{h/p}(p_T) \otimes f_{l/p}(p_T) \otimes h(hl \to h + X) \otimes D_{H/h}(p_T)$$

$f_{h/p}$ and $D_{H/h}$ calculated perturbatvely at $\mu=m_Q$ and evolved to $\mu=p_T$

Such calculation are said to be in the "massless" or "5FNS" scheme

Since one uses $m_Q \ll p_T$, only gets $g_{k,i}(0,p_T)$ (power corrections)
A combination of both methods can be obtained through matching and is called FONLL

“4FNS”:
\[
\frac{d\sigma}{dp_T} = \alpha_s^2 [a_0(m_Q, p_T) + \alpha_s a_1(m_Q, p_T)]
\]

“5FNS”:
\[
\frac{d\sigma}{dp_T} = \alpha_s^2 \sum_{k=0}^{\infty} \sum_{n=k-1}^{k} \alpha_s^k g_{k,n}(0, p_T) \log^n \left( \frac{m_Q}{p_T} \right)
\]

Combination is obtained by replacing the first \(\alpha_s^2\) and \(\alpha_s^3\) term by the exact result \(a_0(m_Q, p_T)\) and \(a_1(m_Q, p_T)\)

“FONLL”:
\[
\frac{d\sigma}{dp_T} = \alpha_s^2 [a_0(m_Q, p_T) + \alpha_s a_1(m_Q, p_T)]
\]
\[
+\alpha_s^2 \sum_{k=2}^{\infty} \sum_{n=k-1}^{k} \alpha_s^k g_{k,n}(0, p_T) \log^n \left( \frac{m_Q}{p_T} \right)
\]

However, this result can not be combined with a parton shower algorithm to obtain exclusive events
For production of D mesons, can compare to results from ALICE and preliminary results from ATLAS

Relatively good agreement between FONLL, 5FNS and ALICE data, but significant dependence on parton shower implementation.
For production of D mesons, can compare to results from ALICE and preliminary results from ATLAS

Again, reasonable agreement with theoretical predictions
For production of D mesons, can compare to results from ALICE and preliminary results from ATLAS.

Figure 1: Differential cross sections for $D^{\ast\pm}$ mesons as a function of $p_T$ (top plot) and $|\eta|$ (bottom plot) for data (points) compared to the NLO QCD calculations of FONLL, GM-VFNS, POWHEG-PYTHIA and MC@NLO (histograms). The data points are drawn at the bin centres of gravity in the $d\sigma/dp_T$ distribution and at the bin centres in the $d\sigma/d|\eta|$ distribution. The inner error bars show the statistical uncertainties and the outer error bars show the statistical and systematic uncertainties added in quadrature. The bands show the theoretical uncertainty of the FONLL calculation.

Again, reasonable agreement with theoretical predictions.
For production of B mesons, can compare to results from CMS

Very good agreement with data. Deviation between fixed order and FONLL can be seen for large $p_T$
In the forward region, there are much larger differences between fixed order calculations and FONLL

Will be interesting to see results from LHCb in the future
While there is overall good agreement, there are some interesting discrepancies between theory and data as well.

Could this be an issue with the tuning of non-perturbative fragmentation functions?
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Just as in open heavy quark production, onia production at large $p_T$ has large logarithms that can be resummed

\[
\frac{d^2 \sigma}{dp_T^2 \, dy} \propto \int dx_1 dx_2 f_q/p(x_1) f_{\bar{q}/p}(x_2) \left[ \hat{\sigma}^{\beta}(x_1, x_2, p_\perp, y) \otimes D_{Q\bar{Q}/\beta} \right]
\]

**Contribution from $g \to J/\Psi$ fragmentation:**
Logs resummed in similar fashion to open heavy flavor production

**Contribution from $cc \to J/\Psi$ fragmentation:**
New kind of fragmentation function, running not simply governed by DGLAP

**Work to complete resummation for all terms under way**
Fleming, Leibovich, Mehen, Rothstein (in progress)
Would be nice to have theoretical predictions at large $p_T$ that can be interfaced with a parton shower

In order to interface a theoretical calculation with a parton shower, need an “exclusive” prediction

Let a parton shower fill out the “jets” integrated over in the theoretical calculation

Theoretical difficulty: Sum logarithms of both $m_Q/p_T$ as well as logarithms of jet size

Can be done using soft-collinear effective theory (SCET)

CWB, Mereghetti (in progress)
In summary, theoretical predictions compare reasonably well with first data from LHC

But there are interesting discrepancies that should be sorted out

I am looking forward to seeing new results from the LHC and more precise theoretical calculations

Thank you!