Testing Perturbative QCD on $J/\psi$ production and polarization

Jian-Xiong Wang
Institute of High Energy Physics, Chinese Academy of Science, Beijing

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Testing Perturbative QCD on $J/\psi$ production and polarization

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2. The calculations performed by using FDC-loop in last four years
3. $J/\psi$ production at the B factories
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   - To automatically construct the Lagrangian and deduce the Feynman
   - Automatically phase space treatment
   - FDC: tree diagram calculation application
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Introduction

- Perturbative and non-perturbative QCD, hadronization, factorization
- Color-singlet and Color-octet mechanism was proposed based on NRQCD since c-quark is heavy.
- Clear signal to detect $J/\psi$.
- Heavy quarkonium production is a good place to testify these theoretical framework.
- But there are still many difficulties.
  - $J/\psi$ photoproduction at HERA
  - $J/\psi$ production at the B factories
  - $J/\psi$ polarization at the Tevatron
- NLO corrections are important.
  - Data on inelastic $J/\psi$ photoproduction are adequately described by the color singlet channel alone at NLO
  - Double charmonium production at the B factories
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Introduction

![Graph showing BR(J/ψ → μ⁺μ⁻) dσ(pp → J/ψ + X)/dp_T (nb/GeV) vs. p_T (GeV) with data points and theoretical curves.](image)

PRL 99, 132001 (2007)
Brief Introduction to FDC package

Feynman Diagram Calculation (FDC).
This first version of FDC was presented at AIHENP93 workshop, 1993.

FDCC Homepage:

**FDC-LOOP**
FDC-PWA
FDC-EMT

FDCC-SM-and-Many-Extensions
FDCC-NRQCD
FDCC-MSSM

Written in REDUCE, RLISP, C++. To generate Fortran

Event Generator
The calculations by using FDC-loop in last three years

- Our work concentrate on QCD correction to heavy quarkonium production in B-factory, z boson decay, Υ decay, HERA, Tevatron, LHC.
- It is found that that QCD corrections to these processes are very important.
- There are six-point, five-point, ... Feynman diagrams are accounted in the calculations. In many case, five-point scalar integral can not be decomposed into four-point ones due to special kinematic range in bound state related problem.
Testing Perturbative QCD on $J/\psi$ production and polarization

$J/\psi$ production at the B factories

Double charmonium production

$e^+ e^- \rightarrow J/\psi + \eta_c$

**Experimental Data**

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<tr>
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<th>Cross Section</th>
<th>Reference</th>
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<tr>
<td>BELLE</td>
<td>$\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (25.6 \pm 2.8 \pm 3.4) \ fb$</td>
<td>[Abe et al.(2002), Pakhlov(2004), Aubert et al.(2005)]</td>
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<td>BARAR</td>
<td>$\sigma[J/\psi + \eta_c] \times B^{\eta_c}[\geq 2] = (17.6 \pm 2.8^{+1.5}_{-2.1}) \ fb$</td>
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**LO NRQCD Predictions**

$2.3 \sim 5.5 \ fb$  

[Braaten and Lee(2003), Liu et al.(2003), Hagiwara et al.(2003)]
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### LO NRQCD Predictions

2.3 $\sim$ 5.5 fb

[Braaten and Lee(2003), Liu et al.(2003), Hagiwara et al.(2003)]

### NLO QCD corrections

$K \equiv \sigma^{NLO}/\sigma^{LO} \sim 2$

Confirmed by the analytic result in PRD77, (2008), B. Gong and J. X. Wang

### Relativistic corrections

$K \sim 2$

PRD67, (2007) E. Braaten and J. Lee
PRD75, (2007), Z. G. He, Y. Fan and K. T. Chao
PRD77,(2008),G.T. Bodwin, J. Lee and C. Yu
Testing Perturbative QCD on $J/\psi$ production and polarization

$J/\psi$ production at the B factories

double charmonium production

e$^+e^-$ → $J/\psi + J/\psi$

**Problem**

LO NRQCD prediction indicates that the cross section of this process is larger than that of $J/\psi + \eta_c$ production by a factor of 1.8, but no evidence for this process was found at the B factories.

PRL90, (2003) G. T. Bodwin, E. Braaten and J. Lee
Testing Perturbative QCD on $J/\psi$ production and polarization

- $J/\psi$ production at the B factories
- Double charmonium production

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PRL90, (2003) G. T. Bodwin, E. Braaten and J. Lee

**NLO QCD corrections**

- Greatly decreased, with a $K$ factor ranging from $-0.31 \sim 0.25$ depending on the renormalization scale.
- Might explain the situation.

Testing Perturbative QCD on $J/\psi$ production and polarization

**Inclusive $J/\psi$ production**

**LO NRQCD Predictions:**

\[
\begin{align*}
e^+ e^- & \rightarrow J/\psi + c\bar{c} & & 0.07 \sim 0.20 \text{pb} \\
e^+ e^- & \rightarrow J/\psi + gg & & 0.15 \sim 0.3 \text{pb} \\
e^+ e^- & \rightarrow J/\psi^{(8)}(3P_J, 1S_0) + g & & 0.3 \sim 0.8 \text{pb}
\end{align*}
\]


**Experimental Data:**

- **BARAR**
  \[\sigma[e^+ e^- \rightarrow J/\psi + X] = (2.54 \pm 0.21 \pm 0.21) \text{ pb}\]

- **CLEO**
  \[\sigma[e^+ e^- \rightarrow J/\psi + X] = (1.9 \pm 0.20) \text{ pb}\]

- **BELLE**
  \[\sigma[e^+ e^- \rightarrow J/\psi + X] = (1.45 \pm 0.10 \pm 0.13) \text{ pb}\]
  \[\sigma[e^+ e^- \rightarrow J/\psi + c\bar{c} + X] = (0.87^{+0.21}_{-0.19} \pm 0.17) \text{ pb}\]


**New BELLE Data**

\[
\begin{align*}
\sigma[e^+ e^- \rightarrow J/\psi + X] &= (1.17 \pm 0.02 \pm 0.07) \text{ pb} \\
\sigma[e^+ e^- \rightarrow J/\psi + c\bar{c}] &= (0.74 \pm 0.08^{+0.09}_{-0.08}) \text{ pb} \\
\sigma[e^+ e^- \rightarrow J/\psi + X_{\text{non}-c\bar{c}}] &= (0.43 \pm 0.09 \pm 0.09) \text{ pb}
\end{align*}
\]

[Pakhlov et al.(2009)]
Cross section at NLO for $e^+e^- \rightarrow J/\psi + gg$

$$\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[ a(\hat{s}) + \beta_0 \ln \left( \frac{\mu^2}{2m_c} \right) \right] \right\}$$

<table>
<thead>
<tr>
<th>$m_c$ (GeV)</th>
<th>$\alpha_s(\mu)$</th>
<th>$\sigma^{(0)}$ (pb)</th>
<th>$a(\hat{s})$</th>
<th>$\sigma^{(1)}$ (pb)</th>
<th>$\sigma^{(1)}/\sigma^{(0)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>0.267</td>
<td>0.341</td>
<td>2.35</td>
<td>0.409</td>
<td>1.20</td>
</tr>
<tr>
<td>1.5</td>
<td>0.259</td>
<td>0.308</td>
<td>2.57</td>
<td>0.373</td>
<td>1.21</td>
</tr>
<tr>
<td>1.6</td>
<td>0.252</td>
<td>0.279</td>
<td>2.89</td>
<td>0.344</td>
<td>1.23</td>
</tr>
</tbody>
</table>

Consistent results from two group:
PRL102, (2009) Y. Q. Ma, Y. J. Zhang and K. T. Chao

Relativistic Correction enhance results about a factor 1.3 from two group:
PRD82, (2010). Y. Jia
Testing Perturbative QCD on $J/\psi$ production and polarization

- $J/\psi$ production at the B factories
- Inclusive $J/\psi$ production

\[ e^+ e^- \rightarrow J/\psi + c\bar{c} \]

\[
\sigma^{(1)} = \sigma^{(0)} \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[ a(\hat{s}) + \beta_0 \ln \left( \frac{\mu}{2m_c} \right) \right] \right\}
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<tr>
<td>1.4</td>
<td>0.267</td>
<td>0.224</td>
<td>8.19</td>
<td>0.380</td>
<td>1.70</td>
</tr>
<tr>
<td>1.5</td>
<td>0.259</td>
<td>0.171</td>
<td>8.94</td>
<td>0.298</td>
<td>1.74</td>
</tr>
<tr>
<td>1.6</td>
<td>0.252</td>
<td>0.129</td>
<td>9.74</td>
<td>0.230</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Cross sections with different charm quark mass $m_c$ with the renormalization scale $\mu = 2m_c$ and $\sqrt{s} = 10.6$ GeV.

The former result given by PRL98, (2007) Y. J. Zhang and K. T. Chao
confirmed by PRD80, (2009) B. Gong and J. X. Wang
More about the scale and comparison with data

Use Brodsky, Lepage and Mackenzie (BLM) scale setting \[\text{[Brodsky et al.} (1983)]\]

\[
\sigma^{(1)} = \sigma^{(0)}(\mu^*)[1 + \frac{\alpha_s(\mu^*)}{\pi} b(\hat{s})].
\]

<table>
<thead>
<tr>
<th>$m_c$ (GeV)</th>
<th>$\alpha_s(\mu^*)$</th>
<th>$\sigma^{(0)}$ (pb)</th>
<th>$b(\hat{s})$</th>
<th>$\sigma^{(1)}$ (pb)</th>
<th>$\sigma^{(1)}/\sigma^{(0)}$</th>
<th>$\mu^*$ (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>0.348</td>
<td>0.381</td>
<td>3.77</td>
<td>0.540</td>
<td>1.42</td>
<td>1.65</td>
</tr>
<tr>
<td>1.5</td>
<td>0.339</td>
<td>0.293</td>
<td>4.31</td>
<td>0.429</td>
<td>1.47</td>
<td>1.72</td>
</tr>
<tr>
<td>1.6</td>
<td>0.332</td>
<td>0.222</td>
<td>4.90</td>
<td>0.337</td>
<td>1.52</td>
<td>1.79</td>
</tr>
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</table>

Cross sections with different charm quark mass $m_c$. The renormalization scale $\mu = \mu^* \sim m_c$. 
Momentum distribution of inclusive $J/\psi$ production with $\mu = \mu^*$ and $m_c = 1.4$ GeV is taken for the $J/\psi cc$ channel. The contribution from the feed-down of $\psi'$ has been added to all curves by multiplying a factor of 1.29.
Testing Perturbative QCD on $J/\psi$ production and polarization

- $J/\psi$ production at the B factories
- Inclusive $J/\psi$ production

Momentum and angular distributions of inclusive $J/\psi$ production.

The contribution from the feed-down of $\psi'$ has been added to all curves by multiplying a factor of 1.29.
Testing Perturbative QCD on $J/\psi$ production and polarization

$J/\psi$ production at the B factories

Inclusive $J/\psi$ production

Polarization parameter $\alpha$ and angular distribution parameter $A$ of $J/\psi$ as functions of $p$. 
Testing Perturbative QCD on $J/\psi$ production and polarization

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### Constraint for color-octect matrix element of $c\bar{c}(^{1}S_{0}^{8}, 3P_{j}^{8})$

\[
\sigma[e^+ e^- \rightarrow J/\psi + X_{\text{non-}c\bar{c}}] = (0.43 \pm 0.09 \pm 0.09) \text{ pb}
\]

\[
\sigma[e^+ e^- \rightarrow J/\psi + X_{\text{non-}c\bar{c}}]_{\text{color-\textit{singleTh}}} > (0.43) \text{ pb}
\]

\[
\sigma[e^+ e^- \rightarrow J/\psi + X_{\text{non-}c\bar{c}}]_{\text{color-\textit{octetTh}}} > (0.6) \text{ pb}
\]

From the contribution of $e^+ e^- \rightarrow J/\psi(^{1}S_{0}^{8}, 3P_{j}^{8}) + g$ at NLO

Testing Perturbative QCD on $J/\psi$ production and polarization

- Experimental and Leading-order Theoretical Results. [Acciarri:1998]

$$Br(Z \rightarrow J/\psi_{\text{prompt}} + X) = (2.1^{+1.4}_{-1.2}) \times 10^{-4}$$

Dominant process: $Z \rightarrow J/\psi + c\bar{c} + X$, and the total decay width is presented as

$$\Gamma^{NLO}(\mu) = \Gamma^{LO}(\mu)[1 + \frac{\alpha_s(\mu)}{\pi}(A + \beta_0 \ln \frac{\mu}{2m_Q} + Bn_f)].$$

$$Br_{\text{total}} = (7.3 \sim 10) \times 10^{-5}$$

The situation for $J/\psi$ production in $\Upsilon$ decay

**LO NRQCD Predictions:**

\[ Br(\Upsilon \rightarrow J/\psi(3S_1^2) + gg) = 6.2 \times 10^{-4} \quad \text{M. Napsuciale, Phys. Rev. D 57, 5711 (1998)} \]

\[ Br(\Upsilon \rightarrow J/\psi + c\bar{c}g) = 5.9 \times 10^{-4} \quad \text{S. Y. Li, Q. B. Xie and Q. Wang, Phys. Lett. B 482, 65 (2000)} \]

\[ Br(\Upsilon \rightarrow J/\psi + gg) = \text{order at} \times 10^{-4} \quad ??? \]

**Experimental Data for $Br(\Upsilon \rightarrow J/\psi + X)$:**

CLEO $(11 \pm 4 \pm 2) \times 10^{-4}$ *Phys. Lett. B 224, 445*

ARGUS $< 6.8 \times 10^{-4}$ *Z. Phys. C55, 25(1992)*

CLEO $(6.4 \pm 0.4 \pm 0.6) \times 10^{-4}$ *Phys. Rev. D70, 072001(2004)*

The situation is quite strange ????

The correct leading order prediction is

\[ B_{\text{Direct}}(\Upsilon \rightarrow J/\psi + c\bar{c}g) = 3.9 \times 10^{-5}. \]


Part of NLO prediction from $\Upsilon \rightarrow J/\psi + gg$ is

\[ B_{\text{Direct}}(\Upsilon \rightarrow J/\psi + gg) = 3.1 \times 10^{-5}. \]


The full QCD correction for the inclusive $J/\psi$ production in $\Upsilon$ decay would be a very interesting and challenge work for explaining the experimental data.
Testing Perturbative QCD on $J/\psi$ production and polarization

- $J/\psi$ production at the Tevatron and LHC
- QCD Correction to color-singlet $J/\psi$ production

QCD Correction to color-singlet $J/\psi$ production

$P_t$ distribution of $J/\psi$ production at QCD NLO was calculated in PRL98,252002 (2007), J. Campbell, F. Maltoni F. Tramontano

Some technique problems must be solved to calculate $J/\psi$ polarization

$P_t$ distribution of $J/\psi$ polarization at QCD NLO was calculated in PRL100,232001 (2008), B. Gong and J. X. Wang

Transverse momentum distribution of $J/\psi$ production

NLO*: contribution from $J/\psi + c\bar{c}$ is included

$J/\psi$ polarization status drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO
QCD Correction to color-singlet $\Upsilon$ production

$\Upsilon$ polarization drastically changes from transverse polarization dominant at LO into longitudinal polarization dominant at NLO.

$P_t$ distribution of $\Upsilon$ polarization at QCD NLO was calculated with detail in PRD78 074011 (2008), B. Gong and J. X. Wang.

NLO QCD corrections to $J/\psi$ production via S-wave color octet states

3 tree processes at LO

\[ g(p_1) + g(p_2) \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right](p_3) + g(p_4), \quad (267, 413) \]
\[ g(p_1) + q(p_2) \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right](p_3) + q(p_4), \quad (49, 111) \]
\[ q(p_1) + \bar{q}(p_2) \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right](p_3) + g(p_4). \quad (49, 111) \]

Real Correction (8 processes at NLO)

\[ gg \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]gg, \quad gg \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]q\bar{q}, \]
\[ gq \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]gq, \quad q\bar{q} \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]gg, \]
\[ qq \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]qq, \quad q\bar{q} \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]q'\bar{q}', \]
\[ qq \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]qq, \quad qq' \to J/\psi\left[ 1S^{(8)}_0, 3S^{(8)}_1 \right]qq', \]
To fit the Tevatron $P_t$ distribution give more $\langle O^{\psi}_{8} (\bar{S}_0) \rangle = 0.075$ GeV$^3$ and less $\langle O^{\psi}_{8} (\bar{S}_1) \rangle = 0.0021$ GeV$^3$ than they are at LO fitting The experimental data with $p_t < 6$ GeV have to abandon PLB673:197,2009, Erratum-ibid.693:612,2010 , B. Gong X. Q. Li and J. X. Wang

Correction to color-octet $J/\psi (^{1}S^8_0, ^3S^8_1, ^3P^8_J)$ production was done recently and gave almost the same prediction for $p_t$ distribution as before without calculation of polarization, by arXiv:1009.3655, Yan-Qing Ma, Kai Wang, Kuang-Ta Chao
arXiv:1009.5662, Mathias Butenschoen, Bernd A. Kniehl
QCD Correction to color-octet $\Upsilon(1S^8_0, 3S^8_1)$ production

QCD Correction to $J/\psi$ production at HERA.

$P_t$ distribution of production and different scheme of polarization for $J/\psi$
(color-singlet)

at QCD NLO was calculated in
PRL102, 142001 (2009), P. Artoisenet, John M. Campbell, F. Maltoni, F. Tramontano,

$P_t$ distribution of production $J/\psi$ (color-octet) at QCD NLO was calculated in

It include p-wave state and some progress in technique must be archived.
Other New Progress

χ_cJ production at hadron colliders with QCD radiative corrections
It include p-wave state and some progress in technique must be archived.

A new factorization scheme for J/ψ hadron production proposed by
J. W. Qiu, et al, Qiu’s talk

Fragmentation function of c → J/ψ at QCD NLO was calculated by
B. Gong and J. X. Wang, in prepare
Testing Perturbative QCD on $J/\psi$ production and polarization

Brief Introduction to FDC project

FDC System

Input for physical model

Physical model evaluation

Full Feynman Rules
Physical parameters

Latex version of then model

Input for physical process
Choose physical model and processes

Feynman diagram generation

Amplitude manipulation

Treatment of kinematics

Numerical integration fitting

Numerical results & Required plots in Hbook format

FIG.1: FDC system flow chart
To prepare first principle model

Input the description of the first principle model:
- Standard model and its extensions
- Supersymmetry model and its extensions

Construct the Lagrangian according to the following conditions:
- Gauge invariance, global symmetry, supersymmetry,
- Yukawa coupling, $H^\dagger=H$
- and then deduce Feynman rules, mixing of particles, ...

The generated physical model for system use include FORTAN77
- source to calculate mixing matrices if needed
To prepare phenomenological model

- List of all the non-elementary particles and their quantum numbers
- Standard Model input without QCD
- Construct all the possible interaction vertices from all the particles by applying the following conditions: \( H^\dagger = H \), Lorentz invariance, CP invariance, P invariance, C invariance, Isospin invariance, Baryon number conservation, ...
- The generated physical model for FDC system
- Latex version of the genearted physical model
  - List of all the particles
  - List of all the propagators
  - List of all the interaction vertices

**FIG.3: System flow chart for physical process**
Physical Process

Input for a physical process: physical model can be chosen
Many options, histograms, scatter plots can be demanded.

Generate Feynman Diagram

Manipulate amplitudes for each diagram and generate FORTRAN77
source for calculation of amplitudes and their square
FORTRAN77 source to do likelihood fitting for all the free parameters
that were introduced in physical model

Find and properly treat all the resonance, t-channel
singularities, ...
and generate FORTRAN77 source for phase space integral

Control flag and parameters files
generated by FDC which can be
changed later by users:
flag.inp, amtable.inp,
fpara.inp, reson.inp

Users should prepare two files:
pdata1.dat –
experiment events data file
pdata1.mc -
phase space monte carlo event
file

Compile FORTRAN77 programs and run 'fit' for
likelihood fitting

Output: mplot.info, pep.res, mplot.hbook,
dplot.hbook
To automatically construct the Lagrangian and deduce the Feynman rules for SM, MSSM

From a simple and easy understanding input. Input and Output can be viewed on http://v-www.ihep.ac.cn/ wjx/

Advantages:

Easy to change soft-breaking terms ....
Easy to change global symmetry
Easy to add more matter fields
Easy to switch to different gauge
Easy to choose different parameterization scheme
Automatically phase space treatment

It was presented at AIHENP96 and many improvements had been made.

The program do analysis each Feynman diagram and look for:

- t-channel peaks (calculate $t_{\text{min}}$, $t_{\text{max}}$)
- s-channel peaks (calculate $s_{\text{min}}$, $s_{\text{max}}$)
- sub-kinematics arrangement,
- next sub-kinematics, ....

To generate Fortran source for these arrangement, and each sub-kinematics located in a sub-range. Sub-range divided by behave of Denominator of each diagram.
FDC-PWA: Powerful Tool

- To work with high spin states (0, 1/2, 1, 3/2, 2, 5/2, 3, 7/2, 4, 9/2) and to construct effective Lagrangians.

- The expression of the effective interaction vertices and the propagators for the high spin states are quite lengthy.

- The related amplitudes and amplitude squares are complicated.

- There are many free parameters in the effective Lagrangian and these parameters will be fixed when the generated program is used to do Likelihood fitting of experimental data.

- To generate a complete set of the Fortran sources to do the partial wave analysis on experimental data.
To do Partial Wave Analysis by using FDC-PWA

To use following command in FDC-PWA to do the job

- gmodel
- diag
- amp
- kine
- cd fort
- make
- fit
2. The Rule to Construct Effective Lagrangian For PWA

- Lorentz Invariance
- C-parity conservation
- P-parity conservation
- CP conservation
- $H=H$
- $\ldots\ldots$ Decay

The coefficients of all the independent terms are constant

The Input is a list of all related particles.

The output is all interaction vertices

Each Coefficient has independent phase factor

Each Propagator has suppression factor
FDC-NRQCD

The method to calculate heavy quarkonium production and decay has been built in FDC

SM+heavy-quarkonium

http://v-www.ihep.ac.cn/ wjx/
MSSM has been built in FDC and all the possible two particle decay channels of all the possible particles are calculated.

http://v-www.ihep.ac.cn/ wjx/
The way to manipulate the amplitude

Two way for amplitude square calculation:
One is directly amplitude square.
the other is numerical amplitude and the square.
For higher order tree part (real gluon or photon emition)

It usually contains soft and collinear divergence and can not be calculated numerically. two-cutoff method in phase space (B. W. Harris and J. F. Owens, Phys. Rev. D65, 094032 (2002)) are realized in our program.

- Parton distribution functions are proper used in the program.
- The higher-order tree are divided into two part. The part with soft or/and collinear divergence is plused into virtual correction part. And the other part is calculated numerically.
- this method is realized in FDC.
For the scalar integral in one-loop calculation, we choose to perform the integration analytically in N-dimension regularization.

It is hard to find a general way to perform scalar integration in N-dimension for 4-point, or, 5-point, ... scalar integrals.

We need a general way to realize in computer program.
Testing Perturbative QCD on $J/\psi$ production and polarization

Brief Introduction to FDC project

Automatical way for One-loop calculation in FDC

General way

A scalar N-point function in $D$-dimension can be defined as

$$T_0^{(N)}(p_1, \ldots, p_{N-1}, m_0, m_1, \ldots, m_{N-1}) = \mu^{4-D} \int \frac{d^Dq}{(2\pi)^D} \frac{1}{N_0 \ldots N_{N-1}},$$

where $N_n = (q + p_n)^2 - m_n^2 + i\epsilon$, $n = 0, \ldots, N - 1$.

According to S. Dittmaier: Nucl. Phys. B675,447 (2003), the IR singularities part can be expressed as sum of a few 3-point with IRS

$$T_0|(N)_{\text{sing}} = \sum_{n=0}^{N-1} \sum_{k=0}^{N-1} A_{nk} C_0(p_0, \ldots, p_k, m_n, m_{n+1}, m_k).$$

We can evaluate the scalar integral by

$$T_0^D = T_0^\epsilon - T_0|^\epsilon_{\text{sing}} + T_0|^\epsilon_{\text{sing}}. \quad (2)$$

Where $T_0^\epsilon, T_0|^\epsilon_{\text{sing}}$ means to us $i\epsilon$ in the propagators to regularize singularities.
**i\epsilon-regularization**

- Let the N-dimension back to 4-dimension.
- to keep $i\epsilon$ in the propagators make the scalar integrals well defined.
- to do expansion on $i\epsilon$ in the final results will give an analytic expression of the result.
- This way is suitable to program and we realized it in FDC package.
Summary

- For B-factories: NRQCD at NLO of $\alpha_s$ and $\nu$ can well described $J/\psi$ production data. Strong constraint to the values of color-octect matrix element of $c\bar{c}(1S^8_0, 3P^8_j)$ to almost zero. The dominant part $c\bar{c}(3S^8_1)$ for hadron production is still there.

- For $J/\psi$ production in $\Upsilon$ decay, the LO prediction is one order in magnitude smaller than experimental measurement.

- The NLO results for $J/\psi$ production in $z^0$ decay is just half of experimental measurement.

- $c \rightarrow J/\psi$ fragmentation function is obtained at NLO level for the first time.

- The polarization problem for $J/\psi$ hadroproduction is still there even at QCD NLO.

- New Progress, ....
Thank you!
Testing Perturbative QCD on $J/\psi$ production and polarization

Summary


P. Pakhlov (Belle) (2004), hep-ex/0412041.


Y.-Q. Ma, Y.-J. Zhang, and K.-T. Chao, Phys. Rev. Lett. 102, 162002 (2009), 0812.5106.


