\[ \mathcal{L} = \frac{1}{4} F_{\mu \nu}(x) F^{\mu \nu}(x) + \bar{\psi}(x) \left( i \slashed{D} - m \right) \psi(x) \]
Outline

- Experimental Review
  - Jets at the Tevatron
  - Inclusive $b$ production at the Tevatron
  - $e^+e^- \rightarrow J/\psi + \eta_c$ as measured by Belle

- Theoretical Review
  - Quick review of NNLO QCD technique
  - Soft Collinear Effective Theory (SCET)
Tevatron: Run II

- Run IIa (2001-2005)
- Run IIb (2006-2009)

\[ \int \text{Luminosity} \]

- \( \sim 0.1 \text{ fb}^{-1} \) \( \sqrt{s} = 1.8 \text{ TeV} \)
- \( \sim 1 \text{ fb}^{-1} \) \( \sqrt{s} = 1.96 \text{ TeV} \)
- \( \sim 4 - 8 \text{ fb}^{-1} \)
Jets at the Tevatron

Almost 500 pb$^{-1}$ written to tape

between about 350 pb$^{-1}$ and 150 pb$^{-1}$ analyzed
Jets at the Tevatron: what’s new

- Detectors Upgraded
- Increase center-of-mass energy ($1.8 \rightarrow 1.96 \text{ TeV}$)
  - Increased cross section $2 \times$ at 400 GeV and $5 \times$ at 600 GeV
- Higher $E_T$
- New Jet cone algorithm
- Infrared & Collinear safe
CDF Run II Preliminary
Integrated $L = 177 \text{ pb}^{-1}$
$0.1 < |\eta_{\text{Det}}| < 0.7$
JetClu Cone $R = 0.7$

$\frac{d^2 \sigma}{dE_T \ d\eta} \ (\text{nb/GeV})$

- Run II Data
- +/- Systematic Uncertainty
- NLO pQCD Uncertainty (CTEQ 6.1)
Run I data exhibited an excess at large $E_T$ which could be explained by an enhanced gluon density at high $x$: fit by CTEQ6.1.
kT clustering algorithm
DØ Data
Talk by B. Hirosky
Inclusive Jet Cross Section in Different Rapidity Bins

Large rapidity put constraints on gluon content of the proton at high $x$ values.
Central region $|y_{\text{jet}}| < 0.5$, data sample $\sim 143$ pb$^{-1}$

Run II midpoint algorithm

Agreement within uncertainties with NLO/CTEQ6M

Jet Energy Scale ($< 7\%$) dominant error on measurement
Jets at the Tevatron

- First results: good agreement between theory and data
- Explore high $P_T$ and $M_{jj}$ regions over wide range of rapidities
  - Constrain high-$x$ gluon contributions
  - Direct searches for new physics
- Measurements will become increasingly precise
- Tevatron is essential for
  - Precision measurements & searches for new physics
  - Expectations for LHC
b-production at the Tevatron
b-quark production at the Tevatron 1993


“...the next-to-leading QCD calculation tends to underestimate the inclusive b-quark cross section.”
DØ weighs in...

By 2000 excess is established


DØ weighs in...
...and a Mystery


- b-jets: hadronic jets carrying b flavor
- Directly observable
- Reduces model dependency

Get to this in a moment
More CDF Results

CDF (Phys. Rev. D65, 052005 (2002))

- data/theory
  $2.9 \pm 0.2 \text{(stat } \oplus \text{syst}_{p_T}) \pm 0.4 \text{(syst}_f \text{c})$

- does not include theory uncertainty

- Model dependence
  Non-pert. Peterson fragmentation func.

- Information on hadronization $b \rightarrow B$
New Theory Analysis

\[ pp \rightarrow B^+ + X, \ \sqrt{s} = 1.8 \text{ TeV, } y < 1 \]
dashed: \( \mu_R = \mu_F = \mu_0 = \sqrt{m_b^2 + p_T^2} \)
solid: \( \frac{\mu_0}{2} < \mu_R, \mu_F < 2\mu_0 \)

CTEQ5M1
\( m_b = 4.75 \text{ GeV} \)
\( f(b \rightarrow B) = 0.375 \)
dotted: Peterson,
\( \epsilon = 0.006 \)

\( \Phi \)

\( \Phi \)

O: CDF data
Theory: FONLL with N=2 fit

- data/theory
- 1.7 \pm 0.5(\text{expt}) \pm 0.5(\text{th})
- does include theory uncertainty
- Change due to fragmentation function!
Fragmentation Function

Fit fragmentation function to LEP data

- Use the same theory ingredients as in b-production
- including NLO and NLL
- b-production is most sensitive to the $N=3,4,5$ moments
CDF Run II Preliminary Data
\( \sqrt{s} = 1.96 \text{ TeV} \)

\[ p\bar{p} \rightarrow H_b \rightarrow J/\psi \]

|y(J/ψ)| < 0.6

Points: CDF
Curves: FONLL

\[ \sigma(p\bar{p} \rightarrow H_b \rightarrow J/\psi; P_\perp > 1.25, |y| < 0.6) \]

\[ \sigma_{\text{CDF}} = 19.9^{+3.8}_{-3.2} \text{ (stat + syst) nb} \]

\[ \sigma_{\text{FONLL}} = 19.0^{+8.4}_{-6.0} \text{ nb} \]

\[ \sigma(p\bar{p} \rightarrow H_bX; P_\perp > 0, |y| < 0.6) \times B(H_b \rightarrow J/\psi) \]

\[ \sigma_{\text{CDF}} = 24.5^{+4.7}_{-3.9} \text{ (stat + syst) nb} \]

\[ \sigma_{\text{FONLL}} = 22.9^{+9.5}_{-6.8} \text{ nb} \]

\[ \sigma(p\bar{p} \rightarrow bX; P_\perp > 0, |y| < 1.0) \]

\[ \sigma_{b}^{\text{CDF}} (|y| < 1) = 29.4^{+6.2}_{-5.4} \text{ (stat + syst) \mu b} \]

\[ \sigma_{b}^{\text{FONLL}} (|y| < 1) = 23.6^{+11.9}_{-7.6} \text{ \mu b} \]

Excellent Agreement!

Why is agreement so good?

- Improved determination of fragmentation function from LEP data
- New pdf determinations from data increase theory cross section
- Run II CDF data is about 30% lower than Run I data

Phenomenological input extremely important
Run II analysis in progress

- Both CDF and DO have b-jet analysis in progress
- CDF and DO also looking at di-jet production with b-tagging
  - study b-jet production mechanism and di-jet mass
- A lot more data coming: 400 pb\(^{-1}\) collected and by summer 2006 expect 1.5 fb\(^{-1}\)

Can theory keep up?!?!!
Double Charmonium Production in $e^+e^-$ collisions measured by Belle

Talk by T. Ziegler

- 140 fb$^{-1}$ on-resonance
- 15 fb$^{-1}$ off-resonance
- 155 fb$^{-1}$ total
set $\ast$ to

---

set $\ast$ to 90\% C.L.

upper limits

<table>
<thead>
<tr>
<th>State</th>
<th>$M_{\text{recoil}}$</th>
<th>$N_{\text{evt}}$</th>
<th>$\sigma$</th>
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</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>$2.972 \pm 0.007$</td>
<td>$235 \pm 26$</td>
<td>10.7</td>
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<tr>
<td>$J/\psi$</td>
<td>Fixed @ PDG</td>
<td>$-14 \pm 20$</td>
<td>$\ast$</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>$3.407 \pm 0.011$</td>
<td>$89 \pm 24$</td>
<td>3.8</td>
</tr>
<tr>
<td>$\chi_{c1} + \chi_{c2}$</td>
<td>Fixed @ PDG</td>
<td>$10 \pm 27$</td>
<td>$\ast$</td>
</tr>
<tr>
<td>$\eta_c(2S)$</td>
<td>$3.630 \pm 0.008$</td>
<td>$164 \pm 30$</td>
<td>6.0</td>
</tr>
<tr>
<td>$\Psi(2S)$</td>
<td>Fixed @ PDG</td>
<td>$-26 \pm 29$</td>
<td>$\ast$</td>
</tr>
</tbody>
</table>

$\ast$ Masses fixed at PDG value
Comparison to Theory


<table>
<thead>
<tr>
<th>$H_2 \backslash H_1$</th>
<th>$J/\psi$</th>
<th>$\psi(2S)$</th>
<th>$h_c(1P)$</th>
<th>$\psi_1(1D)$</th>
<th>$\psi_2(1D)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>2.31 ± 1.09</td>
<td>0.96 ± 0.45</td>
<td>0</td>
<td>0.052 ± 0.021</td>
<td>1.04 ± 0.23</td>
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<tr>
<td>$\eta_c(2S)$</td>
<td>0.96 ± 0.45</td>
<td>0.40 ± 0.19</td>
<td>0</td>
<td>0.022 ± 0.009</td>
<td>0.43 ± 0.09</td>
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<tr>
<td>$\chi_{c0}(1P)$</td>
<td>2.28 ± 1.03</td>
<td>0.95 ± 0.43</td>
<td>0.053 ± 0.019</td>
<td></td>
<td></td>
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<tr>
<td>$\chi_{c1}(1P)$</td>
<td>0.47 ± 0.16</td>
<td>0.19 ± 0.07</td>
<td>0.258 ± 0.064</td>
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<tr>
<td>$\chi_{c2}(1P)$</td>
<td>0.59 ± 0.13</td>
<td>0.25 ± 0.05</td>
<td>0.017 ± 0.002</td>
<td></td>
<td></td>
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<tr>
<td>$\eta_{c2}(1D)$</td>
<td>0.27 ± 0.05</td>
<td>0.11 ± 0.02</td>
<td></td>
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</tr>
</tbody>
</table>

**Belle Data**

$(c\bar{c})_{\text{res}}$  $\sigma_{\text{Born}} \times B(c\bar{c})_{\text{res}} \rightarrow > 2 \text{ charged [fb]}$

<table>
<thead>
<tr>
<th></th>
<th>$J/\psi$</th>
<th>$\psi(2s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta_c$</td>
<td>25.6 ± 2.8 ± 3.4</td>
<td>16.3 ± 4.6 ± 3.9</td>
</tr>
<tr>
<td>$J/\Psi$</td>
<td>&lt; 9.1</td>
<td>&lt; 16.9</td>
</tr>
<tr>
<td>$\chi_{c0}$</td>
<td>6.4 ± 1.7 ± 1.0</td>
<td>12.5 ± 3.8 ± 3.1</td>
</tr>
<tr>
<td>$\chi_{c1} + \chi_{c2}$</td>
<td>&lt; 5.3</td>
<td>&lt; 8.6</td>
</tr>
<tr>
<td>$\eta_c(2S)$</td>
<td>16.5 ± 1.7 ± 0.4</td>
<td>16.3 ± 4.6 ± 3.9</td>
</tr>
<tr>
<td>$\Psi(2S)$</td>
<td>&lt; 9.1</td>
<td>&lt; 16.</td>
</tr>
</tbody>
</table>

- **Factor of 10 discrepancy!!**
- **Extra th. errors ~ 60%**
- **Relativistic corrections not under control**
Double Charmonium Production

- Exclusive double charmonium exhibits a remarkable factor of 10 discrepancy between Belle data and theory.
- Data is quality is very good with errors on $e^+e^- \rightarrow J/\psi + \eta_c$ at $\sim 15\%$.
- Theoretical errors need to be brought under control.
  - Understand relativistic corrections.
- Belle has more data.
  - Angular analysis.
  - Inclusive data: $e^+e^- \rightarrow J/\psi + c\bar{c}$.
Theory Overview

- New Techniques For higher order QCD calculations
- Soft Collinear Effective Theory

\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x) + \bar{\psi}(x)(iD - m)\psi(x) \]
QCD at NNLO


“...the Tevatron and LHC physics programs require NNLO calculations for differential distributions in kinematic variables; knowledge of inclusive rates is insufficient.”

Process considered: $h_1 + h_2 \rightarrow V + X$

$V$: vector boson ($W, Z, \gamma^*$)

$X$: any number of additional hadrons

Differential CS $\frac{d\sigma^V}{dY} = \sum_{ab} \int_1^{\sqrt{\tau}e^Y} \int_0^{\sqrt{\tau}e^{-Y}} dx_1 dx_2 f_a(h_1)(x_1) f_b(h_2)(x_2) \frac{d\sigma^V}{dY}(x_1, x_2)$

Calculated to NNLO: $\frac{d\sigma^V_{ab}}{dY} = \frac{1}{2s} \int d\Pi f \|M_{ab \rightarrow V+X}\|^2 \delta\left(\frac{p_V \cdot p_1}{p_V \cdot p_2} - u\right)$

Requires a new calculation technique
Run I Result

\[ p\bar{p} \rightarrow (Z,\gamma^*)+X \]

**Comparison to Run I CDF data**

- 3.9% normalization error to data
- 4 – 5% difference between different PDFs
- Approximate NNLO running of PDFs
Run II prediction

- Scale uncertainty at NNLO $\approx 0.3 - 0.7\%$ !!!!
- Approximate NNLO running of PDFs
- Full NNLO running now available

QCD at higher orders

- New Technique allows for the calculation of NNLO differential distributions in hadronic collisions: **Unprecedented!**

- Precision calculations with errors $O(1\%)$

- Compare to precision data from Tevatron Run II and LHC

- Interest from string theory community: *Perturbative gauge theory as a string theory in twistor space*, E. Witten hep-th/0312171
Soft Collinear Effective Theory
Soft-Collinear Effective Theory: An Overview
Bauer, Fleming, Luke, Pirjol, Stewart

SCET is: Effective theory of a highly energetic, approximately massless particle interacting with a soft background

Expansion in a small parameter $\lambda \sim \frac{\Lambda_{\text{QCD}}}{Q}$

Make an Analogy with HQET

Expansion in: $\frac{\Lambda_{\text{QCD}}}{M}$

Energetic: $Q \gg \Lambda_{\text{QCD}}$

Light-like: $n^\mu = (1, 0, 0, 1)$

Residual Momentum: $k \sim \Lambda_{\text{QCD}}$

Heavy: $M \gg \Lambda_{\text{QCD}}$

Static: $v^\mu = (1, 0, 0, 0)$

Residual Momentum: $k \sim \Lambda_{\text{QCD}}$

$p^\mu = Qn^\mu + k^\mu$

Brown Muck
Soft-Collinear Effective Theory

Analogy with HQET breaks down:

**HQET**

\[ p'^\mu = m z v^\mu \]

\[ p^\mu = m v^\mu \]

\[ q^\mu = m (1 - z) v^\mu \]

\[ q^2 = m^2 (1 - z)^2 \]

Not Allowed!!!

**SCET**

**O.K.**

\[ p^\mu = \frac{1}{2} Q n^\mu \]

\[ p'^\mu = \frac{1}{2} z Q n^\mu \]

\[ q^\mu = \frac{1}{2} (1 - z) Q n^\mu \]

\[ q^2 = 0 \]
SCET Lagrangian

QCD

Collinear

Soft

\[ \psi(x) \rightarrow \psi_s(x) + \xi_n(x) \]

\[ A^\mu(x) \rightarrow A^\mu_s(x) + A^\mu_n(x) \]

\[ L_c = \bar{\xi}_n \left\{ i n \cdot D_c + i \slashed{P}_c \cdot \frac{1}{i \bar{n} \cdot D_c} i \slashed{P}_c + (g n \cdot A_s) \right\} \frac{\bar{\psi}}{2} \xi_n \]

\[ L_s = \bar{\psi}_s i \slashed{D}_s \psi_s \]

- **Collinear sector:** QCD in boosted frame
- **Soft sector:** QCD
- **Coupled through a single term**
Symmetries

- **Separate collinear and soft gauge symmetries**

- Powerful restriction on the form of operators allowed

- Soft fields act as a background field to collinear fields

- Any gauge symmetry connecting soft to collinear introduces a large scale

- **Global $U(1)$ helicity spin symmetry**

- Reparameterization invariance which is a consequence of Lorentz invariance of QCD

- Relates operators
Currents

Two important points:

1. Introduce a collinear Wilson line: \( W = P \exp \left( ig \int_{-\infty}^{x} ds \: \bar{n} \cdot A_n(s\bar{n}) \right) \)

\[ W^\dagger \xi_n(x) \rightarrow W^\dagger \xi_n(x) \quad \text{under collinear gauge transformations} \]

2. Wilson coefficients are a function of the large light-cone component of the collinear momentum

\[ C(\bar{n} \cdot P) \quad \text{Hard-Collinear Factorization in SCET} \]

Example: Energetic up quark produced in \( b \rightarrow u\ell\nu \) decays (leading order in \( \lambda \) )

\[ u(p_u) \Gamma u(p_b) \rightarrow \sum \mathcal{C}_i(M) \bar{\xi}_{n,p} \Gamma_i h_{\nu} \]

\[ \bar{u}(p_u) \Gamma u(p_b) \rightarrow \sum \xi_{n,p} W^\dagger C_i(\bar{n} \cdot \vec{P}_{\text{op}}) \Gamma_i h_{\nu} \]
Heavy-Light Current: $b \rightarrow u$

Origin of the collinear Wilson line

- Leading order in $\alpha_s$

- Higher orders

\[
\begin{align*}
&\text{Leading order in } \alpha_s \\
&\text{Higher orders}
\end{align*}
\]
Decoupling Collinear & Soft

- **Decouple** Soft from Collinear in the Lagrangian

1) **Soft Wilson Line**

\[ Y(x) = \text{Pexp} \left( ig \int_{-\infty}^{x} ds \, n \cdot A_s(ns) \right) \]

2) **Field Redefinition**

\[ \xi_n(x) = Y(x) \xi_n^{(0)}(x) \]

- Complicates vertex: For our Heavy-Light example

\[ \bar{\xi}_n W \Gamma h_v \rightarrow \bar{\xi}_n^{(0)} W^{(0)} \Gamma Y^\dag h_v \]

Origin of Soft-Collinear Factorization in SCET
Soft-Collinear Effective Theory:

What have we learned:
- SCET: EFT of collinear d.o.f. coupled to soft d.o.f.
- Powerful **gauge symmetries** constrain operators
- **Decoupling** via field redefinition

What is it good for?
- SCET is useful for understanding:
  - **Factorization**: Obtained from field redefinition and simple algebraic manipulations
  - **Summation of Logarithms** at the edges of phase space: Obtained from Renormalization Group Equations (RGEs)
  - **Systematic Power Corrections in** $\lambda$ : Turn the crank
An Example: Factorization in DIS

- **OPE**: integrate out final state below the scale $Q^2$ by **matching** onto **SCET**

\[
P_x^2 \approx \frac{Q^2}{x(1-x)}
\]

- **Match onto SCET operators**

\[
\mathcal{O}(\omega_1, \omega_2) = \left[ \bar{\chi}_{n,\omega_1} \frac{\not{p}}{2} \chi_{n,\omega_2} \right]
\]

Wilson coefficient depends on large light-cone momentum in hard scattering: Standard Convolution form of cross section

\[
T^{\text{eff}}_{\mu\nu} \sim \int d\omega_1 d\omega_2 \, C_{\mu\nu}(\omega_1, \omega_2) \, \mathcal{O}(\omega_1, \omega_2)
\]

- **Fix $C_{\mu\nu}(\omega_1, \omega_2)$ by forcing** $T_{\mu\nu} = T^{\text{eff}}_{\mu\nu}$
Factorization in DIS

- Decouple soft from Collinear $\chi_{n,\omega} \rightarrow Y \chi_{n,\omega}^{(0)}$

\[
\left[\bar{\chi}_{n,\omega_1} \frac{\not{\!p}}{2} \chi_{n,\omega_2}\right] \rightarrow \left[\bar{\chi}_{n,\omega_1} \frac{\not{\!p}}{2} Y^+ Y \chi_{n,\omega_2}^{(0)}\right]
\]

- Parton distributions in SCET

\[
\frac{1}{4} \sum_{\text{spin}} \langle p_n | \bar{\chi}_{n,\omega} \not{\!p} \chi_{n,\omega'} | p_n \rangle = \int_0^1 d\xi \delta(\omega_-) \delta\left(\frac{\omega + 2\bar{n} \cdot p - \xi}{2\bar{n} \cdot p}\right) f_{i/p}(\xi)
\]

- Factored form

\[
d\sigma \sim \int \frac{d\xi}{\xi} H\left(\frac{\xi}{x}; \mu\right) f_{i/p}(\xi; \mu)
\]
Operator Evolution Equations

Operator running

\[ \mu \frac{d}{d\mu} \mathcal{O}(\omega_1, \omega_2; \mu) = \int dx dy \, \gamma(\omega_1, \omega_2, x, y; \mu) \mathcal{O}(x, y; \mu) \]

Different momentum constraints give different running:

\[ \omega_1 = \omega_2 \rightarrow \text{DGLAP or } \omega_1 + \omega_2 = \text{Const.} \rightarrow \text{BL} \]
Some More Applications

- Color Suppressed $B \to D\pi$ Decays
- $J/\psi$ Production at Belle & Babar
\[ B \rightarrow D \pi \]

**Mantry, Pirjol, Stewart**

- **"Tree"**
  - \( \bar{B}^0 \rightarrow D^+\pi^- \)
  - \( B^- \rightarrow D^0\pi^- \)

- **"Color suppressed"**
  - \( B^- \rightarrow D^0\pi^- \)
  - \( \bar{B}^0 \rightarrow D^0\pi^0 \)
  - \( \bar{B}^0 \rightarrow D^0\pi^0 \)

- **"Exchange"**
  - \( \bar{B}^0 \rightarrow D^+\pi^- \)
  - \( \frac{1}{N_c} \)
  - \( \frac{1}{N_c} \)

**Observed 2001**

\[ N_C^0 \]
Color- Suppressed decays are indeed suppressed

But

Large is $N_c$ not very predictive

How about using SCET & HQET?
Possible to derive a factorization formula in SCET

Complicated because SCET operators are suppressed

\[ \lambda \sim \frac{\Lambda_{\text{QCD}}}{E_\pi} \sim 0.2 \]

\[
A_{00}^{D(*)} = N_0^{(*)} \int dx \ dz \ dk_1^+ \ dk_2^+ \ T^{(i)}(z) \ J^{(i)}(z, x, k_1^+, k_2^+) \ S^{(i)}(k_1^+, k_2^+) \ \phi_M(x)
\]

\[ + A_{\text{long}}^{D(*)} M \]

\[ Q^2 \gg Q\Lambda \gg \Lambda^2 \]

New non-perturbative function: \( S^{(i)}(k_1^+, k_2^+) \)
$S^{(i)}(k_1^+, k_2^+) = \langle D^{(*)} | O_s | B \rangle$ is the lightcone distribution function for the spectator quarks in the $B$ and $D$

- It is universal for a particular set of directions $\{v, v', n\}$
  - Will be the same for $D$ and $D^*$

- It is a complex function: large strong phases are natural
Comparison to Date

- **Universality for $D$ and $D^*$**
  - **Branching ratio**
    \[ Br(D^0\pi^0) = (0.29 \pm 0.03) \times 10^{-3} \]
    \[ Br(D^{*0}\pi^0) = (0.26 \pm 0.05) \times 10^{-3} \]
  - **Strong Phase**
    \[ \delta(D\pi) = 30.4 \pm 4.8^\circ \]
    \[ \delta(D^{*}\pi) = 31.0 \pm 5.0^\circ \]

- **Predict**
  \[ r_{00}^\rho = \frac{A(\bar{B}^0 \to D^{*0}\rho^0)}{A(\bar{B}^0 \to D^0\rho^0)} = 1 \]

- **Explain naturally**
  \[ |r^{D\pi}| = \frac{|A(\bar{B}^0 \to D^+\pi^-)|}{|A(B^- \to D^0\pi^-)|} = 0.77 \pm 0.05, \quad |r^{D\rho}| = 0.80 \pm 0.09 \]

**SCET Predicts**

\[ r^{DM} = 1 - \frac{16\pi\alpha_s m_D}{9(m_B + m_D)} \frac{\langle x^{-1}\rangle_M}{\xi(w_{max})} \frac{s_{\text{eff}}}{E_M} \]

Natural sized parameter fits the data: \( s_{\text{eff}} \simeq (430 \text{ MeV})e^{i44^\circ} \)
One More Application

$\J/\psi$ Production at Belle & Babar
$e^+ e^- \rightarrow J/\psi + X \ (\sqrt{s} = 10.6 \text{ GeV})$

Angular distribution

$$\frac{d\sigma}{dp\ d\cos\theta} = S(p)(1 + A(p)\cos^2\theta)$$

$A(p)$

$\sigma_{tot} (\text{pb})$

<table>
<thead>
<tr>
<th></th>
<th>$p \lesssim 3.5$ GeV</th>
<th>$p \gtrsim 3.5$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Babar</td>
<td>$2.52 \pm 0.21 \pm 0.21$</td>
<td>$0.05 \pm 0.22$</td>
</tr>
<tr>
<td>Belle</td>
<td>$1.47 \pm 0.10 \pm 0.13$</td>
<td>$0.7 \pm 0.3$</td>
</tr>
</tbody>
</table>

$\frac{\sigma(e^+e^- \rightarrow J/\psi c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12$
NRQCD

**Color Singlet**

\[ \sigma = 0.73 \text{ pb} \]

\[ \sigma = 0.20 \text{ pb} \]

**Color Octet**

\[ \sigma = 0.79 \text{ pb} \]

\[ \sigma = 0.08 \text{ pb} \]

\[ \sigma_{\text{tot}}^{(1)} = 0.93 \text{ pb} + \sigma_{\text{tot}}^{(8)} = 0.87 \text{ pb} \rightarrow \sigma_{\text{tot}} = 1.8 \text{ pb} \]

\[ \frac{\sigma(e^+e^- \rightarrow J/\psi \ c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi \ X)} = 0.1 \]
Differential Distribution

\[ \rightarrow d\sigma \propto \delta(1 - z_p) \quad z_p = \frac{p}{p_{\text{max}}} \]

Theory

\[ e^+ e^- \rightarrow J/\psi + g g \]

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

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

Babar

\[ \text{Entries / 500 MeV/c} \]

\[ p^* (\text{GeV/c}) \]
SCET & NRQCD

In the Endpoint region:
- use **SCET** for the fast & soft d.o.f.
- use **NRQCD** for the heavy quark-antiquark

+ crossed diagram

**c\bar{c}**

**collinear gluon**
Factorization

New factorization formula in the endpoint region:
(Similar to $B \to X_s \gamma$)

Nonperturbative shape function

$$\frac{d\sigma}{dz} \propto \int_z^1 d\xi \ S(\xi; \mu) J(\xi - z; \mu)$$

Jet function: perturbatively calculable in $\alpha_s \left( \sqrt{\frac{s}{m_c}} \Lambda_{QCD} \right)$

Shape function is universal

Used a simple model with 2 parameters: require moments to scale appropriately

Overall normalization includes color-octet matrix element
Not well determined

Sum logs using RGEs
Comparison to Babar Data


Endpoint

\[ z \gtrsim 0.7 \]
\[ p \gtrsim 2.57 \text{ GeV} \]
Comparison to Belle Data
SCET Summary

- Flavor of Soft Collinear Effective Theory
  - Theory of light-like particles interacting with a soft background
  - Derive factorization
  - Sum logarithms
  - Systematically treat power corrections

- Scope of applications is large
  - B decays, sub-leading pion form factor, event shapes, Quarkonium production and decay

- A very active field: more to come...
  - Watch for collider physics applications
Summary

- **Experiment**
  - Jets at the Tevatron: Precision Physics
  - Tevatron b-production: resolved
  - Double charmonium at Belle???

- **Theory**
  - New methods for high order QCD perturbation theory
  - Soft Collinear Effective Theory
Di-Jet Azimuthal Decorrelations

Talk by M. Begel

Sensitive to higher-order QCD radiation without explicitly measuring 3rd and 4th jets

- Di-Jets produced at LO in perturbation theory
  \[ \Delta \phi_{\text{dijet}} = \pi \]

- Soft radiations results in small decorrelations
  \[ \Delta \phi_{\text{dijet}} \sim \pi \]

- Hard radiation (\( k_\perp \) large) leads to large decorrelations
  \[ \frac{2\pi}{3} \leq \Delta \phi_{\text{dijet}} < \pi \]
Di-Jet Azimuthal Decorrelations

- LO: QCD calculation of three jet production $O(\alpha_s^3)$
- NLO: QCD calculation of four jet production $O(\alpha_s^4)$
An Example: Factorization in DIS

**Kinematics: Breit frame**

\[ q^\mu = Q (\bar{n}^\mu - n^\mu) / 2 \quad \text{with} \quad q^2 = -\frac{\bar{n} \cdot n}{2} Q^2 = -Q^2 \]

\[ x = \frac{Q^2}{2 p \cdot q} \]

\[ p^\mu = n^\mu \frac{Q}{2x} + \bar{n}^\mu x \frac{m_p^2}{2Q} + \mathcal{O} \left( \frac{m_p^2}{Q^2} \right) \]

\[ P_X^\mu = p^\mu + q^\mu \quad \text{with} \quad P_X^2 = \frac{Q^2}{x} (1 - x) + m_p^2 \]