Inclusive Production of Heavy Flavor and Quarkonium

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Purdue University, January 4, 2011

Heavy Flavor

heavy quark: $Q = b$ or c

charm hadrons:

$H_c = D^0, D^+, D_s^+,$ mesons

D^{*0}, D^{*+}, D_s^{*+}

$\Lambda_c^+, \ldots$ baryons

bottom hadrons:

$H_b = B^-, \overline{B}^0, B_s^0, B_c^-,$ mesons

$B^{*-}, \overline{B}^{*0}, B_s^{*0}, B_s^{*0}$

$\Lambda_b, \ldots$ baryons

Production of Heavy Flavor

Creation of the heavy quark

- What are the relevant parton processes?
- Can they be calculated using perturbative QCD?

Binding with light quarks to form heavy hadron

- Can it be parametrized by a few functions or (better yet) by a few constants?*
- Can they be measured in experiment or (better yet) calculated using QCD?

* Albert Einstein:
"Make everything as simple as possible, but not simpler."

Heavy Quark Cross Section

$$\sigma[b] = \sum_{H_b} \sigma[H_b]$$

- summed over heavy hadrons
- integrated over momentum
- calculable using perturbative QCD
  as power series in $\alpha_s(m_b)$
- calculated to NNLO

Differential Cross Section for *Specific* Heavy Hadron

Simple model

consistent with heavy quark cross section

$$d\sigma[H_b] = d\sigma[b] \times P_{b \to H_b}$$

$P_{b \to H_b}:$ probability for *b* to hadronize into H_b

assumed independent of process (e^+e^-, *ep*, *pp*, $p\bar{p}$)

independent of kinematics (p_T,*y*)

Differential Cross Section for *b* Quark

Leading Order: $\alpha_s^2(m_b)$

$q\bar{q} \rightarrow b\bar{b}$

$gg \rightarrow b\bar{b}$

NLO

Nason, Dawson, and Ellis 1989

NNLO

$q\bar{q}$, gq, $g\bar{q}$: complete

Korner, Merebashvili, & Rogal, Anastasios & Aybat, Kniehl et al, Czakon 2008

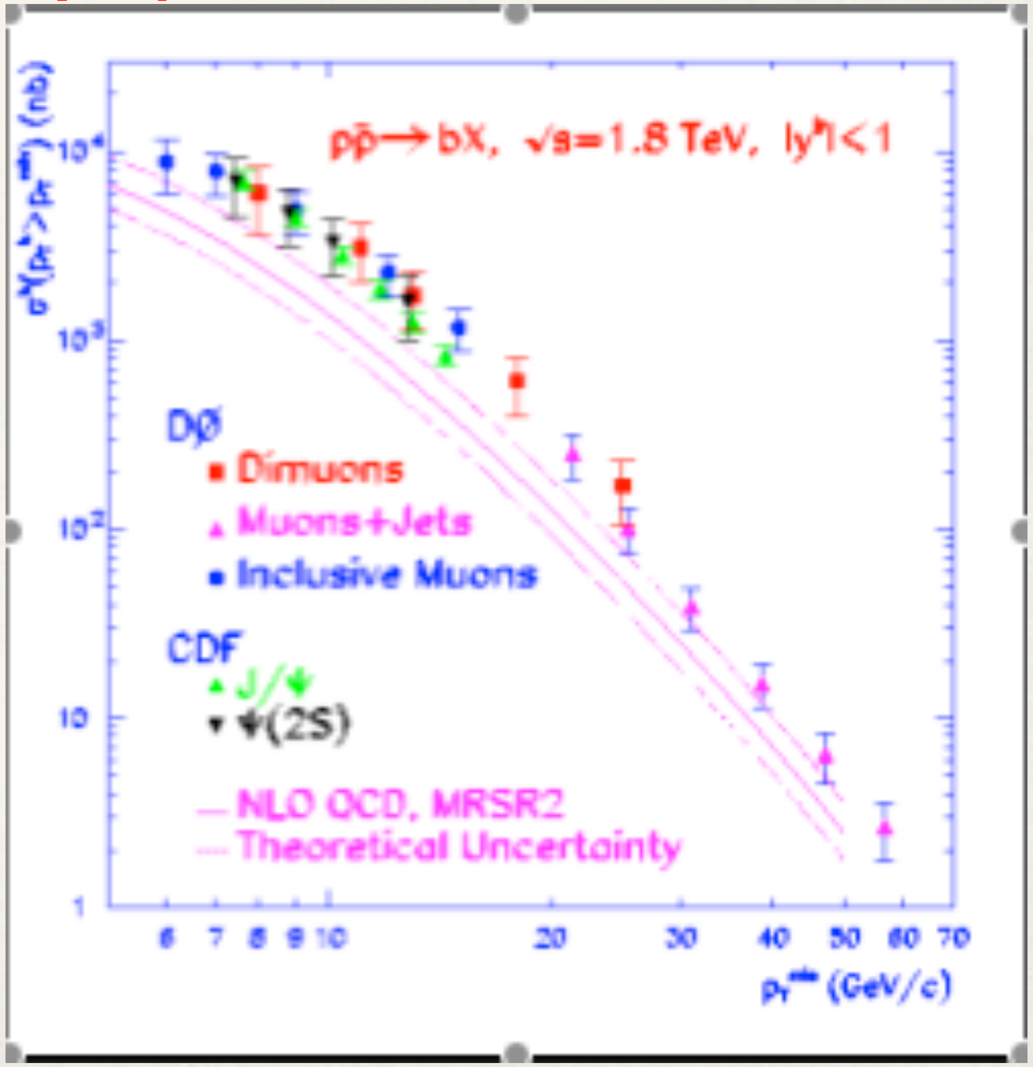
gg: only LO in $1/N_c$ or expansion in m_b^2/s

Heavy Quark Cross Section

Most reliable predictions are for highest possible energies:
Tevatron (and now LHC)

Predictions should be more reliable for bottom than charm

For many years, measurements of heavy quark cross section at the Tevatron were
.... consistent with theory for charm
.... systematically lower for bottom



Problem may be resolved by taking into account fragmentation

PQCD Factorization Theorem
for inclusive single-particle production

Collins & Soper 1982

Production of hadron with large transverse momentum is dominated by *fragmentation*

- hard scattering produces parton with larger momentum
- parton hadronizes into a jet that includes the hadron
- probability for hadron to carry fraction *z* of jet momentum is given by fragmentation function *D(z)*

PQCD Factorization Theorem

Collins & Soper 1982

Production of *b* hadron with large transverse momentum
is dominated by *fragmentation* of *b* quark or gluon

$$d\sigma[H_b(P)] = \int_0^1 dz\ d\hat{\sigma}[b(P/z)]\ D_{b\to H_b}(z) + \int_0^1 dz\ d\hat{\sigma}[g(P/z)]\ D_{g\to H_b}(z) + \mathcal{O}(m_b^4/p_T^4) + \mathcal{O}(\Lambda_{\rm QCD}^2/p_T^2)$$

- parton cross section $d\hat{\sigma}$
  calculate using PQCD, power series in $\alpha_s(p_T)$
- fragmentation functions $D_{i\to H}(z)$
  different for B, B^*, Λ_b, ...
  nonperturbative but universal
  determine from e^+e^- annihilation

J/ψ from b hadron decays

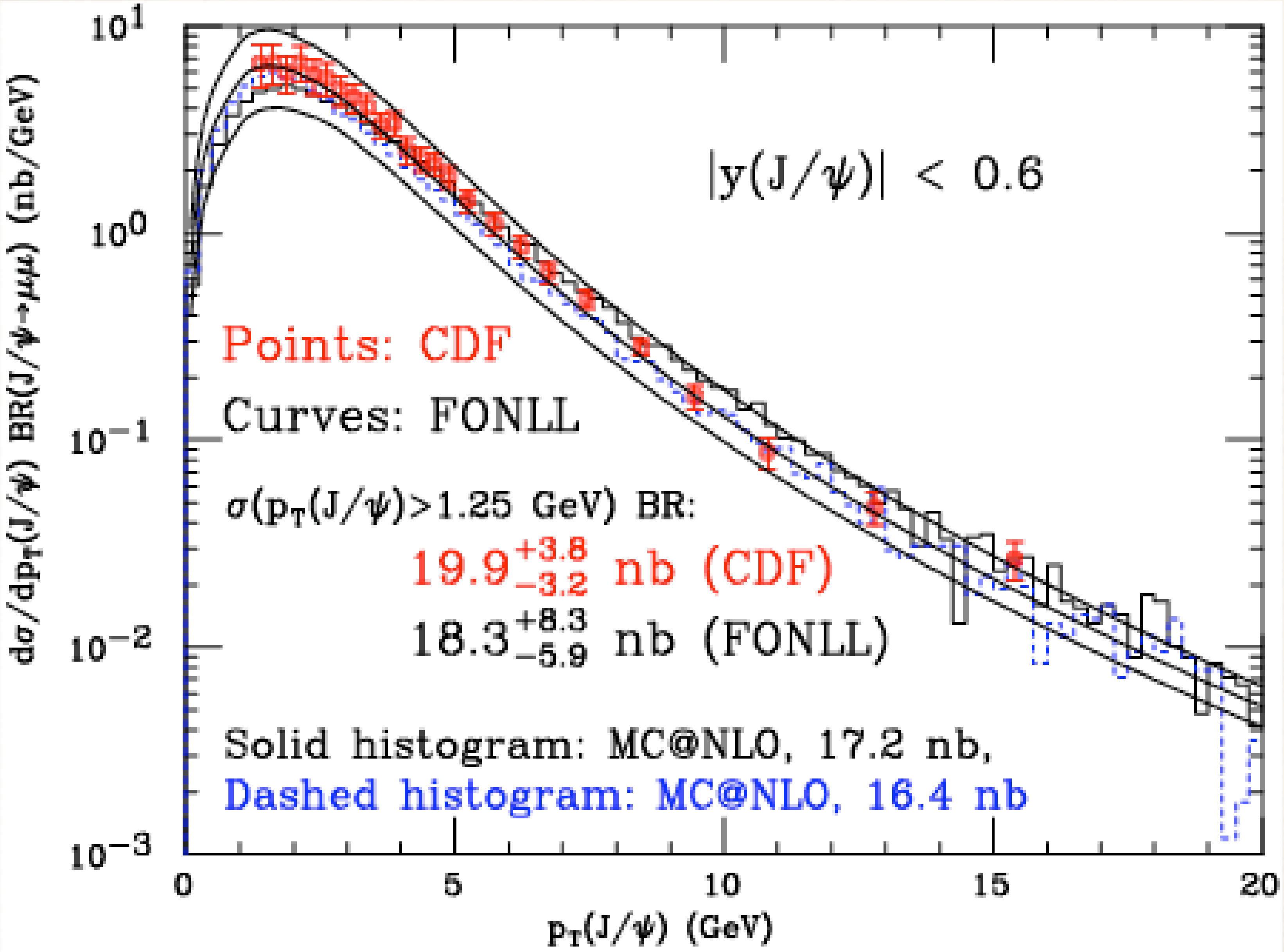
State-of-the-art analysis

- FONLL scheme
  at moderate p_T, Fixed Order (NLO) calculation
  at large p_T, fragmentation approximation
  with logarithms of p_T/m_b summed to
  Next-to-Leading-Log accuracy
  matching at intermediate p_T

- Nonperturbative inputs
  gluon and quark parton distributions
  fragmentation function $D(z)$ for b quark to H_b
  fit to data from LEP
  branching fraction and decay spectrum for H_b to J/ψ
  fit to data from Belle, Babar

J/ψ from *b* hadron decays at the Tevatron

- Cacciari, Frixione, Mangano, Nason, Ridolfi 2004



- Good agreement with the data
- Scale, mass and PDF uncertainties summed in quadrature

Heavy Quark Cross Section

Solution to the problem of the
b quark cross section at the Tevatron

- should be tested at the LHC
- should also apply to charm (but with larger errors)
- requires nonperturbative functions rather than constants*

* Albert Einstein:
"Make everything as simple as possible, but not simpler."

Production at Large Rapidity or x_F

Leading particle effect

enhancement of charm hadrons
whose light flavors coincide with constituents of colliding hadron
in forward direction of colliding hadron

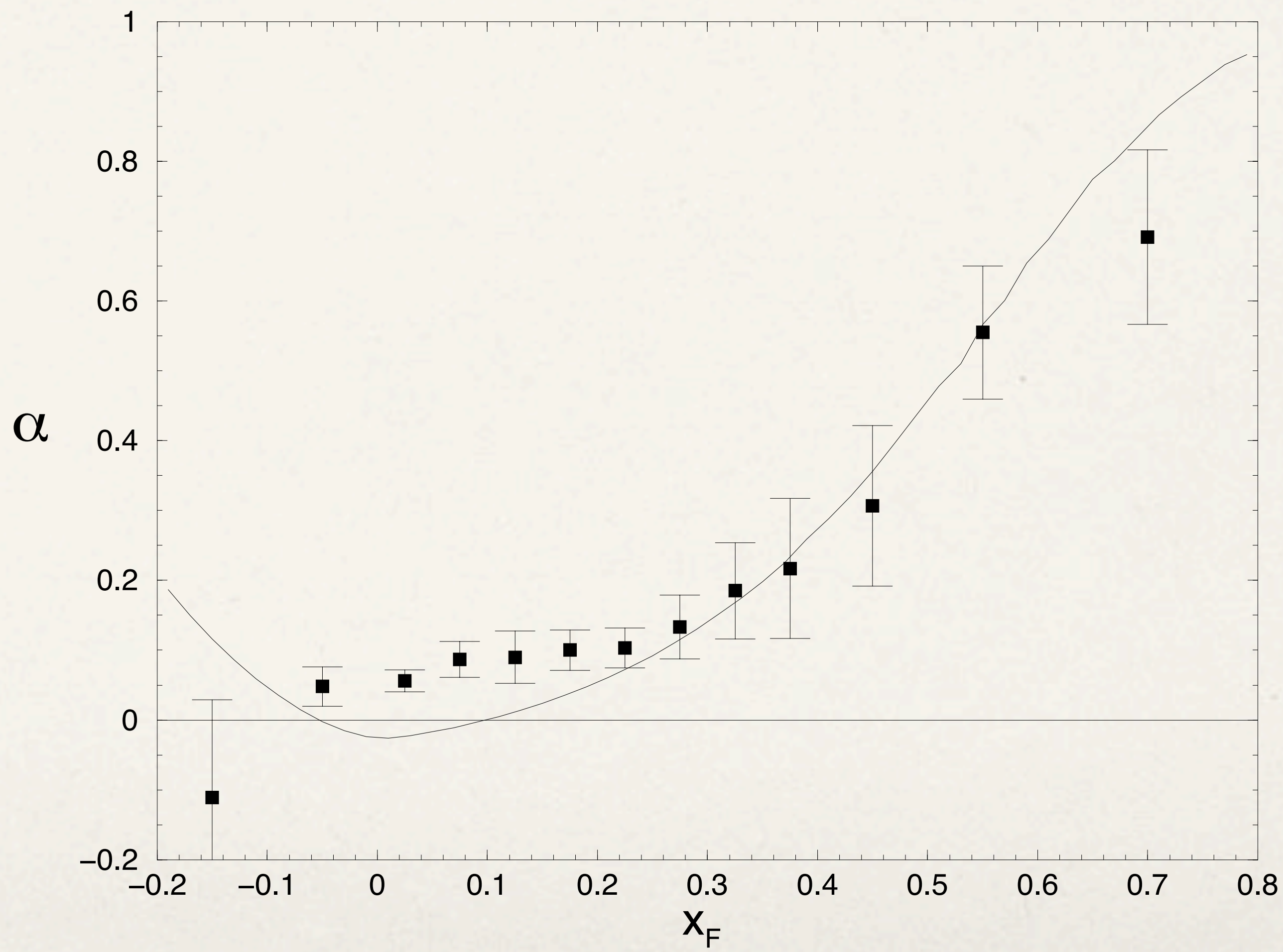
(e.g. enhancement of $\overline{D}^0 = \bar{c}u$, $D^- = \bar{c}d$
in forward direction of colliding proton = uud)

leads to dramatic asymmetries between charm hadrons
and their antiparticles

Production at Large x_F

charm asymmetry: $$\alpha = \frac{\sigma[D^+] - \sigma[D^-]}{\sigma[D^+] + \sigma[D^-]}$$

photoproduction
data from E791



Charm Asymmetries

Perturbative QCD asymmetries at NLO
but too small by order of magnitude

Pythia asymmetries too small with standard tunings
can be tuned to reproduce observed asymmetries

Recombination

$\bar{c}$ from hard scattering, q from proton remnant Kartvelishvili, Likhoded & Slabopitskii 1978

$\bar{c}$ and q from hard scattering Braaten, Jia & Mehen 2004

Intrinsic Charm

$\bar{c}$ and q from proton remnant Brodsky, Hoyer, Peterson & Sakai 1980

q from hard scattering, $\bar{c}$ from proton remnant Cuautle, Herrera & Magnea 1998

Light Quark Fragmentation de Deus & Duraes 2000

q from hard scattering, $\bar{c}$ from fragmentation of q

Production at Large Rapidity or x_F

- dramatic asymmetries
- no rigorous theory
- only models

  most involve adjustable functions

  exception: heavy quark recombination (Braaten, Jia & Mehen)

  involves adjustable constants (too simple?)
- to be tested by LHC-b, Alice?

Heavy Quarkonium

charmonium

$H_{c\bar{c}}$ = η_c, J/ψ, η_c', ψ' S-waves

χ_{c0}, χ_{c1}, χ_{c2} P-waves

bottomonium

$H_{b\bar{b}}$ = η_b, Υ, η_b', Υ', η_b'', Υ'' S-waves

χ_{c0}, χ_{c1}, χ_{c2}, χ_{c0}', χ_{c1}', χ_{c2}' P-waves

D-waves

B_c mesons

$H_{\bar{b}c}$ = B_c, B_c^*, ...

Production of Heavy Quarkonium

Creation of heavy quark pair

- What are the relevant parton processes?
- Can they be calculated using perturbative QCD?

Binding to form heavy quarkonium

- Can it be parametrized by a few functions or better yet by a few constants?*
- Can they be measured in experiments or better yet calculated using QCD?

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Production of Heavy Quarkonium

Creation of heavy quark pair?

Binding to form heavy quarkonium?

Theoretical developments

- Color-Singlet Model 1976-1981
- Color-Evaporation Model 1977
- Fragmentation Mechanism 1993
- NRQCD Factorization 1995
- $Q\bar{Q}$ Fragmentation 2010

Color-singlet Model

Ellis, Einhorn, Quigg 1976; Carlson and Suaya 1976; Kuhn 1980; Degrand, Toussaint 1980; Kuhn, Nussinov, Ruckl 1980; Wise 1980; Chang 1980; Baier, Ruckl 1981; Berger, Jones 1981

- $c\,\bar{c}$ is created by parton collisions with negligible relative momentum

- $c\,\bar{c}$ can bind into charmonium only if it is created in same color/angular momentum as in charmonium

  $\underline{1}\ {}^3S_1$ for J/ψ

  $\underline{1}\ {}^3P_J$ for χ_{cJ}

- probability that $c\,\bar{c}$ binds into charmonium is determined by wavefunction near origin

  $\propto R(0)$ for $J/\psi, \eta_c$

  $\propto R'(0)$ for χ_{cJ}, h_c

  one constant for each multiplet can be determined from annihilation decays:

  $J/\psi \to e^+ e^-$

  $\chi_{c0} \to \gamma\,\gamma$

Color Evaporation Model

Fritzsch 1977; Halzen 1977

- $c\,\bar{c}$ pair is created by parton collisions
  with invariant mass below $D\,\bar{D}$ threshold
  (between $2m_c$ and $2m_D$)

- $c\,\bar{c}$ pair can bind into charmonium regardless
  of its color/angular momentum state

- probability that $c\,\bar{c}$ binds to form charmonium H
  is adjustable constant f_H for each multiplet

Color-singlet Model vs Color Evaporation Model

Theoretical status in early 1990's

- inconsistency of CSM:
  infrared divergences for P-waves $\chi_{cJ} \to q\,\bar{q}\,g$
  $b \to \chi_{cJ} + s + g$

- perturbative corrections
  CSM: LO calculations only
  CEM: NLO, using heavy quark cross section
  Nason, Dawson, Ellis 1988

- Dominant theoretical prejudice
  CSM: can probably be extended
  to a theory based on QCD
  CEM: purely phenomenological model

Color-singlet Model vs Color Evaporation Model

Experimental status in early 1990's

- Fixed target experiments (pN, πN, γN)

  feeddown to J/ψ from $\psi(2S)$, χ_{cJ} decays
  contributions from small p_T ⇒ nonperturbative?

  large experimental errors
  roughly compatible with CSM or CEM

- $p\,\bar{p}$ collisions at the Tevatron

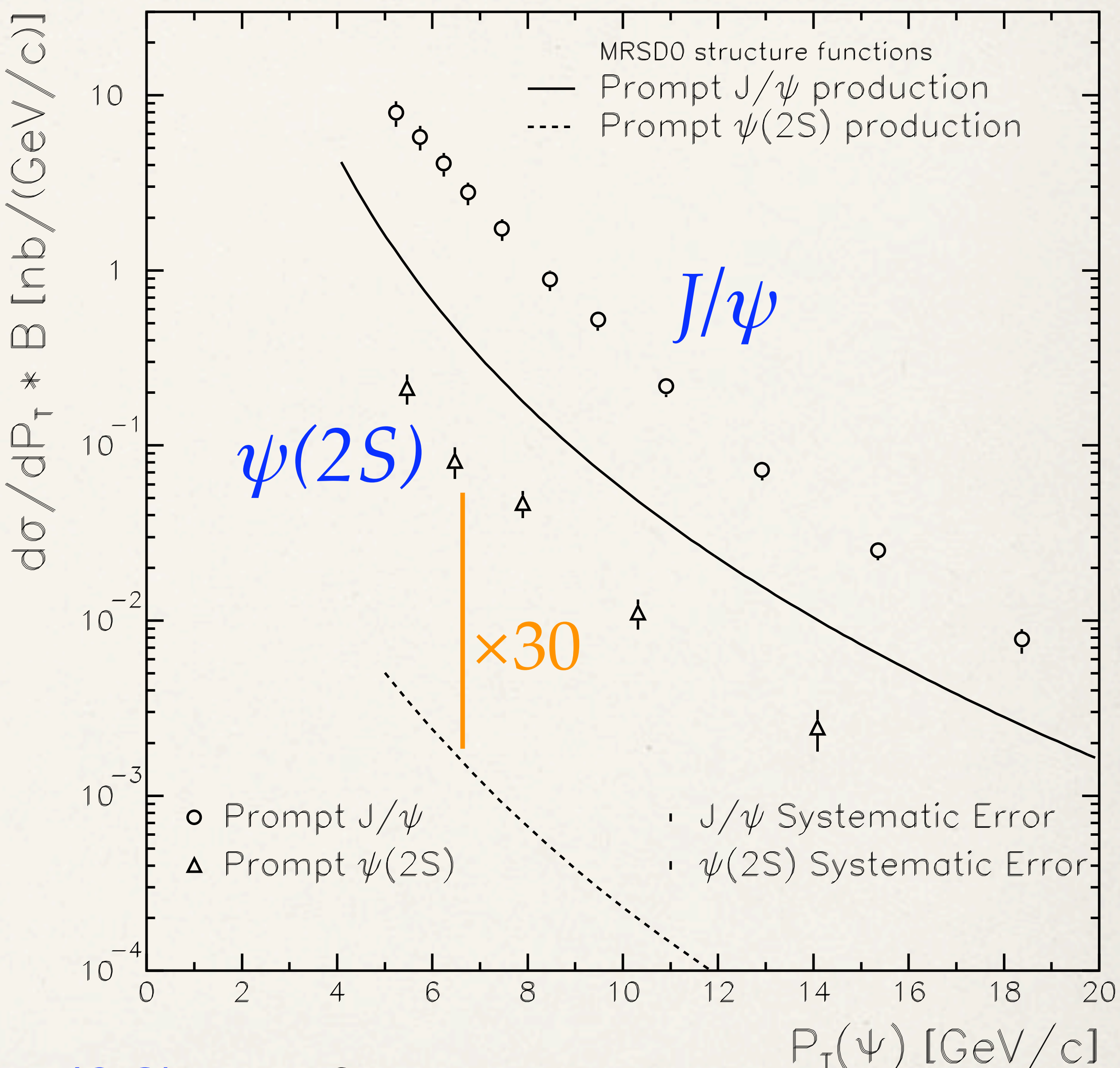
  feeddown to J/ψ from $\psi(2S)$, χ_{cJ} decays
  feeddown from B decays
  $p_T > 5$ GeV ⇒ perturbative?

  production rates much larger than predicted by CSM?

Demise of Color-singlet Model

CDF collaboration 1997

- use vertex detector to remove *B* feeddown



- prompt J/ψ: complicated by $\psi(2S)$, χ_{cJ} feeddown
- prompt $\psi(2S)$: 30 times larger than CSM prediction (in retrospect, compatible with CEM)

Fragmentation mechanism

PQCD Factorization Theorem Collins & Soper 1983

at sufficiently large transverse momentum $p_T >> m_Q$
quarkonium production must be dominated by fragmentation
of heavy quark and gluon

$$d\sigma[H_{c\bar{c}}(P)] = \sum_{i=c,\bar{c},g} \int_0^1 dz\; d\hat{\sigma}[i(P/z)]\; D_{i\to H_{c\bar{c}}}(z) + \mathcal{O}(m_c^2/p_T^2)$$

in Color-Singlet Model,
fragmentation functions $D(z)$ for quarkonium can be calculated
using perturbative QCD Braaten and Yuan 1993
but not accurate approximation at accessible values of p_T

NonRelativistic QCD

Caswell and Lepage 1986

- effective field theory for $Q\bar{Q}$ sector of QCD
  at energies << m_Q from $Q\bar{Q}$ threshold

- in quarkonium, small velocity v is generated dynamically
  by balance between potential energy and kinetic energy
  charmonium: $v^2 \approx 1/3$
  bottomonium: $v^2 \approx 1/10$

- nonperturbative effects
  can be organized according to their scaling with v

- Lattice NRQCD Lepage et al. 1992
  calculate properties of quarkonium nonperturbatively

NRQCD Factorization

Bodwin, Braaten & Lepage 1995

Conjectured factorization formula

for inclusive production of charmonium *H*

motivated by perturbative QCD factorization theorems

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)]\ \langle \mathcal{O}_n^H \rangle$$

- sum over color/angular momentum channels

  1 or 8 $\quad {}^1S_0, {}^3S_1, {}^1P_1, {}^3P_0, {}^3P_1, {}^3P_2, \ldots$

- parton cross sections for creating $c\bar{c}$

  expand in powers of $\alpha_s(m_c)$

- NRQCD matrix elements for formation of *H*

  scale as definite powers of *v*

NRQCD factorization

- Color-Singlet Model reproduced
  by color-singlet terms of leading order in v
- solves problem of infrared divergences for P-waves
- Color Evaporation Model reproduced by S-wave terms

<u>Simplest viable truncation of expansion in v</u>

- for S-waves, truncate after order v^7

$$J/\psi: \qquad \langle \underline{1}\ {}^3S_1 \rangle \sim v^3$$
$$\langle \underline{8}\ {}^3P_J \rangle, \langle \underline{8}\ {}^1S_0 \rangle, \langle \underline{8}\ {}^3S_1 \rangle \sim v^7$$

$\Rightarrow$ 4 universal constants for J/ψ, η_c

(1 determined by $J/\psi \to e^+e^-$)

- for P-waves, truncate after order v^5

$$\chi_{cJ}: \qquad \langle \underline{1}\ {}^3P_J \rangle, \langle \underline{8}\ {}^3S_1 \rangle \sim v^5$$

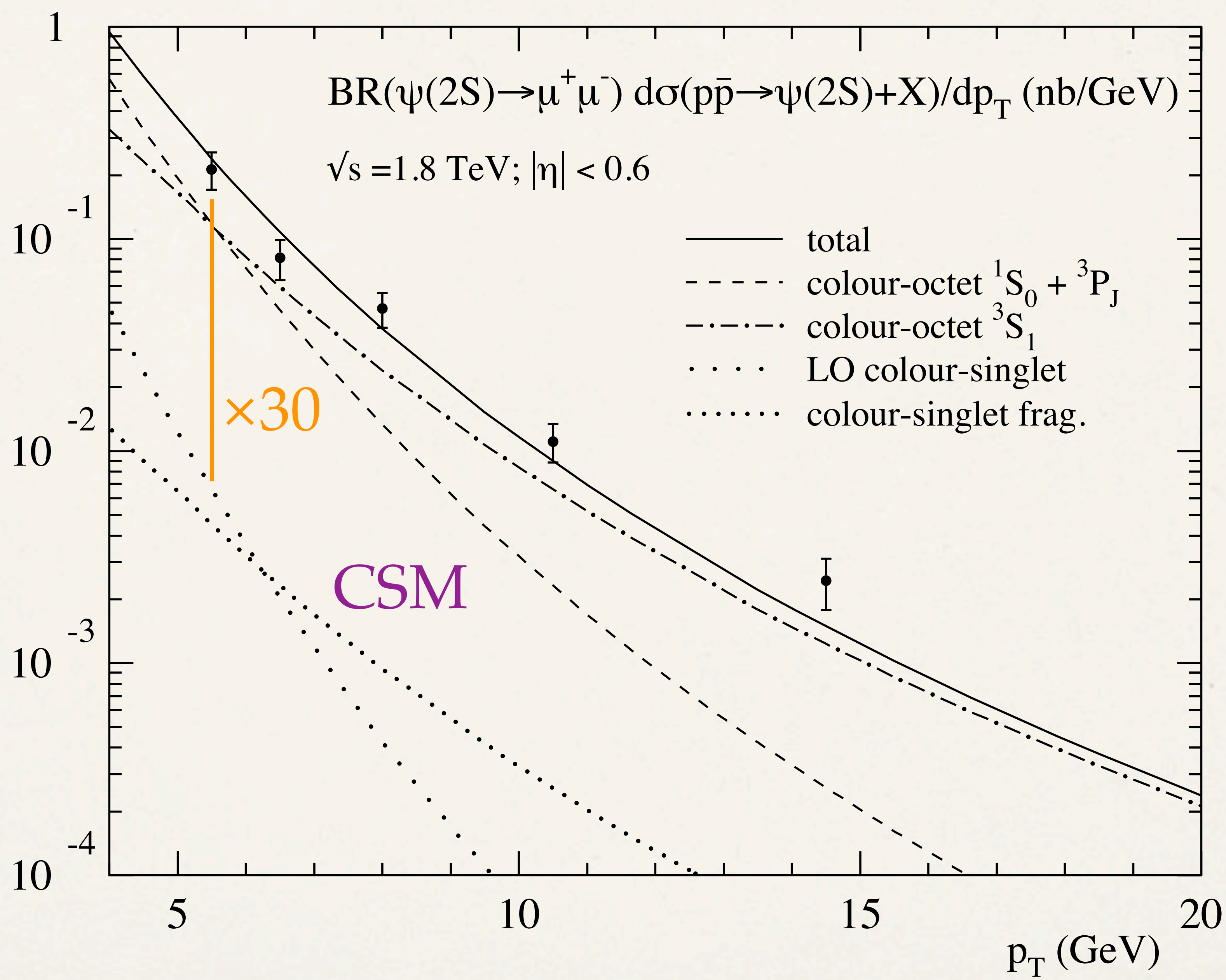
$\Rightarrow$ 2 universal constants for χ_{c0}, χ_{c1}, χ_{c2}, h_c

(1 determined by $\chi_{c0} \to \gamma\gamma$)

NRQCD Factorization

NRQCD factorization can accomodate the Tevatron data

CDF data on prompt $\psi(2S)$



fit $\langle \underline{8}\ {}^3S_1 \rangle$ and $\langle \underline{8}\ {}^1S_0 \rangle$ (or $\langle \underline{8}\ {}^3P_J \rangle$) Kramer 2001

Parton cross sections

$$d\sigma[H] = \sum_n d\hat{\sigma}[c\bar{c}(n)] \langle \mathcal{O}_n^H \rangle$$

accurate predictions require at least NLO in α_s

for charmonium, $\alpha_s(m_c) \approx 0.25$

for bottomonium, $\alpha_s(m_b) \approx 0.18$

- photoproduction — Kramer, Zunft, Steegborn, Zerwas 1995; Kramer 1996; Artoisenet, Campbell, Maltoni, Tramontano 2009; Chang, Li, Wang 2009; Li, Chao 2009; Butenschoen, Kniehl 2009
- γγ collisions — Klasen, Kniehl, Mihaila, Steinhauser 2005
- $e^+ e^- \rightarrow$ double charmonium — Zhang, Gao, Chao 2005; Zhang, Ma, Chao 2008; Gong, Wang 2008
- $e^+ e^- \rightarrow$ charmonium + X — Zhang, Chao 2006; Ma, Zhang, Chao 2008; Gong, Wang 2008, 2009; Zhang, Ma, Wang, Chao 2009
- hadron collisions — Petrelli, Cacciari, Greco, Maltoni, Mangano 1988; Campbell, Maltoni, Tramontano 2008; Artoisenet, Lansberg, Maltoni, 2008; Li, Wang 2008; Gong, Wang 2008; Gong, Li, Wang 2009; Ma, Wang, Chao 2010; Butenschon, Kniehl 2010

NRQCD Factorization

NLO perturbative QCD corrections

- increase cross sections by large K factors
  in some channels but not in others
  (large K factors in Color-Singlet Model channels
  decreases importance of color-octet terms)

- have removed most dramatic discrepancies
  between NRQCD factorization and experiment
  for spin-averaged cross sections
  (an important exception is polarization)

- fragmentation contribution appears at
  LO in color-octet $^3S_1$ channel
  NLO in most channels
  NNLO in color-singlet $^3S_1$ channel

⇒ NLO in α_s is not NLO accuracy at large p_T

Polarization

NRQCD factorization

predicts the polarization of quarkonium
with no additional parameters

dramatic qualitative prediction for hadron collisions:

direct J/ψ, Υ transversely polarised at large p_T

Cho, Wise 1995

- at sufficiently large p_T, charmonium production
  is dominated by gluon fragmentation

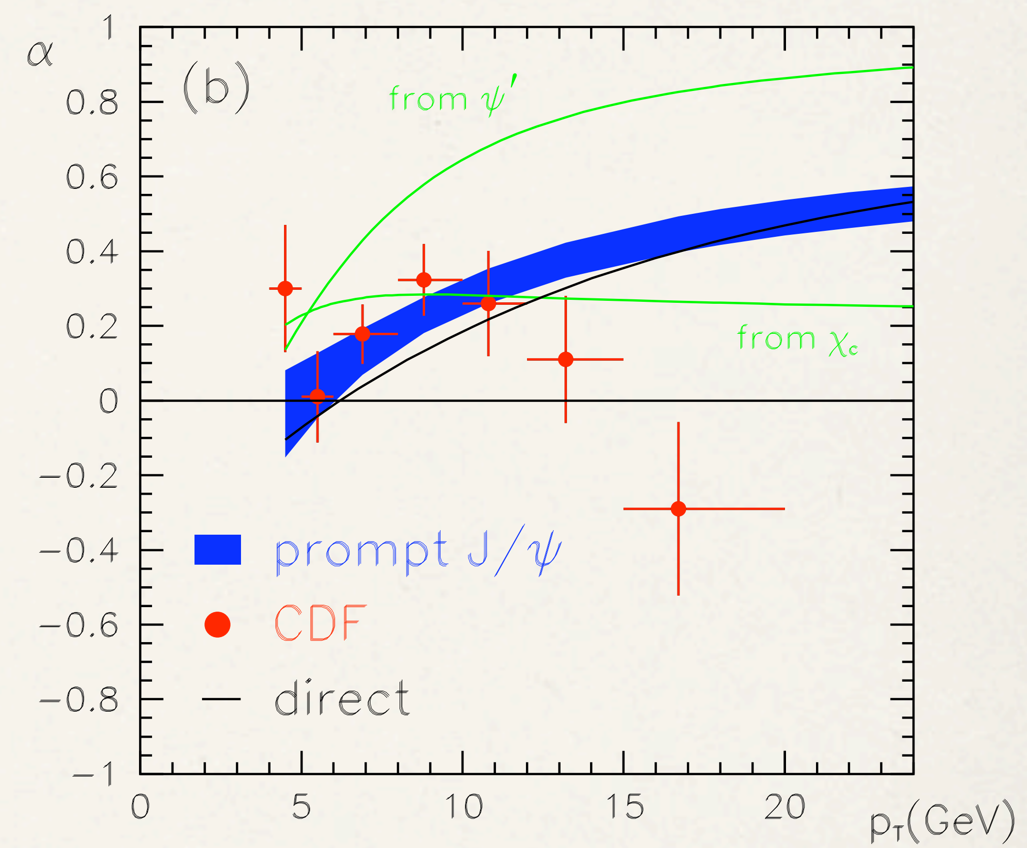
- at LO in α_s, gluon fragments into color-octet $c\bar{c}$ pair
  that inherits transverse polarization of gluon

- at LO in v, hadronization into $^3S_1$ charmonium
  preserves transverse polarization of $c\bar{c}$ pair

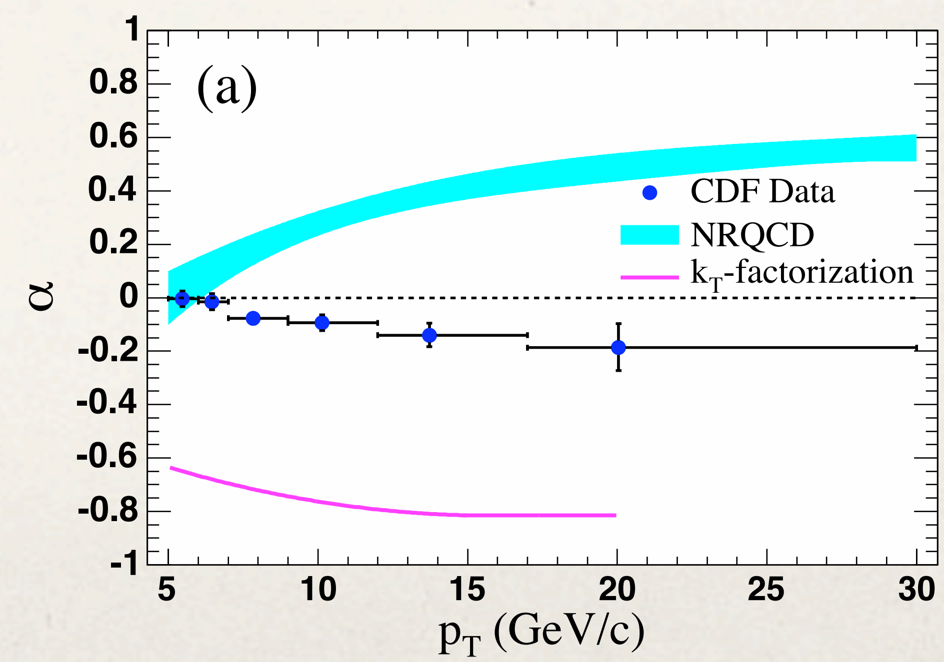
Polarization of J/ψ

- NRQCD predictions at LO fail dramatically in comparison with CDF data
- NLO calculations for polarization are incomplete but do not seem to improve agreement
- incompatibility between CDF data from Run I and Run II

Run I:



Run II:



$Q\bar{Q}$ Fragmentation

Dramatic new development in 2010!
Proof of factorization for quarkonium production at large p_T

Kang, Qiu, Sterman (in progress)

- at leading order in m_Q/p_T,
  fragmentation of single partons (Q, $\bar{Q}$, g)

  Collins & Soper 1983

- at order m_Q^2/p_T^2,
  $Q\bar{Q}$ fragmentation into quarkonium

–

- at order m_Q^4/p_T^4, factorization breaks down

$$
\begin{aligned}
d\sigma[H_{c\bar{c}}(P)] \quad = \quad & \sum_{i=c,\bar{c},g} \int_0^1 dz \; d\hat{\sigma}[i(P/z)] \; D_{i\to H_{c\bar{c}}}(z) \\
& + \int_0^1 dz \; d\hat{\sigma}[c\bar{c}(P/z)] \; D_{c\bar{c}\to H_{c\bar{c}}}(z) \\
& + \mathcal{O}(m_c^4/p_T^4)
\end{aligned}
$$

$Q\bar{Q}$ Fragmentation

Rigorous factorization formula for quarkonium production
separates hardest momentum scales $\sim p_T$
from softer momentum scales $\lesssim m_Q$

Kang, Qiu, Sterman (in progress)

$\sim p_T$: parton cross sections for producing Q, $\bar{Q}$, g, and $Q\bar{Q}$
calculable using PQCD as power series in $\alpha_s(m_Q)$

$\lesssim m_Q$: fragmentation functions for Q, $\bar{Q}$, g, and $Q\bar{Q}$
into quarkonium
nonperturbative (but involves hard scale m_Q)

needed: NLO calculations of parton cross sections for $Q\bar{Q}$
determination of fragmentation functions

Quarkonium Production

In rigorous factorization formula for quarkonium production, fragmentation functions for Q, $\bar{Q}$, g, and $Q\bar{Q}$ into quarkonium involve momentum scales $\gtrsim m_Q$

NRQCD factorization can plausibly be used to
separate hard scale m_Q from
softer nonperturbative scales
reduce fragmentation functions
to a few constants for each multiplet

needed: NLO calculations of fragmentation functions

Albert Einstein:
"Make everything as simple as possible, but not simpler."

Summary

Heavy hadron production

Rigorous factorization formula at large p_T
involves nonperturbative fragmentation functions
parton cross sections should soon be available at NNLO

Quarkonium production

Rigorous factorization formula at large p_T
involves nonperturbative fragmentation functions
NRQCD factorization could reduce them to constants
parton cross sections at NLO available for moderate p_T
NLO calculations of fragmentation functions also needed

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