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Outline

- The colour evaporation model
- The colour singlet model
- NRQCD

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The colour evaporation model

- model from about 1977 [1,2]
- main point: needed soft gluon is emitted "invisibly"
  (which is considered to have "little detailed theoretical justification" by Ellis)
- the production of quarkonium states is $\propto$ heavy quark production
  that is, all $c\bar{c}$-pairs in above threshold make charmonium

  originally only lowest-order processes ($\gamma V \to c\bar{c}$ and $q\bar{q}/VV \to c\bar{c}$)
- gives predictions for J$/\psi$ production and has implications for the Zweig rule

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The colour singlet model

- developped around the same time as the colour evaporation model
- first a $c\bar{c}$ pair must appear with relative momentum smaller than m_c or it will go to $D\bar{D}$
- takes into account the number of gluons needed to reach a colour singlet state
- production amplitudes factor; one nonperturbative factor per LS-multiplet
- predicts higher rates for η, χ_0 and χ_2 than for J/ψ and χ_1; not in accordance to experiment, especially not with Tevatron data

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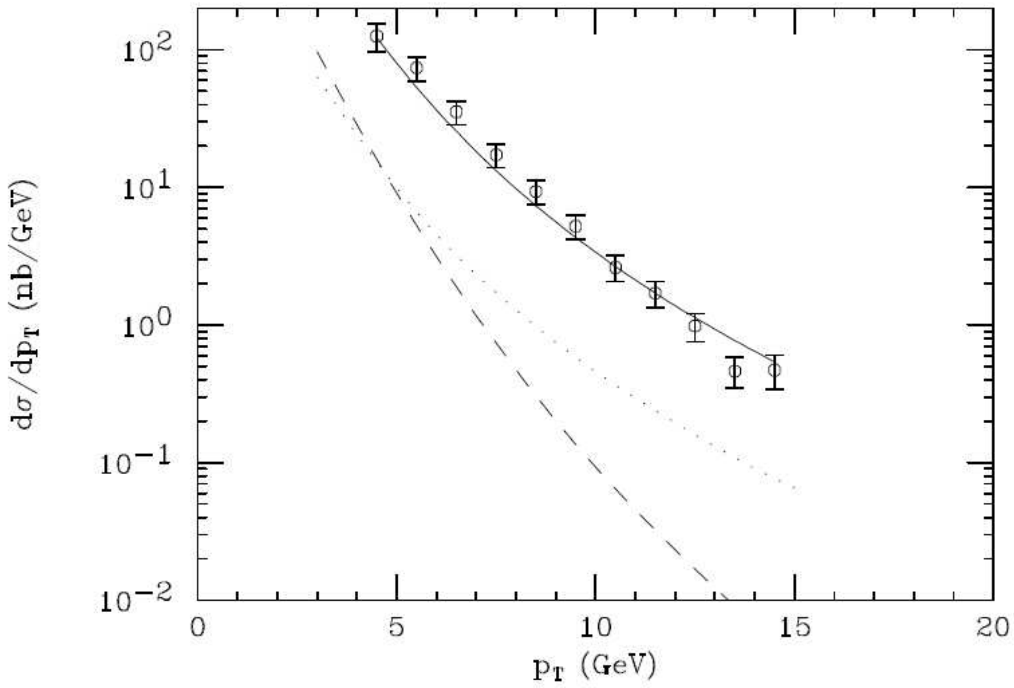
The CSM – some limitations

- no relativistic corrections, and $\bar{8}$-$c\bar{c}$ will never form charmonium

- $c\bar{c}$ pair produced by virtual particles off-shell by m_c or larger (short-distance part);
  if some particle is off-shell by $\ll m_c$, it's considered part of amplitude for formation of bound state

- color-octet mechanisms important; the short-distance part may well leave $c\bar{c}$ in $\bar{8}$ $\Rightarrow$ new terms in the cross sections

CDF data



The differential cross section for prompt ψ as a function of $p_\perp$. Dashed – LO CSM, dotted – LO CSM with fragmentation, solid – gluon fragmentation with colour octets.[3]

NRQCD – NonRelativistic QCD

- the “current” model, again factorization
- separation of the short-distance physics from the longer distance scales
- one scale given by the quark mass m_Q
- good for (e.g.) annihilation decay rates and “sufficiently” inclusive production

fragmentation – hadronization of individual partons

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NRQCD cont'd

The short-distance part is done in pQCD, and the long-distance physics go into matrix elements calculated by the effective field theory that is non-relativistic QCD.

Some different scales in heavy quarkonium:

M – heavy quark mass

Mv – typical momentum

Mv^2 – typical kinetical energy

There's also Λ_{QCD}. v is used as expansion parameter

$|\psi_Q\rangle = \mathcal{O}(1)|Q\bar{Q}[^3S_1^{(1)}]\rangle + \mathcal{O}(v)|Q\bar{Q}[^3P_J^{(8)}]g\rangle + \mathcal{O}(v^2)|Q\bar{Q}[^1S_0^{(8)}]g\rangle + \mathcal{O}(v^2)|Q\bar{Q}[^3S_1^{(1,8)}]gg\rangle ...$

From NRQCD, one gets power counting rules for various matrix elements, and also probabilities for different terms in the Fock state expansion.

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Applications and predictions

- systematic framework: only a finite number of nonperturbative matrix elements contribute at any given order in v^2
- large $p_\perp$-charmonium production
- universal matrix elements $\Rightarrow$ test in production from Z_0
- spin alignment of direct ψ and $\psi\prime$ at large $p_\perp$ [4,5]
- on one hand, need for phenomenological determinations of matrix elements, on the other hand, "lots of quarkonium everywhere"

$\mathrm{d}\sigma(p\bar{p} \to \psi(P) + X) = \int_0^1 \mathrm{d}z \mathrm{d}\hat{\sigma}(p\bar{p} \to g(P/z) + X) D_{g\to\psi}(z)$
with $D_{g\to\psi}(z) = \sum_{mn} d_{mn}(z) \langle \mathcal{O}^{\psi}_{mn} \rangle$

References

[1] H. Fritzsch, Producing heavy quark flavours in hadronic collisions – a test of quantum chromodynamics, Phys. Lett. **67B** (1977) 217
[2] J. Babcock *et al.*, Quantum-chromodynamic estimates for heavy-particle production, Phys. Rev. D **16** (1978) 162
[3] E. Braaten and S. Fleming, Phys. Rev. **74** (1995) 3327
[4] E. Braaten, Introduction to the NRQCD factorization approach to heavy quarkonium, hep-ph/9702225
[5] E. Braaten *et al.*, Production of heavy quarkonium in high energy colliders, hep-ph/9602374