Heavy quarkonium production at collider energies

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Workshop on Physics at the CEPC
IHEP, August. 12th, 2015

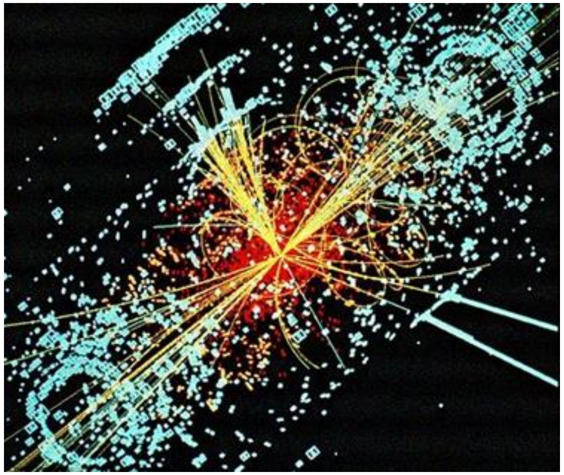
Outline

I. Introduction

II. Theory for high p_T quarkonium production

III. Test the theory

Hadronization

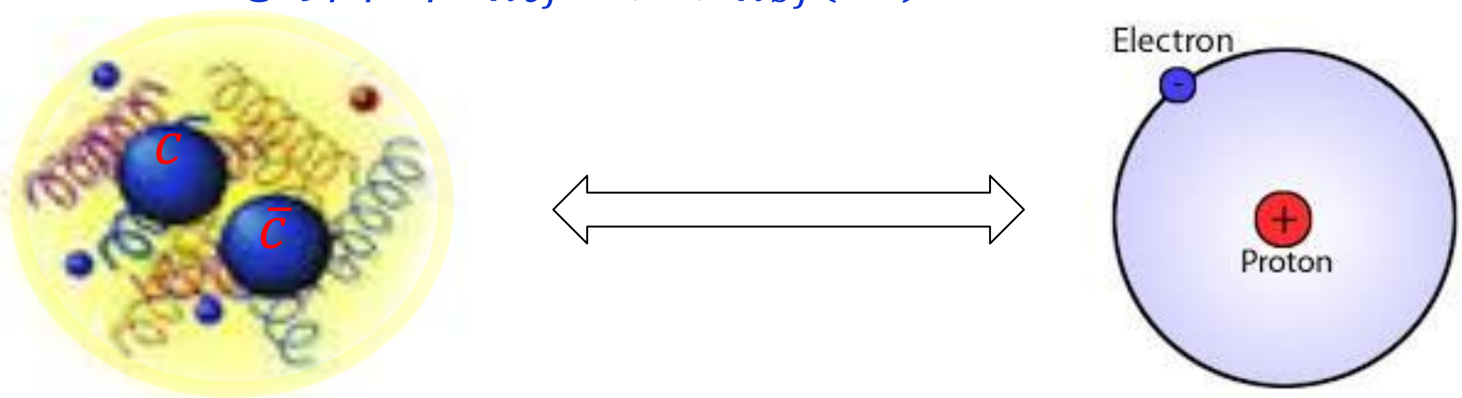


- **Produced at initial:**
  - Partons (guess)
- **Observed by detector:**
  - Hadrons
- **Hadronization in QCD**
- **Why hadronization? How hadronization?**
  - Study hadron production!

Heavy quarkonium

- **Bound state of $Q\bar{Q}$ pair under strong interaction**

  Eg: $J/\psi\ \ \psi', \chi_{cJ}, \Upsilon(nS), \chi_{bJ}(nP) \cdots$



  ✓ The simplest system: two body problem

  ✓ "Hydrogen atom in QCD", "an ideal laboratory in QCD"

- **Production: best way to study hadronization**

  Still hard, not fully understood 40 years

Property

- **A non-relativistic QCD system:** $v \ll 1$

  Charmonium: $v^2 \approx 0.3$

  Bottomonium: $v^2 \approx 0.1$

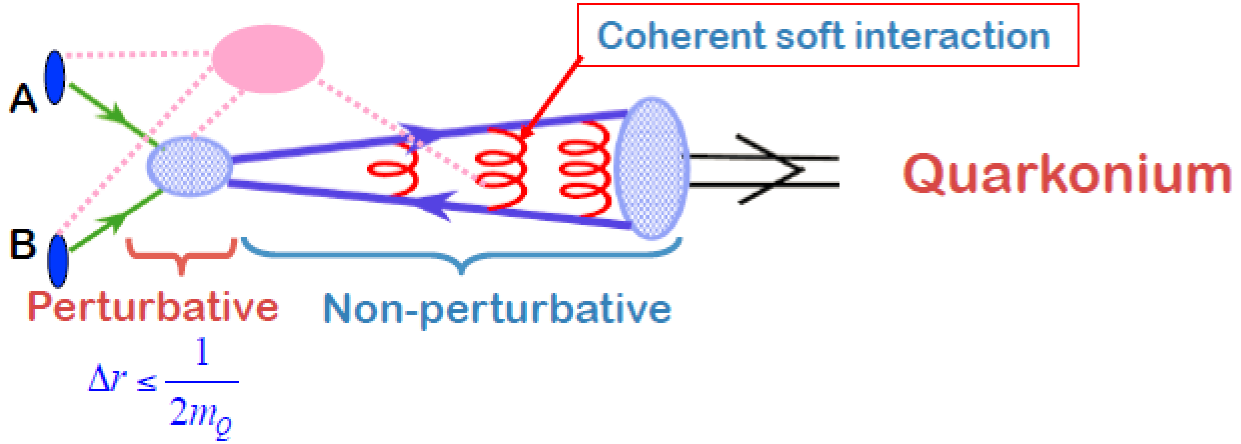
- **Multiple well-separated scales :**

Quark mass:	M	
Momentum:	Mv	M >> Mv >> $Mv^2 \sim \Lambda_{QCD}$
Energy:	Mv^2	

- **Involving both perturbative and nonperturbative physics**

Factorization and hadronization models

- Short-distance and long distance parts



- Approximation: on-shell pair + hadronization

$$\sigma_{AB\to H+X} = \sum_n \int_n d\Gamma_{(Q\bar{Q})_n} \left[\frac{d\hat{\sigma}(Q^2)}{d\Gamma_{(Q\bar{Q})_n}}\right] F_{(Q\bar{Q})_n\to H}(p_Q, p_{\bar{Q}}, P_H)$$

- Hadronization: isolated from perturbative effects
- Different treatment for F: different factorization model

Historical review of quarkonium production

0. 1974 Discovery of J/ψ

E598 Collaboration (1974)
SLAC-SP-017 Collaboration (1974)

1. 1974 - CSM and CEM

Einhorn, Ellis (1975), Chang (1980), Berger, Jone (1981), …
Fritzsch (1977), Halzen (1977), …

- Color Singlet Model: fine until 1994, ψ' surplus
- Color Evaporation Model: wrong for ratio

2. 1994 - NRQCD

Bodwin, Braaten, Lepage, 9407339, …

- CSM and CEM: special cases in NRQCD
- Problem

3. 2014 – Collinear factorization

Collins, Soper (1982)
Kang, Qiu, Sterman, 1109.1520
Fleming, Leibovich, Mehen, Rothstein 1207.2578
Kang, YQM, Qiu, Sterman, 1401.0923, …

NRQCD Factorization

➢ Factorization formula

Bodwin, Braaten, Lepage, 9407339

$$d\sigma_\psi = \sum_{i,j,n} \int \underbrace{dx_1 dx_2 \boxed{G_{i/A} G_{j/B}}}_{\Lambda_{QCD}} \times \underbrace{\boxed{\hat{\sigma}[ij \to c\bar{c}[n] + X]}}_{m_c} \times \underbrace{\boxed{\langle O_n^\psi \rangle}}_{m_c v}$$

Parton distribution function
Long distance (~1/Λ_{QCD})

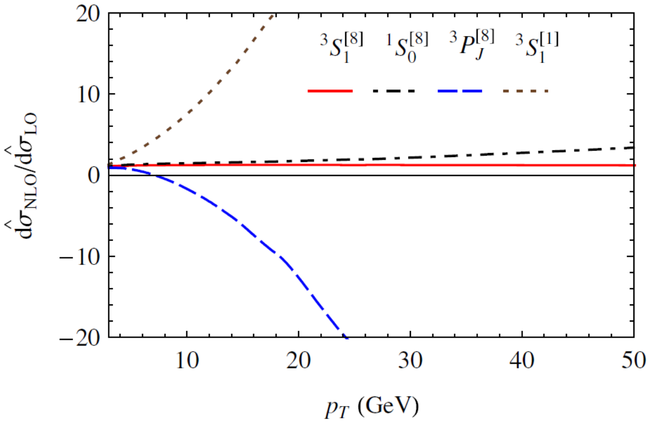
Hadronization (LDMEs)
Long distance (~1/(m_cv))
input from experiments needed.

Production of heavy quark pair
Short distance (~1/m_c)
perturbative calculable.

Problems with NRQCD

➢ High p_T: large corrections for some channels

- Perturbation convergent?
- Need how many orders?



➢ LDMEs: not universal

- B-factories data: $M_0^{J/\psi} < 0.02\ GeV^3$ Zhang, YQM, Wang, Chao, 0911.2166
- LHC data: $M_0^{J/\psi} = 0.074\ GeV^3$ YQM, Wang, Chao, 1009.3655
- Global fit: $\chi^2/\mathrm{d.o.f.} = 857/194 = 4.42$ Butenschöen, Kniehl, 1105.0820

➢ Factorization to all order, correct?

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Collinear factorization for high p_T production

- When $p_T \gg m$, power expansion first: $1/p_T$

- Leading power: collinear factorization, single parton fragmentation

Collins, Soper (1982)
Braaten, Yuan, 9303205
Nayak, Qiu, Sterman, 0509021

- NLP: important for quarkonium produciton

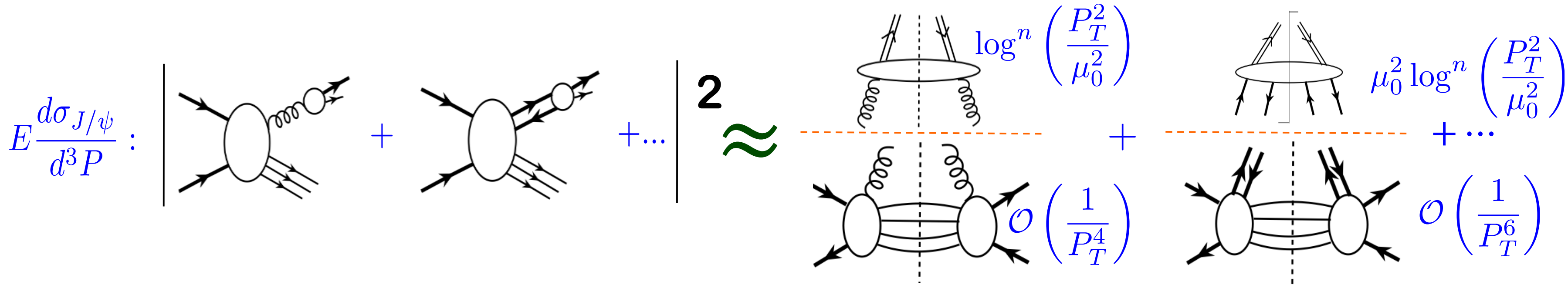
Kang, Qiu, Sterman, 1109.1520

- A rigorous collinear factorization method up to NLP

Kang, YQM, Qiu, Sterman, 1401.0923
Kang, YQM, Qiu, Sterman, 1411.2456

Collinear factorization approach

- **Ideas:**



- **Factorization correct to all order**

Qiu, Sterman (1991)
Kang, YQM, Qiu, Sterman, 1401.0923

Factorization

Kang, YQM, Qiu, Sterman, 1401.0923

➢ Factorization formalism:

produce pair at $1/m_Q$

$$d\sigma_{A+B\to H+X}(p_T) = \sum_f d\hat{\sigma}_{A+B\to f+X}(p_f = p/z) \otimes D_{H/f}(z, m_Q)$$
$$+ \sum_{[Q\bar{Q}(\kappa)]} d\hat{\sigma}_{A+B\to[Q\bar{Q}(\kappa)]+X}(p(1\pm\zeta)/2z, p(1\pm\zeta')/2z)$$
$$\otimes \mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q)$$
$$+ \mathcal{O}(m_Q^4/p_T^4)$$

produce pair at $1/p_T$

$\kappa = v, a, t$ for spin, and $1, 8$ for color

Evolution

Kang, YQM, Qiu, Sterman, 1401.0923

- **Independence of the factorization scale:**

$$\frac{d}{d\ln(\mu)}\sigma_{A+B\to HX}(P_T)=0$$

- **Evolution equations at NLP:**

produce pair between $[1/p_T, 1/m_Q]$

$$\frac{d}{d\ln\mu^2}D_{H/f}(z,m_Q,\mu)=\sum_j\frac{\alpha_s}{2\pi}\gamma_{f\to j}(z)\otimes D_{H/j}(z,m_Q,\mu)$$
$$+\frac{1}{\mu^2}\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s^2}{(2\pi)^2}\Gamma_{f\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

$$\frac{d}{d\ln\mu^2}\mathcal{D}_{H/[Q\bar{Q}(c)]}(z,\zeta,\zeta',m_Q,\mu)=\sum_{[Q\bar{Q}(\kappa)]}\frac{\alpha_s}{2\pi}K_{[Q\bar{Q}(c)]\to[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta')\otimes\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z,\zeta,\zeta',m_Q,\mu)$$

- Large $\log(p_T/m)$: can be resumed by solving evolution equation

Predictive power

- Calculation of short-distance hard parts in pQCD

Kang, YQM, Qiu, Sterman, 1411.2456

- Power series in α_s , without large logarithms
- LO is now available for all partonic channels

- Calculation of evolution kernels in pQCD:

Kang, YQM, Qiu, Sterman, 1401.0923

- Power series in α_s, without large logarithms
- LO is now available for both mixing kernels and pair evolution kernels of all states

- Universality of input fragmentation functions at μ_0

Input fragmentation function

- **FFs at μ_0: fit from data**
  - **Complicated: different quarkonium states require different input distributions!**

- **NRQCD factorization: plausible at $\mu_0 \sim \mathrm{m_Q}$**

$D_{H/f}(z, m_Q, \mu_0)$ $\quad$ $\mathcal{D}_{H/[Q\bar{Q}(\kappa)]}(z, \zeta, \zeta', m_Q, \mu_0)$

- **Apply NRQCD to the input distributions at initial scale**

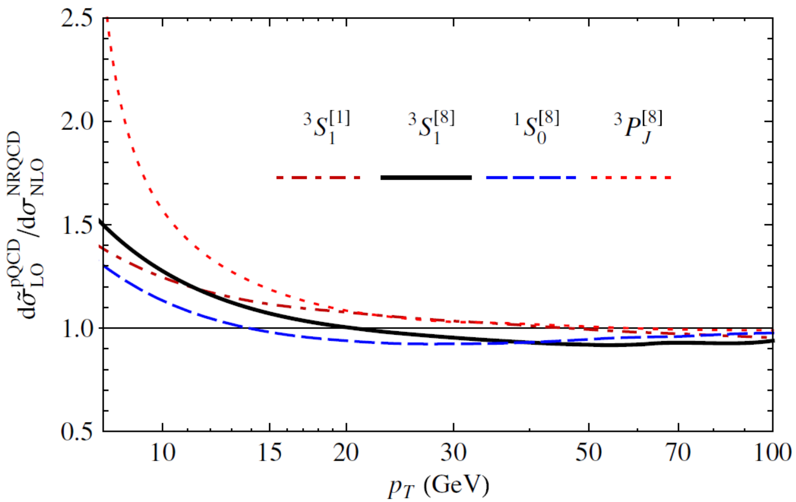
NLO results available for all channels

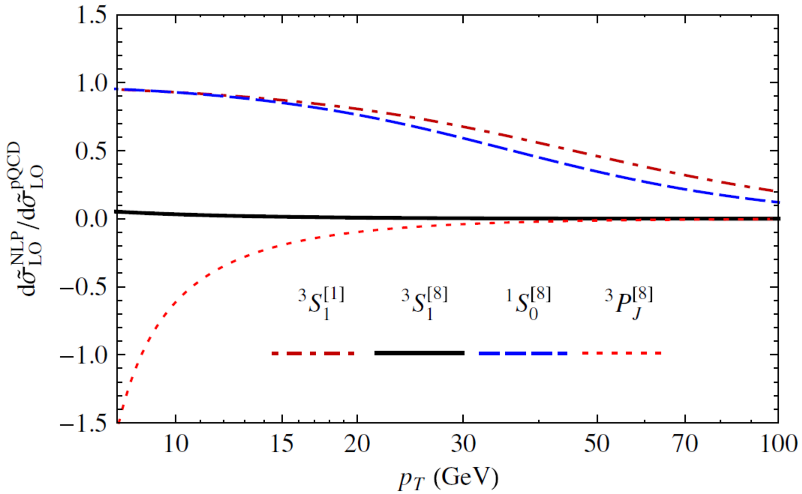
YQM, Zhang, Qiu, 1311.7078
YQM, Zhang, Qiu, 1401.0524
YQM, Zhang, Qiu, 1501.04556

Reproducing plain NRQCD

YQM, Qiu, Sterman, Zhang, 1407.0383

- LP+NLP comparing with NLO NRQCD





- ◊ LO analytical results reproduce NLO NRQCD calculations (numerical) !

- ◊ LP dominates: $^3S_1^{[8]}$ and $^3P_J^{[8]}$ channels
- ◊ NLP dominates: $^1S_0^{[8]}$ and $^3S_1^{[1]}$ channels

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Theoretical status

- Two steps:
  1. Produce massless partons at short distance
  2. Fragmenting to quarkonium at long distance

- Assuming NRQCD at initial scale, everything can be calculated

- Comparison with data: test our understanding of hadronization

Why CEPC?

- **Only LP and NLP are proven to be factorizable**
  - Quarkonium must have high p_T
  - High energy colliders

- **pp collider: gluon fragmentation**

- **e^+e^- collider: heavy quark fragmentation**

Thank you!