Pseudoscalar Quarkonium + γ at NLL+NLO accuracy

arXiv 1906.03275, H.S. Chung, J.H. Ee, DK, U. Kim, J. Lee, X. P. Wang

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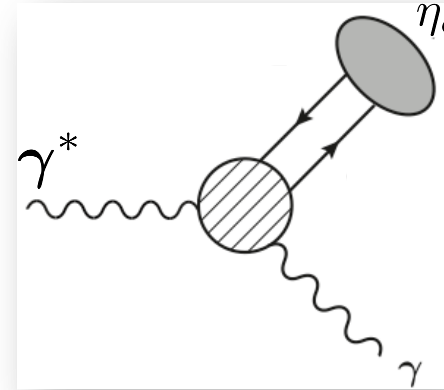
Outline

- Why exclusive quarkonium process?
- Theoretical approach
  - hierarchy in energy scales Q, m_Q, $m_Q v^2$
  - logarithms and resummation
- Numerical results
  - resummation effect
  - comparison with previous results

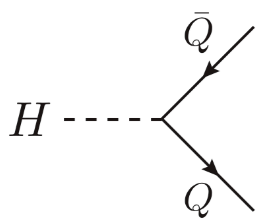


Why exclusive quarkonium process?

- Higgs decays into $J/\psi+\gamma$ is one of most promising channel that could measure the Yukawa couplings of the charm quarks at the LHC

Higgs-quark Yukawa coupling is given by

quark mass



$$: \quad i\mathcal{M}_{HQ\bar{Q}} = -ig\frac{m_Q}{2m_W} \times \kappa_Q$$

In the SM, $\kappa_Q = 1$

- Current CMS, ATLAS upper limits (95% CL) are ~10^2 times larger than SM values and they will be improved at high luminosity LHC.

ATLAS: $3.5 \times 10^{-4} \approx 117 \times \mathrm{Br}(H \to J/\psi + \gamma)|_{\mathrm{SM}}$ $(36.1\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV)

PLB 786 (2018) 134

CMS: $7.6 \times 10^{-4} \approx 260 \times \mathrm{Br}(H \to J/\psi + \gamma)|_{\mathrm{SM}}$ $(35.9\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 13$ TeV)

EPJC 79(2019) 94

Why exclusive quarkonium process?

- $\eta_c+\gamma$ and $\chi_c+\gamma$ are measured by Belle and by BESIII
  - background channel in XYZ decays
  - benchmarking process w/ small samples before XYZ search

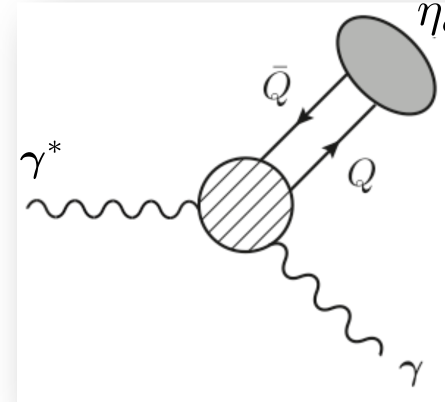
- Accurate theoretical predictions would be useful and it is a good place to test NRQCD predictions improved from previous lessons.
- from double quarkonium: large logarithms, v^2 corrections
- from polarization puzzle: power corrections of m_Q/p_T

We focus on $\eta_c+\gamma$ production in e+e- annihilation improved by

log resummuation (NLL), α_s corr (NLO),

and v^2 and m_Q/Q power corrections

Hierarchy in energy scales



- 3 energy scales : Q (or √s), $2m_Q$ >> $m_Q v^2$
- NRQCD allows separation between SD and LD

$$\mathcal{M}(H) \sim \sum_n C_n(Q, m_Q) \langle H | \mathcal{O}_n | 0 \rangle$$

short-distance coefficient (perturbative $\gtrsim m_Q$)

NRQCD long-distance (decay) matrix elements (non-perturbative $\lesssim m_Q v$)

✓ *v =relative velocity between quark and anti-quark*

- SD contains two scales:

$$r \equiv \frac{4m_Q^2}{Q^2}$$

r spreads in wide ranges

r ~1 in BESIII (3-4 GeV)

r ≈0.1 in Belle (10 GeV)

r ≈0.001 in Higgs/Z decay (100 GeV)

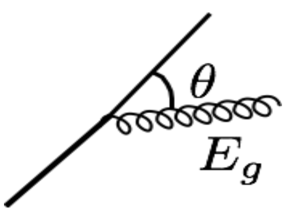
Log Log Log ⋯

- SD at NLO contains log of r and it is large for small r.

$$\lim_{r\to 0}\sigma^{\text{fixed}}(r;\mu)=\sigma_0\left[1+\frac{\alpha_s C_F}{4\pi}c^{\text{sing}}+\langle v^2\rangle c^{\text{sing}}_{v^2}\right]$$

$$c^{\text{sing}}=-\frac{2}{3}\left[(9-6\log 2)\log r+9(3+\log^2 2-3\log 2)+\pi^2\right]$$

- Logarithms are a generic feature in QFT at high energies and come from soft and collinear regions.



probability of splitting $\sim \dfrac{1}{E_g(1-\cos\theta)}$ ➡ $\mathrm{Log}(E_g)\,\mathrm{Log}(\theta)$

soft and collinear enhancements

Log Log Log $\cdots$

- No problem with small log, the ordinary perturbative series works

$$\sigma = 1 + \alpha_s + \alpha_s^2 + \cdots \qquad \alpha_s < 1$$

- For a large log, resummed perturbation with log-power counting

$$\alpha_s L \sim 1$$

LO NLO NNLO

$$\sigma^{\rm sing} = 1 + \alpha_s L + \alpha_s^2 L^2 + \cdots \quad \textbf{Leading Log}$$
$$+\alpha_s + \alpha_s^2 L + \cdots \quad \textbf{Next to LL}$$
$$+\alpha_s^2 + \cdots \quad \textbf{NNLL}$$

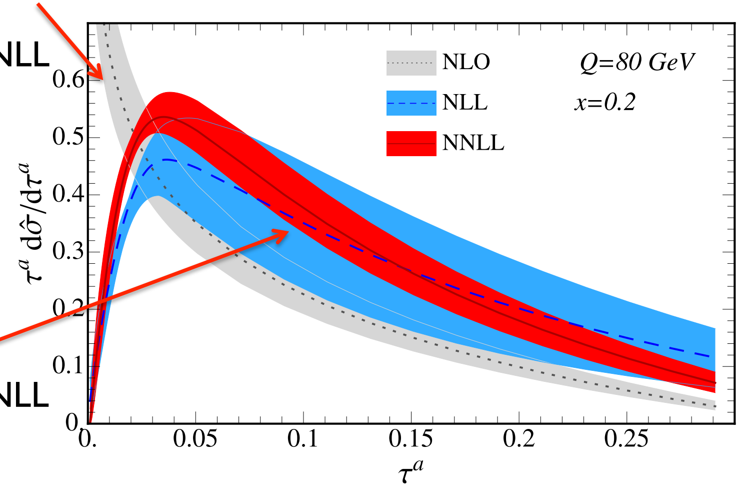
$$\sigma = \sigma^{\rm sing} + (v^2 \text{ corr.}) + (\text{power corr. of } O(r))$$

✓ valid in both small and large r regions

Example: An event shape distribution

- We can get an idea about resummation effect by comparing results before and after resummation in this example.
- event shape (τ^a) cross section contains Log[τ^a]   c.f. Log[r]

Log singularity in NLO
cured in NLL, NNLL



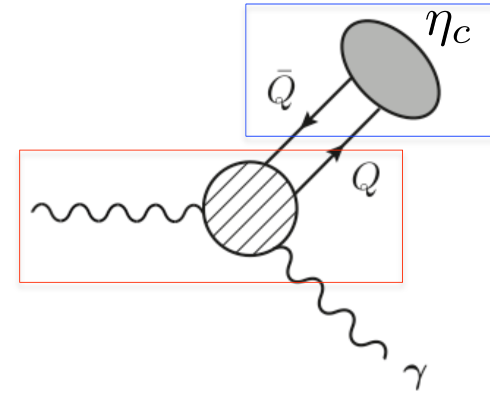
Good convergence from NLL to NNLL

- **large logs are under control after resummation**
- NLO perturbative uncertainty is not reliable without resummation

Theoretical approach

- Ordinary NRQCD factorization

$$\mathcal{M}(H) \sim \sum \underline{C_n(Q, m_Q)} \underline{\langle H|\mathcal{O}_n|0\rangle}$$



- Light-cone approach and refactorization

$$\mathcal{M} \sim T_H(x, Q) \otimes \phi_H(x, m_Q)$$

$$\phi_H(x, m_Q) \to \sum_n \phi_n(x, m_Q)\langle H|\mathcal{O}_n|0\rangle$$

- Hard-scattering kernel produces a pair of collinear quark and anti-quark with fractional momentum 0<x<1 at scale Q
- LCDA is the probability amplitude for the quark pair scattering at scale m_Q and later bounding into quarkonium at scale mv^2.
- factorization valid up to the leading power in m_Q/Q

$$\mathcal{M} \sim T_H(x, Q) \otimes \boxed{\phi_H(x, m_Q)}$$

Lepage and Brodsky, PRD, 1980
Efremov and Radyushkin, PLB, 1980

- The light-cone approach was known since 1980 for light mesons
- The heavy-quarkonium LCDA is refactorized

Wang and Yang, JHEP, 2014

$$\sum_n \phi_n(x, m_Q) \boxed{\langle H|\mathcal{O}_n|0\rangle}$$

- LDMEs are only non-perturbative part and the rest are calculable in pert. theory

$$\phi_P(x, \mu) = \phi^{(0)}(x) + \frac{\alpha_s(\mu)}{4\pi}\phi^{(1)} + \langle v^2\rangle\phi^{(v^2)} + O(\alpha_s^2, \alpha_s v^2, v^4)$$

$$\phi^{(0)} = \delta(x - \tfrac{1}{2}) \qquad \phi^{(v^2)} = \frac{\delta^{(2)}(x - \frac{1}{2})}{24},$$

Resummation by RG evolution

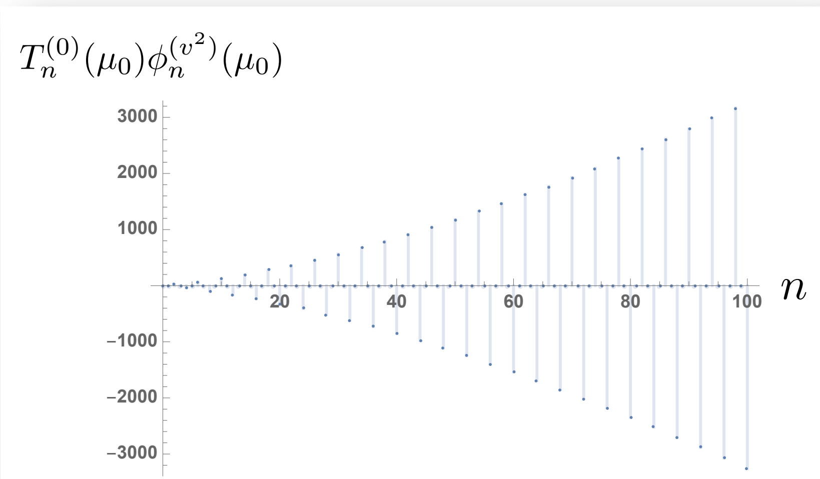
- RG eq of LCDA (called ERBL eq) was also known since 1980's
  LCDA is expanded using eigenfunc. and each coeff. is evolved from m_Q to Q.

$$\phi_n(\mu) = \sum_{k=0}^{n} U_{nk}(\mu,\mu_0)\phi_k(\mu_0)$$

$$\phi_n(\mu_0) = N_n \int_0^1 dx\, \phi_P(x,\mu_0) C_n^{(3/2)}(2x-1)$$

$$\phi_n(\mu)\Big|^{\rm LL} = \phi_n(\mu_0)\left[\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right]^{\frac{\gamma_n^{(0)}-\gamma_0^{(0)}}{2\beta_0}}$$

- alternating between large +/- values makes the sum NON-convergent!



What's the problem?

for light meson, a smooth model function was taken and the sum is convergent.

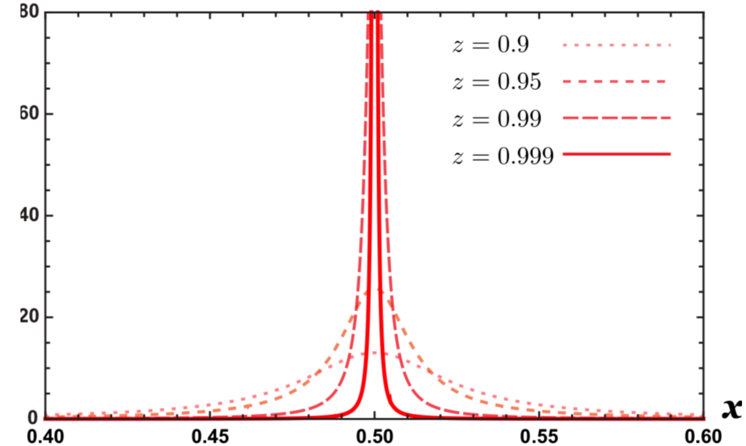
for heavy quarkonium, singular LCDAs due to refactorization.

$$\phi^{(0)} = \delta(x-\tfrac{1}{2}) \qquad \phi^{(v^2)} = \frac{\delta^{(2)}(x-\frac{1}{2})}{24},$$

Abel-Pade method

Bodwin, Chung, **Ee**, Lee, PRD 95, 2017

- Smearing the LCDA with new variable z<*1*



Gegenbauer expansion of δ(x-1/2) as z→1

- Abel summation

$$\phi_n(\mu) = \sum_{k=0}^{n} U_{nk}(\mu, \mu_0)\phi_k(\mu_0)\ z^n$$

$z = 0.80$	$z = 0.90$	$z = 0.95$	$z = 0.99$	Pade
4.49305	4.24087	4.11884	4.02350	4.00000
1.28864	1.31426	1.33389	1.33386	1.33333

- Use the Pade approximation to boost the convergence.

$$f(z) = \frac{P_m(z)}{Q_n(z)} + \mathcal{O}(z^{m+n+1}) \qquad P_m(z) = a_0 + a_1 z + a_2 z^2 + \cdots + a_m z^m$$

γ_5-scheme dependence

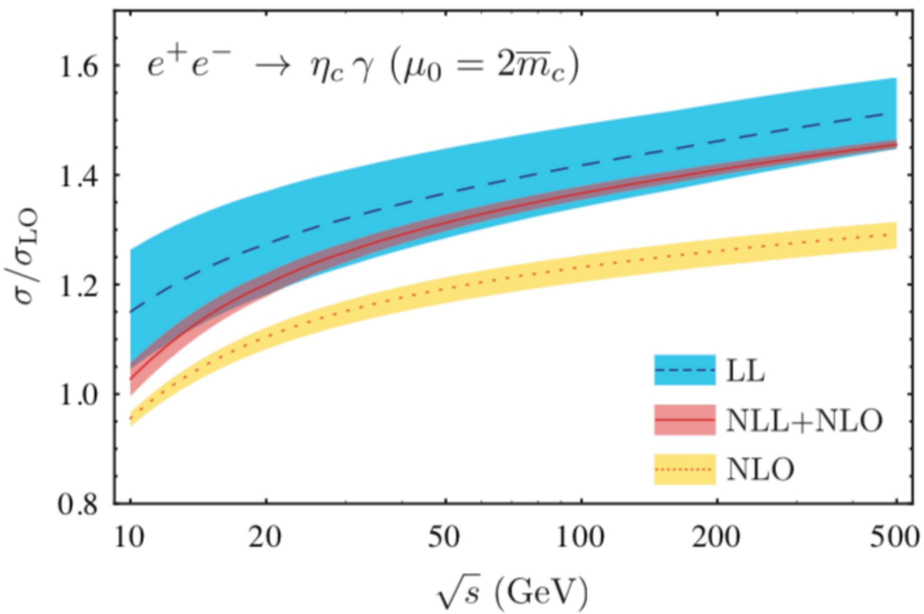
- Pseudoscalar LCDA: $\langle P(p)|\bar{Q}(z)\gamma^+\gamma_5[z,0]Q(0)|0\rangle = p^+ f_P \int_0^1 dx\, e^{ip\cdot zx}\phi_P(x,\mu)$
  - γ_5 in Dim reg is scheme dependent
    $\{\gamma_5, \gamma^\mu\} = 0$ in 4 dim (NDR) or in d dim (HV)

$$\phi^{(1)} = C_F\theta(1-2x)\left\{\left[4x\frac{\frac{1}{2}+\bar{x}}{\frac{1}{2}-x}\left(\log\frac{\mu_0^2}{4m_Q^2} - 2\log(\tfrac{1}{2}-x) - 1\right)\right]_+ + \left[\frac{4x\bar{x}}{(\frac{1}{2}-x)^2}\right]_{++} + \Delta\,[16x]_+\right\}$$

Δ=0 for NDR, Δ=1 for HV

- Checking cancellation of *Δ* dependence is a strong constraint and nontrivial way validating our resummation.
  - *Δ* term in LCDA cancels against one-loop T_H and two-loop anomalous dim. in U_{nk}.
  - cancellations valid up to NLL accuracy

Log resummation effect



- ❑ Uncertainty estimated by typical scale variations
- ❑ LL and NLL are consistent and look perturbatively convergent
- ❑ fixed-order NLO w/o resummation is largely deviated from LL,NLL
  - ✓ underestimates its uncertainty

Numerical results

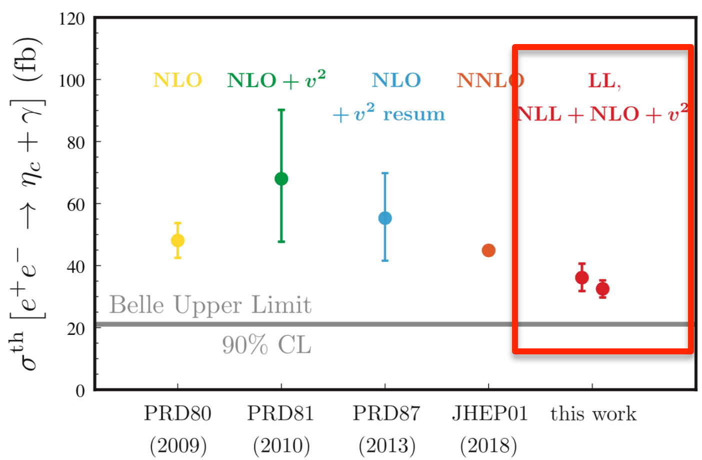
❑ At B-, Z-boson, Higgs factories

$\sqrt{s}$	Cross section η_c	Cross section η_b	Branching fraction η_c	Branching fraction η_b
10.58 GeV	32.7 ± 2.8 fb	-	$(7.42 \pm 0.61) \times 10^{-9}$	$(2.80 \pm 0.53) \times 10^{-8}$
m_Z	0.449 ± 0.037 fb	1.66 ± 0.31 fb		
240 GeV	0.189 ± 0.016 ab	0.0934 ± 0.0176 ab		

input parameters:

$$\overline{m}_c = 1.275^{+0.025}_{-0.035}\ \text{GeV}$$
$$\Gamma[\eta_c \to \gamma\gamma] = 5.0 \pm 0.4\ \text{keV}$$
$$\langle \mathcal{O}_1 \rangle_{\eta_c} = 0.302^{+0.052}_{-0.049}\ \text{GeV}^3$$
$$\langle v^2 \rangle_{\eta_c} = 0.222^{+0.070}_{-0.070}.$$

❑ Various prediction and Belle's upper bound

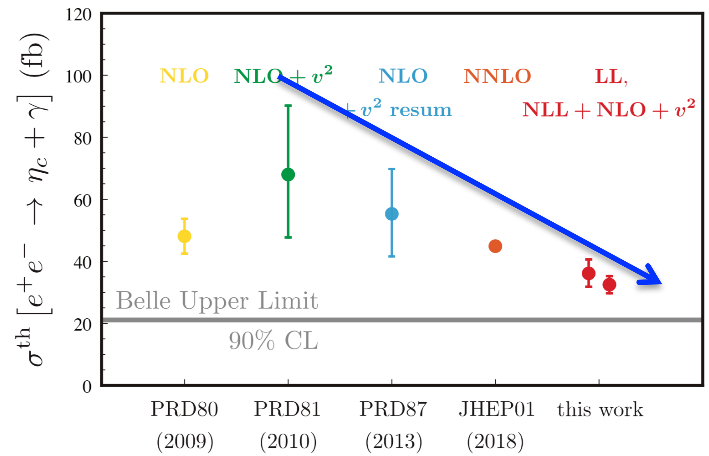


- our results are consistent with other predictions since resum. effect is not large at Belle energy
- lower central value due to smaller decay rate
- our prediction is 4-sigma away from Belle's upper limit (20.1 fb) PRD98 (2018) 0922015

Summary

- Exclusive quarkonium is motivated by experiments, BESIII, Belle, LHC at wide ranges of energies 3-100 GeV

- Predictions for $\eta_c+\gamma$ valid at these energies by NRQCD and LC factorization
  - log resummation at NLL
  - v^2 corrections
  - power corrections of r at NLO



- At Belle energy, consistent with previous predictions but deviated from Belle's upper limit by 4 sigma level.

It looks like that it's moving towards a right direction with time.

Thanks!

Results at BESIII energy (4 GeV)

- BESIII's peak cross section via Y(4260) resonance

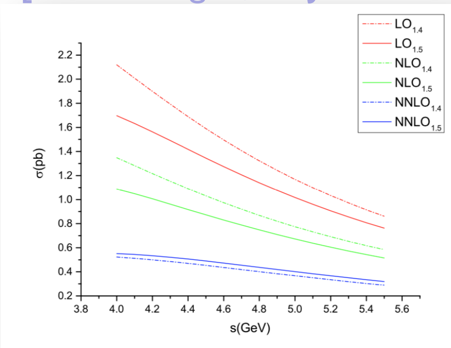
$$2.11 \pm 0.49(\text{stat.}) \pm 0.36(\text{syst.})\ \text{pb}$$

  - Off-resonance cross section must be smaller than the value

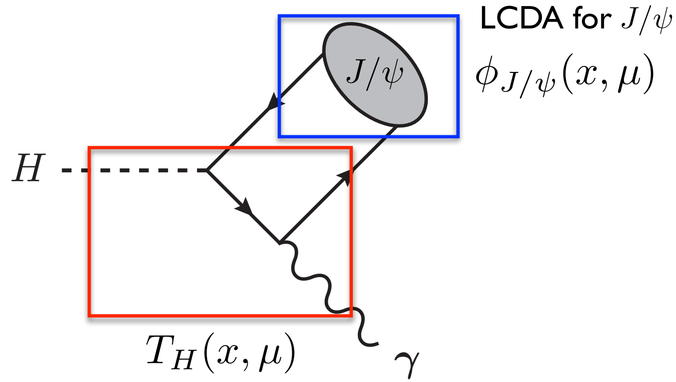
- Our numerical value: 0.53 pb
- A simple extrapolation from our prediction at BELLE energy by using scaling $1/Q^2$: 7x (32.7 fb) =0.23 pb

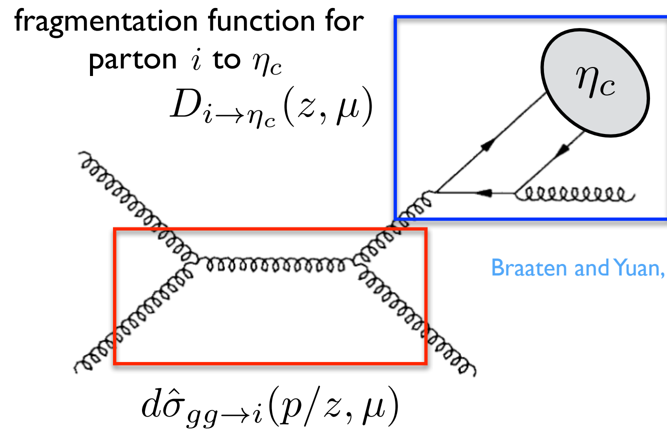
- comparable with NNLO prediction ~0.5 pb

[Chen, Liang, Qiao, JHEP 2018]



Comparison with inclusive process





Braaten and Yuan, PRL, 1993

exclusive production process	inclusive production (fragmenting) process

Exclusive production process

x: longitudinal momentum fraction of quark in J/ψ

$$\mathcal{M}_{H\to J/\psi+\gamma} = \int_0^1 dx\, T_H(x,\mu)\phi_{J/\psi}(x,\mu)$$

scale evolution: ERBL equation

$$\mu^2\frac{\partial}{\partial\mu^2}\phi(x,\mu) = \int_0^1 dy\, \underline{V\left[x,y;\alpha_s(\mu)\right]}\,\phi(y,\mu)$$

Evolution kernel

↑

perturbation theory

Inclusive production (fragmenting) process

z: longitudinal momentum fraction of η_c to fragmenting parton i

$$d\sigma_{\eta_c}(p) = \sum_i \int_0^1 dz\, d\hat{\sigma}_i(p/z,\mu) D_{i\to\eta_c}(z,\mu)$$

(sum over parton i)

scale evolution: DGLAP equation

$$\mu\frac{\partial}{\partial\mu}D_{i\to\mathcal{O}}(z,\mu) = \sum_j \int_z^1 \frac{dy}{y}\, \underline{P_{i\to j}(z/y,\mu)}\, D_{j\to\mathcal{O}}(y,\mu)$$

DGLAP splitting function

↑

perturbation theory