CGC description of double quarkonia production

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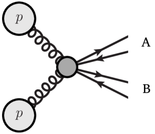
Heavy quarkonia (bound states of $c\bar{c}$ or $b\bar{b}$)

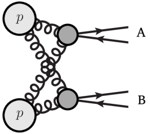
Production mechanism:

- ⋆ Color evaporation model (CEM)
- ⋆ Non-relativistic QCD (NRQCD)
- ⋆ Color-singlet model (part of NRQCD)

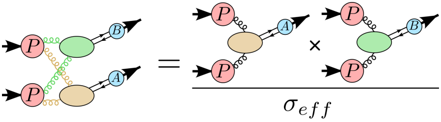
Why double quarkonia production?

- ⋆ Gives access to double-parton scatterring (DPS)
- ⋆ SPS and DPS do not have the same kinematics
- ⋆ Uncertainties on σ_{eff}, pocket formula

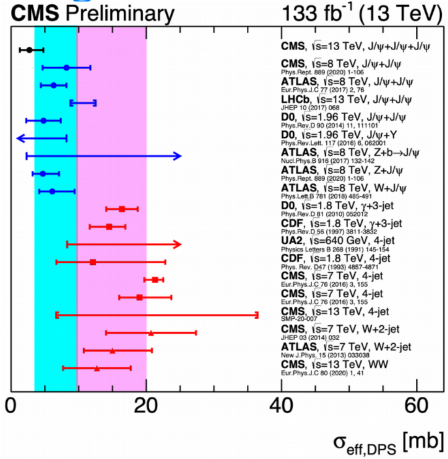




$$\sigma^{\text{DPS}} = \frac{\sigma^{\text{SPS}}(pp \to A)\sigma^{\text{SPS}}(pp \to B)}{\sigma_{\text{eff}}}$$



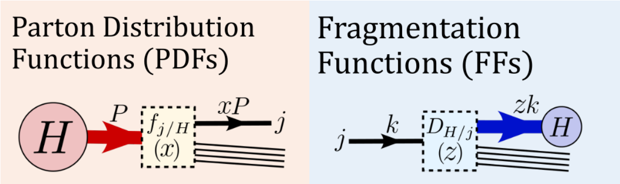
Studying the fragmentation mechanism



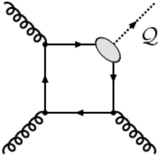
- σ_{eff} smaller for quarkonia.
- Since $\sigma^{\text{SPS}} + \sigma^{\text{DPS}} \simeq \sigma^{\text{exp}}$
- It suggests a missing contribution.

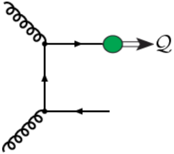
Our main goal: Evaluate the fragmentation contribution

What is a fragmentation function?



Direct versus fragmentation production (SPS)





Direct contribution:

Included in estimations of the SPS.

Evaluated with NRQCD.

Fragmentation contribution:

Not included for double-quarkonia production.

Non relativistic QCD

- Top-down effective field theory built from QCD.
- $\mu \sim m_Q$ is the ultraviolet scale.
- Expansion parameters: α_s and v, the relative velocity.
- $\sigma_{Q\bar{Q}(\kappa)}$: Feynman rules + projector for quatum state κ.

Factorization hypothesis:

$$\sigma^H = \sum_{\kappa} \sigma_{Q\bar{Q}(\kappa)}(\mu) \otimes \mathscr{O}^H_{\kappa}(\mu) \tag{1}$$

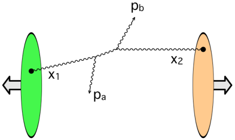
$\mathscr{O}^H_{\kappa}$: Long-distance-matrix element (LDME)

	$1, {}^1S_0$	$1, {}^3S_1$	$8, {}^1S_0$	$8, {}^3S_1$	$1, {}^1P_1$	$1, {}^3P_0$	$1, {}^3P_1$	$1, {}^3P_2$	$8, {}^1P_1$	$8, {}^3P_0$	$8, {}^3P_1$	$8, {}^3P_2$
NRQCD Factorization												
η_c	1		v^4	v^3					v^4			
J/ψ		1	v^3	v^4						v^4	v^4	v^4

Color Glass Condensate effective theory

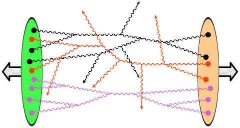
Factorization theorems:

- Proven to all orders in simple cases, e.g., DIS.
- Require a hard scale Q^2: allows ignoring graph suppressed by $\left(\frac{1}{Q^2}\right)^n$.
- Large $Q^2 \to$ small occupation number: at most 1 parton collided.



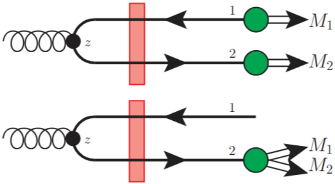
CGC:

- At small Q^2 and small x, the gluon occupation number is large.
- The CGC is an effective theory built to describe this regime.



Pictures taken from Gelis, Iancu, Jalilian-Marian, Venugopalan, Ann.Rev.Nucl.Part.Sci. 60 (2010).

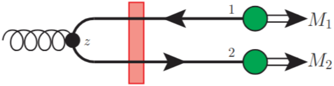
Color Glass Condensate effective theory



Dilute-dense colliding system:

- The gluon comes from the dilute proton.
- The red lines (the shock wave) represents the interaction of the of the $Q\bar{Q}$ with the dense proton.
- $0+1+2+...$ interactions.
- Standard Feynman rules + specific CGC rules (for the Wilson line).
- Single and double fragmentation.

Single fragmentation

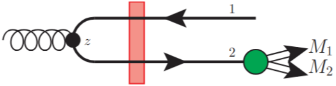


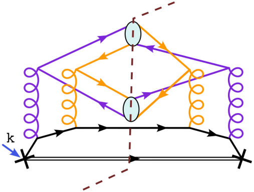
$$\frac{d\sigma_{g+\text{proton}\to H_1+H_2+X}}{dy_1 d^2\boldsymbol{P}_1^\perp dy_2 d^2\boldsymbol{P}_2^\perp} = \int \frac{dz_1}{z_1^2}\frac{dz_2}{z_2^2}\frac{d\hat{\sigma}_{g+P\to Q+\bar{Q}}}{dy_1 d^2\boldsymbol{p}_1^\perp dy_2 d^2\boldsymbol{p}_2^\perp} D_{Q\to H_1}(z_1) D_{Q\to H_2}(z_2)$$

with $\boldsymbol{P}_1^\perp = z_1\boldsymbol{p}_1^\perp$ and $\boldsymbol{P}_2^\perp = z_2\boldsymbol{p}_2^\perp$.

- Heavy numerical simulations for the fully-differential X-section.
- Integrating on transverse momenta simplifies the result.
- We considered two cases: $D_{c\to H}$ and $D_{b\to H}$.
- The FFs taken from literature: perturbative + NRQCD.

Double fragmentation



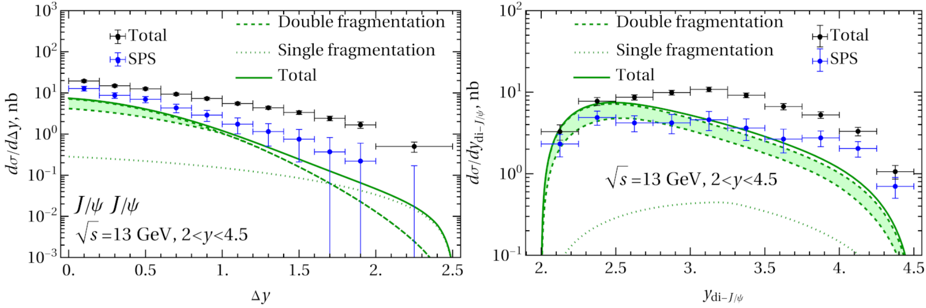


$$\frac{d\sigma_{g+\text{proton}\to H_1+H_2+X}}{dy_1 dy_2} = \int dz \left(\frac{d\hat{\sigma}_{g+P\to Q+\bar{Q}}}{dy_1 dy_2} \int_{\color{red}{M_{\text{min}}}} dM_{12} D_{b\to H_1 H_2}(z,\zeta,M_{12}) \right)$$

$$D_{b\to H_1 H_2}(z_1, z_2, M_{12}, R) \propto \frac{1}{4z} \sum_X \text{Tr}\{\gamma^+ \times \text{cut diagram}\}$$

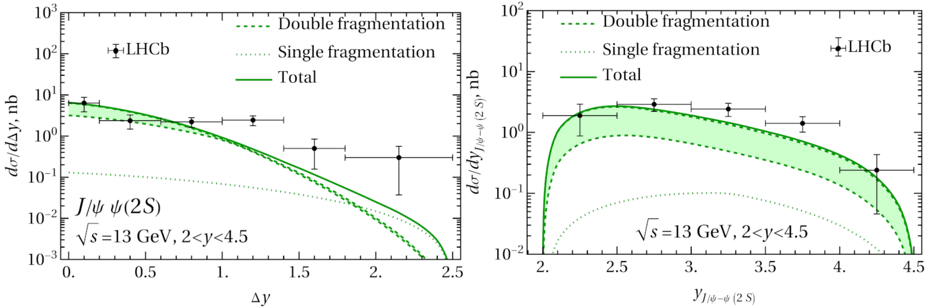
- The di-quarkonia FF was unknown.
- We did the calculation for the bottom quark with the help of Feyncalc.
- Not clear if our result is still valid at $M_{\text{min}} = 2m_{J/\psi}$ (near-threshold kinematics).

Results: double J/ψ



- Single fragmentation (SF) dominated by the charm contribution.
- SF negligible, except at large Δy.
- $M_{\text{min}} = 6.2$ and 7 TeV $\rightarrow$ theoretical uncertainty green color band.
- Our results show that the SPS contribution may be larger than expected.
- $\Rightarrow$ smaller DPS $\Rightarrow$ Larger σ_{eff}?

Results: J/ψ-$\psi(2S)$



Similar conclusions for the J/ψ-$\psi(2S)$ measurement.

Conclusion

- ⋆ We have evaluated the single- and double-fragmentation contribution to double-quarkonia production.
- ⋆ The double fragmentation is significant.
- ⋆ Possible smaller DPS (larger σ_{eff}): may bring agreement with other measurements.
- ⋆ We have computed for the first time the $D_{b \to H_1 H_2}$ di-quarkonia fragmentation function.

Thanks for your attention!