Longitudinal double-spin asymmetries for charmonium production

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Outline

- Short theoretical introduction: NRQCD-factorization and asymmetries
- Observables: p_T vs. rapidity-differential
- p_T-differential asymmetries at LO
- situation at NLO

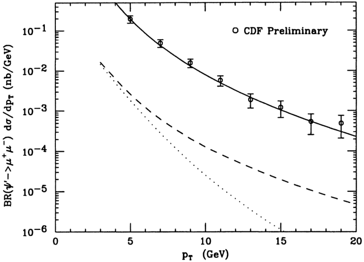
A bit of history

Historically, the first model of heavy-quarkonium production was the **color-singlet model**: *The production of state X_Q $(J/\psi, \chi_{cJ}, ..., \Upsilon(nS), \chi_{bJ}, ...)$ is dominated by production of* **color-singlet** *$Q\bar{Q}$-pair with L and S quantum numbers given by NR potential model for this state. Probability of hadronization is proportional to $|\Psi^{(k)}(0)|^2$, $(k = 0, 1, ...)$ from potential model.*

This model has two problems:

- Leads to a wrong shape of p_T-spectrum at high energies (Tevatron, LHC) both at LO and NLO of CPM and in k_T-factorization, which **under-estimates** the cross-section for $p_T > 10$ GeV by factor of 30 (*Tevatron $\psi(2S)$ puzzle*).
- Is **theoretically inconsistent at NLO for production of P-wave states:** In QCD, non-cancelling IR-divergences arise at NLO.

[Braaten, Fleming, 1994]



Dotted line – LO CPM color-singlet contribution. Solid line – ${}^3S_1^{(8)}$.

NRQCD factorization

To solve above-mentioned problems, two approaches have been proposed: **NRQCD-factorization** and **Color-Evaporation Model**.

- **NRQCD-factorization:** *Different L, S and* **color** *states of $Q\bar{Q}$-pair hadronize to X with different "probability" –* **long-distance matrix element (LDME):** $\left\langle \mathcal{O}^X \left[{}^{2S+1}L_J^{(\text{color})} \right] \right\rangle$.
- LDME-s of states different from CSM-state are suppressed by powers of v^2 (~ 0.3 for J/ψ, ~ 0.1 for Υ) – *velocity-scaling rules for LDMEs*. E.g. for J/ψ and $\psi(2S)$: CSM$={}^3S_1^{(1)} = O(1)$ and ${}^3P_J^{(8)}$ and ${}^3S_1^{(8)}$, ${}^1S_0^{(8)}$, contribute up to $O(v^4)$.

Double-spin asymmetry

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\Delta\sigma}{\sigma},$$

Collinear Parton Model + NRQCD-factorization:

$$\Delta\sigma = \sum_{n} \langle \mathcal{O}^X[n] \rangle \sum_{i,j} \Delta f_i \otimes \Delta f_j \otimes \Delta\hat{\sigma}_{ij}[n],$$

$$\sigma = \sum_{n} \langle \mathcal{O}^X[n] \rangle \sum_{i,j} f_i \otimes f_j \otimes \hat{\sigma}_{ij}[n].$$

Possible observables:

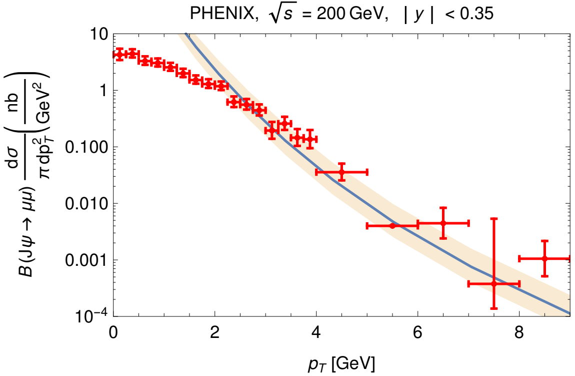
- p_T-**dependent** (and y-dependent) asymmetry:
  - $2 \to 2$: $\boxed{i + j \to c\bar{c}[n] + k}$ processes at LO ⇒ **NLO-complicated**
  - scale $\mu \sim \sqrt{M^2 + p_T^2}$, CPM valid for $p_T > M$
- p_T-**integrated**, y-dependent asymmetry
  - $2 \to 1$: $\boxed{i + j \to c\bar{c}[n]}$ processes at LO ⇒ **NLO-simple** (but not done yet...)
  - scale $\mu \sim M$

Some references

- Un-polarized partonic cross-sections $\hat{\sigma}_{ij}[n]$ are well-known at LO.
- p_T**-dependent** asymmetry first studied at LO in [Teryaev, Tkabladze, Phys.Rev.D 56 (1997) 7331-7340], but expressions for $\Delta\hat{\sigma}_{ij}[n]$ are not given
- LO results for $\Delta\hat{\sigma}_{ij}[n]$ are written in [Klasen, Kniehl, Steinhauser, Phys.Rev.D **68** (2003) 034017, hep-ph/0306080], however I have some issues with this results, they need to be checked. In the present analysis **only gluon-gluon channels** are included, which I have reproduced.
- p_T**-dependent** asymmetry was studied at NLO in [Feng, Zhang, JHEP **11** (2018) 136]
- p_T**-integrated** asymmetry first studied in [Gupta, Mathews, Phys.Rev.D **55** (1997) 7144-7151]
- NLO results for **un-polarized** p_T**-integrated** partonic cross-sections had been obtained in closed form in [Petrelli, Cacciari, Greco, Maltoni, Mangano, Nucl.Phys.B **514** (1998) 245-309]

Validation: PHENIX data

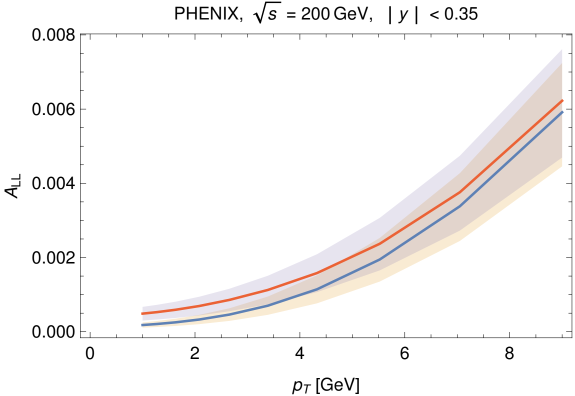
LO LDMEs from [Braaten, Kniehl, Lee, Phys.Rev.D**62** (2000) 094005] together with `NNPDF30_nlo_as_0119_nf_6` PDF set and `NNPDFpol11_100` polarized PDF set.
The J/ψ p_T-spectrum from RHIC had been reproduced, taking into account direct and feed-down contributions:



Asymmetry and uncertainties

At LO, main uncertainty in LDMEs comes from the fact, that LO fits determine only linear combination of LDMEs:

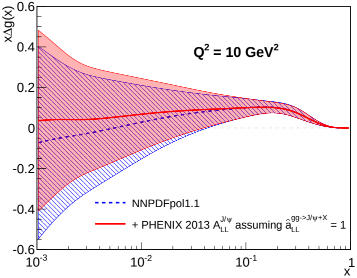
$$\mathcal{M}_8 = \left\langle \mathcal{O}^{J/\psi}\left[{}^1S_0^{(8)}\right]\right\rangle + \frac{r}{m_c^2}\left\langle \mathcal{O}^{J/\psi}\left[{}^3P_0^{(8)}\right]\right\rangle,\ r = 3.5$$



Bands – scale uncertainties, blue curves – $\mathcal{M}_8$ saturated by ${}^1S_0^{(1)}$, orange – ${}^3P_0^{(1)}$.

Validation: PHENIX data

Plot from hep-ex/1606.01815:



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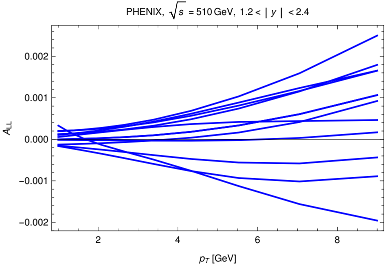
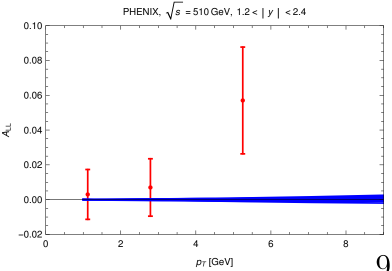
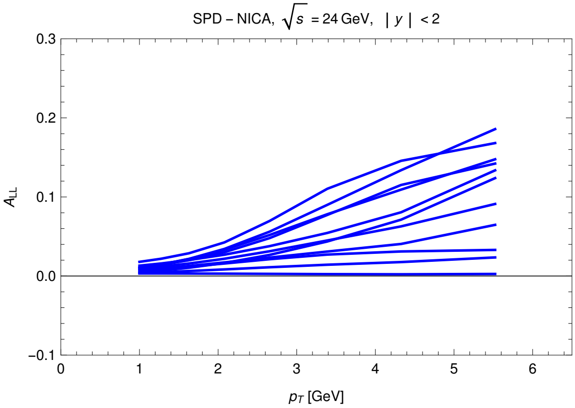
Results for different replicas of Δg vs. PHENIX data:





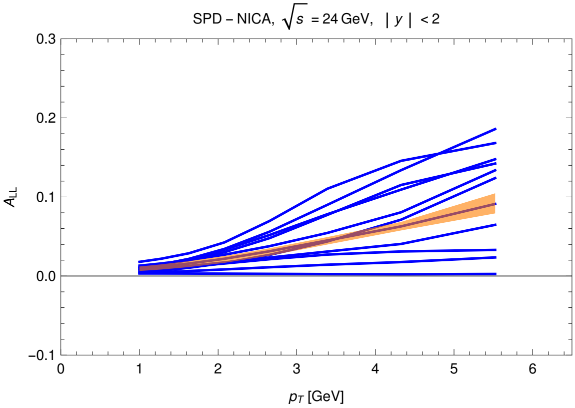
LO asymmetry at 24 GeV

A_{LL} for ten replicas of Δg:



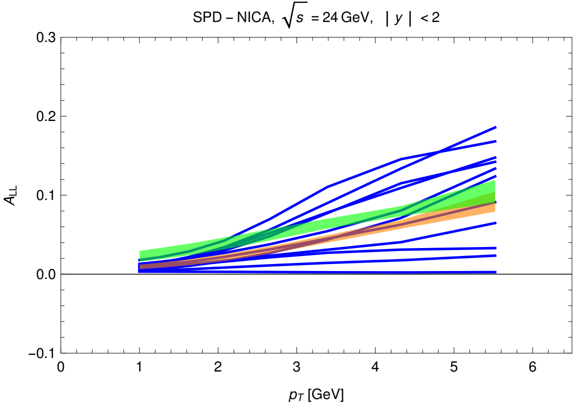
LO asymmetry at 24 GeV

A_{LL} for ten replicas of Δg, band– scale:



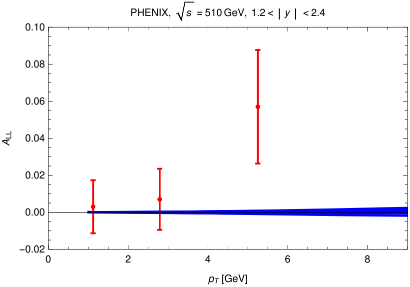
LO asymmetry at 24 GeV

A_{LL} for ten replicas of Δg, bands – scale and LDME-variation :

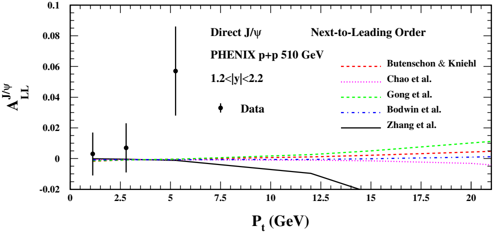


CAUTION: different LDME sets at NLO!

Compare A_{LL} for different replicas:



with it's **LDME-set dependence at NLO** [Feng, Zhang, JHEP **11** (2018) 136]:



Outlook

- A_{LL} up to 10% for J/ψ at NICA is consistent with latest NNPDF parametrization for Δg
- At LO, LDME and scale uncertainties look small, but this may be misleading
- Estimates in color-evaporation model should be done
- LDME sets predicting different polarization of quarkonium at high-p_T lead to significantly different asymmetry at RHIC. Impact for NICA is not clear...
- if color-singlet model for η_c is correct, then there is no LDME-set problem for this state!

Thank you for your attention!