Physics with charmonia at SPD

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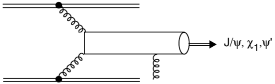
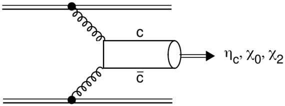
J/ψ production in hadronic collisions

- Extraction of TMD PDFs from DY at SPD is complicated experimentally.
- J/ψ (and charmonia) production:
  - is sensitive to gluon and quark PDFs,
  - has large cross-section and very distinct signal in the dimuon mode,
  - is theoretically ambiguous,
  - is a sum of direct and feed-down processes.
- J/ψ production is complimentary to the **DY** and **prompt photons** studies.
- Study and verification of J/ψ production mechanisms would be crucial for extraction of gluon PDF in AMBER at similar c.m.s. energies.



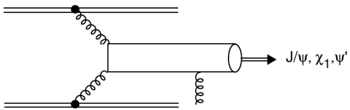


Diagrams from
Int.J.Mod.Phys.A10:3043-3070,1995

J/ψ production Vs. DY

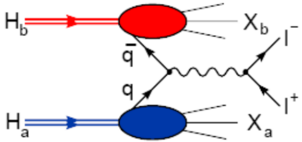
$$\sqrt{s} = 24 - 26\text{GeV}$$

J/ψ:



- cross-section of 150-250 nb,
- clean dimuon mode (9-15 nb),
- 20M J/ψ are expected to be produced at SPD per year (LOI),
- sensitive to gluon and quark PDFs,
- J/ψ production is suggested to probe the Sivers effect for gluons in pp collisions (PRD96 036011 (2017), Boer 2017)) and quark spin asymmetries in $\bar{p}p$ collisions (Phys.Lett.B594(2004)97, hep-ph/0604176).

DY:



- cross-section $\approx 0.06 - 0.07$ nb for $M(l^+l^-) > 4\text{GeV}$,
- only quarks,
- much more simple process, no model-dependence.

Feed-down contributions

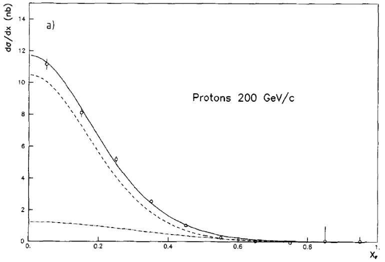
- $\chi_{cJ} \to \gamma J/\psi$: $\approx 30\%$

Tech	$\sqrt{s}$ (GeV)	$\frac{\sigma(\chi_{cJ})Br(\chi_{cJ}\to\gamma J/\psi)}{\sigma(J/\psi)}$, $J = 1, 2$	Note
E673	18.9	0.47 ± 0.23	pBe
E705	23.8	0.30 ± 0.04	pLi
HERA-B	41.6	$0.188 \pm 0.013^{+0.024}_{-0.022}$	pA, $-0.35 < xF < 0.15$
E806	62	0.47 ± 0.08	pp

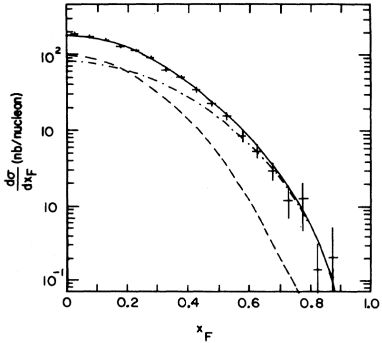
- $\psi' \to J/\psi X$: $\approx 10\%$
- In total feed-down contributions account for $\approx 40\%$ of the inclusive cross-section.
- The are no feed-down contributions for ψ'.

One separation of quark-antiquark annihilation and gluon fusion in the past

Hard part of $d\sigma/dx_F$ for pp ($\sqrt{s} = 19$ GeV) fitted by NA3 (Z.Phys.C 20,101(1983)). Dashed line is gluon fusion and dot-dashed is $q\bar{q}$ annihilation.



$d\sigma/dx_F$ for $\bar{p}W$ ($\sqrt{s} = 15$ GeV) fitted by E537 (PRD 48 5067 (1993)). Dashed line is gluon fusion and dot-dashed is $q\bar{q}$ annihilation.



Current approaches to quarkconia production

- Color evaporation model (CEM)

- Non-relativistic QCD (NRQCD)

Color evaporation model

Phys.Rev.C61:035203,2000

- Inclusive ($A + B \to J/\psi + X$) production is proportional to cross-section of $c\bar{c}$ production below open charm threshold (e.g. see PRC 61 035203).

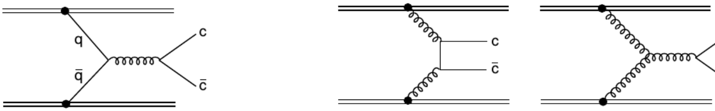
$$\frac{d\sigma_H^{AB}}{dx_F} = F_H \int_{4m_c^2}^{4m_D^2} \frac{dm^2}{\sqrt{x_F^2 s^2 + 4m^2 s}} H_{AB}(x_1, x_2, m^2),$$

where

$$H_{AB}(x_1, x_2, m^2) = f_g^A(x_1) f_g^B(x_2) \cdot \hat{\sigma}_{gg}(m^2) + \sum_{q=u,d,s} \left[f_q^A(x_1) f_{\bar{q}}^B(x_2) + f_{\bar{q}}^A(x_1) f_q^B(x_2) \right] \hat{\sigma}_{q\bar{q}}(m^2),$$

$$x_{1,2} = \frac{1}{2}\left(\pm x_F + \sqrt{x_F^2 + 4m^2/s} \right).$$

- F_H are assumed to be process independent.
- LO $c\bar{c}$ production diagram (calculations beyond LO are also available):

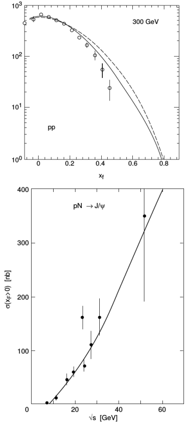


(diagrams from Int.J.Mod.Phys.A10(1995) 3043)

Color Evaporation Model

- **Sum over colors and spins of $c\bar{c}$ pair is assumed** (emission of one or more soft gluons is assumed to neutralize color). **No predictions on charmonia polarization.**
- Relative contributions from $q\bar{q}$ annihilation and gg fusion is given by parton cross-sections and can be validated with x_F distribution.
- CEM predicts $\sqrt{s}$-dependence.
- The p_T can be approximately reproduced with NLO and random k_T-smearing for Tevatron energies.
- Process independence of F_H factors holds only approximately (Phys.Rev. D72 (2005) 014004).
- In PRD85, 094013 (2012) used to estimate TSSA for photoproduction of J/ψ.

Data from E705 Collaboration



Figures from Int.J.Mod.Phys.A10(1995) 3043

NRQCD

NRQRD

Phys.Rev.D54:2005,1996

For the process $A + B \to H + X$ in the collinear factorization:

$$\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{i/B}(x_2) \hat{\sigma}(ij \to H).$$

1. **Conjecture** of the cross-section factorization to short-distance ($x \approx 1/m_c$) and long-distance parts:

   $$\hat{\sigma}(ij \to H) = \sum_n C^{ij}_{Q\bar{Q}[n]} \langle O^H_n \rangle.$$

   $C^{ij}_{Q\bar{Q}[n]}$ (SDC) describe heavy quark pair production, $\langle O^H_n \rangle$ long distance matrix elements (LDME) describe its hadronization to quarkonium H and $n = {}^{2S+1} L^{(1,8)}_J$.
   Proven only for sufficiently large p_T.
2. **Hierarchy** of LDME $\langle O^H_n \rangle$ with respect to v ($v^2 \approx 0.2-0.3$ for charmonium).

Expression for cross-section is a **double** series in α_s and v. There are indications that the series is well-converged.

NRQCD

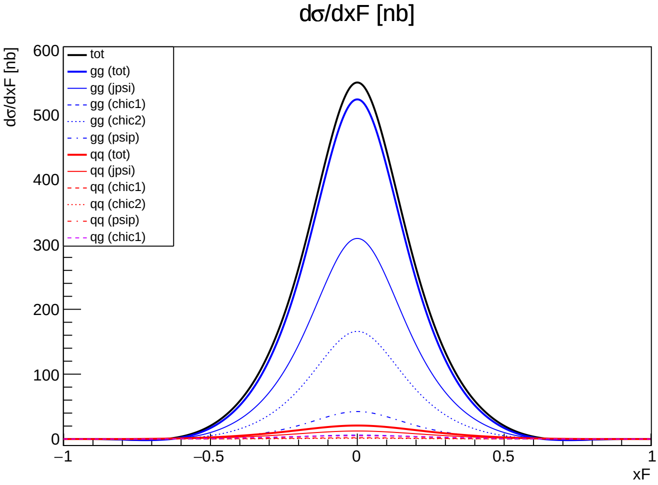
Ingredients:

- **SDC** are determined from NRQCD.
- The **singlet LDME** are determined from charmonium decays or charmonium wave function in potential models ($O(v^2)$).
- The **octet LDME** are determined from the fits to experimental data.
- The are **lattice** calculations only for $\langle O_1^{\chi_{cJ}}(^3P_J)\rangle$ and $\langle O_8^{\chi_{cJ}}(^3S_1)\rangle$ (Phys.Rev.Lett.77(1996)2376). They are reasonably consistent with global fits (Braaten, Lectures on NRQCD factorization).

Predictions:

- x_F, sensitive to relative contributions from quark-antiquark annihilation and gluon-gluon fusion;
- p_T in for $p_T > 2m_c$ for collinear factorization (not at SPD energies);
- charmonia polarization;
- $\sqrt{s}$ dependence.

$d\sigma/dx_F$: contribution of subprocesses

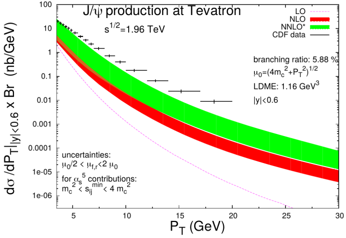


- pp at $\sqrt{s} = 26$ GeV
- Formulas and LDME from Phys.Rev.D54:2005,1996
- PDF: NNPDF23 NLO

NRQCD: NLO

- **LO NRQCD fits**: **severe inconsistency** in LDME (Tevatron data + cross-section of the fixed target experiments (Beneke and Rothstein, 2005)), unable to described J/ψ polarization.
- **NLO corrections are significant** (here as function of p_T):

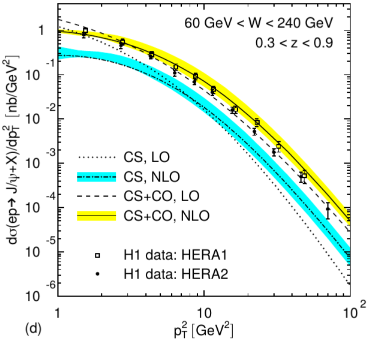
Color singlet:



Plot by Artoisenet based on work by Artoisenet, Campbell, Lansberg, Maltoni, Tramontano.

Complete NLO:

Butenschon and Kniehl (2010), Ma, Wang, and Chao (2010).

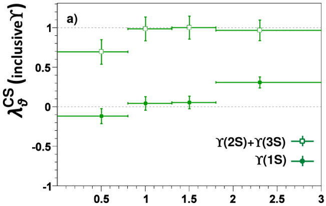


Plot from Butenschon and Kniehl (2010)

J/ψ polarization

- $d\sigma/d\cos\theta \propto 1 + \alpha\cos^2\theta$
  - $\alpha = 1$ – transverse
  - $\alpha = -1$ – longitudinal
- The J/ψ polarization is **sensitive to elementary J/ψ production processes** and is a **nontrivial test to the NRQCD**.
- **NLO corrections are significant** (Butenschoen and Kneihl, 2013)
- **Polarization of χ_{cJ} states has not been measured yet!**
- Previous measurement from fixed-target experiments are not precise and may suffer from 1D efficiency corrections (Faccioli, Mod. Phys. Lett. A Vol. 27, 1230022 (2012))

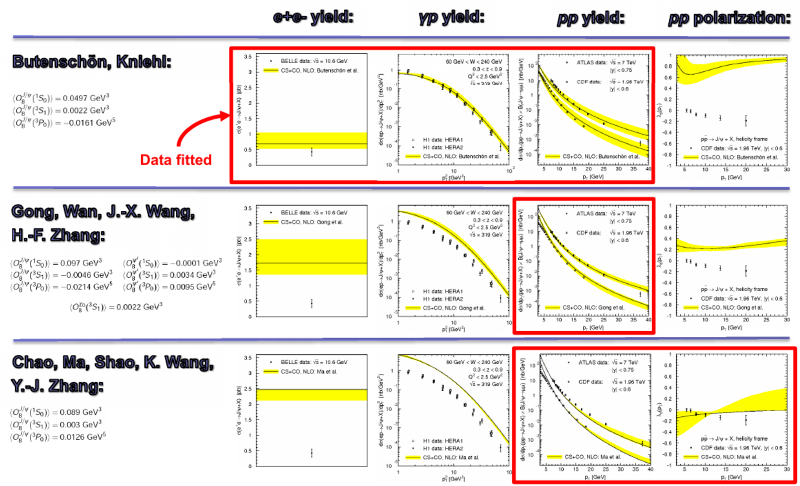
Feed-down contributions may play significant role in the polarization puzzle!



E866 data on Υ polarization. Figure from Mod.Phys.Lett. A27 (2012) 1230022

NLO NRQCD fits

Slide borrowed from M. Butenschon DIS 2016 (DESY Hamburg)



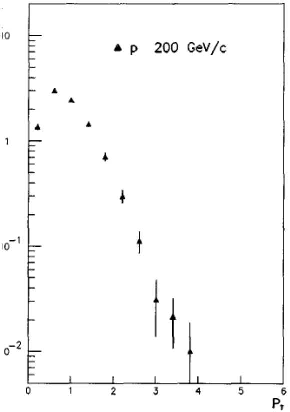
Details in Mod.Phys.Lett.A,Vol.28,No.9(2013) 1350027.

No SDML set can described all e^+e^-, γp, pp and pp polarization data.

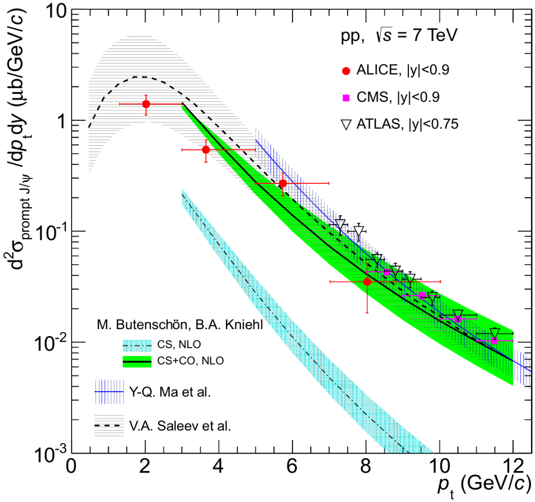
The SPD p_T range below 3-4 GeV is very complicated for the analysis:

- Collinear factorization is not applicable below 4 GeV (or even higher values) and the p_T spectrum diverges for $p_T \to 0$.
- k_T of hadrons must be taken into account.
- Parton reggeization approach (PRA, Kniehl, Vasin, Saleev 2006) is expected to work in the SPD p_T range. See the dedicated previous talk.
- k_T-factorization approach of Baranov and Lipatov (Eur.Phys.J.C75(2015)no.9,455, Phys.Rev. D93 (2016) no.9, 094012, ...) may be also applicable.
- In the k_T factorization approaches partons become massive, which notable affects polarization of charmonia states.

The J/ψ p_T distribution from NA3 at $\sqrt{s} = 19.4$ GeV



PRA: $d\sigma/dp_T$

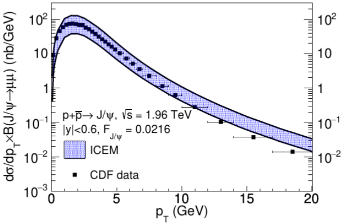


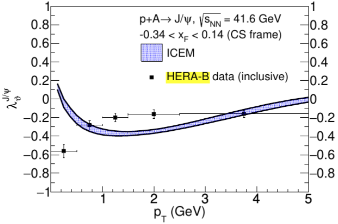
ALICE Collaboration, JHEP 1211 (2012) 065

ICEM

Improved CEM (ICEM, Phys.Rev.D 94, 114029 (2016), Phys.Rev. D98 114029 (2018)):

- PRA,
- $c\bar{c}$ pair must be produced with invariant mass above the mass of charmonia state and below open charm threshold,
- hadronization does not change angular momentum of $c\bar{c}$ pair.





Phys.Rev. D98 114029 (2018)

Charmonia group

Our group:

- Alexey Guskov
- Igor Denisenko
- Jose Rubiera
- Dario Zaldivar

Jose and Dario have done everything possible with the current detector description and available software. It is not possible to proceed to more realistic studies without tracking and detailed simulation of the detector subsystems.

Summary

- Charmonia production is a powerful tool to probe parton distributions. It is complimentary to the DY and prompt photons program. It seems that SPD may obtain important results.
- Modern k_T-factorization approaches are expected to be appropriate in our kinematic region.
- We have a group working on simulation, but in the absence of tracking and detailed description of detector subsystems and their performance we can do only basic simulation of physical processes.
- For the moment exclusive charmonia production has not been considered, and such contribution would be welcome.

Thank you!

Backup

Dimuon spectrum from NA51 ($\sqrt{s} = 29.1$ GeV)