Study of charmonia production in hadron collisions at SPD

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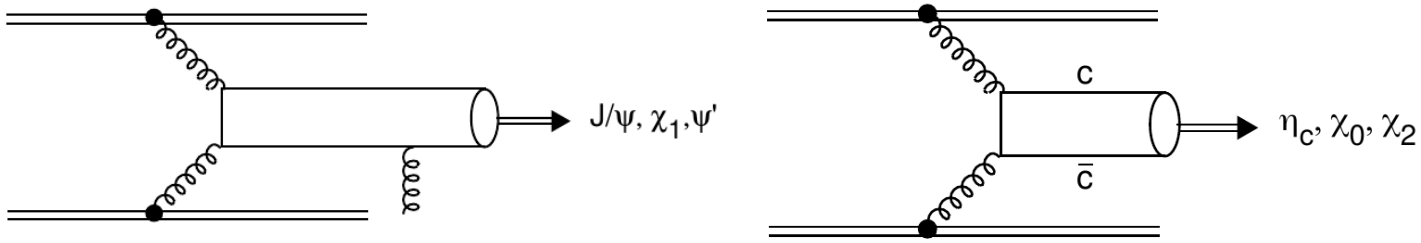
J/ψ production in hadronic collisions

- J/ψ production in hadronic collisions is a powerful tool to access gluon distributions in hadrons. In case of pion and kaon (the gluon pdf of the pion is poorly known and the gluon pdf of kaon has not been measured yet) it is one two processes that allow measurement of gluon pdf.
- Applicability of the method is limited due the lack of understanding J/ψ (and charmonia in general) production mechanism.
- Proton-proton collisions at SPD provide ideal opportunity for verification of theoretical approaches to J/ψ production.
- A remarkable feature of the SPD detector (compared to "typical" DY experiments) is a potential ability to study production of other charmonium states.
- If inclusive J/ψ production is used to probe spin asymmetries, contribution of $q\bar{q}$ annihilation in J/ψ production must be known for interpretation of results.

Inclusive J/ψ production

The inclusive J/ψ production:

- For SPD the expected number of produced J/ψ events is approximately 20 million per year ($\sqrt{s} = 24-26$ GeV, PYTHIA).
- Charmonia production is sensitive to gluon distributions of colliding hadrons.

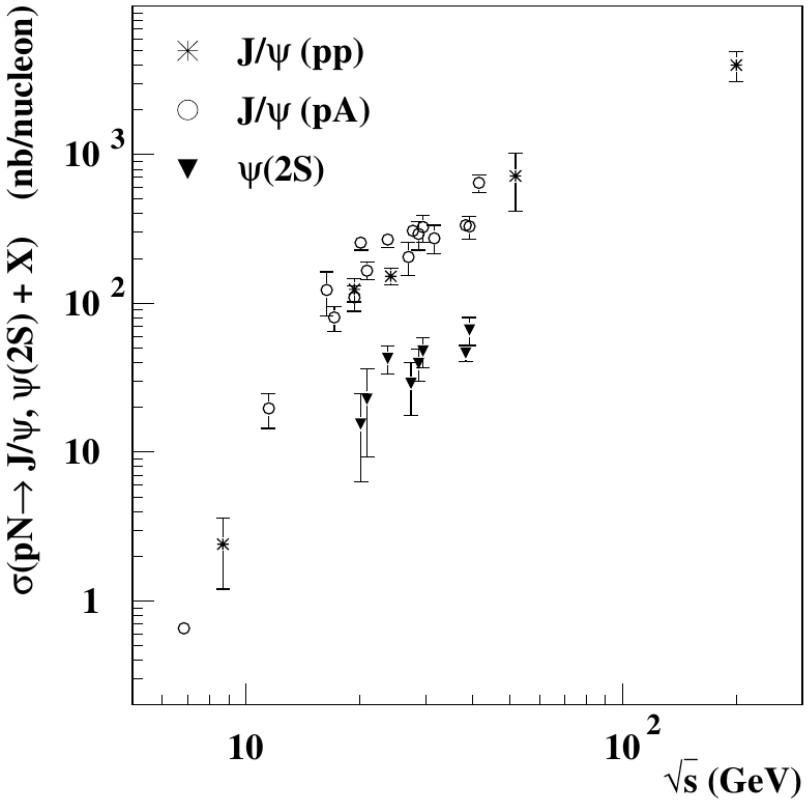


CS diagrams from Int.J.Mod.Phys.A10:3043-3070,1995

- Despite the J/ψ production mechanisms have been long studied, they are not well understood.
- Analysis of the process is further complicated by J/ψ produced through decays of charmonium states with higher mass (approximately 10% from ψ' and 30% from χ_{c1} and χ_{c2}).
- Observables: total **cross-section**, $\mathbf{p_T}$, $\mathbf{x_F}$ and **polarization**.

Total cross-section (J/ψ and ψ')

The J/ψ production in fixed-target experiments and low energy *pp* collisions. The cross-section for nuclear target is $\sigma^{pA}_{J/\psi} = \sigma_{J/\psi} \cdot A^{\alpha}$, where $\alpha = 0.96$.

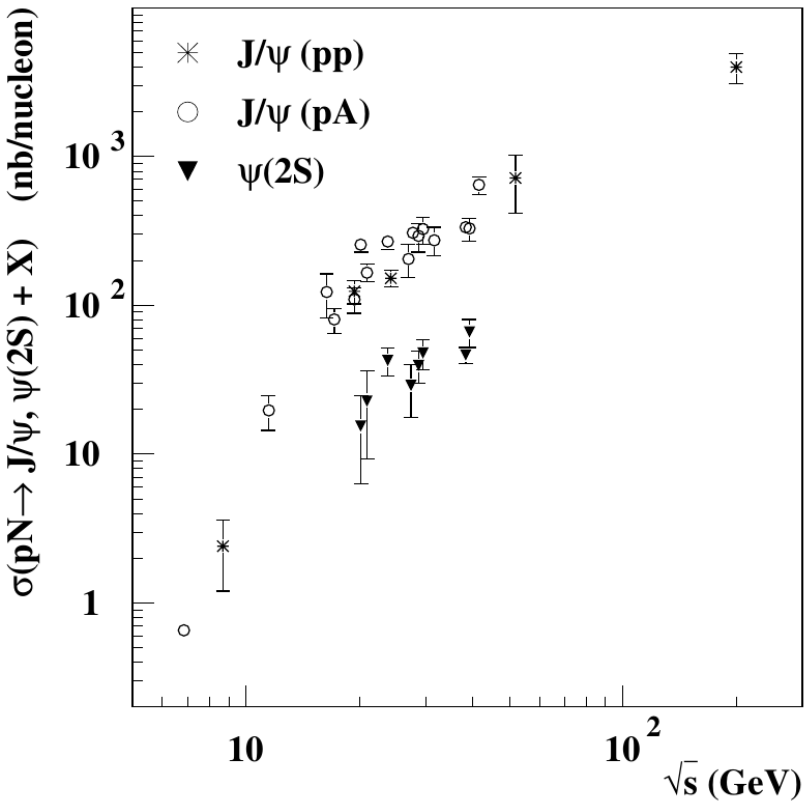


Experiment	Reaction	$\sqrt{s}$ (GeV)	$\frac{d\sigma_{J/\psi}}{dy}\|_{y=0}$ (nb/nucleon)	$\sigma_{J/\psi}$ (nb/nucleon)
CERN-PS [23]	pA	6.8		0.65 ± 0.06
WA39 [24]	pp	8.7		2.4 ± 1.2
IHEP [25]	pBe	11.5	16 ± 5.2	20 ± 5.2
E331 [26]	pBe	16.8	84 ± 20	122 ± 40
NA3 [27]	pPt	16.8		80 ± 15
NA3 [27]	pPt	19.4		110 ± 21
NA3 [27]	pp	19.4		124 ± 22
E331 [28]	pC	20.6		256 ± 30
E444 [29]	pC	20.6		166 ± 23
ISR [30]	pp	23.0	100 ± 77	
E705 [31]	pLi	23.8		267 ± 30
UA6 [32]	pp	24.3	104 ± 19	152 ± 20
E288 [33]	pBe	27.4	131 ± 33	204 ± 51
E595 [34]	pFe	27.4	187 ± 12	306 ± 18
NA38/51 [35, 36]	pA	29.1	169 ± 13	292 ± 64
NA50 [37]	pA	29.1	188 ± 14	325 ± 67
ISR [38]	pp	30	154 ± 42	
ISR [39]	pp	30.6	111 ± 30	
ISR [30]	pp	31	142 ± 93	
E672/706 [40]	pBe	31.6		274 ± 60
E771 [41]	pSi	[illegible]	[illegible]	[illegible]

Figure and table from Phys.Lett.B638:202-208,2006.

Total cross-section (J/ψ and ψ')

The ψ' production in fixed-target experiments and low energy *pp* collisions. The cross-section for nuclear target is $\sigma^{pA}_{\psi'} = \sigma_{J/\psi'} \cdot A^{\alpha}$, where $\alpha = 0.96$.



Experiment	Reaction	$\sqrt{s}$ (GeV)	$\sigma_{\psi(2S)}$ (nb/nucleon)	$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ (R_{ψ})
E331 [28]	pC	20.6	15.4 ± 9.1	0.060 ± 0.035
E444 [29]	pC	20.6	22.8 ± 13.5	0.137 ± 0.079
E705 [31]	pLi	23.8	42.5 ± 9.0	0.159 ± 0.029
E288 [33]	pBe	27.4	28.9 ± 11.3	0.141 ± 0.042
NA38/51 [35, 36]	pA	29.1	39.3 ± 9.6	0.135 ± 0.015
NA50 [37]	pA	29.1	47.1 ± 10.9	0.145 ± 0.017
E771 [41]	pSi	38.8	46.3 ± 5.7	0.139 ± 0.020
E789 [42]	pAu	38.8	66.1 ± 14.1	0.202 ± 0.055

- ψ' production cross-section is by ≈ 0.15 lower than for J/ψ;
- $Br(\psi' \to \mu^+\mu^-) \approx 0.1 \times Br(J/\psi \to \mu^+\mu^-)$;
- The ψ' statistics is expected to worser by factor of 60, but there are no feed-down contributions!

Figure and table from Phys.Lett.B638:202-208,2006.

Measurements of χ_c production

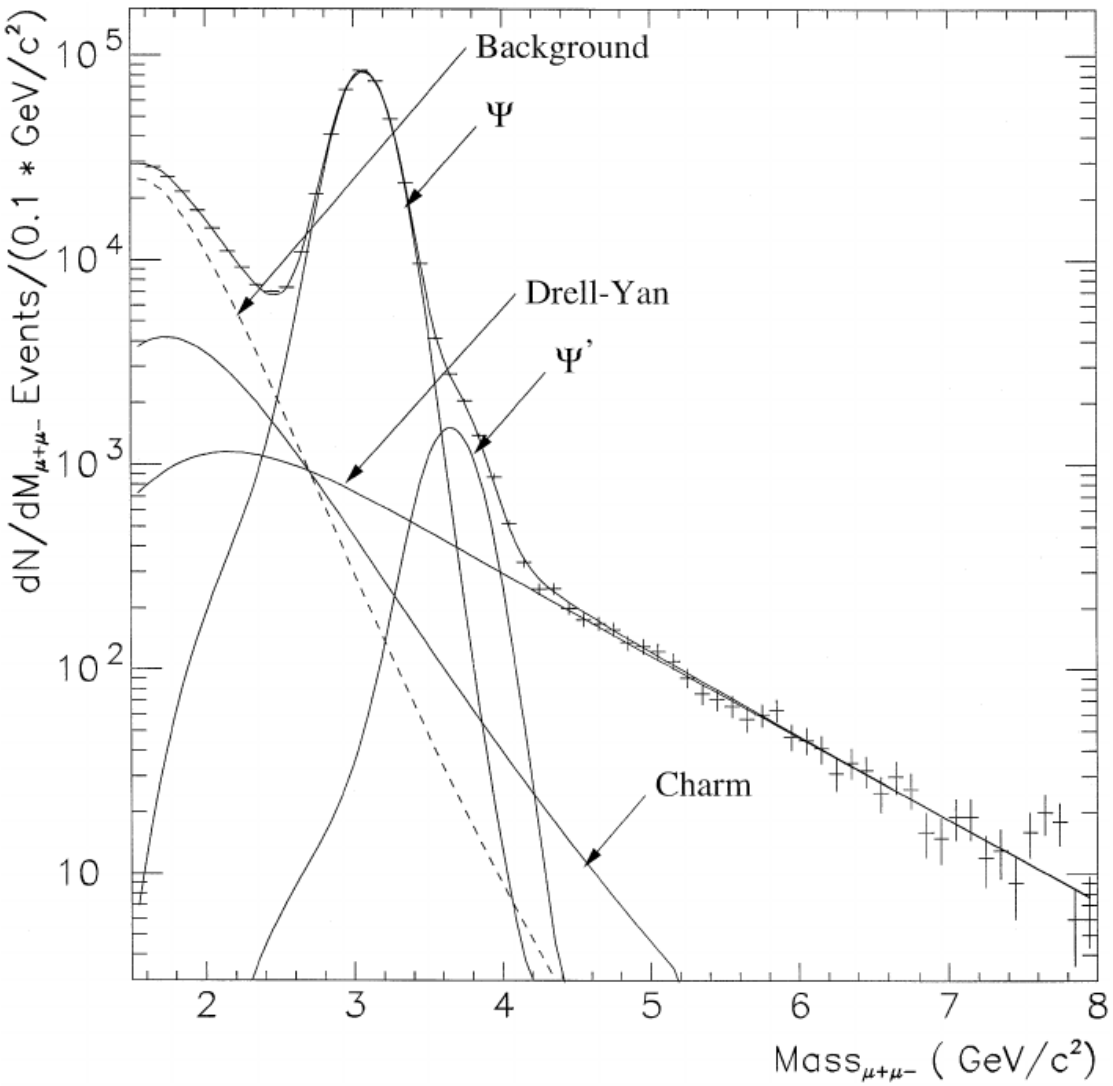
The relative fraction of indirect to prompt J/ψ is usually reported.

Table: Ratio of J/ψ events produced in χ_c decays.

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

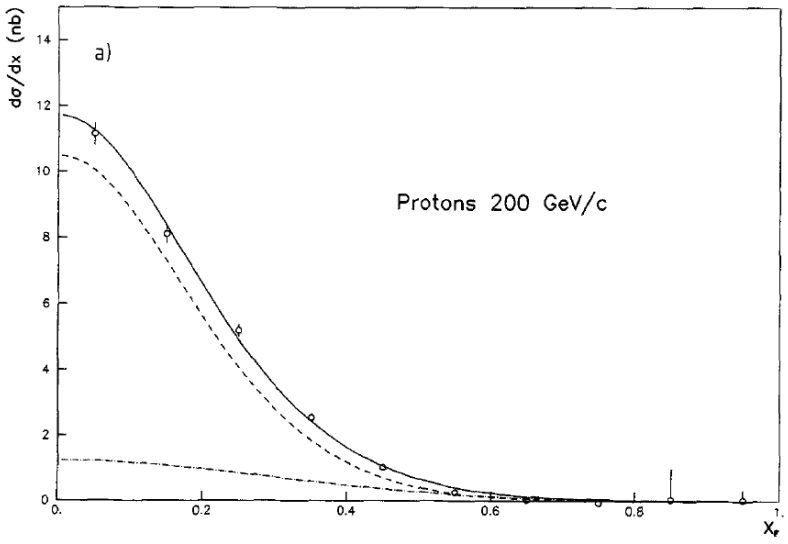
Relative contribution of J/ψ events of order of 30% is expected.

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

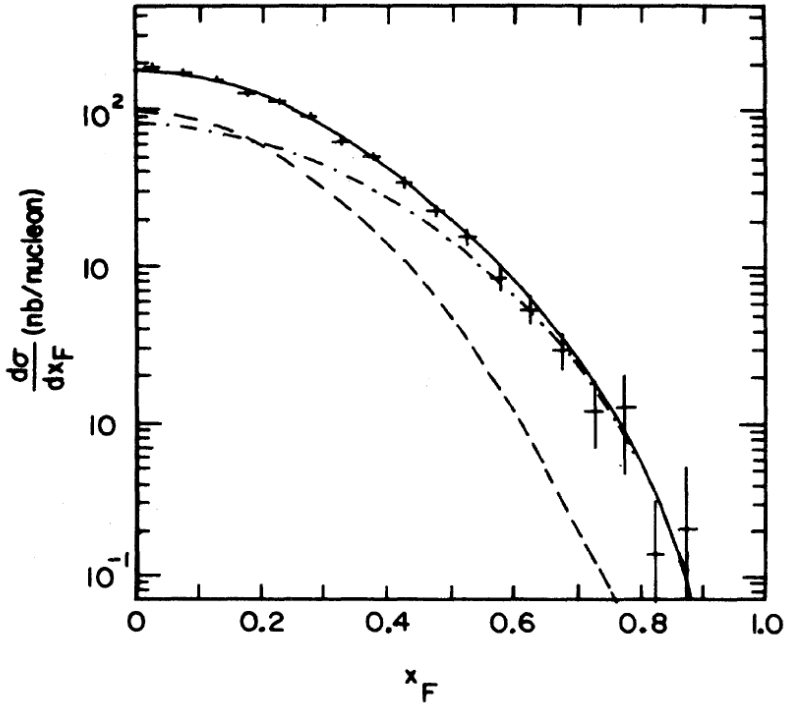


One separation of quark-antiquark annihilation and gluon fusion in the past

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)
- NRQCD

Color evaporation model

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).

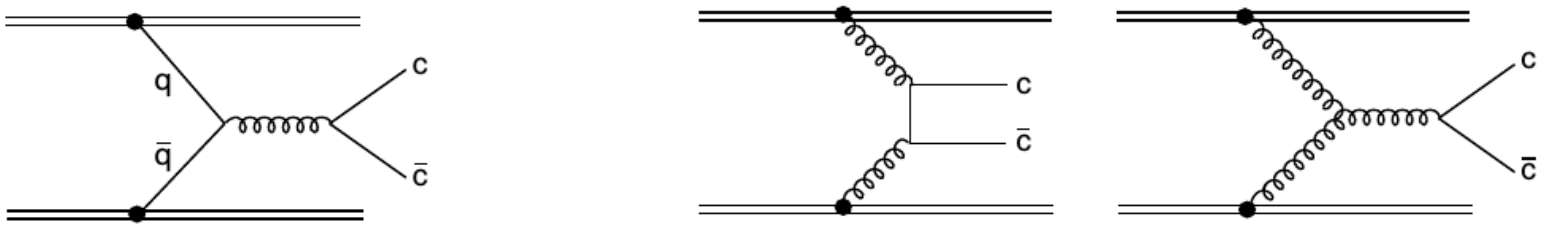
$$\frac{d\sigma_H^{AB}}{dx_F} = F_H \int_{4m_c^2}^{4m_D^2} \frac{dm^2}{\sqrt{x_F^2 s^2 + 4m^2 s}} H_{AB}(x_1, x_2, m^2),$$

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):

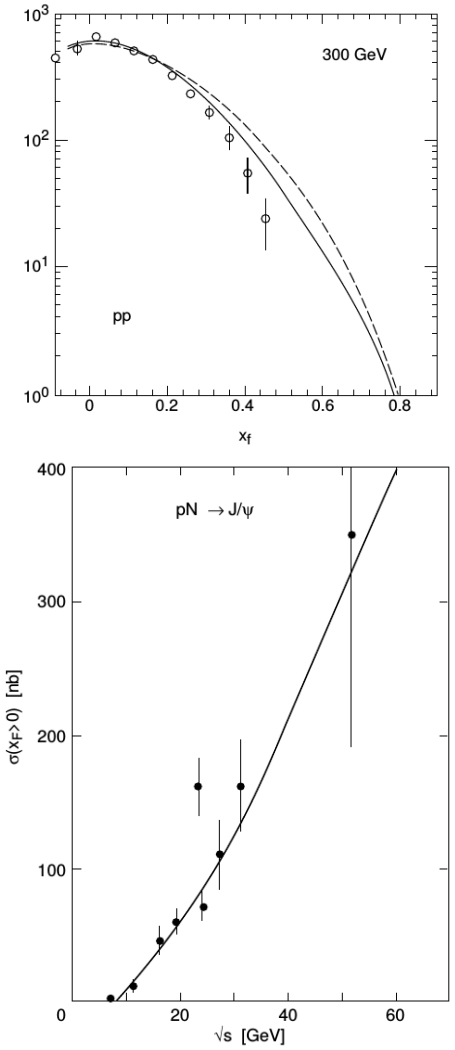


(diagrams from Int.J.Mod.Phys.A10(1995) 3043)

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.**
- The p_T can be approximately reproduced with NLO and random k_T-smearing for Tevatron energies.
- The predicated x_F distribution can be used to separate $q\bar{q}$ and gg contributions.
- CEM predicts $\sqrt{s}$-dependence.
- Factors F_H should be constant and process and energy independent ("feed-down" contribution sometimes are included in F_H). Holds only approximately (Phys.Rev. D72 (2005) 014004).

Data from E705 Collaboration



(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:

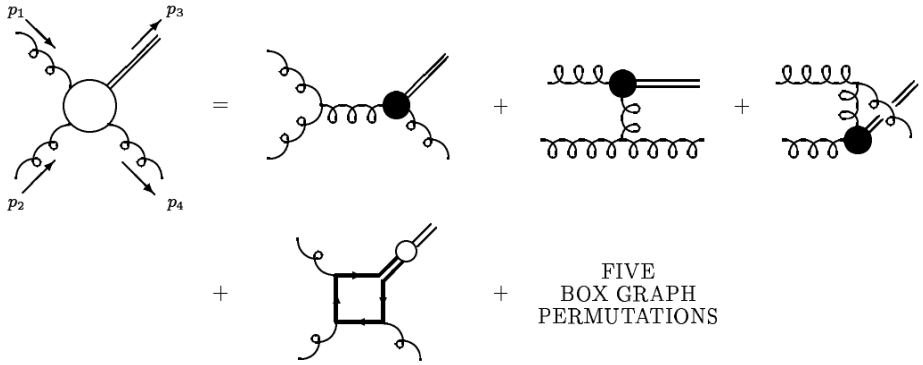
$$\sigma_H = \sum_{i,j} \int_0^1 dx_1 dx_2 f_{i/A}(x_1) f_{i/B}(x_2) \hat{\sigma}(ij \to H).$$

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 $n =^{2S+1} L_J^{(1,8)}$. **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.

NRQRD: diagrams

- Example 1: LO same as shown for the CEM model.
- Example 2: diagrams (NLO process) which mediate $q\bar{q} \to J/\psi g$, $qg \to J/\psi q$ and $gg \to J/\psi g$ through $c\bar{c}(^3P_J^{(8)})$ $c\bar{c}(^1S_0^{(8)})$ (*from Phys.Rev. D53 (1996) 6203-6217):*



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, separate 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.

NRQRD: explicit formulas for $\hat{\sigma}(ij \to H)$ for J/ψ and ψ'

Phys.Rev.D54:2005,1996

Example: parton scattering explicit formulas for J/ψ and ψ' ($\alpha_s^2 v^7$ and $\alpha_s^3 v^3$)

$$\begin{aligned}
\hat{\sigma}(gg \to \psi') &= \frac{5\pi^3\alpha_s^2}{12(2m_c)^3 s}\,\delta(x_1x_2 - 4m_c^2/s)\left[\langle \mathcal{O}_8^{\psi'}(^1S_0)\rangle + \frac{3}{m_c^2}\langle \mathcal{O}_8^{\psi'}(^3P_0)\rangle + \frac{4}{5m_c^2}\langle \mathcal{O}_8^{\psi'}(^3P_2)\rangle\right] \\
&\quad + \frac{20\pi^2\alpha_s^3}{81(2m_c)^5}\,\Theta(x_1x_2 - 4m_c^2/s)\,\langle \mathcal{O}_1^{\psi'}(^3S_1)\rangle\, z^2\left[\frac{1 - z^2 + 2z\ln z}{(1-z)^2} + \frac{1 - z^2 - 2z\ln z}{(1+z)^3}\right] \\
\hat{\sigma}(gq \to \psi') &= 0 \\
\hat{\sigma}(q\bar{q} \to \psi') &= \frac{16\pi^3\alpha_s^2}{27(2m_c)^3 s}\,\delta(x_1x_2 - 4m_c^2/s)\,\langle \mathcal{O}_8^{\psi'}(^3S_1)\rangle
\end{aligned}$$

where $z(x_1, x_2) = (2m_c)^2/(sx_1x_2)$.

- 6 LDME for the direct ψ production.
- The singlet LDME ($\langle O_1(^3S_1)\rangle$) is determined from charmonium decays or charmonium wave function in potential models.
- The $\langle O_8(^3S_1)\rangle$ LDME is extracted from large p_t Tevatron data.
- $\Delta_8 = \left[\langle O_8^{\psi'}(^1S_0)\rangle + \frac{3}{m_c^2}\langle O_8^{\psi'}(^3P_0)\rangle + \frac{4}{5m_c^2}\langle O_8^{\psi'}(^3P_2)\rangle\right]$ is extracted from fit to data of fixed-target energies.

NRQCD: on $\hat{\sigma}(ij \to H)$ for χ_{cJ}

Phys.Rev.D54:2005,1996

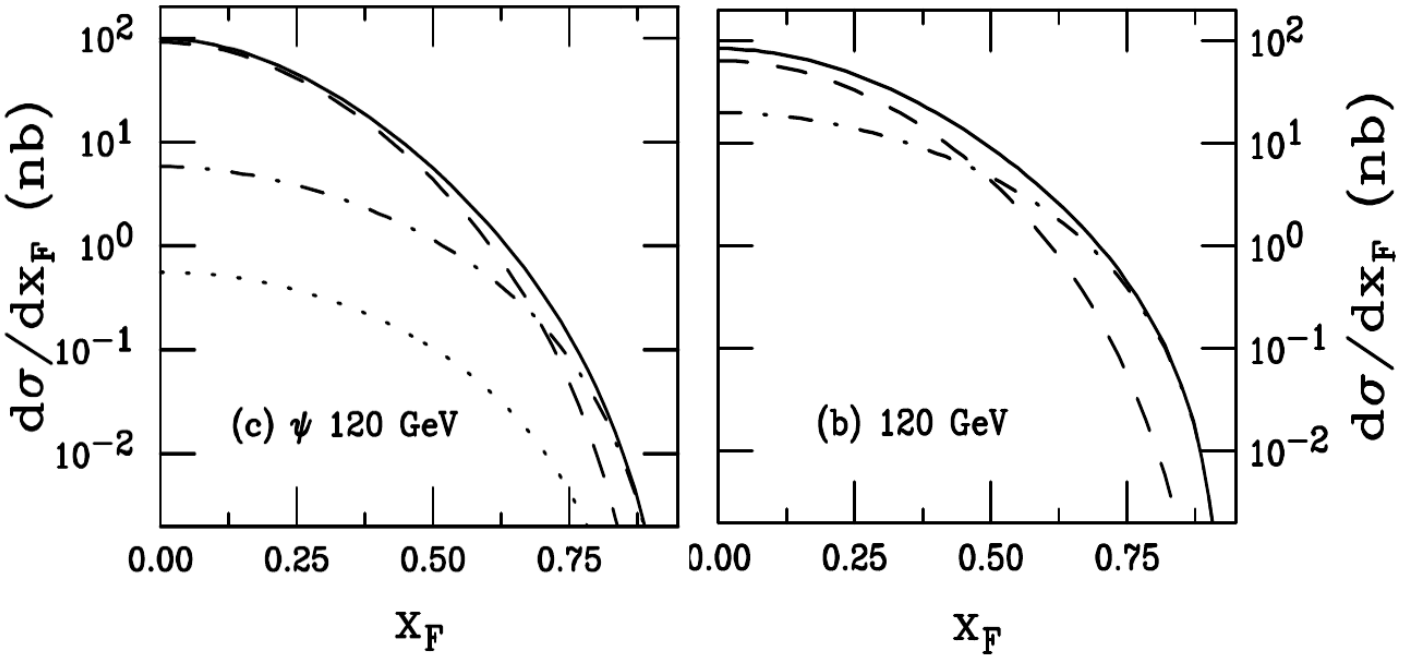
- Similar expressions can be written for χ_{cJ} production.
- χ_{c1} has an extra qg contribution.
- Due to heavy quark spin symmetry (holds up to $O(v^2)$) production of all χ_{cJ} states can be written as a function of two matrix elements $\langle O_1^{\chi_{c0}}(^3P_0)\rangle$ and $\langle O_8^{\chi_{c0}}(^3S_1)\rangle$.

$$\langle \mathcal{O}_1^{\chi_{cJ}}(^3P_J)\rangle = (2J+1)\,\langle \mathcal{O}_1^{\chi_{c0}}(^3P_0)\rangle$$
$$\langle \mathcal{O}_8^{\chi_{cJ}}(^3S_1)\rangle = (2J+1)\,\langle \mathcal{O}_1^{\chi_{c0}}(^3S_1)\rangle$$

- The singlet ME is determined from potential models wave functions.
- The octet ME is extracted from Tevatron data ($\langle O_8^{\chi_{c1}}(^3S_1)\rangle = 9.8 \pm 1.3$ GeV^3).

x_F predictions for NRQCD and CEM

Phys.Rev.C61:035203,2000

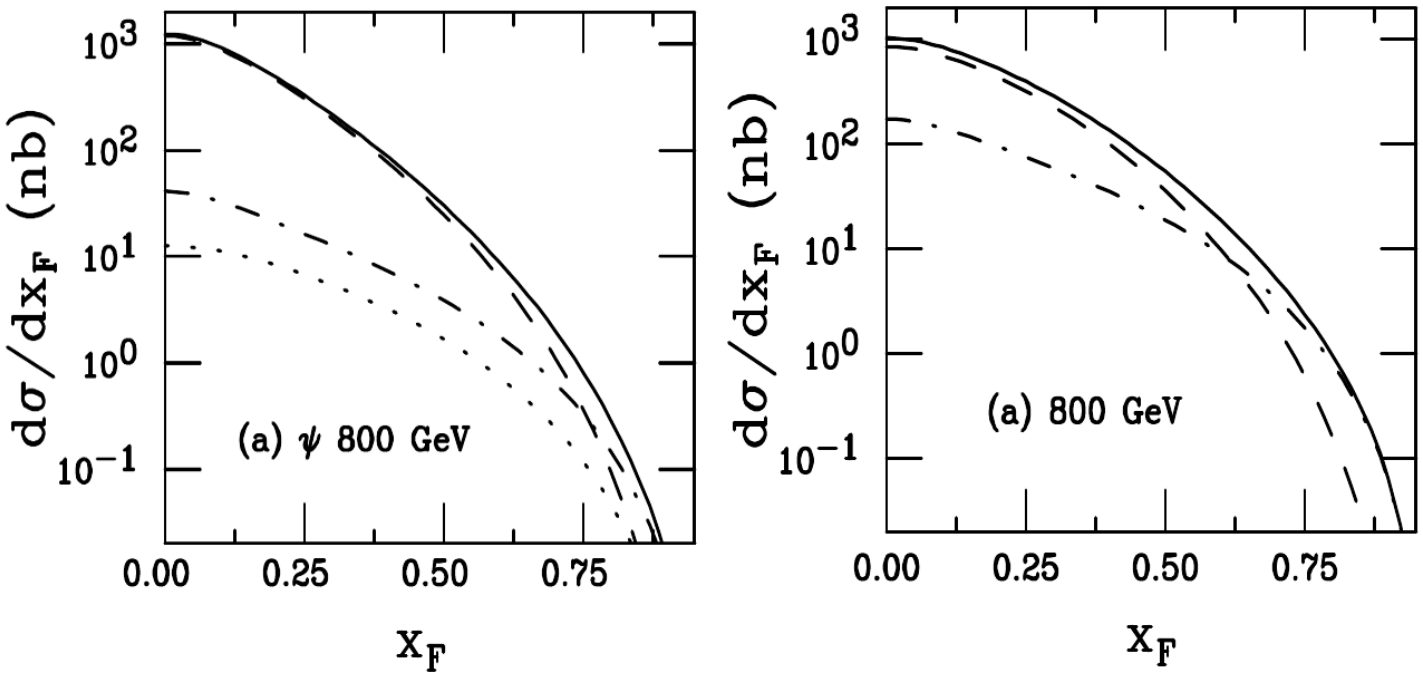


NRQCD (left) and **CEM (right)** predictions for $\sqrt{s} = 15$ GeV. The contributions from gg fusion (dashed) $q\bar{q}$ annihilation (dot-dashed) and qg diagram for NRQCD are given along with the total.

Proton PDF: CTEQ 3L LO pdf. The dominant contribution from the gg Δ_8 term.

x_F predictions for NRQCD and CEM

Phys.Rev.C61:035203,2000



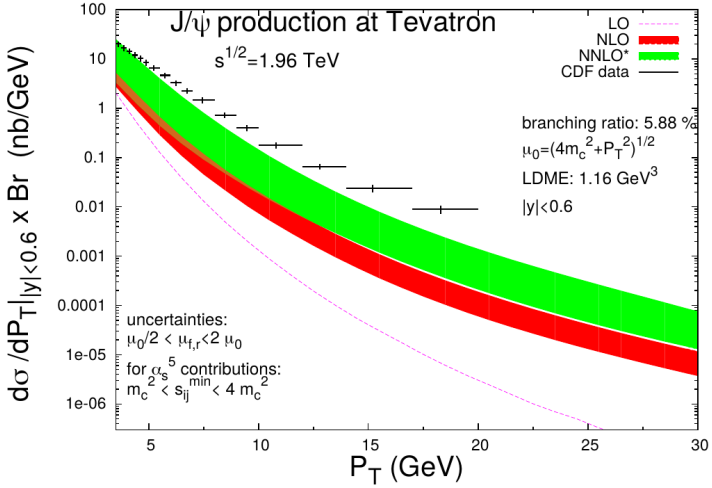
NRQCD (left) and **CEM (right)** predictions for $\sqrt{s} = 39$ GeV. The contributions from gg fusion (dashed) $q\bar{q}$ annihilation (dot-dashed) and qg diagram for NRQCD are given along with the total.

Proton PDF: CTEQ 3L LO pdf. The dominant contribution from the gg Δ_8 term.

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):

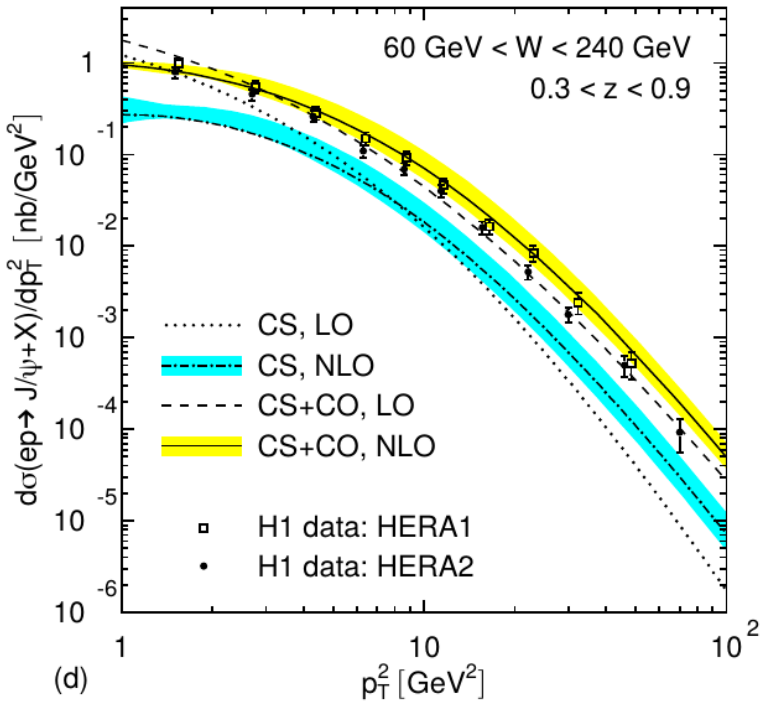
Color singlet:



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

Complete NLO:

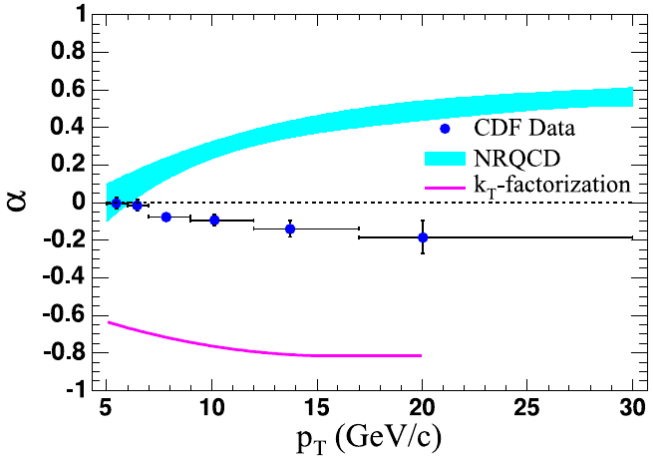
Butenschon and Kniehl (2010), Ma, Wang, and Chao (2010).



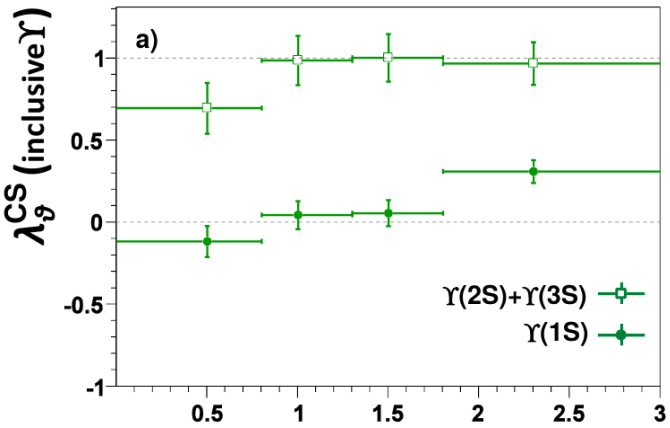
Plot from Butenschon and Kniehl (2010)

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**.
- **Not described in LO**, starting from Tevatron data, also true for the fixed-target experiments (Beneke and Rothstein, 2005).
- **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))



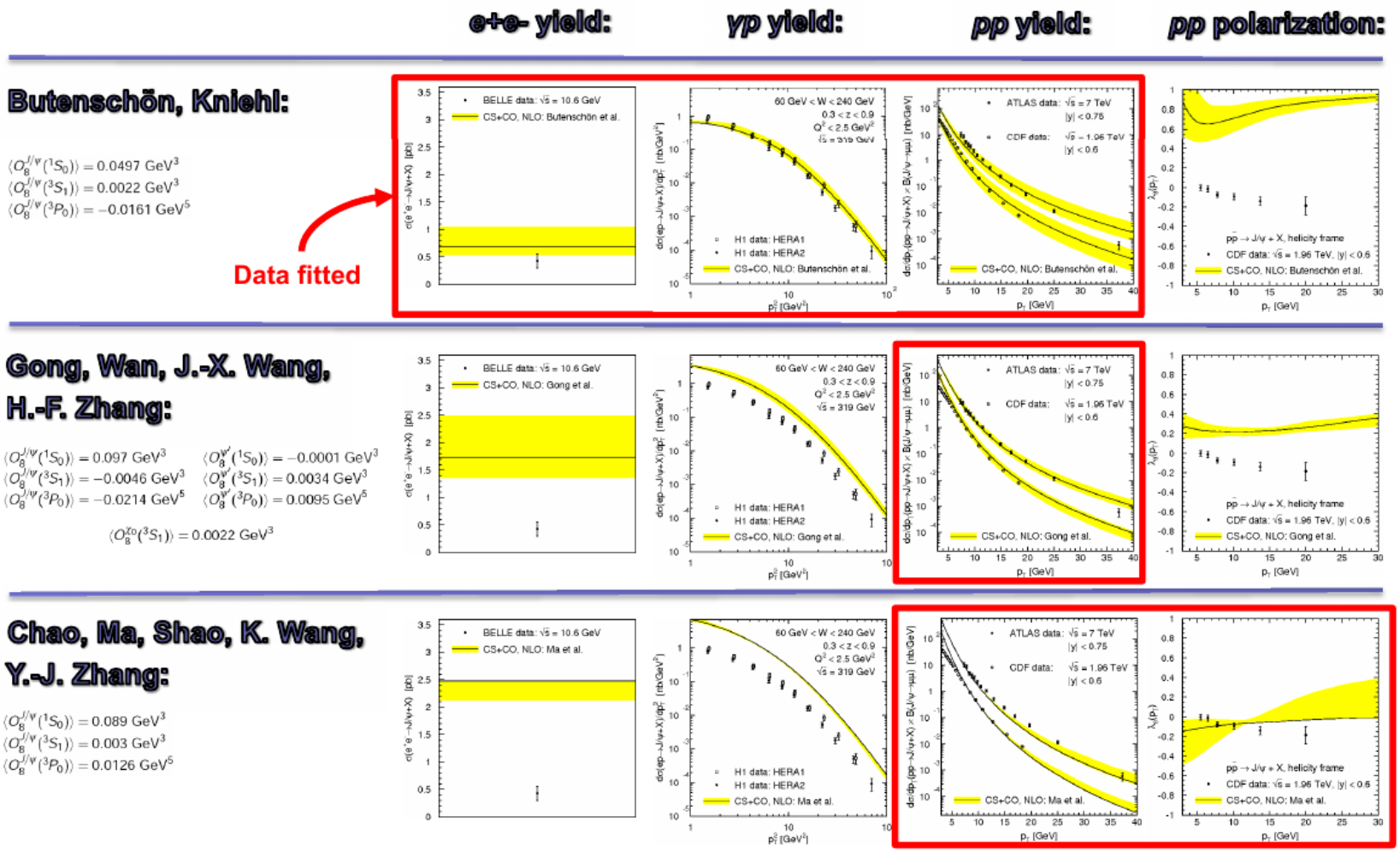
CDF data (Run II) and LO NRQCD predictions (Braaten, Kniehl and Lee, 2000)



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

NLO NRQCD fits

Slide borrowed from M. Butenschoen 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.

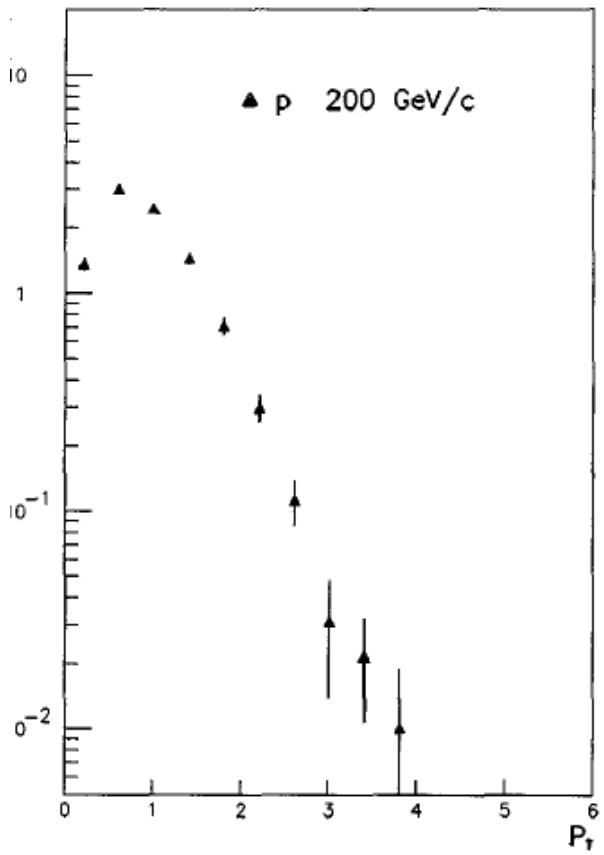
NRQCD: applicability

NRQCD still experiences difficulties in description of all available data. It may mean that

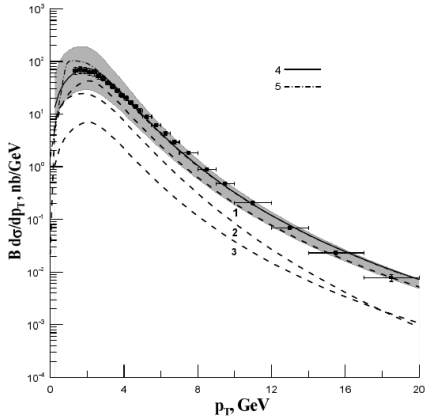
- NRQCD factorization holds only for sufficiently high p_T.
- NRQCD may hold only for spin-averaged values.
- Need for NNLO calculations or calculations beyond fixed-order perturbation theory.
- The series in v^2 converges slowly. Further relativistic correction involve another set of LDME, which makes sense only if they can be reliably extracted from lattice calculations.

p_T at SPD energies

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



- NRQCD fits reasonably described data for $p_T > 3$ GeV or at higher momenta. Likely caused by soft gluon emission and limited applicability of the fixed order perturbative calculations.
- Neglecting parton k_T in the collinear factorization may not be appropriate. k_T factorization approaches can be used instead:
  - Saleev, Nefedov, Shipilova (2012)



CDF

  - Baranov, Lipatov, Zotov (2011, 2012).

Summary

- Despite many years of investigation and considerable recent progress, charmonia production mechanisms remain not well understood. Using inclusive J/ψ production to access gluon distribution functions of hadrons and to interpret spin asymmetries in J/ψ production would require validation of theoretical approaches.
- SPD might be an ideal place for study and validation of theoretical approaches at low energies.
- One might expect rigorous measurements for J/ψ (p_T, x_F and polarization). Similar measurements for $\psi(2S)$ and χ_{cJ} are of a great interest, especially χ_{cJ} polarization, which has never been measured before. Studies of η_c, if feasible, are important to validate NRQCD.
- Realistic MC simulations are required to study these possibilities.