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 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

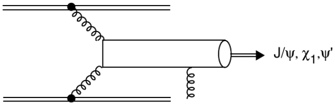
The inclusive J/ψ and DY cross section (from SPD loi):

$\sqrt{s}$, GeV	24	26	$\sqrt{s}$, GeV	24	26
$\sigma_{J/\Psi} \cdot B_{e+e-}$, nb	12	16	σ_{DY}, nb	0.06	0.07
Events "per year"	$18 \cdot 10^6$	$23 \cdot 10^6$	Events "per year"	$92 \cdot 10^3$	$142 \cdot 10^3$

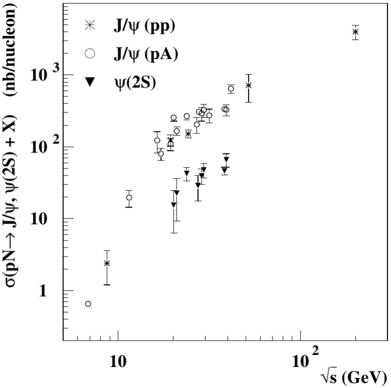
Complications compared to DY:

- Apart from quark annihilation there is notable contribution from gluon fusion.
- Formation of J/ψ is nonperturbative and not well understood.
- Significant amount of J/ψ events come from ψ' and χ_{cJ} decays.

LO gluon fusion diagram:



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
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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

On previous measurements (χ_c)

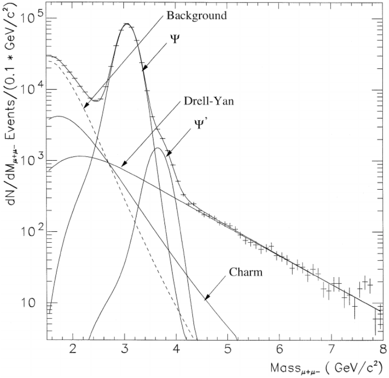
Table: Ratio of J/ψ events produced in χ_c decays.

Tech	$\sqrt{s}$ (GeV)	$\frac{\sigma(\chi_{cJ} \to \gamma J/\psi)}{\sigma(J/\psi)}$, $J = 1, 2$	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, $-0.35 < xF < 0.15$
R806	62	0.47 ± 0.08	pp

Also WA102 measured $\sigma(\chi_{cJ}) < 2$ nb @90% C.L. and $\sqrt{s} = 29.1$ GeV.
So relative contribution of J/ψ events of order of 30% is expected as well as about 10% for ψ' decays.

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

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

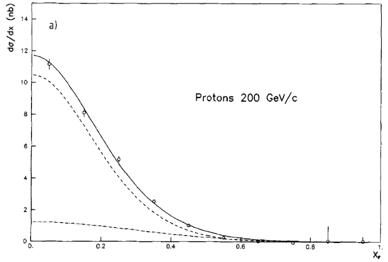


Phys.Lett.B638:202-208 (2006)

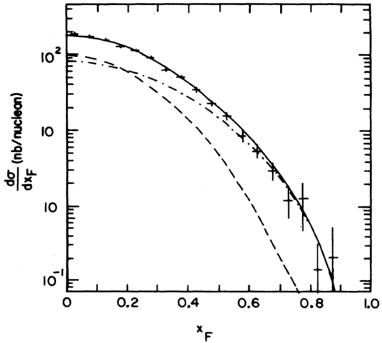
Experiment	Reaction	$\sqrt{s}$ (GeV)	$\sigma_{\psi(2S)}$ (nb/nucleon)	$\sigma_{\psi(2S)}/\sigma_{J/\psi}$ (R_{ψ})
E331 [28]	pC	20.6	15.4 ± 9.1	0.060 ± 0.035
E444 [29]	pC	20.6	22.8 ± 13.5	0.137 ± 0.079
E705 [31]	pLi	23.8	42.5 ± 9.0	0.159 ± 0.029
E288 [33]	pBe	27.4	28.9 ± 11.3	0.141 ± 0.042
NA38/51 [35, 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!

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.



Currently used models

- Color evaporation model (CEM)
- NRQCD

Color evaporation model

Color Evaporation Model

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).

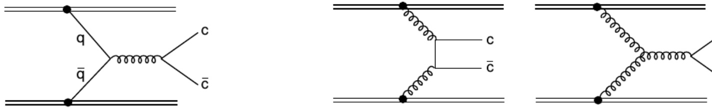
$$\frac{d\sigma_H^{AB}}{dx_F} = F_H \int_{4m_c^2}^{4m_D^2} \frac{dm^2}{\sqrt{x_F^2 s^2 + 4m^2 s}} H_{AB}(x_1, x_2, m^2),$$

where

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

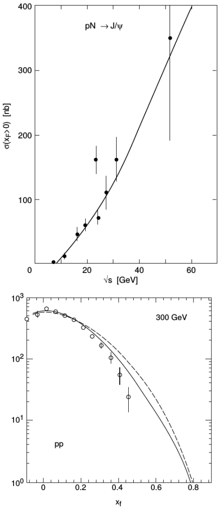
$$x_{1,2} = \frac{1}{2}\left(\pm x_F + \sqrt{x_F^2 + 4m^2/s} \right).$$

LO $c\bar{c}$ production diagram:



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).
- Factors F_H should be constant and process and energy independent ("feed-down" contribution sometimes are included in F_H).
- CEM predicts $\sqrt{s}$-dependence and fractions of gluon fusion and quark annihilation. Ratio of produced charmonia states should be constant. No prediction on polarization.



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

NRQCD

NRQRD

Phys.Rev.D54:2005,1996

For the process $A + B \to H + X$

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

- Cross-section factorizes to short-distance ($x \approx 1/m_c$) and long-distance parts:

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

.

- $C^{ij}_{Q\bar{Q}[n]}$ describe heavy quark pair production and $\langle O^H_n \rangle$ matrix elements describe its adronization to quarkonium H.
- There is hierarchy of operators $\langle O^H_n \rangle$ with respect to v ($v^2 \approx 0.2-0.3$).
- Expression for cross-section is series in α_S/π and v.

NRQRD: $\hat{\sigma}(ij \to H)$ for ψ'

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

$$\hat{\sigma}(gq \to \psi') = 0$$

$$\hat{\sigma}(q\bar{q} \to \psi') = \frac{16\pi^3\alpha_s^2}{27(2m_c)^3 s}\,\delta(x_1x_2 - 4m_c^2/s)\,\langle\mathcal{O}_8^{\psi'}({}^3S_1)\rangle$$

$z = (2m_c)^2/(sx_1x_2)$

- The singlet ME ($\langle O_1(^3S_1)\rangle$) is determined from charmonium decays or charmonium wave function in potential models.
- The $\langle O_8(^3S_1)\rangle$ ME is extracted from large p_t Tevatron data.
- Δ_8 is extracted from fit of data at fixed-target energies.

NRQRD

Predictions:

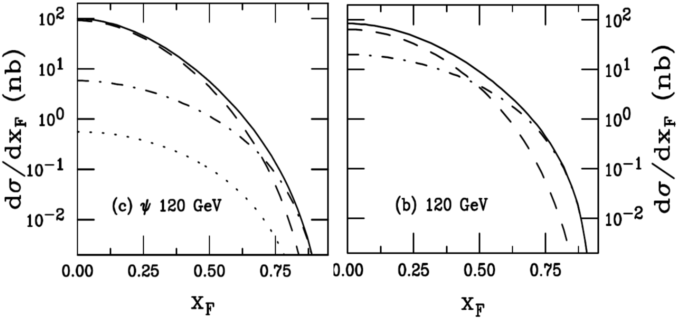
- relative contribution of quark-antiquark annihilation and gluon-gluon fusion,
- p_t (needs studies for SPD energies)
- charmonia polarization,
- $\sqrt{s}$ dependence.

Problems:

- values of some color-octet matrix elements obtained in Tevatron and fixed target experiments seems to be not consistent (Phys.Lett.B638:202-208,2006),
- polarization of J/ψ is not well consistent with data (Phys.Rev.D54:2005,1996).

Comparison of CEM and NRQCD predictions

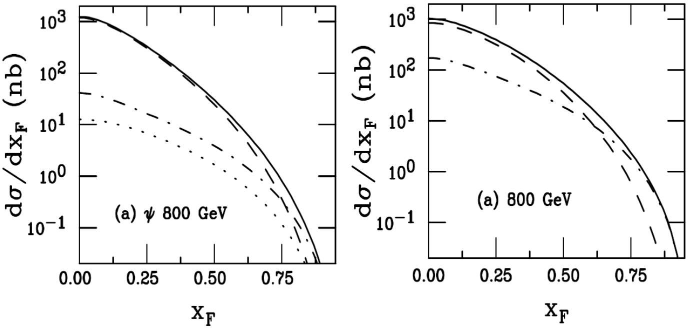
Phys.Rev.C61:035203,2000



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.

Comparison of CEM and NRQCD predictions

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.

Possible measurements at SPD

J/ψ:

- production cross-section, $d\sigma/dp_t$
- $d\sigma/dx_F$ (validation of CEM and NRQCD),
- polarization as function p_t (x_F).

ψ':

- production cross-section, $d\sigma/dp_t$
- $d\sigma/dx_F$ (CEM and NRQCD fits, if feasible),
- polarization (if feasible).

χ_{c1} and χ_{c1}:

- production cross-section,
- polarization(if feasible).

Conclusions

- J/ψ (charmonia) production mechanism remains interesting and open question in QCD. SPD J/ψ data in future can be used to validate common theoretical approaches.
- Huge statistics of inclusive J/ψ events was suggest to measure spin asymmetries. Interpretation of these results will require understanding of J/ψ production mechanism and, in particular, contribution $q\bar{q}$ annihilation to the process.
- Open spectrometer may allow dedicated study of χ_{cJ} and ψ' states. The study of inclusive ψ' production analogous J/ψ one might be possible. Realistic simulation is required to study this possibilities.