Probing J/ψ Production Mechanisms in Proton–Proton Collisions at SPD/NICA Energies

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About Me

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- **PhD:** *Completed from NIT Jalandhar, India*
- **Background:** *Tomography of hadrons using light-front dynamics*
- **Current:** *Young Scientist at MIPT, Russia*

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Outline

Gluon Probes at SPD

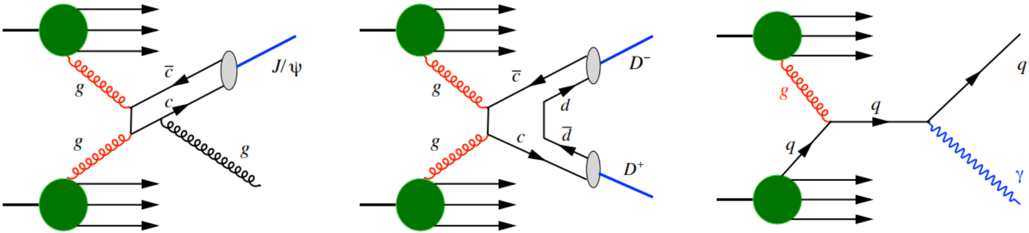
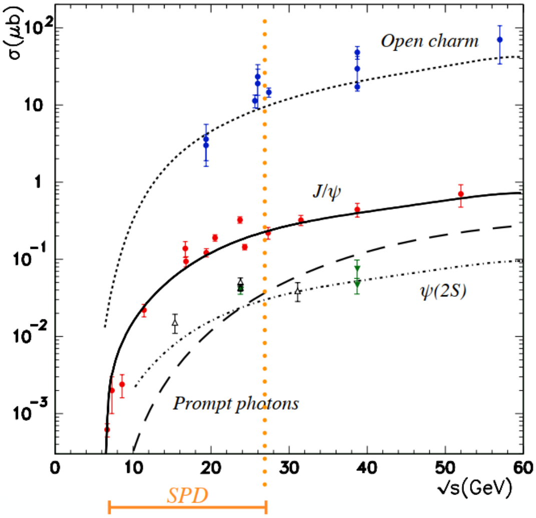


Figure: Charmonium, open charm, and prompt photons as probes to access gluon content of proton in polarized collisions at NICA SPD

https://arxiv.org/pdf/2011.15005



Behavior of the cross sections for the inclusive production of J/ψ, $\psi(2S)$, open charm, and high-p_T prompt photons in p-p collisions as a function of $\sqrt{s}$ (CEM-NLO model)

- J/ψ provides a clean experimental signature of dimuon decay but but Feed-down complicates its analysis.
- gluon fusion to open-charm mesons has highest statistics but also very high background.
- quark-gluon to prompt-photons is the cleanest channel for interpretation but Backgrounds limit its studies at low p_T.

https://arxiv.org/pdf/2011.15005

Outline

Motivation

J/ψ Production Across Experiments

Production Mechanisms of J/ψ

Theoretical Models

Discussion

J/ψ Production Across Colliders

Collision Systems

- e^+e^- (Belle, BaBar)
- e^-p (HERA, EIC)
- pp (LHC, RHIC, SPD/NICA)
- pA, AA (LHC, RHIC)

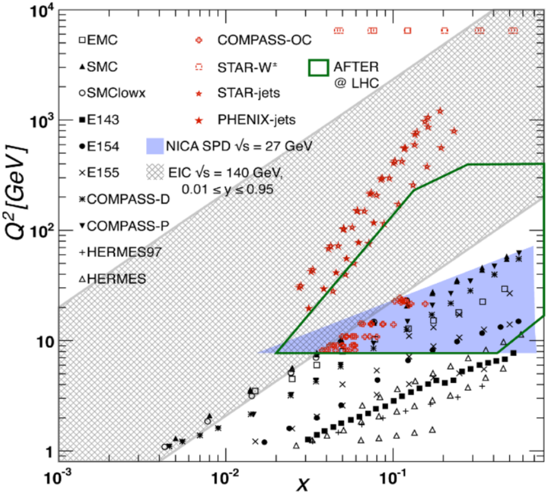
Physics Focus

- Test NRQCD, color mechanisms
- Probe gluon content in ep
- Study TMDs, saturation in pp
- Nuclear modification, QGP

My focus: J/ψ in pp collisions at SPD/NICA energy range

https://arxiv.org/abs/1506.03981

https://arxiv.org/abs/1212.1701



Main present and future gluon-spin-physics experiments

Experimental facility	SPD @NICA [41]	RHIC [45]	EIC [36]	AFTER @LHC [34]	LHCspin [35]
Scientific center	JINR	BNL	BNL	CERN	CERN
Operation mode	collider	collider	collider	fixed target	fixed target
Colliding particles & polarization	$p^\uparrow$-$p^\uparrow$ $d^\uparrow$-$d^\uparrow$ $p^\uparrow$-d, p-$d^\uparrow$	$p^\uparrow$-$p^\uparrow$	$e^\uparrow$-$p^\uparrow$, $d^\uparrow$, $^3He^\uparrow$	p-$p^\uparrow$, $d^\uparrow$	p-$p^\uparrow$
Center-of-mass energy $\sqrt{s_{NN}}$, GeV	≤27 (p-p) ≤13.5 (d-d) ≤19 (p-d)	63, 200, 500	20-140 (ep)	115	115
Max. luminosity, 10^{32} cm^{-2} s^{-1}	~1 (p-p) ~0.1 (d-d)	2	1000	up to ~10 (p-p)	4.7
Physics run	>2025	running	>2030	>2025	>2025

https://arxiv.org/abs/2011.15005

Outline

Mechanisms of J/ψ Production

- **Prompt Production:** From direct partonic interactions.
  - Contributing subprocesses: $g + g \to J/\psi$, $g + g \to J/\psi + g$
  - Involving intermediate color-singlet or color-octet $c\bar{c}$ states:
    - Singlet: $g^* + g^* \to Q\bar{Q}[^3S_1^{(1)}] + g$
    - Octet: $g^* + g^* \to Q\bar{Q}[^1S_0^{(8)}, {}^3S_1^{(8)}, {}^3P_J^{(8)}]$
- **Feed-down Production:** From decays of higher charmonium states.
  - Examples: $\psi(2S) \to J/\psi + \pi\pi$, $\chi_{cJ} \to J/\psi + \gamma$
  - These originate from channels like:
    - $g^* + g^* \to Q\bar{Q}[^3P_J^{(1)}, {}^3S_1^{(8)}]$
  - Spin correlations and decay kinematics are modeled explicitly.
- **Non-prompt Production:** From decays of long-lived B-hadrons.

Focus of this work: Prompt production via $g + g \to J/\psi$ or $J/\psi + g$ at $\sqrt{s} = 27$ GeV.

A. V. Lipatov et al. 2020

Outline

Colour Singlet Model (CSM)

- Assumes that the $Q\bar{Q}$ pair is produced directly in a color-singlet state with the same quantum numbers as the physical quarkonium.
- The production amplitude includes the perturbative partonic cross section and the non-relativistic wavefunction at the origin.

$$d\sigma[\mathcal{Q}] = \int d\xi_i \, d\xi_j \, f_i(\xi_i) \, f_j(\xi_j) \, d\hat{\sigma}_{i+j\to\mathcal{Q}+X} \, |R(0)|^2$$

◦ *Applicable to S-wave states like J/ψ, $\psi(2S)$, $\Upsilon(1S)$*
◦ *$|R(0)|^2$ is the radial wavefunction at the origin (non-perturbative)*

Baier and Rückl 1983

Colour Evaporation Model (CEM)

- Treats the $Q\bar{Q}$ pair as evolving into quarkonium if its invariant mass M lies below the open-flavor threshold ($2M_D$ for charm).
- The probability to form a specific quarkonium state is given by a universal factor $F_{\mathcal{Q}}$.

$$\frac{d\sigma[\mathcal{Q}]}{dP_{\mathcal{Q}}} = F_{\mathcal{Q}} \int_{M_{\mathcal{Q}}}^{2M_H} dM \, \frac{d\sigma_{Q\bar{Q}}(M, P_{\mathcal{Q}})}{dM \, dP_{\mathcal{Q}}}$$

- *No need to specify quantum numbers of $Q\bar{Q}$*
- *Works well for total cross sections, but lacks predictive power in p_T or y distributions*

improved by Ma and Vogt 2016

Non-Relativistic QCD (NRQCD)

- Factorizes the production into:
  - Short-distance partonic cross sections
  - Long-distance matrix elements (LDMEs)
- Allows $Q\bar{Q}$ to be produced in color-octet or color-singlet states.

$$d\sigma[\mathcal{Q}] = \sum_n \int d\xi_i \, d\xi_j \, f_i(\xi_i) \, f_j(\xi_j) \, d\hat{\sigma}_{i+j \to Q\bar{Q}[n]+X} \, \langle \mathcal{O}_{\mathcal{Q}}[n] \rangle$$

- *Sum over all allowed $Q\bar{Q}$ quantum states n*
- *$\langle \mathcal{O}_{\mathcal{Q}}[n] \rangle$ are non-perturbative, fit from data*
- *Color-Octet contributions help explain high-p_T data*

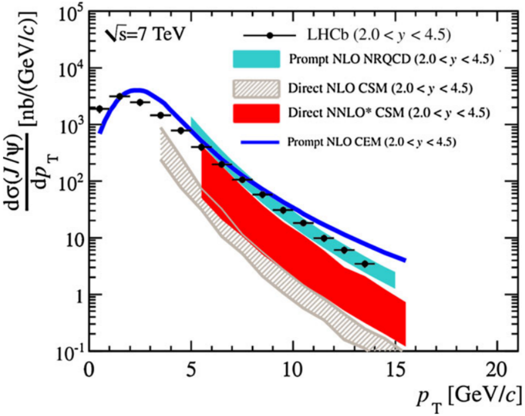
Bodwin et al. 1997

Summary: Theoretical Models of Quarkonium Production

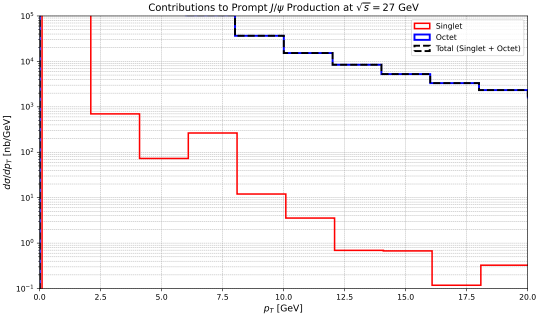
Aspect	**CSM**	**CEM**	**NRQCD**
Color State	Singlet only	All (color summed)	Singlet + Octet
p_T Spectrum	Poor at high p_T	No structure	Better high p_T match
Quantum Numbers	Explicit	Ignored	Controlled via LDMEs
Factorization	Simple	No	Yes (QCD-based)
Status	Oldest model	Phenomenological	Most complete

Fragmentation mechanism is also possible but subdominant at SPD energies.

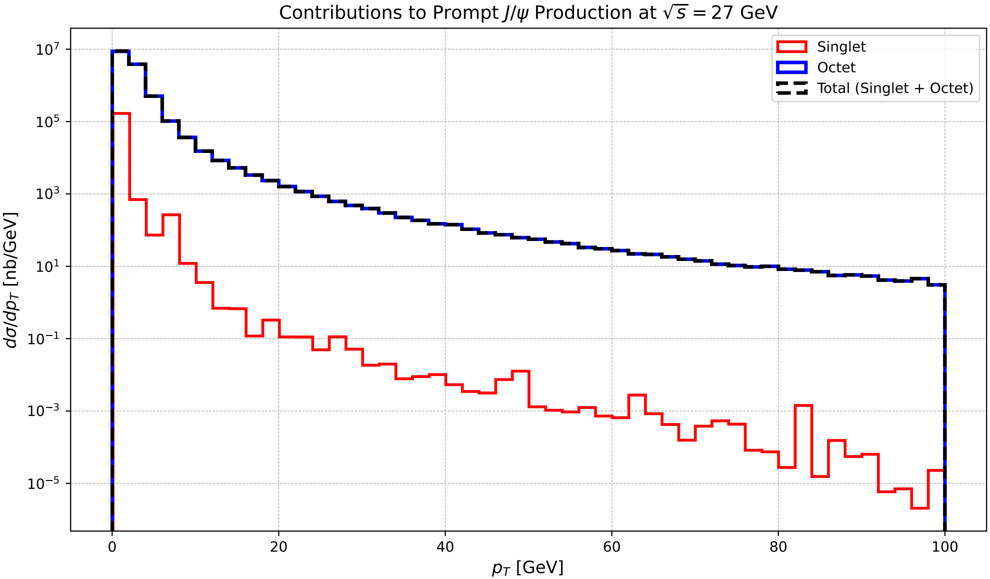
Outline

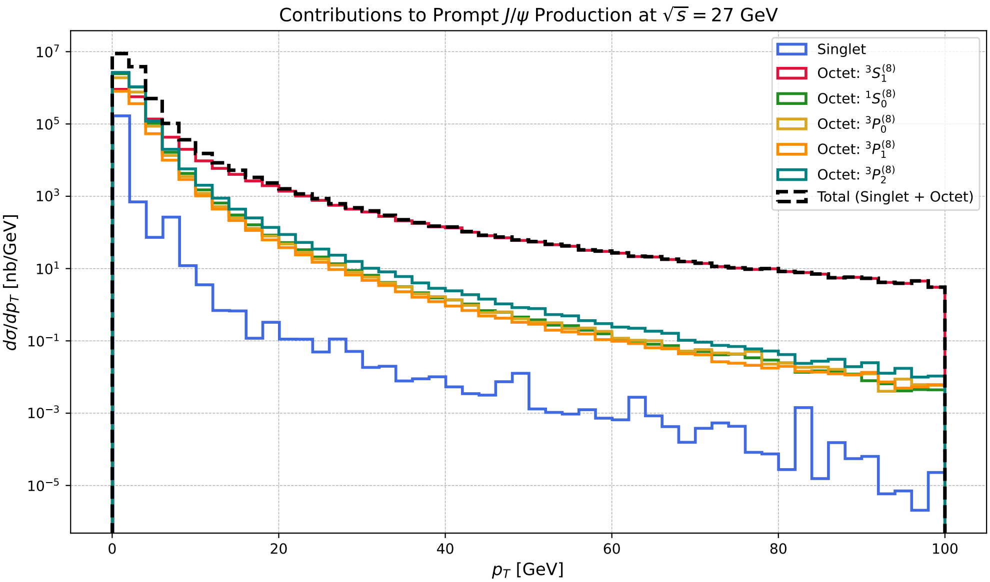


Prompt J/ψ yield as measured by LHCb at $\sqrt{s} = 7$ TeV compared to different theory predictions referred to as prompt NLO NRQCD, Direct NLO CS, Direct NNLO CS and Prompt NLO CEM *Eur. Phys. J. C (2016) 76:107*



Prompt J/ψ yield as measured by PEGASUS at $\sqrt{s} = 27$ GeV


Contributions to Prompt J/ψ Production at $\sqrt{s} = 27$ GeV
Singlet
Octet
Total (Singlet + Octet)
10^7
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
$d\sigma/dp_T$ [nb/GeV]
0
20
40
60
80
100
p_T [GeV]


Contributions to Prompt J/ψ Production at $\sqrt{s} = 27$ GeV
10^{7}
10^{5}
10^{3}
10^{1}
10^{-1}
10^{-3}
10^{-5}
$d\sigma/dp_T$ [nb/GeV]
0
20
40
60
80
100
p_T [GeV]
Singlet
Octet: ${}^3S_1^{(8)}$
Octet: ${}^1S_0^{(8)}$
Octet: ${}^3P_0^{(8)}$
Octet: ${}^3P_1^{(8)}$
Octet: ${}^3P_2^{(8)}$
Total (Singlet + Octet)

Thank you!