# $J/\psi$ Production Studies at Spin Physics Detector Energies

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# Outline

# Gluon Probes at SPD

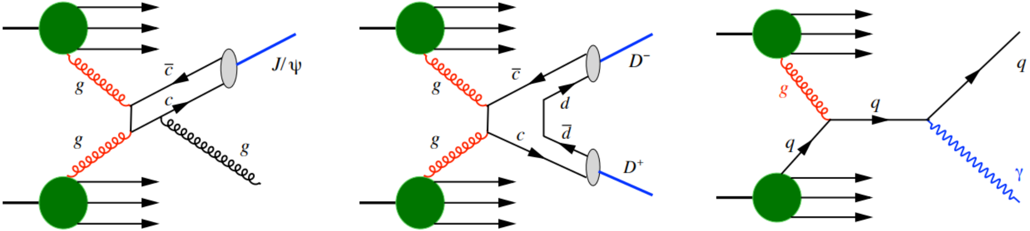
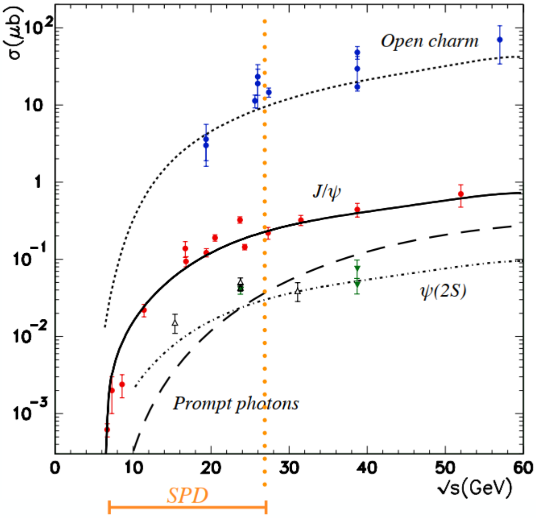



Figure: Charmonium, open charm, and prompt photons as probes to access gluon content of proton in polarized collisions at NICA SPD

[Arbuzov et al., 2021]




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

- $\mathrm{J}/\psi$ 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 $p_T$.

[Arbuzov et al., 2021]

# Outline

# J/$\psi$ Production Across Colliders

## Collision Systems

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

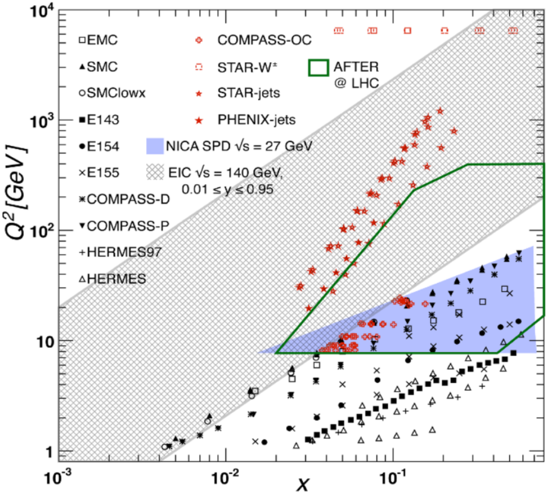
## Physics Focus

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

**My focus: J/$\psi$ in $pp$ collisions at SPD/NICA energy range**

*[Andronic et al., 2016]*

*[Accardi et al., 2016]*




*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 | $p^\uparrow$-$p^\uparrow$ $d^\uparrow$-$d^\uparrow$ $p^\uparrow$-$d$, $p$-$d^\uparrow$ | $p^\uparrow$-$p^\uparrow$ | $e^\uparrow$-$p^\uparrow$, $d^\uparrow$, $^3\mathrm{He}^\uparrow$ | $p$-$p^\uparrow$, $d^\uparrow$ | $p$-$p^\uparrow$ |
| 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

# Mechanisms of $J/\psi$ 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.

# Outline

# Theoretical Framework

Within the NRQCD factorization approach, the inclusive $J/\psi$ production cross section is written as a sum over intermediate $c\bar{c}$ states $n$
[Bodwin et al., 1995, Petrelli et al., 1998],

$$d\sigma(pp \to J/\psi + X) = \sum_n d\hat{\sigma}(pp \to c\bar{c}[n] + X)\,\langle \mathcal{O}^{J/\psi}[n] \rangle, \tag{1}$$

where $d\hat{\sigma}$ represents the perturbatively calculable short-distance coefficient (SDC) for the production of a heavy-quark pair in state $[n]$, and $\langle \mathcal{O}^{J/\psi}[n] \rangle$ denotes the long-distance matrix element (LDME) governing its nonperturbative transition into a physical $J/\psi$ meson.

# Theoretical Framework

At leading order in $\alpha_s$, two classes of partonic subprocesses contribute:

(i) CS mechanism:

$$g^* + g^* \to c\bar{c}\left[{}^3S_1^{(1)}\right] + g, \tag{2}$$

where the $c\bar{c}$ pair is produced directly in a CS configuration with the same quantum numbers as the $J/\psi$ [Petrelli et al., 1998]. The final-state gluon ensures color conservation and carries part of the recoil momentum.

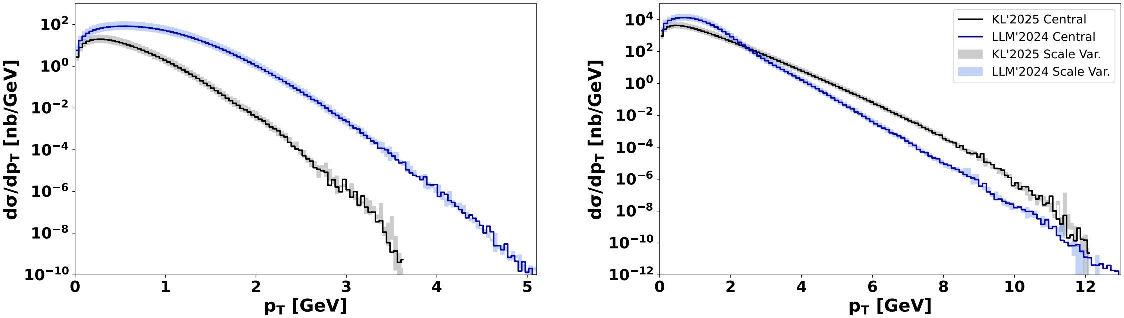
(ii) CO mechanisms:

$$g^* + g^* \to c\bar{c}[n], \quad n \in \left\{{}^1S_0^{(8)},\, {}^3S_1^{(8)},\, {}^3P_J^{(8)}\,(J = 0, 1, 2)\right\}, \tag{3}$$

where the $c\bar{c}$ pair is produced in a color-octet state and subsequently evolves into the physical $J/\psi$ through soft-gluon emissions, with the $P$-wave octet states undergoing electric dipole (E1) transitions treated in the formalism of Ref. [Baranov, 2016]. These $2 \to 1$ subprocesses contribute at the same order in $\alpha_s$ as the CS $2 \to 2$ process.

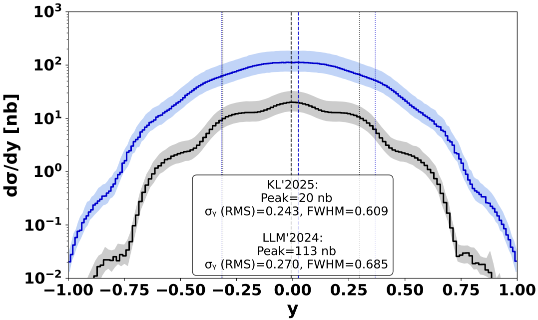
- Both CS and CO channels are implemented in the $\mathrm{PEGASUS}$ event generator [Lipatov et al., 2020] within the TMD factorization framework, where the initial gluons are off-shell $(g^*)$ and carry intrinsic transverse momentum $k_T$.
- KL$'$2025 [Kotikov and Lipatov, 2025] and LLM$'$2024 [Lipatov et al., 2024] gluon densities are used for comparison purpose.
- In this study, the LDMEs are set to unity to isolate the kinematic dependence of the SDCs and the impact of the gluon TMDs on the cross section.
- The renormalization and factorization scales are chosen as $\mu^2 = m_T^2 = M_{J/\psi}^2 + p_T^2$, with the $J/\psi$ mass consistent with PDG values [Tanabashi et al., 2018, Lipatov et al., 2020].

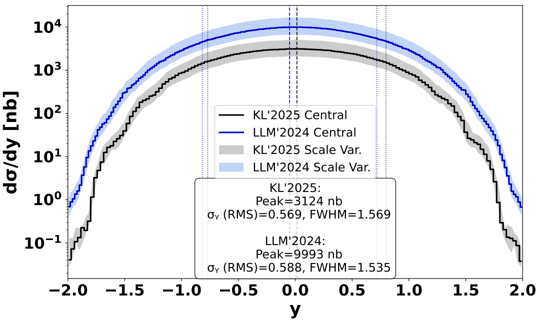
# Outline



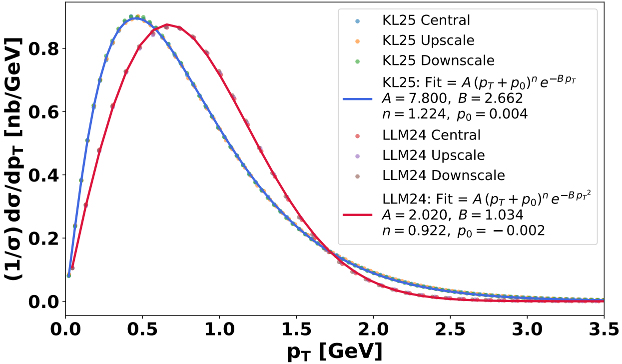

Differential cross sections $d\sigma/dp_T$ for inclusive $J/\psi$ production in pp collisions obtained using the KL′2025 [Kotikov and Lipatov, 2025] and LLM′2024 [Lipatov et al., 2024] gluon densities: $\sqrt{s} = 9$ GeV and $\sqrt{s} = 27$ GeV. The shaded bands indicate the uncertainty due to renormalization-scale variation. The comparison illustrates the evolution of the $p_T$ spectrum with increasing collision energy.

*[Sharma and Aparin, 2026]*



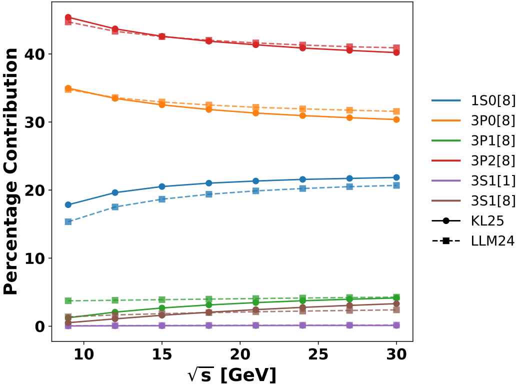




Rapidity distributions $d\sigma/dy$ for inclusive $J/\psi$ production in pp collisions obtained using the KL′2025 [Kotikov and Lipatov, 2025] and LLM′2024 [Lipatov et al., 2024] gluon densities: $\sqrt{s} = 9\ \mathrm{GeV}$,and $\sqrt{s} = 27\ \mathrm{GeV}$. The shaded bands represent the uncertainty from renormalization-scale variation. A clear broadening and enhancement of the distributions with increasing $\sqrt{s}$ reflect the expanding rapidity phase space and growing gluon-gluon luminosity at higher energies. *[Sharma and Aparin, 2026]*

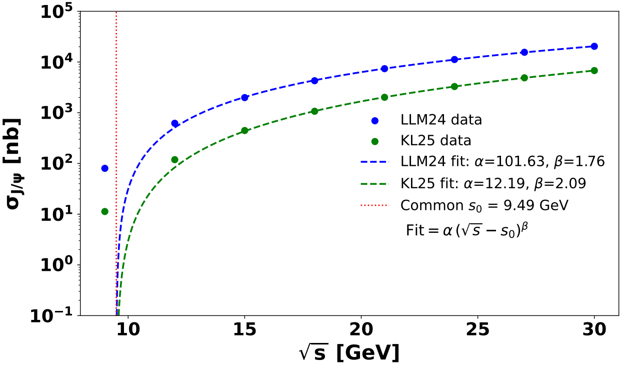



Normalized differential cross sections $(1/\sigma)\,d\sigma/dp_T$ for $J/\psi$ production in $pp$ collisions at $\sqrt{s}=27$ GeV obtained using the KL′2025 [Kotikov and Lipatov, 2025] and LLM′2024 [Lipatov et al., 2024] gluon densities. The solid curves represent empirical fits to the simulated spectra with parameters shown in the legend. The distributions are normalized to emphasize differences in spectral shape between the two TMD sets.

[Sharma and Aparin, 2026]




Relative contributions of different intermediate $c\bar{c}$ states to the total $J/\psi$ production cross section in $pp$ collisions as a function of $\sqrt{s}$ for the KL′2025 [Kotikov and Lipatov, 2025] and LLM′2024 [Lipatov et al., 2024] gluon densities. The dominance pattern ${}^3P_2^{[8]} > {}^3P_0^{[8]} > {}^1S_0^{[8]} > {}^3P_1^{[8]} > {}^3S_1^{[8]} > {}^3S_1^{[1]}$ persists across the entire SPD energy range, with minimal model dependence. *[Sharma and Aparin, 2026]*




Total inclusive $J/\psi$ production cross section in $pp$ collisions as a function of the center-of-mass energy $\sqrt{s}$, obtained with the KL′2025 [Kotikov and Lipatov, 2025] and LLM′2024 [Lipatov et al., 2024] gluon densities. The cross section increases with $\sqrt{s}$, reflecting the growth of gluon luminosity. The shifted power-law fit provides an excellent description for $\sqrt{s} \geq 12$ GeV; the deviation at $\sqrt{s} = 9$ GeV likely signals threshold or model-limit effects. *[Sharma and Aparin, 2026]*

# Outline

# Summary

- First quantitative predictions for inclusive $J/\psi$ production at SPD/NICA using modern TMD gluon densities.
- Theoretical uncertainties, production channels, and collision energies have been systematically studied.
- CCFM and KMR frameworks provide a benchmark for future SPD measurements.
- Quarkonium production remains a powerful probe of gluon dynamics in the SPD regime.

**Thank you for your attention!**

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