# Challenges and problems in charmonium production at the SPD NICA

V. Saleev[1,2]

[1] Samara National Research University
[2] Joint Institute for Nuclear Research

6 October 2022
JINR, Dubna

*In collaboration with:*
A. Anufriev[1],A. Alimov[1],A. Chernyshev[1],A. Karpishkov[1,2],K. Shilyaev[1]

# Outline

# Introduction

## The published predictions for $J/\psi$ production at the SPD NICA

- A. Arbuzov, A. Bacchetta, M. Butenschoen, F. G. Celiberto, U. D'Alesio, M. Deka, I. Denisenko, M. G. Echevarria, A. Efremov and N. Y. Ivanov, *et al.* "On the physics potential to study the gluon content of proton and deuteron at NICA SPD," Prog. Part. Nucl. Phys. **119** (2021), 103858
- A. Karpishkov, M. Nefedov and V. Saleev, "Estimates for the single-spin asymmetries in the $pp^{\uparrow} \to J/\psi X$ process at PHENIX RHIC and SPD NICA," Phys. Rev. D **104** (2021) no.1, 016008
- A. V. Karpishkov, M. A. Nefedov and V. A. Saleev, "Spectra and polarizations of prompt J/$\psi$ at the NICA within collinear parton model and parton Reggeization approach," J. Phys. Conf. Ser. **1435** (2020) no.1, 012015
- A. Chernyshev, V. Saleev. "Pair production of $J/\psi$ in the color evaporation model using the Parton Reggeization Approach", Talk at the International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology. 18-21 July 2022 BLTP, JINR

# Factorization approaches: CPM and TMD PM

- **Collinear parton model:** $q_{1,2T} << p_T$ and $\mu_F = M_T \geq M$

$$\sigma(pp \to J/\psi X) = \int dx_1 \int dx_2 f_g(x_1, \mu_F) f_g(x_2, \mu_F) \hat{\sigma}(g + g \to J/\psi + X)$$

- **TMD PM** by Collins, Soper, Stermann: $q_{1,2T} \sim p_T$ and $p_T << \mu_F$

$$\sigma(pp \to J/\psi X) = \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F, \mu_Y) \times$$

$$\times F_g(x_2, q_{2T}, \mu_F, \mu_Y) \hat{\sigma}(g + g \to J/\psi + X)$$

- **Generalized parton model:** $q_{1,2T} \sim p_T$ and $p_T \sim \mu_F$

$$\sigma(pp \to J/\psi X) = \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F) \times$$

$$\times F_g(x_2, q_{2T}, \mu_F) \hat{\sigma}(g + g \to J/\psi + X)$$

$$F_g(x, q_T, \mu_F) = f_g(x, \mu_F) \times \exp(-q_T^2 / < q_T^2 >) / (\pi < q_T^2 >)$$

# Hadronization mechanisms: CSM, NRQCD and CEM (ICEM)

## $J/\psi$ production

- Baier, Ruckl, Berger, Jones [1983] – Color Singlet Model (CSM): $g+g \to c\bar{c}[^3S_1^{(1)}]+g$ and $g+g \to c\bar{c}[^1S_0^{(1)}]$, LDME $< \mathcal{H}[^{1,3}S_{0,1}^{(1)}] >\sim |\Psi_{\mathcal{H}}(0)|^2$.
- Bodwin, Braaten, and Lepage [1995] – NRQCD: $g+g \to c\bar{c}[^3S_1^{(1)}], [^1S_0^{(8)}], [^3P_J^{(8)}]$ as perturbative series in $v^0$, $v^2$, ....
- Fritzsch, Halzen [1977] – Color Evaporation Model (CEM):

$$\sigma(J/\psi) = F_{J/\psi} \int_{2m_c}^{2m_D} \frac{d\sigma(gg \to c\bar{c})}{dM_{c\bar{c}}} dM_{c\bar{c}}$$

## Ma and Vogt [2016] – Improved Color Evaporation Model (ICEM)

$$\sigma(J/\psi) = F_{J/\psi} \int_{M_{J/\psi}}^{2m_D} \frac{d\sigma(gg \to c\bar{c})}{dM_{c\bar{c}}} dM_{c\bar{c}}$$

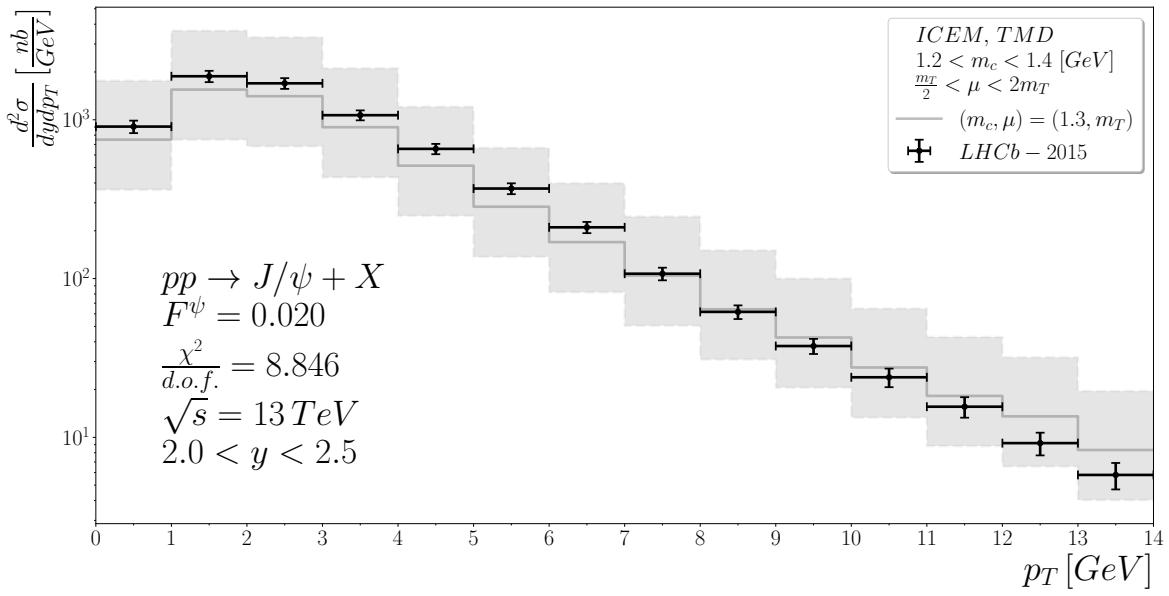
$$p_{T\,J/\psi} = \frac{M_{J/\psi}}{M_{c\bar{c}}} p_{Tc\bar{c}}$$

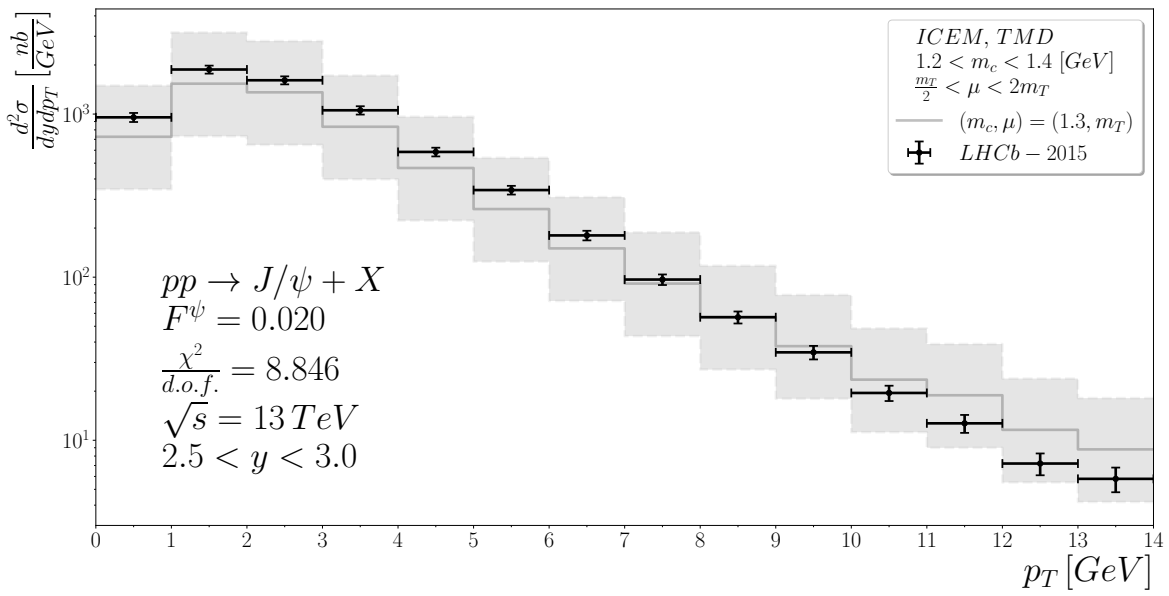
# 1. Prompt $J/\psi$ production in the ICEM versus NRQCD

## MC parton-level event generator KaTie

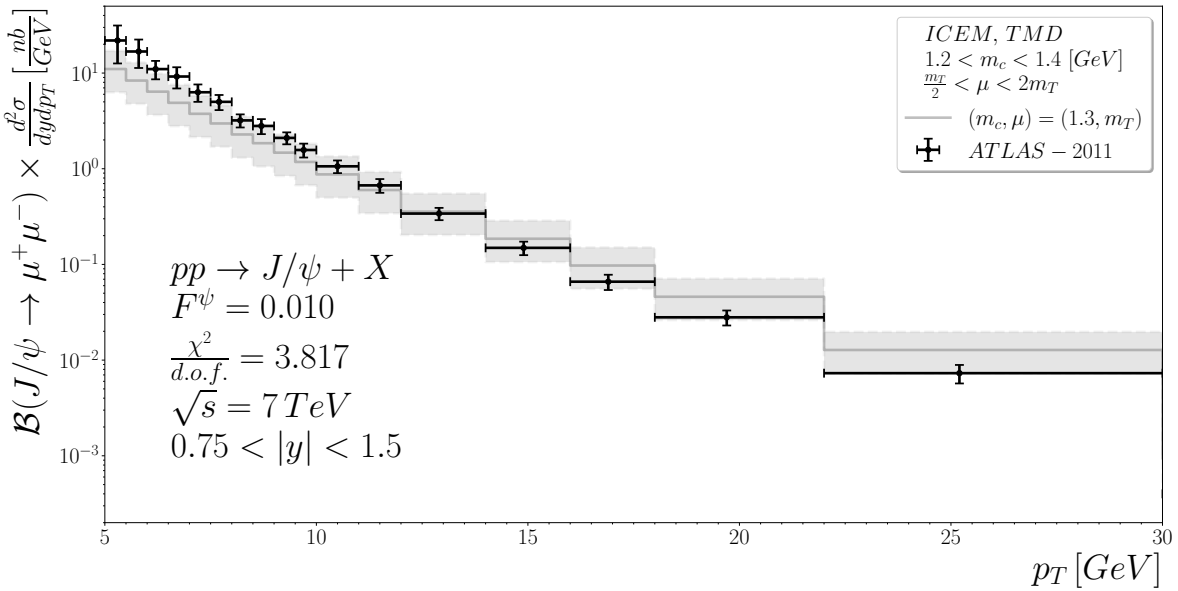
- A. van Hameren, "KaTie : For parton-level event generation with $k_T$-dependent initial states," Comput. Phys. Commun. **224** (2018), 371-380
- TMD PDFs from TMDlib: https://tmdlib.hepforge.org/
- We use our TMD PDF, based on Kimber-Martin-Ryskin model, see M. A. Nefedov and V. A. Saleev, "High-Energy Factorization for Drell-Yan process in $pp$ and $p\bar{p}$ collisions with new Unintegrated PDFs," Phys. Rev. D **102** (2020), 114018.

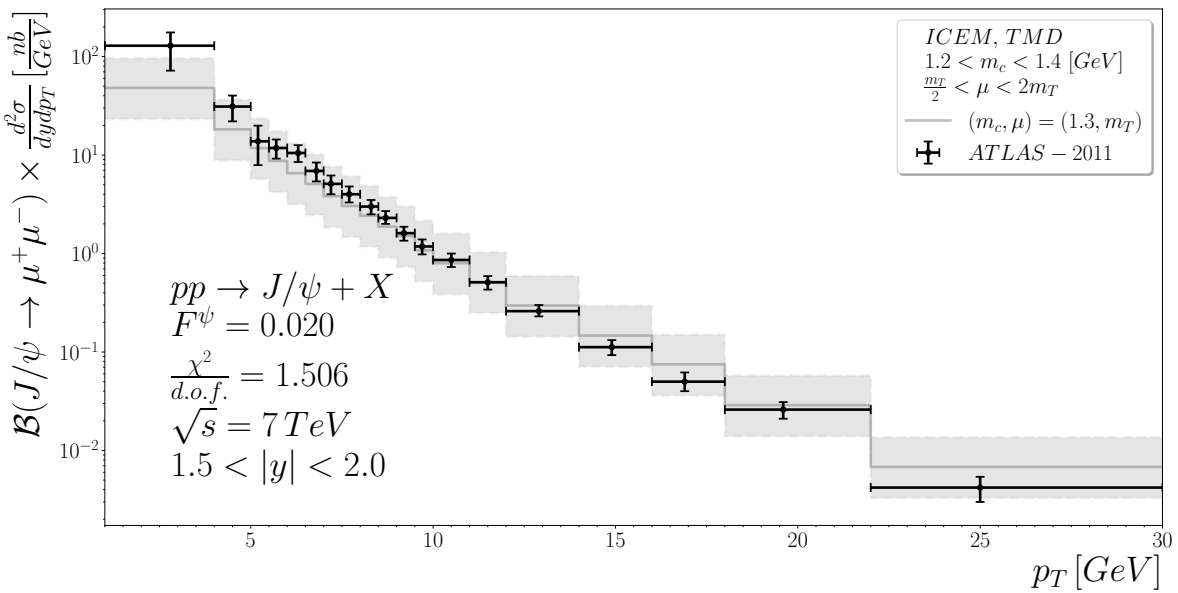
# ICEM fit at $\sqrt{s} = 13$ TeV, LHCb



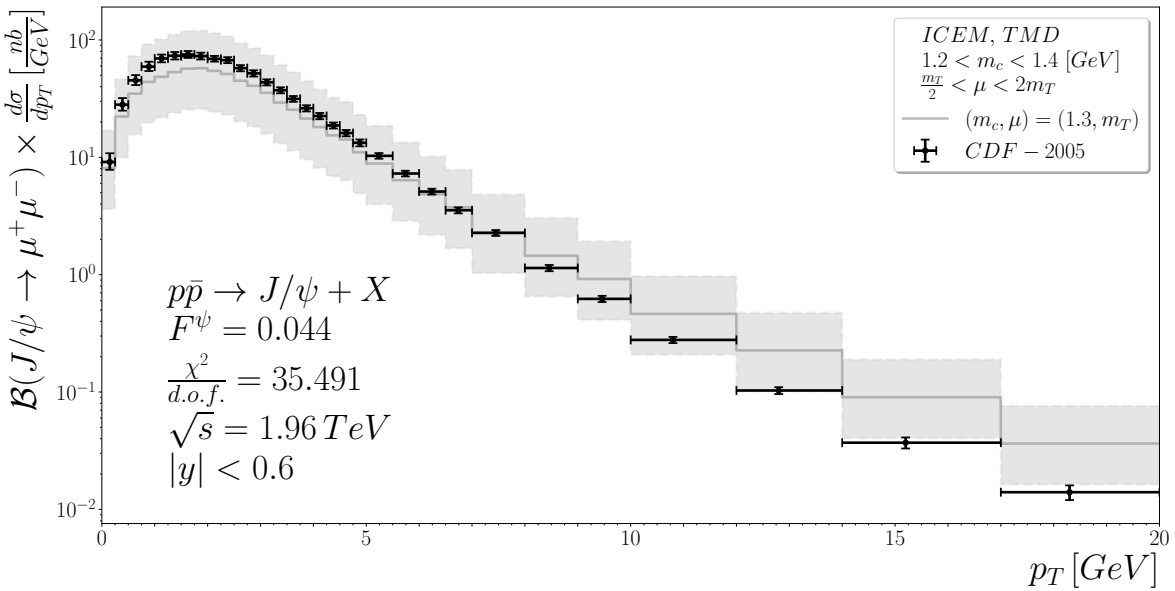



# ICEM fit at $\sqrt{s} = 7$ TeV, ATLAS

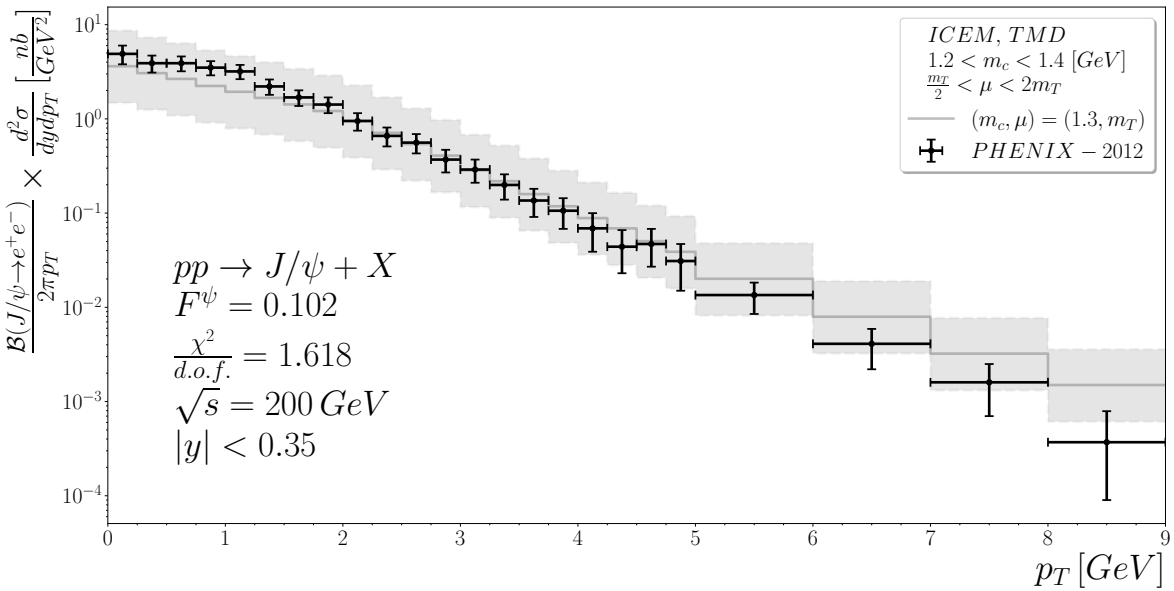


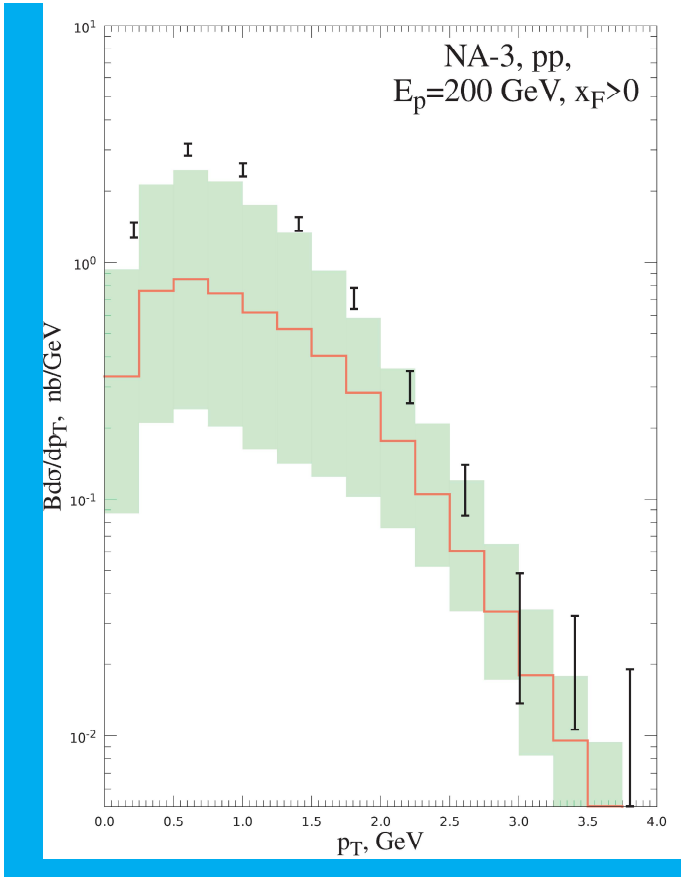
# ICEM fit at $\sqrt{s} = 2$ TeV, CDF



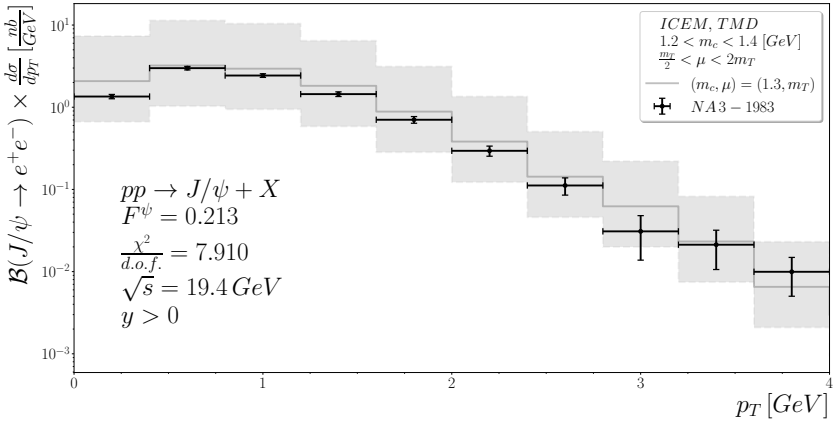
# ICEM fit at $\sqrt{s} = 200$ GeV, PHENIX



# ICEM fit at $\sqrt{s} = 19$ GeV, NA3

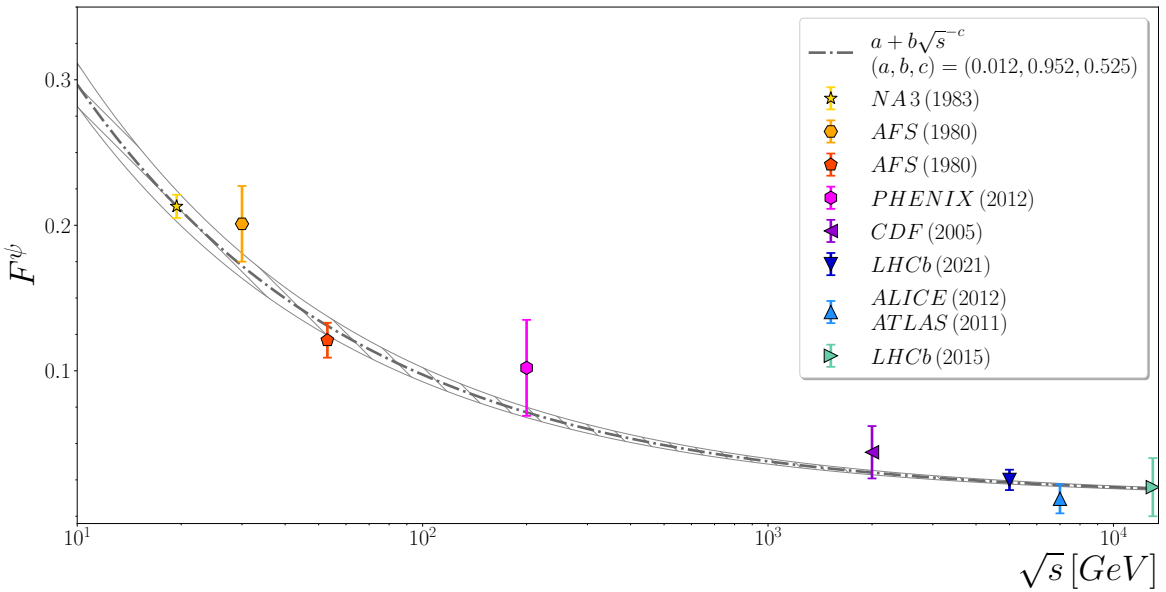



NRQCD

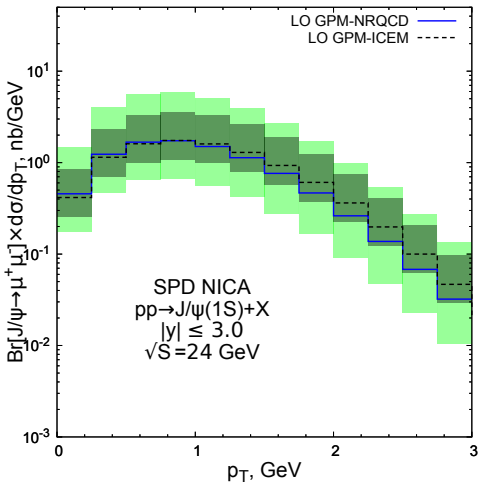


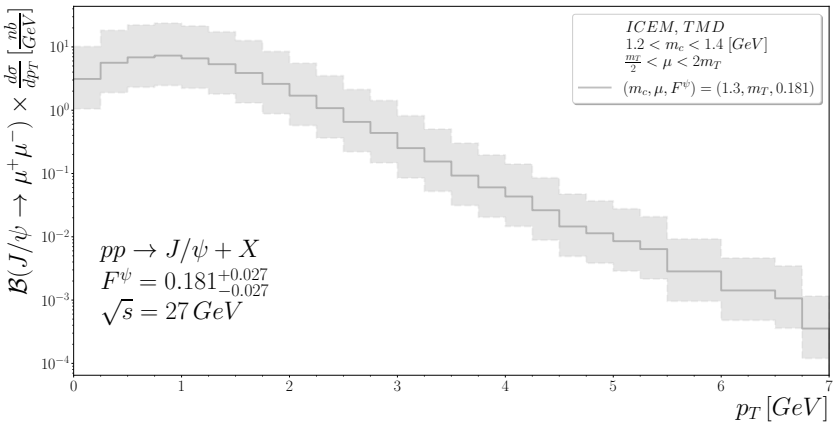

ICEM

# ICEM fit from $\sqrt{s} = 19$ GeV to $\sqrt{s} = 13$ TeV

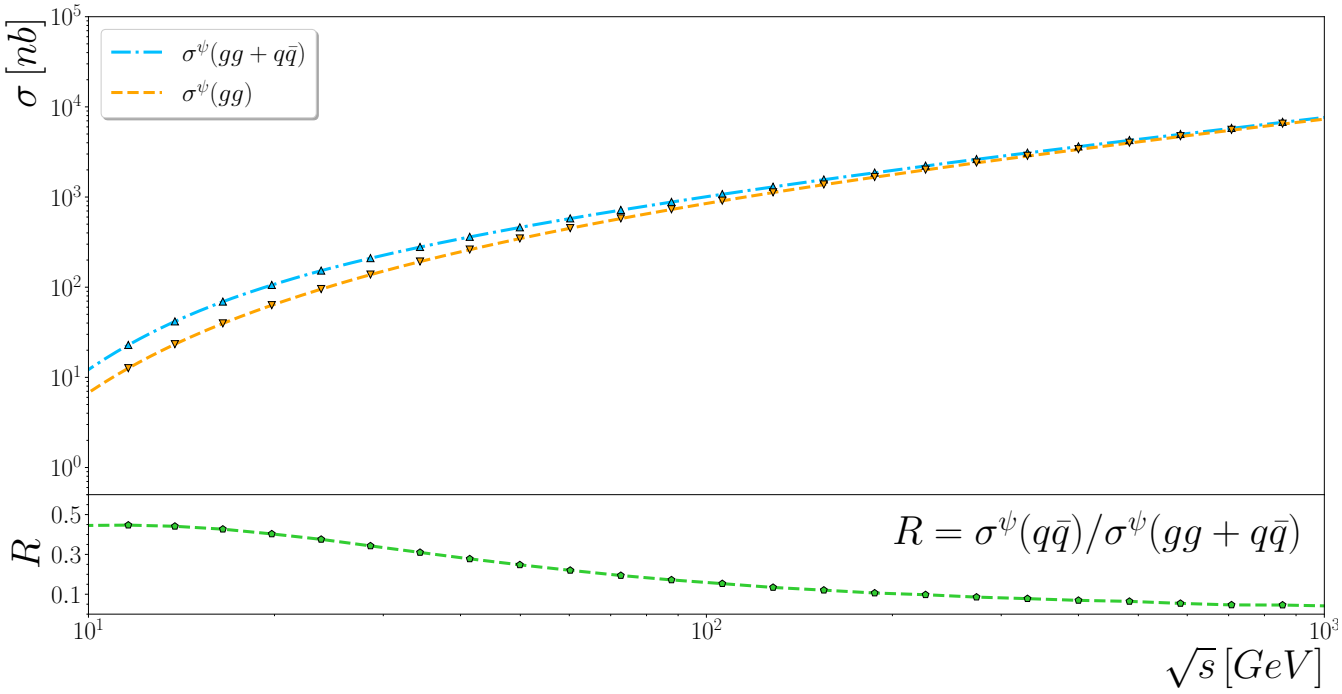


# ICEM predictions for SPD NICA



# Relative contributions to the prompt $J/\psi$ production



# Conclusion I:

- The hadronization factor $F^{J/\psi}(s)$ in the ICEM strongly depends on energy
- Predicted prompt $J/\psi$ production cross section at $\sqrt{s} \sim 20 - 30$ GeV may be about 5-10 times large than it was estimated previously in the ICEM and NRQCD
- Relative contribution of annihilation processes $q\bar{q} \to J/\psi + X$ is about 30–40 % at energies $\sqrt{s} \sim 20 - 30$ GeV in the ICEM, instead of about 5–10 % in the NRQCD.

# 2. $\eta_c$ production with the two-photon decay

**$\eta_c = c\bar{c}[^1S_0]$, $M(\eta_c) = 2.981$ GeV, $\Gamma = 29.7$ MeV**

$$Br(\eta_c \to p\bar{p}) = 1.4 \times 10^{-3}$$

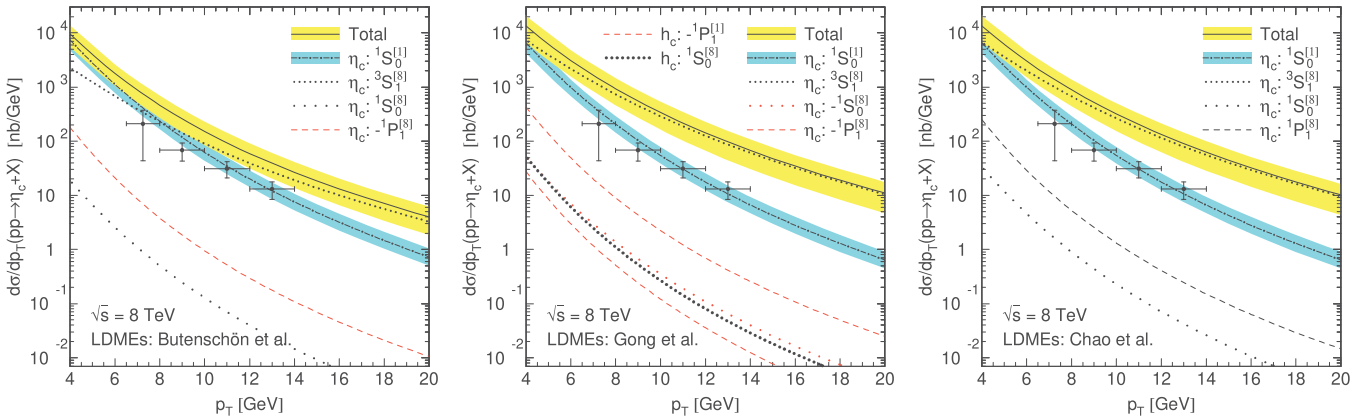
$$Br(\eta_c \to \Lambda\bar{\Lambda}) = 9.4 \times 10^{-4}$$

$$Br(\eta_c \to K\bar{K}\pi) = 7.2 \times 10^{-2}$$

$$\boxed{Br(\eta_c \to \gamma\gamma) = 1.78 \times 10^{-4}}$$

# $\eta_c$ production at the LHC

[Butenschön, Kniehl, He, 2014] Experimental data from [LHCb, 2014]: $pp \to \eta_c(\to p\bar{p}) + X$ with $\sqrt{S} = 7$ and 8 TeV.




Conclusions:

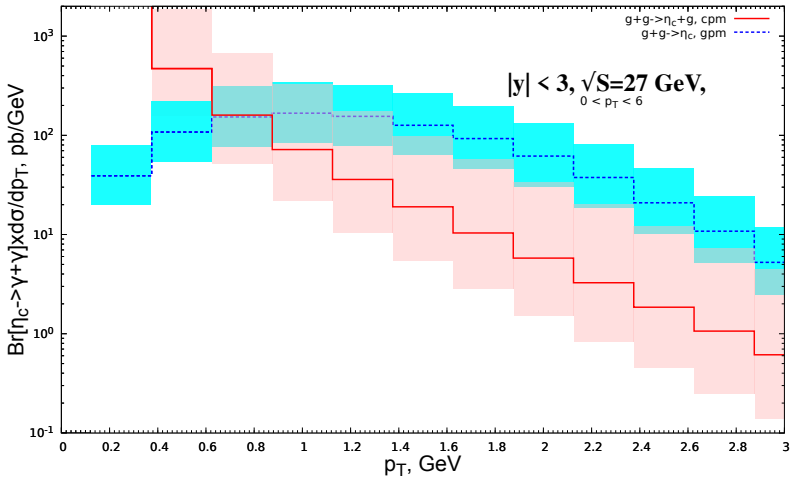
- CS-model ($^1S_0^{(1)}$) describes LHCb data! CO-contrs. lead to significant overshoot. $\Rightarrow$ **HQSS-relations fail!**
- **Feeddown from $h_c$ is negligible**

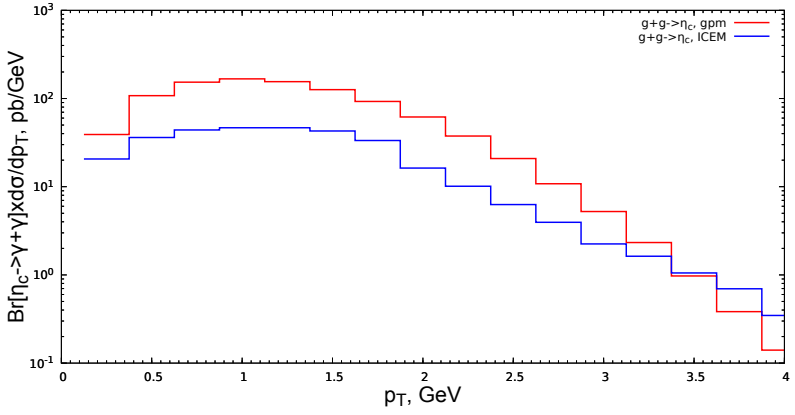
# $\eta_c$ production in GPM + CSM

**$\eta_c$ production at the LHC leads us to following conclusions:**

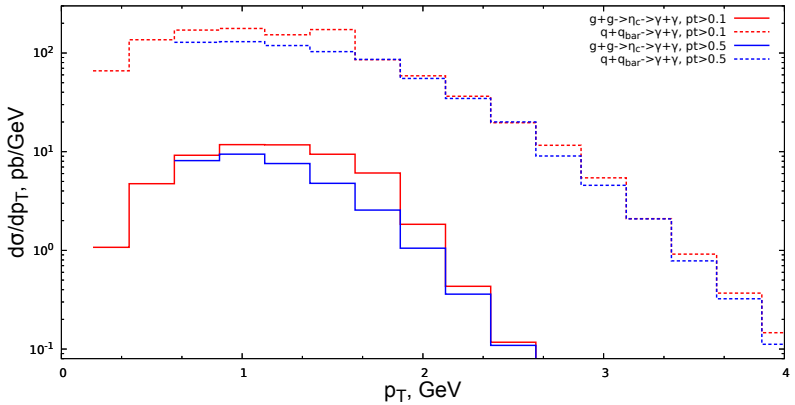
- Color octet LDMEs are don't needed. Color Singlet Model can be used. In the GPM: $g + g \to c\bar{c}[^1S_0^{(1)}] \to \eta_c$.
- Final state is colorless and we can neglect final-state interactions with soft gluons, which destroy hard-soft factorization. The $\eta_c$ production in two-gluon fusion may be considered as "Drell-Yan" process, only for initial gluons.
- There is only direct production of $\eta_c$, contributions from high-mass states can be neglected.

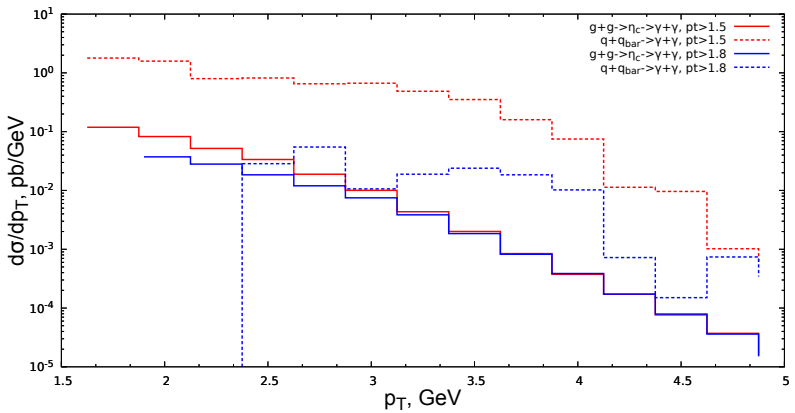
# $\eta_c$ production in GPM and CPM, CSM and ICEM



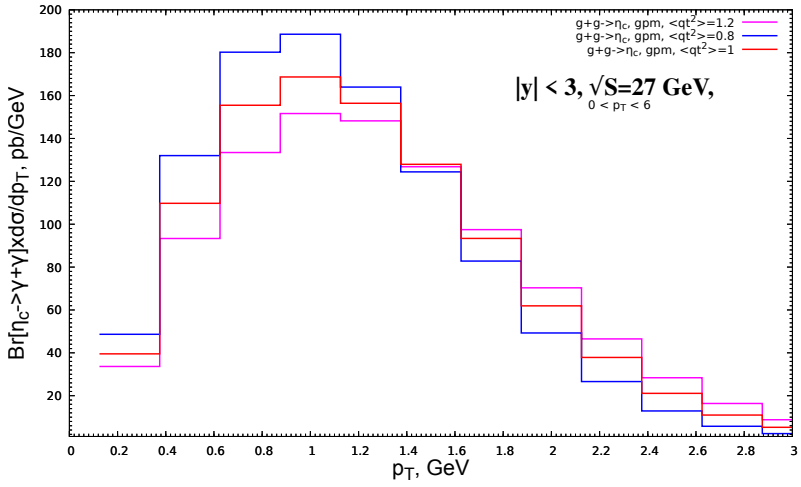



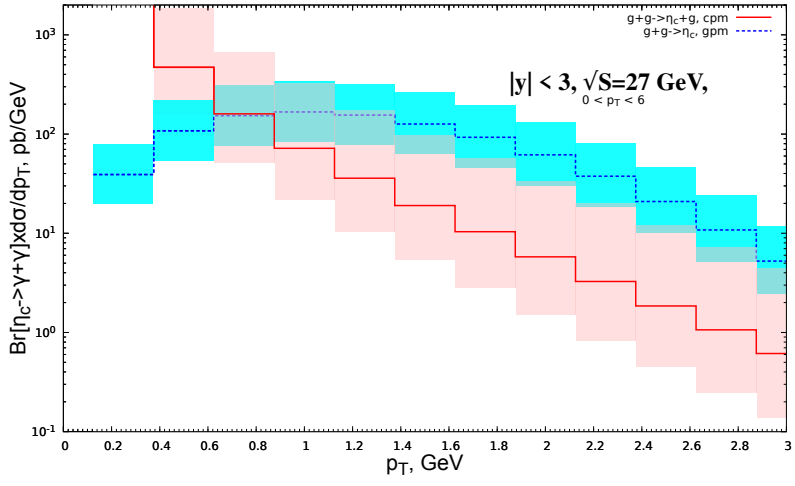
# Signal: $g + g \to \eta_c \to \gamma + \gamma$ and background: $q + \bar{q} \to \gamma + \gamma$ $2.9 < M_{\gamma\gamma} < 3.1$ GeV



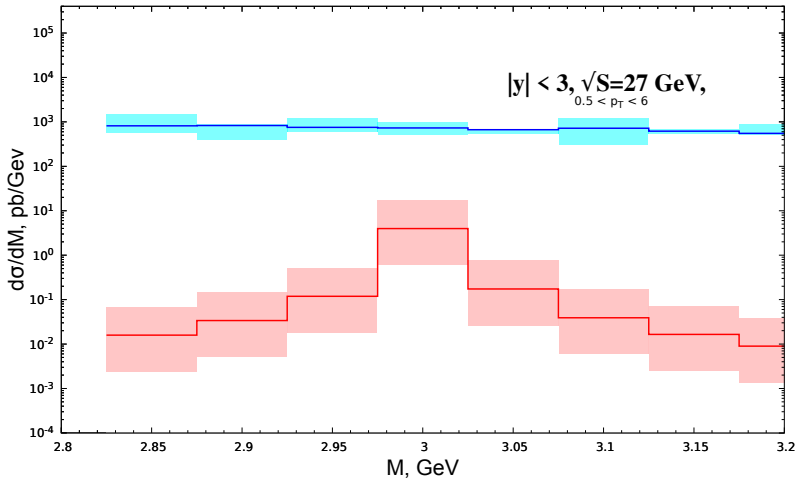



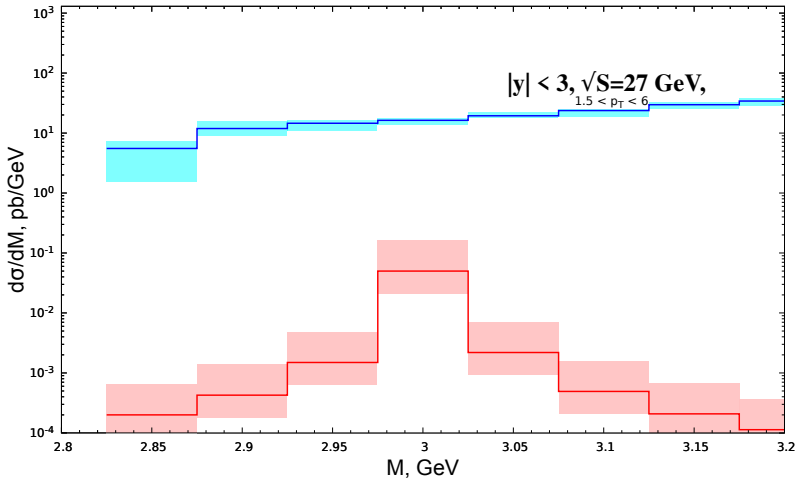
# Transverse momentum spectra at the different $< q_T^2 >= 0.8, \quad 1.0, \quad 1.2$ GeV$^2$.

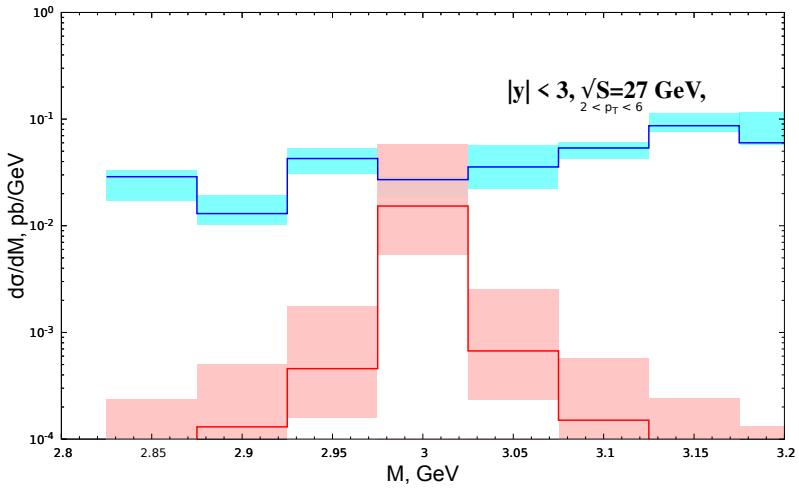


# Signal/background ratio as function of $M_{\gamma\gamma}$.



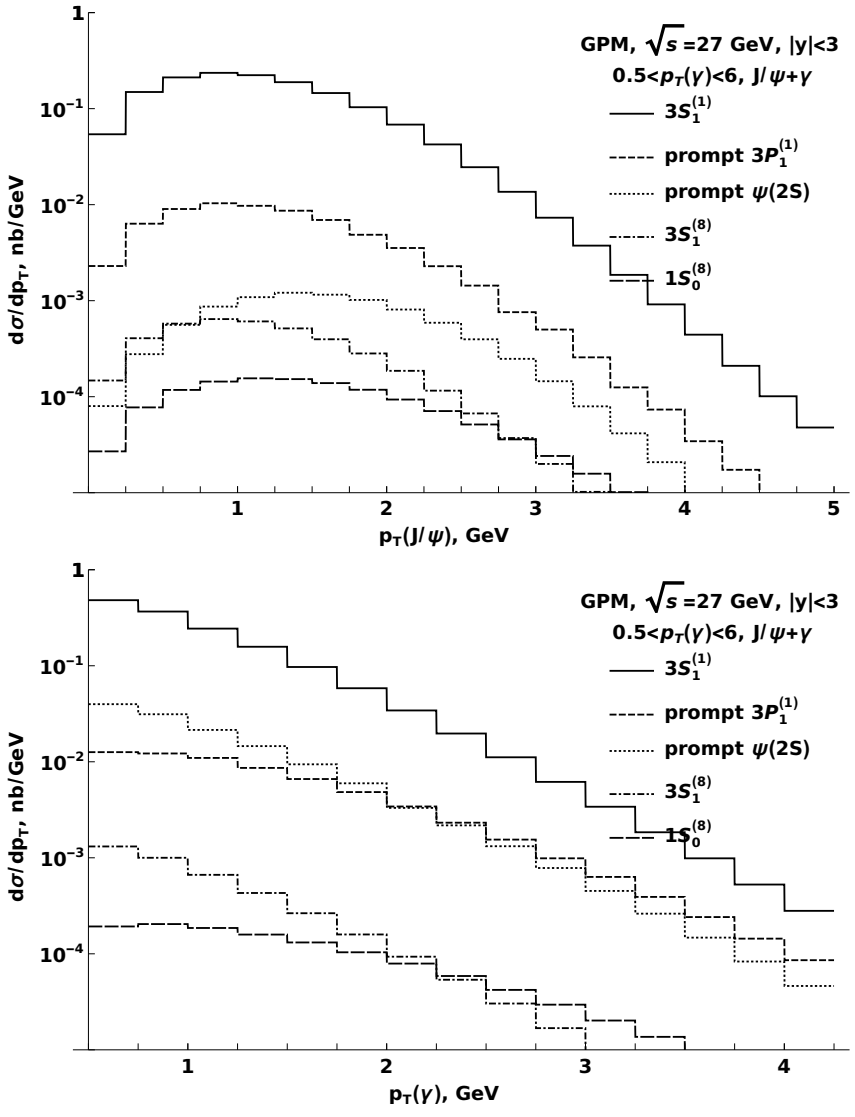
# Conclusion II:

- The estimated $B(\eta_c \to \gamma\gamma) \times \sigma(pp \to \eta_c X) \approx 34$ pb ($p_{T\gamma} > 0.5$ GeV).
- Signal/Background as function of $M_{\gamma\gamma}$ ratio is about $0.1 - 1.0$ at the $p_{T\gamma} > 1.8$ GeV
- The background from $\pi^0 \to \gamma\gamma$ is also small for $p_{T\gamma} > 1.8$ GeV, but additional study is needed (with PYTHIA).

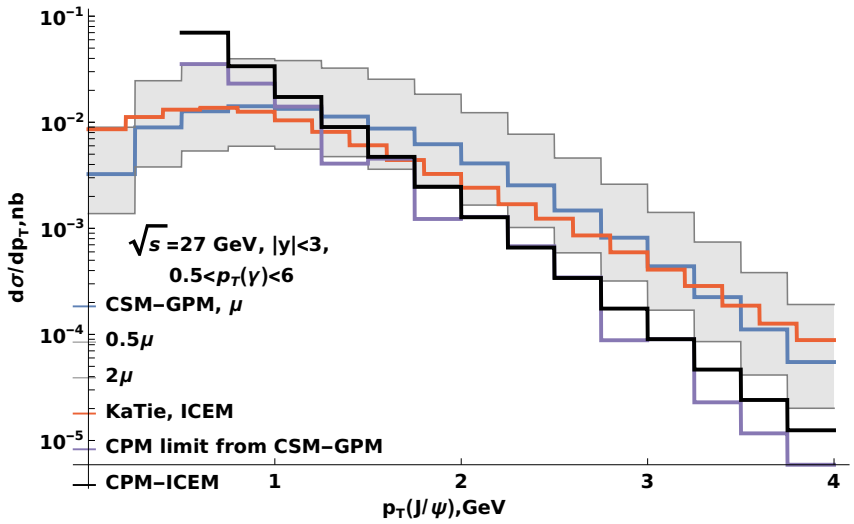
# 3. $J/\psi + \gamma$ as a clean test of gluon PDF

- M. Cacciari, M. Greco and M. Krämer, "Associated $J/\psi + \gamma$ photoproduction as a probe of the color octet mechanism," Phys. Rev. D **55** (1997), 7126-7133
- M. A. Doncheski and C. S. Kim, "Associated $J/\psi + \gamma$ production as a probe of the polarized gluon distribution," Phys. Rev. D **49** (1994), 4463-4468
- W. J. den Dunnen, J. P. Lansberg, C. Pisano and M. Schlegel, "Accessing the Transverse Dynamics and Polarization of Gluons inside the Proton at the LHC," Phys. Rev. Lett. **112** (2014), 212001.
- **Color Singlet mechanism is dominant:** $g + g \to c\bar{c}[^3S_1^{(1)}] + g$
- $q + \bar{q}$ and $q + g$ channels are suppressed
- **There are no experimental data for $J/\psi + \gamma$ till now...**

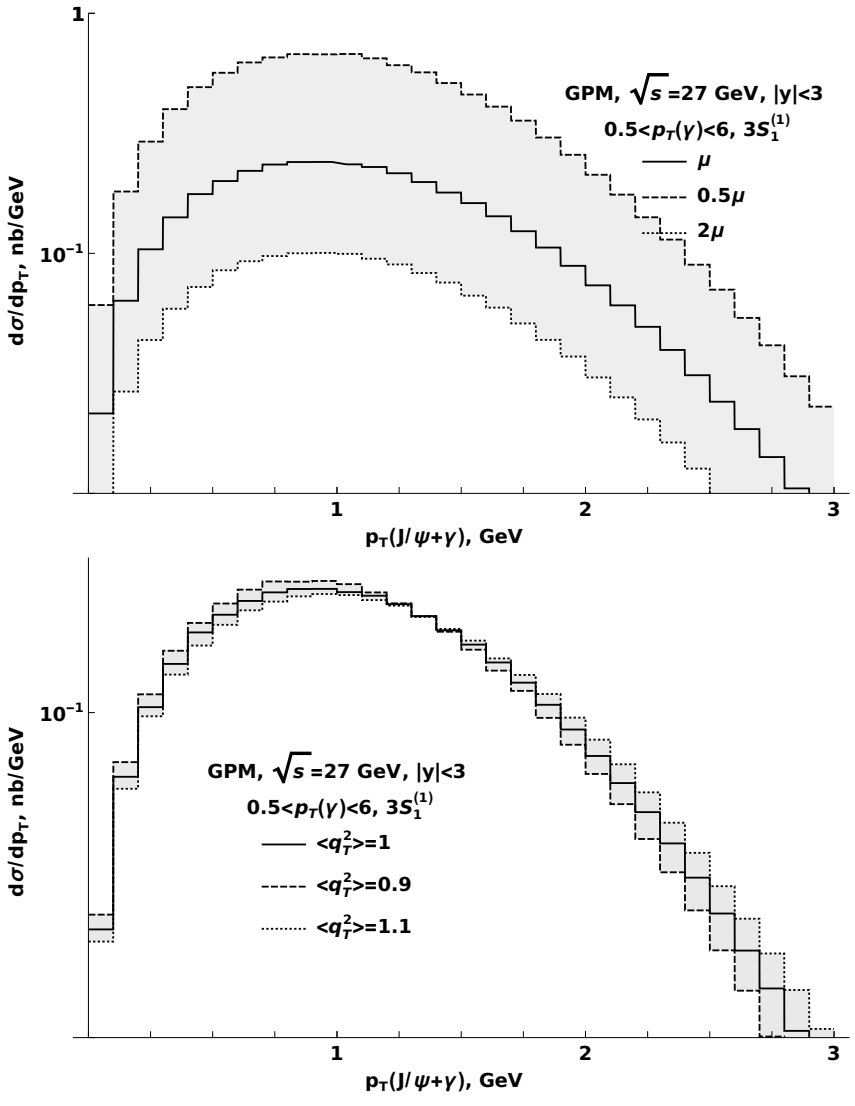
# $J/\psi$ and $\gamma$ transverse momentum spectra in the NRQCD, different contributions.



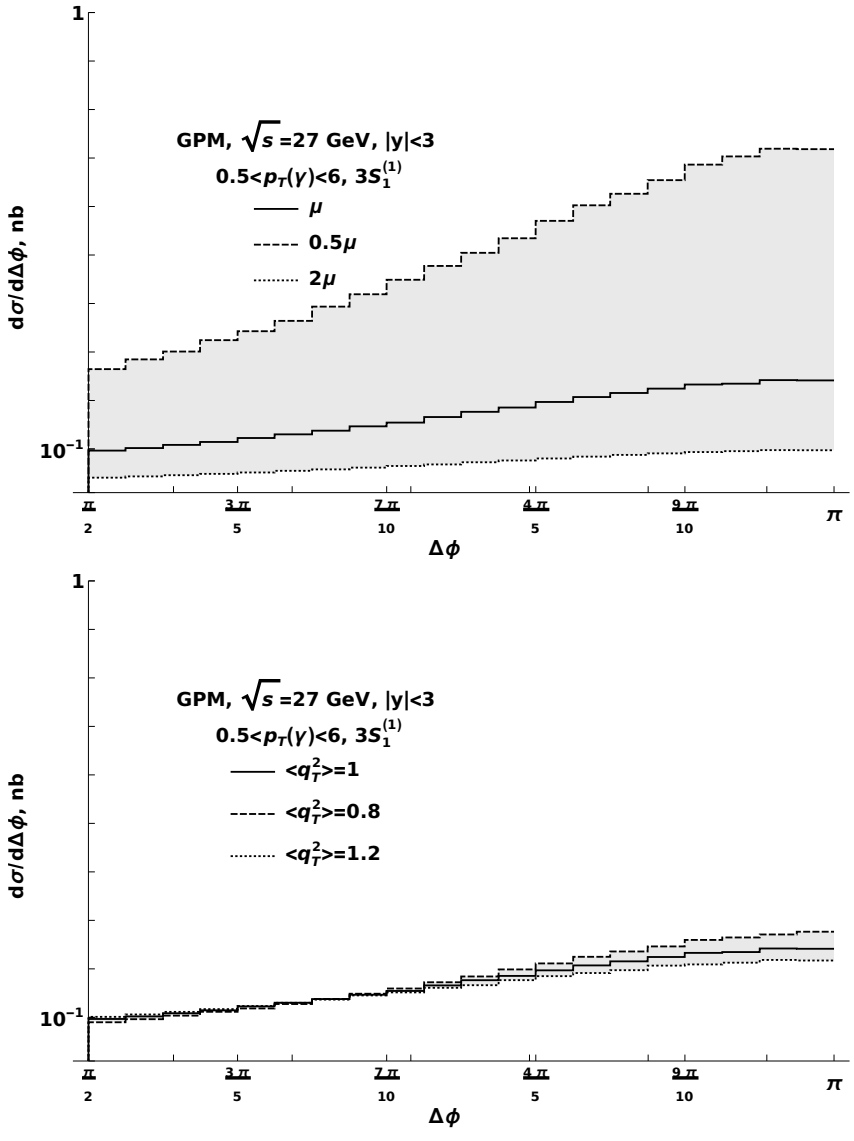
# $J/\psi$ transverse momentum spectra in the NRQCD and ICEM.



# $J/\psi + \gamma$ transverse momentum spectrum.



# Azimuthal angle $\Delta\phi_{\psi\gamma}$ difference spectra, scale dependence and $< q_T^2 >$ −dependence



# Conclusion III:

- At the energy $\sqrt{s} = 27$ GeV, we estimate $\sigma(pp \to J/\psi + \gamma X) \approx 0.45$ nb ($p_{T\gamma} > 0.5$ GeV).
- The colorless final state, as well as in case of $\eta_c$ production, is favorable for theoretical models based on TMD factorization.
- The dominant role of gluon-gluon fusion in $J/\psi + \gamma$ instead of $J/\psi + g$ production.
- The study of Boer-Mulders TMD PDF (polarized gluon in unpolarized proton)

$$\Phi_g^{\mu\nu}(x, \mathbf{q}_T, ...) = -\frac{1}{2x}\left[g_T^{\mu\nu} f_1^g - \left(\frac{q_T^\mu q_T^\nu}{m_p^2} + g_T^{\mu\nu}\frac{\mathbf{q}_T^2}{2m_p^2}\right) h_1^{\perp g}\right]$$

# 4. Polarized $J/\psi$ production

The "spin crisis" in the $J/\psi$ production is in focus of experimental and theoretical study already many years ...

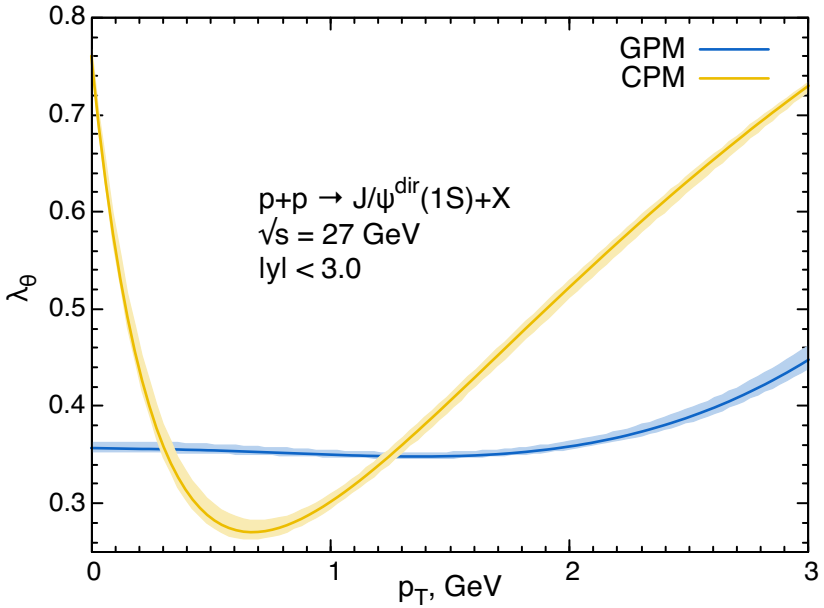
$$W(\theta,\phi) \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \cos\phi$$

$$\lambda_\theta = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L} = \frac{\sigma - 3\sigma_L}{\sigma + \sigma_L}$$

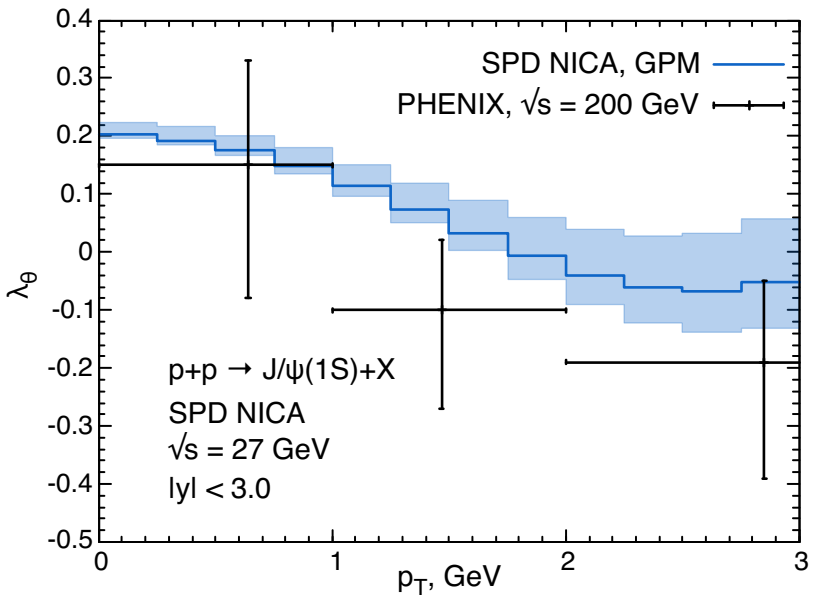
We estimate $A_N$ in the polarized $J/\psi$ production

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\Delta\sigma}{2d\sigma}$$

# Polarized $J/\psi$ production

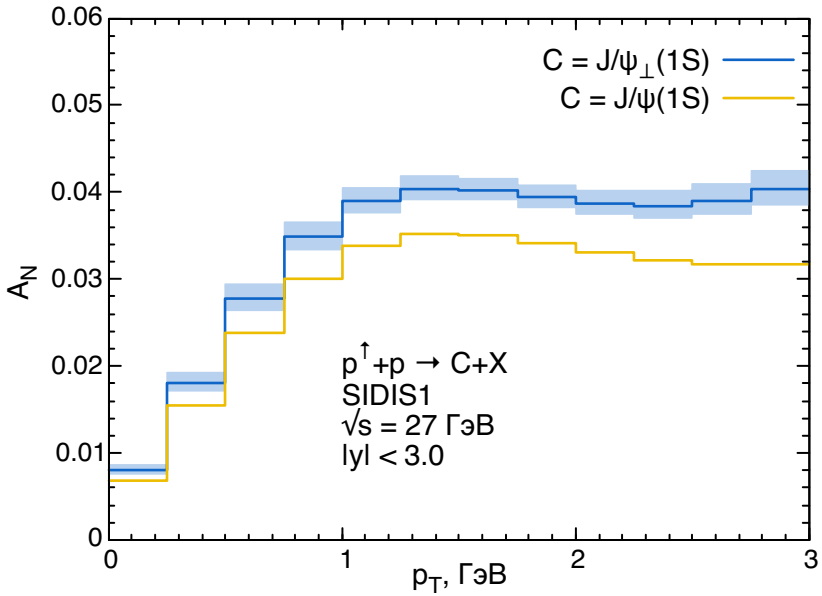



DIRECT $J/\psi$ PRODUCTION

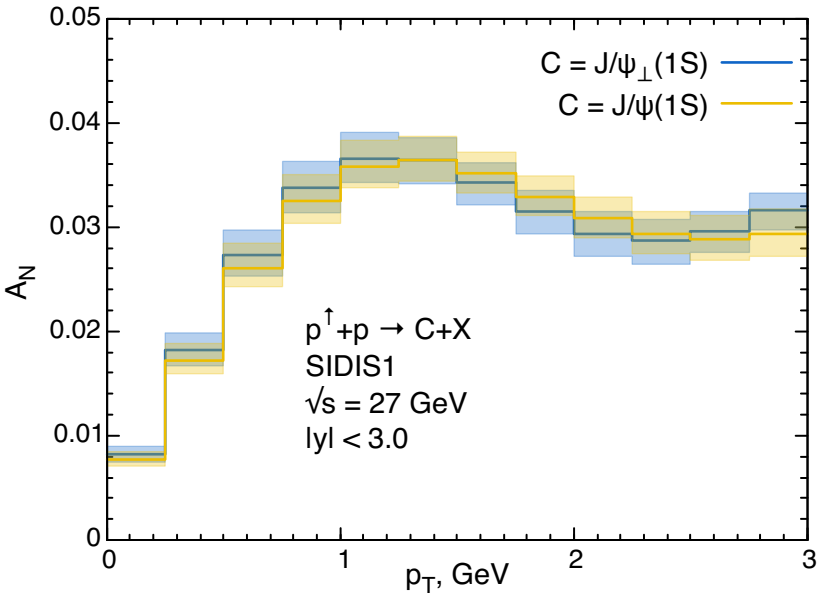



PROMPT $J/\psi$ PRODUCTION (GPM)

# $A_N$ in the polarized $J/\psi$ production

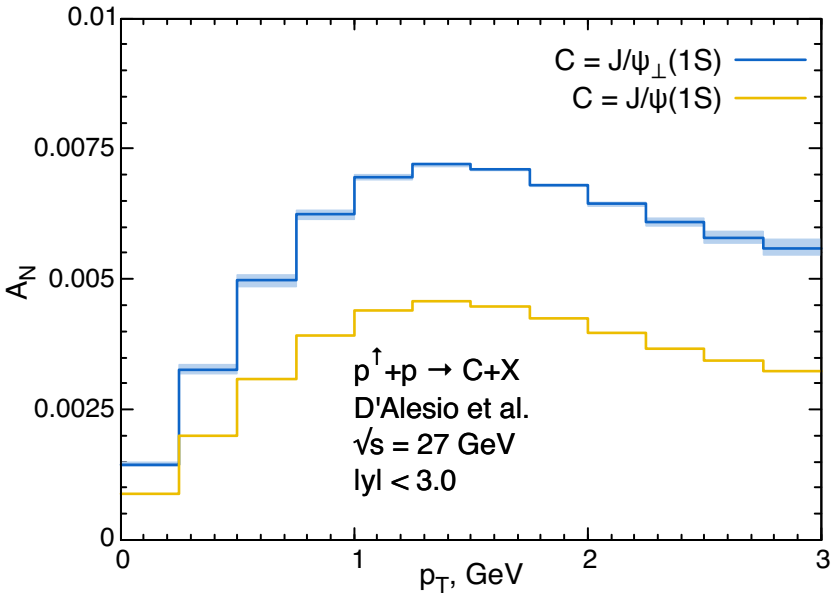



DIRECT $J/\psi$ PRODUCTION

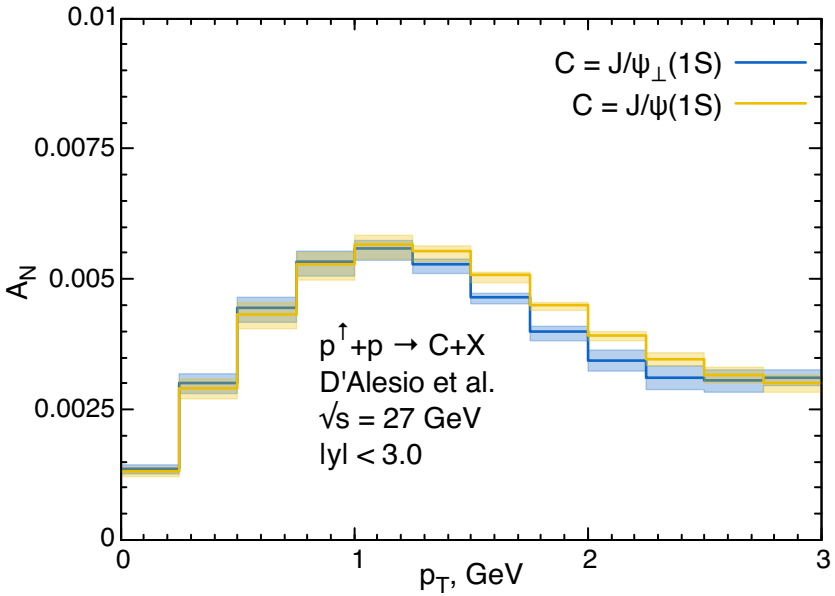



PROMPT $J/\psi$ PRODUCTION (GPM)

# $A_N$ in the polarized $J/\psi$ production




DIRECT $J/\psi$ PRODUCTION




PROMPT $J/\psi$ PRODUCTION (GPM)

# Conclusion IV:

- Our prediction in the CSM+GPM for spin parameter $\lambda_\theta^{HS}$ in the prompt $J/\psi$ production very close to PHENIX data.
- $A_N$ depends on $J/\psi$ polarization in the direct production of $J/\psi$.
- It is interesting to check contribution of the gluon Boer-Mulders TMD PDF in polarized $J/\psi$ production

**Thank you for your attention!**