Prompt J/ψ hadroproduction in the ICEM: from low to high energy

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2. Factorization approaches: CPM, GPM, and **TMD/PRA**
3. Hadronization mechanisms: CSM, NRQCD and CEM (ICEM)
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Introduction

Charmonium

- $J/\psi = c\bar{c}[^3S_1]$
- $M_{J/\psi} = 3.1$ GeV
- $\Gamma = 92.9$ keV
- $Br(J/\psi \to \mu^+\mu^-) = 0.06$

Introduction

- There are data for J/ψ hadroproduction from $\sqrt{s} = 19$ GeV to $\sqrt{s} = 13$ TeV
- "Inclusive" production $pp \to J/\psi X$
- "Prompt" production $pp \to J/\psi X$ without $B-$hadron contribution, via $b \to J/\psi X$
- "Direct" production = Prompt without productions via decays of the $\chi_{cJ}, \psi(2S) \to J/\psi\gamma$

Factorization approaches: CPM, GPM and TMD PM / PRA

Hard (factorization + renormalization) scale $\mu_F \sim \mu_R \sim M_{J/\psi}$

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

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

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

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

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

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

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

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

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

Factorization approaches: CPM, GPM and TMD PM / PRA

The Parton Reggeization Approach (PRA)

- High-energy factorization: $q_{1,2T} \sim p_T$

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

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

- $q_{1,2}^2 = -\vec{q}_{1,2}^{\,2}$, $q_{1,2}^\mu = x_{1,2} P_{1,2}^\mu + q_{T1,2}^\mu$, $q_T^\mu = (0, \vec{q}, 0)$
- k_T-factorization: Gribov, Levin, Ryskin [1984], Collins and Ellis [1991], Catani and Hautmann [1994],..
- QCD in multi-Regge limit: Kuraev, Lipatov, and Fadin [1976], Balitskii, Lipatov [1978]
- Effective Theory of Reggeized gluons and qaurks: Lipatov [1995], Lipatov, Vyazovsky [2001]
- unPDF: Watt, Kimber, Martin, and Ryskin [2001]
- unPDF with exact normalization: Nefedov and Saleev [2020]

Factorization approaches: CPM, GPM and TMD PM / PRA

PRA and TMD PM

- In the limit $q_{T1,2} \to 0$ in Reggeized amplitude we obtain $|M(RR \to c\bar{c})|^2 \to |M(gg \to c\bar{c})|^2$
- Nefedov and Saleev [2020]: in the limit $q_{T1,2} << \mu_F$ we have $F_R(x, q_T, \mu_F) \simeq F_g^{TMD}(x, q_T, \mu_F, \mu_Y = \mu_F)$
- $\int F_{R,Q}(x, t, \mu_F)dt = x f_{g,q}(x, \mu_F)$, $t = -q_T^2 > 0$
- $F_{R,Q}(x, t, \mu_F) = \frac{d}{dt}[T_{R,Q}(t, \mu_F, x) x f_{g,q}(x, \mu_F)]$
- NLO in PRA is in progress, Nefedov, Saleev [2018,2019], Nefedov[2020,2021].

PRA smoothly interpolates QCD predictions between high-energy and low-energy regions AND between small-p_T and large-p_T of final partons

Hadronization mechanisms: CSM, NRQCD and CEM (ICEM)

J/ψ production

- Baier, Ruckl, Berger, Jones [1983] – Color Singlet Model (CSM):
  $R + R \to c\bar{c}[^3S_1^{(1)}]$ and LDME $< J/\psi[^3S_1^{(1)}] >= 18 \times |\Psi(0)|^2$
- Bodwin, Braaten, and Lepage [1995] – NRQCD:
  $R + R \to c\bar{c}[^3S_1^{(1)}], [^1S_0^{(8)}], [^3P_J^{(8)}]$ as perturbative series in v^0, v^2, ...
- Fritzsch, Halzen [1977] – Color Evaporation Model (CEM):

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

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

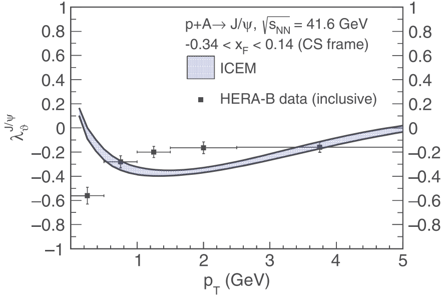
$$\sigma(J/\psi) = F_{J/\psi} \int_{M_{J/\psi}}^{2m_D} \frac{d\sigma(RR \to c\bar{c})}{dM_{c\bar{c}}} dM_{c\bar{c}}$$

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

ICEM in work

Recent studies

- V. Cheung and R. Vogt, “Production and polarization of direct J/ψ up to $O(\alpha_s^3)$ in the improved color evaporation model in collinear factorization,” Phys. Rev. D **104** (2021) no.9, 094026
- V. Cheung and R. Vogt, “Production and polarization of prompt J/ψ in the improved color evaporation model using the k_T-factorization approach,” Phys. Rev. D **98** (2018) no.11, 114029
- V. Cheung and R. Vogt, “Polarized Heavy Quarkonium Production in the Color Evaporation Model,” Phys. Rev. D **95** (2017) no.7, 074021

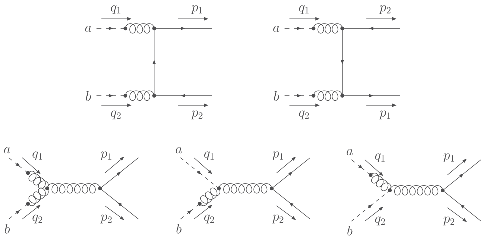


I. Calculations in the PRA

Master formula for semi-analytical calculation

$$\frac{d\sigma(pp \to J/\psi X)}{dp_T dy} \sim \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} \times F_R(x_1, q_{1T}^2, \mu_F) F_R(x_2, q_{2T}^2, \mu_F) \times$$
$$\times \quad |M(RR \to c\bar{c})|^2$$

Feynman rules of the Lipatov effective theory



II. Calculations in the PRA

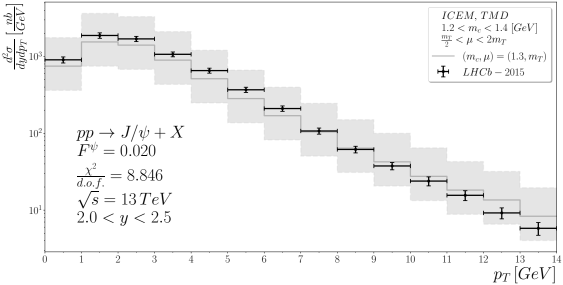
MC parton-level event generator KaTie

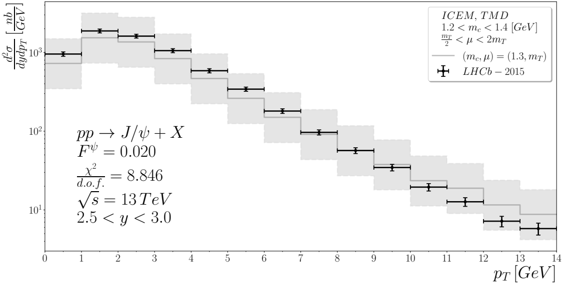
- A. van Hameren, "KaTie : For parton-level event generation with k_T-dependent initial states," Comput. Phys. Commun. **224** (2018), 371-380
- TMD PDFs from TMDlib: https://tmdlib.hepforge.org/
- Output files are in LHEF format (Les Houches Event File)

Abstract

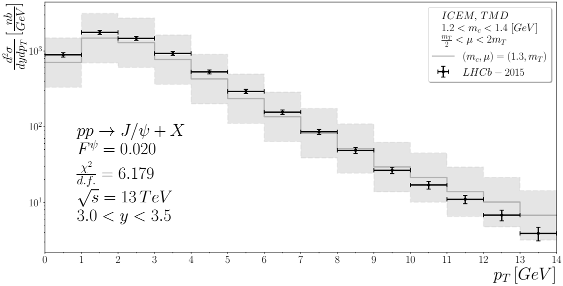
KaTie is a parton-level event generator for hadron scattering processes that can deal with partonic initial-state momenta with an explicit transverse momentum dependence causing them to be space-like. Provided with the necessary transverse momentum dependent parton density functions, it calculates the tree-level off-shell matrix elements and performs the phase space importance sampling to produce weighted events, for example in the Les Houches Event File format. It can deal with arbitrary processes within the Standard Model, for up to at least four final-state particles. Furthermore, it can produce events for single-parton scattering as well as for multi-parton scattering.

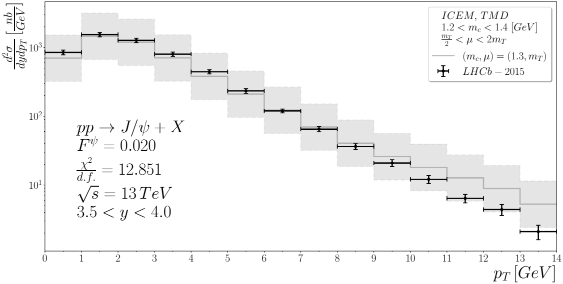
ICEM fit at $\sqrt{s} = 13$ TeV, LHCb



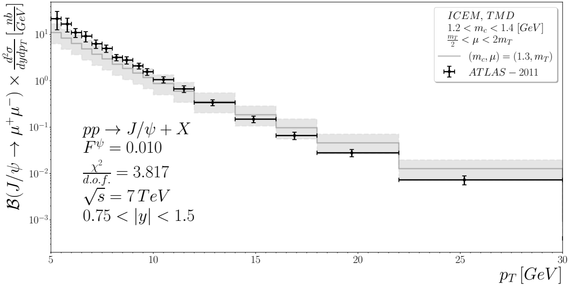


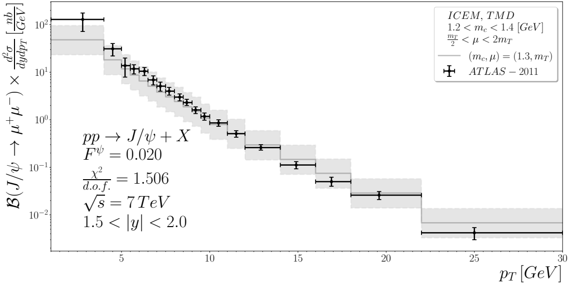
ICEM fit at $\sqrt{s} = 13$ TeV, LHCb



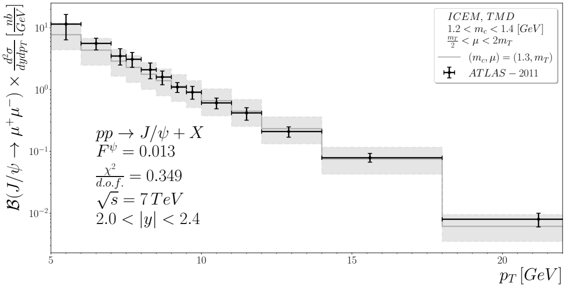


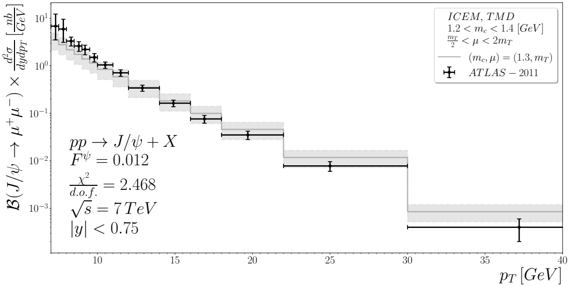
ICEM fit at $\sqrt{s} = 7$ TeV, ATLAS



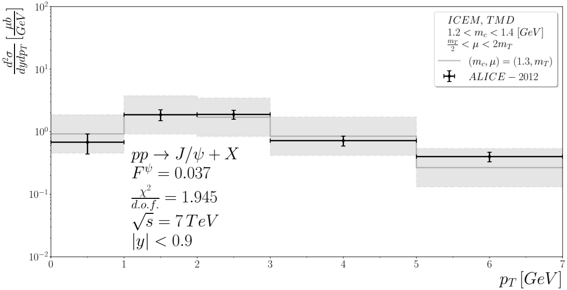


ICEM fit at $\sqrt{s} = 7$ TeV, ATLAS

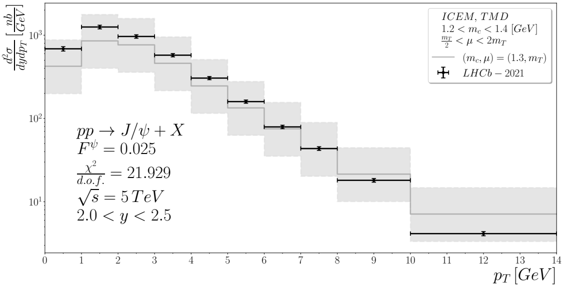




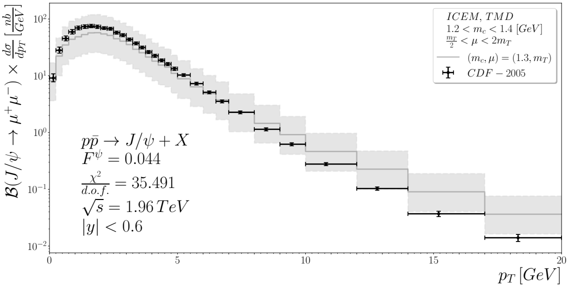
ICEM fit at $\sqrt{s} = 7$ TeV, ALICE



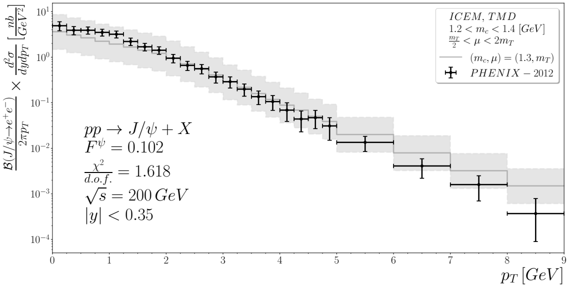
ICEM fit at $\sqrt{s} = 5$ TeV, LHCb



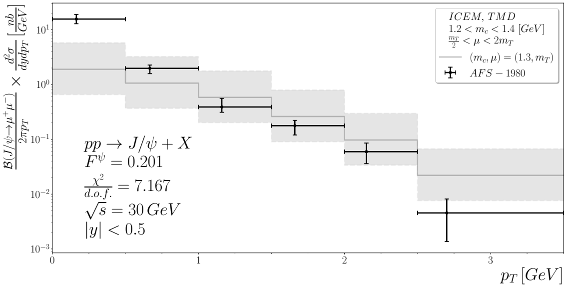
ICEM fit at $\sqrt{s} = 2$ TeV, CDF

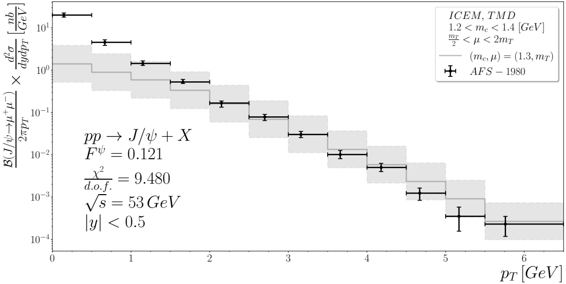


ICEM fit at $\sqrt{s} = 200$ GeV, PHENIX

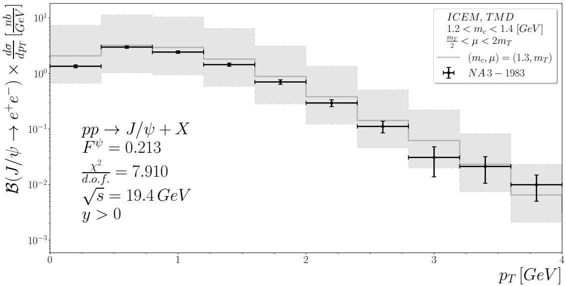


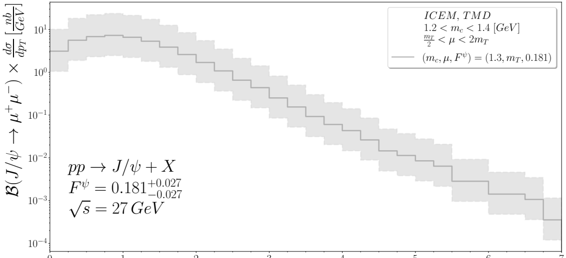
ICEM fit at $\sqrt{s} = 30, 53$ GeV, ASF (ISR)





ICEM fit at $\sqrt{s} = 19$ GeV, NA3 and prediction for $\sqrt{s} = 27$ GeV, NICA

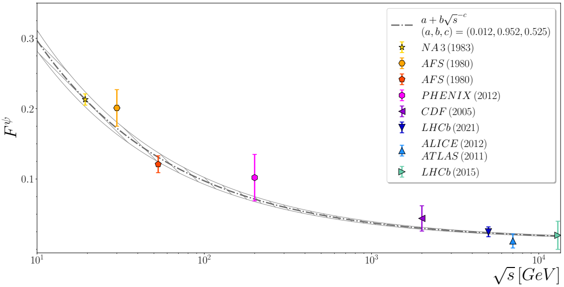




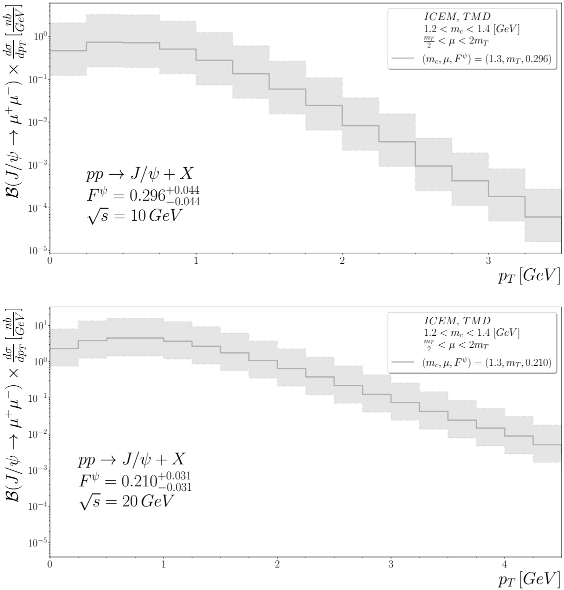
ICEM fit from $\sqrt{s} = 19$ GeV to $\sqrt{s} = 13$ TeV

ICEM, prompt J/ψ, fit F^{ψ}
NA3: $\sqrt{s} = 19.4$ GeV, $y > 0$, $p_T \in [0, 5]$ GeV
$0.213^{+0.008}_{-0.008}$
AFS: $\sqrt{s} = 30$ GeV, $\|y\| < 0.5$, $p_T \in [0, 5]$ GeV
$0.201^{+0.026}_{-0.026}$
AFS: $\sqrt{s} = 53$ GeV, $\|y\| < 0.5$, $p_T \in [0, 7]$ GeV
$0.121^{+0.012}_{-0.012}$
PHENIX: $\sqrt{s} = 0.2$ TeV, $\|y\| < 0.35$, $p_T \in [0, 9]$ GeV
$0.102^{+0.033}_{-0.033}$
CDF: $\sqrt{s} = 1.96$ TeV, $\|y\| < 0.6$, $p_T \in [0, 20]$ GeV
$0.044^{+0.018}_{-0.018}$
LHCb: $\sqrt{s} = 5$ TeV, $2.0 < y < 2.5$, $p_T \in [0, 14]$ GeV
$0.025^{+0.007}_{-0.007}$
ALICE: $\sqrt{s} = 7$ TeV, $\|y\| < 0.9$, $p_T \in [0, 7]$ GeV
$0.037^{+0.007}_{-0.007}$
ATLAS: $\sqrt{s} = 7$ TeV, $0.75 < \|y\| < 1.5$, $p_T \in [5, 30]$ GeV
$0.010^{+0.003}_{-0.003}$
ATLAS: $\sqrt{s} = 7$ TeV, $1.5 < \|y\| < 2.0$, $p_T \in [1, 30]$ GeV
$0.020^{+0.005}_{-0.005}$
ATLAS: $\sqrt{s} = 7$ TeV, $2.0 < \|y\| < 2.4$, $p_T \in [5, 30]$ GeV
$0.013^{+0.001}_{-0.001}$
ATLAS: $\sqrt{s} = 7$ TeV, $\|y\| < 0.75$, $p_T \in [7, 30]$ GeV
$0.012^{+0.004}_{-0.004}$
LHCb: $\sqrt{s} = 13$ TeV, $2.0 < y < 2.5$, $p_T \in [0, 14]$ GeV
$0.021^{+0.004}_{-0.004}$
LHCb: $\sqrt{s} = 13$ TeV, $2.5 < y < 3.0$, $p_T \in [0, 14]$ GeV
$0.022^{+0.004}_{-0.004}$
LHCb: $\sqrt{s} = 13$ TeV, $3.0 < y < 3.5$, $p_T \in [0, 14]$ GeV

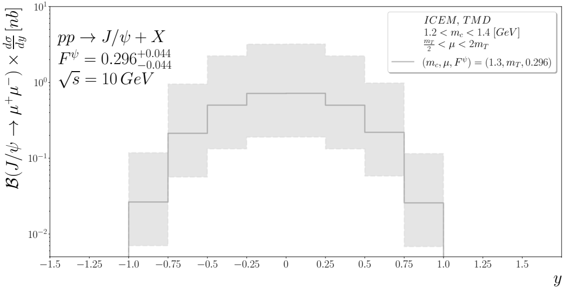
ICEM fit from $\sqrt{s} = 19$ GeV to $\sqrt{s} = 13$ TeV

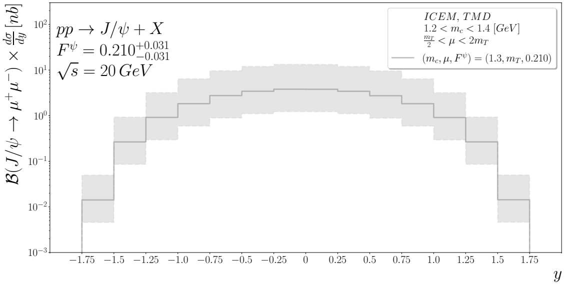


Predictions for $\sqrt{s} = 10$ GeV and $\sqrt{s} = 20$ GeV

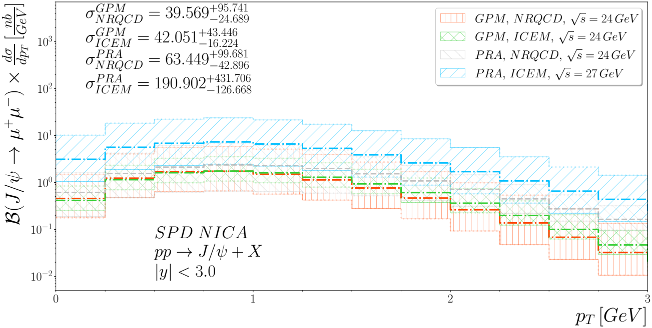


Predictions for $\sqrt{s} = 10$ GeV and $\sqrt{s} = 20$ GeV

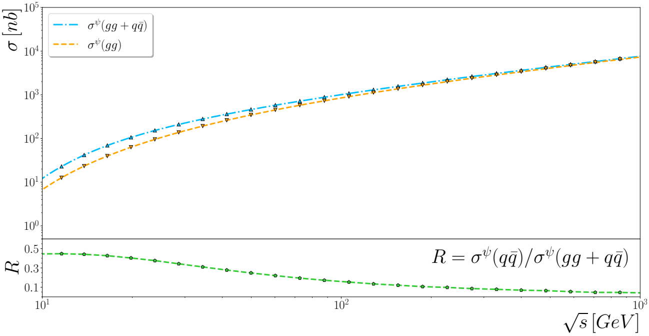




Prompt J/ψ production at NICA



Relative contributions to the prompt J/ψ production



Conclusions

- The hadronization factor $F^{J/\psi}(s)$ in the ICEM strongly depends on energy
- Predicted prompt J/ψ production cross section at $\sqrt{s} \sim 20 - 30$ GeV may be about 4-5 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.

Thank you for your attention!