Pair production of J/ψ in the color evaporation model using the Parton Reggeization Approach

A. Chernyshev[1],V. Saleev[1,2]

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

18 July 2022
JINR, Dubna

Talk at the International Conference on Quantum Field Theory, High-Energy Physics, and Cosmology

Outline

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

Single J/ψ hadroproduction

- 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 $\chi_{cJ}, \psi(2S) \to J/\psi\gamma$

Double J/ψ hadroproduction

- There are data for double J/ψ hadroproduction from $\sqrt{s} = 1.96$ TeV to $\sqrt{s} = 13$ TeV
- LHCb, 13 TeV, $2 < y < 4.5$, $0 < p_{T2\psi} < 14$ GeV
- CMS, 7 TeV, $0 < p_{T2\psi} < 40$ GeV, $|y_\psi| < 2.2$, $p_{T\psi} > 4.5$ GeV
- ATLAS, 8 TeV, $|y_\psi| < 2.1$,$0 < p_{T2\psi} < 70$ GeV, $p_{T\psi} > 8.5$ GeV

Factorization approaches: CPM, TMD PM and High Energy Factorization

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

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

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

- **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, TMD PM and High Energy Factorization

The High Energy Factorization ⇒ 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, TMD PM and High Energy Factorization

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 the 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

Factorization approaches: CPM, TMD PM and High Energy Factorization

PRA,the main publications:

- M. A. Nefedov, V. A. Saleev and A. V. Shipilova, "Dijet azimuthal decorrelations at the LHC in the parton Reggeization approach," Phys. Rev. D **87** (2013) no.9, 094030
- A. V. Karpishkov, M. A. Nefedov and V. A. Saleev, "$B\bar{B}$ angular correlations at the LHC in parton Reggeization approach merged with higher-order matrix elements," Phys. Rev. D **96** (2017) no.9, 096019
- M. Nefedov and V. Saleev, "On the one-loop calculations with Reggeized quarks," Mod. Phys. Lett. A **32** (2017) no.40, 1750207
- M. A. Nefedov, "Towards stability of NLO corrections in High-Energy Factorization via Modified Multi-Regge Kinematics approximation," JHEP **08** (2020), 055 doi:10.1007/JHEP08(2020)055
- 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

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

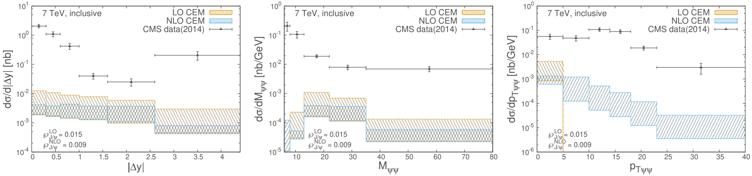
I. Recent studies

- 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

ICEM in work

II. Recent studies

- J. P. Lansberg, H. S. Shao, N. Yamanaka, Y. J. Zhang and C. Noûs, "Complete NLO QCD study of single- and double-quarkonium hadroproduction in the colour-evaporation model at the Tevatron and the LHC," Phys. Lett. B **807** (2020), 135559
- The main hypothesis was $F^{\psi\psi} = F^{\psi} \times F^{\psi}$



(a) (b) (c)

Double J/ψ production in the NRQCD + PRA

Relevant publications:

- Z. G. He, B. A. Kniehl, M. A. Nefedov and V. A. Saleev, “Double Prompt J/ψ Hadroproduction in the Parton Reggeization Approach with High-Energy Resummation,” Phys. Rev. Lett. **123** (2019) no.16, 162002
- Z. G. He, B. A. Kniehl, M. A. Nefedov and V. A. Saleev, “Double prompt J/ψ production at hadron colliders,” Mod. Phys. Lett. A **36** (2021) no.19, 2130018

NRQCD+PRA versus experimental data

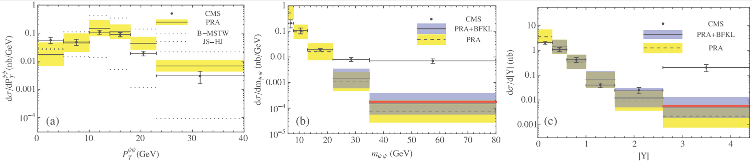


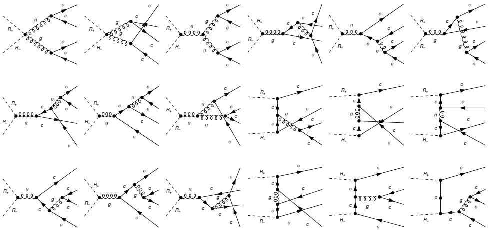
FIG. 2. The (a) $p_T^{\psi\psi}$, (b) $m_{\psi\psi}$, and (c) $|Y|$ distributions of double prompt J/ψ production measured by the CMS Collaboration [10] are compared to our LO NRQCD predictions in the PRA without (dashed lines) and with BFKL resummation (solid lines) including their scale uncertainties (yellow and blue bands). Adding the total NLO* NLT contributions on top of the central LO NRQCD predictions in the PRA with BFKL resummation yields the red solid lines. Frame (a) also contains the evaluations with the UPDF sets of Refs. [28,32] (B-MSTW, dotted lines) and Ref. [33] (JS-HJ, dot-dashed lines).

I. Calculations in the PRA

Master formula for semi-analytical calculation

$$\begin{aligned}\frac{d\sigma(pp\to 2J/\psi X)}{dp_T dy} &\sim \int dx_1 d^2q_{1T}\int dx_2 d^2 q_{2T}\times F_R(x_1,q_{1T}^2,\mu_F)F_R(x_2,q_{2T}^2,\mu_F)\\ &\times F^{\psi\psi}|M(RR\to c1\bar{c}1c2\bar{c}2)|^2 \qquad (1)\\ &\times [\theta(M_{c1\bar{c}1}-M_\psi)-\theta(M_{c1\bar{c}1})-2M_D]\\ &\times [\theta(M_{c2\bar{c}2}-M_\psi)-\theta(M_{c2\bar{c}2})-2M_D]\end{aligned}$$

Feynman rules of the Lipatov effective theory ⇒ 72 diagrams



II. Calculations in the PRA

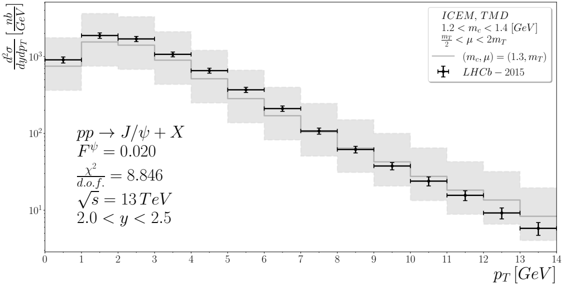
MC parton-level event generator KaTie

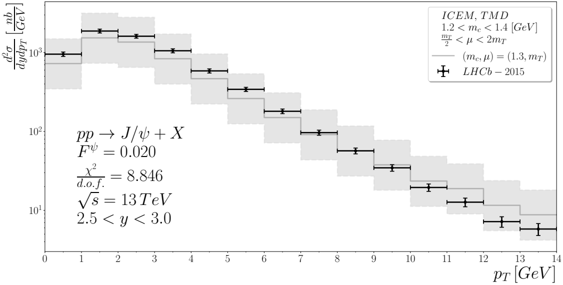
- A. van Hameren, "KaTie : For parton-level event generation with k_T-dependent initial states," Comput. Phys. Commun. **224** (2018), 371-380
- TMD PDFs from TMDlib: https://tmdlib.hepforge.org/
- Output files are in LHEF format (Les Houches Event File)

Abstract

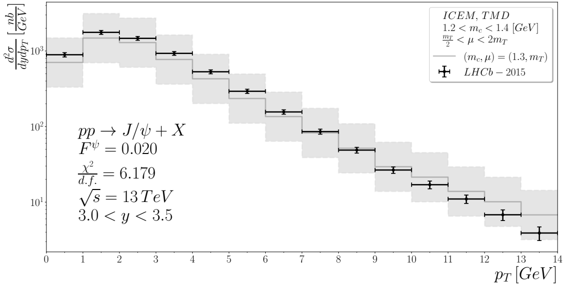
KaTie is a parton-level event generator for hadron scattering processes that can deal with partonic initial-state momenta with an explicit transverse momentum dependence causing them to be space-like. Provided with the necessary transverse momentum dependent parton density functions, it calculates the 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.

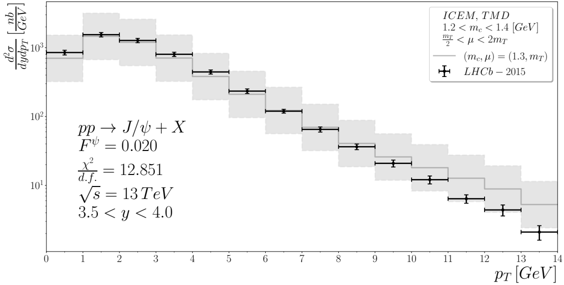
Single J/ψ production in the ICEM + PRA



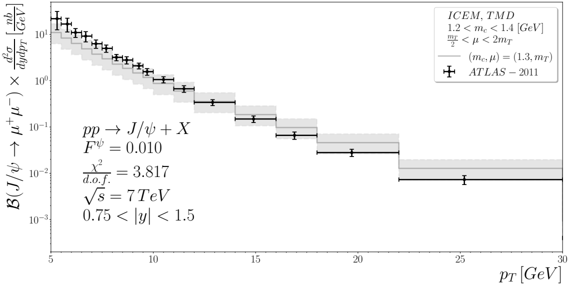


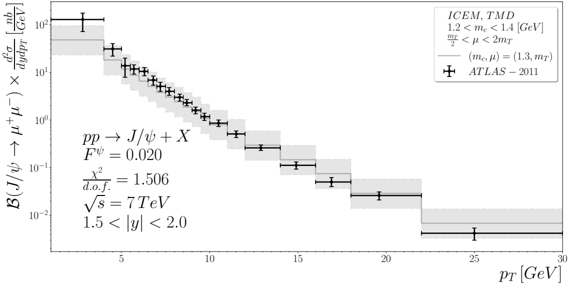
Single J/ψ production in the ICEM + PRA



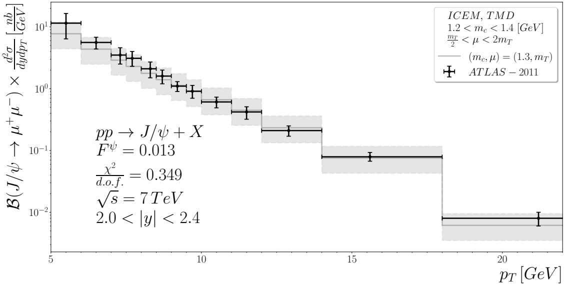


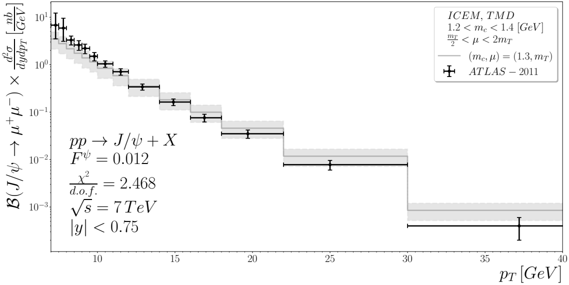
Single J/ψ production in the ICEM + PRA



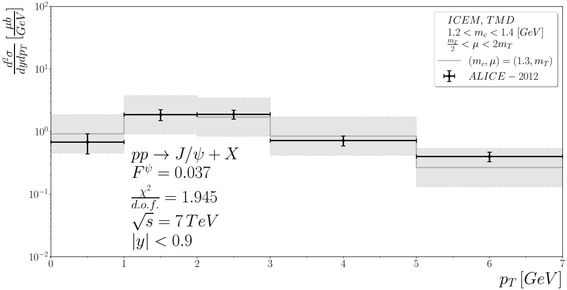


Single J/ψ production in the ICEM + PRA

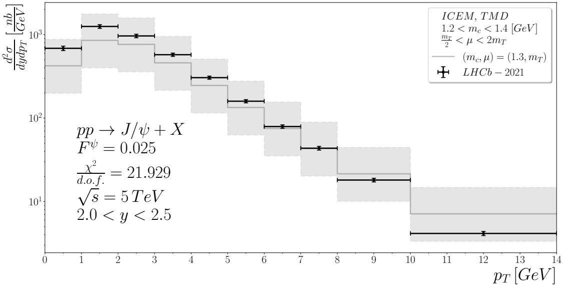




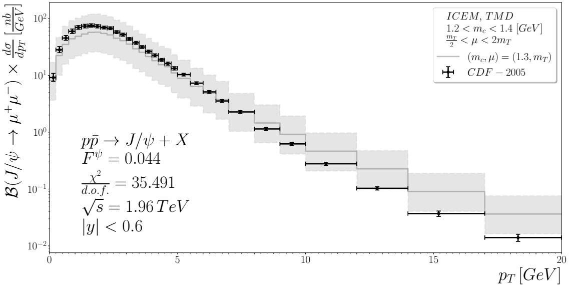
Single J/ψ production in the ICEM + PRA



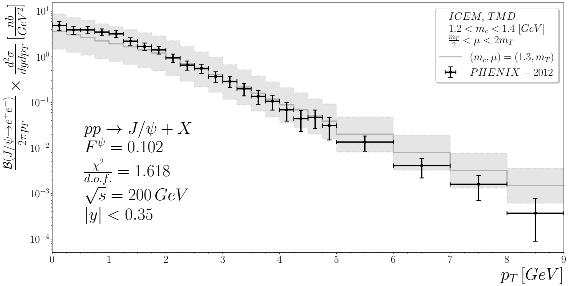
Single J/ψ production in the ICEM + PRA



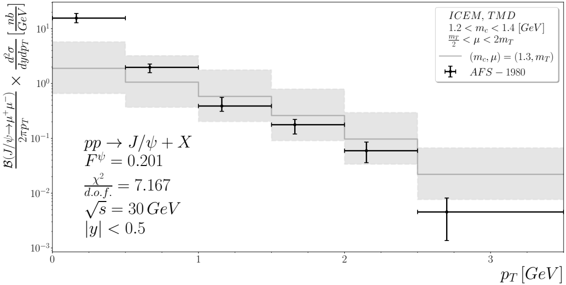
Single J/ψ production in the ICEM + PRA

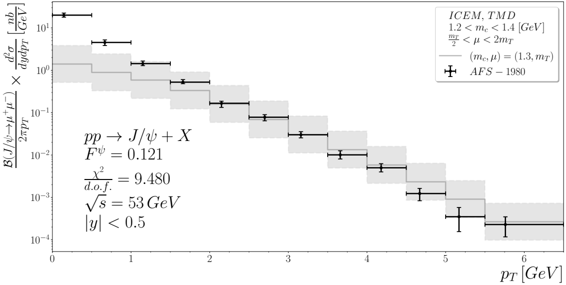


Single J/ψ production in the ICEM + PRA

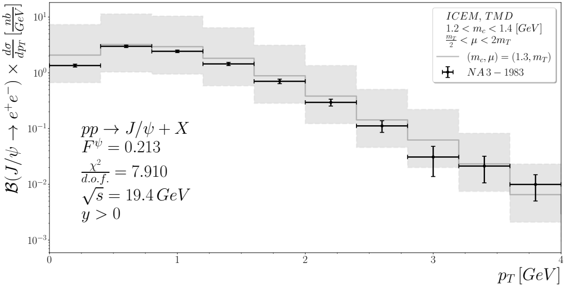


Single J/ψ production in the ICEM + PRA

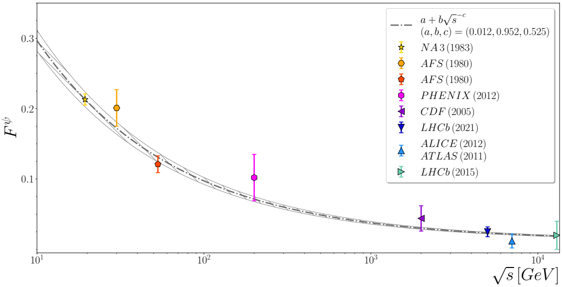




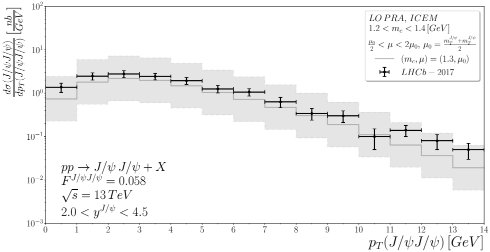
Single J/ψ production in the ICEM + PRA

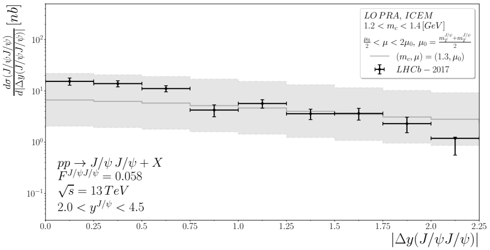


ICEM fit from $\sqrt{s} = 19$ GeV to $\sqrt{s} = 13$ TeV

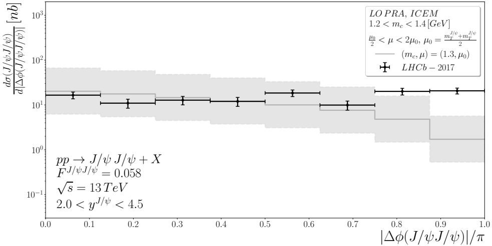


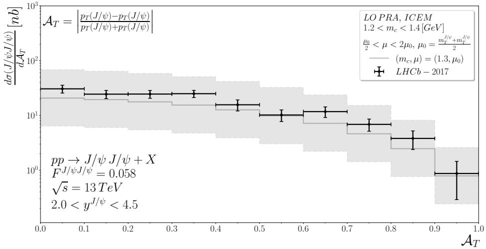
Double J/ψ production in ICEM+PRA: LHCb data



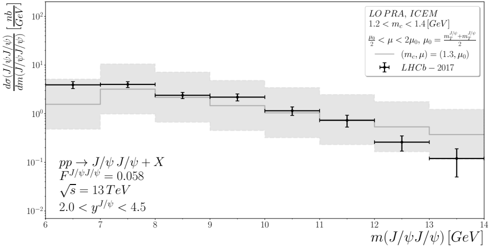


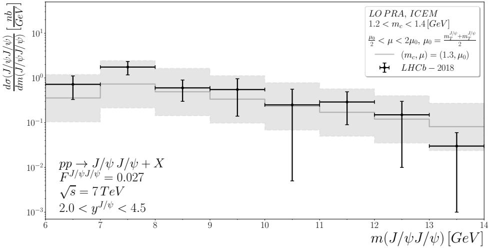
Double J/ψ production in ICEM+PRA: LHCb data



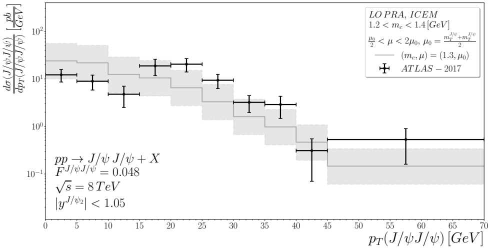


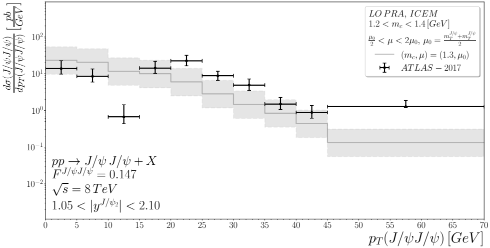
Double J/ψ production in ICEM+PRA: LHCb data



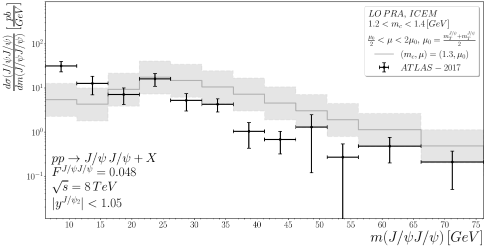


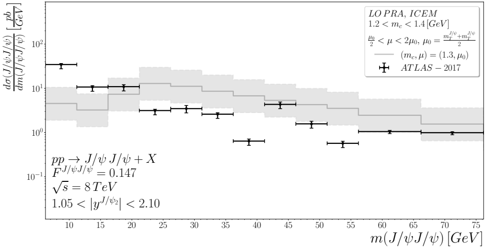
Double J/ψ production in ICEM+PRA: ATLAS



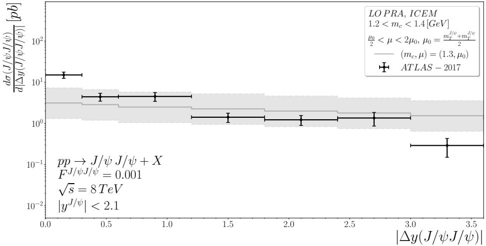


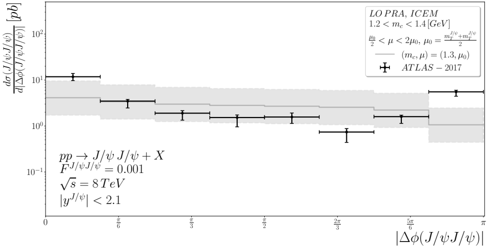
Double J/ψ production in ICEM+PRA: ATLAS



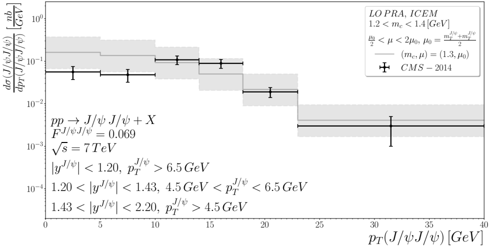


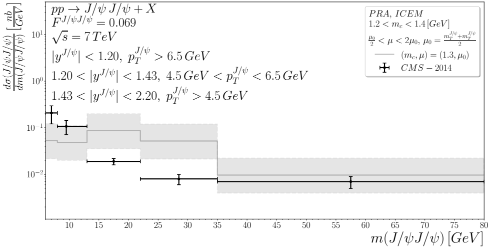
Double J/ψ production in ICEM+PRA: ATLAS



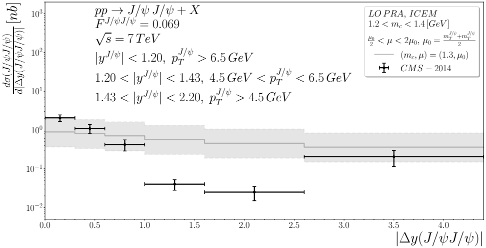


Double J/ψ production in ICEM+PRA: CMS





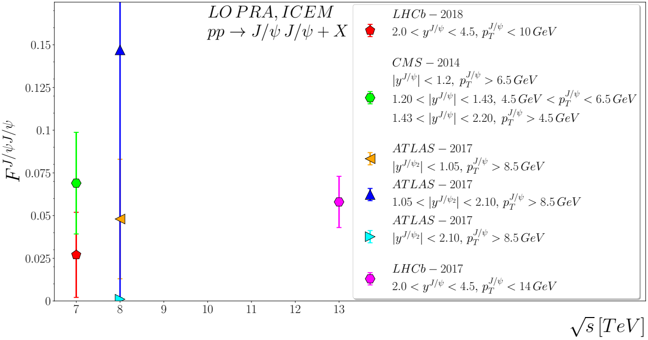
Double J/ψ production in ICEM+PRA: CMS



Double J/ψ production in ICEM+PRA: results

ICEM, pair J/ψ, fit $F^{J/\psi J/\psi}$
LHCb: $\sqrt{s} = 7$ TeV, $2.0 < y^{J/\psi} < 4.5$, $p_T^{J/\psi} > 14$ GeV
$0.027^{+0.025}_{-0.025}$
CMS: $\sqrt{s} = 7$ TeV, $\lvert y^{J/\psi}\rvert < 1.2$, $p_T^{J/\psi} > 6.5$ GeV $1.20 < \lvert y^{J/\psi}\rvert < 1.43$, $4.5 < p_T^{J/\psi} < 6.5$ GeV $1.43 < \lvert y^{J/\psi}\rvert < 2.20$, $p_T^{J/\psi} > 4.5$ GeV
$0.069^{+0.030}_{-0.030}$
ATLAS: $\sqrt{s} = 8$ TeV, $y^{J/\psi_2} < 1.05$, $p_T^{J/\psi} > 8.5$ GeV
$0.048^{+0.035}_{-0.035}$
ATLAS: $\sqrt{s} = 8$ TeV, $1.05 < y^{J/\psi_2} < 2.10$, $p_T^{J/\psi} > 8.5$ GeV
$0.147^{+0.320}_{-0.147}$
ATLAS: $\sqrt{s} = 8$ TeV, $y^{J/\psi_2} < 2.10$, $p_T^{J/\psi} > 8.5$ GeV
$0.001^{+0.017}_{-0.001}$

Double J/ψ production in ICEM+PRA: results



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 (The good news for future NICA experiment at $\sqrt{s} \leq 27$ GeV)
- The factorization prescription $F^{\psi\psi} = F^{\psi} \times F^{\psi}$ dos't work in the ICEM, in fact $F^{\psi\psi} \sim F^{\psi}$
- We have found sufficient differences in $F^{\psi\psi}$ extracted at the different energies and rapidity intervals.
- The ICEM works for the prompt double J/ψ production rather badly than in case of the single J/ψ production.

Thank you for your attention!