PAIR PRODUCTION OF HEAVY QUARKONIA IN THE COLOR EVAPORATION MODEL

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Outline

Introduction: experimental data

Single $J/\psi(\Upsilon)$ hadroproduction

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

Double J/ψ and *Upsilon* 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
- There are data for double Υ hadroproduction at the $\sqrt{s} = 13$ TeV

Collinear and TMD Factorizations

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

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

$$q_1^\mu = x_{1,2} P_1^\mu, \qquad q_1^2 = 0$$

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

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

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

$$q_1^\mu = x_1 P_{1,2}^\mu + \tilde{x}_1 P_2^\mu + q_{1,T}^\mu, \qquad q_1^2 = 0$$

High Energy Factorization or k_T-Factorization

The High Energy Factorization ⇒ Parton Reggeization Approach (PRA)

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

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

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

- $$q^\mu_{1,2} = x_{1,2} P^\mu_{1,2} + q^\mu_{T1,2}, \qquad q^2_{1,2} = -\vec{q}^{\,2}_{1,2} \neq 0$$

  ,
- 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 quarks: Lipatov [1995], Lipatov, Vyazovsky [2001]
- unPDF: Watt, Kimber, Martin, and Ryskin [2001]
- unPDF with exact normalization: Nefedov and Saleev [2020]

TMD 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 $F_R(x, q_T, \mu_F) \simeq F_g^{TMD}(x, q_T, \mu_F, \mu_Y = \mu_F)$
- $\int F_{R,Q}(x, t, \mu_F)dt = xf_{g,q}(x, \mu_F)$, $t = -q_T^2 > 0$
- $F_{R,Q}(x, t, \mu_F) = \frac{d}{dt}[T_{R,Q}(t, \mu_F, \mathbf{x})xf_{g,q}(x, \mu_F)]$
- NLO in the PRA is in progress, Nefedov, Saleev [2018,2019], Nefedov[2020,2021].

PRA smoothly interpolates QCD predictions between very-high-energy and high-energy regions AS WELL AS between small-p_T and large-p_T regions

The Parton Reggeization Approach

The list of 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):

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

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

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

$$p^{\mu}_{J/\psi} = \frac{M_{J/\psi}}{M_{c\bar{c}}} p^{\mu}_{c\bar{c}}, \qquad p^{\mu}_{c\bar{c}} = p^{\mu}_{c} + p^{\mu}_{\bar{c}}$$

ICEM at work

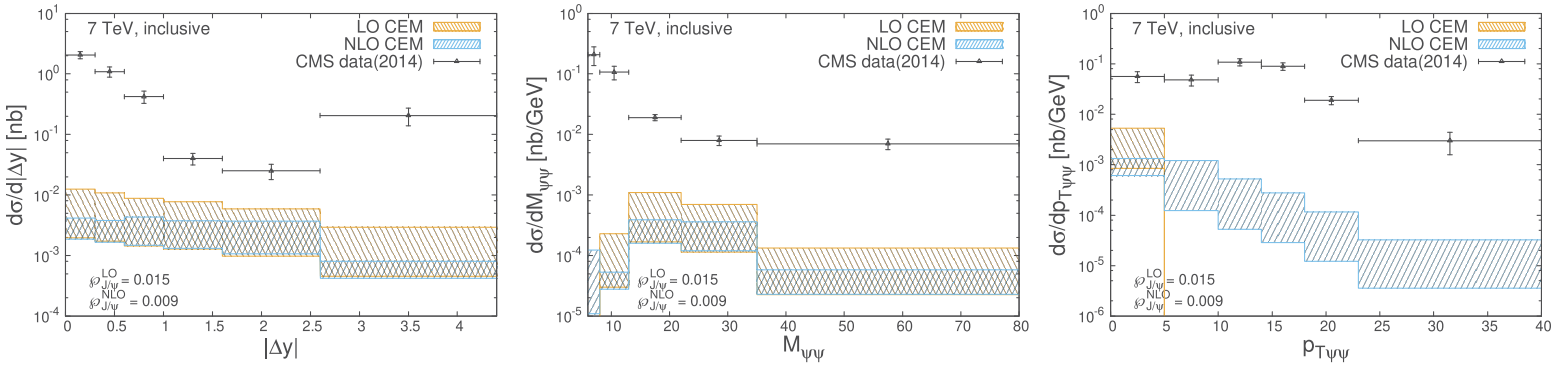
I. The recent studies

- 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
- R. Maciuła, A. Szczurek, A. Cisek. "J/ψ-meson production within improved color evaporation model with the k_T-factorization approach for $c\bar{c}$ production", Phys. Rev. **99** (2019) 054014.
- V. Cheung and R. Vogt, "Polarized Heavy Quarkonium Production in the Color Evaporation Model," Phys. Rev. D **95** (2017) no.7, 074021

Double J/ψ production in the ICEM + CPM

The complete NLO QCD study in the CPM

- 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 $\mathcal{F}^{\psi\psi} = \mathcal{F}^{\psi} \times \mathcal{F}^{\psi}$



(a) (b) (c)

Double J/ψproduction in the ICEM

In general:

$$\mathcal{F}^{\psi\psi} \neq \mathcal{F}^{\psi} \times \mathcal{F}^{\psi}$$

$\mathcal{F}^{\psi\psi}$ and $\mathcal{F}^{\psi}$ are independent parameters

In the fragmentation production only

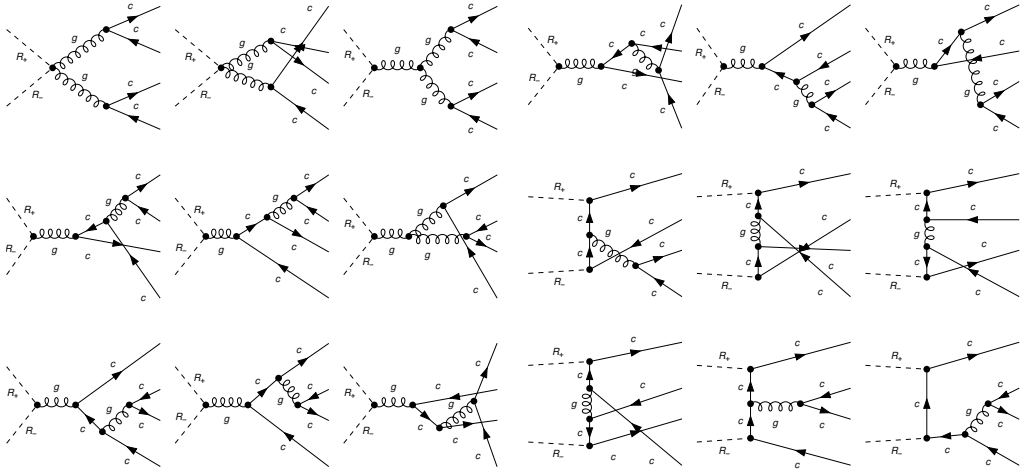
$$\mathcal{F}^{\psi\psi} = \mathcal{F}^{\psi} \times \mathcal{F}^{\psi}$$

SPS calculations in the PRA

The master formula

$$\sigma^{SPS}(pp \to J/\psi J/\psi + X) = \mathcal{F}^{\psi\psi} \int_{m_\psi}^{2m_D} \frac{d\sigma(p + p \to c_1 + \bar{c}_1 + c_2 + \bar{c}_2 + X)}{dM_1 dM_2} dM_1 dM_2$$

Feynman rules of the Lipatov effective theory ⇒ 72 diagrams



DPS calculations in the PRA

The master pocket-formula

$$\sigma^{DPS}(p{+}p \to J/\psi{+}J/\psi{+}X) = \frac{\sigma^{SPS}(p+p \to J/\psi + X_1)\sigma^{SPS}(p+p \to J/\psi + X_2)}{2\sigma_{eff}}, \tag{1}$$

Numerical calculations in the PRA

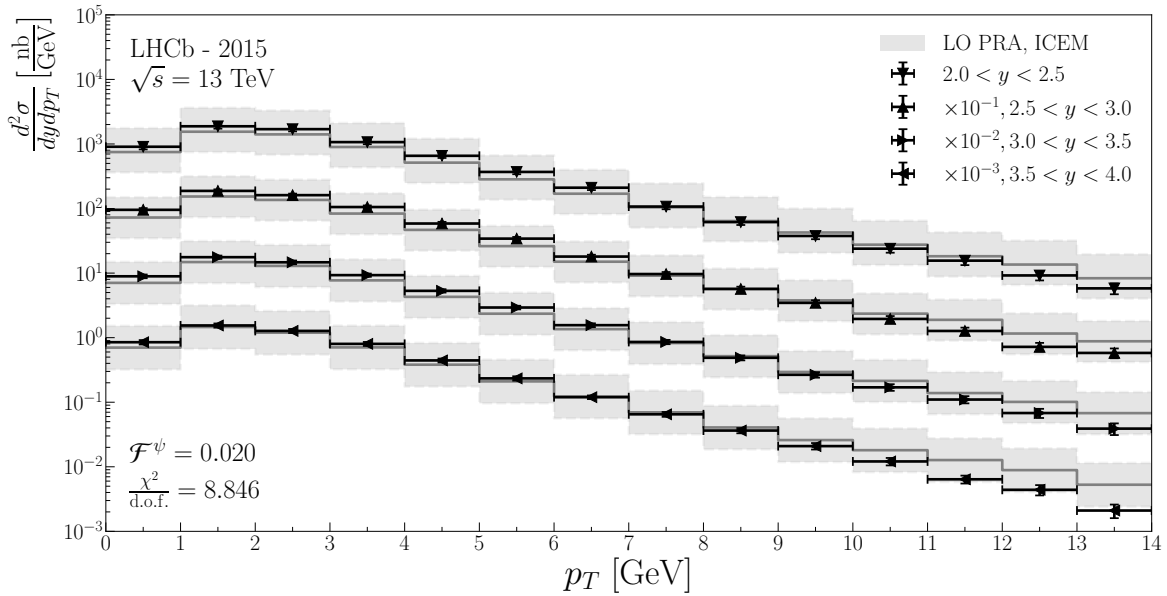
MC parton-level event generator KaTie

- A. van Hameren, "KaTie : For parton-level event generation with k_T-dependent initial states," Comput. Phys. Commun. **224** (2018), 371-380
- Calculations up to $2 \to 4$ with off-shell initial partons
- unPDF with exact normalization in the improved KMRW model, [Nefedov, Saleev, 2020].

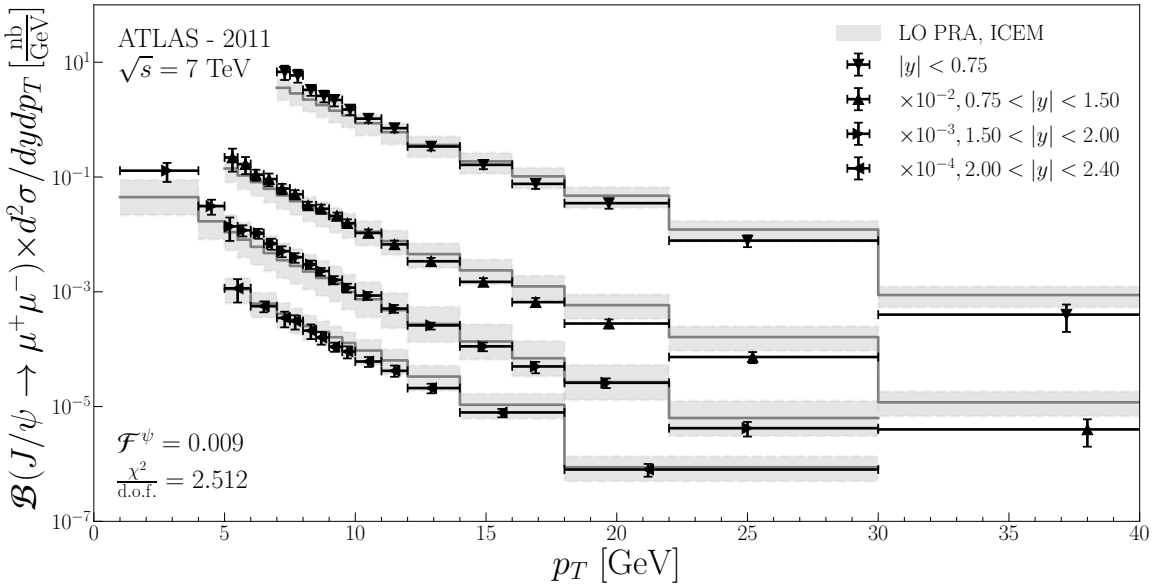
Abstract

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.

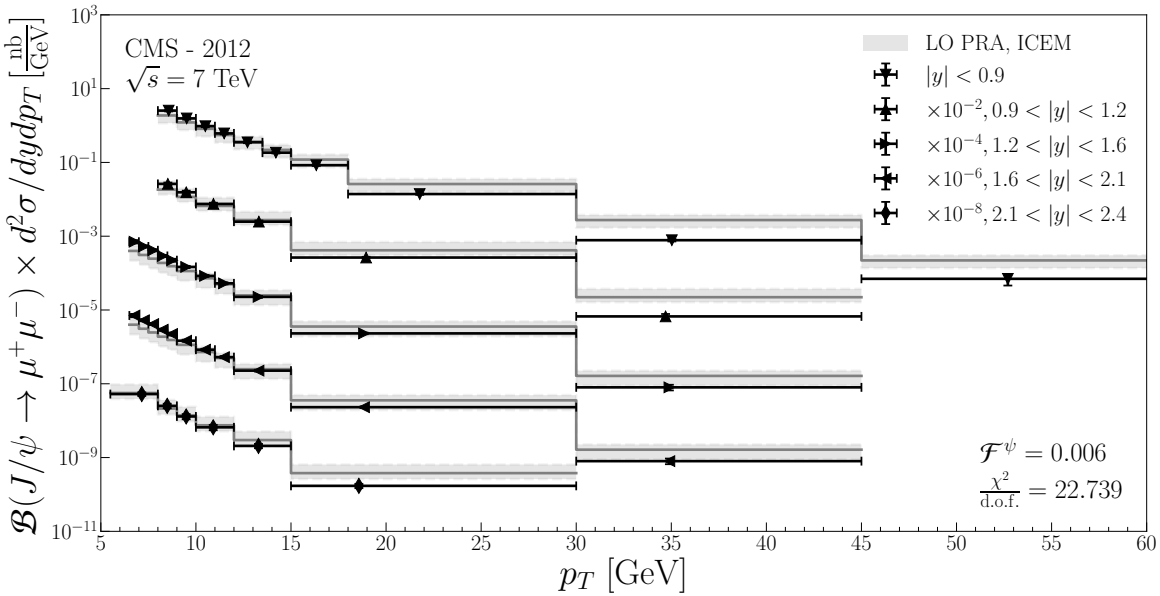
Single J/ψ production in the ICEM + PRA, LHCb



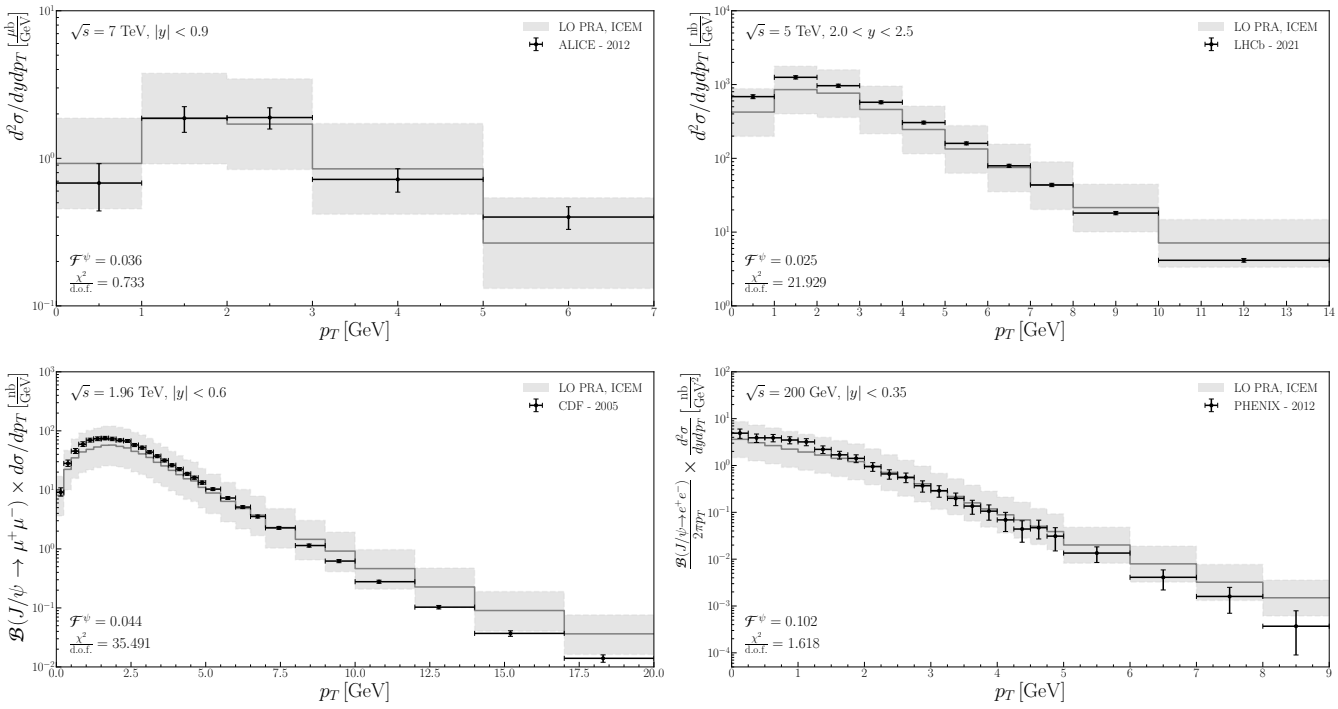
Single J/ψ production in the ICEM + PRA, ATLAS



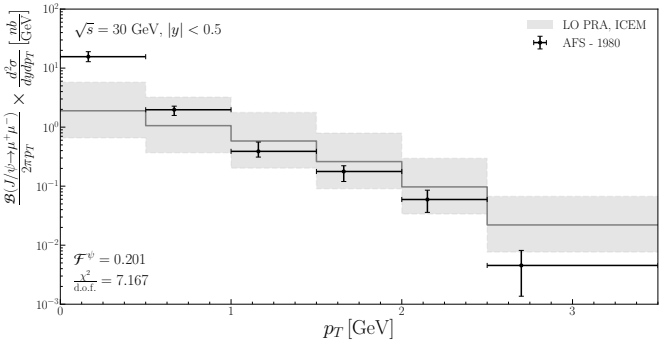
Single J/ψ production in the ICEM + PRA, CMS

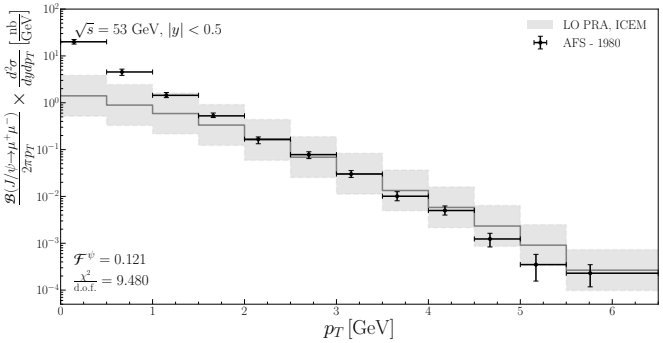


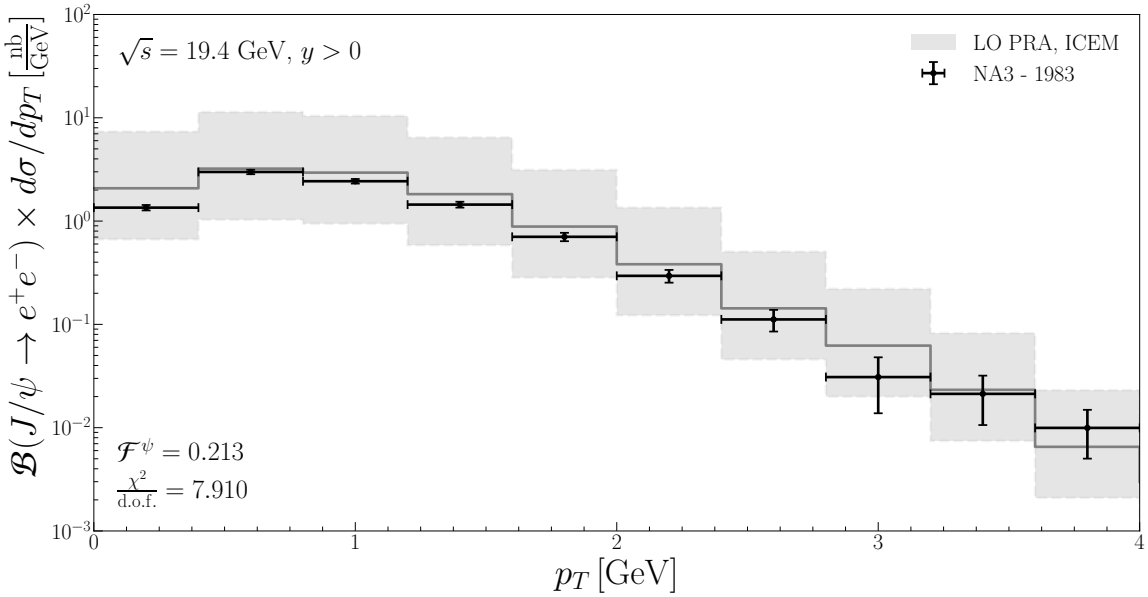
Single J/ψ production in the ICEM + PRA, ALICE



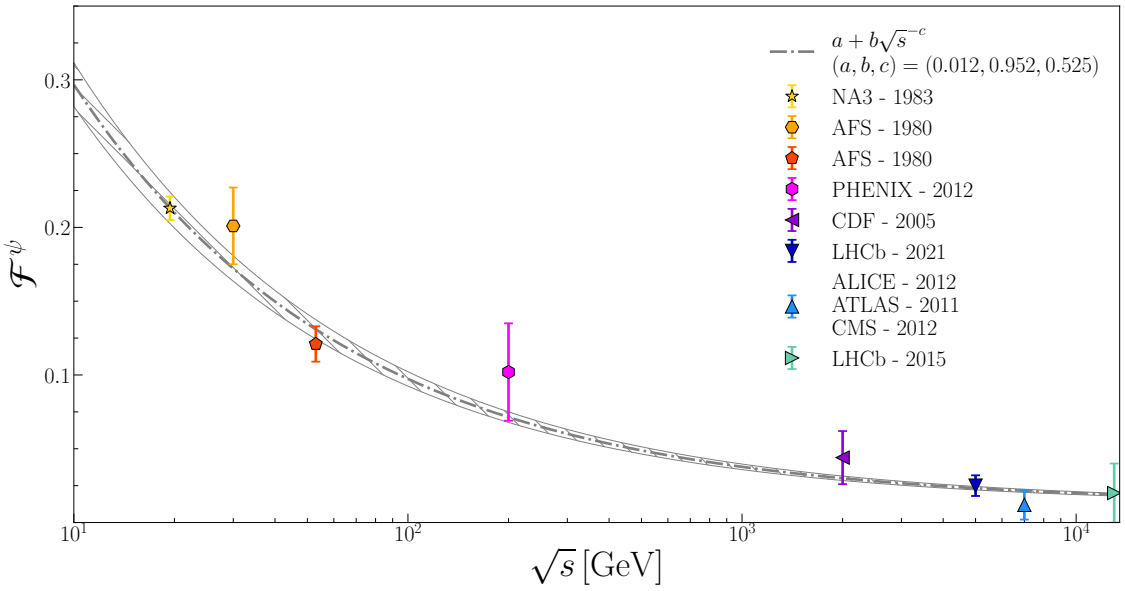
Single J/ψ production in the ICEM + PRA, AFS



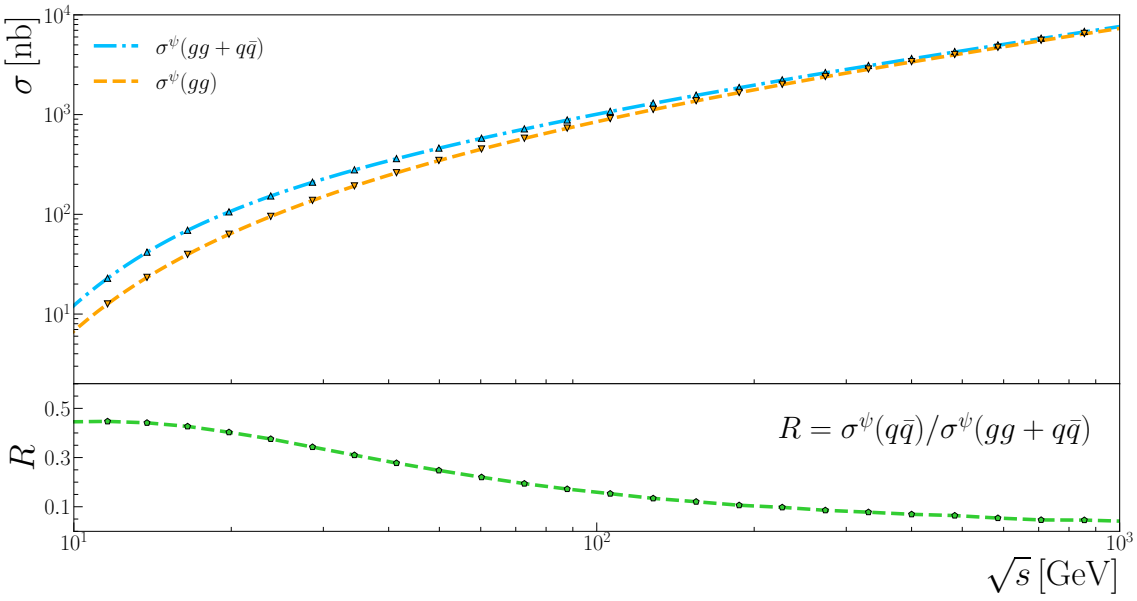




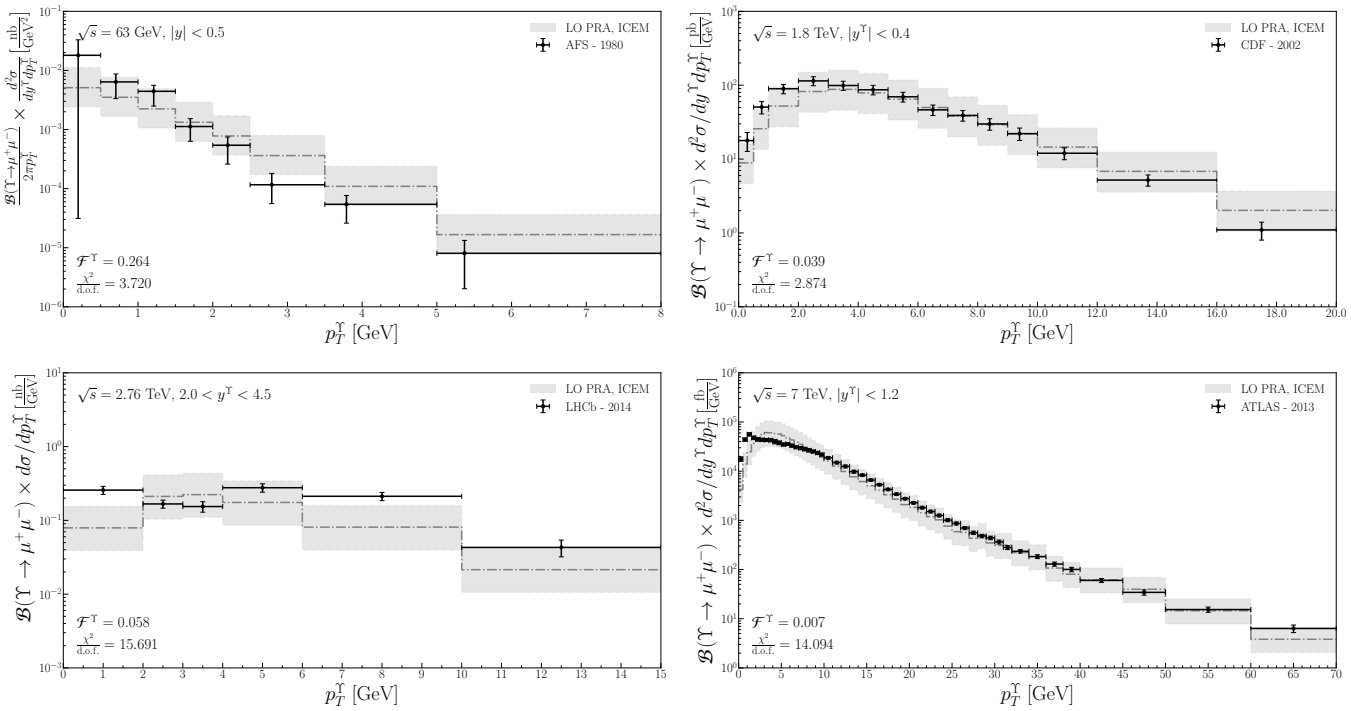
ICEM+PRA single J/ψ fit from $\sqrt{s} = 19$ GeV to $\sqrt{s} = 13$ TeV



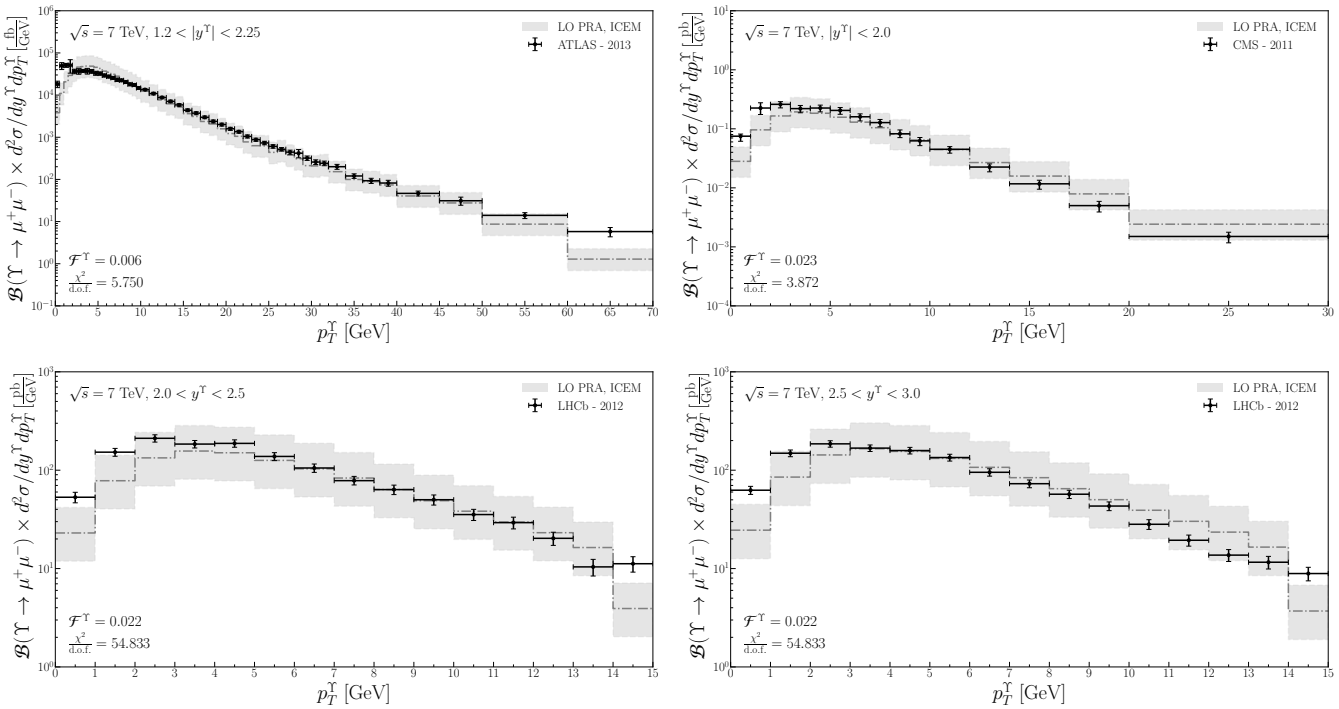
Relative contributions to the prompt J/ψ production



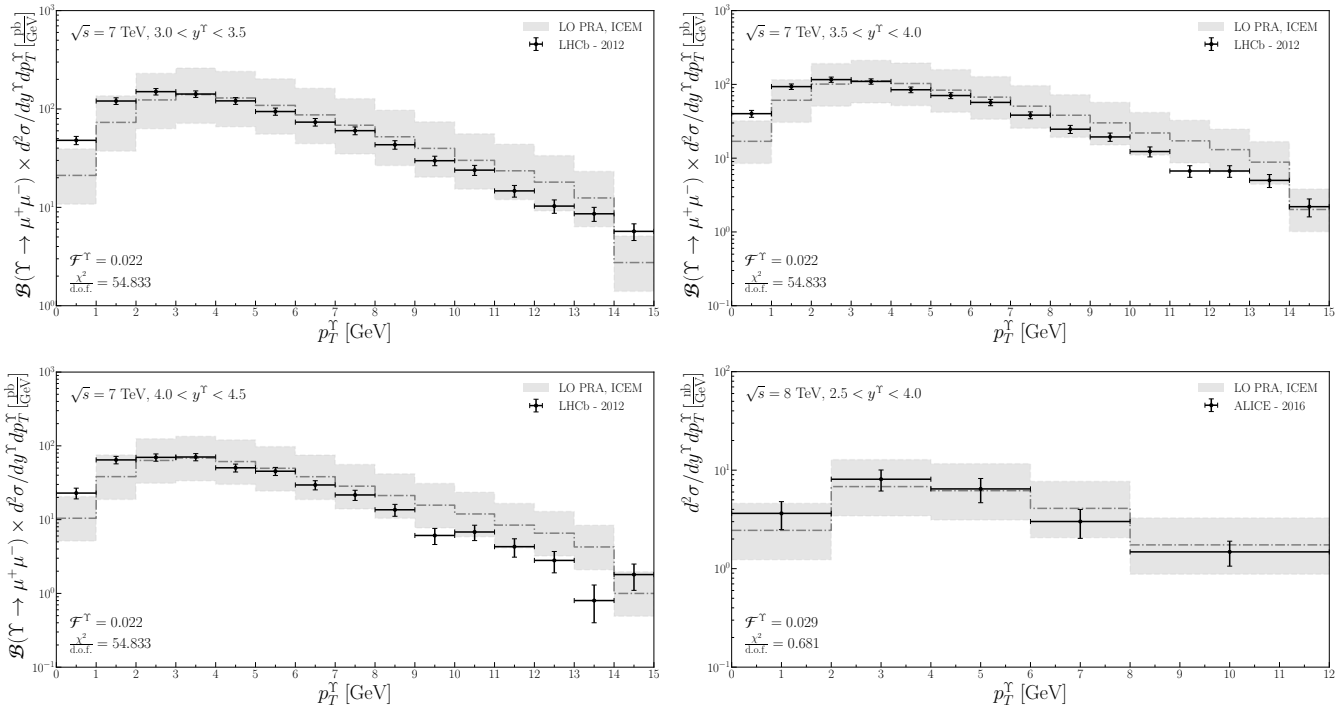
Single Υ production in the ICEM + PRA: AFS ATLAS, LHCb and CDF



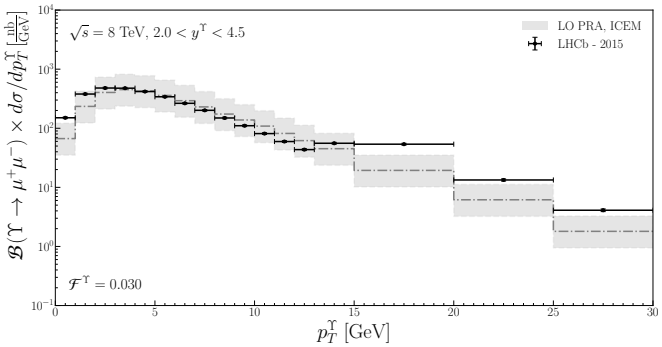
Single Υ production in the ICEM + PRA: LHCb and CMS

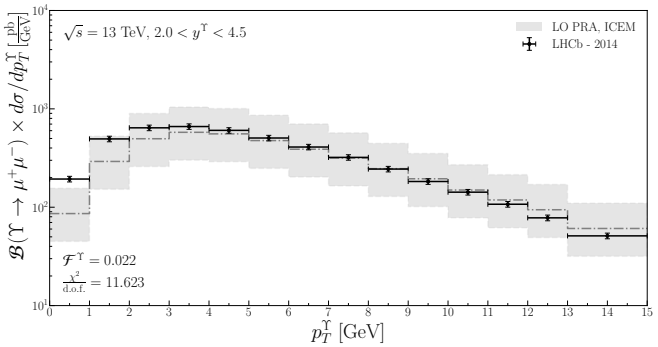


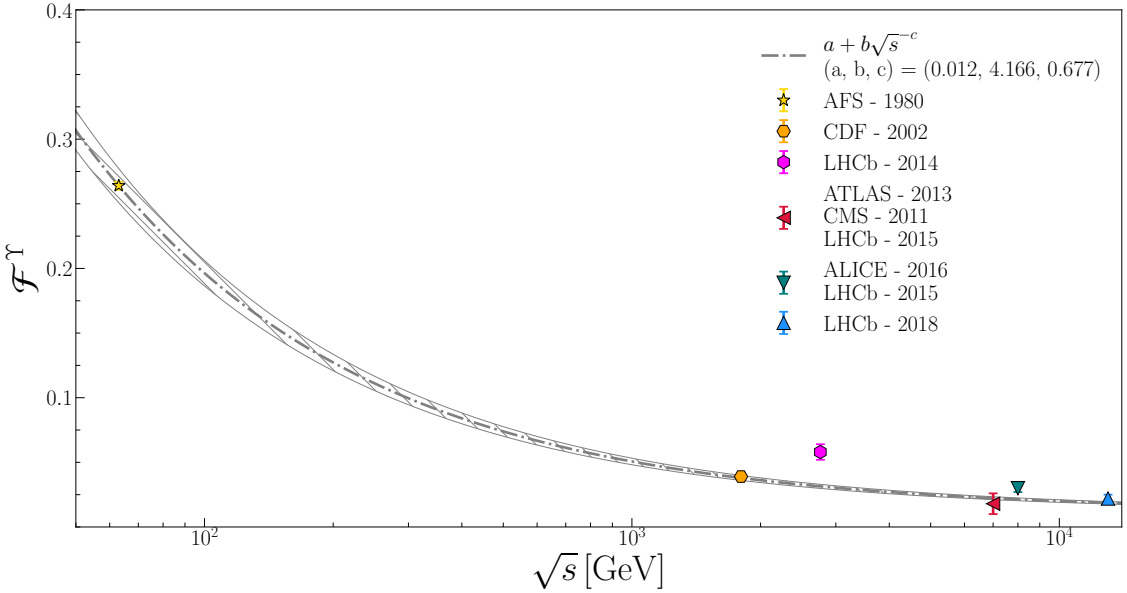
Single Υ production in the ICEM + PRA: LHCb, ALICE



Single Υ production in the ICEM + PRA: LHCb and $\mathcal{F}^{\Upsilon}(s)$







Double J/ψ production in the NRQCD + PRA

Relevant calculations in the NRQCD + PRA:

- 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

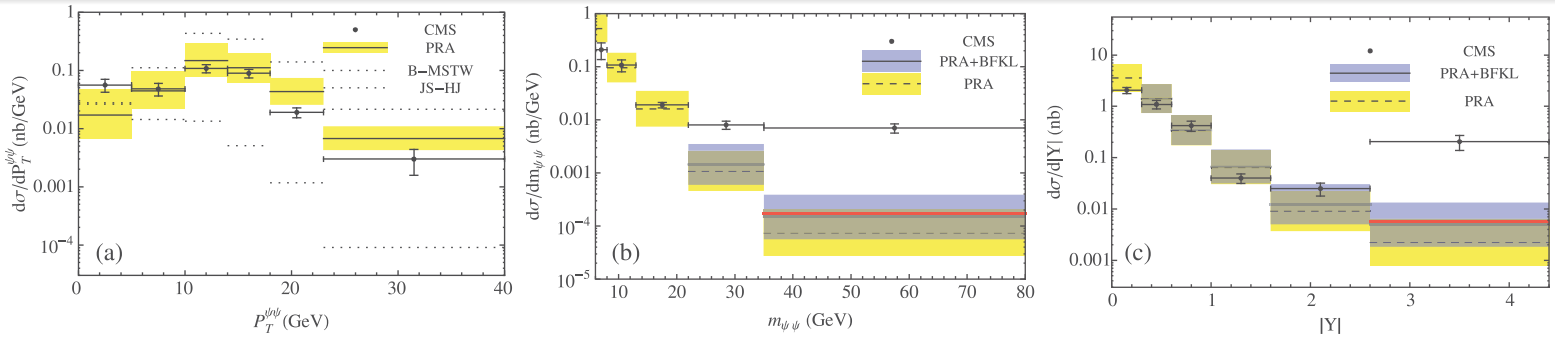
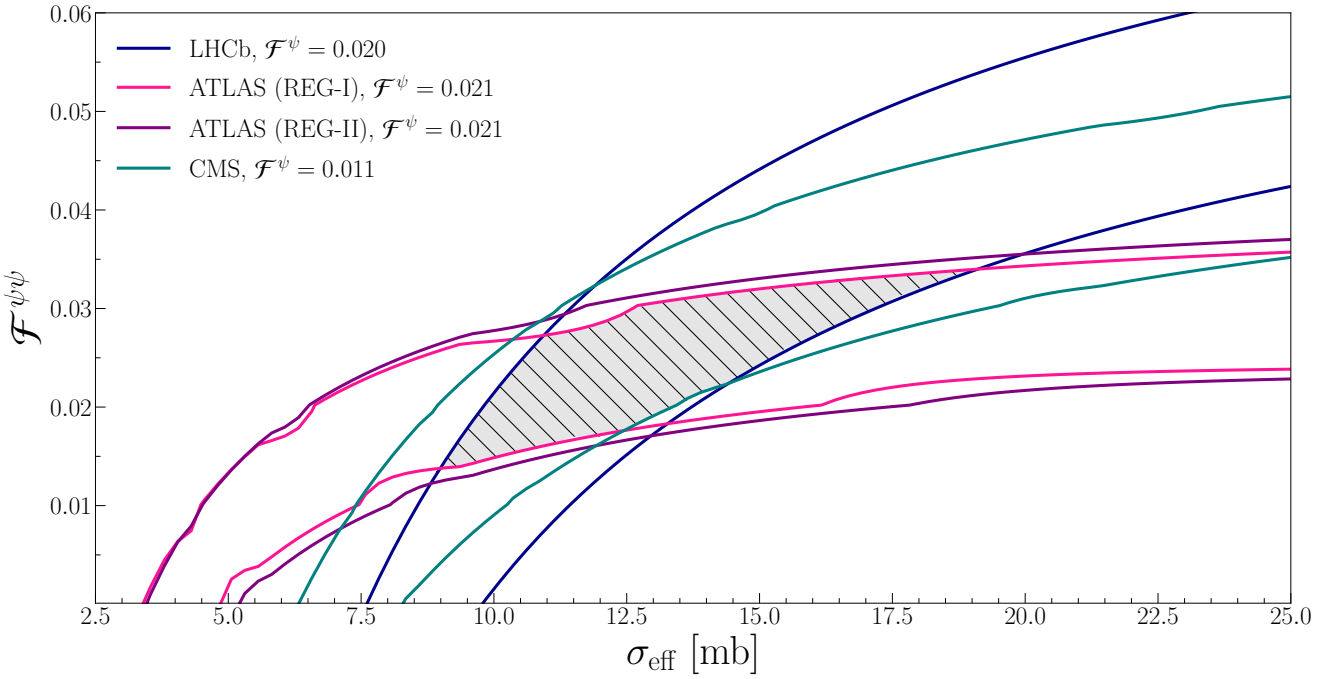


FIG. 2. The (a) $p_T^{\psi\psi}$, (b) $m_{\psi\psi}$, and (c) $|Y|$ distributions of double prompt J/ψ production measured by the CMS Collaboration [10] are compared to our LO NRQCD predictions in the PRA without (dashed lines) and with BFKL resummation (solid lines) including their scale uncertainties (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).

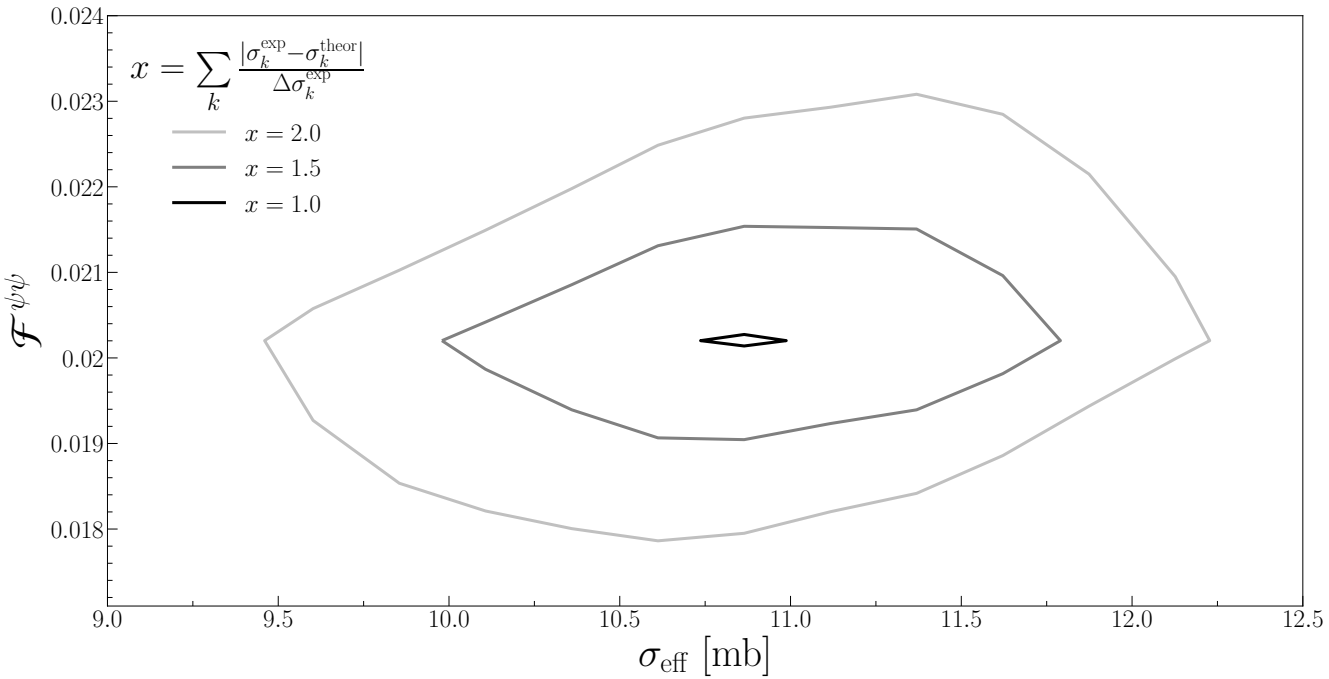
Double J/ψ production in ICEM+PRA: results



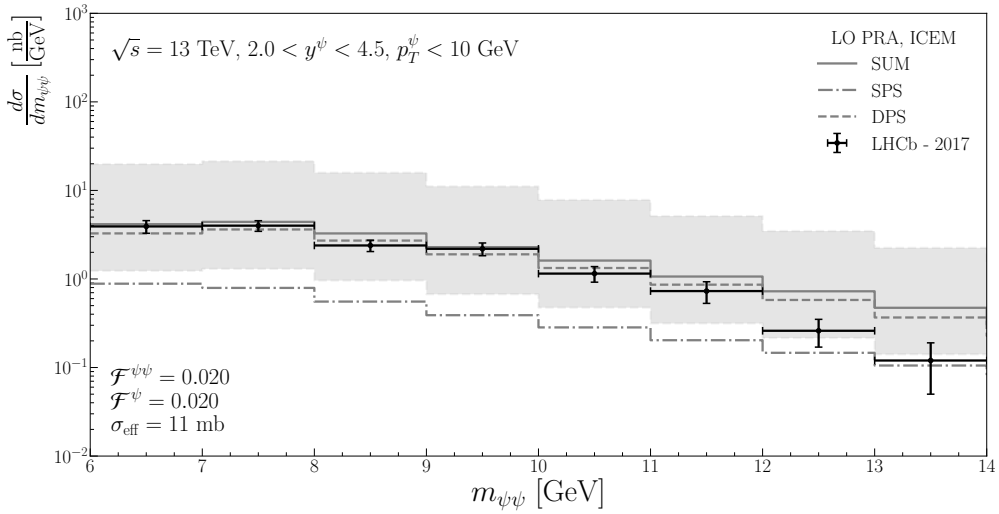
For each experiment, $k = ATLAS, CMS, LHCb$, the two lines correspond condition $x_k < 1$

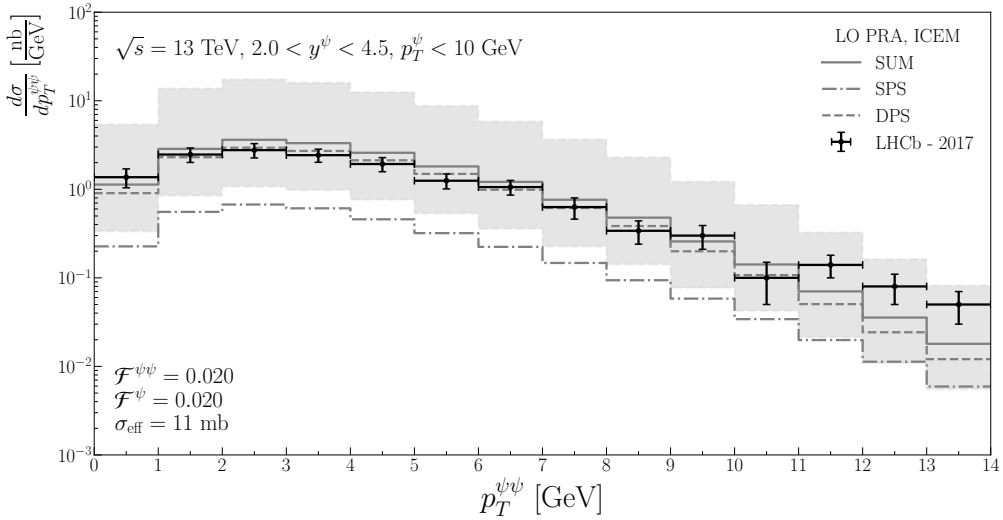
$$x_k = \frac{|\sigma_k^{exp} - \sigma_k^{theor}|}{\Delta\sigma_k^{exp}}$$

Double J/ψ production in ICEM+PRA: results

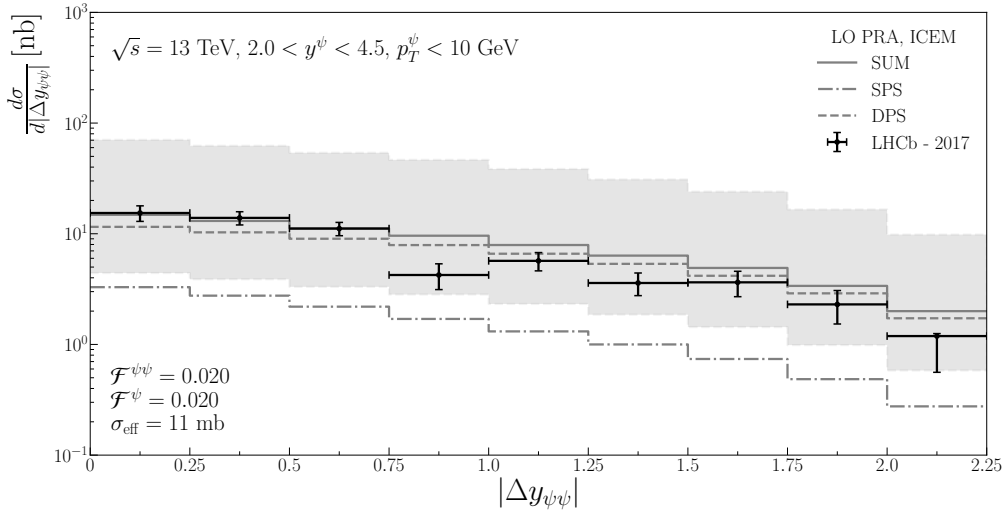


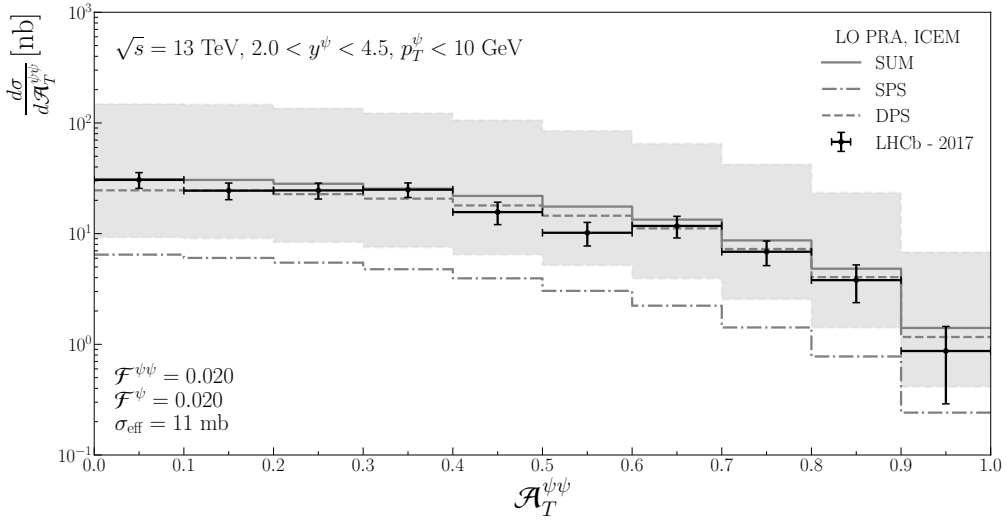
Double J/ψ production in ICEM+PRA: LHCb data, $SPS/DPS \sim 0.2$



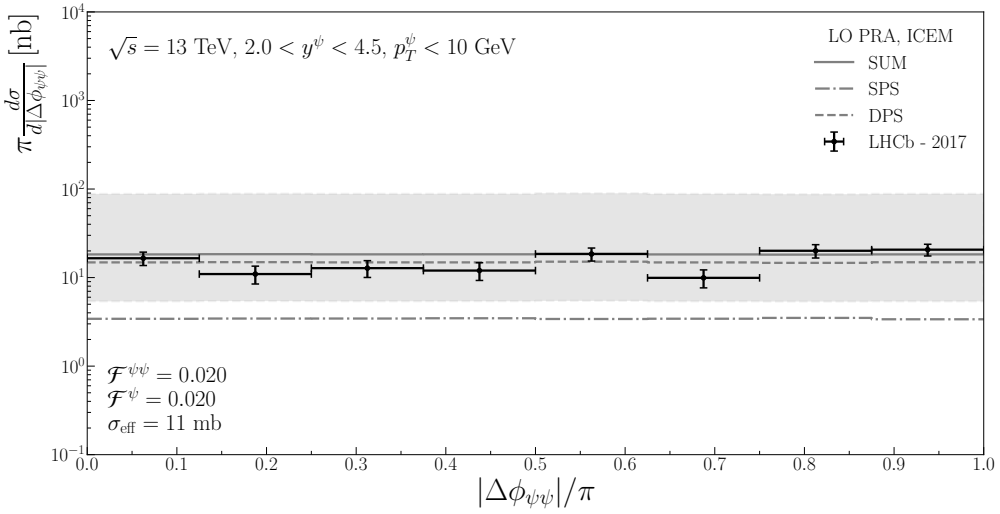


Double J/ψ production in ICEM+PRA: LHCb data

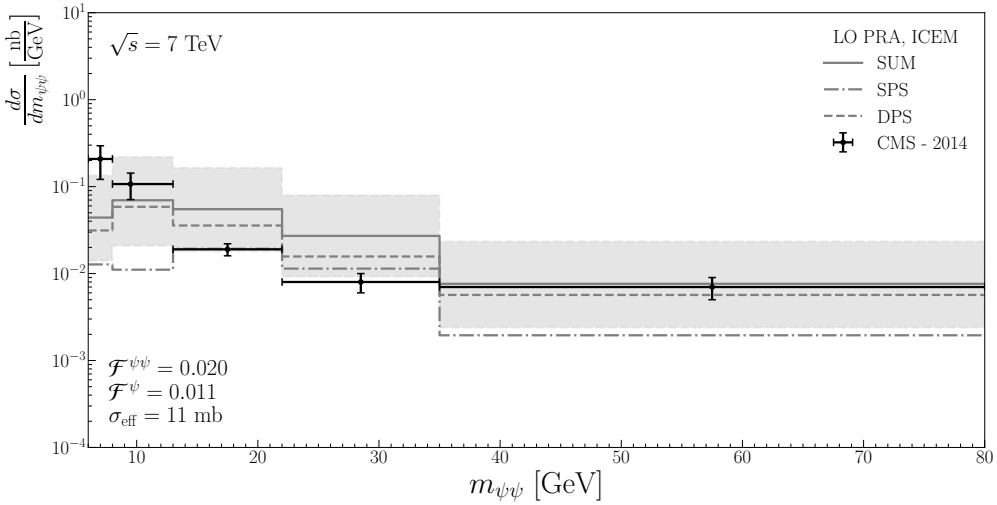


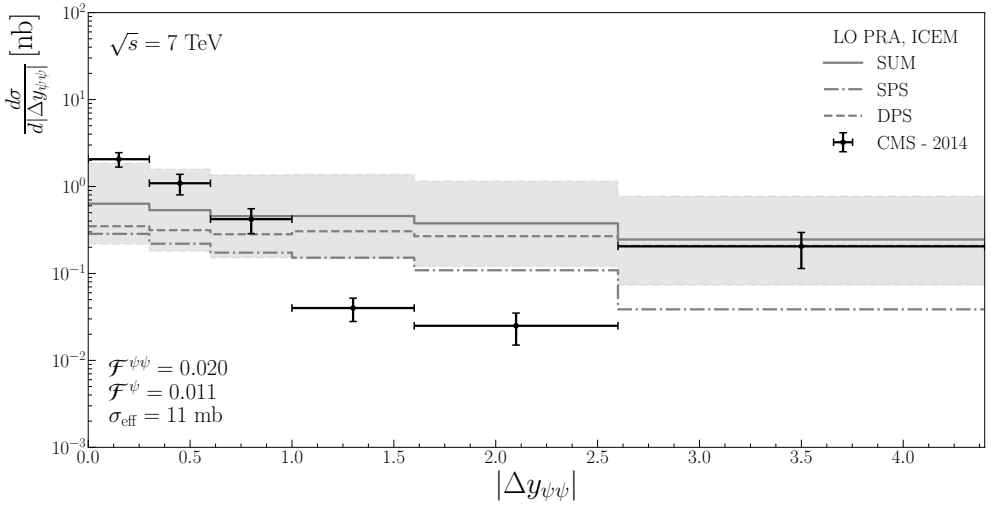


Double J/ψ production in ICEM+PRA: LHCb data

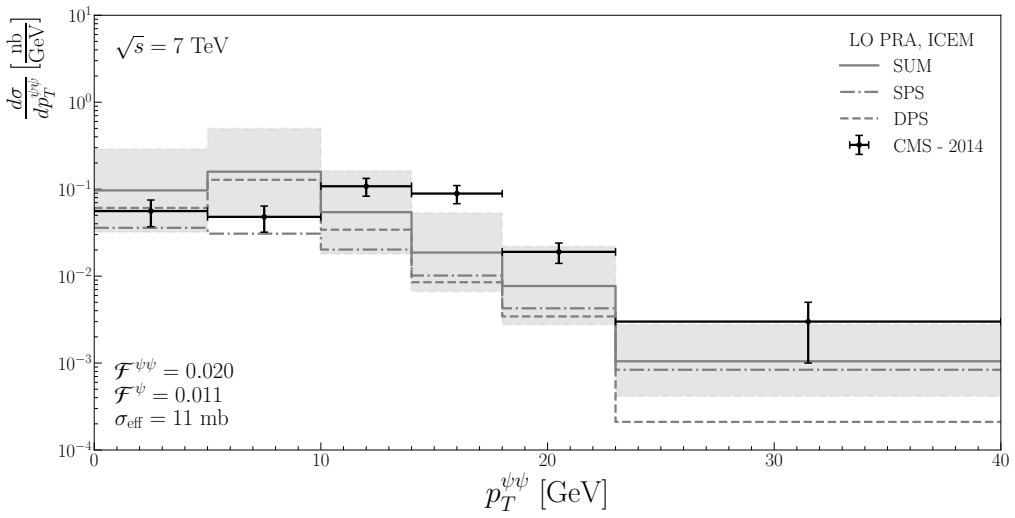


Double J/ψ production in ICEM+PRA: CMS, $SPS/DPS \sim 0.5$

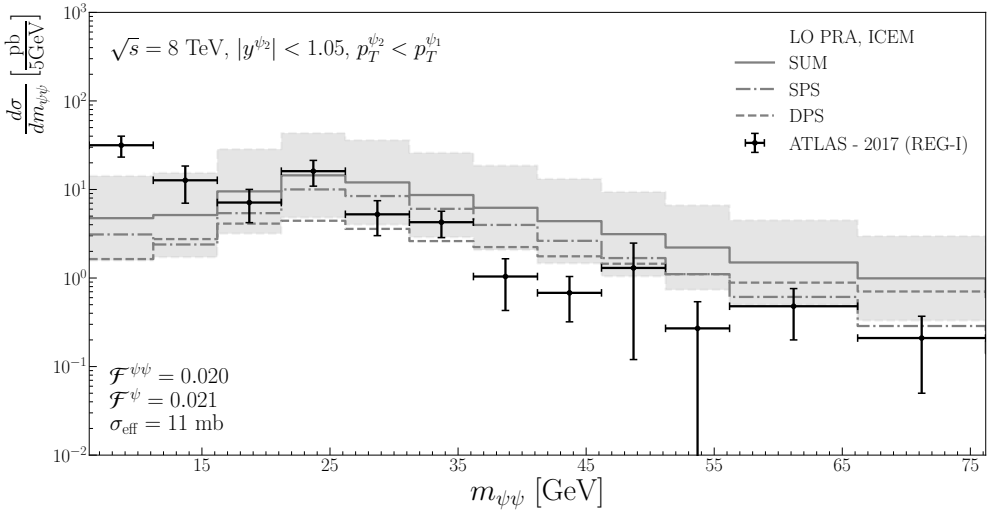


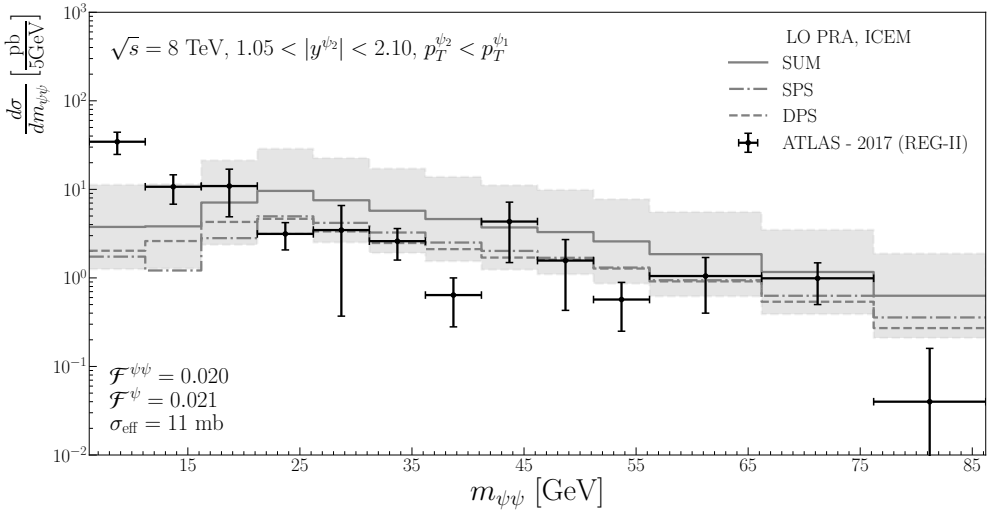


Double J/ψ production in ICEM+PRA: CMS

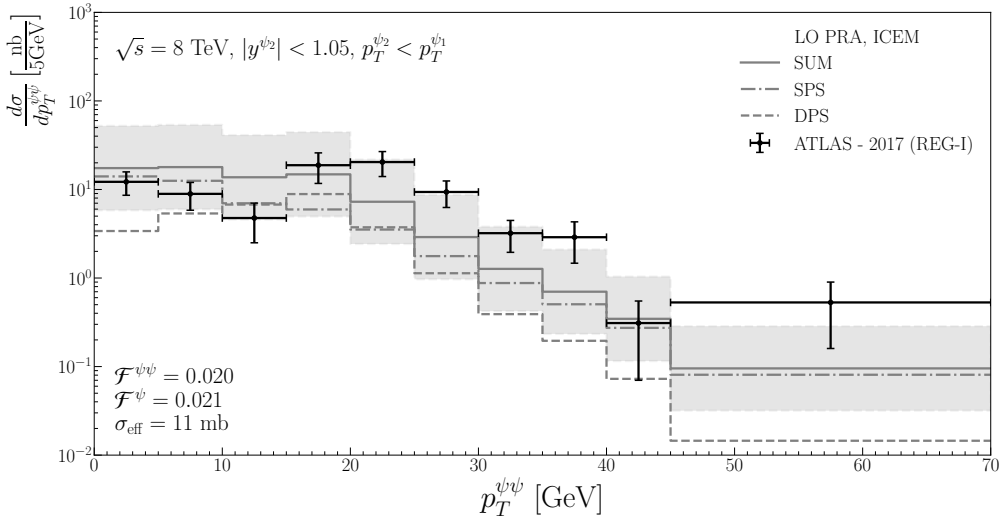


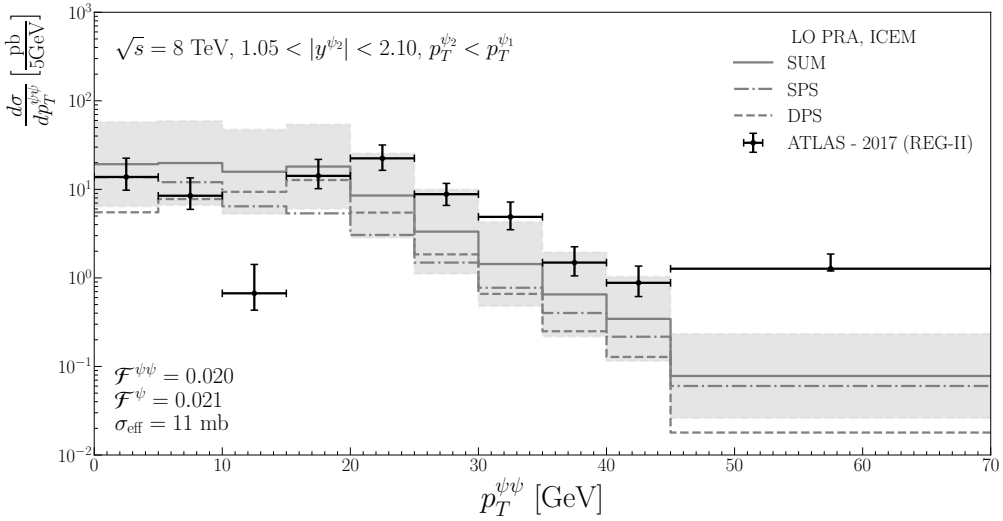
Double J/ψ production in ICEM+PRA: ATLAS, $SPS/DPS \sim 1.5$



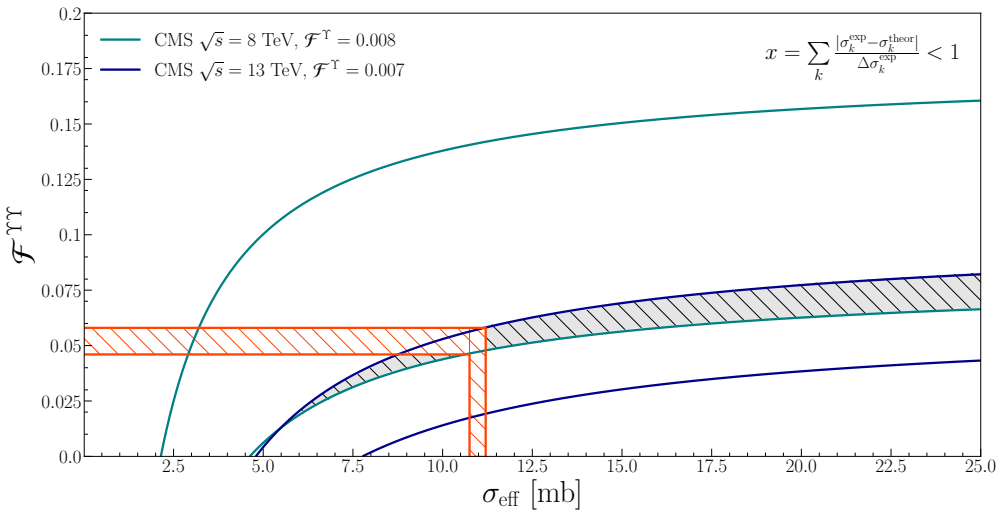


Double J/ψ production in ICEM+PRA: ATLAS

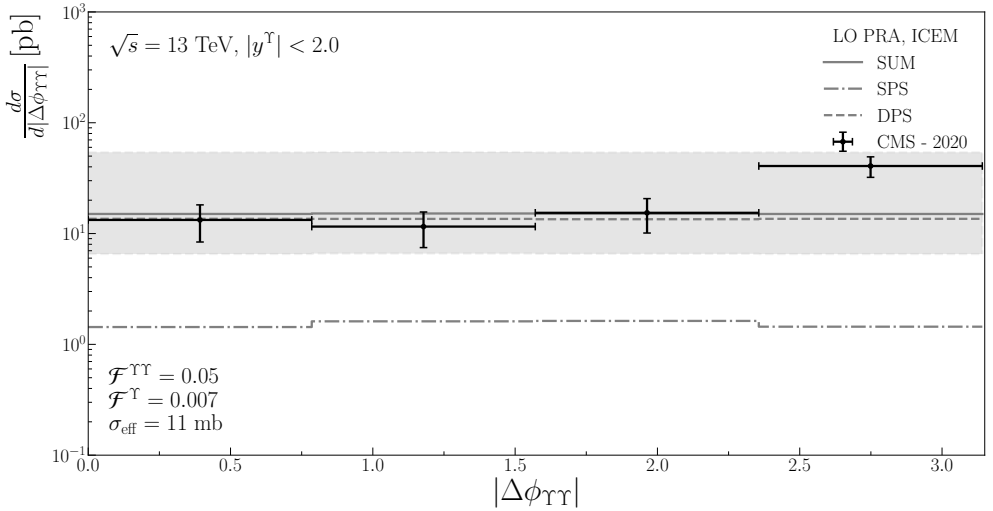


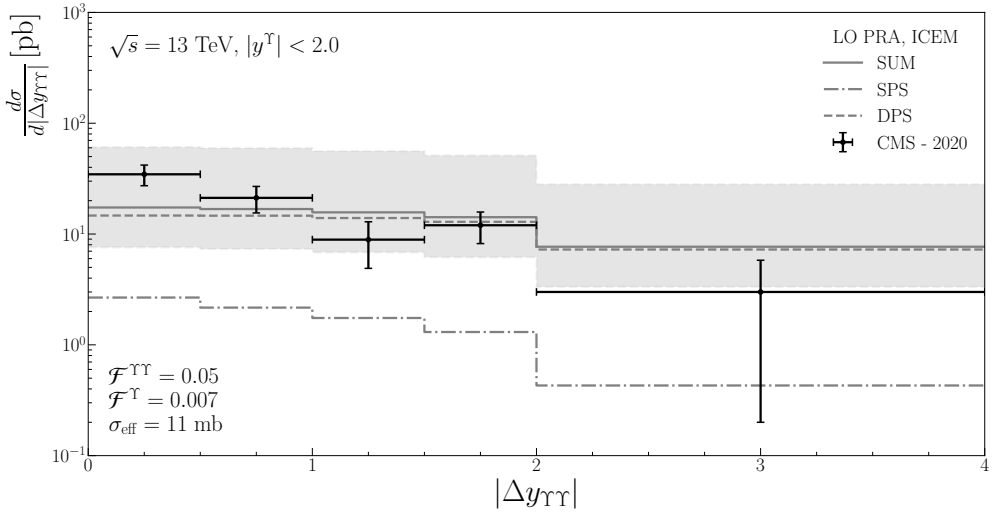


Double Υ production in ICEM+PRA: $\sigma_{eff} = 10$ mb $\Rightarrow \mathcal{F}^{\Upsilon\Upsilon} \simeq 0.05$

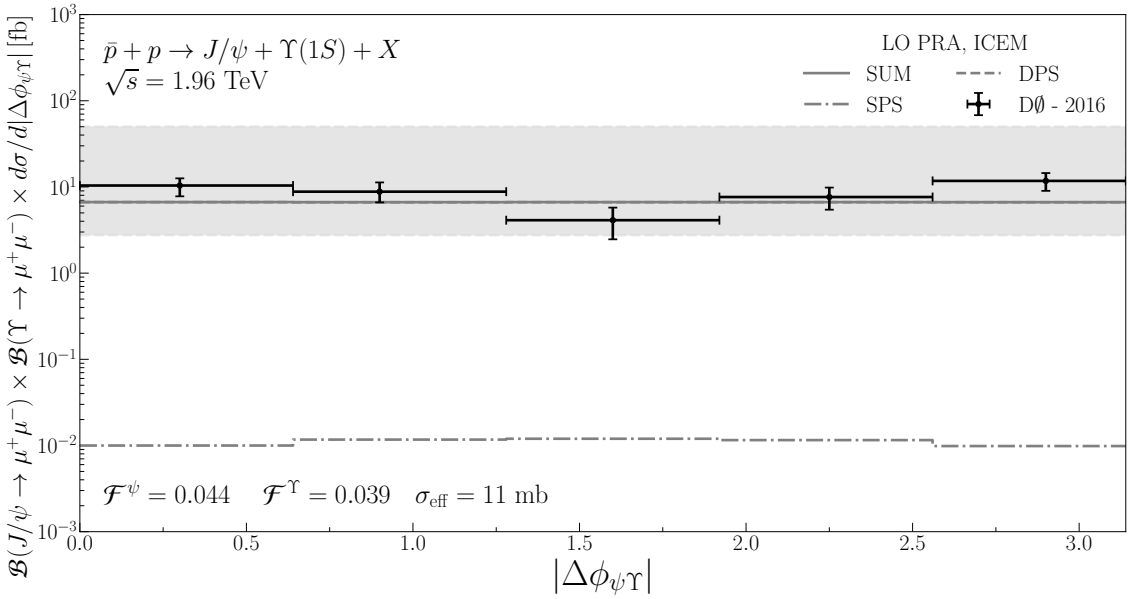


Double Υ production in ICEM plus PRA: CMS





$\Upsilon + J/\psi$ production in ICEM plus PRA: D0



Conclusions

- The hadronization factors $F^{\psi,\Upsilon}(s)$ in the ICEM strongly depend on energy:
  $F^{\psi}(\sqrt{s}) = 0.012 + 0.952(\sqrt{s})^{-0.525}$ and $F^{\Upsilon}(\sqrt{s}) = 0.012 + 4.166(\sqrt{s})^{-0.677}$
- Predicted prompt J/ψ 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 and quark-antiquark annihilation contribution may be about 30-40 % .
- The factorization prescription $F^{\psi\psi} = F^{\psi} \times F^{\psi}$ dos't work in the ICEM, it has $F^{\psi\psi} \sim F^{\psi}$ at the high energy
- Double J/ψ (Υ) production cross sections at the energy range $7 - 13$ TeV are described with $\sigma_{eff} \simeq 11.0$ mb, $\mathcal{F}^{\psi\psi} \simeq 0.02$ and $\mathcal{F}^{\Upsilon\Upsilon} \simeq 0.05$
- $R = \sigma^{SPS}/\sigma^{DPS}$ ratio from double J/ψ production cross sections is about:
  CMS (7 TeV) $\simeq 0.5$,
  ATLAS (8 TeV) $\simeq 1.5$,
  LHCb (13 TeV) $\simeq 0.2$
  at the $\mathcal{F}^{\psi\psi} \simeq 0.02$ and $\sigma_{eff} \simeq 11.0$ mb.

Thank you for your attention!

Modified KMRW model for uPDFs

The unPDFs can be written as follows from the modified KMR model:

$$\Phi_i(x,t,\mu) = \frac{\alpha_s(\mu)}{2\pi}\frac{T_i(t,\mu^2,x)}{t}\sum_{j=q,\bar{q},g}\int_x^1 dz\ P_{ij}(z)F_j\left(\frac{x}{z},t\right)\theta\left(\Delta(t,\mu)-z\right),$$

To resolve collinear divergence problem, we require that modified unPDF $\Phi_i(x,t,\mu)$ should be satisfied exact normalization condition:

$$\int_0^{\mu^2} dt\Phi_i(x,t,\mu^2) = F_i(x,\mu^2),$$

which is equivalent to:

$$\Phi_i(x,t,\mu^2) = \frac{d}{dt}\left[T_i(t,\mu^2,x)F_i(x,t)\right],$$

where $T_i(t,\mu^2,x)$ is referred to as Sudakov form-factor, satisfying the boundary conditions $T_i(t=0,\mu^2,x)=0$ and $T_i(t=\mu^2,\mu^2,x)=1$.

Modified KMRW model for uPDFs

The solution for Sudakov form-factor has been obtained in [Nefedov, Saleev, 2020]:

$$T_i(t,\mu^2,x) = \exp\left[-\int_t^{\mu^2} \frac{dt'}{t'}\frac{\alpha_s(t')}{2\pi}\left(\tau_i(t',\mu^2)+\Delta\tau_i(t',\mu^2,x)\right)\right]$$

with

$$\begin{aligned}\tau_i(t,\mu^2) &= \sum_j \int_0^1 dz\; zP_{ji}(z)\theta(\Delta(t,\mu^2)-z),\\ \Delta\tau_i(t,\mu^2,x) &= \sum_j \int_0^1 dz\;\theta(z-\Delta(t,\mu^2))\left[zP_{ji}(z)-\frac{F_j\left(\frac{x}{z},t\right)}{F_i(x,t)}P_{ij}(z)\theta(z-x)\right].\end{aligned}$$

Important differences between the Sudakov form-factor obtained in our mMRK approach and the KMR approach are

- The Sudakov form-factor contains the $x-$depended $\Delta\tau_i$-term in the exponent which is needed to preserve exact normalization condition for arbitrary x and μ.
- The numerically-important difference that in our mMRK approach the rapidity-ordering condition is imposed both on quarks and gluons, while in KMR approach it is imposed only on gluons.