

Associated production of Υ plus D in the improved color evaporation model

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Description of production of hadrons in QCD = pQCD + *hadronization*.

- ### i. Light and heavy-light hadrons hadroproduction

studied in processes: $p p \rightarrow D X, \bar{D} \bar{X}, D Z/W X, \dots$

- ## ii. Quarkonium hadroproduction:

- fragmentation mechanism (dominant at large $p_T^Q \gtrsim 15$ GeV [Kniehl, Nefedov, and Saleev '16]);
- fusion mechanisms (CSM, NROCD, DCDEM);

Studied in processes (LHC and Tevatron data): $p p(\bar{p}) \rightarrow \psi(nS) X$, $\Upsilon(nS) X$, and:

$J/\psi \Upsilon X^{\checkmark}$	DØ: $\sqrt{s} = 1.8$ TeV LHCb: $\sqrt{s} = 13$ TeV, $p_T^{\psi,\Upsilon} < 10, 30$ GeV
$J/\psi J/\psi X^{\checkmark}$	LHCb: $\sqrt{s} = 7, 13$ TeV, $p_T^{\psi} < 10$ GeV CMS: $\sqrt{s} = 7$ TeV, $p_T^{\psi} > 6.5$ GeV ATLAS: $\sqrt{s} = 8$ TeV, $p_T^{\psi} > 8.5$ GeV
$\Upsilon \Upsilon X^{\checkmark}$	CMS: $\sqrt{s} = 13$ TeV
$J/\psi Z X^{\checkmark}$	ATLAS: $\sqrt{s} = 8$ TeV, $p_T^{\psi} > 8.5$ GeV
$J/\psi W X^{\checkmark}$	ATLAS: $\sqrt{s} = 7, 8$ TeV, $p_T^{\psi} > 8.5$ GeV
$J/\psi/\Upsilon D X^{\checkmark}$	LHCb: $\sqrt{s} = 7$ TeV, $p_T^{\psi,\Upsilon} < 13, 15$ GeV

Processes of associated quarkonium and open charm production are a good test for both hadronization models.

Factorization approaches

Collinear Parton Model (CPM)

- On-shell initial states: $k_i^\mu = x_i P_i^\mu$, $k_i^2 = 0$;
 - Collinear factorization: $a(k_1) + b(k_2) \rightarrow \dots (k_f)$

$$d\sigma = \sum_{a, b} \int dx_1 f_{a/p}(x_1, \mu_F) \int dx_2 f_{b/p}(x_2, \mu_F) \times d\hat{\sigma}_{ab},$$

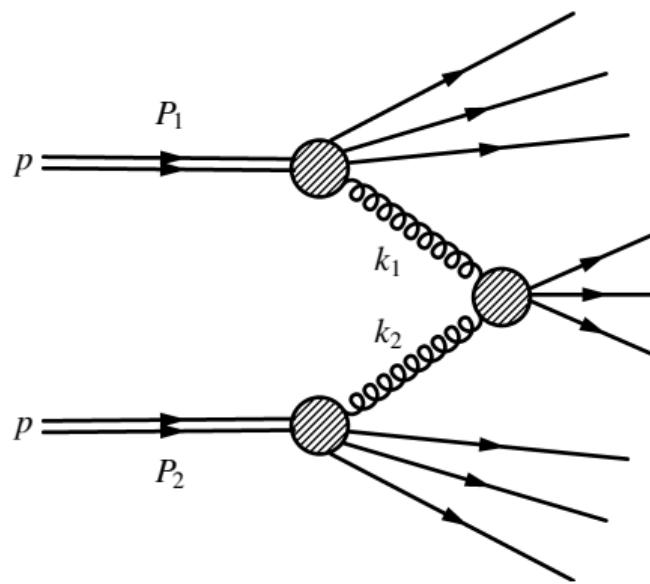
where $a, b \in \{g, q, \bar{q}\}$. Partonic cross-section:

$$d\hat{\sigma}_{ab}(t_1, t_2, k_f) = (2\pi)^4 \delta^{(4)}(k_1 + k_2 - \sum k_f) \frac{|\mathcal{A}(a b \rightarrow \dots)|^2}{I} d\Phi(k_f)$$

with $I \simeq 2x_1x_2s$;

- Framework: $\mu_F \sim p_T \gg \Lambda_{\text{QCD}}$

$$P_1 = \frac{\sqrt{s}}{2}(1,0,0,1), \quad P_2 = \frac{\sqrt{s}}{2}(1,0,0,-1)$$



Parton Reggeization Approach (PRA) [Nefedov, Saleev, and Shipilova '13]

- ◀ Off-shell initial states: $k_i^\mu = x_i P_i^\mu + k_{Ti}^\mu$, $k^2 = -\mathbf{k}_{Ti}^2$;
 - ◀ k_T -factorization kinematics: $a(k_1) + b(k_2) \rightarrow \dots (k_\ell)$

$$d\sigma = \sum_{\bar{i}} \int \frac{dx_1}{x_1} \int dt_1 \int \frac{d\phi_1}{2\pi} \int \frac{dx_2}{x_2} \int dt_2 \int \frac{d\phi_2}{2\pi} \Phi_{a/p}(x_1, t_1, \mu^2) \Phi_{b/p}(x_2, t_2, \mu^2) \times d\hat{\sigma}_{ab}^{\text{PRA}},$$

where $t := -k_1^2$, and $a, b \in \{R, Q, \bar{Q}, \}\}$. Partonic cross section:

$$d\hat{\sigma}_{ab}^{\text{PRA}}(t_1, t_2, k_f) = (2\pi)^4 \delta^{(4)}(k_1 + k_2 - \sum k_f) \frac{|\mathcal{A}^{\text{PRA}}(a \ b \rightarrow \dots)|^2}{\pi} d\Phi(k_f)$$

with $L \approx 2x_1 x_2 s$, $\overline{|\mathcal{A}^{\text{PRA}}|^2}$ calculated in the Linatou's FET_(n) [10]:

- ¹ Exact normalization condition for the modified upBDE.

$$\int dt_i \Phi_{a/p}(x_i, t_i, \mu^2) = x_i f_{a/p}(x_i, \mu^2)$$

- $$- \frac{1}{2} \mathbf{E} \left[\left(\frac{1}{2} \mathbf{m}^T \mathbf{m} - \frac{1}{2} \mathbf{m}^T \mathbf{A}^{-1} \mathbf{A} \mathbf{m} \right)^2 \right] = \frac{1}{2} \mathbf{m}^T \mathbf{m} - \frac{1}{2} \mathbf{m}^T \mathbf{A}^{-1} \mathbf{A} \mathbf{m}$$

Main PRA 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;
 - 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.

Quarkonium production

$M_{J/\psi} \simeq 3.097$ GeV and $M_\Upsilon \simeq 9.460$ GeV—non-relativistic. Quarkonium in the potential model:

$$\mathcal{V}_{\text{Cornell}}(r) = -C_F \frac{\alpha_S(1/r)}{r} + \sigma r \quad \Rightarrow \quad \boxed{\alpha_S(M_Q v) \sim v \sim 0.2 - 0.3}$$

Color Singlet Model (CSM) [Baier, Rückl, Berger, and Jones / 83]

$$d\sigma(Q[^3S_1^1]) \equiv d\sigma(Q\bar{Q}[^3S_1^1]) \times \langle QQ[^3S_1^1] \rangle,$$

where $\langle Q^Q[{}^3S_1^1] \rangle \approx |\Psi_Q(0)|^2$

Non-relativistic QCD (NRQCD) [Bodwin, Braaten, and Lepage /95]

$$d\sigma(Q) = \sum d\sigma(Q\bar{Q}[n]) \times \langle O^Q[n] \rangle,$$

here $n = 2S+1$

Color Evaporation Model (CEM) [Fritzsch and Halzen '77] \hookrightarrow **Improved CEM (ICEM)** [Ma and Vogt '16]

$$\frac{d\sigma_Q}{d^3 p} = \mathcal{F}^Q \times \int_{M_Q}^{2M_H} dM \, d^3 p' \, \delta^{(3)} \left(\mathbf{p} - \frac{M_Q}{M} \mathbf{p}' \right) \frac{d\sigma_{Q\bar{Q}}}{dM \, d^3 p'} + O(\lambda^2/M_Q^2)$$

$$\simeq \mathcal{F}^Q \times \int_{M_Q}^{2M_H} dM [\theta(M - M_Q) - \theta(M - 2M_H)] \frac{d\sigma_{Q\bar{Q}} \left(\mathbf{p}' = \frac{M}{M_Q} \mathbf{p} \right)}{d^3 p'}$$

- ◀ One free parameter \mathcal{F}^Q for each Q ;
 - ◀ All quarkonium Q states are treated like $Q\bar{Q}$ pairs below $H\bar{H}$ threshold;
 - ◀ All $Q\bar{Q}$ production diagrams included independent of color;
 - ◀ The $Q\bar{Q}$ pairs produce quarkonium Q through proto-quarkonium state with 4-momentum $p' = p_Q + p_{\bar{Q}}$;
 - ◀ Matching condition: $p = (M_Q/M) p'$;
 - ◀ ICEM predicts non-zero polarization [Cheung and Vogt /21]:

Recent ICEM publications:

- V. Cheung and R. Vogt, «Production and polarization of direct J/ψ up to $\mathcal{O}(\alpha_S^3)$ 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;
 - J.-P. Lansberg et.al., «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;
 - A.A. Chernyshev and V.A. Saleev, «Single and pair J/ψ production in the improved color evaporation model using the parton Reggeization approach», Phys. Rev. D. **106** (2022) no.11, 114006;
 - A.A. Chernyshev and V.A. Saleev, «Pair production of heavy quarkonia in the color evaporation model», Contribution to: ICPPA 2022;
 - A.A. Chernyshev and V.A. Saleev, «Associated production of J/ψ plus Z/W in the improved color evaporation model using the parton Reggeization approach», arXiv:2304.07481.

Open charm production

Fragmentation mechanism [D'Alesio and Murgia '04]

$$a \pm b \Rightarrow c(a) (\Rightarrow D(p)) \pm \bar{c}$$

Master formula for the differential cross section:

$$p^0 \frac{d\sigma_D}{d^3 p} = \int dz \, \mathcal{D}_{c \rightarrow D}(z, \mu_0^2) \, q^0 \frac{d\sigma_{c\bar{c}}(q=q(z))}{d^3 q}$$

- Parameter: $z = (p^0 + |\mathbf{p}|) / (q^0 + |\mathbf{q}|)$;
 - Parameter cut: $z_{\text{cut}} = m_D / (q^0 + |\mathbf{q}|)$;
 - Peterson's fragmentation function (FF) [Bjorken, 1969; 1/32]

$$\mathcal{D}_{c \rightarrow D}(z, \mu_0^2) = \mathcal{N} \frac{z(1-z)^2}{[(1-z)^2 + \varepsilon z]^2}, \quad \sum_{z=0}^1 \int dz \mathcal{D}_{c \rightarrow D}(z, \mu_0^2) = 1,$$

with $c = 0.06$:

- Fragmentation fractions: $f(c \rightarrow D^0) = 0.542$ and $f(c \rightarrow D^+) = 0.225$ [CERN NA3 (1995)]

Single and Double parton scatterings

Via combined approach of EM, ICEM, and LO PRA

$$d\sigma \equiv d\sigma^{\text{SPS}} \pm d\sigma^{\text{DP}}$$

► SPS master formula:

$$\begin{aligned} d\sigma^{\text{SFS}}(p \ p \rightarrow \Upsilon \ D \ X) = & \mathcal{F}^\Upsilon \times \int dM \ [\theta(M - M_\Upsilon) - \theta(M - 2M_B)] \\ & f(c \rightarrow D) \times \int dz \ \mathcal{D}_{c \rightarrow D}(z, \mu_0^2) \\ & \times \sum_{\bar{t}} \Phi_{a/p}(x_1, t_1, \mu^2) \otimes \Phi_{b/p}(x_2, t_2, \mu^2) \otimes d\hat{\sigma}_{ab} \end{aligned}$$

where we considered parton subprocesses $BB \rightarrow Q\bar{Q} \rightarrow b\bar{b}$, $c\bar{c}$.

DPS pocket formula

$$d\sigma^{\text{DPS}}(p \ p \rightarrow \Upsilon \ D \ X) = \frac{d\sigma^{\text{SPS}}(p \ p \rightarrow \Upsilon \ X_1) \times d\sigma^{\text{SPS}}(p \ p \rightarrow D \ X_2)}{(1 + \frac{S}{\sqrt{N_{\text{part}}}})^2},$$

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From equation (a) and $\mathcal{F}^r = 0.021$ and $\tau = 11 \text{ ns}$

Numerical methods

- i. ReggeQCD [Karpishkov, Nefedov, and Saleev '17]—FeynCalc model file
 - ◀ Tree-level matrix elements for up to $2 \rightarrow 4$ partonic subprocesses with reggeized partons;
 - ii. KaTie [Hameren '16]—MC generator
 - ◀ Calculations up to $2 \rightarrow 4$ parton subprocesses with off-shell amplitudes;
 - ◀ Tree-level matrix elements from AVHLIB [Hameren '13];
 - ◀ Collinear PDFs from LHAPDF and TMD PDFs from TMDlib;
 - ◀ unPDF with exact normalization in the modified KMRW model;
 - ◀ Multiparton interactions;
 - ◀ Event files in LHE format

Inclusive Υ mesons production in the ICEM via PRA¹

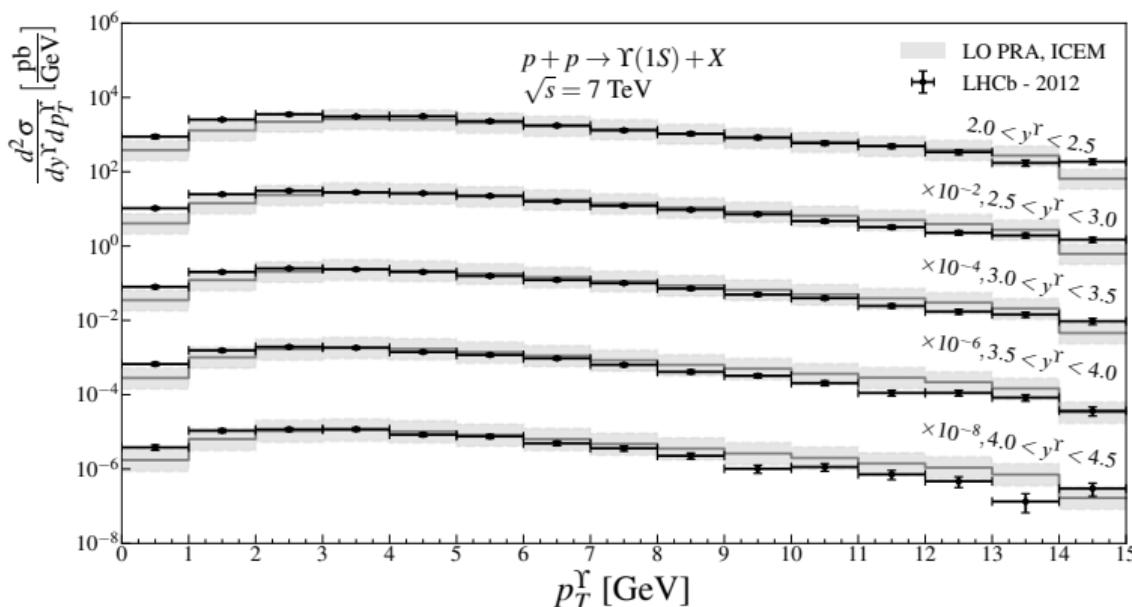


Figure 1: Spectra of inclusive Υ production on transverse momentum p_T^Υ of Υ meson with $\mathcal{F}^\Upsilon = 0.021$.

¹The data are from LHCb Collaboration [Aaij et al '12].

Inclusive D mesons production in the FM via PRA²

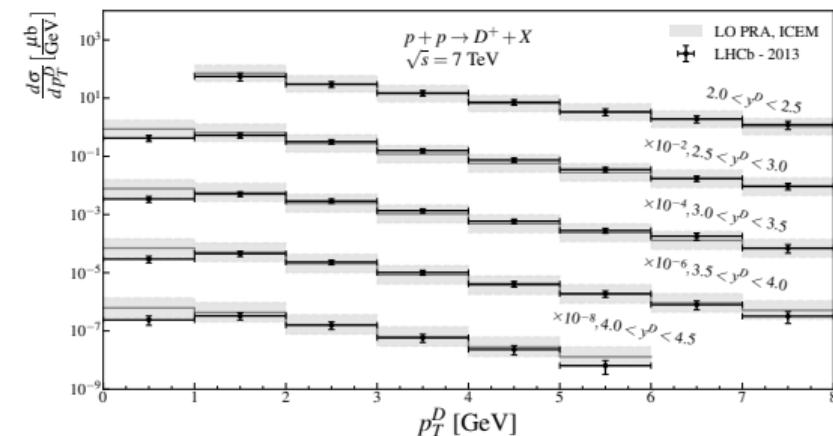
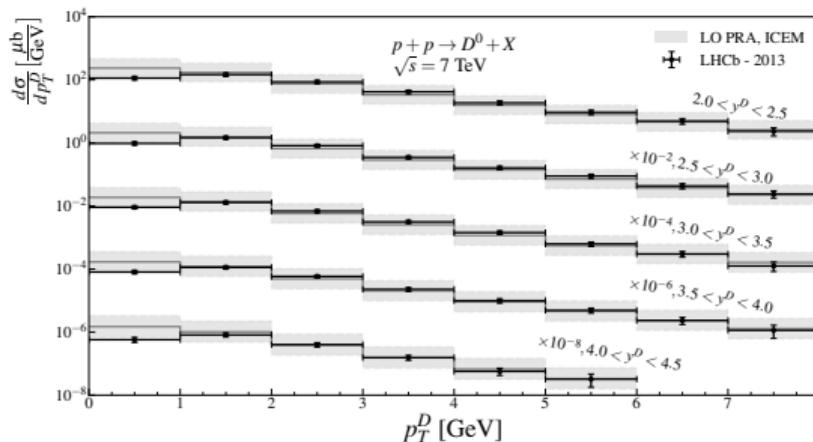


Figure 2: Spectra of inclusive D mesons production on transverse momentum p_T^D of $D^{0,+}$ mesons.

²The data are from LHCb Collaboration [Aaij et.al '13].

Associated $\Upsilon + D$ production in the combined approach of ICEM, FM, and PRA³

Comparison of theoretical and experimental total cross sections:

Final state	Energy	Cross section	Exp. \pm (stat.) \pm (syst.)	LO PRA \pm (Δ_{SPS}) \pm (Δ_{DPS})
$\Upsilon + D^0$	$\sqrt{s} = 7 \text{ TeV}$	$\mathcal{B}(\Upsilon \rightarrow \mu\bar{\mu}) \times \sigma$	$155 \pm 21 \pm 7 \text{ [pb]}$	$145^{+16}_{-6}{}^{+124}_{-65} \text{ [pb]}$
$\Upsilon + D^+$	$\sqrt{s} = 7 \text{ TeV}$	$\mathcal{B}(\Upsilon \rightarrow \mu\bar{\mu}) \times \sigma$	$82 \pm 19 \pm 5 \text{ [pb]}$	$78^{+14}_{-2}{}^{+140}_{-38} \text{ [pb]}$
$\Upsilon + D^0$	$\sqrt{s} = 8 \text{ TeV}$	$\mathcal{B}(\Upsilon \rightarrow \mu\bar{\mu}) \times \sigma$	$250 \pm 28 \pm 11 \text{ [pb]}$	$255^{+25}_{-9}{}^{+189}_{-113} \text{ [pb]}$
$\Upsilon + D^+$	$\sqrt{s} = 8 \text{ TeV}$	$\mathcal{B}(\Upsilon \rightarrow \mu\bar{\mu}) \times \sigma$	$80 \pm 16 \pm 5 \text{ [pb]}$	$85^{+8}_{-3}{}^{+63}_{-37} \text{ [pb]}$

$$R = \frac{\sigma^{\text{SPS}}}{\sigma^{\text{DPS}}} \simeq \frac{1}{10}$$

³The data are from LHCb Collaboration [Aaij et al.] [16].

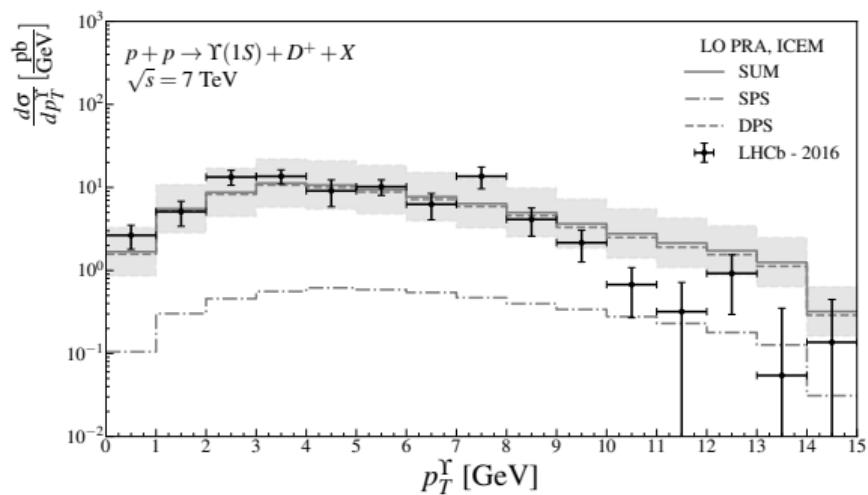
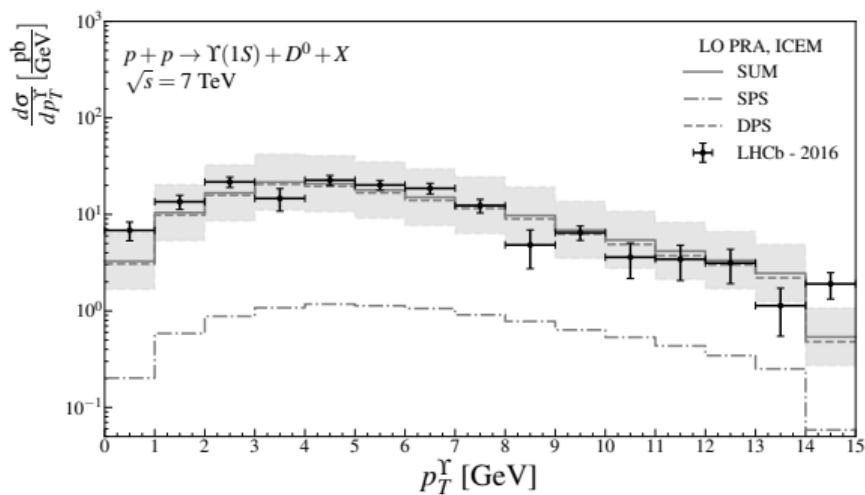


Figure 3: Spectra of associated $\Upsilon + D$ production on transverse momentum p_T^Υ of Υ meson.

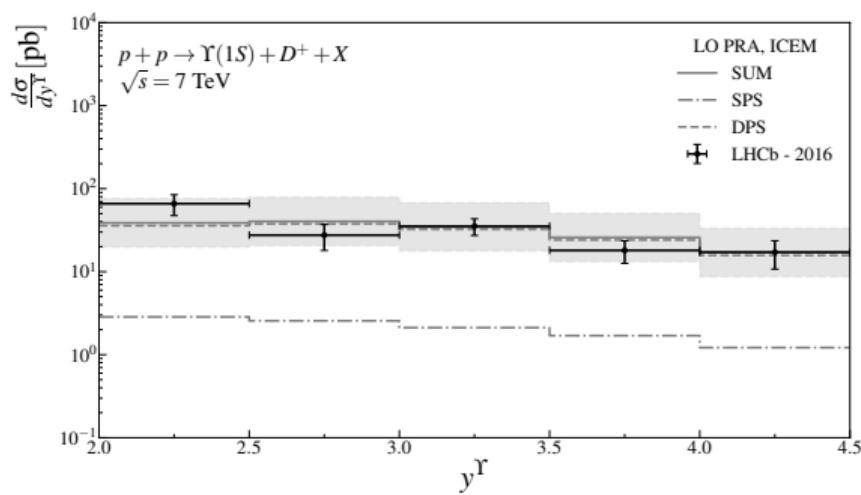
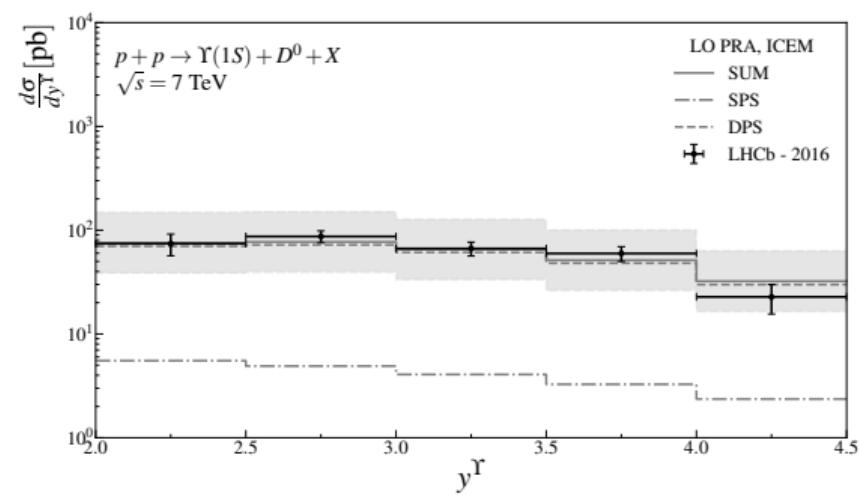


Figure 4: Spectra of associated $\Upsilon + D$ production on rapidity y^Υ of Υ meson.

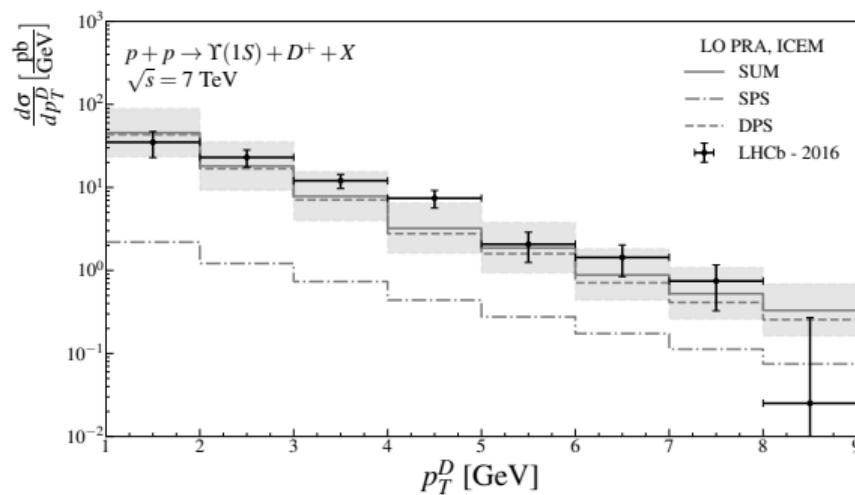
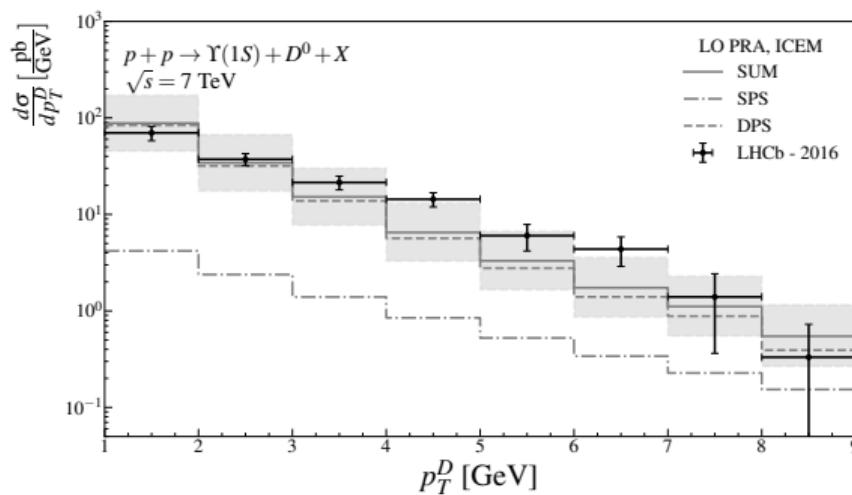


Figure 5: Spectra of associated $\Upsilon + D$ production on transverse momentum p_T^D of D meson.

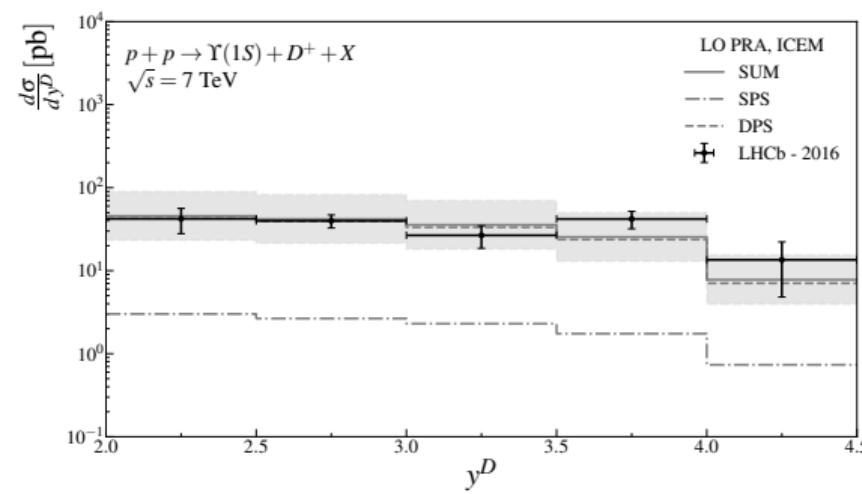
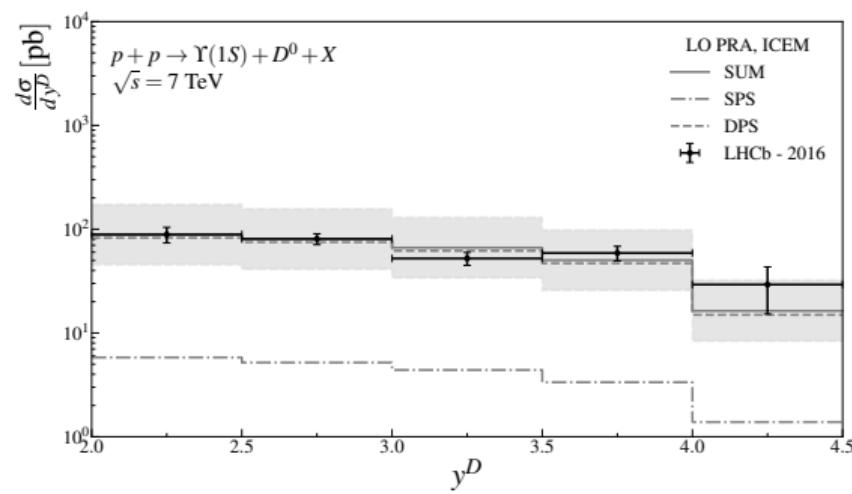


Figure 6: Spectra of associated $\Upsilon + D$ production on rapidity y^D of D meson.

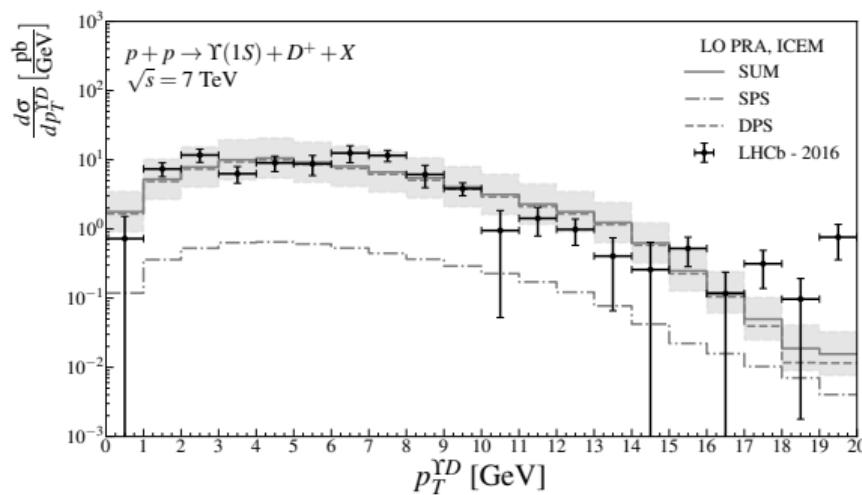
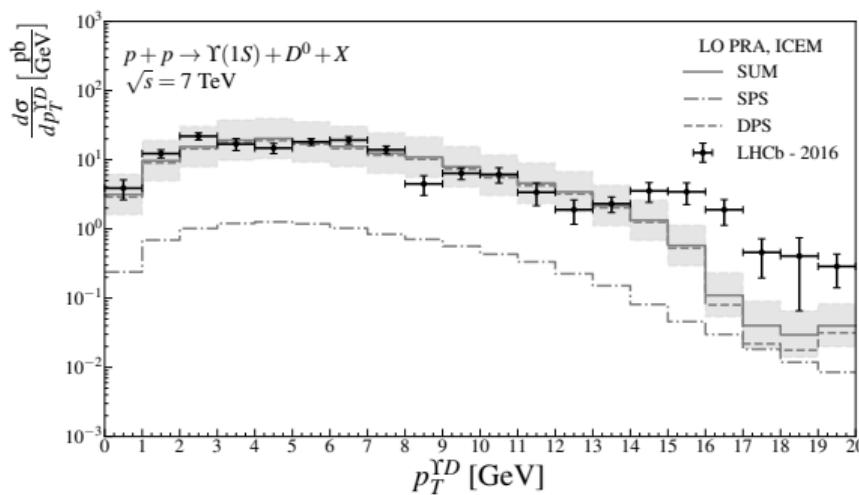


Figure 7: Spectra of associated $\Upsilon + D$ production on transverse momentum p_T^{YD} of $\Upsilon + D$ pair.

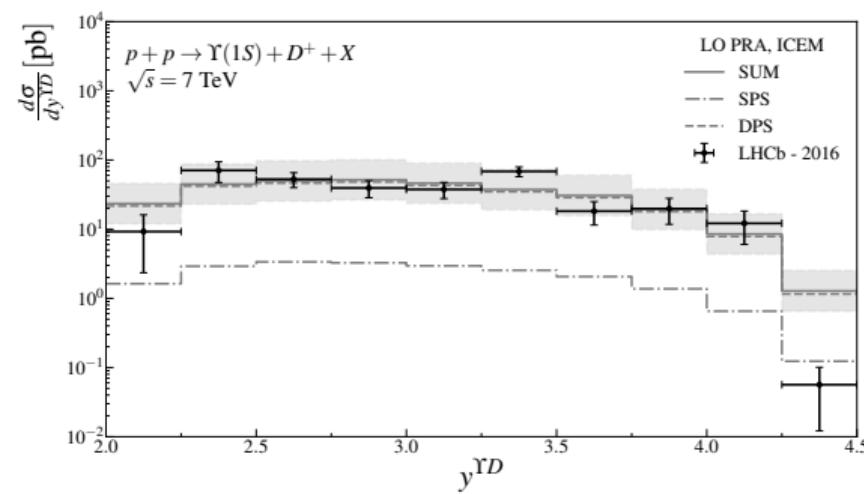
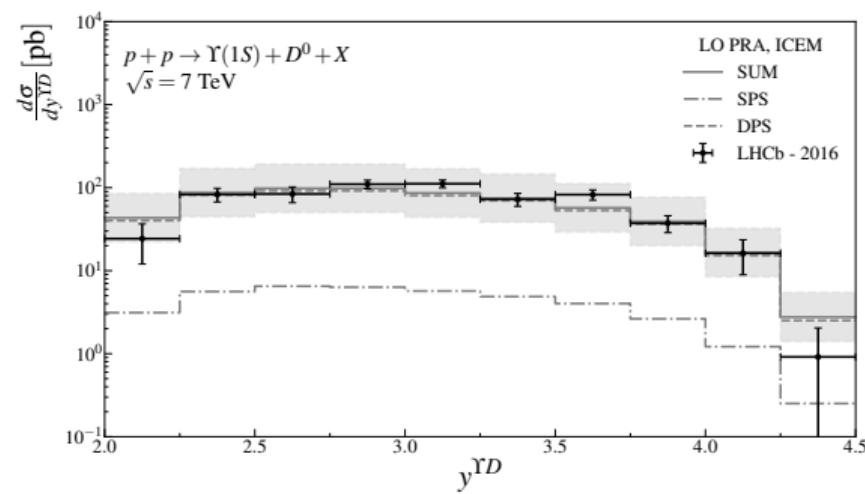


Figure 8: Spectra of associated $\Upsilon + D$ production on rapidity y^{UD} of $\Upsilon + D$ pair.

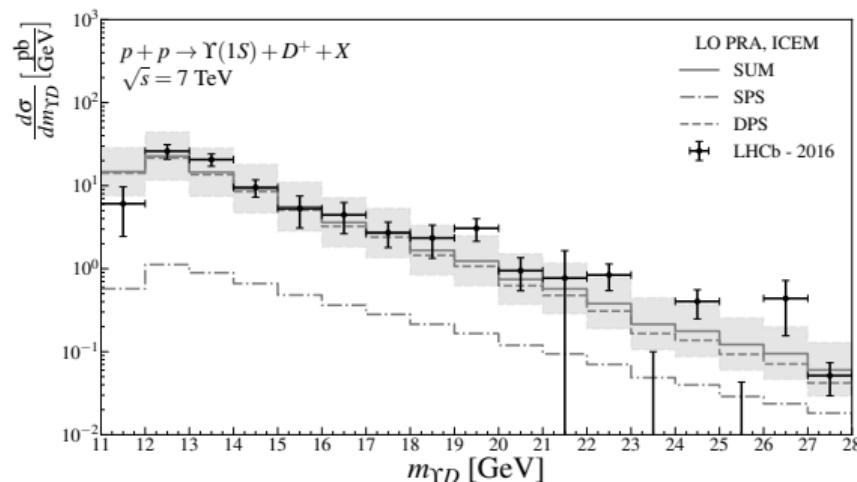
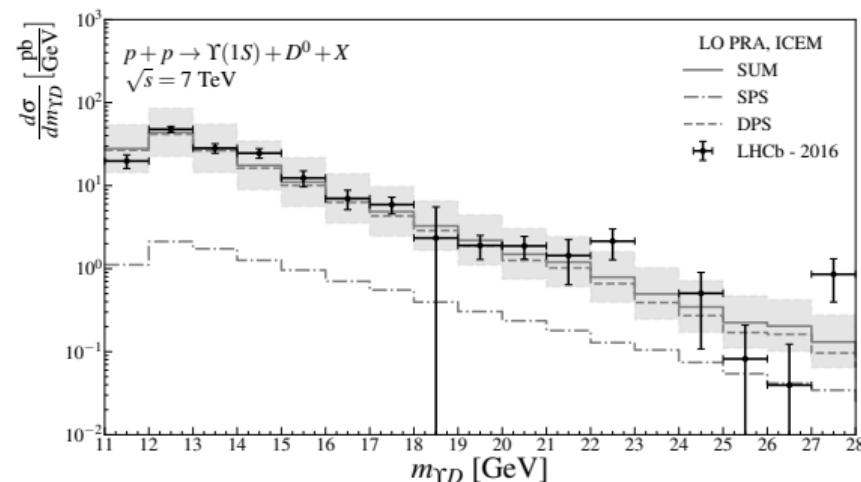


Figure 9: Spectra of associated $\Upsilon + D$ production on invariant mass m_{YD} of $\Upsilon + D$ pair.

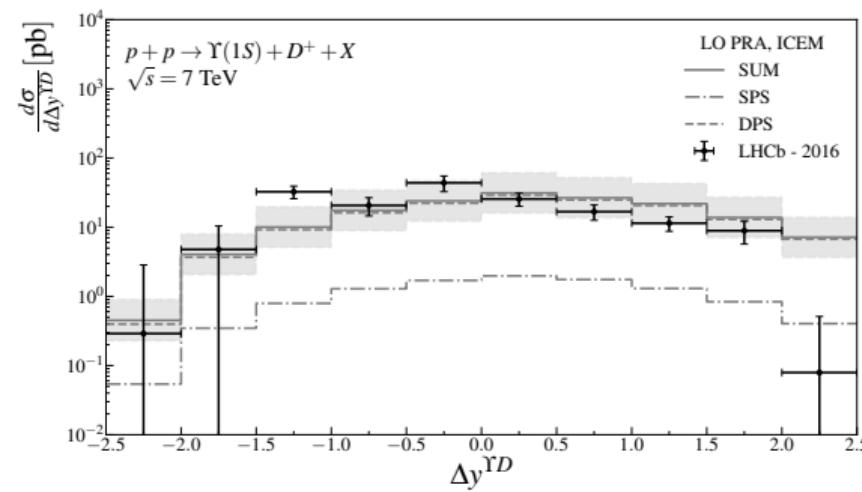
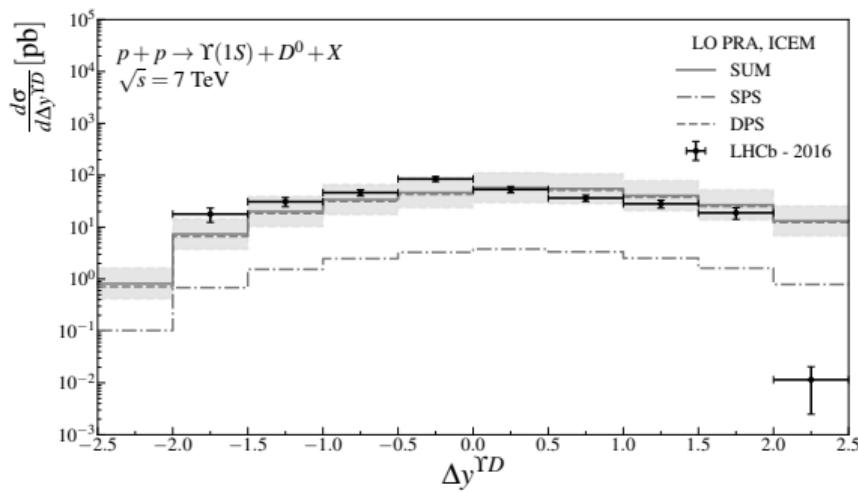


Figure 10: Correlation spectra of associated $\Upsilon + D$ production on rapidity difference Δy^{YD} between Υ and D mesons.

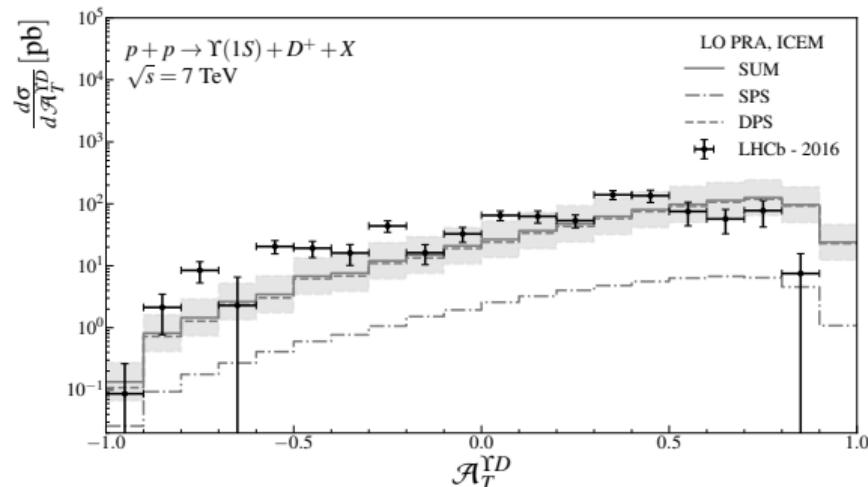
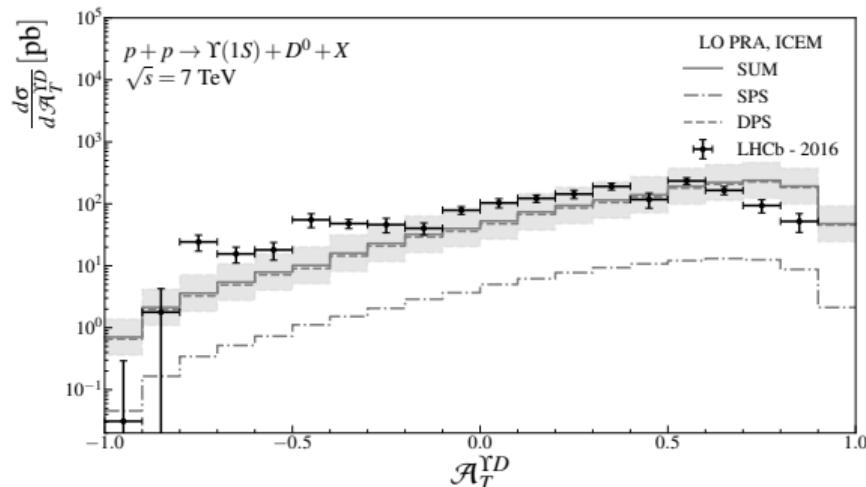


Figure 11: Correlation spectra of associated $\Upsilon + D$ production on transverse assymetry \mathcal{A}_T^{YD} between Υ and D mesons.

$$\mathcal{A}_T^{YD} = \frac{|\mathbf{p}_T^{\Upsilon} - \mathbf{p}_T^D|}{|\mathbf{p}_T^{\Upsilon} + \mathbf{p}_T^D|}$$

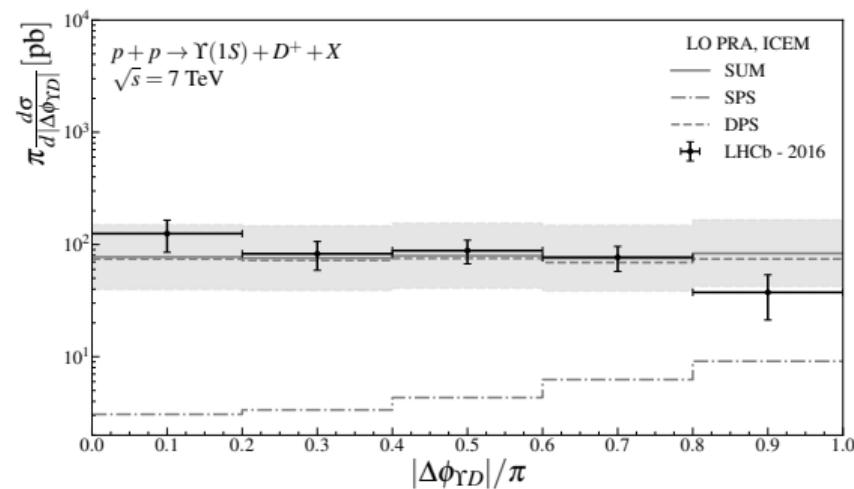
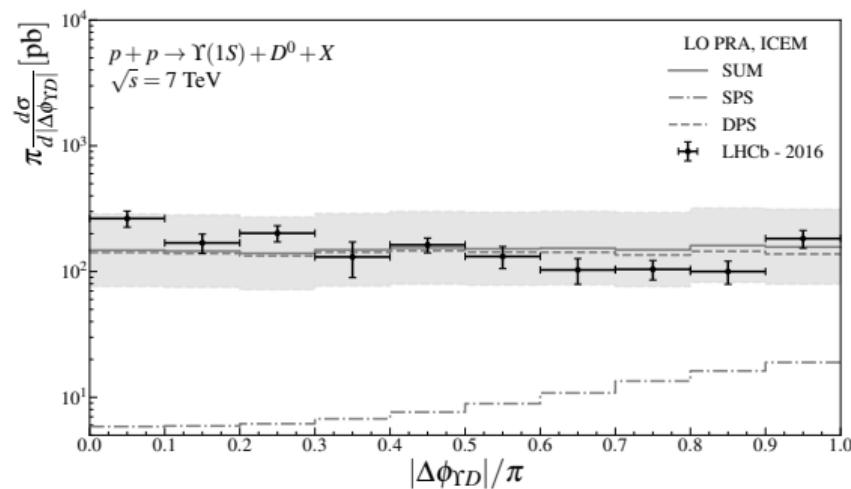


Figure 12: Correlation spectra of associated $\Upsilon + D$ production on azimuthal angles difference $\Delta\phi_{YD}$ between Υ and D mesons.

Conclusions

- i. We obtained a quite satisfactory description for the $\Upsilon + D^{0,+}$ associated production cross section in the ICEM using the PRA without fitting any free parameters;
 - ii. Associated $\Upsilon + D^{0,+}$ production cross sections at the energies $\sqrt{s} = 7$ and 8 TeV are described well with $\mathcal{F}^\Upsilon = 0.021$ and $\sigma_{\text{eff}} = 11$ mb;
 - iii. We find dominant role of the DPS production mechanism in the processes of associated $\Upsilon + D^{0,+}$ production, such as $\sigma^{\text{SPS}} / \sigma^{\text{DPS}} \simeq 1/10$;
 - iv. The azimuthal angle difference spectrum of $\Delta\phi_{\chi_D}$ is flat due the DPS production mechanism;

Thank you for your attention!