Measurements of associated production at LHCb

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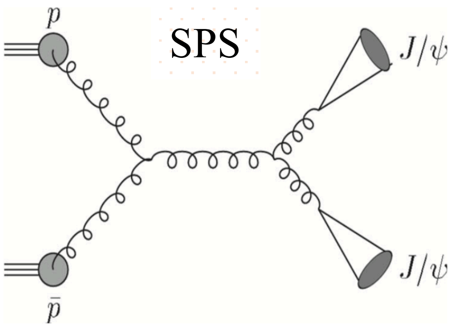
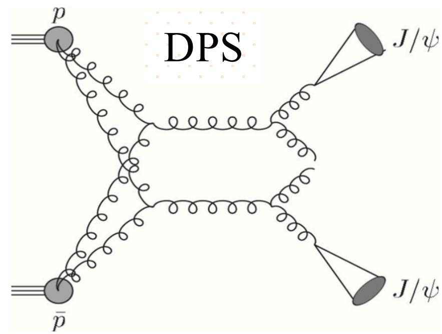
Introduction

- Associated productions probe double parton scattering (DPS), to understand multiple gluon PDF





Example diagrams for SPS and DPS production of 2 J/ψ

- Theoretical formulation for DPS: $\sigma_{\rm DPS}^{1,2} = \frac{m}{2}\frac{\sigma_1^{\rm inc}\sigma_2^{\rm inc}}{\sigma_{\rm eff}}$
  - $m = 1$ if particles 1 and 2 are identical, otherwise $m = 2$
  - $\sigma_{\rm eff}$ non perturbative, related to size of interaction region, $\sim r_p^2 \approx 10\text{mb}$
  - $\sigma_{\rm eff}$ supposed to be process and energy independent
  - Production of particle 1 and 2 are independent

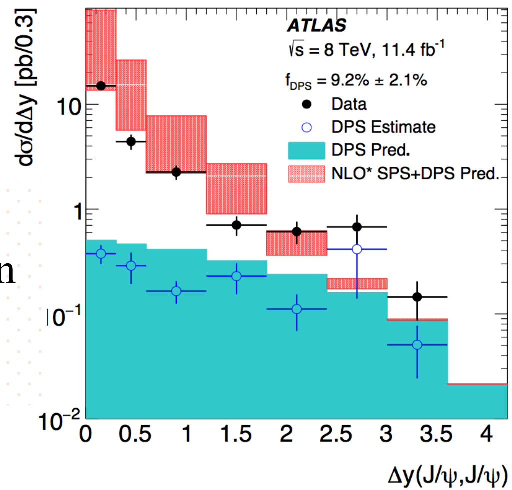
It assumes factorization of multiple parton PDF, breaks down at large x

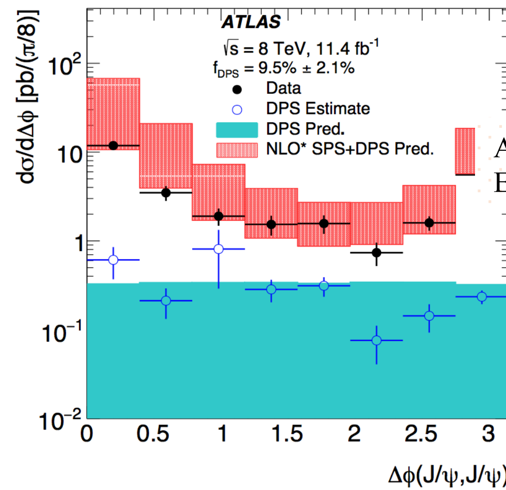
- SPS/inclusive calculations using QCD-based models: CSM, NRQCD, FONLL …

Experiments

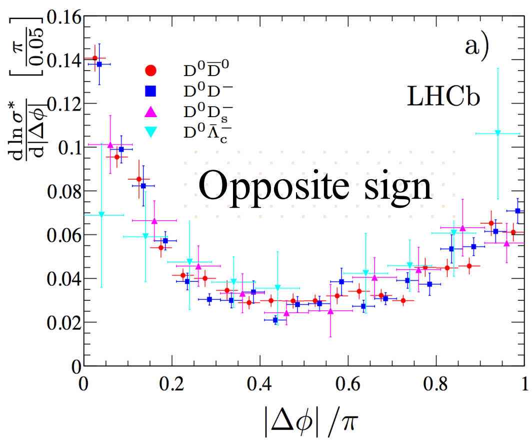
- DPS identification
  - ➢ Separation of DPS and SPS relies on inputs of templates for discriminant variables

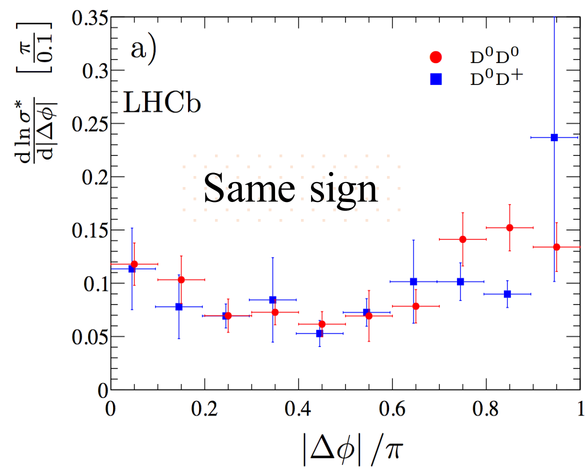
DPS signatures:
Large δy correlation
Flat $\delta \phi$ distribution
…





ATLAS:
EPJC 77 (2017) 76



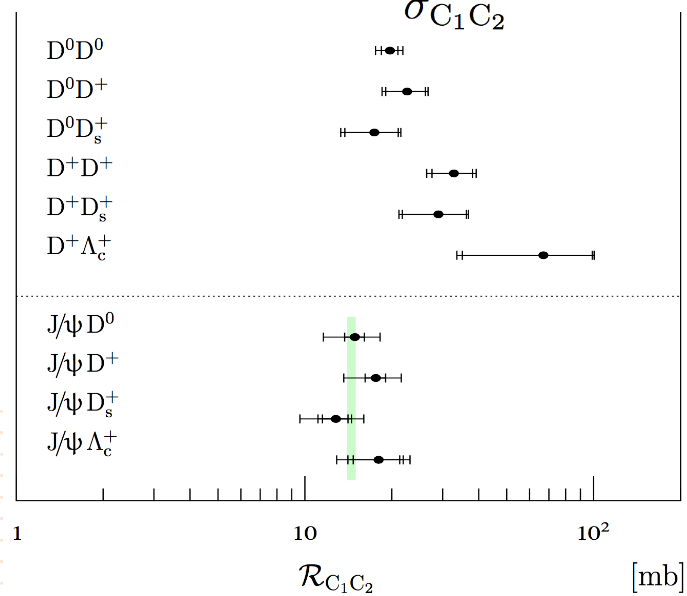


LHCb:
JHEP 06 (2012) 141

Experimental status

- Extraction of DPS/SPS yields from templates
  - DPS: random combination of inclusive productions for processes 1 and 2
  - SPS: theoretical predictions or data driven methods
- A variety of measurements by Tevetron, LHC and others
  - **Jets+jets, γ+ jets** by AFS, UA2, D0, CDF, ATLAS, CMS
  - ***W/Z*+charm/quarkonium** by ATLAS, LHCb
  - **Quarkonium pair** by CMS, ATALAS, LHCb D0
  - **Charm hadron pair** by LHCb
- σ_{eff} determination
  - Multiple jets production : 12 − 20 mb
  - Double quarkonia production (GPD): 2 − 8 mb
  - J/ψ + charm hadron (LHCb): ≥ 15 mb
  - Double charm hadron (LHCb): ≥ 20 mb
  - $Z + D$ production (LHCb): ≥ 20 mb

$$\mathcal{R}_{C_1C_2} \equiv \alpha' \frac{\sigma_{C_1} \times \sigma_{C_2}}{\sigma_{C_1C_2}}$$



LHCb and results using jets:
Smaller associated production than DPS predication
σ_{eff} not universal, factorization not all correct

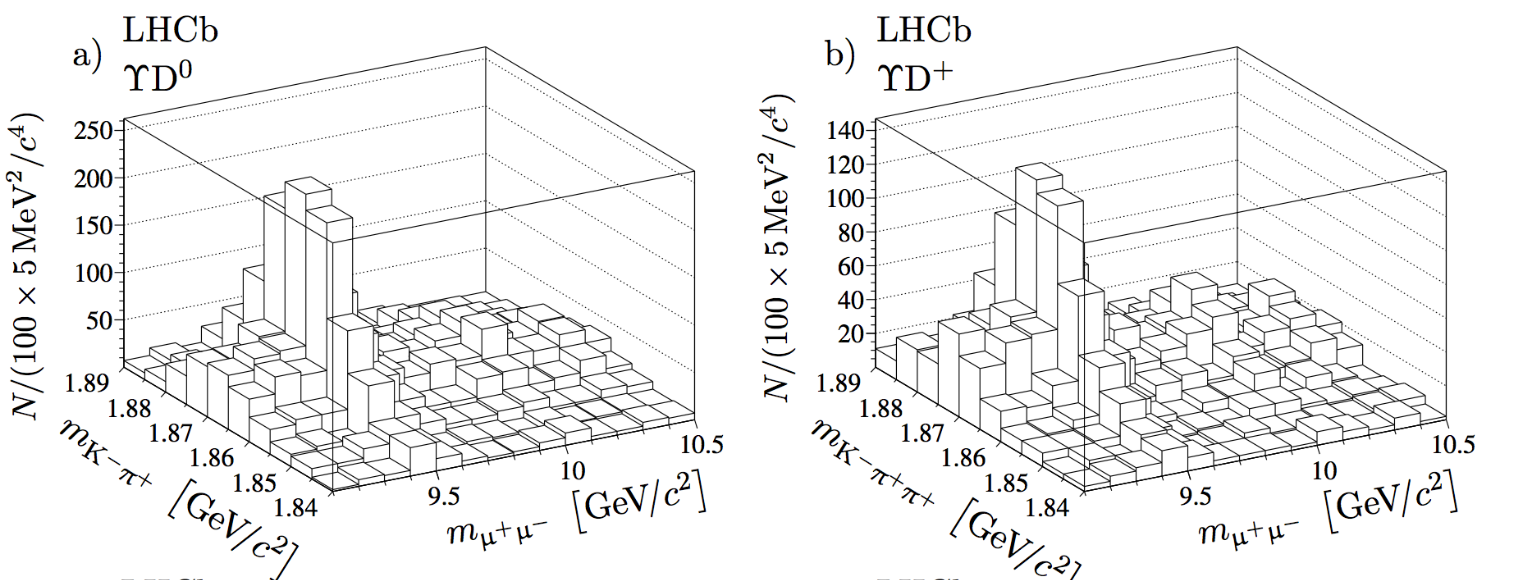
Recent LHCb measurements

- $\Upsilon + D$ associated production [JHEP 07 (2016) 052]
- J/ψ pair production [JHEP 06 (2017) 047]

JHEP 07 (2016) 052

$\Upsilon + D$ associated production

- Full RunI data: 1 fb^{-1}@7TeV + 2 fb^{-1}@8TeV

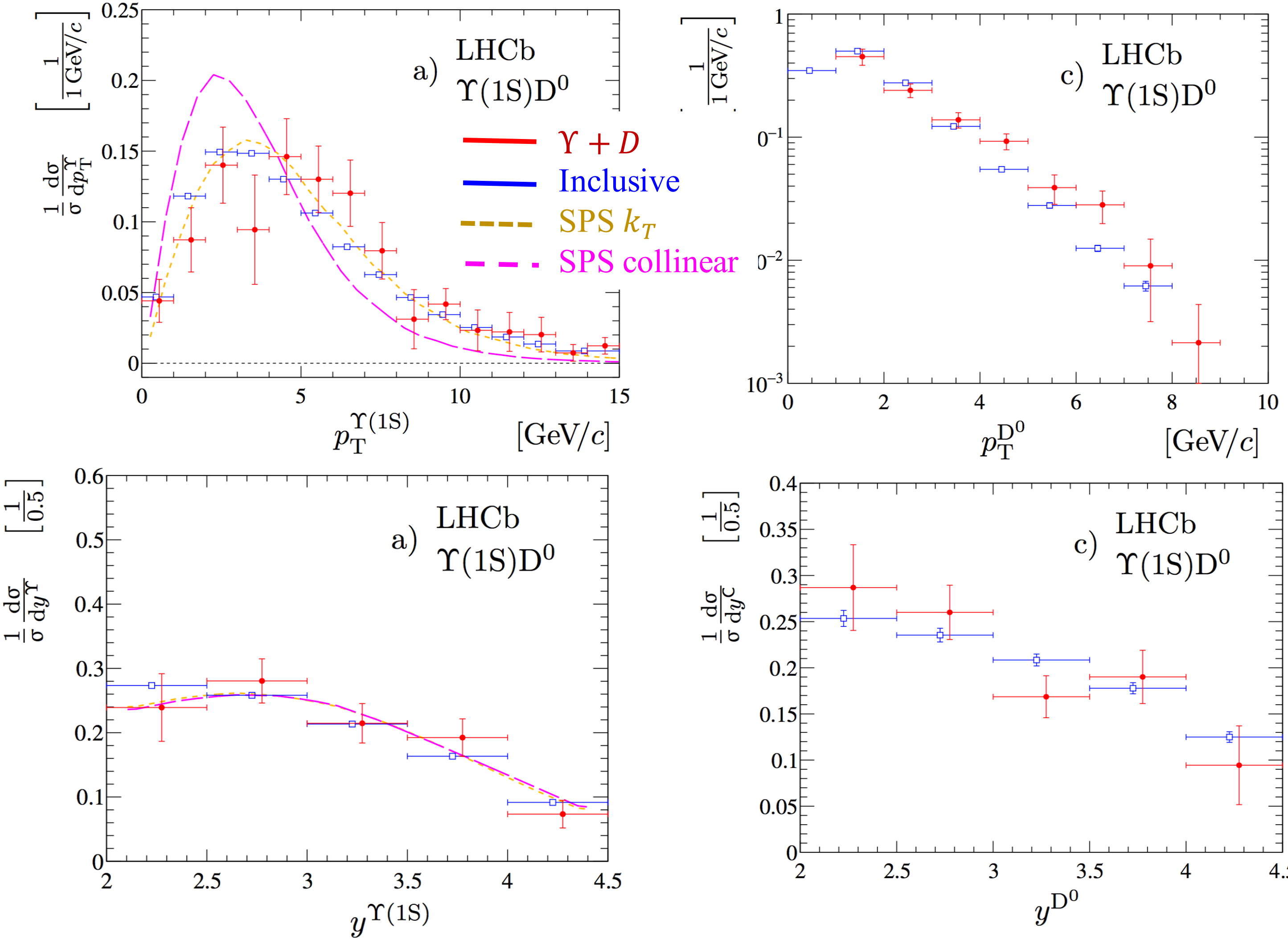


	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	184 ± 27	60 ± 22
D^+	556 ± 35	116 ± 20	55 ± 17
D_s^+	31 ± 7	9 ± 5	6 ± 4
Λ_c^+	11 ± 6	1 ± 4	1 ± 3

$\Upsilon + D$ associated production

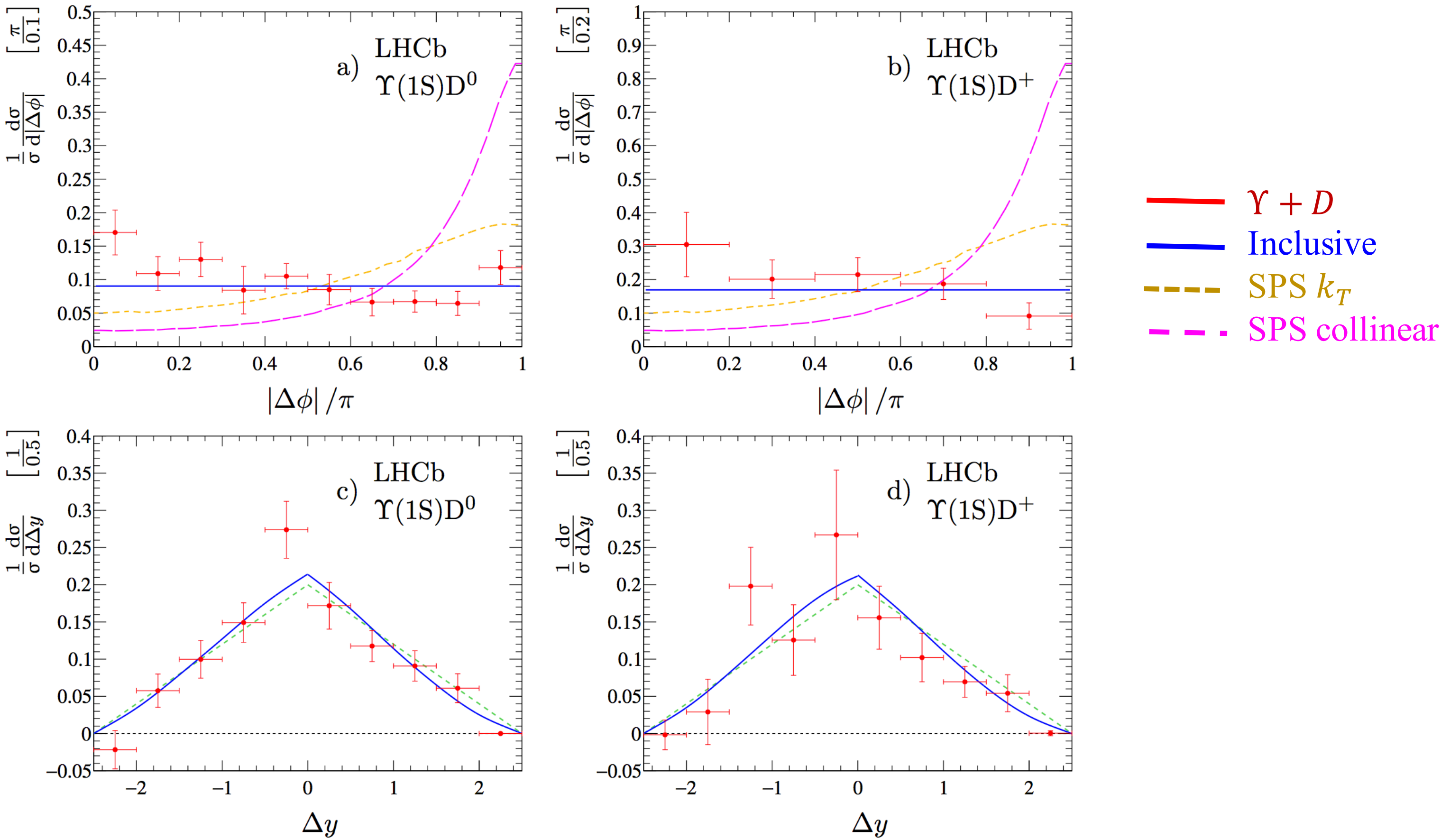
JHEP 07 (2016) 052

- Kinematic distributions: similar to those of inclusive productions



$\Upsilon + D$ associated production

- $\Delta\phi$ distribution
  - SPS predicts enhancement at $\Delta\phi = \pi$, but enhancement smeared out in k_T or at NLO
  - Flat $\Delta\phi$ distribution prefers DPS contribution, even dominating?



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$\Upsilon + D$ associated production

- $\sim$10% of Υ production in LHCb acceptance has a D associated

$$R^{\Upsilon(1S)D^0}_{\sqrt{s}=7\,\mathrm{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)D^0}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (6.3 \pm 0.8\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}))\,\%$$

$$R^{\Upsilon(1S)D^+}_{\sqrt{s}=7\,\mathrm{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)D^+}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=7\,\mathrm{TeV}} = (3.4 \pm 0.8\,(\mathrm{stat}) \pm 0.2\,(\mathrm{syst}))\,\%$$

$$R^{\Upsilon(1S)D^0}_{\sqrt{s}=8\,\mathrm{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)D^0}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (7.8 \pm 0.9\,(\mathrm{stat}) \pm 0.3\,(\mathrm{syst}))\,\%$$

$$R^{\Upsilon(1S)D^+}_{\sqrt{s}=8\,\mathrm{TeV}} = \left.\frac{\sigma^{\Upsilon(1S)D^+}}{\sigma^{\Upsilon(1S)}}\right|_{\sqrt{s}=8\,\mathrm{TeV}} = (2.5 \pm 0.5\,(\mathrm{stat}) \pm 0.1\,(\mathrm{syst}))\,\%$$

- Neglecting SPS contribution gives (a lower limit) $\sigma_{\mathrm{eff}}^{1,2} \geq \frac{m}{2}\frac{\sigma_1^{\mathrm{inc}}\sigma_2^{\mathrm{inc}}}{\sigma_{\mathrm{Asso}}}$

7 TeV

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^0} = 19.4 \pm 2.6\,(\mathrm{stat}) \pm 1.3\,(\mathrm{syst})\,\mathrm{mb}$$

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^+} = 15.2 \pm 3.6\,(\mathrm{stat}) \pm 1.5\,(\mathrm{syst})\,\mathrm{mb}$$

8 TeV

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^0} = 17.2 \pm 1.9\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst})\,\mathrm{mb}$$

$$\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^+} = 22.3 \pm 4.4\,(\mathrm{stat}) \pm 2.2\,(\mathrm{syst})\,\mathrm{mb}$$

Combination: $\sigma_{\mathrm{eff}}|_{\Upsilon(1S)D^{0,+}} \geq 18.0 \pm 1.3\,(\mathrm{stat}) \pm 1.2\,(\mathrm{syst}) = 18.0 \pm 1.8\,\mathrm{mb}$

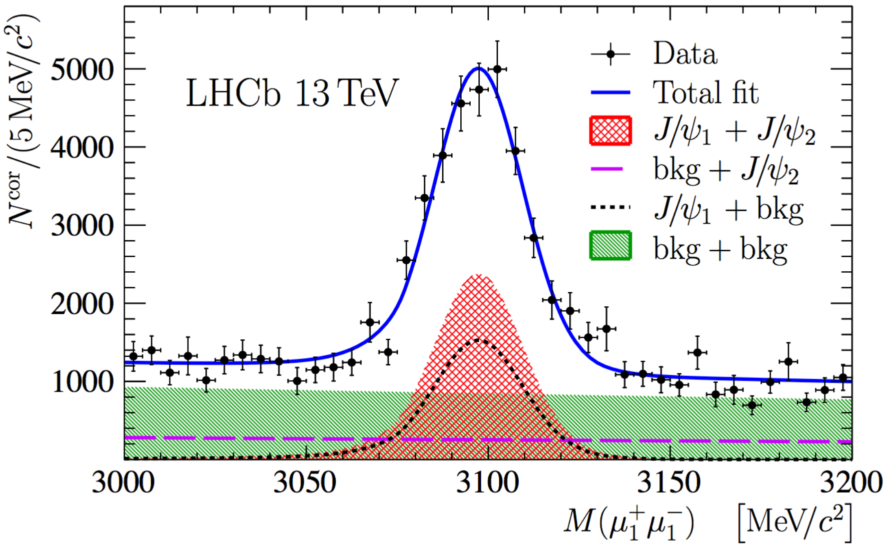
Consistent with LHCb double charm results

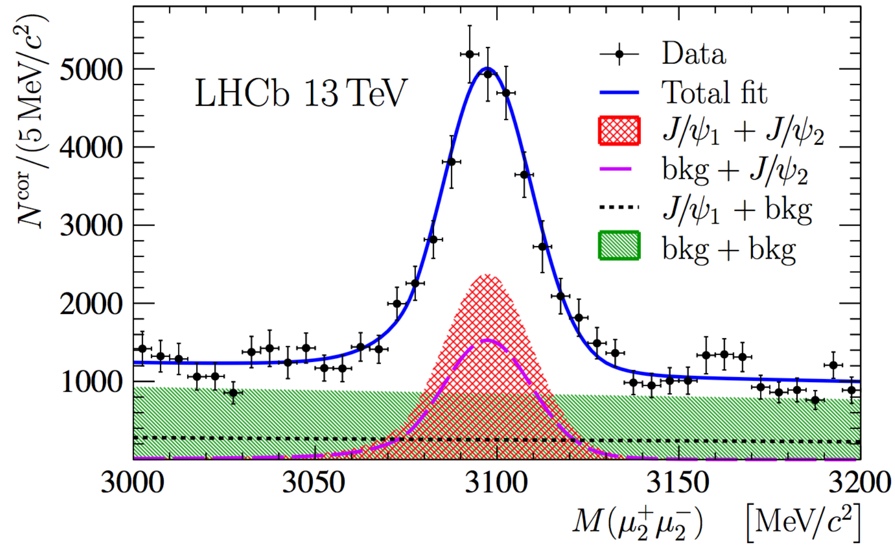
JHEP 06 (2017) 047

Double prompt J/ψ production

- Run II data at 13 TeV, ≈ 280 pb[-1]
  - Signal yields ≈ 1000

$2 < y < 4.5$, $p_T < 10$ GeV





$$\sigma(J/\psi\, J/\psi) = 15.2 \pm 1.0\,(\text{stat}) \pm 0.9\,(\text{syst})\ \text{nb}$$

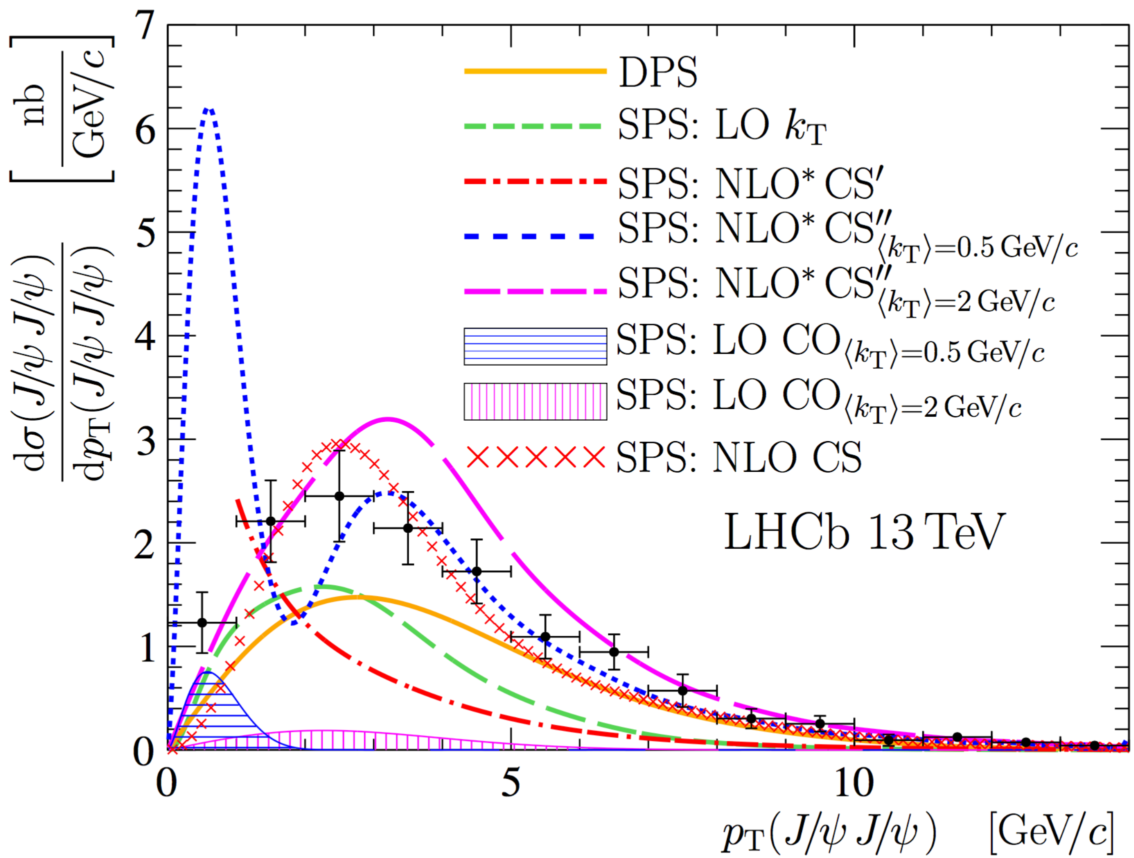
Compared to inclusive cross-section of $\sigma(J/\psi) = 14.94 \pm 0.02\,(\text{stat}) \pm 0.91\,(\text{syst})\ \mu\text{b}$

$$\sigma_{\text{eff}} \geq \frac{1}{2}\frac{\sigma(J/\psi)^2}{\sigma(J/\psi\, J/\psi)} = 7.3 \pm 0.5\,(\text{stat}) \pm 1.0\,(\text{syst})\ \text{mb}$$

Double prompt J/ψ production

- J/ψ pair p_T distribution

DPS obtained from inclusive production with $\sigma_{\text{eff}} = 14.5$ mb



Large variations of SPS calculations in theoretical predictions due to parameters: **both shapes and absolute scales**

Data prefer large $< k_T >$

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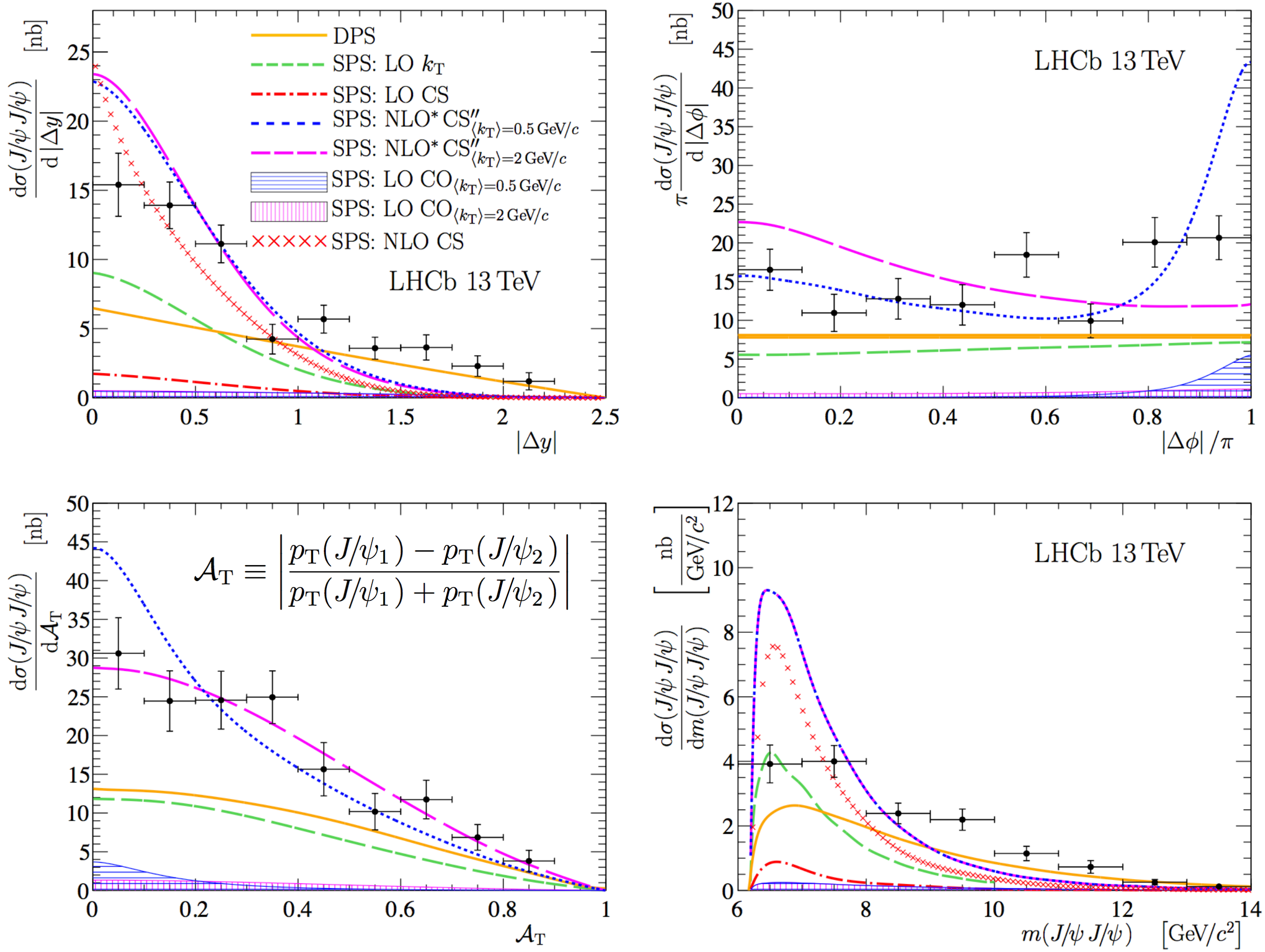
Double prompt J/ψ production

- Two J/ψ correlation variables

DPS obtained from inclusive production with $\sigma_{\text{eff}} = 14.5$ mb



In general both DPS and SPS are needed to describe data

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Double prompt J/ψ production

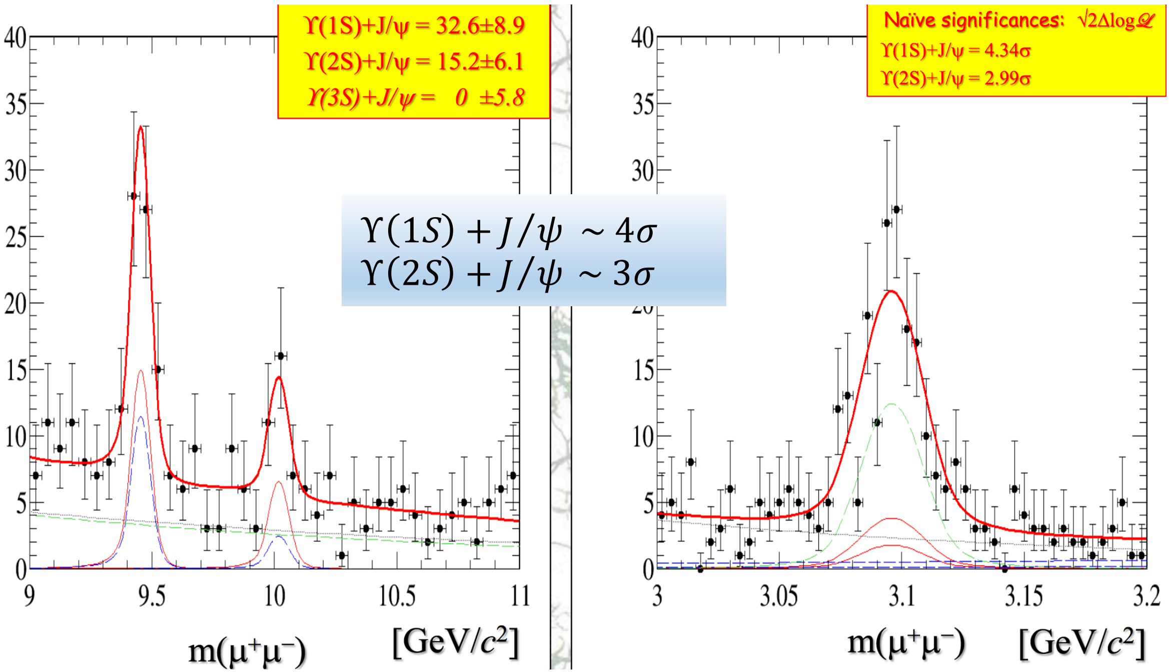
- Data driven method to obtain DPS fraction, templates fit
  - ➢ DPS: shape obtained from random combination of inclusive productions
  - ➢ SPS: using theoretical calculations, varying parameters

Variable	LO CS	LO k_T	NLO* CS′	NLO* CS″ $\langle k_T \rangle = 2\,\text{GeV}/c$	NLO* CS″ $\langle k_T \rangle = 0.5\,\text{GeV}/c$	NLO CS
no $p_T(J/\psi\, J/\psi)$ cut						
$p_T(J/\psi\, J/\psi)$	—	78 ± 3	—	88 ± 56	81 ± 7	—
$y(J/\psi\, J/\psi)$	83 ± 39	—	—	75 ± 37	68 ± 34	—
$m(J/\psi\, J/\psi)$	76 ± 7	74 ± 7	—	78 ± 7		77 ± 7
$\lvert\Delta y\rvert$	59 ± 21	61 ± 18	—	63 ± 18	61 ± 18	69 ± 16
$p_T(J/\psi\, J/\psi) > 1\,\text{GeV}/c$						
$y(J/\psi\, J/\psi)$	—	—	75 ± 24	71 ± 38	68 ± 34	—
$m(J/\psi\, J/\psi)$	—	73 ± 8	76 ± 7	88 ± 1		—
$\lvert\Delta y\rvert$	—	57 ± 20	59 ± 19	60 ± 18	60 ± 19	—
$p_T(J/\psi\, J/\psi) > 3\,\text{GeV}/c$						
$y(J/\psi\, J/\psi)$	—	—	77 ± 18	64 ± 38	64 ± 35	—
$m(J/\psi\, J/\psi)$	—	76 ± 10	84 ± 7	87 ± 2		—
$\lvert\Delta y\rvert$	—	42 ± 25	53 ± 21	53 ± 21	53 ± 21	—

Always large DPS contributions; measured $\sigma_{\text{eff}} = 10 - 12.5$ mb

- ➢ σ_{eff} larger than those determined by other experiments
- ➢ σ_{eff} smaller than LHCb $\Upsilon + D$ and double charm results

Prospects



Evidence of $\Upsilon + J/\psi$ in Run I data
And now new data!

- Could we measure other combinations, for example $J/\psi + \eta_c, J/\psi + \chi_c$ …

  No problem of trigger for then at LHCb

- Very interesting to see DPS in heavy ion collisions, expected to enhanced

Summary

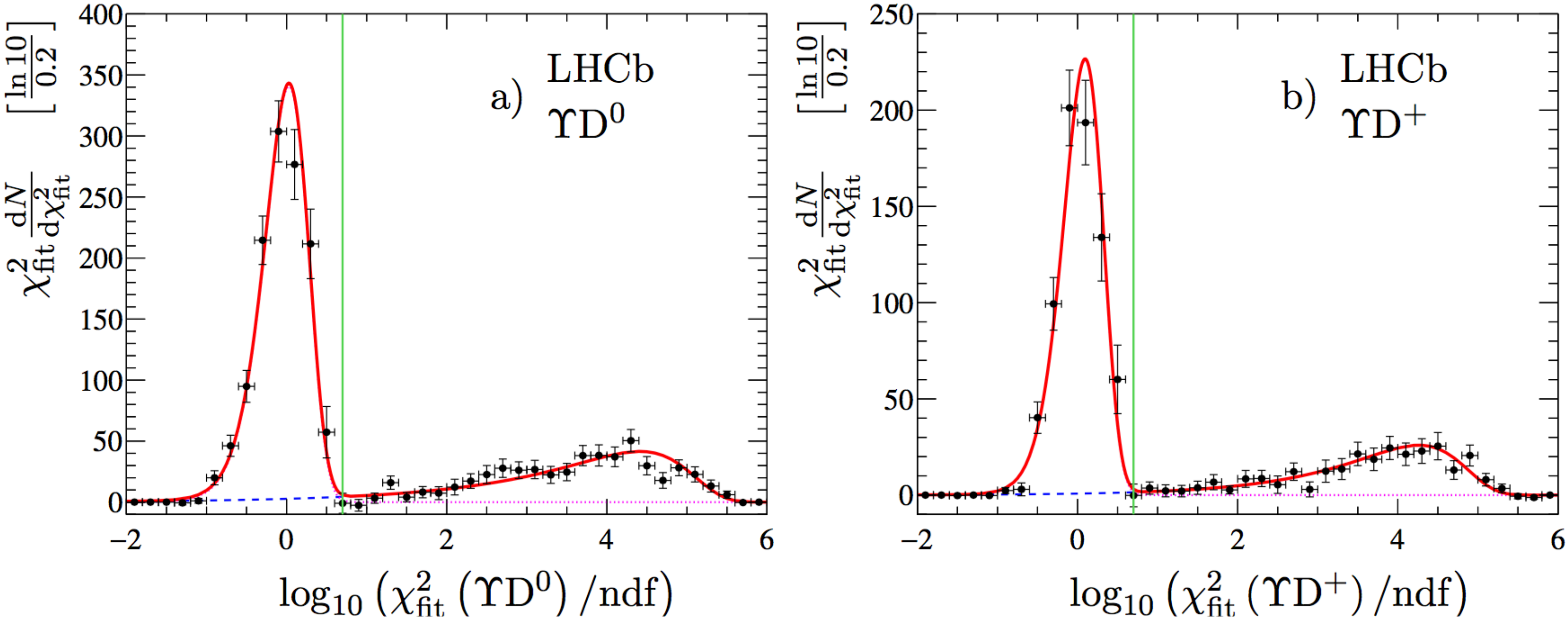
- Associated production is hot to study QCD
- DPS production mechanism: factorization assumption $\sigma_{\mathrm{DPS}}^{1,2} = \frac{m}{2} \frac{\sigma_1^{\mathrm{inc}} \sigma_2^{\mathrm{inc}}}{\sigma_{\mathrm{eff}}}$
- Various results for associated production, σ_{eff} close but not universal
  - Results from jets and LHCb different from quarkonia at GPD
  - Factorization breaks down?
- LHCb measurement of $\Upsilon + D$ suggests large contribution of DPS, but still less than expected (or much larger σ_{eff})
- LHCb double J/ψ measurement also requires strong contribution of DPS, a moderate σ_{eff} obtained by SPS+DPS fit
- Looking forward to new measurements

Thank you

Backups

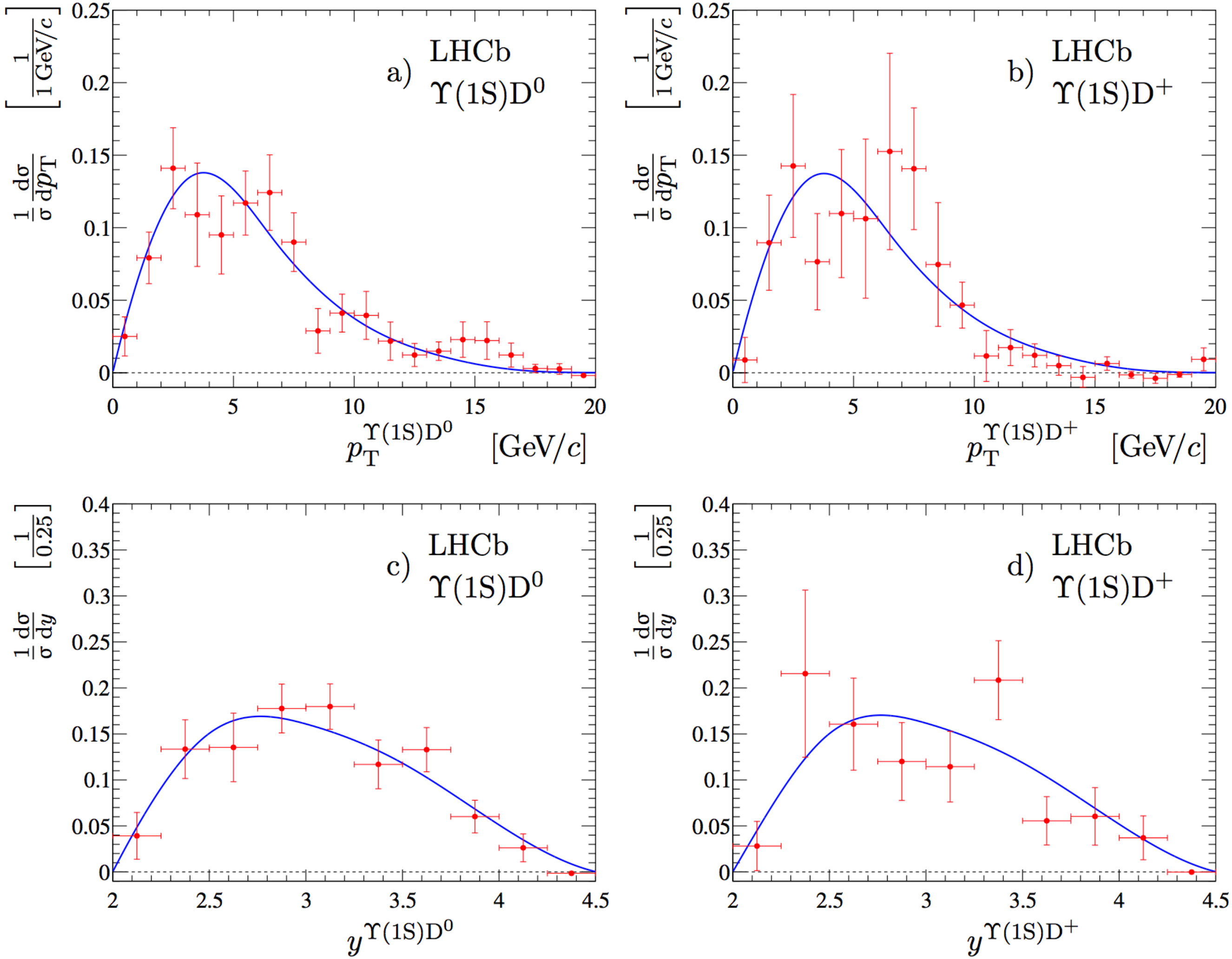
$\Upsilon + D$

- Multiple PV background reduction



$\Upsilon + D$

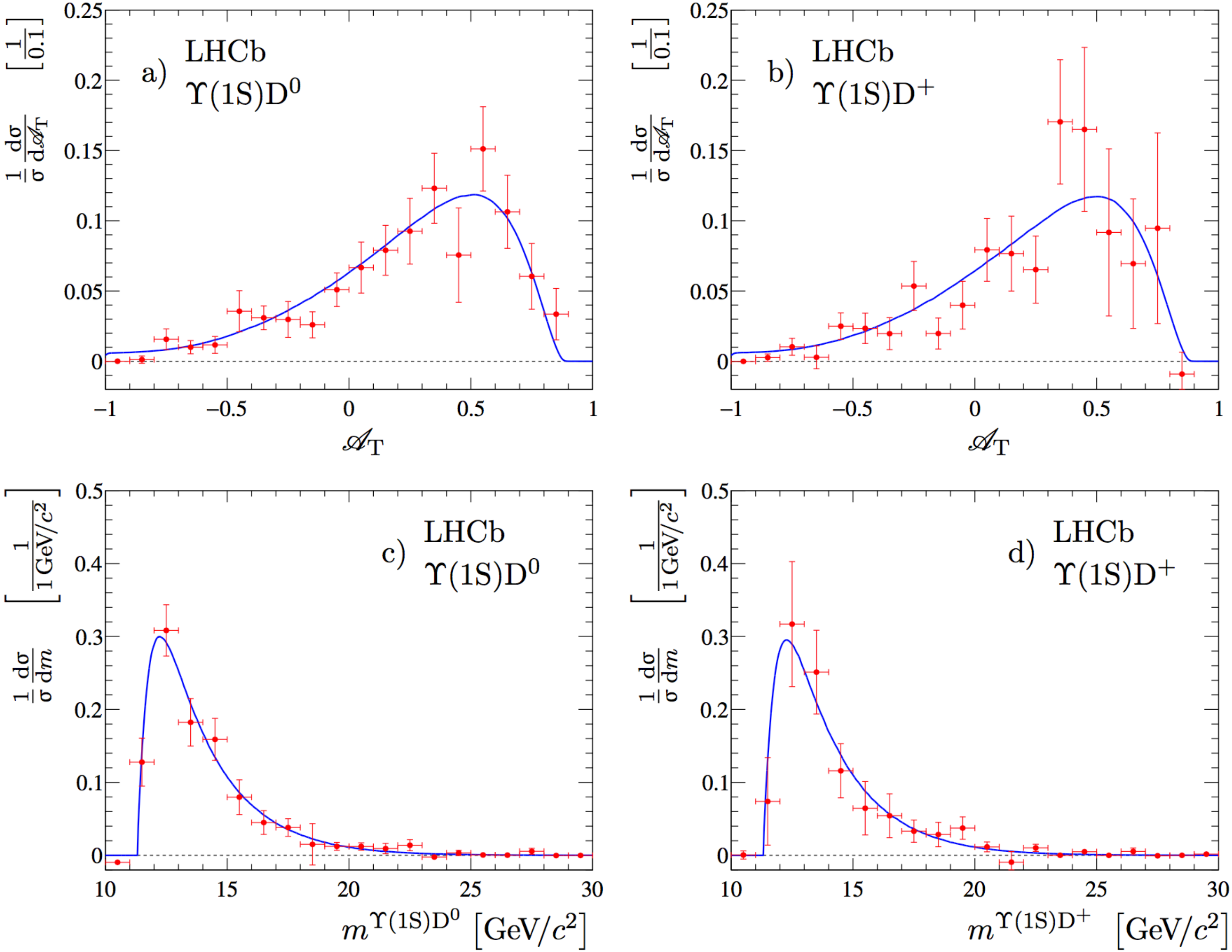
- Kinematic distributions of pairs



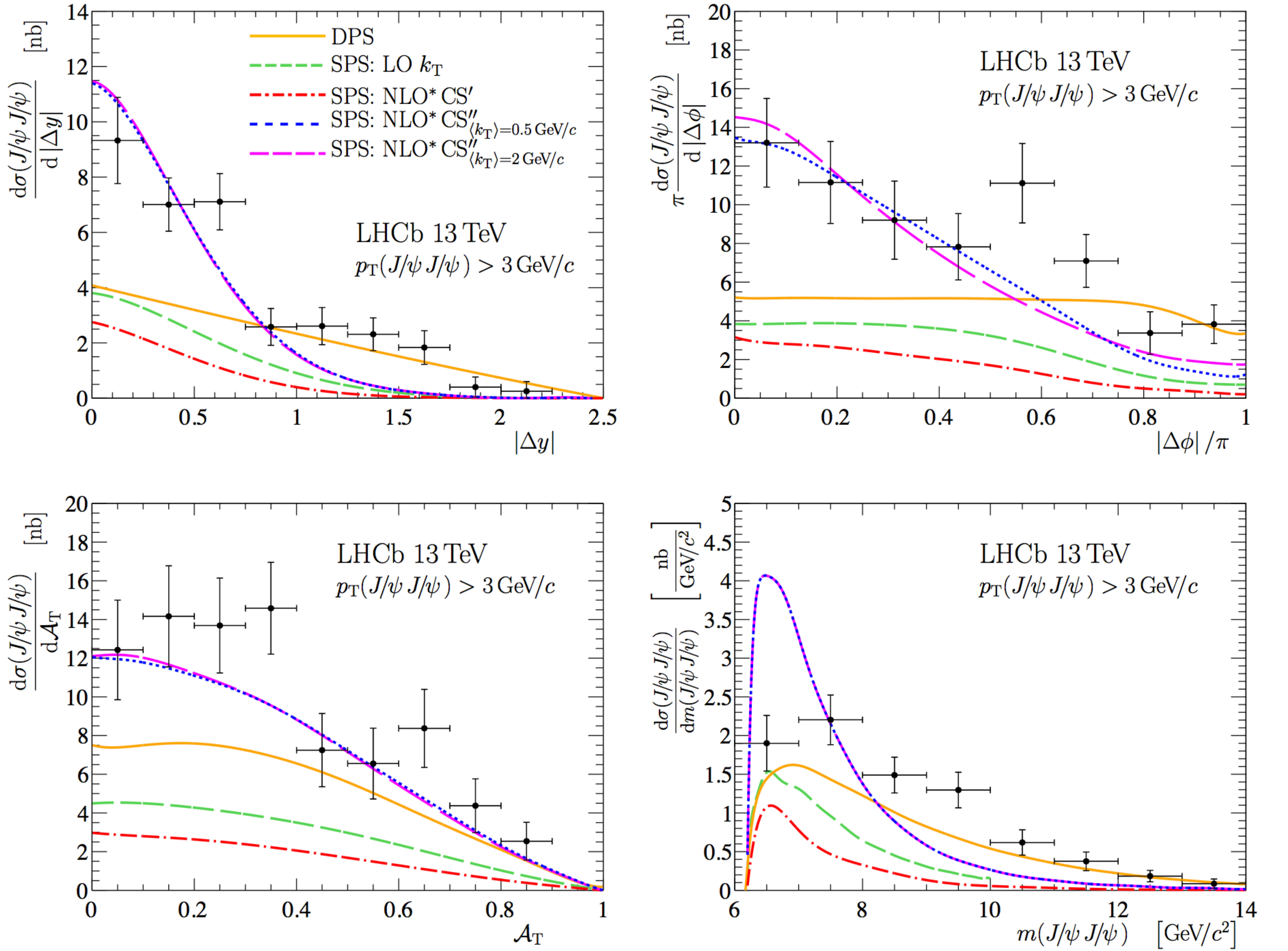
$\Upsilon + D$

- Kinematic distributions of pairs

$$\mathcal{A}_T \equiv \left| \frac{p_T(J/\psi_1) - p_T(J/\psi_2)}{p_T(J/\psi_1) + p_T(J/\psi_2)} \right|$$



Double J/ψ



DPS
SPS: LO k_T
SPS: NLO* CS′
SPS: NLO* CS″ $\langle k_T \rangle = 0.5$ GeV/c
SPS: NLO* CS″ $\langle k_T \rangle = 2$ GeV/c
LHCb 13 TeV
$p_T(J/\psi\, J/\psi) > 3$ GeV/c
$\frac{d\sigma(J/\psi\, J/\psi)}{d|\Delta y|}$ [nb]
$|\Delta y|$
$\pi \frac{d\sigma(J/\psi\, J/\psi)}{d|\Delta\phi|}$ [nb]
$|\Delta\phi|/\pi$
$\frac{d\sigma(J/\psi\, J/\psi)}{d\mathcal{A}_T}$ [nb]
$\mathcal{A}_T$
$\frac{d\sigma(J/\psi\, J/\psi)}{dm(J/\psi\, J/\psi)}$ $\left[\frac{nb}{GeV/c^2}\right]$
$m(J/\psi\, J/\psi)$ [GeV/c^2]