Double parton scattering, experimental point of view

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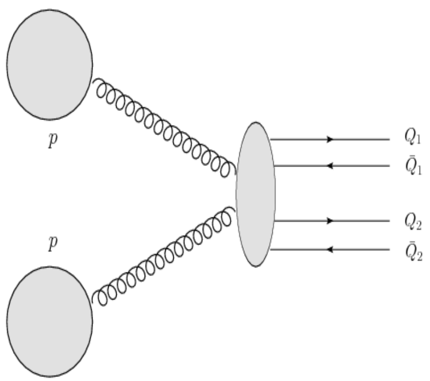
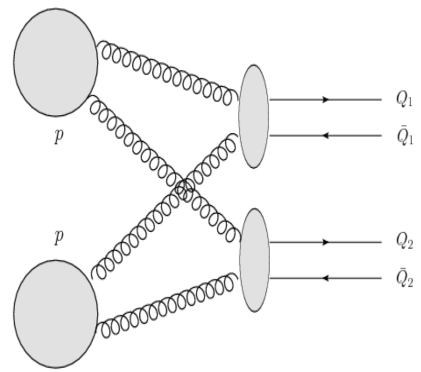
Introduction

- SPS vs DPS? How to disentangle them at high energy colliders?
- Associated heavy quark(onia) production could give us a hint, esp. for gg initial states; while studies involving vector bosons & jets more sensitive to gq or qq initial states (not covered here)



Single-parton scattering (SPS)



Double-parton scattering (DPS)

- Observables from expeirments:
  - Cross-section $\sigma_{(q\bar{q})1(q'\bar{q}')2}$
  - Effective cross-section $\sigma_{\text{eff}} = \sigma_{(q\bar{q})1}\sigma_{(q'\bar{q}')2}/\sigma_{(q\bar{q})1(q'\bar{q}')2}$
  - Angles between two mesons $\Delta\phi$, similarly Δy ...

Content

- Recent experimental results:
  - Double J/ψ
  - $J/\psi + \Upsilon$
  - Υ + open charm
  - Double Υ

LHCb, PLB707 (2012) 52

D0, PRD 90, 111101(R) (2014)

DOUBLE J/ψ

Double J/ψ at LHCb

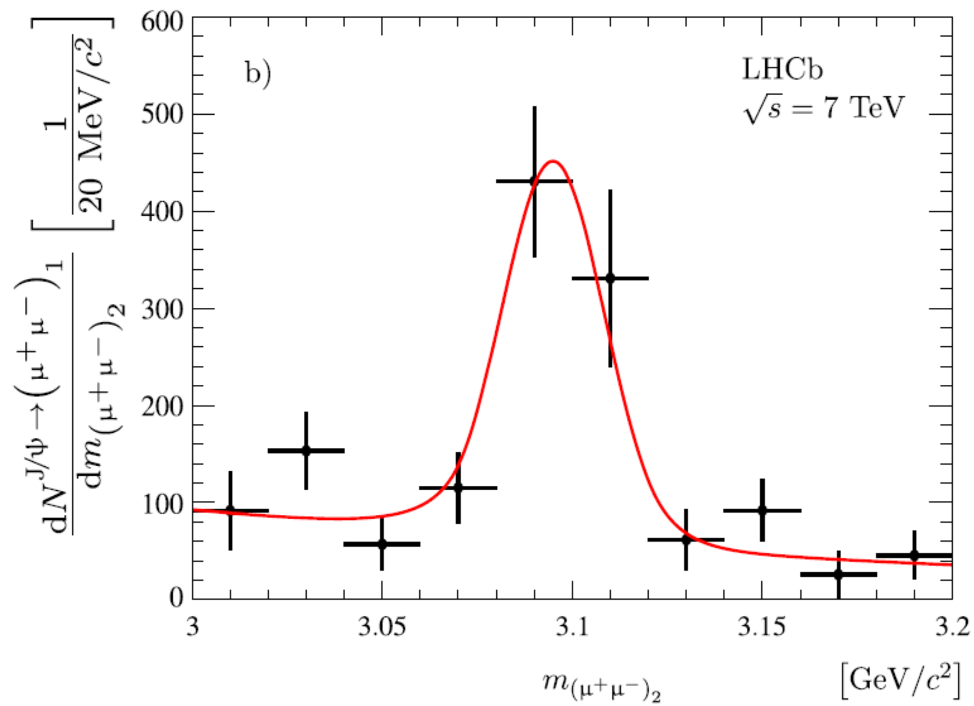
- First evidence of double J/ψ was found by NA3 in π-Pt interactions mainly arising from $q\bar{q}$ annihilation, while at LHC energy gg fusion dominates

- 37.5 pb^{-1} @ 7 TeV
- $2 < y^{J/\psi} < 4.5$, $p_{\mathrm{T}}^{J/\psi} < 10$ GeV

Signal

Efficiency corrected yield of $J/\psi \to (\mu^+\mu^-)_1$ in bins of $(\mu^+\mu^-)_2$ invariant mass

$N_{J/\psi J/\psi} = 141 \pm 19$



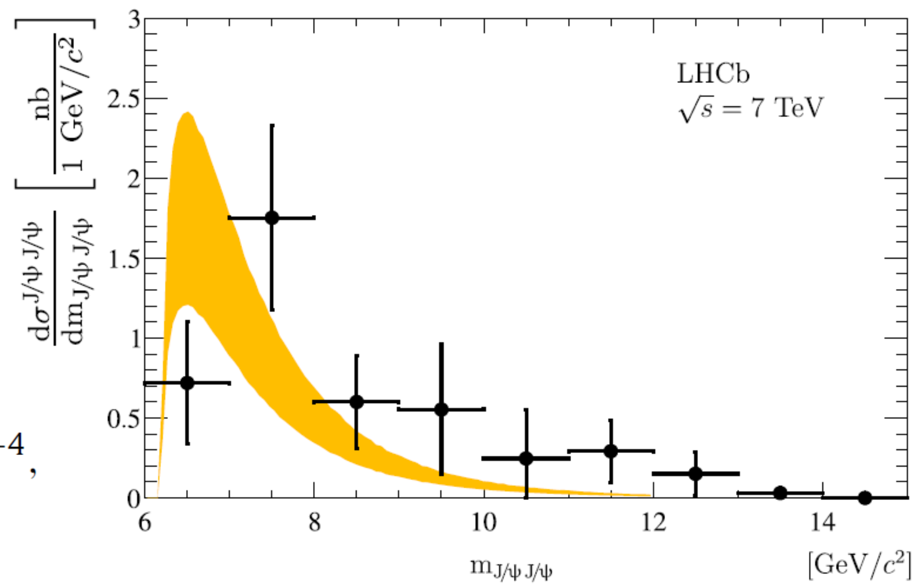
Negligible contributions from:

- Pile-up
- B-hadrons decay

Cross-section

$$\boxed{\sigma^{J/\psi J/\psi} = 5.1 \pm 1.0 \pm 1.1\ \text{nb},}$$

$$\sigma^{J/\psi J/\psi}/\sigma^{J/\psi} = (5.1 \pm 1.0 \pm 0.6^{+1.2}_{-1.0}) \times 10^{-4},$$



Updates with full Run I data and 13 TeV data are ongoing within LHCb

Double J/ψ at D0

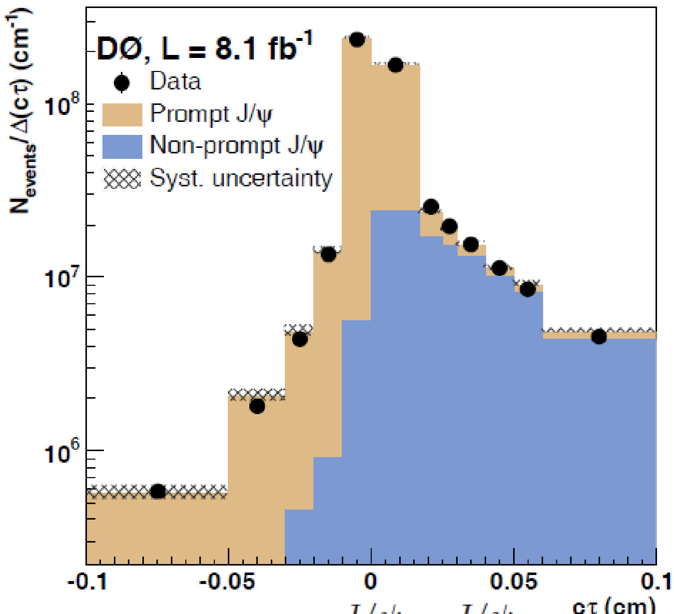
- The fraction of DPS contribution significantly depends on the spatial distribution of gluons in a proton
- For SPS, NRQCD predicts color singlet process contributes ~90% for $p_{\mathrm{T}}^{J/\psi} \geq 4$ GeV

Qiao, PRD 66, 057504 (2002);
Qiao and Sung, Chin.Phys.C 37, 033105 (2013)

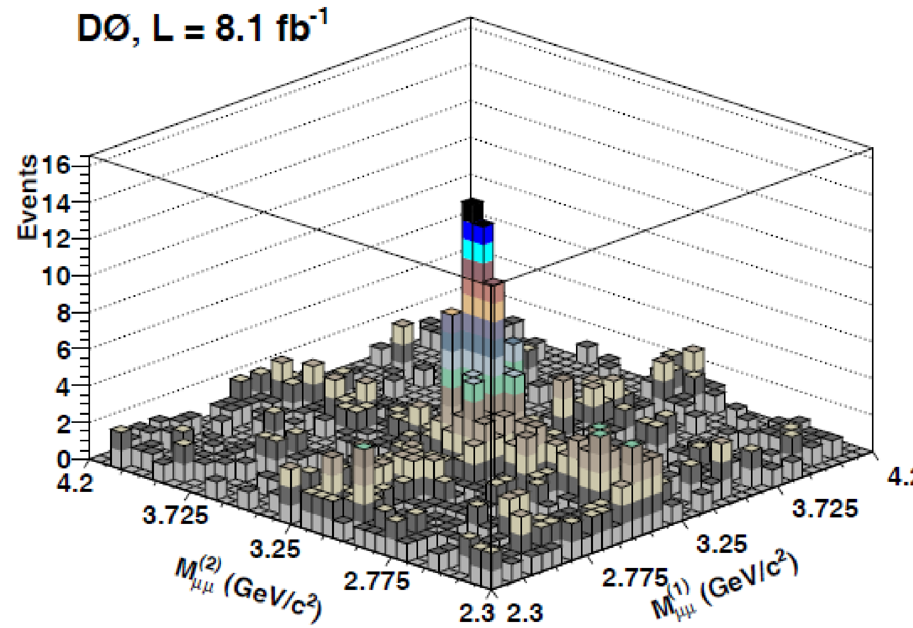
- 8.1 fb^{-1} @ $p\bar{p}$ $\sqrt{s} = 1.96$ TeV, both $J/\psi \to \mu^+\mu^-$
- Fiducial region:
  - $p_{\mathrm{T}}^{J/\psi} > 4$ GeV, $|\eta^{J/\psi}| < 2$
  - $p_{\mathrm{T}}^{\mu} > 2$ GeV if $|\eta^{\mu}| < 1.35$;

  or $|p^{\mu}| > 4$ GeV if $1.35 < |\eta^{\mu}| < 2$

Signal yields



$$c\tau = L_{xy} m_{\mathrm{pdg}}^{J/\psi} / p_T^{J/\psi}$$



Fraction of prompt J/ψ pair: 0.592 ± 0.101

$$\sigma(J/\psi) = 23.9 \pm 4.6(\mathrm{stat}) \pm 3.7(\mathrm{syst})\ \mathrm{nb.}$$

Single J/ψ cross-section agree with calculation using k_T factorization approach, including direct production and $\chi_{c1(2)} \rightarrow J/\psi + \gamma$

Cross-section for SPS & DPS

$$\sigma(J/\psi J/\psi) = 129 \pm 11(\text{stat}) \pm 37(\text{syst})\ \text{fb}.$$

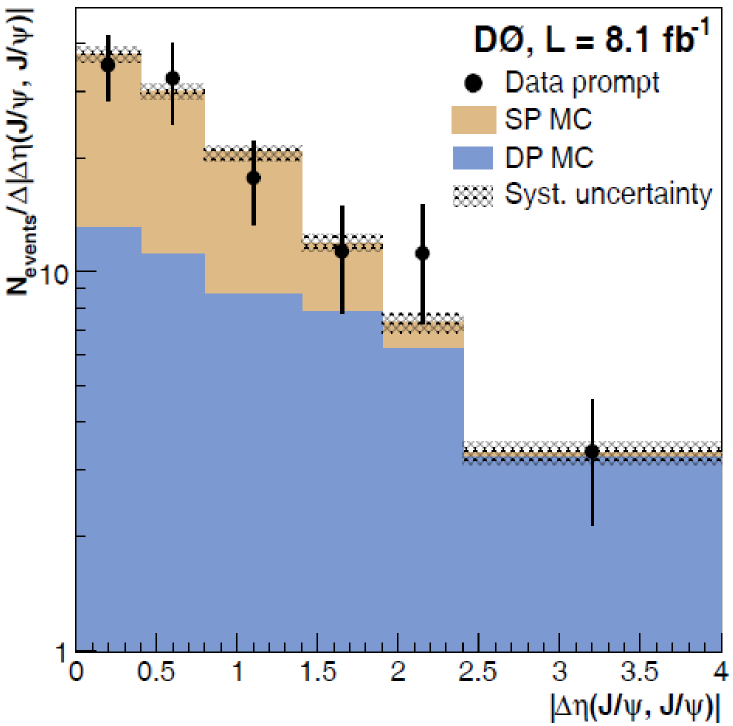
$$\sigma_{\text{DP}}(J/\psi J/\psi) = 59 \pm 6(\text{stat}) \pm 22(\text{syst})\ \text{fb},$$

$$\sigma_{\text{SP}}(J/\psi J/\psi) = 70 \pm 6(\text{stat}) \pm 22(\text{syst})\ \text{fb}.$$

Consistent with predictions from NRQCD and k_T factorization

Baranov et al.,PRD 87, 034035 (2013)

Lansberg and Shao, PRL 111, 122001 (2013)



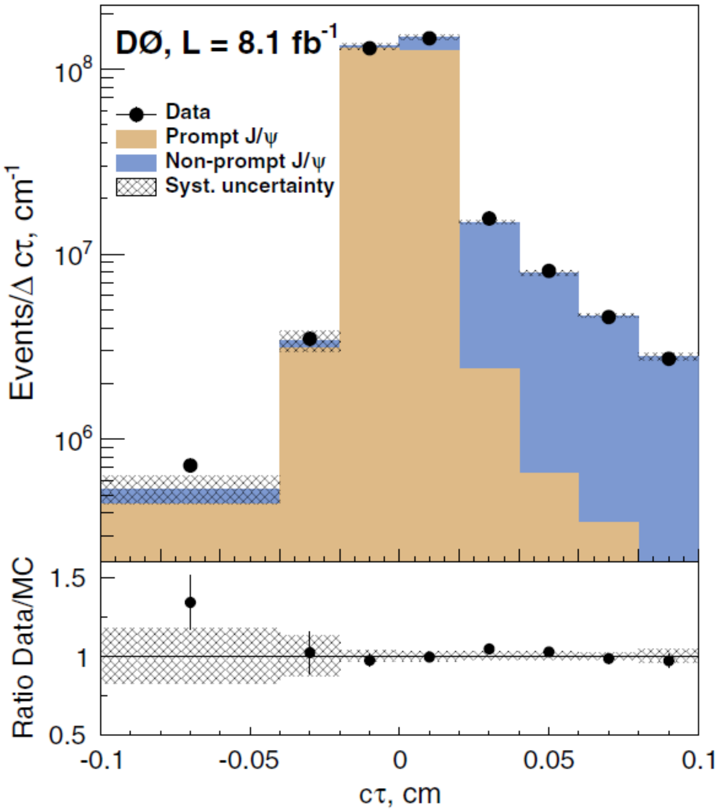
$$\sigma_{\text{eff}} = 4.8 \pm 0.5(\text{stat}) \pm 2.5(\text{syst})\ \text{mb}.$$

D0, PRL 116, 082002 (2016)

$J/\psi + \Upsilon$

Search for $J/\psi + \Upsilon$ @ D0

- Not allowed at LO in SPS
- DPS contribution dominates at Tevatron *Lansberg and Shao, Nucl. Phys. B900, 273 (2015)*
- $p\bar{p}$ @ $\sqrt{s} = 1.96$ TeV, 8.1 fb^{-1}
- All muons:
  - $p_T(\mu) > 2$ GeV, $|\eta(\mu)| < 2.0$
- Prompt J/ψ is separated from non-prompt ones using
  - $c\tau = L_{xy} m_{J/\psi} / p_T^{J/\psi}$



First evidence

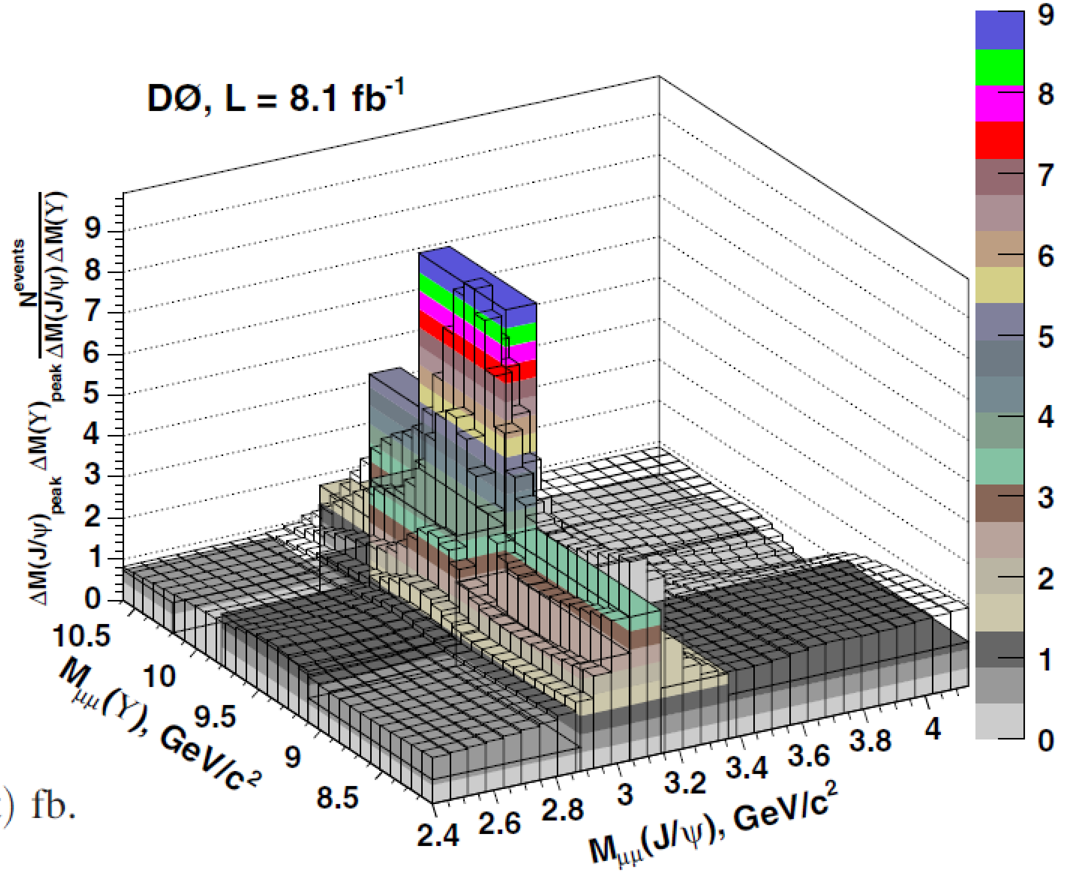
- Prompt $J/\psi + \Upsilon(1S)$
  - $14.5 \pm 4.6 \pm 3.4$

3.2 σ significance

$\sigma(J/\psi) = 28 \pm 7(\text{syst})$ nb.

$\sigma(\Upsilon) = 2.1 \pm 0.3(\text{syst})$ nb.

$\sigma_{\text{DP}}(J/\psi + \Upsilon) = 27 \pm 9(\text{stat}) \pm 7(\text{syst})$ fb.

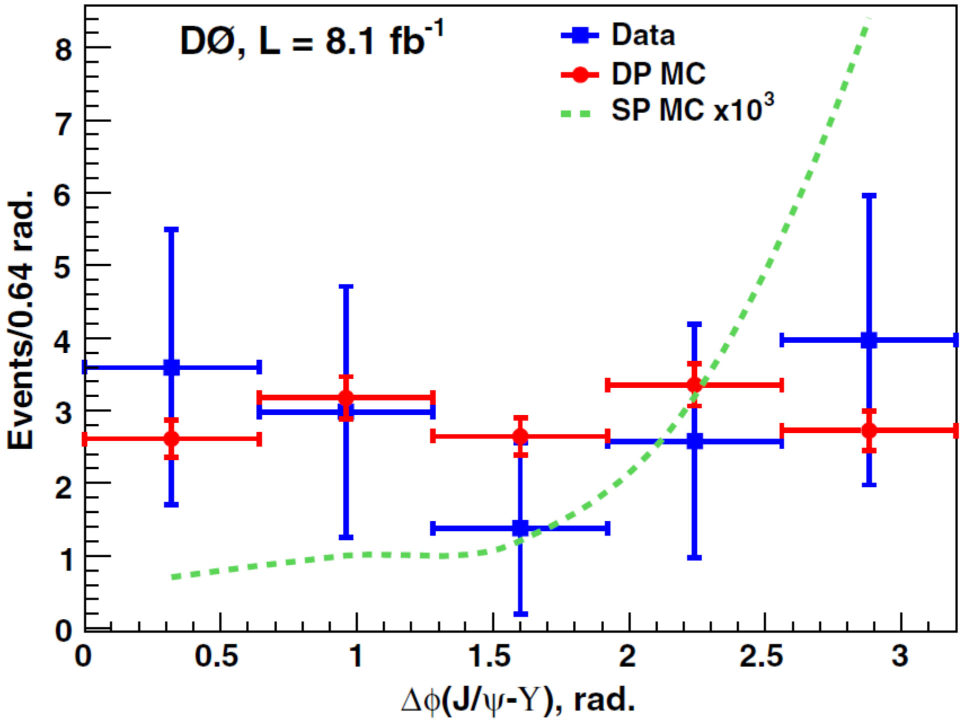


$$\boxed{\sigma_{\text{eff}} = 2.2 \pm 0.7(\text{stat}) \pm 0.9(\text{syst})\ \text{mb.}}$$

Lower than $q\bar{q}$ or qg dominated processes

$\Delta\phi(J/\psi, \Upsilon)$

- DPS simulation shows better consistency



LHCb, JHEP 07 (2016) 052

Υ + OPEN CHARM

ΥC at LHCb

- Production of $b\bar{b}c\bar{c}$ at LHCb mainly studied using B_c^+
  - NRQCD calculation (SPS) in good agreement
- Predictions for $R = \frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}}$ differ for SPS and DPS
  - R_{SPS} small (0.2 - 2.0)%
  - Naive DPS expects $R_{\text{DPS}} \sim 10\%$

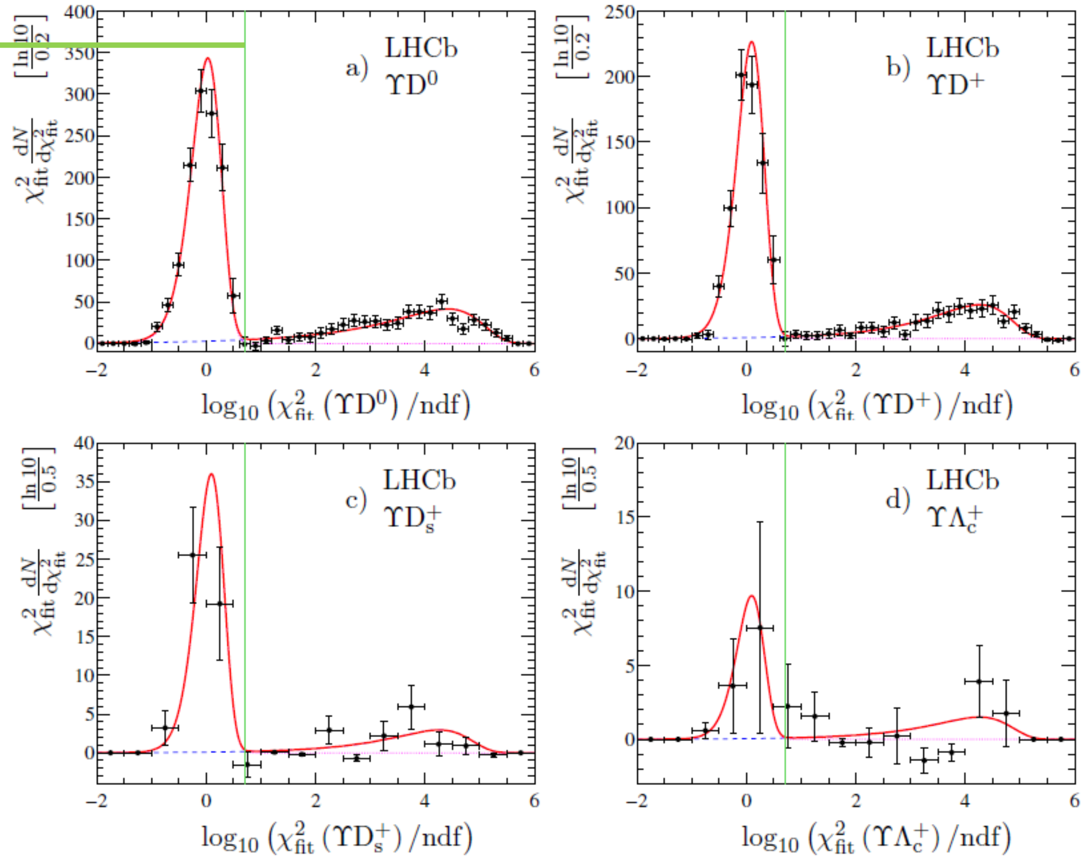
Belezhonov and Likhoded, Int.J.Mod.Phys.A30 (2015)1550125

- LHCb search using 1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV
- Final states:
  - $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S) \to \mu^+\mu^-$
  - $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$, $\Lambda_c^+ \to pK^-\pi^+$
- Main fiducial cuts:
  - $2.0 < y_{\Upsilon,C} < 4.5$, $p_{\text{T}}^{\Upsilon} < 15$ GeV, $1 < p_{\text{T}}^{C} < 20$ GeV

Selection

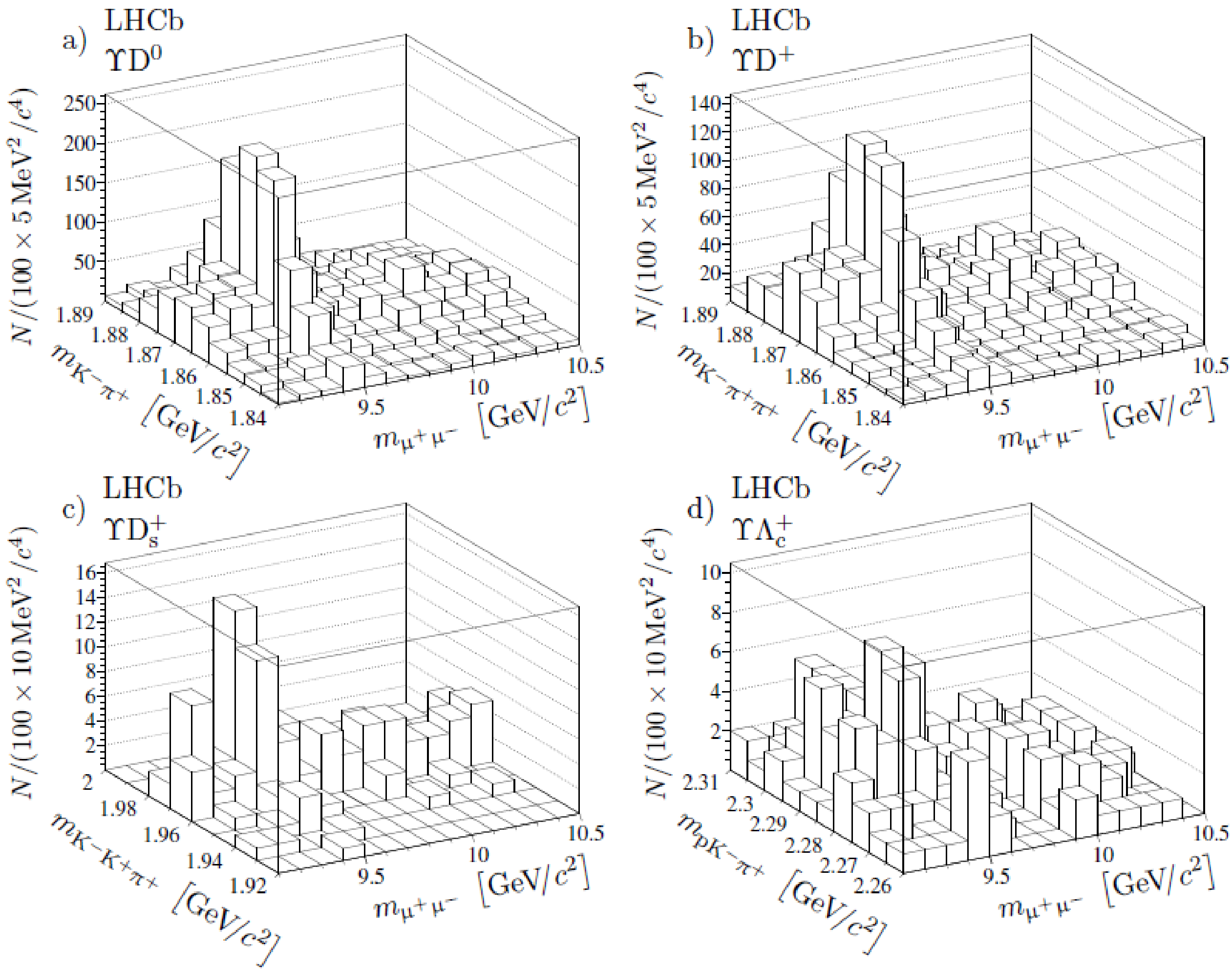
- $c\tau_C > 100\ \mu\mathrm{m}/c$, good track & vertex quality, Υ from PV
- Pile-up negligible by requiring both mesons from the same PV

$\chi^2_{\mathrm{global}}/\mathrm{ndf} < 5$



Signals

$$f = \Sigma_{i=1}^{3} N_i^{\Upsilon C}\, S_\Upsilon \times S_C + \Sigma_1^3\, N^{\Upsilon B} S_\Upsilon \times S_{B_C} + N^{BC} S_{B_\Upsilon} \times S_C + N^{BB} S_{B_C} \times S_{B_\Upsilon}$$

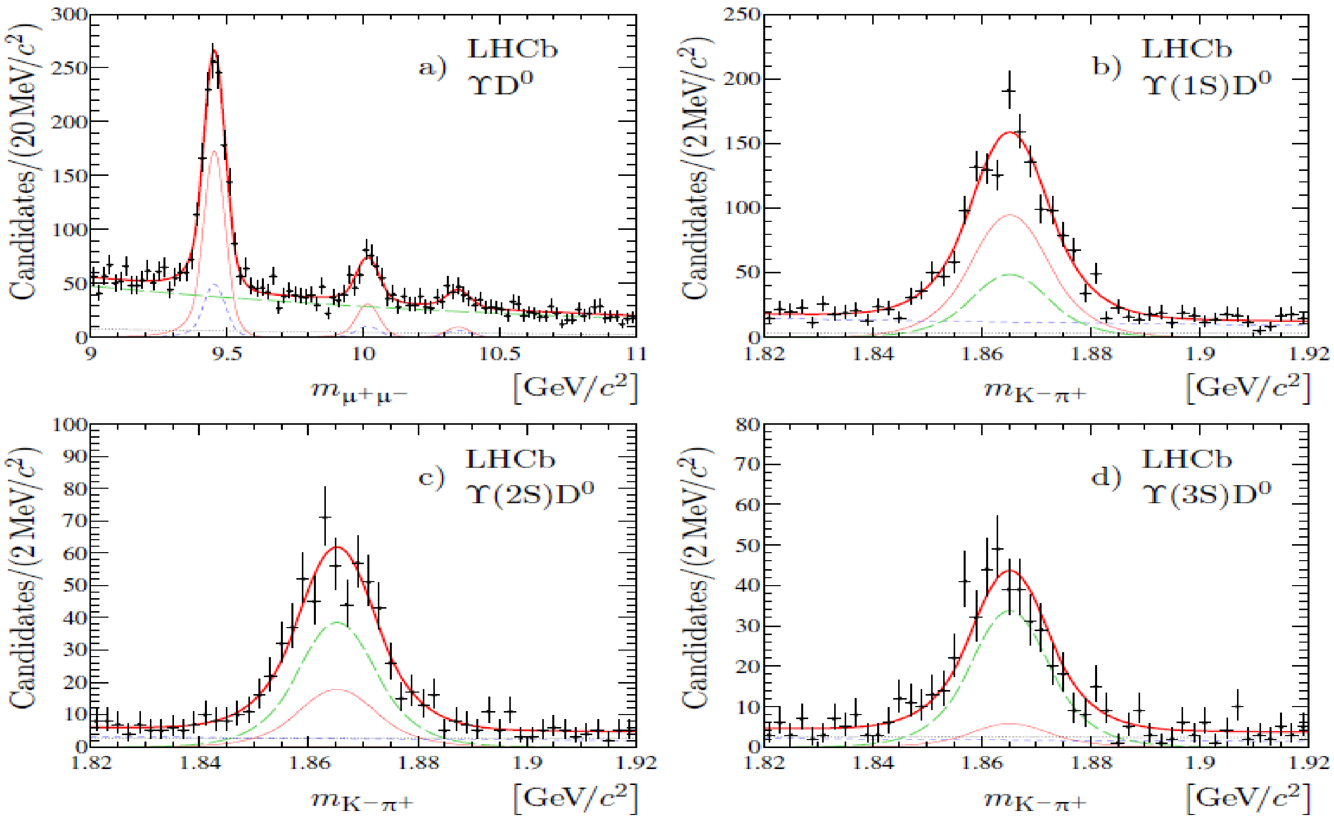


Fitted yields

> 5σ, First observation

No significant signal for $\Upsilon + \Lambda_c^+$

	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
D^0	980 ± 50	84 ± 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



ΥD^0 projection from the 2D fit:

$S_\Upsilon \times S_{D^0}$

$S_\Upsilon \times S_{B_{D^0}}$

$S_{B_\Upsilon} \times S_{D^0}$

Cross-section

	$\sqrt{s} = 7$ TeV	$\sqrt{s} = 8$ TeV
$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^0}$	155 $\pm$ 21 (stat) $\pm$ 7 (syst) pb	250 $\pm$ 28 (stat) $\pm$ 11 (syst) pb
$\mathcal{B}_{\mu^+\mu^-} \times \sigma^{\Upsilon(1S)D^+}$	82 $\pm$ 19 (stat) $\pm$ 5 (syst) pb	80 $\pm$ 16 (stat) $\pm$ 5 (syst) pb
$R^{D^0/D^+} = \frac{\sigma^{\Upsilon(1S)D^0}}{\sigma^{\Upsilon(1S)D^+}}$	1.9 $\pm$ 0.5 (stat) $\pm$ 0.1 (syst)	3.1 $\pm$ 0.7 (stat) $\pm$ 0.1 (syst)
$R^{\Upsilon(1S)c\bar{c}} = \frac{\sigma^{\Upsilon(1S)c\bar{c}}}{\sigma^{\Upsilon(1S)}}$	$(5.5 \pm 1.7)\%$	$(6.2 \pm 0.7)\%$
$R^{\Upsilon(1S)\Upsilon(2S)}_{D^0} = \mathcal{B}_{2S/1S} \times \frac{\sigma^{\Upsilon(2S)D^0}}{\sigma^{\Upsilon(1S)D^0}}$	$(13 \pm 5)\%$	$(20 \pm 4)\%$
$R^{\Upsilon(1S)\Upsilon(2S)}_{D^+} = \mathcal{B}_{2S/1S} \times \frac{\sigma^{\Upsilon(2S)D^+}}{\sigma^{\Upsilon(1S)D^+}}$	$(22 \pm 7)\%$	$(22 \pm 6)\%$

Agrees with DPS estimation:

$$R^{D^0/D^+} = \frac{\sigma^{D^0}}{\sigma^{D^+}} = 2.41 \pm 0.18$$

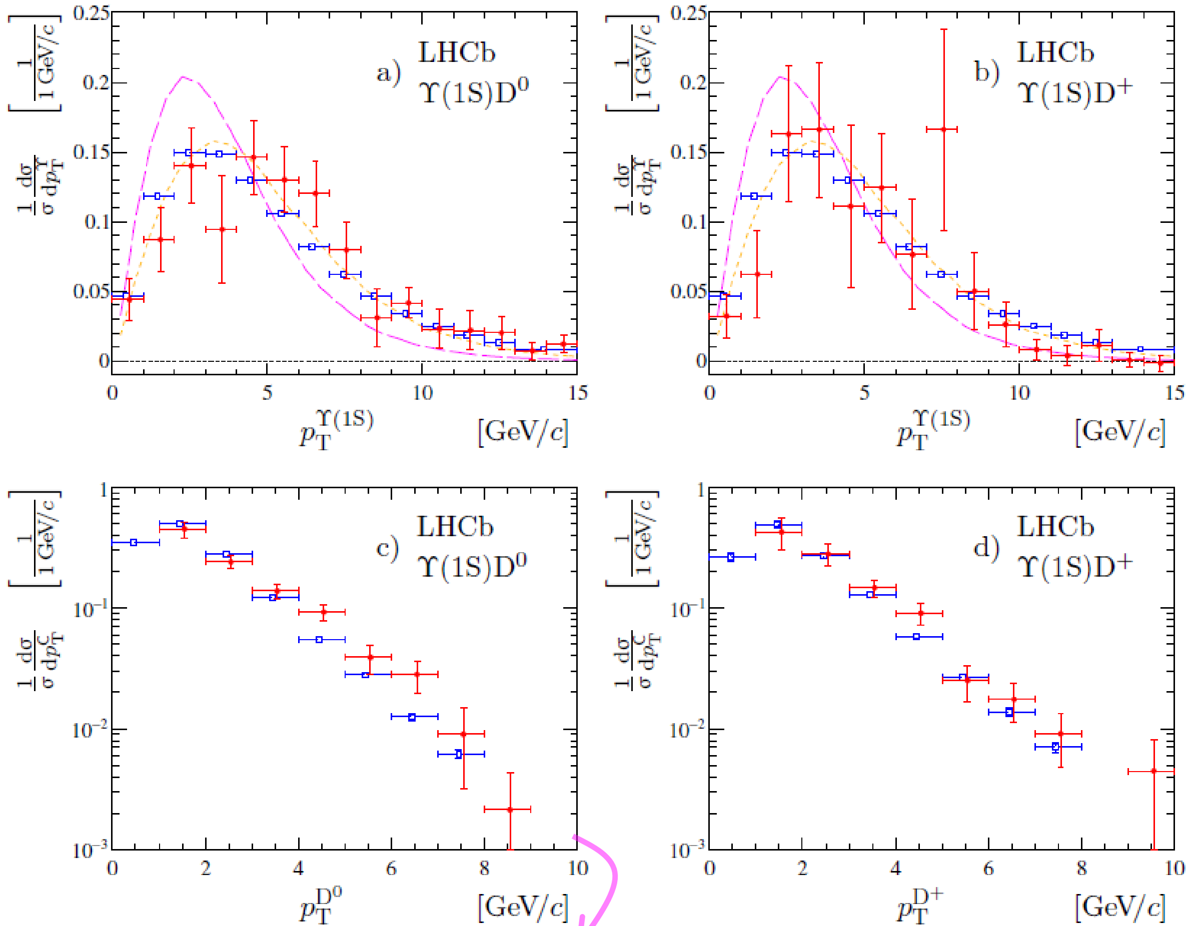
$$R_C^{\Upsilon(2S)/\Upsilon(1S)} = \mathcal{B}_{2S/1S} \times \frac{\sigma^{\Upsilon(2S)}}{\sigma^{\Upsilon(1S)}} = 0.249 \pm 0.033$$

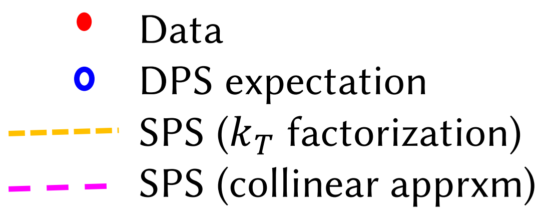
Larger than SPS prediction:
(0.2~2.0)%
Belezhnoy and Likhoded, Int.J.Mod.Phys.A30(2015) 1550125

- Averaging $\Upsilon(1S)D^{0,\pm}$, 7 & 8 TeV:
  - $\boxed{\boldsymbol{\sigma_{\text{eff}} = \frac{\sigma^{\Upsilon} \times \sigma^{C}}{\sigma^{\Upsilon C}} = 18.0 \pm 1.3\ (\text{stat}) \pm 1.2\ (\text{syst}) = 18.0 \pm 1.8\ \text{mb}}}$
  - Large $\sigma^{\Upsilon C} \Rightarrow$ potential for b-flavour tagging

Kinematic properties: p_T

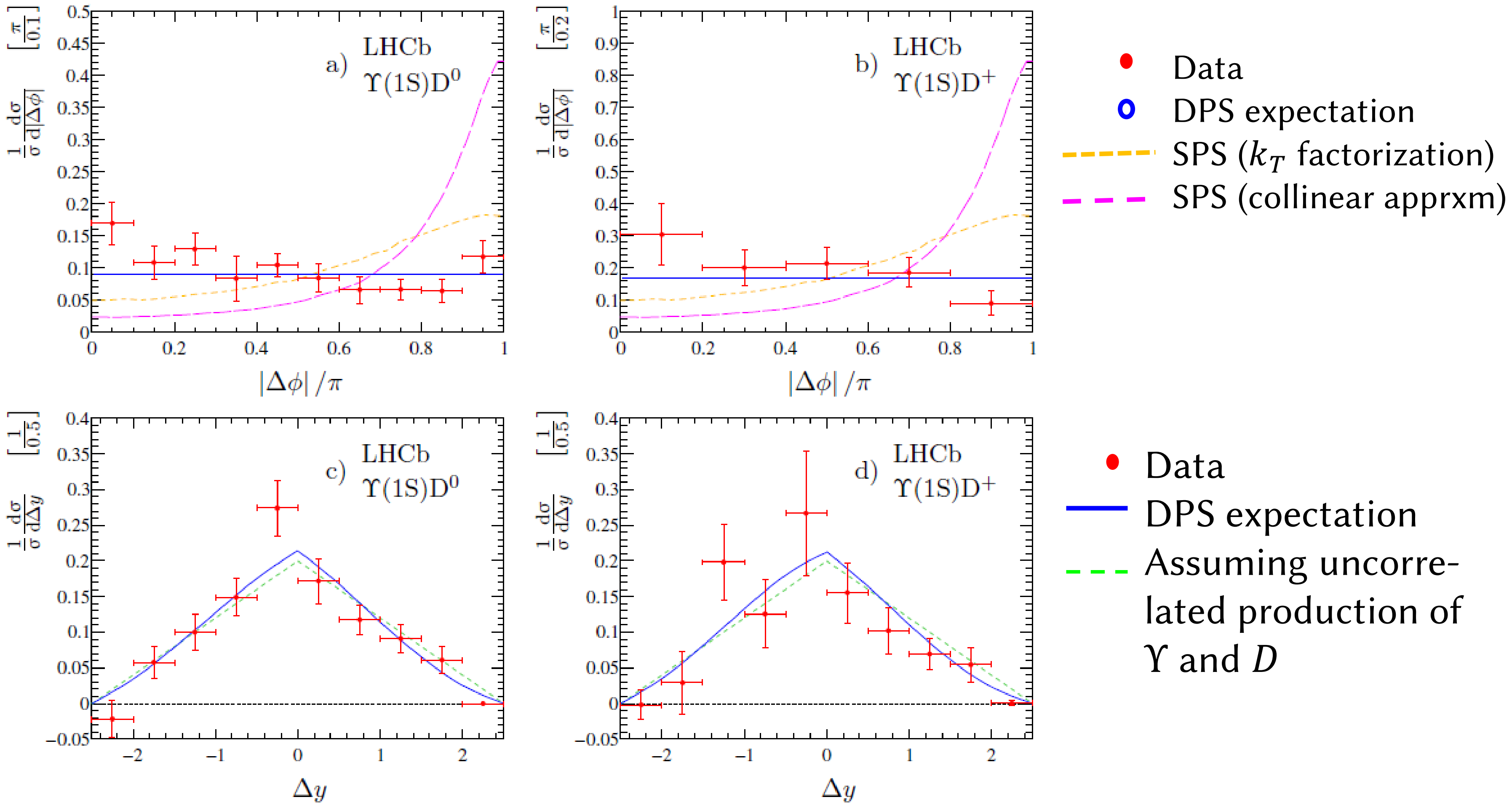
*background substracted & efficiency corrected



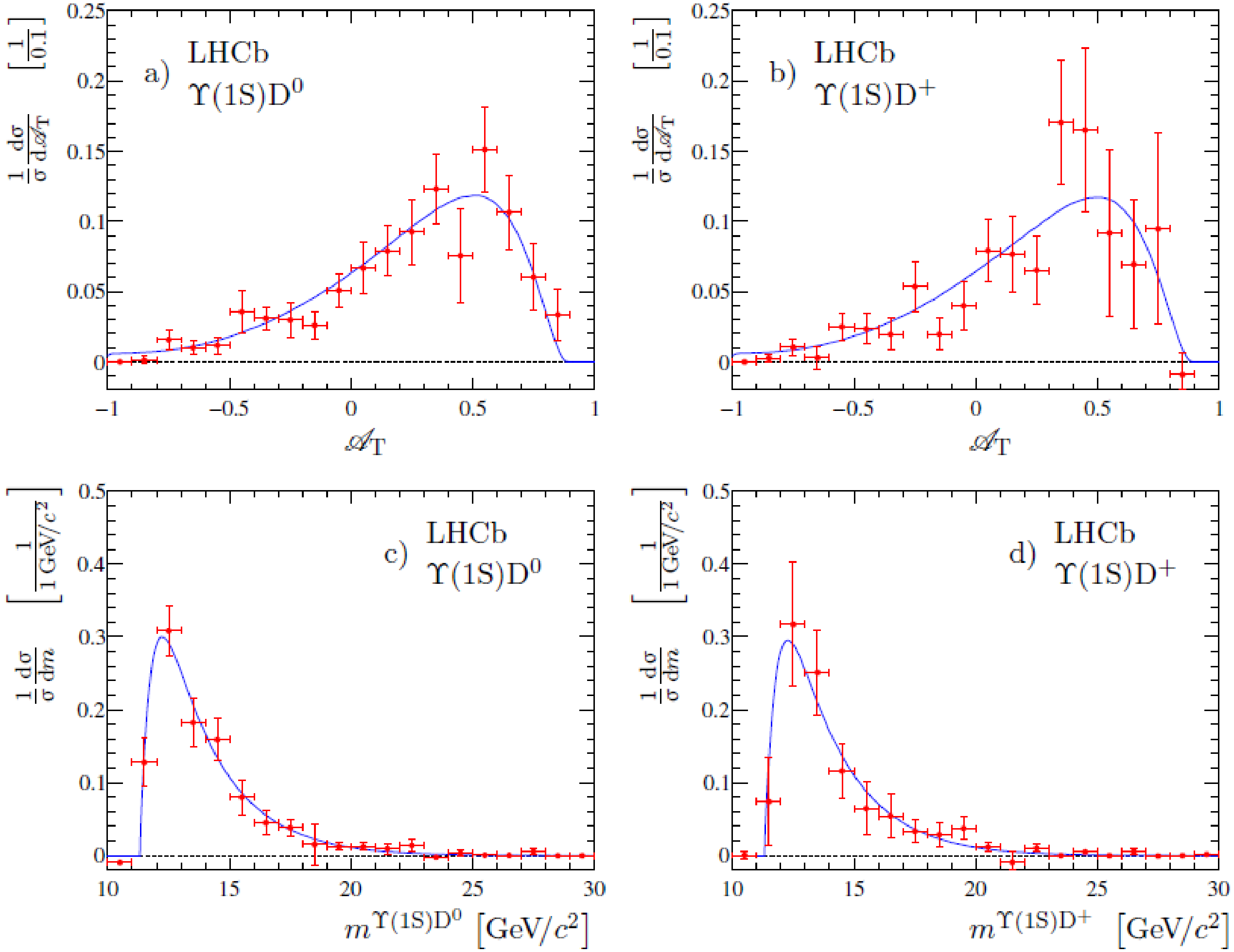


A large contribution from intrinsic charm in the nucleon pdf would expect C with high $p_T > 10$ GeV

Azimuthal angle and rapidity



p_T asymmetry and invariant mass



$$\mathcal{A}_T = \frac{p_T^{\Upsilon(1S)} - p_T^C}{p_T^{\Upsilon(1S)} + p_T^C}$$

- Data
- DPS expectation, using data from Υ and D production

CMS PAS BPH-14-008

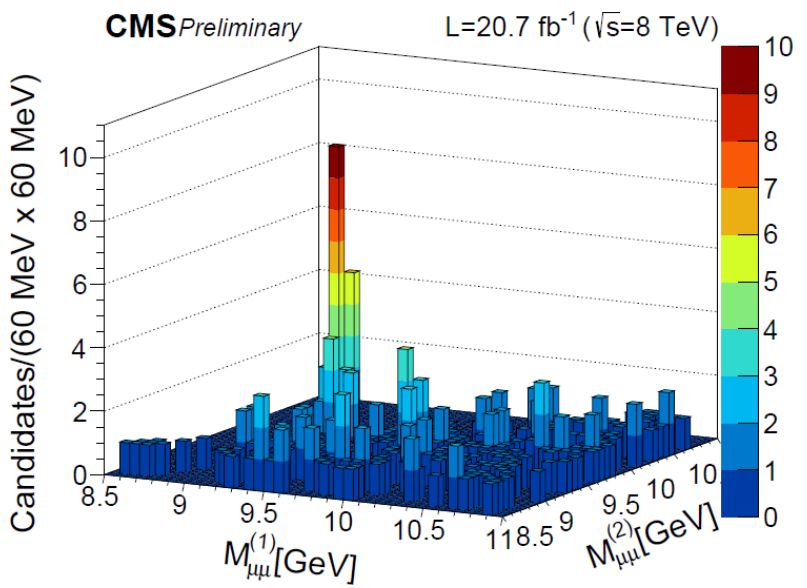
DOUBLE Υ(1S)

Double Υ @ CMS

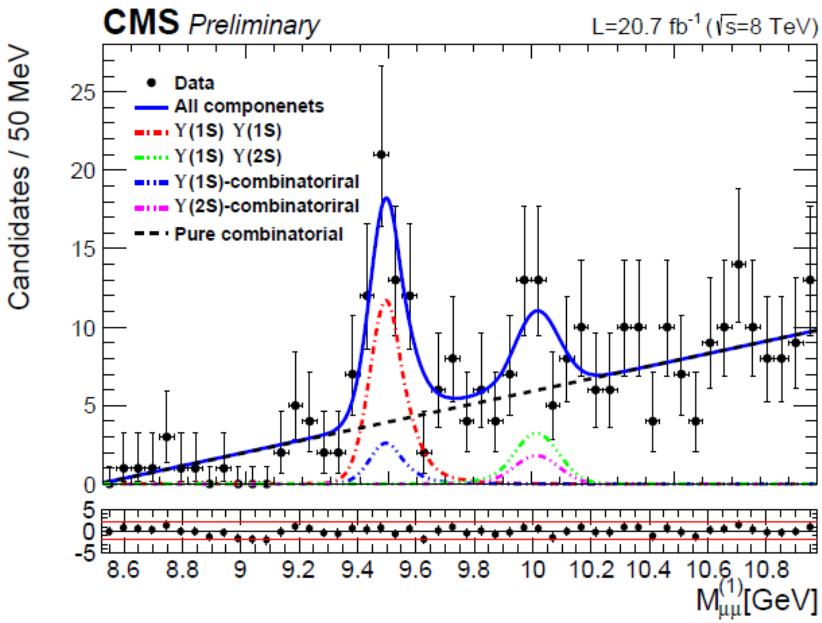
- Both SPS & DPS contributions expected
  - DPS significant *Baranov, Snigirev and Zotov, PLB705 (2011) 116*
  - SPS: CS dominates for $p_T < 24$ GeV, CO dominates above *Ko, Yu and Lee, JHEP 1101 (2011) 070*

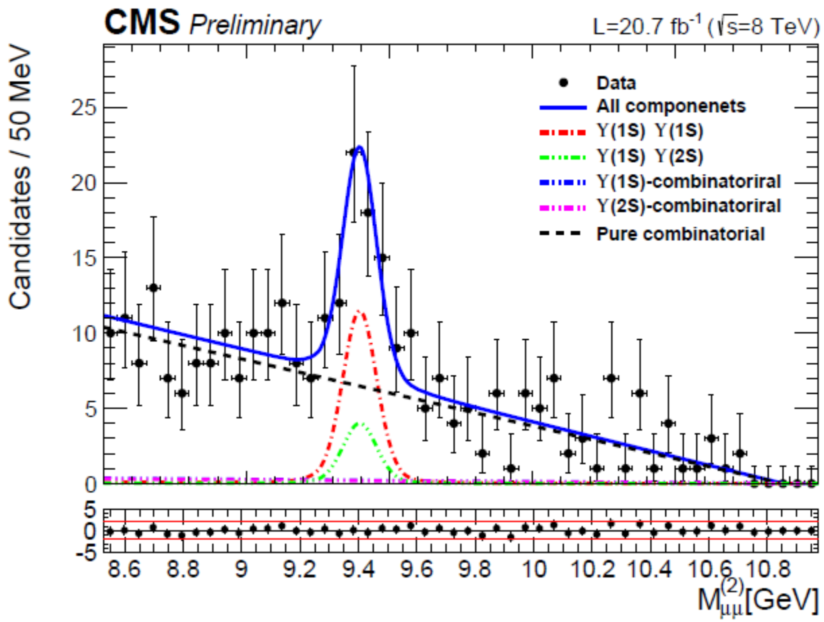
- 20 fb^{-1} @ pp $\sqrt{s} = 8$ TeV
- Both $\Upsilon \to \mu^+\mu^-$:
  - $|y(\Upsilon)| < 2.0$, $p_{\mathrm{T}}(\Upsilon) < 50$ GeV
  - $|\eta(\mu)| < 2.4$, $p_{\mathrm{T}}(\mu) > 3.5$ GeV

- $N_{\Upsilon(1S)\Upsilon(1S)} = 38 \pm 7$
- First observation



Projection of 2D fit





- Cross-section:
  - $\sigma_{2\times\Upsilon(1S)} = 68.8 \pm 12.7\ (\text{stat}) \pm 7.4\ (\text{syst}) \pm 2.8\ (\text{Br})$ pb
  - Assuming isotropic decay of $\Upsilon \to \mu^+\mu^-$

$\lambda_{\theta 1}$	+1	+1	+0.5	-0.5	+0.5	-1	+1	-0.5	-0.5	-1
$\lambda_{\theta 2}$	+1	+0.5	+0.5	+0.5	-0.5	+1	-1	-0.5	-1	-1
Change(%) w.r.t $\lambda_{\theta 1,\theta 2} = 0$	+35.6	+26.4	+18.2	-2.1	-2.6	-8.7	-9.5	-18.9	-29.3	-38.2

Table 2: Relative change of acceptance corrected yield for different polarization assumptions.

100% longitudinal polarization

100% transverse polarization

What do we expect

- σ_{eff} ?
  - CMS measured at 7 TeV, with $p_T(\Upsilon) < 50$ GeV, $|y(\Upsilon)| < 2.4$:
    - $\sigma_{\Upsilon(1S)} \cdot \mathcal{B}(\Upsilon \to \mu\mu) = (8.55 \pm 0.05\ {}_{-0.50}^{+0.56} \pm 0.34)$ nb
  - Assuming $\sigma \propto \sqrt{s}$, $\mathcal{B}(\Upsilon(1S) \to \mu\mu) = (2.48 \pm 0.05)\%$
  - $\sigma_{\Upsilon}(1S) \sim 390$ nb, $\sigma_{\text{eff}} \sim 2$ mb *← Disclaimer: don't trust these numbers!*
- $\Delta\phi$ or Δy ?
  - Both SPS and DPS simulation samples available in the preliminary analysis, would be interesting to see the comparison with data.

Summary

- Tevatron and LHC experiments have made quite a few double quarkonia production measurements, and have shown substantial (dominating in some cases) contributions from double parton scattering

- Several observables to be compared with theoretical calculations
  - Cross-section; σ_{eff} ; kinematic distributions of the two quarkonia states;...

- With LHC Run II ongoing and luminosity accumulating, more experimental results foreseen