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Quarkonium results from LHCb

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on behalf of the LHCb collaboration

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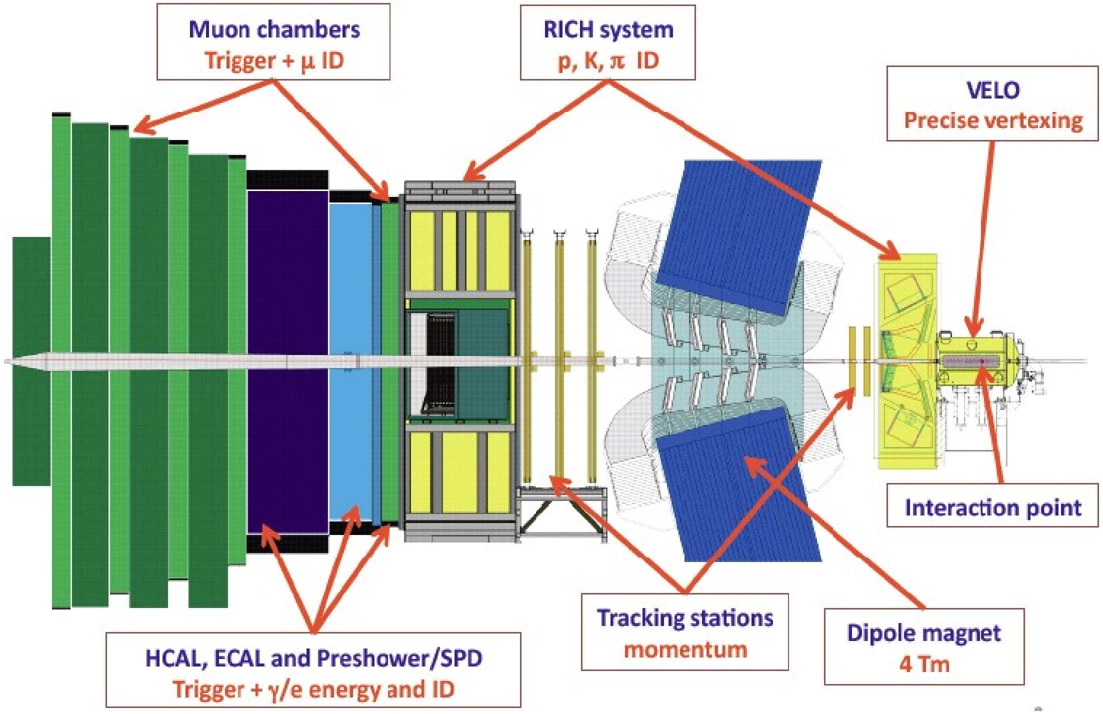
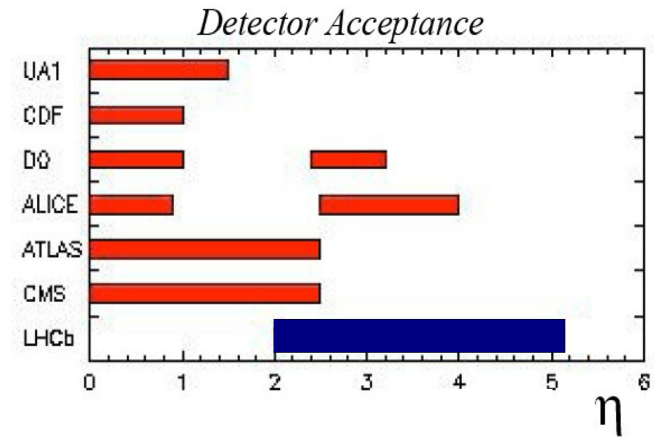
Outline

- LHCb detector description
- Motivations for studying quarkonium
- Selected quarkonium results:
    - $\psi(2S)$
    - χ_c
    - Y(nS)
    - J/ψ + open charm
    - X(3872), X(4140)
- Prospects and conclusions

The LHCb experiment

- An experiment at the LHC designed to study CP violating and rare decays of *b(c)*-hadrons





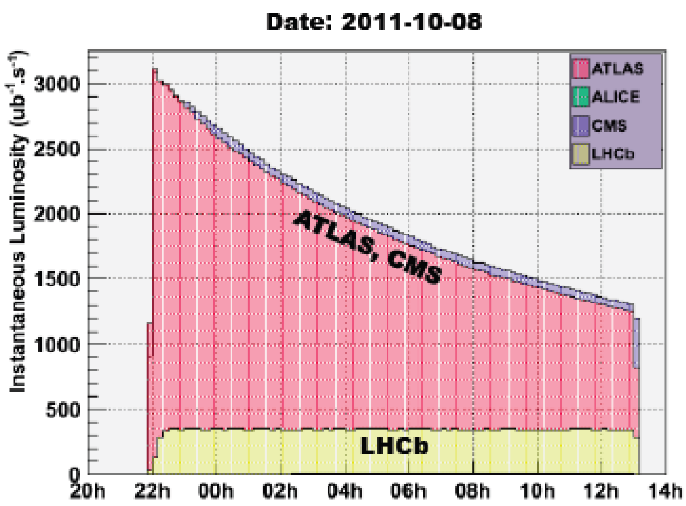
- angular acceptance $2<\eta<5$

- b and $\bar{b}$ are forward(backward) produced: $\sigma_{b\bar{b}} \sim 300$ μb at 7 TeV

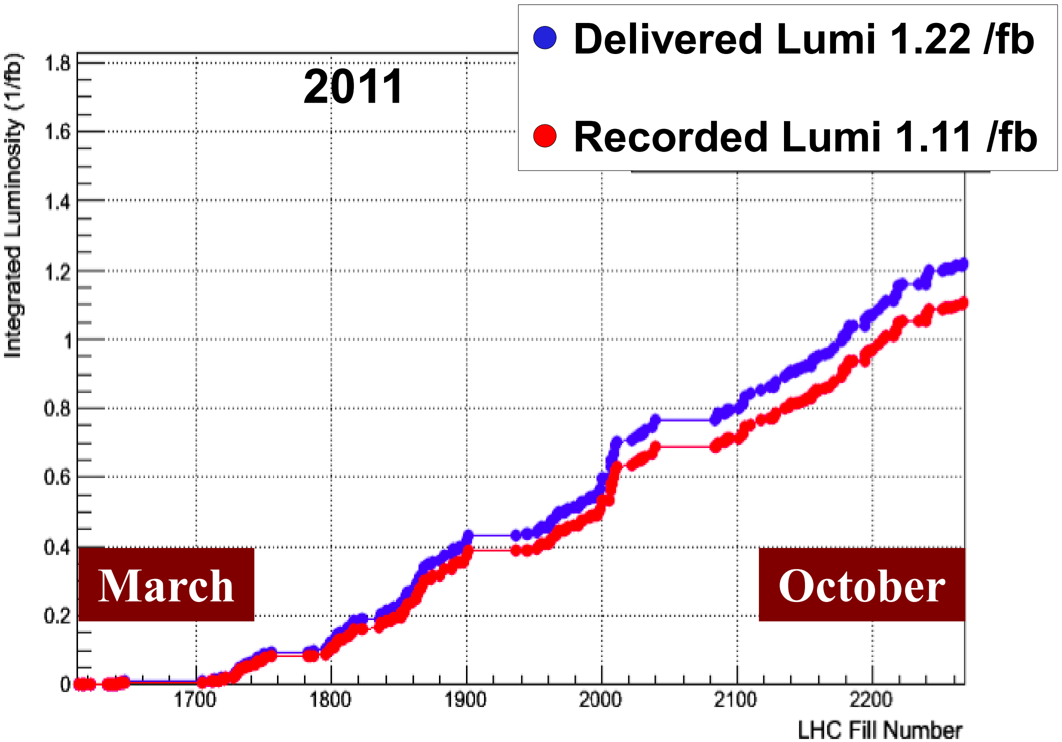
- 3 trigger levels reduce the frequency of accepted events to 3 kHz (Max)

Luminosity during 2011

- LHCb peak luminosity per fill: 3-4 10^{32} / cm^2 s (2011)



- Instantaneous luminosity levelling
  - Obtained through vertical beam displacements



- 91% data taking efficiency
- 99% of data taken are good for physics

Motivations for studying quarkonium

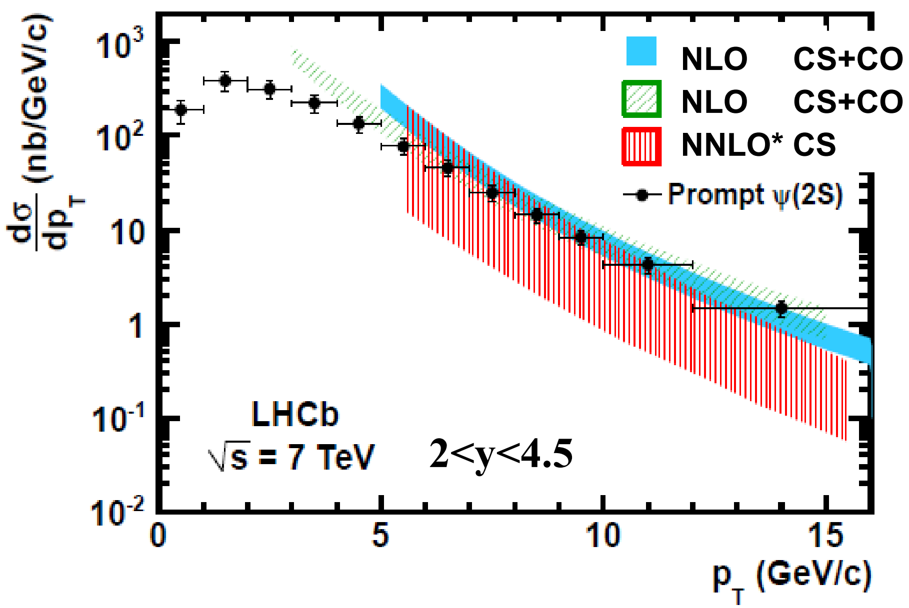
- The production mechanisms are not yet fully understood
- Many theoretical approaches proposed in the last years:
  - NLO Colour Singlet + Colour Octet (CS + CO) in the Non-Relativistic QCD framework
  - NNLO Colour Singlet
  - Colour Evaporation Model
  - FONLL (Fixed-Order-Next-to-Leading-Log), only for charmonium from *b*-decays
- Theory makes predictions of cross-section and polarization
- LHCb can study quarkonium hadroproduction in a unique kinematic region:
  - Large rapidity ($2<y<4.5$)
  - Down to low p_T

Prompt ψ(2S) cross-section

36 pb^{-1}

- The ψ(2S) prompt component has not appreciable feed-down from higher mass states: prompt ψ(2S) = direct ψ(2S)
  - This facilitates the cross-section interpretation
- Reconstructed in the decay channels $\psi(2S) \to \mu^+\mu^-$ (90k events) and $\psi(2S) \to J/\psi(\mu^+\mu^-)\,\pi^+\pi^-$ (12k events) and the results have been averaged

[LHCb-PAPER-2011-045]



$$\sigma_{\mathrm{prompt}} = 1.44 \pm 0.01\ (\mathrm{stat}) \pm 0.12\ (\mathrm{syst})^{+0.20}_{-0.40}\ (\mathrm{pol})\ \mu\mathrm{b}$$

- In the range p_T<16 GeV/c and 2<y<4.5
- Dominant syst. errors from luminosity, trigger and tracking: can be reduced

Y.-Q.Ma,K.Wang,K.-T.Chao arXiv:hep-ph/1012.1030

B.Kniehl,M.Butenschön PRL 106 (2011) 022003

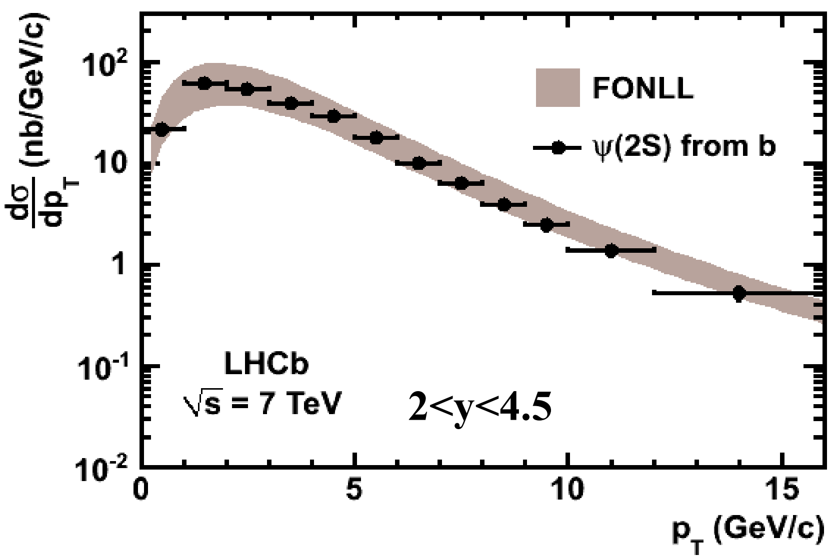
P.Artoisenet, PRL 101 (2008) 152001;
J-P.Lansberg Eur. Phys. J. C 61 (2009) 693

$\psi(2S)$ from *b* cross-section

36 pb^{-1}

- Separation between prompt $\psi(2S)$ and those originating from *b*-hadron decays: study of the pseudo decay time

[LHCb-PAPER-2011-045]
FONLL from [JHEP 0407 (2004) 033]



$$\sigma_b = 0.25 \pm 0.01\ (\text{stat}) \pm 0.02\ (\text{syst})\ \mu b$$

- In the range p_T<16 GeV/c and 2<y<4.5
- Dominant syst. errors from luminosity, trigger and tracking: can be reduced

- Combining the last result with the LHCb J/ψ measurements [Eur.Phys. J.C 71 (2011) 1645] we determine the inclusive $B(b \to \psi(2S)X)$, currently known at 50% level [PDG].
- Good agreement with a recent measurement from CMS

$$B(b \to \psi(2S)X) = 2.73 \pm 0.17(\text{stat} \oplus \text{syst}) \pm 0.24\ (\text{BF}) \cdot 10^{-3}$$ **LHCb**

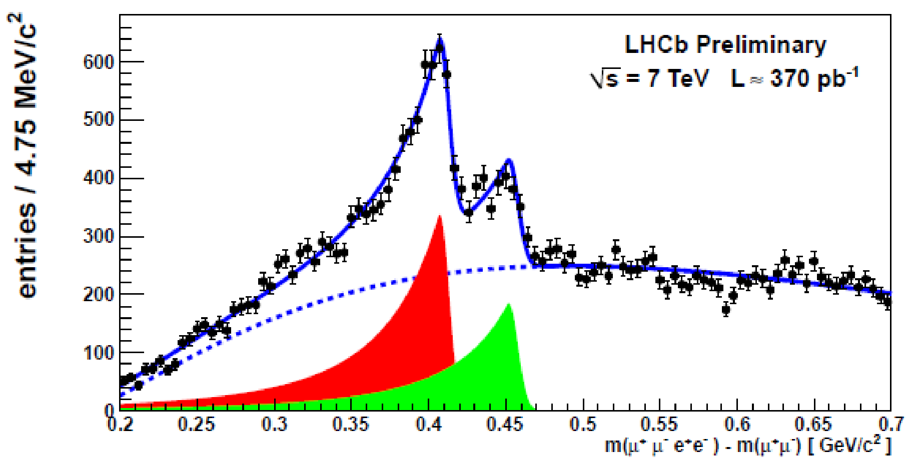
$$B(b \to \psi(2S)X) = 3.08 \pm 0.18(\text{stat} \oplus \text{syst}) \pm 0.42\ (\text{BF}) \cdot 10^{-3}$$ CMS

[CMS-BPH-10-014]

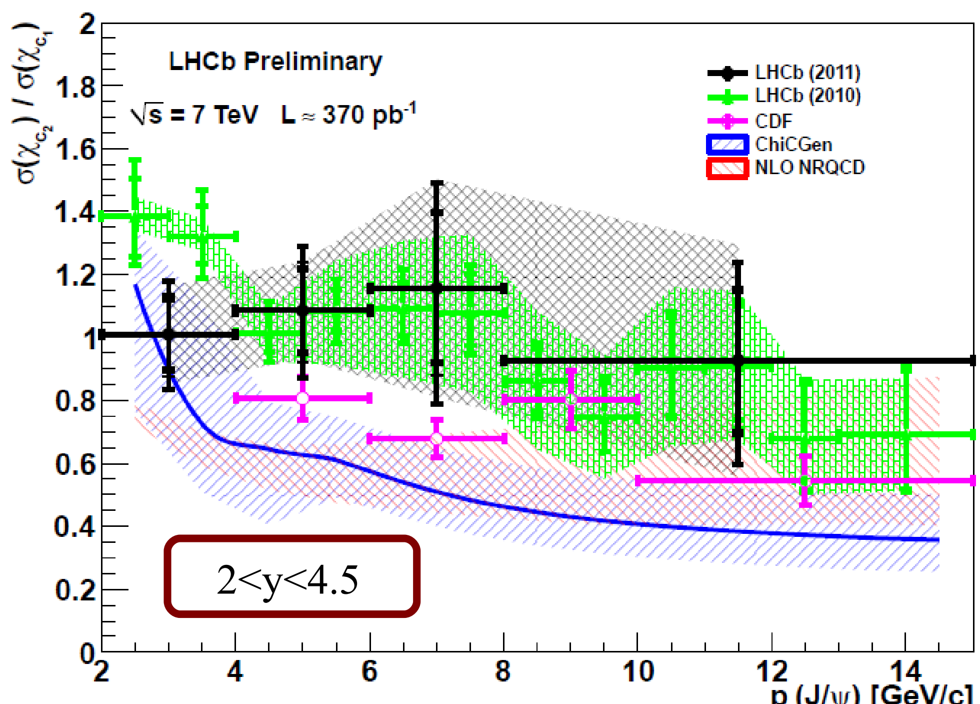
$\sigma(\chi_{c2})/\sigma(\chi_{c1})$

370 pb^{-1}

- χ_{cJ} provides substantial feed-down to the prompt J/ψ through $\chi_{cJ} \rightarrow J/\psi\, \gamma$
  - Impact on the J/ψ polarization and cross-section measurements
- $\chi_{cJ} \rightarrow J/\psi\, \gamma$ with $J/\psi \rightarrow \mu^+\mu^-$ and $\gamma \rightarrow e^+e^-$ using converted photons (2011) in the tracking system: good resolution → χ_c states resolved, lower efficiency



LHCb 2010: [LHCb-PAPER-2011-019]
LHCb 2011: [LHCb-CONF-2011-062]
CDF: PRL 98 (2007) 232001
ChiCGen: http://projects.hepforge.org/superchic/chigen.html
NRQCD: PR D83 (2011) 111503

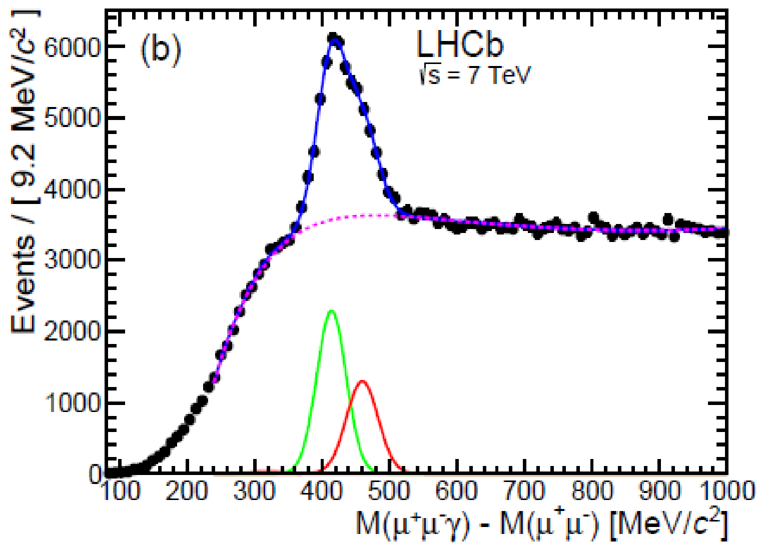


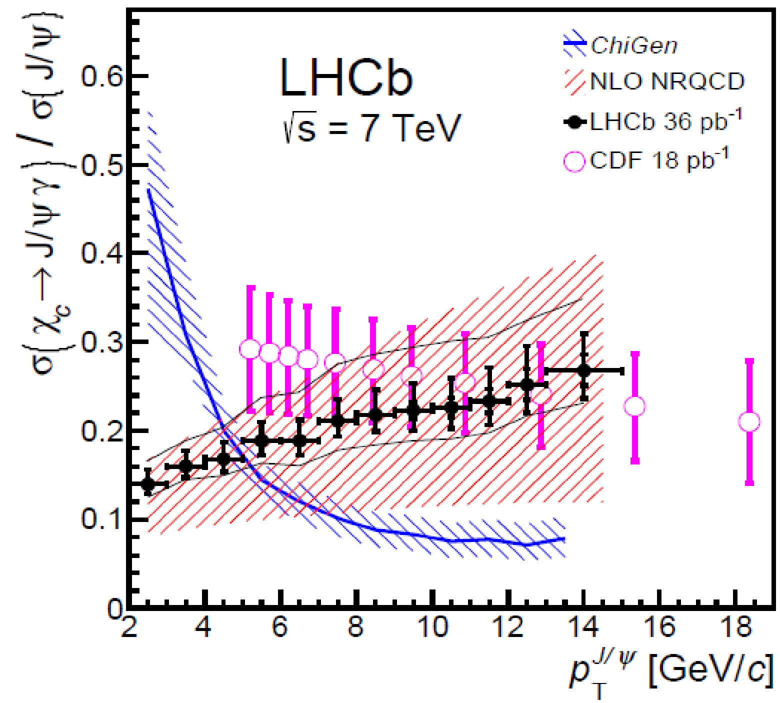
- χ_{c0}: very few expected events
- Good agreement with LHCb 2010 analysis (γ using calorimeter clusters only) and CDF.
- Agreement with NLO CS + CO above 8 GeV/c

$\sigma(\chi_c \to J/\psi\gamma)/\sigma(J/\psi)$

36 pb^{-1}

- γ reconstruction using calorimeter clusters only (lower resolution)
- Prompt charmonium selection: requiring $d_z\, M_{J/\psi}/p_z < 0.1\ ps$ (pseudo decay time)





- Separate errors to take into account all possible polarization scenarios of (χ_{c1}, χ_{c2}, J/ψ)
- Results in agreement with NLO CS + CO

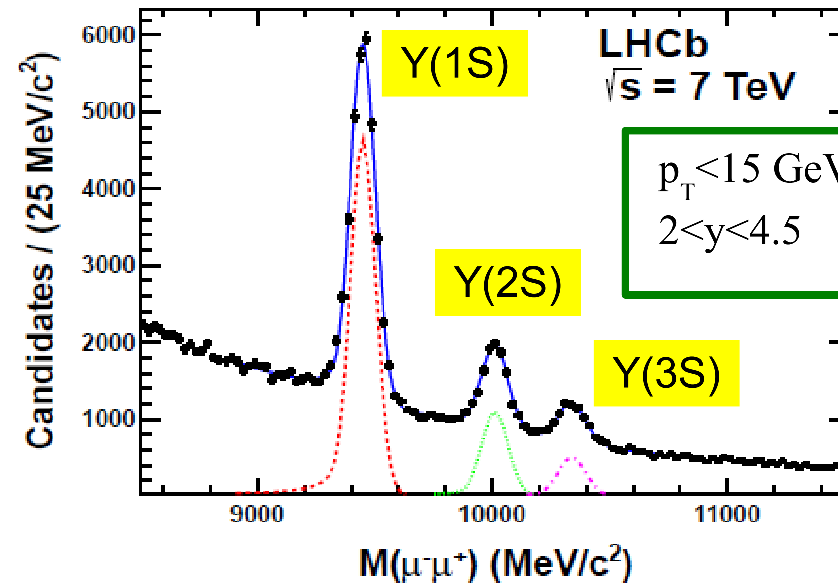
Ma, Wang and Chao [PR D83 (2001) 111503]
ChiGen [hepforge.org/superchic/chigen.html]
[LHCb-PAPER-2011-030]

Bottomonium: Y(nS)

25 pb^{-1}

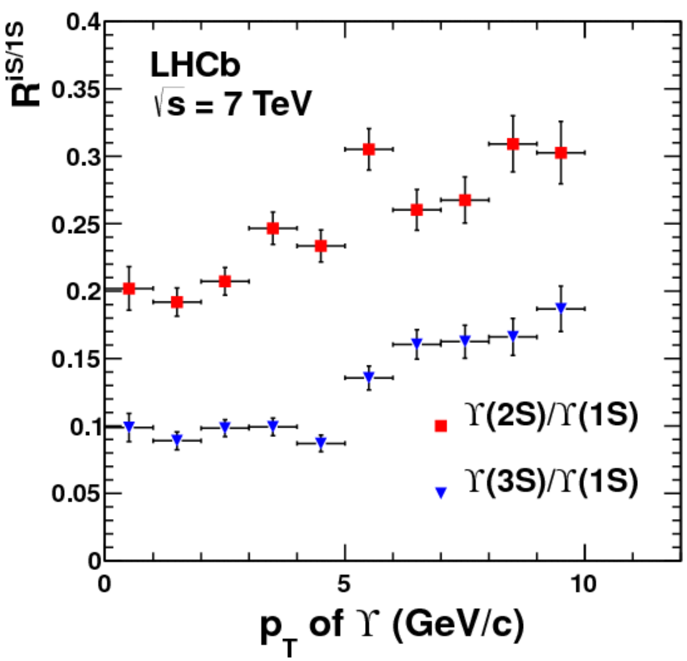
[LHCb-PAPER-2011-036]

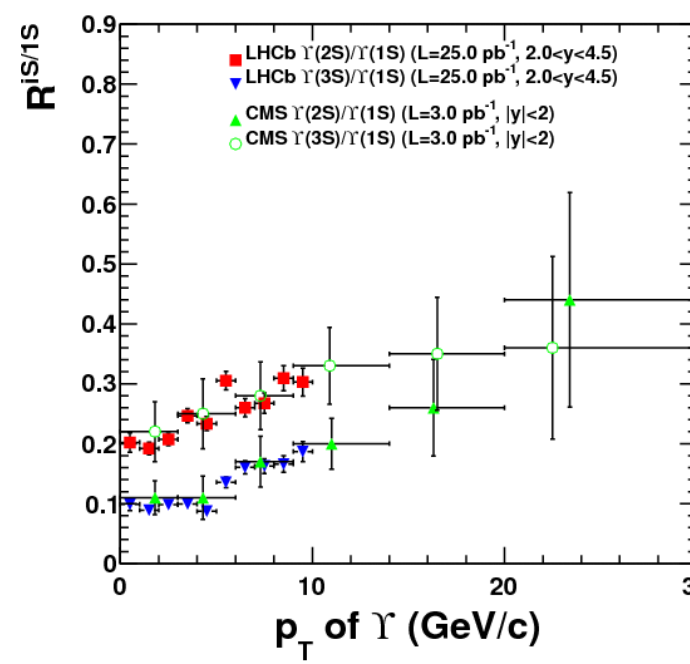
- Direct production or feed-down from higher bottomonium states
- Through the decay channel $Y(nS) \rightarrow \mu^+\mu^-$
- Signal fitted by Crystal Ball functions.
Background fitted by an exponential
    - Yields: 26400 Y(1S), 6700 Y(2S), 3300 Y(3S)
- Unknown polarization taken as syst. error
(last asymmetrical error)



p_T<15 GeV/c
2<y<4.5

$$\sigma(pp \to \Upsilon(1S)\,X) \times \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = 2.29 \pm 0.01 \pm 0.10 \,^{+0.19}_{-0.37}\ \text{nb}$$
$$\sigma(pp \to \Upsilon(2S)\,X) \times \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = 0.562 \pm 0.007 \pm 0.023 \,^{+0.048}_{-0.092}\ \text{nb}$$
$$\sigma(pp \to \Upsilon(3S)\,X) \times \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = 0.283 \pm 0.005 \pm 0.012 \,^{+0.025}_{-0.048}\ \text{nb}$$





For CMS
[PR D83 (2011) 112004]

Double Charm(onium)

355 pb^{-1}

- $J/\psi C$, $C\bar{C}$, CC where $C = D^0, D^+, D^+_s, \Lambda^+_c$
- Predictions for the production cross-sections are given by
  - **LO pQCD:** $gg \to J/\psi J/\psi$ excellent agreement with the LHCb measurements [PLB 707 52]
  - **Intrinsic Charm (IC):** based on charm PDFs. Quite large uncertainties on the predictions
  - **Double Parton Scattering (DPS):** two independent scattering processes. Assumes the factorization of the PDFs

$J/\psi \to \mu^+\mu^-$
$D^0 \to K^-\pi^+$
$D^+ \to K^-\pi^+\pi^+$
$D^+_s \to K^-K^+\pi^+$
$\Lambda^+_c \to pK^-\pi^+$

- LHCb performed the first observation of the modes $J/\psi C$ at hadron machines
  - $3<p_T^C<12$ GeV/c, $p_T^{J/\psi}<12$ GeV/c, $2<y_{J/\psi}, y_C< 4$

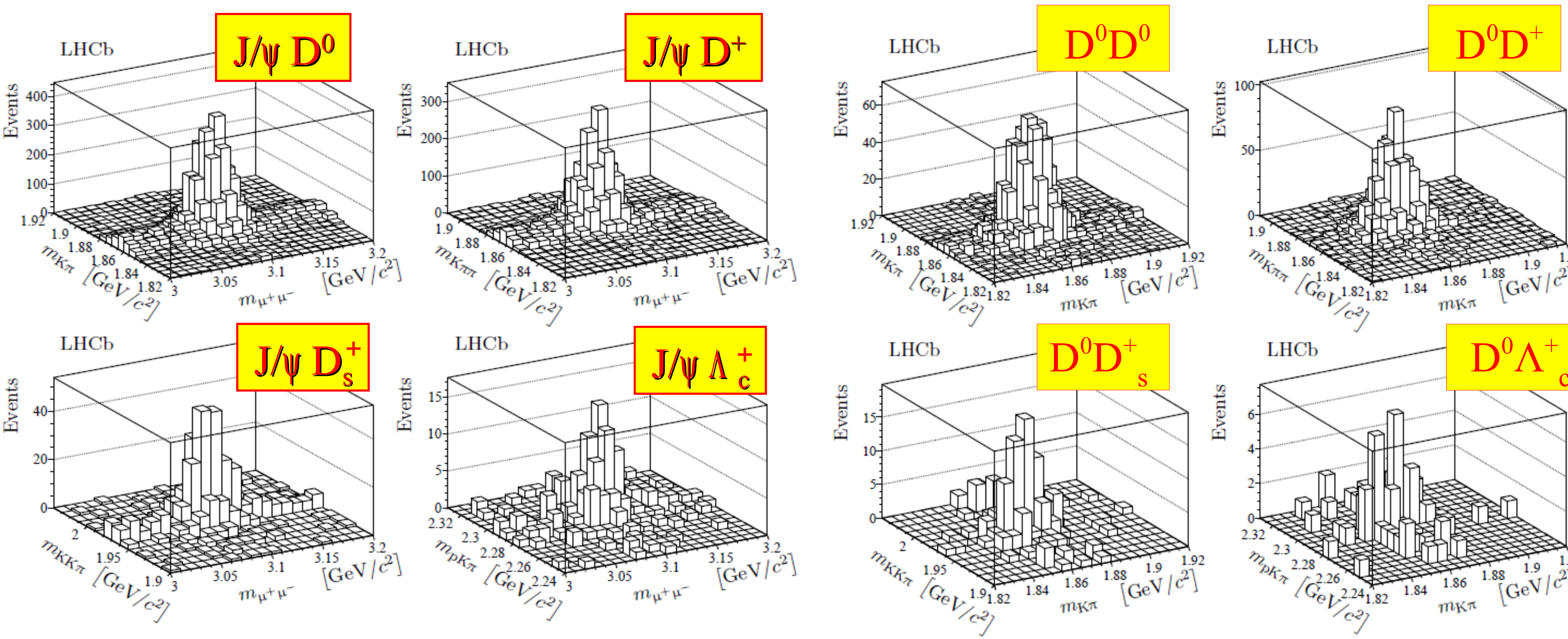
- Require both hadrons consistent with the same PV

- Use *per-event* efficiency correction
  - Efficiencies extracted from data (when possible)

[LHCb-PAPER-2012-003]

Double Charm(onium)

355 pb^{-1}



- Pileup is negligible (real data + MC)
- Signal significance > 5σ

Dominant systematic

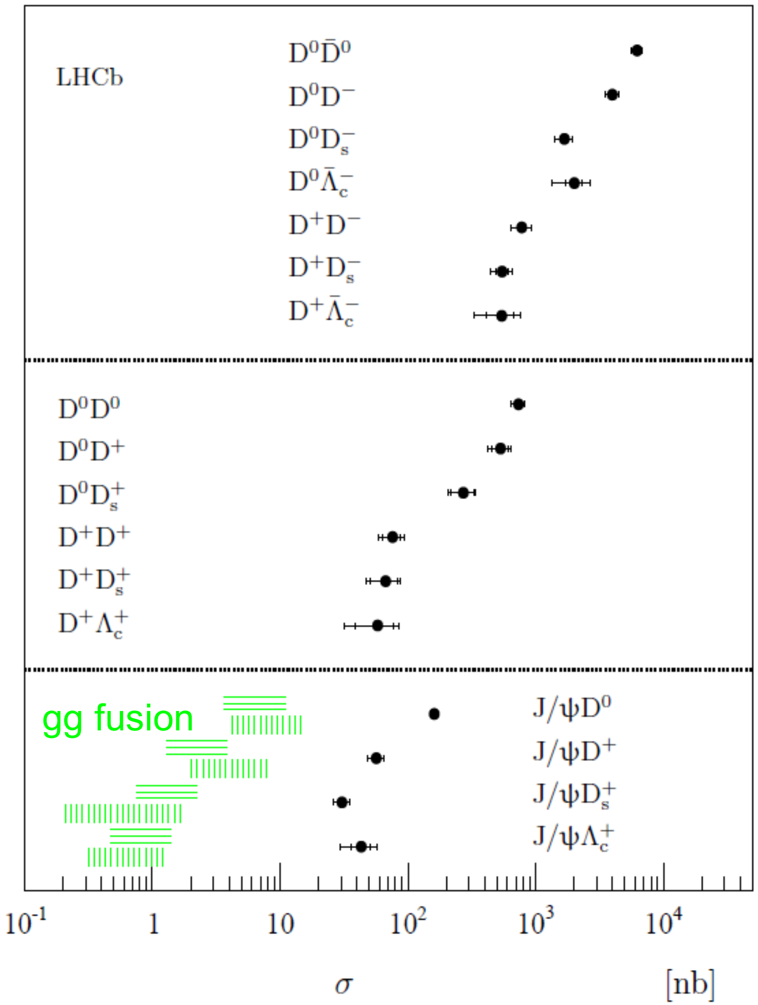
- Hadron track reconstruction: 2% per track

Mode	Fitted signal
$J/\psi D^0$	4875±86
$J/\psi D^+$	3323±71
$J/\psi D^+_s$	328±22
$J/\psi \Lambda^+_c$	116±14

Mode	Fitted signal
D^0D^0	1087±37
D^0D^+	1177±39
$D^0D^+_s$	111±12
$D^0\Lambda^+_c$	41±8

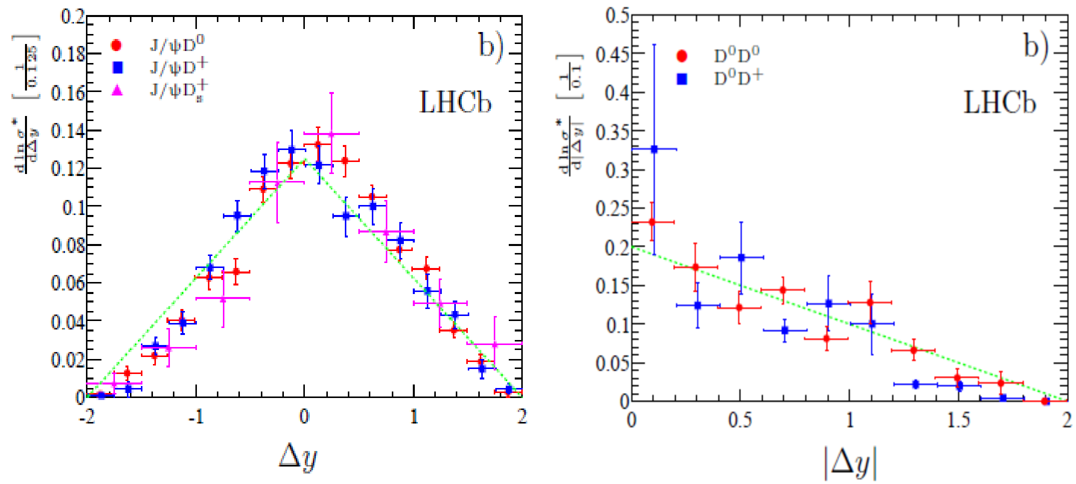
Double Charm(onium)

355 pb^{-1}

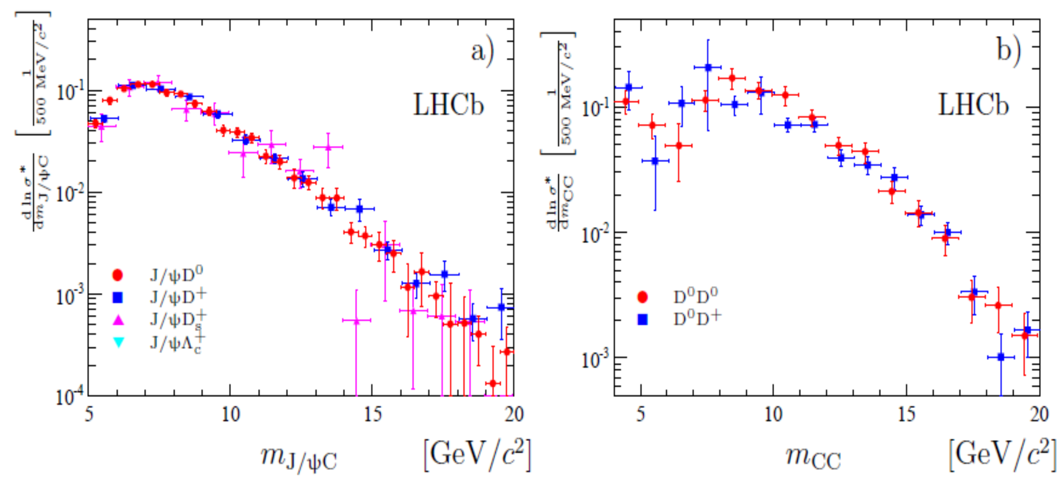


green horizontally hatched areas
[EPJ C61 (2009) 693]

green vertically hatched areas
[PR D57 (1998) 4385]
[PR D73 (2006) 074021]



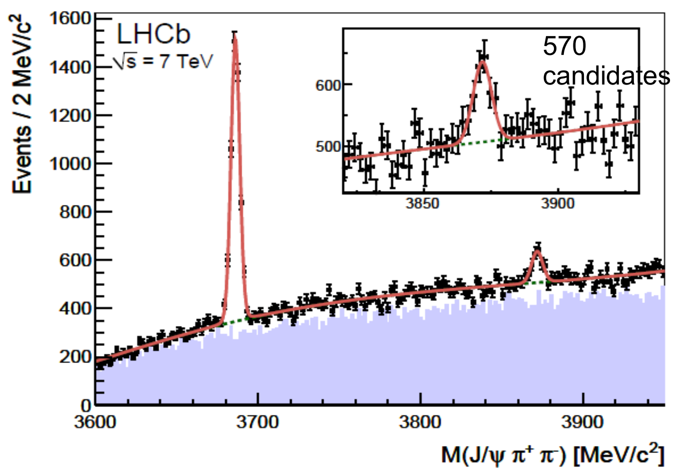
Green line: expected distribution for uncorrelated events

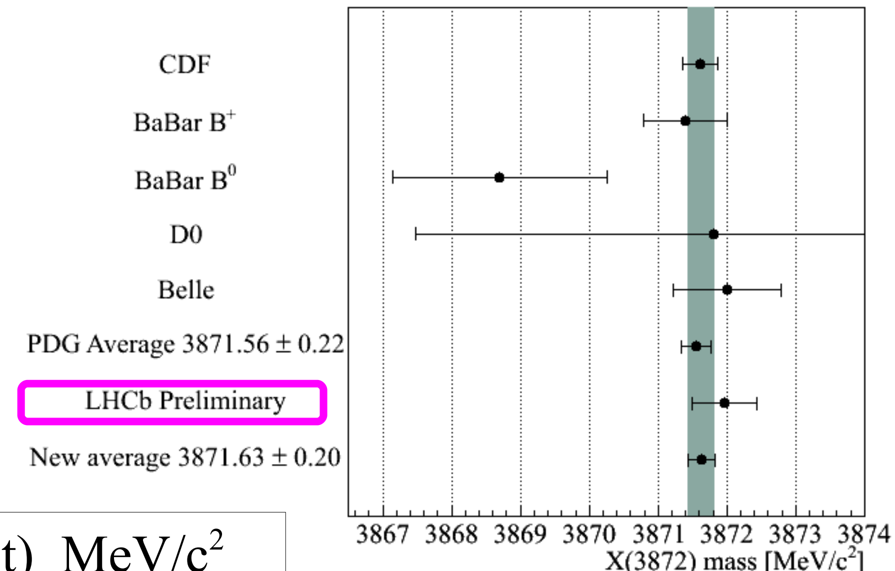


X(3872)

35 pb^{-1}

- Observed for the first time by Belle (2003) in B decays. Confirmed by CDF, D0 and BaBar
- Quantum numbers not yet established ($J^{PC}=2^{-+}$ or 1^{++}). Its nature is still uncertain: conventional charmonium? Di-Charm molecule? Tetraquark state? → Mass is a crucial input to theories





$$M_{X(3872)} = 3871.95 \pm 0.48\ (\text{stat}) \pm 0.12\ (\text{syst})\ \ \text{MeV}/c^2$$

$$\sigma_{X(3872)} B_{J/\psi\ \pi+\ \pi-} = 4.7 \pm 1.1\ (\text{stat}) \pm 0.7\ (\text{syst})\ \ \text{nb}$$

[LHCb-PAPER-2011-034]

- dominant systematics (mass): 10% momentum calibration scale; 5% energy loss correction
- dominant systematics (σ): 7% tracking efficiency; 6% background model

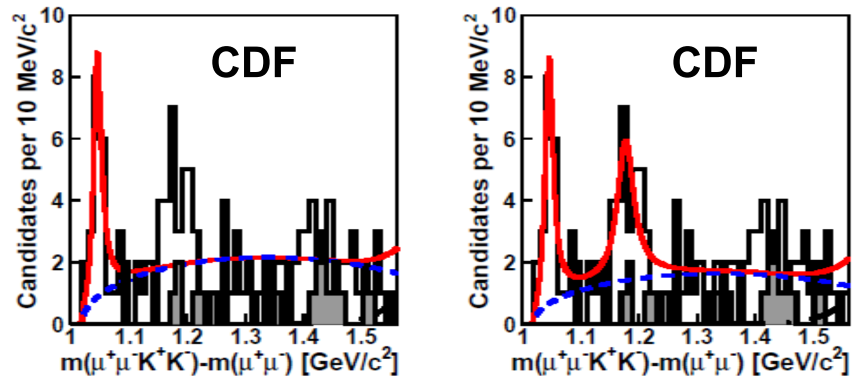
X(4140)

376 pb^{-1}

[PRL 102 (2009) 242002]

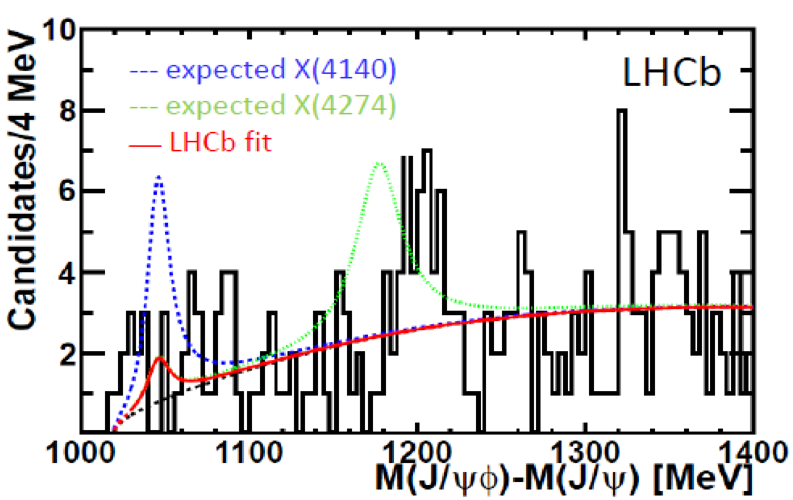
- Observed by CDF in $B^+ \to J/\psi\phi K^+$:

19±6 X(4140) and 22±8 X(4274). →



- $J/\psi\phi$ close to the kinematic threshold: should be unobservable
- Its nature: molecule? Tetraquark? ...

- Belle found no evidence for X(4140) in $\gamma\gamma \to J/\psi\phi$



- 380 $B^+ \to J/\psi\phi K^+$ selected events at LHCb

No evidence for the X(4140) nor for the X(4274): upper limits at 90% CL

$$\frac{\mathcal{B}(B^+ \to X(4140)K^+) \times \mathcal{B}(X(4140) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.07$$ **LHCb**

$$\frac{\mathcal{B}(B^+ \to X(4274)K^+) \times \mathcal{B}(X(4274) \to J/\psi\,\phi)}{\mathcal{B}(B^+ \to J/\psi\,\phi K^+)} < 0.08$$ **LHCb**

[LHCb-PAPER-2011-033]

Prospects and conclusions

- LHCb is in good shape and performs better than expectations
- More than 1/fb recorded (about 50% analyzed)
- Very active quarkonium group working in close connection with theorists community
- Latest quarkonium analyses presented here. Many others in progress. Active plans for new measurements at $\sqrt{s}=8$ TeV

- Stay tuned for news!

Thank you for listening