The XXth International Workshop
High Energy Physics and Quantum Field Theory
September 24 – October 1, 2011, Sochi, Russia

LHCb;
inclusive bb-quarkonium production

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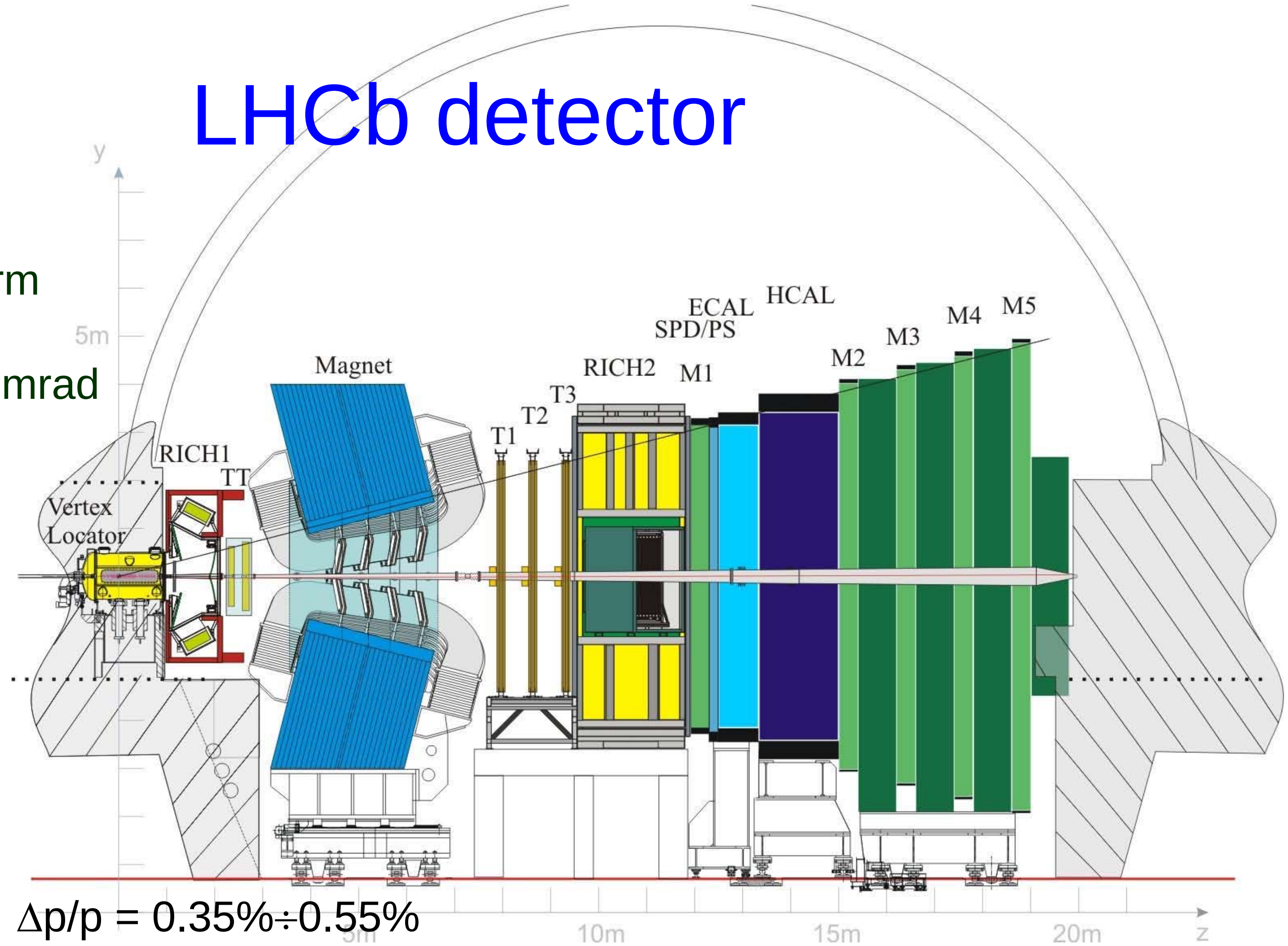
Outlook:

- Reminder: LHCb detector and status
- Υ(1S) production
- Sources of Υ(1S) and χ_b(1P) observation
- Quarkonia at LHCb
- Conclusion

LHCb detector

Forward single arm spectrometer covering 15÷300 mrad ($2 < \eta < 4.9$)

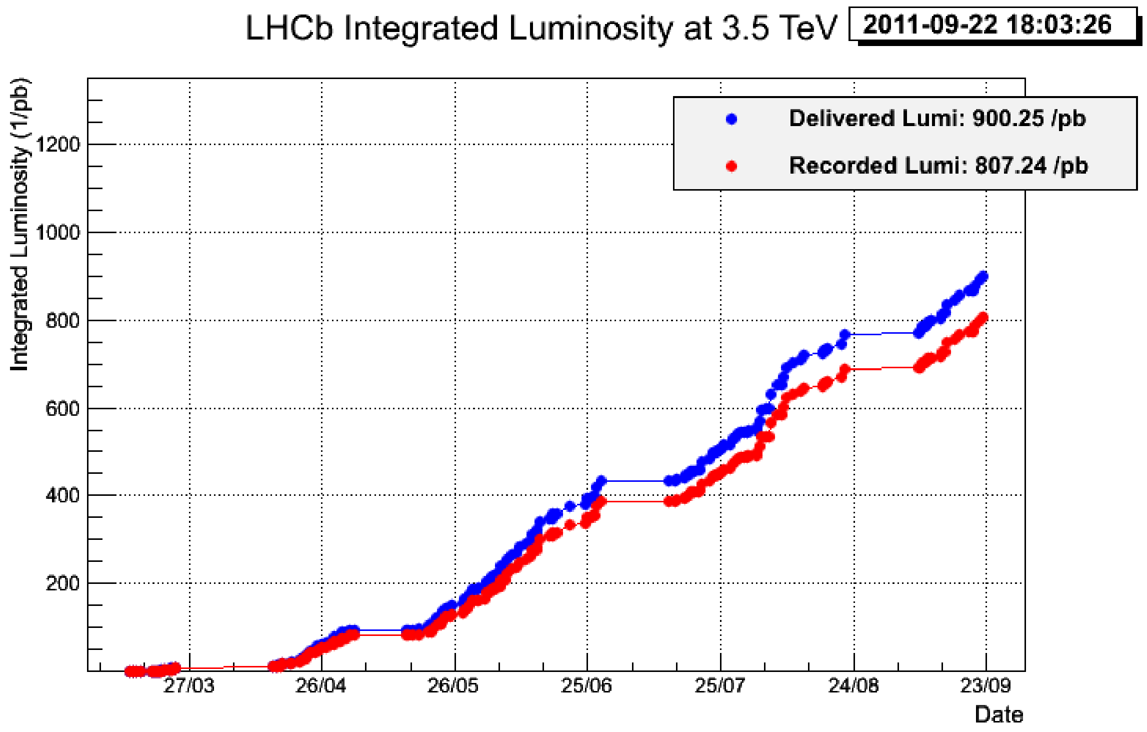


- charged tracks $\Delta p/p = 0.35\% \div 0.55\%$
  mass resolution ≈ 13 MeV/c^2 on $J/\psi \to \mu\mu$ and ≈ 50 MeV/c^2 on $\Upsilon \to \mu\mu$
- vertexing: PV resolution ≈ 16 μm in X,Y and ≈ 76 μm in Z
  proper time resolution 30÷50 fs
- Muon ID: $\varepsilon(\mu \to \mu) = 97\%$, mis-ID rate $(\pi \to \mu) = 1 \div 3\%$

Status

- LHCb is in very good shape
  - 37 pb^{-1} at $\sqrt{s}$ = 7 TeV recorded in 2010
  - 800 pb^{-1} already in 2011
  - Expect 1 fb^{-1} at the end of the year

- Most of the quarkonia analyses use data of 2010



Motivation

- Many quarkonia states is discovered
- Nevertheless the production mechanism in **pp**-collision is not fully understood
- Large cross-section is expected at LHC
  High rate makes quarkonia central player for detector and software calibration
- Several theory models of production mechanism is around
  - Started with Color singlet (CSM)
    under-predict, no polarization prediction
  - Extended to Color octet (COM) mechanisms, *(NRQCD)*
    better agreement for cross-sections; predicts transverse polarization, not confirmed by experiments
  - NLO CSM better describes cross-section and allow longitudinal polarization
  - Other models (Color evaporation (CEM), kt factorization, soft color interaction)
- New data from LHC experiments will help to resolve this issue

$\Upsilon(1S) \rightarrow \mu^{+}\mu^{-}$

$\Upsilon(1S)$ production cross-section

LHCb-CONF-2011-016
Analysis performed on 2010 data

$\Upsilon(1S)$; Trigger and Event Selection

Trigger lines important for $\Upsilon \to \mu^+\mu^-$ events

L0 Trigger	Single Muon	$p_T > 1.4$ GeV/c
	Di-Muon	$p_{T1} > 0.56$ GeV/c, $p_{T2} > 0.48$ GeV/c
HLT1 Trigger	Single Muon	Confirm L0 Single Muon and $p_T > 1.8$ GeV/c (*Prescaled)*
	Di-Muon	Confirm L0 Di-Muon and $m(\mu^+\mu^-) > 2.5$ GeV/c^2
HLT2 Trigger	Di-Muon	$m(\mu^+\mu^-) > 2.9$ GeV/c^2 *or cuts on vertex and track quality*

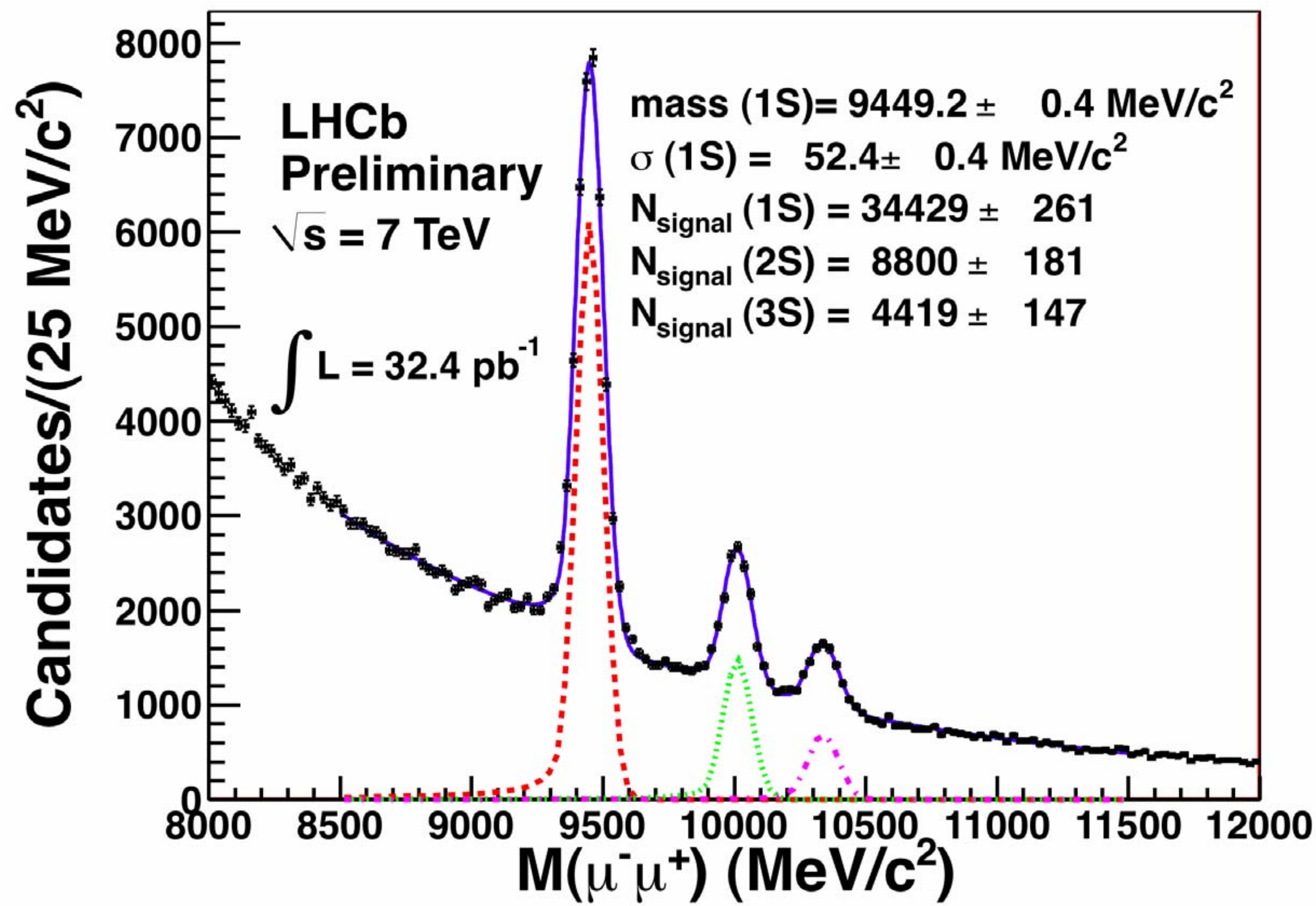
μ-tracks:

- well reconstructed tracks identified as muons in muon detector,
- $p_T > 1$ GeV/c,
- Track fit quality

Reconstructed Υ:

- vertex fit quality Prob(χ^2) > 0.5%
- mass window: 8 – 12 GeV/c^2

Di-muon invariant mass spectra



Cross-section measurement strategy

$$\frac{d\sigma\left(pp \to \Upsilon\right)}{dp_T dy} \cdot Br\left(\Upsilon \to \mu^+\mu^-\right) = \frac{N^{fit}\left(p_T, y, \varepsilon_{tot}\right)}{\int L dt \cdot \Delta p_T \cdot \Delta y}$$

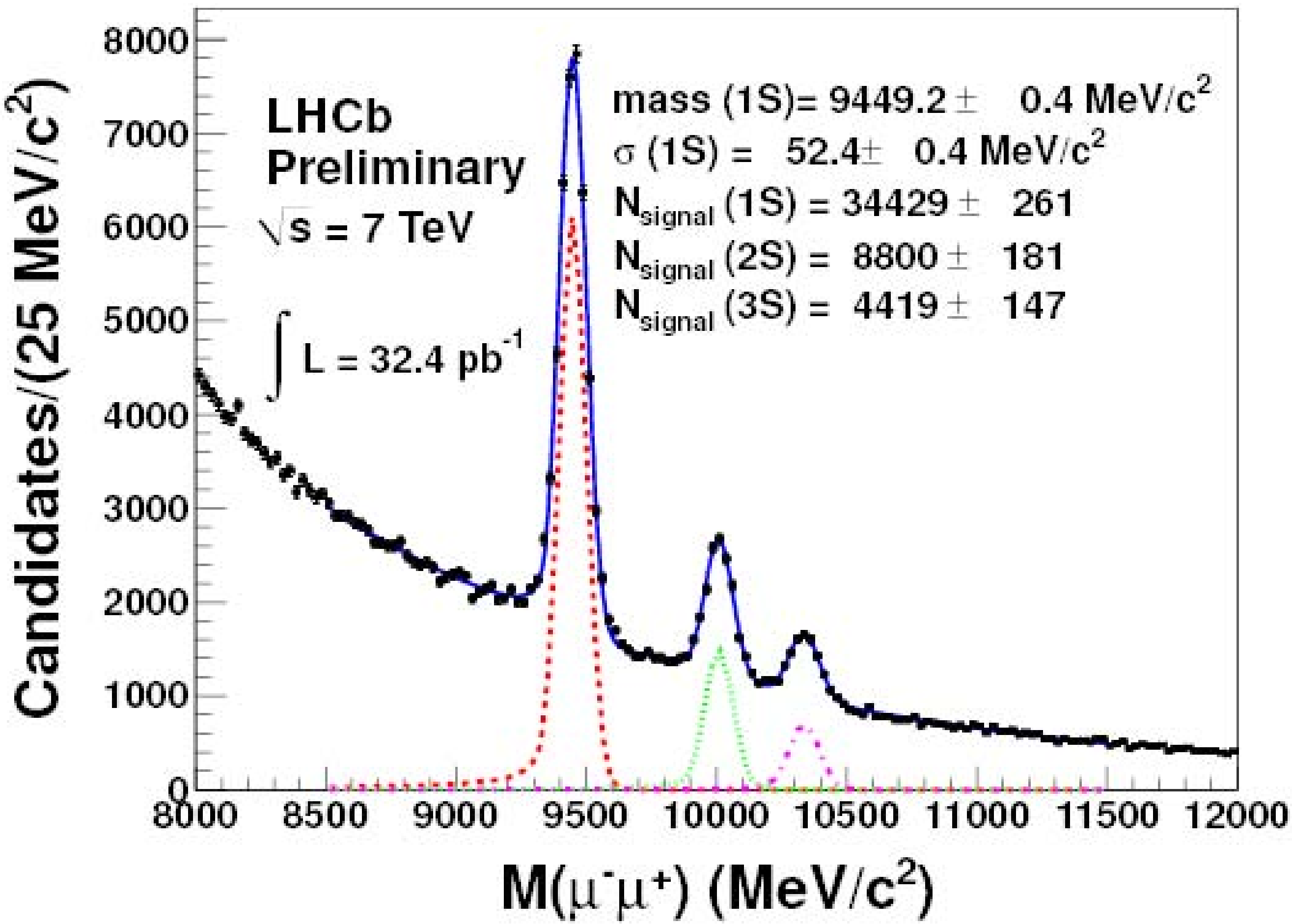
- N^{fit} – number of candidates in the mass peak in each Δp_T, Δy bin, obtained from the fit and corrected for acceptance and efficiency
- ε_{tot} – total efficiency *(including acceptance)*
- Δp_T, Δy – bins of p_T and y
- $\int L dt$ – integrated luminosity

Number of Υ candidates

- Parameters α and n of Crystal Ball functions are fixed:
$\alpha = 2$, $n = 1$

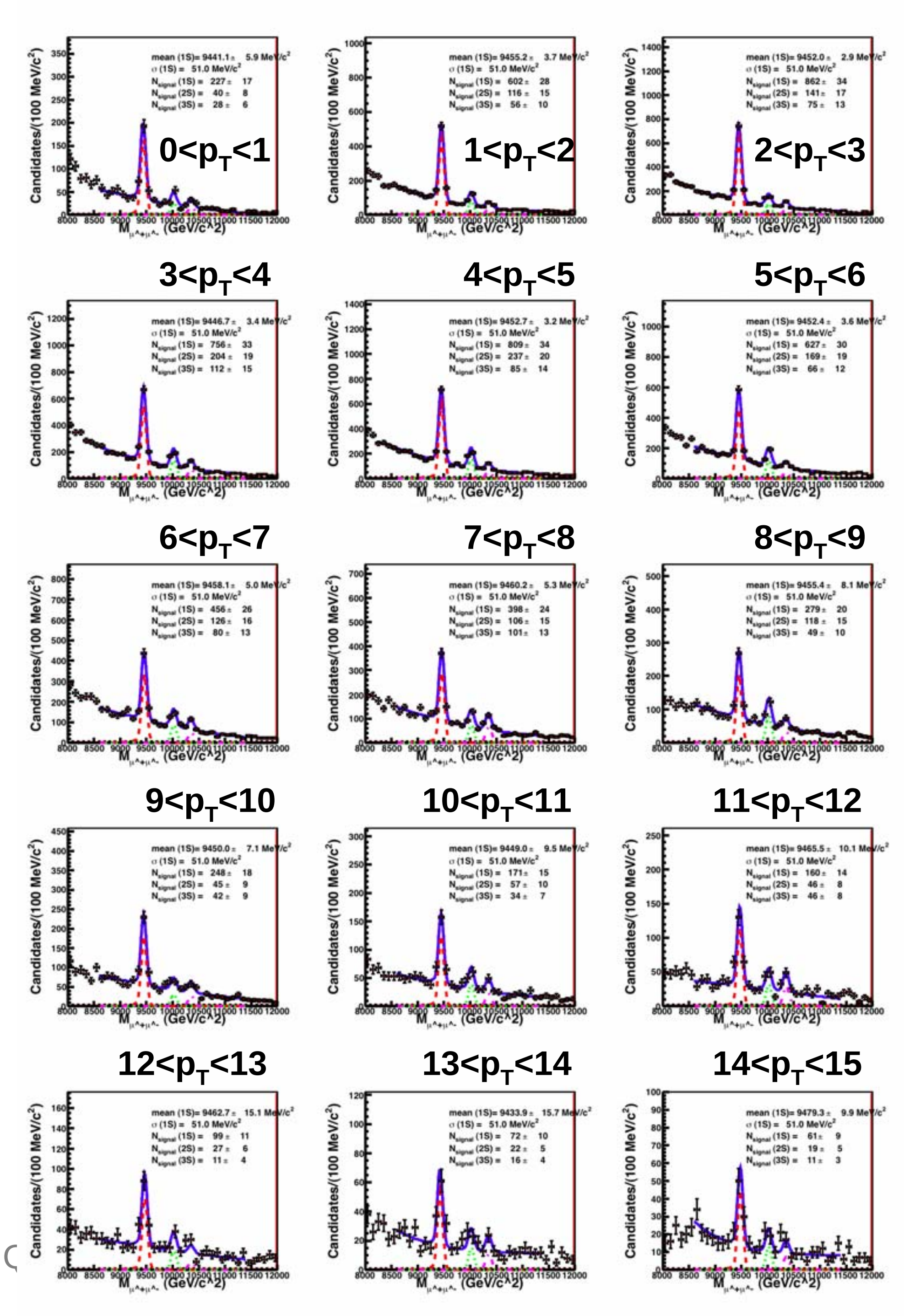
- The same function is used for individual bin fits

3 Crystal Balls(CB) + exponential *for background*



Number of Υ candidates

- Numbers of Υ(1S) candidates are extracted from Crystal Ball (CB) part of the fit with 3·CB+exponential.
- Only Υ(1S) considered:
  - Width and masses of Υ(2S) and Υ(3S) are fixed.
- Rapidity interval $2.0 < y < 2.5$



Number of $\Upsilon(1S)$ candidates

p_T (GeV/c)	2.0< y <2.5	2.5< y <3.0	3.0< y <3.5	3.5< y <4.0	4.0< y <4.5
0- 1	228 ± 15	516 ± 23	437 ± 21	308 ± 18	88 ± 9
1- 2	602 ± 25	1244 ± 35	1153 ± 34	766 ± 28	231 ± 15
2- 3	863 ± 29	1553 ± 39	1358 ± 37	841 ± 29	254 ± 16
3- 4	757 ± 28	1453 ± 38	1284 ± 36	824 ± 29	253 ± 16
4- 5	809 ± 28	1268 ± 36	1102 ± 33	636 ± 25	182 ± 14
5- 6	627 ± 25	1070 ± 33	845 ± 29	481 ± 22	157 ± 13
6- 7	457 ± 21	774 ± 28	651 ± 26	452 ± 21	110 ± 11
7- 8	398 ± 20	600 ± 24	546 ± 23	298 ± 17	91 ± 10
8- 9	279 ± 17	482 ± 22	392 ± 20	208 ± 14	57 ± 8
9-10	249 ± 16	379 ± 19	271 ± 16	162 ± 13	31 ± 6
10-11	171 ± 13	253 ± 16	214 ± 15	104 ± 10	27 ± 5
11-12	160 ± 13	176 ± 13	139 ± 12	64 ± 8	20 ± 4
12-13	100 ± 10	139 ± 12	108 ± 10	74 ± 9	16 ± 4
13-14	70 ± 8	123 ± 11	87 ± 9	37 ± 6	5 ± 2
14-15	61 ± 8	78 ± 9	60 ± 8	27 ± 5	5 ± 2

Efficiency

The efficiency ε_{tot} has been subdivided into three pieces:

$$\varepsilon_{\text{tot}} = N^{\Upsilon}(\text{accepted, reconstructed, triggered}) / N^{\Upsilon}(\text{generated}) =$$

$$= \varepsilon_{\text{acc}} \cdot \varepsilon_{\text{rec}} \cdot \varepsilon_{\text{trg}} =$$

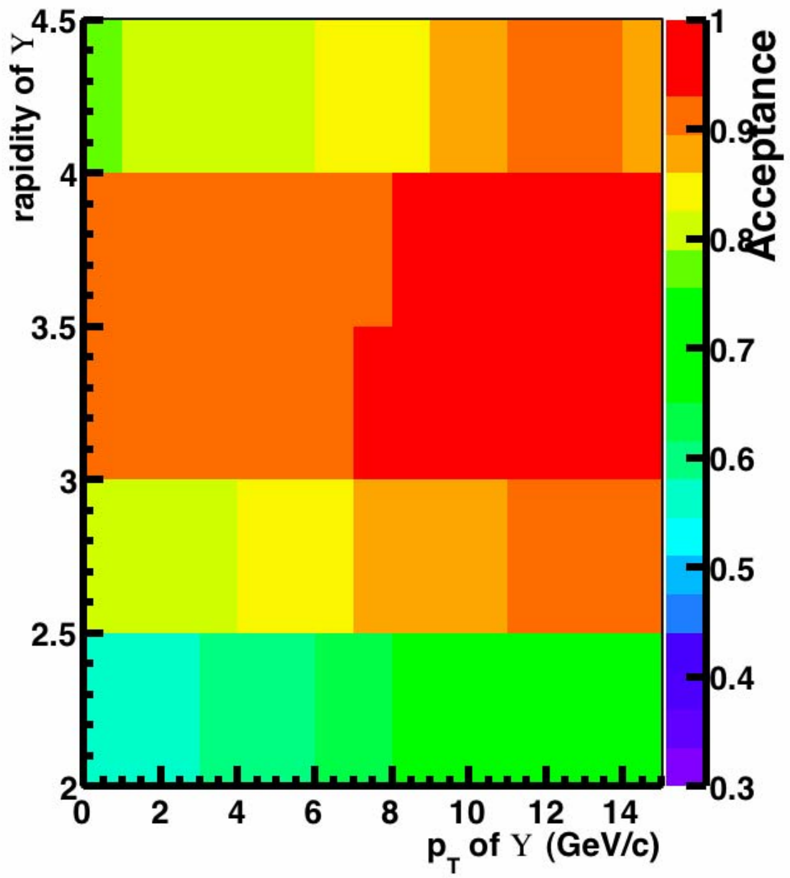
$$= \frac{N^{\Upsilon}(\text{accepted})}{N^{\Upsilon}(\text{generated})} \cdot \frac{N^{\Upsilon}(\text{reconstructed})}{N^{\Upsilon}(\text{accepted})} \cdot \frac{N^{\Upsilon}(\text{triggered})}{N^{\Upsilon}(\text{reconstructed})}$$

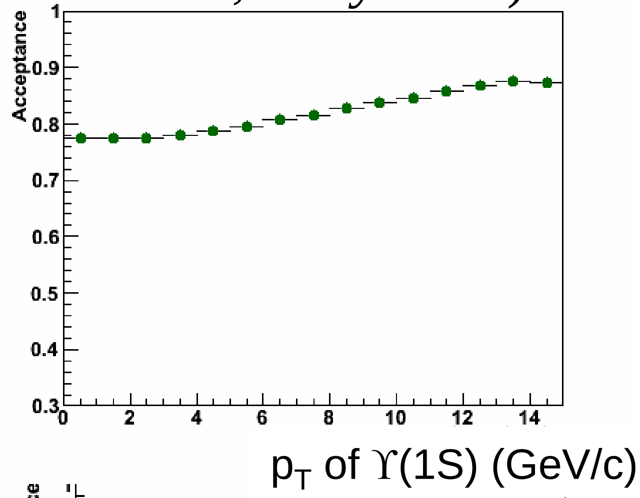
For each p_T,y range the following subsequent sub-samples and numbers of Υ(1S) in them are defined:

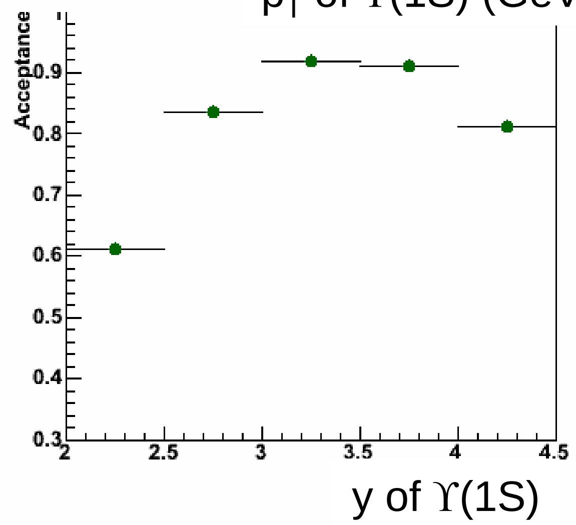
- N^{Υ}(generated) – Total number of Υ(1S) generated
- N^{Υ}(accepted) – Number of Υ generated inside LHCb acceptance *(10-400 mrad)*
- N^{Υ}(reconstructed) – Number of Υ accepted, detected and reconstructed
- N^{Υ}(triggered) – Number of triggered Υ

Acceptance

$$\varepsilon_{\mathrm{acc}} = \frac{N^{\Upsilon}(\text{gen. with } \mu^+\mu^- \text{ in } 0 < p_T < 15\ \mathrm{GeV}/c,\ 2 < y < 4.5,\ 10 < \theta < 400\ \mathrm{mrad})}{N^{\Upsilon}(\text{generated with } \mu^+\mu^- \text{ in } 0 < p_T < 15\ \mathrm{GeV}/c,\ 2 < y < 4.5)}$$

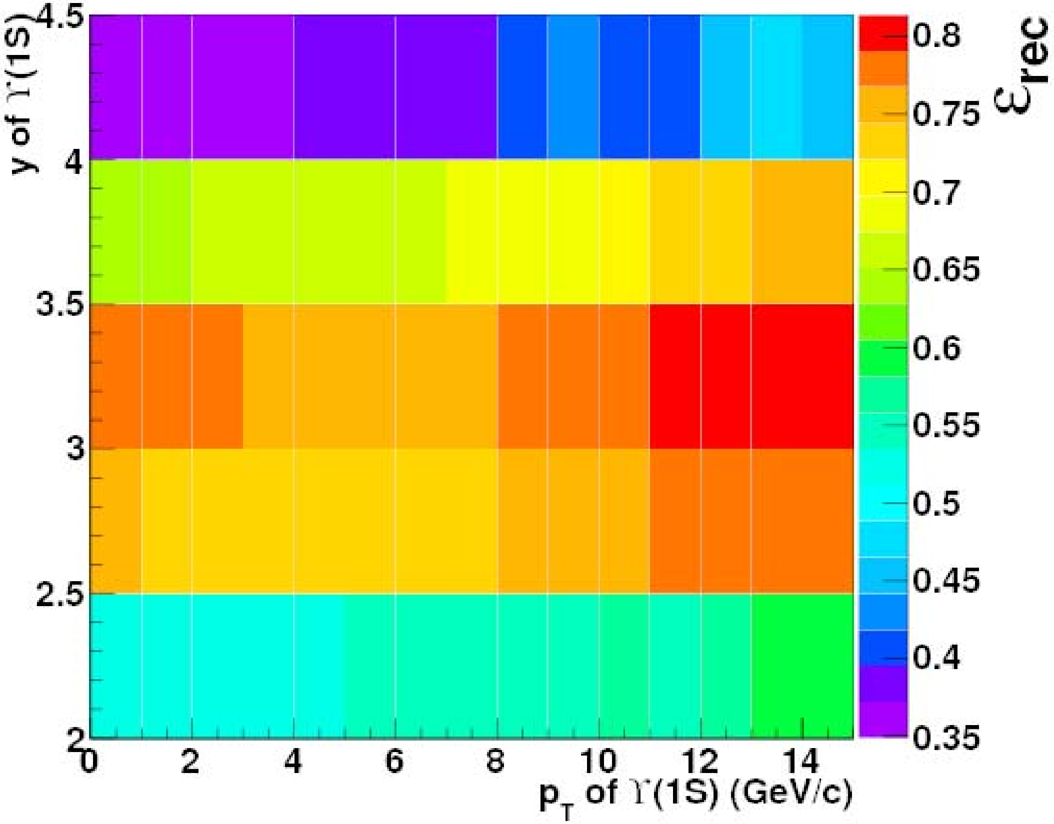


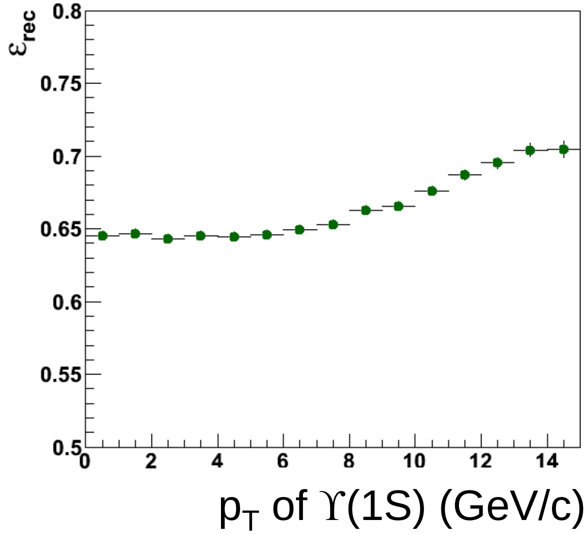


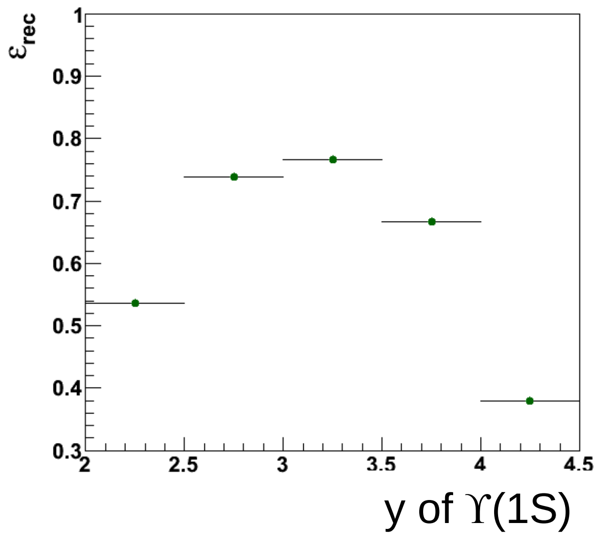


Reconstruction efficiency

$$\varepsilon_{rec} = \frac{N^{\Upsilon}\text{detected and reconstructed in } p_T, y \text{ range}}{N^{\Upsilon}\text{generated in angular acceptance in } p_T, y \text{ range}}$$



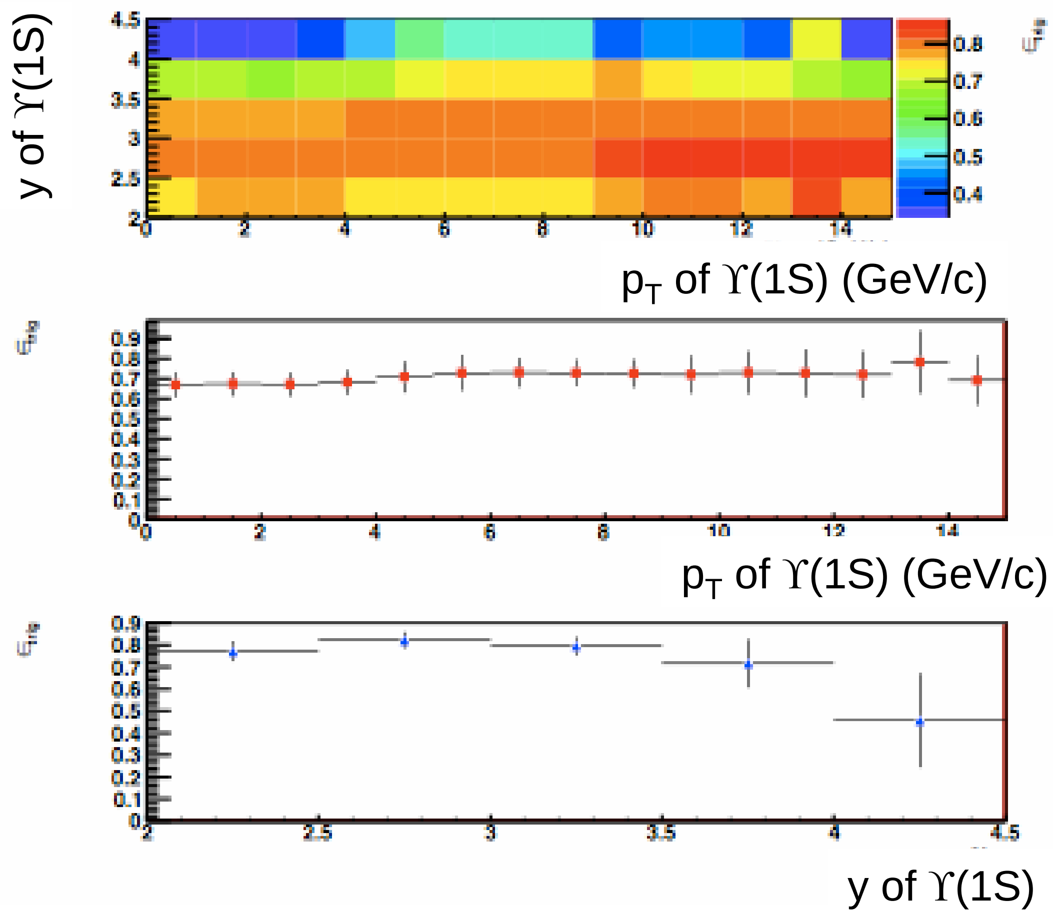




Trigger efficiency

$$\varepsilon_{trg} = \frac{N^{\Upsilon}\text{detected, reconstructed, triggered in range}}{N^{\Upsilon}\text{detected, reconstructed in range}}$$

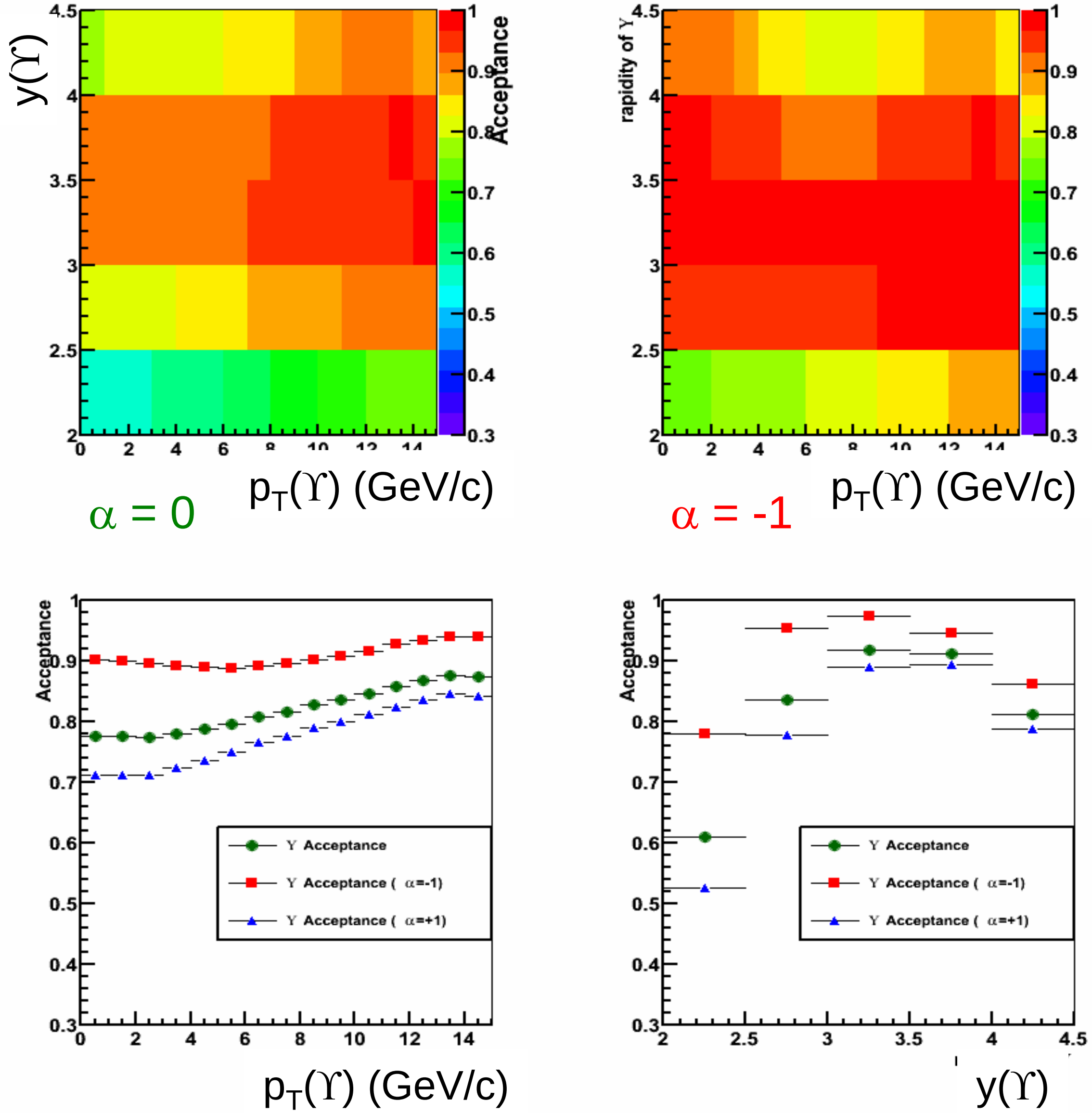
- Calculated in data for J/ψ events as a function of $(p_T\mu1 + p_T\mu2)$ and y
- Systematic uncertainty is estimated using J/ψ and ϒ(1S) Monte Carlo



Systematic uncertainties

Source	**Method**	**Value**
luminosity	luminosity for 2010 data	10% *(the same for each bin)*
ε_{trg} calculation	difference MC – MC truth	2-67% *(bin-by bin; big for some bins with low statistics)*
polarization on ε_{acc}	extreme polarization scenario	0-33% *(bin-by-bin)*
polarization on ε_{rec}	extreme polarization scenario	0-21% *(bin-by-bin)*
choice of fit function	different function	1%
unknown p_T spectrum	p_T spectrum distribution	1%
GEC (Global Event Cuts)	statistical uncertainty of data	2%
ε(track quality)	difference data – MC	0.5% per track
ε(track finding)	difference data – MC	4% per track
vertexing	difference data – MC	1%
Muon ID ε	tag and prob	1.1%

Effect of polarization on acceptance

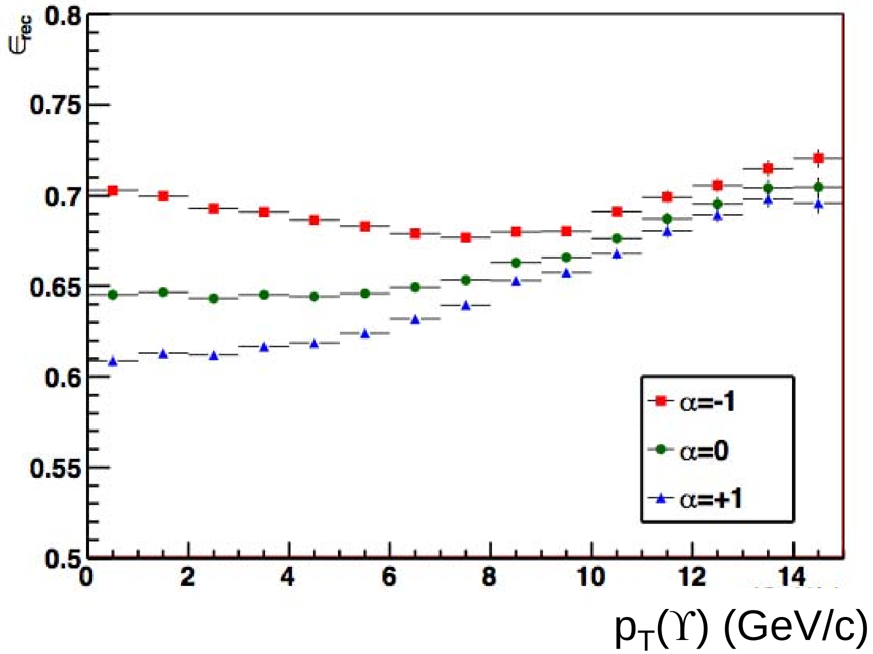


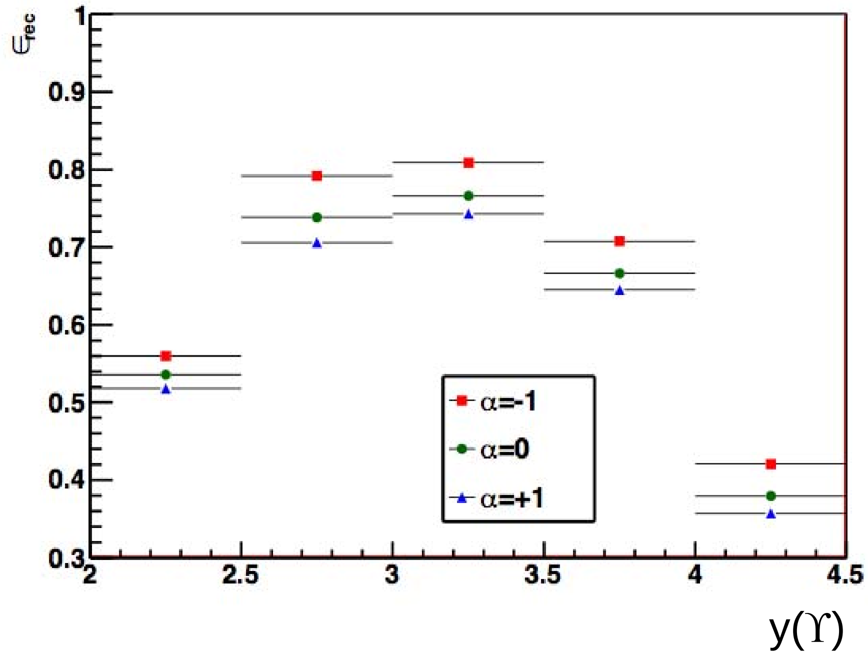
α = -1 – full longitudinal polarization

α = +1 – full transverse polarization

α = 0 – no polarization

Effect of polarization on ε_{rec}



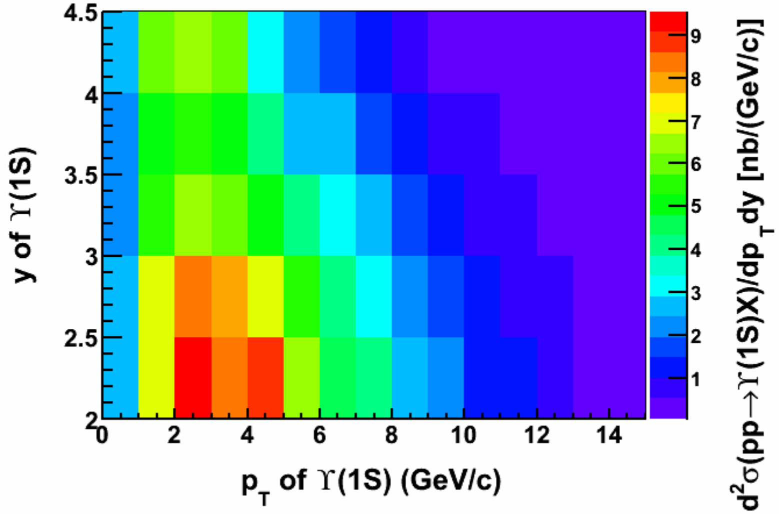


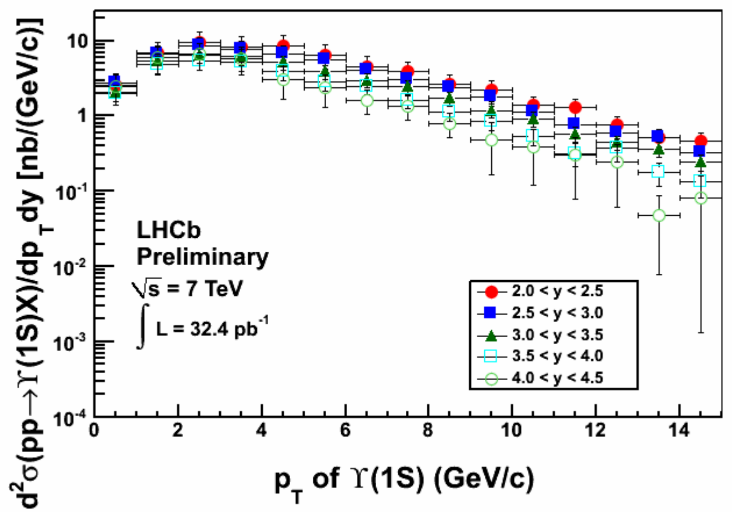
$\alpha = -1$ – full longitudinal polarization

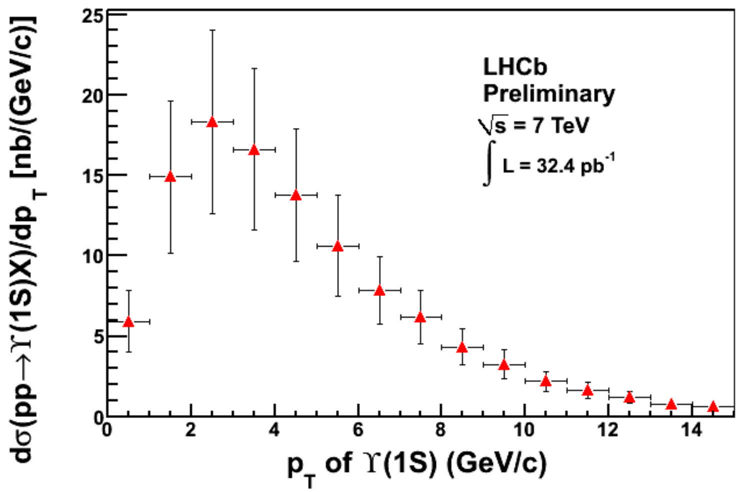
$\alpha = +1$ – full transverse polarization

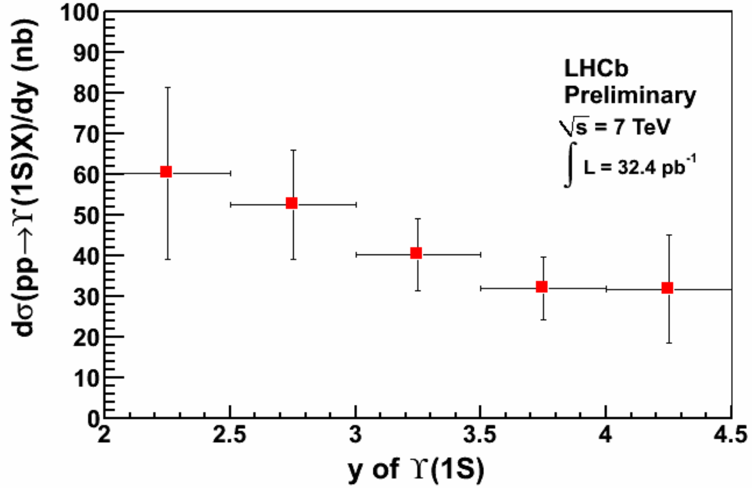
$\alpha = 0$ – no polarization

ϒ(1S) cross-section





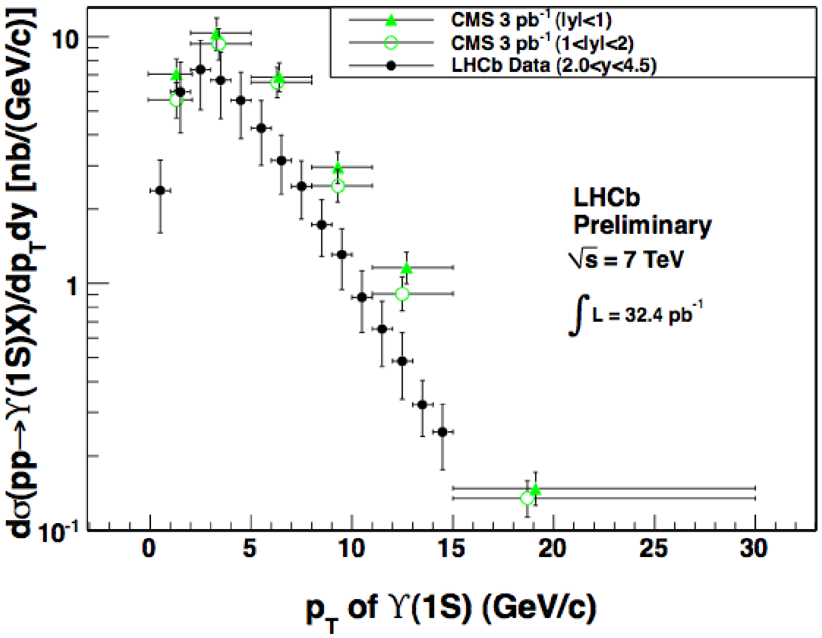


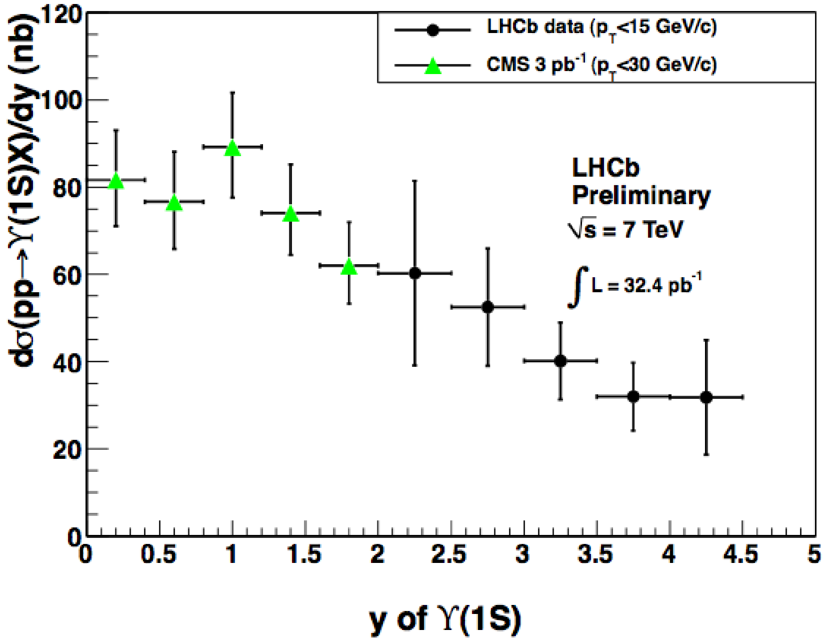


$108.3 \pm 0.7(\text{stat.})^{+30.9}_{-25.8}(\text{syst.})\ \text{nb}$, $0 < p_T(\Upsilon) < 15\ \text{GeV/c},\ 2 < y < 4.5$

Comparison with CMS

CMS publication: [Phys. Rev. **D**83 (2011) 112004; arXiv: hep-ex/1012.5545v1]



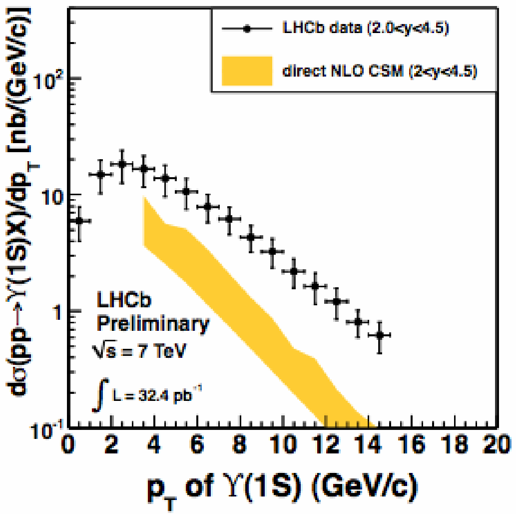


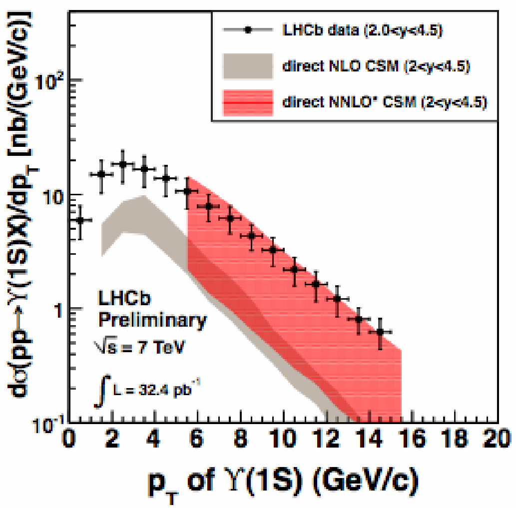
- CSM measurement as a function of p_T is higher, but it should be noted that CMS measure cross-section for |y|<2, while LHCb for 2.0<y<4.5.
- These two measurements supplement each other and in a good agreement.

Comparison with theory

NLO CSM

P.Artoisenet, PoS ICHEP 2010 (2010) 192.



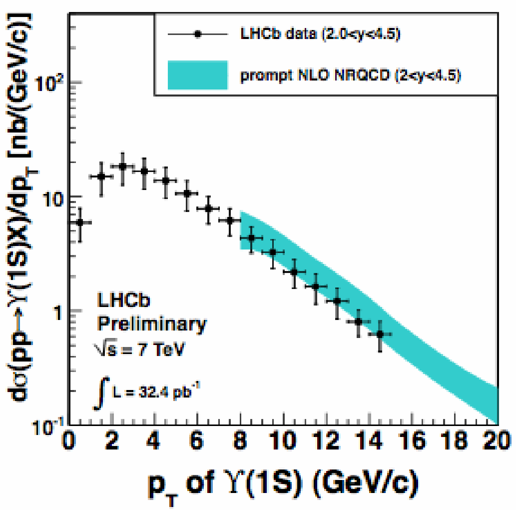


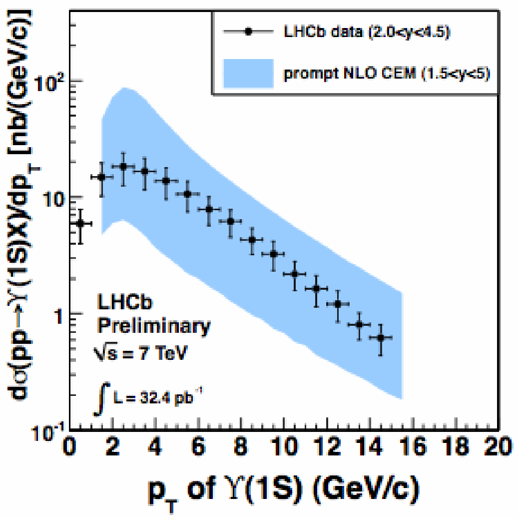
NLO & NNLO CSM

J.-P.Lansberg, Eur. Phys. J. **C** 61 (2009) 693

NLO NRQCD

Y.Q.Ma, K.Wang and K.T.Chao, Phys. Rev.Lett. 106 (2011) 042002.





NLO CEM

A.D.Frawley, T.Ullrich and R.Vogt, Phys. Rep. 462 (2008) 125.

Sources of $\Upsilon(1S)$

- Feed down from higher bottomonium states ($\Upsilon(2S)$, $\Upsilon(3S)$, χ_b, etc.) need to be understood in order to interpret the measurement of $\Upsilon(1S)$ production and study its polarization.
- CDF experiment analyzed the sources of $\Upsilon(1S)$ production based on statistics of RUN I period (90 pb^{-1}, $\sqrt{s}$=1.8 TeV, 1994-1995 years). PRL **84** (2000) 2094, hep-ex/9910025.
  For:
  - $pT(\Upsilon) > 8$ GeV/c
  - $|\eta(\Upsilon)| < 0.7$

  they obtain…

	Source	Fraction in %
calculated	Direct	50.9±8.2±9.0
35.3±9 events	$\chi_b(1P)$	27.1±6.9±4.4
28.5±12 events	$\chi_b(2P)$	10.5±4.4±1.4
from $\sigma(\Upsilon(2S))$ and *Br*$(\Upsilon(2S)\rightarrow\Upsilon(1S)\,\pi^+\pi^-$	$\Upsilon(2S)$	10.7+7.7-4.8
from $\sigma(\Upsilon(3S))$ and *Br*$(\Upsilon(3S)\rightarrow\Upsilon(1S)\,\pi^+\pi^-$	$\Upsilon(3S)$	0.8+0.6-0.4

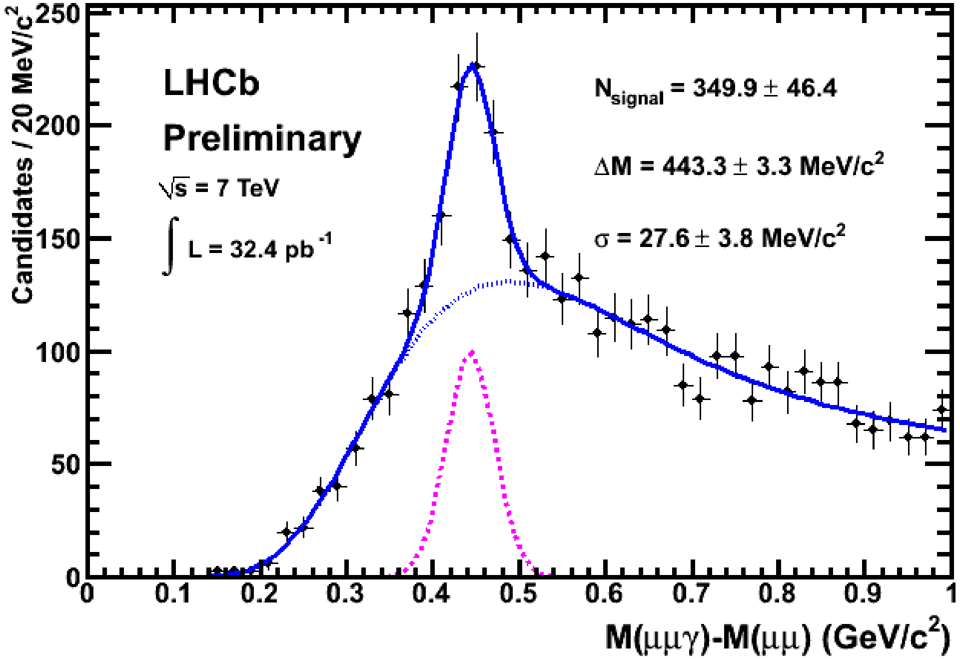
χ_b(1P) observation

χb selection criteria:

Υ(1S) mass band	9.36÷9.56 GeV/c^2
Polar angle of μ^+ in Υ rest frame	$\lvert\cos\theta^*_\mu\rvert < 0.7$
p_T of photon	$p_T(\gamma) > 700$ MeV/c
Polar angle of γ in χ_b rest frame	$\cos\theta^*_\gamma > 0$
p_T of χ_b candidate	$p_T(\chi_b) > 7$ GeV/c

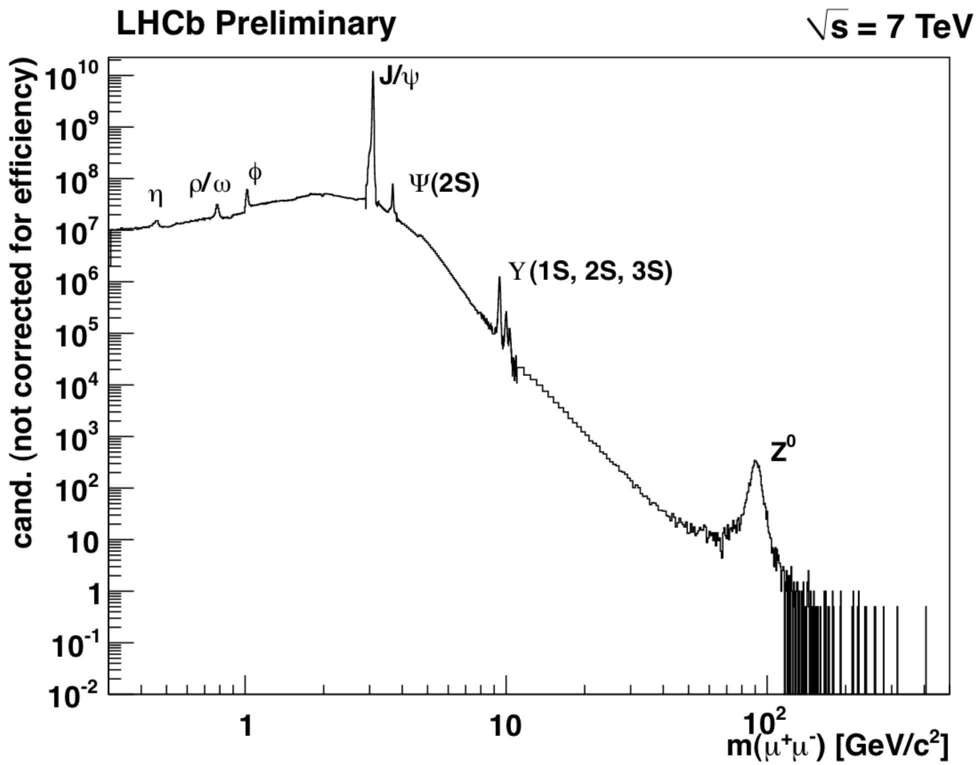
- A clear signal for χ_b(1P) production is seen.
- No hint for χ_b(2P) signal ($\Delta M \approx 800$ MeV/c^2).
- Cannot do a separation of the states (χ_{b0}(1P), χ_{b1}(1P), χ_{b2}(1P)) yet.
- Gaussian *(for signal)* + smooth background function is used for fitting to obtain the number of signal candidates.

$$\frac{dN}{dx} = A1 \cdot \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\Delta M)^2}{2\sigma^2}} + A2 \cdot (x - x_0)^{\alpha} \cdot e^{-(a1 \cdot x + a2 \cdot x^2 + a3 \cdot x^3)}$$



Quarkonia at LHCb

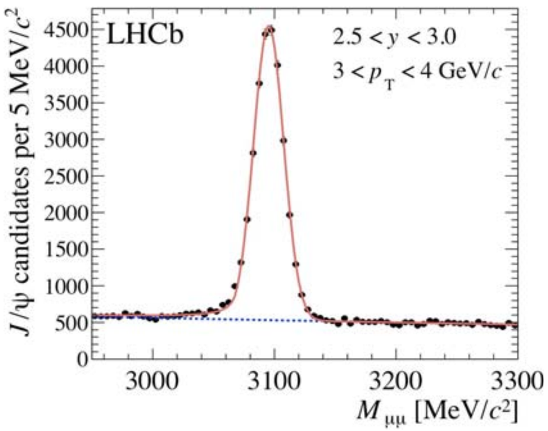
- Prompt quarkonia production probe NRQCD and help to understand color-singlet and color-octet contributions.
- LHCb has already a lot of interesting results:
  - Υ(1S) production cross-section
    LHCb-CONF-2011-016
  - J/ ψ production cross-section
    *Eur.Phys.J **C**71 (2011) 1645*
  - Double J/ψ production
    LHCb-CONF-2011-009
    arXiv: hep-ph/1109.0963v1
  - ψ(2S) production cross-section
    LHCb-CONF-2011-026
  - Inclusive X(3872) production
    LHCb-CONF-2011-043
  - χ_{c2}/χ_{c1} cross-sections ratio
    LHCb-CONF-2011-020

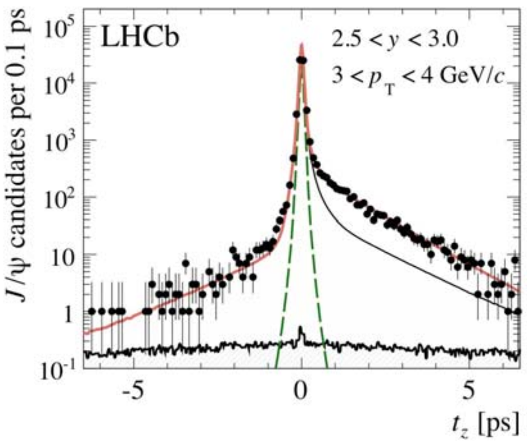


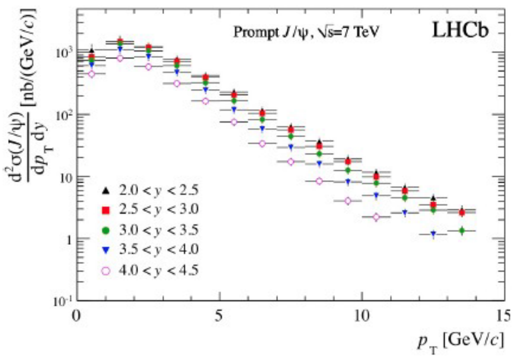
J/ψ production cross-section

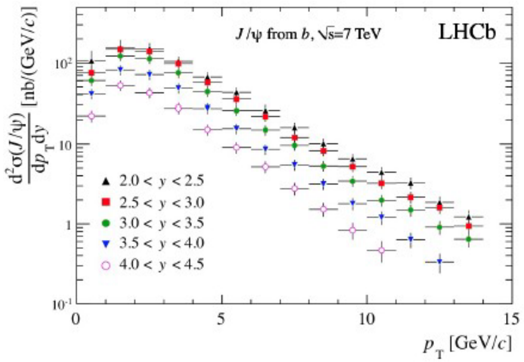
Performed on first data 5.2 pb^{-1}
with $J/\psi \rightarrow \mu\mu$

Eur. Phys. J. ***C****71 (2011) 1645*







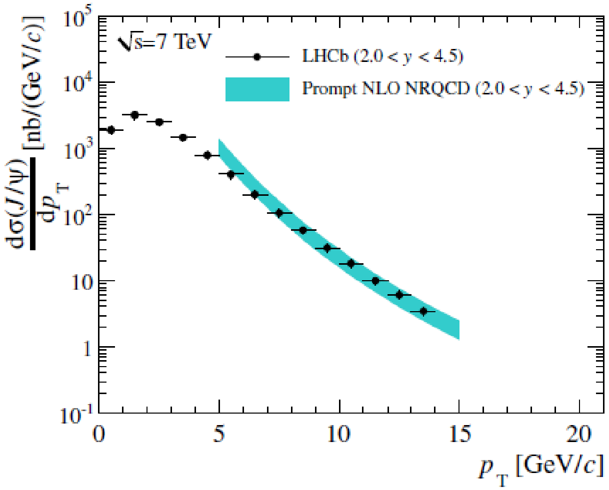


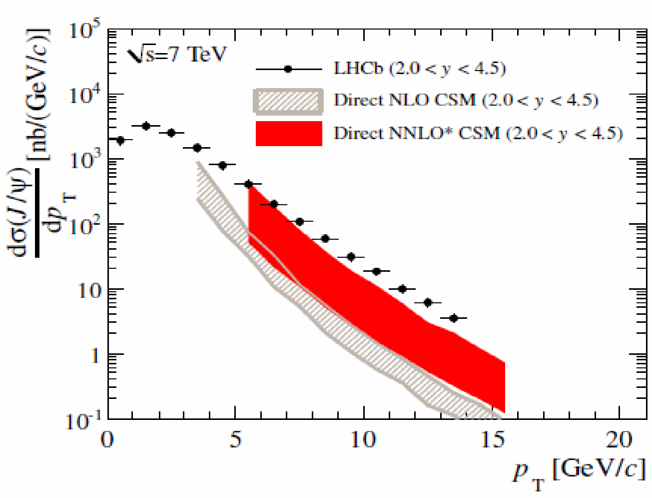
- Measured in bins of
  - rapidity $2.0<y<4.5$ (5 bins)
  - p_T $0<p_T<15$ GeV/c (15 bins)
- Prompt and J/ψ from b are subdivided using proper time
- $\sigma(\text{prompt})=10.52\pm0.04\pm1.40^{+1.64}_{-2.20}\,\mu b$
  the last error due to unknown polarization
- $\sigma(\text{from } \mathbf{b})=1.14\pm0.01\pm0.16\ \mu b$

J/ψ production cross-section

NLO NRQCD

K.T.Chao *et al.*
[Phys.Rev.Lett. **106** (2011) 042002, arXiv: hep-ph/1009.3655]



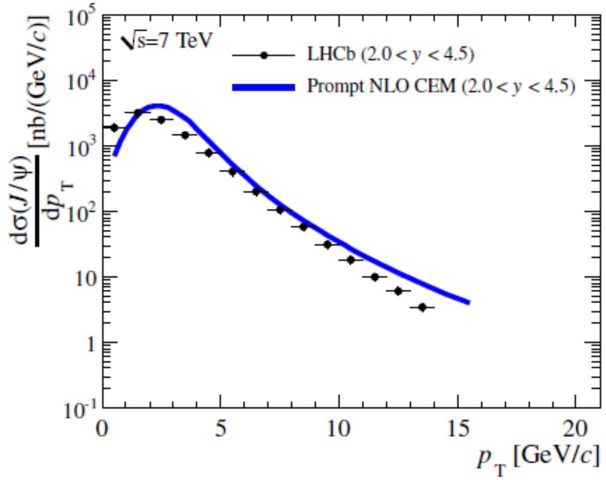


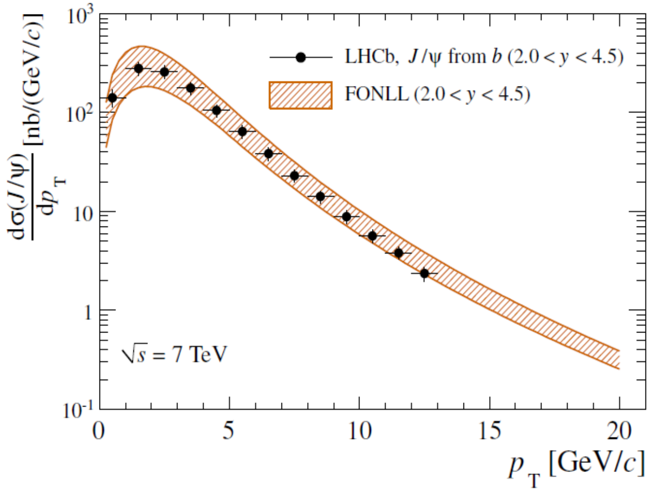
NLO CSM
NNLO CSM

J.-P. Lansberg
[Eur.Phys.J. **C**61 (2009) 693, arXiv: hep-ph/0811.4005]

NLO CEM

R.Vogt
[Phys.Rep. **462** (2008) 125, arXiv: nucl-ex/0806.1013]

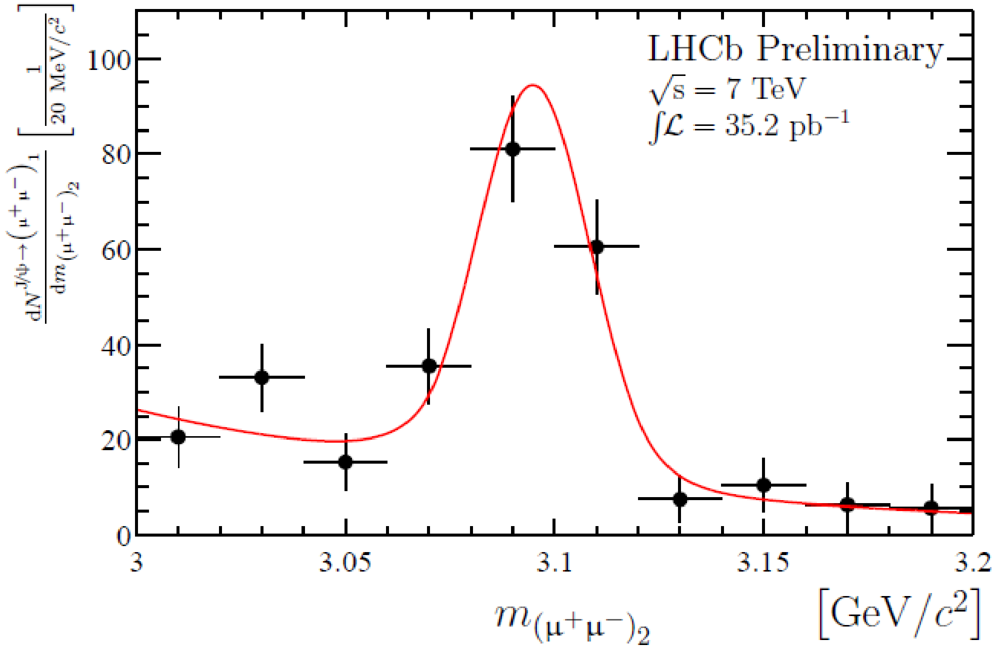




FONLL *(fron **b**)*
M.Cacciari, M.Greco, P.Nason,
[J. High Energy Phys. 9805 (1998) 007 hep-ph/9803400]
M.Cacciari, S.Frixione, P.Nason,
[J. High Energy Phys. 0103 (2001) 006 hep-ph/0102134]

Double J/ψ production

LHCb-CONF-2011-009
arXiv: hep-ph/1109.0963v1
Analysis performed on 2010 data

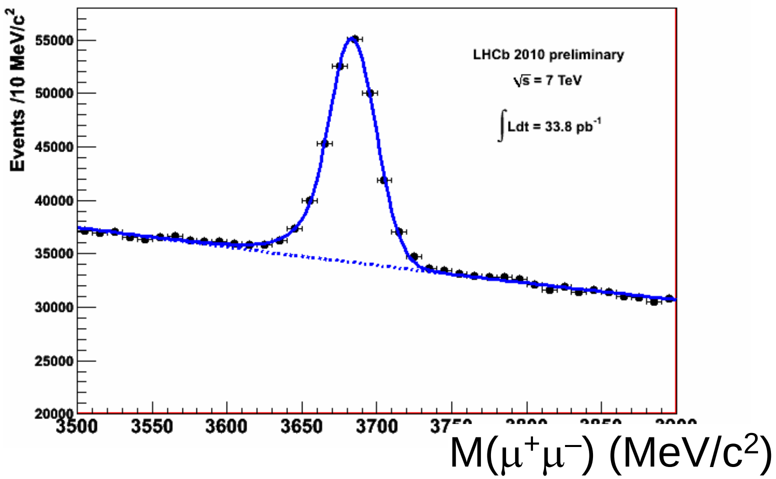


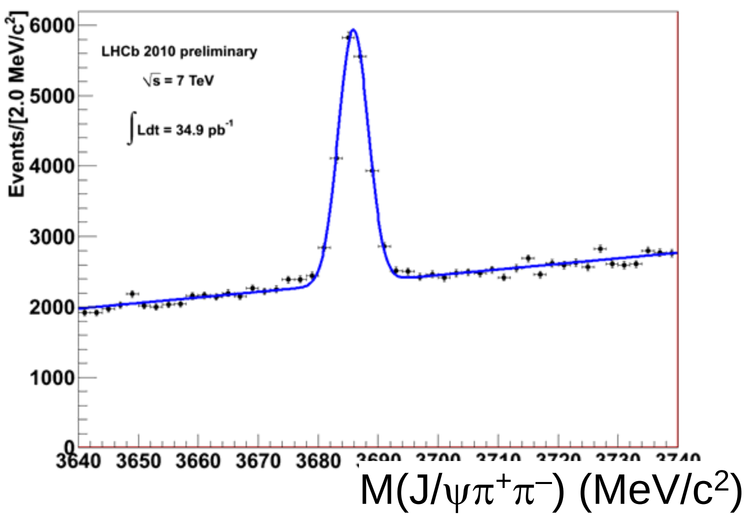
- 4 muons from the same vertex
- Fit $M(\mu^+\mu^-)_1$ in bins of $M(\mu^+\mu^-)_2$
- 140 ± 18 double J/ψ
- $\sigma(J/\psi\ J/\psi) = 5.6\pm1.1\pm1.2$ nb
- QCD calculations [A.V.Berezhnoy, *et al.*, arXiv: hep-ph/1101.5881v1], which does not includes non-direct J/ψ J/ψ, predicts:
  $\sigma(pp\to J/\psi\ J/\psi\ X) = 4.15\div4.34$ nb

$\psi(2S)$ production

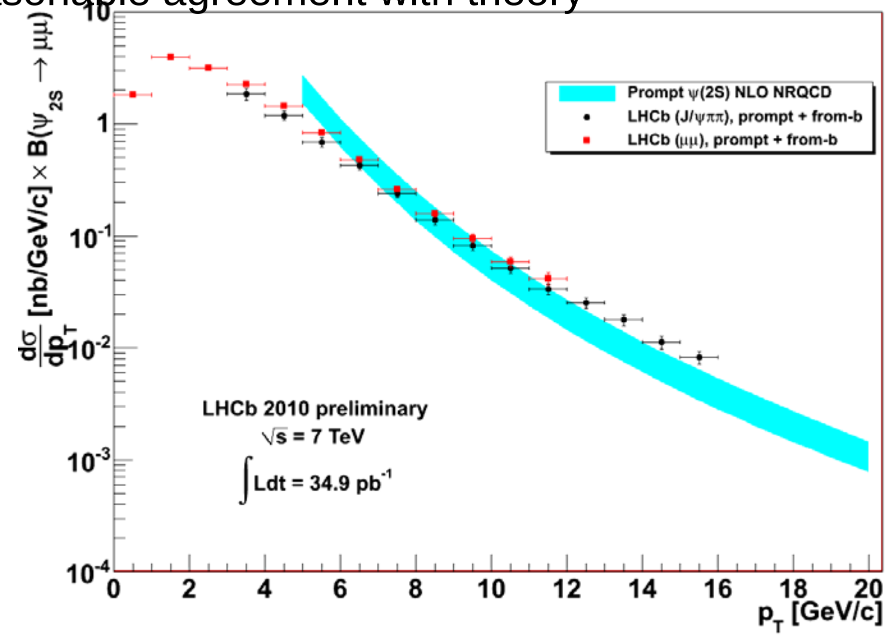
LHCb-CONF-2011-026

Analysis performed on 2010 data

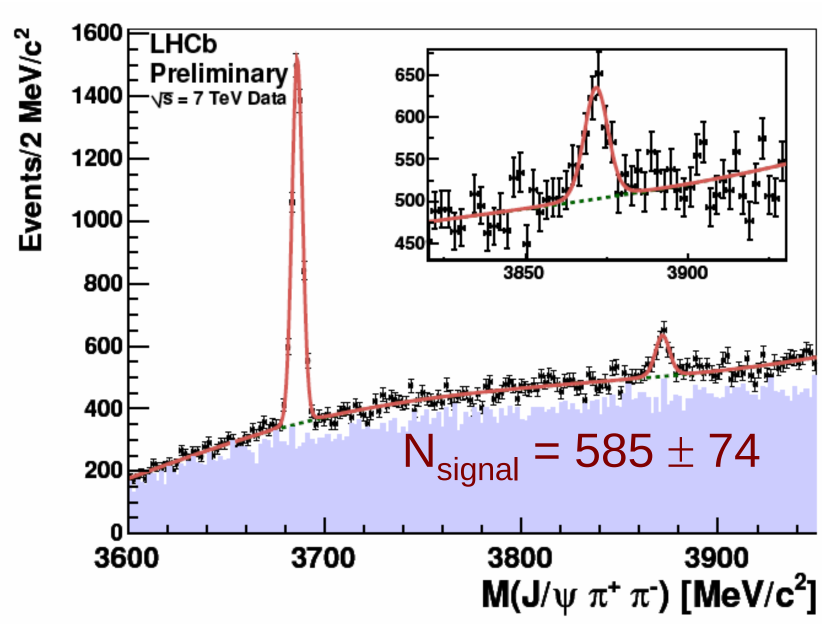


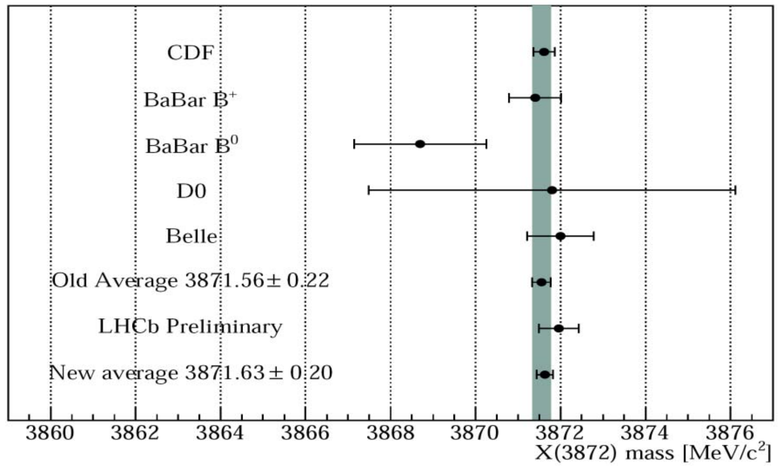


- Theoretically interesting state. No feed down contribution.
- Differential cross-sections measured:
  $\psi(2S) \to \mu^+\mu^-$
  $\sigma(0<p_T<12\ \mathrm{GeV/c};\ 2<y<4.5) = 1.88 \pm 0.02 \pm 0.31^{+0.25}_{-0.48}\ \mu b$
  $\psi(2S) \to J/\psi\ \pi^+\pi^-$
  $\sigma(3<p_T<16\ \mathrm{GeV/c};\ 2<y<4.5) = 0.62 \pm 0.04 \pm 0.12^{+0.07}_{-0.14}\ \mu b$
- Good agreement between two results
- Reasonable agreement with theory



X(3872) production and mass



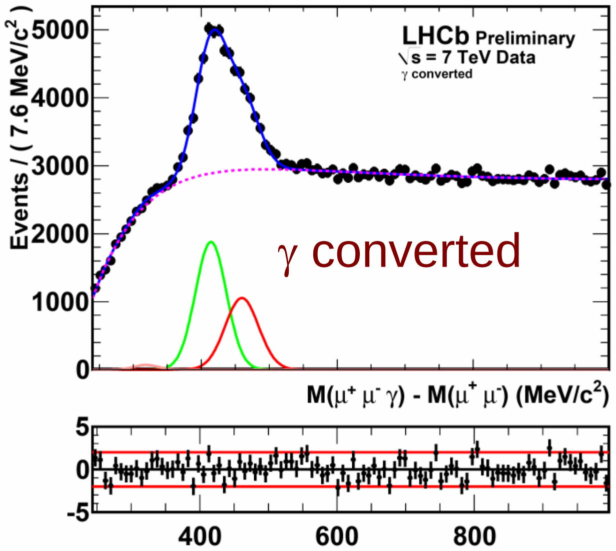


LHCb-CONF-2011-021
LHCb-CONF-2011-043
Analysis performed on 2010 data

$\int L = 34.7\ pb^{-1}$

- Exotic meson discovered by Belle in 2003 in b meson decays
  Nature still uncertain: most popular model is molecular state with $J^{PC} = 1^{++}$
- $M_{X(3872)} = 3871.96 \pm 0.46 \pm 0.10$ MeV/c^2
- $\sigma_{X(3872)} \times Br(X(3872) \to J/\psi\ \pi^+\pi^-) =$
  $= 4.74 \pm 1.10 \pm 1.01$ nb

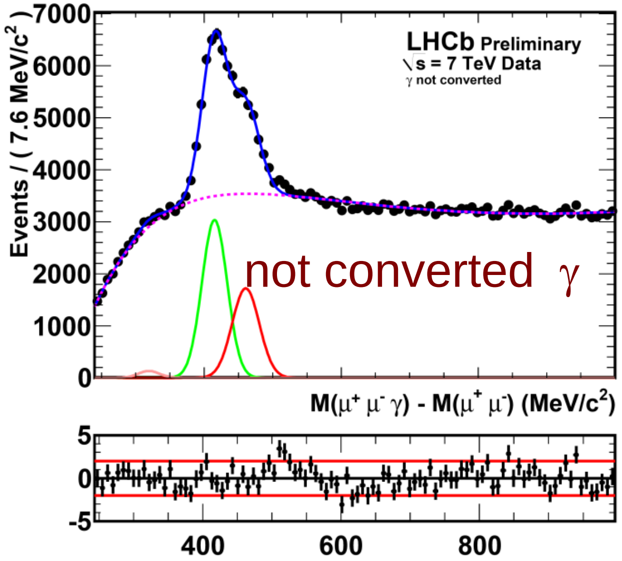
χ_{c2}/χ_{c1} cross-section ratio



LHCb-CONF-2011-020

Analysis performed on 2010 data

$\int L = 35.6\ pb^{-1}$

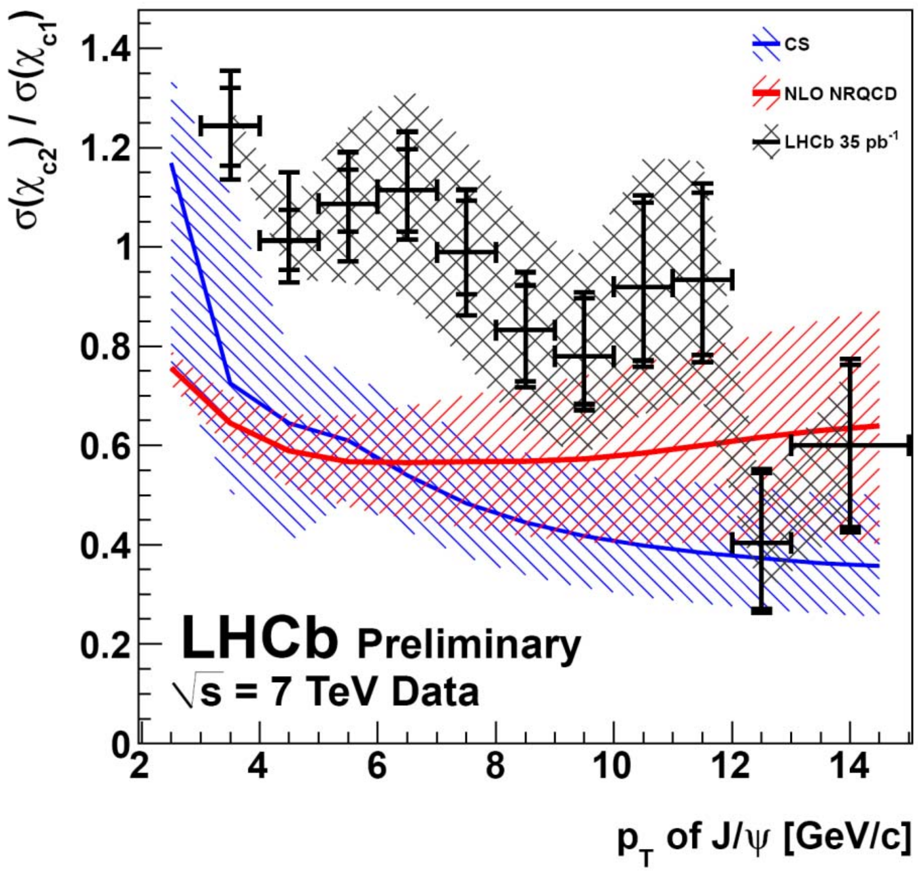


$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \cdot \frac{\varepsilon_{J/\psi}^{\chi_{c1}} \varepsilon_{\gamma}^{\chi_{c1}} \varepsilon_{\text{sel}}^{\chi_{c1}}}{\varepsilon_{J/\psi}^{\chi_{c2}} \varepsilon_{\gamma}^{\chi_{c2}} \varepsilon_{\text{sel}}^{\chi_{c2}}} \cdot \frac{Br(\chi_{c1} \to J/\psi\gamma)}{Br(\chi_{c2} \to J/\psi\gamma)}$$

- converted γ (e^+e^- clusters) and not converted γ (γ cluster) treated separately
- Efficiencies cancel out, lower systematic uncertainty

$$\frac{Br(\chi_{c1} \to J/\psi\gamma)}{Br(\chi_{c2} \to J/\psi\gamma)} = \frac{(34.4 \pm 1.5)\%}{(19.5 \pm 0.8)\%}$$

χ_{c2}/χ_{c1} cross-section ratio



- **Internal error bars**: statistical error from the yield extraction
- **External error bars**: systematic uncertainty included:
  - decay branching fractions
  - stability of fit
  - MC statistics
- **Shaded area (black)**: maximum effect of unknown polarization
- **Shaded area** – theory predictions:
  - **(red)**: CSM
  - **(blue)**: NLO NRQCD

Conclusion

- LHCb performs many analyses of quarkonium states using 2010 collected data
  - Υ(1S)
  - J/ψ (separately prompt and non-prompt)
  - double J/ψ
  - ψ(2S)
  - χ_{c2} to χ_{c1} cross-section ratio
- These results are useful to test theoretical models
- Good agreement of cross-section (J/ψ,ψ(2S),Υ(1S)) measurements with NRQCD
- The experimental error is lower than the theoretical one

- LHCb collect high statistics in 2011
  - more than 800 pb^{-1} collected do far
  - 1 fb^{-1} expected at the end of 2011
  - a lot of new results expected in the future