Review of LHC Results on Onia

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Andrea Coccaro
University of Genoa / INFN

on behalf of the ALICE, ATLAS,
CMS and LHCb collaborations

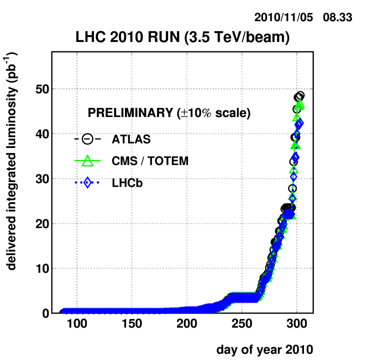
Outline

Timeline

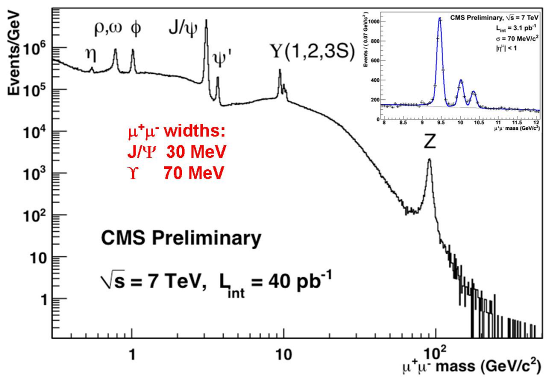
- $\int \mathcal{L} \sim 10\ \mathrm{nb}^{-1}$: understand detector performance
- $\int \mathcal{L} \sim 10\ \mathrm{pb}^{-1}$: first measurements of B hadrons, J/Ψ and Υ to test QCD predictions at the TeV scale
- $\int \mathcal{L} \sim 1\ \mathrm{fb}^{-1}$: limits on rare decay branching ratios and contribution to world averages on several particle properties
- ....

Where we are?

- 45 pb^{-1} collected by LHC experiments in 2010
- wonderful job by machine and experiments
- excellent detector performance and already lot of public results



Di-muon resonances



- lot of information condensed: in this context a nice snapshot of onia production!

Onia production at the LHC

Motivations

1. constrain QCD quarkonium production models
   $\Rightarrow$ no theory can simultaneously explain experimental measurements of both cross section and polarization
2. ingredient for exclusive decays studies, i.e. $B \to J/\Psi X$
3. suppression mechanism in heavy-ion collisions
4. perfect candidate for detector performance studies

With 2010 data

- J/Ψ inclusive production cross-section (ALICE, ATLAS, CMS and LHCb)
- J/Ψ non-prompt fraction (ATLAS, CMS and LHCb)
- J/Ψ production in Pb-Pb collisions (ATLAS)
- double J/Ψ inclusive production cross-section (LHCb)
- Υ inclusive production cross-section (CMS and LHCb)

Not possible to cover all analyses in detail here!

Inclusive J/Ψ cross-section analysis (ATLAS)

- single muons and minimum bias triggers
- select events with at least 2 muons and at least one of which is MS-ID combined
- di-muon invariant mass using ID tracks associated to a vertex and to muons
- each J/Ψ candidate is weighted by a correction factor w

$$w^{-1} = \mathcal{A} \cdot \mathcal{M} \cdot \epsilon$$

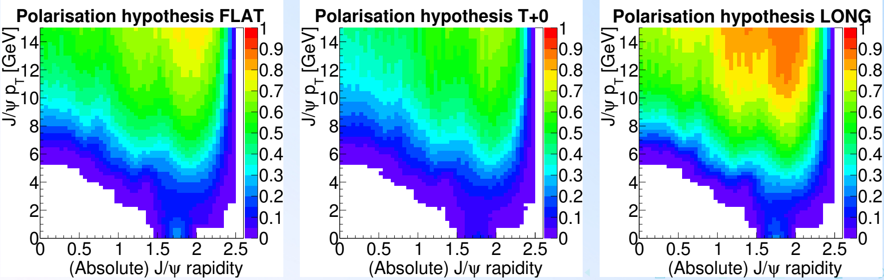
  $\mathcal{A}$: acceptance which depends on spin alignment
  $\mathcal{M}$: factor to take into account bin migrations due to resolution effects
  ϵ: global efficiency taking into account trigger, track and muon reconstruction

- number of J/Ψ is obtained using a binned minimum-χ^2 fit to the di-muon mass distribution
- measurement presented in momentum and rapidity bins

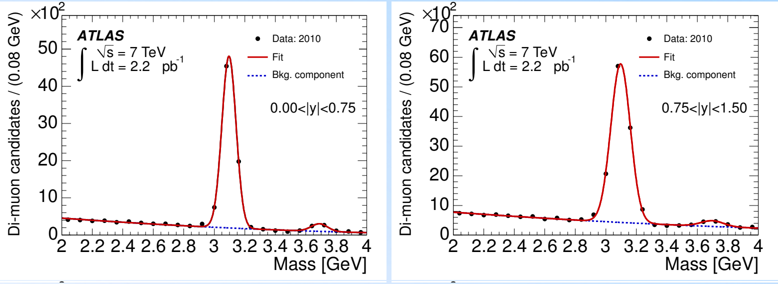
$$\frac{d^2\sigma(J/\Psi)}{dp_T dy} \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = \frac{N_{corr}^{J/\Psi}}{\mathcal{L}\Delta p_T \Delta y} \quad ; \quad N_{corr}^{J/\Psi} = N_{J/\Psi} \cdot w$$

Detector acceptance for J/Ψ analysis (ATLAS)

- $\mathcal{A}$ is the acceptance that muons from J/Ψ decays are produced in the fiducial volume of the detector
- the muon angular distribution is correlated with the J/Ψ spin alignment, which is not known at the LHC energies and depends on the production mechanism
- five spin-alignment cases are considered to study the different acceptance within the ATLAS detector
- isotropic distribution is the baseline while the other scenarios are considered for systematics studies



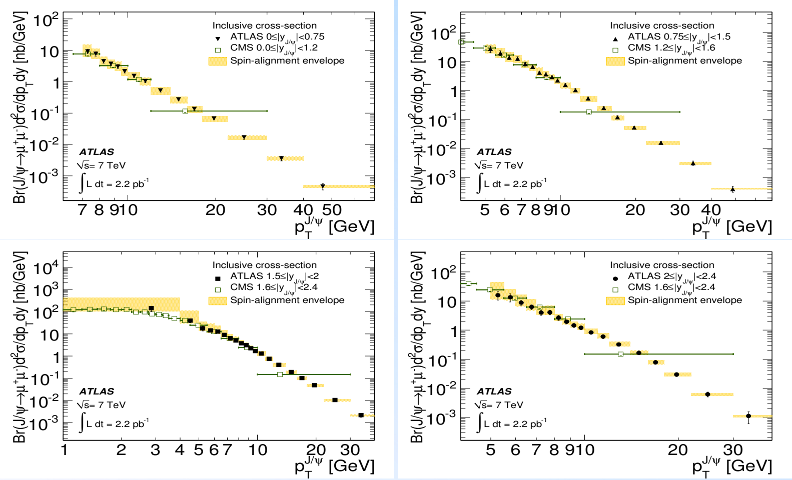
Observed J/Ψ signal (ATLAS)



	$0.0 \leq \lvert y \rvert < 0.75$	$0.75 \leq \lvert y \rvert < 1.5$	$1.5 \leq \lvert y \rvert < 2.0$	$2.0 \leq \lvert y \rvert < 2.4$
Signal yield	6710 ± 90	10710 ± 120	9630 ± 130	4130 ± 90
Mass [GeV]	3.096 ± 0.001	3.097 ± 0.001	3.097 ± 0.001	3.109 ± 0.002
Resolution [MeV]	46 ± 1	64 ± 1	84 ± 1	111 ± 2

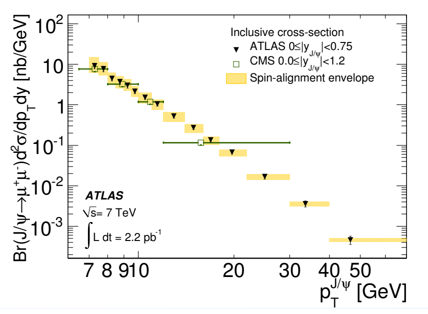
- gaussian fit for signal and quadratic polynomial for background
- irreducible background: $c/b \to \mu + X$ and π/K decays in flight

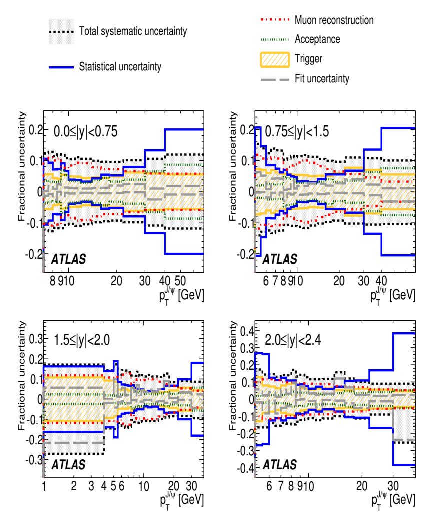
Inclusive J/Ψ cross-section (ATLAS)



- CMS result with higher statistics is shown later

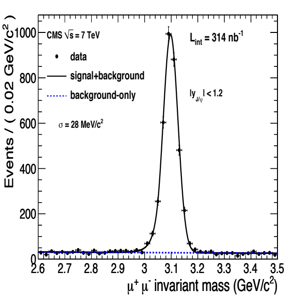
Inclusive J/Ψ cross-section (ATLAS)

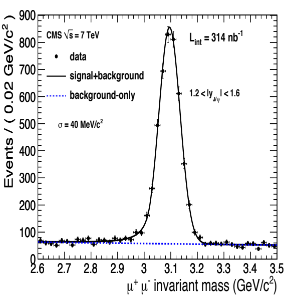


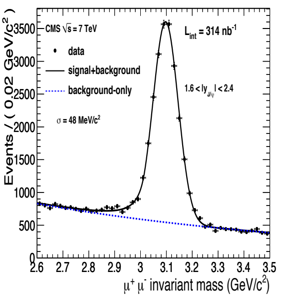


- main error systematic contribution from muon reconstruction efficiency measurement
- good agreement with CMS and good complementarity in the p_T spectrum

Observed J/Ψ signal (CMS)



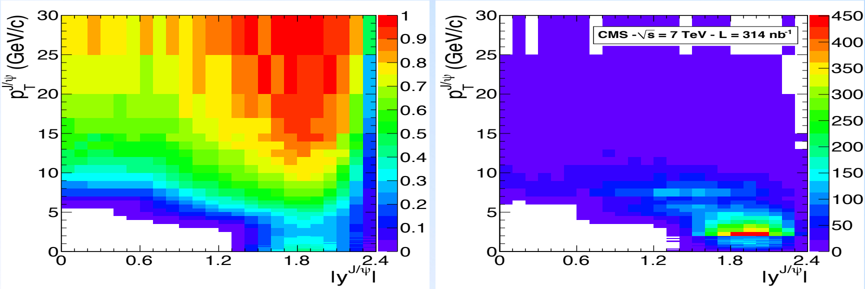




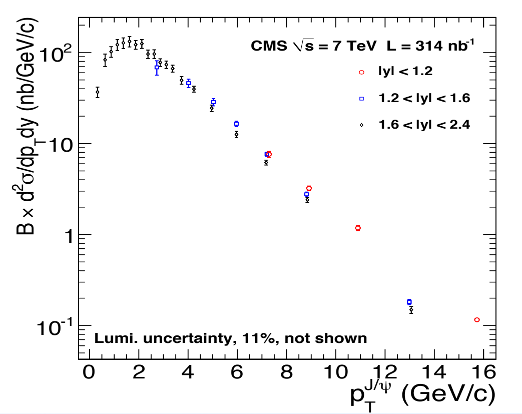
- similar analysis
- Crystal Ball function plus exponential fit

Detector acceptance for J/Ψ analysis (CMS)

- isotropic distribution corresponding to unpolarized J/Ψ production taken as reference
- other polarization scenarios are considered for systematic studies



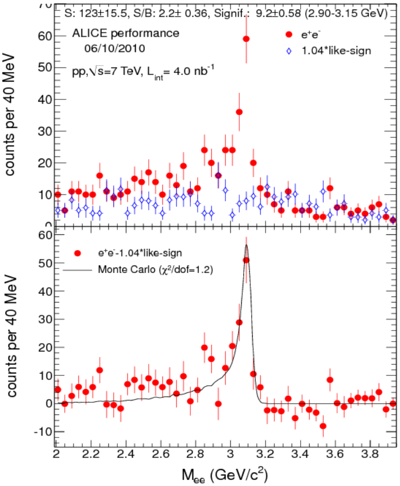
Inclusive J/Ψ cross-section (CMS)



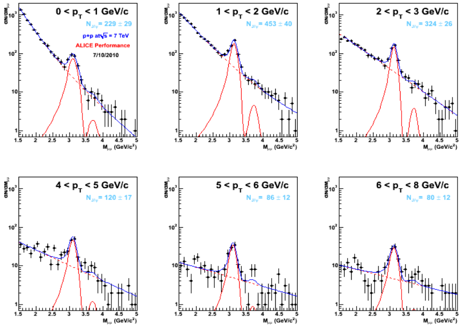
- three different rapidity intervals
- unpolarized production scenario

Observed J/Ψ signal (ALICE)

ee, mid-y

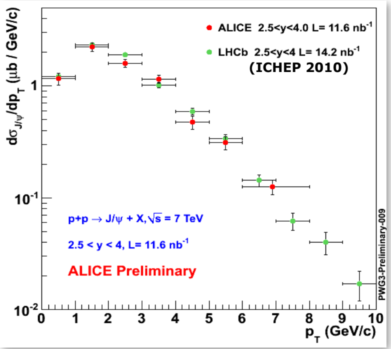


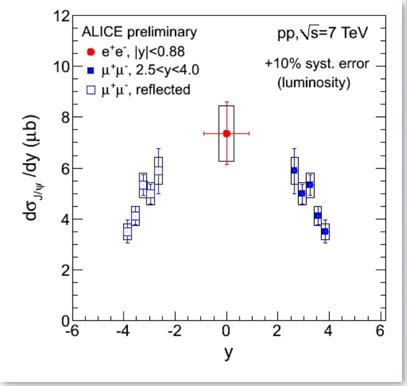
mum, forward y



Inclusive J/Ψ cross-section (ALICE)

- J/psi→$\mu\mu$ in 2.5<y<4 and p_t>0
- J/psi→ee in |y|<0.9 and p_t>0





Final results coming soon: including $d\sigma/dp_t$ at y=0 down to p_t=0

J/Ψ prompt to non-prompt ratio analysis (LHCb)

- J/Ψ from B-decays can be separated due to the typical lifetime of B hadrons ($\tau \sim 1.6$ ps and $< l >= \beta\gamma c\tau \sim 3$ mm)
- the J/Ψ pseudo-proper time is a good discriminator:

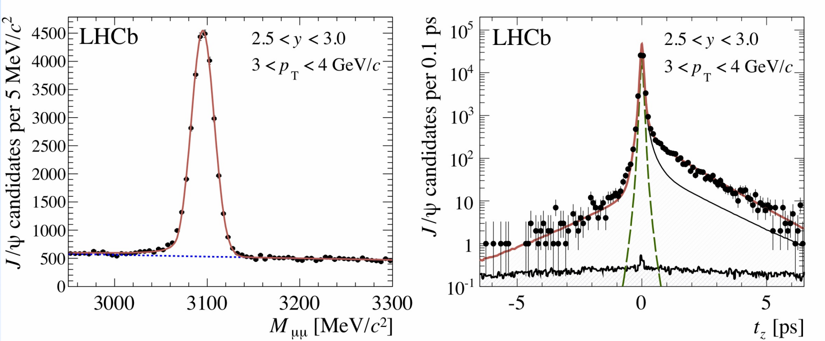
$$t = \frac{(z_{J/\Psi} - z_{PV}) \cdot M_{J/\Psi}}{p_z}$$

  $z_{J/\Psi}$, z_{PV}: coordinate along the beam axis of the J/Ψ and primary vertex positions
  p_z: J/Ψ momentum along the beam axis
- differential measurement

$$\frac{d^2\sigma}{dydp_T} = \frac{N(J/\Psi \to \mu^+\mu^-)}{\mathcal{L} \cdot \epsilon_{tot} \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) \cdot \Delta y \cdot \Delta p_T}$$

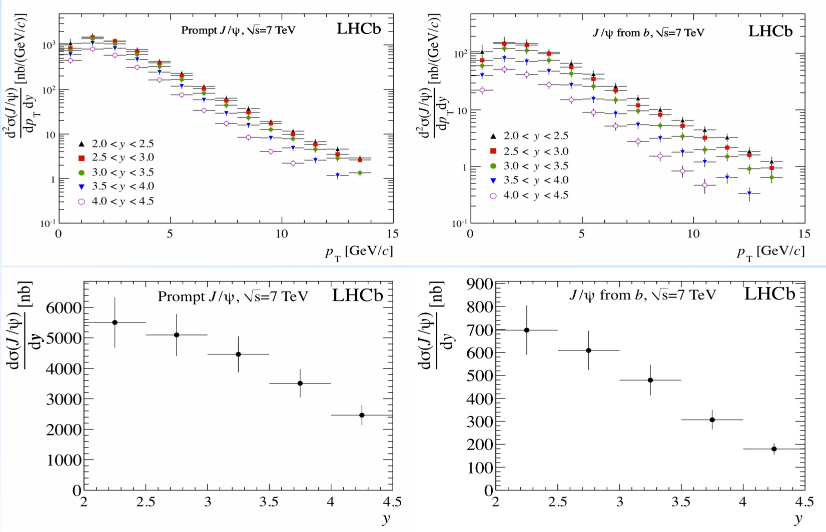
- in each bin the fraction of signal J/Ψ from all sources is estimated from an extended unbinned maximum likelihood fit to the invariant mass distribution of the reconstructed J/Ψ in the invariant mass interval $2.95 < M_{jj} < 3.30$ GeV

J/Ψ prompt to non-prompt ratio (LHCb)

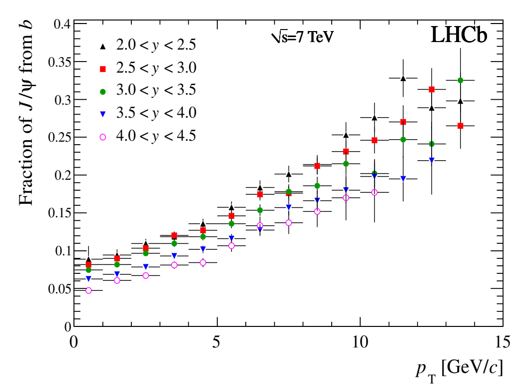


- delta function to describe the proper-time distribution at $t_z = 0$ for the prompt J/Ψ signal
- exponential decay function for the J/Ψ from the b component
- long tail from events with a wrongly associated primary vertex

J/Ψ prompt to non-prompt ratio (LHCb)



J/Ψ prompt to non-prompt ratio (LHCb)

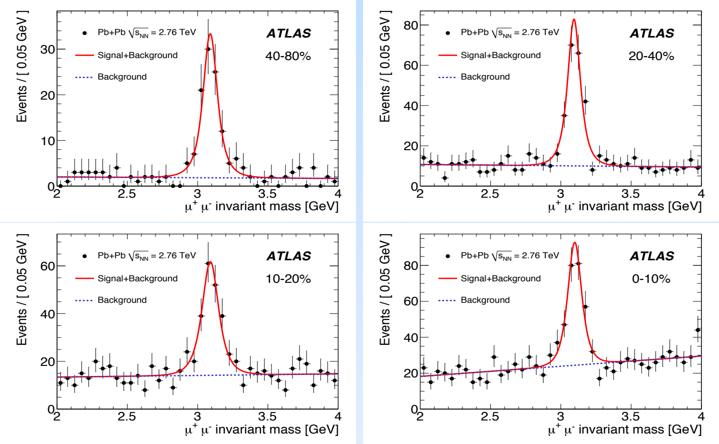


- assuming unpolarized prompt J/Ψ production
- fraction of J/Ψ from b increases (decreases) as a function of p_T (y)
- using the average $\mathcal{B}(b \to J/\Psi X) = (1.16 \pm 0.10)\%$ from LEP a total cross section $\sigma(pp \to b\bar{b}X) = 288 \pm 4 \pm 48\ \mu$b is estimated

Total J/Ψ cross-section at 7 TeV proton collisions

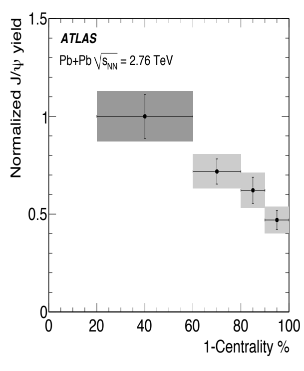
- ALICE
  $\Rightarrow 2.5 < |y| < 4,\ p_T > 0$ GeV and assuming unpolarized scenario
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 7.25 \pm 0.29(stat) \pm 0.98(syst) \pm^{0.87}_{1.50}(spin)\mu\text{b}$$
  $\Rightarrow |y| < 0.88,\ p_T > 0$ GeV and assuming unpolarized scenario
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 7.36 \pm 1.22(stat) \pm 1.32(syst) \pm^{0.88}_{1.84}(spin)\mu\text{b}$$
- ATLAS
  $\Rightarrow |y| < 2.4,\ p_T > 7$ GeV and assuming unpolarized scenario
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 81 \pm 1(stat) \pm 10(syst) \pm^{25}_{20}(spin) \pm 3(lumi)\text{nb}$$
  $\Rightarrow 1.5 < |y| < 2.0,\ p_T > 1$ GeV and assuming unpolarized scenario
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 510 \pm 70(stat) \pm^{84}_{123}(syst) \pm^{919}_{134}(spin) \pm 17(lumi)\text{nb}$$
- CMS
  $\Rightarrow |y| < 2.4,\ 6.5 < p_T < 30$ GeV and assuming unpolarized scenario
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 97.5 \pm 1.5(stat) \pm 3.4(syst) \pm 10.7(lumi)\text{nb}$$
- LHCb
  $\Rightarrow 2 < |y| < 4.5,\ p_T < 14$ GeV and assuming unpolarized scenario (prompt)
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 10.52 \pm 0.04 \pm 1.40^{+1.64}_{-2.20}\mu\text{b}$$
  $\Rightarrow 2 < |y| < 4.5,\ p_T < 14$ GeV and assuming unpolarized scenario (from b)
  $$\sigma(pp \to J/\Psi X) \cdot \mathcal{B}(J/\Psi \to \mu^+\mu^-) = 1.14 \pm 0.01 \pm 0.16\mu\text{b}$$

J/Ψ yields in lead collisions (ATLAS)



- from most peripheral $(40 - 80\%)$ to most central $(0 - 10\%)$ lead-lead collision events

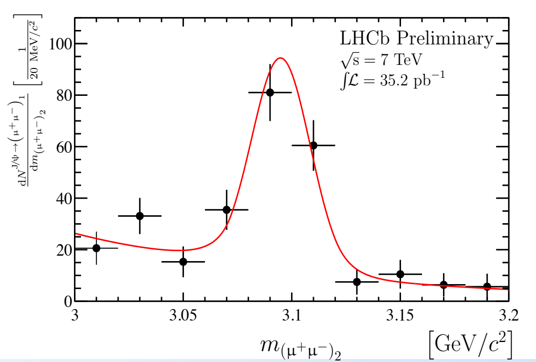
J/Ψ centrality dependent suppression (ATLAS)



Centrality	Yield	$\epsilon/\epsilon_{40-80}$	Syst error
$0-10\%$	190 ± 20	0.93 ± 0.01	8.6%
$10-20\%$	152 ± 16	0.91 ± 0.02	8.4%
$20-40\%$	180 ± 16	0.97 ± 0.01	7.5%
$40-80\%$	91 ± 10	1	6.1%

- significant decrease from peripheral to central collisions
- same trend highlighted in the jet quenching ATLAS paper

Double J/Ψ cross section (LHCb)



- integrated cross section $\sigma^{J/\Psi J/\Psi} = 5.6 \pm 1.1 \pm 1.2$nb
- theoretical prediction $\sigma^{J/\Psi J/\Psi} \sim 4.34$nb

Inclusive Υ cross-section analysis (CMS)

- di-muon event selection with invariant mass between 8 and 12 GeV
- fit with a vertex constraint requiring a χ^2 probability larger than 0.1%
- muons are required to have $p_T > 3.5$ GeV if $|\eta| < 1.6$ and $p_T > 2.5$ GeV if $|\eta| < 2.4$ to ensure high acceptance in the phase space used by the analysis
- each Υ candidate is weighted by a correction factor w

$$w^{-1} = \mathcal{A} \cdot \epsilon$$

  $\mathcal{A}$: acceptance which again depends on spin alignment
  ϵ: global efficiency taking into account trigger, track and muon reconstruction
- acceptance is studied with a dedicated MC Υ sample using the unpolarized scenario:

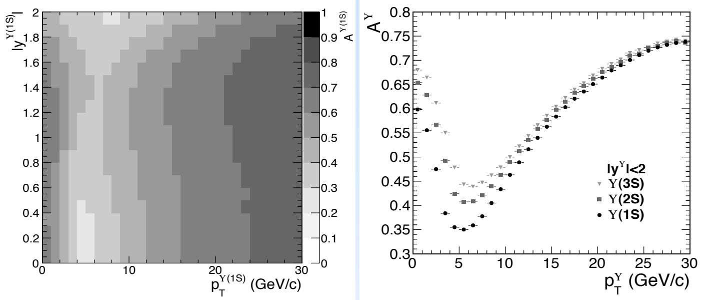
$$\mathcal{A}(\Delta p_T, \Delta y) = \frac{N^{Y}_{rec}(\Delta p_T, \Delta y)}{N^{Y}_{gen}(\Delta p_T, \Delta y)}$$

- measurement presented in momentum bins and $|y| < 2$

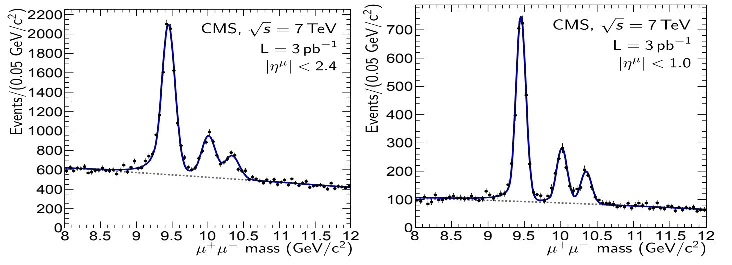
$$\frac{d\sigma(pp \to Y(nS))}{dp_T} \cdot \mathcal{B}(Y(nS) \to \mu^+\mu^-) = \frac{N^{\Upsilon}_{corr}}{\mathcal{L}\Delta p_T} \quad ; \quad N^{\Upsilon}_{corr} = N_{\Upsilon} \cdot w$$

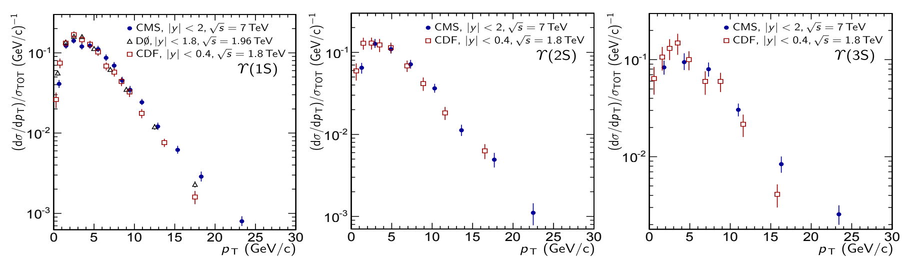
Detector acceptance for Υ analysis (CMS)

- $\mathcal{A}$ is the acceptance that muons from Υ decays are produced in the fiducial volume of the detector
- same arguments described for the J/Ψ analysis apply here
- isotropic distribution consequence of the unpolarized scenario is the baseline while the other scenarios are considered for systematics studies

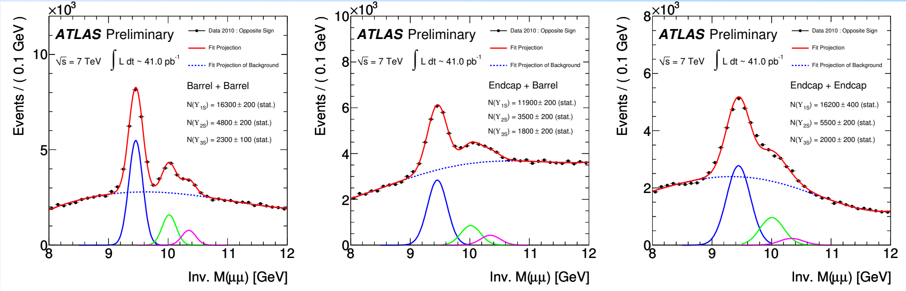


Observed Υ signal and cross section (CMS)



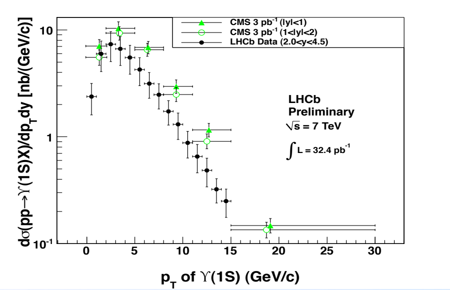


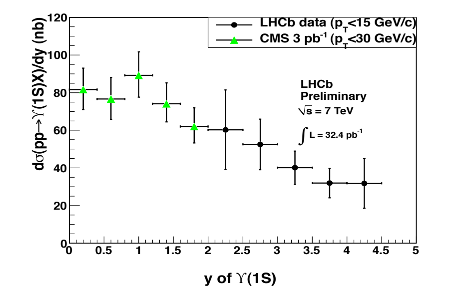
Observed Υ signal (ATLAS)



- similar selection described in J/Ψ analysis
- different mass resolution depending on η regions

Inclusive Υ cross section (LHCb)





- complementarity in CMS and LHCb in terms of explored phase space

Total Υ cross-section at 7 TeV proton collisions

- CMS
  $\Rightarrow |y| < 2$, $p_T < 30$ GeV and assuming unpolarized scenario

$$\sigma(pp \rightarrow \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 7.37 \pm 0.13(stat) \pm^{0.61}_{0.42} (syst) \pm 0.81(lumi)\text{nb}$$
$$\sigma(pp \rightarrow \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \rightarrow \mu^+\mu^-) = 1.90 \pm 0.09(stat) \pm^{0.20}_{0.14} (syst) \pm 0.24(lumi)\text{nb}$$
$$\sigma(pp \rightarrow \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \rightarrow \mu^+\mu^-) = 1.02 \pm 0.07(stat) \pm^{0.11}_{0.08} (syst) \pm 0.11(lumi)\text{nb}$$

- LHCb
  $\Rightarrow 2 < |y| < 4.5$, $0 < p_T < 15$ GeV and assuming unpolarized scenario

$$\sigma(pp \rightarrow \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 108.3 \pm 0.7 \pm^{30.9}_{25.8} \text{ nb}$$

- all results for the unpolarized scenario
- extreme scenario yield variations by 20% in the final cross section

Conclusions

- mechanism for quarkonia production and spin alignment to be understood. LHC data is crucial for deeper understanding
- more than $\sim 10^6$ J/Ψ and $\sim 10^5$ Υ in the data analyzed by LHC experiments so far and more precise cross-section and polarization measurements are expected in 2011
- nice agreement between various experiments but also different phase-space analyzed by the different collaborations
- quarkonia production also actively explored in heavy ion collisions