XIV International Conference on Hadron Spectroscopy
München, 13-17 June 2011

# Results on charmonium and charmonium-like production from the LHC

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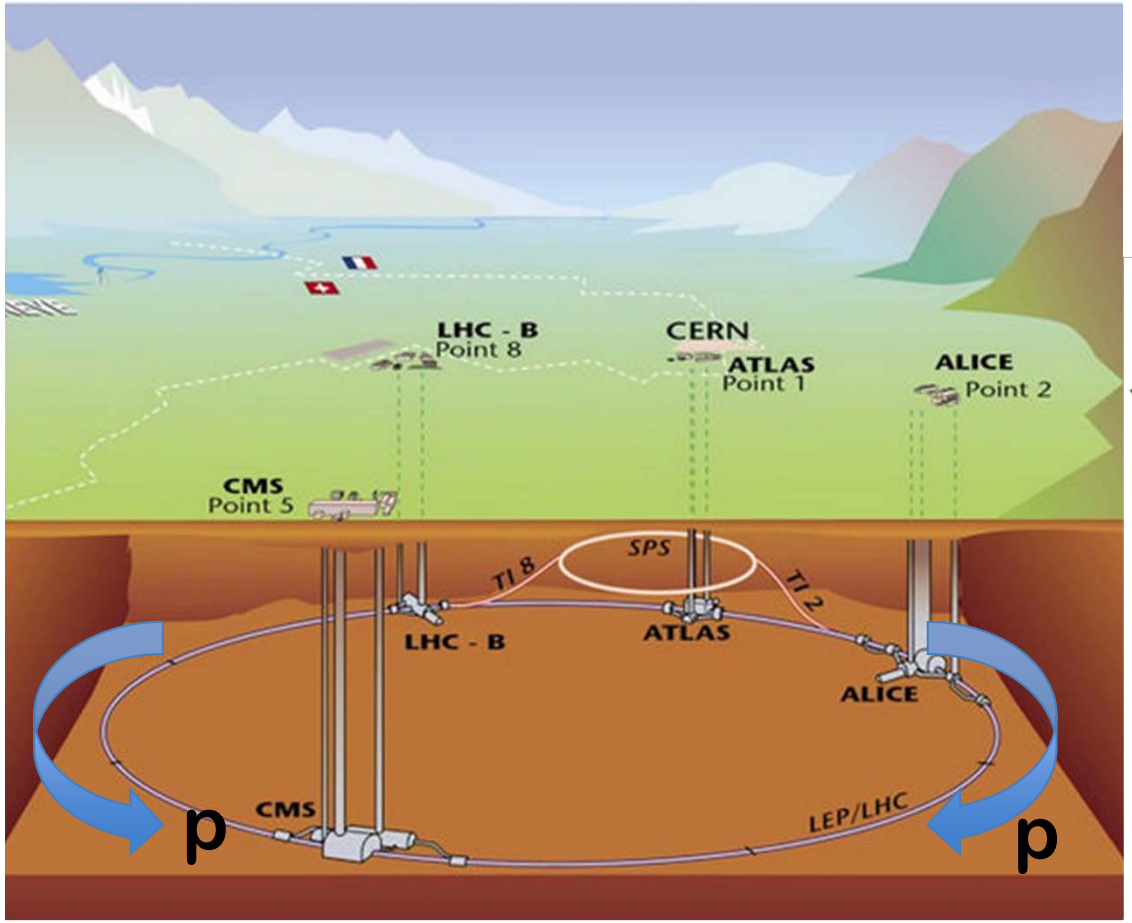
On behalf of the ALICE, ATLAS, CMS and LHCb Collaborations

# Outline

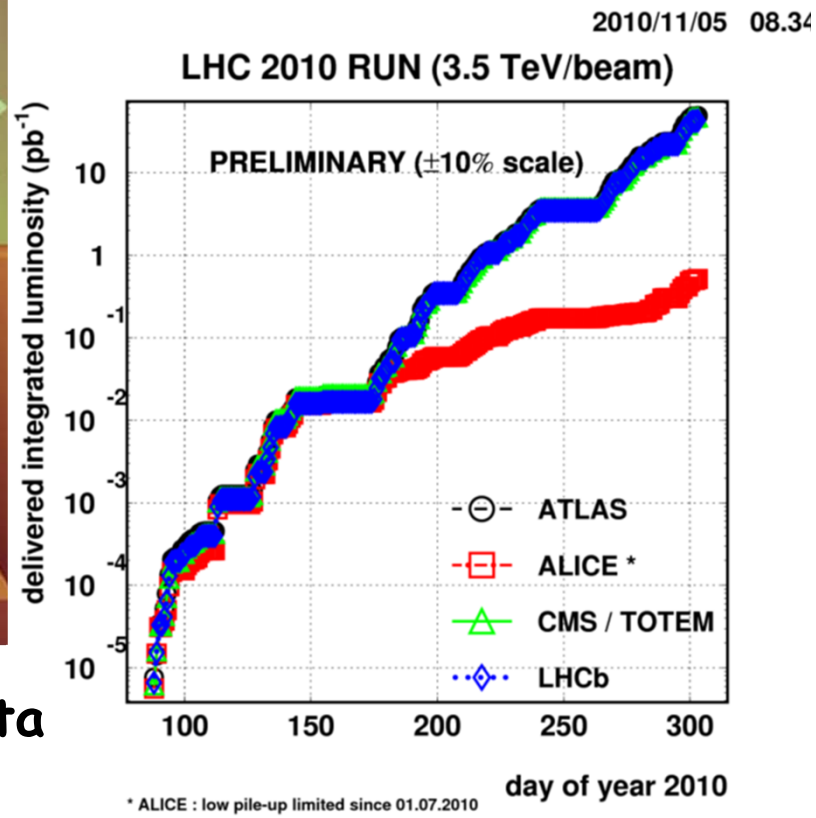
- LHC and ALICE, ATLAS, CMS, LHCb
- $J/\psi$ productions: single, double & central exclusive
- $\psi(2S)$ production
- $\chi_{c1,2}$ cross-section ratio measurement
- X(3872) production and mass measurement
- Early results on $B_c$ production
- Summary

# LHC in 2010-2011



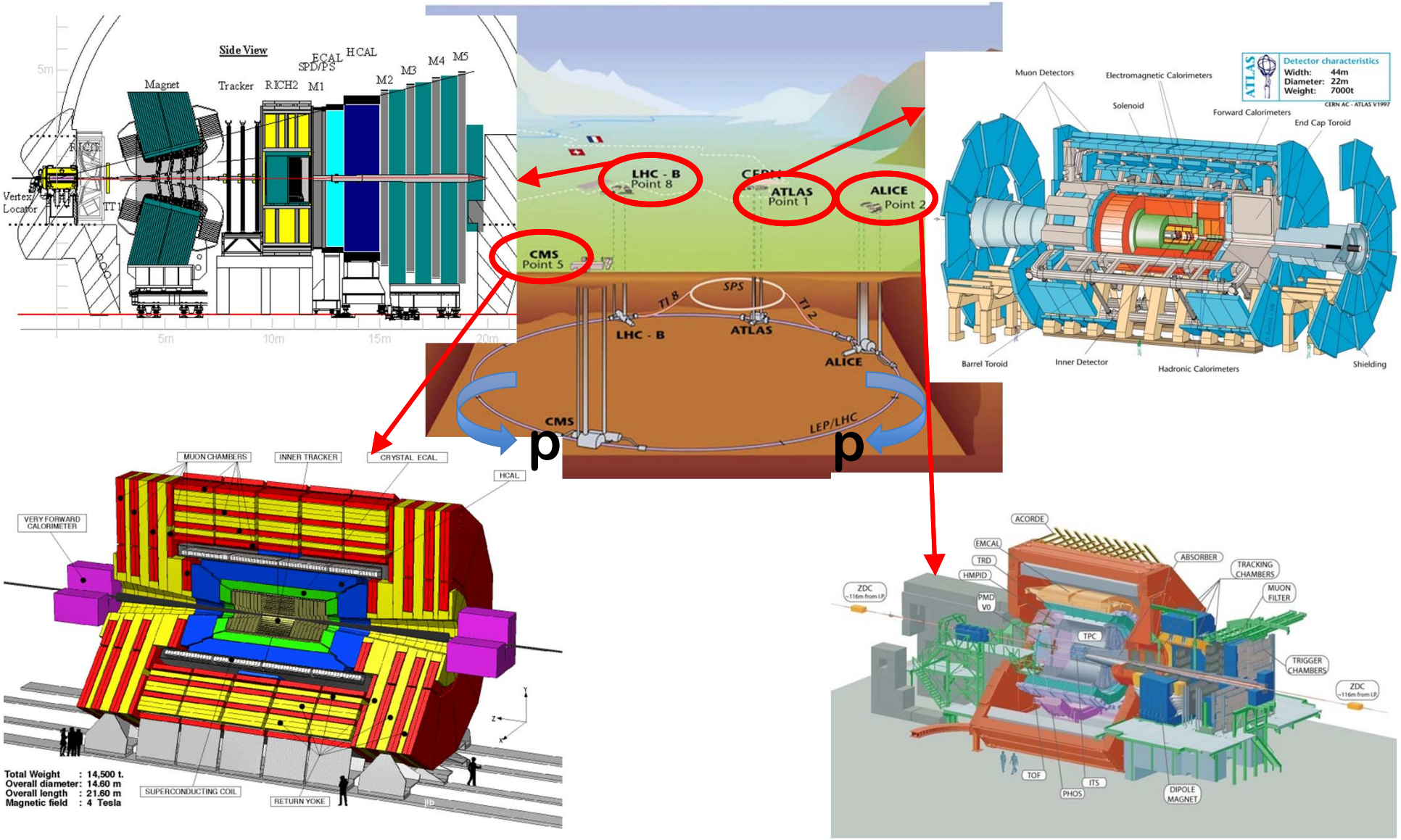

pp collider 2010-2011:

- ➡ @ $\sqrt{s}$ = 7 TeV
- ➡ L ≈ $10^{31}$ - $10^{33}$ $cm^{-2}$ $s^{-1}$

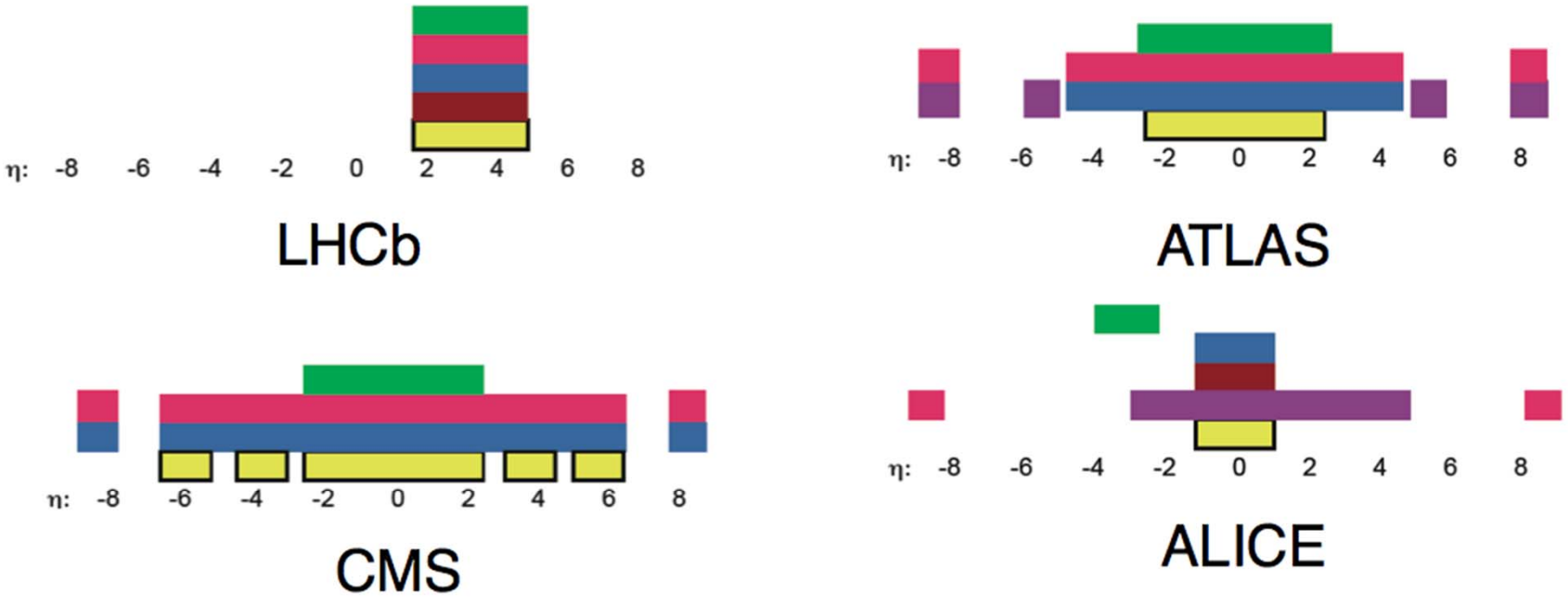



In THIS talk: results based on 2010 data ( up to 40$pb^{-1}$)

# Detectors


Side View
Magnet
Tracker
RICH2
M1
SPD/PS
ECAL
HCAL
M2
M3
M4
M5
Vertex Locator
TT
5m
10m
15m
20m
LHC - B
Point 8
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
p
p
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
MUON CHAMBERS
INNER TRACKER
CRYSTAL ECAL
HCAL
VERY FORWARD CALORIMETER
Total Weight : 14,500 t.
Overall diameter: 14.60 m
Overall length : 21.60 m
Magnetic field : 4 Tesla
SUPERCONDUCTING COIL
RETURN YOKE
ACORDE
EMCAL
TRD
HMPID
ZDC
PMD
V0
ABSORBER
TRACKING CHAMBERS
MUON FILTER
TPC
TRIGGER CHAMBERS
ZDC
TOF
PHOS
ITS
DIPOLE MAGNET

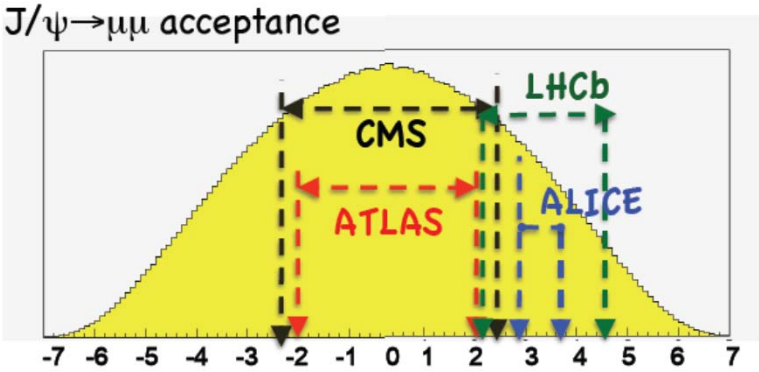
# (Pseudo-)Rapidity coverage

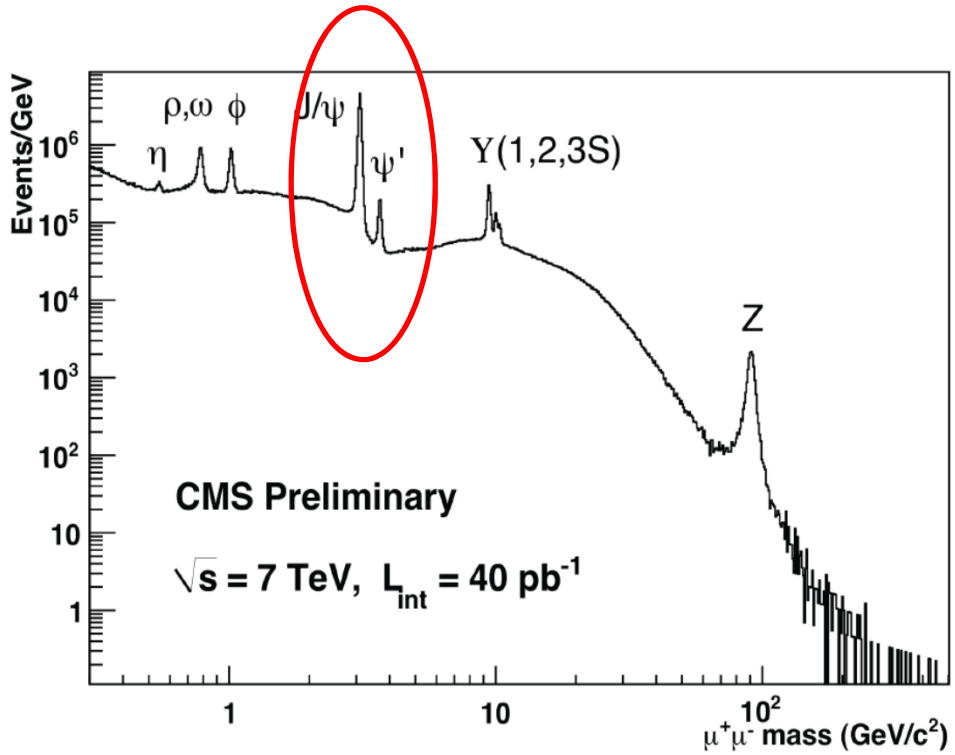



tracking, ECAL, HCAL, counters lumi, muon, hadron PID

# $J/\psi, \psi(2S) \rightarrow \mu\mu$

- $J/\psi$, $\psi(2S) \rightarrow \mu\mu$ plays a central role in all analyses covered in this talk



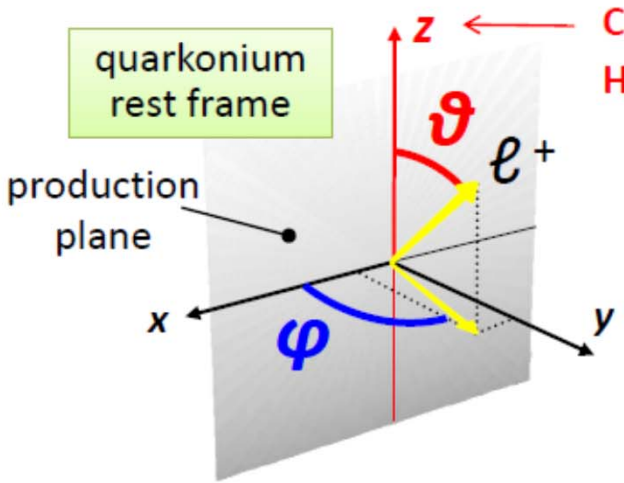

- All experiments have efficient trigger(s) for the dimuon final state

# J/ψ production: Notations

- For p+p → J/ψ (→μμ) + X, the differential cross-section can be parameterized as

$$\frac{\mathrm{d}^4\sigma}{\mathrm{d}p_t\mathrm{d}y\mathrm{d}\cos\theta\mathrm{d}\phi} = \underbrace{\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_t\mathrm{d}y}}_{\text{cross-section}} \cdot \underbrace{\rho(\theta,\phi)}_{\text{polarization}}$$

- Polarization parameters depend on $p_t$, y, and frame choices




Collins-Soper axis (CS): ≈ dir. of colliding partons

Helicity axis (HX): dir. of quarkonium momentum

$$\rho(\theta,\phi) \propto 1 + \lambda_\theta(p_t,y)\cos^2\theta + \lambda_\phi(p_t,y)\sin^2\theta\cos 2\phi + \lambda_{\theta\phi}(p_t,y)\sin 2\theta\cos\phi$$

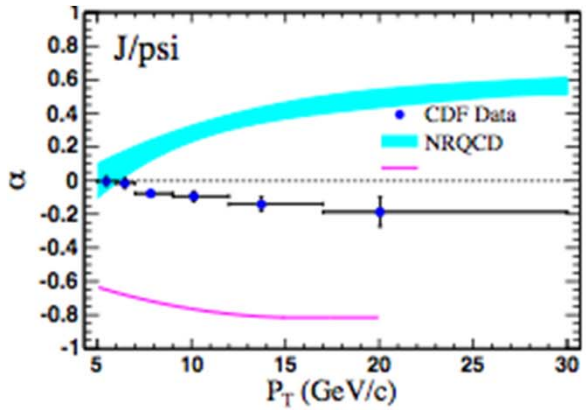
# J/ψ production: An introduction

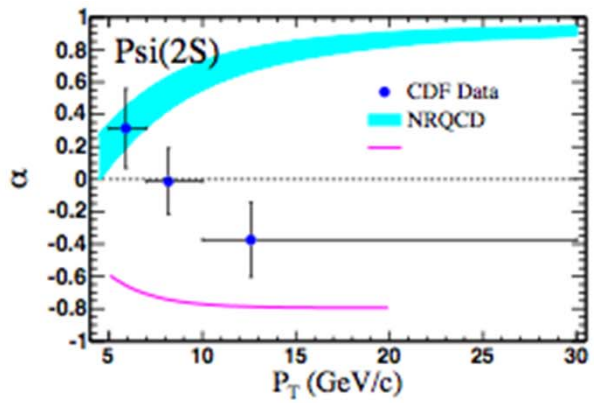
- Long history cross-section/polarization measurements and theoretical calculations, still not so satisfactory. Predictions from NRQCD Color Singlet Mechanism and Color Octet Mechanism:

  - CSM: LO + NLO + part. NNLO
    CSM + COM: LO + NLO

    } can reproduce cross-section data at the Tevatron

  - CSM alone is not able to predict the polarization (J/ψ & ψ(2S))

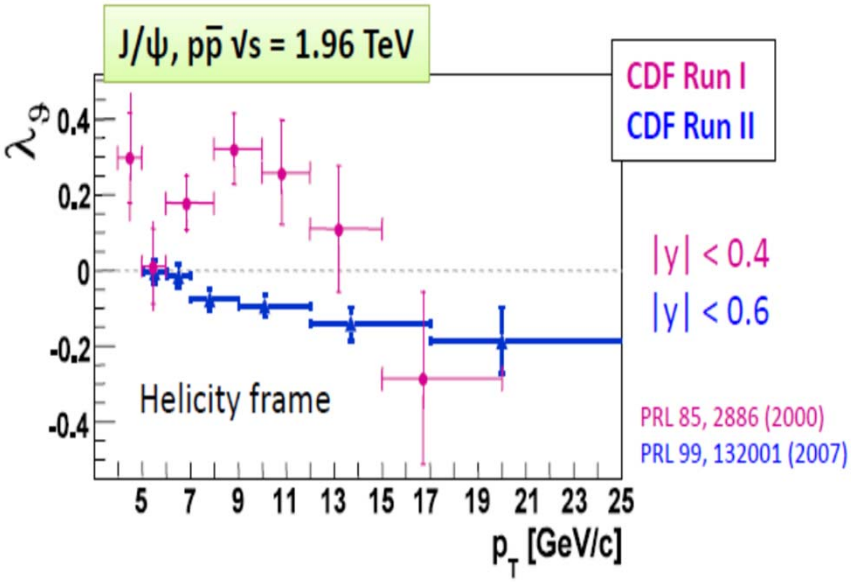


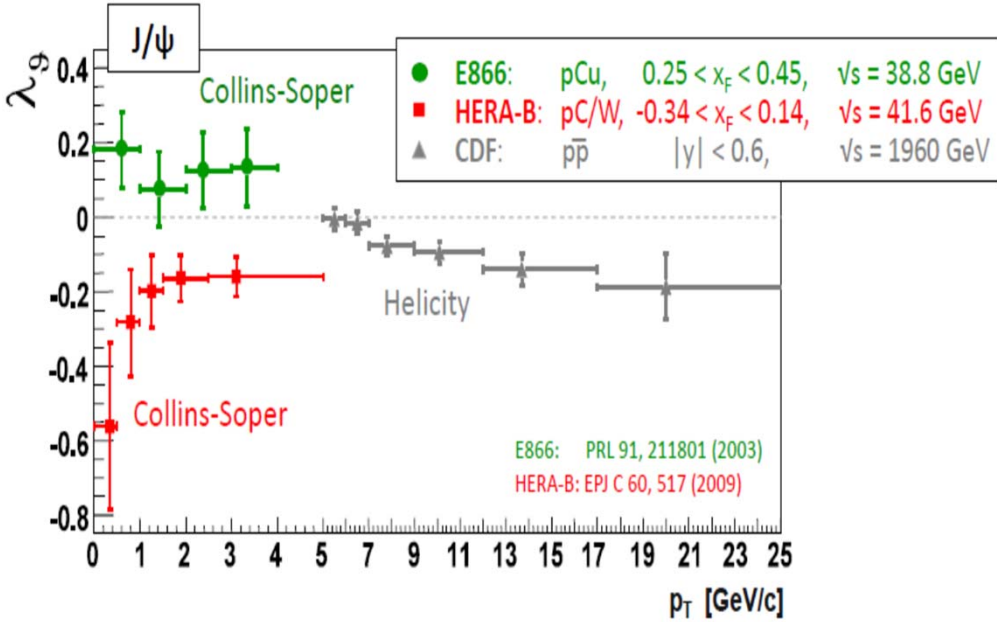




( For a recent review, see J.P.Lansberg's talk at Quarkonium Production: Probing QCD at the LHC, April 18-21 2011, Vienna University of Technology, Vienna, Austria)

# J/ψ production: An introduction

- Polarization results maybe highly depend on rapidity range, frame…




- The detector acceptance is also a function of

$p_t$, y, θ, ϕ

# J/ψ production : An introduction

- The task is further complicated due to different sources of J/ψ production.

  prompt: direct + feed down from $\chi_c$, ψ(2S)

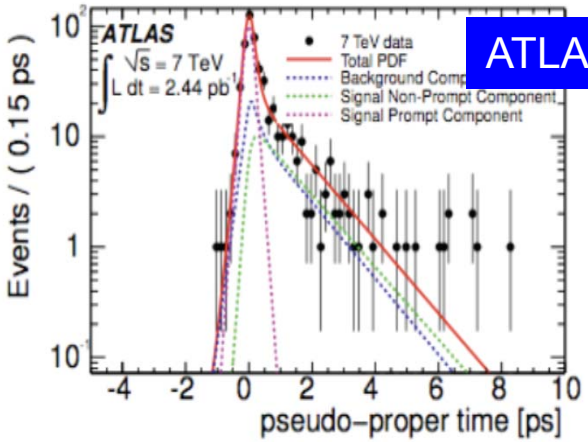
  non-prompt: from b hadron decays

- Separation of feed down component is challenging

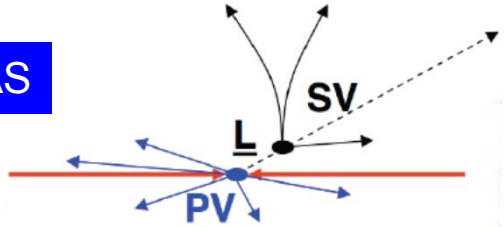
  ~ 30% from $\chi_c$ at Tevatron (CDF Collab. PRL 98(2007) 232001)

- B→ J/ψ + X component could be separated from the prompt component by a quasi-proper time variable

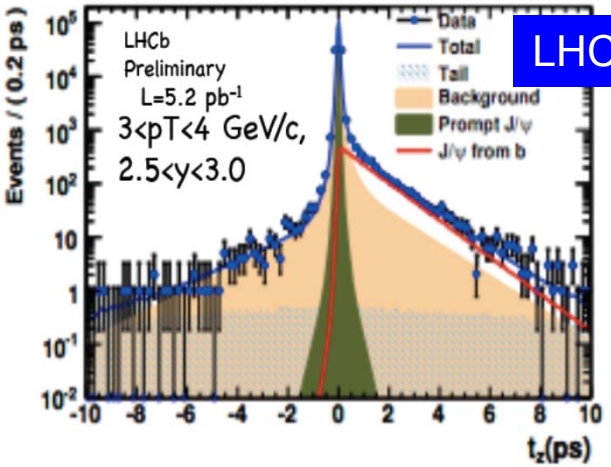
$t_{xy} = L_{xy}/p_t * M_{J/\psi}$ (ATLAS, CMS)




ATLAS




$t_z = L_z/p_z * M_{J/\psi}$ (LHCb)




LHCb

Y. Gao Hadron2011

# J/ψ production : Strategy

- Ideally a joint fit at each ($p_t$, y) bin on ($M^{J/\psi}$, t, cosθ, ϕ) can simultaneously measure

$$\frac{\mathrm{d}^2\sigma^{\mathrm{prompt}}}{\mathrm{d}p_t\mathrm{d}y} \quad \frac{\mathrm{d}^2\sigma^{\mathrm{B}\to\mathrm{J}/\psi}}{\mathrm{d}p_t\mathrm{d}y} \quad \lambda_\theta(p_t,y) \quad \lambda_\phi(p_t,y) \quad \lambda_{\theta\phi}(p_t,y)$$

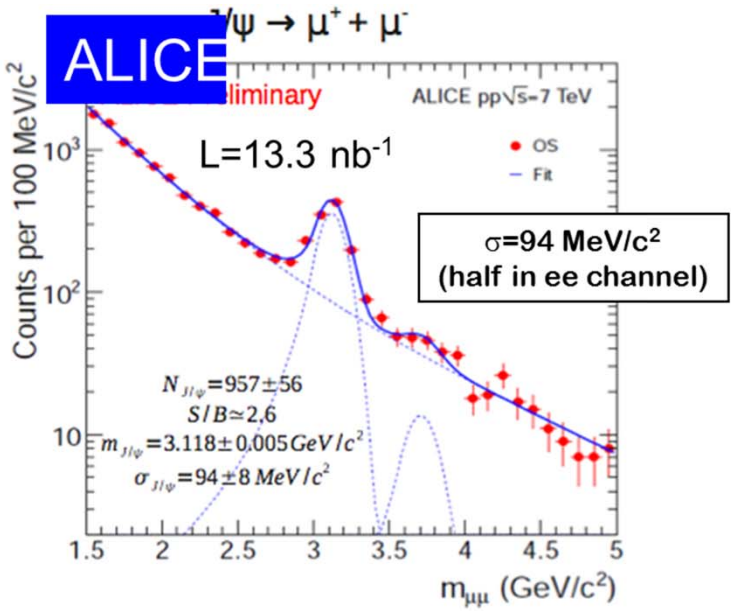
- High production rate of J/ψ makes it possible, even with 2010 data.

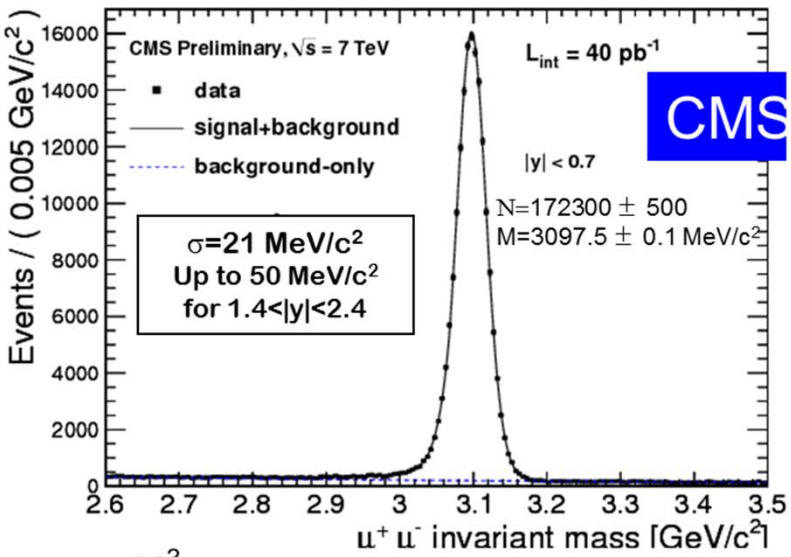
- In practice for the first LHC measurements,
  - inclusive $\frac{\mathrm{d}^2\sigma}{\mathrm{d}p_t\mathrm{d}y}$ ;
  - separately $\frac{\mathrm{d}^2\sigma^{\mathrm{prompt}}}{\mathrm{d}p_t\mathrm{d}y}$ and $\frac{\mathrm{d}^2\sigma^{\mathrm{B}\to\mathrm{J}/\psi}}{\mathrm{d}p_t\mathrm{d}y}$ ;
  - unknown polarization taken as systematics

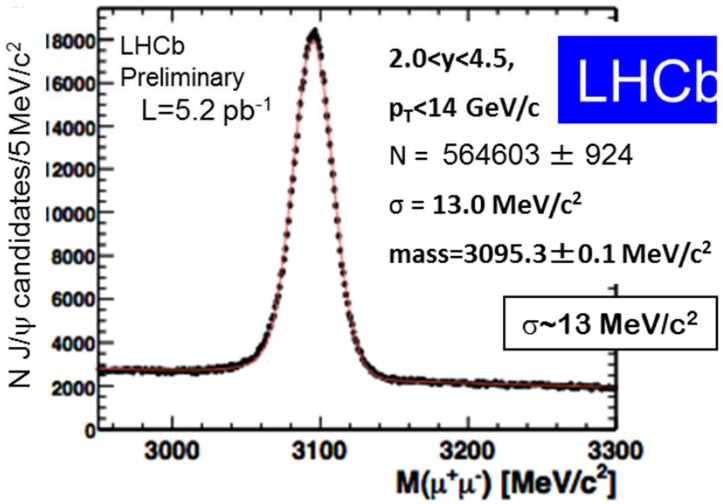
ALICE, arXiv:1105.0380
ATLAS, arXiv:1104.3038
CMS, arXiv:1011.4193
LHCb, arXiv:1103.0423

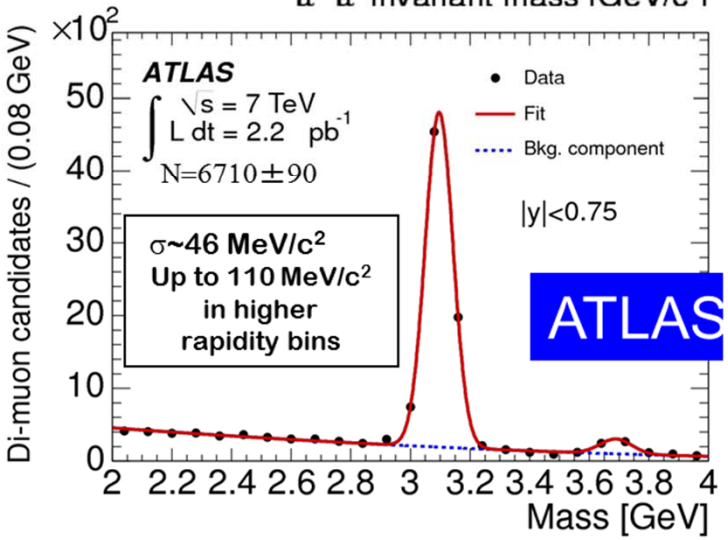
Parallel session talks:
C. Schiavi(ATLAS) @Heavy Hadrons
F. Kramer(ALICE) @ Quarkonia
B. Akgun (CMS) @ Quarkonia
G. Sabatino(LHCb) @ Quarkonia

# J/ψ→ μμ mass distribution



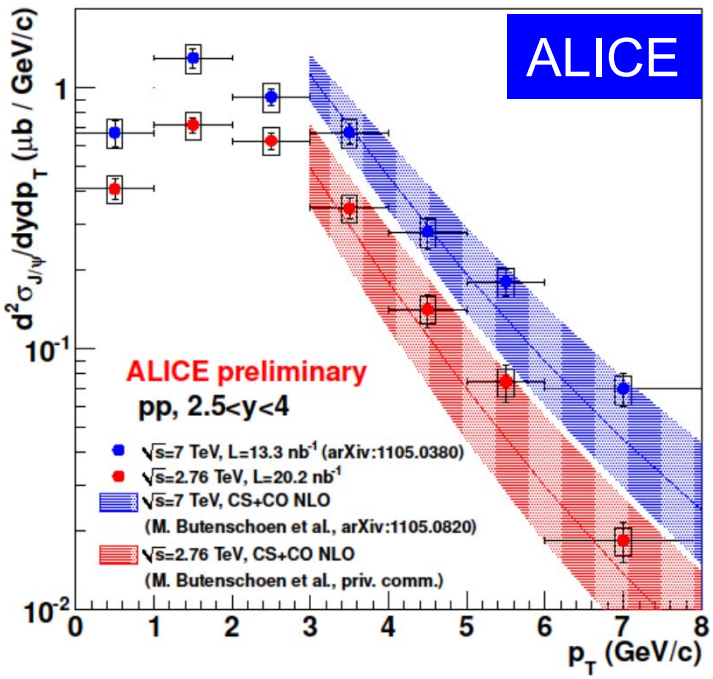



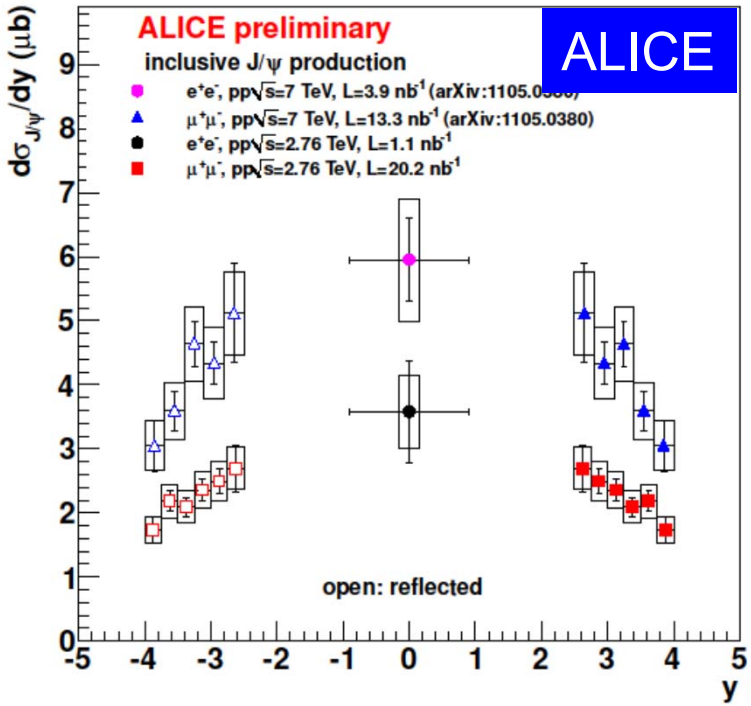



# Inclusive J/ψ production

**ALICE studies:**

- $\sqrt{S}$ = 2.76, 7 TeV
- $\mu^+\mu^-$ channel at forward region (2.5<y<4)
- also able to reconstruct J/ψ's in the $e^+e^-$ channel (|y|<0.9)
- acceptance for J/ψ down to $p_t \rightarrow 0$



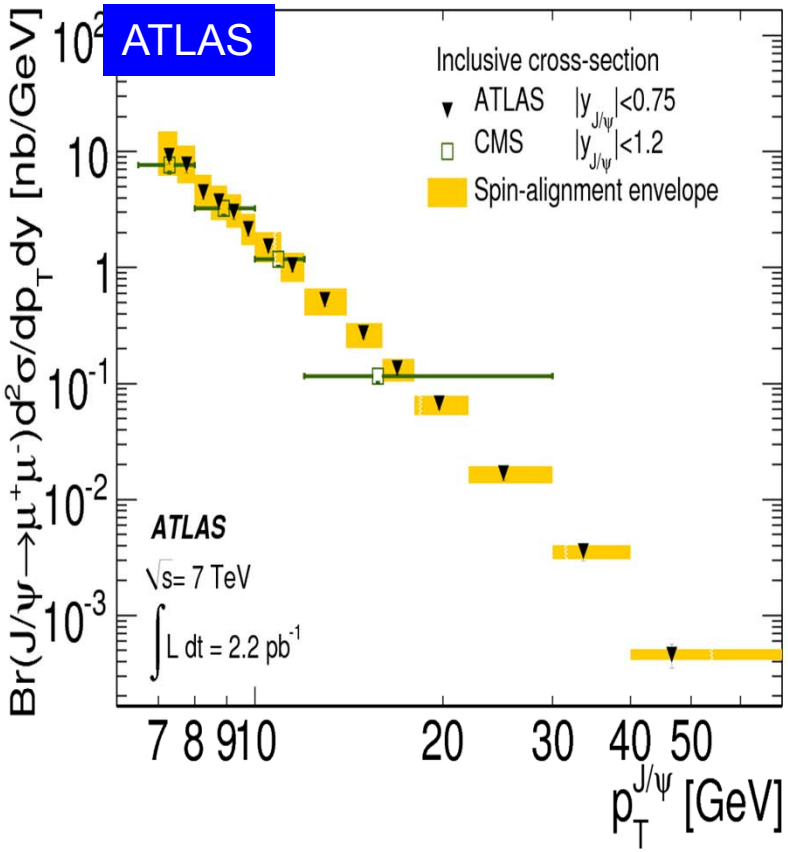




**ALICE:**

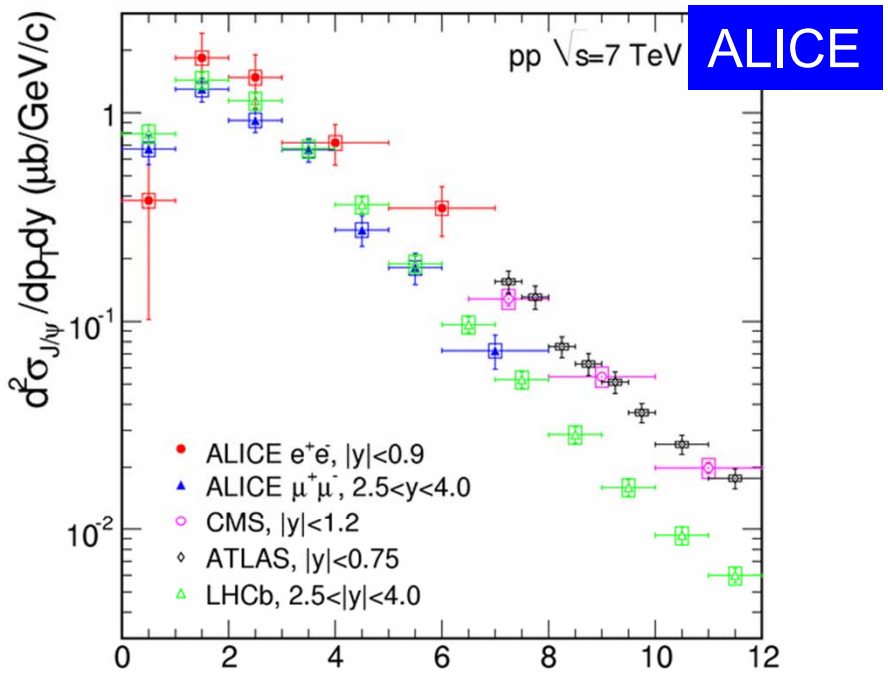
$\sigma_{J/\psi}$ (|y|<0.9) = 10.7±1.2(stat)±1.7(syst)+1.6($\lambda_{HE}$=1)-2.3($\lambda_{HE}$=-1) μb

$\sigma_{J/\psi}$ (2.5<y<4) = 6.31±0.25(stat)±0.80(syst)+0.95($\lambda_{CS}$=1)-1.96($\lambda_{CS}$=-1) μb

# Inclusive J/ψ production



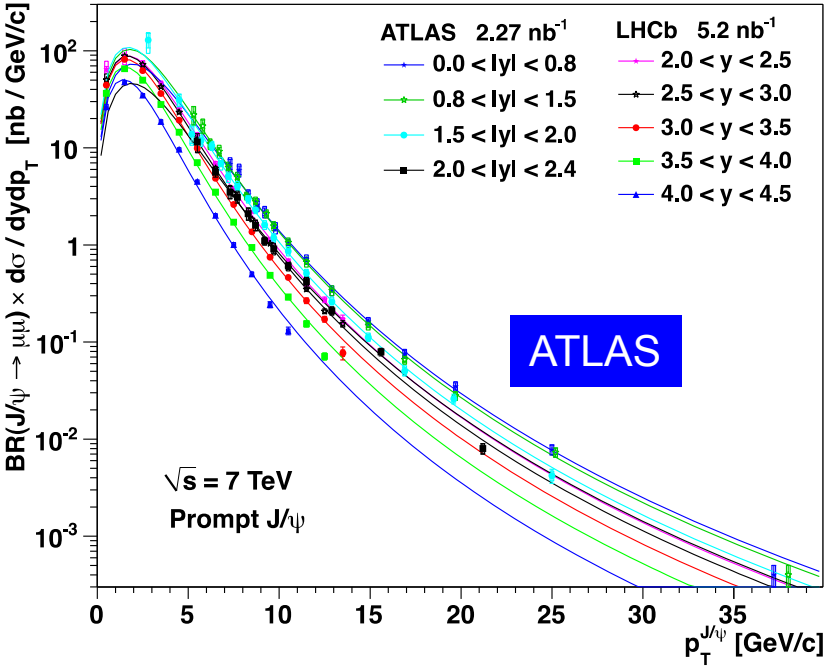

↓ measurements are consistent

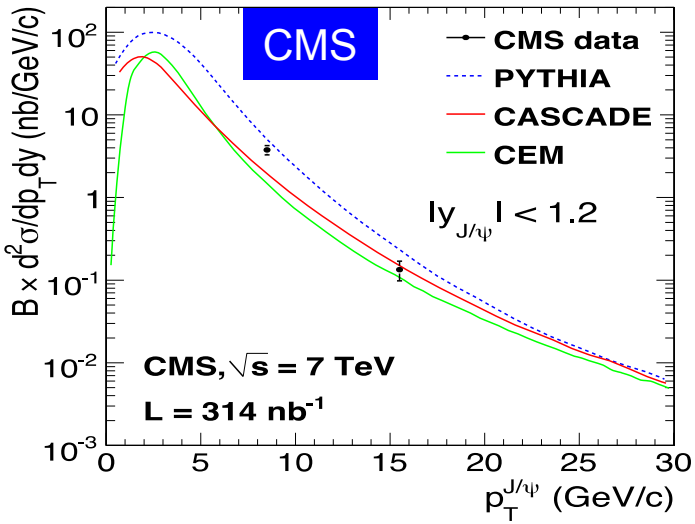



ATLAS: $Br(J/\psi \to \mu^+\mu^-)\cdot\sigma(pp \to J/\psi X; |y^{J/\psi}| < 2.4, p_T^{J/\psi} > 7.0\ \mathrm{GeV})$

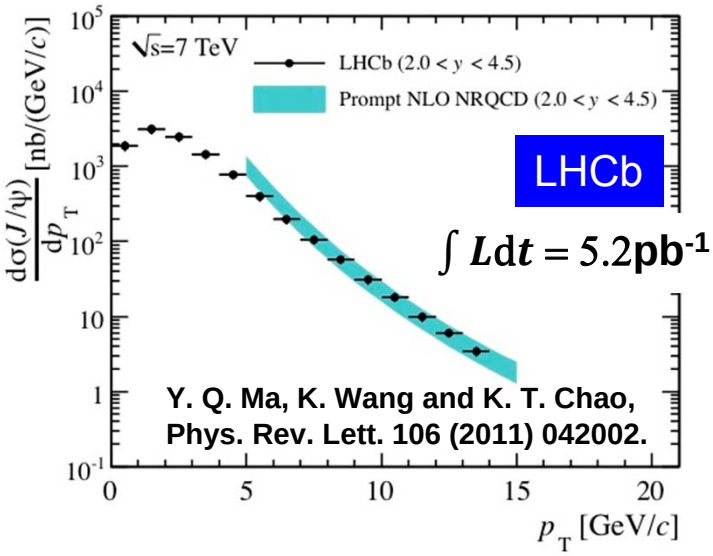
$= 81 \pm 1\ (\mathrm{stat.}) \pm 10(\mathrm{syst.}) \pm^{25}_{20}\ (\mathrm{spin}) \pm 3\ (\mathrm{lumi.})\ \mathrm{nb}$

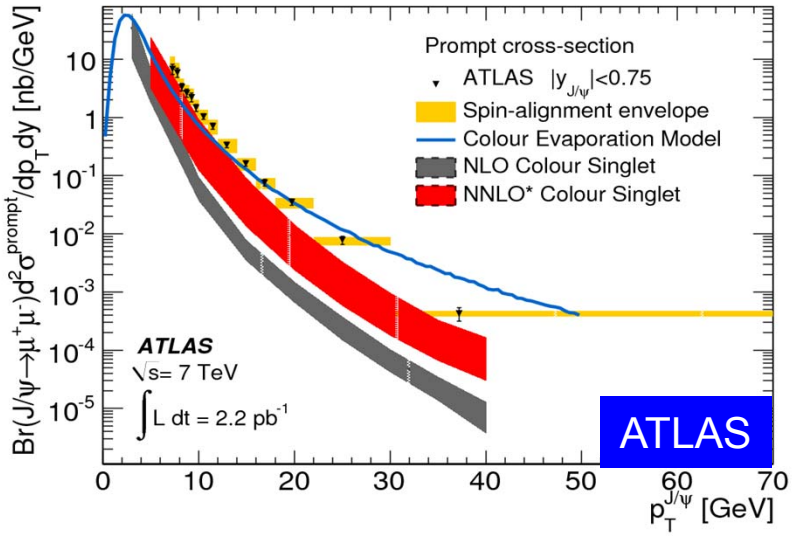
# Prompt J/ψ production



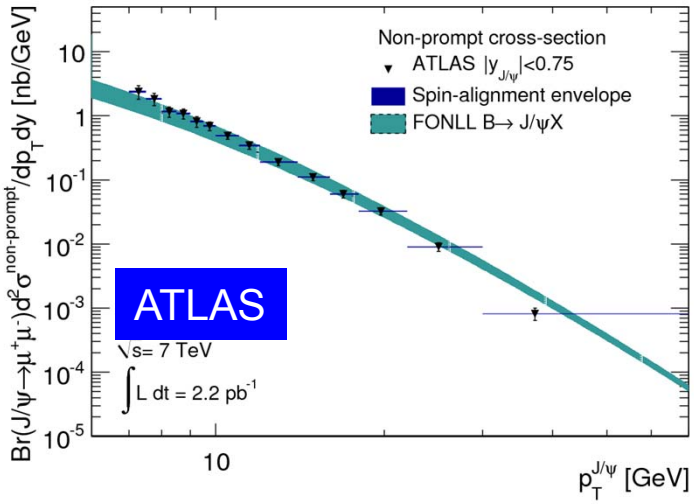



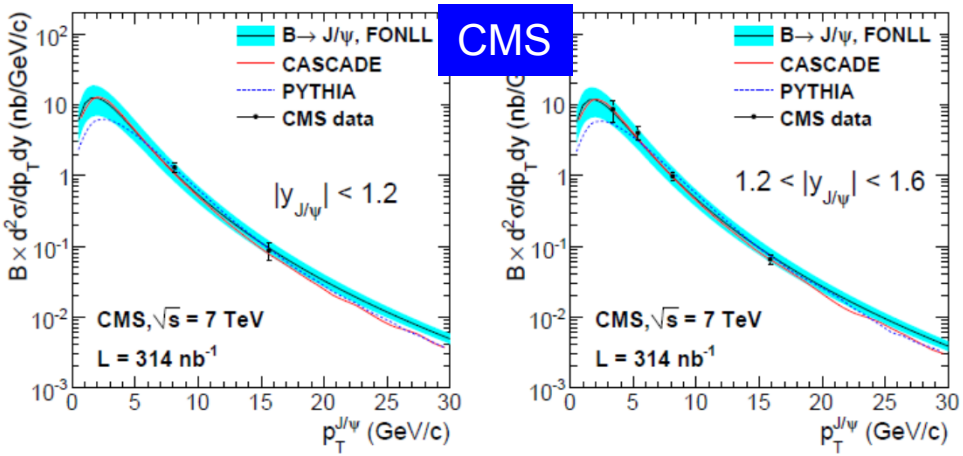

- Results consistent among experiments
- Models represent data reasonably well

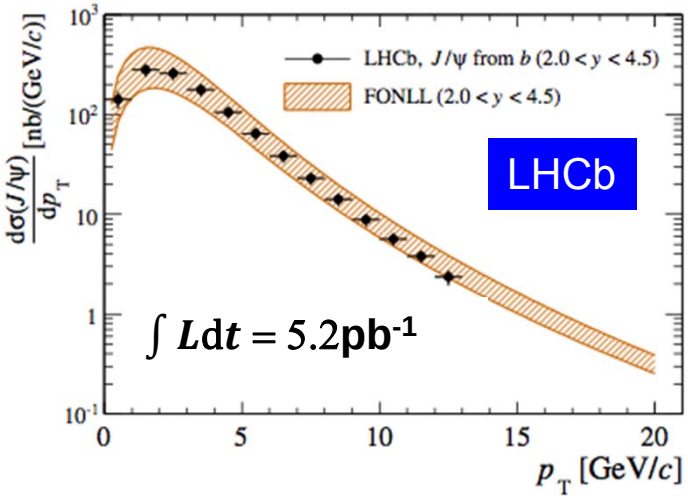


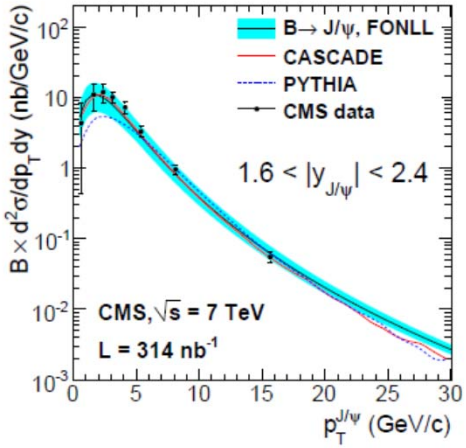



# J/ψ from b-hadron decays



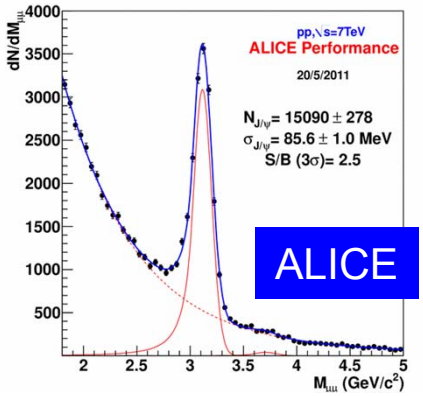


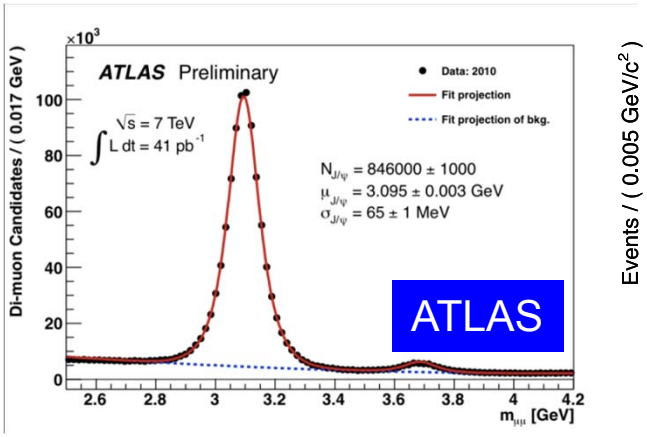
M. Cacciari, M. Greco and P. Nason, J. High Energy Phys. 9805 (1998) 007,
M. Cacciari, S. Frixione and P. Nason,J. High Energy Phys. 0103 (2001) 006
H. Jung, Comput. Phys. Commun. 143 (2002) 100.
H. Jung et al., arXiv:1008.0152

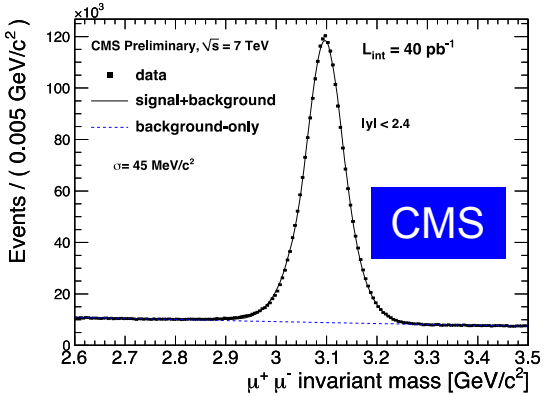
# Remarks on J/ψ production

- The first results shown based on ~ $pb^{-1}$ data.

- Much larger samples collected in 2010-2011




- Detail studies including polarization measurements are underway.

  → provide more results to test theory

  → reduce systematic uncertainties

# LHCb: Double J/ψ production observation

- Ever seen in NA3 (p-platinum) in 1982, first observation at hadron colliders.
- Sensitive on CSM vs. COM

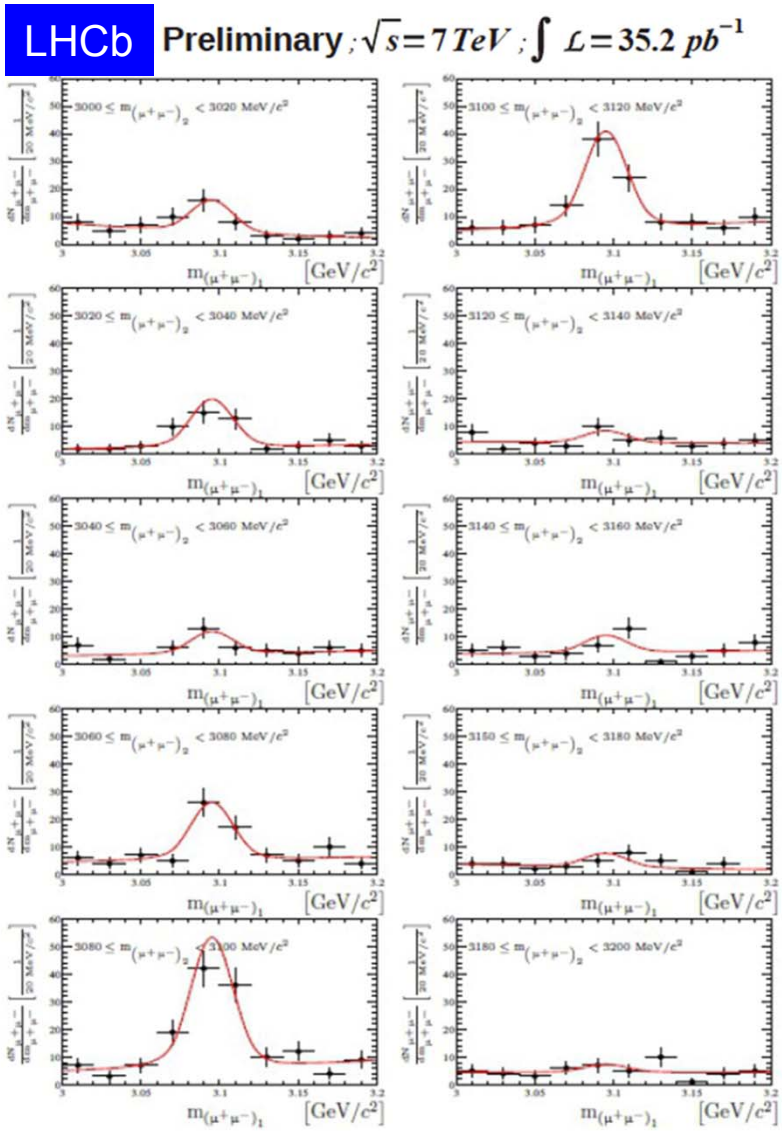
  C.F.Qiao et al., J. Phys. G37(2010) 075019
  A.V.Berezhnoy et al., arXiv:1101.5881

- Analysis performed in the range $2<y<4.5$, $p_t<10$ GeV/c

-4 muons from the same vertex

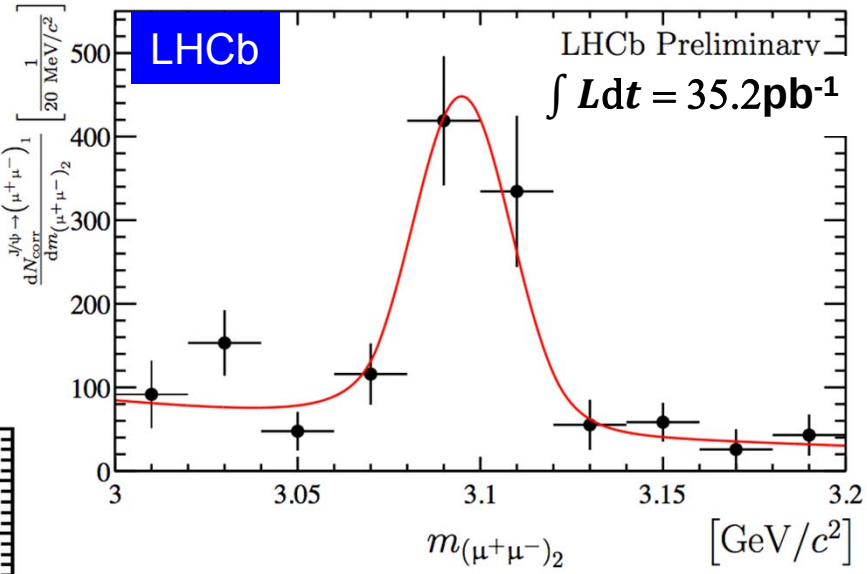
- Fit $M(\mu^+\mu^-)_1$ in bins of $M(\mu^+\mu^-)_2$:
  Double Crystal Ball for the signal
  Exponential for the background.

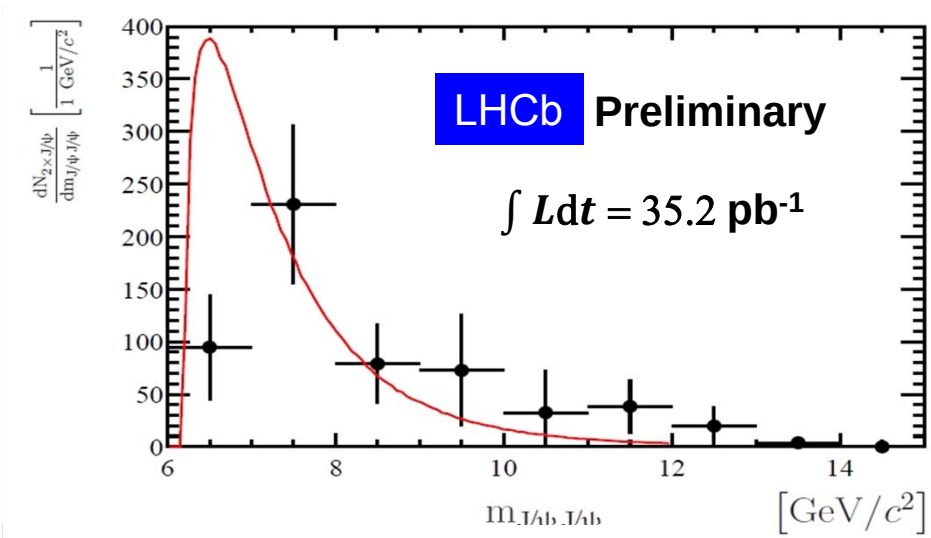
LHCb-CONF-2011-009
Parallel session talk:
G. Sabatino (LHCb) @ Quarkonia



# LHCb: Double J/ψ production observation

- Correct each event with $\varepsilon^{-1}$
- Fit $M(\mu^+\mu^-)_1$ event yields projected $M(\mu^+\mu^-)_2$ dist.




$$N_{J/\psi J/\psi} = 139.6 \pm 17.8$$
$$N^{corr}_{J/\psi J/\psi} = 667.1 \pm 127.0$$

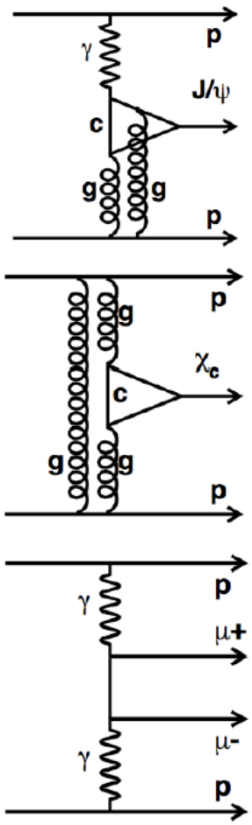
$$\sigma^{J/\psi J/\psi} = \frac{1}{\mathcal{L} \times \mathcal{B}^2_{\mu^+\mu^-}} \times N^{corr}_{J/\psi J/\psi} = 5.6 \pm 1.1 \pm 0.5 \pm 0.9 \text{ (tracking)} \pm 0.6 \text{ (lumi) nb}$$

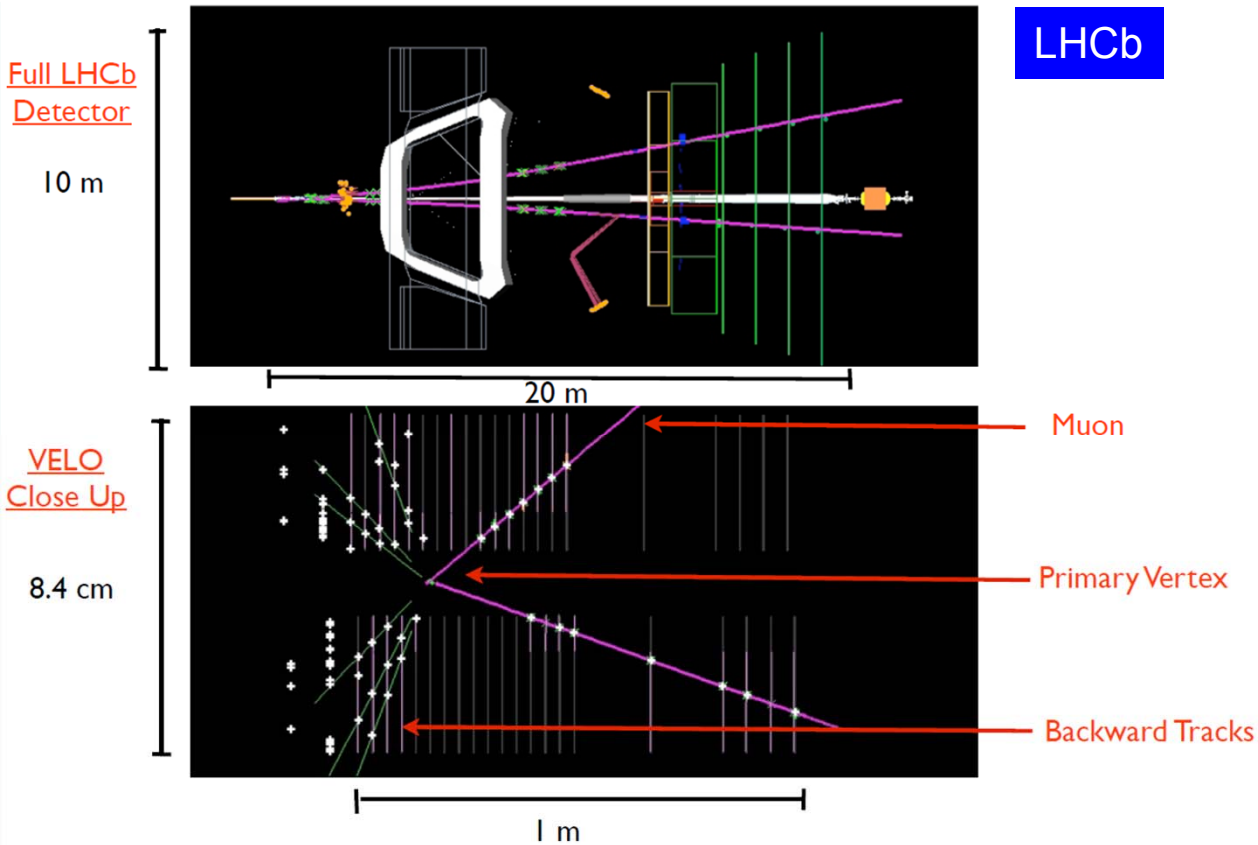
# LHCb: Exclusive J/ψ and ψ (2S) production

- Production of 1 J/ψ and nothing else: possible if one colourless object is exchanged.

LHCb-CONF-2011-022

Parallel session talks:
G. Sabatino @ Quarkonia

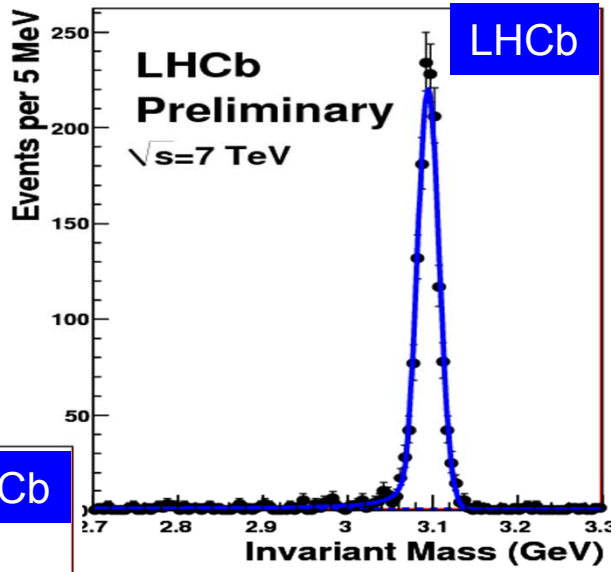


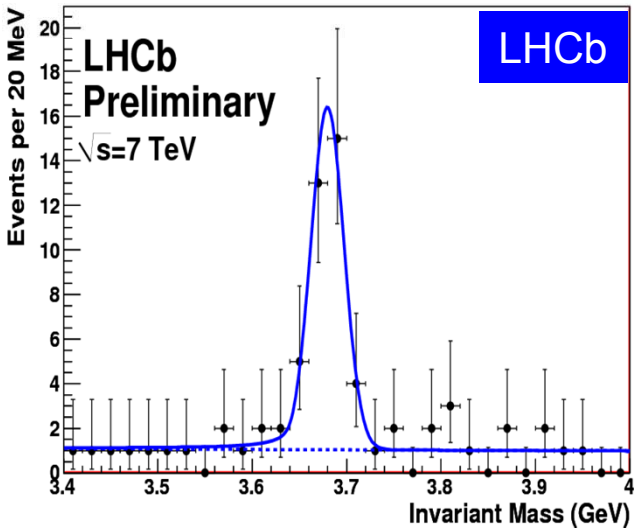



# LHCb: Exclusive J/ψ and ψ (2S) production

- Unambiguous evidence of pomeron, search for odderon.

- Selection:
  - No backward tracks (gap of 2 units of rapidity)
  - Only 2 forward muons.
  - $p_T(\mu\mu)<900$ MeV/c
  - No photons




$\int L dt = \sim 3 \text{pb}^{-1}$

# LHCb: Exclusive production (several modes)

| | Experimental Results | | Theory Predictions |
|---|---|---|---|
| $J/\psi \to \mu^+\mu^-$ : | 474 +/- 103 pb | → | 292 pb (Starlight) 330 pb (SuperChic)<br>330 pb (Motyka&Watt) 710 pb (Schafer&Szczurek) |
| $\psi' \to \mu^+\mu^-$ : | 12.2 +/- 3.2 pb | → | 6.1 pb (Starlight) 17 pb (Schafer&Szczurek) |
| $X_0 \to \mu^+\mu^-\gamma$ : | 9.3 +/- 4.5 pb | → | 14 pb (SuperChic) |
| $X_1 \to \mu^+\mu^-\gamma$ : | 16.4 +/- 7.1 pb | → | 10 pb (SuperChic) |
| $X_2 \to \mu^+\mu^-\gamma$ : | 28 +/- 12.3 pb | → | 3 pb (SuperChic) |
| $\gamma\gamma \to \mu^+\mu^-$ : | 67 +/- 19 pb | → | 42 pb (LPAIR) |

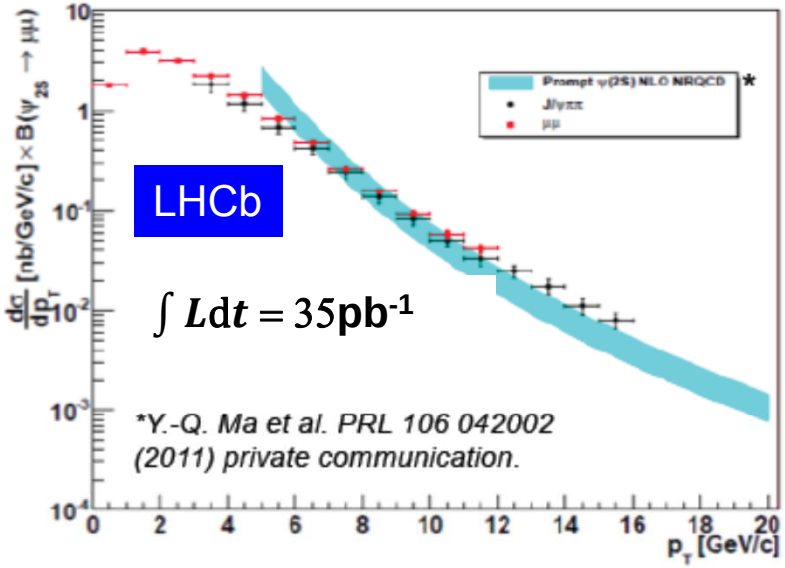
- Large Theoretical uncertainties (Except DiPhoton DiMuon prediction, uncertainty ~ 1%)
- Predictions contain Rescattering Corrections
  (Extra strong Interaction between protons alters cross-section by ~20%)
- Results are consistent with predictions

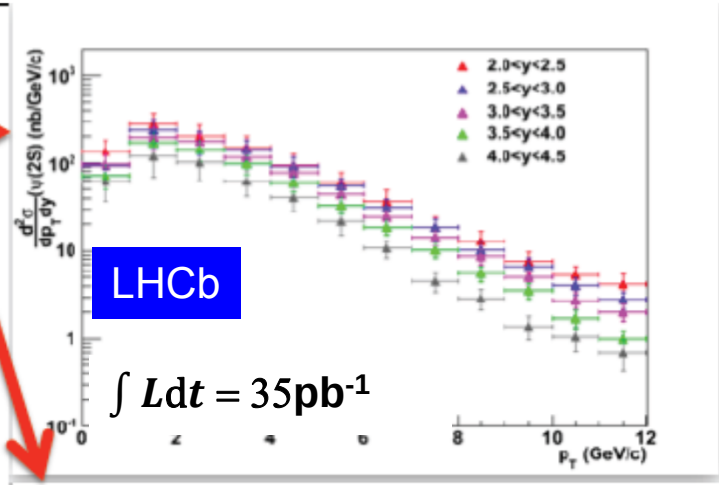
# LHCb: ψ(2S) production

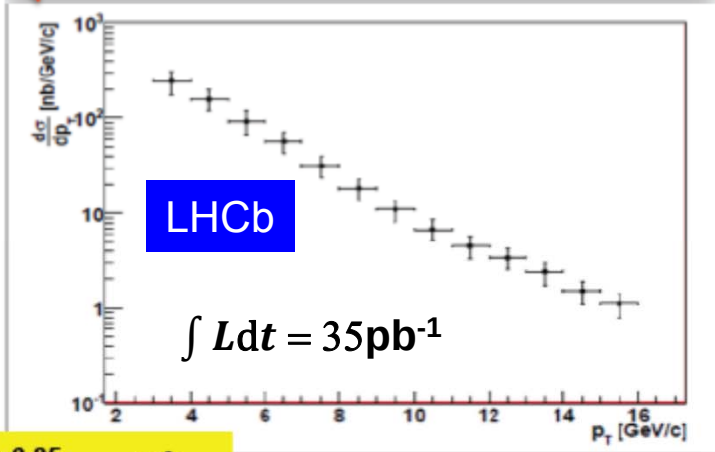
Parallel session talks:
G. Sabatino (LHCb) @ Quarkonia
B. Liu (LHCb) @ Quarkonia

- Exploited in two modes
  - $\psi(2S) \rightarrow \mu^+\mu^-$ [BR=7.7±0.8 × $10^{-3}$]
  - $\psi(2S) \rightarrow J/\psi(\mu^+\mu^-)\,\pi^+\pi^-$ [BR=19.9±0.3 × $10^{-3}$]

Cross section in bins $0<p_T<12$ GeV/c, $2<y<4.5$




$\sigma$(inclusive $\psi$ ;0< p ≤12GeV/c,2< y≤4.5)=1.88±0.02±0.31$^{+0.25}_{-0.48}$ μb
$\sigma$(inclusive $\psi$ ;3< p ≤16GeV /c,2< y≤4.5)=0.62±0.04±0.12$^{+0.07}_{-0.14}$ μb

Main systematics : polarisation (up to 12%), trigger (18%) & tracking efficiencies (16%)

# $\chi_c$ first appearance at LHC

- $R=\sigma(\chi_{c2})/\sigma(\chi_{c1})$ is an important observable for model builders

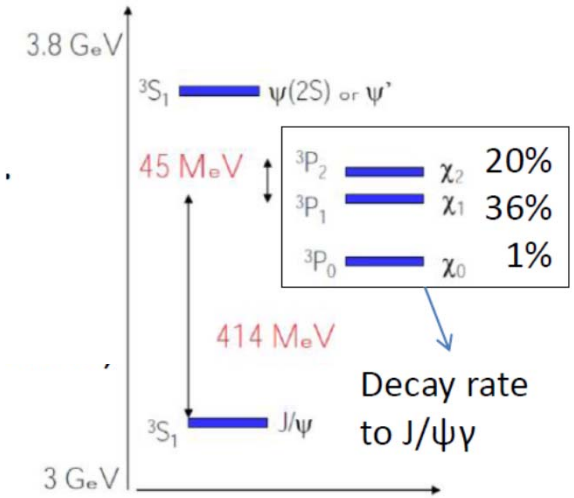
- $\chi_c \rightarrow J/\psi + \gamma$
  challenge to reconstruct low $p_t$ photon

- Good mass resolution to resolve the small mass difference

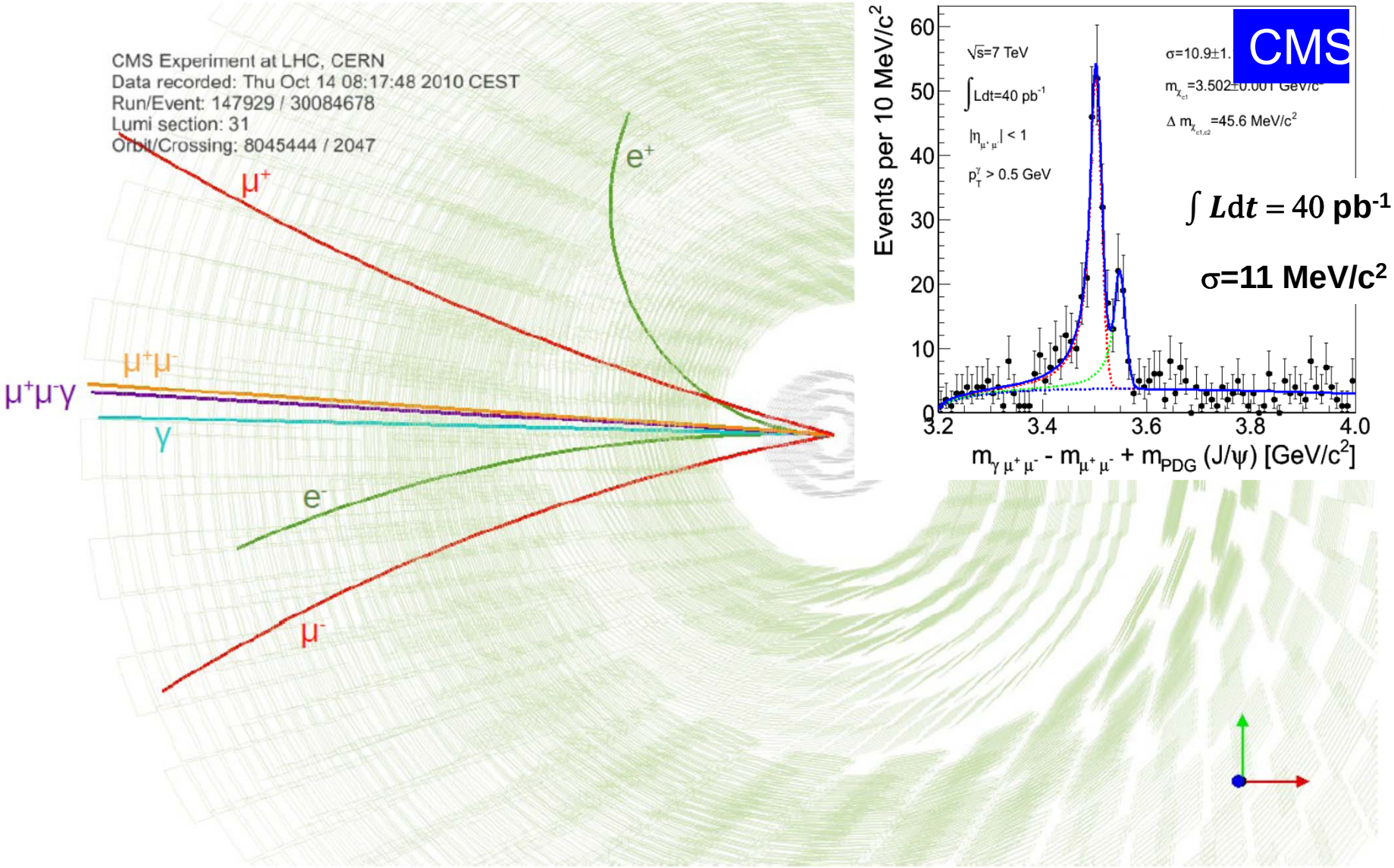
- Photon reconstructed by
  - CMS: converted $e^+e^-$ pair
  - LHCb: converted $e^+e^-$ pair + EM shower

CMS DPS-2011/006
LHCb-CONF-2011-020

Parallel session talks:
B. Akgun (CMS) @ Quarkonia 3
B. Liu (LHCb) @ Quarkonia 5

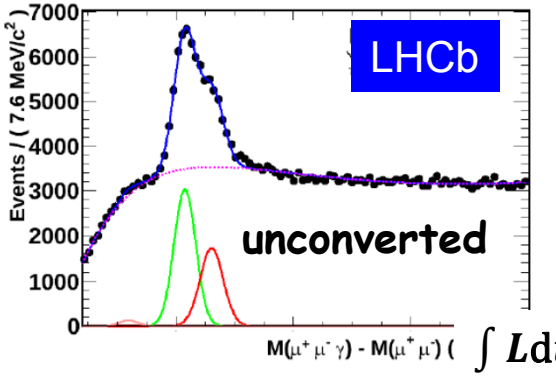


# $\chi_c$ first appearance at LHC

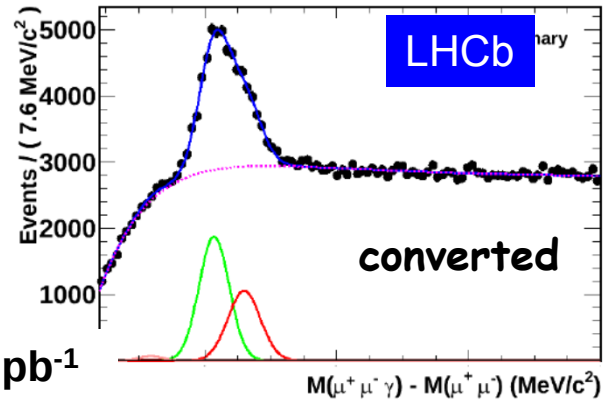


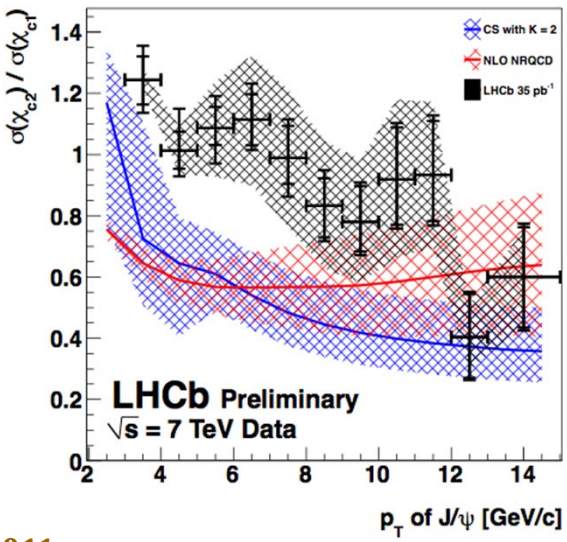
# $\chi_c$ first appearance at LHC

- LHCb able to use converted and unconverted photons to reconstruct $\chi_{c1,2}$




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




- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ disagrees with NLO NRQCD (!)
- Next step: $\sigma(\chi_{c1}\text{->}J/\psi\gamma)/\sigma(J/\psi)$

Y. Ma, K. Wang, K.T.Chao, arXiv:1002.3987

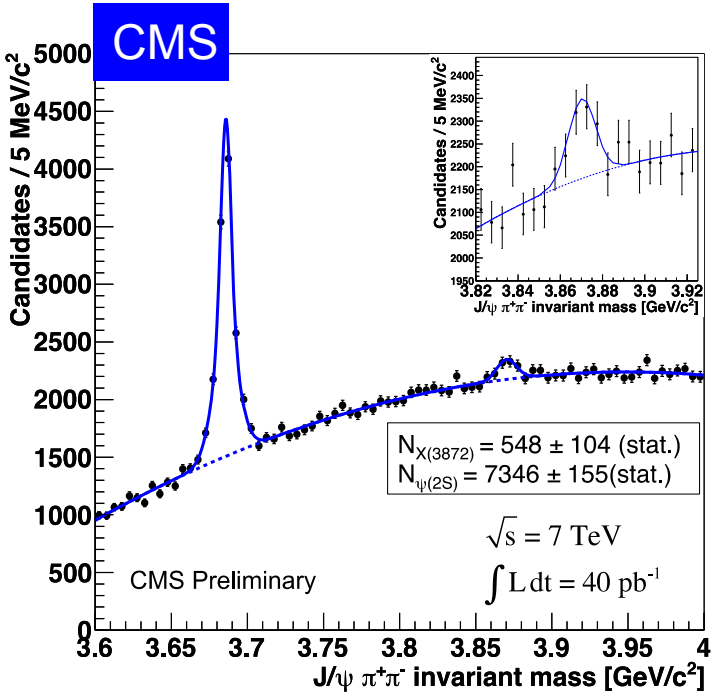
# X(3872) at LHC

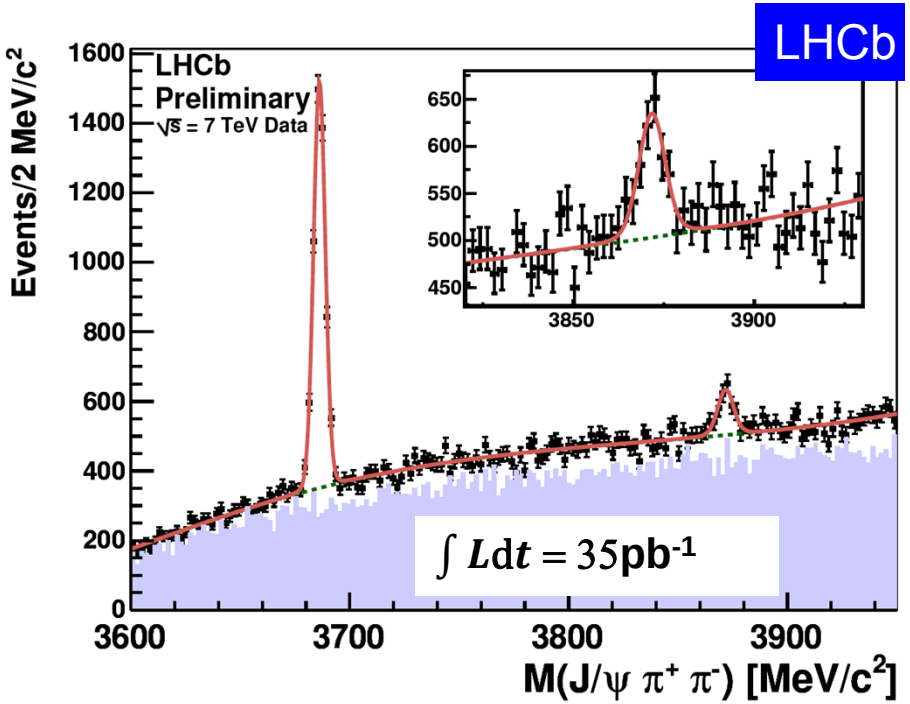
CMS PAS BPH-10-018
LHCb-CONF-2011-021

Parallel session talks:
- J. Wang(CMS) @ Quarkonia
- B. Liu (LHCb) @ Quarkonia
- R. Cardinale @ Heavy Hadrons

- X(3872) discovered by Belle in 2003, and confirmed by experiments at $e^+e^-$ and hadron colliders (BaBar, CDF, D0).

- At LHC, the first observations through $X(3872) \to J/\psi\pi\pi$



# X(3872) at LHC: production

- Using 40pb$^{-1}$ data, CMS measured the ratio

$$R = \frac{\sigma\left(X(3872) \to J\psi\pi\pi\right)}{\sigma\left(\psi\left(2S\right) \to J\psi\pi\pi\right)}$$

- Corrections due to kinematical differences of the decay products estimated by MC.

- Remaining sources of systematics:
  - Background parameterization and signal extraction. 5.3%
  - non-prompt fraction of X(3872) 6.0%
  - X(3872) production mechanism 3.5%
  - limited statistics in MC samples 1.8%
  - Uncertainty on the pion tracking efficiency 4.0%

$$R = 0.087 \pm 0.017(\mathrm{stat}) \pm 0.009(\mathrm{syst})$$

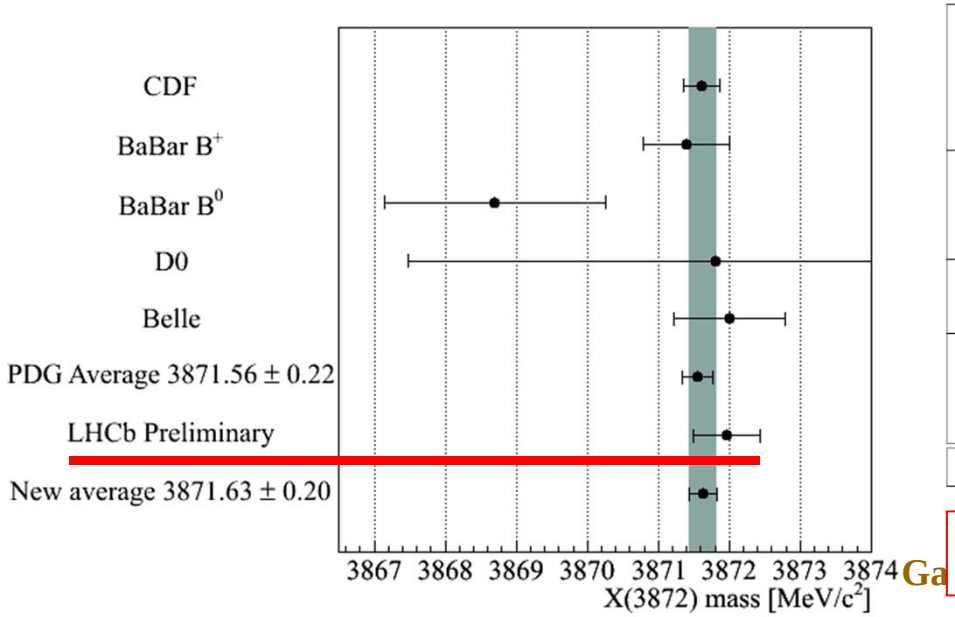
# X(3872) at LHC: mass determination

- Using 35pb$^{-1}$ data, LHCb measured the mass of X(3872)
- Momentum scale calibrated by the 2-body decays

| Decay | Measured mass $[MeV/c^2]$ | PDG average $[MeV/c^2]$ |
|---|---|---|
| $\Upsilon(1S) \to \mu^+\mu^-$ | $9459.90 \pm 0.54$ | $9460.30 \pm 0.26$ |
| $J/\psi \to \mu^+\mu^-$ | $3096.97 \pm 0.01$ | $3096.916 \pm 0.011$ |
| $D^0 \to K^-\pi^+$ | $1864.75 \pm 0.07$ | $1864.83 \pm 0.14$ |
| $K^0_S \to \pi^+\pi^-$ | $497.62 \pm 0.01$ | $497.61 \pm 0.02$ |

and checked by $\psi(2S) \to J/\psi\pi\pi$:

3686±0.06 (stat)  3686.9±0.04




| Source of uncertainty | Value $[MeV/c^2]$ |
|---|---|
| **Mass fitting:** | |
| Natural width | 0.02 |
| Background model | 0.02 |
| Fit range | 0.01 |
| **Momentum calibration:** | |
| Average momentum scale | 0.05 |
| $\eta$ dependence of momentum scale | 0.03 |
| **Detector description:** | |
| Energy loss correction | 0.05 |
| **Detector alignment:** | |
| Tracking stations (TT information) | 0.05 |
| Vertex detector (track slopes) | 0.01 |
| Quadratic sum | 0.10 |

$3871.96 \pm 0.46 \pm 0.10$ MeV/c$^2$

# X(3872) at LHC: prospects

- Is X(3872) charmomium ( $\eta_{c2}(1D)$ ) or charmonium-like(DD*, tetraquark,…)?

  - understand the prompt & b→ X(3872) component
  - determination of the quantum numbers from B → X(3872)K
    ( ~ 1000 events reconstructed in 2 $fb^{-1}$)
  - determination of the width (PDG: Γ< 2.3 MeV/c2, CL = 90%)
  - study the decay mechanism…

- Observation & Study of other (and more?) X, Y, Z states

# Very first result on $B_c$ at LHC

- $B_c$ is a unique meson formed by two different heavy flavor quarks in SM – neither charmonium nor charmonium-like!

- Based on 32.5 $pb^{-1}$ collected at LHCb, a ~4σ signal seen

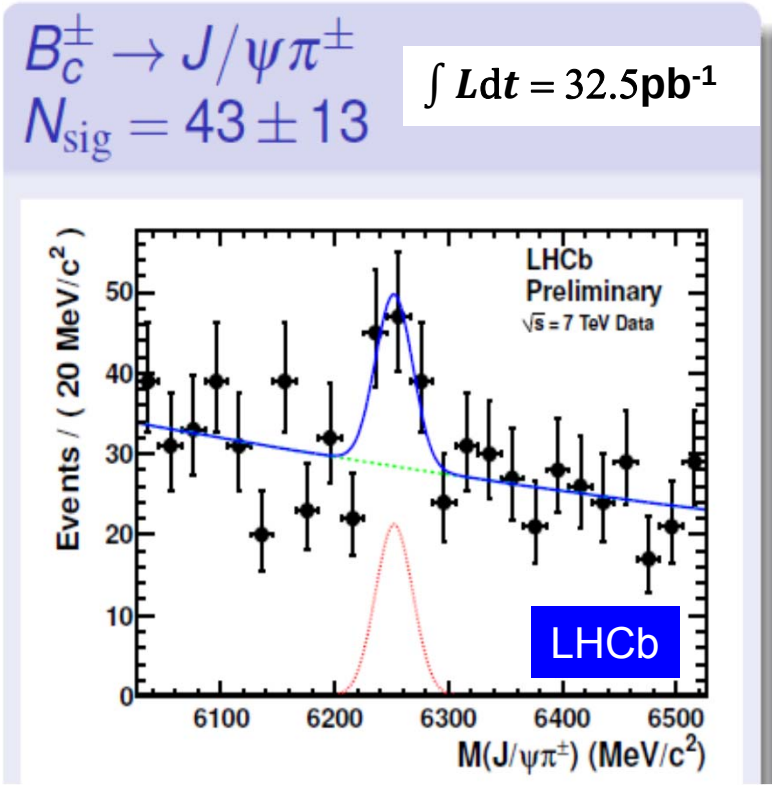
- With almost identical selection on $B \to J/\psi K$, the ratio

$$\mathscr{R}_{c+} = \frac{\sigma(B_c^{\pm}) \times BR(B_c^{\pm} \to J/\psi\pi^{\pm})}{\sigma(B^{\pm}) \times BR(B^{\pm} \to J/\psi K^{\pm})}$$

is measured to be

$$(2.2 \pm 0.8|_{\text{stat.}} \pm 0.2|_{\text{sys.}})\%$$
for $p_T(B) > 4$ GeV/$c$ and $\eta \in (2.5, 4.5)$

LHCb-CONF-2011-017



# Summary & prospects

- $J/\psi$ production has been studied with the first ~$pb^{-1}$ of data, prompt & from b hadron decays, agrees with theoretical predictions. Polarization measurements are under way.

- Double $J/\psi$ production, exclusive $J/\psi$ production, $\psi(2S)$ Production, and $\chi_{c1,2}$ production have been studied by LHCb with 2010 data. More results to come…

- X(3872) seen again at LHC ! More results on quantum numbers, production and decay mechanism are foreseen, in addition to the cross-section measurement (CMS) and mass determination (LHCb).

- With the first appearance of $B_c$, precise measurements on mass/lifetime/cross-section, observations of new decay modes etc…