Heavy Flavours in ATLAS

Standard Model Benchmarks at the Tevatron & LHC

Fermilab, 19-20 November 2010

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On behalf of ATLAS Collaboration

Outline

Open charm

Observation of D, D*, D_s

Charmonium

Observation of J/ψ and ψ'

Measurement of J/ψ inclusive production cross section

Measurement of non-prompt to prompt ratio

Open beauty

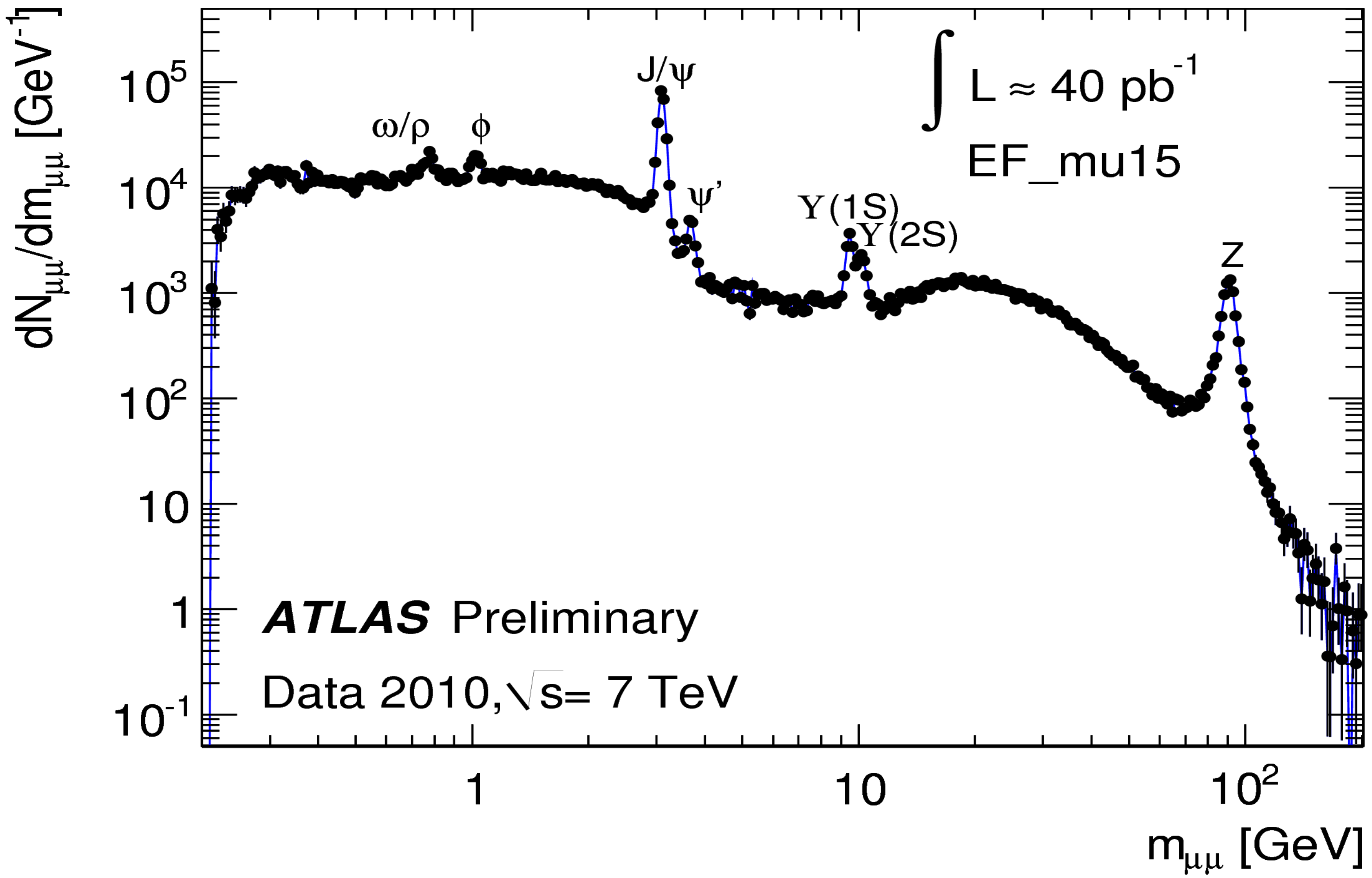
Observation of $B^{\pm} \rightarrow J/\psi\ K^{\pm}$

Bottomonium

Observation of Υ system

Plans for near and not-so-near future

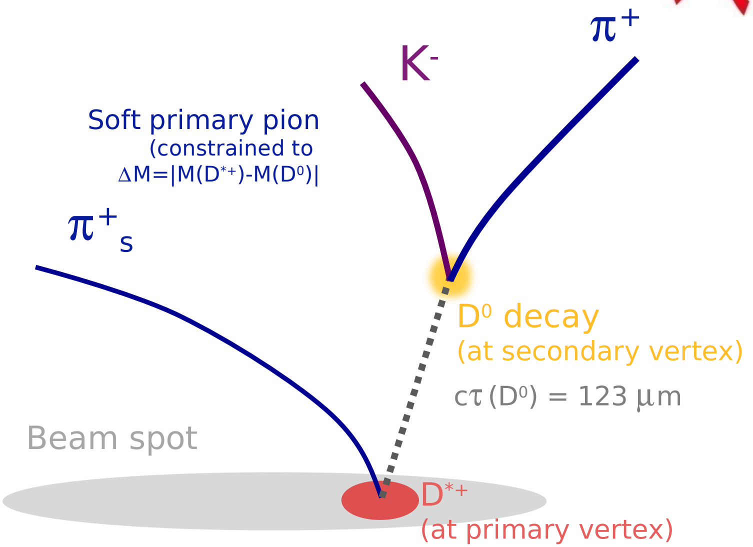
Dimuon mass spectrum in ATLAS

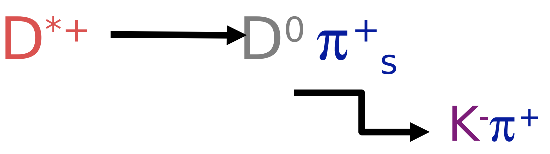


One muon with p_T > 15 GeV, the other >2.5 GeV

$D^{*\pm}$ meson reconstruction

The decay $D^{*\pm} \rightarrow D^0 \pi^\pm_s$ relies on ID track reconstruction and vertexing of the $D^0 \rightarrow K^- \pi^+$





Uses MBTS trigger: > 99.5% efficient, independent of track multiplicity

Combine two oppositely-charged tracks assign K/π mass hypothesis to each, and

$p_T(K,\pi) > 1.0$ GeV

Third (soft) track added with pion mass, same charge as the pion, and

$p_T(\pi) > 0.25$ GeV

Build D^0 signal from $M(K\pi)$ for $D^{*\pm}$ candidates

Additional discrimination from mass difference $\Delta M = M(K\pi\pi_s) - M(K\pi)$

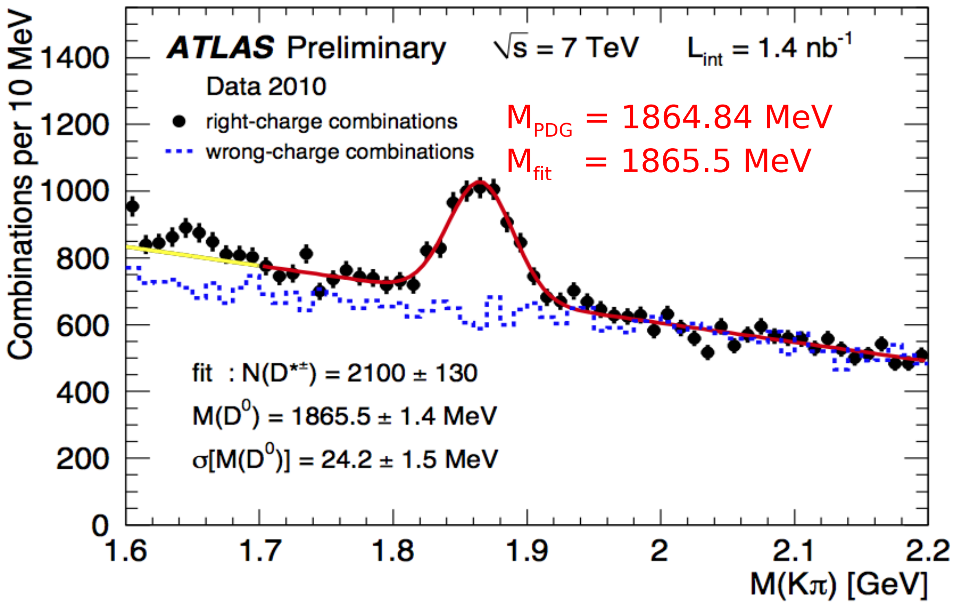
Use presence of secondary vertex and properties of hard process to guide cut selection to enhance signal

$D^{*\pm}$ reconstructed signal

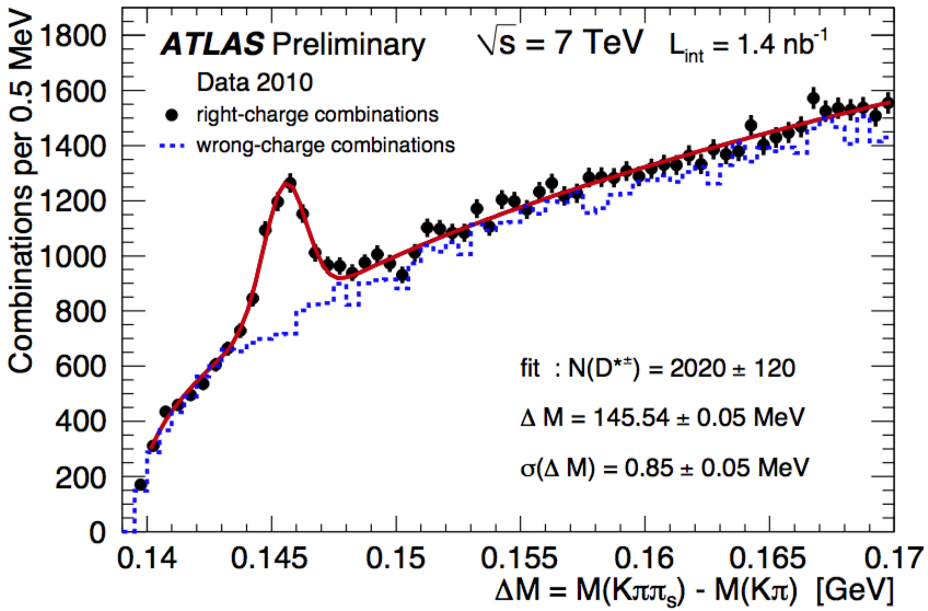
Approx. 2000 $D^{*\pm}$ in both M and ΔM peaks Mass of D^0 compatible with PDG value

Not (yet) corrected for acceptance and efficiency

$D^{*\pm}$ satisfying $144<\Delta M<147$ GeV



$D^{*\pm}$ satisfying $1.83<M(K\pi)<1.90$ GeV



$D^+ \to K^- \pi^+ \pi^+$

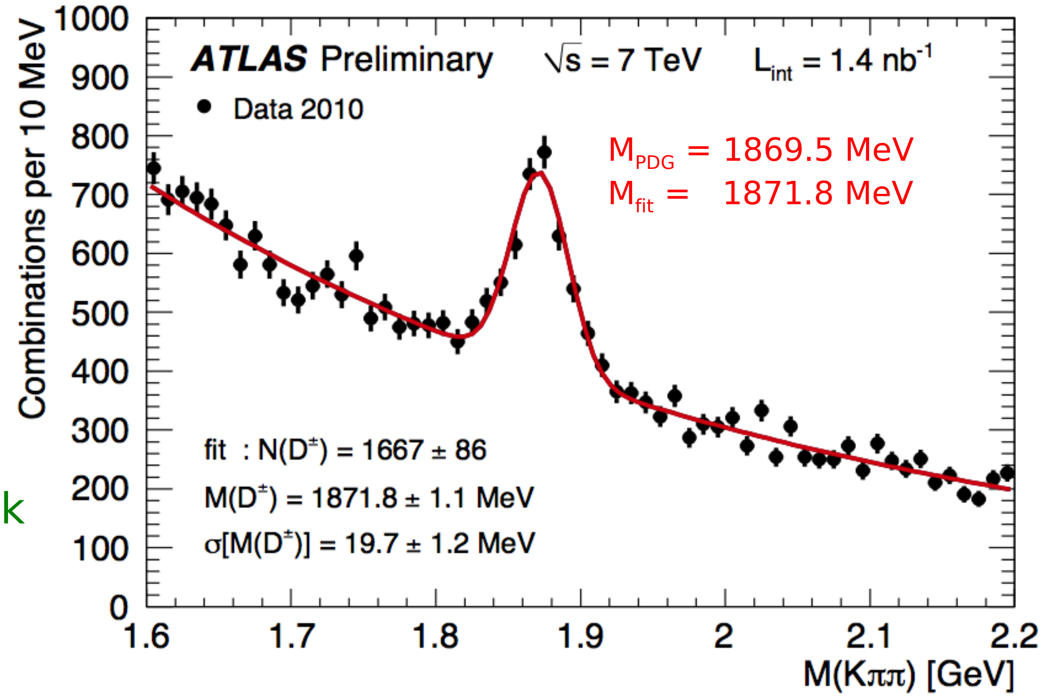
Similar strategy to D*:
combine two oppositely charged tracks, assign pion mass, $p_T(\pi_1)>1.0$ GeV, $p_T(\pi_2)>0.8$ GeV

Combine with third track with kaon mass $p_T(K)>1.0$ GeV

Suppression of D^{*+}:
require $M(K\pi\pi)-M(K\pi)>150$ MeV
Suppression of $D^+_s \to \phi(K^+K^-)\pi^+$:
require $|M(K^+K^-)-M(\phi)_{PDG}|>8$ MeV

Combinatorial background reduced with cut on angle between kaon in D^+ rest frame and D^+ momentum direction in lab frame

~1600 candidates seen in clear peak
Mass in good agreement with PDG



$D^{\pm}_s \longrightarrow \phi\ \pi^{+}$

$\quad\quad\quad\quad \hookrightarrow K^{+}K^{-}$

Again combine two oppositely charged tracks, assign kaon mass, $p_T(K)>0.7$ GeV

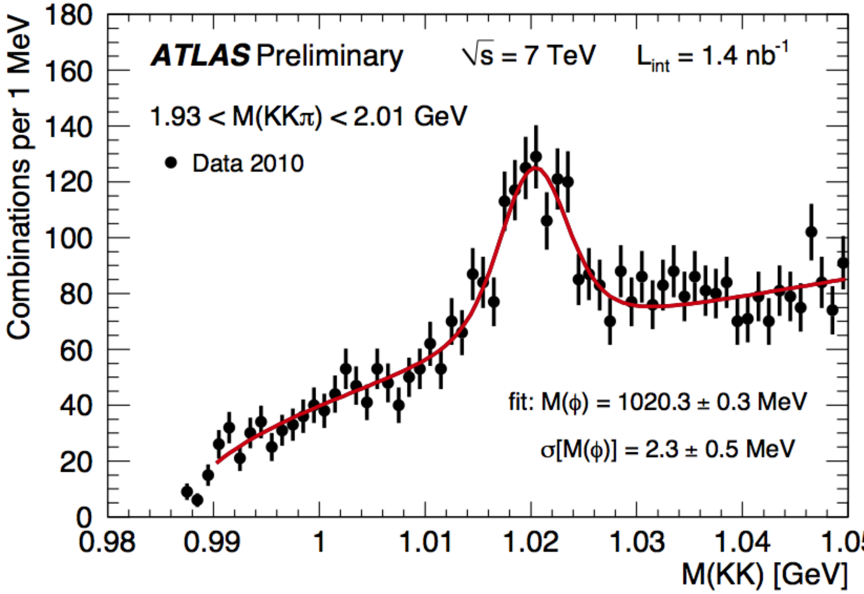
Consider good ϕ candidate if M(KK) within 6 MeV of PDG ϕ mass

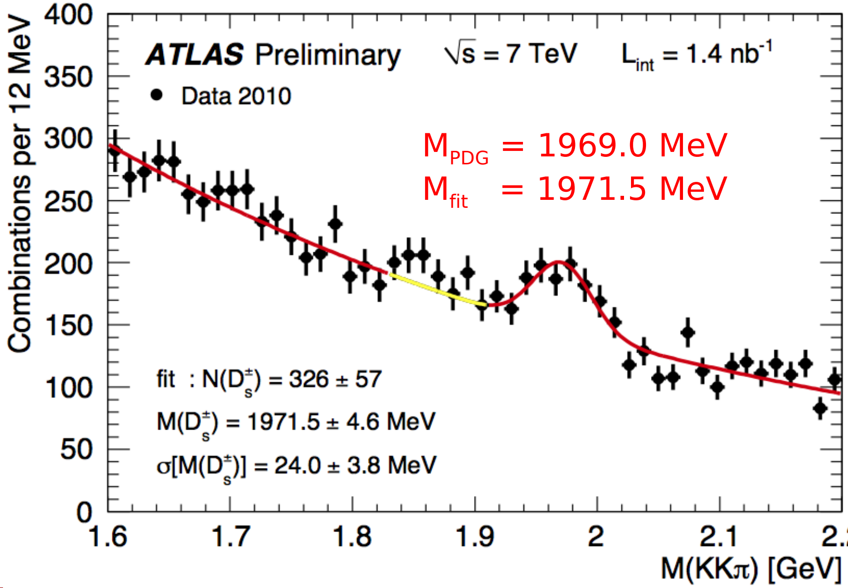
ϕ peak clearly visible on M(KK) plot

Combine with third track (π hypothesis) $p_T(\pi)>0.8$ GeV

326 $D^{\pm}_s$ candidates seen in M(KKπ) peak

https://atlas.web.cern.ch/Atlas/GROUPS /PHYSICS/CONFNOTES/ATLAS-CONF-2010-034/





First ATLAS measurement of J/ψ production

Inclusive J/ψ differential cross-section in bins of J/ψ p_T and y

Key considerations:

- Acceptance: possible strong dependence on J/ψ spin-alignment, which is not fully known/understood
- Trigger and offline reconstruction efficiency

Ratio of non-prompt to prompt J/ψ production cross sections (as a function of J/ψ p_T)

$$\mathcal{R} \equiv \frac{d\sigma(pp \to b\bar{b}X \to J/\psi\, X')}{d\sigma(pp \to J/\psi\, X'')_{\mathrm{prompt}}}$$

Many dependencies and systematics cancel in this ratio, making this an attractive “early data” measurement

Preliminary results

Data taking period between 23rd April - 4th June

Trigger selection:

Differential cross section:

only process events passing a trigger chain seeded by the minimum-bias trigger, requiring a muon signature at HLT

Prescaled in later periods, but highly efficient, even at low pT

Effective integrated luminosity 9.5 nb^{-1}

Ratio measurement:

process events which pass *either* the above trigger, or level-1 single-muon trigger

Take advantage of an unprescaled trigger: increased statistics at higher pT

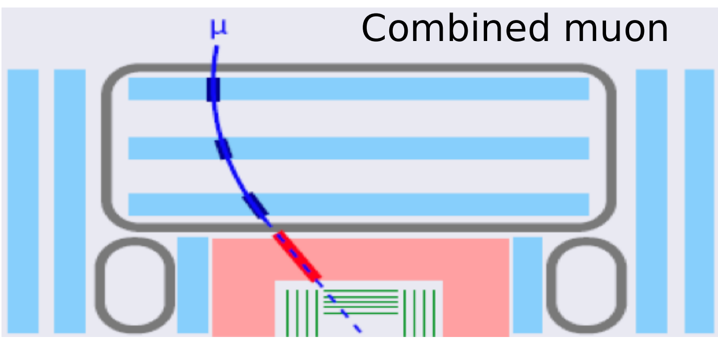
Effective integrated luminosity 17.5 nb^{-1}

Muon reconstruction and selection for J/ψ

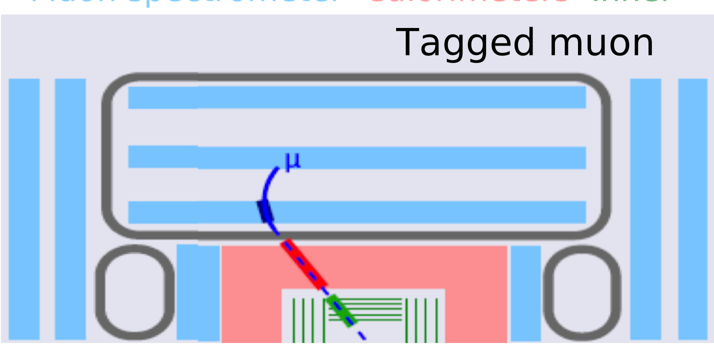
Observation of charmonium requires good Inner Detector tracking (for track parameter measurement) and Muon Spectrometer performance (for muon identification and triggering)

At the muon momenta typical for J/ψ, measurement dominated by Inner Detector tracking

In selection of J/ψ candidates we consider two types of muon:



Muon spectrometer Calorimeters Inner



Combined muons have an ID track matched to a MS track and refitted through the detector to give the best measurement. At least one muon in a pair must be combined.

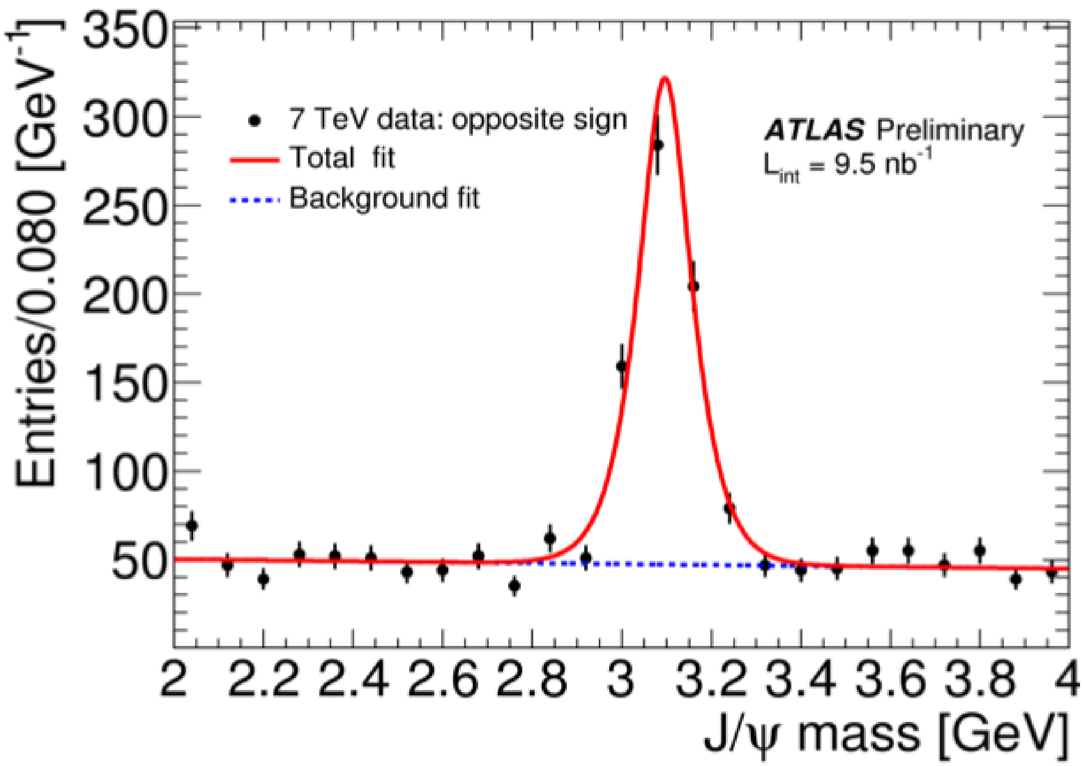
Tagged muons are ID tracks matched to muon segments when extrapolated to the MS. Such muons generally have low momentum.

J/ψ candidate reconstruction

Select oppositely-charged muon pairs with associated ID track (Comb-Comb and Comb+Tag pairs) with $p_\mu > 3$ GeV, $|\eta_\mu| < 2.5$,

Background dominated by fake muons, decays in flight, heavy flavour decays

Unbinned maximum likelihood fit, with per-event errors



$$L = \prod_{i=1}^{N} \left[a_0 \, f_{\rm sig}(m^i_{\mu\mu}, \delta m^i_{\mu\mu}) + (1 - a_0) \, f_{\rm bkg}(m^i_{\mu\mu}) \right]$$

$$f_{\rm sig}(m_{\mu\mu}, \delta m_{\mu\mu}) \equiv \frac{1}{\sqrt{2\pi}\, S\, \delta m_{\mu\mu}} \, e^{-\frac{(m_{\mu\mu} - m_{J/\psi})^2}{2(S\,\delta m_{\mu\mu})^2}}$$

Signal yield @ 9.5 nb^{-1} = 592±30

Mass position 3.095±0.003 GeV

in good agreement with PDG

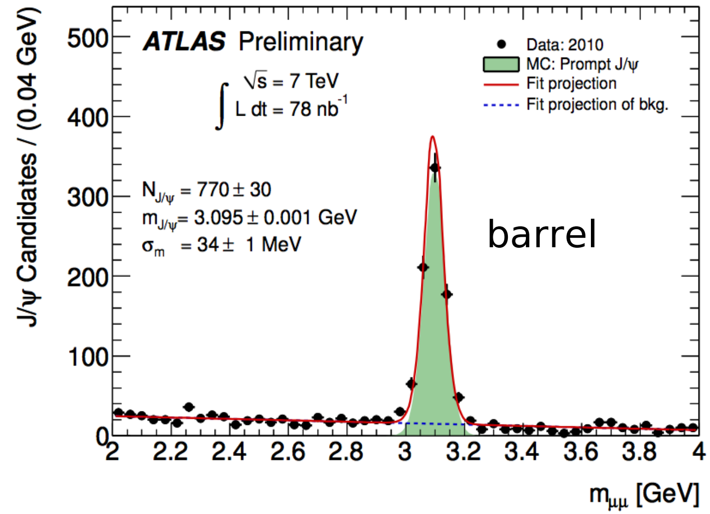
Resolution 71±4 MeV

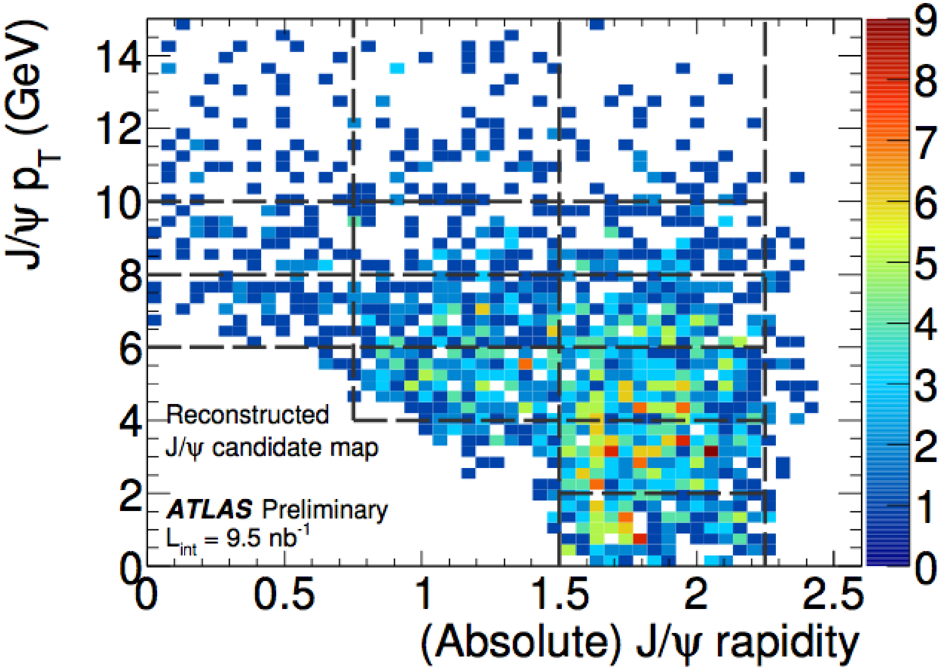
consistent with simulation

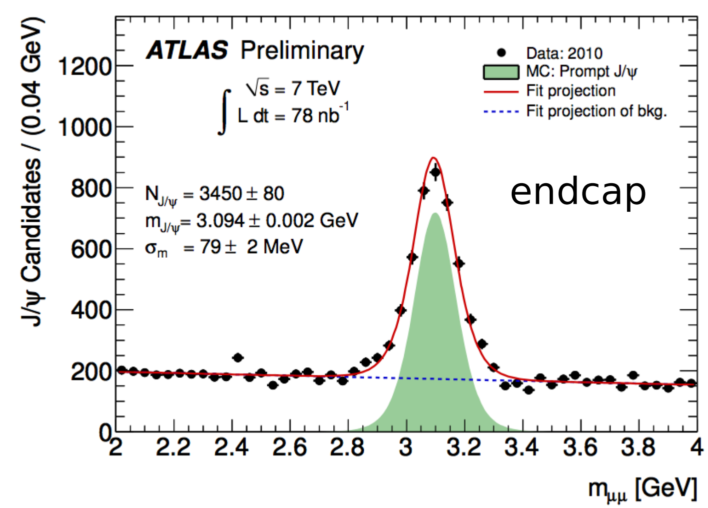
Accessible kinematics

Acceptance limited by muon momentum cut p>3 GeV and η-coverage of ID

Mass resolution better in the “barrel” region, but more entries at high rapidity







Event weighting: yields → cross-section

Each event in given bin at reconstruction level weighted by:

$$w^{-1} = \mathcal{A}(p_T, y, \lambda_i) \times \mathcal{E}_\mu(\vec{p}_1) \times \mathcal{E}_\mu(\vec{p}_2) \times \mathcal{E}_{\text{trig}}(\vec{p}_1, \vec{p}_2)$$

- $\mathcal{A}(p_T, y, \lambda_i)$: Detector acceptance
- $\mathcal{E}_\mu(\vec{p}_1) \times \mathcal{E}_\mu(\vec{p}_2)$: Reconstruction efficiency
- $\mathcal{E}_{\text{trig}}(\vec{p}_1, \vec{p}_2)$: Trigger efficiency

Acceptance maps built from generator-level MC for a variety of spin-alignment “working points”

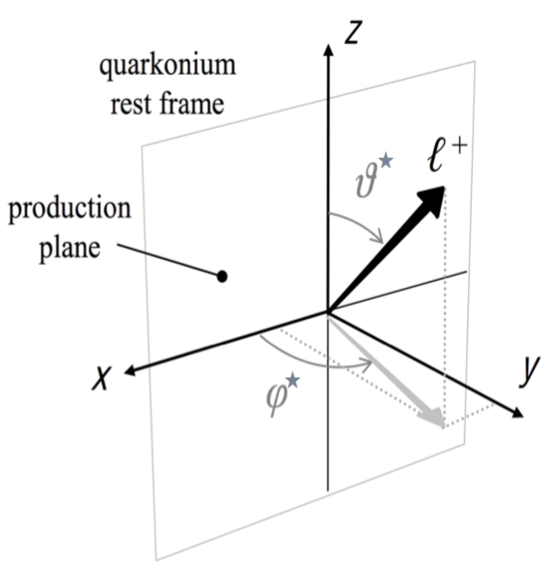
As yet unmeasured, assess variation in final results due to spin-alignment as separate systematic

Spin alignment working points

For a general vector state: $|\psi\rangle = a_{-1}\,|1,-1\rangle + a_0\,|1,0\rangle + a_{+1}\,|1,+1\rangle$

$$\frac{dN}{d\Omega} = 1 + \lambda_{\theta^\star}\cos^2\theta^\star + \lambda_{\phi^\star}\sin^2\theta^\star\cos 2\phi^\star + \lambda_{\theta^\star\phi^\star}\sin 2\theta^\star\cos\phi^\star$$

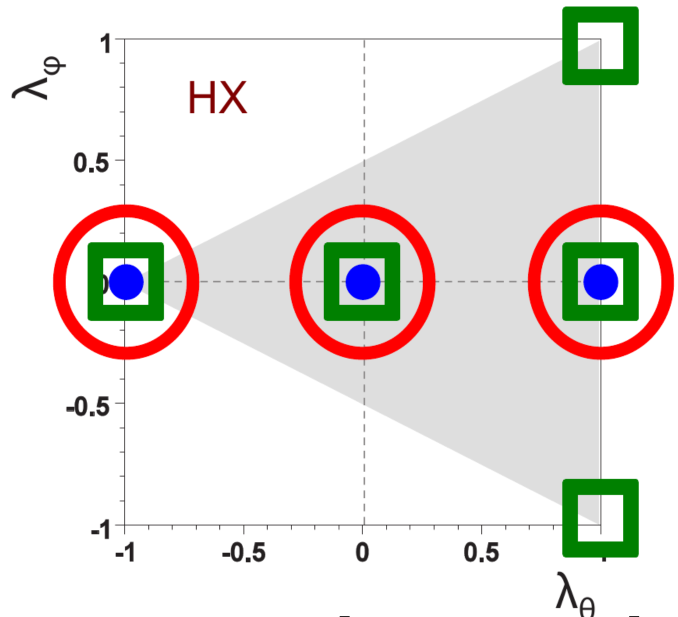
$$\lambda_{\theta^\star} = \frac{1-3|a_0|^2}{1+|a_0|^2} \qquad \lambda_{\phi^\star} = \frac{2Re\,a^*_{+1}a_{-1}}{1+|a_0|^2} \qquad \lambda_{\theta^\star\phi^\star} = \frac{\sqrt{2}Re\,[a^*_0(a_{+1}-a_{-1})]}{1+|a_0|^2}$$



For the time being, use extremes to determine the “envelope” of possible values

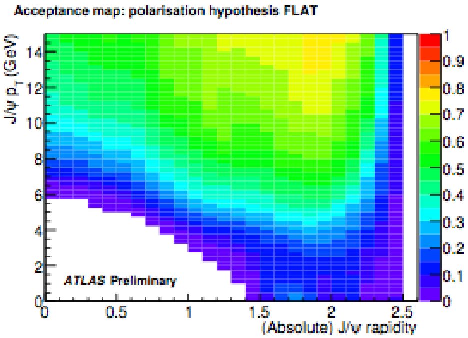
Choice used by:

ATLAS	CMS	ALICE
HX	(both HX & CS)	

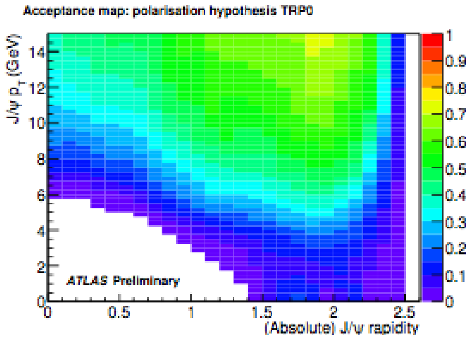


[C.Lourenço]

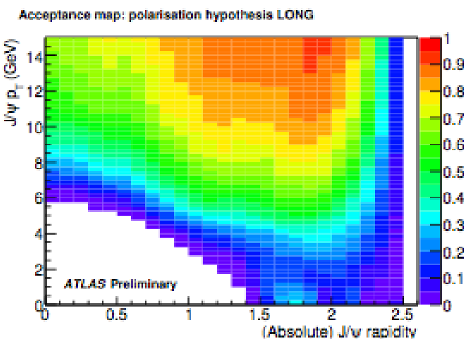
Effect of spin-alignment uncertainty



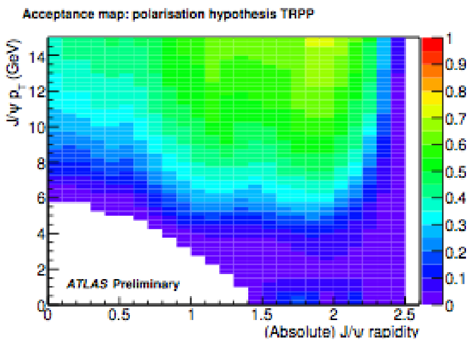
(a) $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$



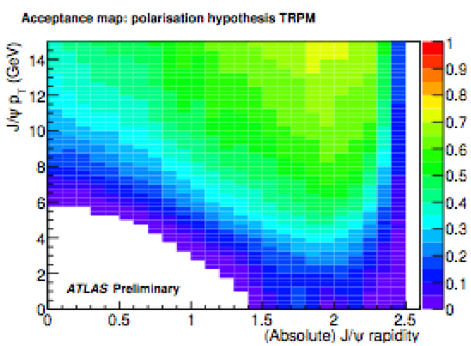
(b) $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$



(c) $\lambda_\theta = -1, \lambda_\phi = \lambda_{\theta\phi} = 0$



(d) $\lambda_\theta = +1, \lambda_\phi = +1, \lambda_{\theta\phi} = 0$



(e) $\lambda_\theta = +1, \lambda_\phi = -1, \lambda_{\theta\phi} = 0$

Acceptance maps and weight factors for J/ψ at spin alignment working points

p_T, GeV	FLAT	LONG	TRP0	TRPP	TRPM
	$0 < y \leq 0.75$				
6 – 8	1.00	0.67	1.31	1.30	1.32
8 – 10	1.00	0.69	1.29	1.32	1.26
10 – 15	1.00	0.72	1.24	1.25	1.23
	$0.75 < y \leq 1.5$				
4 – 6	1.00	0.69	1.29	1.55	1.15
6 – 8	1.00	0.72	1.25	1.29	1.22
8 – 10	1.00	0.74	1.21	1.22	1.20
10 – 15	1.00	0.77	1.18	1.18	1.18
	$1.5 < y \leq 2.25$				
0 – 2	1.00	0.81	1.15	1.55	0.96
2 – 4	1.00	0.73	1.23	3.23	0.77
4 – 6	1.00	0.64	1.18	1.98	0.87
6 – 8	1.00	0.79	1.15	1.44	0.98
8 – 10	1.00	0.80	1.15	1.26	1.05
10 – 15	1.00	0.82	1.08	1.18	1.08

Efficiency corrections

Data-driven trigger efficiency, from minimum-bias stream data

- Determined for J/ψ candidate events from single-muon trigger efficiencies, separately for Combined and Tagged muons
- Calculated for each pT-y bin used in the analysis, from actual distribution of J/ψ candidates

Offline muon reconstruction efficiency for the preliminary results derived from MC simulations

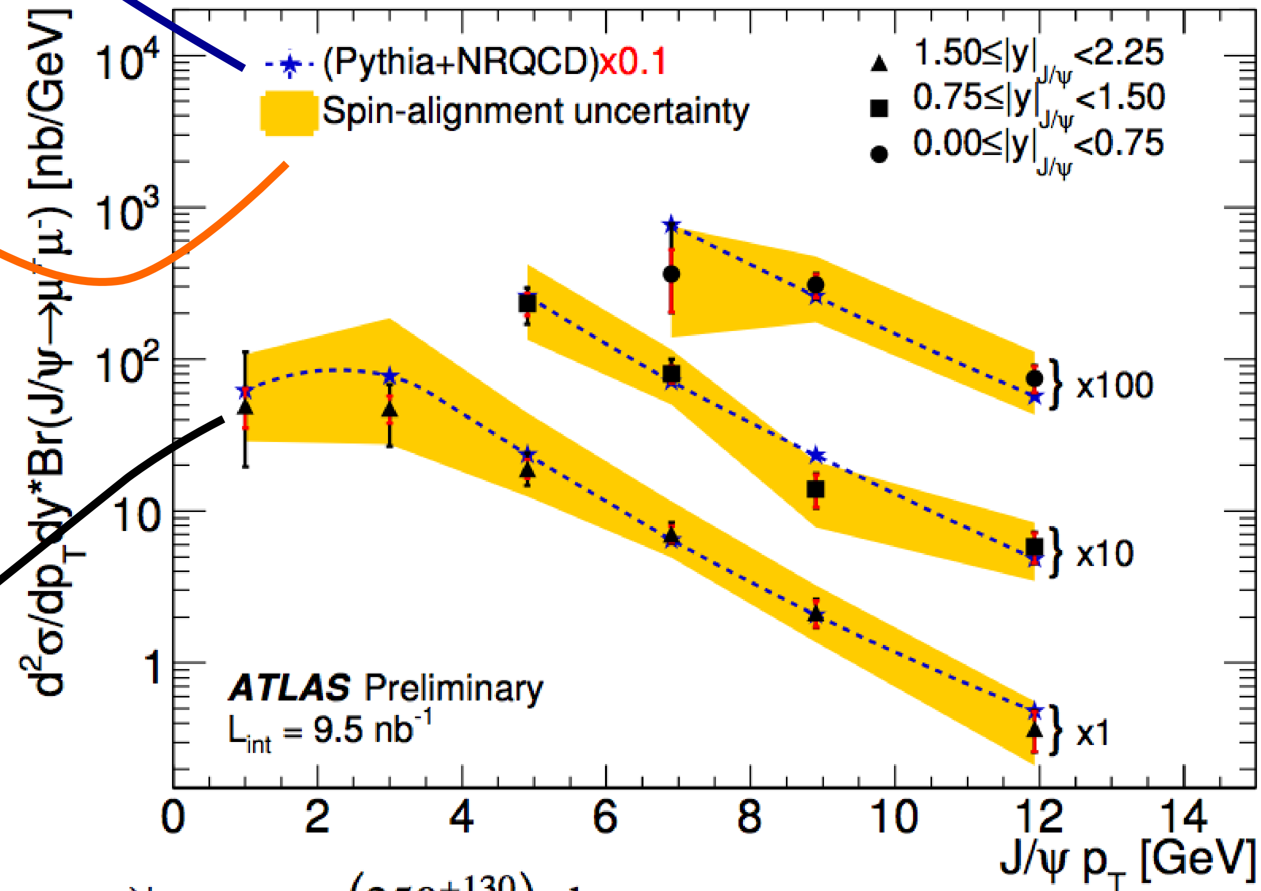
- MC-based efficiency maps validated with data, difference assigned as systematic
- Plan to use fully data-driven maps in the ongoing analyses

Differential cross-section

Pythia prediction with NRQCD ME's and ATLAS-wide MC09 tuning (based on MRST LO* PDFs)

Spin-alignment envelope:
From applying acceptance maps with different working points to data distributions (100% correlated to central data)

Central data is *inclusive* J/ψ for 'flat' polarisation hypothesis
(Red: statistical error)



$$d\sigma/dy \times \mathrm{Br}(J/\psi \to \mu\mu)|_{\langle y\rangle \simeq 1.85} = \left(250^{+130}_{-80}\right)\,\mathrm{nb}$$

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2010-062/

Differential cross-section in numbers

Systematics-dominated @low p_T:

Main systematics are from trigger and muon reconstruction

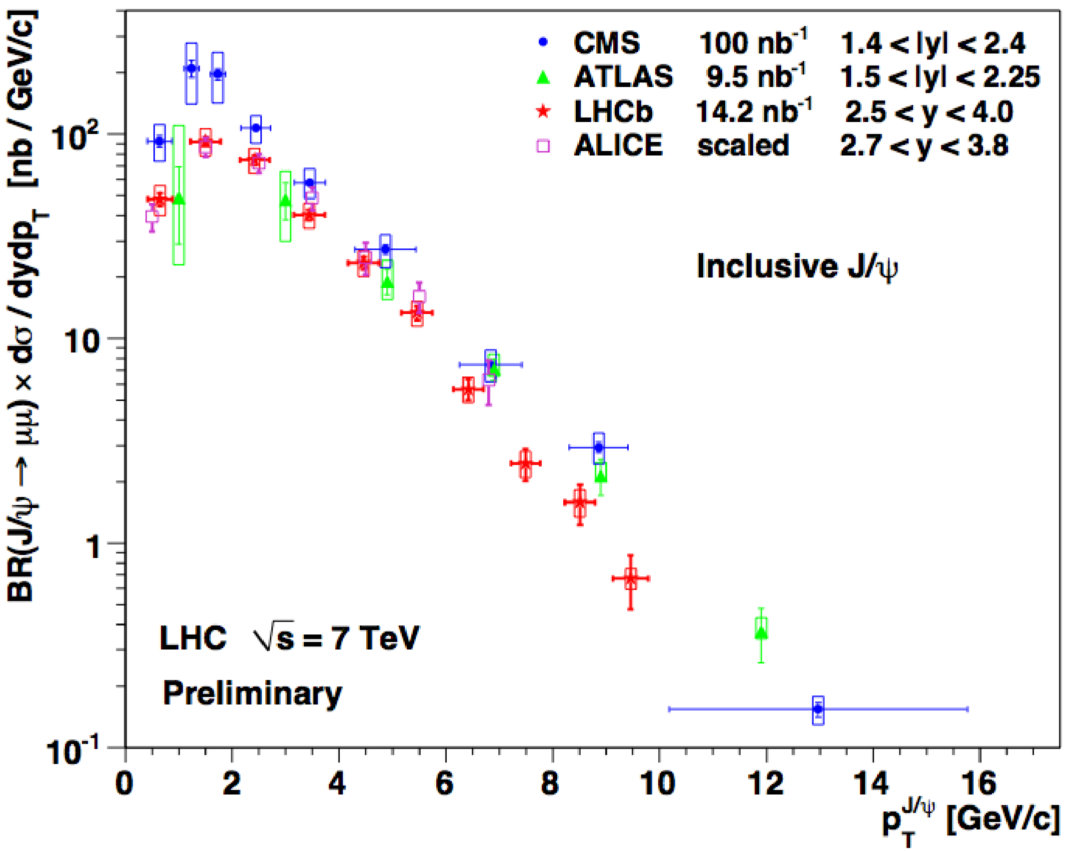
Will improve somewhat with more data, but will always be limited in this region of phase space

Comparable variation from spin-alignment uncertainty

Can only be reduced by direct measurement --- may take a while

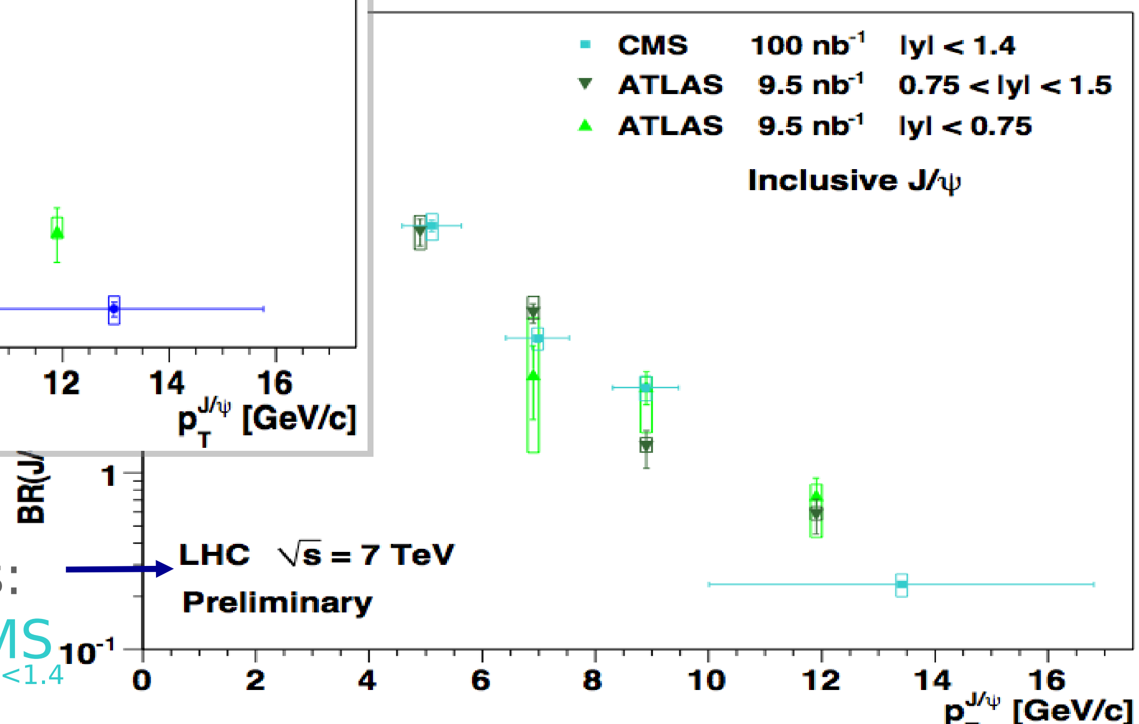
$p_T(J/\psi)$ GeV	Mean p_T GeV	$\frac{d\sigma}{dp_T dy} \cdot \mathrm{Br}[J/\psi \to \mu^+\mu^-]$ (nb/GeV)	
		$0.0 \le \lvert y \rvert < 0.75$	
		Data	PYTHIA
6 – 8	6.9	3.6 ± 1.6 (stat) $^{+3.9}_{-0.3}$ (syst) $^{+3.9}_{-2.3}$ (theory)	76.5 ± 1.5
8 – 10	8.9	3.08 ± 0.66 (stat) $^{+0.40}_{-0.22}$ (syst) $^{+1.7}_{-1.4}$ (theory)	26 ± 1
10 – 15	11.9	0.75 ± 0.18 (stat) $^{+0.11}_{-0.05}$ (syst) $^{+0.37}_{-0.32}$ (theory)	5.7 ± 0.3
		$0.75 \le \lvert y \rvert < 1.50$	
		Data	PYTHIA
4 – 6	4.9	23.2 ± 4.0 (stat) $^{+5.2}_{-4.9}$ (syst) $^{+18.9}_{-9.9}$ (theory)	260 ± 3
6 – 8	6.9	8.0 ± 1.0 (stat) $^{+1.9}_{-0.6}$ (syst) $^{+3.6}_{-3.0}$ (theory)	72 ± 2
8 – 10	8.9	1.40 ± 0.34 (stat) $^{+0.18}_{-0.09}$ (syst) $^{+0.73}_{-0.62}$ (theory)	23.3 ± 0.9
10 – 15	11.9	0.58 ± 0.13 (stat) $^{+0.06}_{-0.04}$ (syst) $^{+0.26}_{-0.24}$ (theory)	4.9 ± 0.3
		$1.50 \le \lvert y \rvert < 2.25$	
		Data	PYTHIA
0 – 2	1.0	49 ± 20 (stat) $^{+61}_{-26}$ (syst) $^{+58}_{-21}$ (theory)	621 ± 3
2 – 4	3.0	48 ± 10 (stat) $^{+18}_{-18}$ (syst) $^{+139}_{-20}$ (theory)	773 ± 3
4 – 6	4.9	19.1 ± 2.7 (stat) $^{+5.1}_{-3.5}$ (syst) $^{+25.1}_{-6.6}$ (theory)	235 ± 2
6 – 8	6.9	7.10 ± 0.88 (stat) $^{+1.32}_{-0.57}$ (syst) $^{+4.5}_{-2.2}$ (theory)	64 ± 1
8 – 10	8.9	2.14 ± 0.43 (stat) $^{+0.33}_{-0.10}$ (syst) $^{+1.1}_{-0.8}$ (theory)	20.7 ± 0.9
10 – 15	11.9	0.37 ± 0.11 (stat) $^{+0.06}_{-0.03}$ (syst) $^{+0.19}_{-0.16}$ (theory)	4.8 ± 0.3

ATLAS preliminary results in comparison



ATLAS preliminary results compatible with other LHC experiments

Forward rapidities:
ALICE ATLAS CMS LHCb



[H.Woehri]

Central rapidities:

ATLAS $0.0<|y|<0.75$ ATLAS $0.75<|y|<1.5$ CMS $|y|<1.4$

Comparison with NNLO* CSM

Perturbative QCD calculations --- relatively little ambiguity

NNLO* calculations include tree-level corrections to NLO

Only for direct vector quarkonium production (PRL 101 (2008) 152001)

In order to be compared to inclusive ATLAS data, needs correcting for:

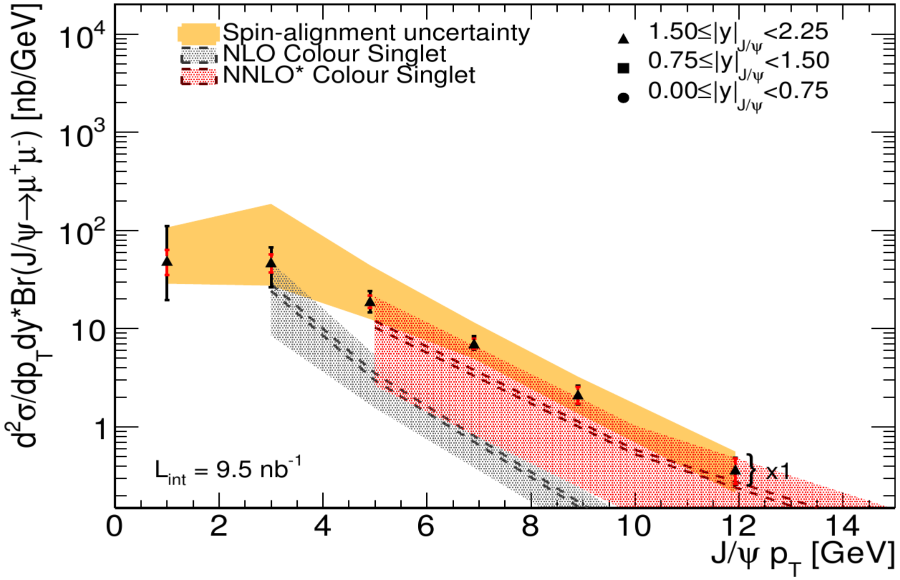
- feeddown from χ_c-states and ψ'
- non-prompt contribution from $B \rightarrow J/\psi$ X decays

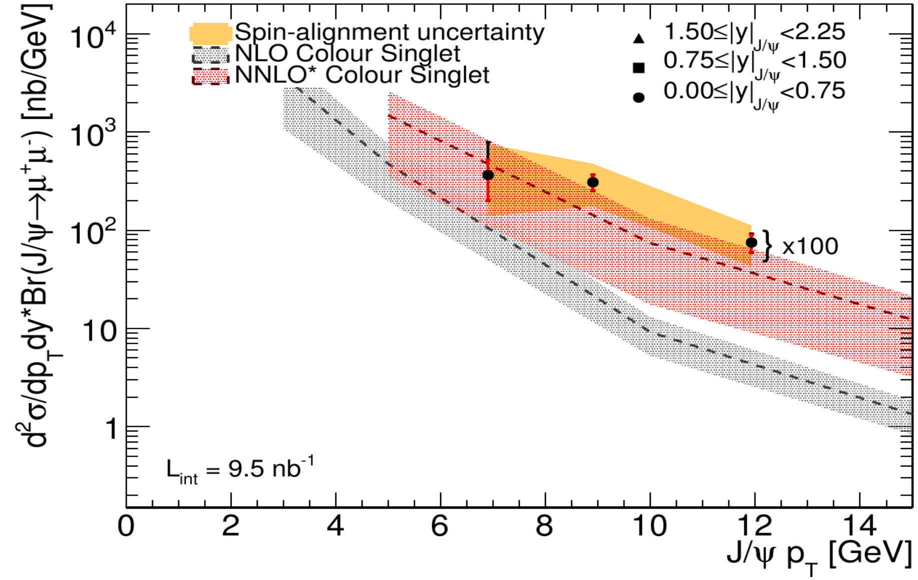
Corrections made using Tevatron measurements

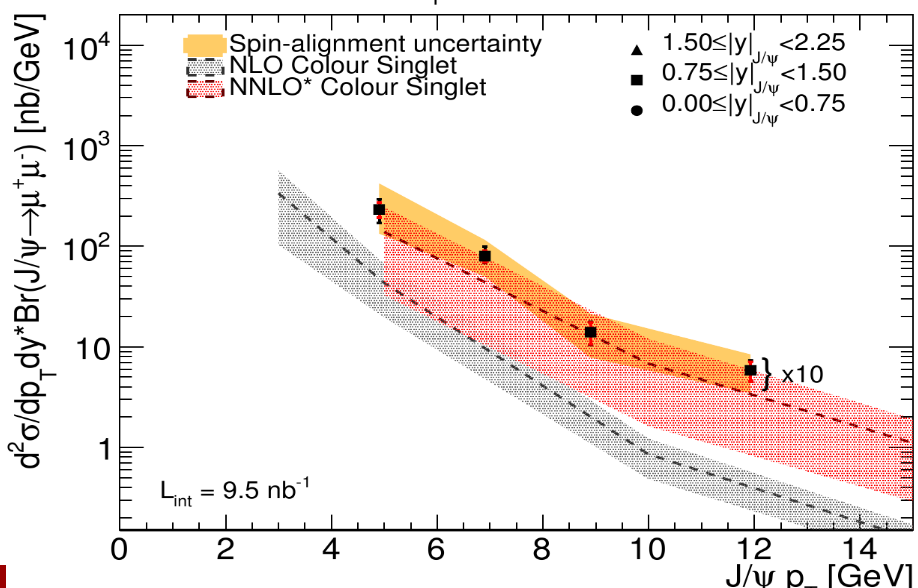
- B feeddown correction now verified at higher energy by all LHC collaborations, including ATLAS (see below)

Comparison with NNLO* CSM

With these corrections, the agreement with ATLAS looks remarkably good







[J-P Lansberg]

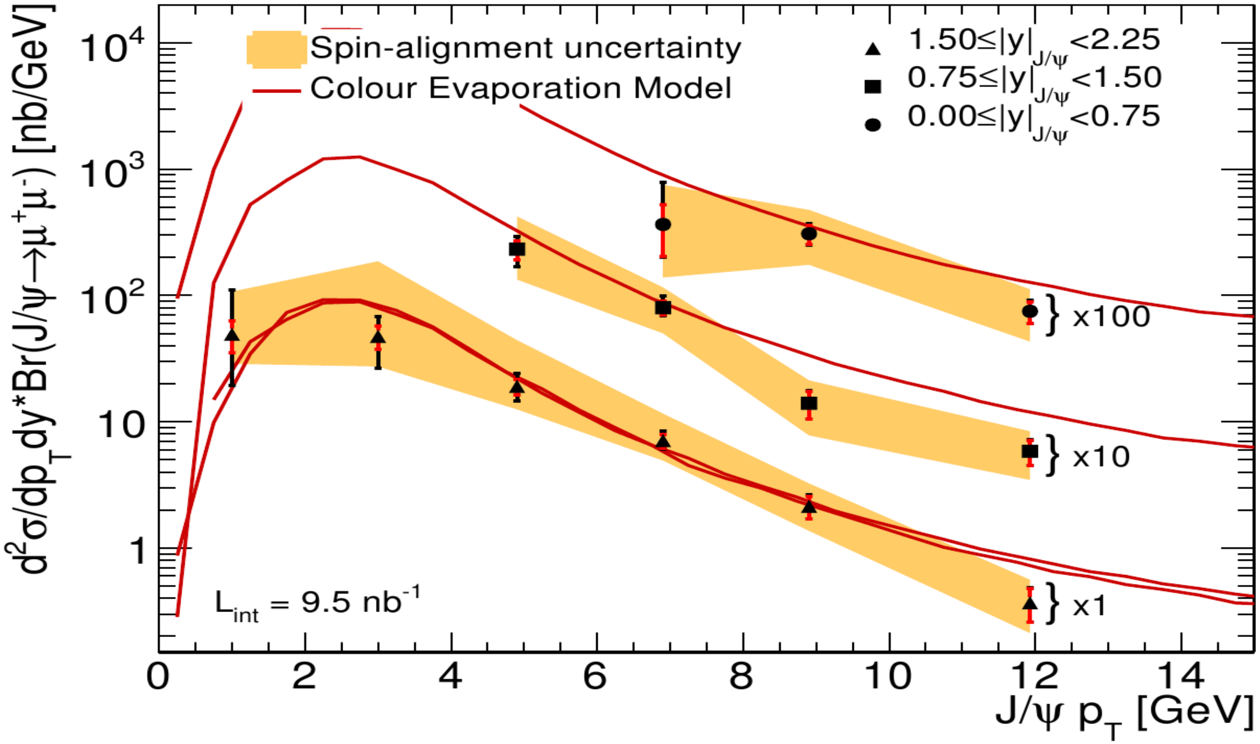
Comparison with Colour Evaporation Model

CEM: once a c-cbar pair is produced, creation of colour singlet bound states is governed by a suppression factor (Phys.Rep.462(2008)125)

No extra parameters used to extrapolate from Tevatron, using CTEQ6M

Agreement with preliminary ATLAS data remarkably good at low pt

Will be very interesting to compare at higher transverse momenta (soon!)



[R.Vogt]

A few comments

All experiments are trying very hard to produce results as free as possible from dependence on Monte Carlo model, to provide input for theorists.

This may be even more important now than ever before:

With a 3 GeV mass, J/Ψ has (almost?) lost its “hard probe” status:

Many talks yesterday mentioned 5 GeV scale as the separator

While for CDF the values of parton $x_{1,2}$ are safely above 10^{-3}, at LHC one needs to go down to 10^{-4} for y=0 and 10^{-5} - 10^{-6} for y=2 and 4

Can we even trust factorization here?

If so, is J/Ψ the only usable probe for such x?

Colour reconnection: by increasing reconnection, it's far too easy to allow **any** heavy quark-antiquark pair to merge into quarkonia, thus creating lots of spurious “unsolicited” J/Ψ and Υ

Should serve as another constraint on reconnection, easy to check

Nonprompt-to-prompt J/ψ ratio

Non-prompt (from B decays) and prompt (from QCD sources) production proceed via different mechanisms

Discriminating variable used is the “pseudo-proper time”

xy displacement of candidate from PV

Invariant mass of candidate

$$\tau = \frac{L_{xy}\, m(J/\psi)}{p_T(J/\psi)}$$

p_T of candidate

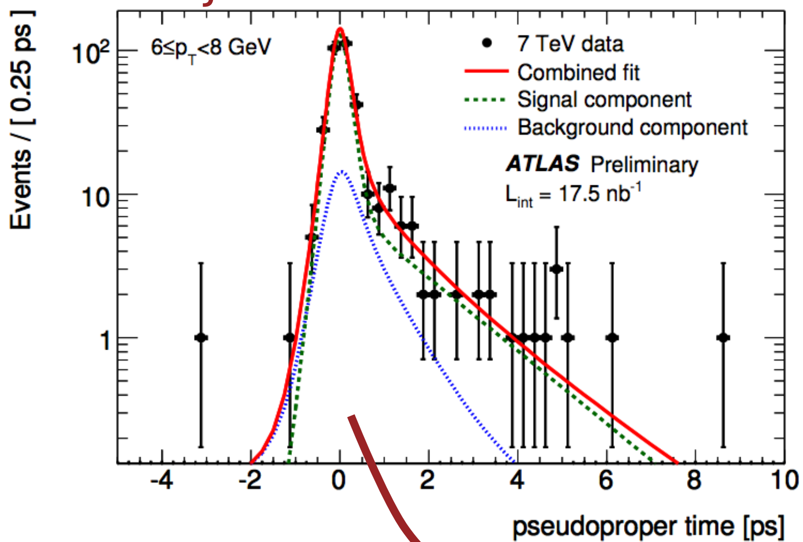
Variables and their errors calculated on candidate-by-candidate basis
Mass and lifetime fitted simultaneously using unbinned maximum likelihood fit

Different p.d.f. used for J/ψ signal region and sidebands

Delta-function plus exponential for signal
Delta-finction plus a sum of several exponentials for continuum background
(both convoluted with the resolution function)

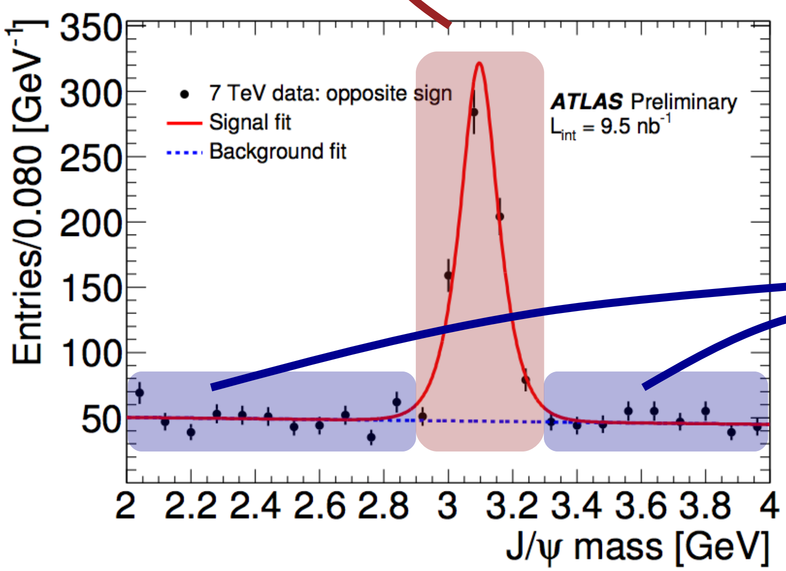
Nonprompt-to-prompt J/ψ ratio

PROJECTION: SIGNAL REGION

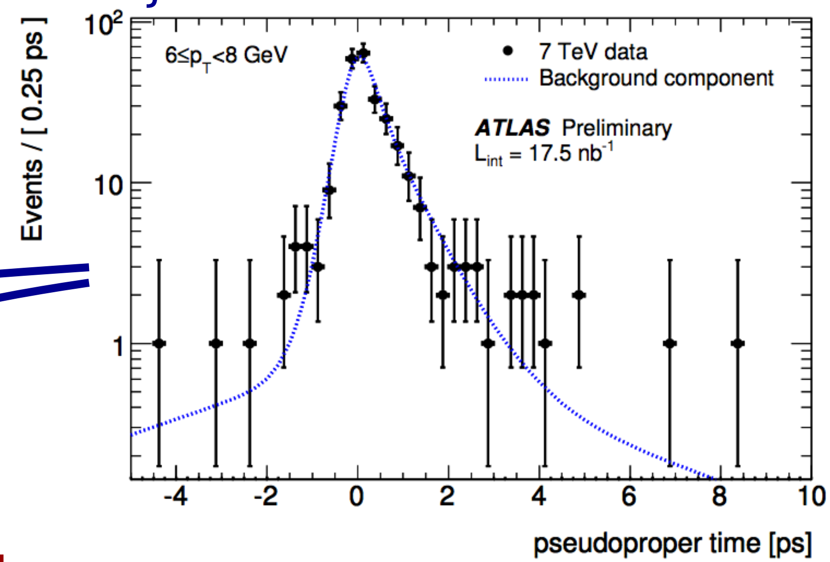


Measure nonprompt (B-decay) to prompt (incl. feed-down) production cross-section ratio, in bins of J/ψ p_T

Shown here are projections in lifetime (one bin for illustration) of simultaneous mass/lifetime fit



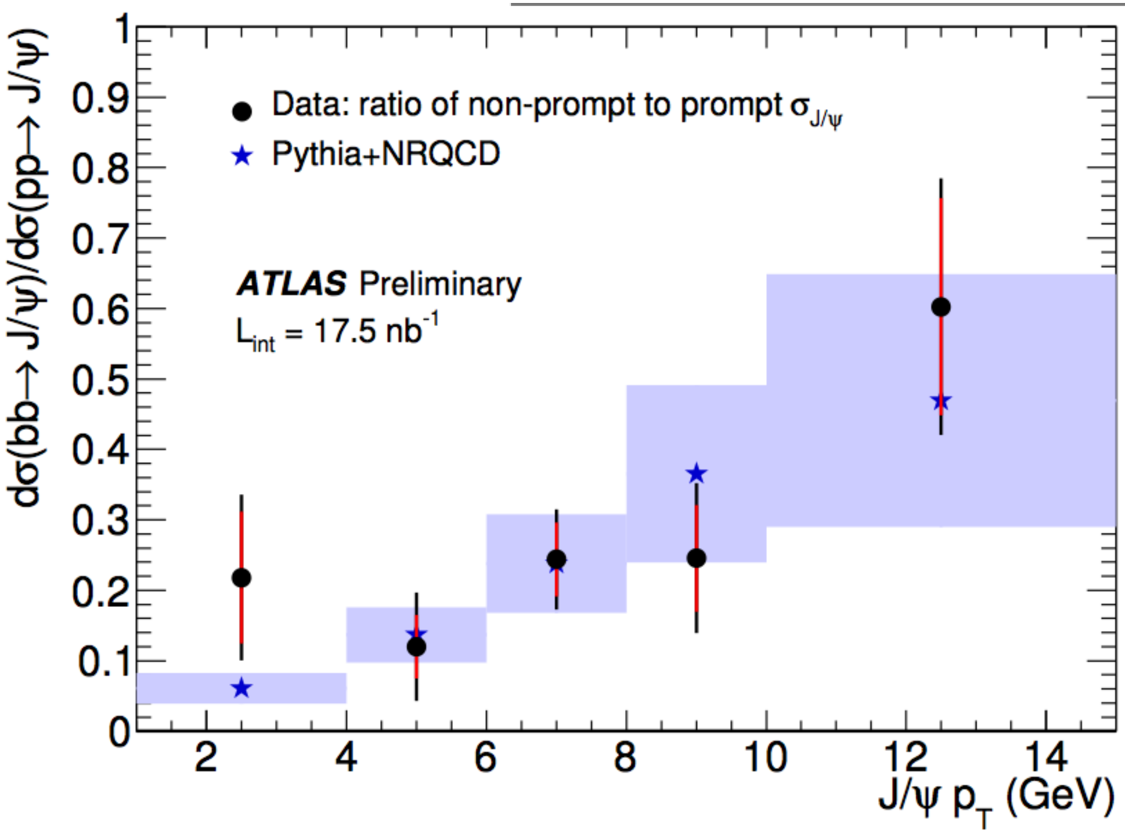
PROJECTION: SIDEBAND REGION



Nonprompt-to-prompt J/ψ ratio

L_{int} = 17.5 nb^{-1}

$p_T(J/\psi)$ GeV	$\mathcal{R} \equiv \sigma(pp \to b\bar{b}X \to J/\psi\, X')/\sigma(pp \to J/\psi\, X'')_{\text{prompt}}$		χ^2/DoF	p-value
	Data	MC		
1 – 4	0.22 ± 0.09(*stat*) ± 0.07(*syst*)	0.061 ± 0.022	33.5/34	0.49
4 – 6	0.12 ± 0.05(*stat*) ± 0.06(*syst*)	0.137 ± 0.039	23.2/25	0.57
6 – 8	0.24 ± 0.05(*stat*) ± 0.05(*syst*)	0.238 ± 0.070	22.0/20	0.34
8 – 10	0.25 ± 0.08(*stat*) ± 0.07(*syst*)	0.365 ± 0.126	10.1/15	0.81
10 – 15	0.60 ± 0.15(*stat*) ± 0.10(*syst*)	0.469 ± 0.180	6.9/16	0.97

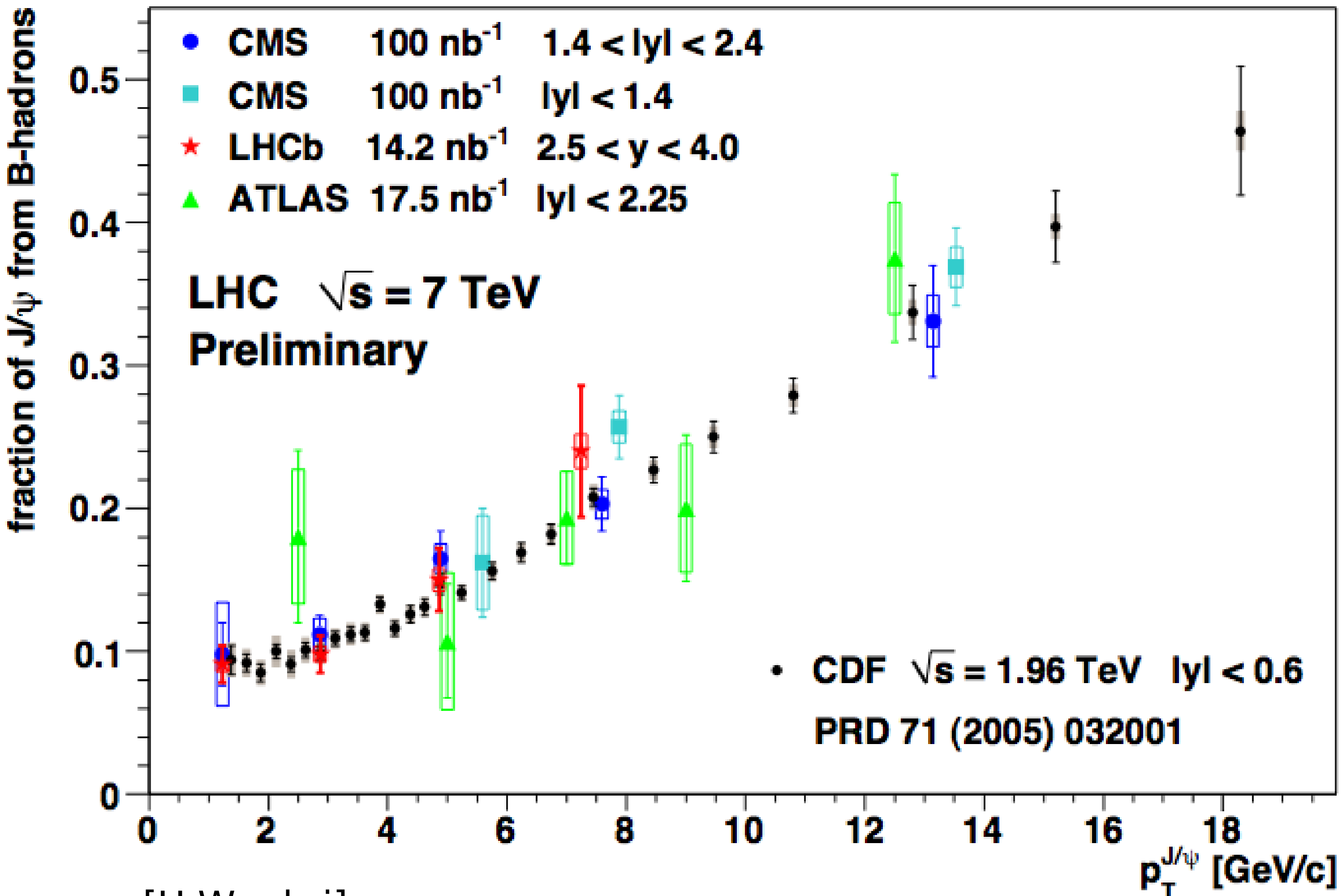


Again compare to ATLAS Pythia 6.4 (MC09)

Ratio described well

ATLAS preliminary results in comparison

Fraction of non-prompt J/ψ

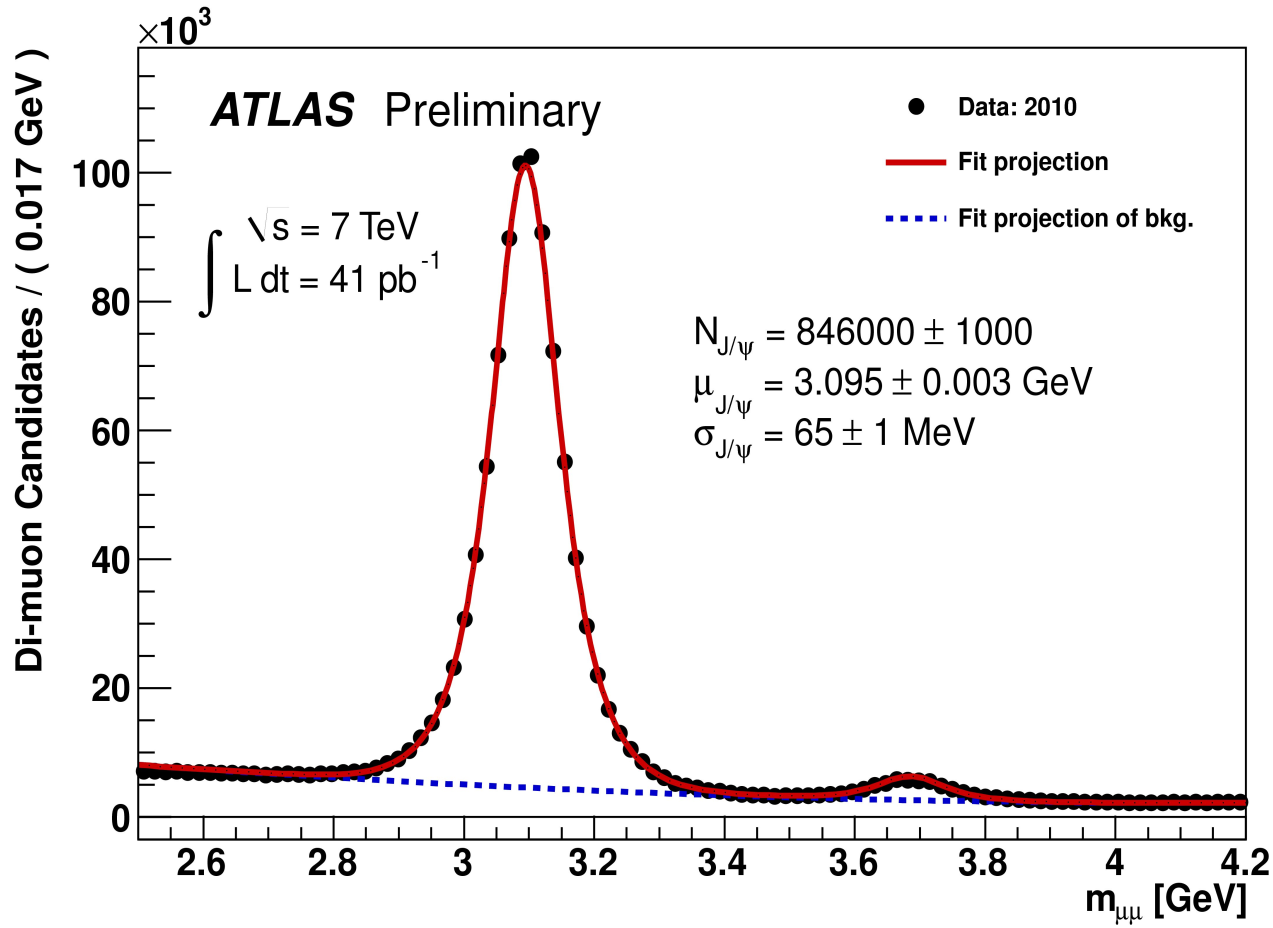


[H.Woehri]

Latest mass plot of J/ψ mass range

4 GeV p_T cut on first muon, 2.5 GeV cut on second muon

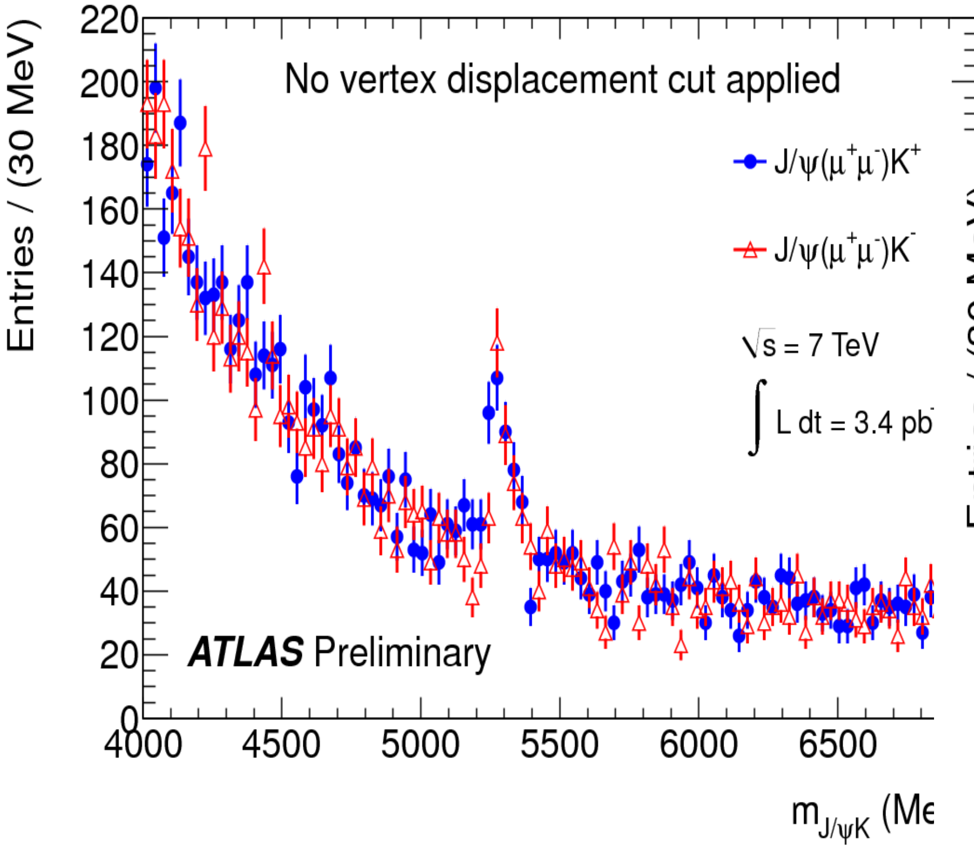
Whole accessible range of rapidities

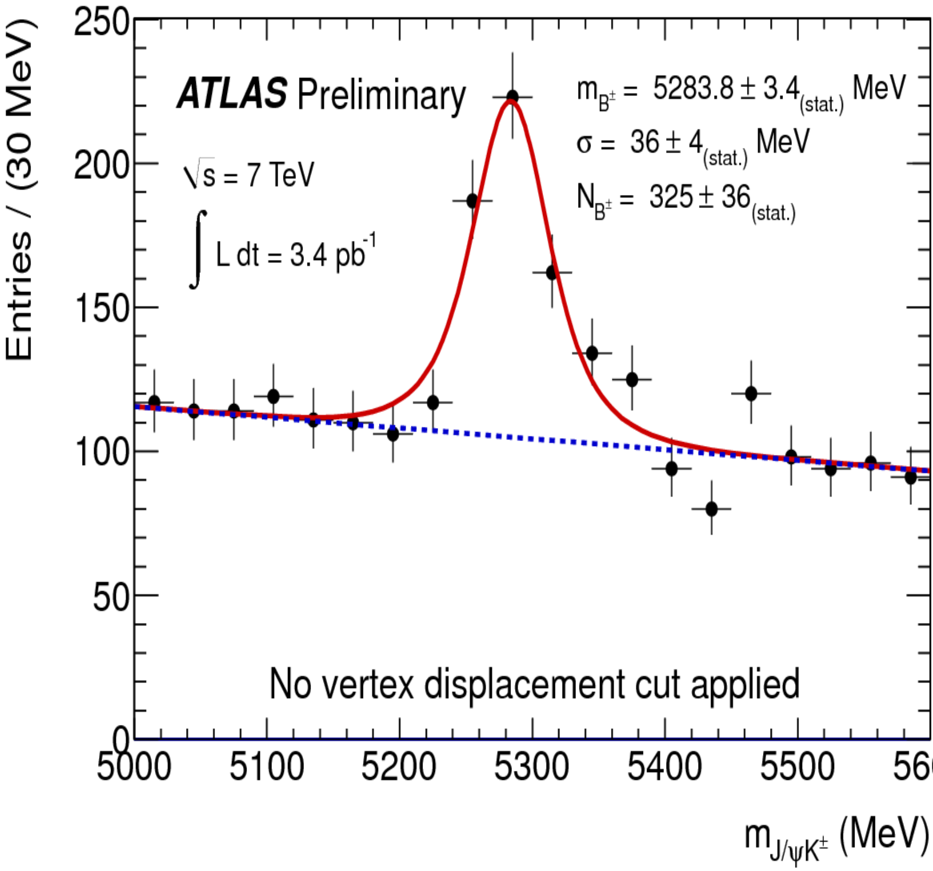


Resolution sightly better, as a larger fraction comes from the barrel area

Observation of B± mesons

Dimuons in J/ψ mass range combined with a third track (kaon mass assigned)
Fitted to a common vertex, with J/ψ mass constraint on dimuon

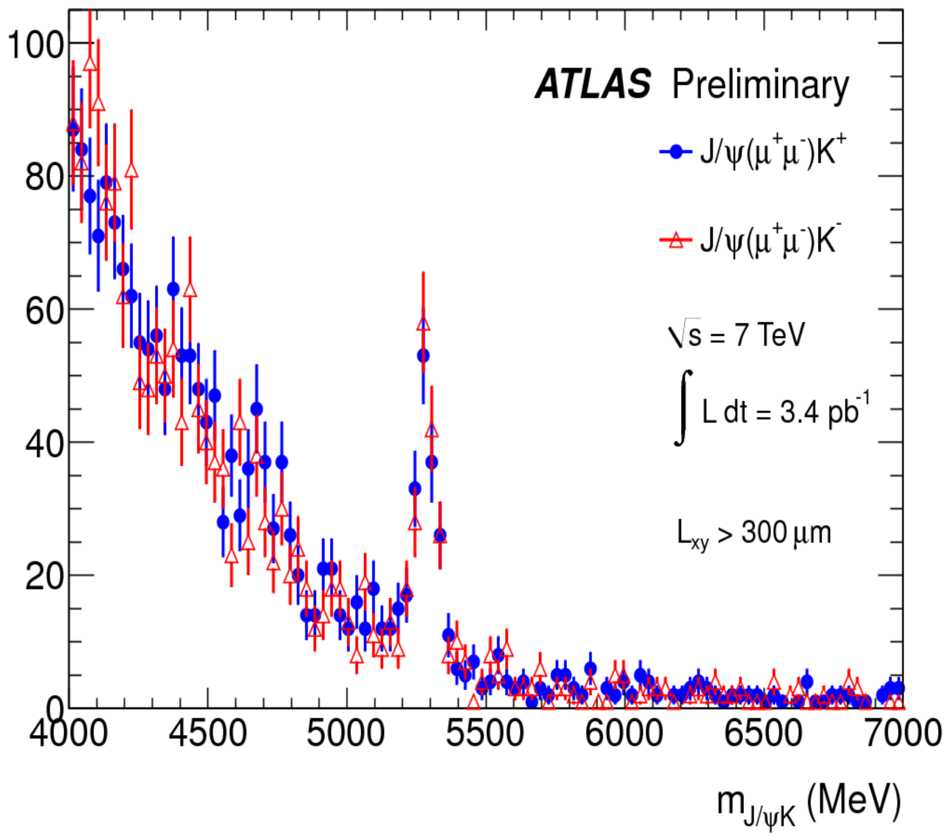


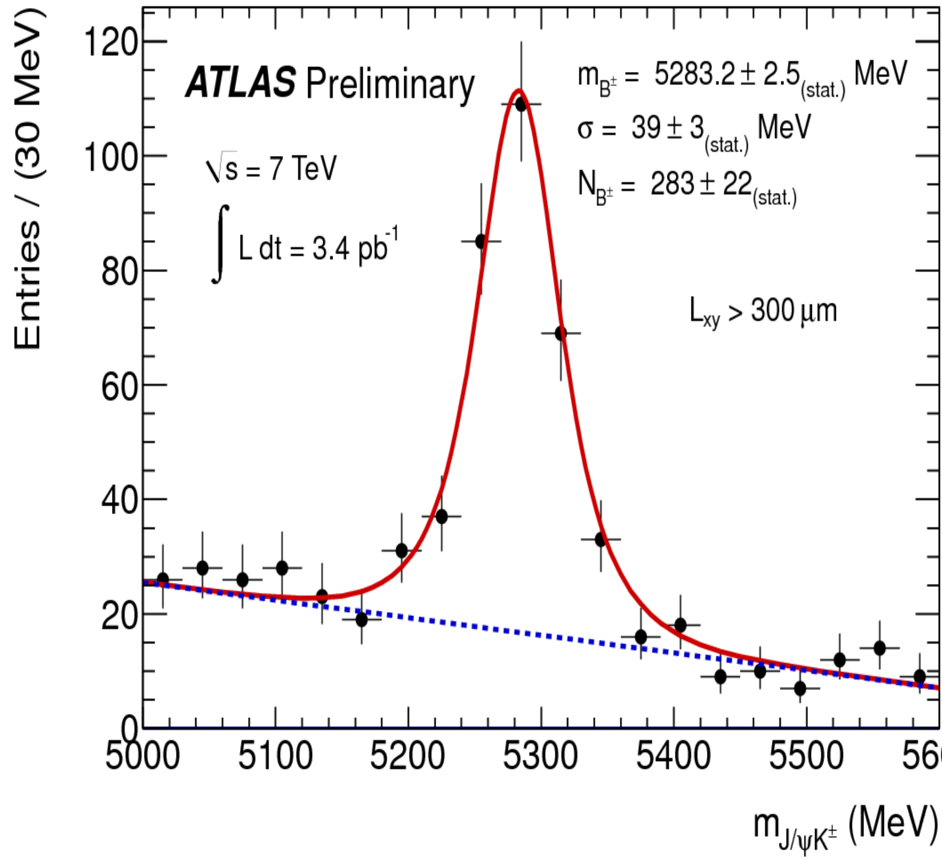


Observation of B± mesons

B mesons being long-lived, suppress background by applying a cut on transverse decay length, $L_{xy} > 0.3$ mm

Mass compatible with PDG value 3279 MeV





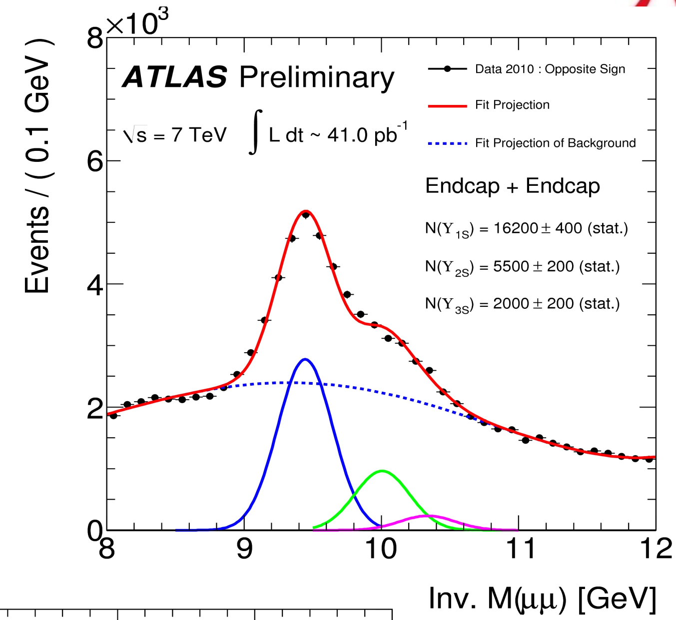
https://atlas.web.cern.ch/Atlas/GROUPS /PHYSICS/CONFNOTES/ATLAS-CONF-2010-098/

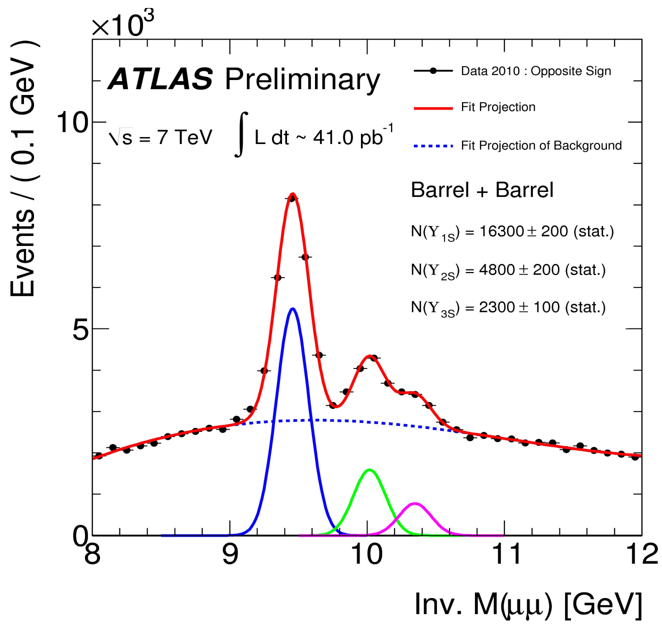
Observation of Υ resonances

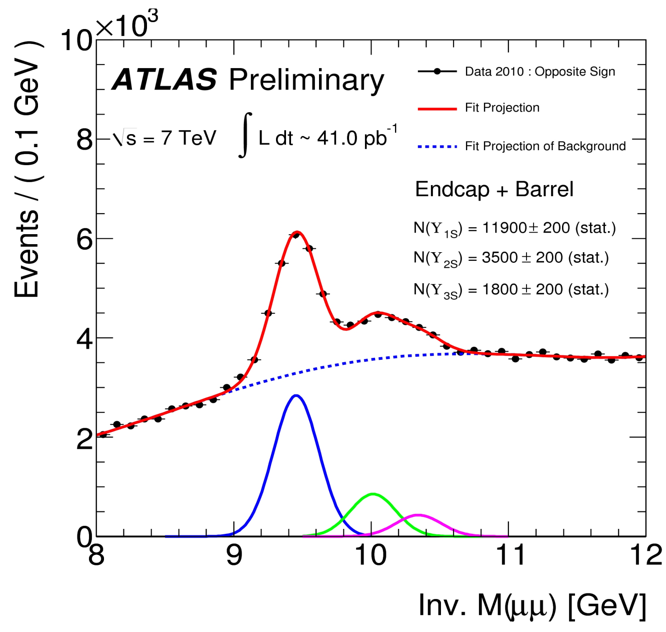
Three single Gaussians for Upsilon signals
ΔM fixed, common resolution σ
$p_T(\mu)>\{4, 2.5\}$ GeV, $E(\mu)>3$ GeV, $|\eta_\mu|<2.5$
Extended unbinned maximum likelihood fit

Resolution noticeably better in Barrel

Roughly similar numbers in BB, EB, EE







Summary of results so far

Excellent performance of the ATLAS detector

Observation of $D^{*\pm}$, $D^{\pm}$, $D_s^{\pm}$ in hadronic decay modes

Observation of J/ψ and ψ'

Observation of $B^{\pm}$ decay into J/ψ + K

Observation of the three Υ states

Preliminary measurement of J/ψ differential cross section and non-prompt to prompt ratio

Short-term plans --- few pb^{-1} of data

Measurement of open charm cross sections, for all observed charmed mesons:

- Assess kinematic acceptance, selection efficiency
- For some states, statistics can be enough for differential cross section

Full publication on J/ψ cross section and ratio

- Data-driven efficiencies
- Increased statistics, finer binning, extended to much higher pT values
- Comparison to theoretical models

Measurement of the cross section and relative fractions of Υ states

Observation of various exclusive beauty decays:

- $B_d \to J/\psi K^*$, $B_d \to J/\psi K$, $B_s \to J/\psi \phi$, $B_c \to J/\psi \pi$, $\Lambda_b \to J/\psi \Lambda^0$

Measurement of ψ' production cross section and nonprompt fraction

All these analyses ongoing, at varying degree of completion

Long(er) term plans

Based on 2010 data sample (in no particular order):

Further extend J/ψ and Upsilon measurements:

- higher pt
- polarisation of J/ψ, ψ' and Y
- feeddown from χ_c and χ_b states via radiative decays
- observation of X, Y, Z exotic quarkonium states

Insight into production mechanisms --- associated production of prompt J/ψ (Y) with:

- jets
- open charm (beauty)
- non-resonant photons

Cross section measurement for exclusive beauty decays
Inclusive b cross section measurement

Continue preparations to search for rare decays and CP violation

Lots of interesting results to come, watch this space!