Measuring J/ψ production at ATLAS

SCSWT'2010

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with thanks to D. Price, A. Nelson, J.Walder
and the rest of B physics group

Outline of talk

Introduction

- Some background information to J/ψ production
- Theoretical models and current status

Measurement

- Experimental acceptance, trigger and event selection
- Yields and methodology
- Cross-section result
- B-fraction result

Results in context

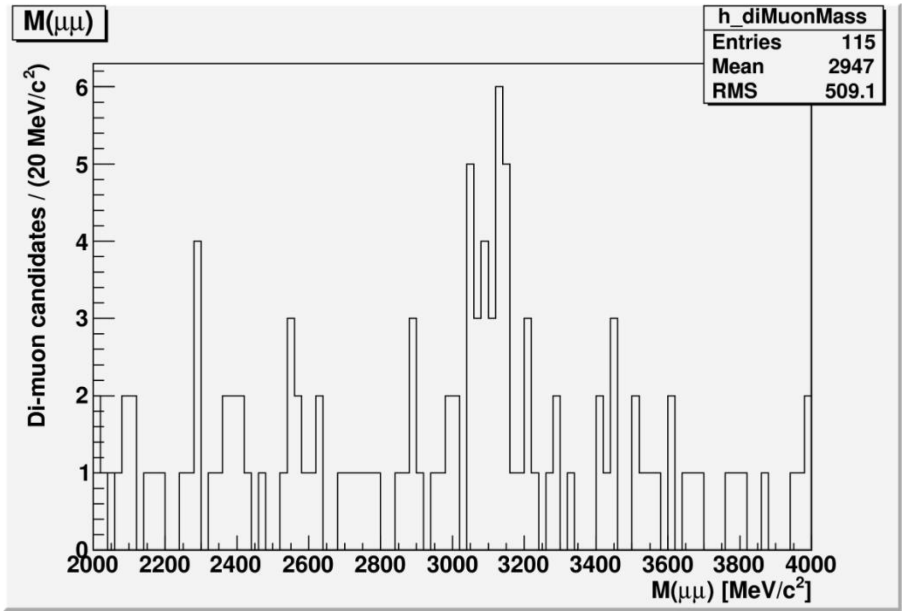
- Comparison to other experiments
- Theory comparison
- Future plans

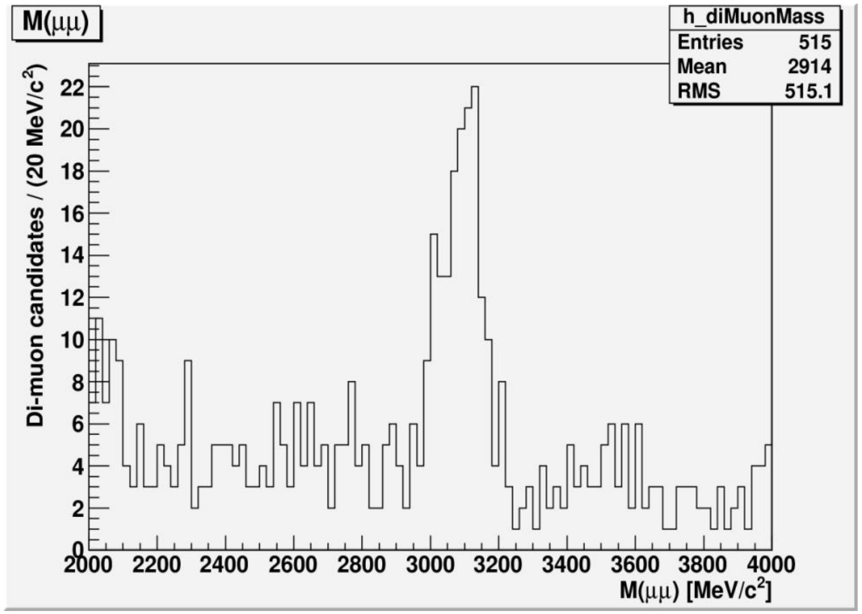
Links to history – and to this tutorial

ATLAS analysis tutorial outcome:

Dimuon invariant mass spectrum

Clear J/ψ peak, with a (few) hundred entries





Links to history – and to this tutorial

Some people saw a similar peak 36 years ago…

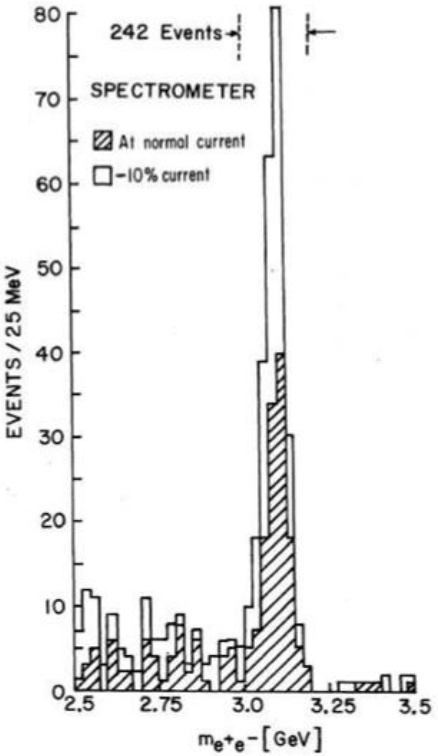
… and eventually got a Nobel Prize for it!

It's personal

I clearly remember reading about J/ψ discovery in a Georgian newspaper in November 1974

as a fourth year student, in the foyer of the TSU Physics Department

Since then, spent a big chunk of my life studying J/ψ



The Color Singlet Model @ LO

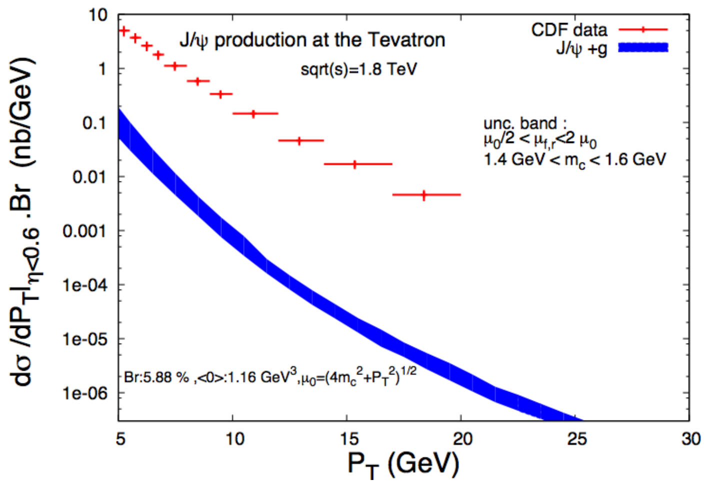
Color Singlet Model assumes:

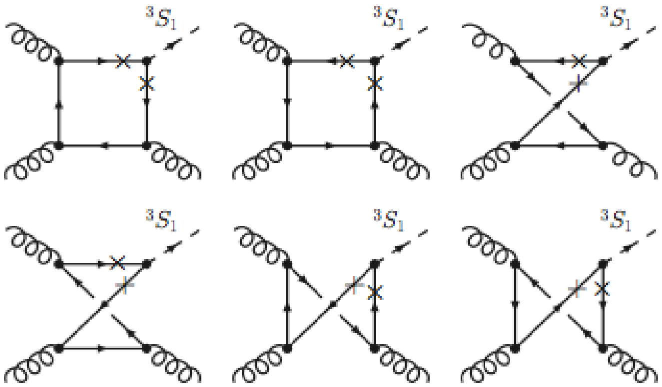
Factorisation theorem:
decompose quarkonium formation into:
1)Creation of two on-shell heavy quarks

Typical scale makes this perturbative

2)Binding into physical meson

Non-perturbative QCD





Static approximation:
Heavy quarks have small velocity *v* in meson, so can be treated as "at rest" in J/ψ frame (double power expansion in α_s and *v*)

Quantum number conservation in binding:
Assume color & spin preserved in binding – implies states *produced* in color singlet state

Extending the model: singlet → octet

Experimental evidence had shown the Color Singlet Model at the time was not able to describe the data

Unable to describe p_T dependence or normalisation

Theoretically, was understood there were missing contributions

Model had IR divergences in P-wave states that could not be reconciled

Understanding of NLO contributions and p_T scaling of diagrams suggested model was too strict and significant contributions were being ignored

Should the pair be perturbatively produced in a color singlet state?

Why can't it non-perturbatively evolve into singlet physical state during formation, via the emission of soft gluons?

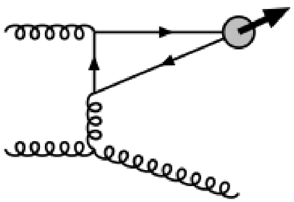
Loosening of the colour/spin conservation constraint led to Color Octet Mechanism based on Non-Relativistic QCD (NRQCD)

Color Octet Mechanism / NRQCD

Color octet model solves a number of problems:

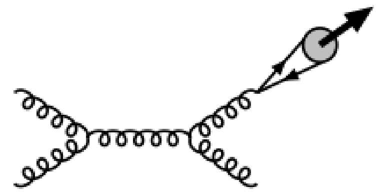
Adds additional diagrams = more rate
(e.g., vector quarkonia can be produced via a single gluon):

colour-octet t-channel gluon exchange: $g + g \to c\bar{c}[{}^1S_0^{(8)}, {}^3P_J^{(8)}] + g$



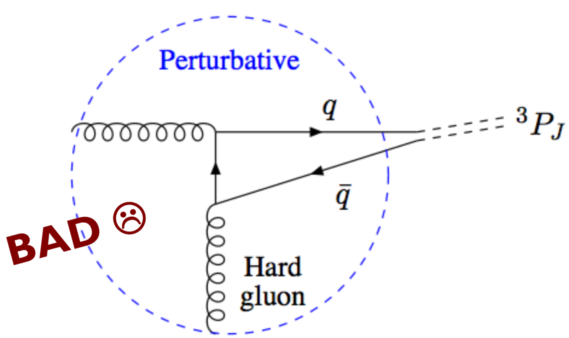
$+ \ldots \qquad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

colour-octet fragmentation: $g + g \to c\bar{c}[{}^3S_1^{(8)}] + g$

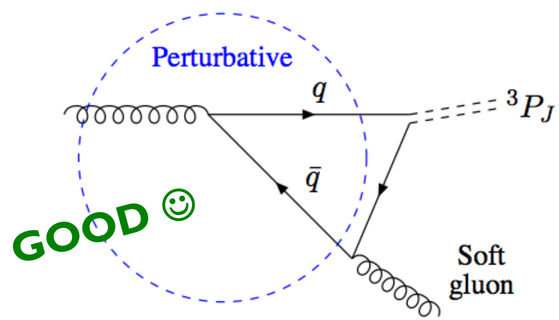


$+ \ldots \qquad \sim \alpha_s^3 \frac{1}{p_t^4} v^4$

Cancels IR divergences in singlet contributions:



${}^3P_J(\mathbf{1})$ production in CSM

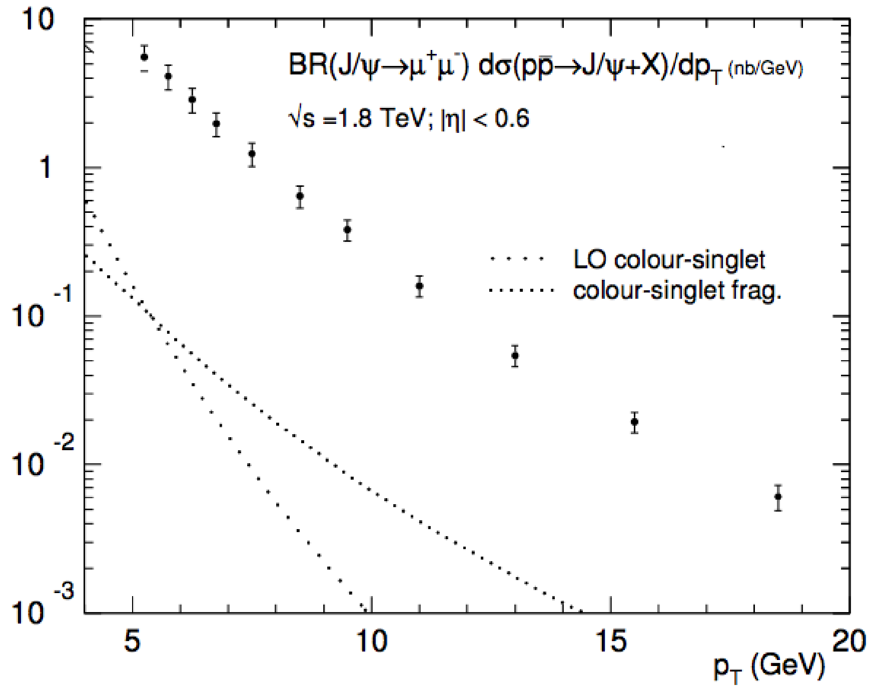


${}^3S_1(\mathbf{8})$ to ${}^3P_J(\mathbf{1})$ production in NRQCD

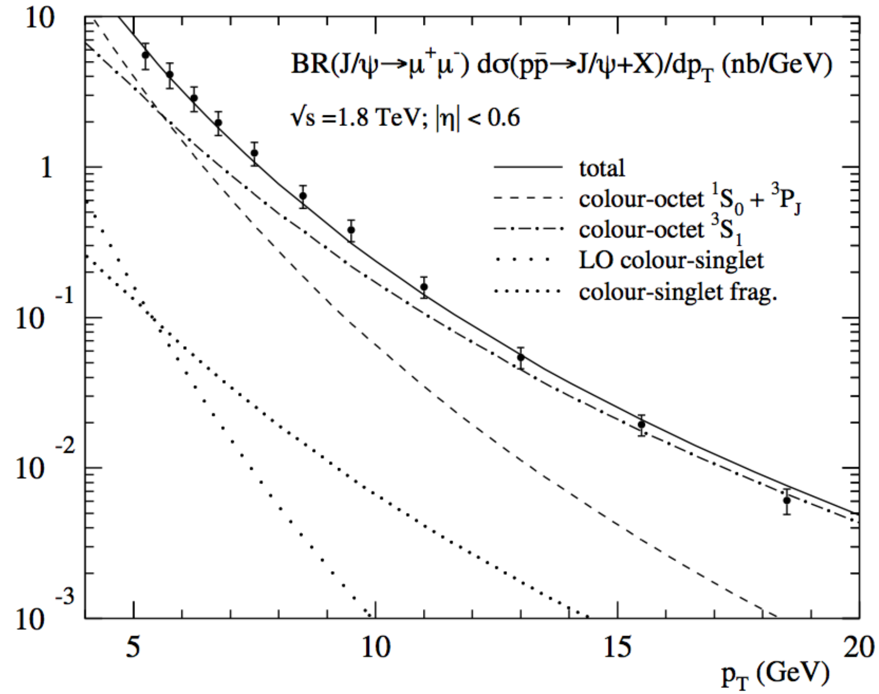
Color Octet Mechanism / NRQCD

Color octet model needs many parameters, but still has some predictive power

- **Various non-perturbative octet matrix elements have specific p_T dependences, but normalisations must be taken from data**
- **Give good data description at the Tevatron!**



LO (+fragmentation) singlet only…

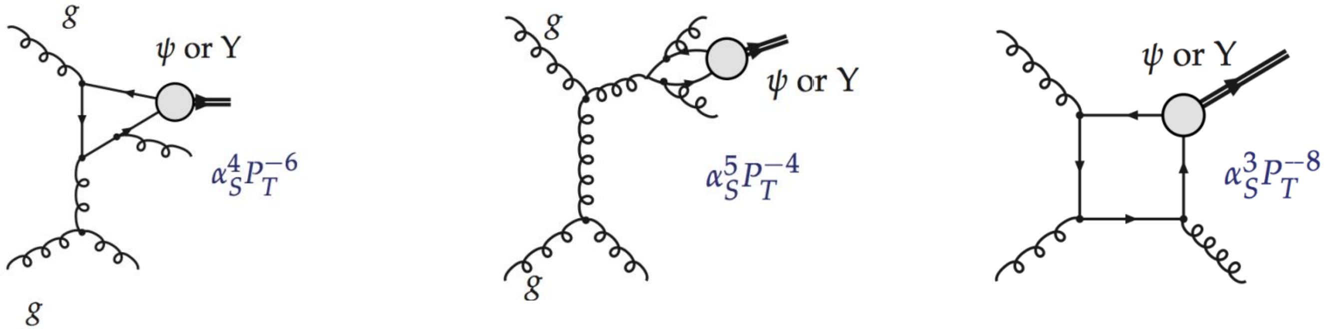


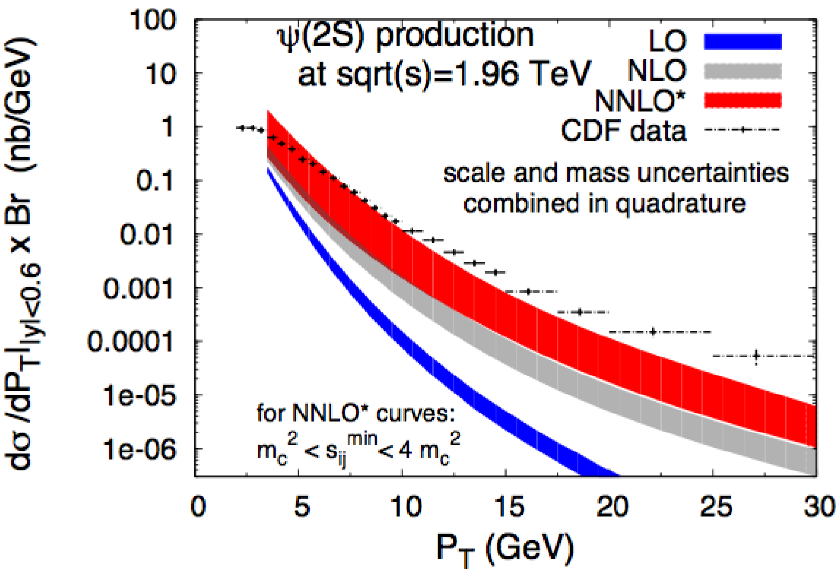
… + octet contributions

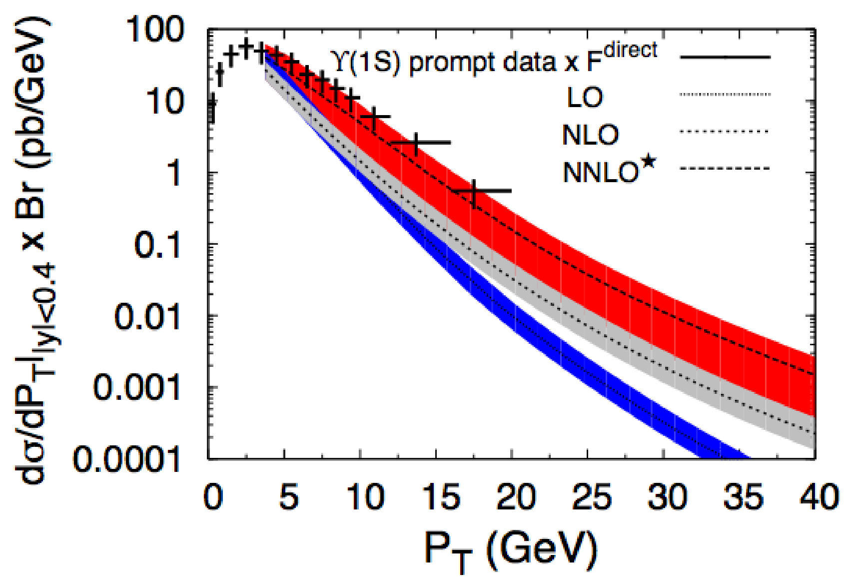
Color Singlet Model returns @ NNLO*

In the past couple of years, advances have allowed NNLO* predictions in the Color Singlet Model: show contributions to be (very) large!

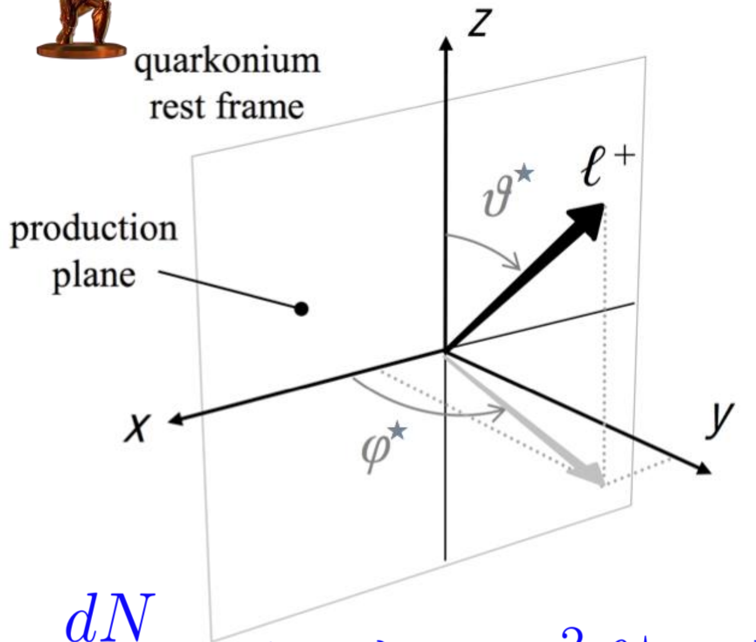
Good agreement with CDF data: now testing predictions at ATLAS







The question of spin alignment

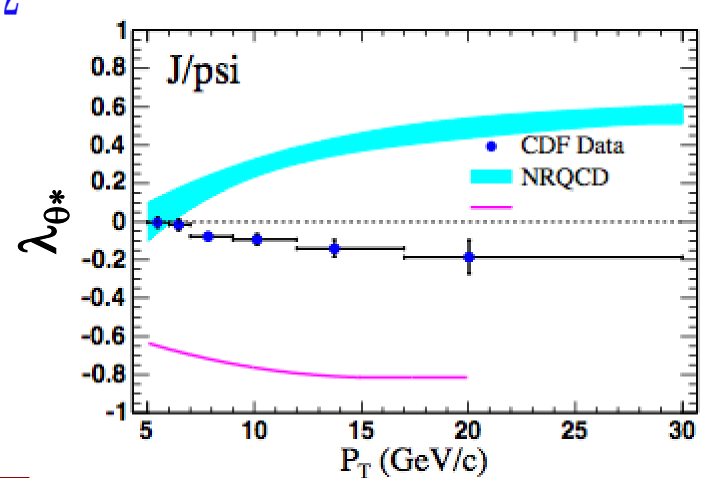


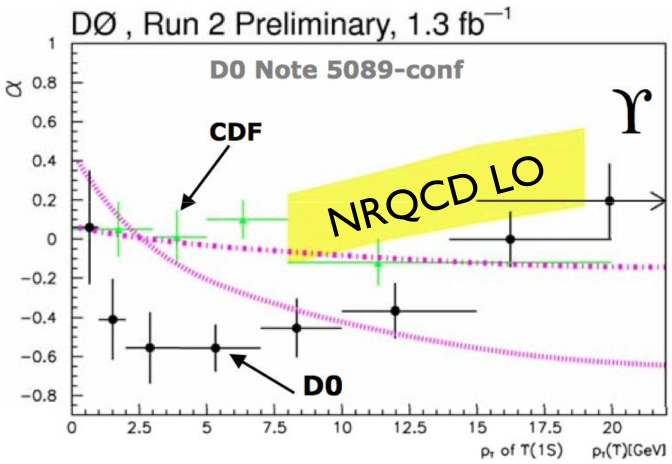
Various competing models gave predictions for the spin alignment distribution of produced J/ψ

Spin alignment could be measured and used as probe of production mechanism

Experimental data from Tevatron gave confusing results: not yet a clear picture

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





So what are ATLAS measuring?

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 indirect-to-prompt J/ψ production cross-section

(as a function of J/ψ p_T)

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

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

Future measurements will directly measure spin-alignment and other observables of interest for probing production mechanisms

Run and event selection (ICHEP)

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Data taking periods B and C (23rd April-4th June)

"May" reprocessing and muon_yellowPlus DQ selection (also requires good tracking DQ flags) --- "Good Run List"

Trigger selection:

Differential cross section: only process events passing minimum-bias seeded EF trigger EF_mu4_MSonly_MB2_noL2_EFFS (9.5 nb^{-1})

Prescaled in period C (and some late runs of B) but efficiency is close to 100%

Ratio measurement:

process events which pass *either* the above trigger or L1_MU0 (17.5 nb^{-1})

Take advantage of unprescaled trigger for measurement where the efficiencies are expected to cancel

Publication will use data from periods B through F and HLT single muon triggers (EF_mu4 and EF_mu6) in later periods

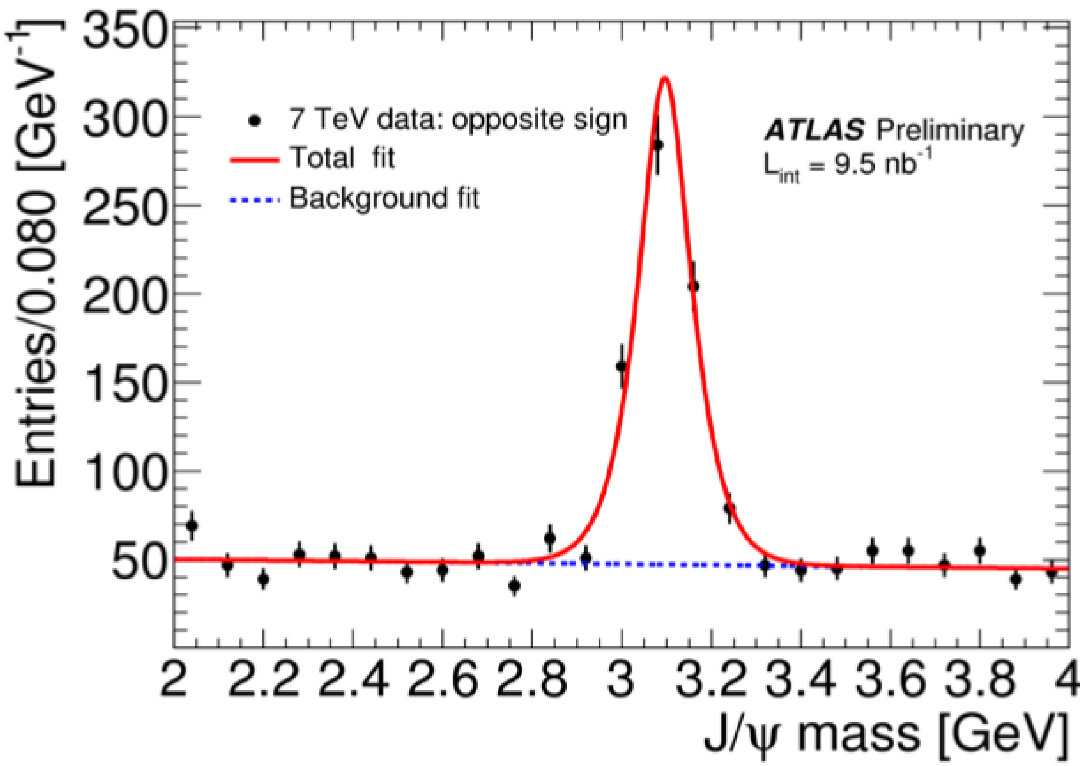
Specific B-physics trigger chains are under validation for period F and beyond

J/ψ candidate reconstruction (ICHEP)

Select oppositely-signed muon pairs with associated ID track (Comb-Comb and Comb+Tag pairs) with p_μ>3 GeV, $|\eta_\mu|$<2.7,

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

Unbinned maximum likelihood fit used to fit background and signal in data/MC



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

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

Signal yield @ 9.5 nb^{-1} = 592±30

Mass position 3.095±0.003 GeV

Mass in good agreement with PDG

Resolution 71±4 MeV

Resolution consistent with simulation prediction

Increase in yields from ICHEP to publication

$p_T(J/\psi)$ GeV			
	$0.0 \le \lvert y \rvert < 0.75$		
		Yield	Mass, GeV
6 – 8	Observed	12 ± 4	3.109 ± 0.019
	Weighted	101 ± 45	3.095 ± 0.018
8 – 10	Observed	23 ± 5	3.102 ± 0.005
	Weighted	87 ± 18	3.102 ± 0.005
10 – 15	Observed	22 ± 5	3.107 ± 0.008
	Weighted	53 ± 12	3.108 ± 0.007
	$0.75 \le \lvert y \rvert < 1.5$		
		Yield	Mass, GeV
4 – 6	Observed	52 ± 9	3.095 ± 0.013
	Weighted	534 ± 91	3.085 ± 0.017
6 – 8	Observed	68 ± 9	3.088 ± 0.008
	Weighted	218 ± 27	3.077 ± 0.008
8 – 10	Observed	18 ± 5	3.098 ± 0.013
	Weighted	39 ± 10	3.099 ± 0.013
10 – 15	Observed	22 ± 5	3.071 ± 0.015
	Weighted	41 ± 9	3.067 ± 0.014
	$1.5 \le \lvert y \rvert < 2.25$		
		Yield	Mass, GeV
0 – 2	Observed	23 ± 10	3.153 ± 0.030
	Weighted	790 ± 340	3.141 ± 0.032
2 – 4	Observed	87 ± 13	3.093 ± 0.011
	Weighted	860 ± 180	3.101 ± 0.015
4 – 6	Observed	97 ± 13	3.089 ± 0.011
	Weighted	454 ± 65	3.093 ± 0.013
6 – 8	Observed	77 ± 10	3.102 ± 0.011
	Weighted	191 ± 24	3.102 ± 0.012
8 – 10	Observed	34 ± 7	3.074 ± 0.018
	Weighted	59 ± 12	3.074 ± 0.018
10 – 15	Observed	16 ± 5	3.134 ± 0.027
	Weighted	26 ± 8	3.127 ± 0.028

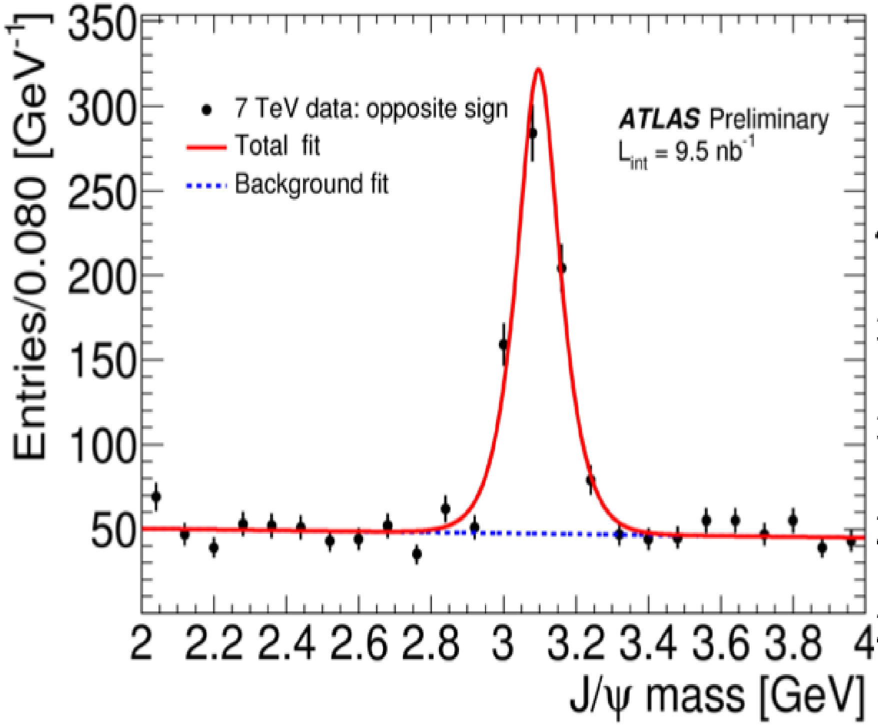
In preliminary result for ICHEP, observed signal yields were with 9.5 nb^{-1} data.

Publication will be on ~3 pb^{-1} data (B to F)

Yields to end of period D shown below, with *much* more data still to include!

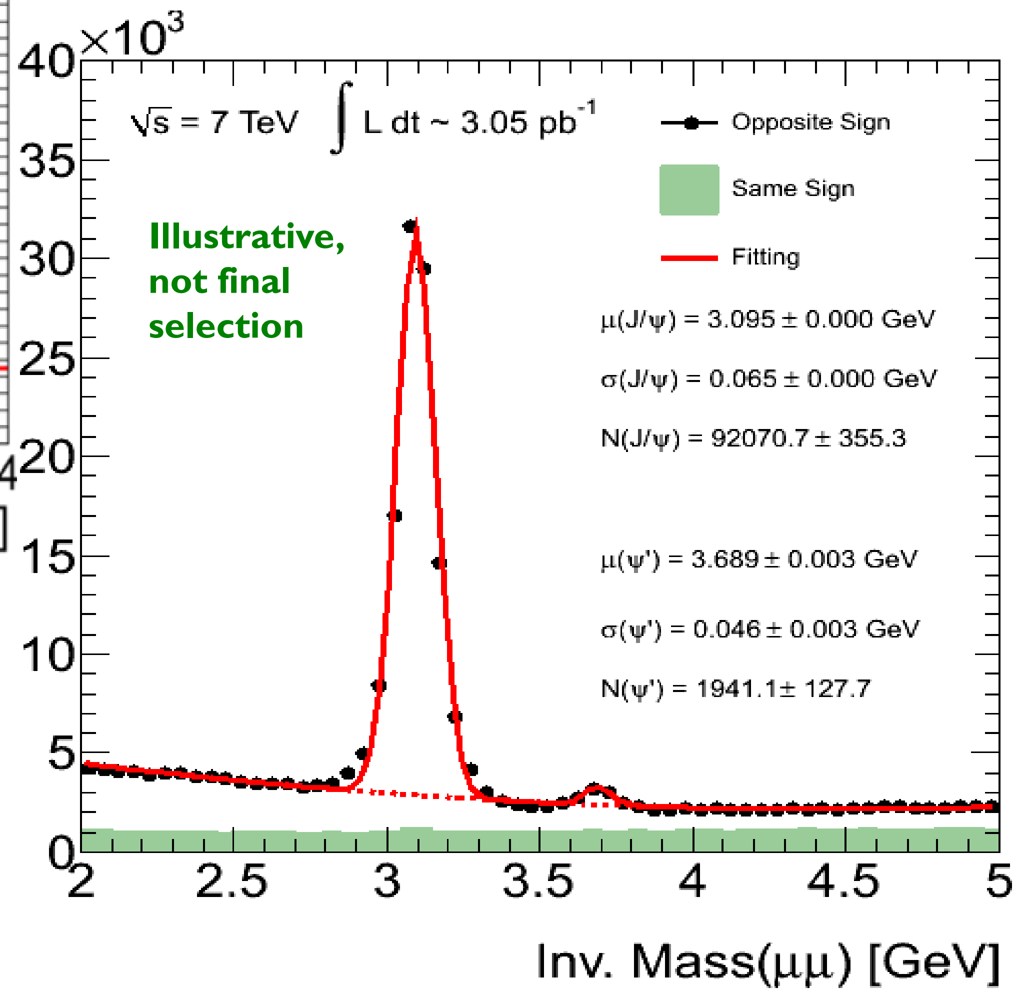
	J/ψ rapidity 0 – 0.75	J/ψ rapidity 0.75 – 1.50	J/ψ rapidity 1.50 – 2.00	J/ψ rapidity 2.00 – 2.40
22. – 30. GeV	25.91 ± 5.52	30.16 ± 5.97	10.11 ± 4.05	4.72 ± 2.52
18. – 22. GeV	50.94 ± 7.55	46.34 ± 8.04	34.17 ± 6.45	0.00 ± 0.48
16. – 18. GeV	40.45 ± 6.71	56.91 ± 8.55	32.31 ± 6.40	25.17 ± 7.73
14. – 16. GeV	96.32 ± 10.61	69.40 ± 9.77	57.34 ± 8.97	41.42 ± 8.02
12. – 14. GeV	130.00 ± 11.98	171.95 ± 15.17	100.73 ± 12.15	48.44 ± 9.26
10. – 12. GeV	271.41 ± 17.70	366.34 ± 21.40	244.93 ± 18.96	90.17 ± 12.09
9.5 – 10. GeV	84.10 ± 9.75	106.88 ± 11.69	103.24 ± 11.91	40.95 ± 7.85
9.0 – 9.5 GeV	116.19 ± 11.40	150.60 ± 13.77	119.49 ± 13.34	72.58 ± 10.23
8.5 – 9.0 GeV	109.39 ± 11.35	177.06 ± 15.69	142.68 ± 14.71	63.70 ± 9.12
8.0 – 8.5 GeV	126.11 ± 12.01	227.60 ± 17.32	188.14 ± 16.29	81.80 ± 11.24
7.5 – 8.0 GeV	132.38 ± 12.00	225.31 ± 17.81	213.42 ± 17.40	89.93 ± 11.52
7.0 – 7.5 GeV	103.86 ± 10.90	254.92 ± 18.50	282.81 ± 20.40	84.28 ± 11.78
6.5 – 7.0 GeV	68.69 ± 8.84	319.32 ± 20.31	322.73 ± 21.56	108.11 ± 13.27
6.0 – 6.5 GeV	36.66 ± 6.47	305.63 ± 20.83	332.03 ± 22.33	103.72 ± 16.06
5.5 – 6.0 GeV	No events	246.44 ± 19.64	339.43 ± 22.69	105.84 ± 15.02
5.0 – 5.5 GeV	No events	206.46 ± 17.97	358.61 ± 25.56	149.54 ± 17.94
4.0 – 5.0 GeV	No events	189.46 ± 19.07	521.05 ± 30.80	212.21 ± 20.83
3.0 – 4.0 GeV	No events	82.08 ± 12.50	348.13 ± 26.59	125.40 ± 18.64
2.0 – 3.0 GeV	No events	No events	125.35 ± 20.58	34.75 ± 9.66
0.0 – 2.0 GeV	No events	No events	48.90 ± 16.09	47.70 ± 17.00

Increase in yields from ICHEP to publication



B+C

B+C+D+E+F



Event weighting: yields → cross-section

Each event in given analysis 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 using a variety of spin-alignment models

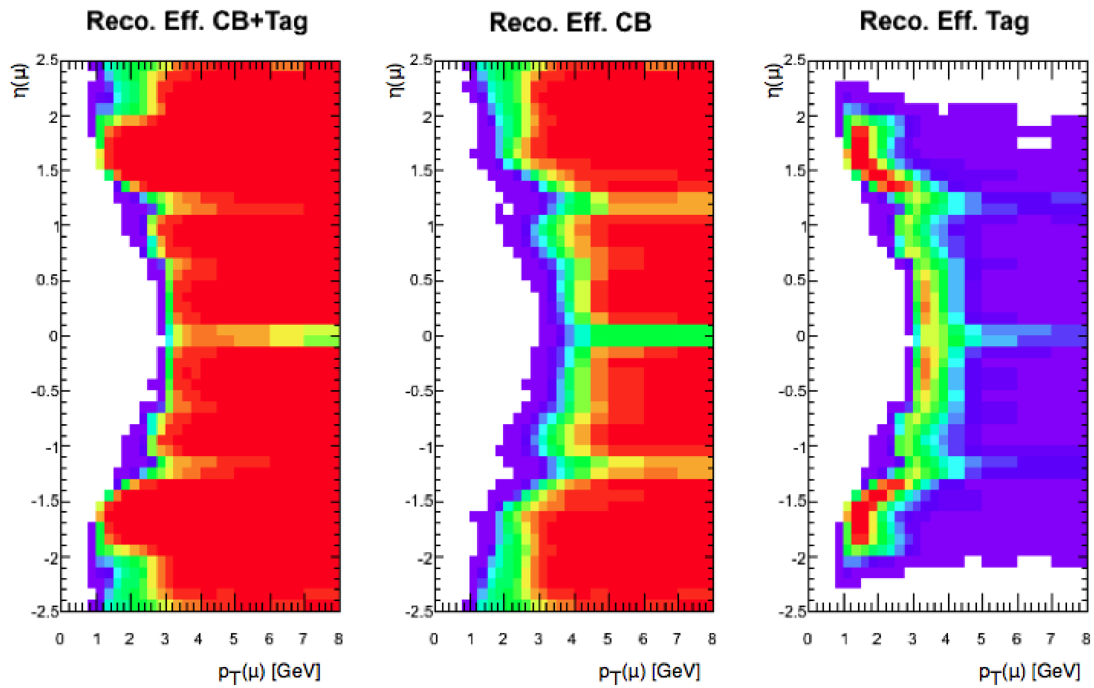
As yet unmeasured, assess variation in final results due to spin-alignment as separate ("theoretical" or "model-dependent") systematic

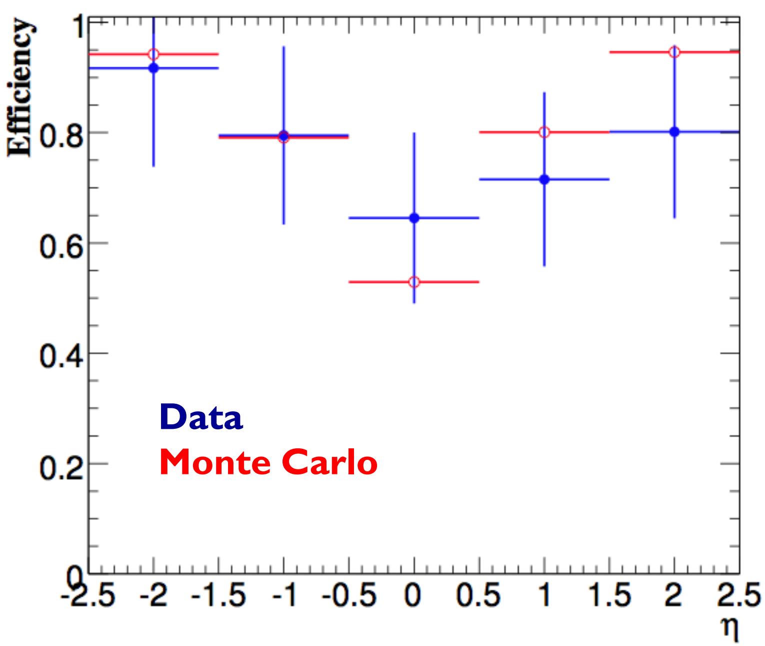
Reconstruction maps for preliminary result based on MC, validated with data and difference assigned as systematic

Work is in progress to use data-driven efficiencies in the publication

Single muon reco efficiency maps

Single muon efficiency maps from prompt J/ψ Monte Carlo for "All", "Combined" and "Tagged" muons (from MC) →





Validated by comparing with (limited at the time) Tag &Probe data

Any differences within the analysis bins were assigned as a systematic error

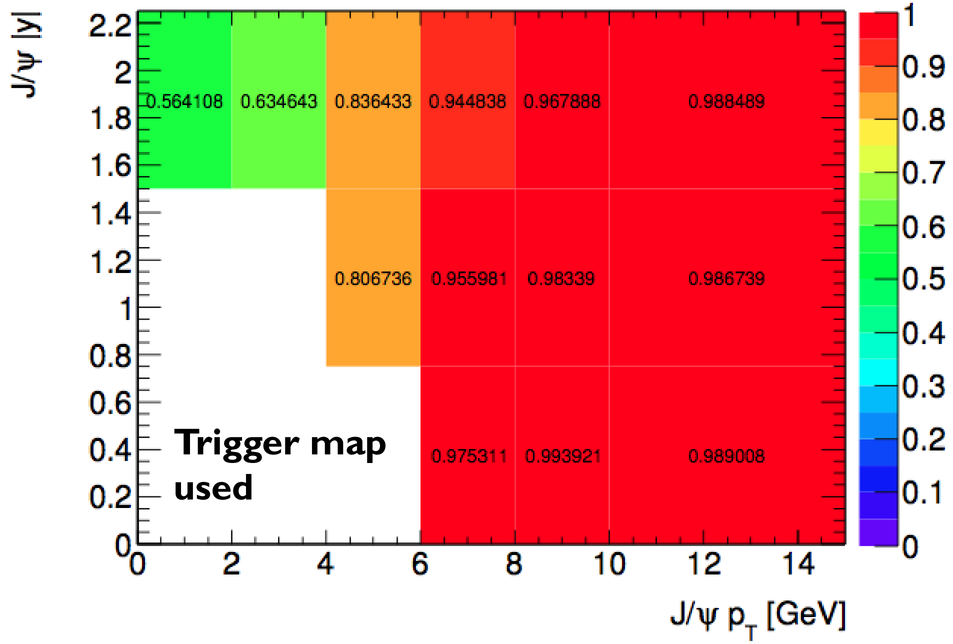
EF_mu4_MSonly_MB2_noL2_EFFS trigger

Trigger efficiency determined from MinBias stream data

Studied separately for combined and tagged muons

Denominator is events passing L1_MBTS_2 trigger

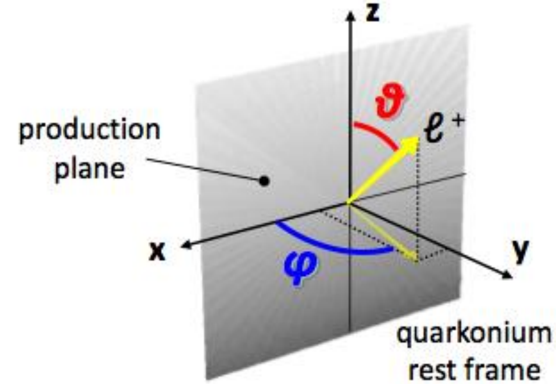
Average efficiency in given bin is determined from *actual distribution of J/ψ candidates* in data



Trigger matching: making sure that the muon(s) that fired the selected event are those from the J/ψ candidate.

Not used for ICHEP result, but tools are available now for the publication.

Spin-alignment working points



We know acceptance depends on spin-alignment

State with generalised angular decay distribution:

$$|\psi\rangle = a_{-1}\,|1,\text{-}1\rangle + a_0\,|1,0\rangle + a_{+1}\,|1,+1\rangle$$

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

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

Before we can explicitly measure spin-alignment, we work with five specific working points that provide an envelope for expectation.

FLAT

$$\lambda_{\theta^\star} = \lambda_{\phi^\star} = \lambda_{\theta^\star\phi^\star} = 0$$

TRPM

$$a_0 = 0, \quad a_{+1} = -a_{-1}$$

LONG

$$\lambda_{\theta^\star} = -1$$

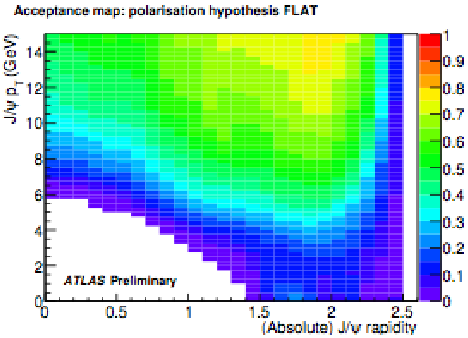
TRP0

$$\lambda_{\theta^\star} = +1$$

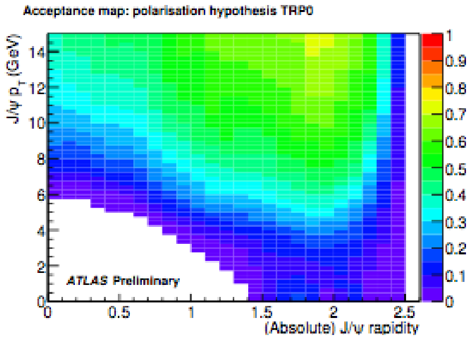
TRPP

$$a_0 = 0, \quad a_{+1} = +a_{-1}$$

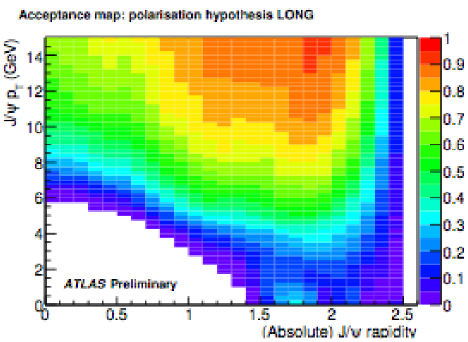
Effect of spin-alignment uncertainty



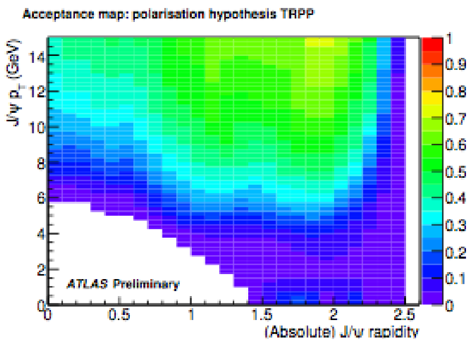
(a) $\lambda_\theta = \lambda_\phi = \lambda_{\theta\phi} = 0$



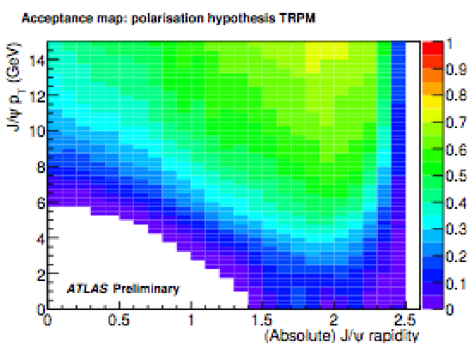
(b) $\lambda_\theta = +1, \lambda_\phi = \lambda_{\theta\phi} = 0$



(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
	$0 < y \le 0.75$				
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
	$0.75 < y \le 1.5$				
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
	$1.5 < y \le 2.25$				
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

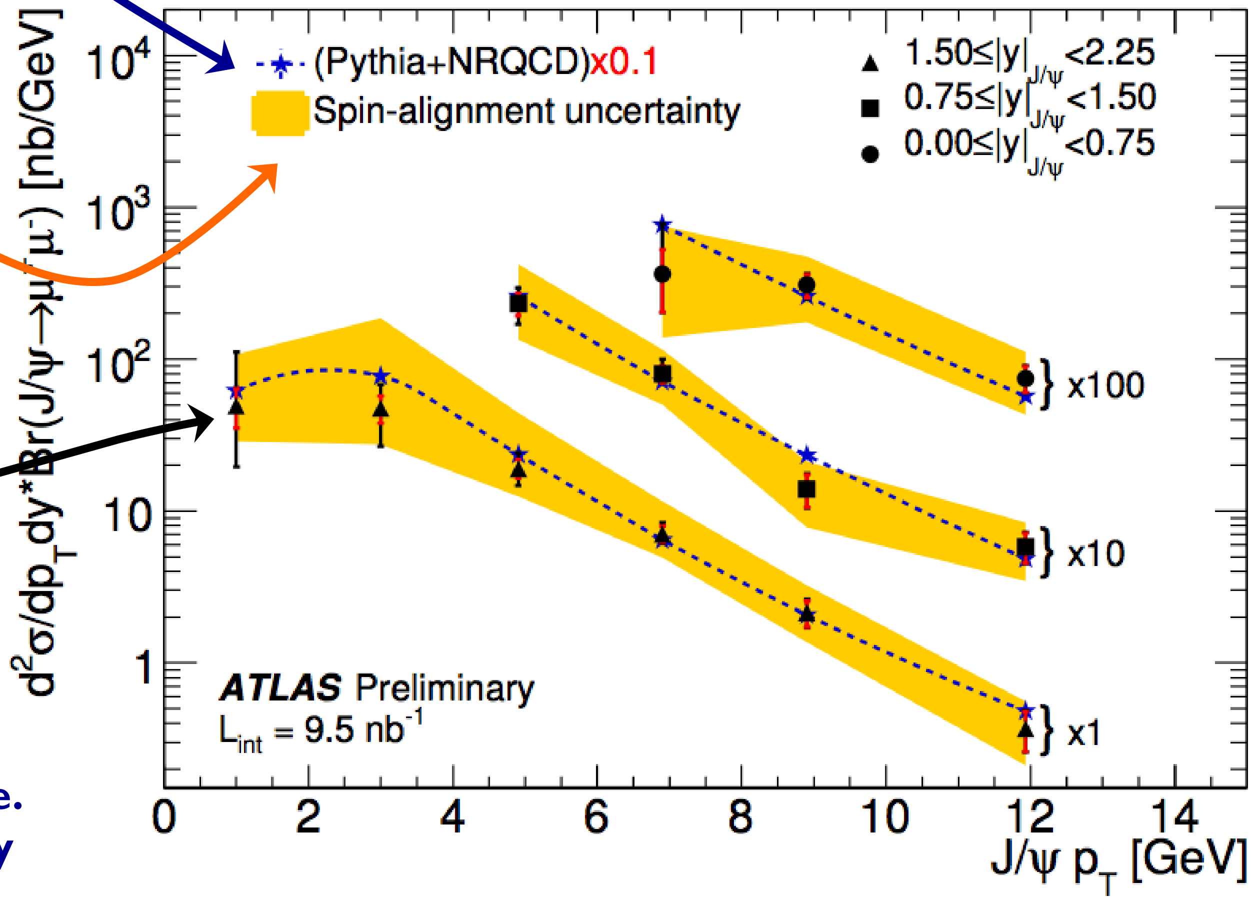
Differential cross-section (ICHEP)

$L_{int} = 9.5\ nb^{-1}$

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 'null'/'flat' polarisation hypothesis
(Red: statistical error)



No theory comparisons here. More extensive MC & theory comparisons in publication

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

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

Differential cross-section (ICHEP)

Systematics-dominated @low p_T:

Main systematics are from trigger and muon reconstruction

Should be somewhat improved for publication, but will always be limited in this region of phase space

Comparable variation from spin-alignment uncertainty

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

In close contact with theorists for latest higher order calculation predictions for publication, and studying various Monte Carlo predictions

$p_T(J/\psi)$ 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

Indirect-to-prompt J/ψ ratio

Indirect (from B decays) and prompt (from QCD sources) production proceed via different mechanisms:

Discriminating variable 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

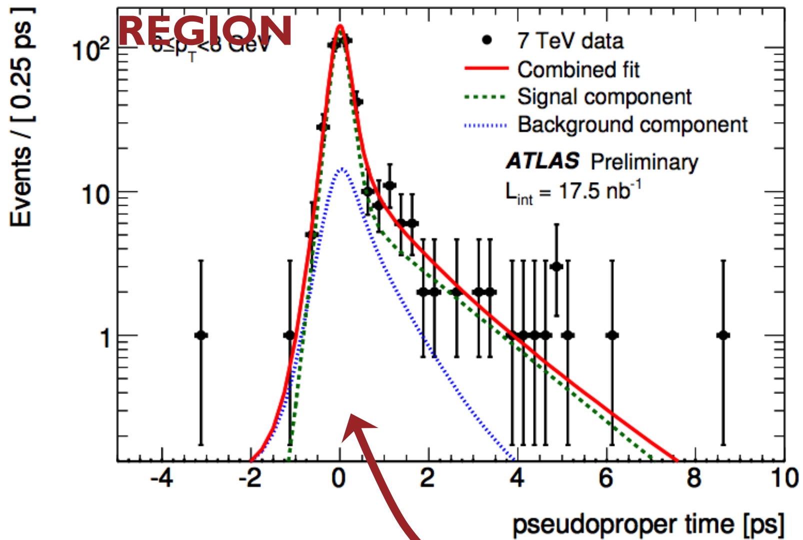
Variables and their errors calculated on candidate-by-candidate basis
Mass and lifetime fitted simultaneously using unbinned maximum likelihood fit

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)

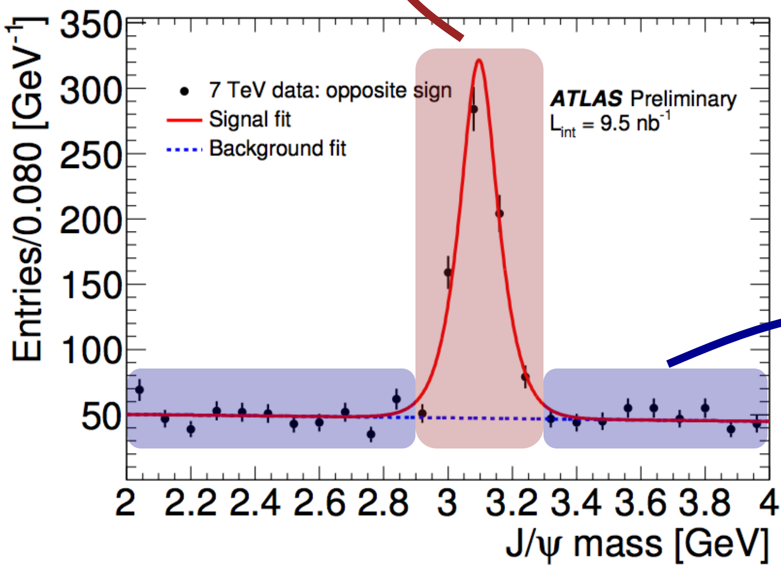
Indirect-to-prompt J/ψ ratio

SIGNAL REGION

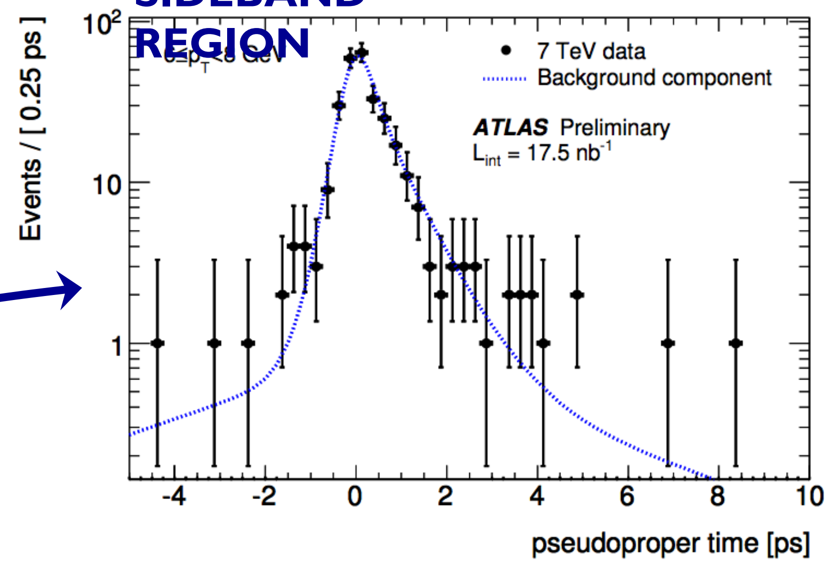


Calculate indirect (B-decay) to prompt (incl. feed-down) production cross-section ratio in bins of J/ψ p_T

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



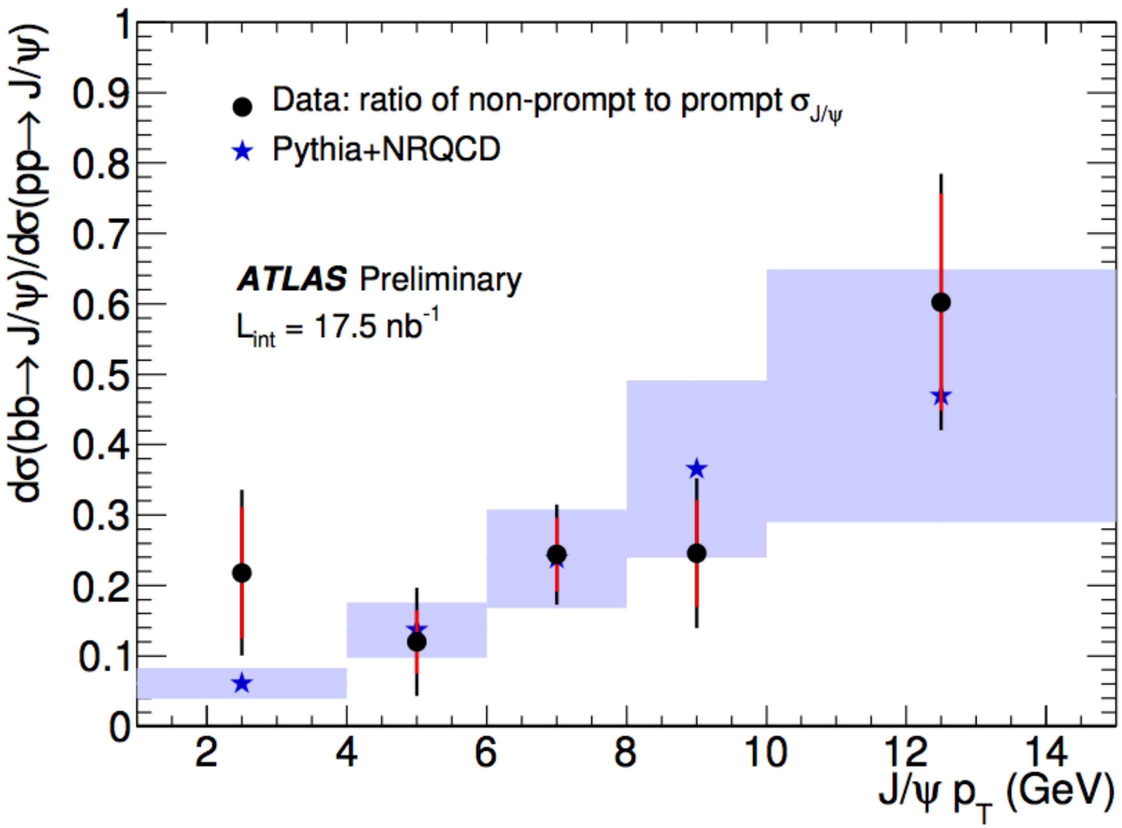
SIDEBAND REGION



Indirect-to-prompt J/ψ ratio

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

$p_T(J/\psi)$ GeV	$\mathcal{R} \equiv \sigma(pp \to b\bar{b}X \to J/\psi\, X')/\sigma(pp \to J/\psi\, X'')_{prompt}$ Data	MC	χ^2/DoF	p-value
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)

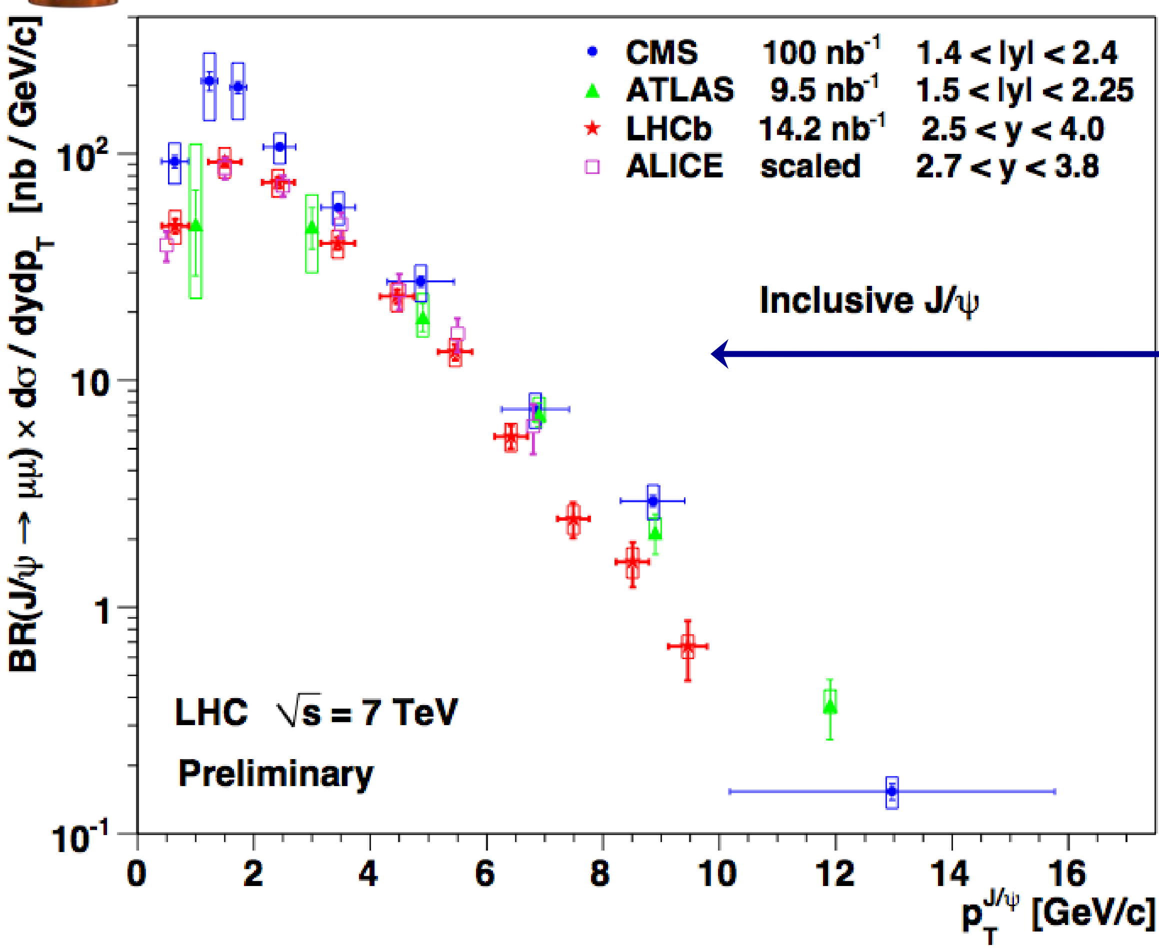
Ratio described well

Update for publication will use same ~3 pb^{-1} as the cross section analysis

Issue of pileup in later runs being addressed

ATLAS preliminary results in comparison

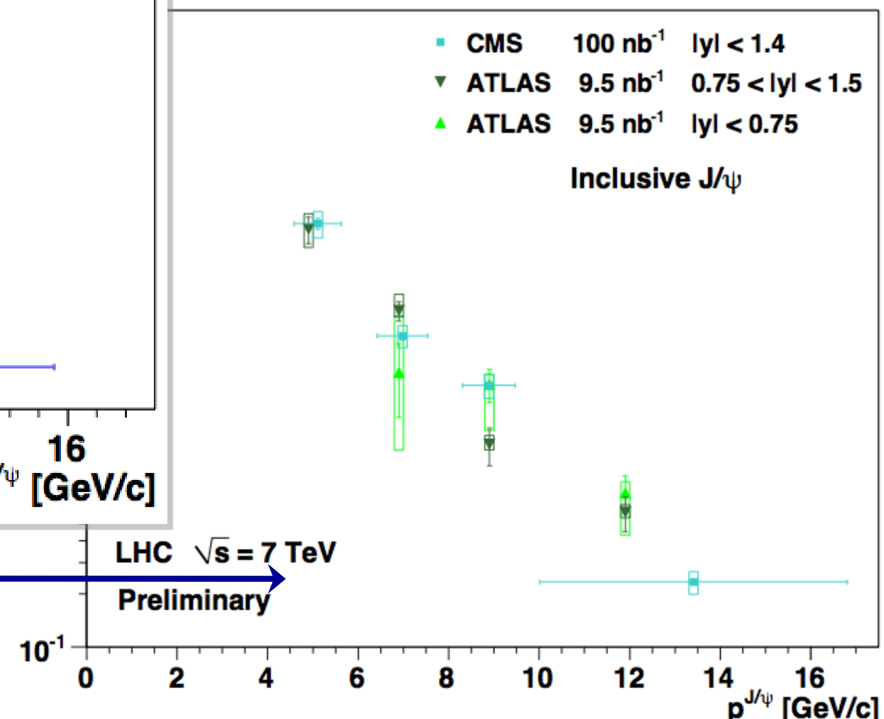
LANCASTER UNIVERSITY



So how do the results line up with other experiments?

Forward rapidities:

ALICE ATLAS CMS LHCb



Central rapidities:

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

Comparison with NNLO* CSM

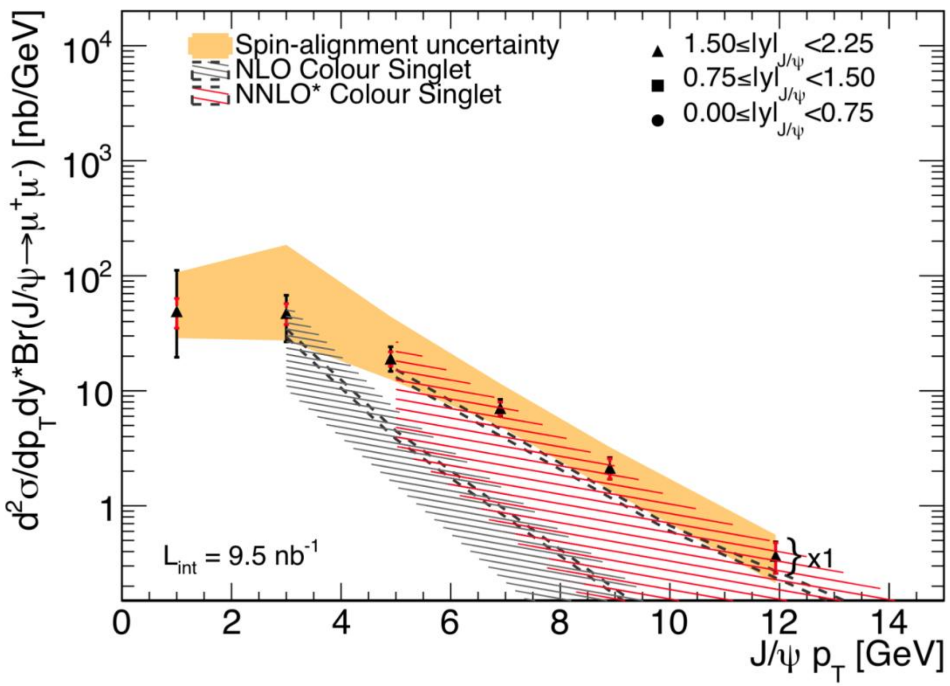
In order to be compared to inclusive ATLAS data, NNLO* calculation needs correcting for:

feeddown from chi-states

indirect contribution from B→J/ψ X decays

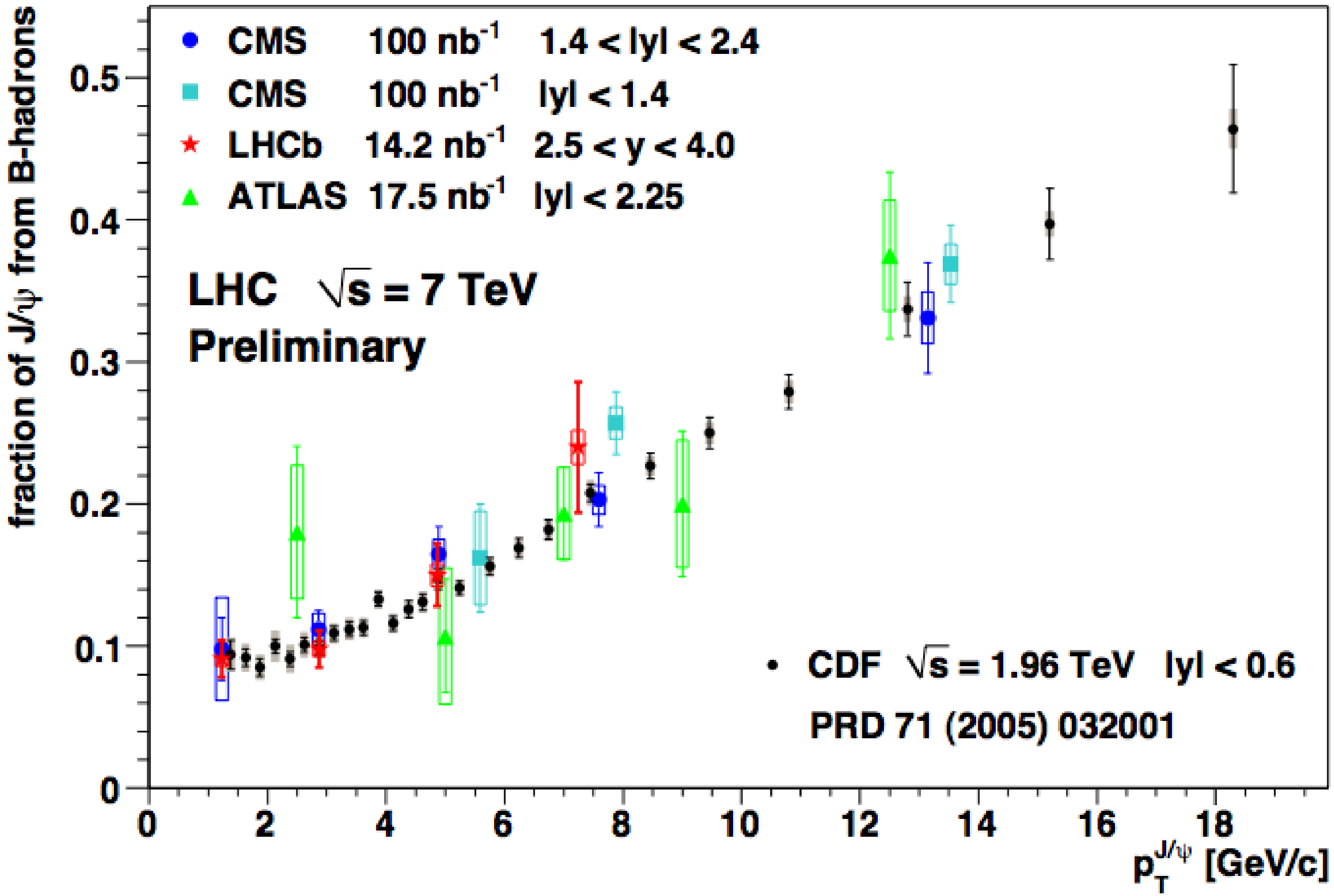
(based on Tevatron measurements)

With these Corrections, the agreement looks remarkably good



Similarly good agreement is found with Colour Evaporation Model

Fraction of indirectly-to-promptly produced J/ψ



Perspectives on current results

Preliminary results for ICHEP were in good agreement with other LHC experiments

- **ATLAS-specific MC tune was not – tracked to a few issues:**
  - PDF/tune interplay with NRQCD matrix elements
  - Color reconnection tune of MB/UE
  - Higher order corrections to J/ψ singlet production large and LO+PS generator has limitations here without significant tuning

Result was in good agreement with various competing theoretical models, but at the time combined theoretical + experimental errors did not allow for more detailed study.

Publication will include comparison to latest NNLO* theoretical calculations made specifically for ATLAS

- Investigating other Pythia tunes/models
- Colour Evaporation Model
- Possibility of using event-by-event reweighting of Pythia to NNLO* in generation

Future plans for J/ψ studies

In the short-term, planning publication to go to collaboration on the order of weeks.

Both updated cross-section and ratio result based on data up to period F (~3 pb^{-1}), a 200-fold increase in statistics over preliminary result (unfortunately, not at lower pT)

Mid-term (10 pb^{-1}+), study of production mechanism in greater detail

Direct studies of J/ψ (and χ_c) spin alignment, using new experimental techniques and taking into account latest phenomenological developments

Longer term (1 fb^{-1}), new observables in J/ψ production will advance these understanding of QCD at the boundary of perturbative/non-perturbative regime

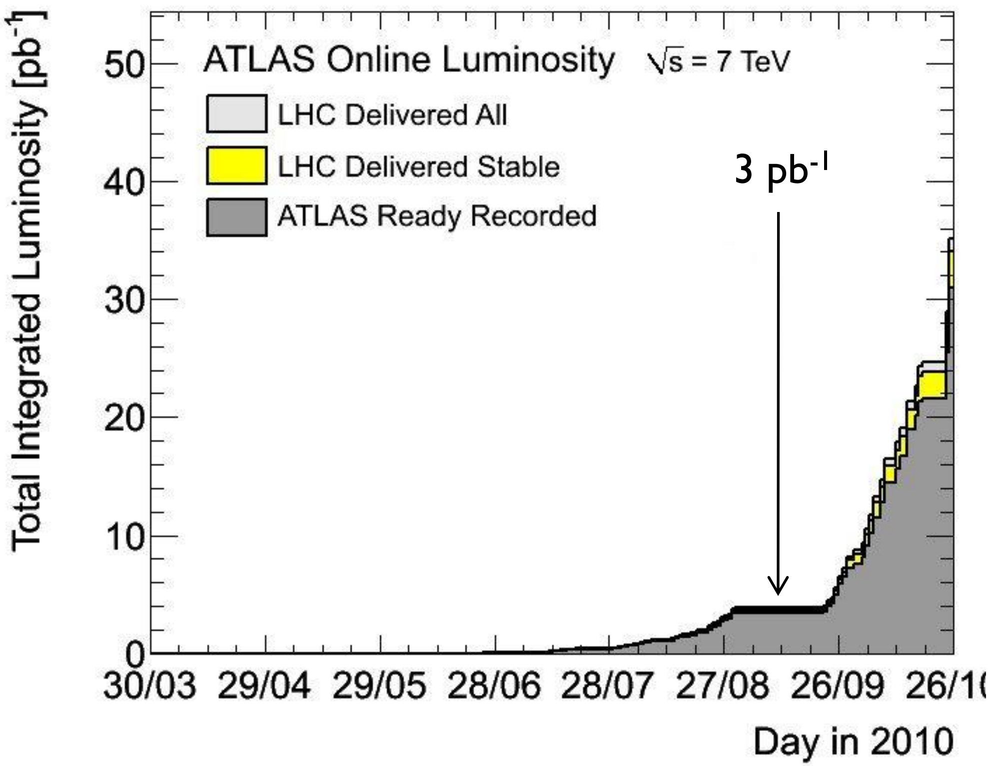
Azimuthal correlations (J/ψ+μ), heavy flavour production in association with J/ψ (J/ψ+cc) and associated hadroproduction (J/ψ+jets)… more?

10 fb^{-1}+ : Double-quarkonium production

Including resonances like η_b (and χ_b) to J/ψ + J/ψ - pinnacle of quarkonium physics!

Finally, a couple of recent relevant plots

Integrated luminosity



Dimuon invariant mass spectrum:
Short history of 20th century particle physics