Quarkonium production and polarisation with early data in ATLAS

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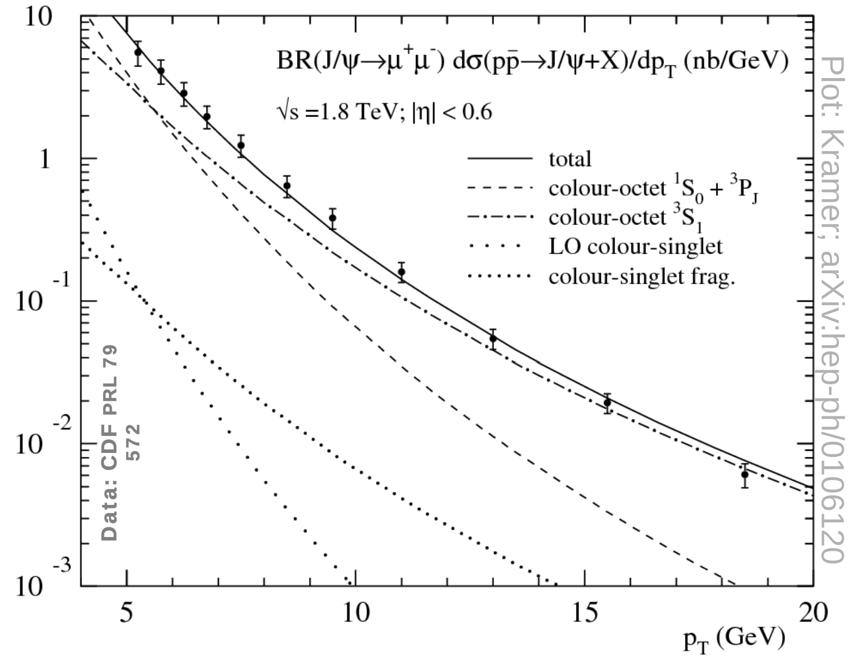
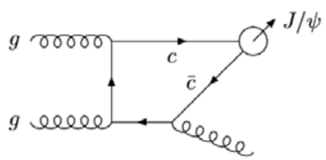
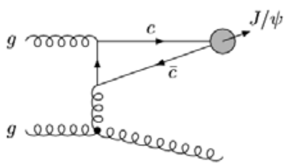
Motivation for study

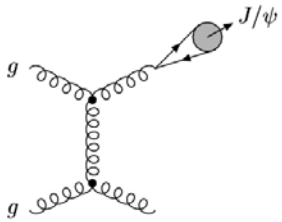
- Detector commissioning
  - Narrow resonances (J/ψ, ϒ, χ and higher states) with clean signature (in muon channel) make them invaluable for calibration of the trigger, tracking and muon systems

- Theoretical interest
  - Production mechanism of quarkonium unexplained
    - Important as testbed for QCD in both perturbative and non-perturbative regimes
    - Once understood, quarkonium production is the perfect probe for determining low x gluon PDFs
  - Quarkonia forms an important background for many other physics processes at LHC



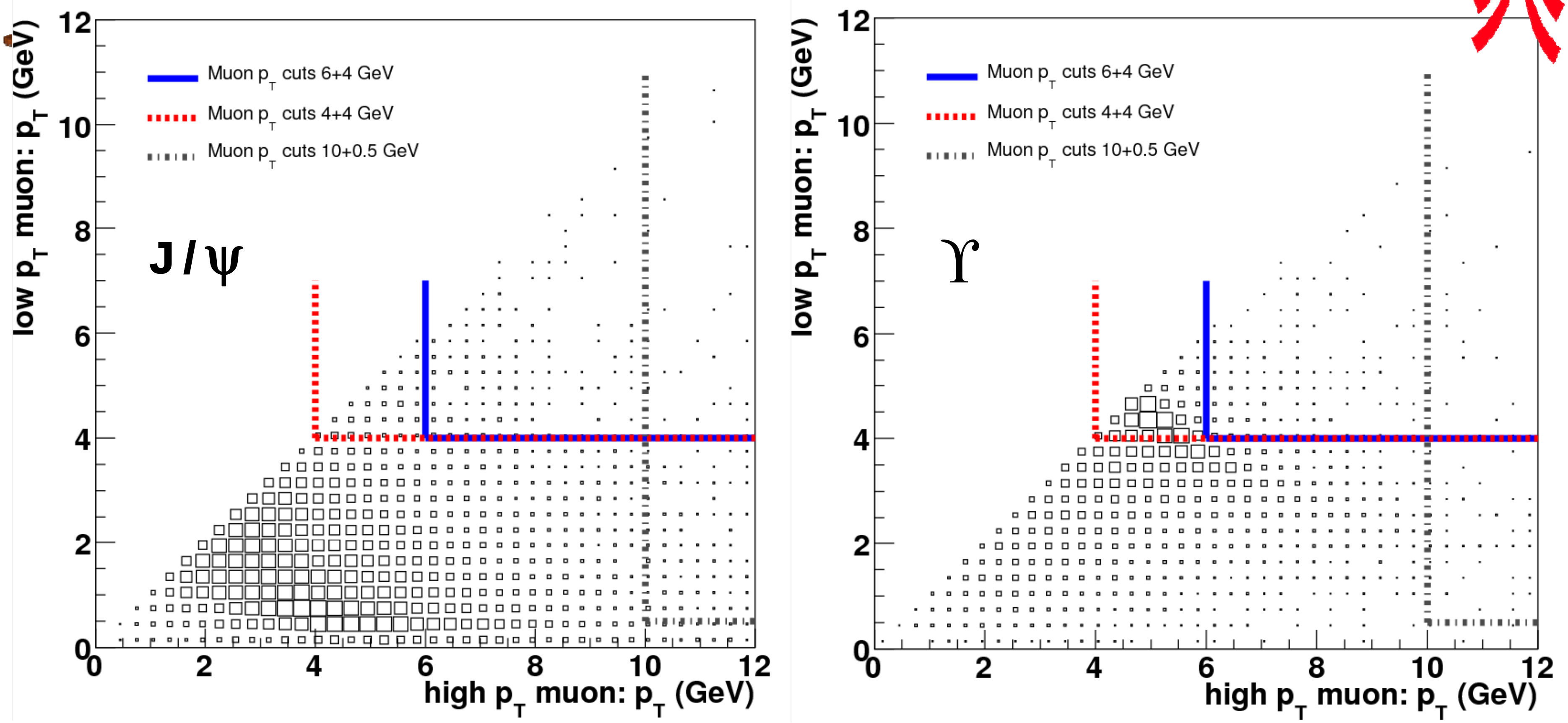






Colour Octet Model provides excellent agreement with p_T cross-section shape and normalisation, but there are problems...

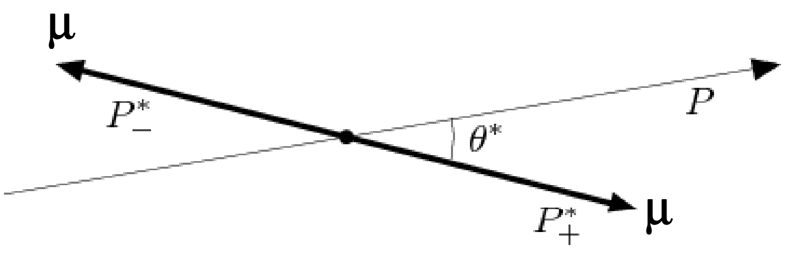
Quarkonia cross-sections



MC cuts	6+4 GeV	4+4 GeV	10+0.5 GeV
$\sigma(J/\psi)$	23 nb	28 nb	23 nb
$\sigma(\Upsilon)$	5.2 nb	48 nb	2.8 nb

Quarkonium spin alignment

- An important consideration when calculating trigger efficiencies (and cross-sections) is the angular distribution of the decay angle cos θ^*



Angle defined between positive muon direction in quarkonium rest frame and quarkonium direction in lab frame, distribution given by:

$$\frac{d\,\Gamma}{d\cos\theta} \propto \left(1 + \alpha\cos^2\theta^*\right)$$

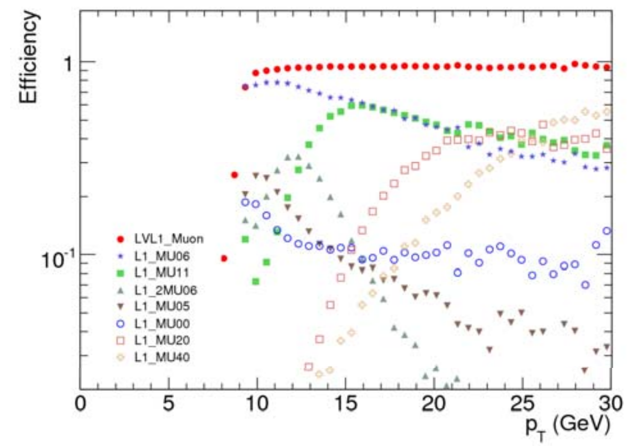
- Polarisation parameter $\alpha=0$ corresponds to unpolarised mesons, while $\alpha=+1$ and $\alpha=-1$ correspond to 100% transverse and longitudinal polarised mesons respectively

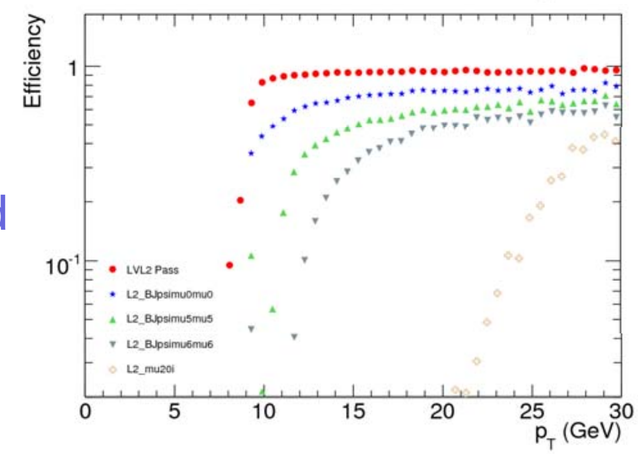
- Polarisation of quarkonium states is not understood!

- Polarisation of quarkonium may vary with p_T, and different polarisation states have significant effects on overall acceptance (and thus x-section),
  - Makes calculation of trigger efficiency in real data a tricky job… discuss this later

Muon trigger thresholds and efficiency

- ATLAS has excellent efficiency for identifying muons from quarkonium
  - Plot shows trigger efficiencies at p_T>10GeV
  - Muons from J/ψ in μ(6 GeV)μ(4 GeV) simulation have 87% efficiency at LVL1, 97% at LVL2





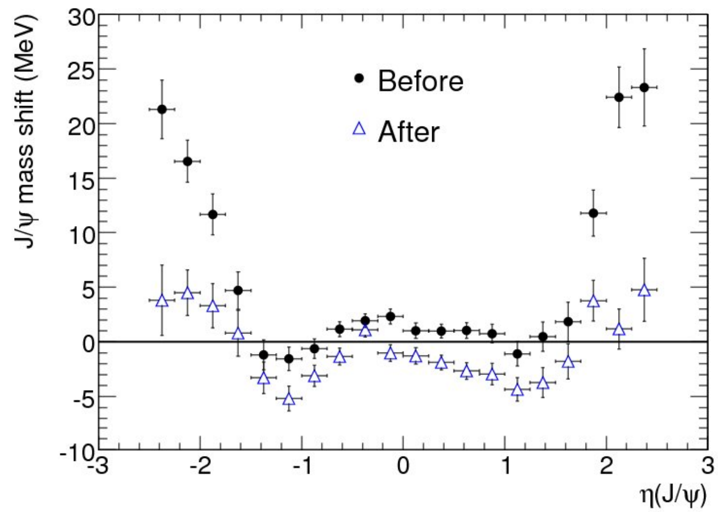
- In addition to triggering on quarkonium with a di-muon trigger, it will be possible to trigger with single muon trigger with 10 GeV threshold
  - Combine μ10 with all tracks in event (down to 0.5 GeV) and apply offline cuts to reduce backgrounds from beauty and charm decays

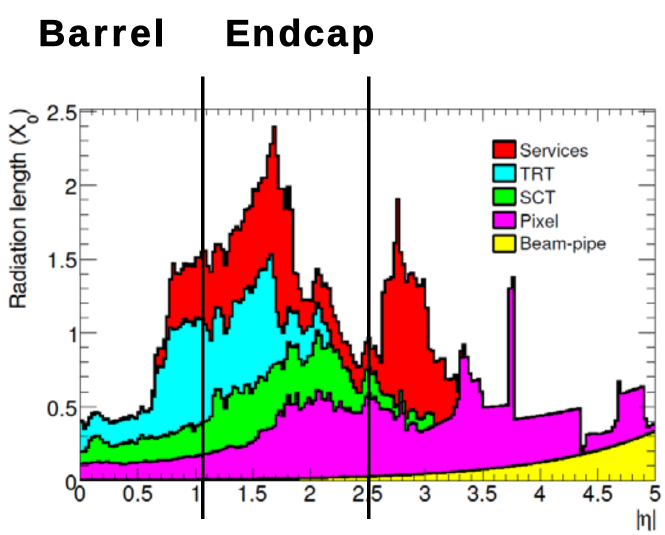
Crucially, with large p_T difference between the two muons, this will allow for acceptance in the high |cosθ*| region at similar J/ψ p_T's as for μ6μ4

Reconstruction of prompt quarkonia (μ6μ4)

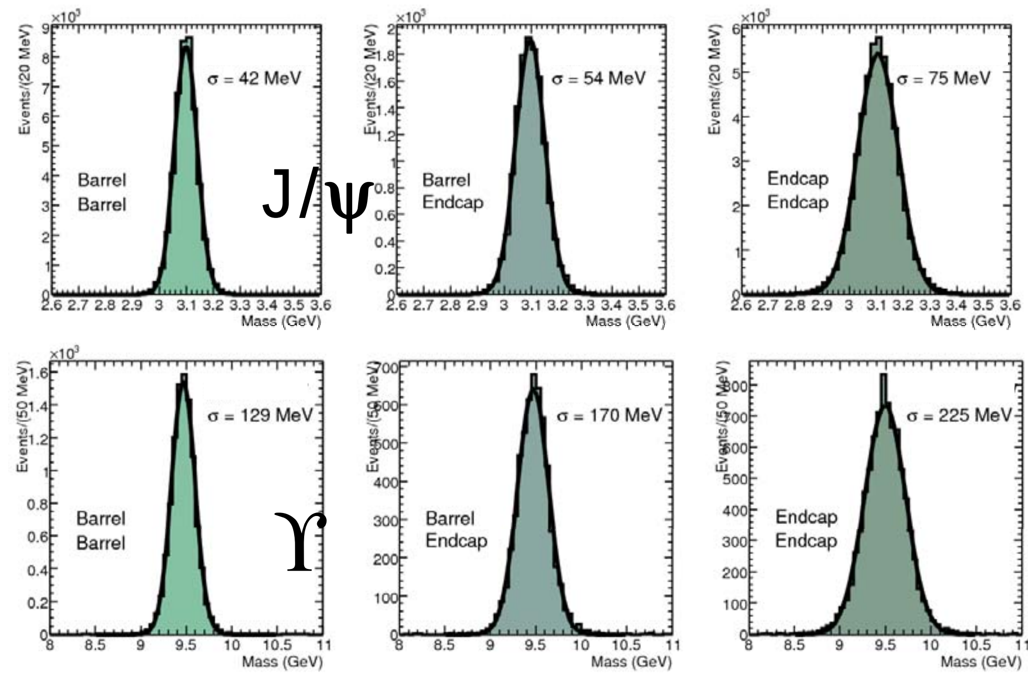
- Muon pairs which are triggered are fit to a common vertex; those from prompt quarkonia survive vertexing with a 99.9% efficiency

- Invariant mass resolution depends on the pseudorapidity of the two muons from the decay





Inner Detector material budget

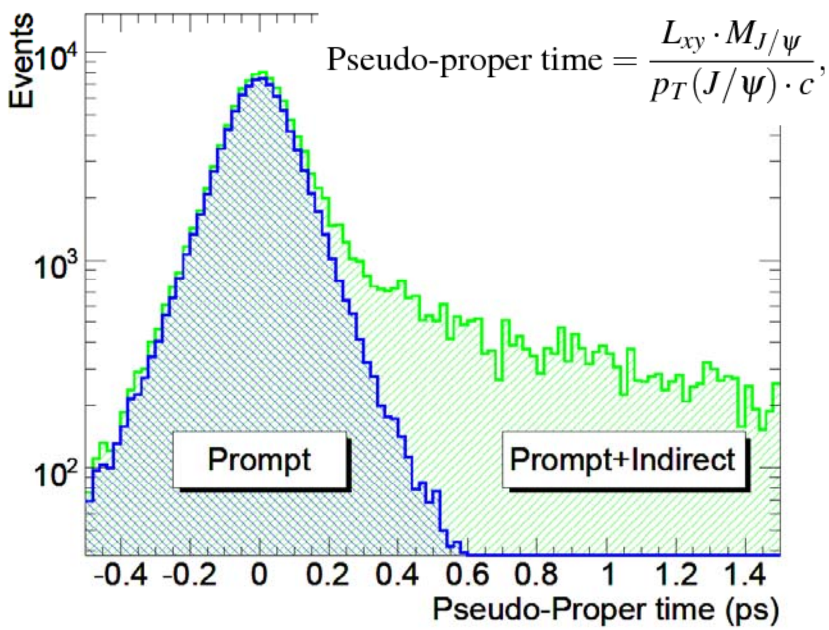


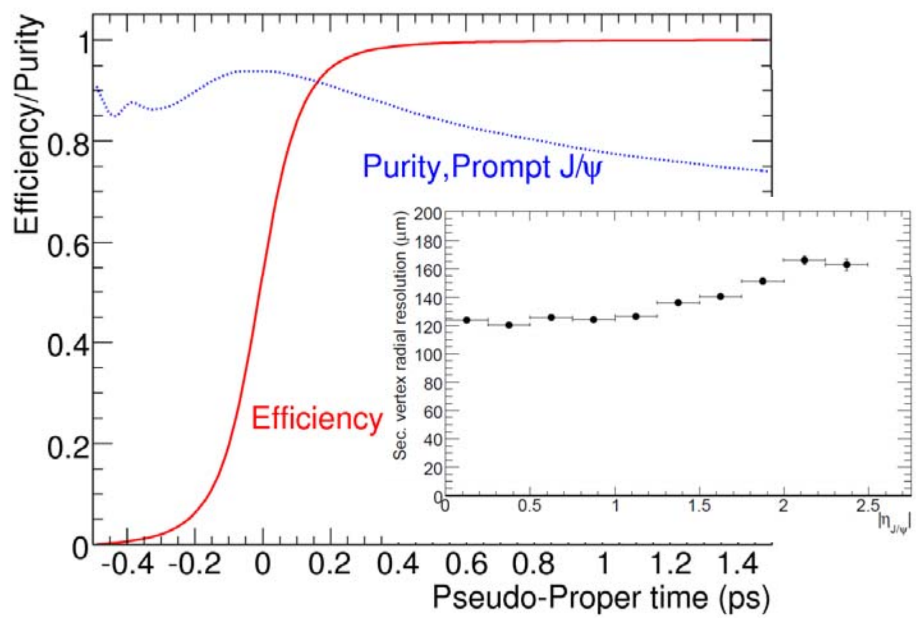
Background separation (μ6μ4)

- J/ψ from B-decays form significant background to prompt J/ψ (rate of 11 nb compared to 23 nb for prompt with μ6μ4 cuts)

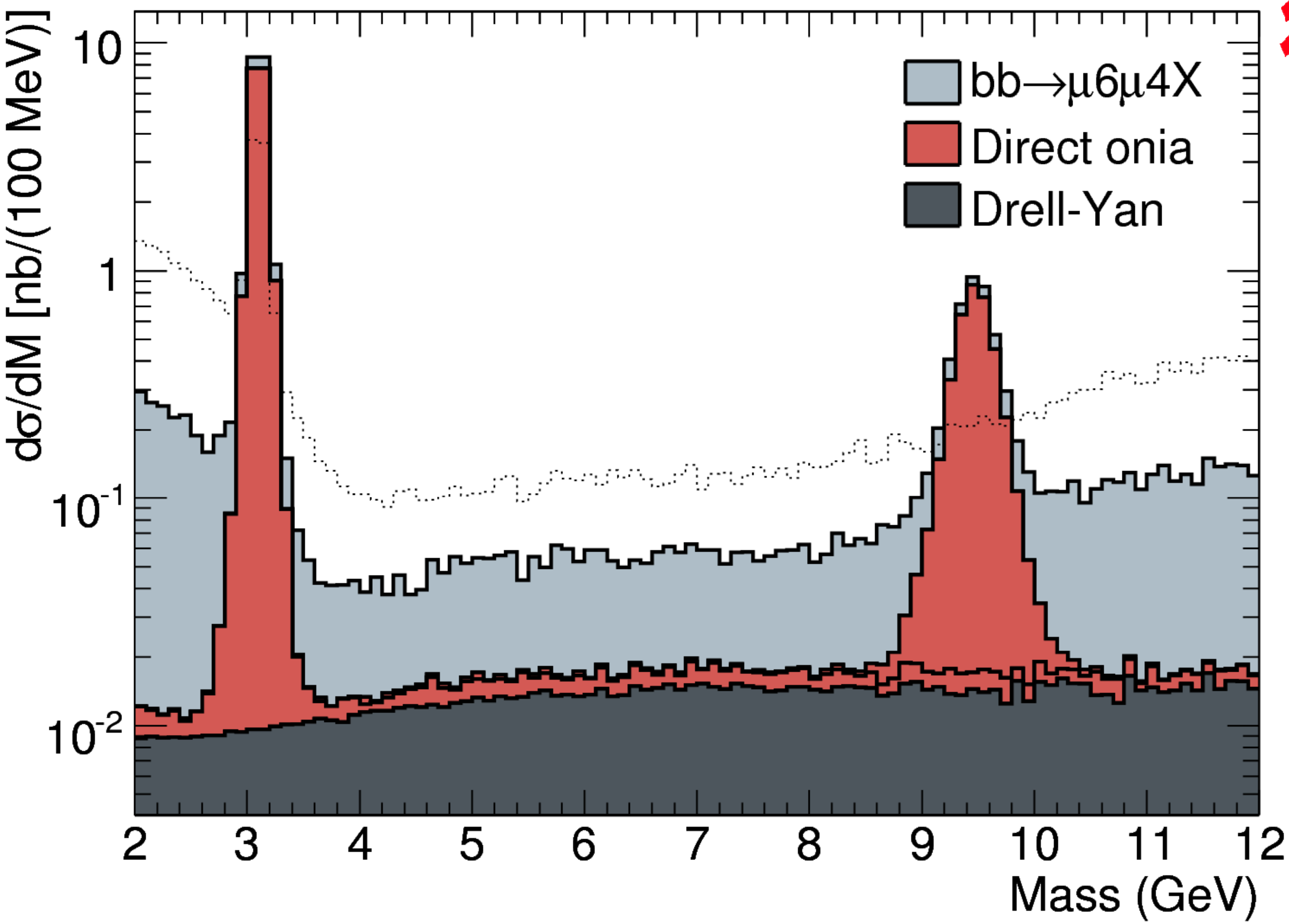
- Proper time of zero characteristic of prompt J/ψ, those from B-decays have positive proper-time
  - Prompt sample can be used to determine vertex resolution of detector

Pseudo-proper time cut of <0.2 ps gives prompt J/ψ efficiency of 93% with 8% contamination



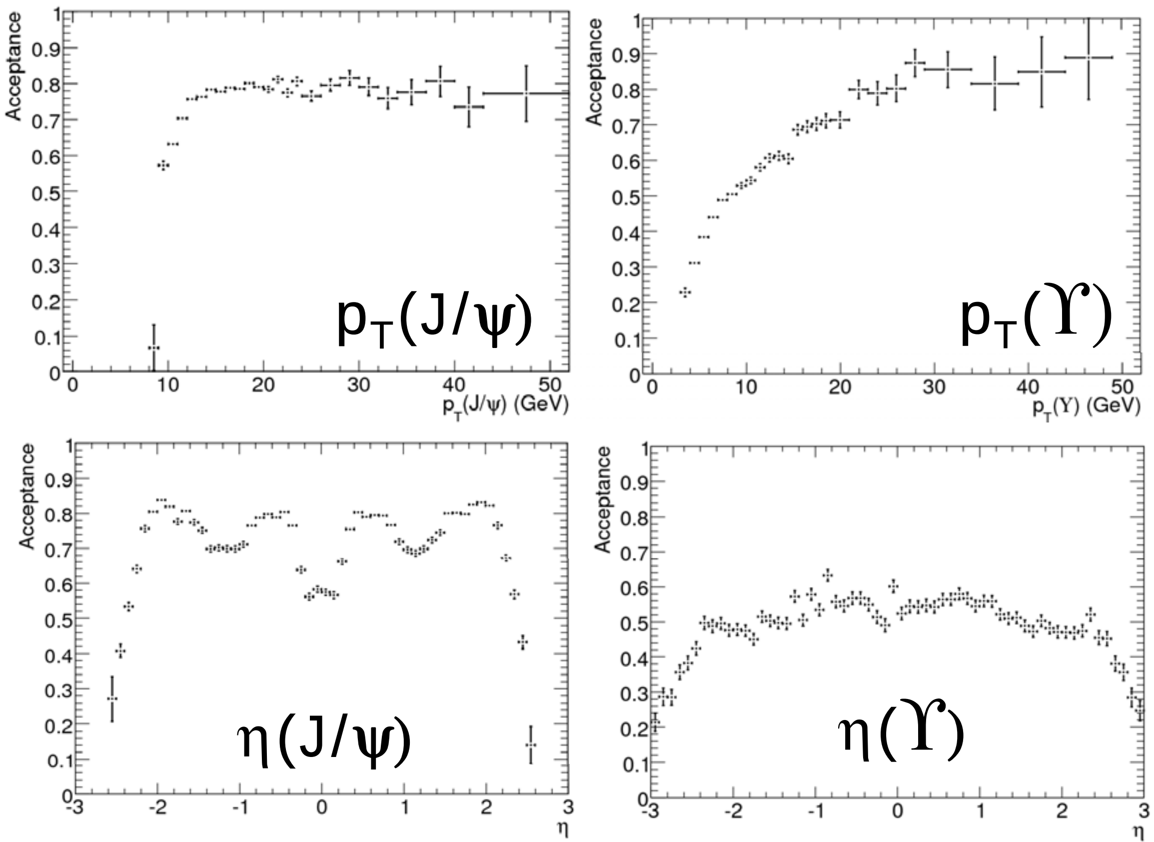


Low mass di-muon sources (μ6μ4)



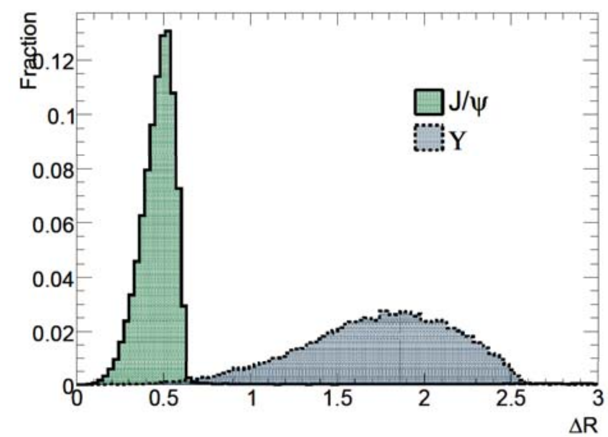
Acceptance and efficiencies

- Plots below show trigger efficiency and geometric acceptance of reconstructed quarkonium candidates in p_T and η
- High p_T reach (50 GeV) with 10 days of data-taking and relatively flat and broad η acceptance



Stark differences in p_T and η for J/ψ and Υ are due to kinematic configurations imposed by di-muon trigger

$$\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2}$$



Errors on simulated statistics correspond to approximately 10 days of low luminosity data-taking

Expected rates at low luminosity (10^{31} $cm^{-2}s^{-1}$)

After μ6μ4 di-muon trigger, geometric acceptance and background reduction cuts, ATLAS expects to achieve a yield of:

15,000 J/ψ
4,000 ϒ(1,2,3S) per 1 pb^{-1}

[~1-2 days running at low luminosity (10^{31} $cm^{-2}s^{-1}$)]

	Tevatron 'today'	ATLAS
1×10^6 J/ψ	**CDF 1.1 fb^{-1}**	**66 pb^{-1}**
4.2×10^5 ϒ(1,2,3S)	**D0 1.3 fb^{-1}**	**105 pb^{-1}**

With a μ4μ4 trigger which will run for early data,

18,000 J/ψ
36,500 ϒ(1,2,3S) per 1 pb^{-1}

Quarkonium spin-alignment as a probe

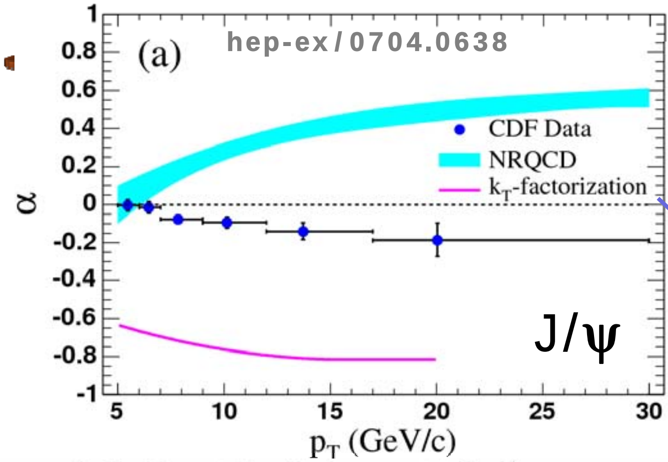
- Earlier alluded to the unknown quarkonium polarisation

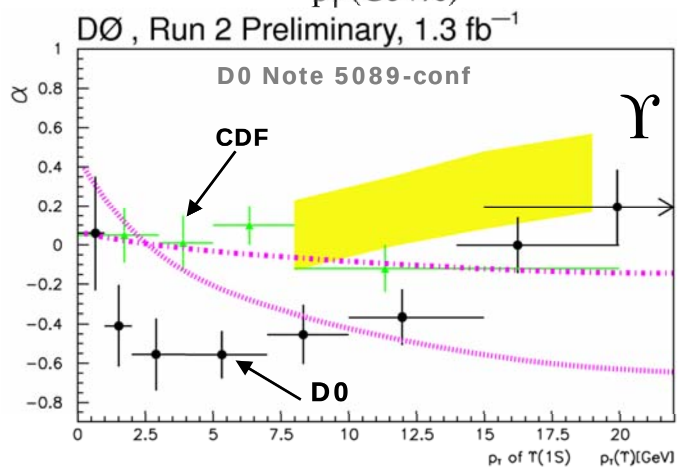
- Different models of quarkonium production predict differing p_T dependencies of quarkonium spin-alignment
  - Makes measurement of this a key factor in determining production model
  - A difficult measurement due to correlation between polarisation state and efficiency

- Theory predicts high p_T data important for discrimination
  - CDF/D0 suffer from statistics in this regard
  - ATLAS has complementary coverage, can provide high stats from 9 GeV+

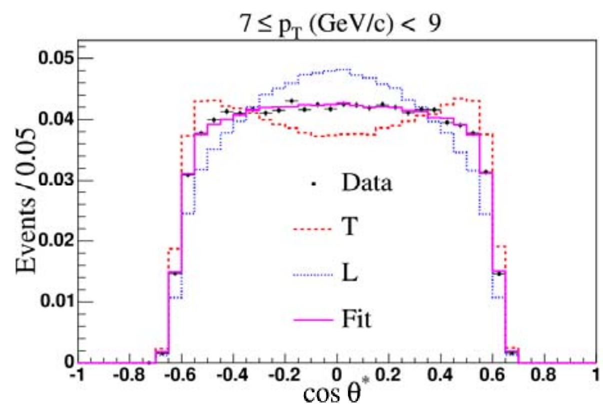
- Current techniques at Tevatron use fits to MC template polarisation samples
  - Rely heavily on fidelity of MC templates run through detector simulation
  - Detector acceptance across cos θ^* very variable -- high |cos θ^*| suppressed at Tevatron due to trigger requirements

The problem of limited cos θ* acceptance





Latest D0 Run II measurements disagree with theoretical models *and* CDF Run I results!



Easy to lose discrimination between longitudinal, transverse and unpolarised templates in restricted central cosine area

- With 6+4 GeV trigger cuts, we see similar acceptance issues at ATLAS
  - Need to extend cos θ* acceptance to achieve more discrimination at high cos θ*
- Would like to have a complementary, independent, high cos θ* sample of onia to give better discrimination and provide cross-check for efficiencies

Single muon $\mu 10$ trigger to the rescue

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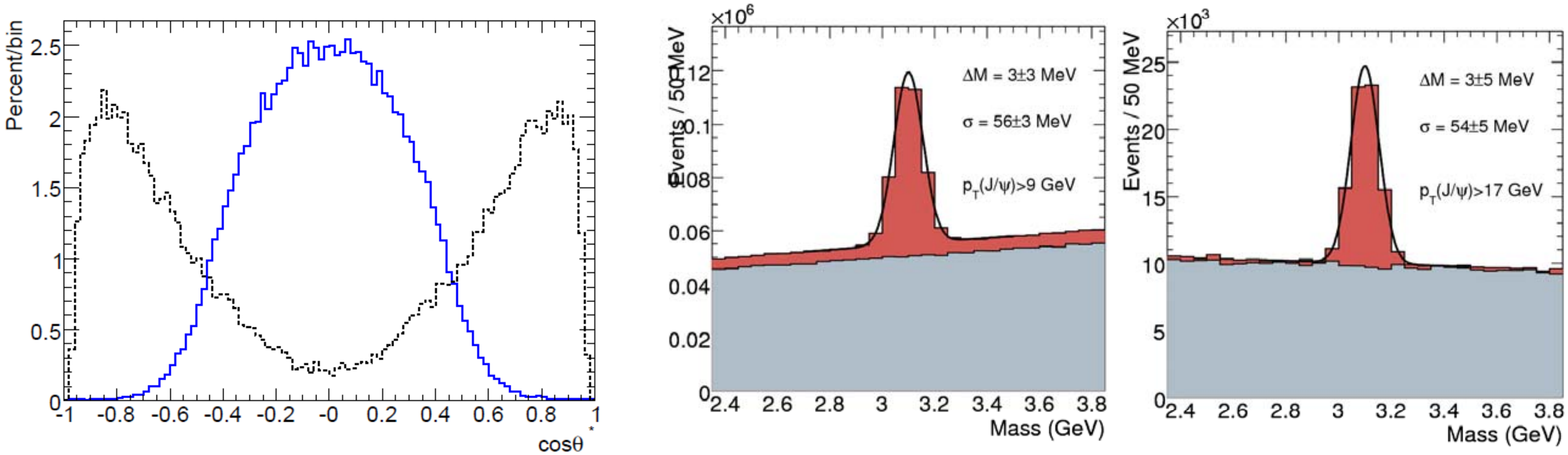
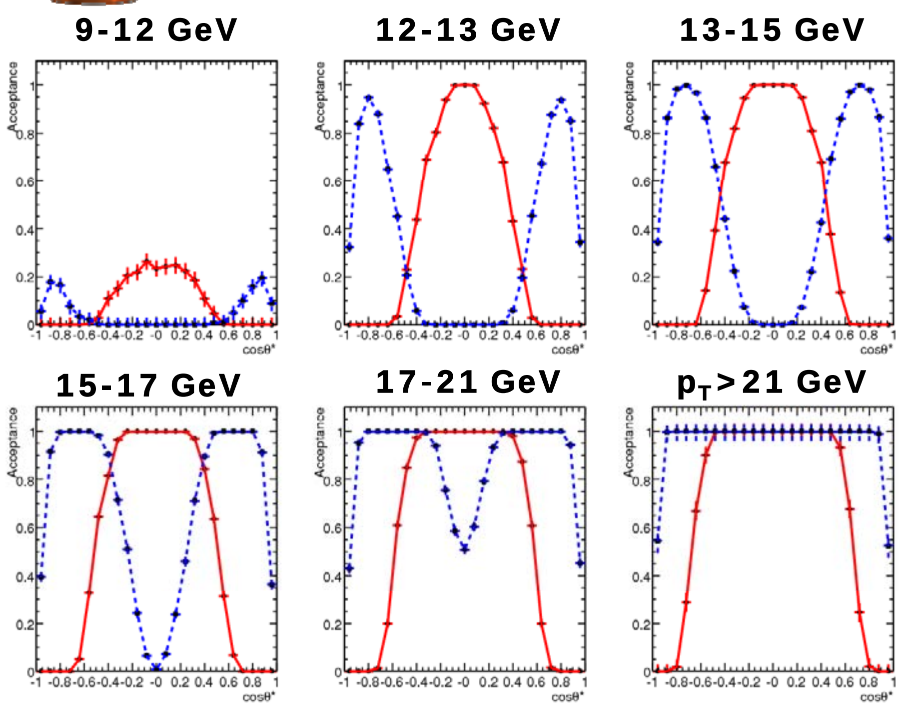
- We can achieve exactly what we want by using a single $\mu 10$ trigger:
  - ✓ Second muon can be reconstructed offline from track (>0.5 GeV p_T)
  - ✓ $|\cos\theta^*| \sim 1$ corresponds to a configuration where one muon is fast, the other slow
  - ✓ Provides similar p_T range of onia to $\mu 6\mu 4$ configuration
- Go from a distribution in $\mu 6\mu 4$ **(blue curve)** to that in $\mu 10$ **(black curve)**



- Invariant mass distributions in $\mu 10$ suffer from larger, but manageable, backgrounds. Expect 16K $J/\psi(\mu 10)$ and 2K $\Upsilon(\mu 10)$ after efficiencies and cuts
- So why is this any better? We still don't recover a the true distribution…

Spin-alignment measurement at ATLAS



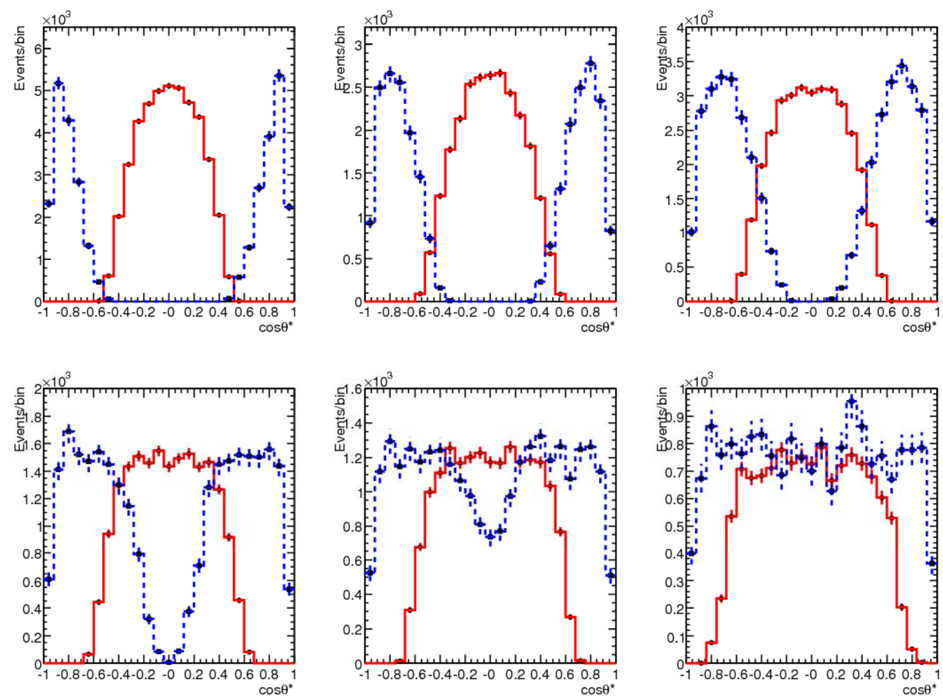
ACCEPTANCE AND EFFICIENCY (from Monte Carlo predictions)

μ6μ4 sample in red

μ10+track sample in blue

- We start with an unpolarised (α=0), simulated 10 pb^{-1} sample of J/ψ
- Split into six bins of transverse momenta
- Measure reconstructed distributions

'MEASURED' DISTRIBUTIONS

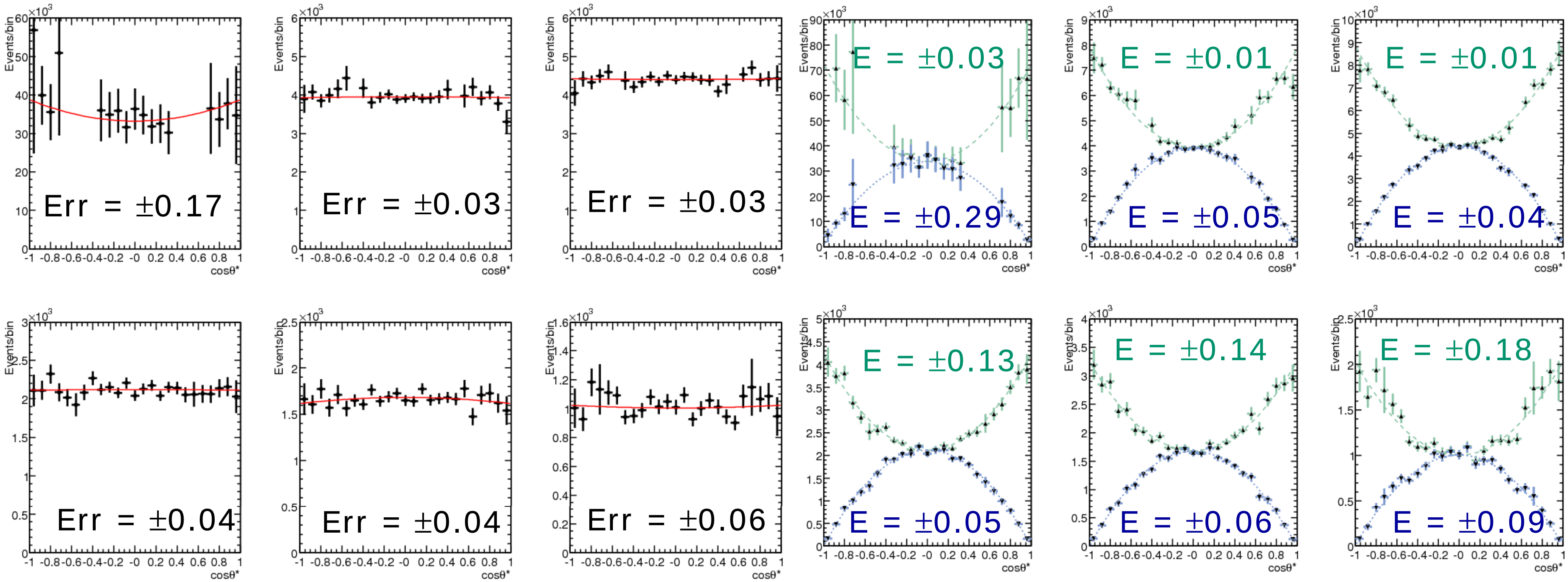


Spin-alignment measurement at ATLAS

- Measured distributions from μ6μ4 and μ10 are corrected for their individual acceptances and efficiencies

- Both samples normalised to each other using overlapping high p_T events

- Use pre-defined acceptance mask to combine the two (now non-overlapping) datasets and make a fit to the corrected distributions (total errors shown below)



UNPOLARISED SAMPLE **LONGITUDINAL AND TRANSVERSE SAMPLE**

Summary

- Quarkonium spin-alignment measurements at ATLAS will have the capability to distinguish various production models of quarkonium
  - Various theoretical production models have different polarisation predictions
  - Need high statistics at high transverse momenta
  - ATLAS can measure polarisation with methods that lead to significantly reduced systematics from previous measurements

- Total (stat+syst) errors on measurement of J/ψ polarisation with <u>10 pb</u>$^{-1}$ of data are expected to be of similar magnitude to that of Tevatron results with <u>1 fb</u>$^{-1}$ of data, but with all data in the important high p_T area
  - μ10 sample allows for measurement of full range of cosθ* distribution
  - Similar results can be achieved for Υ but need 100 pb^{-1} of data to reach same precision, due to increase backgrounds

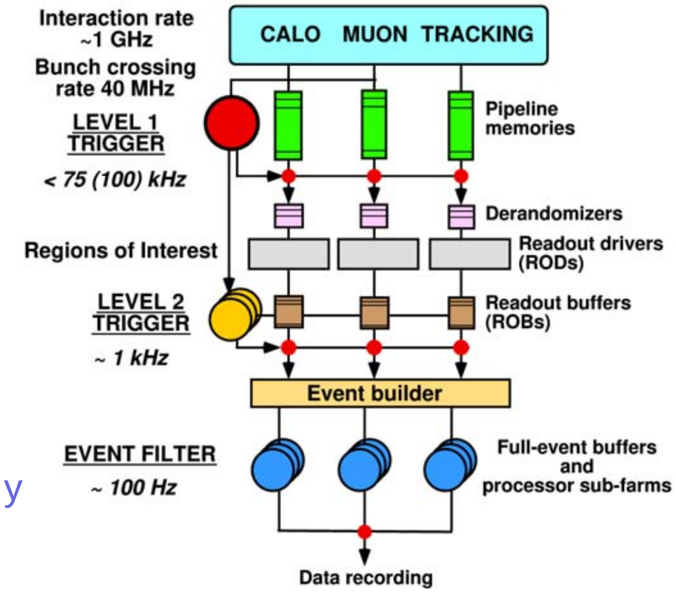
- Large predicted onia cross-sections at LHC mean that J/ψ and Υ will play a central role for initial calibrations of the ATLAS detector in the near future

Backup slides

ATLAS trigger

- Due to the bunch crossing rate and multiple interactions, need to reduce events written to tape to small fraction: **challenge is to keep the interesting ones!**

- **Trigger system at ATLAS has three levels:**
  - Level 1 (Hardware, Online)
    Define region-of-interest in small area of detector, coarse measurements of 'interesting' features -- high p_T muons etc.
  - Level 2 (Software, Online)
    Confirm LVL1 result, refine the physics object measurements and look for additional features
  - Event Filter (Software, Offline)
    Offline algorithms do further refinement using all relevant detector information at full granularity



- **Must use triggers to reduce event rate!**
  - Di-muon triggers based on the presence of muons with certain particular p_T thresholds are of particular relevance.
  - LVL1 muon with p_T>X GeV followed by LVL2 muon with p_T>Y GeV with (X>=Y) and $|\eta|<2.5$ -- a common trigger in ATLAS, important for quarkonium

(Nomenclature in this talk for this type of trigger is ***μXμY****)*

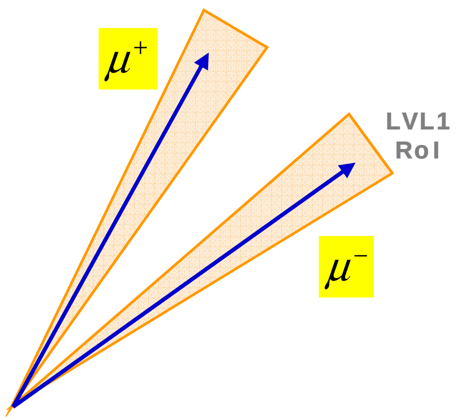
Calibration of muon trigger efficiency

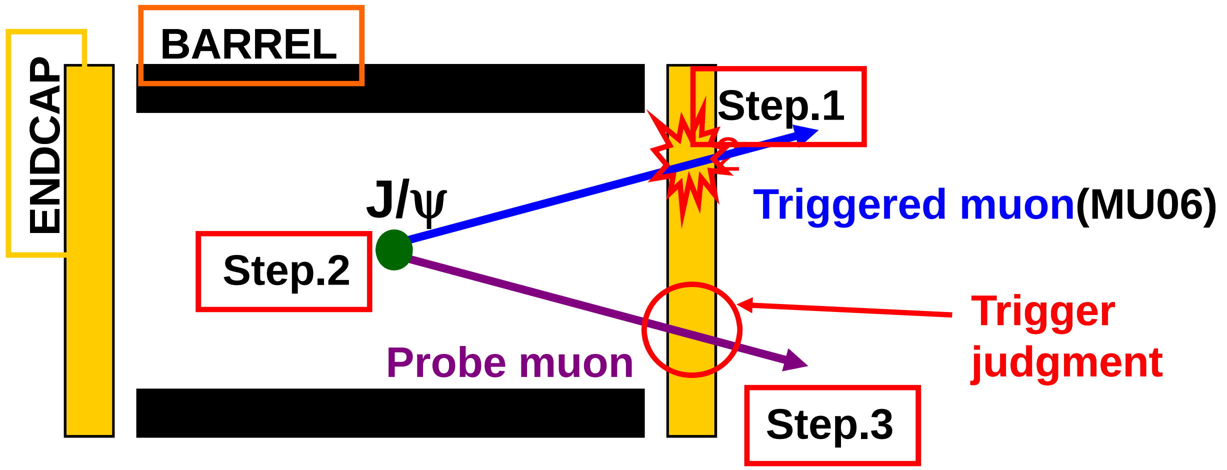
- Simulation has been done to develop an online calibration method to obtain single muon efficiency (μ6 threshold):

  1) Select events where one single muon was triggered at LVL1

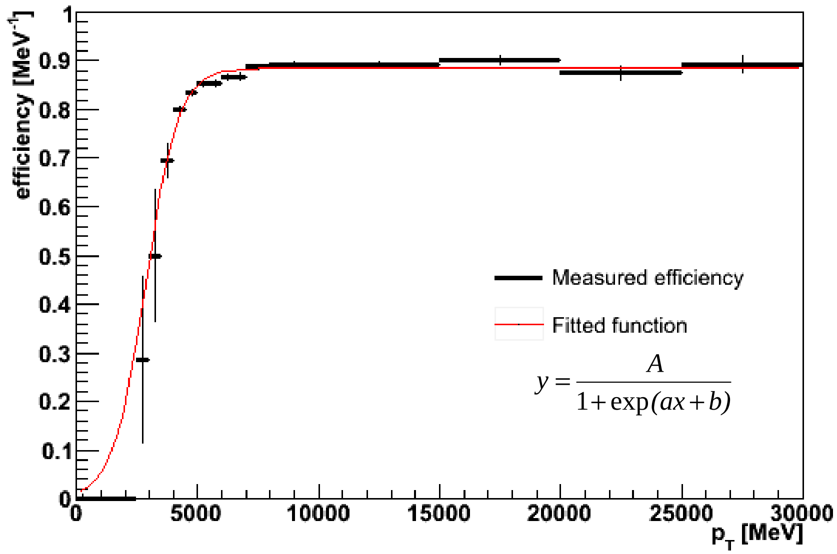
  2) Offline reconstruction -- build object (e.g. J/ψ) with invariant mass cut and remove triggered muon

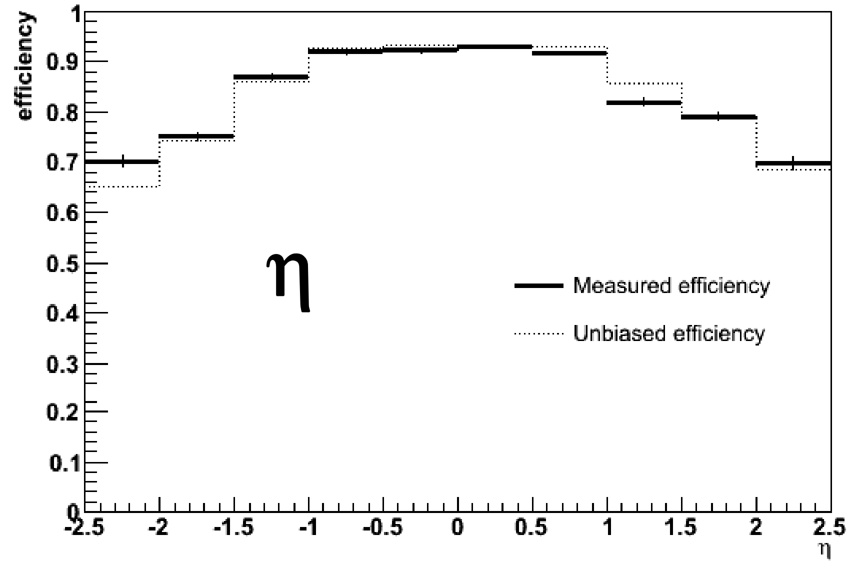
  3) Analysis of probe muon to calculate single muon efficiency

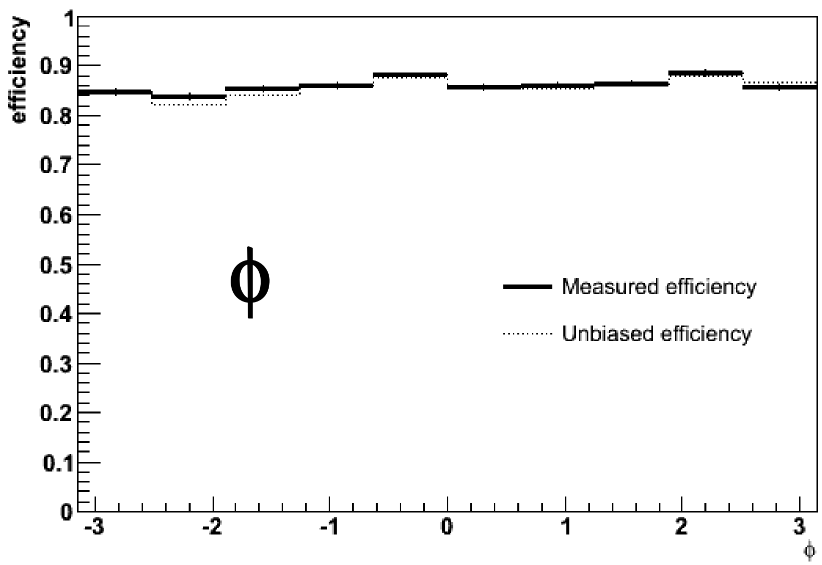




LVL1 single muon efficiency



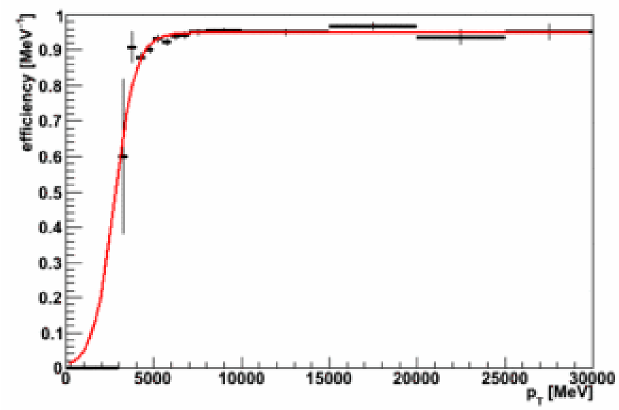




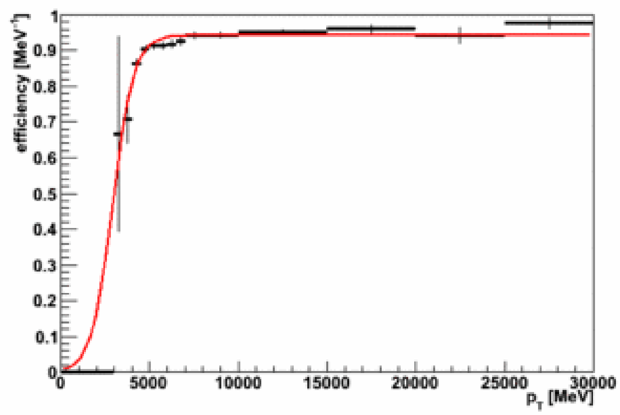
- Efficiency
  - At threshold steeply increases with p_T
  - Is flat in ϕ
  - Is symmetric in η
- Good match to *unbiased efficiency* calculated using Monte Carlo truth

Single muon trigger efficiency map

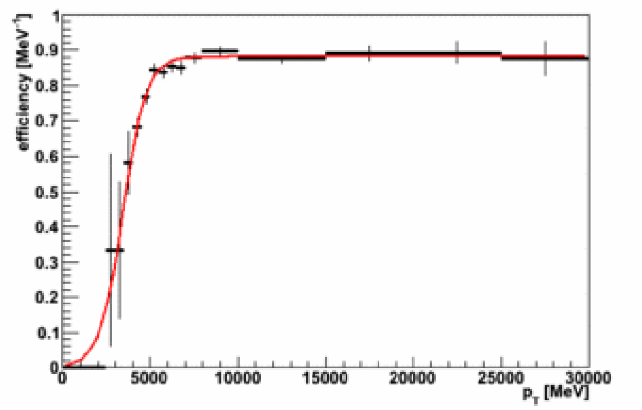
$0 < |\eta| < 0.5$



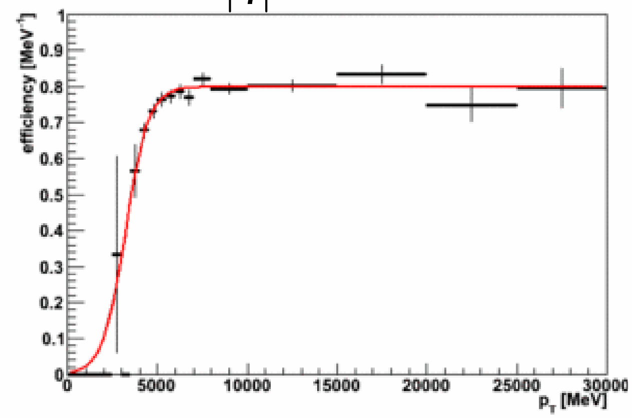
$0.5 < |\eta| < 1$



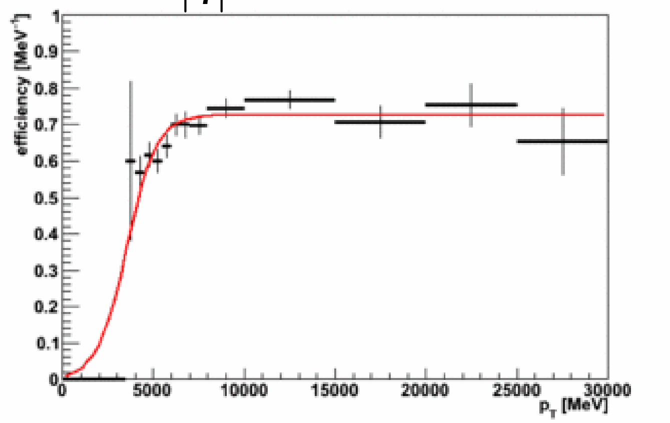
$1 < |\eta| < 1.5$



$1.5 < |\eta| < 2$



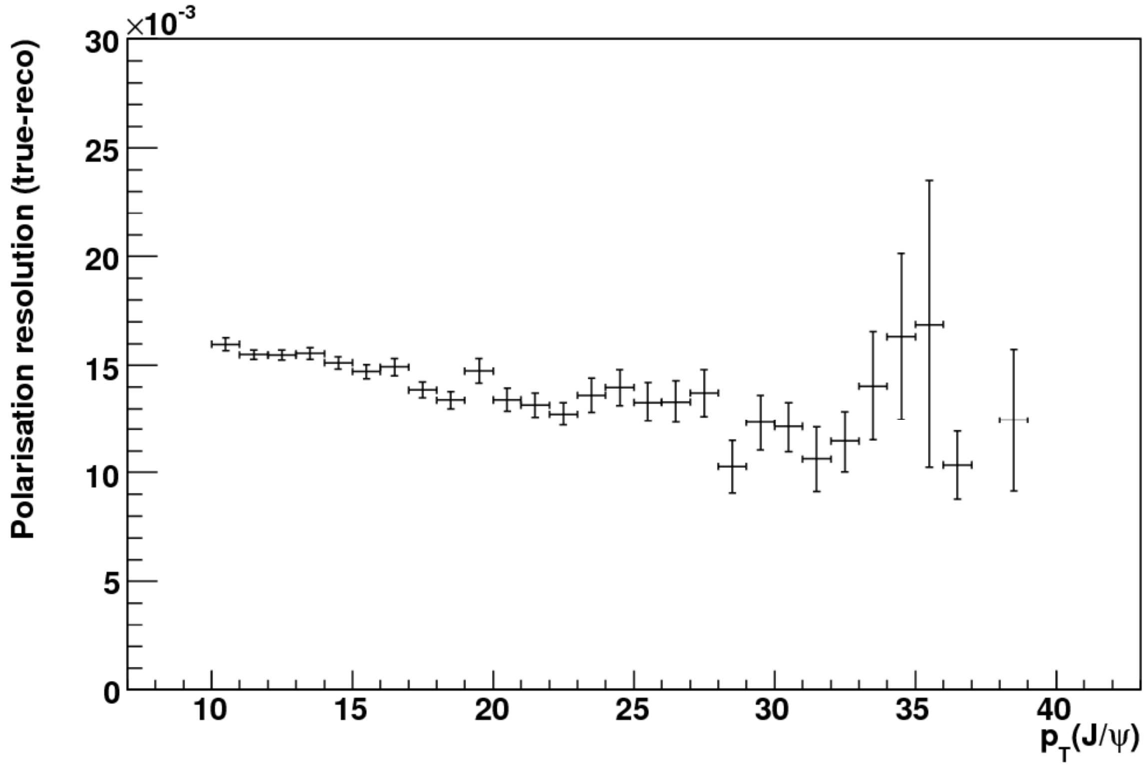
$2 < |\eta| < 2.5$



Spin alignment: cos θ* resolution

- Reconstruction of cos θ* through MC data reconstructed in ATLAS simulation, compared to truth information has resolution of **0.0015**

- Monte Carlo templates can be relied upon to give accurate predictions of what we see after reconstruction



χ reconstruction and searches

- For J/ψ, ~30% of total cross-section from χ_c to $J/\psi\,\gamma$ feed-down
  - When we have a J/ψ candidate, look in narrow cone ($\cos\alpha > 0.98$) around quarkonium momentum direction for photon (to reduce combinatorial background)
- $\mu\mu\gamma - \mu\mu$ invariant mass difference shows peaks where χ_{c0}, χ_{c1} or χ_{c2} was reconstructed
- By fixing the masses of the signals in a simultaneous fit of three Gaussians and quadratic background, can find the three peaks with a typical resolution of 40 MeV
- A related decay under study is χ_b to $J/\psi\,J/\psi$ for which a signal is expected to be seen within 3 years of data-taking, with similar mass resolution
- This decay mode also tests the feasibility of the discovery channel η_b to $J/\psi\,J/\psi$, which should be seen using the same analysis