Quarkonium production and polarisation

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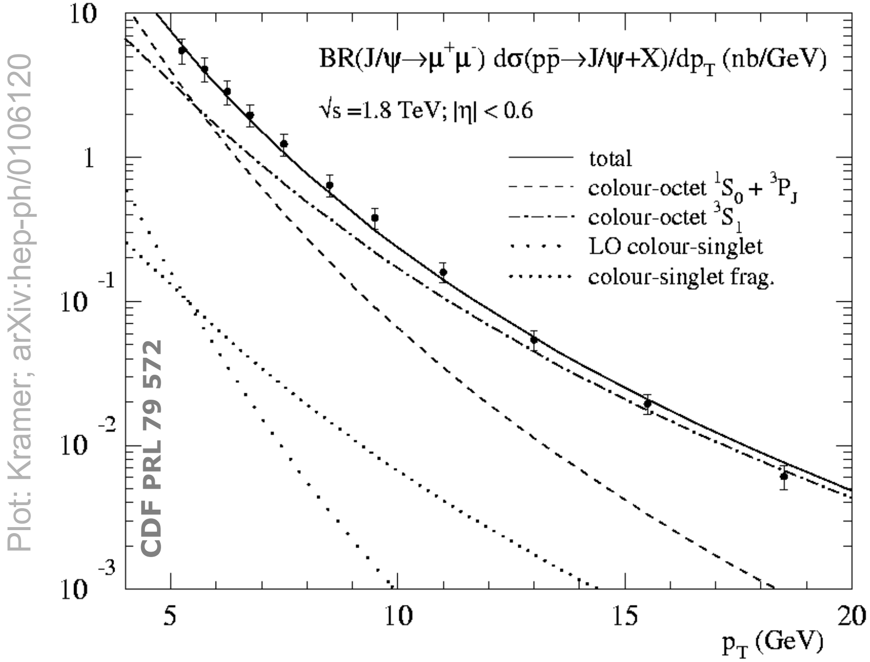
Outline of talk

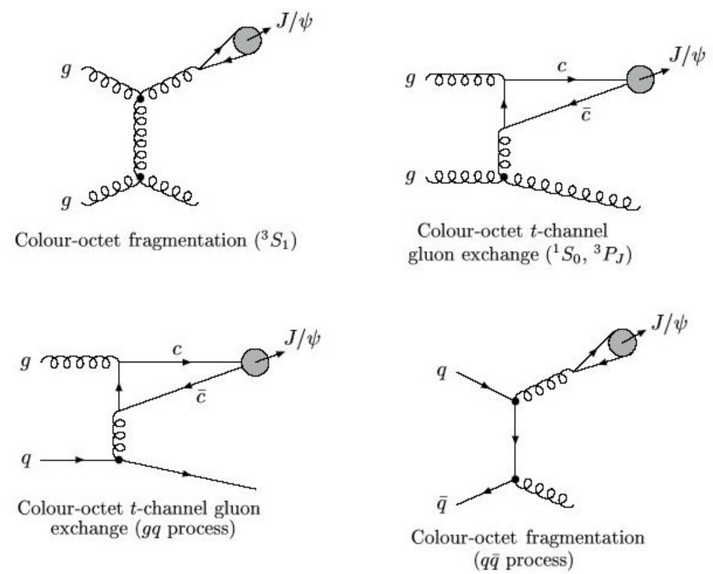
- Introduction
  - Theoretical motivation for studying production
  - Introduction to ATLAS detector and measurement capability
- Predictions at the Large Hadron Collider
  - Predicted quarkonium cross-sections at ATLAS
  - Status of backgrounds
  - Reconstruction performance
- Physics studies
  - Separation of octet states
  - Analysis of χ_c production
  - Spin-alignment studies

Theoretical motivation

- Production mechanism of quarkonium unexplained
  - Number of models suggested to account for production theory-data discrepancy
- Progress came with application of Non-Relativistic QCD (NRQCD) effective field theory to quarkonia production
  - This formalism led to Colour Octet Mechanism (COM)
  - **Current understanding suggests octet production is dominant contribution**



Quark pairs produced in octet state may non-perturbatively evolve into a singlet state through radiation of soft gluons



- COM provides excellent agreement with p_T cross-section shape and normalisation

Monte Carlo samples

- Currently basing our studies on Colour Octet Mechanism implemented in Pythia and fully simulated through ATLAS reconstruction in GEANT
- Using Pythia 6.403, switching to Pythia 6.412 in latest ATLAS software
  - Use Leading Order PDF CTEQ6L1 (previous studies have used CTEQ6M)
- Produced samples look at muon channel: include χ feed-down but not higher 2S and 3S states
- Colour octet NRQCD matrix elements describe non-perturbative quarkonium evolution
  - Matrix elements set to values derived from Tevatron data (see table)

$$\underbrace{d\sigma(pp \to H + X)}_{\text{total cross-section}} = \sum_{n_i} \underbrace{d\hat{\sigma}\left(pp \to Q\bar{Q}[n_i] + x\right)}_{\text{short distance heavy quark production}} \underbrace{\langle \mathcal{O}^H[n_i] \rangle}_{\text{matrix element}}$$

PYTHIA parameter	NRQCD matrix element	Value
PARP(141)	$\langle O(J/\psi)[^3S_1(1)]\rangle$	1.16
PARP(142)	$\langle O(J/\psi)[^3S_1(8)]\rangle$	0.0119
PARP(143)	$\langle O(J/\psi)[^1S_0(8)]\rangle$	0.01
PARP(144)	$\langle O(J/\psi)[^3P_0(8)]\rangle / m_c^2$	0.01
PARP(145)	$\langle O(\chi_{c0})[^3P_0(1)]\rangle / m_c^2$	0.05
PARP(146)	$\langle O(\Upsilon)[^3S_1(1)]\rangle$	9.28
PARP(147)	$\langle O(\Upsilon)[^3S_1(8)]\rangle$	0.15
PARP(148)	$\langle O(\Upsilon)[^1S_0(8)]\rangle$	0.02
PARP(149)	$\langle O(\Upsilon)[^3P_0(8)]\rangle / m_b^2$	0.02
PARP(150)	$\langle O(\chi_{b0})[^3P_0(1)]\rangle / m_b^2$	0.085

Based on hep-ph/0003142

The ATLAS detector

- ATLAS is one of the general purpose experiments at the LHC
  - Collisions at centre-of-mass energy 14 TeV every 25 nanoseconds

Calorimetry:

$|\eta|<5$ hermetic coverage

EM calo: Liquid Argon $\sigma/E \sim 10\%/\sqrt{E}$

Hadronic calo: Fe Cu-LAr $\sigma/E \sim 50\%/\sqrt{E}+0.03$

Inner Detector:

Pixel layers, silicon strips and transition radiation tracker with 2 Tesla solenoid

Precision track reconstruction for tracks with $|\eta|<2.5$ and $p_T>0.5$ GeV

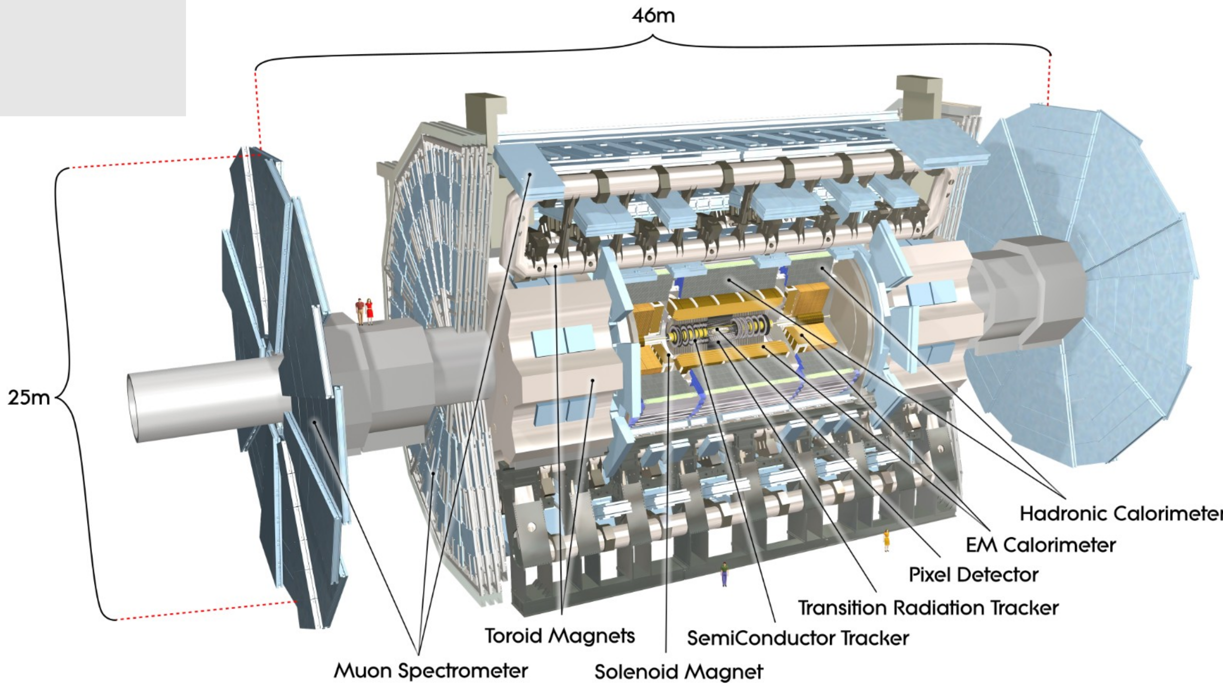
$\sigma/p_T \sim 4\text{x}10^{-4} p_T + 0.01$

Muon spectrometry:

Coverage out to $|\eta|<2.7$

Drift chambers and trigger chambers in an air-core toroid of 0.6 Tesla

Good standalone performance: $\sigma/p_T \sim 7\%$ at 1 TeV



ATLAS trigger

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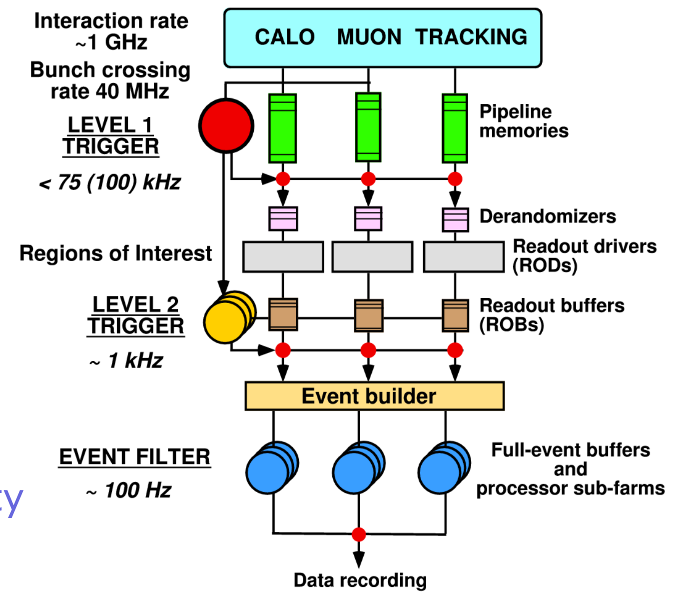
- Due to the bunch crossing rate and multiple interactions, need to reduce events written to tape to small fraction: **challenge is to keep the interesting ones!**

- **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

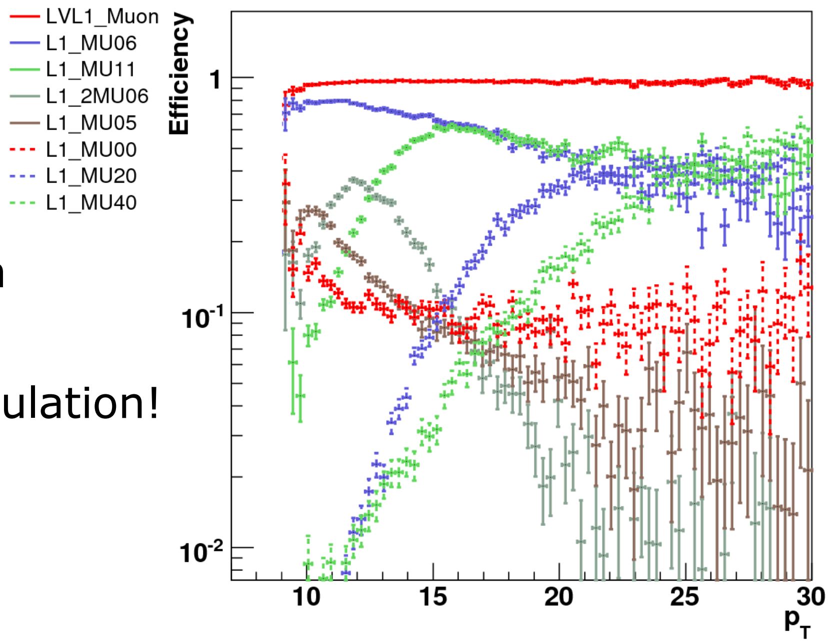


- **Must use triggers to reduce event rate**!
  - Di-muon triggers based on the presence of muons with certain particular p_T thresholds are of particular relevance.
  - LVL1 muon with p_T>X GeV followed by LVL2 muon with p_T>Y GeV with (X>=Y) and $|\eta|$ <2.5 -- a common trigger in ATLAS, important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

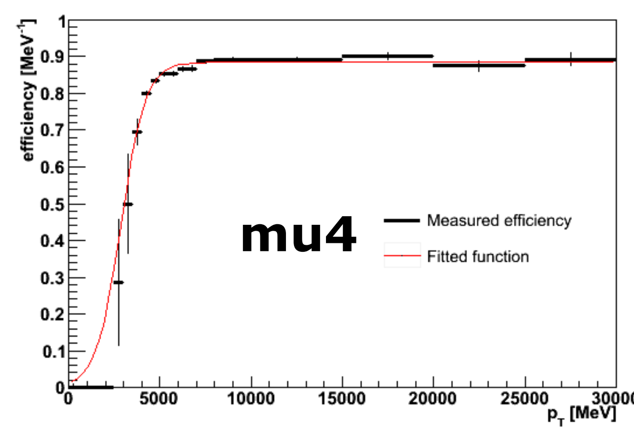
(Nomenclature in this talk for this type of trigger is ***μXμY****)*

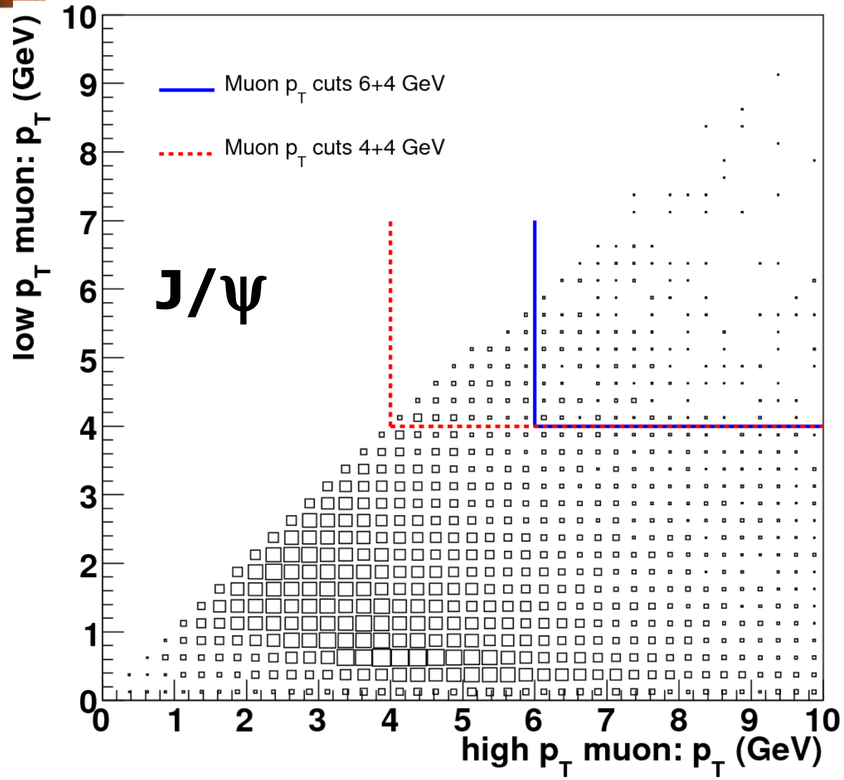
Muon trigger thresholds + efficiency

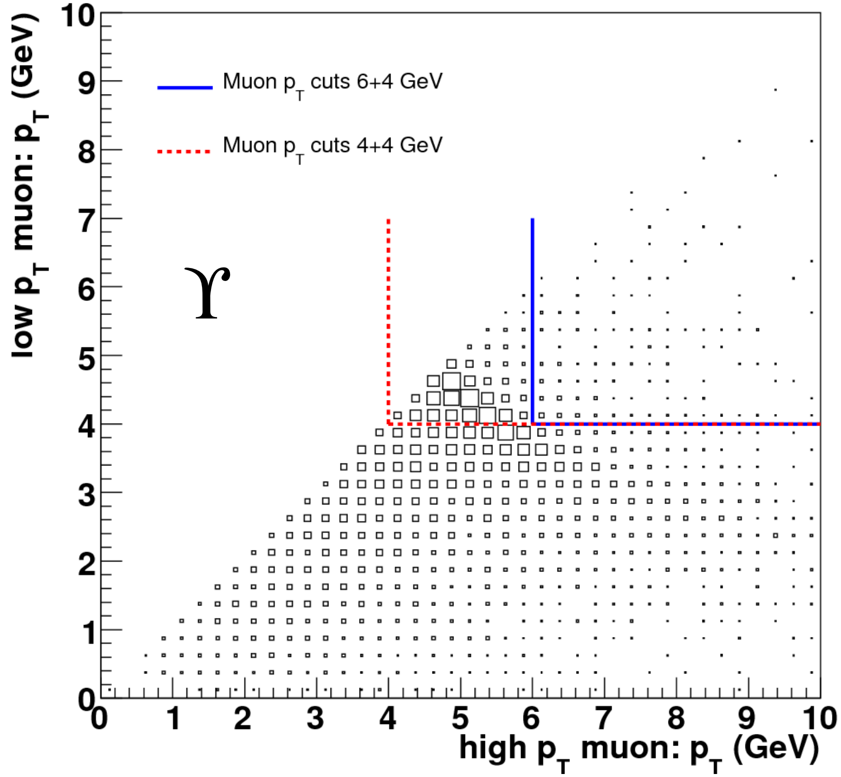
- ATLAS has excellent efficiency for identifying muons from quarkonium
  - Plot shows example of some LVL1 muon trigger efficiencies at p_T>10GeV
  - Efficiency better than 96% on $\mu6\mu4$ simulation!



- In early data-taking quarkonium will be important for commissioning.
  - May be able to use single muon trigger:
    - *Find muon at **LVL1** with threshold 4 GeV (can find momenta lower than this [see right])*
    - *Will require prescale, or associate with another candidate track at **LVL2** (no momenta requirement)*
  - Can allow access to very low onia p_T region







- Lowering of muon p_T requirements from μ6μ4 to μ4μ4 increases J/ψ and substantially increases ϒ cross-section
- By lowering cuts to 4+4 GeV we accept the bulk of the ϒ production, due to the high mass of the ϒ

Trigger cuts	6+4 GeV	4+4 GeV
σ(J/ψ)	22 nb	27 nb
σ(ϒ)	4.6 nb	43 nb

STATISTICS

ATLAS expects to achieve current Tevatron onia yield with 60—85 pb^{-1} [2—3 months running at low luminosity (10^{31} $cm^{-2}s^{-1}$) with μ6μ4 trigger], based on *latest publications* from CDF/D0 [Spring/Summer 2007] :

	Tevatron today	ATLAS
1×10^6 J/ψ	CDF 1.1 fb^{-1}	60 pb^{-1}
4.2×10^5 Υ(1,2,3S)	D0 1.3 fb^{-1}	85 pb^{-1}

Corresponds to around 1000 J/ψ's per hour

AN EXCELLENT TOOL FOR DETECTOR COMMISSIONING

Reconstruction of J/ψ and ϒ to muons is a perfect tool for alignment and calibration of the ATLAS detector

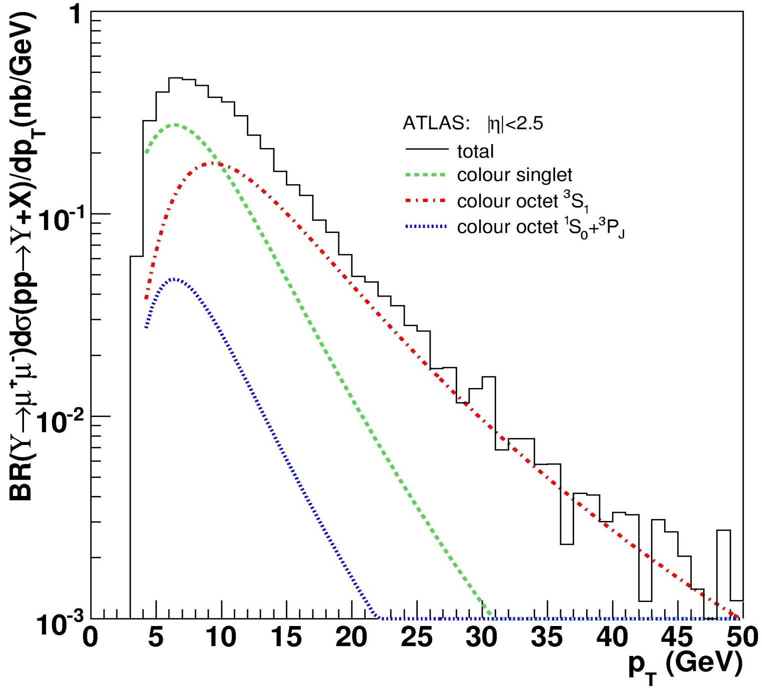
This talk is dedicated to physics aims so this aspect will not be discussed further

Range of p_T events for NRQCD studies

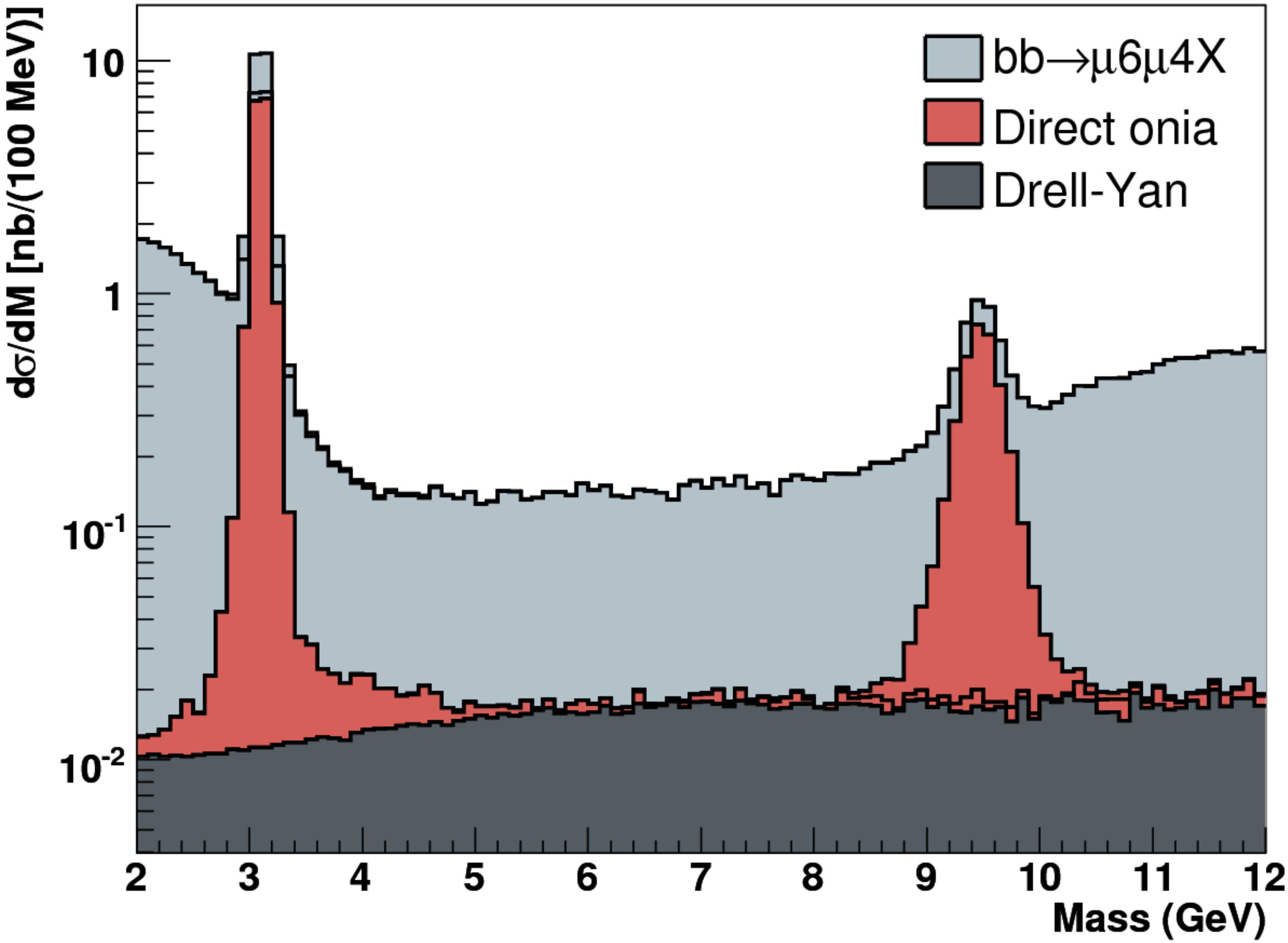
- Both low and high p_T regions important for measuring contributions from singlet and octet production

- With 10 pb^{-1} will be able measure ratios of onia cross-sections, which will also help place constraints on NRQCD octet matrix elements.

- Somewhat higher statistics will also allow analysis of various χ states, measurement of colour octet contributions and fixing of NRQCD matrix elements



Low mass di-muon sources (μ6μ4)

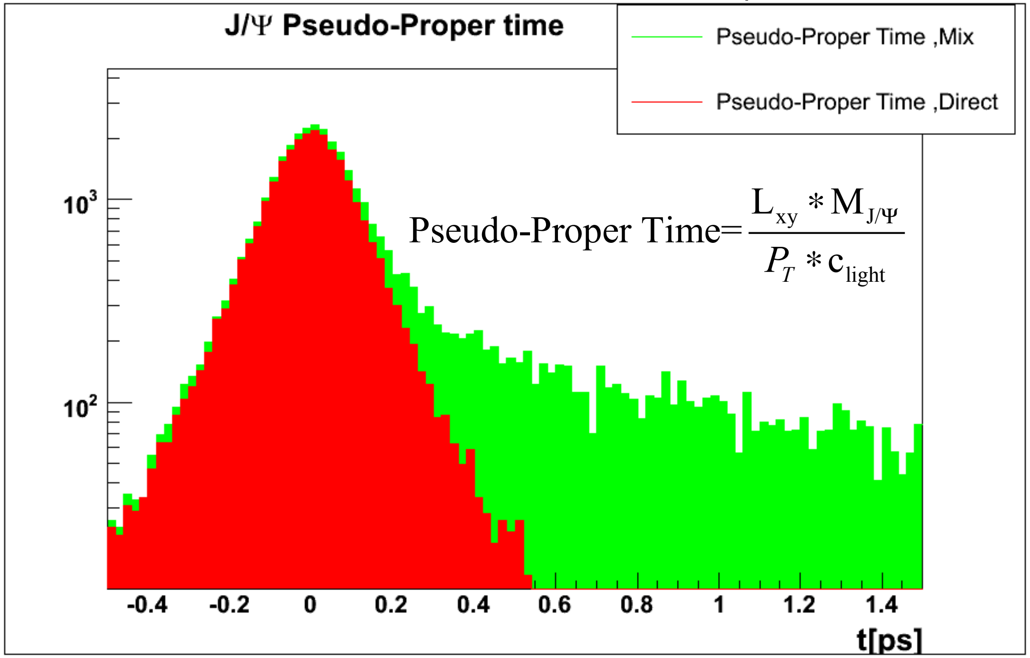


Vertex separation (μ6μ4)

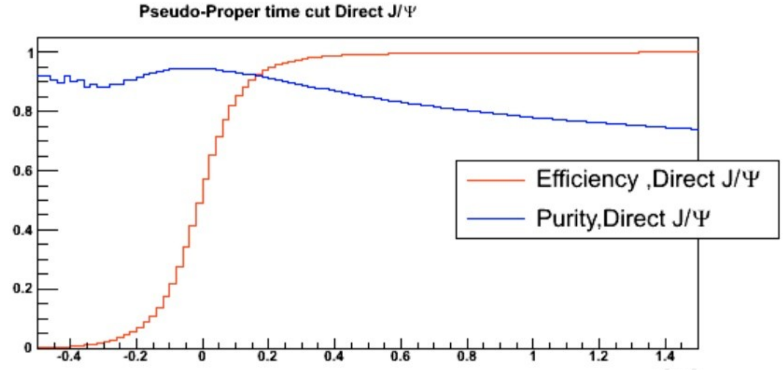
❖ Proper time used to separate direct J/ψ from indirect (B-decays)

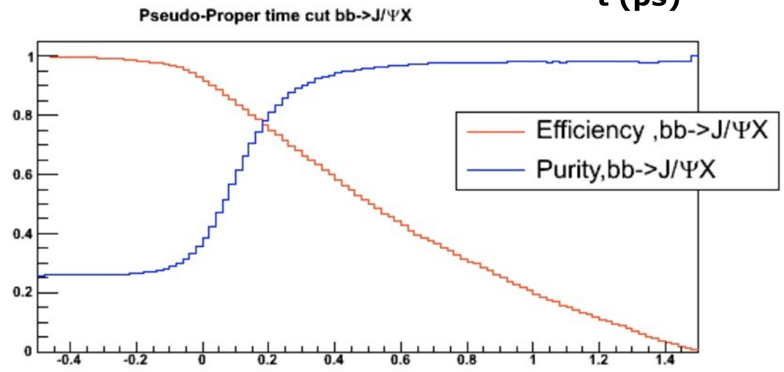
- Mean at zero -- $L_{xy}=0$ is characteristic of direct J/ψ, B's positive L_{xy}
- 'Pseudo-proper time' cut of <0.2 ps gives prompt J/ψ efficiency of 95% with 5% contamination (removes grey background on previous slide)
- Cut of >0.15 ps gives bb→J/ψX efficiency of 80% with 20% prompt J/ψ contamination

'Mix' sample is direct and indirect J/ψ combined

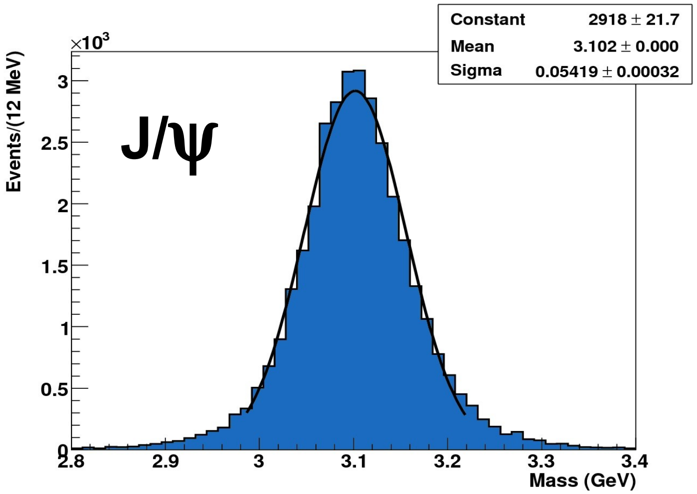


$$\text{Pseudo-Proper Time} = \frac{L_{xy} * M_{J/\Psi}}{P_T * c_{light}}$$





Reconstruction of prompt quarkonia (μ6μ4)



From all $\mu^+\mu^-$ pairs in J/ψ mass range, **~96%** of generated events reconstructed (depending on reconstruction algorithm and if require vertex refit).

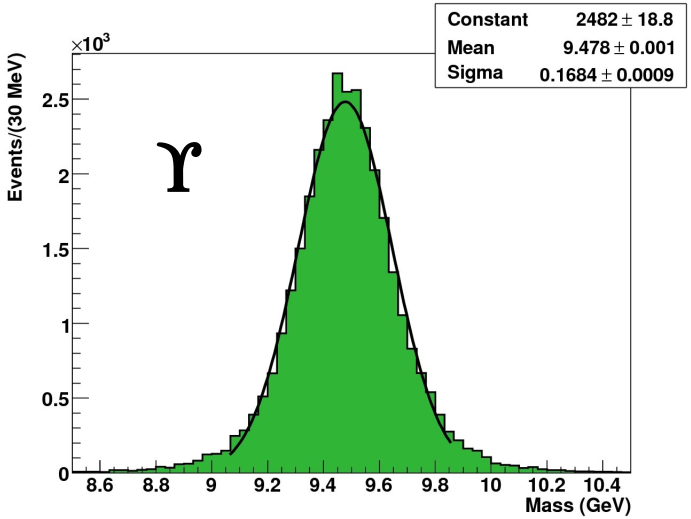
Mass resolution 54 MeV.

From all $\mu^+\mu^-$ pairs in ϒ mass range, **~92%** of generated events reconstructed.

Mass resolution 168 MeV.

- **Can reconstruct muons from Inner Detector tracks, muon spectrometer standalone, or combined muon information**
- Looking into possibility of triggering on only one muon with p_T>4 GeV in low luminosity run
  - Can then search to find second muon p_T>1 GeV
  - Higher cross-section, and better for some physics studies

p_T slices	5-10 GeV	10-15 GeV	15-20 GeV	>20 GeV
σ(J/ψ)	54 MeV	52 MeV	51 MeV	49 MeV
σ(ϒ)	174 MeV	171 MeV	169 MeV	169 MeV

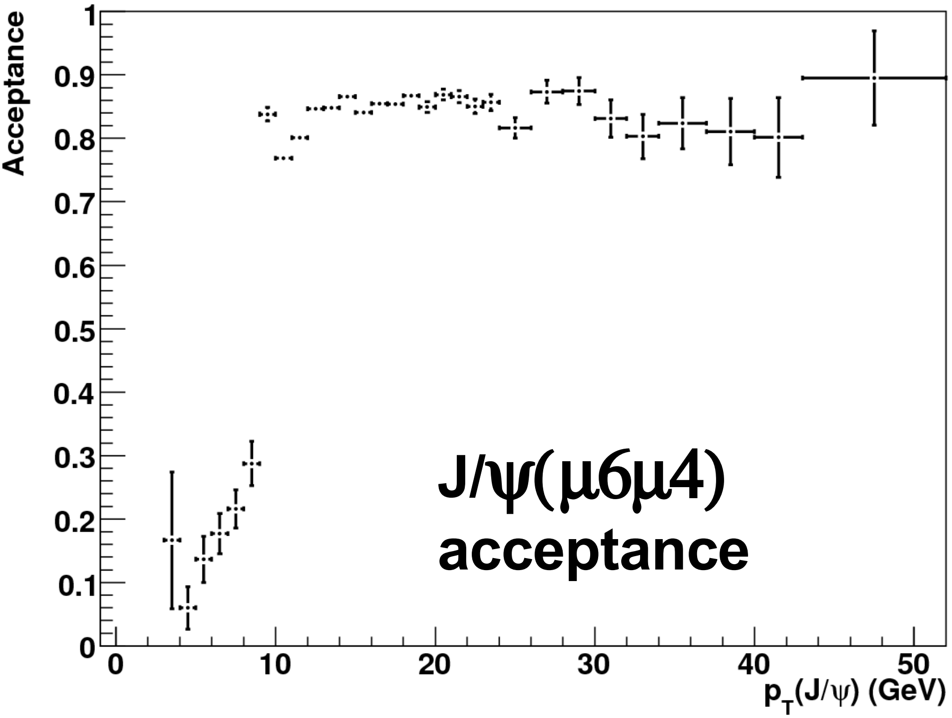


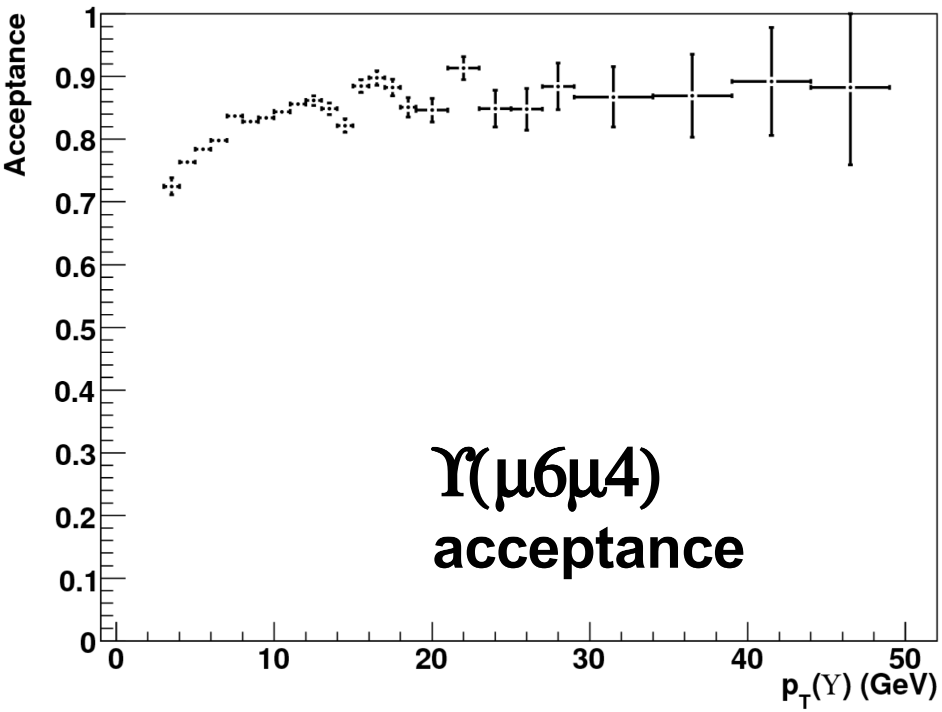
Reconstructed onia transverse momentum

- **Studies of high p_T onia production are important as the high momenta accessible by the LHC are not within the reach of the Tevatron**

- Acceptance of onia is ratio of MC generated to reconstructed in each p_T bin
  - **acceptance rises to a plateau at >12 GeV**

- Acceptance of Υ much better at low p_T's due to mass





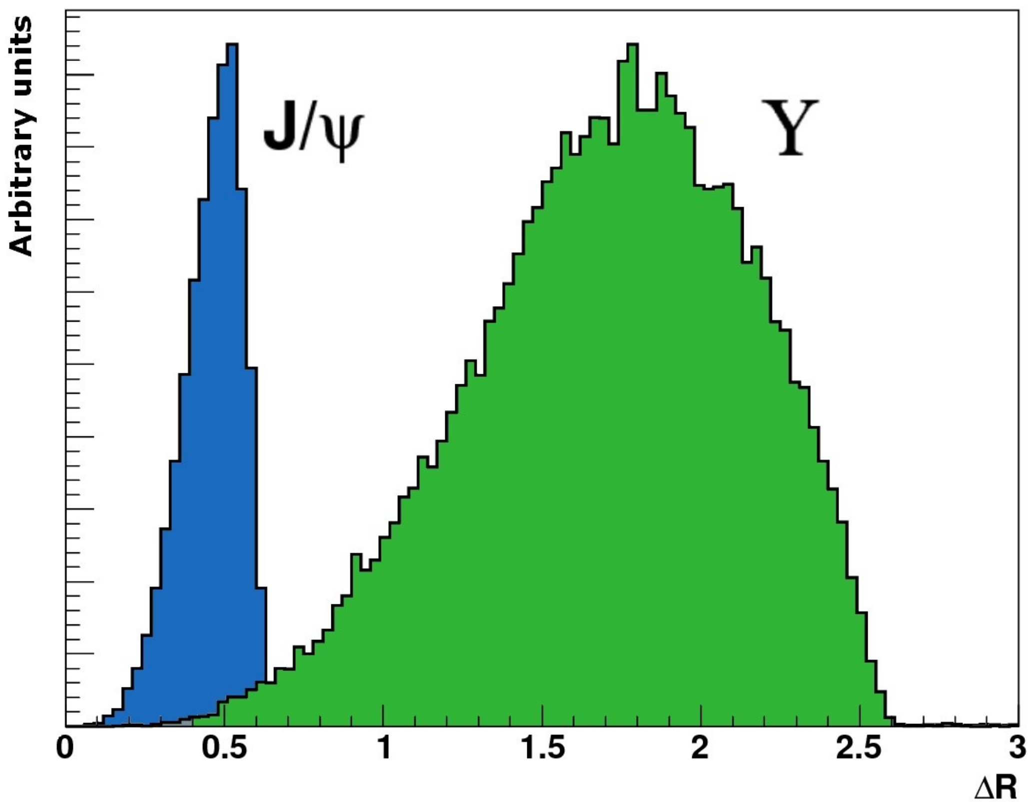
Errors on simulated statistics correspond to approximately 10 days of low luminosity data-taking

Onia decay muon angular separation ΔR

ΔR measure defined as $=(\Delta\eta^2+\Delta\phi^2)^{1/2}$

- Muons from J/ψ have a ΔR<0.5 the majority of the time
  - Effective cut-off at ΔR>0.6 due to J/ψ kinematics with μ6μ4 trigger

- In contrast, ϒ muons are free to be produced with large separation due to mass

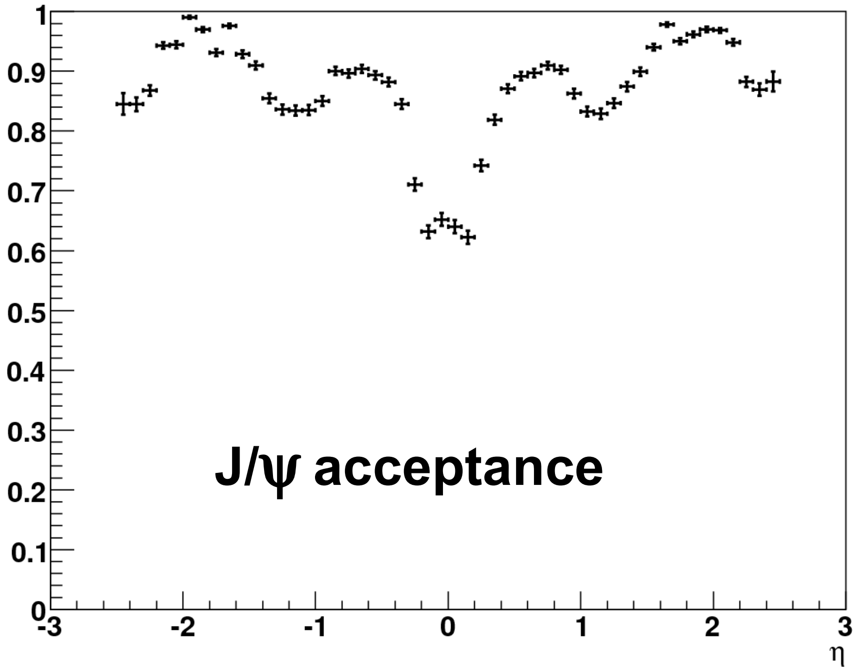


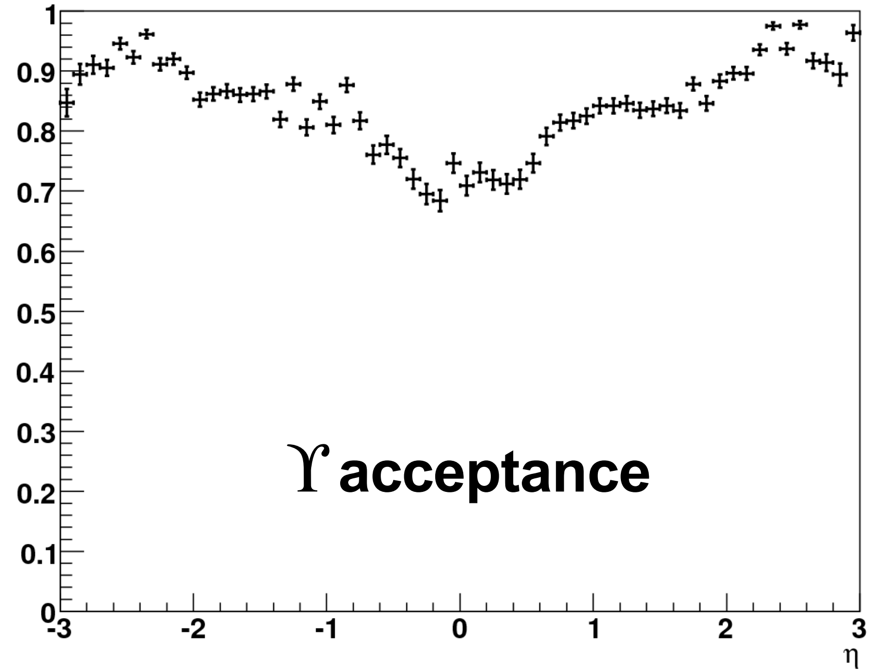
ΔR differences have implications

for χ reconstruction and studies of hadronic activity from onia

Onia acceptance with pseudorapidity

- Lose most J/ψ's in barrel, acceptance best in endcaps
  - J/ψ muons produced close in ΔR, hence J/ψ distribution reflects single muon acceptance
- Situation for ϒ somewhat different:
  - ϒ have dip at central η due to decay kinematics (muon η's themselves do not have dip)
  - ΔR broader for ϒ, so smearing is greater
  - Reconstructed ϒ's follow MC closely – still have best acceptance in endcap region, but losses in barrel have smaller fluctuations





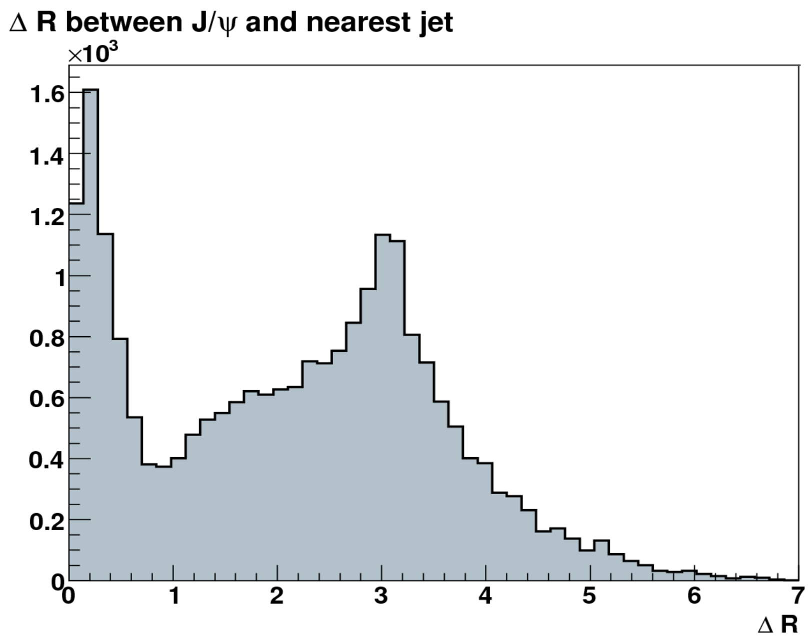
Separating onia production contributions

At ATLAS we hope to be able to separate both octet and singlet contributions within both $\chi_c(\chi_b)$ production as well as direct $J/\psi(\Upsilon)$

- Discrimination of production mechanisms:
  - Associated hadronic/jet activity with onia
  - Associated open charm/beauty
  - Analysis of quarkonium spin-alignment
  - Low p_T trigger cuts on muons allows for analysis of singlet contributions, expected to dominate at p_T<10 GeV
  - ATLAS will have high statistics above 50 GeV p_T, useful for octet production analysis
- Observation of χ_b and χ_c and their p_T dependence

Associated hadronic/jet activity

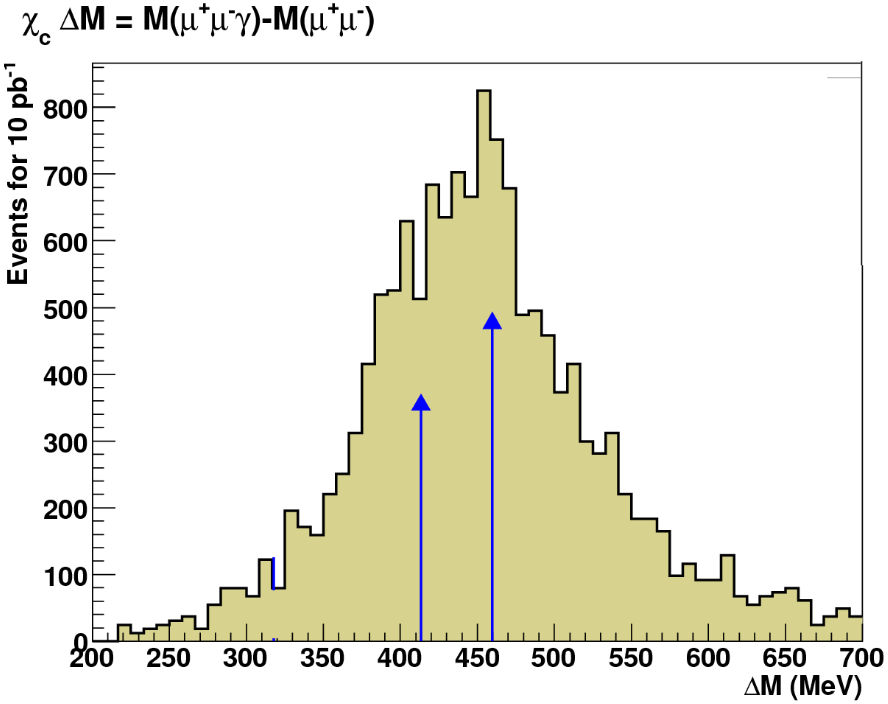
- Studies ongoing into feasibility of measurement of predicted additional hadronic activity around the onia momentum direction for octet states
  - Information on associated jets from onia decays may provide insights into production mechanisms
    - By using E_T and charged track isolation cones, may be able to recognise and classify production process
  - Additional complications in J/ψ case because muons **and** photon follow J/ψ direction to calorimeters within very small angle



- A recoil jet is often seen opposite the J/ψ in singlet production, originating from a hard gluon
- May be able to use this jet information to make cuts on candidate singlet production events

Chi decays

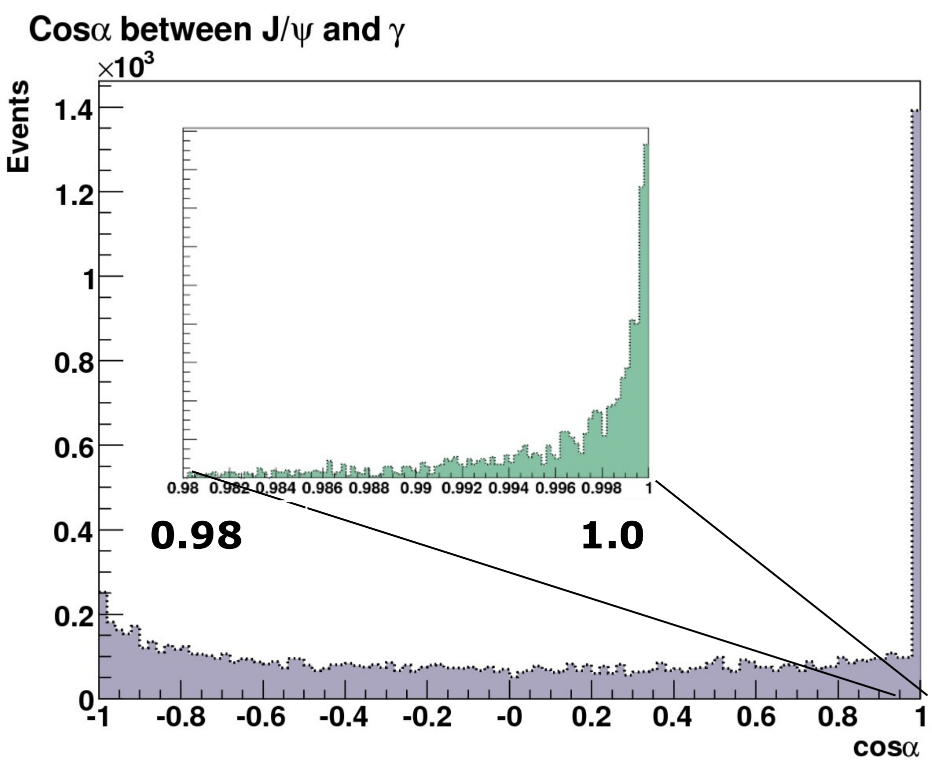
- For J/ψ, ~30% of total cross-section from χ_c feed-down
- For Υ, ~50% of total cross-section from χ_b feed-down
  - Interested in χ decays to J/ψ or Υ and a gamma: we have a low χ reconstruction efficiency due to the difficulty in retrieving this gamma
- Preliminary studies suggest we can expect to recover few % of those χ events from reconstructed J/ψ's or Υ
- $\mu\mu\gamma-\mu\mu$ invariant mass difference should help determine whether χ_{c0}, χ_{c1} or χ_{c2} was reconstructed
- Currently see little defined structure, but resolution can be dramatically improved by using conversions

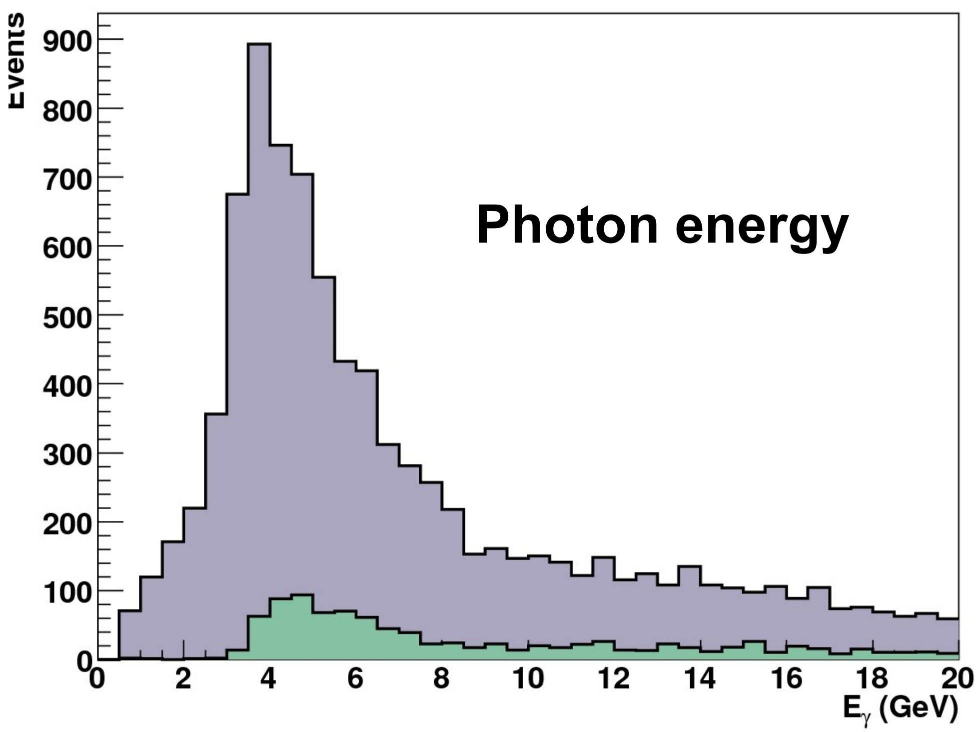


Photons with onia production

- χ_c decays have a energetic photon associated with them
- Angle between photon and J/ψ direction provides very strong signature of 'interesting' decays

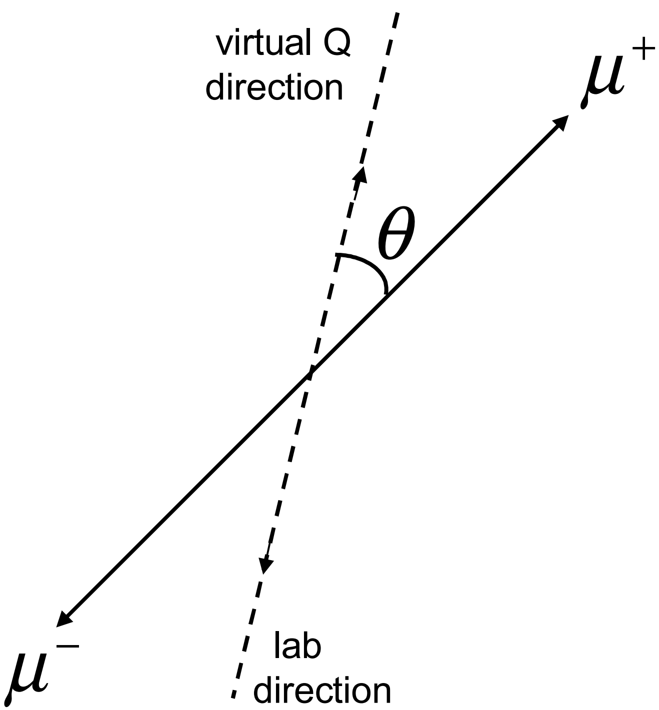
- True χ have cos α very close to 1
- Can be used to reduce trigger rate by 2-3 orders of magnitude and sub-select χ decays whilst keeping full range of J/ψ p_T's





Quarkonium spin alignment

- Distribution of quarkonium spin alignment an important test of production models
- Octet production mechanism specifically predicts onia to be produced with 100% transverse polarisation at large p_T



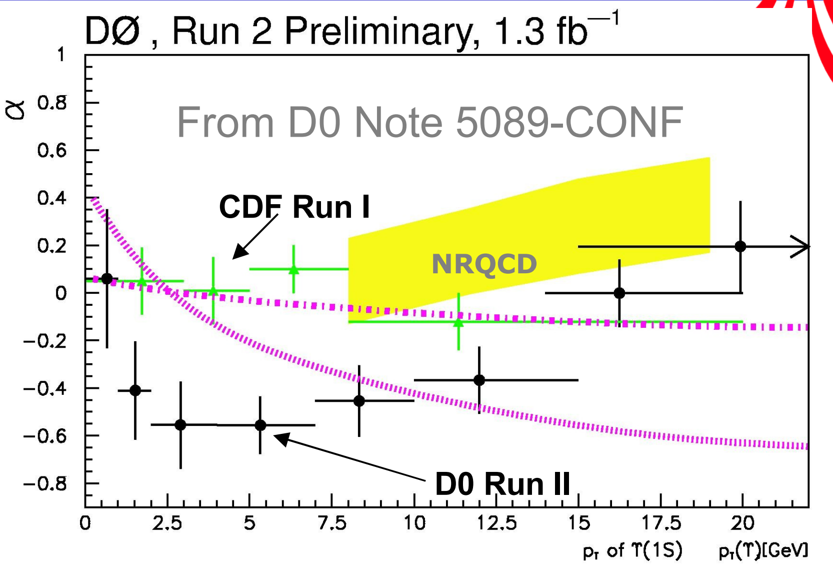
- Angle defined between positive muon direction in quarkonium rest frame and quarkonium direction in lab frame, distribution given by:

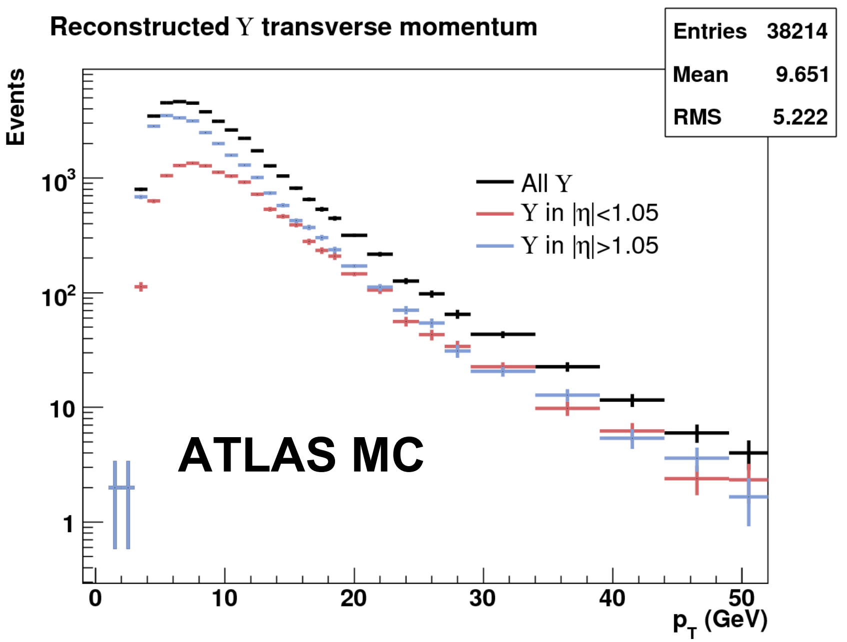
$$\frac{d\Gamma}{d\cos\theta} \propto \left(1+\alpha\cos^2\theta\right)$$

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

Direct quarkonium polarisation

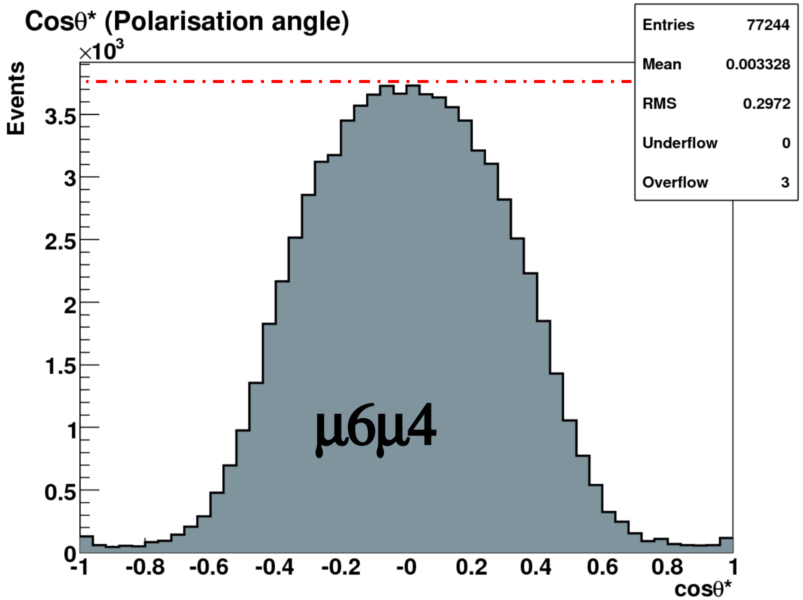
- Latest D0 Run II measurements disagree with theoretical models *and* CDF Run I results!
- High p_T data important, Tevatron suffers from statistics in this regard
  - ATLAS predicts same cross-section for Υ above 20 GeV as Tevatron has in total
  - ATLAS has capability to fully test validity of production models using polarisation
- Current techniques at e.g. Tevatron use fits to MC template polarisation samples

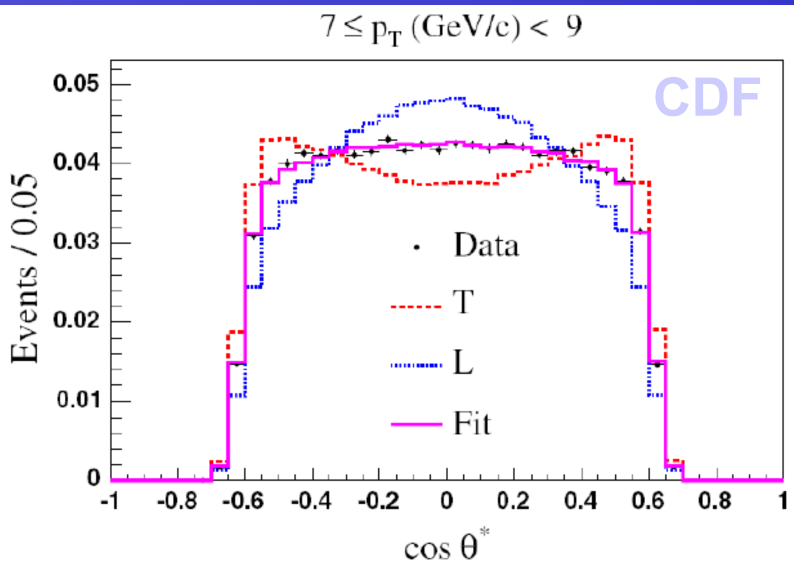




Spin alignment: cos θ* acceptance

- Fits to MC template polarisation samples used at Tevatron
  - 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

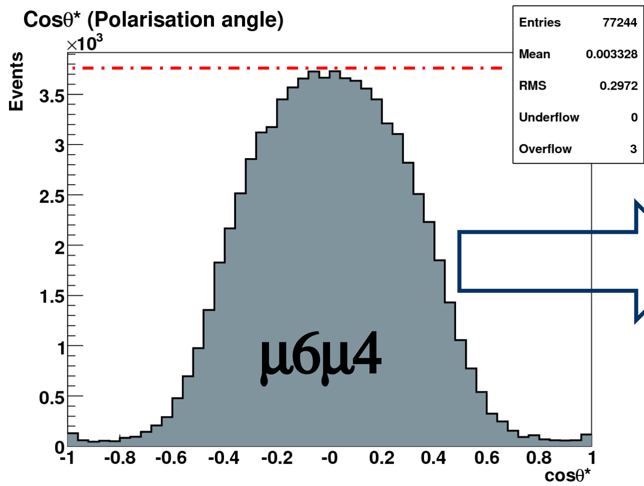


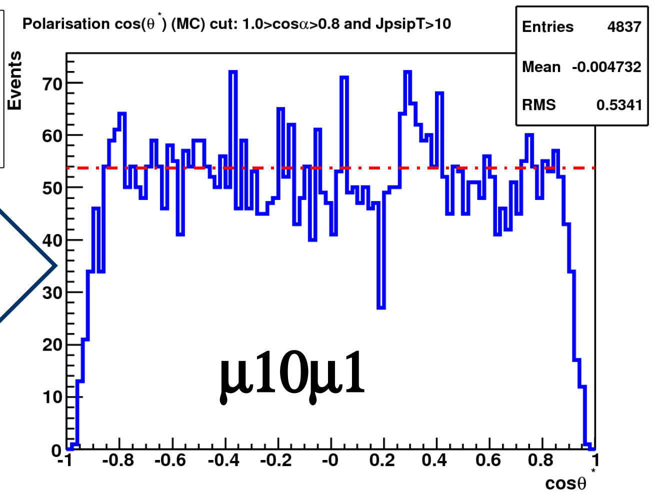


- Easy to lose discrimination between longitudinal, transverse and unpolarised templates in restricted central cosine area

- With 6+4 GeV trigger cuts, we see similar acceptance issues at ATLAS
  - Unpolarised sample has angular distribution distorted significantly
  - Need more discrimination at high cos θ*
  - Need to extend cos θ* acceptance to distinguish different polarisations

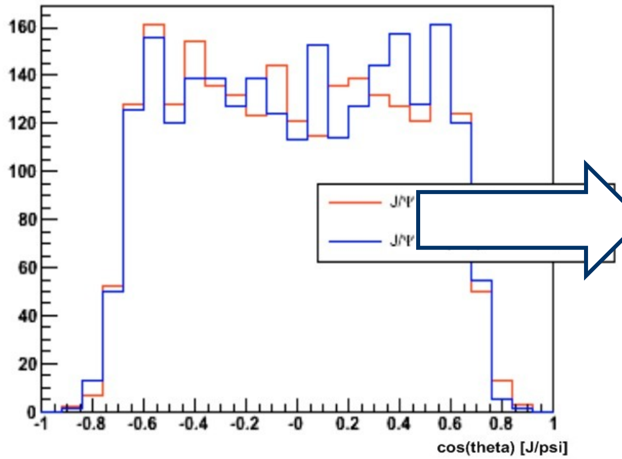
Spin alignment: cos θ* acceptance

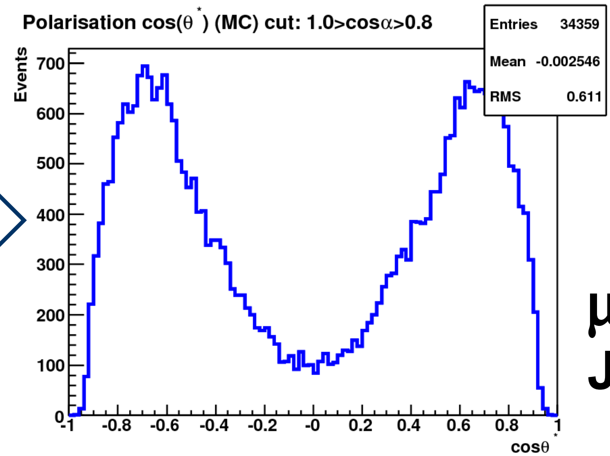




- Changing trigger cuts from μ6μ4 to μ10μ1 means we can have excellent acceptance across almost full range of cos θ*
- Improvements in high cos θ* are much more pronounced at high J/ψ p_T

μ6μ4 and J/ψ p_T>21





μ10μ1 and J/ψ p_T>21

Spin alignment measurement

- By taking data with $\mu10\mu1$ we increase our acceptance in important high cos θ^* area and effectively double our overall cross-section

- With increased acceptance across polarisation angle, should be able to distinguish polarisation state in real data with reduced systematics

- Important to be able to access the high $|\cos\theta^*|$ region to determine if we are measuring cross-section correctly (especially as acceptance changes with p_T)!

- 100 pb^{-1} should allow for competitive measurement of quarkonium polarisation, with enough statistics across the accessible range of p_T

Summary

- 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 next year

- ATLAS will be able to substantially extend Tevatron reach on onia production

  - Separating colour-singlet/octet mechanisms
    - Differences in associated jets
    - Onia from octet states should have additional associated hadronic activity

  - Detailed study of $\chi_c \rightarrow J/\psi + \gamma$ and $\chi_b \rightarrow \Upsilon + \gamma$
    - Photon detection efficiency (in both calorimetry and conversions)
    - Specific features of χ decays allow for efficient triggering

  - Quarkonium spin-alignment
    - Colour-octet mechanism predicts transversely polarised onia
    - Needs high statistics at high transverse momenta

- Still a lot of work to do before data-taking begins!

Backup slides

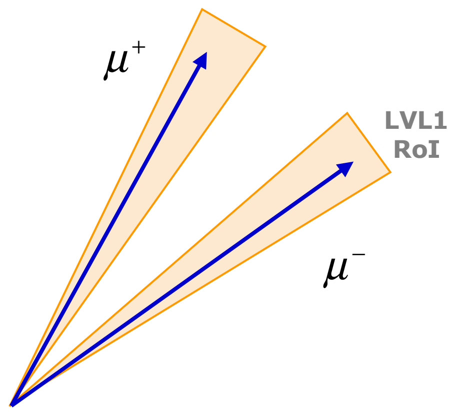
Calibration of muon trigger efficiency

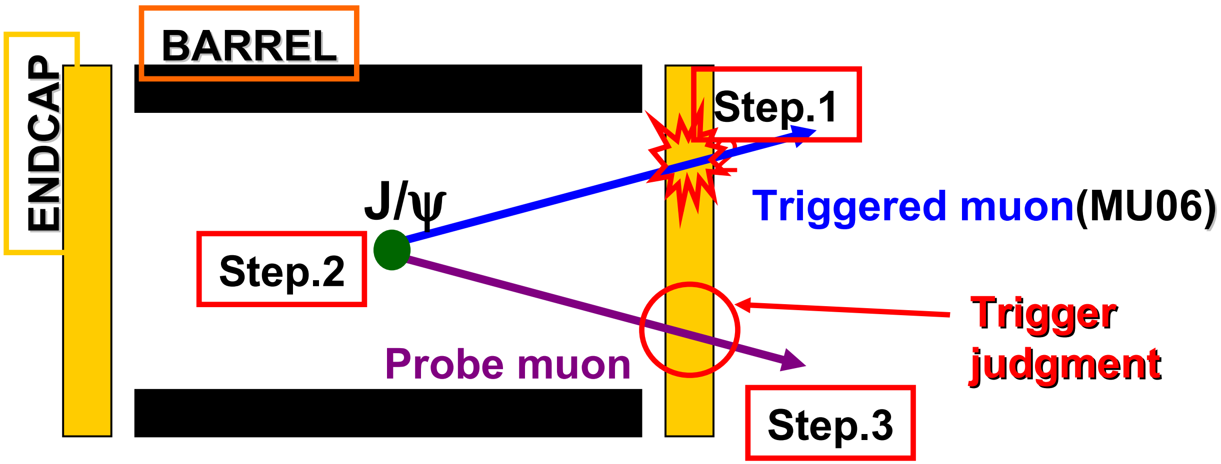
- Simulation has been done to develop an online calibration method to obtain single muon efficiency (μ6 threshold):

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

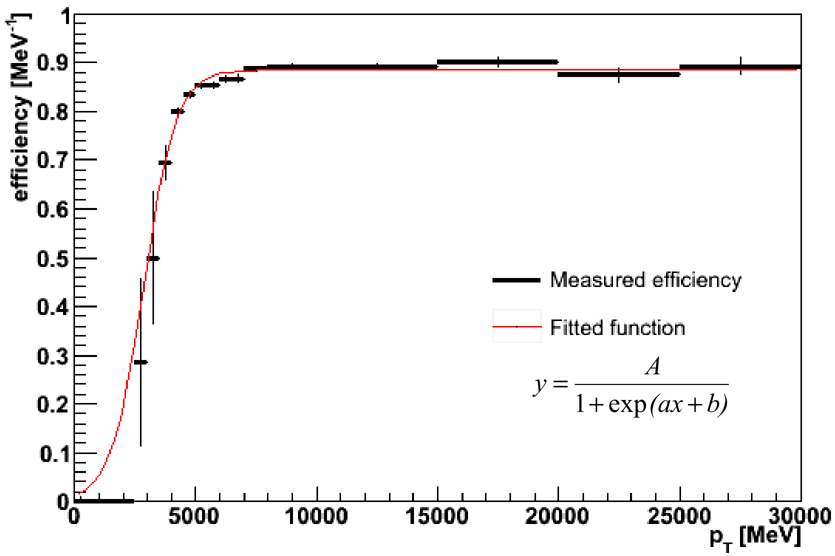
  2) Offline reconstruction -- build object (e.g. J/ψ) with invariant mass cut and remove triggered muon

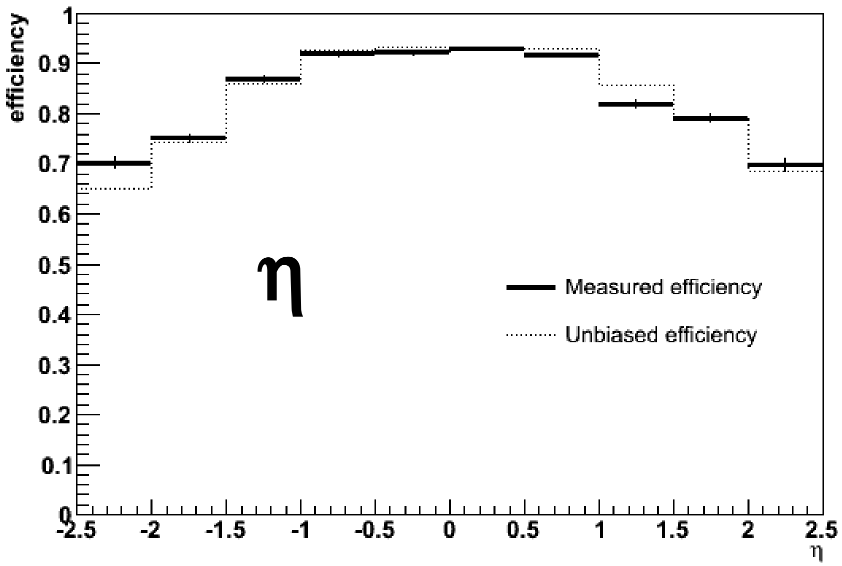
  3) Analysis of probe muon to calculate single muon efficiency

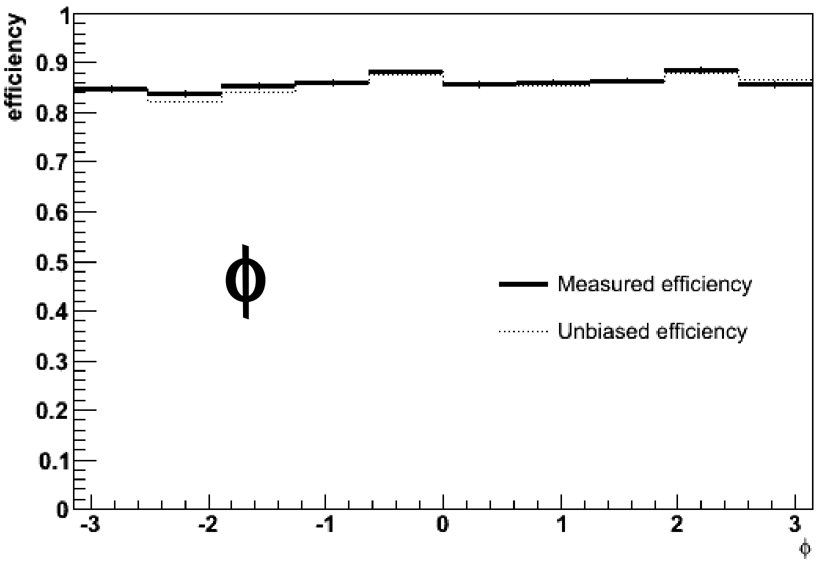




LVL1 single muon efficiency



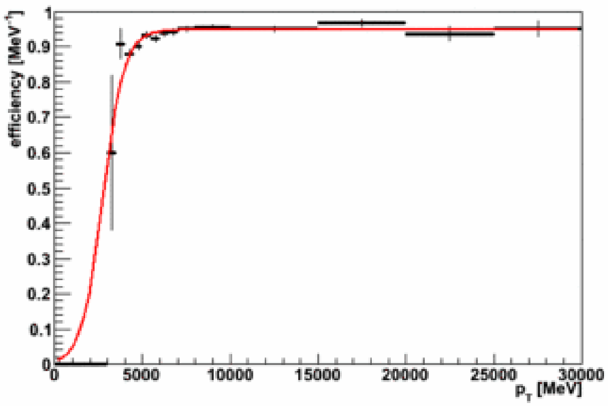




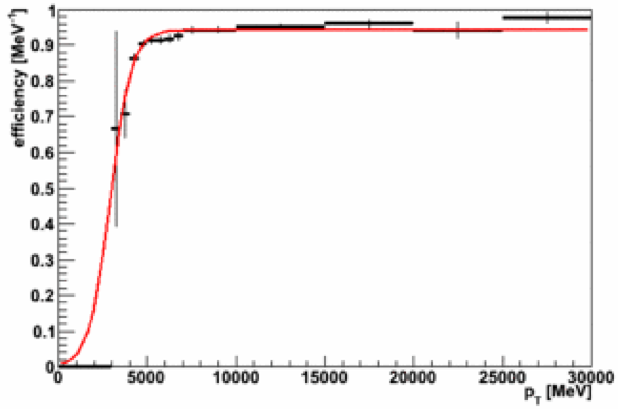
- Efficiency
  - At threshold steeply increases with p_T
  - Is flat in ϕ
  - Is symmetric in η
- Good match to *unbiased efficiency* calculated using Monte Carlo truth

Single muon trigger efficiency map

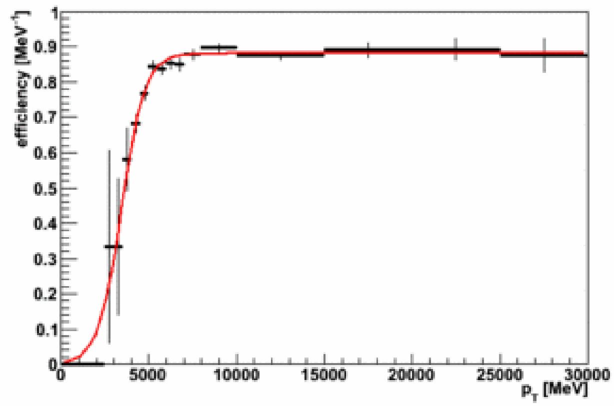
$0 < |\eta| < 0.5$



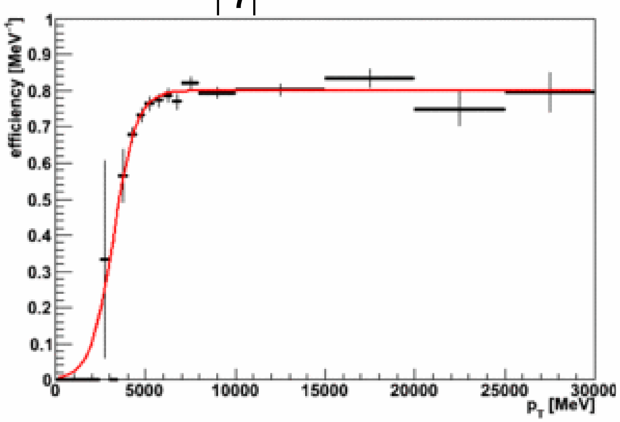
$0.5 < |\eta| < 1$



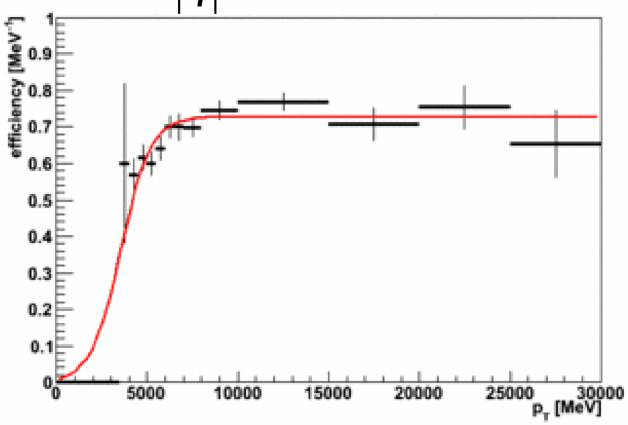
$1 < |\eta| < 1.5$



$1.5 < |\eta| < 2$

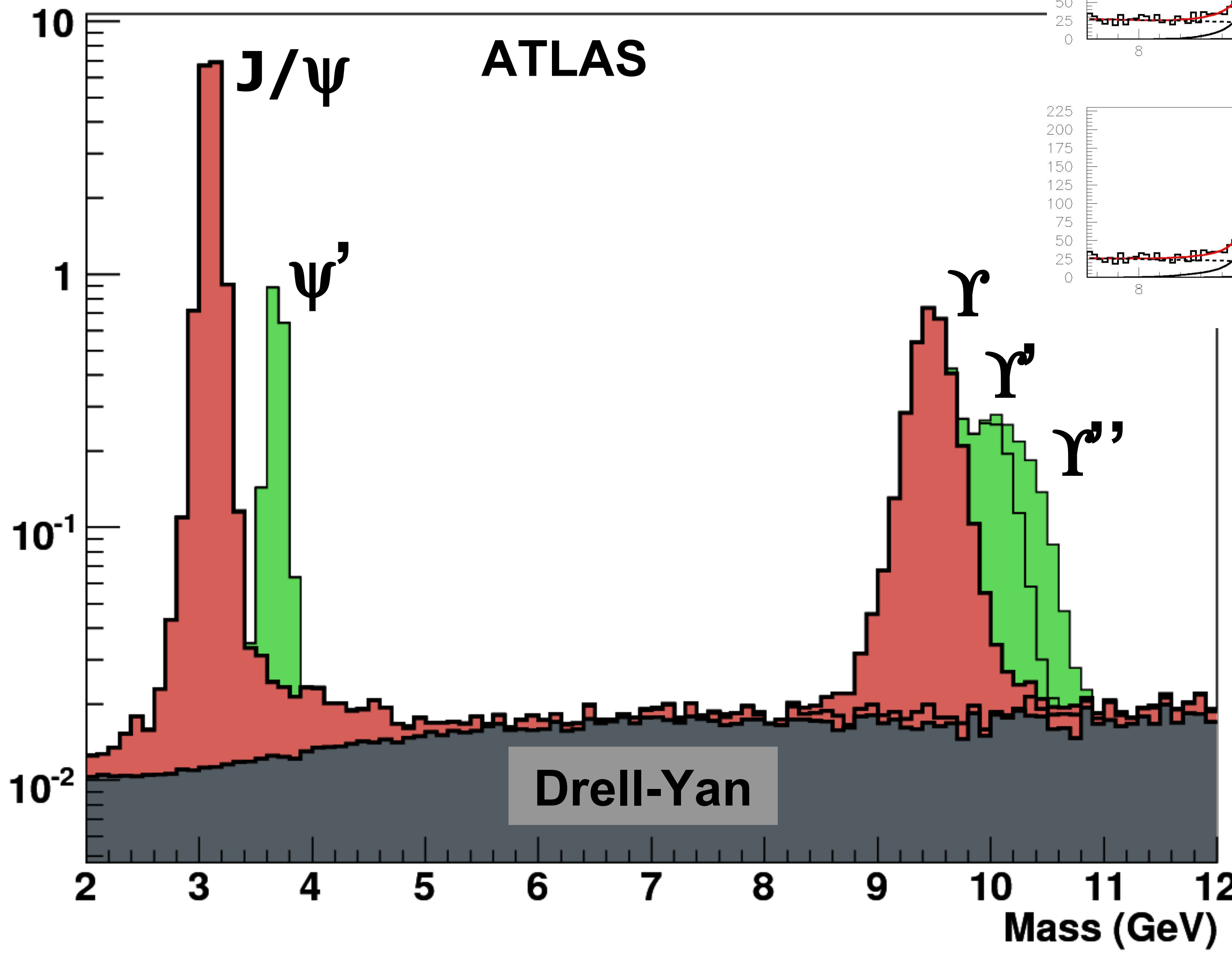


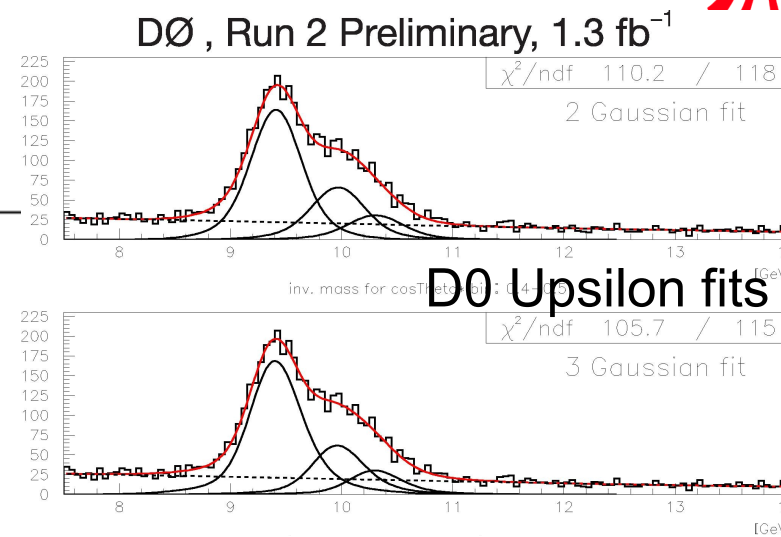
$2 < |\eta| < 2.5$



Direct onia – di-muon mass plot

Sources of low invariant mass di-muons





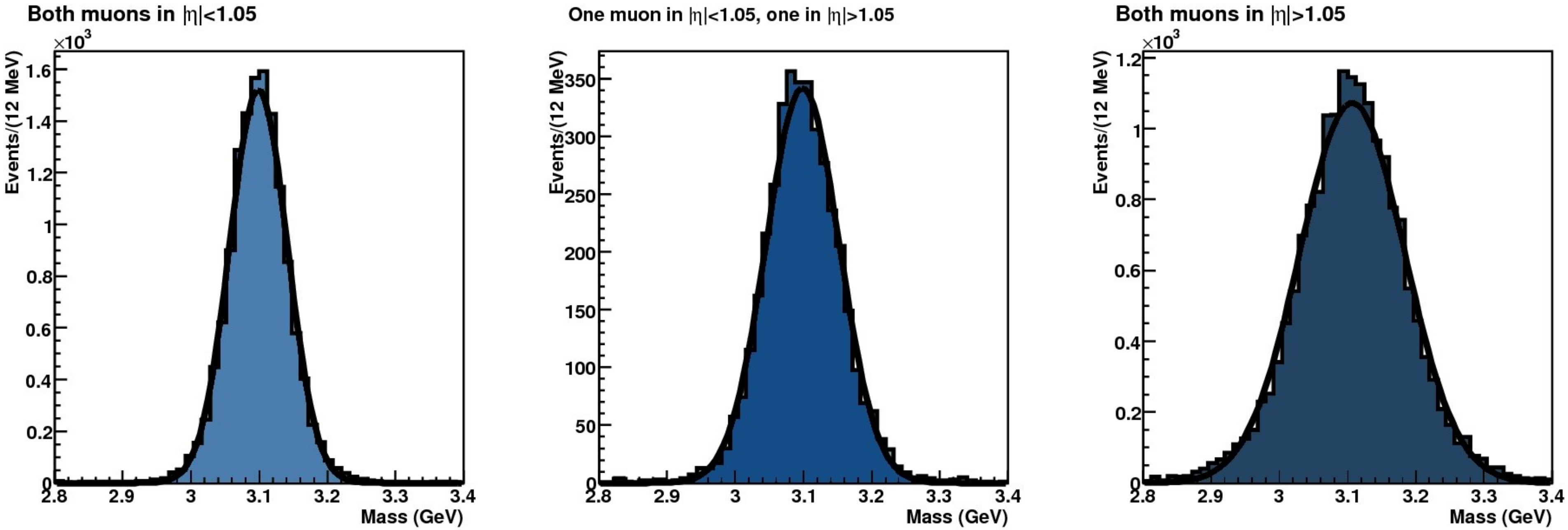
From D0 Note 5089-CONF

(Higher state contributions have been stacked)

Higher state contributions are for illustration only -- correct normalisation and expected resolutions, but are **NOT** fully simulated events!

Reconstruction of prompt quarkonia (μ6μ4)

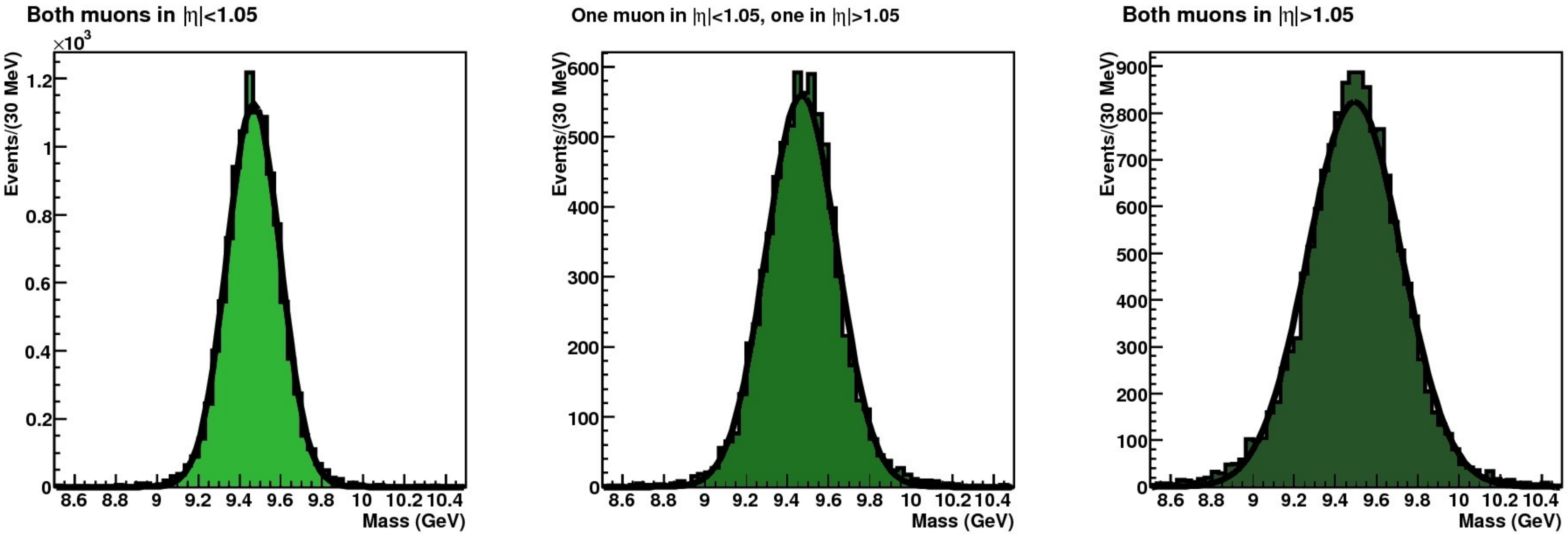
- J/ψ mass resolution increases with larger |η| of muons



Both in barrel (|η|<1.05)	One in barrel, one in endcap	Both in endcap (|η|>1.05)
Δm = 2 MeV, Resolution 42 MeV	Δm = 2 MeV, Resolution 53 MeV	Δm = 10 MeV, Resolution 77 MeV

Υ mass resolution as function of η and p_T

- Υ mass resolution again increases at high muon η



Both in barrel ($|\eta|<1.05$)	One in barrel, one in endcap	Both in endcap ($|\eta|>1.05$)
Δm = 9 MeV, Resolution 129 MeV	Δm = 11 MeV, Resolution 172 MeV	Δm = 30 MeV, Resolution 228 MeV

- Υ mass resolution also improves slightly with larger p_T

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