Physics studies with J/ψ and Upsilon in early ATLAS data

Berkeley Workshop on Physics Opportunities with Early LHC Data

Darren Price on behalf of the ATLAS Collaboration
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Planned studies of quarkonia at ATLAS

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- Early data studies (10-100 pb^{-1} integrated luminosity) planned in ATLAS include measurement of:
  - Prompt/indirect J/ψ cross-section ratio: $\frac{\sigma(bb \to J/\psi(\mu\mu)\,X)}{\sigma(pp \to J/\psi(\mu\mu)\,X)}$
  - Prompt $J/\psi\to\mu\mu$ and prompt $\Upsilon\to\mu\mu$ differential production cross-sections
  - Polarisation of J/ψ and Υ as a function of quarkonium transverse momentum
  - $\chi_c(nP)\to J/\psi(\mu\mu)\gamma$ cross-section(s)
- Large predicted cross-sections and range of transverse momenta accessible at ATLAS can give new insight into quarkonium production and tests of QCD
  - Production mechanism of quarkonium has many features still unexplained
  - Quarkonia forms an important background for many other physics processes at LHC
- Large predicted quarkonia rates at LHC mean that J/ψ and Υ have, and will continue to play a **central role for initial calibrations** of the ATLAS detector and software
  - Ongoing efforts in alignment, magnetic field mapping, trigger monitoring, data quality monitoring, low p_T ID tracking, muon reconstruction, efficiency determination, software validation…

Predicted rates at 10 TeV

- Current ATLAS simulations suggest we can expect **10,000's of quarkonia** written to tape with **each inverse picobarn** of integrated luminosity
- Previous studies conducted at 14 TeV c.m.s energy, but using muon p_T thresholds of $\mu6\mu4$
  - Dropping to 10 TeV loses us some cross-section
  - Drop in leading muon p_T threshold cut to 4 GeV, plus continuing improvements in trigger algorithms mean predicted rates are not significantly affected – and in the case of Upsilon have increased! ($\mu6\mu4 \rightarrow \mu4\mu4$ will allow acceptance of bulk of Υ with p_T~0)
  - **Can accept muons down to ~2.5 GeV, but with low efficiency ~O(10%) so we place analysis cut of 4 GeV where we have high acceptance (and reduced background/fakes), but may re-evaluate this in data-taking**

$\sigma(pp\rightarrow Q[\mu4\mu4]\ X)$ @ 10 TeV	J/ψ	U(1S)	U(2S)	U(3S)	DY*	bb*
Generator-level cross-section	27 nb	18.5 nb	10.2 nb	8.8 nb	0.24 nb	16.2 nb
Available rates after trigger/reco/bg reduction	17 nb	12.1 nb	5.5 nb	4.1 nb	0.14 nb	9.5 nb

* in 8—12 GeV mass range

Proper time resolution for background separation

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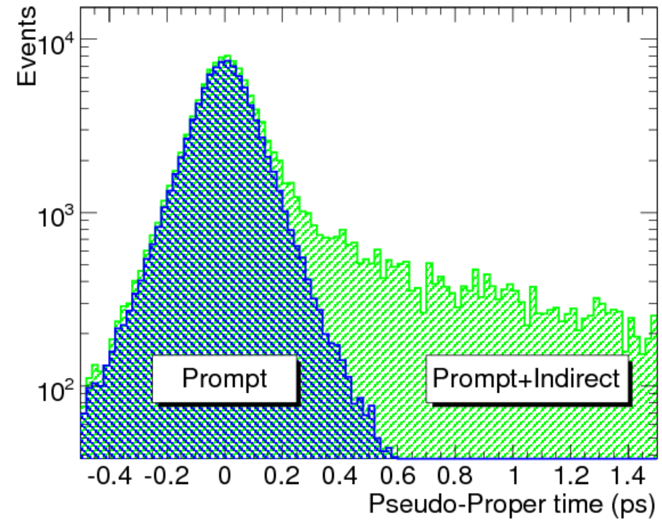
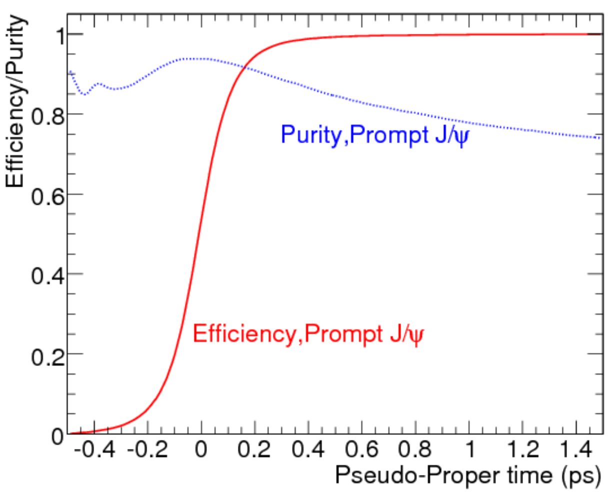
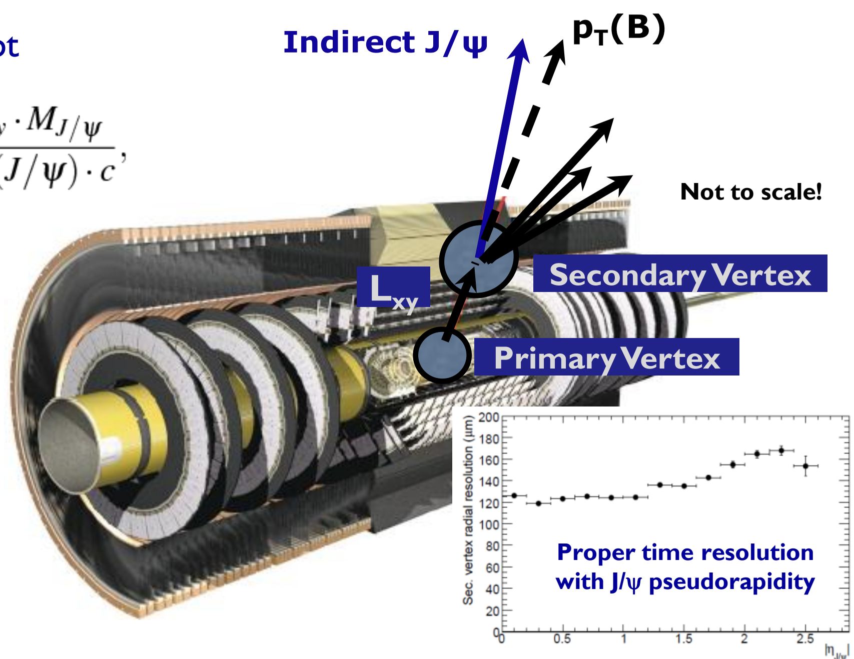
- J/ψ from B-decays form significant background to prompt J/ψ, in addition to muons from b-quark decays
- Measurement of prompt J/ψ to indirect cross-section relies on separation (and understanding of separation) of these two processes
- Proper time of zero characteristic of prompt J/ψ, while those from B-decays have positive proper-time
  - Cut on pseudo-proper time to separate indirect/prompt



$$\text{Pseudo-proper time} = \frac{L_{xy} \cdot M_{J/\psi}}{p_T(J/\psi) \cdot c},$$



Prompt J/ψ purity/efficiency



Quarkonium invariant mass distributions
After triggering and reconstruction [di-muon case]

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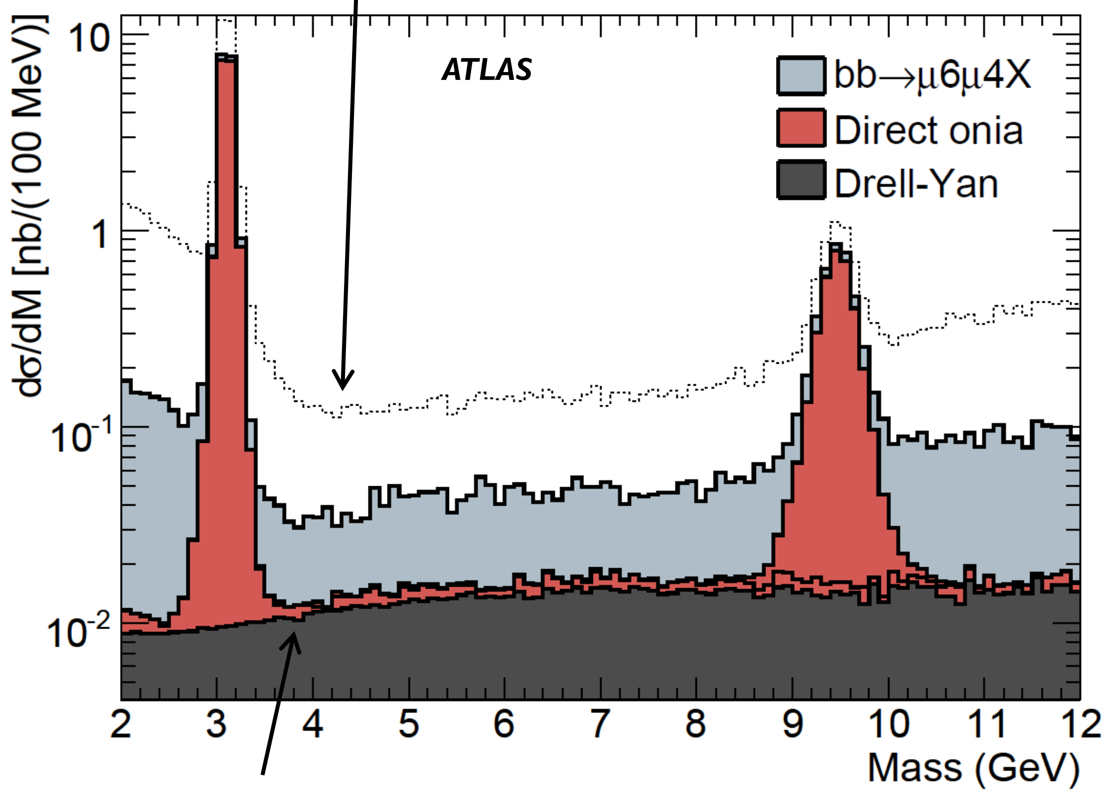
Mass Resolutions after trigger (μ4μ4)

	J/ψ	ϒ(1-3S)
Resolution (MeV)	53	160±5

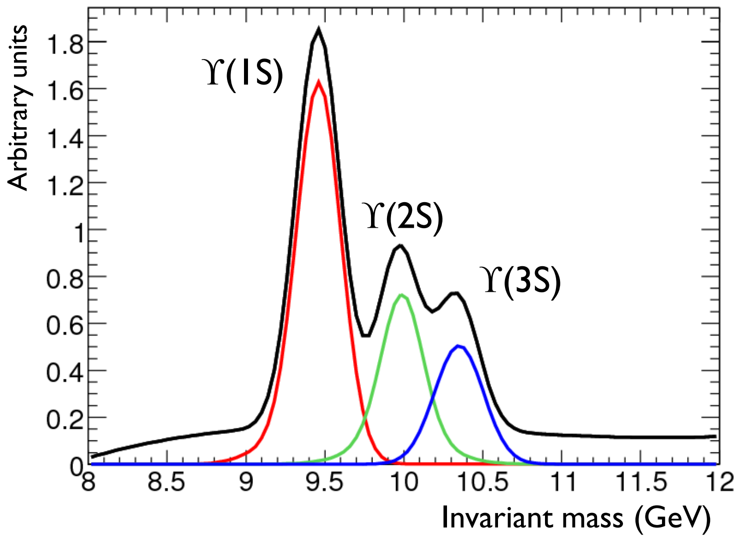
Height of background + signal before transverse decay length and vertexing cuts

Statistics equivalent to approx. ~8 pb^{-1} integrated luminosity



No simulation of ψ(2S) included here!

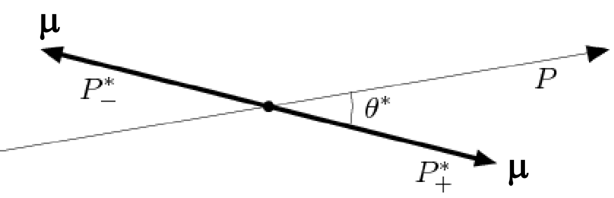
Based on predictions for Upsilon mass resolution scaling, all three peaks should be distinguishable



Quarkonium spin-alignment/polarisation

- Theoretical calculations such as NRQCD and higher order (NLO+NNLO) singlet contributions offer clear predictions for polarisation of produced quarkonium states

- Different models/calculations offer differing predictions of polarisation (amongst other things) which ATLAS can measure as a way of determining the underlying production mechanism



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 **α=0** corresponds to **unpolarised** mesons, whilst **α=+1** and **α=-1** correspond to 100% **transverse** and **longitudinal** polarised mesons respectively

- Polarisation of quarkonium may vary with p_T, and different polarisation states have significant effects on overall acceptance (**and thus cross-section**)
  - Correlations between measured efficiencies and polarisation state an important consideration!

The problem of limited cos θ* acceptance

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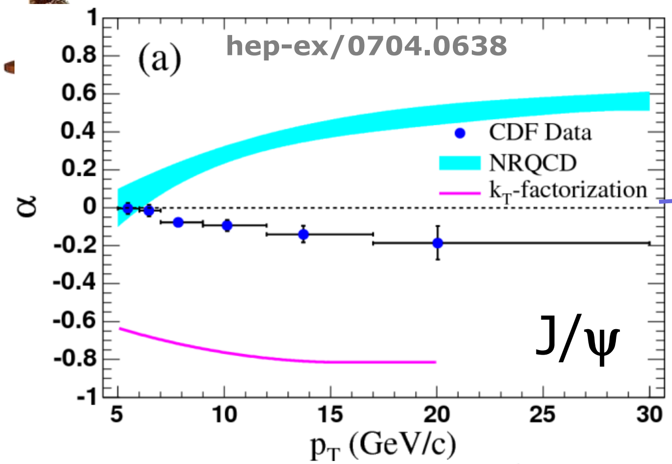
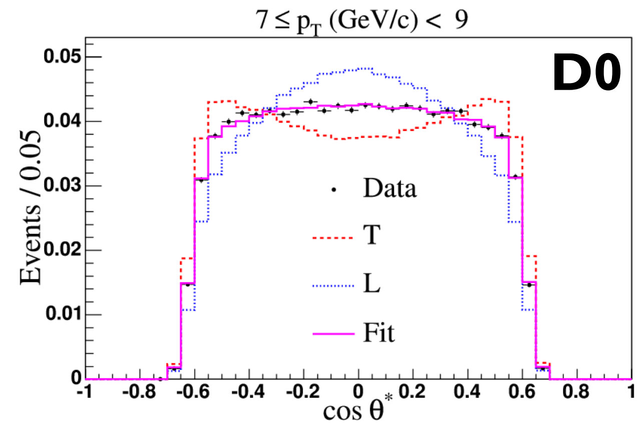
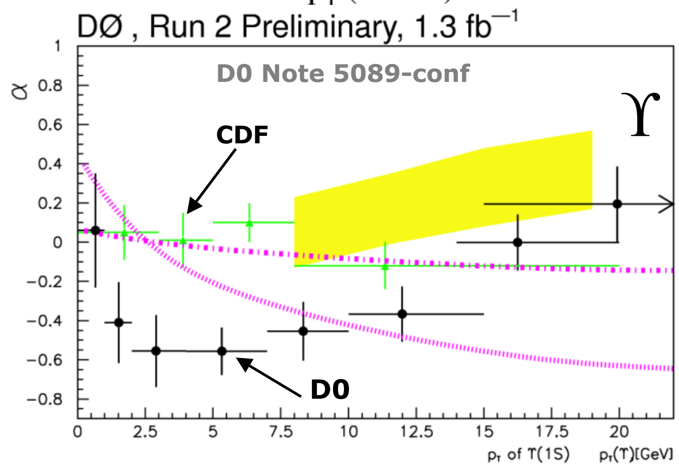


D0 Run II measurements disagree with theoretical models *and* CDF Run I results!





Restricted cos θ* acceptance causes problems for discrimination of different polarisation regimes

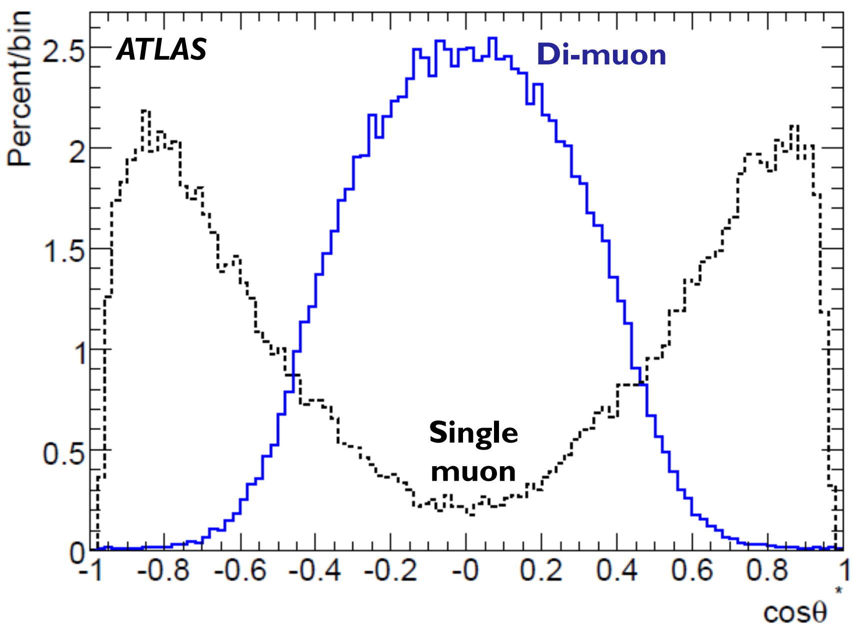
A difference in polarisation looks very much like a modification to trigger efficiency in this variable!

Without full range of cos θ*, hard to disentangle these effects: could incorrectly assign a polarisation effect to a trigger effect [see the problem for cross-section calculation?]

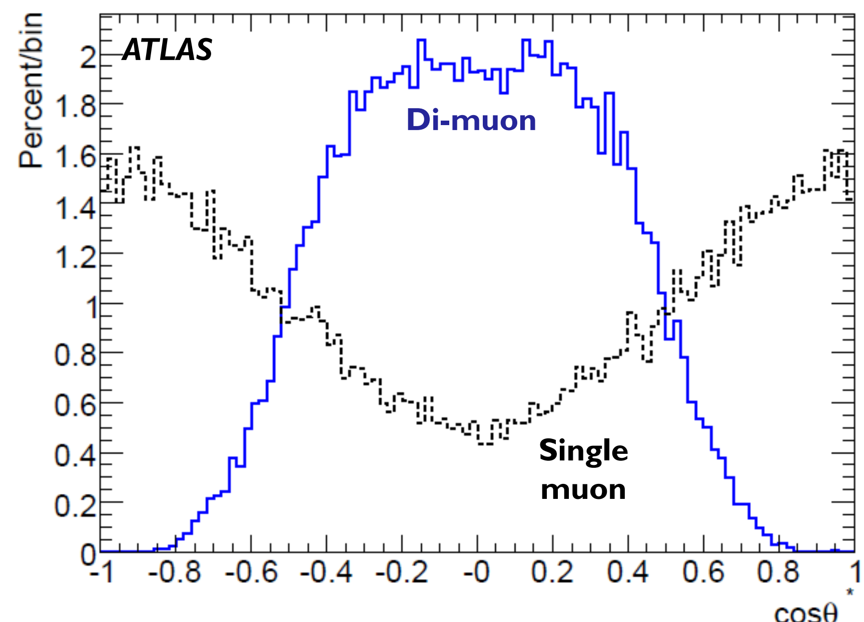
- With di-muon trigger cuts, we see similar acceptance issues at ATLAS
- Would like to have a complementary, independent, high cos θ* sample of quarkonia to give better discrimination and provide cross-check for efficiencies

Single muon μ10 trigger to the rescue

- We can achieve exactly what we want by using a single μ10 trigger:
  - ✓ Second muon can be reconstructed offline from track (>0.5 GeV p_T)
  - ✓ |cos θ*| ~ 1 corresponds to a configuration where one muon is fast, the other slow
  - ✓ Provides similar p_T range of onia to the di-muon configuration and similar rates!
- Go from a distribution in μ6μ4 **(blue curve)** to that in μ10 **(black curve)**



J/ψ acceptance



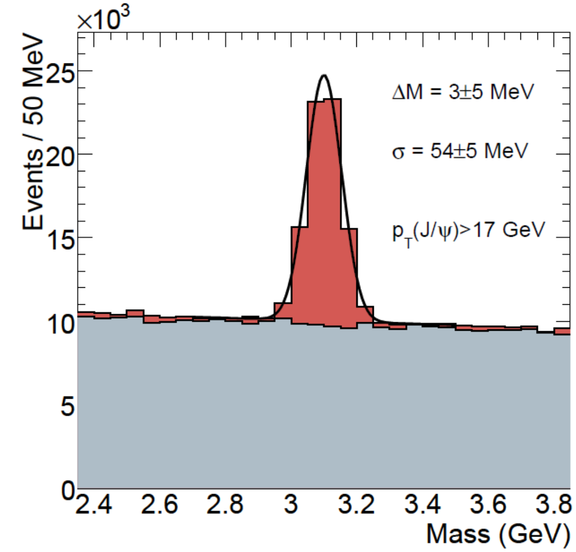
Υ acceptance

Quarkonium invariant mass distributions

After triggering and reconstruction [single-muon case]

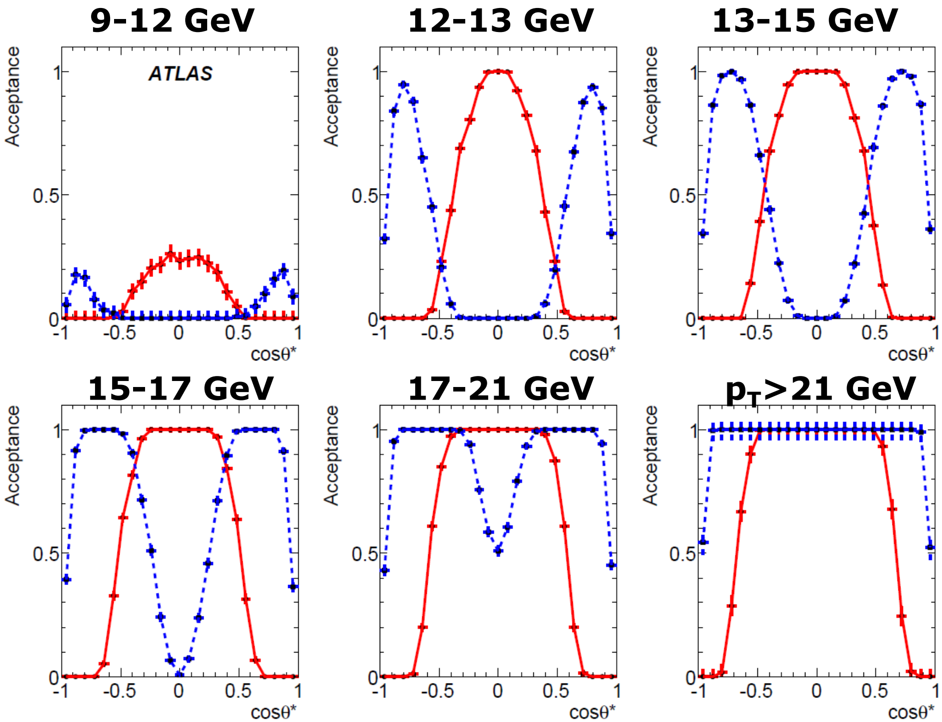
- Single muon selection similar to di-muon analysis but this time…
  - Pair **one** identified muon with p_T>10 GeV with **all** Inner Detector tracks in the event fulfilling certain selection criteria (down to p_T of 0.5 GeV)
- Kinematics are such that we expect similar numbers of J/ψ (and ϒ) in both the di-muon and single-muon channels after efficiencies and cuts
- Invariant mass distributions in μ10 suffer from larger, but manageable, backgrounds **(and remember this is with just 10 pb^{-1} data equivalent)**
  - Lower signal-to-background in Upsilon μ10 case means we will likely need higher integrated luminosities (~100-200 pb^{-1}) to make use of single-muon sample
  - Larger ϒ mass means range of accessible cos θ* in di-muon case is larger than in J/ψ case anyway, so problem is somewhat reduced

J/ψ signal in μ+track selection



- **So, why do we do this? We still don't recover the true distribution… but…**

Spin-alignment measurement at ATLAS



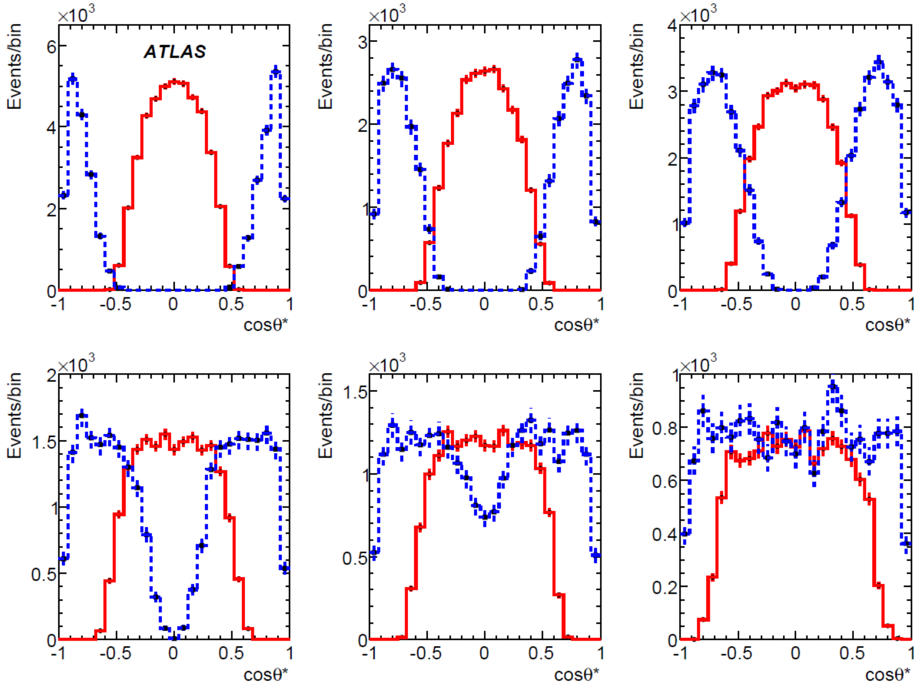
ACCEPTANCE AND EFFICIENCY
(from geometric considerations + data-driven efficiency studies)

di-muon sample in red

single muon 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

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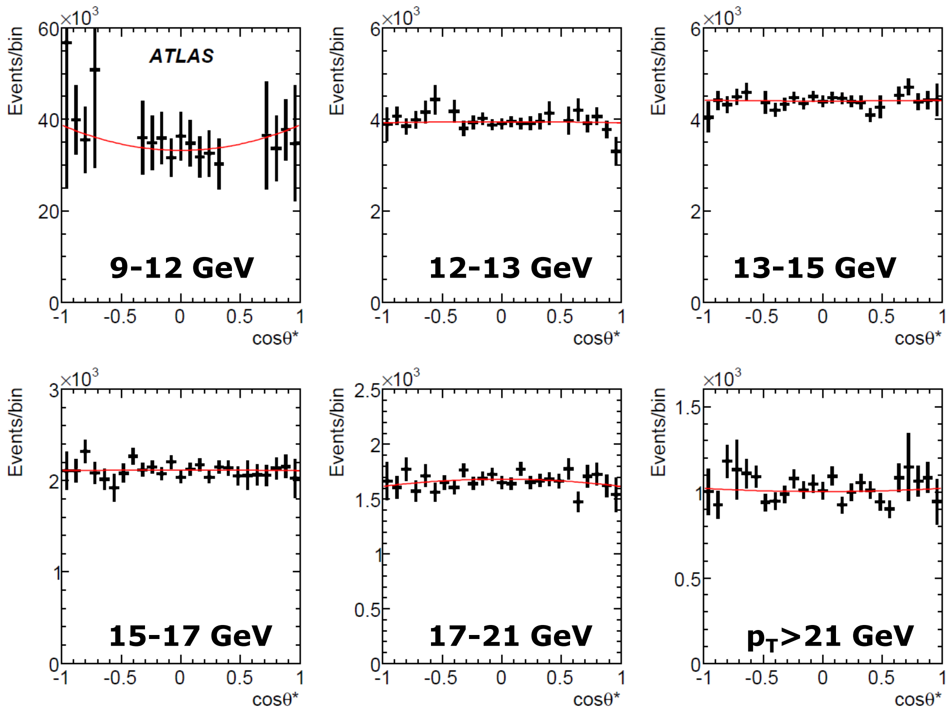
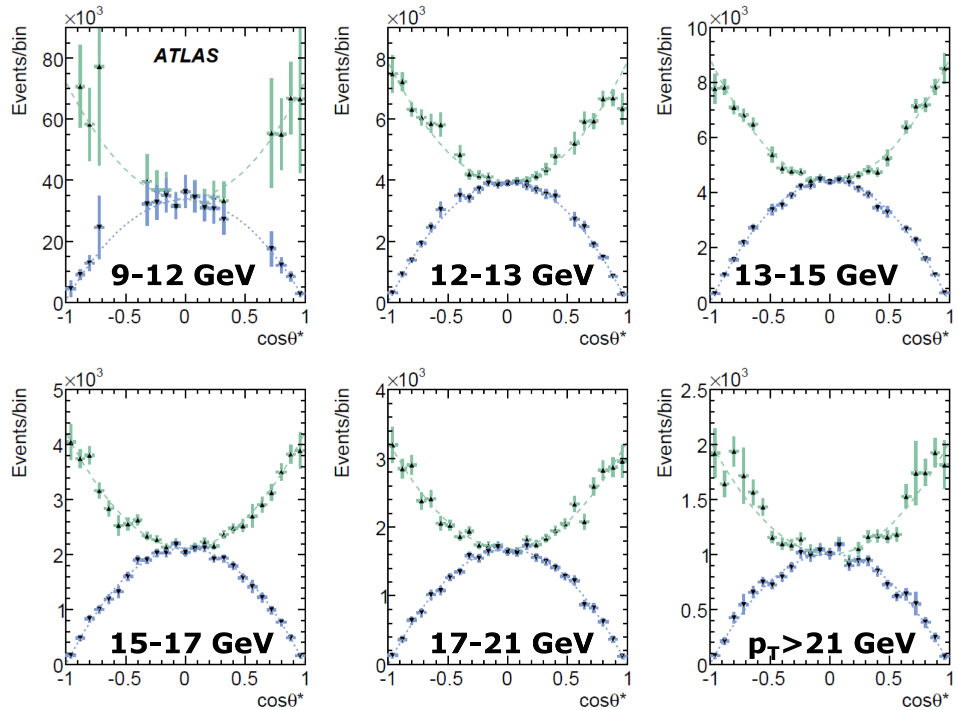
- Measured distributions from di-muon and single muon are corrected for their individual acceptances and efficiencies

- The existence of overlapping regions at higher p_T's allows for a cross-check of cross-normalisation of the two samples
- Use pre-defined acceptance mask to combine the two (now non-overlapping) datasets and make a fit to the **corrected distributions (shown below)**



UNPOLARISED SAMPLE



LONGITUDINAL AND TRANSVERSE SAMPLE

Measurement sensitivity at 10 pb^{-1}

- With 10 pb^{-1} of data (taking into account quarkonium polarisation state and resultant systematics in the corrections) can expect cross-section measurement precision in bins of p_T of the order of 1% (dependent on the polarisation)

- By taking data with μ10 sample and combining them in the way outlined:
  - Increase our acceptance in the important high cos θ* area
  - Increase our quarkonia yield in partially overlapping kinematic region
  - Significantly reduce systematic errors on polarisation measurement

Sample	p_T, GeV	9 – 12	12 – 13	13 – 15	15 – 17	17 – 21	> 21
J/ψ, $\alpha_{gen} = 0$	α	0.156 ±0.166	−0.006 ±0.032	0.004 ±0.029	−0.003 ±0.037	−0.039 ±0.038	0.019 ±0.057
	σ, nb	87.45 ±4.35	9.85 ±0.09	11.02 ±0.09	5.29 ±0.05	4.15 ±0.04	2.52 ±0.04
J/ψ, $\alpha_{gen} = +1$	α	1.268 ±0.290	0.998 ±0.049	1.008 ±0.044	0.9964 ±0.054	0.9320 ±0.056	1.0217 ±0.088
	σ, nb	117.96 ±6.51	13.14 ±0.12	14.71 ±0.12	7.06 ±0.07	5.52 ±0.05	3.36 ±0.05
J/ψ, $\alpha_{gen} = -1$	α	−0.978 ±0.027	−1.003 ±0.010	−1.000 ±0.010	−1.001 ±0.013	−1.007 ±0.014	−0.996 ±0.018
	σ, nb	56.74 ±2.58	6.58 ±0.06	7.34 ±0.06	3.53 ±0.04	2.78 ±0.03	1.68 ±0.02
Υ, $\alpha_{gen} = 0$	α	−0.42 ±0.17	−0.38 ±0.22	−0.20 ±0.20	0.08 ±0.22	−0.15 ±0.18	0.47 ±0.22
	σ, nb	2.523 ±0.127	0.444 ±0.027	0.584 ±0.029	0.330 ±0.016	0.329 ±0.015	0.284 ±0.012

J/ψ polarisation

J/ψ cross-section

Results at extrema of polarisation states

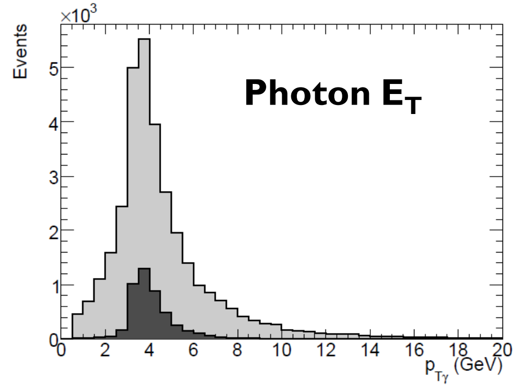
ϒ polarisation

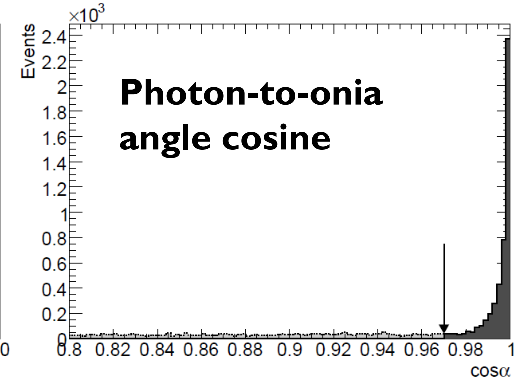
ϒ cross-section

$\chi_c \to J/\psi\ \gamma$ reconstruction with calorimetry

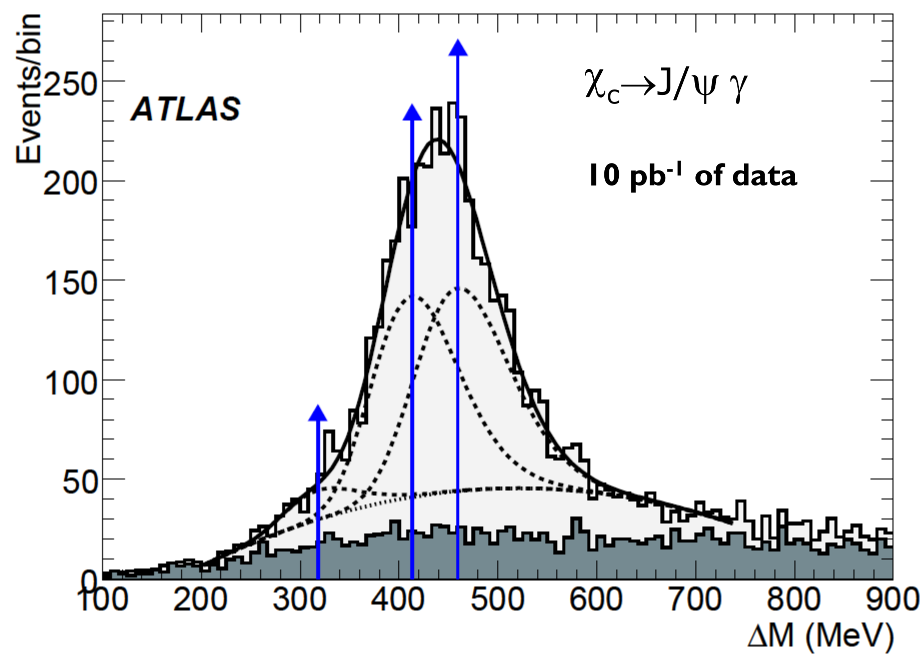
- For J/ψ, ~30% of total prompt cross-section comes from $\chi_c \to J/\psi\ \gamma$ feed-down, and we would like to study this contribution

  1. Have a J/ψ candidate
  2. Look in narrow cone ($\cos\alpha > 0.98$) around quarkonium momentum direction for photon (reduces combinatorics)
  3. $\mu\mu\gamma - \mu\mu$ invariant mass difference shows peaks where χ_{c0}, χ_{c1} or χ_{c2} was reconstructed





- Fixing the mass differences 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



- Only ~4% of χ_c decays into $J/\psi\ \gamma$ have the right kinematics for photons to be reliably reconstructed and identified in ECAL
- Studies on-going to include photon conversions using ID tracks, which should have better resolution, at the price of much reduced efficiency.

Summary & conclusions

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- Quarkonium spin-alignment measurements at ATLAS will have the **capability to distinguish various production models** of quarkonium
  - ATLAS polarisation measurement methods can lead to **significantly reduced systematics**
  - Important to be able to access the high |cos θ*| region to determine if we to measure cross-section correctly (especially as acceptance changes with p_T)!
  - Expect **competitive polarisation measurement** to Tevatron publications (at 1 fb^{-1}), with reduced systematics, with around **10—100 pb^{-1}** data
  - Complementary to other ongoing production mechanism studies into associated hadroproduction
  - 100 pb^{-1} will allow for precise measurement of quarkonium polarisation to high (~50 GeV) transverse momenta (including Υ)

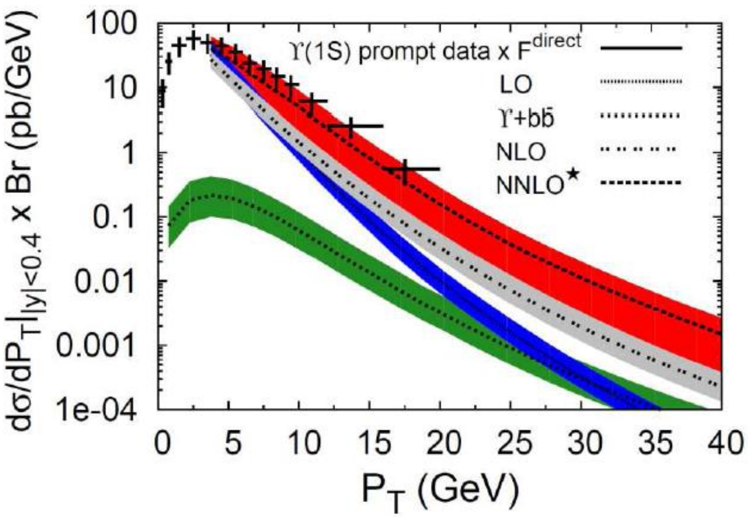
- With 10 pb^{-1} predict to be able to **measure J/ψ cross-section** in bins of p_T to an **accuracy of around 1%** (excluding detector systematics e.g. luminosity uncertainty)
  - Measurement of **ratio of prompt/indirect cross-section** will **eliminate a lot of uncertainties** in measurements performed with very early data
  - At these integrated luminosities will be able to begin to measure χ_c (>10 pb^{-1}) and χ_b (>100 pb^{-1}) cross-section contributions to J/ψ and Υ production

- Meaningful quarkonium studies can be performed with early data and are expected to have the reach to make authoritative statements about the underlying production mechanism and provide cross-sections in this new energy regime

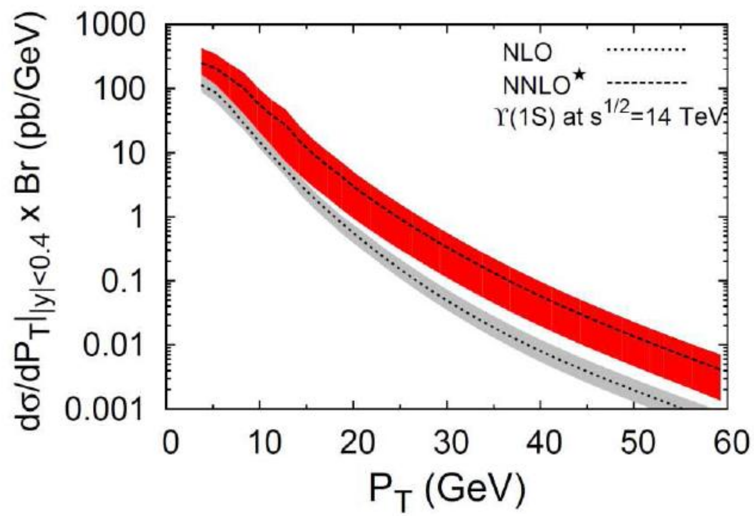

Thank you!

Backup slides

Higher state (NLO & NNLO) singlet contributions

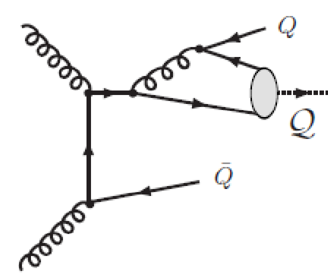


$p\bar{p} \rightarrow \Upsilon(1S)X$ at CDF



$pp \rightarrow \Upsilon(1S)X$ prediction for LHC

- New calculations show that higher order terms are important: **p_T scaling**
- Higher order corrections give rise to predictions of significant **associated hadroproduction at high p_T**



- This, along with spin-alignment analysis will provide **sensitive tests of production at ATLAS**

Implementation of NRQCD in ATLAS

- ATLAS studies currently based on Colour Octet Mechanism as implemented in Pythia and fully simulated through ATLAS reconstruction in GEANT 4
- NRQCD matrix elements describe non-perturbative quarkonium evolution
  - Matrix elements tuned within ATLAS to values derived from Tevatron data and tested at Tevatron settings in the ATLAS framework.
  - Values for J/ψ and Upsilon are now Pythia defaults as standard

PYTHIA parameter	J/ψ	Matrix element
PARP(141)	1.16	$\langle \mathcal{O}(J/\psi)[^3S_1^{(1)}]\rangle$
PARP(142)	0.0119	$\langle \mathcal{O}(J/\psi)[^3S_1^{(8)}]\rangle$
PARP(143)	0.01	$\langle \mathcal{O}(J/\psi)[^1S_0^{(8)}]\rangle$
PARP(144)	0.01	$\langle \mathcal{O}(J/\psi)[^3P_0^{(8)}]\rangle/m_c^2$
PARP(145)	0.05	$\langle \mathcal{O}(\chi_{c0})[^3P_0^{(1)}]\rangle/m_c^2$

PYTHIA parameter	NRQCD matrix element	ψ(2S)
PARP(141)	$\langle \mathcal{O}(\psi(XS))[^3S_1^{(1)}]\rangle$	0.76
PARP(142)	$\langle \mathcal{O}(\psi(XS))[^3S_1^{(8)}]\rangle$	0.005
PARP(143)	$\langle \mathcal{O}(\psi(XS))[^1S_0^{(8)}]\rangle$	0.0088
PARP(144)	$\langle \mathcal{O}(\psi(XS))[^3P_0^{(8)}]\rangle/m_c^2$	0.0039
PARP(145)	$\langle \mathcal{O}(\chi_{c0}(XP))[^3P_1^{(1)}]\rangle/m_c^2$	0.0

$$d\sigma(pp \to H + X) = \sum_{n_i} d\hat{\sigma}\left(pp \to Q\bar{Q}[n_i] + x\right) \langle \mathcal{O}^H[n_i]\rangle$$

total cross-section | short distance heavy quark production | matrix element

- Note that despite Monte Carlo samples being for the NRQCD hypothesis, ATLAS quarkonium analysis predictions do not depend a priori on this production model!

PYTHIA parameter	NRQCD matrix element	Υ(1S)	Υ(2S)	Υ(3S)
PARP(146)	$\langle \mathcal{O}(\Upsilon(XS))[^3S_1^{(1)}]\rangle$	9.28	4.63	3.54
PARP(147)	$\langle \mathcal{O}(\Upsilon(XS))[^3S_1^{(8)}]\rangle$	0.150	0.055	0.039
PARP(148)	$\langle \mathcal{O}(\Upsilon(XS))[^1S_0^{(8)}]\rangle$	0.020	0.008	0.005
PARP(149)	$\langle \mathcal{O}(\Upsilon(XS))[^3P_0^{(8)}]\rangle/m_b^2$	0.020	0.008	0.005
PARP(150)	$\langle \mathcal{O}(\chi_{b0}(XP))[^3P_0^{(1)}]\rangle/m_b^2$	0.085	0.103	0.110

Quarkonia rates with muon p_T

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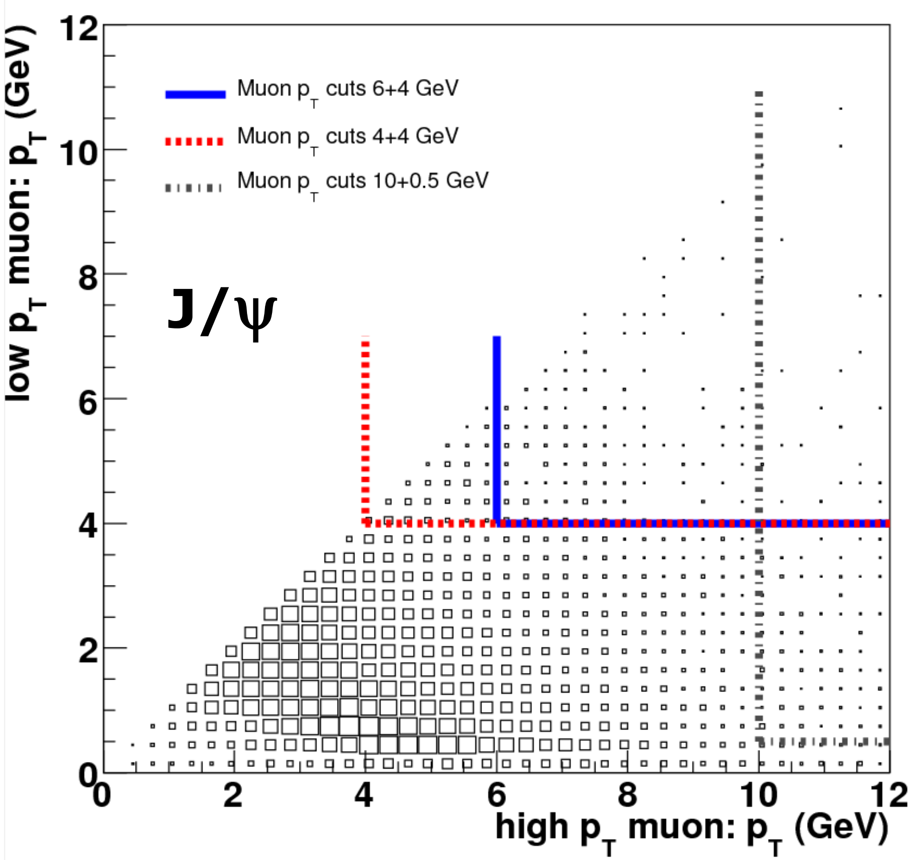
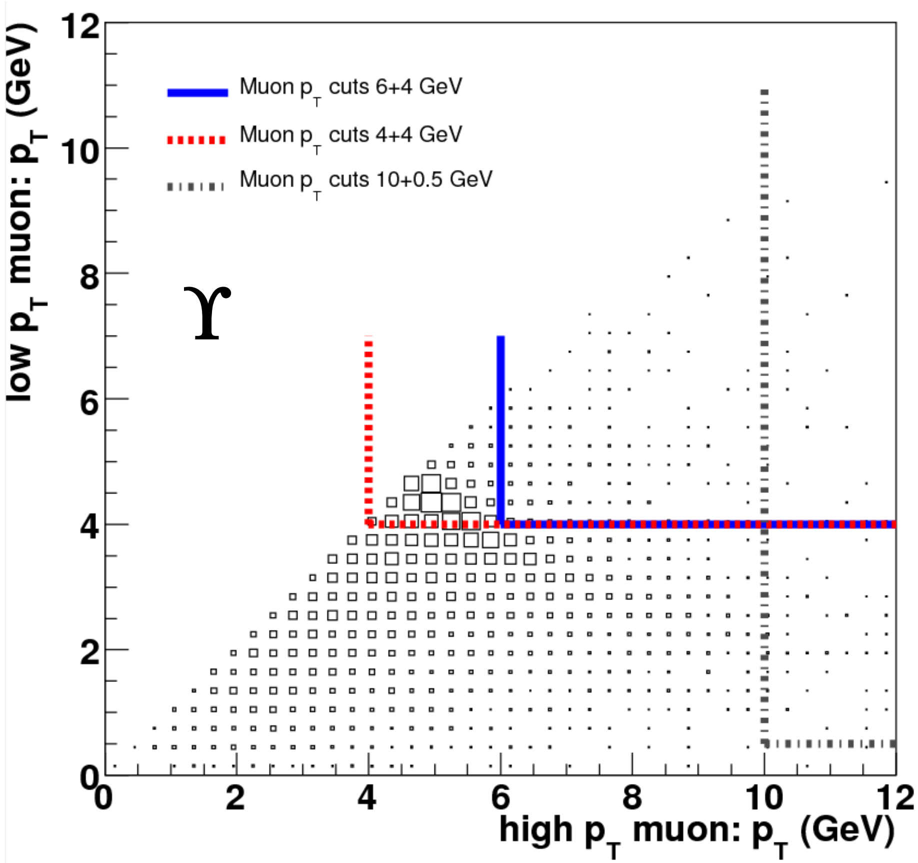




The ATLAS detector

Inner Detector:

3 pixel layers, 4 barrel silicon strips and transition radiation tracker with 2 Tesla solenoid: total 0.5—1.5 radiation lengths

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

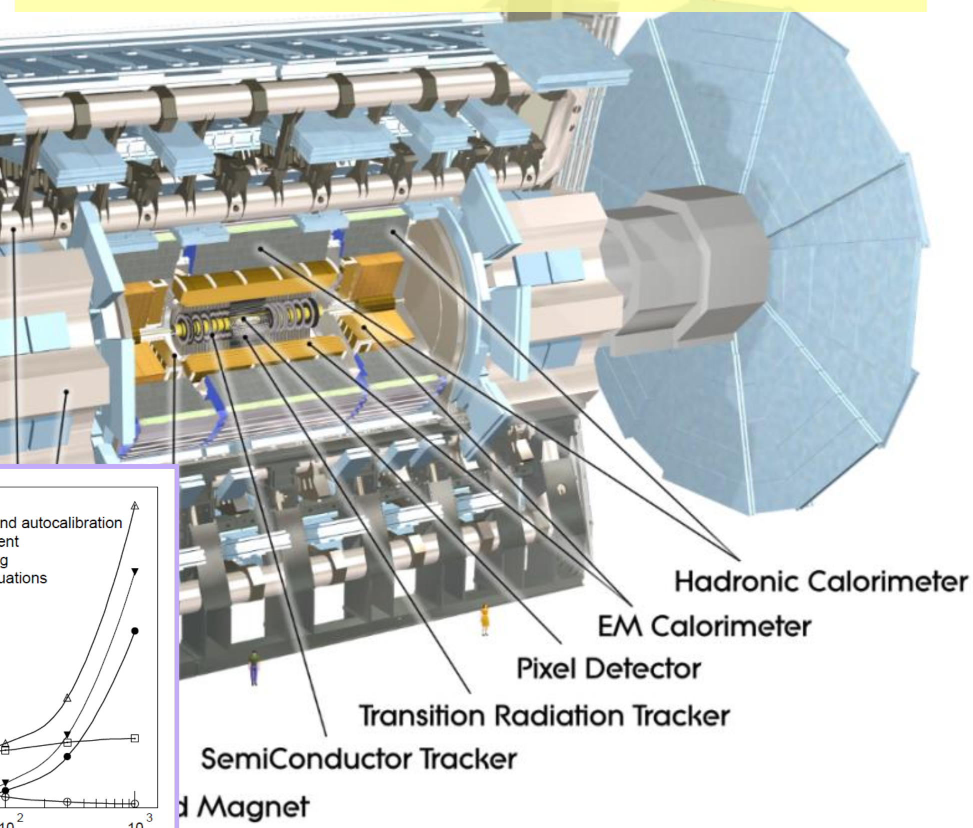
$$\sigma\left(\frac{1}{p_T}\right) \sim (0.34-0.41\,\text{TeV}^{-1}) + \left(1 \oplus \frac{(44-80\,\text{GeV}^{-1})}{p_T}\right)$$

Calorimetry:

$|\eta|<4.9$ hermetic coverage

EM calo: Liquid Argon $\sigma/E \sim 11.5\%/\sqrt{E} + 0.5\%$

Hadronic calo: Fe Cu-LAr $\sigma/E \sim 50\%/\sqrt{E} + 3\%$

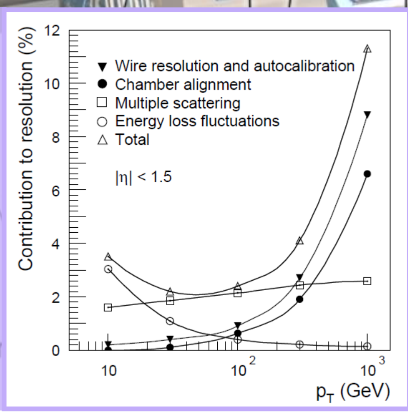


Muon spectrometry:

Coverage out to $|\eta|<2.7$

Drift chambers & trigger chambers in an air-core toroid of 0.5 Tesla

Good standalone performance: $\sigma/p_T \sim 10\%$ at 1 TeV



The quarkonium family and decays

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