Quarkonium production and polarization with early data at ATLAS

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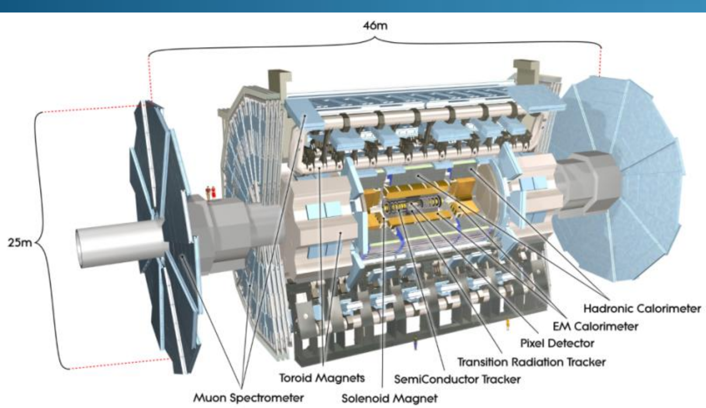
on behalf of the ATLAS Collaboration



BEACH 2008
The 8th International Conference on Hyperons, Charm, and Beauty Hadrons
22 – 28 June 2008 UNIVERSITY OF SOUTH CAROLINA

Motivation

- Large number of $J/\psi \to \mu^+ \mu^-$ and $\Upsilon \to \mu^+ \mu^-$ decays is expected at the LHC;
  - Alignment and calibration of trigger & tracking.
  - Onia production a testbed for QCD calculations.
  - Among the decay products of heavier states. Prompt quarkonia a main source of background to other processes some are quite rare. (see **E. De La Cruz Burelo**)

- Production was described via the Color Singlet Model.
- Inconsistency with the Tevatron Xsection =>Color Octet Model suggested.
- However the COM fails to predict other effects (quarkonia polarization dependence on its P_T
- Alternative suggestions κ_T factorization

- ATLAS is starting soon.
- Prompt quarkonia a key player in the early data taking.
- At low luminosity can lower P_T threshold to collect large sample.
- ATLAS reach for P_T >TEVATRON => enhance its analysis power.
- Crucial for understanding the detector.

Expected data at early LHC

ATLAS expects to achieve current Tevatron onia yield with 60—85pb^{-1} [= a couple of months with LHC low luminosity] (based on recent publications from CDF/D0 [Spring/Summer 2007]) :

	Tevatron	ATLAS
1×10^6 J/ψ	**CDF 1.1 fb^{-1}**	**60 pb^{-1}**
4.2×10^5 Υ	**D0 1.3 fb^{-1}**	**85 pb^{-1}**

~1000 J/ψ's per hour

- 60 pb^{-1} should allow for competitive measurement of quarkonium polarization, with enough statistics in the crucial high p_T region
- High p_T data important, Tevatron suffers from statistics in this region
- ATLAS has capability to fully test validity of theoretical models for onia 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.

Previous measurements

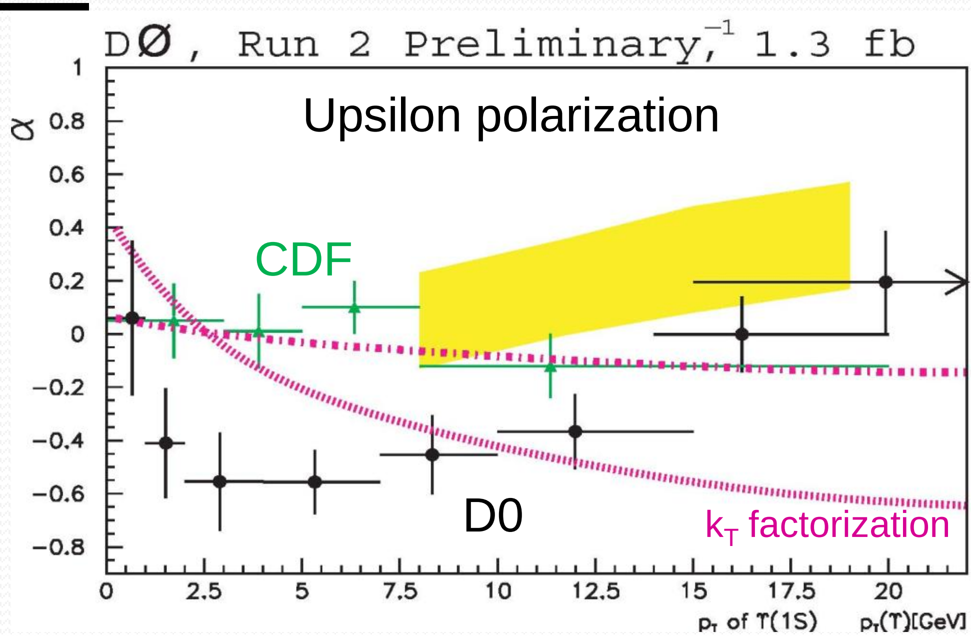
- Measurements done at CDF and DO are not consistent with the predictions of the J/ψ and Upsilon polarization P_T dependence and with each other. There is a large discrepancy between some theoretical prediction and the CDF/D0 measurements .
- *Recent measurements*

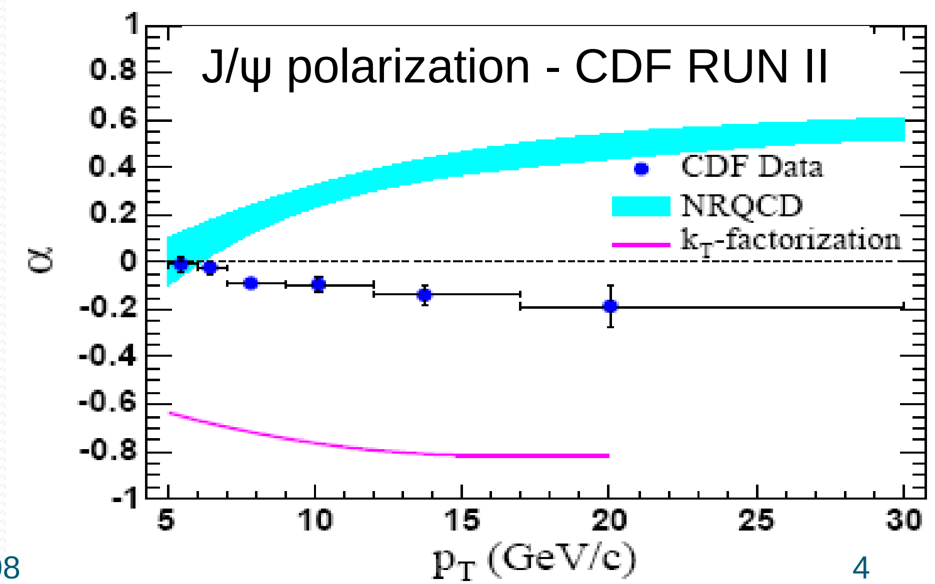
DO July 19,2007 (top plot)

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B50/

CDF April 4, 2007 (bottom plot)

http://arxiv.org/abs/0704.0638v1/





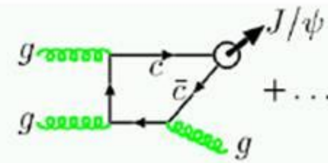
K_T-factorization approach
The crossection of the quark production is given by the convolution of the integrated gluon distribution of nuclei with quark production amplitude .

NRQCD

- NRQCD makes systematic nonrelativistic corrections to effective field theory using an expansion series in *v*, the velocity of the heavy quark in the quarkonium rest frame.
- At high P_T (P_T >>mc) the dominant process in NRQCD is the fragmentation of a single gluon to a pair in a $[8,{}^3S_1]$ state (c). In comparison to the color singlet fragmentation process in (b) this occurs at a higher order of v_c (v_c^7 versus v_c^3) but at a lower order of α_s (α_s^3 versus α_s^5).
- Taking into account these facts, it is indeed plausible that the color octet process could explain the observed direct cross sections.

leading-order colour-singlet: $g + g \to c\bar{c}[{}^3S_1^{(1)}] + g$

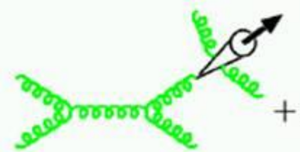
Two gluon fusion



$+ \ldots \quad \sim \alpha_s^3 \frac{(2m_c)^4}{p_t^8}$

a

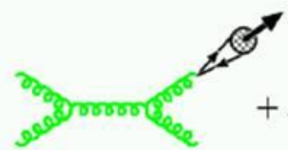
colour-singlet fragmentation: $g + g \to [c\bar{c}[{}^3S_1^{(1)}] + gg] + g$



$+ \ldots \quad \sim \alpha_s^5 \frac{1}{p_t^4}$

b

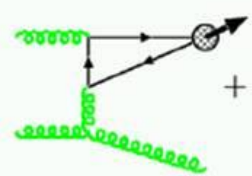
colour-octet fragmentation: $g + g \to c\bar{c}[{}^3S_1^{(8)}] + g$



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

c

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



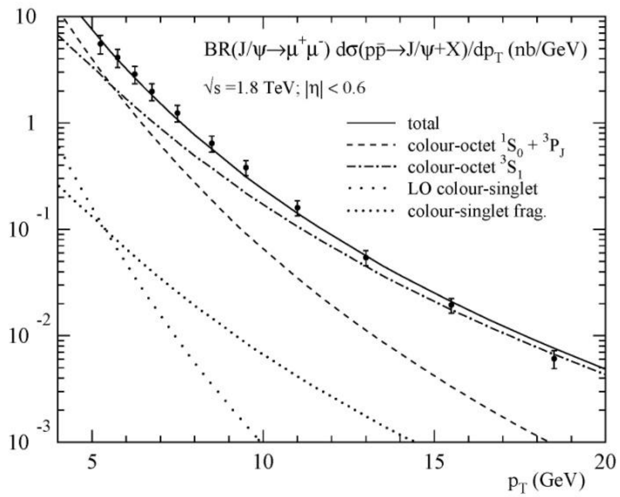
$+ \ldots \quad \sim \alpha_s^3 \frac{(2m_c)^2}{p_t^6} v^4$

d

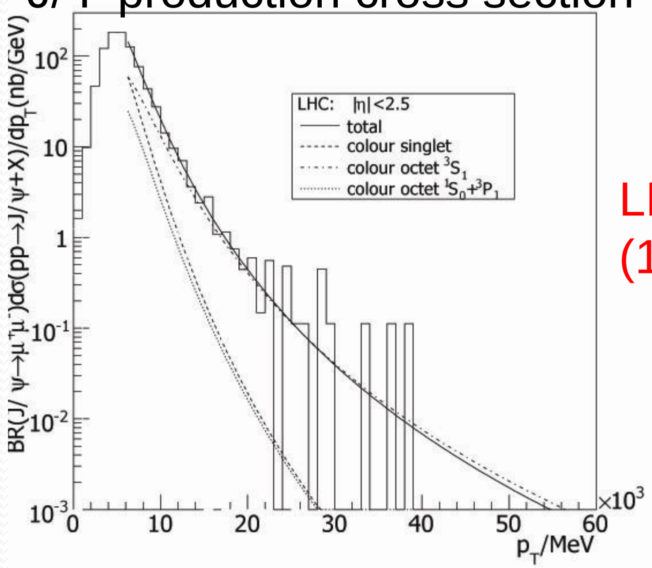
fragmentation process – transverse polarization

Quarkonium production cross-section

Tevatron (1.8 TeV)



J/Ψ production cross section

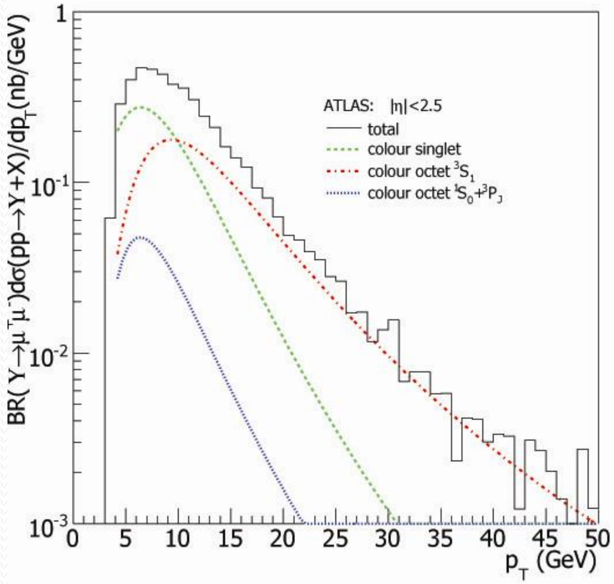


LHC MC (14 TeV)

MC Onia production p_T and the differential cross-section contributions from color singlet, color octet and singlet/octet of χ .

The dominant contribution at high p_T range is the $^3S_1$ color octet fragmentation (dashed dotted line).

Y production cross section



The Trigger system

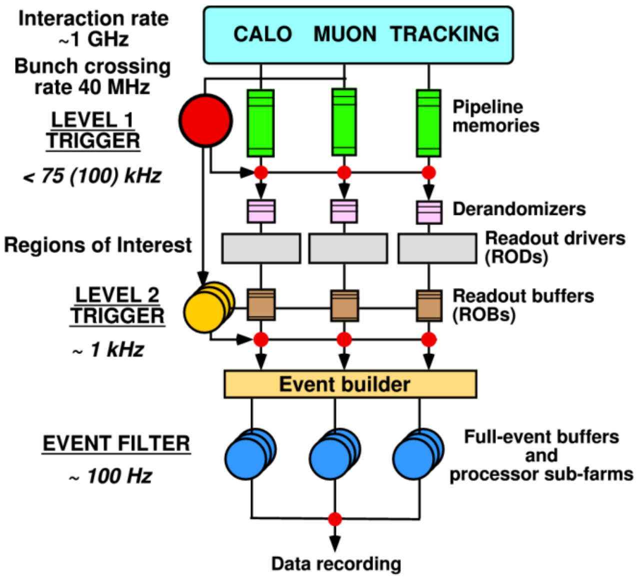
Reduces the high data rate by selecting interesting events through 3 steps:

hardware

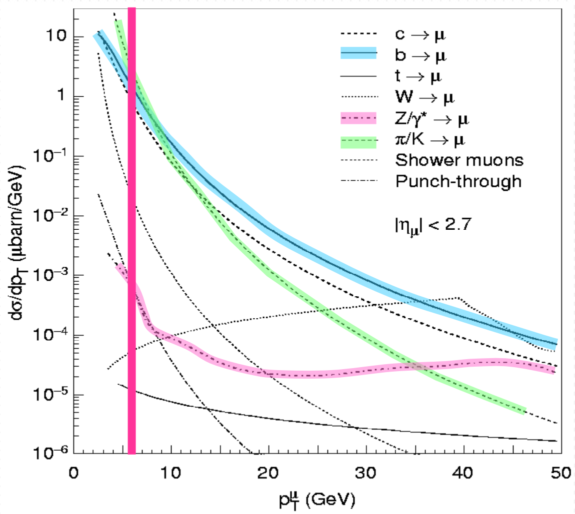
- Level - 1 decision made
  - Muon Trigger Chambers and Calorimeter data to find e, γ, τ, jet, μ candidates above thresholds
  - Identifies Regions of Interest
  - Processing time 2.5μs

software

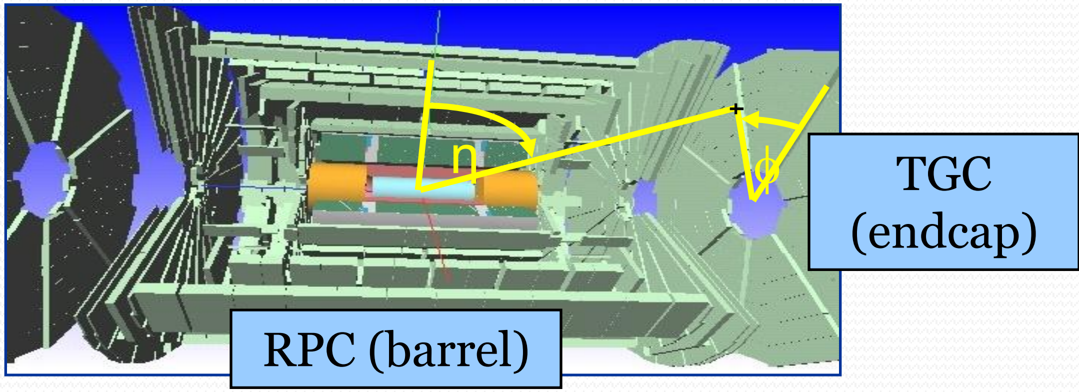
- Level – 2 uses Region of Interest data
  - Combines information from all detectors
  - Performs fast rejection.
  - Processing time 10ms
  - Output rate ~2kHz
- Event Filter
  - Can be "seeded" by Level - 2 result
  - Potential full event access
  - Processing time 1s
  - Output rate ~100Hz (event size of 1.3Mbyte)

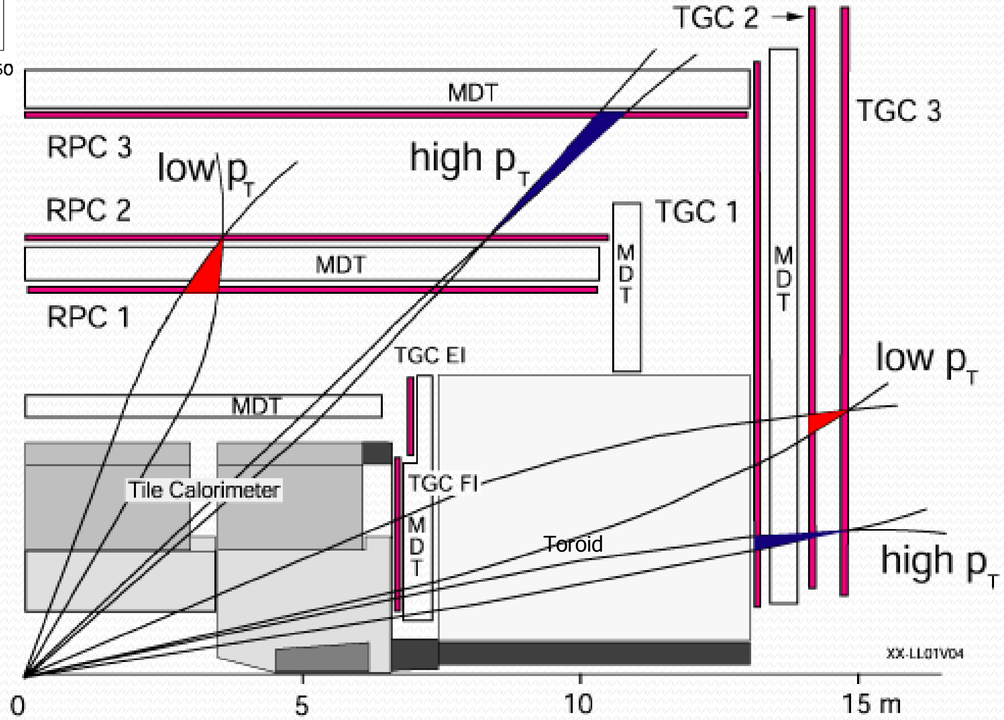


Level-1: muon trigger



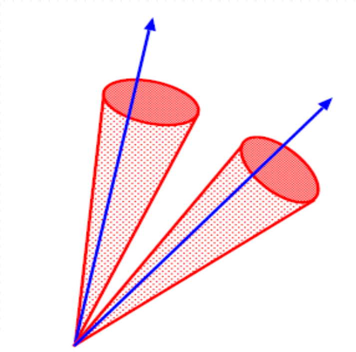
p_T of muons from different processes





Muon chambers layout and curved muon tracks

B-physics trigger strategy: level-2

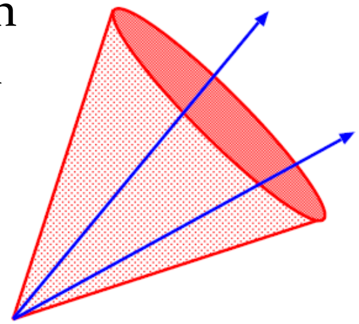


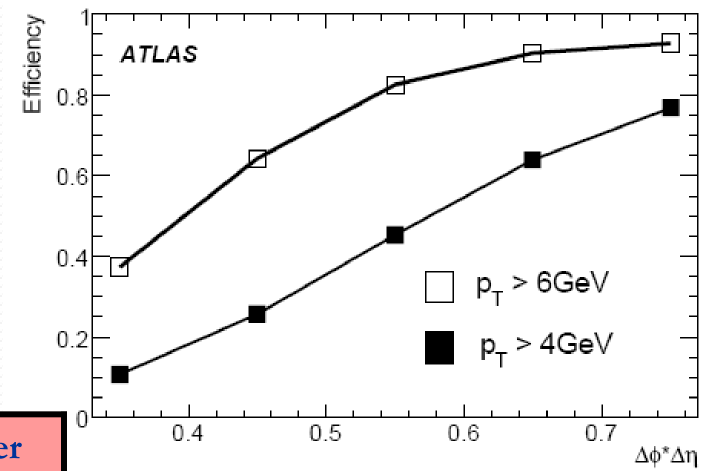
Two Level-2 di-muon trigger algorithms:

- Topological trigger

Start with a di - μ trigger at level-1 + confirmation at level-2

  - Standalone μ reconstruction
  - Combined μ reconstruction





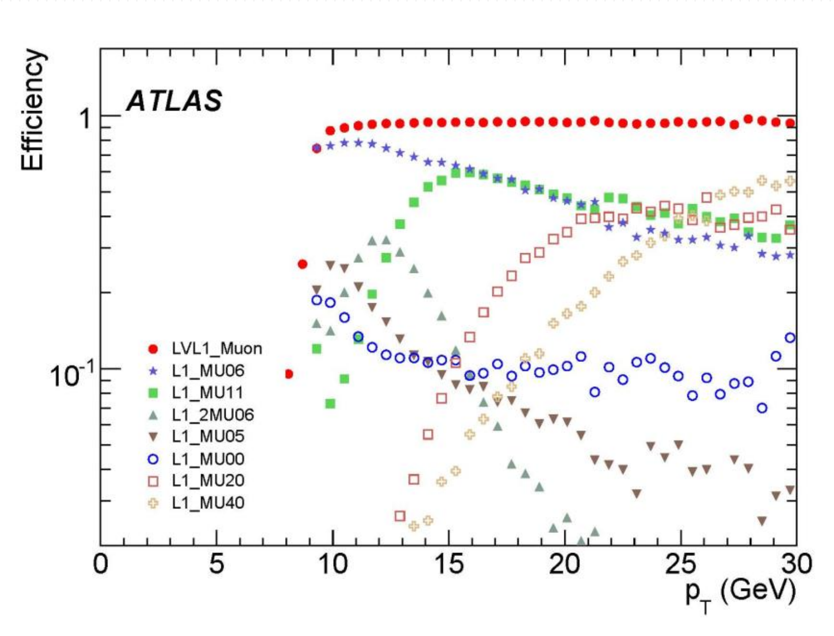
- TrigDiMuon

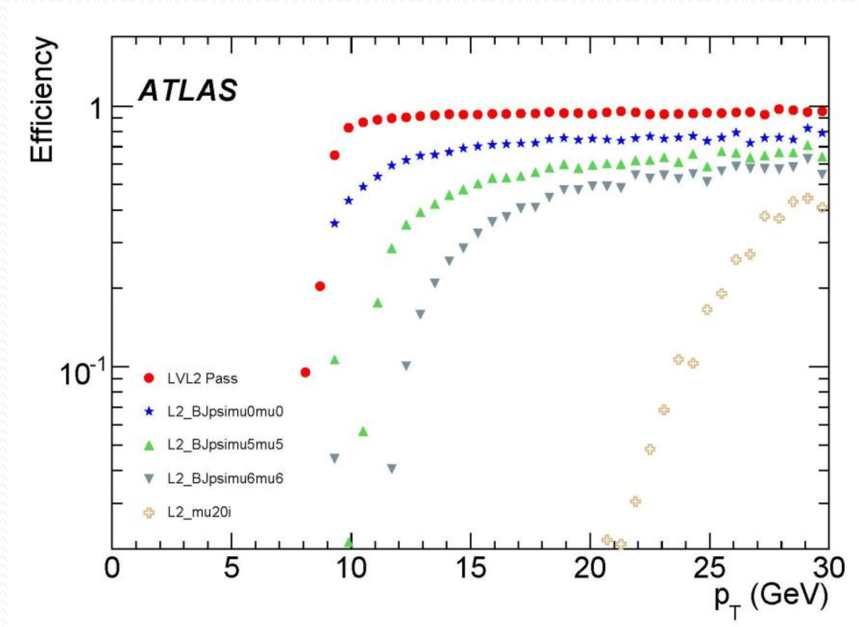
Start with a single μ trigger at level-1/level-2 and search for two μ in a wider Region of Interest

Threshold (GeV)	Chain starting from	TrigDiMuon		Topological trigger	
		J/ψ rate (Hz)	Total rate (Hz)	**J/ψ rate (Hz)**	Total rate (Hz)
4 (10^{31})	Level – 1	**1.2**	3.5	**0.8**	24
	Level - 2	**1.15**	2.7	**0.5**	0.6
6 (10^{33})	Level - 1	**43.5**	180.5	**32.5**	357.5
	Level - 2	**35**	126	**8.7**	9.3

Trigger efficiency

- ATLAS has excellent efficiency for identifying muons from quarkonium.



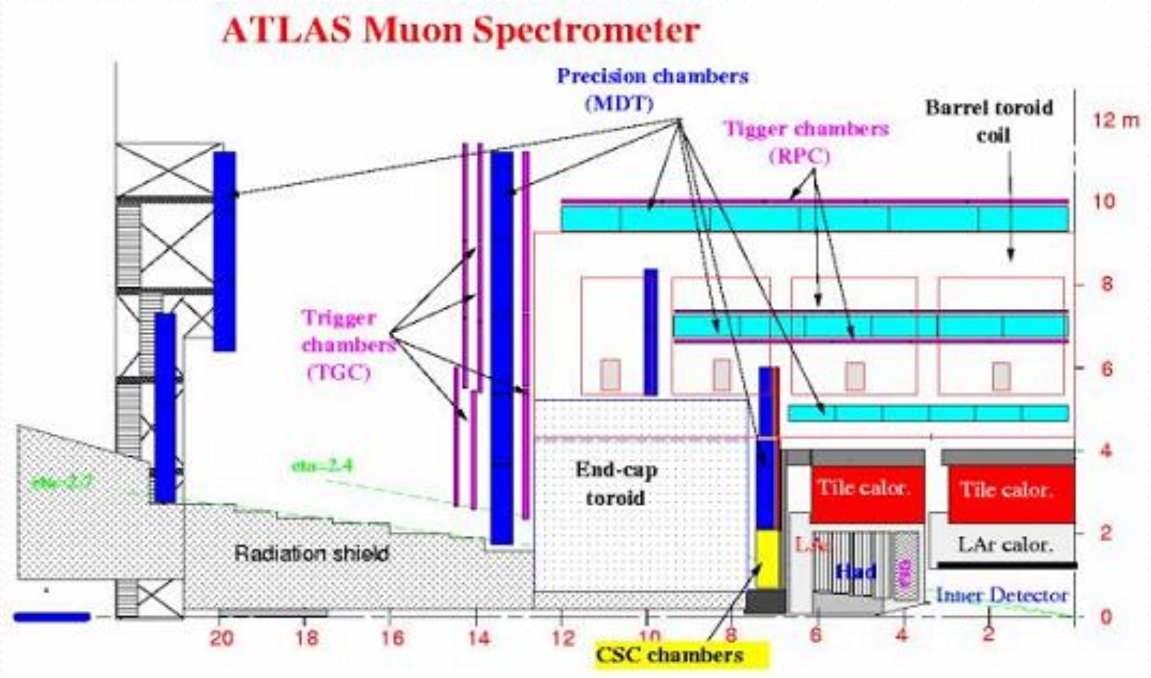


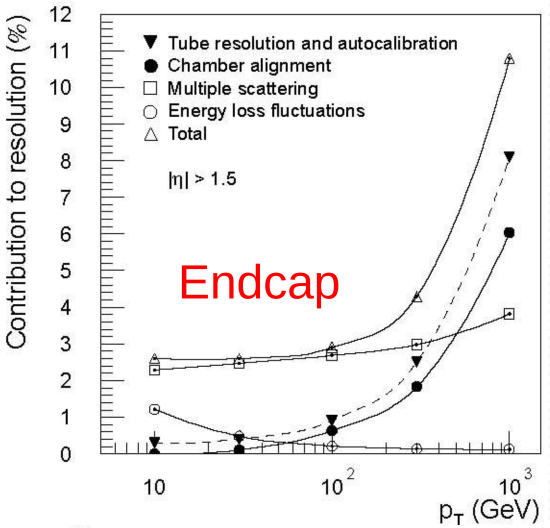
Left plot shows example of some Level 1 (LVL1) muon trigger efficiencies and Right plot shows it of Level 2 (LVL2)

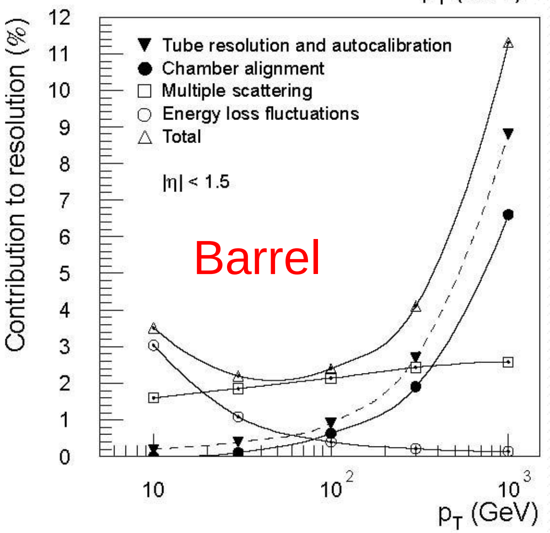
DiMuon trigger efficiency better than 96% on full simulation!

Tracking in Muon Spectrometer

- The momentum of the muons is determined from the curvatures of their tracks in a toroidal magnetic field.
- Muon tracks are identified and measured after their passage through ~2m of material.

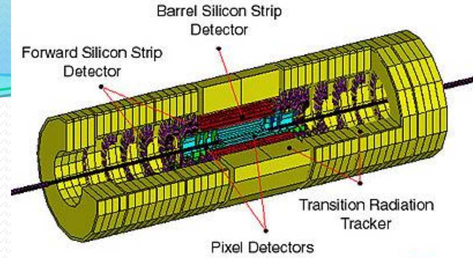






- Track measurement with σ=60μm intrinsic resolution in three precision measurement stations (MDT).

Tracking in the Inner Detector



Inner Tracker

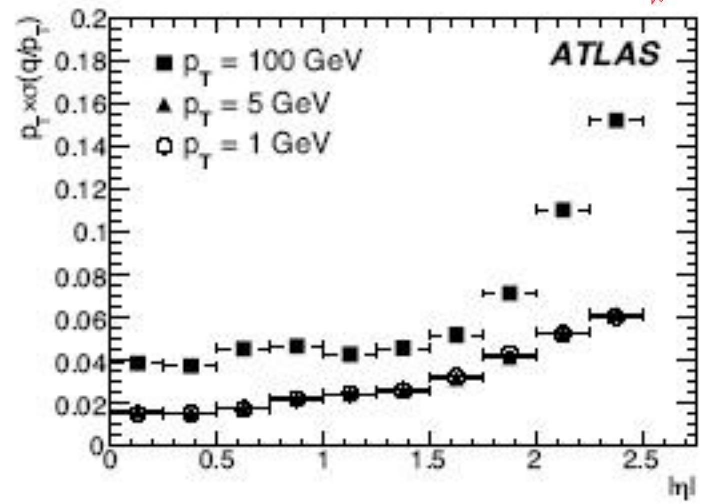
Pixel Detectors -The silicon sensors closest to the collision point. (Resolution: σ_{φ}=12 μm, σ_z=66 μm)

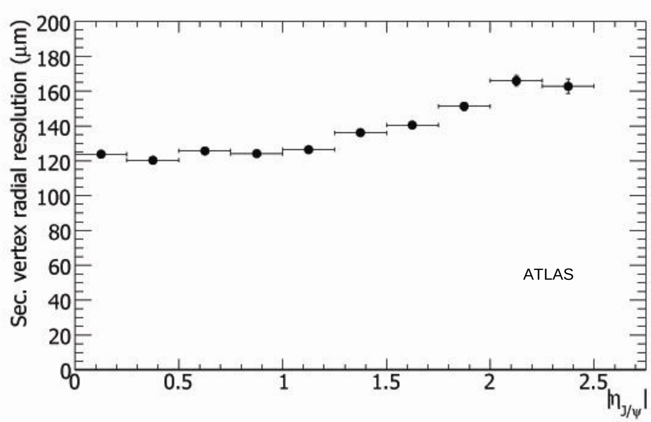
Strip Detectors – additional layers of silicon narrow strips aimed to provide additional position measurements. (5cm<radii<50cm) Resolution :σφ=16μm,σz=580μm

Transition Radiation Tracker (TRT)-
collections of gas-wire drift detectors consist of 4mm-straw tubes with thin wires in the center. (50<radii<100 cm). Resolution :σ=170μm per straw .

The silicon pixel and strip detectors provide about 10 azimuthal position measurements, each with precision of 10 - 20 microns. The TRT provides about 36 azimuthal position measurements, each with precision of 150 microns.

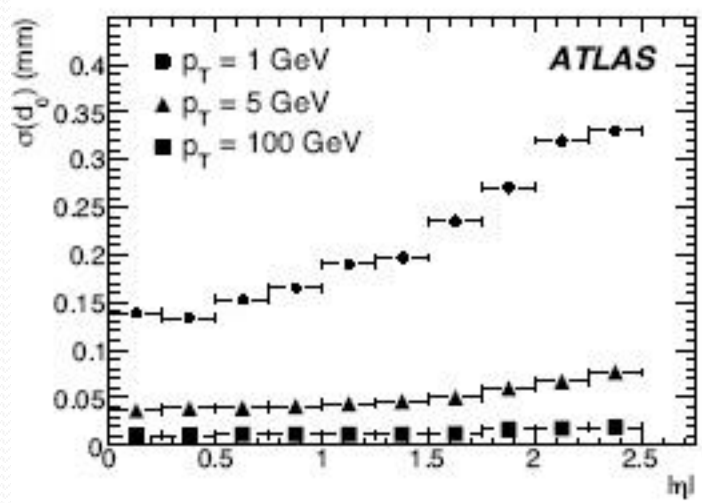
P_T resolution



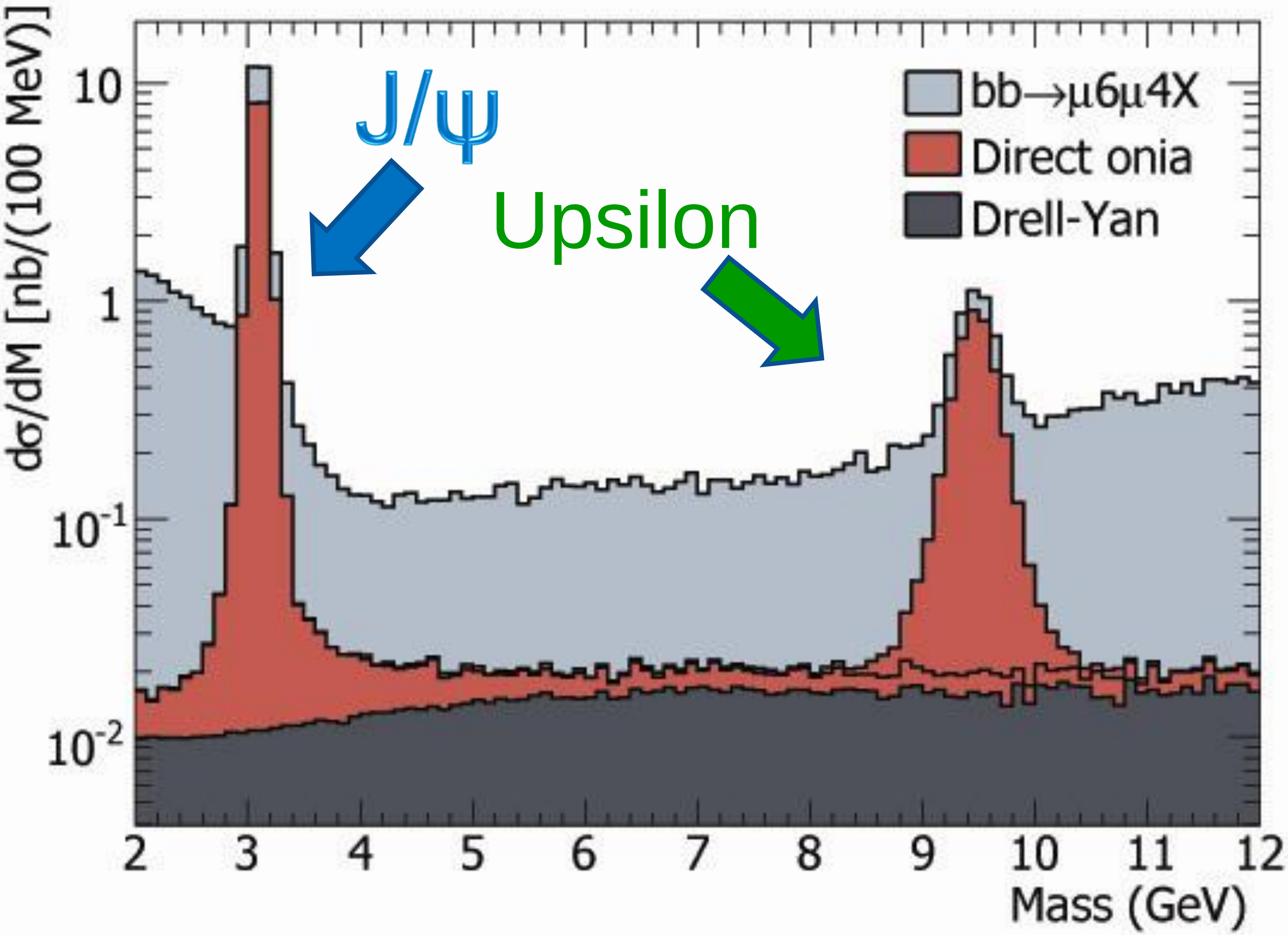


J/ψ secondary vtx resolution

Impact par. resolution



Low mass sources



Vertex separation

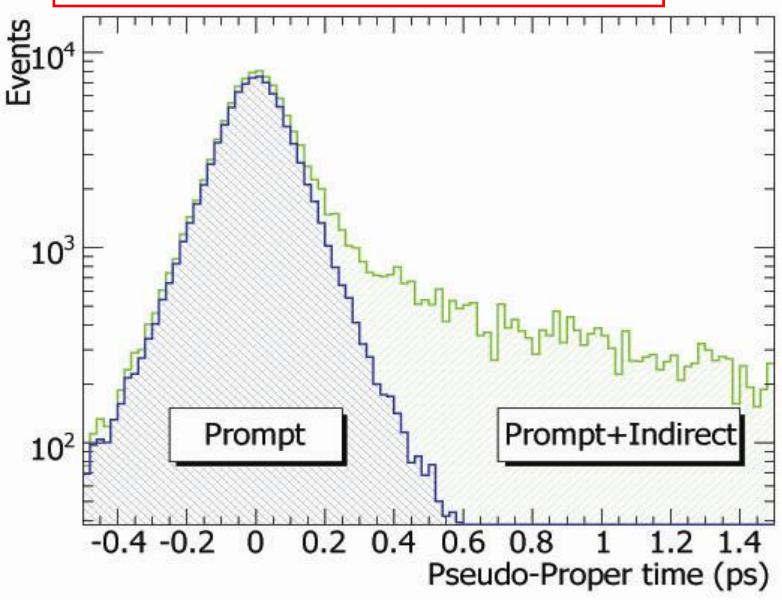
❖ Proper time used to separate direct J/ψ from indirect (B-decays)

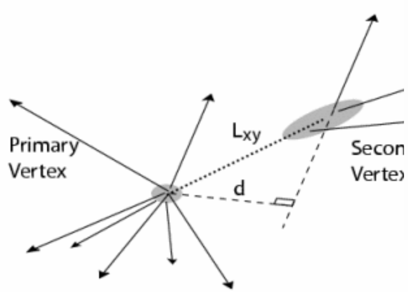
❖ Mean at zero -- $L_{xy}=0$ is characteristic of direct J/ψ, B's positive L_{xy}

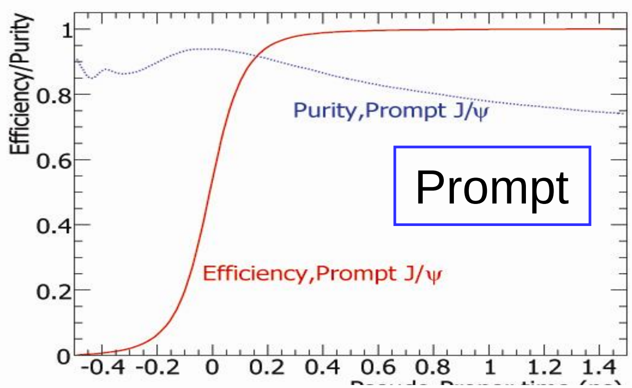
❖ 'Pseudo-proper time' cut of <0.2 ps gives prompt J/ψ efficiency of 95% with 5% contamination (removes grey background on previous slide)

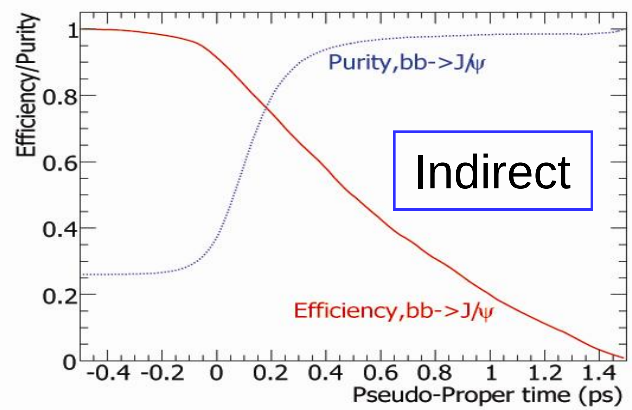
❖ Cut of >0.15 ps gives bb→J/ψX efficiency of 80% with 20% prompt J/ψ contamination (see E. De La Cruz Burelo prev. talk)

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





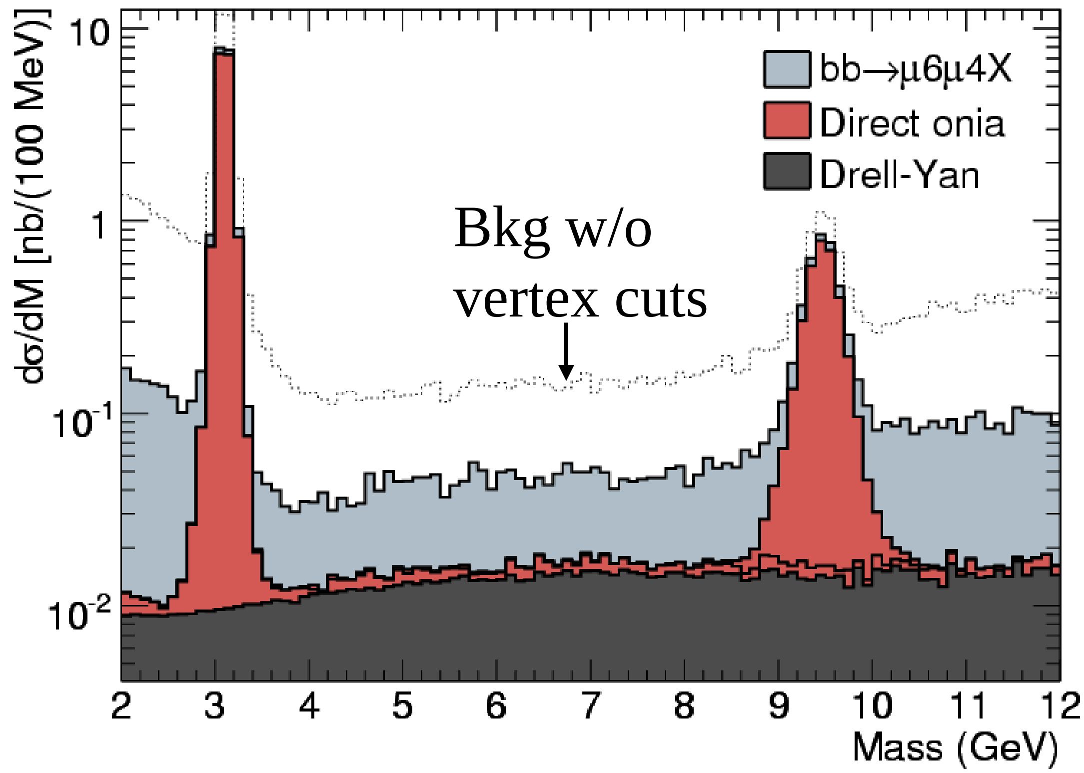




Dimuons: Results

Require: muons from same vertex and proper time < 0.2 ps

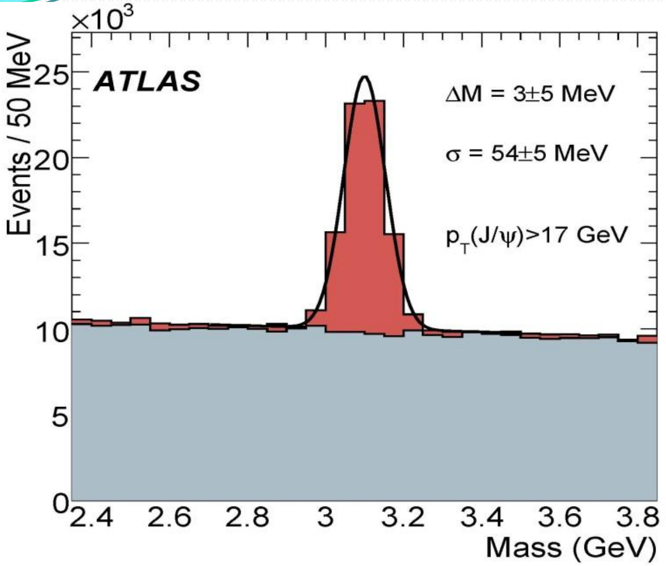
$\mathcal{L} = 10^{31}cm^{-2}s^{-1}$
With $p_{T1} \geq 6$ GeV,
$p_{T2} \geq 4$ GeV: ($\mu6\mu4$)
~15k J/ψ's
2.5k ϒ's (1S)
per 1 pb^{-1} 1-2 days with



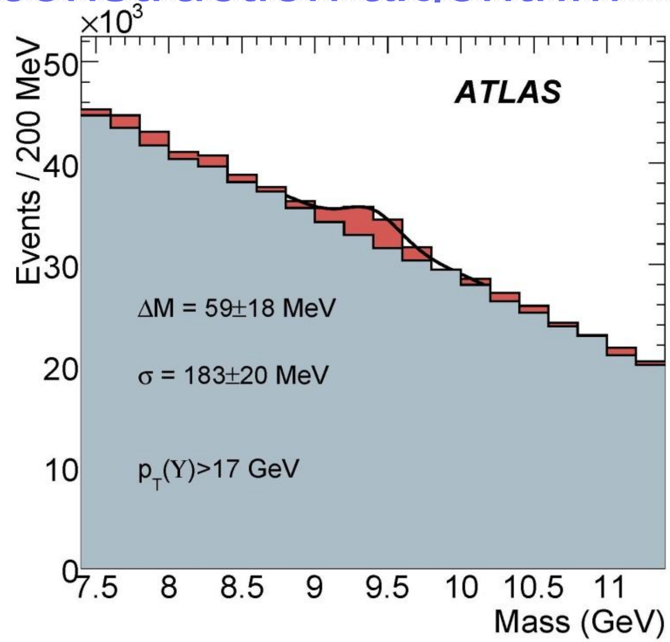
With $p_{T1} \geq 4$ GeV,
$p_{T2} \geq 4$ GeV: ($\mu4\mu4$)
~10k J/ψ's,
2k ϒ's (1S)
/ 8 hours (shift)

10 pb^{-1}: also measurement of
$\chi_c \rightarrow J/\psi(\mu\mu)\,\gamma$
~ 1 fb^{-1}: $\chi_b \rightarrow \Upsilon(\mu\mu)\,\gamma$

Reconstruction of prompt quarkonia



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



- Can reconstruct muons from Inner Detector tracks, muon spectrometer standalone, or combined muon information

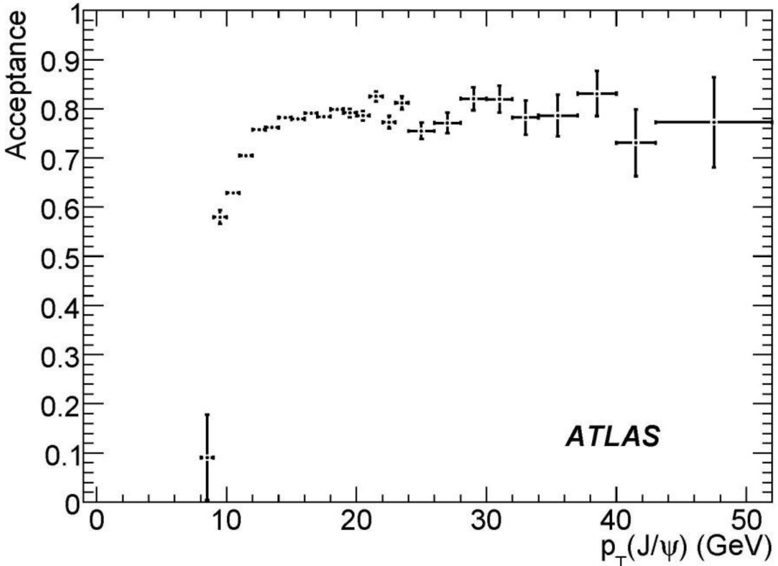
From all $\mu^+\mu^-$ pairs in Υ mass range, ~92% of generated events reconstructed.

p_T slices [GeV]	5-10	10-15	15-20	>20
$\sigma(J/\psi)$	54 MeV	52 MeV	51 MeV	49 MeV
$\sigma(\Upsilon)$	174 MeV	171 MeV	169 MeV	169 Mev

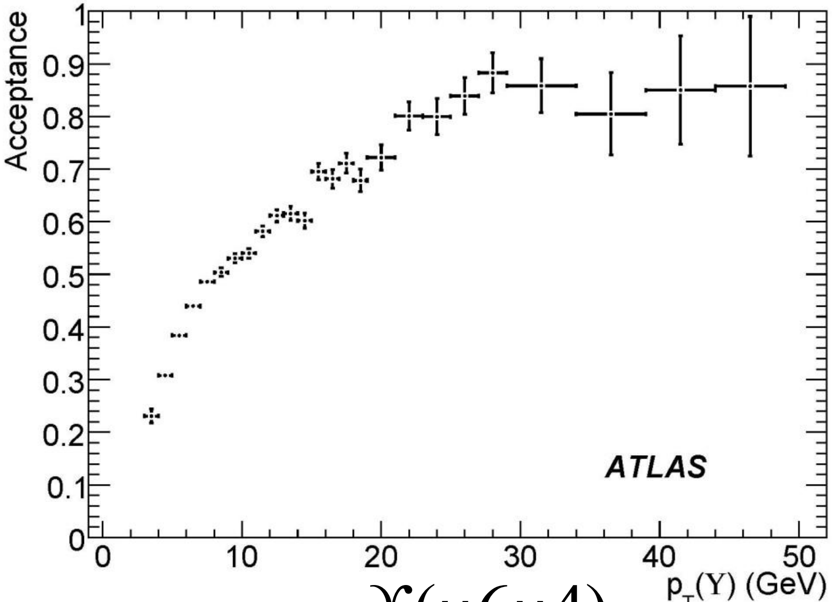
With cut on Pt(mu)>10GeV
+ Background
Corresponding to 10 pb^{-1}

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**



$J/\psi(\mu6\mu4)$
acceptance

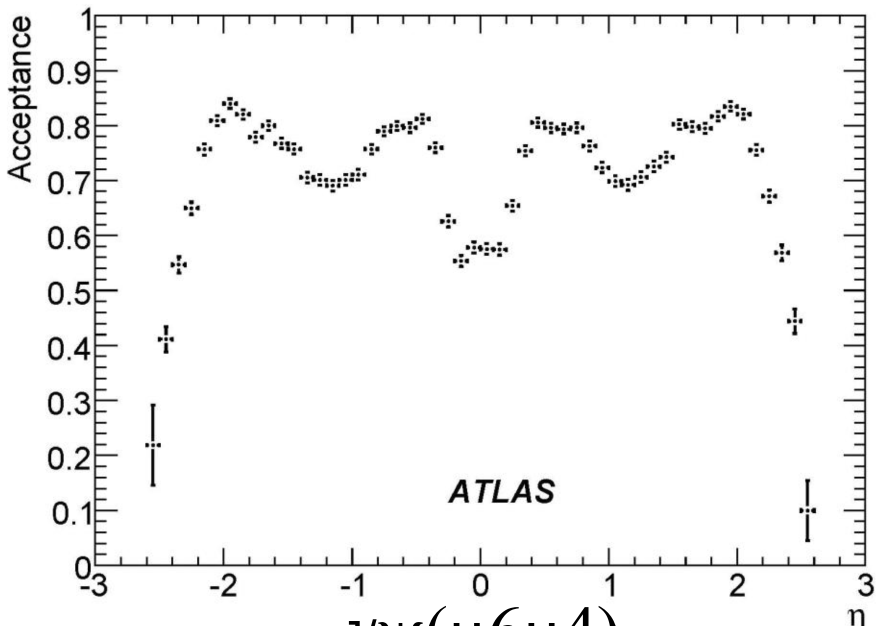


$\Upsilon(\mu6\mu4)$
acceptance

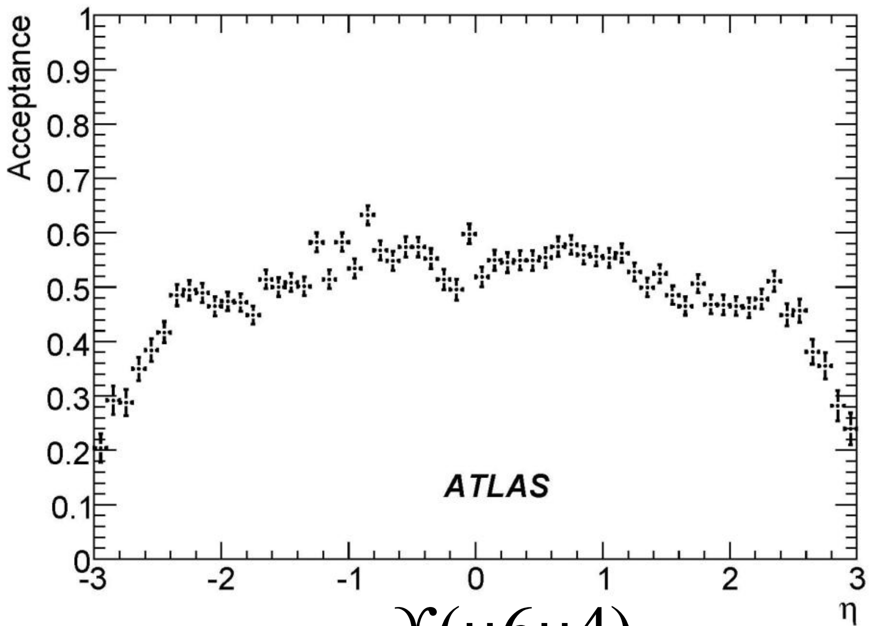
Errors on simulated statistics correspond to approximately 10 days of low luminosity data-taking

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



J/ψ(μ6μ4) acceptance



ϒ(μ6μ4) acceptance

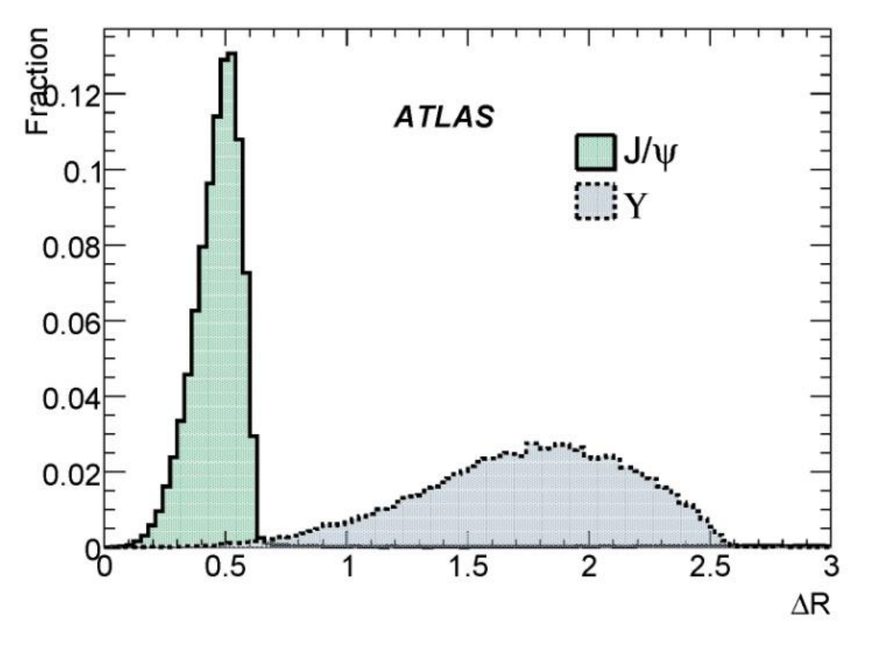
Onia decay muon angular separation ΔR

ΔR 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

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

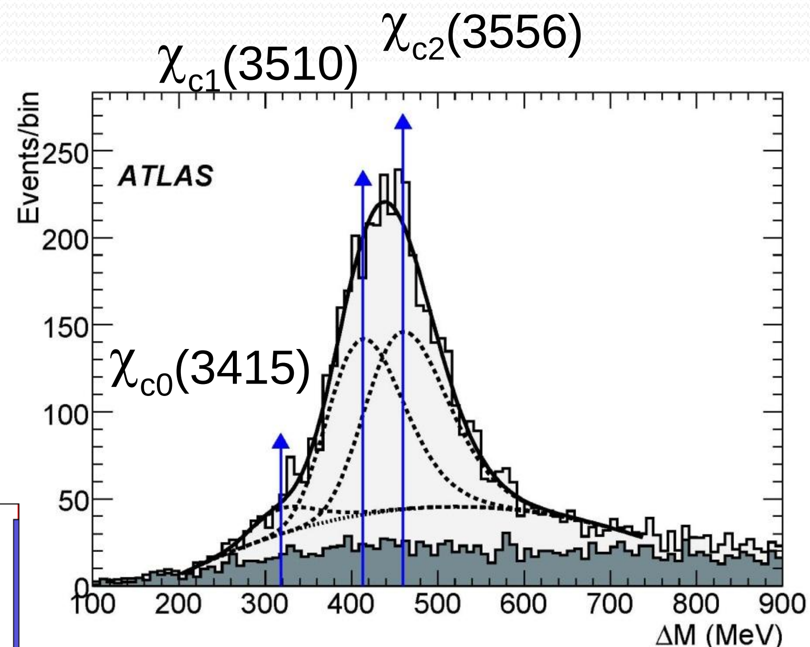
ΔR differences have implications for χ reconstruction and studies of hadronic activity from onia



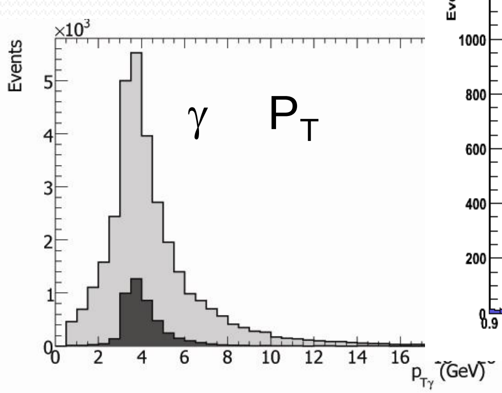
ΔR (μ6μ4)

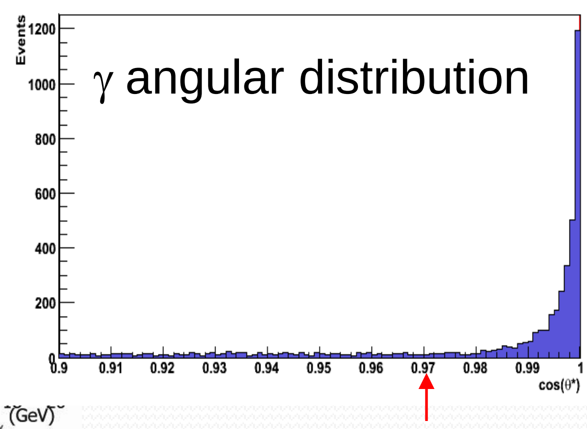
χ decays $\chi_c \rightarrow J/\Psi+\gamma$ events

- 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, resolution can be dramatically improved by using conversions

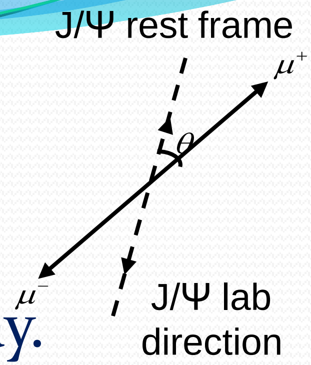


M(μμγ)-M(μμ)





Polarization definition

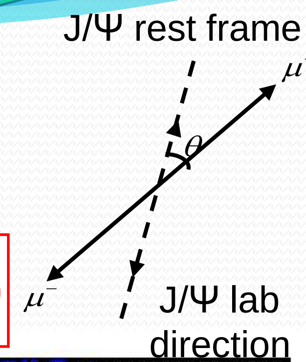


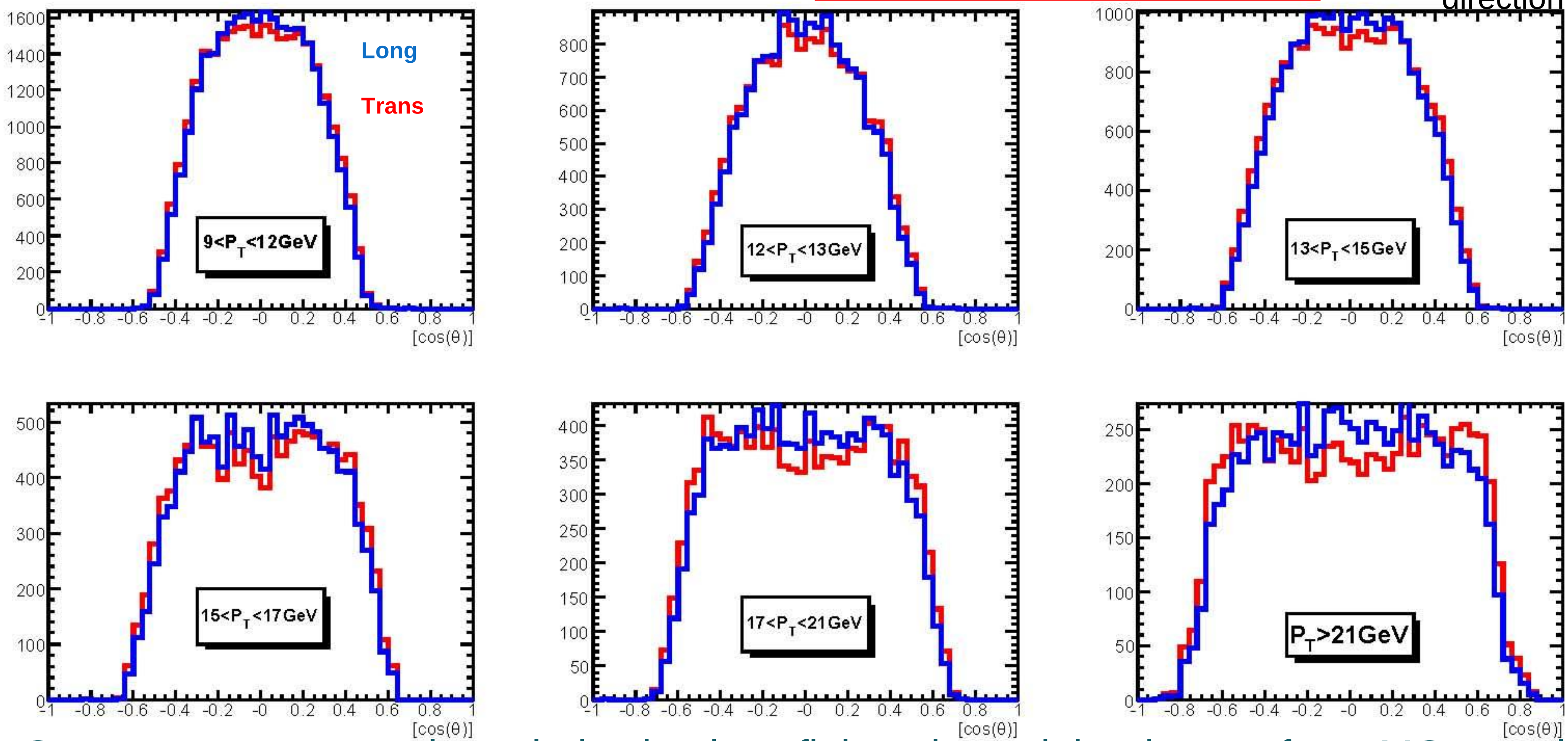
- Polarizations measured using the angular distribution of the daughter particles produced in the particle decay.
- The angle is measurede with respect to the direction of the movement in the pp cm (= the ATLAS lab frame).
- The polarization parameter α, defined as
  $$\alpha = \frac{\sigma_T + 2\sigma_L}{\sigma_T - 2\sigma_L}$$
  - Trasnsvers polarization **α=+1** refers to helicity $\pm$1.
  - Longitudinal (helicity 0) polarization **α=-1** .
- Between these two extremes lies a mixture of transverse and longitudinal production.
- Unpolarized production consists of equal fractions of helicity states +1, 0 and -1, and corresponds to α= 0.

Angular distribution of J/Ψ

- The decay angle is called θ* and is defined to lie between the direction of μ^+ in the J/Ψ rest frame and the J/Ψ direction in the lab frame. .

$$\frac{d\Gamma}{d\cos\theta^*} = \frac{C}{2\alpha+6}\left(1+\alpha\cos^2\theta^*\right)$$





- One way to measure the polarization is to fit it to the weighted sum of two MC samples produced with transversally and longitudinally polarization.

Polarization calculation

D-is the measured sample

T-is the transversally polarized temple

L-is the longitudinally polarized temple

B-is the background sample

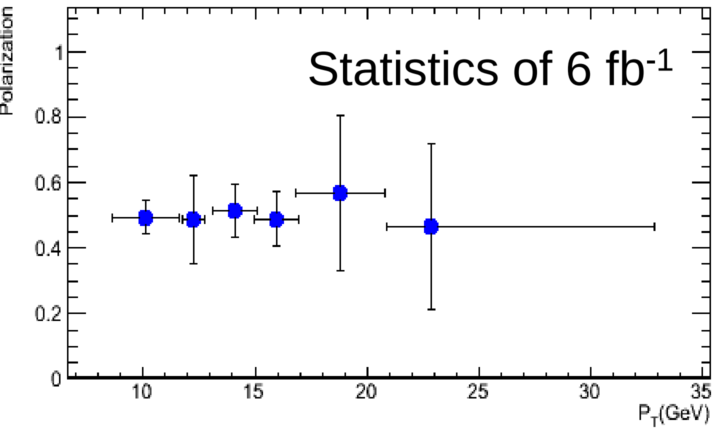
$N_{1,2}$ - are the Normalization parameters

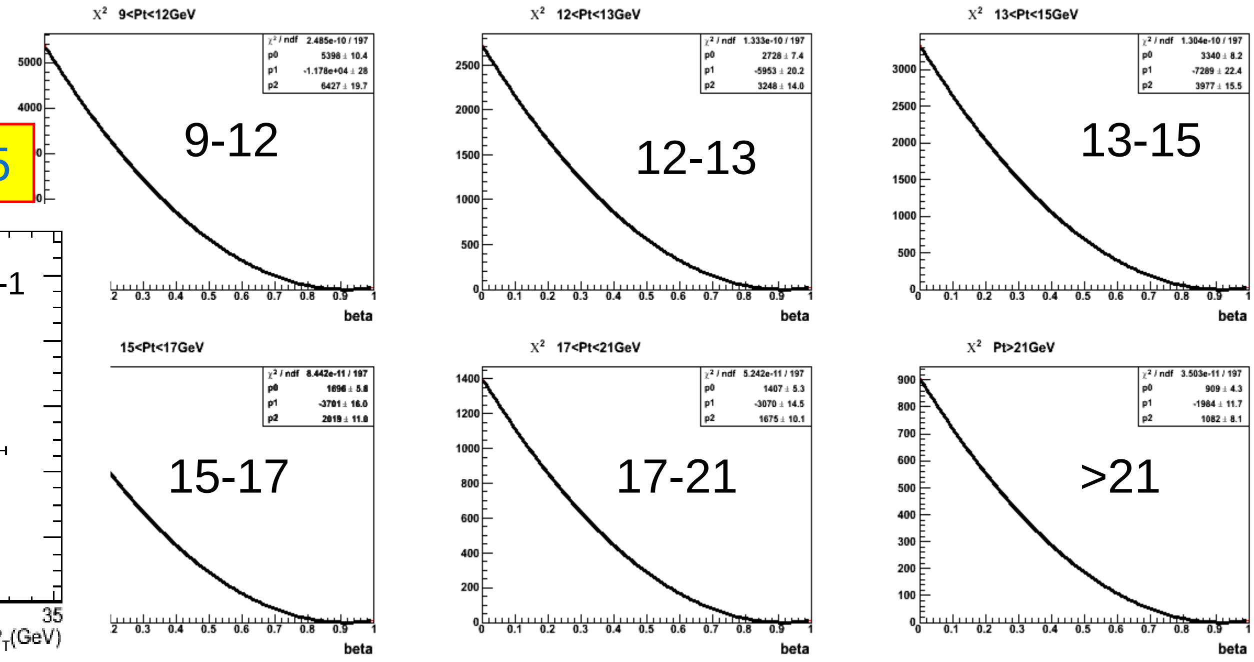
$$\chi^2 = \sum_i^N \frac{(D_i - [\beta \cdot T_{i1} - (1-\beta)\cdot L_i]\cdot N_1 - B_i \cdot N_2)^2}{D_i + (\beta^2 \cdot T_i + (1-\beta)^2 \cdot L_i)\cdot N_1^2 + B_i \cdot N_2^2}$$

β - is the transversally polarized fraction

$$\beta = \frac{2\alpha + 2}{\alpha + 3}$$

α of the sample was set to 0.5



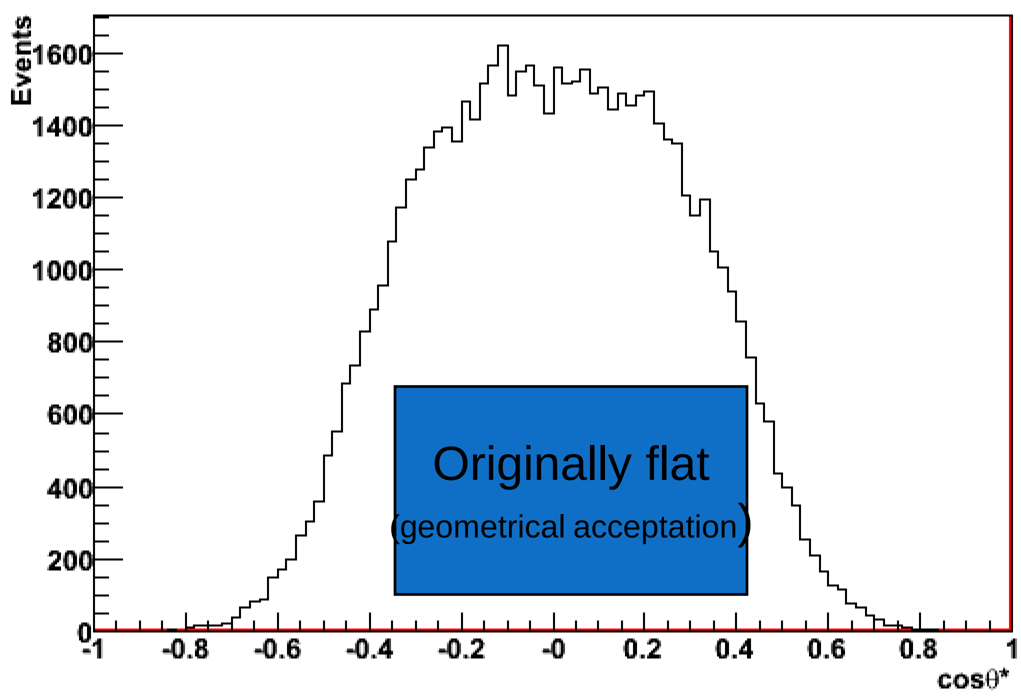


cosθ*acceptance and di-muon trigger

- Using di-muon trigger, both muons from J/Ψ must have relatively large $p_{T.}$
- It is required to get both muons pass the trigger constraints
- As a result it severally affect the polarization angle distribution.
- In the J/ Ψ p_T range, a fraction of ~60% (μ6μ4 trig.) of the sample is lost.

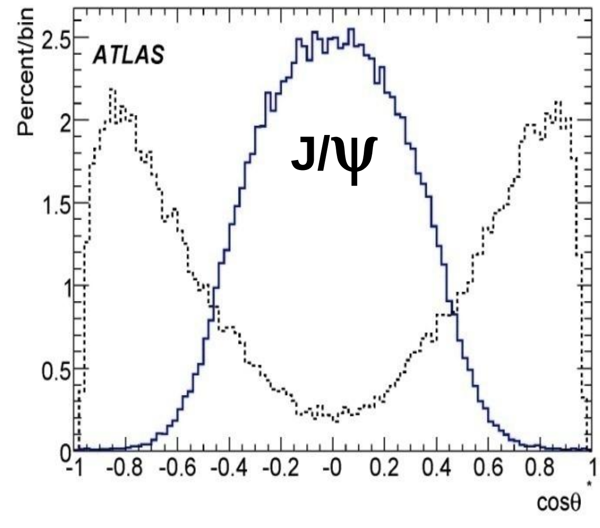
➢cosθ*~0 correspond to events with both muons with roughly equal p_T.
➢While for cosθ*=±1 one muon's p_T should be very high compared to the second one.
➢ In the case of |cosθ*|~1 the ratio of muons p_T is:

$$\frac{p_{\mu 1}}{p_{\mu 2}} \approx \left(\frac{M_Q}{m_\mu}\right)^2 \approx 900$$

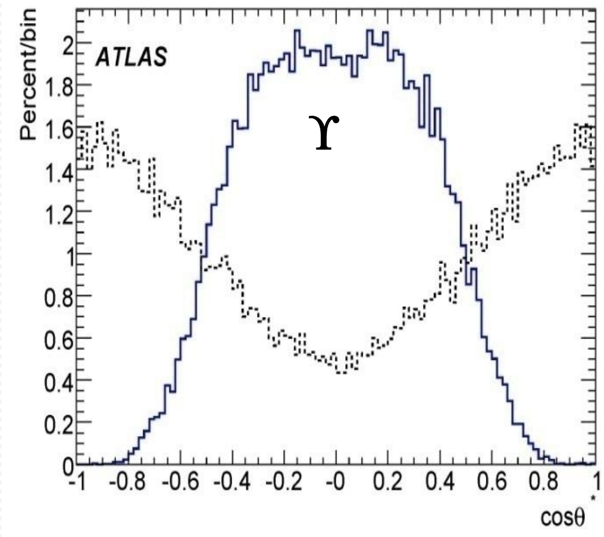


Single muon μ10 trigger to the rescue

- 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)
  - ✓ $|\cos\theta^*| \sim 1$ corresponds to a configuration where one muon is fast, the other slow
  - ✓ Provides similar p_T range of onia to $\mu6\mu4$ configuration
- Go from a distribution in $\mu6\mu4$ (blue curve) to that in $\mu10$ (black curve)

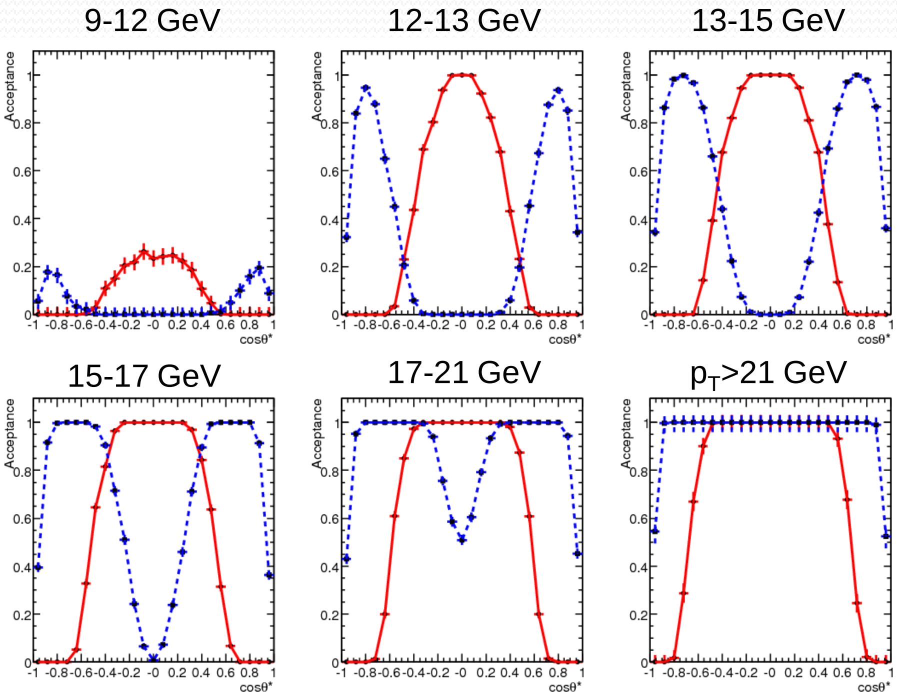


μ6μ4
μ10μ1



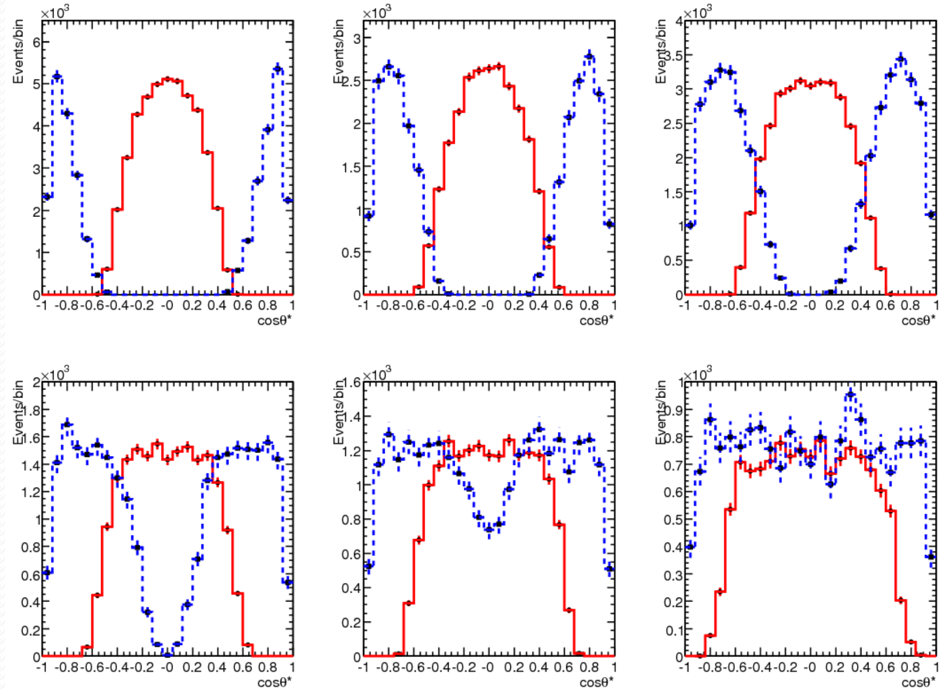
- Invariant mass distributions in μ10 suffer from larger, but manageable, backgrounds.

Combined polarization measurement



ACCEPTANCE AND EFFICIENCY
(from Monte Carlo predictions)

'MEASURED' DISTRIBUTIONS



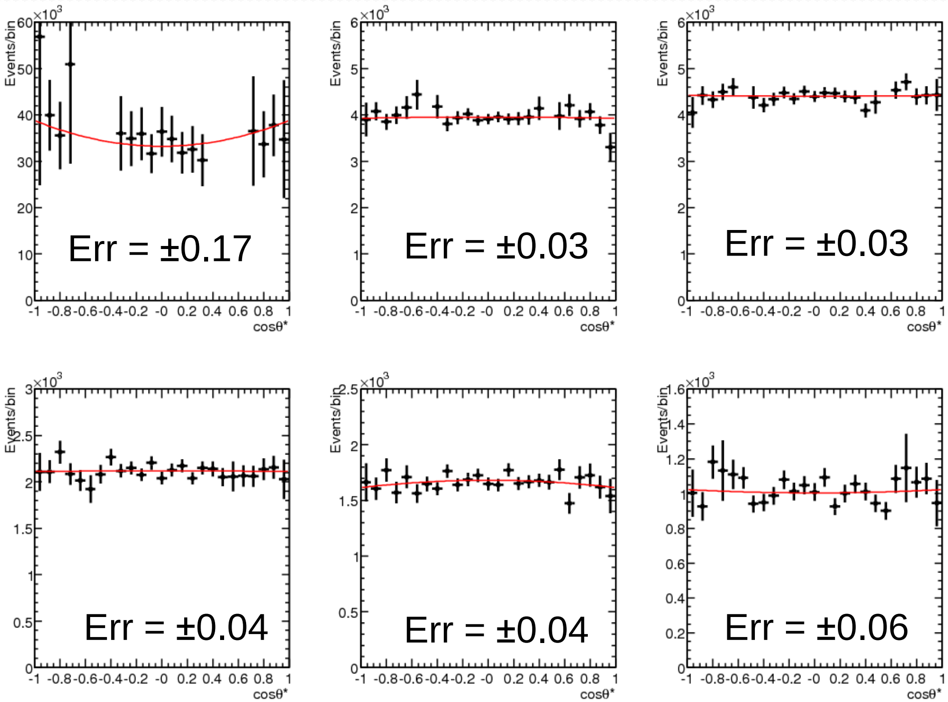
$\mu6\mu4$ sample in red

$\mu10$+track sample in blue

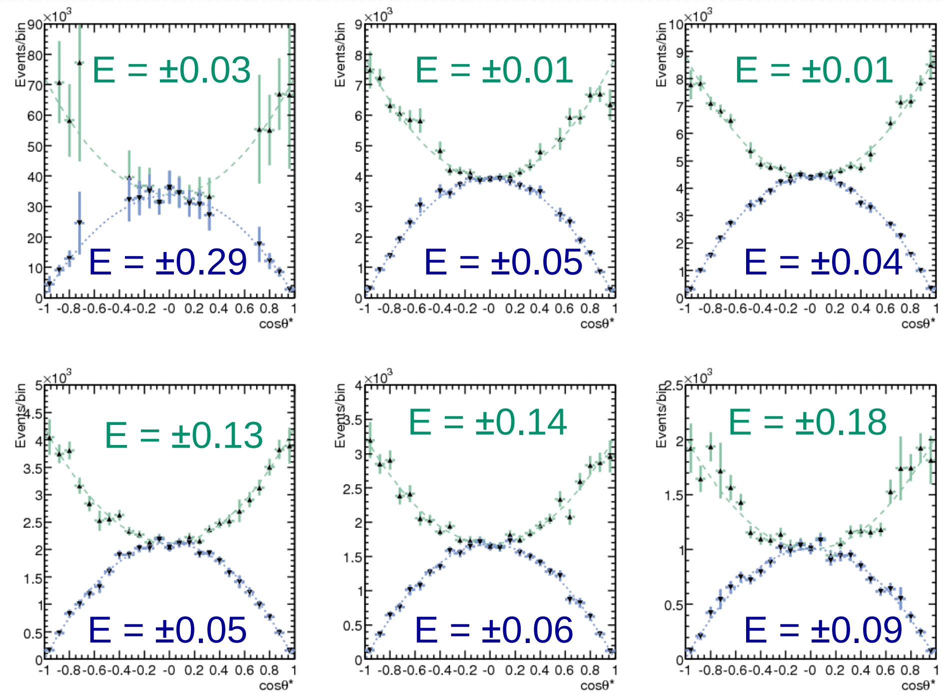
Combined polarization measurement -II

- Measured distributions from $\mu6\mu4$ and $\mu10$ 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)
- Fit polarization α in bins of p_T

$$\frac{dN}{d\cos\theta^*} \propto \frac{C}{2\alpha+6}\left(1+\alpha\cos^2\theta^*\right)$$



UNPOLARISED SAMPLE

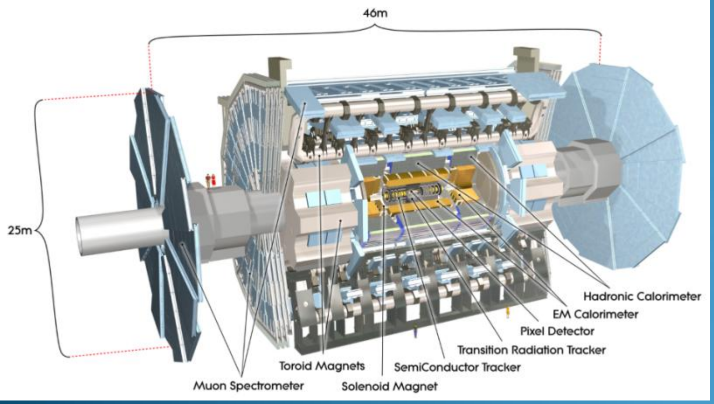


LONGITUDINAL AND TRANSVERSE SAMPLE

Summary - J/Ψ and ϒ in early ATLAS data

- Although ATLAS is designed to probe the O(1 TeV) scale, it can still make some useful measurements in the heavy quarks physics sector.
- The Quarkonia ->di-muons will be one of the main channels in the analysis of the early data to be collected in the experiment.
- The clear signature enables using it for Event Quality monitoring and for calibration, alignment of the various sub-detectors and algorithms.
- The J/Ψ directly produced at PP collisions will be a main source of background to J/Ψ produced in B hadrons which is a key channel in the B Physics program.
- There is a discrepancy between the polarization P_T dependence in the previous measurements and theoretical predictions resulted in different predictions.
- With its large statistics at high transverse momentum and the methods suggested here ATLAS can improve both statistics and systematic of the existing measurements.
- The errors on J/ψ polarisation with <u>10 pb</u>$^{-1}$ of data are expected to be of similar magnitude to that of Tevatron <u>1 fb</u>$^{-1}$ of data, in the important high p_T area.
- Similar results can be achieved for ϒ but need 100 pb^{-1} of data to reach same precision, due to increase backgrounds

Backup


46m
25m
Hadronic Calorimeter
EM Calorimeter
Pixel Detector
Transition Radiation Tracker
Toroid Magnets
SemiConductor Tracker
Muon Spectrometer
Solenoid Magnet

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)

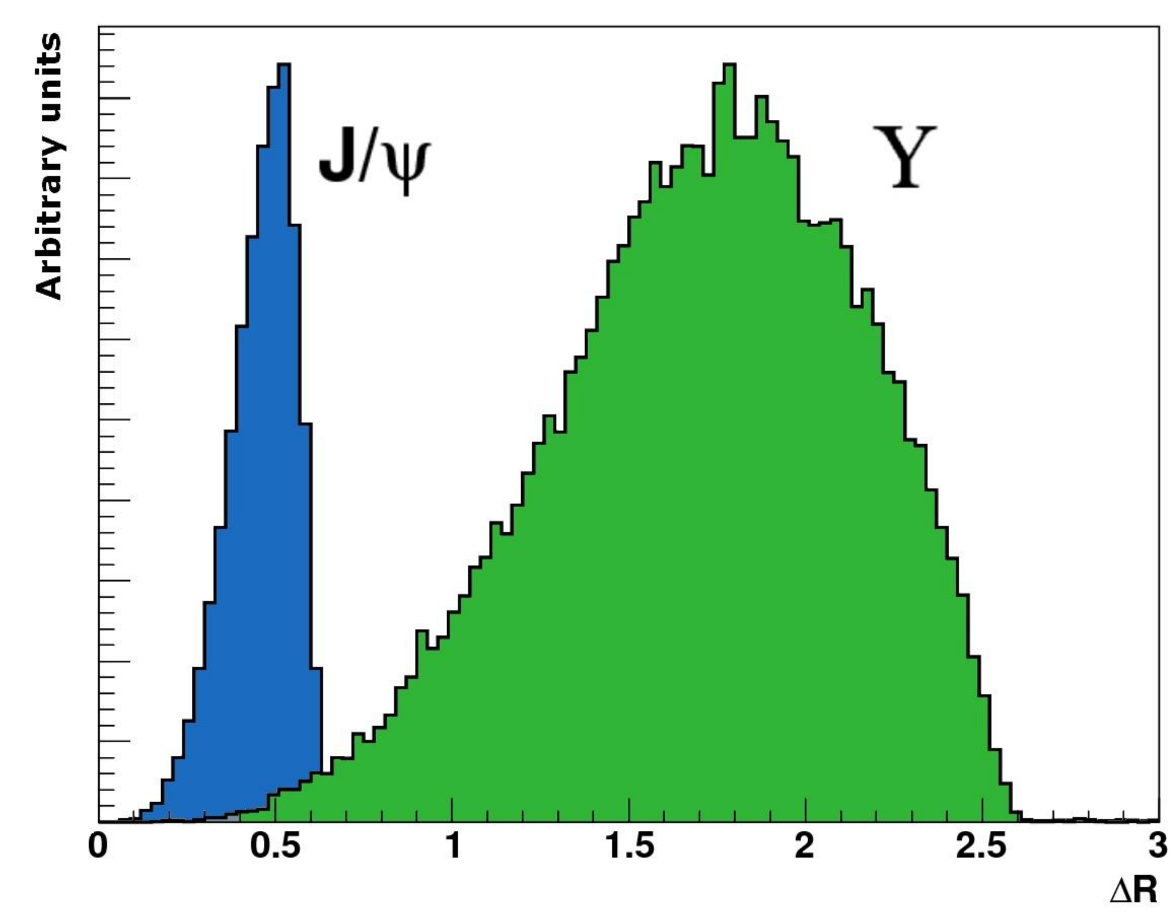
$$d\sigma(pp \to H + X) = \sum_{n_i} d\hat{\sigma}\left(pp \to Q\bar{Q}[n_i] + x\right) \langle \mathcal{O}^H[n_i] \rangle$$

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

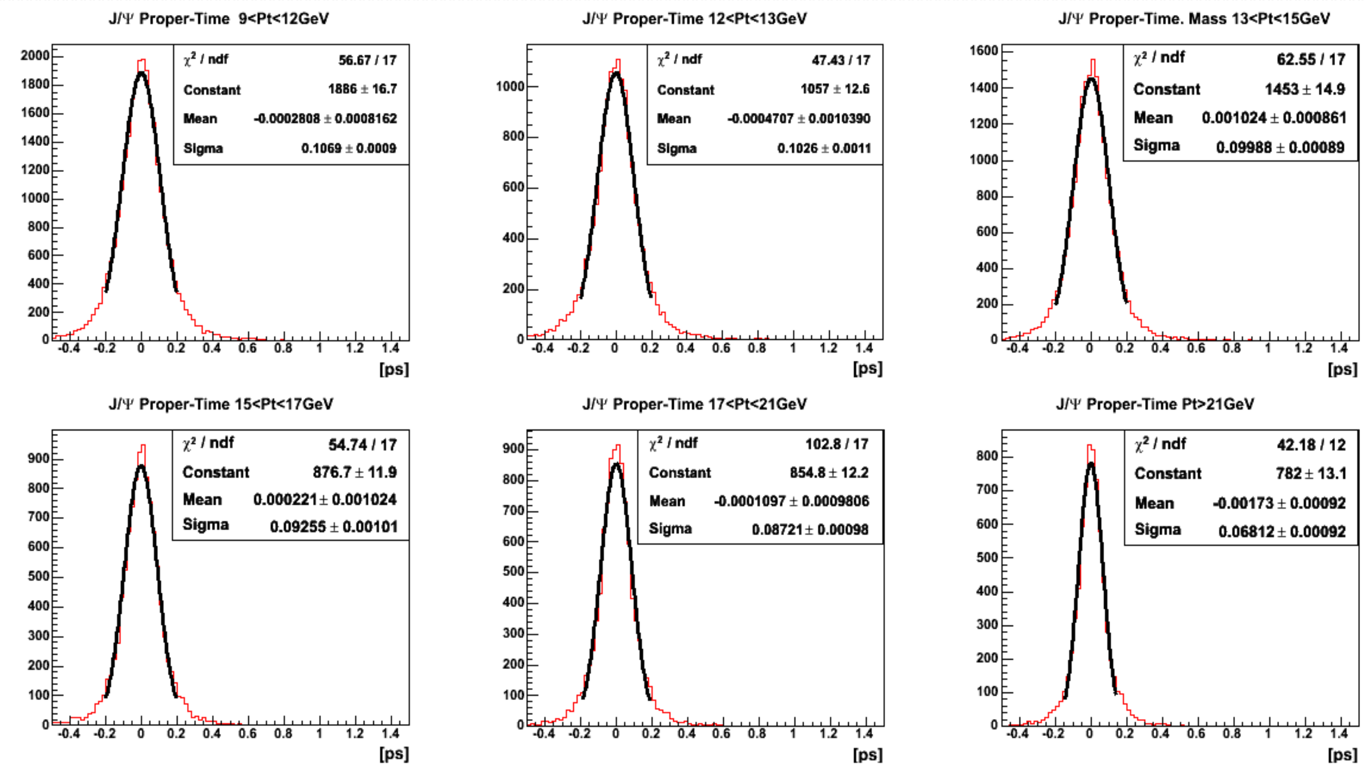
PYTHIA parameter	NRQCD matrix element	Value
PARP(141)	$\langle O(J/\psi)[^3S_1(1)] \rangle$	1.16
PARP(142)	$\langle O(J/\psi)[^3S_1(8)] \rangle$	0.0119
PARP(143)	$\langle O(J/\psi)[^1S_0(8)] \rangle$	0.01
PARP(144)	$\langle O(J/\psi)[^3P_0(8)] \rangle / m_c^2$	0.01
PARP(145)	$\langle O(\chi_{c0})[^3P_0(1)]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

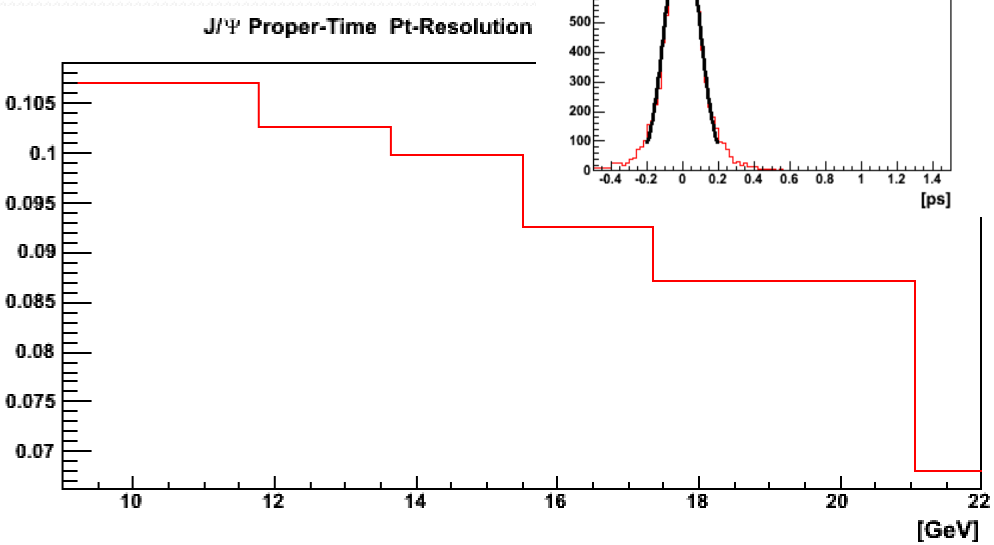
Based on hep-ph/0003142

deltaR before cuts



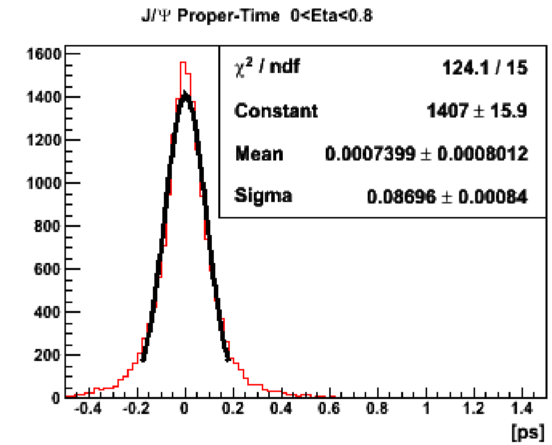
Proper time resolution vs. p_T

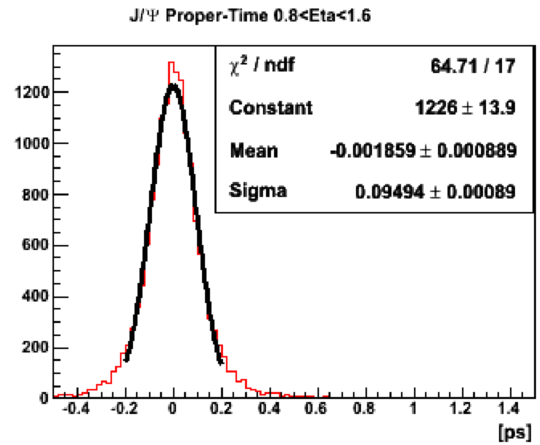


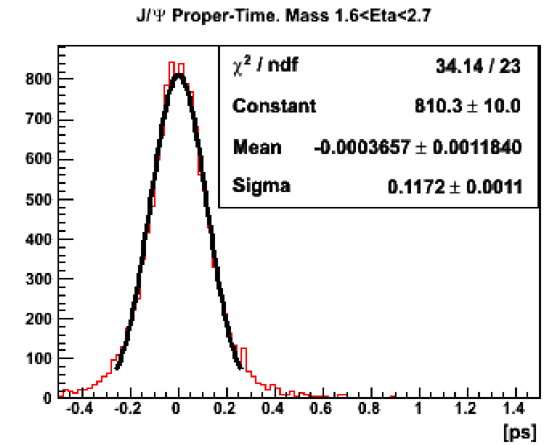


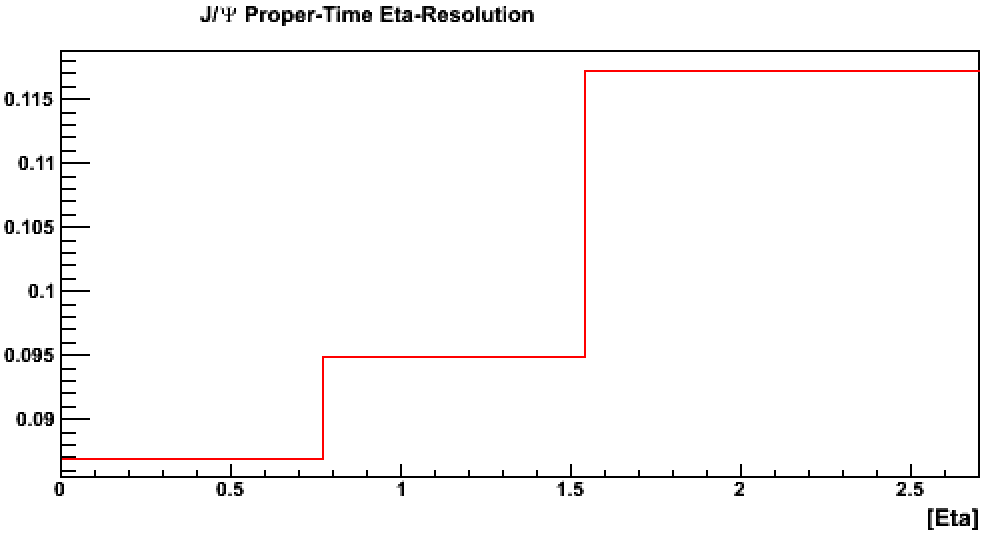
The Pseudo Proper time fit resolution decrease with p_T

Proper time resolution vs. Eta









The Pseudo Proper time fit resolution getting worth at Endcaps.

Event quality Monitoring

➢ Want to use J/Ψ as calibration and monitoring tools for Detector alignment, material and field tests

STATISTICS:

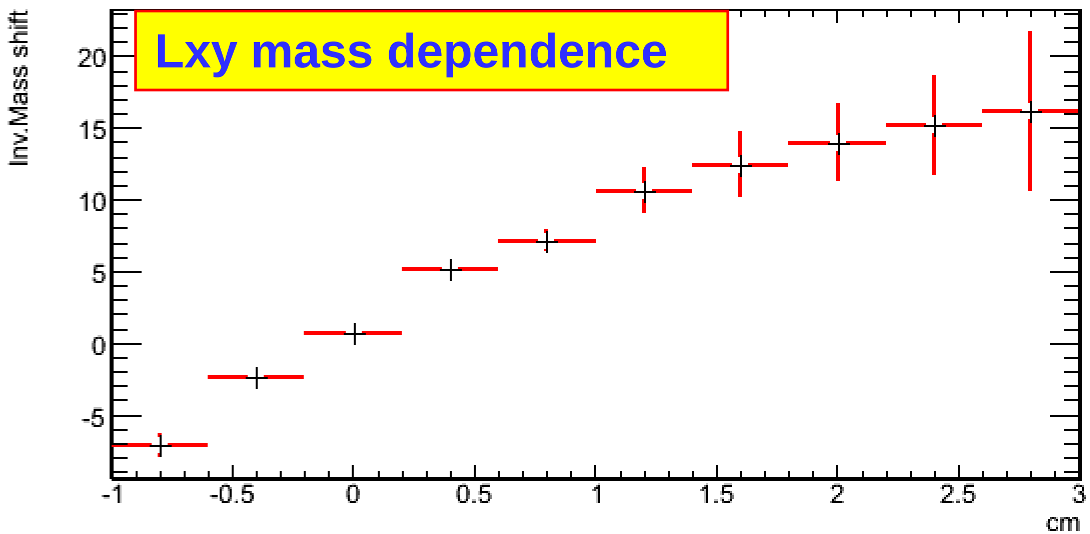
Express stream: 10 hours

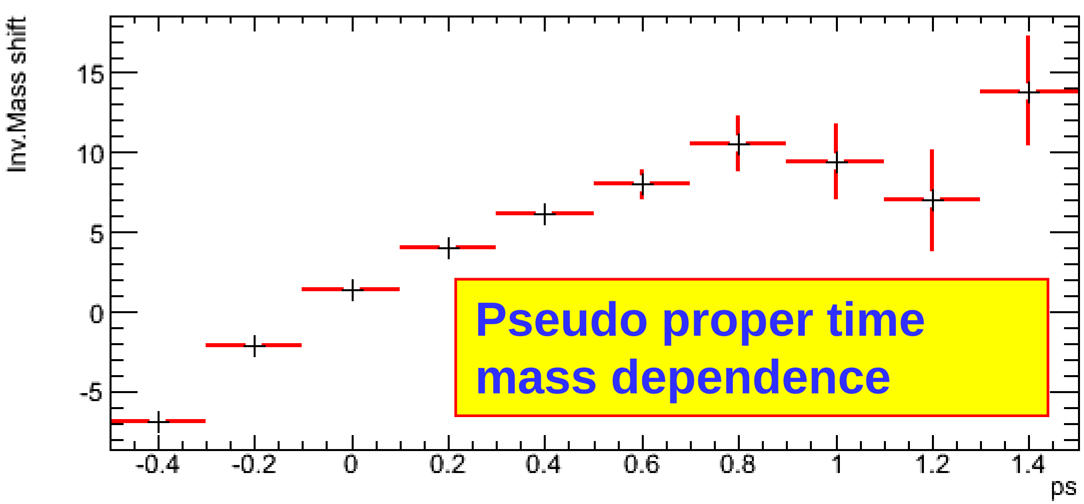
~15,000 J/ψ

➢ By looking at mass shifts in J/Ψ with a number of variables, can disentangle various causes of detector effects

➢ By using the same monitoring techniques for J/ψ ,ϒ and Z particles it can remove systematics when moving to different kinematic regime and decay topologies.

J/Ψ invariant mass shift dependences

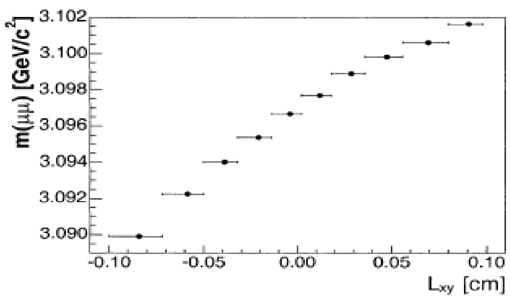




<u>Lxy mass dependence</u>

At CDF this showed a strong dependence, due to track reconstruction algorithms;

the dependence was also different in different sub-detectors

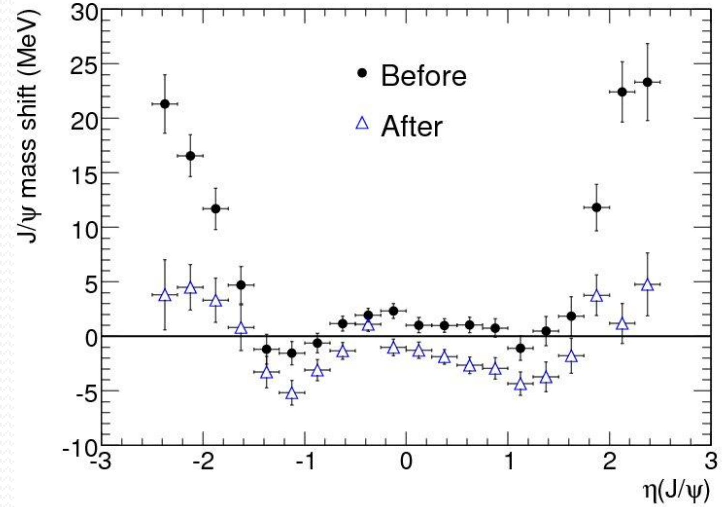


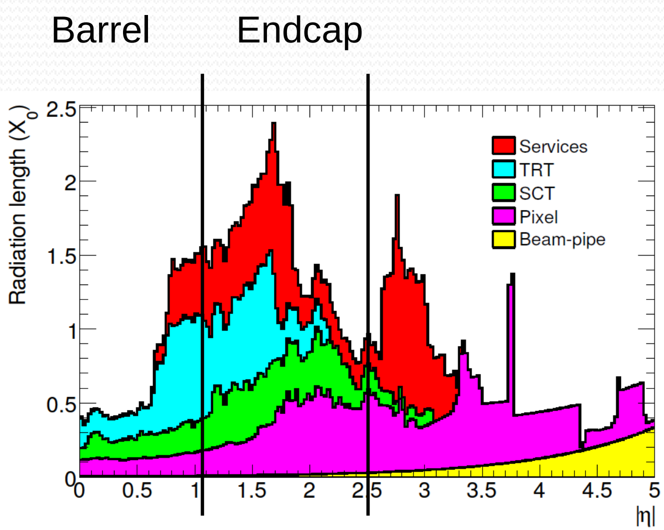
Andreas Korn at CDF Run II

Reconstruction of prompt quarkonia (μ6μ4)

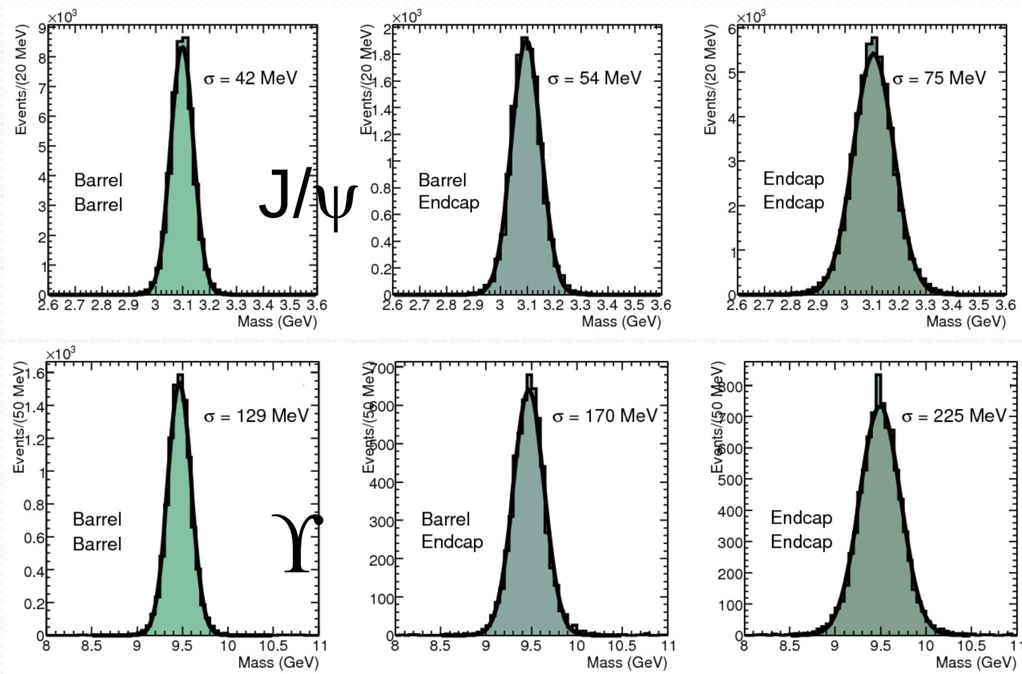
- Muon pairs which are triggered are fit to a common vertex; those from prompt quarkonia survive vertexing with a 99.9% efficiency

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





Inner Detector material budget



TEL AVIV UNIVERSITY

First glance on systematics

Very preliminary

J/ψ P_T [GeV]	9-12	12-13	13-15	15-17	17-21	>21
Initial α	0.01	0.03	0.05	0.05	0.08	0.1
S/B	0.05	0.05	0.03	0.07	0.1	0.1
Inv. mass	0.03	0.03	0.02	0.02	0.02	0.02
Eta	0.18	0.04	0.04	0.015	0.01	0.01
Xc	0.01	0.005	0.02	0.03	0.02	0.02
Prop. time	0.21	0.2	0.2	0.2	0.2	0.1
LVL1	0.3	0.15	0.005	0.005	0.01	0.01
LVL2	0.3	0.1	0.08	0.05	0.02	0.02