B Decay Measurements Towards CPV in ATLAS

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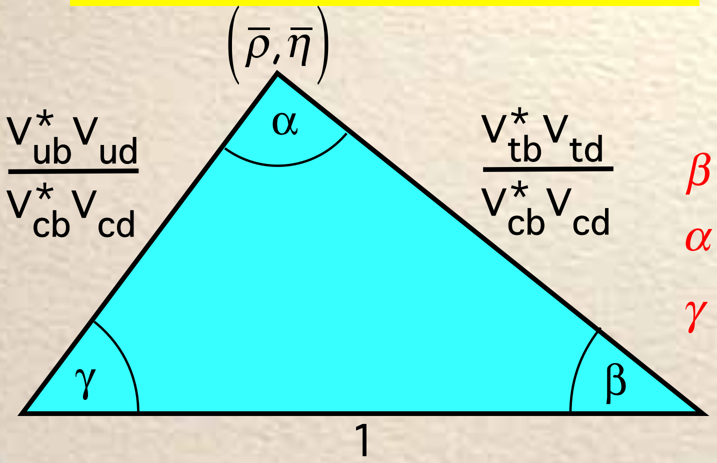
Outline

- Introduction
- ATLAS detector and performance
- Vertex and impact parameter resolution
- Exclusive B reconstruction
- B_d^0 and B_s^0 lifetimes
- Tagging performance
- Expectations by end of 2012
- Conclusion

Introduction

- Precision measurements in the B_d^0 system by BABAR & Belle show that the phase in the CKM matrix is the main source of CP violation in B system

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



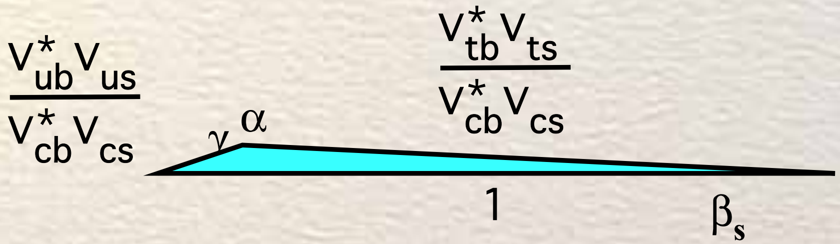
$\beta = (21.4 \pm 0.8)^\circ$

$\alpha = (89^{+4.4}_{-4.2})^\circ$

$\gamma = (71^{+21}_{-25})^\circ$

HFAG/CKMfitter 2010

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



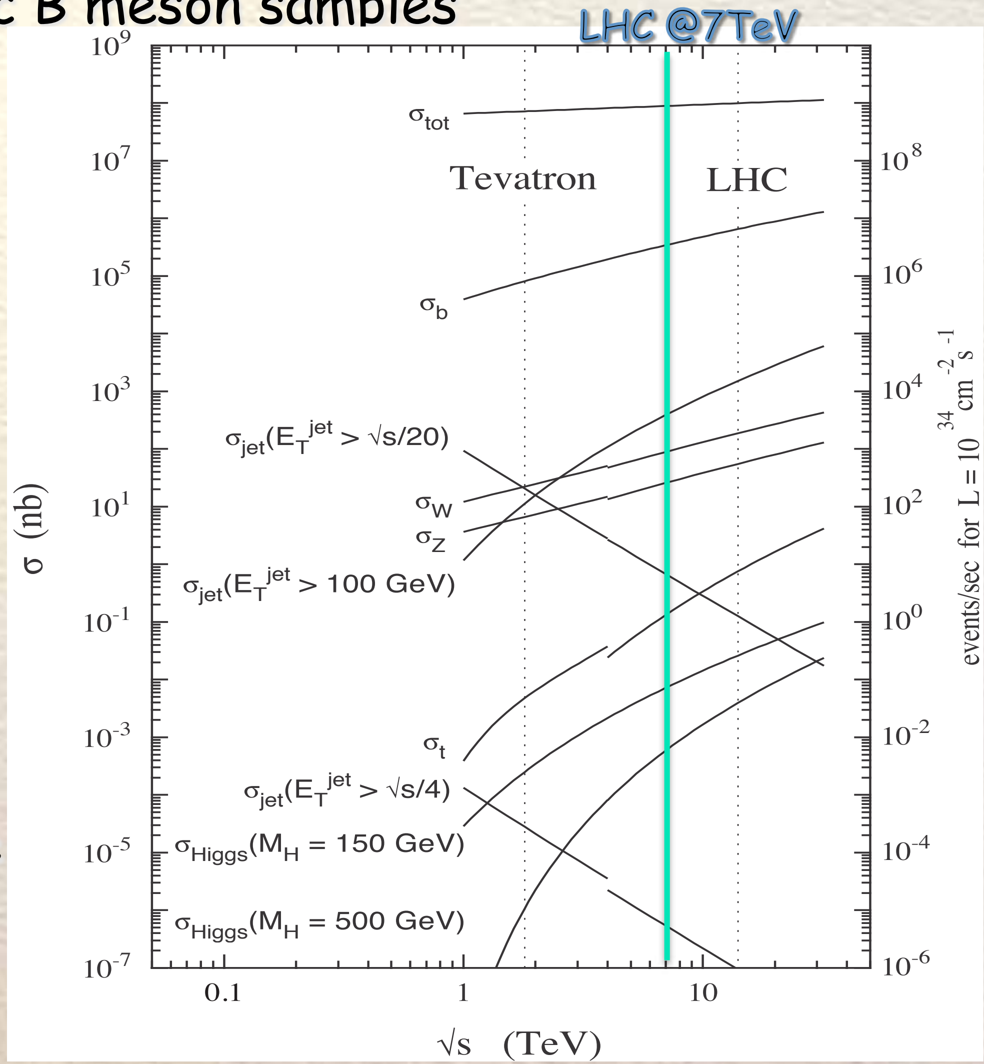
$\beta_s = (18.18 \pm 0.85) \times 10^{-3}$

SM: Lenz et al, hep-hp/1008.1593

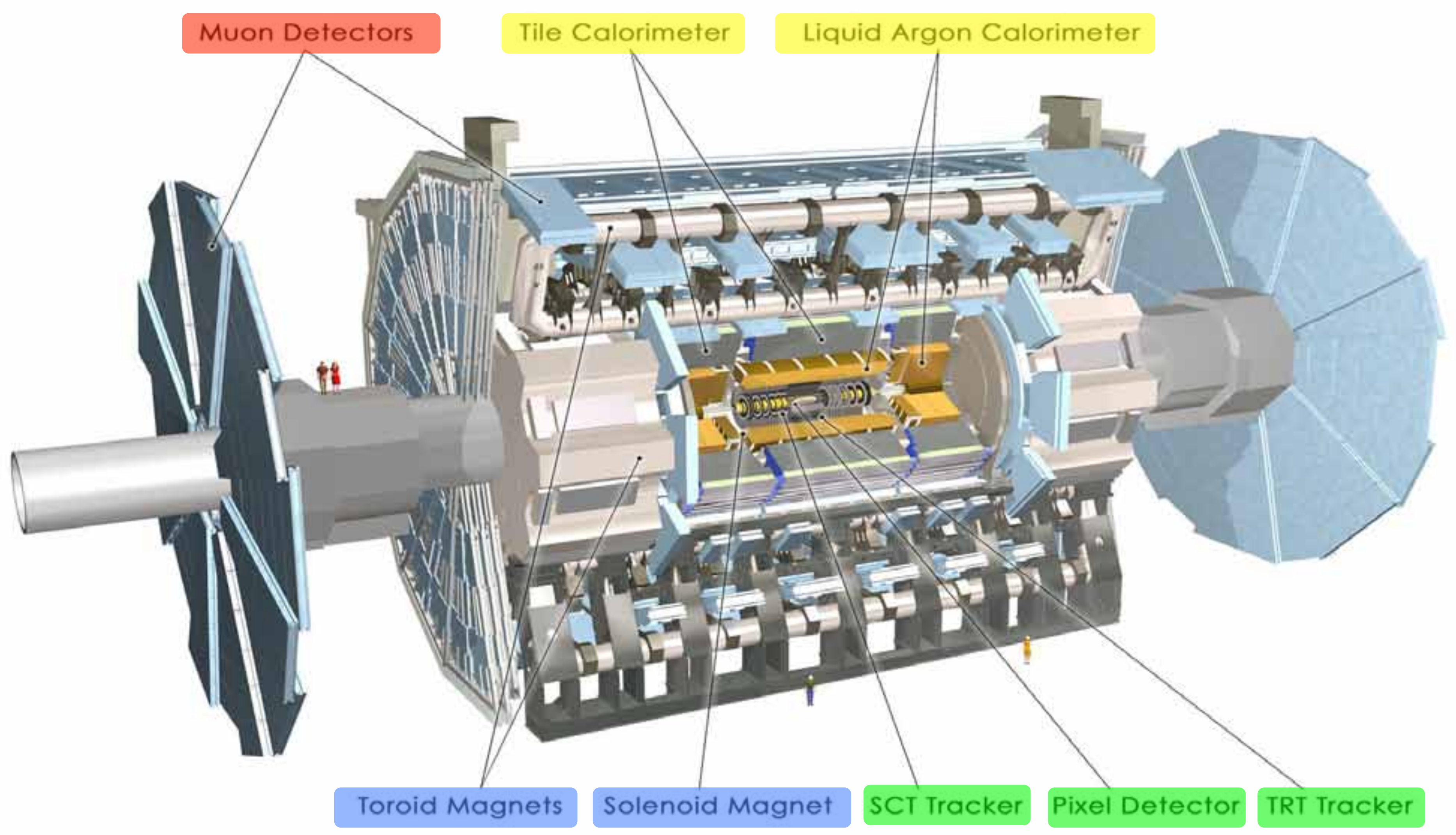
- Angle β is measured to 4%, angle α to 5% and angle γ to 35%
- New physics contributions are constrained to < $\mathcal{O}$(10%)
- Next step is to measure CP violation in the B_s^0 system studying time dependent decay rates for B_s^0 and $\overline{B}_s^0$

Requirements for CPV Measurements

- The $b\bar{b}$ cross section in pp collisions at 7 TeV is huge ➔ at high luminosities LHC produces gigantic B meson samples
- ATLAS has excellent capabilities to perform time-dependent decay rate measurements
  - Reconstruct exclusive final states with good resolution
  - Measure vertices with high precision
  - Tag b flavor at production with Q_{jet} (validate with data)
- $B_s^0 \to J/\psi\Phi$ is most promising mode observed in ATLAS for β_s
- Need validation measurements in $B_d^0 \to J/\psi K_s^0$ (for CPV), $B_d^0 \to J/\psi K^{*0}$ (angular analysis) & $B^+ \to J/\psi K^+$ (tags)



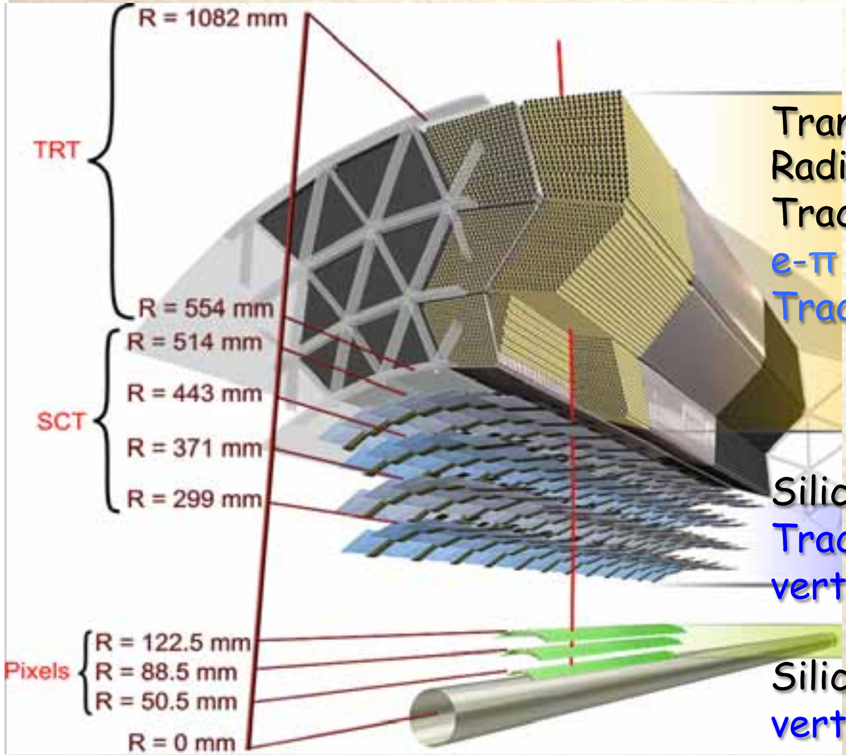
The ATLAS Detector



- The fraction of operational channels is close to 100% for all systems

Subdetectors Important for B Physics

Inner Detector



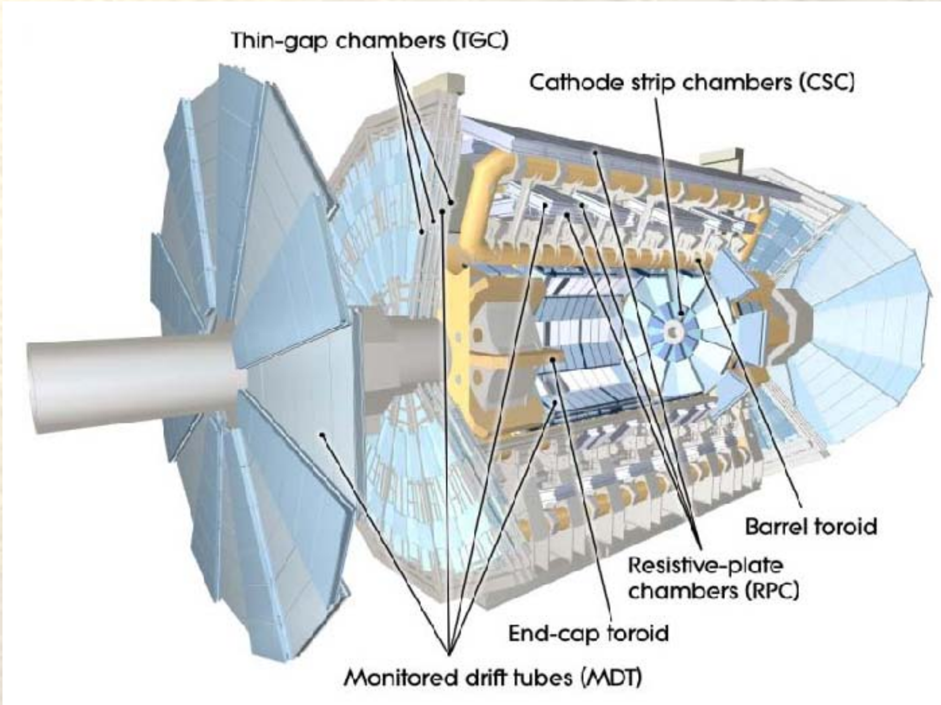
Transistion Radiation Tracker:
e-π separation
Tracking

Silicon strips
Tracking+ vertex

Silicon pixels
vertex

- Solenoidal 2T B field
- Coverage |η|<2.5
- $\sigma/p_T \cong 3.4\times10^{-4}\, p_T + 0.015$ for $|\eta|<1.5$

Muon system

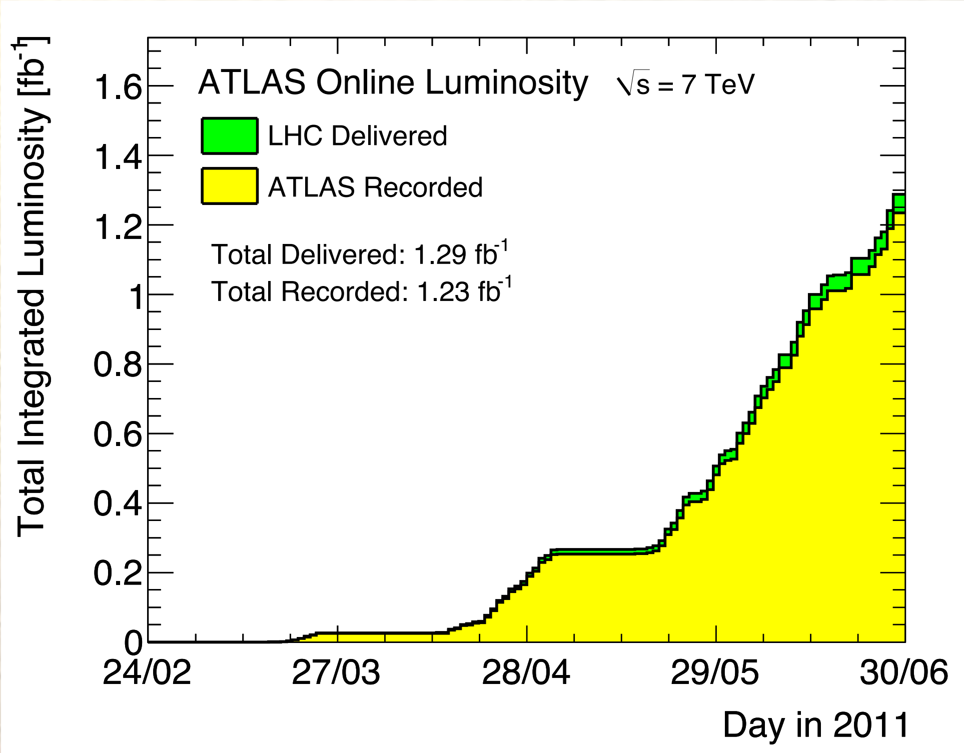


- Precise tracking chambers & trigger chambers
- Coverage |η|<2.7
- 0.5 T torroidal field (average)
- σ/p_T<0.1 up to 1 TeV

Luminosity

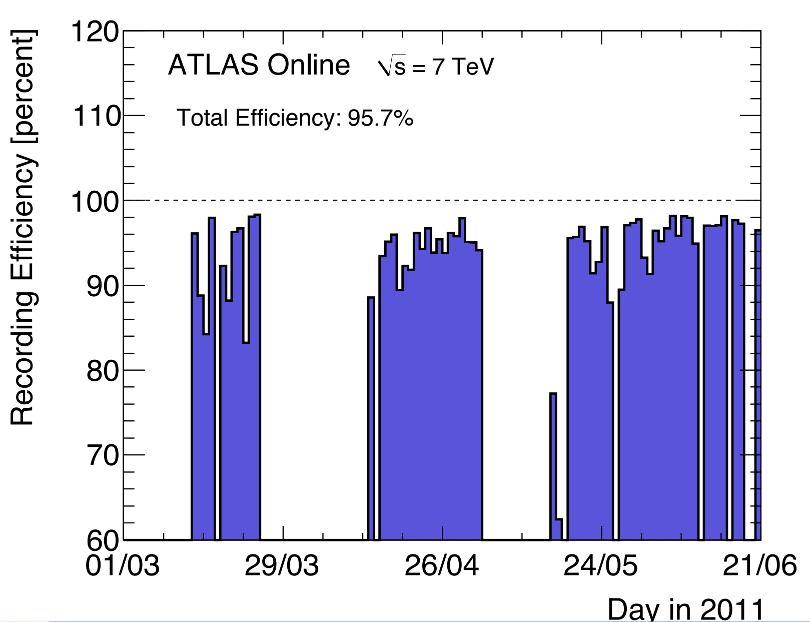
- ATLAS already has recorded an integrated luminosity **1.23 fb^{-1}** by end of June
- Delivered luminosity: 1.29 fb^{-1}
- Peak luminosity: 1.26×10^{33} cm^{-2}s^{-1}
- Preliminary uncertainty on 2011 luminosity: 4.5%
- Expect integrated luminosity **>10 fb^{-1}** by end of 2012

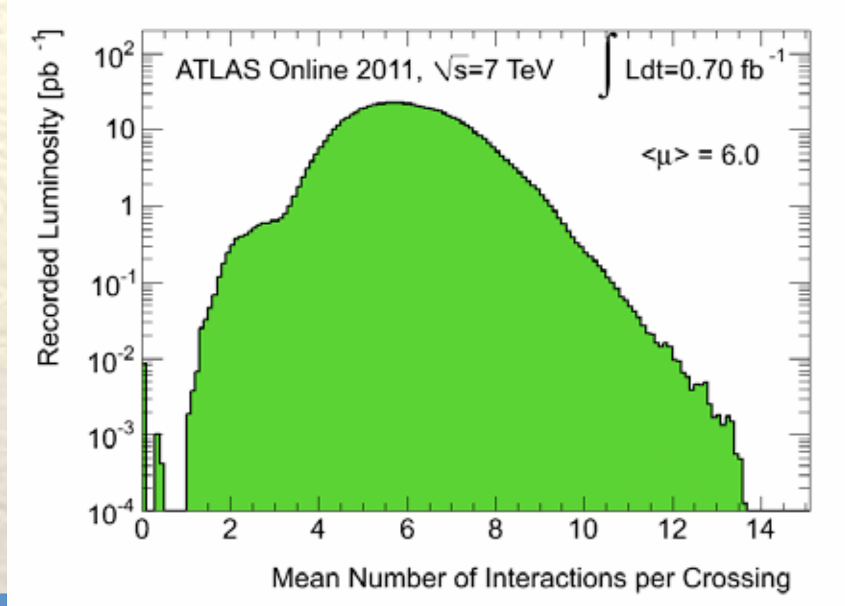
$\mathcal{L}_{tot}$ in 2011



Data Recording

- Total efficiency is >95%
- Efficiency in the subsystems is 90-100%
- Average number of interactions per crossing is 6



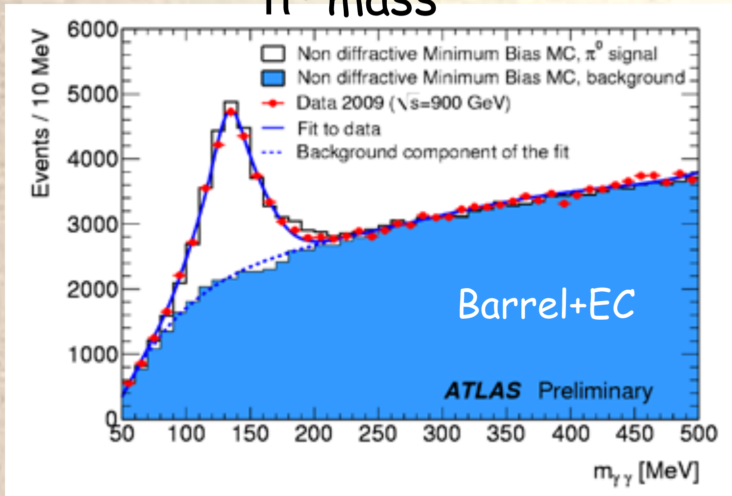


Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.5	100	89.3	92.7	94.3	99.5	100	99.5	100	99.9	98.5	97.9

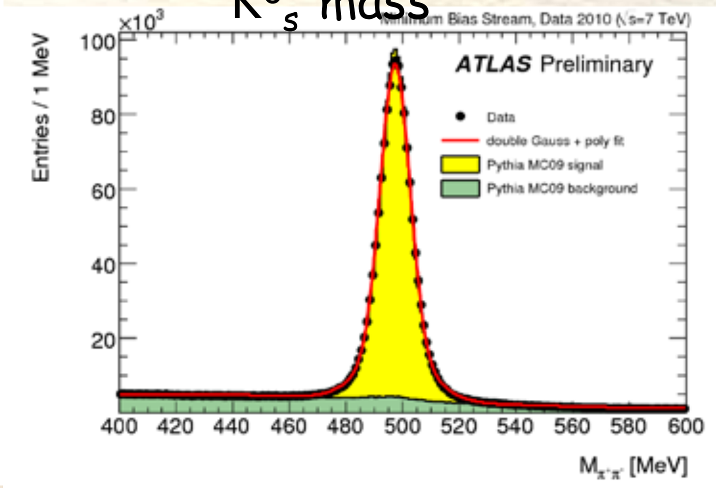
Performance on Particle Reconstruction

- ATLAS reconstructs various particles with good resolution

π^0 mass



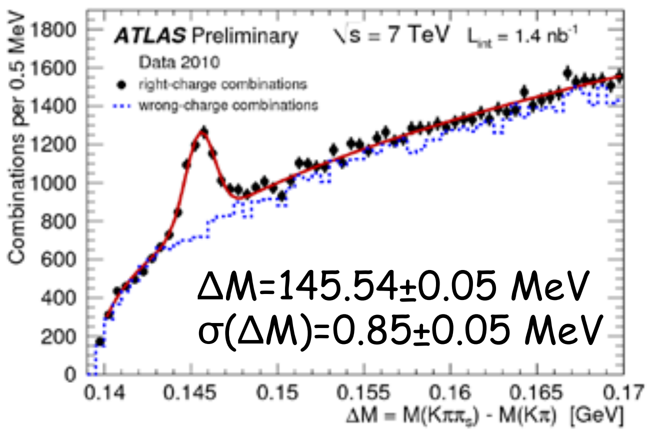
K^0_s mass



$m_{\pi 0}$ =134.0±0.8 MeV
$\sigma(m_{\pi 0})$=24MeV

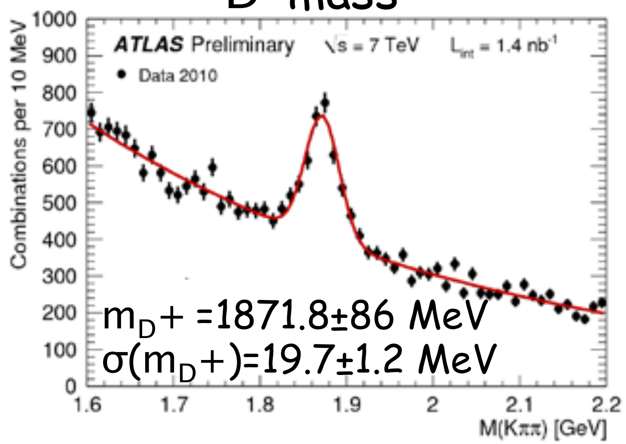
m_{K0s} 497.427=±0.006 MeV
$\sigma(m_{K0s})$=2.3±0.5 MeV

D^{*+}-D^0 mass difference



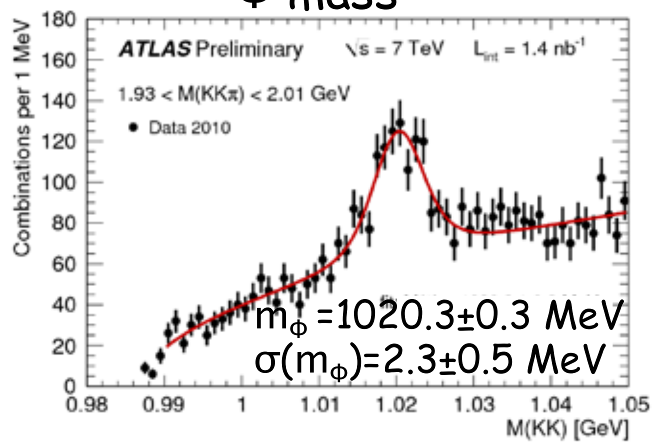
ΔM=145.54±0.05 MeV
$\sigma(\Delta M)$=0.85±0.05 MeV

D^+ mass



$m_{D}+$ =1871.8±86 MeV
$\sigma(m_D+)$=19.7±1.2 MeV

Φ mass



m_Φ =1020.3±0.3 MeV
$\sigma(m_\Phi)$=2.3±0.5 MeV

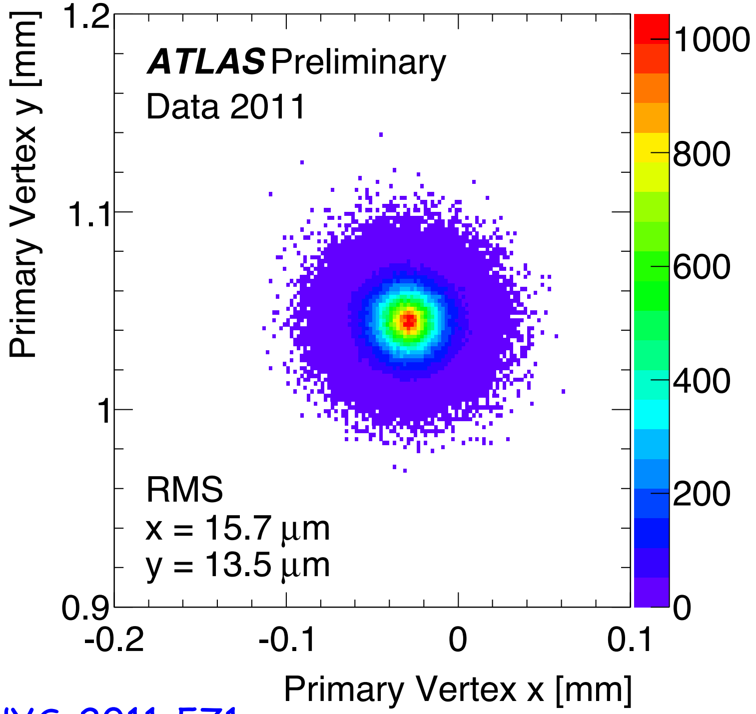
- ATLAS also reconstructs D_s^+, Λ, Σ, Ω, Λ_b, B_d^0, B^+, B_s^0,…

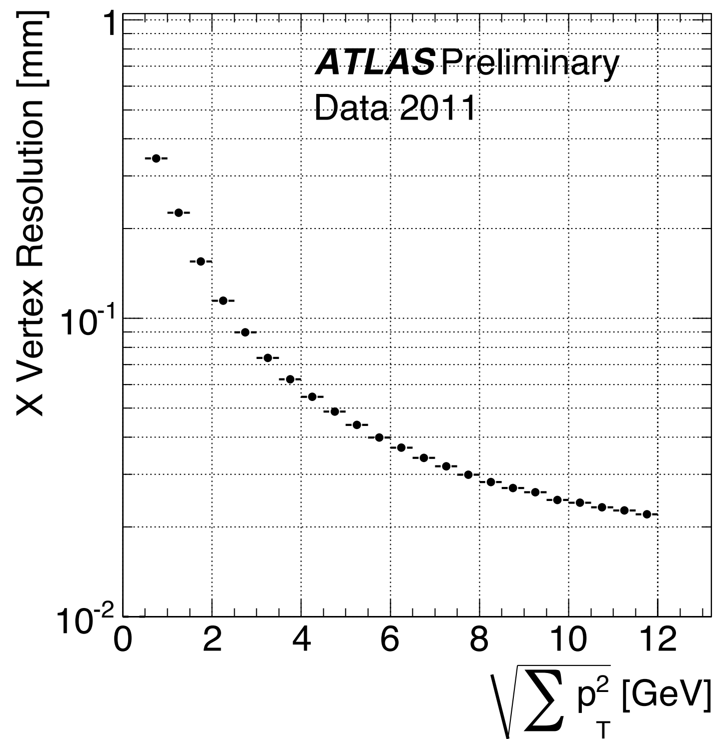
Measurement of Primary Vertex

- Select fully reconstructed tracks with small transverse & longitudinal impact parameter for primary vertex reconstruction
- Determine primary vertex with adaptive vertex fitting algorithm
- Remove tracks that are more than 7σ incompatible with PV and use as seed for new vertex
- Resolution

σ_x=15.7 μm

σ_y=13.5 μm





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Inner Detector Performance

- For precise measurements of secondary vertices, the performance of the Inner Detector is crucial, particularly that of the silicon pixels

- In the barrel measure σ=25 μm for hits from tracks with p_T> 2 GeV

- In the EC measure σ=20 μm for hits from tracks with p_T> 2 GeV

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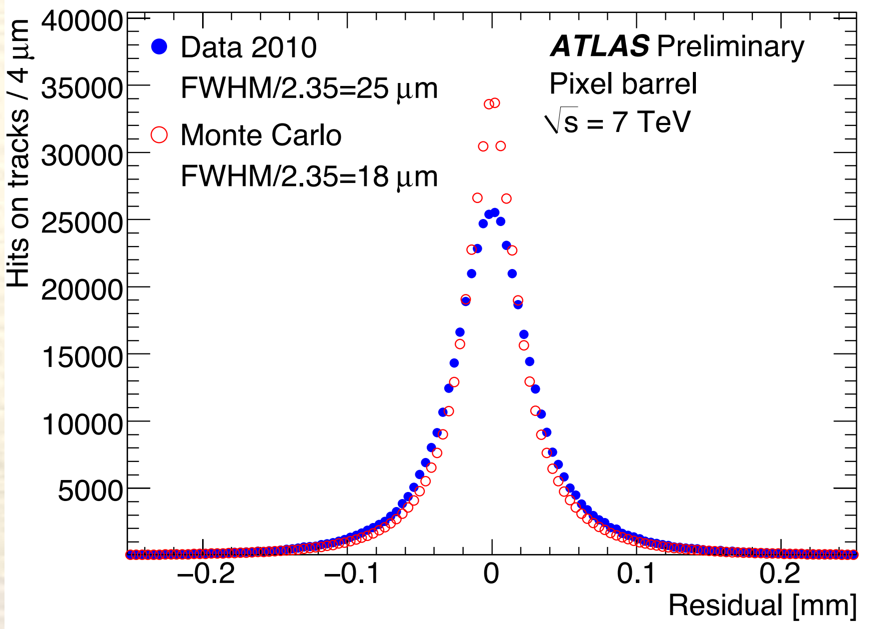
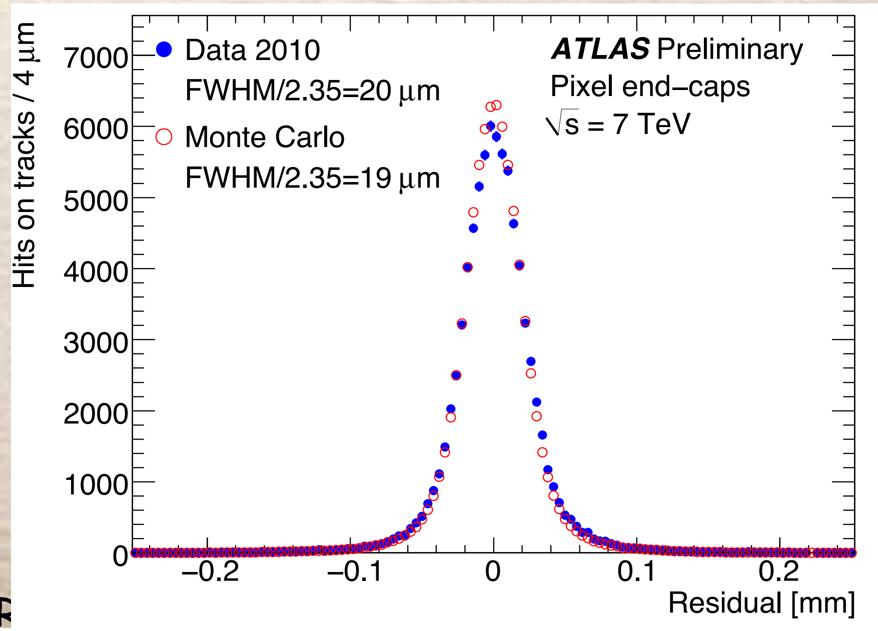
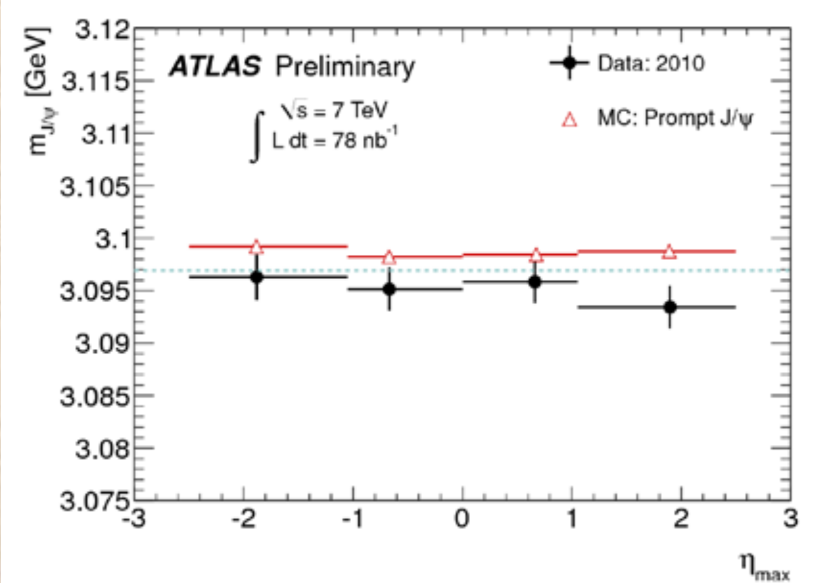
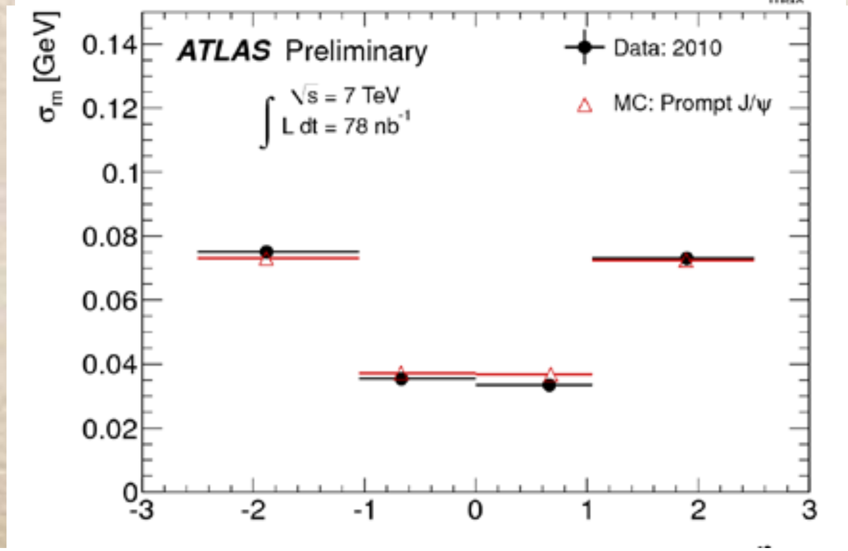


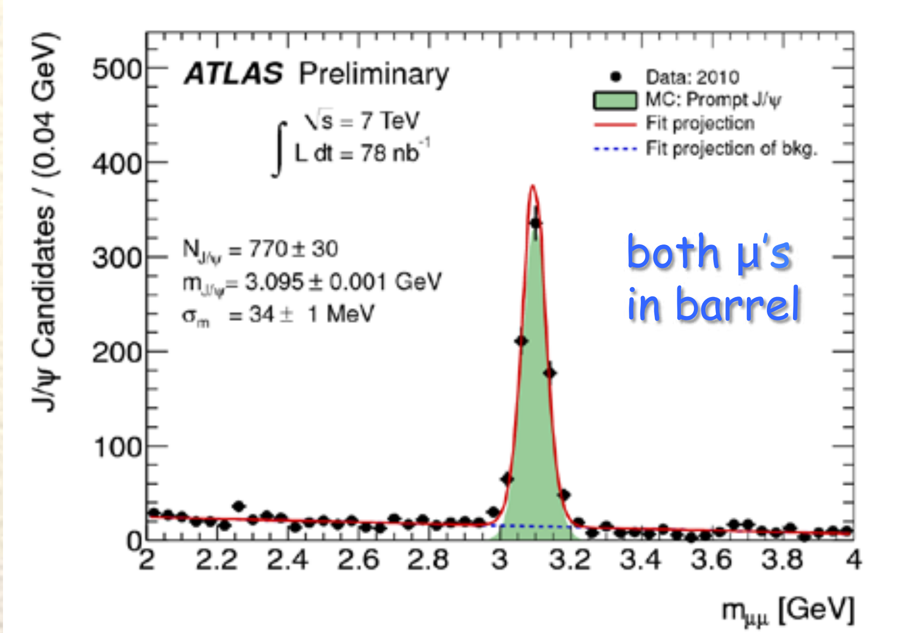


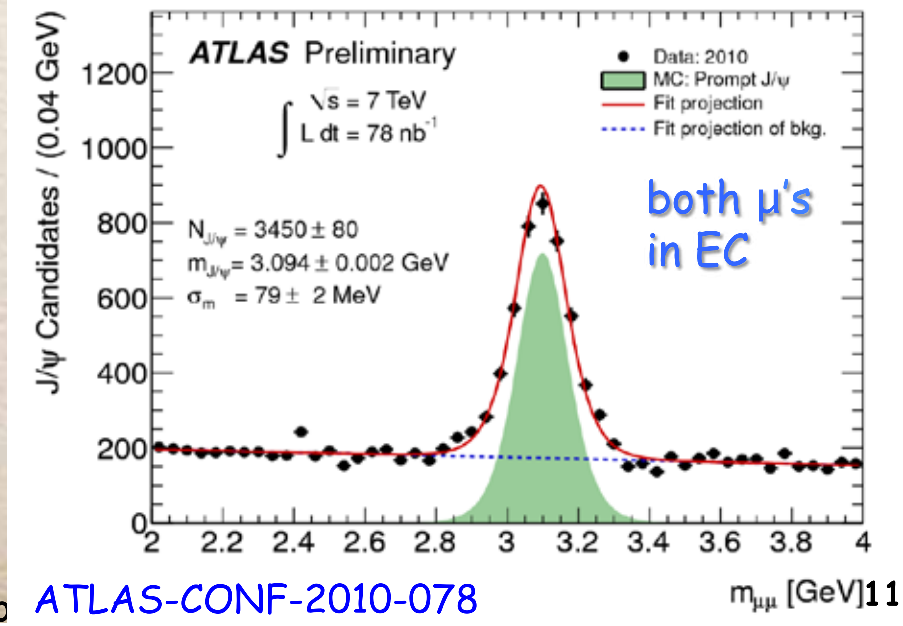
Performance: J/ψ

- Measure same J/ψ mass in different η bins consistent with PDG value









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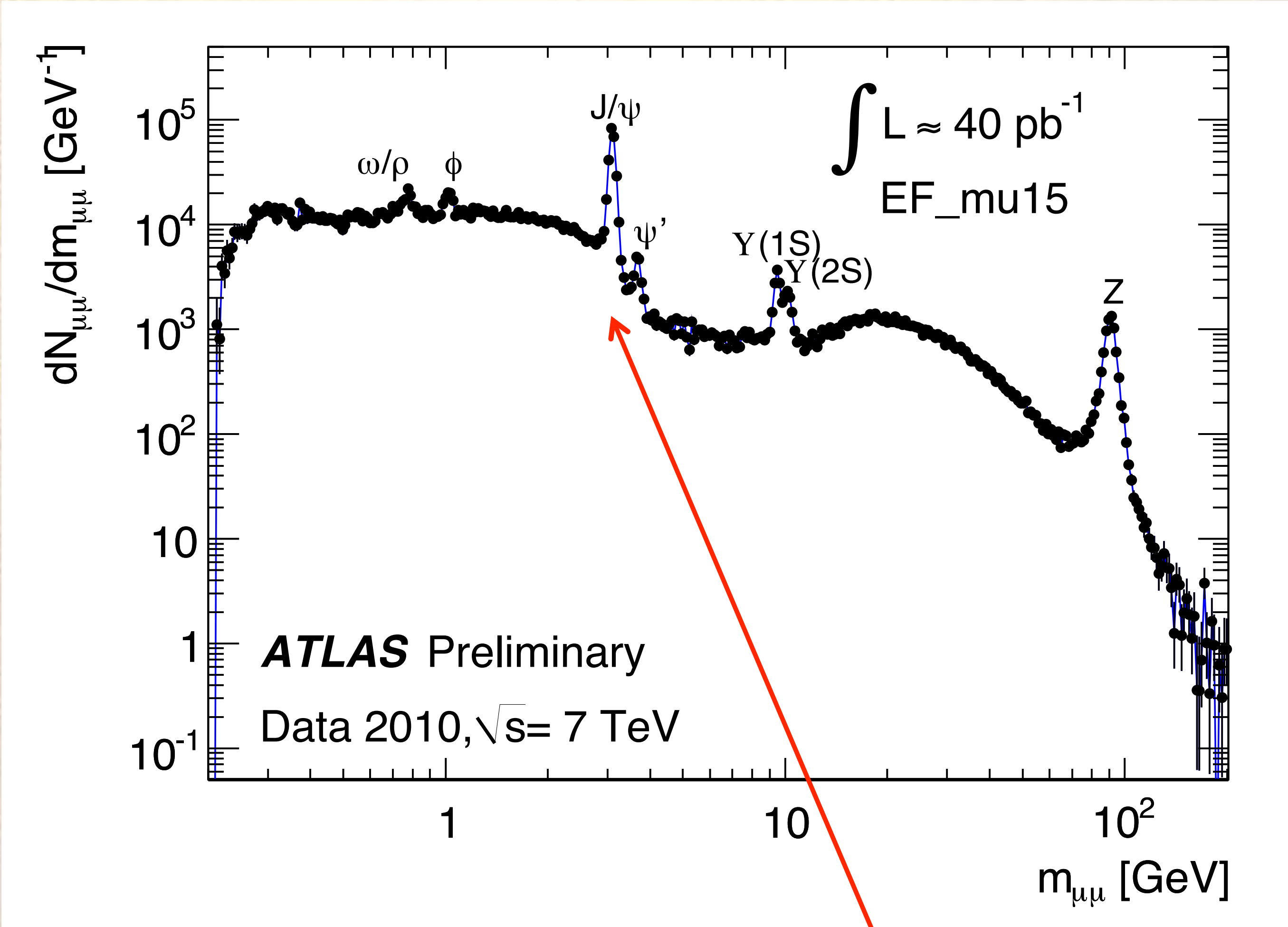
Inclusive Dimuon Mass Spectrum

- The inclusive dimuon mass spectrum reveals known vector states



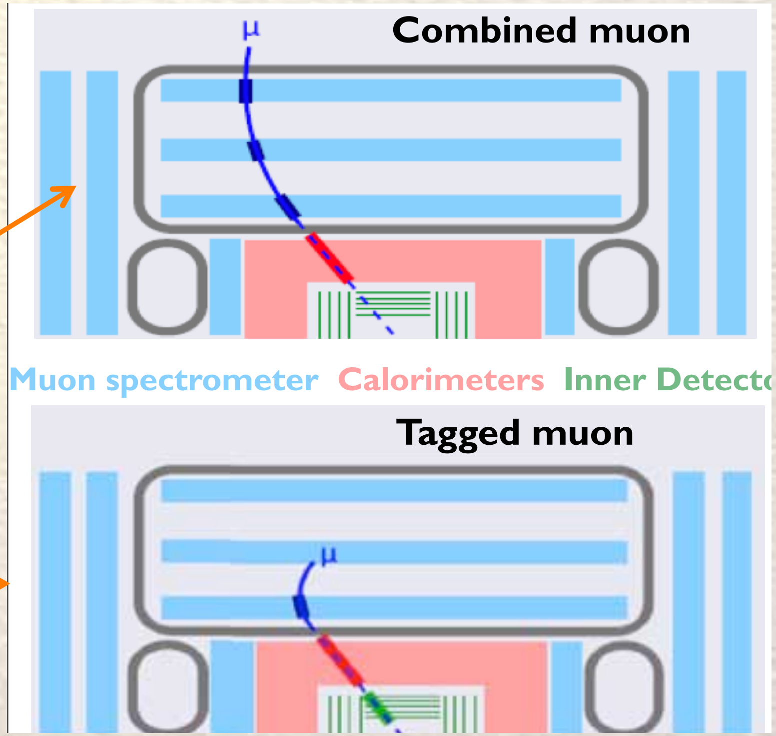
- We focus on exclusive final states with a **J/ψ**

Muon Selection

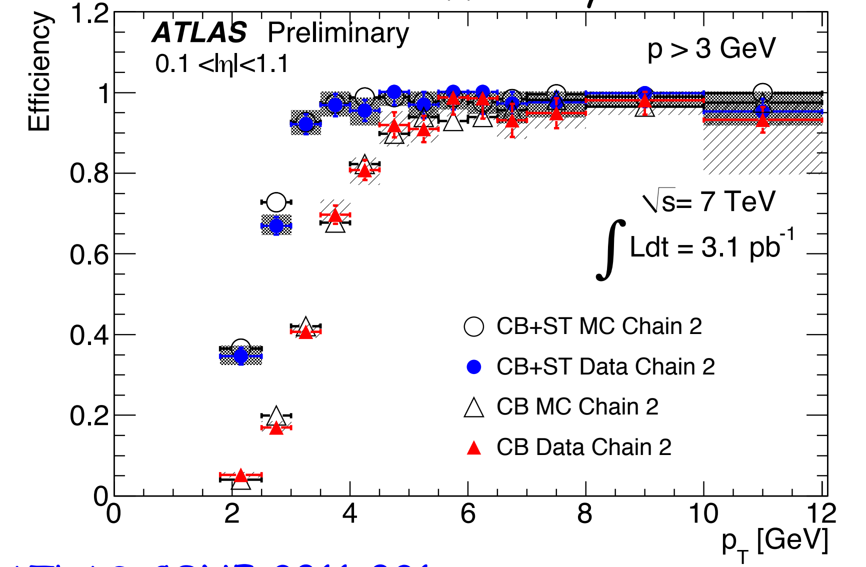
- Define two sets of μ candidates used in the J/ψ selection

Combined μ (CB): full muon spectrometer and track measurements in inner detector with a good fit between both regions

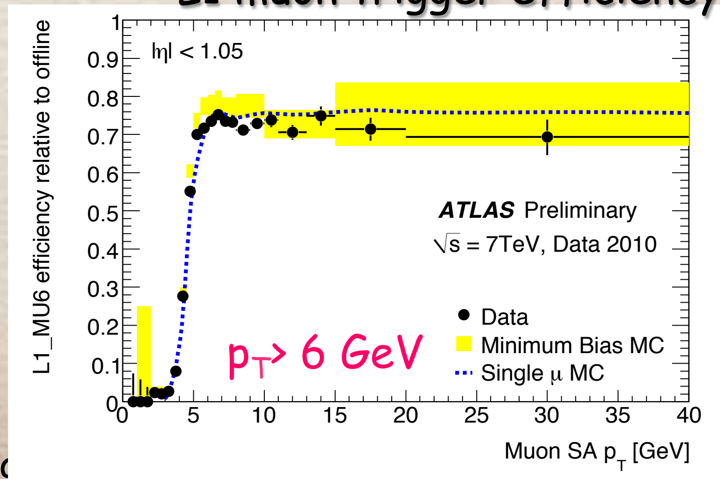
Segment Tagged μ (ST): track measurements in Inner Detector associated to at least one hit in muon spectrometer



Muon efficiency



L1 muon trigger efficiency



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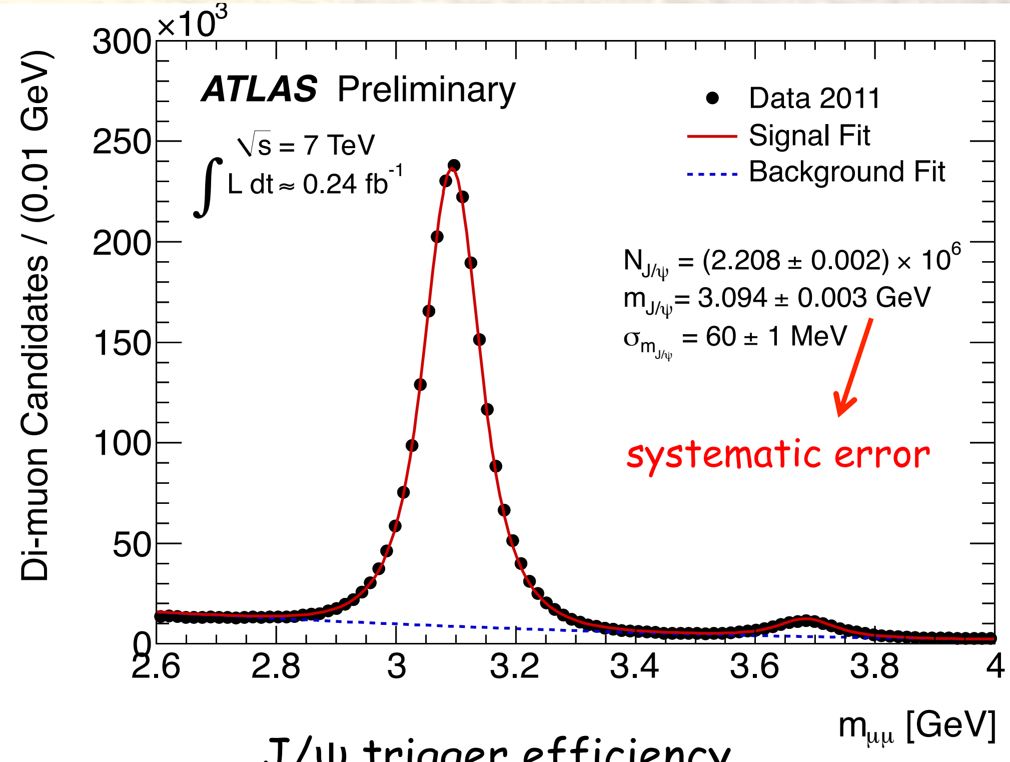
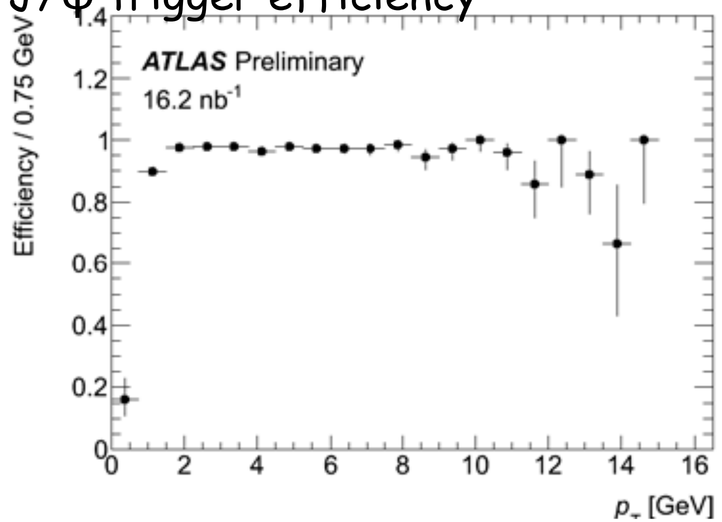
J/ψ Reconstruction

- Fit pairs of oppositely charged muons to common vertex
- Require at least 1 pixel hit & at least 4 SCT hits
- Determine p_T exclusively from Inner Detector track segment
- Select J/ψ candidate in mass windows
  - 2959-3229 MeV if both muons are in the barrel
  - 2913-3273 MeV for 1 muon in barrel, other muon in endcap
  - 2852-3332 MeV if both muons are in the endcaps
- J/ψ efficiency is uniform in p_T at ~100%

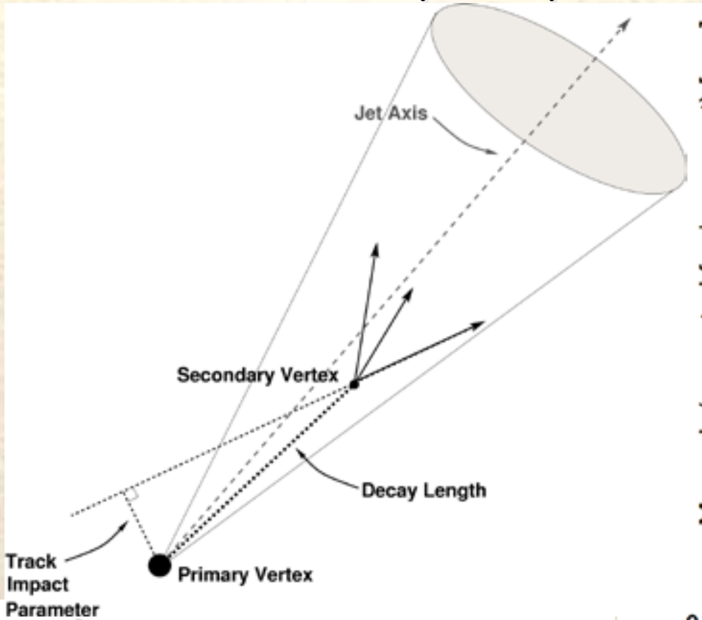


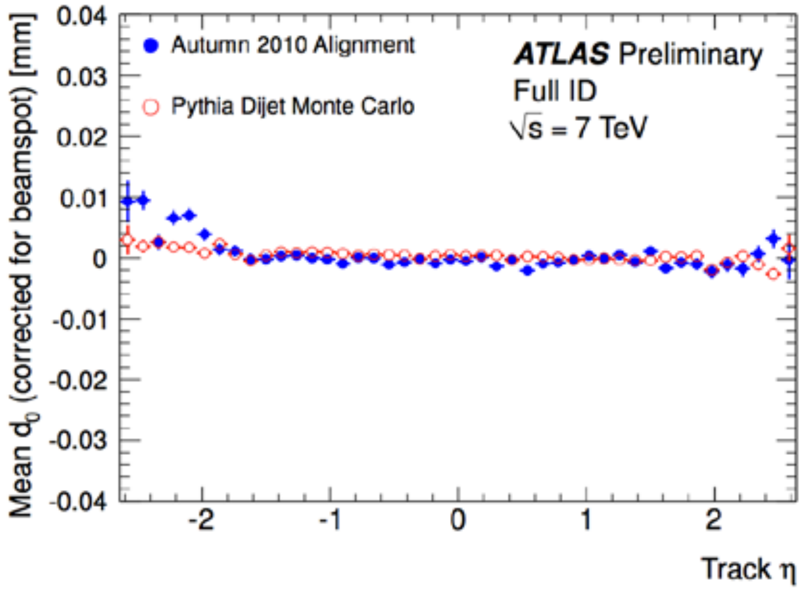
J/ψ trigger efficiency



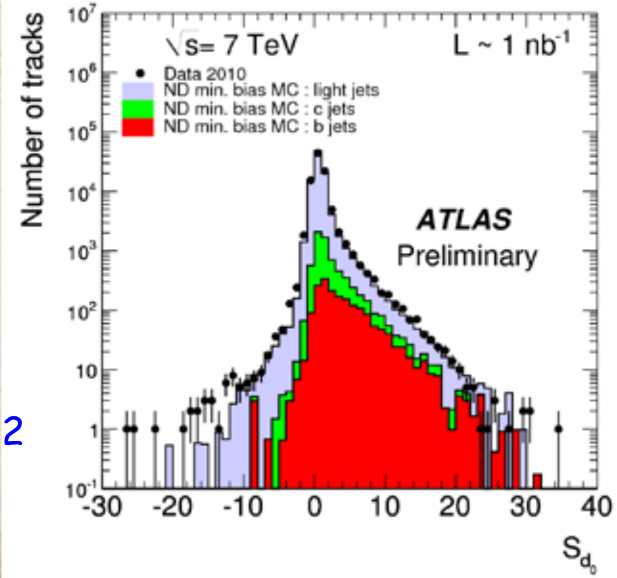
J/ψ Impact Parameter Resolution

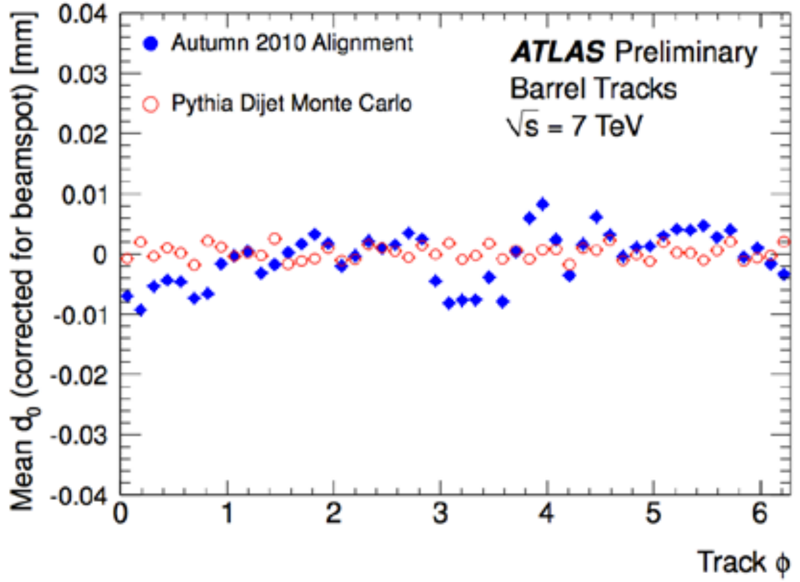
- Look for bias in transverse impact parameter distribution





- Mean value peaks at zero as expected
- Mean value is uniform in η and Φ
- Maximal deviation in η and Φ is less than **10 μm**





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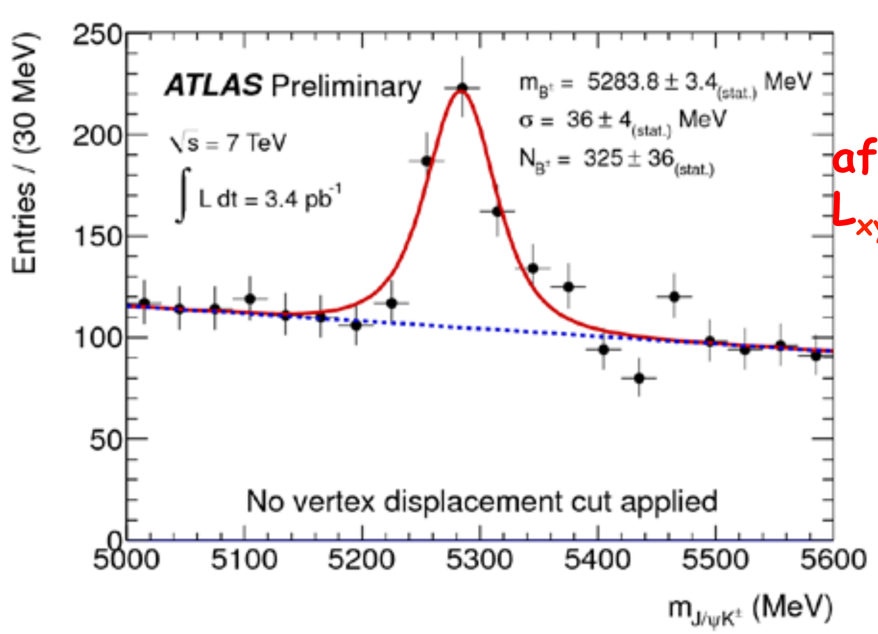
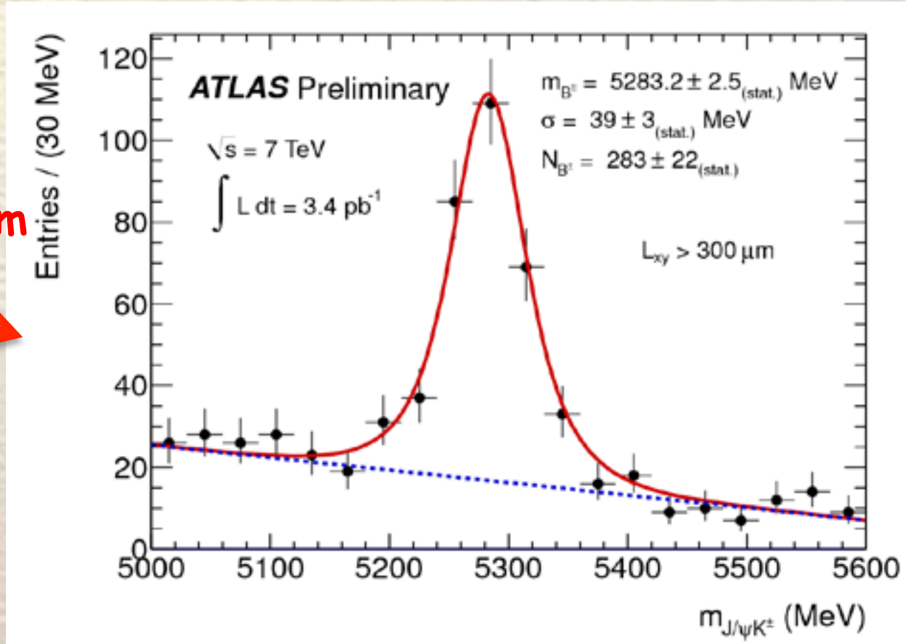
Observation of $B^{\pm} \rightarrow J/\psi(\mu^+\mu^-)K^{\pm}$

- Select additional track, assign kaon mass hypothesis
- Fit 3 track vertex; constrain $\mu^+\mu^-$ mass to $m(J/\psi)$
- Do unbinned maximum likelihood fit with Gaussian signal & linear bg
- Enhance signal-to-background with transverse decay length cut



after L_{xy} >300μm



- Mass consistent with PDG

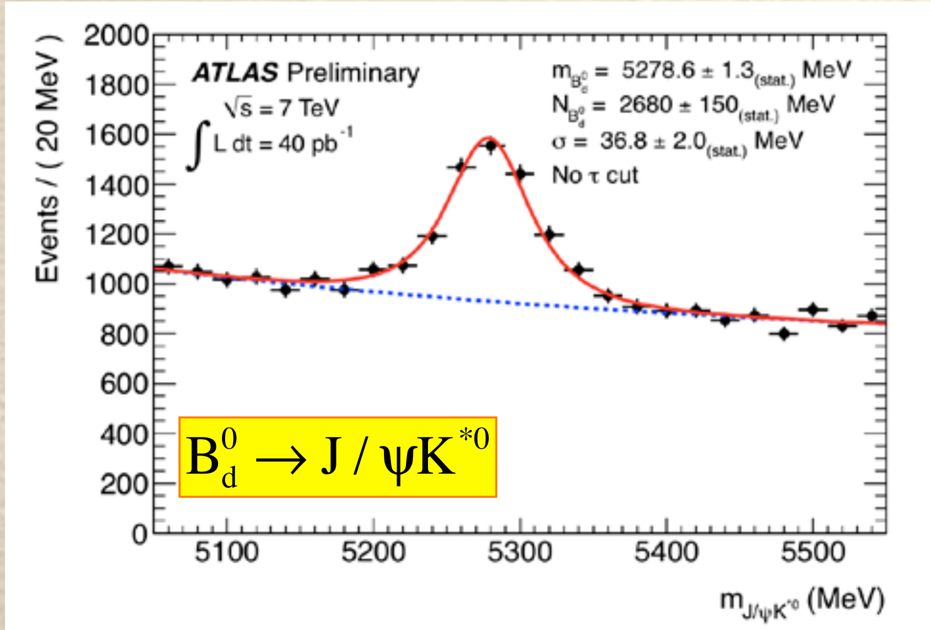
$m(J/\psi)$=5279.17±0.29 MeV

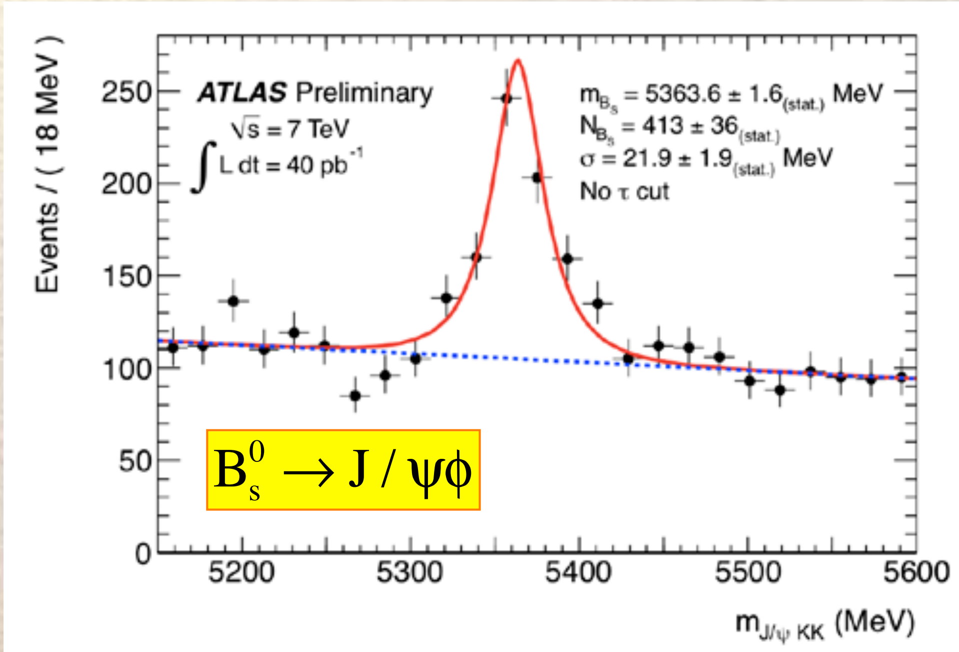
Consistent results for B^+ & B^-

ATLAS-CONF-2010-098

Observation of $B_d^0 \rightarrow J/\psi K^{*0}$ & $B_s^0 \rightarrow J/\psi \Phi$

- Select 2 additional tracks, assume $K^{*0} \rightarrow K^+\pi^-$, $\Phi \rightarrow K^+K^-$
- Fit 4-track vertex; constrain $\mu^+\mu^-$ mass to m(J/ψ)
- Apply mass cuts on $K^+\pi^-$ around K^{*0} and on K^+K^- around Φ
- Do unbinned maximum likelihood fit with Gaussian signal & linear bg





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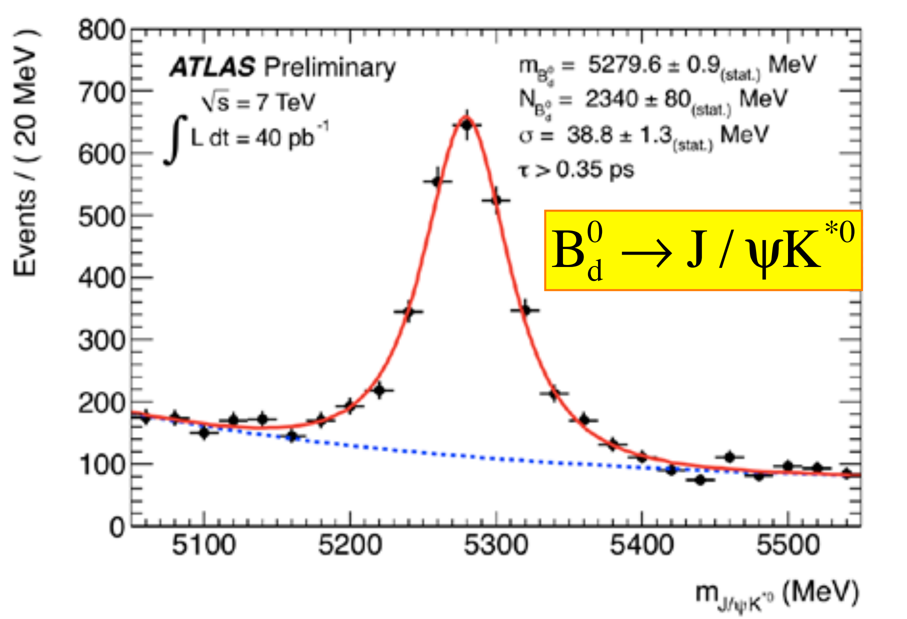
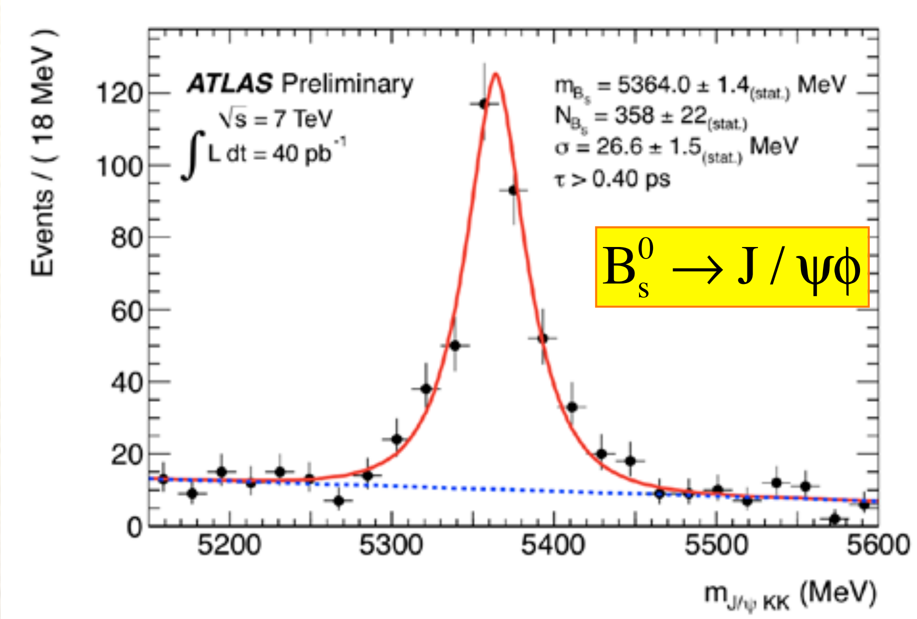
Observation of $B_d^0 \rightarrow J/\psi K^{*0}$ & $B_s^0 \rightarrow J/\psi \Phi$

- Add decay time cut on fitted secondary vertex





		m_B [MeV]	σ_m [MeV]	N_{signal}	$N_{background}$
B_d^0	no τ cut	5278.6±1.3	36.8±2.0	2680±150	10280±110
	w τ cut	5279.6±0.9	38.8±1.2	2340±80	1330±60
B_s^0	no τ cut	5363.6±1.6	21.9±1.9	413±36	764±17
	w τ cut	5364.0±1.4	26.6±1.6	358±22	90±7

- Consistent with PDG masses
- Good mass resolution

Lifetime Measurement Methodology

- Select J/ψ candidate and add $K^+\pi^-$ or K^+K^- to select $J/\psi K^{*0}$ or $J/\psi\Phi$
- For each candidate calculate the proper decay time

$$\tau = \frac{L}{\beta\gamma c}$$

L: distance between primary vertex & B decay vertex
βγ: Lorentz boost factor ≅ p/m
c: speed of light

- Precision is higher in the transverse plane

$$\tau = \frac{L_{xy} m}{p_T(B)}$$

L_{xy}: L in the transverse plane
p_T: transverse momentum
m: B invariant mass

- Perform simultaneous unbinned maximum likelihood fit to reconstructed B_d^0 (B_s^0) masses and proper decay times

$$L = \prod_{i=1}^{N} \left(f_{sig} \mathcal{M}_{sig}(m_i) \mathcal{T}_{sig}(\tau_i) + (1 - f_{sig}) \mathcal{M}_{bg}(m_i) \mathcal{T}_{bg}(\tau_i) \right)$$

- Background contributions
  - J/ψ from other B combined with random $K^+\pi^-$ (K^+K^-)
  - $J/\psi X$ from signal B with/without random $K^+\pi^-$ (K^+K^-)
  - Direct J/ψ production with random $K^+\pi^-$ (K^+K^-)

PDFs in ML Fit

- Signal mass is parameterized by a Gaussian using scale factor in width

$$\mathcal{M}_{sig}(m_i) = \frac{1}{\sqrt{2\pi}S_m\delta_{m_i}} \exp\left(\frac{-(m_i - m_B)^2}{2(S_m\delta_{m_i})^2}\right)$$

S_m: scale factor

- Background mass distribution is modeled with a linear function

$$\mathcal{M}_{bg}(m_i) = \frac{1}{m_{max} - m_{min}}\left(1 + d(m_i - m_C)\right)$$

d: slope
$m_C=(m_{max}-m_{min})/2$

- Signal proper decay time pdf is exponential decay convolved with Gaussian resolution function $R(\tau'-\tau,\delta_{\tau i})$ with width $S_\tau \cdot \delta_{\tau_i}$

$$\mathcal{T}_{sig}(\tau_i,\delta_{\tau_i}) = E(\tau') \otimes R(\tau' - \tau_i, S_\tau\delta_{\tau_i})$$

S_τ scale factor

- Background with J/ψ from other B is parameterized by

$$\mathcal{T}_{bg1}(\tau_i,\delta_{\tau_i}) = \left[\frac{b}{\tau_{eff1}}\exp\left(\frac{-\tau'}{\tau_{eff1}}\right) + \frac{1-b}{\tau_{eff2}}\exp\left(\frac{-\tau'}{\tau_{eff2}}\right)\right] \otimes R\left(\tau' - \tau_i, S_\tau\delta_{\tau_i}\right)$$

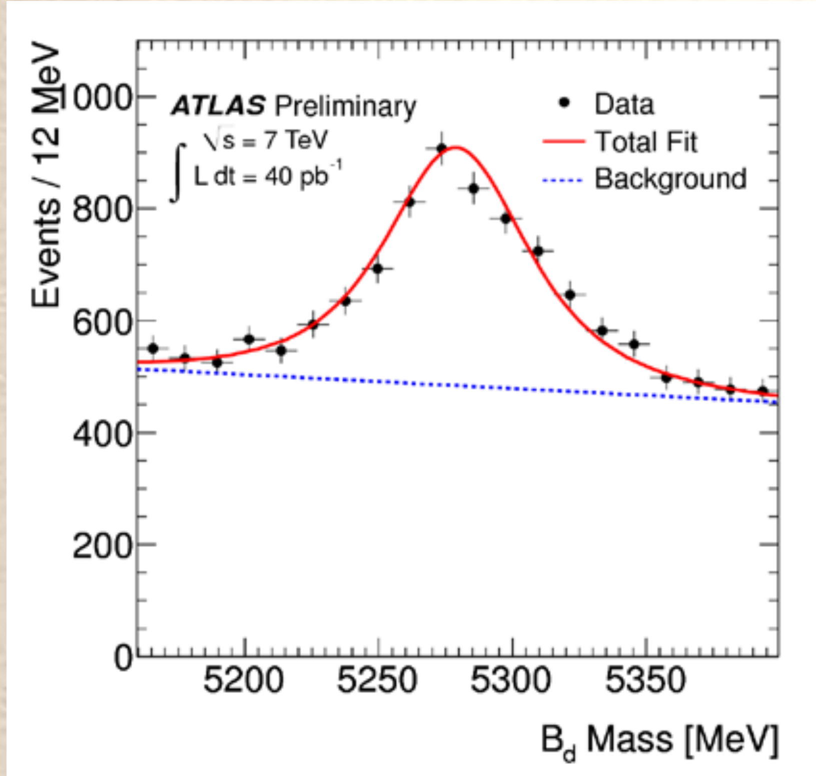
$$\mathcal{T}_{bg2}(\tau_i,\delta_{\tau_i}) = \frac{1}{\tau_{eff3}}\exp\left(\frac{-|\tau'|}{\tau_{eff3}}\right) \otimes R\left(\tau' - \tau_i, S_\tau\delta_{\tau_i}\right)$$

τ_{eff1}, τ_{eff2}, τ_{eff3} are 3 background lifetimes Determined in fit

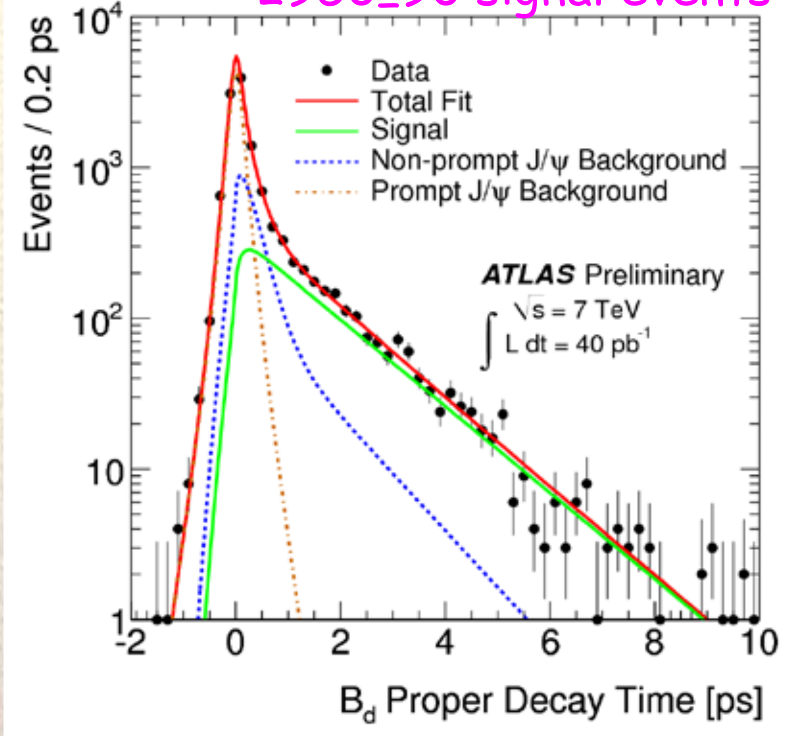
- Background of direct J/ψ is parameterized by $R(\tau_i, S_\tau\delta_{\tau_i})$

Results for $B_d^0 \rightarrow J/\psi K^{*0}$

- Keep 12 parameters free in ML fit: f_{sig}, m_B, S_m, d, τ_B, S_τ, 3 background lifetimes and 3 background fractions



2950±90 signal events



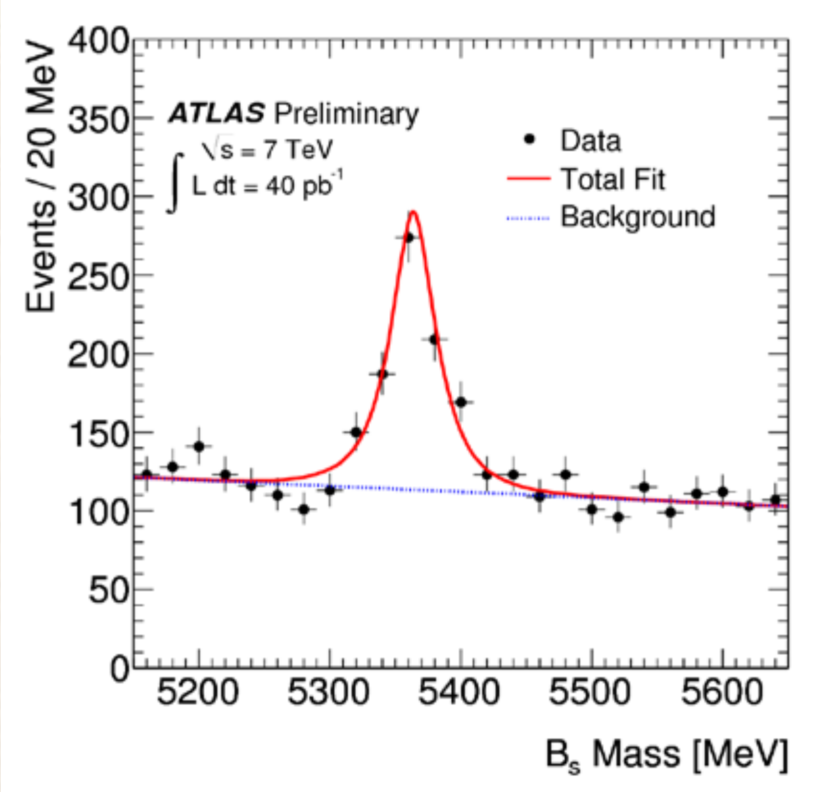
- Measure: $m_{B_d^0} = (5279.0 \pm 0.8)\,\mathrm{MeV}$ $\quad \sigma_m = (34.3 \pm 0.9)\,\mathrm{MeV}$

$$\tau_{B_d^0} = (1.51 \pm 0.04 \pm 0.04)\,\mathrm{ps}$$

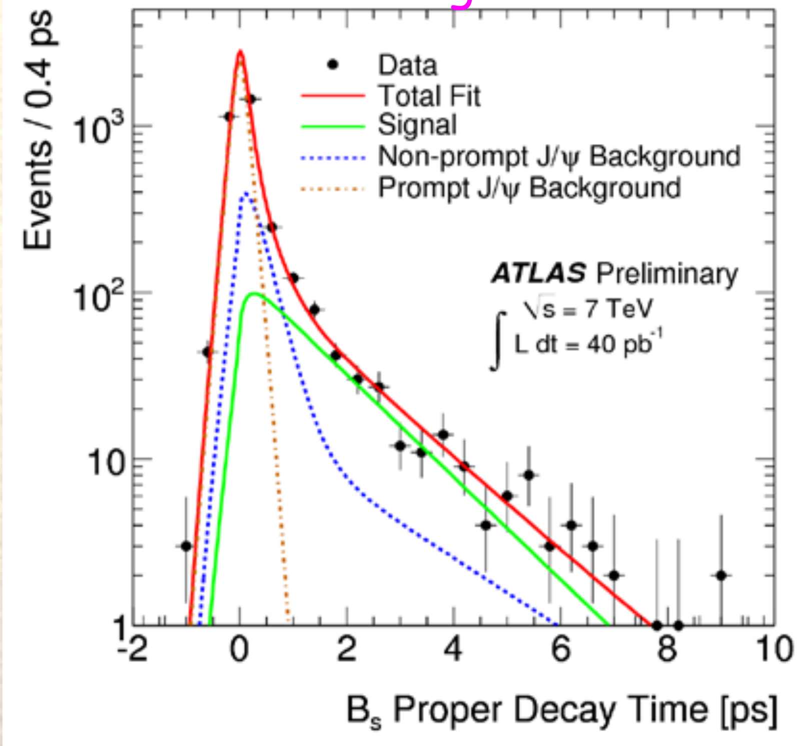
- Good agreement with PDG value

$$\tau_{B_d^0} = (1.525 \pm 0.009)\,\mathrm{ps}$$

Results for $B_s^0 \rightarrow J/\psi\Phi$



463±26 signal events



- Measure $m_{B_s^0} = (5363.7 \pm 1.2)\mathrm{MeV}$
  $\sigma_m = (24.8 \pm 1.2)\mathrm{MeV}$

$$\tau_{B_s^0}(J/\psi\phi) = (1.41 \pm 0.08 \pm 0.05)\,\mathrm{ps}$$

  - Good agreement with HFAG value

$$\tau_{B_s^0}(J/\psi\phi) = (1.429 \pm 0.088)\,\mathrm{ps}$$

- In $B_s^0 \rightarrow J/\psi\Phi$ CP-even and CP odd components that have different lifetimes are not symmetric ➔ τ differs from generic B_s lifetime

B Flavor Tagging

- For tagging of B flavor at production use lepton charge or jet charge

$$Q_{jet} = \sum_i q_i p_i^\kappa \Big/ \sum_i p_i^\kappa$$

$q_i \equiv$ charge of track i $q_i \equiv$ momentum of track i $\kappa \equiv$ weight

- The jet charge is positive for $\bar{b}$ jets and negative for b jets
- Jet consists of all tracks with $p_T > 500$ MeV, $|\eta|<2.5$ inside a cone with opening angle

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

- Remove cases where jet charge is close to zero by "exclusion cut"
- Key quantities in tagging are efficiency and dilution

$$\varepsilon_{tag} = \frac{N_r + N_w}{N_{total}} \qquad D_{tag} = \frac{N_r - N_w}{N_r + N_w} = 1 - 2w_{tag}$$

$N_r \equiv$ correctly tagged

$N_w \equiv$ wrong tagged

$$w_w \equiv \frac{N_w}{N_r + N_w}$$

- The true asymmetry & its error are given by

$$A = \frac{A_{meas}}{D_{tag}} \qquad \sigma \approx \frac{1}{\sqrt{\varepsilon_{tag} D_{tag}^2 N_t}}$$

b Flavor Tagging in Simulation

- Tagging effectiveness is given by

$$Q_{tag} = \varepsilon_{tag} D^2_{tag}$$

- Study jet charge in $B_d^0 \to J/\psi K^{*0}$ or $B_s^0 \to J/\psi \Phi$

- For simulation assume 15000 signal events expected for 150 pb^{-1} in $B_d^0 \to J/\psi K^{*0}$ & 1.5fb^{-1} in $B_s^0 \to J/\psi \Phi$

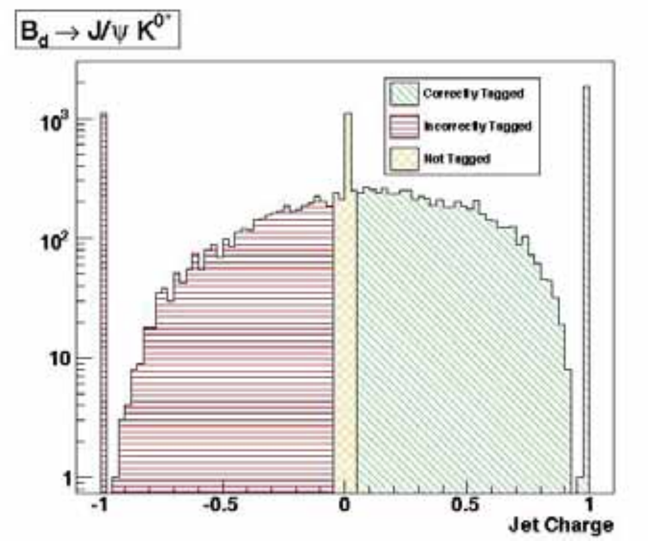
- Simultaneous mass & lifetime fit

- Optimize selection

Parameter	$B_d^0 \to J/\psi K^{0*}$	$B_s^0 \to J/\psi \phi$
κ	0.9	0.8
ΔR cut	0.7	0.6
Exclusion cut	0.05	0.2

- Achieve high efficiency & reasonable dilution

- For lepton tags expect higher purity but lower efficiency,



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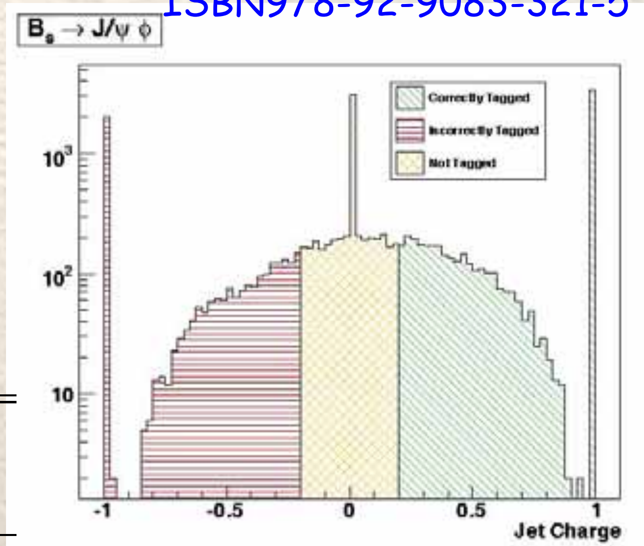
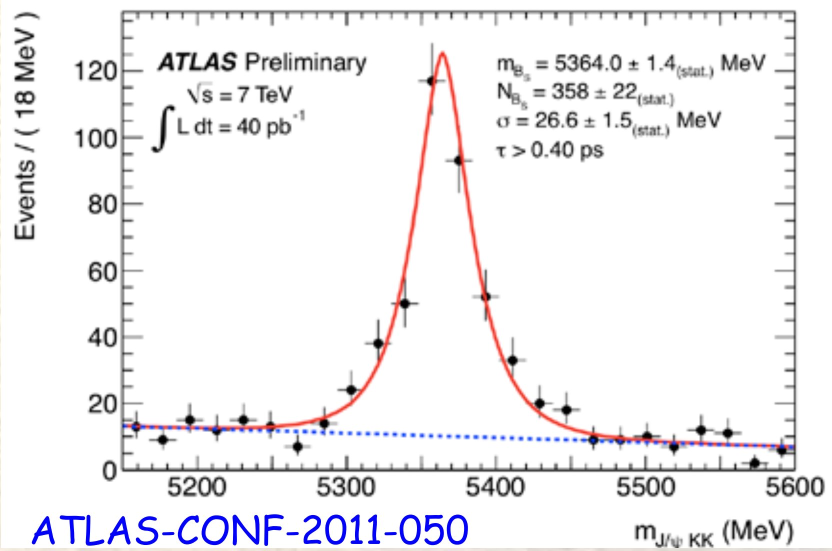


Parameter	$B_d^0 \to J/\psi K^{0*}$	$B_s^0 \to J/\psi \phi$
Equivalent luminosity	150 pb^{-1}	1.5 fb^{-1}
Number of Reconstructed Events	13948	15784
Efficiency, ε_{tag}	0.870 ± 0.003	0.625 ± 0.005
Wrong Tag Fraction, w_{tag}	0.380 ± 0.004	0.374 ± 0.005
Dilution, D_{tag}	0.240 ± 0.009	0.251 ± 0.010
Quality, Q_{tag}	0.050 ± 0.004	0.039 ± 0.003

Estimated J/ψΦ Signal Yields by End 2012

- Use ATLAS and LHCb observed J/ψΦ signal yields to estimate expectation at end of 2012
- ATLAS observes **358±22 signal** events in 40 pb^{-1} after a 0.4ps lifetime cut
- For 10 fb^{-1} with the same trigger conditions, ATLAS expects **89500±5500** J/ψΦ signal events
- Increased trigger thresholds may reduce this yield by 50%
- LHCb sees **760±29** J/ψΦ signal events in 36pb^{-1}
- For 2 fb^{-1} (corresponds to 10 fb^{-1} in ATLAS) LHCb expects **42222±1611** J/ψΦ signal events
  - **ATLAS will make a valuable contribution to the determination of β_s**



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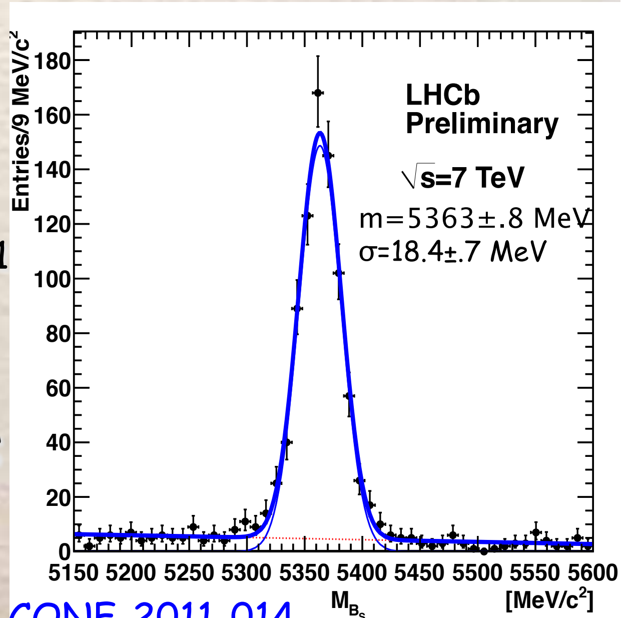

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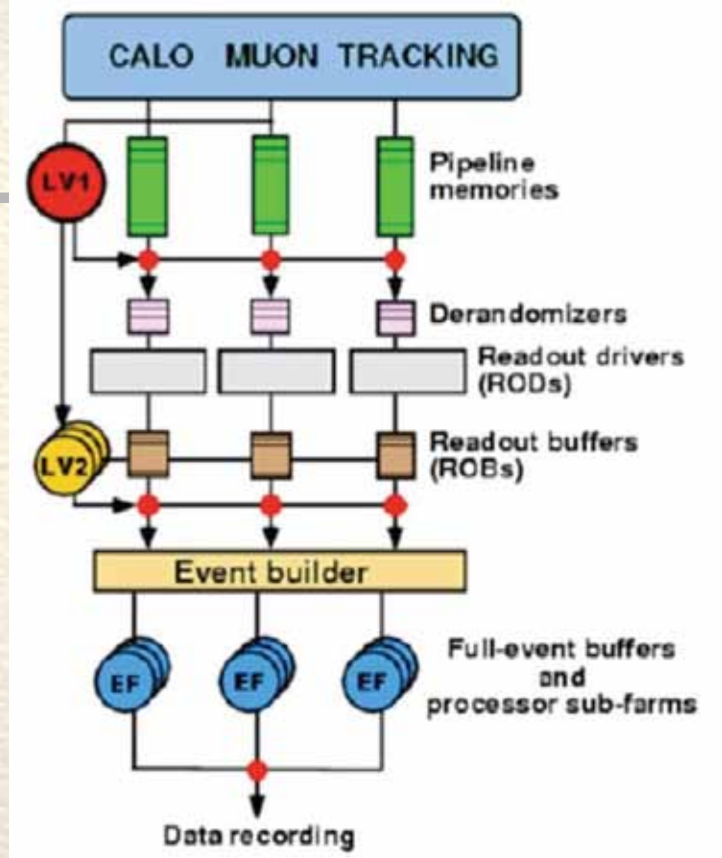
Conclusions

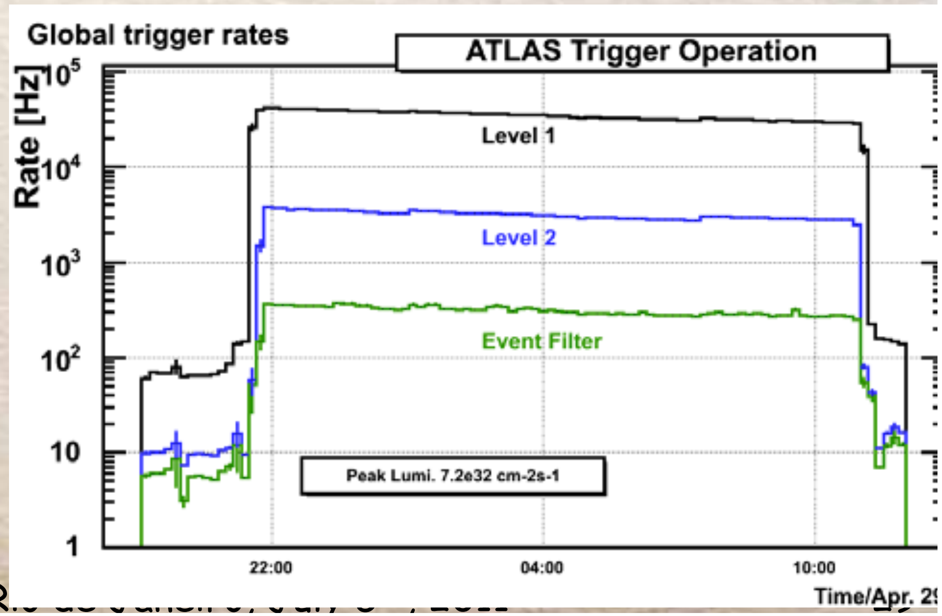
- ATLAS is a well-working detector recording data with high efficiency
- ATLAS has an excellent capability to measure secondary vertices, tag the b flavor at production with high tagging effectiveness and reconstruct B exclusive final states with excellent mass resolution and high efficiency
  - ATLAS measures $B^+ \rightarrow J/\psi K^+$, $B_d^0 \rightarrow J/\psi K^{*0}$ & $B_d^0 \rightarrow J/\psi \Phi$ signals with low background
- ATLAS performes first lifetime measurements in $B_d^0 \rightarrow J/\psi K^{*0}$ & $B_d^0 \rightarrow J/\psi \Phi$
- Thus, ATLAS has excellent capabilities to measure CPV in B decays

Backup Slides

Trigger Operations

- Trigger is organized in 3 levels
  - L1: hardware trigger
    - ➔ 50 kHz rate
  - L2: software selection on reduced granularity (ROI)
    - ➔ 4 kHz rate
  - EF: Based on offline reconstruction, full granularity
    - ➔ 200 Hz rate design with peak to 600 Hz





- Rates of physics objects are very well understood
- Physics rate is ~300 Hz

Systematic Errors in B_d^0 & B_s^0 Lifetimes

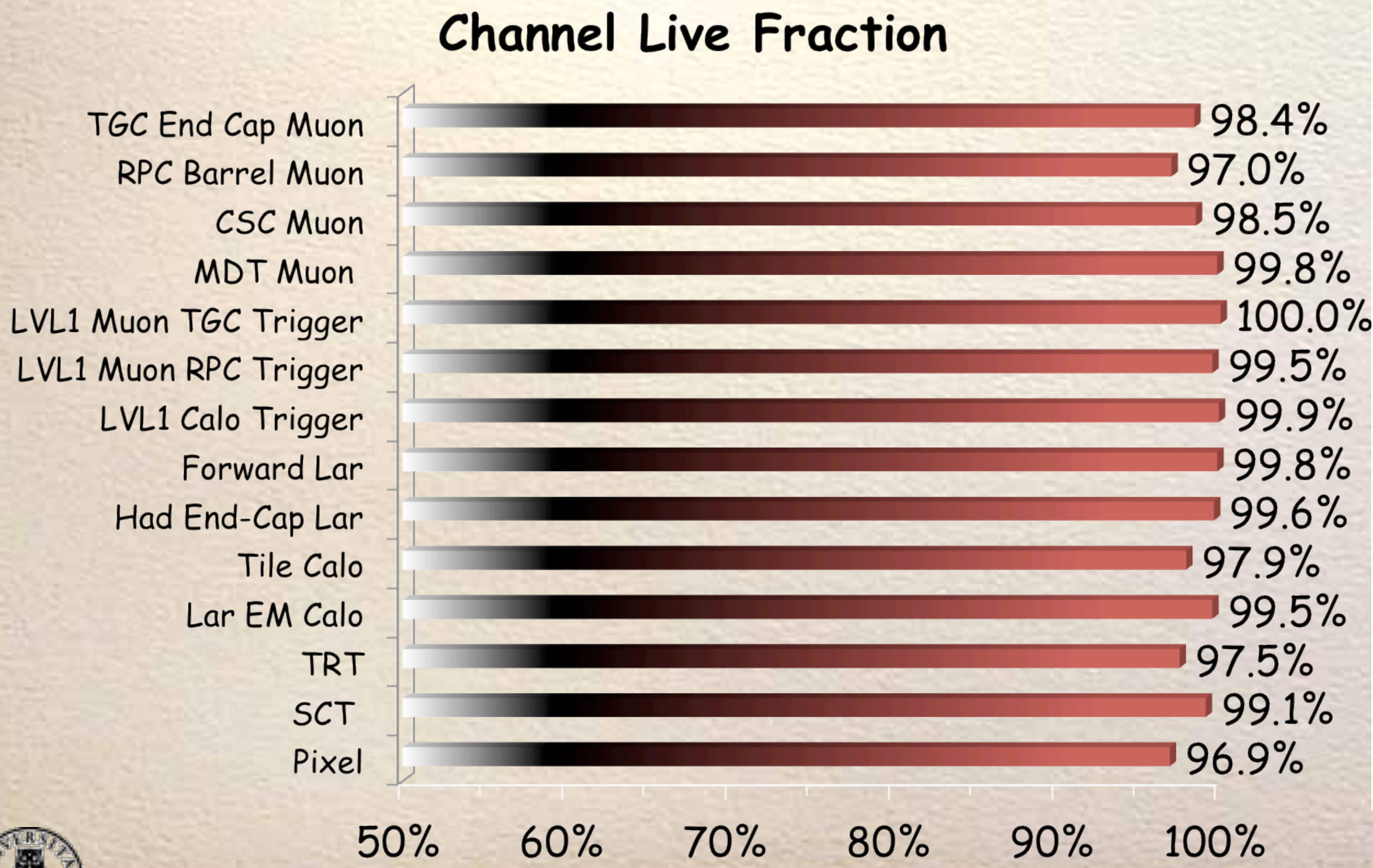
- Modeling of signal and background in ML fit
  ➔ use alternative parameterization

Source of systematics	Systematic uncertainty $\delta_{syst}(\tau_{B_d})$, ps	$\delta_{syst}(\tau_{B_s})$, ps
Modelling signal, background	0.01	0.01
Time uncertainty model	0.03	0.03
Mass window	0.01	0.015
Alignment	0.03	0.03
Total, quadratic sum	0.04	0.05

- Fit procedure
  ➔ run several thousand toy experiments
- Mass window
  ➔ for B_d^0 vary window (5169, 5389) MeV to (5079, 5479) MeV in 14 steps
  ➔ for B_s^0 vary (5150, 5650) MeV to (5220, 5510) MeV in 11 steps
- Time uncertainty model
  ➔ assume different proper time decay models
- Choice of primary vertex
  ➔ use different impact parameter calculation

ATLAS Subsystem Operation

- Fraction of operational channels is close to 100% for all systems



Number of Channels
320 K
370 K
31 K
350 K
320 K
370 K
7 K
3.5 K
5.6 K
9.8 K
170 K
350 K
6.3 M
80 M

J/ψ Candidate Selection