CP Violation in ATLAS

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on behalf of the ATLAS collaboration

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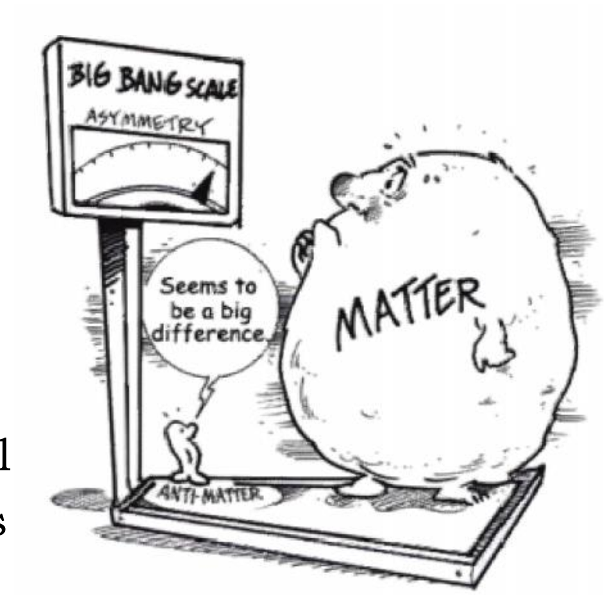
- Summary

Introduction

- One of the main tasks of modern physics is to test key predictions of SM:
  - search for the source of CPV in SM
  - search for discrepancies that would provide evidence for physics BSM
  - establish connection between the observed CPV and the one needed to explain baryon asymmetry
- The most recent results in B-Physics experiments show that the complex phase of CKM quark mixing matrix is the only source of CP violation in SM
  - Precise measurement of other CKM matrix elements at the percent level
- A promising strategy → study the processes where the SM predicts a small CPV, and the extensions of SM predicts large CPV effects
- This strategy is adopted by ATLAS experiment
- Current study on CPV with ATLAS detector is performed by measuring time-dependent asymmetries in 'gold-plated' $B_s \to J/\Psi\Phi$ channel
- The results of the latest exp. study of CPV in this channel are in agreement with SM predictions

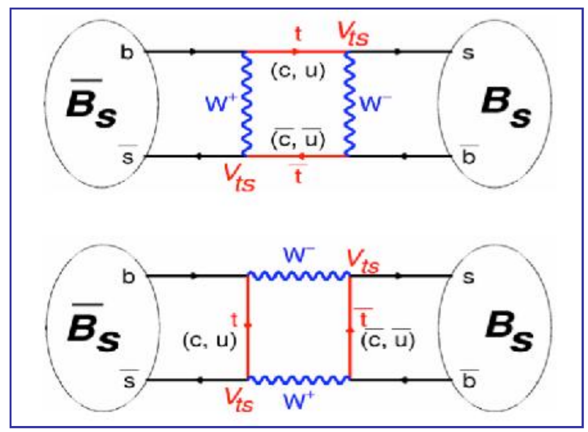


CP violation in neutral B_s system

- Flavour change via weak interaction gives rise to B_s-$\overline{B_s}$ mixing; B meson is then found in the quantum superposition in states B_{sH} and B_{sL} that are CP eigenstates, odd and even respectively; B_s^H and B_s^L states also have different lifetimes
- Contrary to any other system, B_s is strongly mixed
- CPV arises from interference of $B_s \to J/\Psi\Phi$ decay and B_s- $\overline{B_s}$ mixing and is proportional to a phase difference ϕ_s of the two weak amplitudes

mixing of flavour eigenstates is governed by:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = H \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} \equiv \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2} \underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}} \Bigg] \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$



flavour eigenstates:

$$|B_s^0\rangle = (\bar{b}s)$$
$$|\bar{B}_s^0\rangle = (b\bar{s})$$

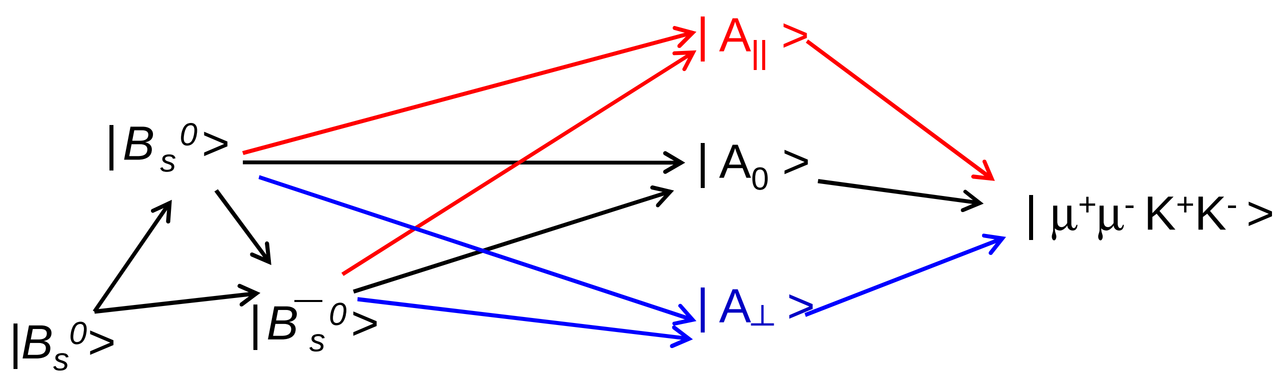
mass eigenstates:

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$$
$$|B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$$

- Different masses $\to$ mixing frequency: $\Delta m_s = m_H - m_L \approx 2|M_{12}|$
  $\to$ phase: $\phi_s = \arg(-M_{12}/\Gamma_{12})$
- Different decay widths: $\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(2\,\phi_s)$

CP violation in neutral B_s system

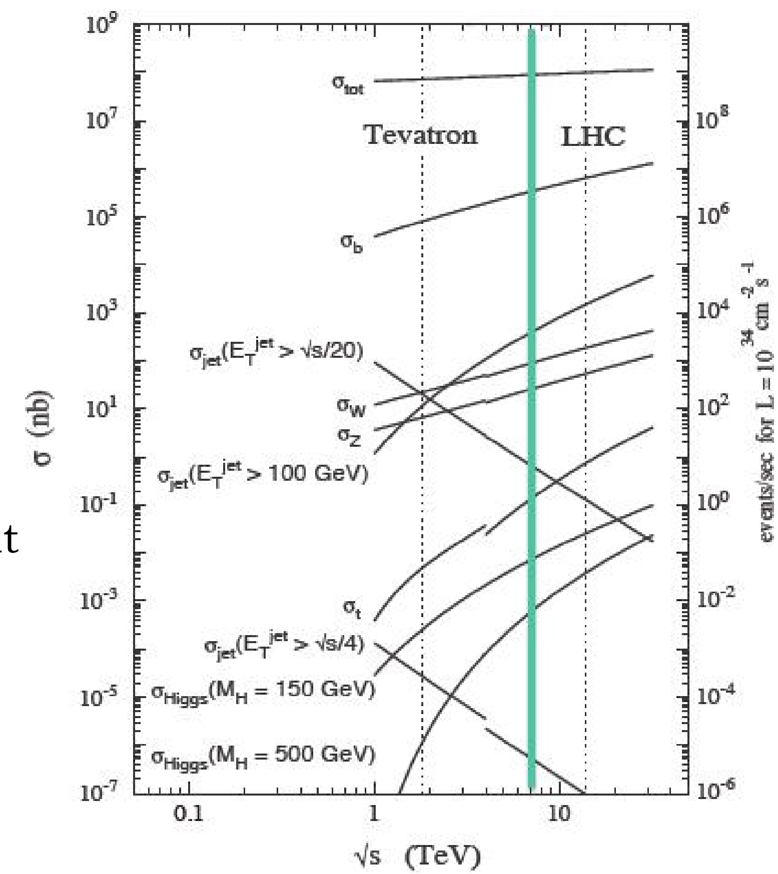
- The final $J/\Psi\Phi$ state can be found in different polarization states/CP eigenstates (L=0, 2 CP-even, L=1 CP-odd)
- The decay is described by 3 complex amplitudes: A_0, $A_\parallel$ and $A_\perp$
- CP-even B_s state decays through A_0, $A_\parallel$ amplitudes; CP-odd state decays through $A_\perp$
- The time evolution of these amplitudes is different as B_s^L and B_s^H have different width
- We can obtain the width of B_s^L and B_s^H and the CP violating phase ϕ_s by studying the evolution in time of the angular distributions of $B_s \to J/\Psi\Phi$ decay products



B Physics potential of ATLAS

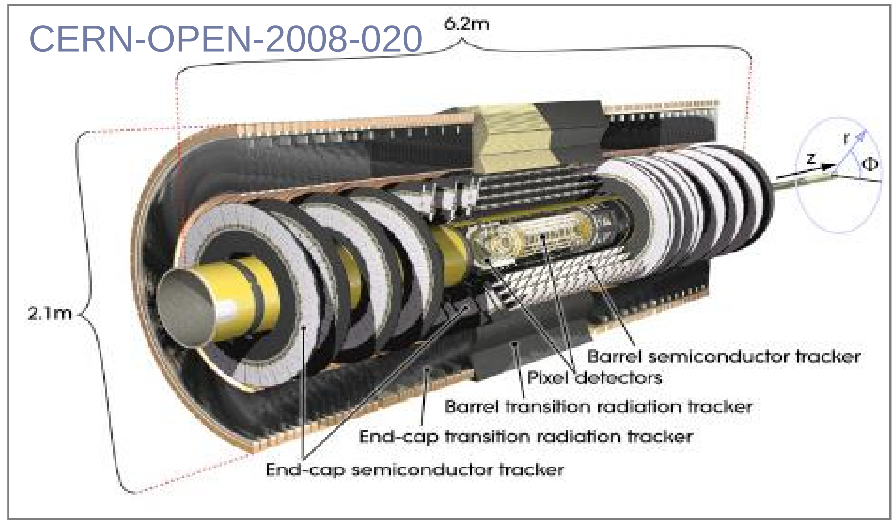
- Large beauty production cross-section in pp collisions at $\sqrt{s}$ = 7 TeV at LHC and high luminosity of the machine ($3.6 \cdot 10^{33}$ $cm^{-2}s^{-1}$ peak luminosity in 2011) → the rate of B-hadron production in LHC is gigantic (10^{12} bbar pairs per year/experiment)
- B Physics at ATLAS:
  - ✓ Measure vertices with high precision
  - ✓ Reconstruction of exclusive final state with good resolution
  - ✓ Flexible trigger scheme, fast identification of interesting events
  - ✓ High resolution calorimetry
  - ✗ Kaon/Pion separation
- $B_s \to J/\Psi\Phi$ is the most promising decay mode observed in ATLAS for CPV measurement
  - Large and clean sample, allowing to extract B_s-$\overline{B_s}$ mixing parameters ΔM_s and $\Delta\Gamma_s$, as well as ϕ_s
  - Good resolution on B_s proper decay time to resolve the rapid oscillations (~50 fs)

LHC@7TeV



Detector’s subsystems important for B Physics

- Inner Detector
  - Solenoidal magnetic field, 2T
  - Coverage $|\eta| < 2.5$
  - $\sigma(1/p_t) \sim 1.5\%$ at low p_t
  - $\sigma(d_0) \sim 10\mu m$ $p_t > 10$ GeV
  - Precision measurement for tracks and vertexing
- Muon system
  - Toroidal magnetic field, 0.5T
  - Large eta range $|\eta| < 2.7$
  - Fast response; LVL1 ~ 25 ns
  - $\sigma/p_t < 10\%$ up to 1TeV
  - Essential for trigger and momentum measurement of muons
- Trigger system
  - B Physics in ATLAS is mostly driven by muon-based triggers



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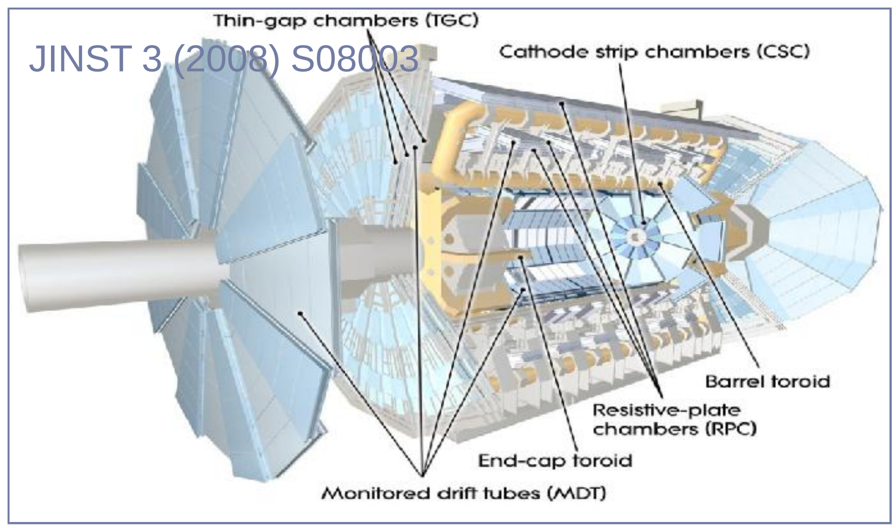

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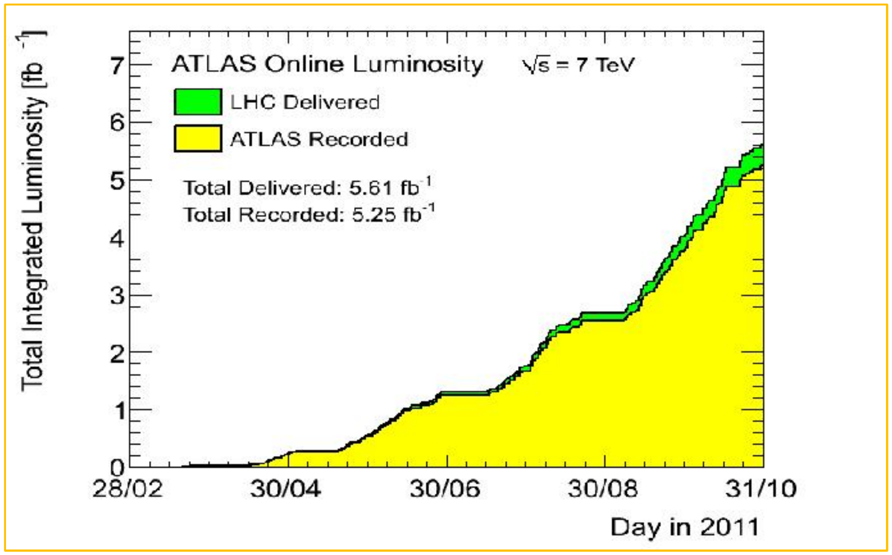
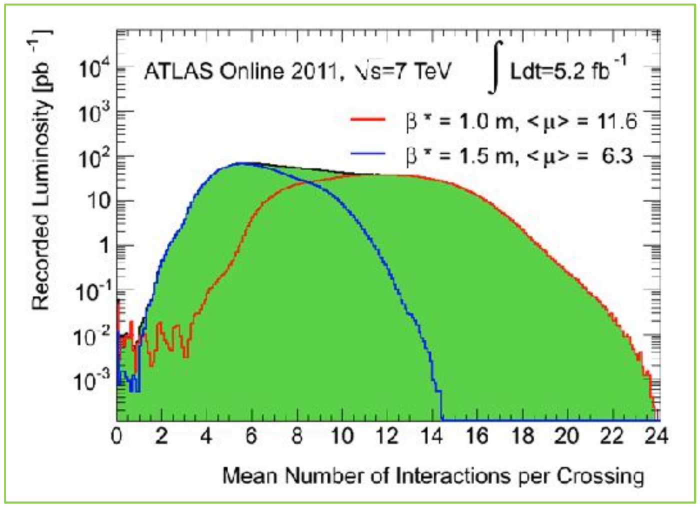
ATLAS 2011 data taking

- ATLAS recorded luminosity in 2011 ~5.2 fb^{-1}
- 3.65×10^{33} cm^{-2} s^{-1} max. inst. luminosity
  - up to 12 collisions/event on average
- Overall data taking efficiency: 93.5%
  - Subdetector efficiency > 90%
- In 2011 ATLAS benefits from increased LHC instantaneous luminosity
  - Attention paid to B Physics triggers and stability of tracking
  - Vertexing performance with growing pile-up

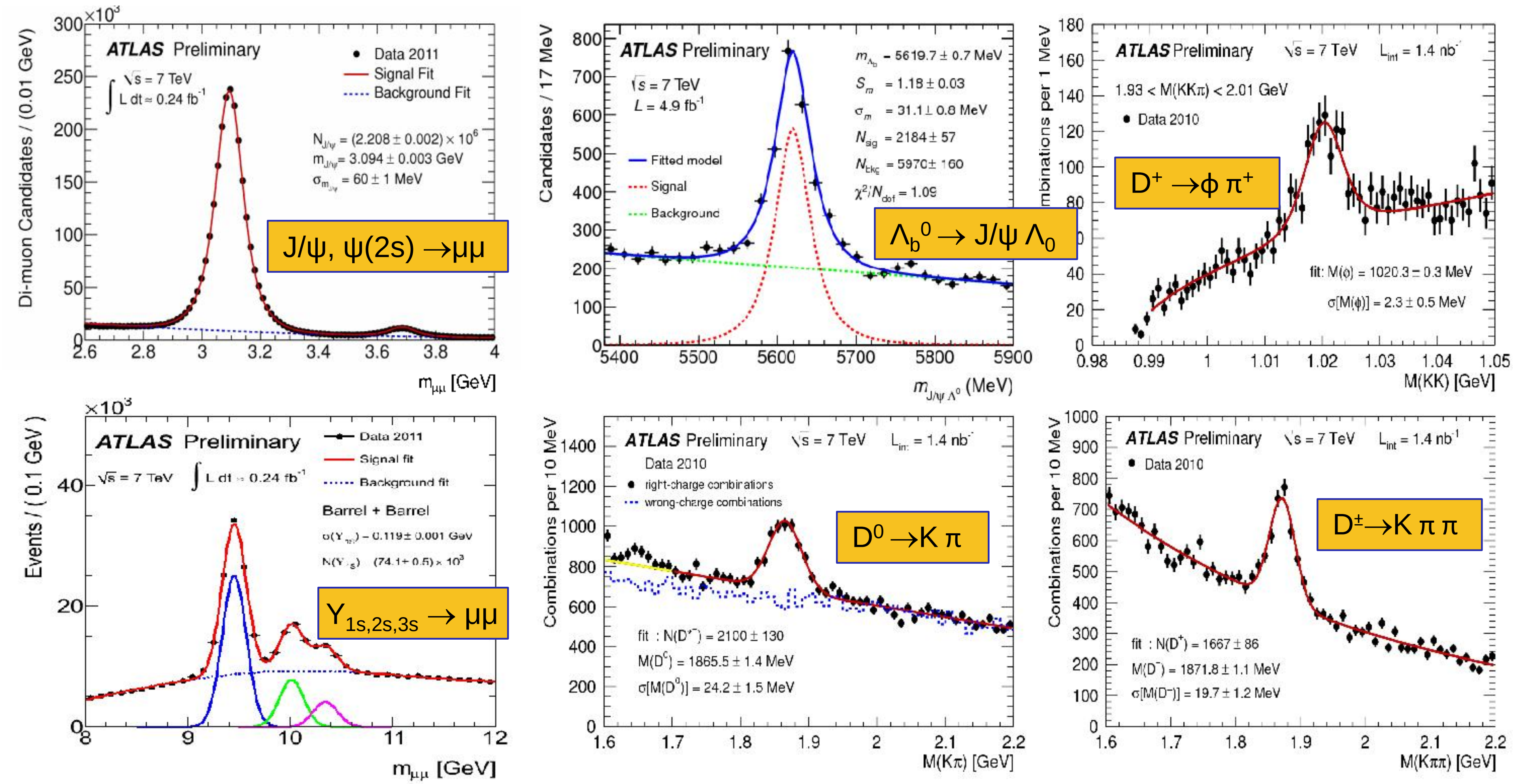




***ATLAS* 2011 p–p run**												
Inner Tracking			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and October 30th (in %), after the summer 2011 reprocessing campaign

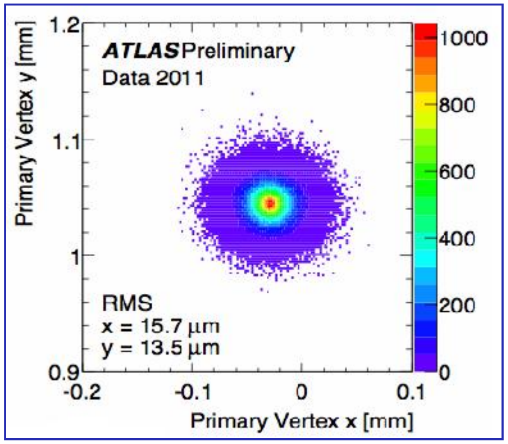
Mass determination at ATLAS



- ATLAS also reconstructs Λ, Σ, Ω,, etc.

Proper time: Tracking & PV determination

- Select fully reconstructed tracks with small transverse & longitudinal impact parameter for primary vertex recon.
- Remove tracks that are more than 7σ incompatible with PV and use them as seed for new vertex
- Resolution of PV: σ_x = 15.7 μm, σ_y = 13.5 μm



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- For precise measurements of secondary vertices, the performance of the Inner Detector is crucial, particularly of silicon pixels
- In barrel measure σ = 25 μm for hits from tracks with p_t > 2 GeV
- In the EC meausure σ=20 μm for hits from tracks with p_t > 2 GeV

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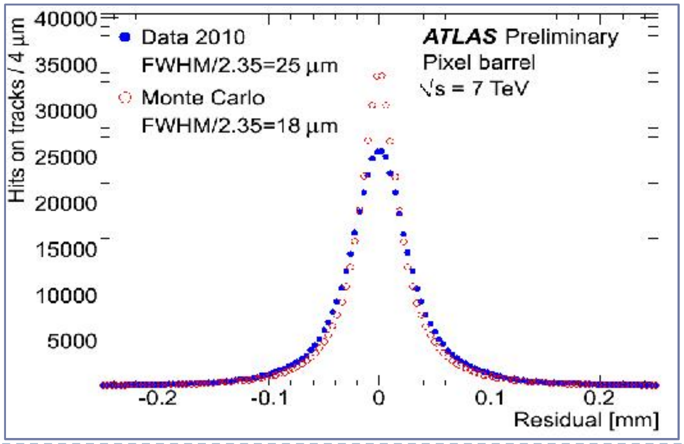
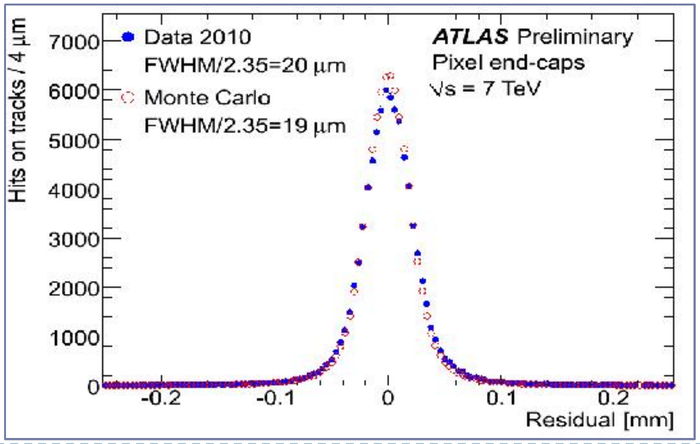
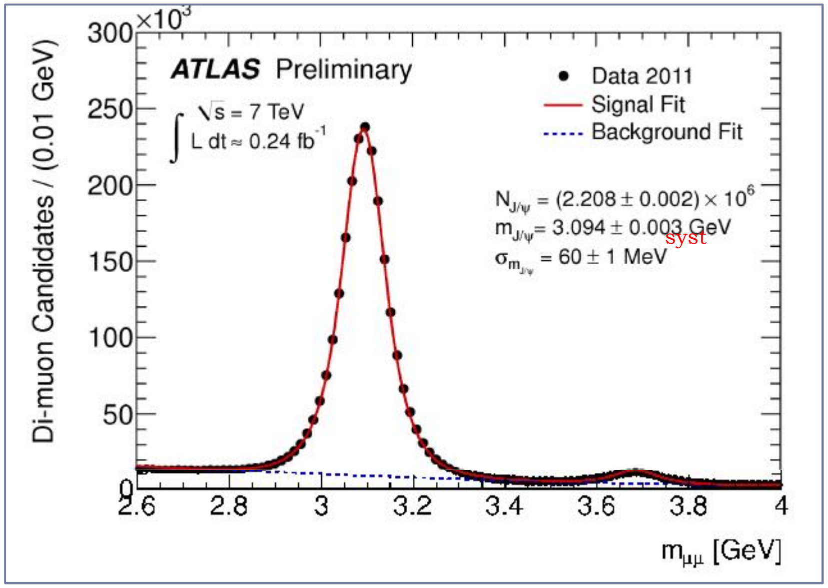


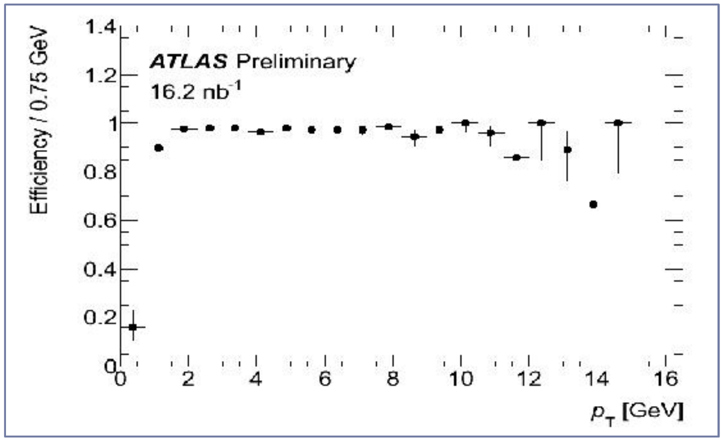


J/Ψ Reconstruction

- Fit pairs of oppositely charged muons to a common vertex to form a J/Ψ
- Require at least one pixel hit and at least 4 SCT hits
- J/Ψ resolution depends on whether muons are in barrel or endcaps
- Select J/Ψ candidate in different mass windows, following the varying mass resolution
  - 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 high and uniform in p_t



Level-2 tracking efficiency with J/Ψ tracks



$B_s^0 \to J/\Psi\Phi$ & $B_d^0 \to J/\Psi K^{*0}$ reconstruction

- In 2010, ATLAS and LHCb collected similar integrated luminosities
- Results discussed based on 2010 data (~40 pb^{-1})
- Selection criteria for B_s and B_d mesons reconstruction (ATLAS-CONF-2011-092):
  - $p_t(K) > 1$GeV; $p_t(K^{*0}) > 2.5$ GeV
  - $1009 < m(\Phi) < 1031$ MeV (for B_s); $846 < m(K^{*0}) < 946$ MeV (for B_d)
  - No explicit p_t cut on muons
  - Muon tracks constrained to J/Ψ mass; J/Ψ mass windows different for muons in barrel and endcap
  - 4-tracks B-vertex quality $\chi/NDF < 2$
  - No cut on proper lifetime in offline selection nor in trigger (follow CDF, D0 approach)

Method of measurement

- For each candidate calculate the proper decay time

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

L: distance between PV and SV
$\beta\gamma$: Lorentz boost factor $\cong$ p/m
c: speed of light

- Precision is higher in the transverse plane

$$\tau = \frac{L_{xy} m_B}{p_t(B)c}$$

L_{xy}: L in the transverse plane
p_t: transverse momentum of B meson candidate
m_B: invariant mass of B meson candidate

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

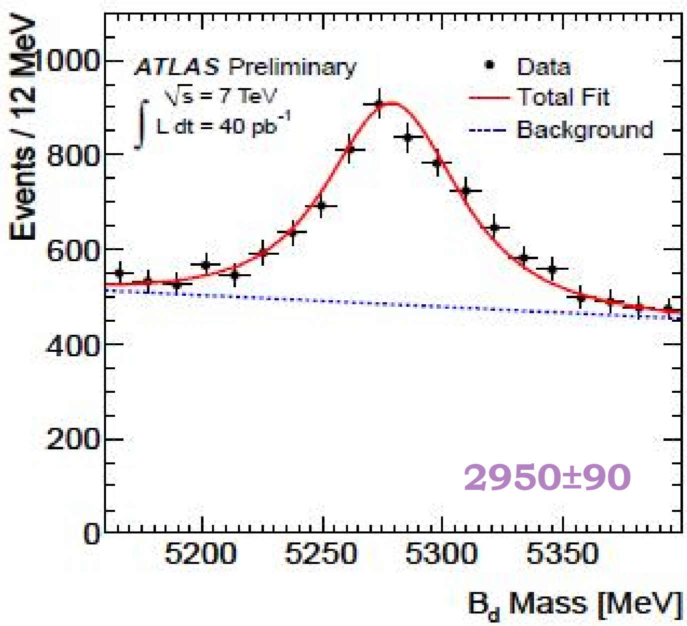
$$L = \prod_{i=1}^{N} \left[f_{sig} M_{sig}(m_i) + (1 - f_{sig}) M_{bkg}(m_i) \right]$$

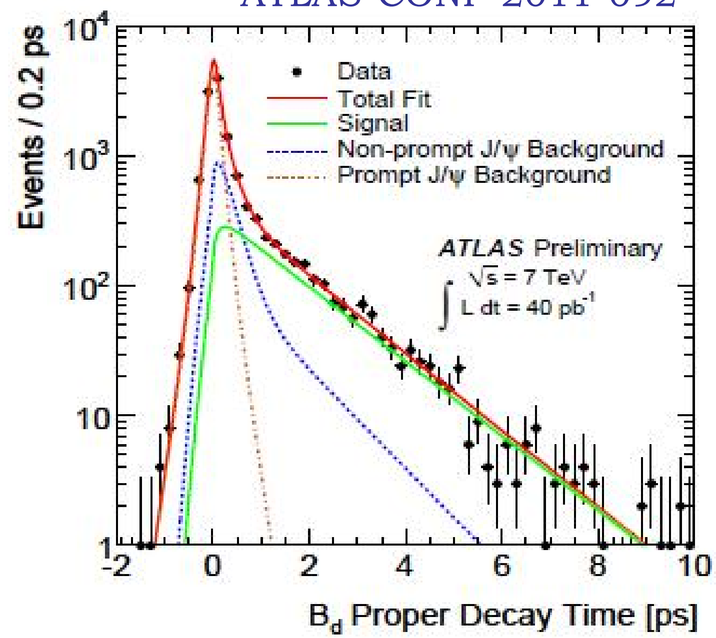
- Background contributions
  - J/Ψ from other B combined with random $K^+\pi^-$ (K^+K^-)
  - J/Ψ from signal and $K^+\pi^-$ (K^+K^-) both coming from the same B meson
  - Direct J/Ψ production with random $K^+\pi^-$ (K^+K^-)

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

- Parameters left free in the fit: f_{sig}, m_B, S_m, d, τ_B, S_τ, τ_{eff1}, τ_{eff2}, τ_{eff3}, 3 bkg fract.

ATLAS-CONF-2011-092



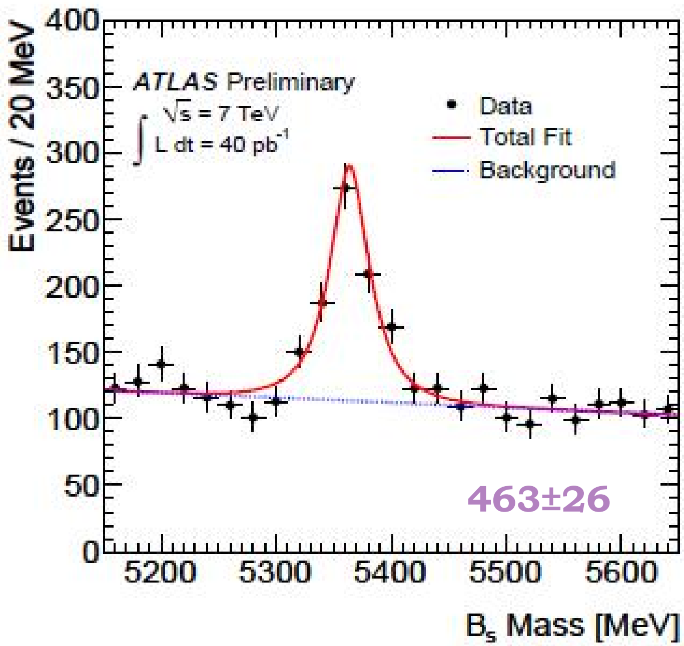


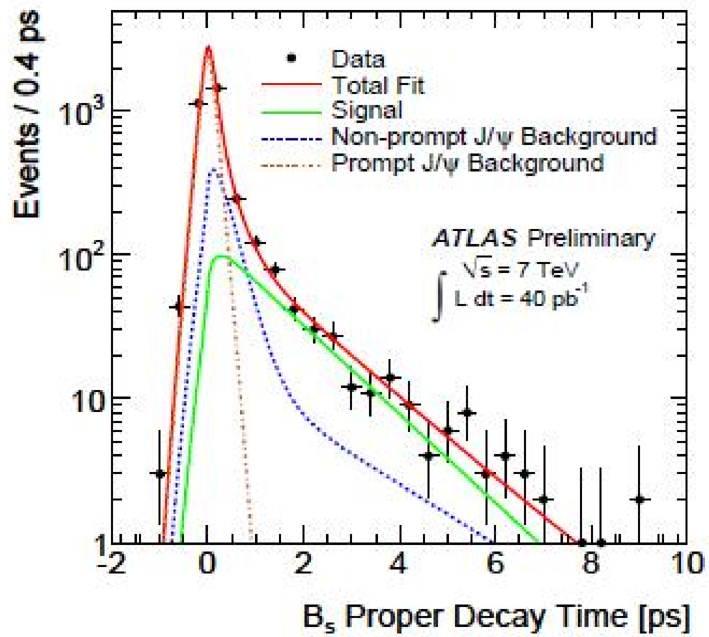
- Measure: m_{Bd} = (5279.0 ± 0.8) MeV
  σ_m = (34.3 ± 0.9) MeV

τ_{Bd} = (1.51 ± 0.04$_{stat}$ ± 0.04$_{sys}$) ps
good agreement with PDG value:
τ_{Bd} = (1.525 ± 0.009) ps

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

ATLAS-CONF-2011-092





- Measure: m_{Bs} = (5363.7 ± 1.2) MeV
  σ_m = (24.8 ± 1.2) MeV

τ_{Bs} = (1.41 ± 0.08$_{stat}$ ± 0.05$_{sys}$) ps
good agreement with HFAG value:
τ_{Bs} = (1.429 ± 0.088) ps

Systematic uncertainties in lifetime measurement

- Modeling of signal and background in likelihood fit
  - Rerunning the fits with alternative parameterization of t: signal and background mass model, lifetime resolution model); for B_d ~ 0.01 ps; for B_s small statistics, the same error used
- Fitting procedure
  - Estimated to be negligibly small
- Event selections (mass window)
  - Testing potential influence of the evens at an edge – the selection cuts intervals are varied and fits repeated; for B_d ~ 0.01 ps , for B_s ~ 0.02 ps
- Time uncertainty model
  - Fit using per-candidate errors: measured uncertainties on mass and proper decay time
  - Varying this model accounts for possible systematic bias; for B_d ~0.03 ps, for B_s the same error used
- Choice of primary vertex
  - Two choices of PV tested: highest tracks sum-p_t vertex, PV with B-momentum minimal 3D impact parameter - negligibly small
- Alignment
  - Produced data-like distorted MC signal sample, results of the fit compared to MC sample with perfect alignment (data residual misalignment estimated using tracks d_0-offset η-φ maps)
  - $B_{d,s}$ ~ 0.03 ps

Summary of systematic uncertainties

- Below is the summary of the systematic uncertainties in the B_d and B_s lifetime measurement

ATLAS-CONF-2011-092

Source of systematics	Systematic uncertainty $\delta_{\text{syst}}(\tau_{B_d})$, ps	$\delta_{\text{syst}}(\tau_{B_s})$, ps
Modelling signal, background	0.01	0.01
Time uncertainty model	0.03	0.03
Mass window	0.01	0.02
Alignment	0.03	0.03
Total, quadratic sum	0.04	0.05

- The total systematic uncertainties are obtained treating all sources of systematics as uncorrelated

Summary

- ATLAS performed first lifetime and mass measurements in $B_d^0 \to J/\Psi K^{*0}$ and $B_s^0 \to J/\Psi\Phi$ with 2010 data
- The results are in good agreement with world average values: PDG, HFAG
- Precision measurement of B meson lifetime essential for the CP violation measurement
- In 2011 ATLAS delivered good and stable quality data allowing to collect statistics of the exclusive $B_s \to J/\Psi\Phi$ decay comparable to LHCb

- **ATLAS is well equipped to measure CP violation in 'gold-plated' $B_s^0 \to J/\Psi\Phi$ decay channel**

Backup

PDFs in ML Fit

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

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

S_m: scale factor

- Background mass distribution is modeled with a linear function

$$\mathcal{M}_{\text{bkg}}(m_i) \equiv \frac{1}{m_{max} - m_{min}} \left[1 + d\,(m_i - m_C)\right]$$

d: slope
$m_c = (m_{max} + m_{min})/2$

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

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

$$R(\tau' - \tau_i, \delta_{t_i}) \equiv \frac{1}{\sqrt{2\pi}\, S_\tau\, \delta_{\tau_i}} \exp\left(\frac{-(\tau' - \tau_i)^2}{2(S_\tau\, \delta_{\tau_i})^2}\right)$$

- Background lifetime is parameterized by:

$$\mathcal{T}_{\text{bkg1}}(\tau_i, \delta_{\tau_i}) = \delta_{Dirac}(\tau') \otimes R(\tau' - \tau_i, \delta_{\tau_i}) = R(\tau_i, \delta_{\tau_i})$$

$$\mathcal{T}_{\text{bkg2}}(\tau_i, \delta_{\tau_i}) = \left[\frac{b}{\tau_{\text{eff1}}} \exp\left(\frac{-\tau'}{\tau_{\text{eff1}}}\right) + \frac{1-b}{\tau_{\text{eff2}}} \exp\left(\frac{-\tau'}{\tau_{\text{eff2}}}\right)\right] \otimes R(\tau' - \tau_i, \delta_{\tau_i})$$

$$\mathcal{T}_{\text{bkg3}}(\tau_i, \delta_{\tau_i}) = \frac{1}{2 \cdot \tau_{\text{eff3}}} \exp\left(\frac{-|\tau'|}{\tau_{\text{eff3}}}\right) \otimes R(\tau' - \tau_i, \delta_{\tau_i})$$

$\tau_{\text{eff1}}, \tau_{\text{eff2}}, \tau_{\text{eff3}}$ are 3 background lifetimes determined in fit

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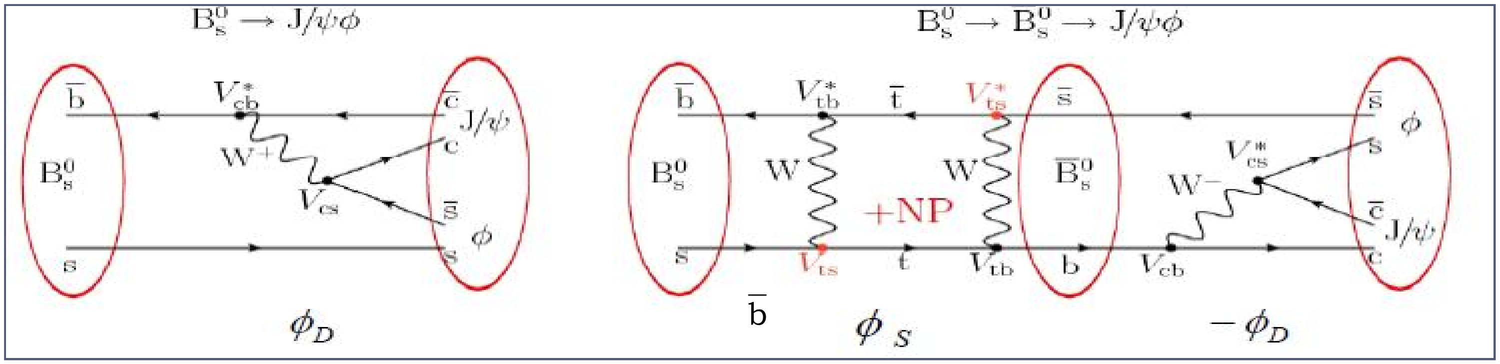
$$\mathcal{T}_{\text{bkg}}(\tau_i, \delta_{\tau_i}) = b_2 \cdot \left(b_1 \cdot \mathcal{T}_{\text{bkg1}} + (1 - b_1)\mathcal{T}_{\text{bkg3}}\right) + (1 - b_2)\mathcal{T}_{\text{bkg2}}$$

CP violation in neutral B_s system

- Measurable CP violation arises from interference of B_s-$\overline{B_s}$ decay and the fact that the both B_s and $\overline{B_s}$ decay to the same $J/\Psi(\mu\mu)\Phi(KK)$ final state and is proportional to a phase difference ϕ_s of the two decay amplitudes:



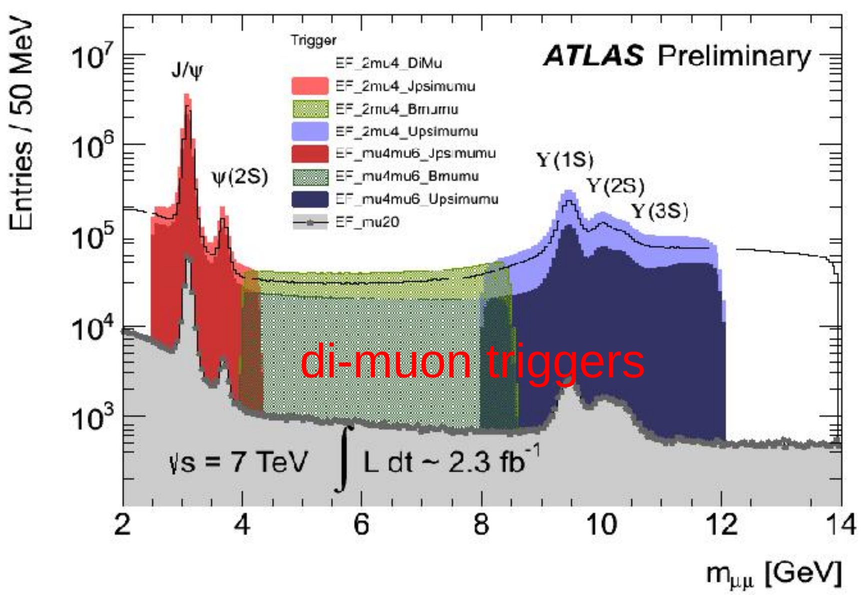
$$\boxed{\phi_s = \phi_M - 2\phi_D}$$

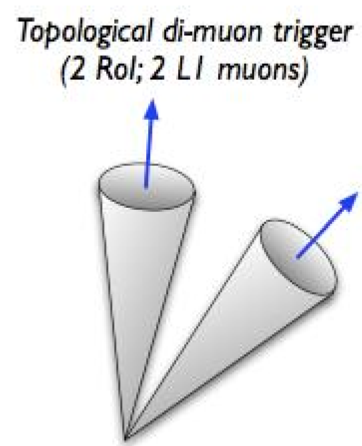
(if we neglect penguin)

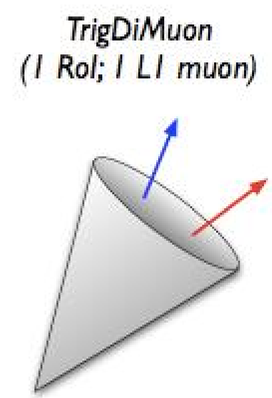
- $B_s \to J/\Psi\Phi$ exhibits CPV effects at the percent level at the SM - they represent a sensitive probe for CP-violating contributions from physics beyond the SM → new particle can contribute to the $B_s - B_s$ box diagrams and significantly modify SM prediction
- ϕ_s is extracted from a cascade decay $B_s \to J/\Psi\Phi$ by time dependent angular analysis alongside with 6 other parameters obtained as result of the measurement: $\Delta\Gamma_s$, Γ_s, 4 independent parameters of three helicity amplitudes (2 phases, 2 absolute values)

ATLAS B Triggers in 2011(I)

- In 2011 ATLAS di-muon triggers dominate B-trigger menus; single muon trigg.-prescaled
- pT thresholds 4&4 GeV or 4&6 GeV with masses in J/ψ (2.5-4.3 GeV), B (4-8.5 GeV) and Υ (8-12 GeV); the combined range of all three (1.5-14 GeV)
- A higher pT trigger (20 GeV) di-muon events over whole mass region
- ATLAS di-muon triggers performed online tracking & vertexing, accepting only a good quality vertices
- In ATLAS NO displaced vertex cuts applied at trigger level during whole 2011 in B-physics menu

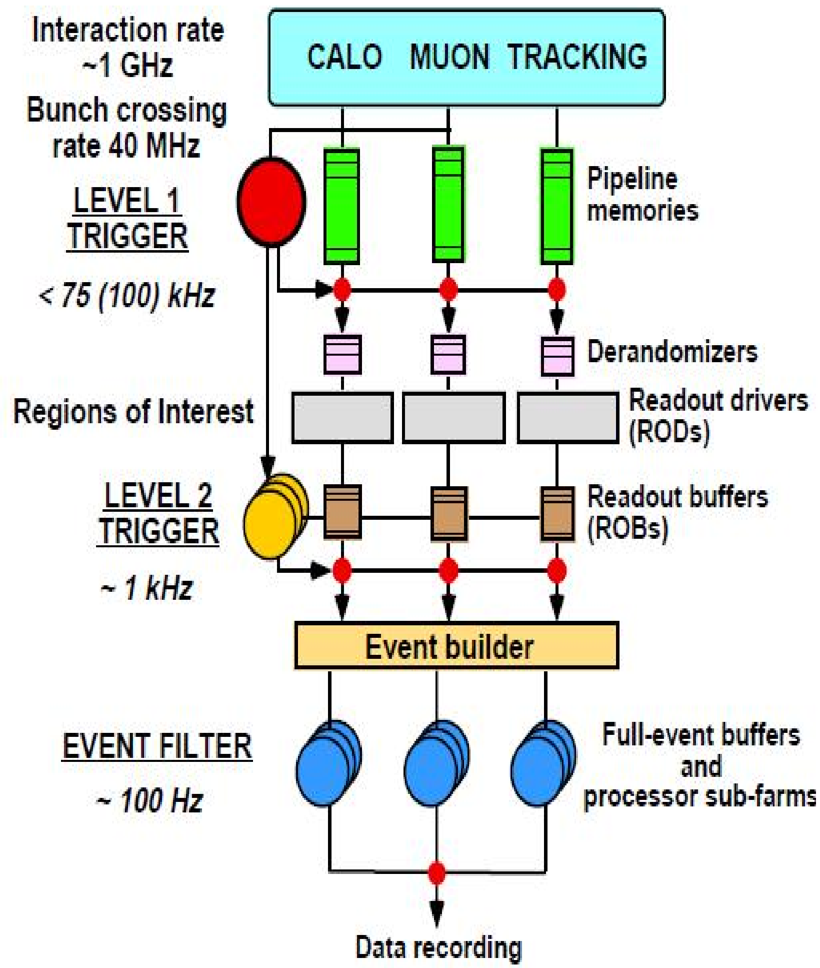






ATLAS Trigger Operations

- ATLAS has 3 different trigger levels:
  - L1: hardware trigger
    → 50 kHz rate, decision time < 2.5 μs
  - L2: software selection on reduced granularity (ROI)
    → 4 kHz rate, ~10 ms
  - EF: based on offline reconstruction, full granularity
    → 200 Hz rate design with peak to 600 Hz, ~ few sec
- Physics rate is ~ 300 Hz



ATLAS-TDR-1998

Stability of $B_s \rightarrow J/\Psi\Phi$ extraction in 2011

Period	Luminosity (pb^1)	Signal statitics	Signal / pb^-1	Average Bs pT (GeV)	Average time resolution, ps	Fitted Tau ps	Fitted Mass MeV
B to F	401	2432+/-55	6.1	18.8	0.1165	1.46 +/- 0.03	5366.6 +/- 0.4
G to H	836	4617+/-78	5.5	19.2	0.1147	1.49 +/-0.02	5366.6 +/- 0.3
I	403	1977	4.9	19.9	0.1124	1.49+/-0.04	5366.4 +/- 0.5
J	231	1134	4.9	20.5	0.1102	1.44 +/- 0.05	5366.8 +/- 0.7
K	595	2627+/-60	4.4	20.2	0.1108	1.51+/- 0.04	5366.6 +/- 0.4
L	1438	5476 +/-84	3.8	20.8	0.109	1.48 +/-0.02	5366.9 +/- 0.3
M	1036	4083 ±73	3.8	20.4	0.110	1.46 ± 0.03	5366.7±0.3
Total	4940	22344 ± 171	4.5	20.0	0.112	1.48+/-0.01	5366.7+/-0.01

- Data performance monitored with every run
- Stable mass and lifetime over all periods despite increasing luminosity
- Quality of vertex/time resolution was monitored over runs
- Signal yield/pb^{-1} slightly reducing due to triggers evolving towards higher muons p_t

Time-Evolution of the Decay Probability Functions

$$
\begin{aligned}
|A_0(t)|^2 &= \frac{|A_0(0)|^2}{2}\left[(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}^{(s)}t}+(1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}^{(s)}t}\pm \underline{2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s}\right]\\
|A_\parallel(t)|^2 &= \frac{|A_\parallel(0)|^2}{2}\left[(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}^{(s)}t}+(1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}^{(s)}t}\pm \underline{2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s}\right]\\
|A_\perp(t)|^2 &= \frac{|A_\perp(0)|^2}{2}\left[(1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}^{(s)}t}+(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}^{(s)}t}\mp \underline{2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s}\right],
\end{aligned}
$$

$$
\begin{aligned}
\Re\{A_0^*(t)A_\parallel(t)\} &= \frac{1}{2}|A_0(0)||A_\parallel(0)|\cos(\delta_2-\delta_1)\\
&\quad\times\left[(1+\cos\phi_s)\,e^{-\Gamma_{\mathrm{L}}^{(s)}t}+(1-\cos\phi_s)\,e^{-\Gamma_{\mathrm{H}}^{(s)}t}\pm \underline{2e^{-\Gamma_s t}\sin(\Delta m_s t)\sin\phi_s}\right]\\
\Im\{A_\parallel^*(t)A_\perp(t)\} &= \pm|A_\parallel(0)||A_\perp(0)|\left[\underline{e^{-\Gamma_s t}\{\sin\delta_1\cos(\Delta m_s t)-\cos\delta_1\sin(\Delta m_s t)\cos\phi_s\}}\right.\\
&\quad\left.\mp\frac{1}{2}\left(e^{-\Gamma_{\mathrm{H}}^{(s)}t}-e^{-\Gamma_{\mathrm{L}}^{(s)}t}\right)\cos\delta_1\sin\phi_s\right]\\
\Im\{A_0^*(t)A_\perp(t)\} &= \pm|A_0(0)||A_\perp(0)|\left[\underline{e^{-\Gamma_s t}\{\sin\delta_2\cos(\Delta m_s t)-\cos\delta_2\sin(\Delta m_s t)\cos\phi_s\}}\right.\\
&\quad\left.\mp\frac{1}{2}\left(e^{-\Gamma_{\mathrm{H}}^{(s)}t}-e^{-\Gamma_{\mathrm{L}}^{(s)}t}\right)\cos\delta_2\sin\phi_s\right].
\end{aligned}
$$

ATLAS Data Taking 2010 vs 2011

- 2010 ATLAS, LHCb collected similar integrated luminosities - thus number of collected B hadrons roughly proportional to the production cross sections in respective fiducial volumes
- 2011 ATLAS benefit from being able to collect data at increasing LHC instantaneous luminosity
- To benefit from higher integrated luminosity B-physics group in ATLAS paid special attention to:
  - B-physics triggers and stability of tracking, vertexing performance with growing pileup
- Quality of vertex/time resolution was monitored over runs
  - Strong dependence on the transverse momentum. 2011 data vs. 2010 collects higher p_t due to triggers → average per-candidate time error improves
  - 4% time-errors improvement after 2011 reprocessing
- Trigger selection
  - a variety of single and di-muon triggers with a threshold between 4 and 10 GeV
  - Signal yield /pb^{-1} slightly reducing due to triggers evolving towards higher muons p_t

B-tagging for CPV studies

- Current $Bs \to J/\psi\phi$ does not use information on B_s flavour at production time. In 2012 adding this information will improve measurement, remove ambiguities
- B-tagging project in ATLAS is in development and will be used also in other CPV measurements in ATLAS neutral B-mesons
- ATLAS supports both same-side tagging (jet-charge) and away-side tagging (muon, electron, jet-charge).
- Calibration samples to be used
  - $B^+ \to J/\psi K^+$
  - $B_d \to J/\psi K^{*0}$
  - $B_d \to D^{*-}\mu^+\nu$ and $B_s \to D_s^+\mu^-\nu X$ under investigation
- Measurements rather complex. First goal: to deliver (some) B-tagging tools in summer 2012. Then continue to improve with 2012 data.