ATLAS Prospects in B-physics Channels Sensitive to New Physics

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ATLAS B-physics Program

$\int L\,dt$

Using well understood B-decays for

- Detector performance validation (trigger, tracking, alignment)
- Data quality monitoring with J/ψ and Υ

10 pb^{-1}

- Measurement of cross sections of
  - direct onia (J/ψ, Υ) production $\Rightarrow$ test QCD predictions
  - $b\bar{b} \to J/\psi X$, $pp \to J/\psi X$ and $B^+ \to J/\psi K^+$

200 pb^{-1}

- B-hadron properties (B^+, B_s, B_c, Λ_b)
- First limits on *rare decay BRs* ($b \to s/d\ \mu\mu$, $B_s \to \mu\mu$)

1 fb^{-1}

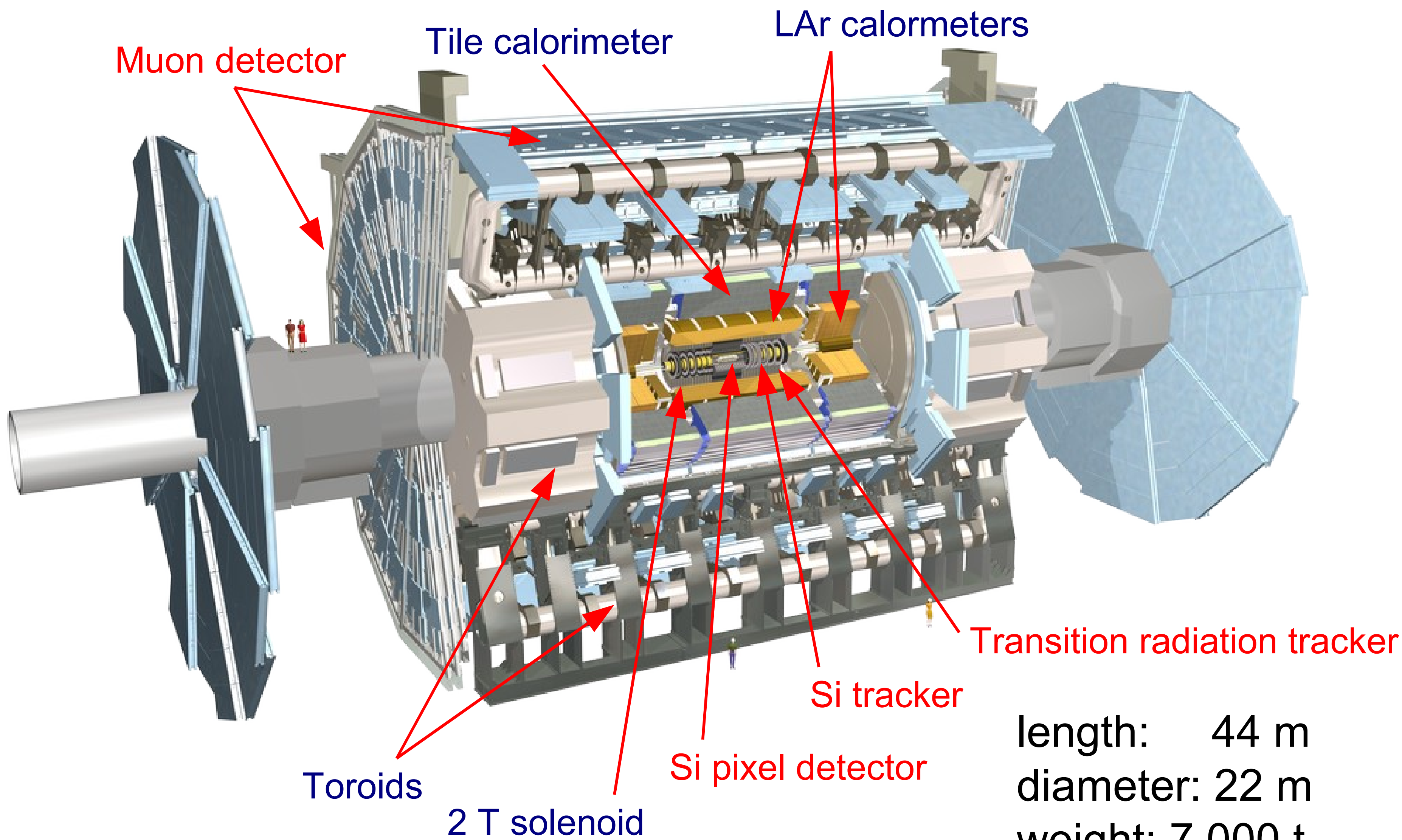
- Onia (J/ψ, Υ) and Λ_b polarization studies
- Searches for *BSM CP-violation in weak B-hadron decays* ($B_s \to J/\psi\, \phi$)
- Measurement of B_s oscillations
- Searches for rare decays

30 fb^{-1}

- Searches for rare di-muonic B-decays (like $B_s \to \mu\mu$)

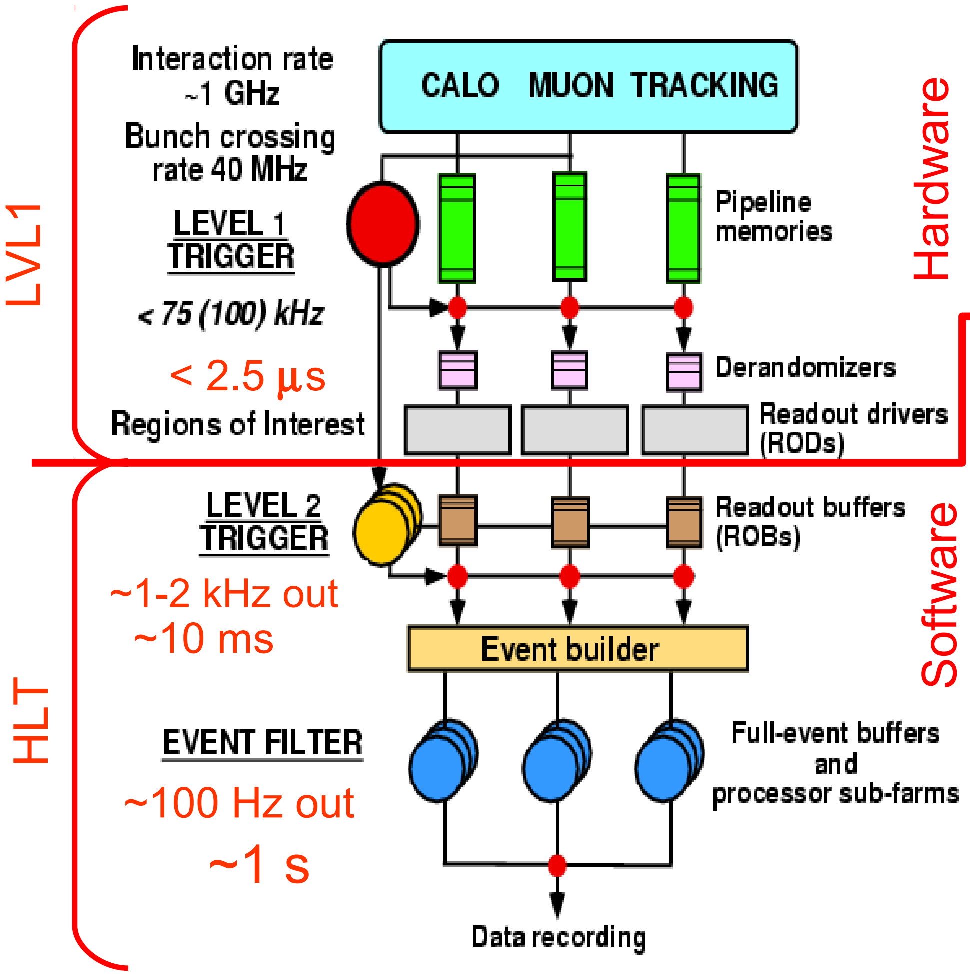
100 fb^{-1}

ATLAS Detector



length: 44 m
diameter: 22 m
weight: 7 000 t

ATLAS Trigger System



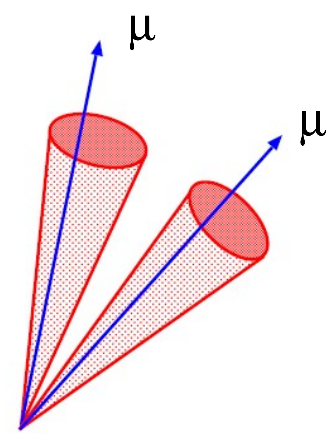
B-physics uses μ-based triggers:

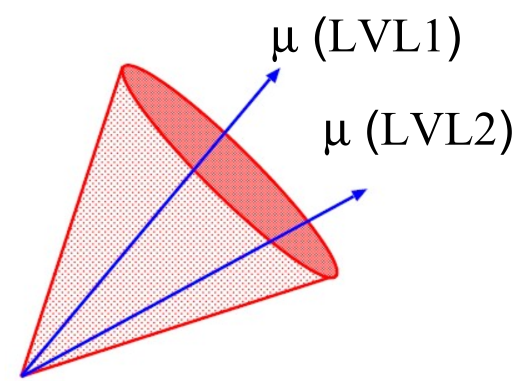
- **LVL1:** coincidences from fast muon trigger chambers (TGCs, RPCs) provide seeds for Regions of Interest (RoI)
- **LVL2:** confirmation of LVL1 signature using precision muon chamber and Inner Detector measurements in RoI; fast vertex fits and invariant mass cuts possible
- **EF:** refinement of LVL2 selection with offline-like algorithms; full event, alignment and calibration data available; vertex fit and invariant mass cuts possible

- 10% of total trigger resources dedicated to B-physics → fast, efficient and selective trigger needed!

B-physics Triggers for Di-muon Events

- Di-μ signature in many B-physics channels
  e.g. $B \to J/\psi(\mu\mu)X$, $b \to s\,\mu\mu$, $B \to \mu\mu$
- Muons have low momenta (often < 10 GeV)
- **Strategy:** Di-μ signature at lowest possible trigger threshold
- **Two approaches:**
  - Topological di-μ trigger (main B-physics data taking)
  - ➔ 2 μ at LVL1 with separate RoIs combined at LVL2 with cuts on $m_{\mu\mu}$ and μμ-vertex fit
  - TrigDiMuon (for early data)
  - ➔ 1 μ at LVL1, at LVL2 search for 2[nd] μ in widened RoI in Inner Detector and confirm in muon detectors; apply $m_{\mu\mu}$ cut

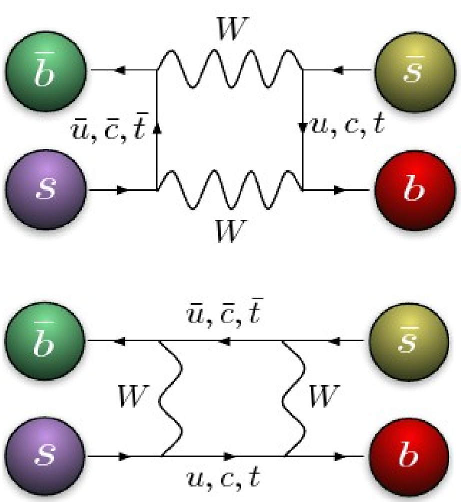




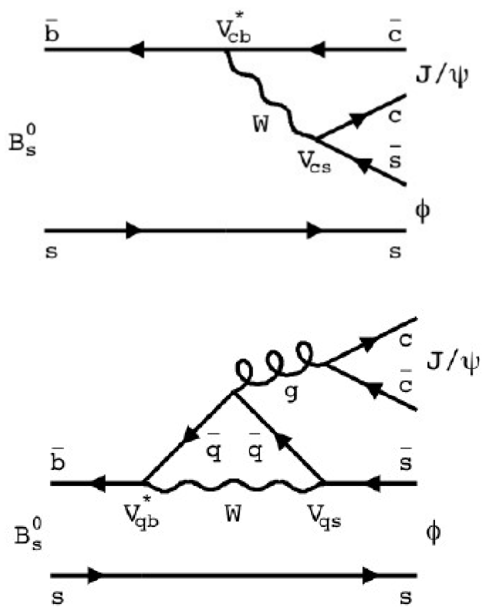
New Physics in $B_s \to J/\psi\, \phi$

$$B_s^0, \bar{B}_s^0 \to J/\psi(\mu^+\mu^-)\,\phi(K^+K^-)$$

Mixing



Decay



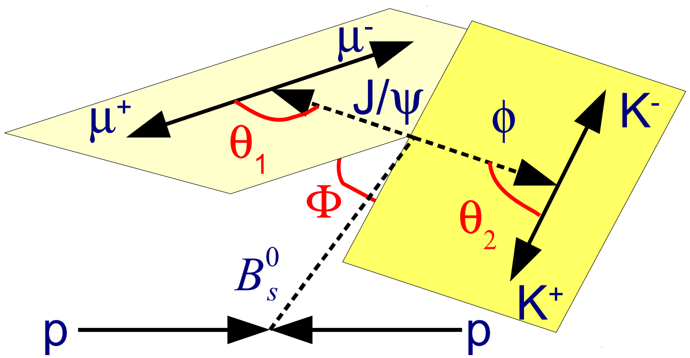
- Same final state for B^0_s and $\overline{B}^0_s$ with possible mixing
- Main parameter of interest: *weak mixing phase*

$$\phi_s \equiv 2\, arg\left[V_{ts}^* V_{tb}\right] + \phi_{BSM}$$
$$\phi_s(SM) \approx -0.04$$

- New sources of CP violation $\Rightarrow \phi_{BSM}$
- Physics parameters: $|A_\parallel|, |A_\perp|, \delta_\parallel, \delta_\perp$ (transversity amplitudes) $\Gamma_s, \Delta\Gamma_s, \Delta m_s, \phi_s$

Interference of mixing and decay amplitudes $\Rightarrow$ CP violation

Introduction to $B_s \rightarrow J/\psi\ \phi$ and $B_d \rightarrow J/\psi\ K^{0*}$



$B_d^0 \rightarrow J/\psi(\mu^+\mu^-)\ K^{*0}(K^+\pi^-)$:

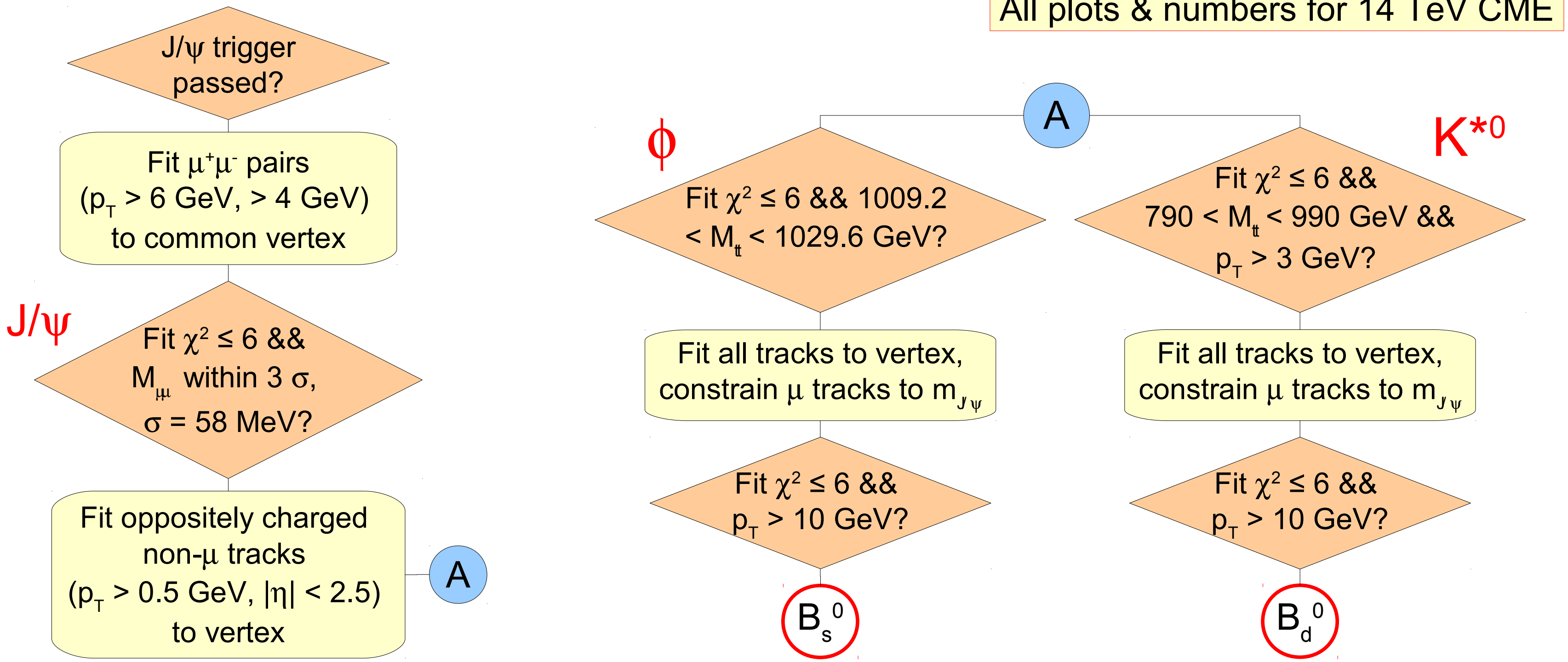
- Topologically identical decay
- 15 x larger statistics
  - Primary background
  - Control channel
- ➔ High precision tests of lifetime systematics
- ➔ Flavor tagging calibration

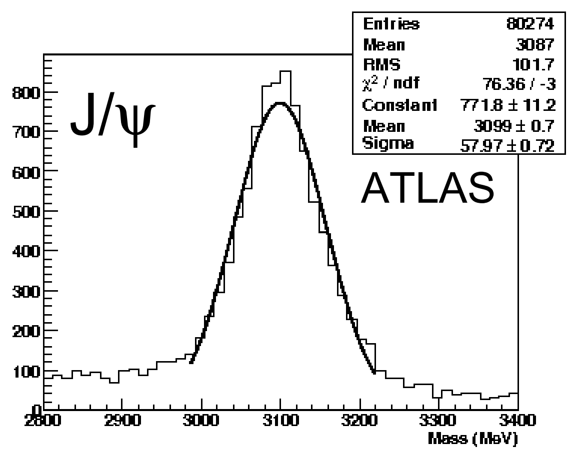
$B_s^0 \rightarrow J/\psi\ \phi$:

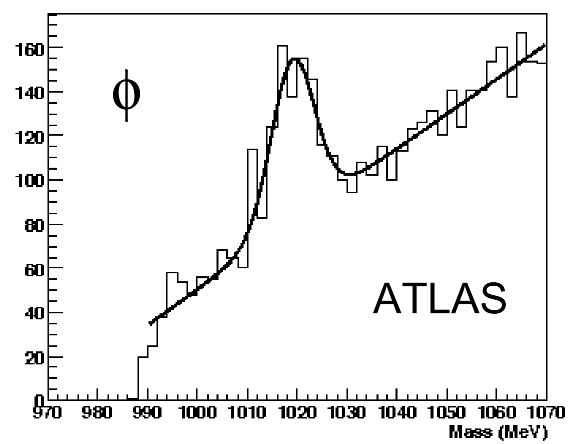
- Physics parameters extraction with *maximum likelihood fit* to angular distributions for θ_1, θ_2, Φ and τ_{B_s}
- Analysis is sensitive to
  - Statistics
  - Experimental resolutions of θ_1, θ_2, Φ, τ_{B_s} and m_{B_s}
  - Flavor tagging performance
  - Background rejection
- Determination of physics parameters needs larger statistics
  - ➔ Begin with calibration measurements

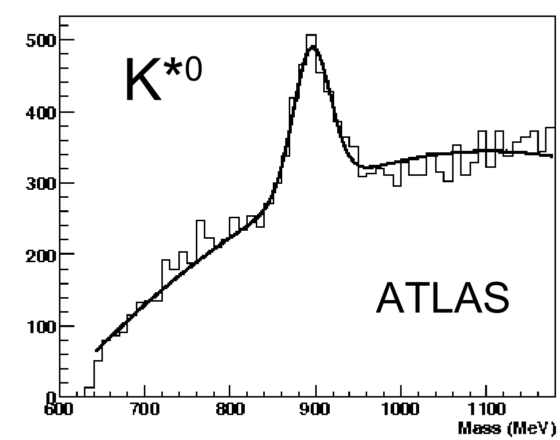
$B_s \to J/\psi\ \phi$ and $B_d \to J/\psi\ K^{0*}$ reconstruction

All plots & numbers for 14 TeV CME









$B_d \to J/\psi\ K^{0*}$ with early data

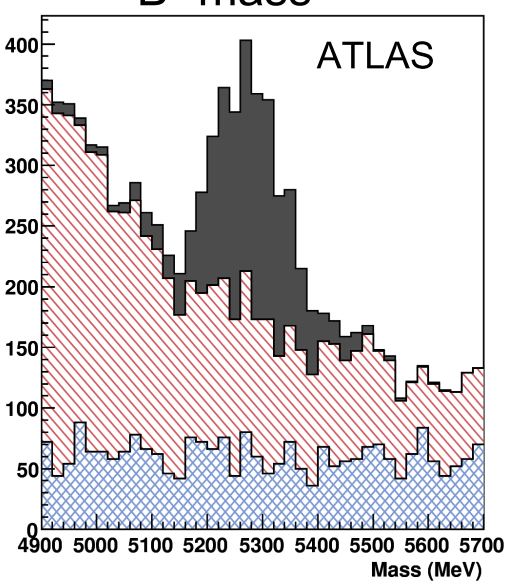
Earliest data (≥ 10 pb^{-1})

- ε_{reco}(signal) = 42.0 %
- 1024 candidates @ 10 pb^{-1}
- Simultaneous fit of m_B and Γ_B
- Precision on Γ_B ~ 10%
- Tests of tracking p_T scale with ≥ 150 pb^{-1}
- Improve world precision on m_B and Γ_B with ≥ 1 fb^{-1}

10 pb^{-1}

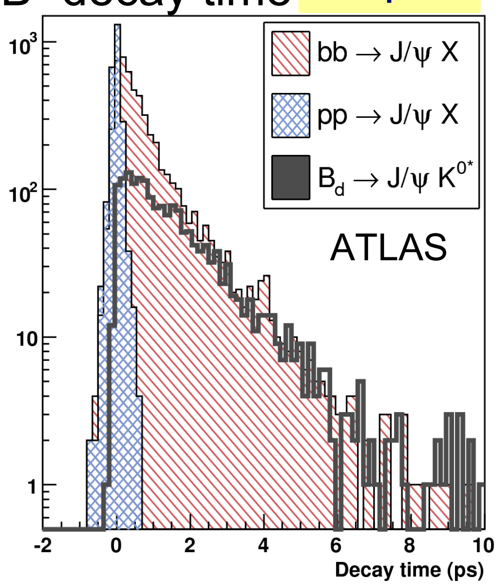
Parameter	Simulated	Fit result
Γ_B [ps^{-1}]	0.651	0.73 ± 0.07
m_B [GeV]	5.279	5.284 ± 0.006
σ_τ [ps]		0.132 ± 0.004
σ_m [GeV]		0.054 ± 0.006

B^0 mass



B^0 decay time

10 pb^{-1}



$B_s \to J/\psi\ \phi$ with early data and later

Early data (≥ 150 pb^{-1})

- ε_{reco}(signal) = 40.5 %
- ~ 1155 candidates @ 150 pb^{-1}
- Simultaneous fit of m_{B_s} and Γ_{B_s}
- Precision on Γ_{B_s} ~ 10%
- Improve world precision on m_{B_s} and Γ_{B_s} with ≥ 1 fb^{-1}

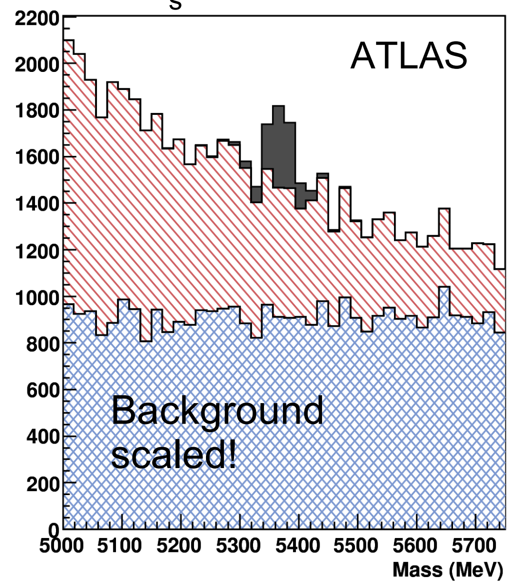
With 30 fb^{-1} (~ 3 years)

- Expect ~ 240 000 events
- Secondary vertex cut
- ~ 30% background, mostly $B^0 \to J/\psi\ K^{*0}$ and $bb \to J/\psi\ X$
- $\sigma_{proper\ time}$ ~ 83 fs

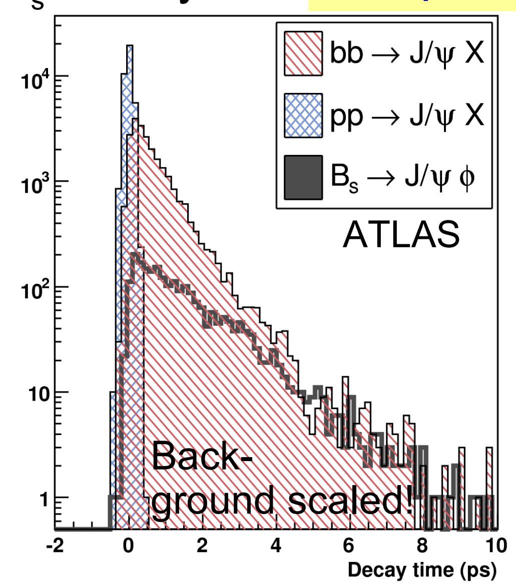
150 pb^{-1}

Parameter	Simulated	Fit result
Γ_{B_s} [ps^{-1}]	0.683	0.743 ± 0.051
m_{B_s} [GeV]	5.343	5.359 ± 0.006
σ_τ [ps]		0.152 ± 0.001
σ_m [GeV]		0.061 ± 0.006

B_s^0 mass



B_s^0 decay time 150 pb^{-1}

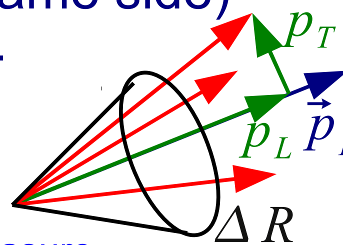


$B_s \to J/\psi\ \phi$ and $B_d \to J/\psi\ K^{0*}$ flavor tagging

p_L

$B_{(s)}^0$ or anti-$B_{(s)}^0$?

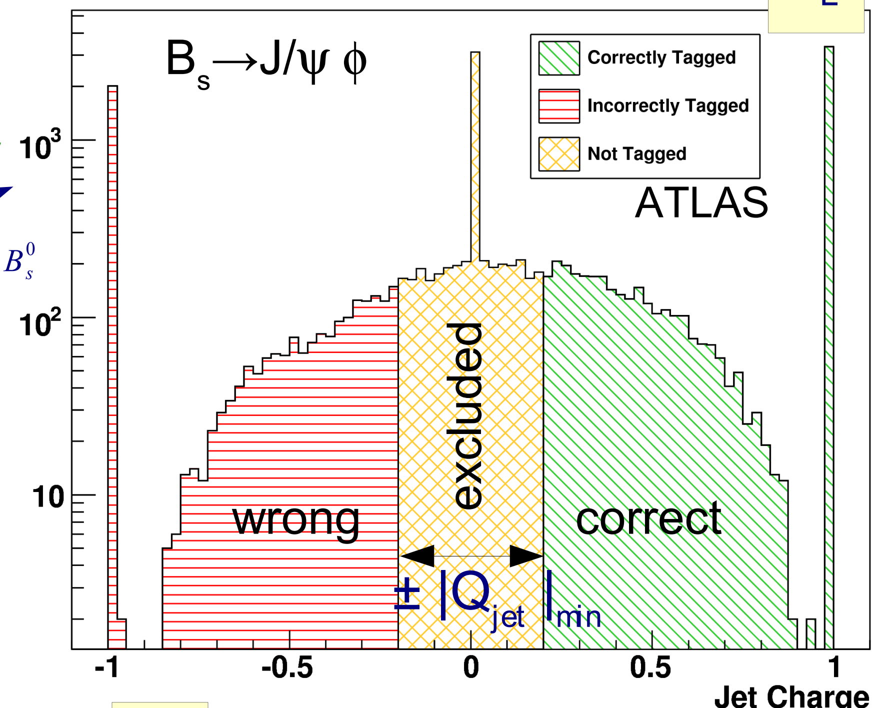
- Jet-charge tagging (same side)
- Tracks from fragmentation process in cone ΔR around B_s^0



Charge of track *i* — Momentum measure (p_L or p_T) of track *i* — Tuning parameter

$$\Rightarrow Q_{jet} = \frac{\sum_i q_i p_i^{\kappa}}{\sum_i |p_i|^{\kappa}}$$

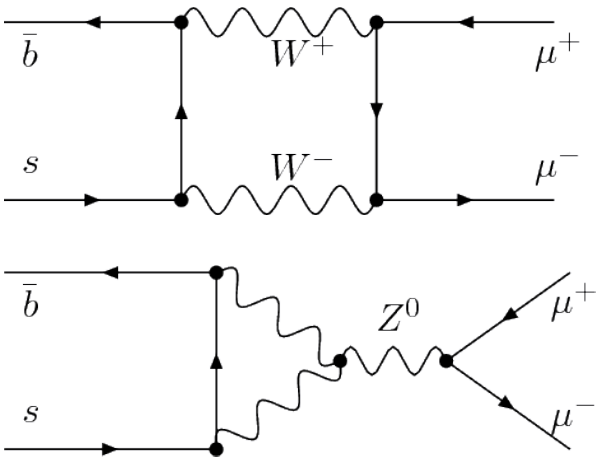
- Parameters: ΔR, κ, $|Q_{jet}|_{min}$
- $B_d \to J/\psi\ K^{0*}$ is self-tagging
  $\Rightarrow$ calibration of jet-charge tag
- $B_s \to J/\psi\ \phi$ needs validated Monte Carlo for calibration



Parameter (p_L)	$B^0 \to J/\psi\ K^{*0}$	$B_s^0 \to J/\psi\ \phi$
Luminosity	150 pb^{-1}	1.5 fb^{-1}
Tag efficiency	0.870 ± 0.003	0.625 ± 0.005
Wrong tag fraction	0.380 ± 0.004	0.374 ± 0.005
Dilution	0.240 ± 0.009	0.251 ± 0.010
Quality	0.050 ± 0.004	0.039 ± 0.003

Search for Rare Decays

Very rare decay $B_s^0 \to \mu^+\mu^-$



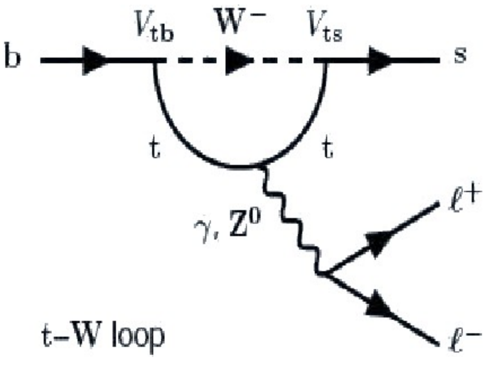
- FCNC decay with helicity suppression
  $\Rightarrow BR_{SM} = (3.42 \pm 0.52) \times 10^{-9}$ tiny!
- Test of SM to high pertubative orders
  - $BR_{meas} \neq BR_{SM} \Rightarrow$ New Physics!
- Current upper limits:
  - D0 (5 fb^{-1}): $BR_{B_s \to \mu\mu} < 4.5\ (5.3) \times 10^{-8}$ @ 90% (95%) CL [D0 Note 5906-CONF 2009]
  - CDF (2 fb^{-1}): $BR_{B_s \to \mu\mu} < 5.8 \times 10^{-8}$ @ 95% CL [Phys. Rev. Lett. 100, 101802 (2008)]

Semi-leptonic rare B-decays ($b \to s(d)\ \mu^+\mu^-$)

- $B_0 \to K^{*0}\ \mu\mu$
- $B_s \to \phi\ \mu\mu$,
- $\Lambda_b \to \Lambda\ \mu\mu$,
- $B^+ \to K^+\ \mu\mu$,
- $B^+ \to K^{*+}\ \mu\mu$

BRs ~ 10^{-6},
mediated by FCNC (1-loop diagrams)
measure di-μ spectra,
differential cross-sections
and forward-backward asymmetry (A_{fb})

Not covered in this talk



Strategy for $B_s \to \mu\mu$

All plots & numbers for 14 TeV CME

- Measure BR relative to $B^+ \to J/\psi\,(\mu^+\mu^-)\,K^+$ as reference:

$$BR(B_s^0 \to \mu^+\mu^-) = \frac{N_{B_s}}{N_{B^+}} \frac{\alpha_{B^+}}{\alpha_{B_s}} \frac{\varepsilon_{B^+}}{\varepsilon_{B_s}} \frac{1}{\varepsilon_N} \frac{f_u}{f_s} BR(B^+ \to J/\psi K^+)\, BR(J/\psi \to \mu^+\mu^-)$$

Acceptance ratio: $\alpha_{B^+}/\alpha_{B_s}$

Ratio of $b \to B^+$ to $b \to B_s$: f_u/f_s

Trigger, reconstruction and selection efficiencies: $\varepsilon_{B^+}/\varepsilon_{B_s}$

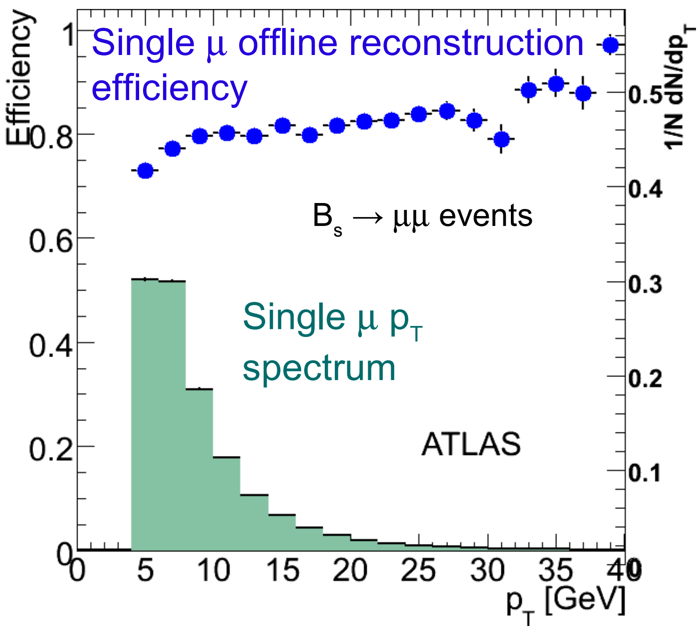
Final signal selection efficiency: ε_N

- Use topological di-μ trigger (at L = 10^{33} cm^{-2}s^{-1})
  - LVL1 & LVL2: 2 μ with p_T > 6 GeV
  - LVL2 & EF: $M_{\mu\mu}$ < 7 GeV, vertex χ^2 < 10
- Trigger performance for $B_s^0 \to \mu\mu$ events
- Possible at 10^{34} cm^{-2}s^{-1} with increased thresholds

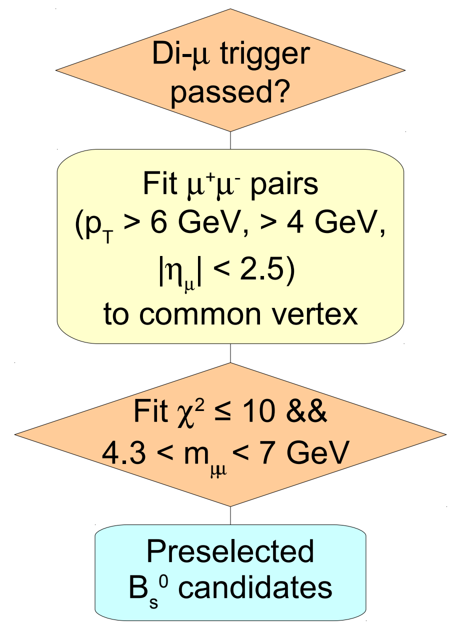
Level	Efficiency
L1 x L2	52 %
EF w.r.t. L2	88 %
Overall	46 %

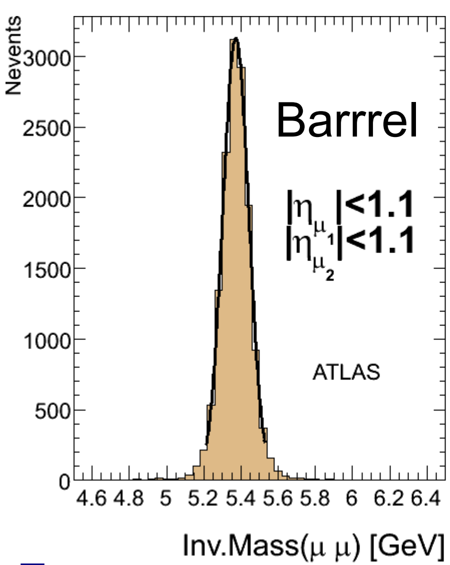
(MC generation with $p_T(\mu)$ > 6 GeV & $|\eta_\mu|$ < 2.5 for both μ)

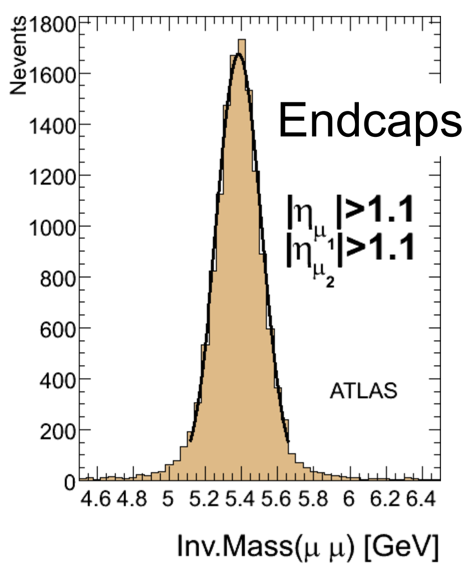
Offline Analysis Strategy for $B_s \to \mu\mu$ (1)



- Use μ tracks from Inner Detector and Muon Spectrometer
- Use lowest possible $p_T(\mu)$ cuts
- Event preselection:







- Barrel: $\sigma(m_{\mu\mu}) = 70 \pm 1$ MeV
- Endcaps: $\sigma(m_{\mu\mu}) = 124 \pm 1$ MeV

Offline Analysis Strategy for $B_s \to \mu\mu$ (2)

Final event selection cuts:

A) Transverse decay length of B-candidate: $L_{xy} > 0.5$ mm

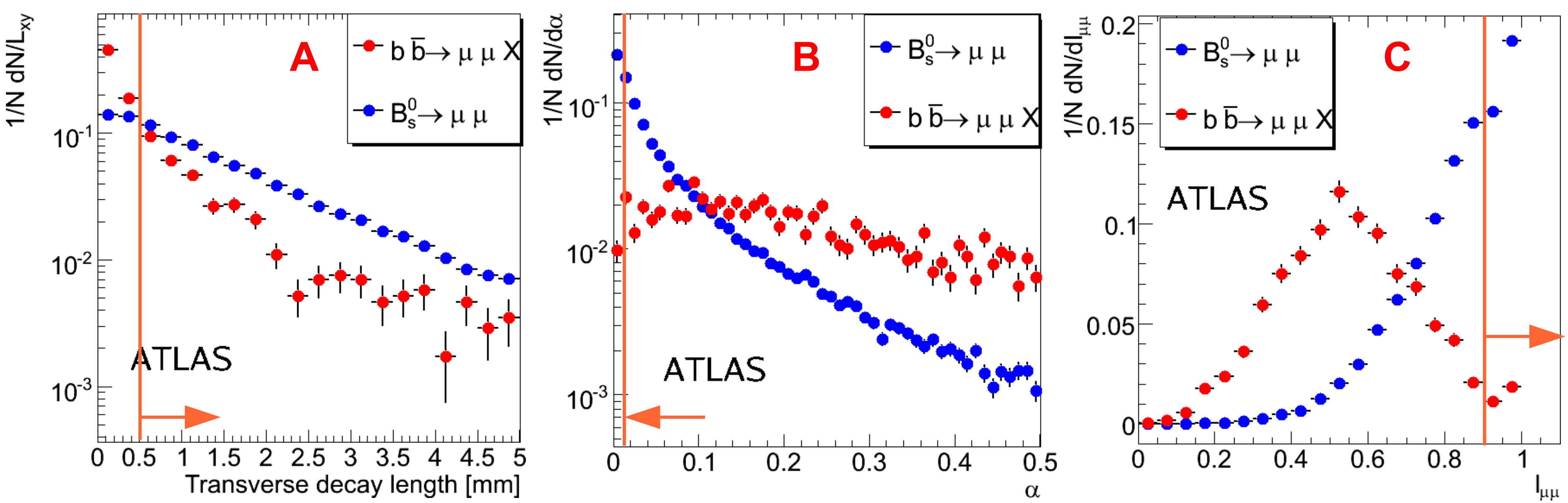
B) Pointing angle between $\vec{p}_{\mu\mu}$ and vertex direction: $\alpha < 0.017$ rad

C) Di-μ isolation inside cone with $\Delta R < 1$ around $\vec{p}_{\mu\mu}$: $I_{\mu\mu} > 0.9$

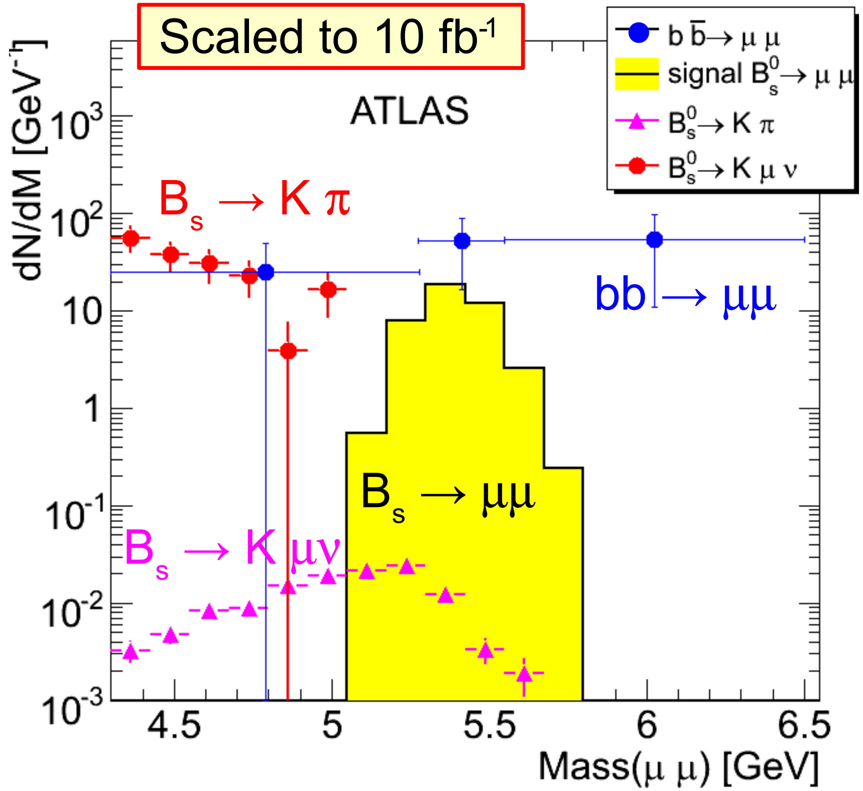
$$I_{\mu\mu} = \frac{p_T^{\mu\mu}}{\sum_i p_T^i}$$

Tracks with $p_T > 1$ GeV within $\Delta R < 1$

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



$B_s \to \mu\mu$ Summary



For 10 fb^{-1} (assuming SM):

- Signal and background of similar order after all cuts
- Expecting about 5.7 signal and 14^{+13}_{-10} background events

Already with 1 fb^{-1}:

- $O(10^6)$ di-μ events with $4 < m_{\mu\mu} < 7$ GeV
  - Tune cuts
  - Train multivariate procedures

$B_s \to \mu\mu$ program will continue for whole life of ATLAS detector

Cut	$\varepsilon(B_s \to \mu\mu)$	$\varepsilon(bb \to \mu\mu X)$	
$I_{\mu\mu} > 0.9$	0.24	$(2.6 \pm 0.3) \times 10^{-2}$	
$L_{xy} > 0.5$ mm	0.26	$(1.4 \pm 0.1) \times 10^{-2}$	$(1.0 \pm 0.7) \times 10^{-3}$
$\alpha < 0.017$ rad	0.23	$(8.5 \pm 0.2) \times 10^{-2}$	
$M_{\mu\mu}$ in $[-\sigma, +2\sigma]$	0.76	0.079	
Total	0.04	0.24×10^{-6}	$(2.0 \pm 1.4) \times 10^{-6}$
Event yield	5.7		14^{+13}_{-10}

Conclusions

- ATLAS B-physics program will start with early data and continue to indirect searches for New Physics via B-hadron decays
- ATLAS provides an efficient, fast and clean di-μ trigger scheme to collect large numbers of B-hadron decays with $\mu\mu$ final states
- ATLAS prospects:
  - ~ 270 000 $B_s \rightarrow J/\psi\ \phi$ events with ~ 30% background @ 30 fb^{-1}
  - 5.7 $B_s \rightarrow \mu\mu$ events with 14^{+13}_{-10} of main background @ 10 fb^{-1} assuming Standard Model branching ratios
- Early data will be used for
  - valuable detector performance studies
  - calibration studies supporting New Physics searches

[Main reference: The ATLAS collaboration, “Expected performance of the ATLAS experiment : detector, trigger and physics”, CERN-OPEN-2008-020]

Backup slides

Angular distributions for $B_s \rightarrow J/\psi\ \phi$

k	$\Omega^{(k)}(t)$		$g(t)$
1	$\vert A_0(t)\vert^2$		$4\sin^2\theta_1\cos^2\theta_2$
	$\frac{1}{2}\vert A_0(0)\vert^2$	$(1+\cos\phi_s)e^{-\Gamma_L^{(s)}t}+$ $(1-\cos\phi_s)e^{-\Gamma_H^s t}+$ $2e^{-\Gamma_s t}\sin(\Delta M_s t)\sin\phi_s$	
2	$\vert A_\parallel(t)\vert^2$		$(1+\cos^2\theta_1)\sin^2\theta_2-\sin^2\theta_1\sin^2\theta_2\cos 2\chi$
	$\frac{1}{2}\vert A_\parallel(0)\vert^2$	$(1+\cos\phi_s)e^{-\Gamma_L^{(s)}t}+$ $(1-\cos\phi_s)e^{-\Gamma_H^s t}+$ $2e^{-\Gamma_s t}\sin(\Delta M_s t)\sin\phi_s$	
3	$\vert A_\perp(t)\vert^2$		$(1+\cos^2\theta_1)\sin^2\theta_2+\sin^2\theta_1\sin^2\theta_2\cos 2\chi$
	$\frac{1}{2}\vert A_\perp(0)\vert^2$	$(1-\cos\phi_s)e^{-\Gamma_L^{(s)}t}+$ $(1+\cos\phi_s)e^{-\Gamma_H^s t}-$ $2e^{-\Gamma_s t}\sin(\Delta M_s t)\sin\phi_s$	
4	$\Re\{A_0^*(t)A_\parallel(t)\}$		$2\sin^2\theta_1\sin^2\theta_2\sin 2\chi$
	$\frac{1}{2}\vert A_0(0)\vert\vert A_\parallel(0)\cos(\delta_2-\delta 1)$	$(1+\cos\phi_s)e^{-\Gamma_L^s(t)}+$ $(1-\cos\phi_s)e^{-\Gamma_H^{(s)}t}+$ $2e^{-\Gamma_s t}\sin(\Delta M_s t)\sin\phi_s$	
5	$\Im\{A_\parallel^*(t)A_\perp(t)\}$		$-\sqrt{2}\sin 2\theta_1\sin 2\theta_2\cos\chi$
	$\vert A_\parallel(0)\vert\vert A_\perp(0)$	$e^{-\Gamma_s t}\{\sin\delta_1\cos(\Delta M_s t)-$ $\cos\delta_1\sin(\Delta M_s t)\cos\phi_s\}-$ $\frac{1}{2}\left(e^{-\Gamma_H^{(s)}t}-e^{-\Gamma_L^{(s)}t}\right)\cos\delta_1\sin\phi_s$	
6	$\Im\{A_0^*(t)A_\perp(t)\}$		$\sqrt{2}\sin 2\theta_1\sin 2\theta_2\sin\chi$
	$\vert A_0(0)\vert\vert A_\perp(0)$	$e^{-\Gamma_s t}\{\sin\delta_2\cos(\Delta M_s t)-$ $\cos\delta_2\sin(\Delta M_s t)\cos\phi_s\}-$ $\frac{1}{2}\left(e^{-\Gamma_H^{(s)}t}-e^{-\Gamma_L^{(s)}t}\right)\cos\delta_2\sin\phi_s$	

+ h.c.

Maximum likelihood fit for $B_s \to J/\psi\ \phi$

$$L = \prod_{i=1}^{N} \int_0^\infty \frac{\left(\varepsilon_{tag}^1 \varepsilon_{rec}^1 W^+(t_i,\Omega) + \varepsilon_{tag}^2 \varepsilon_{rec}^2 W^-(t_i,\Omega) + b\, e^{-\Gamma_0 t_i}\right) \varrho(t-t_i)\, dt}{\int_{t_{min}}^\infty \left(\int_0^\infty \left(\varepsilon_{tag}^1 \varepsilon_{rec}^1 W^+(t_i,\Omega) + \varepsilon_{tag}^2 \varepsilon_{rec}^2 W^-(t_i,\Omega) + b\, e^{-\Gamma_0 t_i}\right) \varrho(t'-t)\, dt \right) dt'}$$

B(t = 0) = B^0_s

Transversity amplitudes

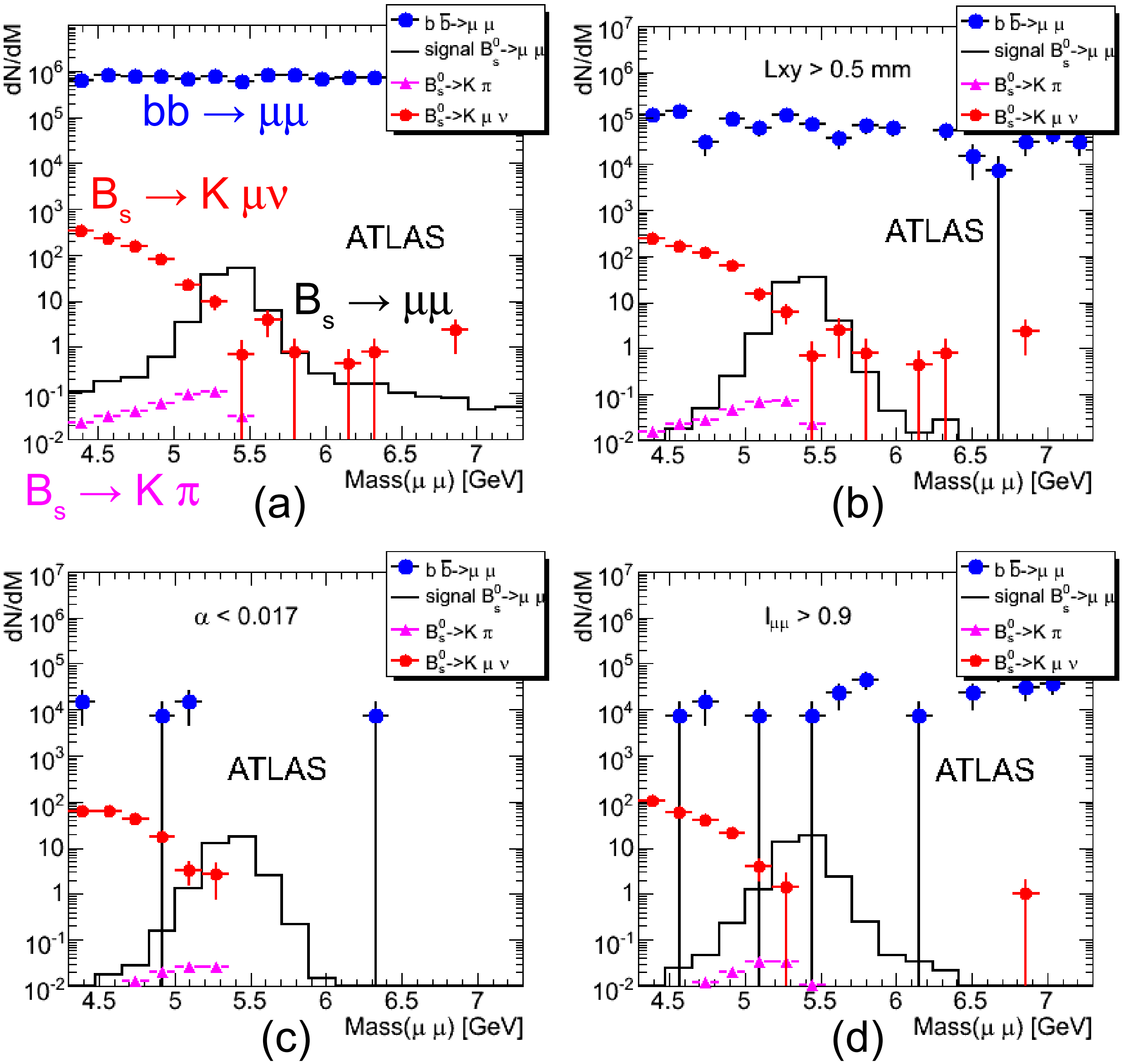
$$W^+(\theta_1,\theta_2,\phi,t) = \frac{d^4\Gamma}{d\theta_1\, d\theta_2\, d\phi\, dt} = \sum_k \Omega^{(k)} g^{(k)}(\theta_1,\theta_2,\phi)$$

$$W^-(\theta_1,\theta_2,\phi,t) = \frac{d^4\bar{\Gamma}}{d\theta_1\, d\theta_2\, d\phi\, dt} = \sum_k \bar{\Omega}^{(k)} g^{(k)}(\theta_1,\theta_2,\phi)$$

B(t = 0) = $\bar{B}^0_s$

Spin dynamics

Effect of Selection Cuts for $B_s \to \mu\mu$



Events scaled to 10 fb^{-1}

- **$m_{\mu\mu}$ after:**

(a) Preselection

(b) After transverse decay length cut

(c) After pointing angle cut

(d) After isolation cut

➔ **$bb \to \mu\mu$ dominates!**