LHC Sensitivity to new physics in B_s parameters

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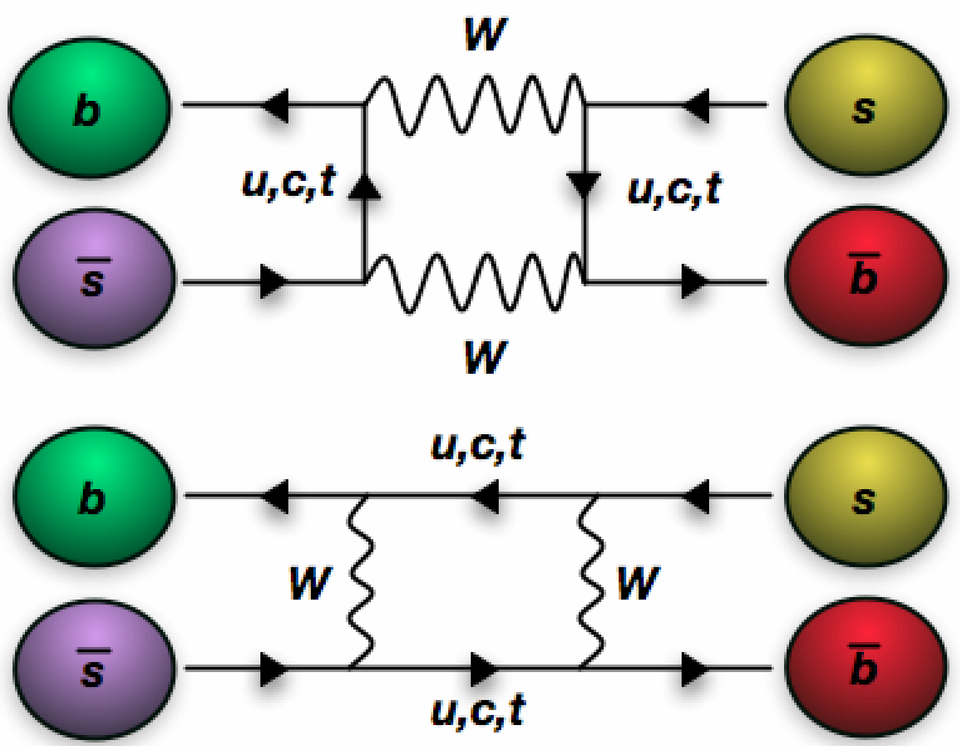
B_s mixing

- Second-order process, $\Delta B=2$
- Leads to two mass eigenstates:

  B_L, B_H

  CP-violation can occur in these processes
  - In the mixing amplitudes
  - In interference terms between the mixing amplitudes and the meson decay amplitudes



Parameters of neutral B mixing

	B_d	B_s
ΔM	~5 ps^{-1}	~20 ps^{-1}
$\Delta\Gamma/\Gamma$	~0	~10%
ϕ_s	$\phi_d = 2\arg[V^*_{td}V_{tb}]$ ≈ 0.8 (SM)	0.04 (SM)

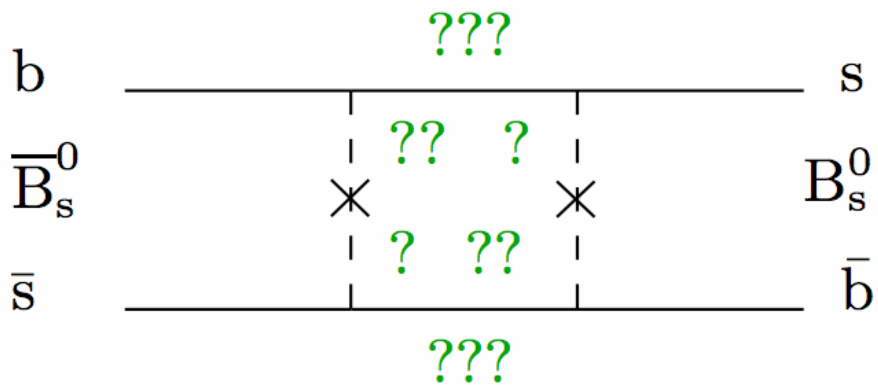
Rapid!

New physics in B_s mixing

- $\phi_s \equiv 2 \arg [V^*_{ts} V_{tb}] + \phi_{NEW}$

S.M. New physics

- $\Delta M_s = \Delta M_{SM} + \Delta M_{NEW}$

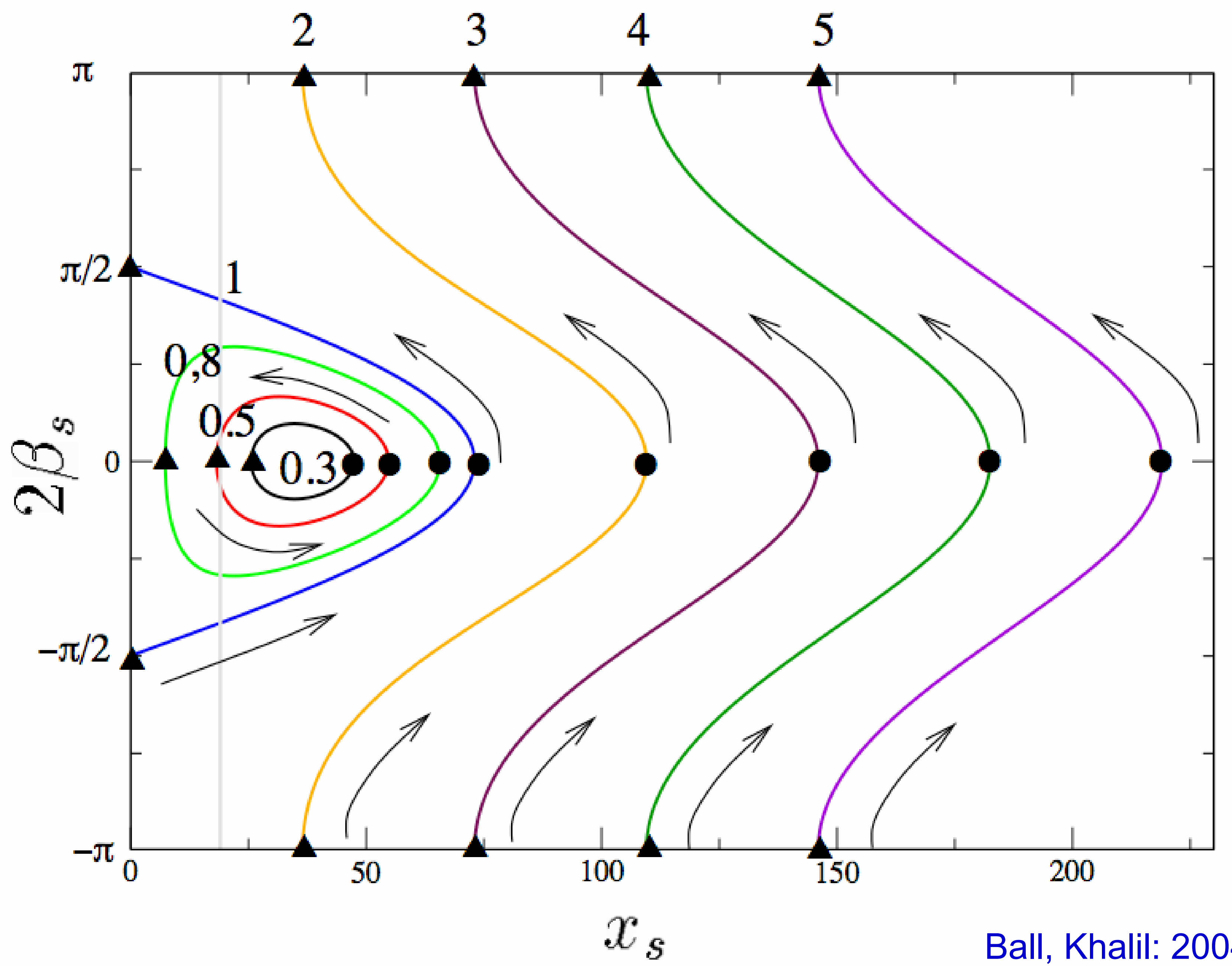


- **Exposition of new physics effects**
  - Notation of Ball, Fleicher (2003)
  - R = ratio of new physics to standard model contributions in the matrix element

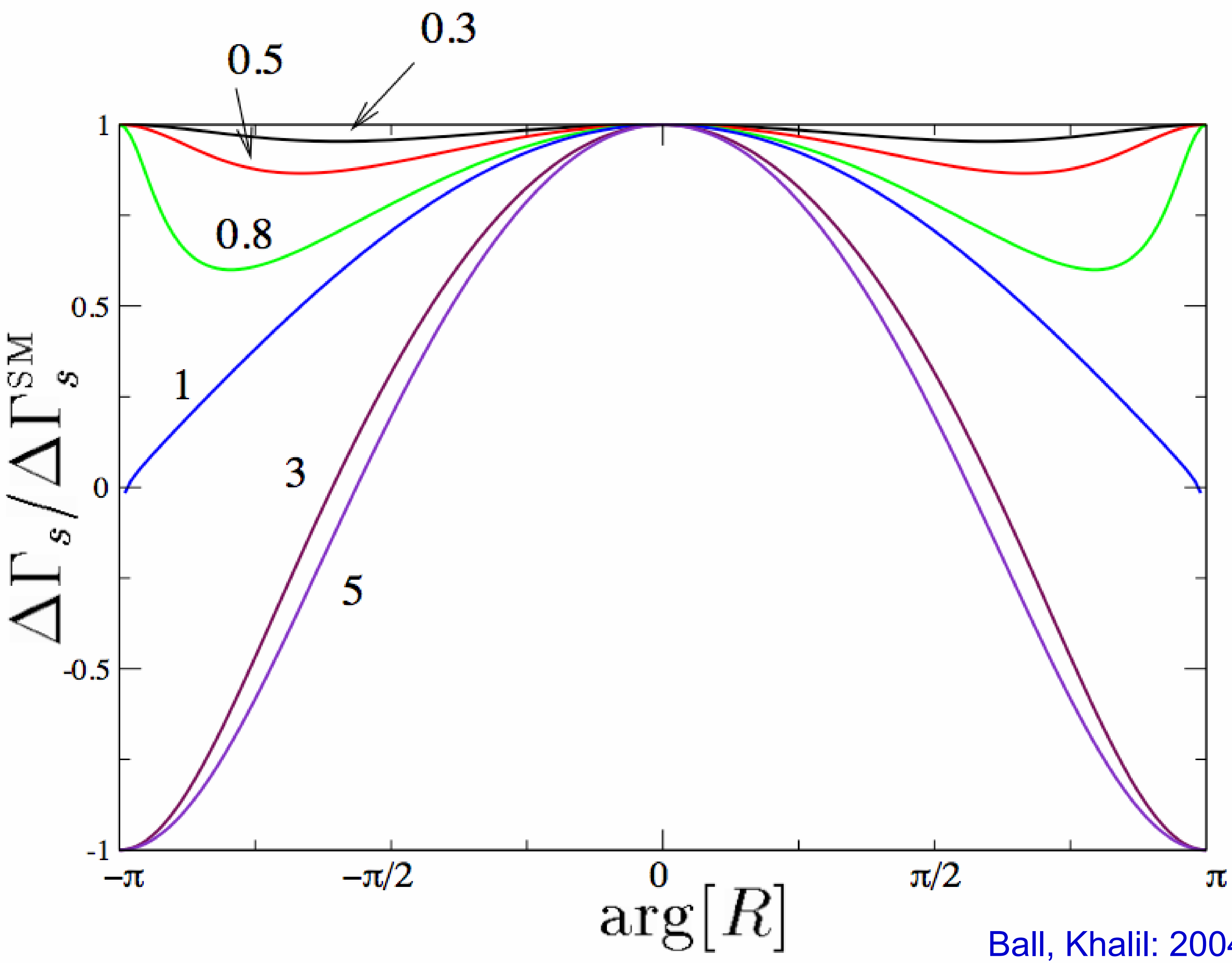
$$R = \frac{M_{12}^{NP}}{M_{12}^{SM}}$$

  - x_s = mixing parameter

$$x = \frac{\Delta M}{\Gamma}$$



Ball, Khalil: 2004



Ball, Khalil: 2004

Measurement of the parameters

- Weak mixing phase $\phi_s \Rightarrow$ angular and lifetime analysis of tagged

  $B_s \to J/\psi(\mu\mu)\phi(KK)$
- Oscillation frequency $\Delta M_s \Rightarrow$ lifetime analysis with

  $B_s \to D_s\pi$
- Ultimately a combined analysis of the two channels must be performed to measure the complete set of B-mixing parameters
  - $B_s \to J/\psi\phi$ has little sensitivity to ΔM_s

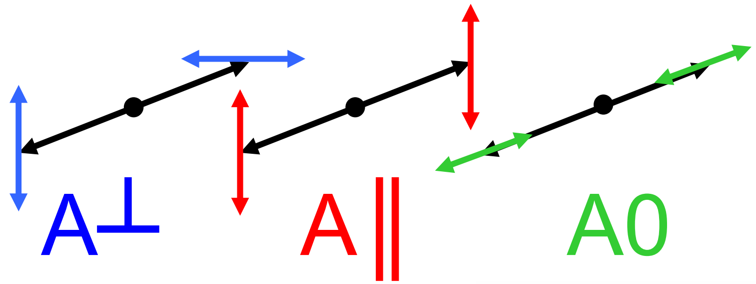
Measurement of ϕ_s with $B_s \rightarrow J/\psi\phi$

Transversity decomposition

B^0_s, $\overline{B}^0_s$ → $J/\psi(\mu^+\mu^-)\phi(K^+K^-)$

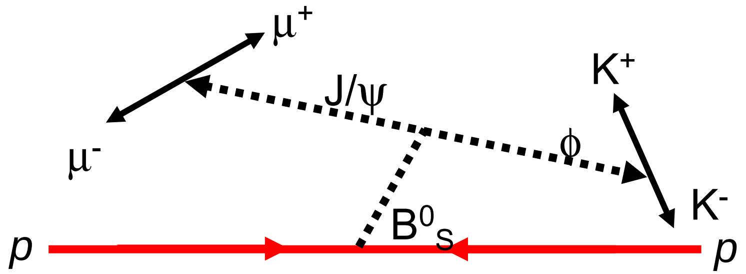
Extracting mixing parameters requires separation of contributions

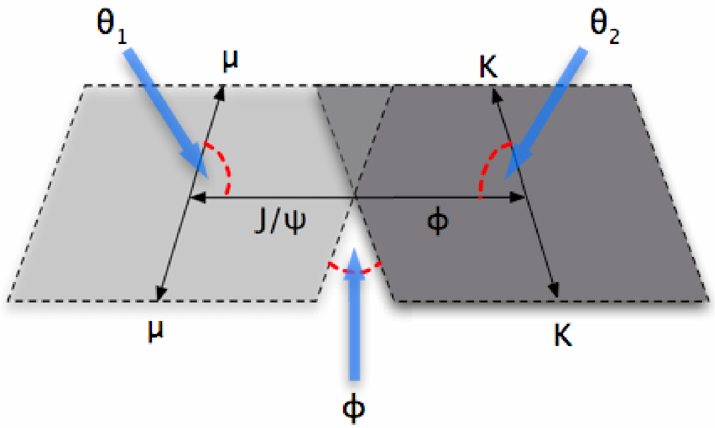
Scalar → Vector + Vector decay



Final state described by three helicity amplitudes

Determined by the angular distribution of the decay





Angular distribution

- **Ultimately we end up with two expressions for the angular and decay time distribution:**

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

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

$B(t=0) = B^0_s$

Mixing terms

Terms governed by spin dynamics

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

- **Expression contains 8 independent parameters which must be extracted from the data:**
  - **Two independent transversity amplitudes and their phases: $|A_\perp|$, $|A_{||}|$, $\delta_\perp$, $\delta_{||}$**
  - **Width difference and mean width: $\Delta\Gamma_s$, Γ_s**
  - **Oscillation frequency: ΔM_s**
  - **Weak mixing phase: ϕ_s**

General analysis technique

1. In each passed by the trigger, select tracks passing relevant kinematic criteria, using particle identification where possible
   - Muon identification in ATLAS and LHCb
   - RICH detectors in LHCb for identification of hadrons
2. Attempt to fit each oppositely charged pair of tracks to a common vertex
   - Mass hypothesis on each track
   - Mass constraint on the J/ψ fit
3. Where the vertex fit succeeds, make appropriate cuts on invariant mass, position, χ^2, opening angle…
4. Fit all doublets of track pairs to a common vertex
   - Mass hypothesis on each track
   - Mass constraint on the J/ψ fit
   - Constrain vertex to point at the primary vertex
5. Make appropriate cuts on lifetime, kinematics, invariant mass and fit quality to produce the final B_s meson candidates
6. Tag the "initial" flavour of the B_s-meson
7. Calculate the decay angles of the final states
8. Fit the angles and decay times to the theoretical distribution to obtain the parameters

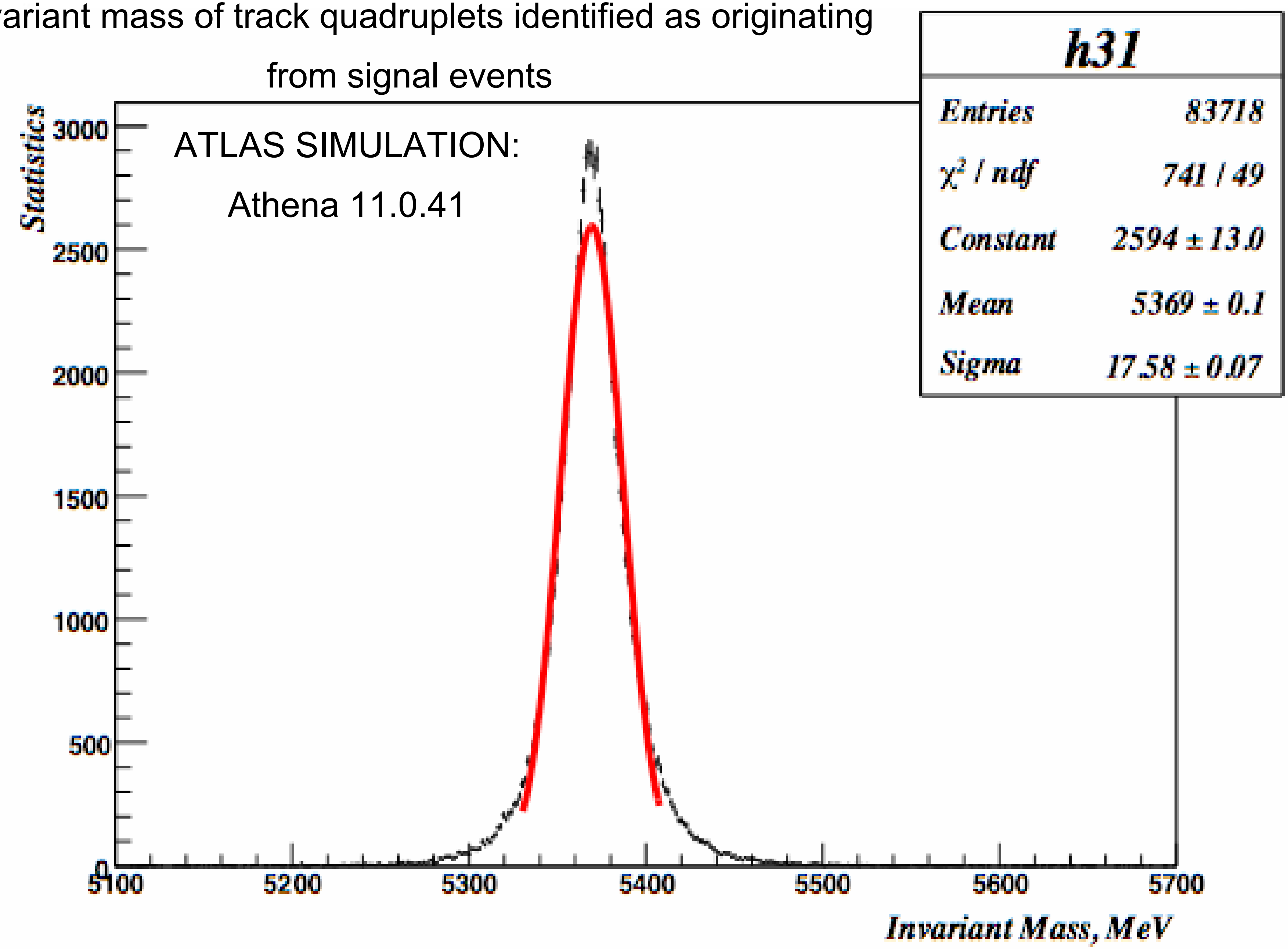
Monte Carlo Studies

- **Measurement of the mixing parameters depends strongly on**
  - Proper decay time resolution
  - Tagging performance
  - Background rejection
- **Large MC data samples produced with the LHC Computing Grid (LCG)**
  - Event generation: Pythia+EvtGen to produce final states with the correct angular distribution
  - Fully simulated and reconstructed to assess detector performance
- **Sensitivity of the detectors to the parameters assessed currently with "Toy Monte Carlo" experiments which take the performance characteristics of the detectors as input**
  - Ultimately the reconstructed data itself will have to be fitted to the distribution
  - This requires a full understanding of the acceptance corrections

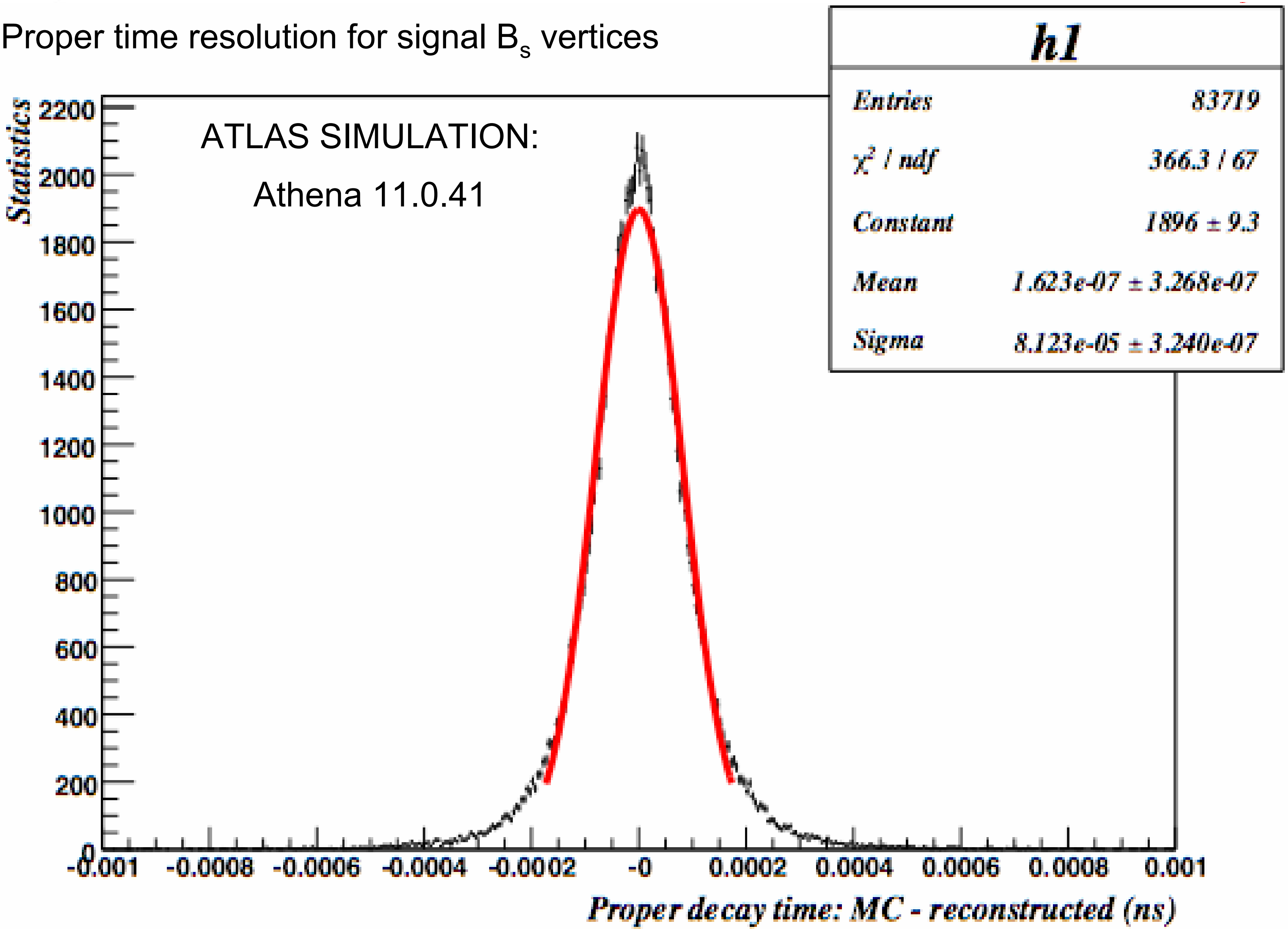
Detector performance

	ATLAS	LHCb (Nakada, 2006)
Statistics	270 000 ($30\ fb^{-1}$)	125 000 ($2\ fb^{-1}$)
σ_τ	81 fs	35 fs
σ_{mass}	18 MeV	8 MeV
Background	15%	S/B > 3

Invariant mass of track quadruplets identified as originating from signal events

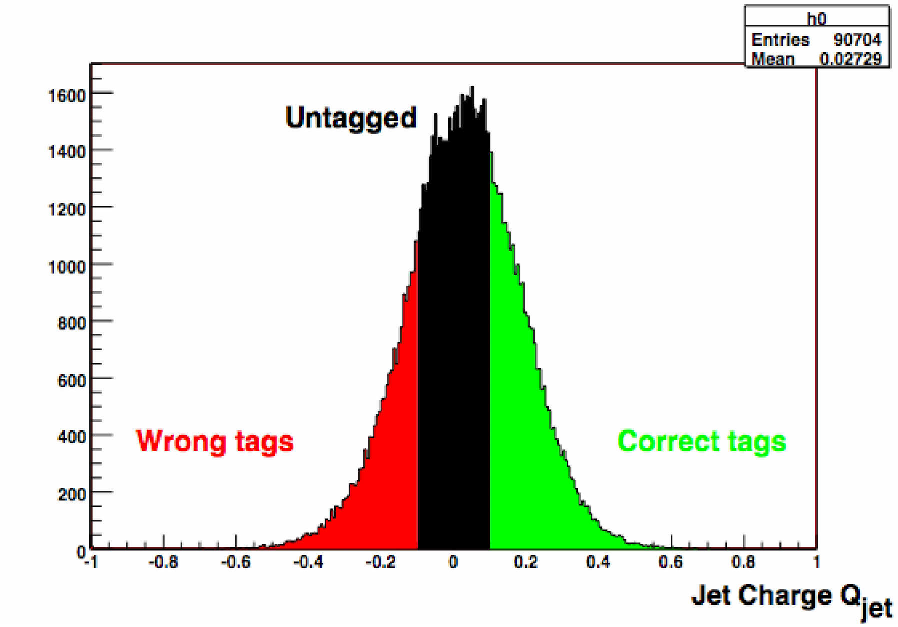


Proper time resolution for signal B_s vertices



Tagging performance

- **ATLAS**
  - Same-side jet-charge tag
    - Efficiency: 0.63
    - Wrong-tag fraction: 0.38
    - Quality factor: 0.036
  - Opposite side muon tag
    - Efficiency: 0.025
    - Wrong-tag fraction: 0.24
    - Quality factor: 0.007



- **LHCb**
  - Combined opposite/same side + neural network
    - Quality factor: 0.09

Toy MC sensitivity studies - ATLAS

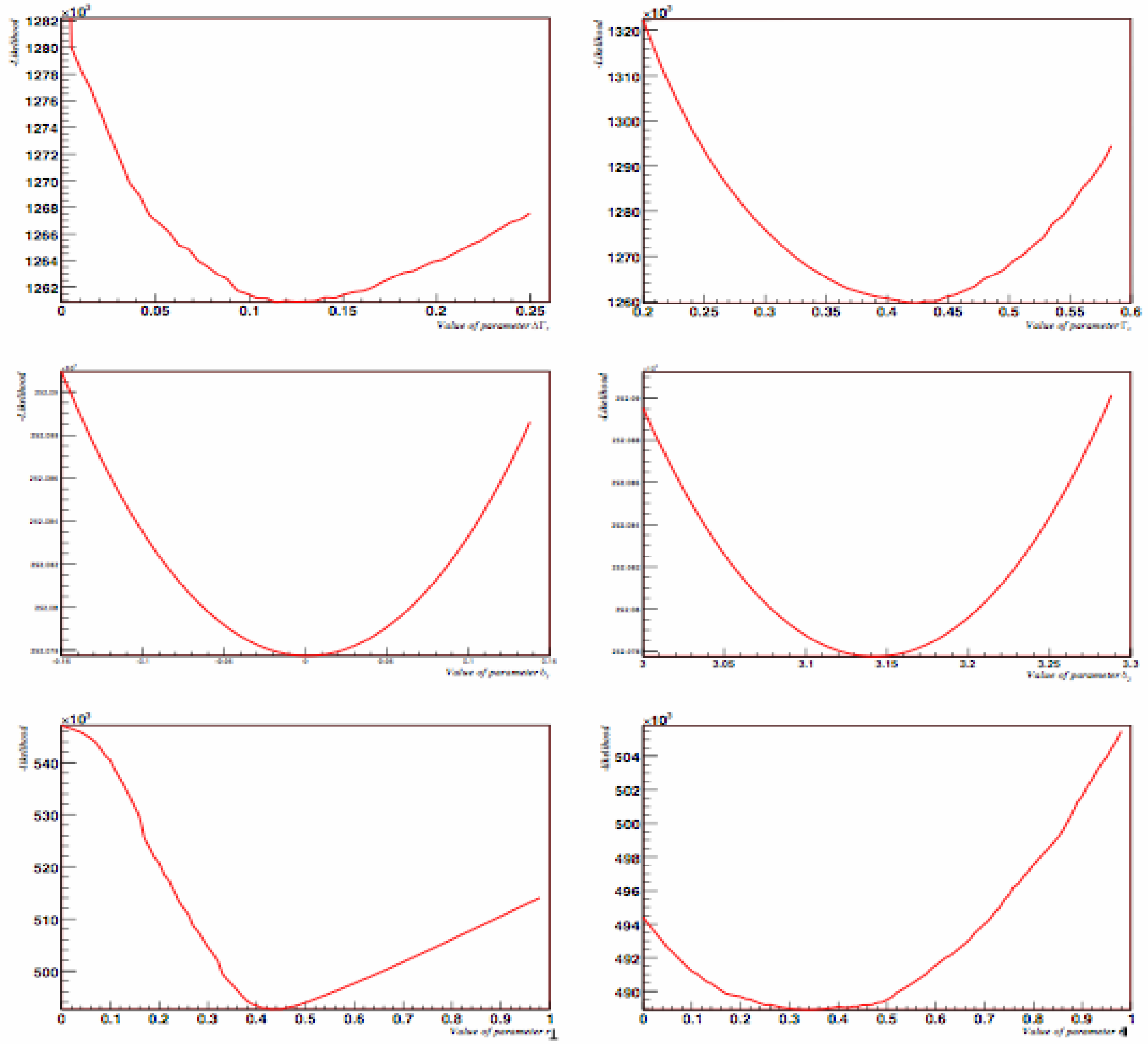
- Sets of angles and times generated according to theoretical distribution with accept-reject MC
- Smeared according to detector performance
- Fitted with MINUIT to the likelihood expression

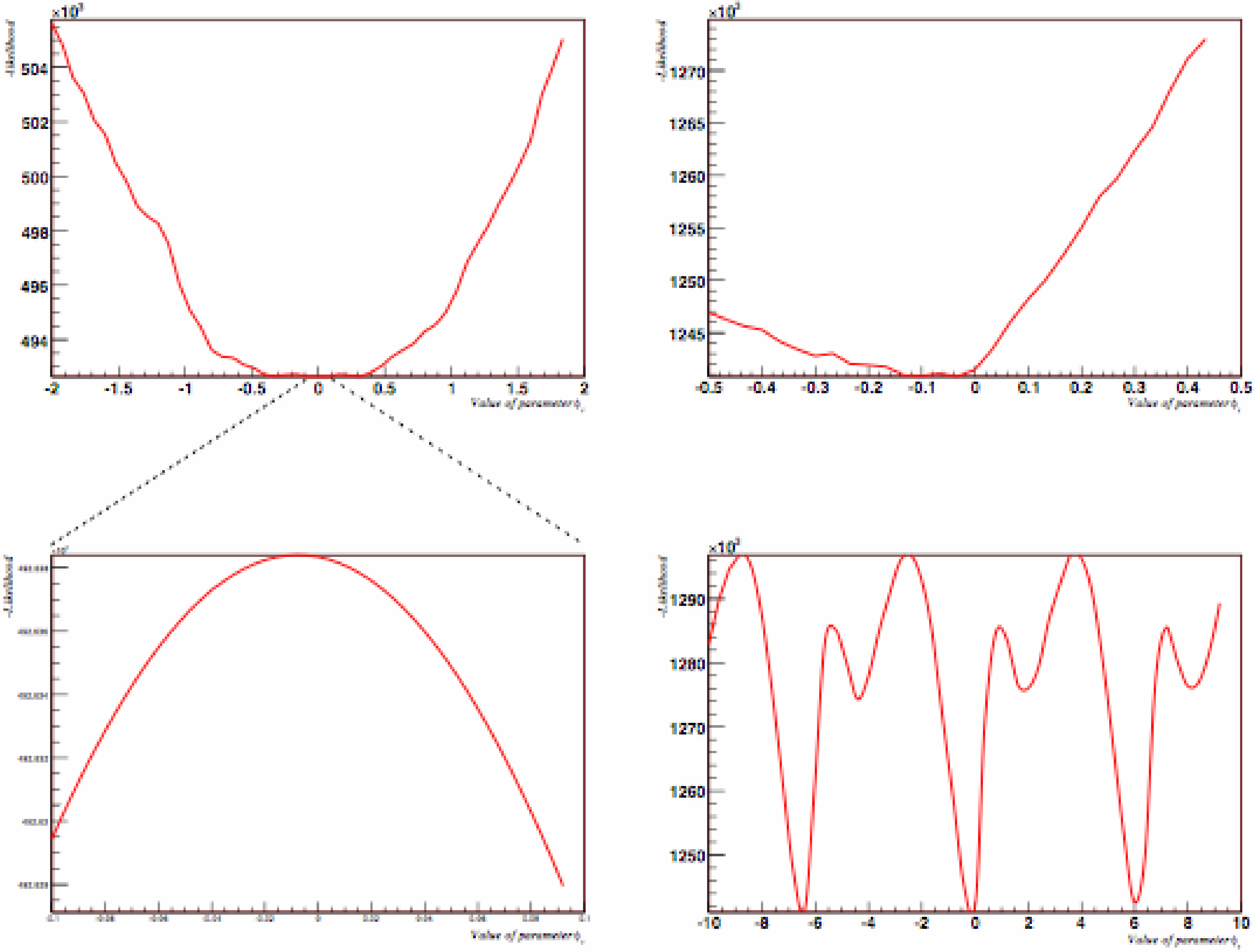
$$\mathcal{L} = \prod_{i=1}^{N} \frac{\left(\epsilon_1 W^+\left(t',\Omega_i\right) + \epsilon_2 W^-\left(t',\Omega_i\right) + b e^{-\Gamma_0 t'}\right) \otimes \rho\left(t_i - t'\right)}{\int_{t_{min}}^{\infty} \int_0^{2\pi} \left(\epsilon_1 W^+\left(t',\Omega\right) + \epsilon_2 W^-\left(t',\Omega\right) + b e^{-\Gamma_0 t'}\right) \otimes \rho\left(t - t'\right) d\Omega dt}$$

Normalisation integrals | Probability distribution | 1-(wrong tag) | Background | Decay time resolution

- **Assumptions:**
  - |R|=50%, i.e. new physics contributions are 50% of the SM
  - No angular dependence in the background
  - Proper time resolution described by a Gaussian
  - No asymmetry in production of B_s, anti-B_s or in tagging parameters
  - Angular resolution not considered

Likelihood scans (ATLAS)





×10³
-Likelihood
504
502
500
498
496
494
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Value of parameter
×10³
-Likelihood
1270
1265
1260
1255
1250
1245
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
0.5
Value of parameter
-Likelihood
Value of parameter
×10³
-Likelihood
1290
1280
1270
1260
1250
-10
-8
-6
-4
-2
0
2
4
6
8
10
Value of parameter

Correlation studies (ATLAS)

	$\Delta\Gamma$	Γ	$A_\perp$	$A_\parallel$	δ_1	δ_2
$\Delta\Gamma$		43%	90%	79%	26%	26%
Γ			45%	38%	8%	7%
$A_\perp$				95%	19%	26%
$A_\parallel$					18%	23%
δ_1						98%
δ_2						

Toy MC: LHCb

- Generate and fit ~ 250 toy experiments corresponding to 1 year data taking at $2\ \mathrm{fb}^{-1}$

- Unbinned (extended) likelihood fit to $\mathcal{L}_{tot}^{\bar{b}\to\bar{c}c\bar{s}}$

$$\mathcal{L}_{tot}^{\bar{b}\to\bar{c}c\bar{s}} = \prod_{i\epsilon \mathrm{B}_s^0\to f} \mathcal{L}_i^{\bar{b}\to\bar{c}c\bar{s}}(m_i, \theta_{\mathrm{tri}}, t_i^{rec}, \sigma_{t_i}, q_i)$$

1. Mass distributions fitted to determine signal and background probabilities

2. Sidebands: background parameters determined, acceptance fitted

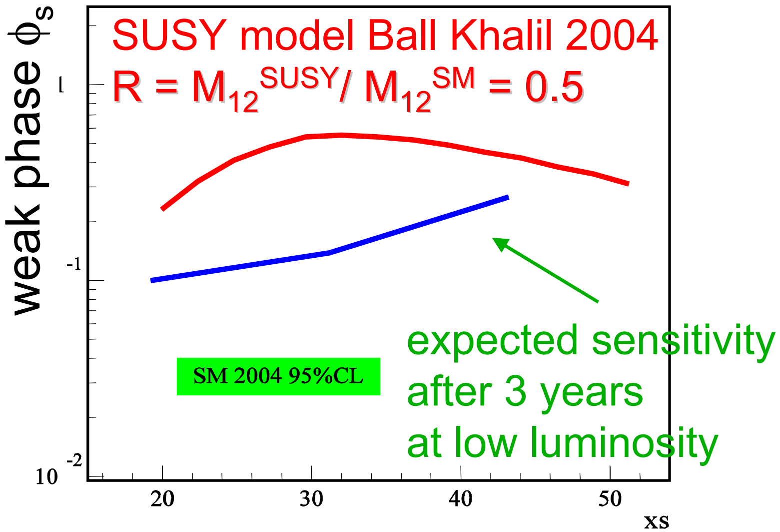
3. Signal window: physics parameters $\vec{\alpha} = (\Delta\Gamma_s/\Gamma_s, \Delta M_s, \phi_s, \tau_{\mathrm{B}_s^0}(, R_T))$ and wrong tag fraction ω fitted

- $\mathcal{L}_{tot}^{\bar{b}\to\bar{c}c\bar{s}}$ simultaneously maximized with likelihood of the $\mathrm{B}_s^0 \to \mathrm{D}_s\pi$ control sample

L. Fernandez, 2005

Expected precisions - ATLAS

	ATLAS after 30fb^{-1} (270 000 events)
$\sigma_{\Delta\Gamma}/\Delta\Gamma$	13%
σ_{Γ}/Γ	1%
$\sigma_{\phi s}$	0.046



Expected precisions: LHCb

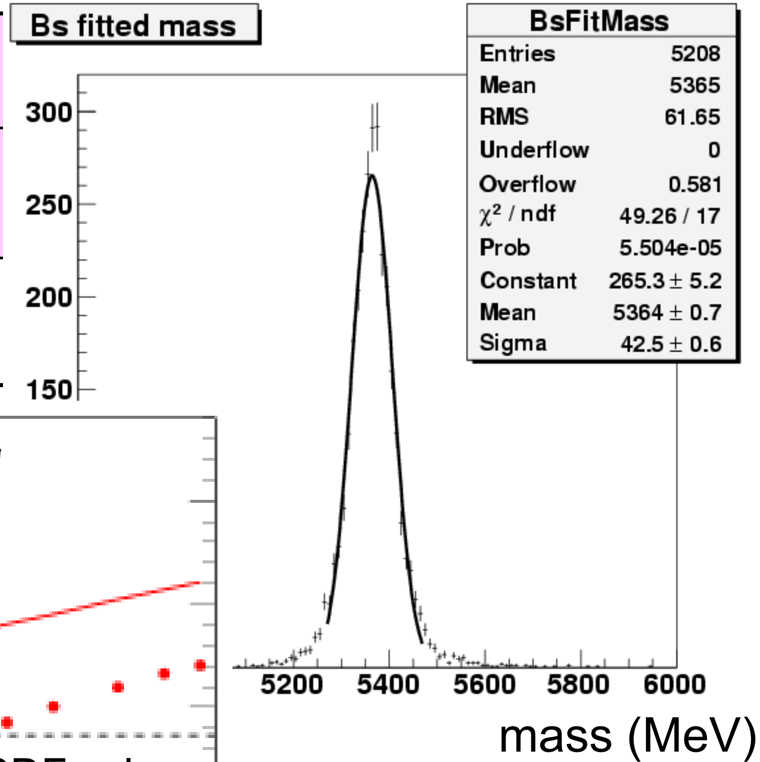
$\sigma(\Delta\Gamma/\Gamma)$ 2fb^{-1}	0.011
$\sigma(\phi_s)$ 2fb^{-1}	0.031
$\sigma(\phi_s)$ 10fb^{-1}	0.013

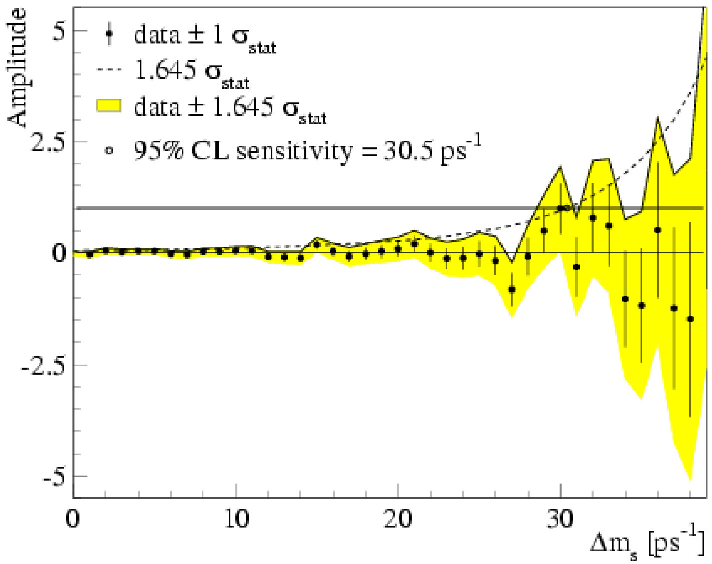
~3σ for $\phi_s \approx 0.04$ (SM)

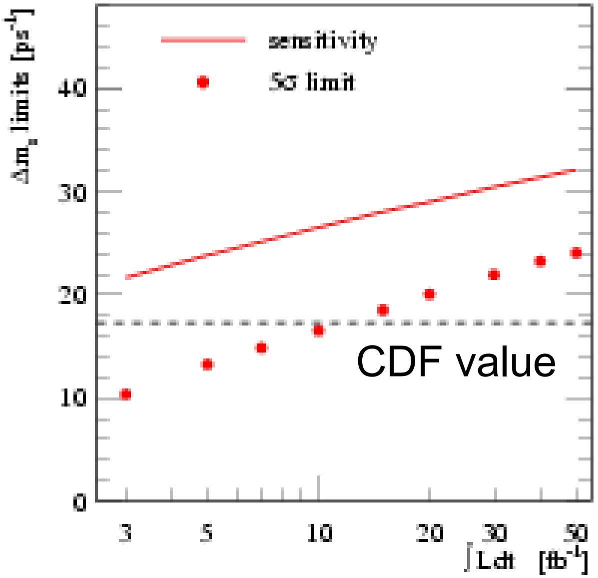
L. Fernandez, 2005

Measurement of ΔM_s with $B_s \rightarrow D_s \pi$

ATLAS		Number of events after trigger + offline rec. 3y@10^{33}cm^{-2}s^{-1}	
		Signal	Backgr
$B_s \rightarrow D^-_s\, \pi^+$	Δm_s	8250	<100%
$B_s \rightarrow D^-_s a_1^+$		4060	<100%







Luminosity (fb^{-1})	5σ limit (ps^{-1})	95% CL sensitivity (ps^{-1})
10	16.5	26.5
20	20.0	29.0
30	21.9	30.5

$$CDF: \Delta m_s = 17.31^{+0.33}_{-0.18} \pm 0.07\ ps^{-1}$$

$$D0: 17 < \Delta m_s < 21\ ps^{-1} \quad @90\%\ c.l.$$

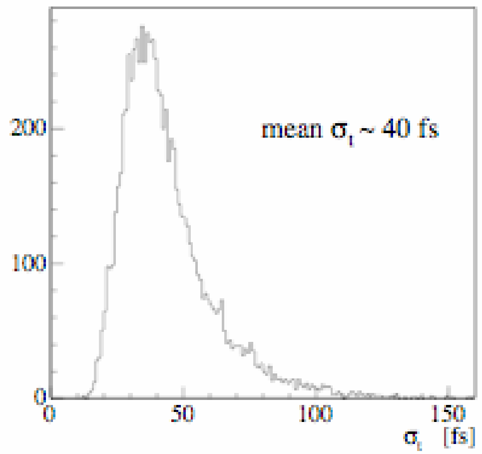
Given the low value measured by CDF, ATLAS will be able to measure Δm_s with ~10 fb^{-1} (one year)

F. Derue, 2006

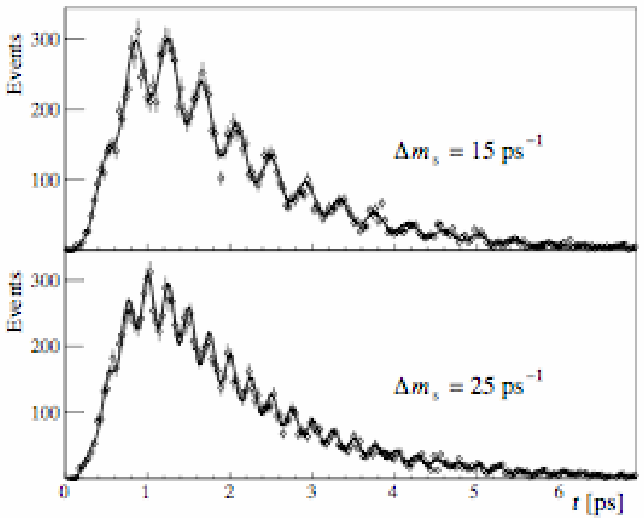
B_s^0 *oscillation frequency with* $B_s^0 \to D_s\pi$

Unbinned likelihood fit:

- rates weighted with acceptance, tagging dilution
- proper-time error σ_t obtained from full MC
  $\to$ uncertainty to generated events
- $\Delta\Gamma_s/\Gamma_s = 0.1$



Once oscillations observed, precise value of ΔM_s obtained: uncertainty $\sim 0.06\%$ (2 fb^{-1})



Decay rate for unmixed B_s^0

Statistical precision on ΔM_s after 1 year (2 fb^{-1})

ΔM_s [ps^{-1}]	15	20	25	30
$\sigma(\Delta M_s)$ [ps^{-1}]	0.009	0.011	0.013	0.016

- $\sigma(\Delta M_s)$ will probably be dominated by systematics, e.g. t scale

  $\to$ even if $\sigma_{\mathrm{sys}} \sim 10 \cdot \sigma_{\mathrm{stat}}$, uncertainty $< 1\%$

In 1 year, $\geq 5\sigma$ observation of B_s^0 oscillations up to $\Delta M_s = 68\ \mathrm{ps}^{-1}$

$\to$ could exclude full SM range

'Immediate' measure of ΔM_s if small: 1/8 year LHCb running! (0.25 fb^{-1}, $\Delta M_s = 40\ \mathrm{ps}^{-1}$)

L. Fernandez, 2005

Conclusions

- ϕ_s
  - ATLAS
    - After three years of low luminosity running, ATLAS could exclude some classes of new physics models at 95% CL
  - LHCb
    - After 5 years, LHCb could approach the 3σ confidence limit for standard model ϕ_s (~0.04)
- ΔM_s
  - ATLAS
    - ATLAS may be able to reach the 5σ confidence limit for ΔM_s after one year (10 fb^{-1}) given the CDF results for this parameter
  - LHCb
    - After 1 year, could reach the 5σ confidence limit for ΔM_s for all values of ΔM_s up to $68 ps^{-1}$, and could make a 5σ measurement in less than a year if ΔM_s is small (CDF result)