

B_s^0 – mixing at ATLAS

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Flavor Physics - Bad Honnef
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bmb+f - Förderschwerpunkt
ATLAS
Großgeräte der physikalischen
Grundlagenforschung





Outline

- Introduction
- B_s^0 oscillations at ATLAS
- Trigger strategies
- Flavor tagging
- Mixing analysis and measurement limits

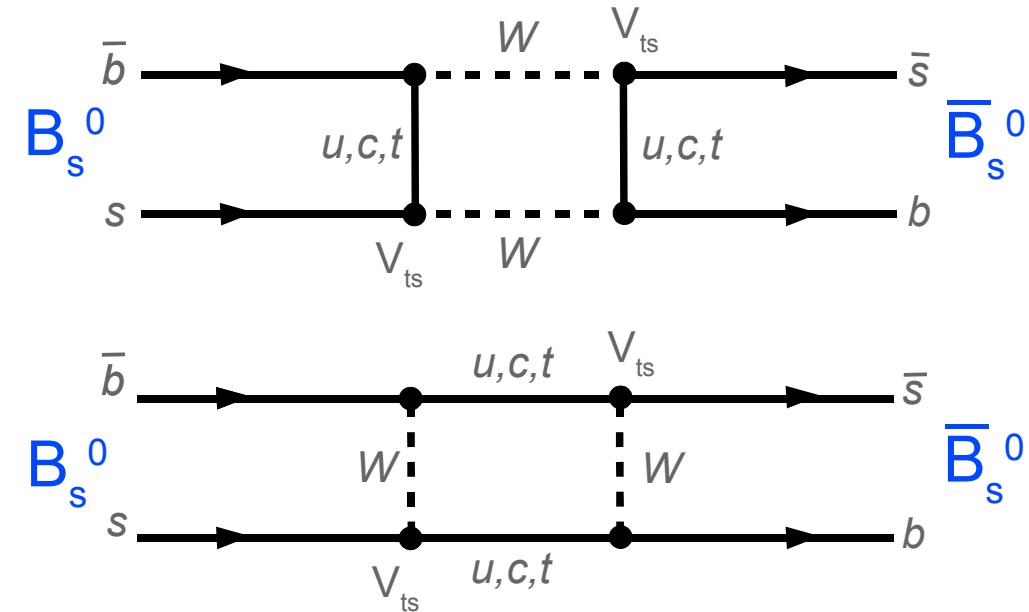
Introduction

- + B_s^0 and \bar{B}_s^0 are superpositions of two eigenstates B_H and B_L .
 - Transitions occur due to flavor non-conservation in charge weak-current interactions
 - Oscillation at lowest order via box diagrams
 - Frequency $\propto \Delta m_s = m_H - m_L$
 - t-quark dominant
 - $\Delta m_s \propto |V_{ts}|^2$

- + Constraint of the unitarity triangle
 - Many uncertainties cancel in ratio

$$\frac{\Delta m_s}{\Delta m_d} \propto \left| \frac{V_{ts}}{V_{td}} \right|^2$$

- Sign for New Physics ?



- + Mixing in B_d^0 -system well measured
 - $\Delta m_d = (0.507 \pm 0.004) \text{ ps}^{-1}$
[HFAG, hep-ex/0603003]
 - $|V_{ts}| \gg |V_{td}| \rightarrow \Delta m_s \gg \Delta m_d$

Experimental status

- + Prediction from direct calculations

[Ball+Fleischer, hep-ph/0604249]

- + $(\Delta m_s)_{\text{JLQCD}} = 16.1 \pm 2.8 \text{ ps}^{-1}$

- + $(\Delta m_s)_{(\text{HP+JL})\text{QCD}} = 23.4 \pm 3.8 \text{ ps}^{-1}$

- + Lattice uncertainties dominate

- + Values arising from fits of the unitarity triangle

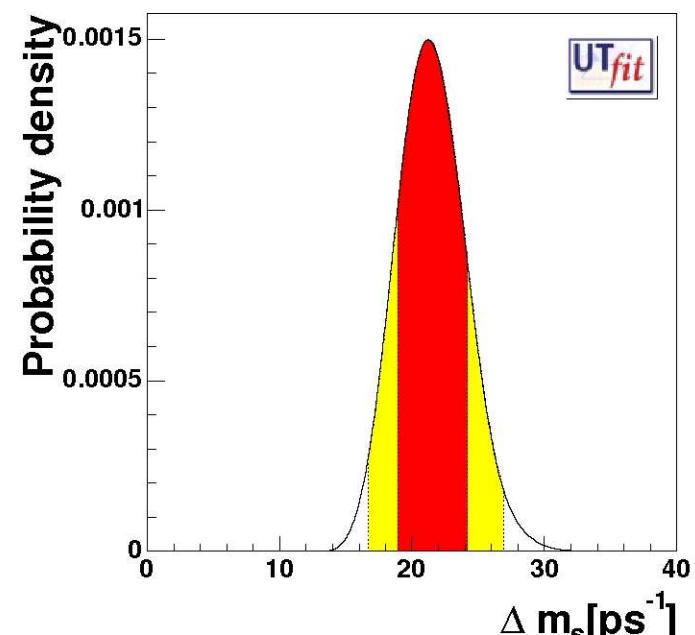
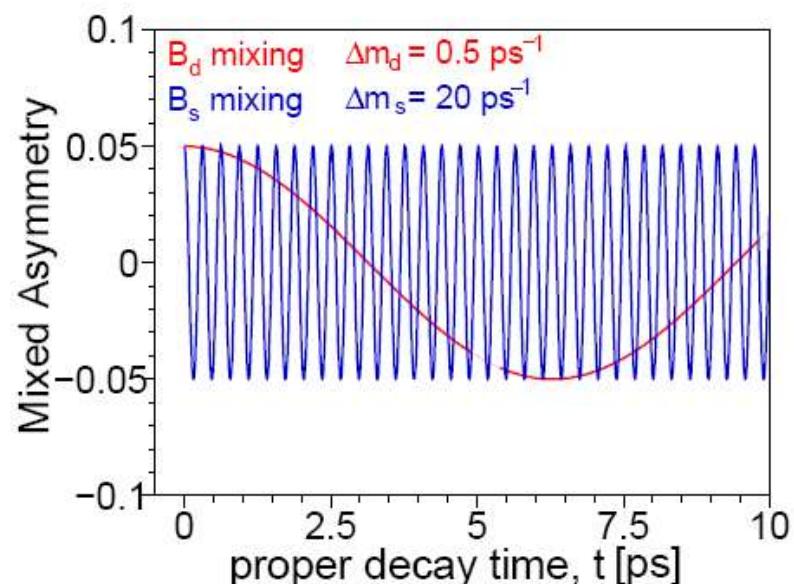
- + $(\Delta m_s)_{\text{CKMfitter}} = 21.7^{+5.9}_{-4.2} \text{ ps}^{-1}$

- + $(\Delta m_s)_{\text{UTfit}} = 21.5 \pm 2.8 \text{ ps}^{-1}$

- + Recent experimental results

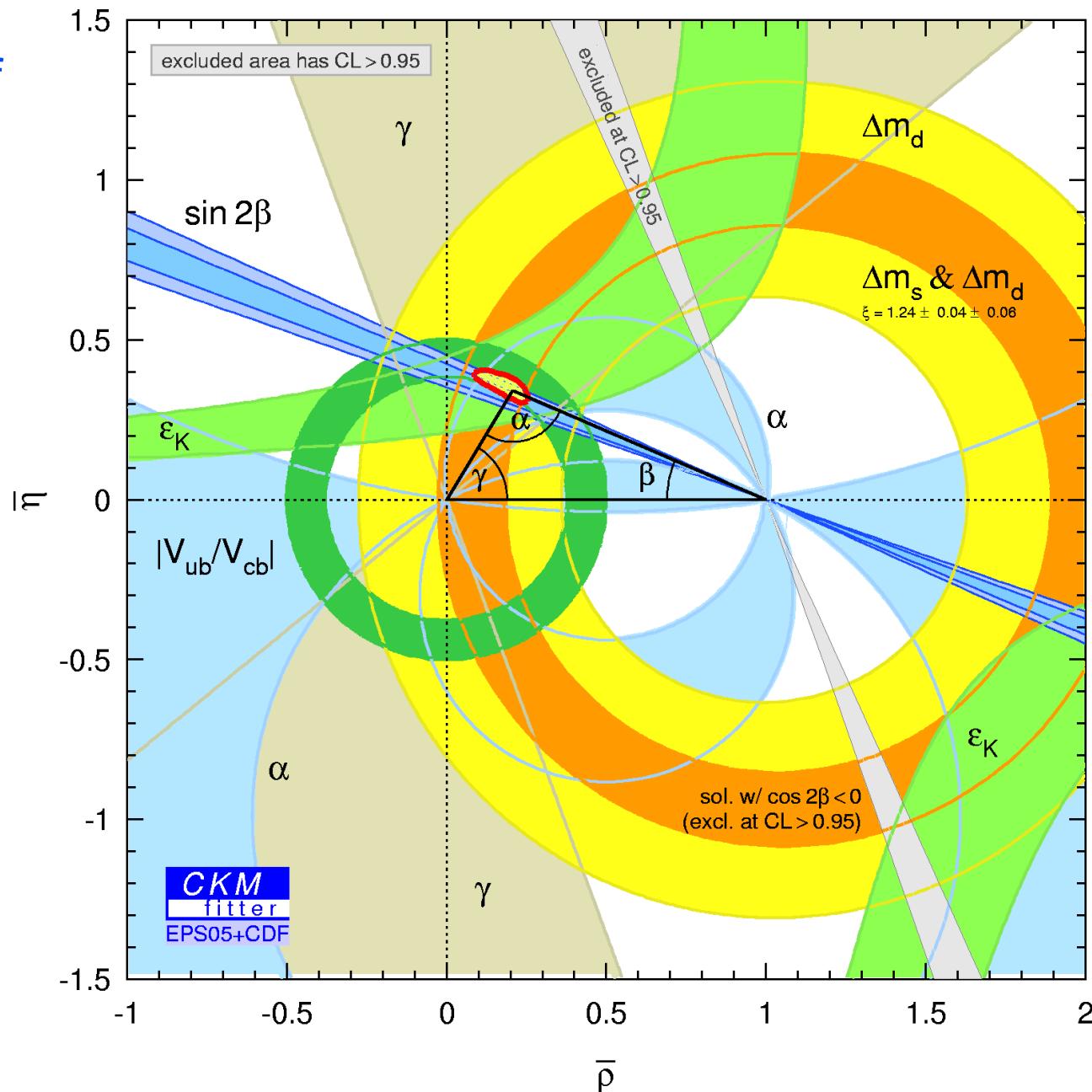
- + D0 : $17 \text{ ps}^{-1} < (\Delta m_s)_{\text{D0}} < 21 \text{ ps}^{-1}$ (90 % CL)

- + CDF : $(\Delta m_s)_{\text{CDF}} = 17.33^{+0.42}_{-0.21} \pm 0.07 \text{ ps}^{-1}$

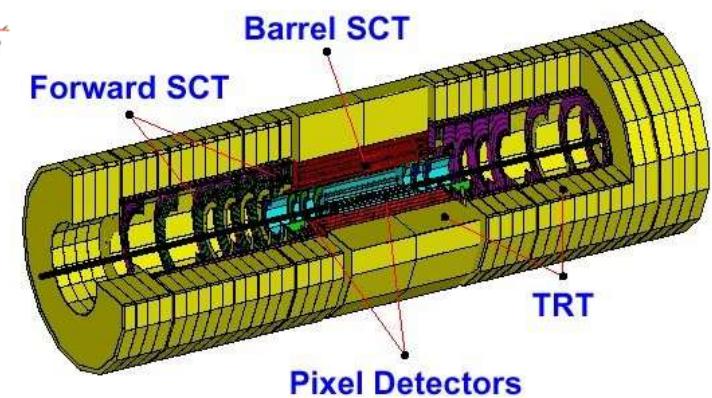
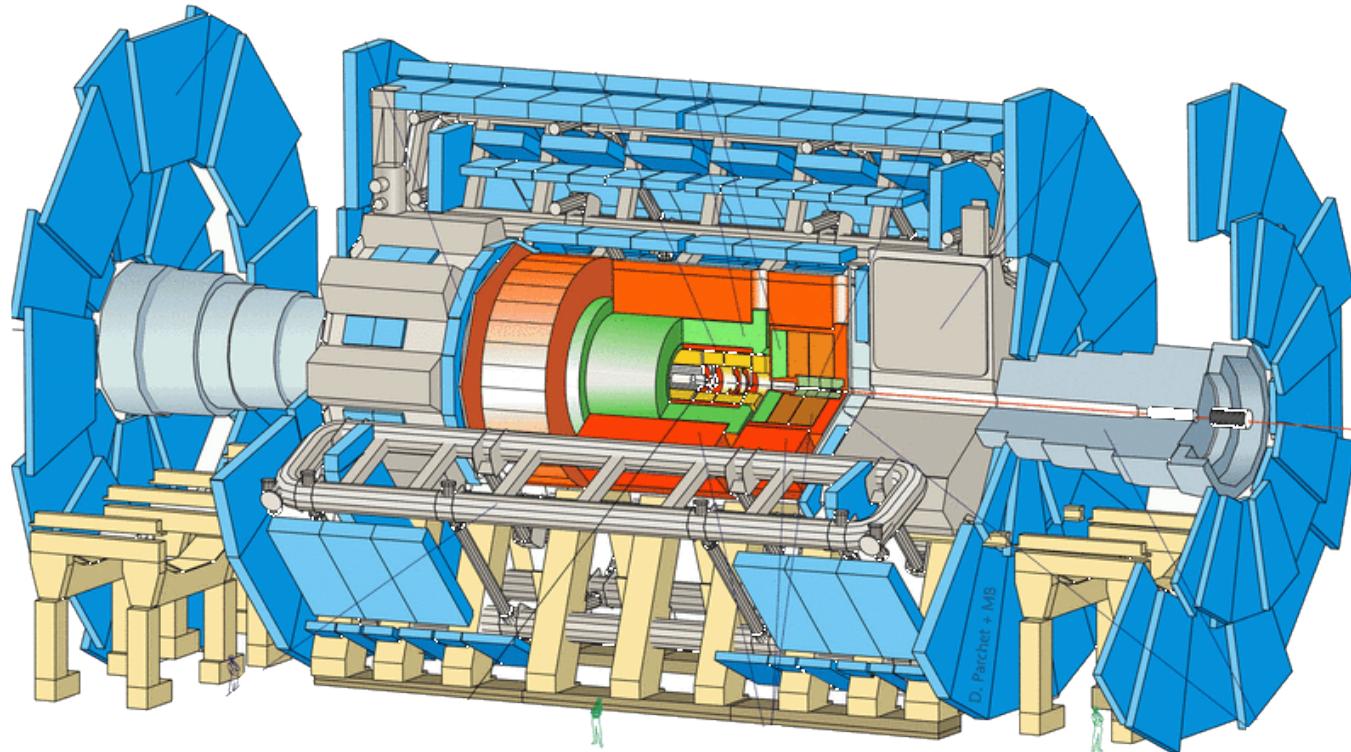


Δm_s prediction from SM
UT fit without using Δm_s
measurements as input

- ✚ Why is a measurement of Δm_s important ?
- ✚ Input for common global fit in $B_s \rightarrow J/\Psi (\mu\mu) \phi (KK)$
 - ✚ Determine CP violating parameter ϕ_s
 - ✚ Determine $\Delta\Gamma_s$
- ✚ Cross check with existing measurements



The ATLAS detector



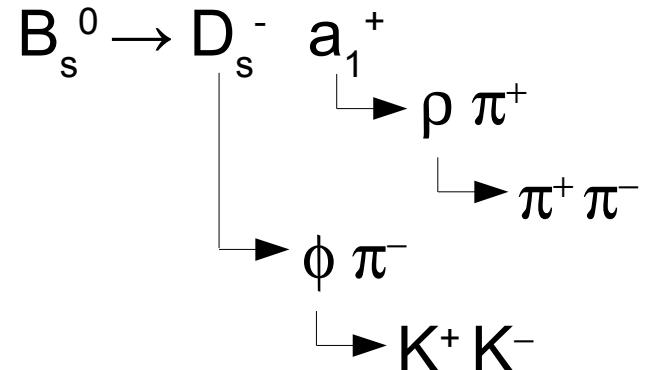
- pp-collisions at $\sqrt{s} = 14$ TeV every 25 ns
- $b\bar{b}$ crosssection $\sim 500 \mu b$
- Muon spectrometer
 - Air-core toroid system average ~ 0.5 T
- Pile-up ~ 23 @ $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Inner detector

- 3 layers of Si-pixel detector with a track resolution in ϕ -z direction of $\sim (12 \times 100) \mu m$.
- Silicon strip detector (SCT) and transition radiation tracker (TRT)

B_s^0 oscillations at ATLAS

- Collaboration with Innsbruck within the ATLAS B-physics group
- Channels used at ATLAS:
 - Purely hadronic final states
 - $B_s^0 \rightarrow D_s^- \pi^+$ – Innsbruck (π -channel)
 - $B_s^0 \rightarrow D_s^- a_1^+$ – Siegen (a_1 -channel)
 - Decays can be fully reconstructed
 - Good proper time resolution
 - Semileptonic final states
 - $B_s^0 \rightarrow D_s^- \mu^+ \nu$ – Siegen (μ -channel)
 - Larger signal yield
 - Missing information from neutrino
 - No direct mass constraint on B_s^0 applicable
 - Momentum of B_s^0 has to be corrected
 - Background and proper time resolution have to be carefully analyzed
 - Channel under first investigation in Siegen



Decay topology

The ATLAS trigger system

40 MHz

2 μ sec

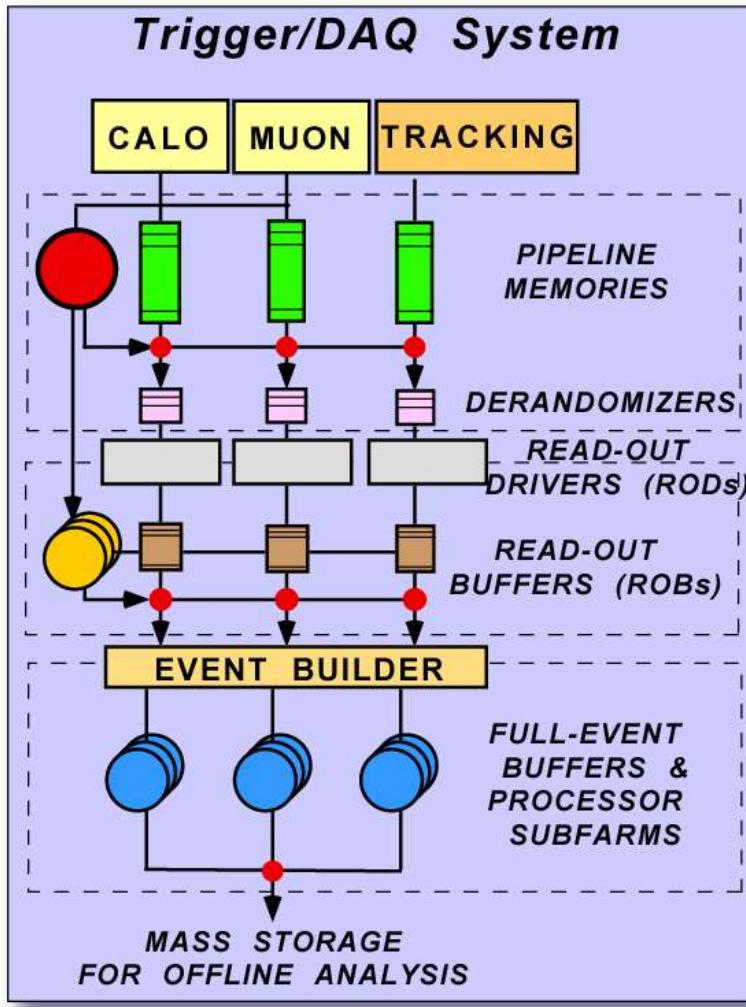
75 kHz

\sim 20msec

2 kHz

\sim 2sec

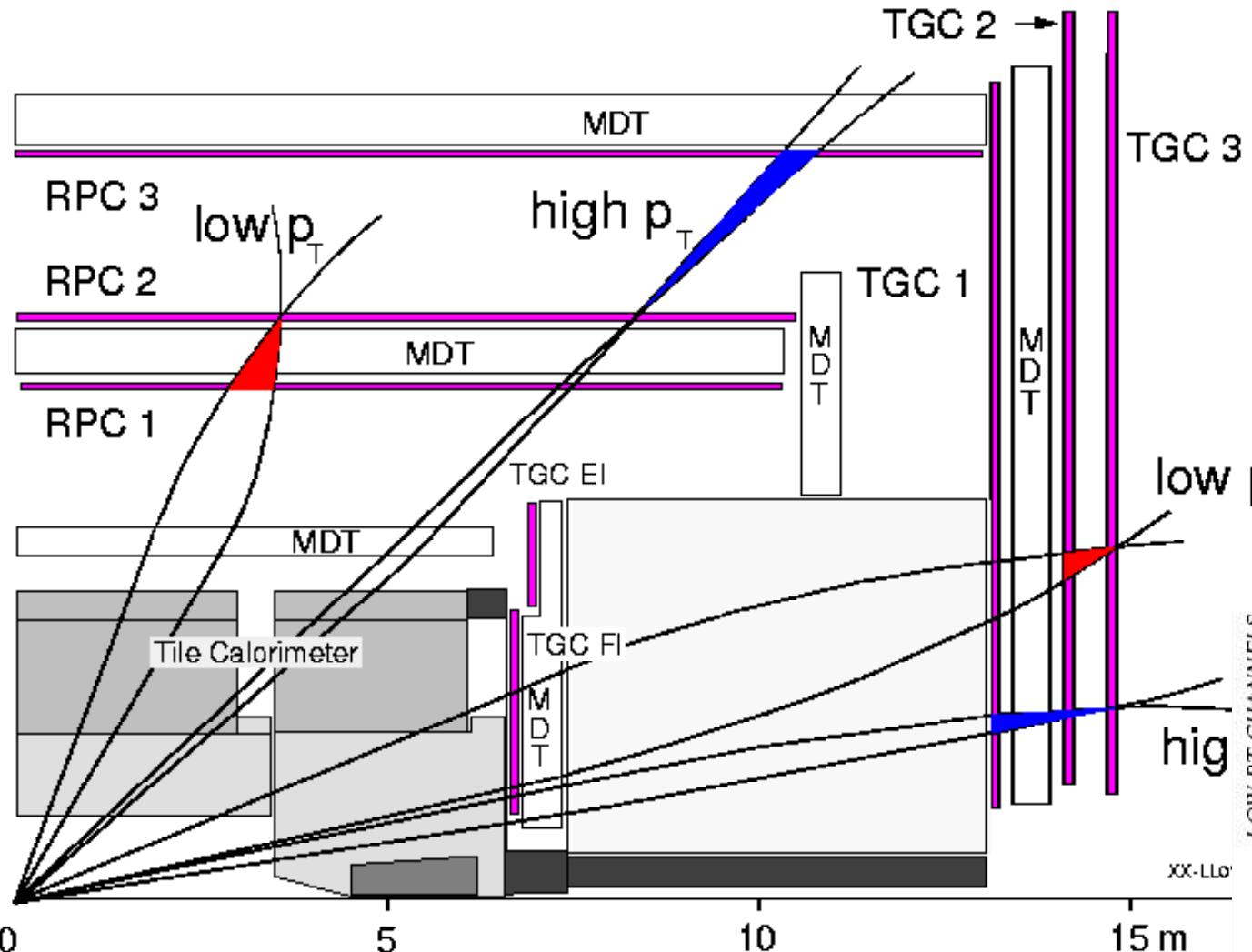
200 Hz



- Level 1 trigger (hardware based)
 - Select e , μ , γ , jet candidates. Info from calorimeter & muon trigger sys. (Coarse granularity)
 - Provides Region's of Interest η , ϕ (**ROI**) of LVL-1 objects & E_{sum} to Level-2
- Level 2 trigger
 - Uses ROI “seeds” to selectively access data with full granularity and precision
 - Fast processing & rejection
- Event Filter
 - Refines selection “seeded” by Level 2 ROI's. **Offline-like Algorithms**
 - Access to alignment & calibration data

[Ch. Petridou]

LVL 1 Muon trigger system



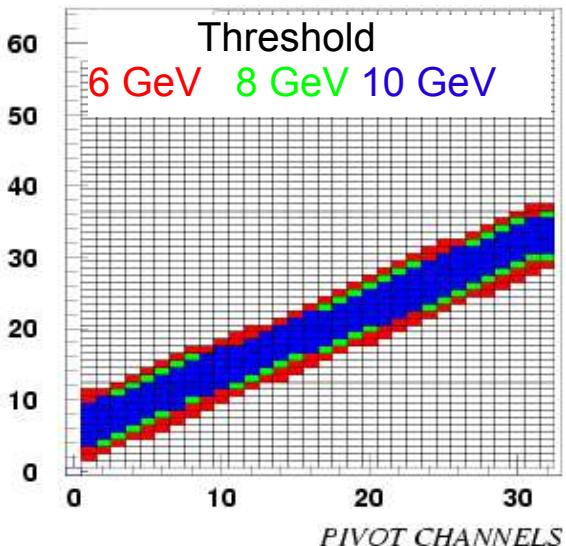
RPC: Resistive Plate Chambers (Trigger)

TGC: Thin Gap Chambers (Trigger)

MDT: Monitored Drift Tubes (Precision)

How to find a μ candidate

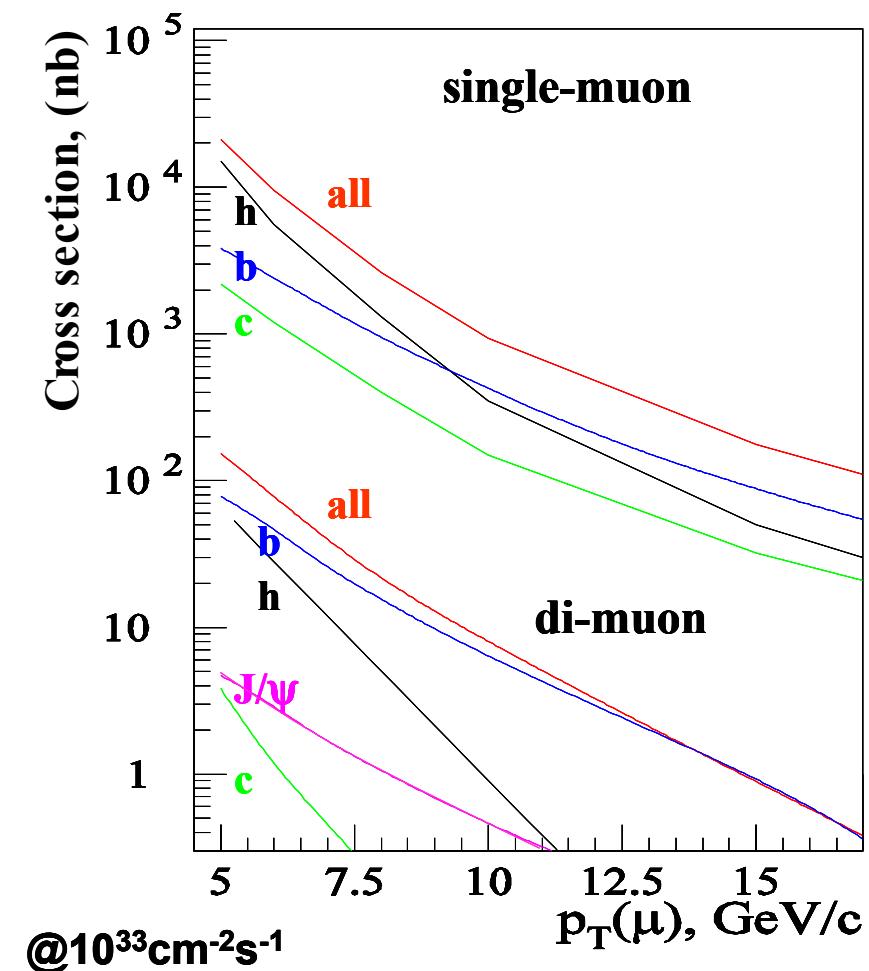
- A hit has to be accompanied by hits in other detector layers
- Coincidence window defines p_t cut
 - Low p_t : $3 / 4$
 - High p_t : $3 / 4 + 1 / 2$



Coincidence matrix [F. Conventi]

Trigger strategies

- Level 2 trigger rate must be reduced to ~ 2 kHz
 - Trigger strategy depends on luminosity
- Di-muon trigger for $\mathcal{L} \sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
 - Low trigger cuts on the muons applicable (for both muons ~ 6 GeV)
 - Hadronic channels need second muon in event
 - Good trigger prerequisite for the semileptonic channel
- Single-muon trigger for \mathcal{L} up to $\sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
 - Estimated rate for $p_t > 6 \text{ GeV}$ @ $\mathcal{L} 10^{33} \text{ cm}^{-2}\text{s}^{-1}$: 22 kHz





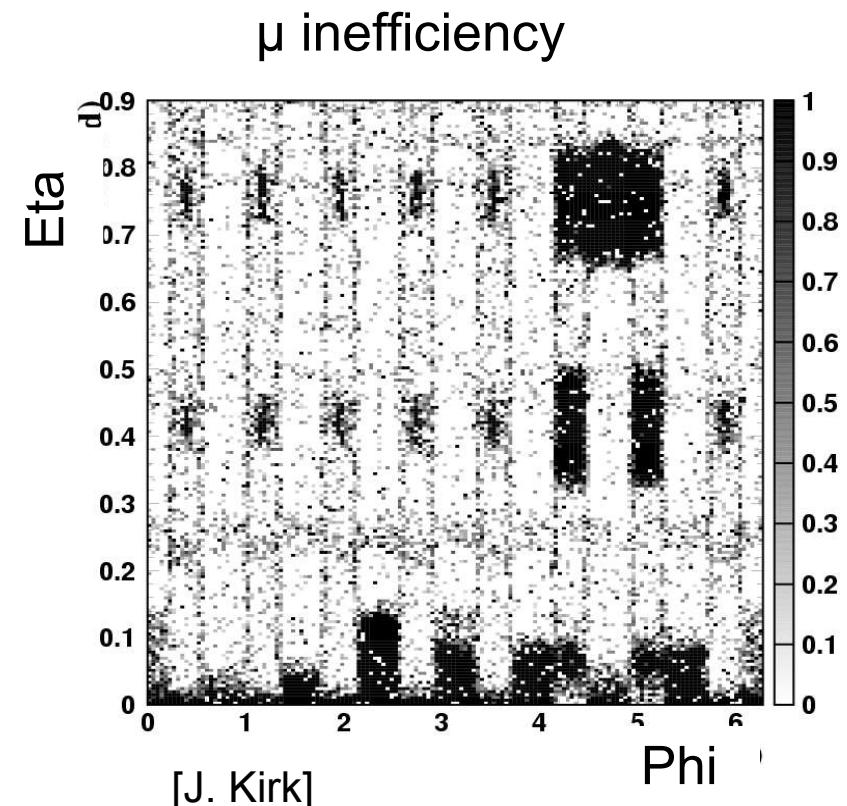
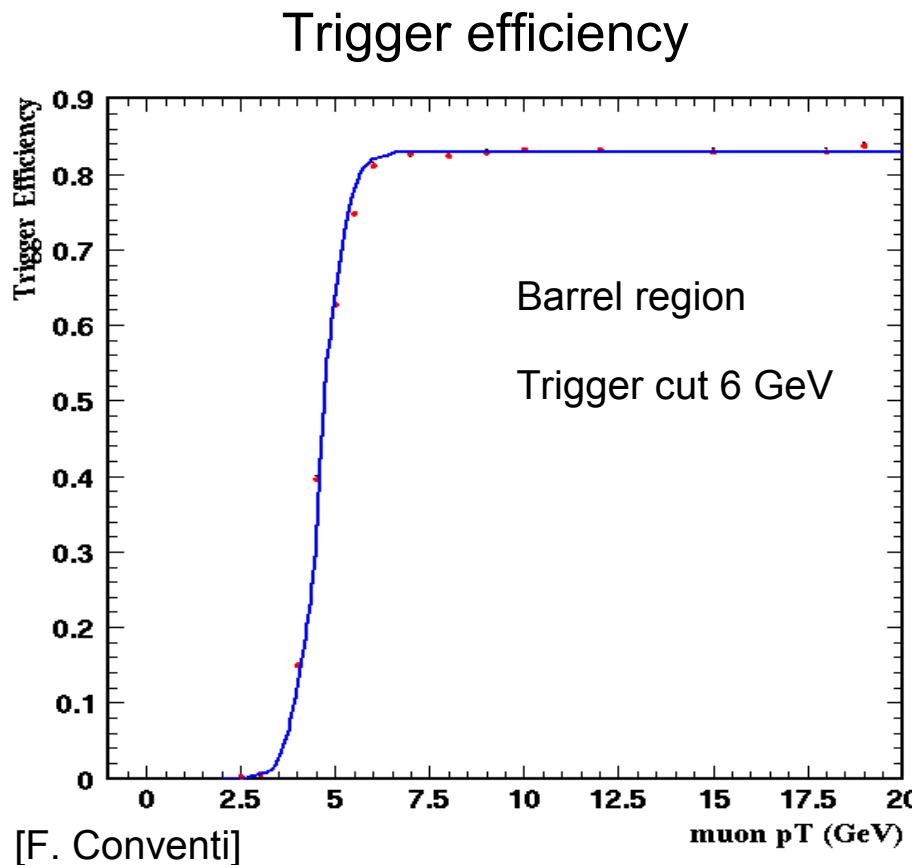
Single muon trigger

- ⊕ Single-muon trigger for \mathcal{L} up to $\sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
 - ⊕ Level 1
 - ⊕ Cut on the transverse momentum $p_t(\mu) \sim 6 - 8 \text{ GeV}$ (mu6 or mu8)
 - ⊕ Cut depends on effective trigger rate
 - ⊕ Level 2
 - ⊕ Confirm the Level 1 decision with a more precise p_t estimation
 - ⊕ Try a reconstruction in secondary Muon-, EM- and Jet- Rol (Region of Interest)
 - ⊕ 1. Search for di-muons inside enlarged Muon Rol
 - ⊕ 2. Search for single e/ γ or e^+e^- pair in EM Rol
 - ⊕ 3. **Search for B decay products in Jet Rol**
 - ⊕ Reconstruct inner detector around Rol center
 - ⊕ Try to reconstruct the ϕ and the D_s

Trigger efficiencies I

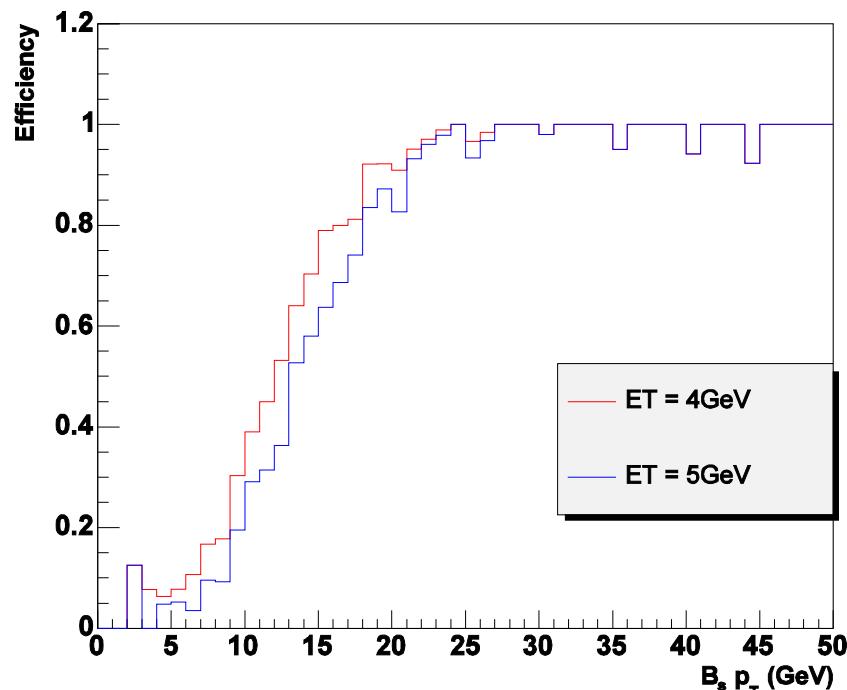
Level 1

- Trigger efficiency is about 85 %
- Loss dominated by detector feet and mountings



- Level 2: Jet Rol

- Efficiency for a B_s to be within a region ($\eta \times \phi$) of 0.4×0.4 around Rol center for different Level 1 jet energy thresholds (ET)



[J. Kirk]

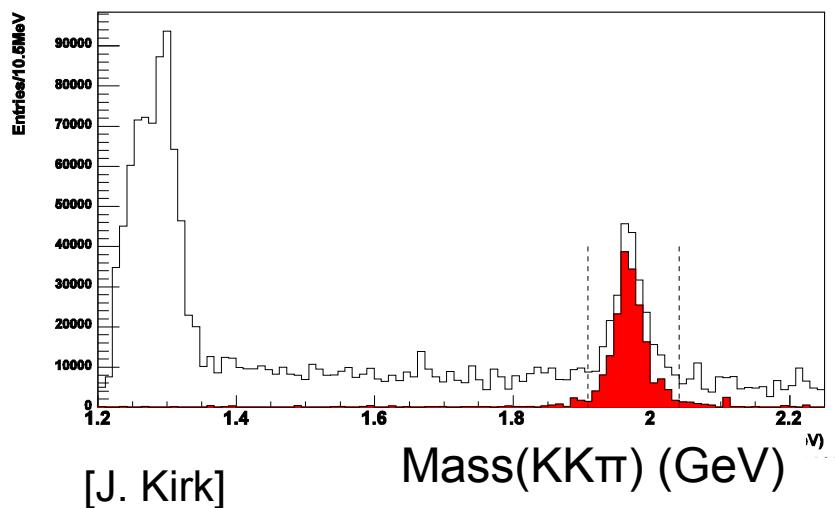
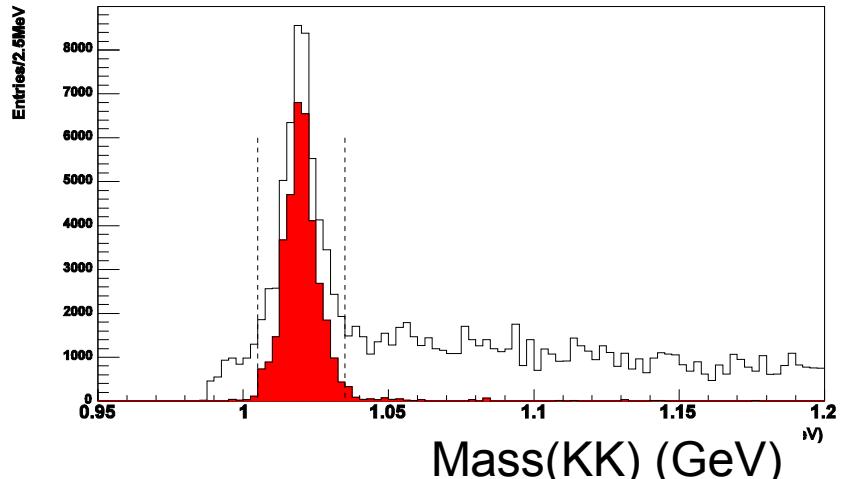
- Fully efficient for a B_s with $p_t > 20$ GeV
- For a B_s with $p_t > 10$ GeV
 - $ET > 5$ GeV : 69 % efficient
 - $ET > 4$ GeV : 76 % efficient

Trigger efficiencies III

- Level 2: Jet Roll

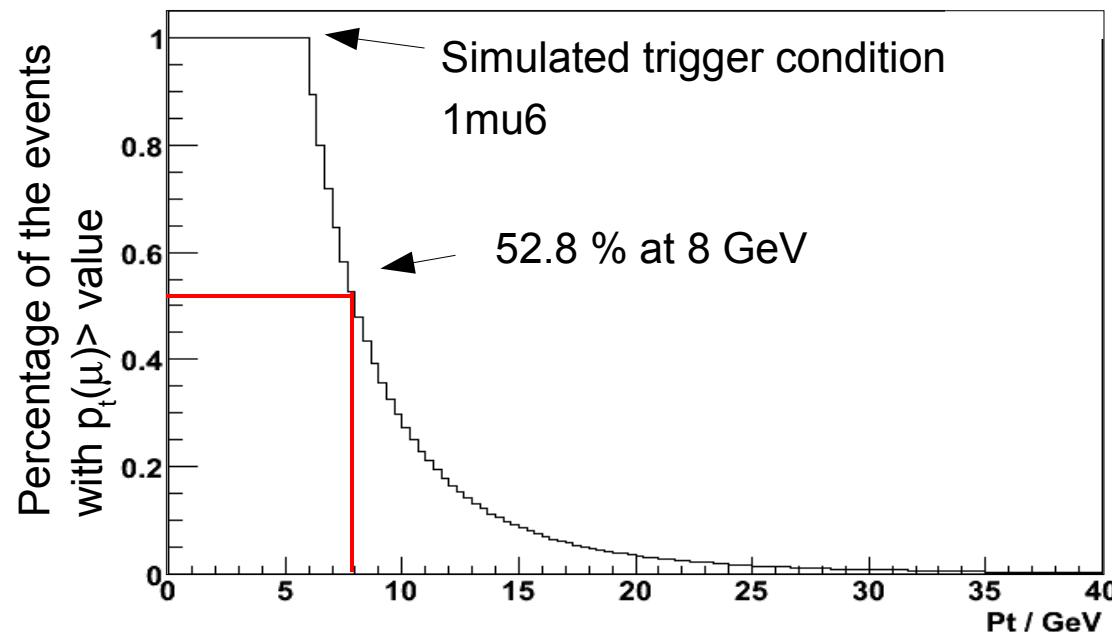
- For a B_s with $p_t > 10$ GeV and $p_t(K, K, \pi) > 1.5$ GeV
 - Efficiency: 48 %
 - Background: 3.6 %

- Cuts used:
 - Tracks: $p_t > 1.5$ GeV
 - Tracks: $|\Delta\phi| < 0.2$ and $|\Delta\eta| < 0.2$
 - 1005 MeV $< m(KK) < 1035$ MeV
 - 1908 MeV $< m(KK\phi) < 2040$ MeV



Number of events expected

- Expected number of events for 10 fb^{-1} (1 year with $\mathcal{L} = 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ and 1mu6) including detection efficiencies
 - $B_s^0 \rightarrow D_s^- a_1^+$: 870 events
 - $B_s^0 \rightarrow D_s^- \pi^+$: 2370 events
- [SN-ATLAS-2002-015]



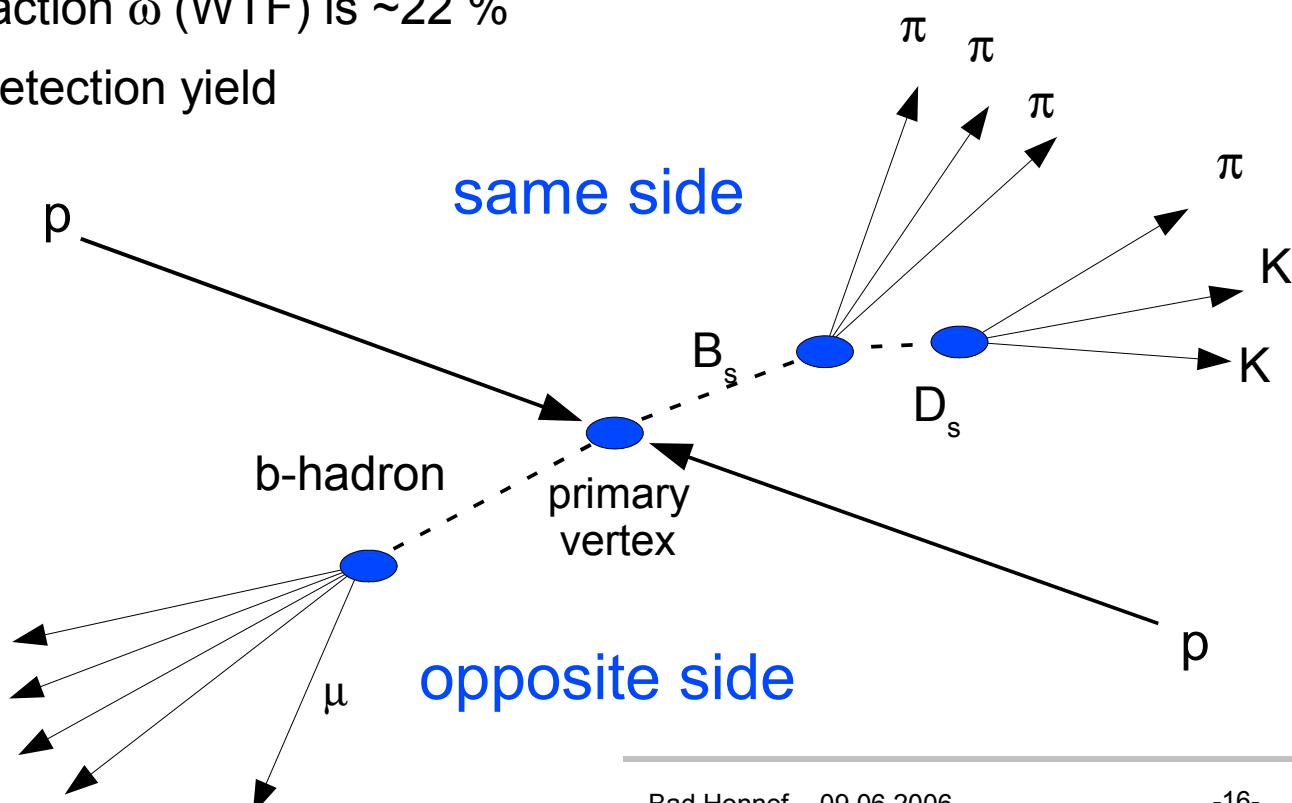
- Number of events expected scaled (MC Truth) for $B_s^0 \rightarrow D_s^- a_1^+$ assumed that detection efficiencies are the same

| Trigger condition | Number of events | Percentage [%] |
|-------------------|------------------|----------------|
| 1mu6 | 870 | 100,0 |
| 1mu8 | 459 | 52,8 |
| 1mu10 | 259 | 29,8 |
| 1mu12 | 157 | 18,0 |
| 1mu20 | 32 | 3,7 |

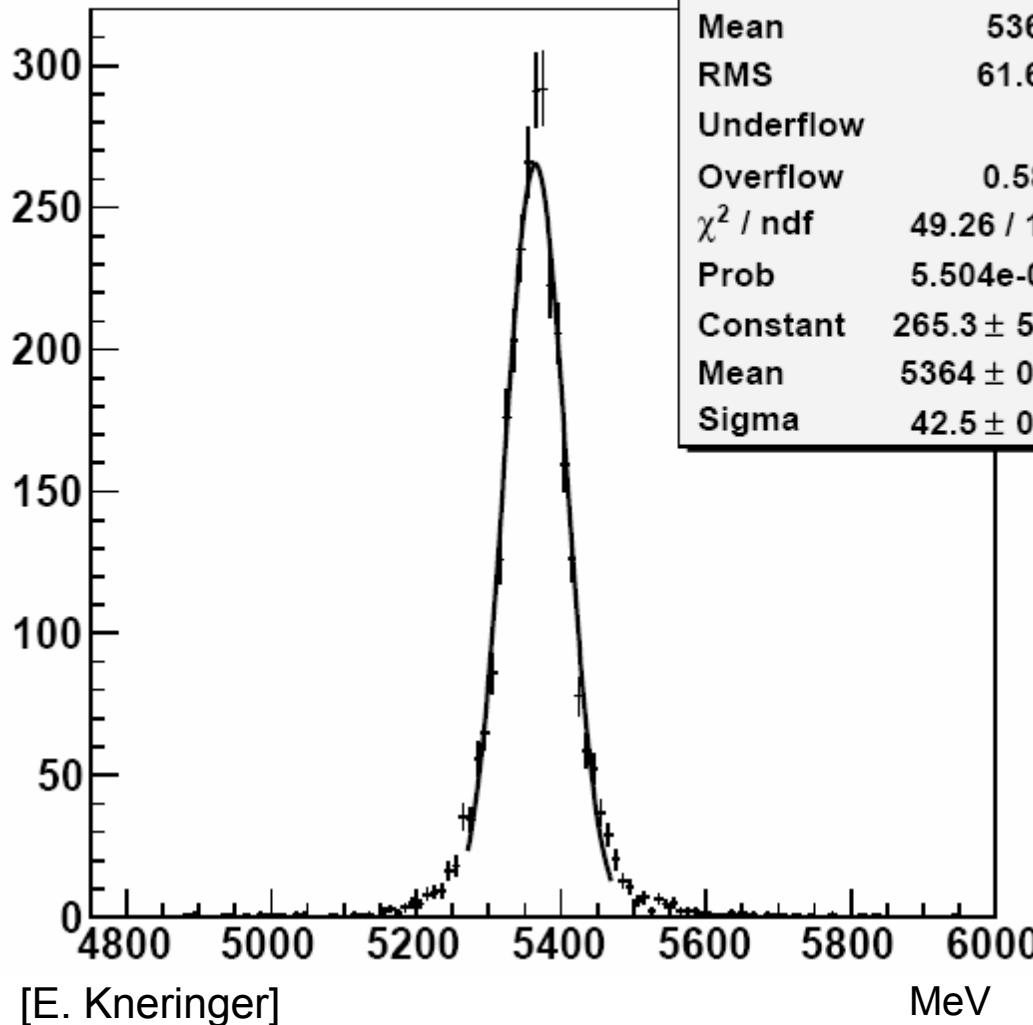
- Loss of ~45% if the trigger cut is raised by 2 GeV
 - Low trigger cut is essential to maximize the number of events

Tagging strategies

- ⊕ What information is needed for a mixing analysis ?
- ⊕ Determine flavor of the B_s^0 at origin and decay vertex
 - ⊕ Decay: Charge of the reconstructed D_s (same side)
 - ⊕ Origin: ATLAS requires a semileptonic decay of the b-hadron (opposite side)
 - ⊕ Charge of the muon correlated with the b-hadron flavor
 - ⊕ B-hadron can oscillate or muon can have wrong charge
 - ⊕ Estimated wrong-tag fraction ω (WTF) is $\sim 22\%$
 - ⊕ Good WTF, but small detection yield
- ⊕ Decay time
 - ⊕ Calculated from distance of primary vertex to decay vertex of the B_s^0
 - ⊕ Transverse momentum p_t needed



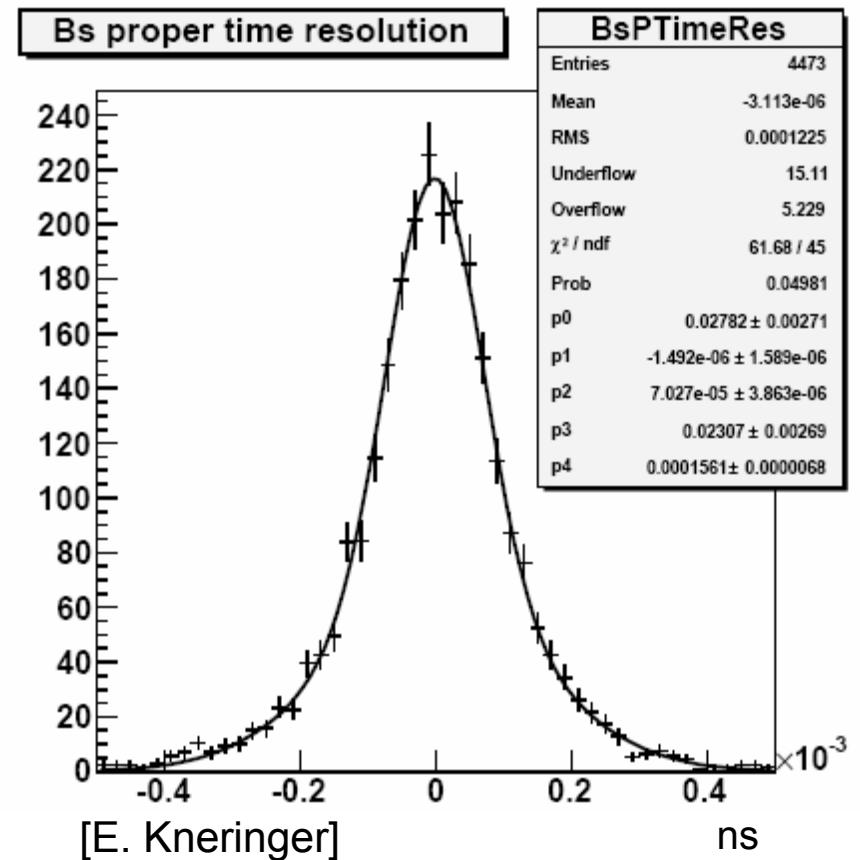
B_s^0 invariant mass resolution

Bs fitted mass

- B_s^0 invariant mass resolution
 - $\sigma = 42.5 \text{ MeV}$
- Mass differences (PDG)
 - $m(B_s) - m(B_d) = 90.2 \pm 2.5 \text{ MeV}$
 - $m(B_s) - m(B^+) = 90.6 \pm 2.5 \text{ MeV}$
 - Good separation
- D_s^+ invariant mass resolution
 - $\sigma = 14.7 \text{ MeV}$

Proper time resolution

- Calculation of the proper time
 - Transverse decay length d_{xy}
 - Distance between primary vertex and the decay vertex of the b-hadron projected to the transverse plane
 - g-factor
 - $g = m_{B_s^0} / (c \cdot p_T)$
 - Proper time
 - $t = d_{xy} \cdot g$
- Resolution
 - Difference to true proper time from MC truth
 - Parametrized with a sum of two Gaussian functions
 - $\sigma_1 = 70.3 \text{ fs}$ (fraction: 54.7 %)
 - $\sigma_2 = 156.1 \text{ fs}$ (fraction: 45.3 %)



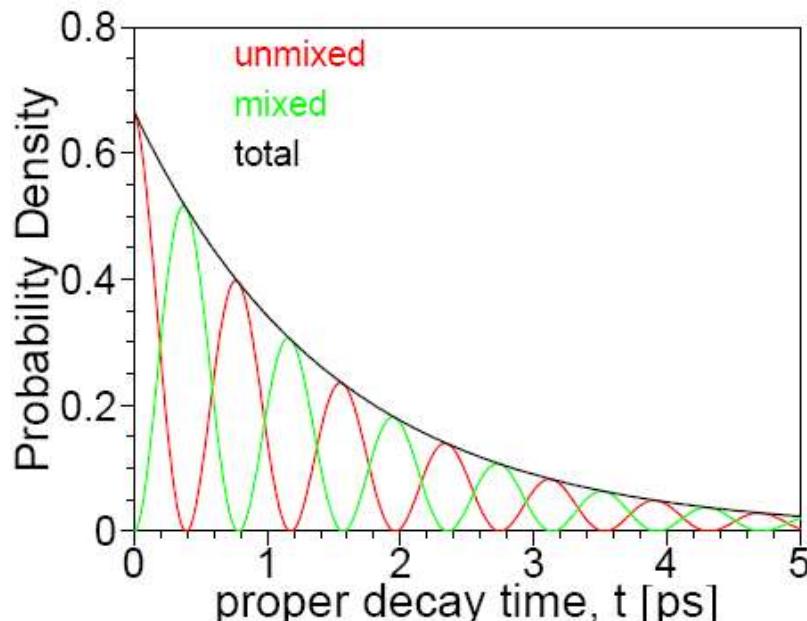
- Innermost pixel layer shifted from 4.3 cm (TDR) to 5.0 cm (Final)
- Proper time resolution worse wrt. TDR values :
 - $\sigma_1 = 52.3 \text{ fs}$
 - $\sigma_2 = 108.5 \text{ fs}$

Likelihood function I

- + Probability density function p:

$$p(t_0, \mu_0) = \frac{\Gamma_s^2 - \left(\frac{\Delta \Gamma_s}{2}\right)^2}{2\Gamma_s} \cdot e^{-\Gamma_s t_0} \cdot \left(\cosh\left(\frac{\Delta \Gamma_s t_0}{2}\right) + \mu_0 \cos(\Delta m_s t_0) \right)$$

- $\mu_0 = -1$: probability that a B_s^0 has **oscillated** and decays as an \bar{B}_s^0 after time t_0
- $\mu_0 = +1$: probability that a B_s^0 has **not oscillated** and decays as an B_s^0 after time t_0
- $\Delta \Gamma_s = \Gamma_H - \Gamma_L$ possibly sizeable



[G. Gomez-Ceballos]

- + Probability density modified through experimental effects

$$q(t_0, \mu_0) = N \int_{t_{min}}^{\infty} p(t_0, \mu_0) \text{Res}(t|t_0) dt_0$$

- $\text{Res}(t|t_0)$: proper time resolution
- N : normalisation factor
- t : reconstructed time

Likelihood function II

- Wrong-tag fraction ω has to be taken into account

$$q'(t, \mu) = (1 - \omega) \cdot q(t, \mu) + \omega \cdot q(t, -\mu)$$

- Considering pdf's from other oscillating sources, combinatorial background and non oscillating background with adequate lifetime.

- Each with fraction f_j^k ($j = \text{sources}$)

- $k = 1 : B_s^0 \rightarrow D_s^- \pi^+$

- $k = 2 : B_s^0 \rightarrow D_s^- a_1^+$

$$pdf_k(t, \mu) = \sum_j f_j^k [(1 - \omega_j) \cdot q_j(t, \mu) + \omega_j \cdot q_j(t, -\mu)]$$

- Likelihood of the sample

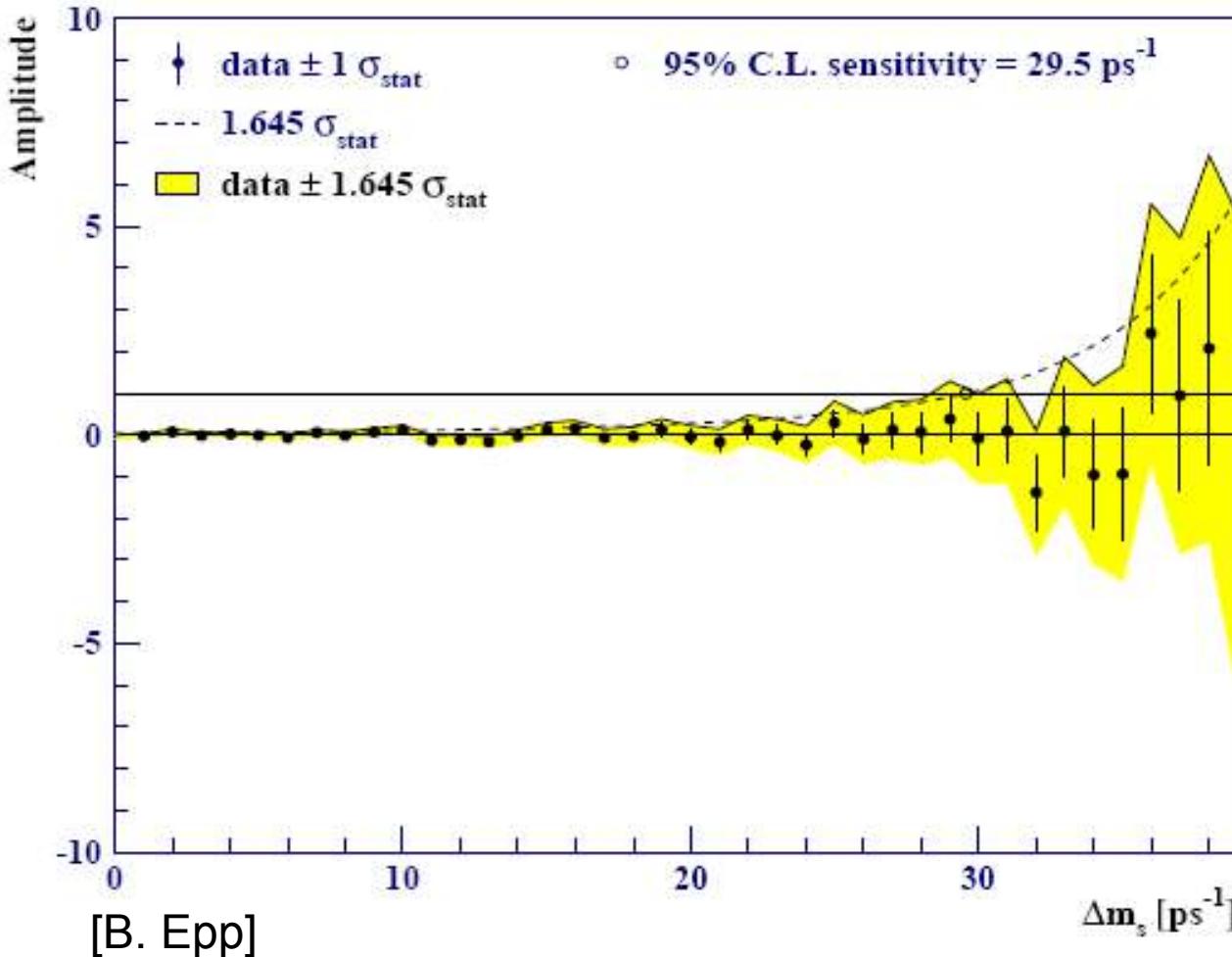
- N_{ev}^k : total number of events

$$L(\Delta m_s, \Delta \Gamma_s) = \prod_{k=1}^2 \prod_{i=1}^{N_{ev}^k} pdf_k(t_i, \mu_i)$$

- Apply B_s^0 oscillation amplitude A as a new parameter in the likelihood function and minimize $-\ln L$ as a function of A :

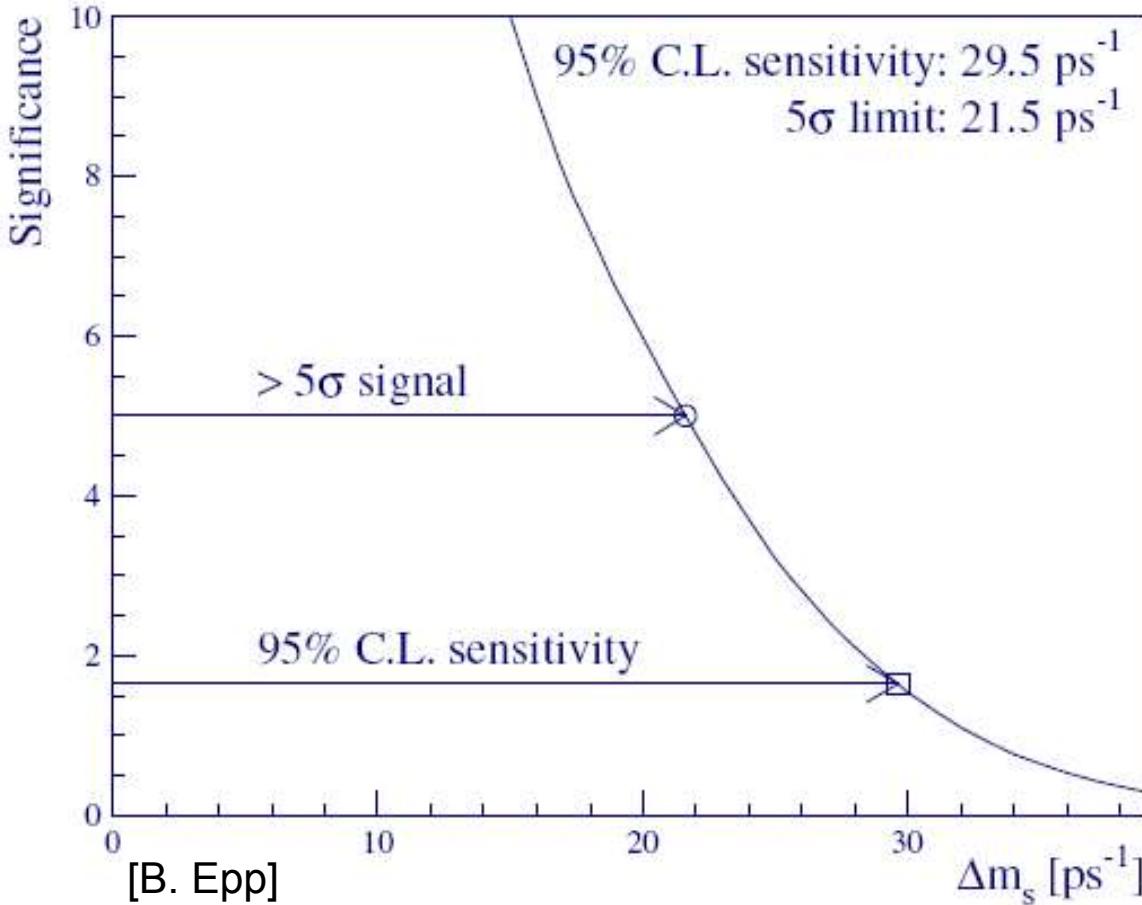
$$L(\Delta m_s, \Delta \Gamma_s) \rightarrow L(\Delta m_s, \Delta \Gamma_s, A)$$

Amplitude fit method



- B_s^0 oszillation amplitude as a function of Δm_s for 30 fb^{-1}
- Obtained from simplified MC model
- Both **hadronic** channels are combined
- 95 % CL sensitivity : 29.5 ps^{-1} ($1.645 \sigma = 1$)
- 5 σ limit: 21.5 ps^{-1} ($5 \sigma = 1$)
- Well above recent measurement from CDF

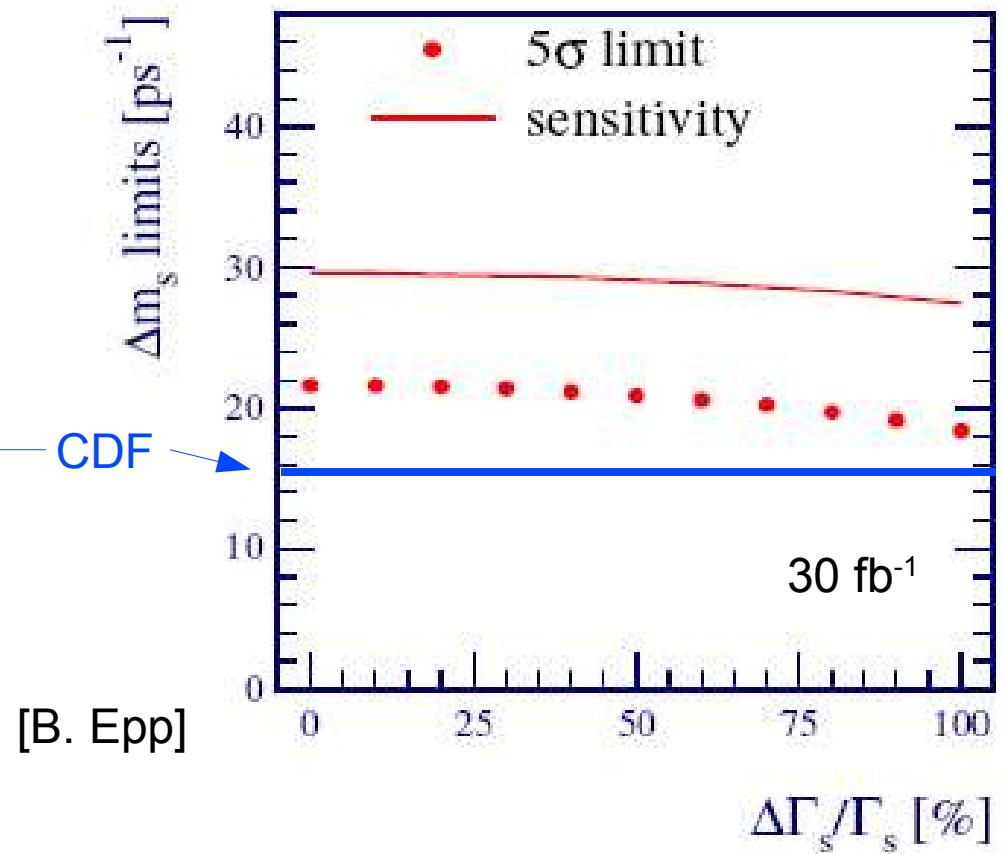
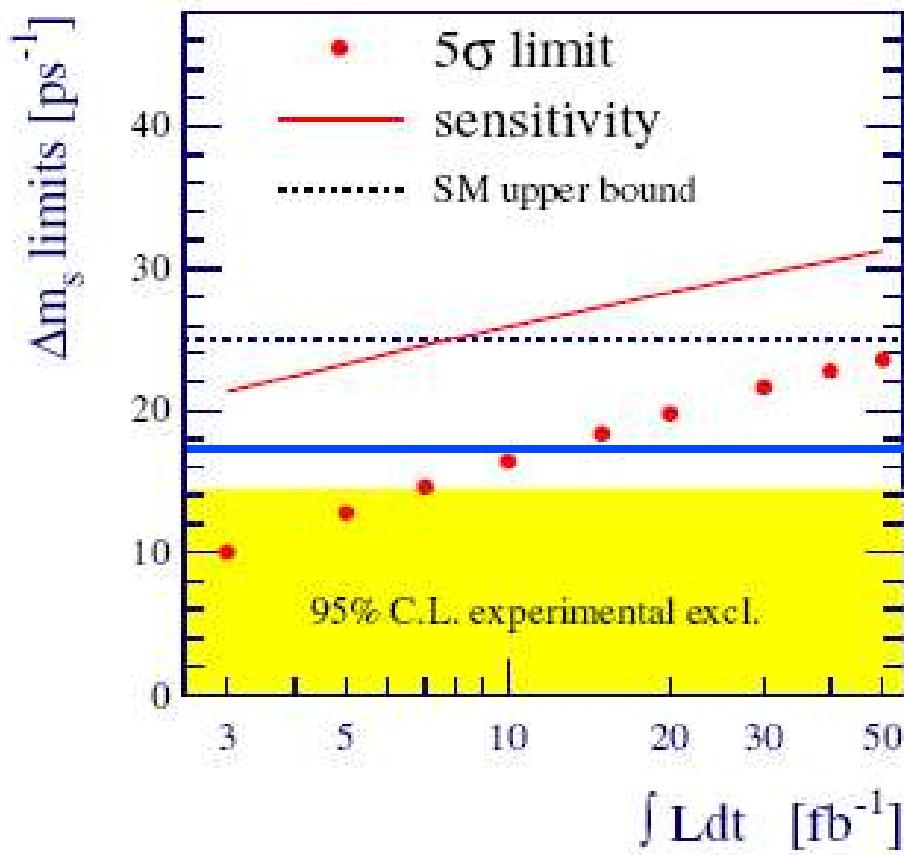
Measurement limits



- For the a_1 -channel:
 - Number of events were extrapolated from TDR values
 - Parametrizations of kinematic distributions are taken from the π -channel
- Improved update currently in progress (Siegen)

- Limits for an integrated luminosity of 30 fb^{-1}
 - Statistical significance of an oscillation signal : $S = 1/\sigma$

Dependence on experimental quantities



- ATLAS is sensitive for Δm_s in the region found by CDF for an integrated luminosity above $\sim 10 \text{ fb}^{-1}$ (95 % CL sensitivity)

- Weak dependence on $\Delta \Gamma_s / \Gamma_s$
- Independent measurement of Δm_s possible

Conclusions

- ⊕ Δm_s will be measured by ATLAS
 - ⊕ Important for extraction of ϕ_s and $\Delta\Gamma_s$ in $B_s \rightarrow J/\Psi (\mu\mu) \phi (KK)$ by common global fit
 - ⊕ Sensitivity (30 fb^{-1}) above the value recently measured by CDF
- ⊕ Mainly hadronic final states are used
 - ⊕ High energetic muons are used to trigger on and to tag the original B-hadron flavor.
 - ⊕ Number of events highly depends on the LVL1 trigger cut
 - ⊕ The contribution of a semileptonic channel is under investigation
- ⊕ An oscillation analysis for the channel $B_s^0 \rightarrow D_s^- a_1^+$ is prepared at the moment in Siegen

