CP violation with the ATLAS detector

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- $J/\psi\ K^0$: the golden channel for β
- $\pi^+\pi^-$: the difficult channel for α
- $J/\psi\ \phi$, $D_{(1)}{}^0 K^{*0}$: even more difficult channels for $\delta\gamma$ and γ

Complete analyses with final detector design and full GEANT simulation for signal and tuned fast simulation for backgrounds:

- Event tagging
- Backgrounds (physics and combinatorial)
- Initial state tagging
- Parameter fitting
- Results, sensitivity for 1 year at low luminosity (10^4 pb^{-1})

Note: ATLAS detector and CP violation introduction in talk by Peter Sherwood

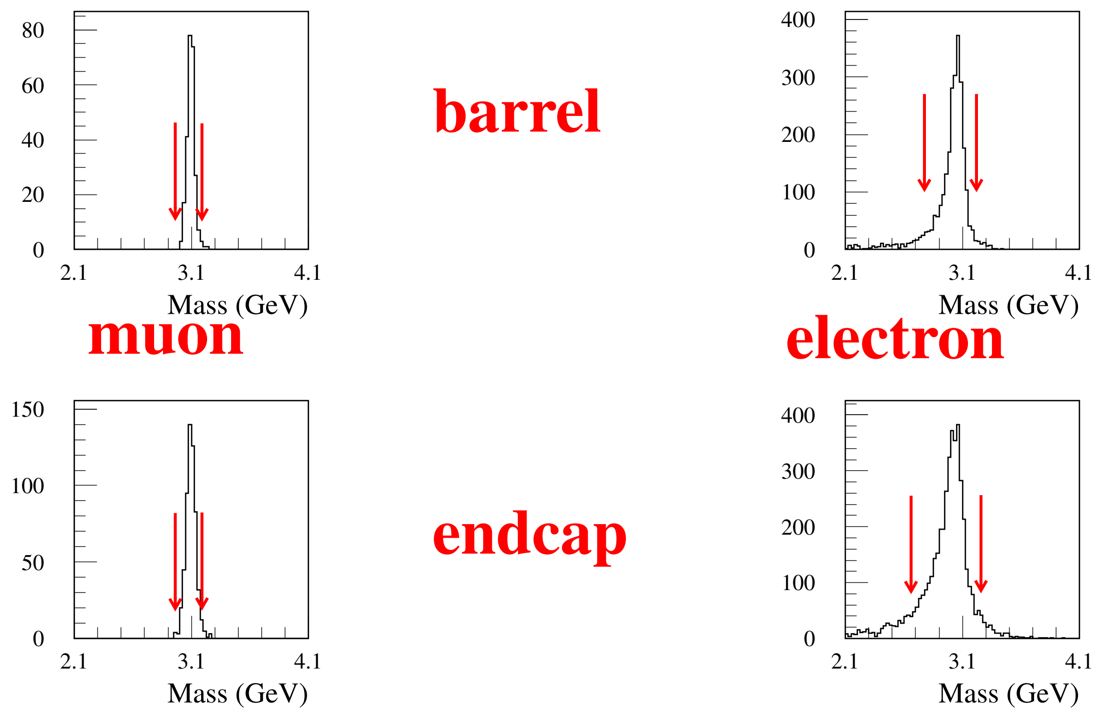
sin (2β): J/ΨK⁰

$$A(t) = \frac{N\left(B_d^0 \to J/\Psi K_S^0\right) - N\left(\bar{B}_d^0 \to J/\Psi K_S^0\right)}{N\left(B_d^0 \to J/\Psi K_S^0\right) + N\left(\bar{B}_d^0 \to J/\Psi K_S^0\right)} = \sin(2\beta)\sin(\Delta m t)$$

- **Tools involved:**
  - Event reconstruction: $J/\psi \to e^+e^-$, $J/\psi \to \mu^+\mu^-$, $K_S^0 \to \pi^+\pi^-$ tagging
  - Initial state tagging (lepton, jet charge, B-π correlation)
  - Proper time reconstruction (if time-integrated measurement dilution factor $D_{int}=0.62$)
- **Samples:**
  - $J/\psi \to e^+e^-$ (p_T e>1 GeV)+μ (p_T>6) trigger
  - $J/\psi \to \mu^+\mu^-$(p_T μ_1>5 GeV, p_T μ_2>3 GeV)+μ, e, B-π, jet (trigger with one μ p_T>6)

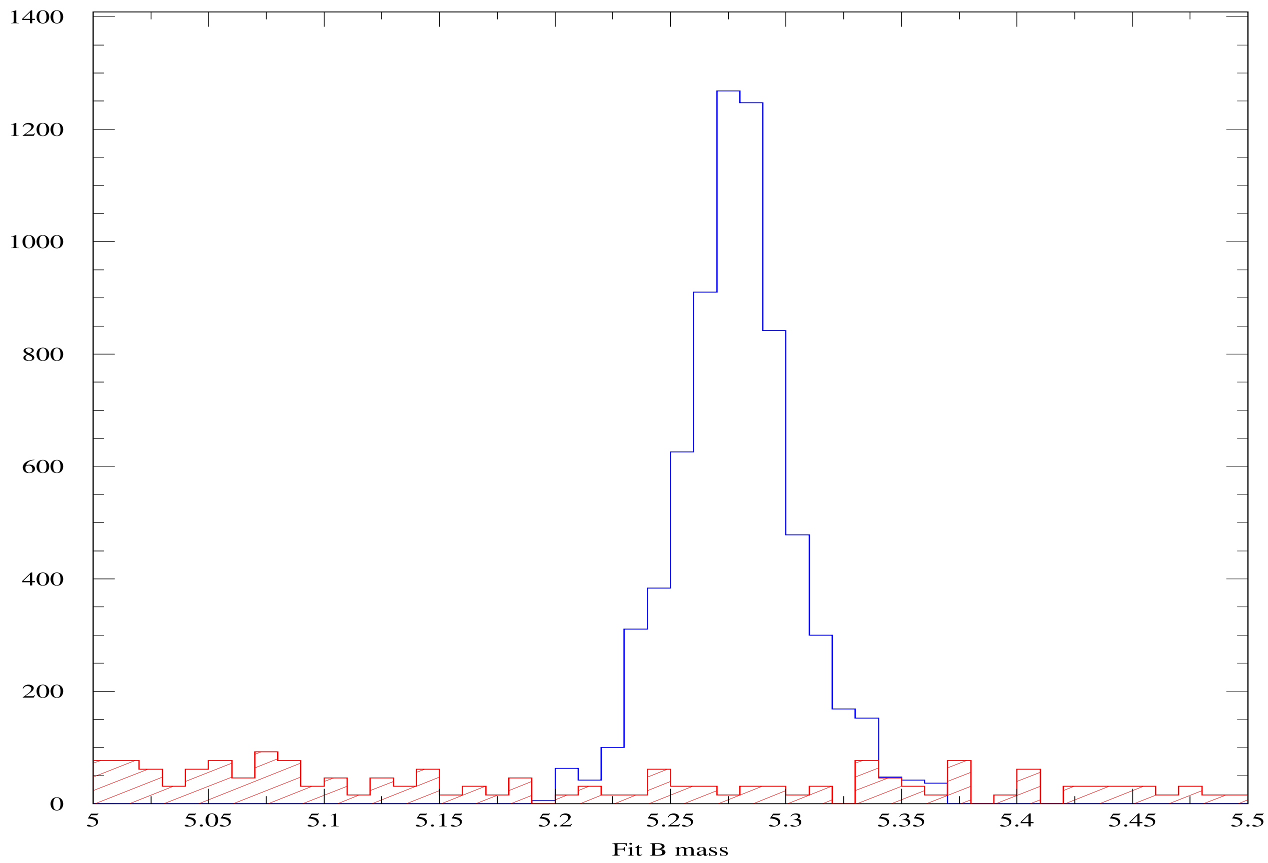
J/ψ tagging

- **Lepton identification:**
  - μ P_t>3 GeV: inner detector track matched to muon toroid (complete or first muon station only) and tile calorimeter. (Note: P_t>3 GeV at LVL2 is under study, P_t>5 GeV certain)
  - e P_t>1 GeV: Transition Radiation hits in inner detector plus (P_t>3 GeV) Argon calorimeter cluster shape and E/p matching
  - electron track fit allows for continuous bremsstrahlung loss ("brem fit")
- **J/ψ identification:**
  - lepton pair fit to common vertex L_{xy}>250μm
  - different mass windows :



B^0 reconstruction

- Fit 3D B^0 vertex with K_S^0 vertex, K_S^0 and J/ψ mass constraint
- Require $\tau > 0.5$ ps and $P_t > 5$ GeV
- Keep B candidates in $\pm 3\sigma$ around nominal mass
- Mass resolution ~22 MeV
- Resolution on decay radius ~66μm (~4% of average B^0 decay radius)



Backgrounds

- **b->J/ψX:**
  - **dominant contribution is true J/ψ combined with true K^0_S from fragmentation**
- **direct J/ψ: not included yet in the analysis but**
  - **cross-section comparable to b->J/ψX**
  - **is mostly removed by 250 μm cut on transverse decay-length (~4σ)**
- **b->μX:**
  - **fake J/ψ (lepton-lepton, lepton-hadron, hadron-hadron) is small compared to b->J/ψX**

Initial state tagging: definitions

- N_S (N_B): number of signal (background) event
- N^+(N^-) :number of right (wrong) signal tag
- tagging efficiency: $\varepsilon = (N^+ + N^-)/N_S$
- wrong tag fraction: $W = N^-/(N^+ + N^-)$
- tagging dilution: $D_{tag} = (N^+ - N^-)/(N^+ + N^-) = 1 - 2W$
- tagging algorithm quality factor: $Q = \varepsilon D_{tag}^2$ (algorithm equivalent to perfect tag with luminosity reduced by factor Q)
- background dilution (equivalent luminosity loss) $D_{bkg} = N_S/(N_S + N_B)$
- time integration dilution:

  $D_{int} = (\sin\Delta m t_0 + x_d \cos\Delta m t_0)/(1 + x_d^2)$
- observed asymmetry (production asymmetry (~0.01) neglected) :

$$A_{obs} = D_{tag} D_{bkg} D_{int} \sin 2\beta$$

- sensitivity:

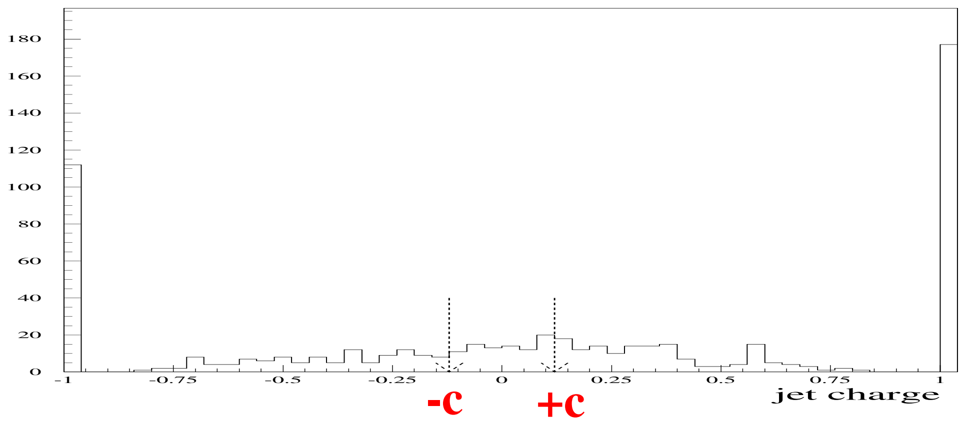
$$\sigma \sin(2\beta) = \frac{\sqrt{1 - A_{obs}^2}}{D_{int} D_{bkg} \sqrt{D_{bkg} N_S}}$$

Lepton tagging

- Look for an additional lepton coming from the semileptonic decay of the other b in the event
- $J/\psi \to e^+e^-$: use the trigger muon
- $J/\psi \to \mu^+\mu^-$: search for an additional electron or muon with P_t>5 GeV
- Wrong tag fraction is 22% due to:
  - mixing of the other b hadron
  - b->c->l cascade decay
  - c->l from additional direct charm

Same side tagging

- **B-π correlation:**
  - identifies B flavour from the charge of hadron nearby in phase space (from B^{**} decay or the fragmentation string)
  - look for track consistent with beam-line with $0.5<P_t<4$ GeV within cone $\Delta R<0.7$
  - if more than one candidate, choose one with maximum p_L (momentum projected onto B^0 direction)
- **jet charge:**
  - collect tracks with Pt>0.5 GeV in cone $\Delta R<0.8$ around B^0
  - compute weighted charge: $q_{jet} = \dfrac{\sum q_i |P_t|^\kappa}{\sum |P_t|^\kappa}$
  - ambiguous events with $|q_{jet}|<$**c** are removed
  - κ and **c** are chosen to optimize quality factor



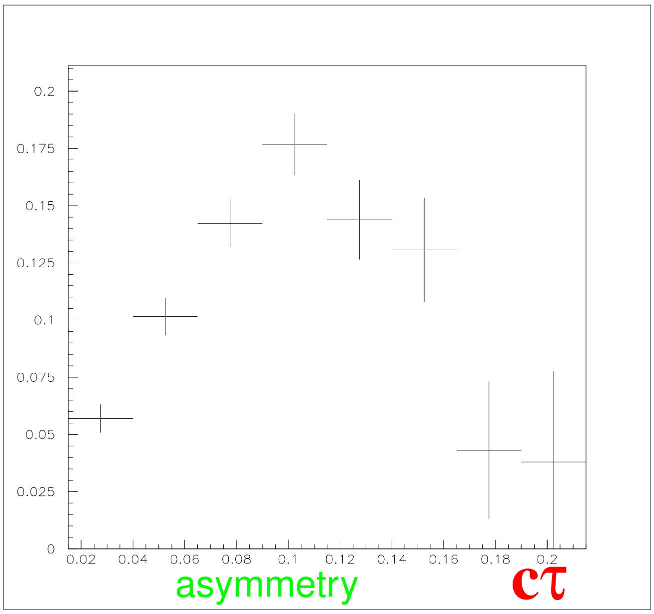
Flavour tagging: performance

Sample	efficiency	D_{tag}	Q
$J/\psi \to \mu^+\mu^-$ lepton tag	0.05	0.56	0.016
$J/\psi \to \mu^+\mu^-$ B-pi tag	0.84	0.17	0.024
$J/\psi \to \mu^+\mu^-$ jet tag	0.66	0.18	0.021
$J/\Psi \to e^+e^-$ lepton tag	1.	0.56	0.31
$J/\psi \to e^+e^-$ B-pi tag	0.80	0.14	0.016
$J/\psi \to e^+e^-$ jet tag	0.71	0.12	0.011

Results

	ee channel	$\mu\mu$ channel
$N(B^0 \to J/\psi K^0)$	7000	213000
N background	470	3600
σ sin(2β) lep tag	0.036	0.029
σ sin(2β) B-π tag	0.16	0.025
σ sin(2β) time fit	0.026	0.017

- **Tag combination is done by defining 4 classes:**
  - **a.only lepton tag available**
  - **b.only B-π tag available**
  - **c.both tags available and in agreement**
  - **d.both tags available and in disagreement**
- **Time dependent fit $A(t)=\sin(2\beta)\sin(\Delta m_d t)$:**
  - **resolution: 0.07ps**



Outlook on sin(2β)

- **All samples combined in a time-dependent fit the statistical sensitivity is:**
  σ sin(2β)=0.014

- **Systematics error expected to be of order 0.01. Production asymmetry, detection asymmetry, flavour tagging to be measured with control channel such as B->J/ψ K$^{(*)}$**
- **More work to be done on lepton ID and flavour tagging**

$\sin(2\alpha)$: $\pi^+\pi^-$

In fact, sensitive to $\sin(2(\beta+\gamma))$

- **Observed asymmetry :**

$$A(t) = a\cos(\Delta m t) + b\sin(\Delta m t)$$

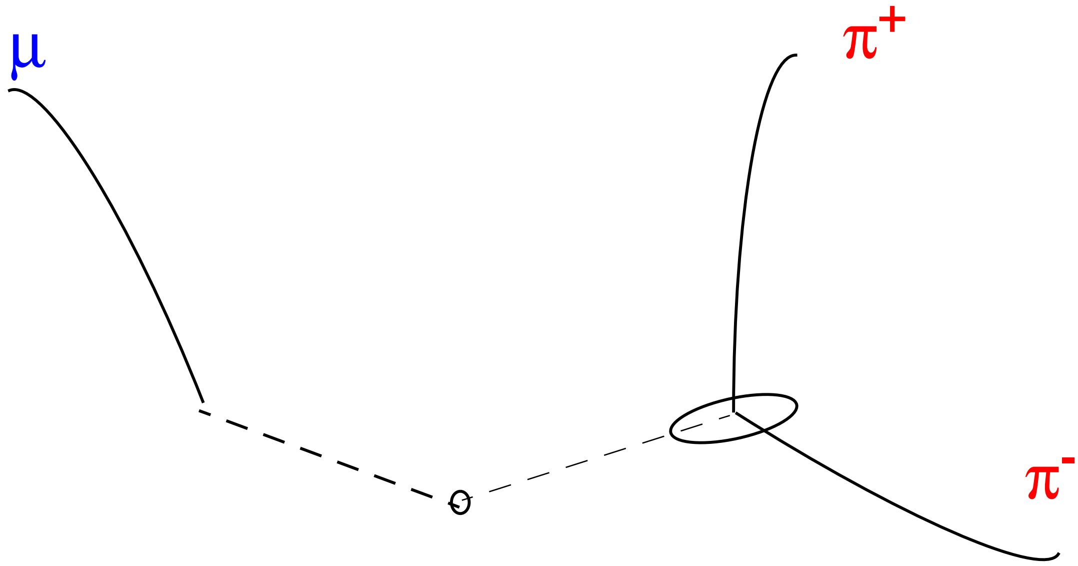
$$a = -2\frac{A_P}{A_T}\sin\delta\sin\alpha$$

$$b = -\left(\sin(2\alpha) + 2\frac{A_P}{A_T}\cos\delta\cos(2\alpha)\sin\alpha\right)$$

- **Unknowns: α, A_P/A_T penguins relative amplitude, δ penguins relative phase**
- **Only two of these parameters can be obtained from a time-dependent fit: A_P/A_T must be given by theory**
- **Note: if α~90^0 and A_P=0, no asymmetry, no CP violation but a constraint on the triangle**
- **Results will be given with A_P=0**

Selection

- LVL2 selection: 2 opposite charge tracks with Pt>5.5 GeV, 4.5<M<6.5 GeV=>80Hz
- Offline slection:
  - 2 tracks with P_t>6 (4)GeV
  - inconsistent with beam-line by >3σ
  - good common 3D vertex
  - B^0 vertex, beam line and flight direction consistency more than 1%
  - both tracks inconsistent in space with triggering muon



Physics backgrounds

- **Physics backgrounds are mainly other two-body decays :**

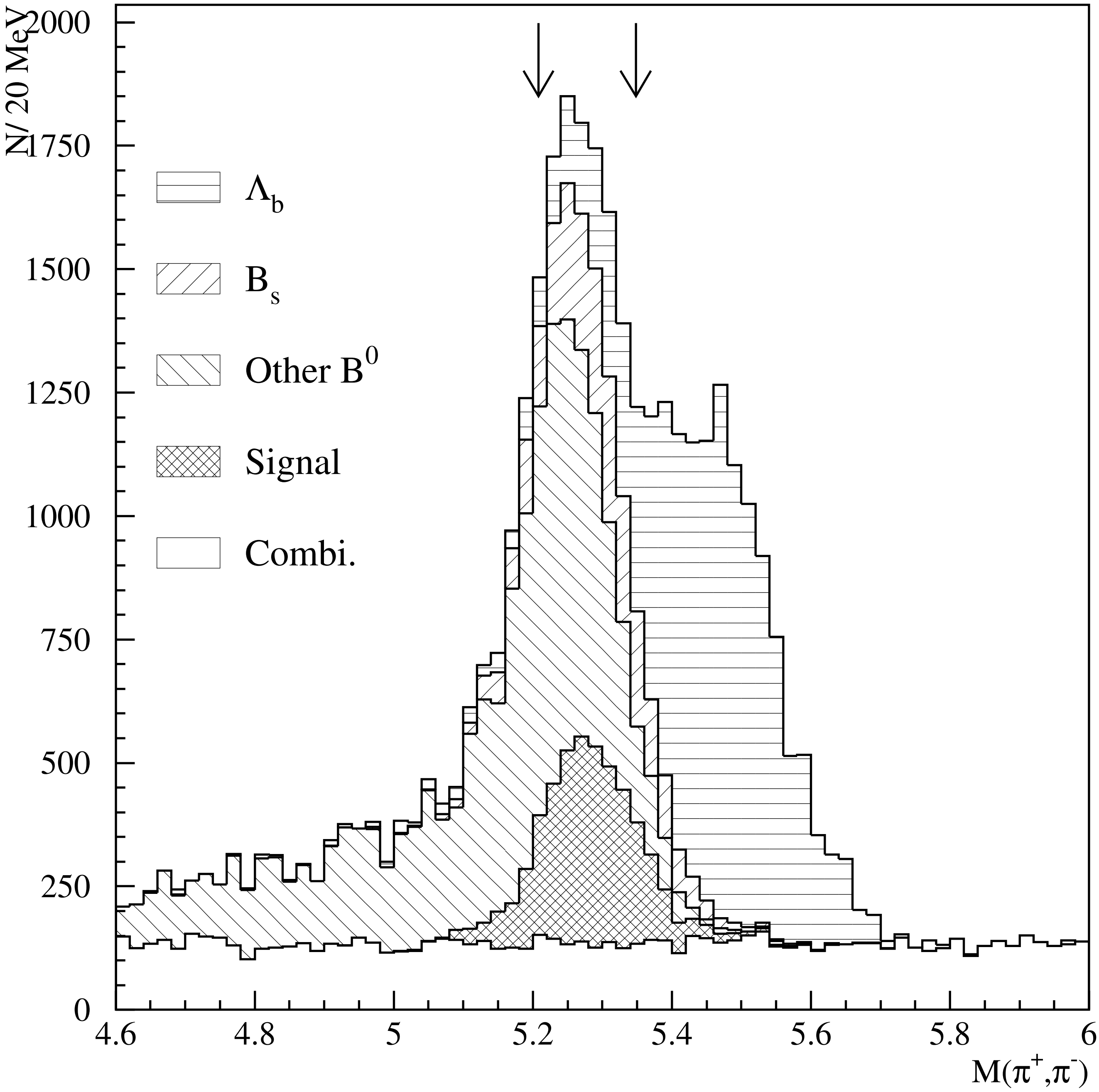
Channels	**BR used**	**BR measured**
$B^0_d \to \pi^+\pi^-$	$0.7\ 10^{-5}$	$<1.5\ 10^{-5}$
$B^0_d \to K^+\pi^-$	$1.5\ 10^{-5}$	$1.5\pm0.4\ 10^{-5}$
$B^0_s \to K^-\pi^+$	$0.7\ 10^{-5}$	
$B^0_s \to K^+K^-$	$1.5\ 10^{-5}$	
$B \to \rho\pi$	$2.5\ 10^{-5}$	
$B^0_d \to \pi^+\pi^-\pi^0$	$5.0\ 10^{-5}$	
$\Lambda_B \to p\pi^-$	$8.0\ 10^{-5}$	$<8.0\ 10^{-5}$
$\Lambda_B \to pK^-$	$8.0\ 10^{-5}$	$<8.0\ 10^{-5}$

- **BR used are rather uncertain (few experimental results with large uncertainties)**

Combinatorial background

- Combinatorial bkg from accidental good vertex of two random tracks, inconsistent with beam-line
  - need to remove sources of displaced tracks, in particular tracks from the triggering B
  - need a good control of impact parameter distribution tails in simulation
- 2.5 10^{10} b->μ6X events per year, for ~ 10^3 signal events. Method used:
  - 5 10^4 fully simulated events b->μ6X
  - Detailed parameterisation of resolutions, tails, as a function of identity, P_t, η
  - Fast simulation of 10^6 b->μ6X
  - Cloning of each event 500 times (=>5 10^8 events equivalent) with new B and D decay-lengthes and decay angles, new track smearing

Final spectrum



- **Mass window ±1σ <=>±70 MeV**
- **ππ vs Kπ mass separation ~40 MeV, (best at small p_T)**

Results

minimum P_T	6 GeV	4 GeV
$N(B_d \to \pi^+\pi^-)$	1100	2500
$N(B_d \to K^+\pi^-)$	2200	4600
$N(B_d \to \rho\pm\pi\pm)$	30	70
$N(B_d \to \pi^+\pi^-\pi^0)$	<20	<20
$N(B_s \to \pi^+K^-)$	300	600
$N(B_s \to K^+K^-)$	600	1300
$N(\Lambda_b \to \pi\pi^-)$	300	600
$N(\Lambda_b \to pK^-)$	400	1000
N(Comb)	500	900
Total bkg	4300	9000
D_{bkg}	0.21	0.21
D_{tag}	0.56	0.56
D_{int}	0.63	0.63
σ sin (2α)	0.18	0.12

Note: 4 GeV threshold at LVL2 is currently under study

Outlook on sin(2α)

- **absence of π/K separation is a clear handicap**
- **$B^0 \to K^+\pi^-$ is the most annoying background because of its abundance, closeness to the signal and because it could be asymmetric itself (in which case it could become a signal and $\pi\pi$ a background...)**
- **But there is hope:**
  - **branching ratios could be more favourable**
  - **a fit of the mass spectrum could be used to control part of the physics background**
  - **lowering the minimum pion P_t from 4 GeV to 1 GeV could potentially improve statistics by factor 4 (combinatorial bkg ? LVL2 trigger ?)**

$\delta\gamma$: B_s->J/$\psi\phi$

- **A(t)~sin(2$\delta\gamma$)sin (x_s t/τ) if J/$\psi\phi$ is pure CP=+1**
- **$\delta\gamma$ expected to be small in standard model=>good place to look for new physics**
- **Analysis similar to B_d->J/ψ K^0 (event tagging, flavour tagging) except for the rapid oscillation of the B_s**
- **=>proper time resolution more important**

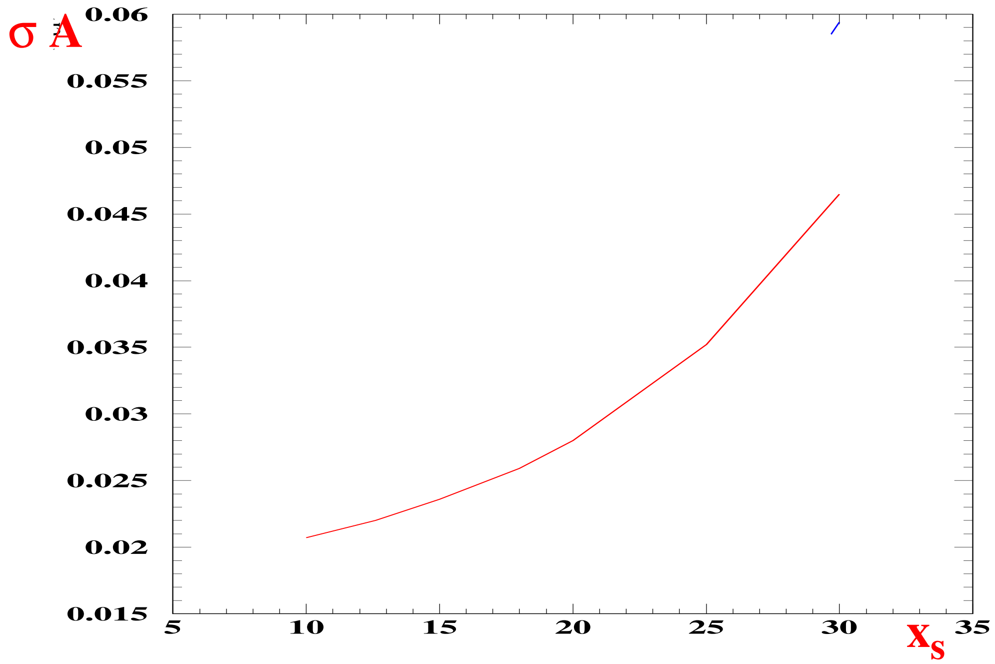
Note: time dependent fit with resolution 0.07 ps => dilution D_{int}=0.47 for x_s=20

Results

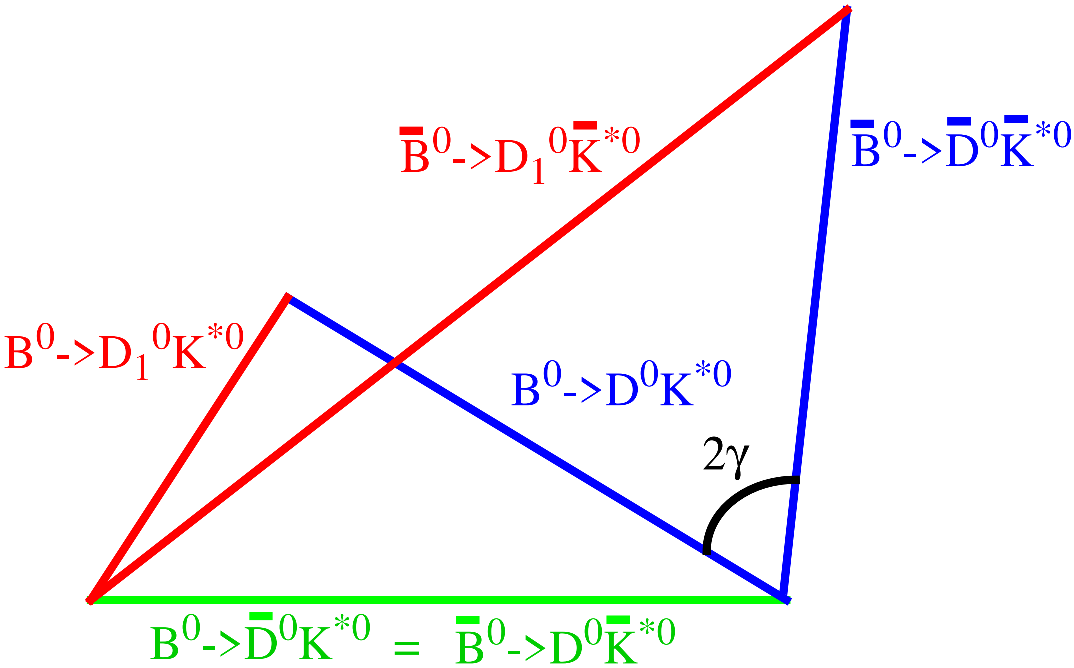
	ee channel	$\mu\mu$ channel
$N(B_s^0 \to J/\psi\phi)$	3500	134000
N background	200	3200
σ A lep tag	0.059	0.049
σ A jet tag	0.224	0.044

- **Combined sensitivity on asymmetry (time-integrated, 1 year data, x_s=20):**

  $\sigma\ A_{CP}=0.027$



γ: $D_{(1)}^0 K^{*0}$



- **Measure BR($B^0 \to \bar{D}^0 K^{*0}$)=BR($\bar{B}^0 \to D^0 \bar{K}^{*0}$)~1.3 10^{-5} proportional to $V_{cb} V_{us}^*$**
- **Measure BR($B^0 \to D^0 K^{*0}$)=BR($\bar{B}^0 \to \bar{D}^0 \bar{K}^{*0}$)~1.7 10^{-6} proportional to $V_{ub} V_{cs}^*$**
- **Measure BR($B^0 \to D_1^0 K^{*0}$)$\neq$BR($\bar{B}^0 > D_1^0 \bar{K}^{*0}$) =f($\gamma$,$\Delta$)**

(D_1^0 is D^0 CP eigenstate, decaying to $\pi^+\pi^-$, K^+K^-)

- **$D^0 \to K^+\pi^-$, $K^-\pi^+$, $\pi^+\pi^-$, K^+K^- and $K^{*0} \to K^+\pi^-$, $K^-\pi^+$ separated by vetoeing ambiguous events**
- **but final rates marginal (~20 evts per year)**
- **background rejection/estimation in progress**

Conclusion

- **B physics analysis using detailed detector description (design frozen) and full simulation and reconstruction (trigger, pattern recognition)**
- **ATLAS will have an excellent sensitivity in the $J/\psi K^0$ channel:**

$$\sigma \sin(2\beta) = 0.014$$

- **the $\pi^+\pi^-$ channel suffers from lack of π/K separation, but will provide information**

$$\sigma \sin(2\alpha) = 0.12$$

- **sensitivity to $\delta\gamma$ also provided by $J/\psi\phi$ channel**
- **γ from $D_{(1)}{}^0 K^{*0}$ channels difficult if rates not more favourable**
- **Lots of work going on on improvements and on other channels**