Sensitivity to the mixing phase from $B_s \rightarrow J/\psi\phi$ decays at LHCb.

Colin Mclean

School of Physics & Astronomy,
University of Edinburgh.
IOP Conference

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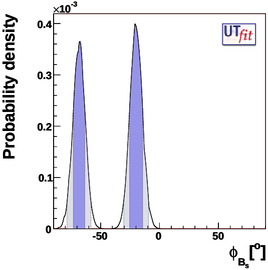

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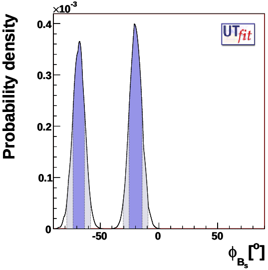

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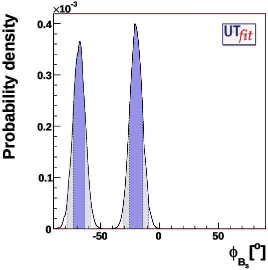

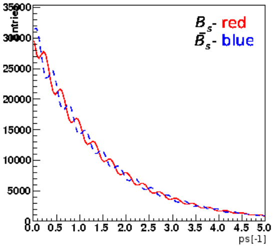

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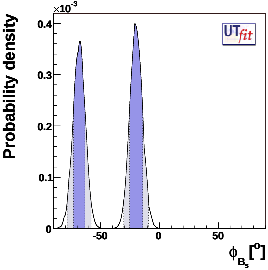
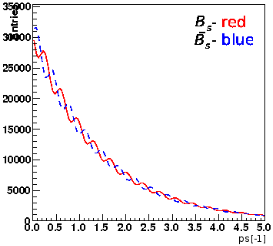
$$|A(t)|^2 \approx |A(0)|^2 \Big[e^{-\Gamma_{\rm L} t} + e^{-\Gamma_{\rm H} t} + 2\ (\mathbf{1} - \mathbf{2}\omega_{\mathbf{tag}})\ e^{-\bar{\Gamma}_s t}\ \sin(\Delta m_s t)\ \sin\phi_s \Big]$$





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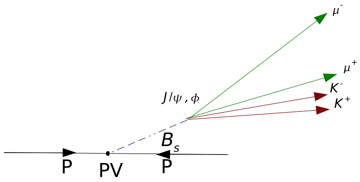

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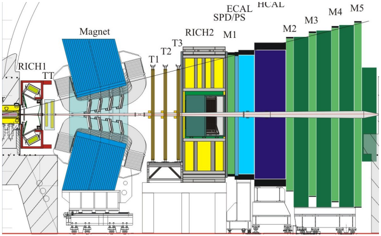
- Clean Signature: 4 charged tracks ($K^{\pm}$,$\mu^{\pm}$) originating from common displaced 2^{nd} vertex.
- Excellent: $\sigma(\tau) \sim 35fs$;
- Kaon ID $\epsilon(K \to K) \sim 83\%$;
- Muon ID $\epsilon(\mu \to \mu) \sim 90\%$;
- With a nominal year $\int \mathcal{L}dt = 2fb^{-1}$, we expect $\sim \times 10^{10}$ B_s mesons.
- Coupled with $\mathcal{BF}_{TOT} \sim (3.9 \pm 1.2) \times 10^{-5}$, means high signal yield.
- All this implies an excellent place to study this channel.



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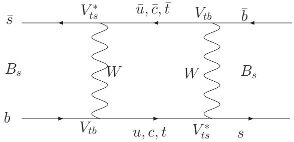

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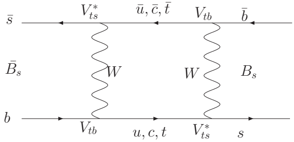

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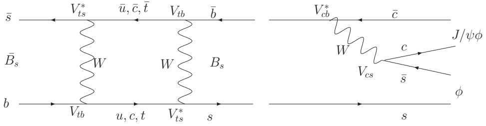

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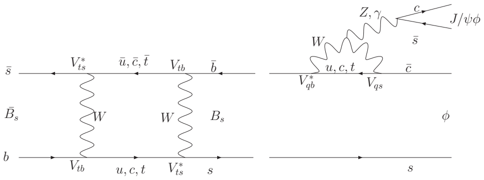

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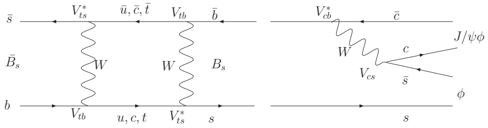

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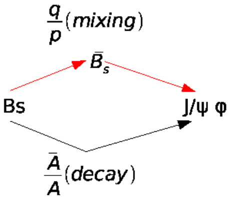

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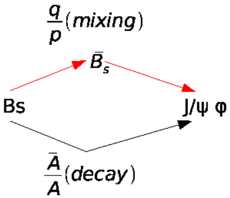

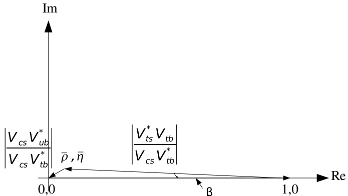

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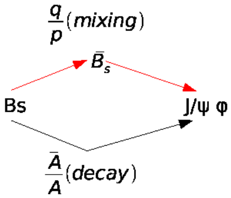

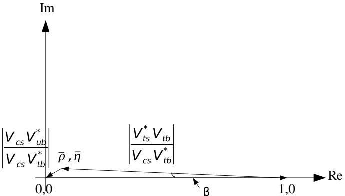

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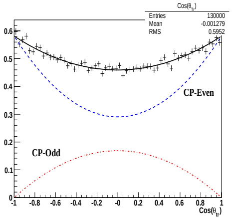

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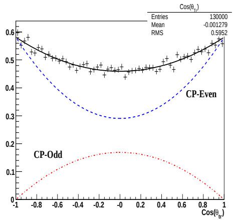

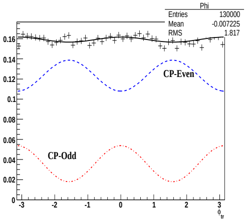

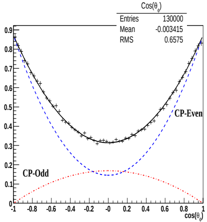

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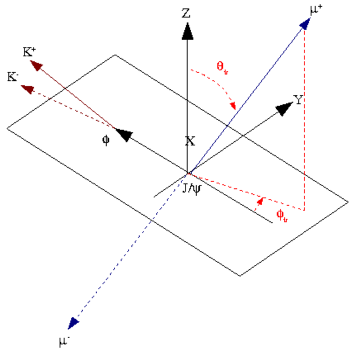
- Define the angles (θ_{tr},ϕ_{tr},θ_{ϕ}) within the transversity basis.
- Where θ_{tr} and ϕ_{tr} are defined within the J/ψ rest frame...



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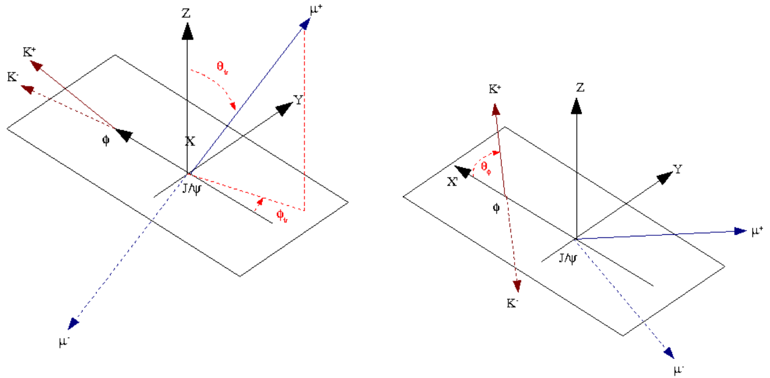

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- 6 time dependent terms enable us to extract ϕ_s and other physics parameters.
- Flavour tagging introduces in $h^{(k)}(t)$ terms a dilution factor, $(1 - 2 \times \omega_{tag}) \sim 0.34$, limiting our sensitivity to ϕ_s.

Expected Sensitivity to ϕ_s from $B_s \rightarrow J/\psi\phi$ decays at LHCb.

Sensitivity to ϕ_s with one nominal year of data

- Perform full angular tagged time-dependent fit to extract *SM* $\sigma(\phi_s)$.

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ϕ_s^{SM}		$0.5 fb^{-1}$	$2 fb^{-1}$	$10 fb^{-1}$
-0.04	$\sigma(\phi_s)$	0.046	0.023	0.01

- D0 [1] $-0.57^{+0.24}_{-0.3}(stat)^{+0.07}_{-0.02}(syst.)$ [2].

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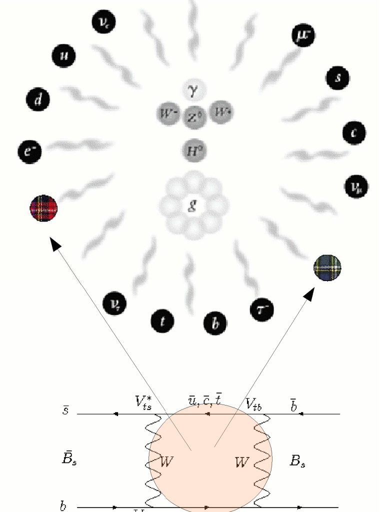
- With higher statistics, it will be LHCb's job to make a precise measurement of this *NP* phase...

Summary

- ... and indirectly perhaps discover new particles.



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2 DO, Measurement of B_s^0 mixing paramters from the flavor-tagged decay $B_s \rightarrow J/\psi\phi$, arXiv:0802.2255v1, 2008.

3 CDF, First Flavor tagged Determination of Bounds on Mixing induced CP violation in $B_s \rightarrow J/\psi\phi$, arXiv:0712.2397v1, 2007.

Selection cuts for $B_s \rightarrow J/\psi\phi$ at LHCb

- Summary of Selection Cuts (applied cuts in red)

Particle	Cut on	DC06 data	ϵ_{sel}^{sig}%
$mu^{\pm}$ $K^{\pm}$	$\Delta \ln \mathcal{L}_{\mu\pi}$ $\Delta \ln \mathcal{L}_{K\pi}$	> -20 > 0	- -
$K^{\pm}$, $\mu^{\pm}$	P_t MeV/c	> 750	67, 28
J/ψ	χ^2 $\Delta M_{J/\psi}$ MeV/c^2	< 6 $\pm$ 85	27 20
ϕ	χ^2 ΔM_{ϕ} MeV/c^2	< 40 $\pm$ 28	32 87
B_s	χ^2 ΔM_{B_s}	< 22.5 $\pm$ 100 MeV/c^2 (tight) $\pm$ 1000 MeV/c^2 (Loose)	20 3

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- Trigger: $\epsilon_{L0} \sim 93\%$, $\epsilon_{HLT} \sim 63\%$.

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- Selection: $\epsilon_{sel} \sim 10\%$.
- Trigger: $\epsilon_{L0} \sim 93\%$, $\epsilon_{HLT} \sim 63\%$.
- $\epsilon_{tot} \sim 1.98\%$.

CP violation in the *SM*

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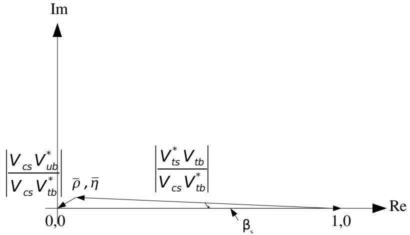
- 3 generations implies 1 phase the source of $\not{CP}$ in the quark sector.

The CKM Matrix

$$\begin{pmatrix} 1-1/2\lambda^2+\frac{1}{4}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^4\lambda^4-A^2\lambda^5(\rho+i\eta) & 1-\frac{1}{2}\lambda^2+\frac{1}{4}\lambda^4(1-2A^2) & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2+A\lambda^4(\frac{1}{2}-\rho-i\eta) & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

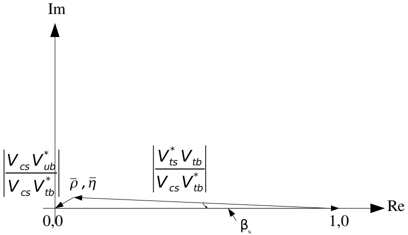
Defining the β_s Unitarity Triangle



B_s mixing

Defining the β_s Unitarity Triangle

(β_s) unitarity triangle



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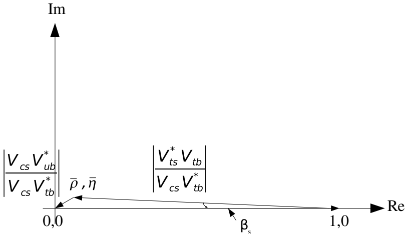

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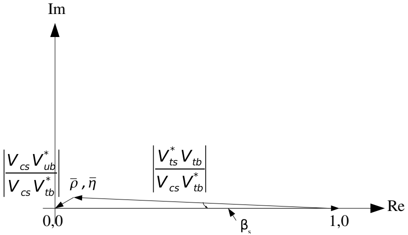

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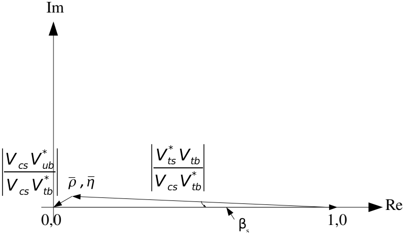

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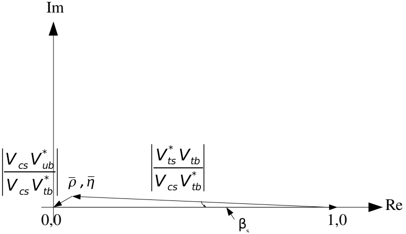

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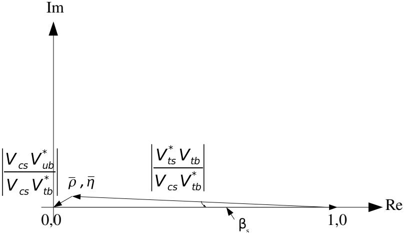

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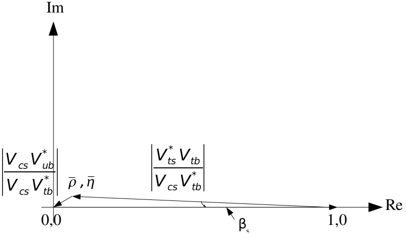
- $\mathcal{O}(0.02)$radians or$\mathcal{O}(1^o)$.



Neutral B_s system

Neutral B_s system

- The time evolution of the B_s flavor eigenstates described by the Schodringer equation:

$$\mathcal{H}_{eff}^{\Delta B=2} = \left[\begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2} \begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix} \right] \begin{pmatrix} |B_s^0\rangle \\ |\bar{B}_s^0\rangle \end{pmatrix},$$

where,

$$M_{12} = \langle \bar{B}_s^0 | \mathcal{H}_{eff}^{\Delta B=2} | B_s^0 \rangle = |M_{12}|\, e^{i\theta_{M_{12}}}, \quad \Gamma_{12} = |\Gamma_{12}|\, e^{i\theta_{\Gamma_{12}}}$$

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- Diagonalize the mass (M) and decay (Γ) matrices gives...
    - .. the mass eigenstates: $|B_L^0\rangle = p|B_q^0\rangle + q|\bar{B}_q^0\rangle, |B_H^0\rangle = p|B_q^0\rangle - q|\bar{B}_q^0\rangle.$

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- Here $\phi_s = arg - \left(\frac{M_{12}}{\Gamma_{12}}\right) \approx 4 \times 10^{-3}$.

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

Reduced angular decay rates.

- θ_{tr} give considerable discriminating power bewteen $\mathcal{CP}$-even and -odd states, and

$$\frac{d\Gamma\left[B_s^o(t) \to J/\psi\phi\right]}{d\cos\theta_{tr}} \propto$$

$$\left(|A_{||}(t)|^2 + |A_o(t)|^2 \frac{1}{2}(1+\cos^2\theta_{tr}) + (|A_\perp(t)|^2)\sin^2\theta_{tr}\right)$$

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

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- simplifies our expressions:

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Reduced angular decay rates

unTagging

$$
\begin{aligned}
& \frac{d\Gamma(t)}{d\cos\theta_{tr}} + \frac{d\bar{\Gamma}(t)}{d\cos\theta_{tr}} \propto \\
& (1-R_\perp)[(1+\cos(\phi_s))e^{-\Gamma_L t} + (1-\cos(\phi_s))e^{-\Gamma_H t} \\
+ \quad & 2e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin(\phi_s)]\frac{1}{2}(1+\cos^2\theta_{tr}) \\
+ \quad & R_\perp[(1-\cos(\phi_s))e^{-\Gamma_L t} + (1+\cos(\phi_s))e^{-\Gamma_H t} \\
- \quad & 2e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin(\phi_s)]\sin^2\theta_{tr}
\end{aligned}
$$

Reduced angular decay rates

Tagging

- Procedure by which we identify the *B* meson flavor at production.

Tagging

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- Inputed from $B_s \to D_s\pi$ decays: $\epsilon_{tag} \sim 57\%$, $\omega_{tag} \sim 33\%$

$$
\begin{aligned}
&(1-\omega_{tag})\frac{d\Gamma(t)}{d\cos\theta_{tr}} + \omega_{tag}\frac{d\bar{\Gamma}(t)}{d\cos\theta_{tr}} \propto \\
&(1-R_\perp)[(1+\cos(\phi_s))e^{-\Gamma_L t} + (1-\cos(\phi_s))e^{-\Gamma_H t} \\
+\quad & 2(\mathbf{1}-\mathbf{2}\omega_{\mathbf{tag}})e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin(\phi_s)]\frac{1}{2}(1+\cos^2\theta_{tr}) \\
+\quad & R_\perp[(1-\cos(\phi_s))e^{-\Gamma_L t} + (1+\cos(\phi_s))e^{-\Gamma_H t} \\
-\quad & 2(\mathbf{1}-\mathbf{2}\omega_{\mathbf{tag}})e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin(\phi_s)]\sin^2\theta_{tr}
\end{aligned}
$$

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

Tagged full angular decay rate

$$(1-\omega_{tag})\frac{d^3\Gamma(t)}{d\cos\theta_{tr}\,d\cos\theta_\phi\,d\phi_{tr}} + \omega_{tag}\frac{d^3\bar{\Gamma}(t)}{d\cos\theta_{tr}\,d\cos\theta_\phi\,d\phi_{tr}} \propto$$

$$\frac{9}{32\pi}\Big[|A_o(t)|^2_{tag}\Theta^1(\theta_{tr},\theta_\phi,\phi_{tr}) + |A_{||}(t)|^2_{tag}\Theta^2(\theta_{tr},\theta_\phi,\phi_{tr})$$
$$+|A_\perp|^2_{tag}\Theta^3(\theta_{tr},\theta_\phi,\phi_{tr}) + \Im(A^*_{||}(t)A_\perp(t))_{tag}\Theta^4(\theta_{tr},\theta_\phi,\phi_{tr}) +$$
$$\Re(A^*_o(t)A_{||}(t))_{tag}\Theta^5(\theta_{tr},\theta_\phi,\phi_{tr}) + \Im(A^*_o(t)A_\perp(t))_{tag}\Theta^6(\theta_{tr},\theta_\phi,\phi_{tr})\Big]$$

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

The time dependent terms

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- Information to extract ϕ_s, $\Delta\Gamma_s$, Δm_s, ω_{tag}.

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

The Angular dependent terms

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Physics potential of the $B_s \to J/\psi\phi$ decay rates.

Time dependent real terms

$$\overbrace{|A_{0,\|}(t)_{tag}|^2}^{\mathcal{CP}\text{-even}} = \frac{|A_{0,\|}(0)_{tag}|^2}{2}\Big[(1+\cos\phi_s)\,e^{-\Gamma_{\rm L}t} + (1-\cos\phi_s)\,e^{-\Gamma_{\rm H}t} + 2(\mathbf{1}-\mathbf{2}\omega_{\mathbf{tag}})e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

$$\overbrace{|A_{\perp}(t)_{tag}|^2}^{\mathcal{CP}\text{-odd}} = \frac{|A_{\perp}(0)_{tag}|^2}{2}\Big[(1-\cos\phi_s)\,e^{-\Gamma_{\rm L}t} + (1+\cos\phi_s)\,e^{-\Gamma_{\rm H}t} - 2(\mathbf{1}-\mathbf{2}\omega_{\mathbf{tag}})e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

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$$\overbrace{|A_{\perp}(t)_{tag}|^2}^{\mathcal{CP}\text{-odd}} = \frac{|A_{\perp}(0)_{tag}|^2}{2}\Big[(1-\cos\phi_s)\,e^{-\Gamma_L t} + (1+\cos\phi_s)\,e^{-\Gamma_H t}$$

$$-\,2(\mathbf{1}-\mathbf{2}\omega_{\mathbf{tag}})e^{-\bar{\Gamma}_s t}\sin(\Delta m_s t)\sin\phi_s\Big]$$

If ϕ_s *SM* like, sensitivity to lifetimes, need interference terms.

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

Time dependent imaginary interference terms

$$\mathrm{Im}\{A_{\parallel}^{*}(t)A_{\perp}(t)\}_{tag} = |A_{\parallel}(0)||A_{\perp}(0)|_{tag}\Big[$$

$$(\mathbf{1}-\mathbf{2}\omega_{\mathbf{tag}})e^{-\Gamma_s t}\sin\delta_1\cos(\Delta m_s t)-\cos\delta_1\sin(\Delta m_s t)\cos\phi_s$$

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- delta's separated from ϕ_s, possible to fit for ϕ_s and the delta's.

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- delta's separated from ϕ_s, possible to fit for ϕ_s and the delta's.
- Interference terms give sensitivity to ϕ_s if *SM* value and additional terms if $\phi_s \neq$ *SM* value.

Physics potential of the $B_s \rightarrow J/\psi\phi$ decay rates.

Simultaneous Fits including: $\delta_{1,2}$, ϕ_s and ω_{tag}

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- Simultaneous fit now possible since fit can separately determine: the period (Δm_s), off-set (δ) and amplitude (1-2ω_{tag}).

Physics potential of the $B_s \to J/\psi\phi$ decay rates.

Simultaneous Fits including: $\delta_{1,2}$, ϕ_s and ω_{tag}

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  - $\frac{(1-2\omega_{tag})}{2} \times (1 + \cos\phi_s)\sin(\delta - \Delta m_s t) + (1 - \cos\phi_s)\sin(\delta + \Delta m_s t)$.

B_s mixing

Pull distibutions of *phis*

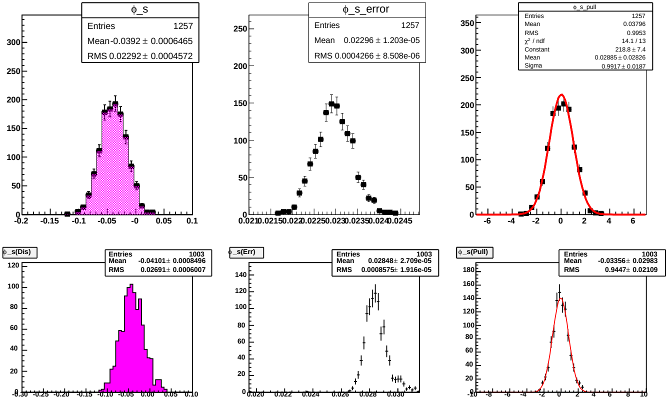

Figure: Including Detector effects

Pull distibutions of *phis*

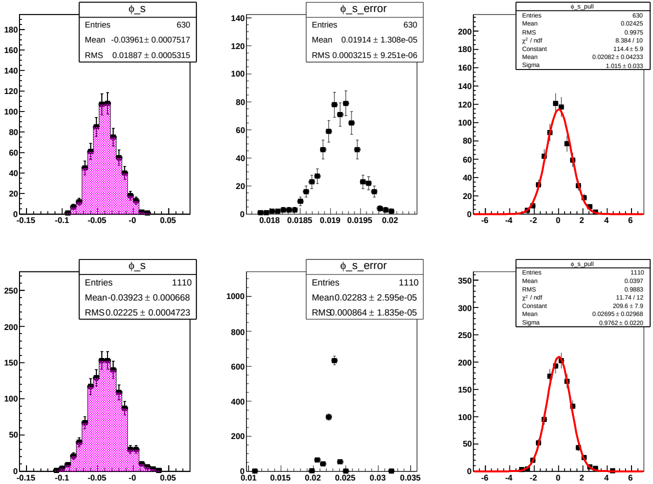

Figure: Not Including Detector effects

Variation studies of ϕ_s sensitivity to ϕ_s

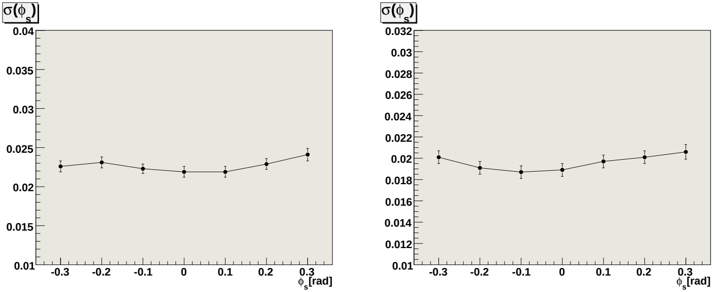

Figure: The effect on ϕ_s sensitivity $\sigma(\phi_s)$ when the central value of ϕ_s is changed. Left: using reduce and Right: using full angular decay rates.