### Measuring the CKM angle $\gamma$

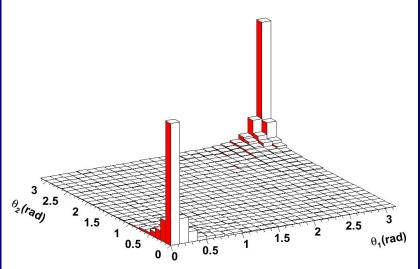
#### J. Blouw

#### Physikalisches Institut, Universitaet Heidelberg

#### Tagungsstaette, Neckarzimmern, March 28-30, 2007



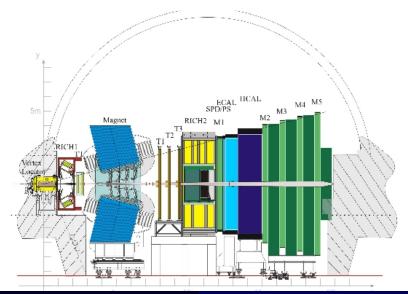
### The LHCb Spectrometer





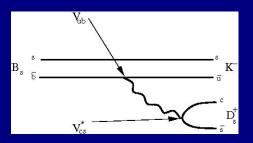
blouw

### The LHCb Spectrometer





#### Feynmann diagram for $B_s \rightarrow D_s^+ K^-$

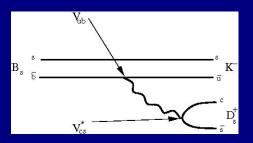


- Only tree diagrams
- But: problem of discrete ambiguities
- Solve by using equivalent decay with B<sub>d</sub>:
- But: very small interference effects for

- Circumvent problems using assumption of U-spin symmetry (s → d)
- 6 Simultaneous analysis of  ${
  m B}_s 
  ightarrow {
  m D}_s^\pm {
  m K}^\mp$  and  ${
  m B}_d 
  ightarrow {
  m D}^\pm \pi^\mp$



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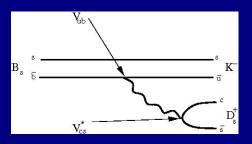


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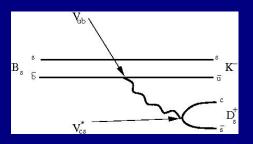
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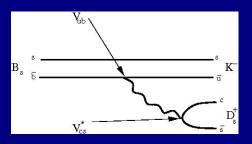


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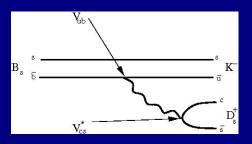
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# $\underset{\gamma \text{ from } B_{\textbf{\textit{s}}} \rightarrow D_{\textbf{\textit{s}}}K}{\text{ from } B_{\textbf{\textit{s}}} \rightarrow D_{\textbf{\textit{s}}}K}$

#### Feynmann diagram for $B_s \rightarrow D_s^+ K^-$

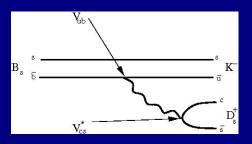


- Only tree diagrams
- But: problem of discrete ambiguities
- Solve by using equivalent decay with B<sub>d</sub>:
- But: very small interference effects for B<sub>d</sub> → D<sup>\*±</sup>π<sup>∓</sup>, andB<sub>d</sub> → D<sup>±</sup>π<sup>∓</sup>
- Solution of U-spin symmetry (s ←→ d)
- 6 Simultaneous analysis of  ${
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#### Feynmann diagram for $B_s \rightarrow D_s^+ K^-$



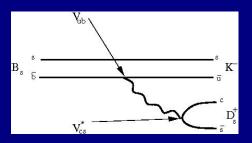
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- <sup>6</sup> Simultaneous analysis of  $B_s \rightarrow D_s^{\pm} K^{\mp}$  and  $B_d \rightarrow D^{\pm} \pi^{\mp}$

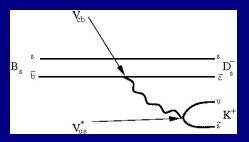


- Sensitivity to  $\gamma$  through
- matrix element  $V_{ub}V_{cs}^*$
- c.f.  $\gamma \sim \arg(V_{ub})$
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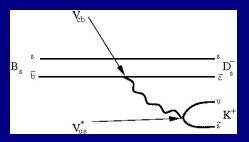
Diagram for  $B_{{\mbox{\scriptsize $s$}}} \to D_{{\mbox{\scriptsize $s$}}}^- K^+$ 





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Diagram for  $B_{{\mbox{\scriptsize $s$}}} \to D_{{\mbox{\scriptsize $s$}}}^- K^+$ 

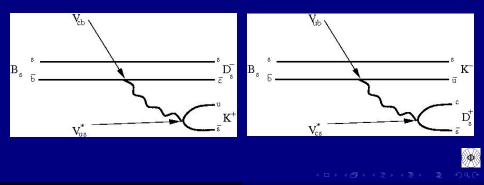




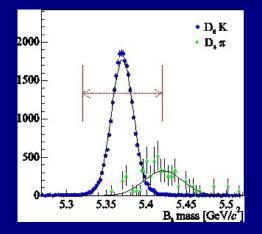
- Sensitivity to  $\gamma$  through
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Diagram for  $B_s \rightarrow D_s^- K^+$ 

Diagram for  ${\rm B}_{\it s} \rightarrow {\rm D}_{\it s}^+ {\rm K}^-$ 



### A Combined $B_s \rightarrow D_s^{\pm} K^{\mp}$ and $B_d \rightarrow D^{\pm} \pi^{\mp}$ Analysis



- Interference through mixing
- CP assymetries measure  $\gamma + \phi_s$
- Tree diagrams only: NO sensitivity to New Physics
- 5400  $B_s \rightarrow D_s K$  events/year at LHCb
- 82000  $B_s \rightarrow D_s \pi$  events/year

$$\mathcal{A}_{\rm CP}({\rm D}_{s}^{+}{\rm K}^{-}) = \frac{{\rm B}_{s} \rightarrow {\rm D}_{s}{\rm K}^{-}(t) - \bar{{\rm B}}_{s} \rightarrow {\rm D}_{s}{\rm K}^{-}(t)}{{\rm B}_{s} \rightarrow {\rm D}_{s}{\rm K}^{-}(t) + \bar{{\rm B}}_{s} \rightarrow {\rm D}_{s}{\rm K}^{-}(t)}$$

dependence:

$$\mathcal{A}_{\rm CP}({\rm D}_{s}^{+}{\rm K}^{-}) = \frac{C_{s}\cos\Delta m_{s}t + S_{s}\sin\Delta m_{s}t}{\cosh(\Delta\Gamma_{s}t/2) - A_{\Delta\Gamma_{s}}\sinh(\Delta\Gamma_{s}t/2)}$$

- 1  $\Delta m_s$ : mass difference between heavy & light B-meson
- <sup>2</sup>  $\Delta\Gamma_s$ : lifetime difference between heavy & light B-meson
- C<sub>s</sub> depends on ratio of amplitudes of Feynmann diagrams
- 4 Similarly done for  $D_s^-K^+$  analysis



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- 4 Similarly done for  $D_s^-K^+$  analysis

 $S_s(\bar{S}_s) \sim sin(\phi_s + \gamma \pm \delta_s)$ 



$$\mathcal{A}_{\rm CP}({\rm D}_{\mathcal{S}}^+{\rm K}^-) = \frac{{\rm B}_{\mathcal{S}} \rightarrow {\rm D}_{\mathcal{S}}{\rm K}^-(t) - \bar{{\rm B}}_{\mathcal{S}} \rightarrow {\rm D}_{\mathcal{S}}{\rm K}^-(t)}{{\rm B}_{\mathcal{S}} \rightarrow {\rm D}_{\mathcal{S}}{\rm K}^-(t) + \bar{{\rm B}}_{\mathcal{S}} \rightarrow {\rm D}_{\mathcal{S}}{\rm K}^-(t)}$$

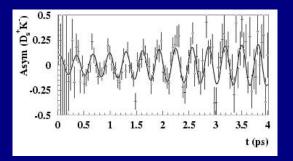
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$$\mathcal{A}_{ ext{CP}}( ext{D}_{s}^{+} ext{K}^{-}) = rac{C_{s}\cos\Delta m_{s}t + S_{s}\sin\Delta m_{s}t}{\cosh(\Delta\Gamma_{s}t/2) - A_{\Delta\Gamma_{s}}\sinh(\Delta\Gamma_{s}t/2)}$$

 Δ*m<sub>s</sub>*: mass difference between heavy & light B-meson
 ΔΓ<sub>s</sub>: lifetime difference between heavy & light B-meson
 C<sub>s</sub> depends on ratio of amplitudes of Feynmann diagrams
 Similarly done for D<sub>s</sub><sup>-</sup>K<sup>+</sup> analysis S<sub>s</sub>(S<sub>s</sub>) ~ sin(φ<sub>s</sub> + γ ± δ<sub>s</sub>)

$$m{A}_{\Delta \Gamma_{m{s}}} \sim -\cos(\phi_{m{s}} + \gamma \pm \delta_{m{s}})$$

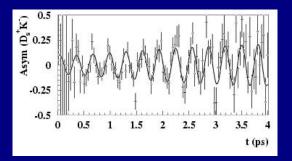




- 1) Phase of  $\mathrm{D}^+_s\mathrm{K}^ \delta_s+(\gamma+\phi_s)$
- <sup>2</sup> Phase of  $D_s^-K^+$   $\delta_s (\gamma + \phi_s)$
- <sup>a</sup>  $\phi_s$  deduced from  $B_s \rightarrow J/\psi \phi$  analysis  $\Longrightarrow$  determine  $\gamma$ .
- 4  $\Delta m_s \sim$  20 ps<sup>-1</sup>:  $\sigma_\gamma \approx$  14°
- <sup>5</sup> Solve discrete ambiguities with help of  $B_d \rightarrow D^+ \pi^-$



From  $\sim$  5 years of LHCb data:

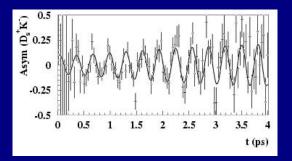


#### 1 Phase of $\mathrm{D}^+_s\mathrm{K}^ \delta_s+(\gamma+\phi_s)$

- <sup>2</sup> Phase of  $\mathrm{D}_{s}^{-}\mathrm{K}^{+}$   $\delta_{s}-(\gamma+\phi_{s})$
- <sup>a</sup>  $\phi_s$  deduced from  $B_s \rightarrow J/\psi \phi$  analysis  $\Longrightarrow$  determine  $\gamma$ .
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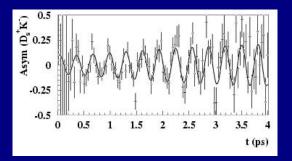
1 Phase of  $\mathrm{D}^+_s\mathrm{K}^ \delta_s+(\gamma+\phi_s)$ 

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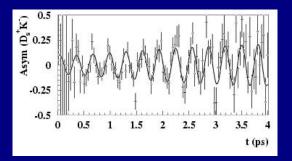
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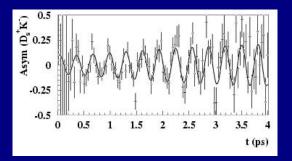
- 1) Phase of  $\mathrm{D}^+_s\mathrm{K}^ \delta_s+(\gamma+\phi_s)$
- 2 Phase of  $D_s^-K^+ \delta_s (\gamma + \phi_s)$
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- $^{_{(4)}}$   $\Delta m_s \sim$  20 ps<sup>-1</sup>:  $\sigma_\gamma pprox$  14°
- <sup>6</sup> Solve discrete ambiguities with help of  $B_d \rightarrow D^+ \pi^-$





- 1) Phase of  $\mathrm{D}^+_s\mathrm{K}^ \delta_s+(\gamma+\phi_s)$
- <sup>2</sup> Phase of  $D_s^-K^+ \delta_s (\gamma + \phi_s)$
- <sup>3</sup>  $\phi_s$  deduced from  $B_s \rightarrow J/\psi \phi$  analysis  $\Longrightarrow$  determine  $\gamma$ .
- $\Delta m_s \sim 20 \text{ ps}^{-1}$ :  $\sigma_\gamma \approx 14^\circ$
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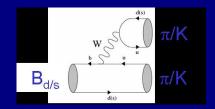
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### $\gamma$ from $\mathbf{B} \rightarrow h^+ h^-$

- 1) time-dependent CP-asymmetries for  ${\rm B}^0_{\rm d} \to \pi^+\pi^-$
- $^{2} \quad \text{and} \ B_{s} \to K^{+}K^{-}$
- But: penguin diagram contributes!
- 4)  $A_{
  m dir}, A_{
  m mix}$  depend on  $\phi_s, \phi_d$  &  $\gamma$
- and on ratio of penguin to tree amplitudes: de<sup>iθ</sup>
- with U-spin symmetry:  $d_{\pi\pi} = d_{\rm KK}, \ \theta_{\pi\pi} = \theta_{\rm KK}$
- 7  $\phi_s$  from  $B_s \rightarrow J/\psi \phi$  and  $\phi_d$  from  $B_d \rightarrow J/\psi K_s$
- 4 measurements, 3 unknowns  $\implies$  extract  $\gamma, \sigma_{\gamma} = 5^{\circ}$

#### Tree diagram:

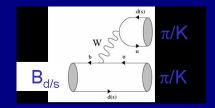




### $\gamma$ from $\mathbf{B} \rightarrow h^+ h^-$

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#### Tree diagram:

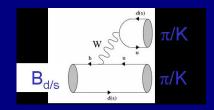




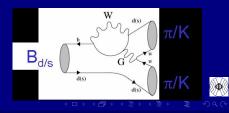
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#### Tree diagram:



#### Penguin diagram:





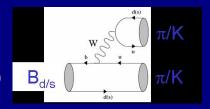
#### $\gamma$ from $\mathbf{B} \rightarrow h^+ h^-$

- time-dependent CP-asymmetries for  $B^0_d \rightarrow \pi^+\pi^-$
- <sup>2</sup> and  $B_s \rightarrow K^+K^-$
- But: penguin diagram contributes!

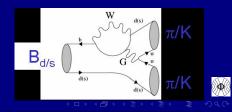
 $A_{CP}(t) = A_{dir} \cos(\Delta m t) + A_{mix} \sin(\Delta m t)$ 

- <sup>4</sup>  $\textit{A}_{
  m dir},\textit{A}_{
  m mix}$  depend on  $\phi_{\textit{s}},\phi_{\textit{d}}$  &  $\gamma$
- and on ratio of penguin to tree amplitudes: de<sup>iθ</sup>
- with U-spin symmetry:  $d_{\pi\pi} = d_{KK}, \ \theta_{\pi\pi} = \theta_{KK}$
- 7  $\phi_s$  from  $B_s \rightarrow J/\psi \phi$  and  $\phi_d$  from  $B_d \rightarrow J/\psi K_s$
- 4 measurements, 3 unknowns ⇒ extract  $\gamma$ ,  $\sigma_{\gamma} = 5^{\circ}$

#### Tree diagram:



#### Penguin diagram:

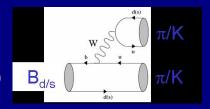


- time-dependent CP-asymmetries for  $B^0_d \rightarrow \pi^+\pi^-$
- <sup>2</sup> and  $B_s \rightarrow K^+K^-$
- But: penguin diagram contributes!

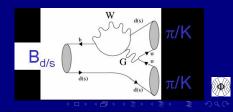
 $A_{CP}(t) = A_{dir} \cos(\Delta m t) + A_{mix} \sin(\Delta m t)$ 

- A<sub>dir</sub>, A<sub>mix</sub> depend on  $\phi_s$ ,  $\phi_d$  &  $\gamma$
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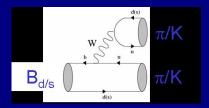


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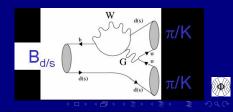
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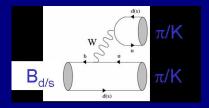
blouw

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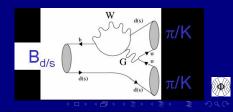
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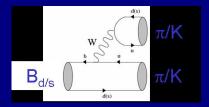
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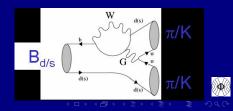
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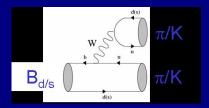
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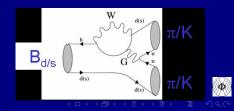
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#### Tree diagram:



#### Penguin diagram:



blouw

#### Determine $\gamma$ from tree-diagrams only: $B_s \rightarrow D_s^{\pm} K^{\mp}$

- Use U-spin symmetry to resolve discrete ambiguities
- Measure time-dependent CP-asymmetry
- $\bigcirc \phi_s$  measured with  $\mathrm{B}_s \to J \ / \ \psi \phi$  analysis
- <sup>2</sup> Determine  $\gamma$  from  $B_s \to K^{\pm}K^{\mp}$  and  $B^0 \to \pi^+\pi^-$ 
  - Measure 2 time-dependent CP
    - asymmetries
  - Problem: penguin diagram contributes
  - Need angles  $\phi_s$  and  $\phi_d$  from
    - $\mathrm{B}_{s} 
      ightarrow J \ / \ \psi \phi \ \mathrm{and} \ \mathrm{B}^{0} 
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- $\circledast \implies$  sensitivity to New Physics through Penguin diagram



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