Physics Program

- Data taking starts September 2008
- 2009: detector calibration
  (To obtain required precision, can not rely on simulation)
  - B field calibration
  - PID calibration
  - Flavour tagging algorithm
  - Reference analysis \((\sin(2\beta), \Delta m_s)\) of known quantities to test/cross-check complete machinery
- 2010: First “real” analysis:
  - CP violation in \(B_s\) System (phase \(\phi_s\))
  - Measurement of CKM angle \(\gamma\)
  - Branching ratio of rare decays: \(B_s \rightarrow \mu^+\mu^-\)
  - Photon helicity in \(B_s \rightarrow \phi\gamma\)
  - Forward Backward Asymmetrie in \(B_d \rightarrow K^*\mu^+\mu^-\)
flavour eigen states $B$ & $\bar{B} \neq$ mass eigen states $B_H$ & $B_L$

<table>
<thead>
<tr>
<th></th>
<th>$B_d$</th>
<th>$B_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m = m_H - m_L$</td>
<td>$0.5 \text{ ps}^{-1}$</td>
<td>$17.8 \text{ ps}^{-1}$</td>
</tr>
<tr>
<td>$\Delta \Gamma = \Gamma_L - \Gamma_H$</td>
<td>$\mathcal{O}(0.01) \Gamma_d$</td>
<td>$\mathcal{O}(0.1) \Gamma_s$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$\arg (V_{tb}V^*_{td})^2 (=2\beta)$</td>
<td>$\arg (V_{tb}V^*_{ts})^2 (=2\beta_s)$</td>
</tr>
<tr>
<td></td>
<td>$\sin(2\beta) \sim 0.7$</td>
<td>$\sim 0.04 \text{ (SM prediction)}$</td>
</tr>
</tbody>
</table>

$B_d$: slow mixing, $\Delta \Gamma$ not measurable, large mixing phase

$B_s$: fast mixing, significant $\Delta \Gamma$, small mixing phase (SM)
Wolfenstein Parameterization: $\lambda, A, \rho, \eta$; ($\lambda \approx 0.22$)

$$V_{CKM} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}$$

$$= \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)$$

Only very small complex contributions, up to third order in $\lambda$ ($\sim 0.5\%$) only in $V_{ub}$ and $V_{td}$
New Physics in $B_s$ System

$\Delta m_s$ sensitive to new particles in the loop. However, $\Delta m_s$ more precisely measured, than current theoretical prediction.

$|V_{td}|/|V_{ts}| = 0.2061 \pm 0.0007 \text{ (exp.)}^{+0.0081}_{-0.0060} \text{ (theo.)}$

Consistent with indirect measurements

$\Rightarrow$ confirmation of the Standard Model

We can exclude large NP contributions, we are not sensitive to small contributions.
\( \Delta \Gamma_s \) can not be affected by any NP (dominated by tree diagram) However \( \Delta \Gamma_s \) so far only purely measured)

There can be potential new physics involved in phase \( \phi_s \). (\( \Delta m_s \) just measures the absolute value of \( V_{ts} \) not the phase!

\[
\rightarrow |\Delta \Gamma_s|_{eff} = \Delta \Gamma_s(SM) \times |\cos \phi_s| \quad \text{(true for any NP)}
\]

Measurements from CDF and D0 from this winter indicate both a 2 \( \sigma \) deviation from SM value! \( \rightarrow \) “smoking gun” for LHCb
How to measure $\phi_s$

Basic idea similar to measurement of $\sin(2\beta)$:

However $J/\psi K_s$ is CP final state, while $J/\psi \phi$ is combination of several CP final states ...
\[ B_d \quad : \quad J^P = 0^{-1} \]
\[ J/\psi \quad : \quad J^{CP} = 1^{-1-1} \]
\[ K_s \quad : \quad J^{CP} = 0^{-1-1} \]

\[ \text{CP}(J/\psi K_s) = \text{CP}(J/\psi)^*\text{CP}(K_s)^*(-1)^L \]

Angular momentum conversation:
\[ 0 = J (J/\psi K_s) = |\vec{S} + \vec{L}|; \to L = 1 \]

\[ B_s \quad : \quad J^P = 0^{-1} \]
\[ J/\psi \quad : \quad J^{CP} = 1^{-1-1} \]
\[ \phi \quad : \quad J^{CP} = 1^{-1-1} \]

\[ \text{CP}(J/\psi \phi) = \text{CP}(J/\psi)^*\text{CP}(\phi)^*(-1)^L \]

Final states no CP eigenstates but linear combination!
Angular Analysis

Different angular momentum in final state
→ different angular distribution of decay products.

→ 3 angles define rel. angular distribution of 4 daughter tracks.

Transversity base
Angular distribution to statistically separate CP even/odd contributions.
\[\Gamma(B_s/\bar{B}_s \rightarrow J/\psi\phi) = f_1(\theta_{tr}, \phi_{tr}, \theta_\phi)e^{-\Gamma_{Lt}} + f_2(\theta_{tr}, \phi_{tr}, \theta_\phi)e^{-\Gamma_{Ht}} + f_3(\theta_{tr}, \phi_{tr}, \theta_\phi)(e^{-\Gamma_{Ht}} - e^{-\Gamma_{Lt}})\cos(\phi_s) + f_4(\theta_{tr}, \phi_{tr}, \theta_\phi)e^{-\Gamma_t}\sin(\Delta m_{st}) + f_5(\theta_{tr}, \phi_{tr}, \theta_\phi)e^{-\Gamma_t}\sin(\Delta m_{st})\sin(\phi_s)\]

Last two terms cancel if no flavour tag is used in the analysis.

Third term provides sensitivity to \(\phi_s\) even in untagged analysis, because \(\Delta \Gamma_s\) is sizeable in \(B_s\) system.
(No untagged analysis possible in \(B_d\) system, \(\Delta \Gamma_d\) too small. )

If true value of \(\phi_s\) around \(\pi/2\), untagged analysis has similar sensitivity than tagged one.

If true value of \(\phi_s\) around 0, tagged analysis is needed.
**$B_s \rightarrow J/\psi \phi$**

- Simultaneous likelihood analysis in time, mass, full 3d-angular distribution
- Include mass sidebands to model the time spectrum and angular distribution of the background
- Model the $\tau$ resolution
  \[ \sigma (\phi_s) = 0.02 \]

See talk of Olivier Leroy
1. Pure CP eigenstates:
Low yield, high background

2. Admixture of CP eigenstates
“Golden mode”: $B_s \rightarrow J/\psi \phi$
Large yield, nice signature
However requires angular analysis to disentangle
CP-even and CP-odd

<table>
<thead>
<tr>
<th>Decay</th>
<th>Yield ($2\text{fb}^{-1}$)</th>
<th>$\sigma(\phi_s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \eta_{\gamma\gamma}$</td>
<td>8.5 k</td>
<td>0.109</td>
</tr>
<tr>
<td>$J/\psi \eta_{\pi\pi\pi}$</td>
<td>3k</td>
<td>0.142</td>
</tr>
<tr>
<td>$J/\psi \eta_{\pi\pi\eta}$</td>
<td>2.2k</td>
<td>0.154</td>
</tr>
<tr>
<td>$J/\psi \eta_{\rho\gamma}$</td>
<td>4.2k</td>
<td>0.008</td>
</tr>
<tr>
<td>$\eta_{c\phi}$</td>
<td>3k</td>
<td>0.108</td>
</tr>
<tr>
<td>$D_s^+ D_s^-$</td>
<td>4k</td>
<td>0.133</td>
</tr>
<tr>
<td>All CP eig</td>
<td>-</td>
<td>0.046</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>130k</td>
<td>0.023</td>
</tr>
<tr>
<td>All</td>
<td>-</td>
<td>0.021</td>
</tr>
</tbody>
</table>
Penguin Decay: $B_s \rightarrow \phi\phi$

$$2\beta_s - 2\omega = 2\beta_s - 2\omega = 0$$

No CP violation in the standard model, phases chancel out (no theoretical uncertainties).

Any phase would be sign of New Physics.

Angular analysis similar to $B_s \rightarrow J/\psi\phi$

20k expected candidates per year

Lower yield rel. to $B_s \rightarrow J/\psi\phi$ due to penguin suppression.

$\sigma_{\phi_s}: 0.08$
Angles of Unitarity Triangle

Rescaled Unitarity Triangle

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \]

\[ \alpha = \arg \left( -\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right) \]

\[ \beta = \arg \left( -\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right) \]

\[ \gamma = \arg \left( -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right) \]
So far $\gamma$ is known up to $\pm$ 15 degree.
Measurement of CKM angle $\gamma$

Two main approaches:

- $\gamma$ from tree decays
  no loops $\rightarrow$ no contributions from new particles $\rightarrow$ pure SM value of $\gamma$

- $\gamma$ in interference of tree and penguin diagrams
  $\rightarrow$ sensitive to new particles in the penguin contribution

Several analysis for both approaches exist.
A significant difference in the result of both methods would be clear sign for new physics!
\[ \gamma + \phi_s \text{ in } B_s \to D_s K \]

- Time dependent CP violation in interference of \( b \to c \) and \( b \to u \) decays:

\[ A^{\overline{B}/B}_{D_s^+K^-} = \frac{\left(1 - |\lambda|^2\right) \cos \Delta m t - 2 |\lambda| \sin (\delta_s + (\gamma + \phi_s)) \sin (\Delta m t) \left(1 + |\lambda|^2\right) \cosh \frac{\Delta \Gamma t}{2} - 2 |\lambda| \cos (\delta_s + (\gamma + \phi_s)) \sinh \frac{\Delta \Gamma t}{2}}{\left(1 + |\lambda|^2\right) \cosh \frac{\Delta \Gamma t}{2} - 2 |\lambda| \cos (\delta_s + (\gamma + \phi_s)) \sinh \frac{\Delta \Gamma t}{2}} \]
\( \gamma \) in \( B_s \to D_s K \)

- Since same topology \( B_s \to D_s K, B_s \to D_s \pi \) combine samples to fit \( \Delta m_s, \Delta \Gamma_s \) and \( W_{tag} \) together with CP phase \( \gamma^+ \phi_s \).

Additional tree level diagrams:

\[
B^\pm \to D^0 K^\pm, \quad B^0 \to D^0 K^* \]

Combined sensitivity \( \sim 5^\circ \) with \( 2 fb^{-1} \)
γ in Loop Diagrams

36k $B_S \rightarrow K^+ K^-$ events
36k $B_d \rightarrow \pi^+ \pi^-$ events
10k $B_S \rightarrow K \pi$ events
138k $B_d \rightarrow K \pi$ events
sensitivity to $\gamma$ of $\sim 10^\circ$ with 2 fb$^{-1}$

Every $h^+ h^-$ channel is potentially a bg for the other channel.
Why are we so keen on rare decays?

Pure statistical reason:
add. 10 NP events on 1000 SM events not significant: $\sigma \propto \sqrt{N}$
However 10 NP events on 0 SM events are very significant!

In SM no quark mixing in neutral currents! (no FCNC)
Therefore only higher order diagrams contribute to this process:

$$BR(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$$

e.g. SUSY up to $\times 1000$ higher rates
$\propto \tan^6\beta$. 
Potential signal at $m(B_s) = 5.37$ GeV

Excellent understanding of trigger and selection cuts required!
$B_s \rightarrow \mu^+\mu^-$ @ the Tevatron

Comb. Tevatron limit: $\text{BR}(B_s \rightarrow \mu^+\mu^-) < 4.0 \times 10^{-8}$

Places already strong restriction on many new physics models!
$B_s \rightarrow \mu^+ \mu^-$

**Event Selection:**

**Main Backgrounds:**
- $b \rightarrow \mu$, $b \rightarrow \mu$
- $B \rightarrow hh$

**Suppressed by:**
- Mass & Vertex resolution
- Particle Identification

<table>
<thead>
<tr>
<th>Channel</th>
<th>SM Yield (2 fb$^{-1}$)</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s \rightarrow \mu\mu$</td>
<td>30</td>
<td>83</td>
</tr>
</tbody>
</table>

With 2 fb$^{-1}$ (1 "year"):
- Observe BR: $6 \times 10^{-9}$ with 5 $\sigma$
- Assuming SM BR: 3$\sigma$ observation

If we only see SM, MSSM is excluded!

MSSM: minimal super symmetric model;
Other SUSY models can in principle still be realized, however they contain significant more problems than they actually solve!
No one really believe in extended SUSY models.
Standard Model: \( W \) couples to LH particles (\& RH antiparticles) (handiness = chirality is a quantum number)

For mass less particles (e.g. photon) chirality \( \equiv \) helicity = \( \frac{\vec{s} \cdot \vec{p}}{||\vec{s}|| \cdot ||\vec{p}||} \)

For particles with mass, e.g. quarks chirality \( \neq \) helicity.

As quark masses are small, \( W \) couples dominantly to helicity=1 quarks, accordingly LH \( \gamma \)

NP can give significant RH component

Potential decays:
\( B_s \rightarrow \phi \gamma; \ B_s \rightarrow K^* \gamma \)
Current Status: $B_s \rightarrow \phi \gamma$

Multi purpose Tevatron experiments not good enough to see $\gamma$ (calorimeter).

$B$ factories Babar & Belle ($e^+ e^- \text{ collider @ SLAC & KEK}$) normally run at a $\sqrt{s}=Y(4s)$, below $B_s \bar{B}_s$ production treshold.

Short run @ Y(5s) resonance gave first $B_s \rightarrow \phi \gamma$ events.

5.5 $\sigma$ observation

$$BR(B_s \rightarrow \phi \gamma) = 5.7^{+1.8}_{-1.5}^{+1.2}_{-1.7} \times 10^{-5}$$

SM predictions: $(3.94 \pm 1.19) \times 10^{-5}$
New Physics in $B_s \rightarrow \phi\gamma$

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>NP</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ polarization</td>
<td>predominantly left handed</td>
<td>right handed components</td>
</tr>
<tr>
<td>CPV in decay</td>
<td>$&lt; 1 %$</td>
<td>0%-40%</td>
</tr>
</tbody>
</table>

Inclusive decays: theory ↑ experiment ↓
Exclusive decays: theory ↓ experiment ↑

CPV in interference mixing & decay

$B^0 (B^0 \bar{b}) \rightarrow X^0 \gamma$

very small

$B^0 (B^0 \bar{b}) \rightarrow X^0 \gamma$

Could be large

exp. event rate in 2 fb$^{-1}$ (1 year):

$B_s \rightarrow K^*\gamma$: 68.000 
$B_s \rightarrow \phi\gamma$: 11.500
\[ B_s \rightarrow \phi \gamma \]

\[ A_{\text{symmetrie}} = \frac{\Gamma(\bar{B}_s \rightarrow V\gamma) - \Gamma(B_s \rightarrow V\gamma)}{\Gamma(\bar{B}_s \rightarrow V\gamma) + \Gamma(B_s \rightarrow V\gamma)} \]

\[ = \frac{A^{\text{dec}} \cos(\Delta m t) + A^{\text{mix}} \sin(\Delta m t)}{\cosh(\frac{\Delta \Gamma t}{2}) + A^\Delta \sinh(\frac{\Delta \Gamma t}{2})} \]

\[ V = K^* \text{ or } \phi \]

\[ A^\Delta \text{ asymmetry due to contribution of RH photons} \]
\[ A^{\text{mix}} \text{ CPV in mixing and decay} \]
\[ A^{\text{dec}} \text{ CPV in decay} \]

**SM predictions:**
\[ A^{\text{dec}} \sim 0, \ A^{\text{mix}} \sim \sin(2\psi) \sin(2\phi_s), \ A^\Delta \sim \cos(2\psi) \cos(2\phi_s) \]
\[ \tan \psi: \text{ratio of } \gamma(RH)/\gamma(LH) \sim 0.25 \]
Expected sensitivity (2 fb$^{-1}$):
72k $B \rightarrow K^*\gamma$, 11k $B_s \rightarrow \phi\gamma$

$\sigma(A^{dec})=0.11$, $\sigma(A^{mix})=0.11$, $\sigma(A^{\Delta})=0.22$

(13 min $\sim$ 37M $b\bar{b}$ events)
$b \rightarrow s \ell^+ \ell^-$

- Second-order diagrams
- Sensitive to
  - SUSY
  - graviton exchange
  - extra dimensions
Observables in $B_s \rightarrow K^* \ell^+ \ell^-$

Problem:

- inclusive decays difficult to access at hadron colliders
- exclusive decays affected by hadronic uncertainties

Solution: Use ratios where hadronic uncertainties cancel out

- CP asymmetry
- Ratio of $e^+e^-$ and $\mu^+\mu^-$ modes
- Forward-backward asymmetry (FBA)
- CP asymmetry in FBA
- Zero of FBA

\[ B \xrightarrow[\theta]{} K^* \]

\[ \mu_- \]

\[ \mu_+ \]

\[ \ell^+ \]

\[ \ell^- \]

\[ s [\text{GeV}^2] \]

\[ \frac{d\sigma(B \rightarrow K^* \ell^+ \ell^-)}{ds} \]

\[ \text{SM} \quad \cdots \quad \text{SUSY} \]

\[ \cdots \quad \text{FV SUSY} \quad \cdots \quad \text{FV SUSY} \]
$B_d \rightarrow K^* \mu^+ \mu^-$

Current best result from BELLE ($e^+e^-$ machine; B factory):

To few statistics to draw any conclusion.
$B_d \rightarrow K^* \mu^+ \mu^-$

Standard model: $s_0 = 4.2 \pm 0.6 \text{ GeV}^2$

LHCb prospects: $\sigma(s_0) = 0.46/0.27 \text{ GeV}^2 \ @ \ 2/10 \text{ fb}^{-1}$
\[ B \rightarrow K\mu^+\mu^- / B \rightarrow Ke^+e^- \]

\[ R_X = \frac{BR(B\rightarrow X\mu^+\mu^-)}{BR(B\rightarrow Xe^+e^-)} = 1 + \mathcal{O}\left(\frac{m_\mu^2}{m_b^2}\right) \text{ (in SM)} \]

Study \( B \rightarrow K\mu^+\mu^- \) (3.8k events/2 fb\(^{-1}\))
and \( B \rightarrow Ke^+e^- \) (1.9k events/2 fb\(^{-1}\))

\( \rightarrow \sigma(R_k) \sim 4.3\% \)

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**Experimental status:**

<table>
<thead>
<tr>
<th>( R_X )</th>
<th>BaBar (208 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_K )</td>
<td>1.06 ± 0.48 ± 0.05</td>
</tr>
<tr>
<td>( R_{K^*} )</td>
<td>0.93 ± 0.46 ± 0.12</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( R_K )</th>
<th>Belle (250 fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_K )</td>
<td>1.38 +0.39 +0.06 -0.41 -0.07</td>
</tr>
<tr>
<td>( R_{K^*} )</td>
<td>0.98 +0.30 ± 0.08</td>
</tr>
</tbody>
</table>

**For \( B_s \rightarrow \mu\mu \):** The present CDF limit is \( 1.5 \cdot 10^{-7} \) at 90\% CL

[hep-ex/0508036]
LHCb is dedicated experiment to exploit enormous B production rate at the LHC.

Precision measurements of loop-suppressed B decays opens a window to look for New Physics.

Asymmetries are a good handle to access New Physics in a theoretical clean way.

This approach is complementary to direct searches for New Physics at CMS & ATLAS.

Precision measurement require a lot of calibration work before!